Sources and detection of high-energy cosmic events:
a journey through neutrinos and fast radio bursts.

Valentin Decoene

The high-energy Universe and the advent of multimessenger astronomy

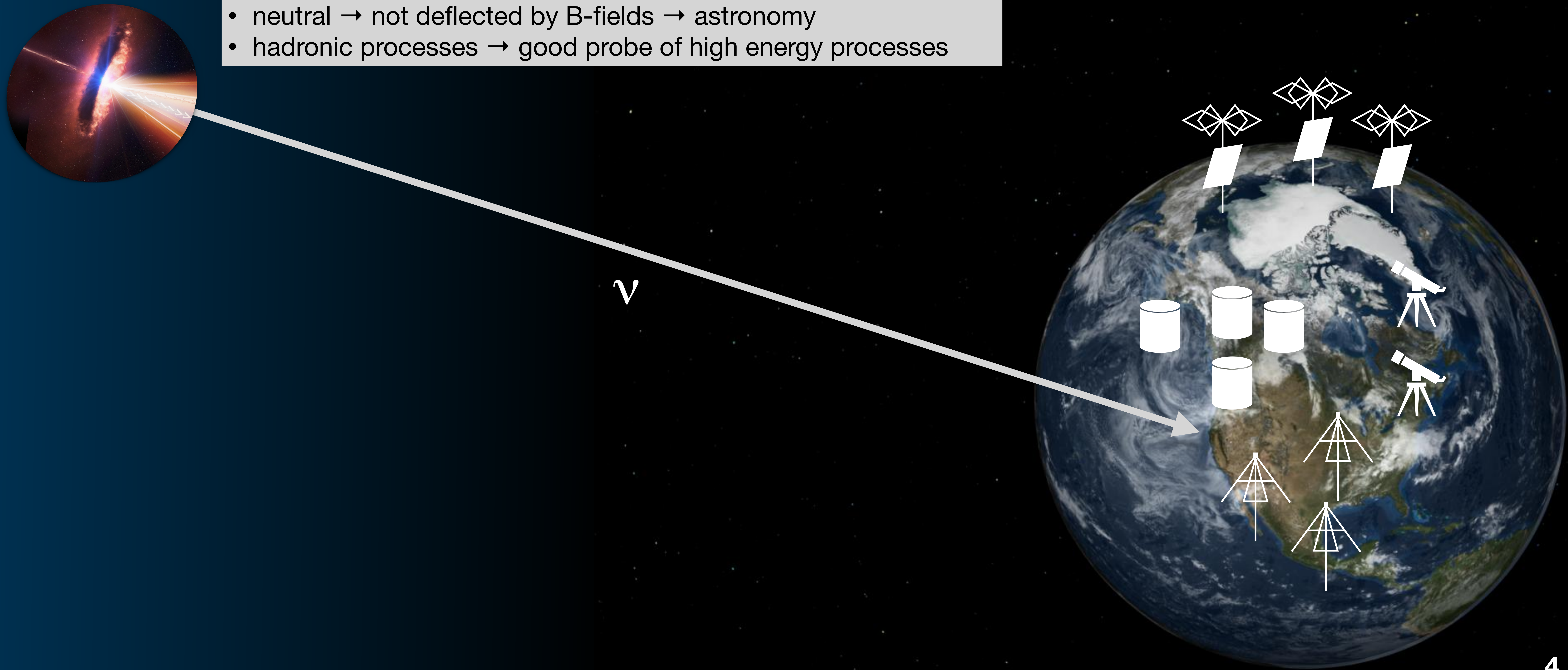
Multi-messenger astronomy

The cosmic neutrino enigma

in the high-energy and ultra high-energy regime

Neutrinos pros:

- low cross section → low interaction length → astronomy
- neutral → not deflected by B-fields → astronomy
- hadronic processes → good probe of high energy processes



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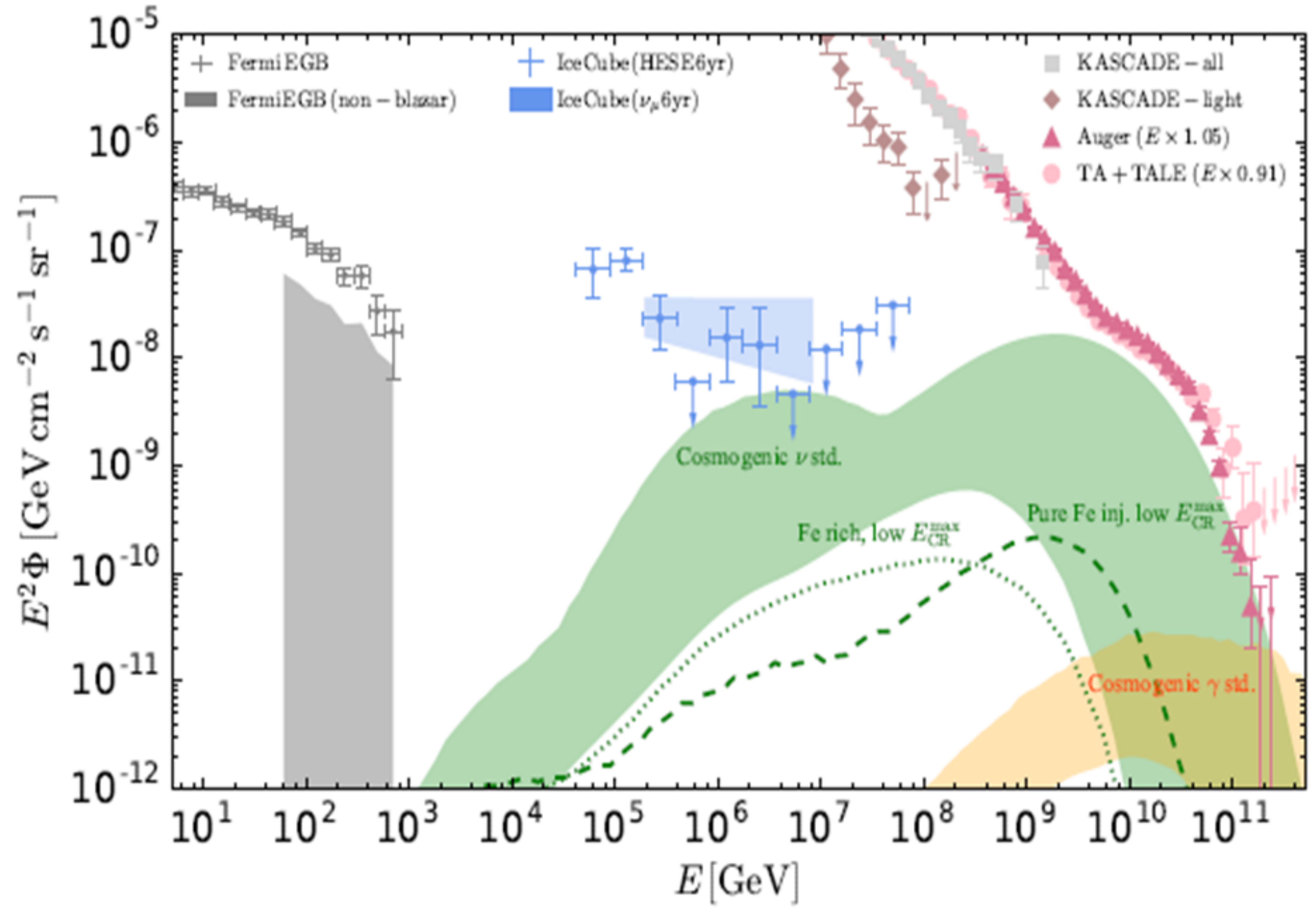


GRAND white paper 2018.

- Sources?
  - what are the sources of observed neutrinos?
  - what could be the sources of more energetic neutrinos?
  - can we detect neutrinos from new transients events?
- How to detect them?
  - new generation of detector?
  - detector optimisation?
  - reconstruction methods?

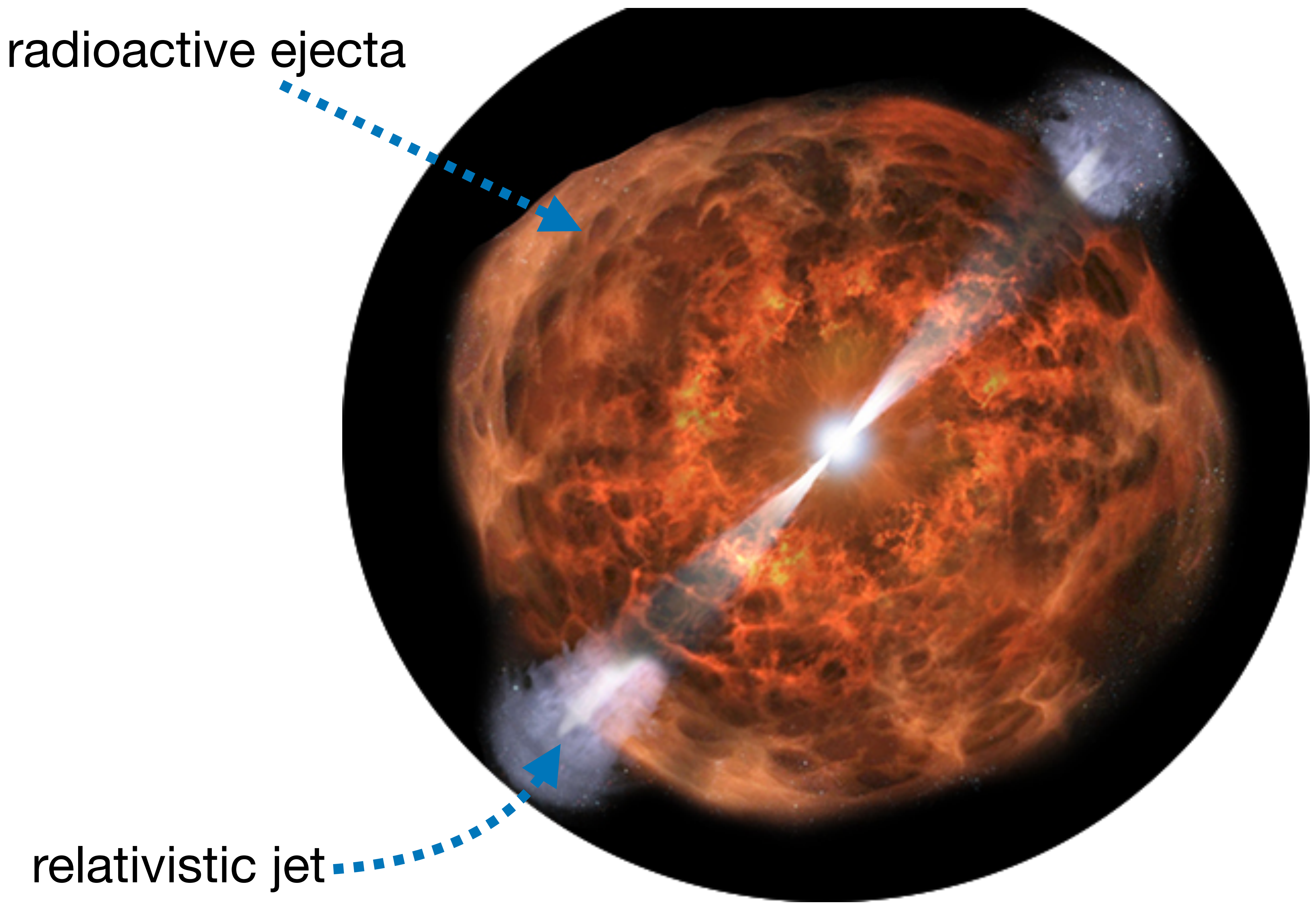
Is GW170817 a neutrino source ?

- highly energetic $L \approx 10^{52}$ erg.s^{-1}
- high baryon loading

good candidates for →

- photons (EM) ✓
- gravitational waves (GW) ✓
- ultra high-energy cosmic rays (UHECR)
- neutrinos

GW170817: neutron star merger (NSM)



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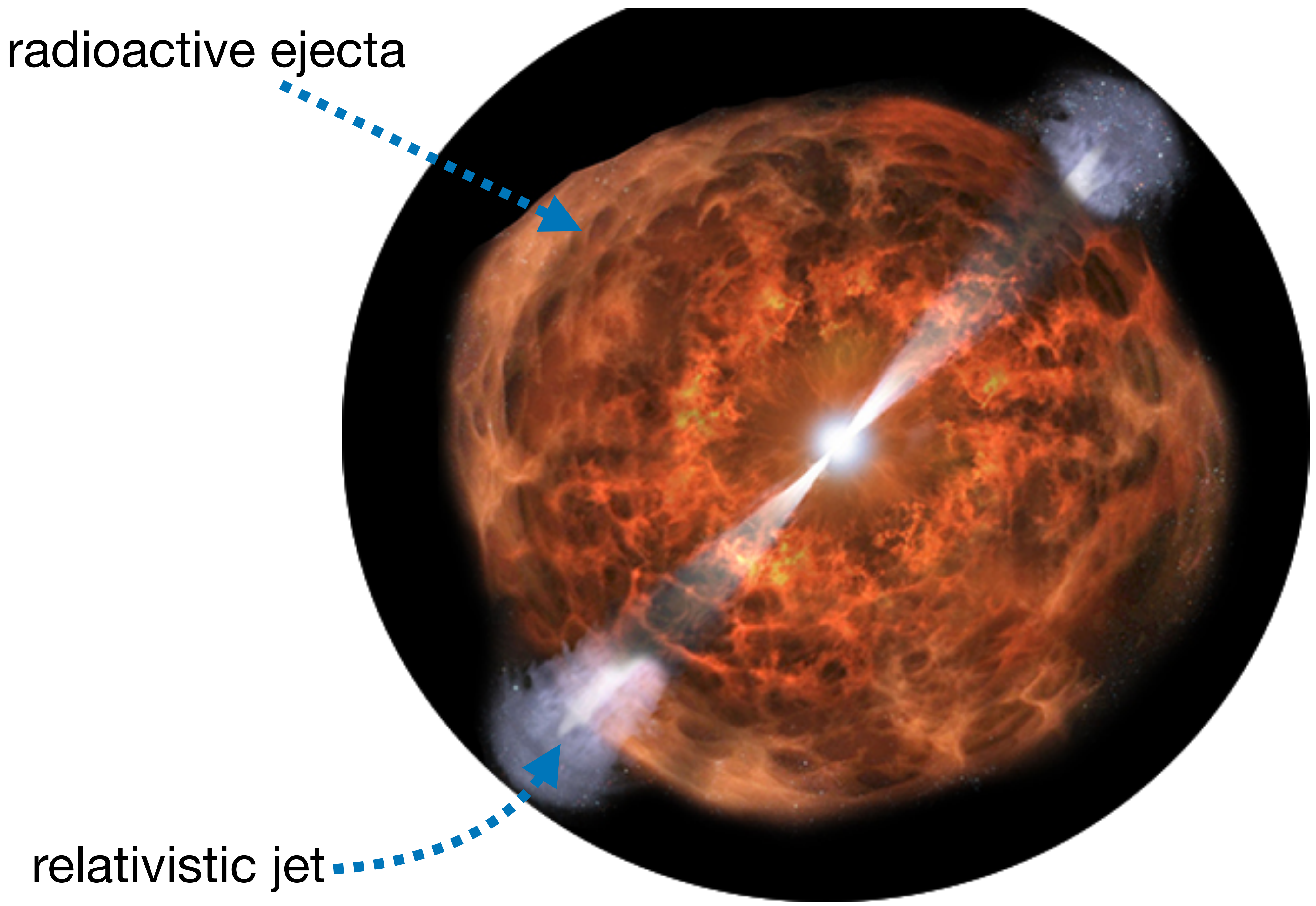

high photon density medium

high baryon density medium

cosmic rays interactions:
- photo hadronic interactions
- purely hadronic interactions

$$p + \gamma \rightarrow p + \pi^{\pm}$$
$$\rightarrow \mu^{\pm} + \bar{\nu}_{\mu}$$
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pion production

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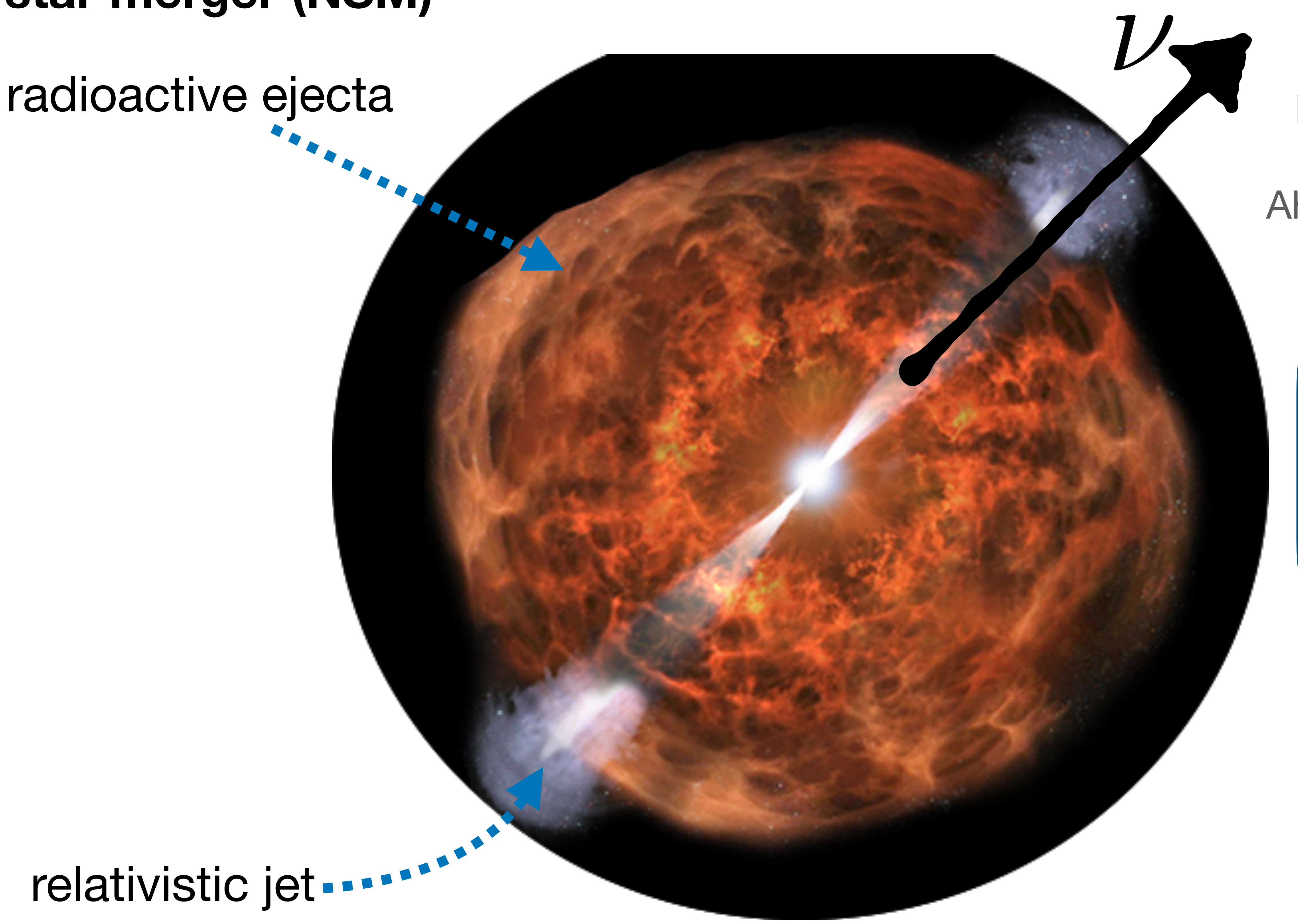

previous works

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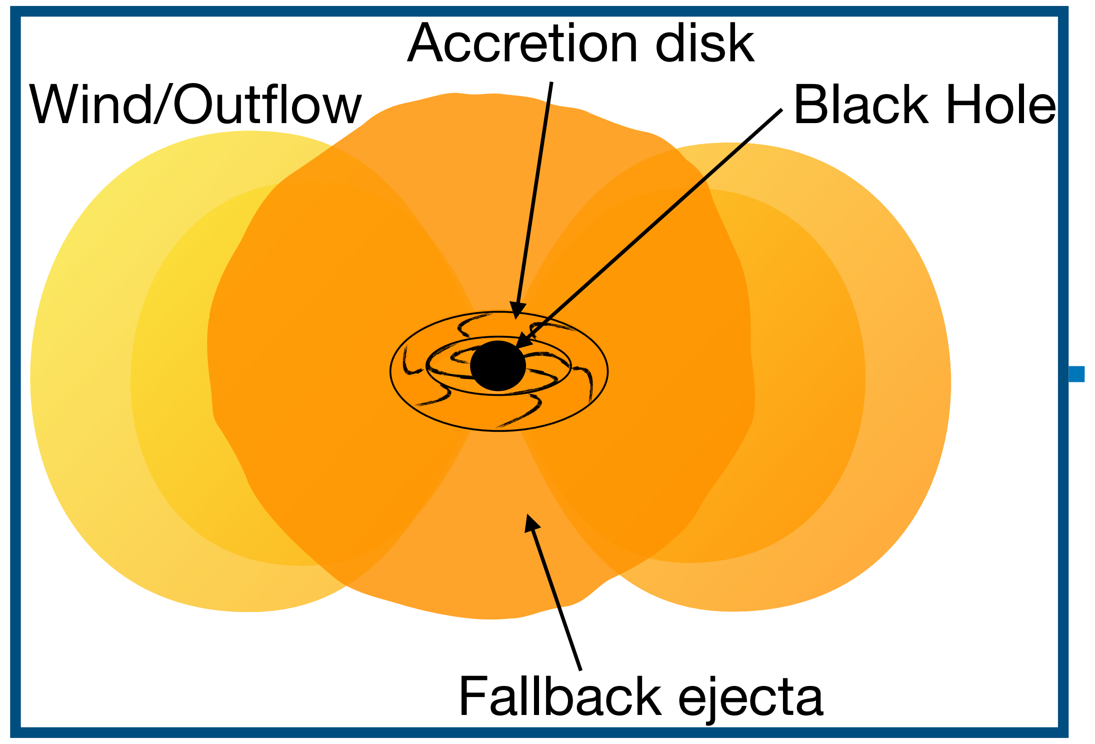
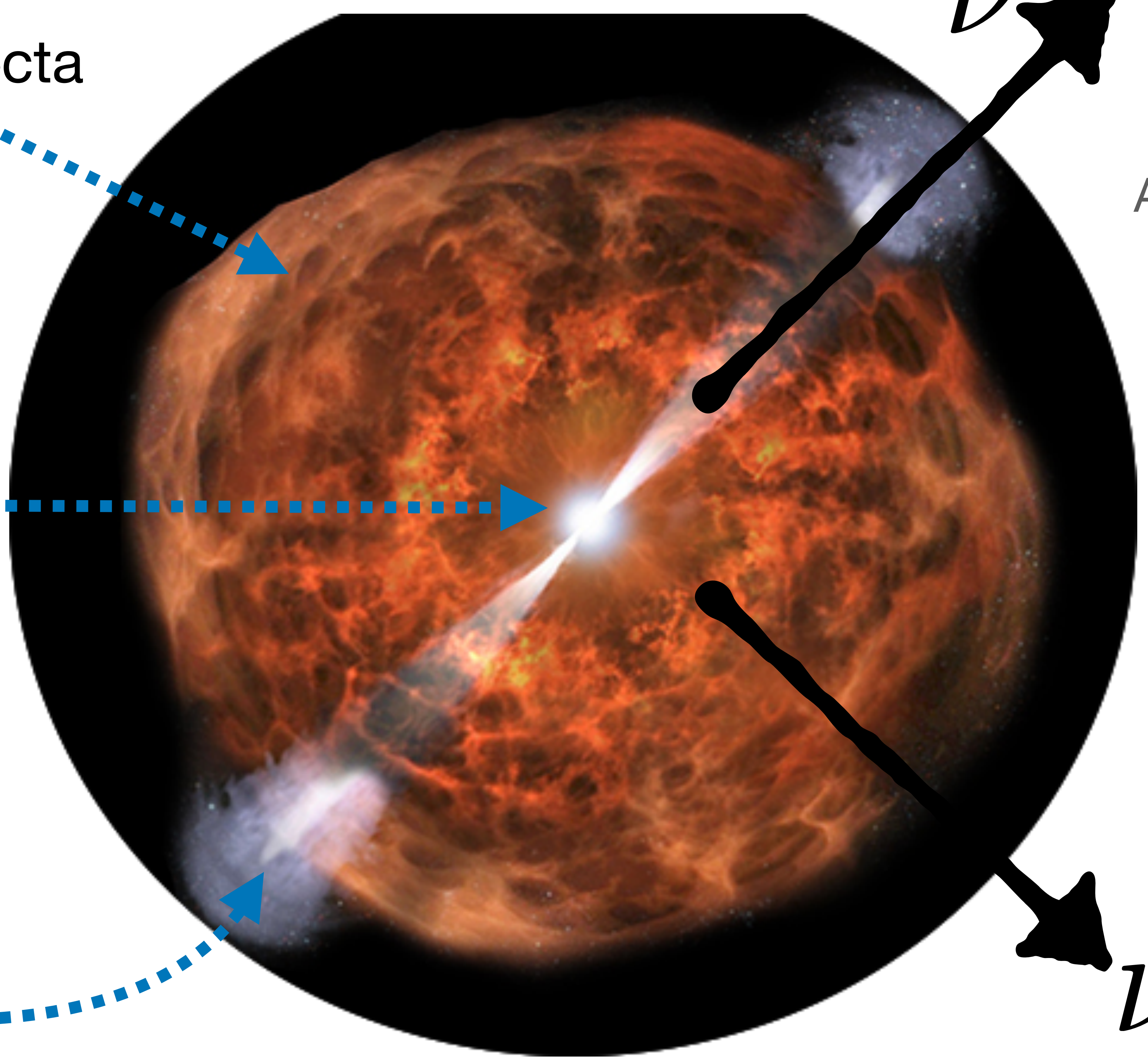
radioactive ejecta





relativistic jet

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We want to compute the neutrino flux from NSM: radiative background + particle interactions

High-energy neutrinos from fallback accretion of binary neutron star merger remnants

V. D., Guépin (UChicago), Fang (Berkley), Kotera (IAP) and Metzger (Columbia) (JCAP 2019)

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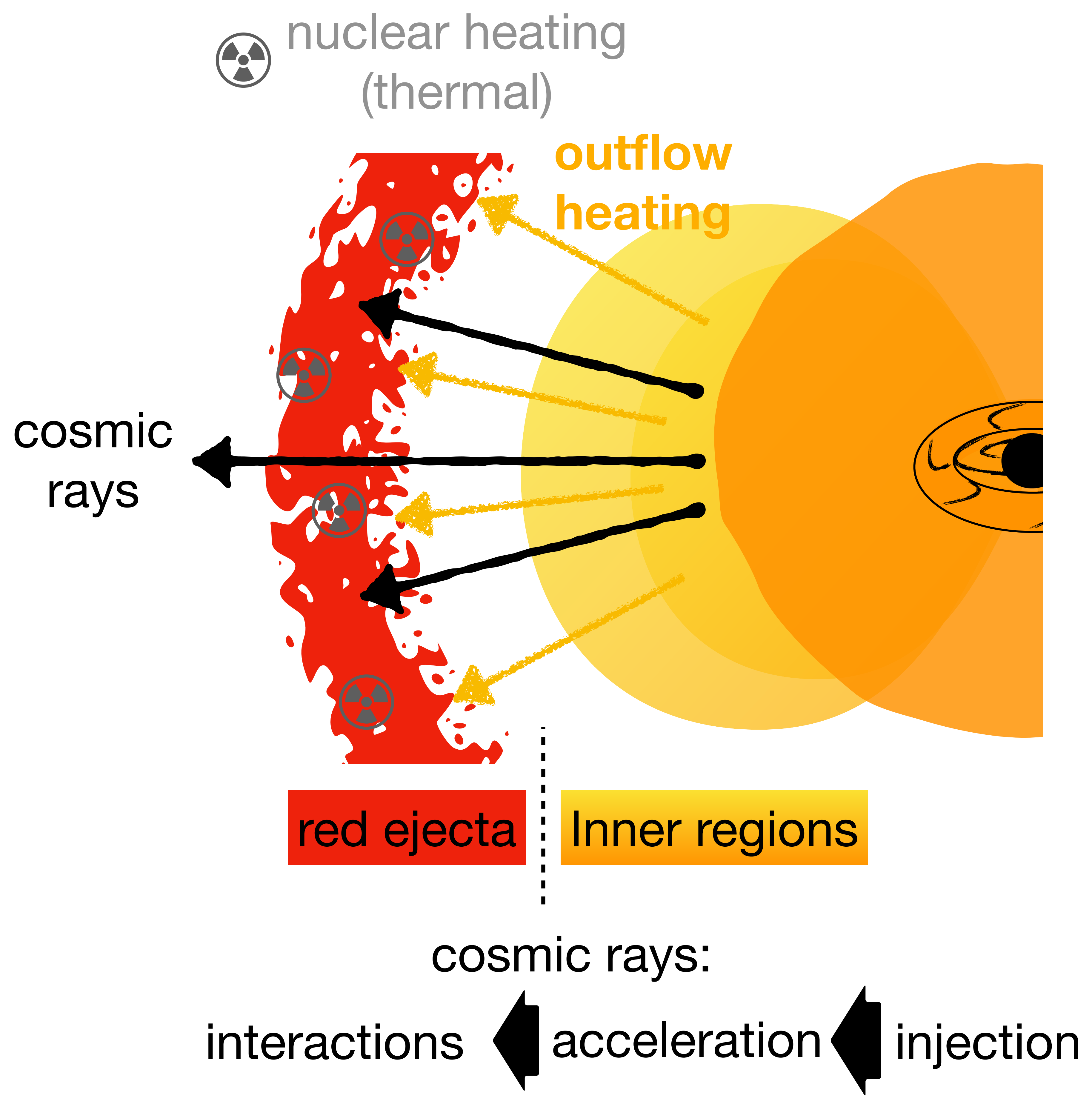

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Metzger et al. 2011

$$\frac{d\mathcal{E}}{dt} = -3\frac{\mathcal{E}}{R}\frac{dR}{dt} - \frac{\mathcal{E}}{t_{\rm esc}} + \dot{Q}_{\rm r} + \dot{Q}_{\rm fb}$$

energy evolution — mechanical losses — radiative losses

$$t_{\rm esc} \approx \left(\frac{3M\kappa}{4\pi R^2} + 1\right)\frac{R}{c}$$

opacity (lanthanides)

- **Fall-back**

$$\dot{Q}_{\rm fb} = \epsilon_{\rm fb}\dot{M}_{\rm fb}c^2$$

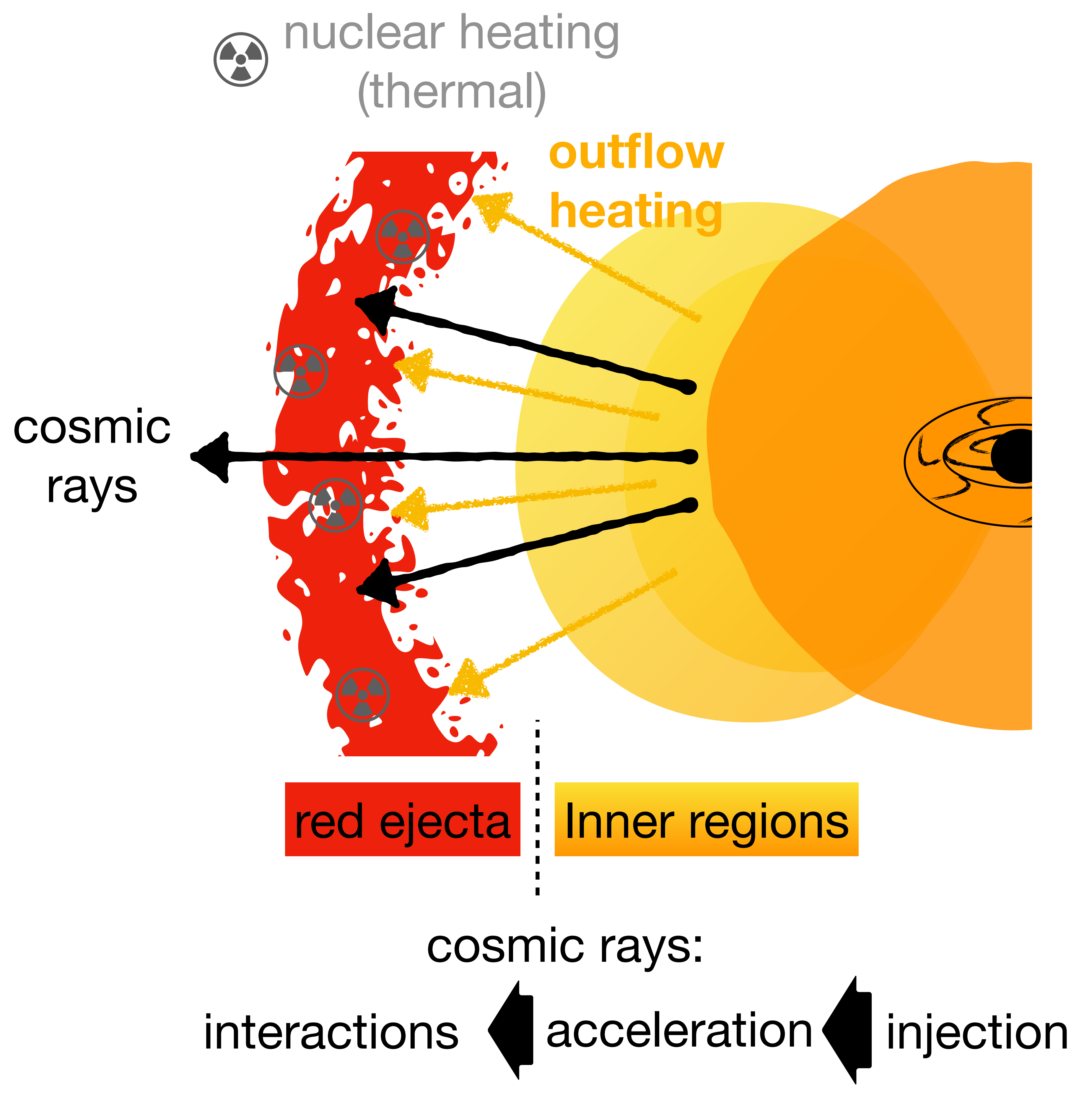
mass accretion rate

- **Nuclear reaction** Barnes et al. 2016, M. R. Drout et al, 2017

$$\dot{Q}_{\rm r} = M\, X_{\rm r}\, \dot{e}_{\rm r}(t)$$

nuclear mass energy

lanthanides mass fraction



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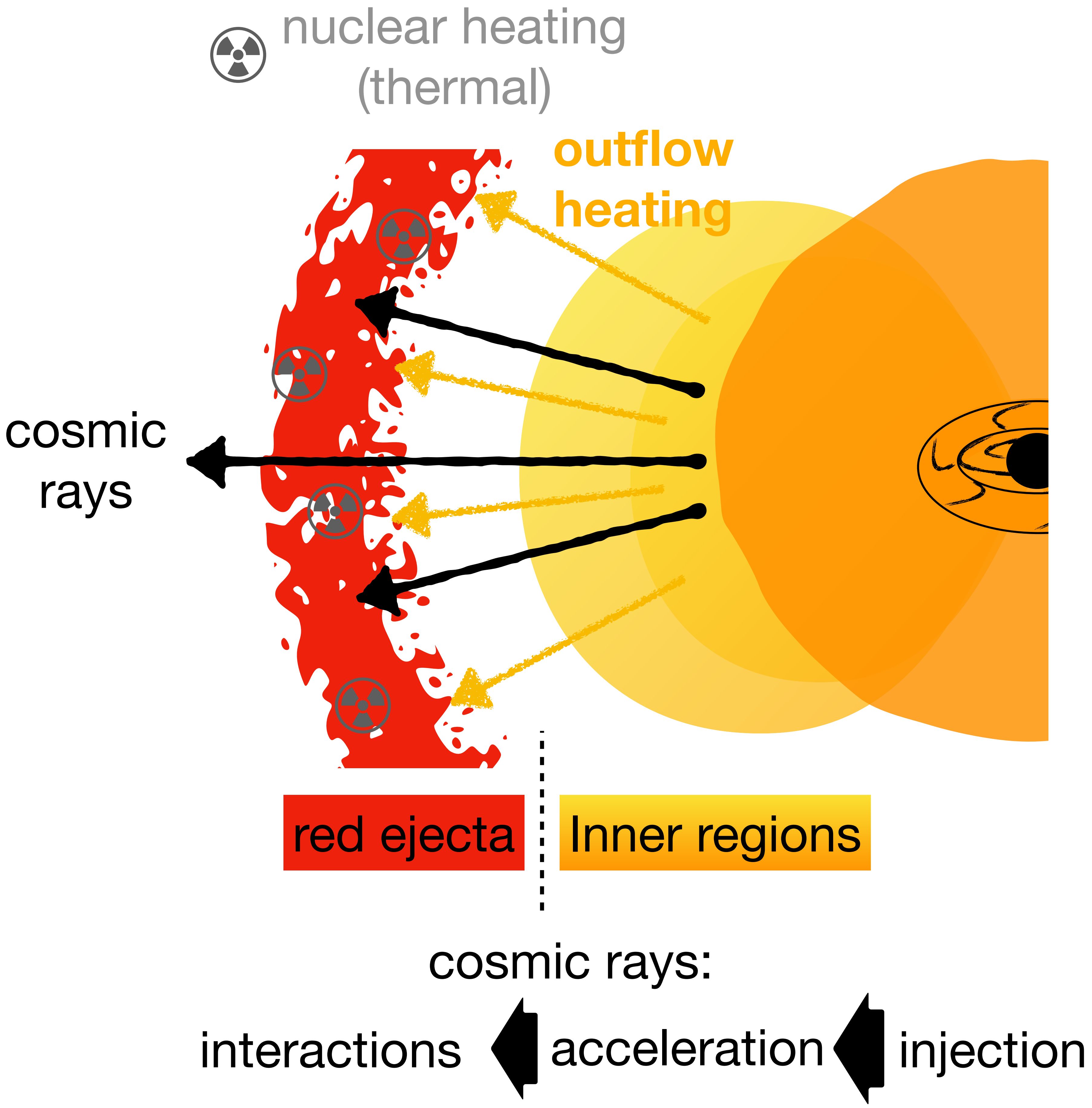

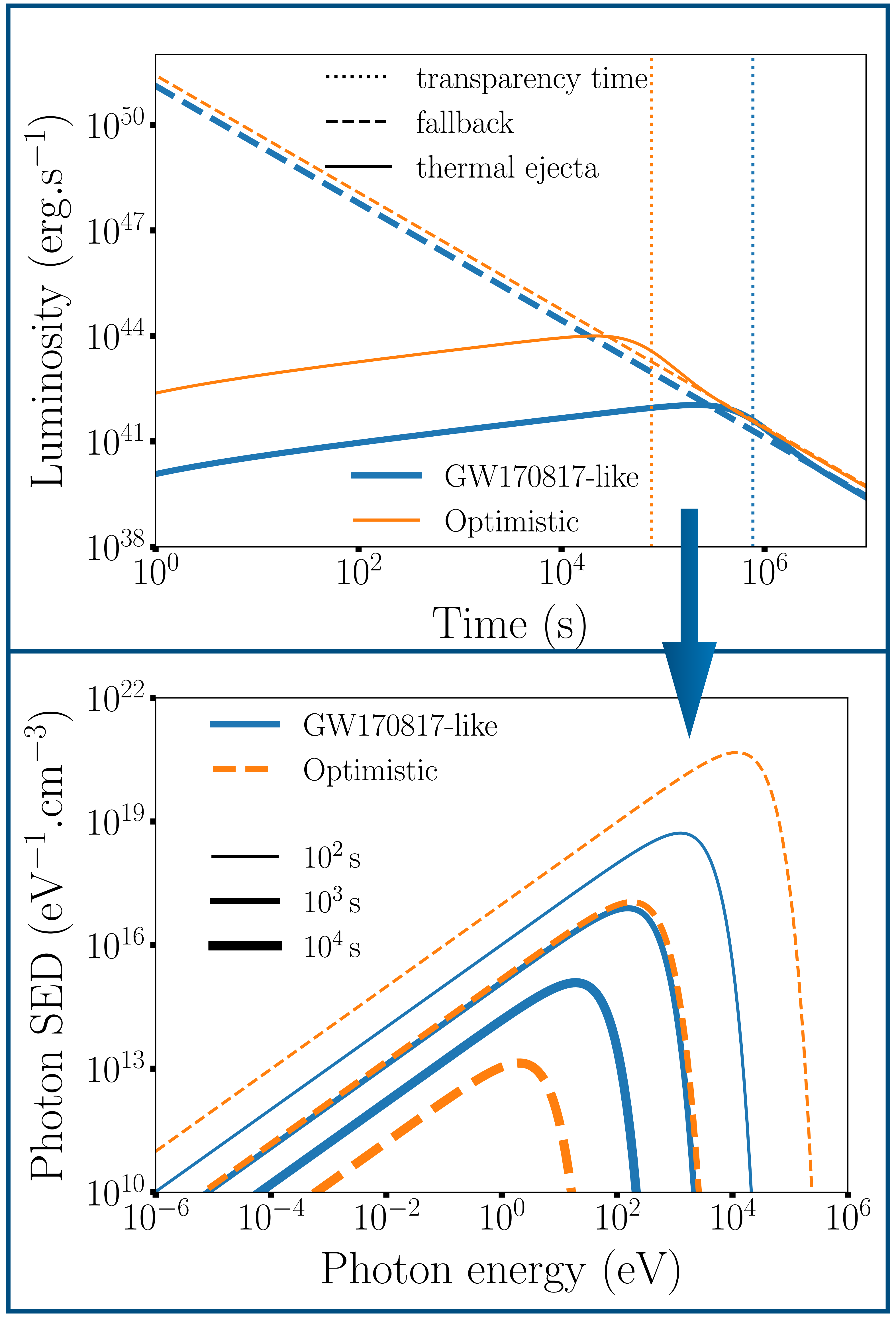

2) Particle interactions computations:

Numerical Mont-Carlo computation (EPOS/TALYS/SOPHIA)

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or

special implementations

$$\to \text{Cascades}$$
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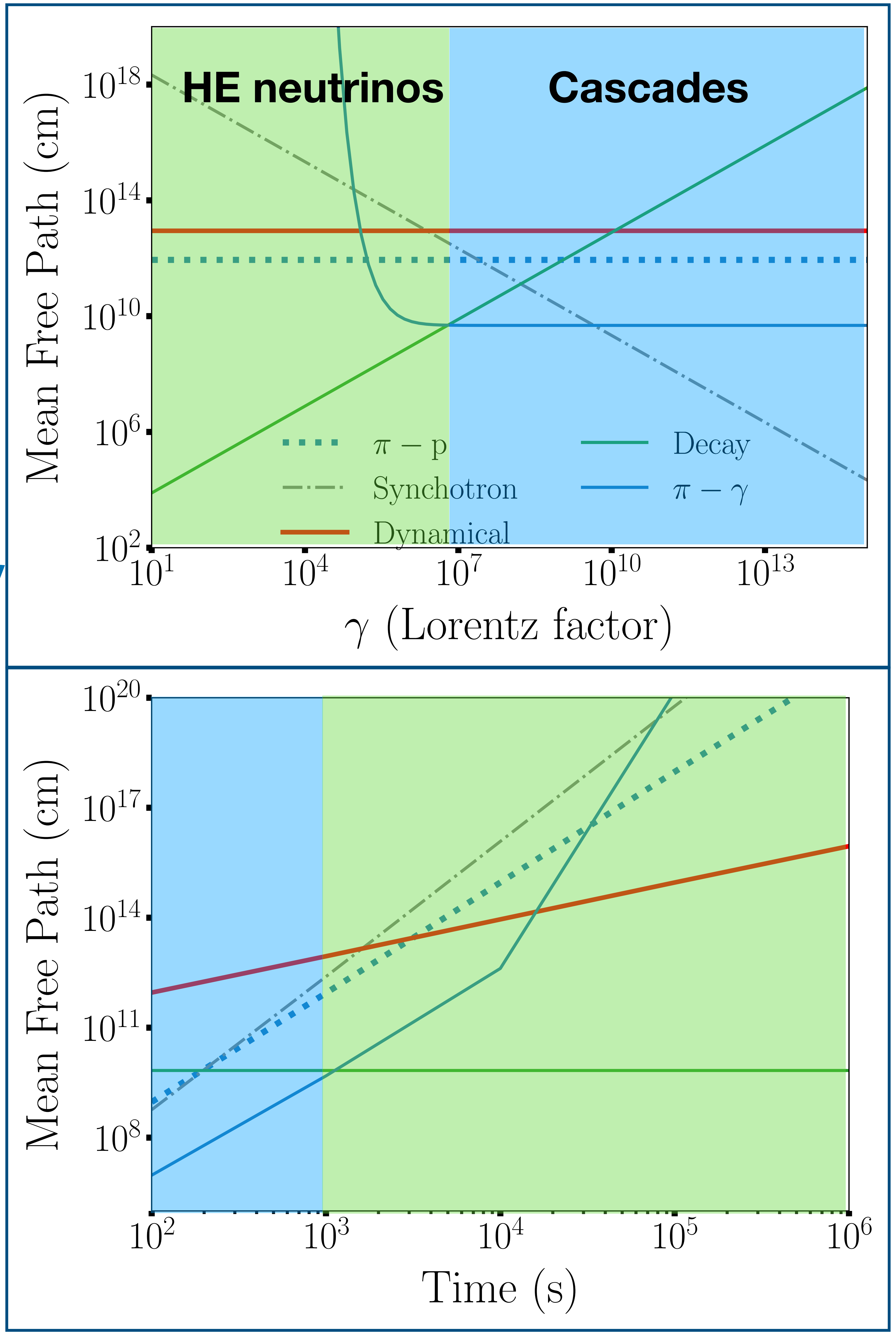
HE neutrino suppression

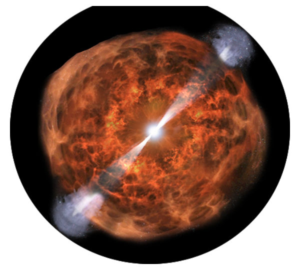
$t = 10^3 s$

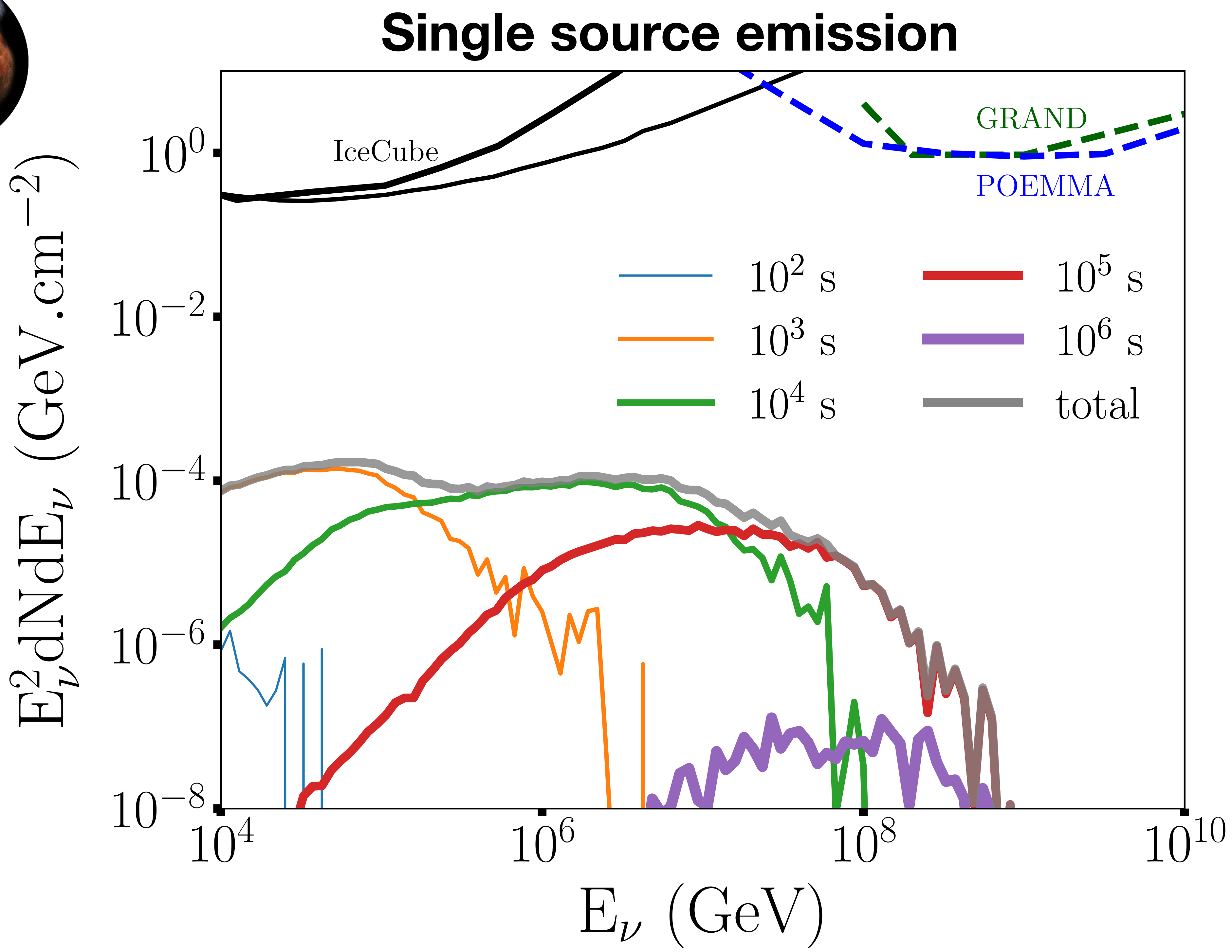
$\gamma = 10^7$



Optimum neutrino production depends on:
- neutrino energy
- production time

Neutrino fluxes





- Maximum neutrino energy increases with time
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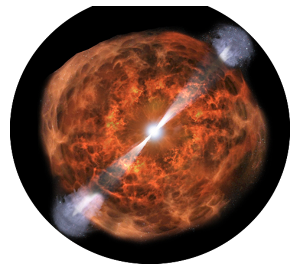
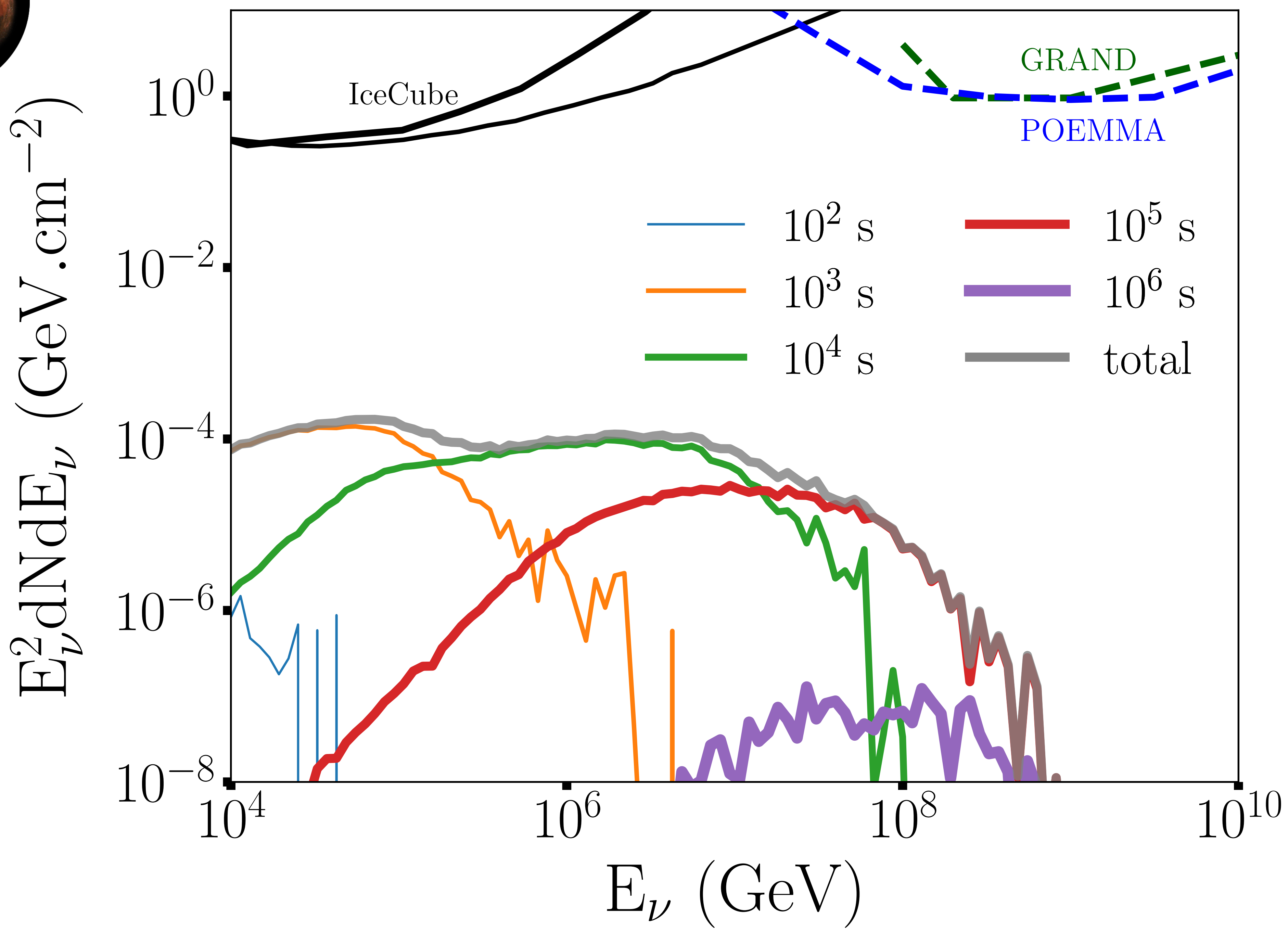


Single source emission



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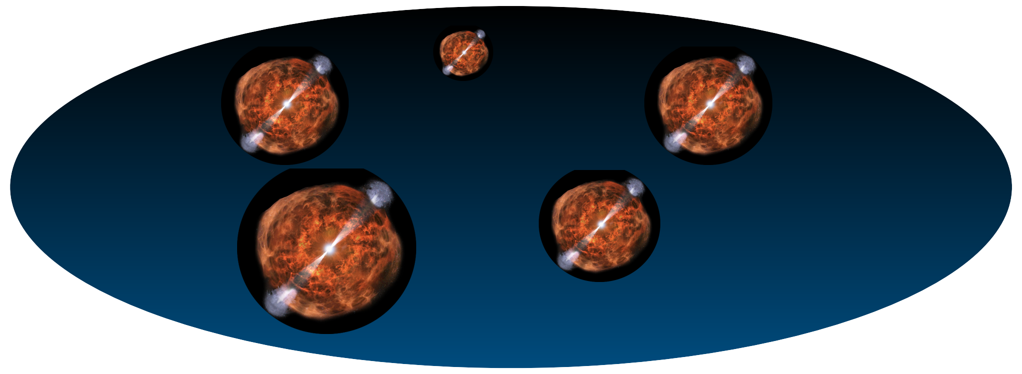
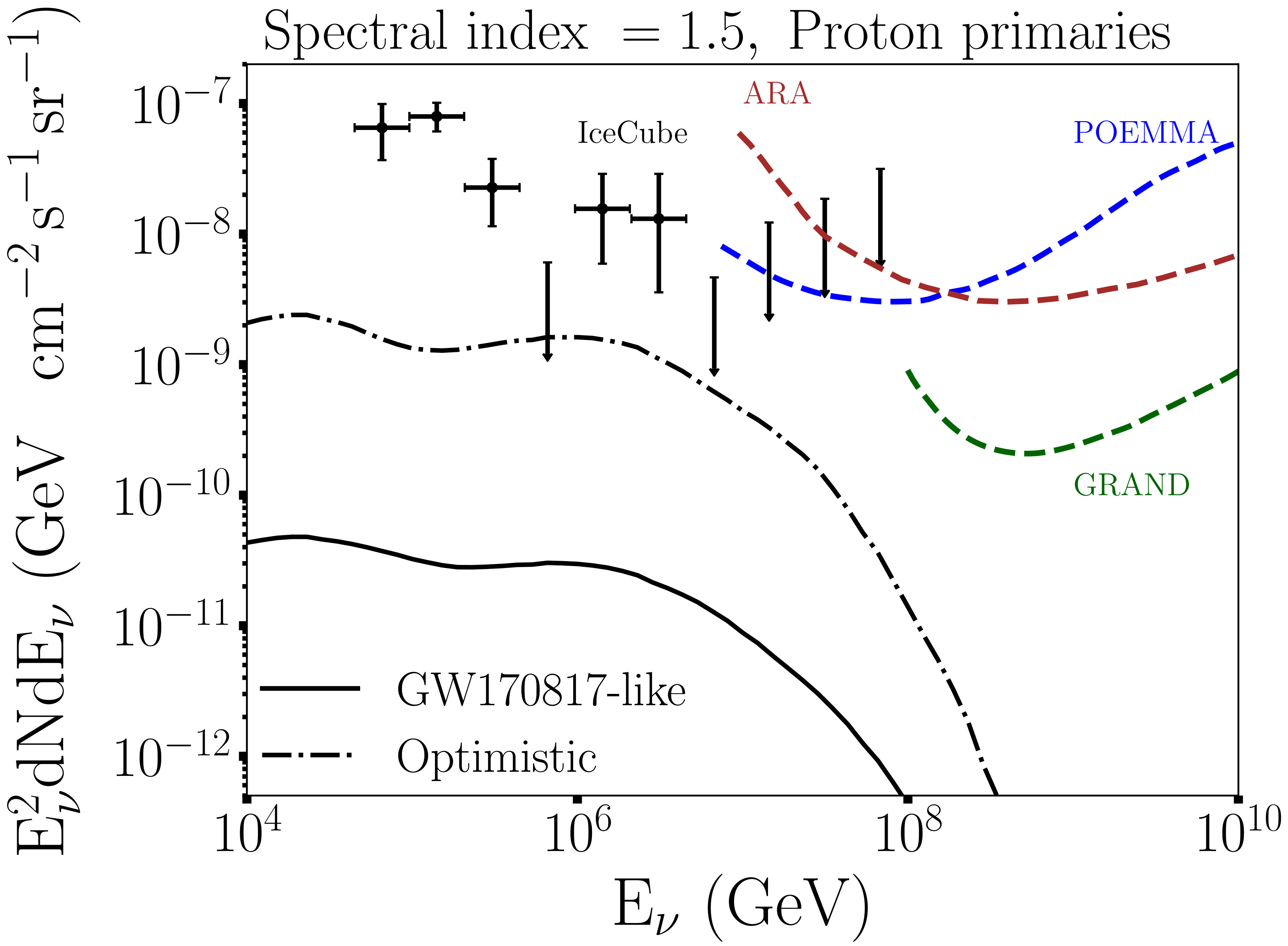
proton injection spectral index 1.5



Diffuse emission



Scenario	M_{ej} [$M_\odot$]	β_{ej}	M_{fb} [$M_\odot$]	β_{wind}	ϵ_{fb}	$\dot{n}_0$ [Gpc^{-3}yr^{-1}]	$\mathcal{R}(z)$
GW170817-like	10^{-2}	0.3	5×10^{-2}	0.1	0.1	600	1
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Two scenarii:
- GW170817 parameters
- optimistic simulated parameters

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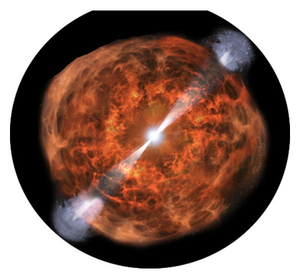

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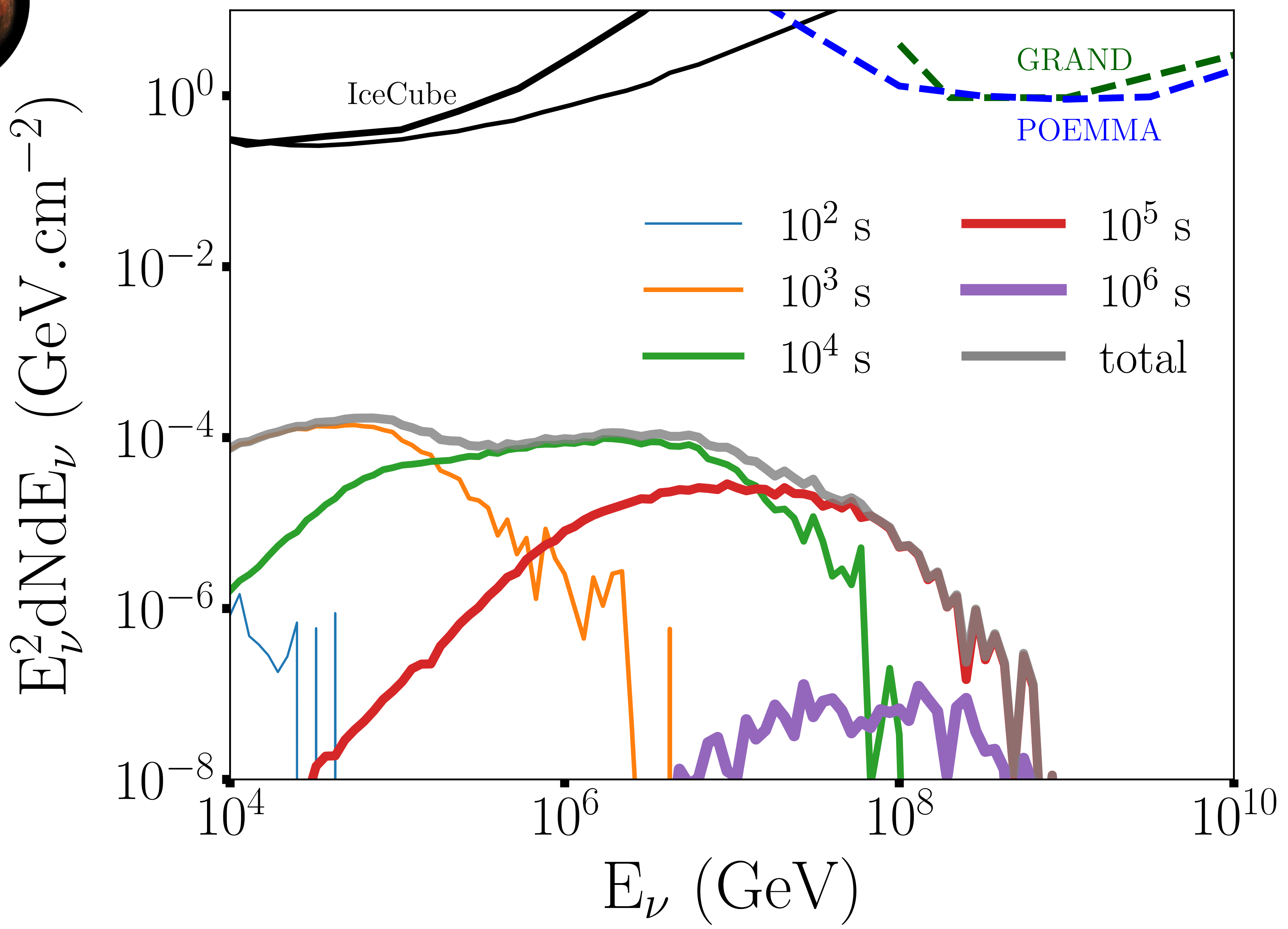

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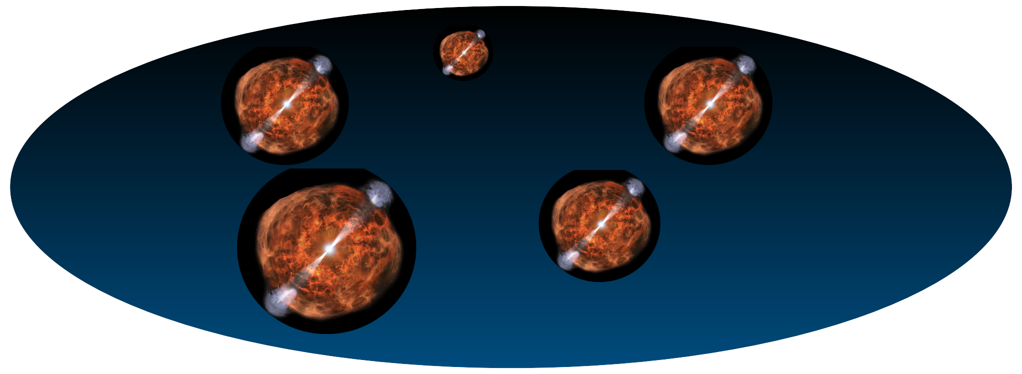

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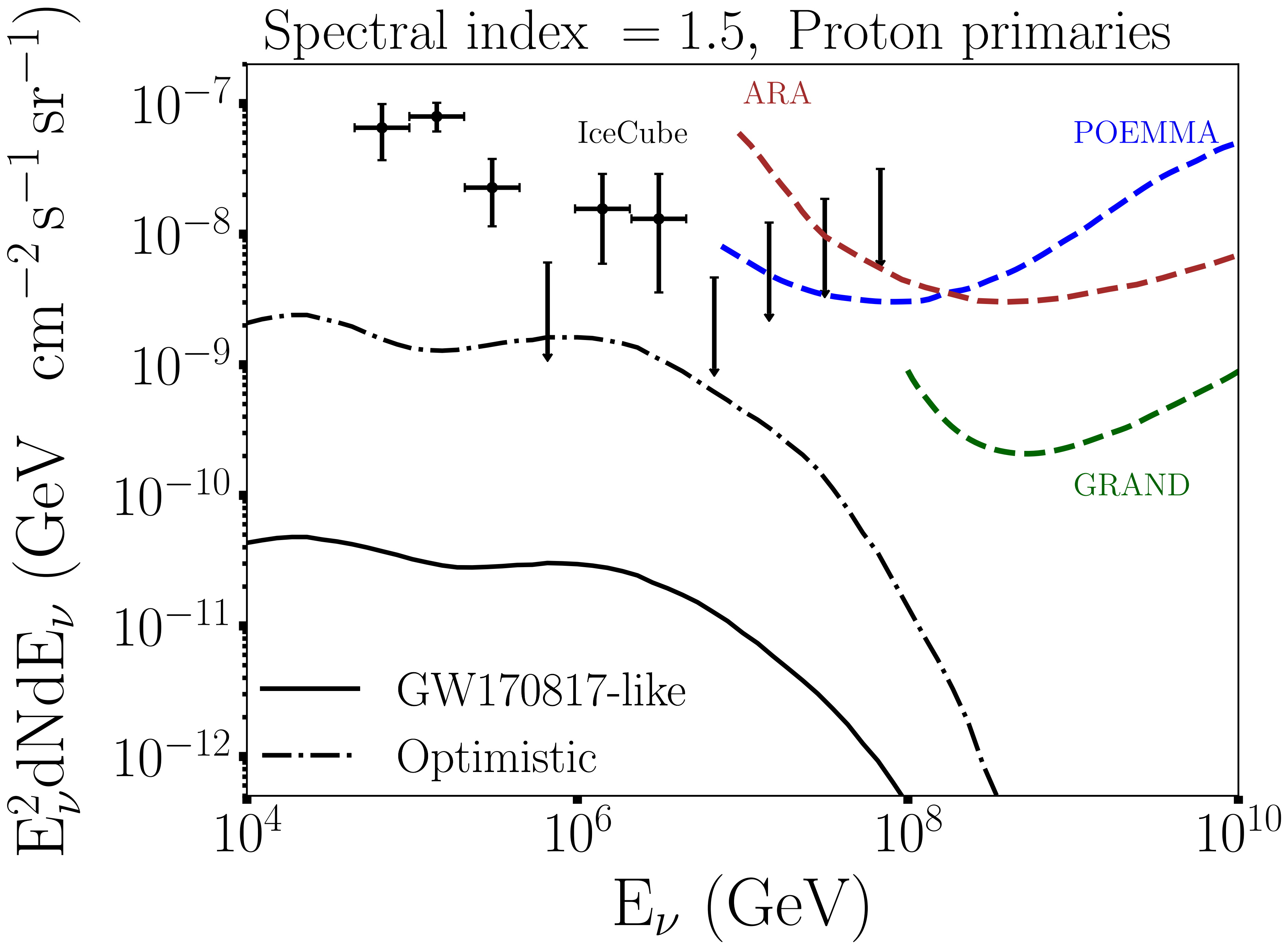

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The diffuse neutrino flux from binary neutron stars mergers can contribute up to 10% of the IceCube measured flux

Neutrino sources are challenging to detect

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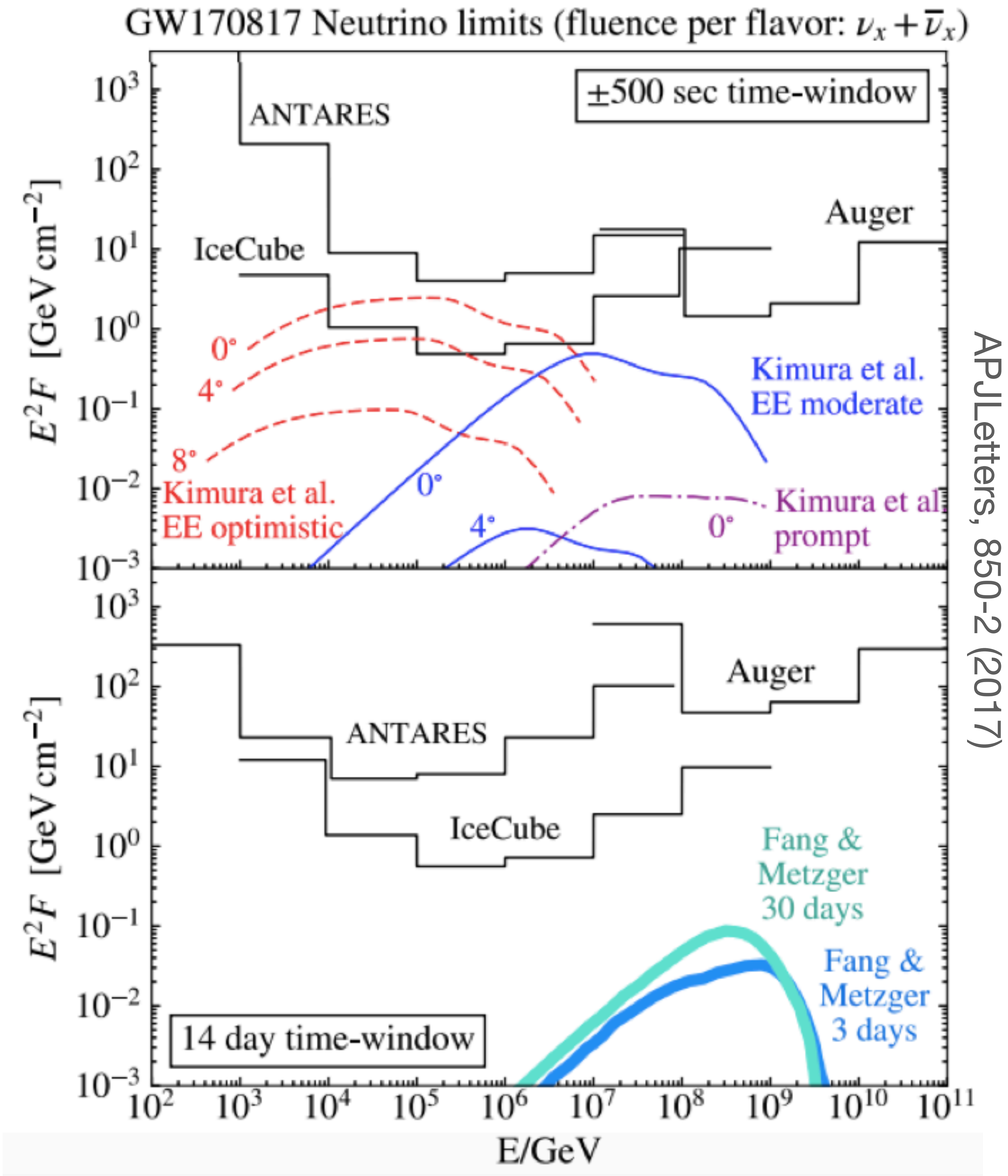
Even for jet emissions!



APJLetters, 850-2 (2017)

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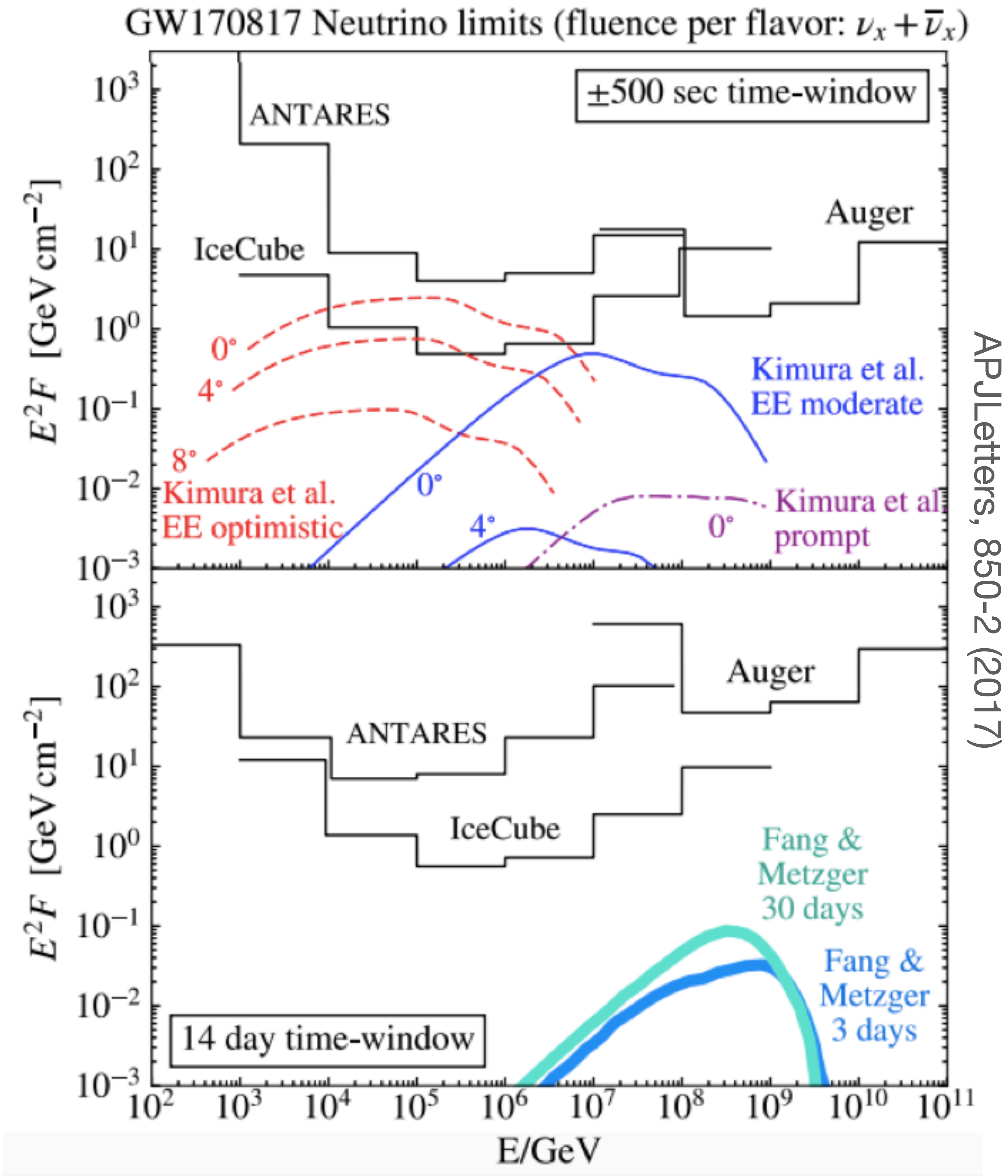

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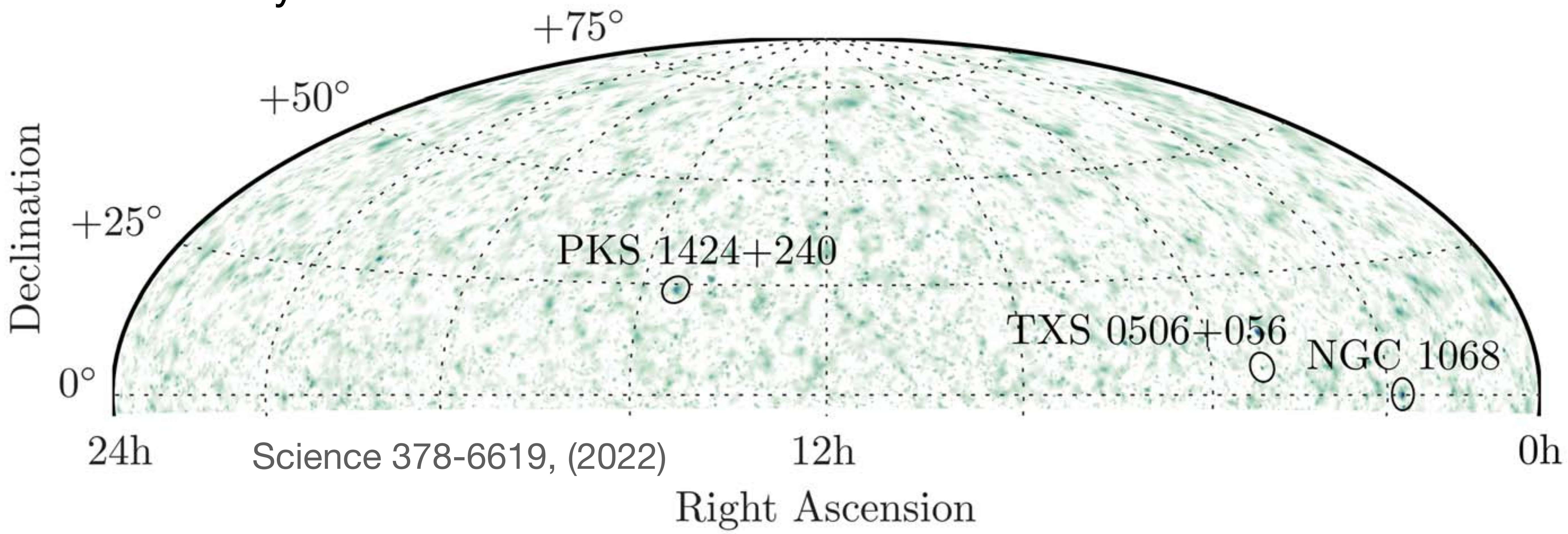
IceCube 19 years of data: 3 candidates



Science 378-6619, (2022)

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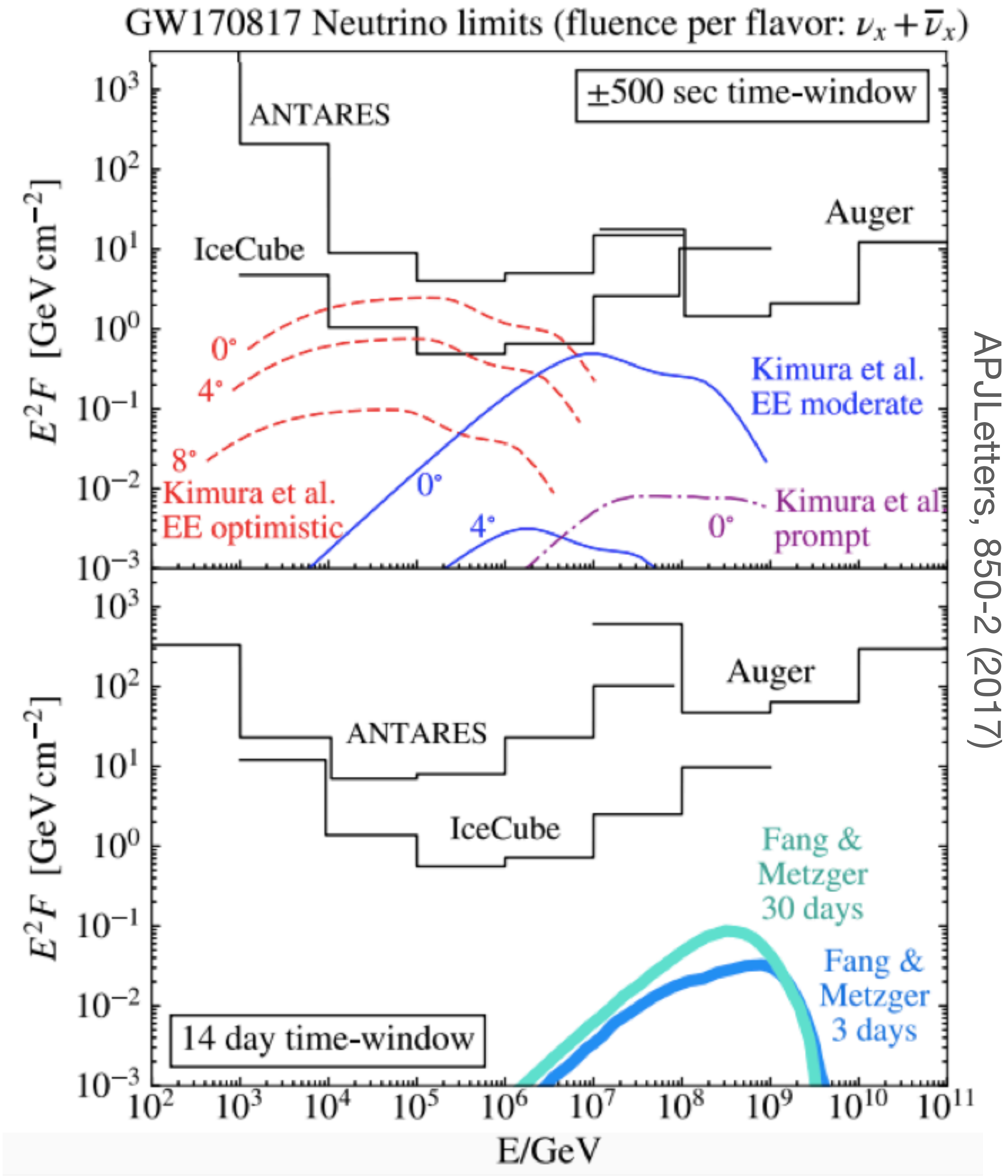

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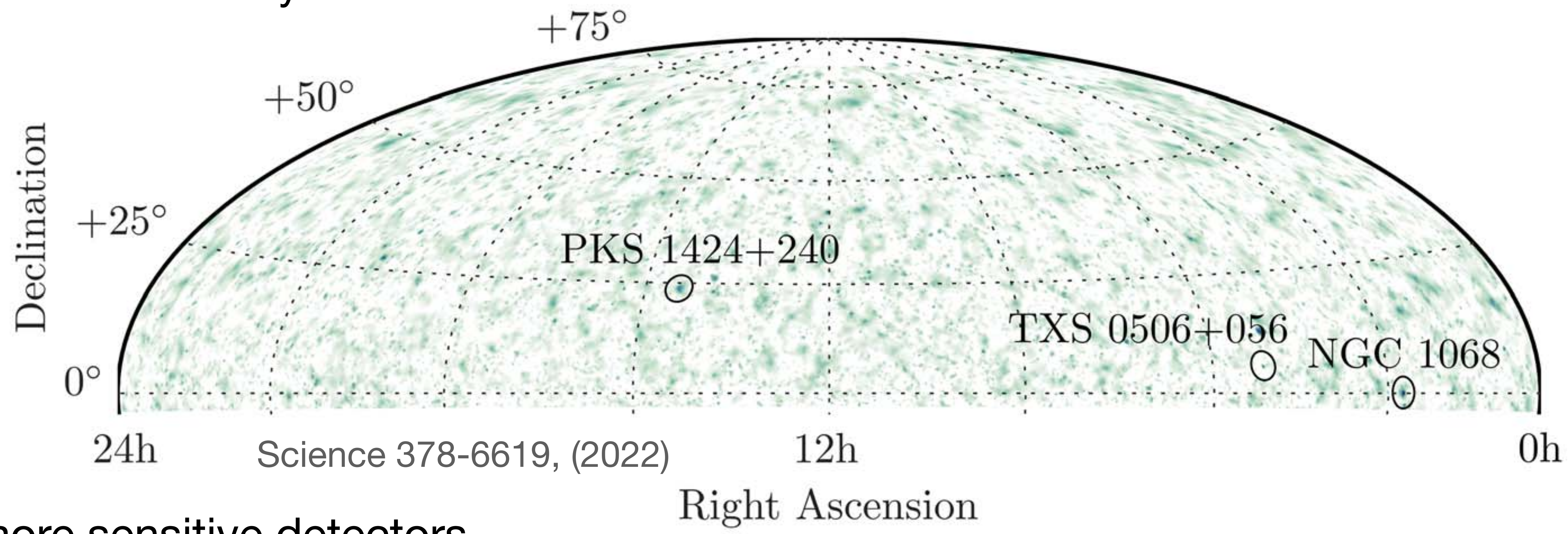

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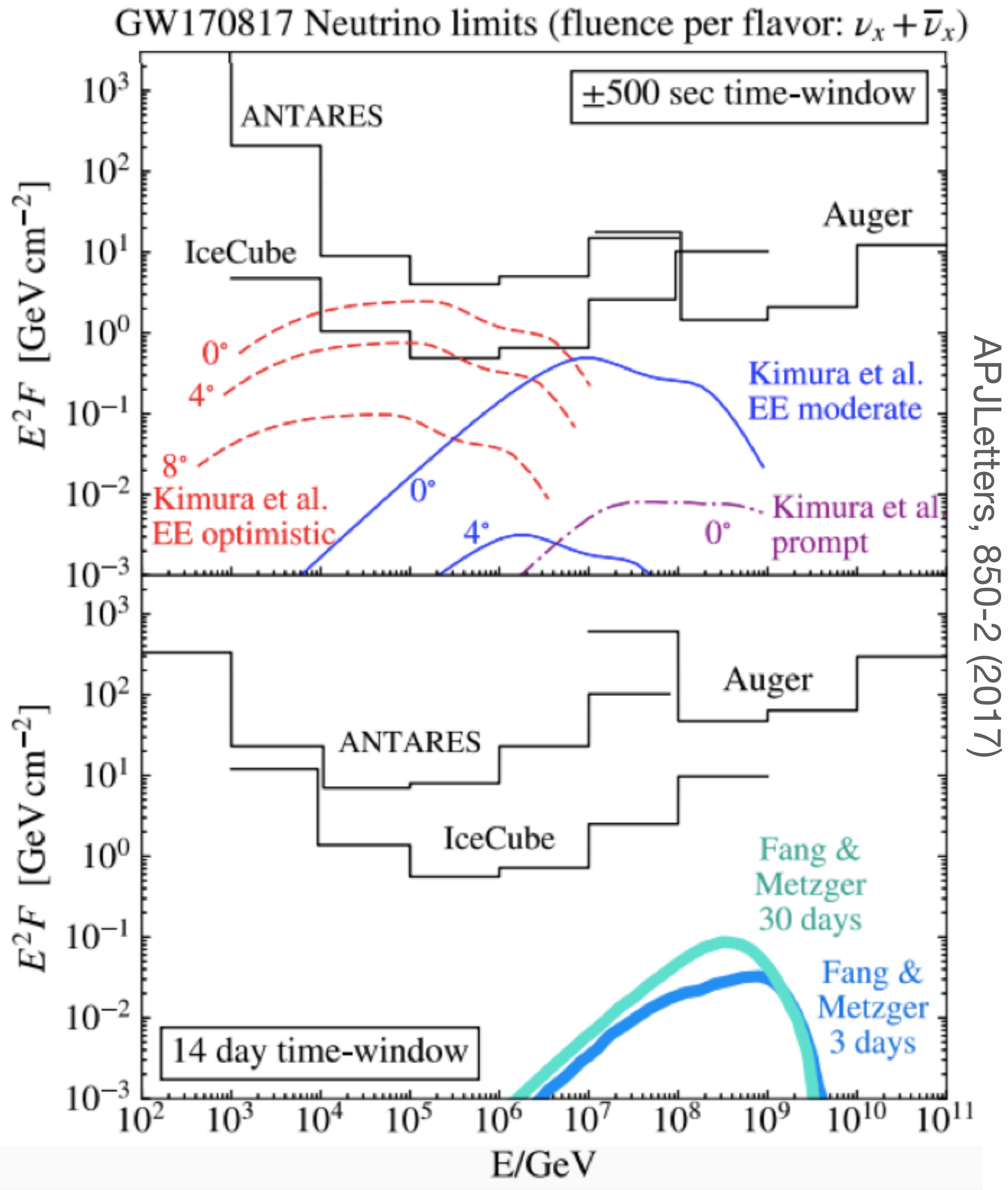

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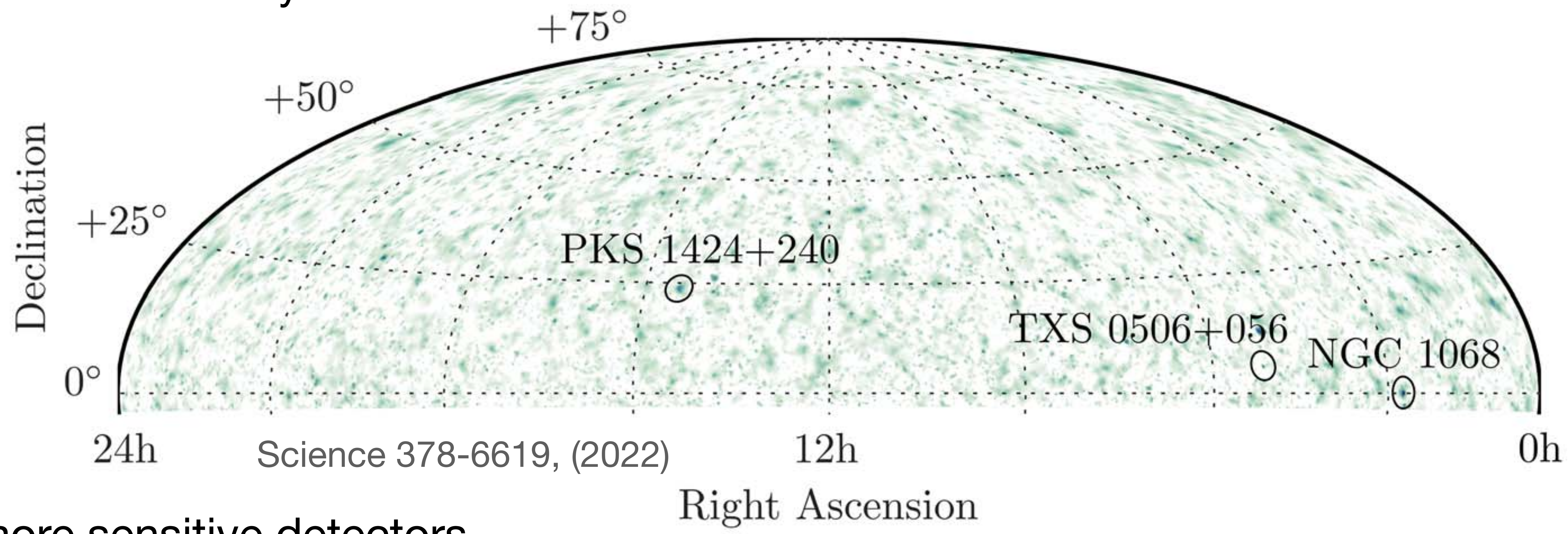

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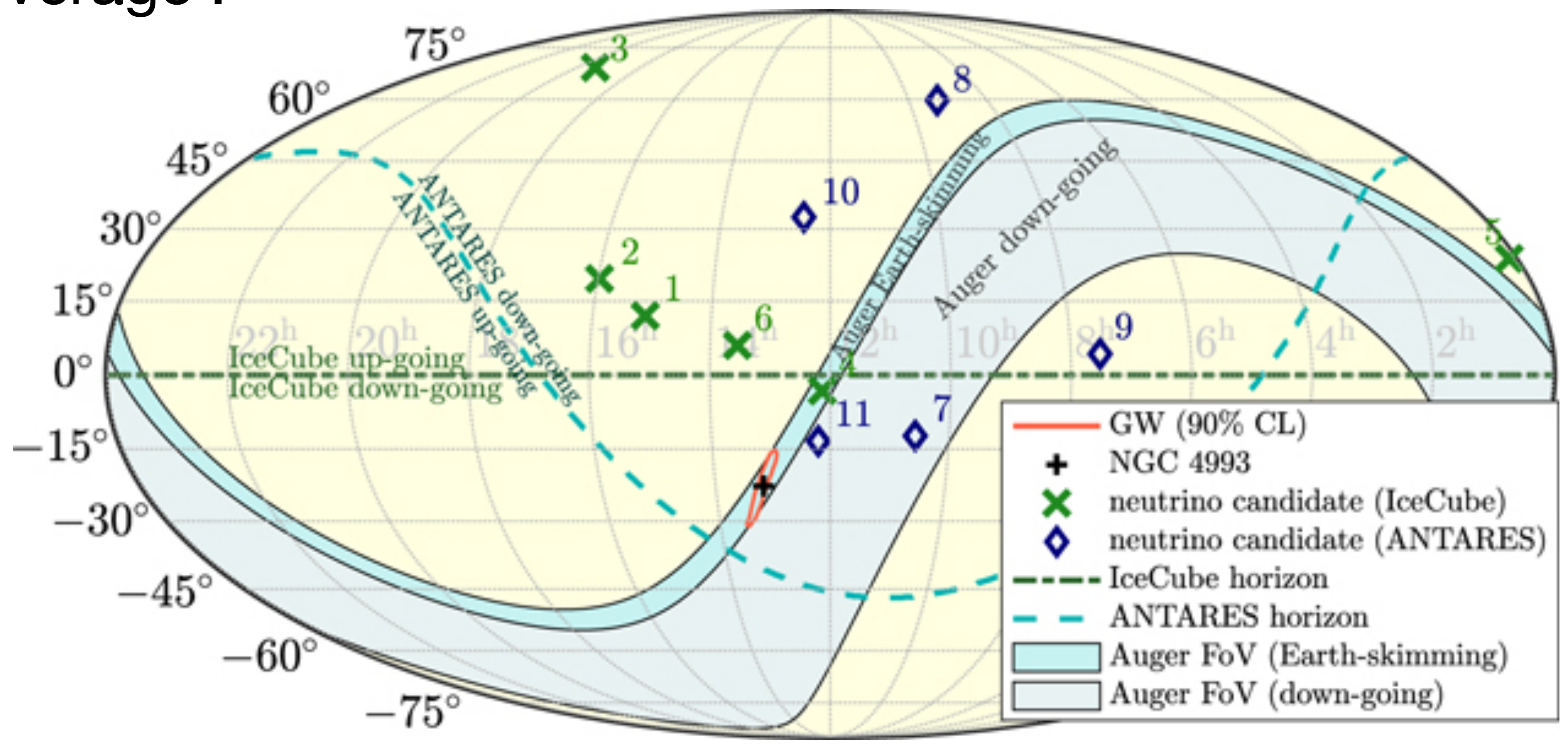

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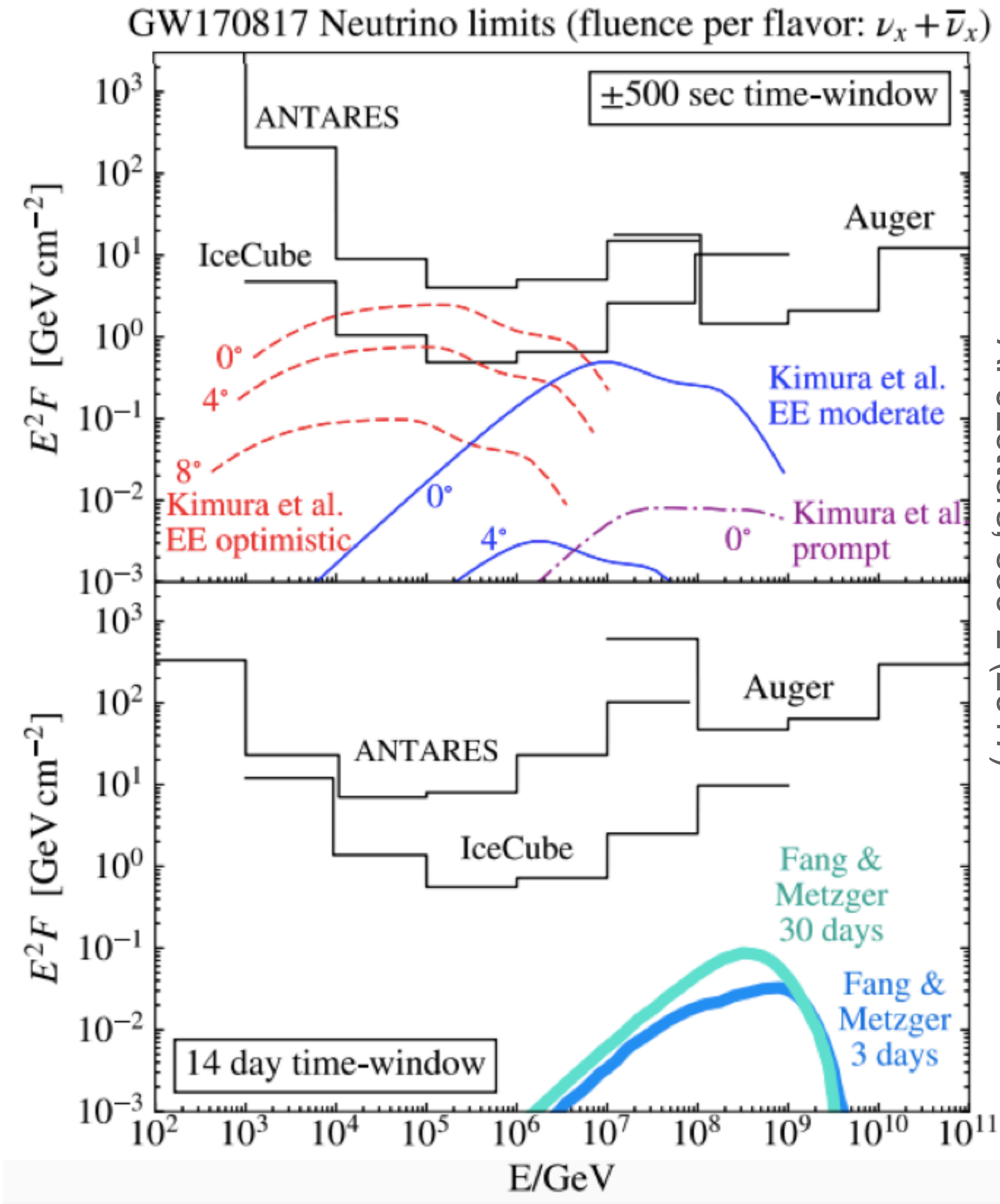

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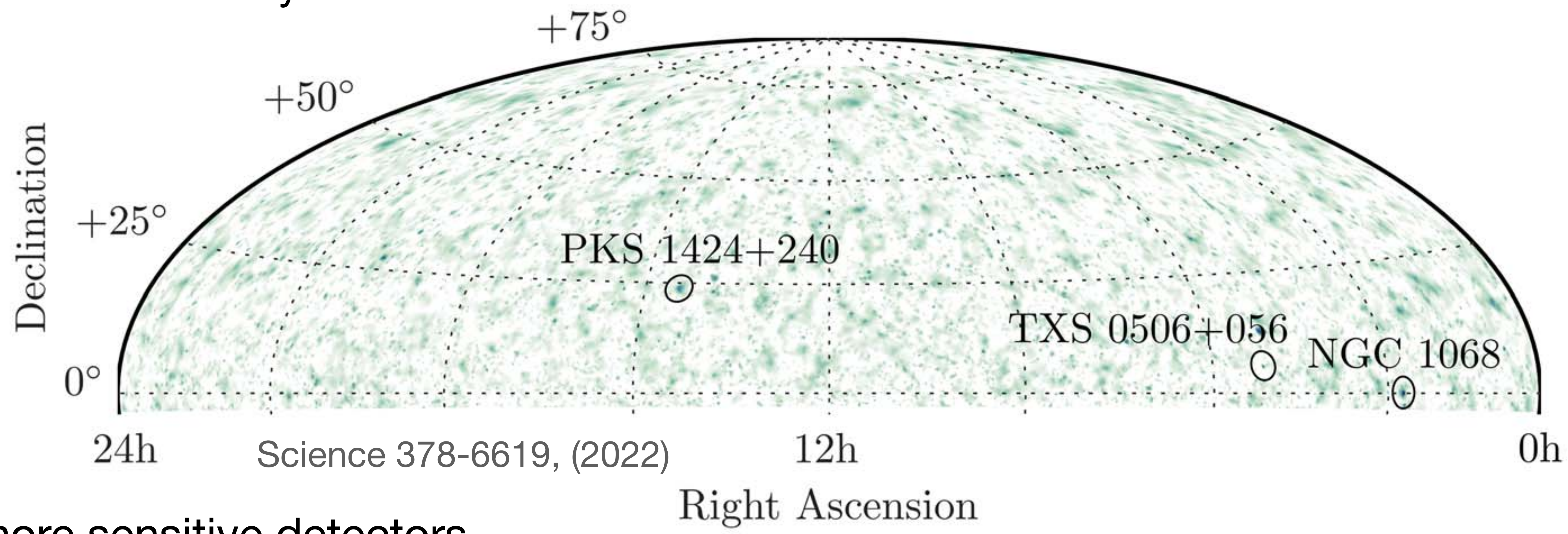

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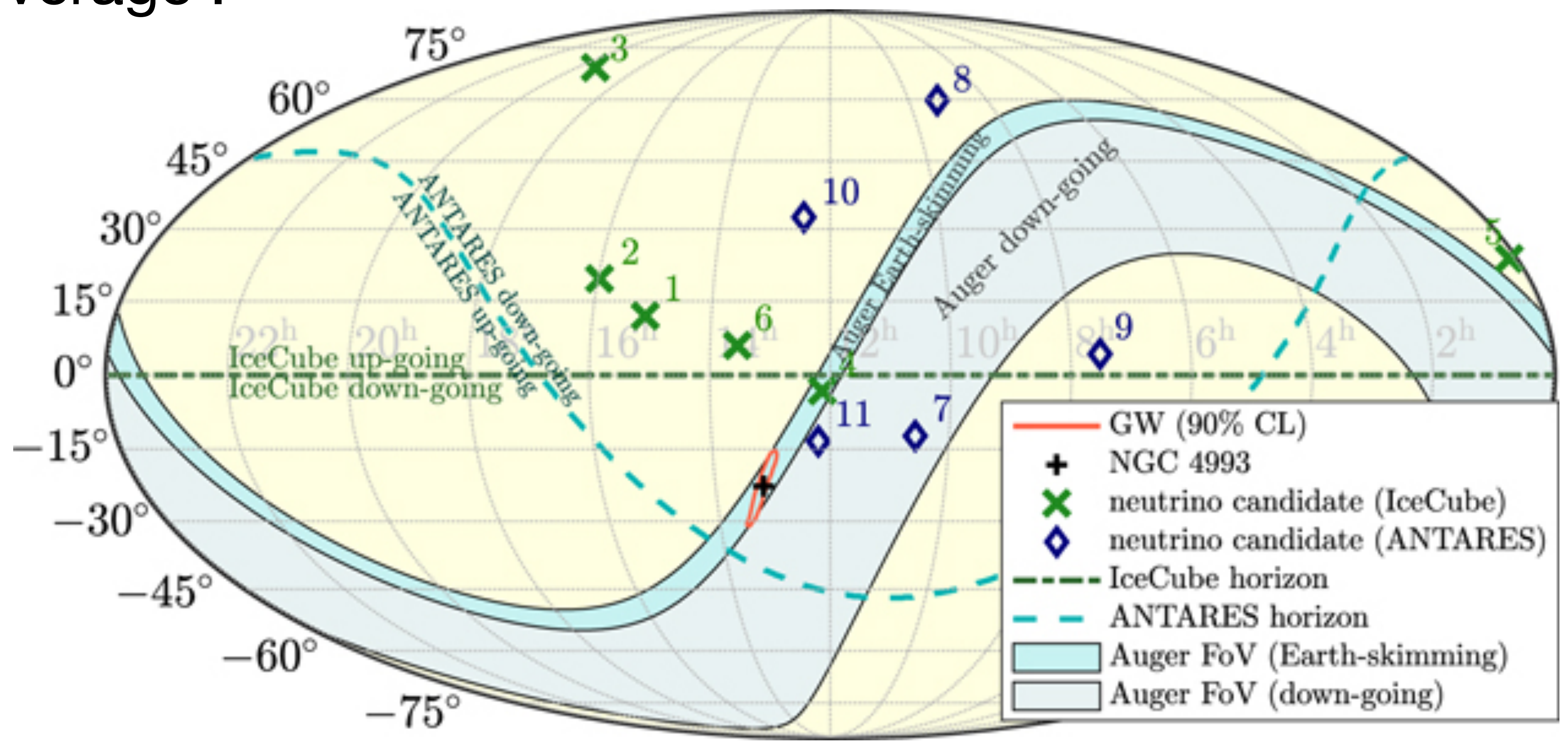
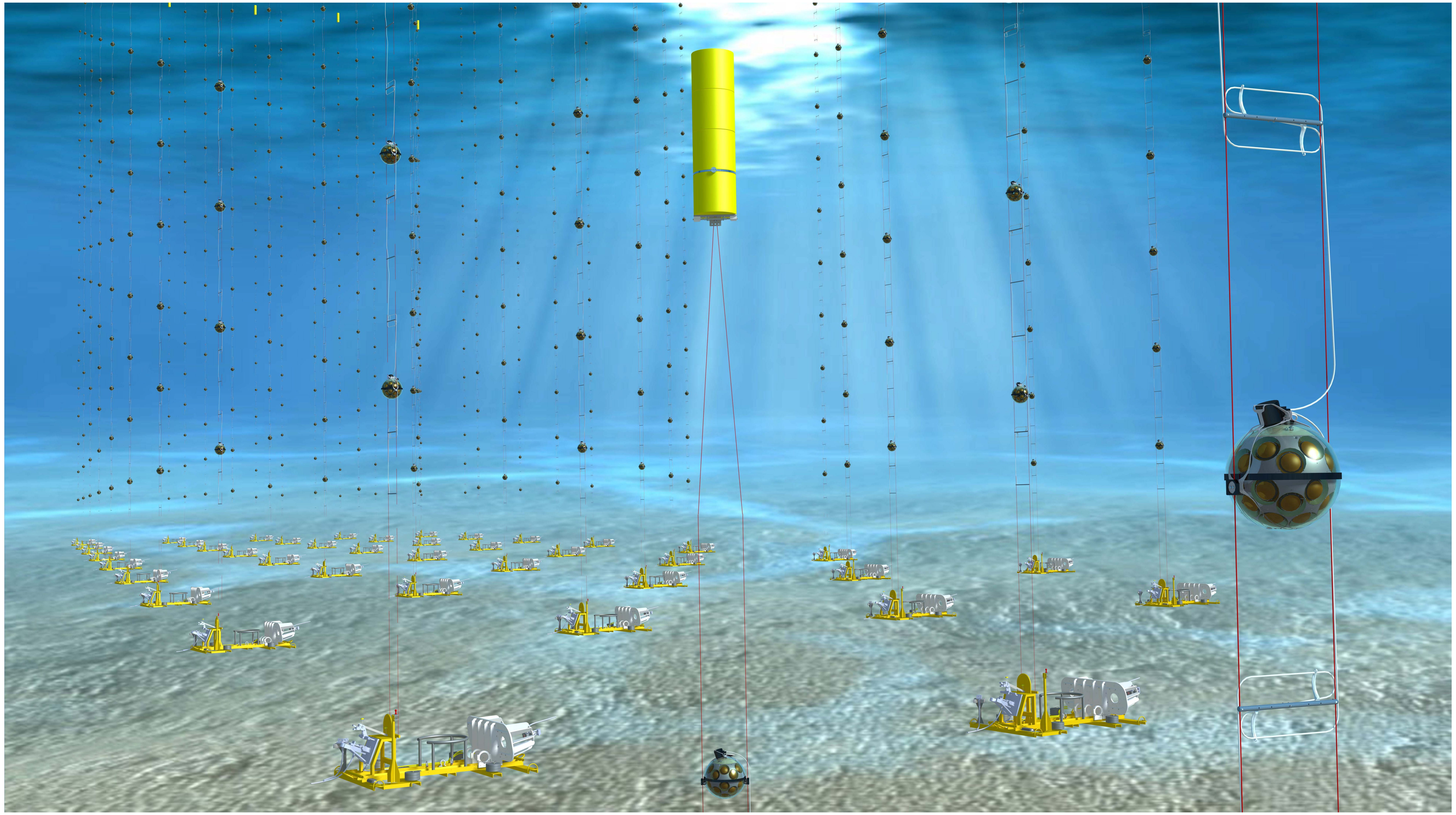


KM3NeT!

The KM3NeT project (in a nutshell)



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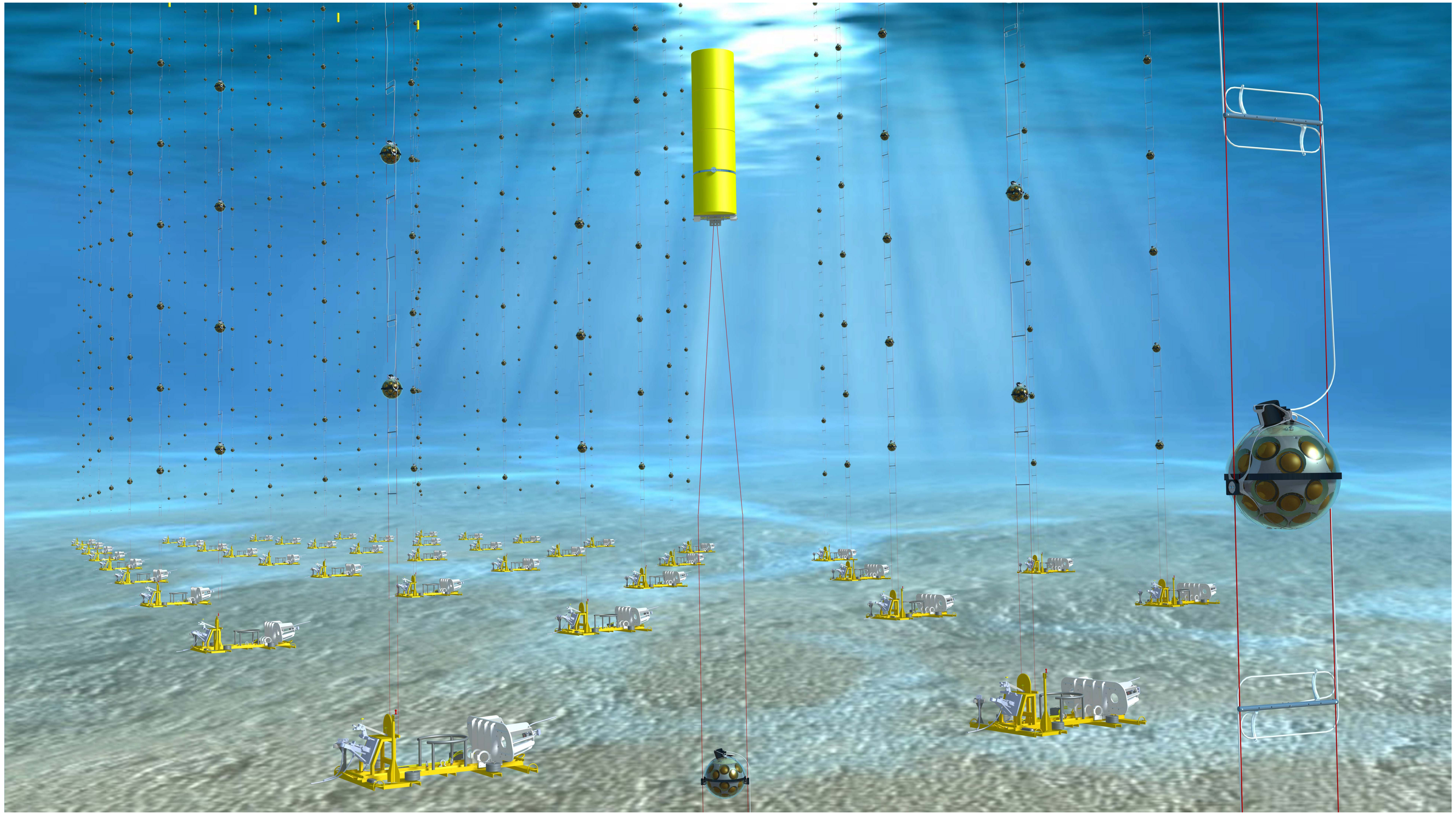
→Successor of Antares
- two Cherenkov detectors (a la IceCube)
- ORCA (compact) and ARCA (sparse)
- in Mediterranean deep sea (~2500-3500m)
- detector volume envisioned of ~1km^3



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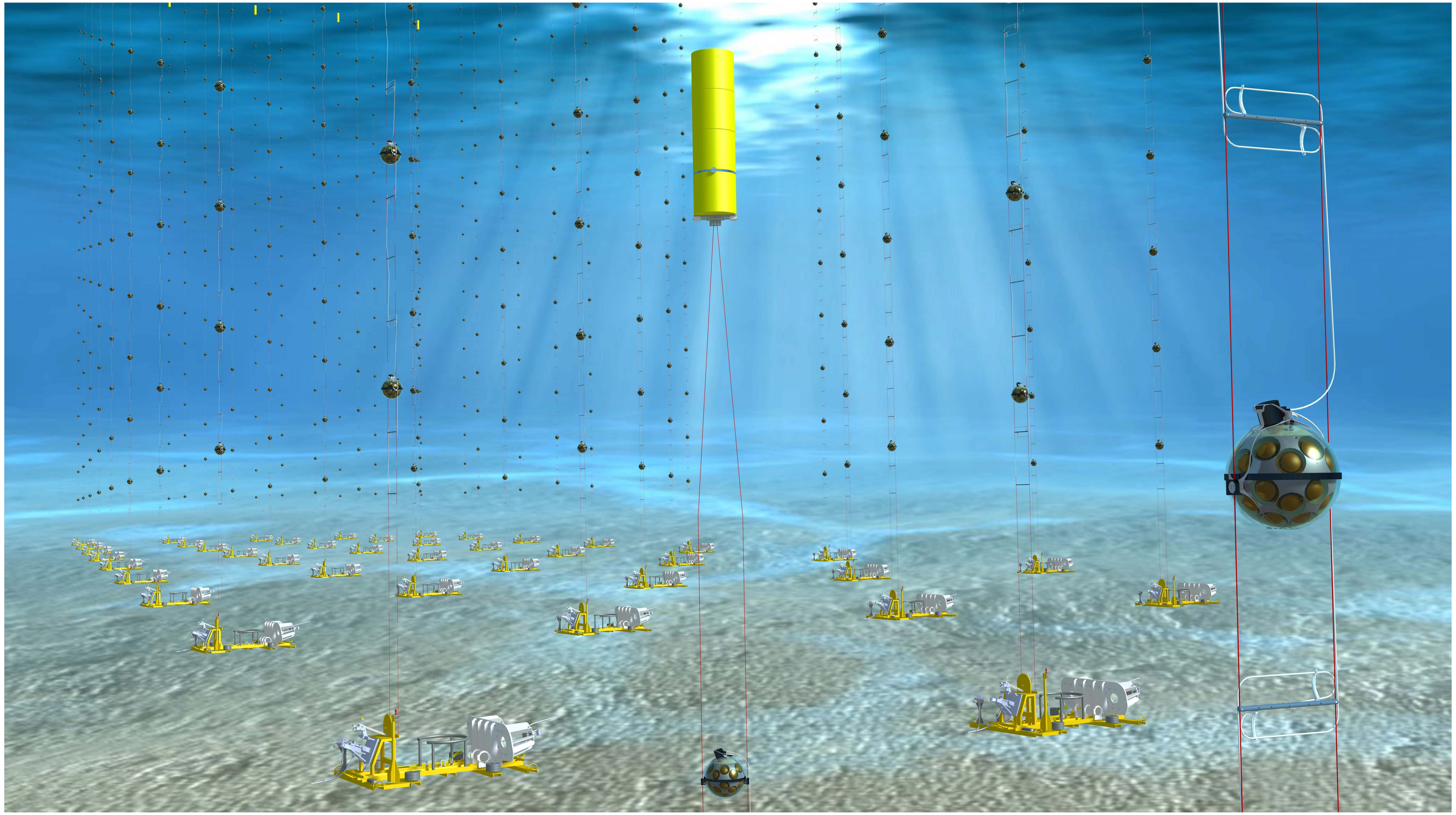

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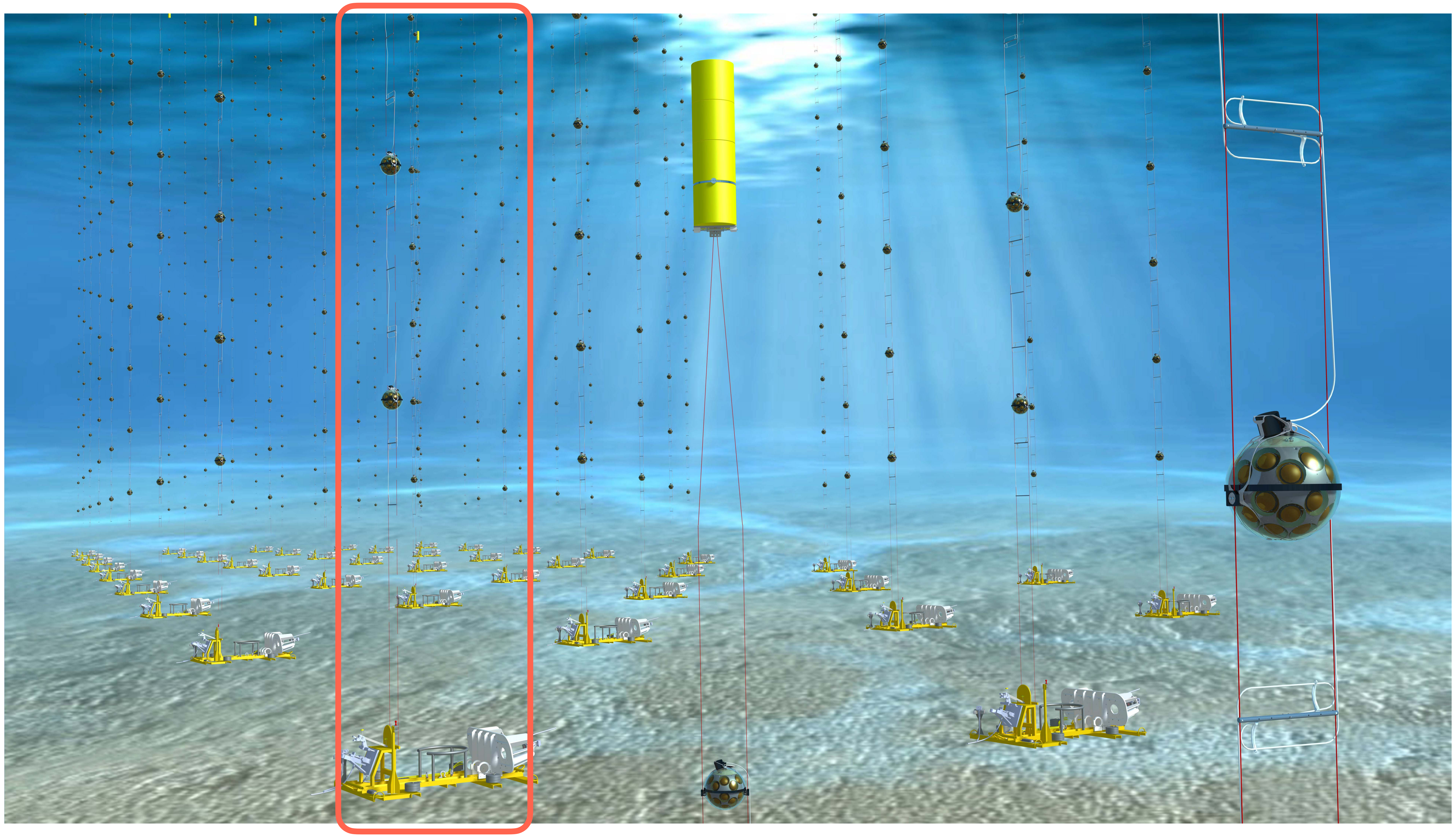

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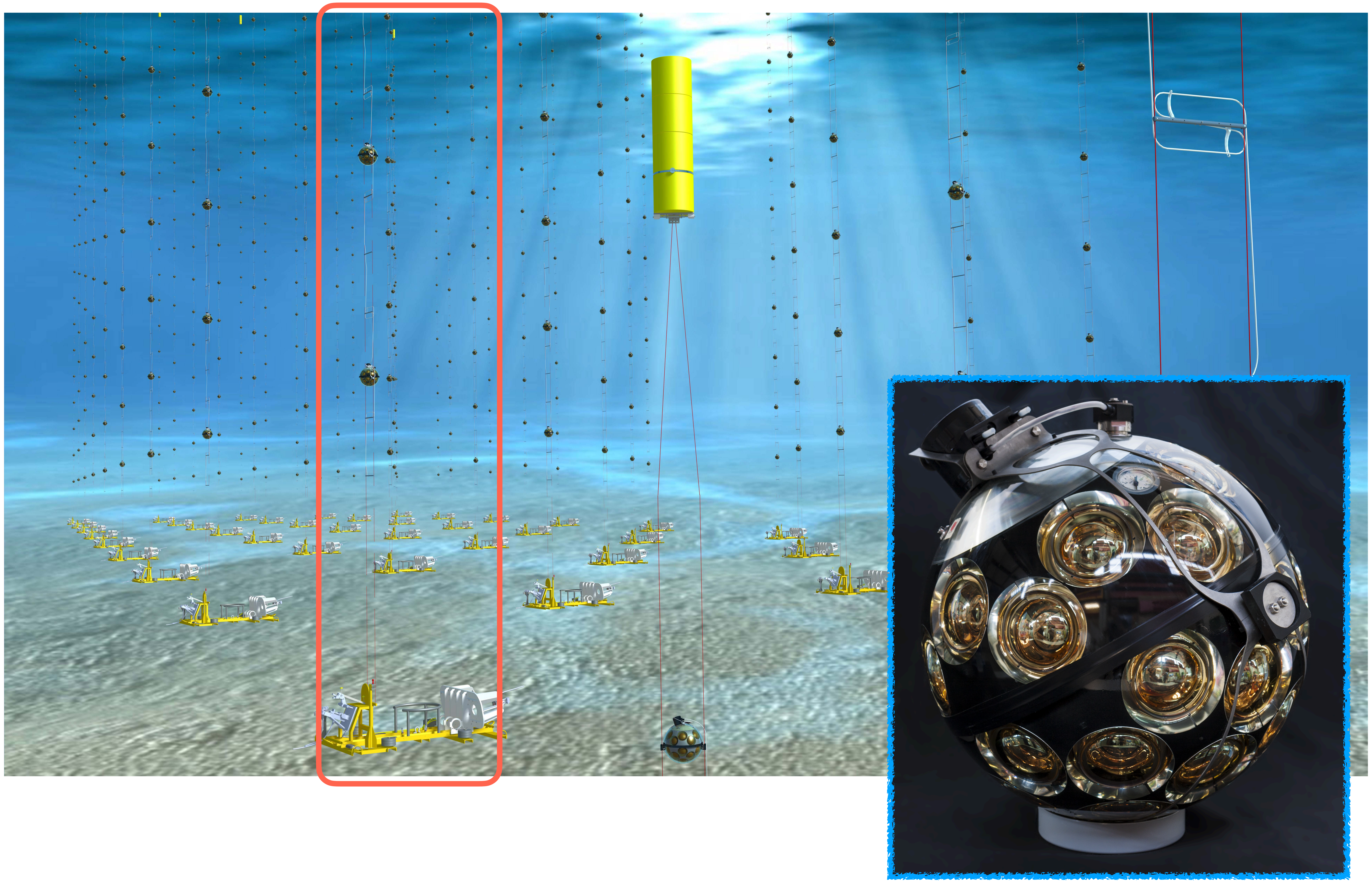

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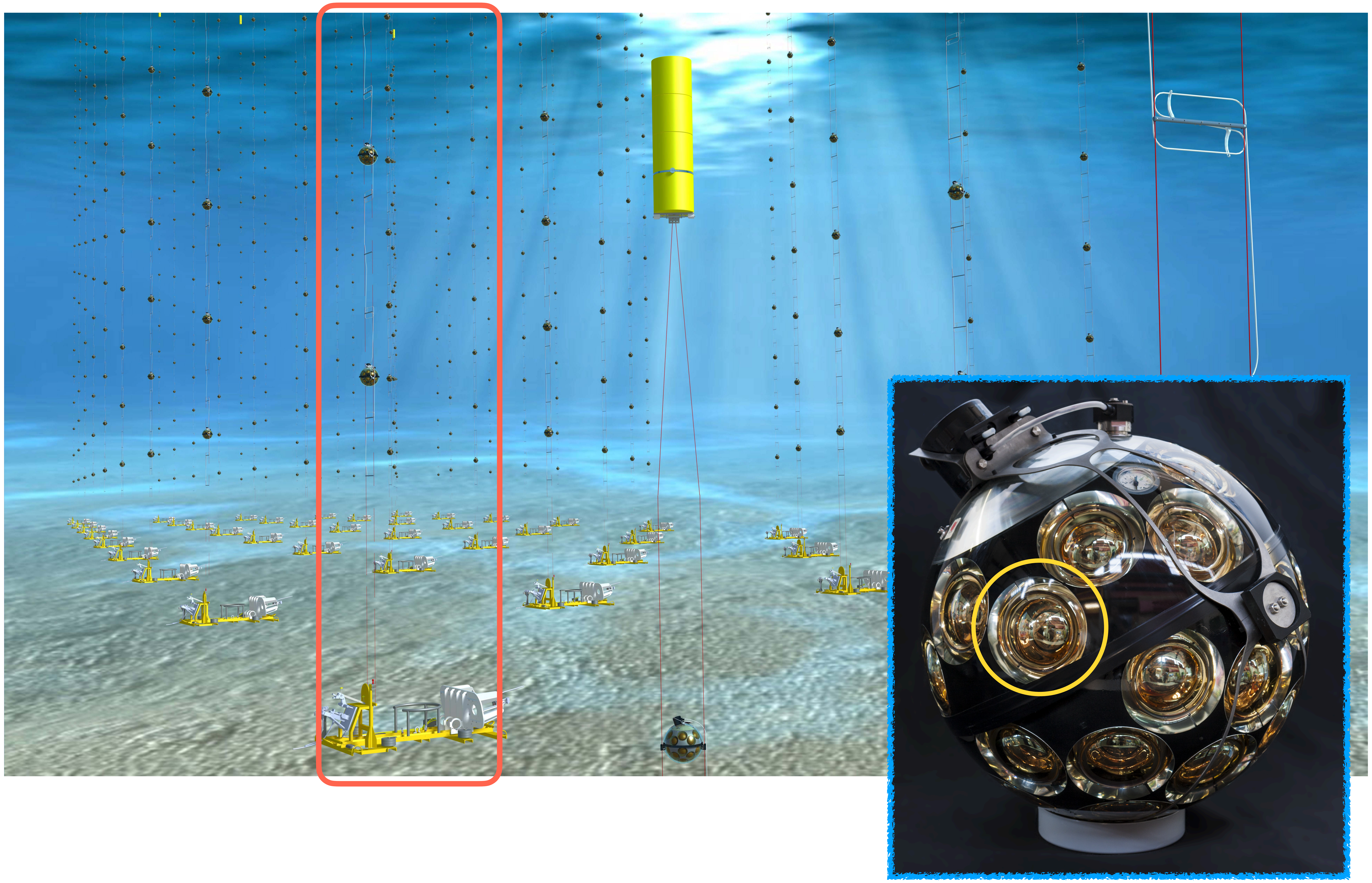

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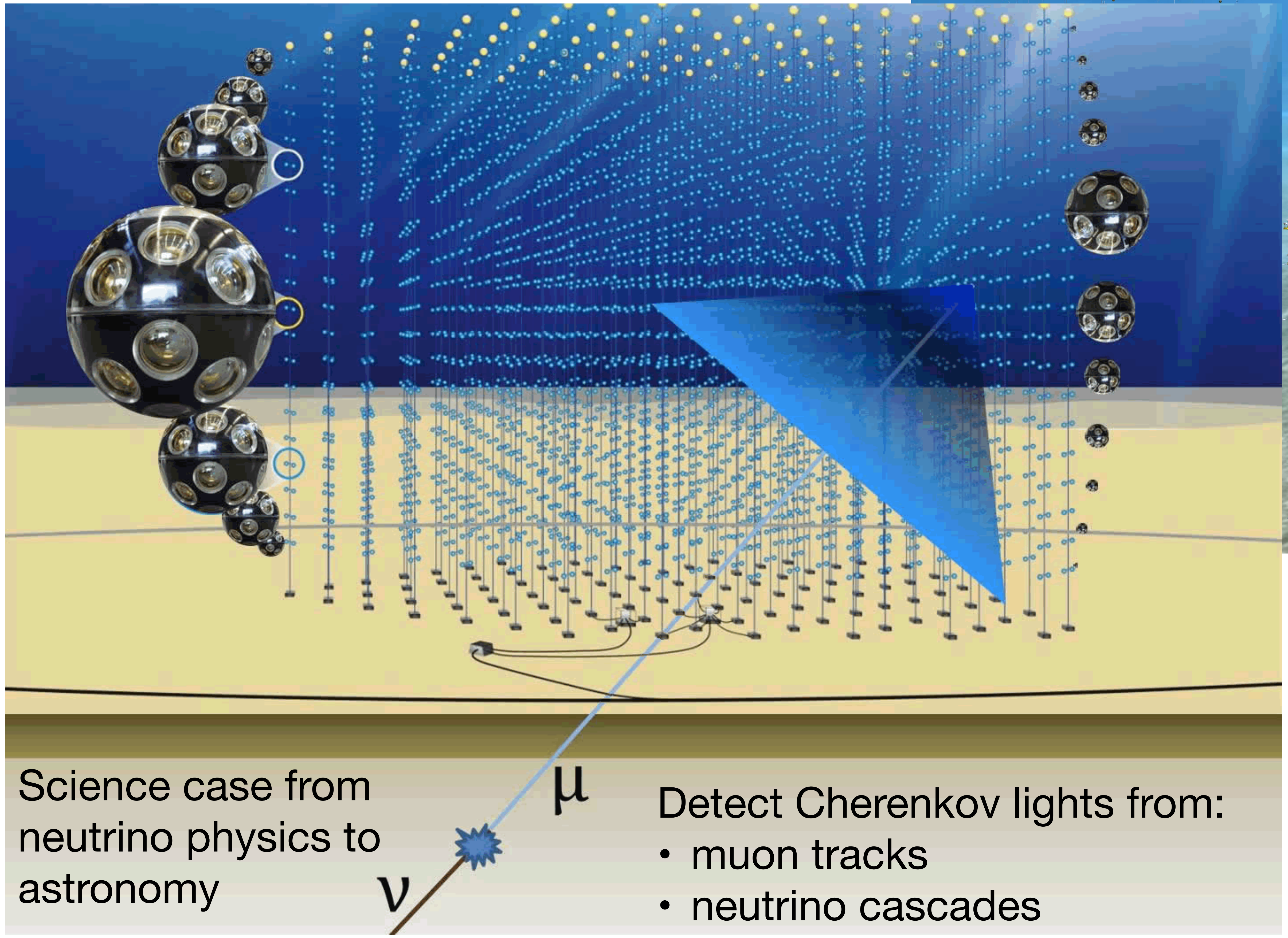
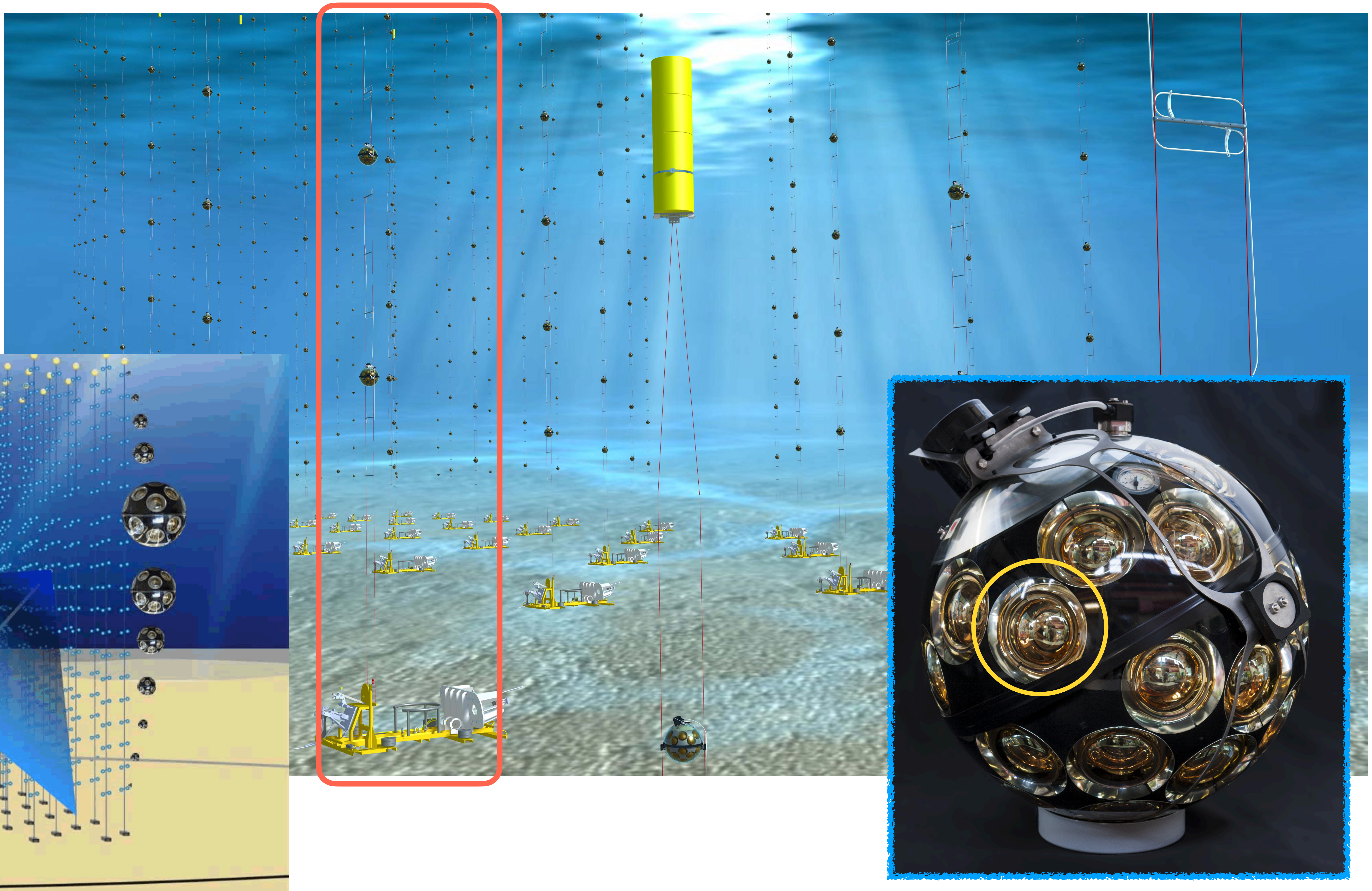


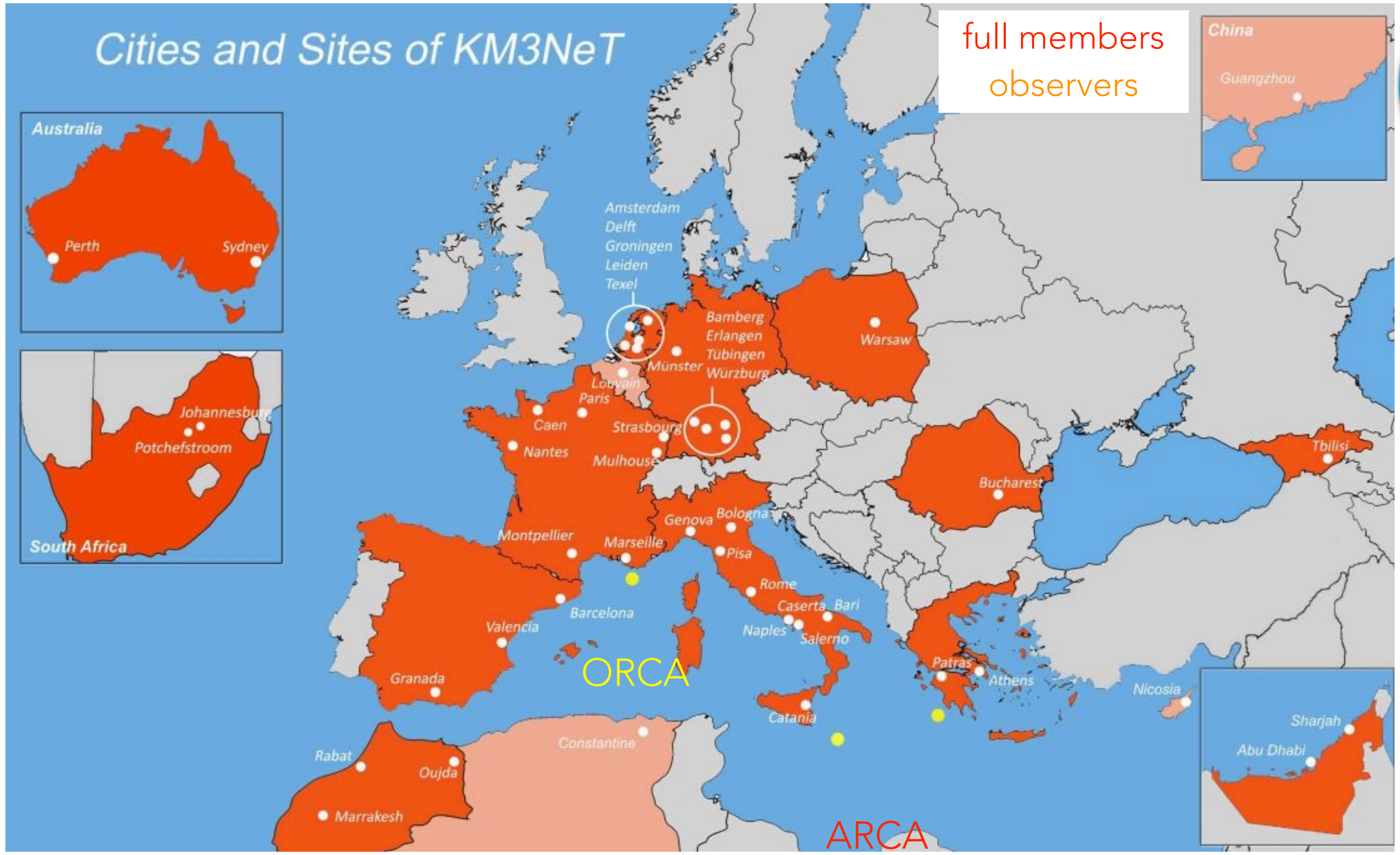
Science case from neutrino physics to astronomy

Detect Cherenkov lights from:
- muon tracks
- neutrino cascades



Technical configuration:
- each Detection Unit (DU) is a line made of 18 DOMs
- each DOMs is made of 31 PMTs

Astronomy potential with KM3NeT



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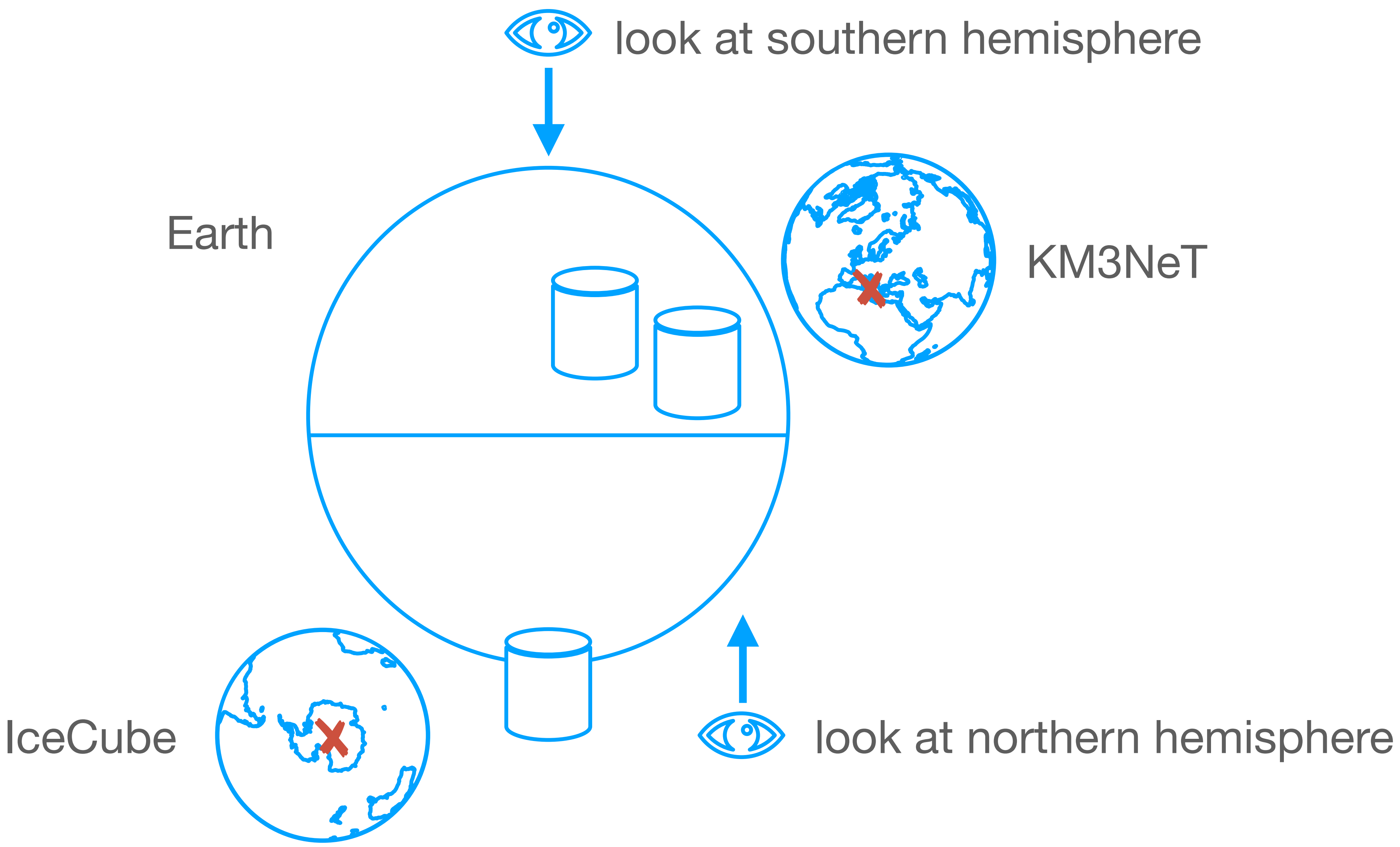

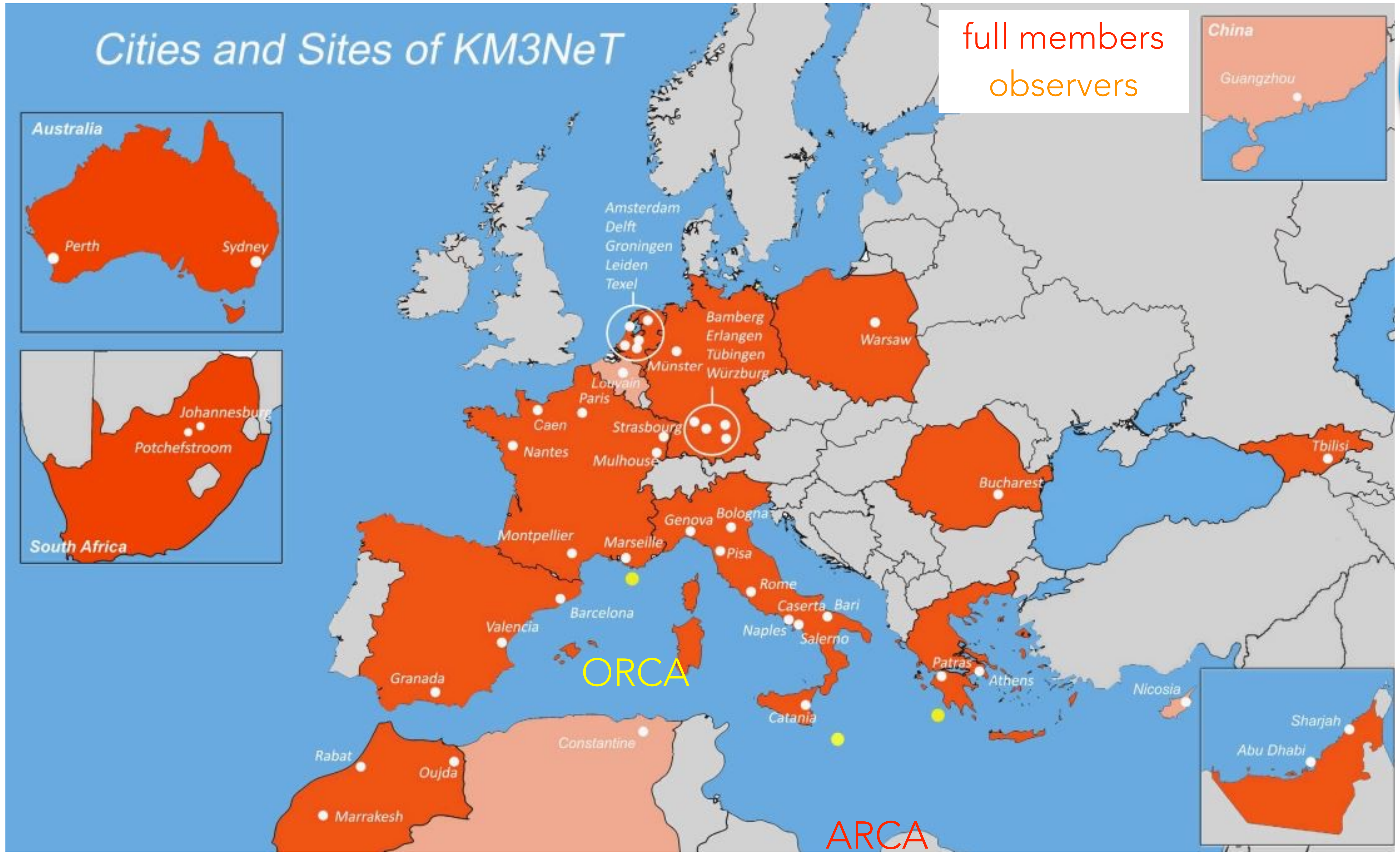

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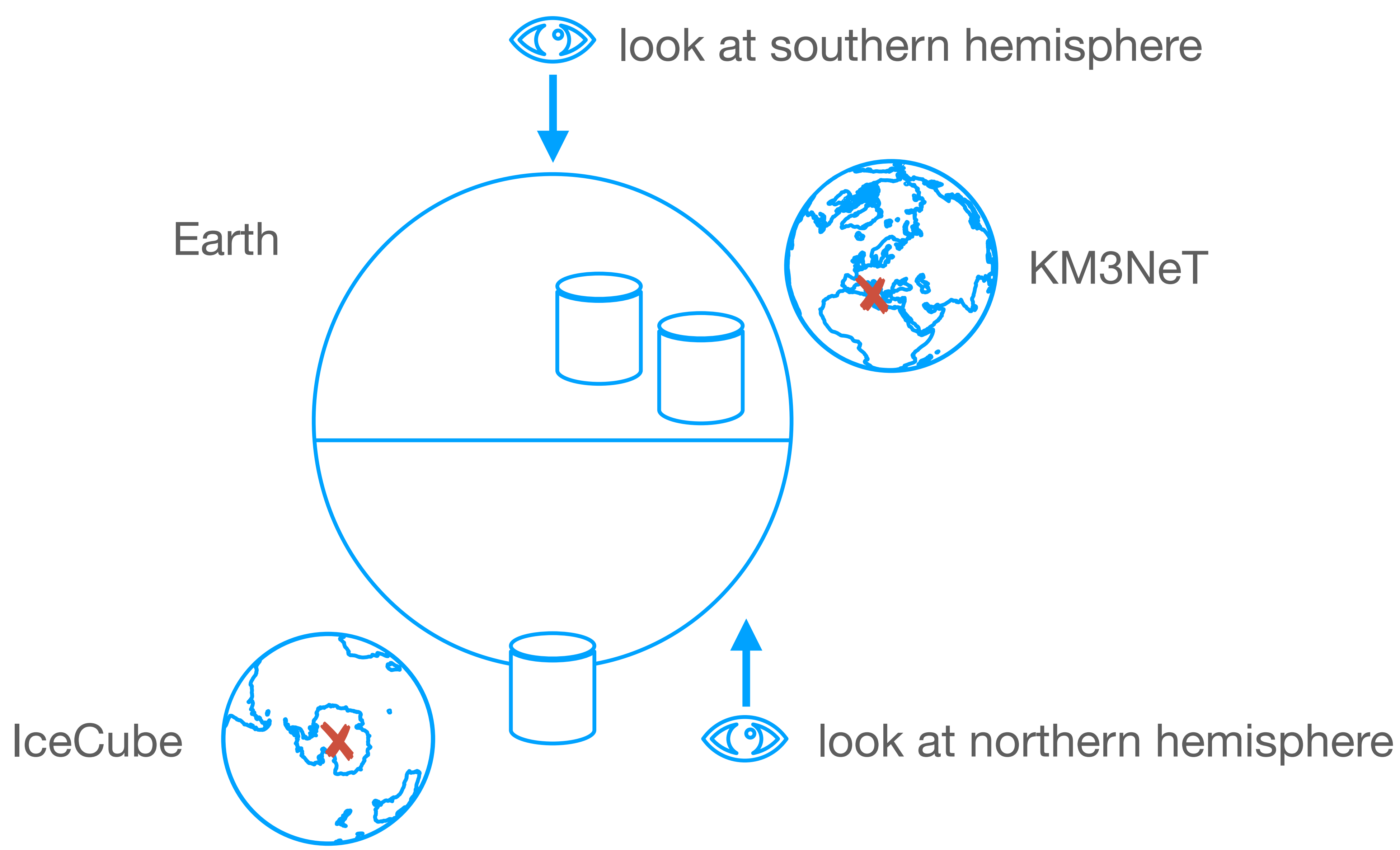

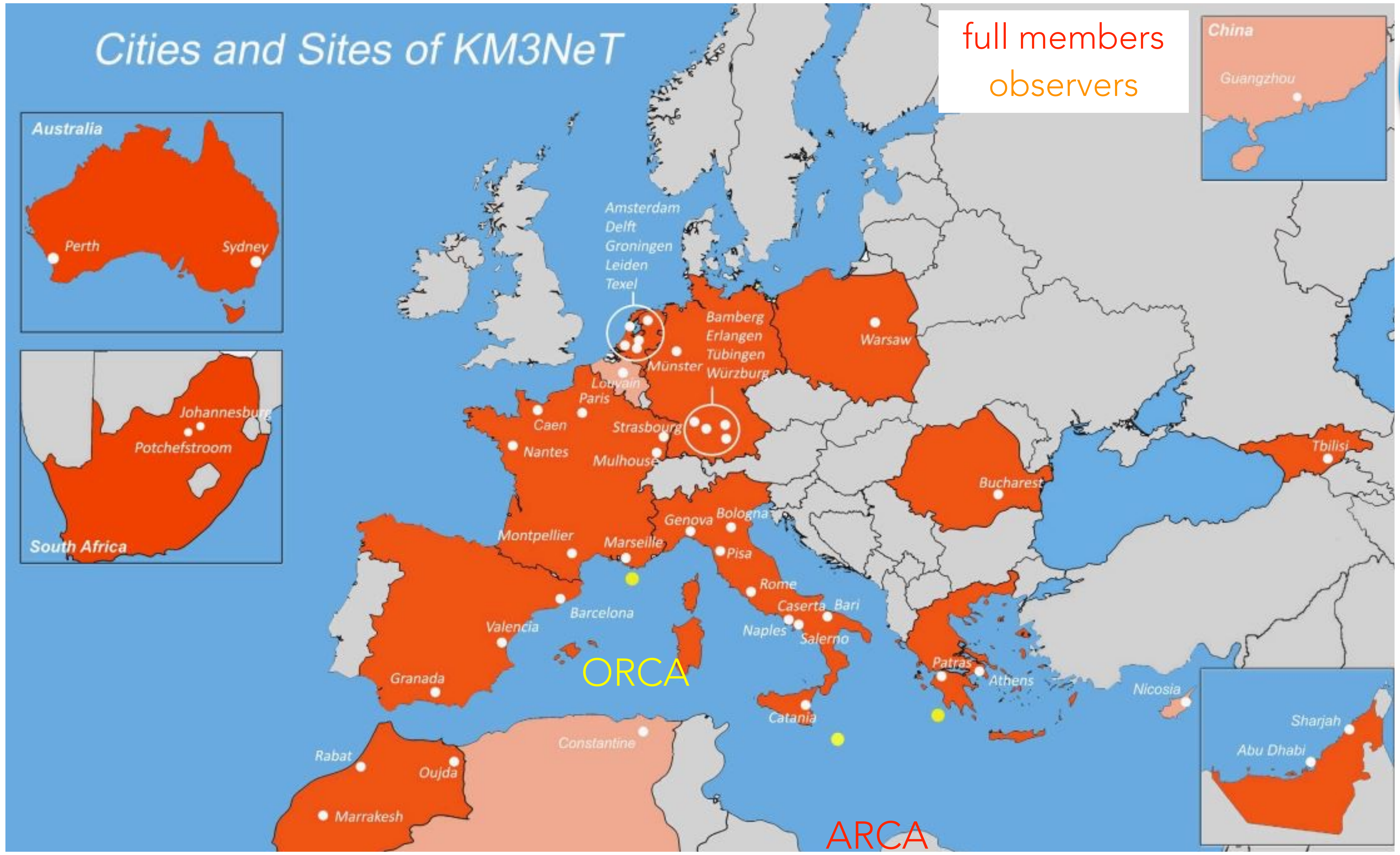

Galaxy centre visible from southern hemisphere!

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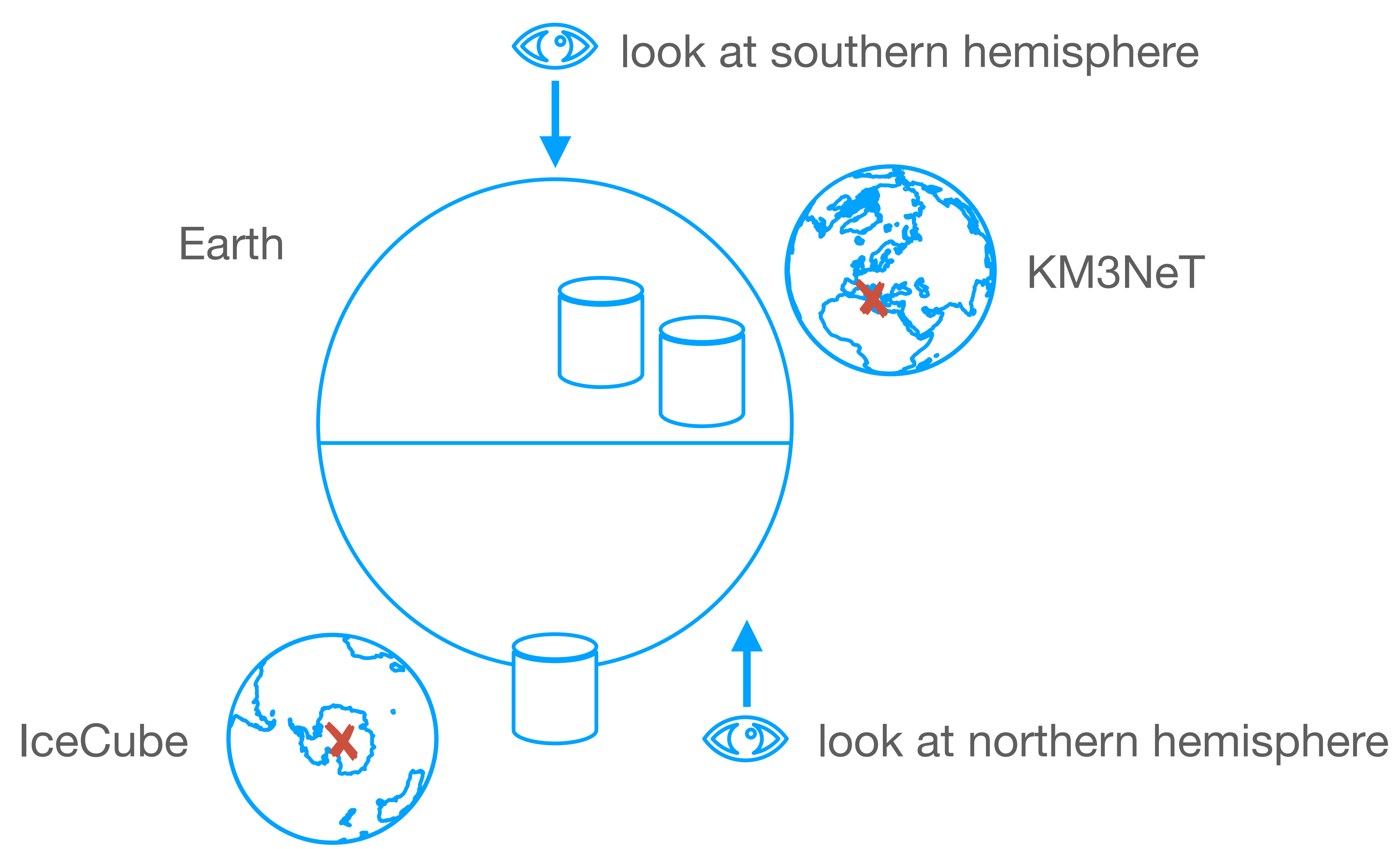

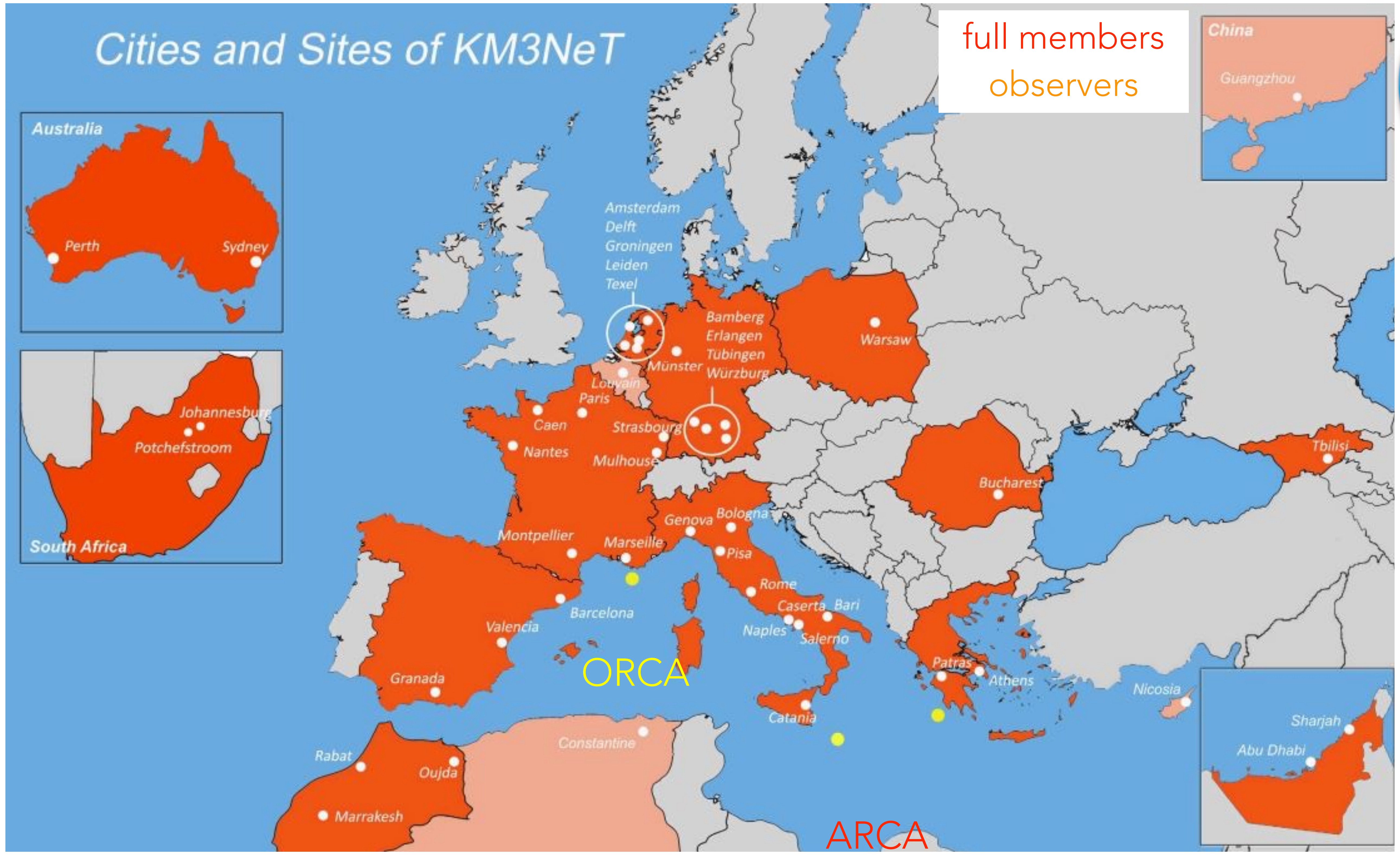

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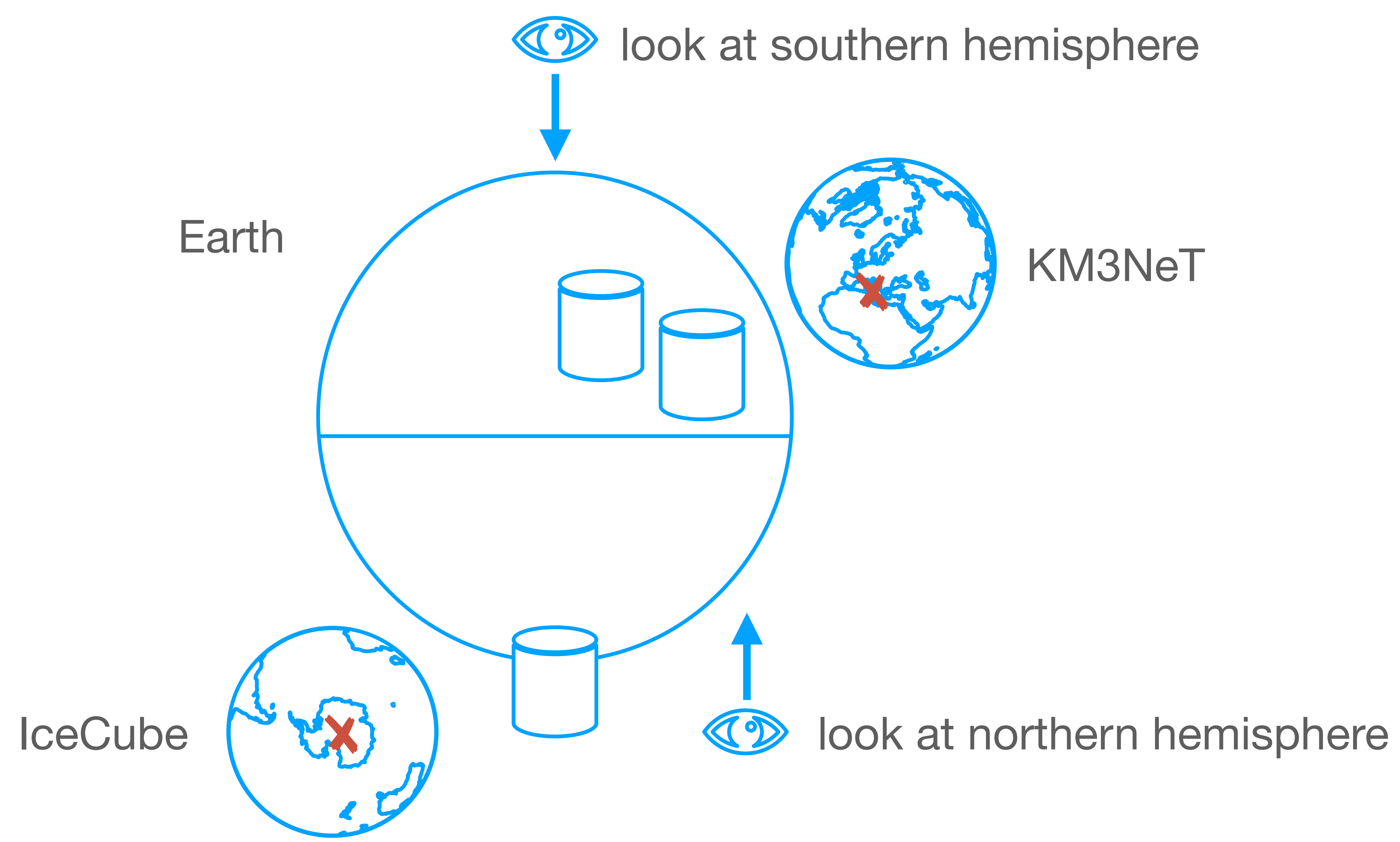

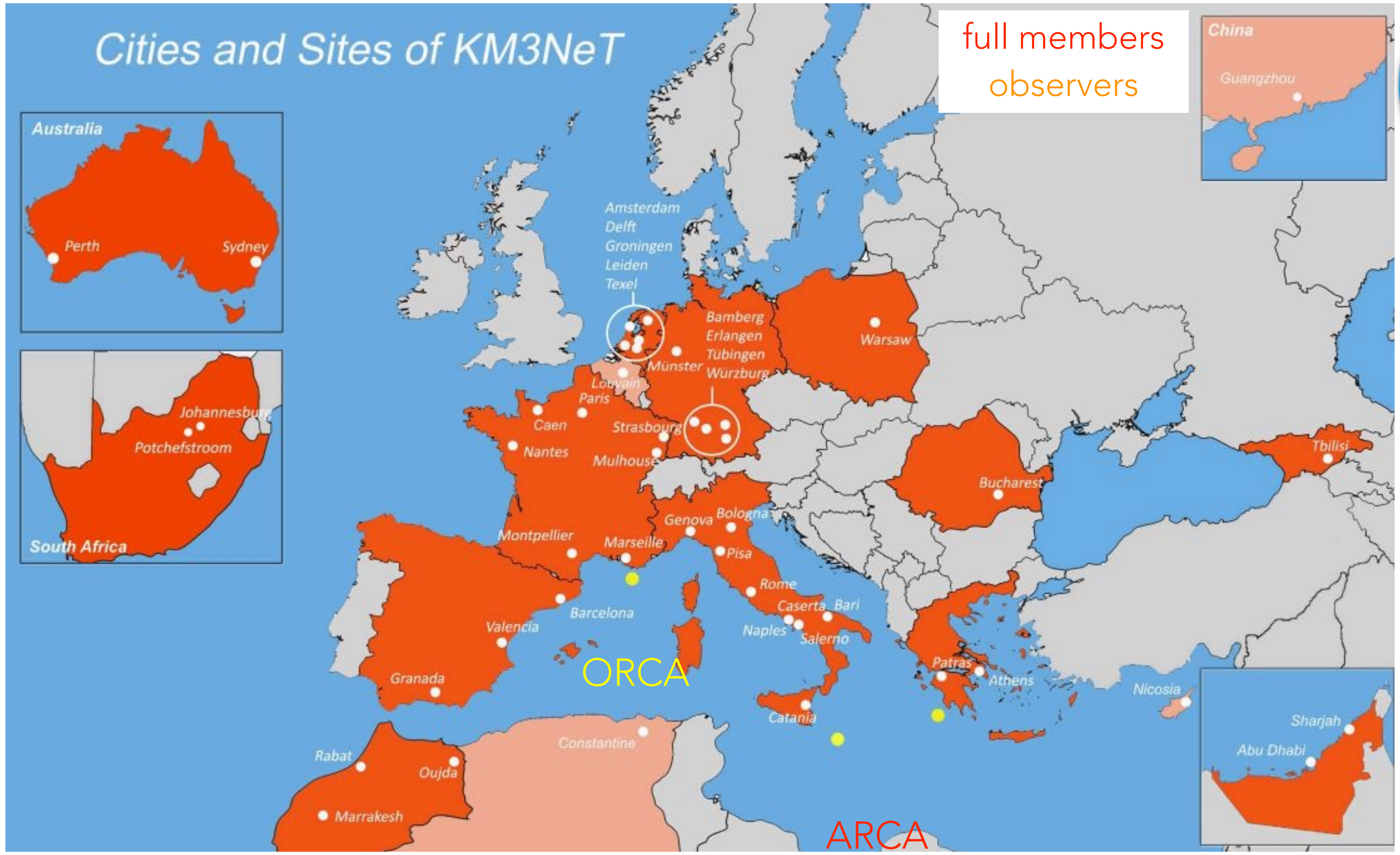

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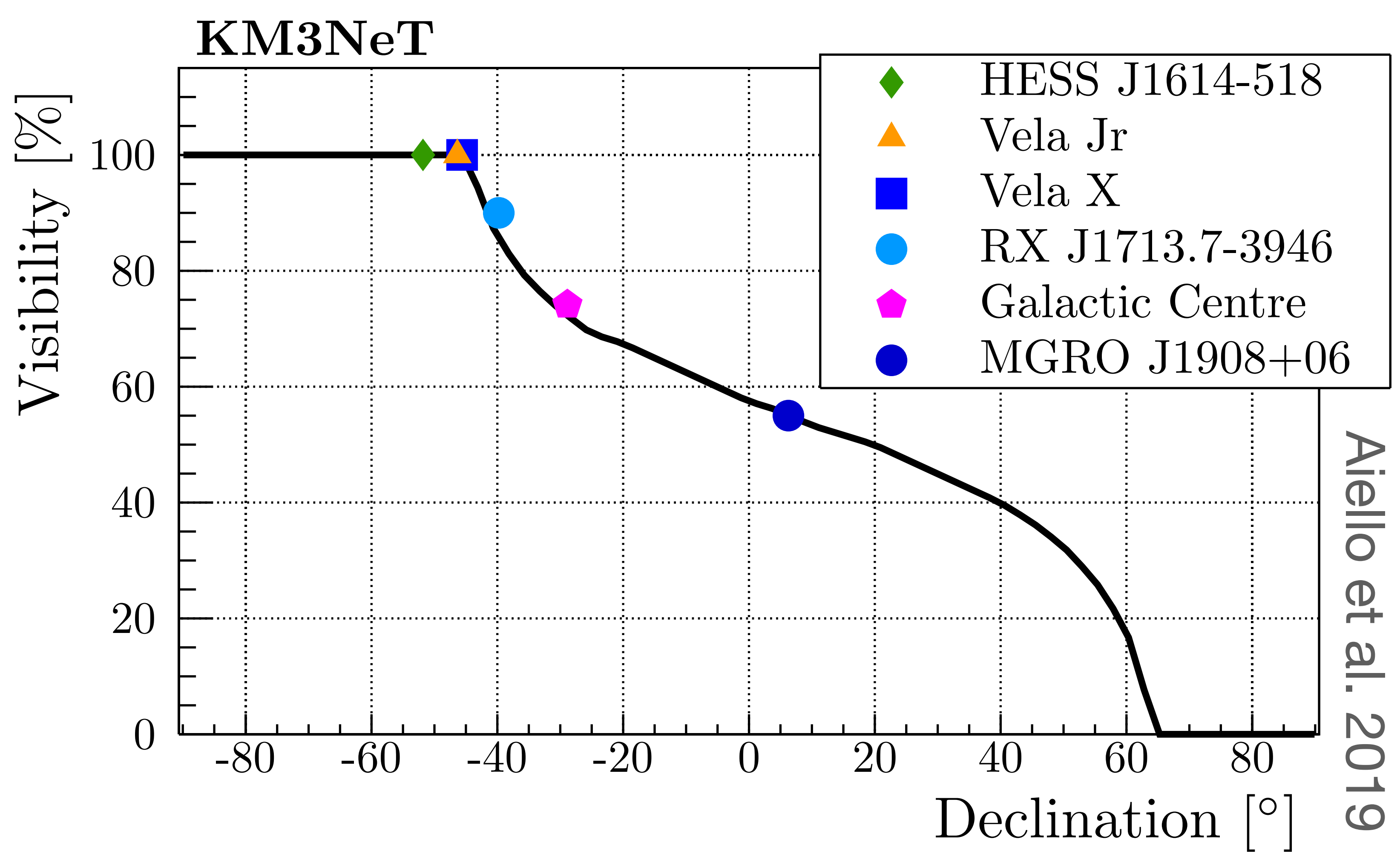
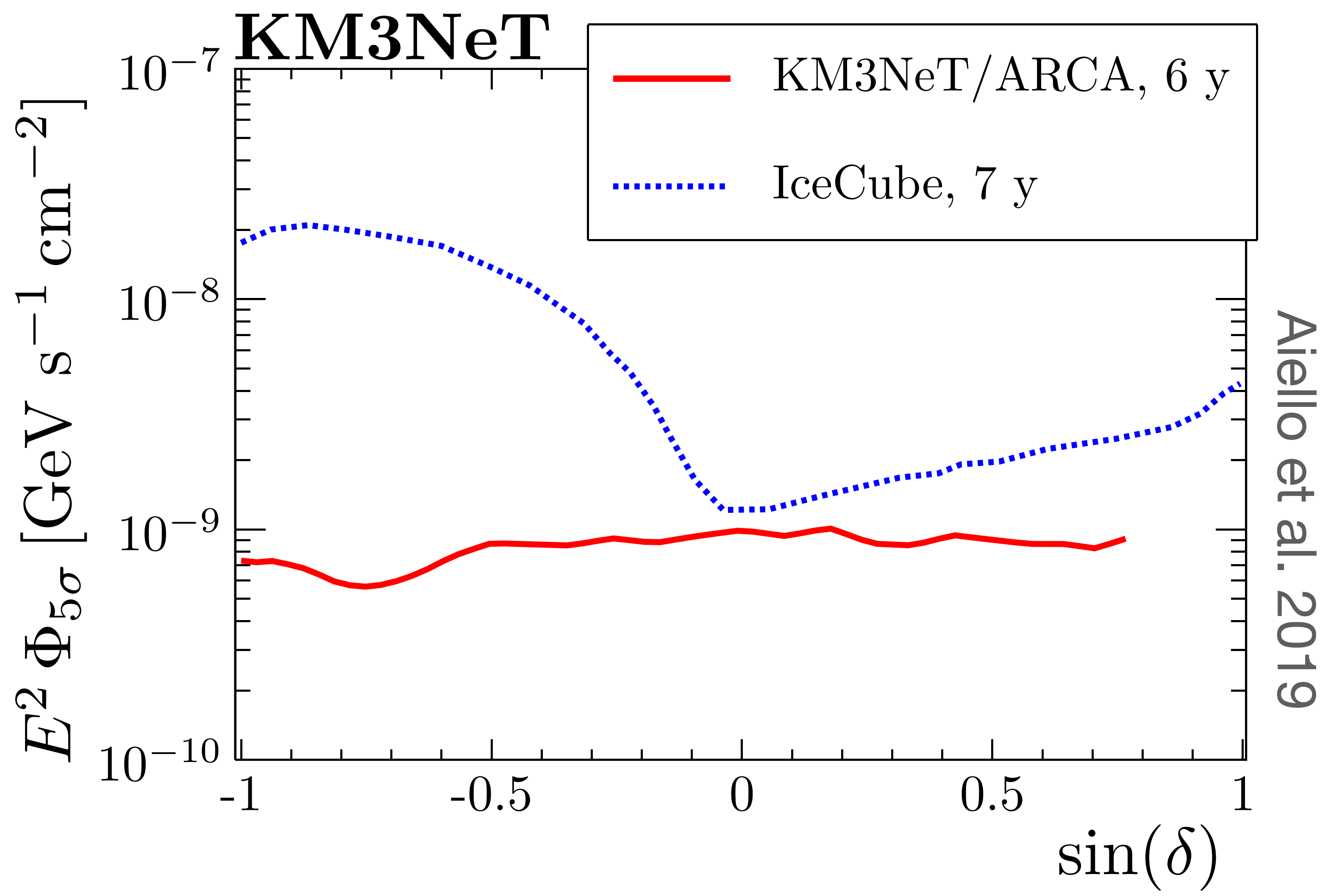
1. field of view
2. sensitivity (over the whole sky)





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Our team is involved in the astronomy analysis

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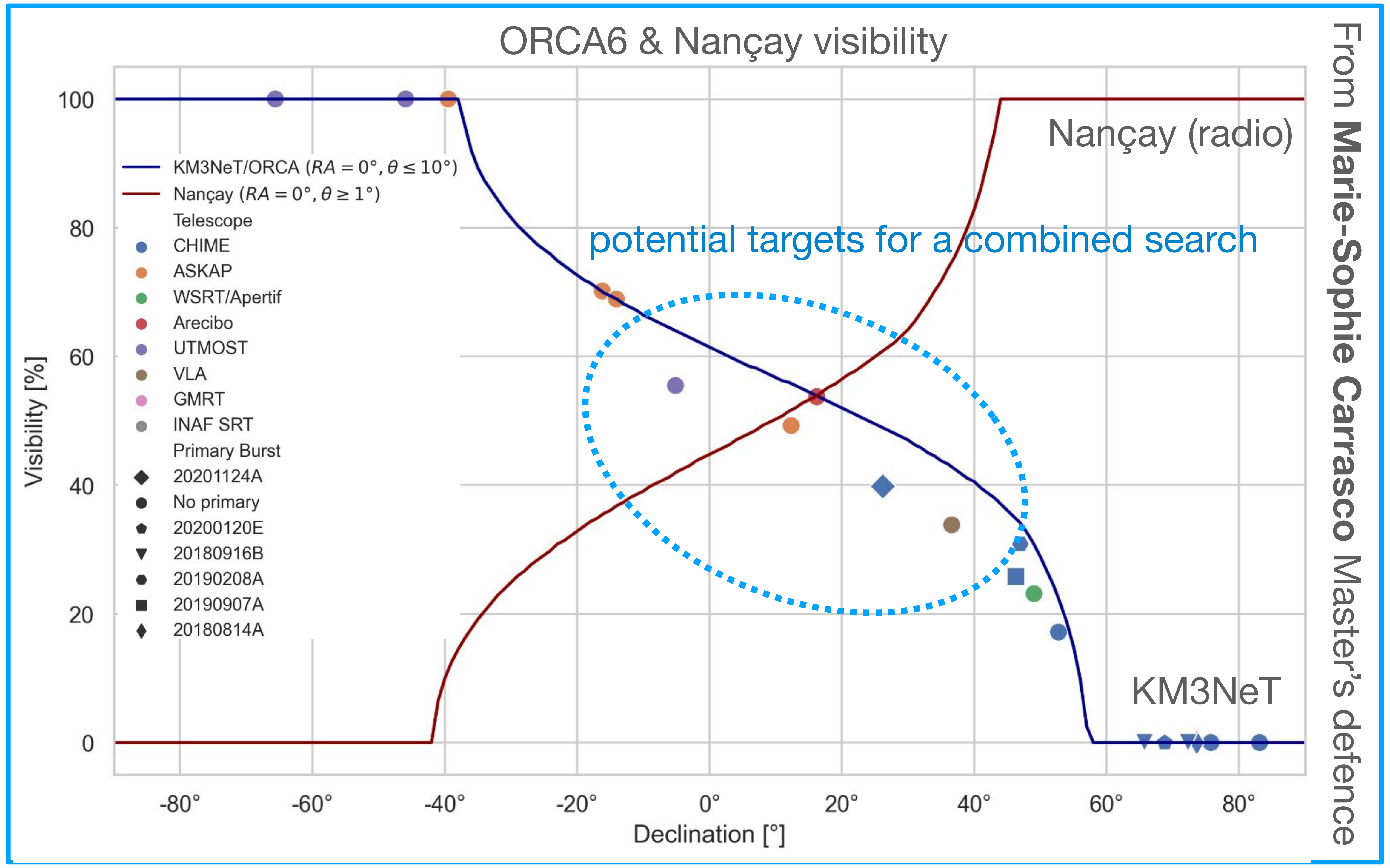

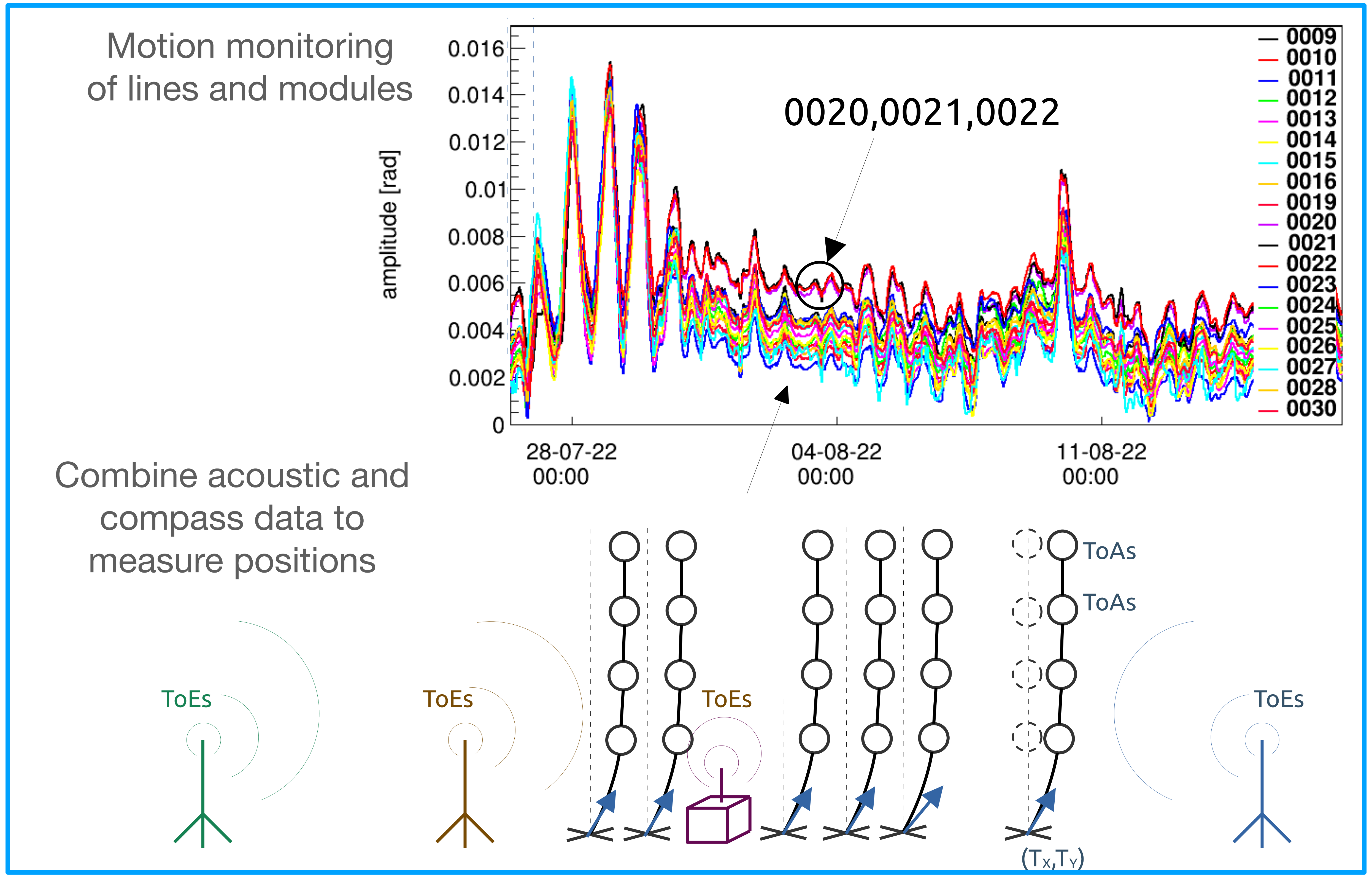

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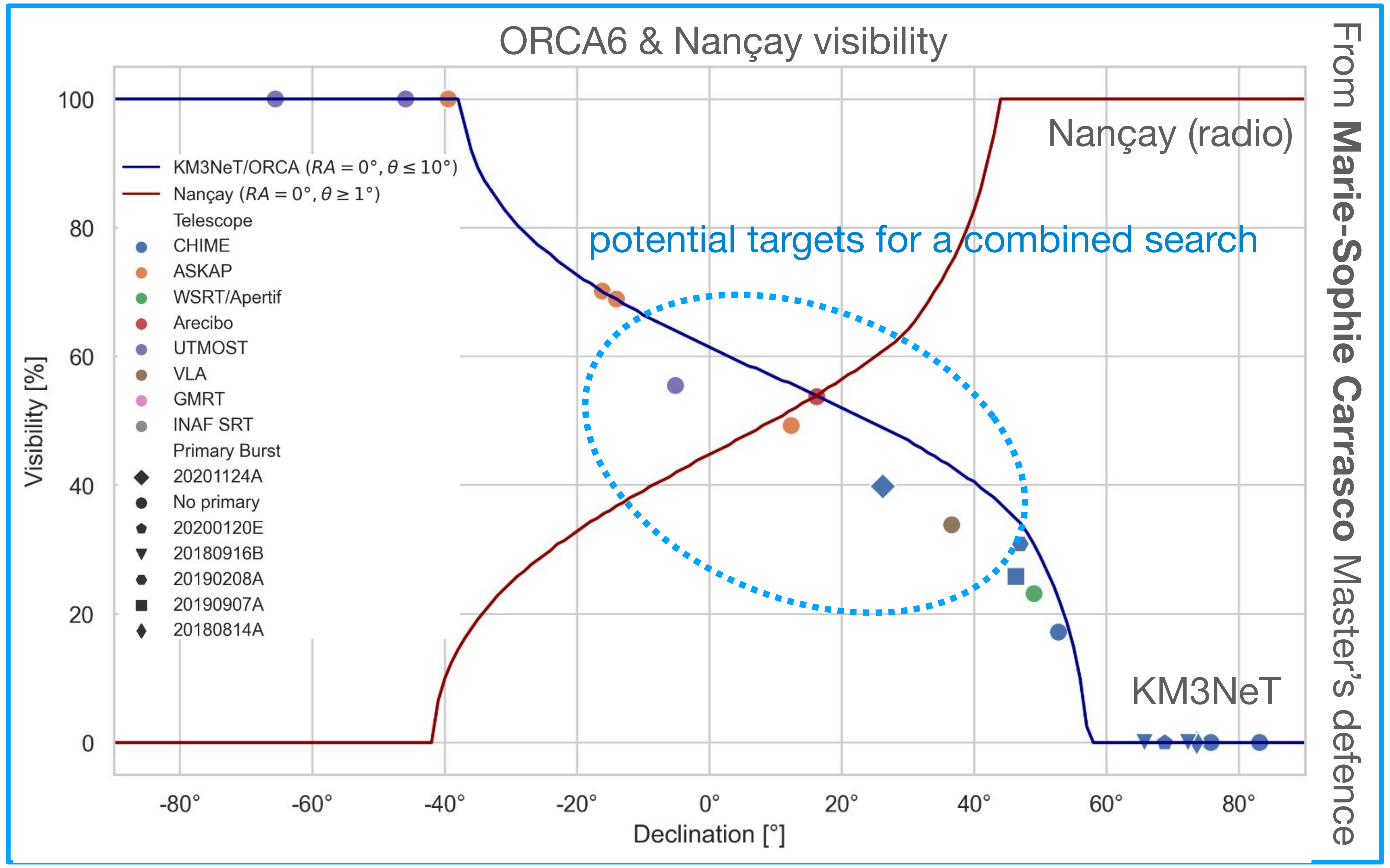

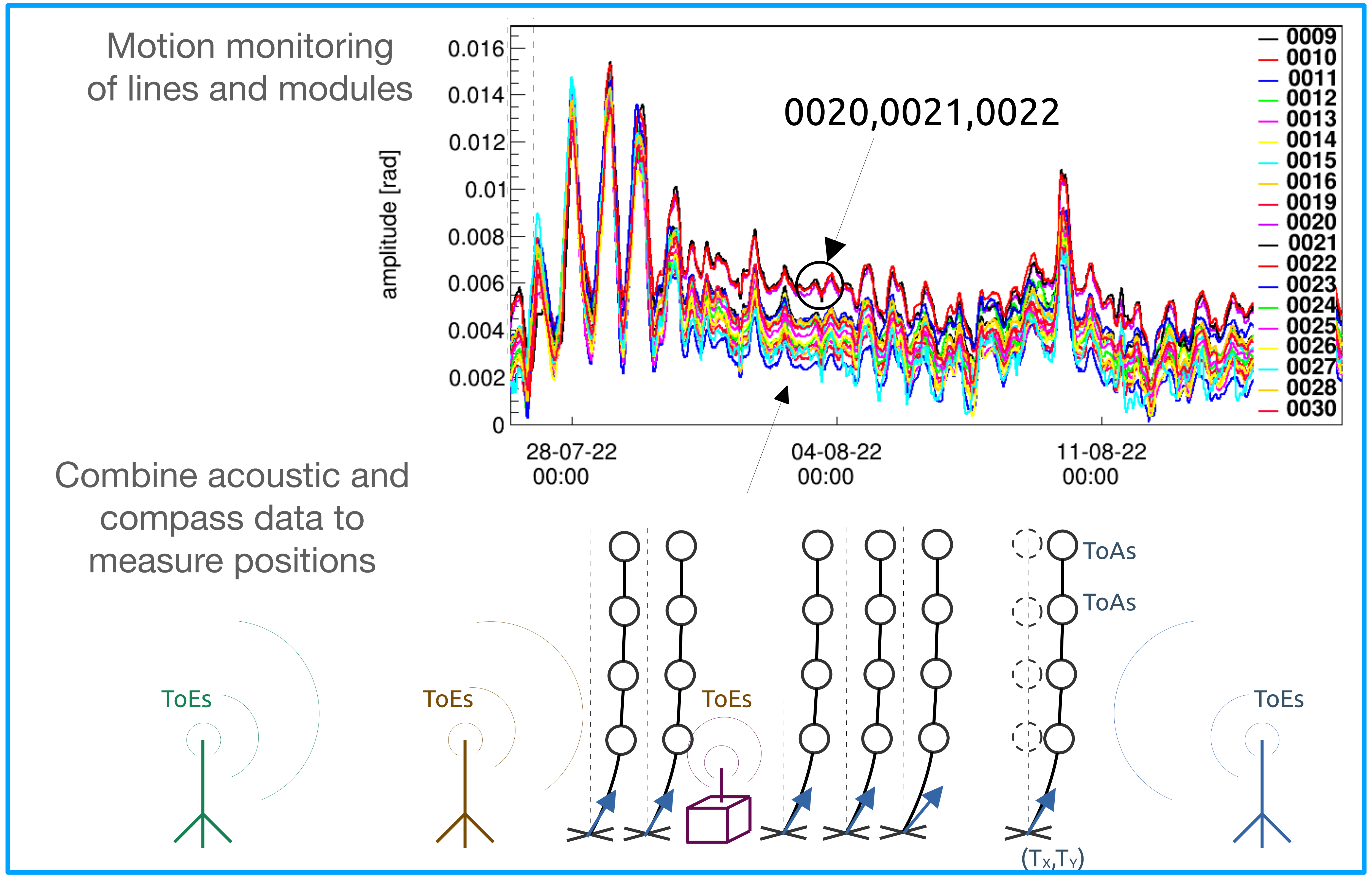

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- extension to southern radio-telescopes (Meerkat, MWA, SKA?)
- alert and observation strategies with radio-telescope (online analysis)
- model développements for multi-messenger fast radio transients sources (iterative with alerts and strategies)

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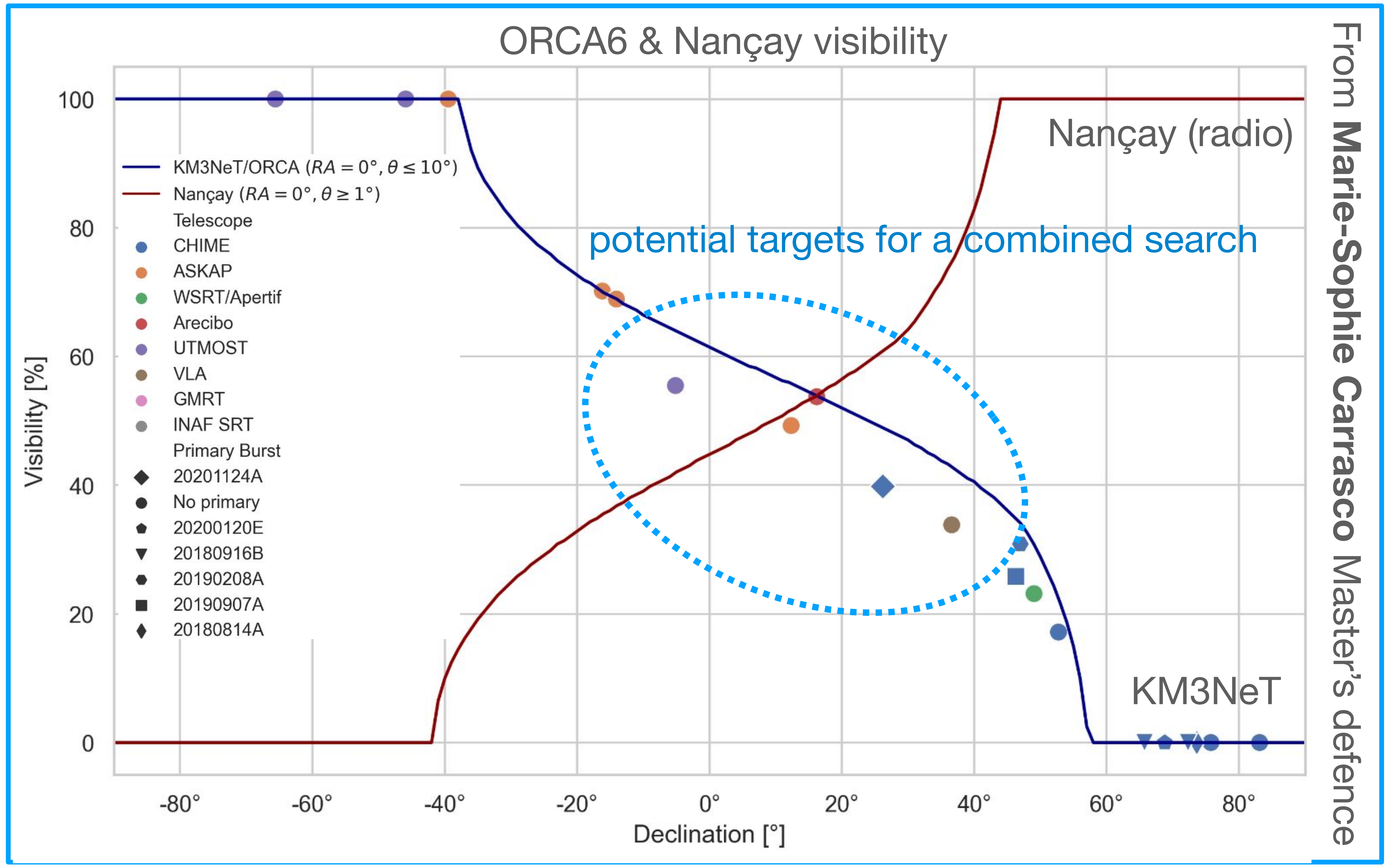

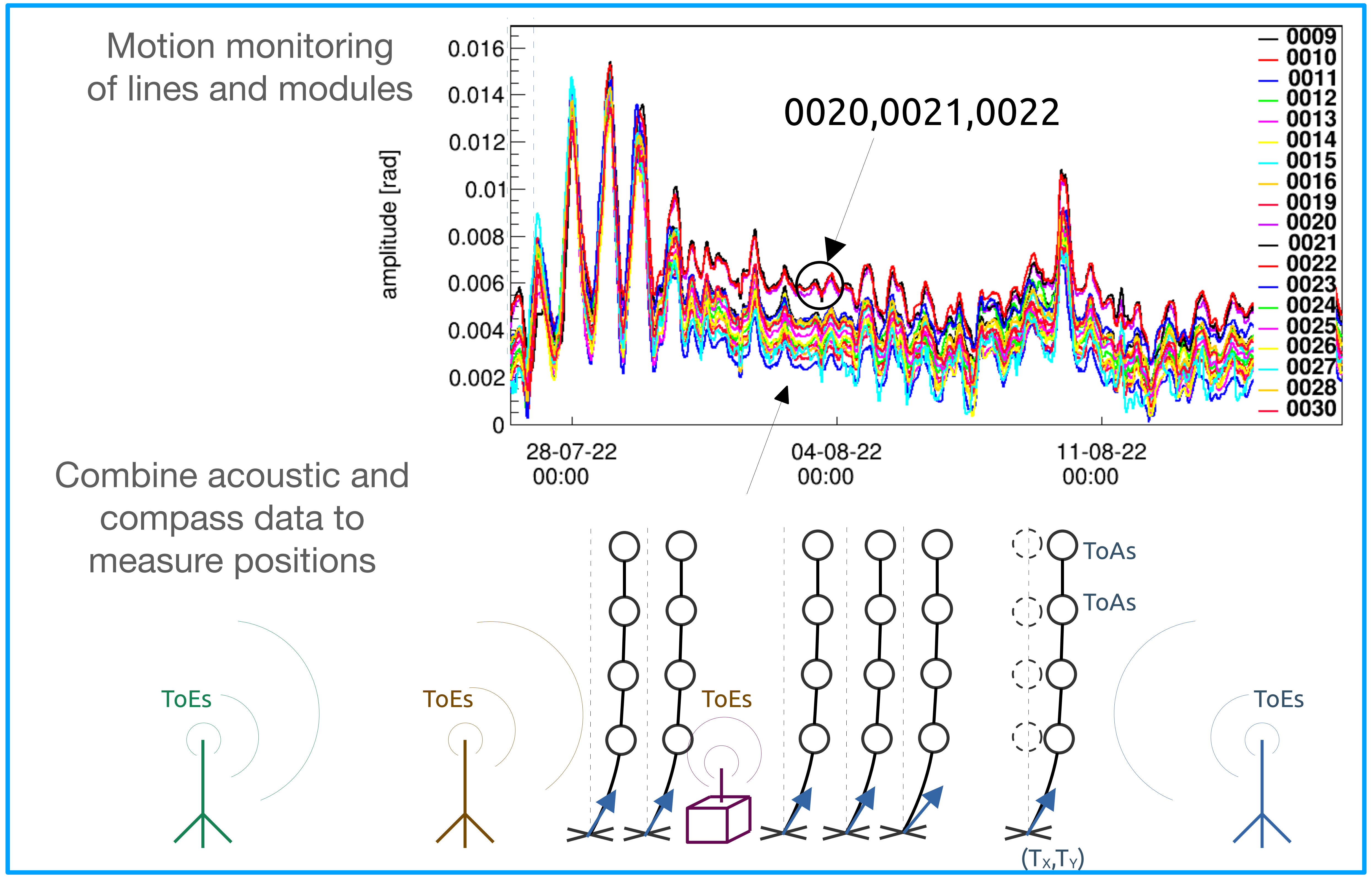

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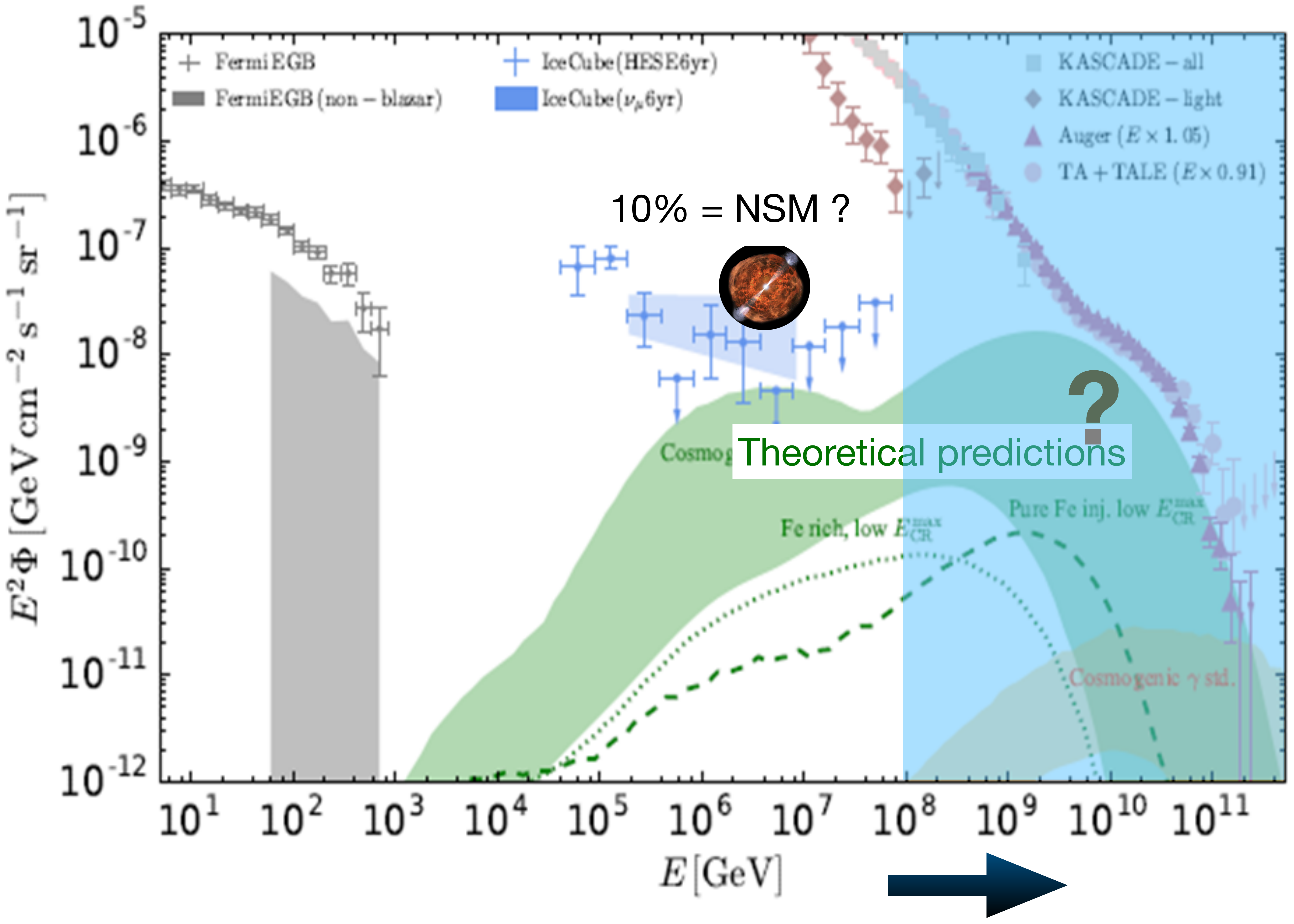
Work in progress, new results are coming soon!

Predicted ultra high-energy neutrinos

- Expand the measurements of the neutrino spectrum
- Reach the cosmogenic flux of ultra high-energy (UHE) neutrinos



Guaranteed cosmogenic neutrinos

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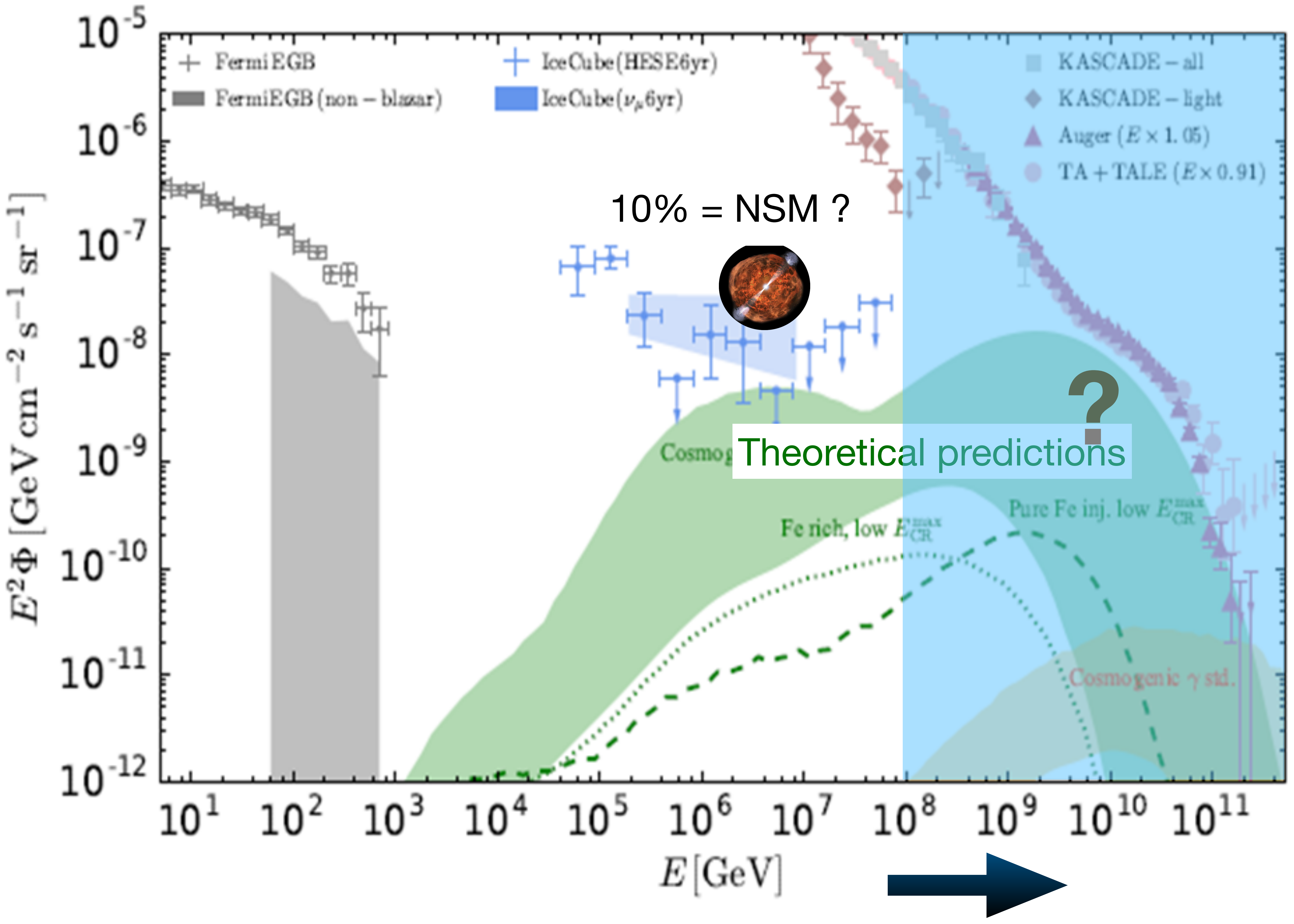

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Which sources and where ?

Constraining the possible sources of cosmogenic neutrinos

V. D., Romero-Wolf (JPL), Deaconu (UChicago), and Wissel (PSU) (in progress)

Which cosmogenic sources are we going to see with which instrument?

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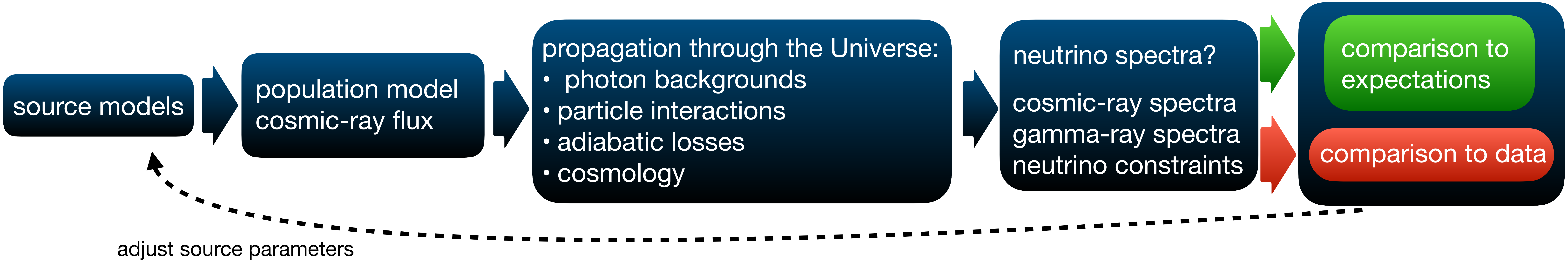

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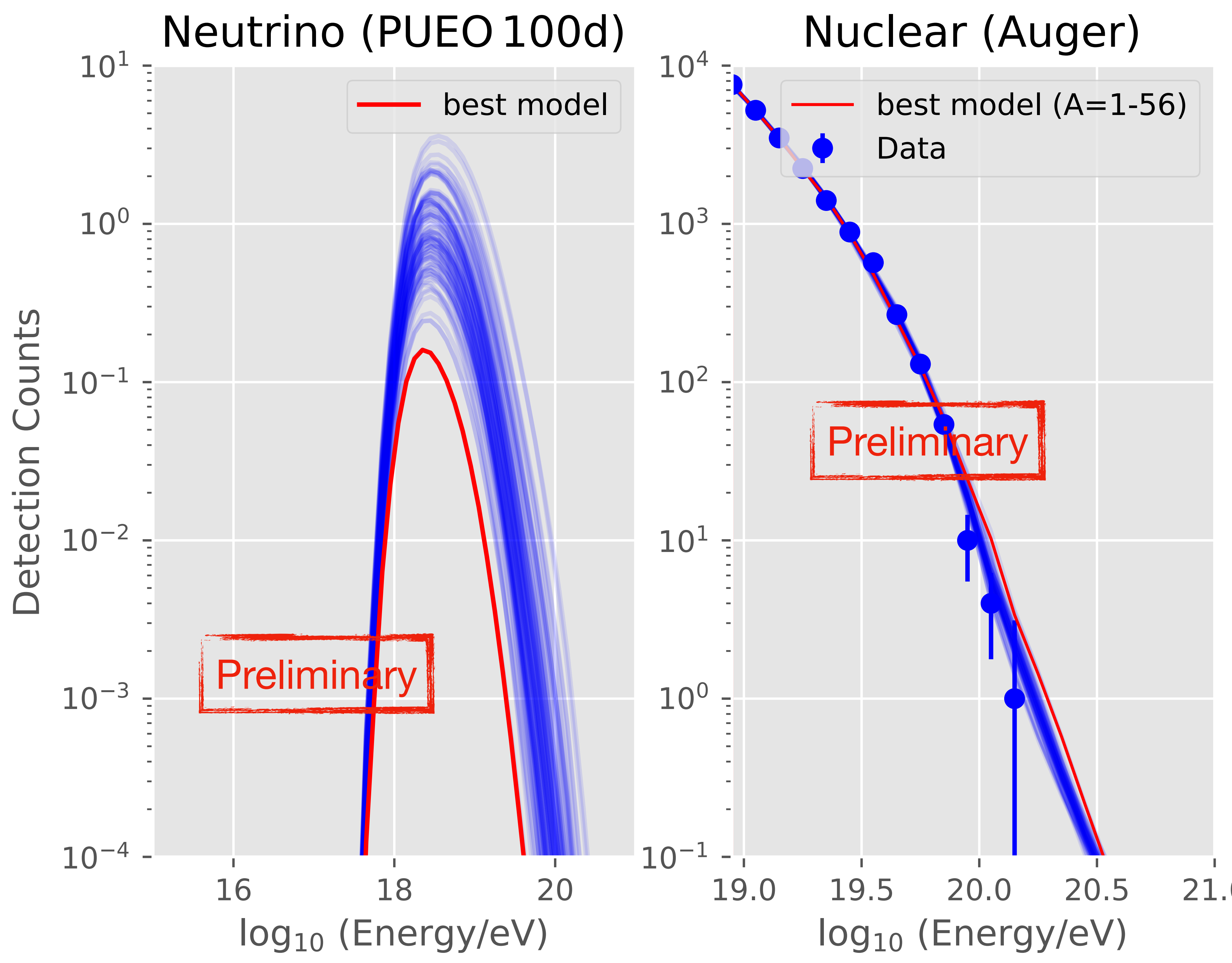

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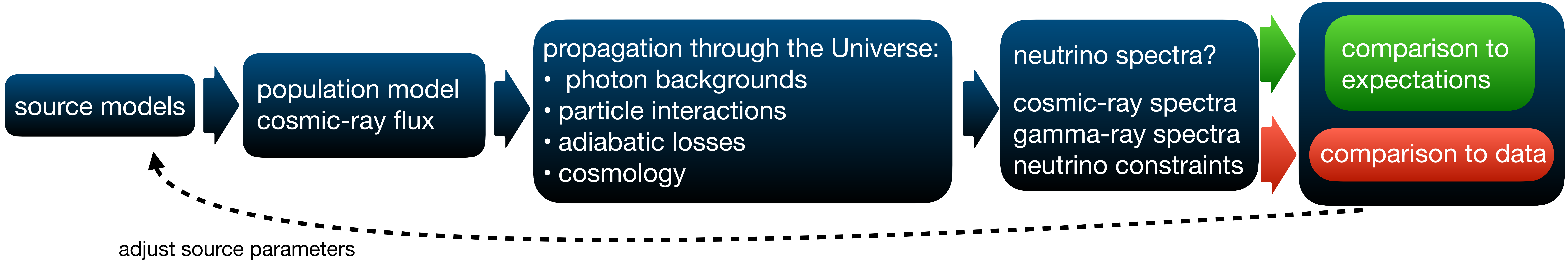
→ Goal is to probe the parameter space from the experimental point of view



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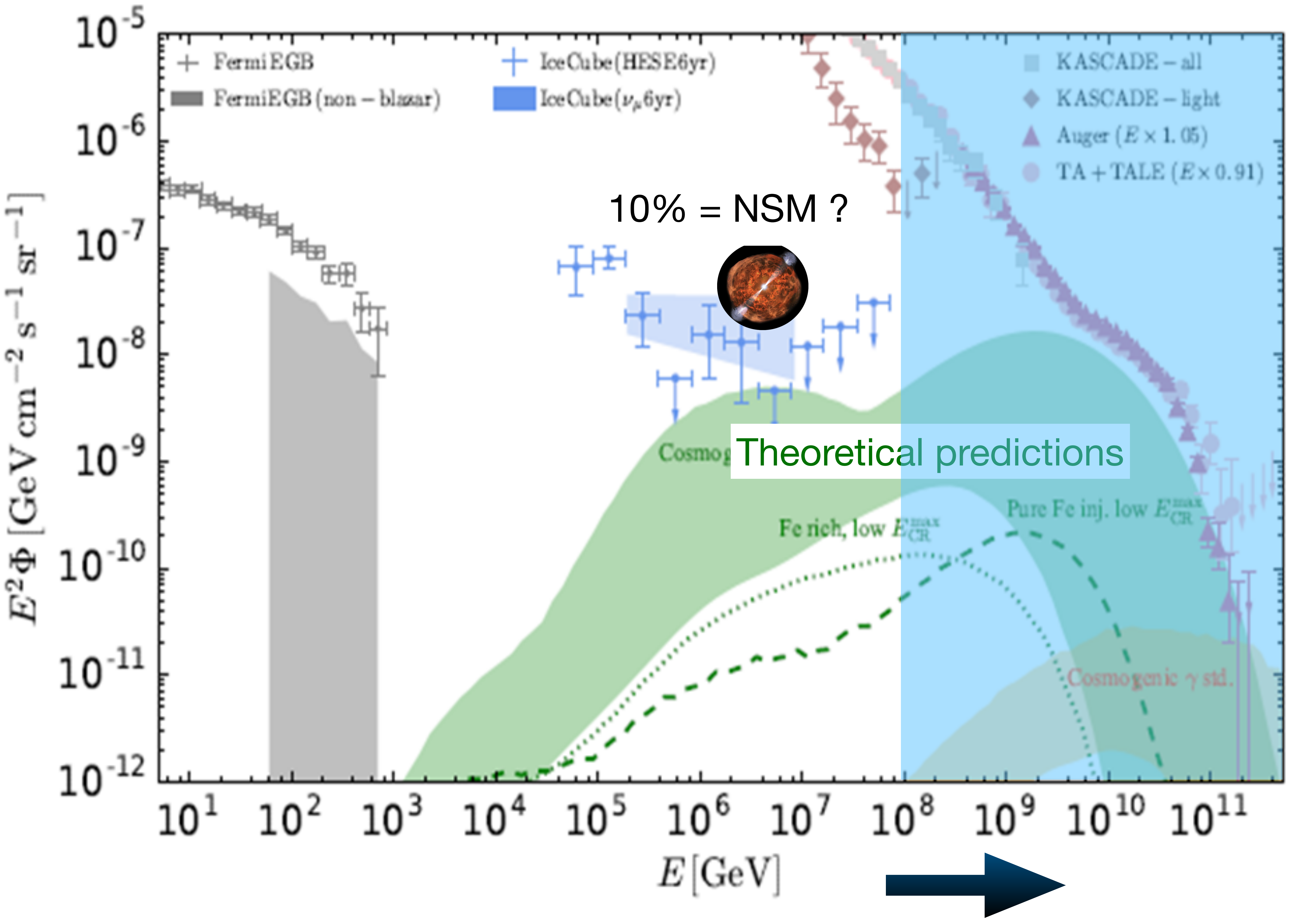

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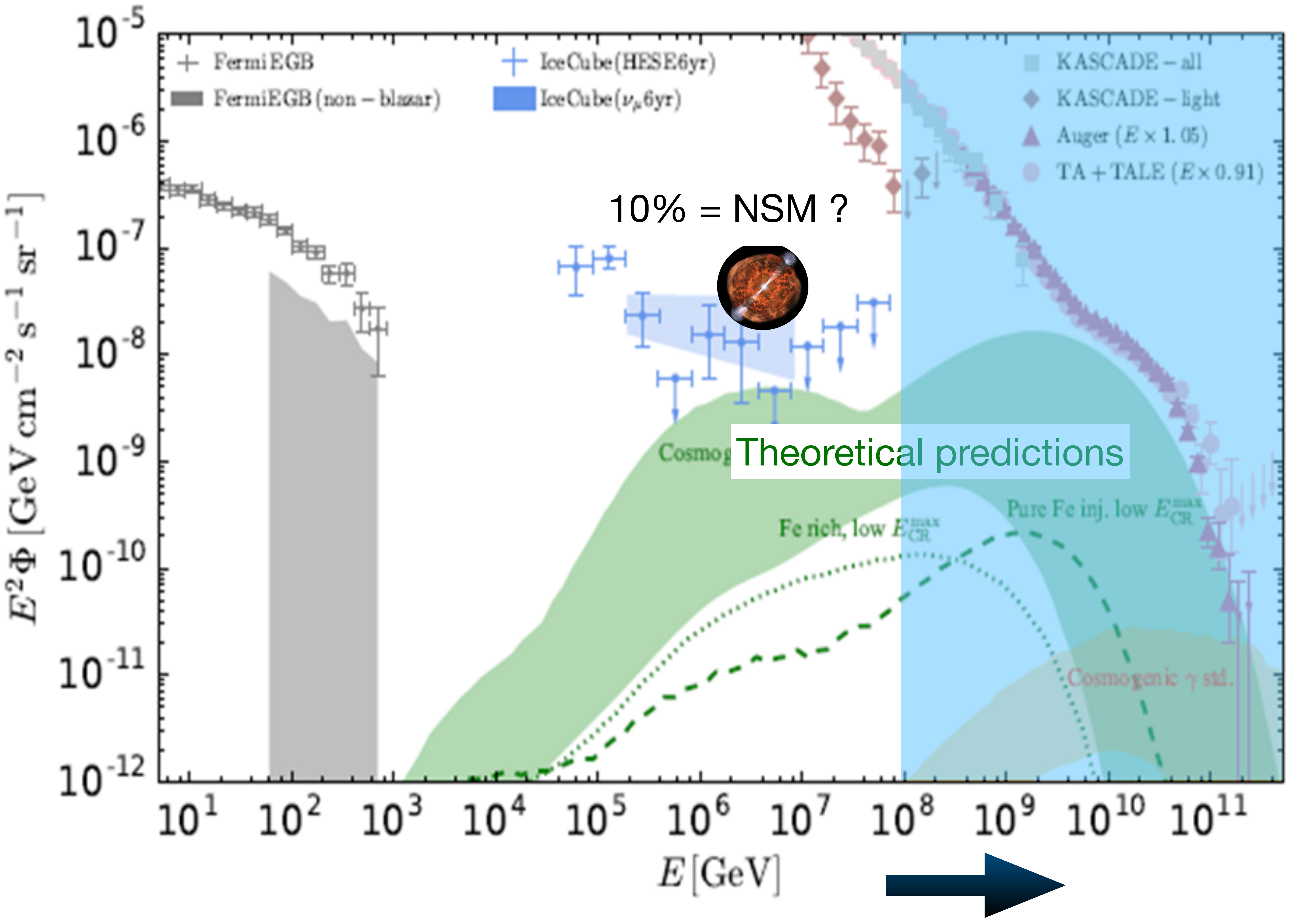

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How to detect them ?

- low fluxes
- low cross sections

→ large volume of target

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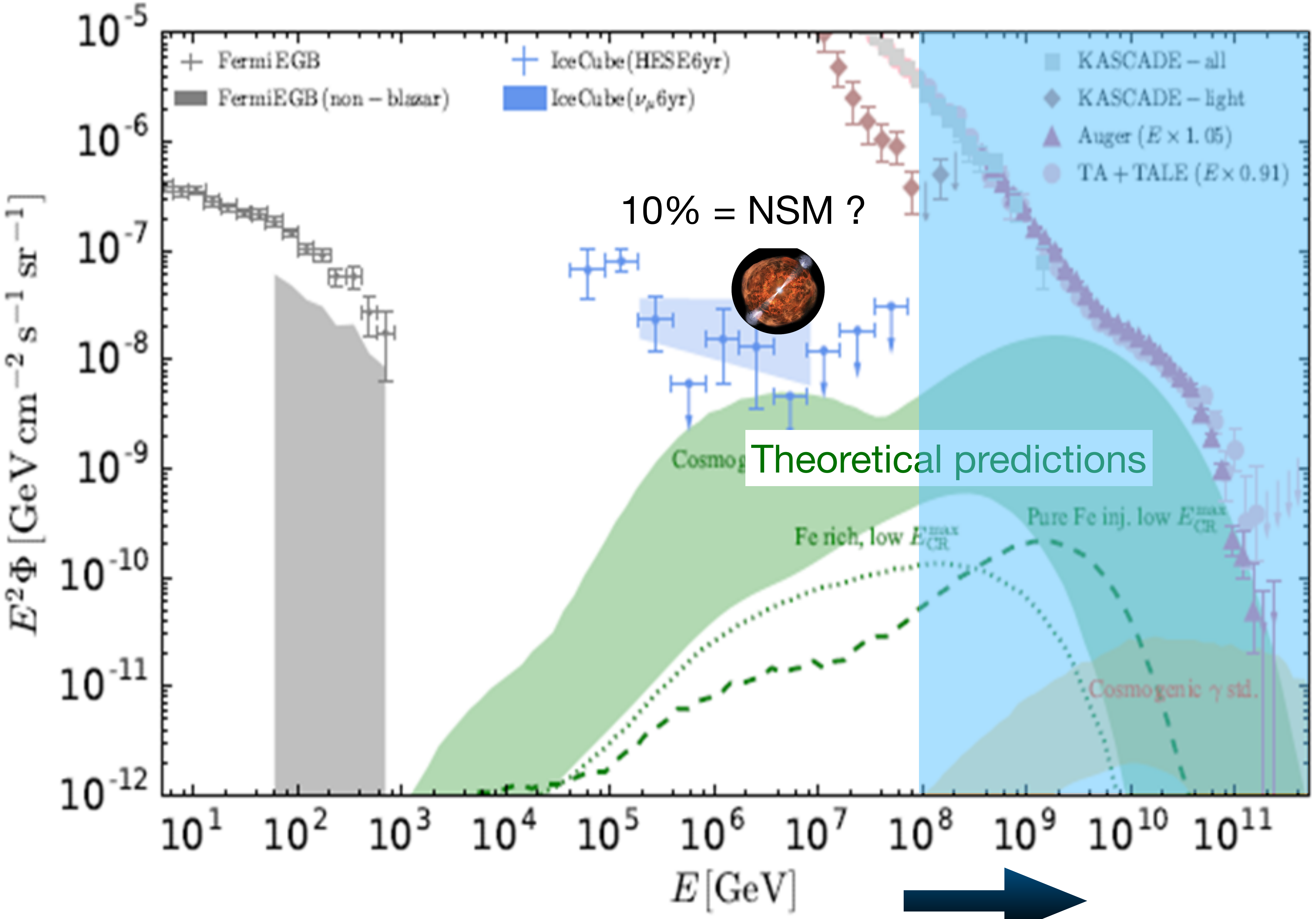

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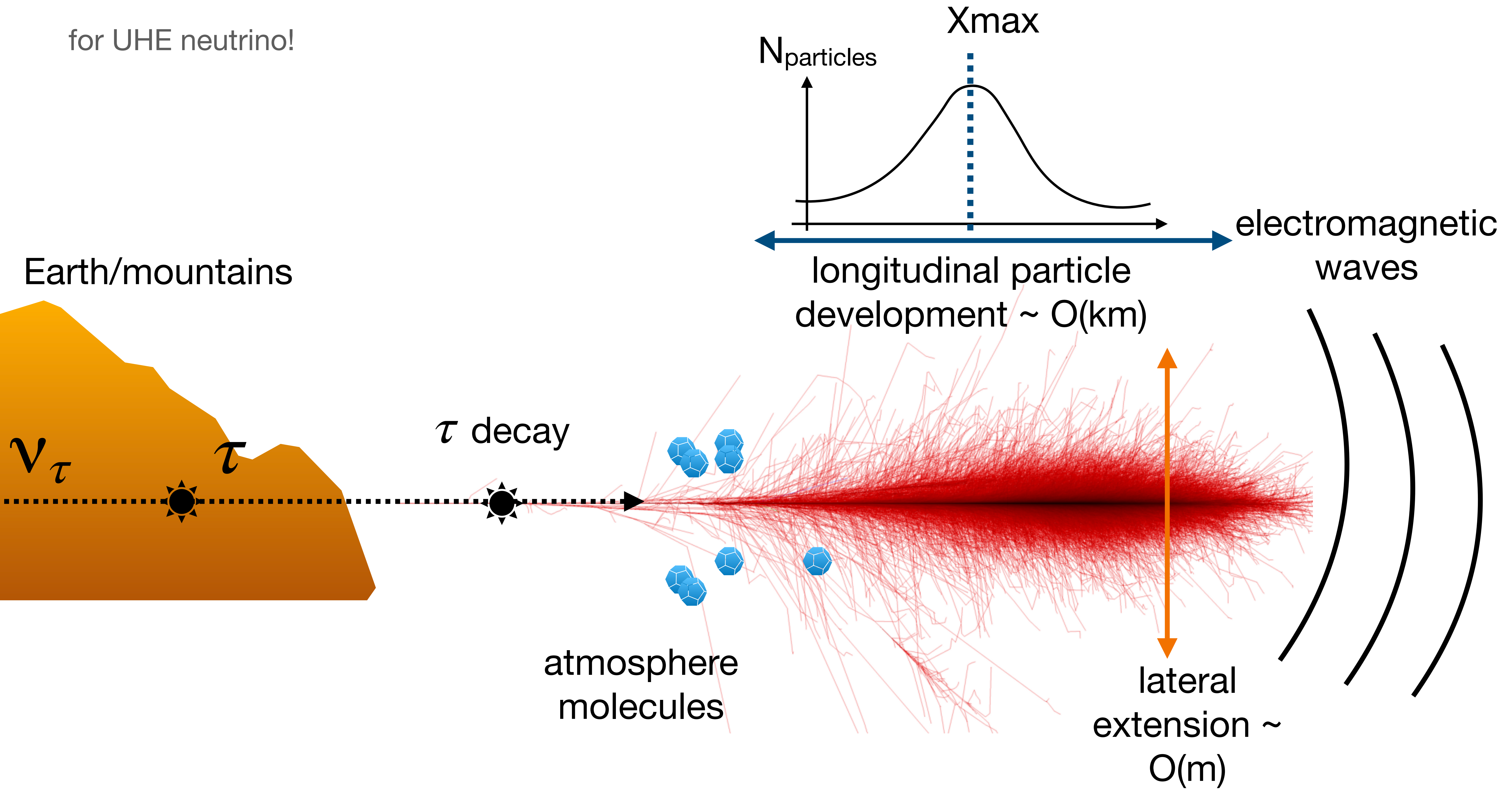
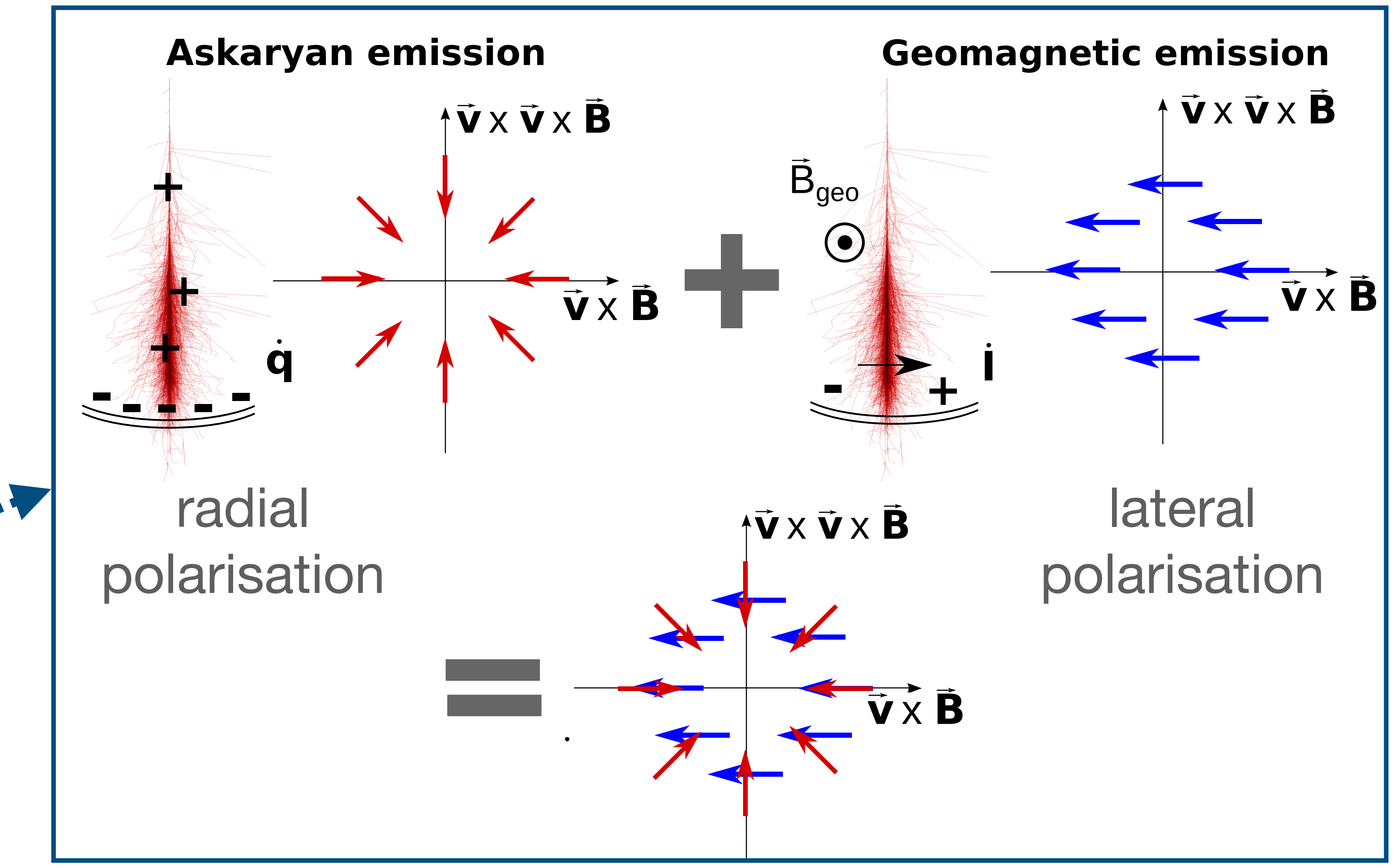
One possibility:

- use Earth as target
- detect product of interactions → extensive air showers
- radio detection of extensive air showers

Extensive air showers (EAS)

for UHE neutrino!





e+ and e- (in motion) + geomagnetic field
= radiation
collective effects lead to
two main mechanisms of emission

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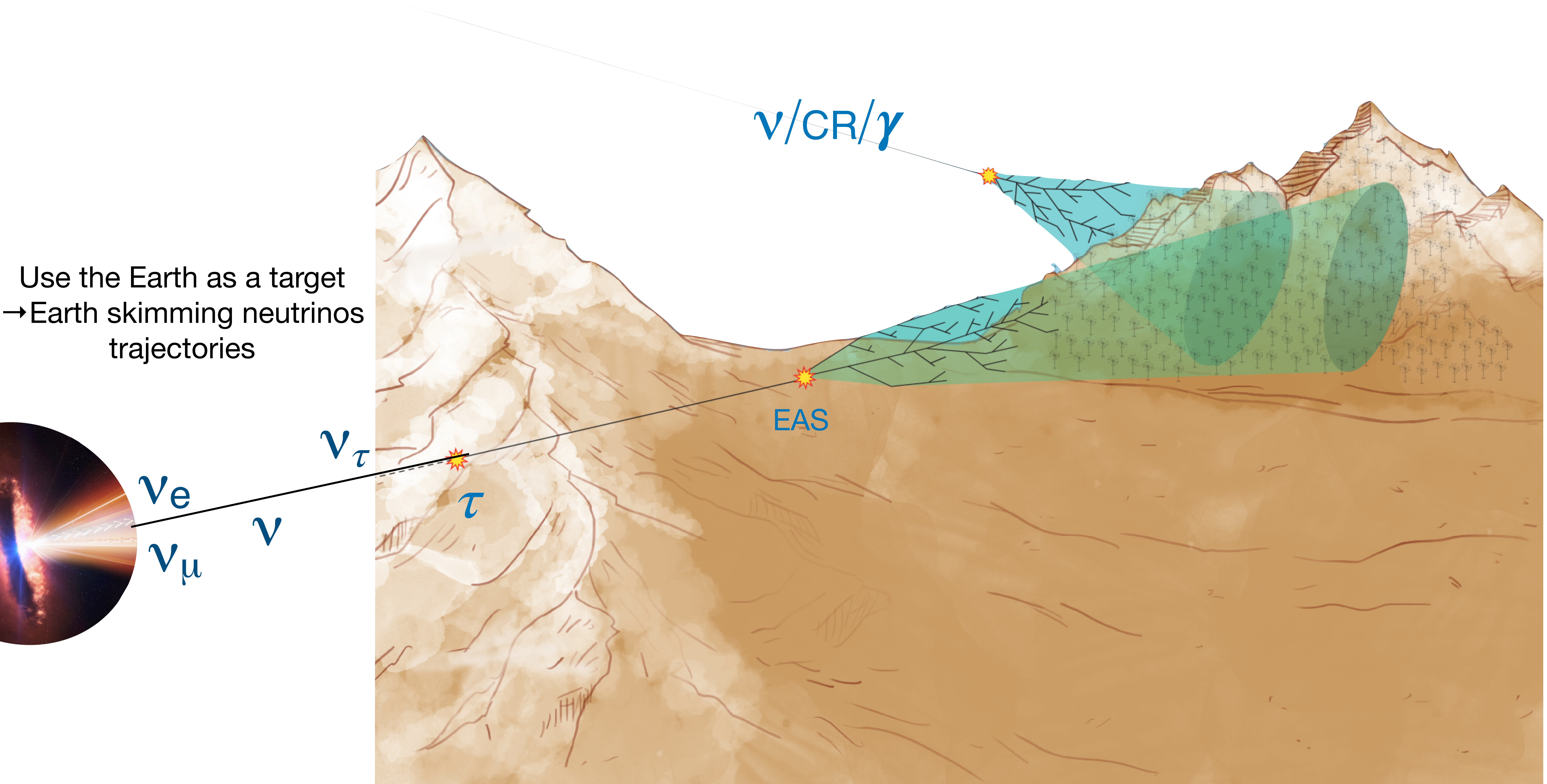
Some Radio Detectors (on which I worked on)

one goal→ maximise effective volume!

Use the Earth as a target
→Earth skimming neutrinos trajectories



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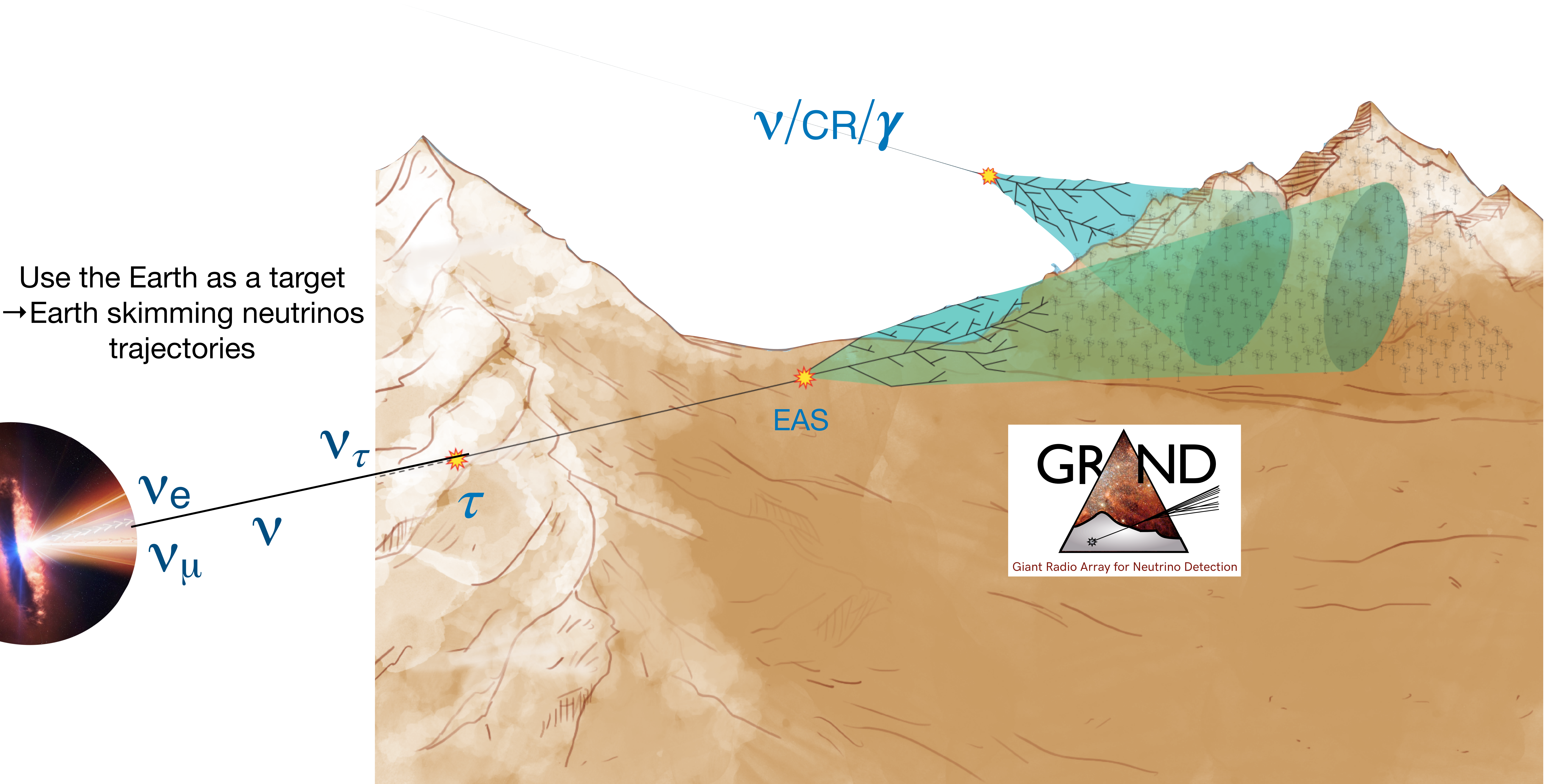

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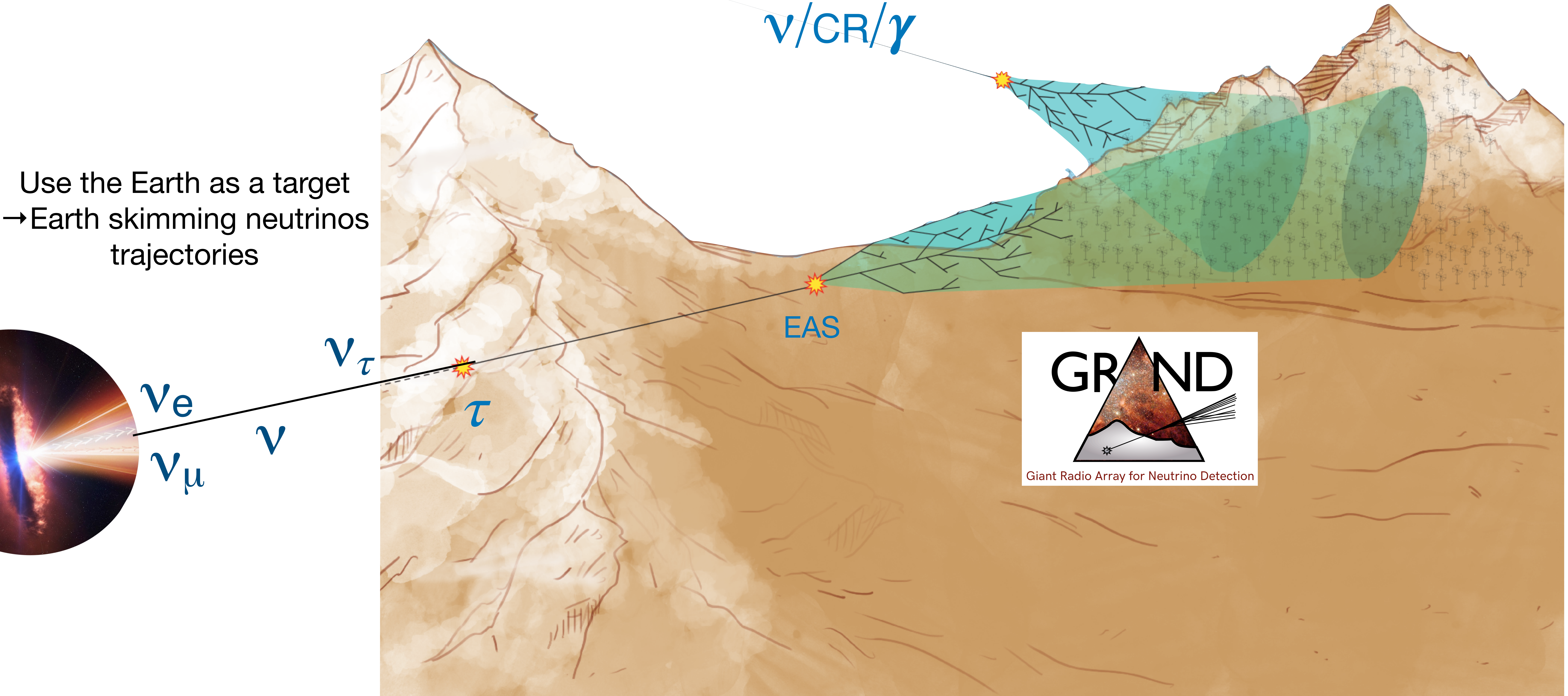

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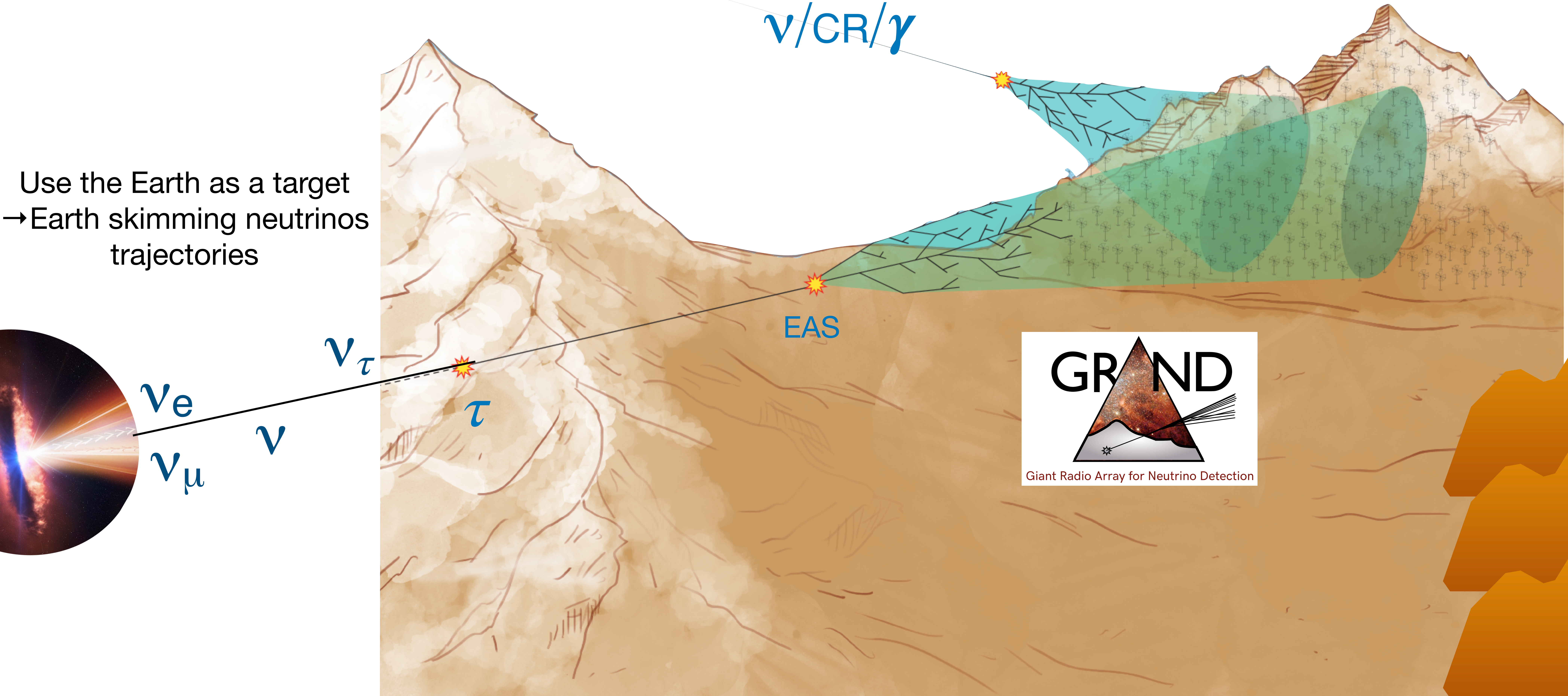

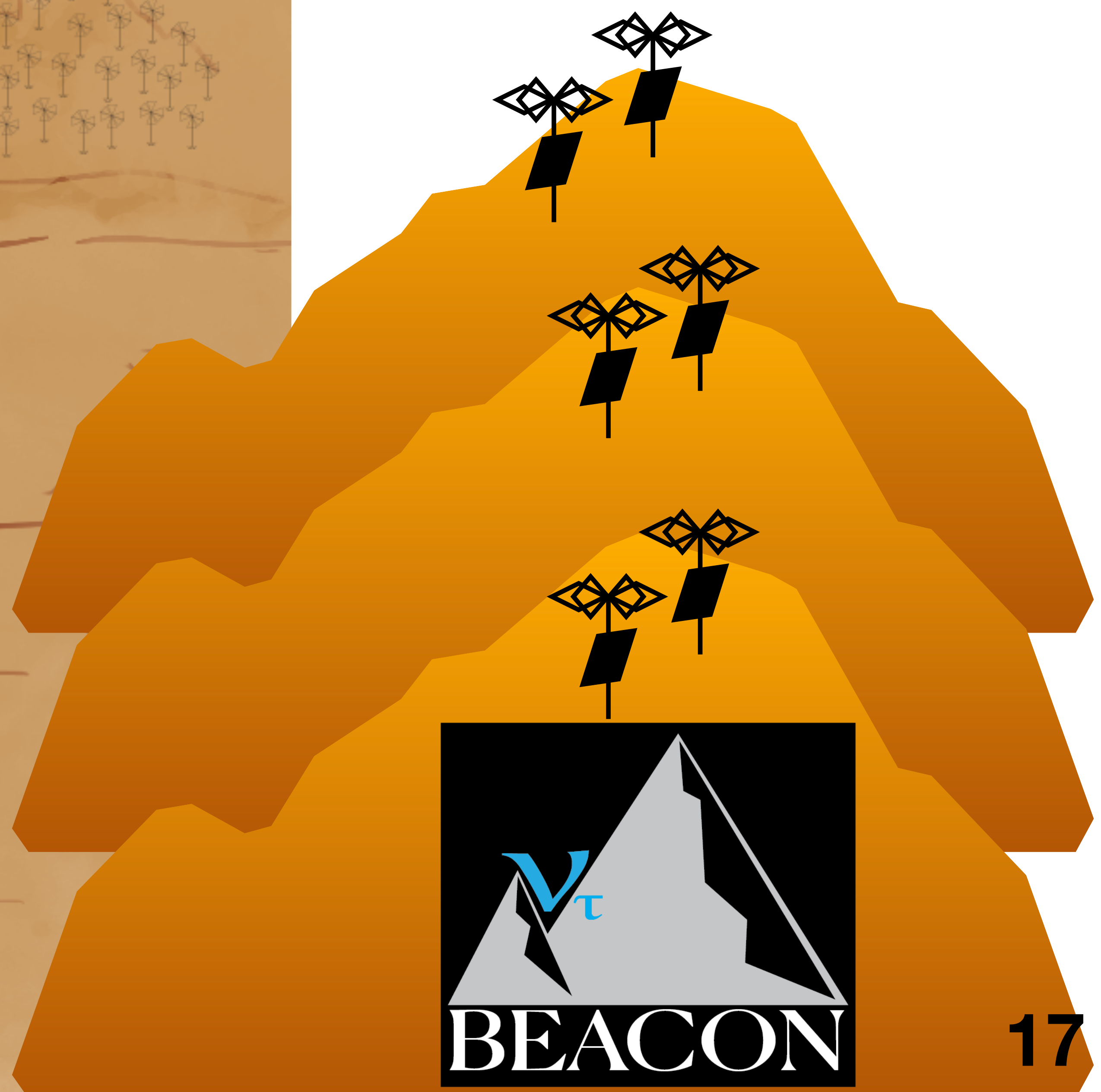

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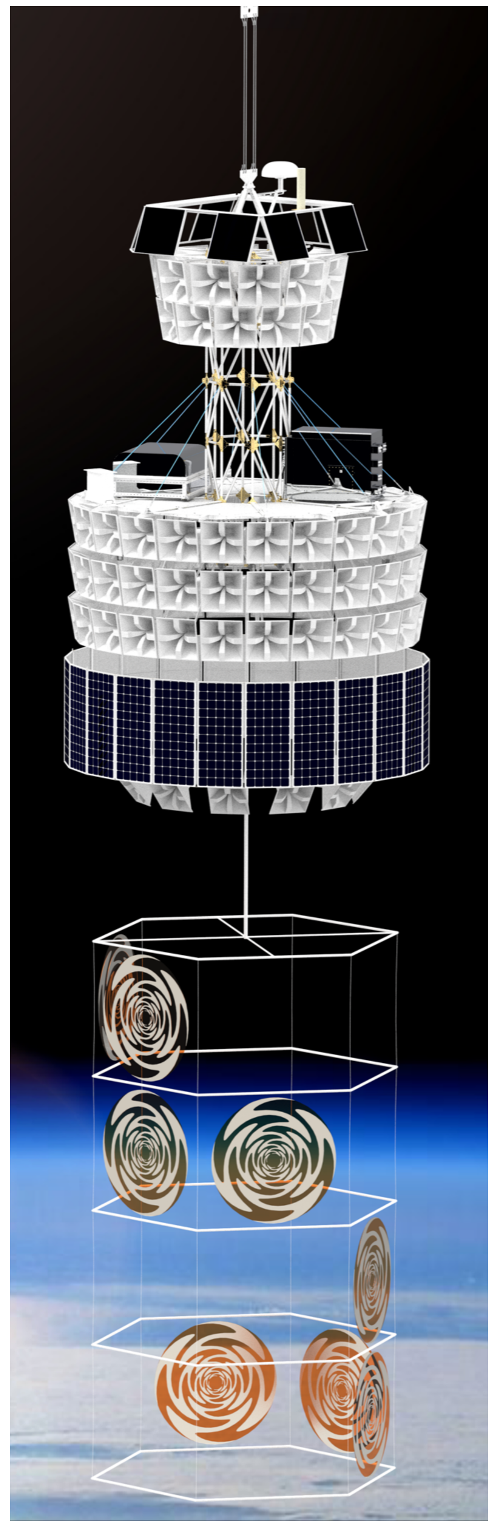

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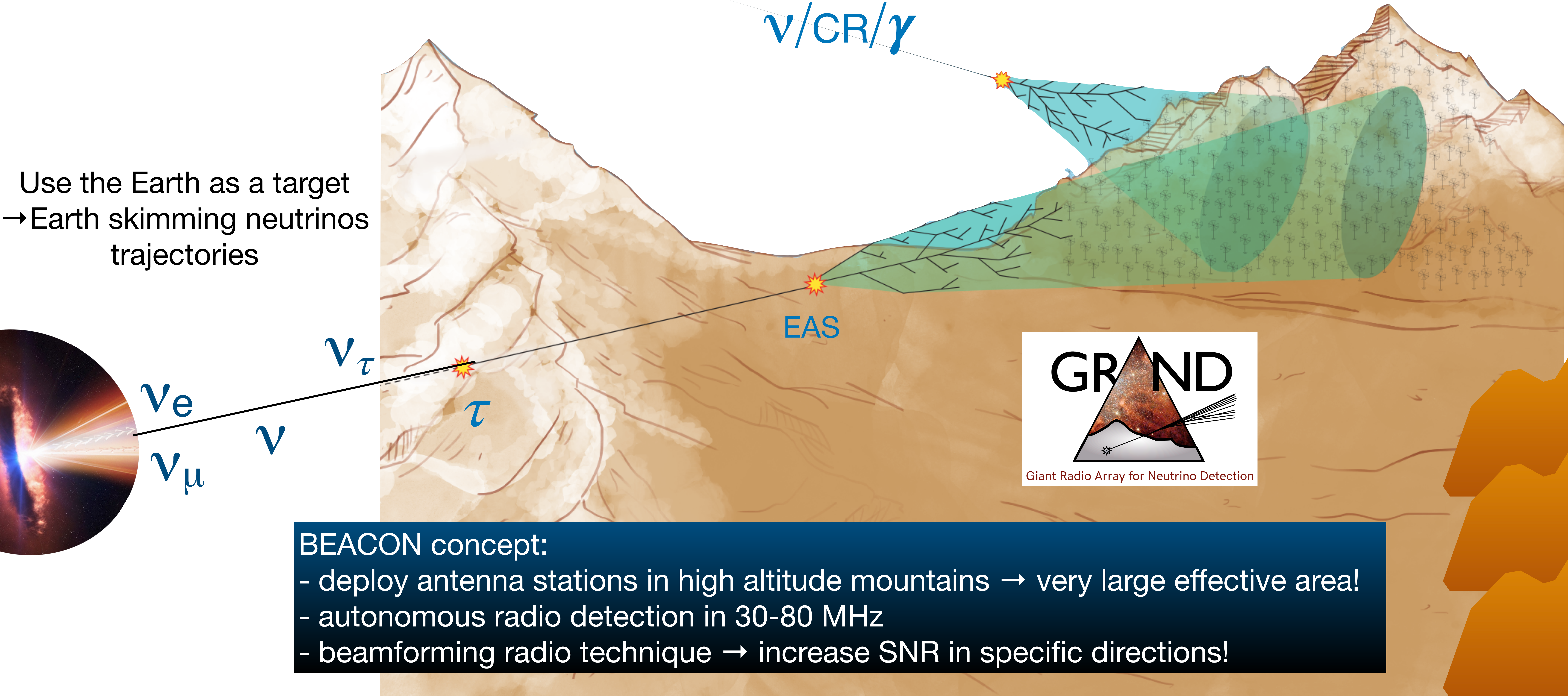

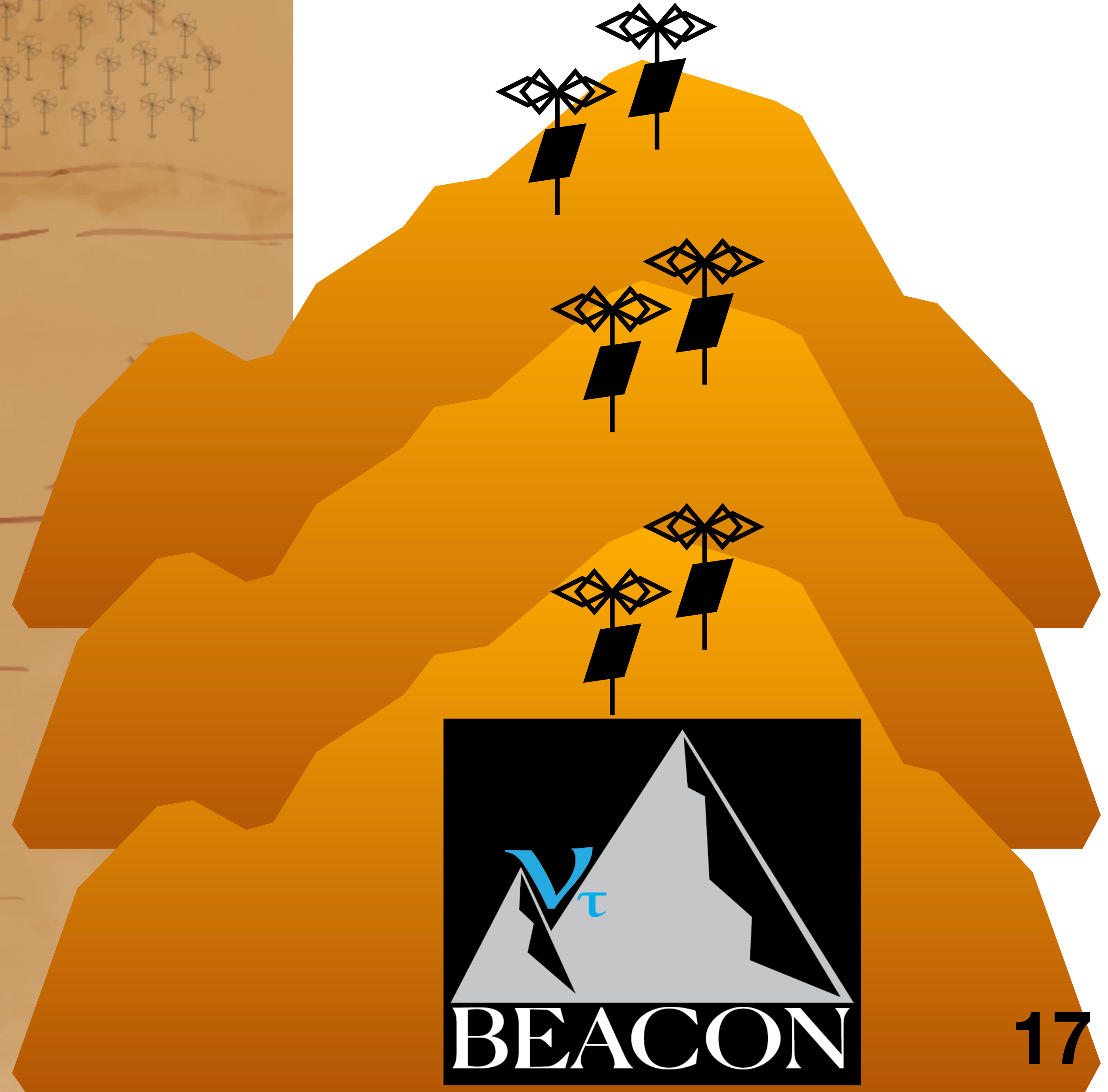

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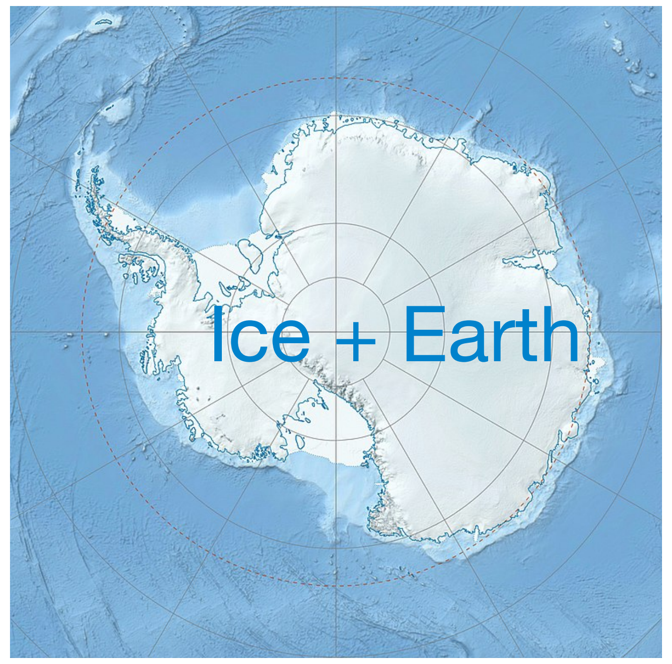
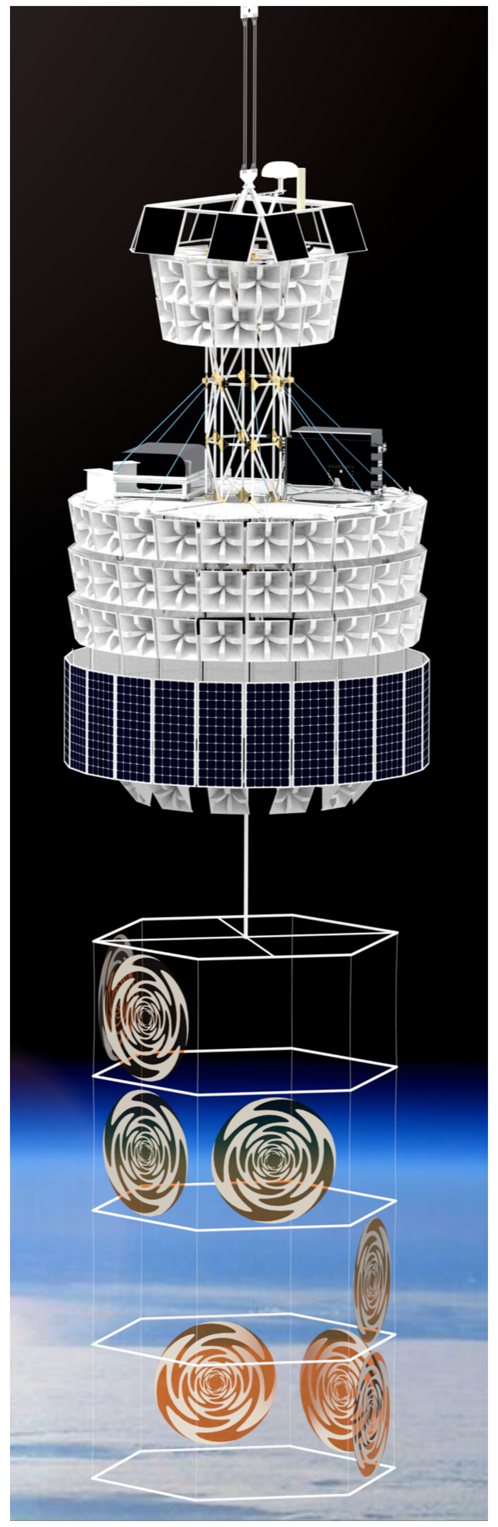
=ANITA++

PUEO





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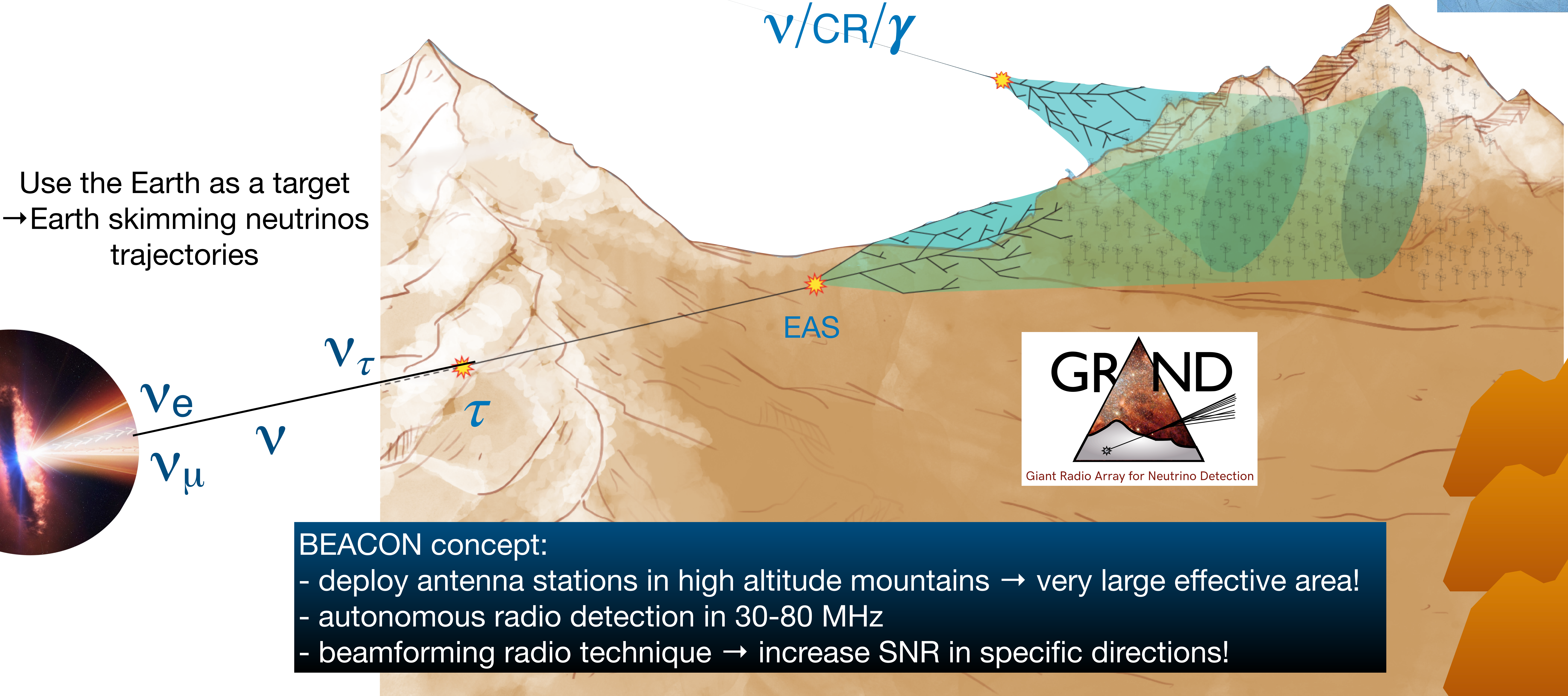

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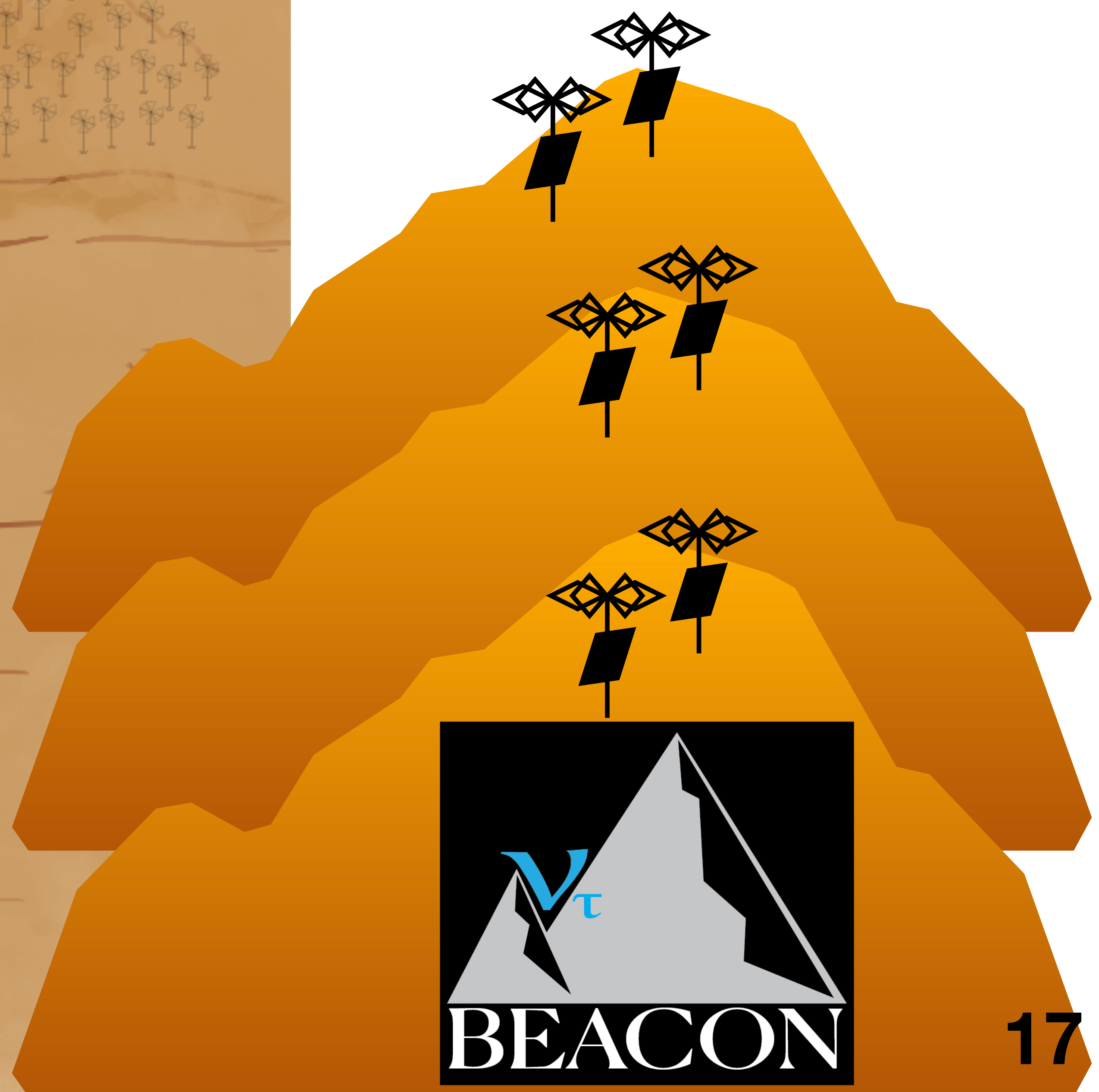

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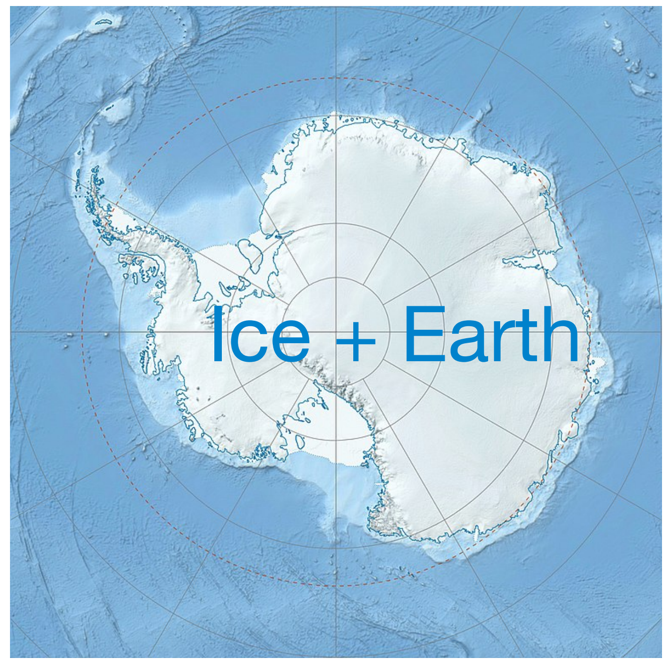
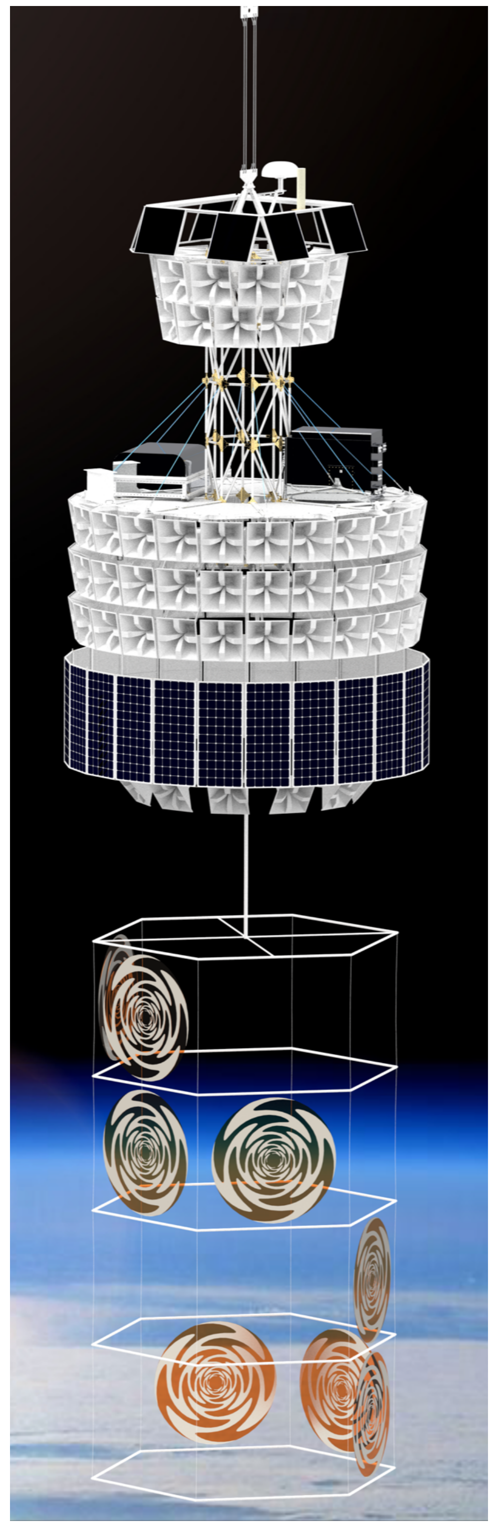
PUEO concept: (50-300 + 300-1200MHz)
- long duration balloon flying in antartica
- payload made of 3 distinct radio instrument
- targeting all EAS configurations!

PUEO =ANITA++





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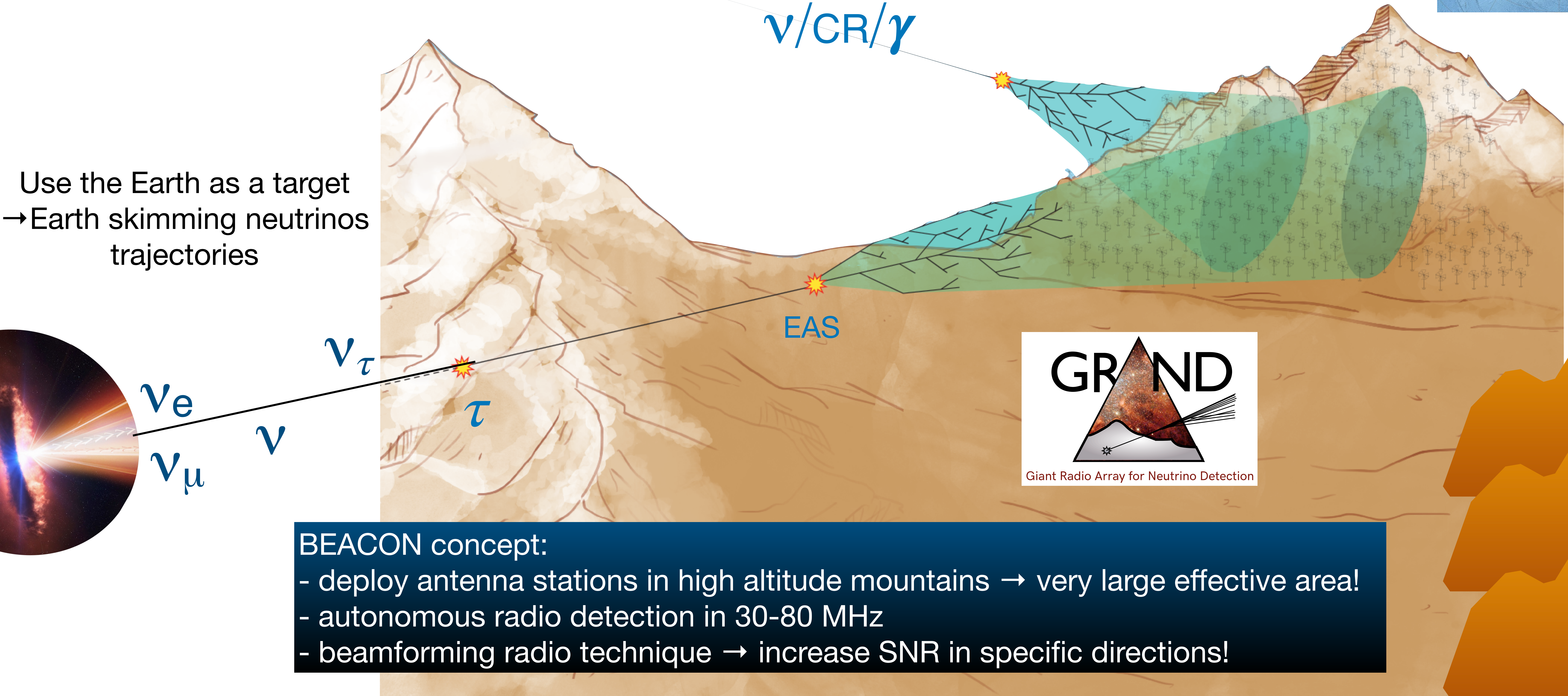

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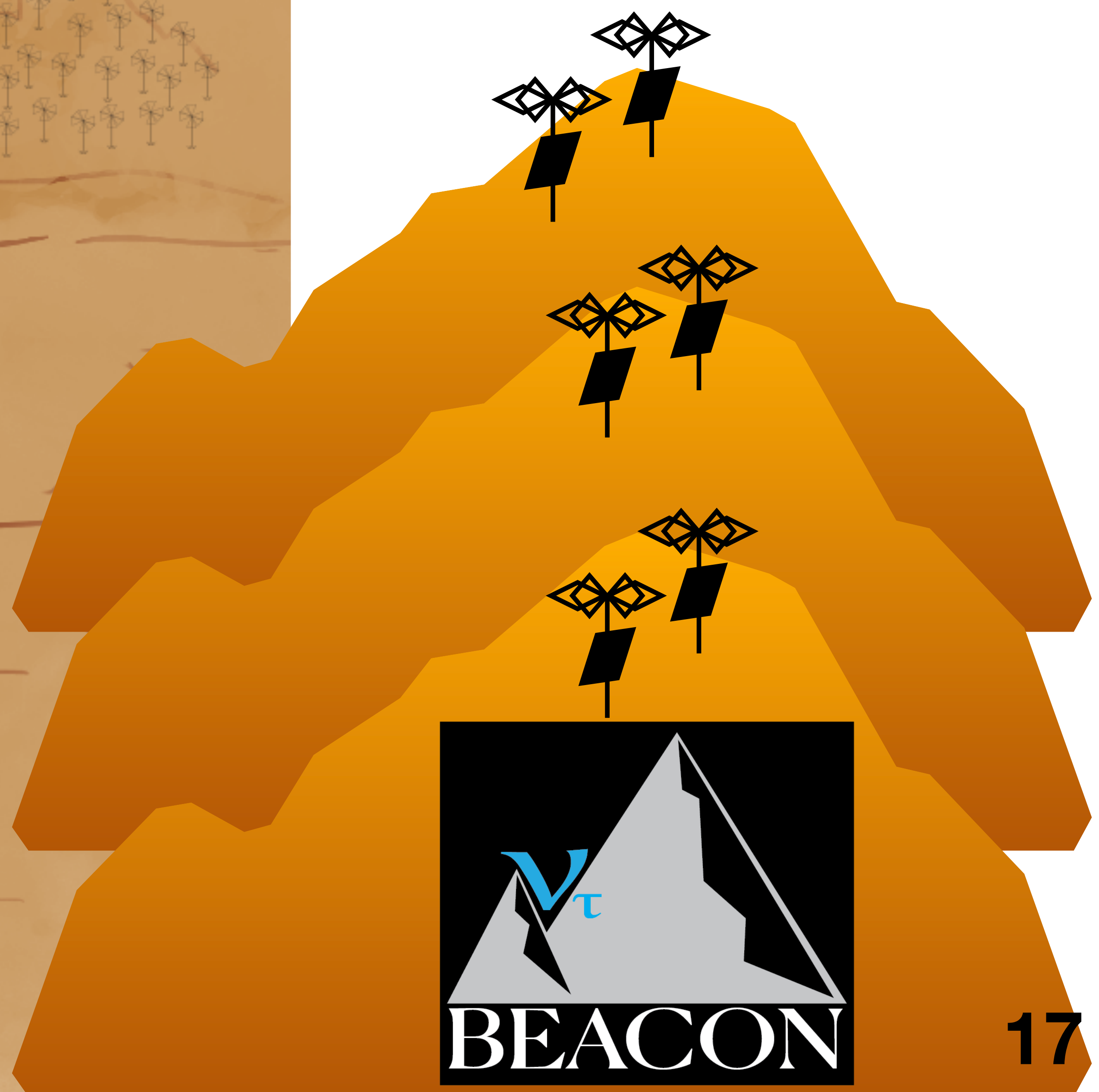
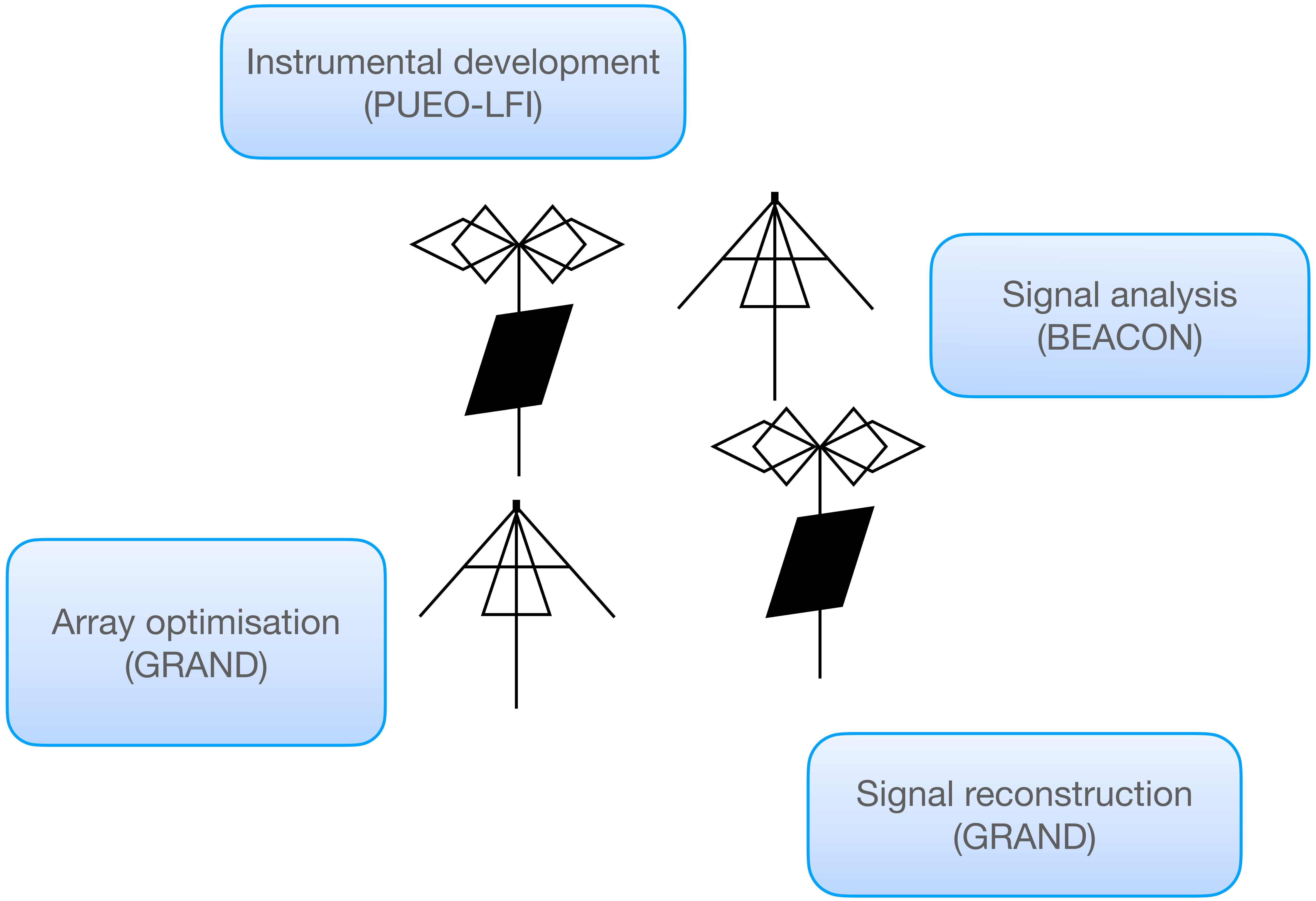


Some challenges of the radio detection of UHE (on which I worked on)



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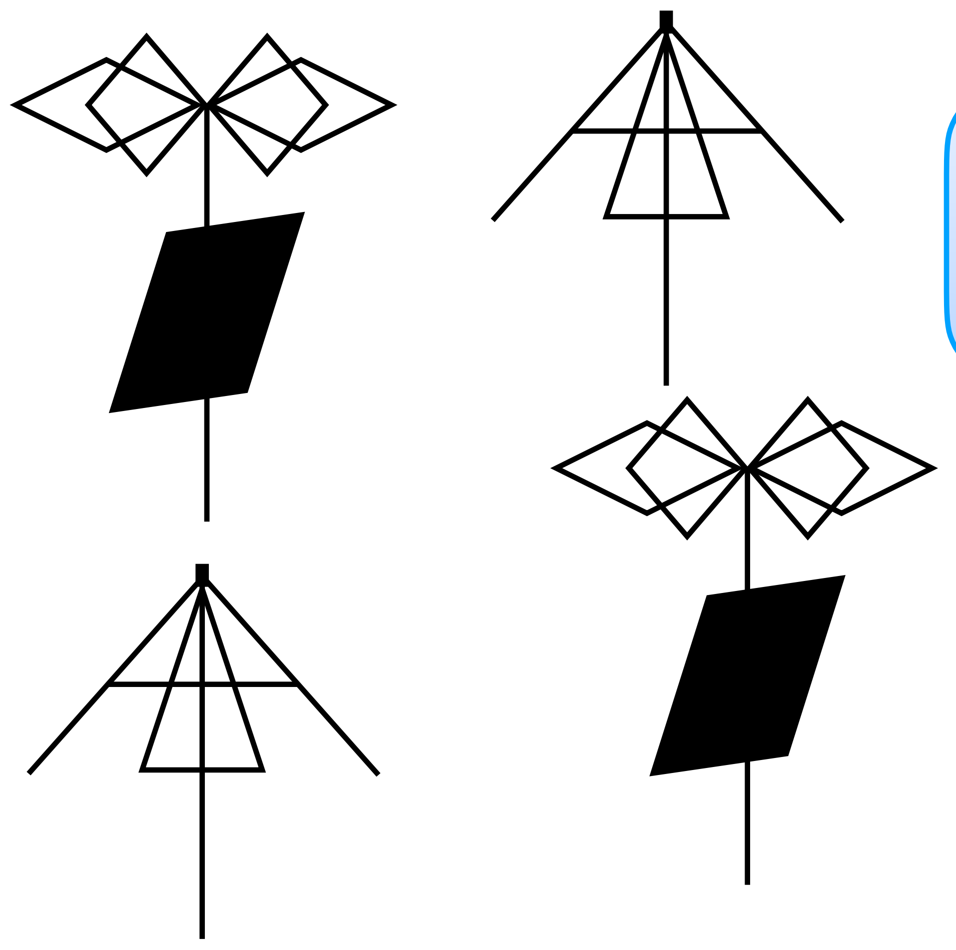
<u>Context</u>: low frequency instrument dedicated to Earth-skimming UHE neutrinos
<u>Goals</u>: optimise antenna and RF chain to neutrino induced EAS

Instrumental development (PUEO-LFI)



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Array optimisation (GRAND)

Signal reconstruction (GRAND)

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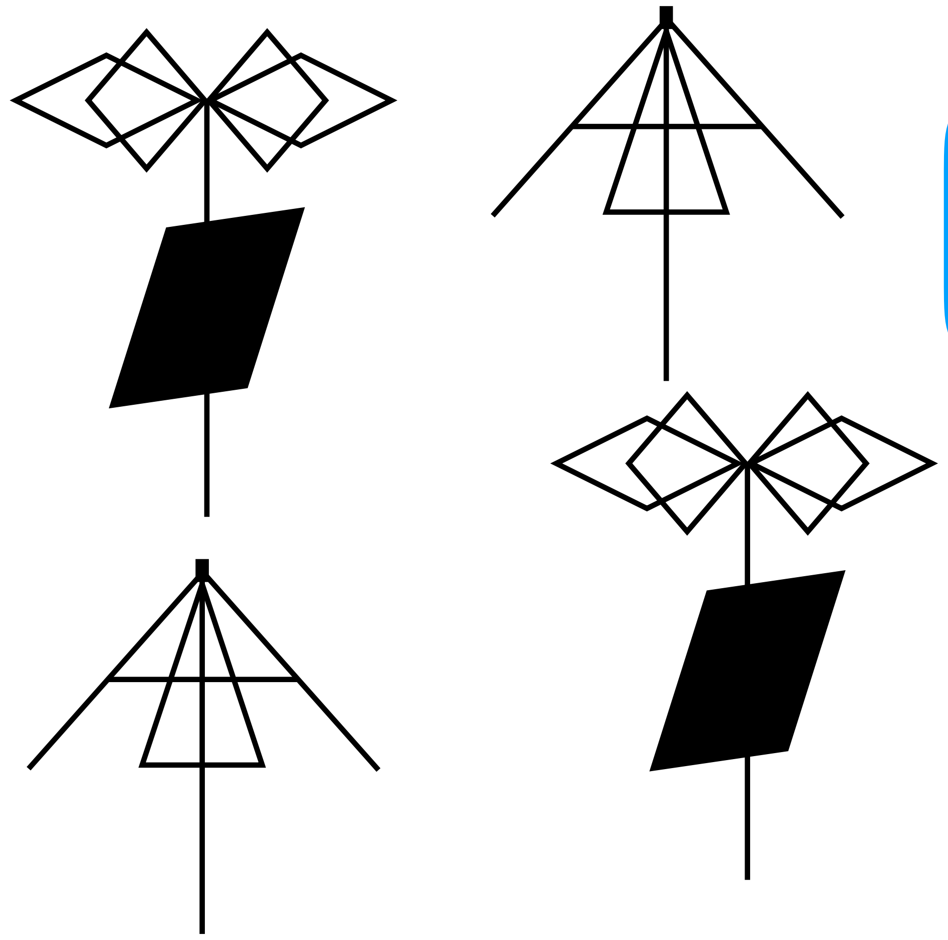

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Context: very extended and sparse radio arrays
Goals: study the optimisation of radio arrays for very inclined EAS

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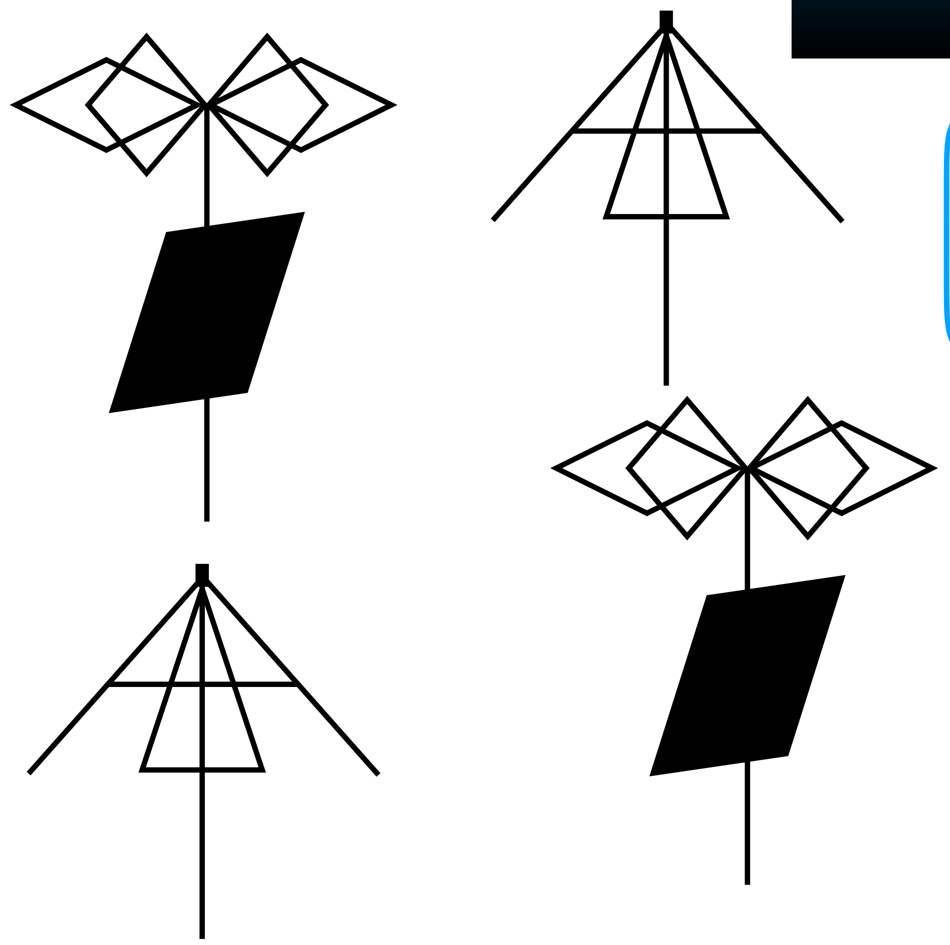
Context: prototype of a beamformed radio detector
Goals: show understanding of background and EAS identification



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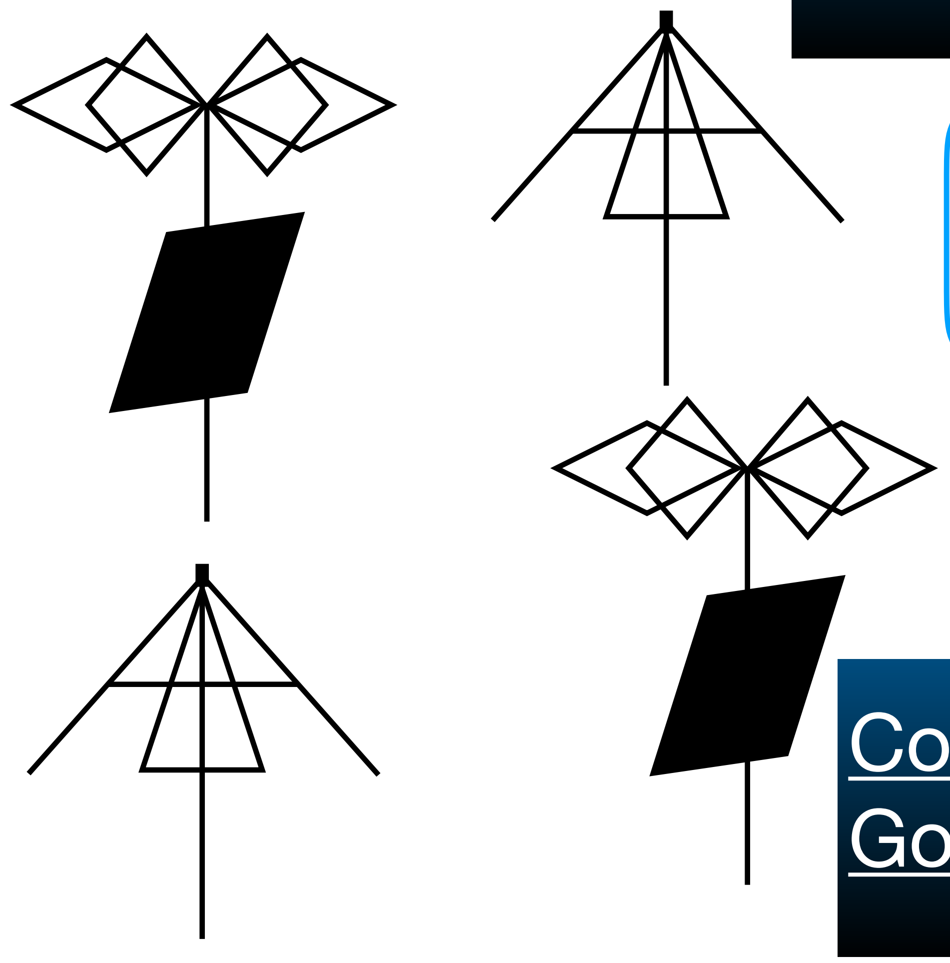

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Goals: develop a reconstruction procedure for very inclined EAS

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Signal reconstruction
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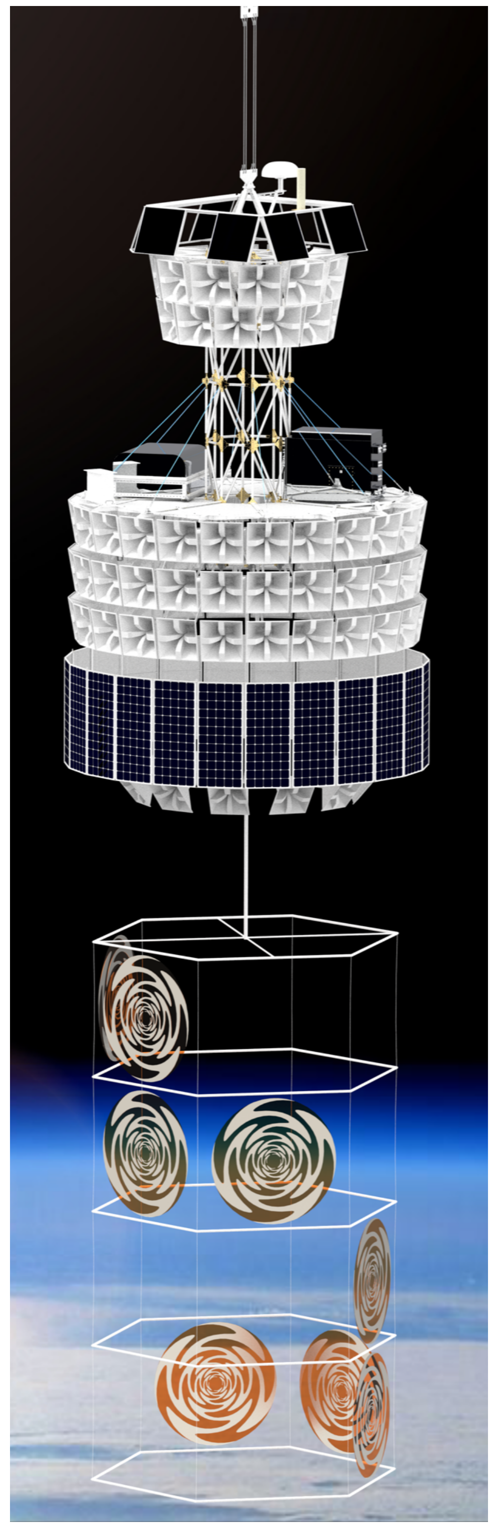
Low Frequency Instrument

PUEO

Target radio emission from EAS in the 50-300 MHz → larger radio beam → larger FoV → better sensitivity



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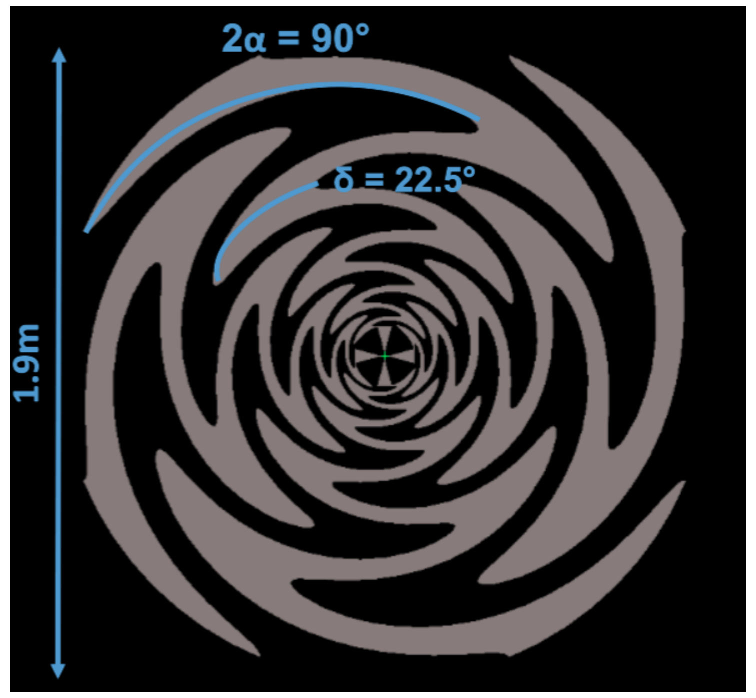
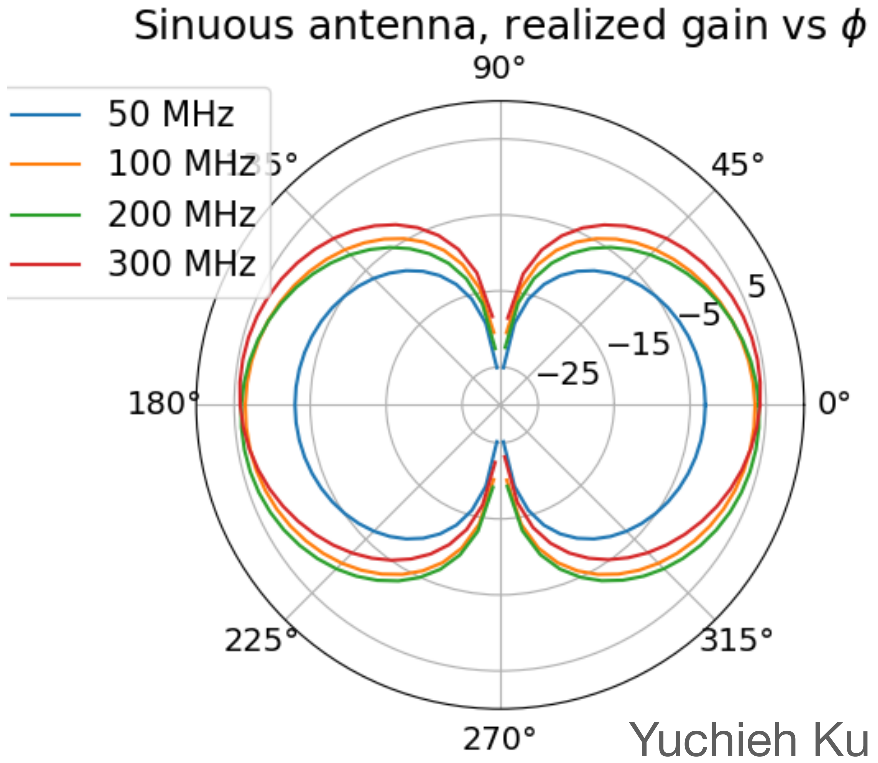
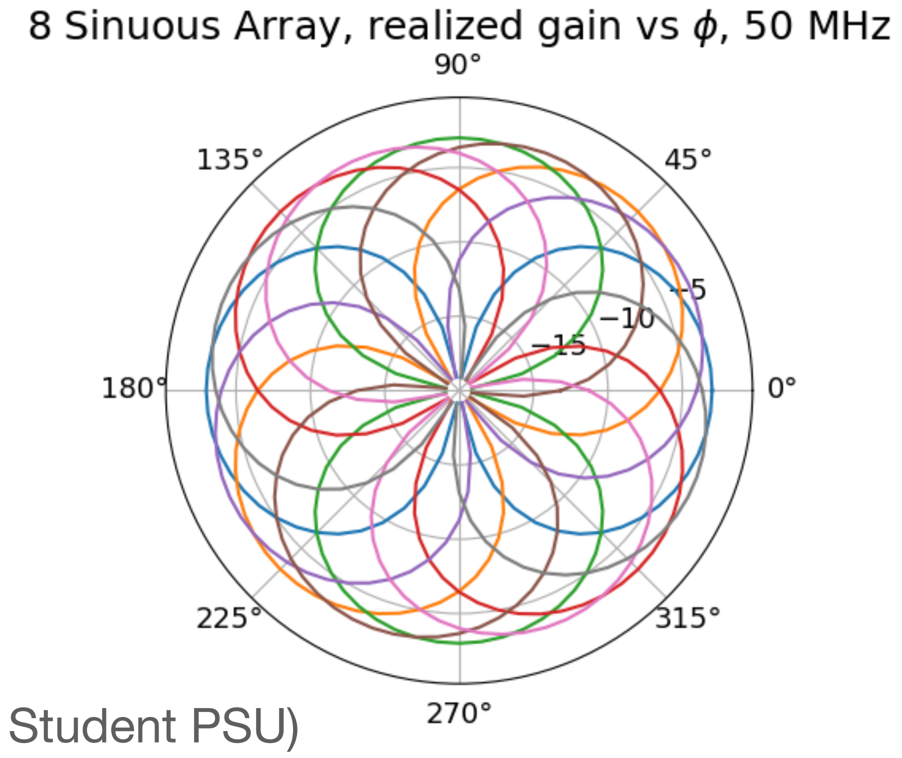
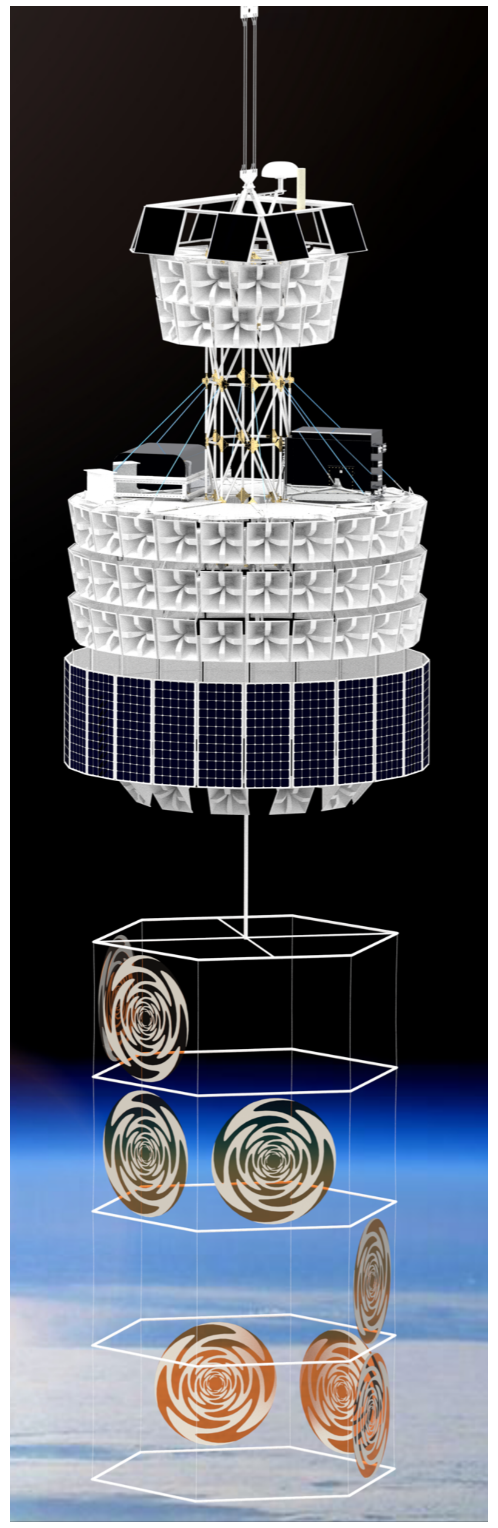






Yuchieh Ku (Grad Student PSU)



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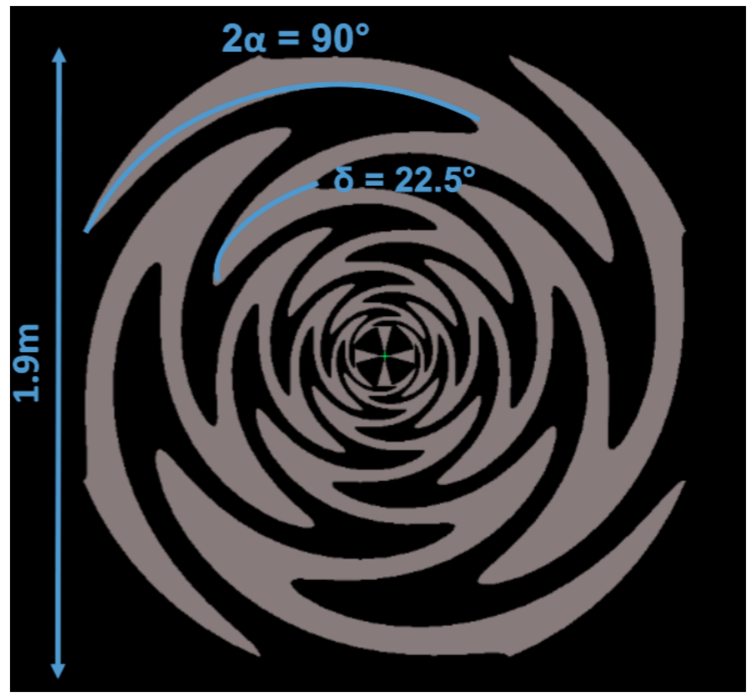

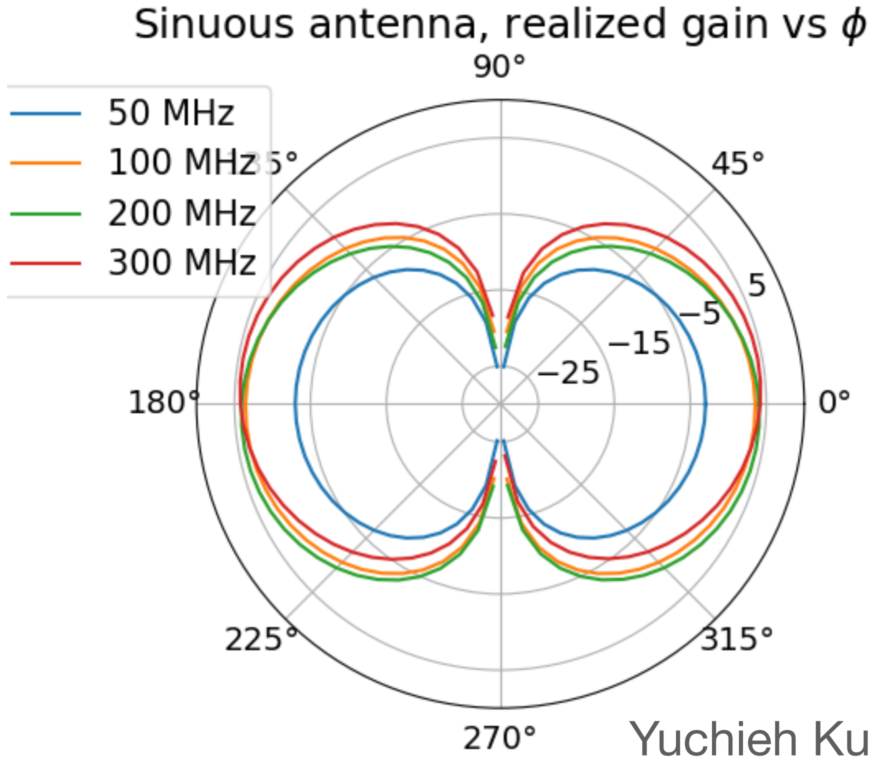

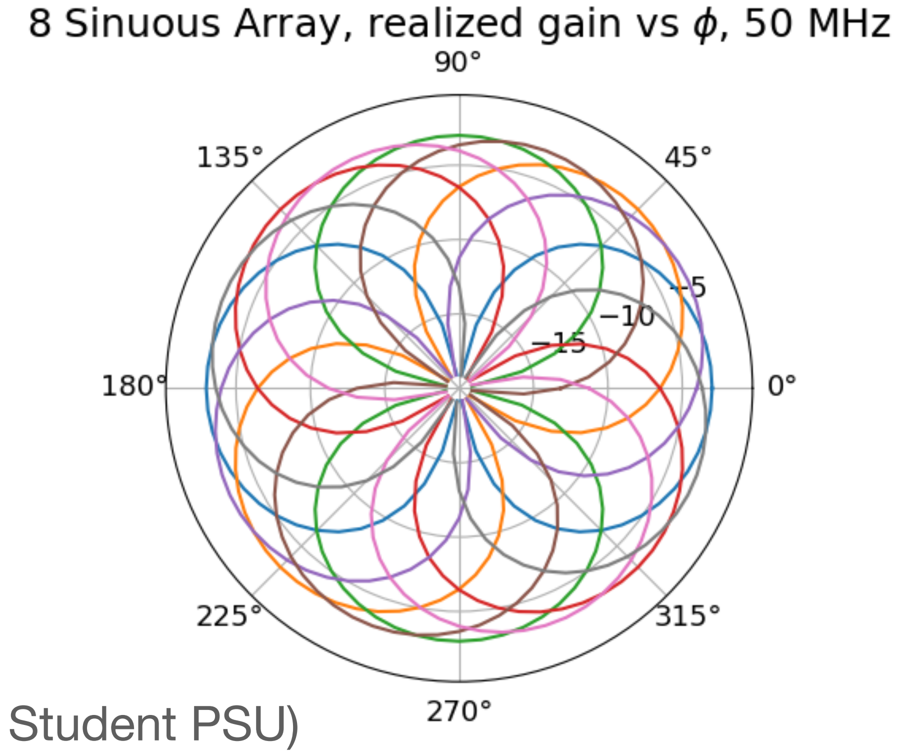

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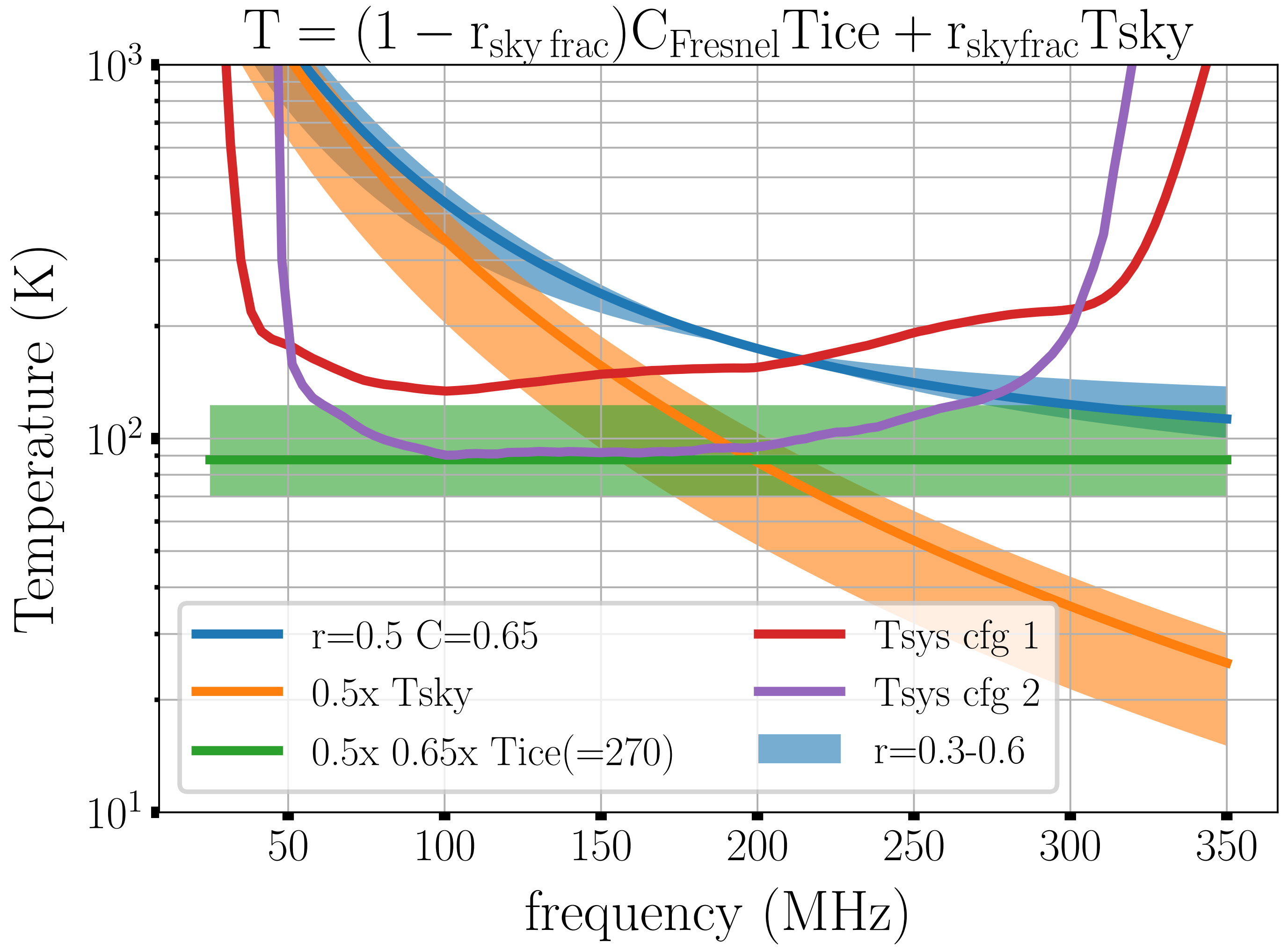
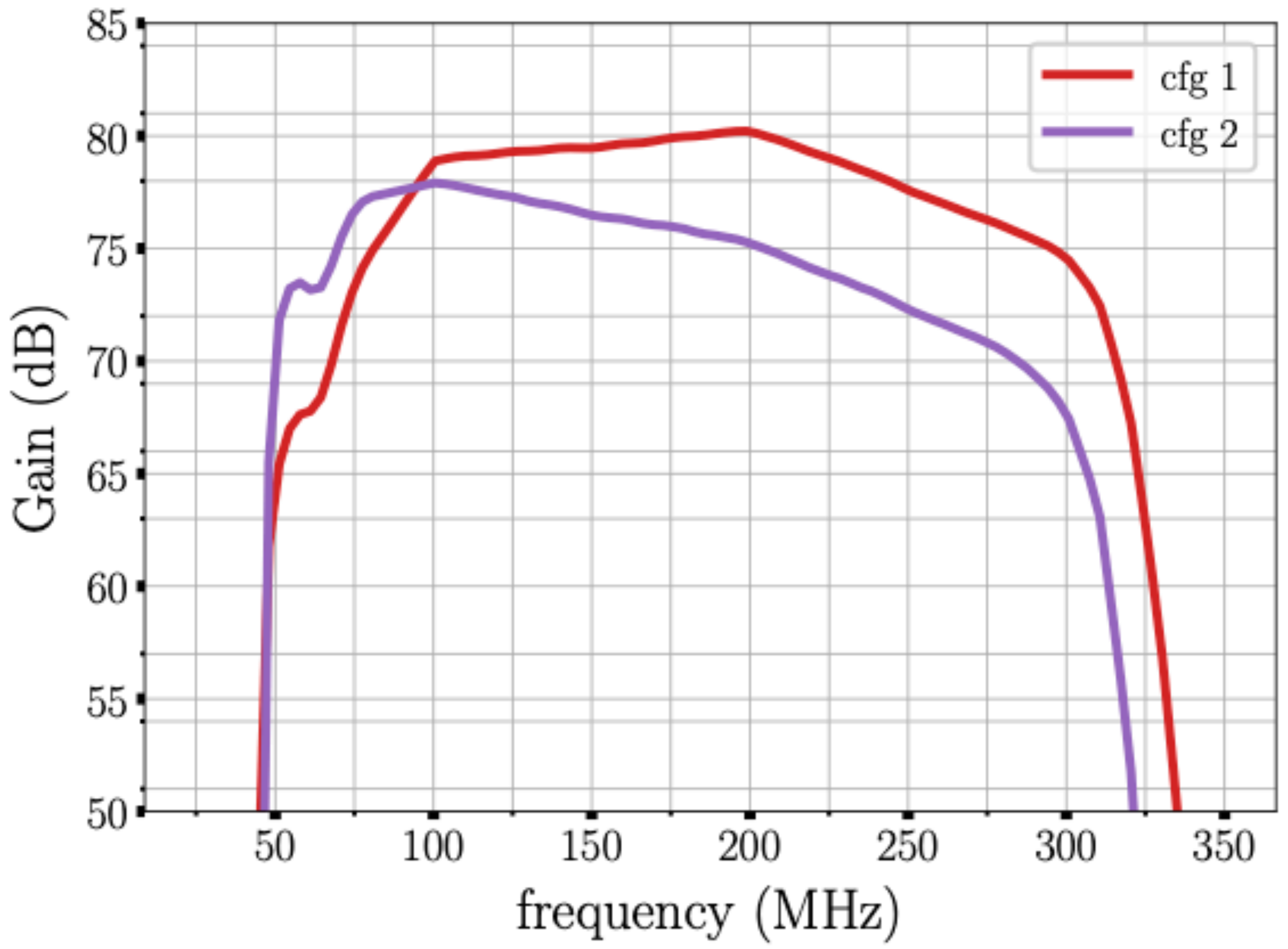
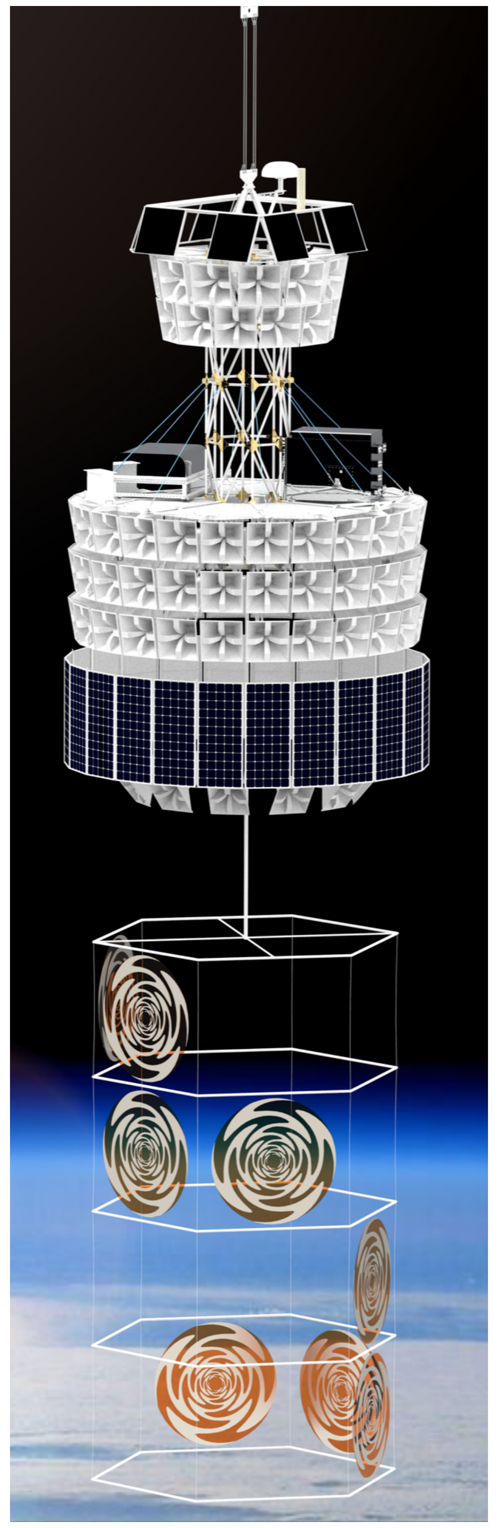
RF chain → sensitive down to ice and sky background + TRL6 requirements (pressure/temp)







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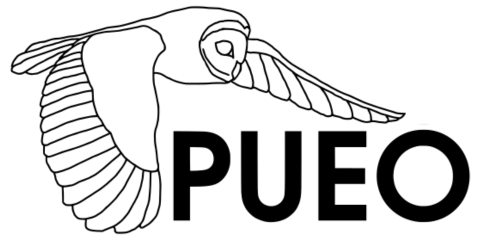

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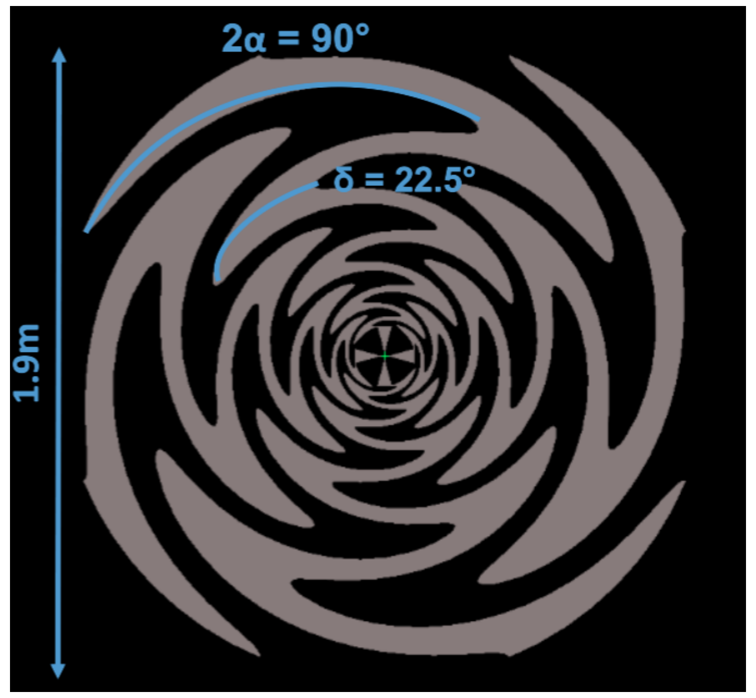

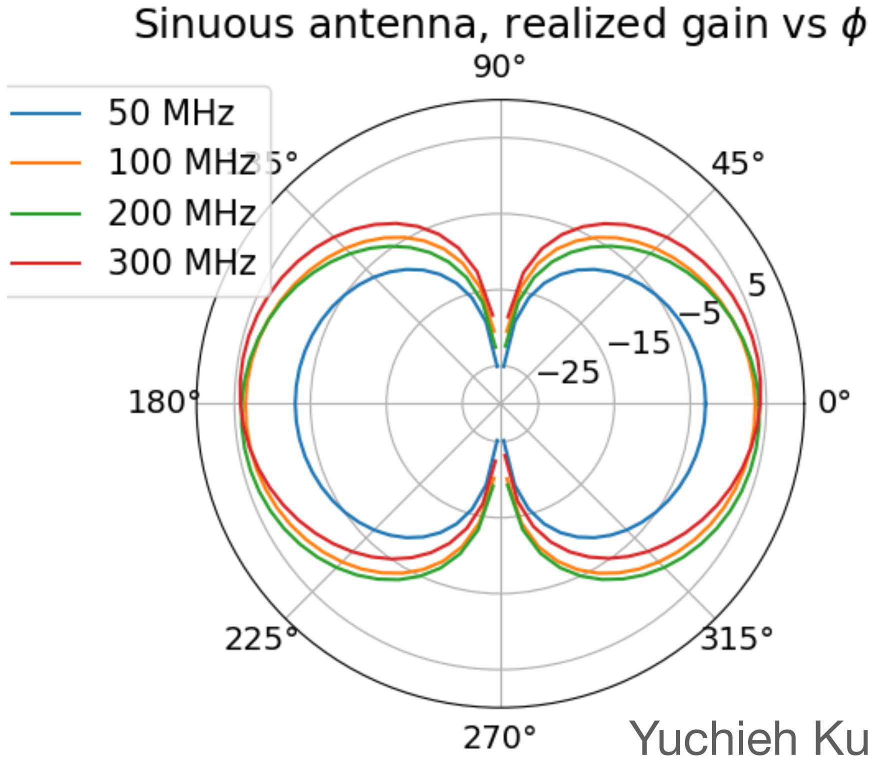

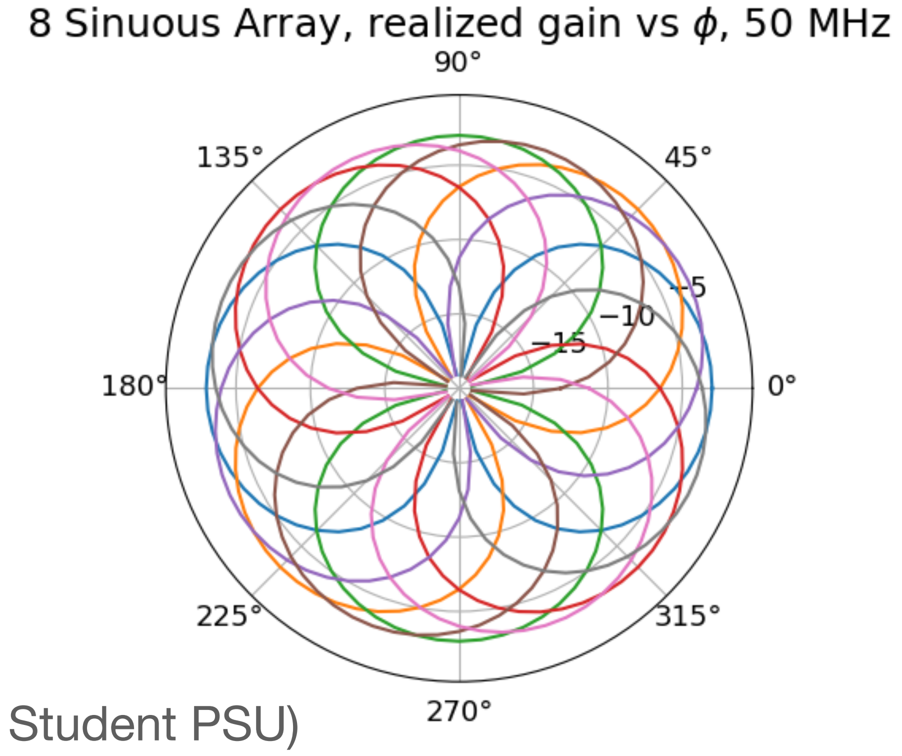

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Thermal vacuum chamber (PSU)

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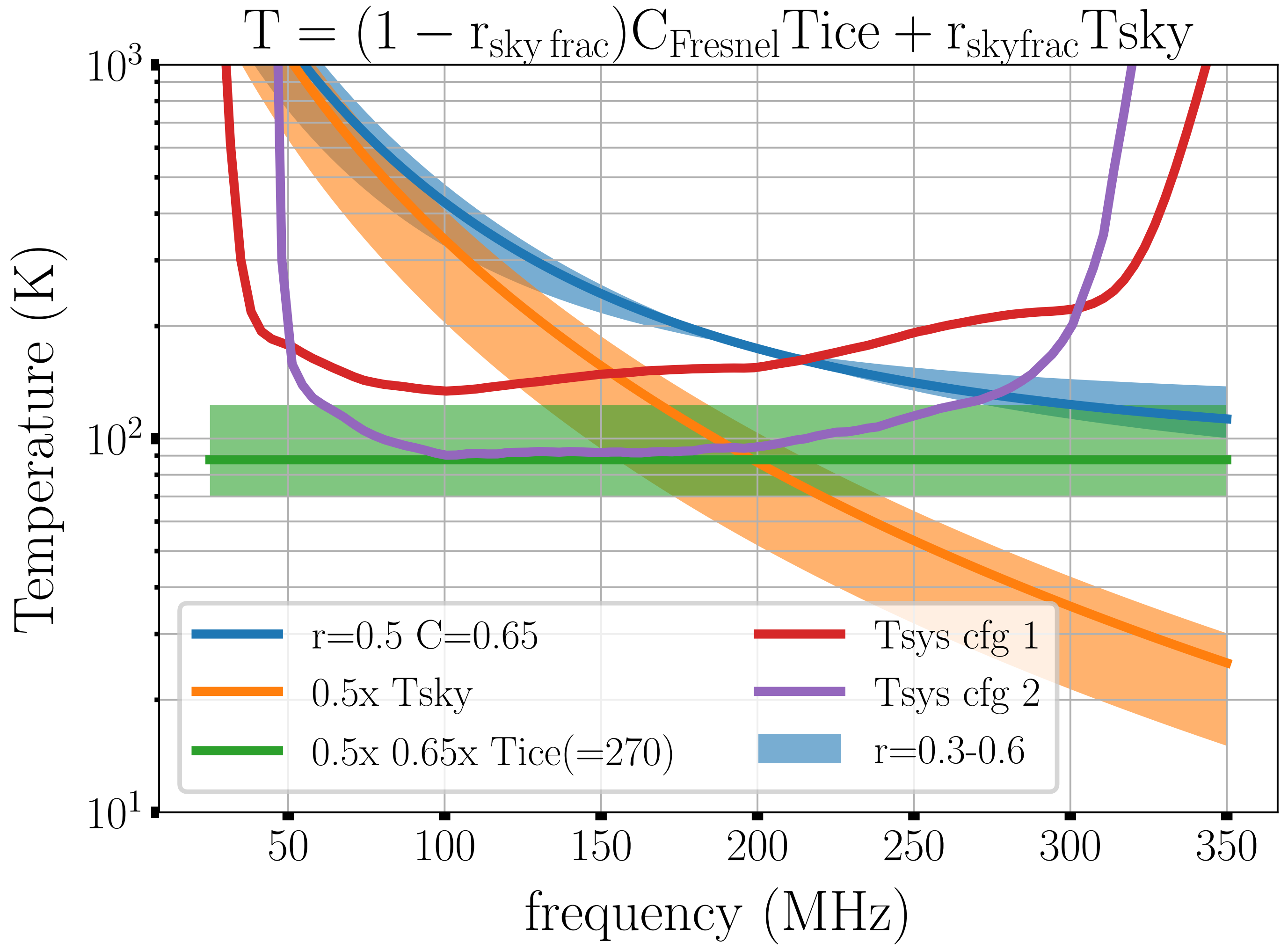

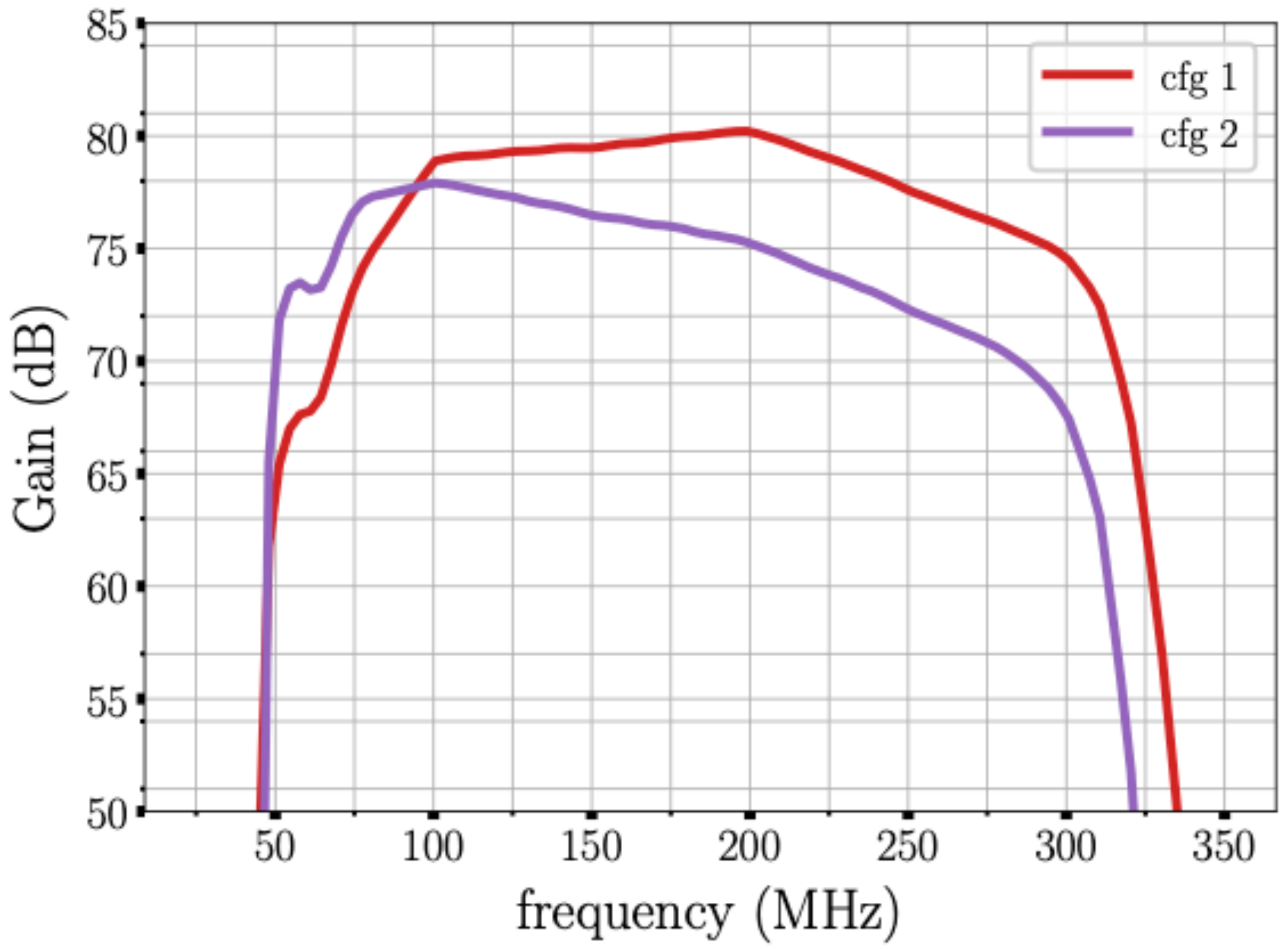

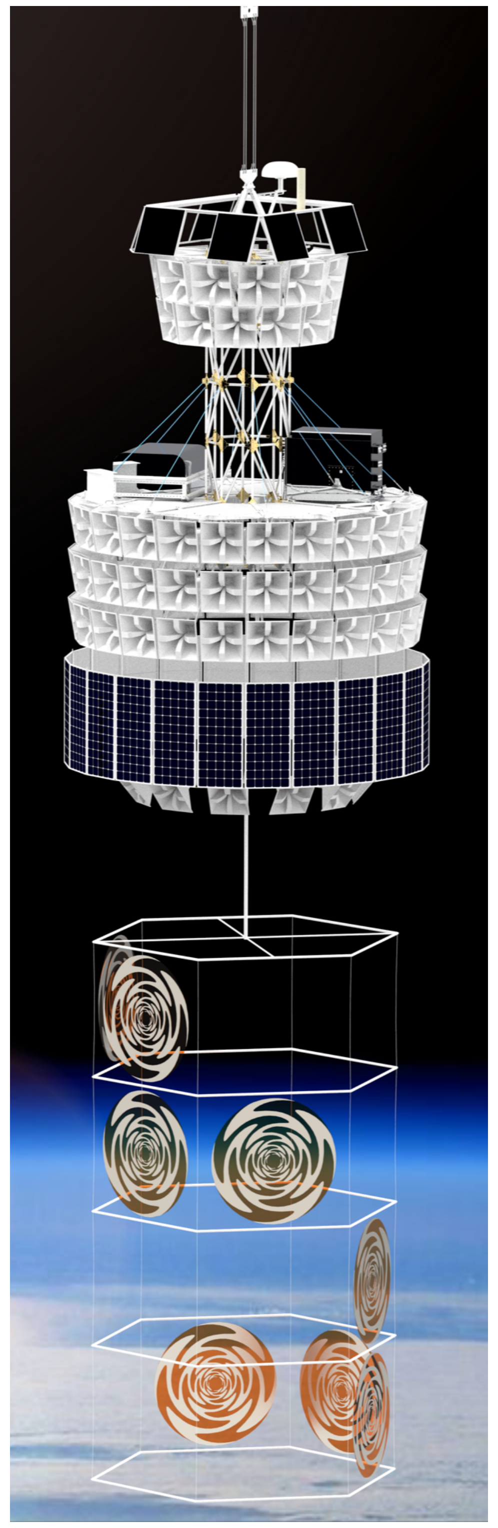

Influence of the topography on the radio detection of neutrino induced air showers

V. D., Renault-Tinacci (IAP), Martineau (LPNHE), Charrier (Subatech), Kotera (IAP), Le Coz (NAOC), Niess (UCA), Tueros (CONICET), Zilles (IAP) (NIMA 2021)

GRAND
Giant Radio Array for Neutrino Detection

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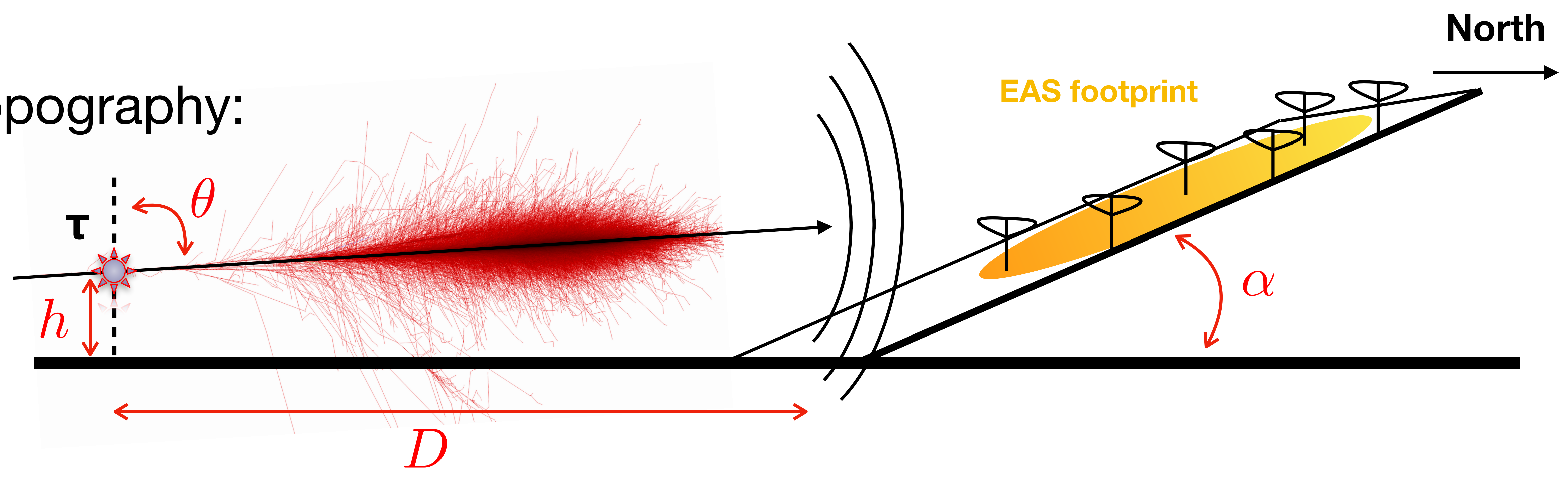
Two parameters to model the topography:

- D = valley depth
- α = the mountain slope



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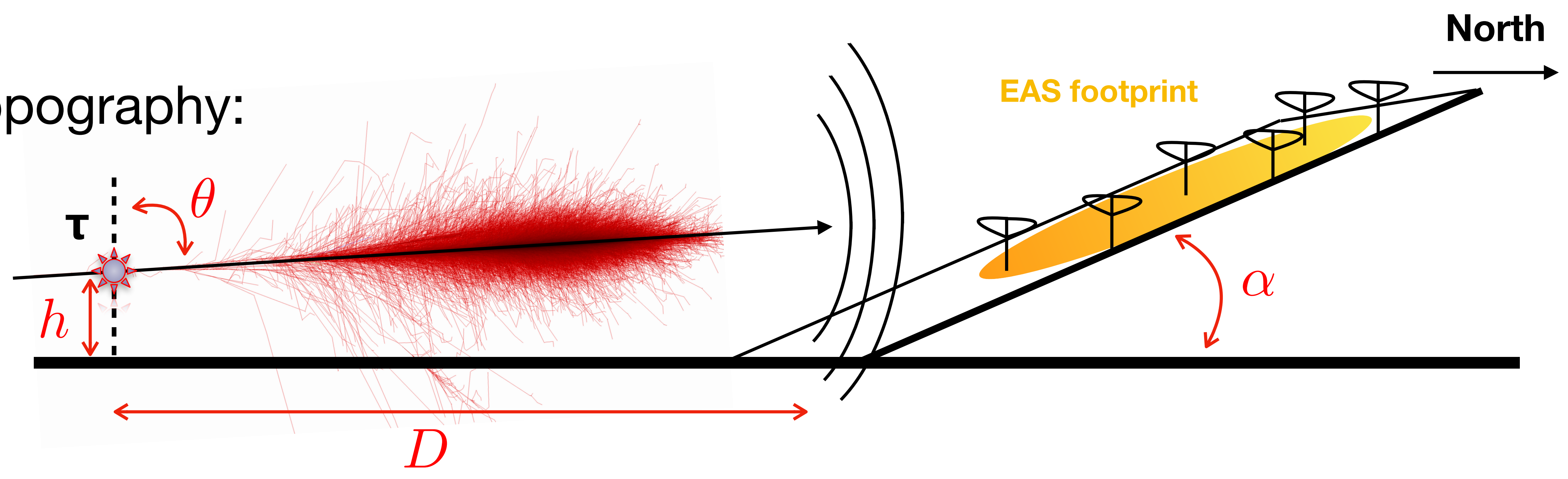

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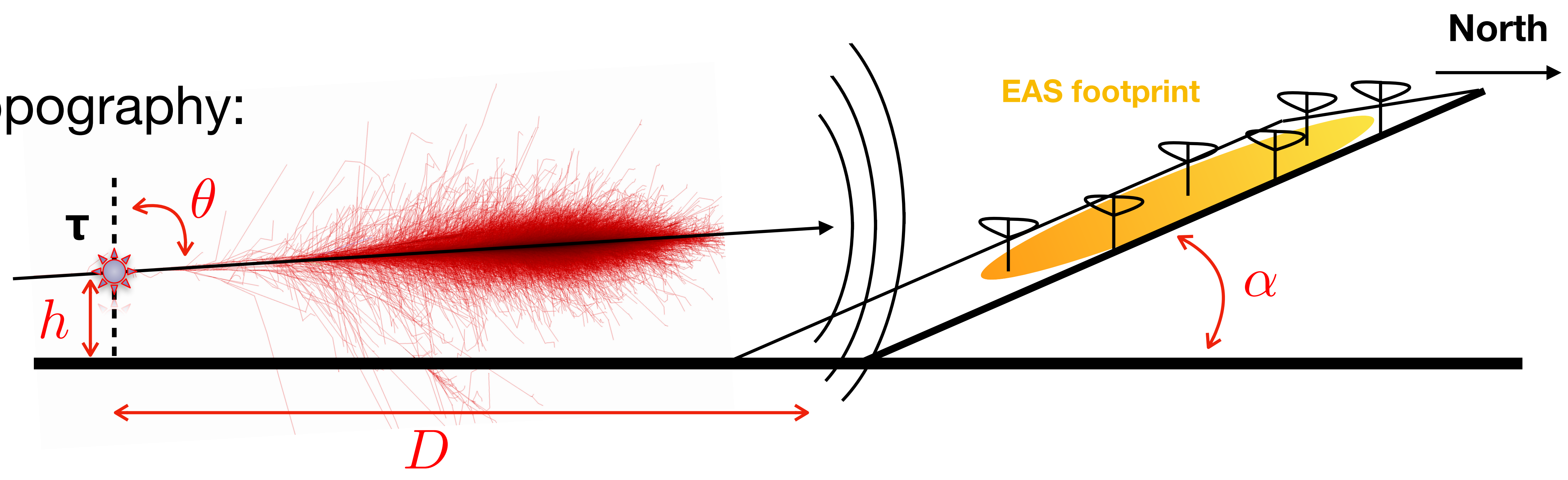

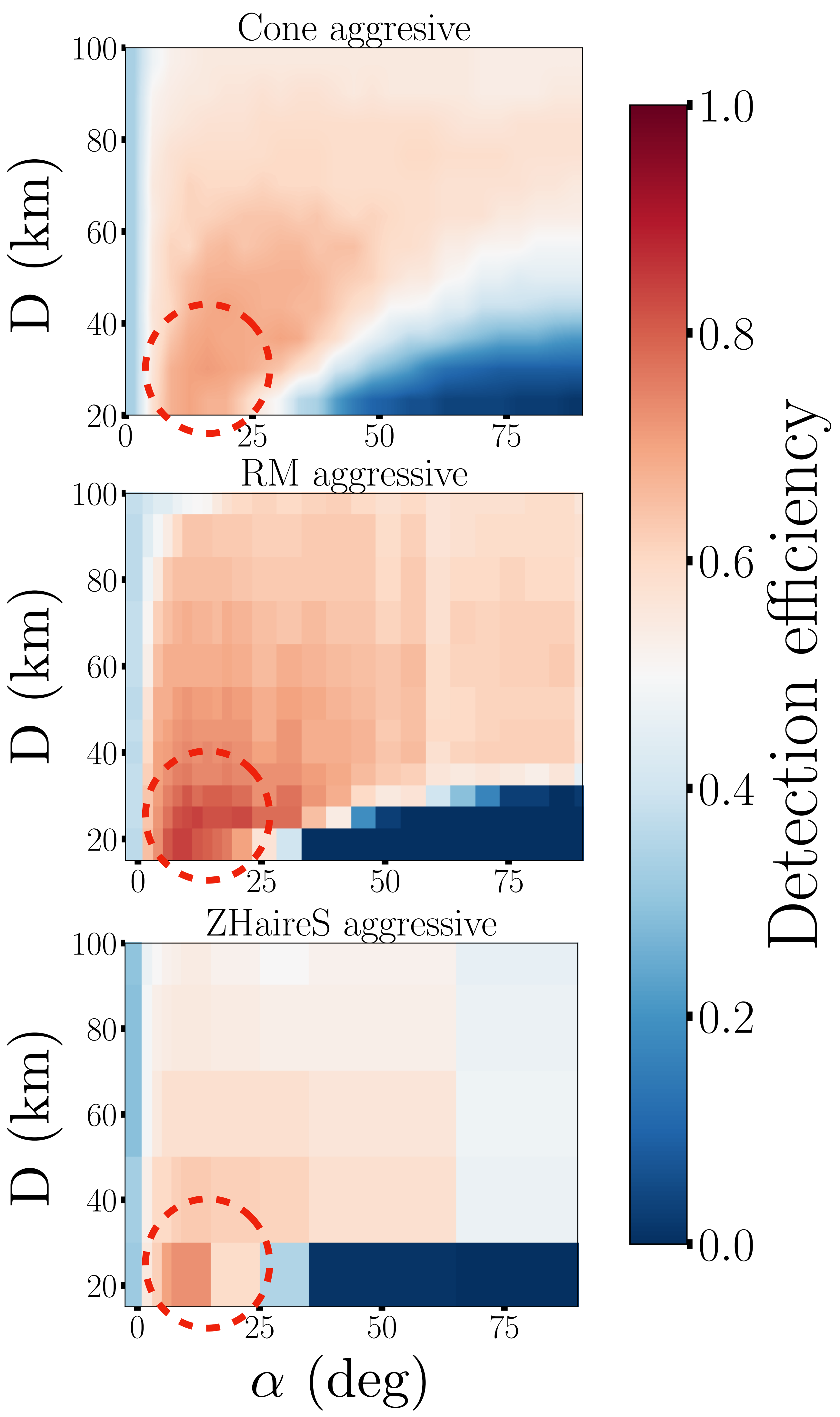

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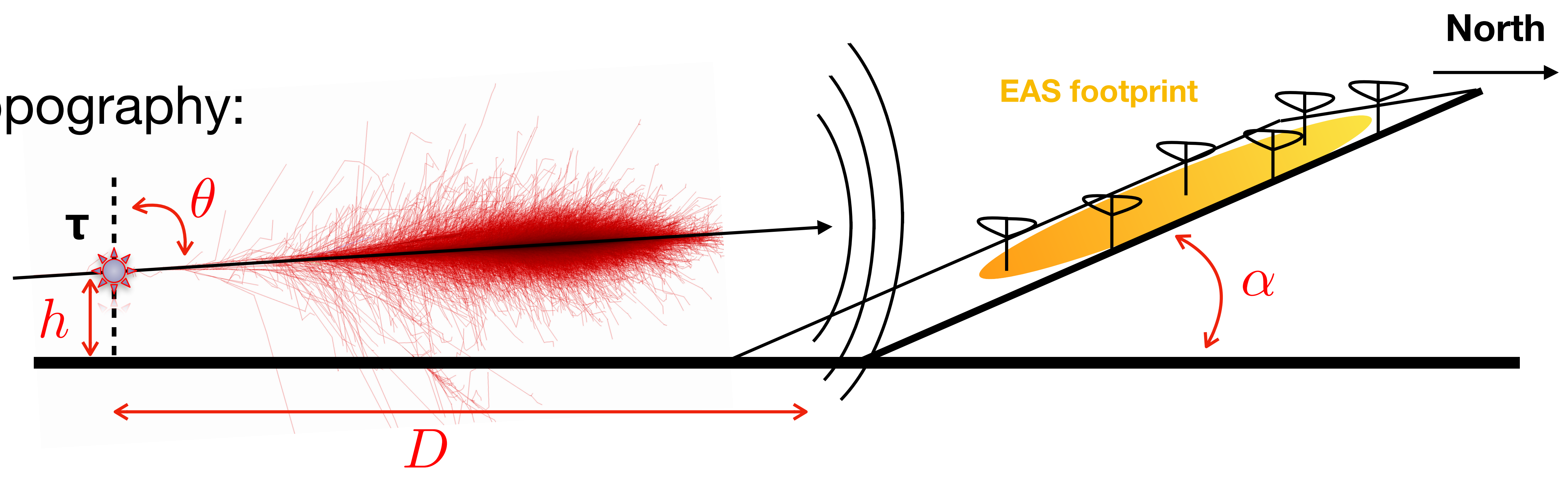

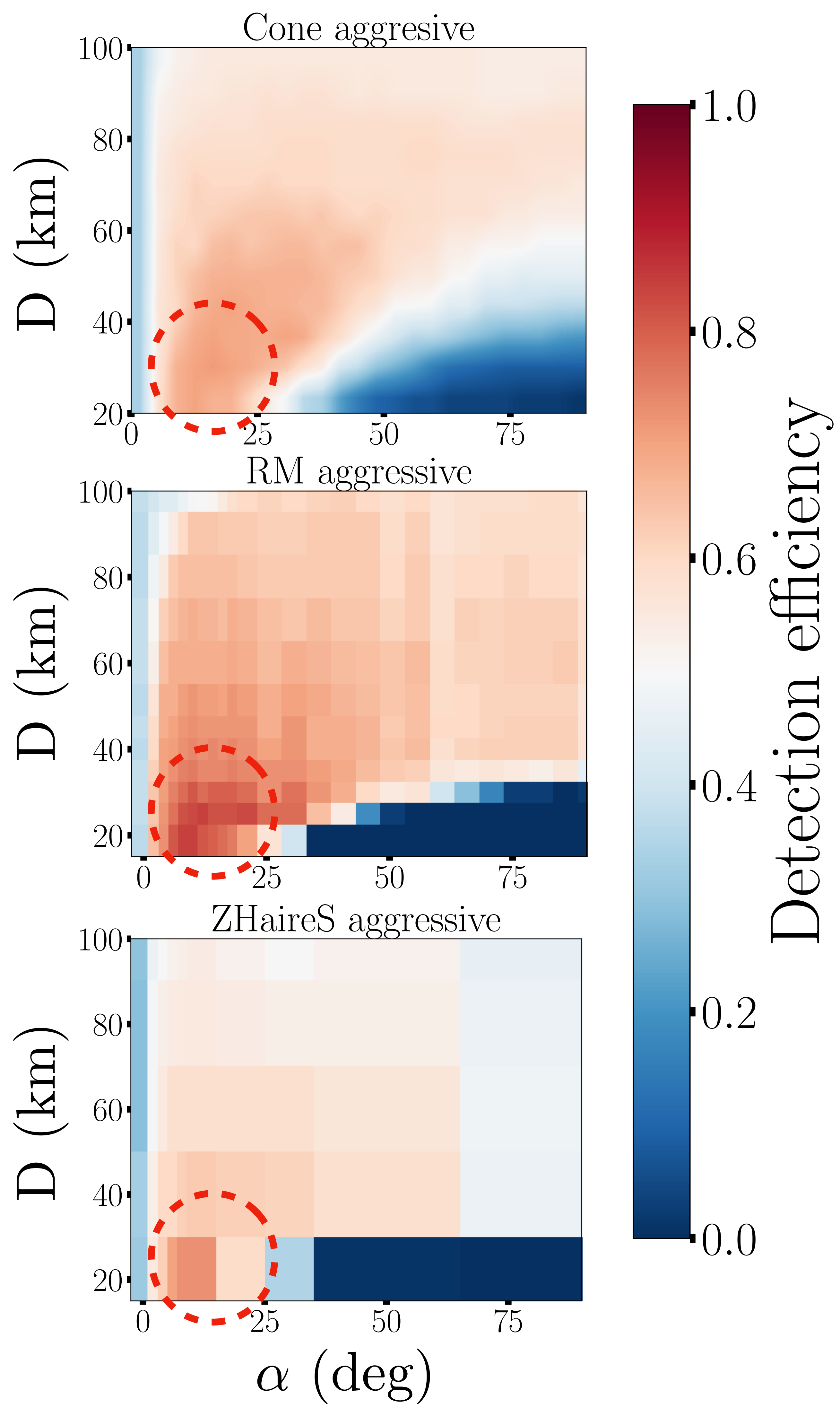

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Consequences: Very mild slopes of wide valleys or large basins could offer optimal topographies for the detection of neutrinos.

The BEACON prototype

Southall (UChicago), Deaconu (UChicago), **V. D.**, et al. (accepted in NIMA)

Prototype deployed (8 antennas x4 pol) and taking data at Barcroft Field Station, in the White Mountains in California

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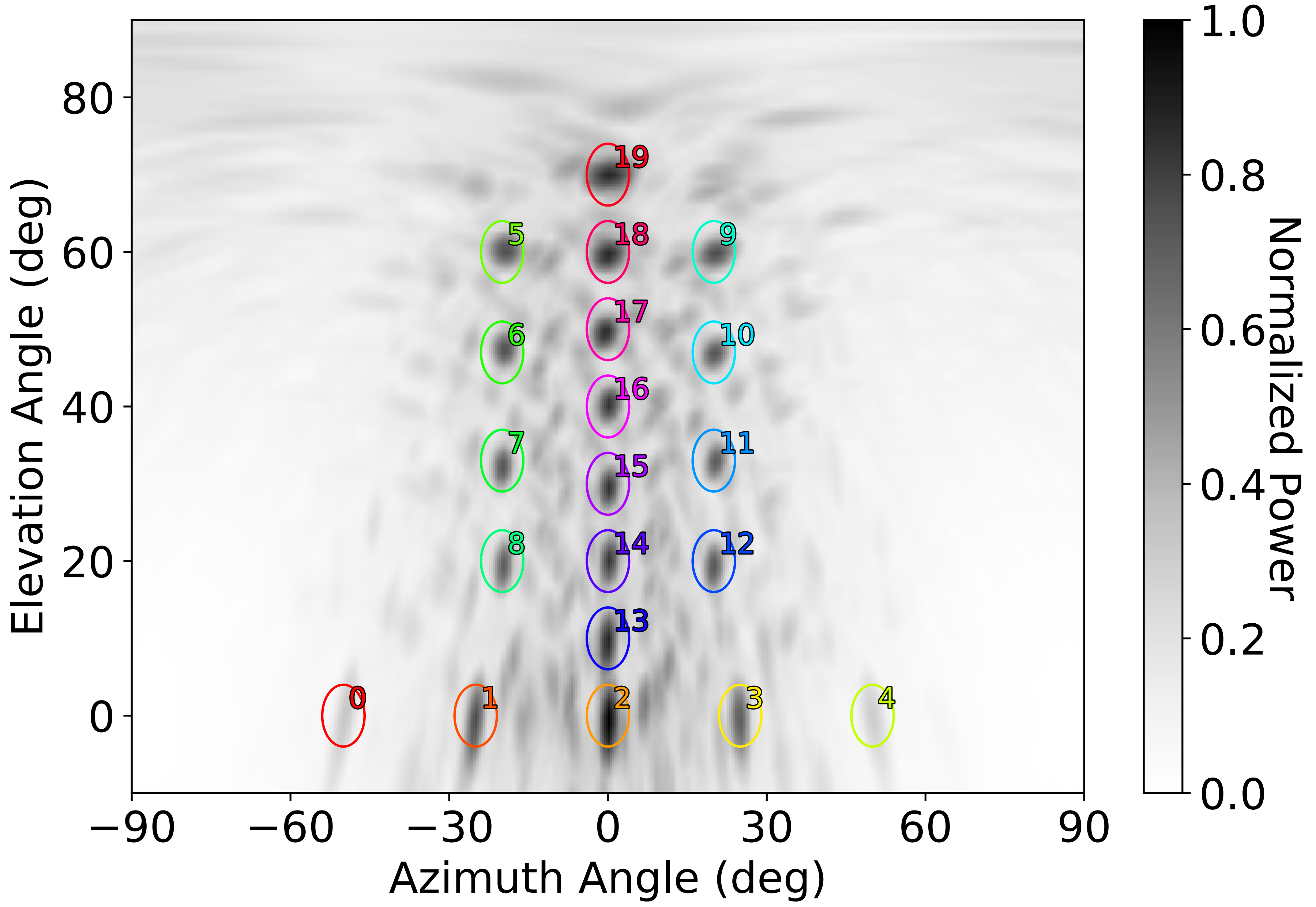

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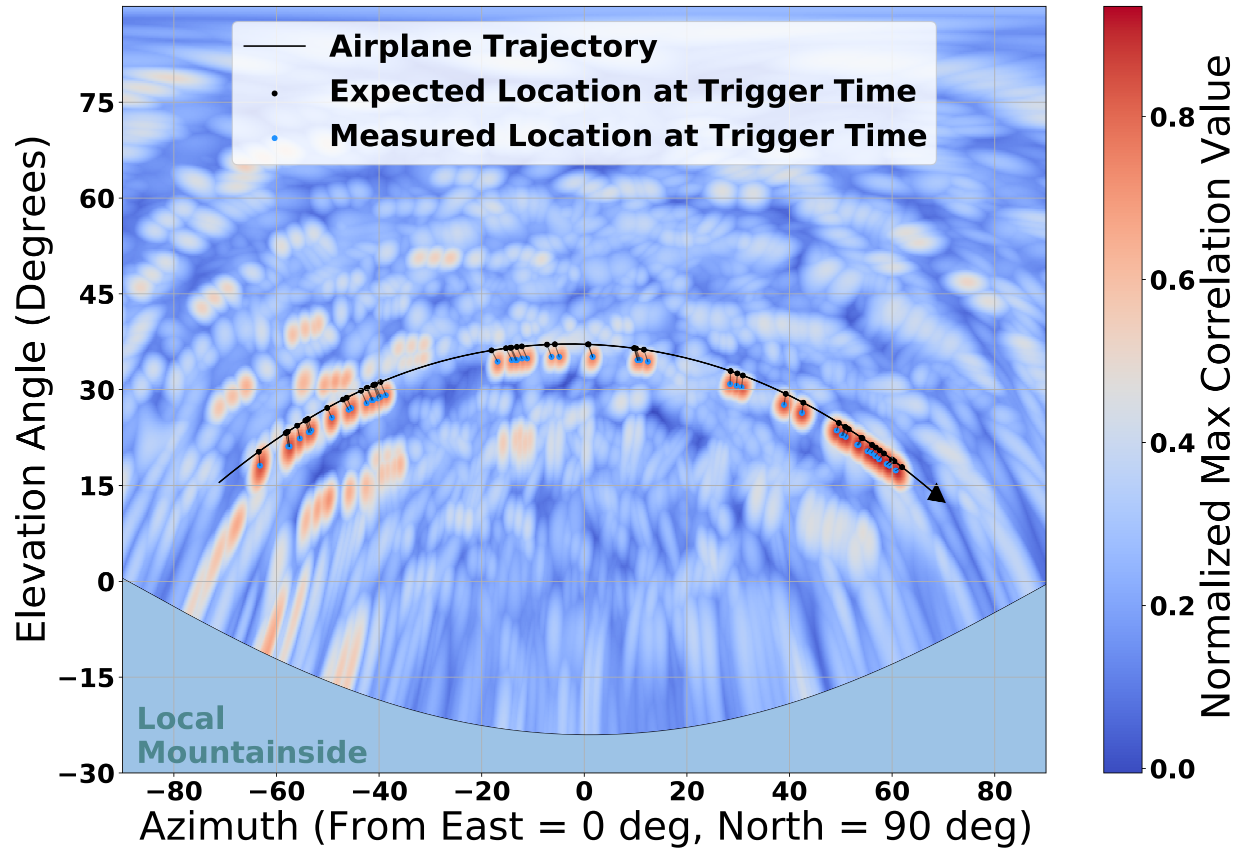

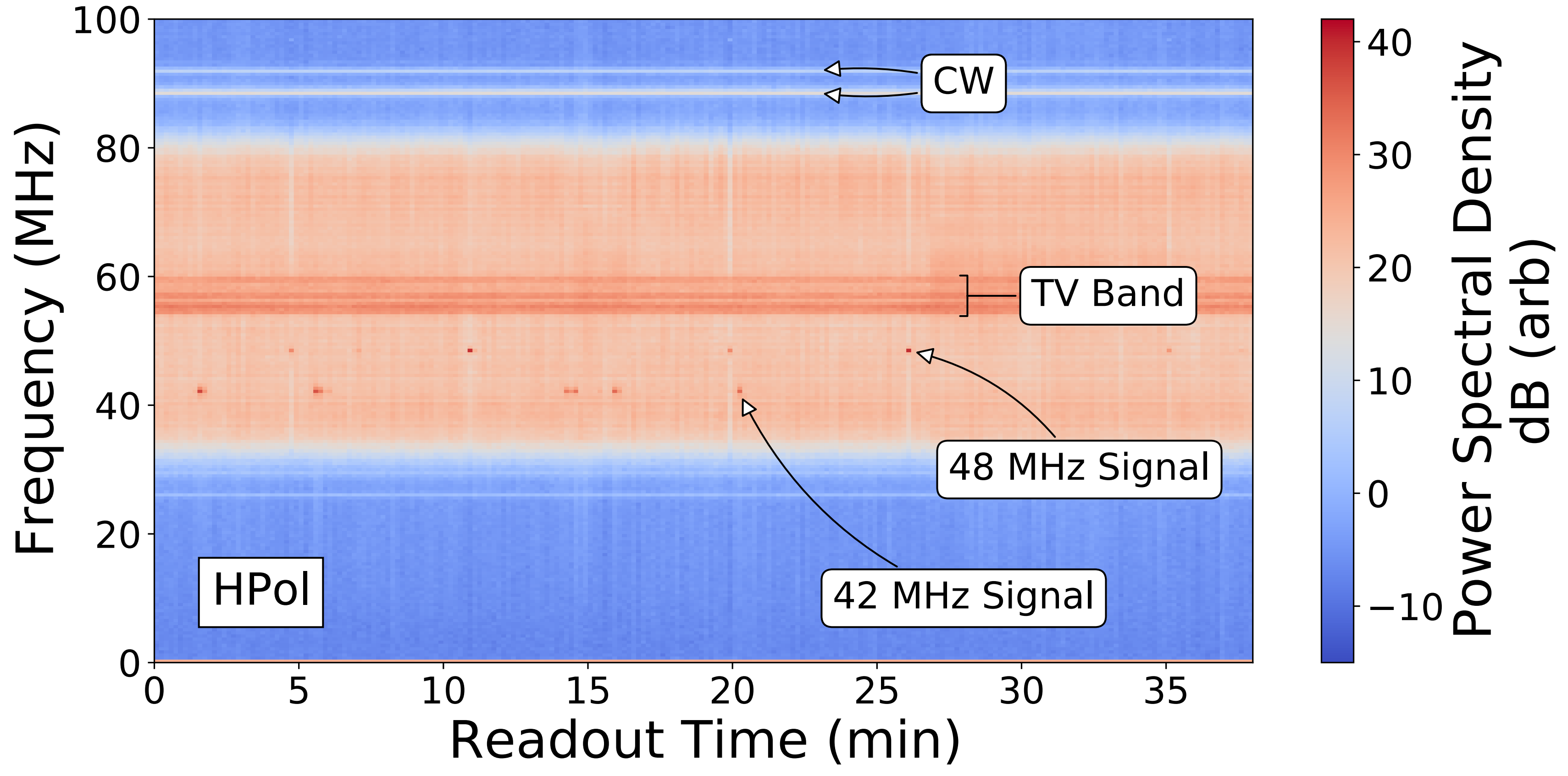

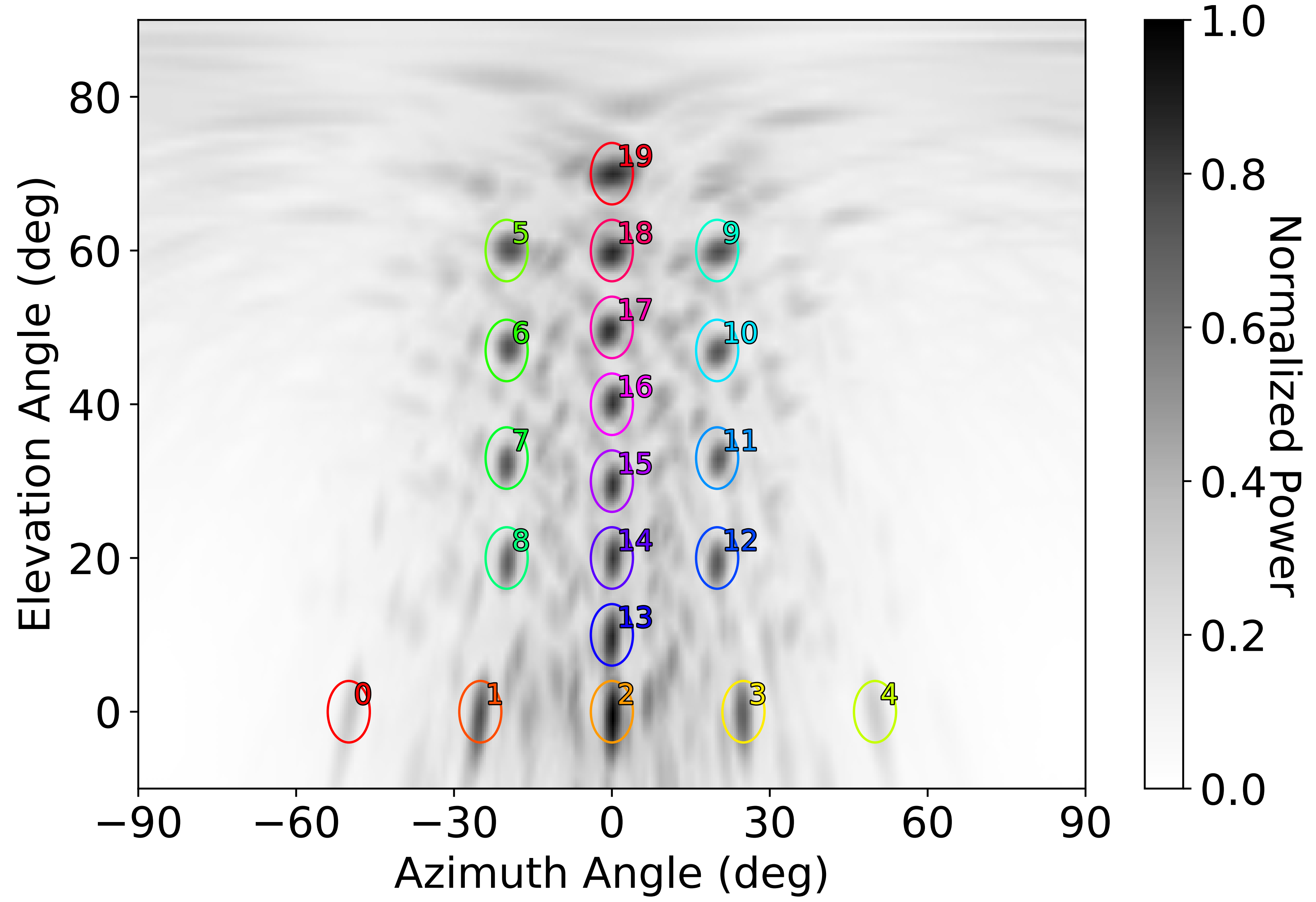

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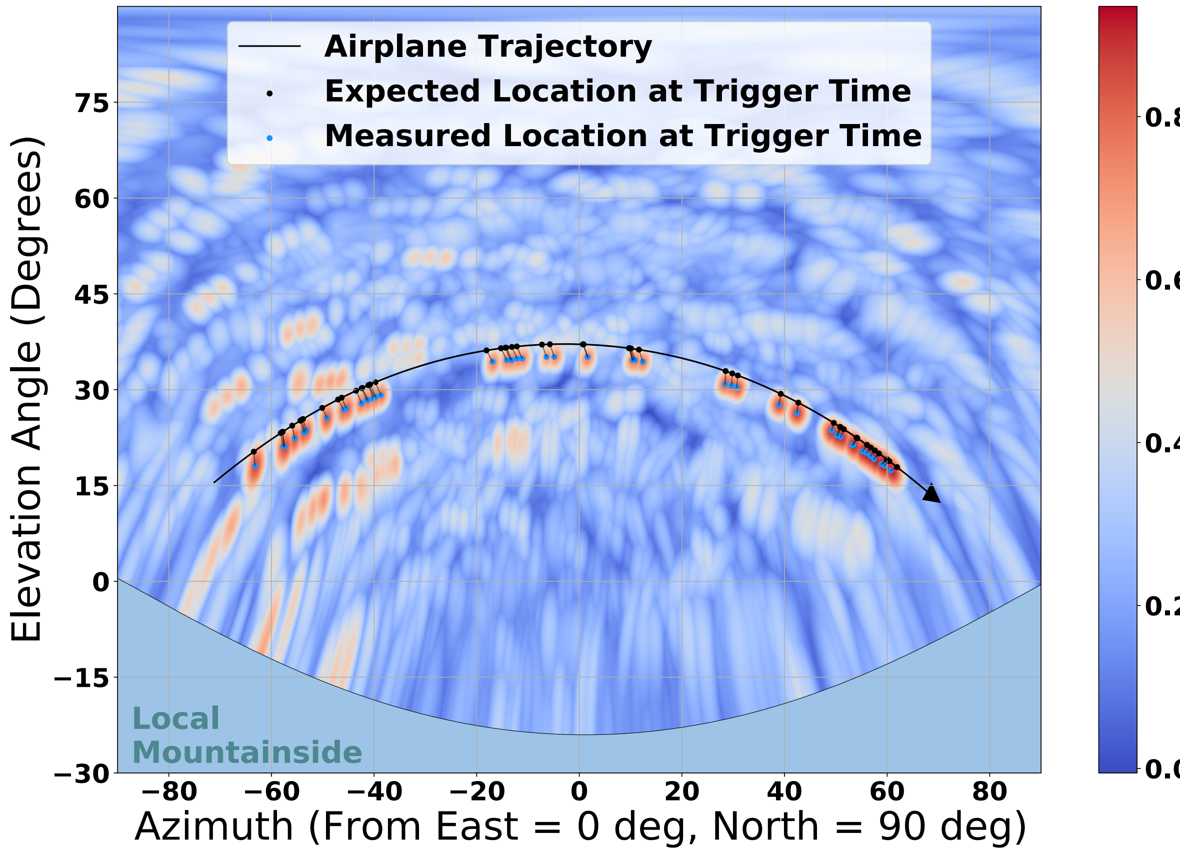

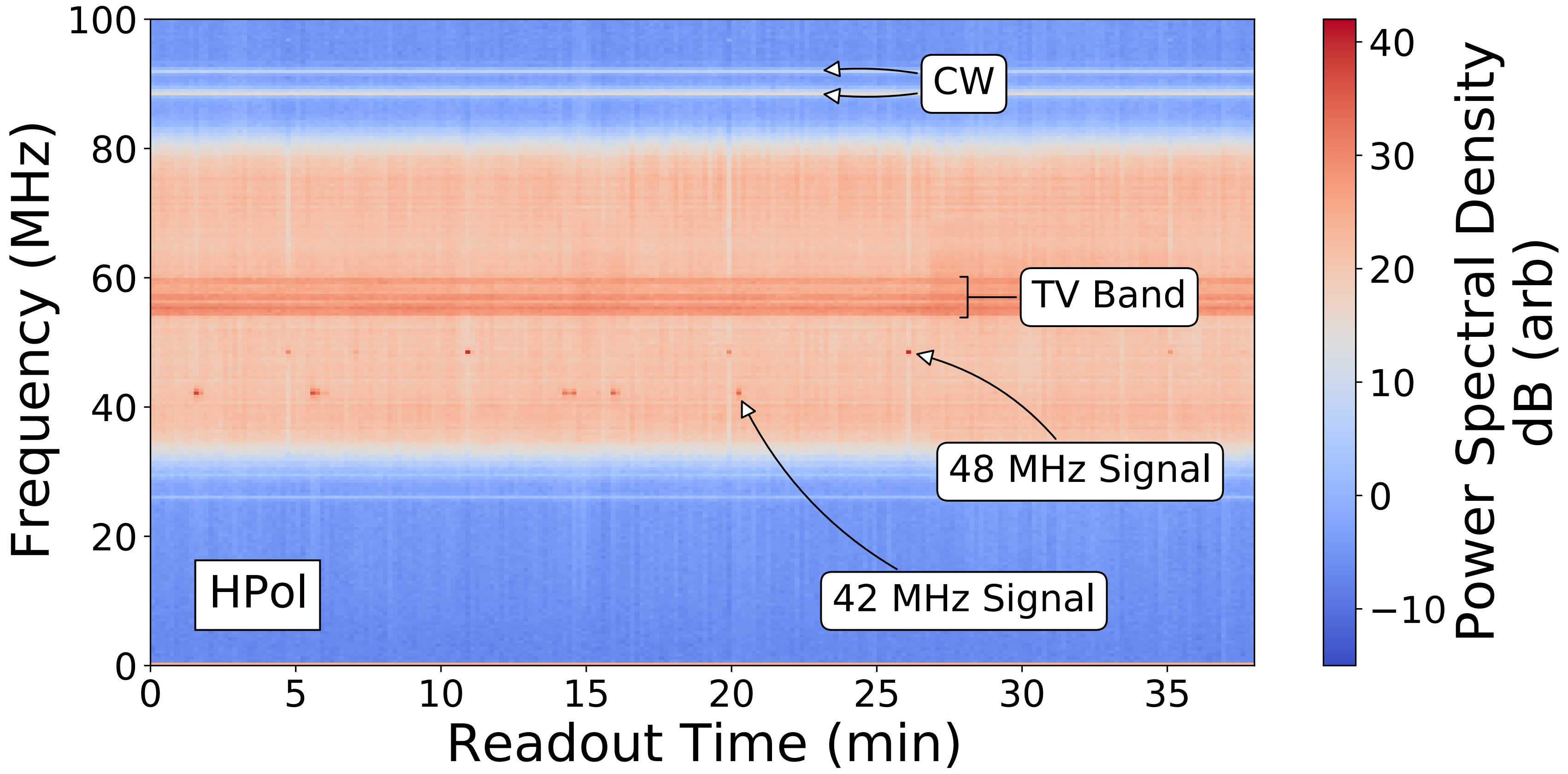

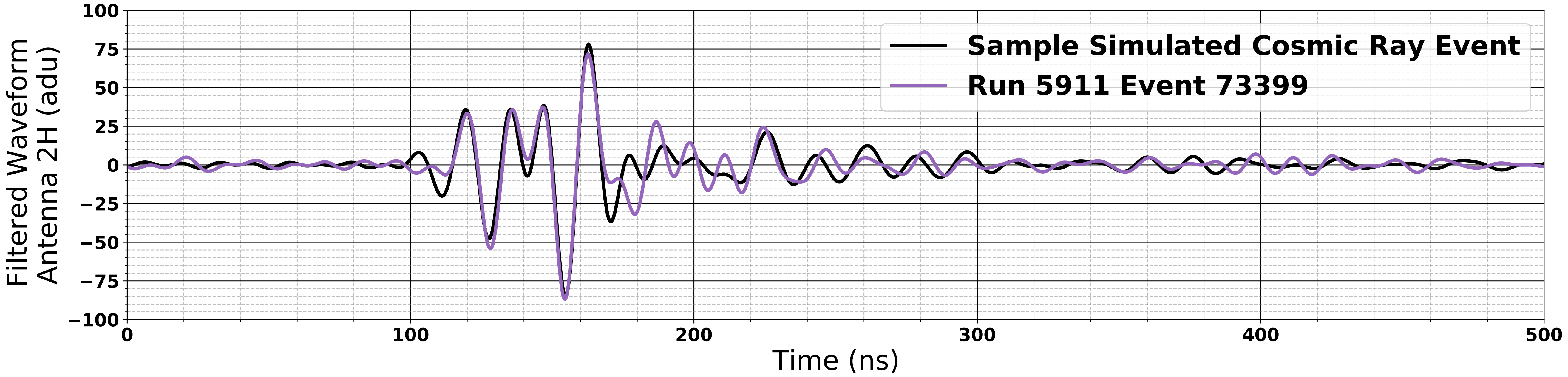

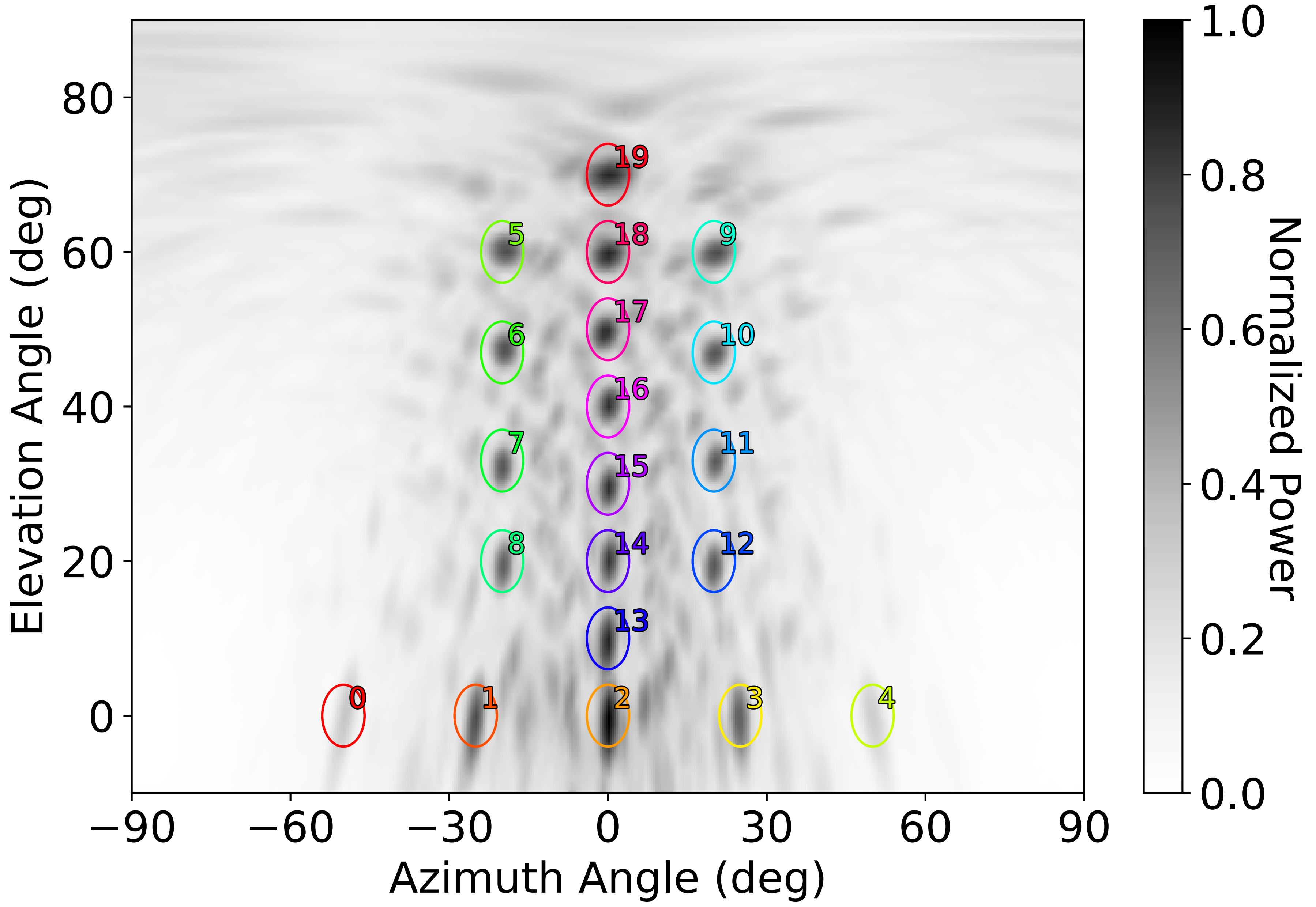

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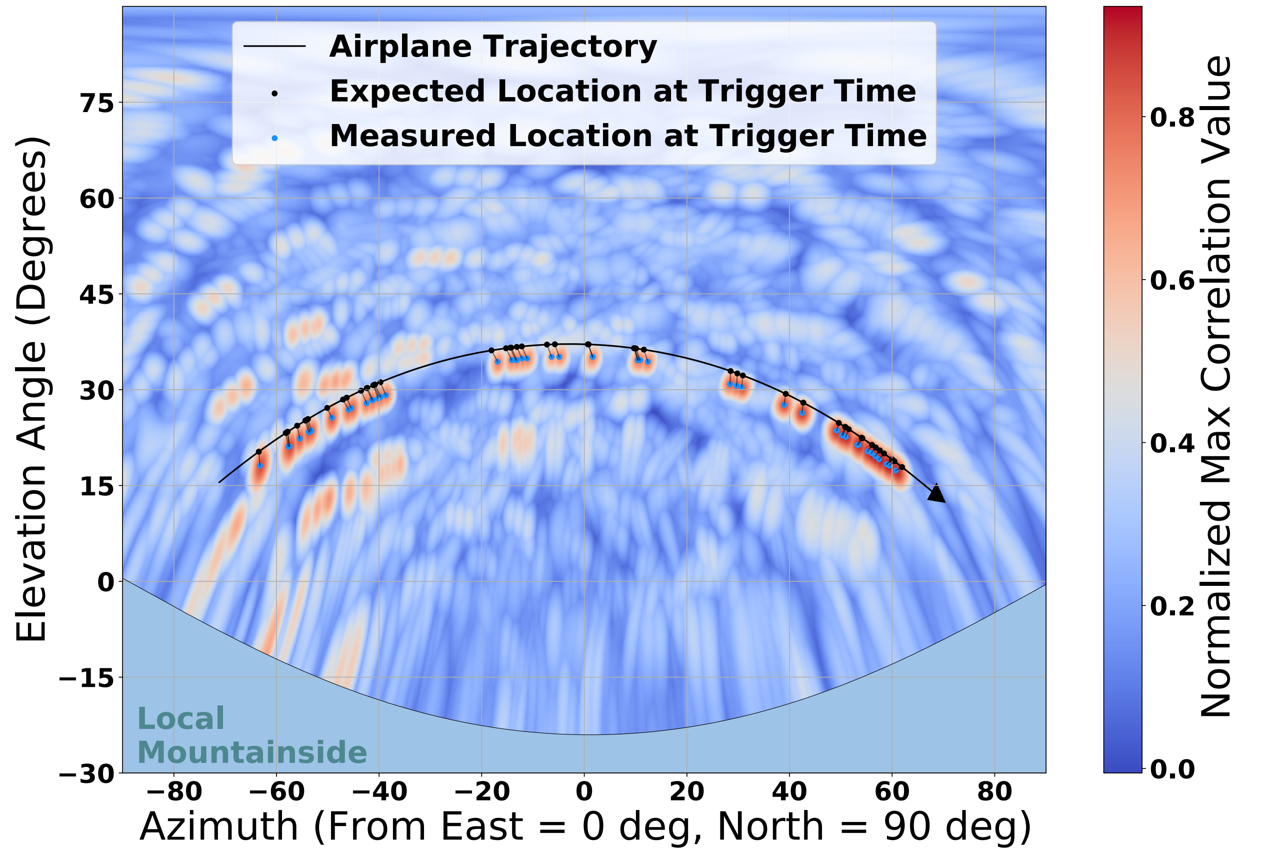

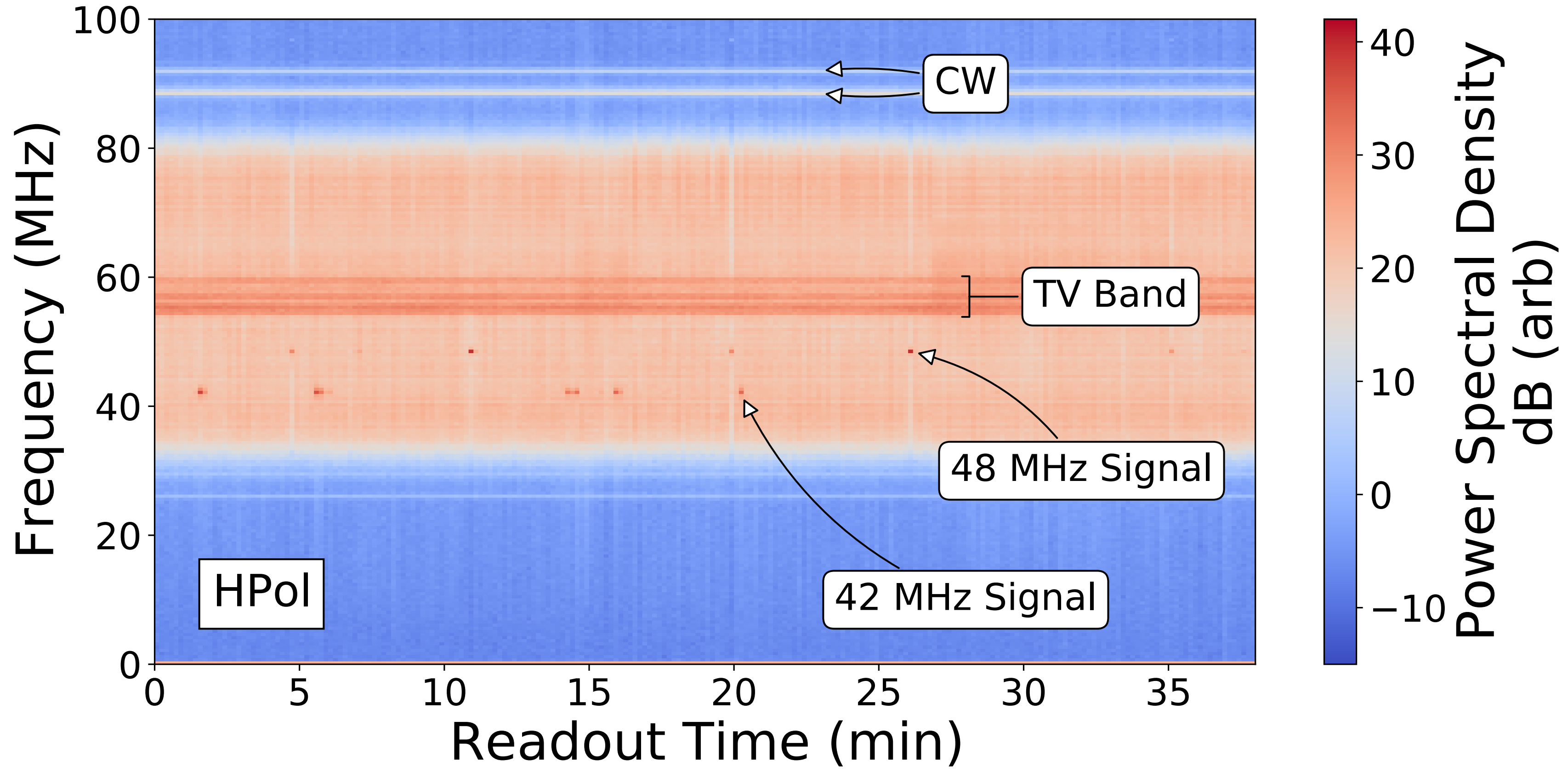

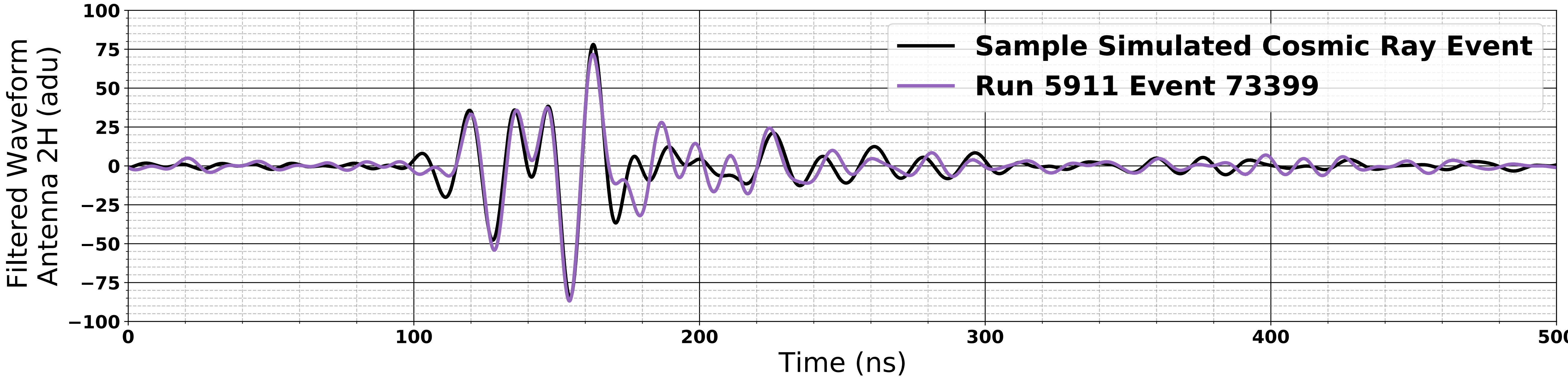

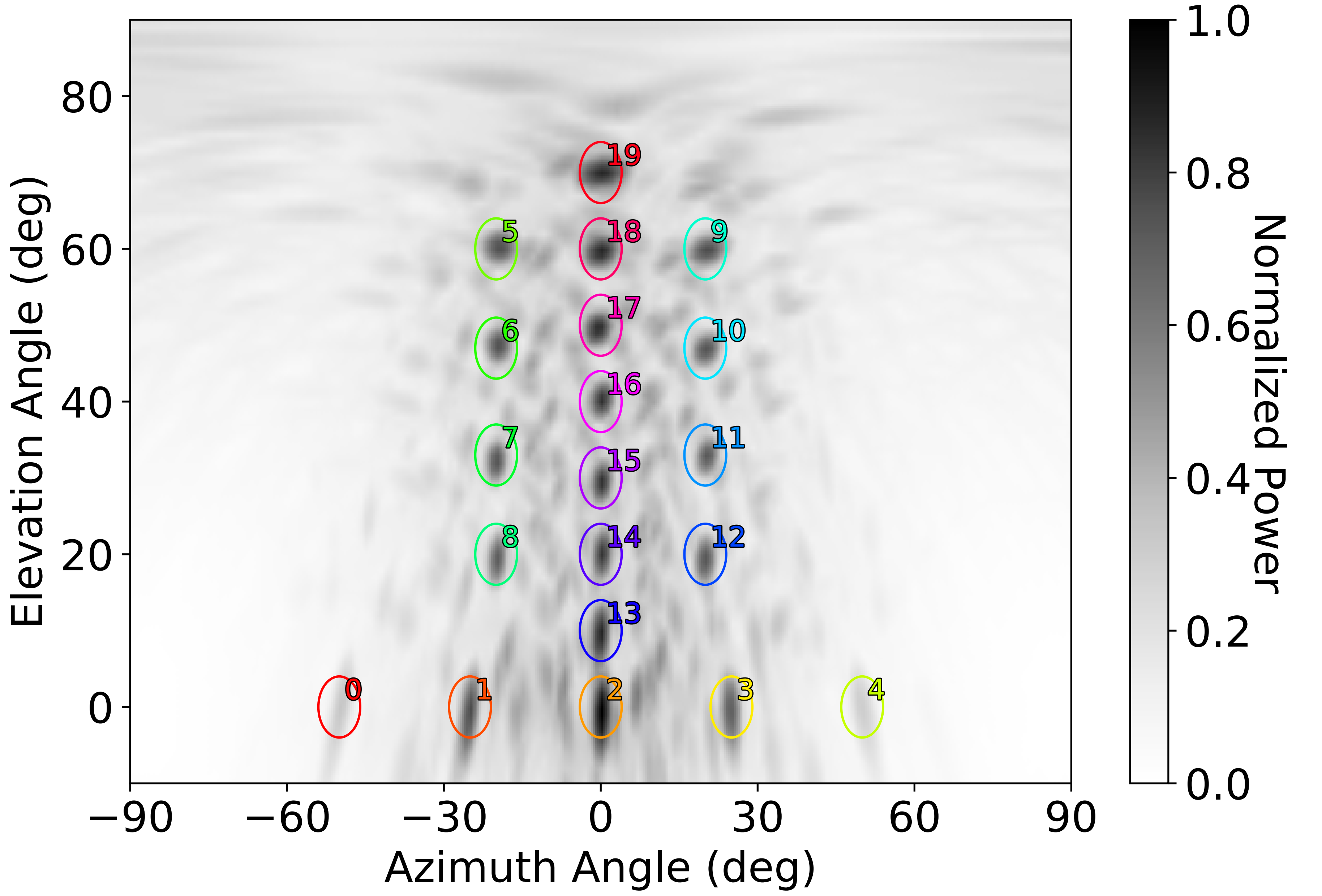

The cosmic-ray search is an excellent test bench for signal analysis development for future neutrino searches!

EAS reconstruction

V.D., Martineau-Huynh and Tueros (published in Astroparticle Physics)

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Goal : develop a reconstruction procedure for very inclined EAS (UHE neutrino induced configuration)

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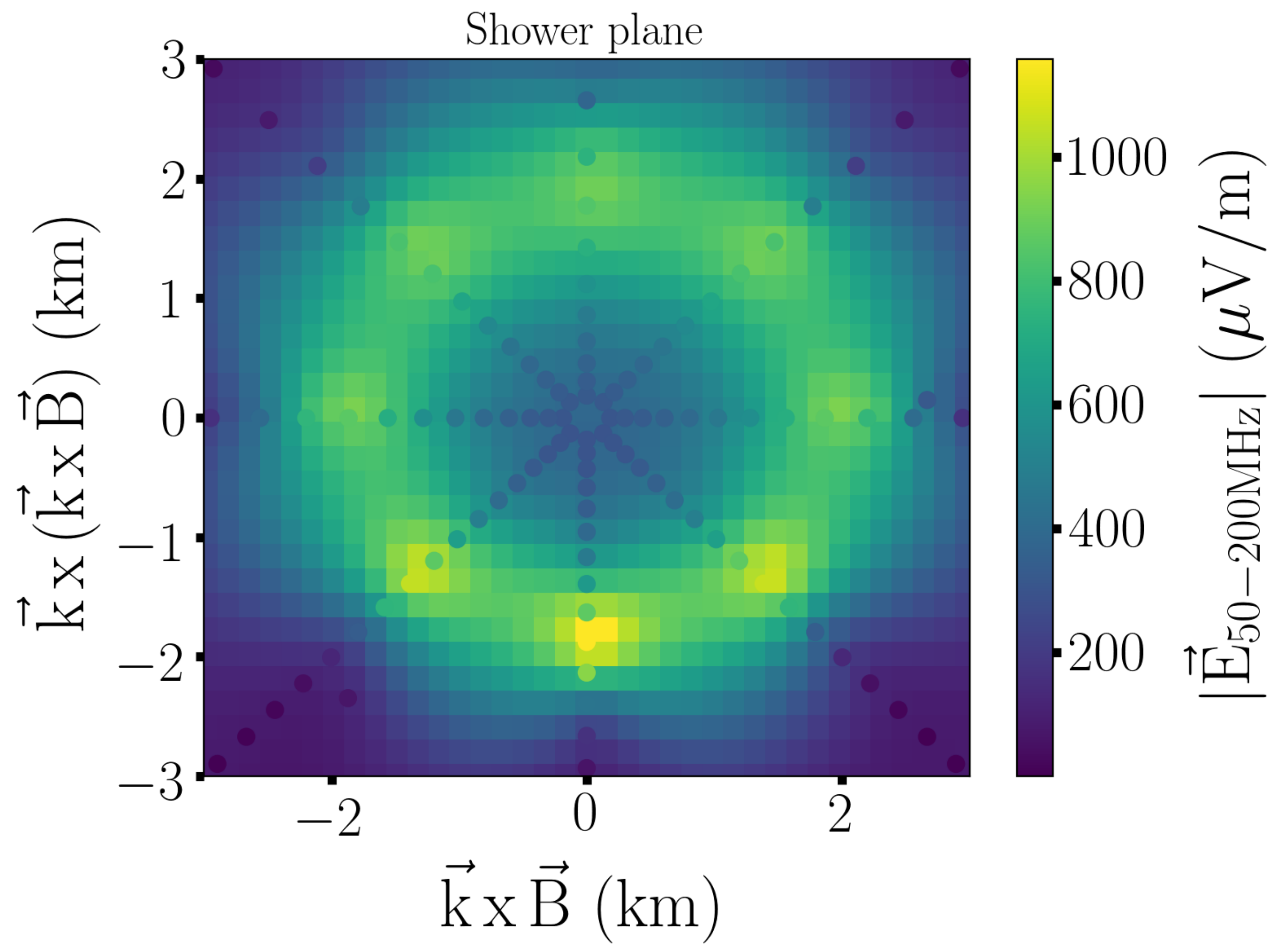

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- modélisation sphérique du **front d'onde**
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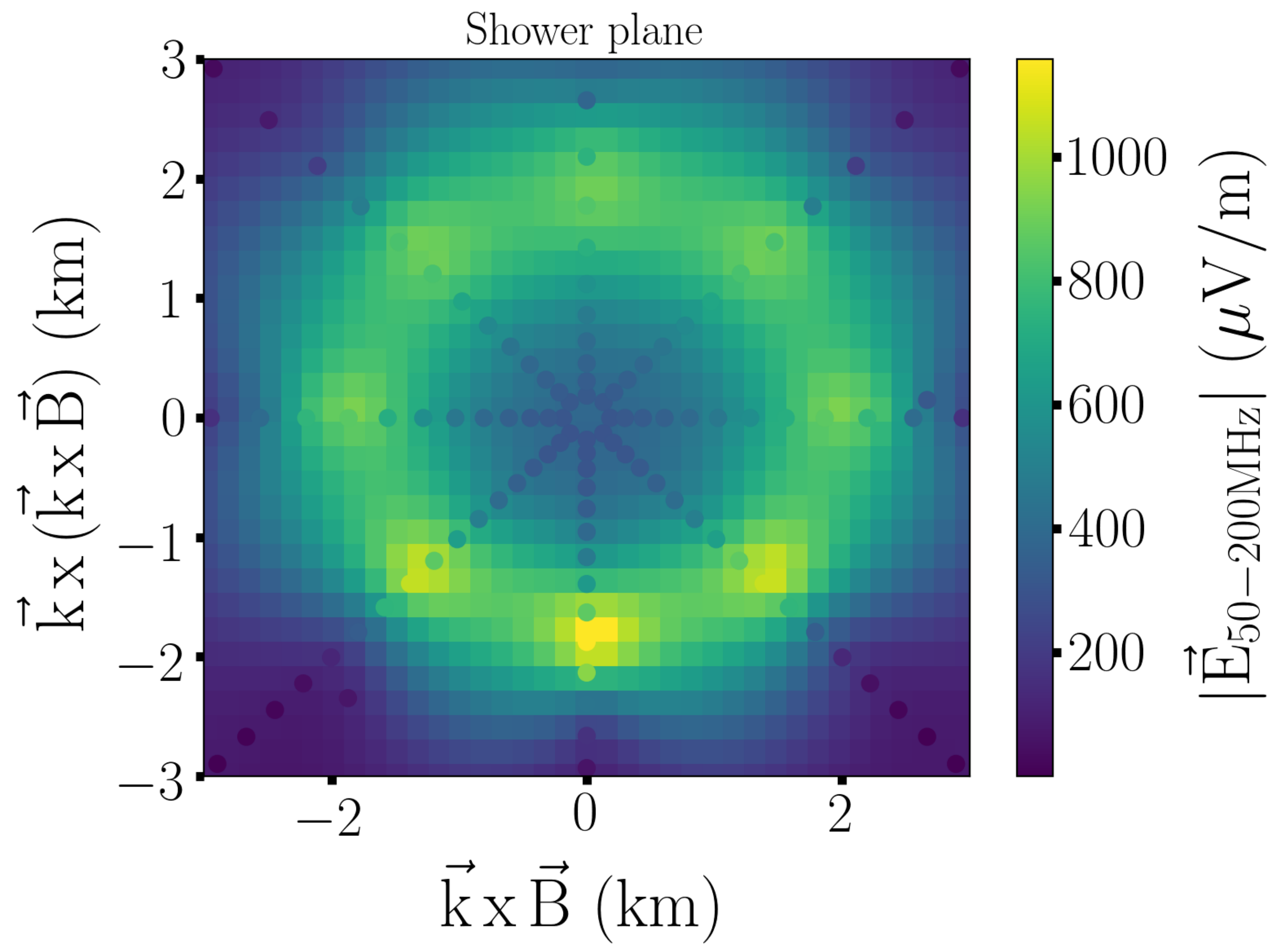

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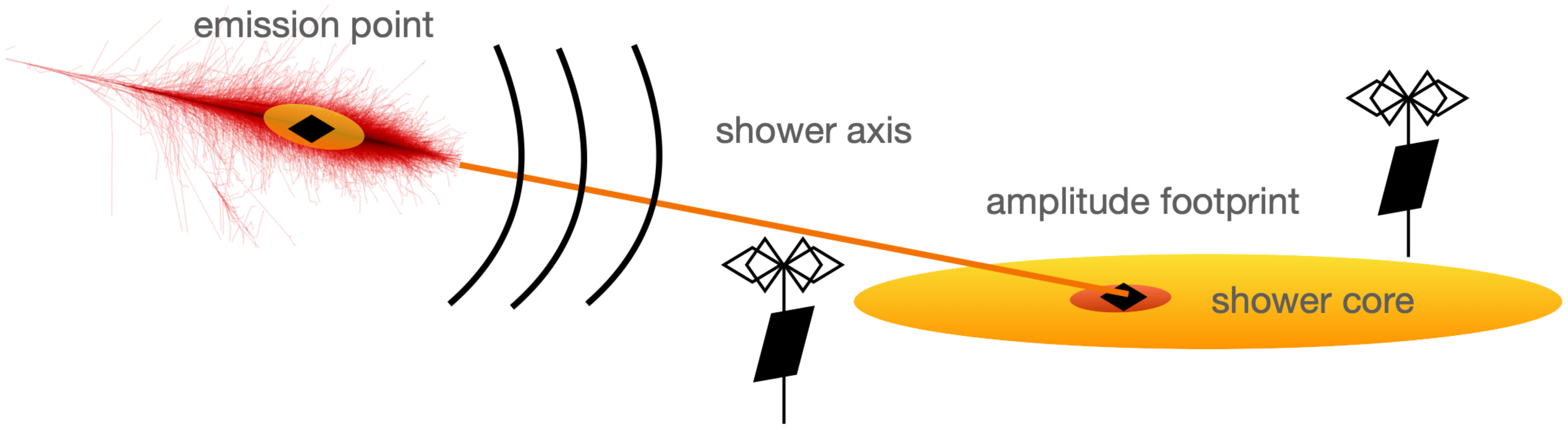

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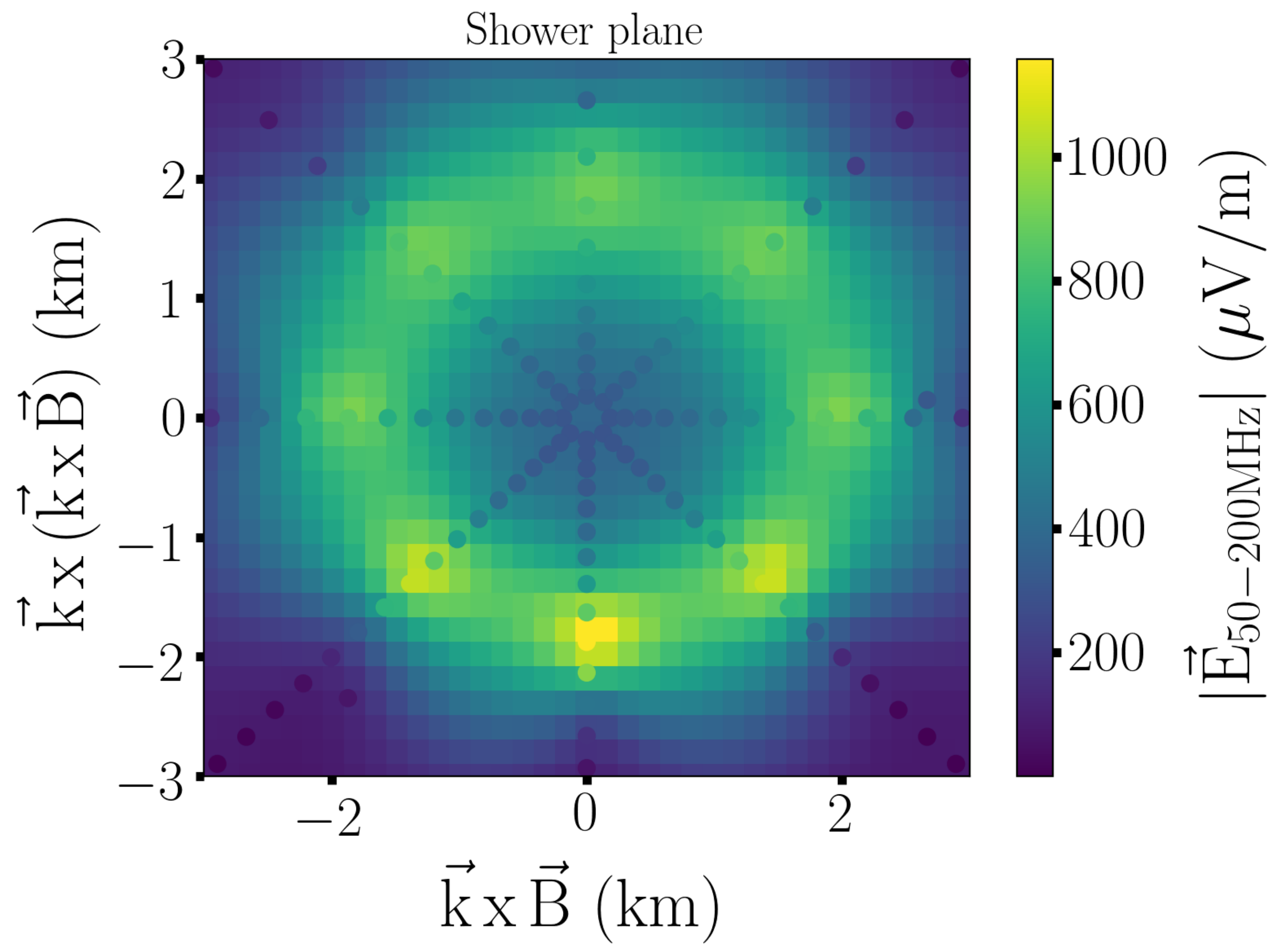

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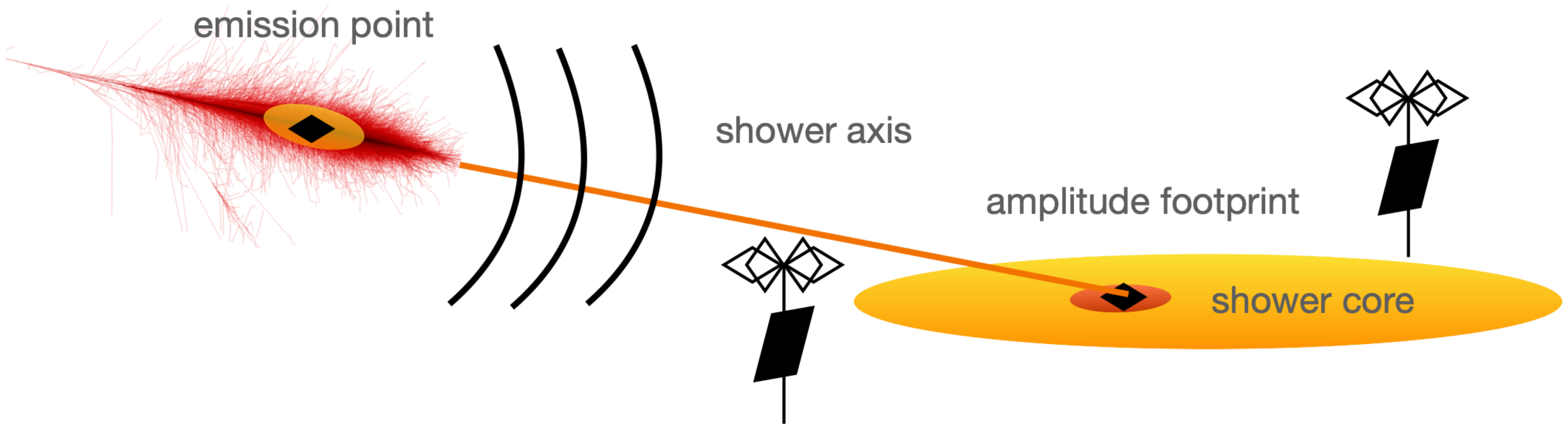

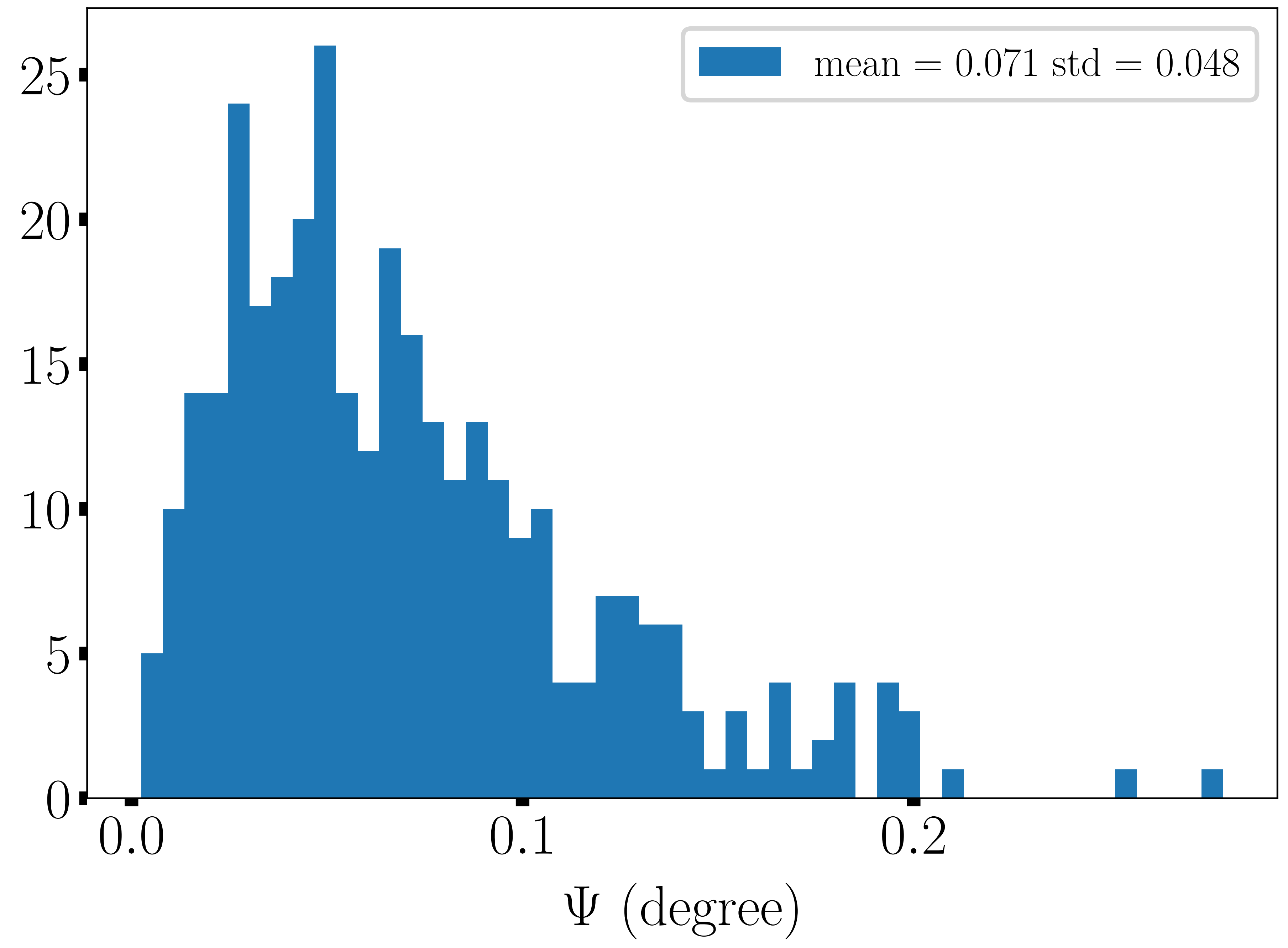

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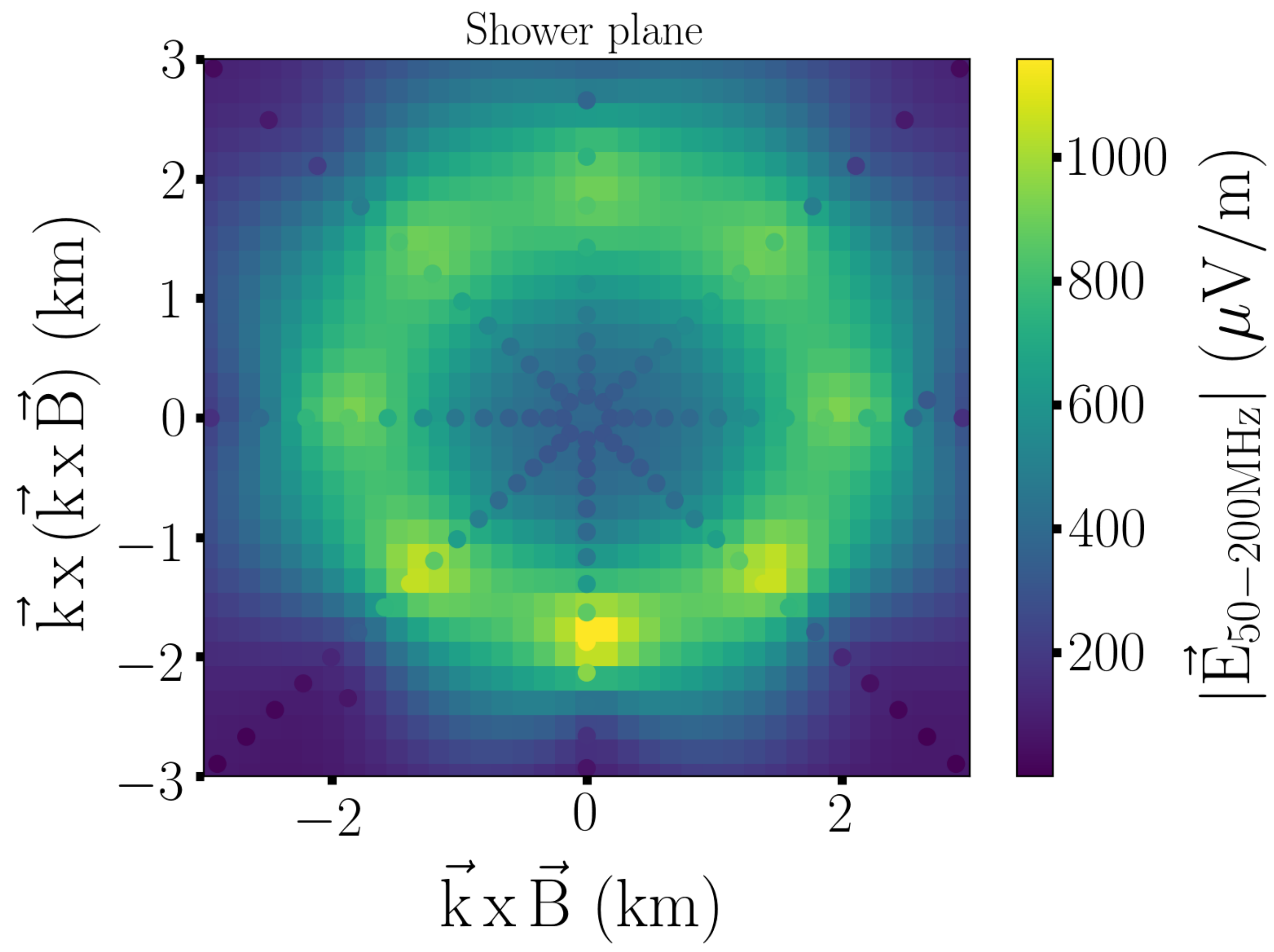

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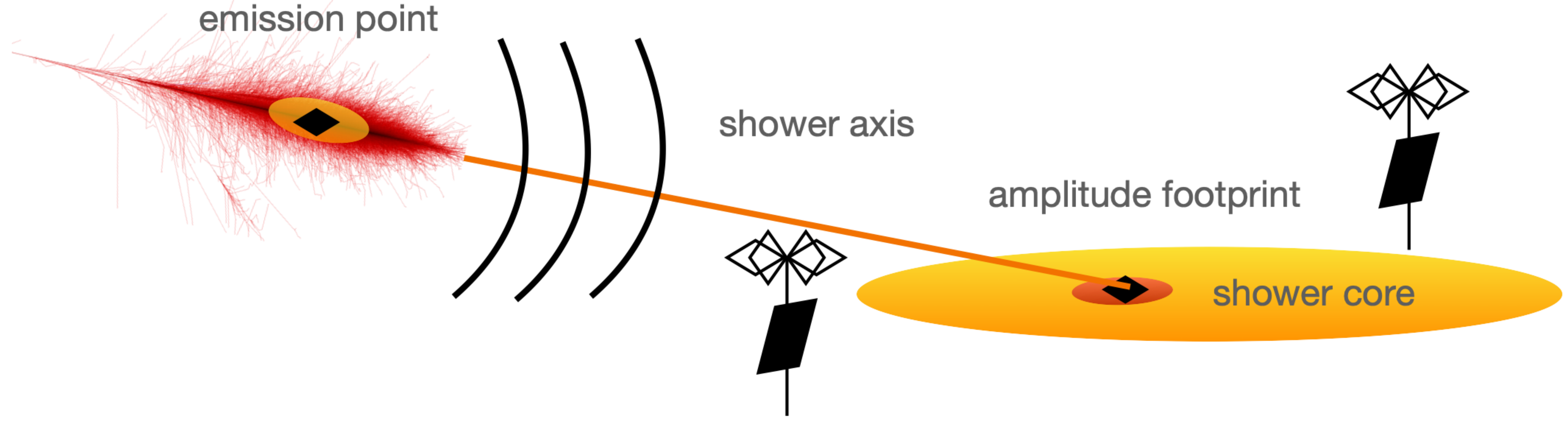
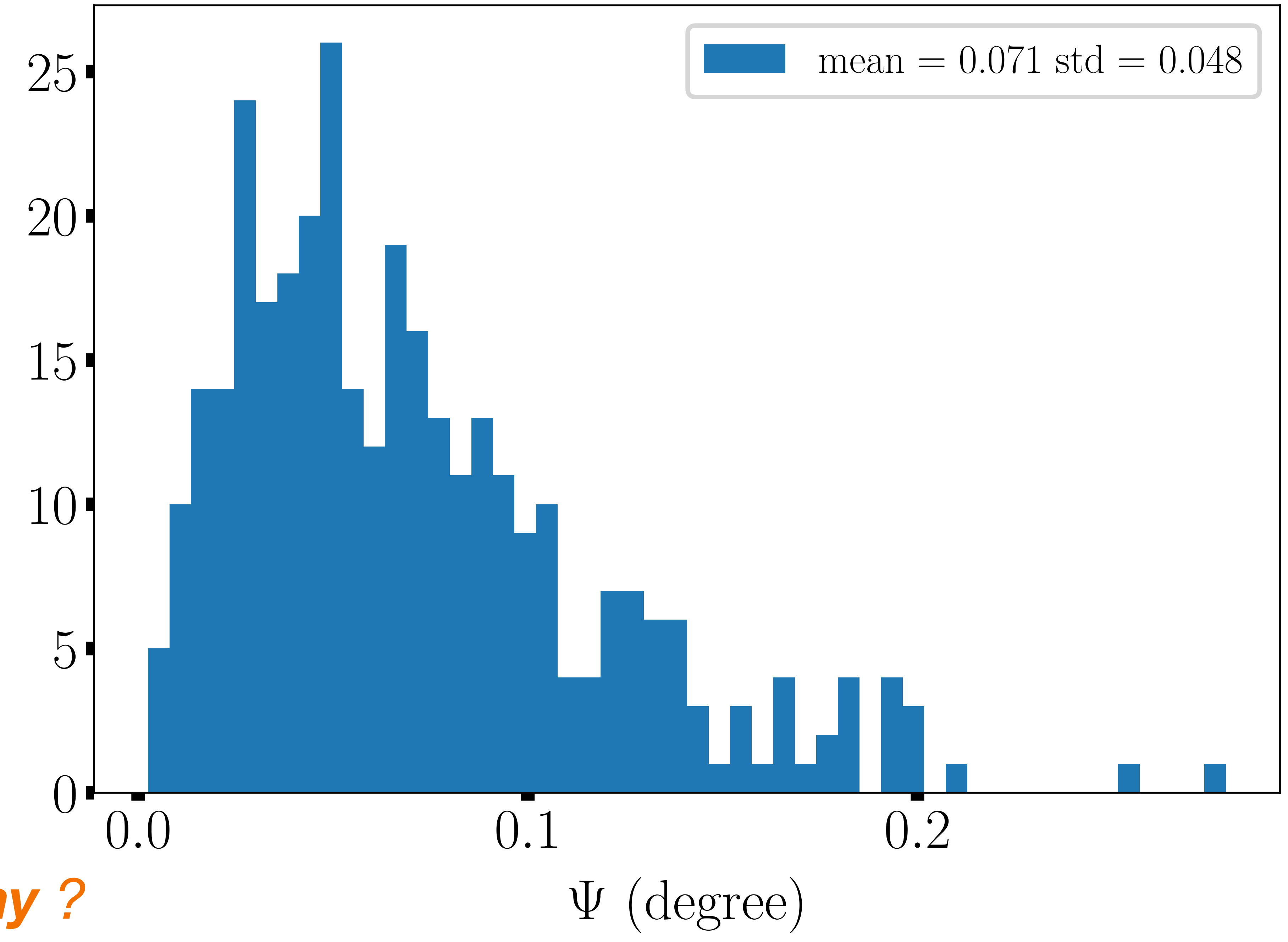
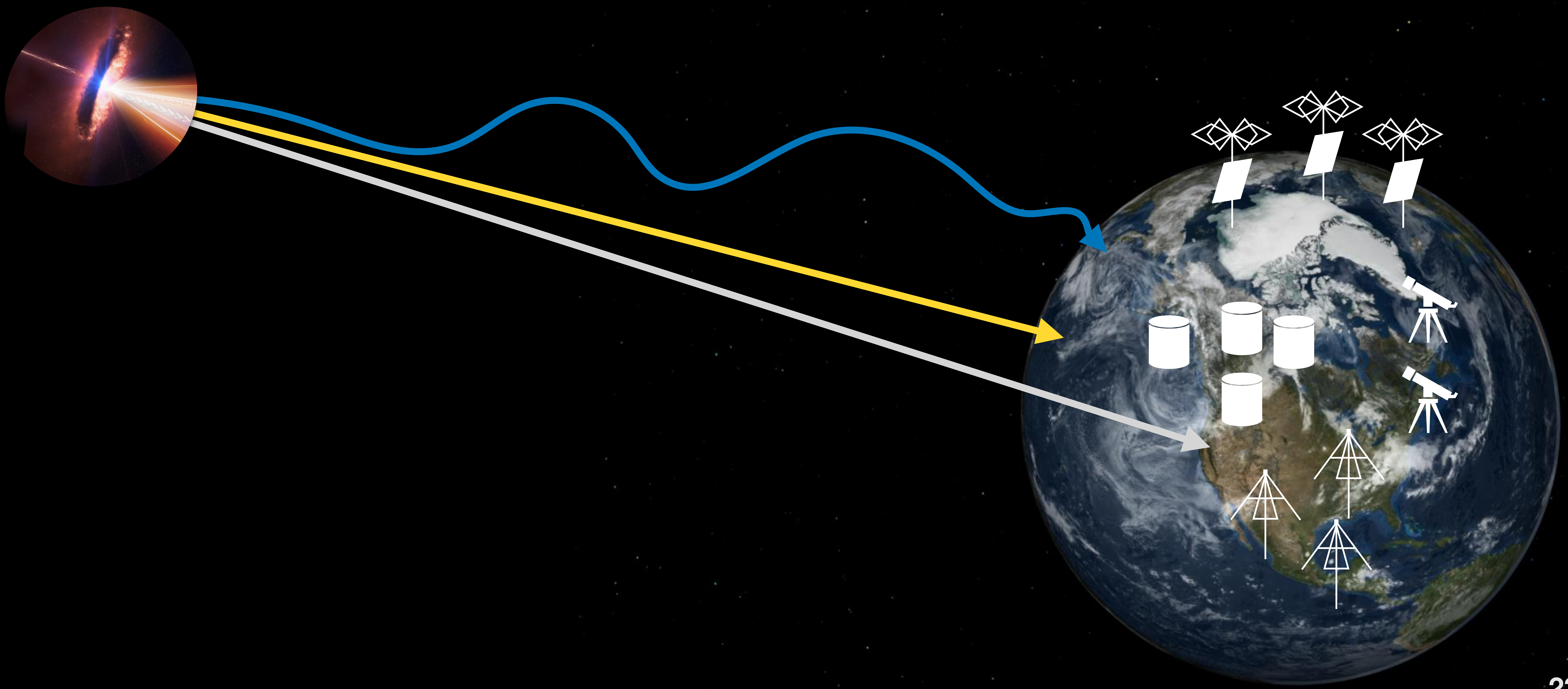




*Results : angular resolution of **0.1°** on average → possibility of **UHE neutrino astronomy** ?*
+ composition and energy estimators

Summary of our journey with HE and UHE neutrinos



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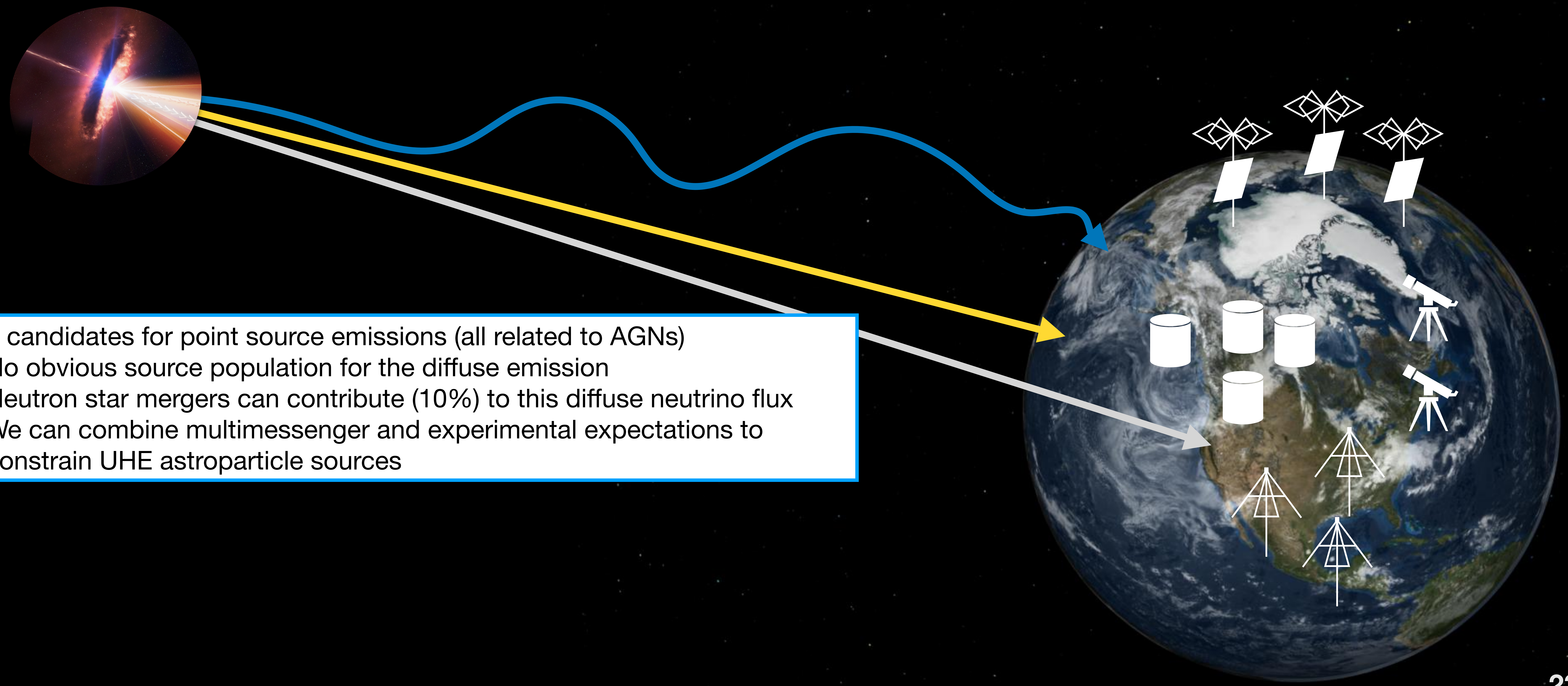

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- No obvious source population for the diffuse emission
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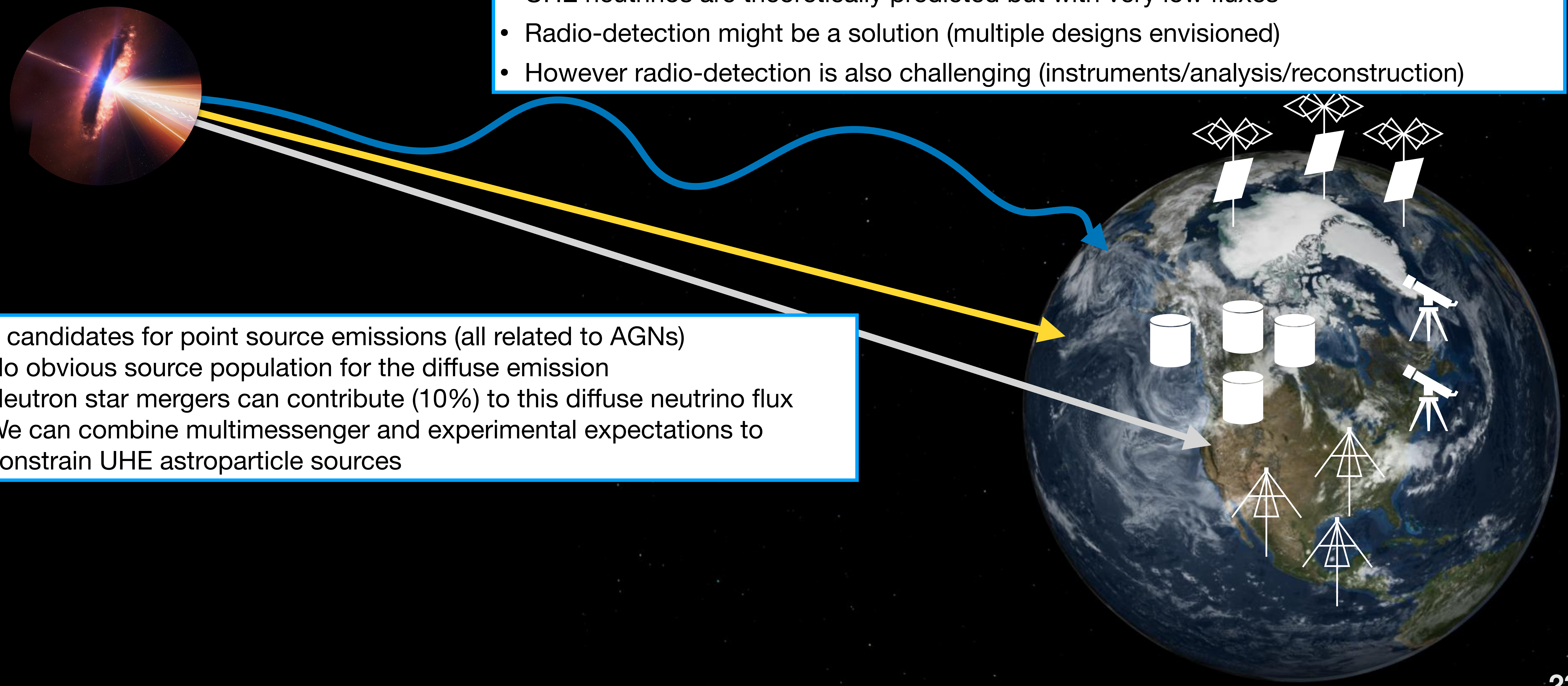

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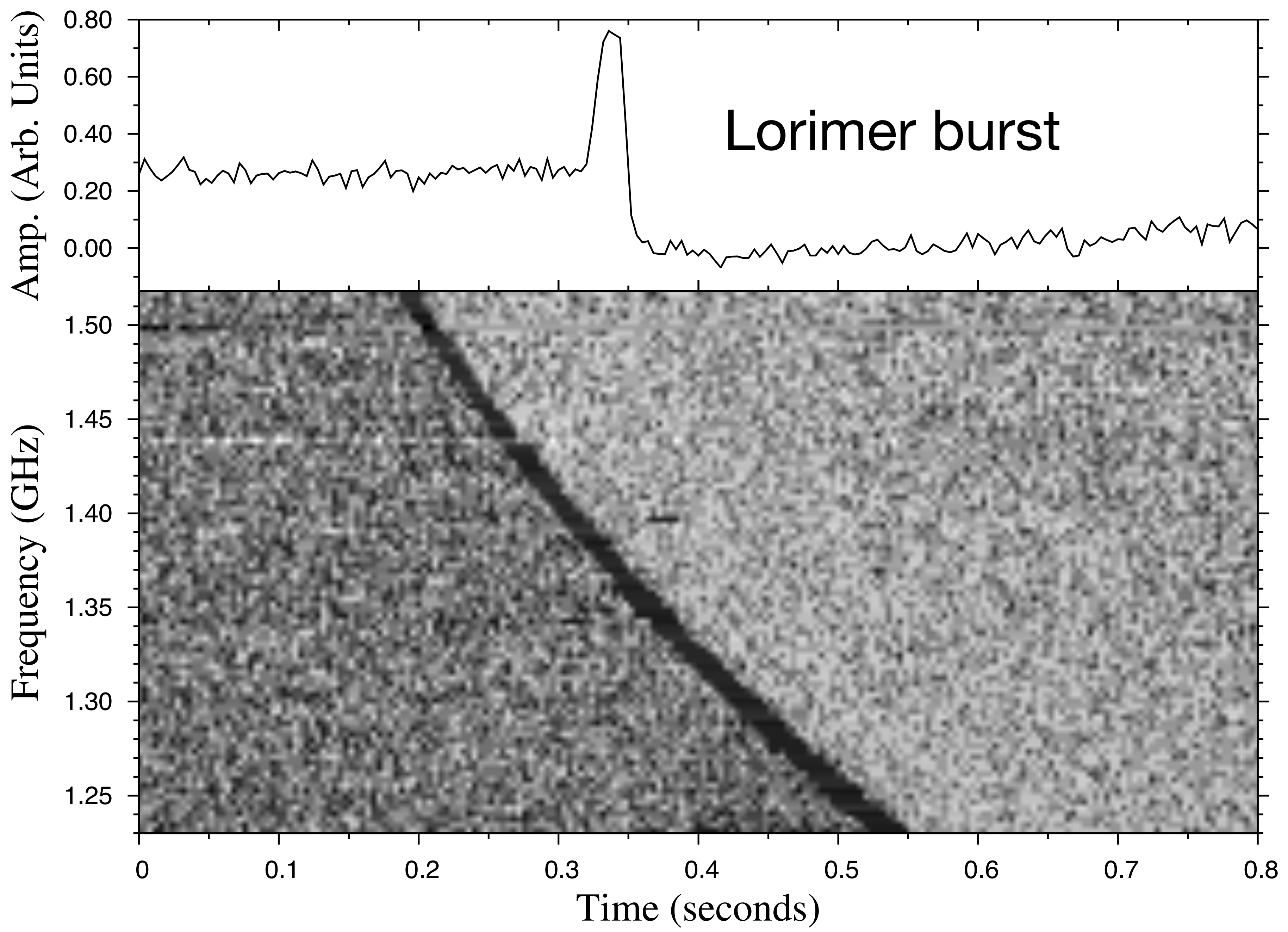
The Fast Radio Burst mystery

a new type of astrophysical radio transient!



FRB010724 - Keane from Lorimer 2018

<u>Observed emission</u>:

- Short radio pulses (≈ms)
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- Broad frequency band emissions
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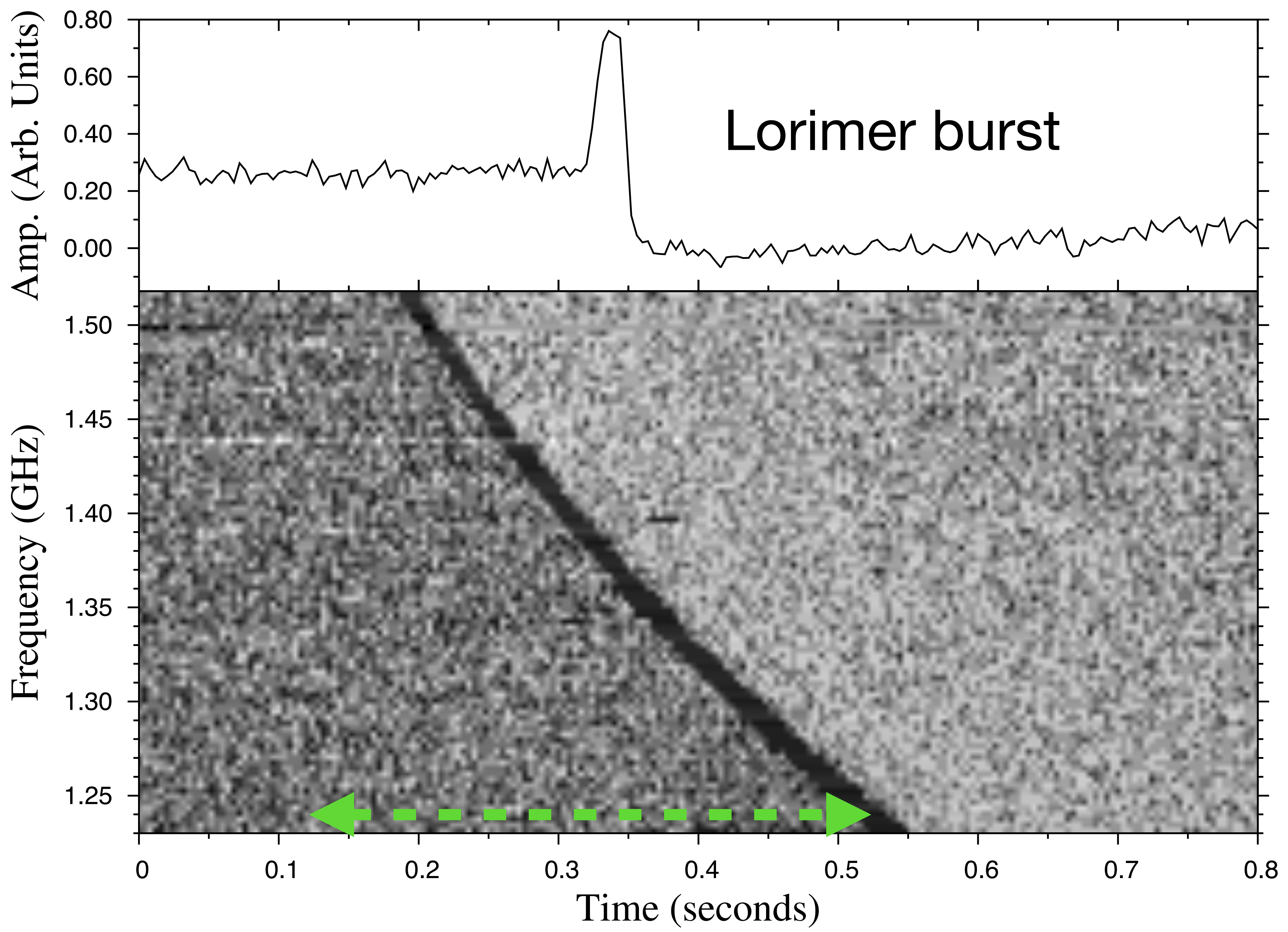

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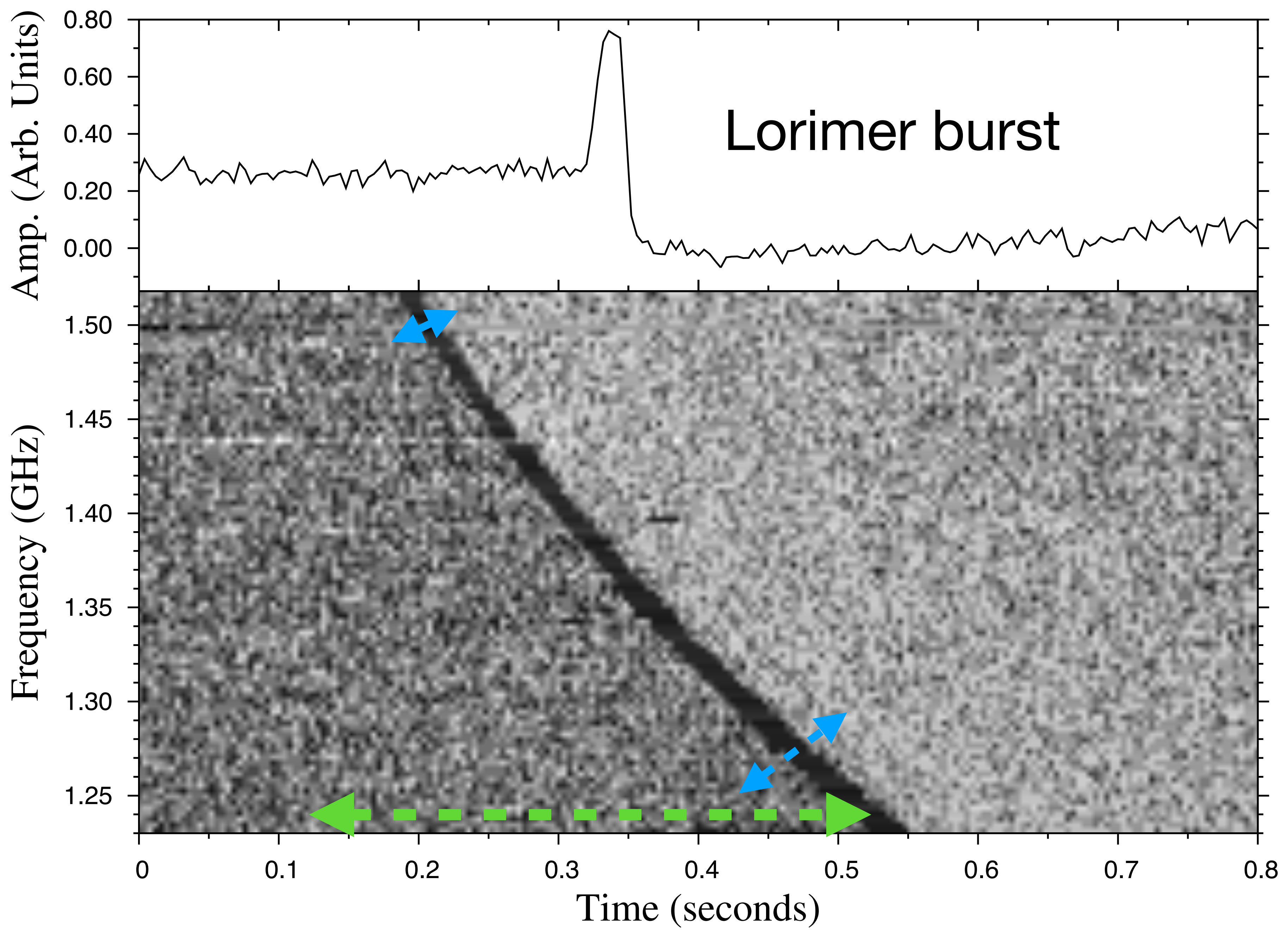

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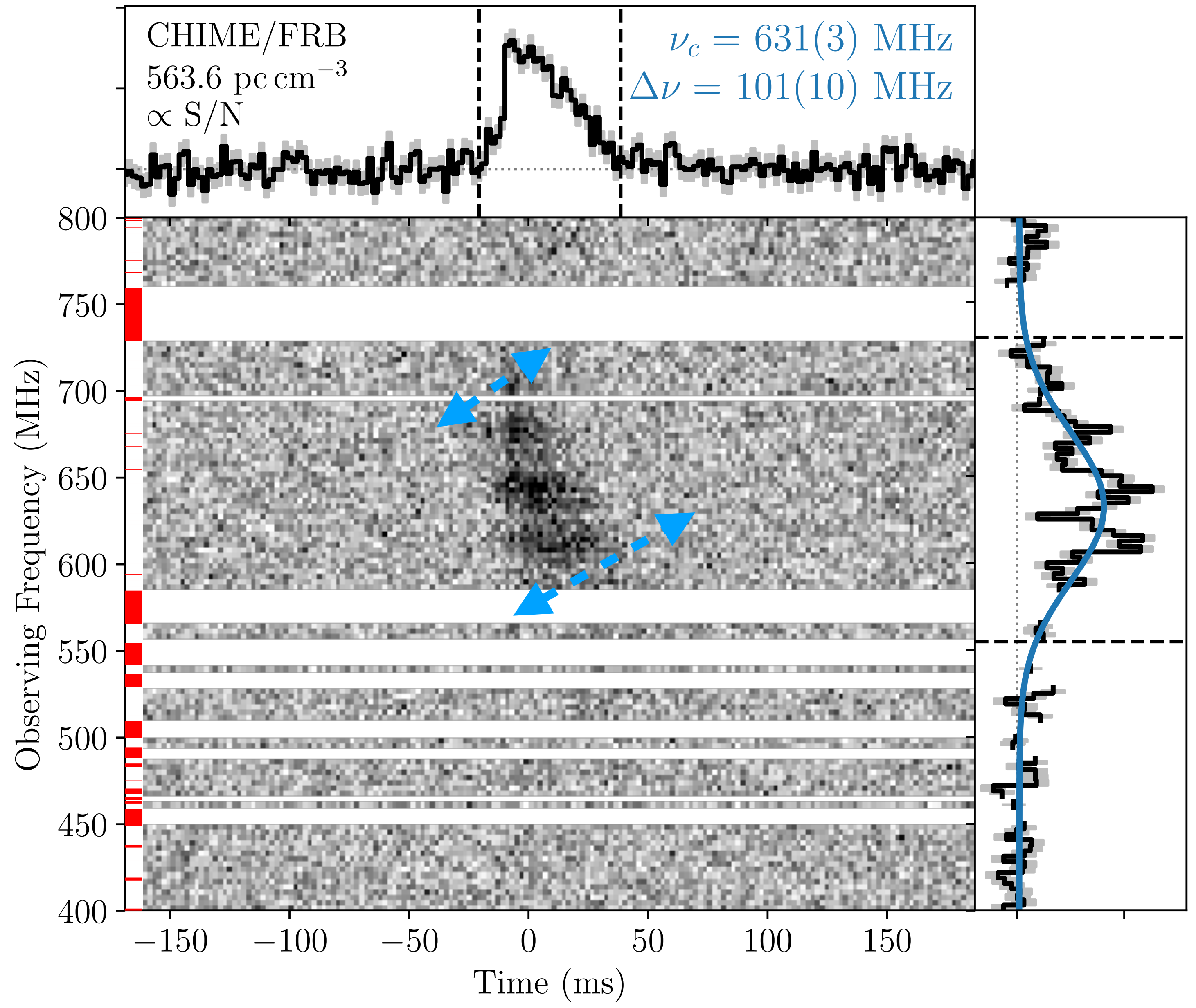

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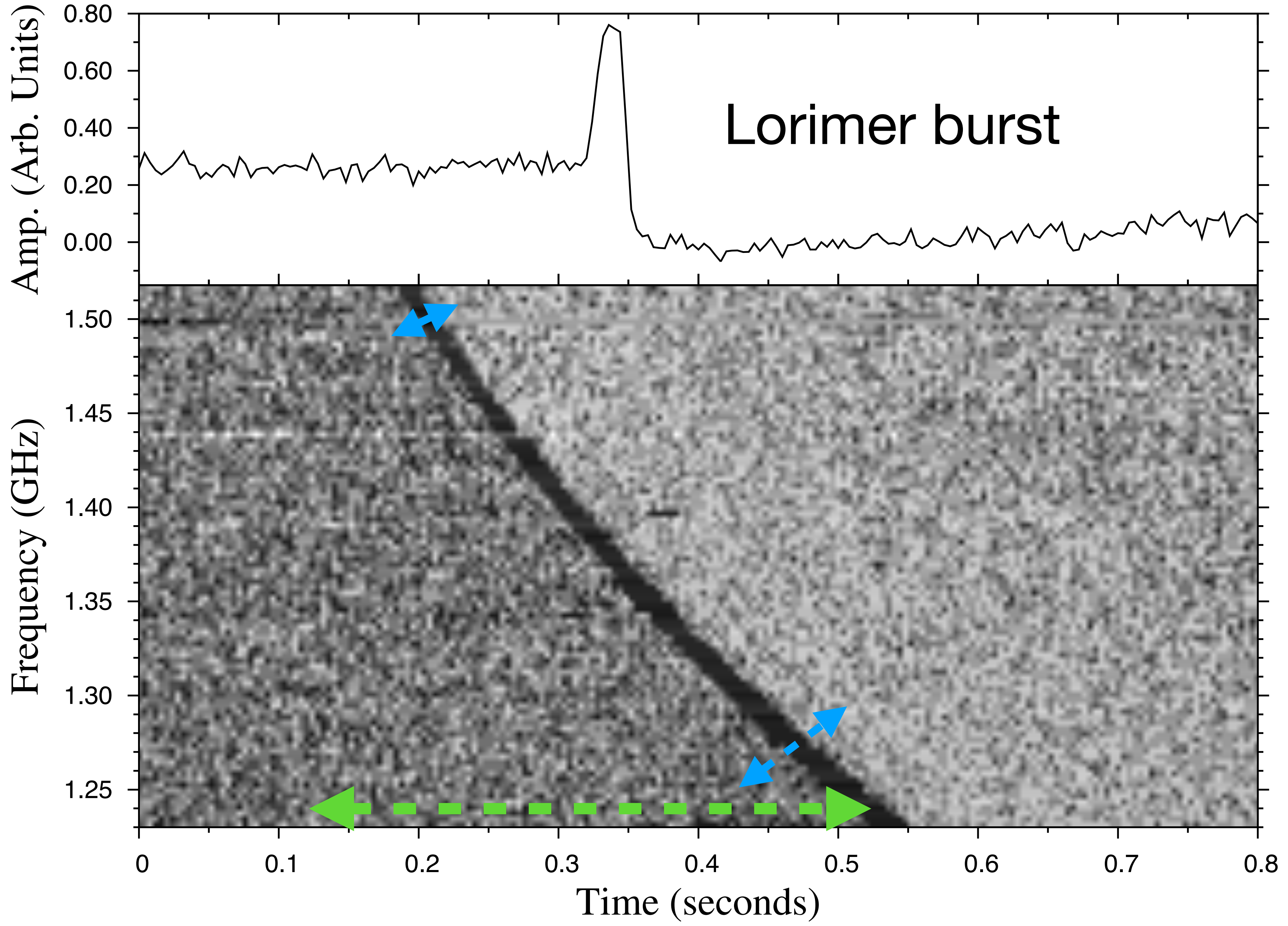

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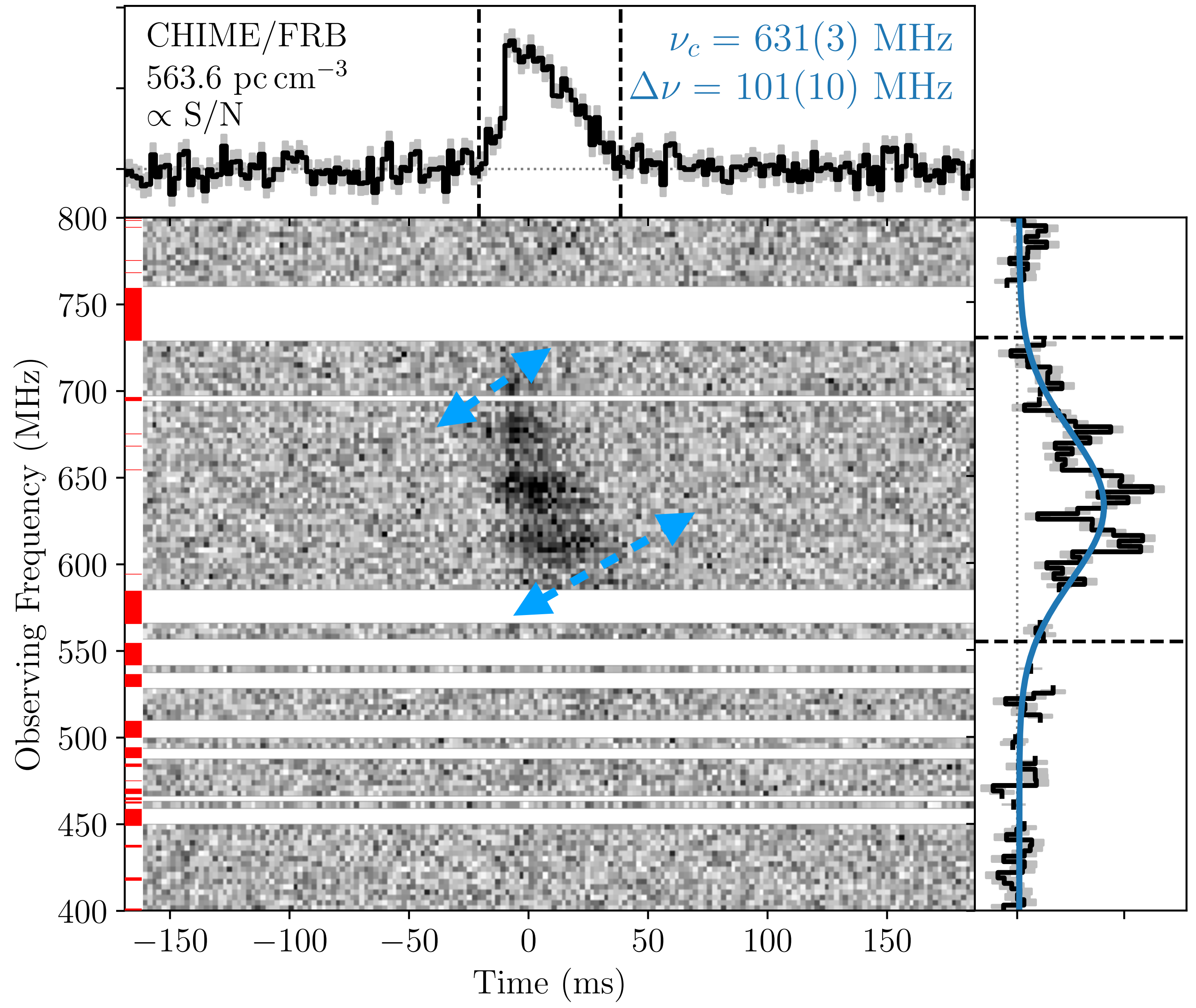

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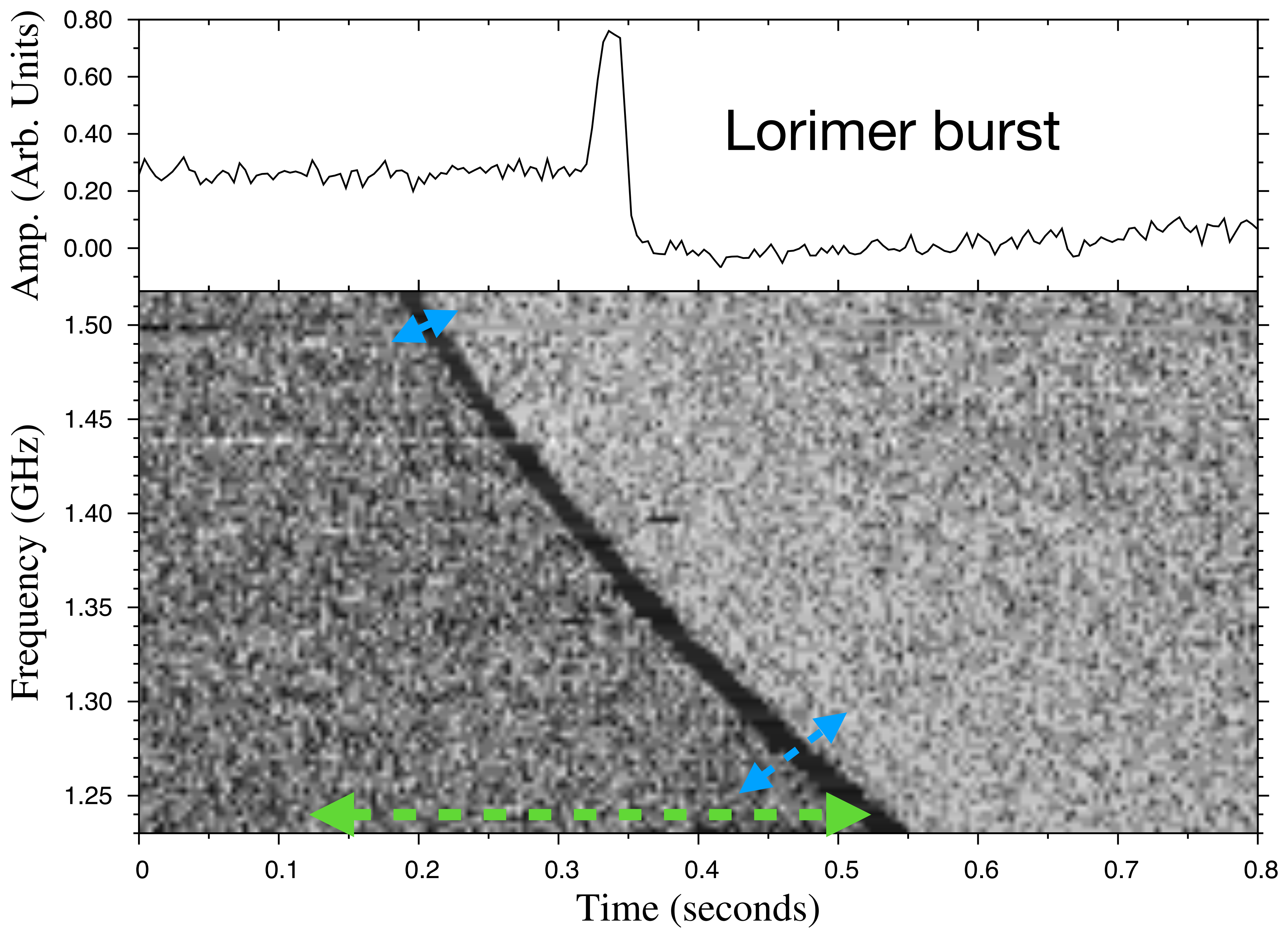

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emission mechanism?

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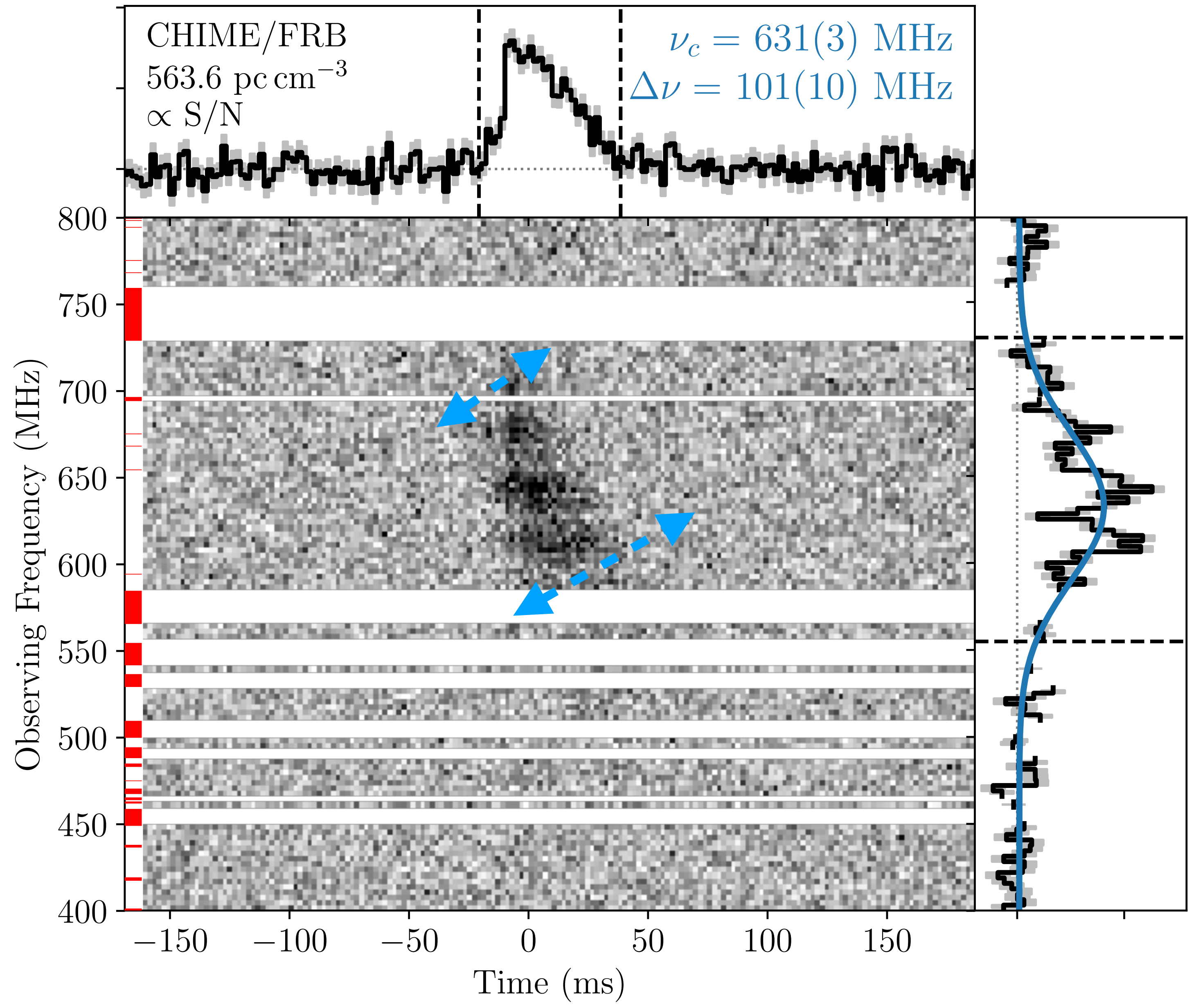
source / population?



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among many other models: https://frbtheorycat.org

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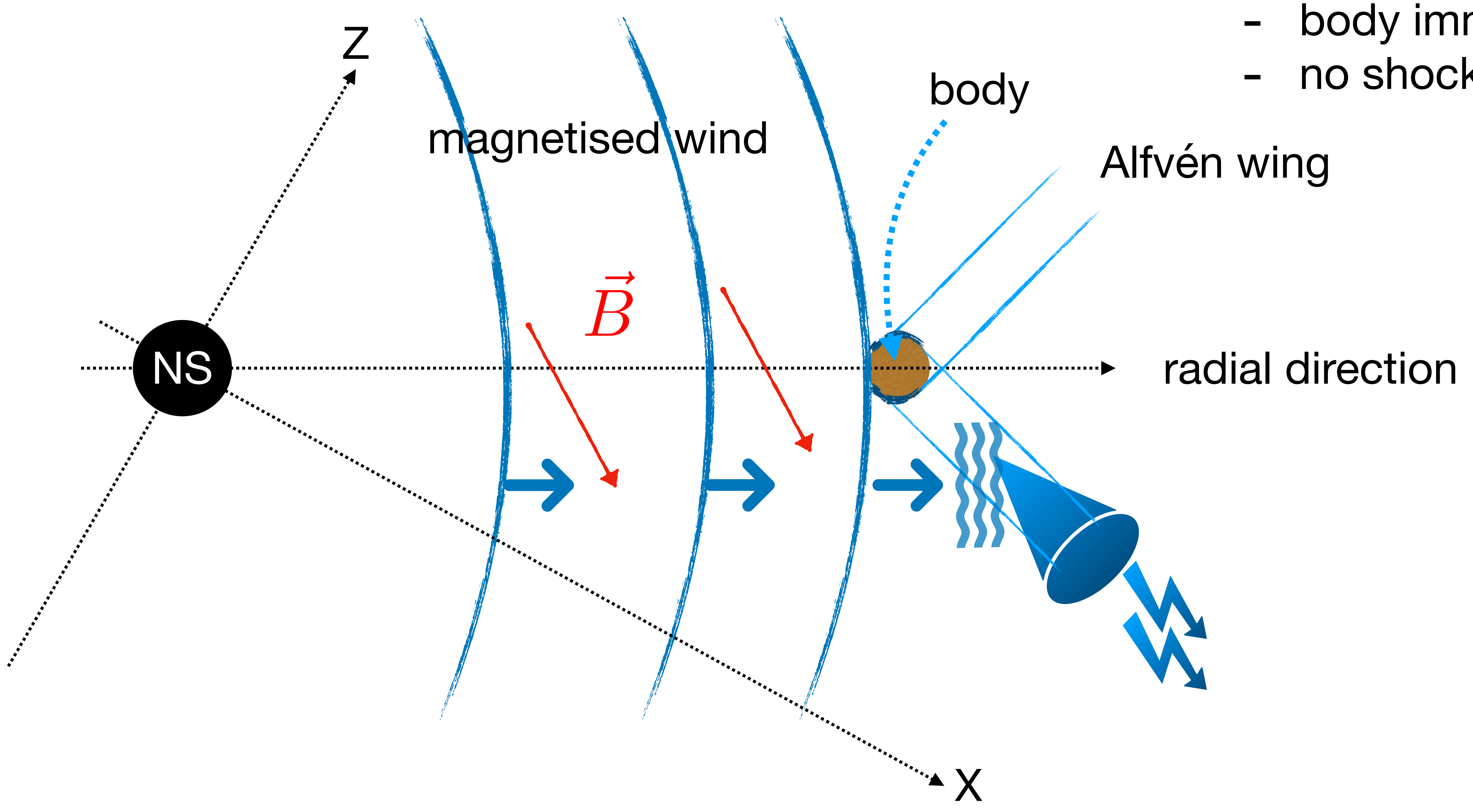

1) Magnetic coupling: Mottez&Heyvaerts 2012
- body immersed in magnetised plasma
- no shock required

2) Alfvén wings:
- potential drop induced by the conductive body
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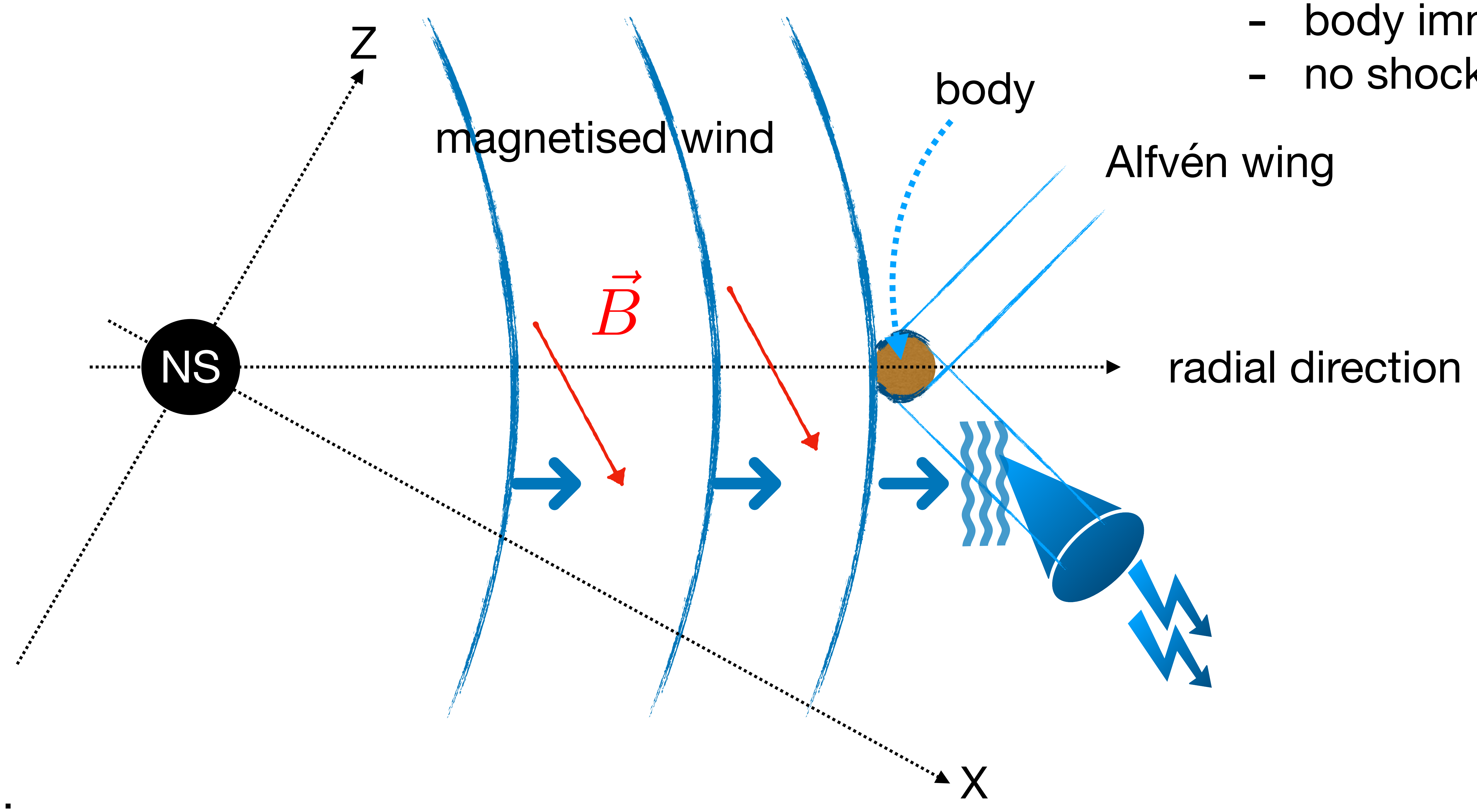

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Pros:
- observed mechanism for non relativistic plasma (Jupiter-Io system for instance)
- reproduce FRB-like emission (lowest amount of energy involved)

Cons:
- how to feed this mechanism with orbiting body immersed in the plasma with (observed) **non-periodical bursts**?
- how to observe such strongly beamed emissions?

A plausible source population model: Kozai-Lidov feeding of compact binary systems

V. D. , Kumiko Kotera (IAP), Joseph Silk (IAP, CEA, JHU, Oxford) (A&A 2021)

Goal: explain FRB repeating rates in the context of the Alfvén wing mechanism
- drive orbiting body as close as possible to the pulsar
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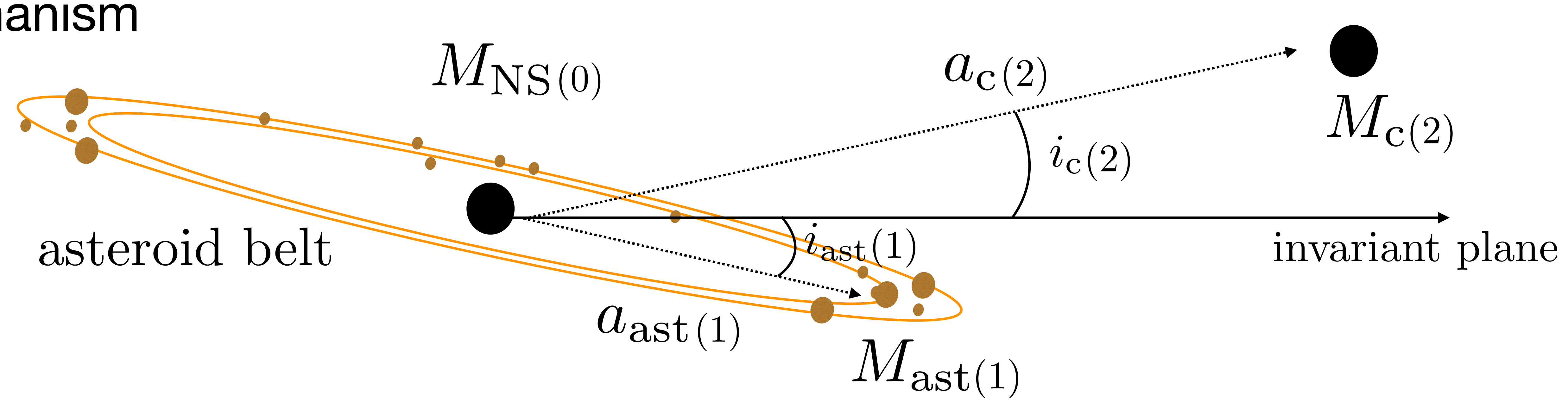
Method: study the dynamical evolutions of asteroids in a 3 body system via Kozai-Lidov perturbations



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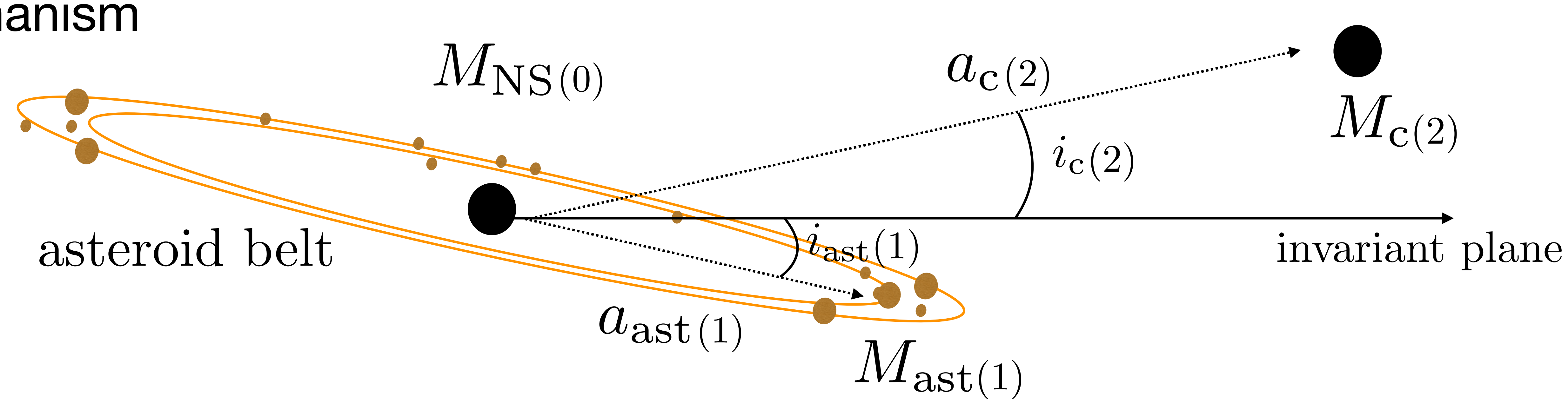
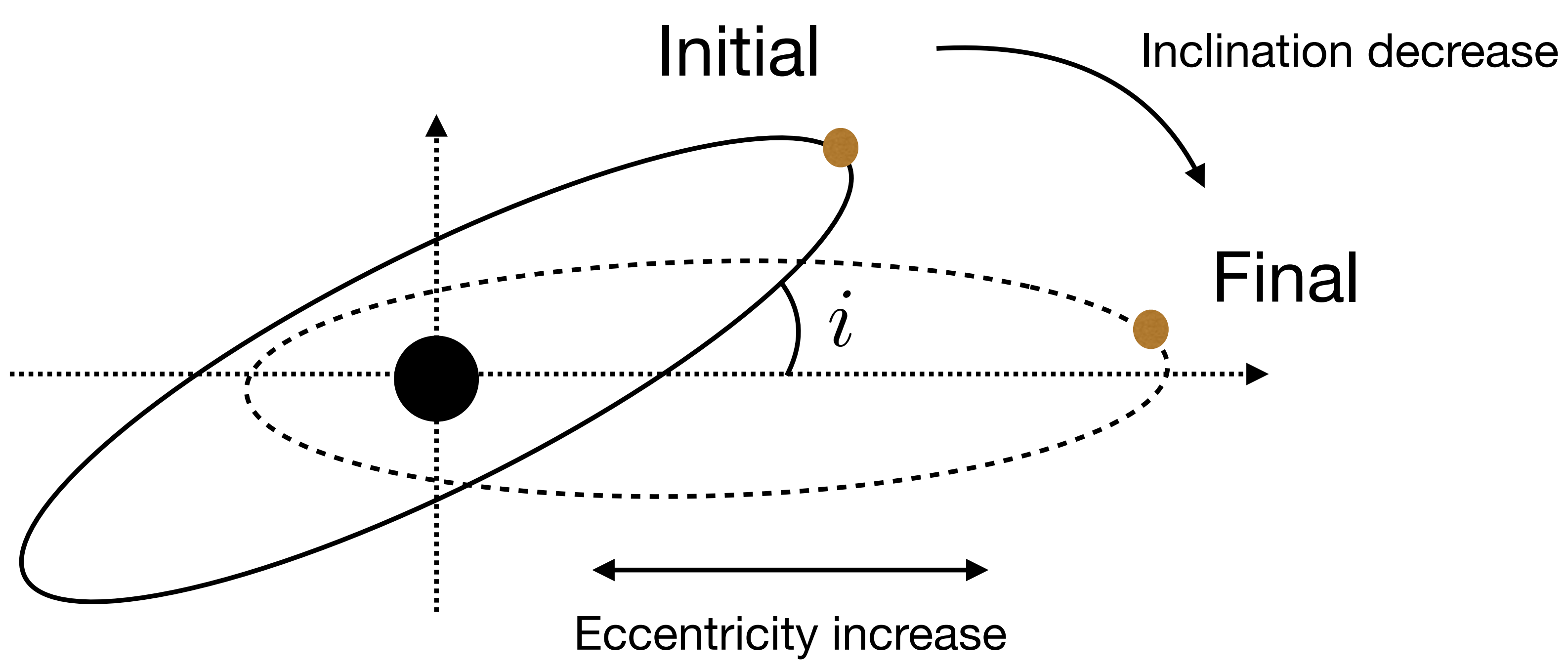
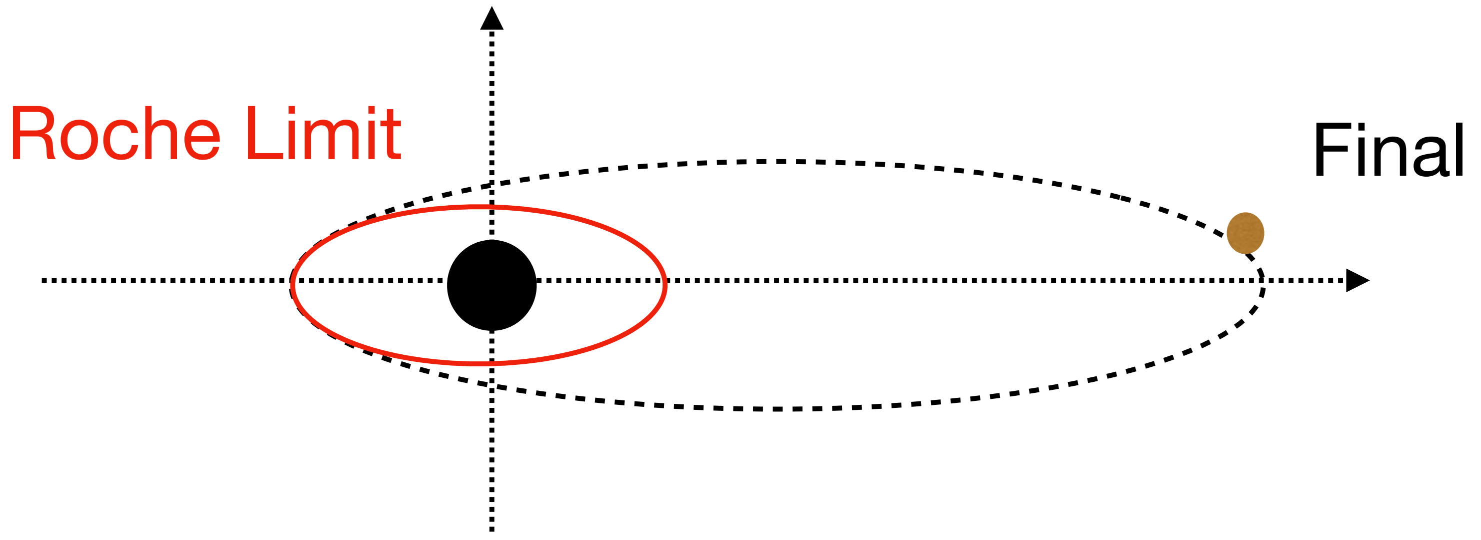


Kozai-Lidov effect: exchanges of orbital momentum → transfer of inclination to the eccentricity



the Roche limit is the closest position beyond which tidal effects disrupt the asteroid



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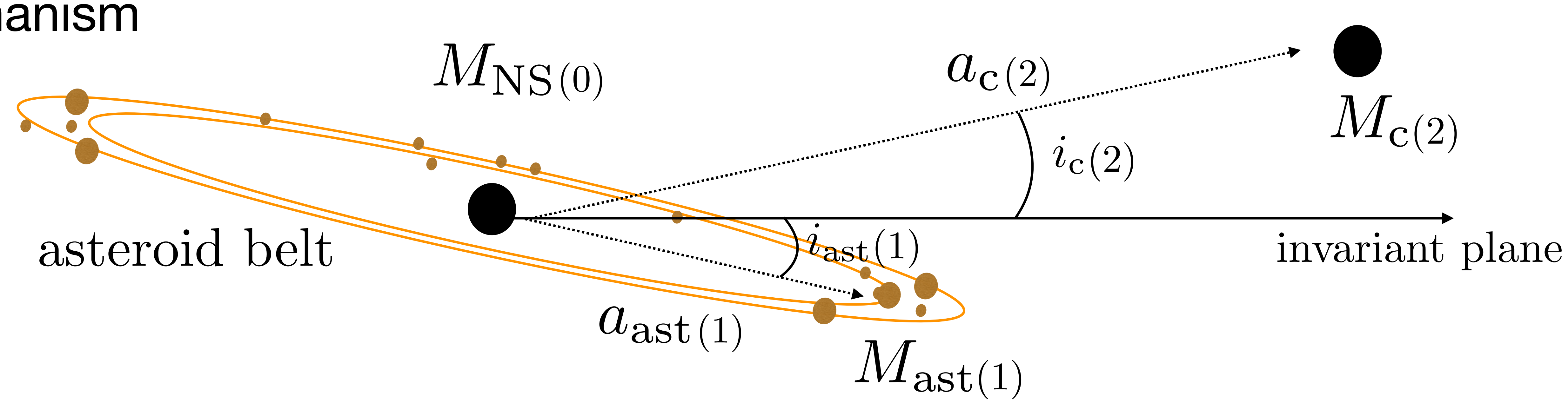

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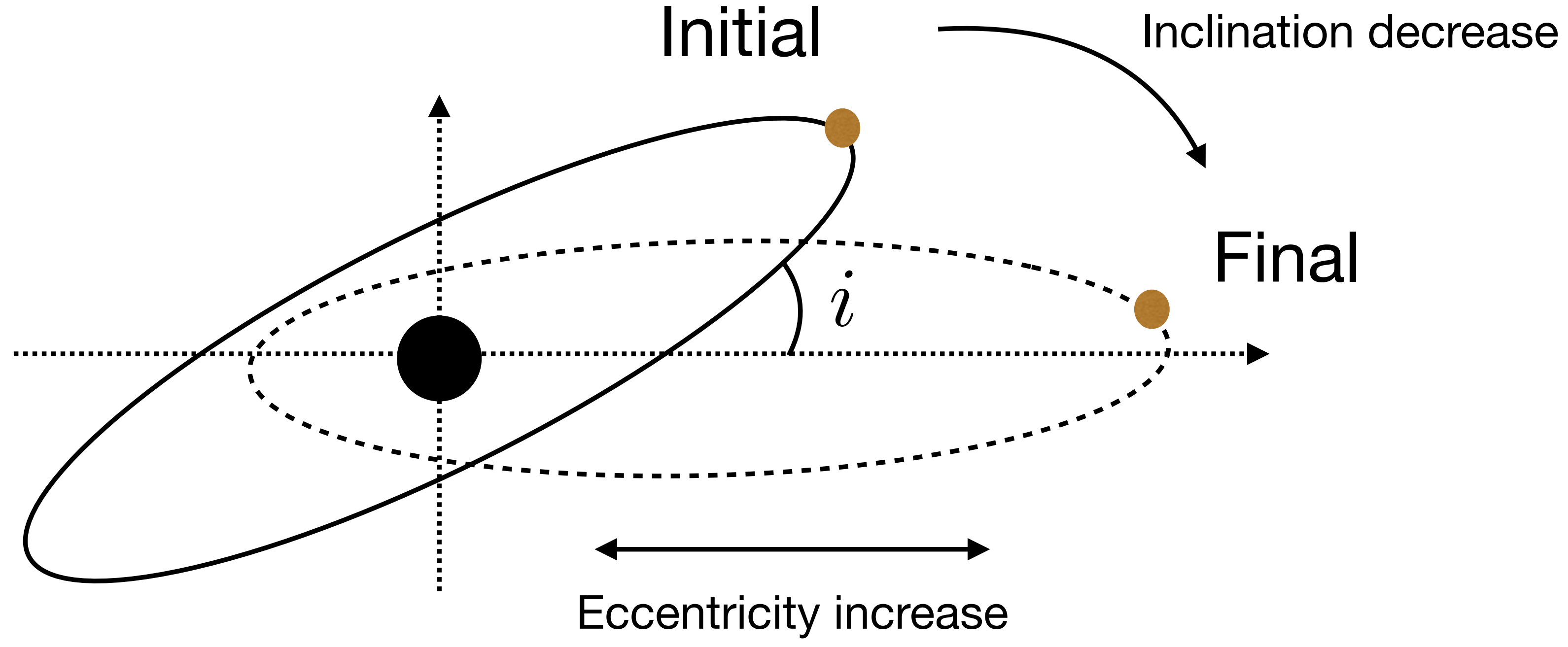

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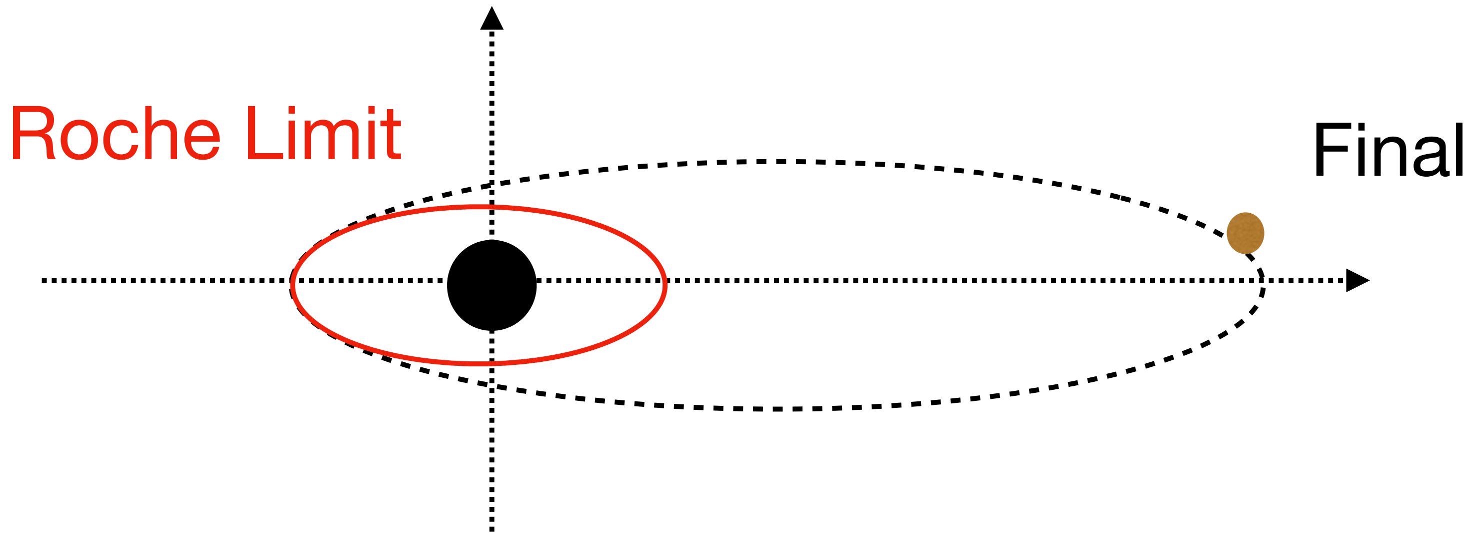

Kozai-Lidov effects can drive the asteroids down to the Roche limit

A shot of Three-Body dynamics

General Three-Body dynamics is complex with no general solution

However some effects such as Kozai-Lidov perturbations can be analytically derived

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Three-body Hamiltonian

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2 two-body system + interaction term

$$\rightarrow \mathcal{H}_{\rm pert} \approx \mathcal{H}_{\rm quad} + \epsilon \mathcal{H}_{\rm oct} \quad \text{with} \quad \epsilon = \frac{a_1}{a_2}\frac{e_2}{1-e_2^2}$$

$\boldsymbol{\epsilon}$ drives the dynamics between quadrupole effects and octupole effects

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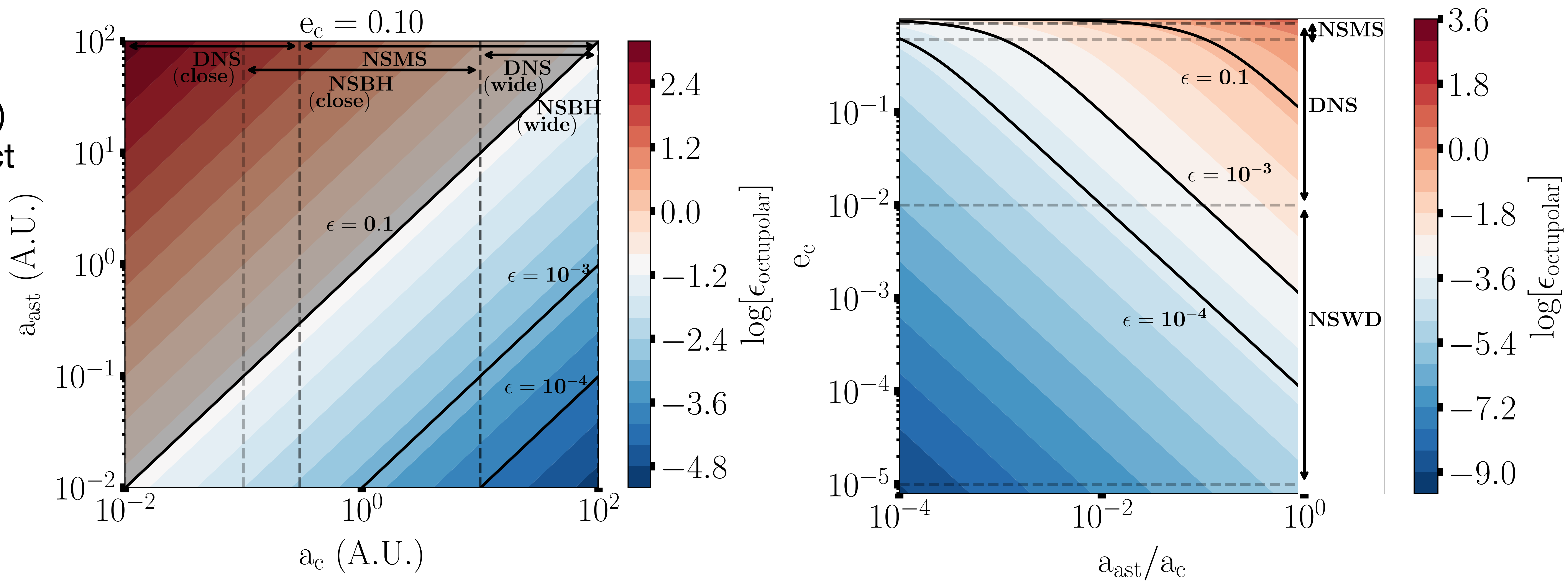
<u>Dynamical regimes</u>:

- quadrupole → Kozai-Lidov effect
  - short timescales (still secular effect!)
- octupole → Excentric Kozai-Lidov effect
  - extreme eccentricity excitations



Parameter space for the different dynamical regimes

Kozai-Lidov times and repeating FRB rates

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Kozai-Lidov effects happen over secular times >> FRB repeaters occurrence times

$$t_{\rm KL} \sim \frac{16}{15}\frac{a_2^3}{a_1^{3/2}}\left(1-e_2^2\right)^{3/2}\frac{1}{\sqrt{G}}\frac{\sqrt{m_0+m_1}}{m_2} \quad \rightarrow \quad t_{\rm EKL} \sim \frac{128\sqrt{10}}{15\pi\sqrt{\epsilon}} t_{\rm KL,i=90^\circ} \sim 4.8\,{\rm yr}\,\epsilon^{-1/2}\left(\frac{a_{\rm ast}}{0.5\,{\rm A.U.}}\right)^{-3/2}\left(\frac{a_c}{\rm A.U.}\right)^{3}\left(\frac{M_{\rm c}}{1\,M_\odot}\right)^{-1}\left(\frac{M_{\rm NS}}{1.4\,M_\odot}\right)^{1/2}$$

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<u>But</u>: relative delays between 2 consecutive asteroid infalls compatible!

$$\Delta t_{\rm KL} = \frac{8}{5}\frac{a_2^3}{a_1^{5/2}}\Delta a_1\left(1-e_2^2\right)^{3/2}\frac{1}{\sqrt{G}}\frac{\sqrt{m_0+m_1}}{m_2} \quad \rightarrow \quad \Delta t_{\rm EKL} = \frac{256\sqrt{10}}{15\pi}\frac{t_{\rm KL,i=90^\circ}}{\sqrt{\epsilon}}\frac{\Delta a_1}{a_1}$$

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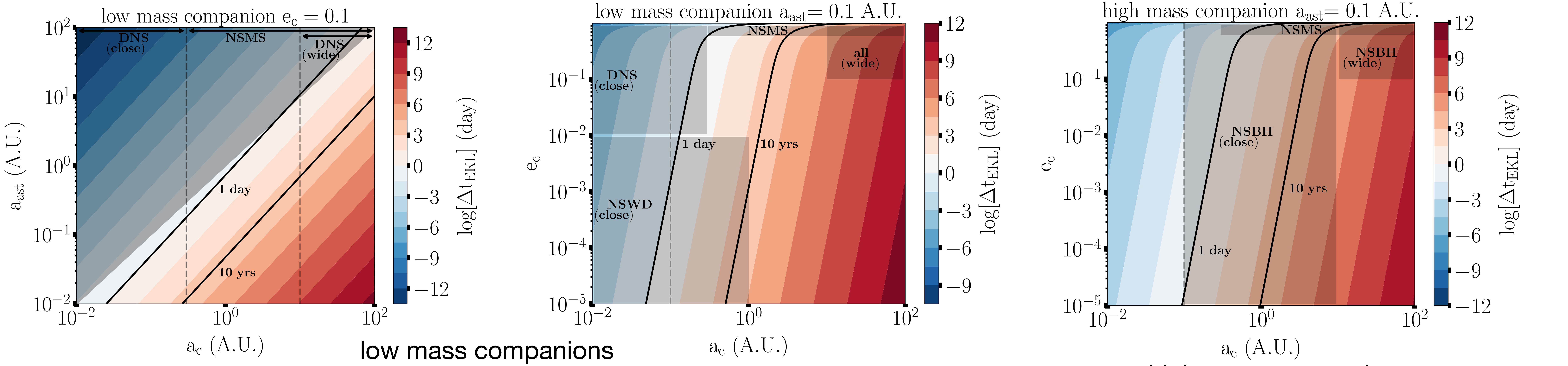

low mass companions

high mass companions

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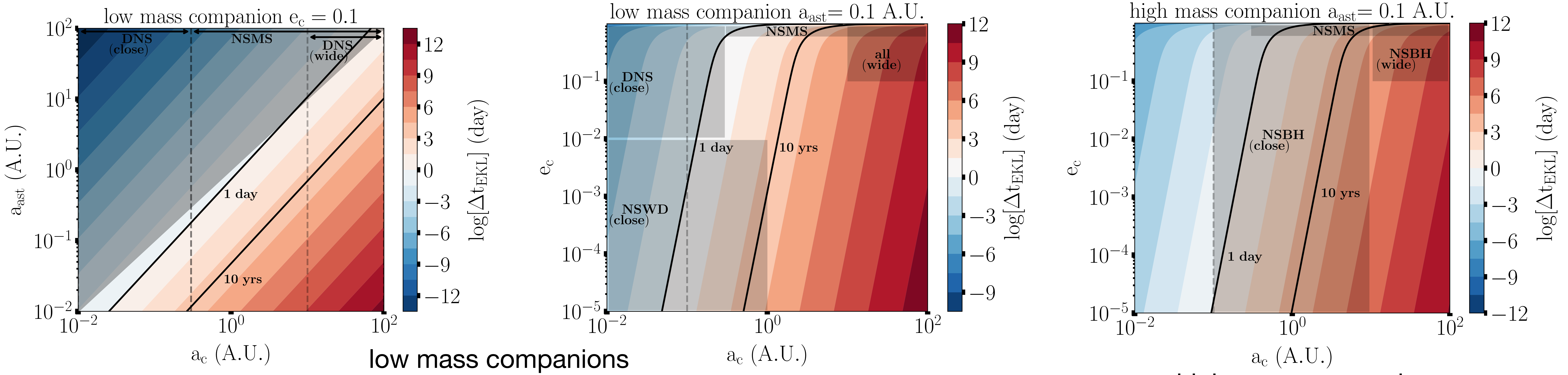

low mass companions

high mass companions

both very short and long timescales can be reached depending on the system parameters

Numerical results

Monte-Carlo simulations of asteroid infall relative time delays (with GR corrections):

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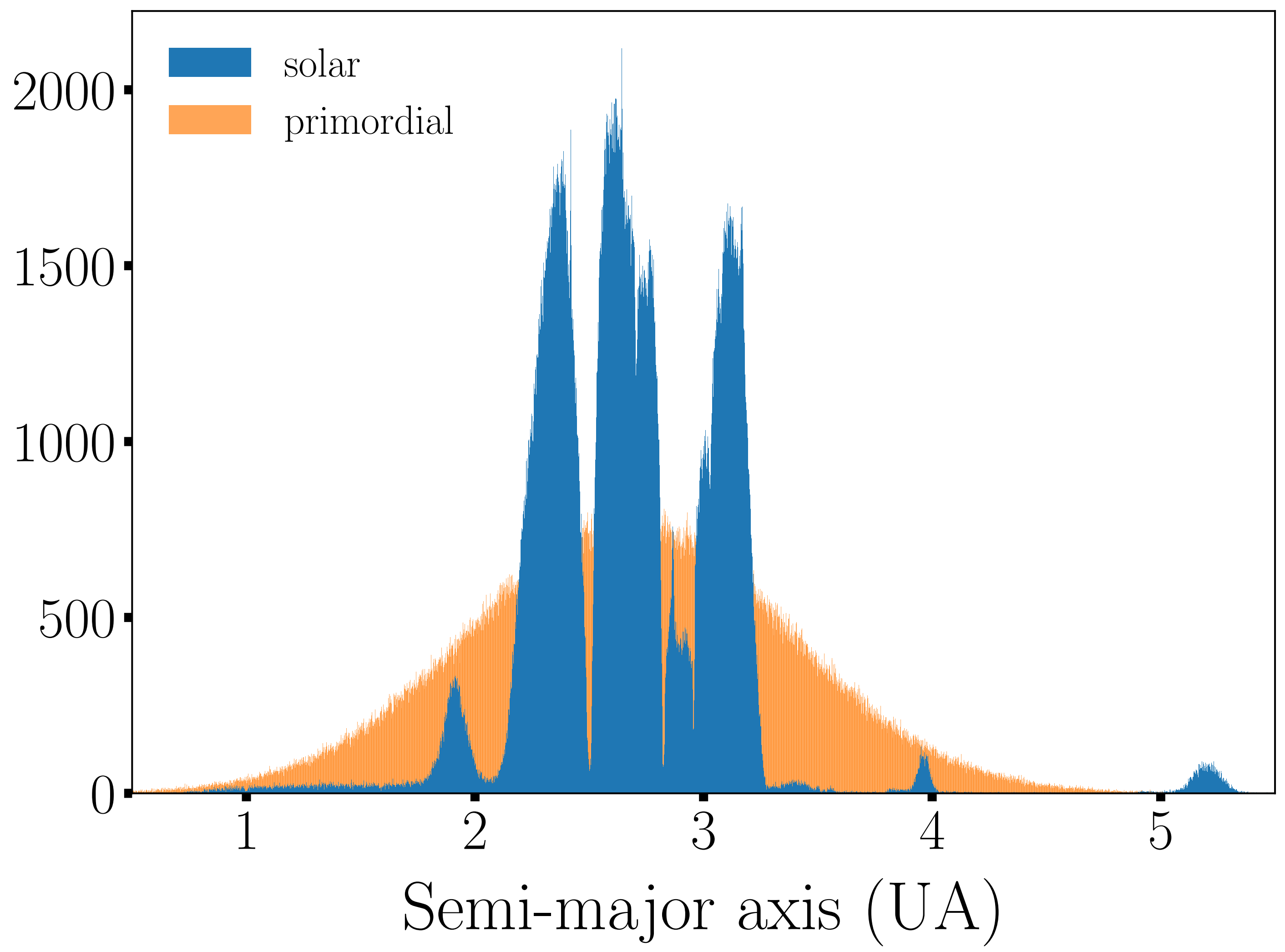
Primordial asteroid belt simulation based on the Solar asteroid belt:
- size / extension
- asteroid masses

Method:
- asteroids randomly draw from the primordial belt
- selection on initial conditions that can trigger Kozai-Lidov effects
- selection on asteroids that reaches the Roche limit
- Kozai-Lidov times are computed
- relative times are extracted from the infall timelines



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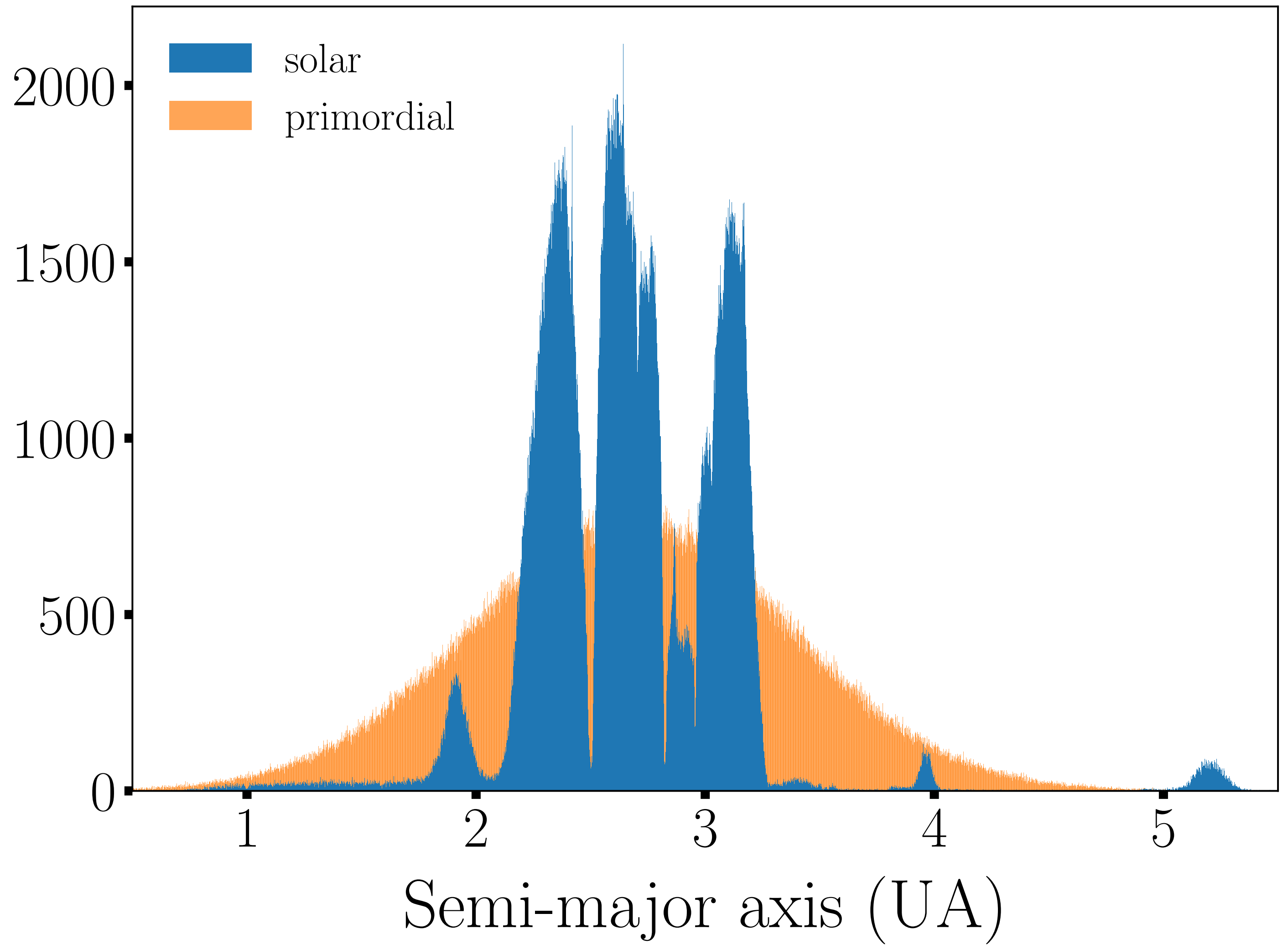

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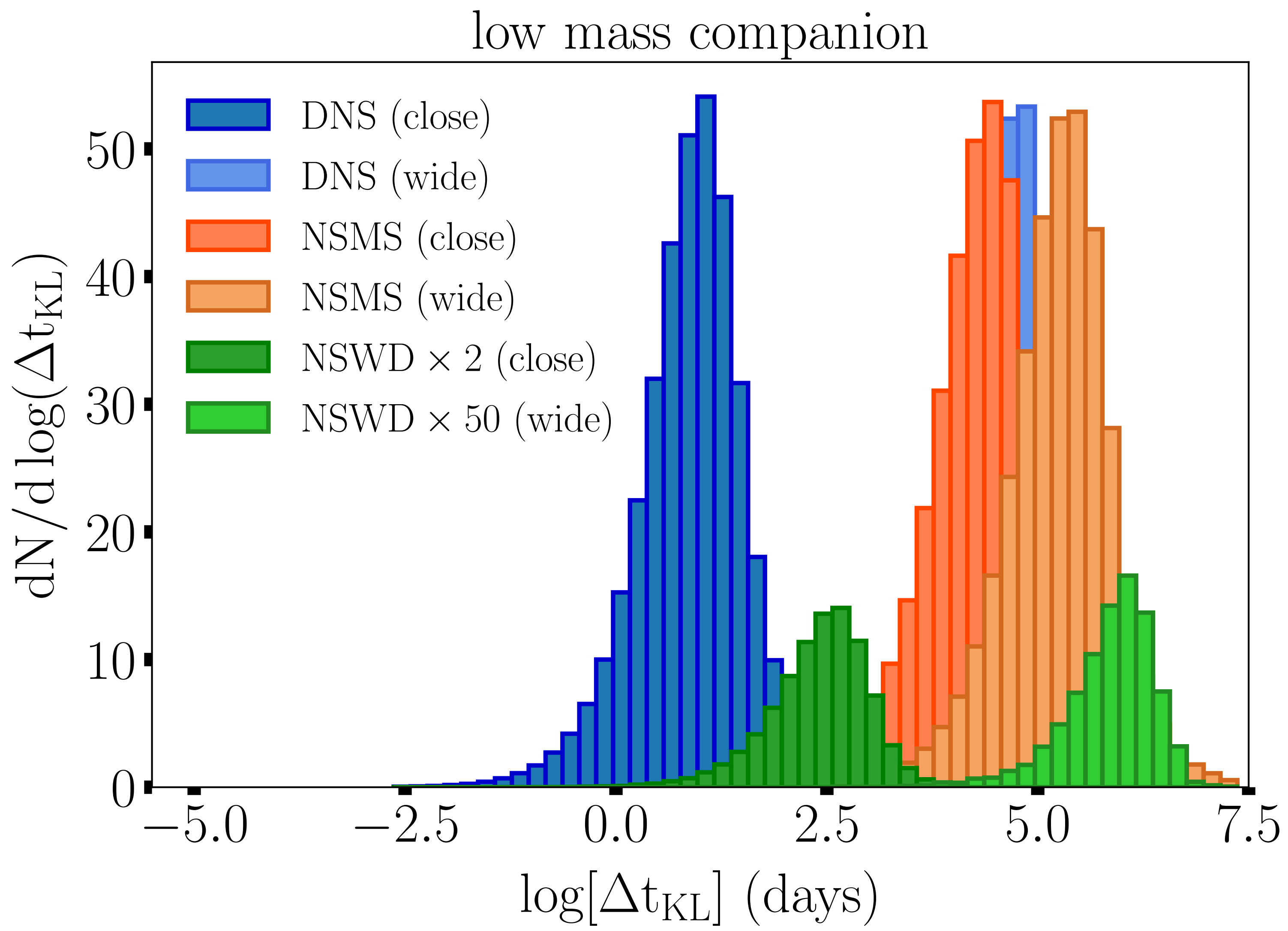

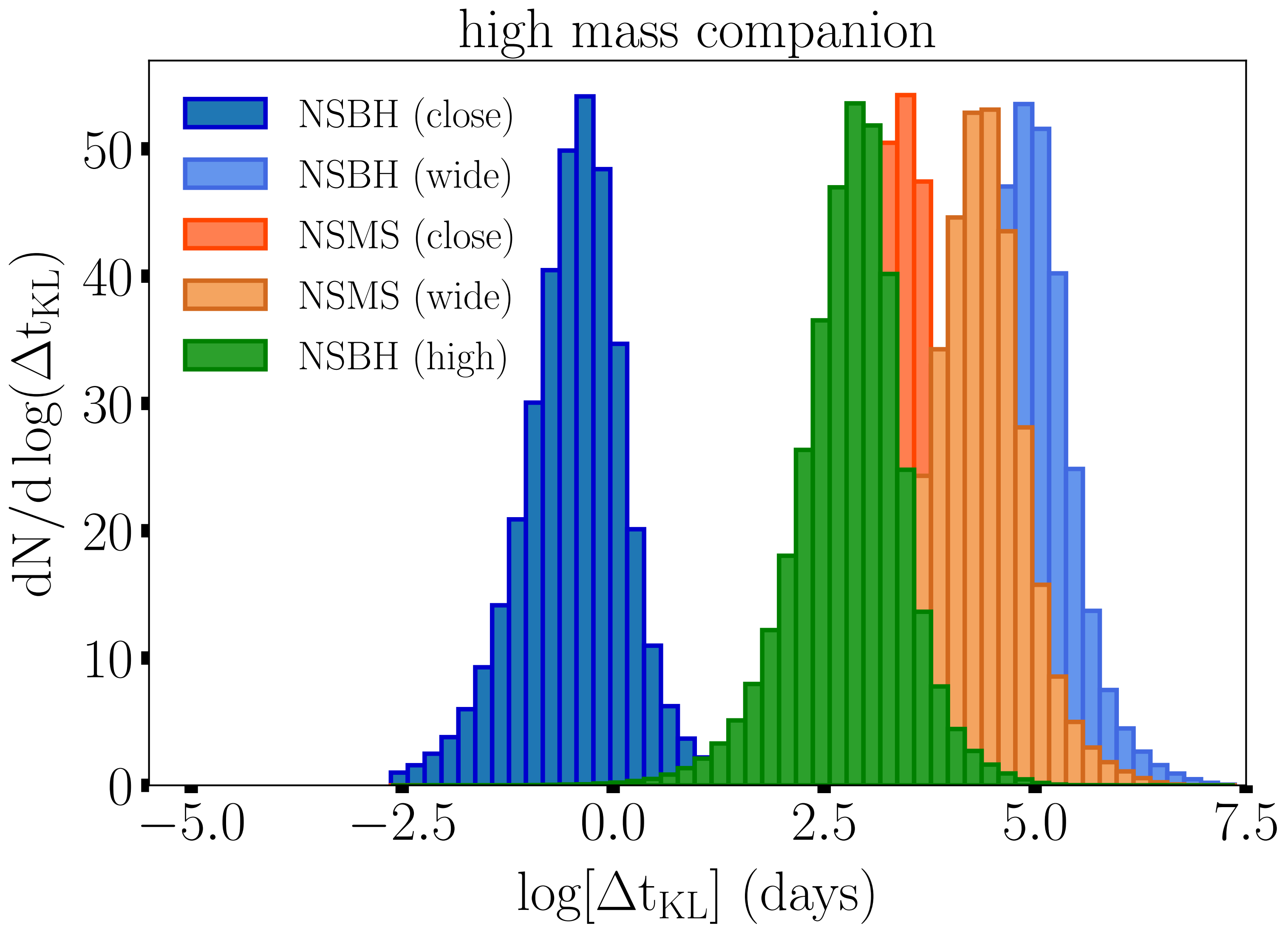

Results: The dichotomy between the two populations is solved via the companion parameters of the systems:
- all FRB are repeaters
- mildly close system -> day/month repeaters with lifetime ~ 10s of years
- wide system are steady sources that will be observed as non repeaters

Dichotomy of repeating and non-repeating FRB

FRB rates from the model (accounting for populations):

non repeaters: $\dot{n}_{\rm FRB,nrep} \sim \frac{t_{\rm EKL}}{\langle \Delta t_{\rm EKL} \rangle} \epsilon_{\rm nrep}\, \epsilon_{\rm wide}\, \dot{n}_{\rm c} = \frac{1}{2} N_{\rm ast}\, \varepsilon_{\rm ast}^{-1} \epsilon_{\rm eff}\, \epsilon_{\rm nrep}\, \epsilon_{\rm wide}\, \dot{n}_{\rm c} \sim 4 \times 10^3\, {\rm Gpc}^{-3}\, {\rm yr}^{-1} \frac{N_{\rm ast}}{100} \frac{\epsilon_{\rm eff}}{0.2} \left(\frac{\varepsilon_{\rm ast}}{0.15}\right)^{-1} \frac{\epsilon_{\rm wide}}{0.3} \frac{\epsilon_{\rm nrep}\, \dot{n}_{\rm c}}{0.2\, {\rm Mpc}^{-3}\, {\rm Myr}^{-1}}$

repeaters: $\dot{n}_{\rm FRB,rep} \sim 200\, {\rm Gpc}^{-3}\, {\rm yr}^{-1} \frac{\epsilon_{\rm rep} \epsilon_{\rm mild-close}\, \dot{n}_{\rm c}}{0.2\, {\rm Mpc}^{-3}\, {\rm Myr}^{-1}}$

FRB rates inferred from observations:

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Consequences: this model can be discriminated against others through:

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  - most repeaters should stop after 10s of years as their asteroid belt becomes depleted
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Situation similar to GRB community 50 yrs ago:
the lack of observational constraints does not allow to discriminate between the great number of models

The low frequency quest:
do FRBs exist at low frequencies (below 111MHz) ?

At low frequencies → signal intensity is reduced (scattering effects) → low frequency hunter needed

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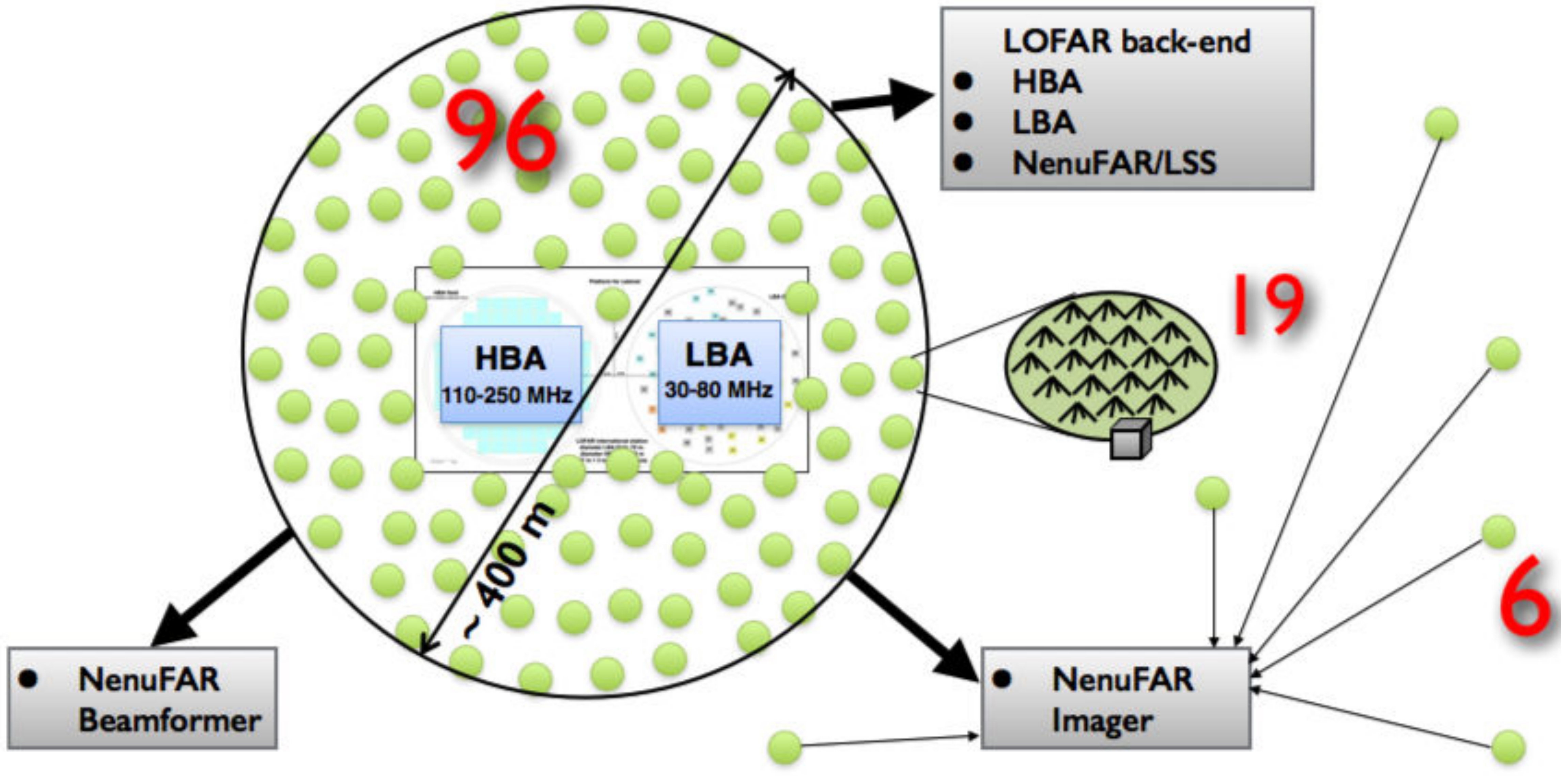


- Core of ≈ 400 m diameter
- + 6 MA at distances up to 3km

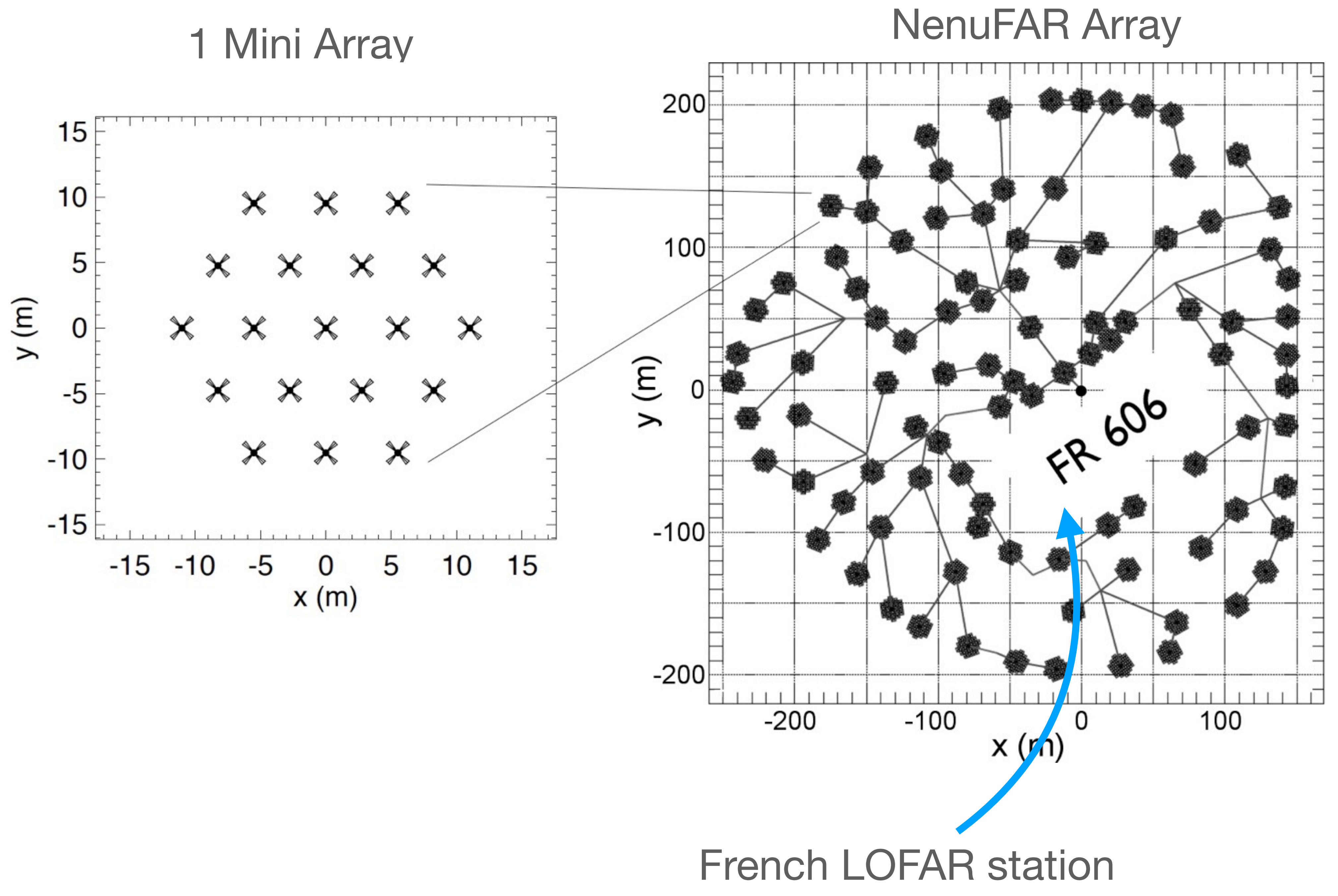
- SKA pathfinder partly constructed and in commissioning in the Nançay Radioastronomy Station
- 1938 dual polarisation antennas, hierarchically distributed in Mini-Arrays (MA)
- 10-85 MHz (from Earth's ionospheric cut-off to radio broadcast FM band)

NenuFAR configuration

NenuFAR configuration

Array:

- Antennas grouped in **mini-arrays of 19** crossed-dipoles → SNR
- **Baselines from 400m to 3km** → angular resolution
- Up to **88000m²** of collecting area



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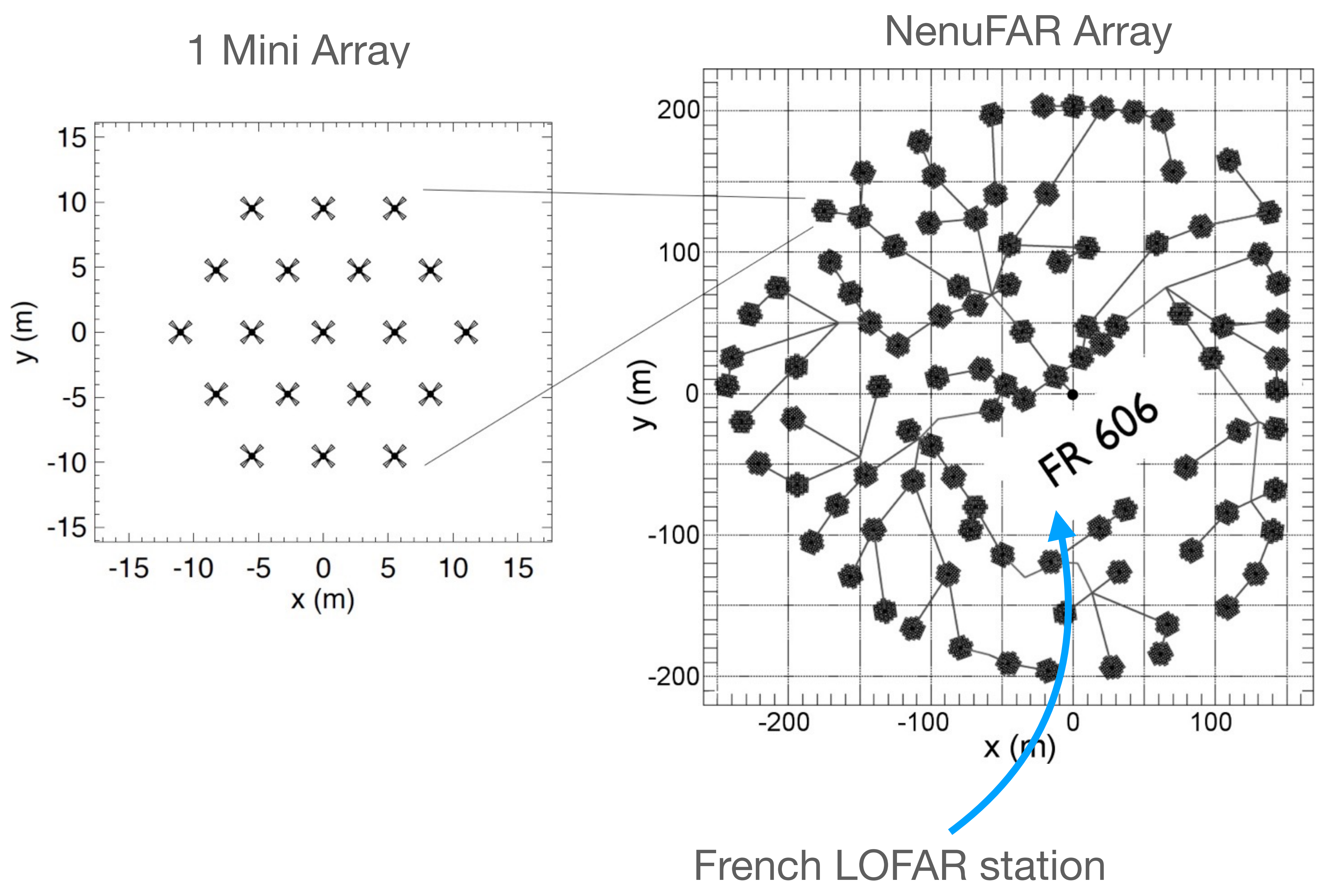

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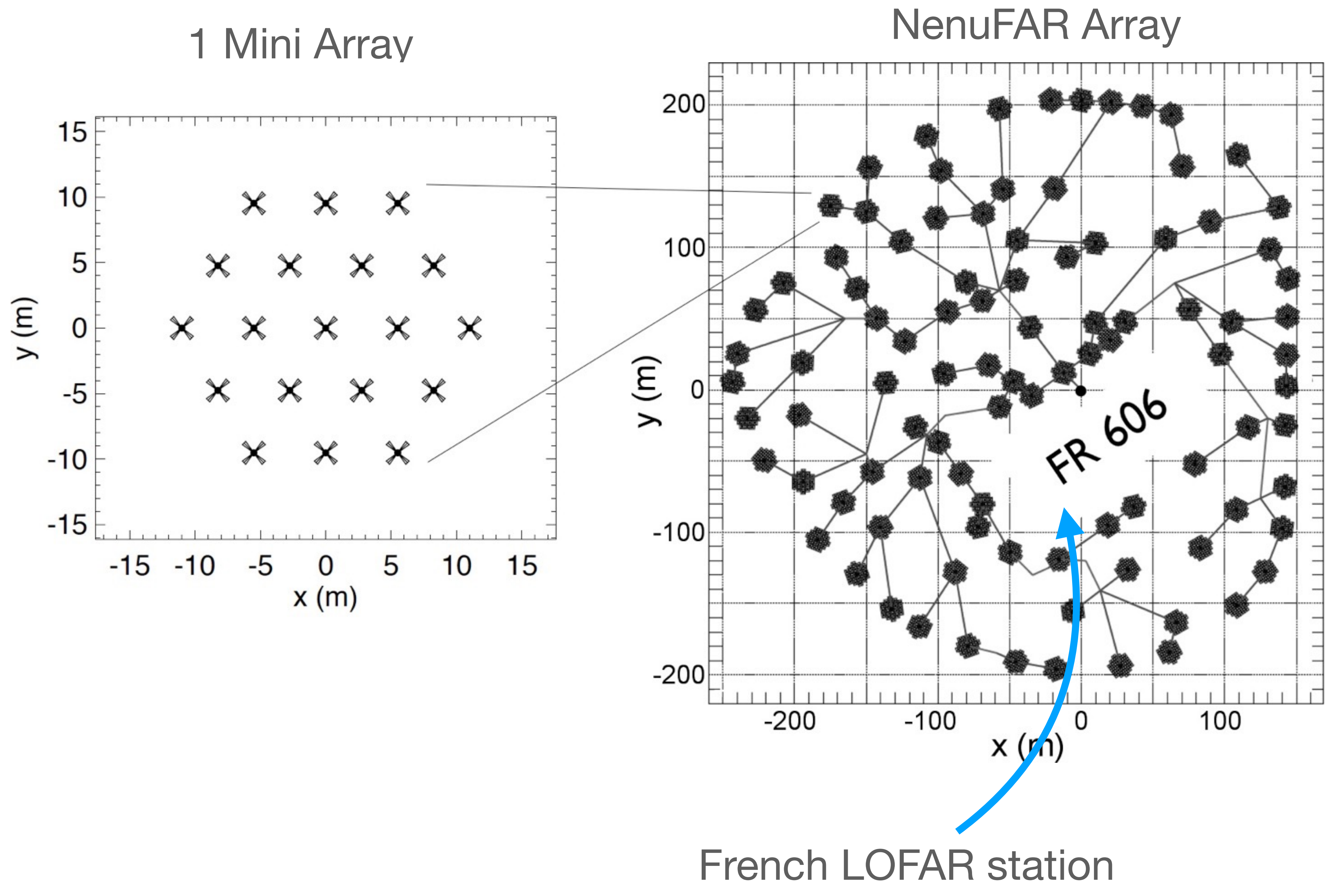

Can operates in 4 distinct modes:

- **standalone beam former** → FRB observation
- capturing waveform → transient buffer
- standalone imager
- Upgraded LOFAR station (low frequency)

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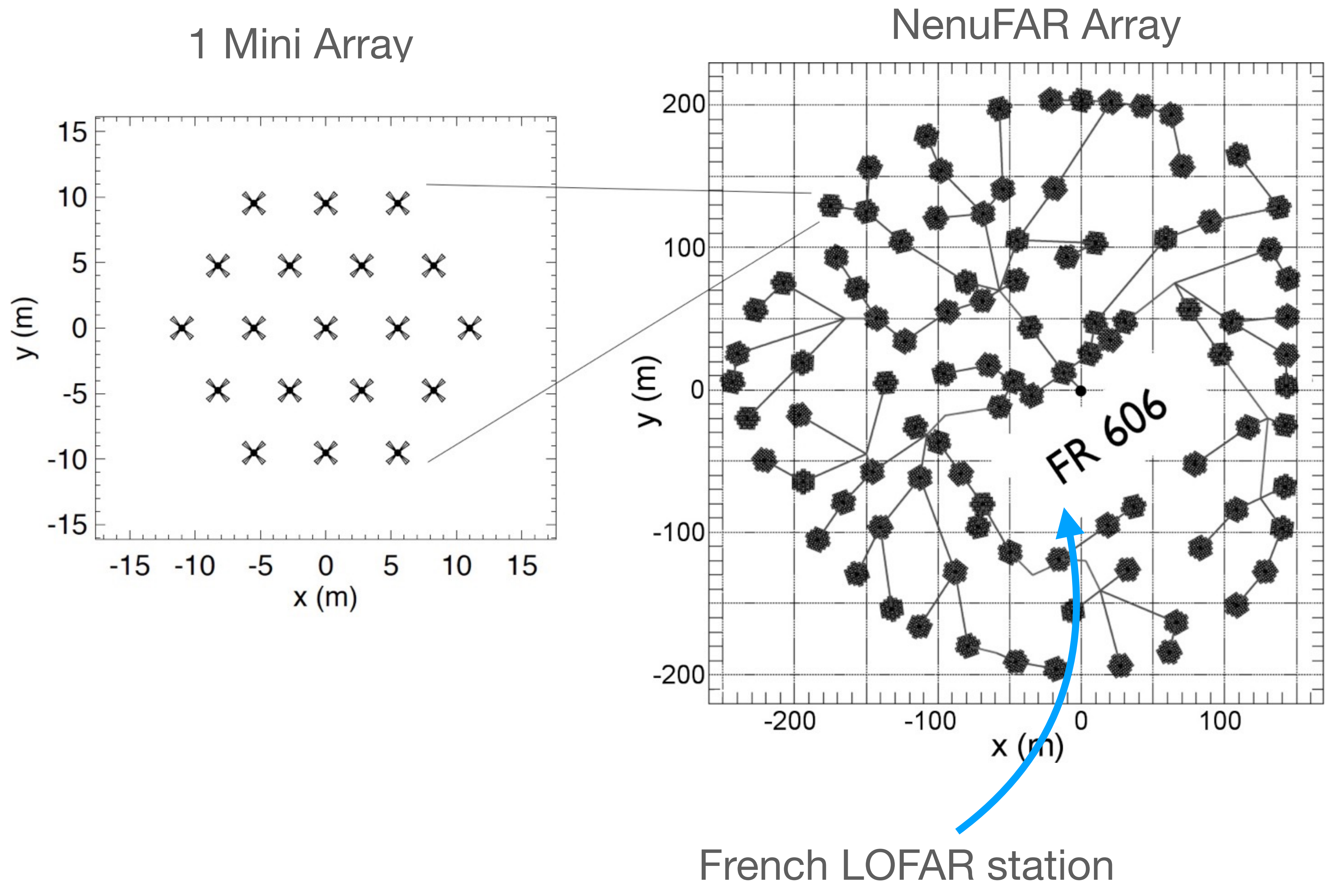

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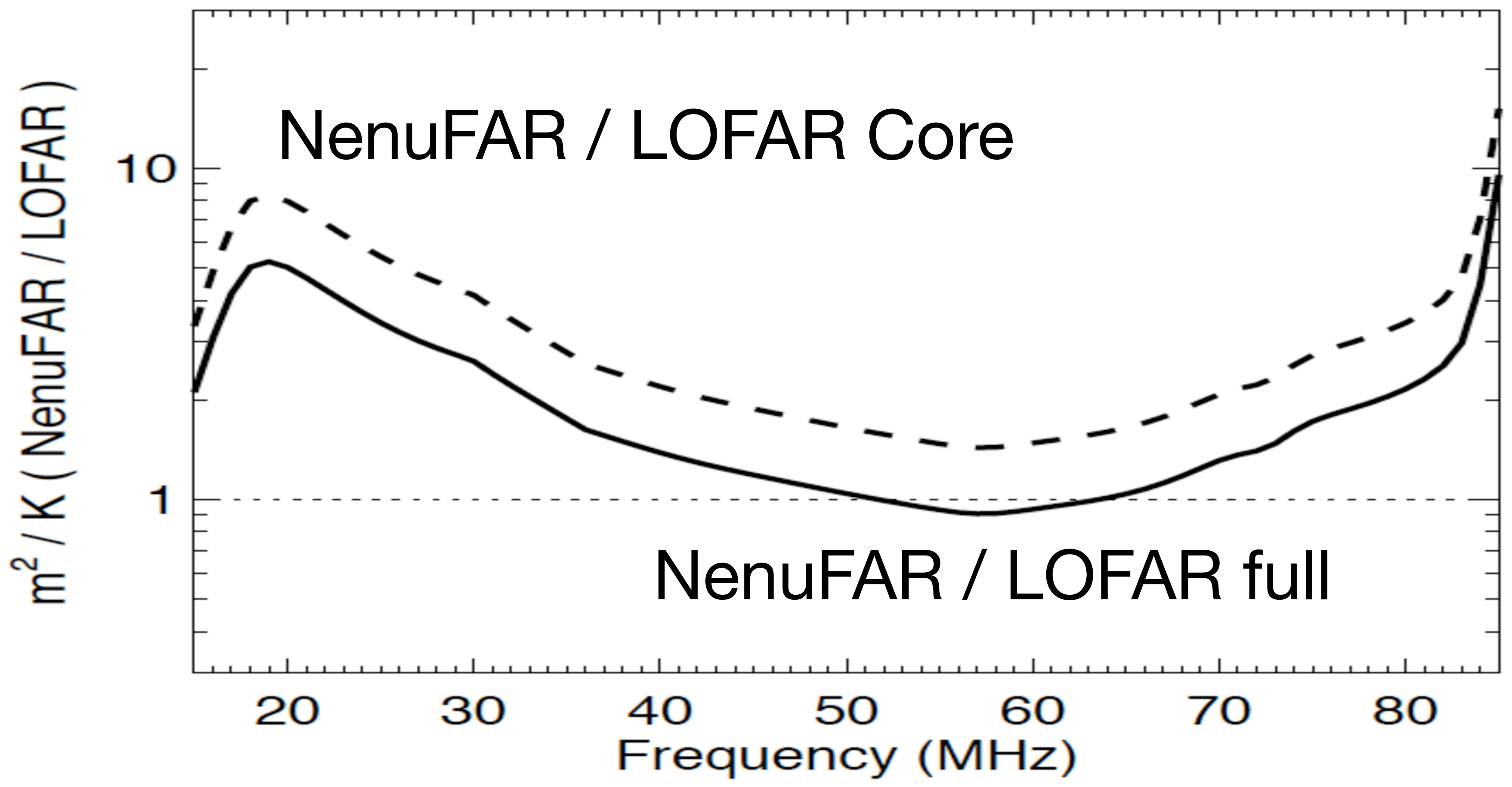

NenuFAR has been designed to reach the highest sensitivity at lowest frequencies

NenuFAR activities

Long Term Program	LT01	Cosmic Dawn
	LT02	Exoplanets & Stars
	LT03	Pulsars
	LT04	Transients
	LT05	Fast Radio Bursts
	LT06	Planetary Lightning
	LT07	Jupiter joint studies
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	SP17	Radio-Amateurs

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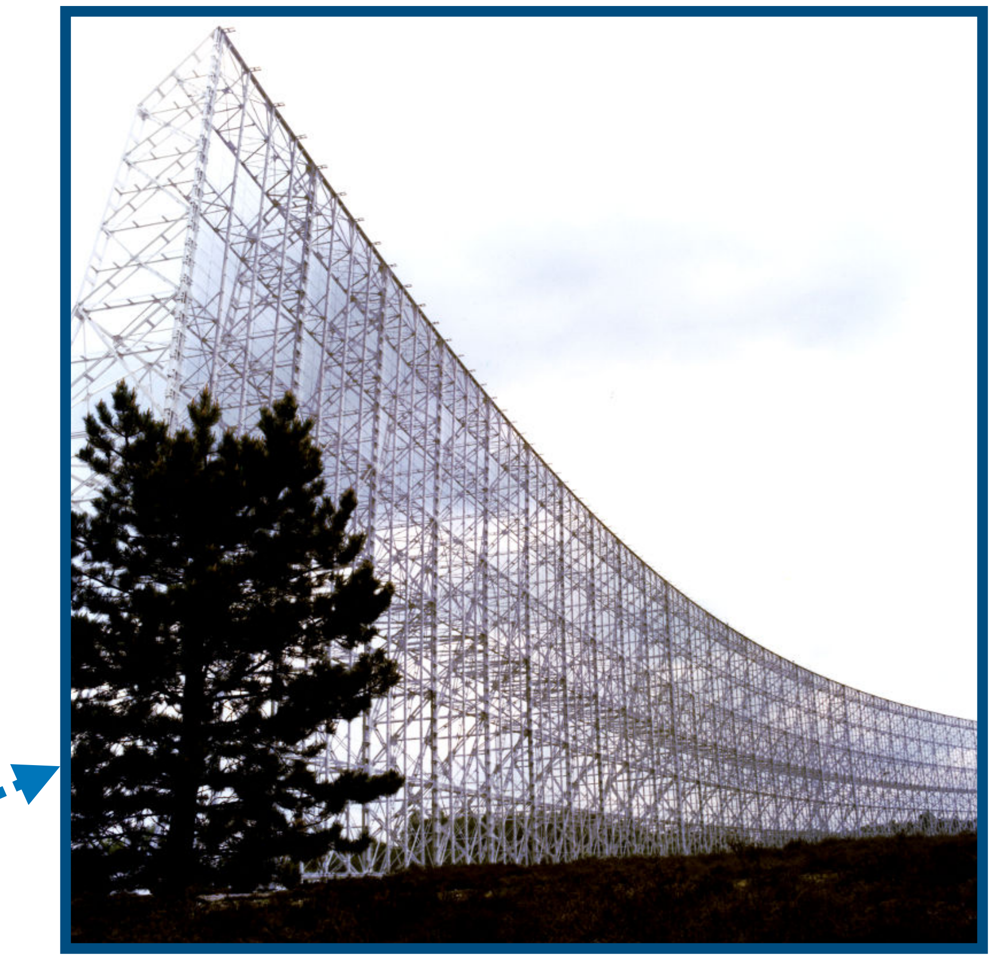

Joint observations:
when possible with the NRT
at higher frequencies
(if observable target)

+LOFAR survey:
multi-wavelength campaign
for FRB180916

Simulation study

Idea: simulate FRB signals of **already observed sources** with prior knowledge on the parameters to extrapolate at low frequency with the NenuFAR telescope

Method:

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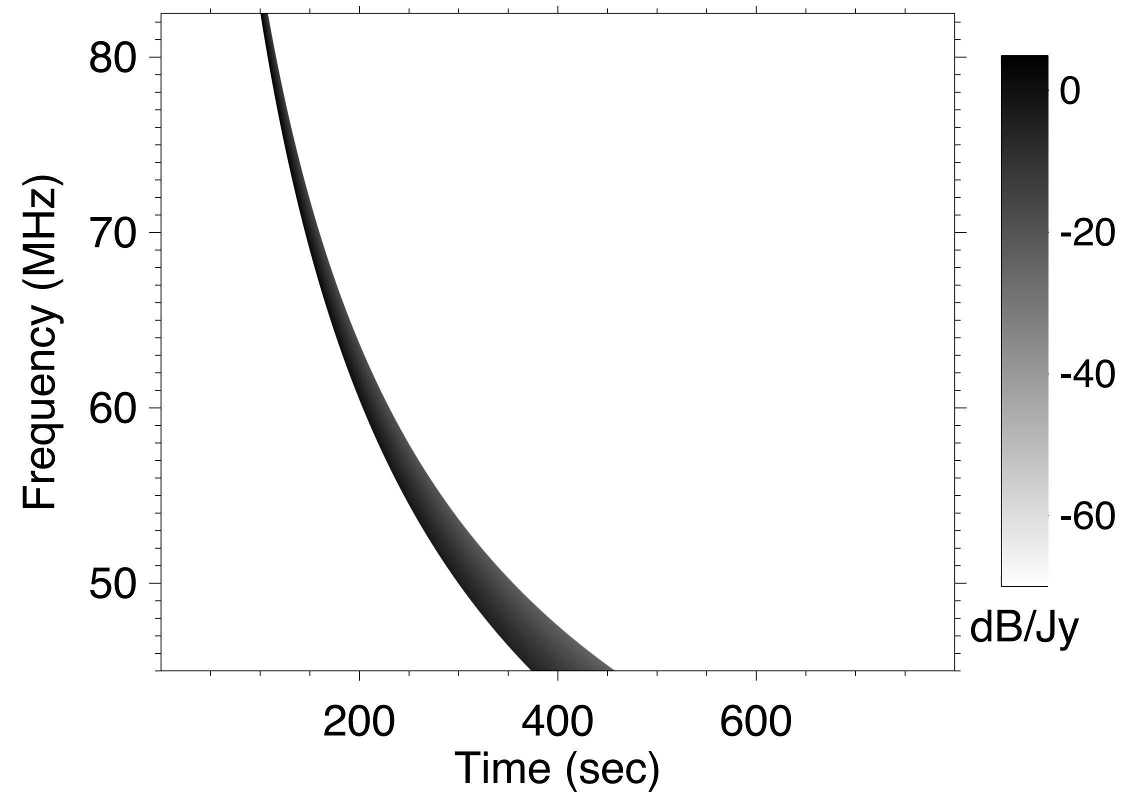
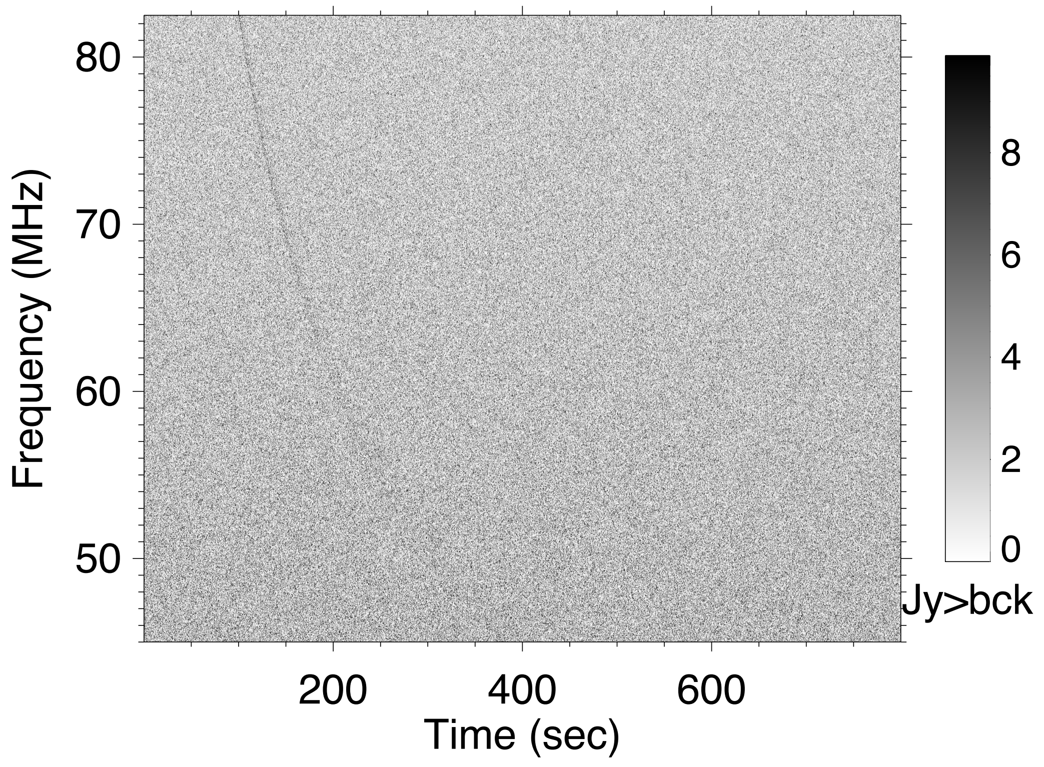


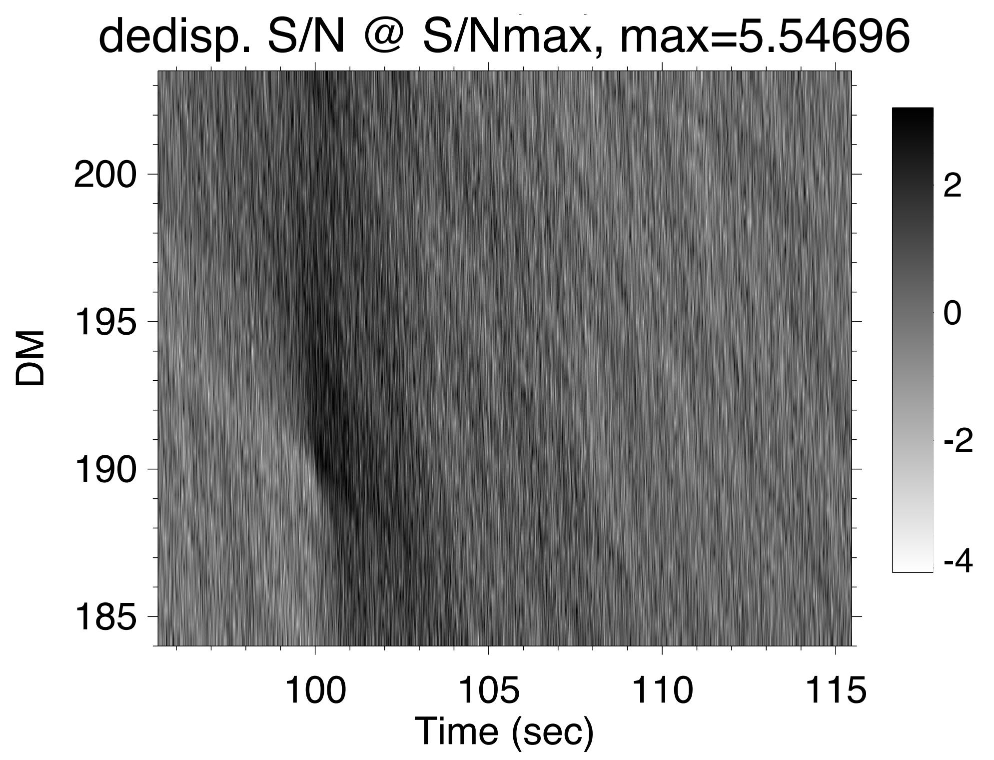
Simulate a FRB dynamical spectrum

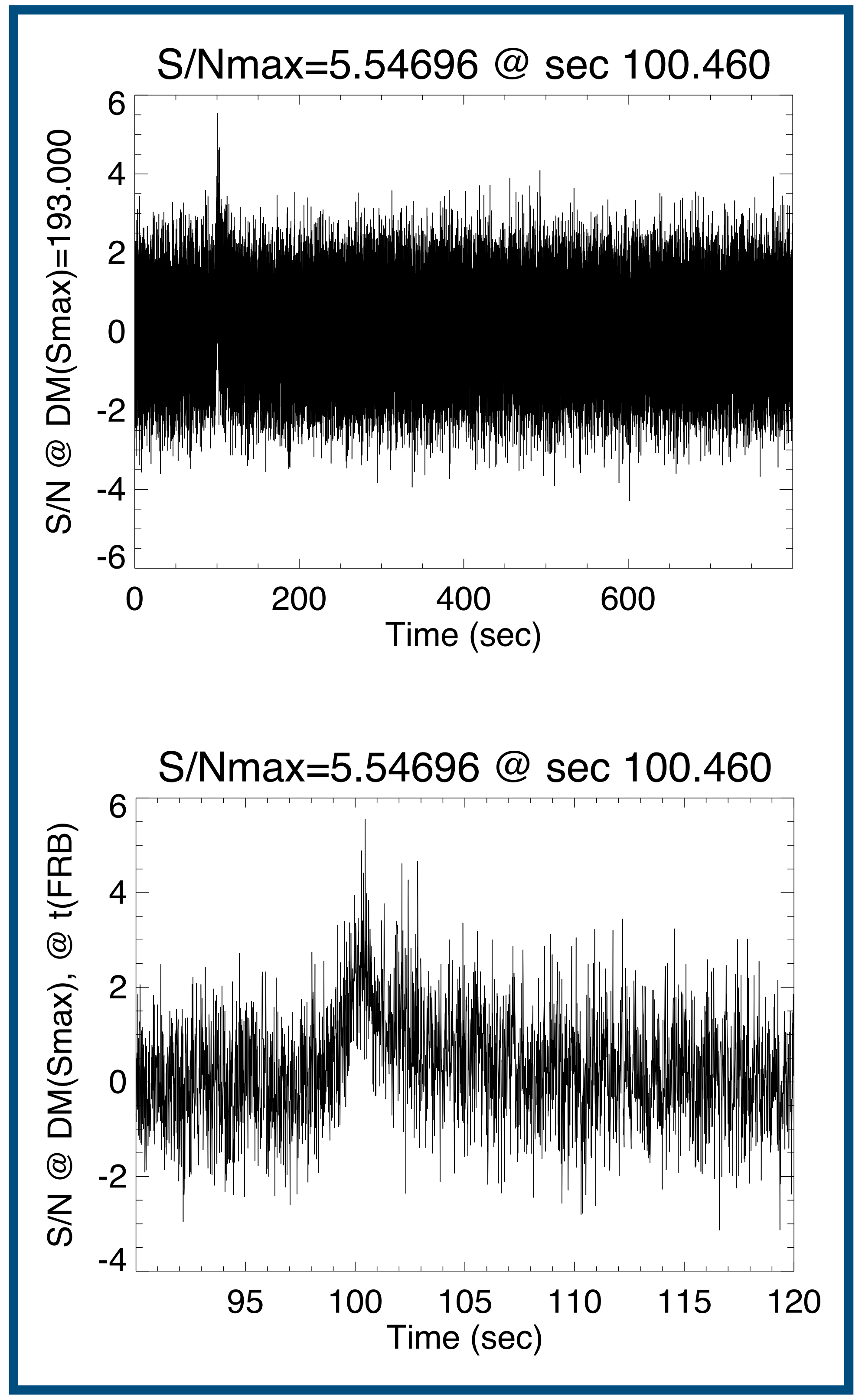
(2)



Dilute the signal in the sky background

(3)





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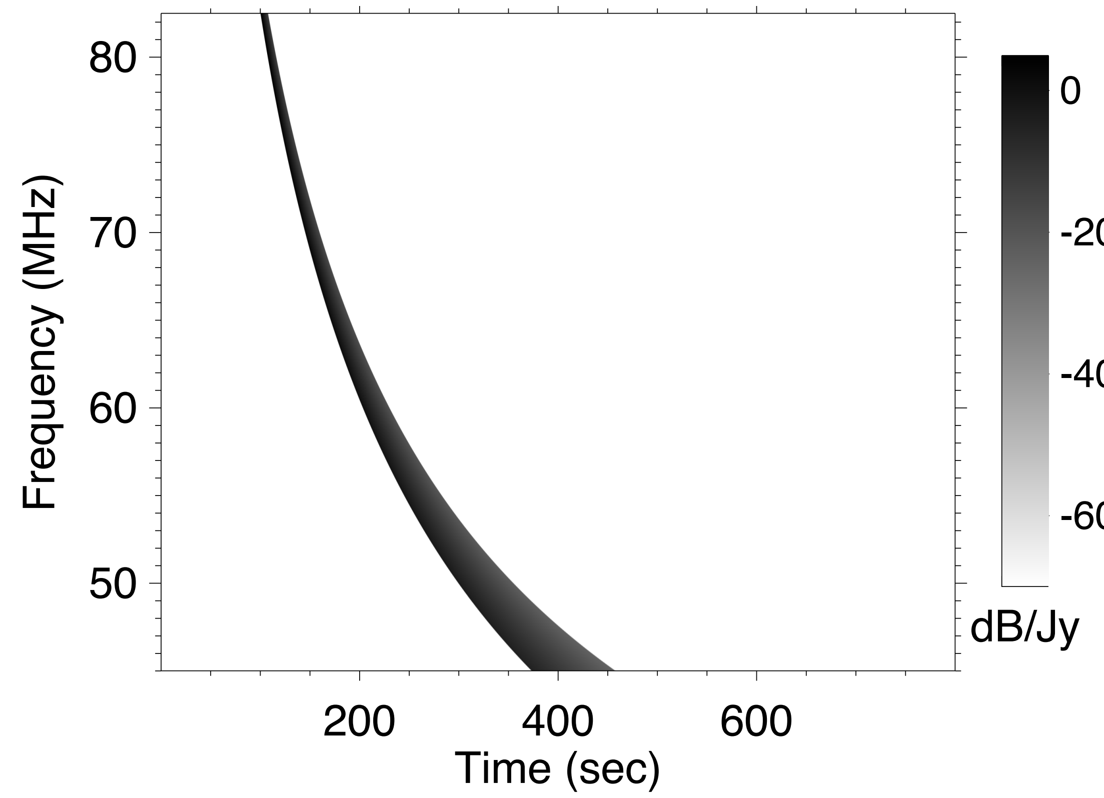

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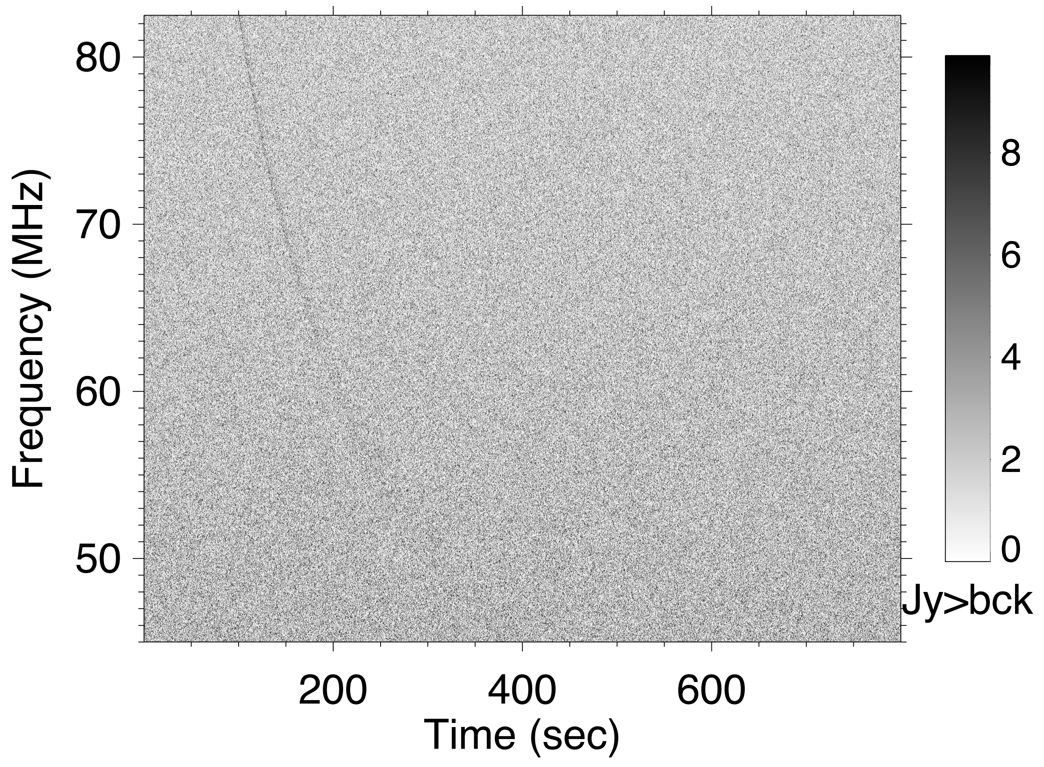

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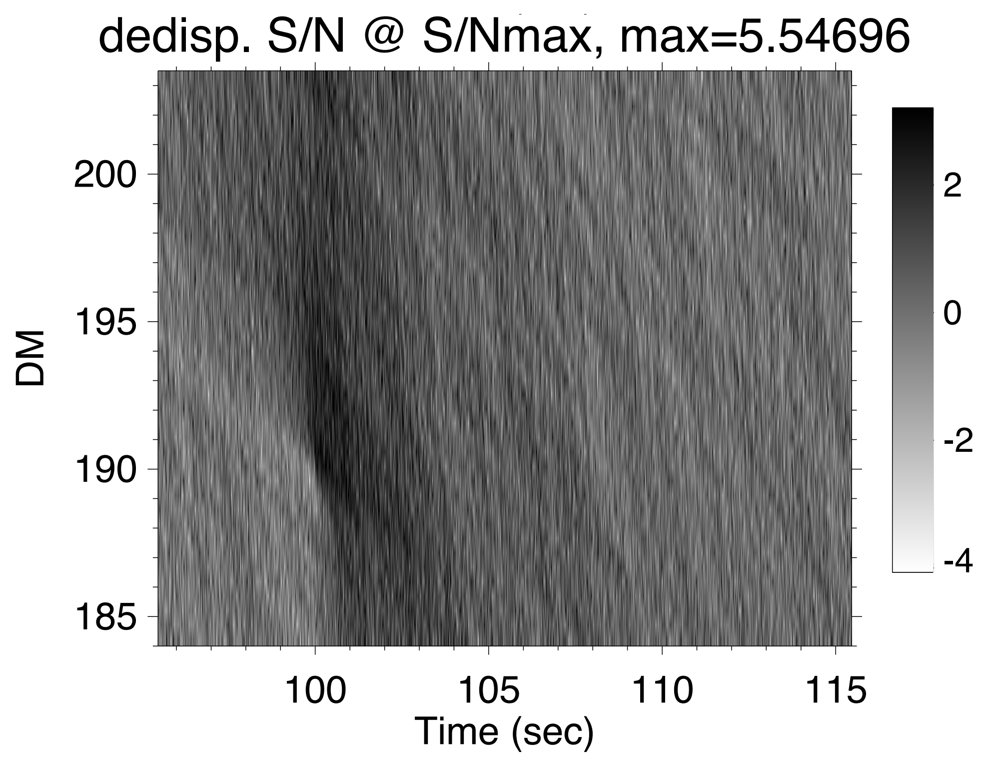
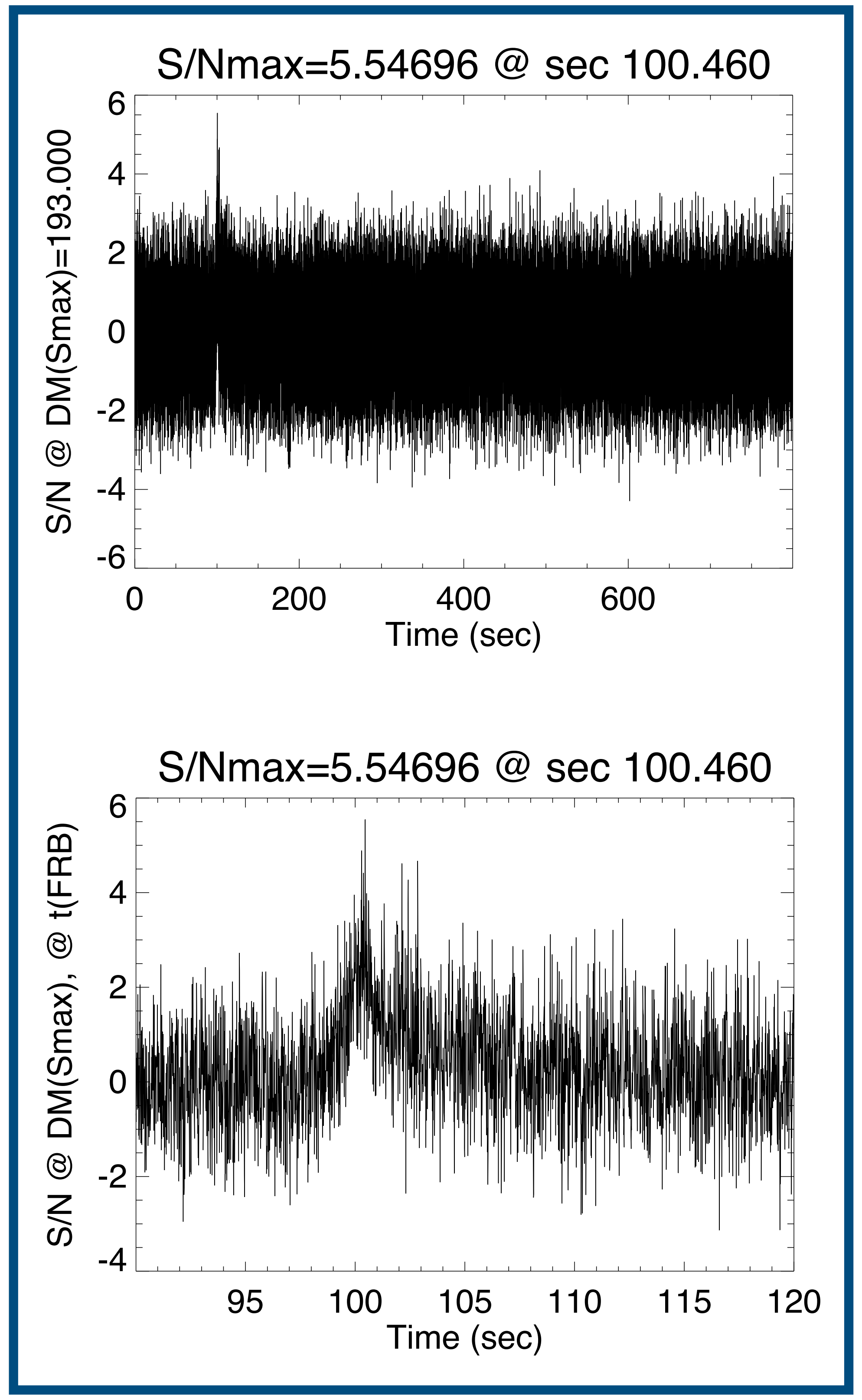


Proceed to a parametric search of the DM within the time and frequency resolution parameters of NenuFAR



Prior knowledge of the DM allows to reduce significantly the parametric search

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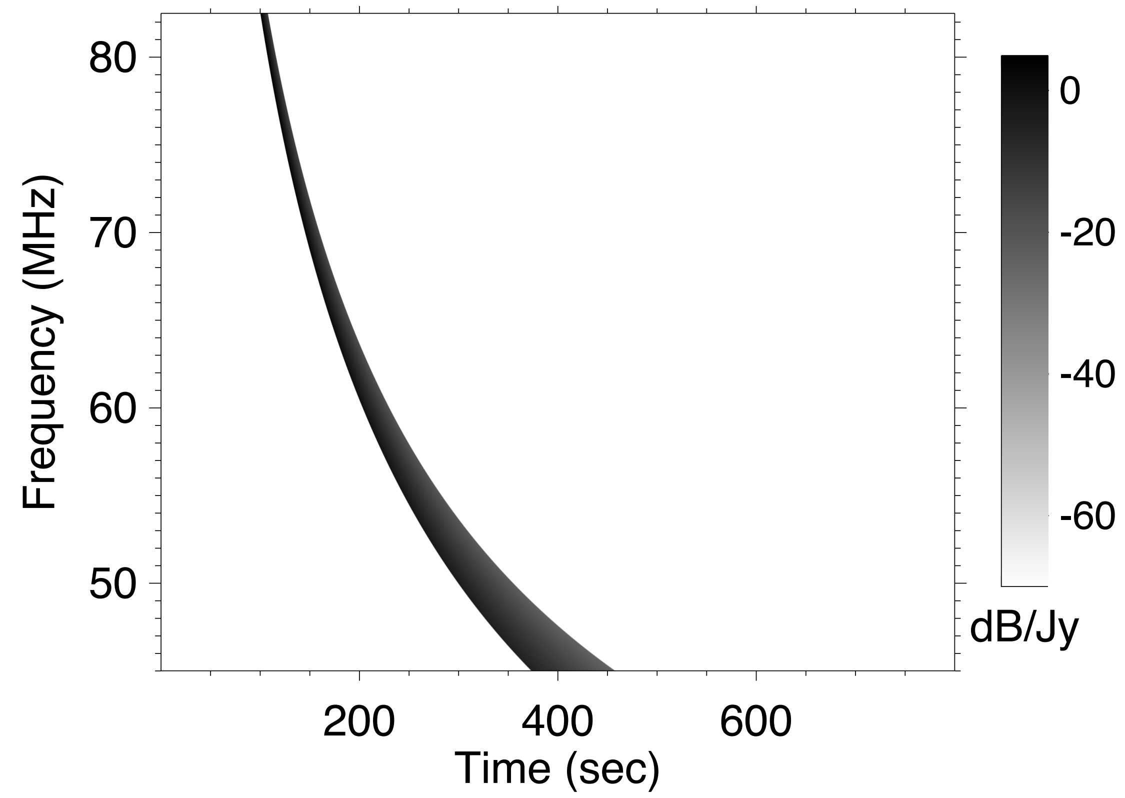

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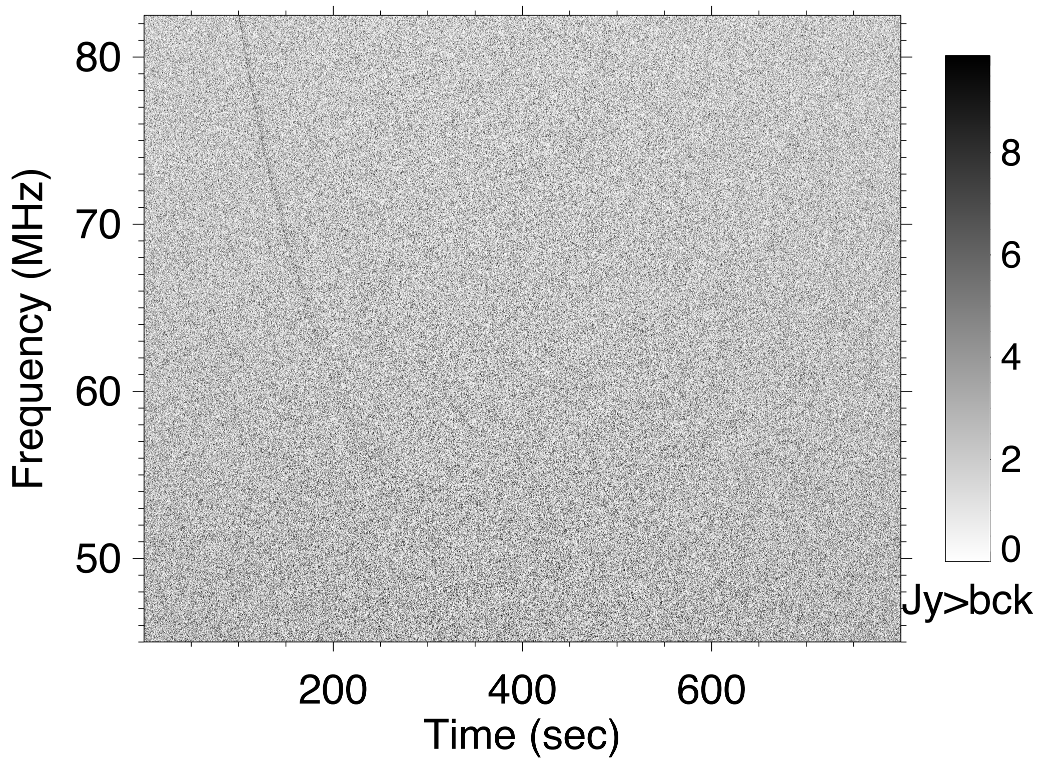

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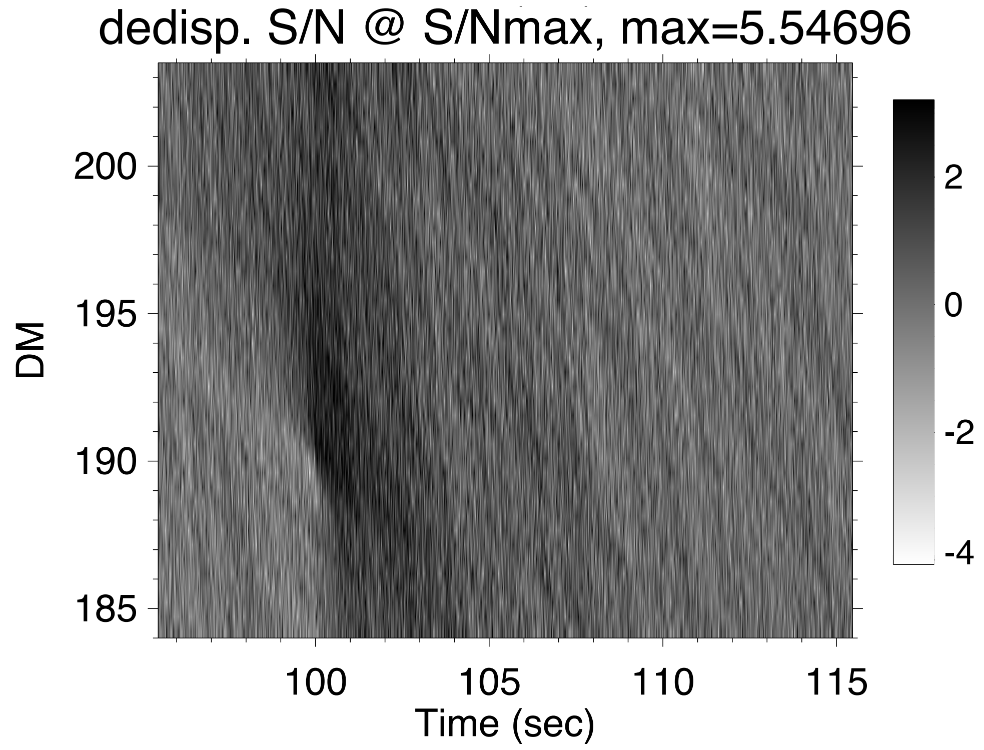

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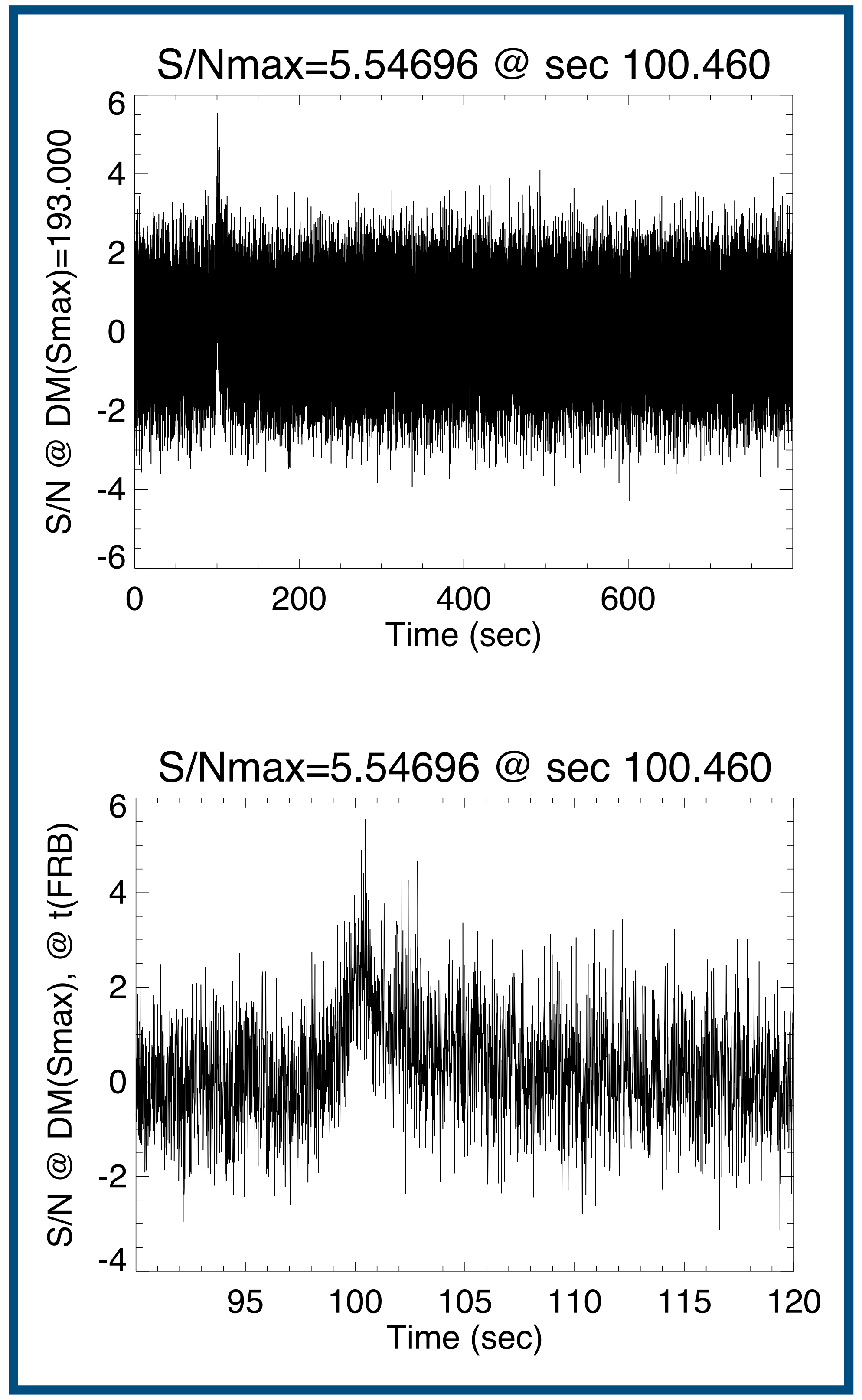

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Maximise the SNR

Fine tuning of the resolution parameters of NenuFAR

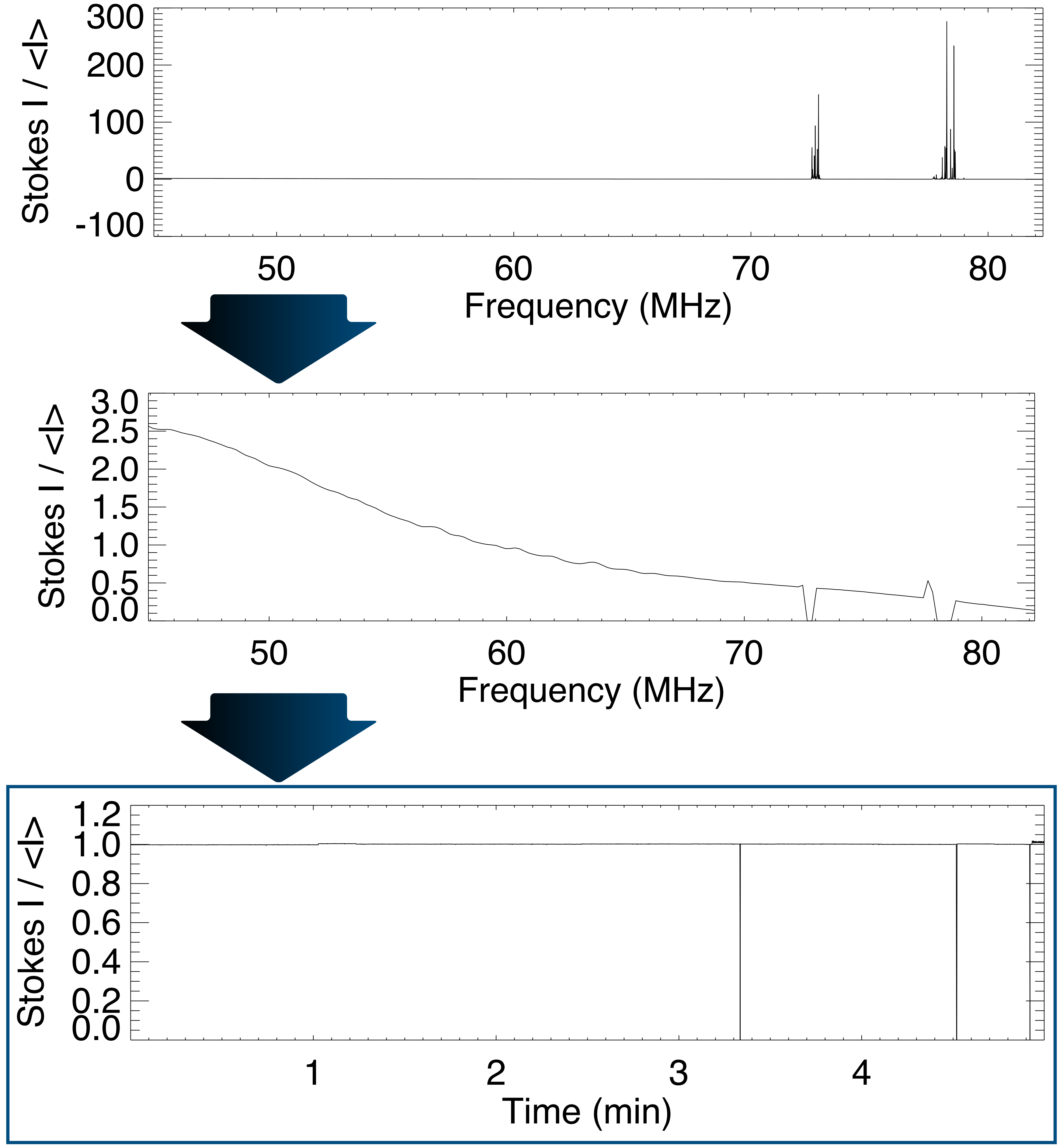
The optimal parameter set used is given by a 1.5kHz frequency resolution and a 21ms integration time to combine flexibility for the analysis and storage gain

Pre-processing and data reduction strategy

Goals: remove noise signals from external interferences and instrumental effets and reduce as much as possible the data volume

Motivation: the data rate at the output of NenuFAR given the resolution parameters chosen is about 60GB/h → reaching a few tens of TBs per semester!

raw spectra



clean spectra

Method:

data cleaning

1. identify and remove Radio Frequency Interferences (RFI):
    1. mask frequency channels fully polluted
    2. proceed to a search in the time integrated plane for frequency spikes
    3. proceed to a search in the frequency integrated plane for narrow broad band emissions
    4. correct for time-frequency slopes
2. De-disperse the signal inside each channel at the expected DM (but not over all channels) and integrate channels up to 2-4 remaining channels
3. Additionally a post integration over time can be applied for a reduction of a factor 2

data reduction

Ongoing work: ~1500 hours of observations to be analysed

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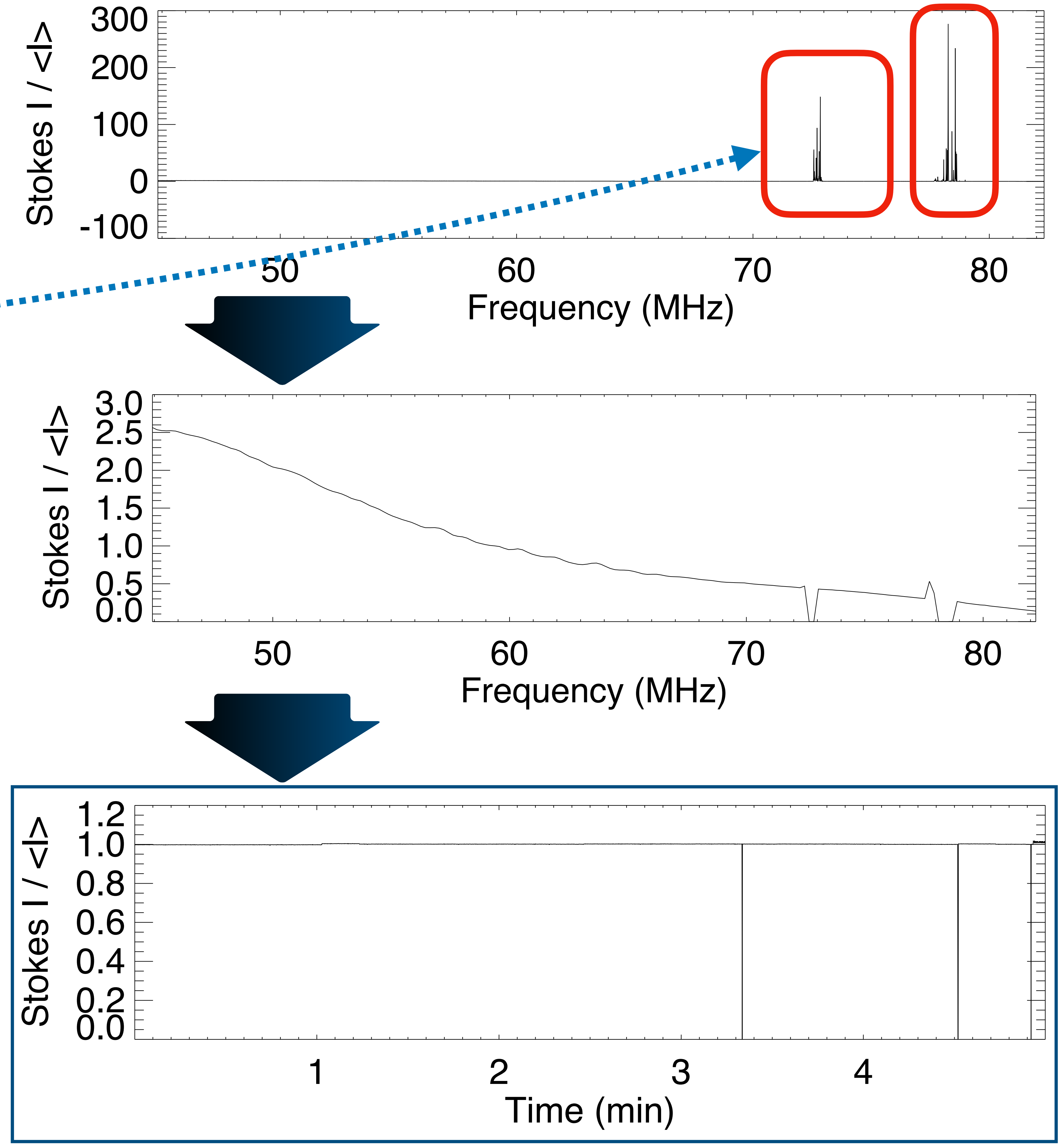

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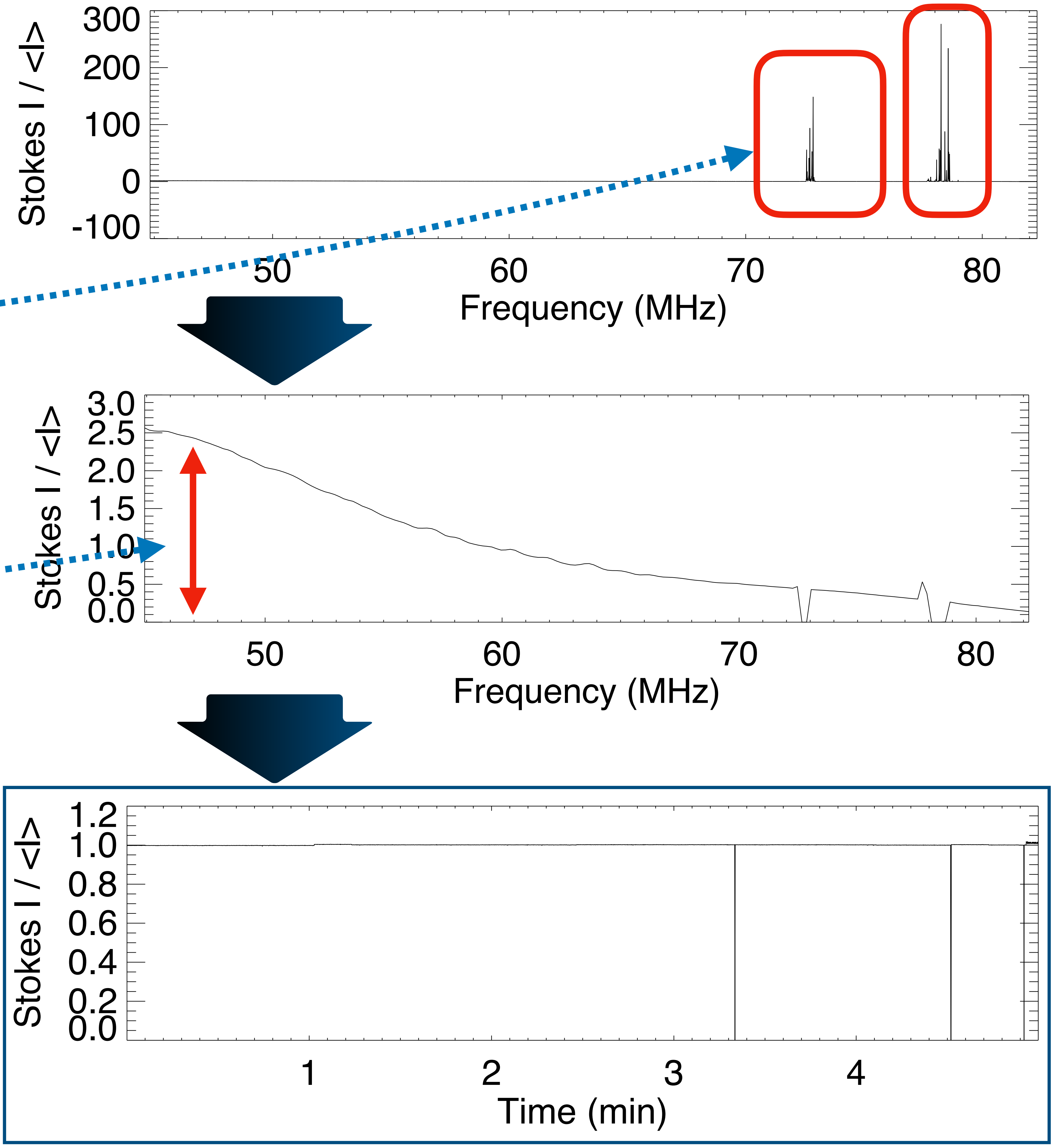

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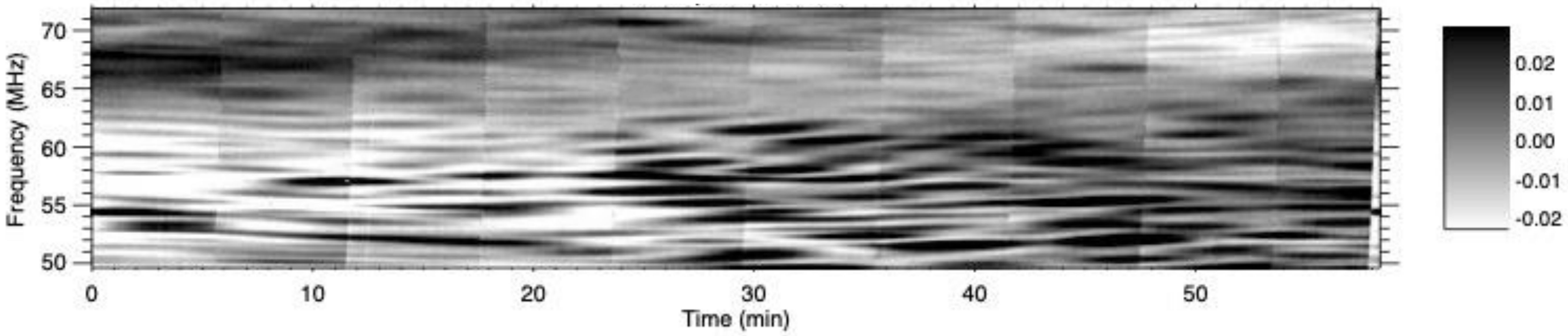
Analysis method on pulsar observations

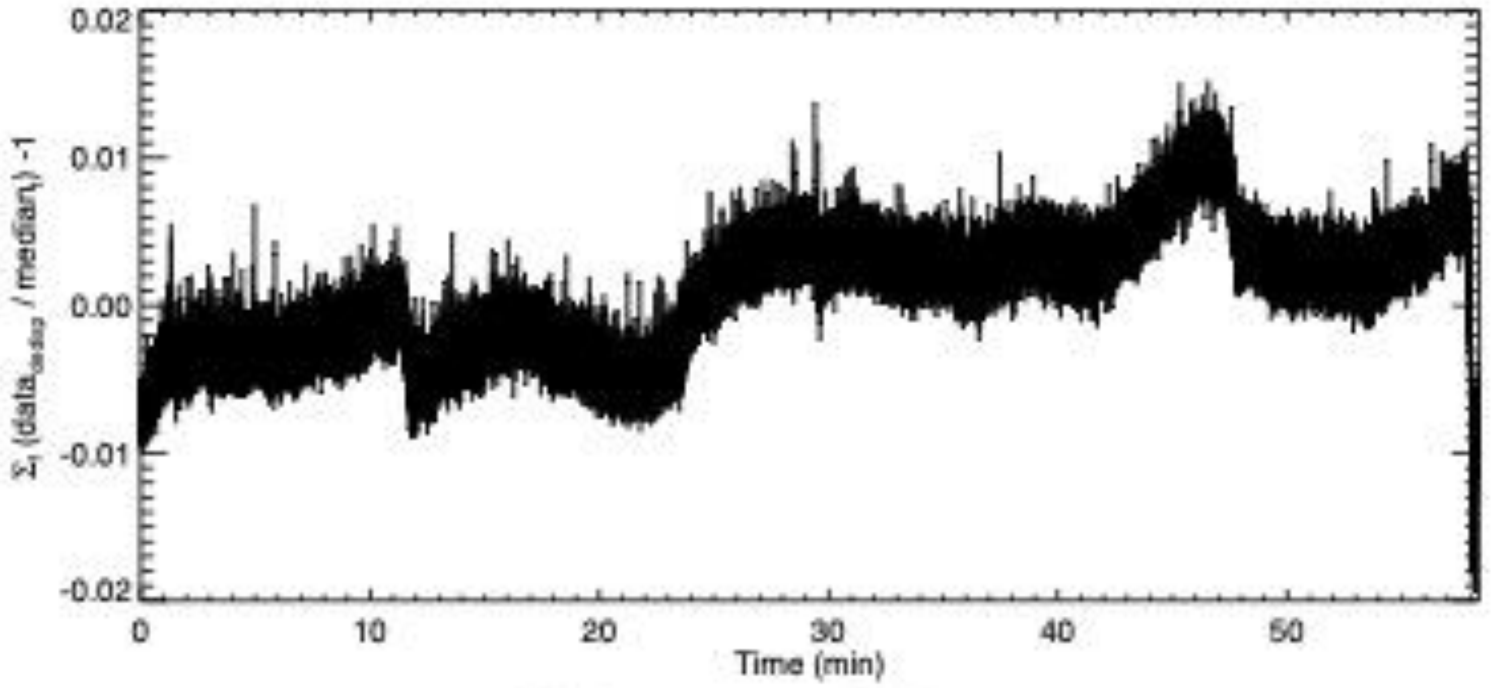
The idea is to clean the time-frequency data in the Fourier domain

test on observations PSRB0329+54

time-frequency plane



integrated time series



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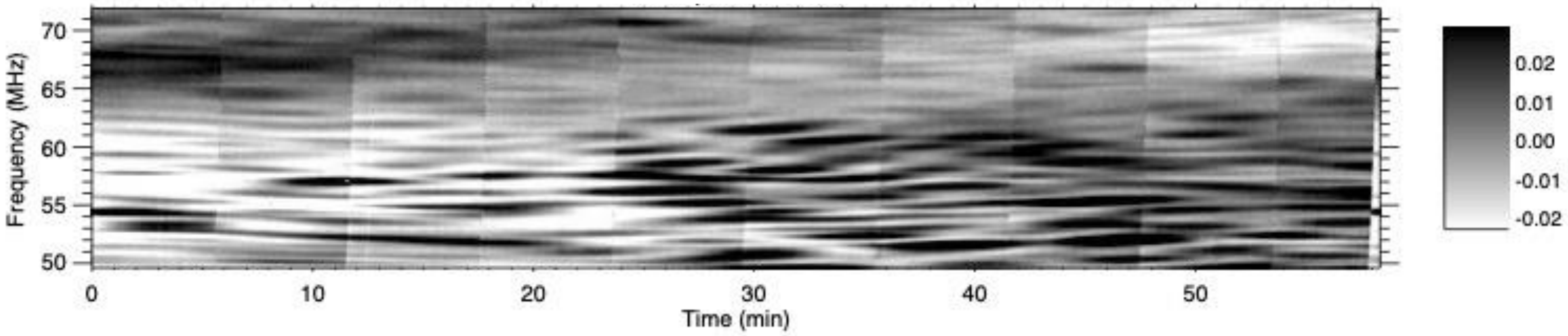

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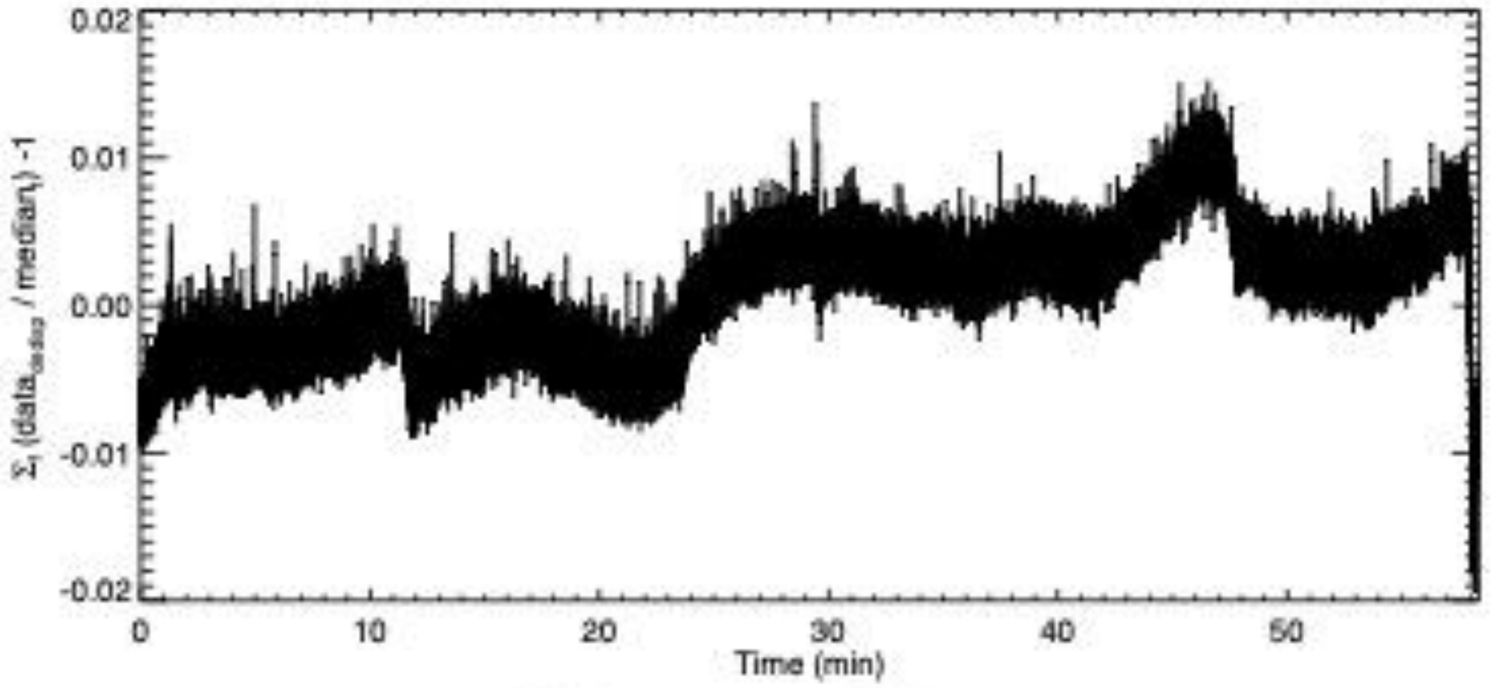
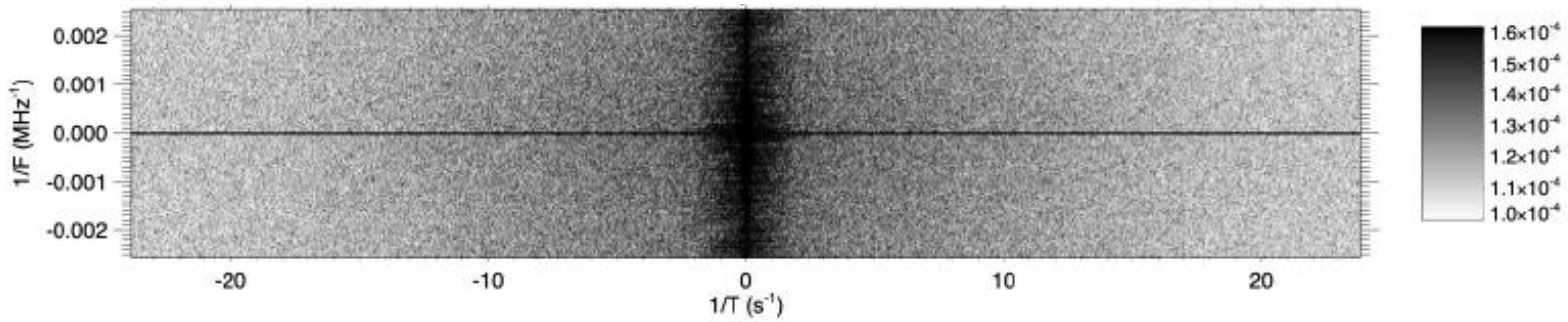
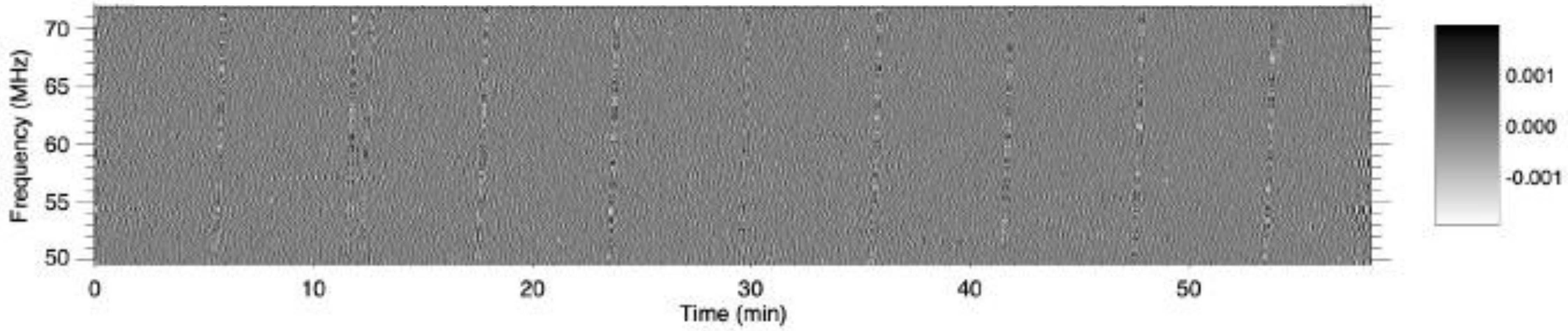


2D Fourier plane of the power spectrum



inverse 2D Fourier transform of the flagged power spectrum



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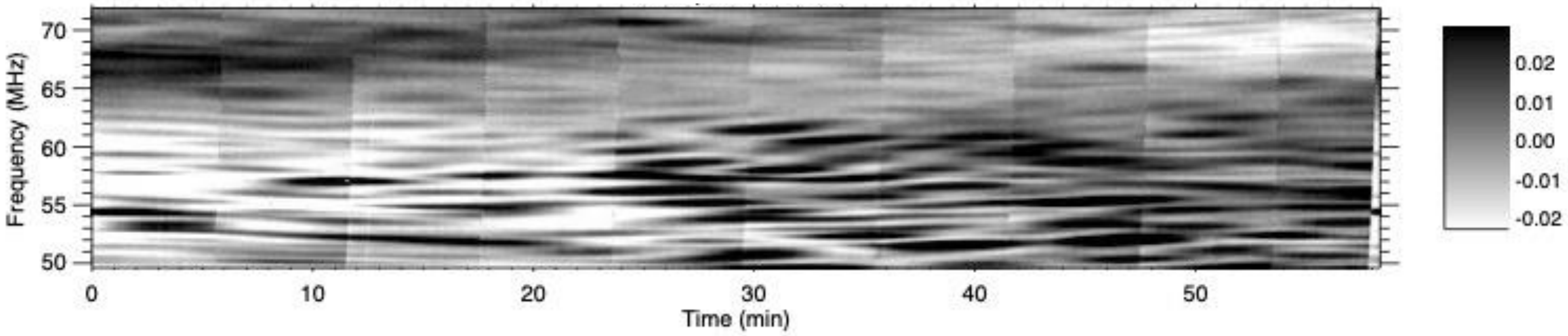

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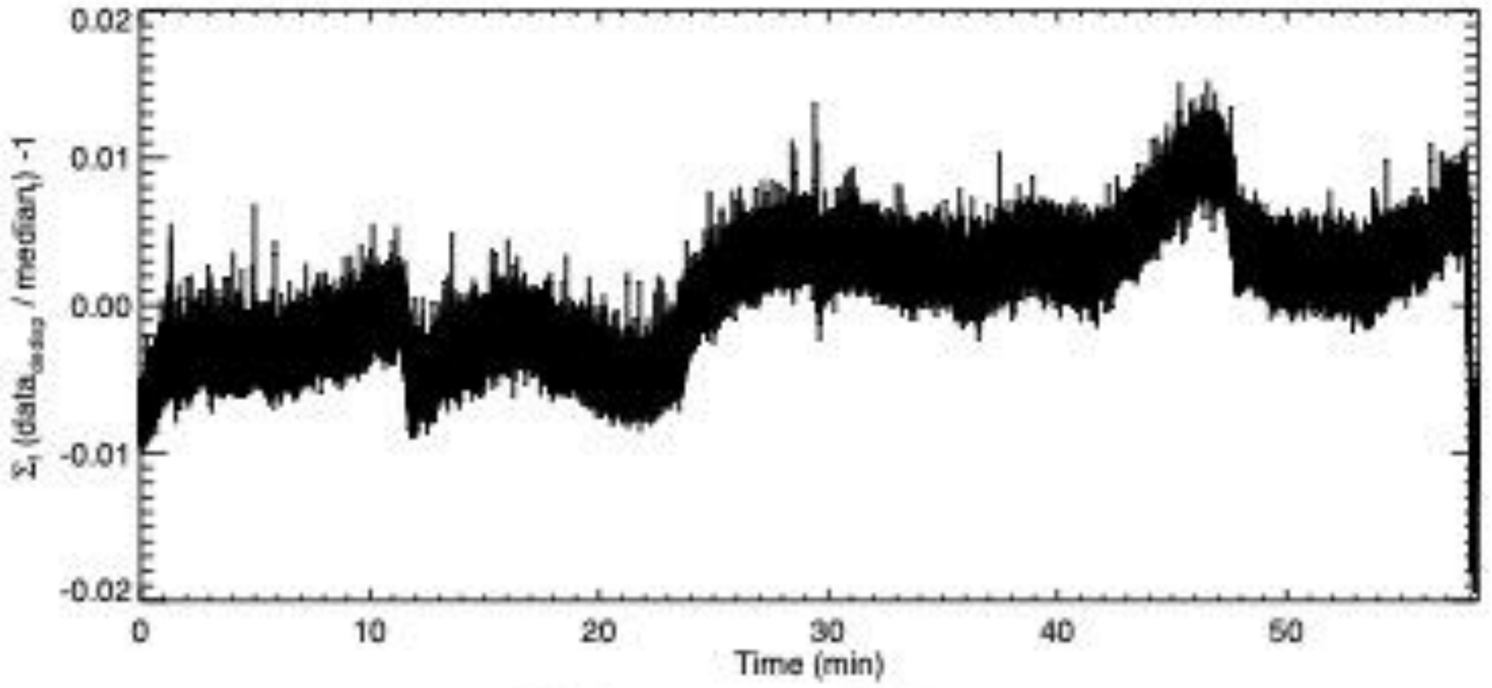

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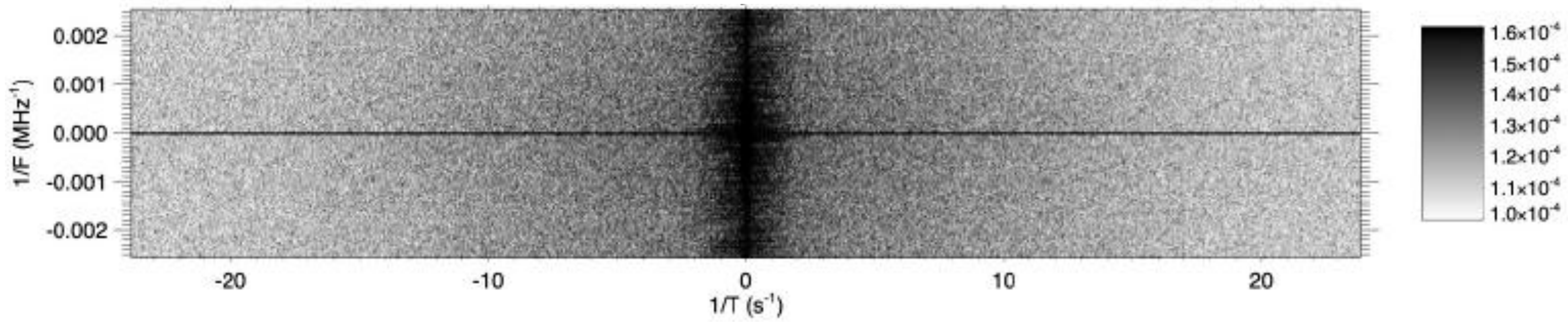

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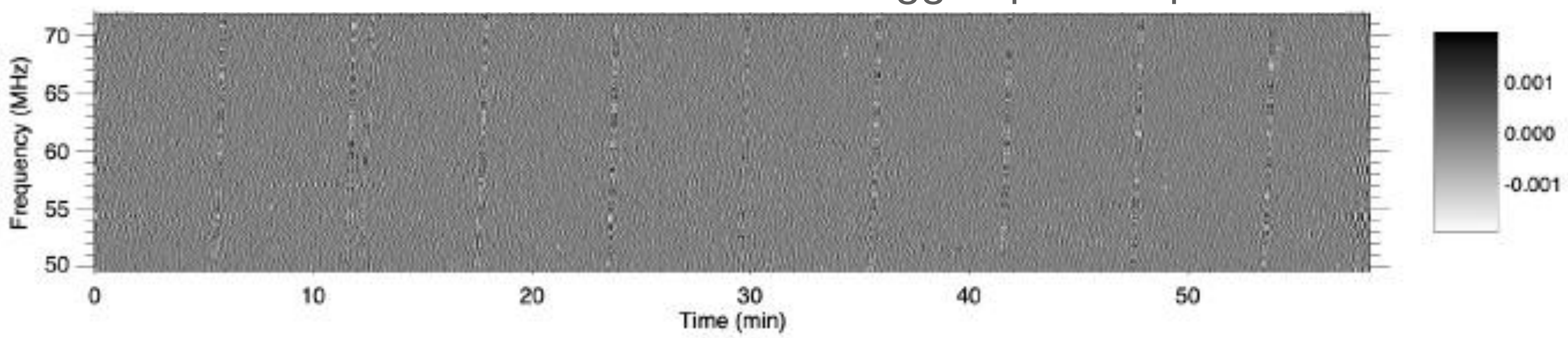
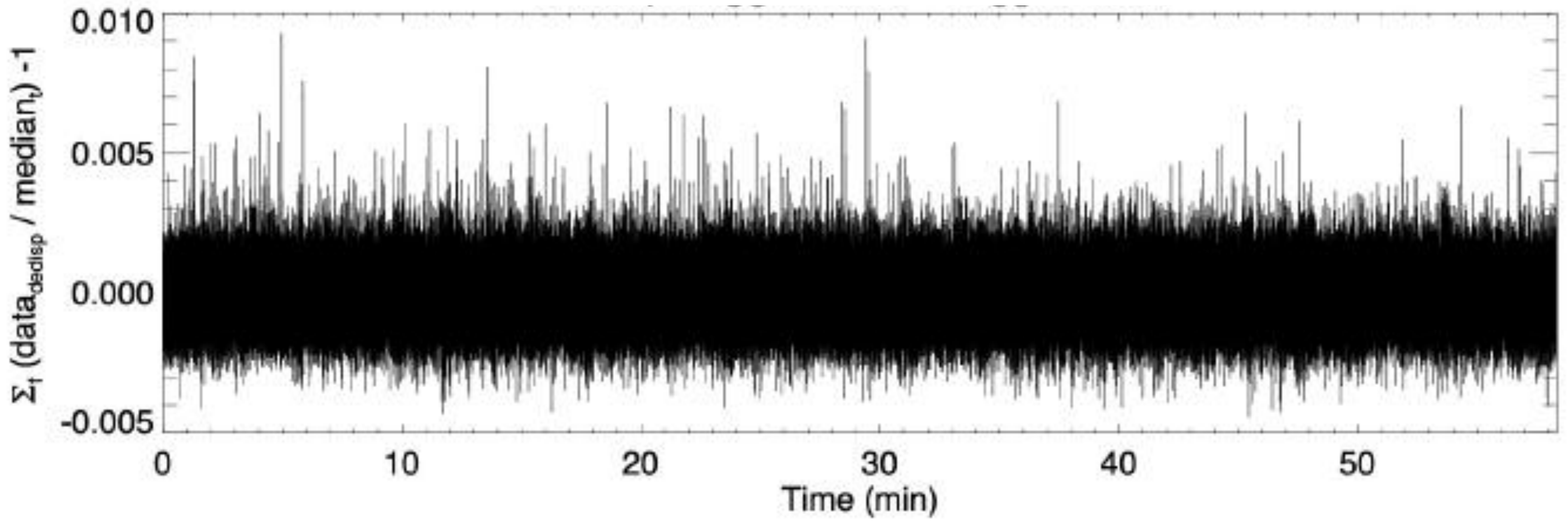
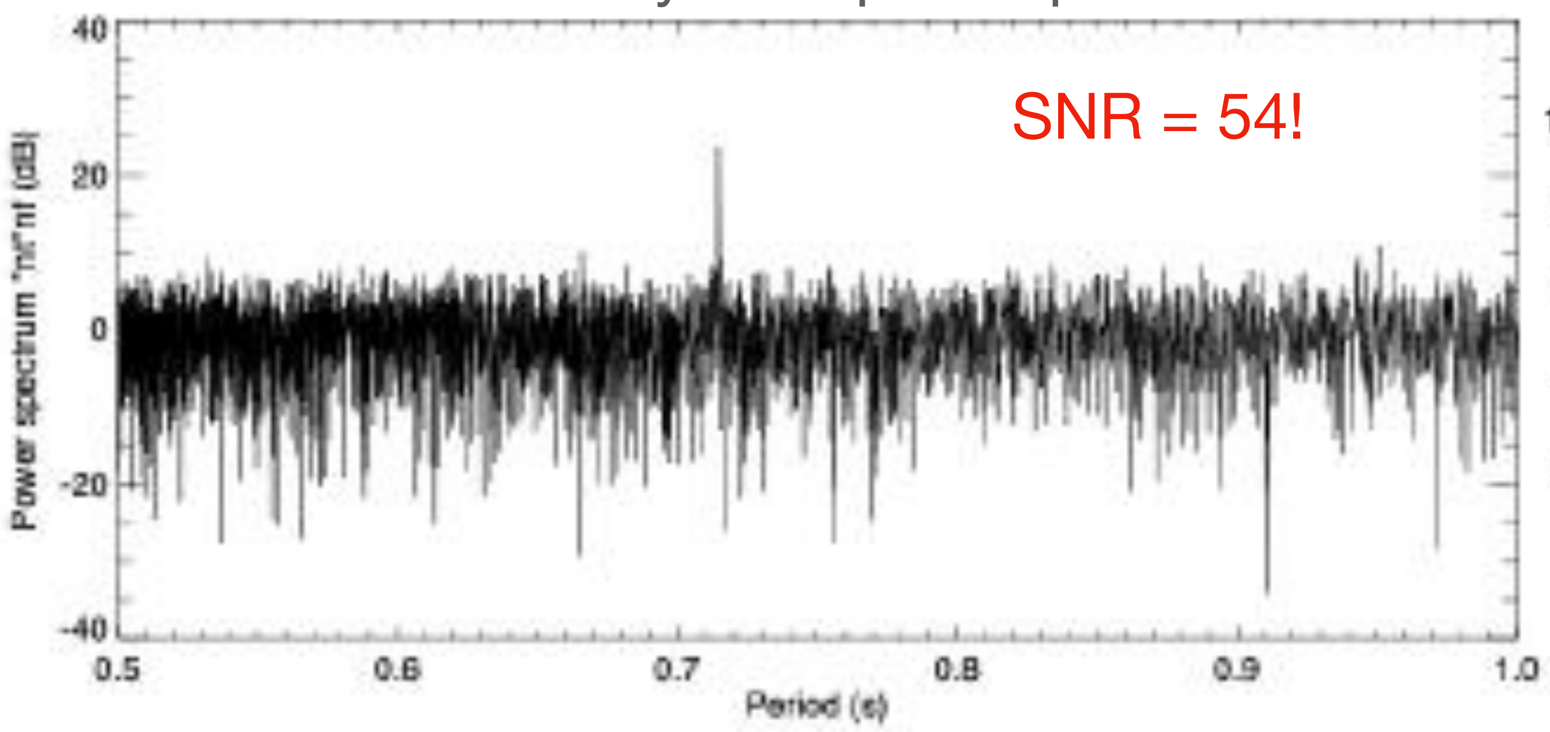


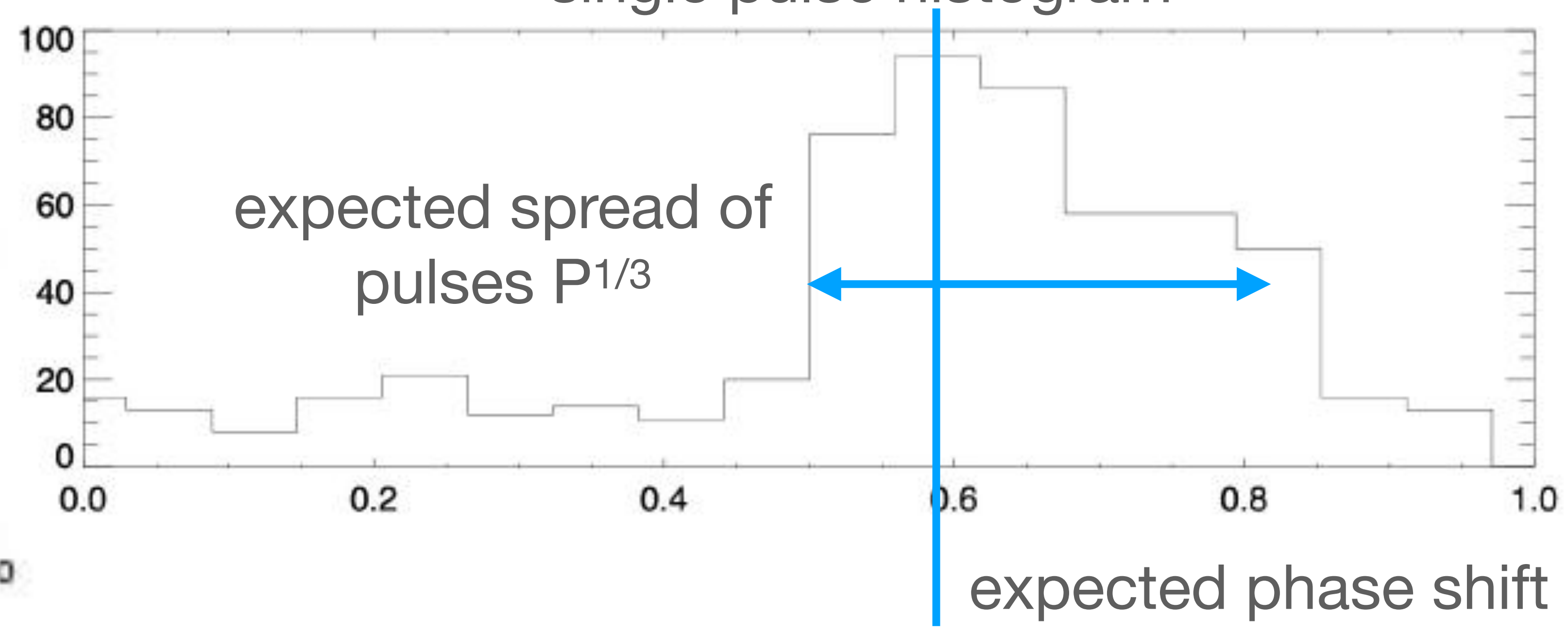
integrated time series



Fourier analysis of pulsar period



single pulse histogram

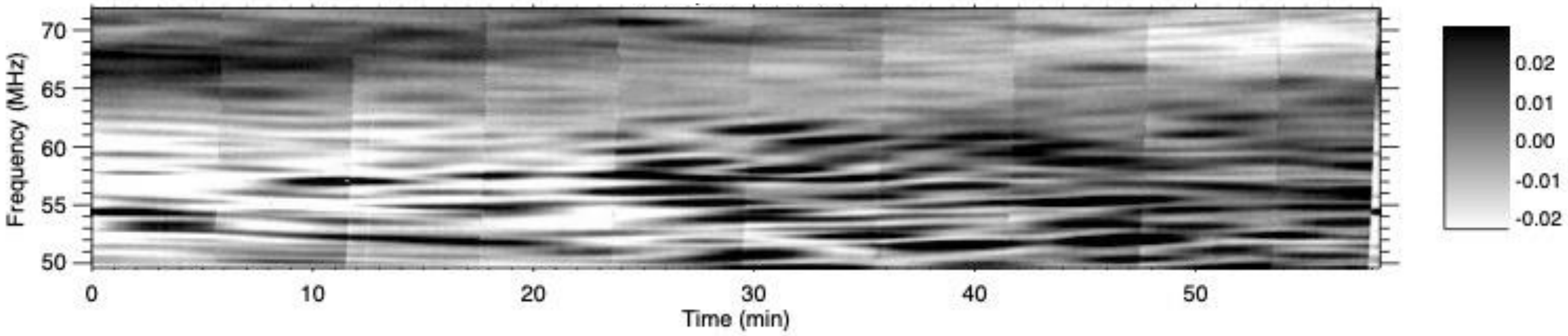


Analysis method on pulsar observations

The idea is to clean the time-frequency data in the Fourier domain

test on observations PSRB0329+54

time-frequency plane



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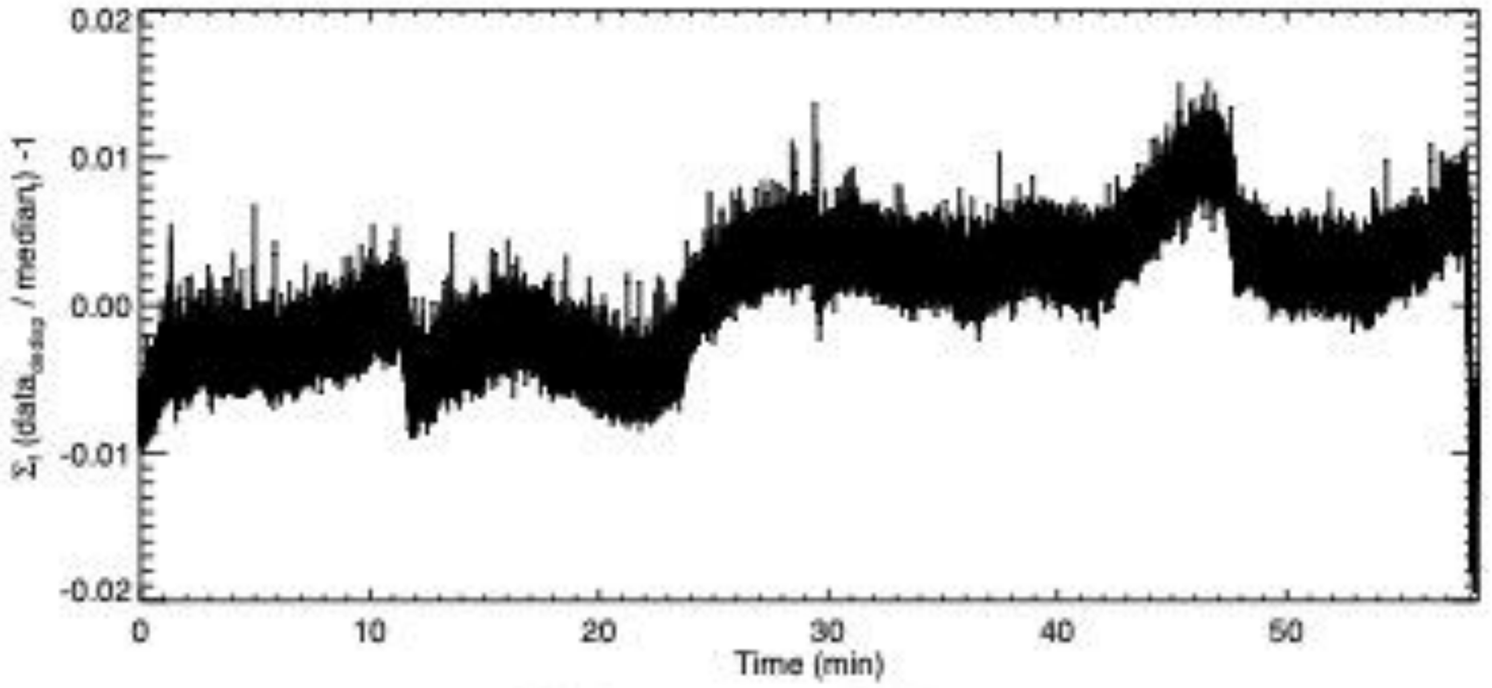
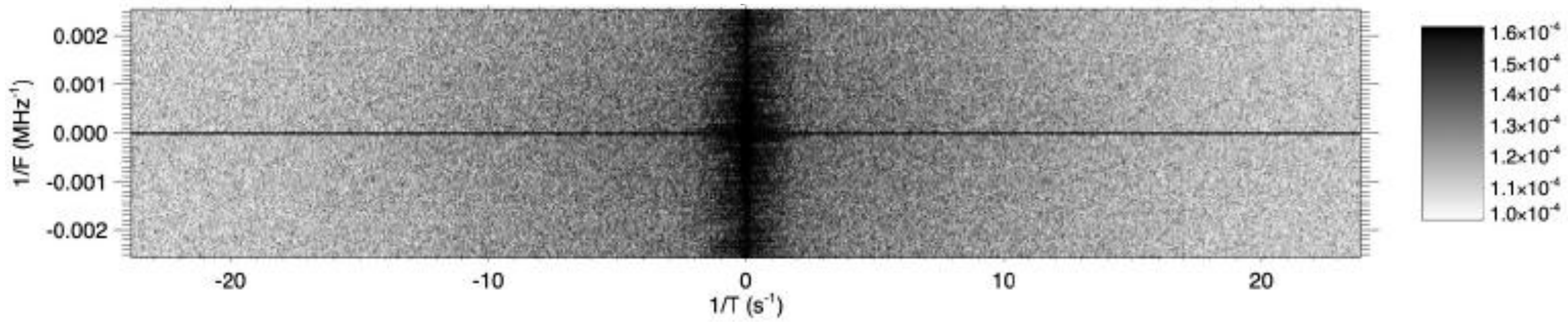


2D Fourier plane of the power spectrum



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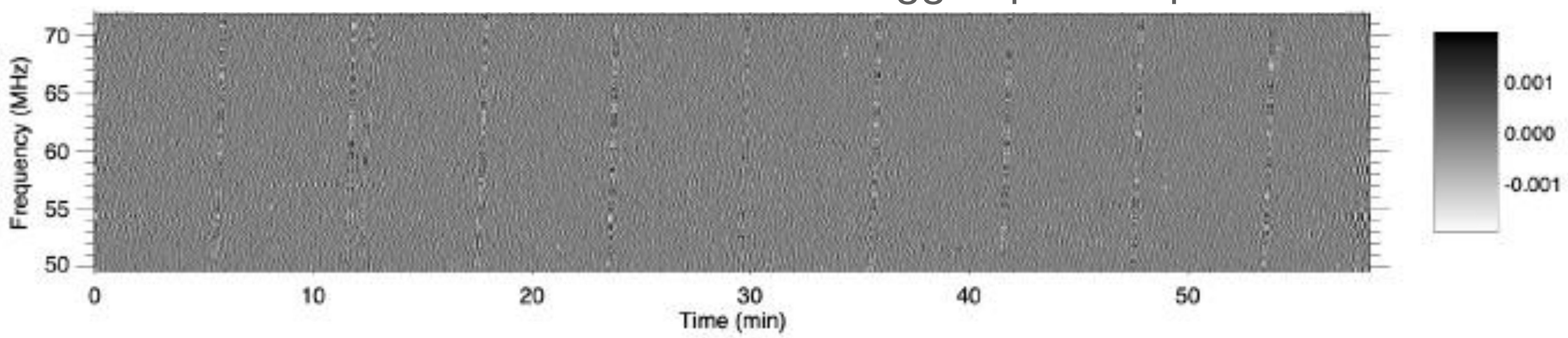

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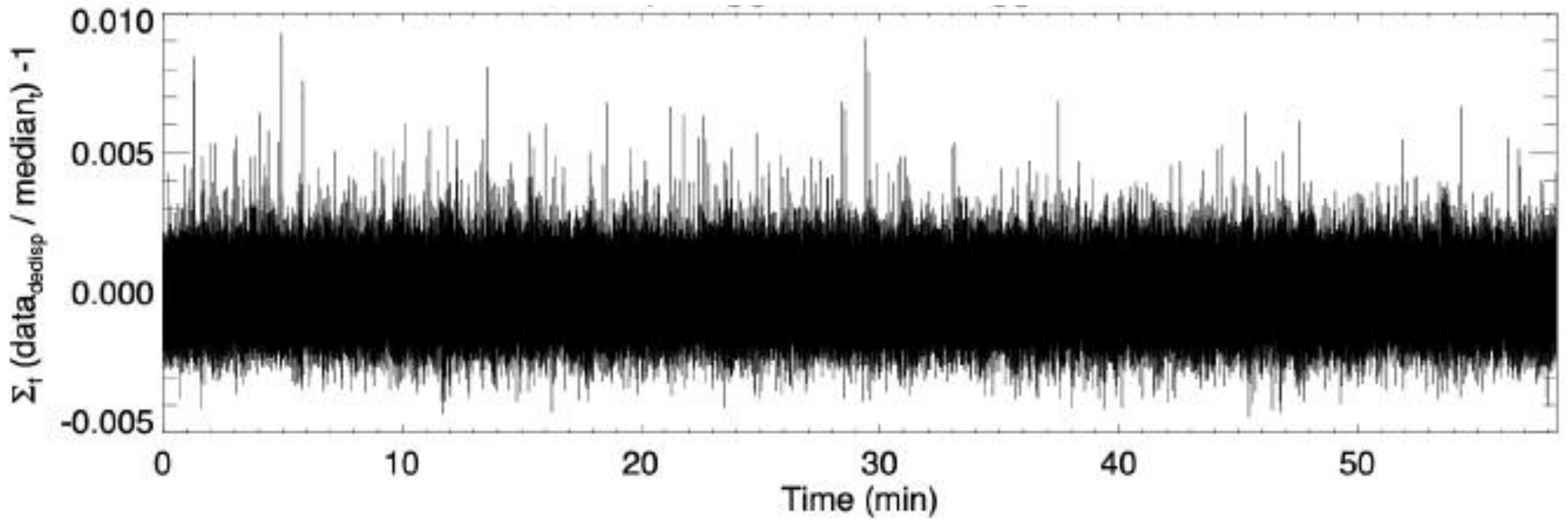

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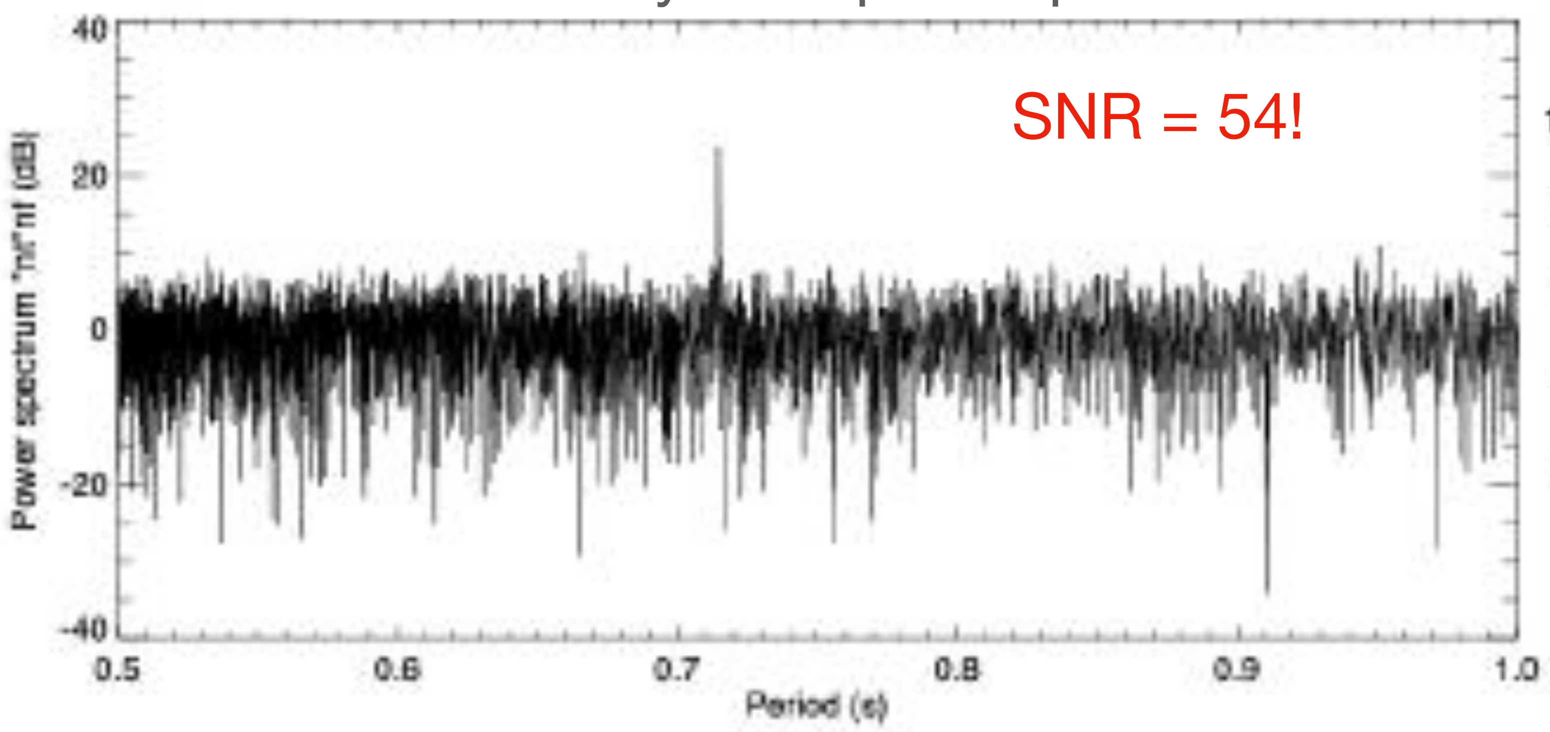

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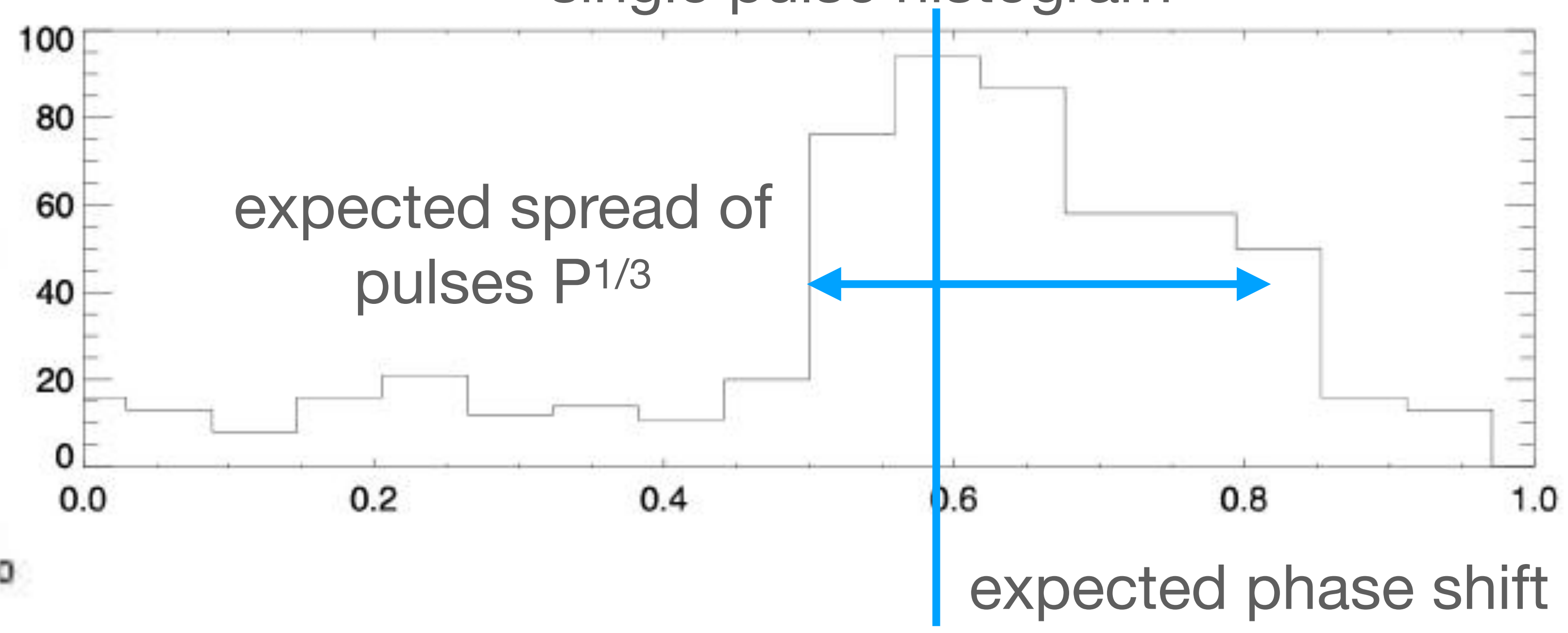
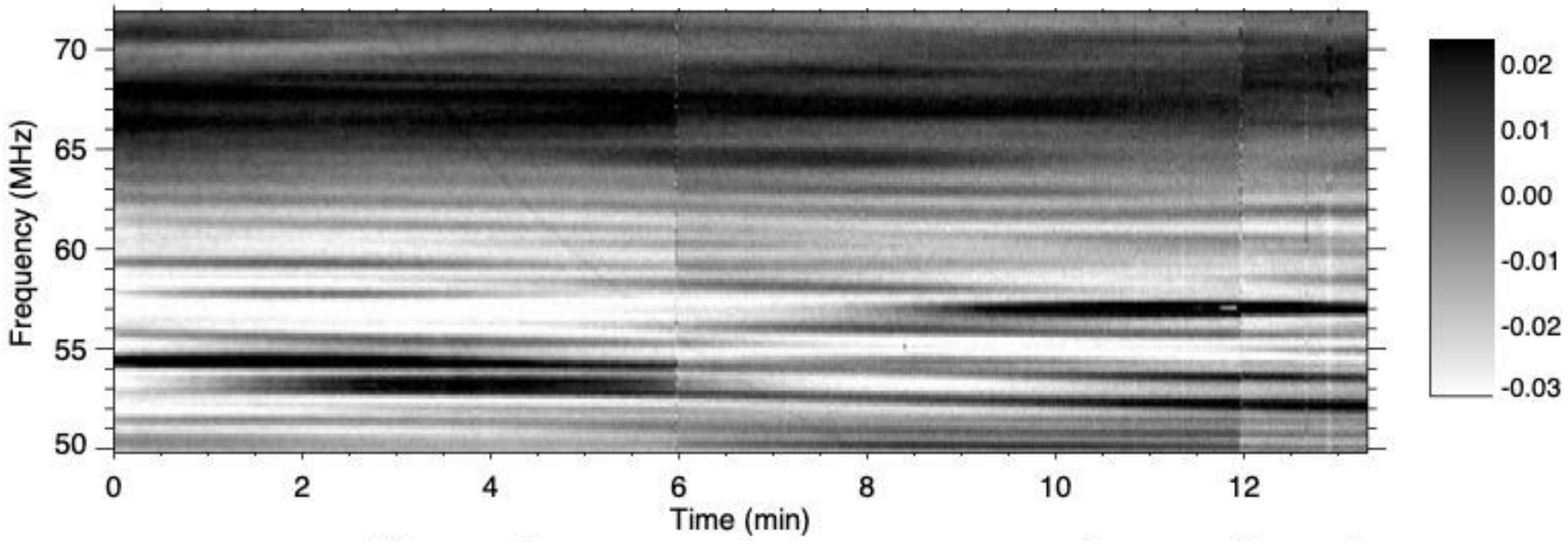


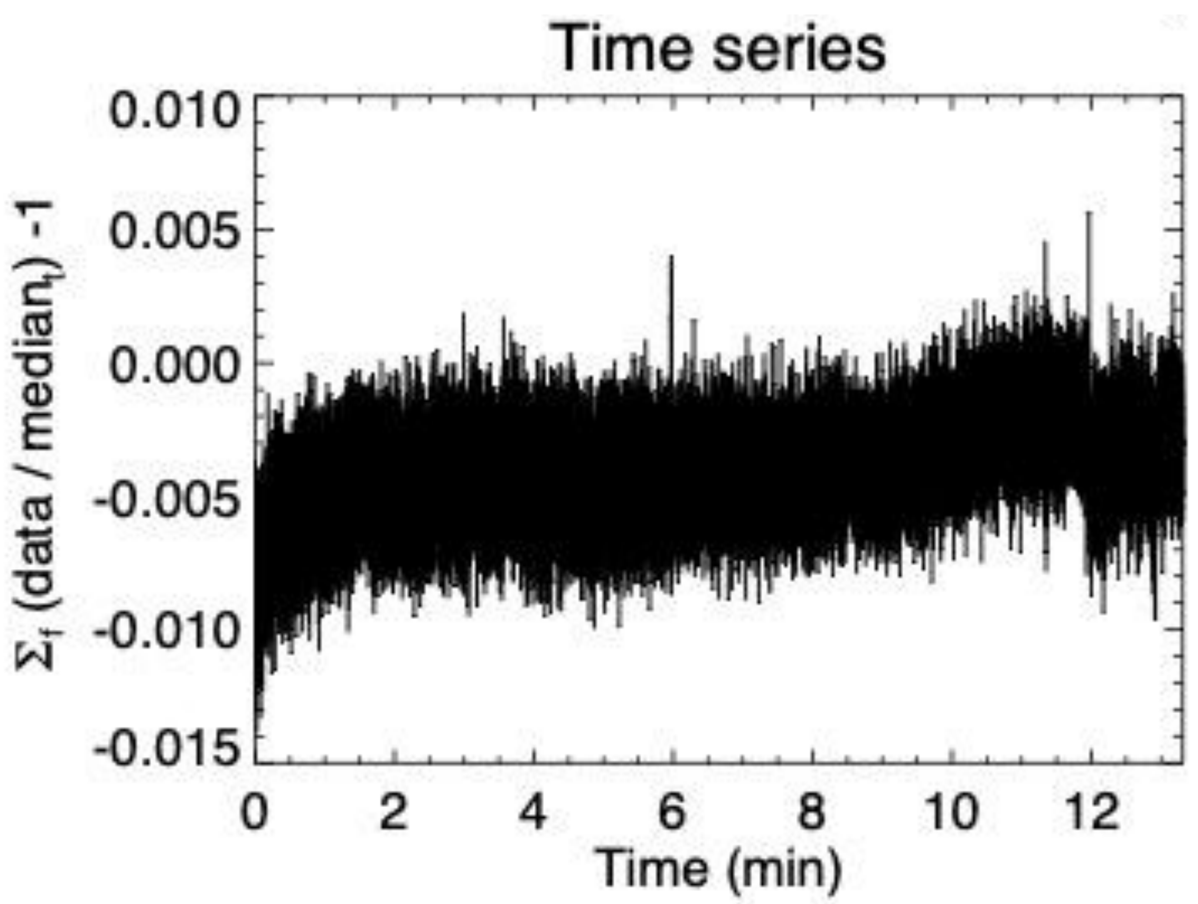
High pass Fourier filtering allows to clean the data efficiently enough to detect single pulses!

Analysis method on FRB simulations with real noise

Test the method on a simulated FRB signal embedded into real observation data

time-frequency plane: FRB simulation + real data





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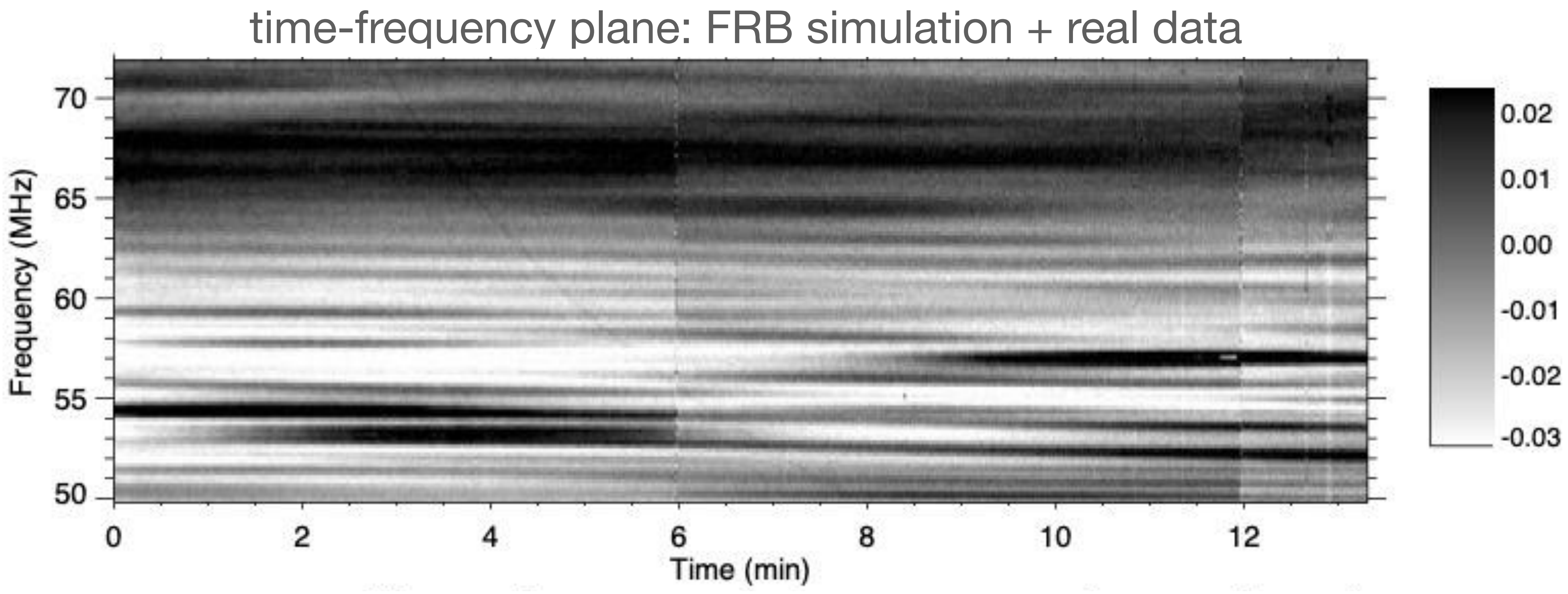
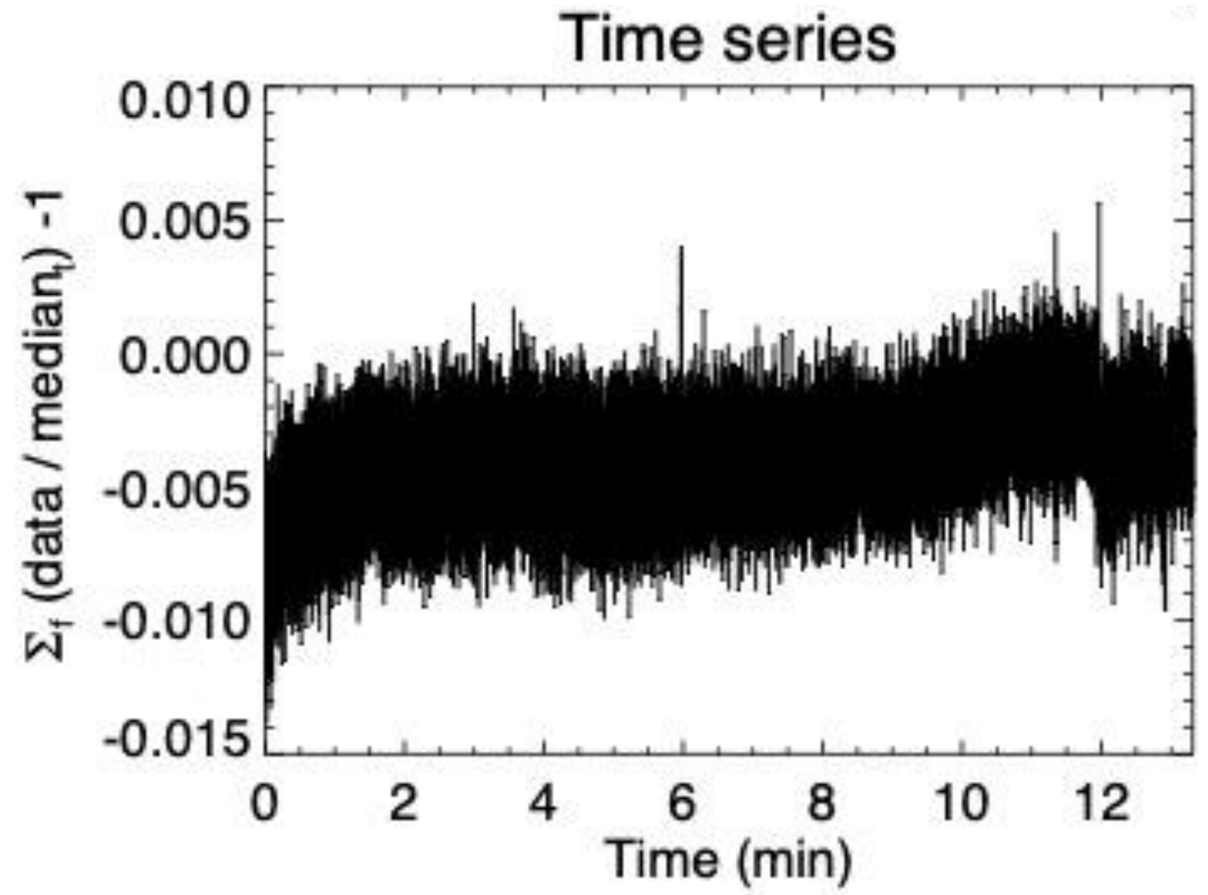
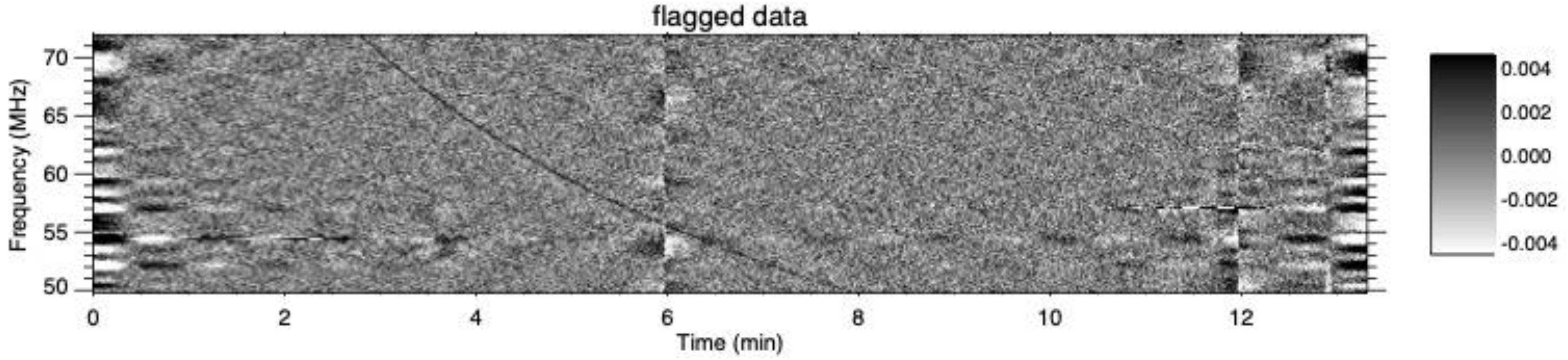




we apply the high pass 2D Fourier filter



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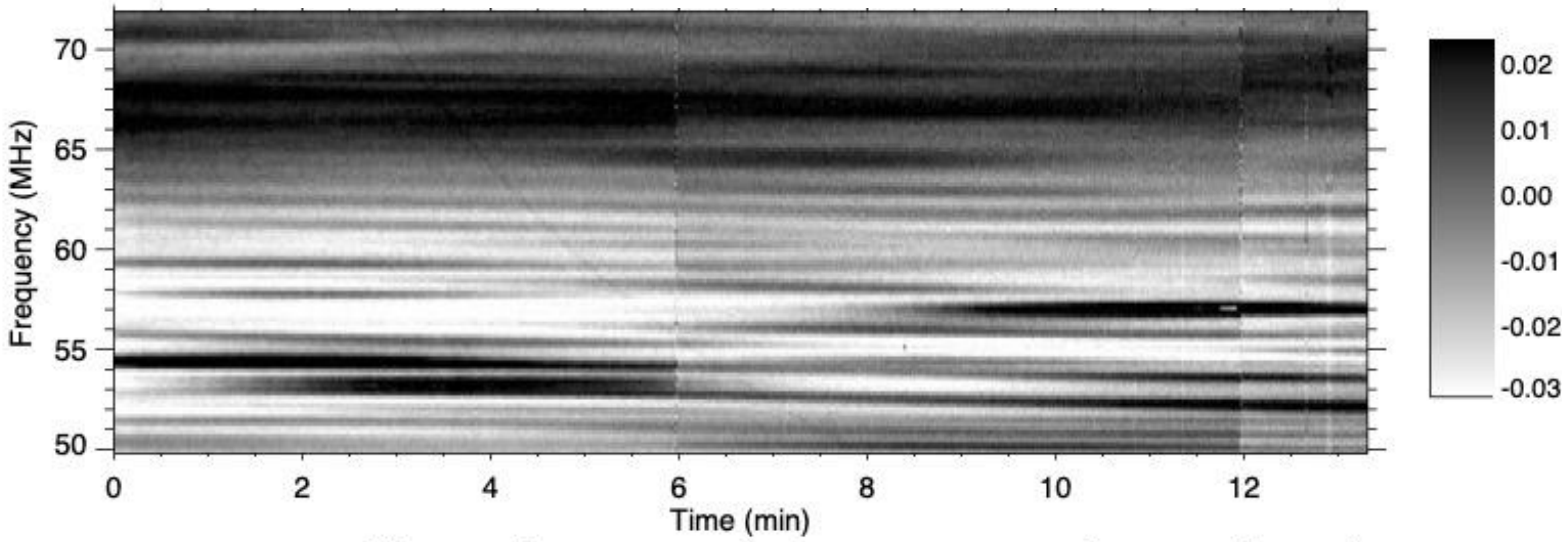

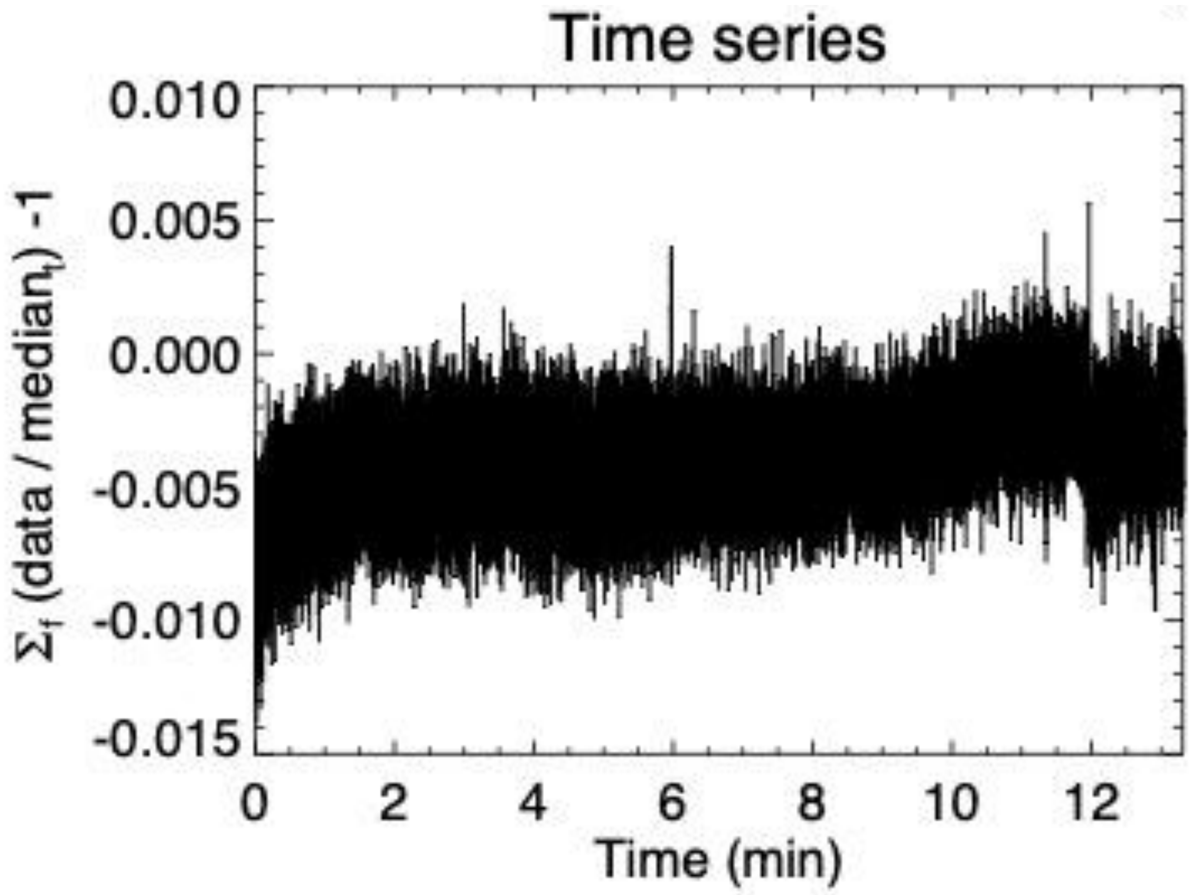

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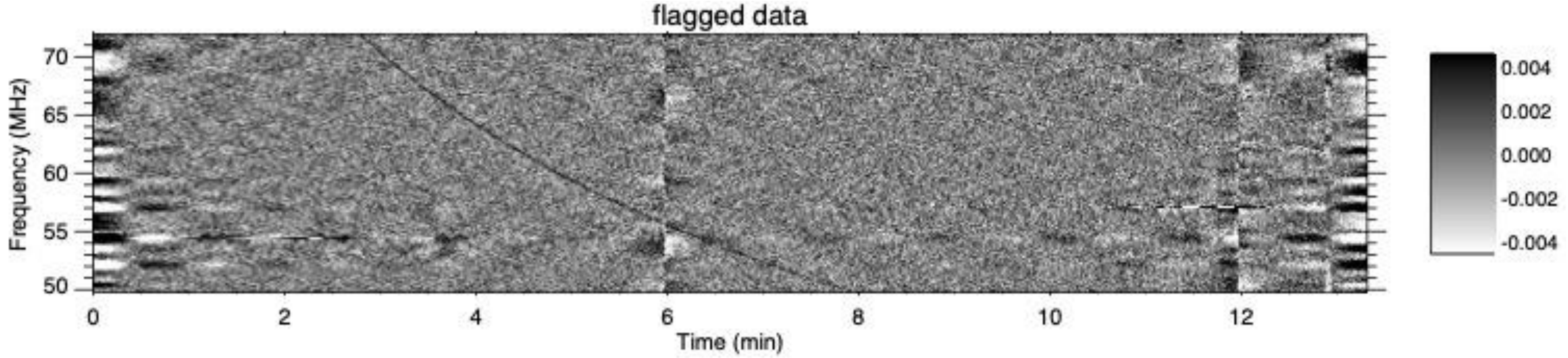
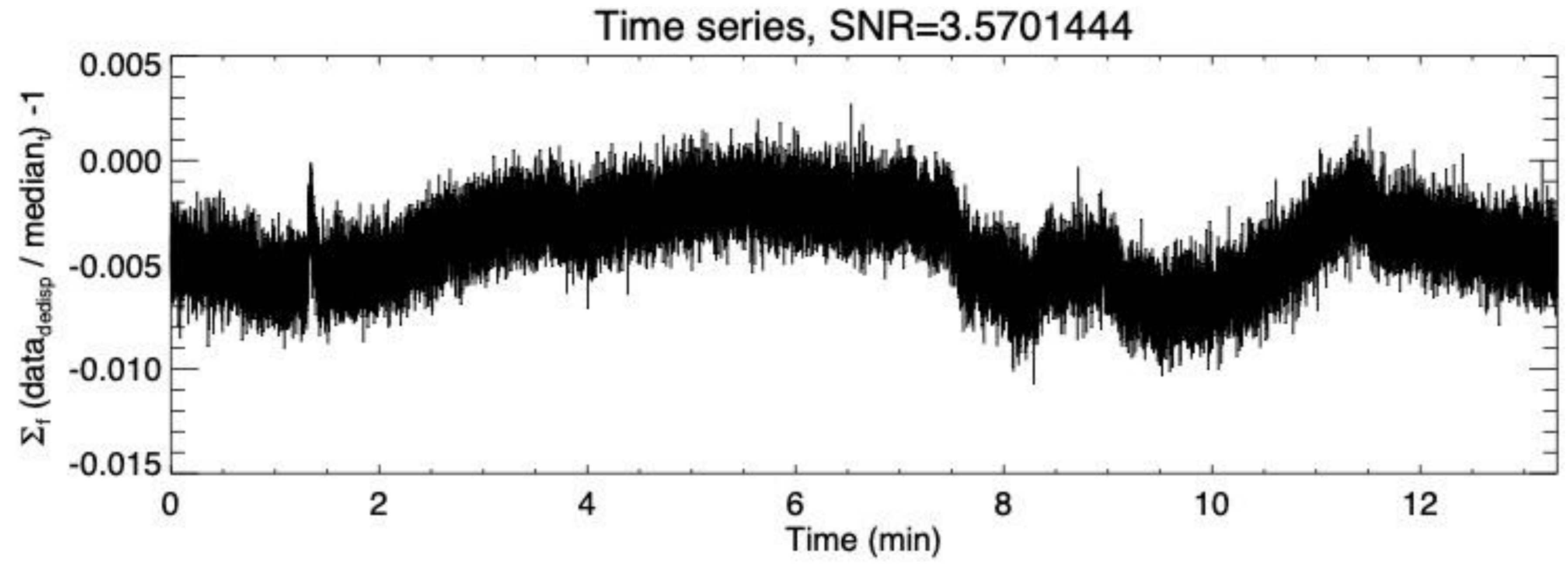
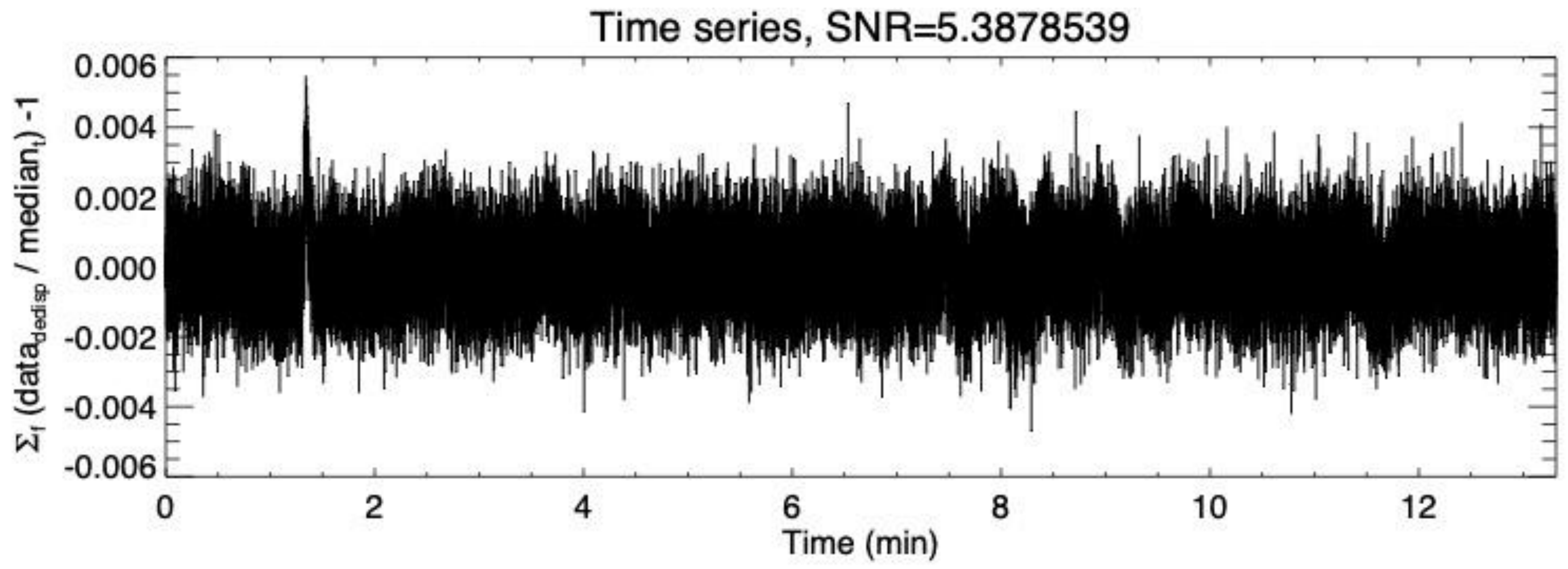


Comparison without and with filtering:





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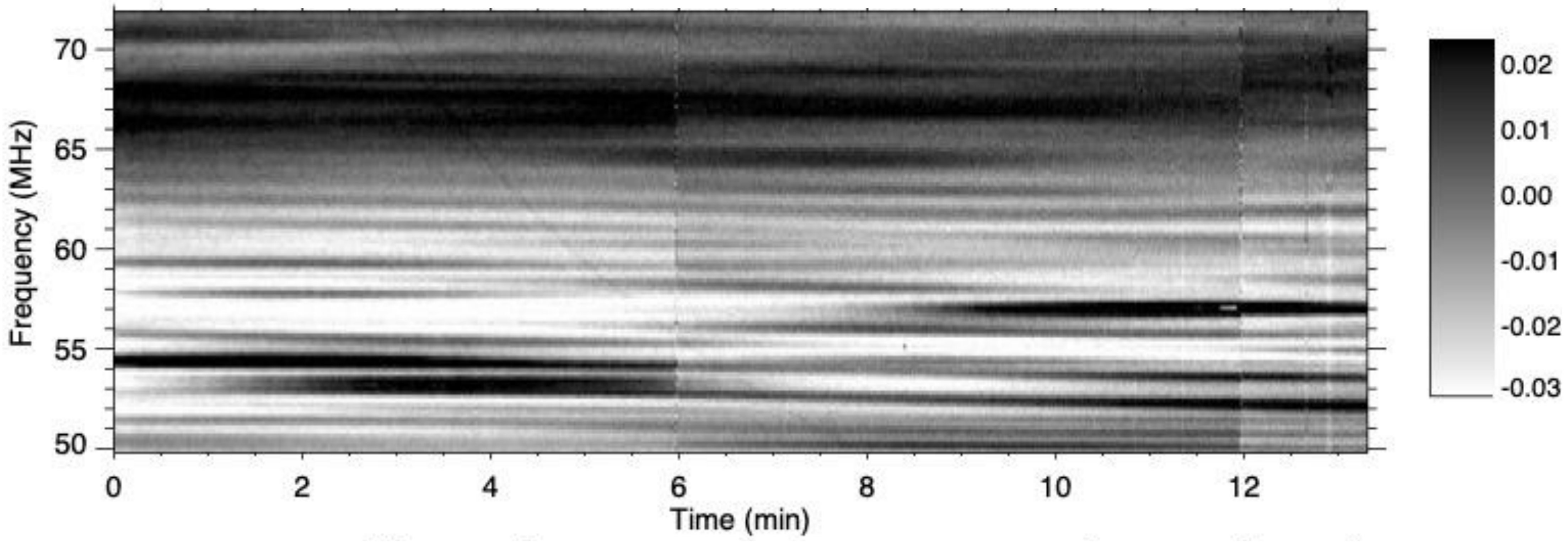

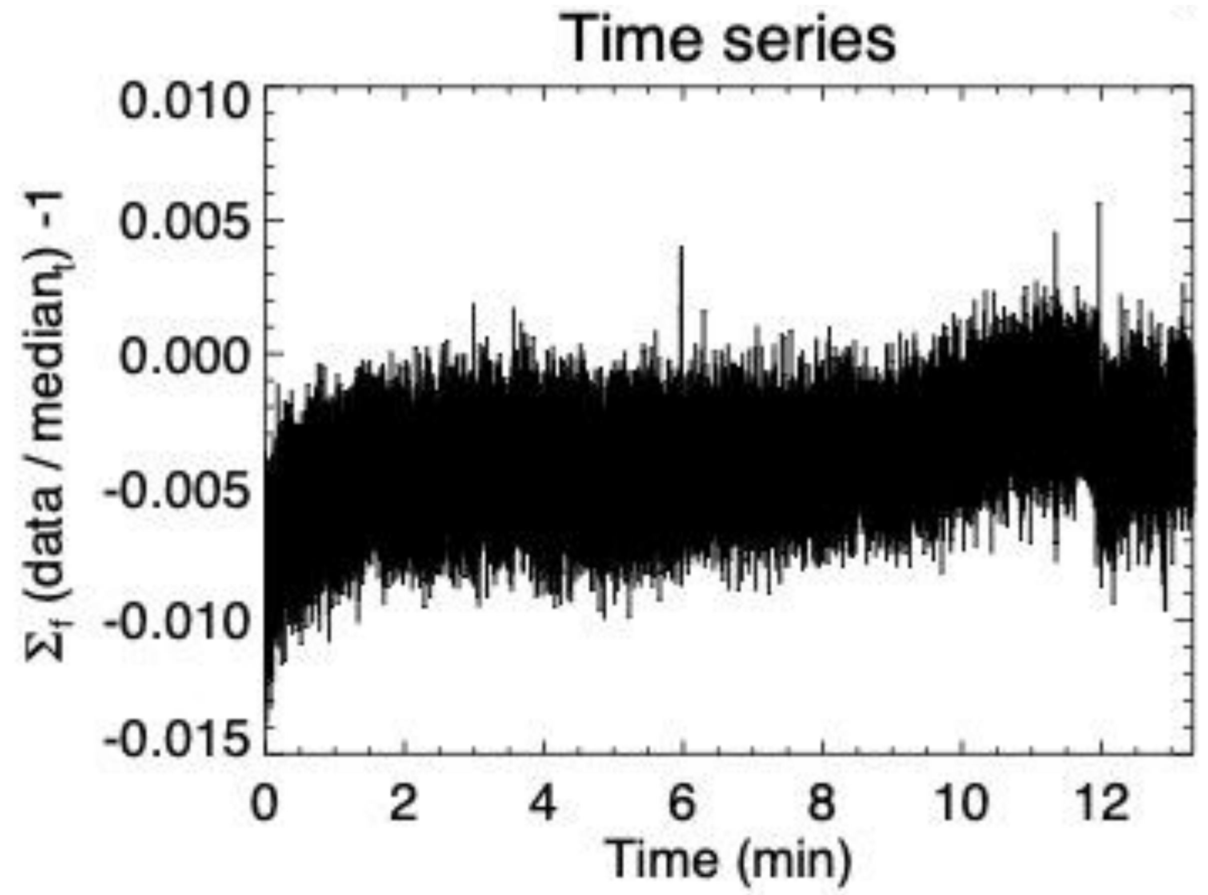

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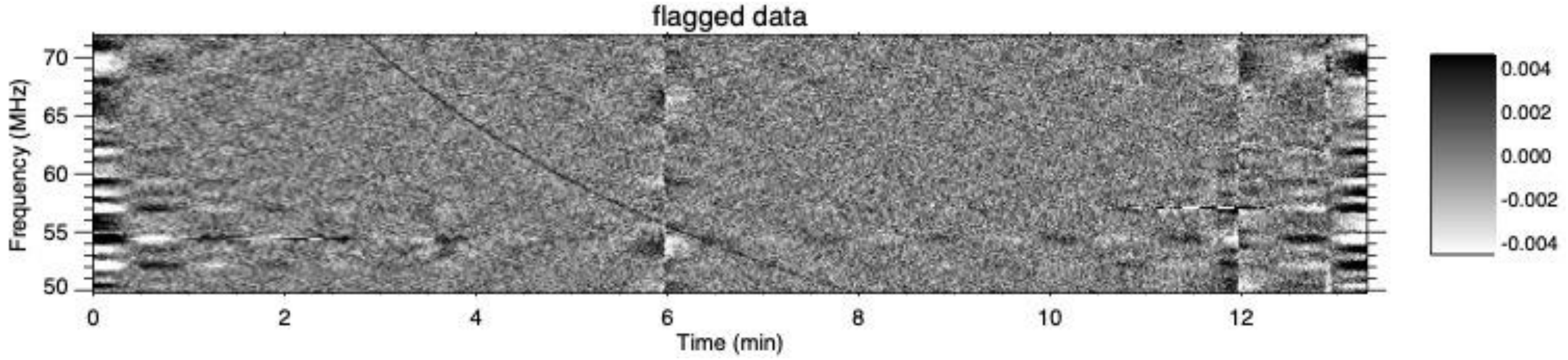

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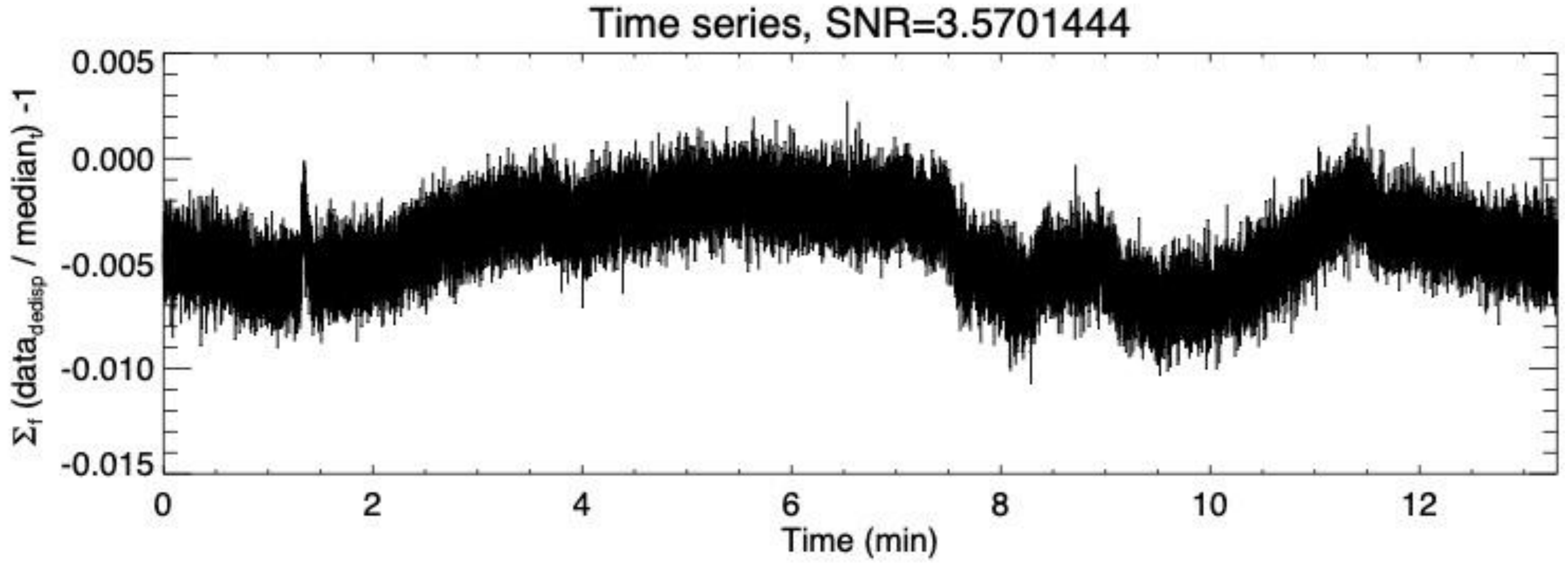
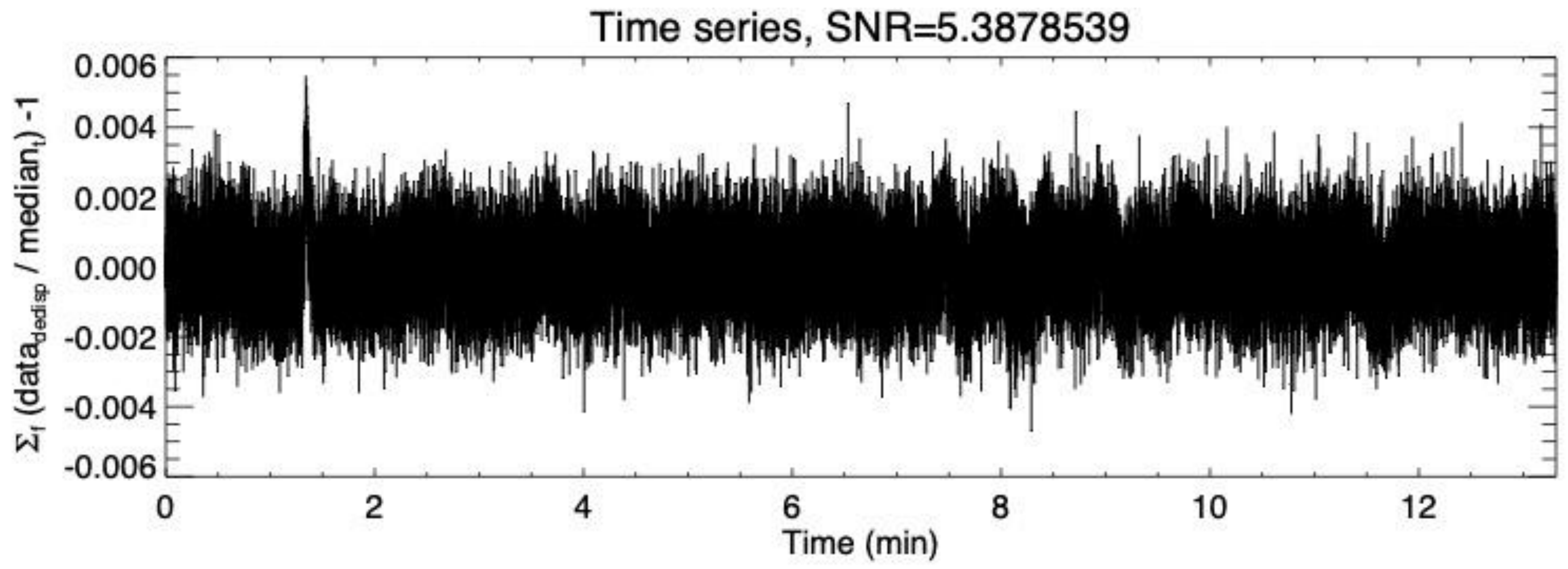
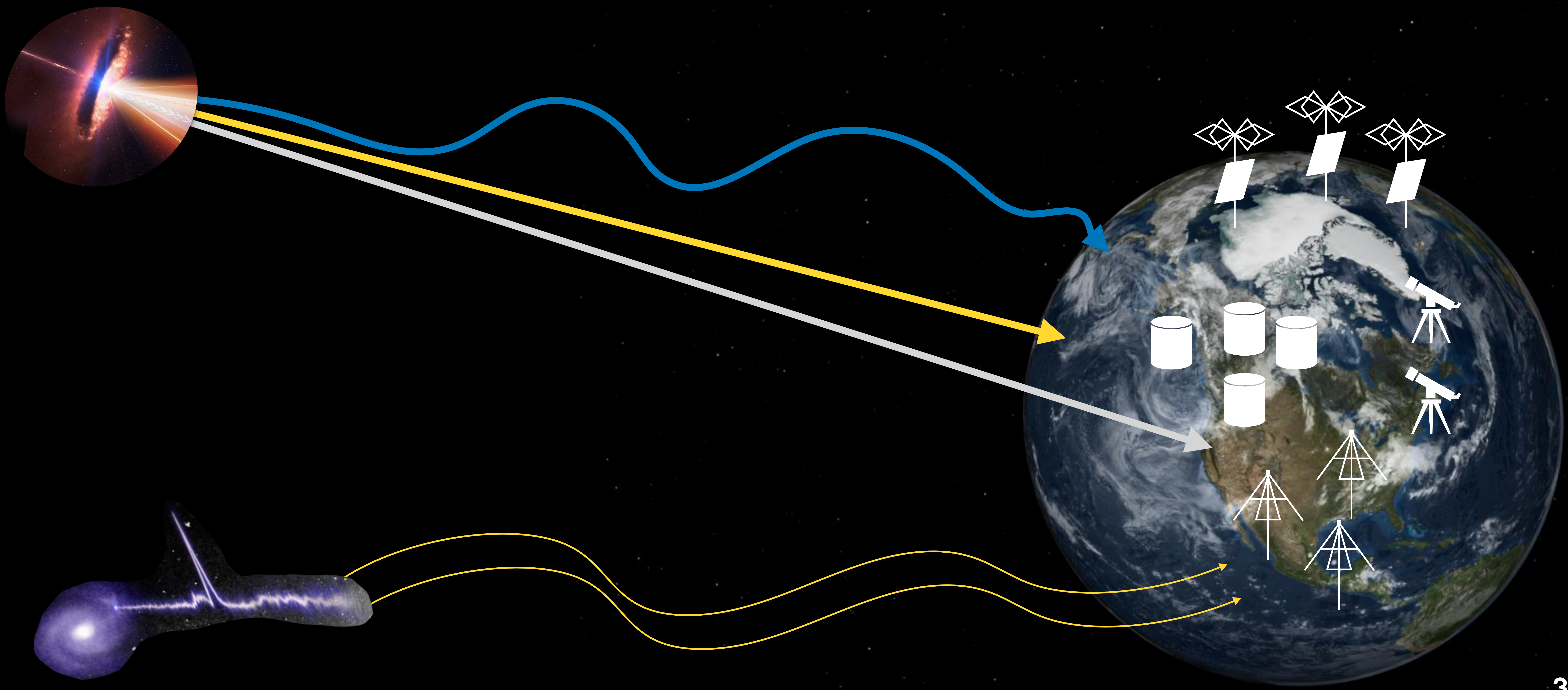




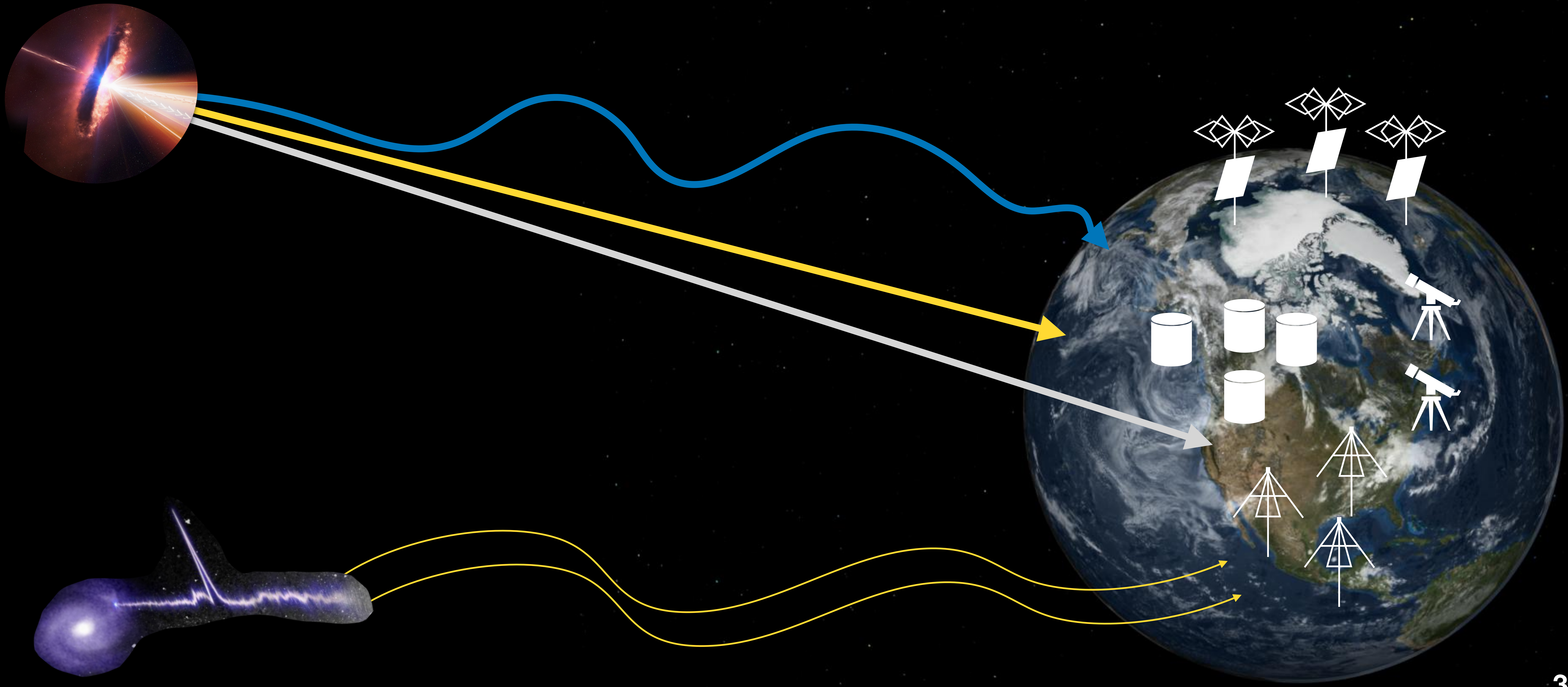
The high pass 2D Fourier filtering allows to increase the SNR by a factor ~1.5!

Summary of our journey with FRBs



Summary of our journey with FRBs

- FRBs are a new type of fast radio transients
- There is very sparse information on them yet
- NenuFAR conducts observations at low frequencies on repeaters
- The existence (or not) of FRBs at low frequencies is critical for the emission models and source candidates



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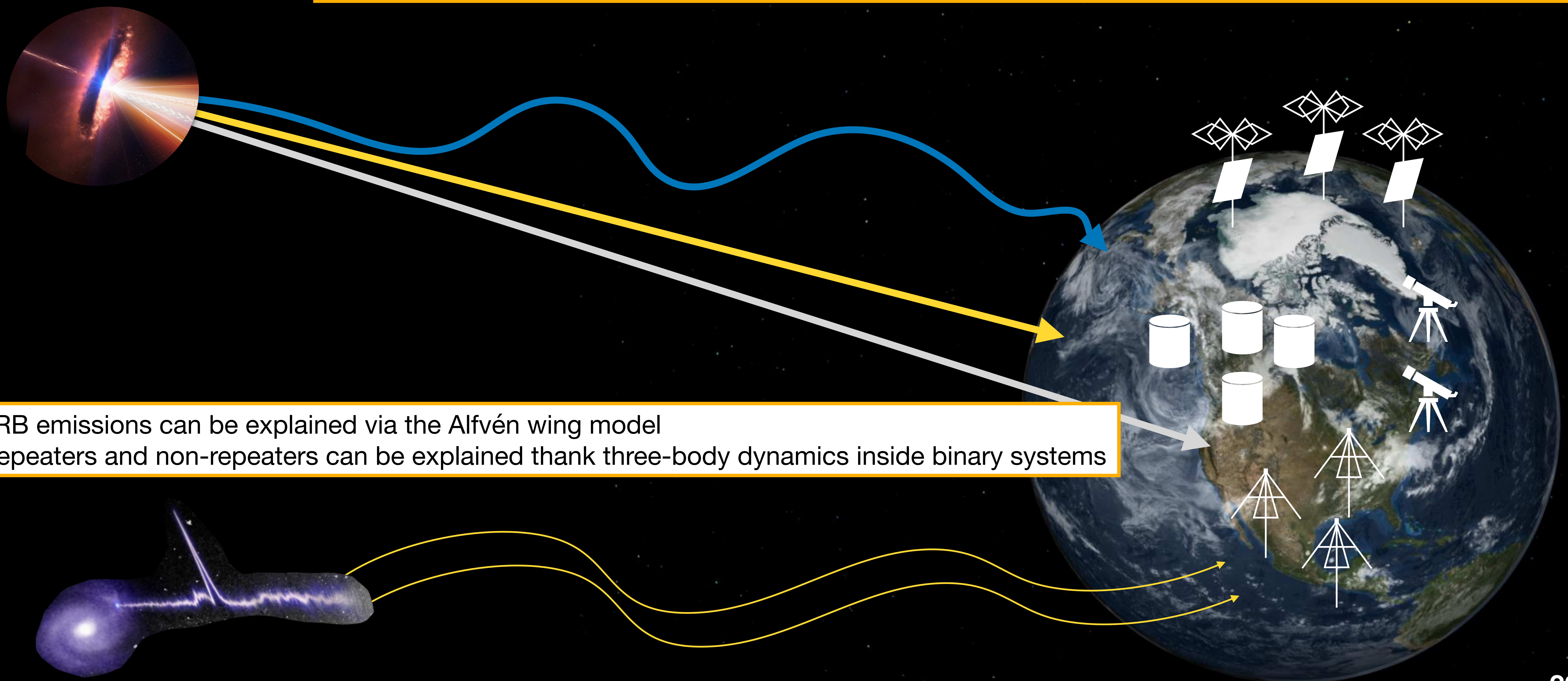

- FRB emissions can be explained via the Alfvén wing model
- Repeaters and non-repeaters can be explained thank three-body dynamics inside binary systems

The journey doesn't end here...

The journey doesn't end here…

- Could FRB sources also emit astroparticles?
- What radio emissions from astroparticles sources can tell us?

Multi-messenger (MM) and multi-wavelength (MW) high energy sources

There is already many hints toward the connections between radio transients and MM emissions

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→ jets/accretion-disks and kilonova
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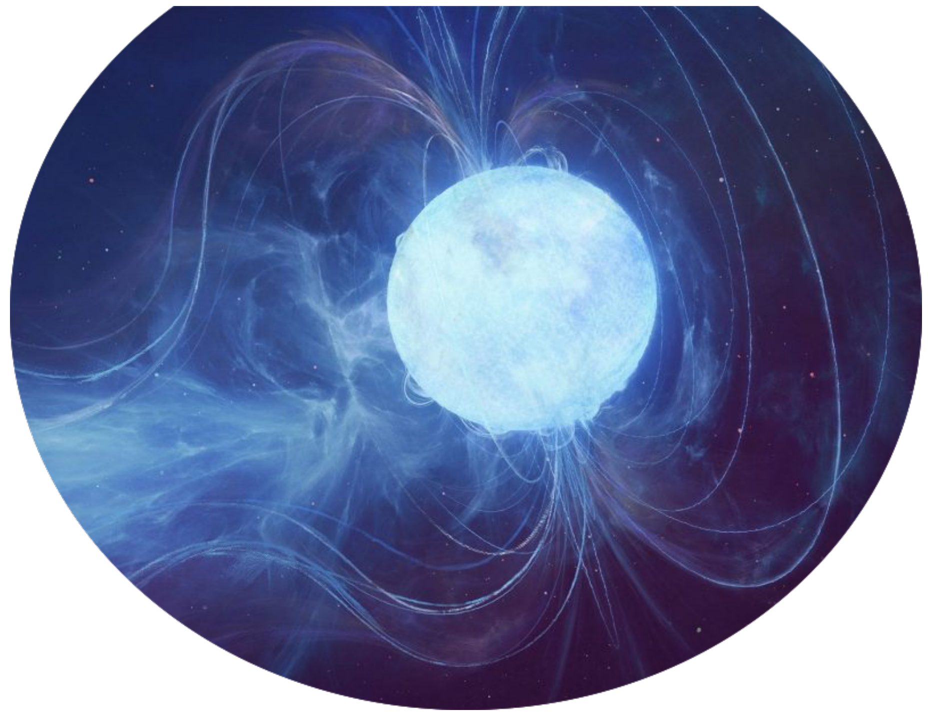
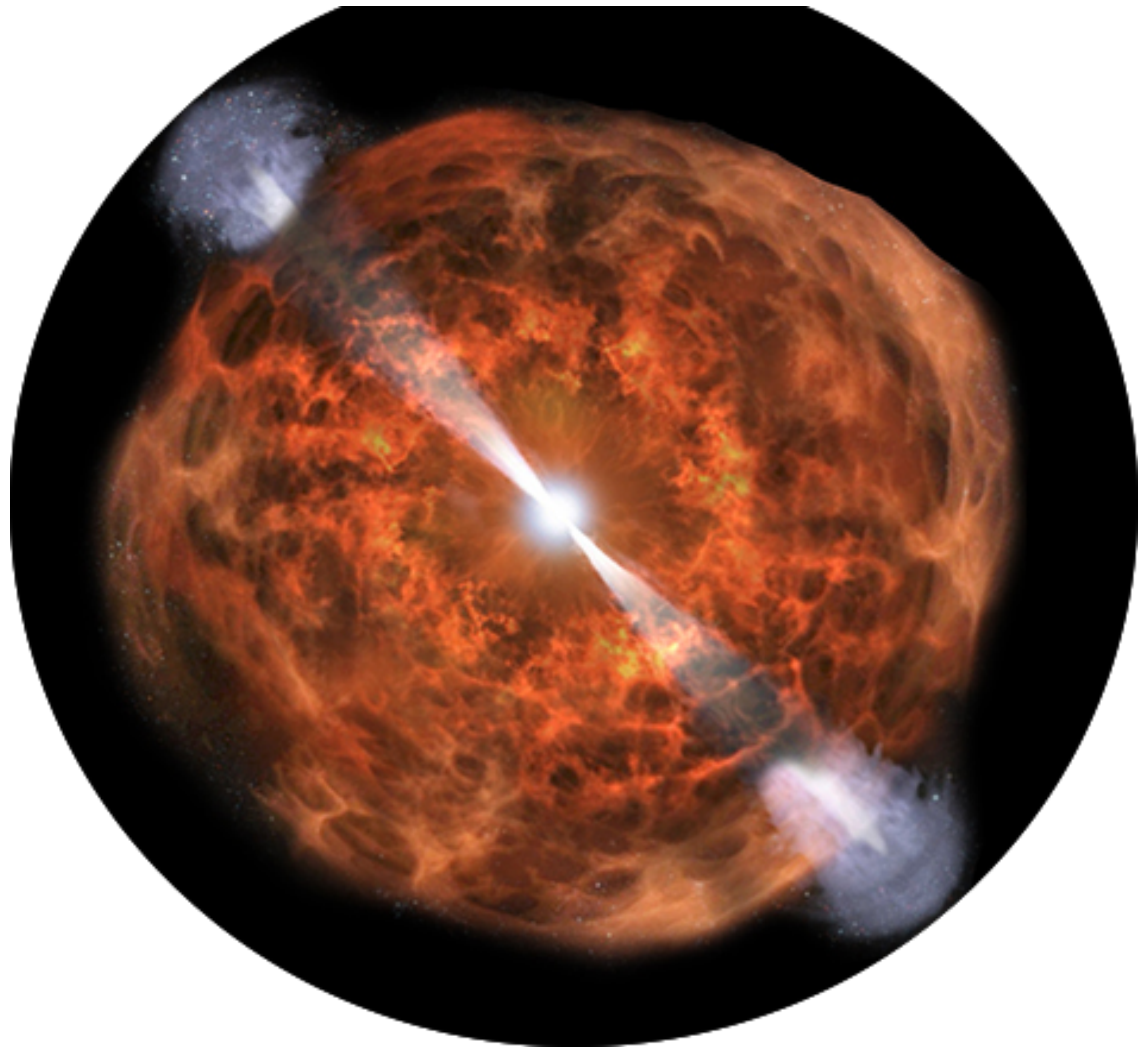
Kilonova

Magnetars





Coalescence

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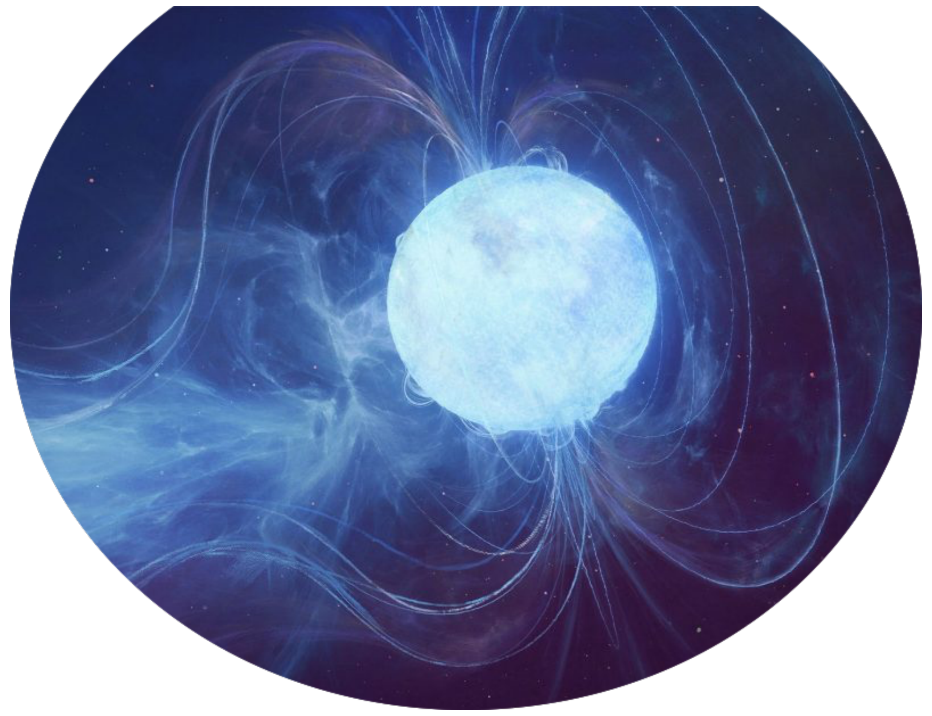
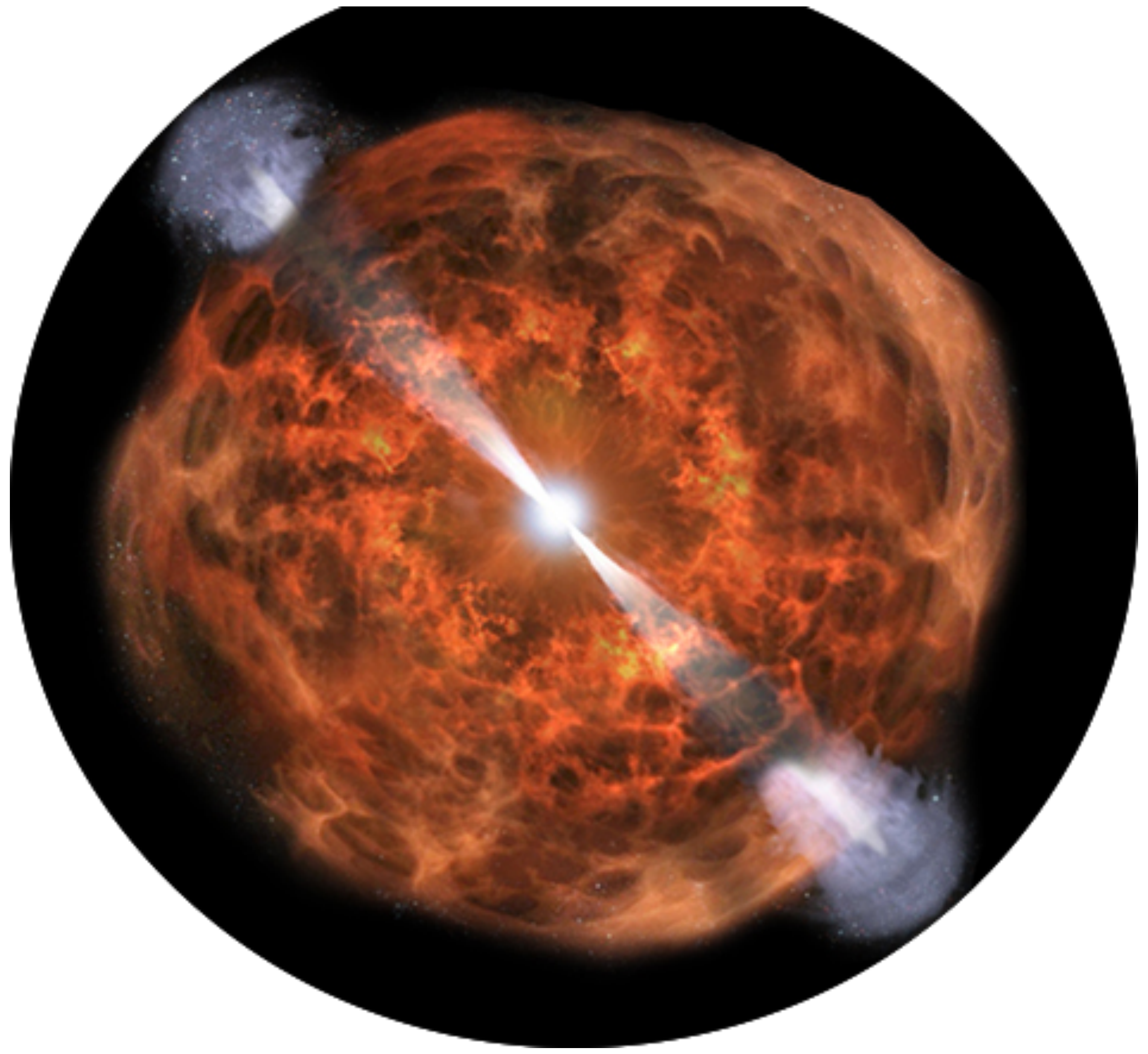


?

Kilonova



?

Coalescence

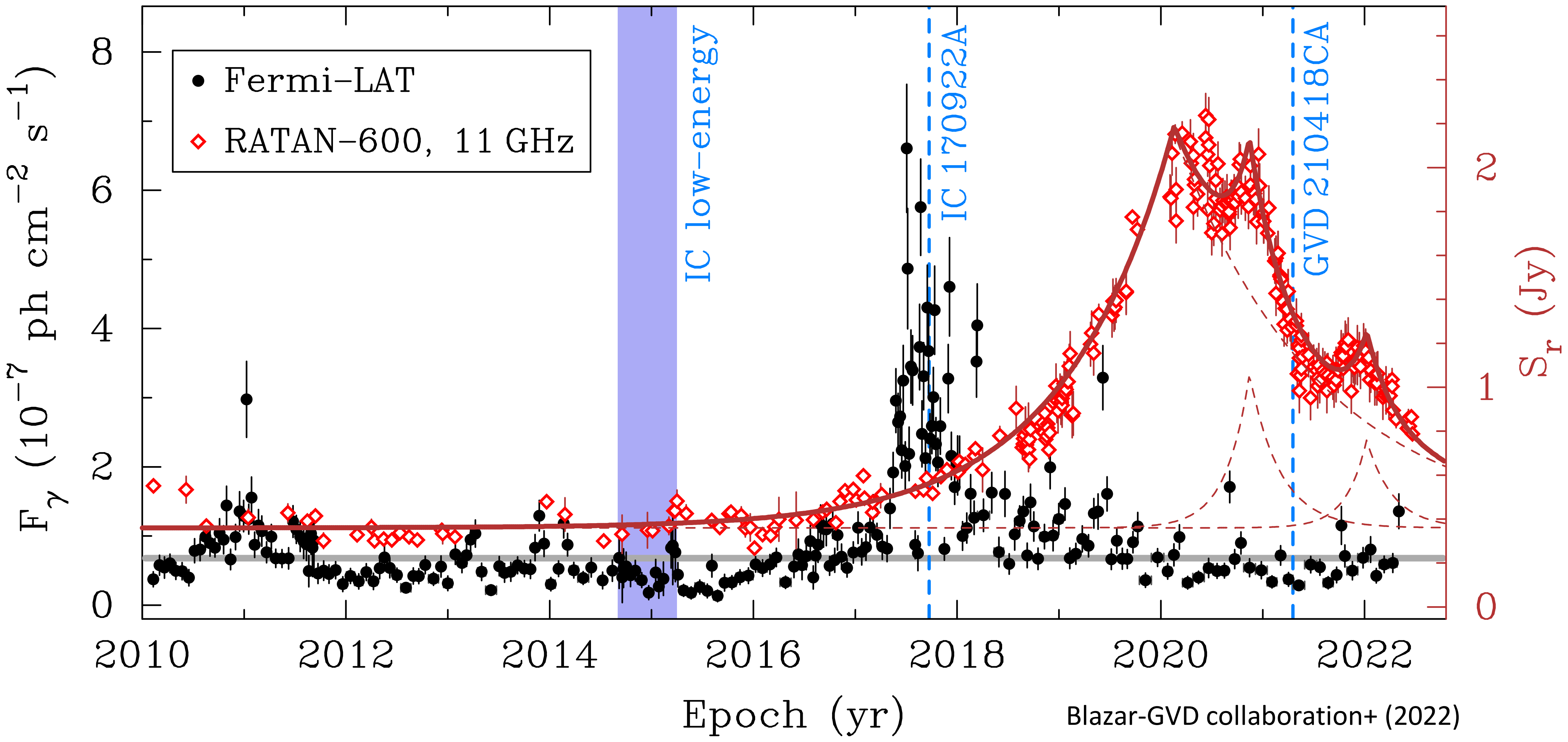
We need to have MM and MW models in order to probe the physics consistently

Combining astroparticle detectors and radio-telescopes

Combining astroparticle detectors and radio-telescopes

- **Observation strategies** → joint observations
  - improve alert strategies
  - bring unique insight for models
- **Alert strategies** → tuned thanks to model predictions and experimental feedbacks

Blazar activity



Blazar-GVD collaboration+ (2022)

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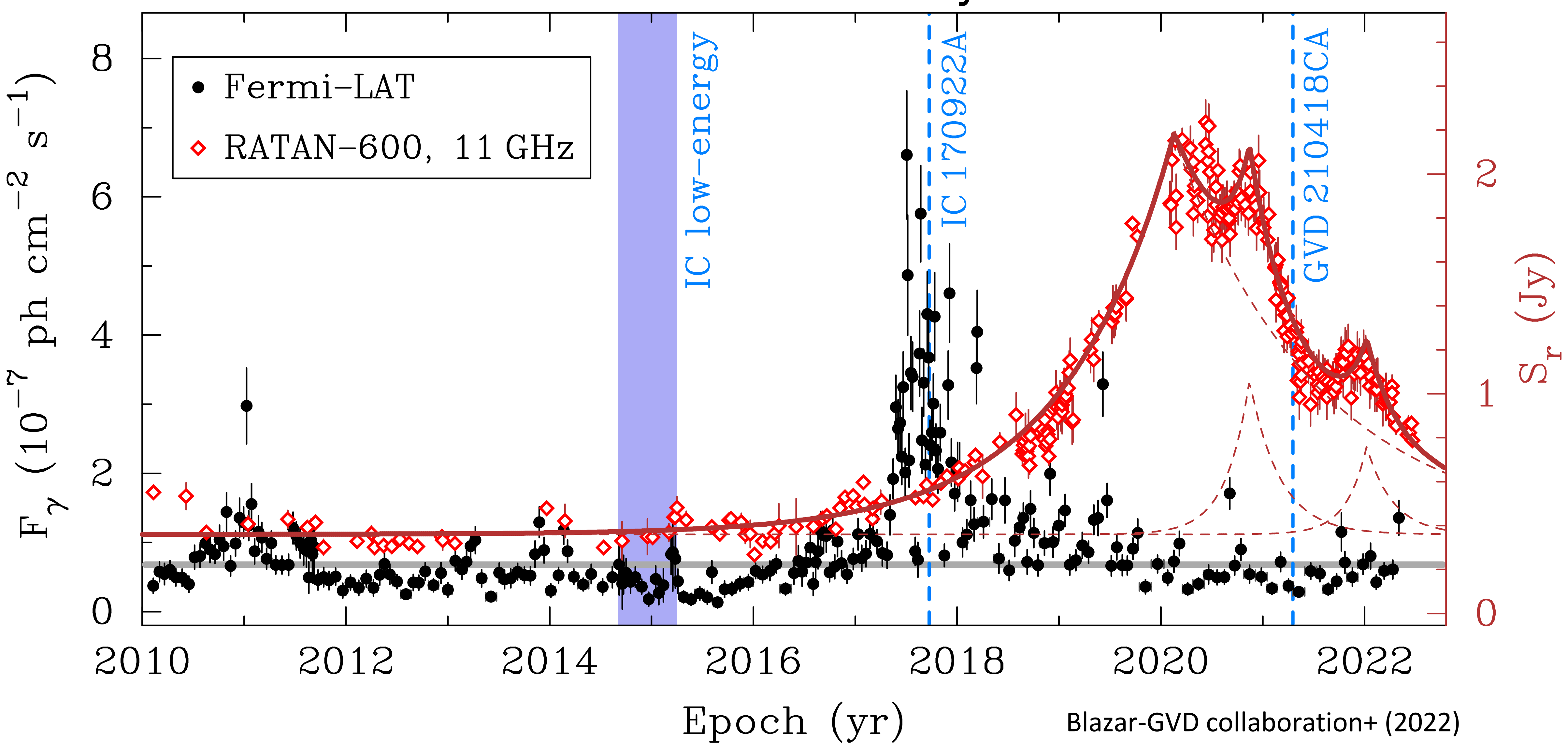

Blazar-GVD collaboration+ (2022)

Transverse experiments: radio-astronomy / radio-detectors

- high background rejection expertise (astroparticle community)
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RadioGaGa:
beamformed radio arrays for EAS gamma ray detection

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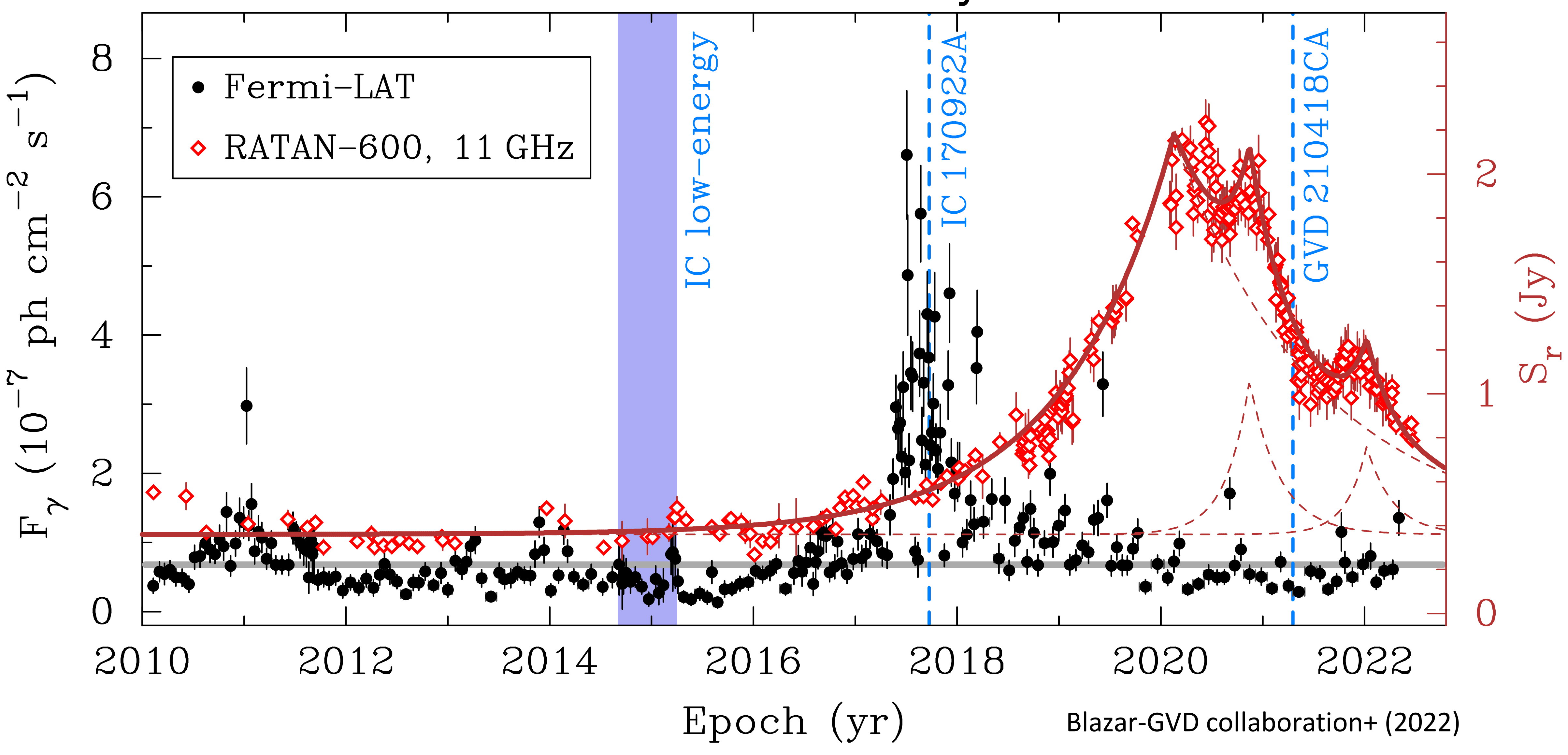

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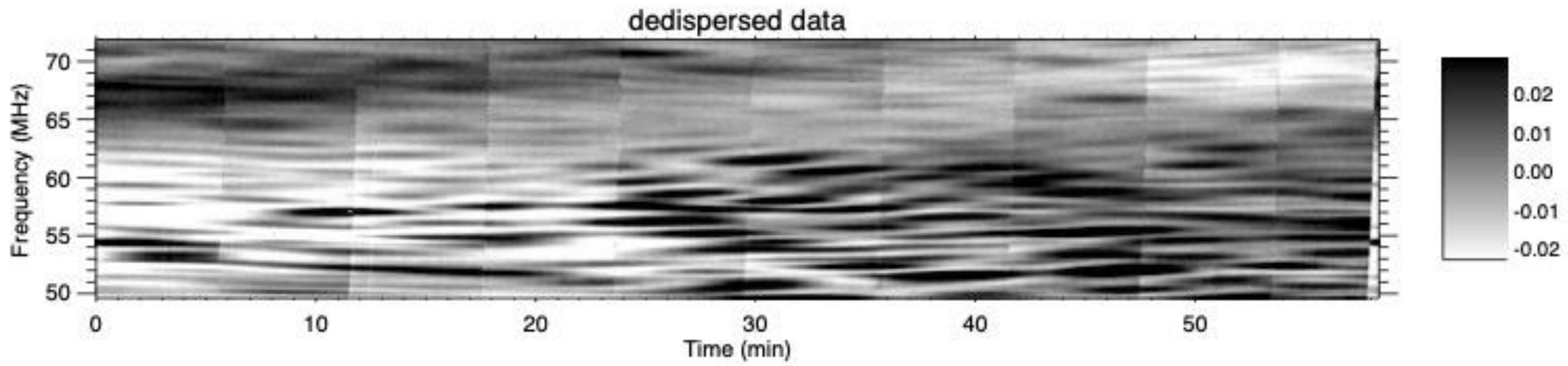
FRB observation



- 1h our of data taking = 99.9% of noise
+ mJy sensitivity (1 Jy → 25 nV/m)

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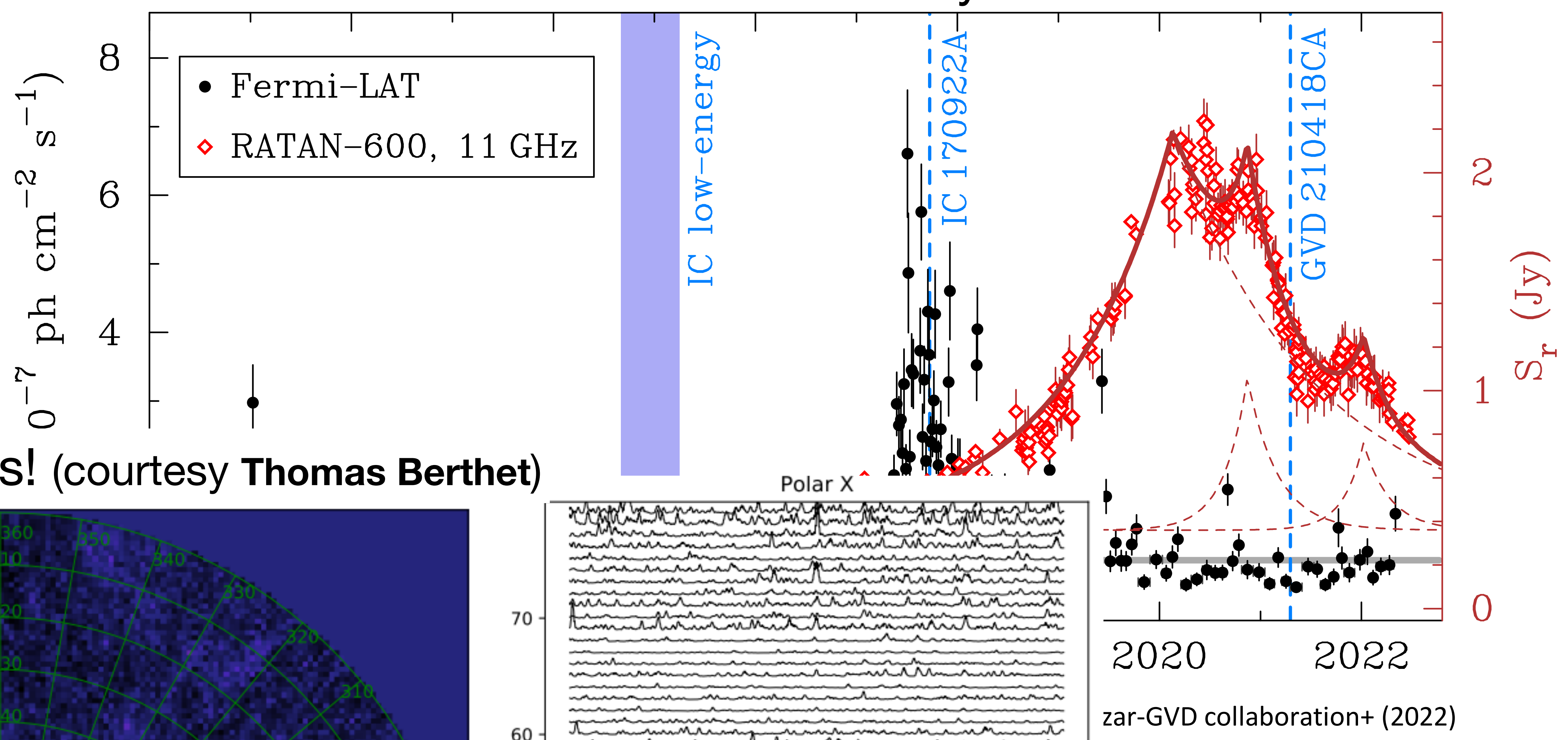
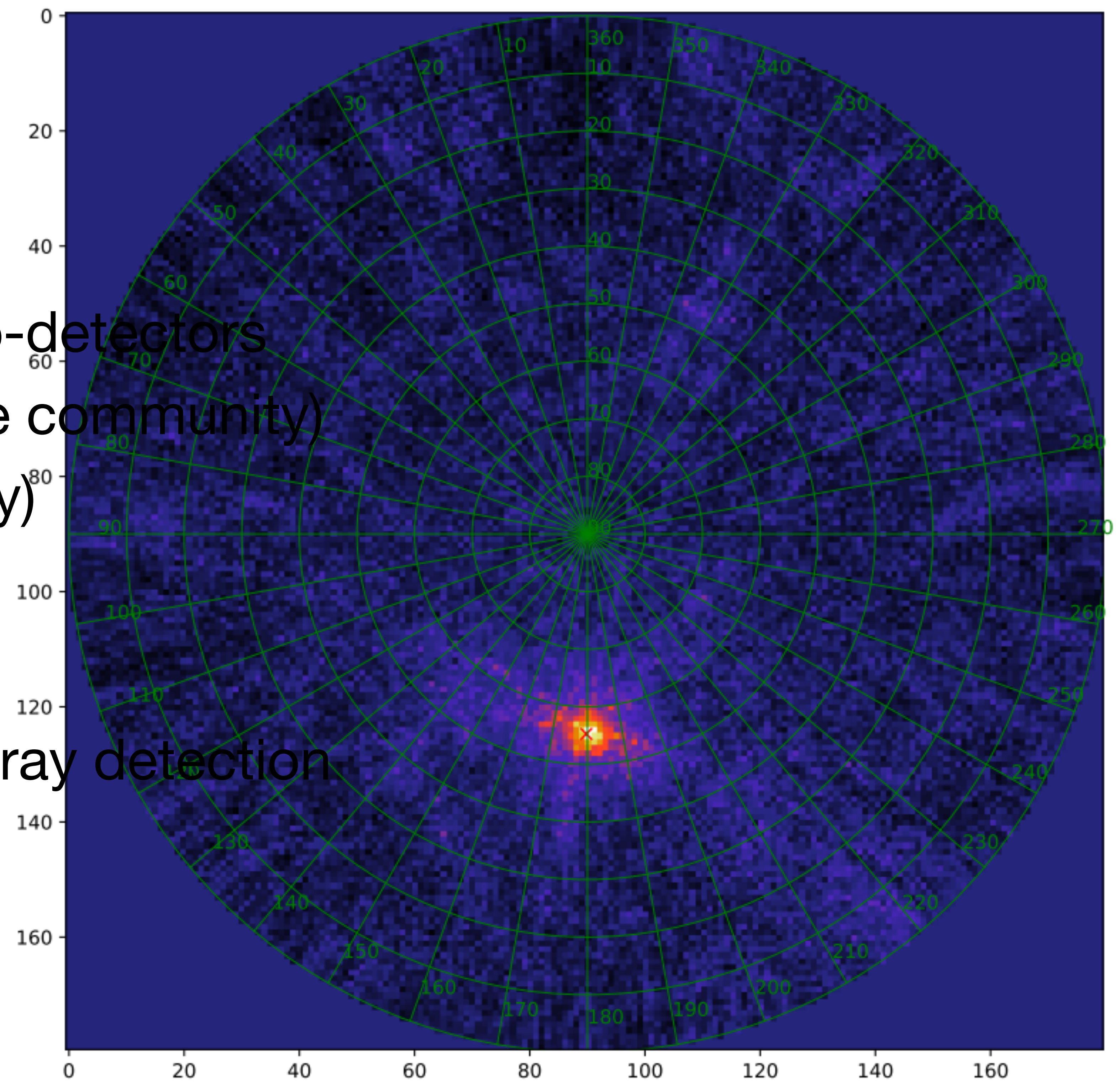
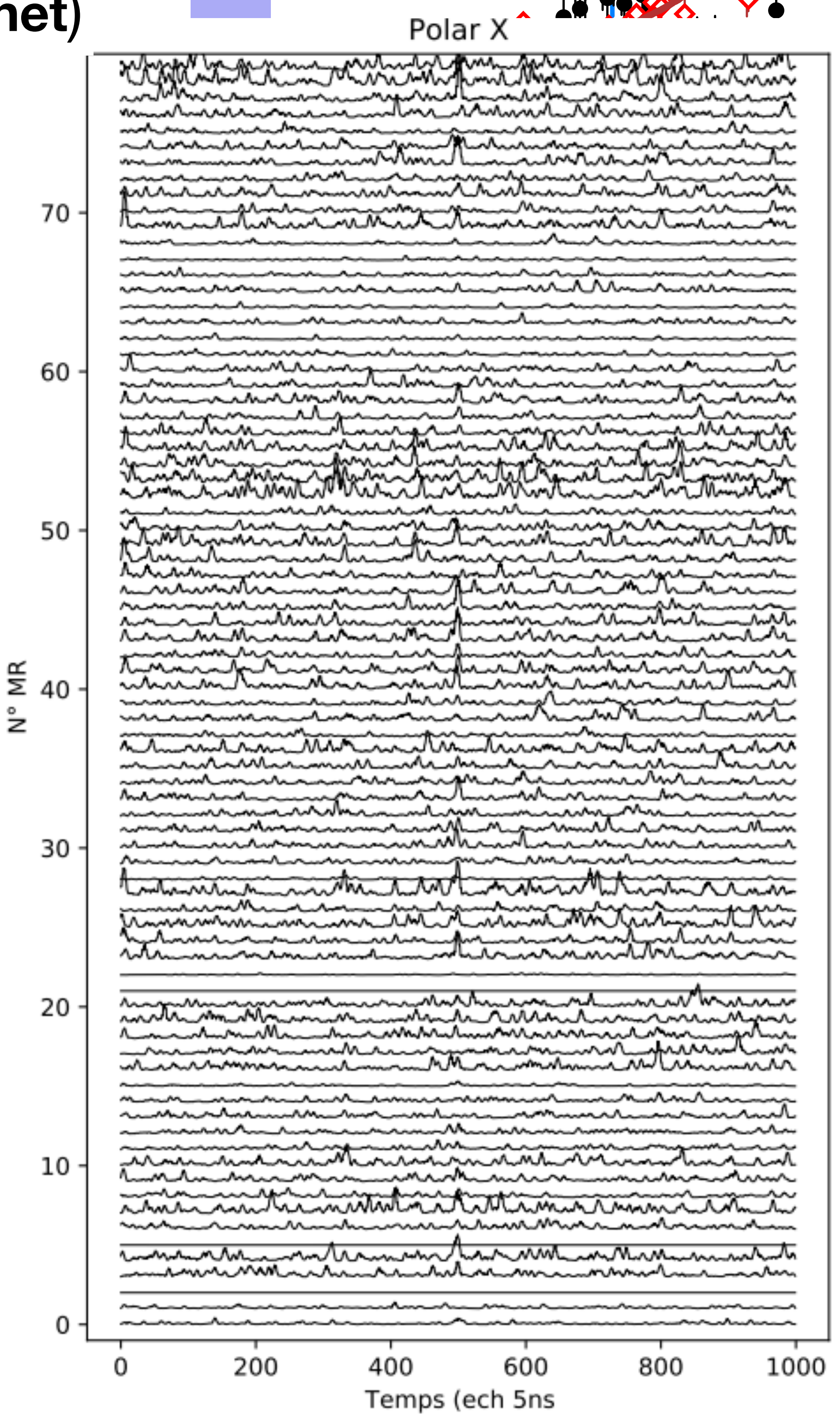
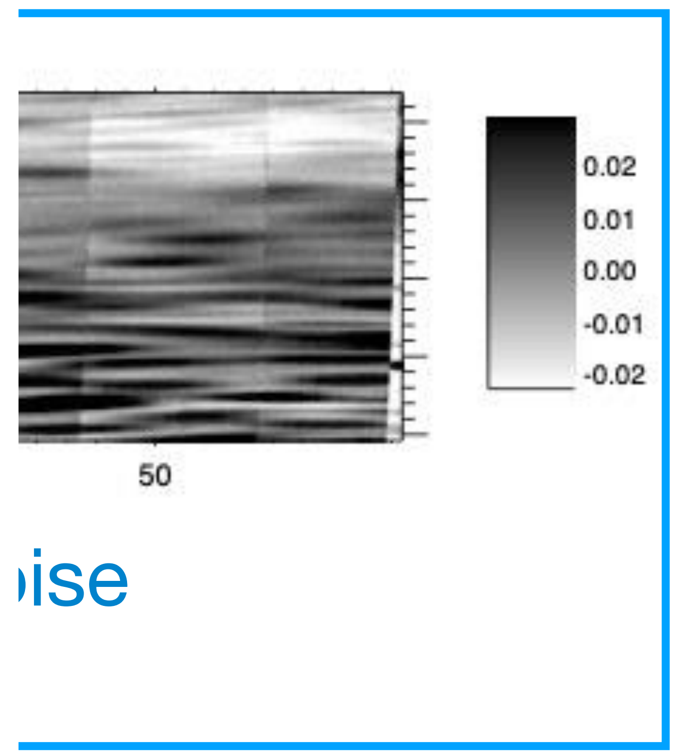


Solar nano pulses! (courtesy **Thomas Berthet**)







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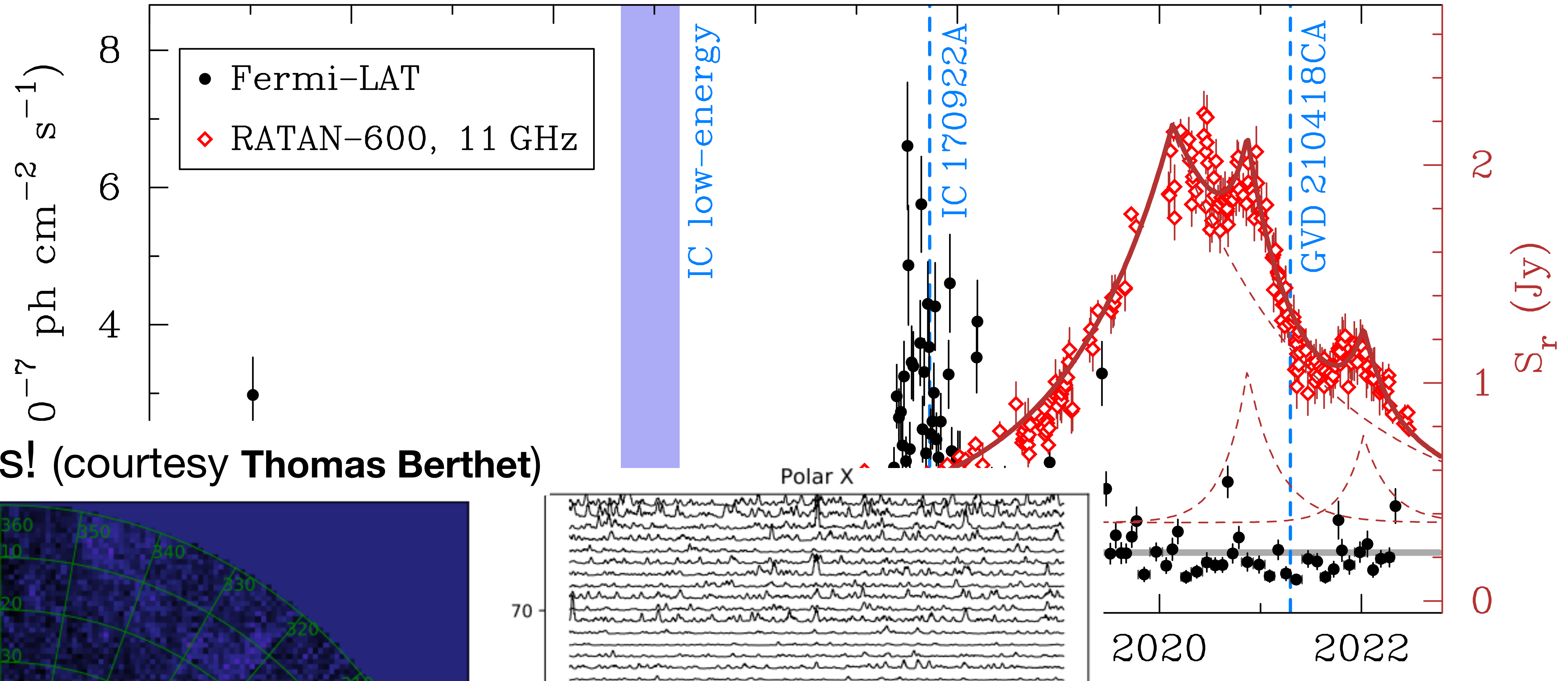

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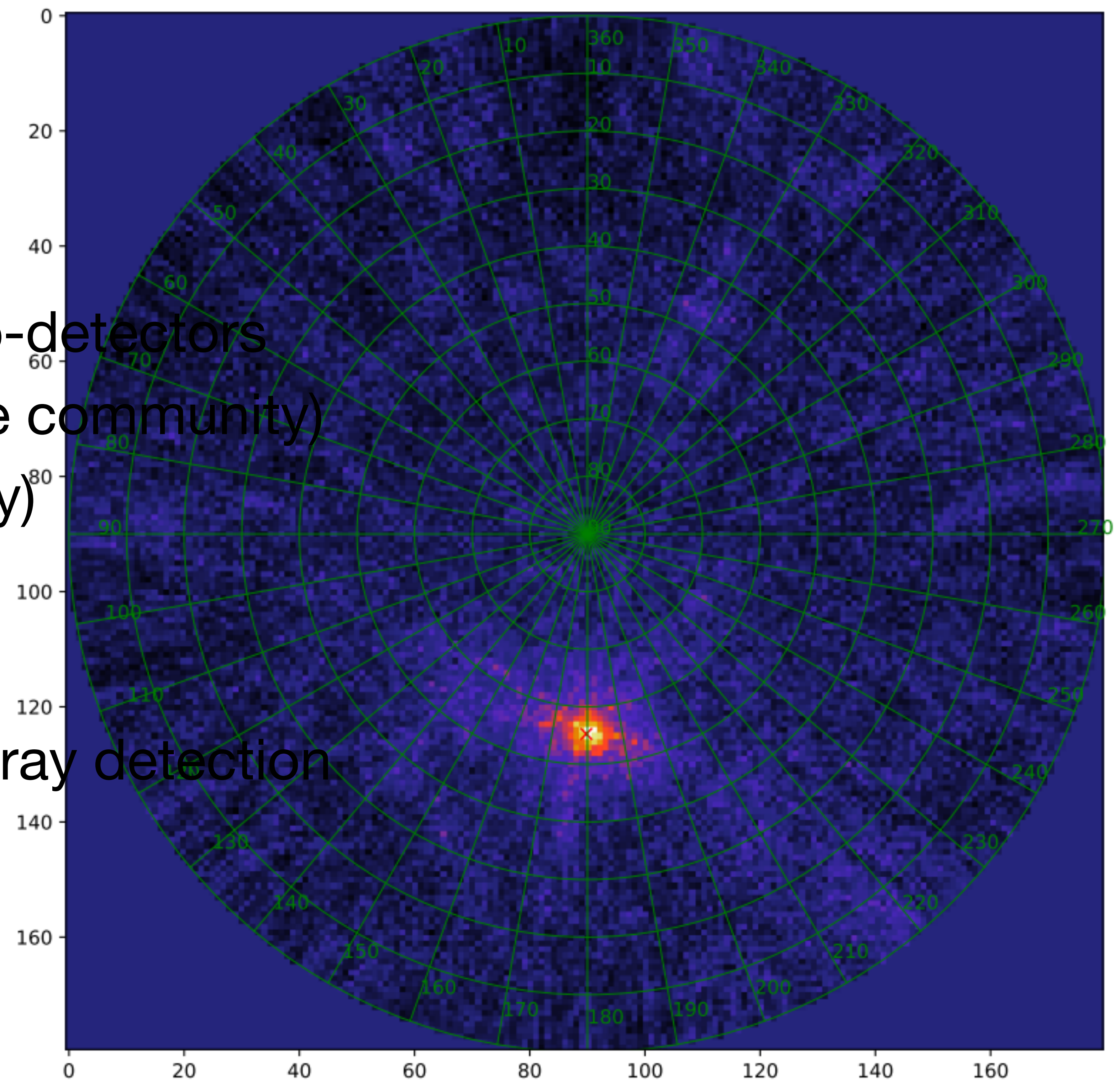

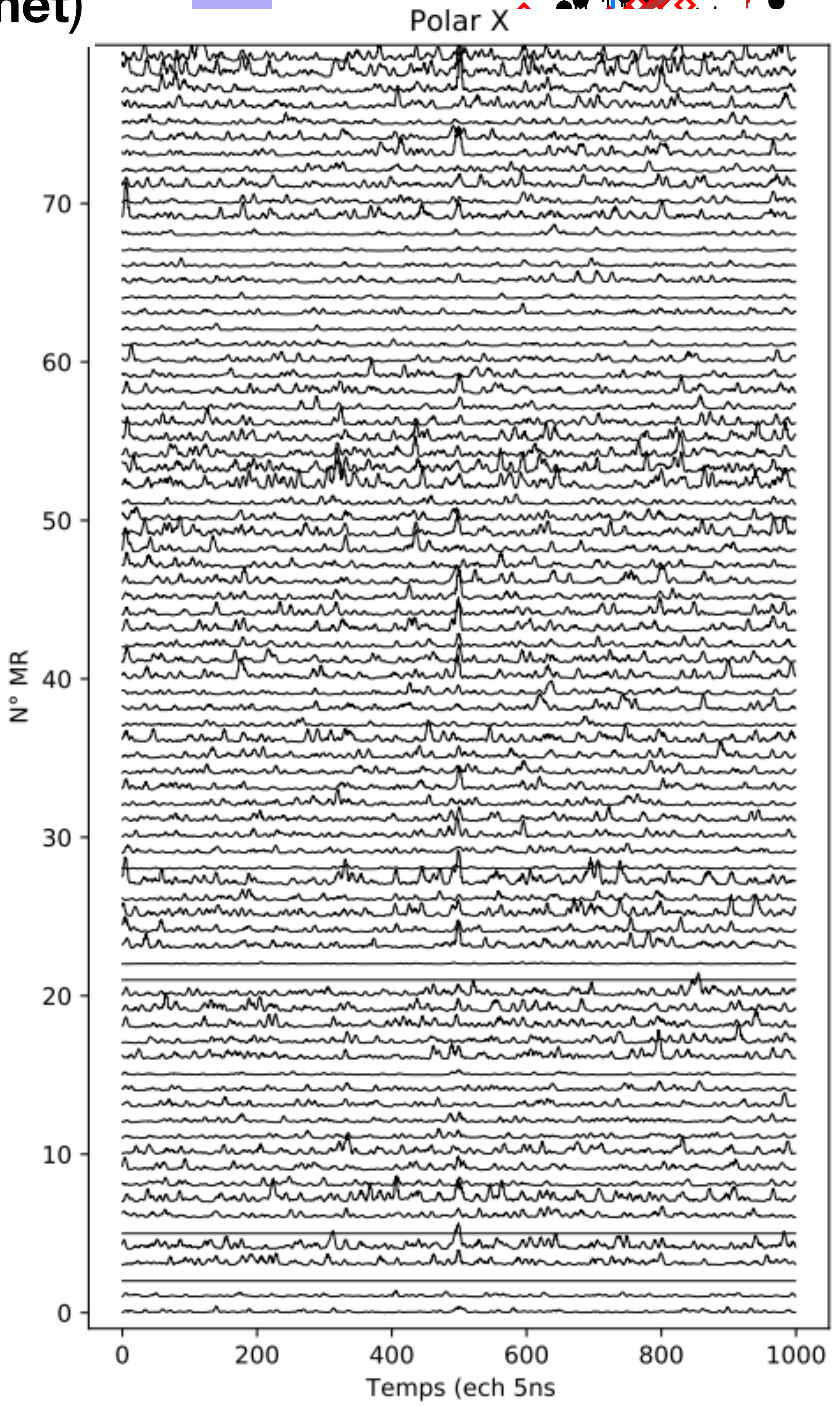

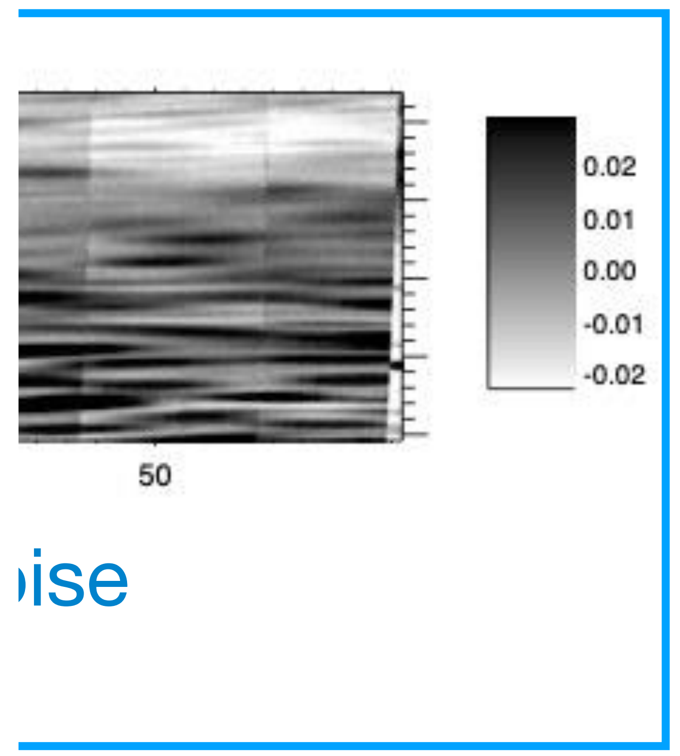

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Astroparticle and radio-astronomy communities can help each other

Conclusion

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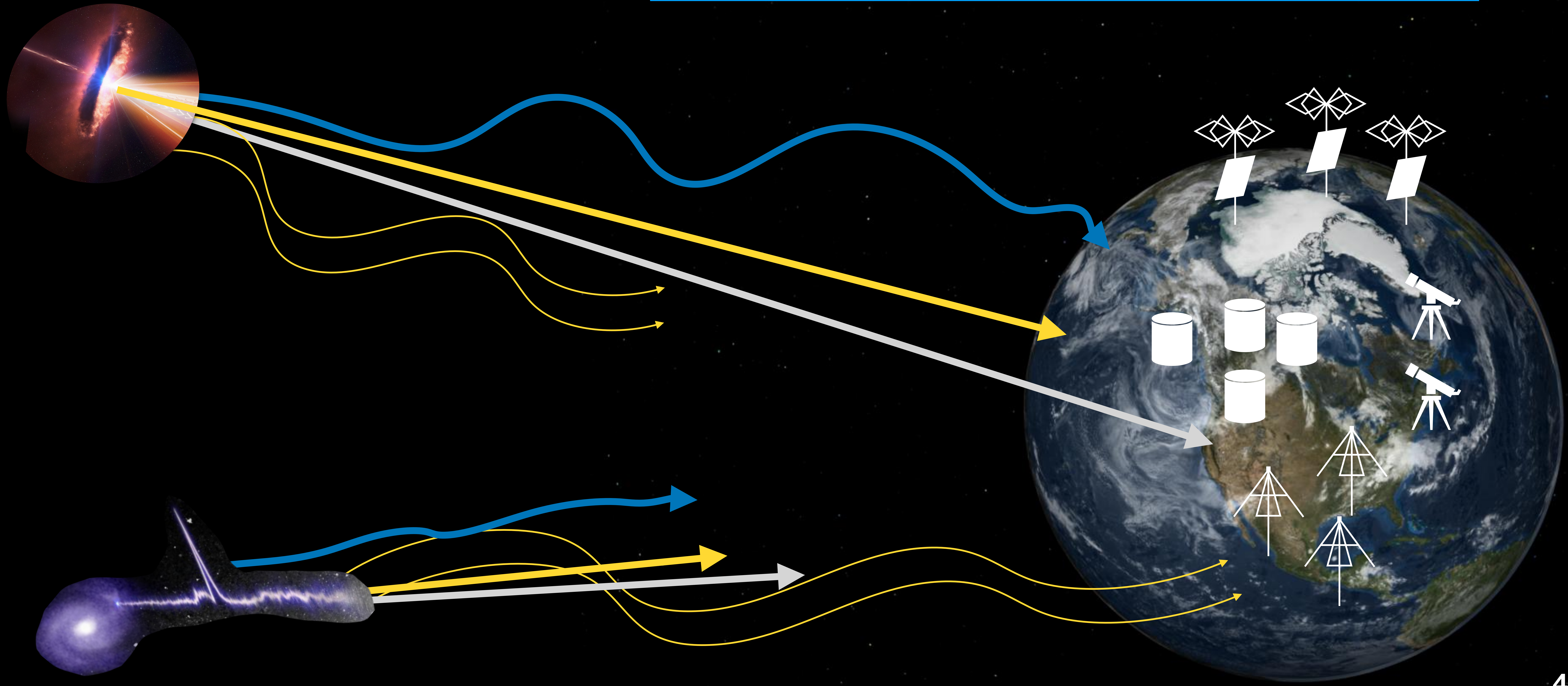
The advent of the multi messenger astronomy mixed the frontiers between astroparticles and radioastronomy sources



Conclusion

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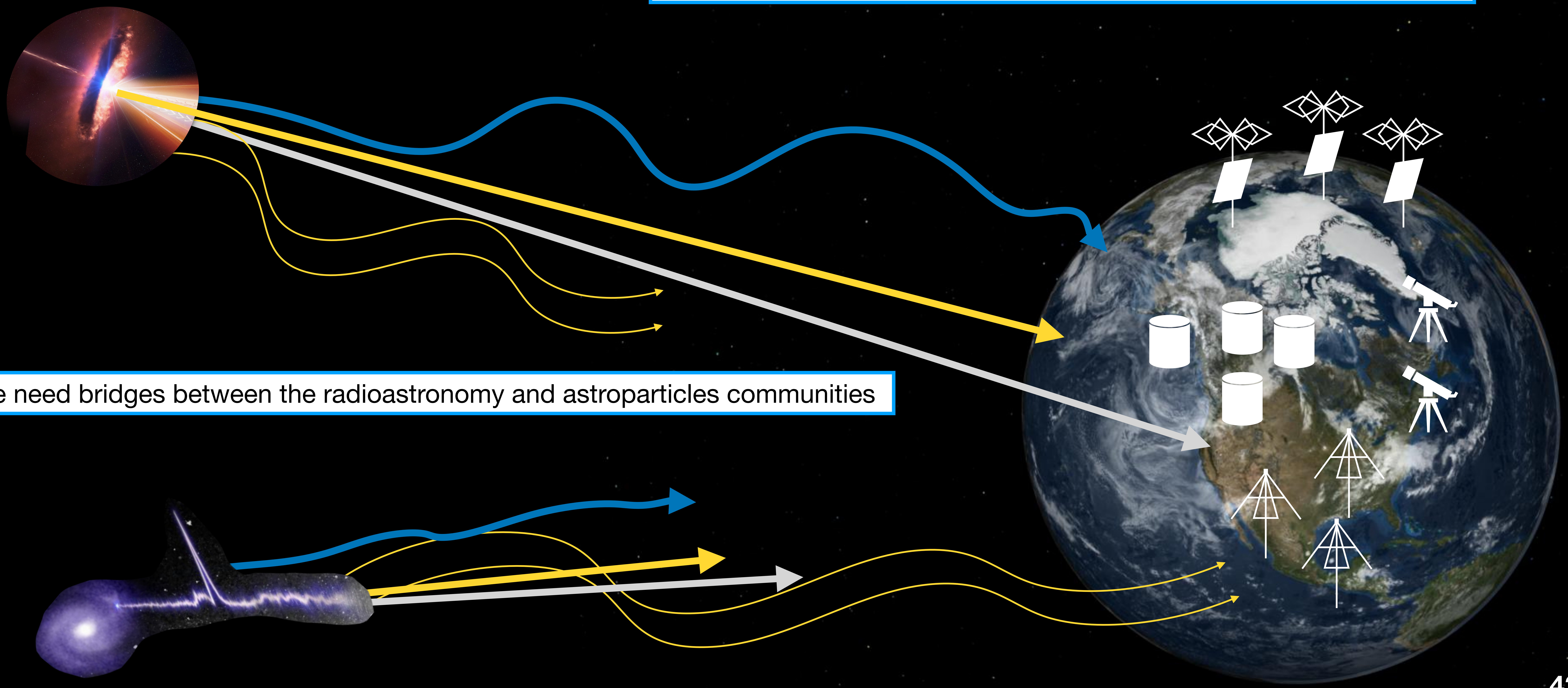
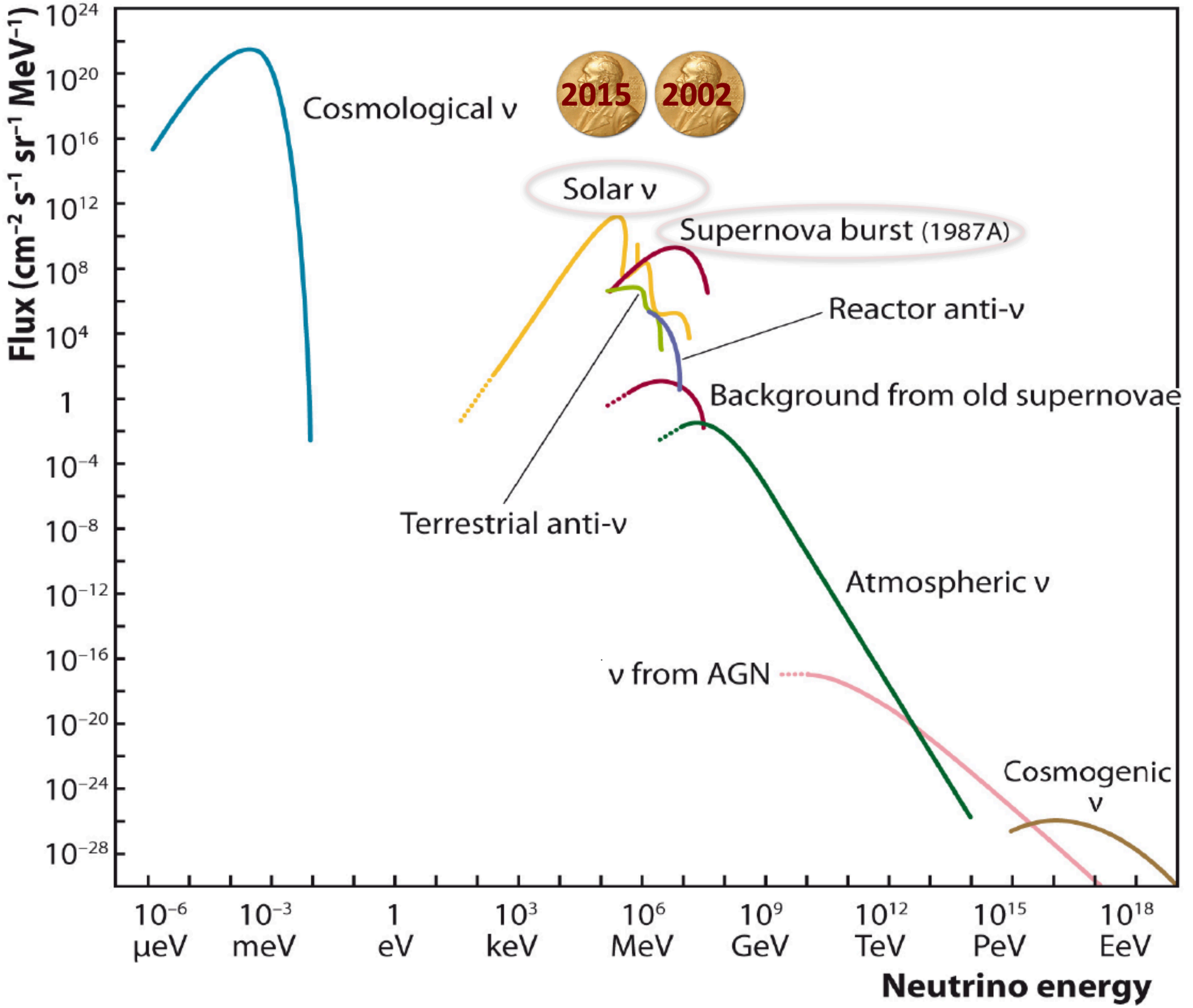
We need bridges between the radioastronomy and astroparticles communities



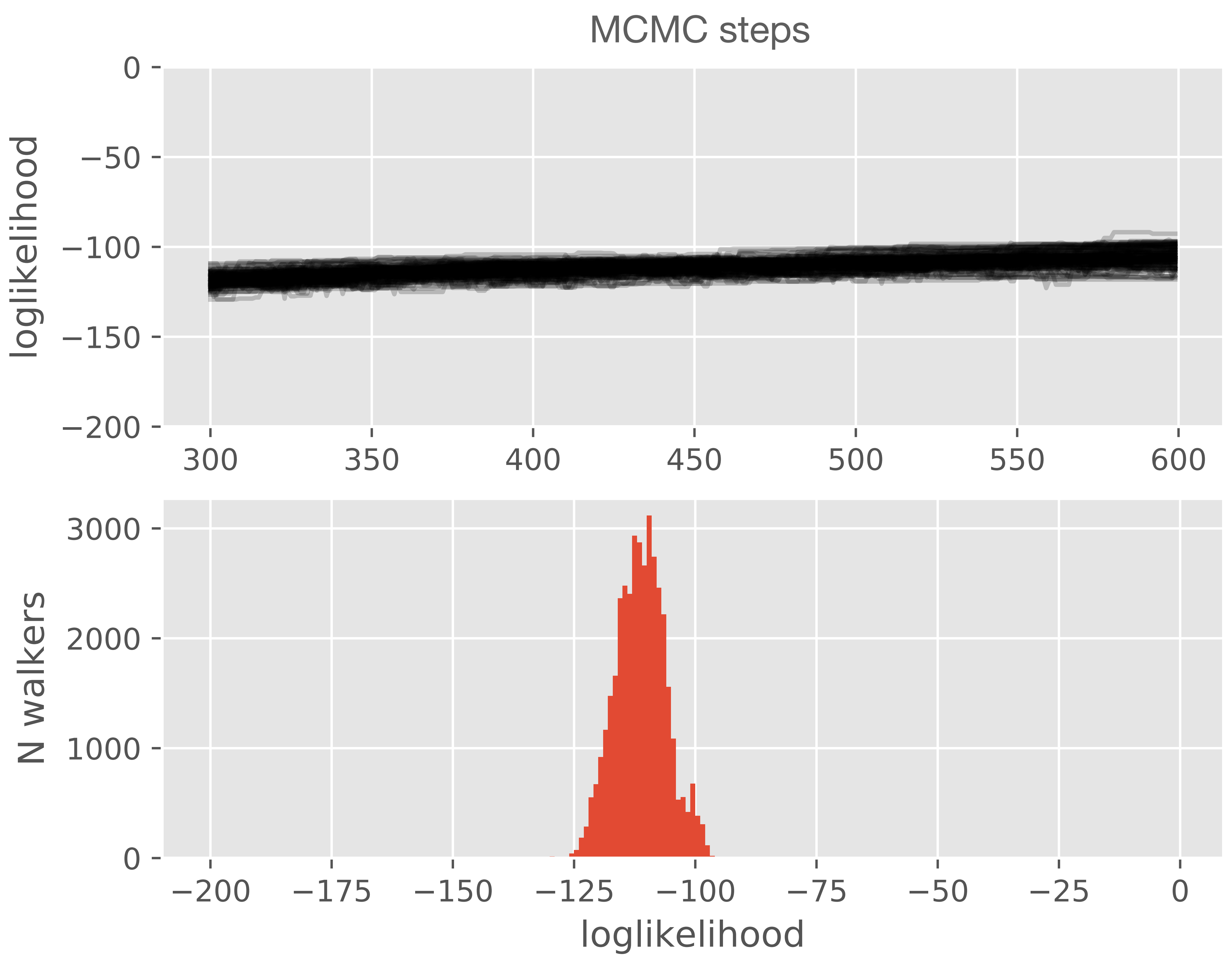
Backup slides

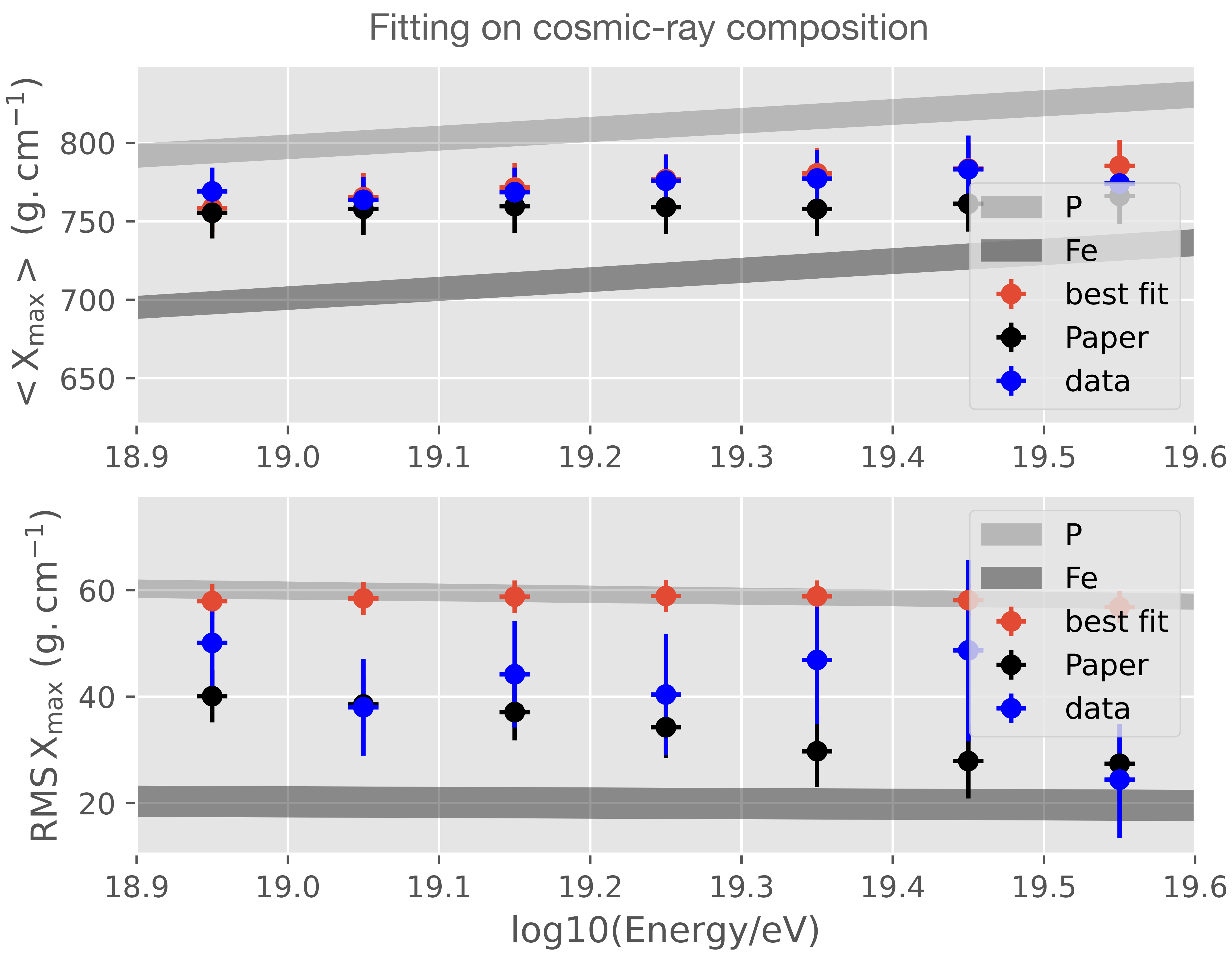
Neutrino landscape



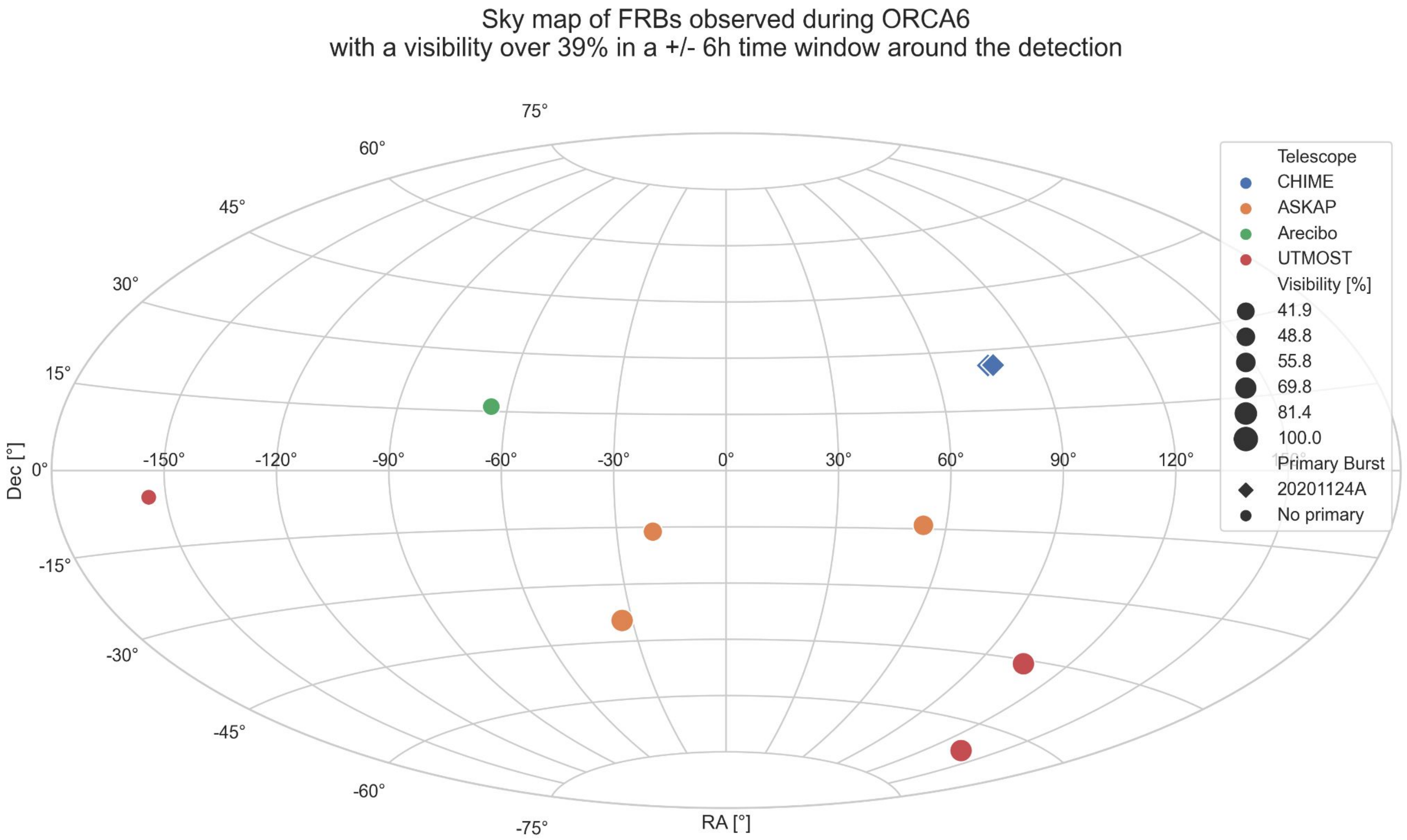
Constraining the possible sources of cosmogenic neutrinos

Parameter space exploration with MCMC methods

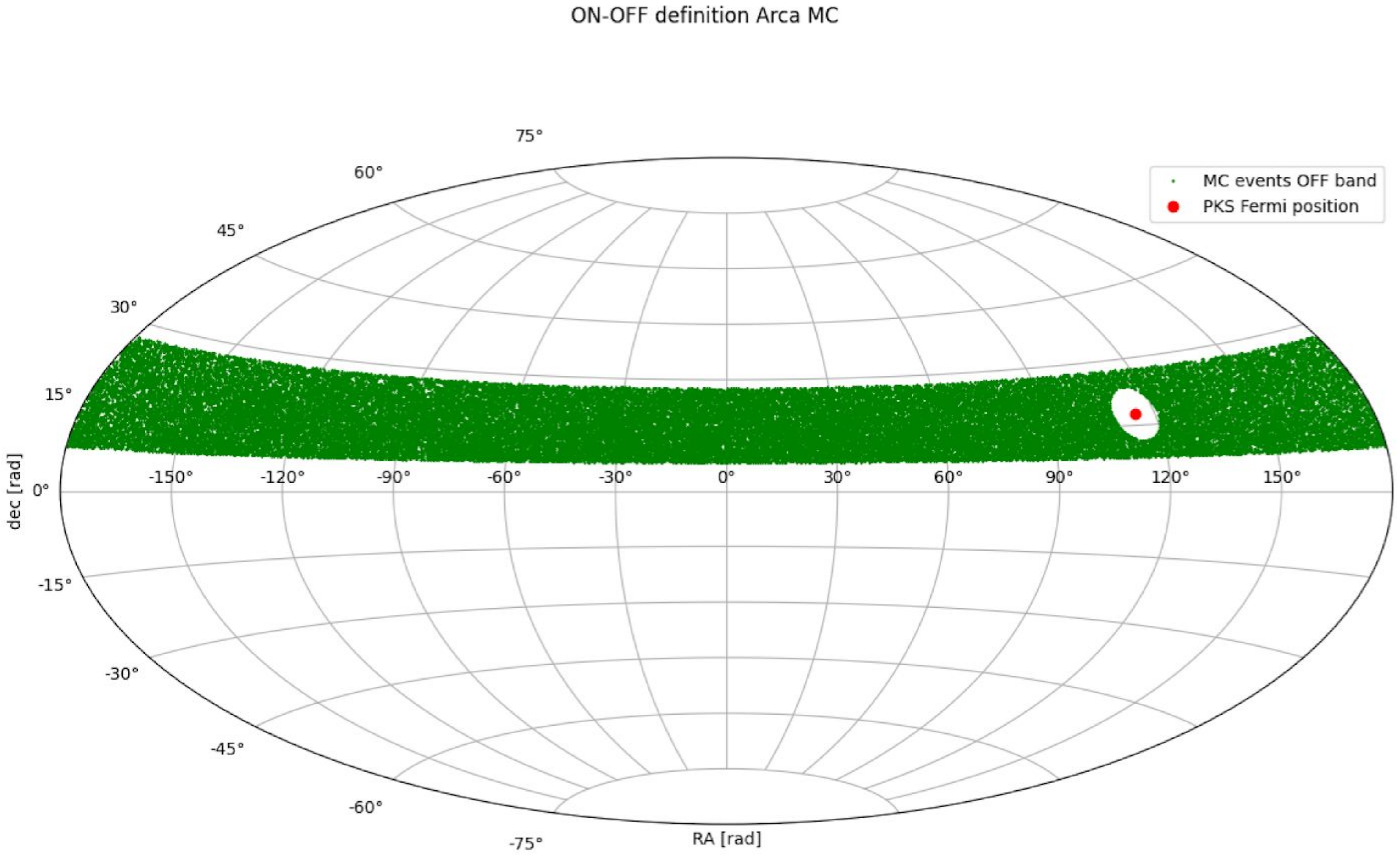




KM3NeT activities at Subatech : FRB analysis



43 targets observed by ORCA6 & Nançay
12 targets with visibility > 39%



Région OFF délimitée par la bande de déclinaison de +/- 10° autour de la position de PKS 0735 [KM3NeT collaboration,2022]

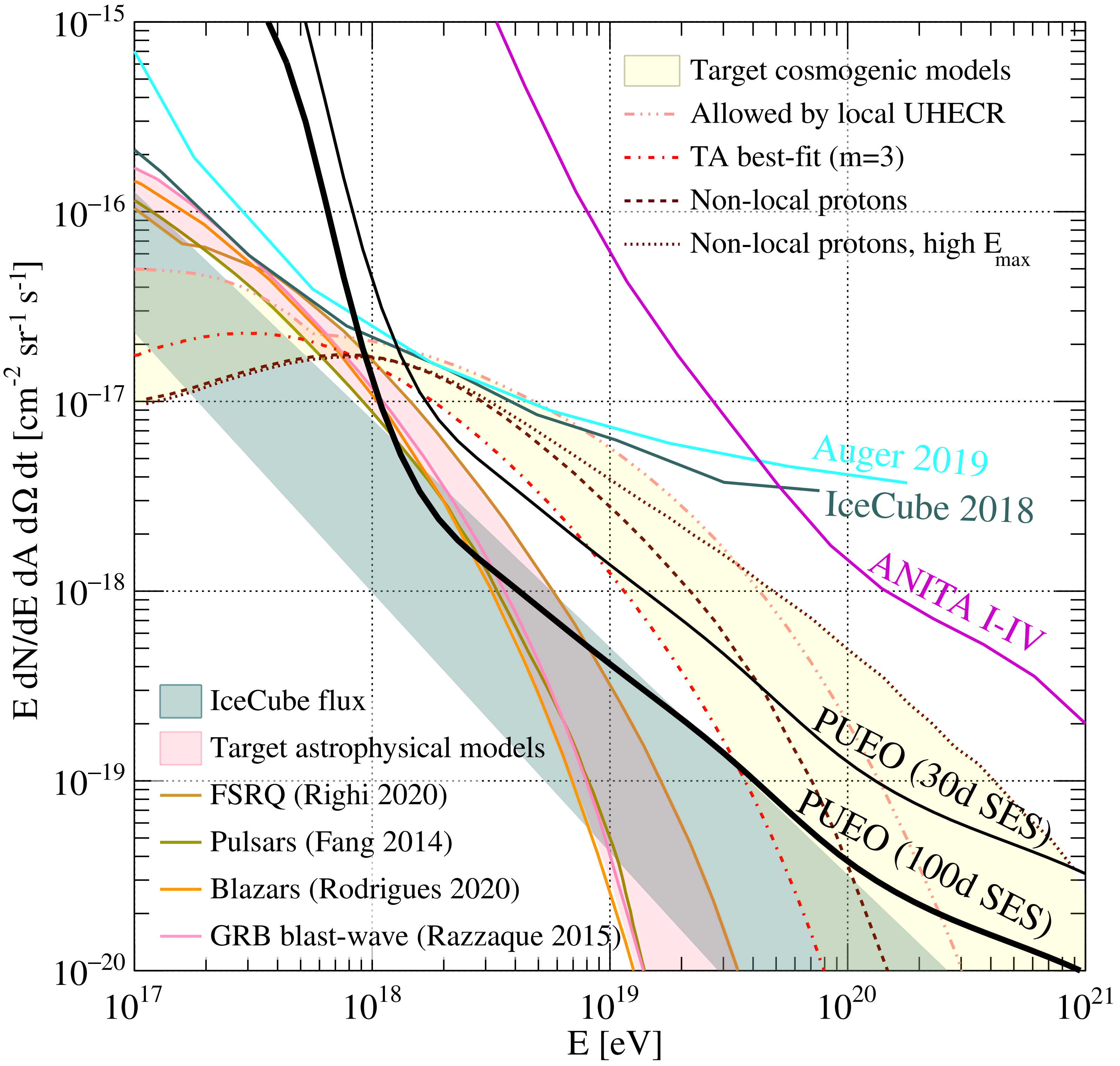
ON/OFF example

From Marie-Sophie Carrasco Master's defence

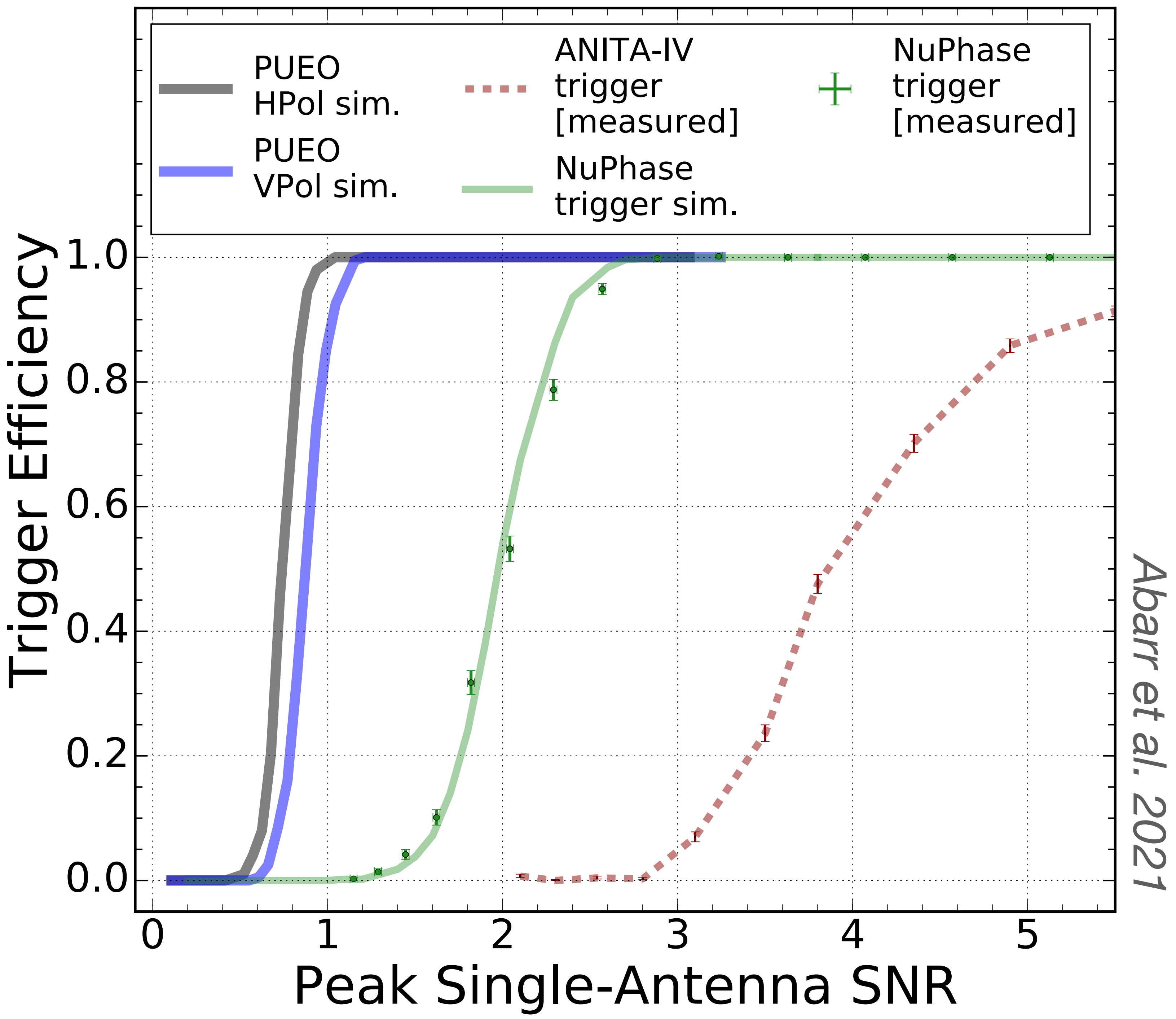
Payload for Ultrahigh Energy Observations (PUEO)

How to do better with same size constraints?

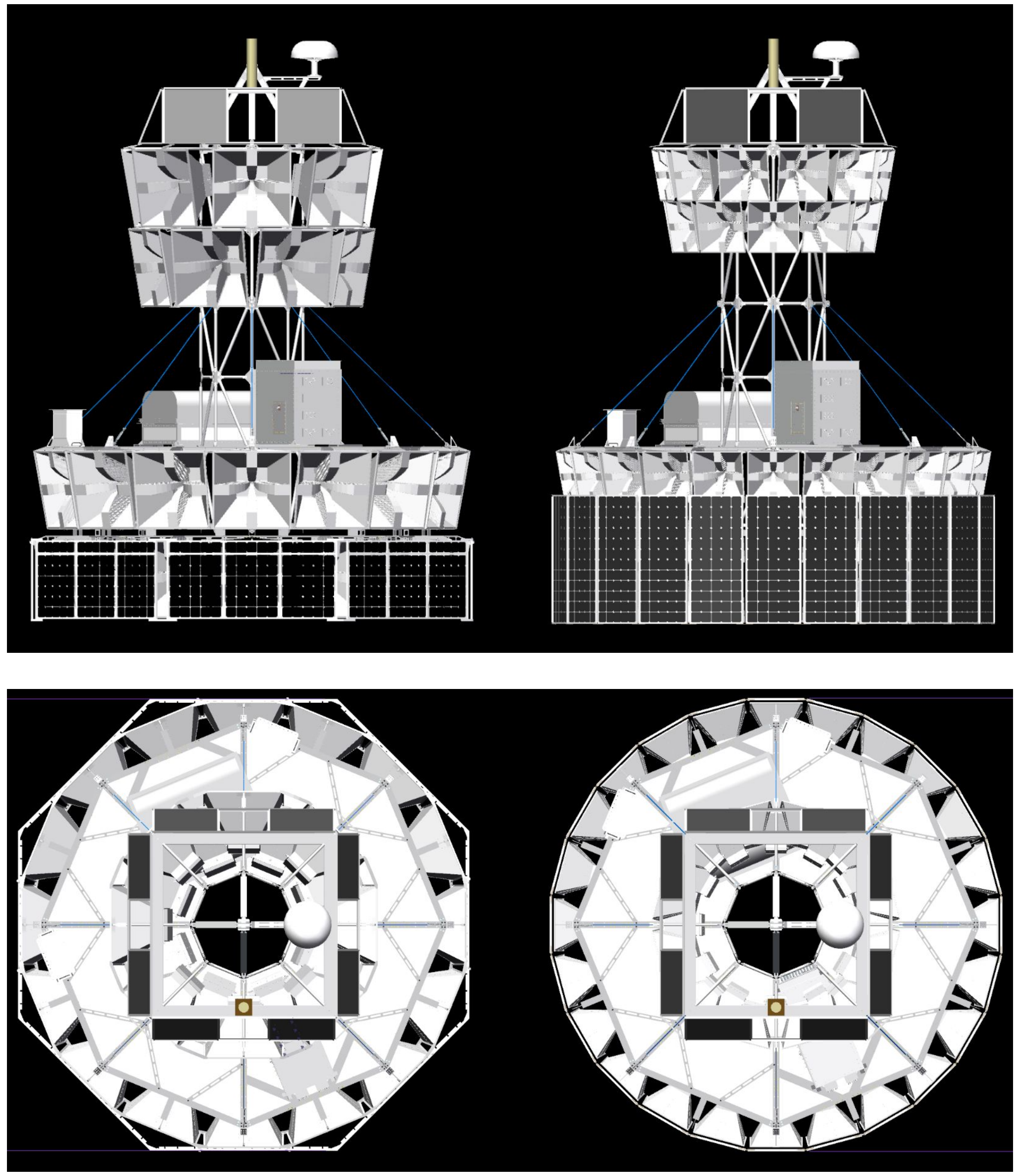
Predicted sensitivity for PUEO



Increase of the detection threshold



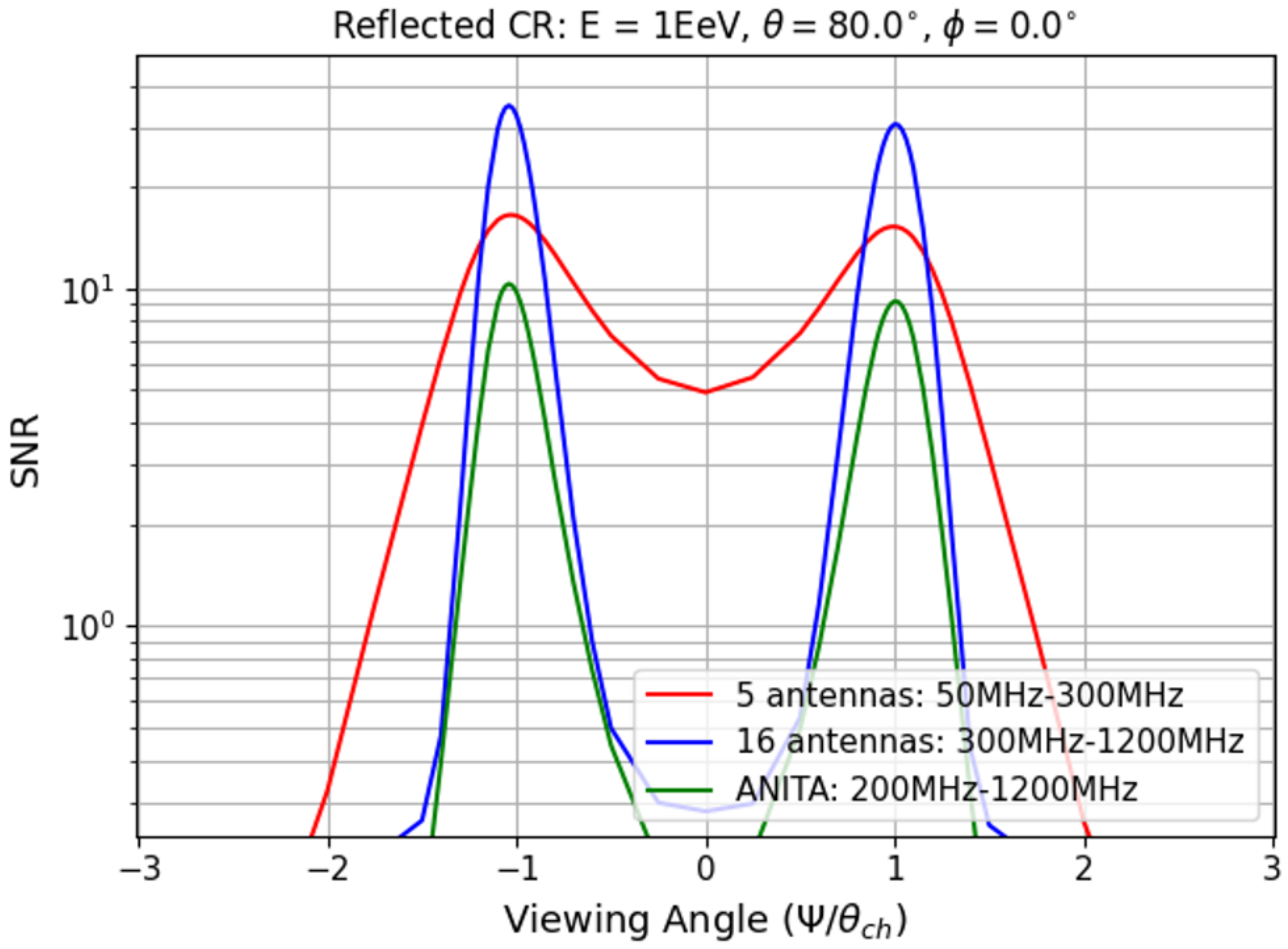
Comparison ANITA IV / PUEO



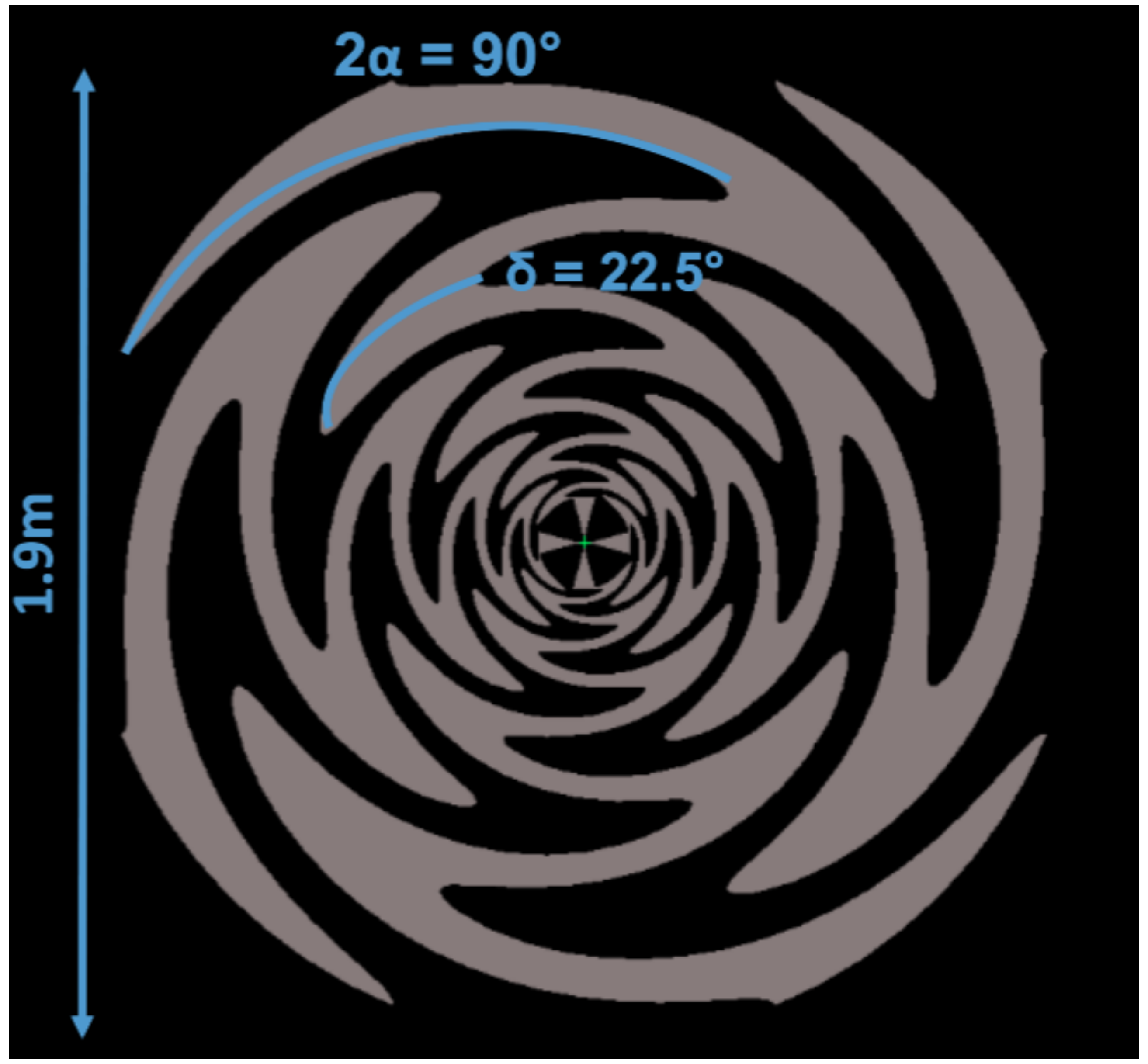
Goal of the Low Frequency Instrument

At low frequency the FoV increases hence the sensitivity

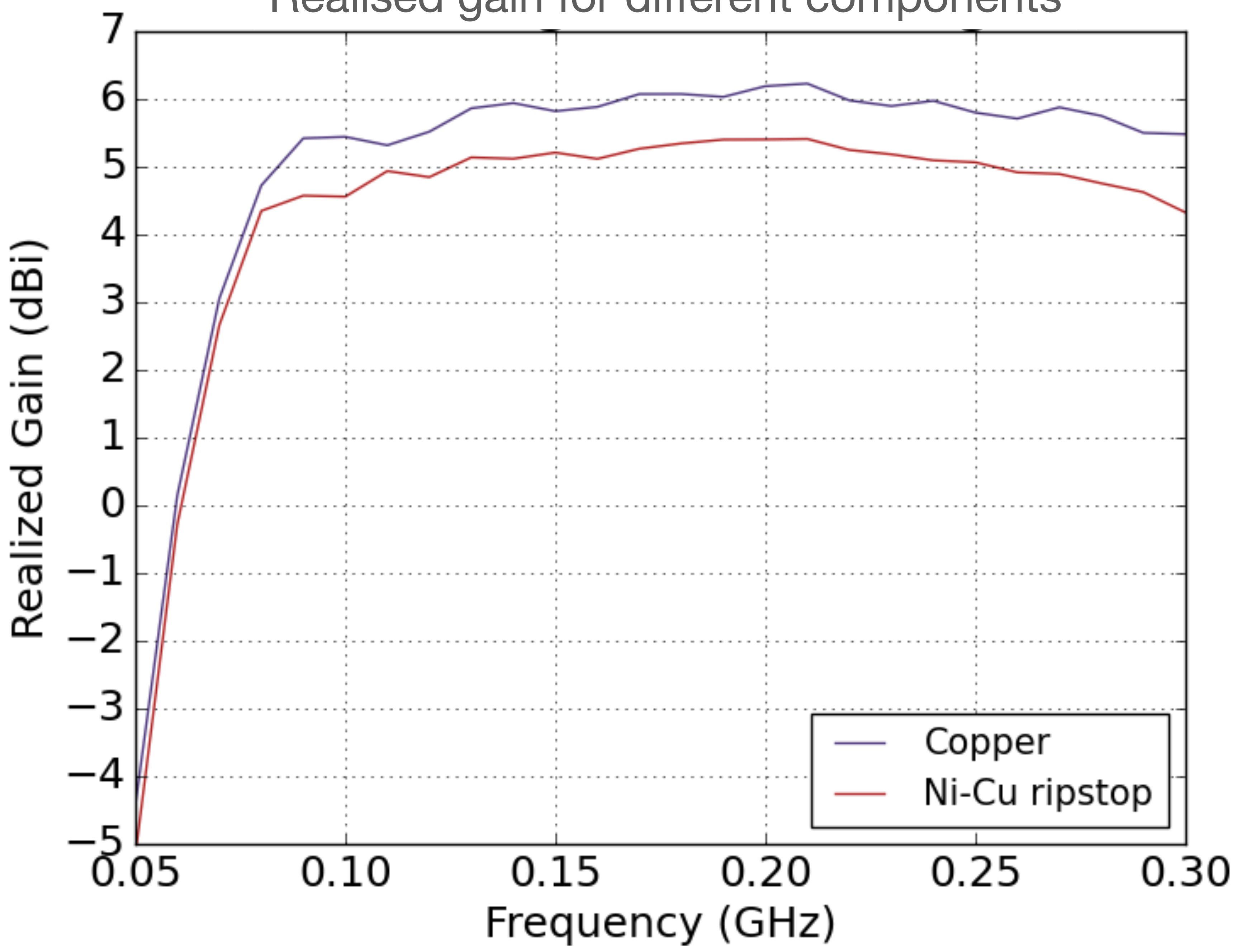
radio beam for EAS



Sinuous antenna

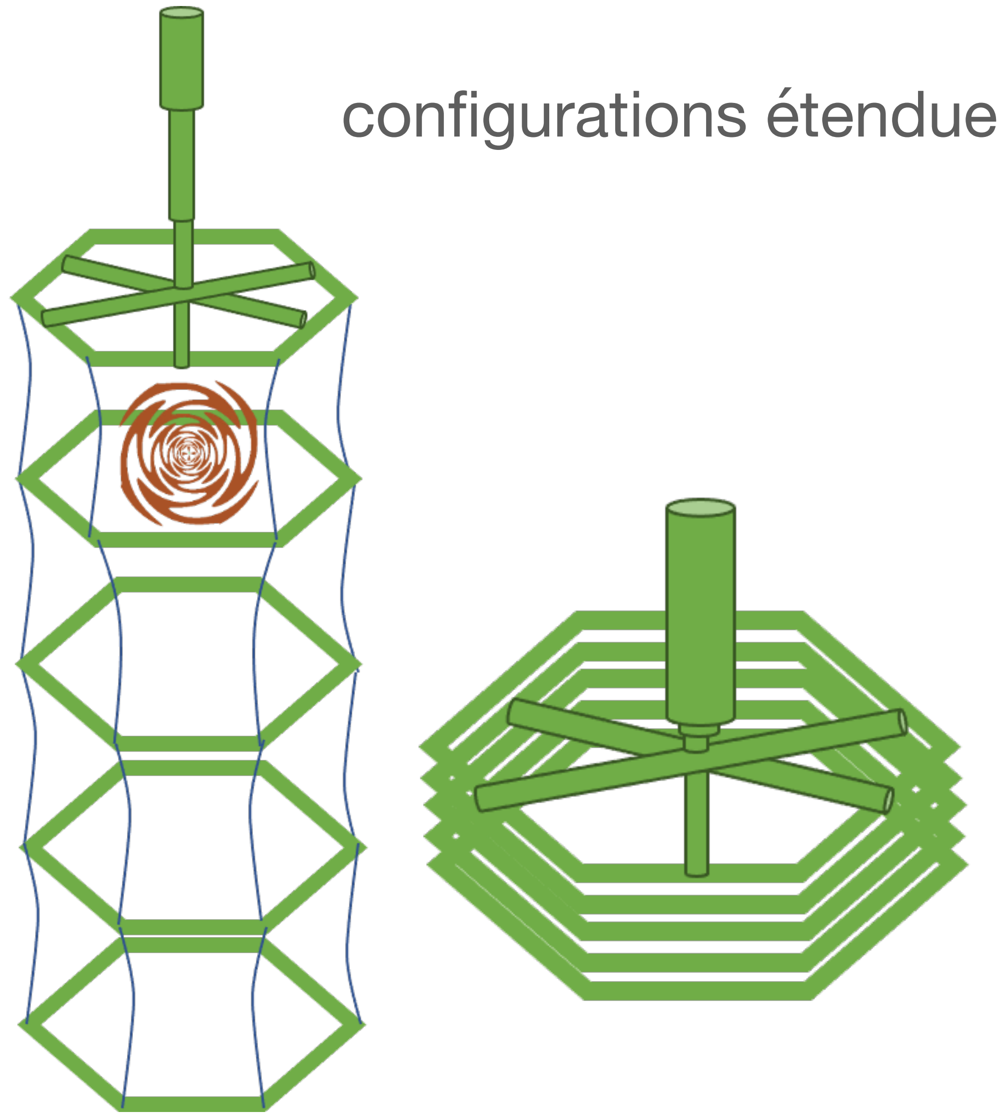


Realised gain for different components

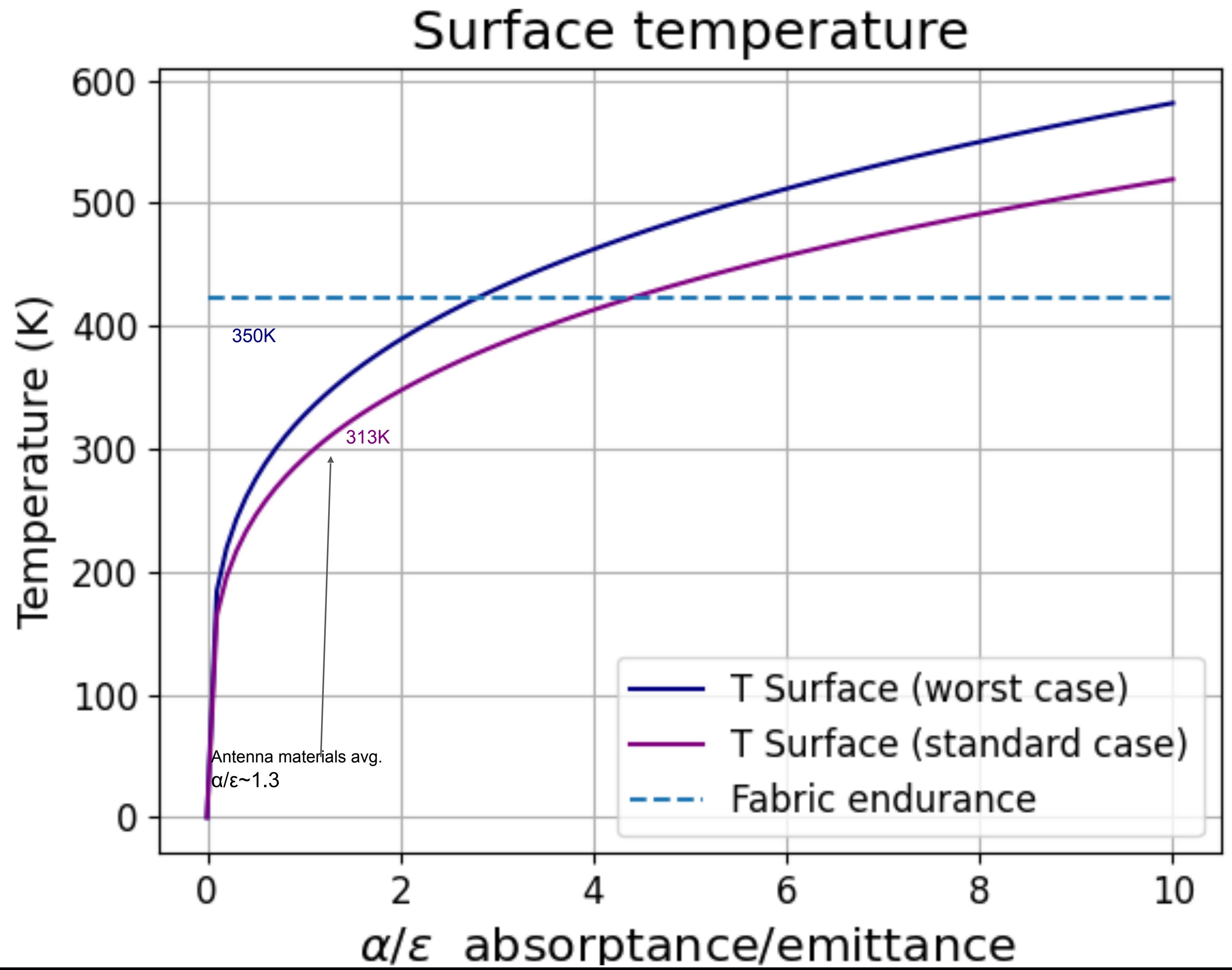


LFI: risk assessment

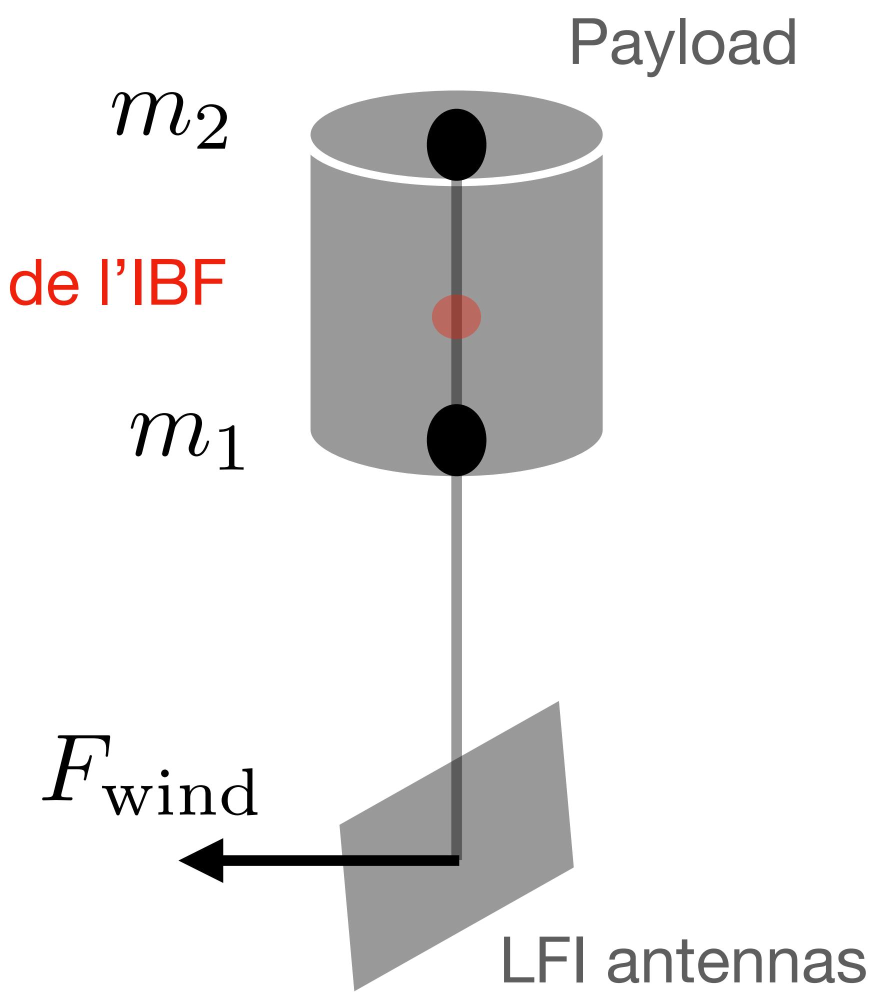
configurations étendue et compacte

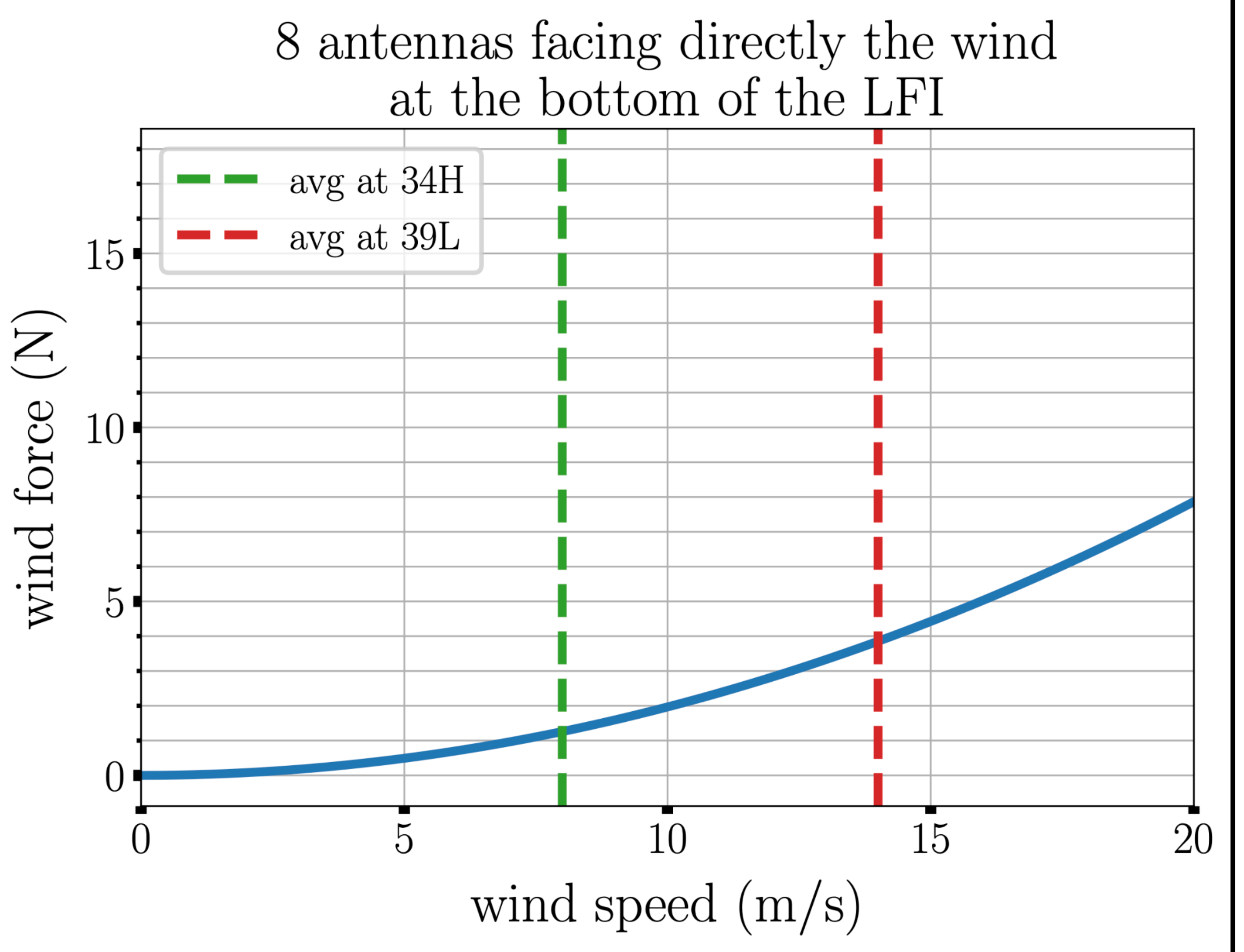


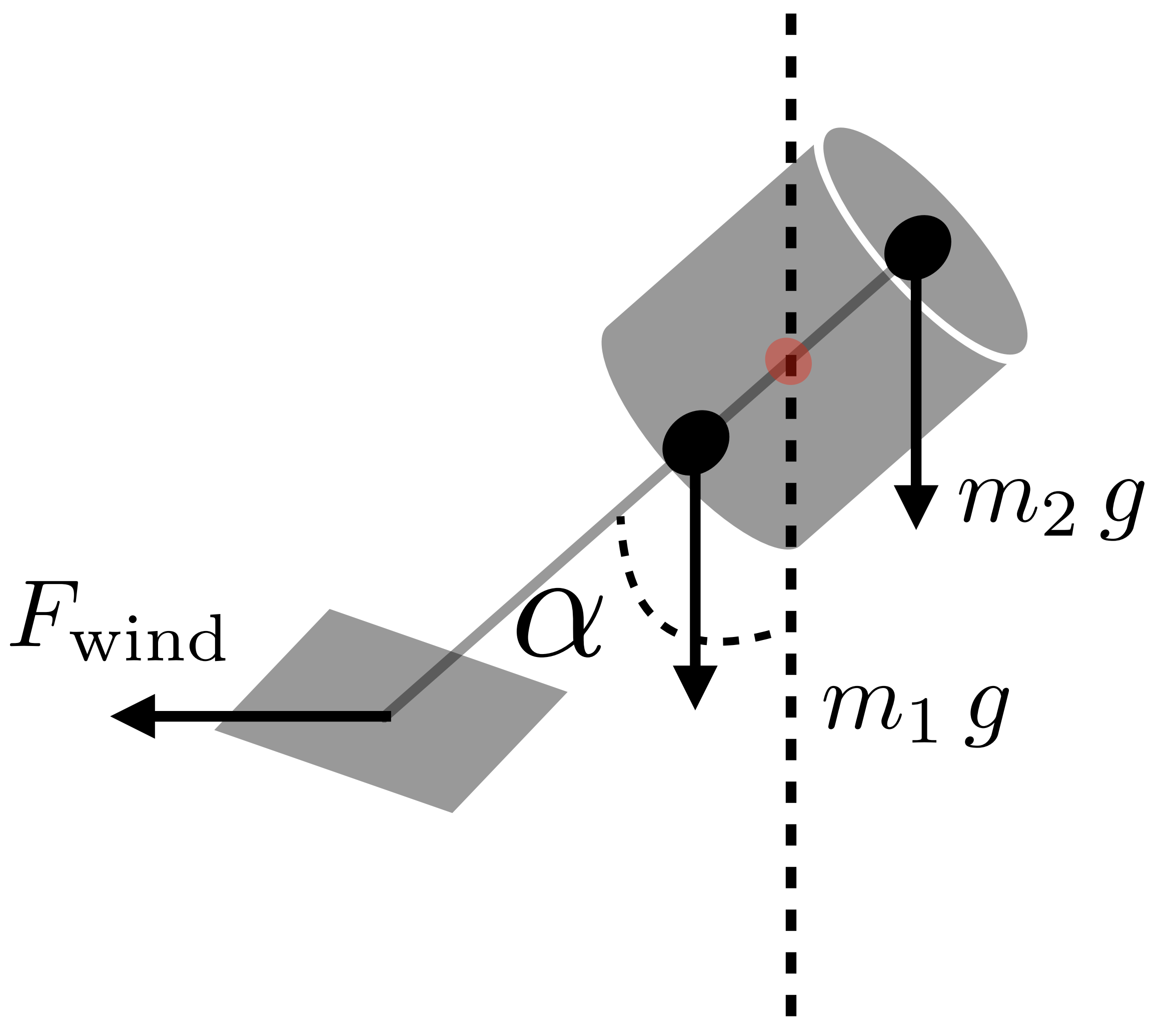
Modélisation des effets thermiques

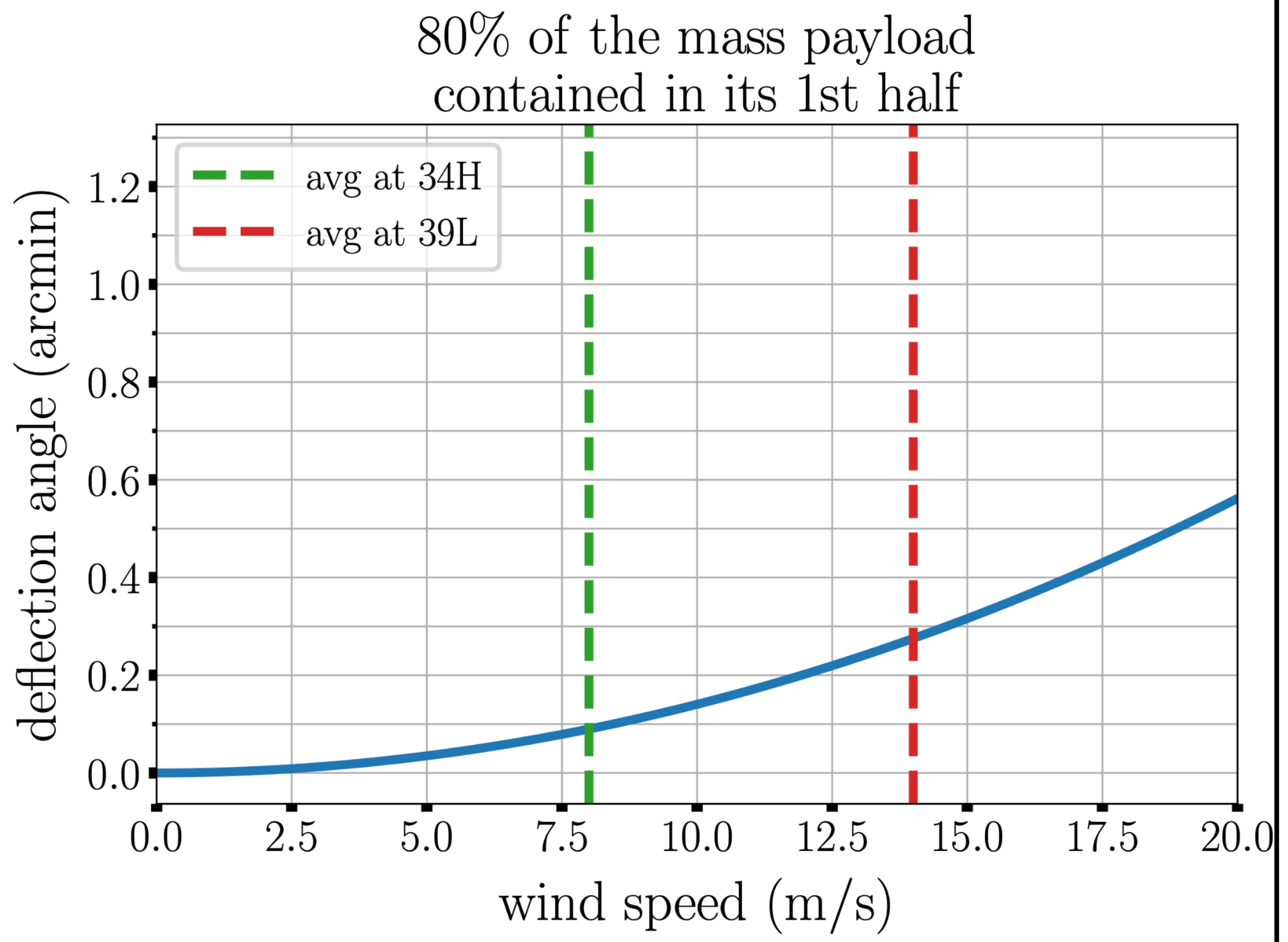


Modélisation des effets du vents



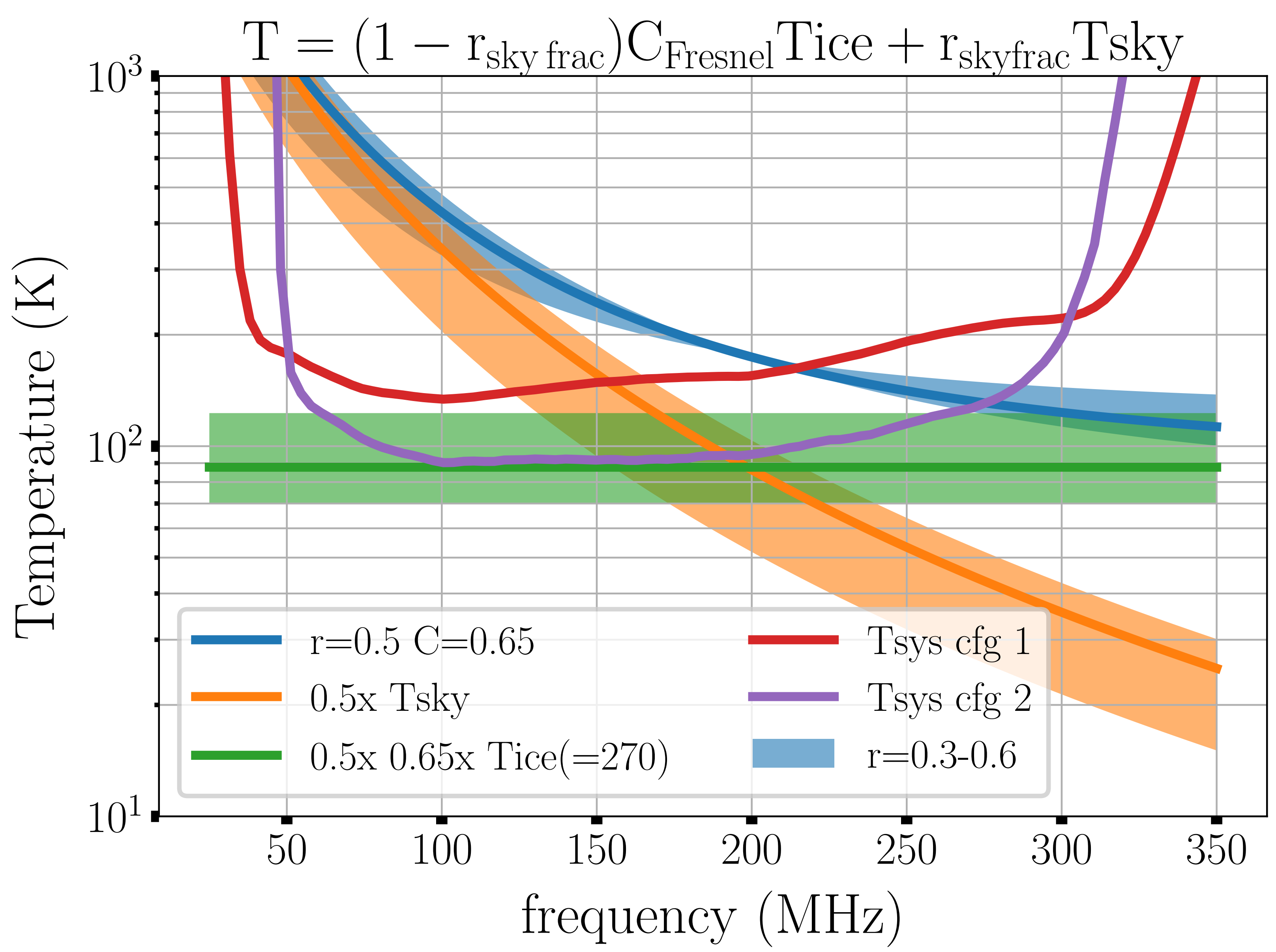


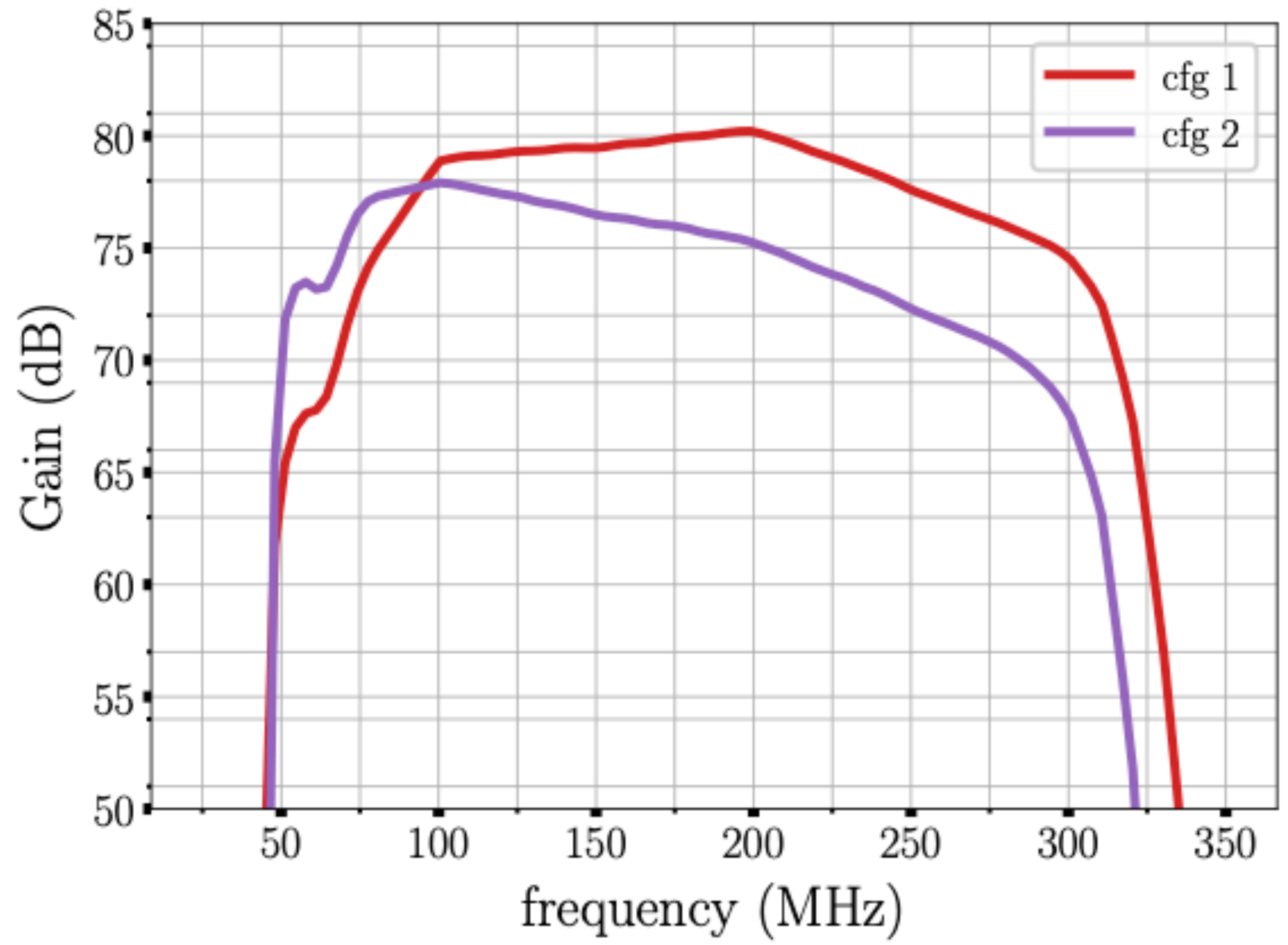




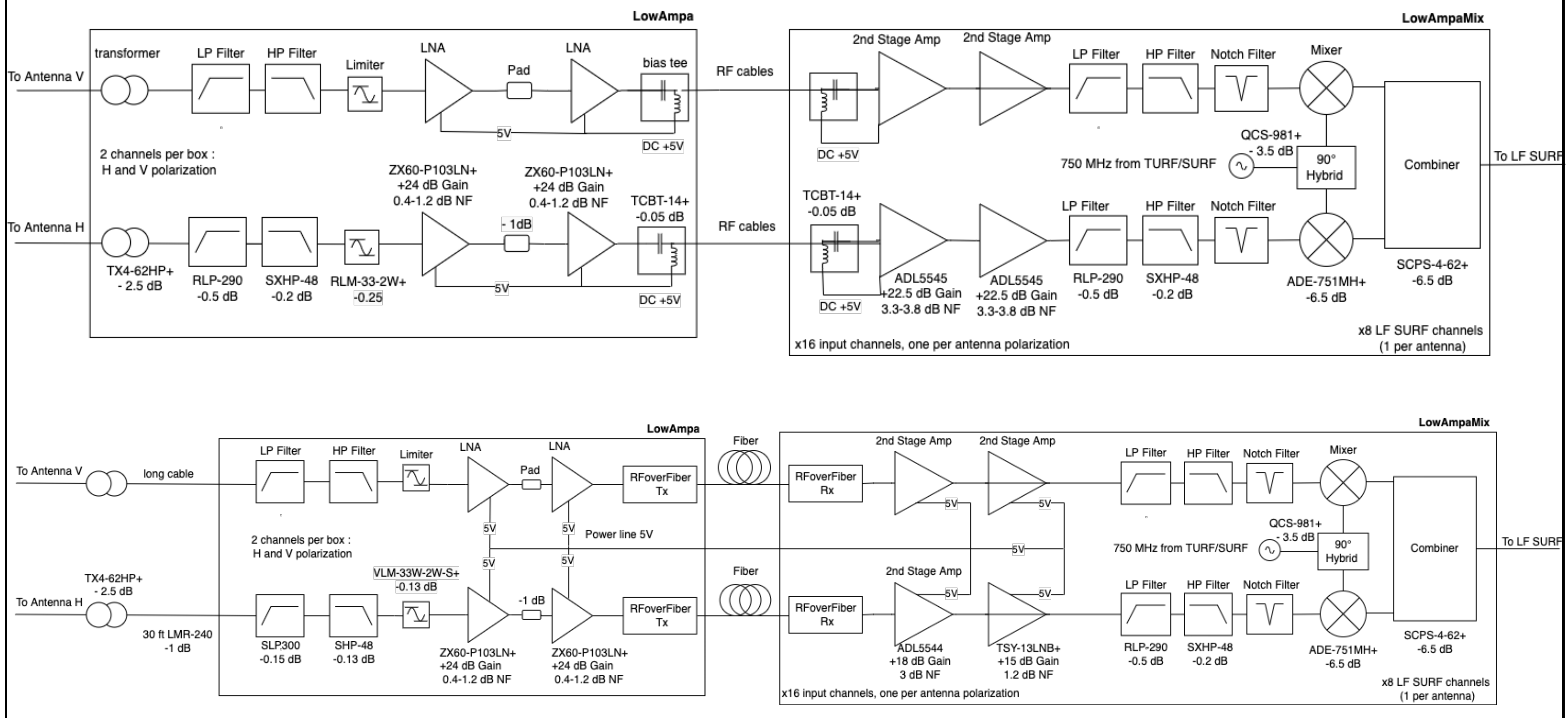
LFI RF chain

Simulated noise and expected gain





Studied configuration for the full RF chain of the LFI



LFI tests and validations

Prototypes and TRL6 flight requirements

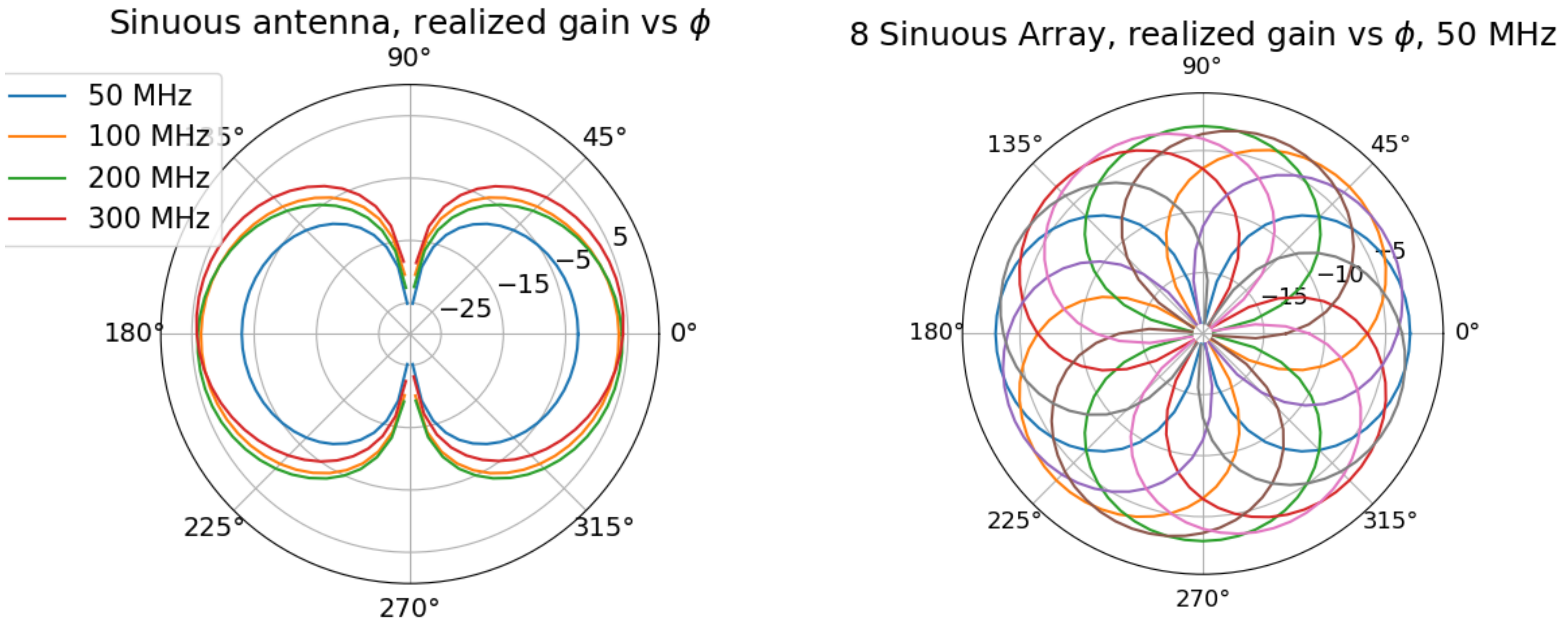
Scaled model (1/4)

Thermal vacuum chamber

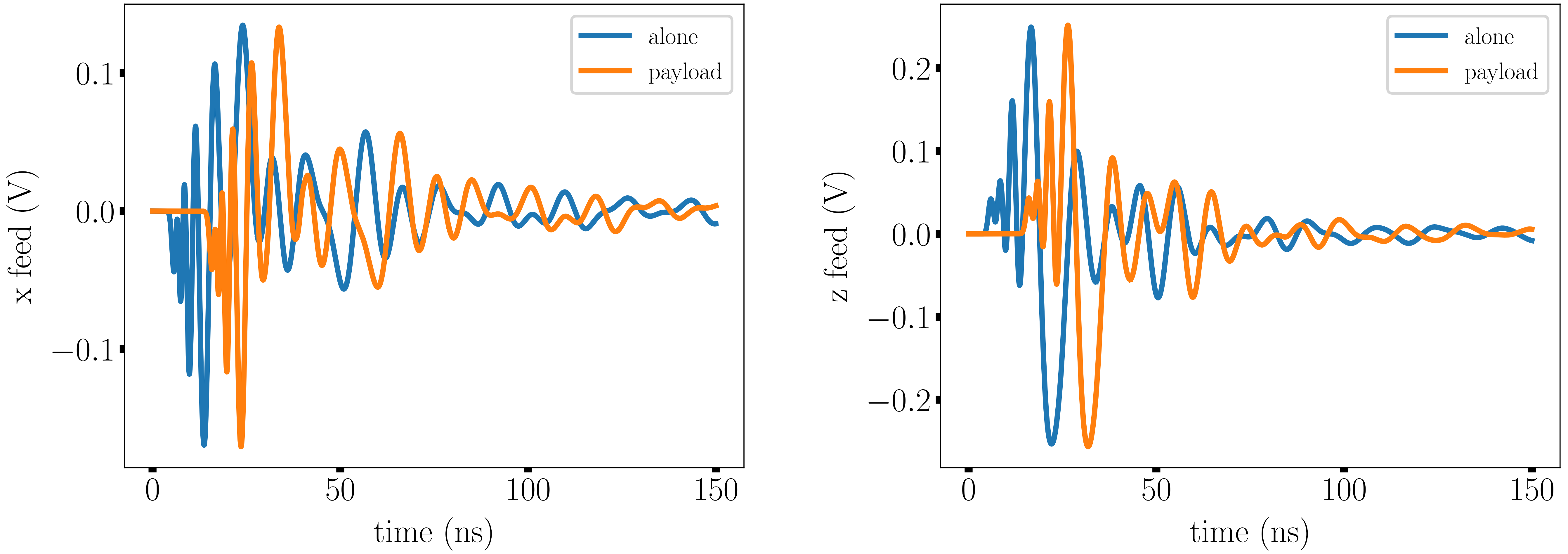
LFI simulations and reconstructions

Simulations of the LFI performances

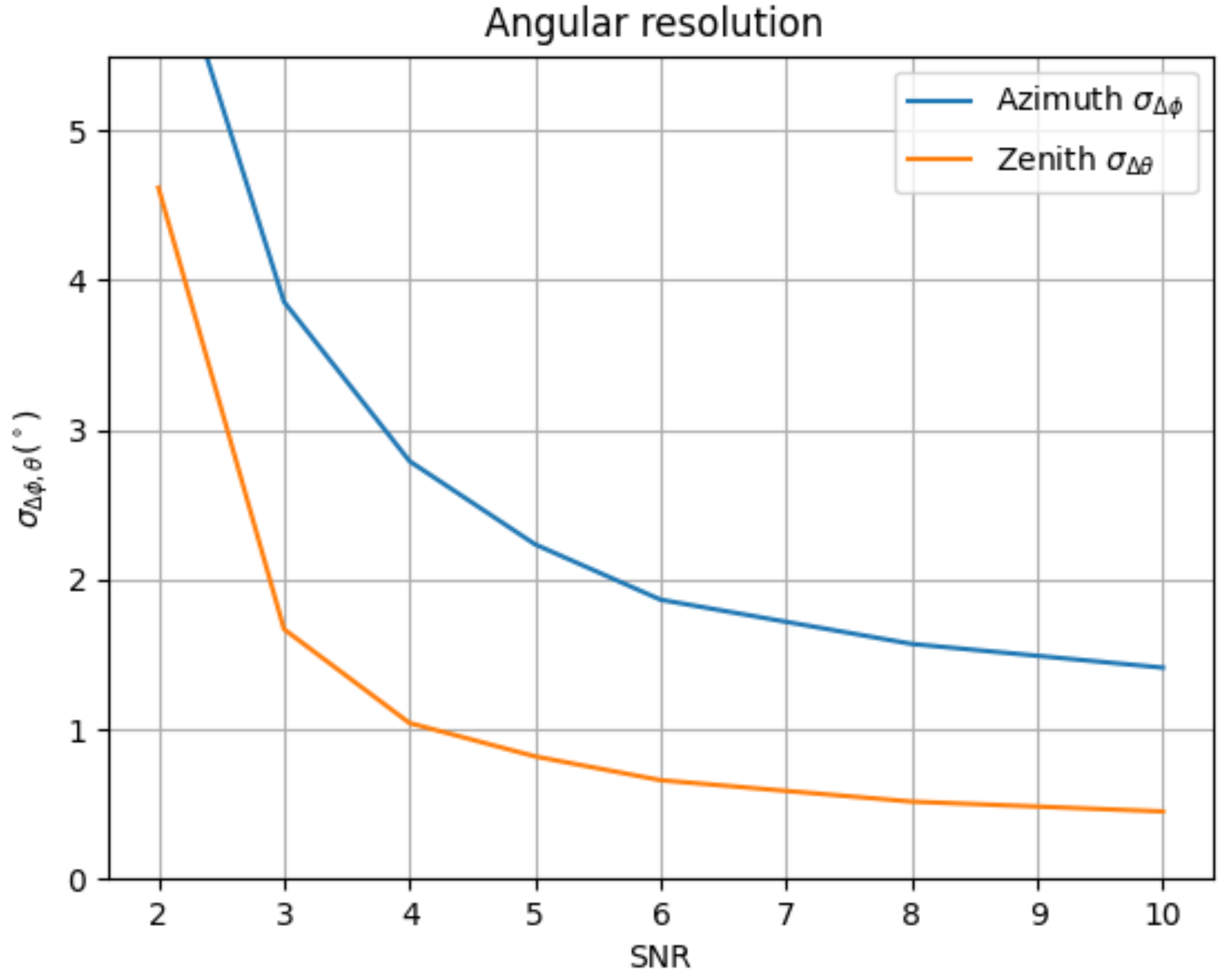
simulation du gain directionnel total



Simulations of the possible interferences with the payload (XFDTD)

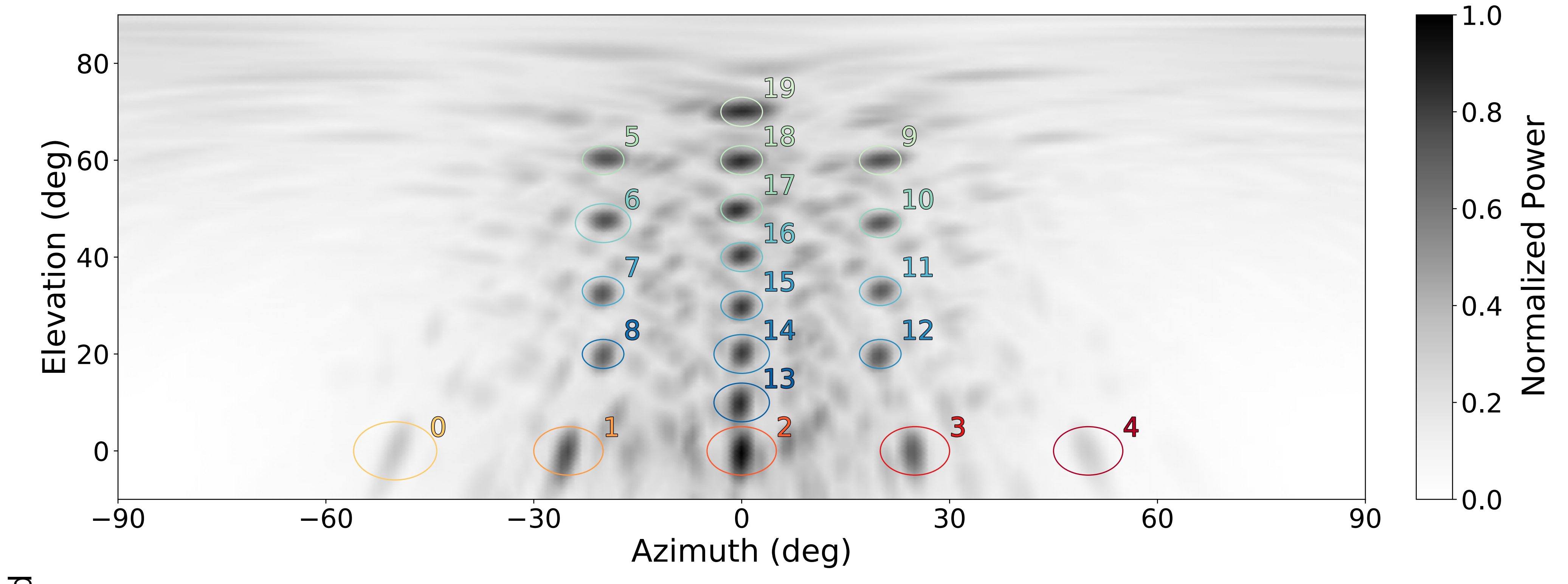


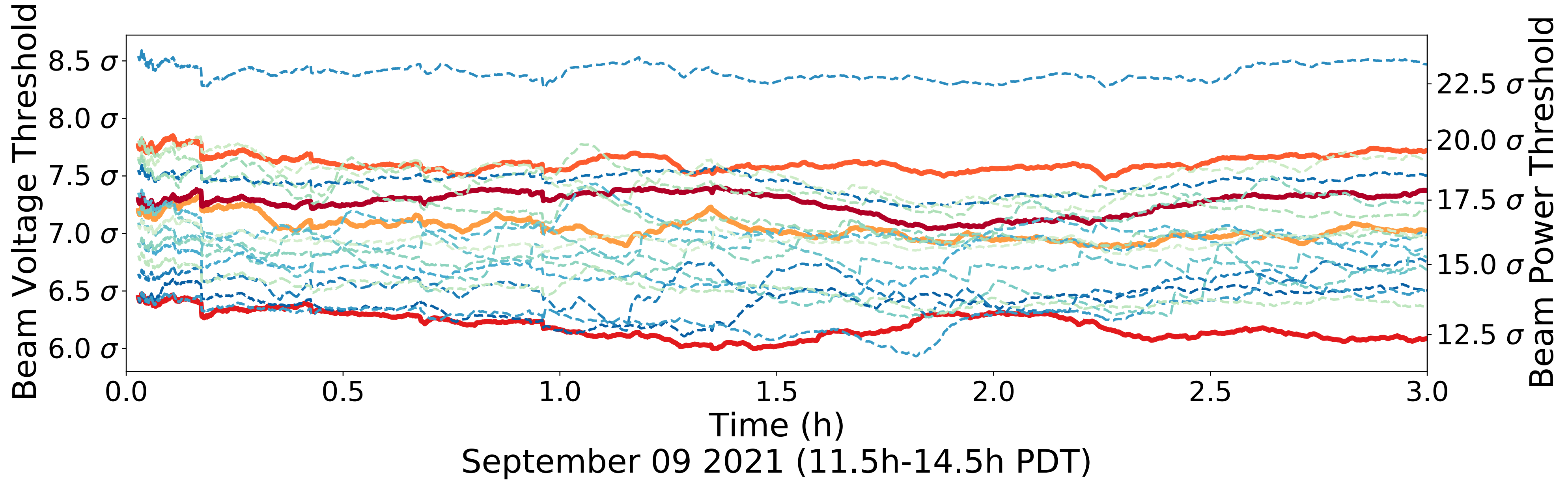
Simulations of the angular reconstruction

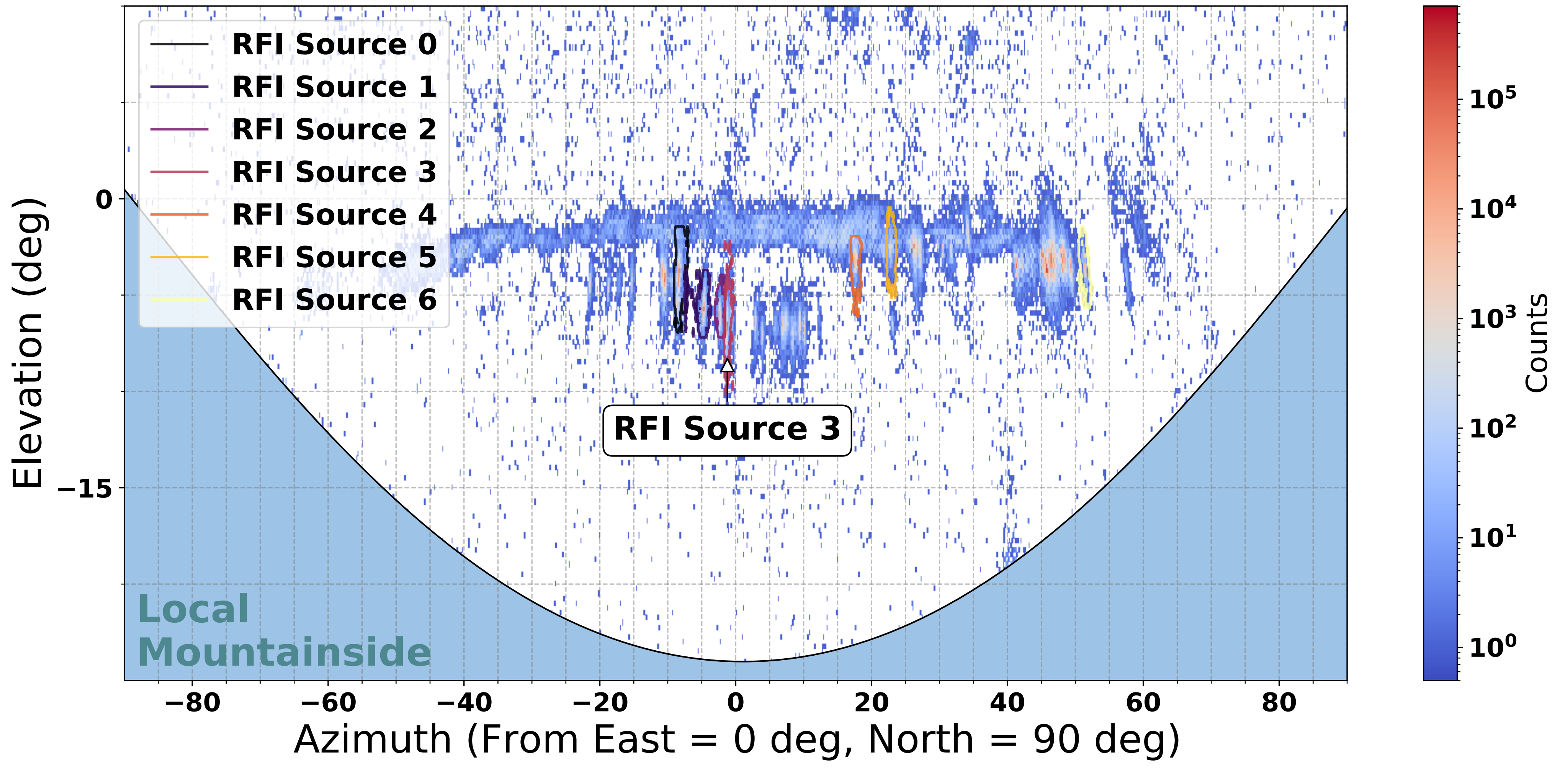


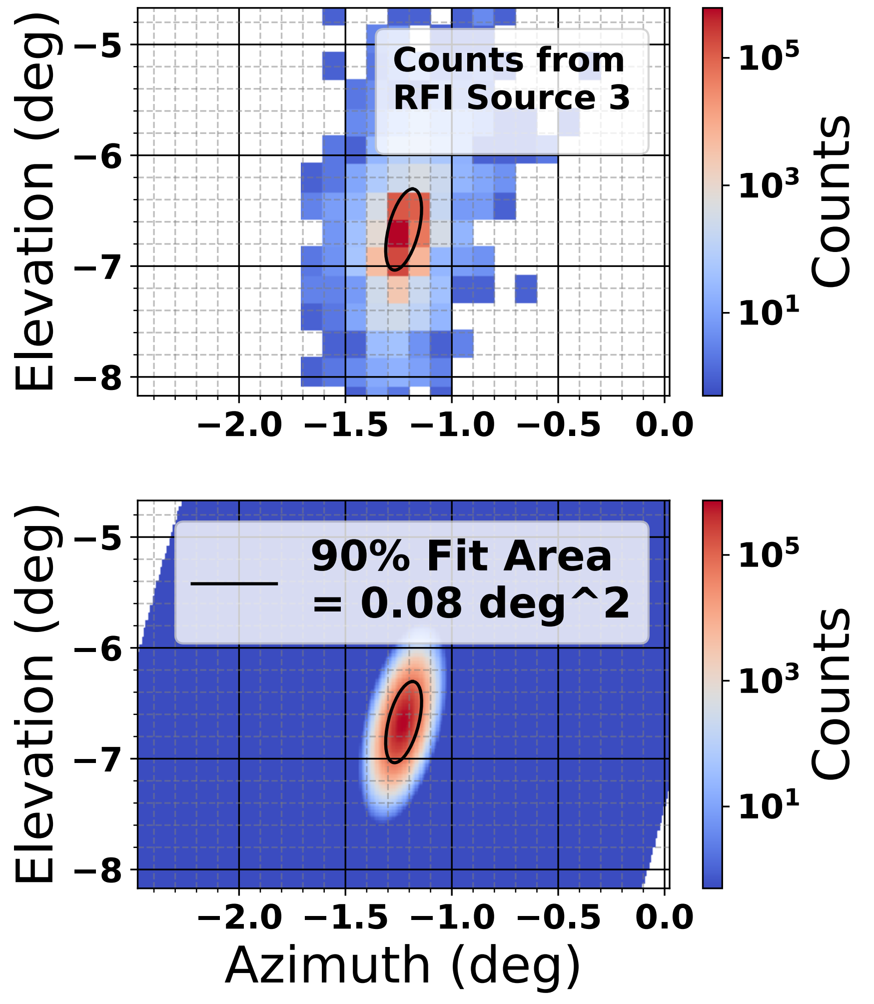
The BEACON prototype

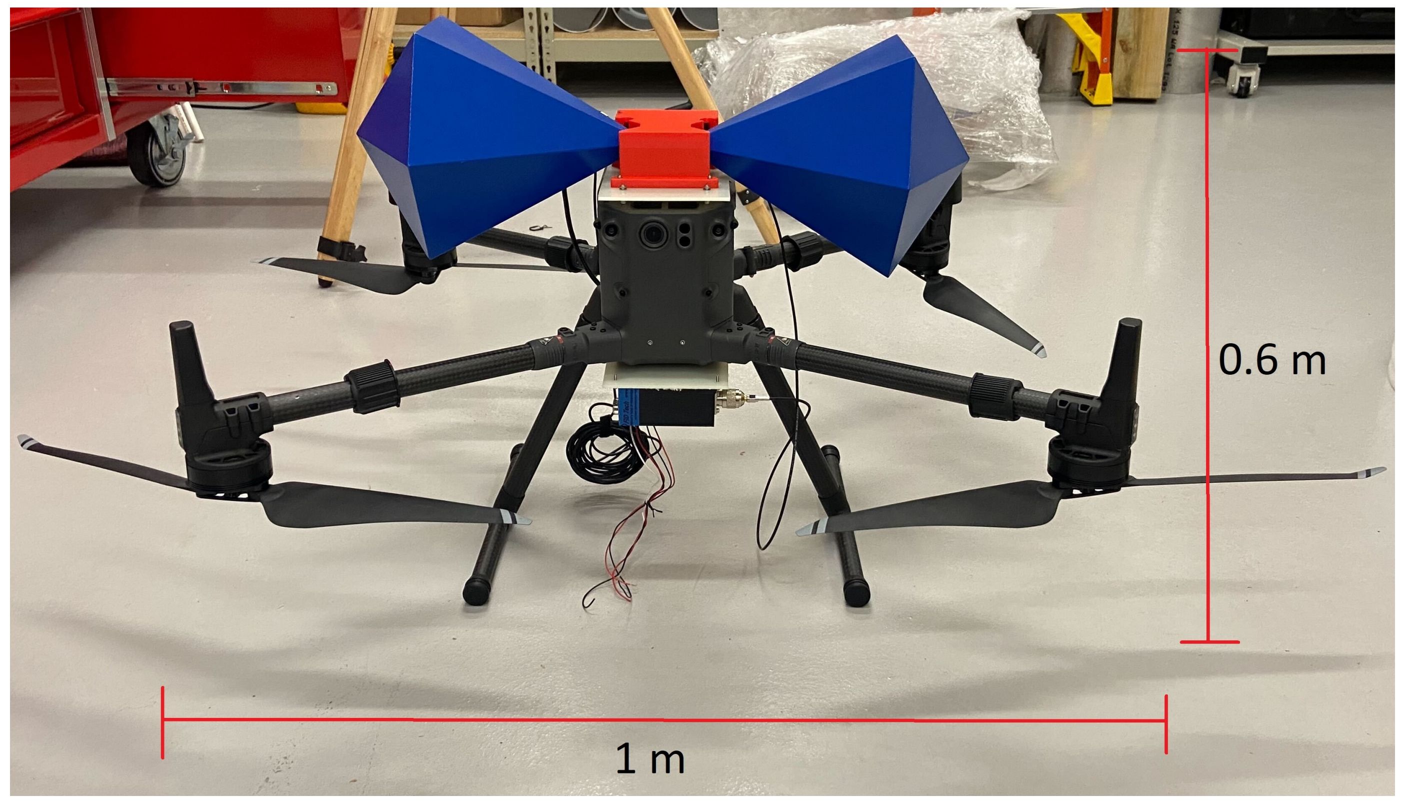
Southall (UChicago), Deaconu (UChicago), **V. D.**, et al. (submitted to NIMA)



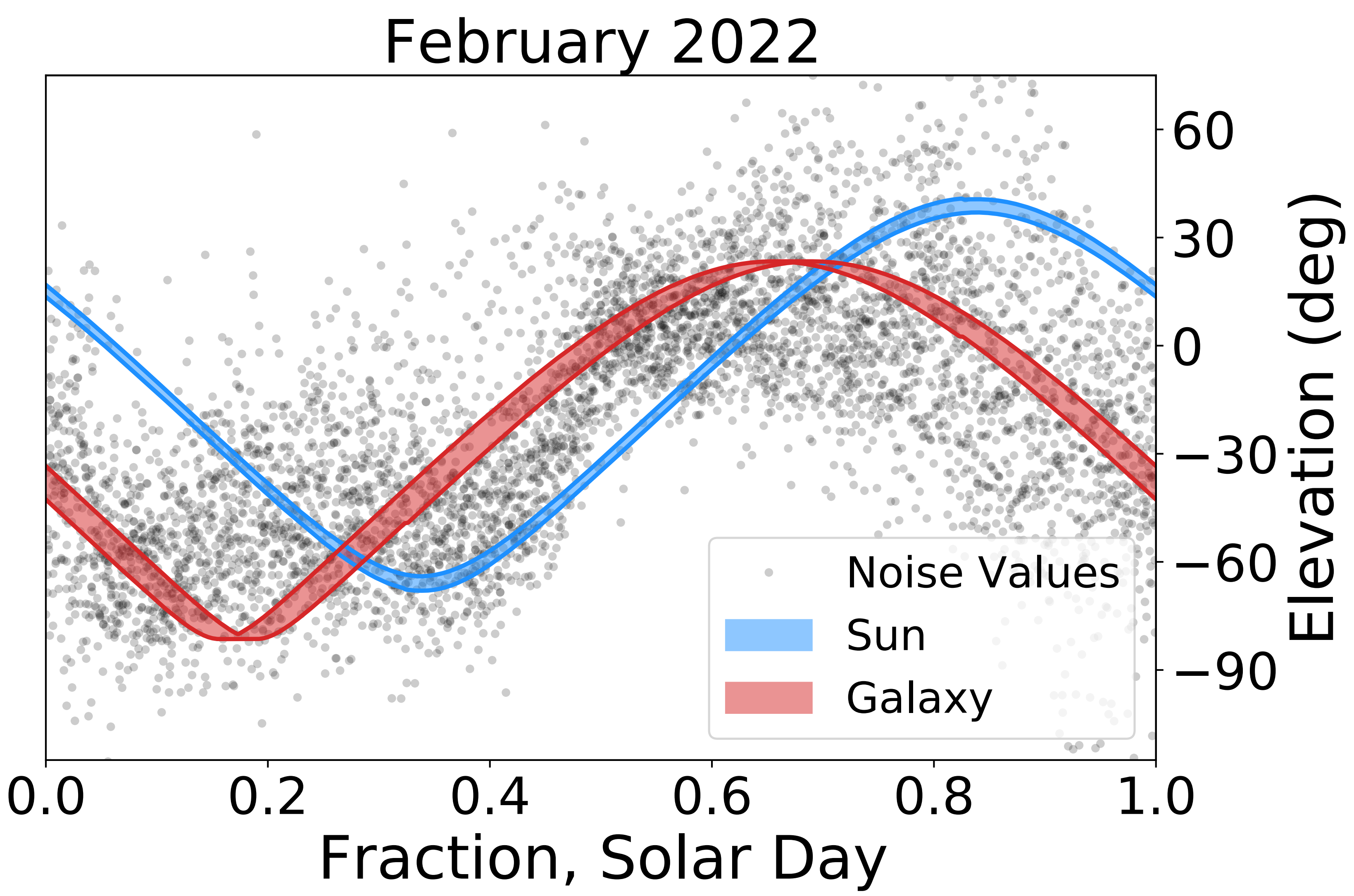


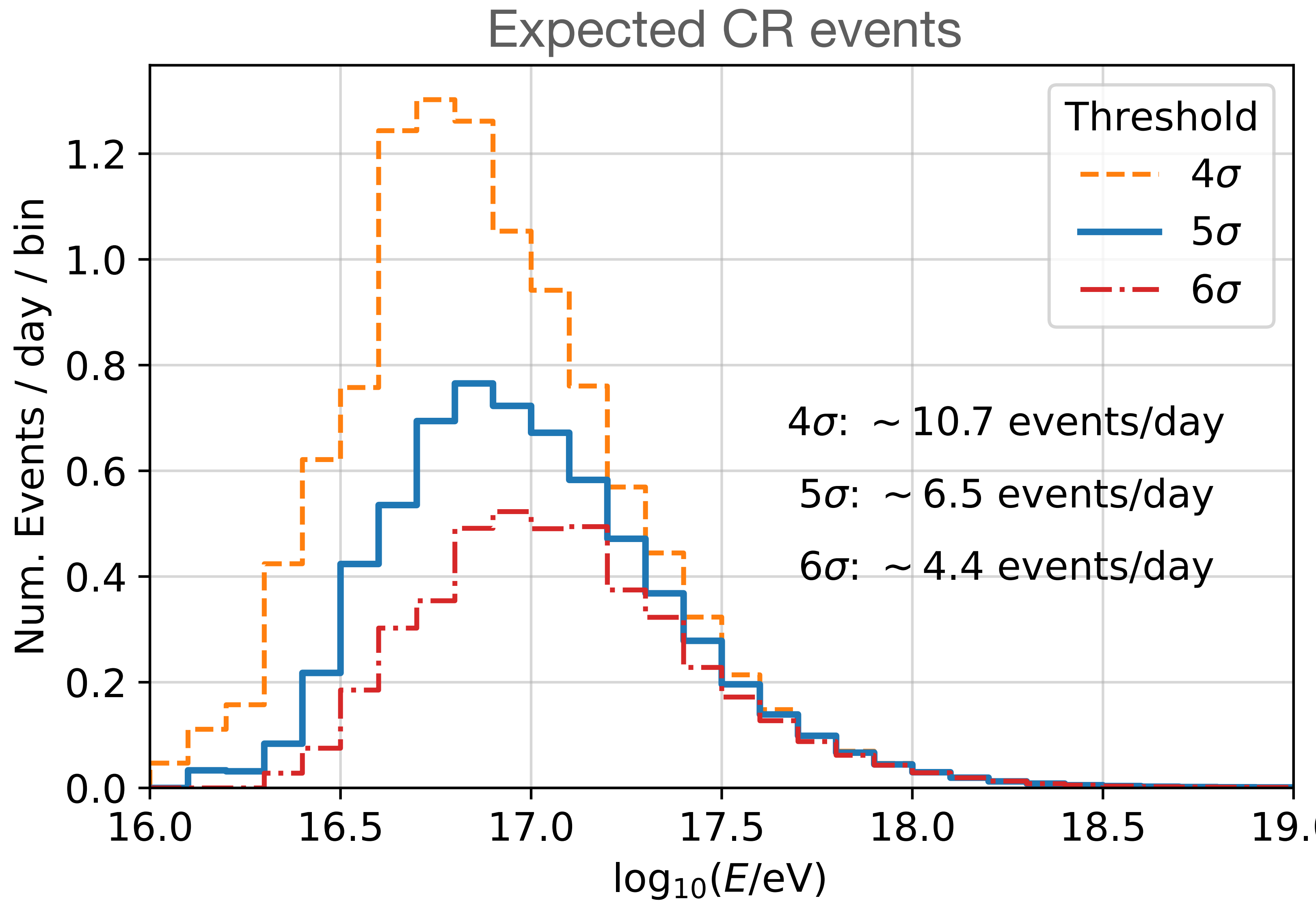






Calibration drone





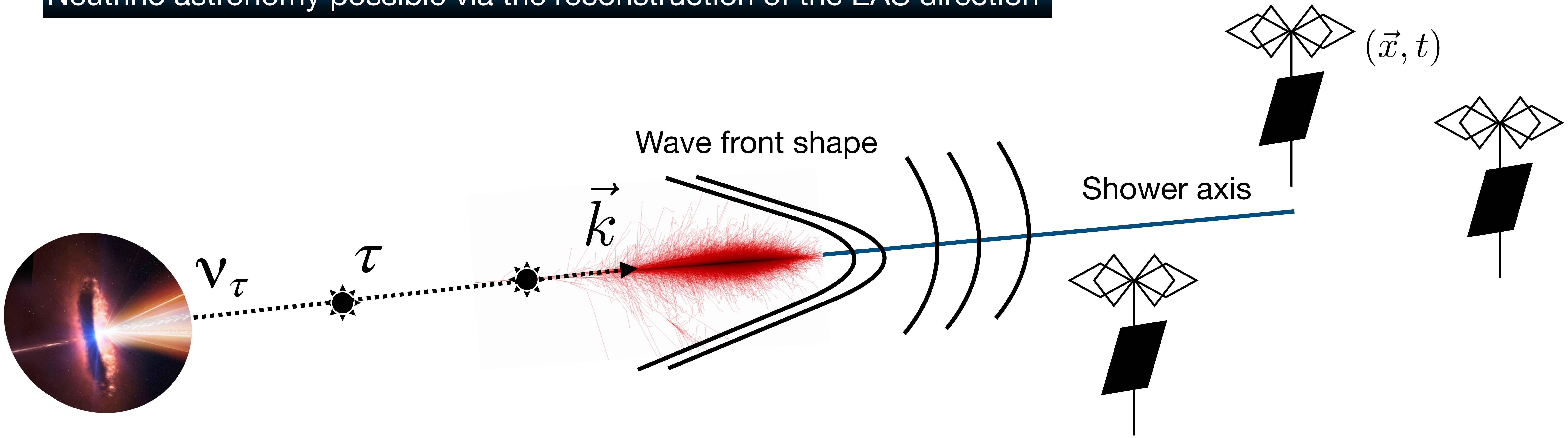
Andrew Zeolla (Grad. student @PSU)

Reconstruction of radio detected extensive air showers

Goal: Neutrino astronomy requires reconstruction of the arrival direction (target of 0.1° of accuracy)

Lorentz boosts → EAS direction = neutrino direction

Neutrino astronomy possible via the reconstruction of the EAS direction



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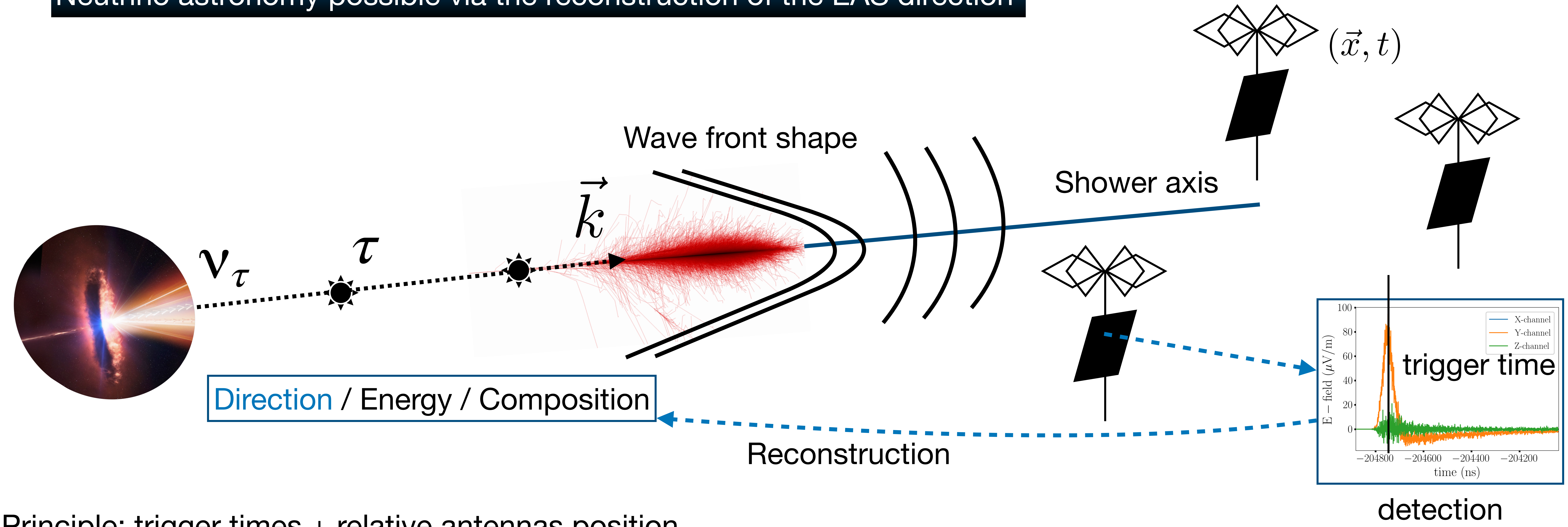

Principle: trigger times + relative antennas position
→ information on the EAS direction

Method: adjust the wave front model to the trigger times ➡ **neutrino astronomy accuracy = wave front shape correctness**

Wave front shape descriptions: state of the art

LOPES and LOFAR measured an hyperbolic wave front shape F.G. Schröder et al, 2014. A. Corstanje et al. 2014.

Wave front shape description depends on:

- distance to ground
- emission extension
- detector size

Conical | Hyperbolical | Spherical | Plane

$\Delta x \ll v\Delta t$ | $\Delta x \sim v\Delta t$ | $\Delta x \gg v\Delta t$ | $\Delta y \ll \Delta x$

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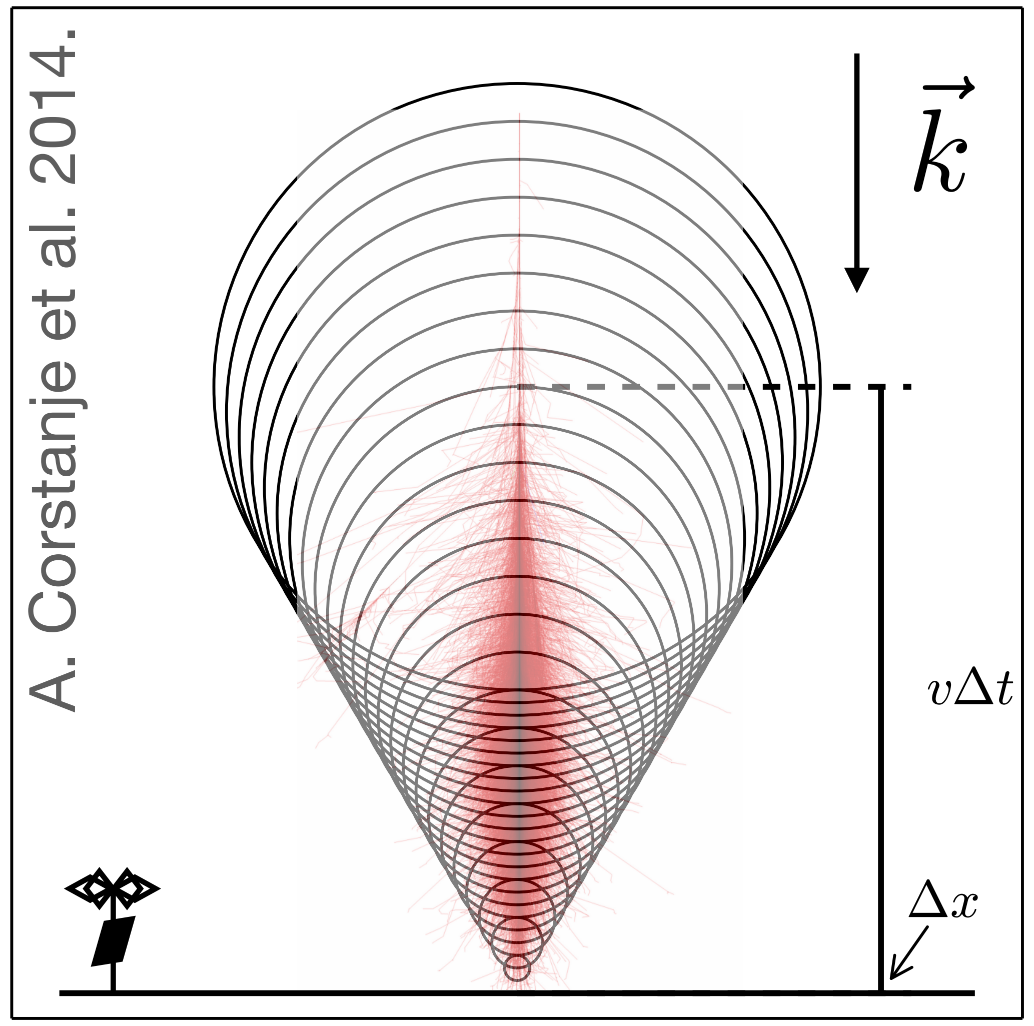
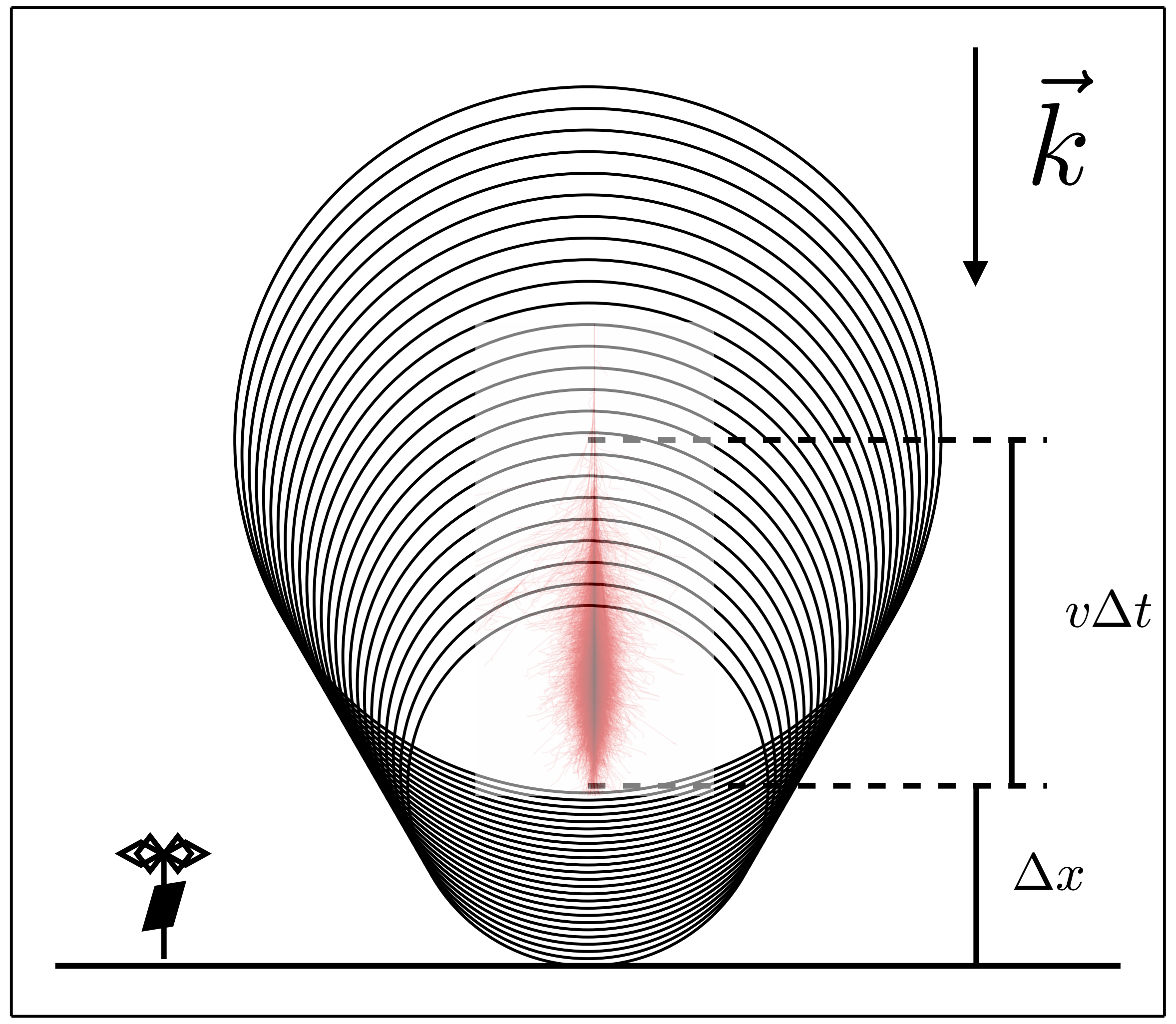


$\Delta x \ll v\Delta t$

Hyperbolical



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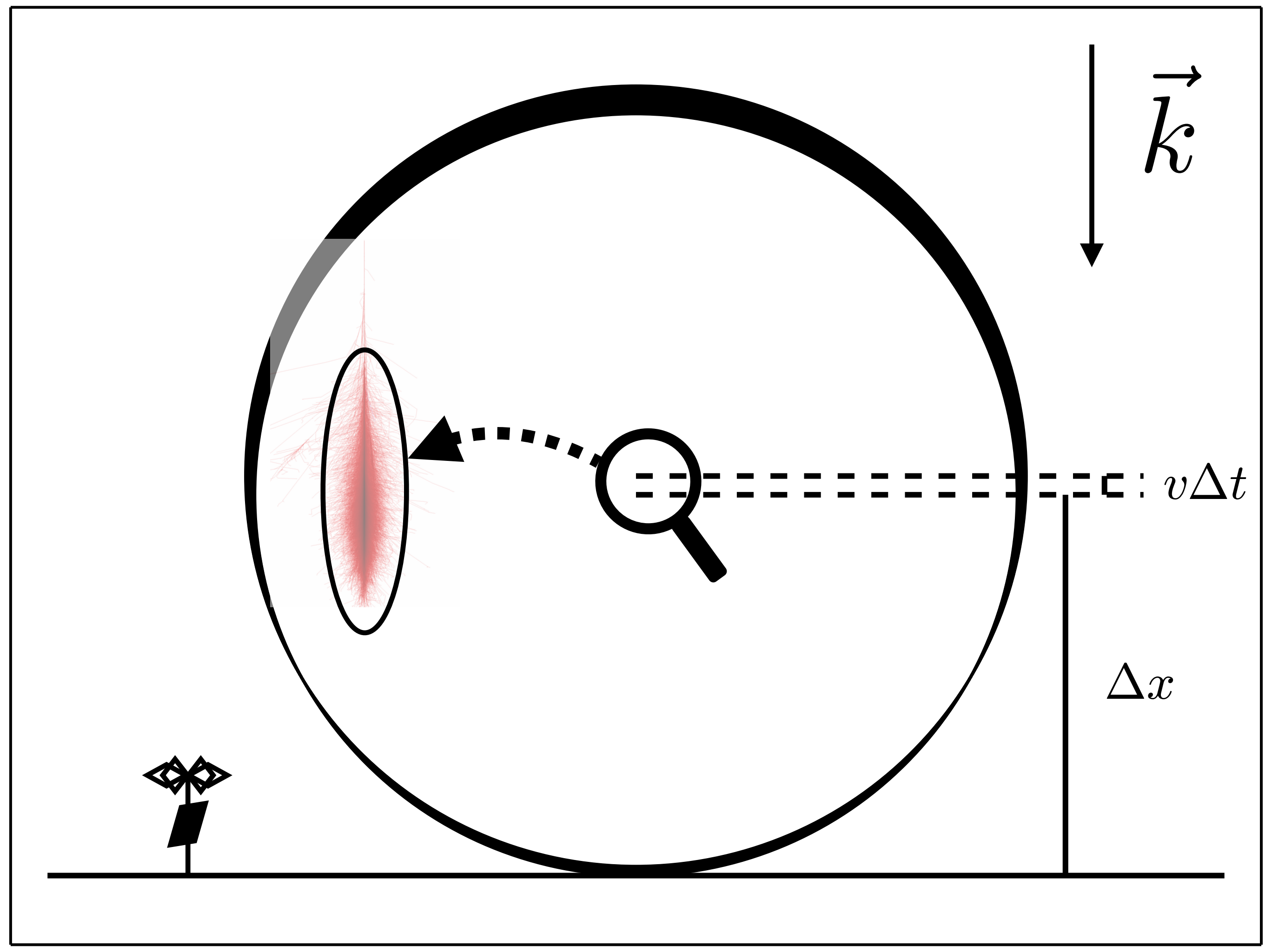
Spherical



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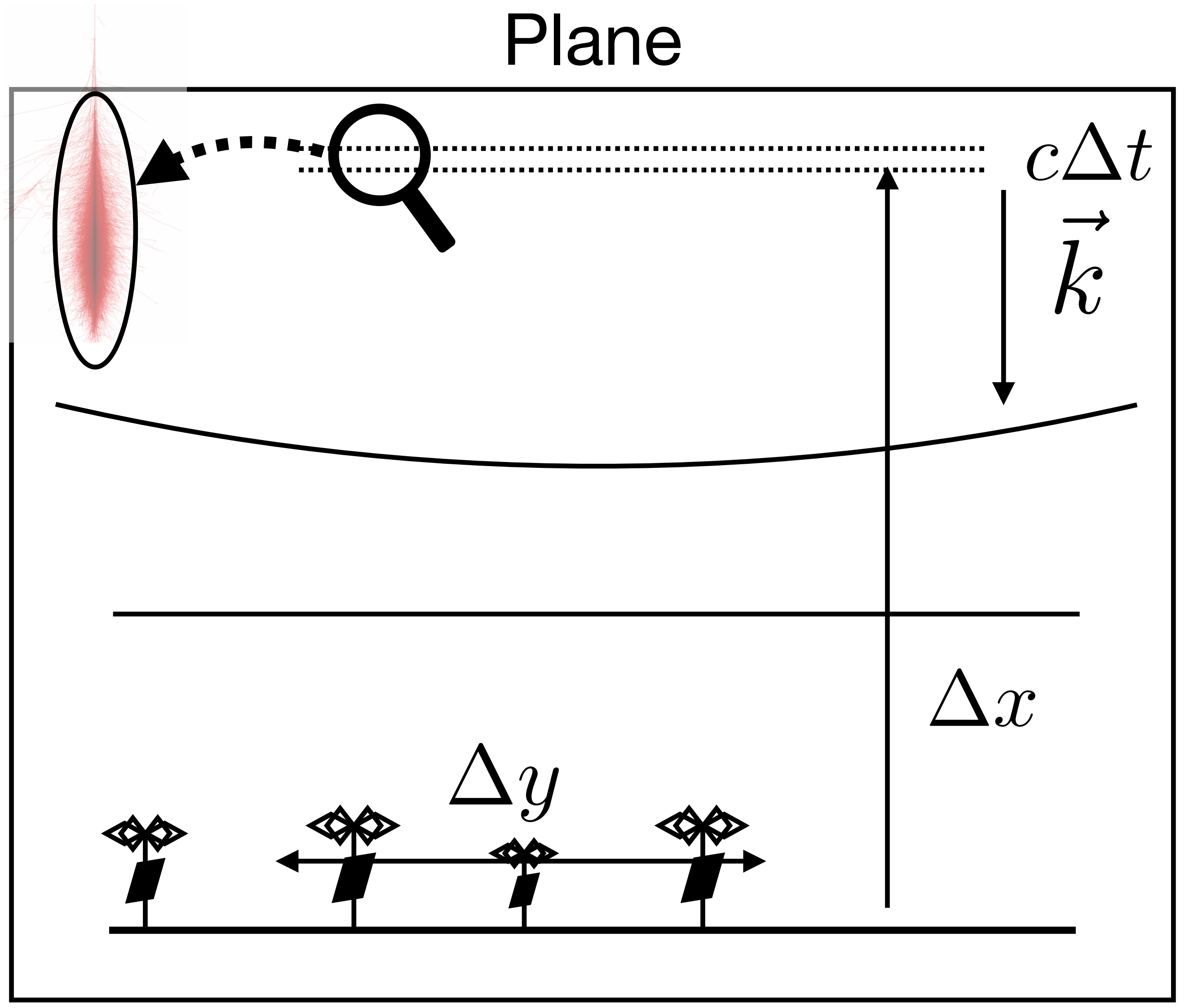
Plane



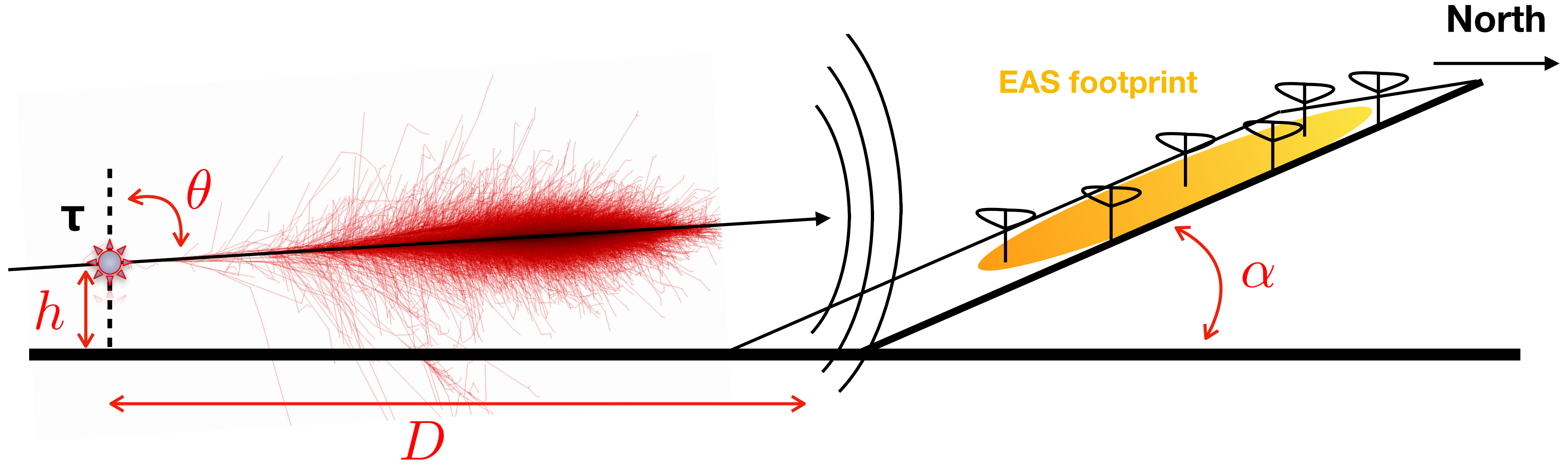
$\Delta y \ll \Delta x$

<u>But</u> in the case of GRAND:
- very inclined EAS → extended emission zone
- very large array → emission changes

A detailed study of GRAND measured wave front shape needed

Hyperbolic wavefront model

Reminder of a ToyModel simulation:



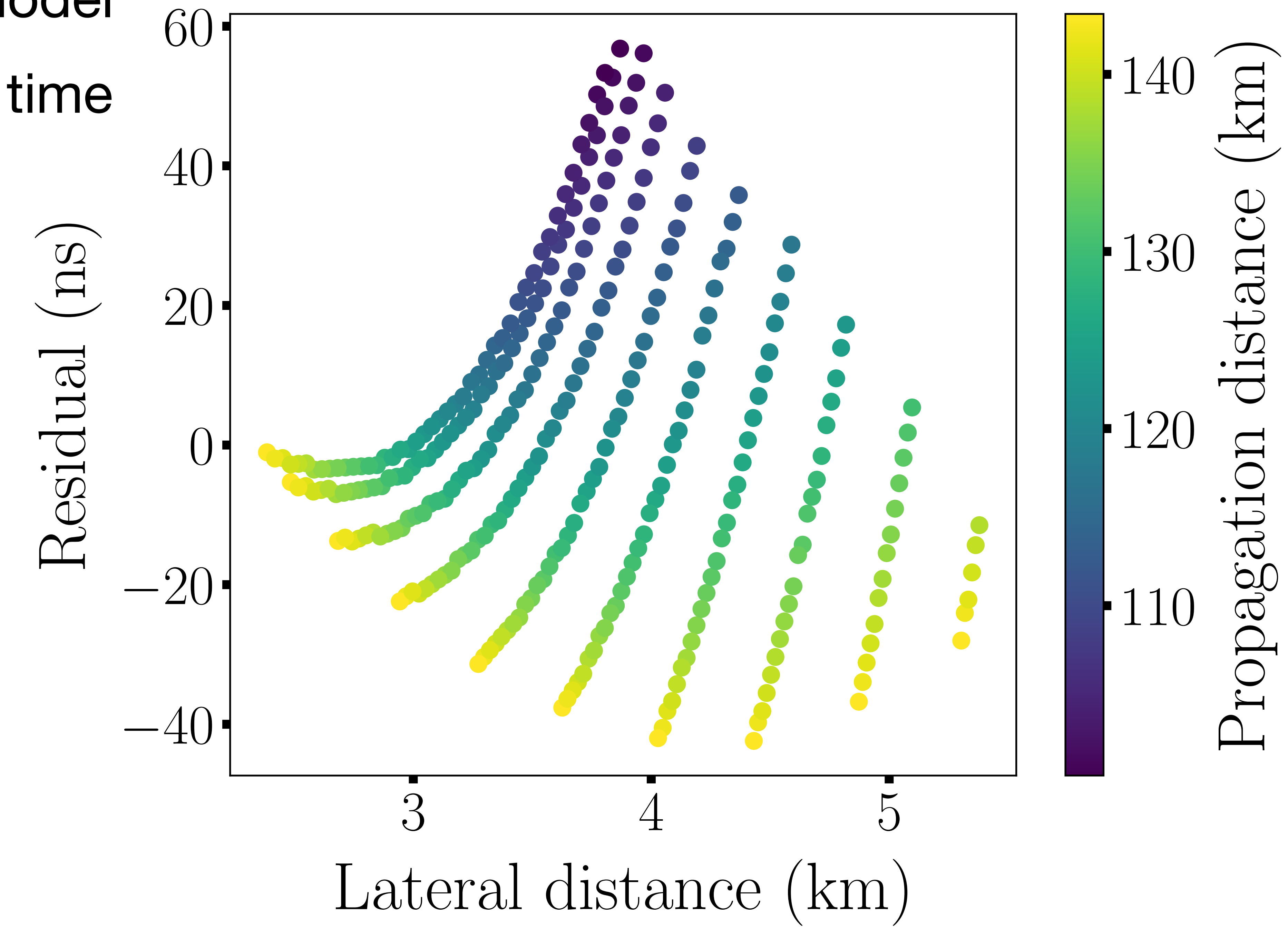
Standard approach: study the wave front curvature

- on simulations
- GRAND-like layout

residuals = trigger time - wave front model

1 dot = 1 antenna trigger time

Standard hyperbolic fit



Standard definition

$$c\,t^{\text{hyp}} = -a + \sqrt{a^2 + b^2 r^2}$$
$$r = \text{lateral distance}$$
$$(a, b) = \text{hyperbolic parameters}$$

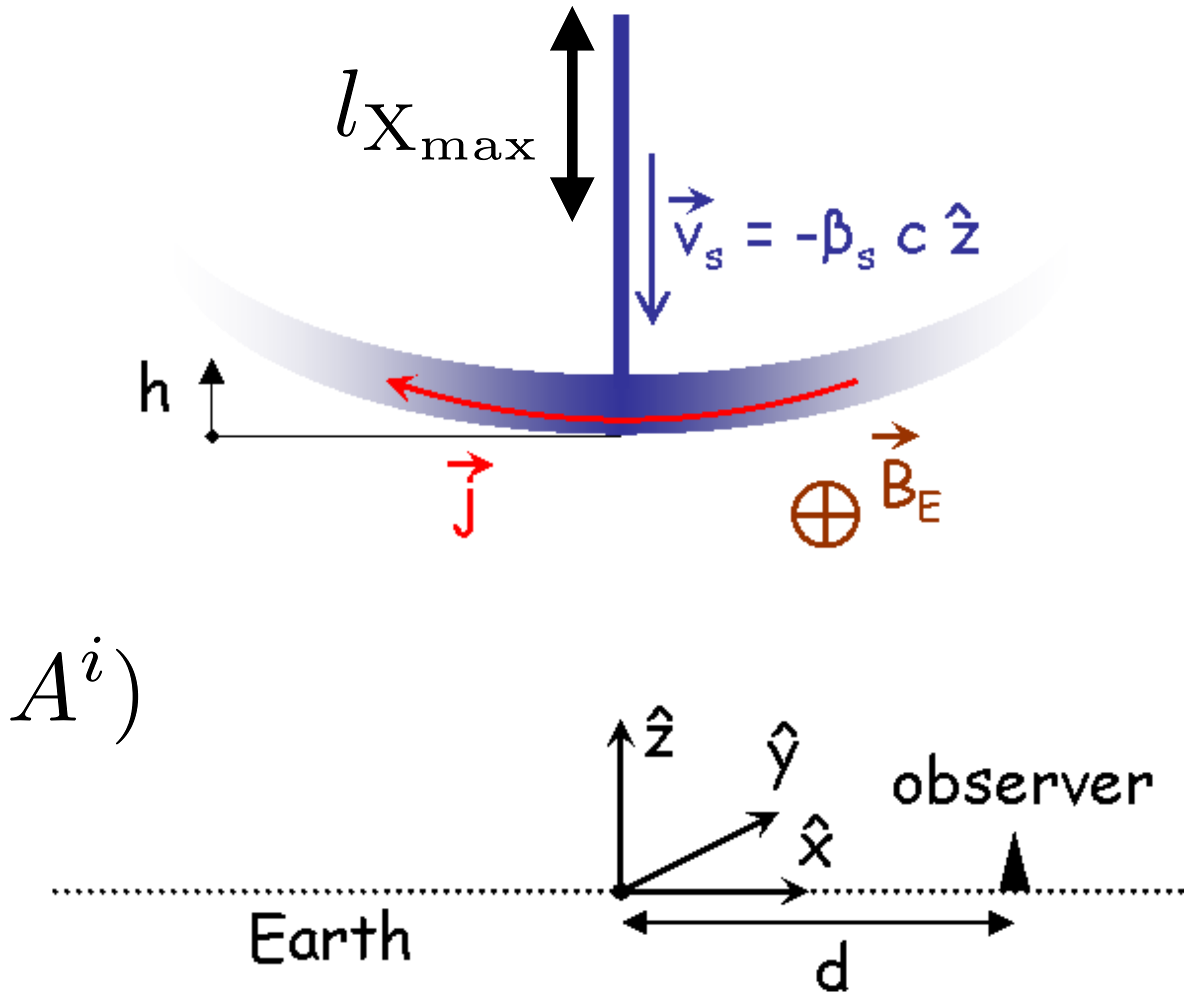
Very inclined showers: evolution of the wave front is visible

Fixed hyperbolic parameters → snapshot of the emission (LOFAR/LOPES)

Hyperbolic parameters physical meaning ?

How does the wave front evolve?

Macroscopic approach of the EAS emission



Scholten et al. (2008)

Can we derive the wave front shape from physical principles ?

- Model the charge current induced by the particle $J^\mu(\vec{x},t)$ in terms of particle density and repartition

Potential-vector (classical electrodynamics) $A^\mu(\vec{x},t)$ ➡ Electric field $\vec{E}(\vec{x},t) = -(\partial_i A^0 + \partial_0 A^i)$

Too many parameters to adjust in this model

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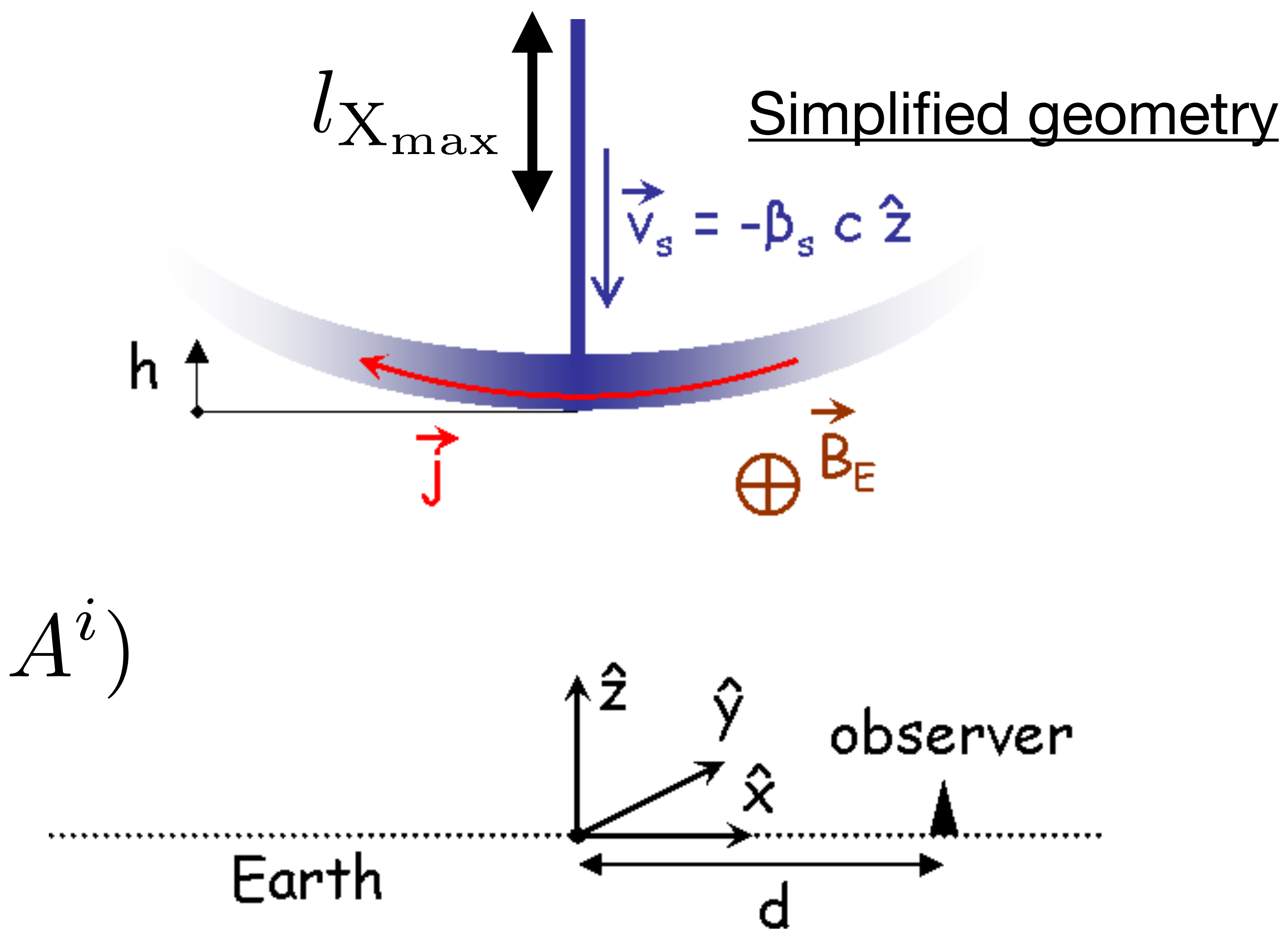

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- In the "Limiting case" and in a simplified geometry

$$E_x(t, r) = -J\frac{n^2\Delta}{c\mathcal{D}^2}\frac{\mathrm{d}f_t(t_r)}{\mathrm{d}t_r} + Jf_t(t_r)\frac{c\beta_s^2 t}{\mathcal{D}^3}$$

where
$n = \text{index of refraction}$
$\Delta = \text{geometrical distance}$
$\mathcal{D} = \text{observer distance}$

Limiting case:

- shower particle front thickness is neglected
- Index of refraction is close to unity

Too many parameters to adjust in this model

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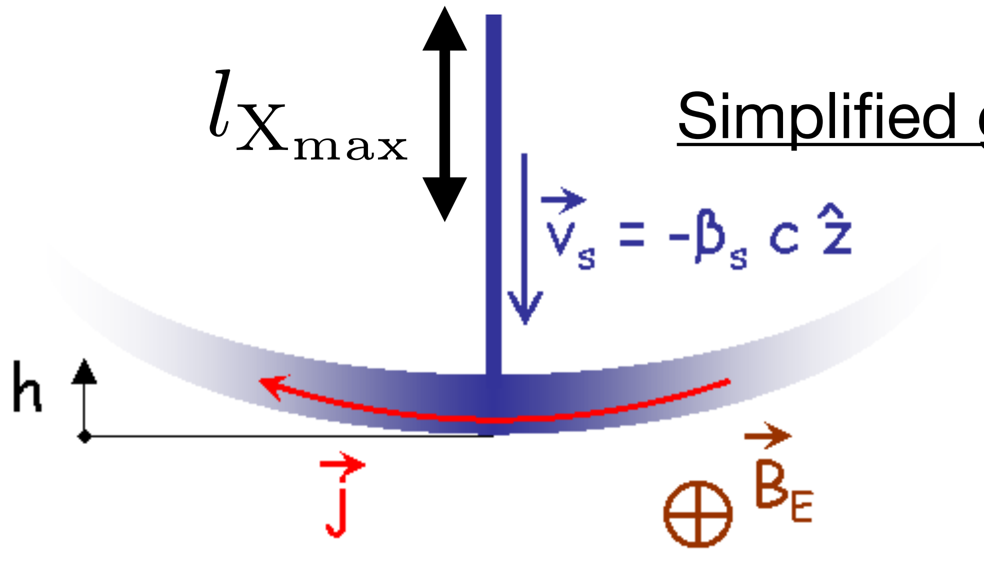

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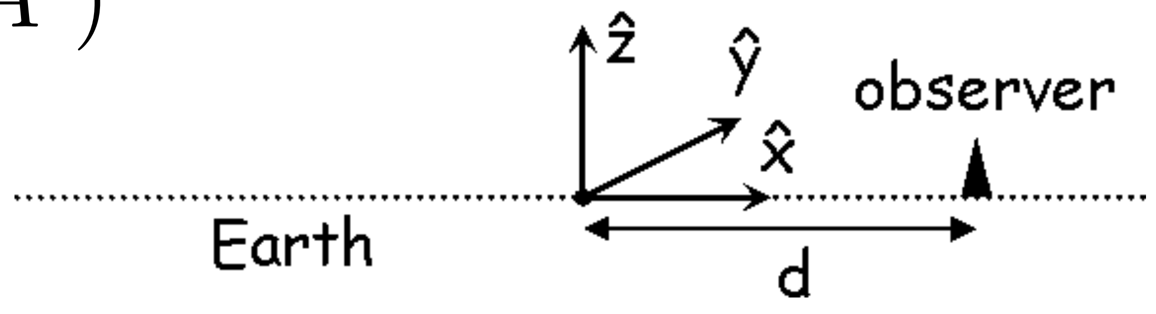

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Limiting case:
- shower particle front thickness is neglected
- Index of refraction is close to unity

- The wave front corresponds to $\frac{\mathrm{d}E_x(t, r)}{\mathrm{d}t} = 0$ maximum of the emission

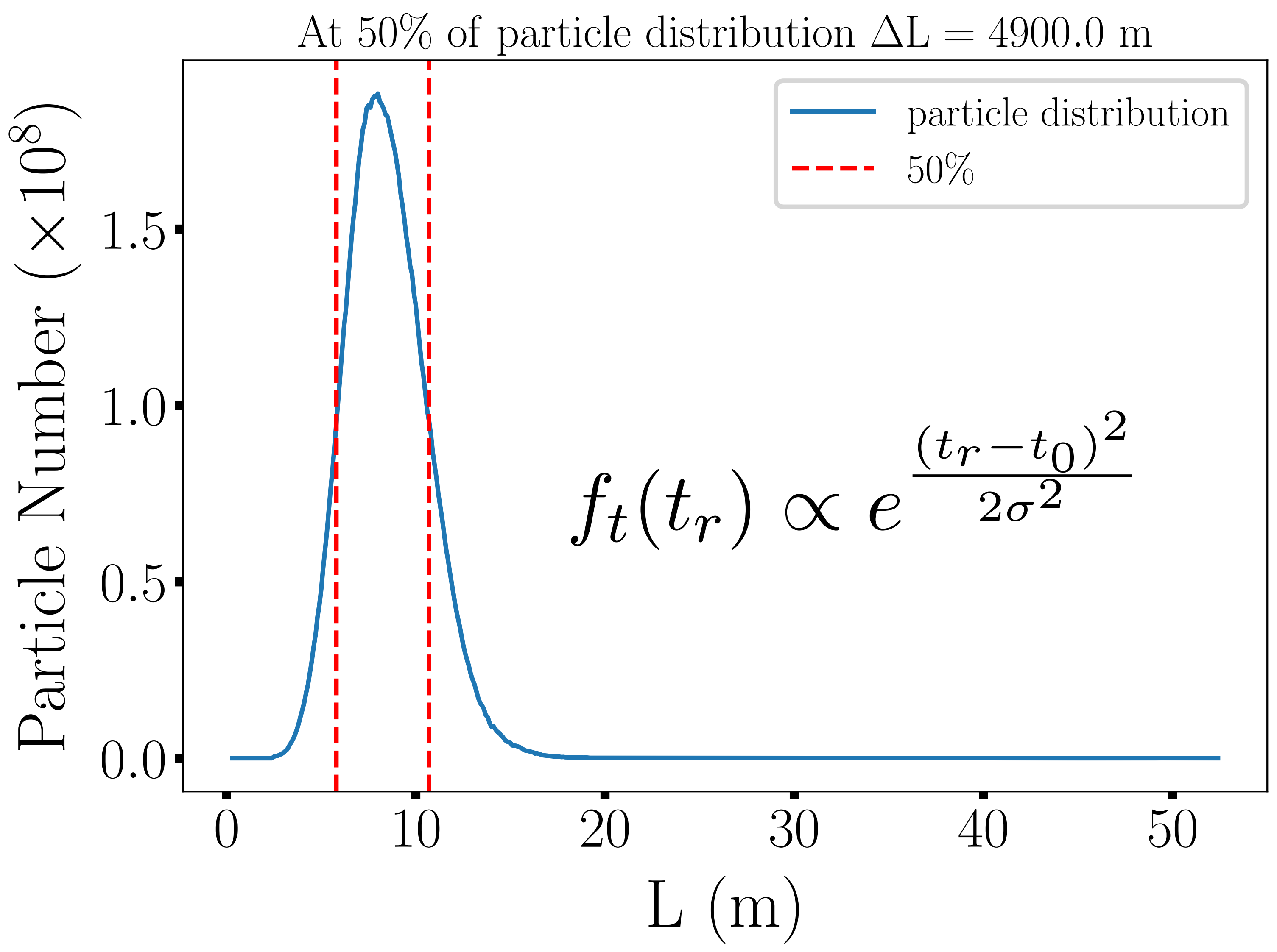
$$\rightarrow \quad t = -\frac{(1+\beta_s)(1+\delta)}{T(\delta+\chi)} \mp \sqrt{\frac{(1+\beta_s)^2(1+\delta)^2}{T^2(\delta+\chi)^2} - \frac{\tau(1+\beta_s)}{T(\delta+\chi)}} \sim -a + \sqrt{a^2 + b^2 r^2}$$

with
$$a = \frac{(1+\beta_s)(1+\delta)}{T(\delta+\chi)}$$
$$b = \frac{(1+\beta_s)}{T(\delta+\chi)} \frac{l}{\beta_s^2 c^3 \sigma^2}$$

and
$$\tau = \frac{l r^2}{\beta_s^2 c^3 \sigma^2} \quad T = \frac{l}{\beta_s c \sigma^2}$$
$$\delta = \frac{l n^2 \Delta}{\beta_s^2 c^2 \sigma^2} \quad \chi = 1 - \frac{n^2 (l - l_{X_{max}})}{\Delta}$$

only physical parameters of the shower

Assuming a gaussian particle distribution

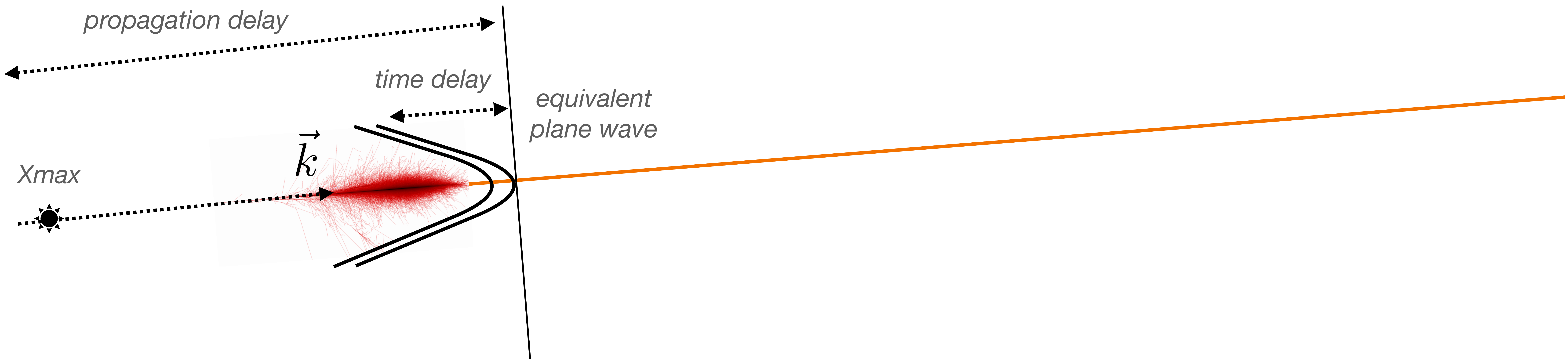


Too many parameters to adjust in this model

Study of the wavefront shape: method

V. D (PSU), Olivier Martineau-Huynh (LPNHE) and Matias Tueros (CONICET) (Astroparticle Physics, 2022)

What time delays tell us about the curvature of the wavefront?



Wavefront shape modelling:

$$\text{wavefront} = \text{propagation} + \text{curvature}$$

propagation delay = plane wave propagation at speed c/n

time delay = intrinsic curvature of the wavefront

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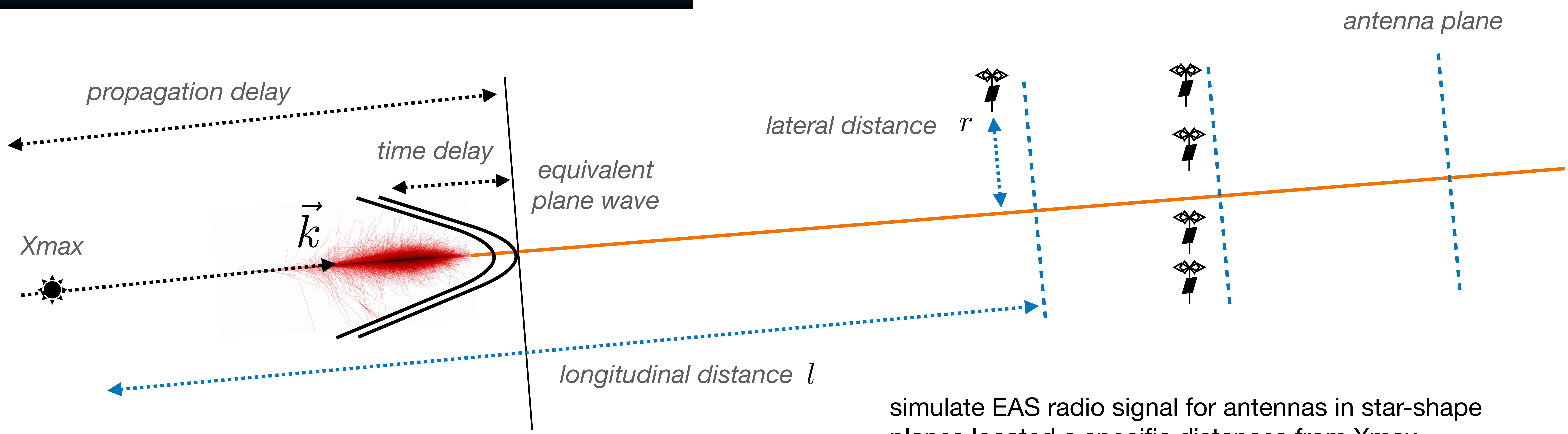

simulate EAS radio signal for antennas in star-shape planes located a specific distances from Xmax

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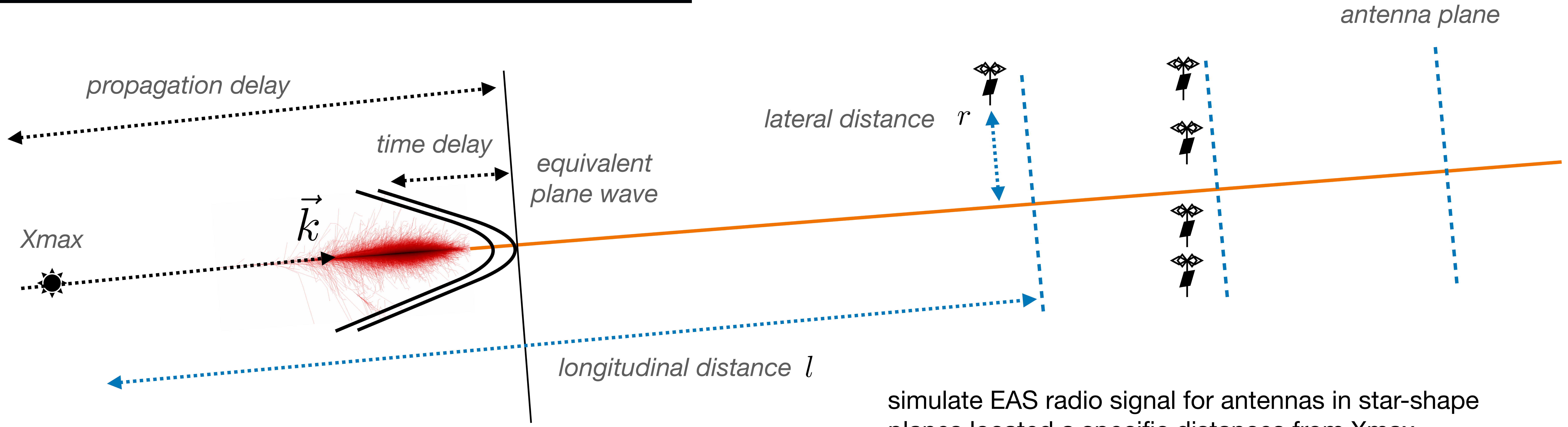


simulate EAS radio signal for antennas in star-shape planes located a specific distances from Xmax

<u>ZHAireS simulation</u>:
- 7 planes from 17km to 200km
- zenith between 63° and 88°
- energies between 0.02EeV and 4EeV
- azimuth values = 0°, 180° and 270° w.r.t. magnetic North

<u>Wavefront shape modelling</u>:

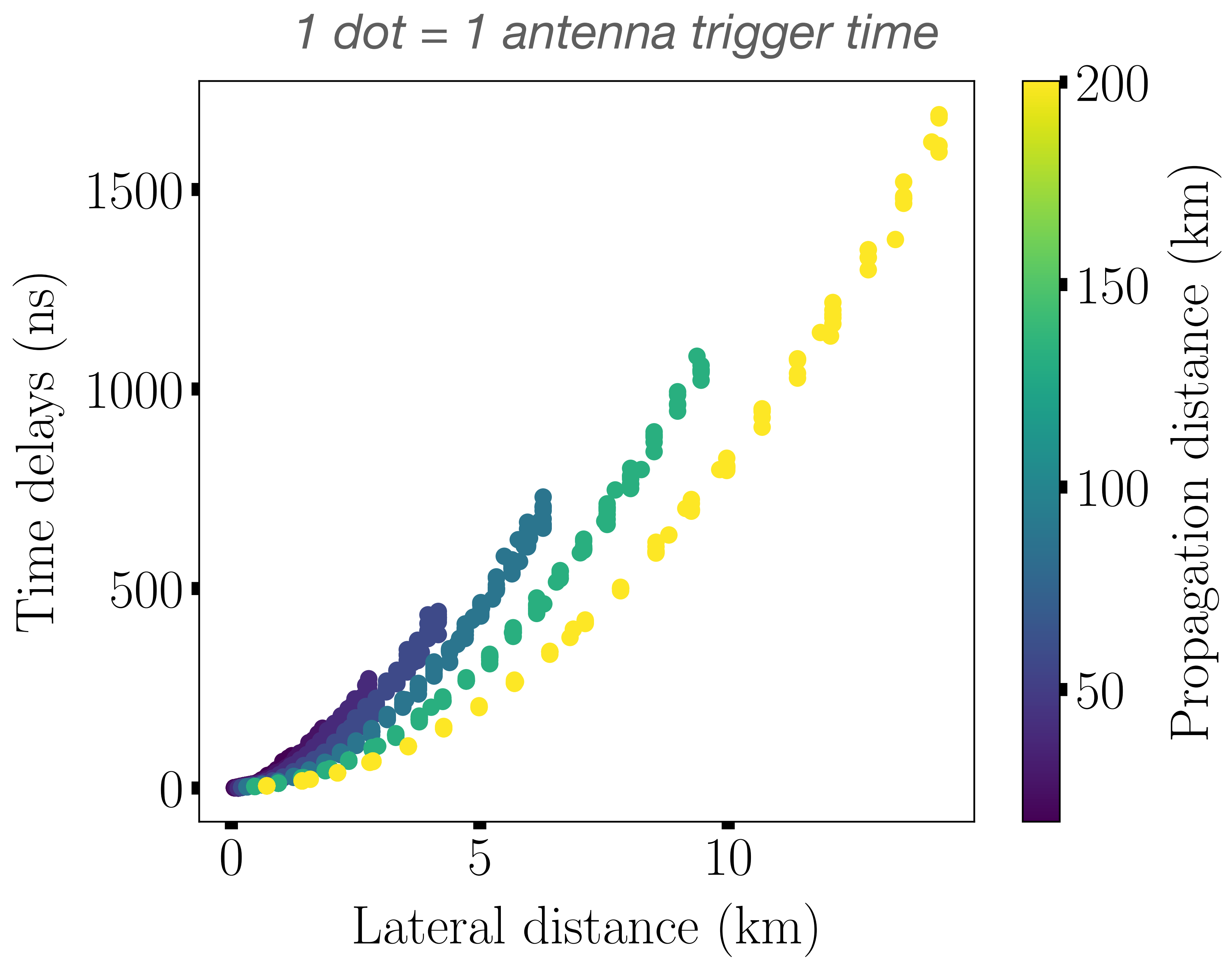
$$\text{wavefront} = \text{propagation} + \text{curvature}$$

propagation delay = plane wave propagation at speed c/n

time delay = intrinsic curvature of the wavefront

→ sample the wavefront along radial and longitudinal distances

Study of the wavefront shape: results

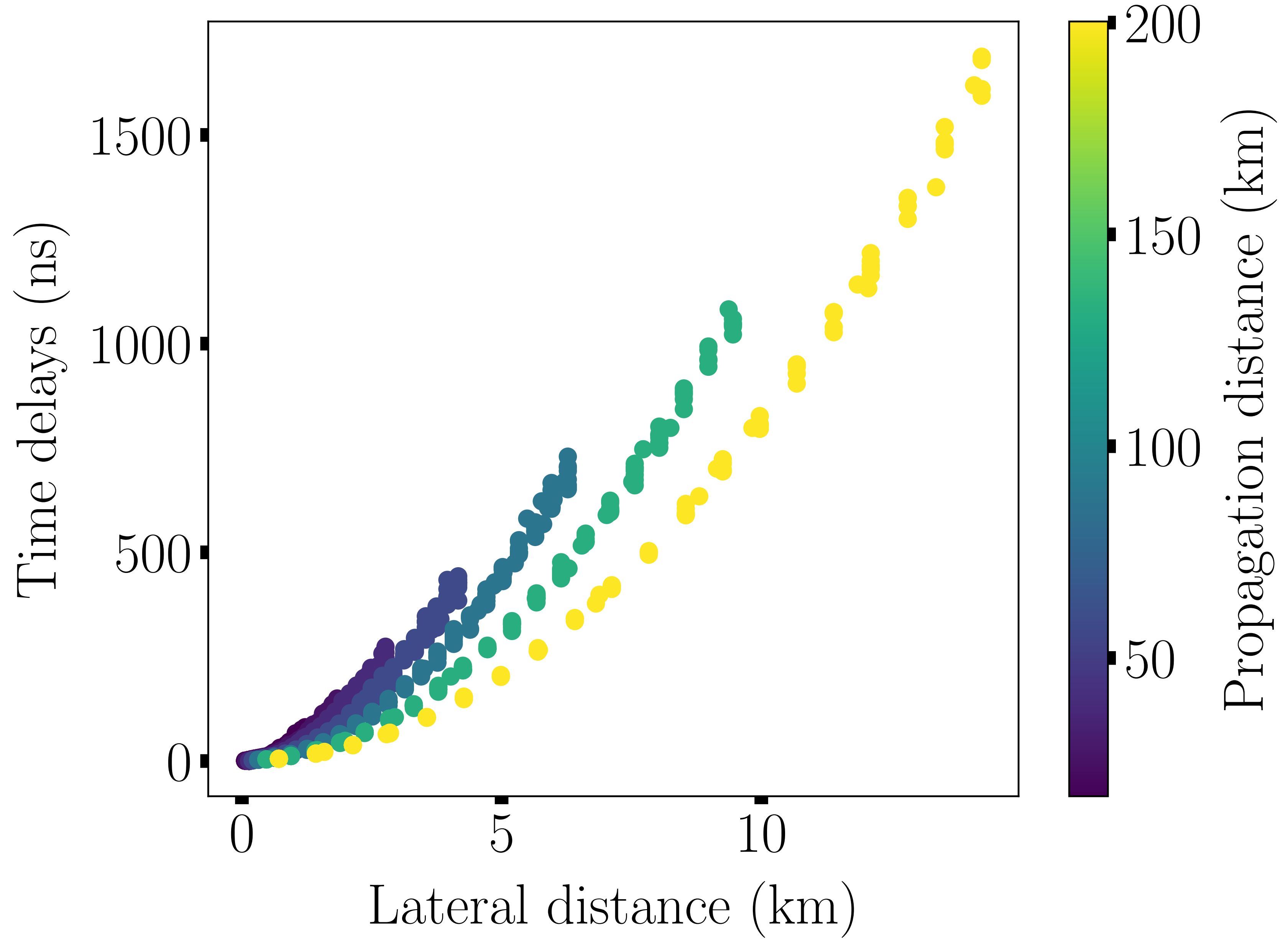


- time delays increase with lateral distance
- curvature reduces with propagation distance

what model describes best this curvature ?

Study of the wavefront shape: results

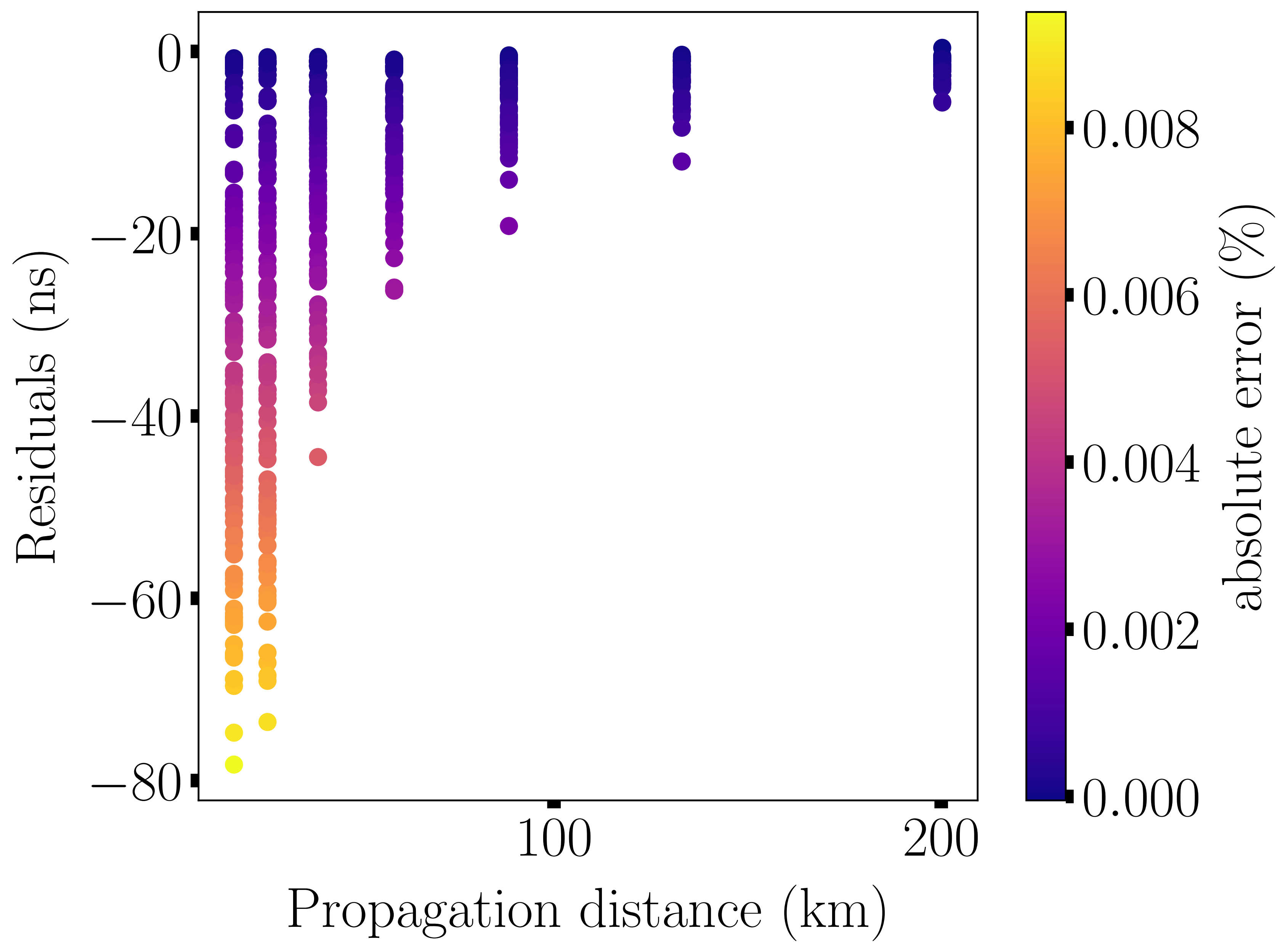
1 dot = 1 antenna trigger time



spherical wavefront model

$$c\,t^{\mathrm{sph}} = n\sqrt{l^2 + r^2}$$

residuals = trigger time - wave front model



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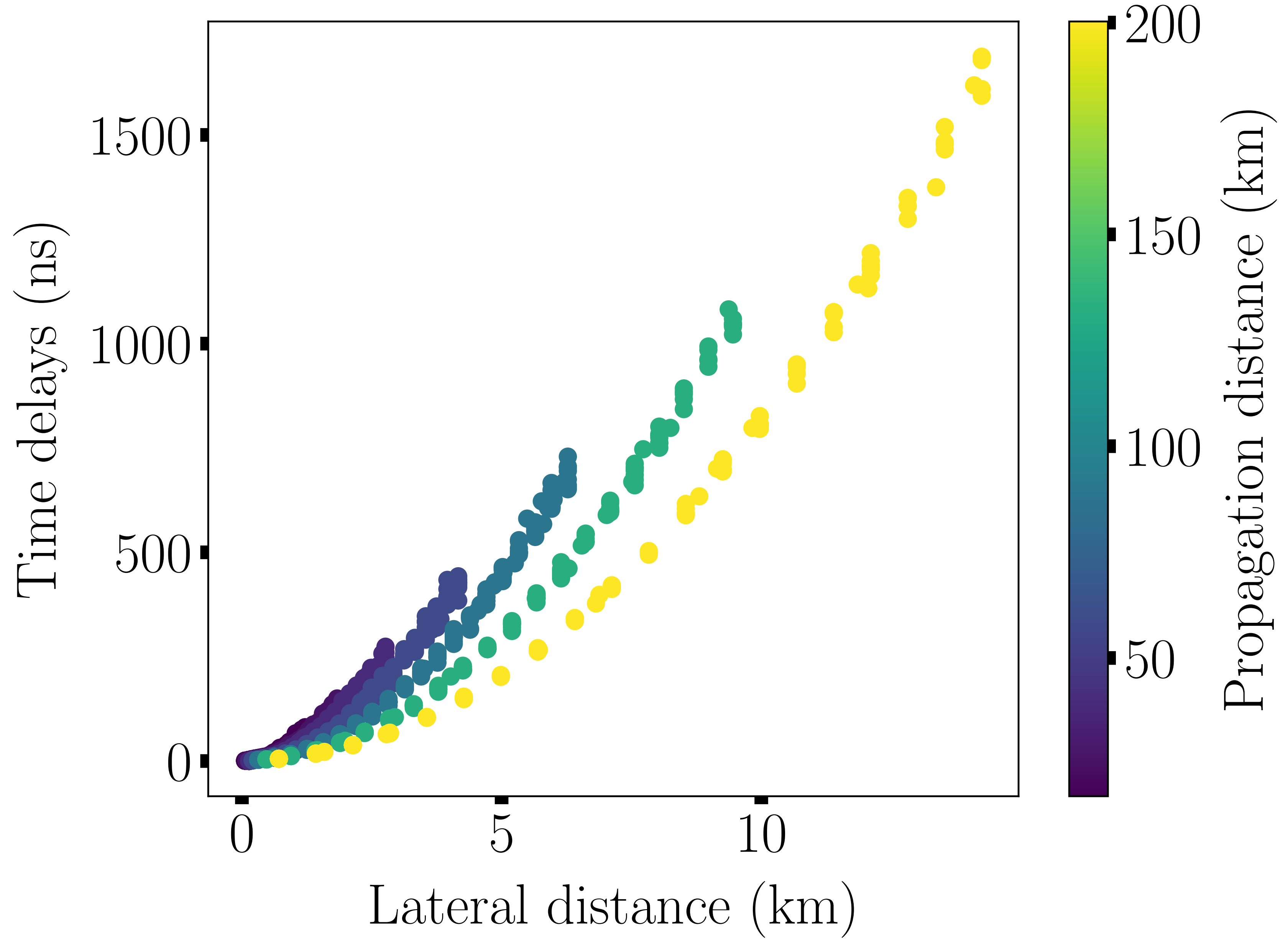

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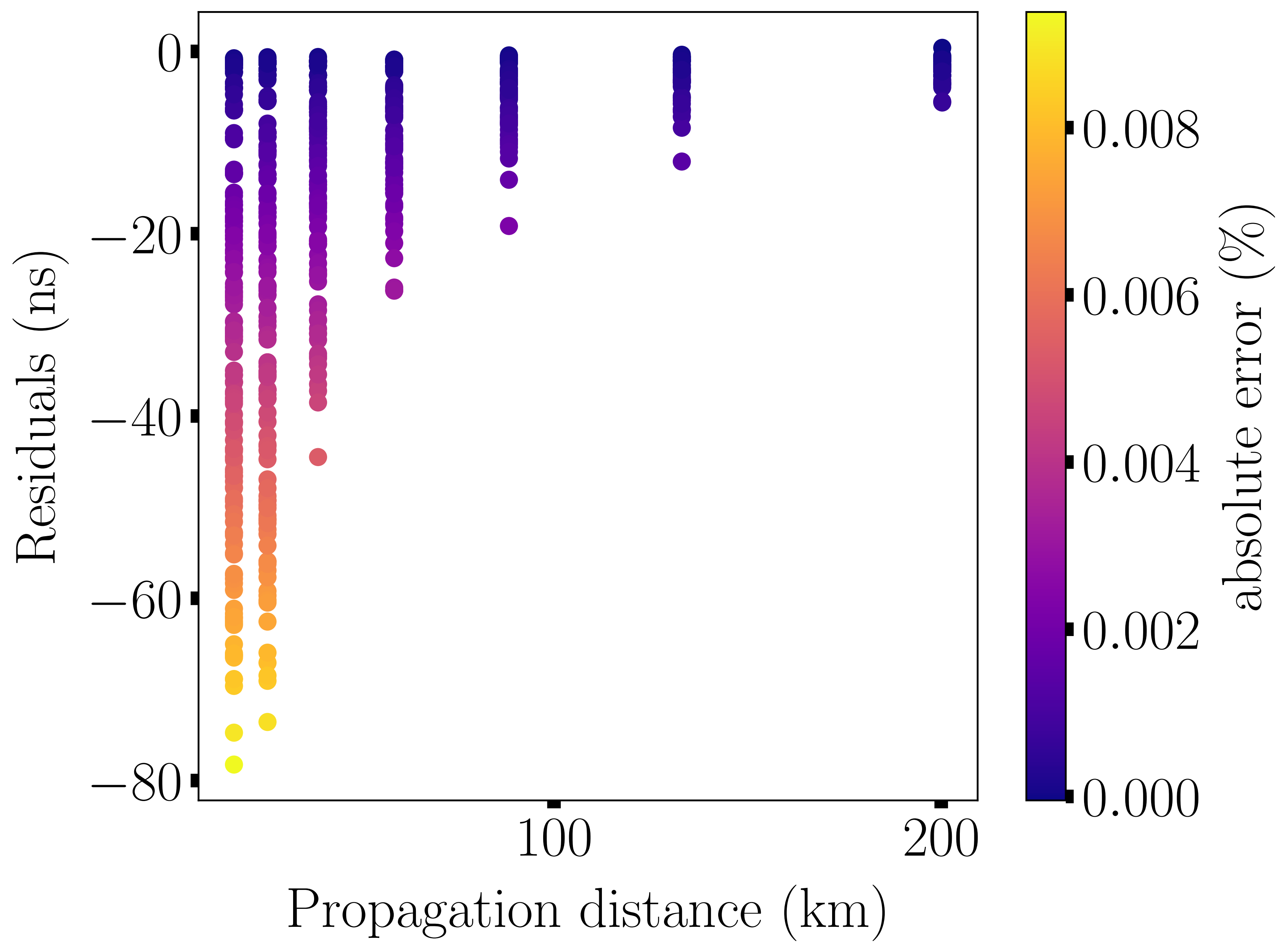

- time delays increase with lateral distance
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what model describes best this curvature ?

Results:
- residuals < experimental time resolution
- arrival times undistinguishable between spherical model and more complex model

Consequences for reconstruction

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Results: spherical wavefront model offers a very good level of description

Consequences: impossible to reconstruct the arrival direction: spherical wave front model → point-like emission = no favoured direction

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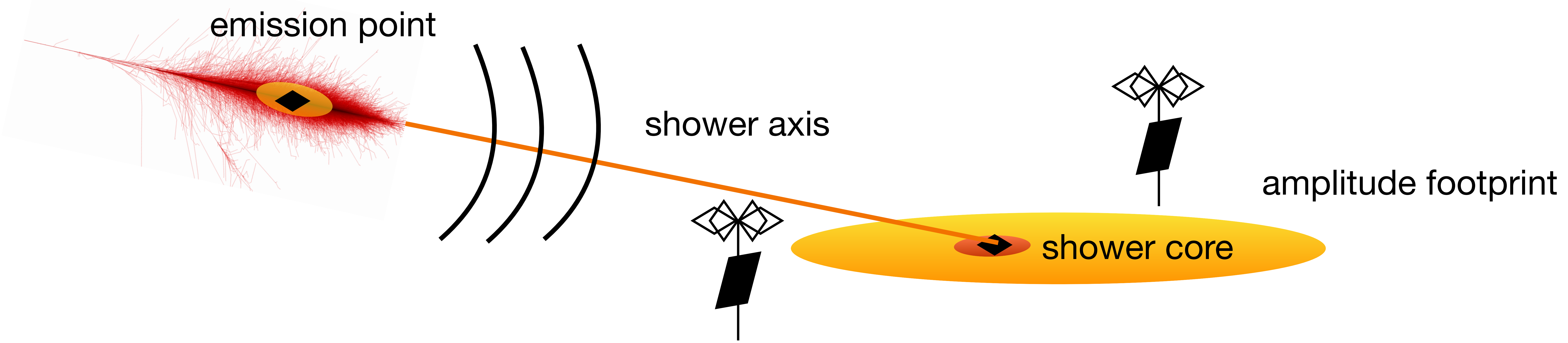
How to reconstruct the arrival direction?



A second natural point along the shower propagation: shower core

Information content in the amplitude distribution of the radiation

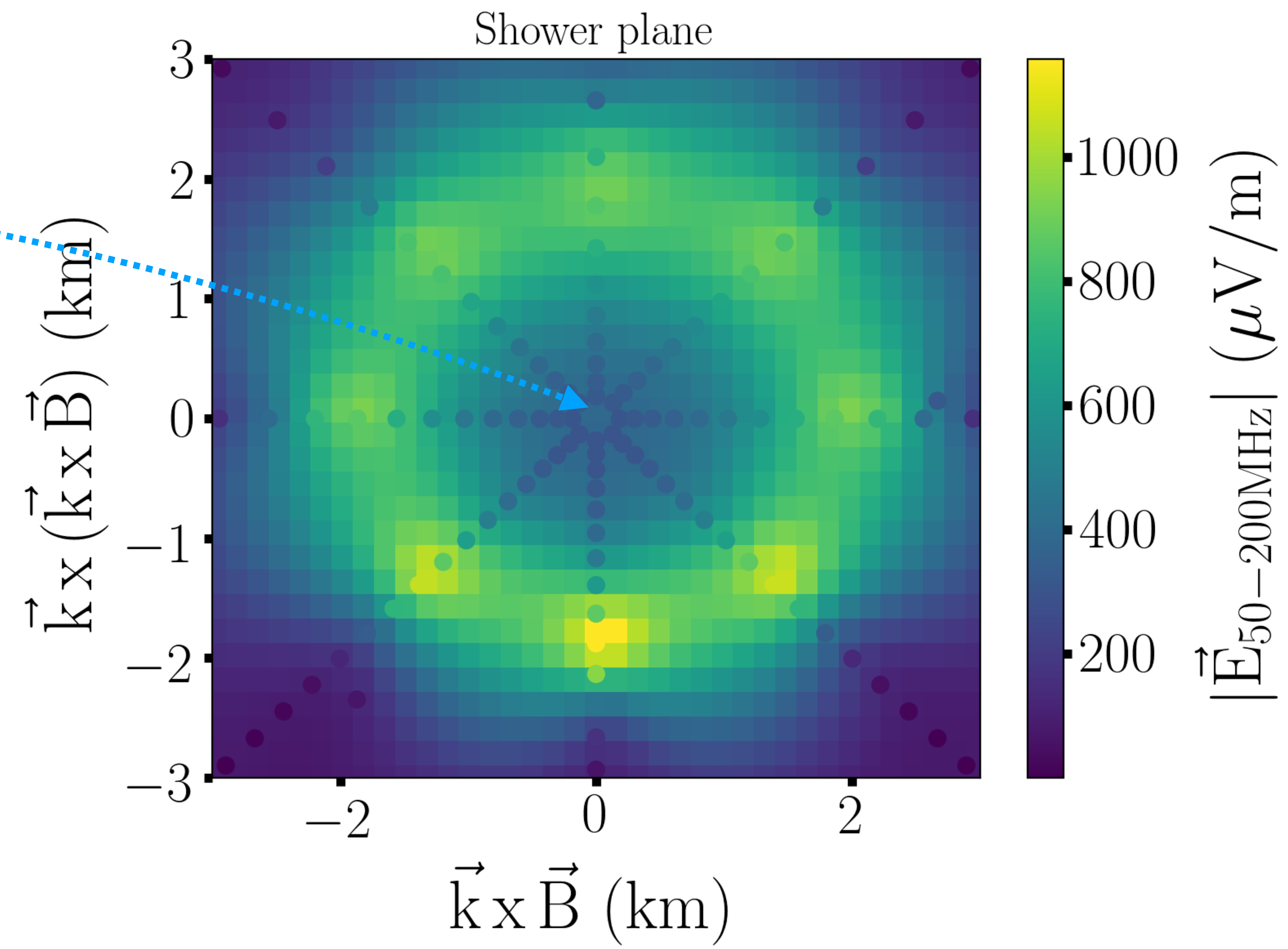
Amplitude distribution (pattern) = antennas measurements → straightforward handle on the core position

Beaming of the emission + Cerenkov effect (signal coherence + compression)

→ Distinct signature of the core position in the signal amplitude

Geomagnetic emission + Askaryan emission = asymmetry features

depends on:
- geomagnetic field orientation
- observer position



Correctness of the amplitude model → accuracy of the reconstruction of the arrival direction

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→ depends on:
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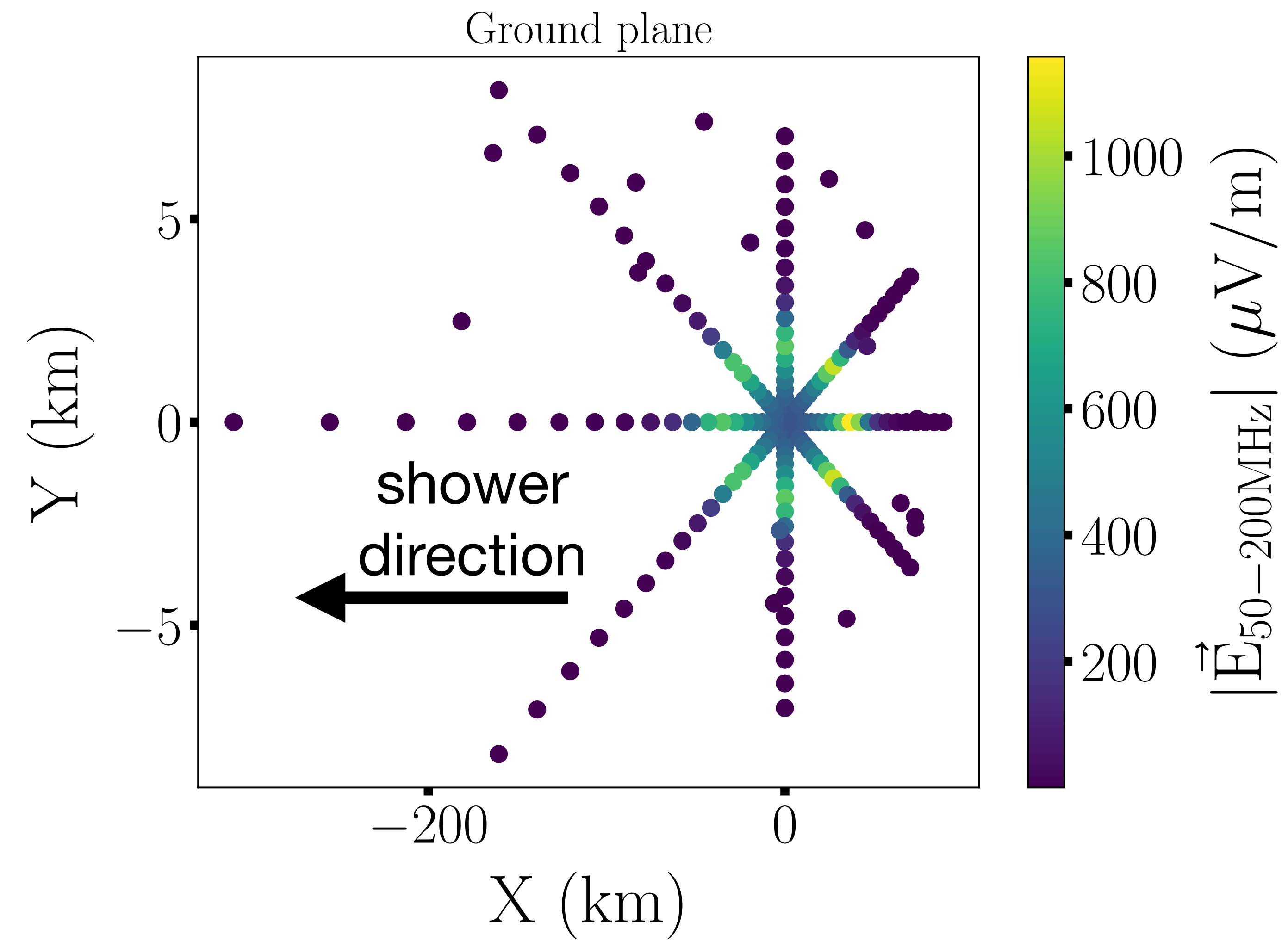
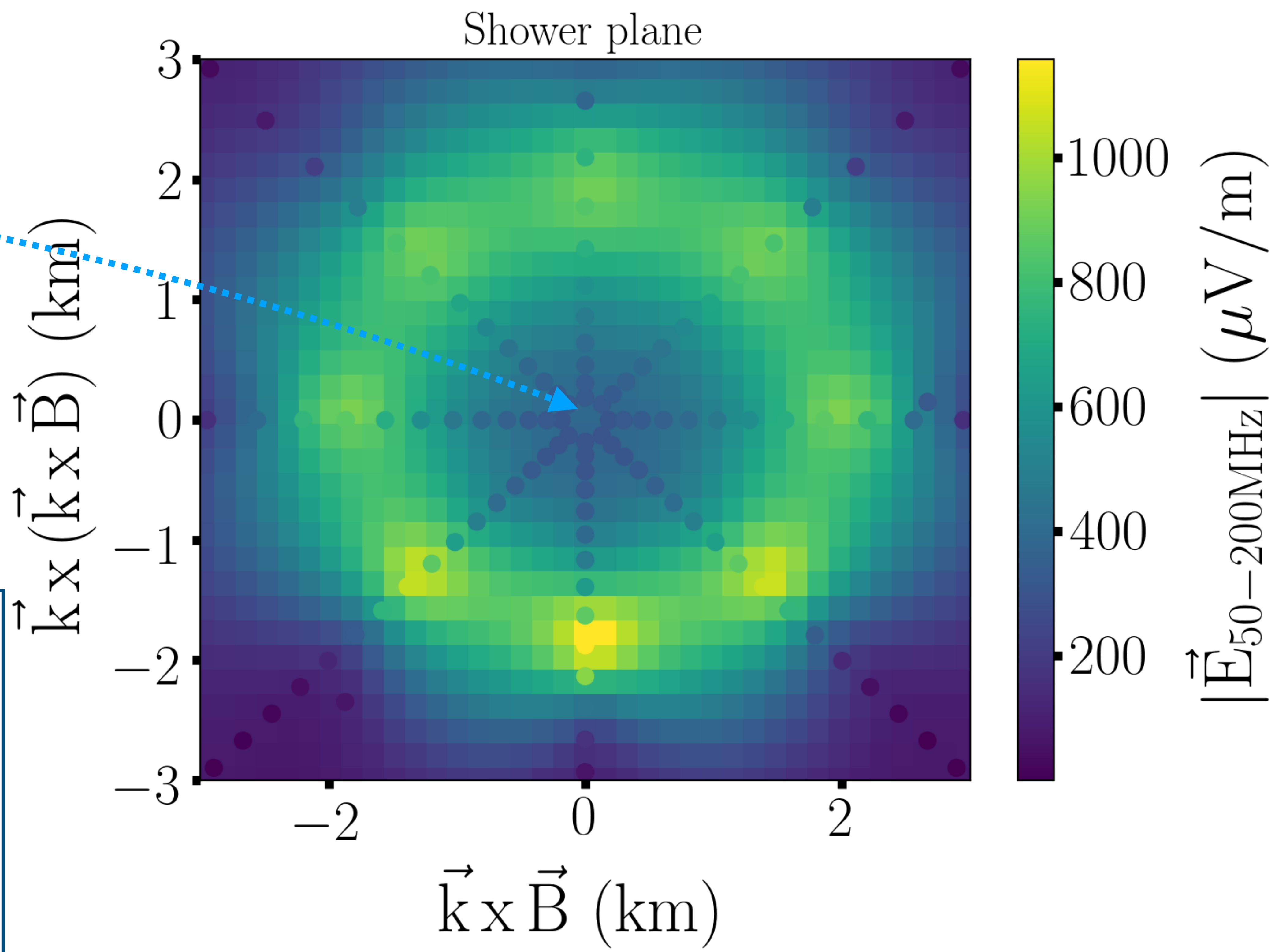
New simulation set used: “StarShape”
- centered on the shower core
- Star shaped

→ better sampling of the amplitude





Correctness of the amplitude model → accuracy of the reconstruction of the arrival direction

Phenomenological description of the amplitude pattern

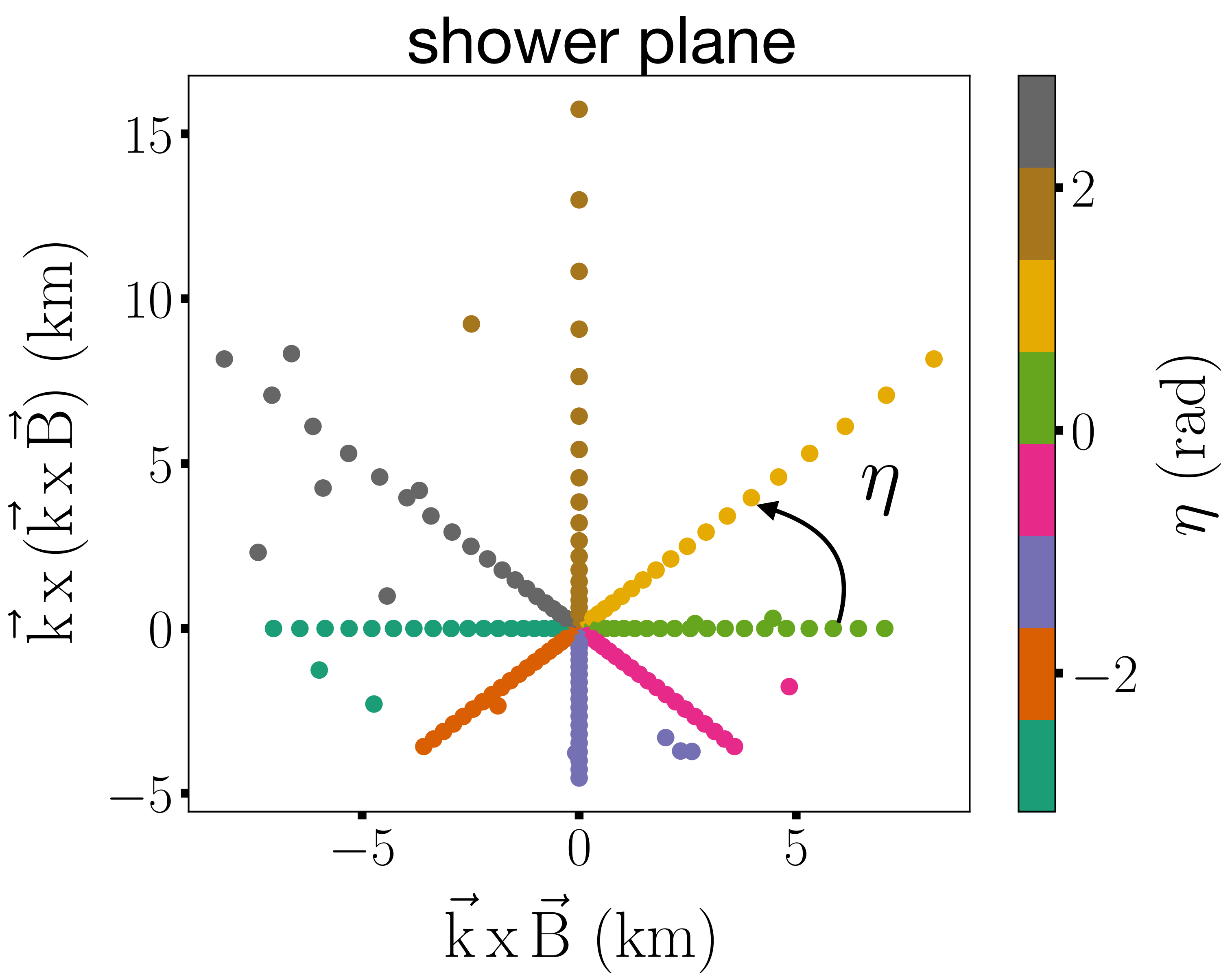
Goal: analytical description of the amplitude:

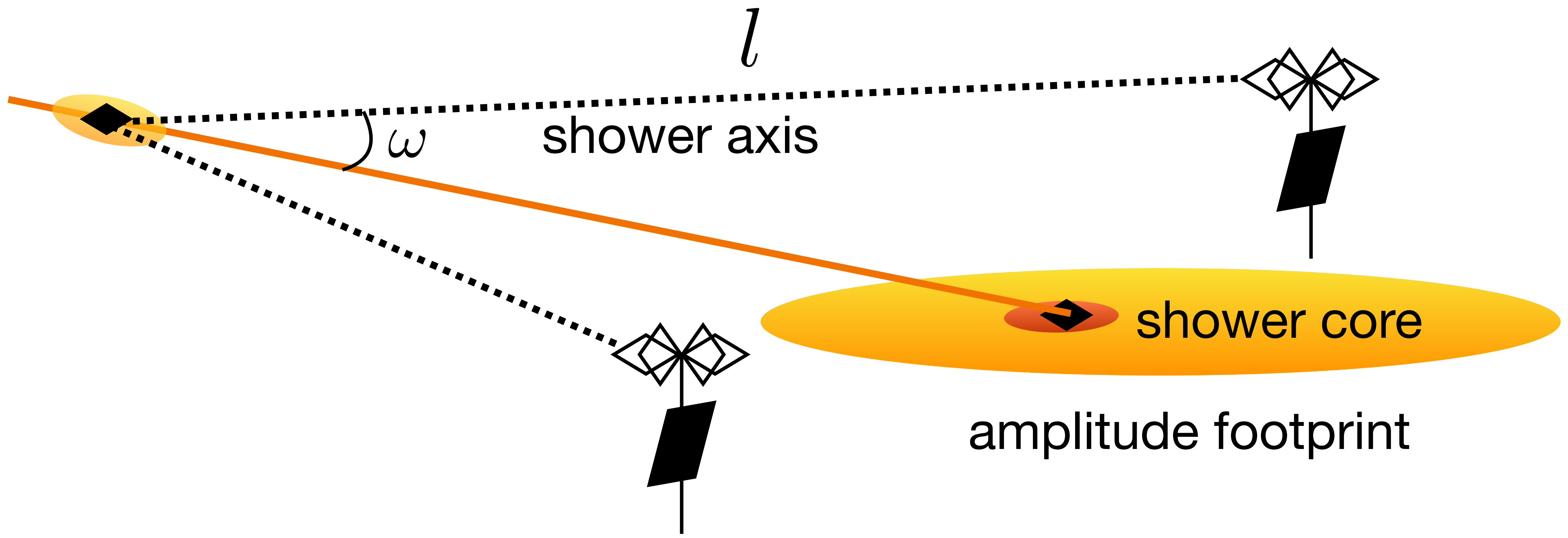
- shower direction
- all the asymmetries effects

Method: phenomenological description as a function of the angular position of the observer

Angular Distribution Function: (ADF)

$$f^{\mathrm{ADF}}(\omega,\eta,\alpha,l;\delta\omega,\mathcal{A}) = \frac{\mathcal{A}}{l} f^{\mathrm{GeoM}}(\alpha,\eta,\mathcal{B})\ f^{\mathrm{Cerenkov}}(\omega,\delta\omega)$$





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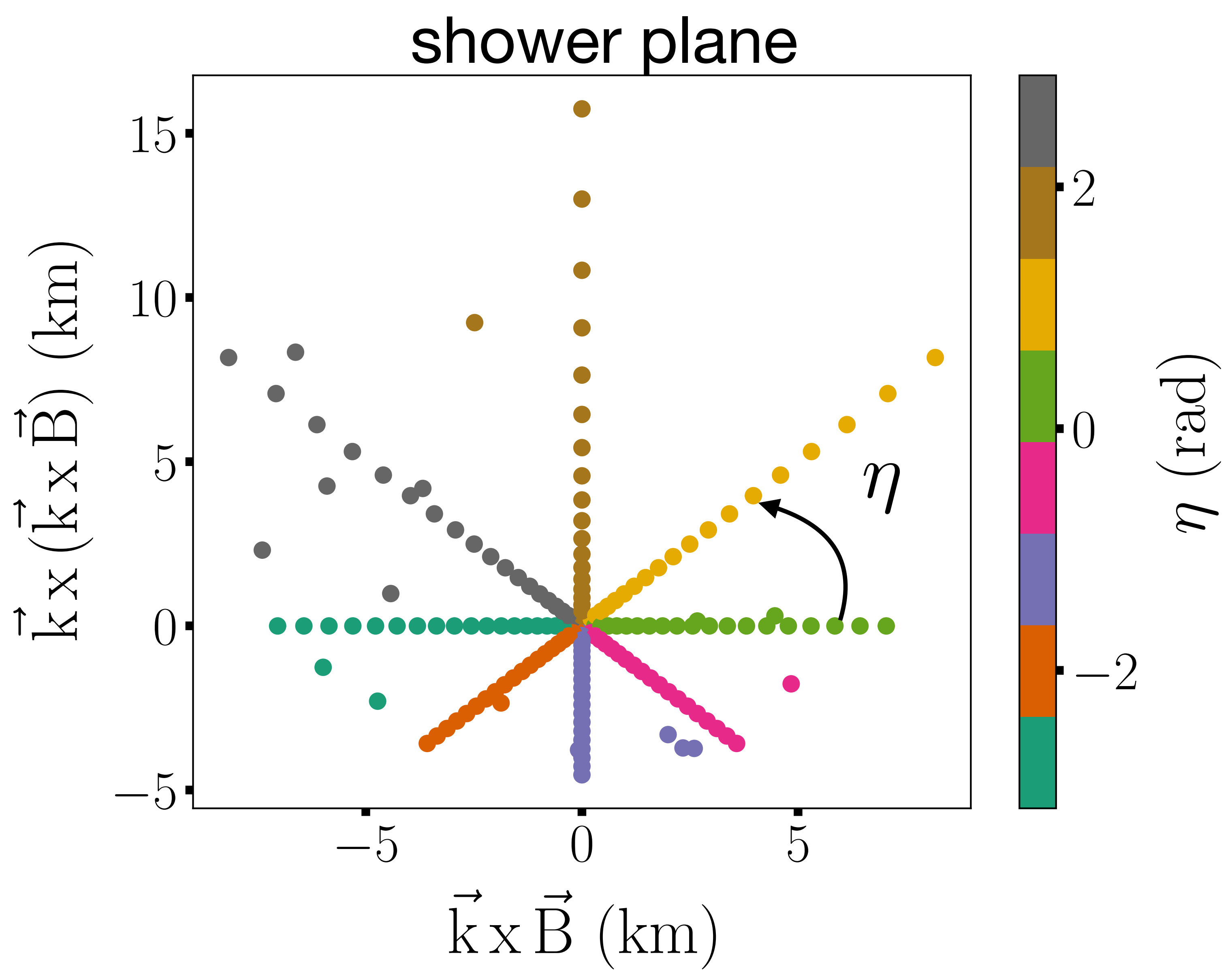


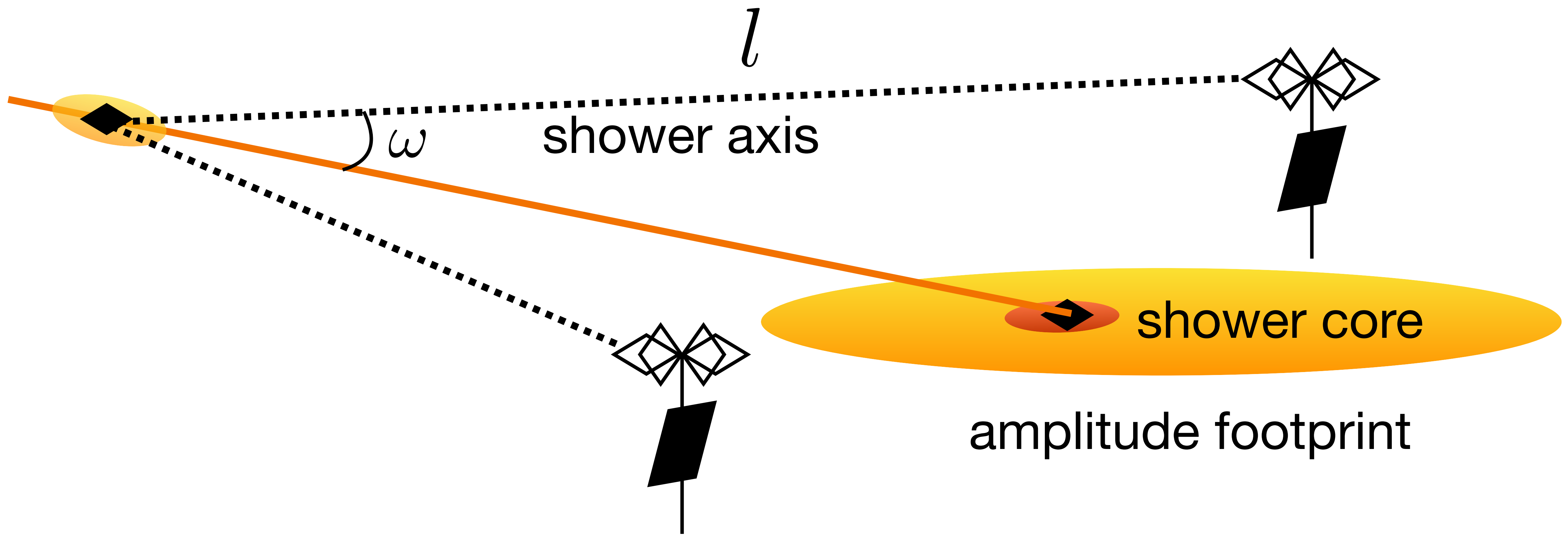
Angular Distribution Function: (ADF)

$$f^{\mathrm{ADF}}(\omega, \eta, \alpha, l; \delta\omega, \mathcal{A}) = \frac{\mathcal{A}}{l} f^{\mathrm{GeoM}}(\alpha, \eta, \mathcal{B}) \; f^{\mathrm{Cerenkov}}(\omega, \delta\omega)$$

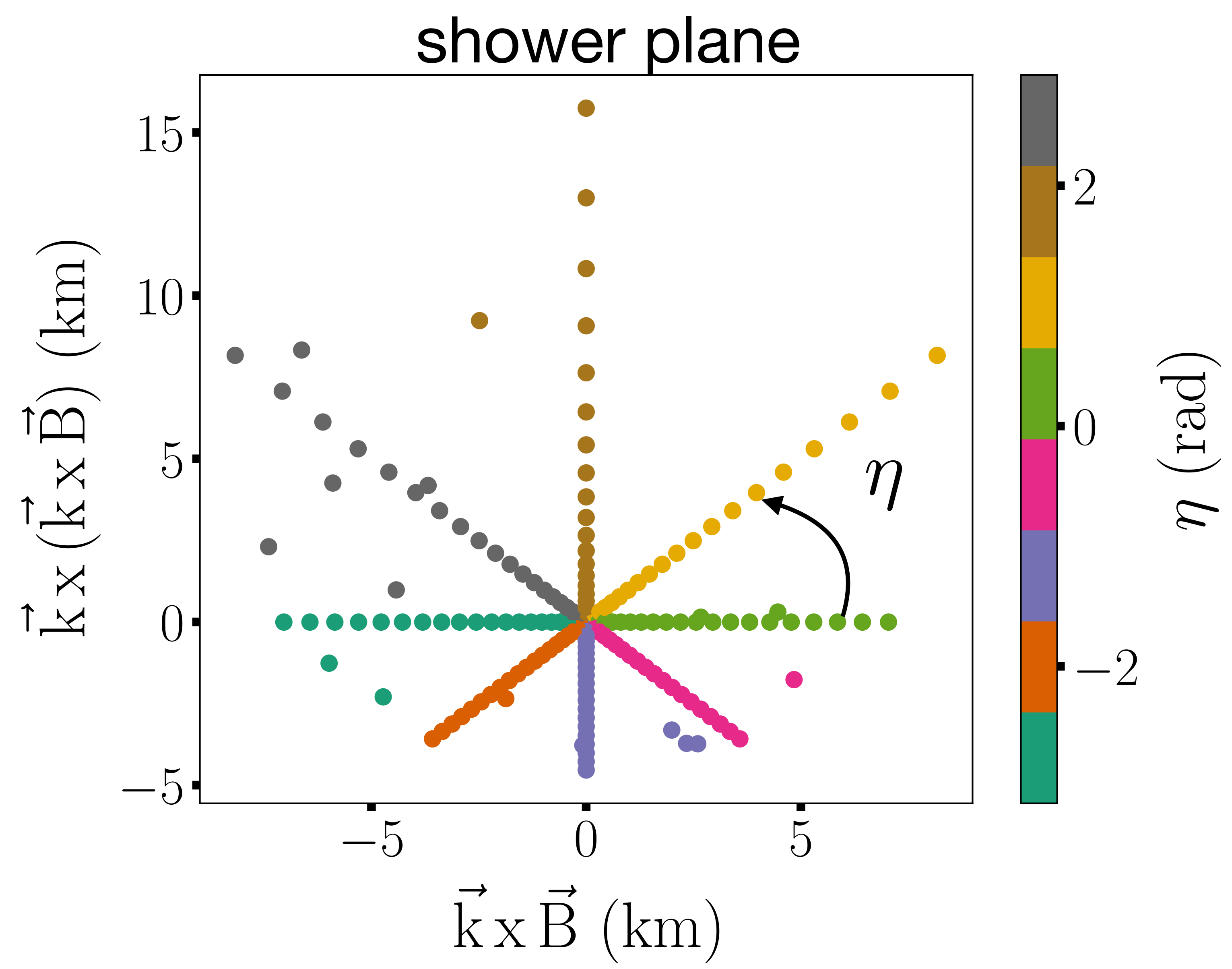
- Geomagnetic asymmetry $f^{\mathrm{GeoM}}(\alpha, \eta, \mathcal{B}) = 1 + \mathcal{B} \sin(\alpha)^2 \cos(\eta)$

α magnetic field inclination $\mathcal{B}$ geomagnetic strength

interplay between emission mechanisms
→ signal excess along the Lorentz force direction



Phenomenological description of the amplitude pattern



Goal: analytical description of the amplitude:
- shower direction
- all the asymmetries effects

Method: phenomenological description as a function of the angular position of the observer

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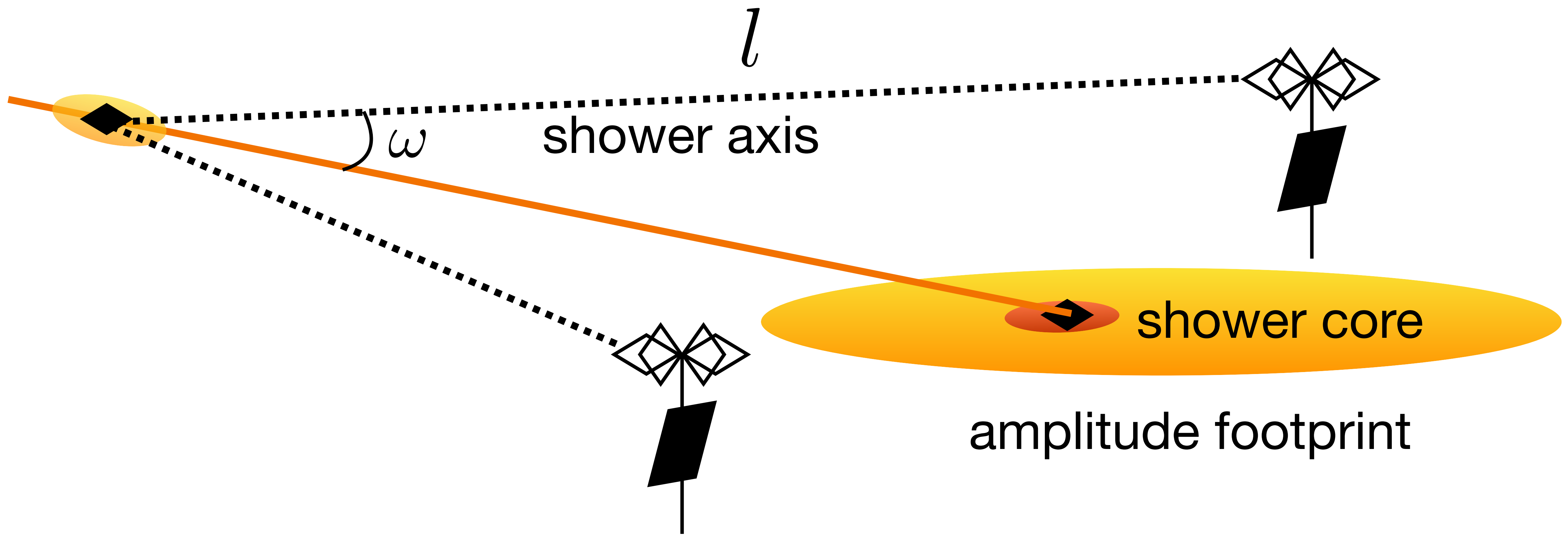
- Early-late asymmetry $\frac{\mathcal{A}}{l}$ → energy dilution



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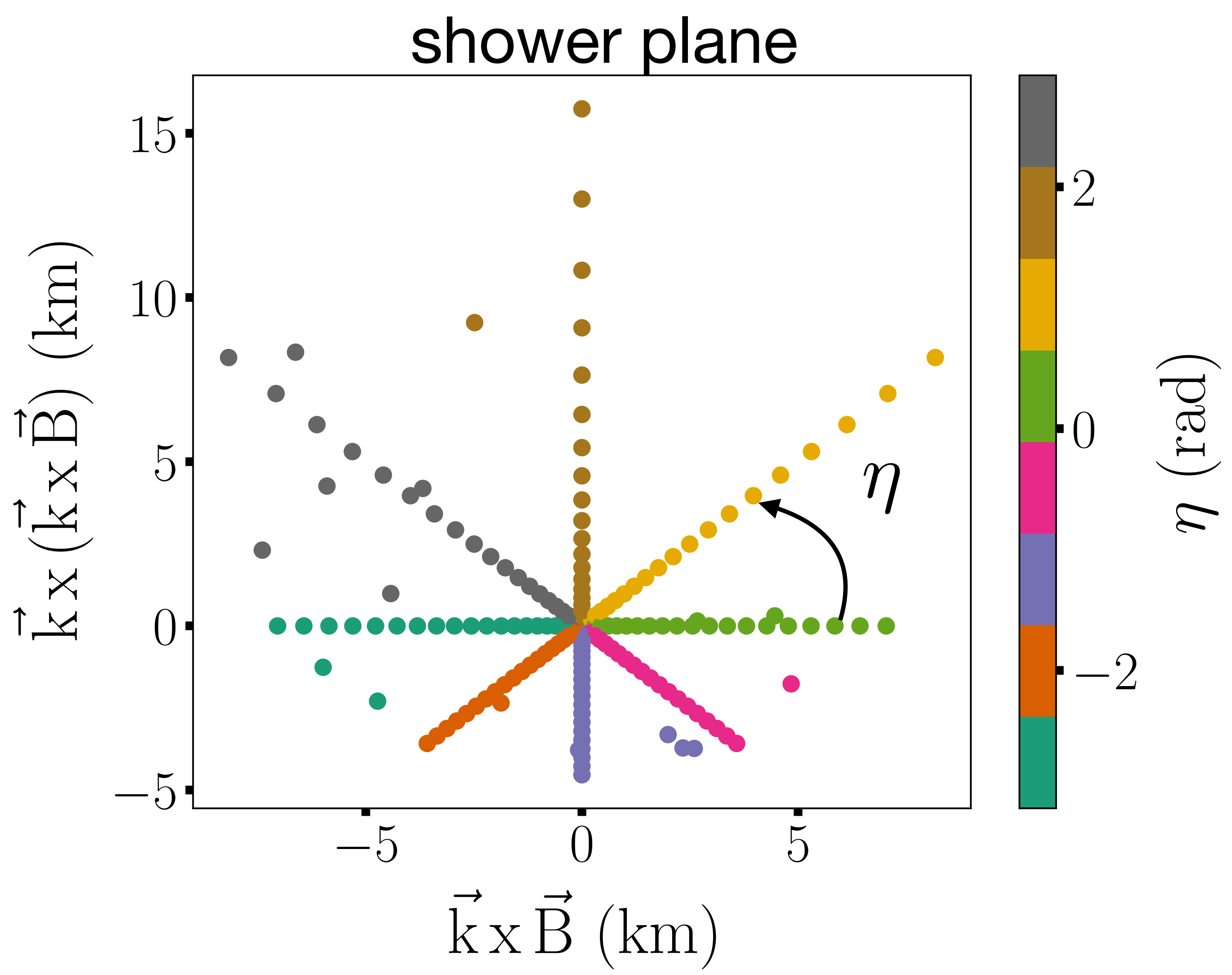

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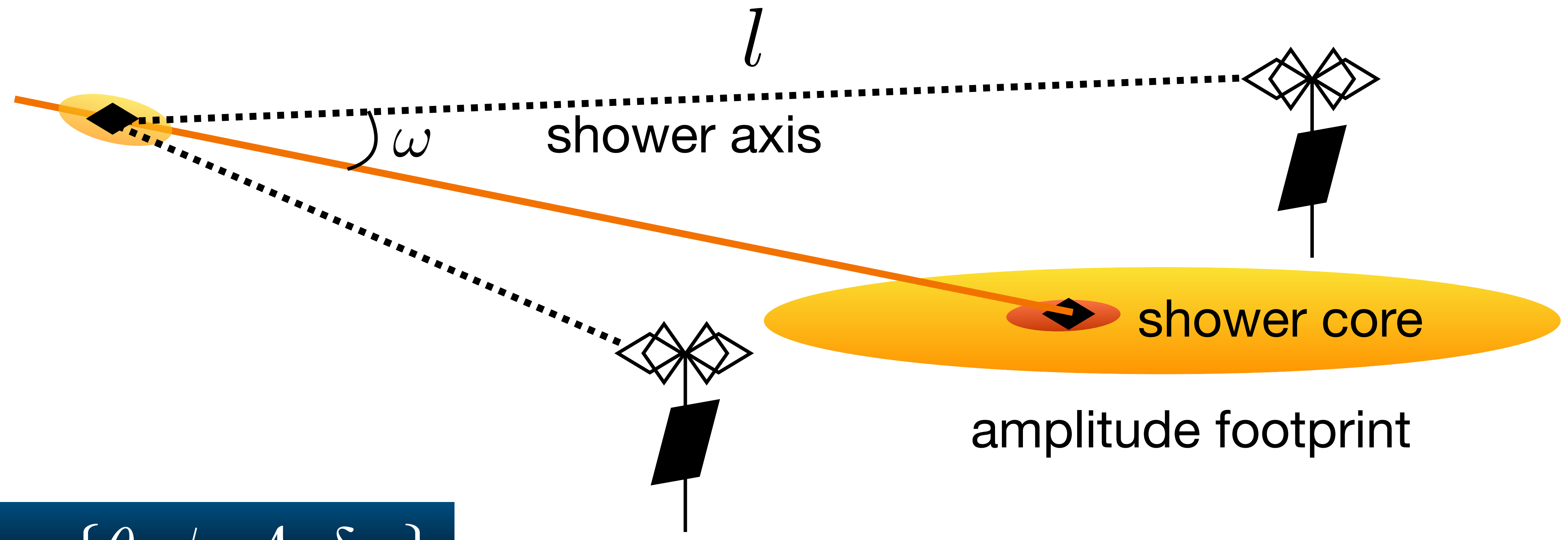
- Early-late asymmetry $\frac{\mathcal{A}}{l}$ → energy dilution

- Cerenkov cone $$f^{\mathrm{Cerenkov}}(\omega,\delta\omega) = \frac{1}{1+4\left[\frac{(\tan(\omega)/\tan(\omega_C))^2-1}{\delta\omega}\right]^2}$$

→ geometrical Cerenkov effect description

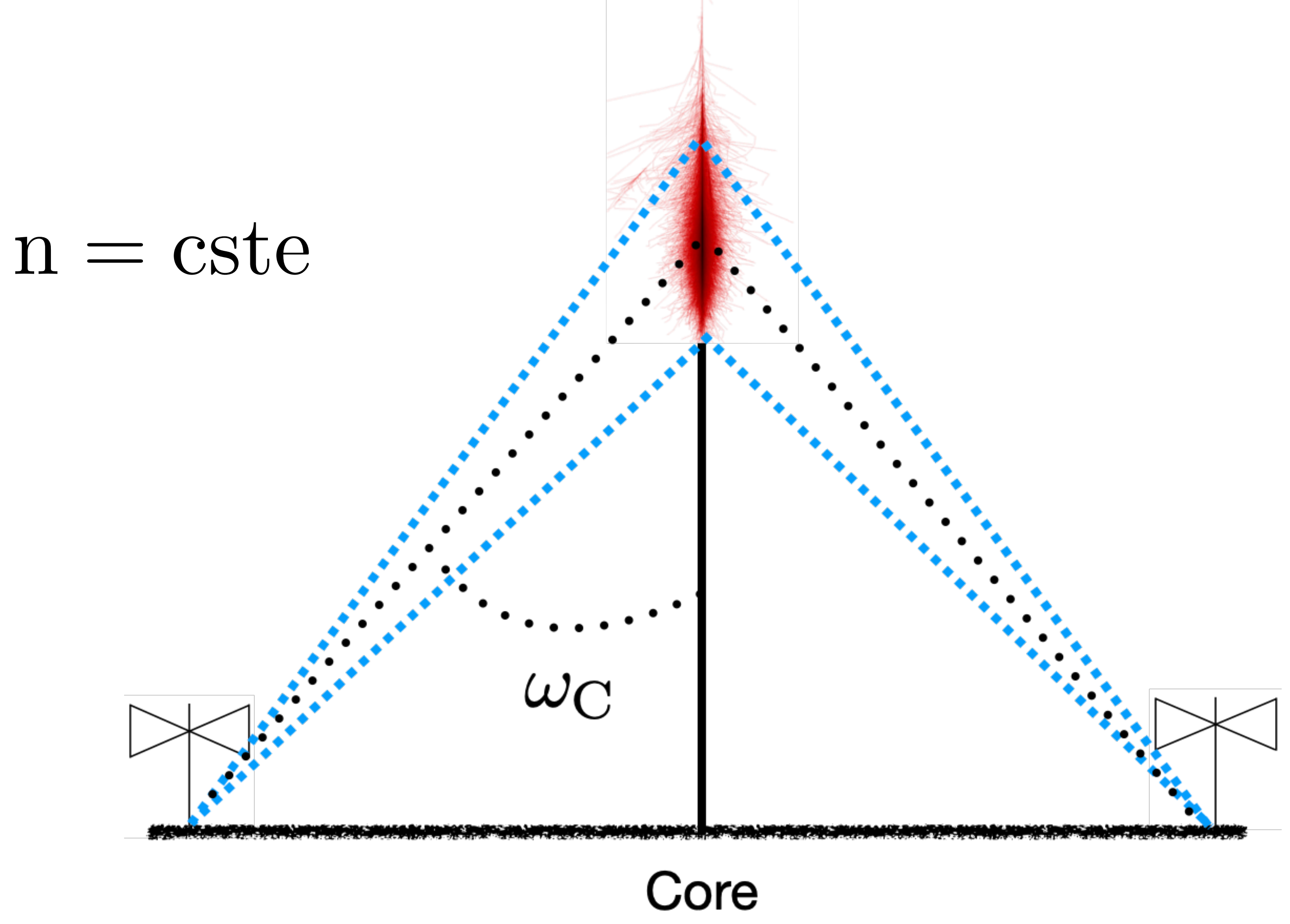
→ ω_C



4 fitting parameters only: $\{\theta,\phi,\mathcal{A},\delta\omega\}$

A side result: Cerenkov cone asymmetry

Cerenkov cone:
- geometrical effect → angle where all emissions arrive at same time
- signal compression → high amplitudes
- standard computation: $\omega_C = \mathrm{acos}(1/\mathrm{n})$ (equal optical paths = constant n)



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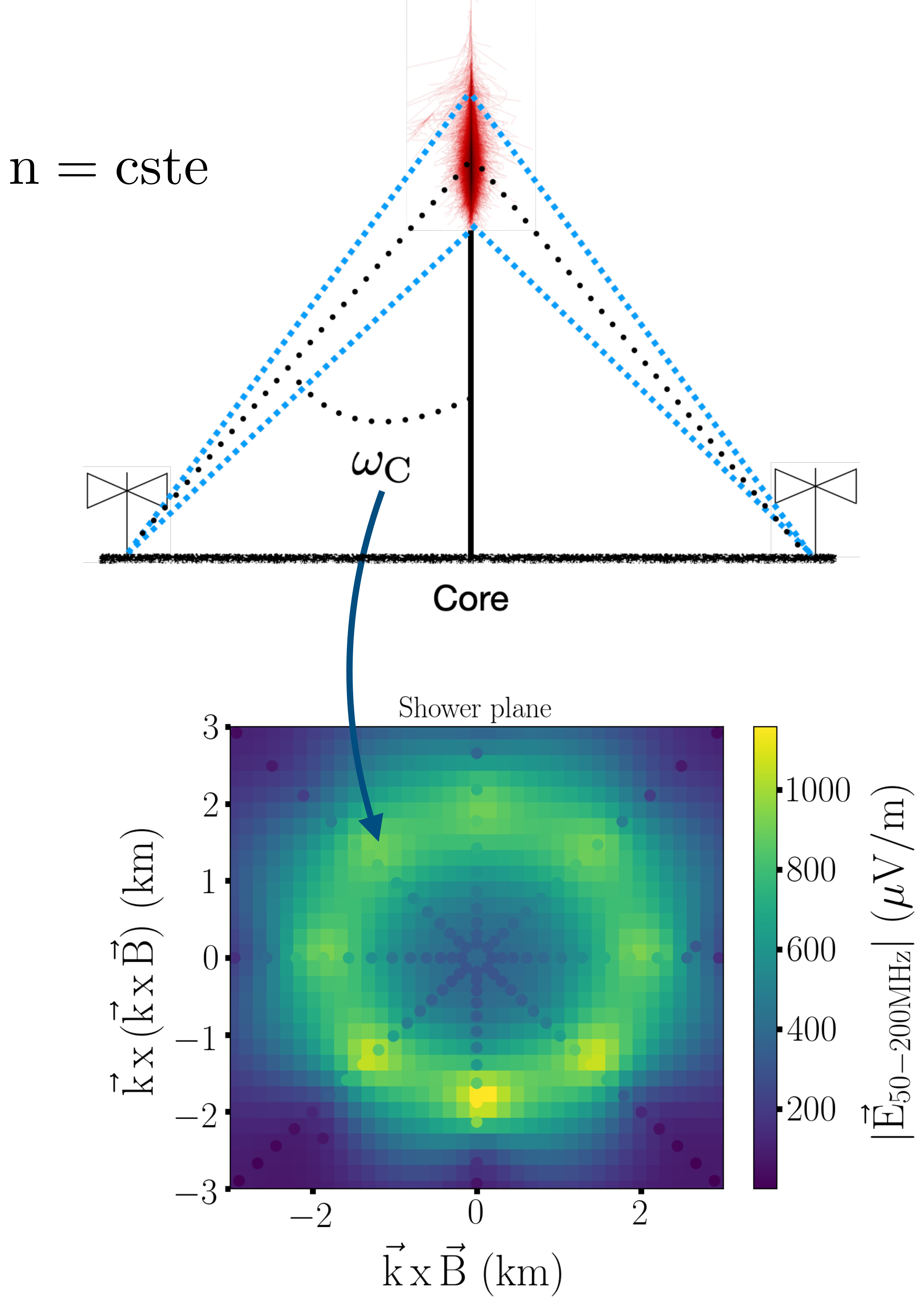

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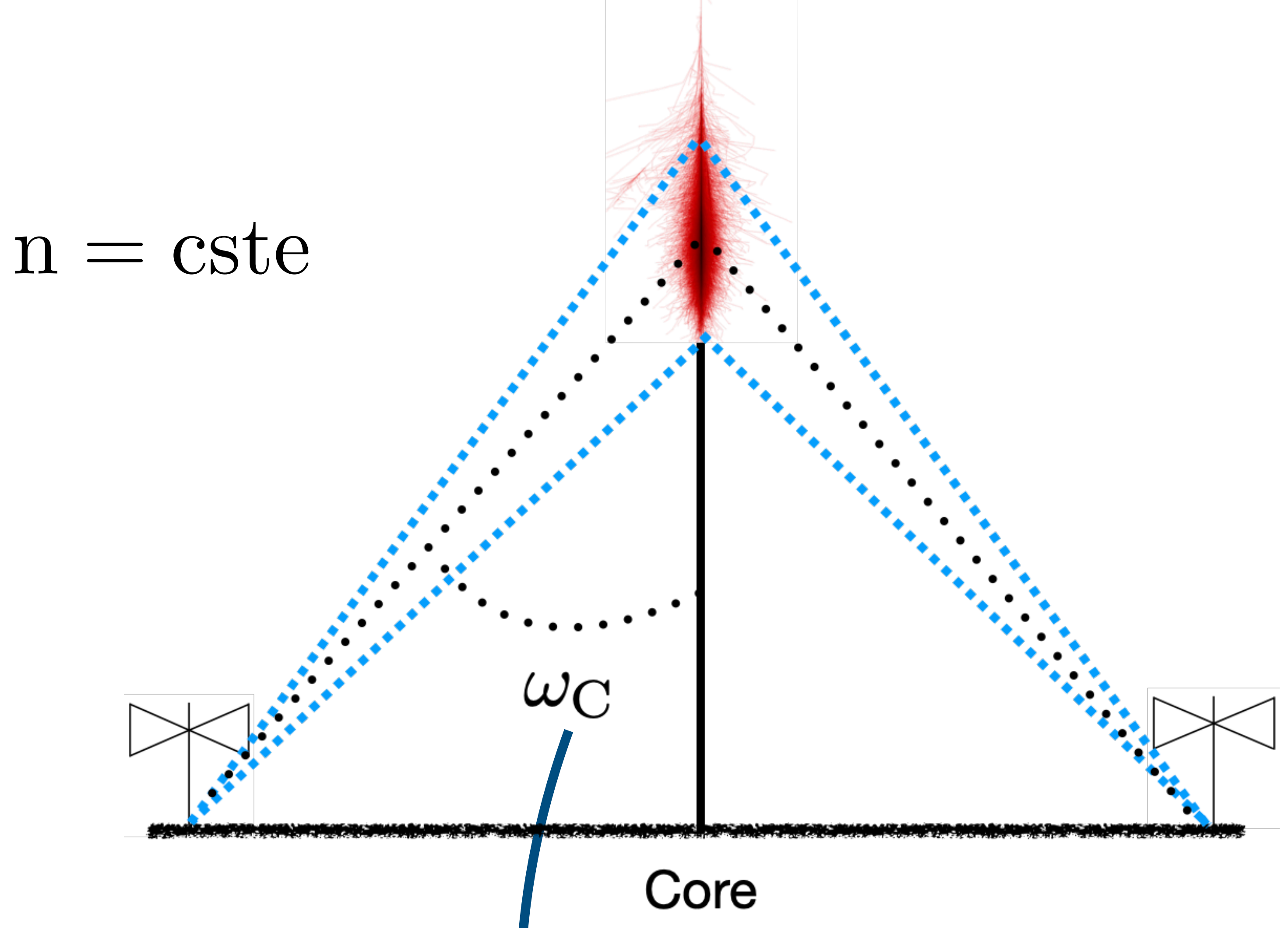

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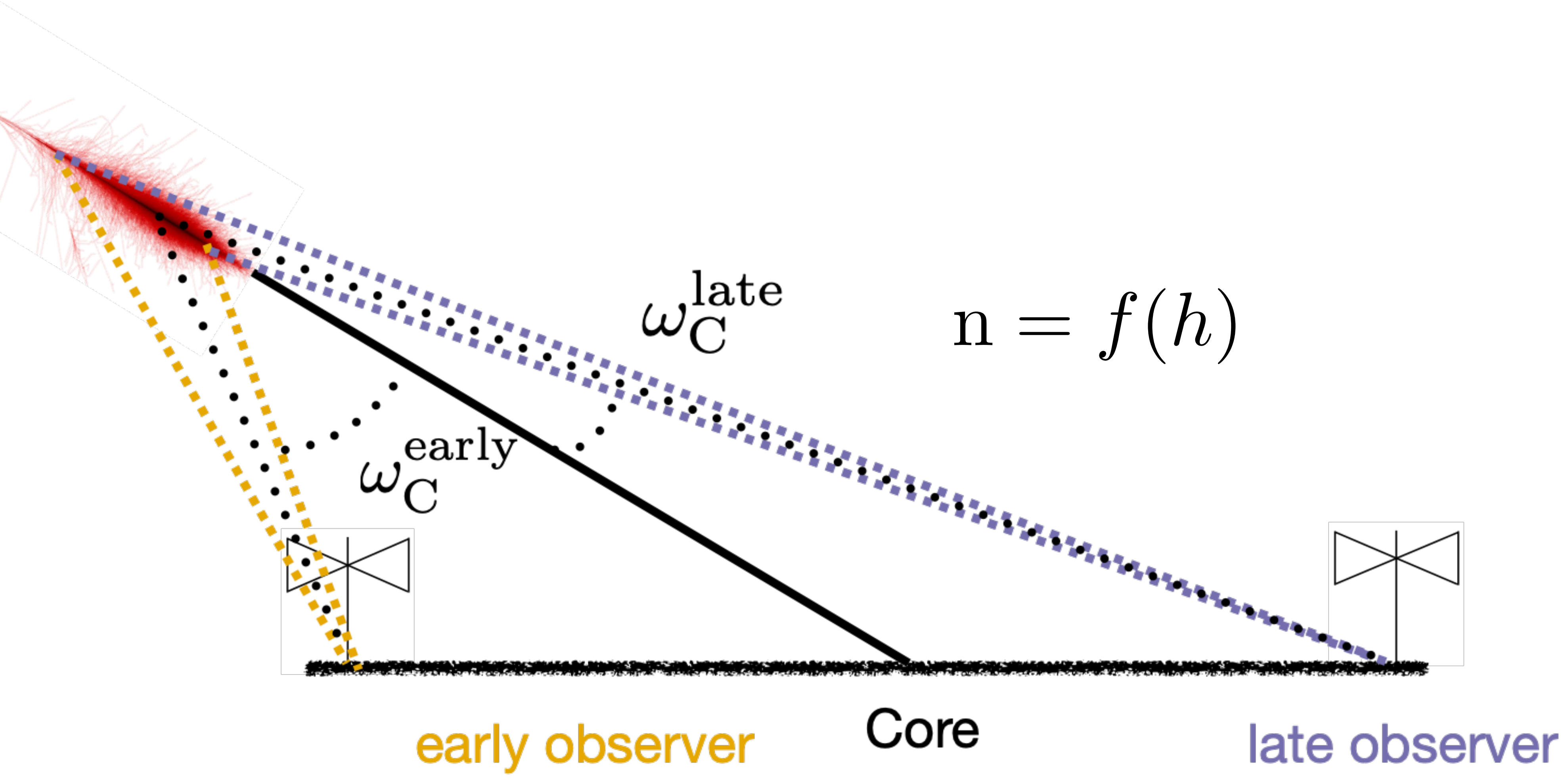

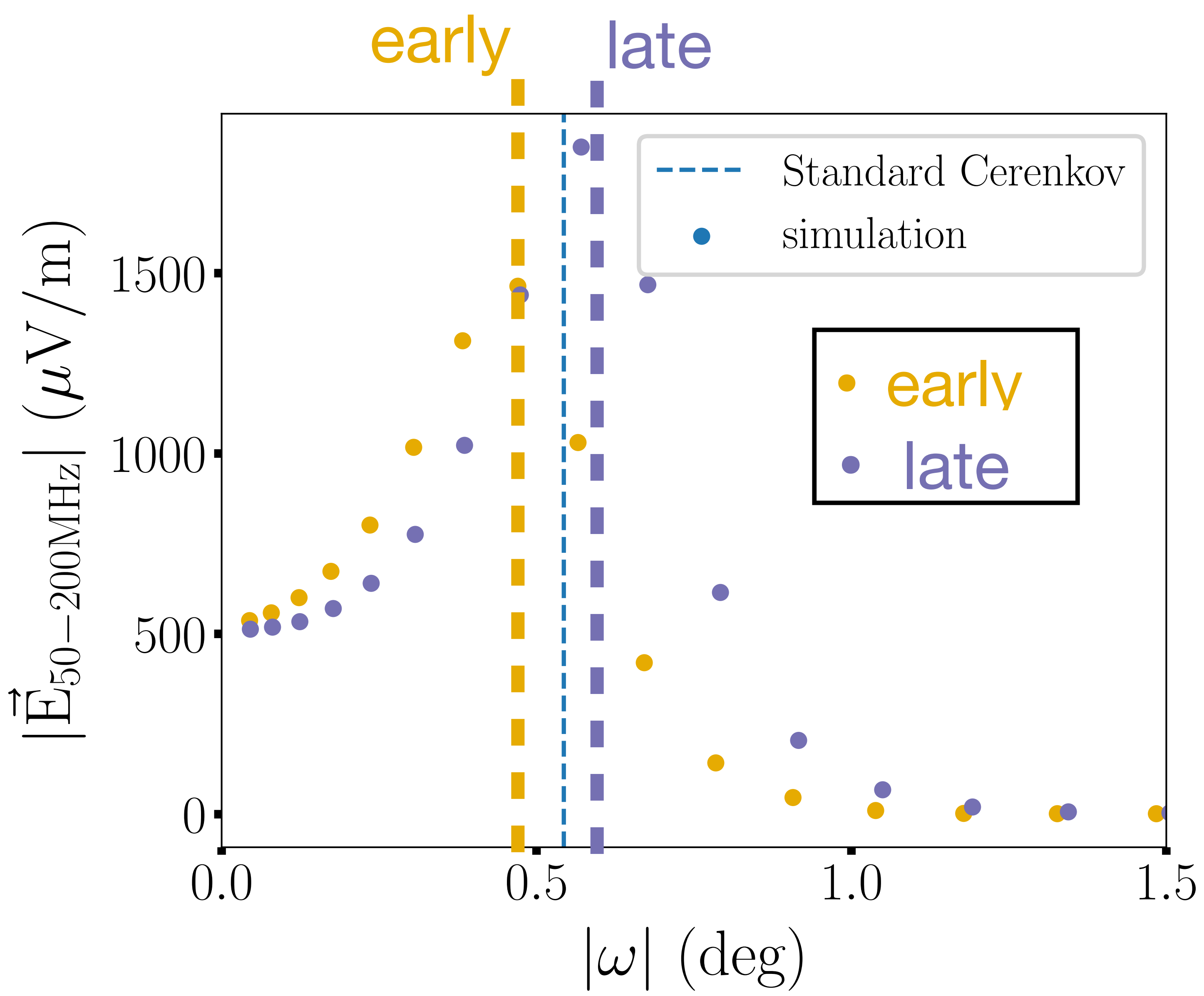

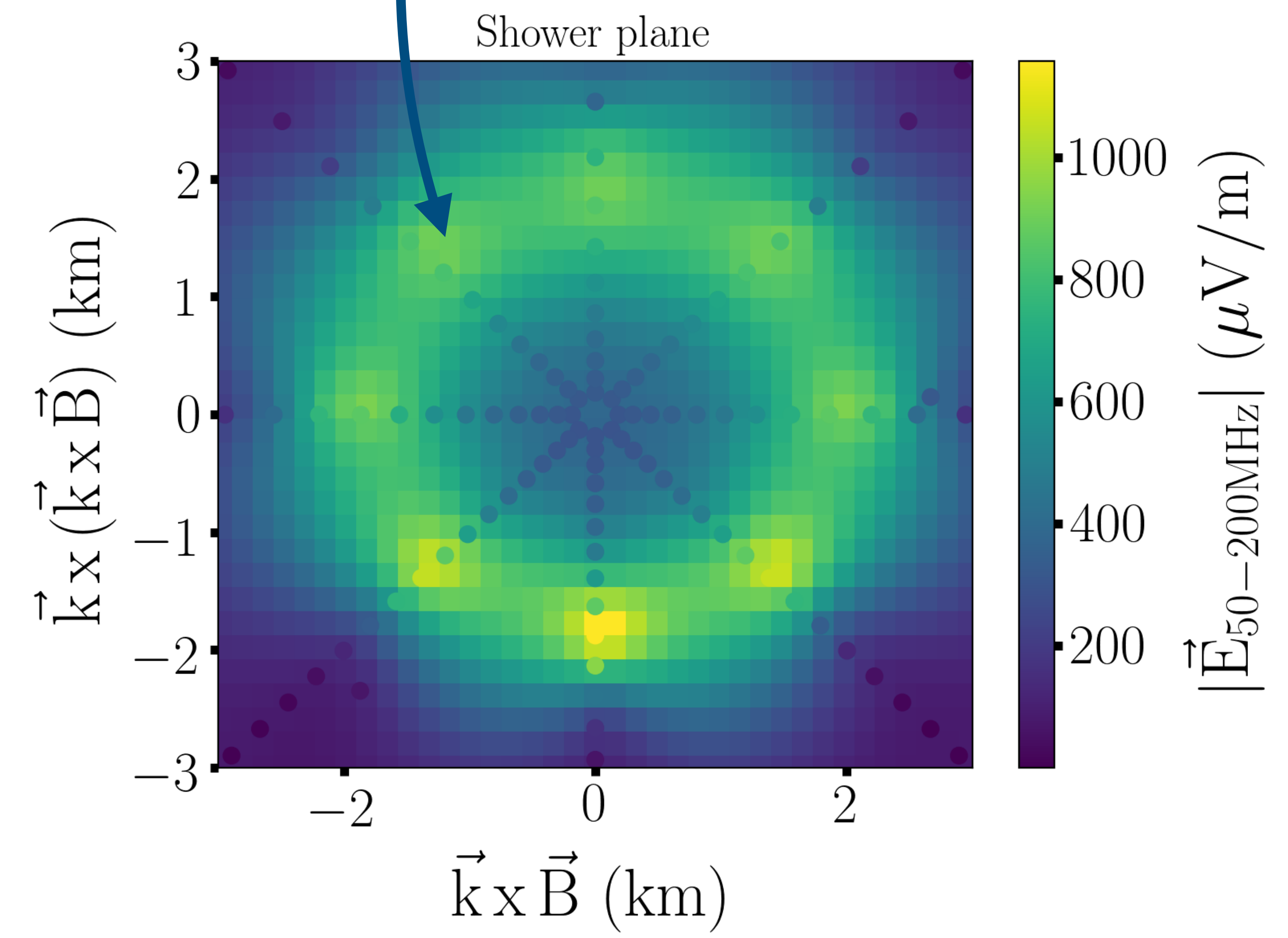

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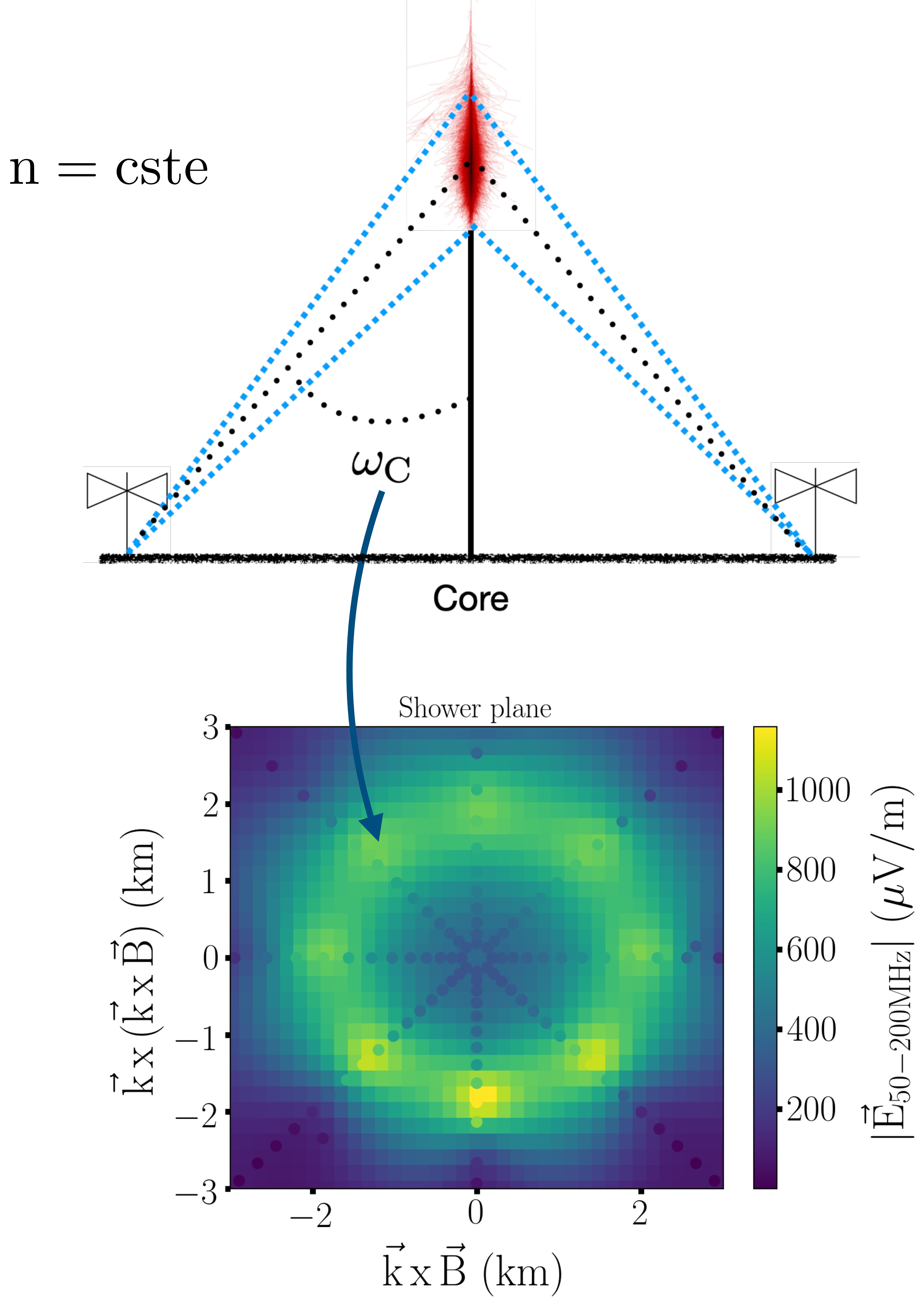
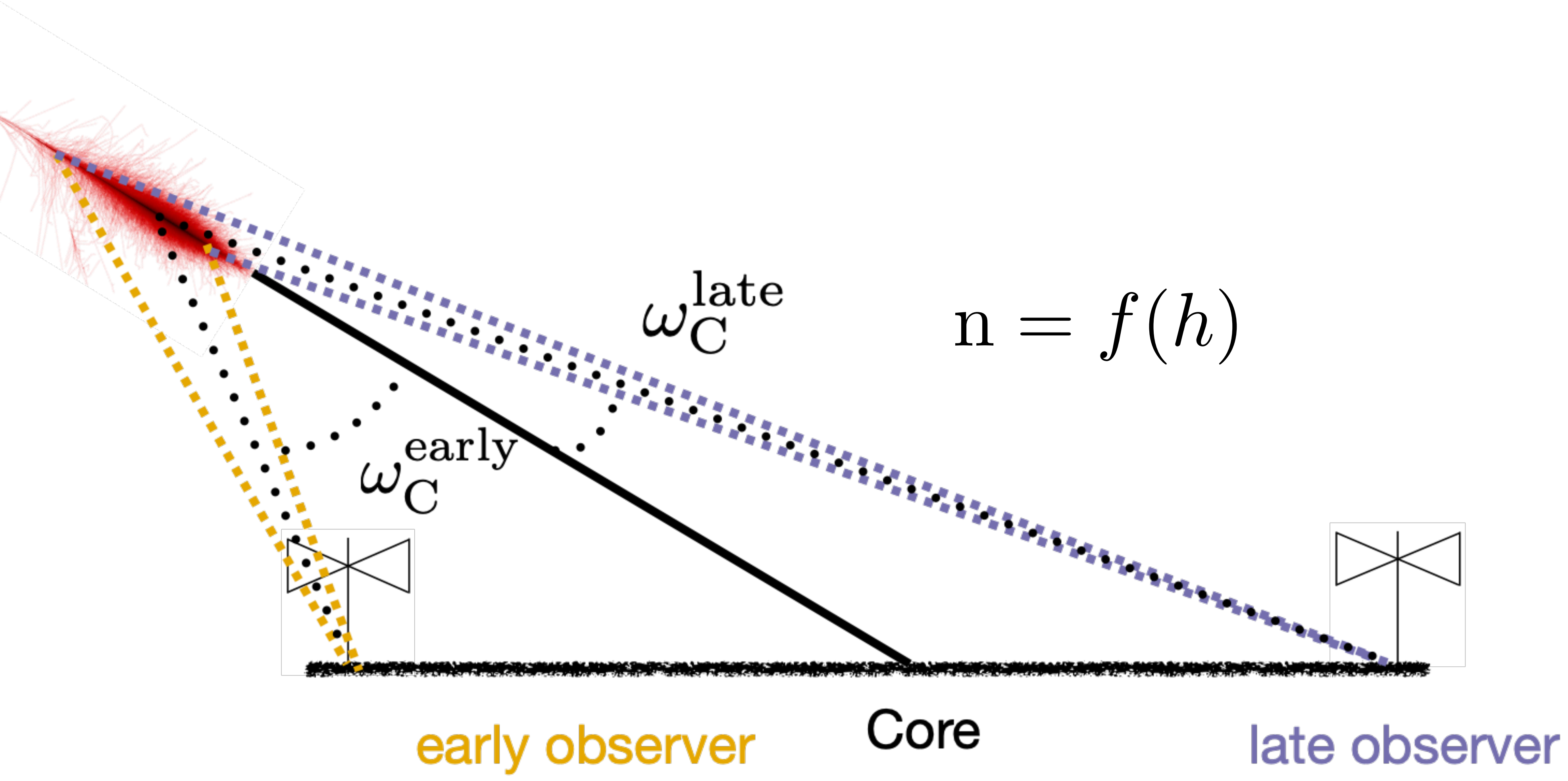
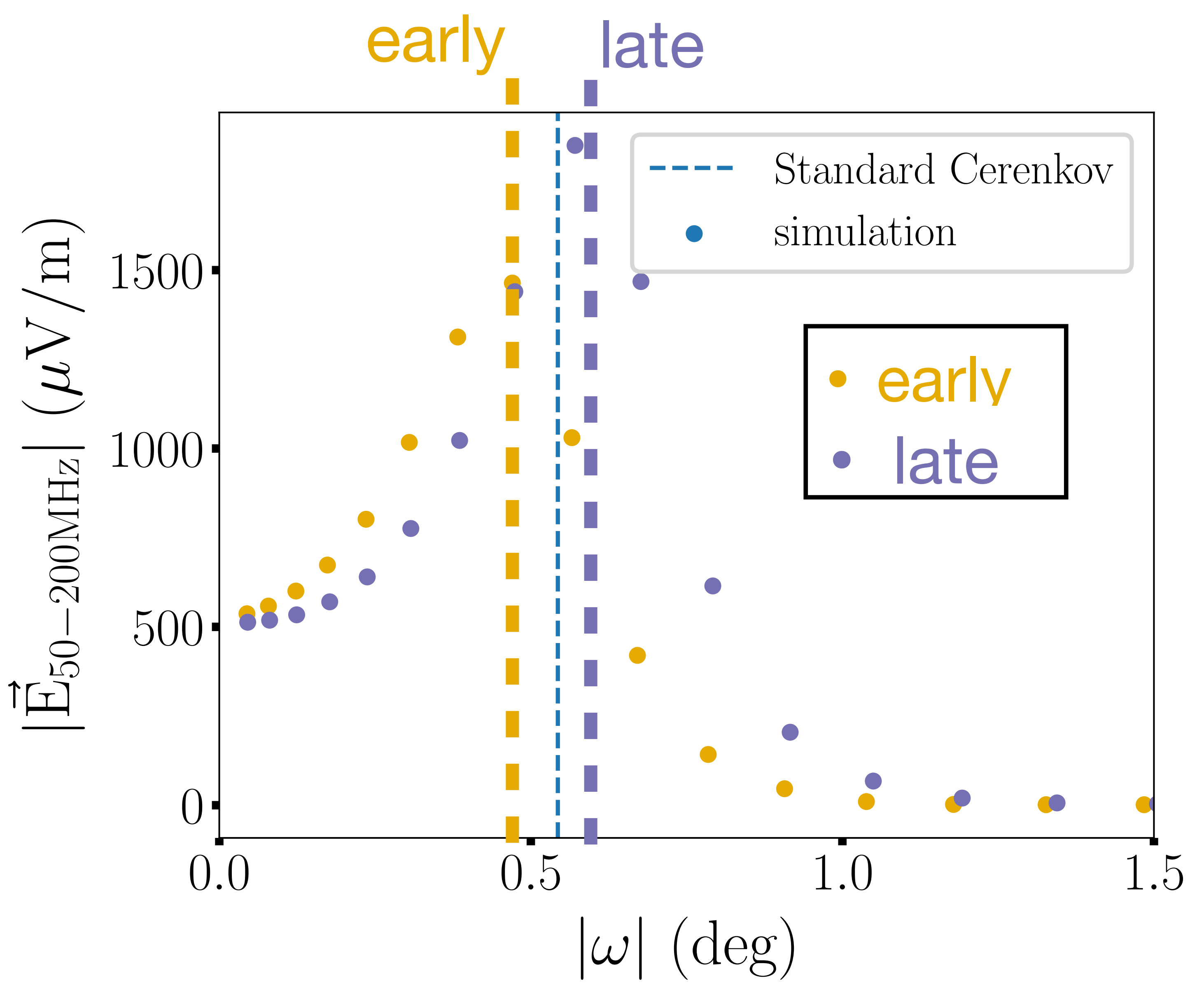




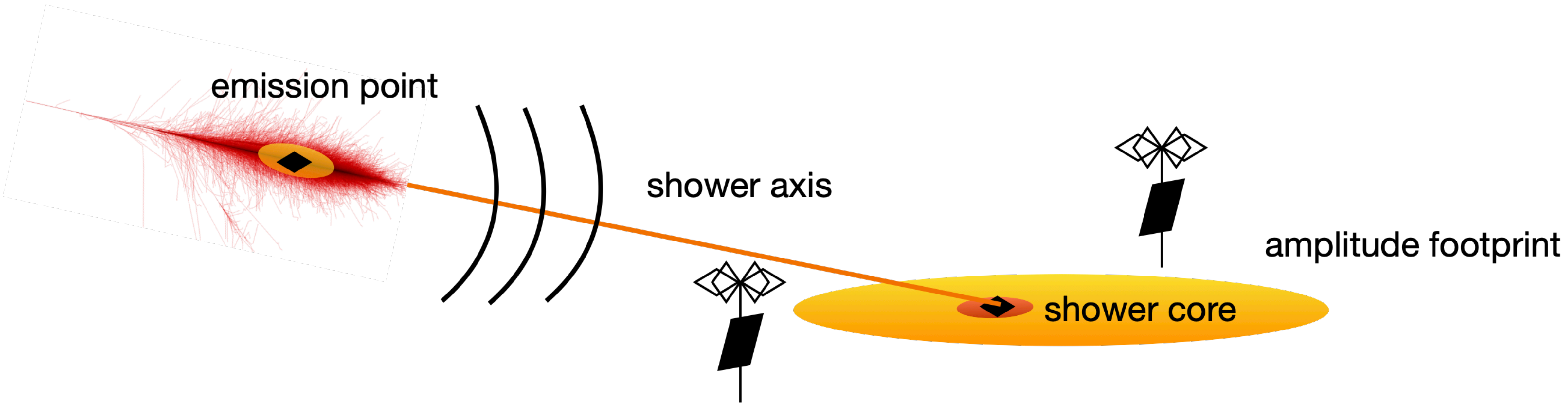


analytical description of $\omega_C = f(\vec{x}, \theta, \phi)$

used into the amplitude model: each antenna “sees” a different Cerenkov cone

The analytical description of the Cerenkov asymmetry matches the simulated data

Arrival direction reconstruction procedure



Principles: reconstruction of two points along the extensive air shower:
- emission point
- Cerenkov cone (signal “valley” around the core)

Procedure:

Plane wave front reconstruction

Inputs:
- trigger times
- antennas positions

Outputs:
- θ, ϕ

Spherical wave front reconstruction

Inputs:
- trigger times
- antennas positions
- θ, ϕ plane

Outputs:
- emission point

Angular Distribution Function reconstruction

Inputs:
- amplitudes
- antennas positions
- θ, ϕ plane
- emission point

Outputs:
- θ, ϕ

measured quantities

t trigger times
A amplitudes
$\vec{x}$ antenna positions

adjusted quantities

$\vec{k}$ shower direction
$(x_{\mathrm{source}}, y_{\mathrm{source}}, z_{\mathrm{source}}, t_{source})$
emission point

same weight for all antennas

Tests on a stationary noise model:
- gaussian time GPS jitter of rms=5ns
- two gaussian amplitude errors of 10% and 20% (aggressive and conservative)

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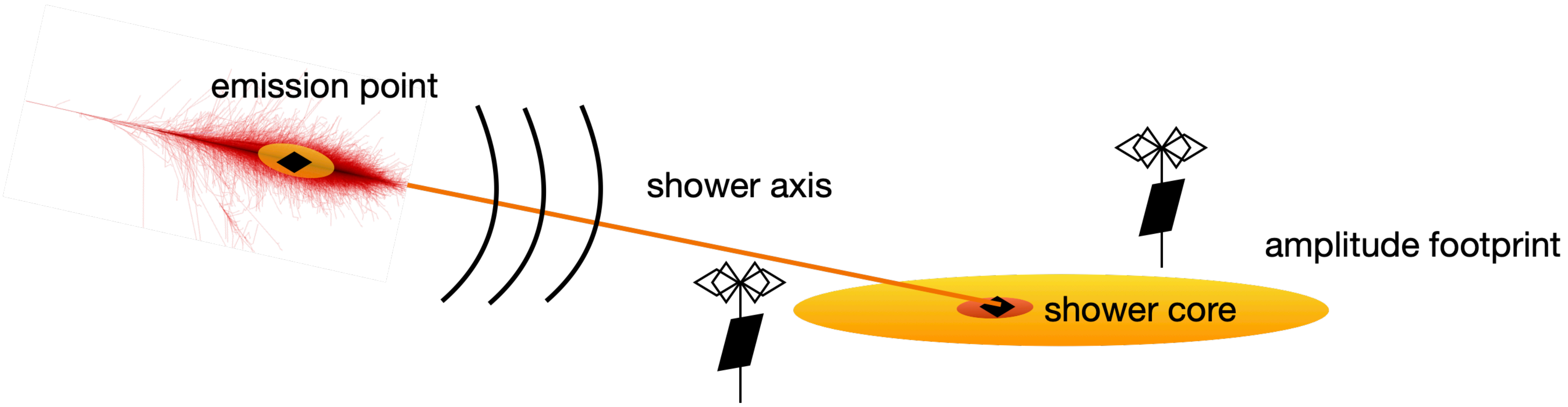

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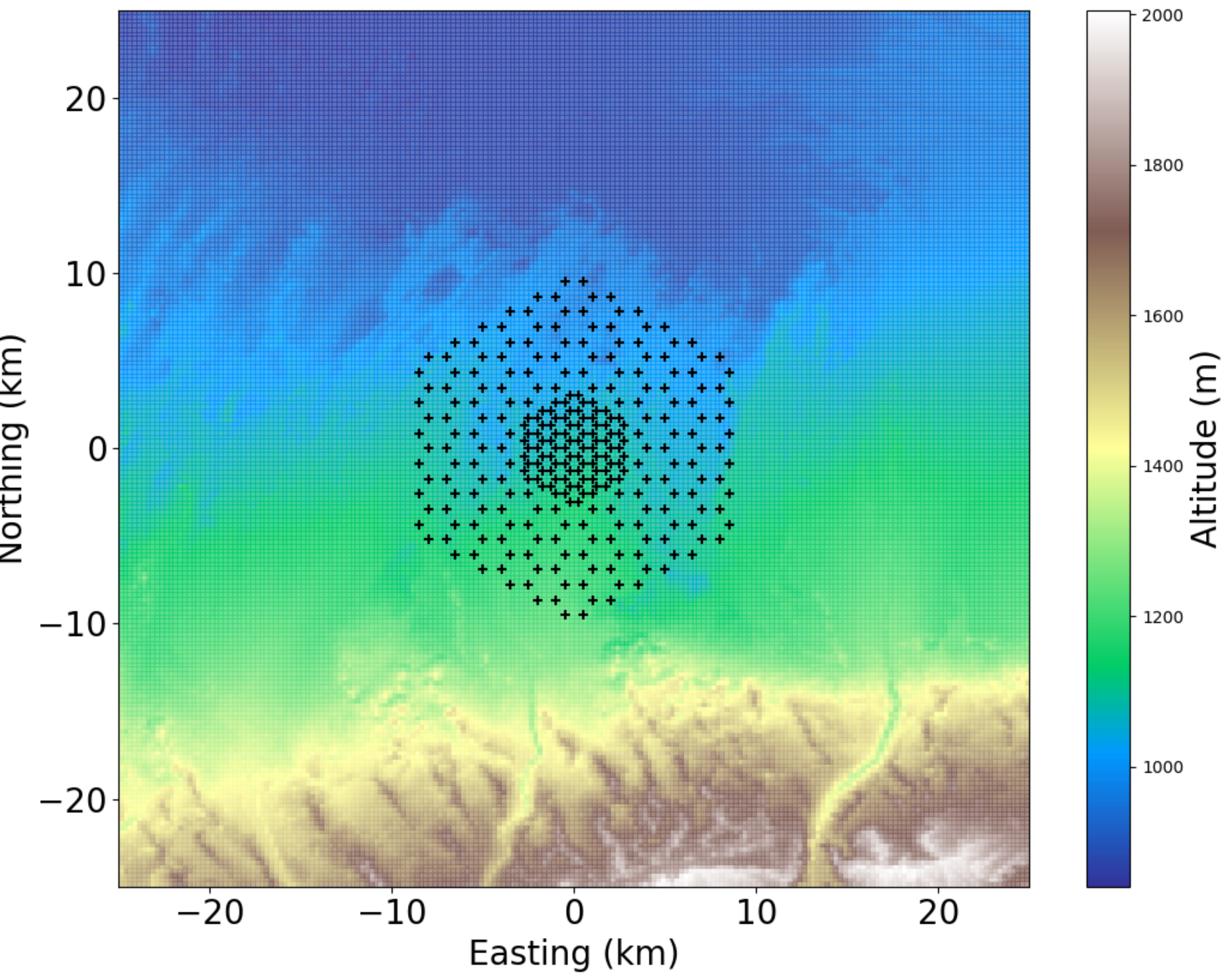
reconstruction procedure validated on StarShape simulations and performances obtained on realistic arrays

Reconstruction performances for GRANDProto300 (GP300)

The 300 antennas GRAND prototype



GP300 layout:

- ~300 antennas over ~200 km^2
- detection of cosmic rays and gamma rays

GP300 simulations:

- real topography
- primaries: proton, iron and gamma

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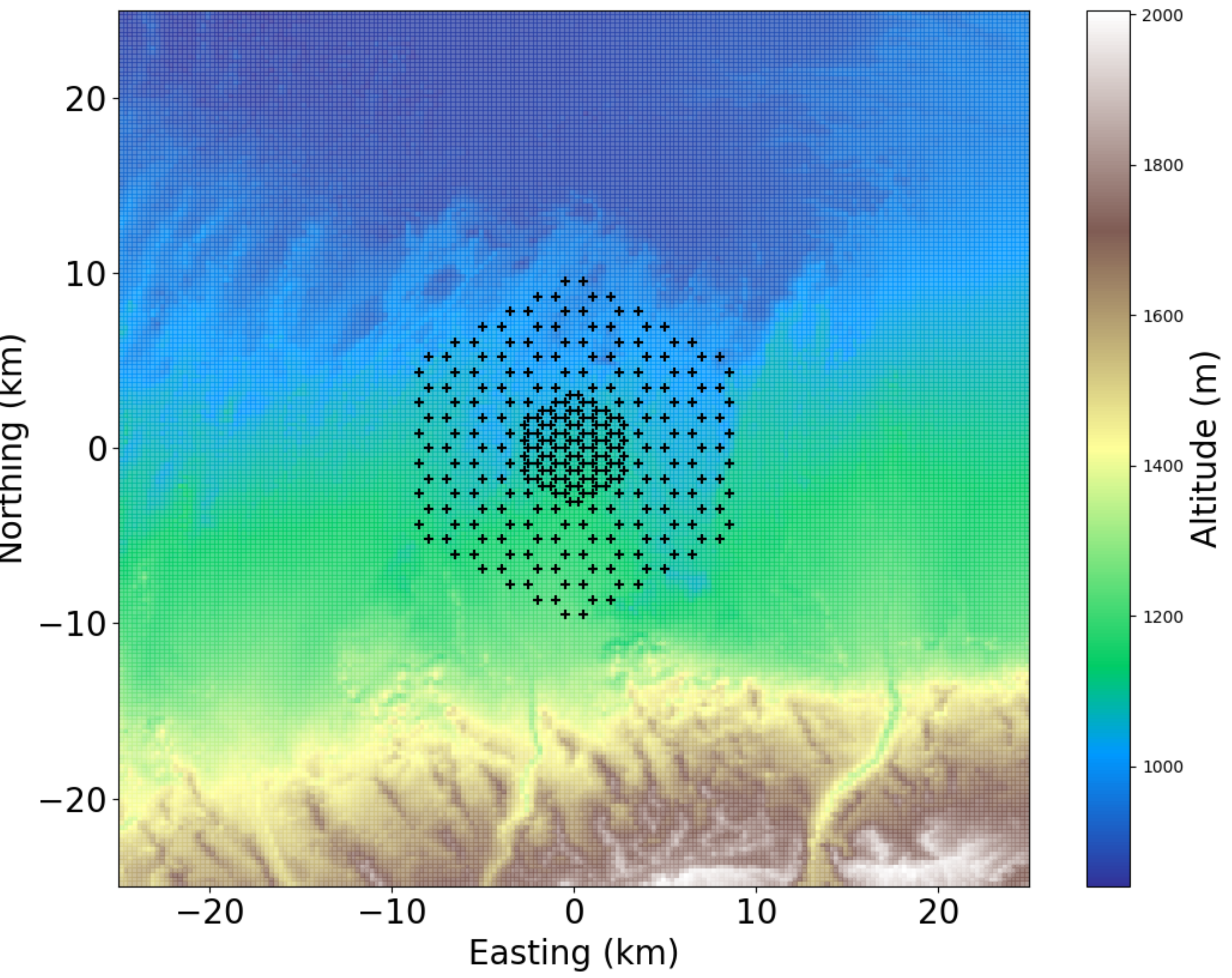

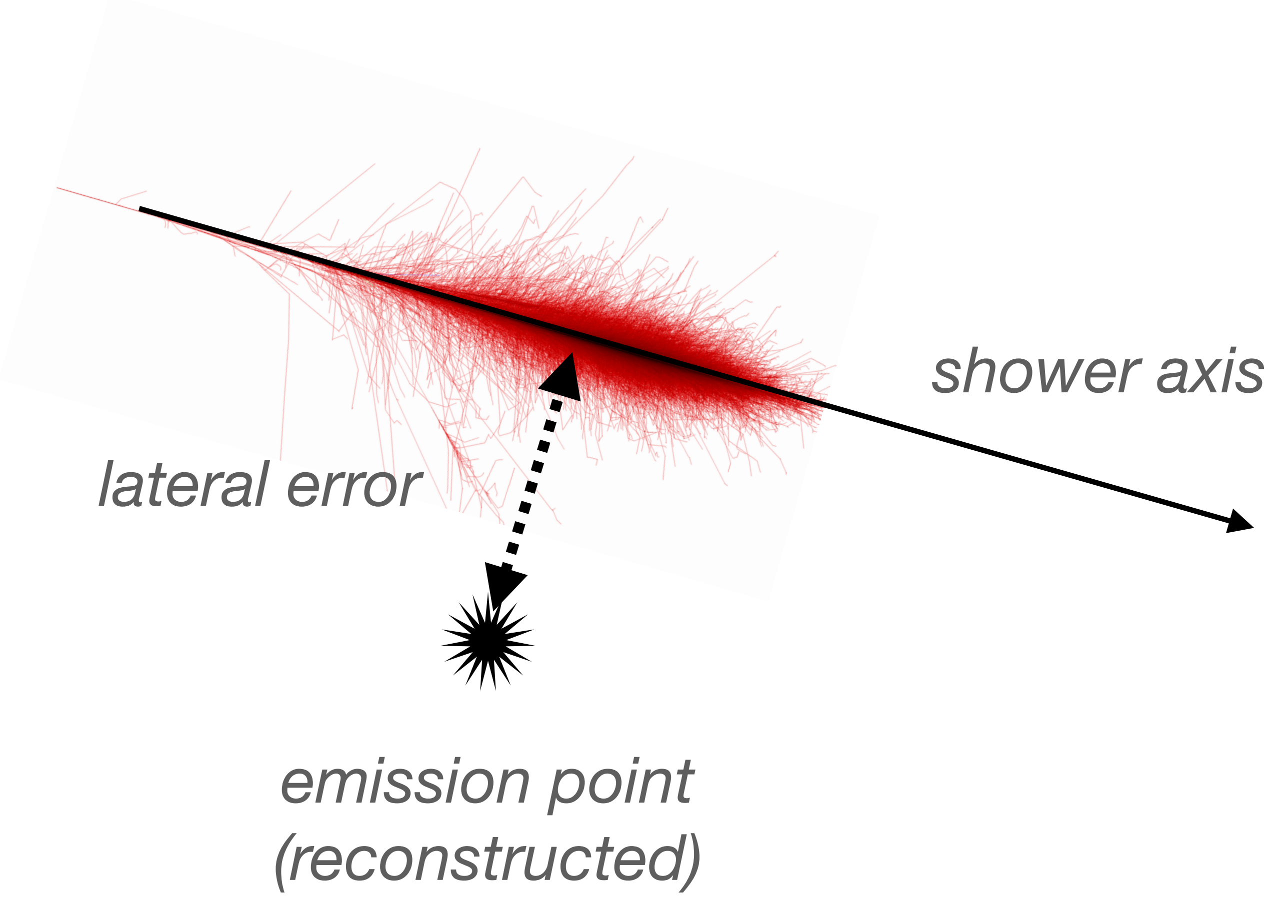

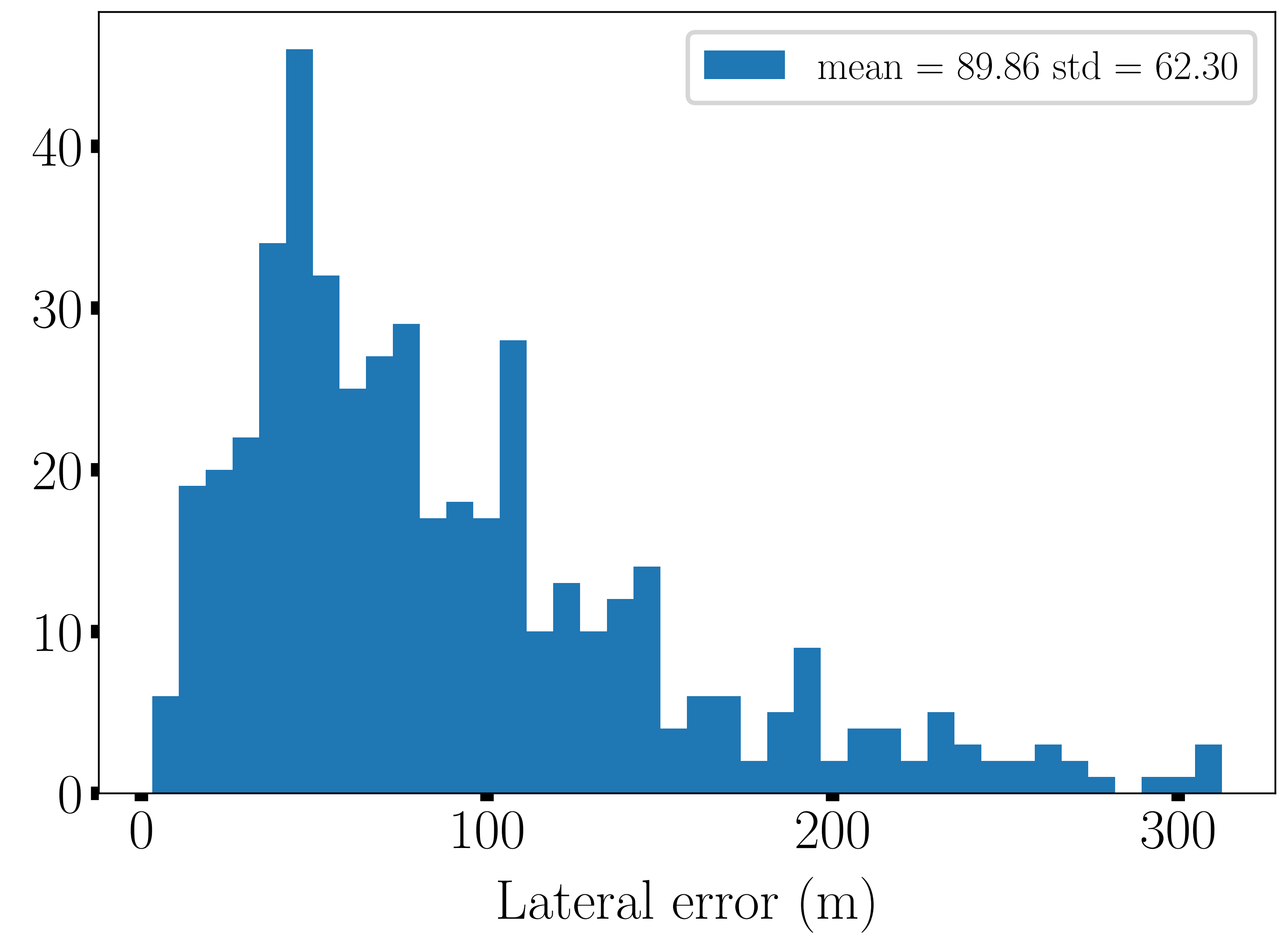

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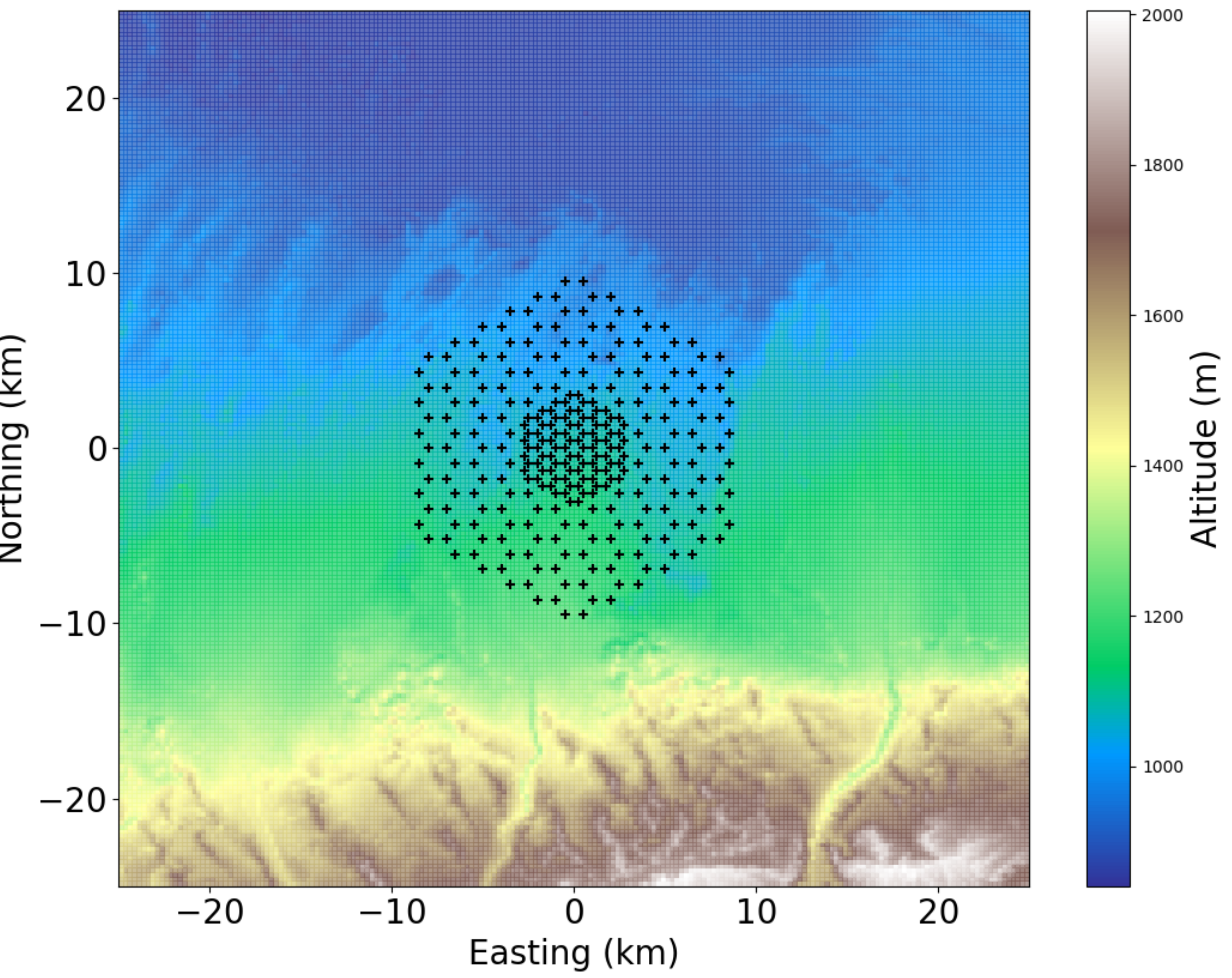

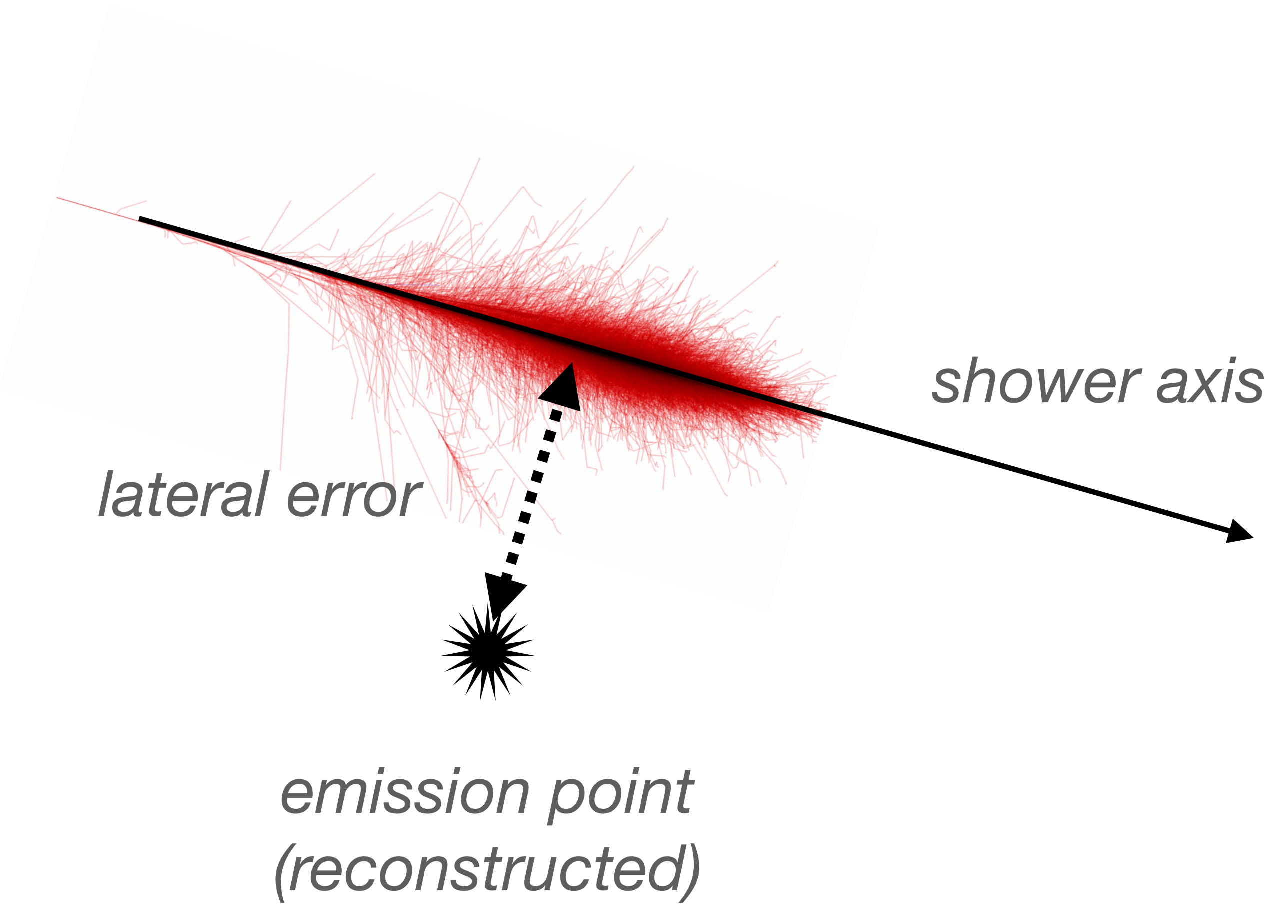

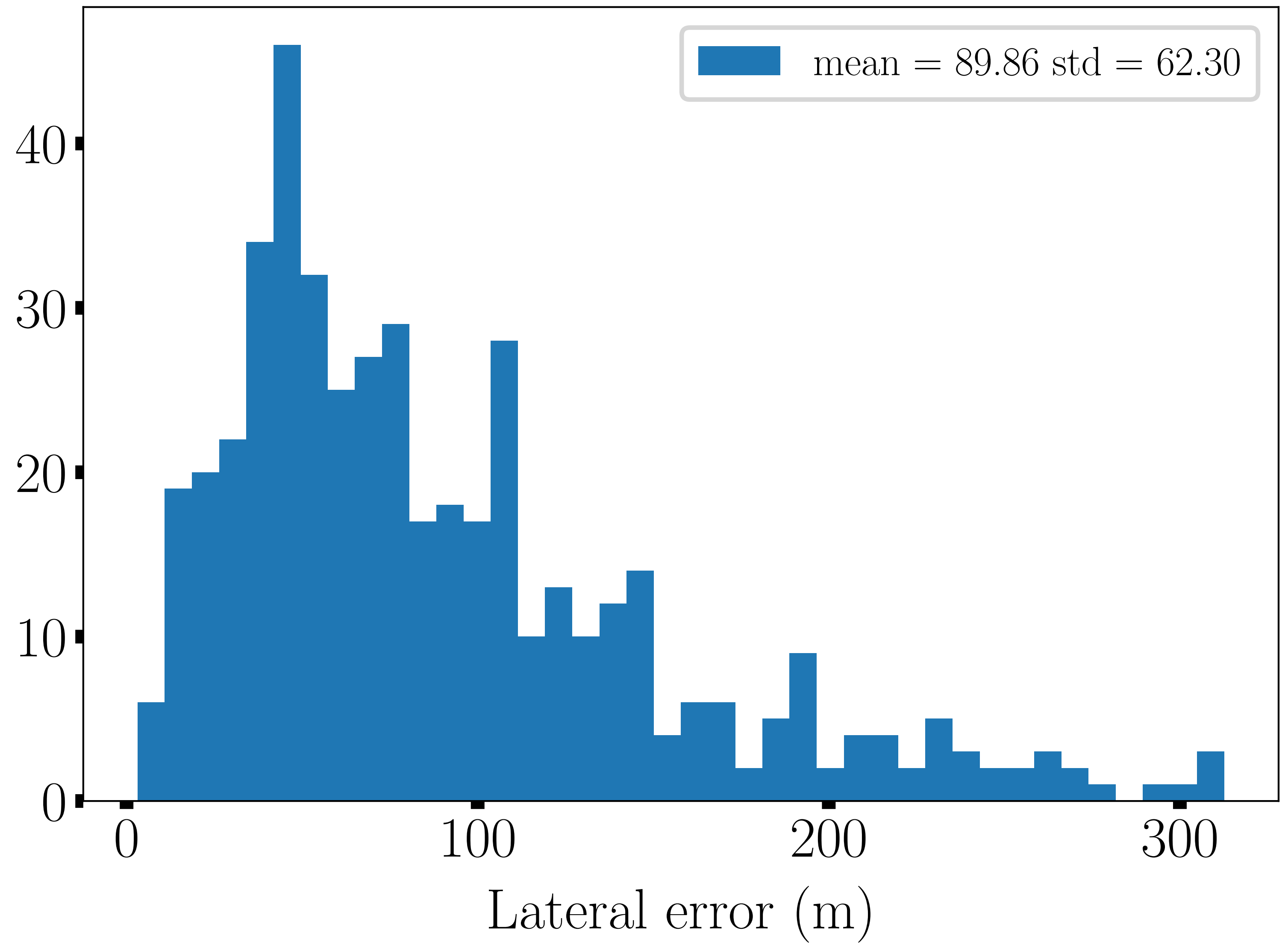

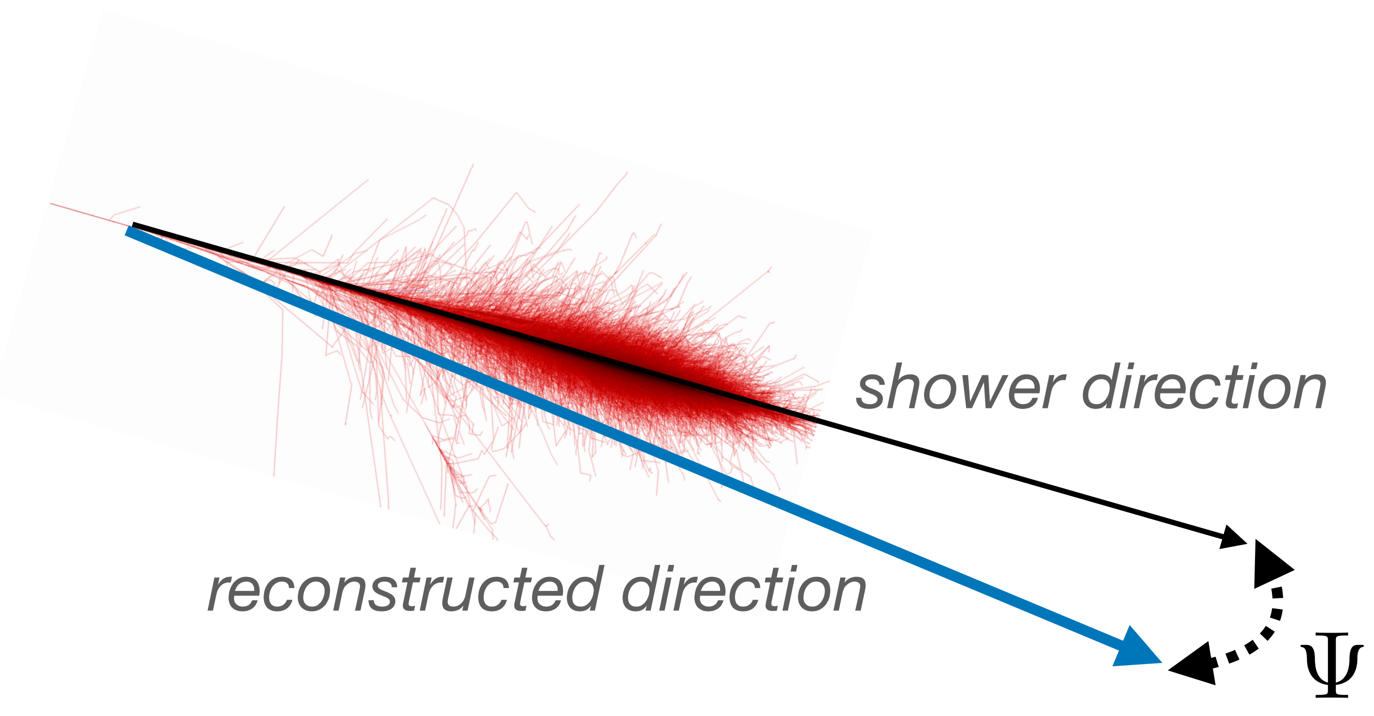

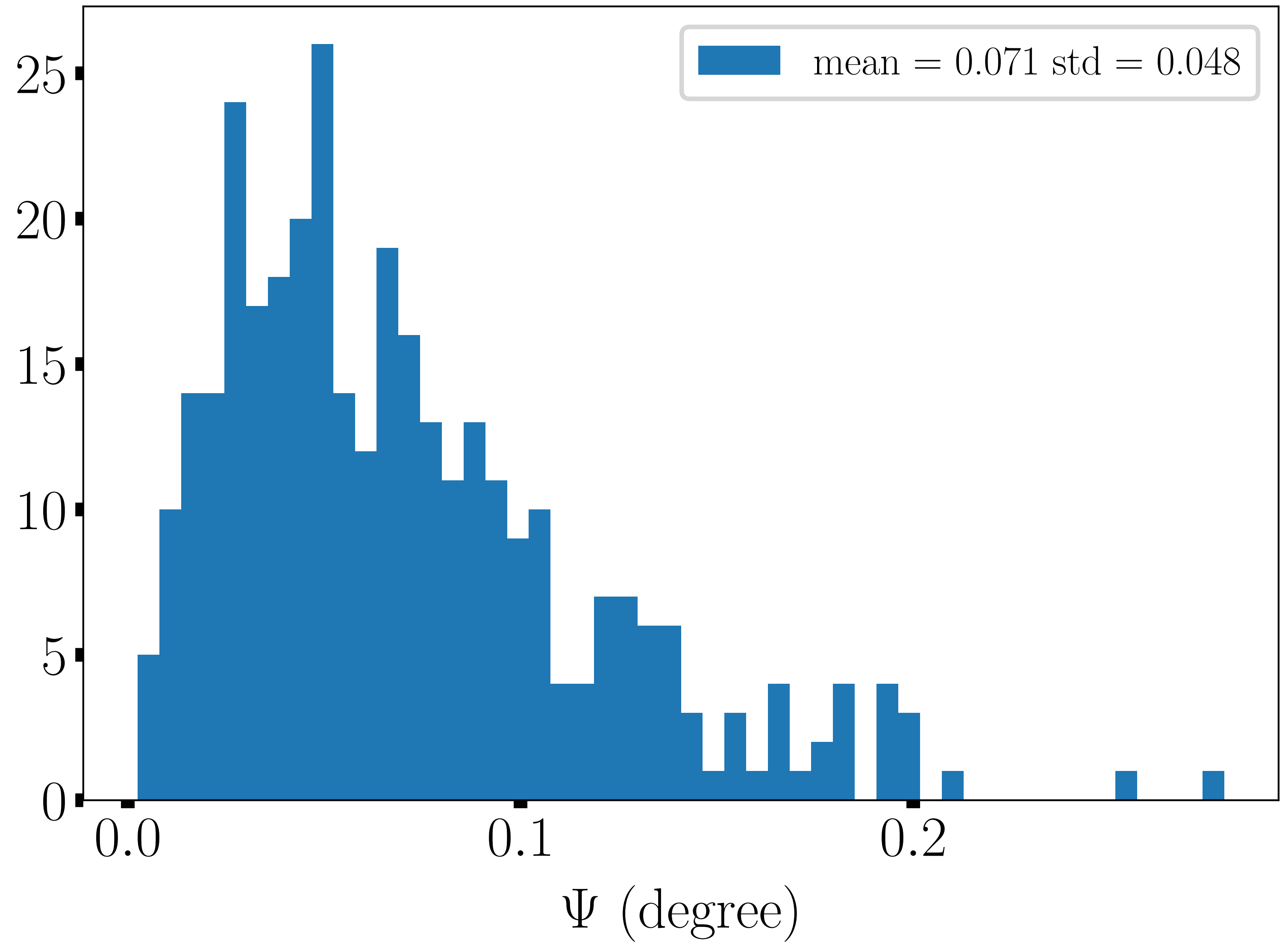

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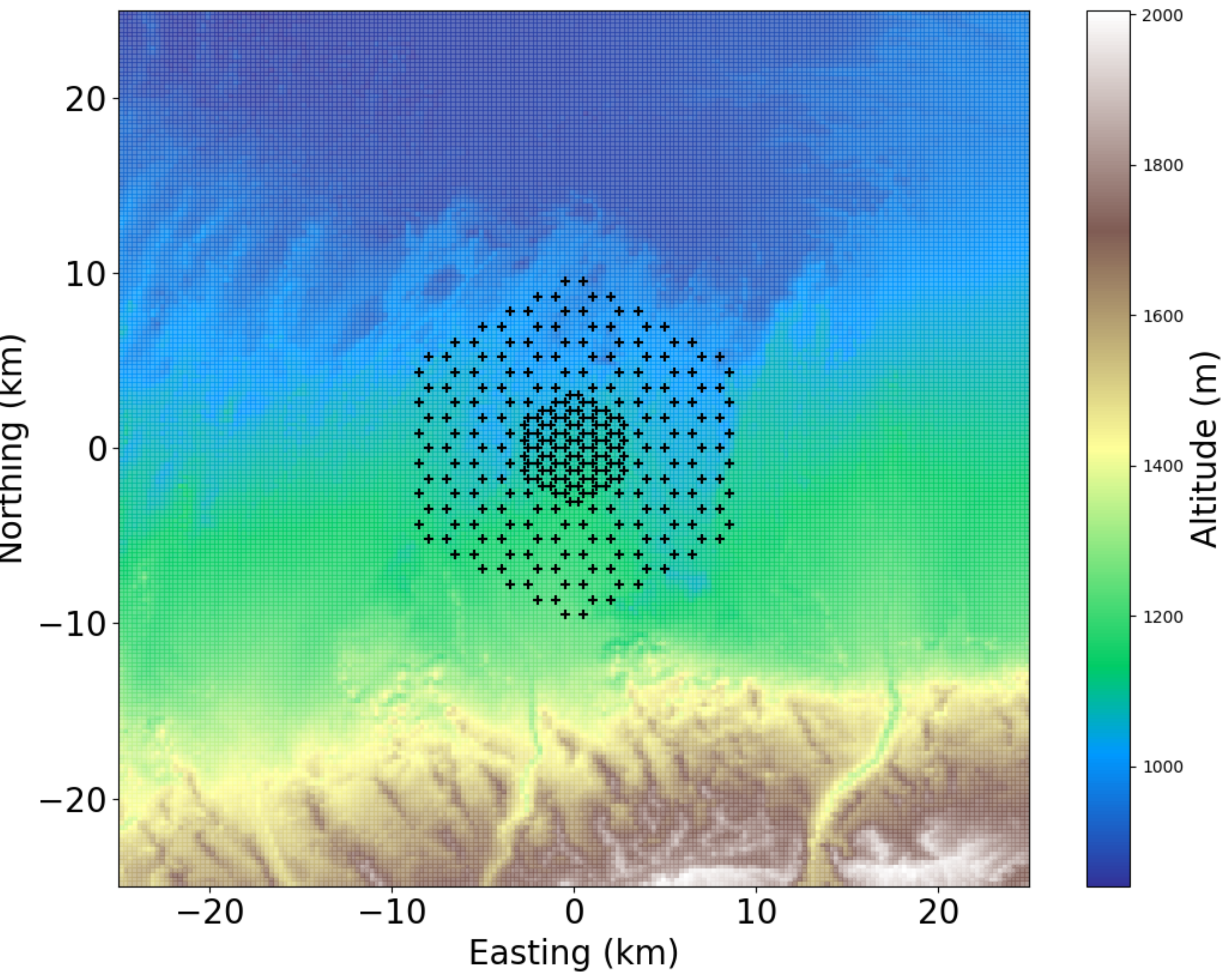
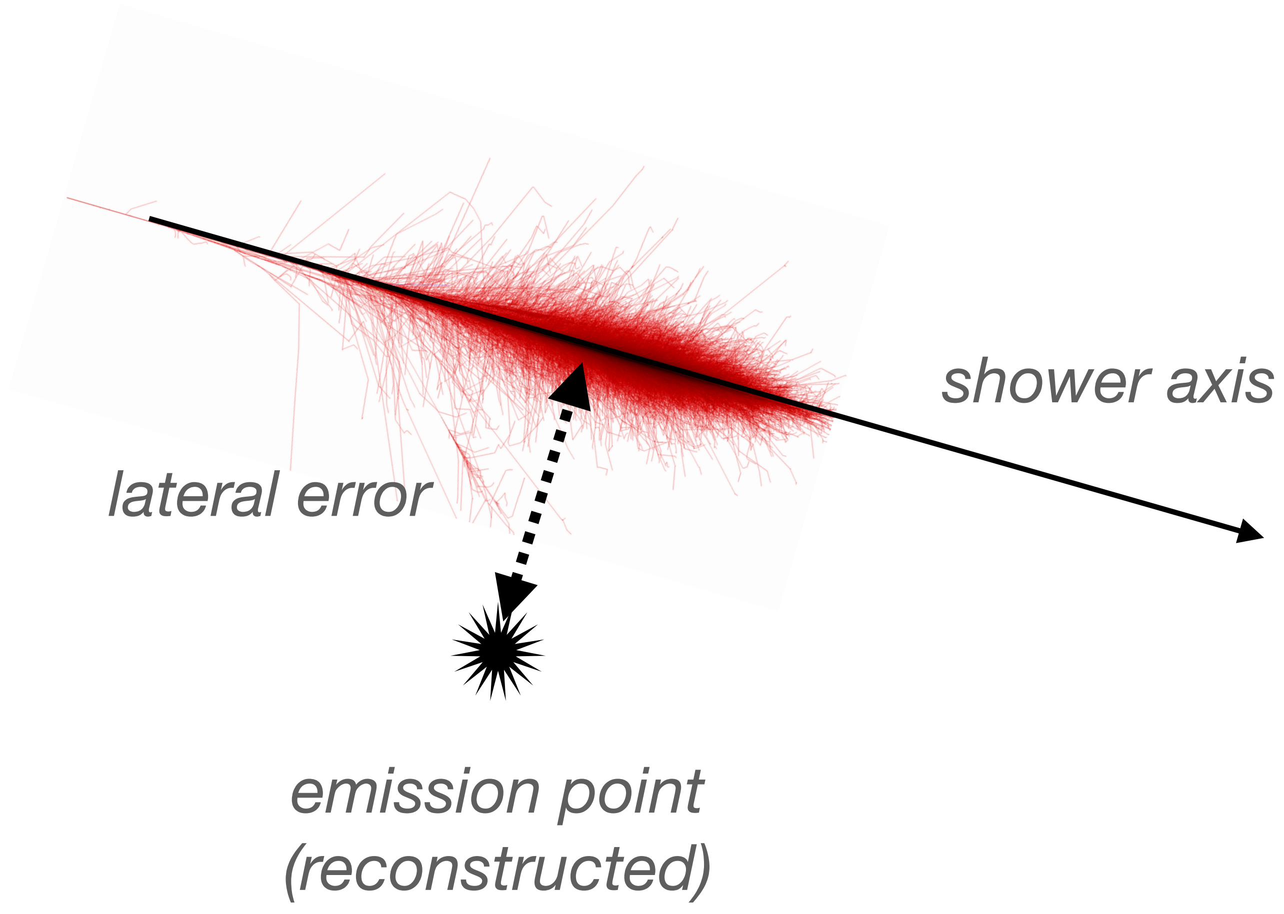
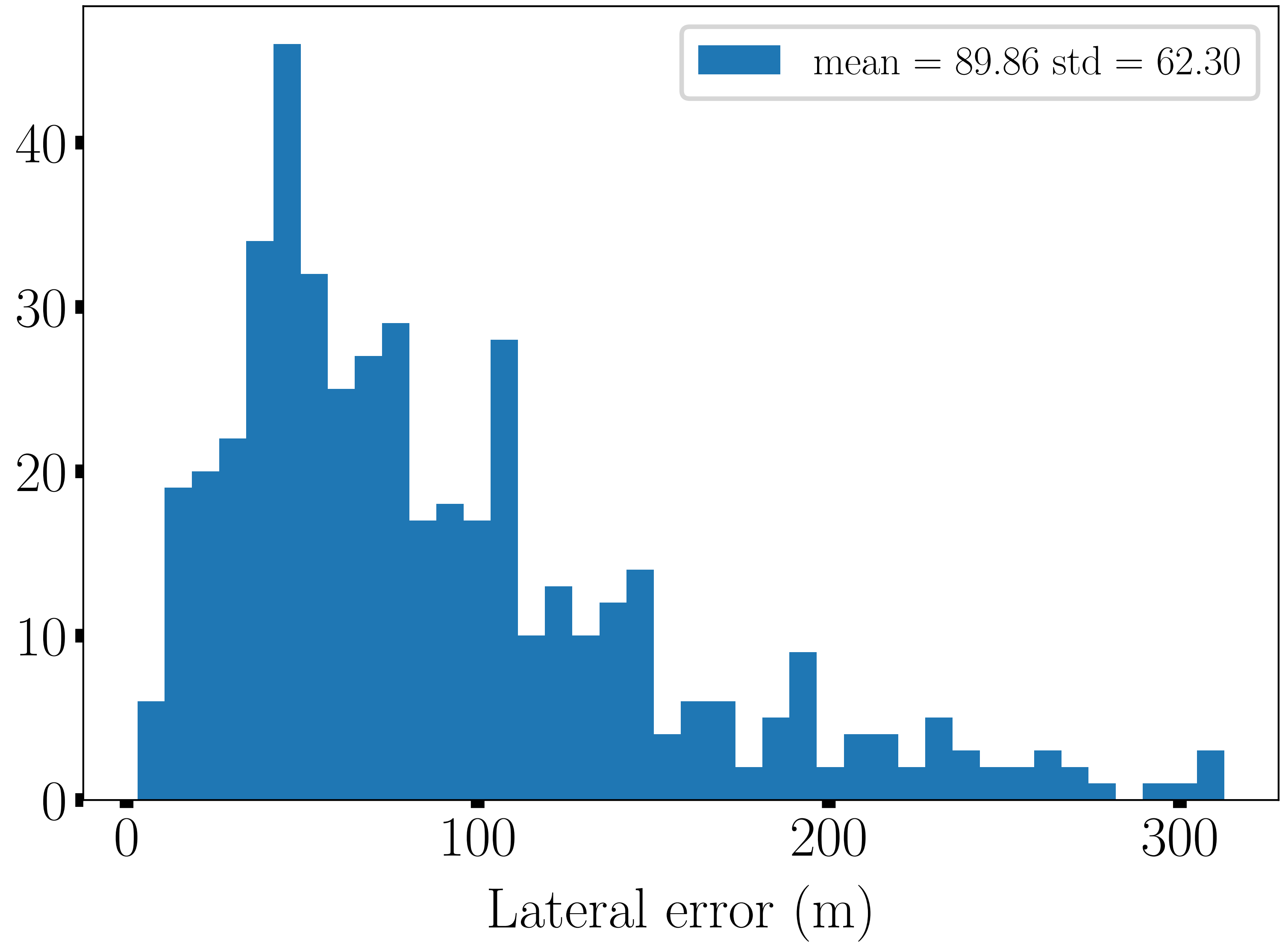
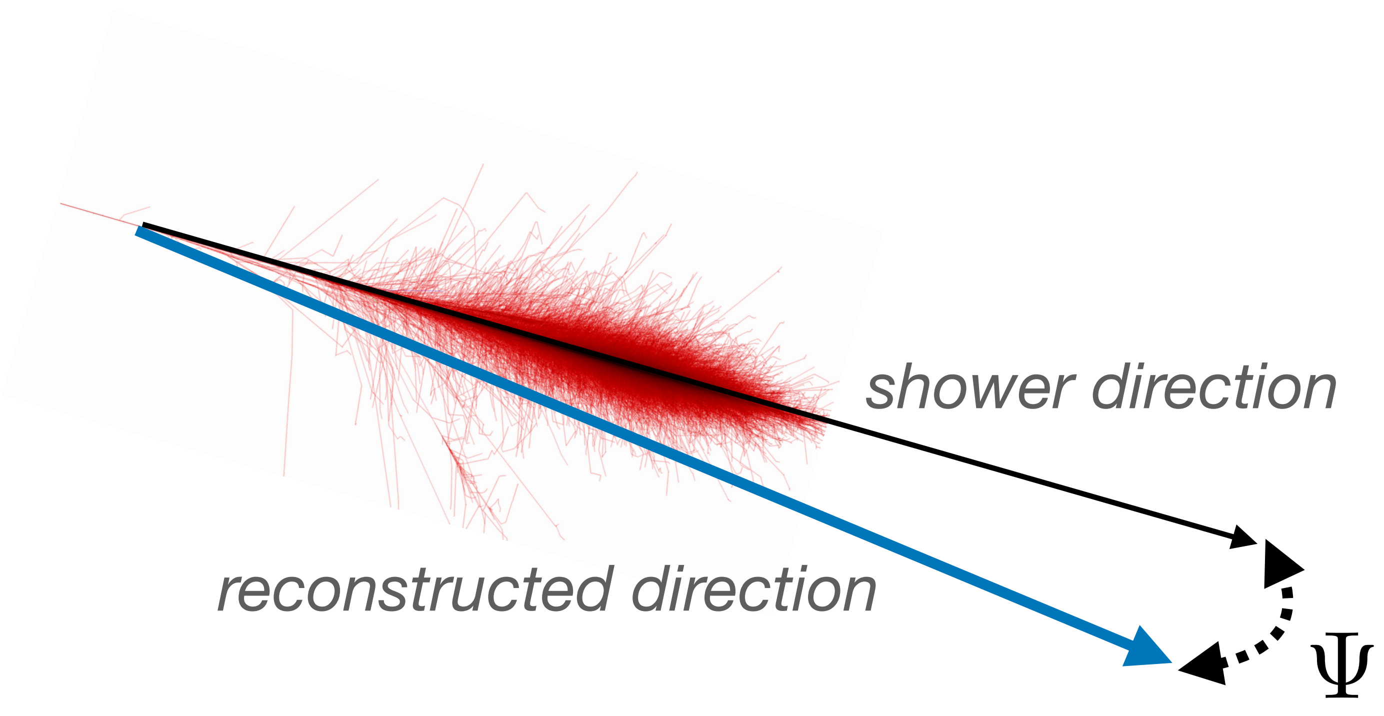


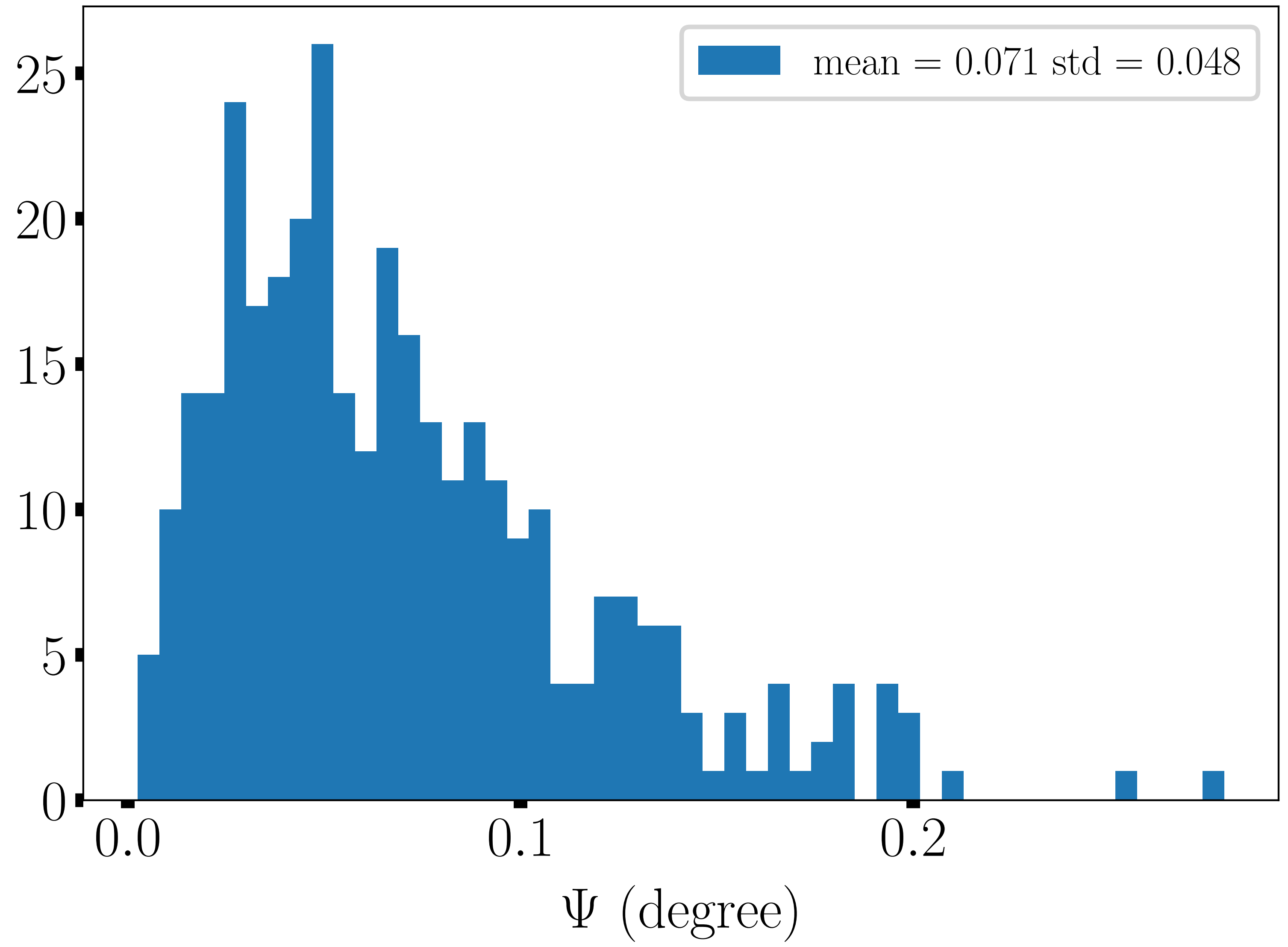




Constraint on the lateral position ~90 m

Angular resolution ~0.07°





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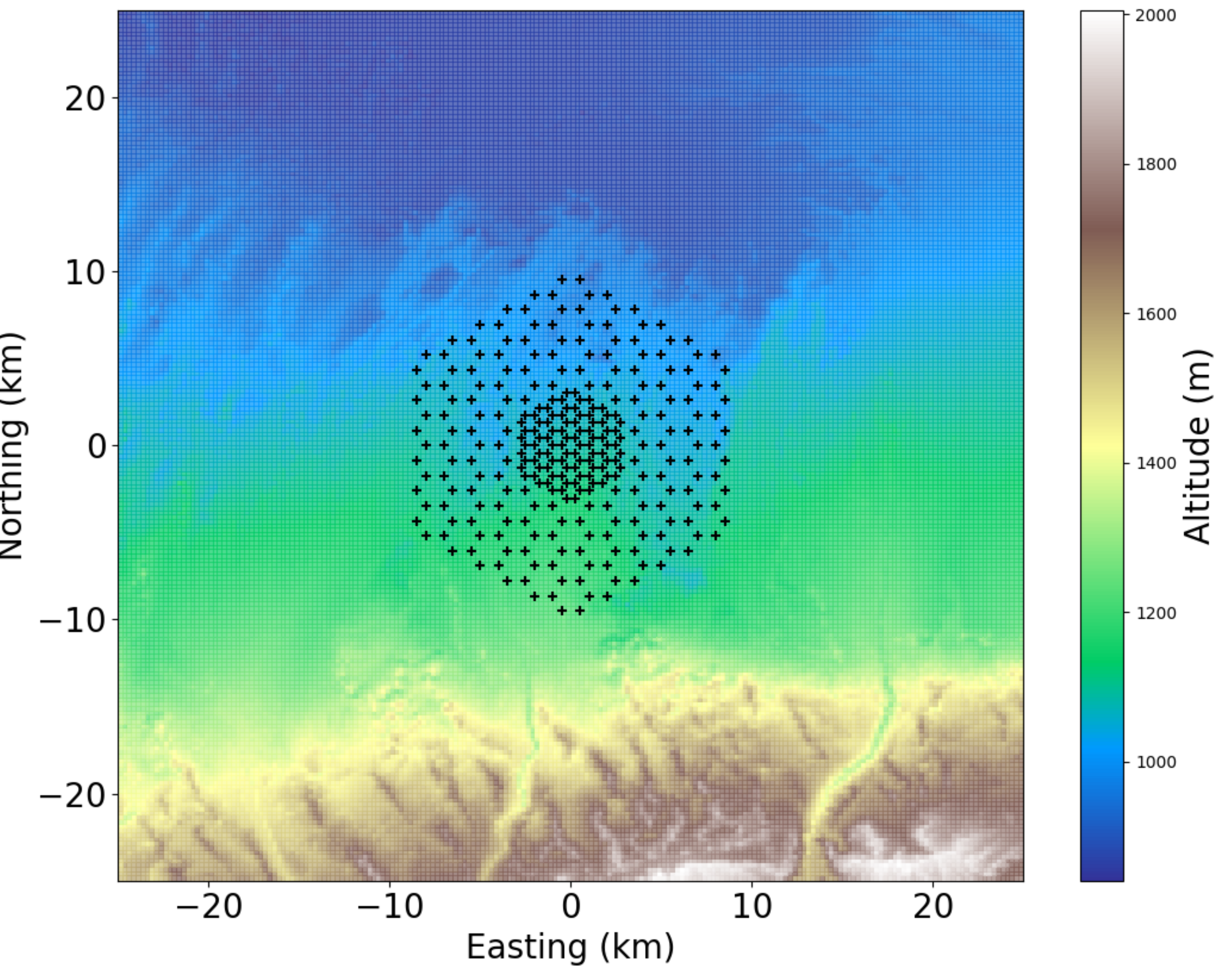

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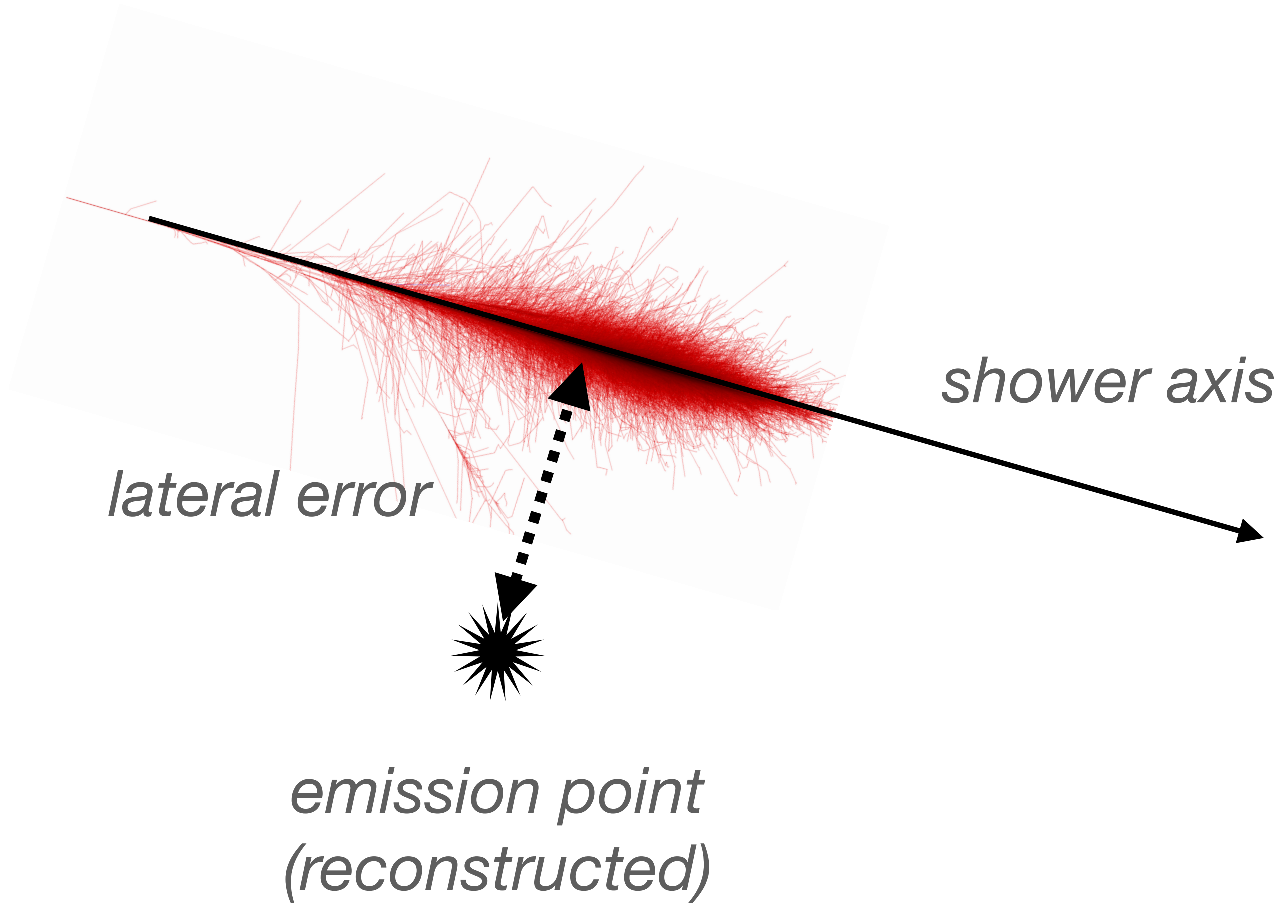
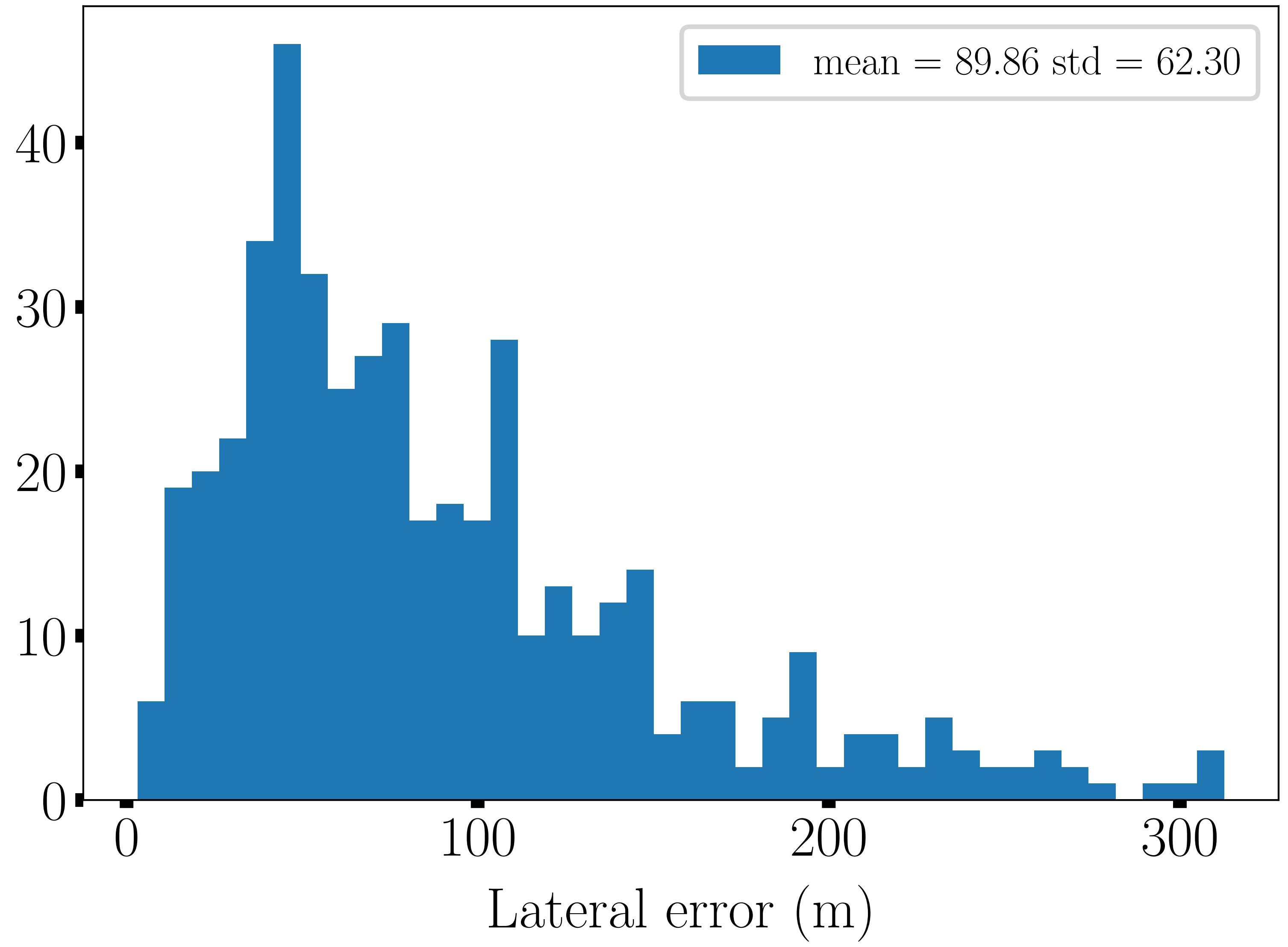
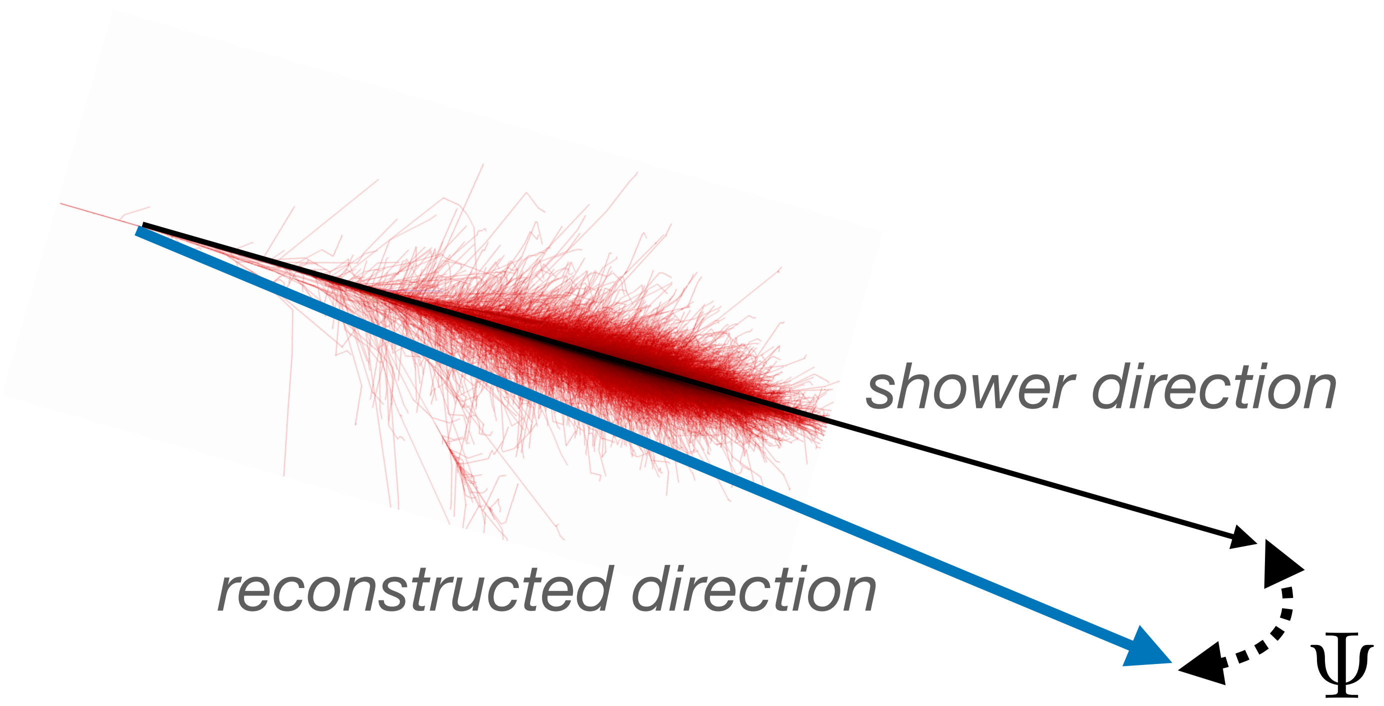
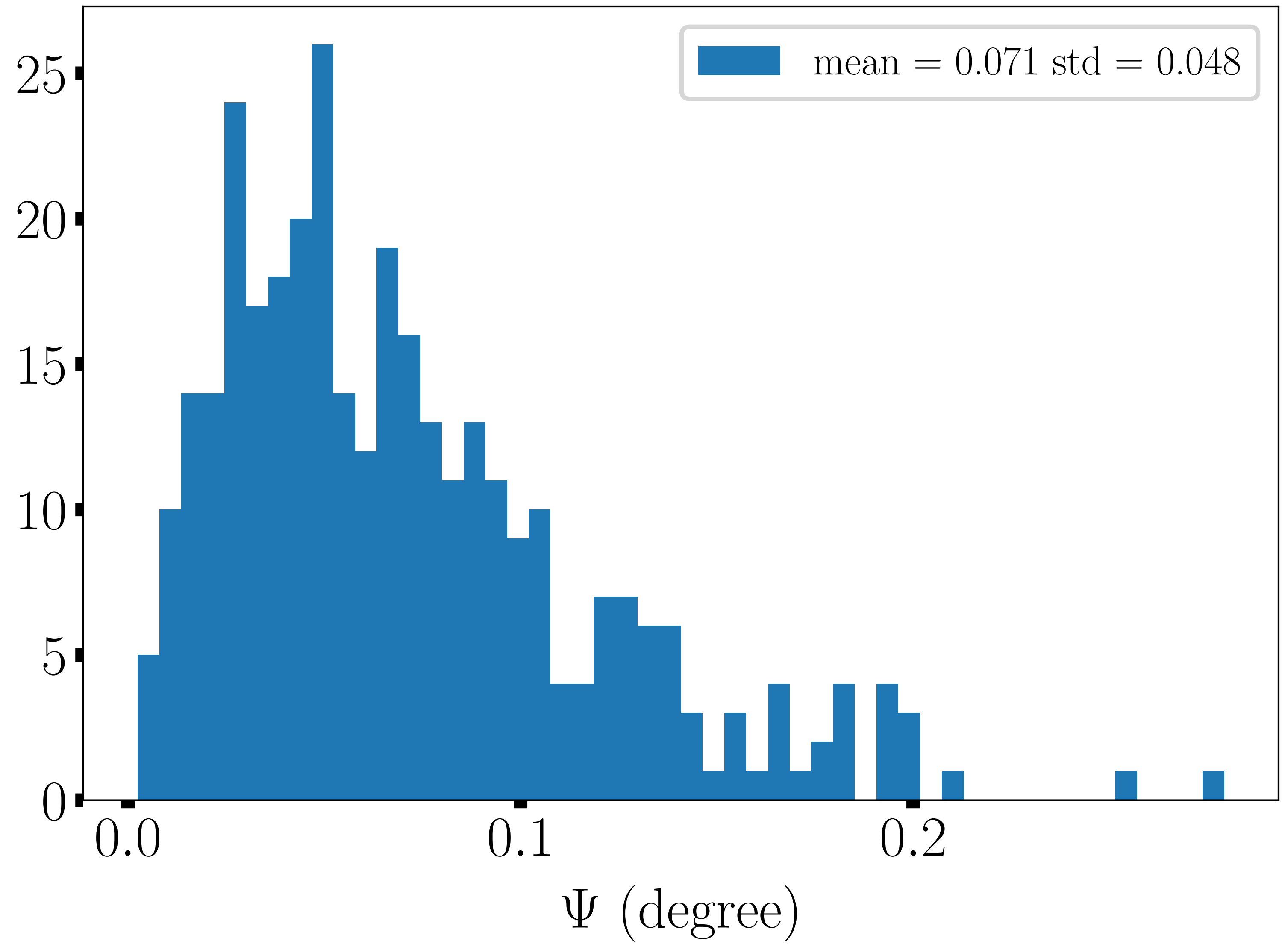




Constraint on the lateral position ~90 m
Angular resolution ~0.07°

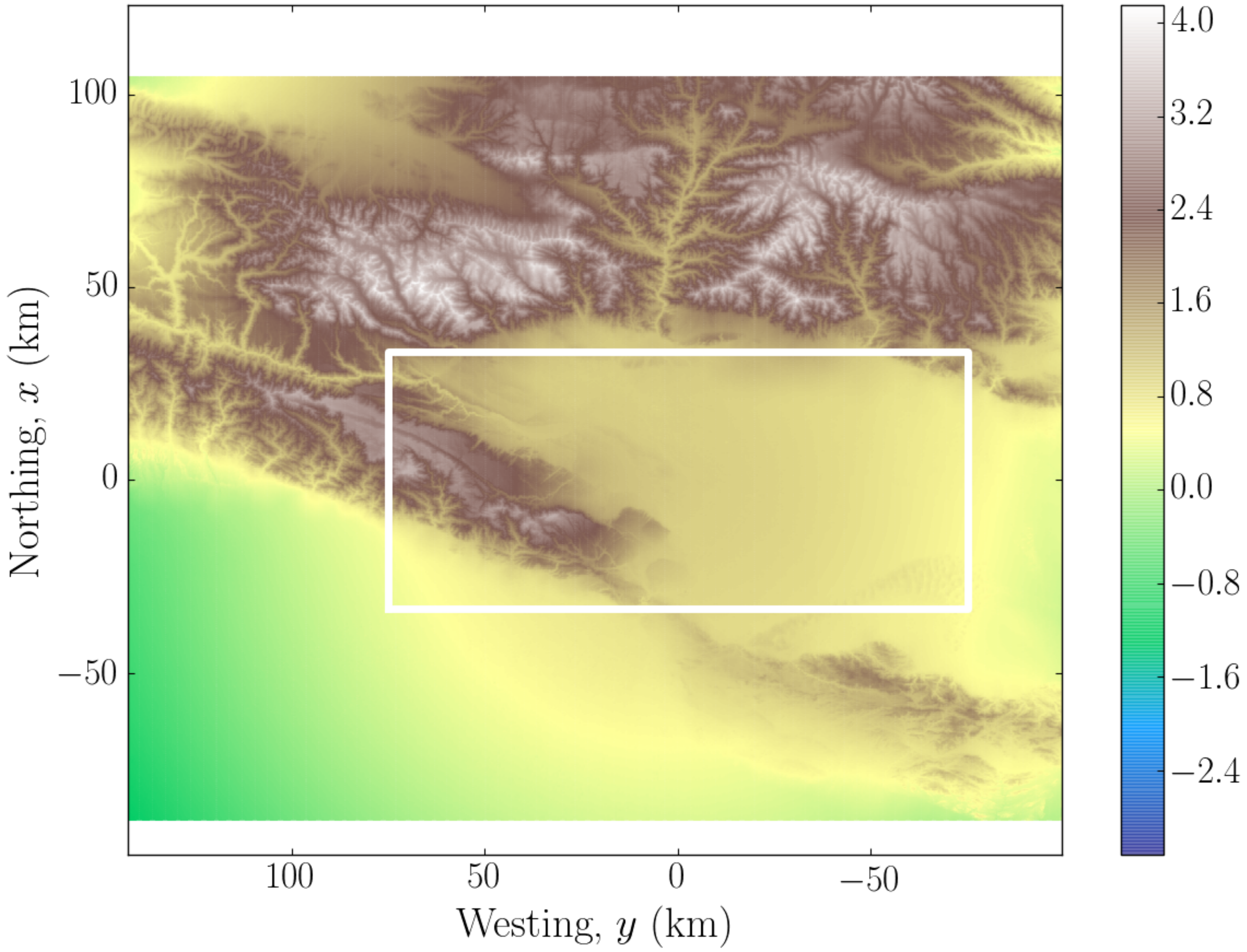




The arrival direction can be reconstructed on average below 0.1°
and the emission point can be localised with precision

Reconstruction performances for Hot Spot 1 (HS1)

HS1: a sensitivity principle study on a realistic topography of a sub-array



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- square grid array with a 1 km spacing
- neutrino induced EAS from realistic isotropic flux

HS1 simulations:

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- primaries: neutrino

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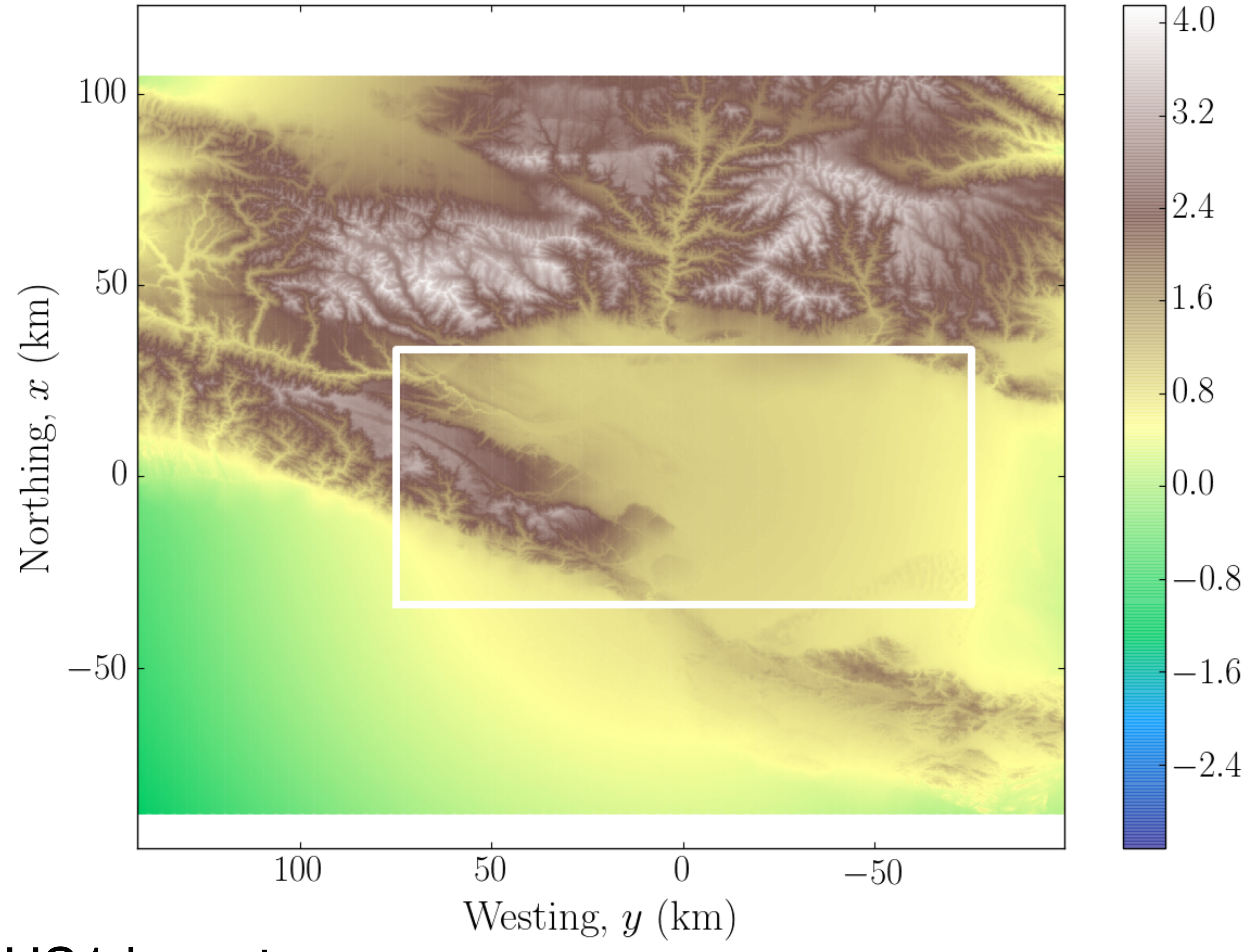

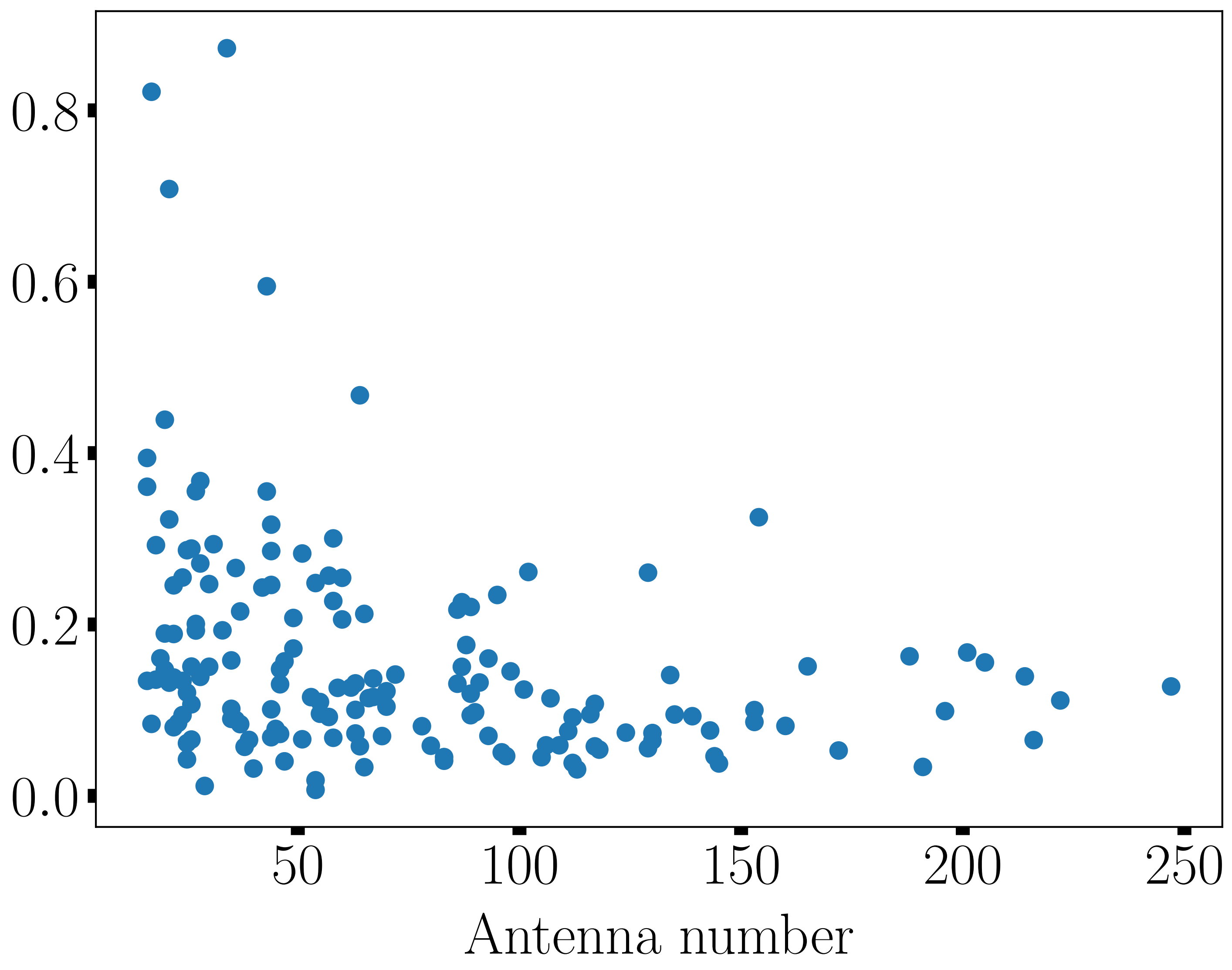

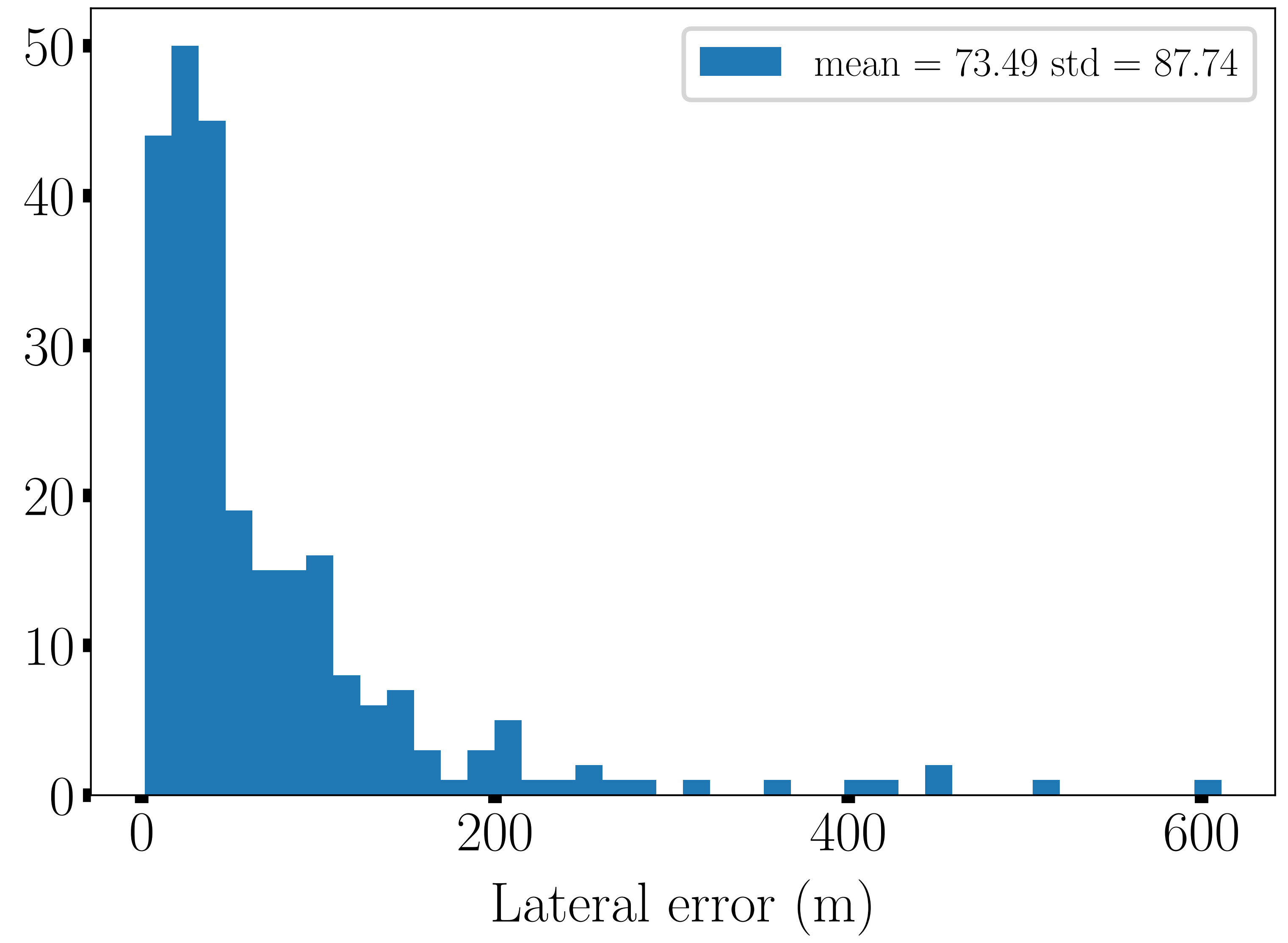

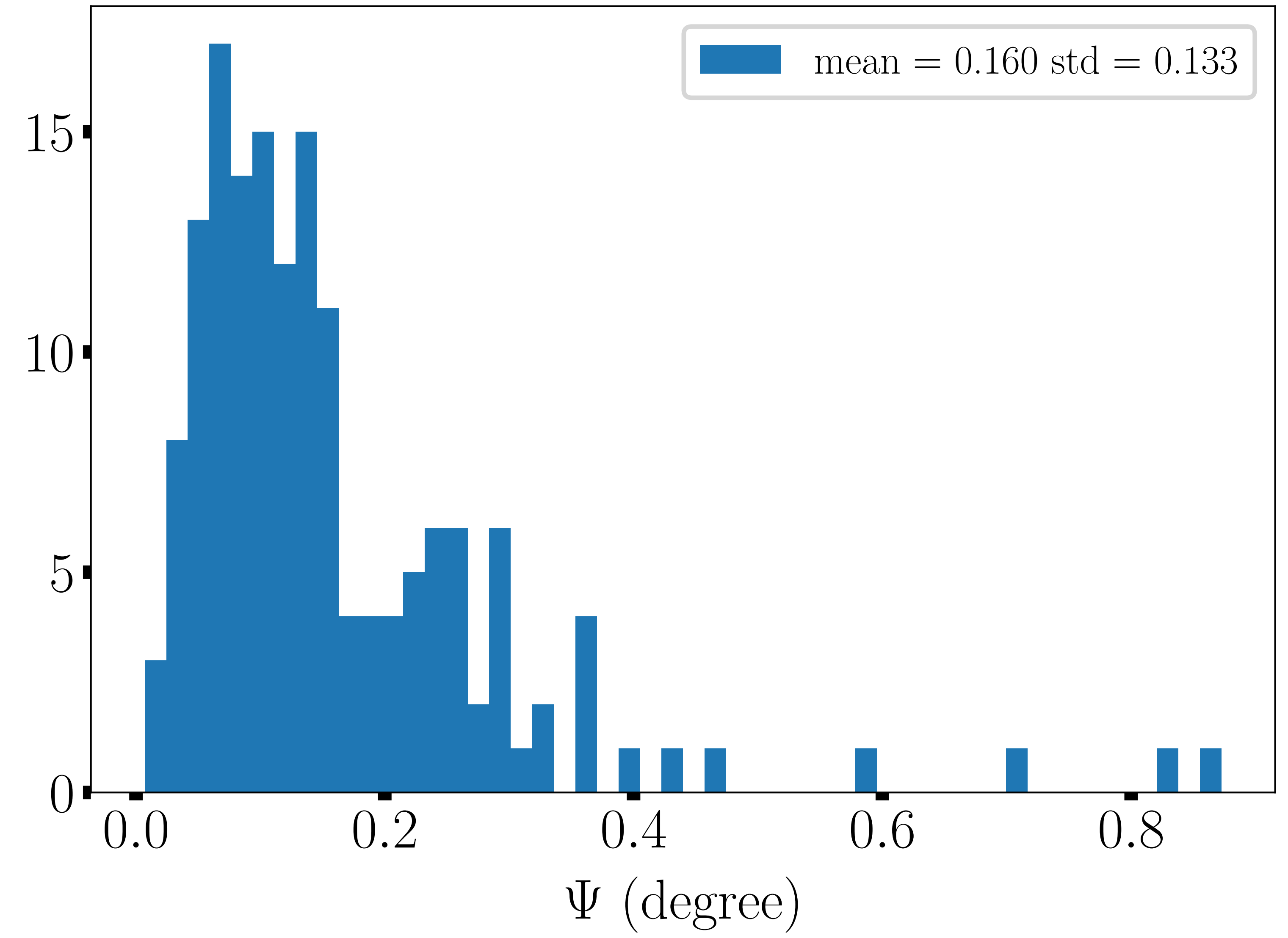

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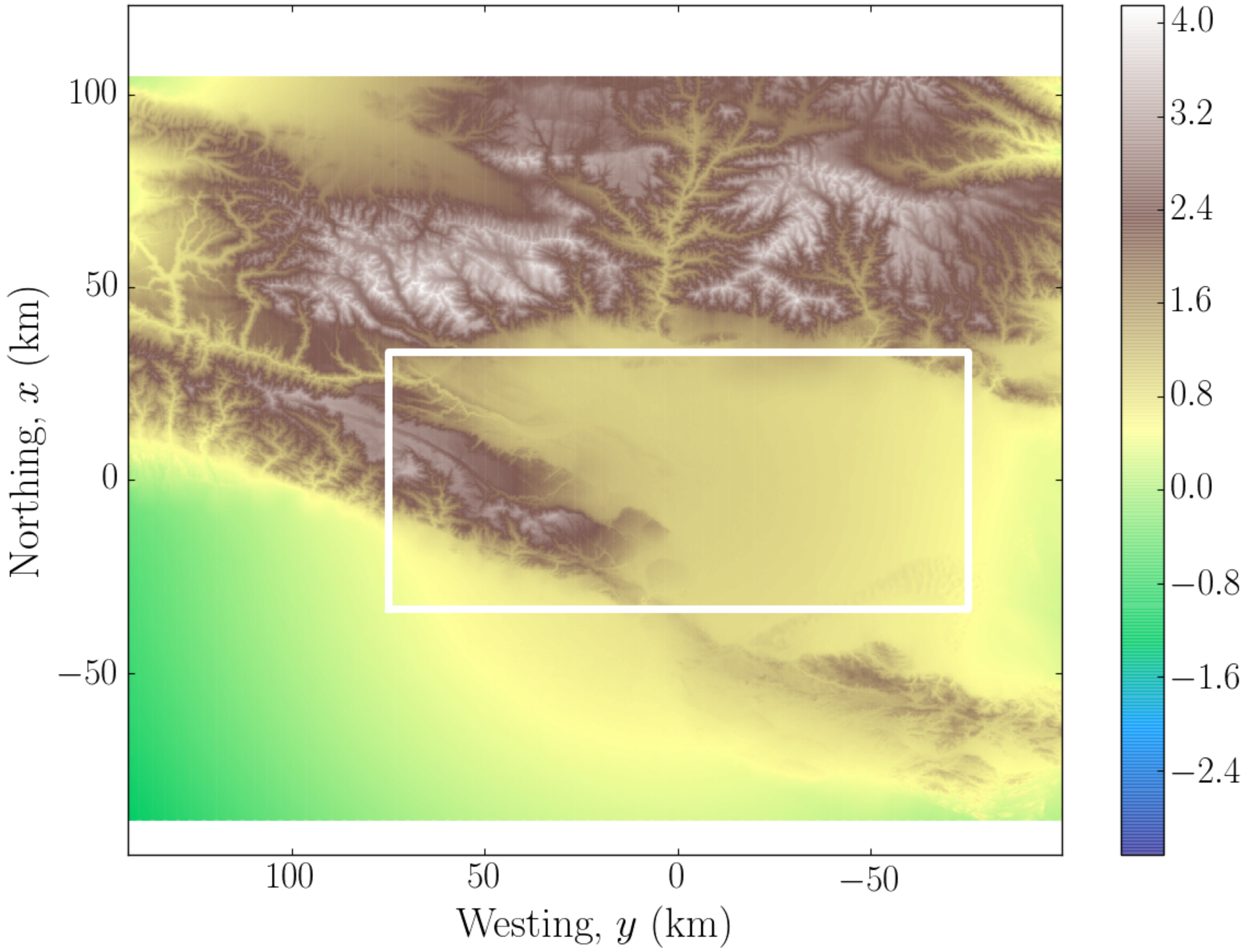

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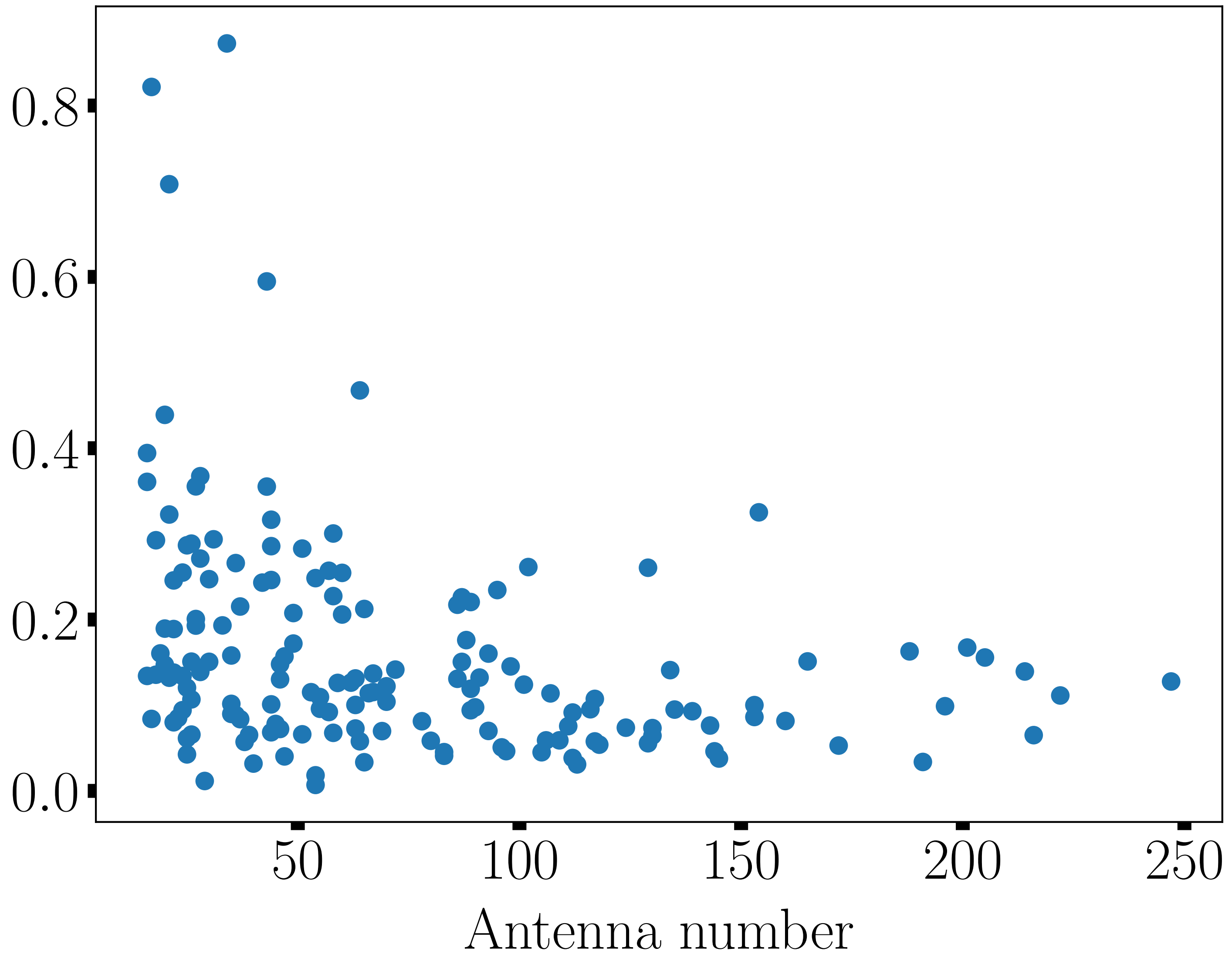
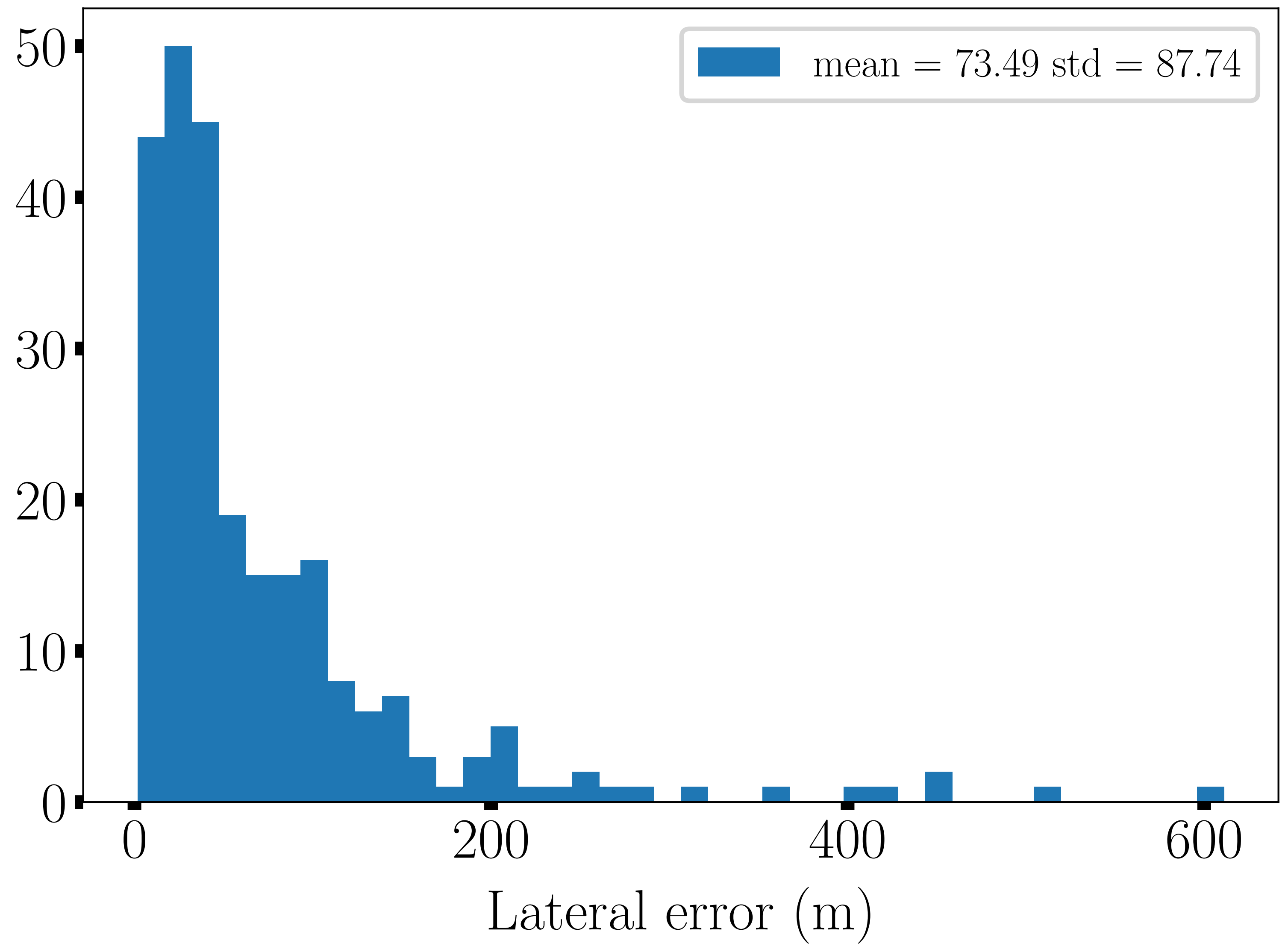
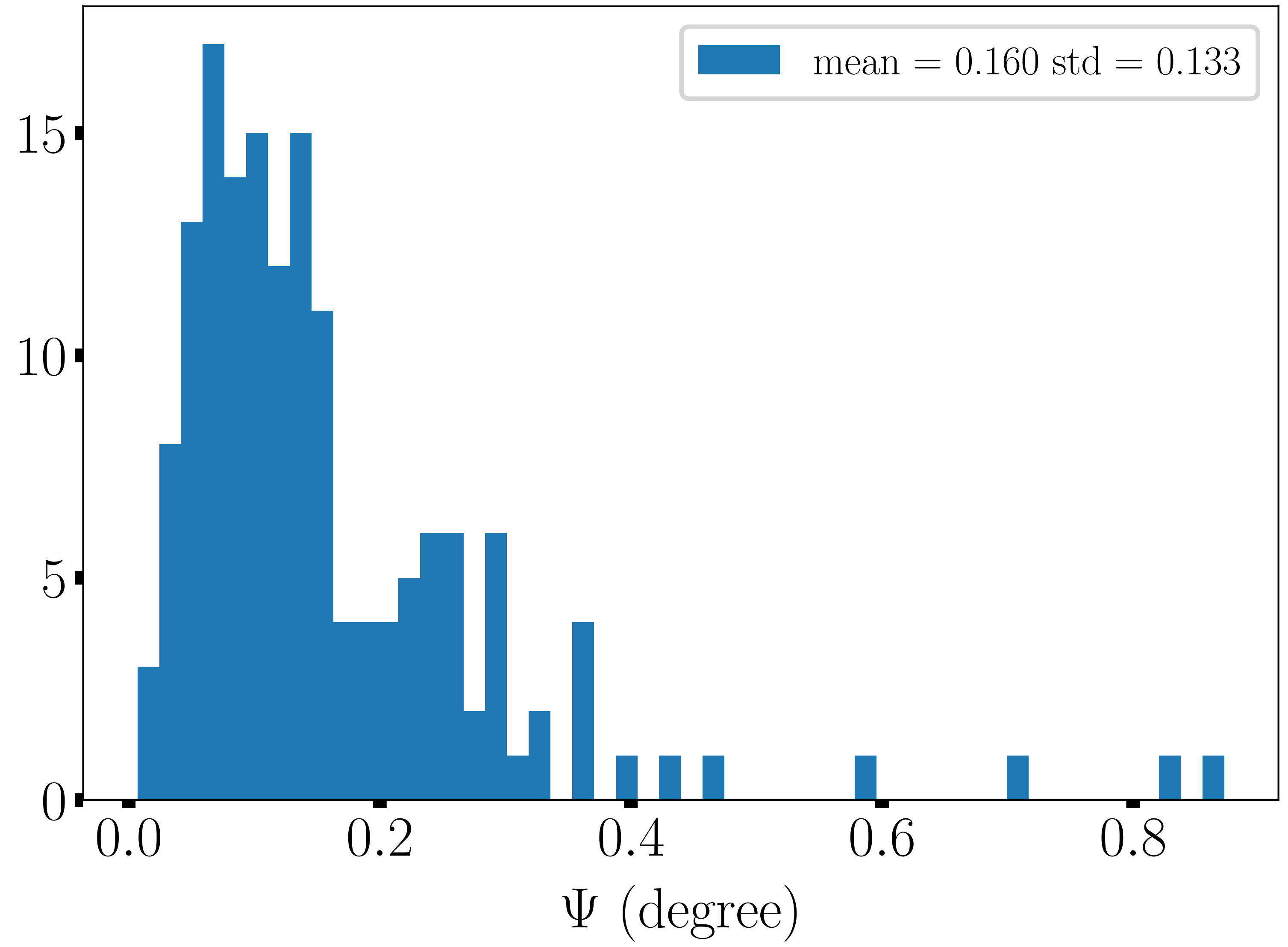
Constraint on the lateral position ~70 m
Angular resolution ~0.1°







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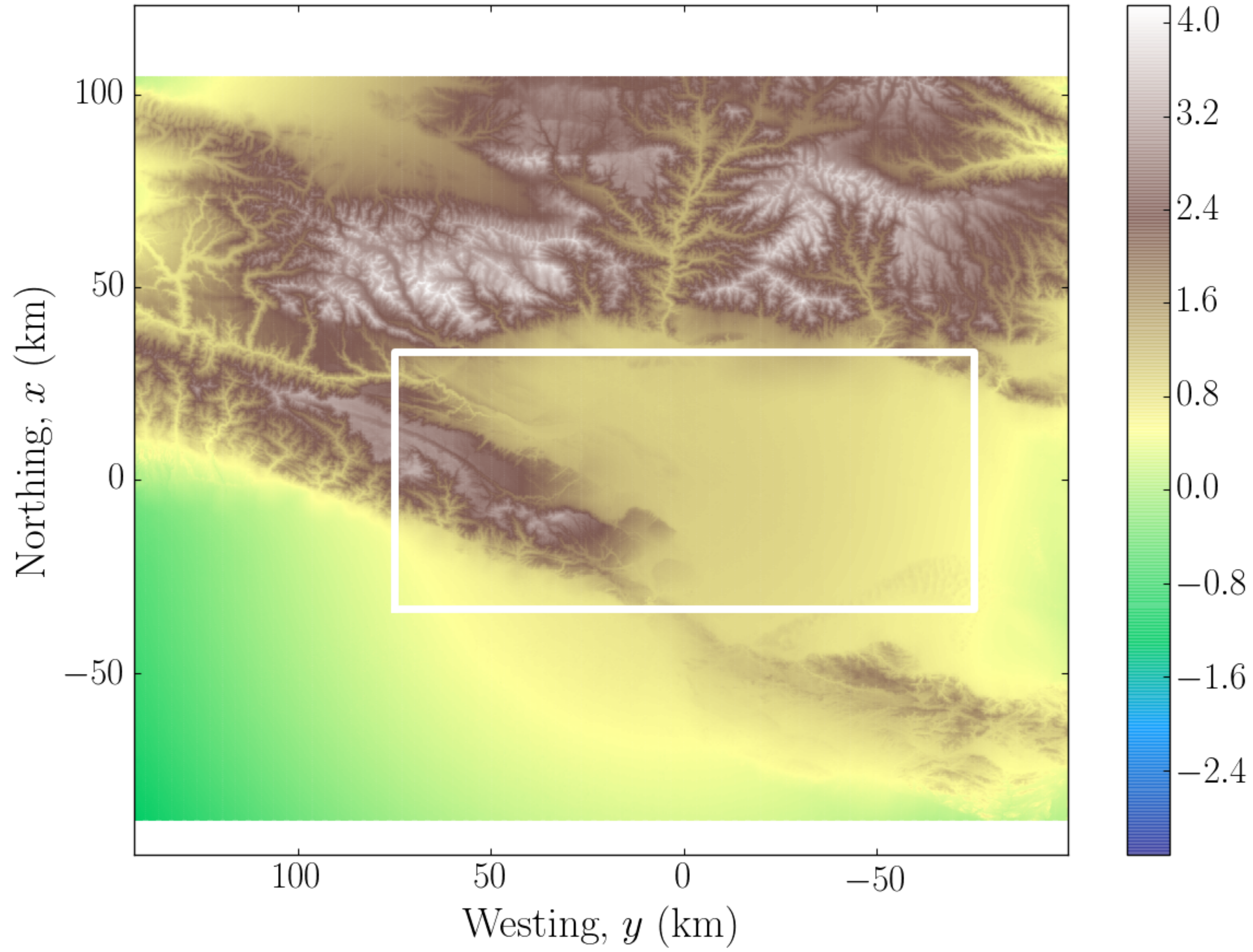

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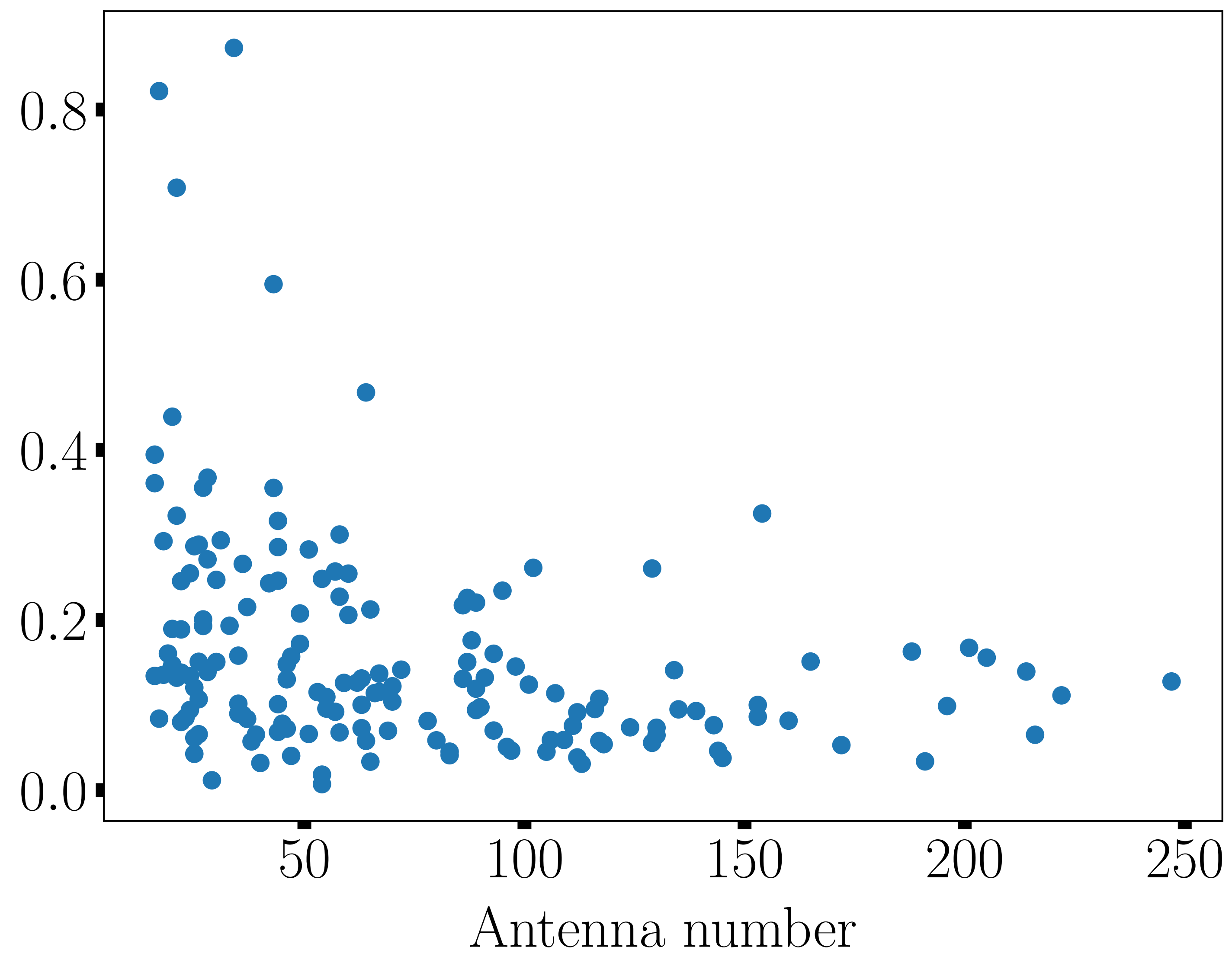
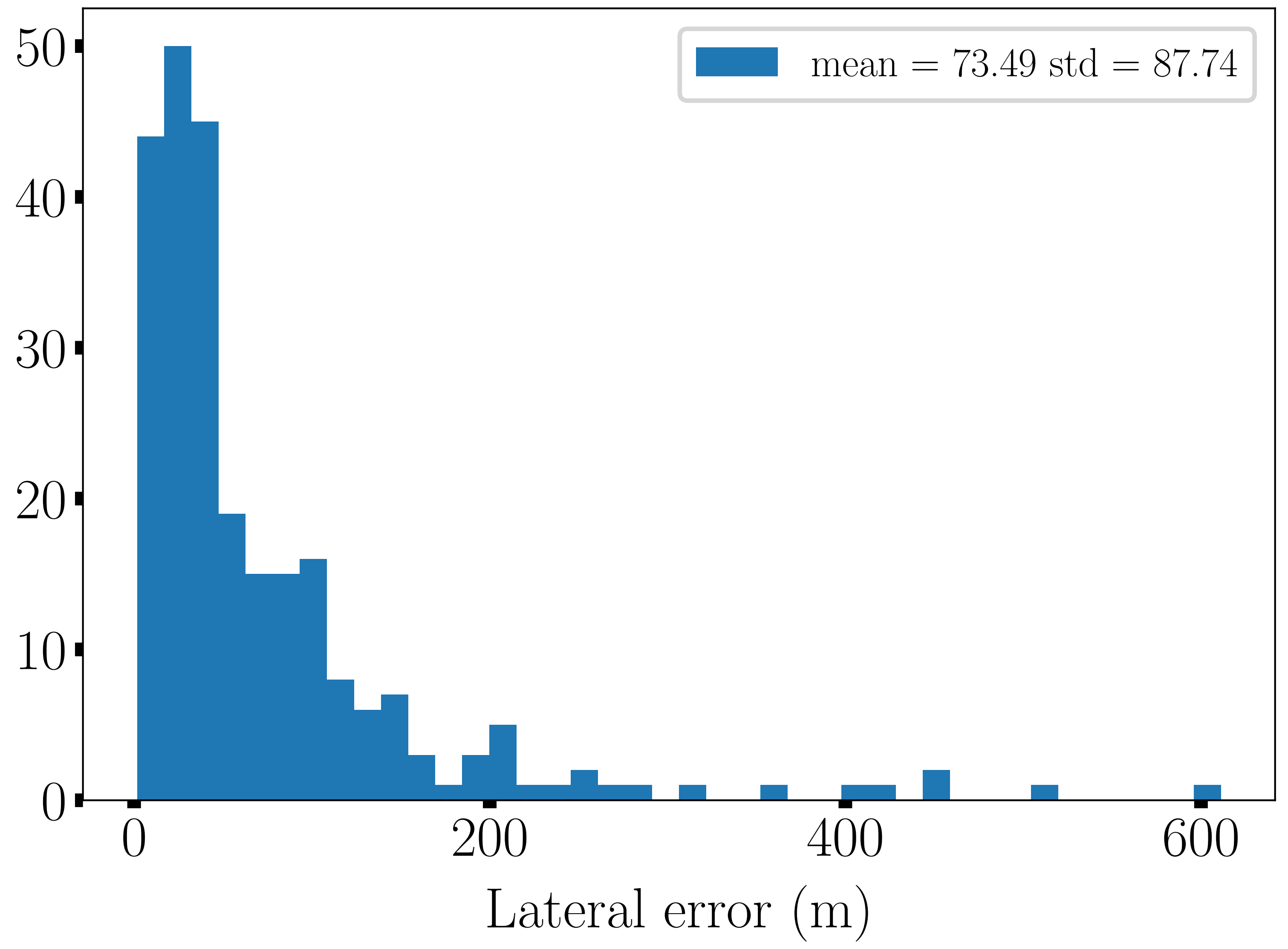
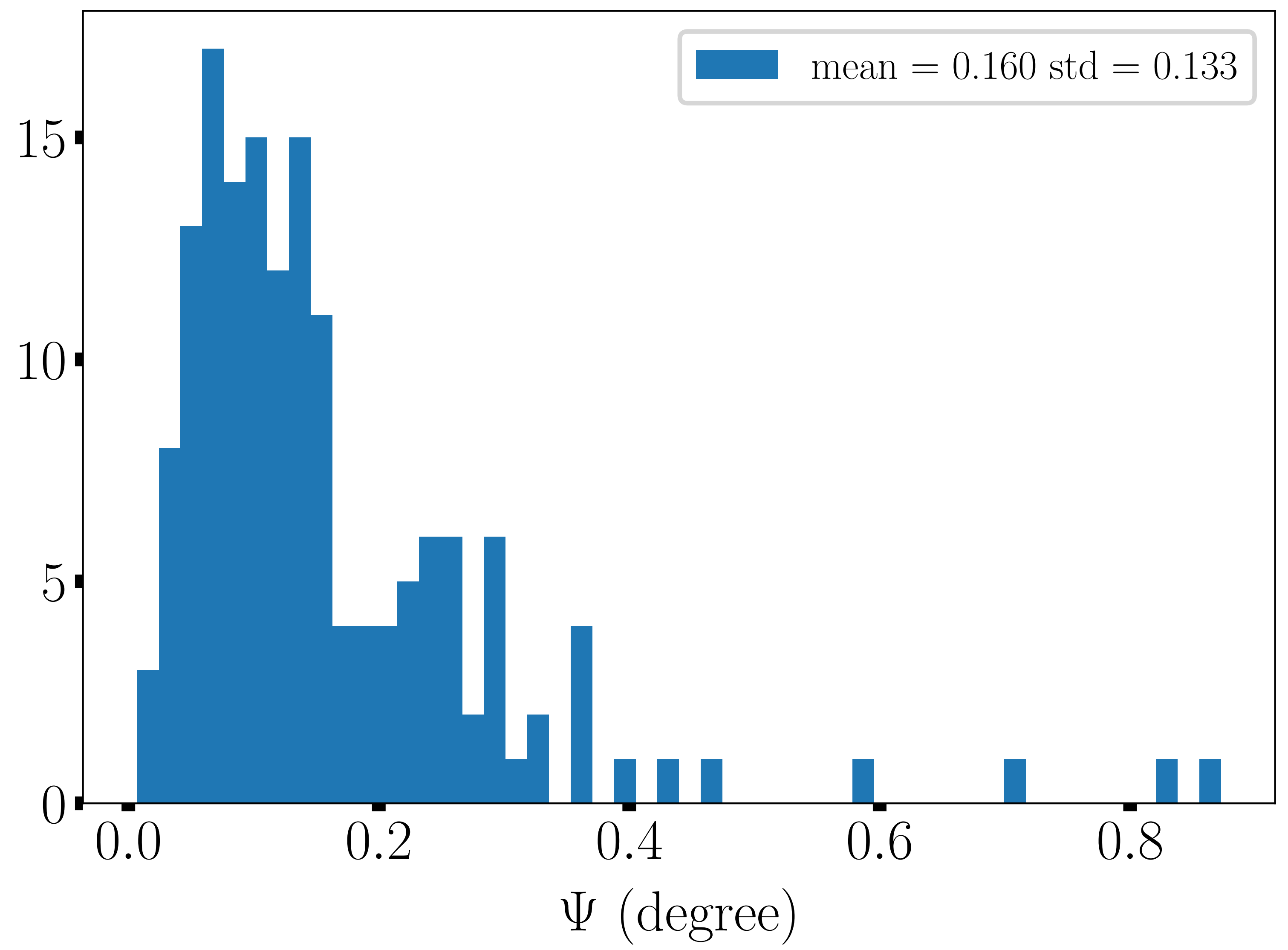


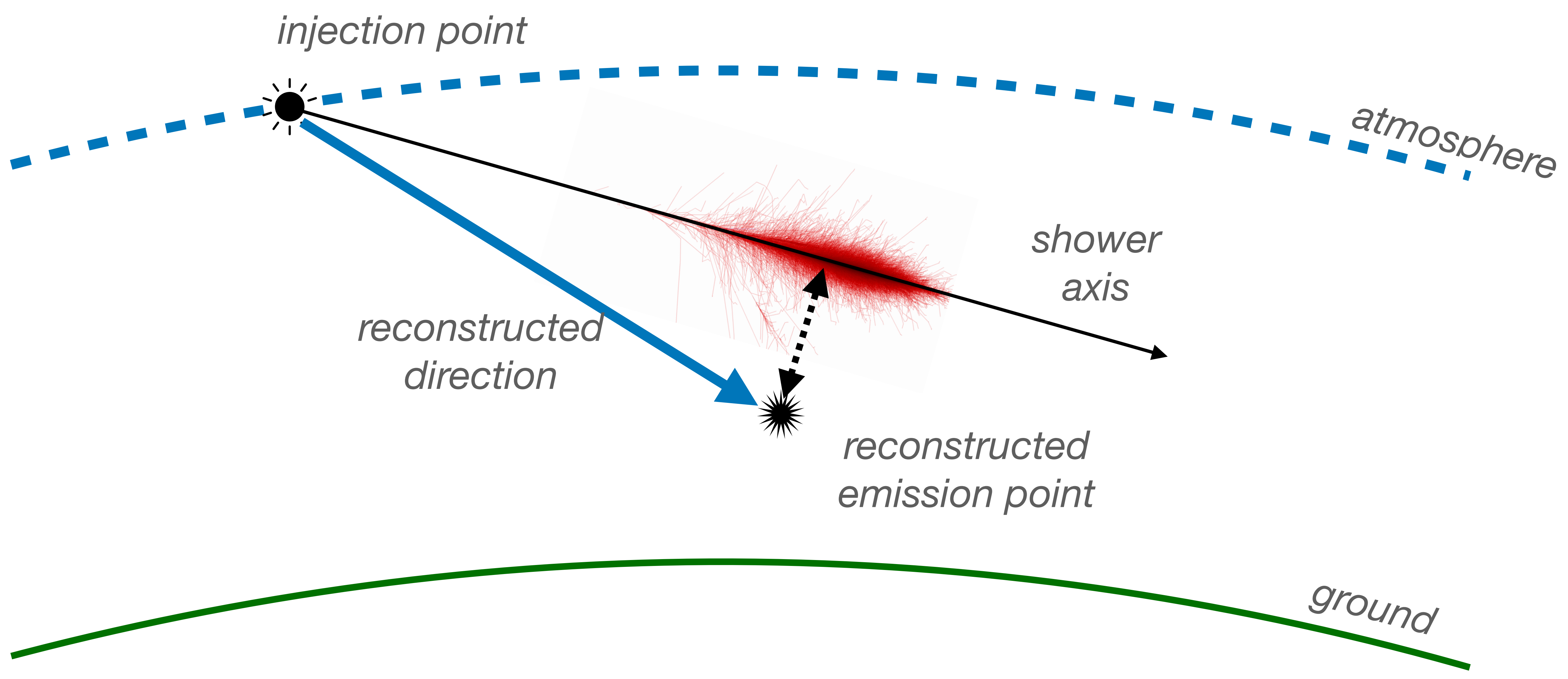




Validation of the reconstruction for the neutrinos:
- source emission very well constrained
- arrival direction within the targeted goal of 0.1°

Constraining the composition?

Indirectly we can compute:
the atmosphere column density integral from injection to reconstructed emission point



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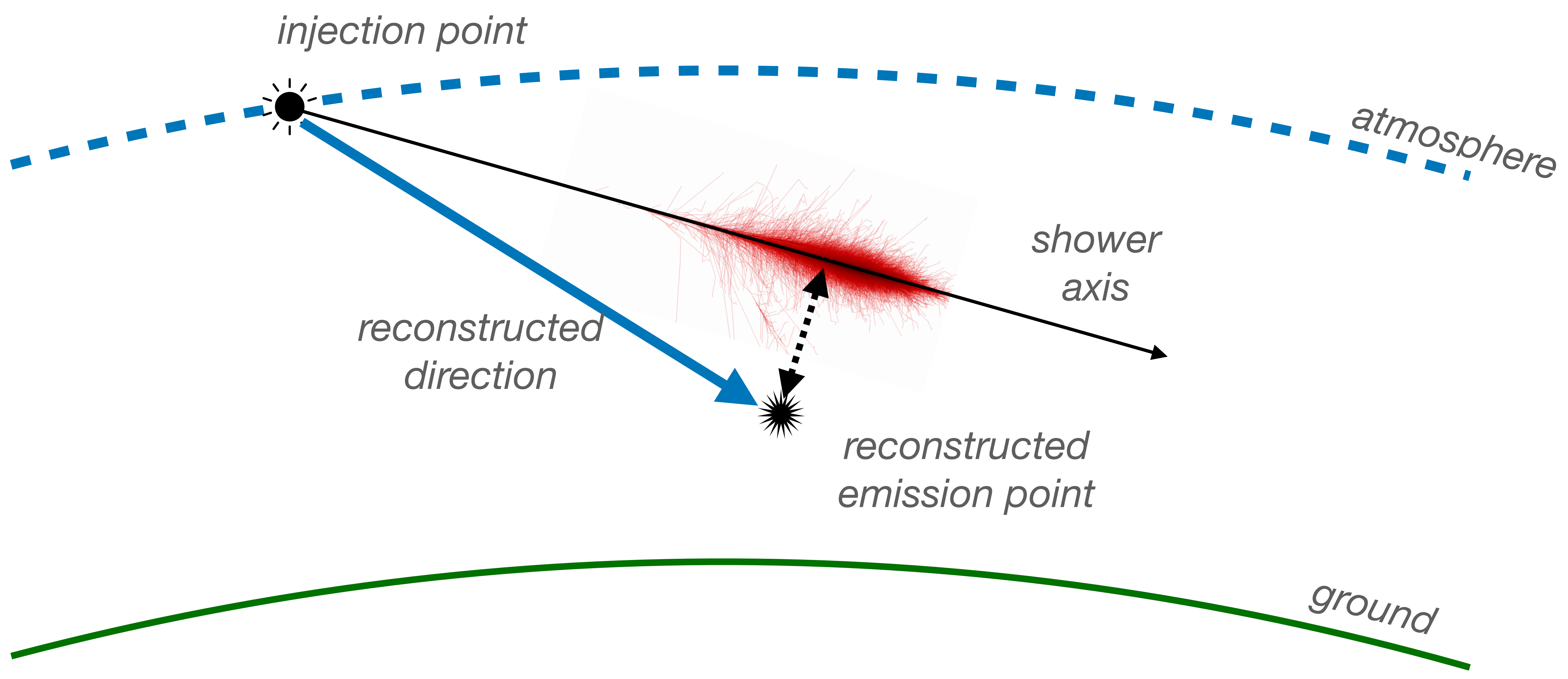
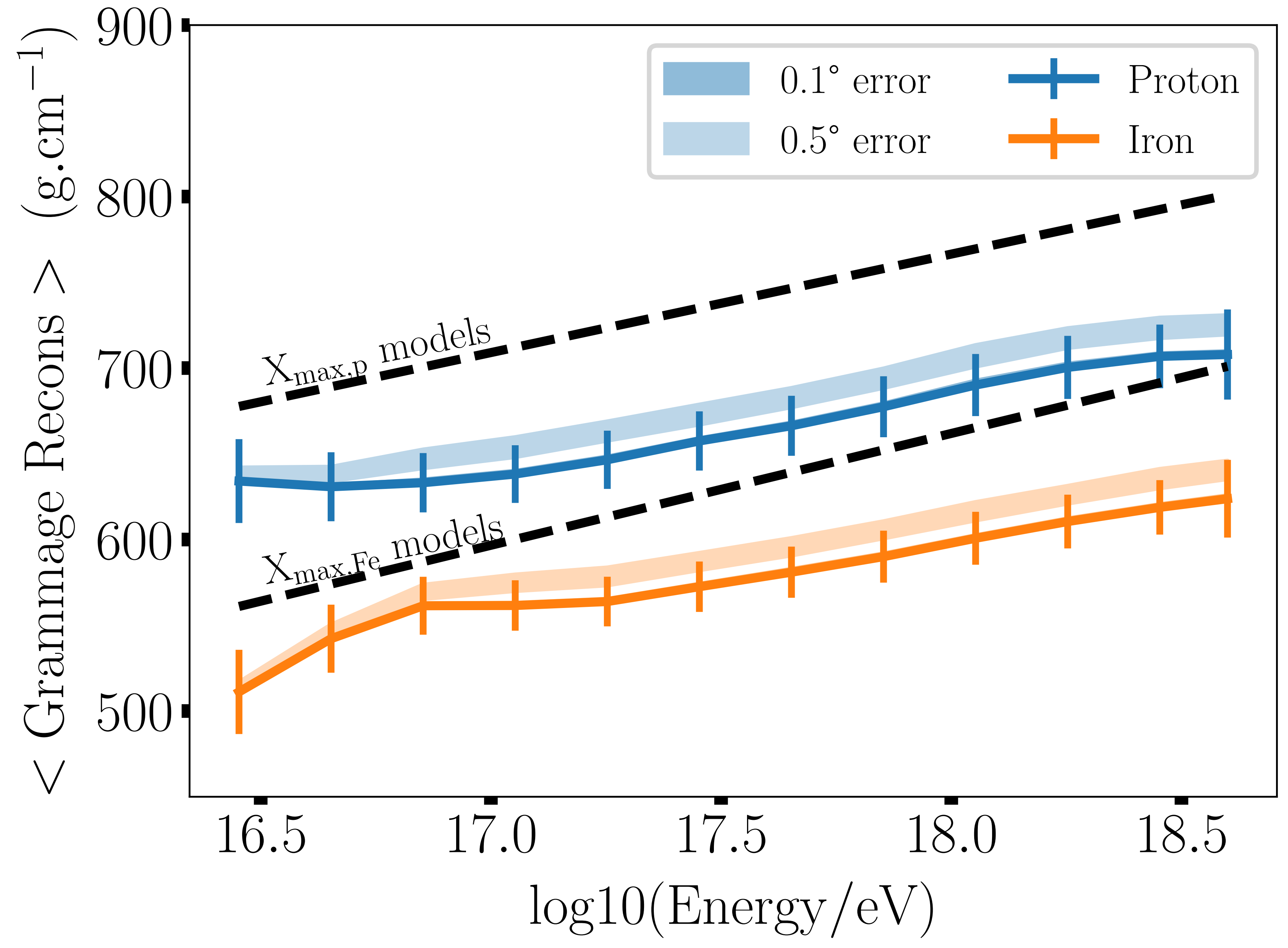
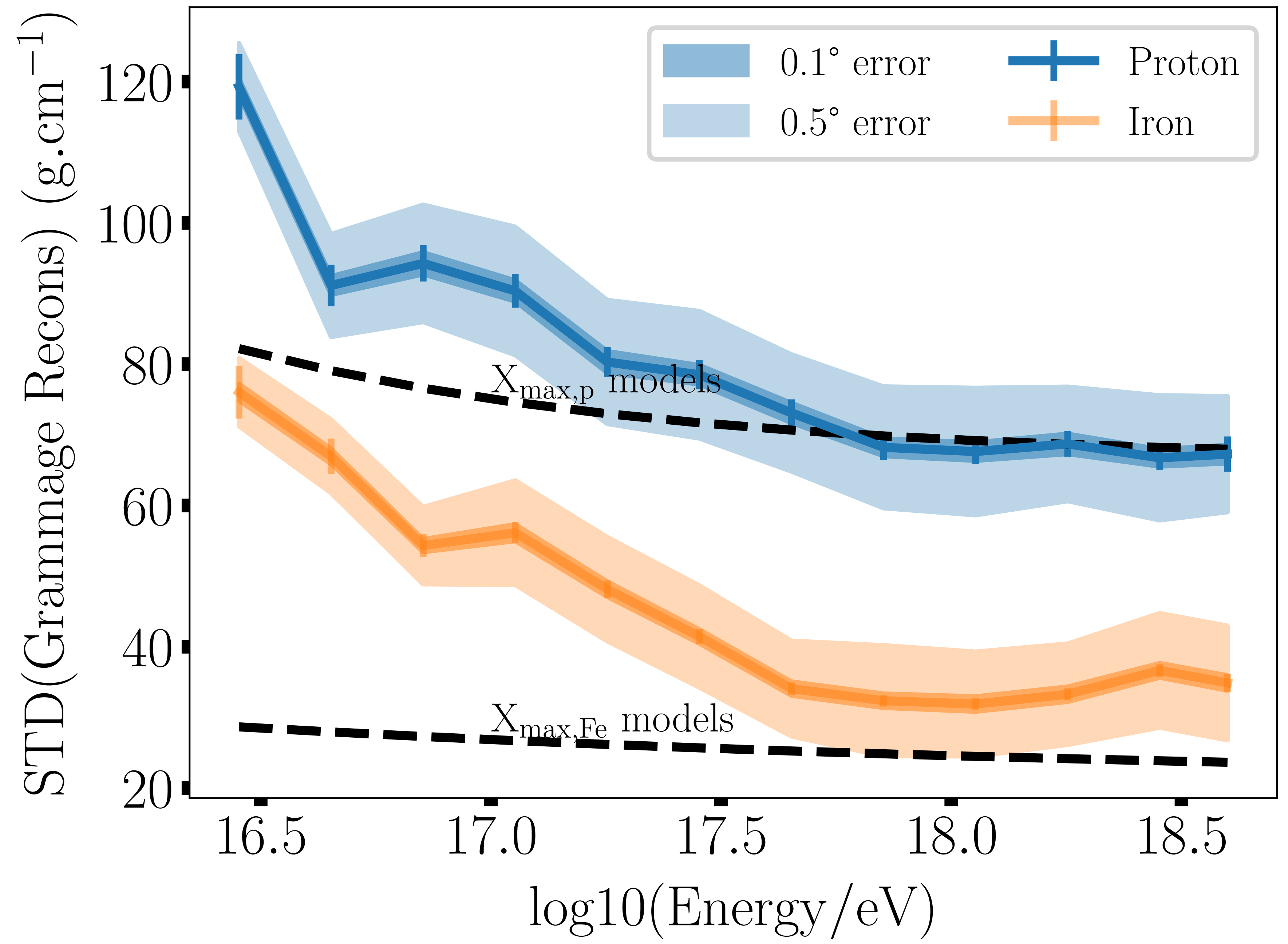


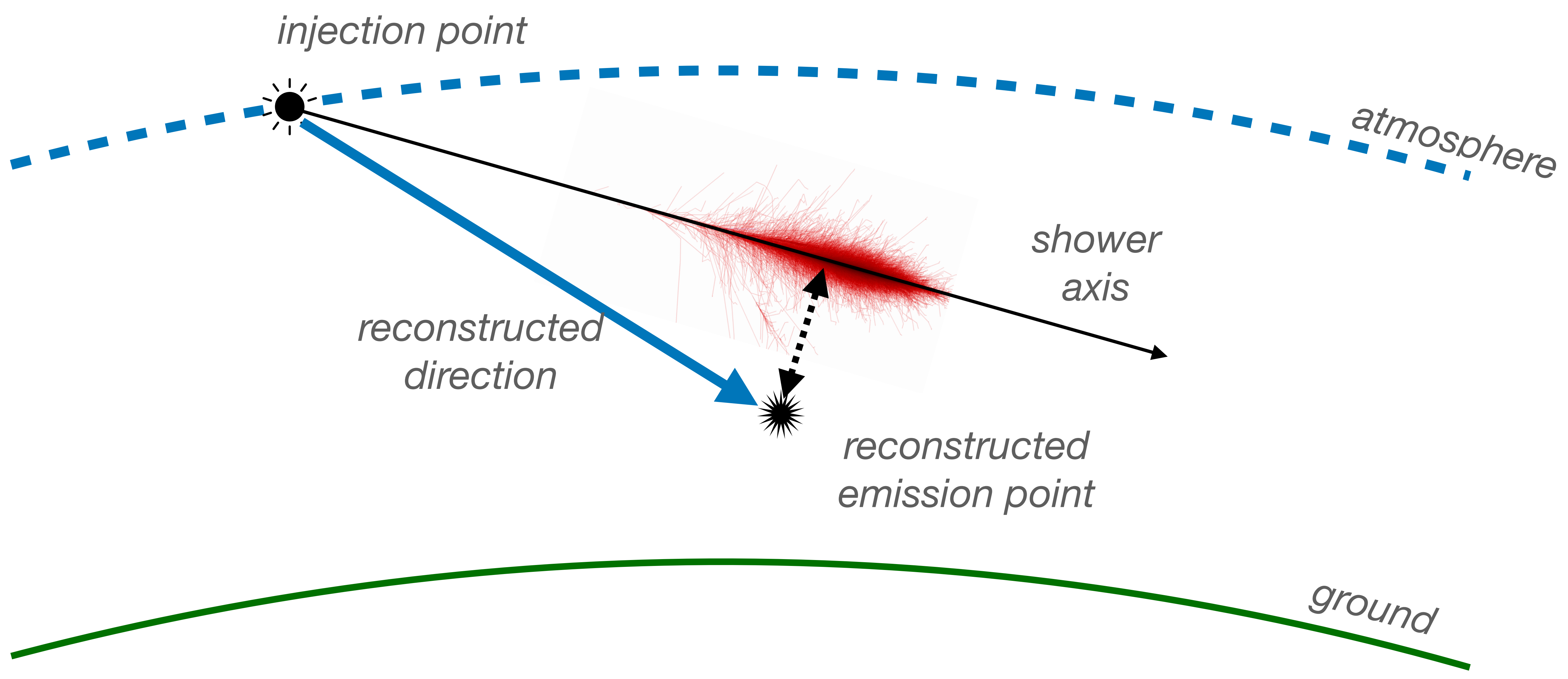


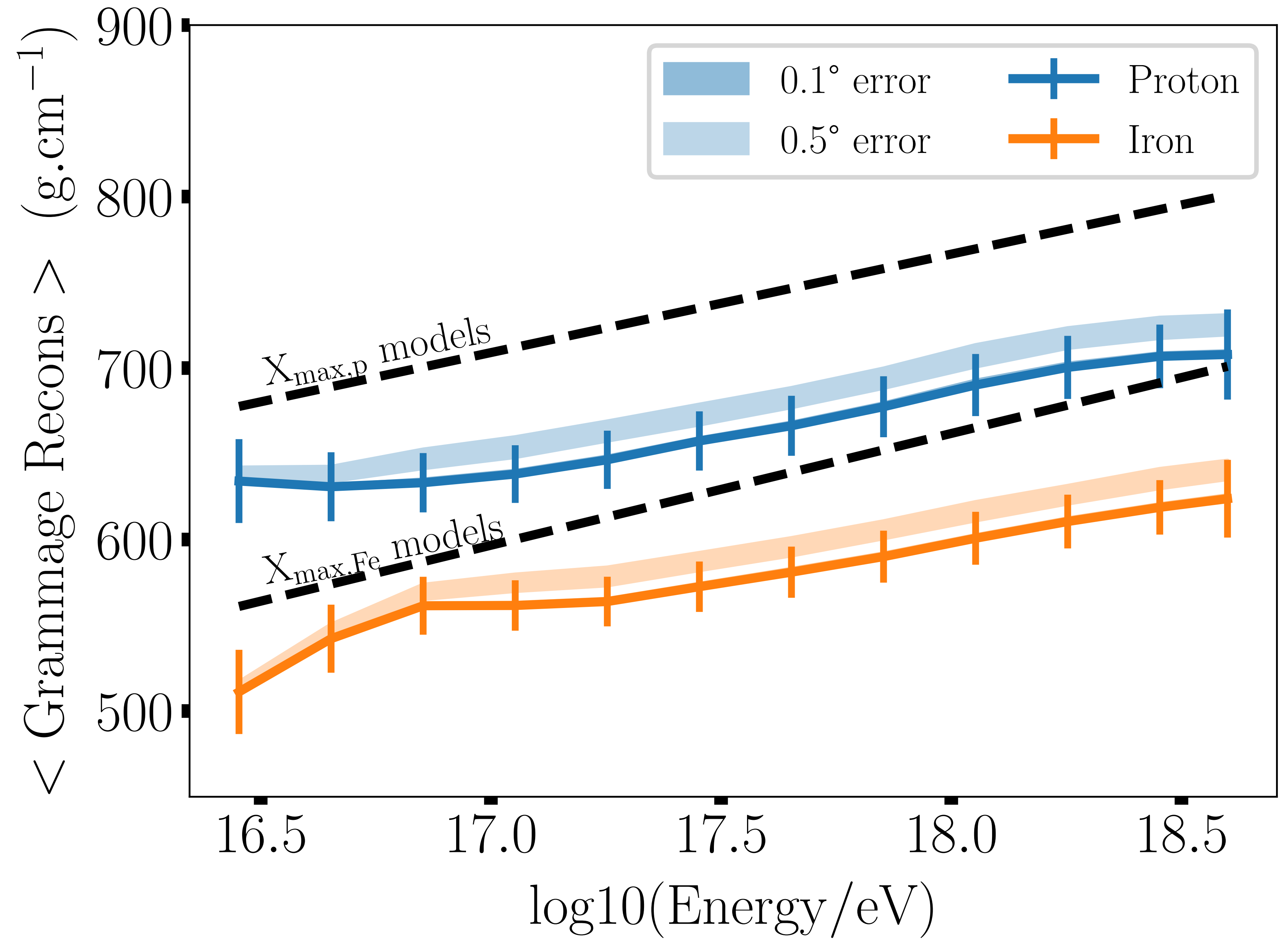


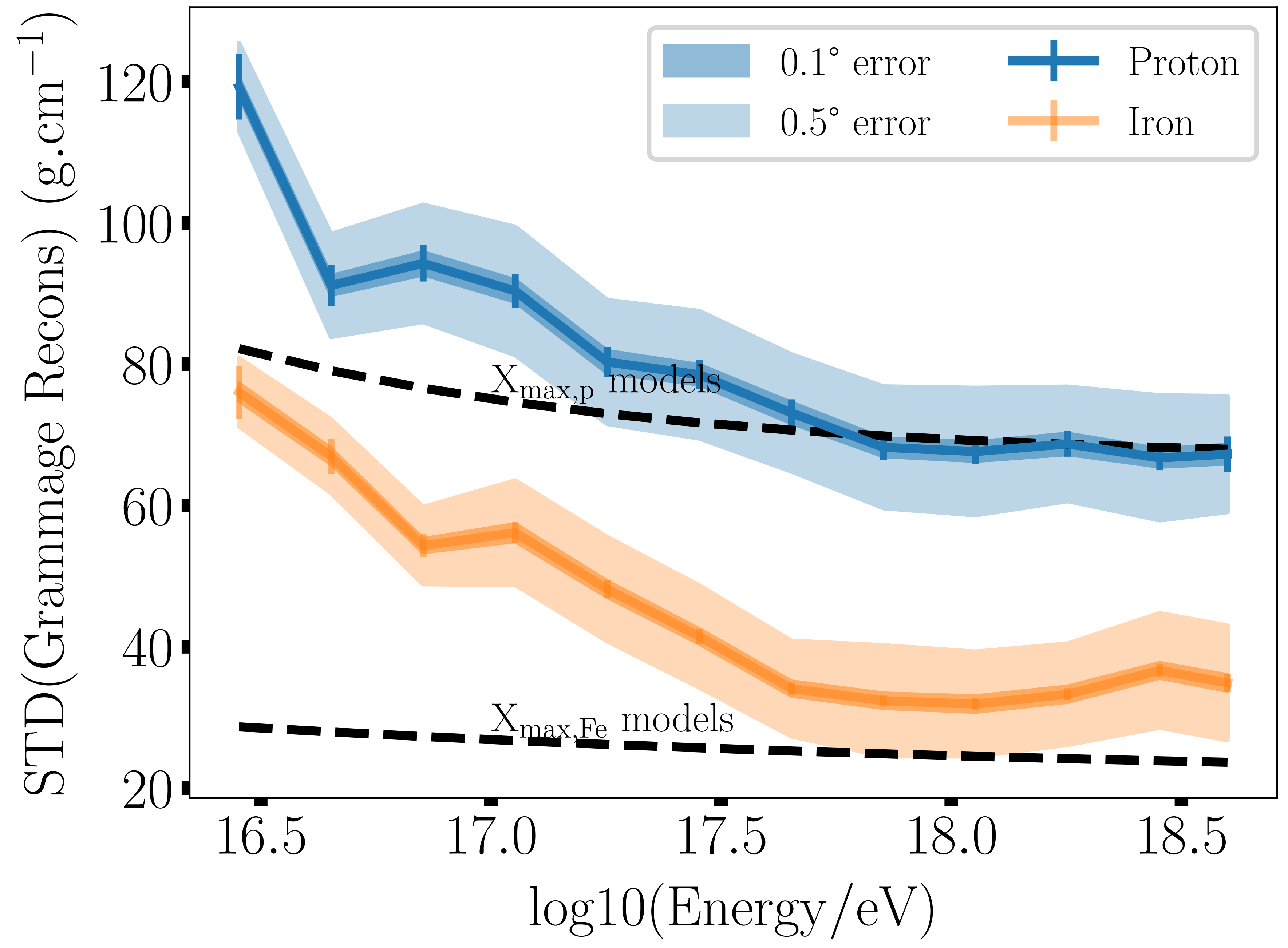
- valid proxy on the mass composition **but** different from Xmax
- nevertheless results are compatible with standard reconstruction of Xmax

Constraining the composition?

<u>Indirectly we can compute</u>:
the atmosphere column density integral from injection to reconstructed emission point







- valid proxy on the mass composition **but** different from Xmax
- nevertheless results are compatible with standard reconstruction of Xmax

constraints on primary identifications comparable to particle Xmax method

Towards energy reconstruction?

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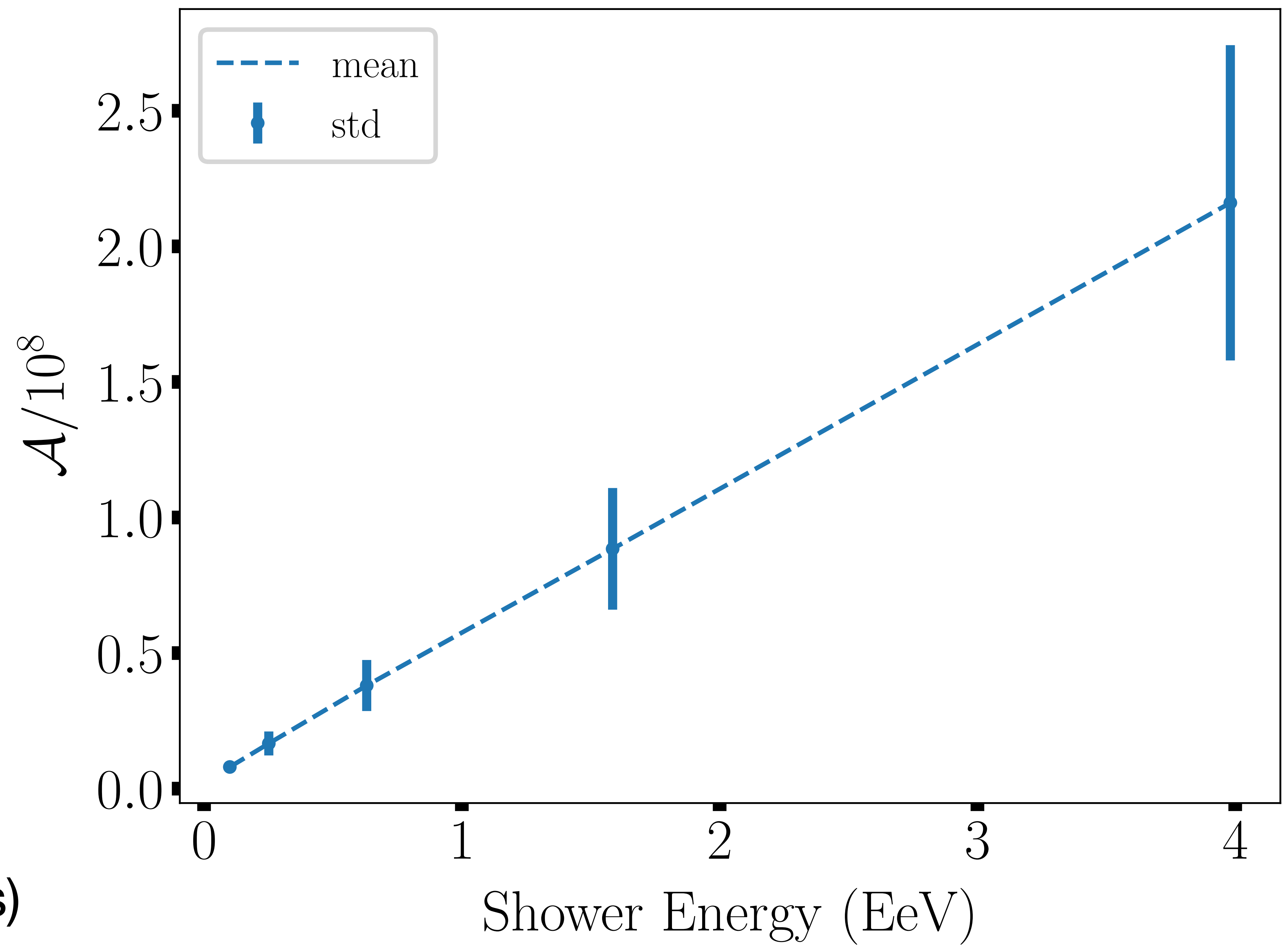

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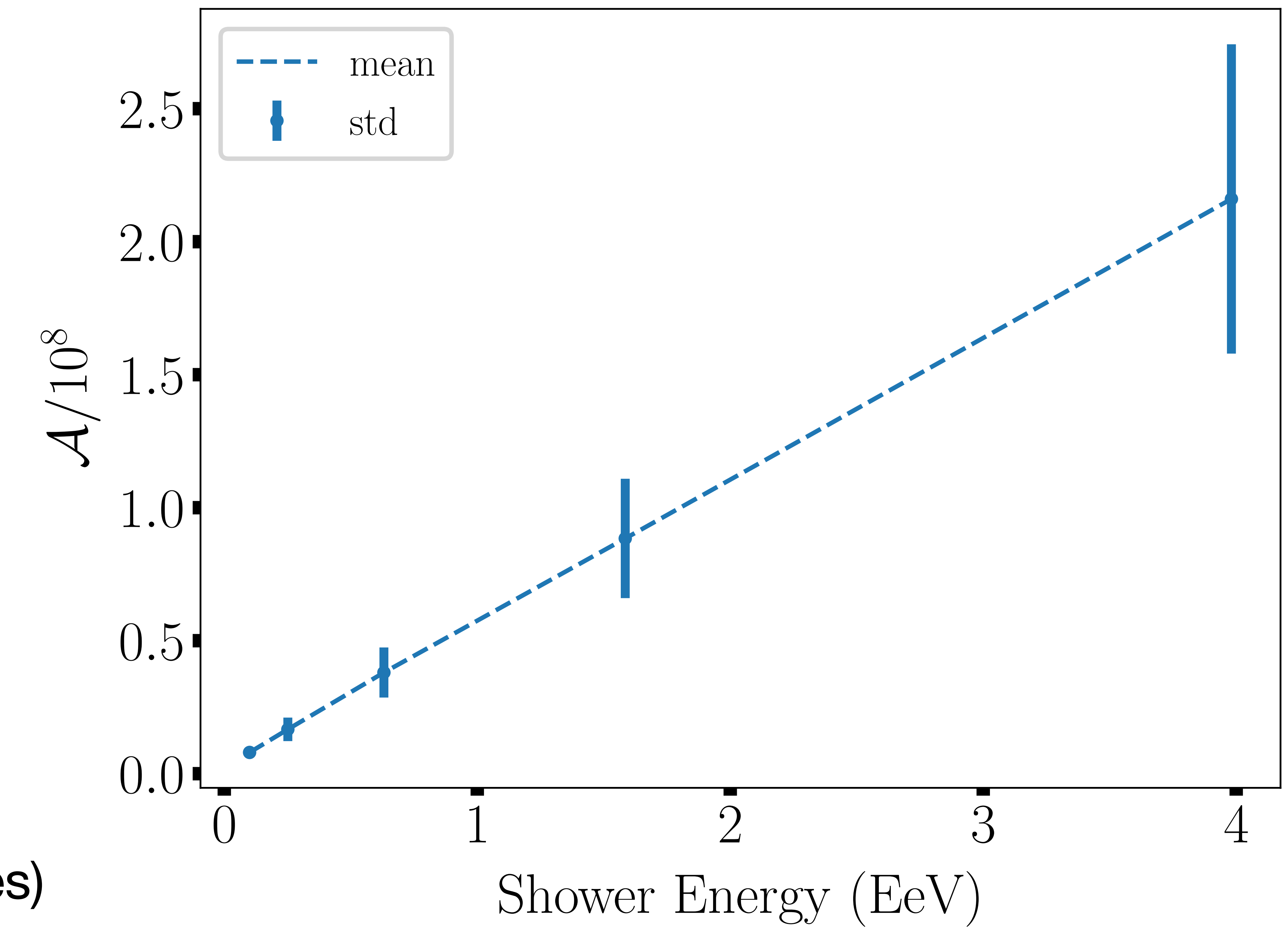

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Good potential for energy reconstruction

NenuFAR full spec sheet

Array:

- Antennas grouped in hexagonal tiles of 19 crossed-dipoles

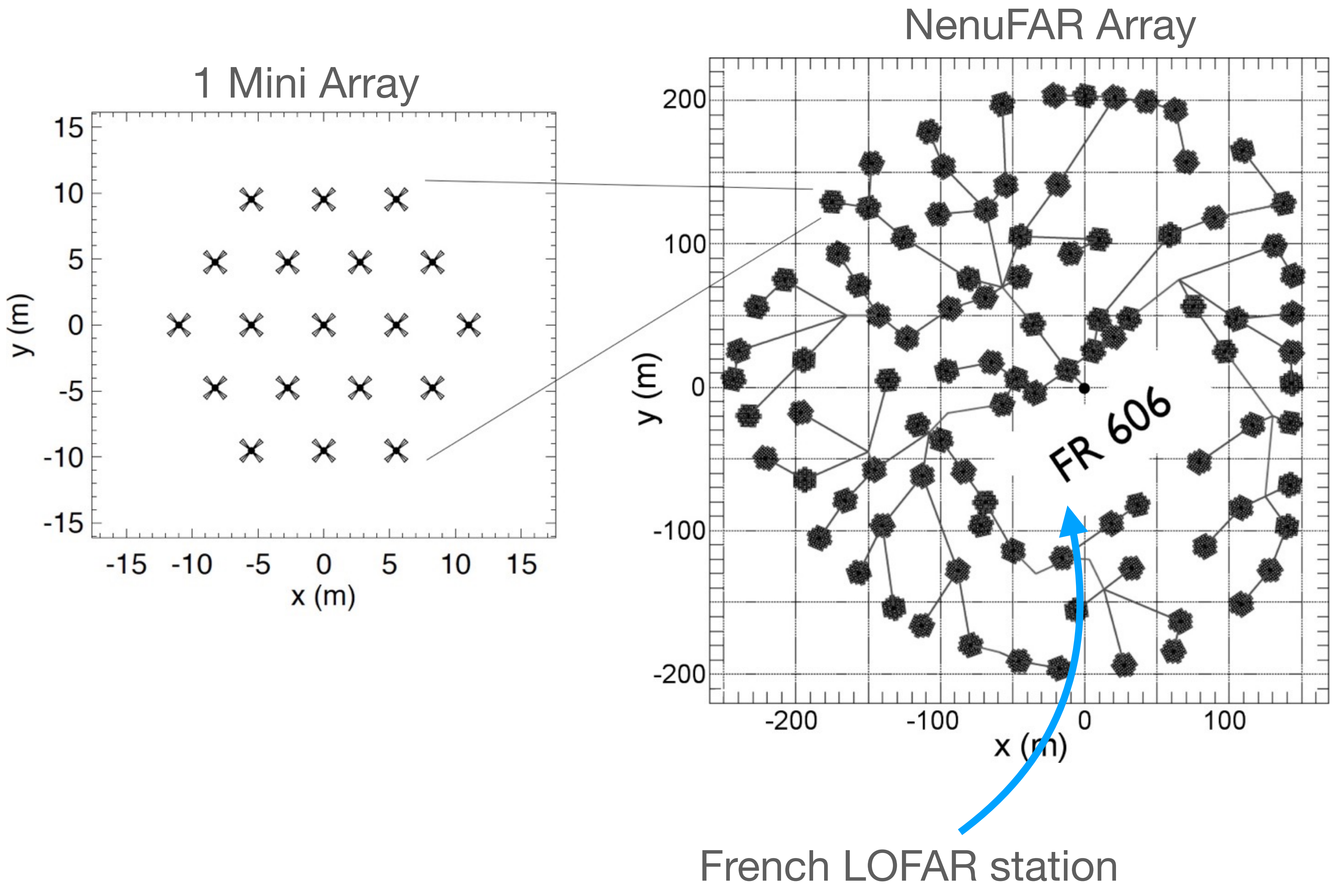
→ **Mini-Arrays** -MA (5.5m antenna step)

- 4560 baselines from 25m to 400M + 591 **baselines from 400m to 3km**
- Collecting area from 88000m^2 at 15MHz to 8000m^2 at 85MHz

Signals:

- Each MA delivers two linearly polarised signals (NE and NW) to receivers
- **Time-frequency resolution → df~195kHz and dt~5µs**
- **With channelisation df->3kHz with dt~1ms**
- Waveforms at 5ns time resolution

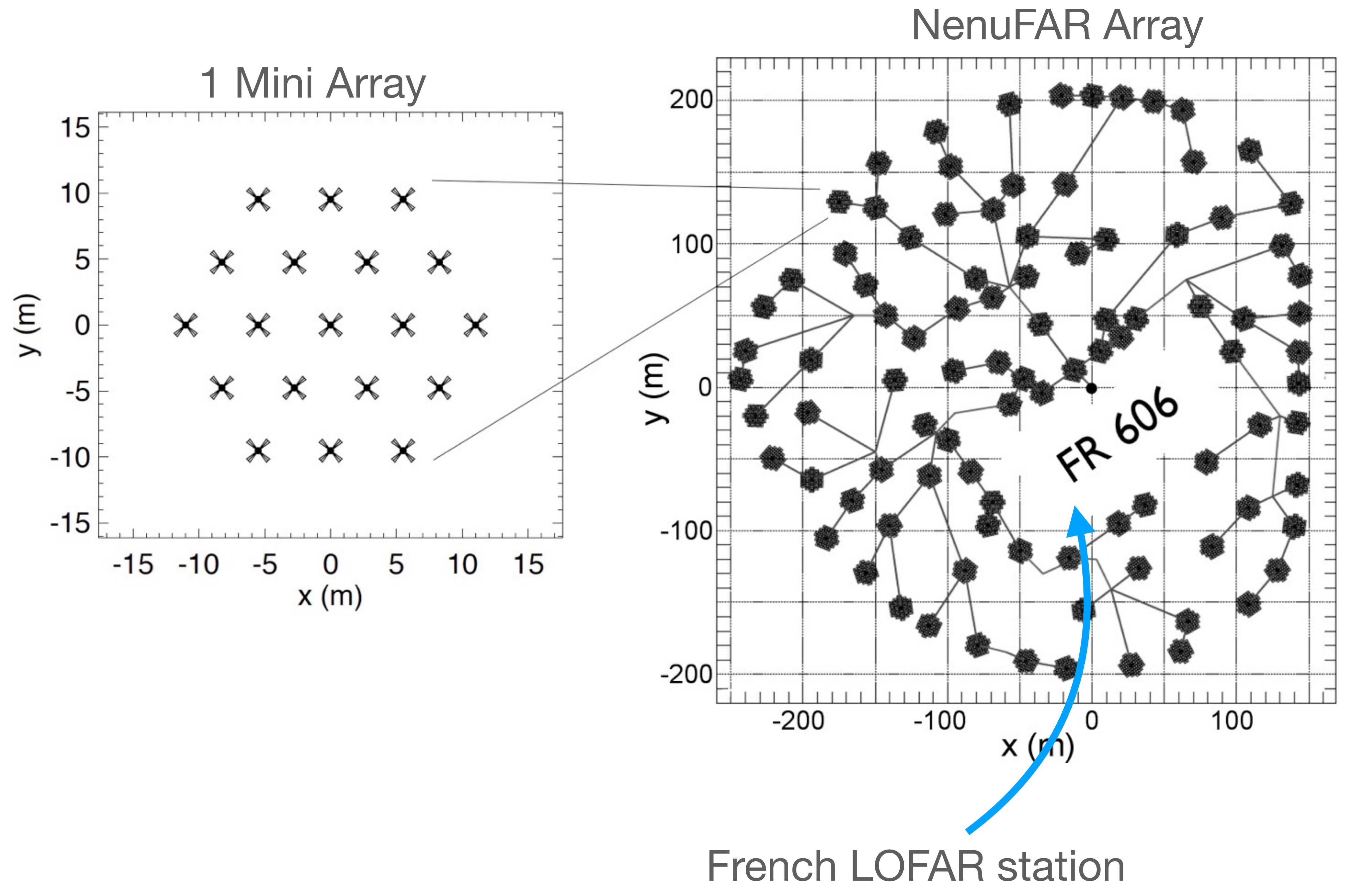
→Sensitivity~130 mJy ar 15MHz to 9 mJy at 85 MHz for df=10MHz x dt=1h



Can operates in 4 distinct modes:

- **standalone beam former** → FRB observation
- capturing waveform → transient buffer
- standalone imager
- Upgraded LOFAR station (low frequency)

NenuFAR full spec sheet



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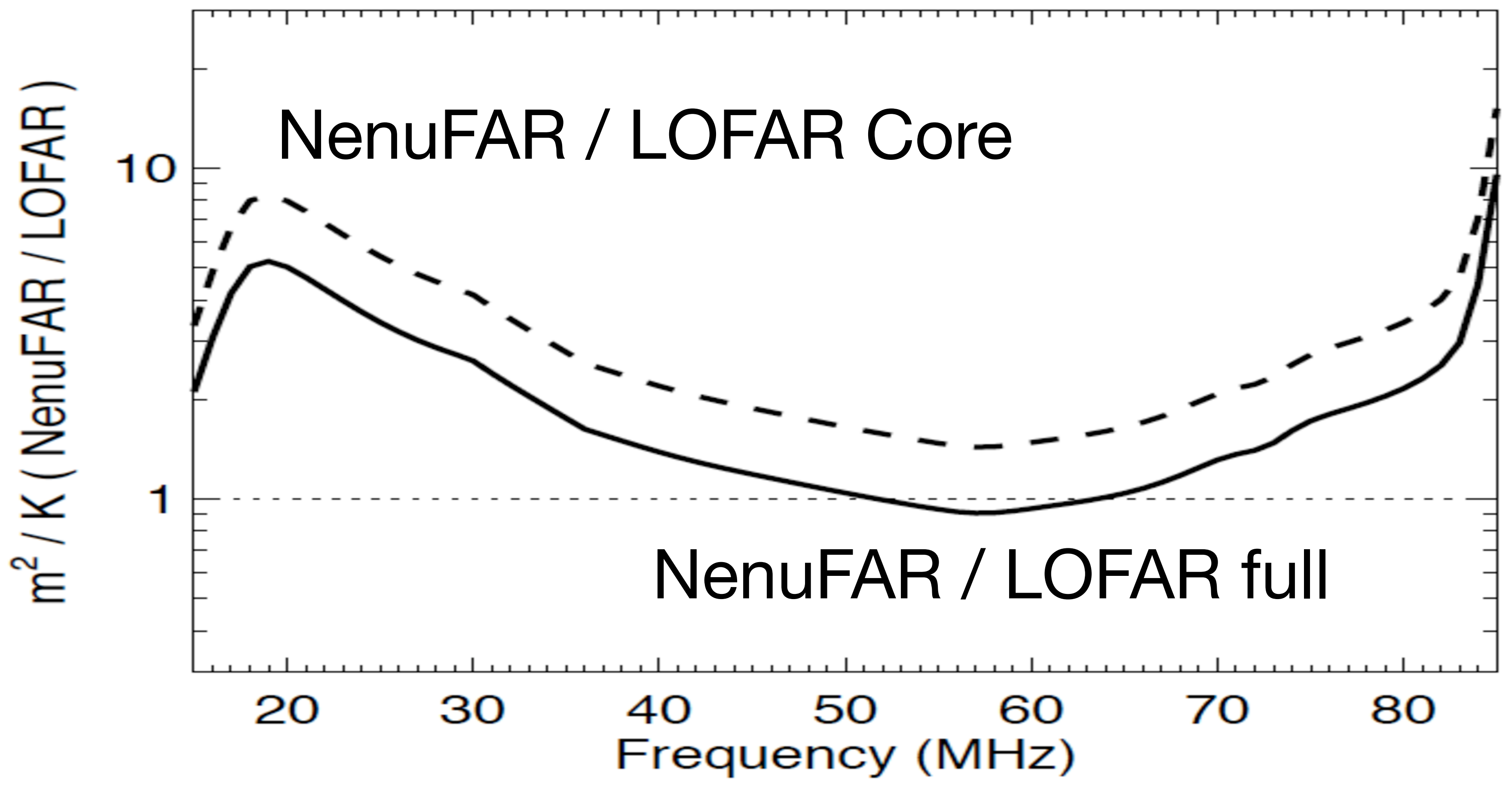
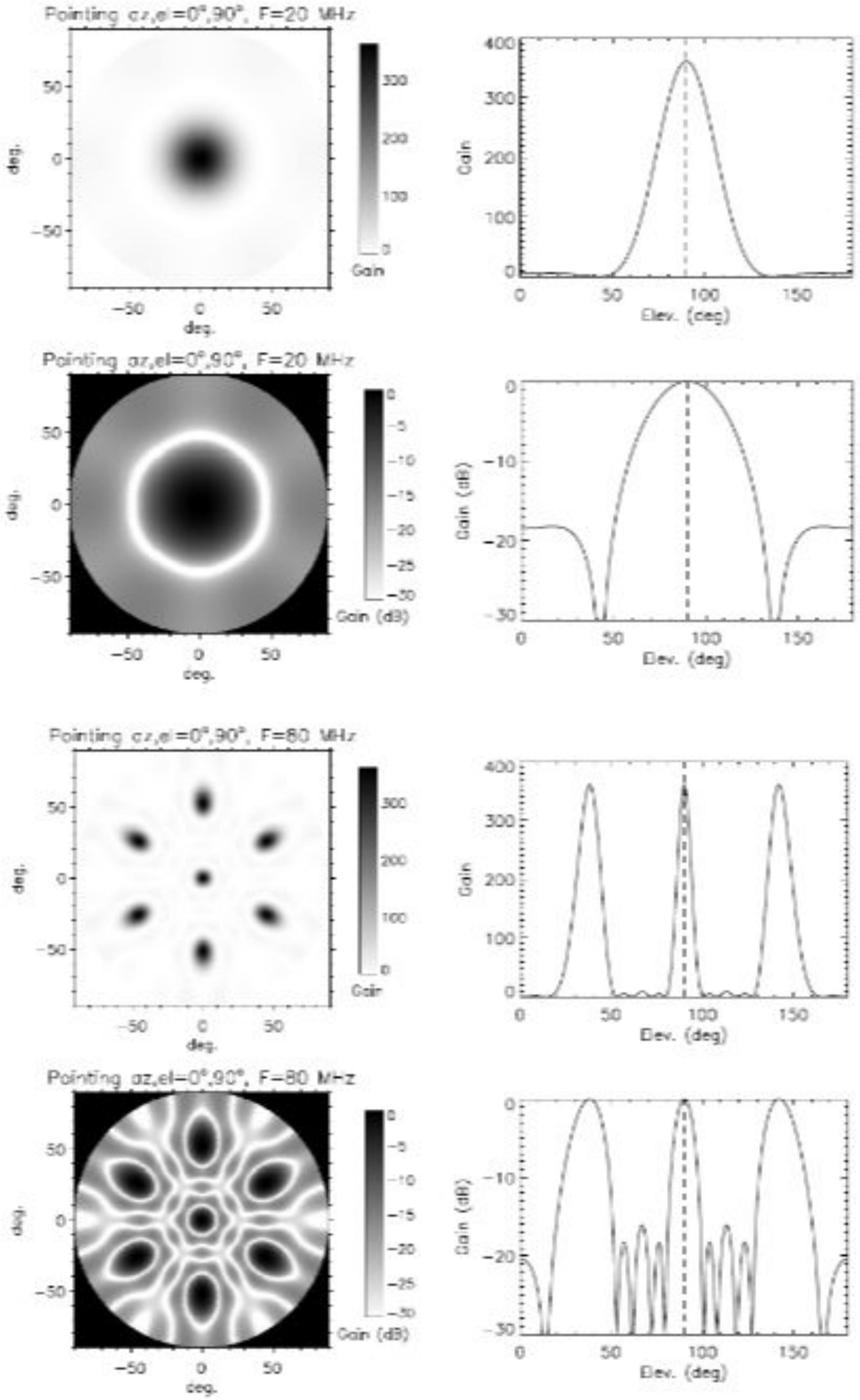
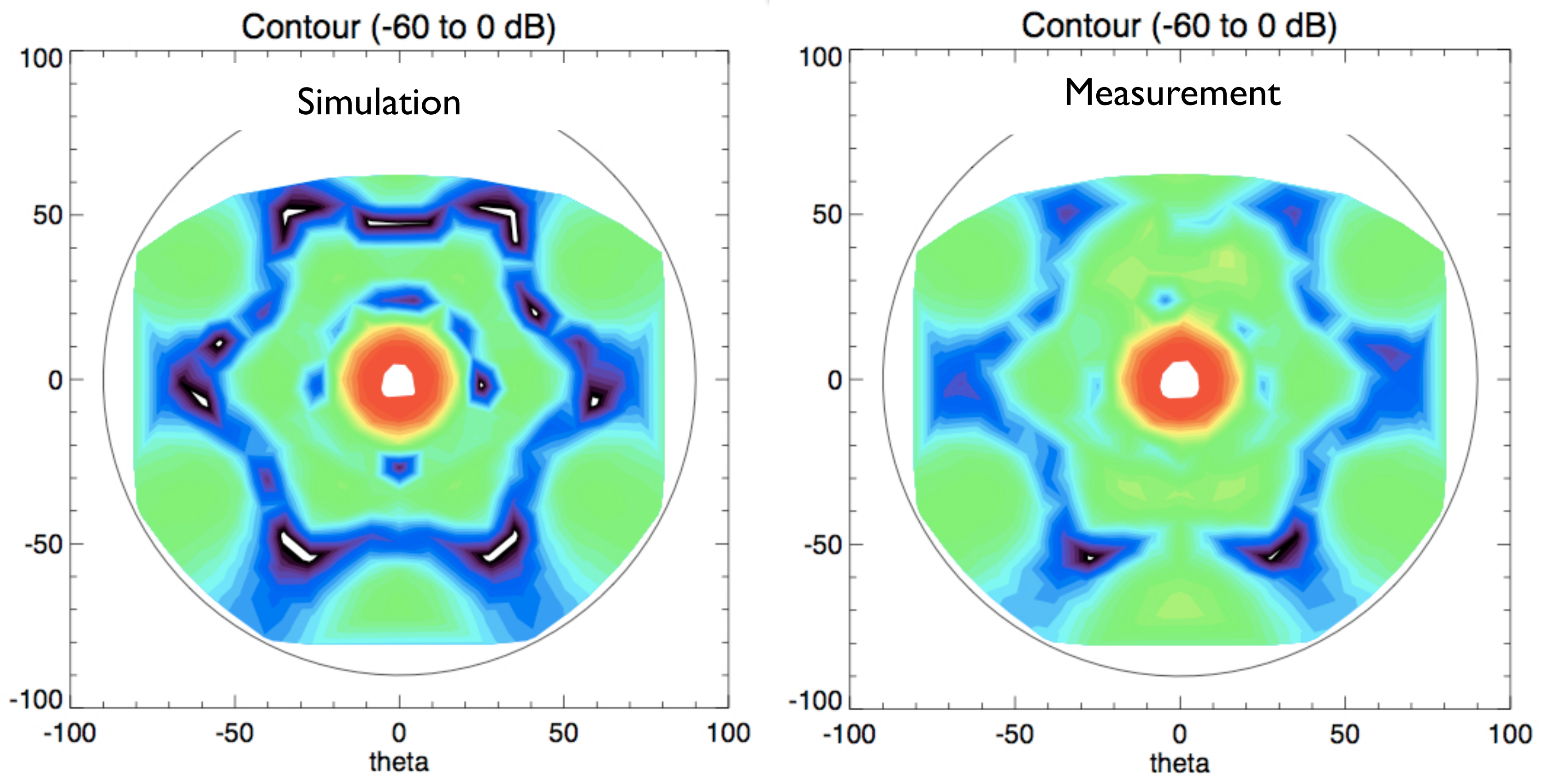


NenuFAR has been designed to reach the highest sensitivity at low frequencies

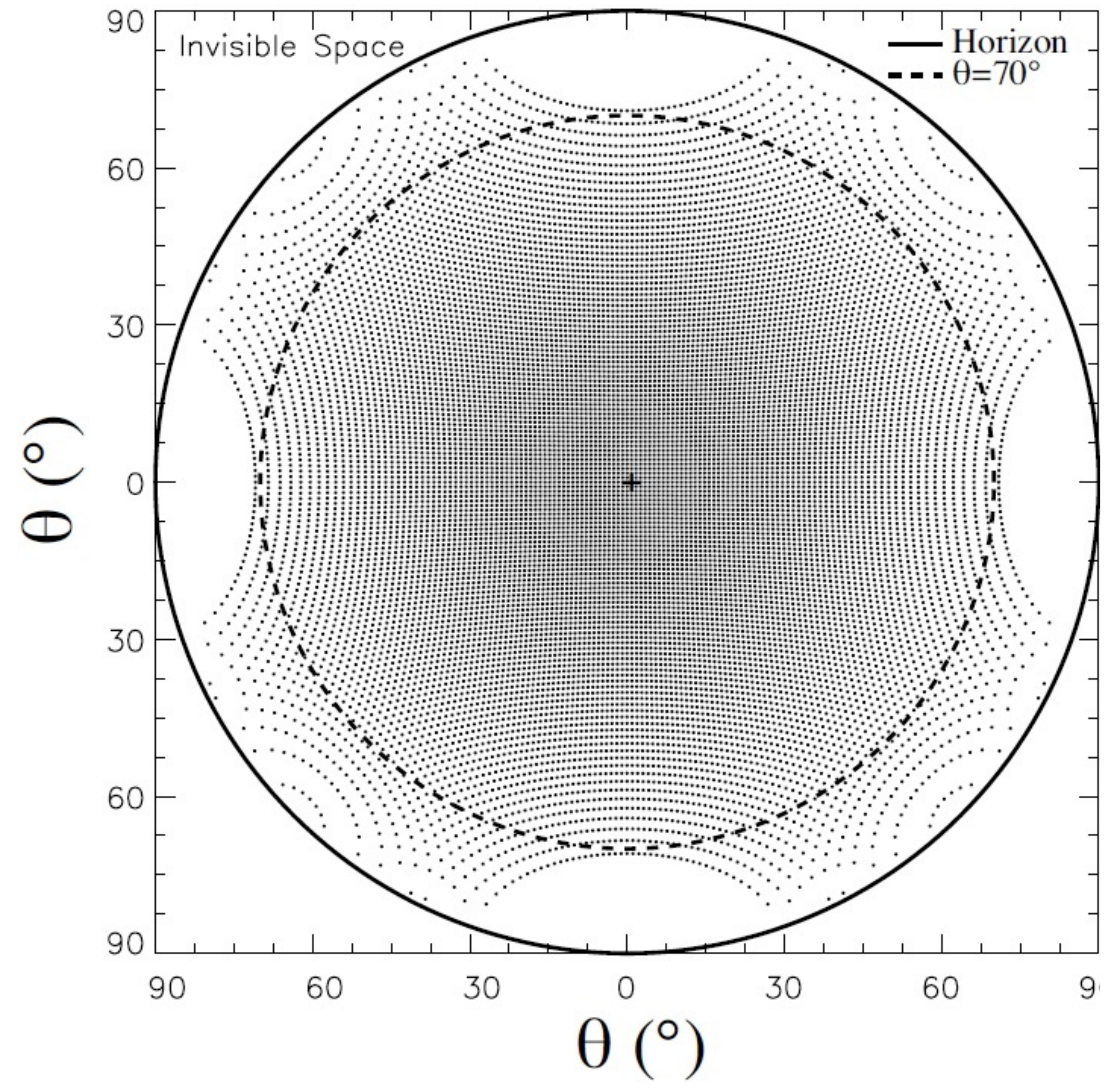
NenuFAR interferometric mode





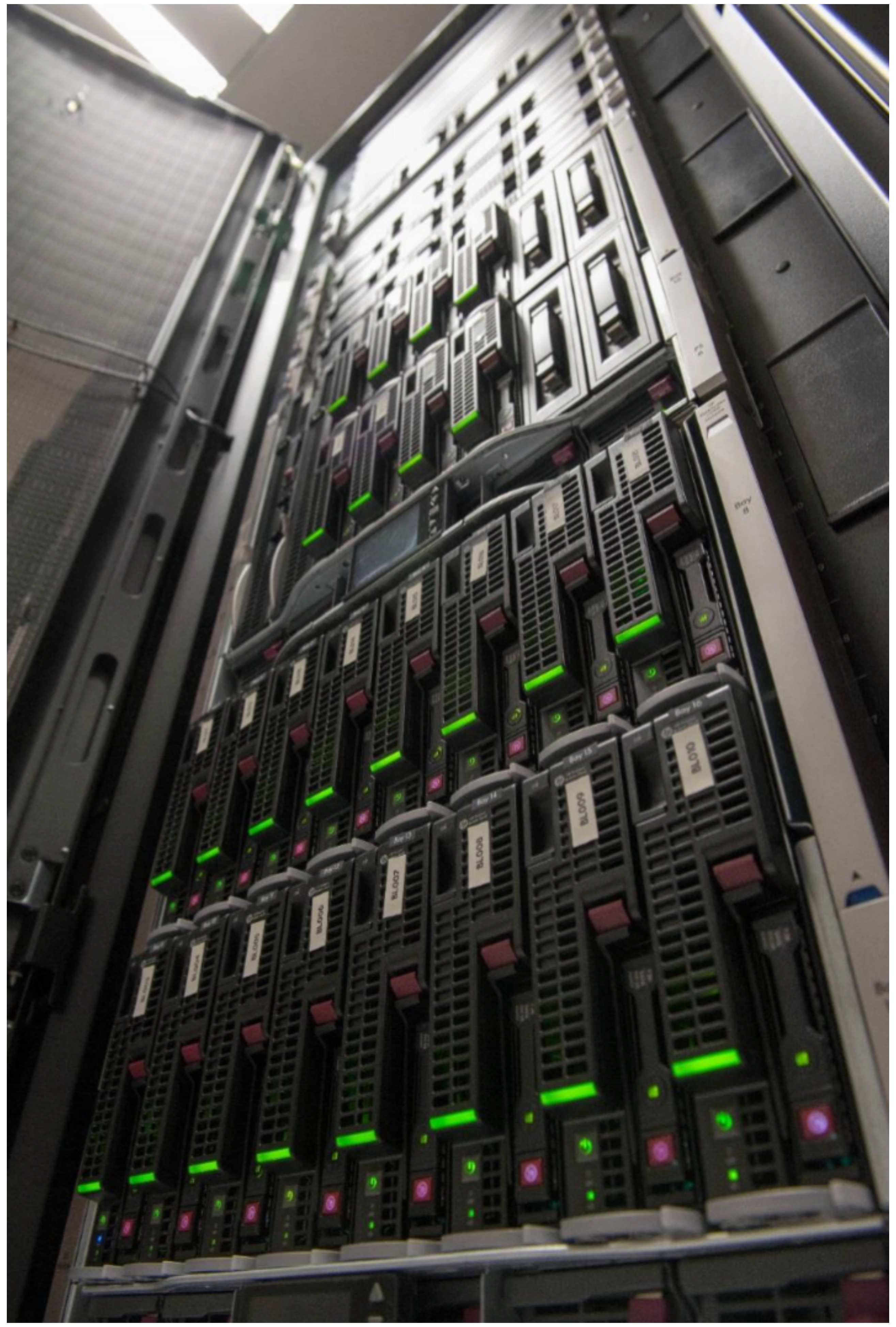
Interferometric measurements:

- In each MA signals are combined through analog phasing + summation system → beam (restrict FoV but higher sensitivity)
- MA are analog phased with delay lines → achromatic
- Delay lines are 7-bit systems of switchable cables → 16384 pointable directions (128x128 = EW x NS) in the sky
- Pointing from declination -23° to +90°
- FoV ~46° at 15MHz to ~8° at 85MHz
- Angular resolution 23’ at 15MHz to 4’ at 85MHz (down to 0.4” in LSS mode)



Astronomers Page : https://nenufar.obs-nancay.fr/en/astronomer/

NenuFAR computing and data storage



Data Centers:

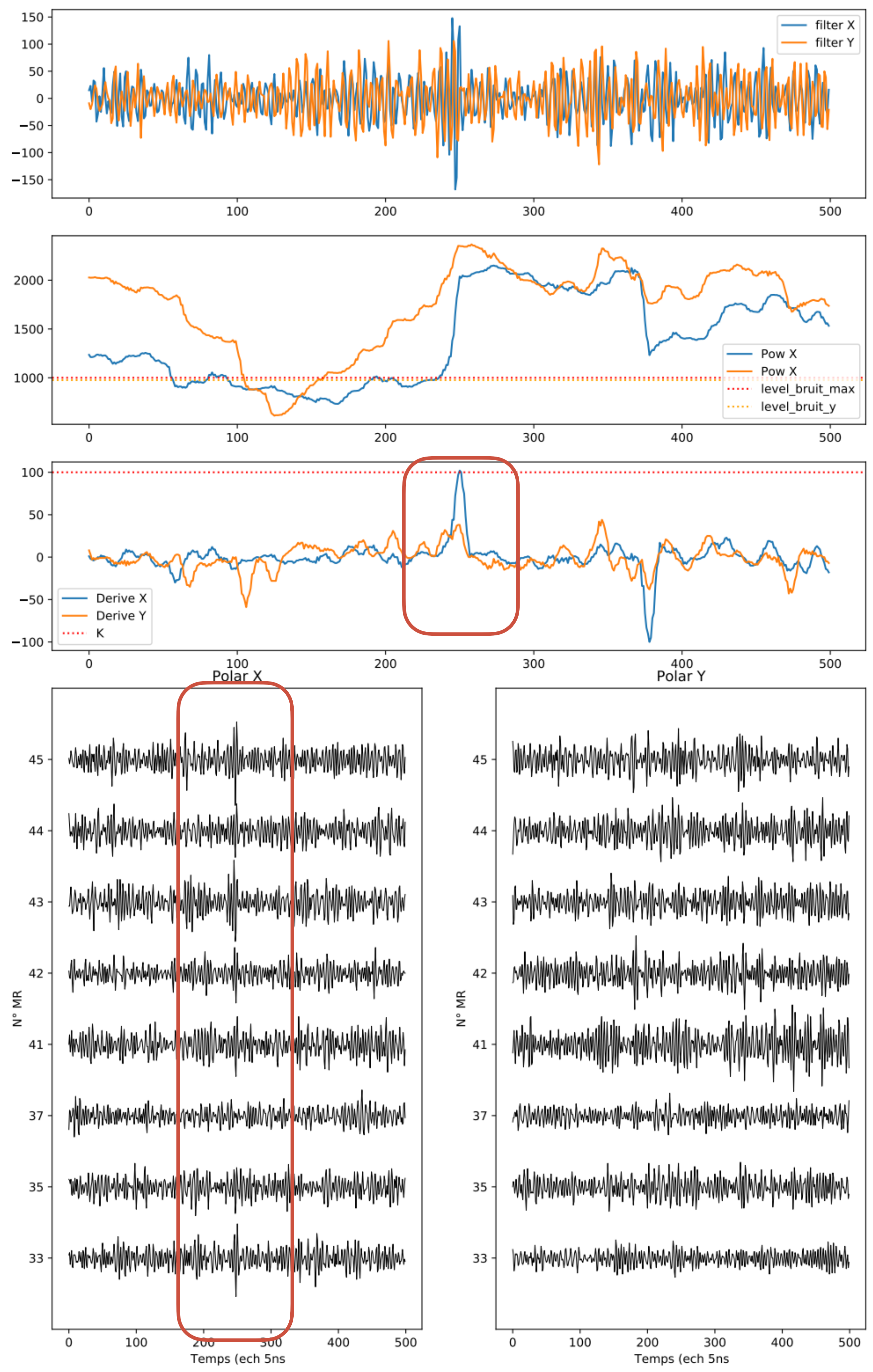
- L0 data ~5-10To/day → Nancay data center (1Po) for reduction
- L1 data ~1-2Po/year → NenuFAR data center (10Po) for analysis and final storage (L2 data)

NenuFAR data center:

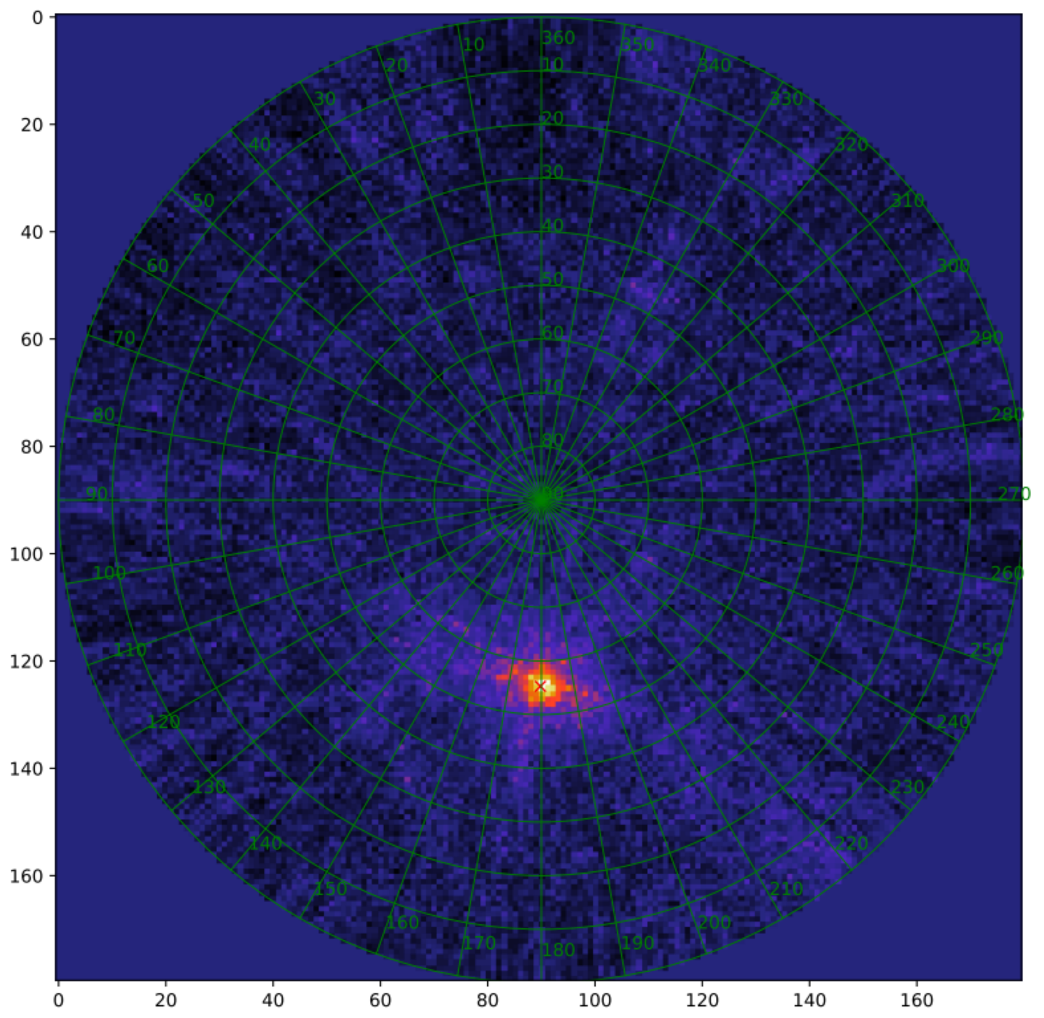
- BRGM cloud technology
- Virtual machine/virtual observatory/GUI NenuFAR
- Space storage and computing power extensions
- Connection to high performance computation centers
- Cost ~2.2M€
- Test bench for SKA-Regional-Center

RadioGaGa: radio detection of gamma-ray EAS

Idea:
- use a subset of MA
- to survey the sky
- trigger on impulsive signals
- retrieve all MA signals



MA used for trigger



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'k2': [0, 0]
'rising_time_min': [1, 1]
'rising_time_max': [5, 5]
'window_w': 128
'level_bruit_max': 1000
'pourcent_20': [18.75, 18.75]
'pourcent_80': [87.5, 87.5]
'polar_min': 0
'polar_max': 0
'binary_test': 0

########PROCESSED##########
'max': [0, 2106]
'max_20': [0, 1187]
'max_80': [0, 1964]
'level_bruit': [0, 976]
'rising_time': [0, 5]
'polar_rapport': 0

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'hdr': b'!T4!'
'cnt': 492033
'gps_second': 1660823592
'gps_nano': 877827790
'utc_second': 1660823592
'utc_nano': 877824790
'tbb_second': 1660823592
'tbb_nano': 877819780
'nb_ech': 16384
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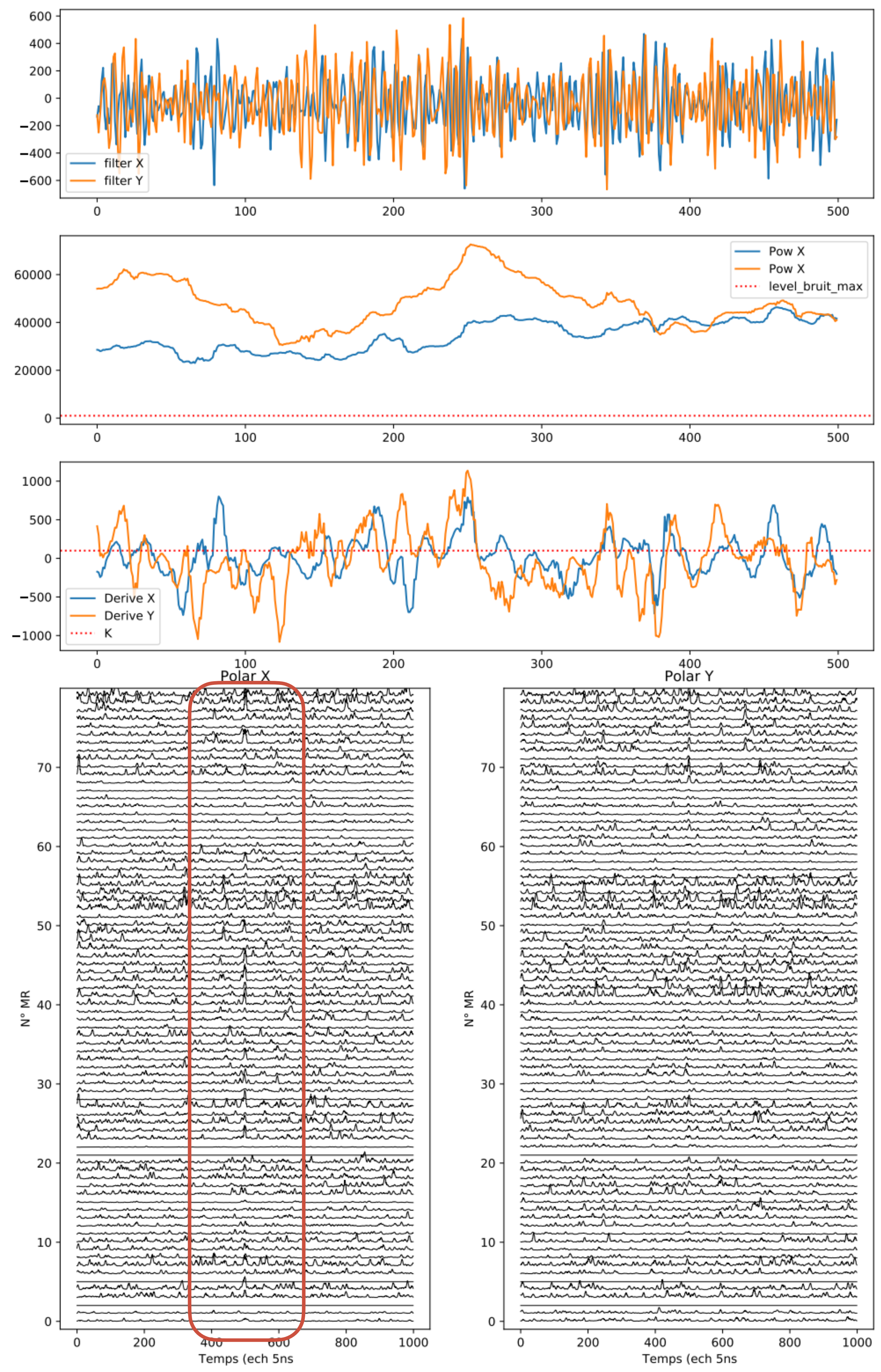

all MA

Multi-messenger (MM) and multi-wavelength (MW) high energy sources

There is already many hints toward the connections between radio transients and MM emissions

X

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→ jets/accretion-disks and kilonova
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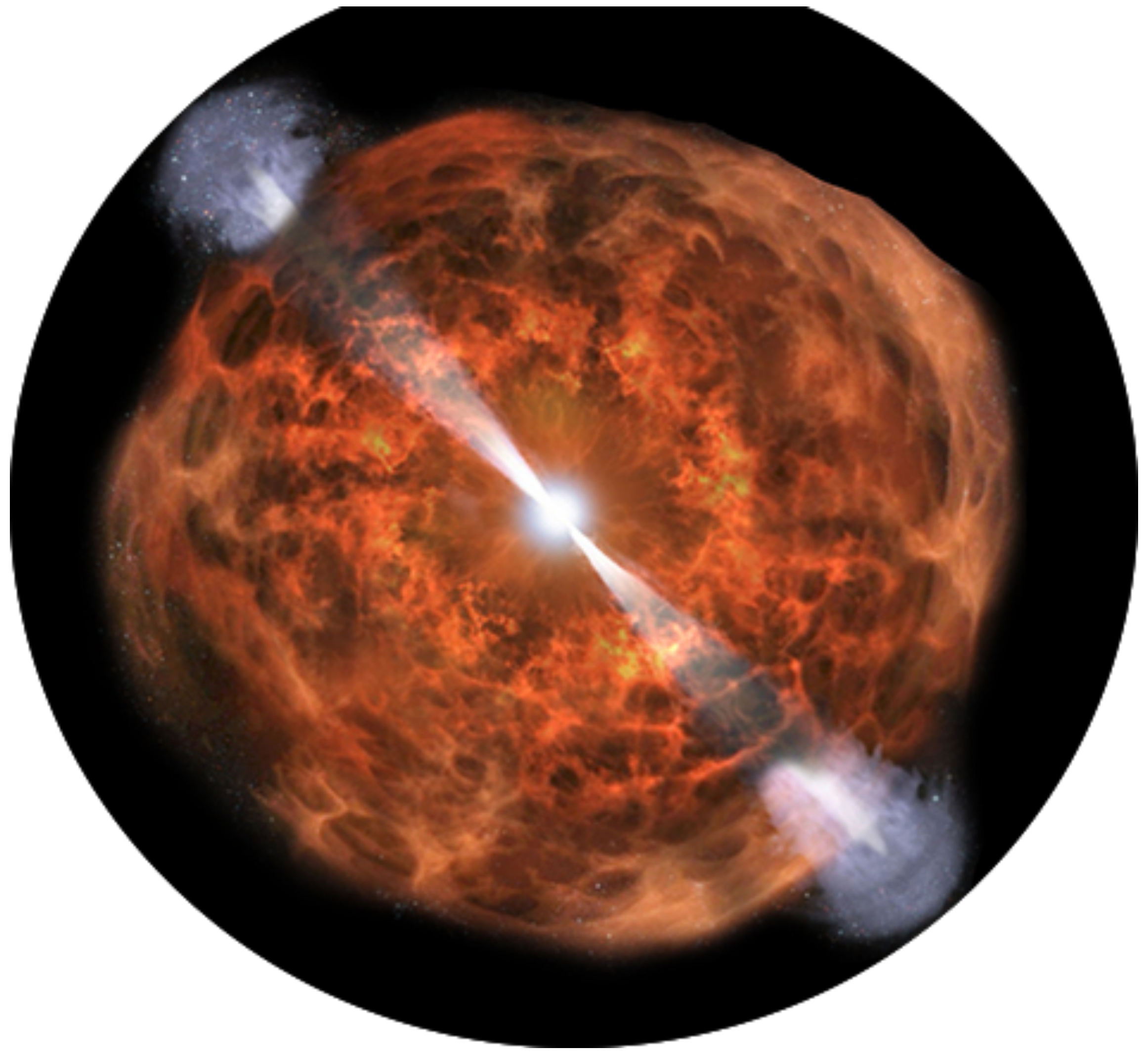
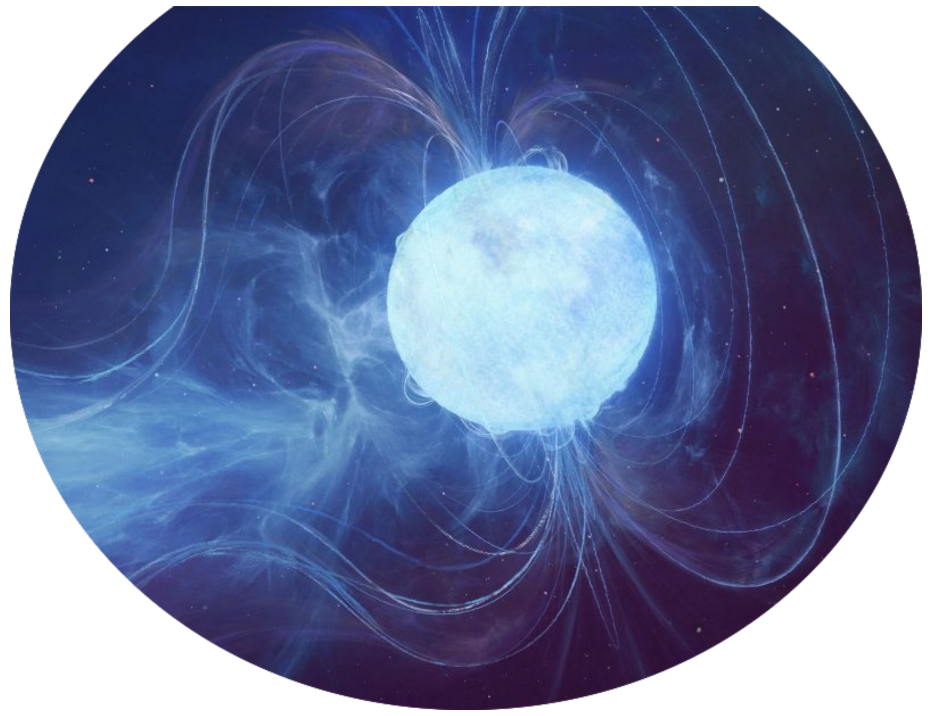
Kilonova



Magnetars



Coalescence

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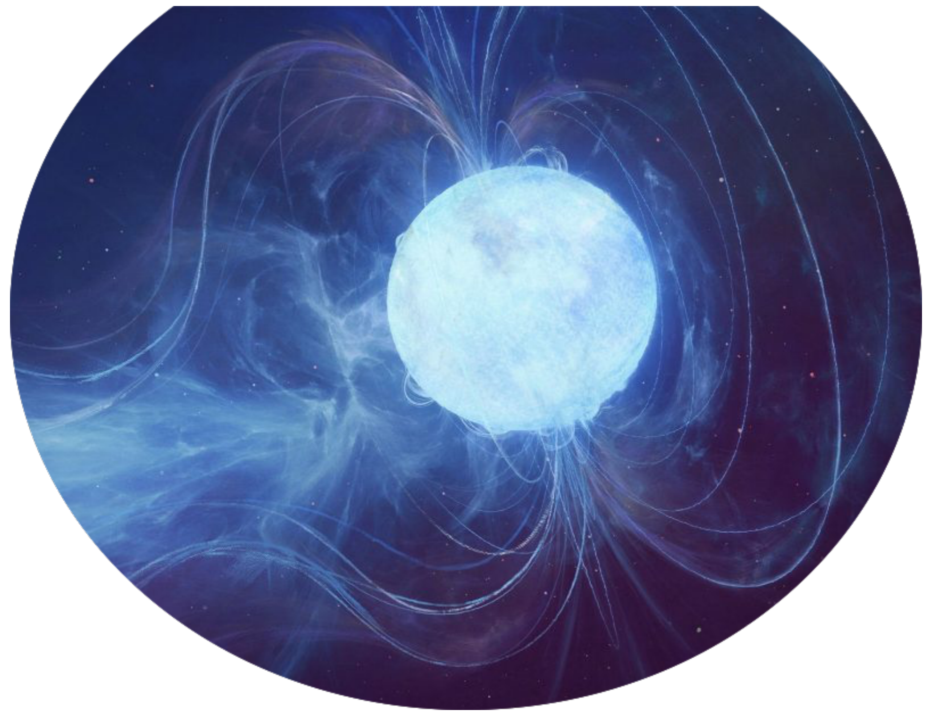

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- Models: Gamma-rays/radio
- observations: X-ray/radio

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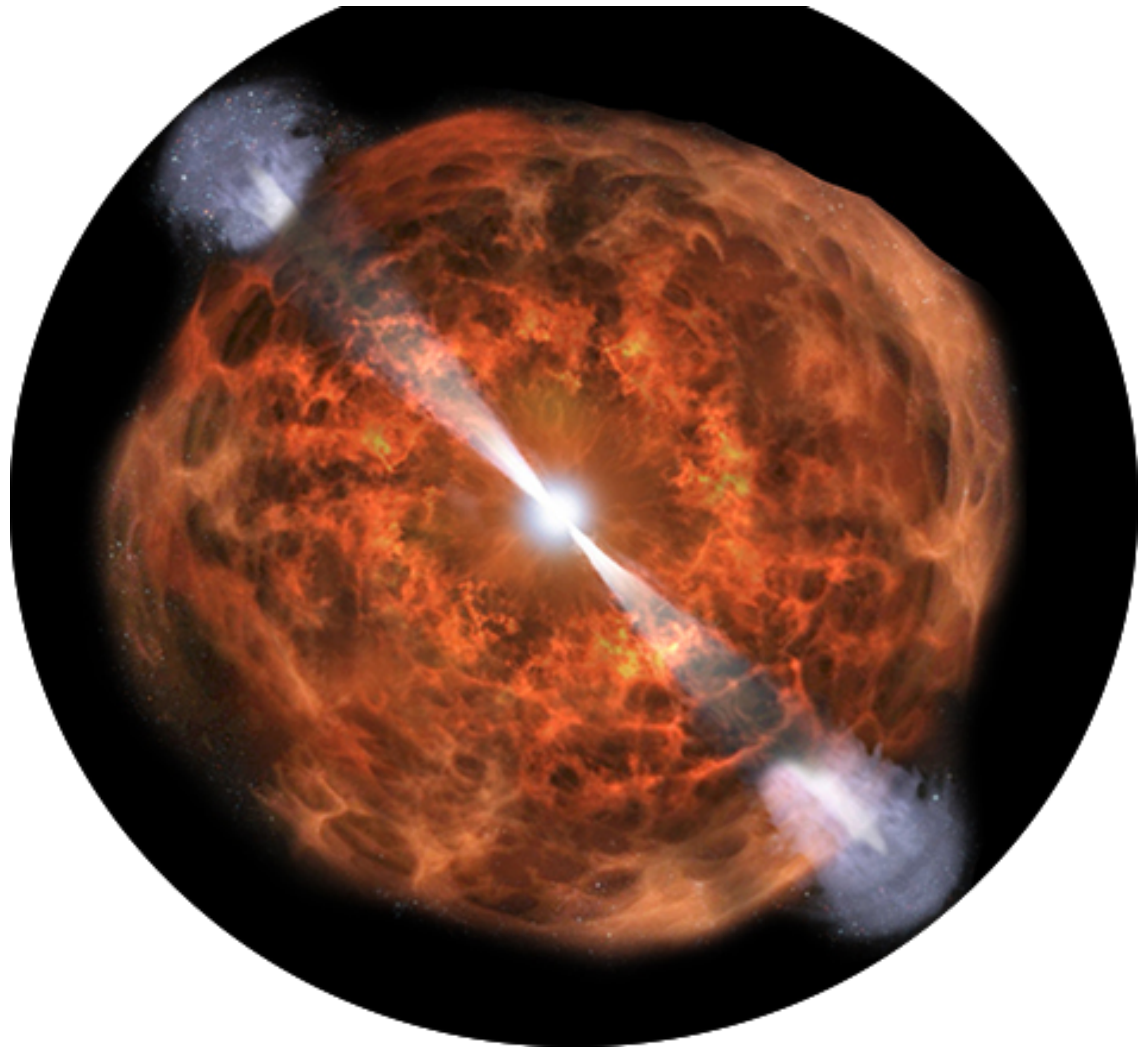

- Progenitors: DNS, WD mergers, NS-WD, NS-BH
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Coalescence

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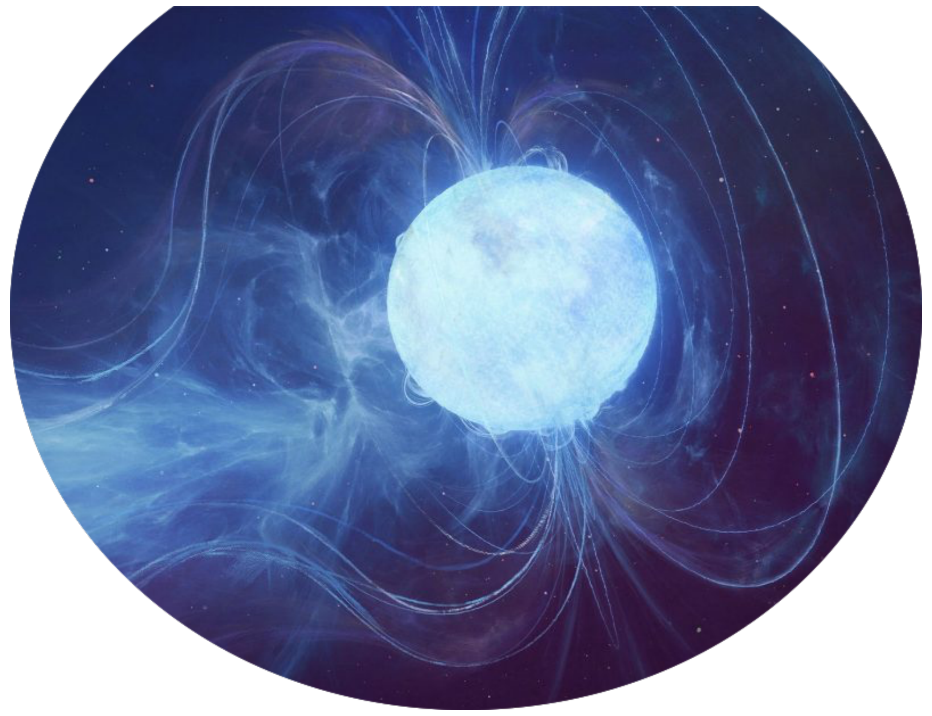

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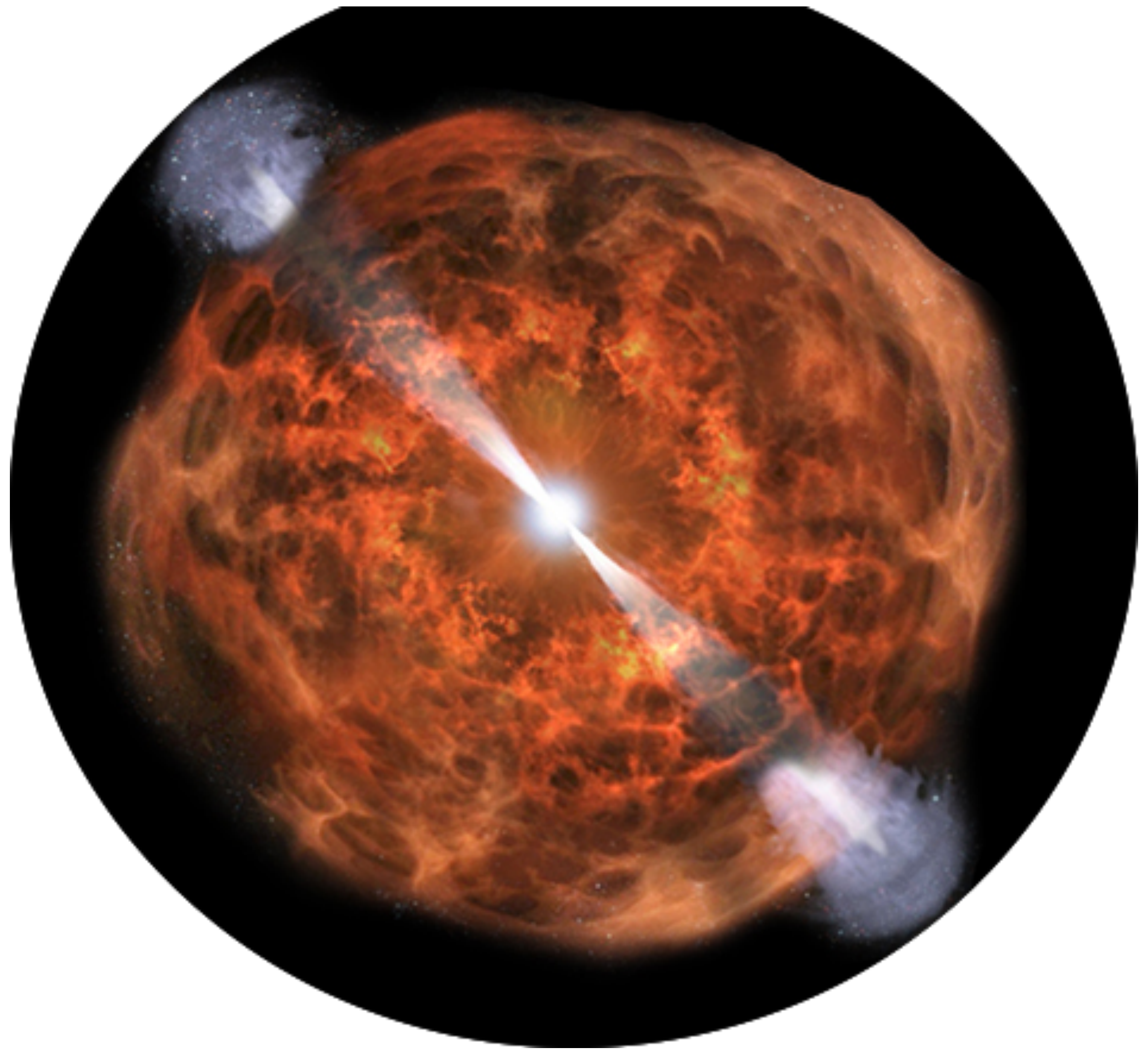

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Coalescence

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We need to have MM and MW models in order to probe the physics consistently