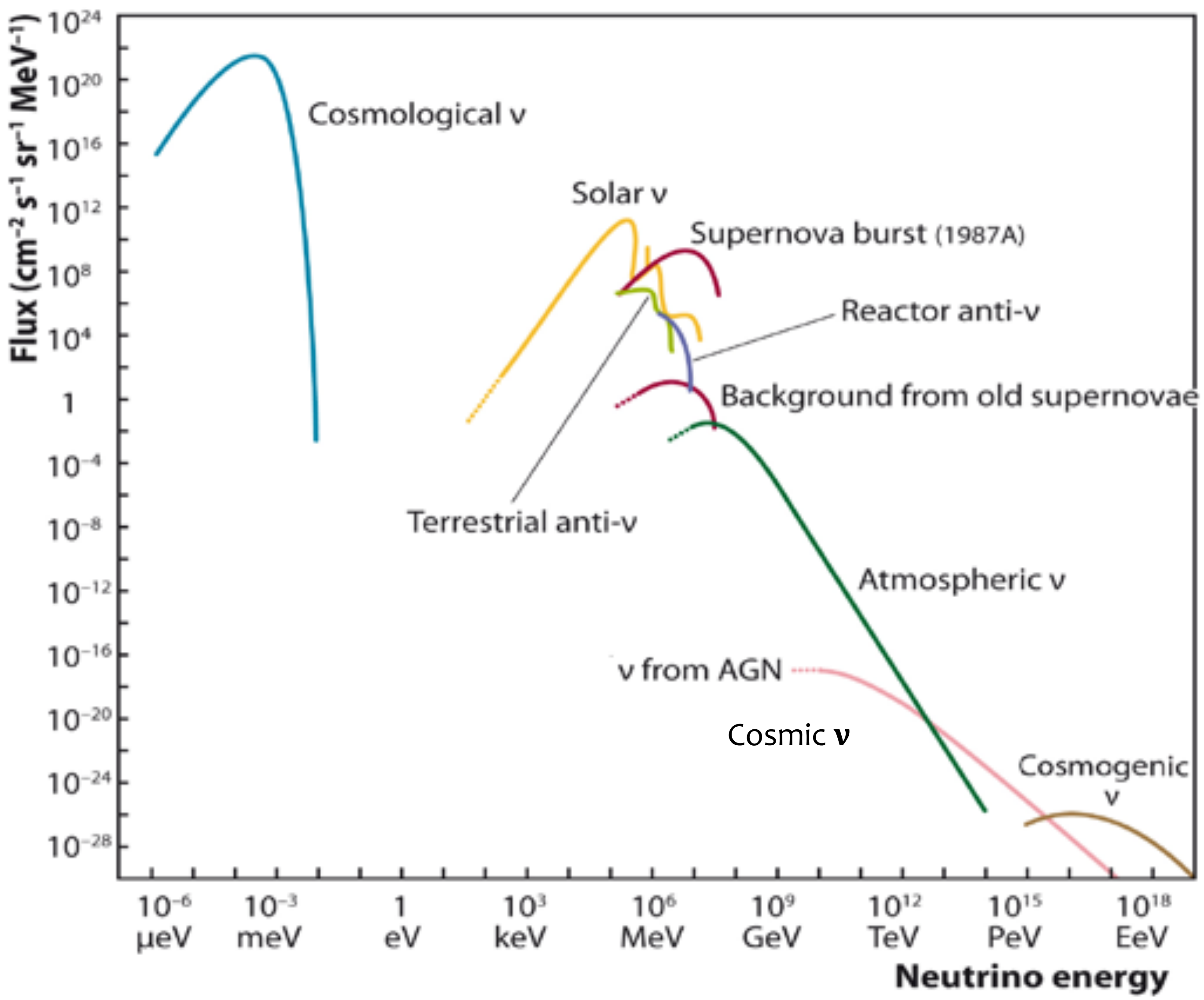
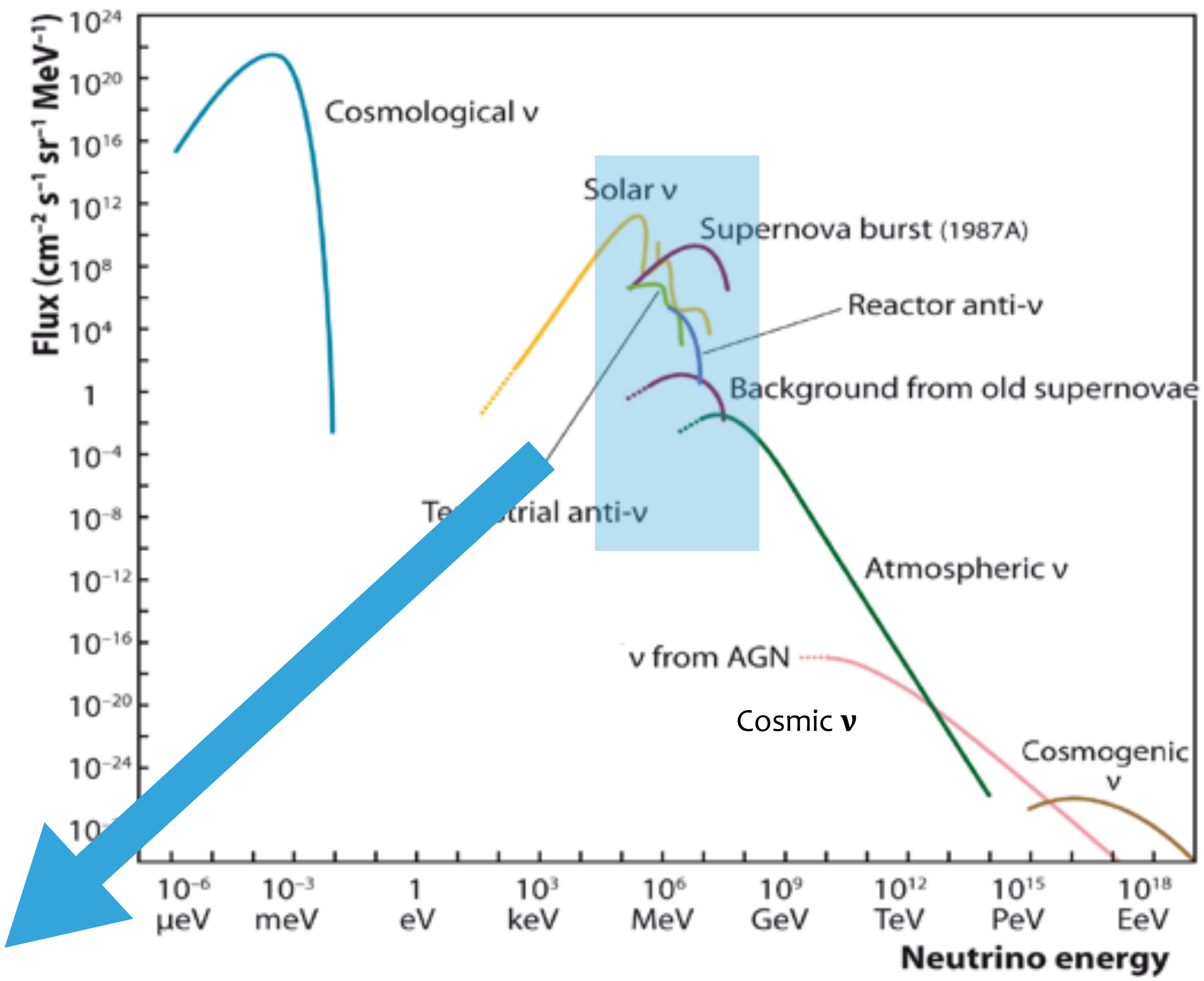
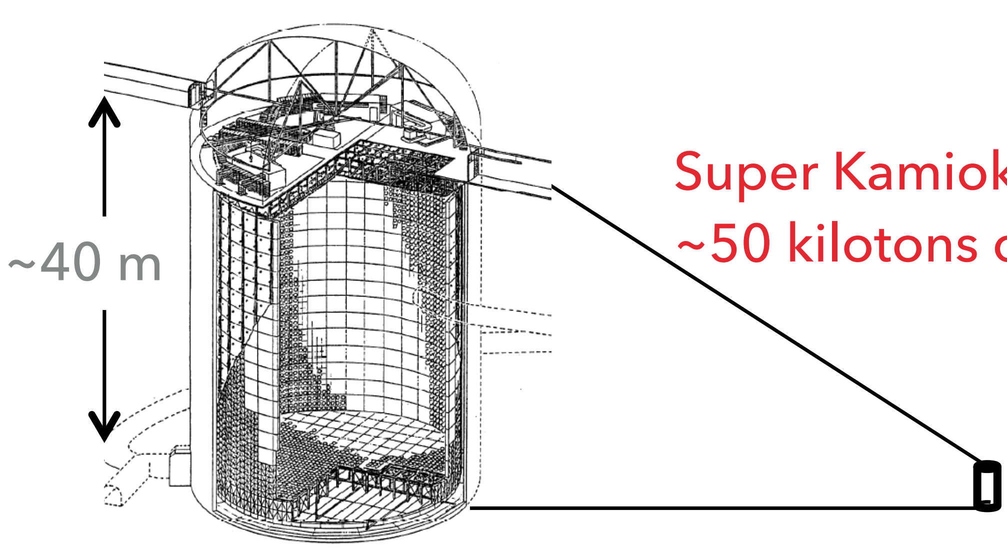
NEUTRINO TELESCOPES AND TRANSIENT SOURCES

ALEXIS COLEIRO

Atelier PNHE Transient Sky TS2020 | LAL Orsay | June 20 - 22 2017

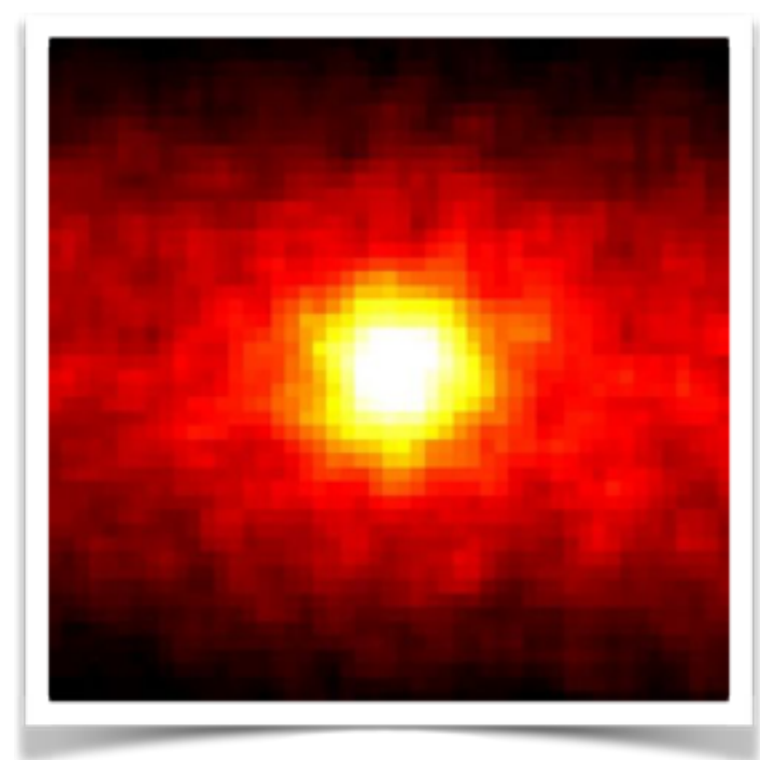

Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmic ν
Cosmogenic ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

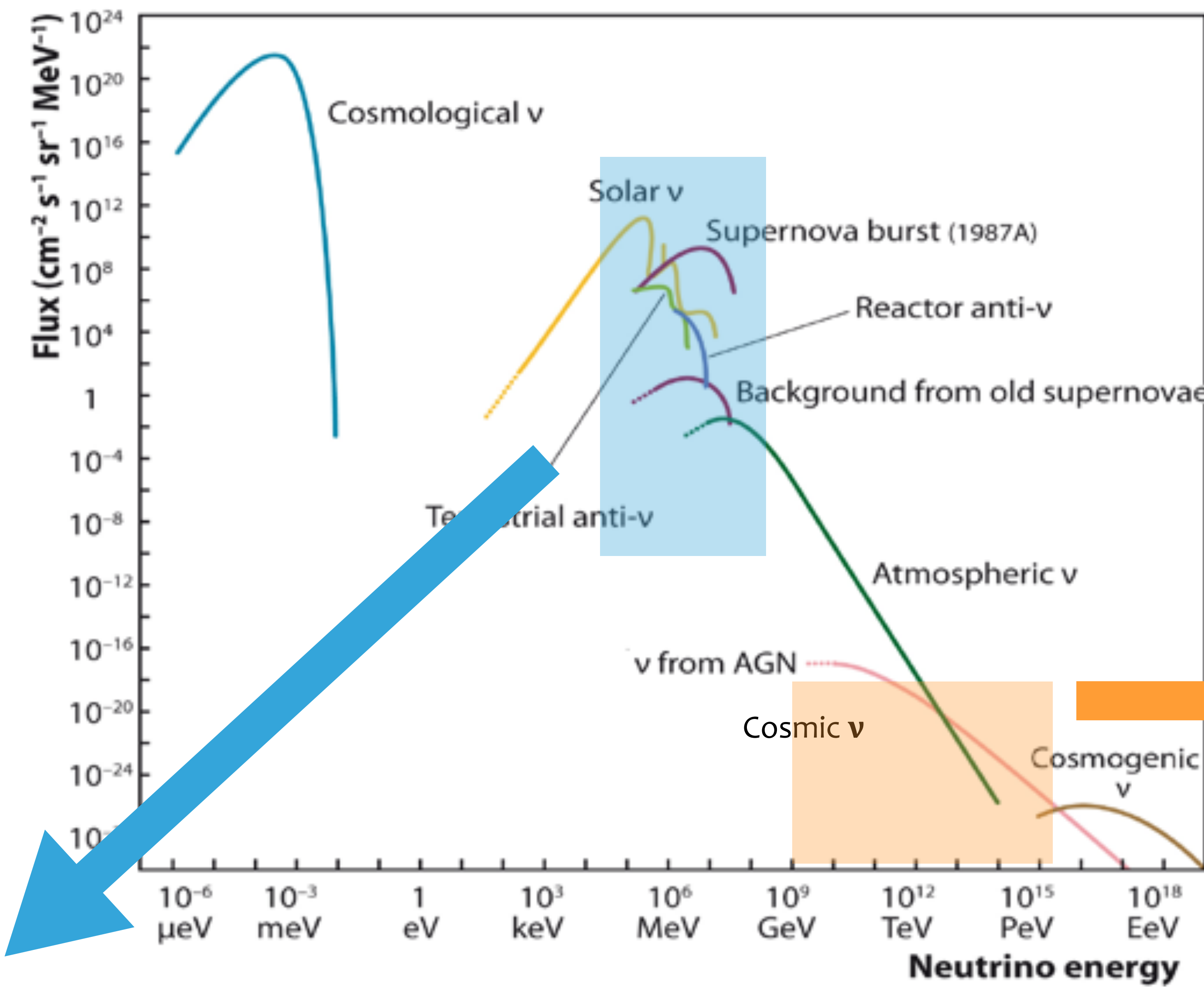




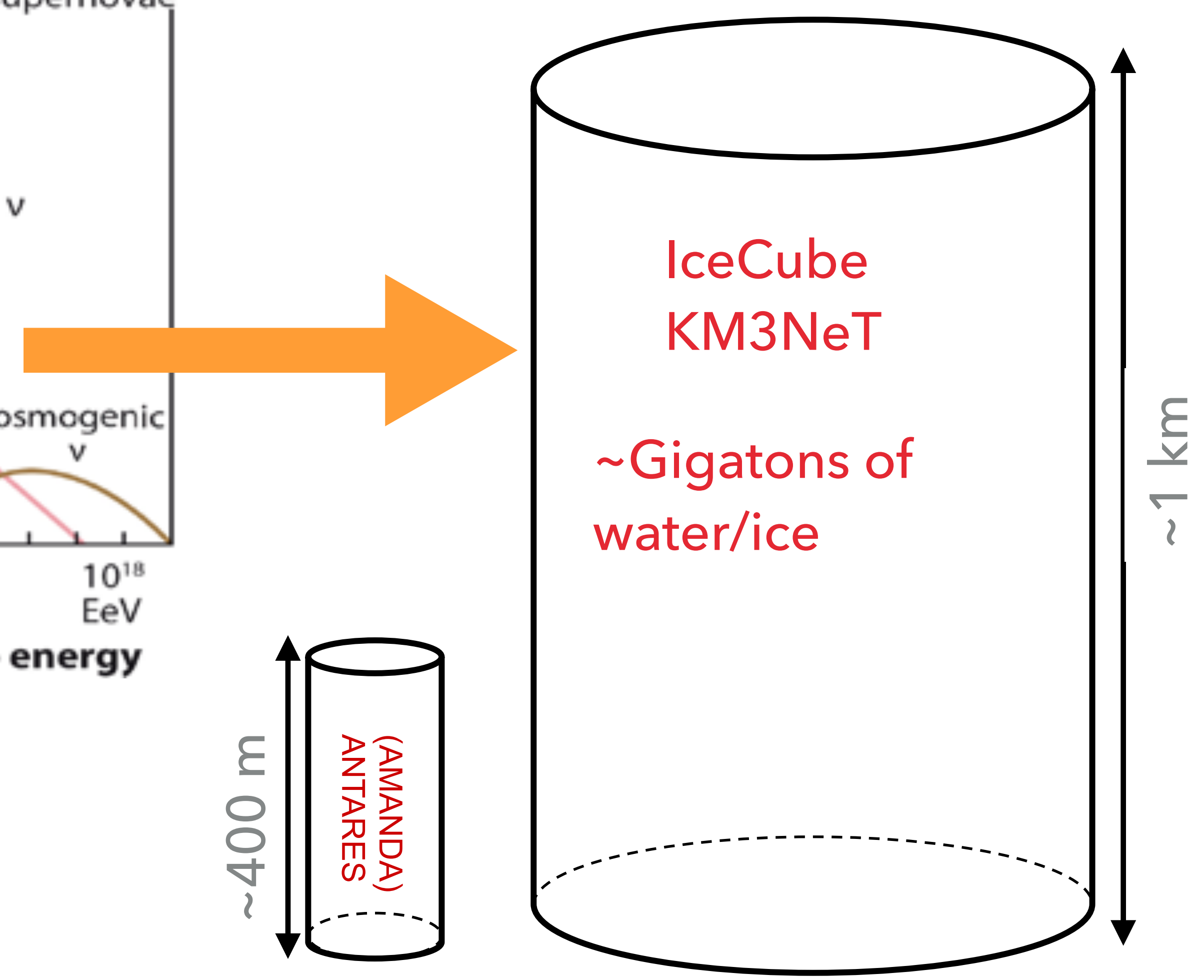
Super Kamiokande
~50 kilotons of water

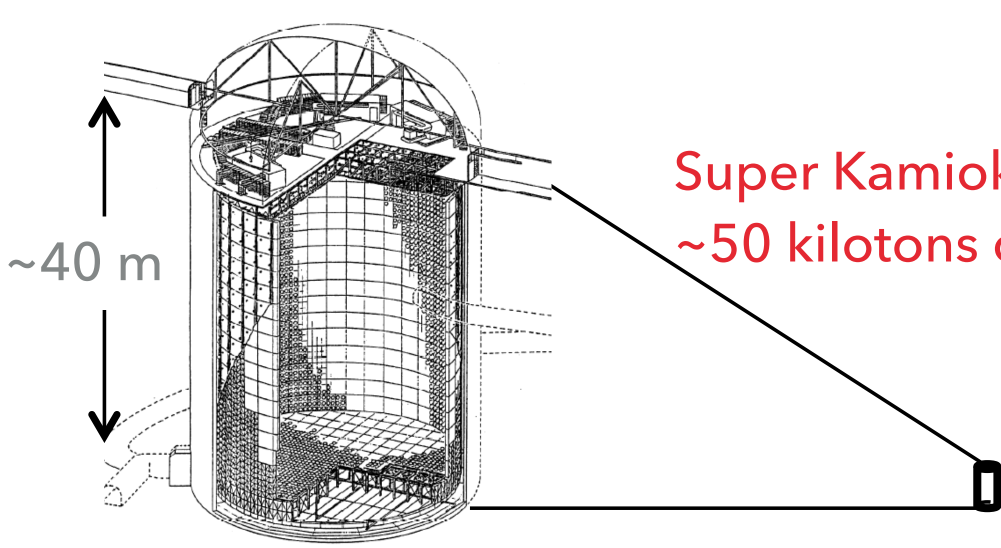
Sun: with 500 days of exposure (90°x90°) from Super-Kamiokande





Neutrino astronomy needs km^3 scale detectors



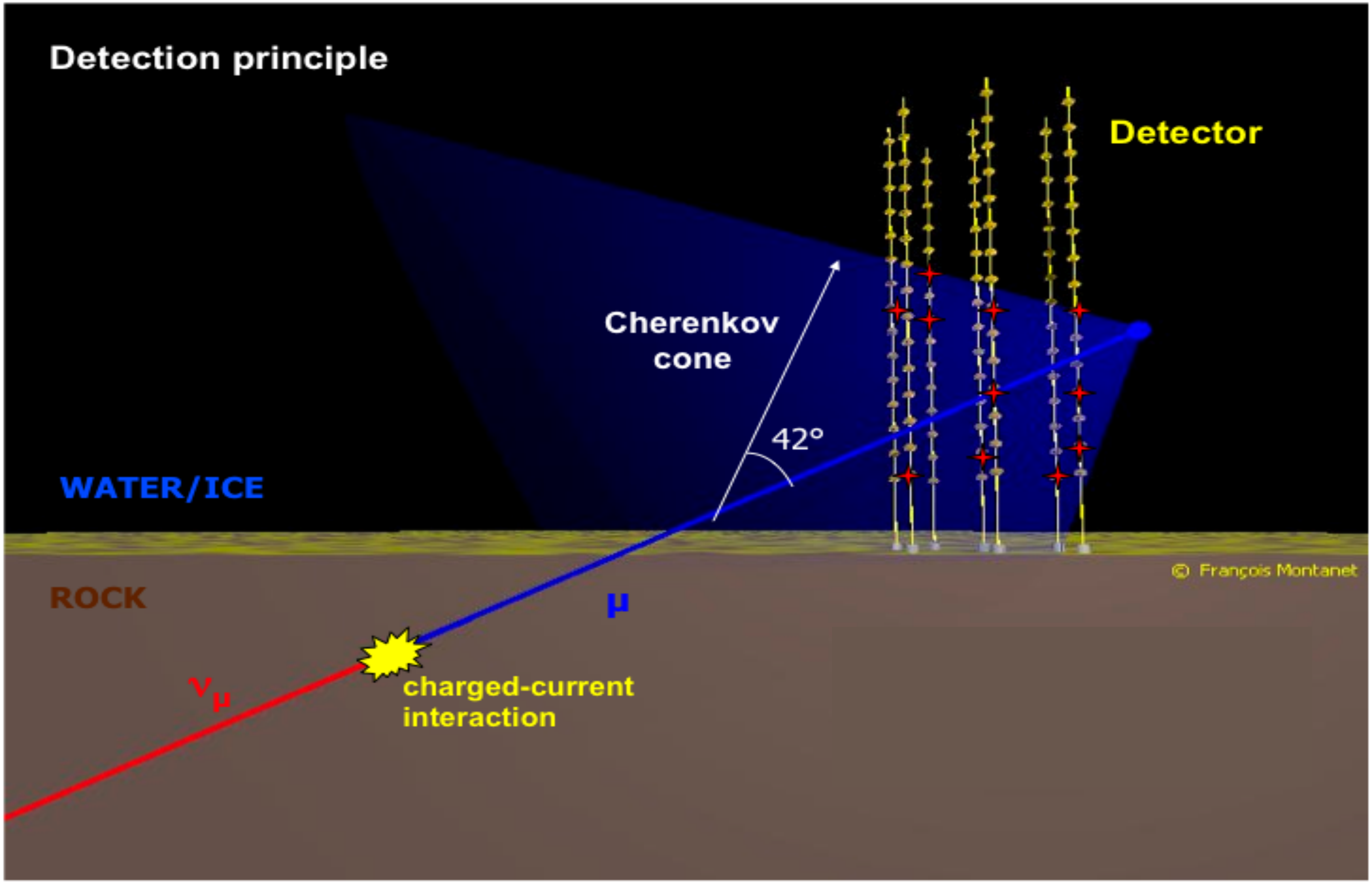


Super Kamiokande
~50 kilotons of water

ν are weakly interacting + low cosmic flux → requires large instrumented volumes under sea/ice to reduce the muon background

Different ways to detect HE ν.

One way particularly useful in astronomy:
observation of muons produced in CC interaction of ν_μ



Different ways to detect HE ν.
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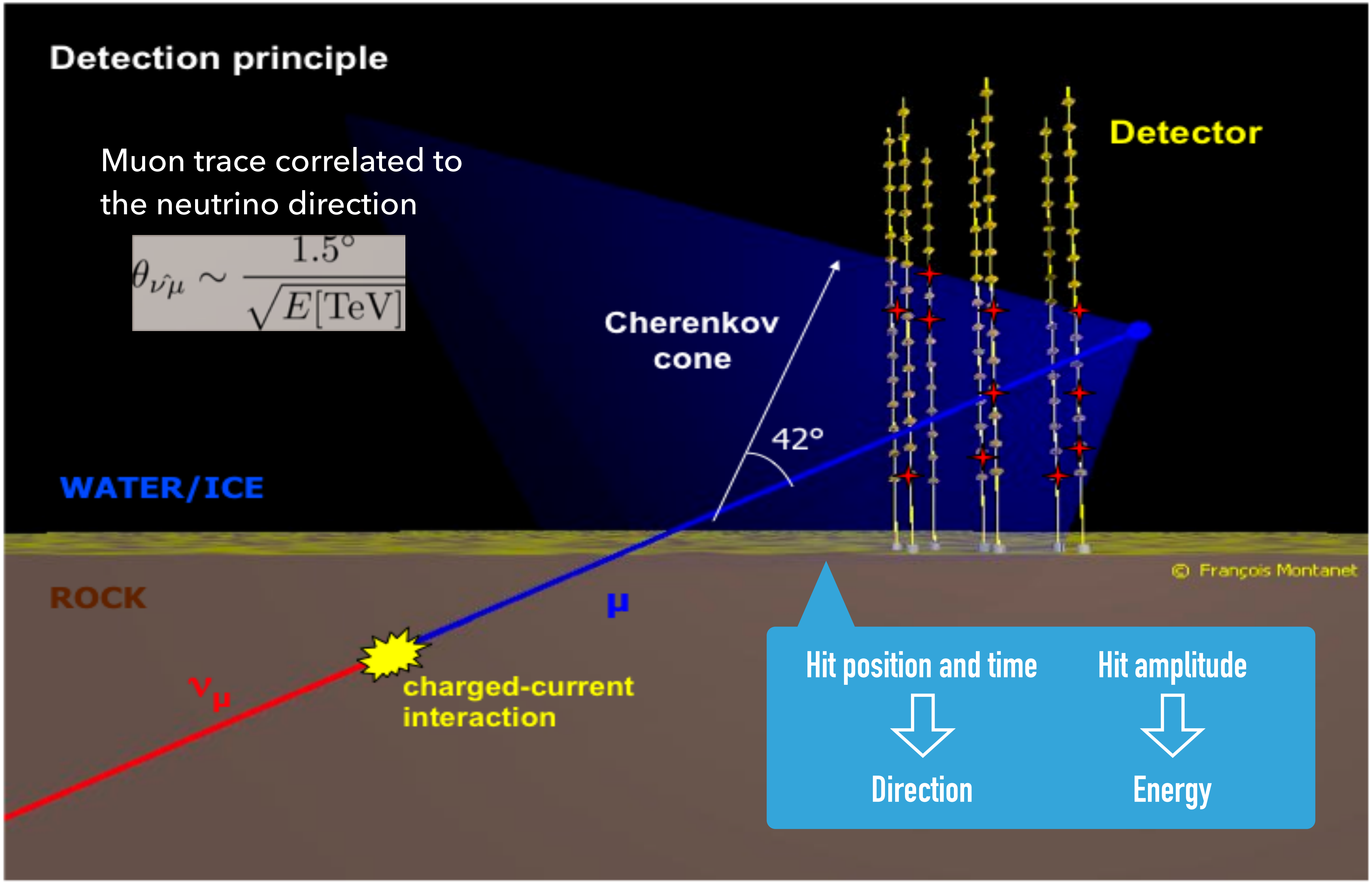
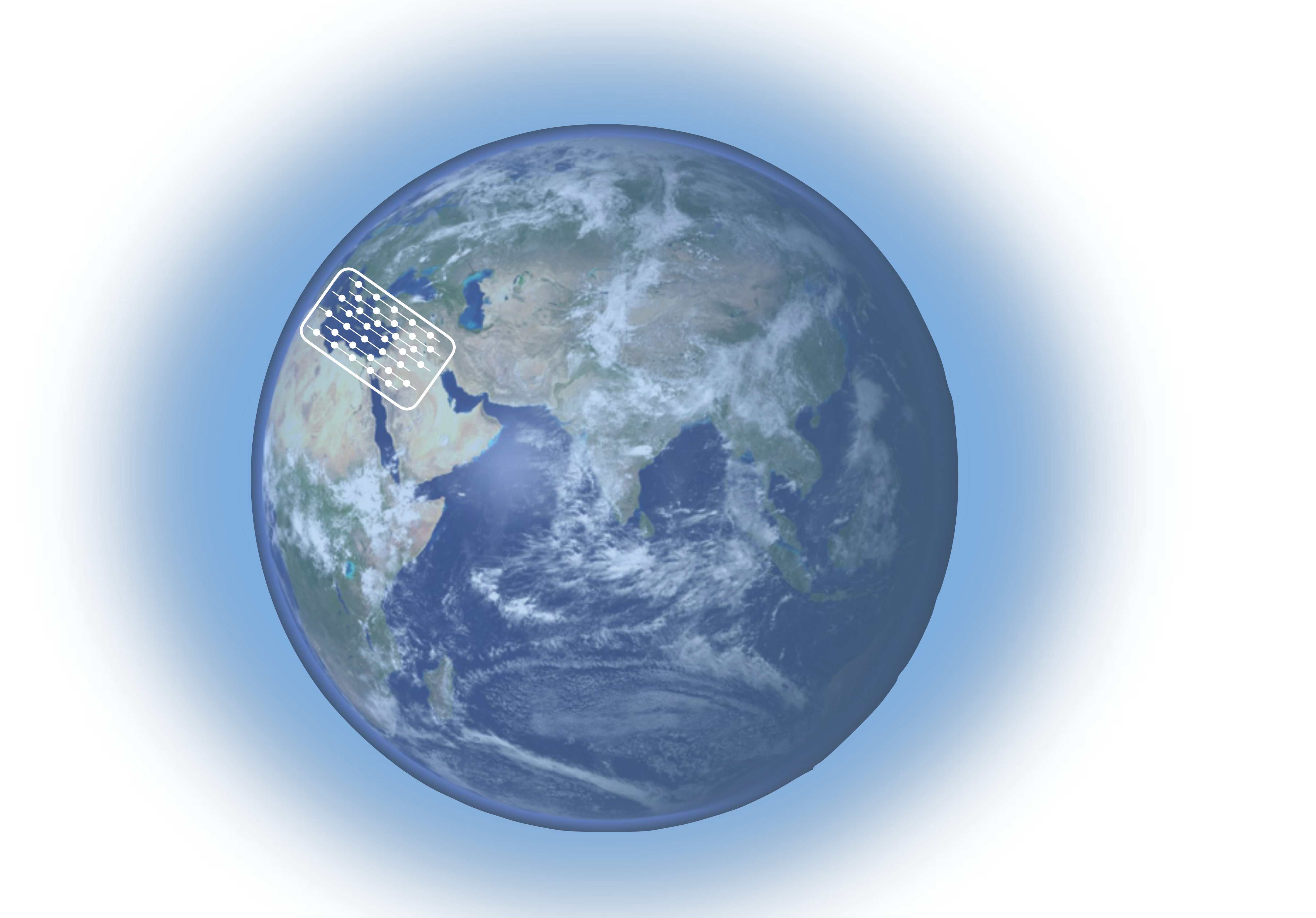
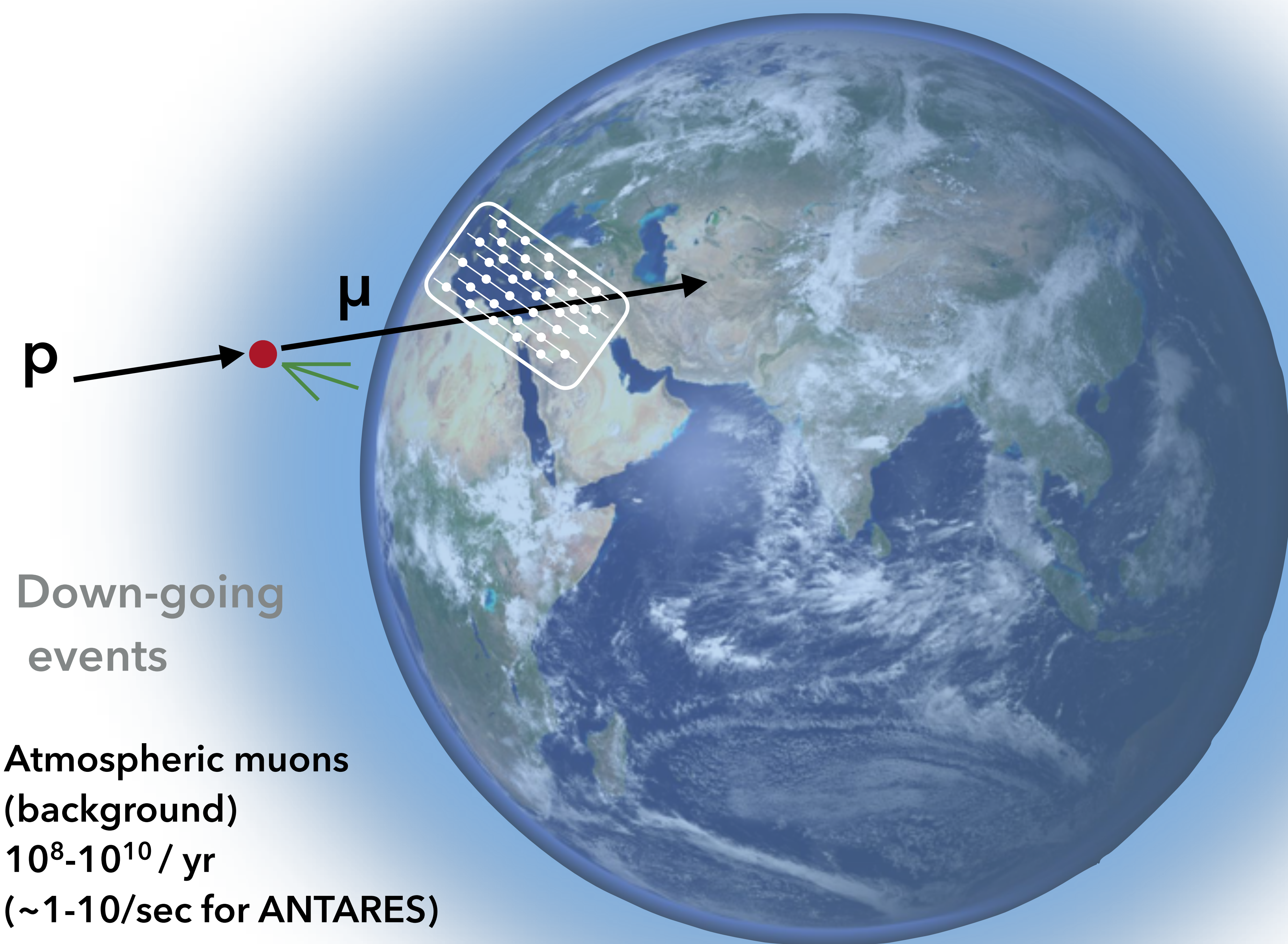




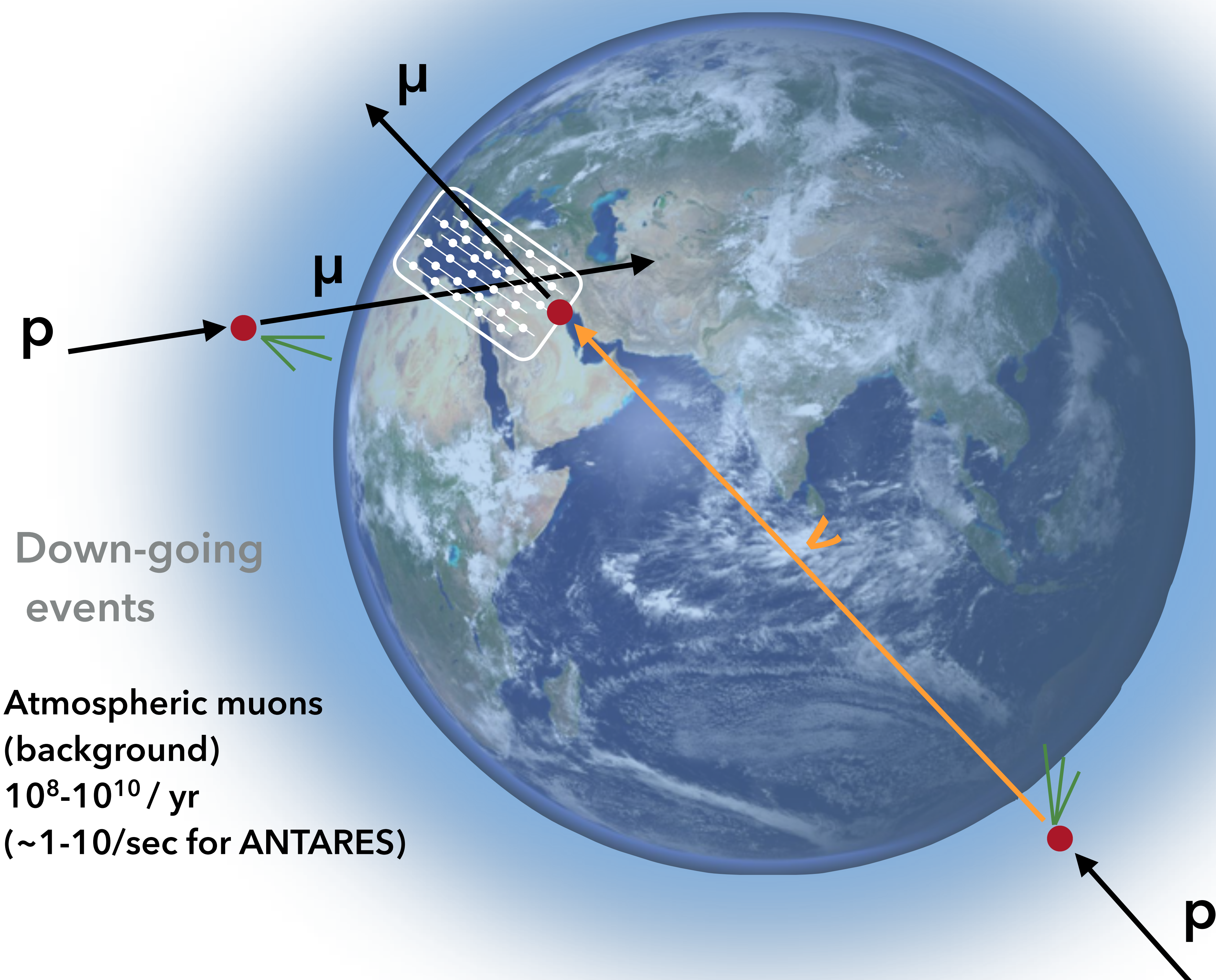


Down-going events

Atmospheric muons (background)
10^8-10^{10} / yr
(~1-10/sec for ANTARES)

Up-going events

Atmospheric neutrinos (background)
10^3-10^5 / yr
(a few/day for ANTARES)



Down-going events

Atmospheric muons (background)
10^8-10^{10} / yr
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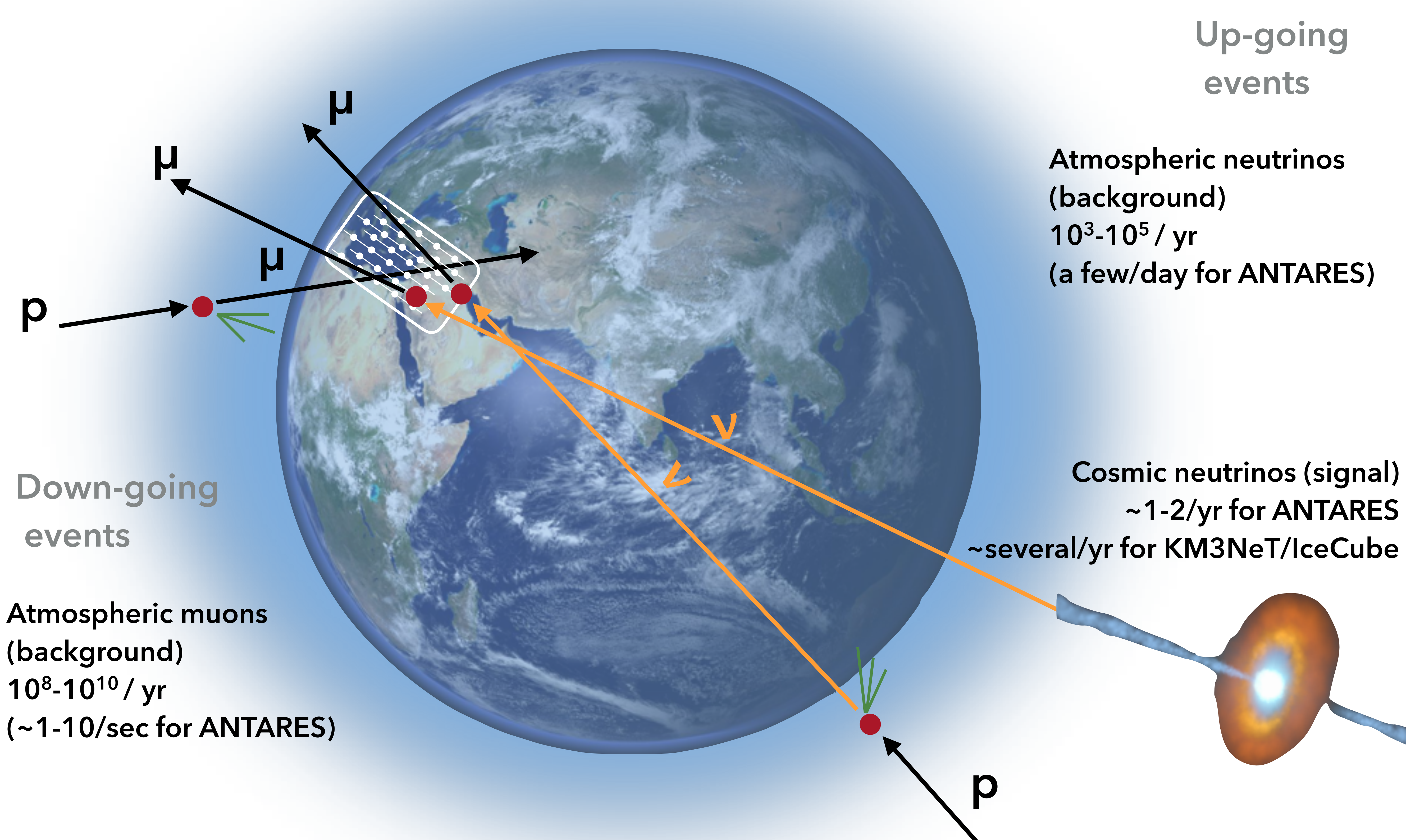
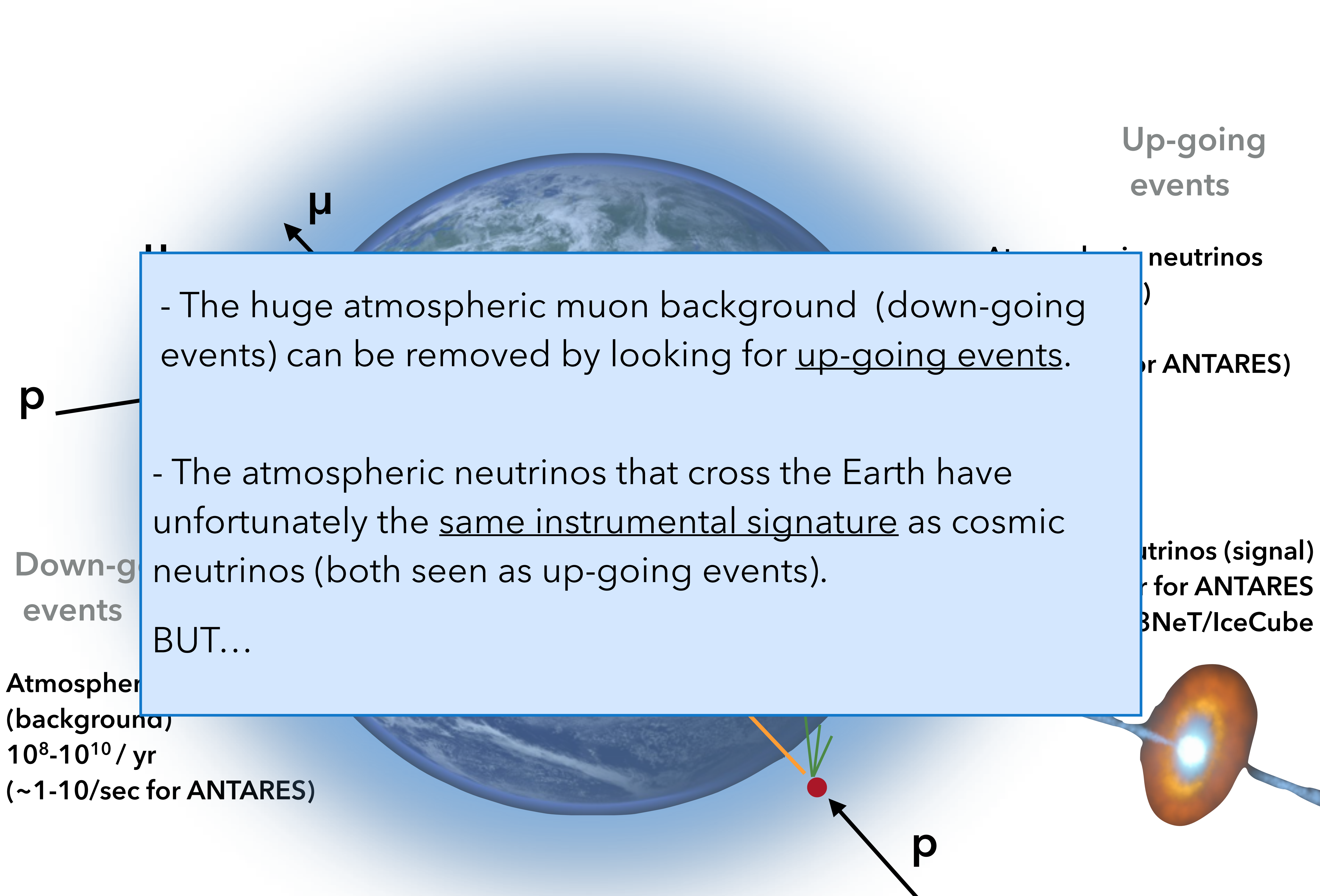

Up-going
events
Atmospheric neutrinos
(background)
10^3-10^5 / yr
(a few/day for ANTARES)
μ
μ
μ
p
ν
ν
Cosmic neutrinos (signal)
~1-2/yr for ANTARES
~several/yr for KM3NeT/IceCube
Down-going
events
Atmospheric muons
(background)
10^8-10^{10} / yr
(~1-10/sec for ANTARES)
p

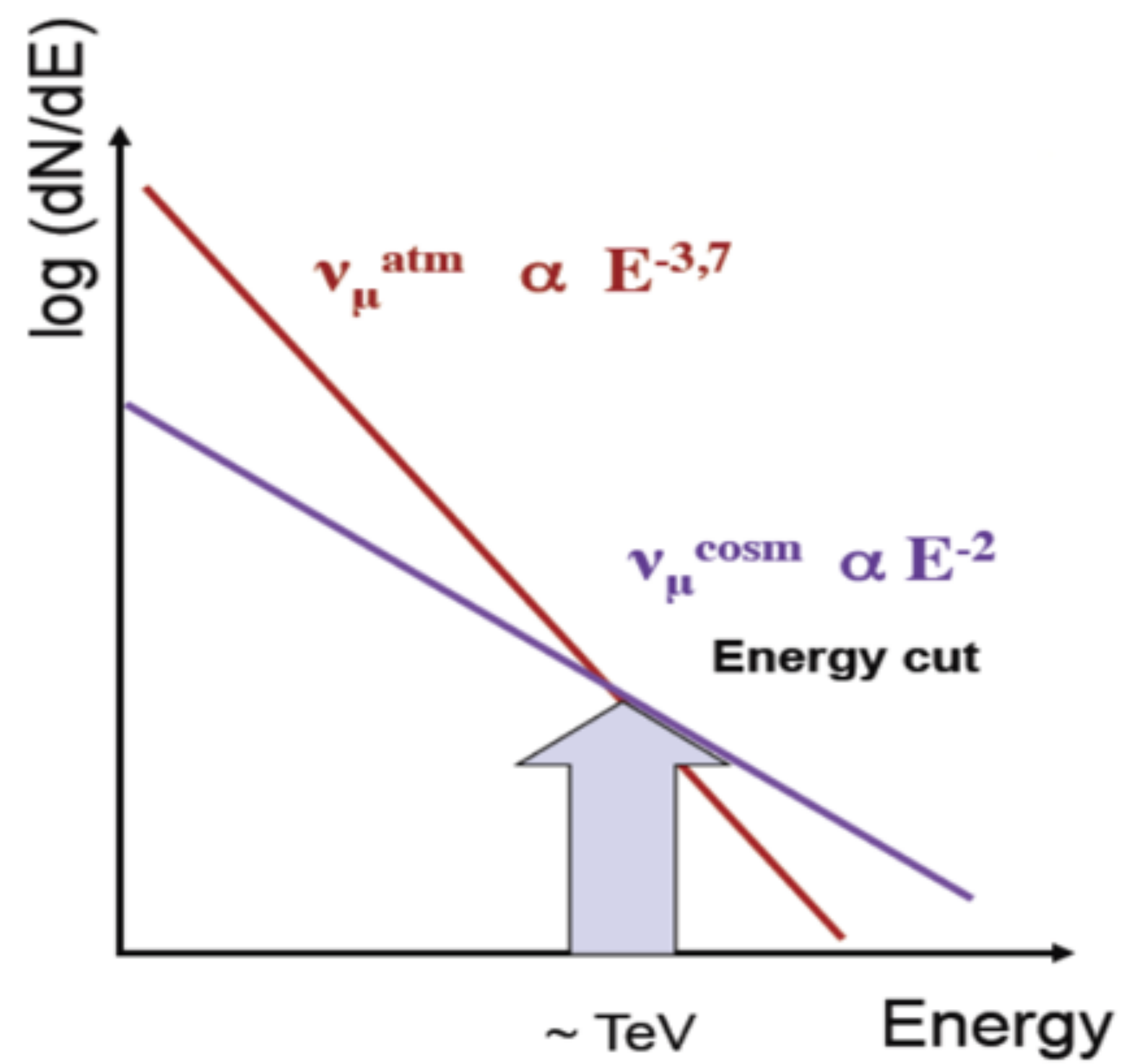


- The huge atmospheric muon background (down-going events) can be removed by looking for <u>up-going events</u>.

- The atmospheric neutrinos that cross the Earth have unfortunately the <u>same instrumental signature</u> as cosmic neutrinos (both seen as up-going events).

BUT…

How to identify cosmic neutrinos ?



But spectrum of atmospheric neutrinos expected to be softer than neutrino spectra from astrophysical sources

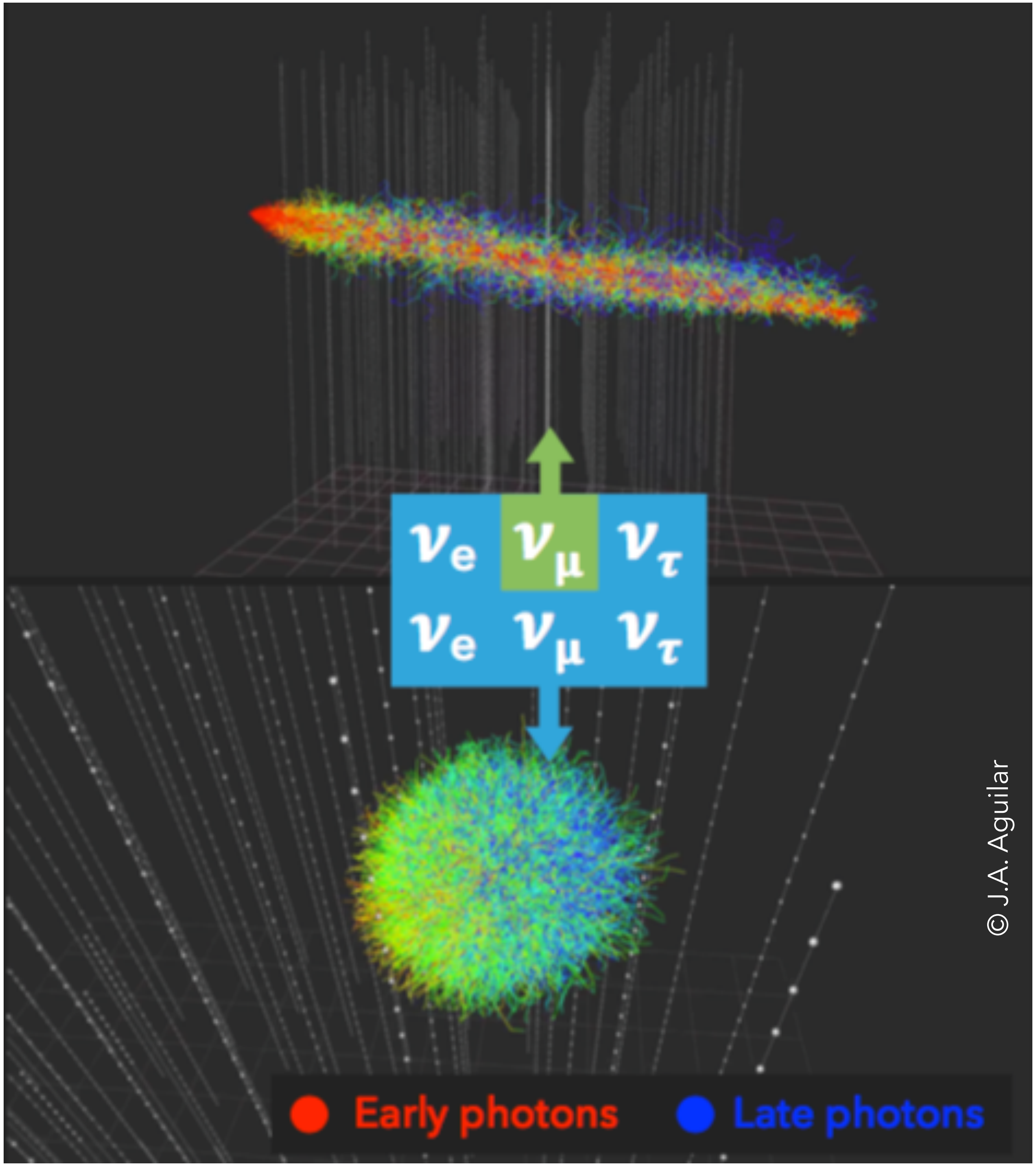
Below ~TeV: difficult to extract astrophysical signal

At high energy: the background should be reduced

Applying a cut in energy should remove most of the atmospheric neutrino background !

Neutrino can interact outside the detector (larger effective volume)

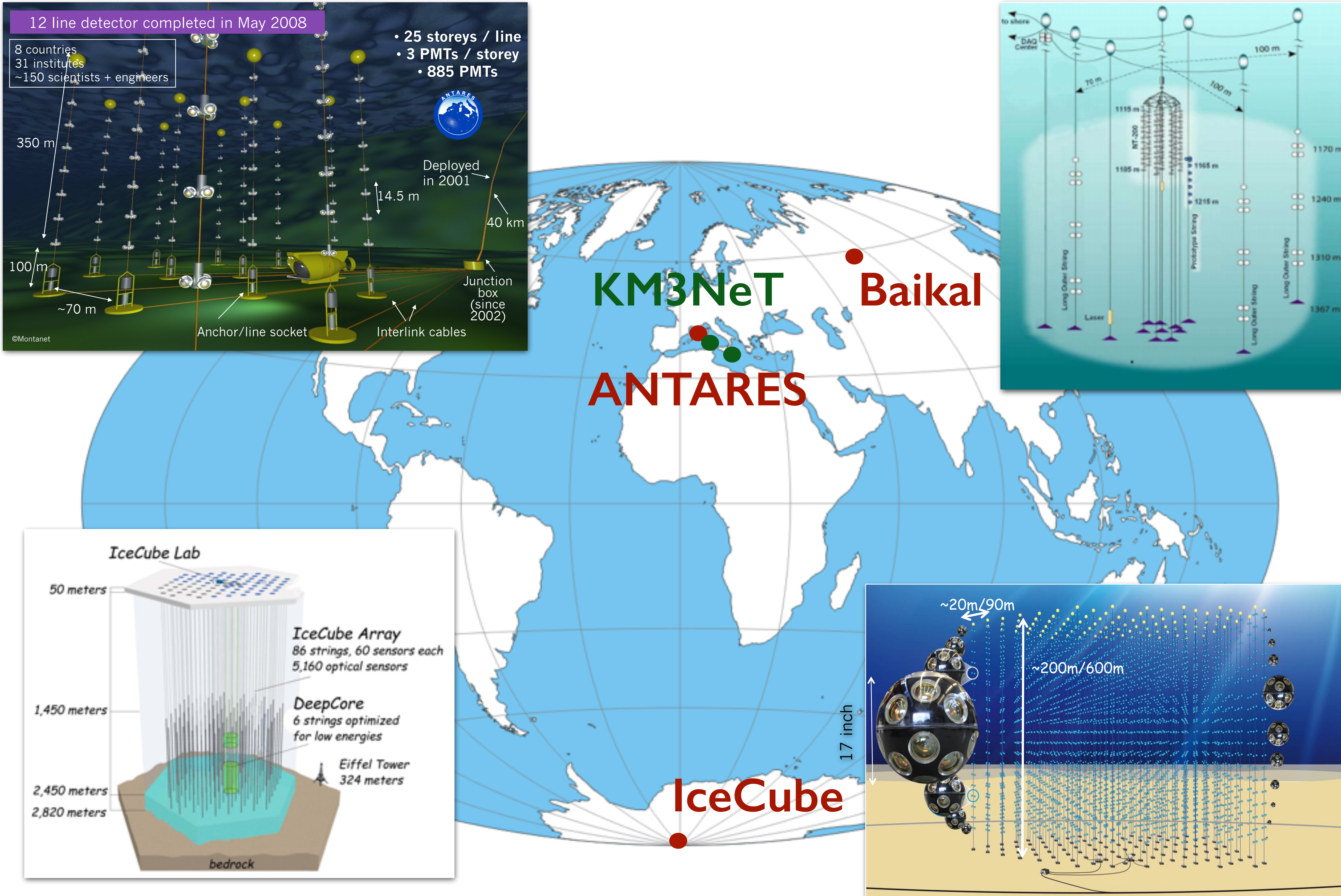
Good angular resolution (~0.2° in the sea)



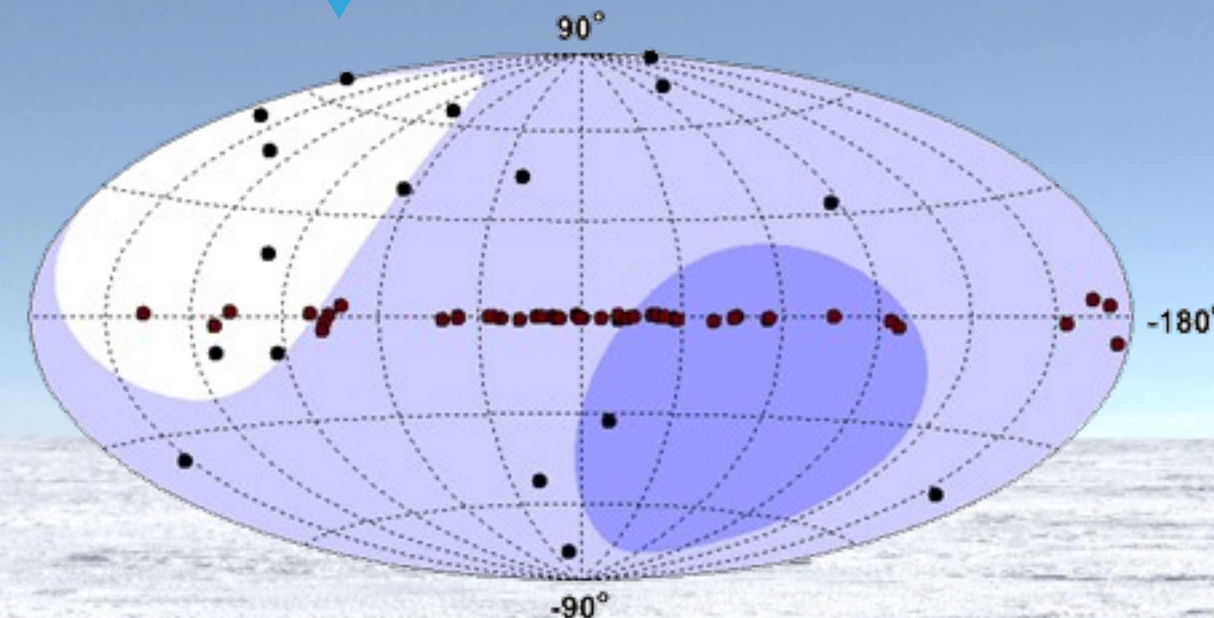
Quasi-spherical events

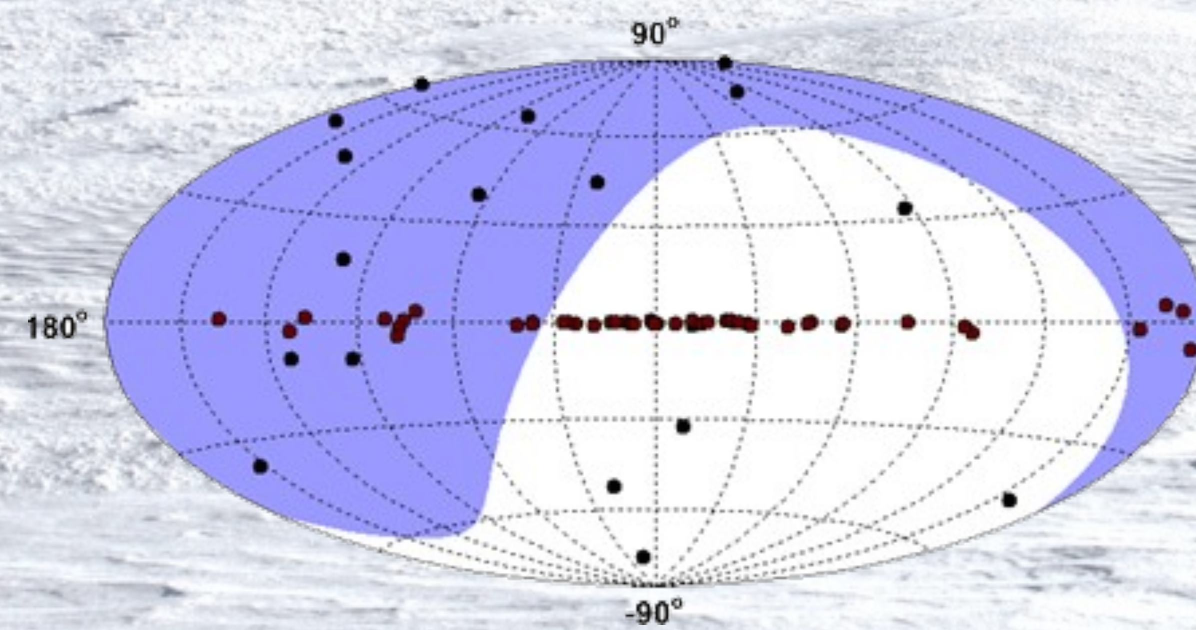
Limited angular resolution (2-10°)

Good energy resolution (10-15%)


12 line detector completed in May 2008
8 countries
31 institutes
~150 scientists + engineers
• 25 storeys / line
• 3 PMTs / storey
• 885 PMTs
350 m
Deployed in 2001
14.5 m
40 km
100 m
~70 m
Junction box (since 2002)
Anchor/line socket
Interlink cables
©Montanet
KM3NeT
Baikal
ANTARES
IceCube
IceCube Lab
50 meters
IceCube Array
86 strings, 60 sensors each
5,160 optical sensors
DeepCore
6 strings optimized for low energies
1,450 meters
Eiffel Tower
324 meters
2,450 meters
2,820 meters
bedrock
~20m/90m
~200m/600m
17 inch
100 m
1170 m
1240 m
1310 m
1367 m

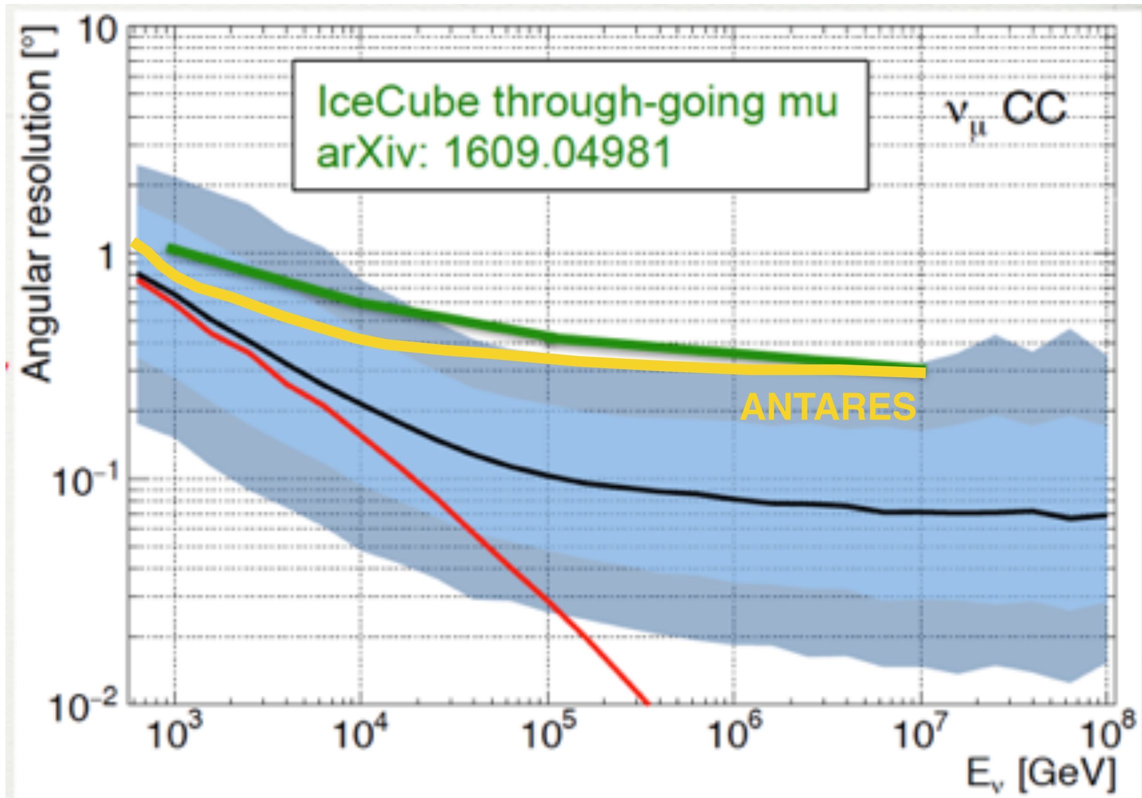
Complementary coverage:
galactic center / extragalactic sources
(true for energy < 100 TeV)

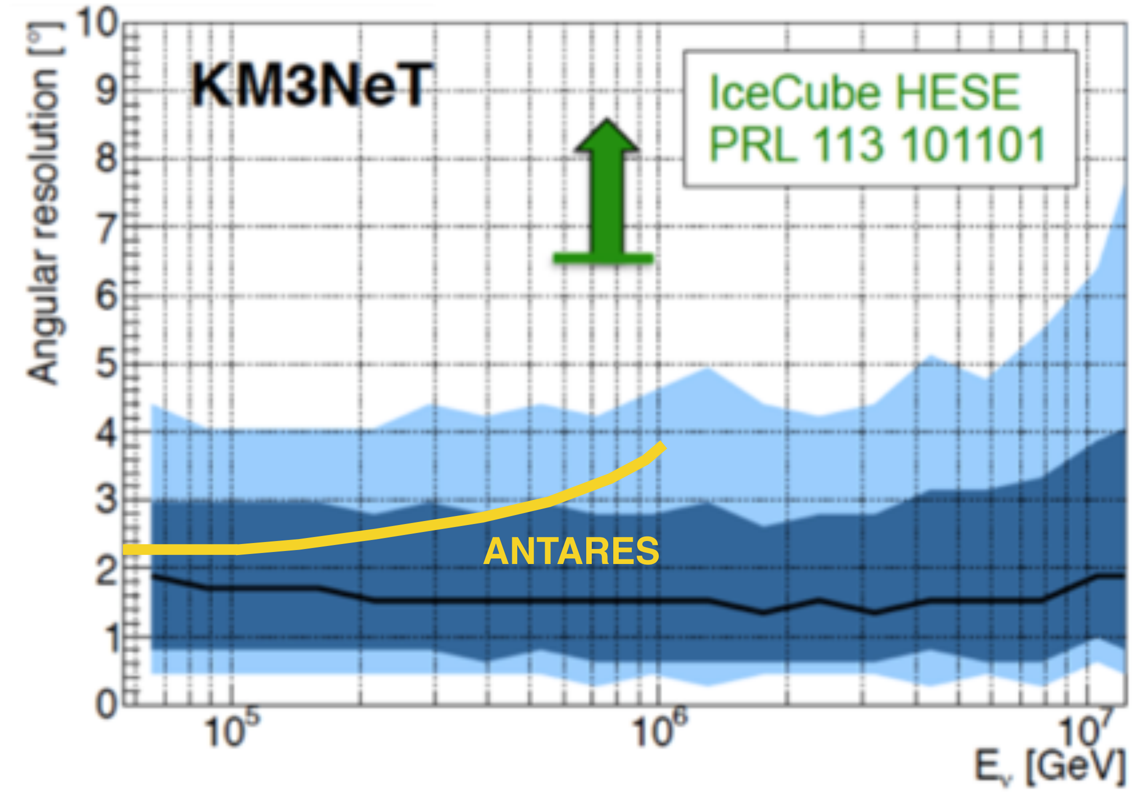




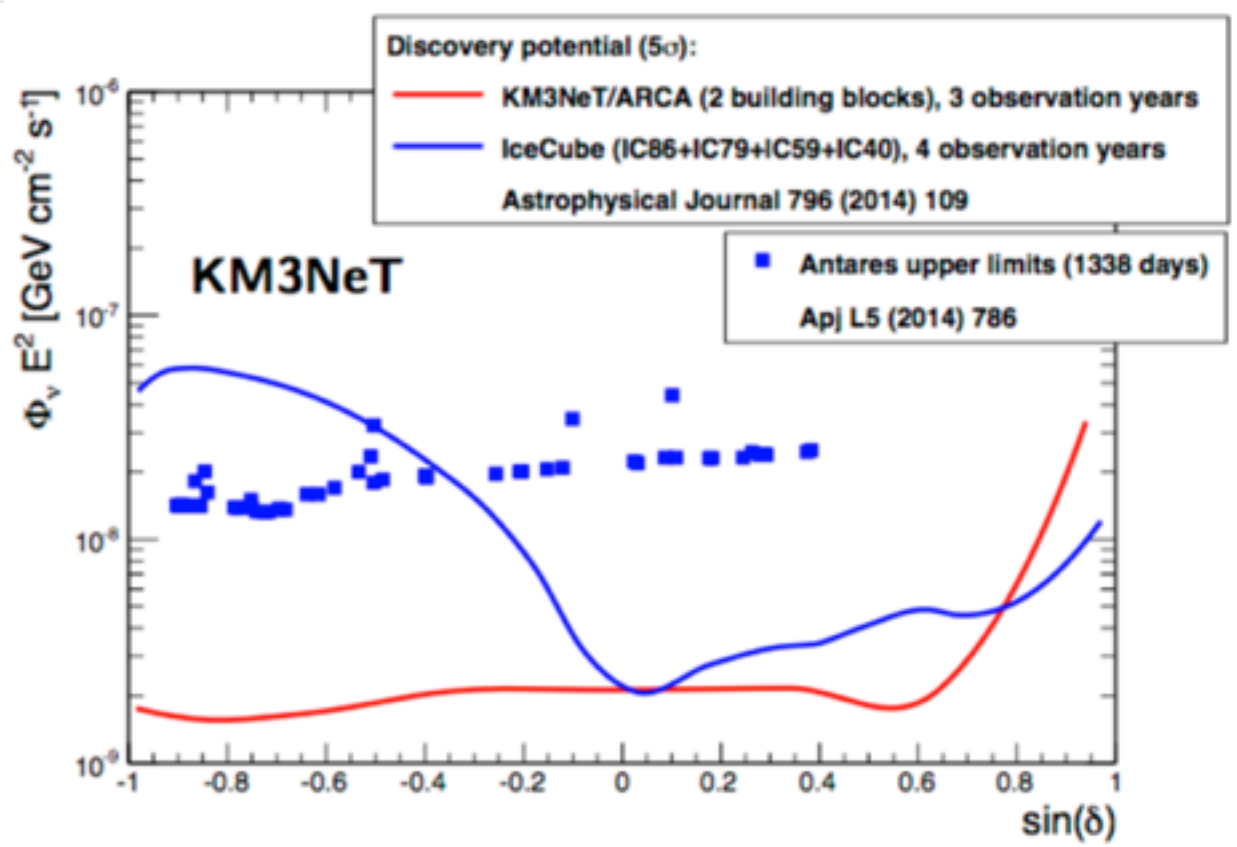
- Complementary coverage
- Optical noise (biolum) + ^{40}K / no noise
- Mediterranean : logistically attractive
- Absorption / diffusion
- Good pointing accuracy / Calorimetry

Angular resolution KM3NeT vs IceCube



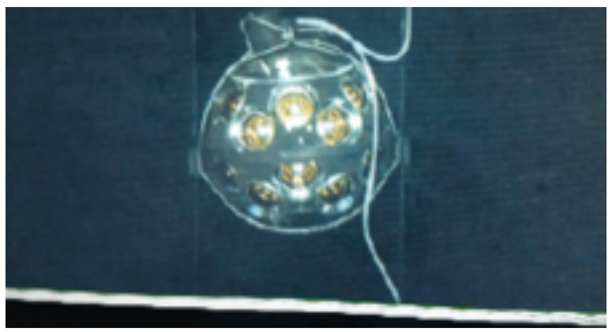


Point-source discovery potential



24 lines @ARCA + 7 lines @ORCA
already funded (currently under deployment)

IceCube Gen-2 phase 1
NSF proposal (7 lines)



2017

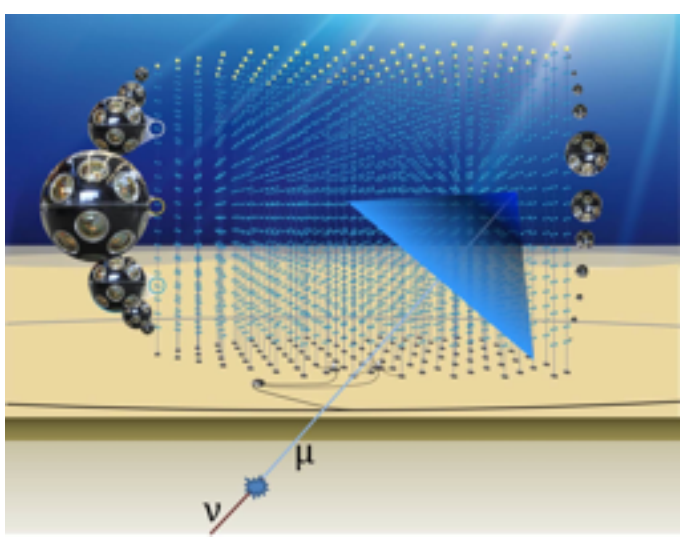
2022

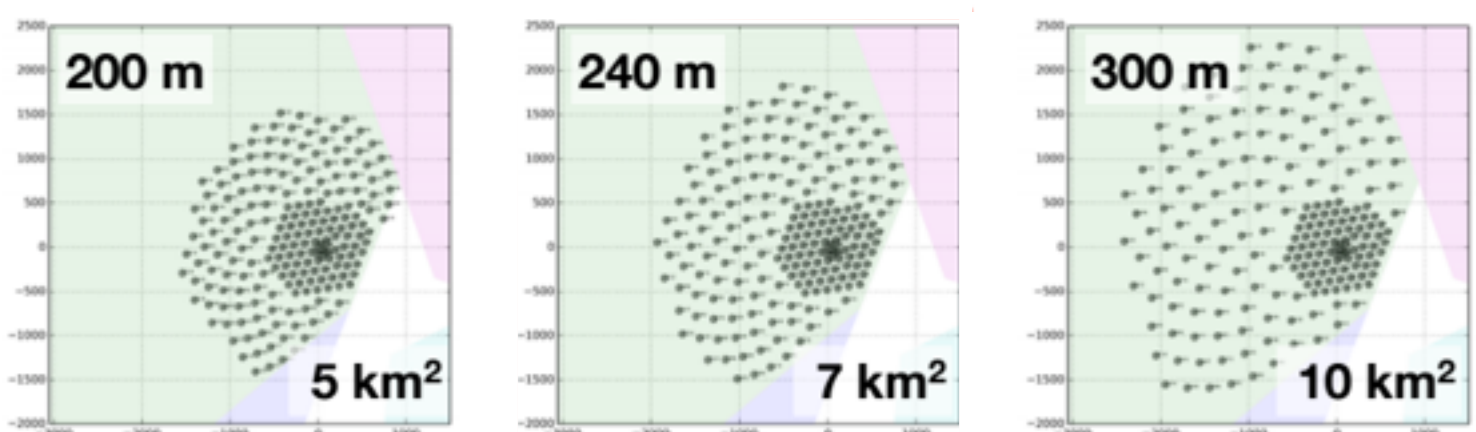
KM3NeT deployment

IceCube Gen-2 deployment

2021

...





2x115 lines in Sicily (ARCA)
115 lines in France (ORCA)

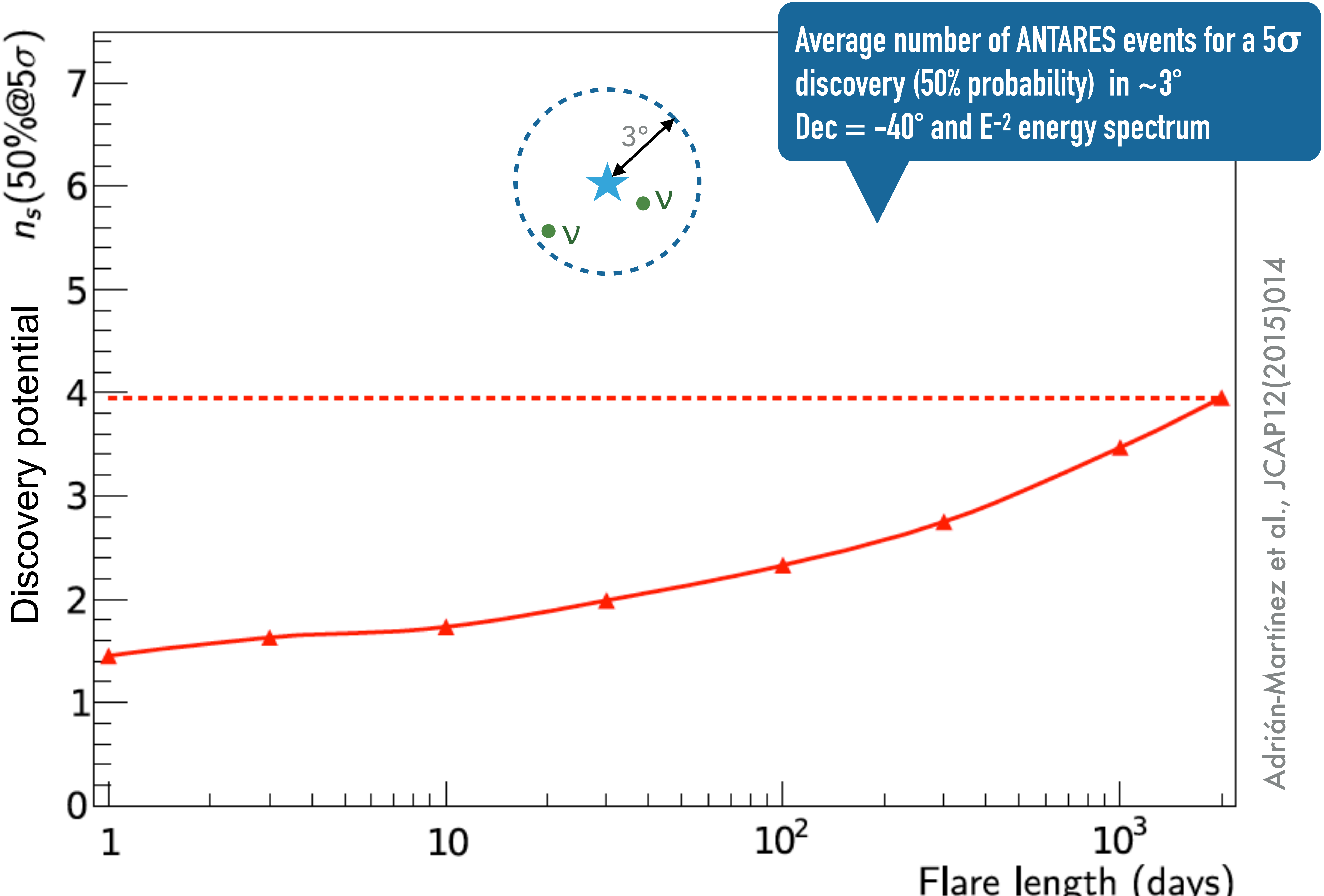
~120 new lines
Perf. increased by 1 order of mag.

MULTI-MESSENGER CONTEXT

Neutrino telescopes suitable to look for transient sources:

- continuously monitoring 2π sr (at least)
- high duty cycle (>98%)

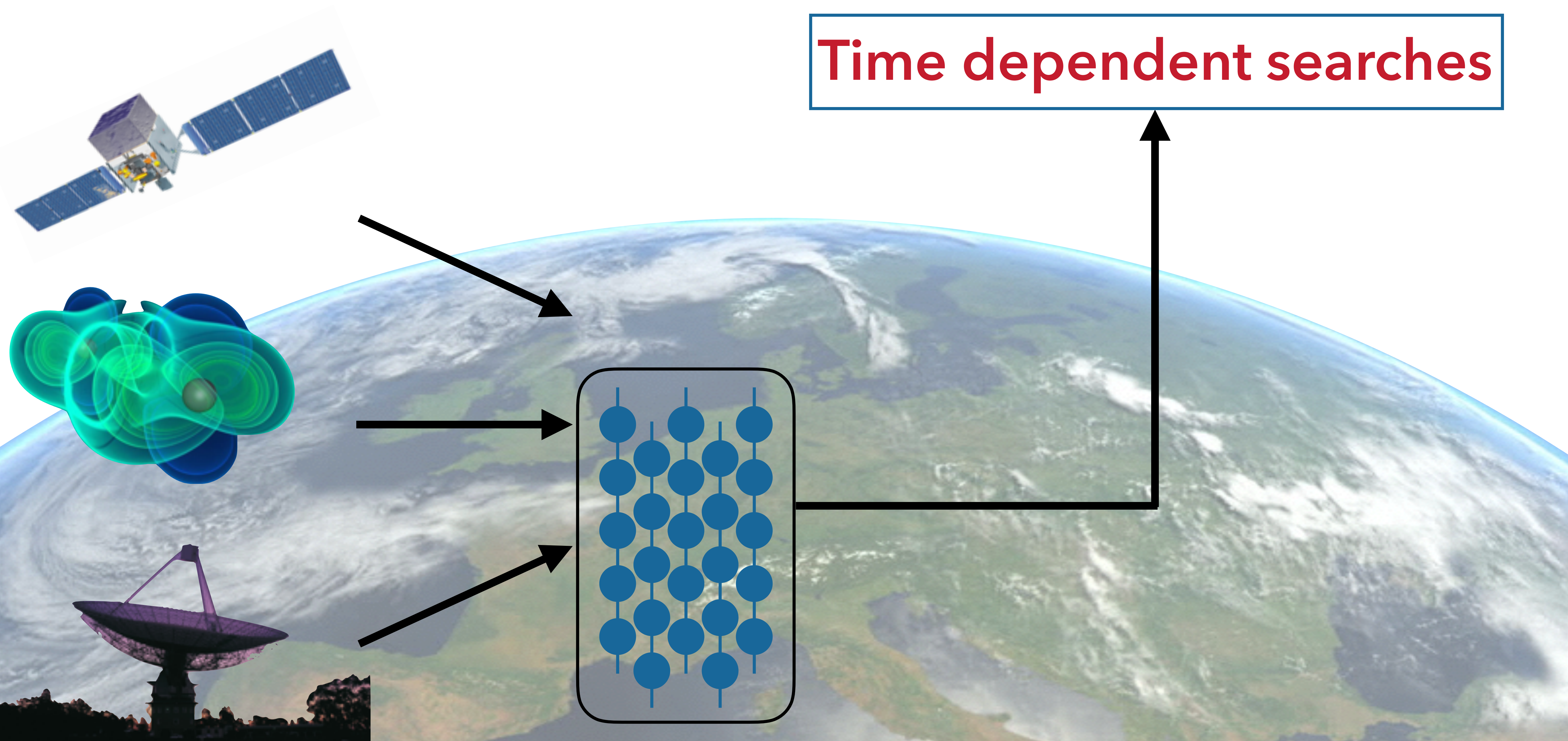
- **Multi-messenger** studies of **transient & variables** sources:
  - increase the sensitivity + discovery potential (reduce the background)
  - increase the statistical significance (requiring joint detection)


Average number of ANTARES events for a 5σ discovery (50% probability) in ~3° Dec = -40° and E-2 energy spectrum
3°
ν
ν
Discovery potential $n_s(50\%@5\sigma)$
0
1
2
3
4
5
6
7
1
10
10^2
10^3
Flare length (days)
Adrián-Martínez et al., JCAP12(2015)014

- **Multi-messenger/transient group just created**
- **Different working-groups:**
  - Online reconstruction algorithm
  - Alert sending system
  - Online physics
  - Supernova detection
  - MoU discussions
- **Takes advantage of ANTARES and IceCube feedback**
- **Reconstruction of cascade events (angular reconstruction ~2°: FoV reachable by follow-up optical telescopes)**
- **Better angular resolution for tracks (~0.1°; reachable by 1-m class optical telescopes).**

LOOKING FOR TRANSIENT MULTI-MESSENGER SOURCES

2 APPROACHES:



LOOKING FOR TRANSIENT MULTI-MESSENGER SOURCES

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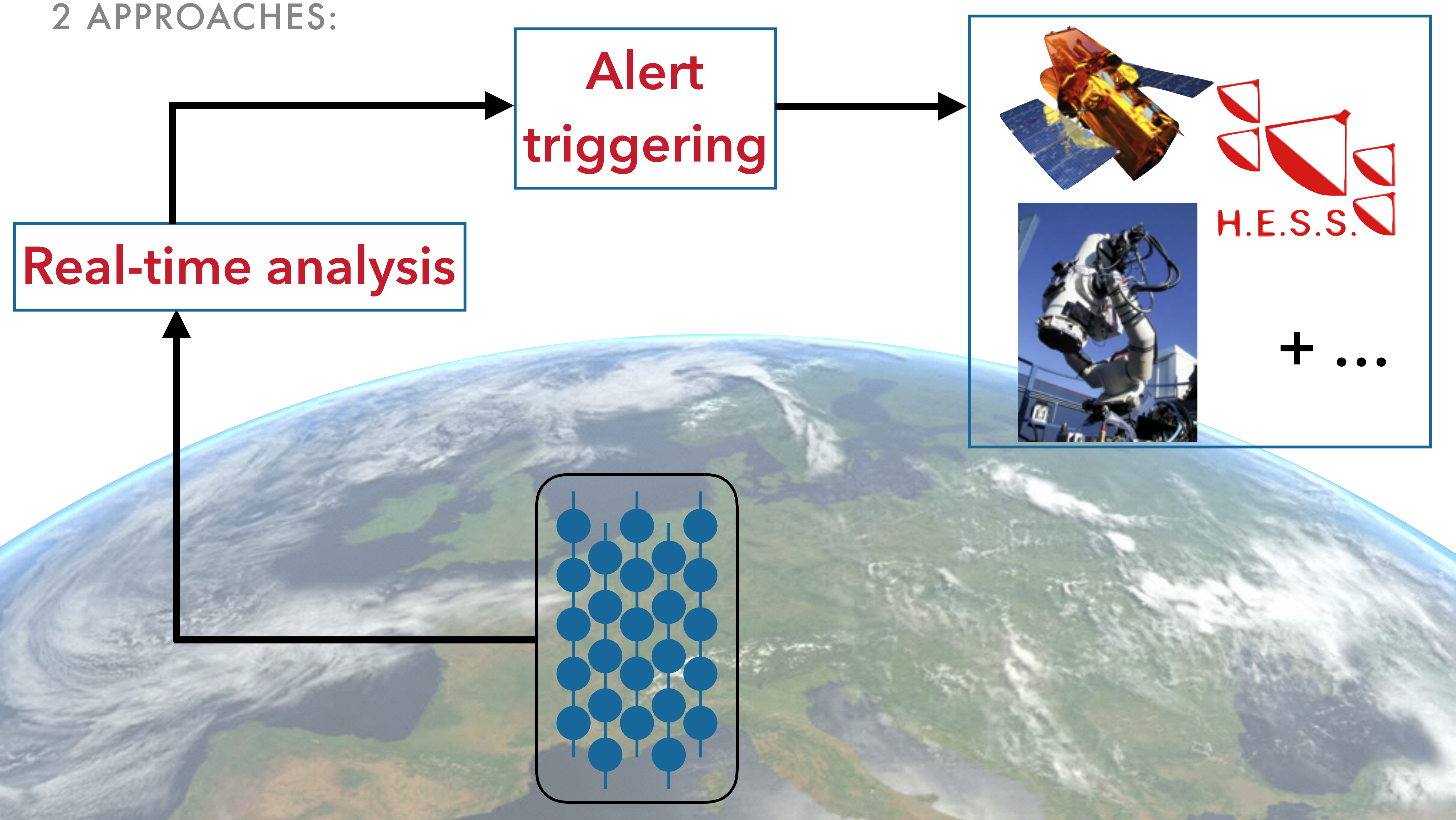

LOOKING FOR TRANSIENT MULTI-MESSENGER SOURCES

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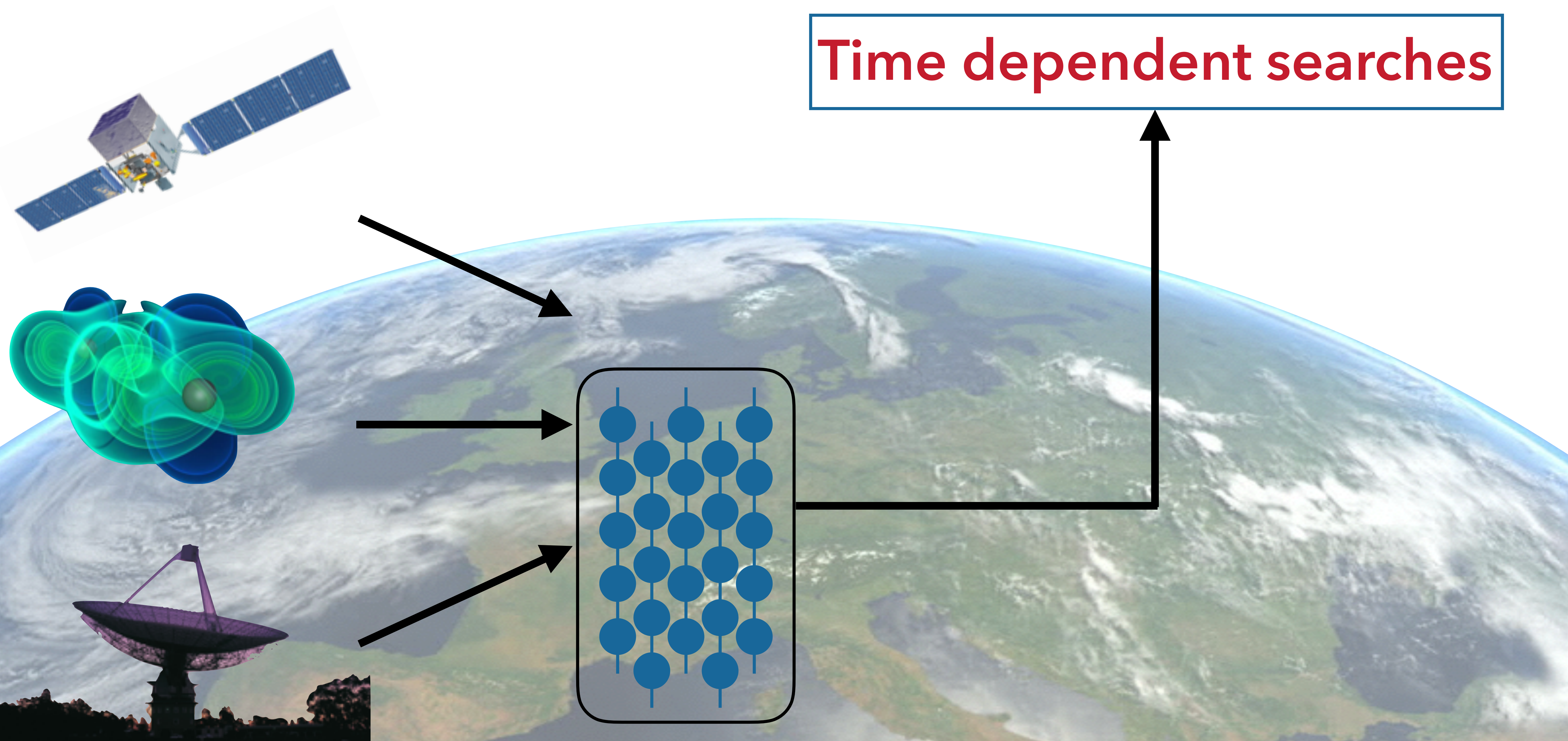


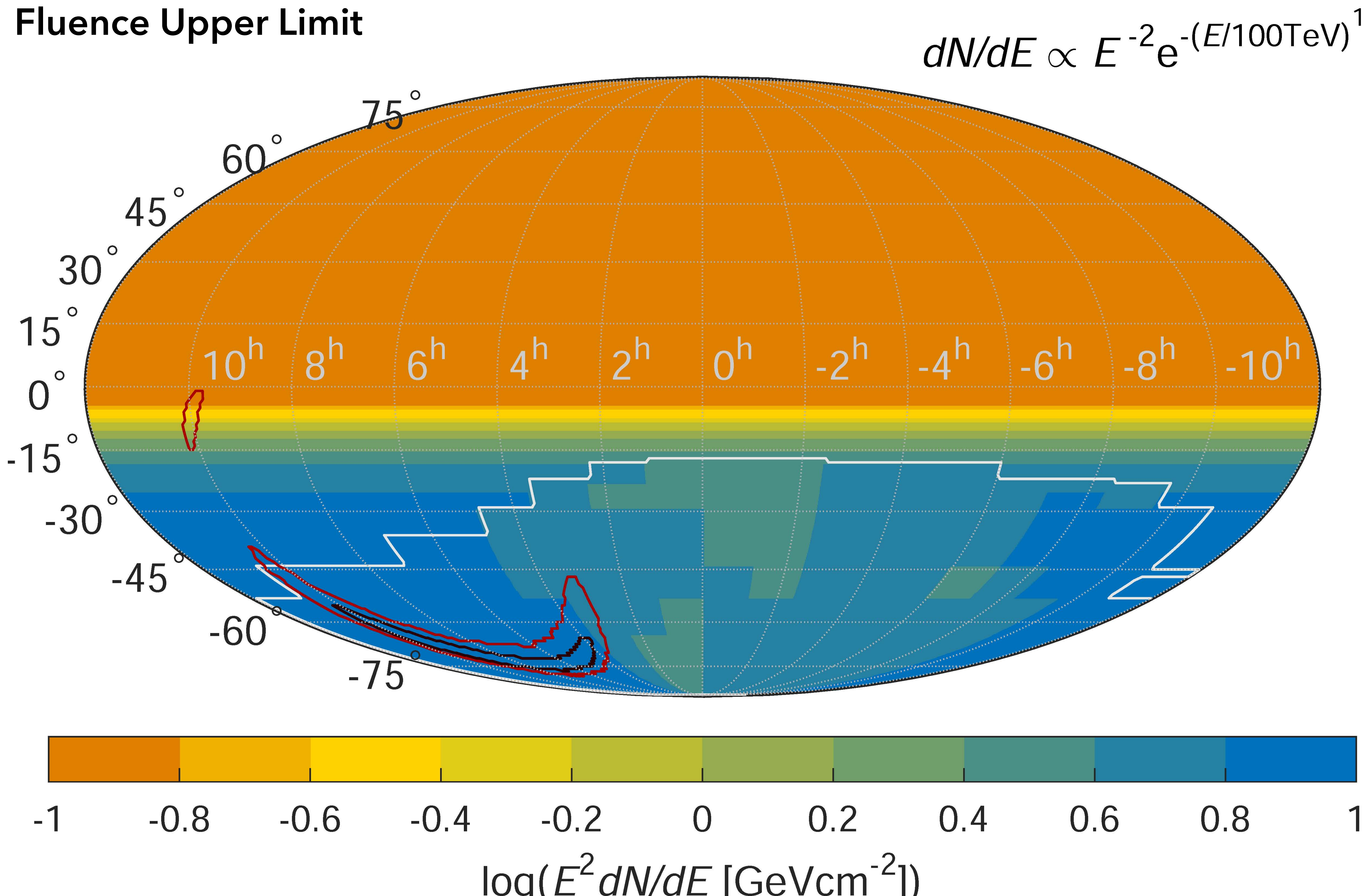
<u>Time-dependent searches</u>:

- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Gamma-ray binaries [Fermi/LAT, IACT]
- Blazars [Fermi/LAT, IACT, TANAMI…]
- Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]
- Fast radio burst [radio telescopes]

<u>Multi-messenger correlation</u>:

- Correlation with the UHE events [Auger]
- Correlation with the gravitational wave [Virgo/Ligo]
- 2pt-correlation with 2FGL catalogue, loc. galaxies, BH , IceCube HESE

Fluence Upper Limit



Adrian-Martinez et al. 2016, (ANTARES, IceCube & LIGO/Virgo)

Constraints on the total energy radiated in neutrinos

$$\mathrm{E}^{\mathrm{ul}}_{\nu,\mathrm{tot}} \sim 10^{52}\text{–}10^{54} \left(\frac{D_{\mathrm{gw}}}{410\,\mathrm{Mpc}} \right)^2 \mathrm{erg}$$

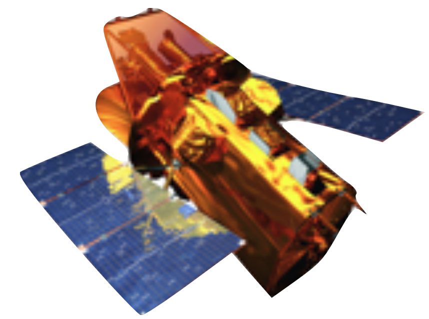
Energy radiated in GW: ~5 x 10^{54} erg

Typical GRB isotropic-equivalent energies are ~10^{51} erg (long GRB) and ~10^{49} erg (short GRB)

May be similar to total energy radiated in neutrinos in GRBs *(Mészaros 2015; Bartos et al., 2013)*

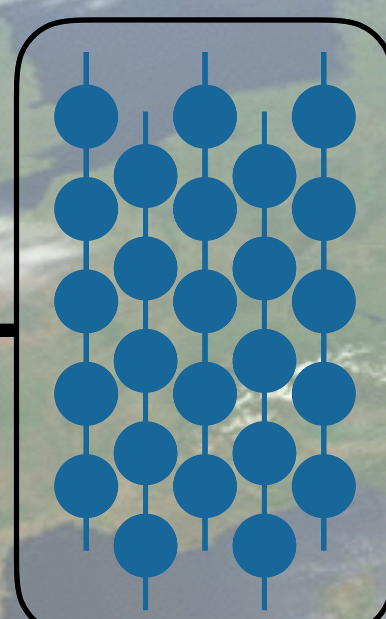
Real-time analysis

Alert triggering



H.E.S.S.

+ …



Triggers:

- single HE (≳7 TeV)
- multiplets (<3° within 15 min)
- specific direction (<0.5° from local galaxies from GWGC catalogue within 20 Mpc).

Ageron et al, Astropart. Phys. 35 (2012) 530-536

Performances

All-data-to-shore concept: each PMT pulse above 0.3 pe sent to computer farm for processing (filtering + reconstruction + selection of events)

Time performances to send the alert: ~5 s

data dispatching time + data filtering + event online reconstruction

- data dispatching time: 1.5 s
- data filtering: < 5 s
- event online reconstruction: a few ms

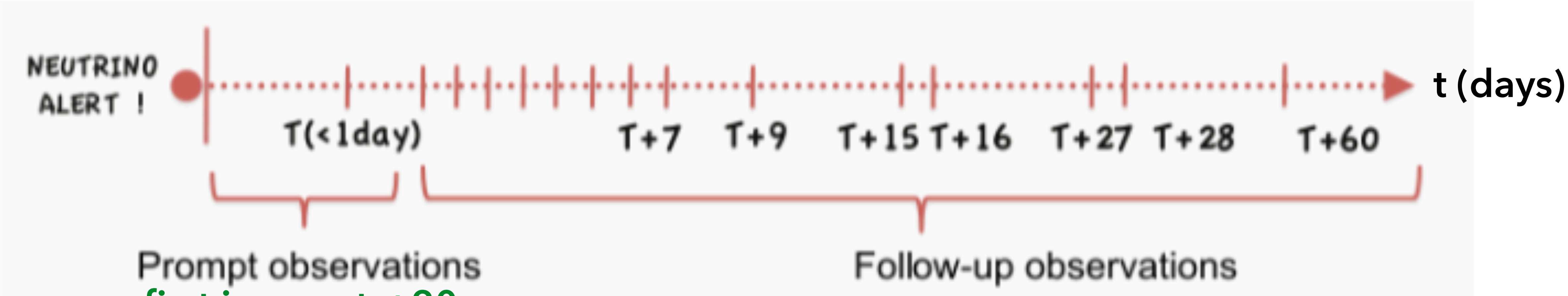
Alerts sent through GCN and VOEvents (identifier, time, coordinates, number of hits and reconstruction quality)

Total trigger rate tuned to 35/yr in agreement with optical telescope, 6/yr for Swift, 2/yr for HESS, 4/yr for MWA

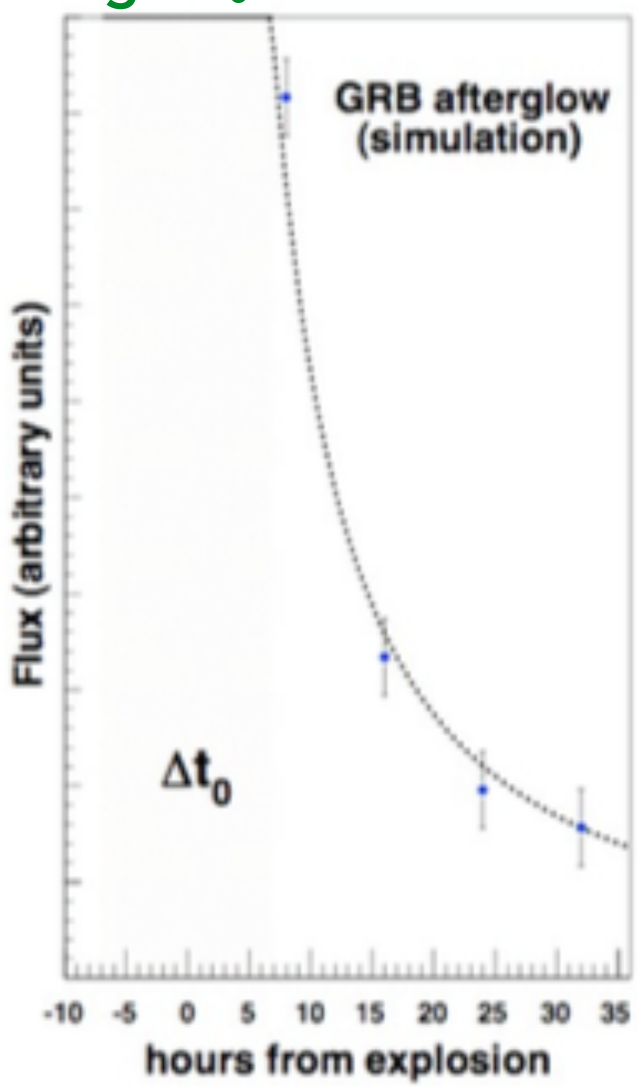
Doublets: accidental coincidence rate due to background events: ~7x10^{-3} /yr (doublet ➜ 3σ ; triplet ➜ 5σ)

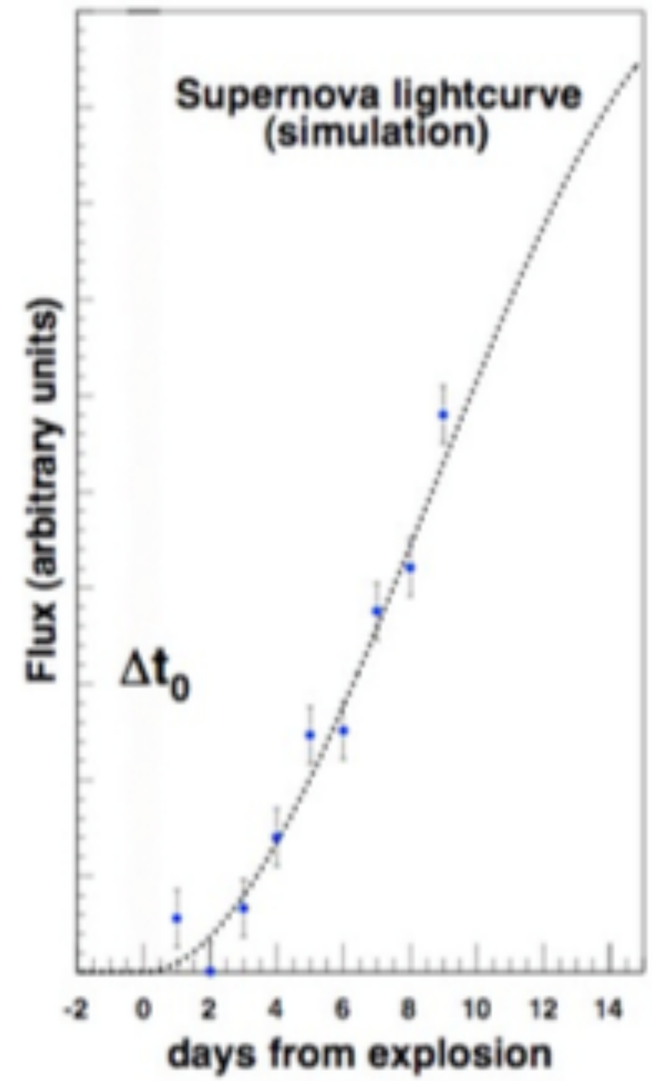
Trigger	Angular Resolution (median)	PSF coverage[a]	Atmospheric muon contamination	Mean energy[b]
High energy	0.25 – 0.3°	96 %	< 0.1 %	~ 7 TeV
Directional	0.3 – 0.4°	90 %	~ 2 %	~ 1 TeV
Doublet	≤ 0.7°		0 %	~ 100 GeV

- **Optical follow-up strategy**



first image: t_0+20 s





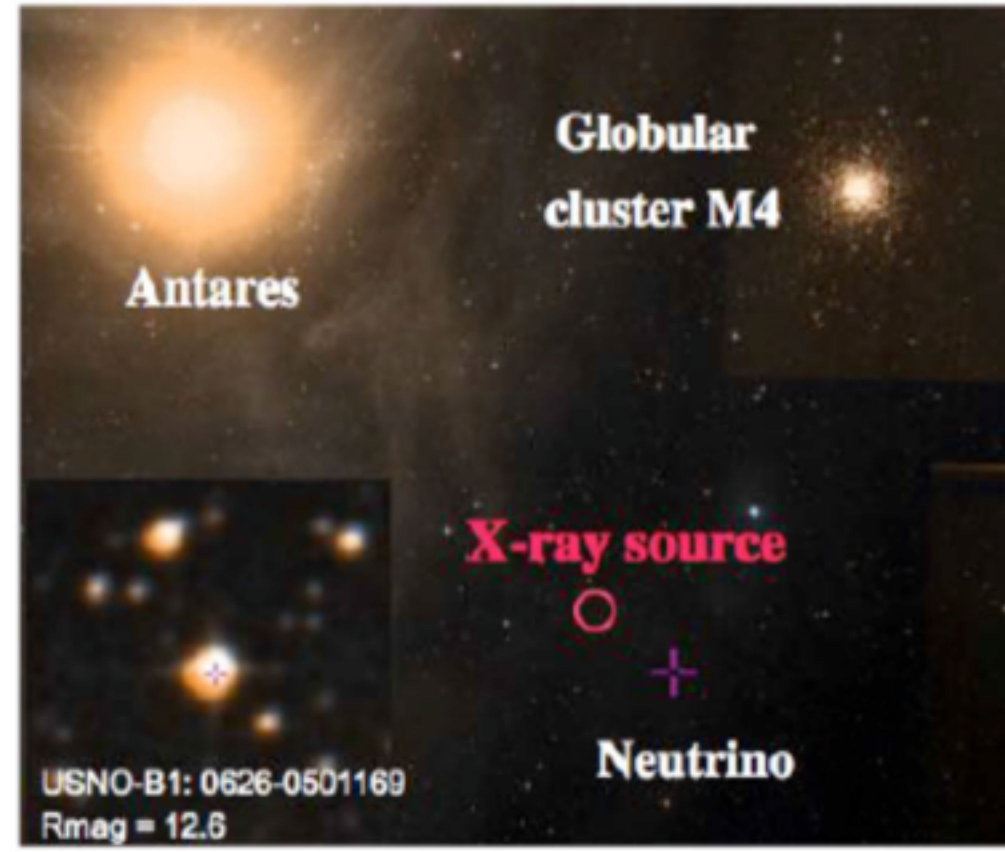
Crédits: D. Dornic

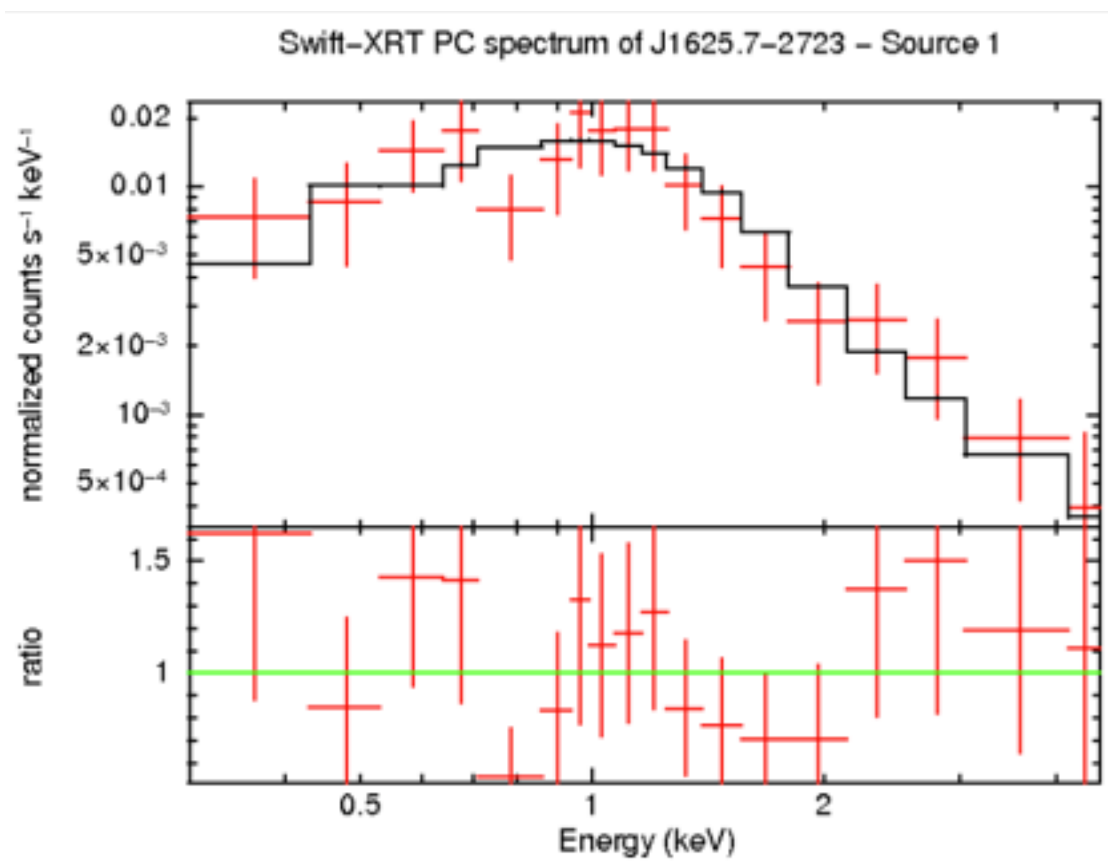
Radio	Optical	X-ray	GeV γ-rays	TeV γ-rays
MWA (12/yr)	TARO T ZADKO MASTER GWAC (30/yr)	Swift (6/yr)	Fermi (offline)	HESS (2/yr) HAWC (offline)

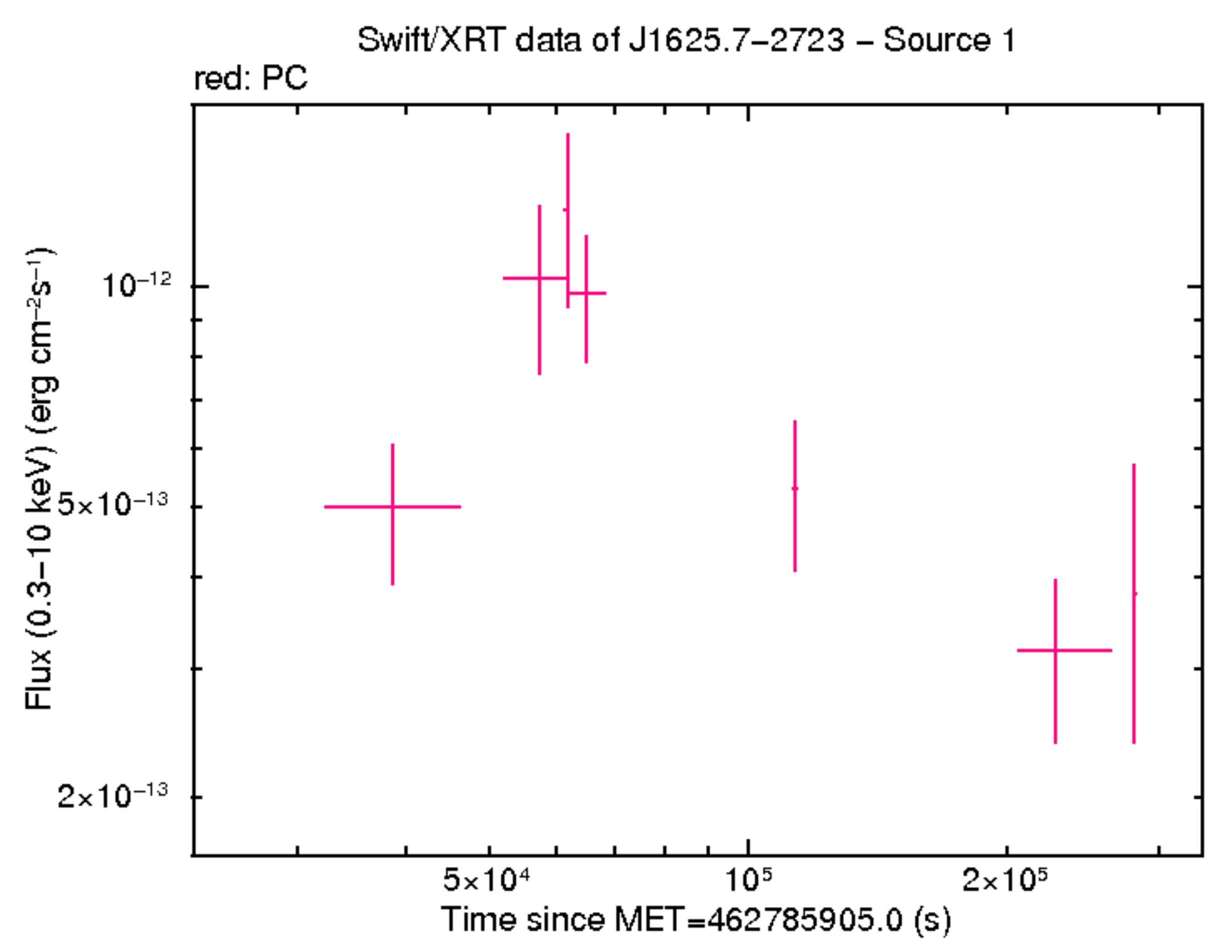
- Private MoU with all the observatories

253 alerts sent to optical telescopes since mid 2009
+14 to Swift since mid 2013
+ 3 to HESS since 2014

- E ~50-100 TeV
- Error box=18 arcmin
- Sent in 10s to Swift and Master
- Swift obs: +9h
- Master obs: +10h

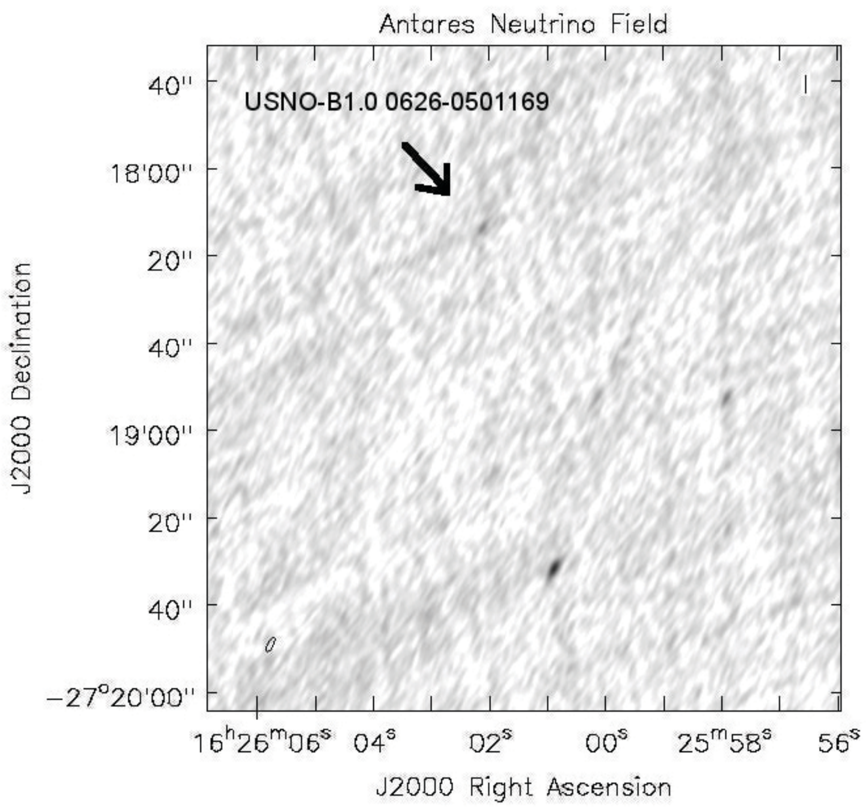


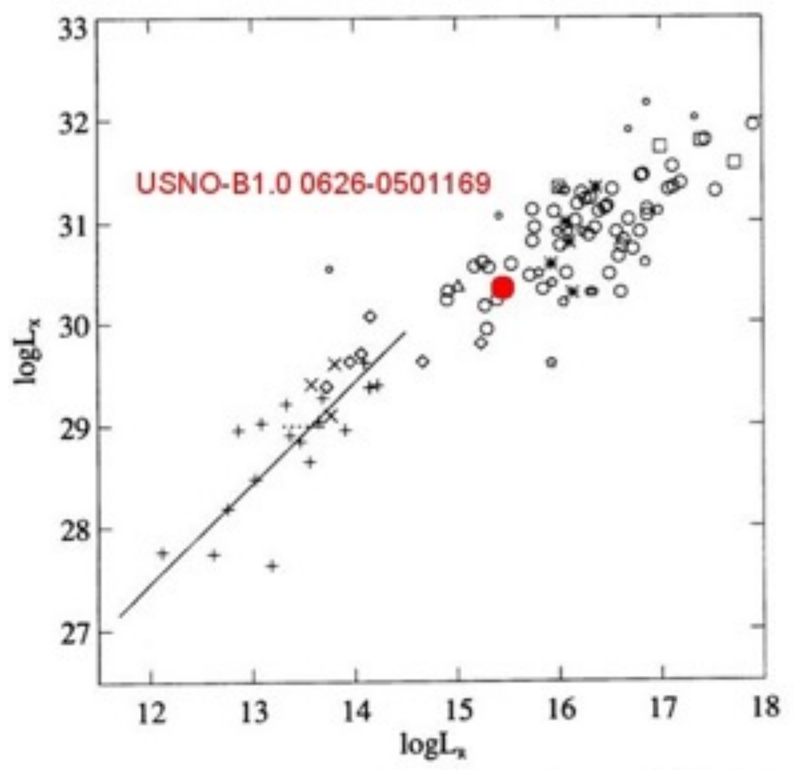




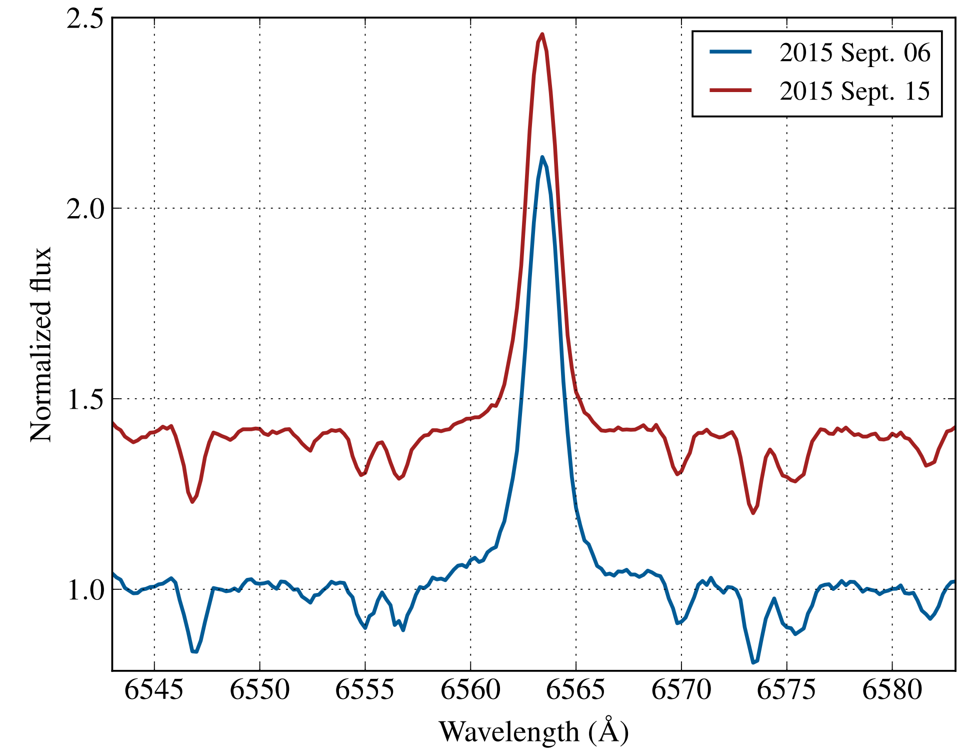
- Neutrinos
  - IceCube: ATel 8097
- Optical
  - Pan-STARRS: ATel 7992, 8027
  - SALT: ATel 7993
  - NOT: ATel 7994 GCN18236
  - WiFeS: ATel 7996
  - CAHA: ATel 7998, GCN18241
  - MASTER: ATel 8000 GCN18240
  - LSGT: ATel 8002
  - NIC: ATel 8006
  - ANU: GCN18242
  - GCM: GCN18239
  - VLT/X-shooter
- X-rays
  - Integral: ATel 7995
  - MAXI: ATel 8003
  - Swift: ATel 8124, GCN18231
- Radio
  - Jansky VLA: ATel 7999, 8034
- Gamma-rays
  - MAGIC: ATel 8203
  - Fermi-GBM: GCN18352
  - HAWC
  - HESS

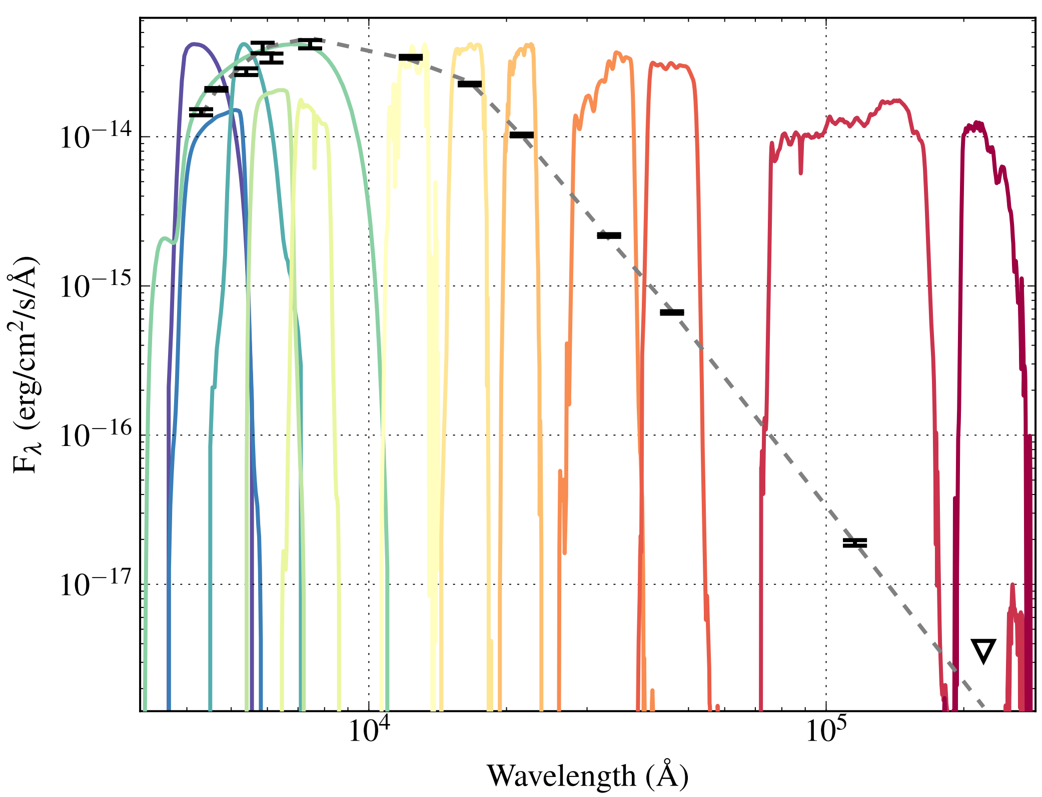
VLA follow-up ATel #7999

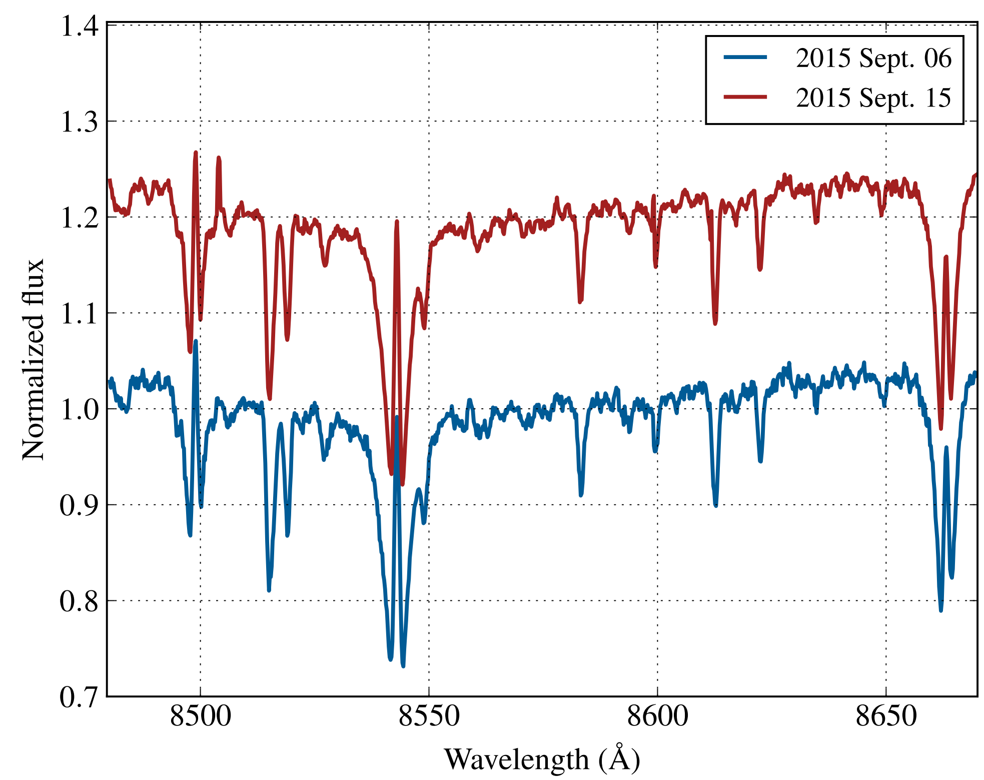




VLT / X-Shooter follow-up

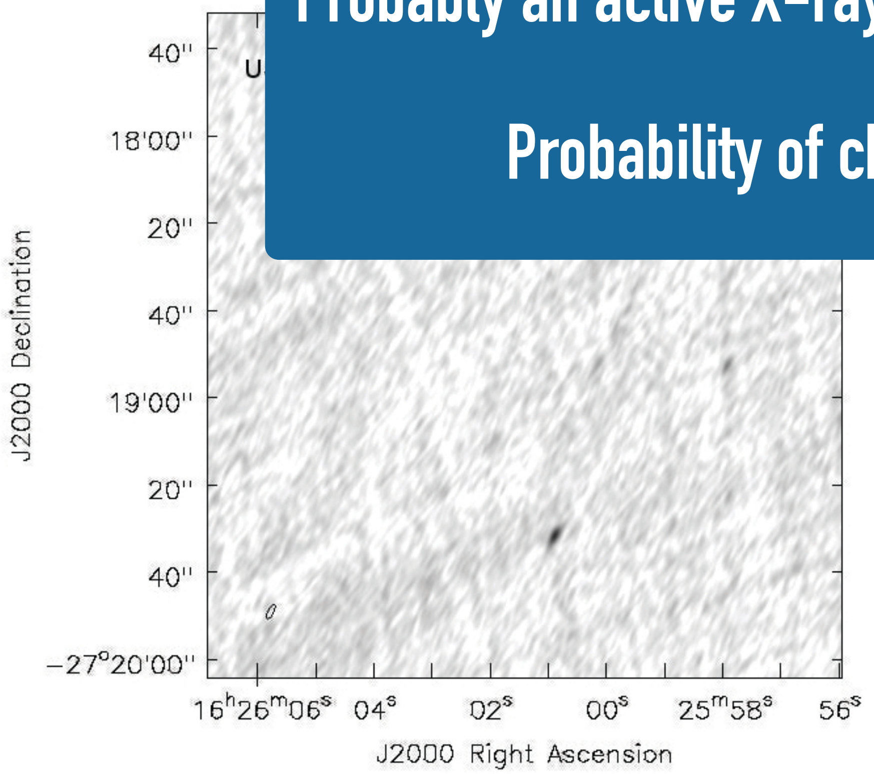


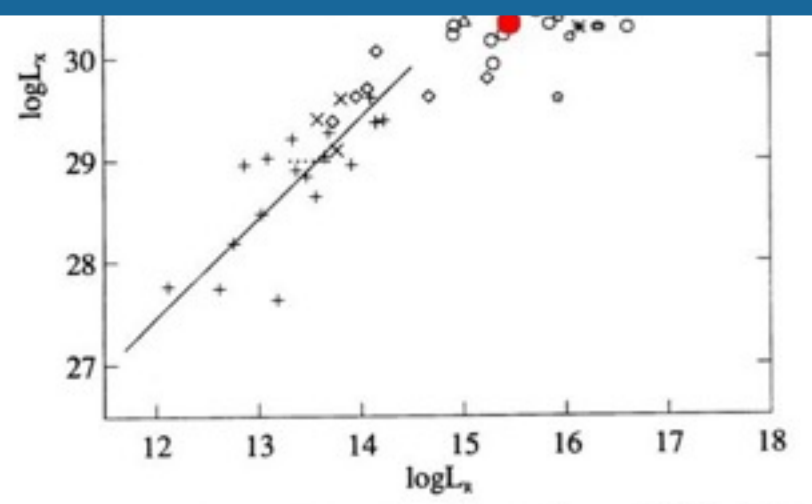




Probably an active X-ray star in a binary system (RS CVn)

Probability of chance coincidence: ~3 %





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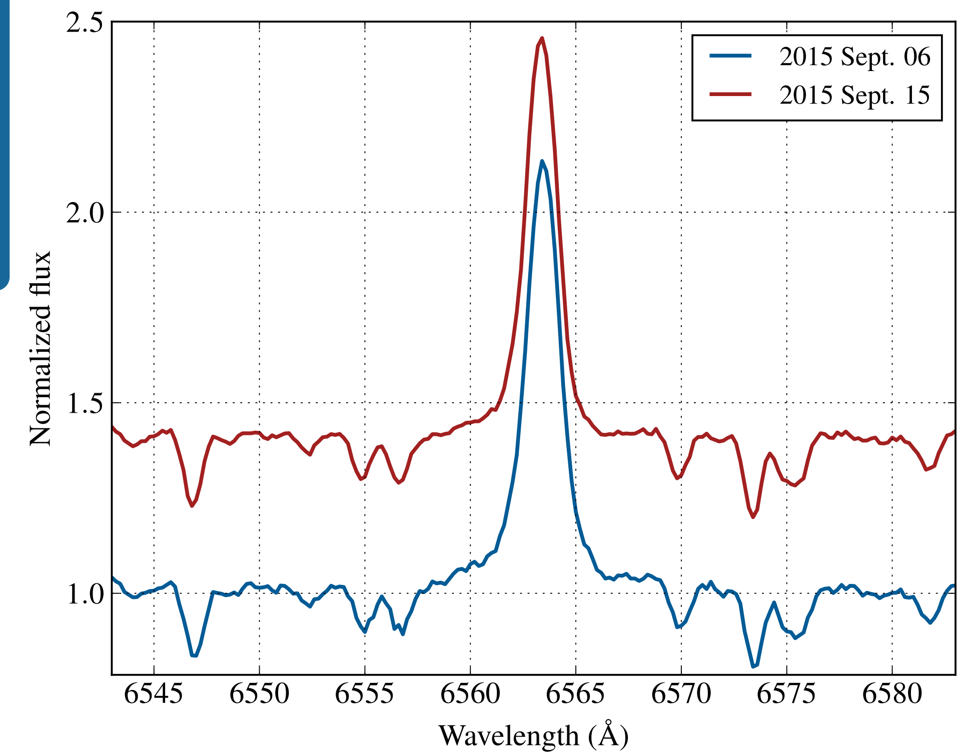
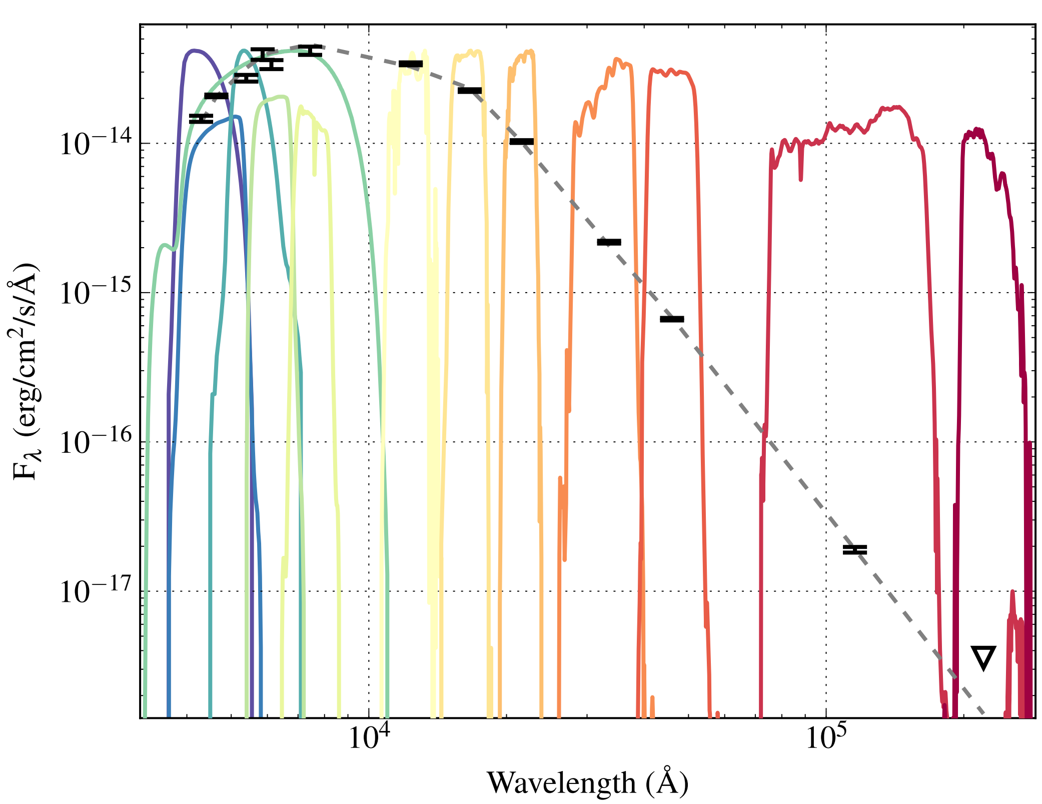
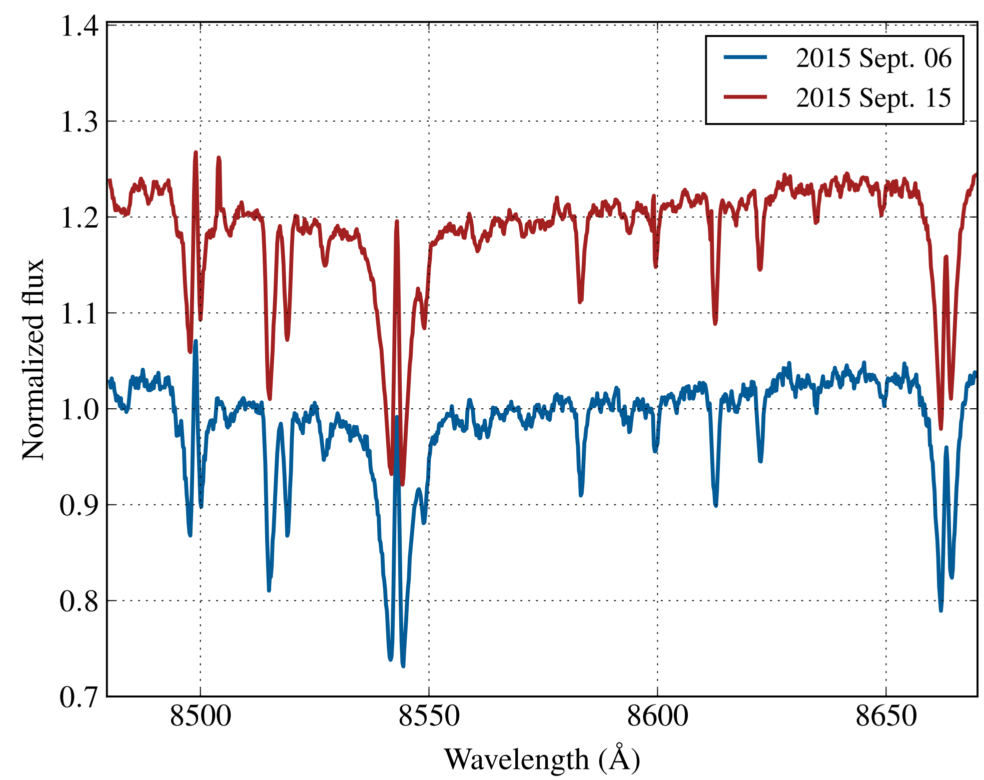
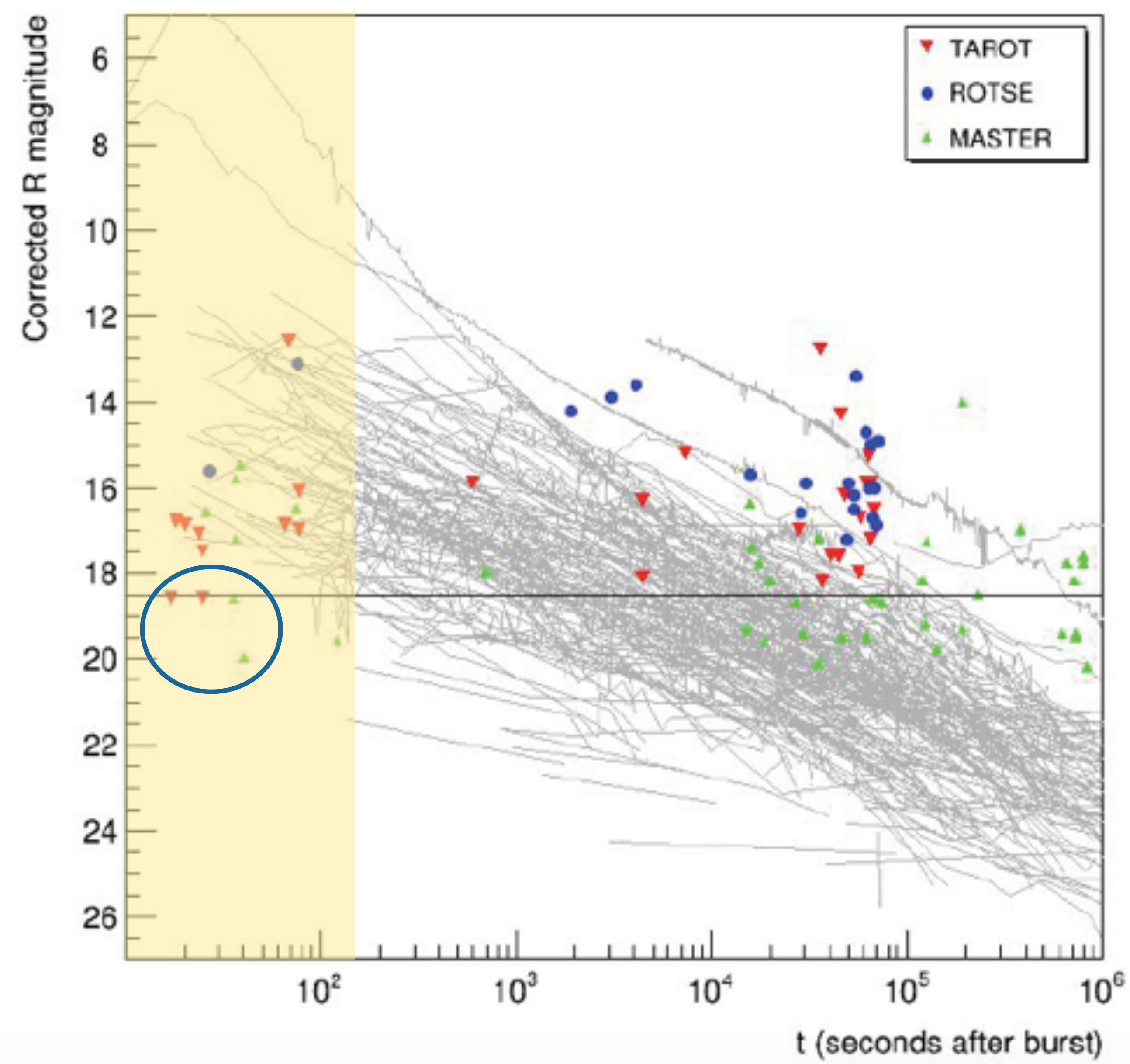






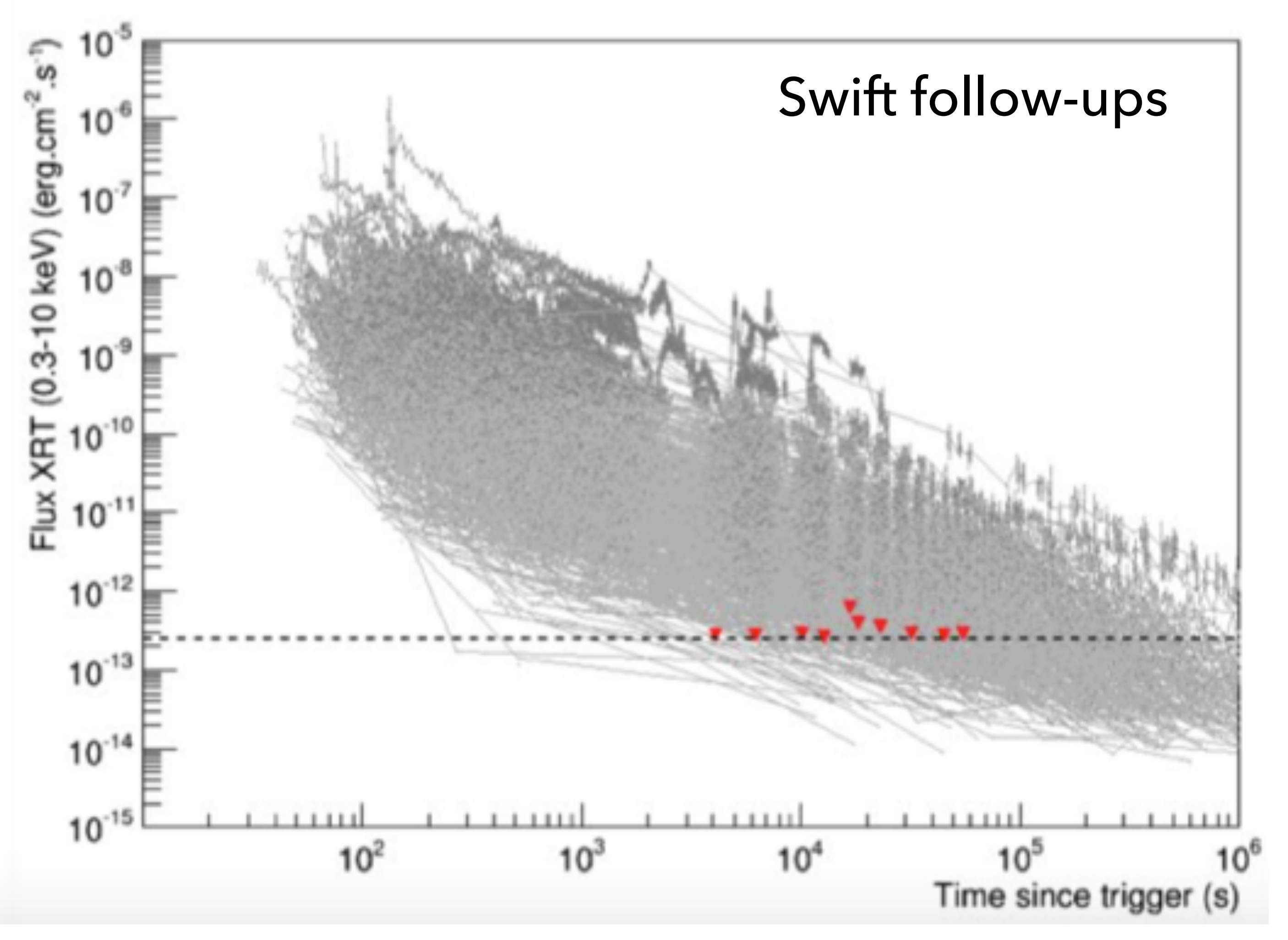
ANTARES COLLABORATION JCAP 02:062, 2016

- Coincident detection (nu/GRB) by chance: Proba ~10^{-6} with optical telescopes
- 93 alerts with early (<24h) optical follow-up analyzed (01/2010 - 01/2016)
- 13 follow-ups with delay <1min (best: 17s)
- no transient candidate associated to neutrinos
- Constraints on origin of individual neutrinos
- GRB origin unlikely



ANTARES COLLABORATION JCAP 02:062, 2016

- Coincident detection (nu/GRB) by chance: Proba ~10^{-7} with Swift
- 13 X-ray follow-ups
- delay of 5-6 h on average
- no transient candidate associated to neutrinos
- Constraints on origin of individual neutrinos
- GRB origin unlikely



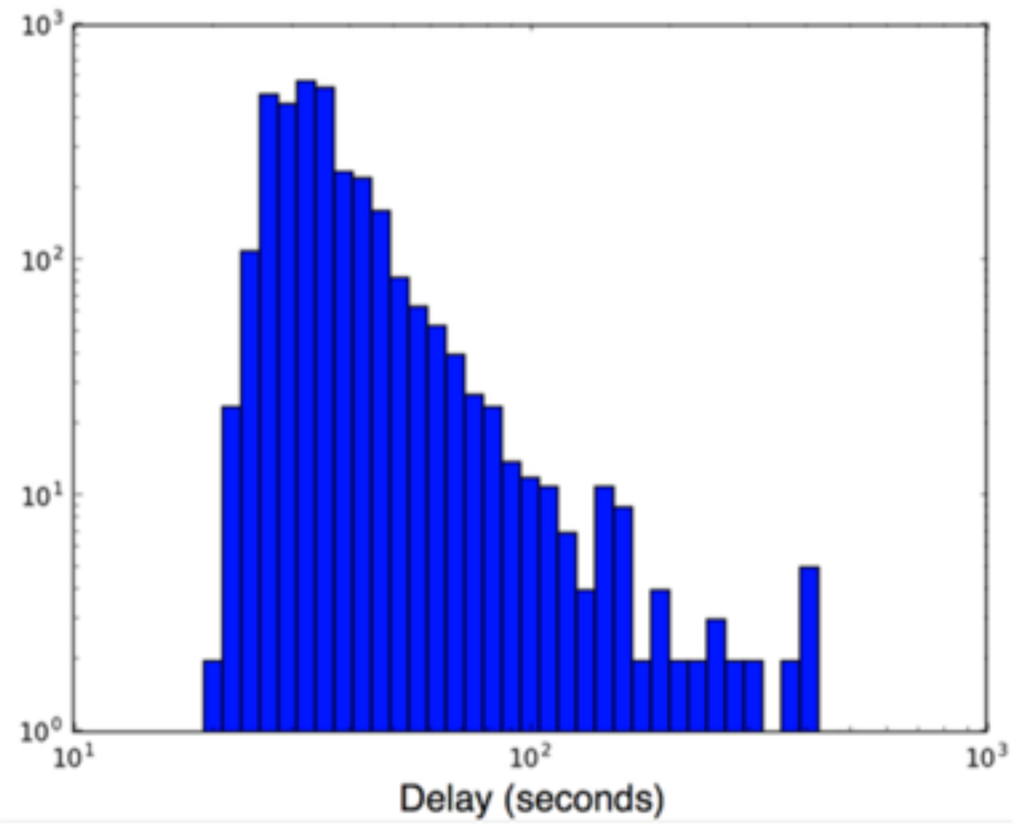
- **Performances**

Limited computing resources at the South Pole

Limited connectivity (Iridium connection: low latency but low bandwidth)
(TDRSS connection: high latency but high bandwidth)

Event selection at South Pole ➜ Basic event info sent North ➜ analyses & alert generation in the North

Alerts sent through AMON and GCN (identifier, time, coordinates, number of hits and reconstruction quality)



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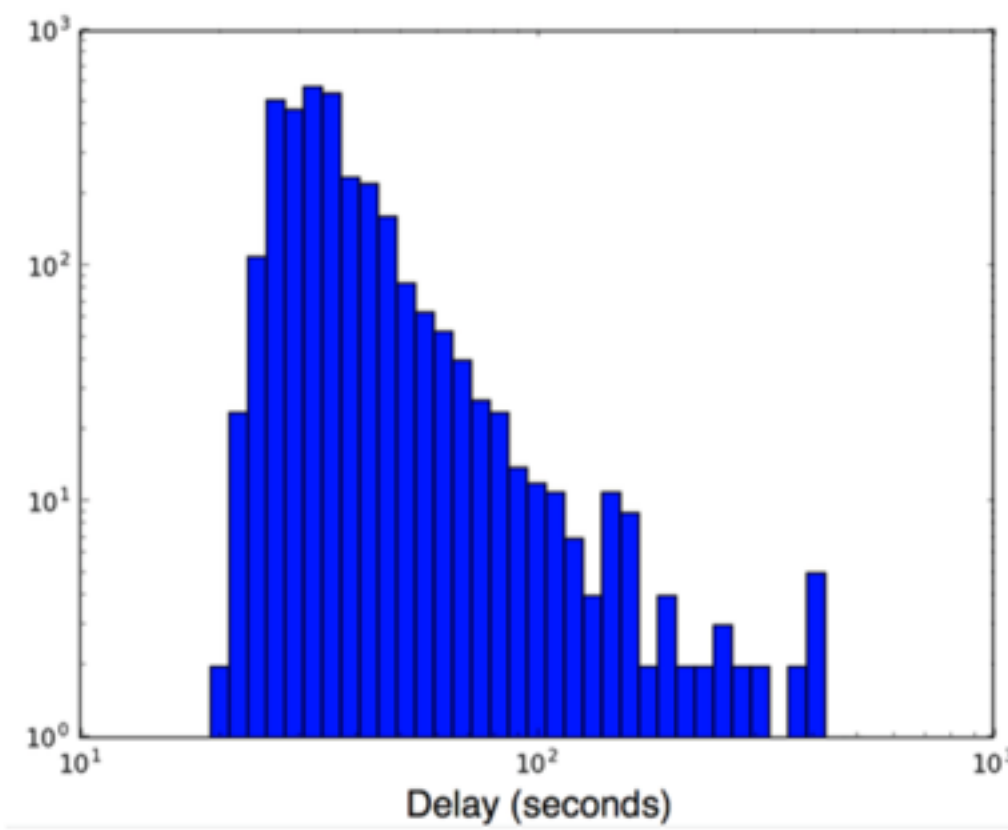
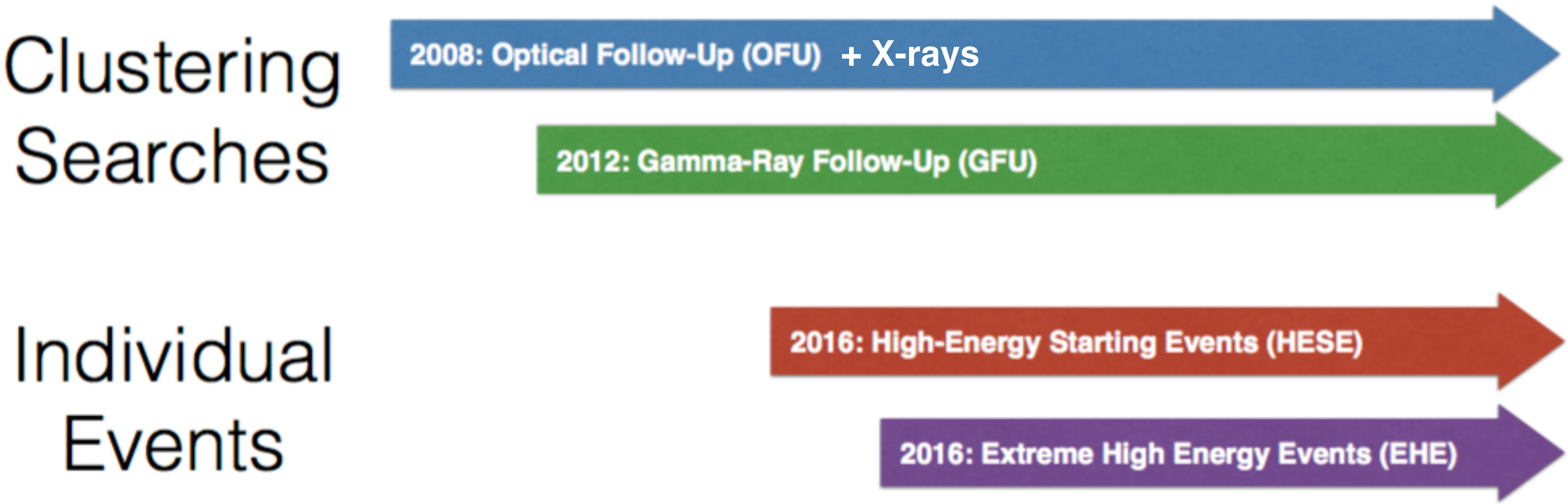
Alerts sent through AMON and GCN (identifier, time, coordinates, number of hits and reconstruction quality)

Quick correlation analyses with HAWC, Auger, etc.

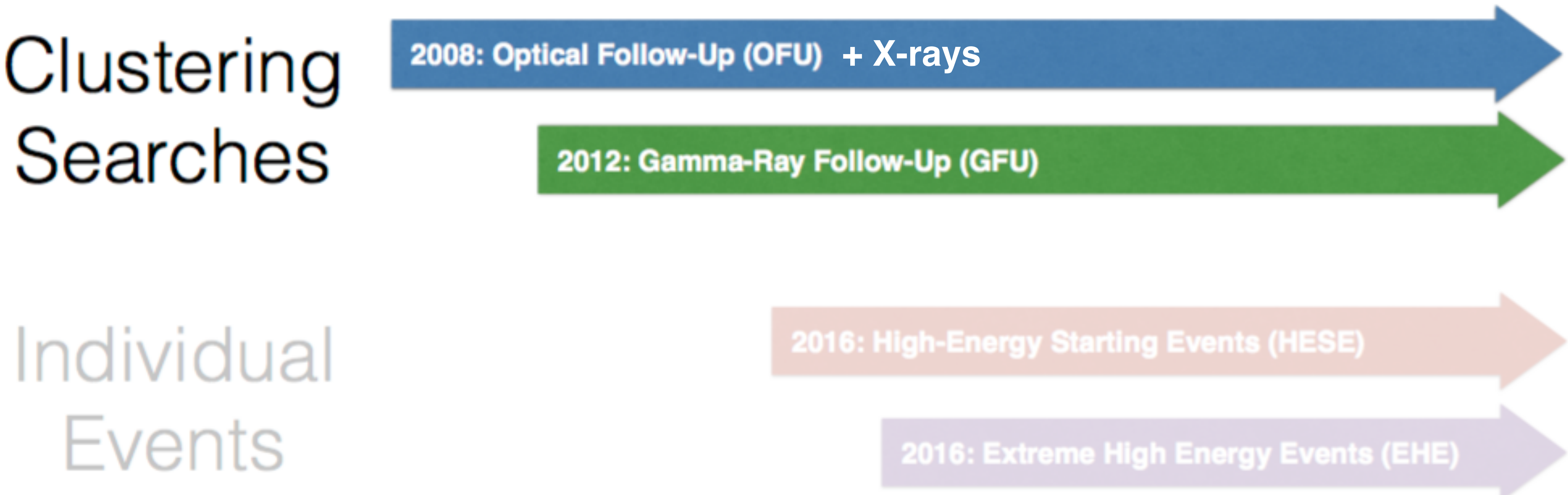


- **Several alert systems**



from T. Kintscher

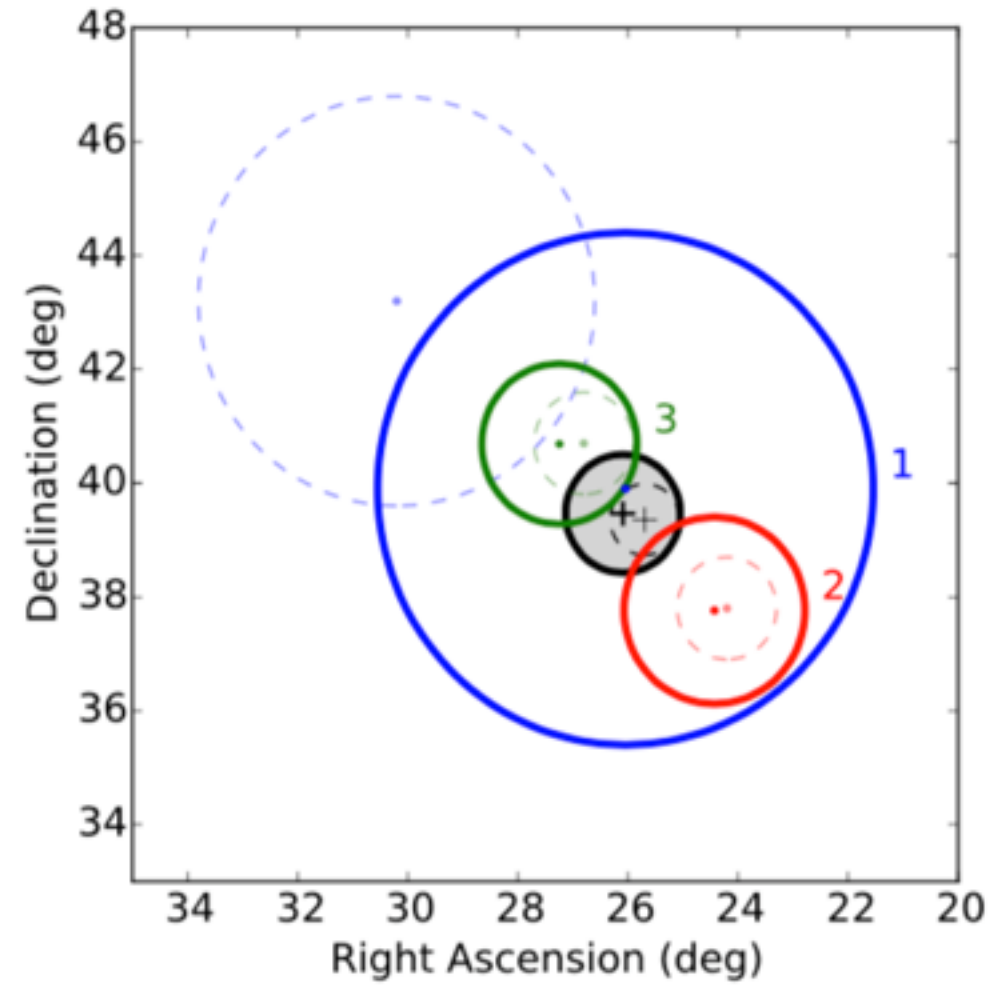
- **Several alert systems**



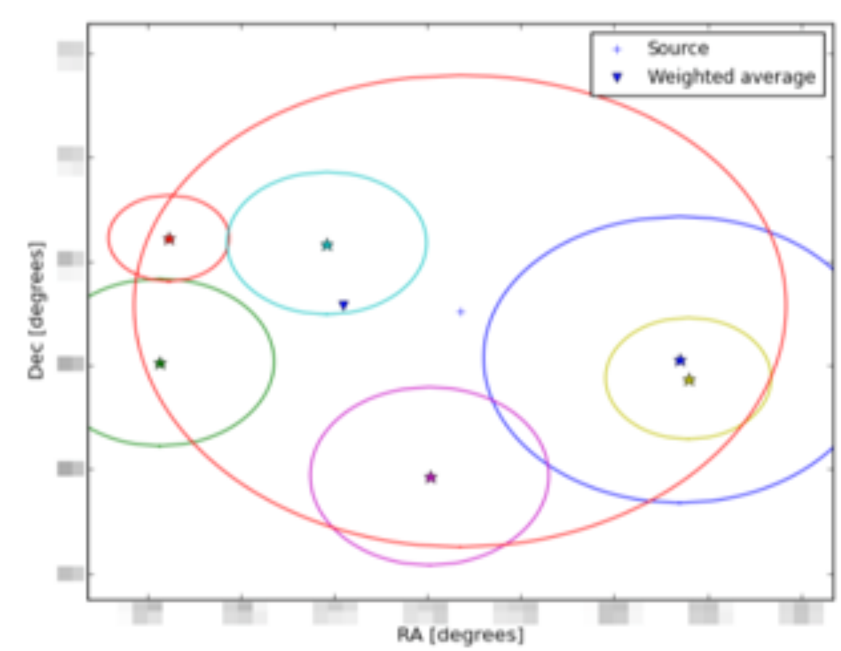
- Search for statistically significant clustering in time and space
- OFU: search for upgoing tracks from northern hemisphere over timescales up to 100 s over the full sky and within 3.5° (7 alerts / year to Swift, 9 alerts / year to PTF).
- GFU: search for tracks from the entire sky over timescales up to 3 weeks around 184 sources (a few alerts / year to IACT).

from T. Kintscher

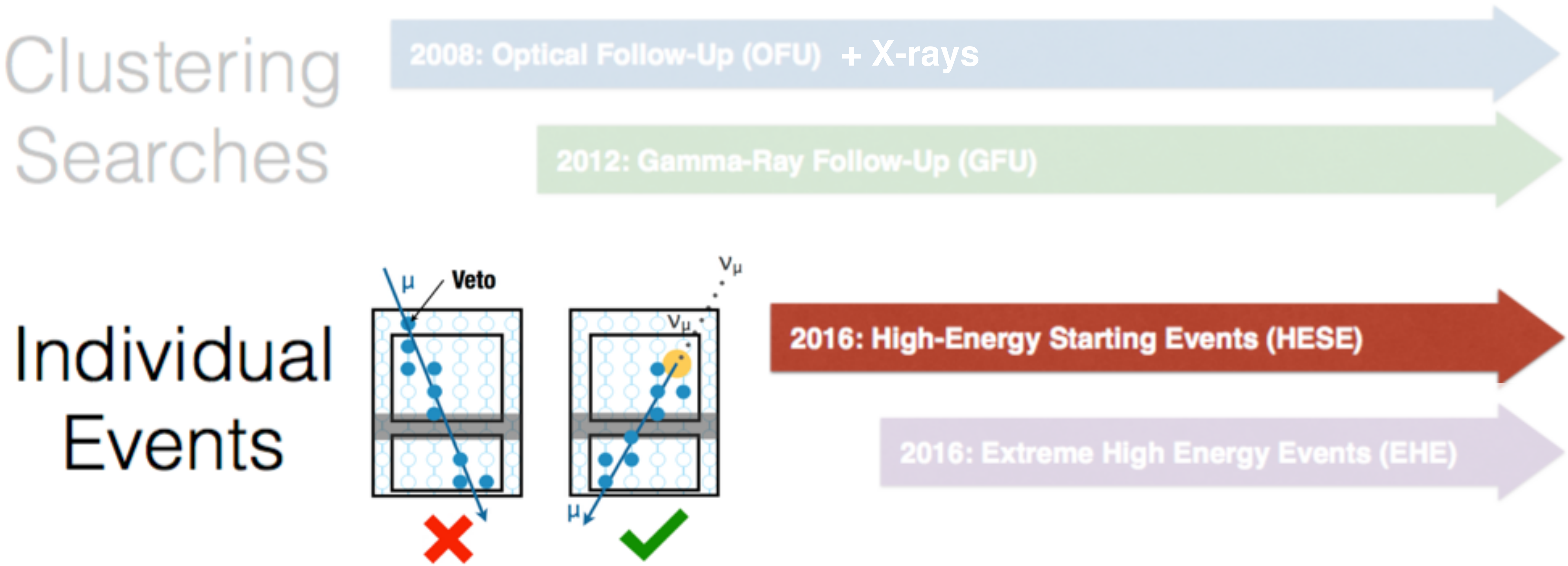
- **Detection of IceCube triplet**
  - On February 17, 2016.
  - **Triplet of events arriving within 100 s** of each other and consistent with a point source origin.
  - Expected only once every 13.7 year as random confidence of bkg events (proba of 32% considering IceCube livetime).
  - Follow-up by ASAS-SN, LCO, MASTER (optical), Swift (X-ray), VERITAS, HAWC, Fermi-LAT (gamma-rays)
  - Rule out a nearby CCSN + bright GRB



- **Gamma-ray follow-up:** most significant alert (2012/11/09): 6 events in 4.2 days (p=0.002%). VERITAS obs: no significant excess seen.



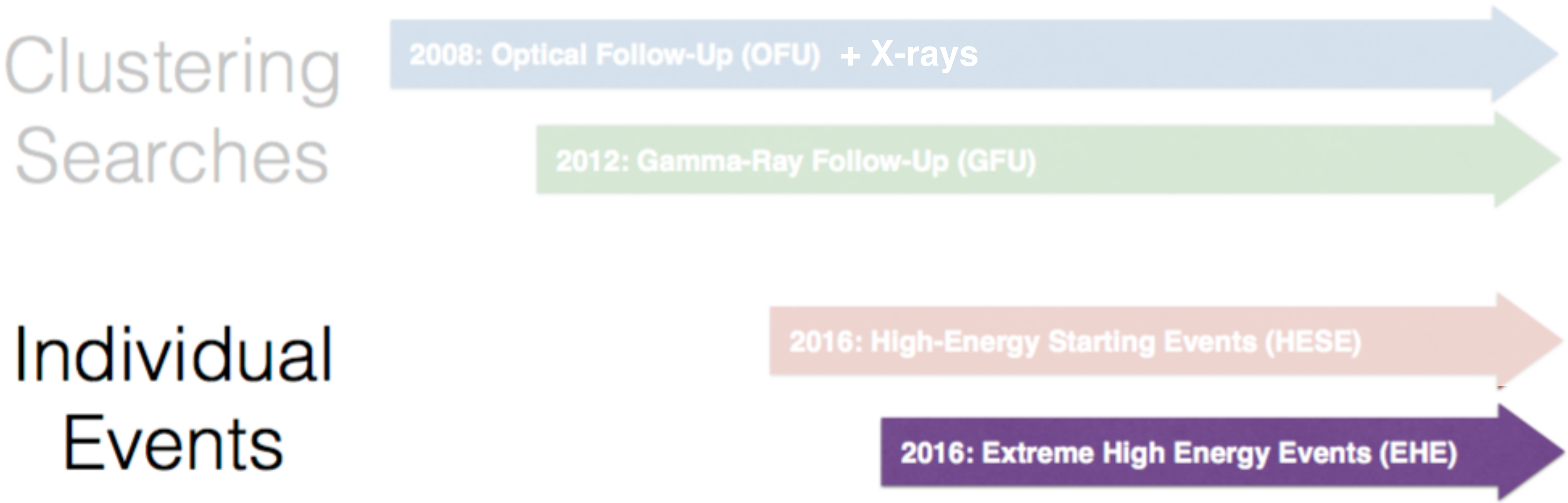
- **Several alert systems**



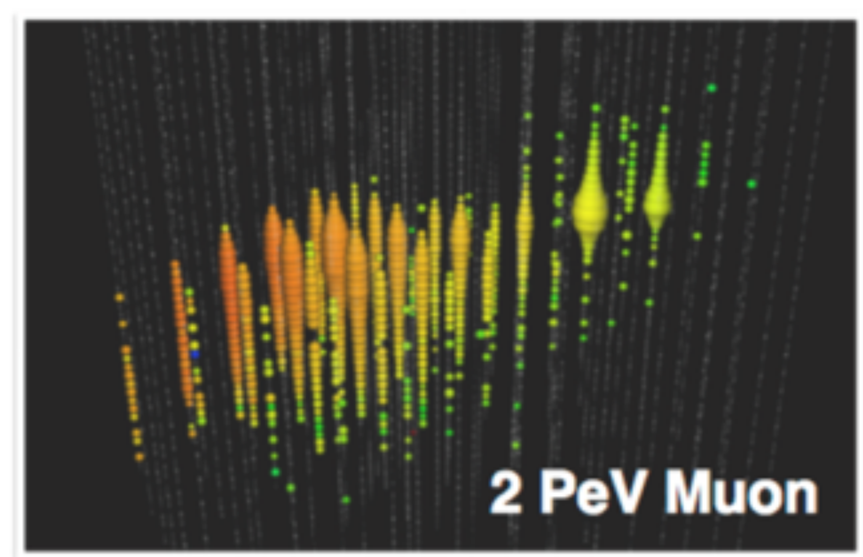
- Veto against atmospheric muons by outer detector layer
- Starting tracks with Q > 6000 pe
- **Public alerts (~4 alerts/year - 1 signal / 3 bkg expected for $E^{-2.58}$ spectrum)**

from T. Kintscher

- **Several alert systems**



- High-energy throughgoing events
- Npe > 3000 pe
- Very good resolution (<0.2°)
- **Public alerts: expected S+B:**
  - **- 4+2 events/year (E^{-2})**
  - **- 2+2 events/year ($E^{-2.5}$)**



from T. Kintscher

- **First HESE/EHE alerts**

Date	Type	RA	Dec	50% Error
2016/04/27	HESE	240.6 deg	9.3 deg	0.6 deg
2016/07/31	EHE + HESE	214.5 deg	- 0.3 deg	0.35 deg
2016/08/06	EHE	122.8 deg	- 0.7 deg	0.11 deg
2016/08/14	HESE	200.3 deg	- 32.4 deg	[illegible]
2016/11/03	HESE	40.9 deg	12.6 deg	[illegible]

Gamma-Rays

Observer	Result
IPN	no detection
Fermi-LAT	5 unrelated blazars
Fermi-GBM	no detection
FACT	no detection
VERITAS	no detection
HAWC	no detection
MAGIC	no detection

Optical

Observer	Result
iPTF	3 transients, all AGN
MASTER	no detection
PanSTARRS	7 SN candidates

+ ANTARES follow-up: no detection

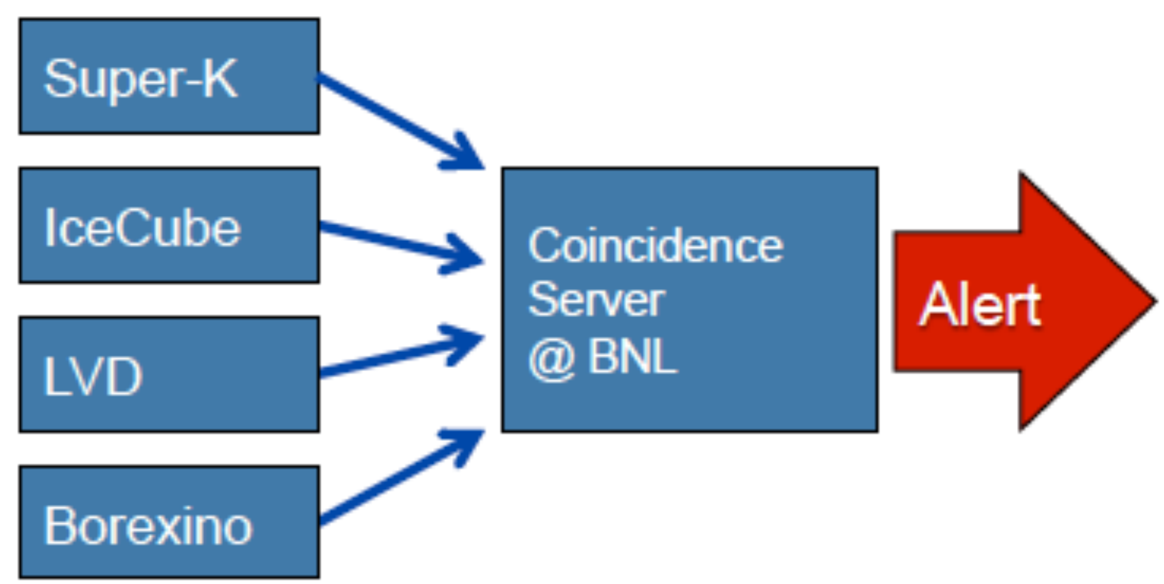
from T. Kintscher

The detection of even a single neutrino in association with a nearby supernova would reduce the uncertainty on the start time from ~ 1 day to ~ 10 seconds, which would help for GW searches for instance.

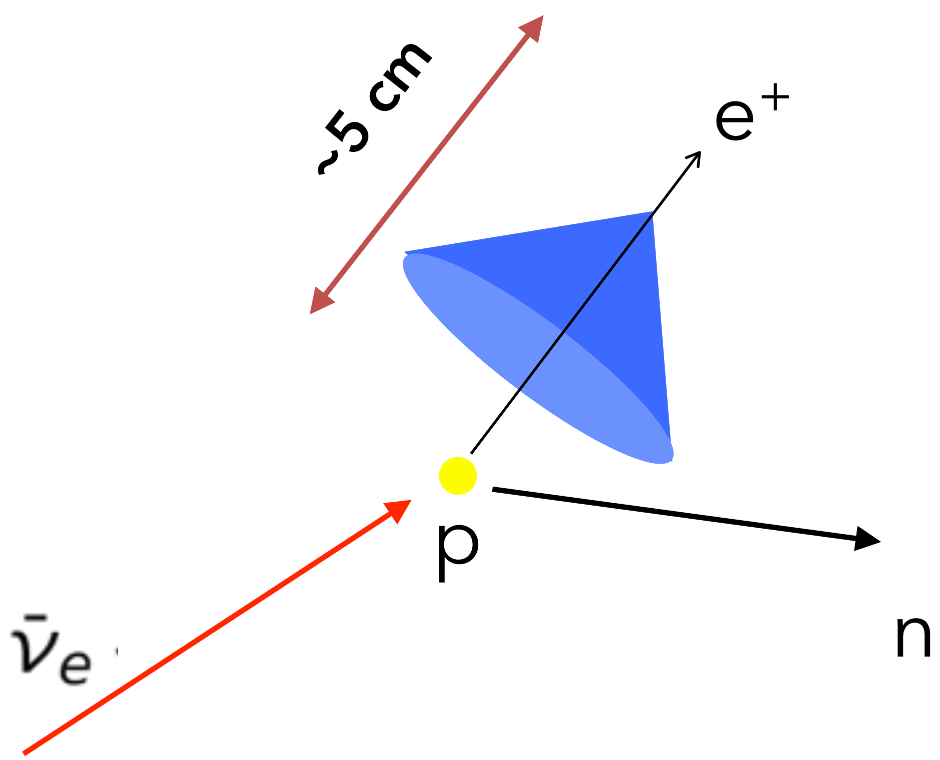
+ trigger of EM observations

http://snews.bnl.gov

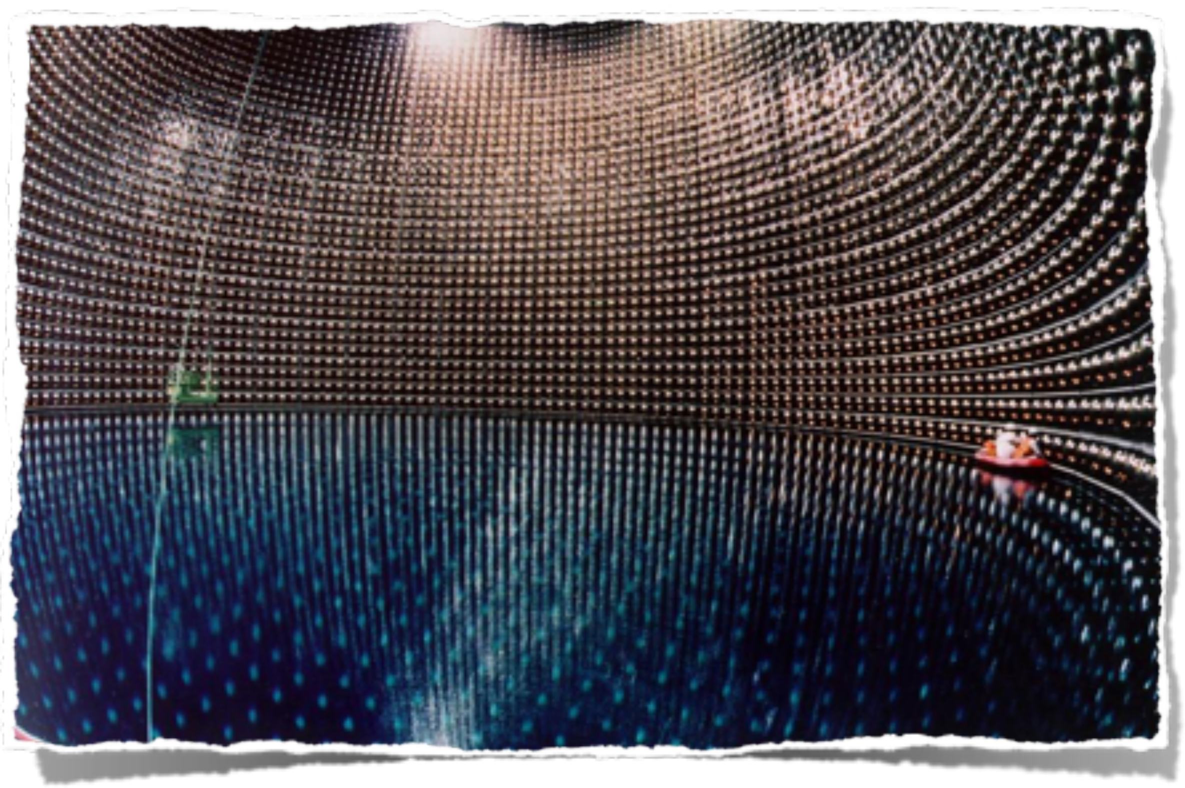
- Neutrinos arrive several hours before photons
- Can alert astronomers several hours in advance



Detecting supernova neutrinos
(with Cherenkov detectors)



- Neutrino interactions dominated by
  $\bar{\nu}_e + p \rightarrow e^+ + n$ at ~10 MeV
- Positron track of some cm detected by photomultipliers through UV/optical Cherenkov light



Detecting supernova neutrinos
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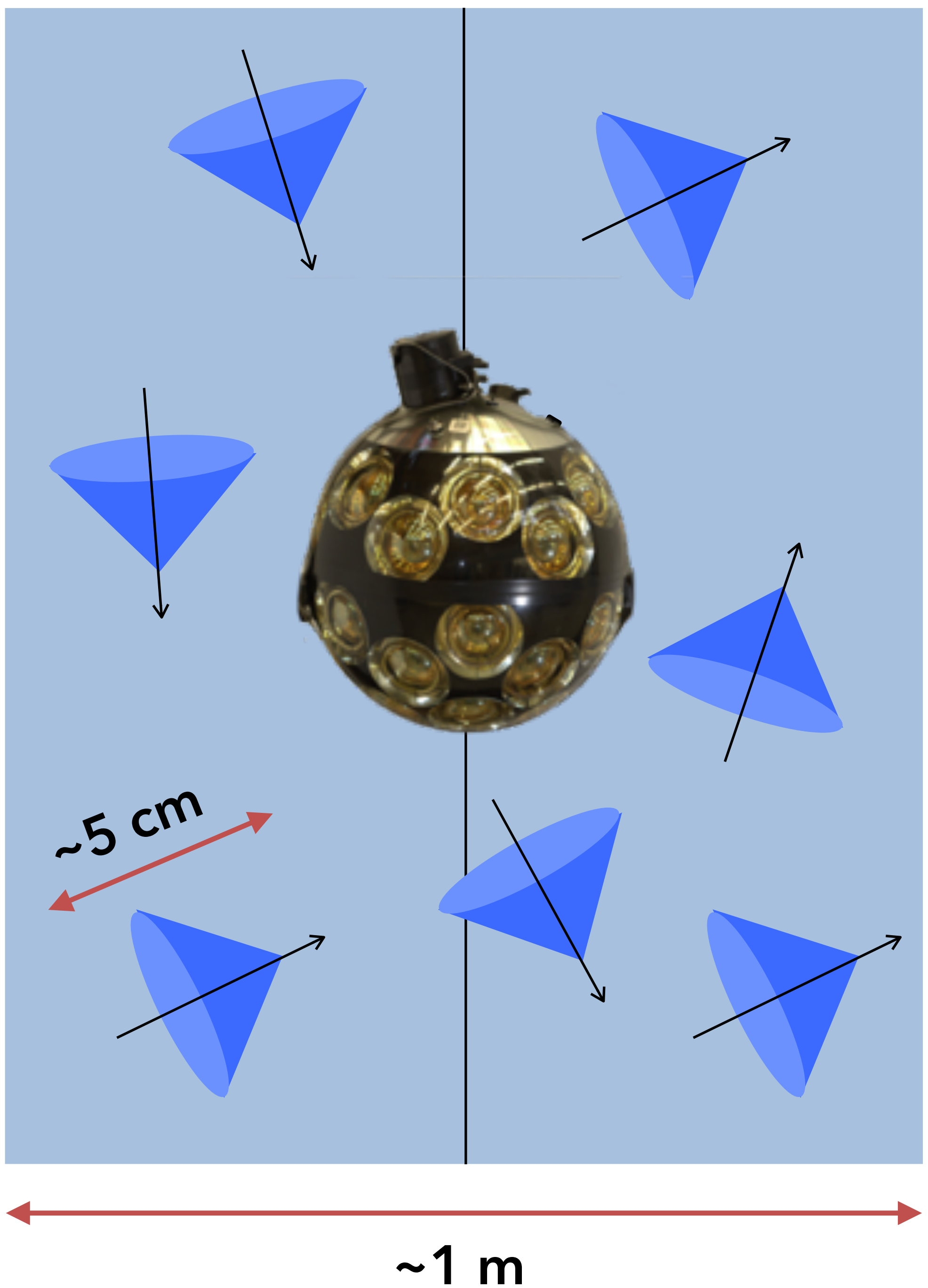
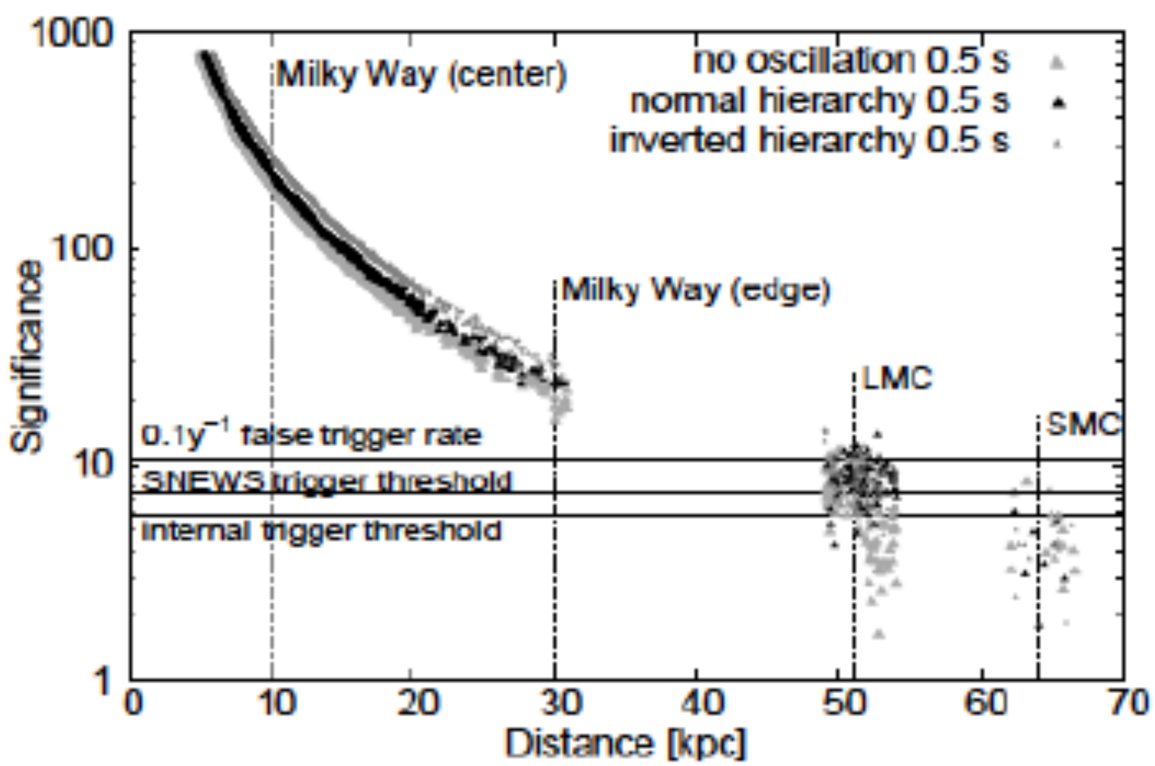


- **HE neutrino telescopes:** optimized for >GeV neutrino detection (cannot resolve MeV events individually)
- Each optical module detects Cherenkov light from its neighborhood
- Increase of the counting rate not significant
- SN signal appears as a collective rise in all optical modules above noise
- Huge volume ⇒ high statistics (might help to resolve the neutrino lightcurve)

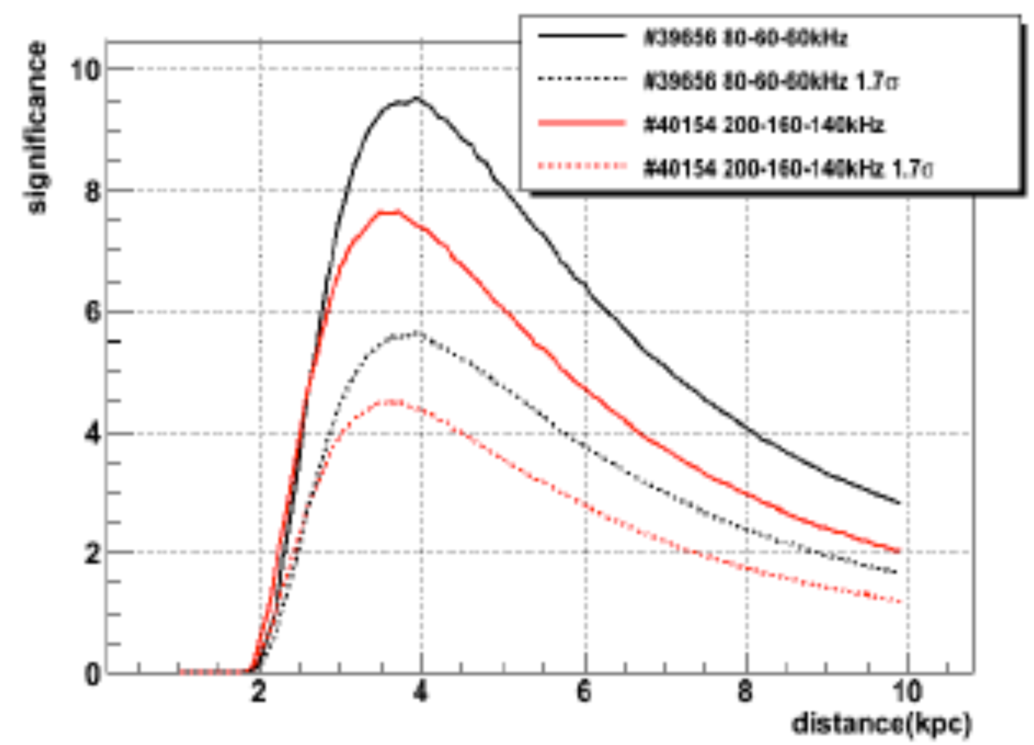
Detecting supernova neutrinos
(with Cherenkov detectors)

$$Significance = \frac{Signal}{\sigma_{measurement}}$$

Single rate method

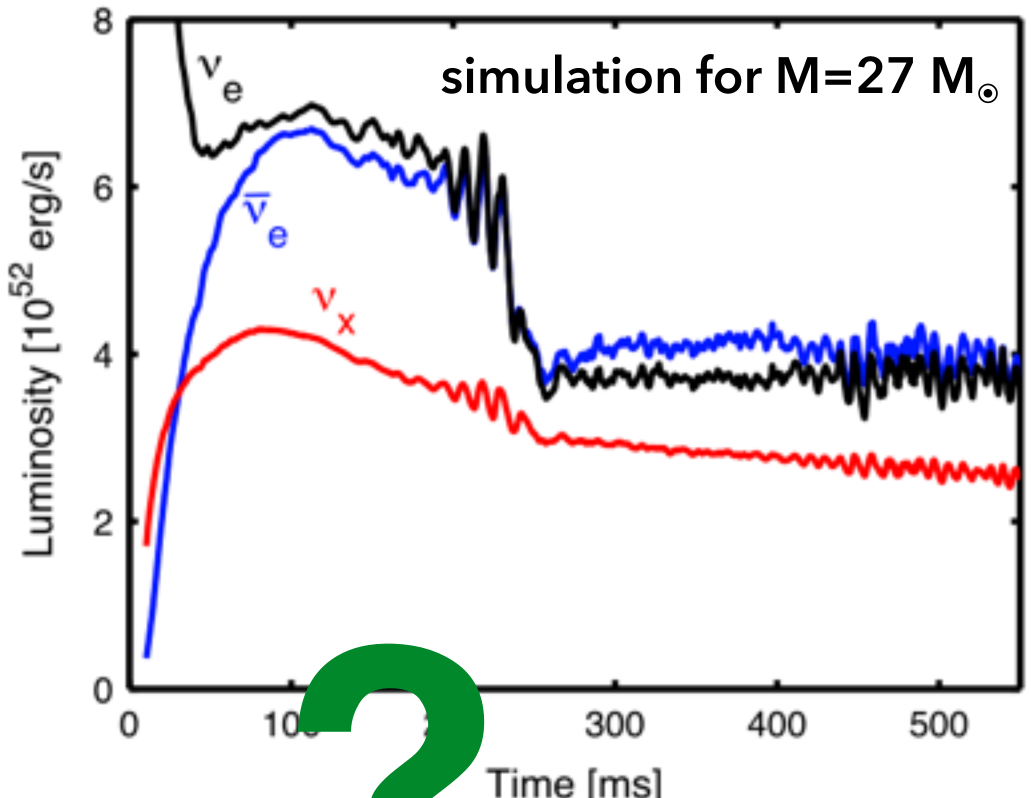


📖 IceCube collaboration, A&A 535 A109 2011



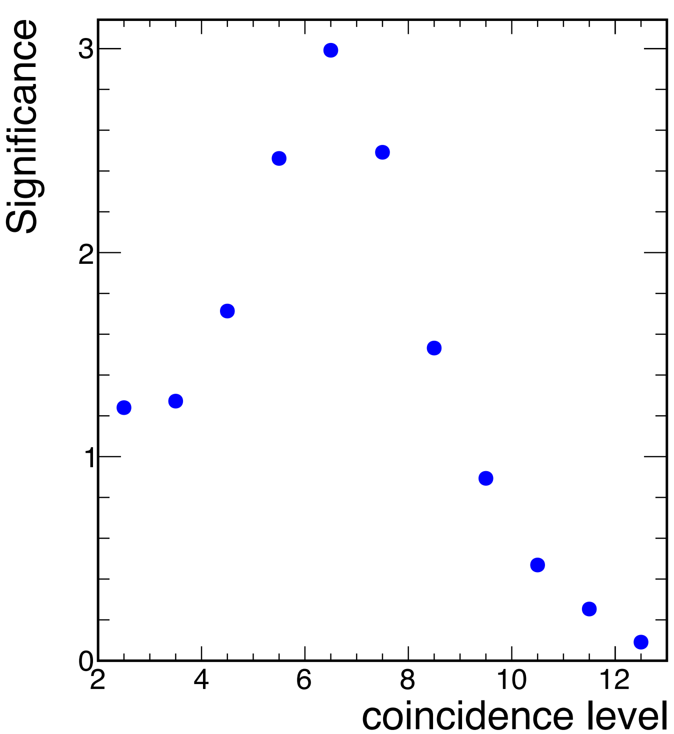
📖 Antares , 32 ICRC proceedings
ArXiv 1112.0478

Detecting supernova neutrinos *with KM3NeT (?)*

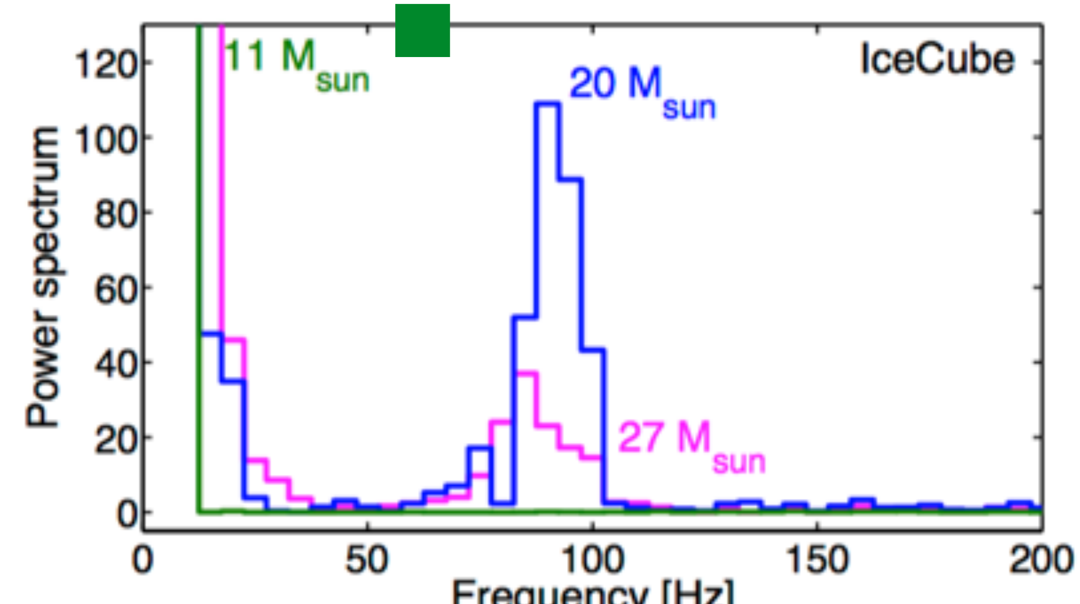


Tamborra et al., PRD90, 2014

- End-to-end Monte-Carlo simulation for KM3NeT under development.



Should give a 3σ sensitivity for Galactic CCSN (preliminary results).



Tamborra et al., PRL111, 2013

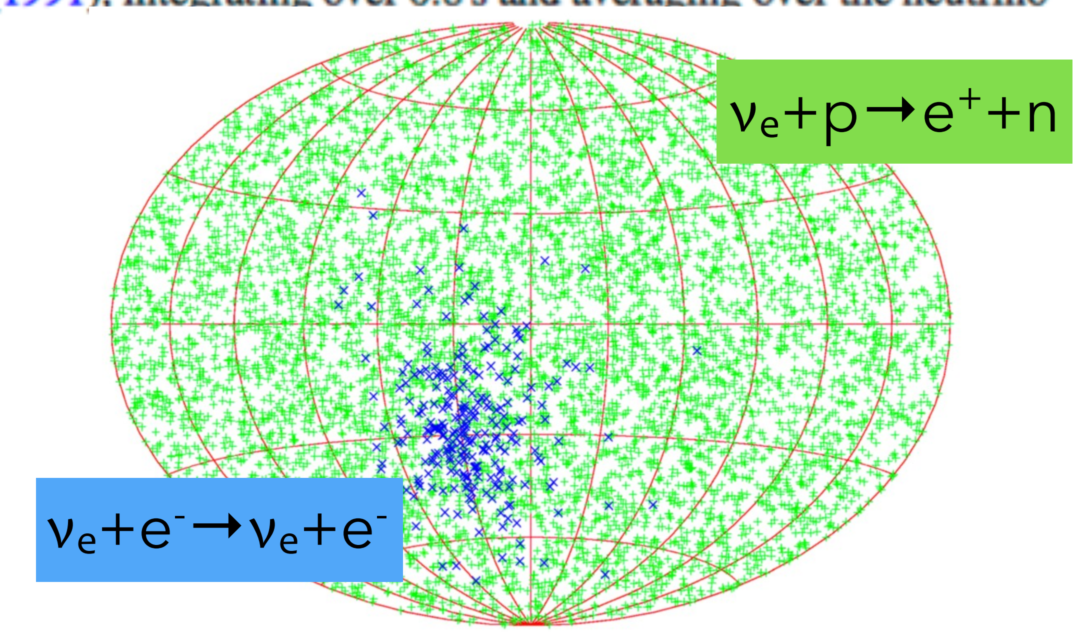
Detecting supernova neutrinos
with KM3NeT (?)

Table 1. Major neutrino reactions.

Pointing quality:
~25°/$N^{1/2}$
without bkg !

Reaction	# Targets	# Signal hits	Signal fraction	Reference
$\bar{\nu}_e + p \to e^+ + n$	6×10^{37}	134 k (157 k)	93.8% (94.4%)	Strumia & Vissani (2003)
$\nu_e + e^- \to \nu_e + e^-$	3×10^{38}	2.35 k (2.25 k)	1.7% (1.4%)	Marciano & Parsa (2003)
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	3×10^{38}	660 (720)	0.5% (0.4%)	Marciano & Parsa (2003)
$\nu_{\mu+\tau} + e^- \to \nu_{\mu+\tau} + e^-$	3×10^{38}	700 (720)	0.5% (0.4%)	Marciano & Parsa (2003)
$\bar{\nu}_{\mu+\tau} + e^- \to \bar{\nu}_{\nu+\tau} + e^-$	3×10^{38}	600 (570)	0.4% (0.4%)	Marciano & Parsa (2003)
$\nu_e + {}^{16}O \to e^- + X$	3×10^{37}	2.15 k (1.50 k)	1.5% (0.9%)	Kolbe et al. (2002)
$\bar{\nu}_e + {}^{16}O \to e^+ + X$	3×10^{37}	1.90 k (2.80 k)	1.3% (1.7%)	Kolbe et al. (2002)
$\nu_{all} + {}^{16}O \to \nu_{all} + X$	3×10^{37}	430 (410)	0.3% (0.3%)	Kolbe et al. (2002)
$\nu_e + {}^{17/18}O/{}^2_1H \to e^- + X$	6×10^{34}	270 (245)	0.2% (0.2%)	Haxton (1999)

Notes. The approximate number of targets in a 1 km^3 ice detector, the detected number of hits at 10 kpc distance and their fraction in stars are given in the second, third and fourth column, respectively. In order to indicate the effect of neutrino oscillations in the star, signal hits and fractions are presented both assuming a normal neutrino hierarchy (Scenario A) and – in brackets – assuming an inverted hierarchy (Scenario B). The numbers are taken from the Garching model using the equation of state by Lattimer & Swesty (1991), integrating over 0.8 s and averaging over the neutrino incidence angle.

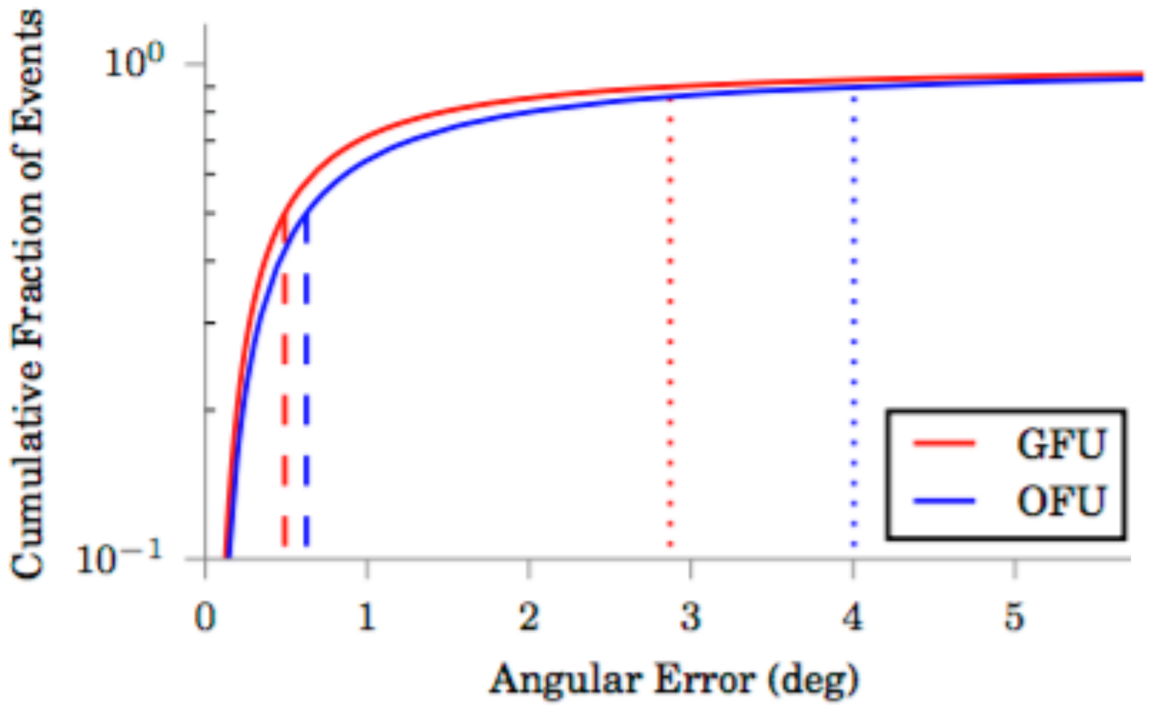


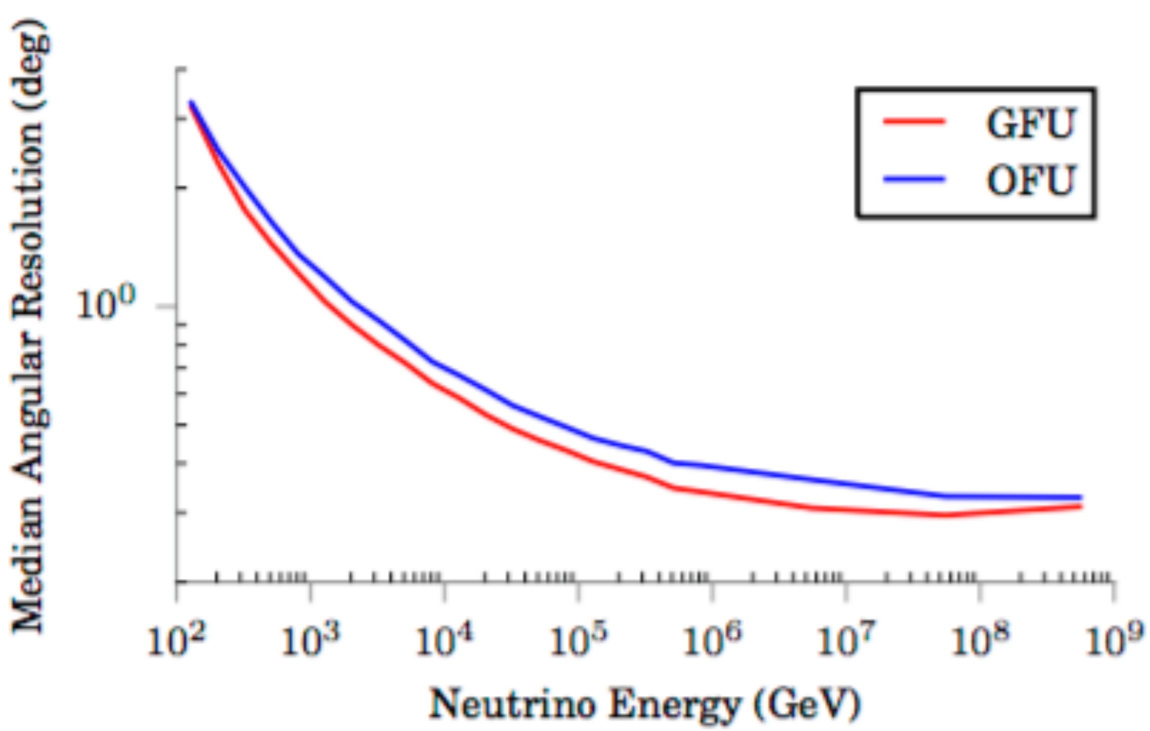
Tomàs, Semikoz, Raffelt, Kachelriess & Dighe: Supernova pointing with low- and high-energy neutrino detectors [hep-ph/0307050]

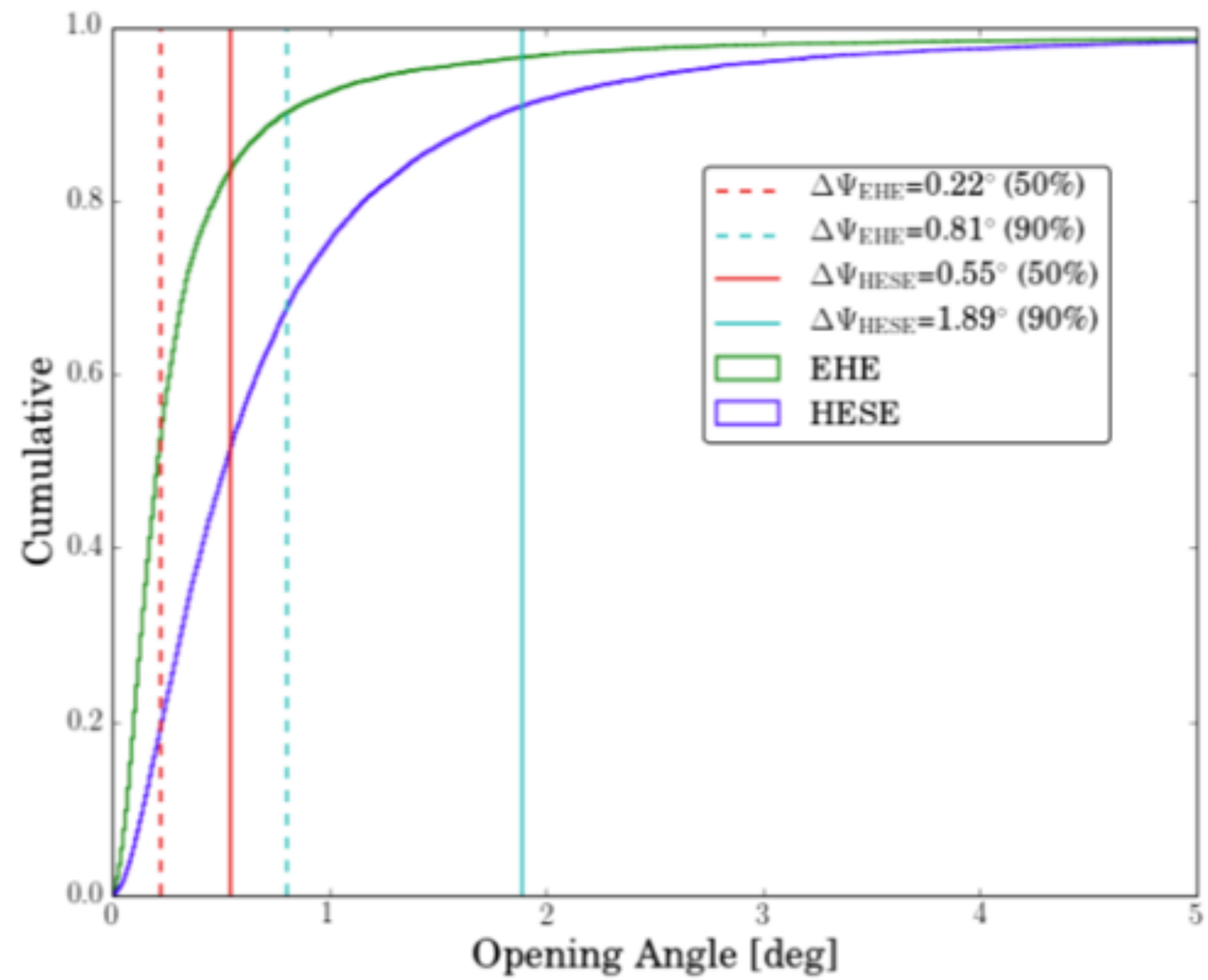
- How to perform accurate follow-ups ? (which messengers/wavelengths are crucial ?)
- Which neutrino candidates will be followed-up ? Selection of interesting events ? In the context of more and more transients.
- Reconstruction/follow-up of cascade events with KM3NeT (~2° of angular reconstruction) + ~0.1° for tracks (reachable by 1-m class optical telescopes).
- Needs an enhanced collaboration between astroparticle physicist / astrophysicists and exchange of know-how.
- Opportunity with GW electromagnetic follow-up.

IceCube angular resolution

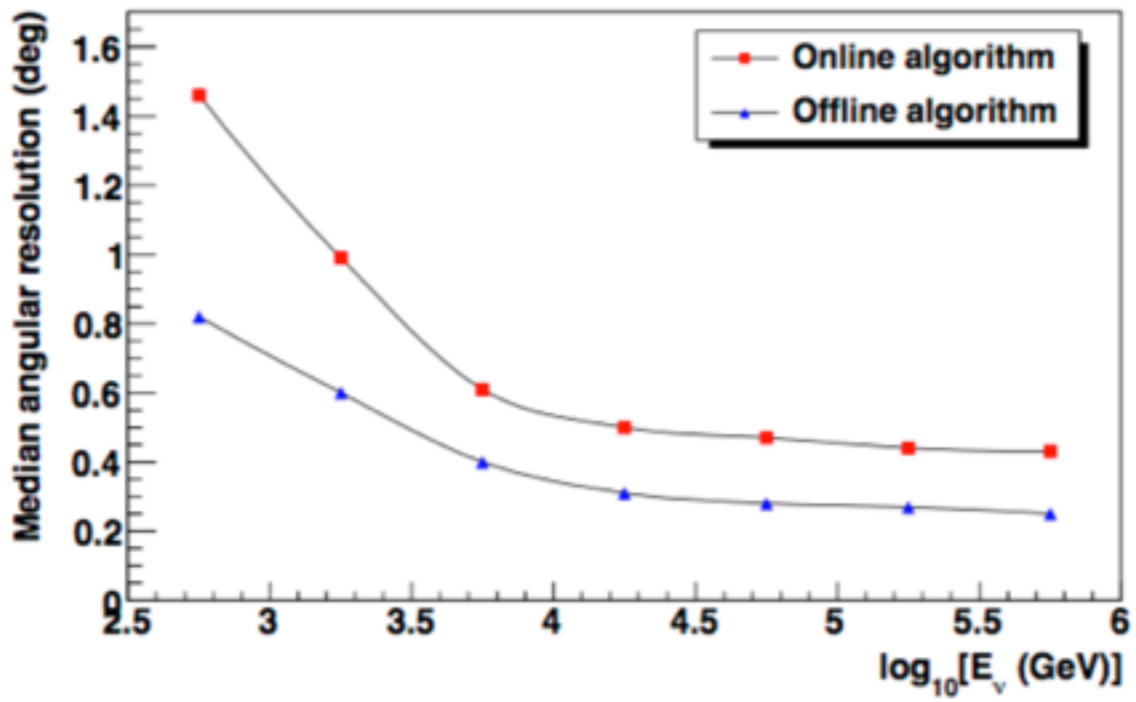
$$\lambda = \frac{\Delta\Psi^2}{\sigma_q^2} + 2\ln(2\pi\sigma_q^2) - 2\ln\left(1 - \exp\left(-\frac{\theta_A^2}{2\sigma_w^2}\right)\right) + 2\ln\left(\frac{\Delta T}{100\,s}\right)$$

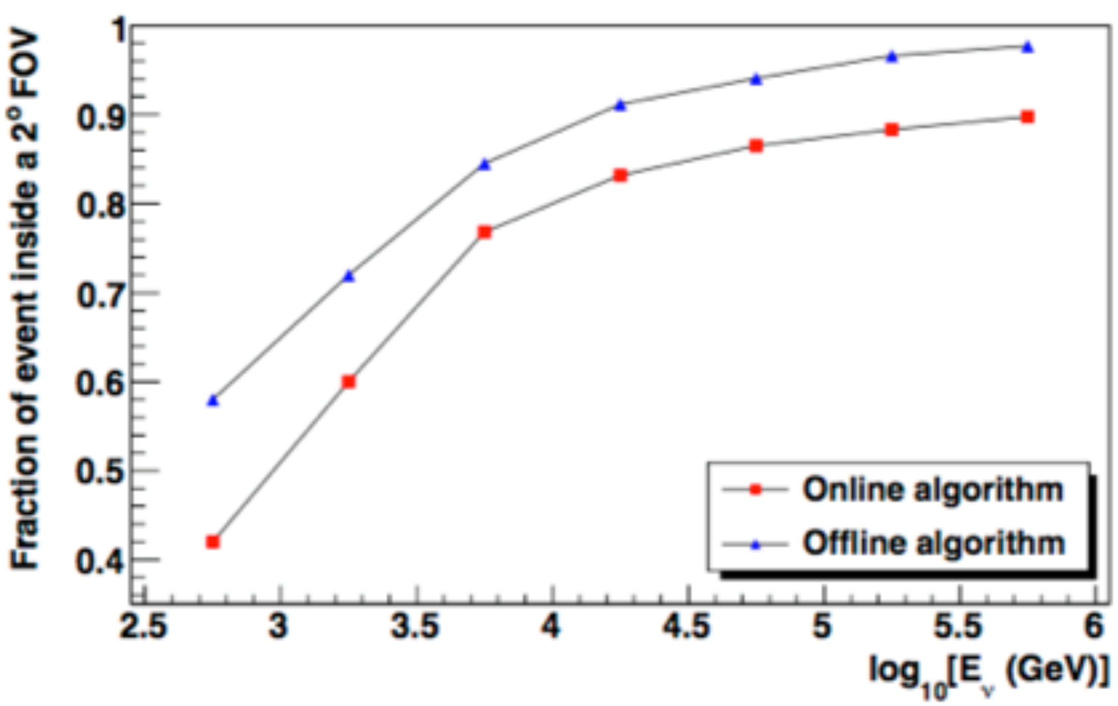




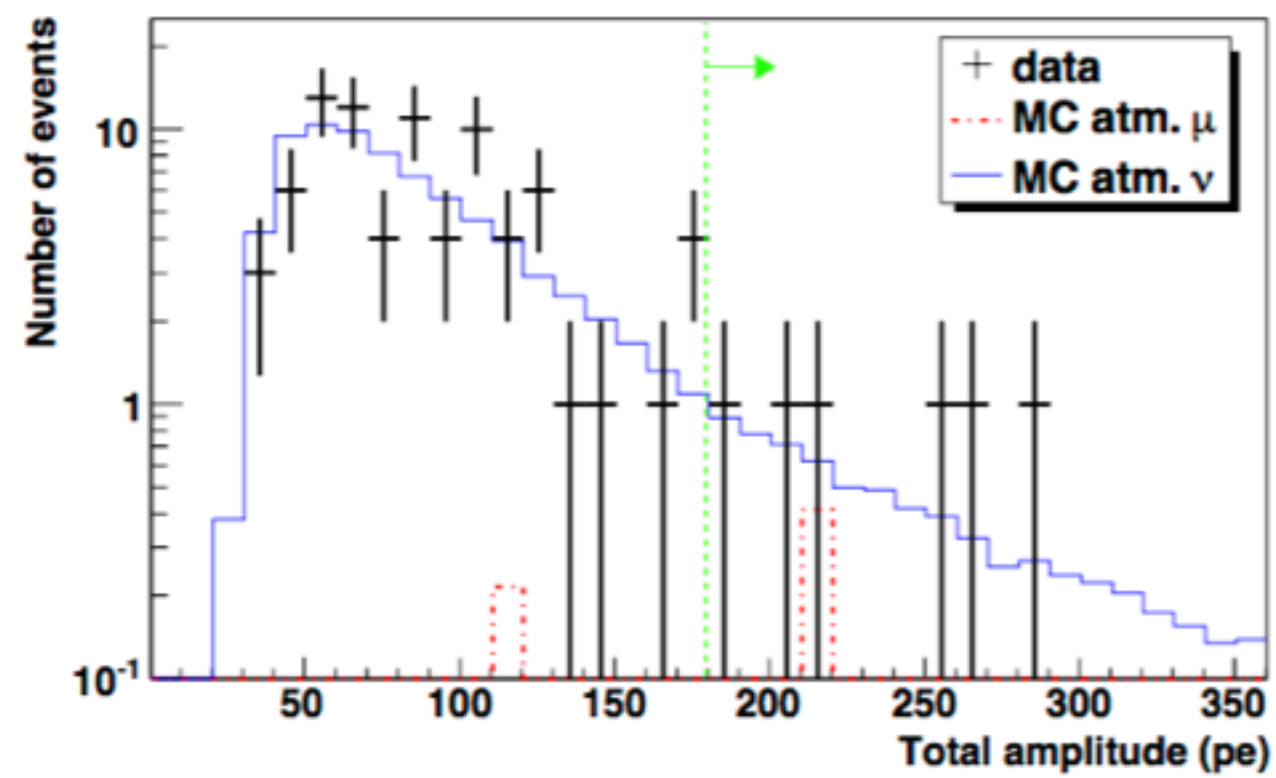


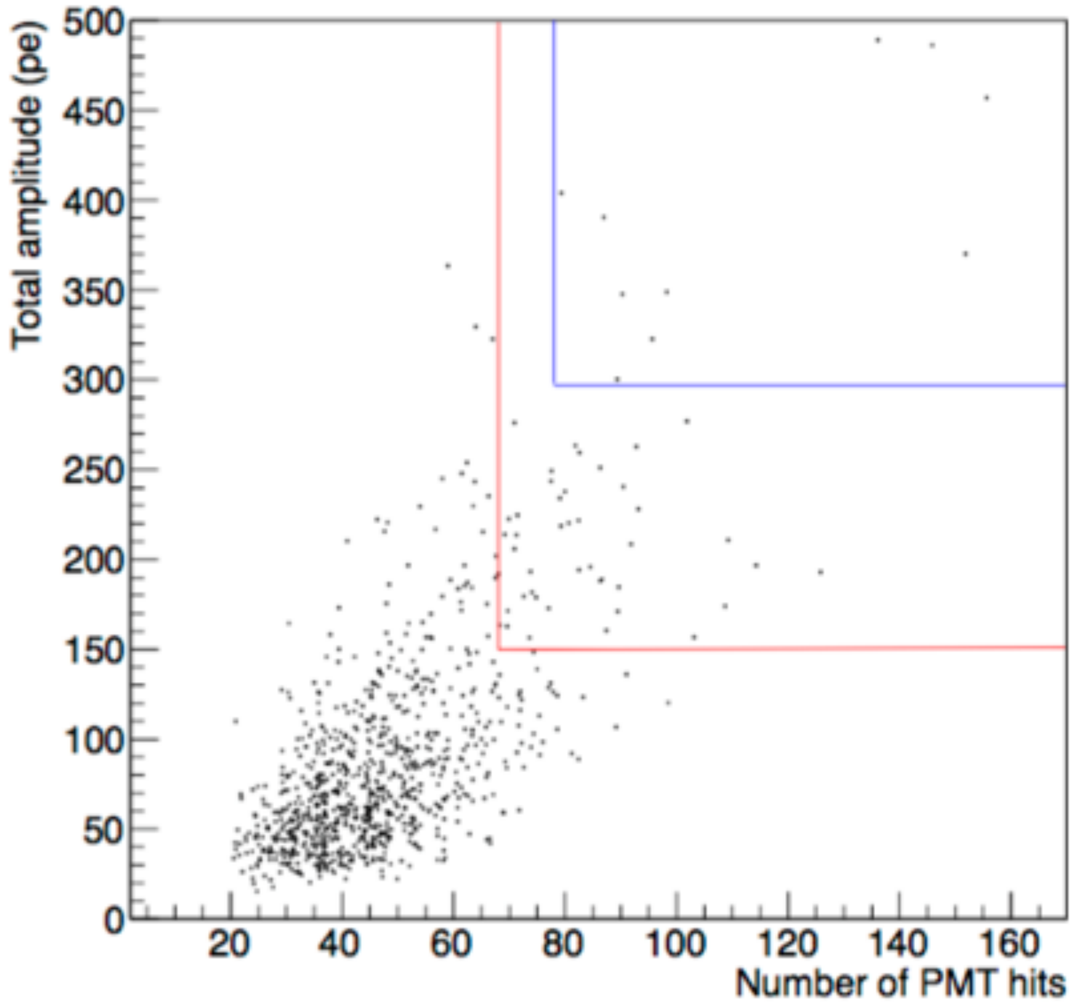
ANTARES angular resolution

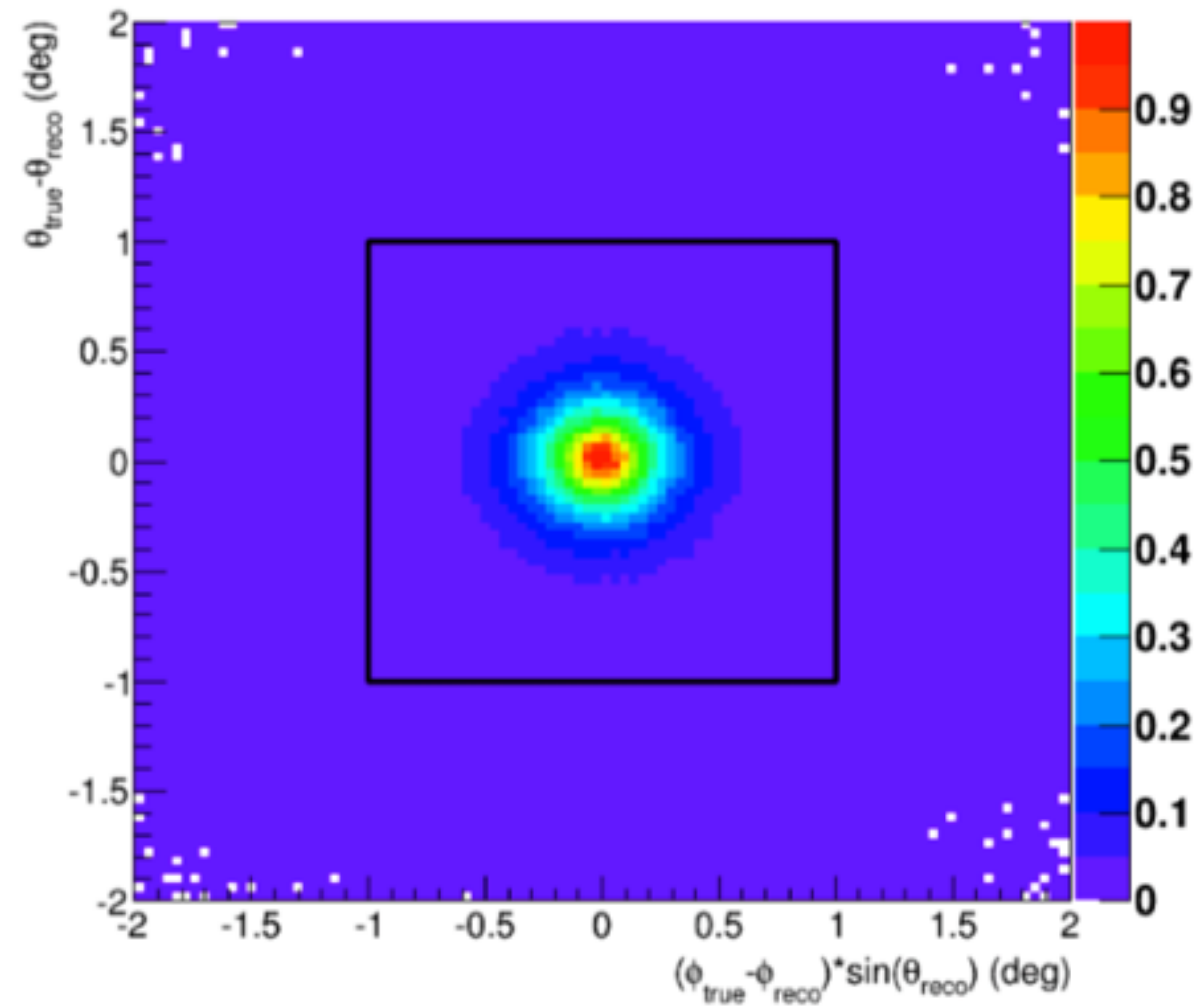


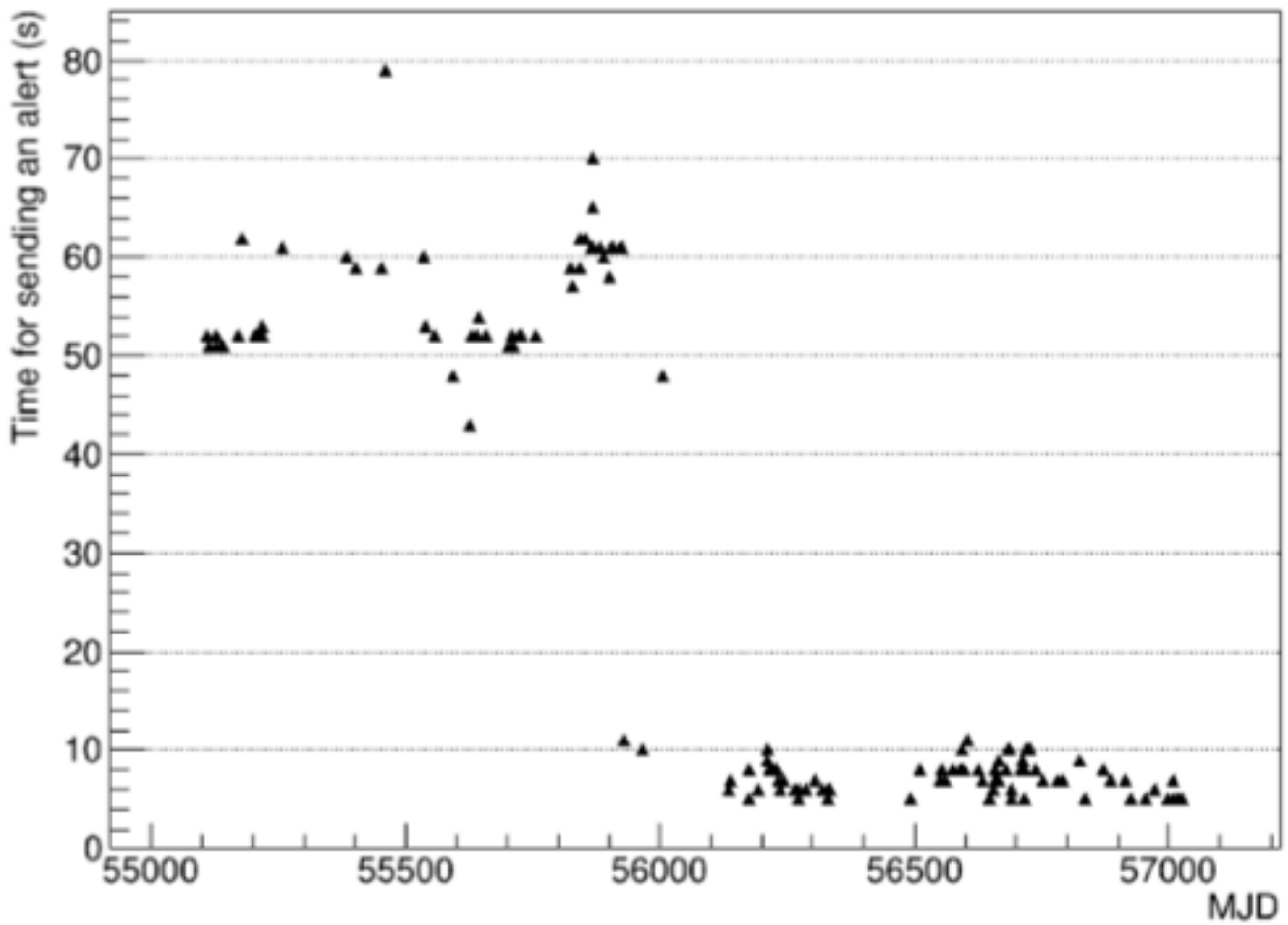


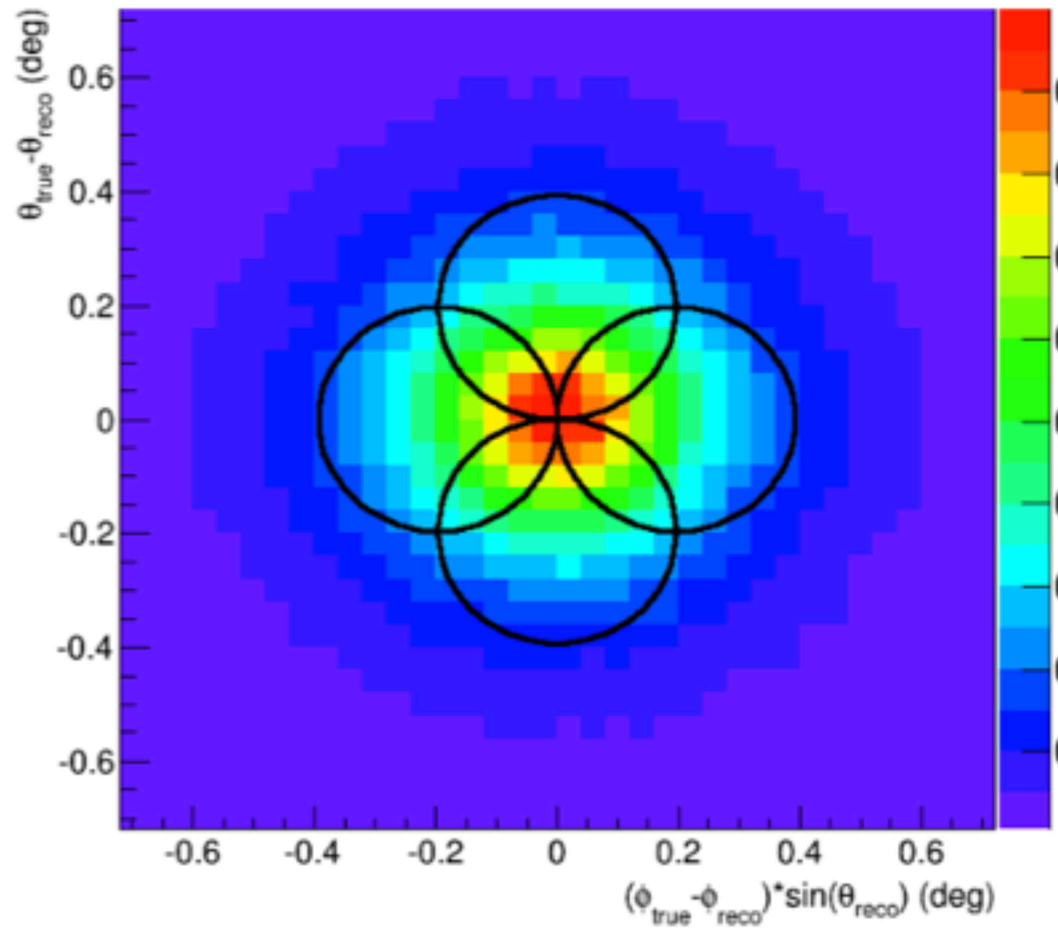
ANTARES charge distribution




Total amplitude (pe)
500
450
400
350
300
250
200
150
100
50
0
20
40
60
80
100
120
140
160
Number of PMT hits


θtrue-θreco (deg)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
(φtrue-φreco)*sin(θreco) (deg)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0


Time for sending an alert (s)
80
70
60
50
40
30
20
10
0
55000
55500
56000
56500
57000
MJD


$\theta_{true}-\theta_{reco}$ (deg)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
$(\phi_{true}-\phi_{reco})$*sin($\theta_{reco}$) (deg)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1