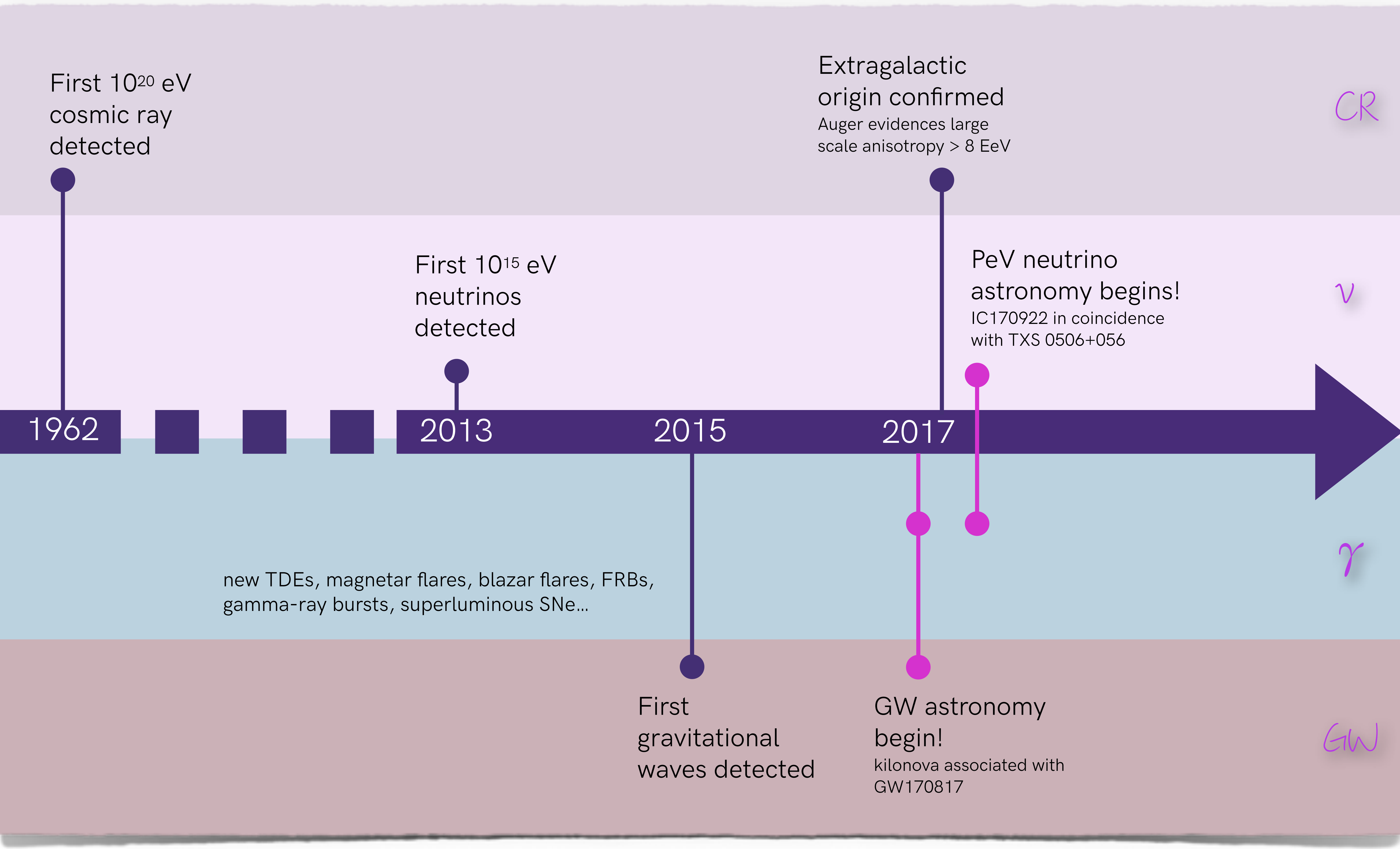
Kumiko Kotera - Institut d'Astrophysique de Paris

LLR - 14/01/2019

Towards EeV Astronomy

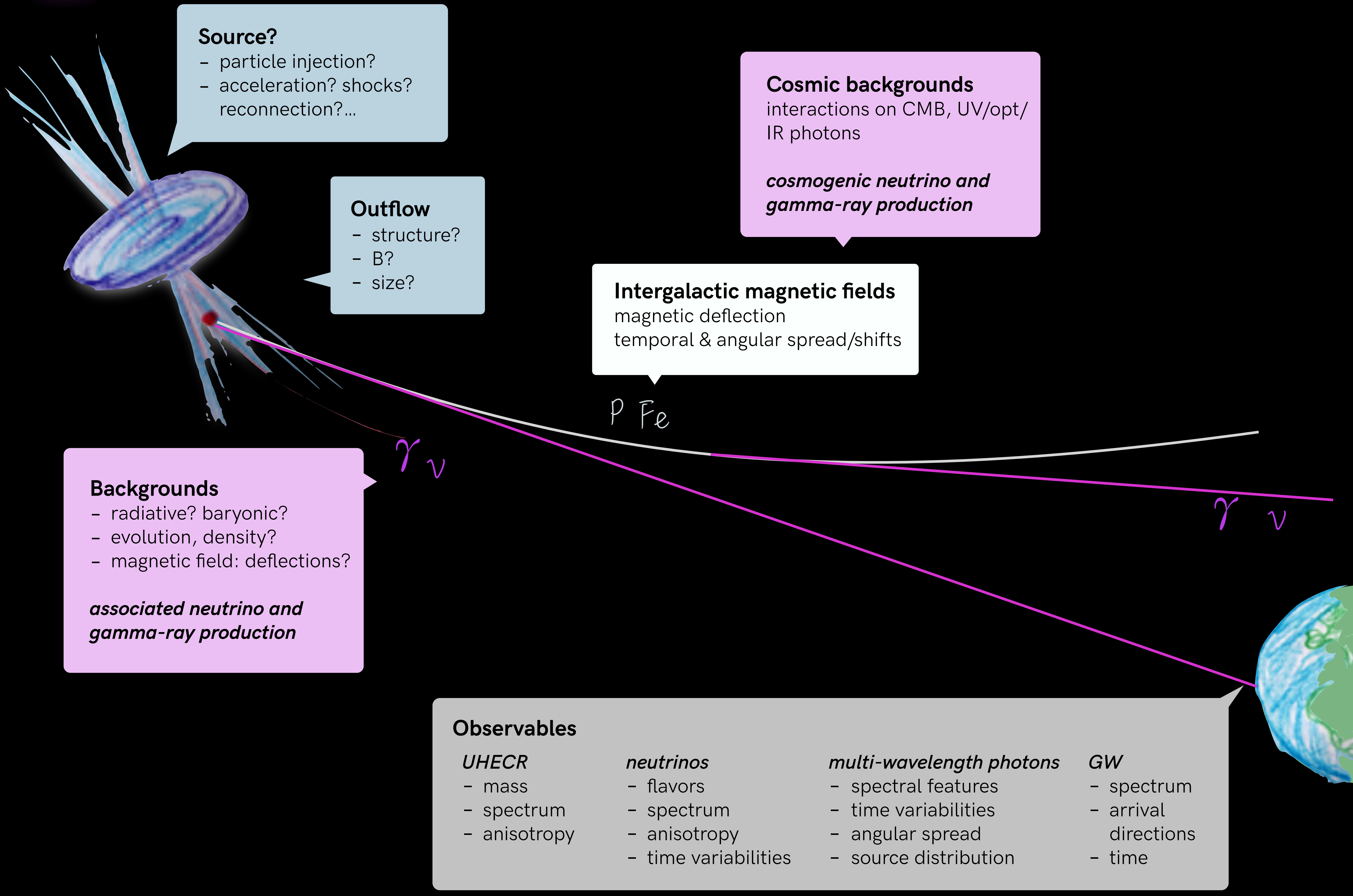
catching the sources of ultra-high-energy cosmic rays

Exciting times!



And we still don't know the origin of UHECRs

A UHECR journey



Current multi-messenger data: useful to understand UHECRs?

Cosmic backgrounds
interactions on CMB, UV/opt/IR photons

cosmogenic neutrino and gamma-ray production

Backgrounds
- radiative? baryonic?
- evolution, density?
- magnetic field: deflections?

associated neutrino and gamma-ray production

Secondaries take up 5-10% of parent cosmic-ray energy

$E_\nu \sim 5\%\ E_{CR}/A$

$E_\gamma \sim 10\%\ E_{CR}/A$

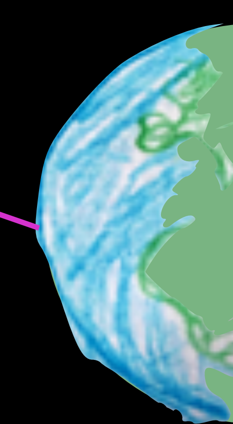
$E_{CR} > 10^{18}$ eV

$E_\nu > 10^{16}$ eV

γ ν

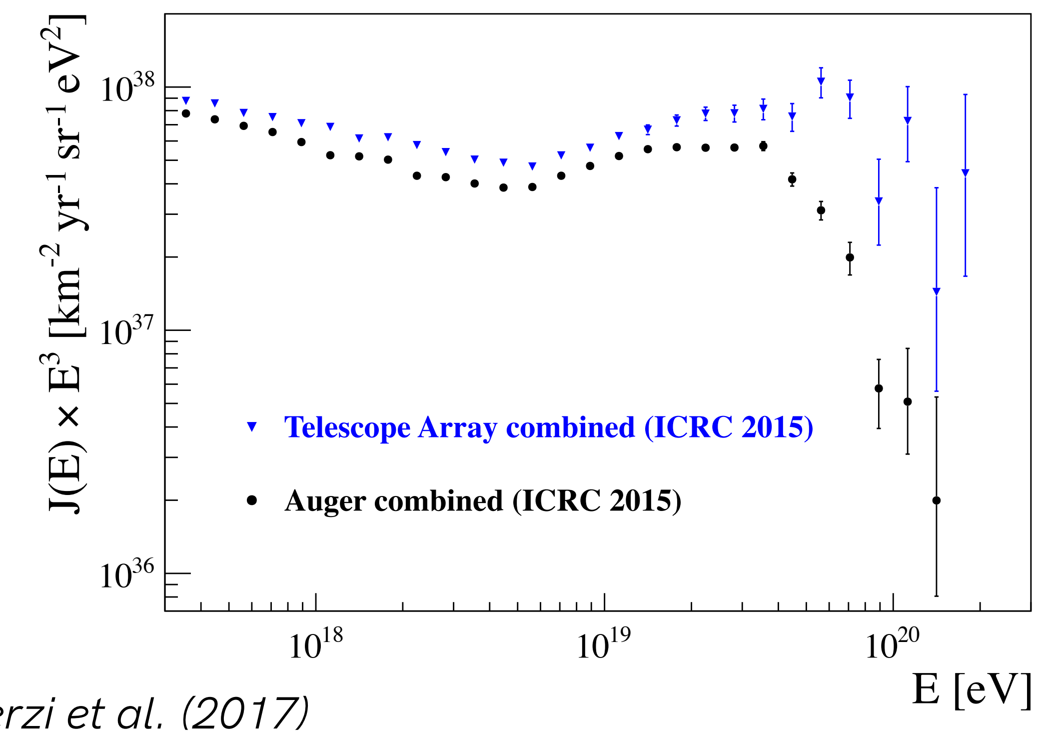
IceCube neutrinos do not directly probe UHECRs

Actually, none of the current multi-messenger data (except UHECR data) can directly probe UHECRs ... but they help :-)



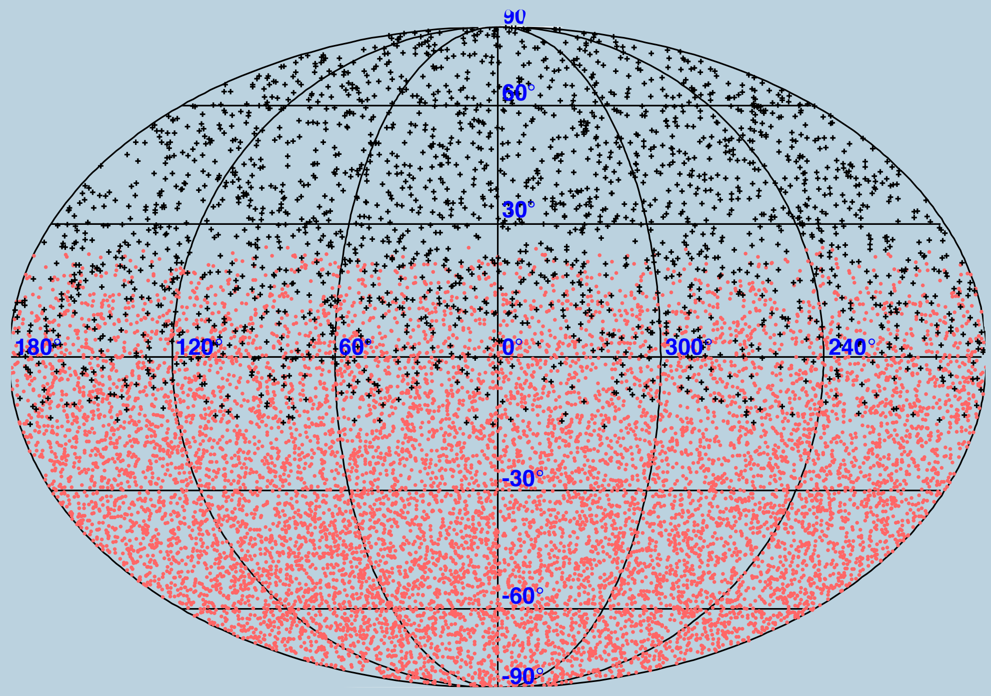
Learning from UHECR data

Energy spectrum

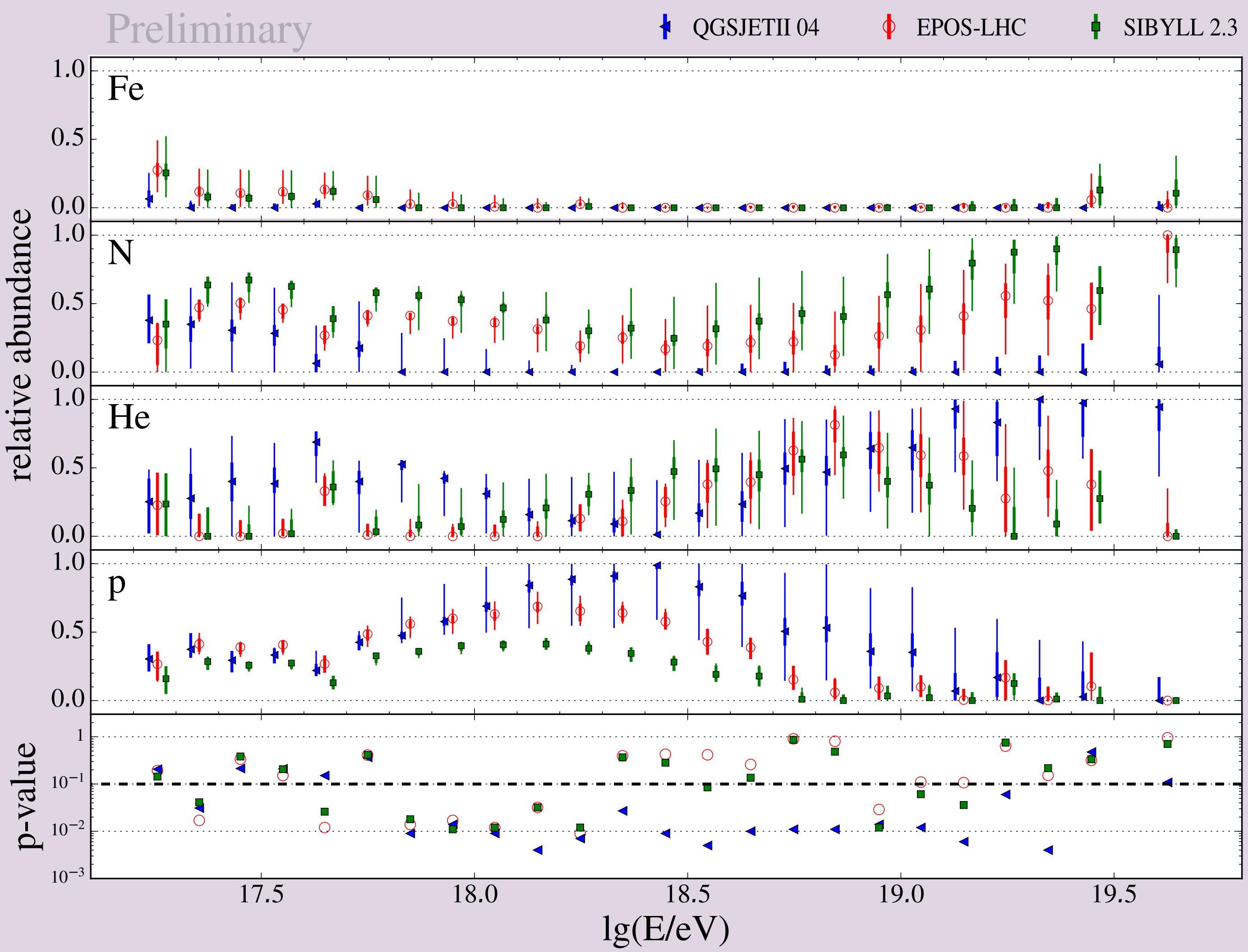


Verzi et al. (2017)

Arrival directions



E>10^{19} eV
Auger & TA combined analysis
Aab et al. (2014)



Auger Coll. ICRC 2017

Mass composition

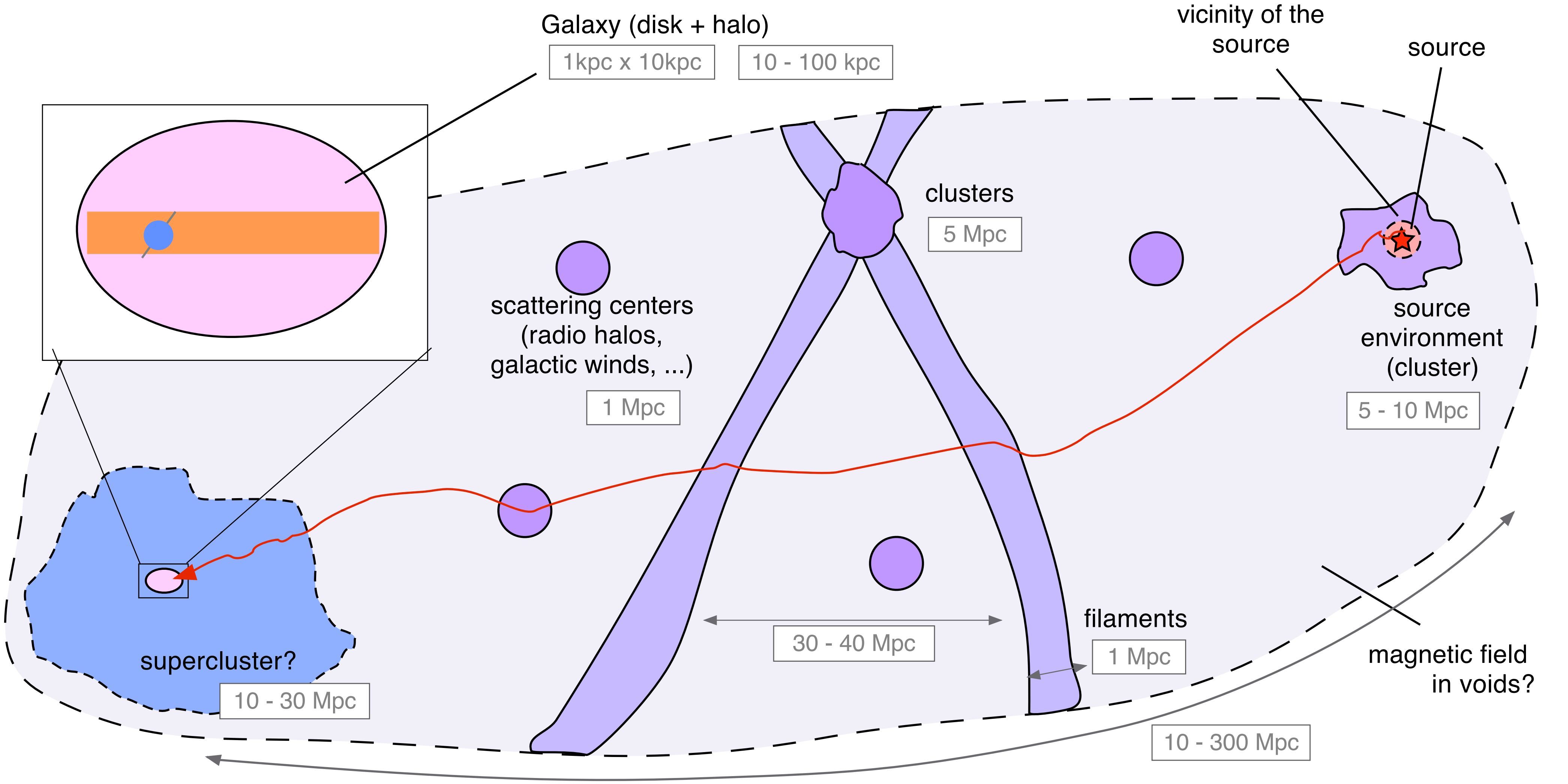
most UHECRs have rigidity E/eZ ~ 3-10 EV

deflections depend on rigidity

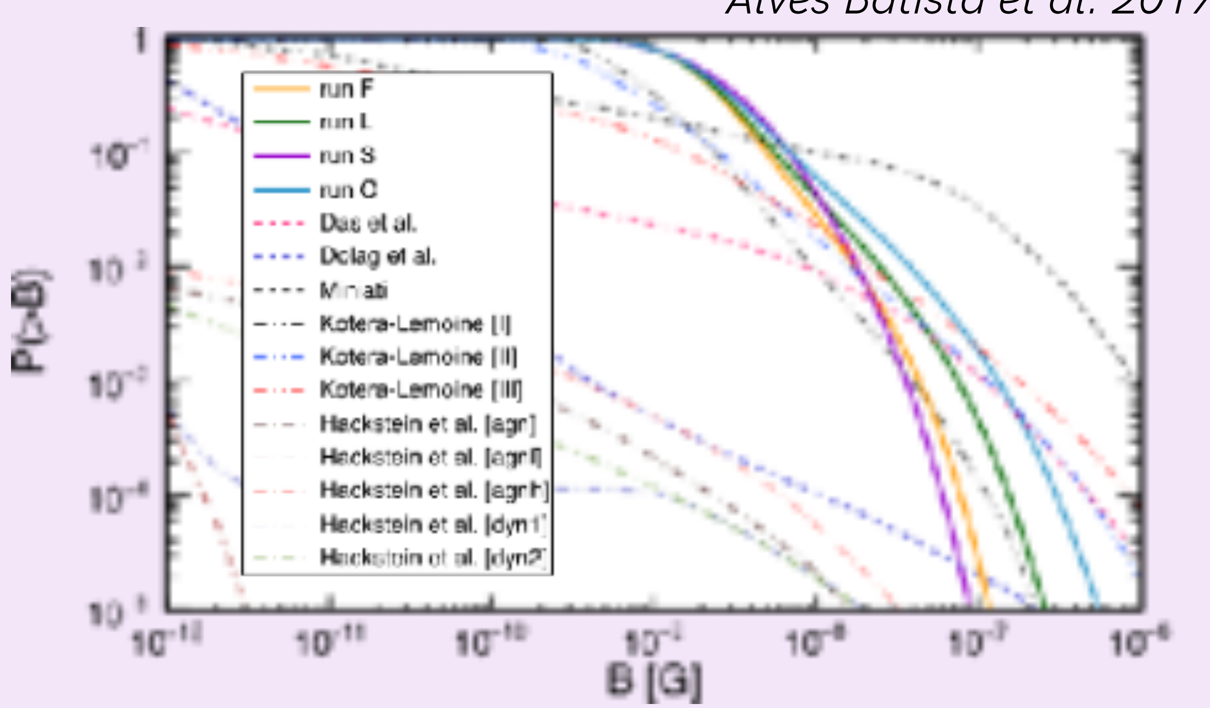
UHECRs and intergalactic magnetic fields

KK & Olinto 2011

few
observations
large
uncertainties!



Alves Batista et al. 2017



cumulative filling factors

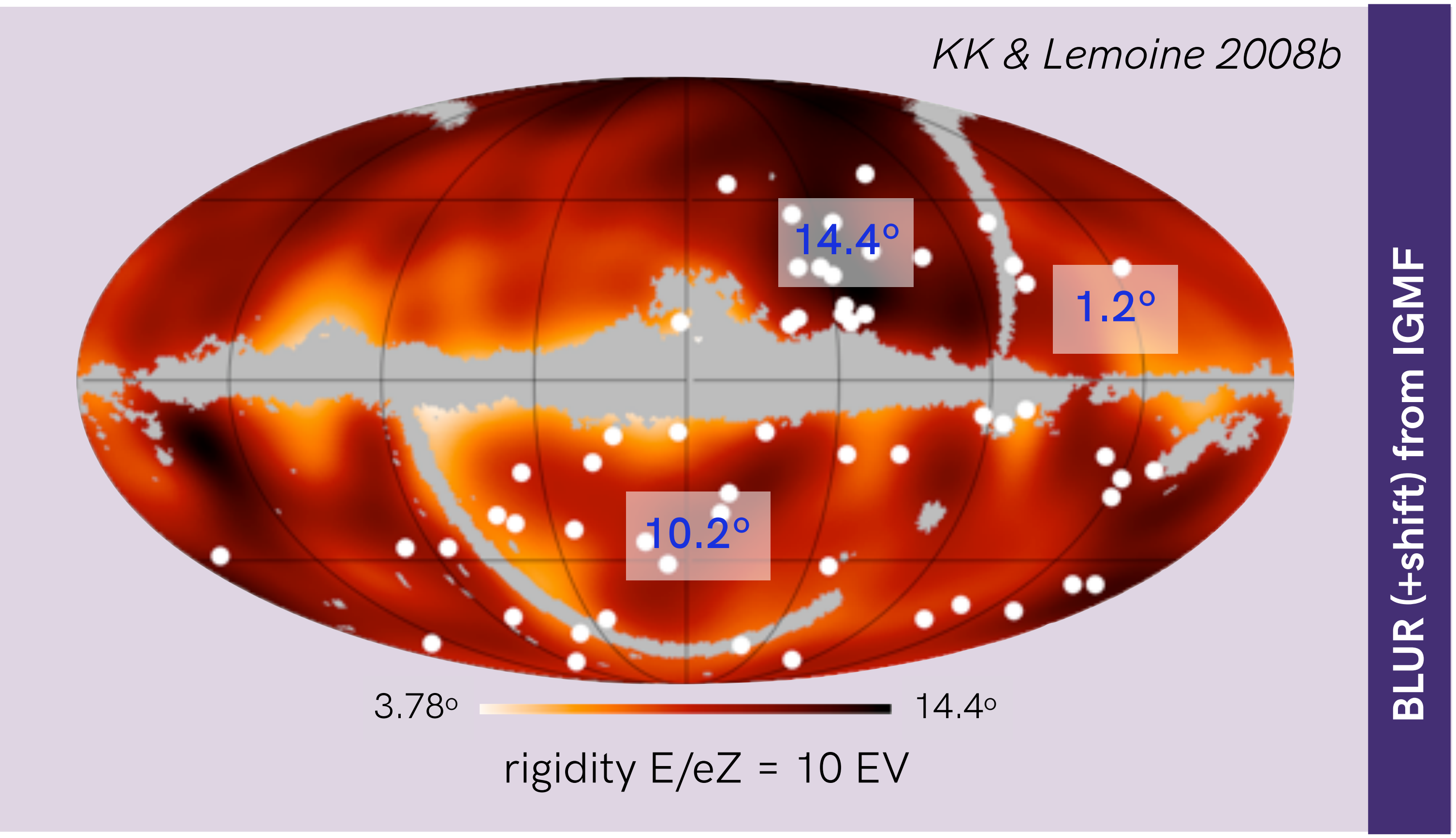
salient structures of the IGMF (scattering centers) determine the deflection of UHECRs

$$\alpha \sim 2^\circ\, Z \left(\frac{E}{60\,\mathrm{EeV}}\right)^{-1} \left(\frac{\tau}{3}\right)^{1/2} \left(\frac{r_{\rm i}}{2\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B_{\rm i}}{10\,\mathrm{nG}}\right) \left(\frac{\lambda_{\rm i}}{0.1\,\mathrm{Mpc}}\right)^{1/2}$$

number — size — strength — coherence length

KK & Lemoine 2008b

Galactic and Intergalactic magnetic fields

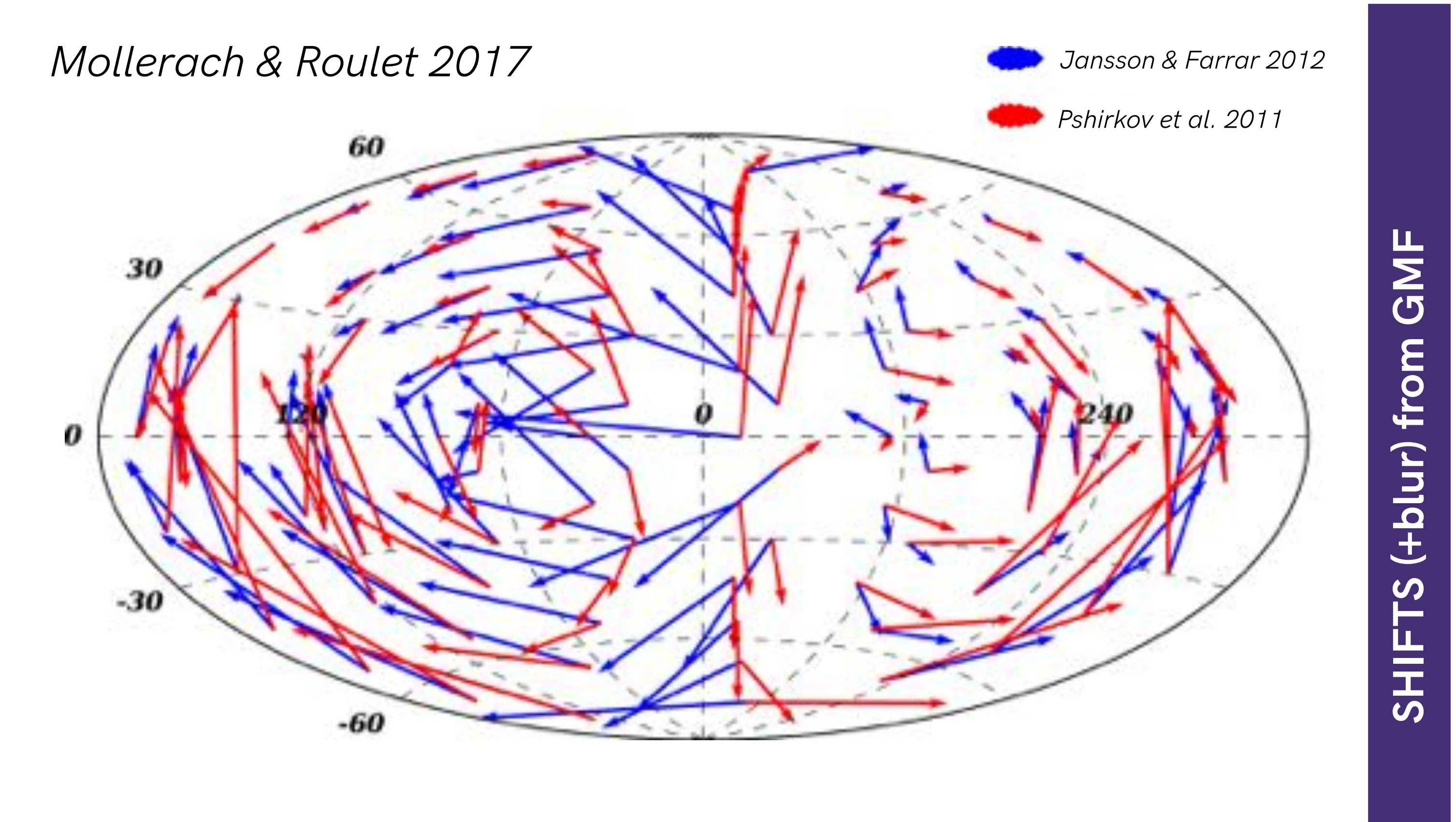


blur: controlled by statistics

IMAGINE
Interstellar MAGnetic
field INference Engine
arXiv: 1805.02496v1

a publicly available Bayesian platform that employs robust statistical methods to explore the multi-dimensional likelihood space using any number of modular inputs

GMF
IGMF
↔
UHECR
arrival
directions



shifts: knowledge on GMF will help

What can we do with rigidities E/eZ~ 10 EV and deflections ~ 10° ?

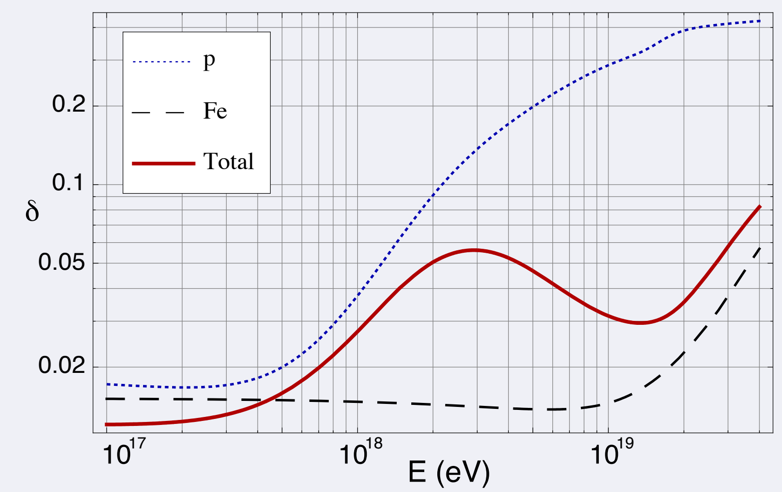
Learning from large scale anisotropies

Galactic or extragalactic?

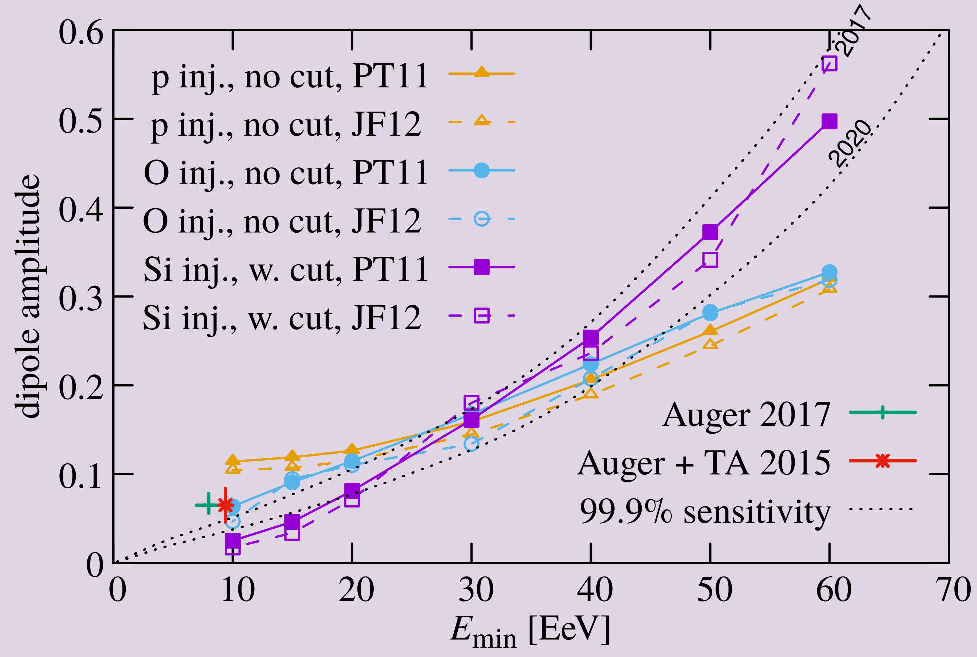
UHECR source(s) in our Galaxy imply high level of dipole amplitude

esp. for light mass composition @ 8 EeV

e.g., Calvez et al. 2010
Giacinti et al. 2011
Eichler et al. 2016



di Matteo & Tinyakov 2018



also Globus & Piran 2018 —> dipole from LSS 5% @[4-8] EeV

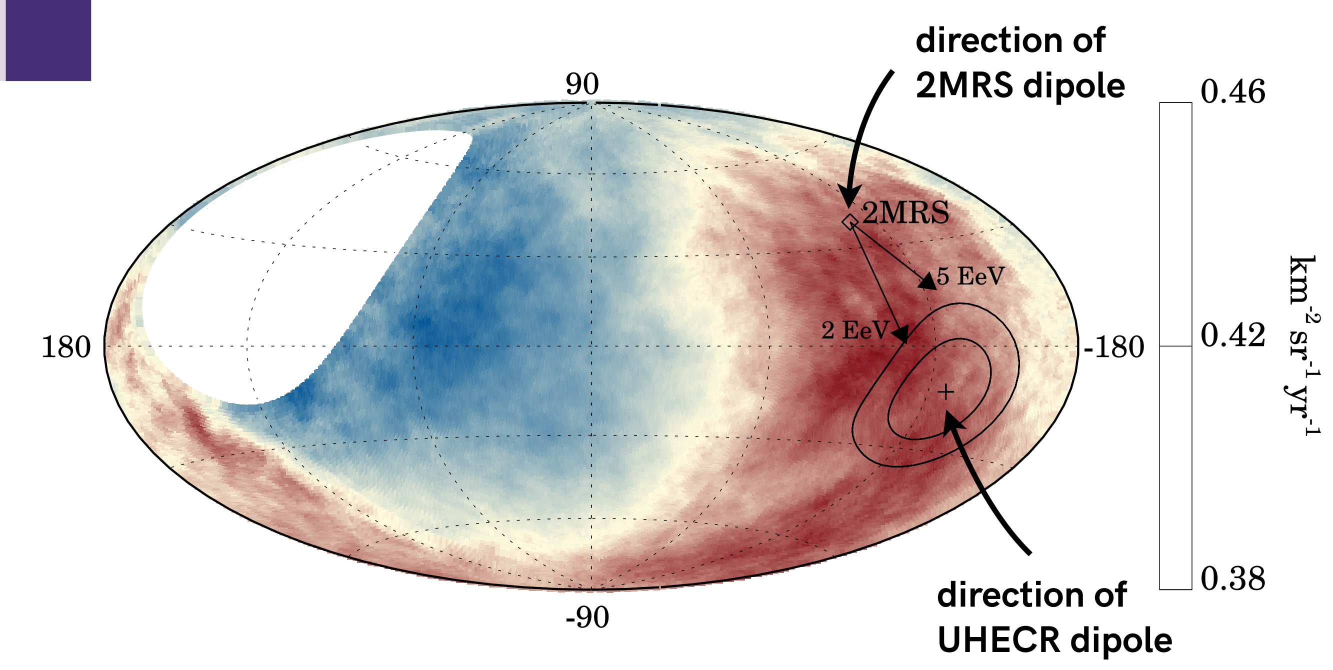
dipole expected from LSS

Auger Coll. Science 2017
Ahlers (2018) 1805.08220v1

Auger confirms that UHECRs are of extragalactic origin

5.2 sigma dipole of 6.5% observed at E>8 EeV

dipole direction, amplitude
and light composition at EeV energies
in tension with source inside Galaxy



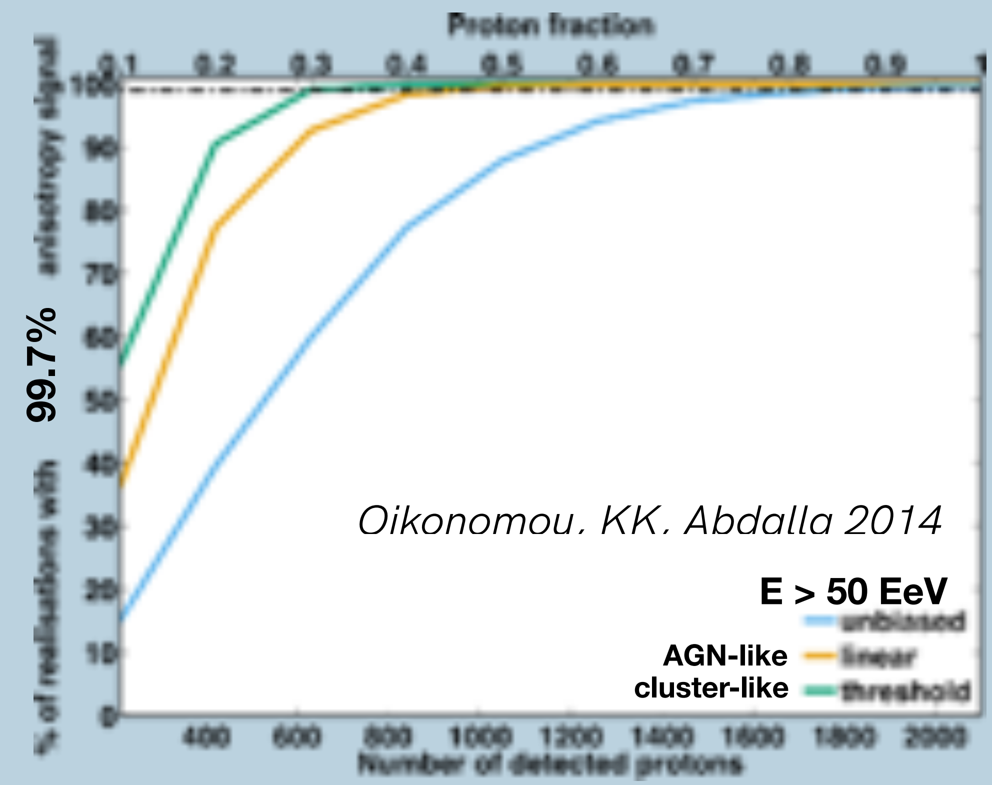
Learning from intermediate scale anisotropies

population of sources?

proton fraction

intermediate scale anisotropy should be detected @ E>50 EeV with proton fraction > 50% and > 2000 events

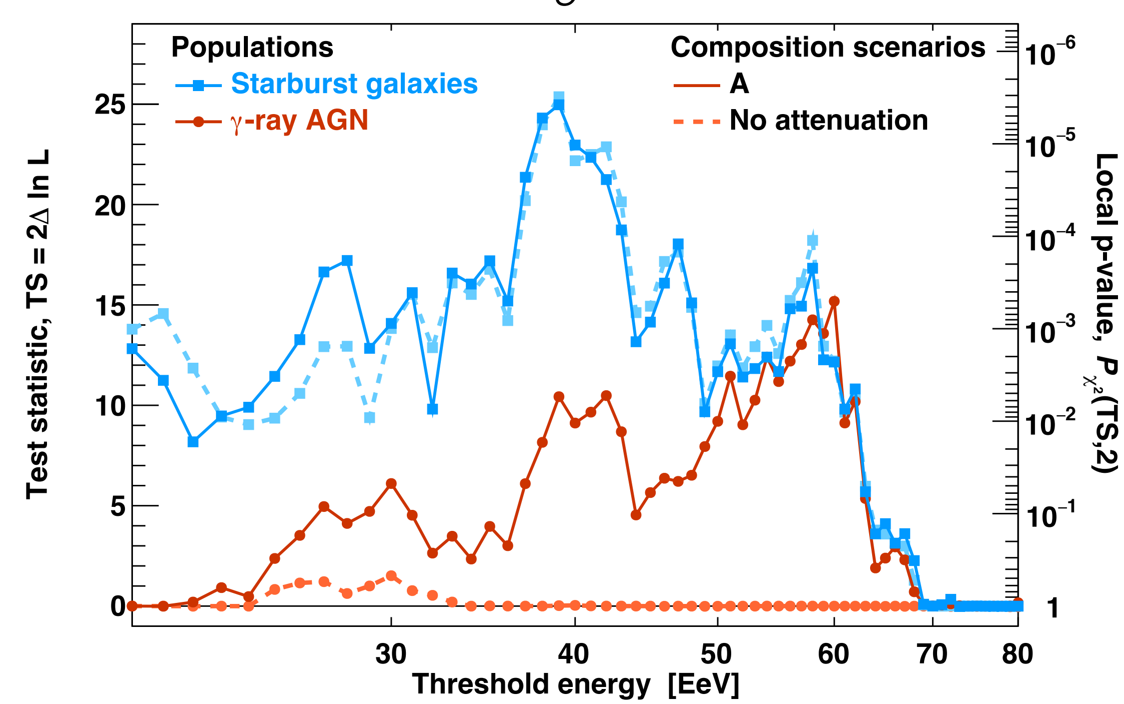
Oikonomou, KK, Abdalla 2014
Rouillé d'Orfeuil et al. 2014



Auger Coll. arXiv:1801.06160

Auger reports anisotropy compatible with starburst galaxy distribution

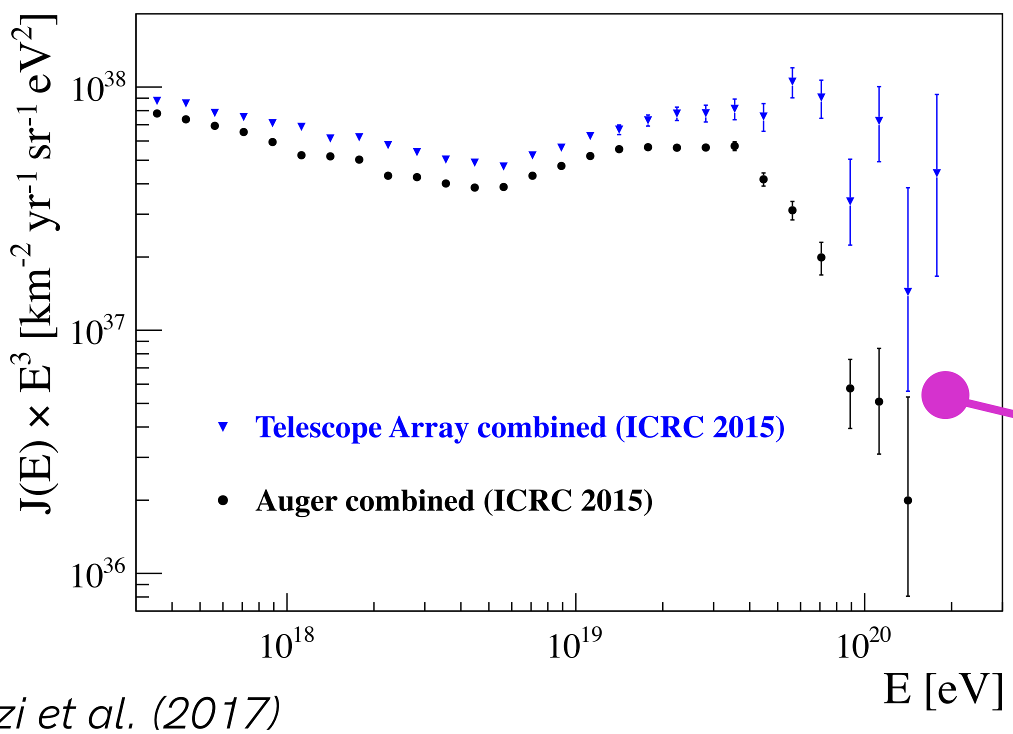
> 5000 events above 20 EeV
starburst model fits the data better than the hypothesis of isotropy with a stat. significance of 4.0σ



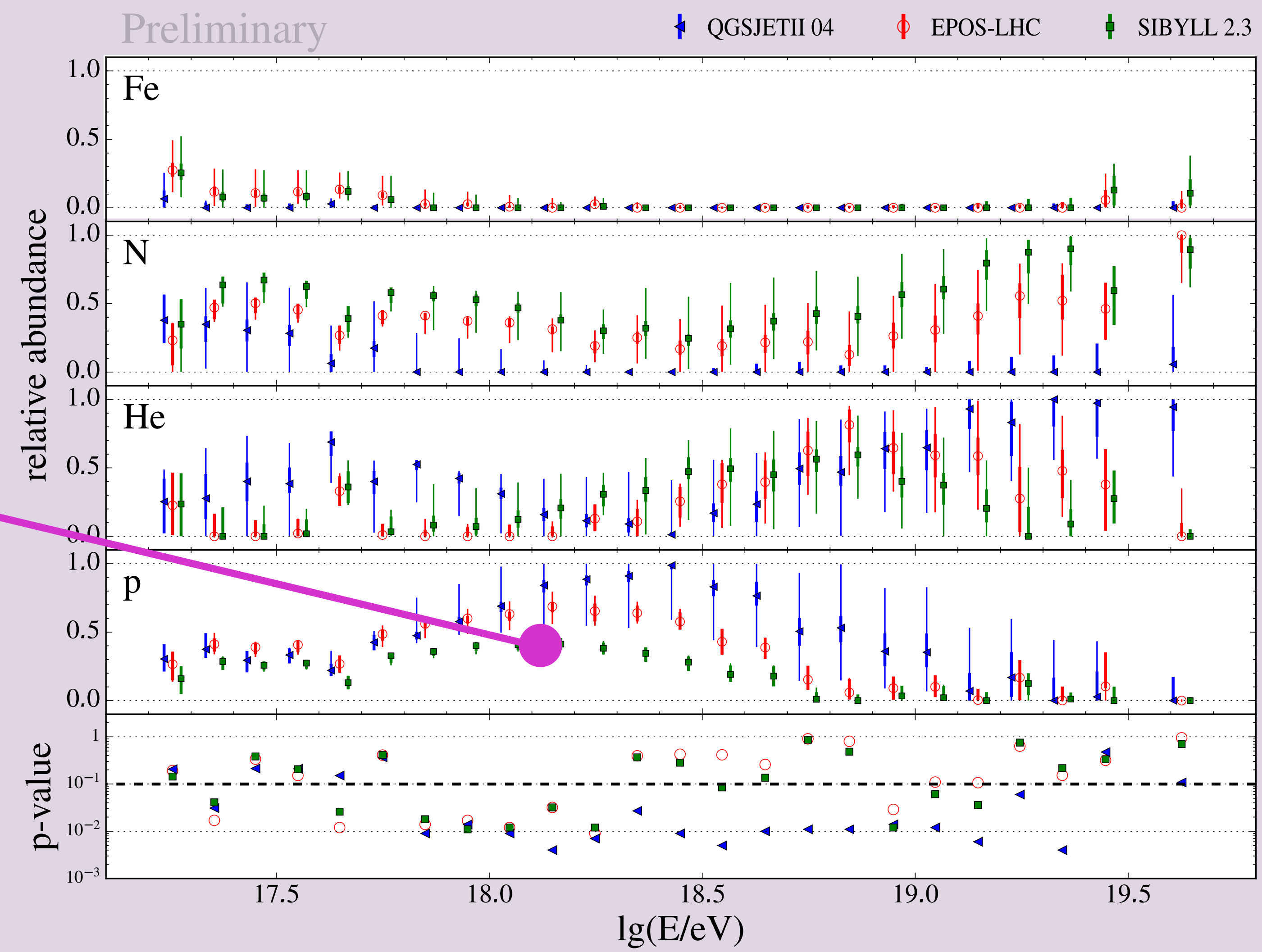
There is a sizable fraction of particles with rigidity E/eZ > 10 EV!

Learning from UHECR data

Energy spectrum



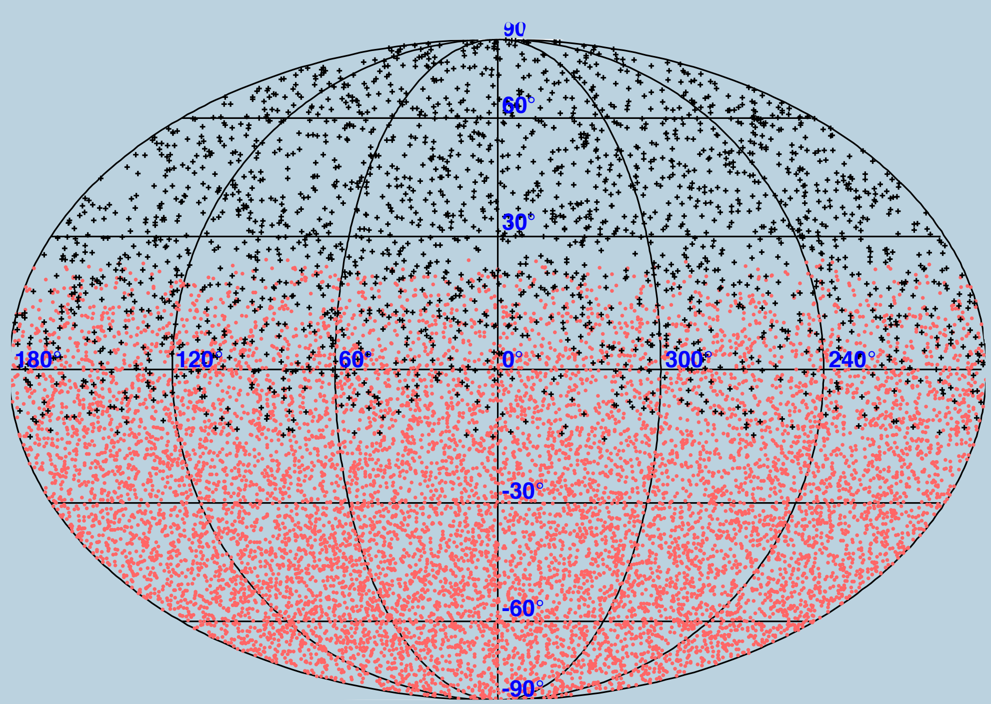
Verzi et al. (2017)



Auger Coll. ICRC 2017

Mass composition

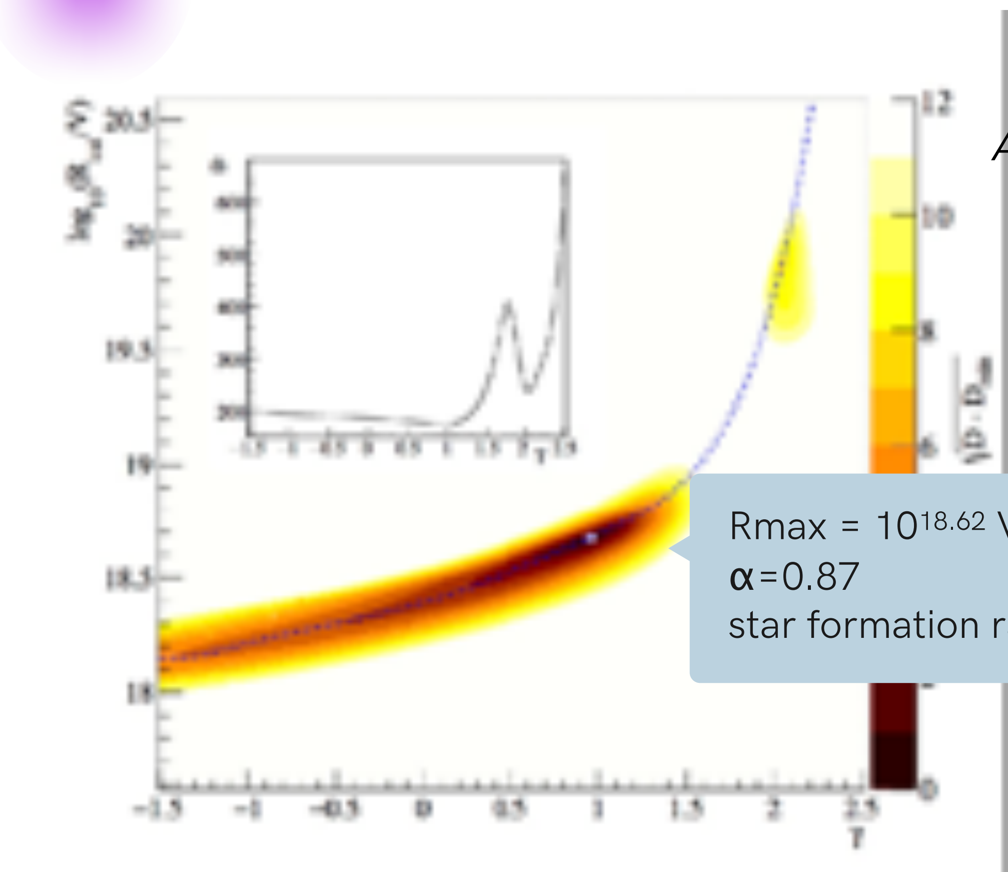
Arrival directions



E>10^{19} eV
Auger & TA combined analysis
Aab et al. (2014)

a combined fit to the data?

Information from UHECR spectra and composition



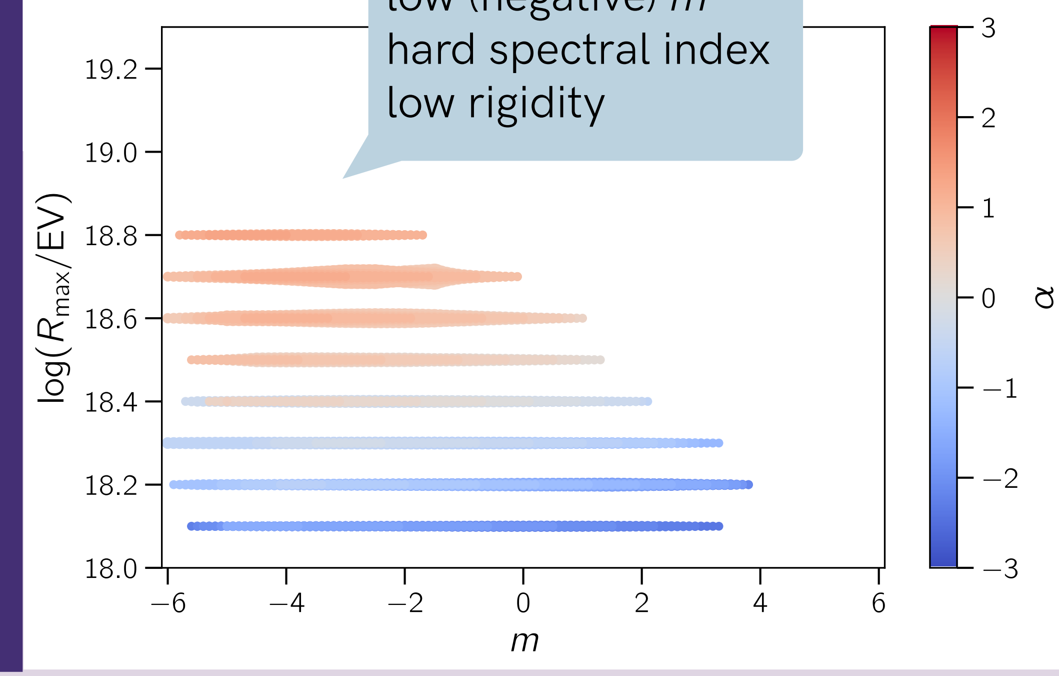
Auger Coll. 2017

Rmax = $10^{18.62}$ V
α=0.87
star formation rate

UHECR parameters

- *A* flux normalisation
- α injection spectral index in $E^{-\alpha}$
- R_{max} (max. rigidity ~ max. proton energy)
- composition
- source evolution e.g., SFR/AGN or in $(1+z)^m$

scan source evolution



favor
low (negative) *m*
hard spectral index
low rigidity

Alves Batista, de Almeida, Lago, KK, submitted

- if emissivity evolution free parameter —> best fit *m* = -1.5
- Negative source evolution:
  - e.g., tidal disruption events
  - cosmic variance local dominant of sources
- very hard spectral indices difficult to reconcile with most particle acceleration models. α>~1 favored in theory.

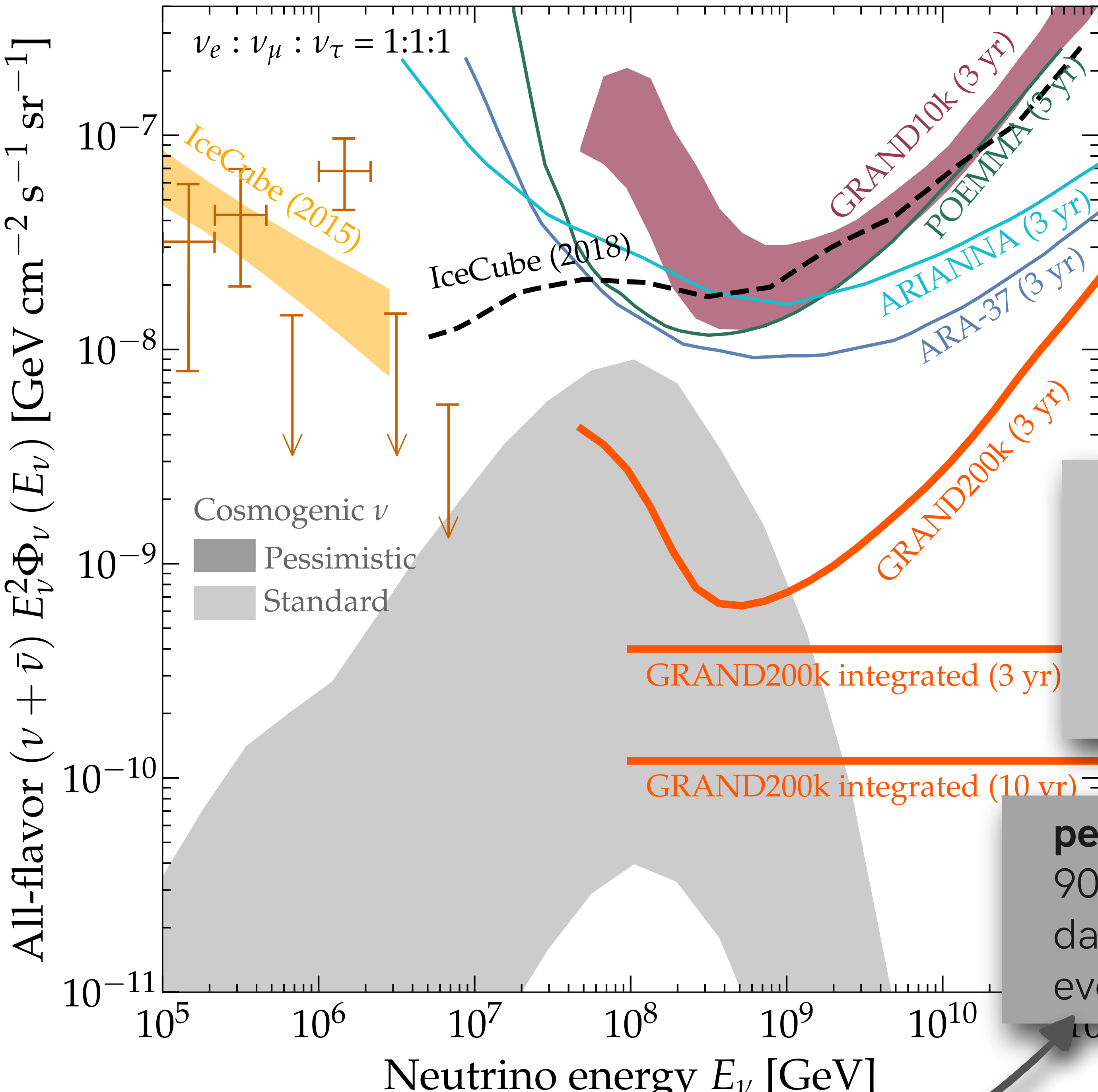
phenomenologically reasonable models with good deviances

Table 1. Best-fit parameters for specific spectral indices.

m	α	$\log(R_{max}/V)$	f_p	f_{He}	f_N	f_{Si}	f_{Fe}	D
-1.5	+1.00	18.7	0.0003	0.0002	0.8867	0.1128	0.0000	1.46
SFR	+0.80	18.6	0.0764	0.1802	0.6652	0.0781	0.0001	1.63
AGN	+0.80	18.6	0.1687	0.1488	0.6116	0.0709	0.0000	1.59
GRB	+0.80	18.6	0.1362	0.1842	0.6059	0.0738	0.0000	1.60

Learning from secondary neutrinos?

Alves Batista, de Almeida, Lago, KK, submitted
GRAND Science & Design, in prep
KK, Allard, Olinto 2010
Van Vliet et al. arXiv:1707.04511



standard
99% C.L. fit to Auger among generic SFR, AGN, GRB source evolutions

pessimistic
90% C.L. fit to Auger data with $(1+z)^m$ source evolution with m < 0

most pessimistic!
adding IGMF —> harder α —> increases neutrino flux
alleviating simplifying assumption —> increases neutrino flux

low rigidities
$R_{max} \sim 10^{18.1\text{-}18.8}$ V

R_{max}
below or above pion prod. threshold

very hard
-1.5 < α <+1.2

spectral index
flux of secondary protons
$E^{-\alpha}$

source evolution history

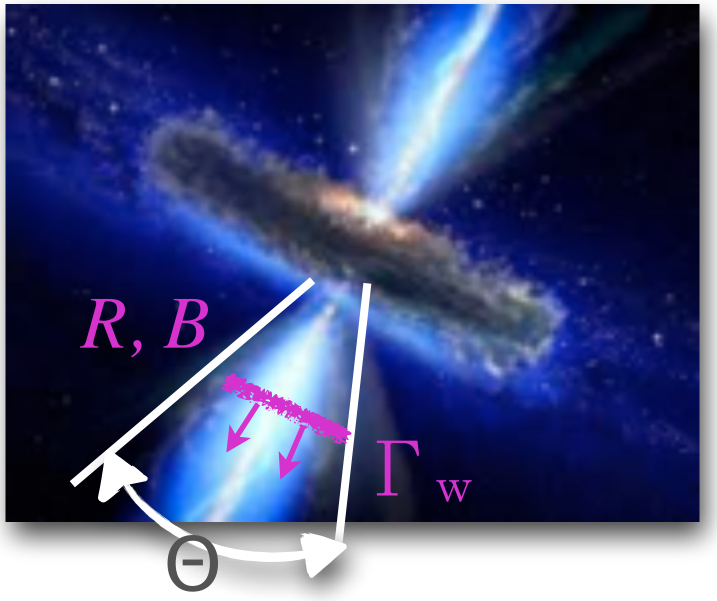
composition

intermediate dominated
p 8%, He 18%, N 67%, Fe 0.01%

UHECR flux normalisation

Learning from multi-wavelength observations

luminosity budget



condition for acceleration

$$t_{\rm acc} \lesssim t_{\rm dyn}$$

$$t_{\rm acc} = \mathcal{A}\, t_{\rm L}$$

depends on acc. mechanism and environment

Larmor time

$\mathcal{A} \gg 1$

$\mathcal{A} \sim 1$ at best

$$t_{\rm dyn} \sim R/\beta_{\rm W}\Gamma_{\rm W}c$$

outflow magnetic luminosity $$L_B \equiv \Gamma_{\rm W} R^2 B^2/2 > 10^{45}\, Z^{-2} E_{20}^2 \;\text{erg s}^{-1}$$

lower bound of the bolometric luminosity of source

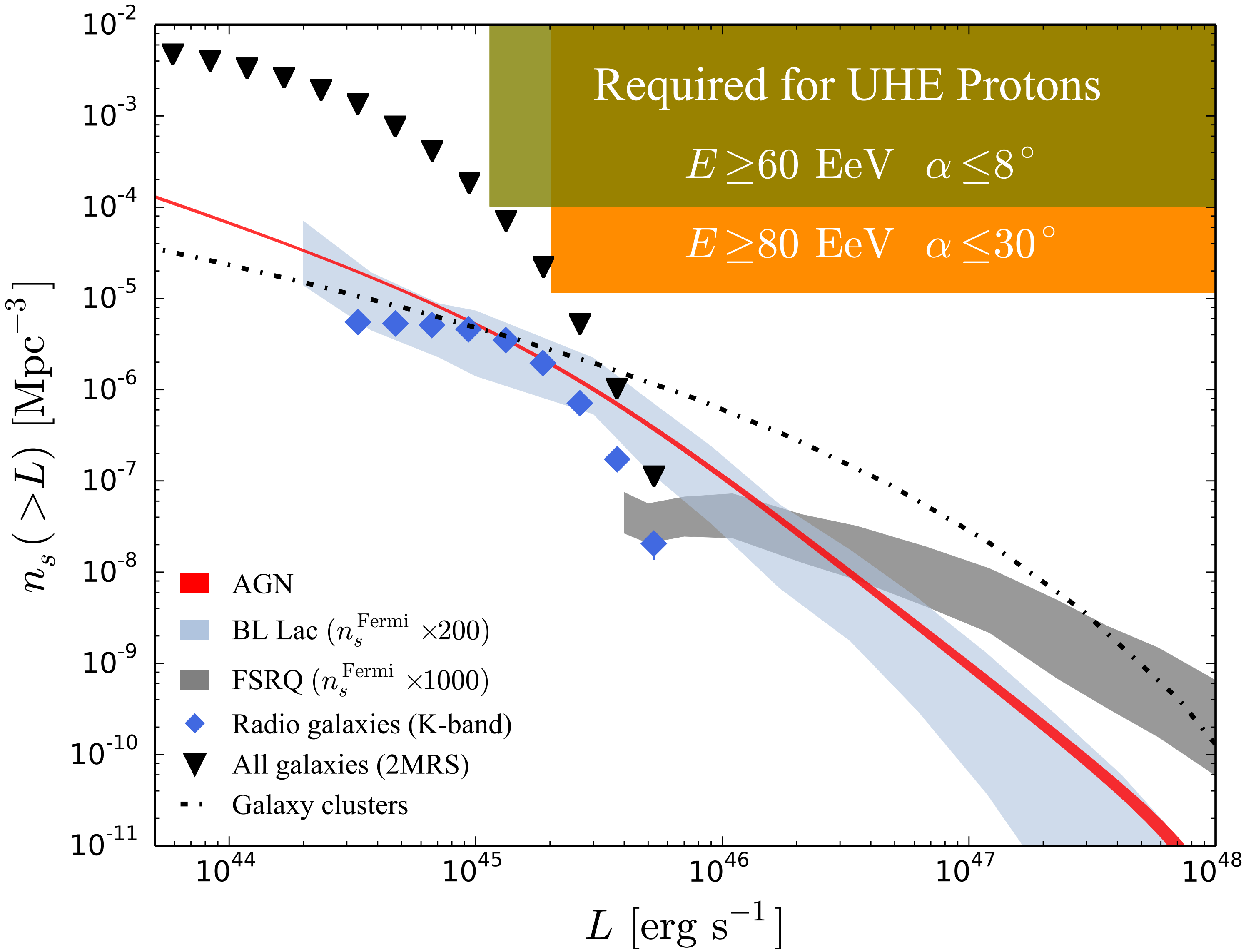
Lemoine & Waxman 2009

Learning from multi-wavelength observations + UHECR anisotropy

source bolometric luminosity $> 10^{45}\, Z^{-2} E_{20}^{2}$ erg s^{-1} *Lemoine & Waxman 2009*

level of clustering in the sky in Auger data
➢ apparent number density of sources @ given energy and angular deflection α *Abreu et al. 2013*

UHECRs cannot be dominantly protons from steady sources



Fang & KK, 2016

possibilities for heavy/intermediate composition from steady sources e.g.,
BH jets: *Fang & Murase 2016*
radio galaxies: *Eichmann et al. 2018*

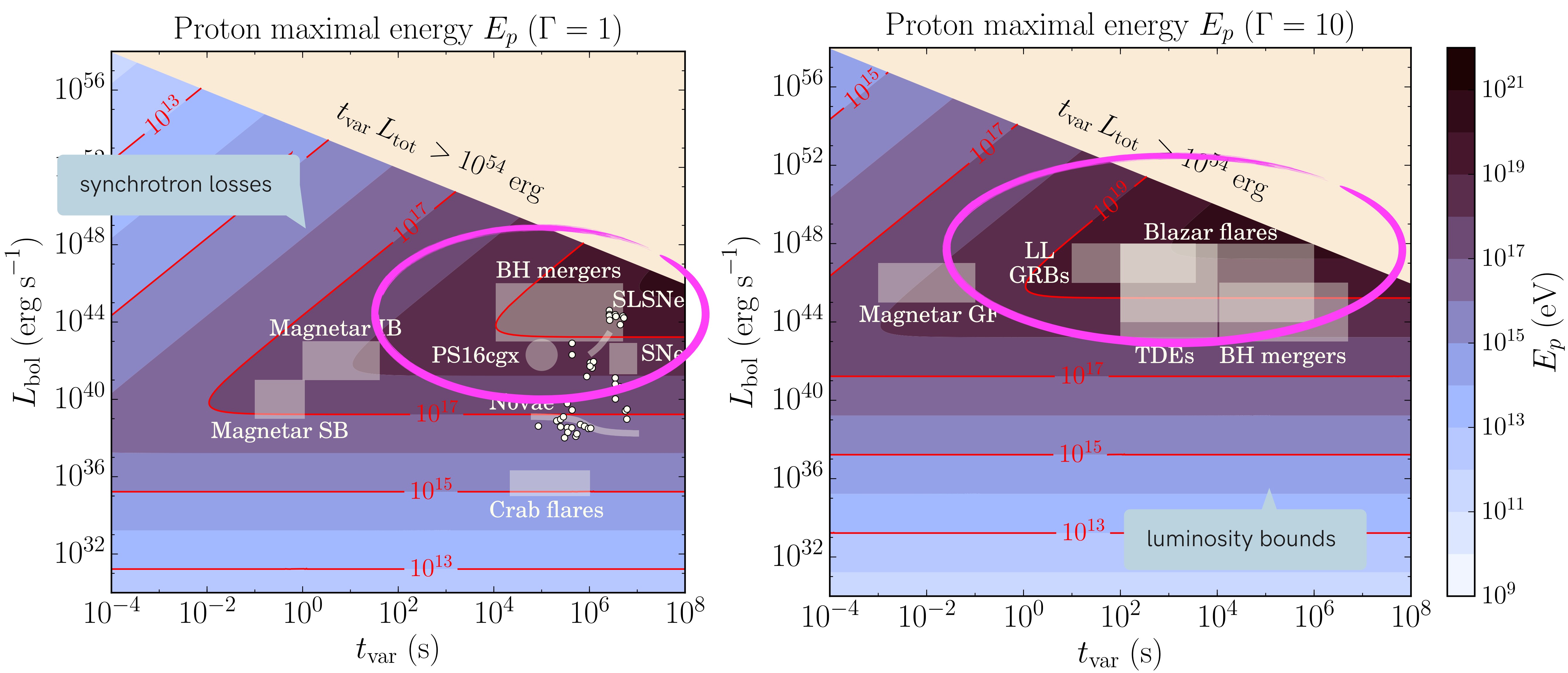
Learning from multi-wavelength observations

luminosity budget

source bolometric luminosity $> 10^{45}\, Z^{-2} E_{20}^{2}$ erg s^{-1} *Lemoine & Waxman 2009*

many transient sources could make it

Guépin & KK 2016



"Hillas plot for transients"

Learning from secondary neutrinos?

a general criterion for transients

Guépin & KK 2016

transient source

observed
- photon flux ϕ
- bolometric luminosity L_{bol}
- time variability t_{var}

choose
- Lorentz factor $\boldsymbol{\Gamma}$

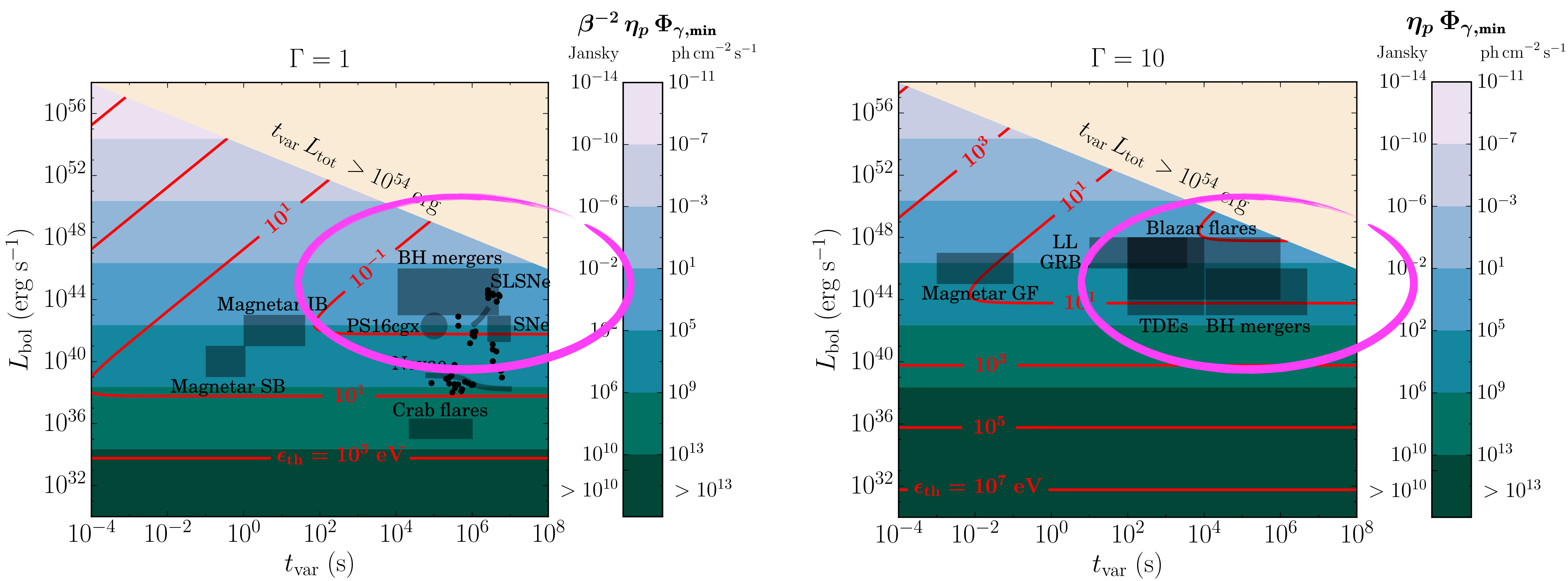
setting all parameters to **worst case scenario** for neutrino production

experimental detection limit

baryon loading to be chosen (theoretically ok + conservative)

minimal photon flux required for detection

$$\Phi_{\gamma,\min} = \frac{8}{3}\frac{4\pi\beta^2c^2\Gamma^4\mathcal{S}_{\rm exp}}{\langle\sigma_{p\gamma}\kappa_{p\gamma}\rangle}\eta_p^{-1}L_{\rm bol}^{-1}(1+z)^{-1}$$
$$\simeq 2\,{\rm Jy}\ \eta_p^{-1}\Gamma_2^4\,L_{\rm bol,52}^{-1}\,(1+z)^{-1}\ .$$



Neutrino flares and TXS 0506+56

Guépin & KK 2016 — photon flux **needed** for detection with GRAND

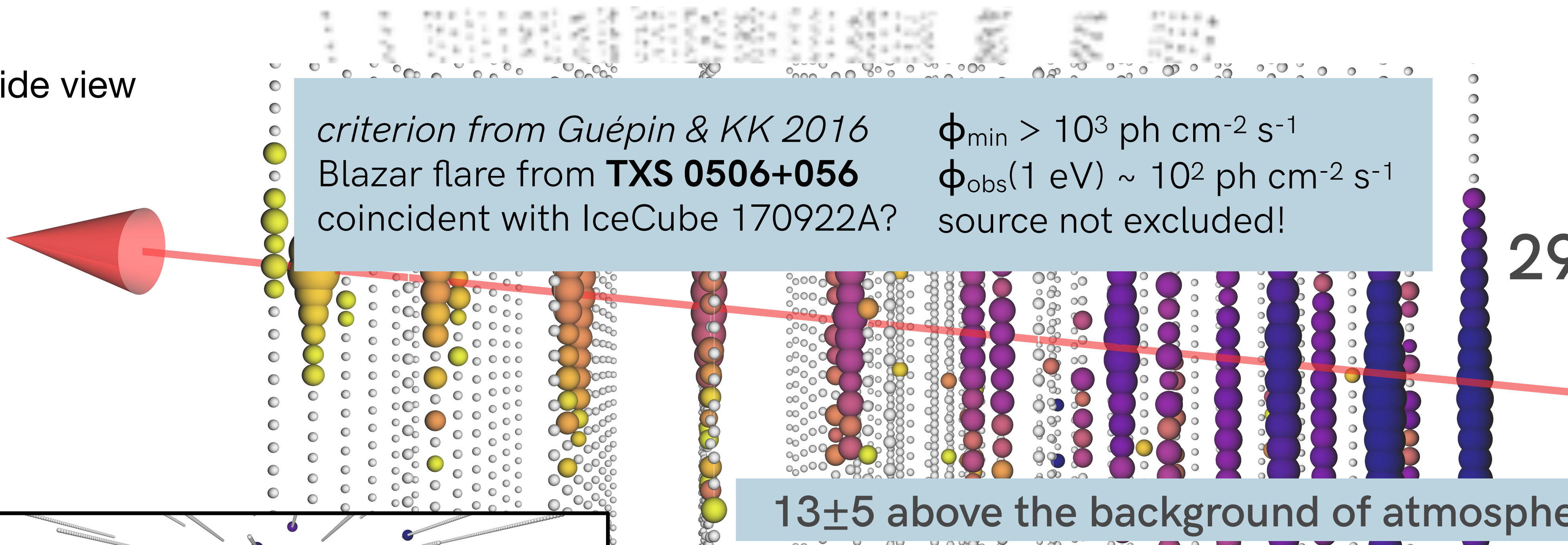
Class	$E_{\nu,\max}$ (GeV)	ϵ_γ (eV)	$\eta_p\,\Phi_{\gamma,\min}$ (ph cm^{-2} s^{-1})	$D_{\rm L,max}$ [$z_{\max}$]
Blazar flares	10^{10}	0.1	10^3	[1.2]
LL GRBs*	10^9	0.1	10^3	18 Mpc
TDEs	10^9	10^4	10^3	25 Mpc
SLSNe	10^9	10^{-3}	10^2	7.9 Mpc
SNe*	10^9	10^{-2}	10^4	79 kpc

L_pk = 1.7e44 erg/s
t_rise = 3e5 s ,
D = 66 Mpc .

Si on considère le ca
\beta^-2 \eta_p \Phi_
cm^-2 s^-1 .

Pour cette source \P
80 ph cm^-2 s^-1 .

side view

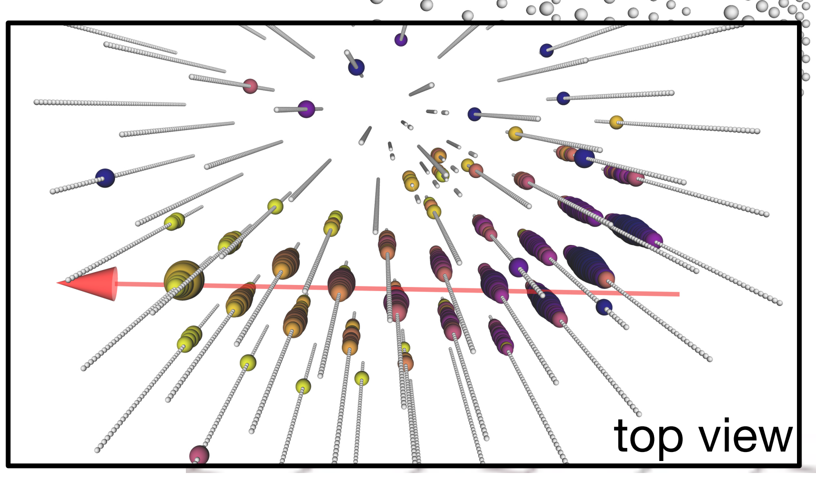


criterion from Guépin & KK 2016
Blazar flare from **TXS 0506+056** coincident with IceCube 170922A?

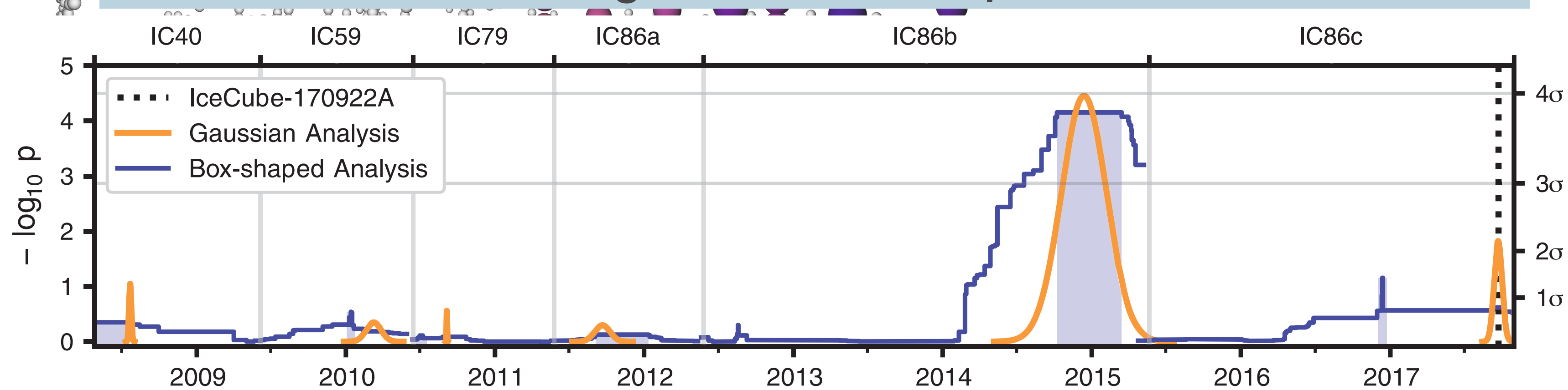
$\phi_{\min} > 10^3$ ph cm^{-2} s^{-1}
$\phi_{\rm obs}(1\ {\rm eV}) \sim 10^2$ ph cm^{-2} s^{-1}
source not excluded!

IC170922A: 290 TeV neutrino

IceCube Coll. Science (2018)

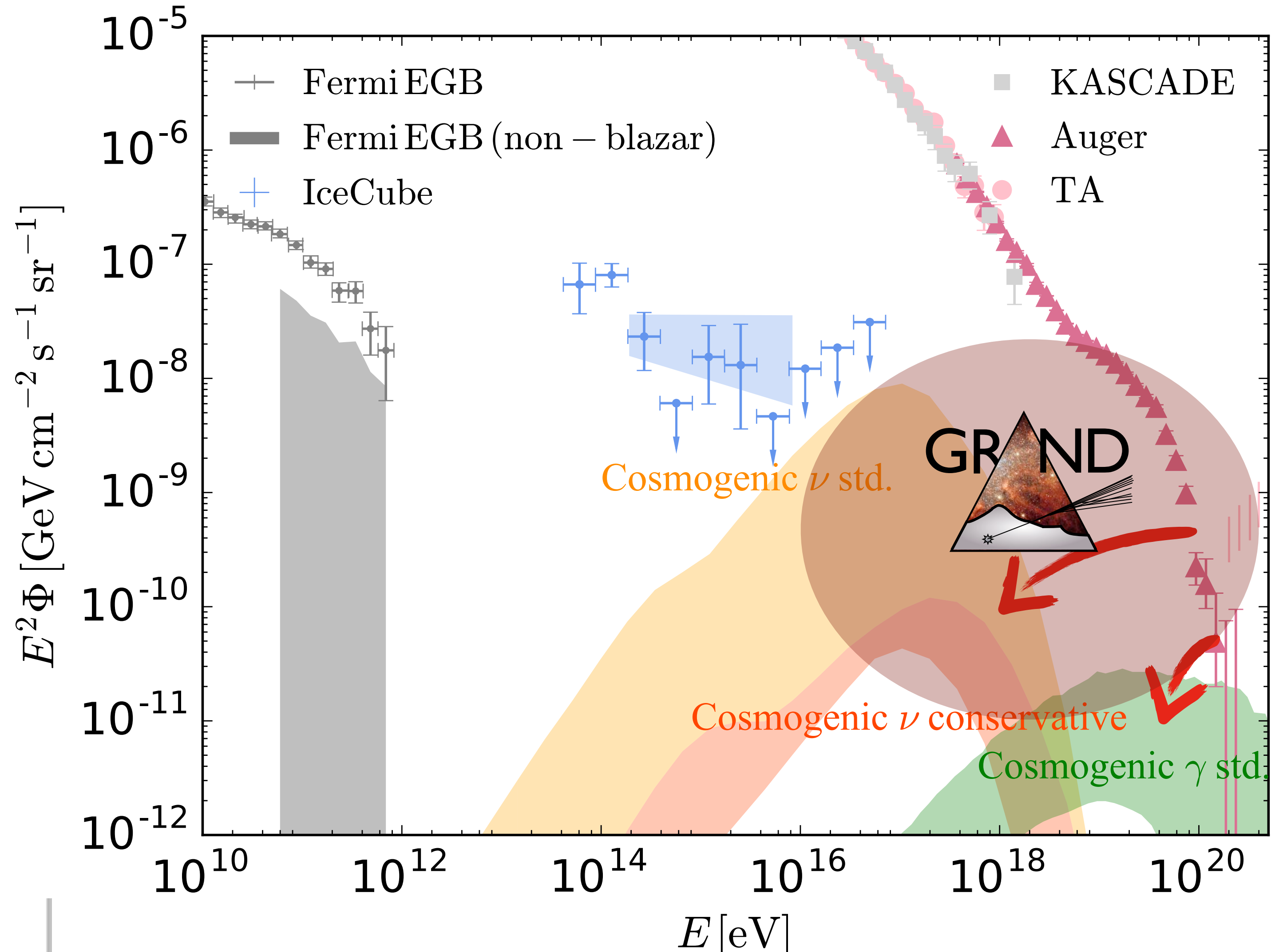


13±5 above the background of atmospheric neutrinos, 3.5σ



Catching the sources of UHECRs

real-time EeV multi-messenger astronomy is the way



Astrophysical Multimessenger Observatory Network

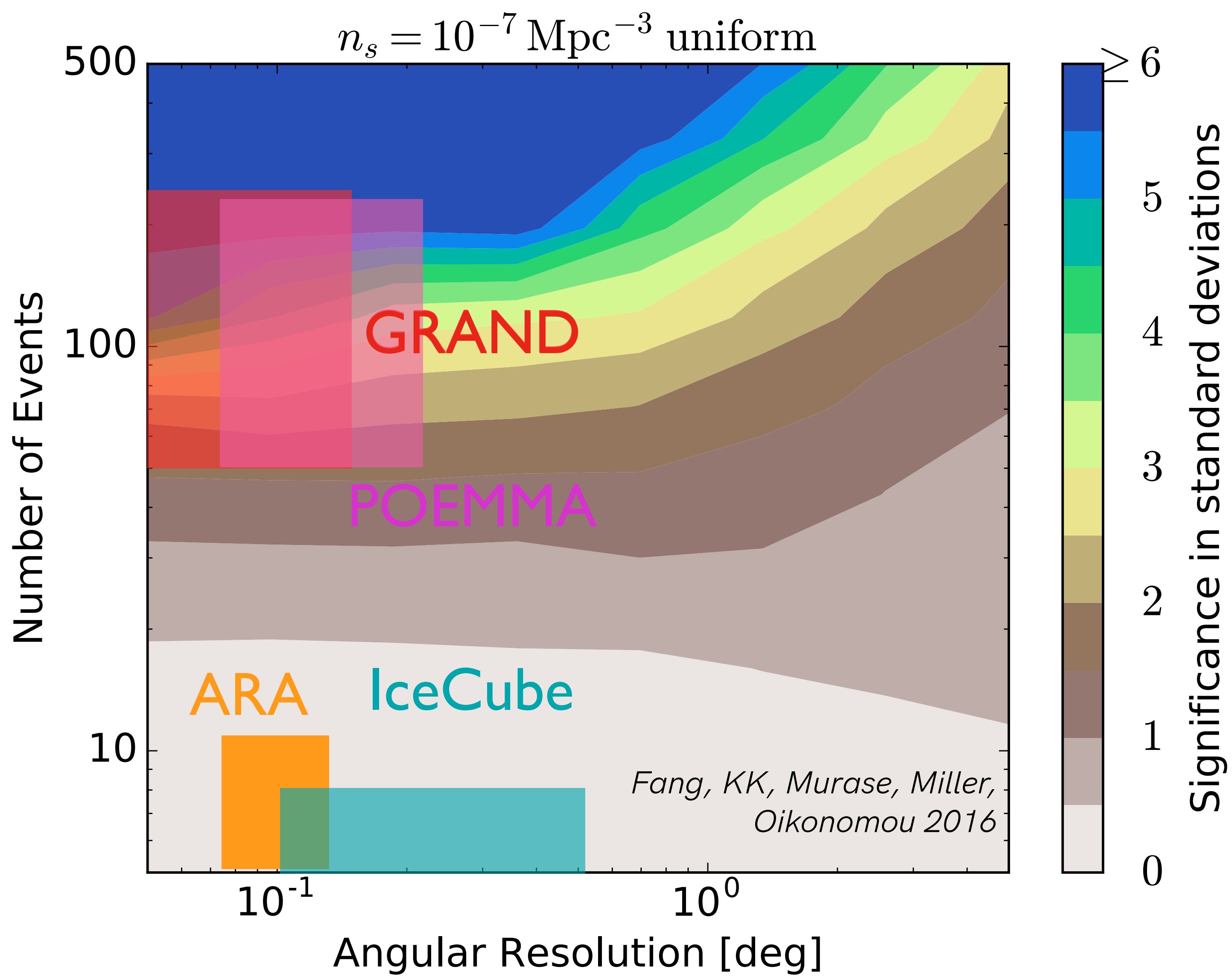
all connected after all

with EeV neutrinos as a principal ingredient

Proposal for
Institute for Multi-Messenger Astrophysics
arXiv:1807.04780

Can we hope to detect very high-energy neutrino sources?

Neutrinos don't have a horizon: won't we be polluted by background neutrinos?



boxes for experiments assuming neutrino flux: 10^{-8} GeV cm^{-2} s^{-1}

YES if

- good angular resolution (< fraction of degree)
- number of detected events > 100s

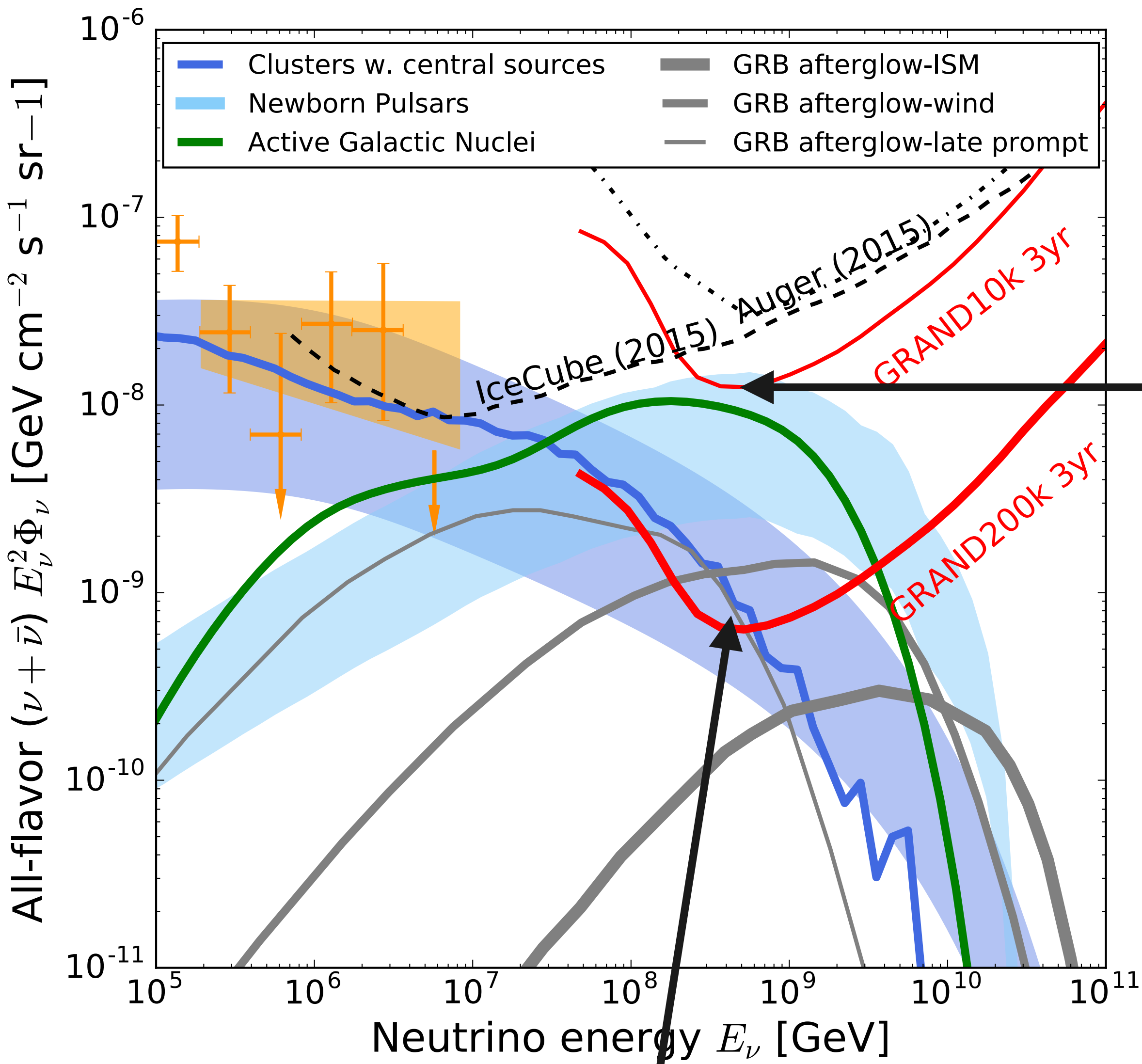
What we can aim to do with future observatories

cosmogenic: guaranteed

direct from source: likely more abundant

pessimistic scenarios of cosmogenic neutrinos = good!

low background for source neutrinos
talk by Heinze Tuesday PM

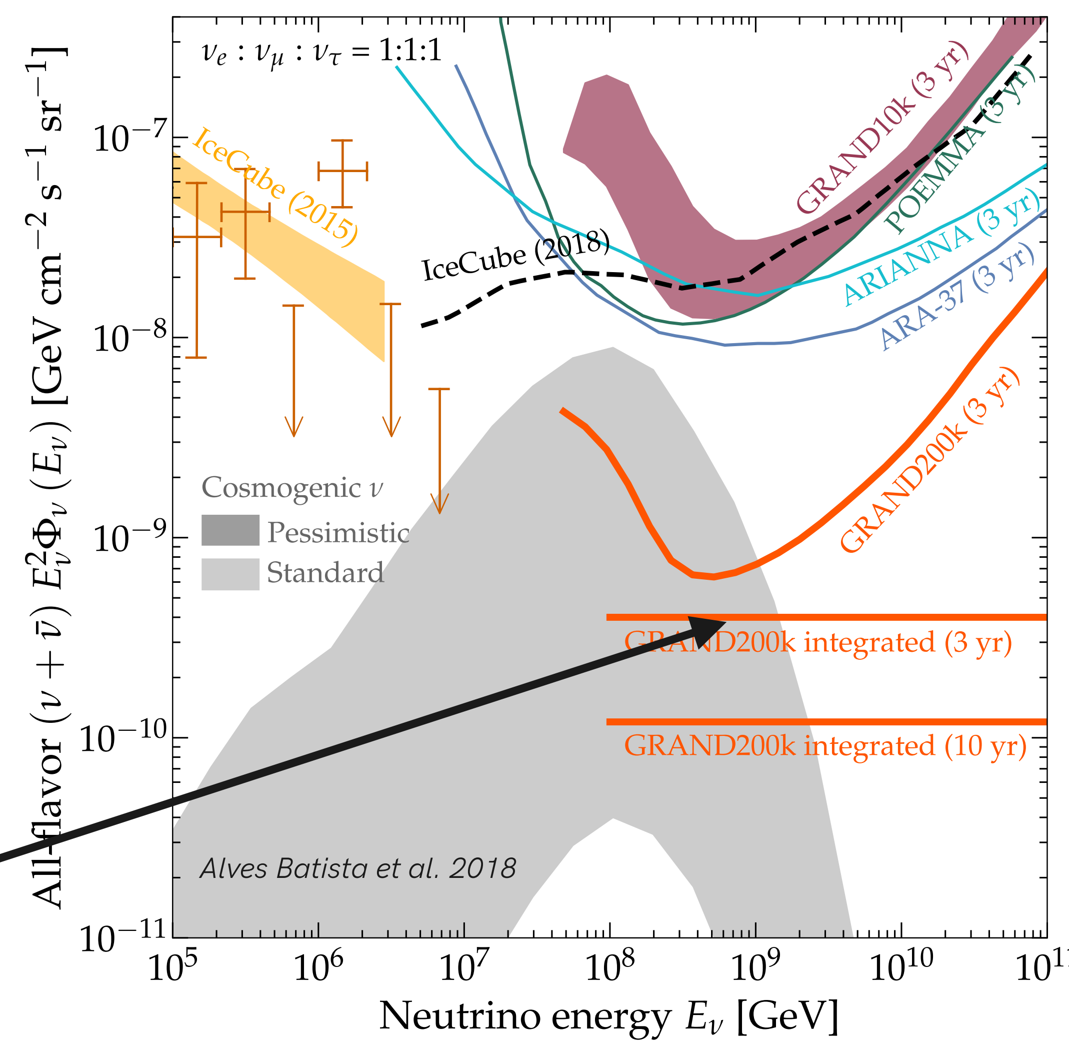


detect the first EeV neutrinos

detect EeV neutrino **point sources**

100s of events
~0.3° angular resolution

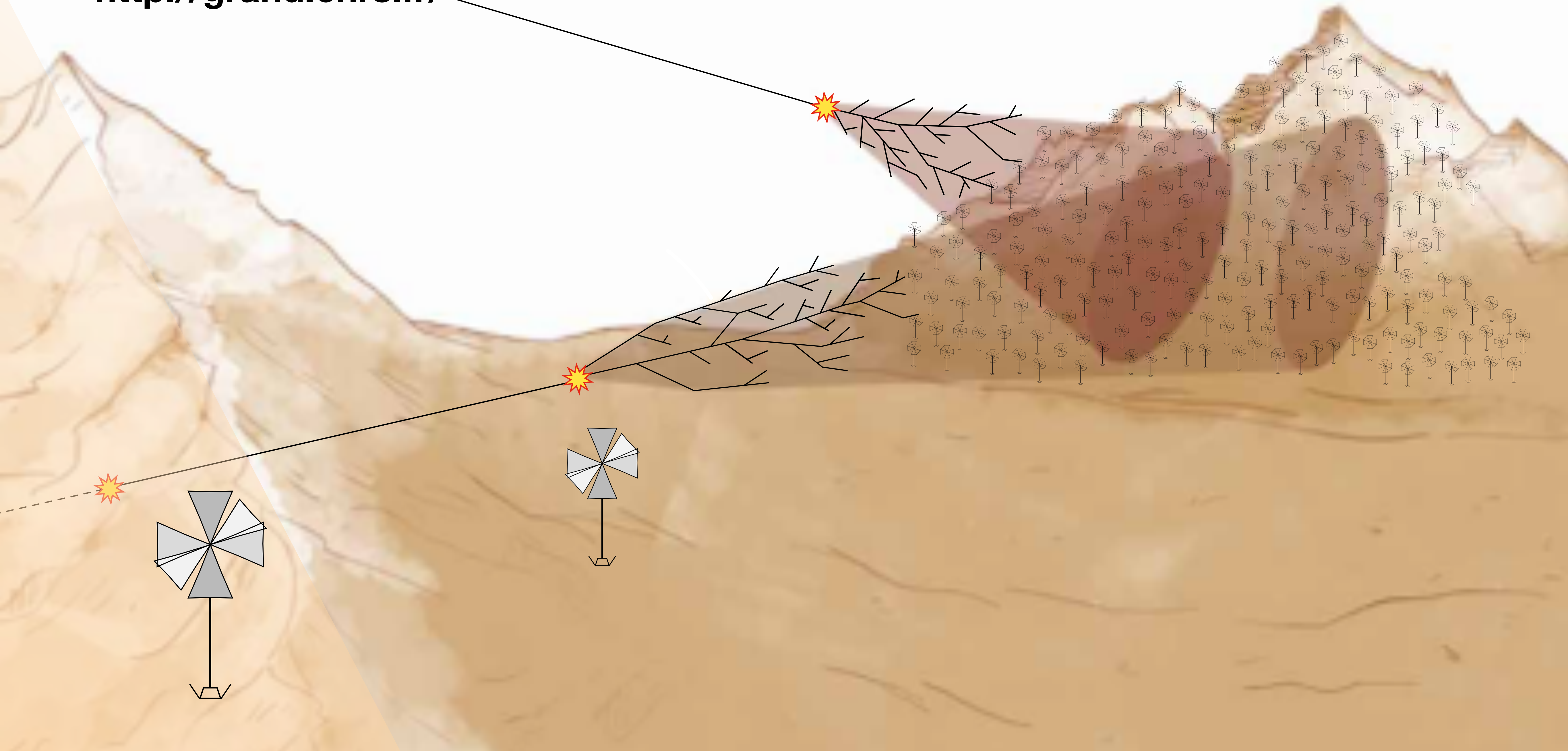
detect **cosmogenic** neutrinos



GRAND

The Giant Radio Array for Neutrino Detection

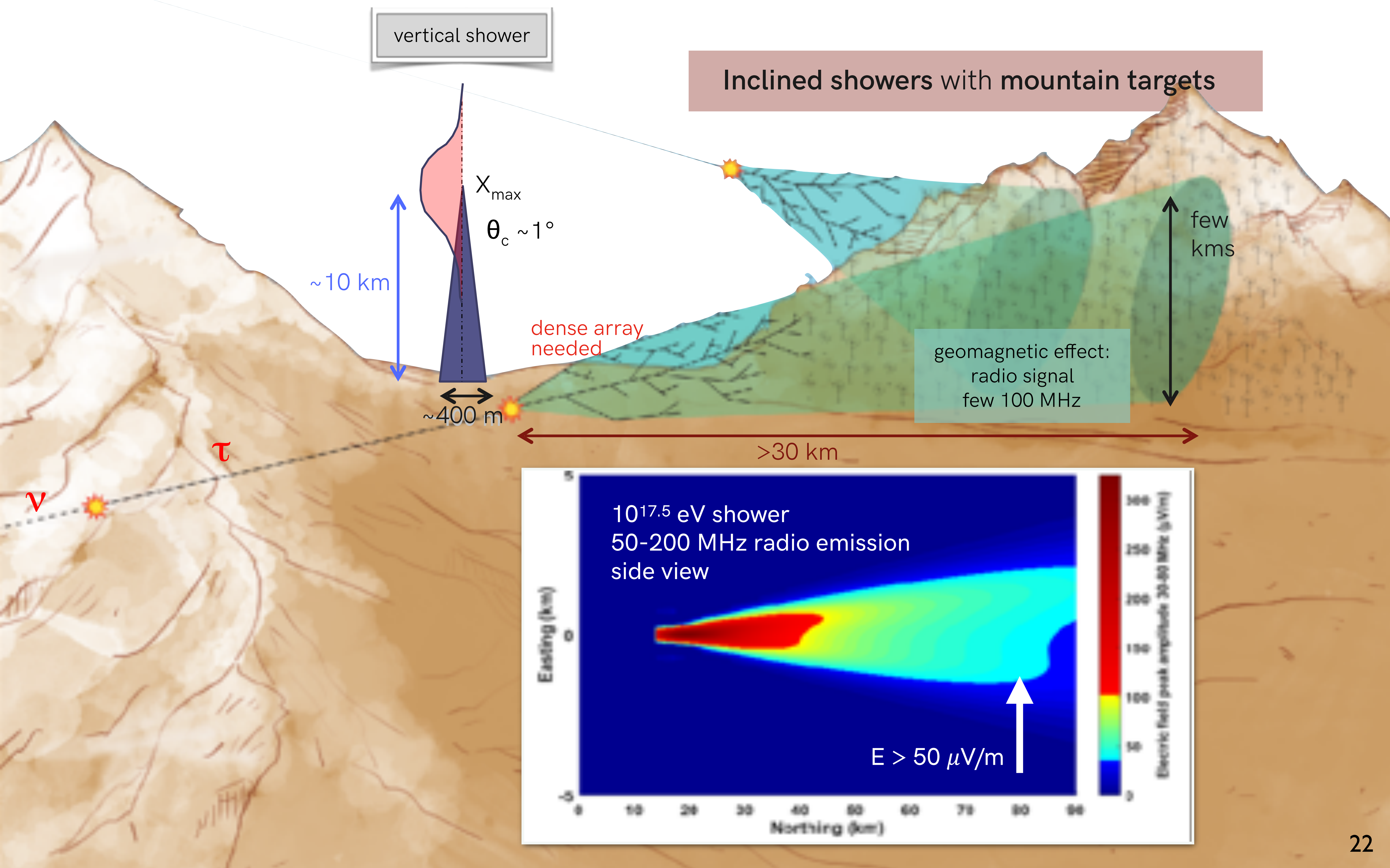
http://grand.cnrs.fr/



The GRAND Concept

radio detection: a mature and autonomous technique
AERA, LOFAR, CODALEMA/EXTASIS, Tunka-Rex, TREND

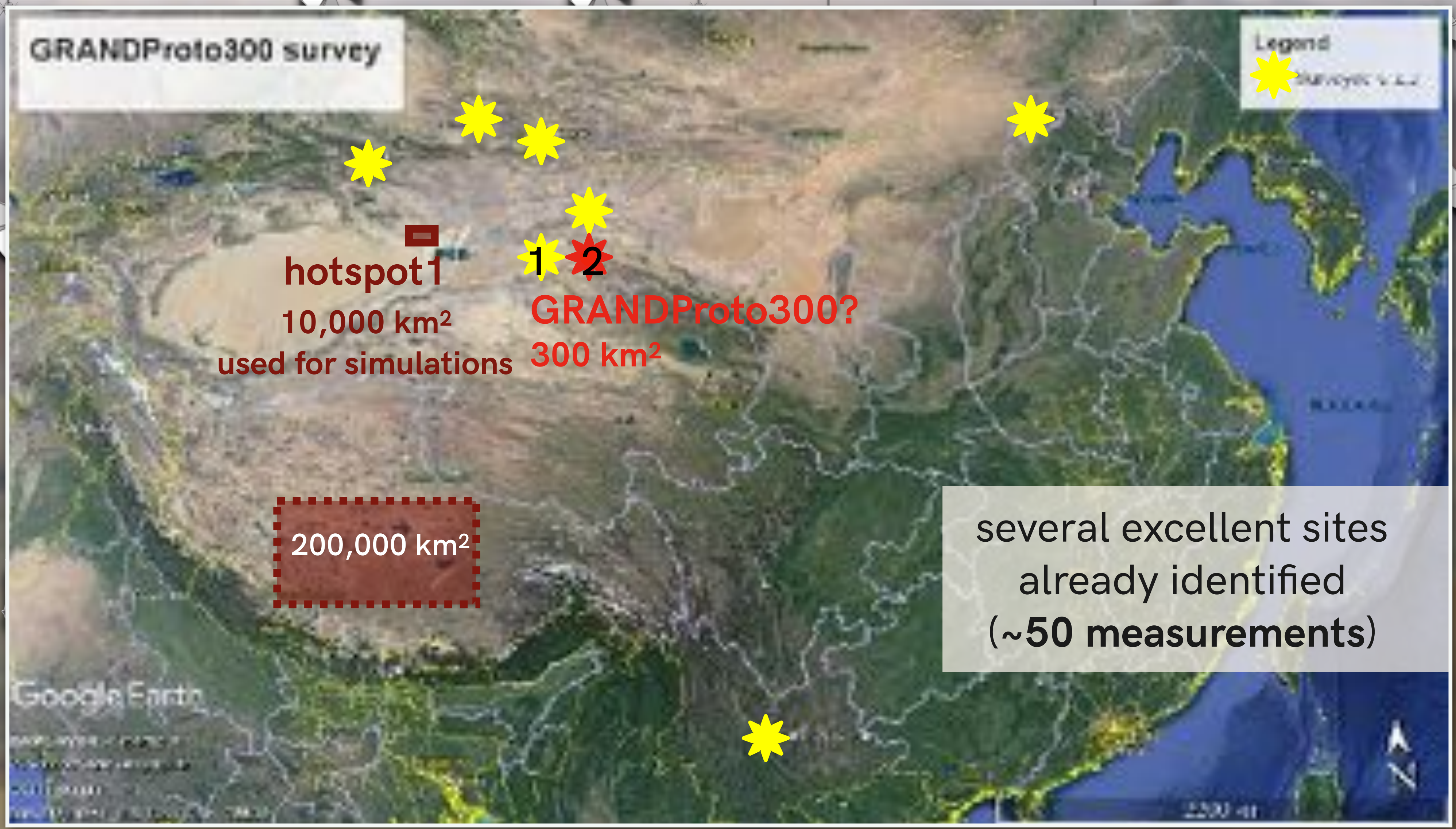
radio antennas cheap and robust: ideal for giant arrays



The GRAND Concept

200,000 radio antennas over 200,000 km²
~20 hotspots of 10k antennas
in favorable locations in China & around the world

- ✓ Radio environment: radio quiet
- ✓ Physical environment: mountains
- ✓ Access
- ✓ Installation and Maintenance
- ✓ Other issues (e.g., political)



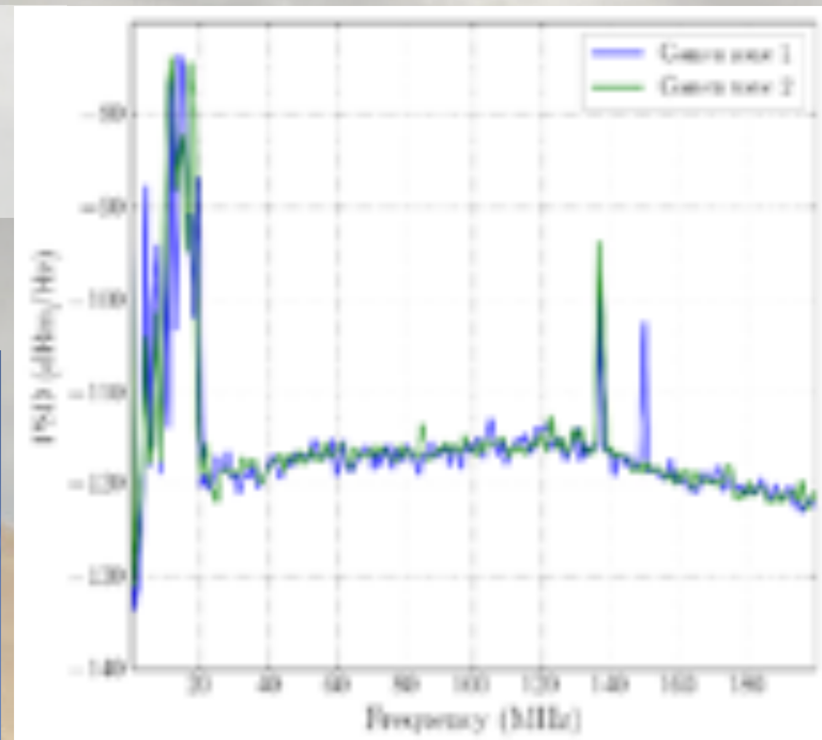
A staged approach with self-standing pathfinders

GRANDProto300

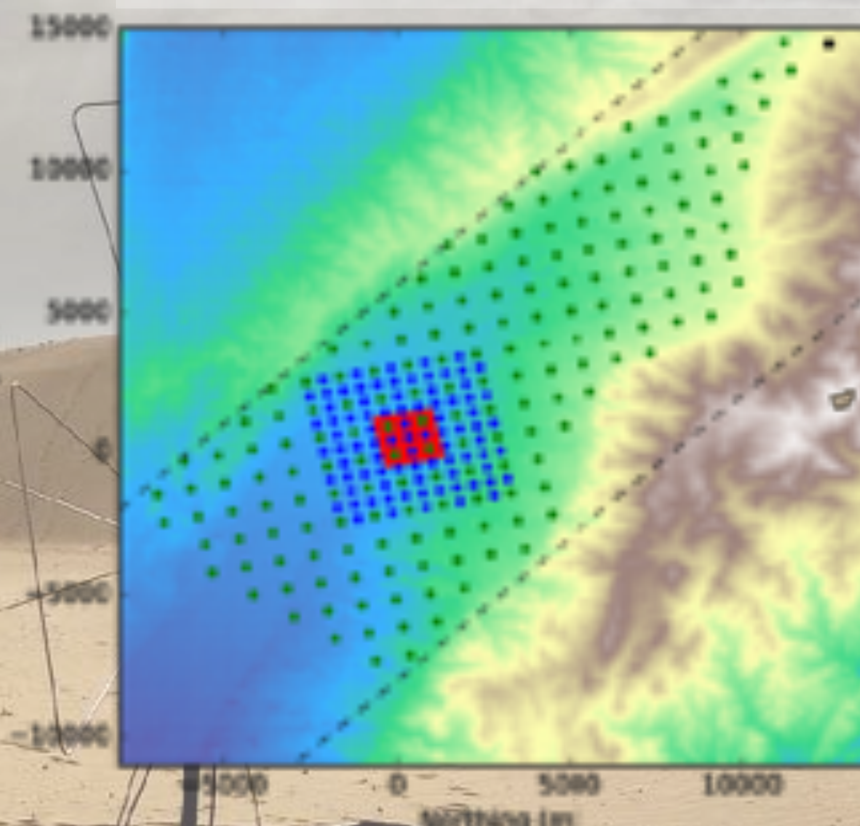
	GRANDProto35		GRAND10k	GRAND200k
	2018	2020	2025	203X
Goals	standalone radio array: test efficiency & background rejection	standalone radio array of very inclined showers (θ_z>70°) from cosmic rays (>$10^{16.5}$ eV) + ground array to do UHECR astro/hadronic physics	first GRAND subarray, sensitivity comparable to ARA/ARIANNA on similar time scale, allowing discovery of EeV neutrinos for optimistic fluxes	first neutrino detection at 10^{18} eV and/or neutrino astronomy!
Setup	35 radio antennas 21 scintillators 	• 300 HorizonAntennas over 200 km² • Fast DAQ (AERA+ GRANDproto35 analog stage) • Solar panels + WiFi data transfer • Ground array (a la HAWC/Auger)	DAQ with discrete elements, but mature design for trigger, data transfer, consumption	200,000 antennas over 200,000 km², ~ 20 hotspots of 10k antennas, possibly in different continents Industrial scale allows to cut down costs: 500€/unit ➔ 200M€ in total
Budget & stage	160k€, fully funded by NAOC+IHEP, deployment ongoing @ Ulastai	1.3 M€ to be deployed in 2020	1500€ / detection unit 	 ASIC Cost ~10M€ ➔ few 10€/board Consomption < 1W Reliability

GRANDProto300: experimental setup almost ready

Site: 9 sites surveyed in China, 7 with excellent electromagnetic conditions



Layout: 300 antennas, 200km^2, 1km step size with denser infield
➔ Erange = $10^{16.5}$-10^{18}eV



HorizonAntenna, successfully tested in the field (August, December 2018)

Electronics:
50-200MHz analog filtering,
500MSPS sampling
FPGA+CPU
Bullet WiFi data transfert

GRAND Technical Challenges

- How to collect data?
  - Optimised trigger (machine learning (?), see Führer et al. ARENA2018) to improve selection @ antenna level
  - Optimised informations to be transmitted to central DAQ
- How to identify air showers out of the ultra dominant background ?
  - Specific signatures of air shower radio signals vs background transients demonstrated (TREND offline selection algorithm: 1 event out 10^8 pass & final sample background contamination < 20%)
  - Improved setup (GRANDproto35, being deployed) should lead to even better performances
  - Deep learning techniques
- How well can we reconstruct the primary particle information
  - Simulations promising (similar performances as for standard showers) + deep learning technique

Need for an experimental setup to test and optimize techniques

GRAND

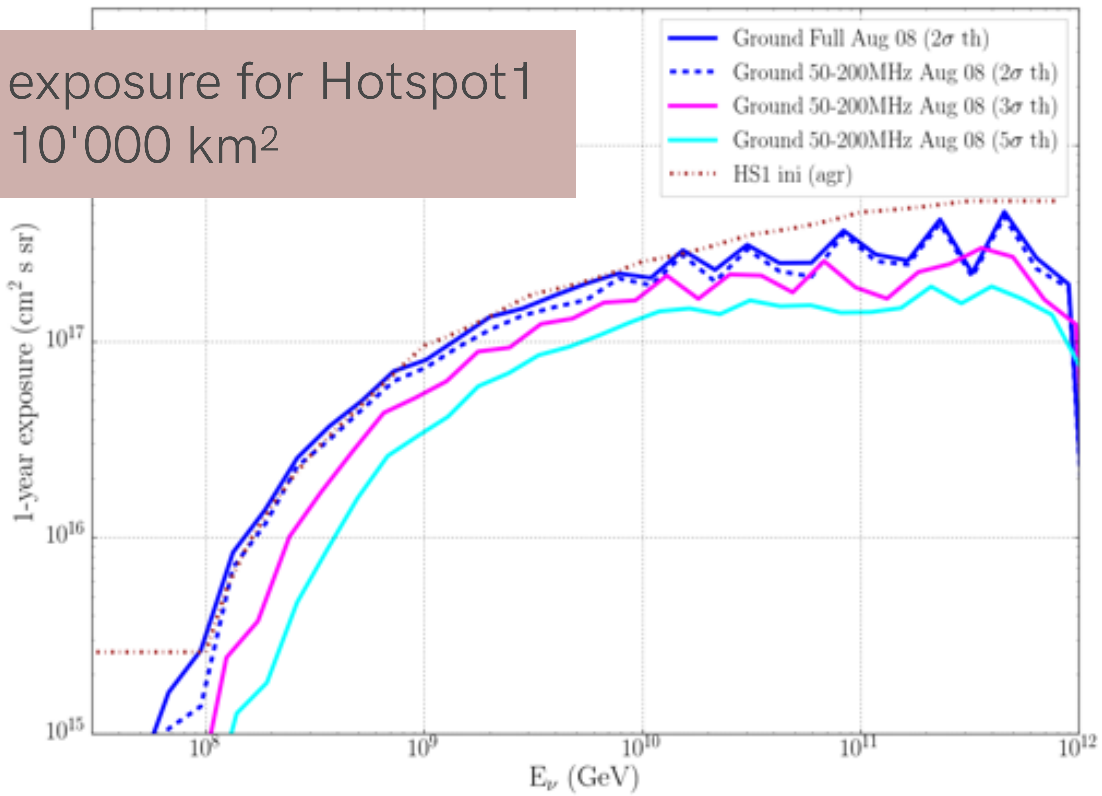
GRANDProto300

- How to deploy and run 200,000 units over 200,000km^2?
- How much will it cost? Who will pay for it?

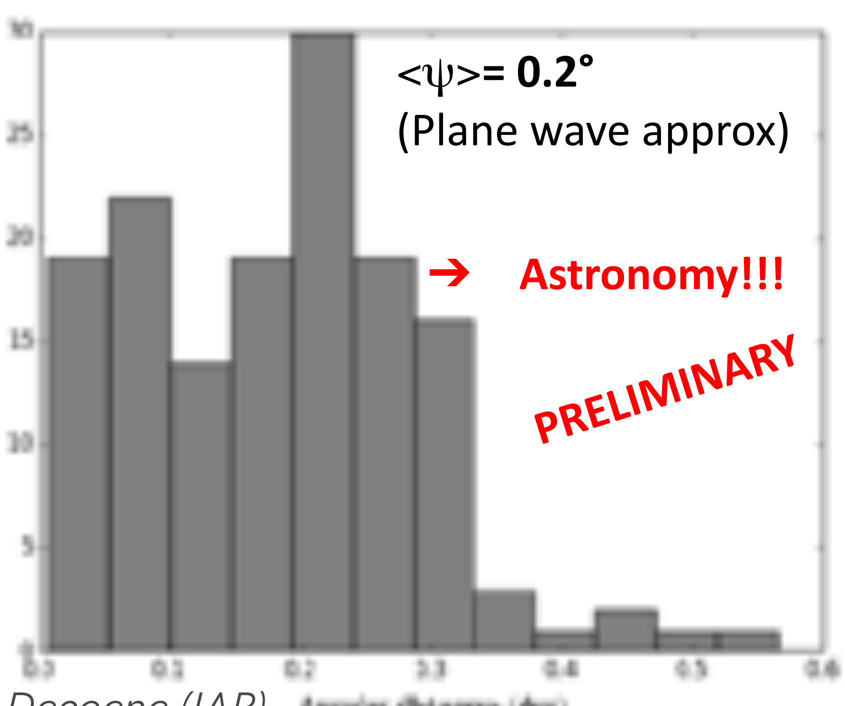
go for industrial approach! answers to be studied at later stage

Simulated performances

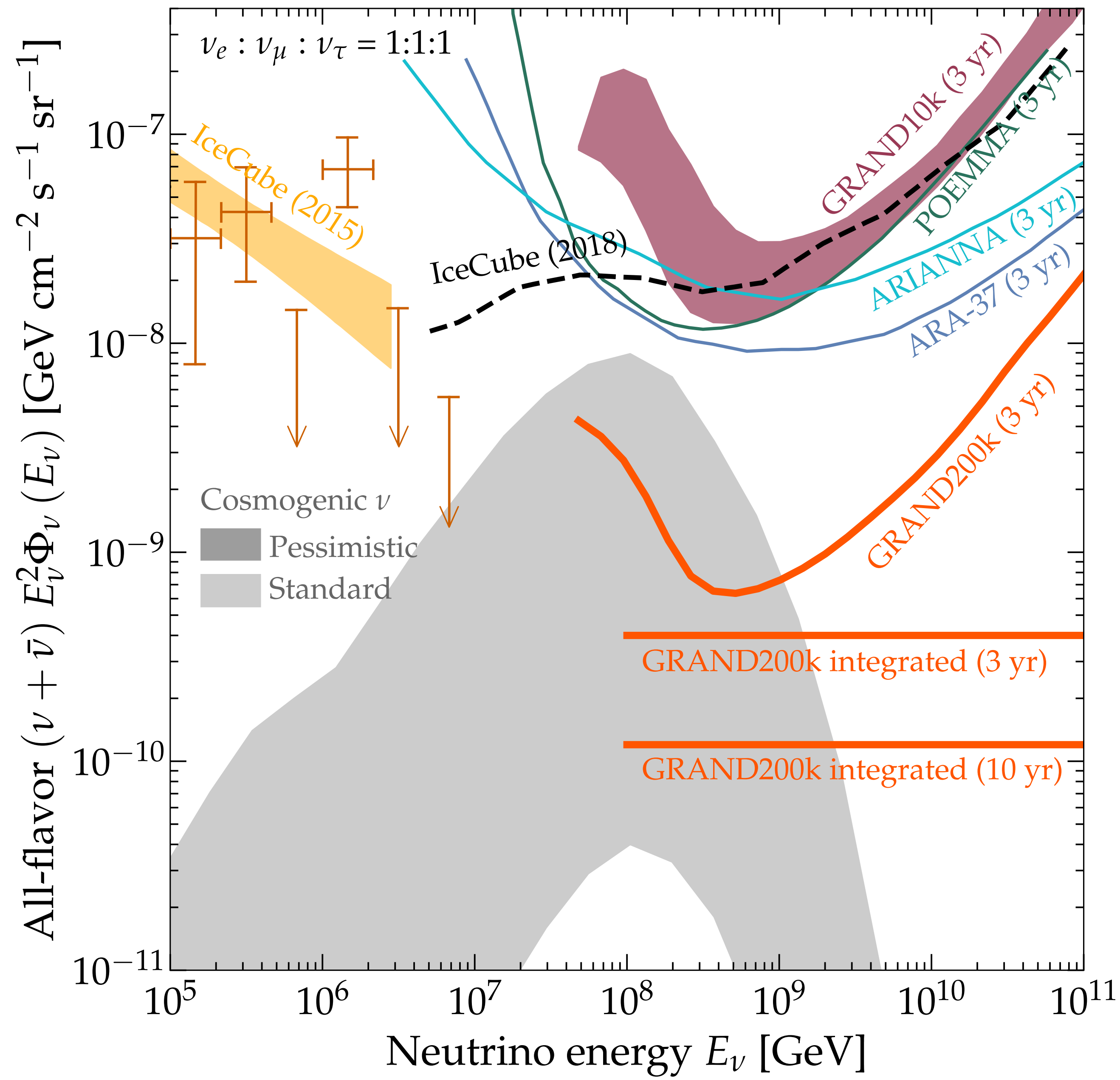
exposure for Hotspot1
10'000 km²



~0.1-0.3° angular resolution for GP300
also achievable for Hotspot1



V. Decoene (IAP)



GRAND full sensitivity ($E>10^{17}$ eV)
~4×10^{-10} GeV cm^{-2} s^{-1} sr^{-1}

X_{max} resolution:
< 40 g/cm^2 achievable for
$E>10^{19}$ eV
with GP300 & further stages

C. Guépin, A. Zilles (IAP)

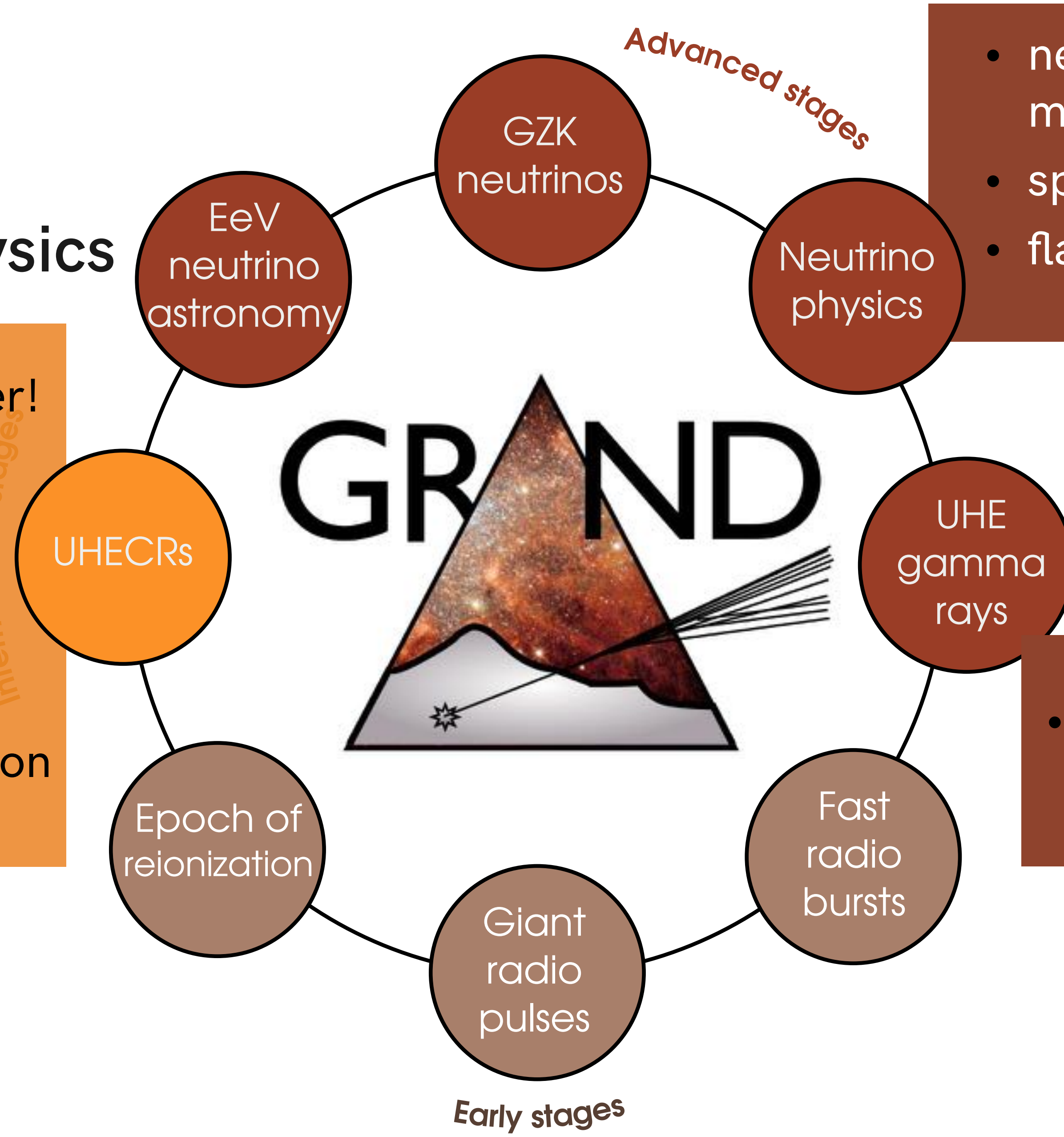
A rich science case

neutrino physics

- neutrino cross-section measurements
- spectral, angular distortions
- flavor ratios

UHECR, hadronic physics

- 20 times the exposure of Auger!
- GRANDProto300: transition from Galactic/ extragalactic
- hadronic physics: muon discrepancy, UHECR mass composition, p-air cross-section



UHE gamma rays

- competitive with Auger at GRANDProto300 stage

radio-astronomy in a novel way

- unphased integration of signals: an almost full-sky survey of radio signals
- can detect FRBs and Giant Radio pulses of the Crab already at the GRANDProto300 stage

GRAND Today

France China Particle Physics Laboratory

Natural Science Foundation of China

France China Particle Physics Laboratory

Chinese Academy of Science

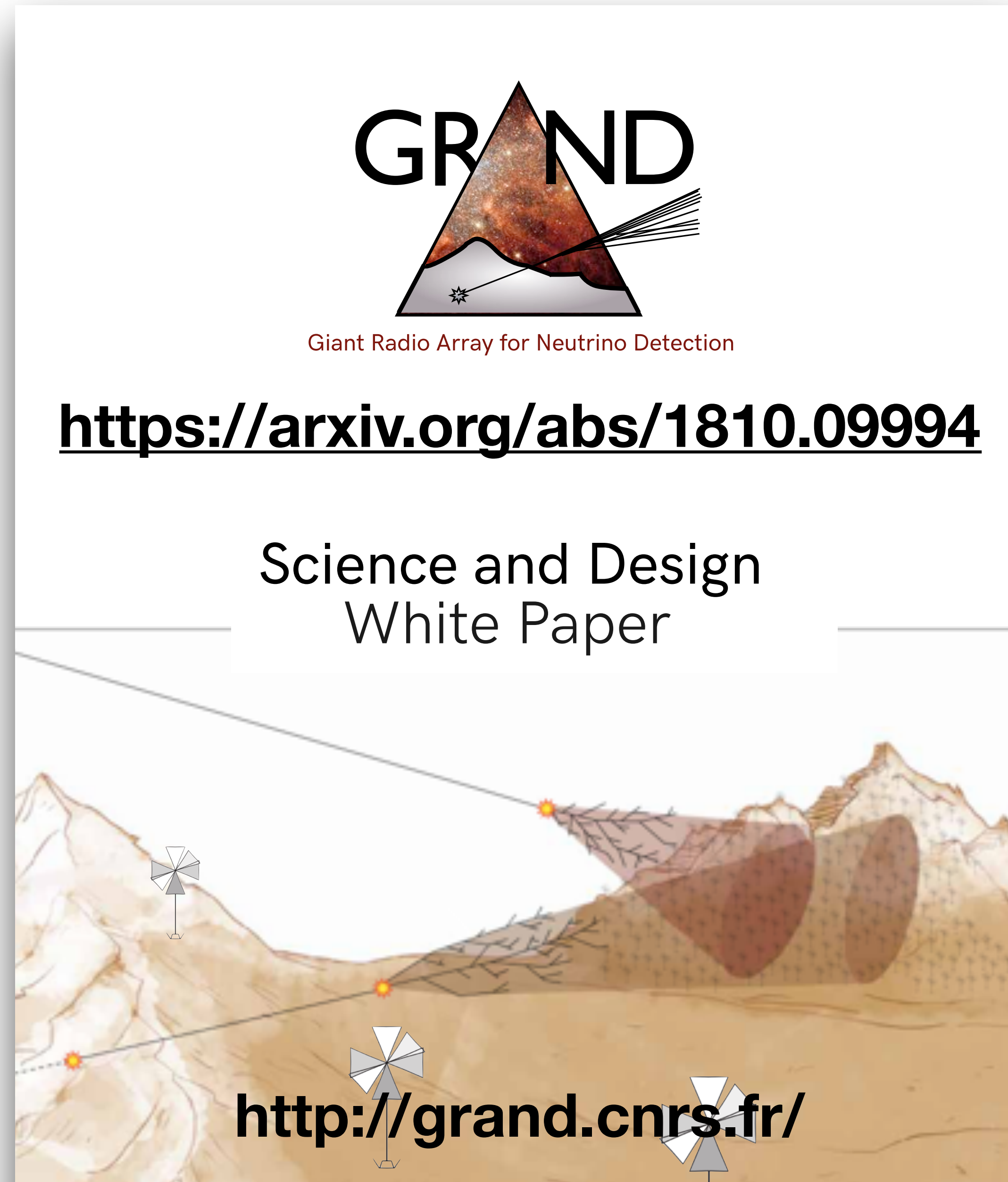
Jaime Álvarez-Muñiz[1], Rafael Alves Batista[2,3], Aswathi Balagopal V.[4], Julien Bolmont[5], Mauricio Bustamante[6,7,8,†], Washington Carvalho Jr.[9], Didier Charrier[10], Ismaël Cognard[11,12], Valentin Decoene[13], Peter B. Denton[6], Sijbrand De Jong[14,15], Krijn D. De Vries[16], Ralph Engel[17], Ke Fang[18,19,20], Chad Finley[21,22], Stefano Gabici[23], QuanBu Gou[24], Junhua Gu[25], Claire Guépin[13], Hongbo Hu[24], Yan Huang[25], Kumiko Kotera[13,*], Sandra Le Coz[25], Jean-Philippe Lenain[5], Guoliang Lü[26], Olivier Martineau-Huynh[5,25,*], Miguel Mostafá[27,28,29], Fabrice Mottez[30], Kohta Murase[27,28,29], Valentin Niess[31], Foteini Oikonomou[32,27,28,29], Tanguy Pierog[17], Xiangli Qian[33], Bo Qin[25], Duan Ran[25], Nicolas Renault-Tinacci[13], Markus Roth[17], Frank G. Schröder[34,17], Fabian Schüssler[35], Cyril Tasse[36], Charles Timmermans[14,15], Matías Tueros[37], Xiangping Wu[38,25,*], Philippe Zarka[39], Andreas Zech[30], B. Theodore Zhang[40,41], Jianli Zhang[25], Yi Zhang[24], Qian Zheng[42,24], Anne Zilles[13]

~50 collaborators from 10 countries

France (15), China (7), USA (7), Netherlands (2), Germany (2), Copenhagen (1), Spain (2), Brazil (2), Belgium, Argentina, Sweden

GRAND Workshop, IAP, August 2018

electronics prototyping: Nikhef/Radboud U., NAOC
antenna prototyping: Subatech, Xidian U.
production: NAOC, Xidian U.
simulations: IAP, LPNHE, Clermont-Ferrand, VUB
particle detectors: Penn State U.
computing resources: KIT
site management: NAOC



GRAND

join us and bring your ideas!

http://grand.cnrs.fr/