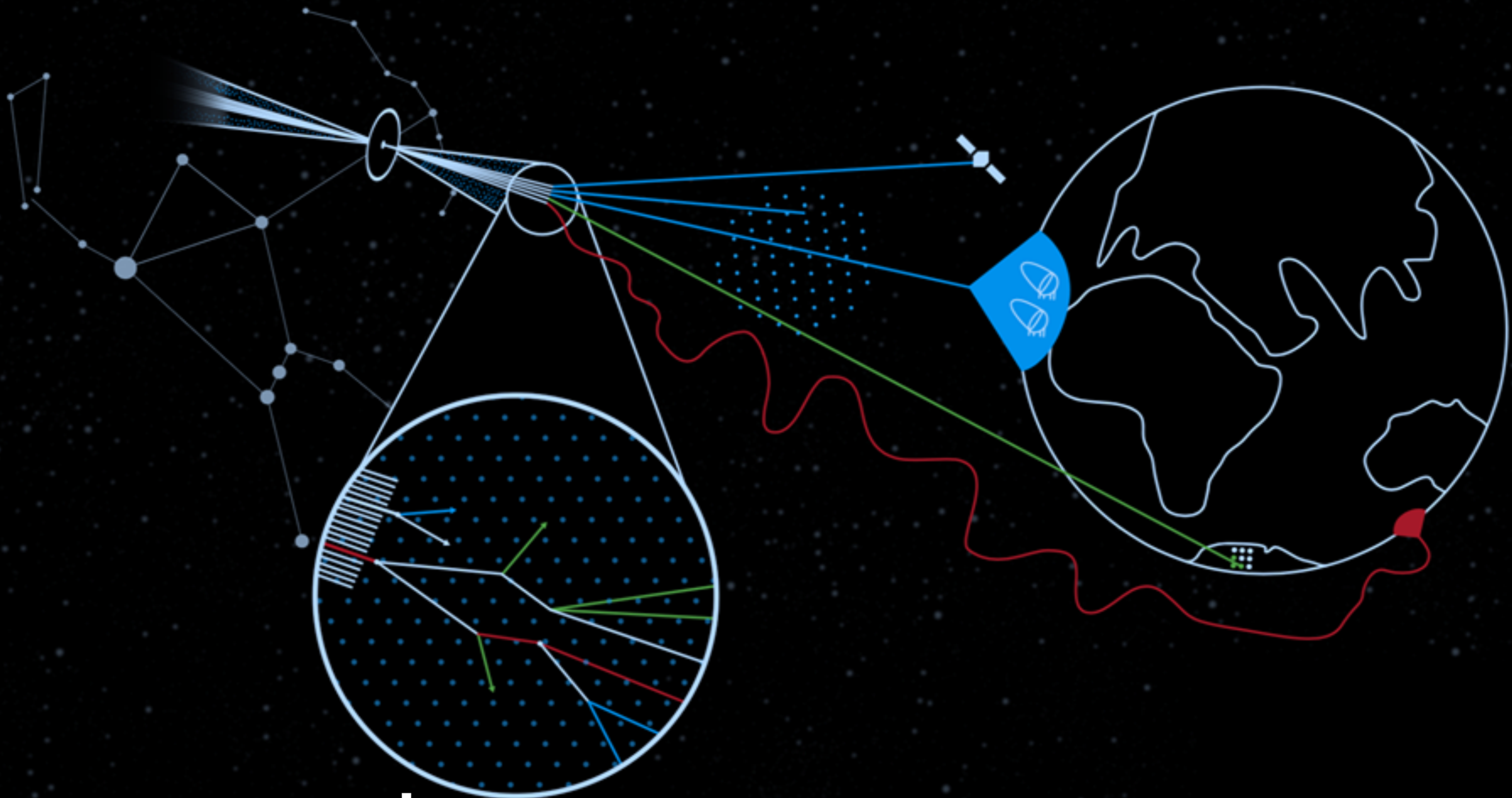


Multi-messenger astro-particle physics observations

Elisa Bernardini
Università degli Studi di Padova (Italy) and DESY (Germany)

Multi-messenger astrophysics

Exploring the Universe by combining information from a multitude of cosmic messengers: electromagnetic radiation, gravitational waves, neutrinos and cosmic rays

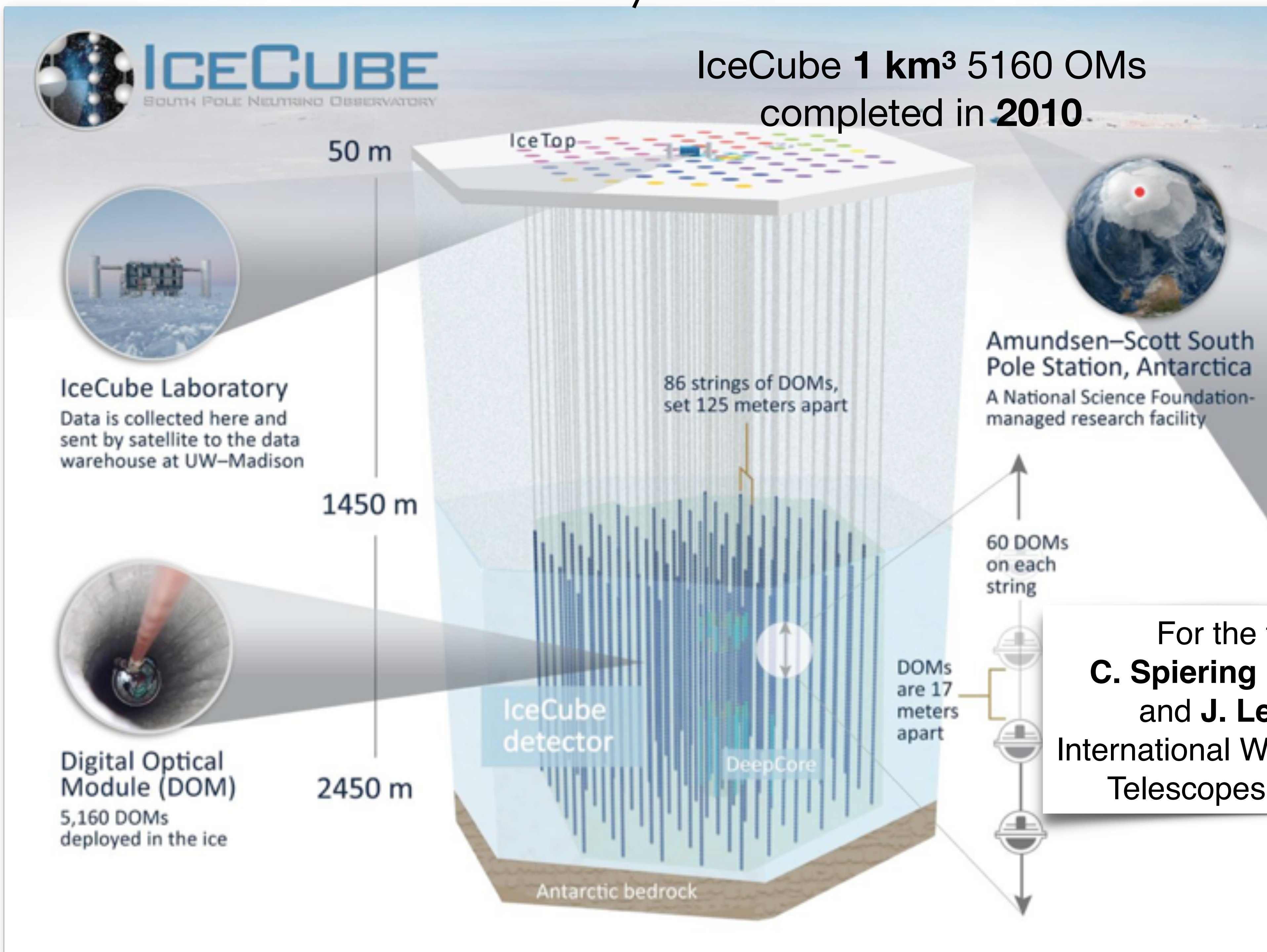
Multi-messenger astrophysics

Exploring the Universe by combining information from a multitude of cosmic messengers: electromagnetic radiation, gravitational waves, neutrinos and cosmic rays

History of neutrino Astronomy in a nutshell

Underwater neutrino detection were envisioned in **1960** (Markov).
In the **'70** it was predicted that to detect **cosmogenic neutrinos** volumes **~1 km^3** are needed. They were reached first in **2010**.

IceCube **1 km³** 5160 OMs completed in **2010**

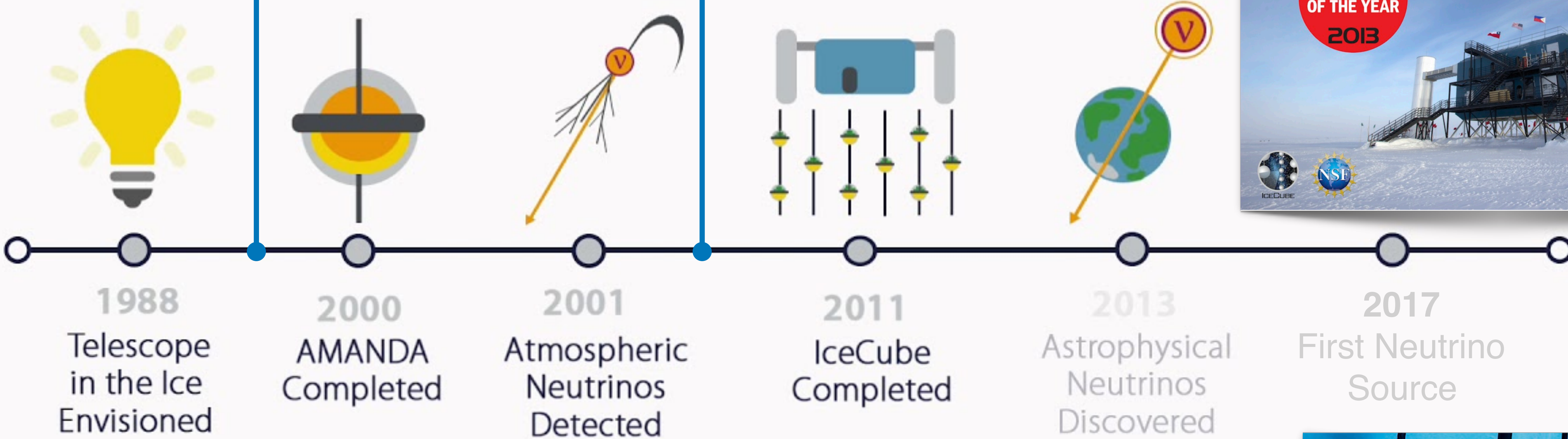


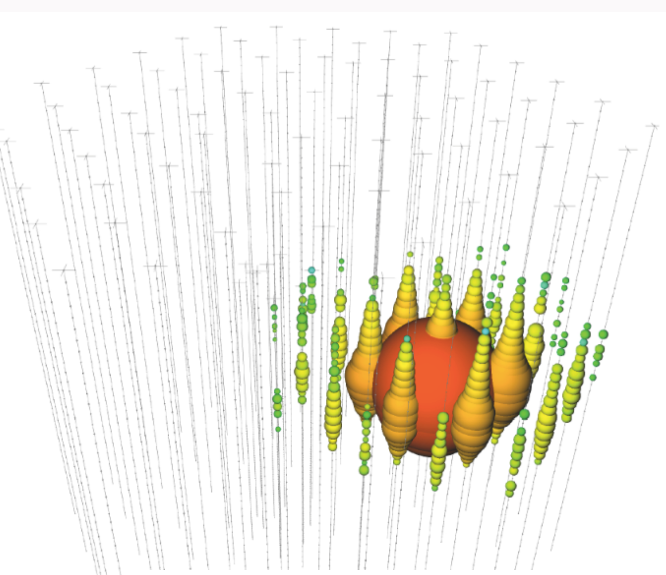
For the full story see:
C. Spiering arXiv: 1903.11481
and **J. Learned** at XVIII International Workshop on Neutrino Telescopes in Venice (2019)

History of neutrino Astronomy in a nutshell

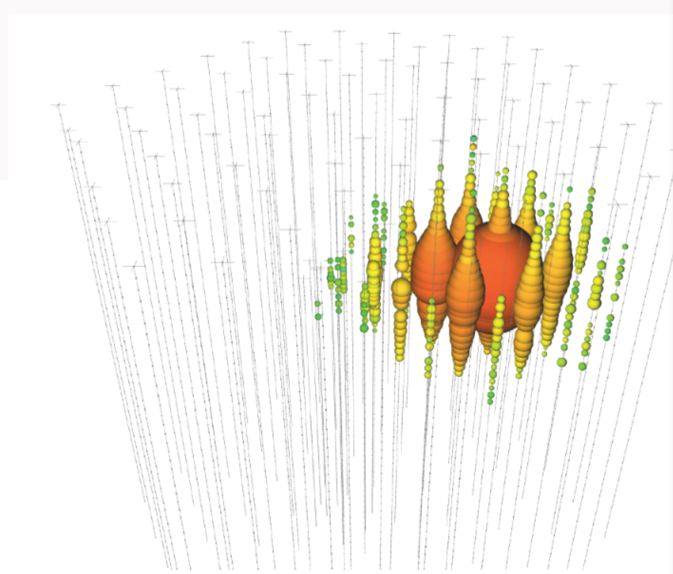
First high energy atmospheric neutrinos were detected underwater at Lake Baikal in 1996.

Construction of ANTARES in the Mediterranean Sea started in 2002

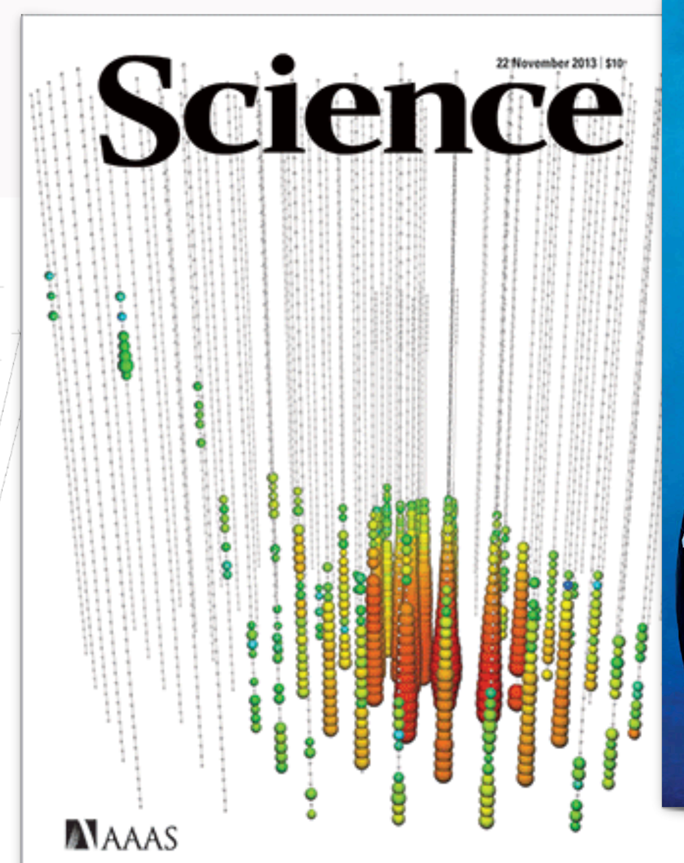




1.1 ± 0.17 PeV

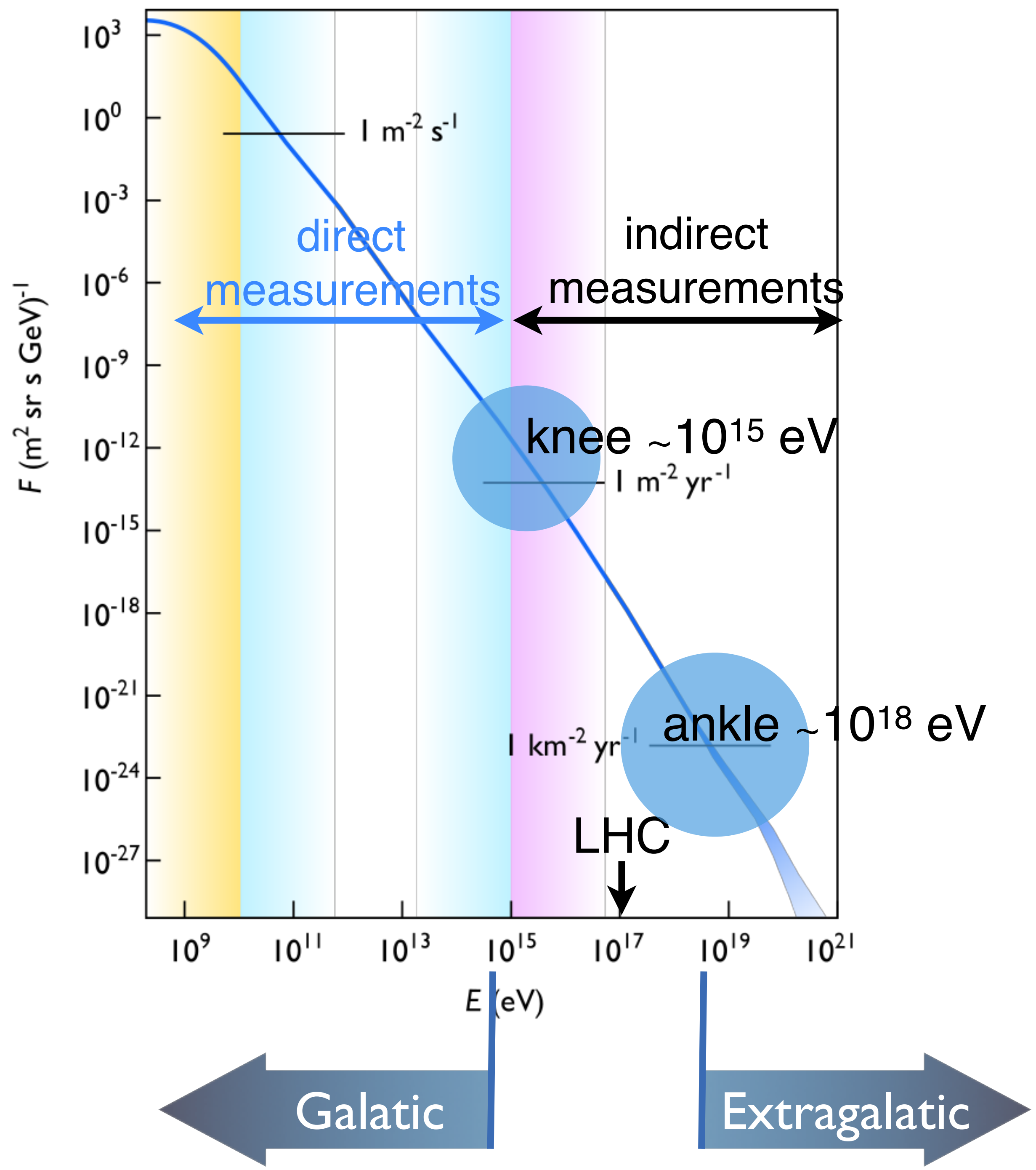


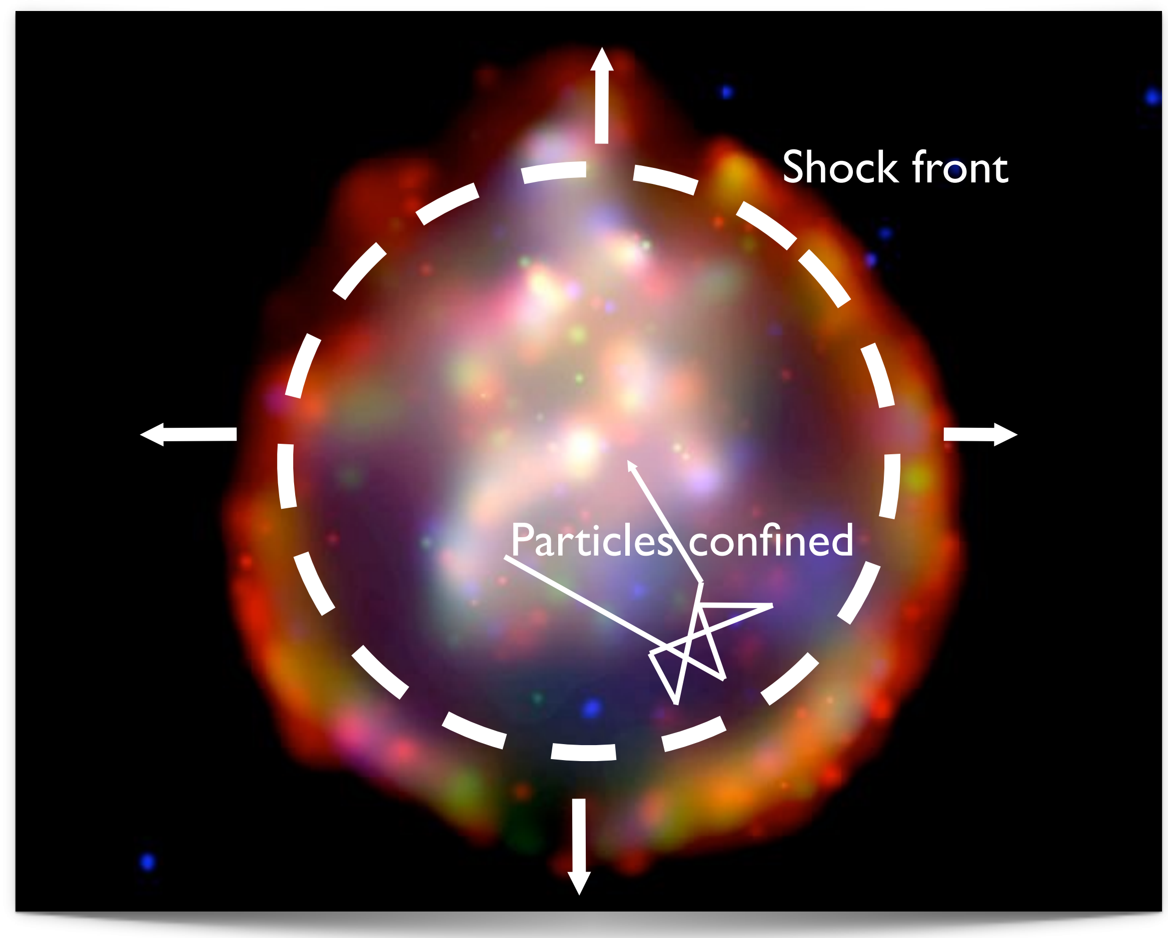
1.0 ± 0.15 PeV



One Step back: Cosmic Rays

Few mechanisms are known that can yield the needed energy. The most popular (Fermi) provides a power-law energy spectrum ($dN/dE \sim E^{-\alpha}$; $\alpha \sim 2.1$) with an efficiency of few %.



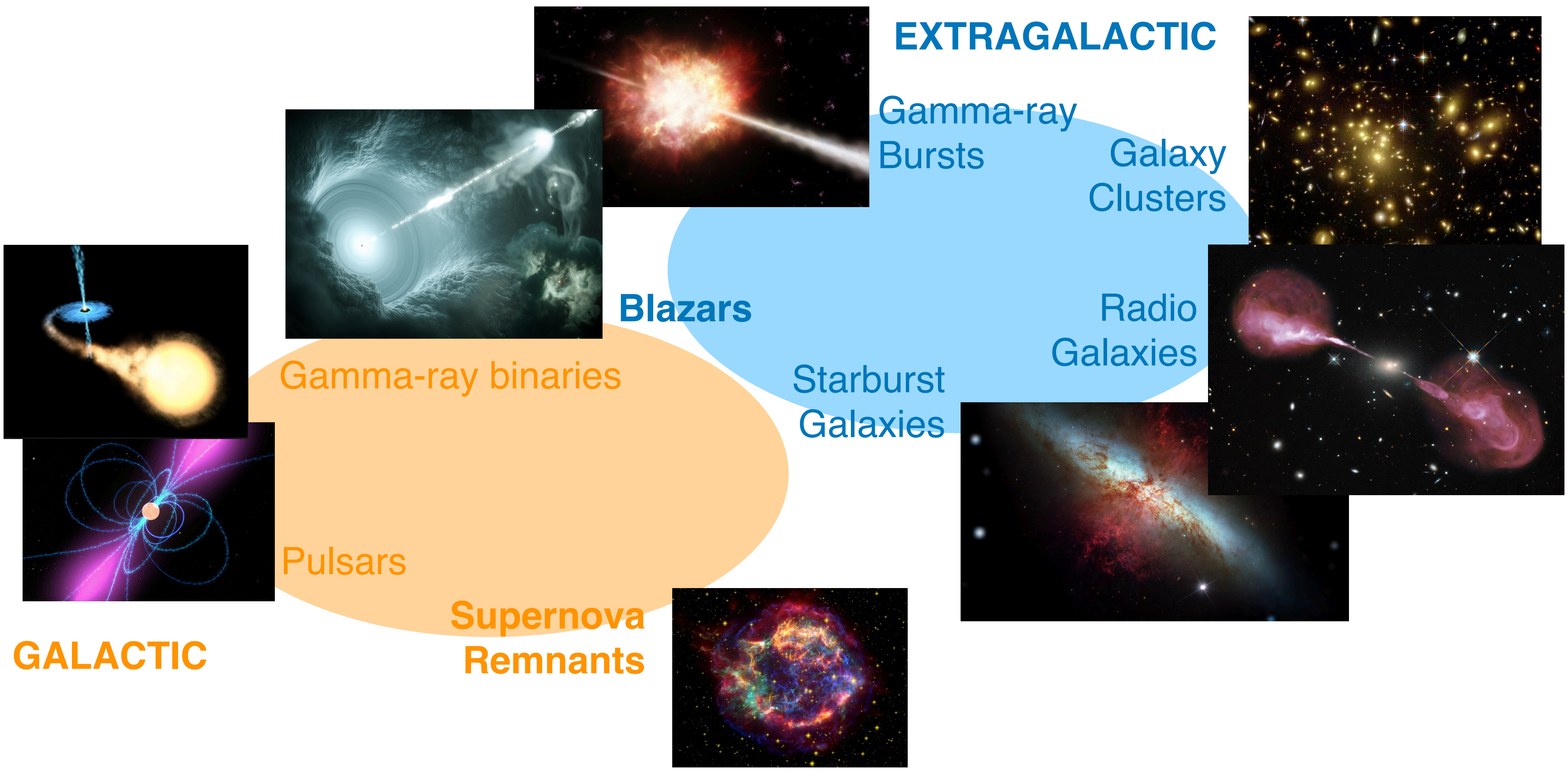


Possible sources of cosmic rays

The Larmor radius of a particle shall not exceed the accelerator size to prevent the particle from escaping the accelerator.

$$E_{max} \simeq 10^{18}\mathrm{eV}\, Z\, \beta \left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)$$

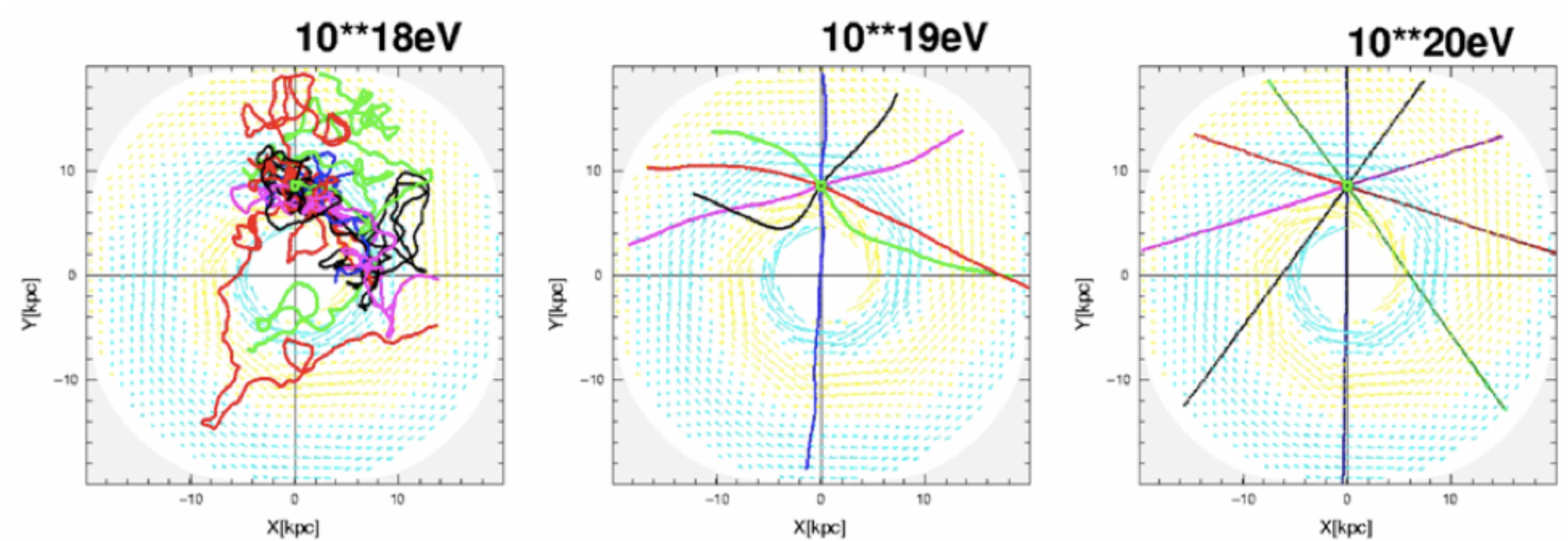
A. M. Hillas. 1984.



The mysteries of Cosmic Rays

At energies below ~10^{18} eV Cosmic Rays are significantly deflected in galactic B-fields. Above ~10^{20} eV the deflection in the Galaxy is less than 1° but Cosmic Rays interact with the Cosmic Microwave Background!

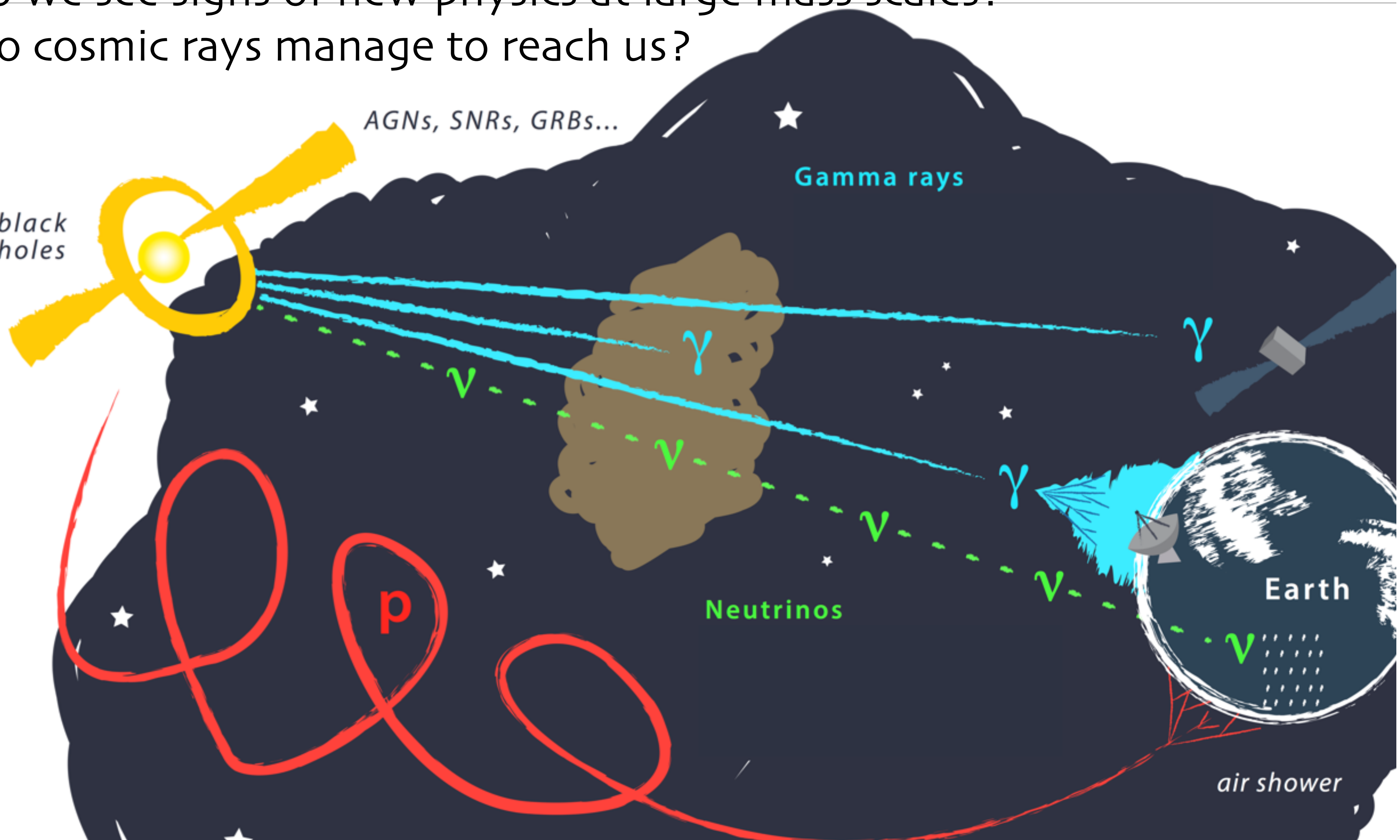
Simulation of deflection of cosmic rays in the Galaxy



Cut-off in the Cosmic Rays spectrums from $p\gamma \rightarrow \Delta \rightarrow \begin{array}{l} p + \pi^0 \ [2/3] \\ n + \pi^+ \ [1/3] \end{array}$

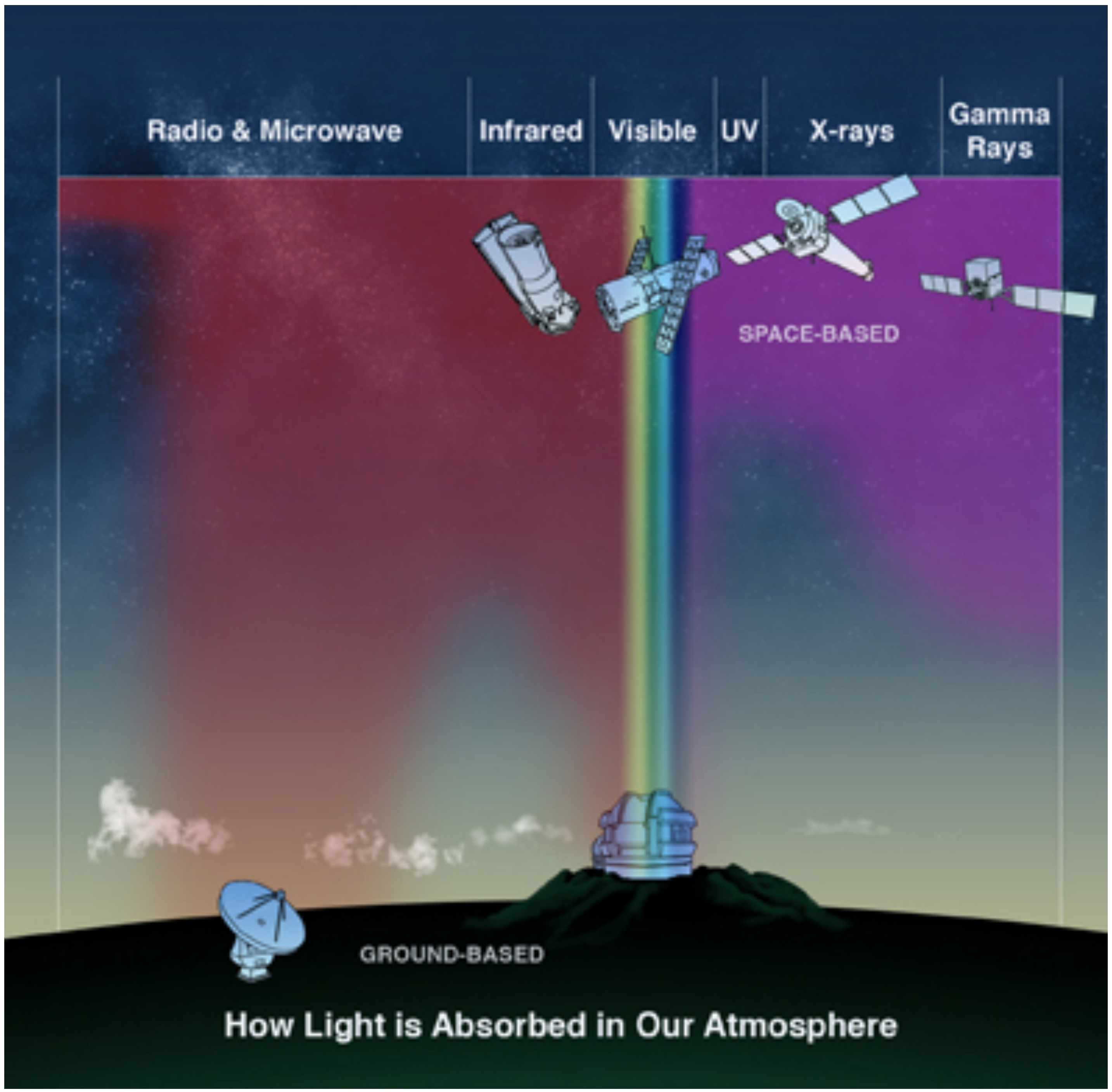
Multi-messenger astro-particles

Which and where are the sources?
How do they work?
Are the particles really accelerated?
…or do we see signs of new physics at large mass scales?
How do cosmic rays manage to reach us?

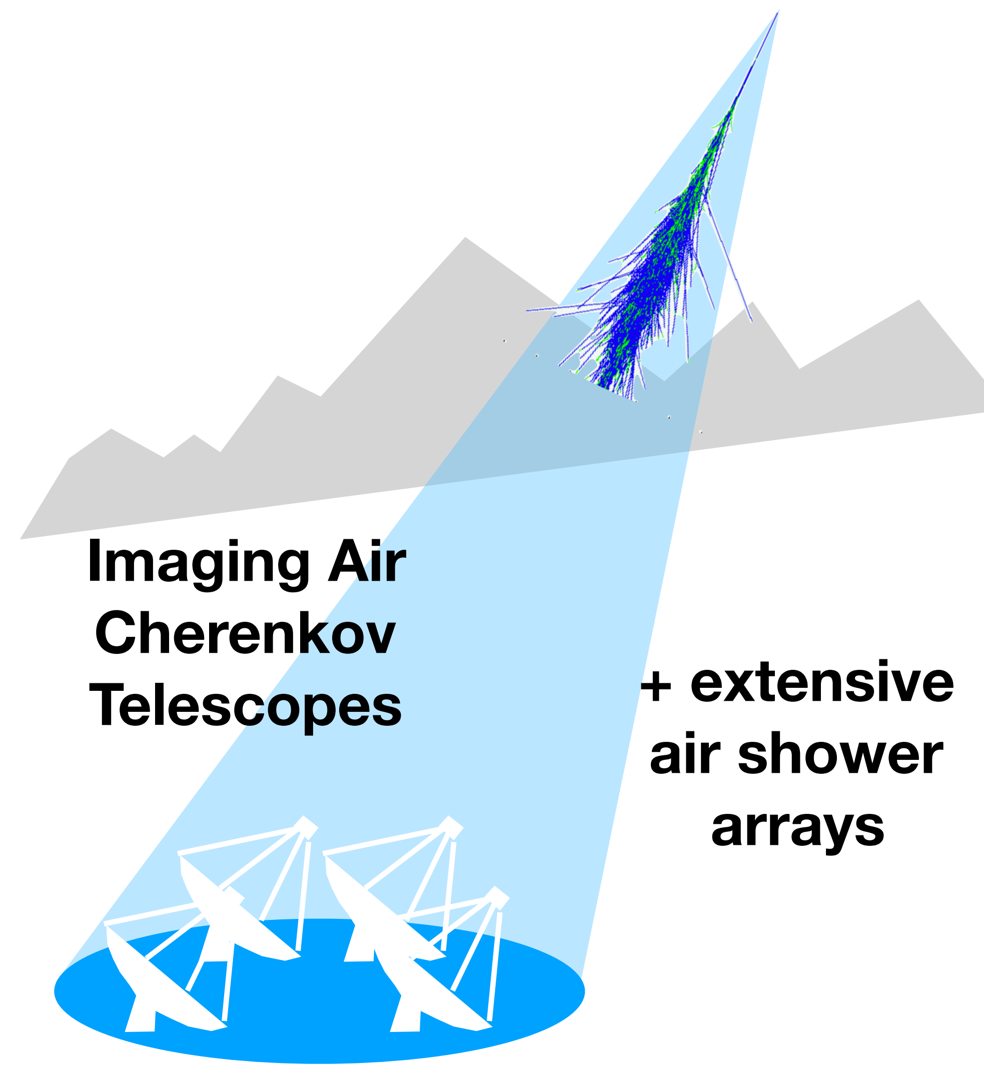


Gamma-ray astrophysics

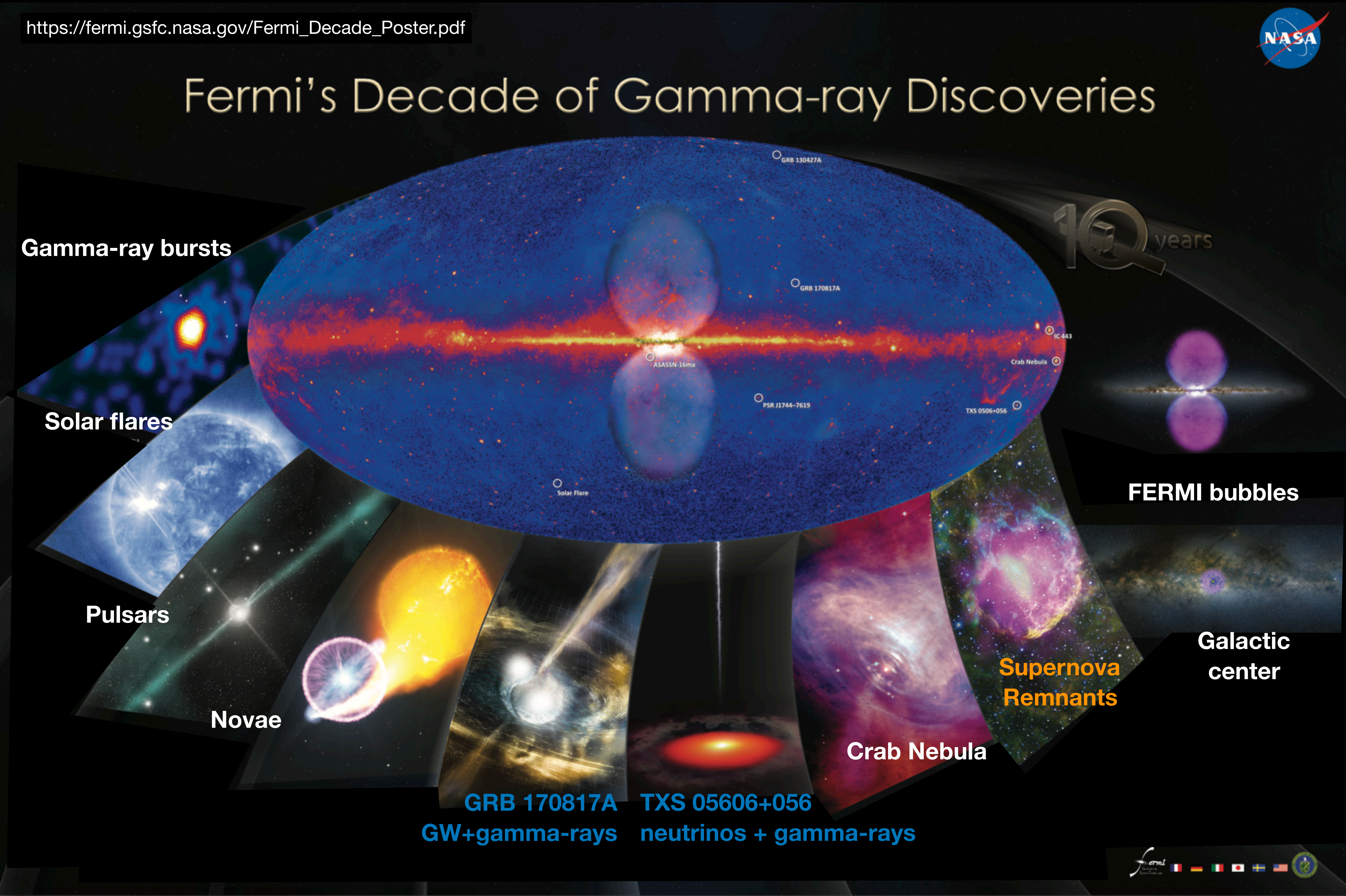
Provides crucial window for exploration of non-thermal phenomena in the Universe in most energetic and violent forms



⇒ **Energy**

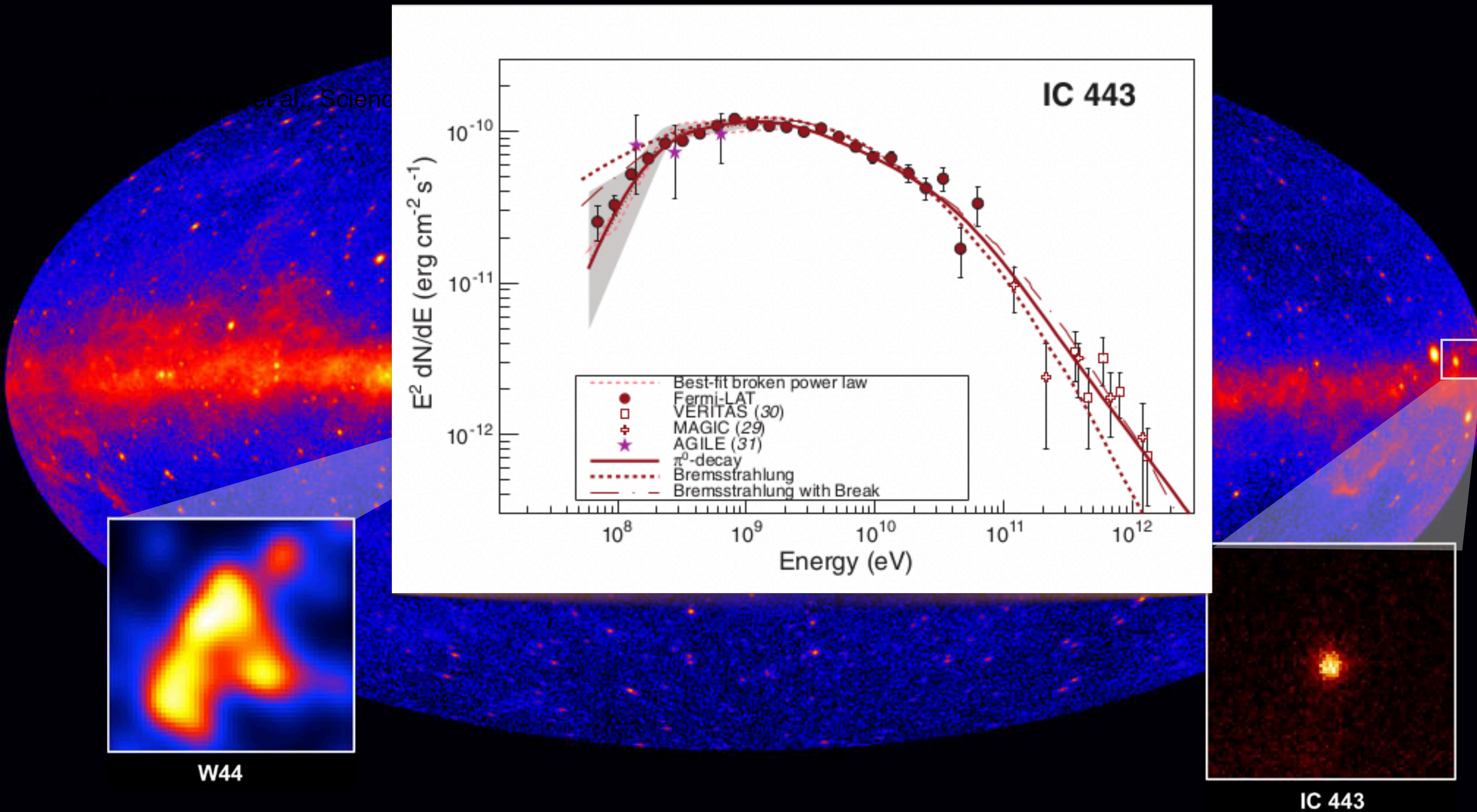


The Sky in E> 1 GeV gamma-rays



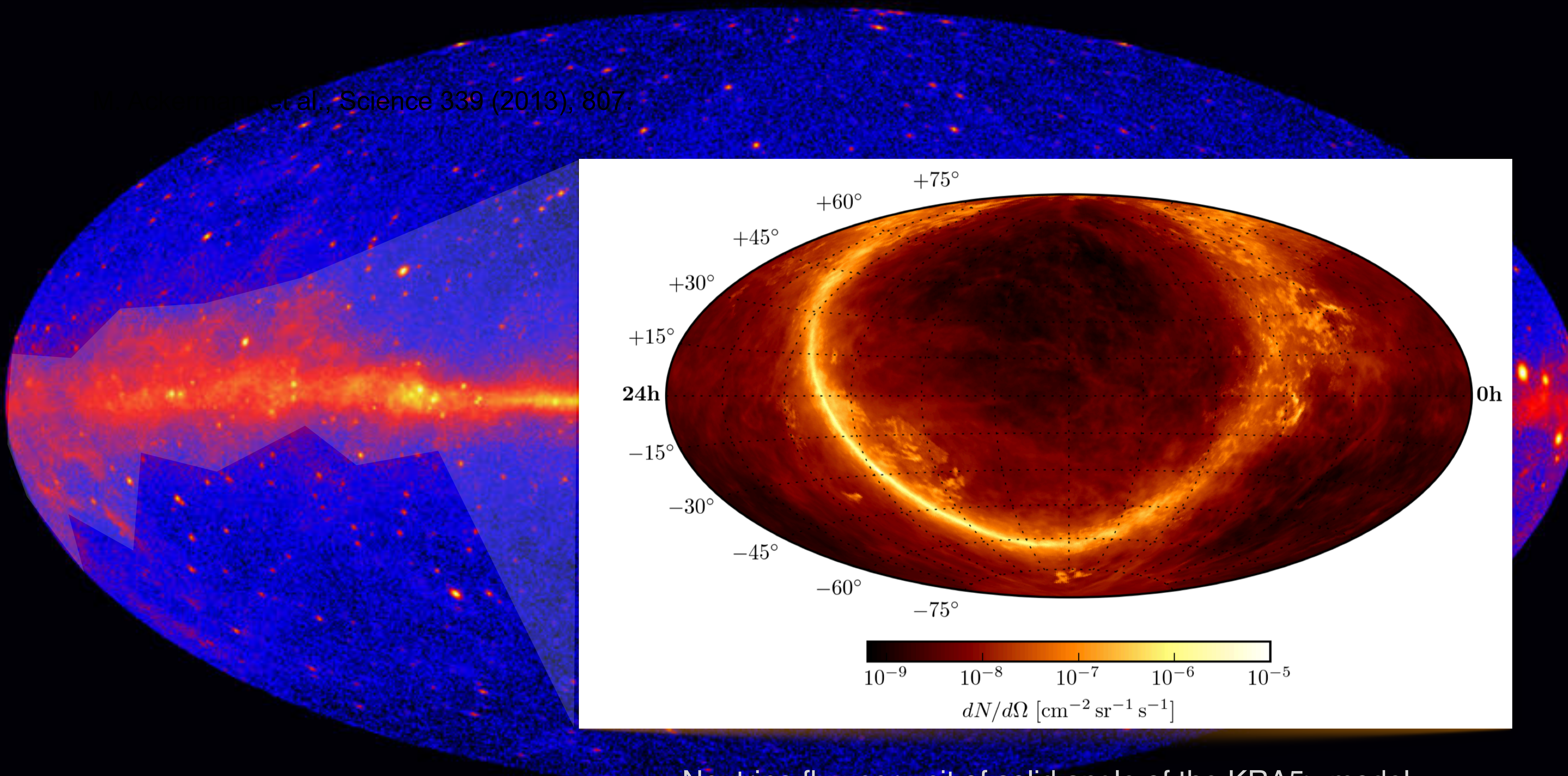
The Sky in gamma-rays

Characteristic pion signature seen in Supernova Remnants: a guaranteed contribution to cosmic rays produced in galaxies



Galactic Cosmic Rays

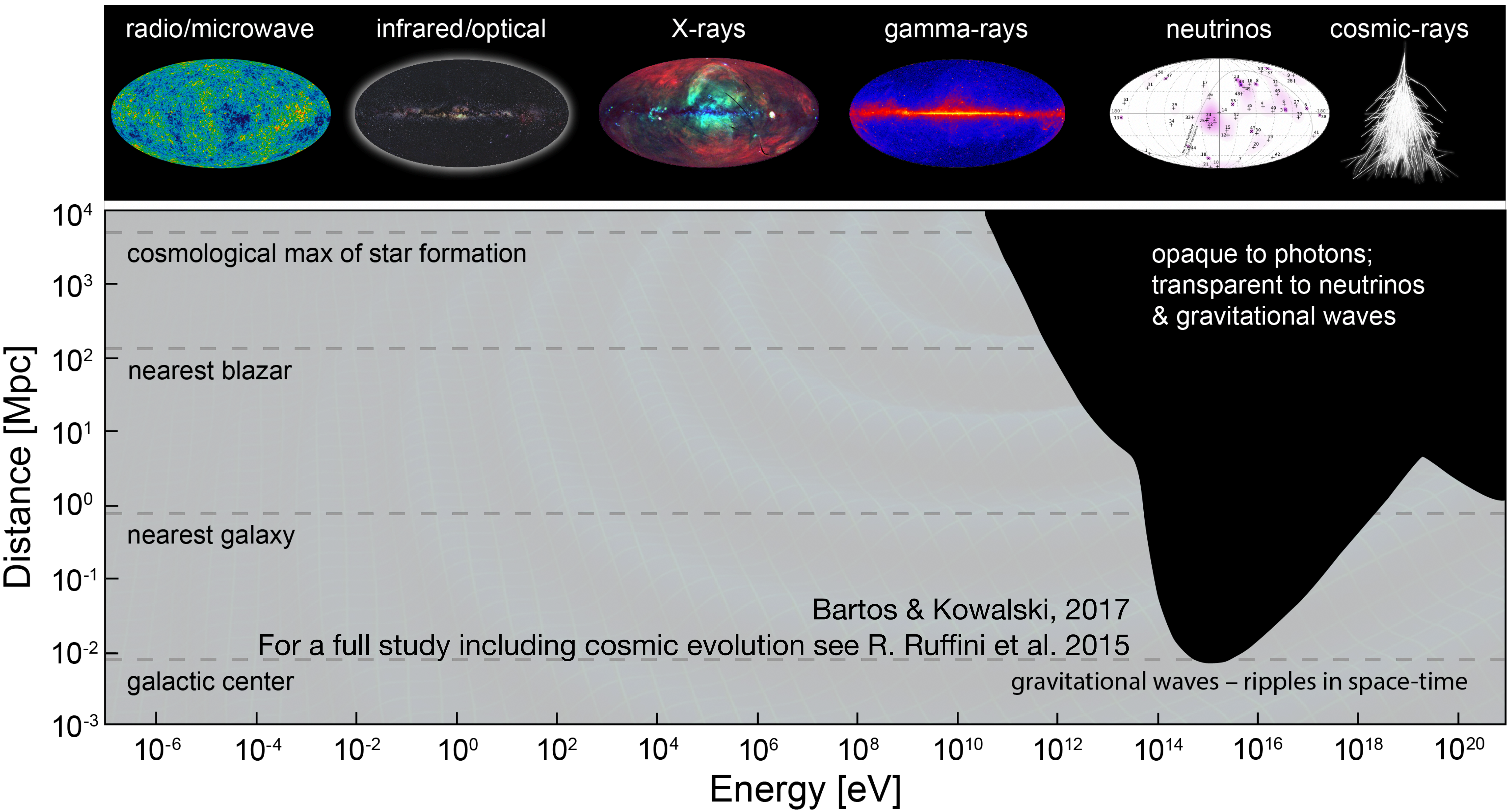
Cosmic rays interact with interstellar gas and radiation leading to the diffuse gamma-rays **observed** by Fermi-LAT and the **predicted** diffuse neutrinos



Neutrino flux per unit of solid angle of the KRA5γ model (Gaggero et al. 2015a), shown in equatorial coordinates.

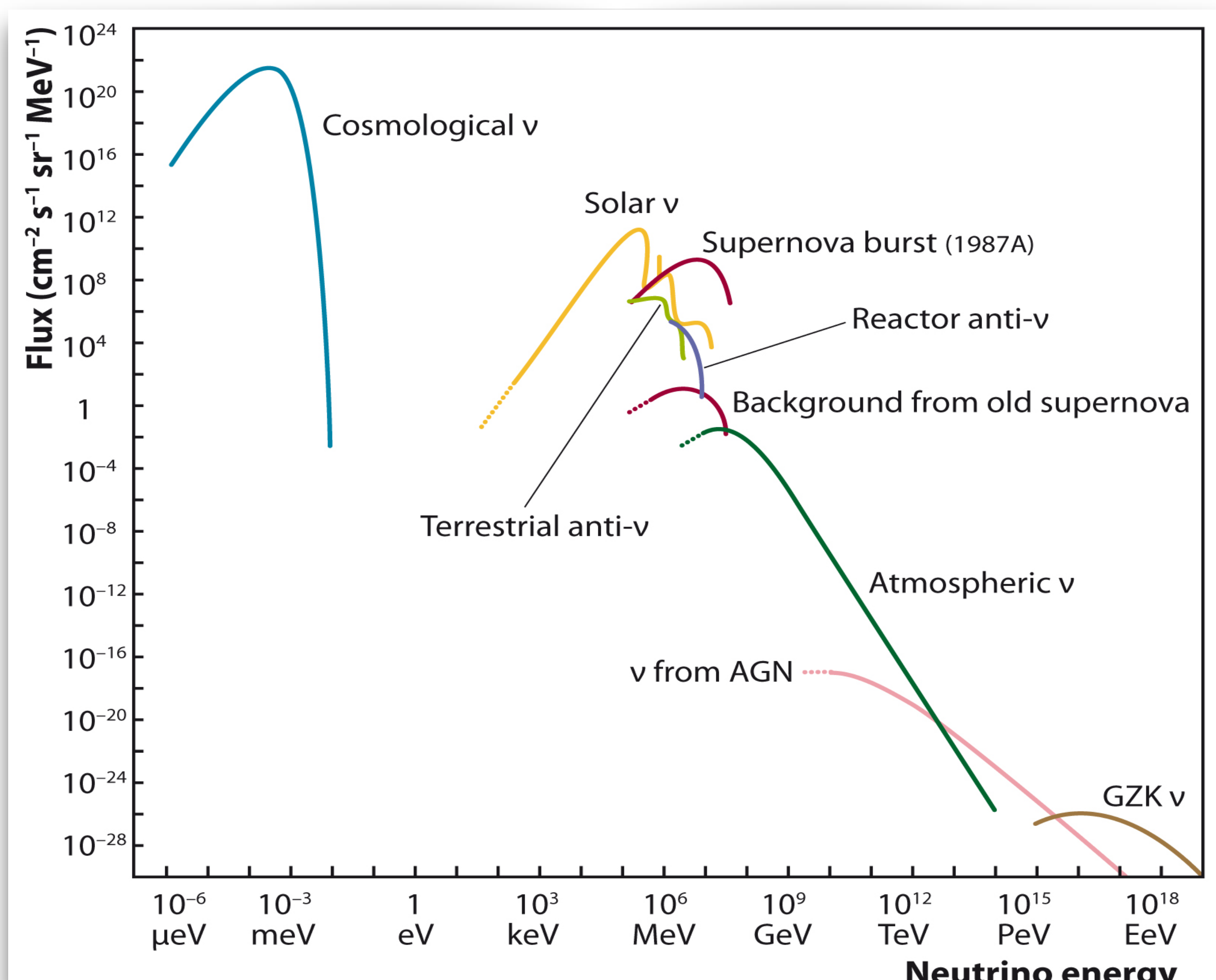
Observable Universe

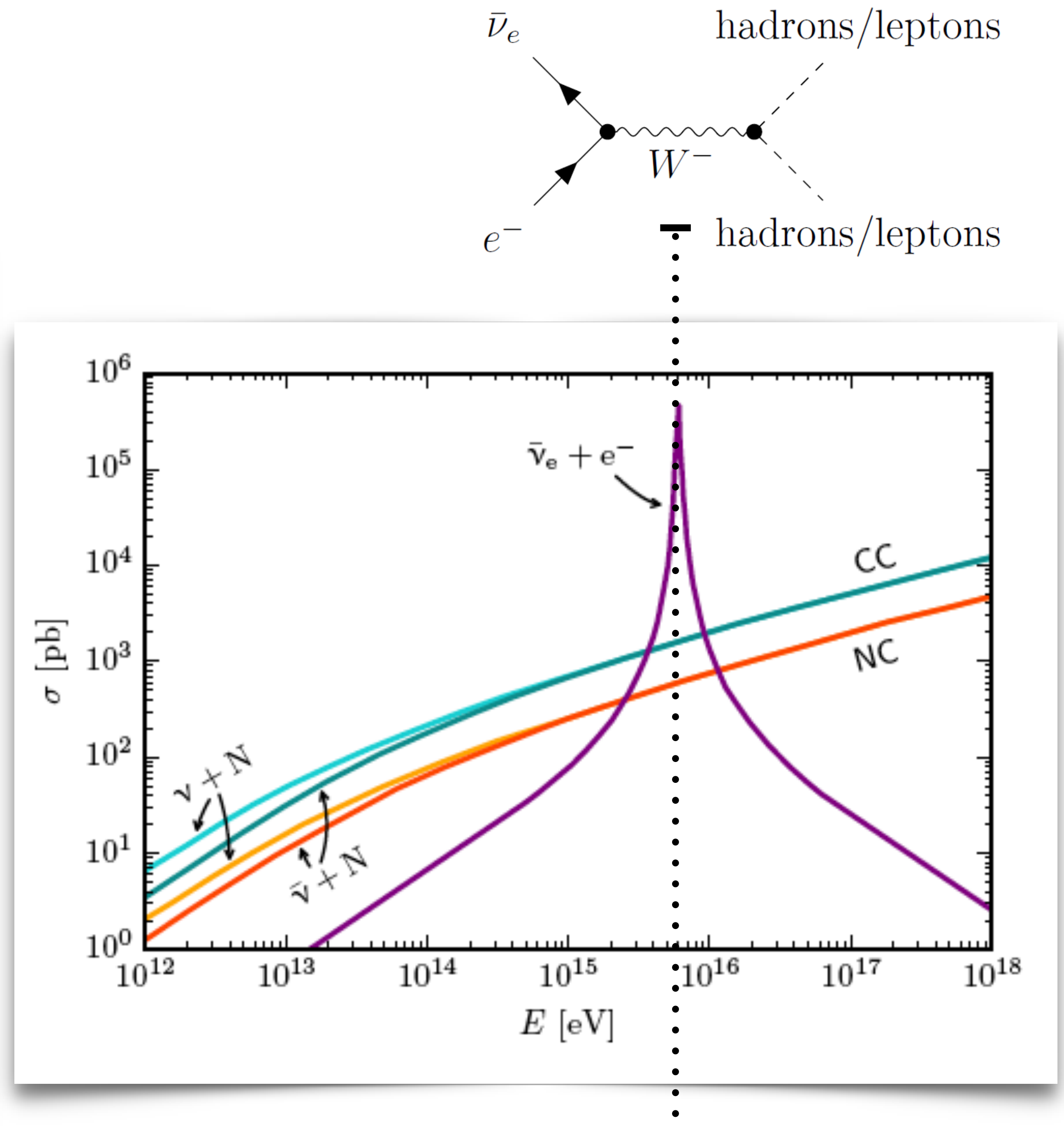
Photons are absorbed in the Extragalactic Background Light (EBL)
Protons ($E>10^{20}$ eV) interact with the Cosmic Microwave Background (CMB)



How to detect astrophysical neutrinos?

For a benchmark astrophysical flux O(10^5)/km^2/year at energies > 100 TeV we need km^3-scale detectors! ⇒use natural water or ice

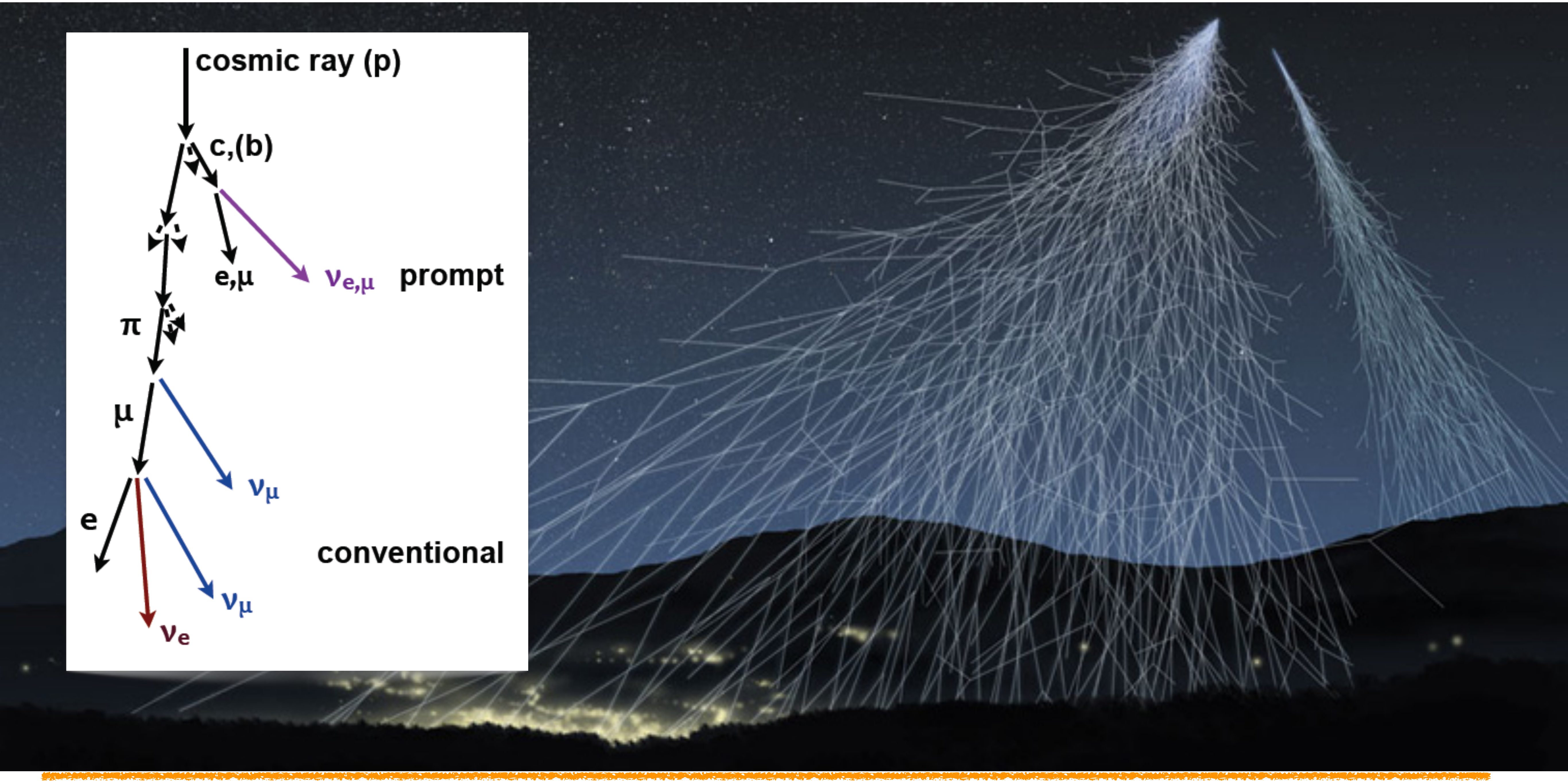




E= $M^2_W/(2m_e)$ = 6.3 PeV

Challenges: backgrounds

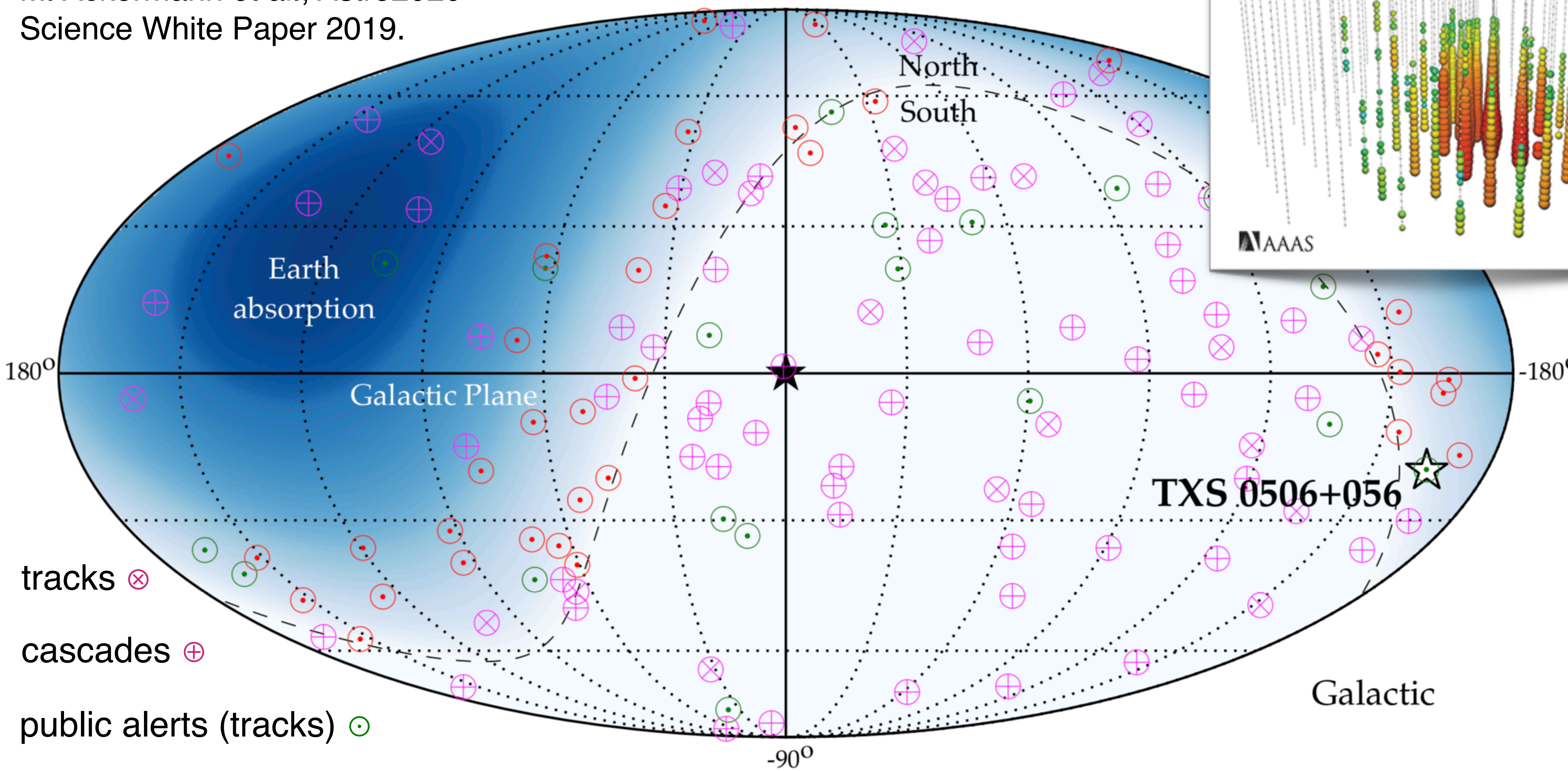
Event rates in IceCube are: **~3000 atmospheric muons per second** (7×10^{10} year^{-1}), **1 atmospheric neutrino every 6 minutes** (8×10^{4} year^{-1}) **and O(10) astrophysical neutrinos per year**

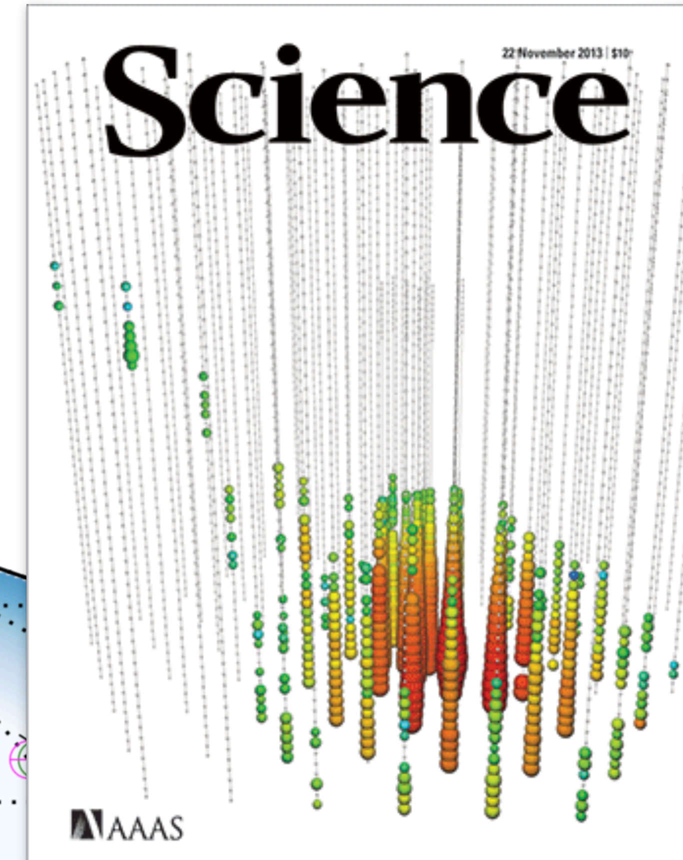


Extragalactic neutrinos

At high energies (few tens TeV) a clear excess of events is observed excluding an atmospheric-only origin. Directions show no obvious accumulation either around individual sources or the Galactic plane

M. Ackermann et al., Astro2020 Science White Paper 2019.

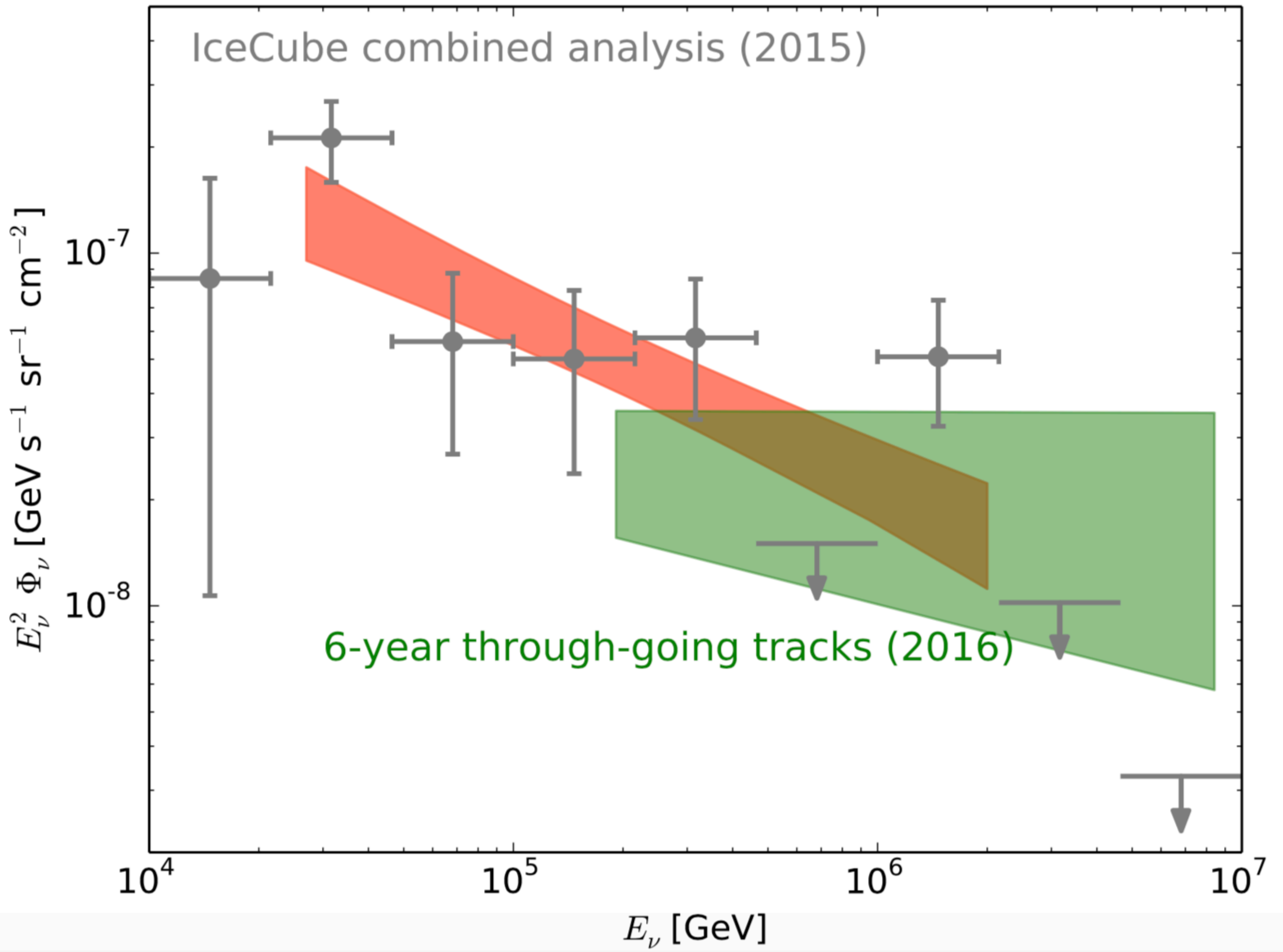




Extragalactic neutrinos

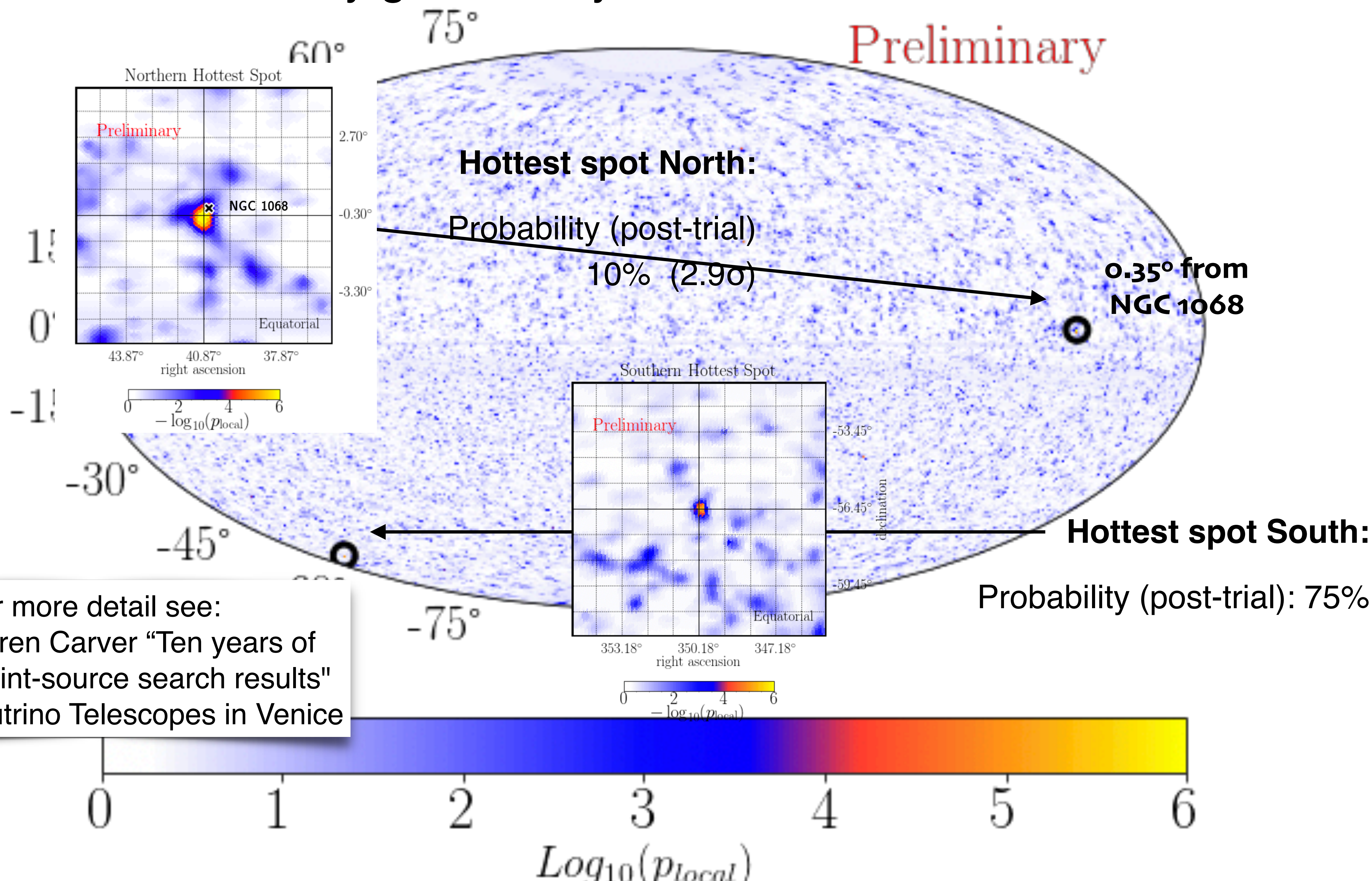
The energy spectrum is compatible with a power-law with a spectral index of 2.5 between 25 TeV and 3 PeV. Evidence for a harder spectrum between 200 TeV and 8 PeV is found, with spectral index of 2.1

M. G. Aartsen et al. Astrophys. J., 833(1):3, 2016.
M. G. Aartsen et al. Adv. Space Res., 62:2902–2930, 2018



The neutrino Sky

A sample of ~1x10^6 neutrinos recorded by IceCube in 10 years provides no evidence for neutrino sources in the full sky and in locations motivated by gamma-ray observations



For more detail see:
Tessa Lauren Carver "Ten years of IceCube point-source search results" @ 2019 Neutrino Telescopes in Venice

The IceCube Target of Opportunity Program

If neutrinos and photons are produced in correlation, observing neutrinos and electromagnetic flares would greatly increase the chances of identifying the sources of cosmic neutrinos (multi-messenger).

Since 2016 IceCube issues public alerts on single events with ~50% astrophysical probability. Since June 2019 alerts with 30% astrophysical probability (BRONZE). Since earlier private alerts based on event multiplets to optical/X-ray/gamma-ray instruments.

E.B "Multi-messenger approaches to search for point sources of high energy neutrinos with AMANDA/IceCube"@ The Multi-Messenger Approach to H]igh-Energy Gamma-Ray Sources, Barcelona (2005)

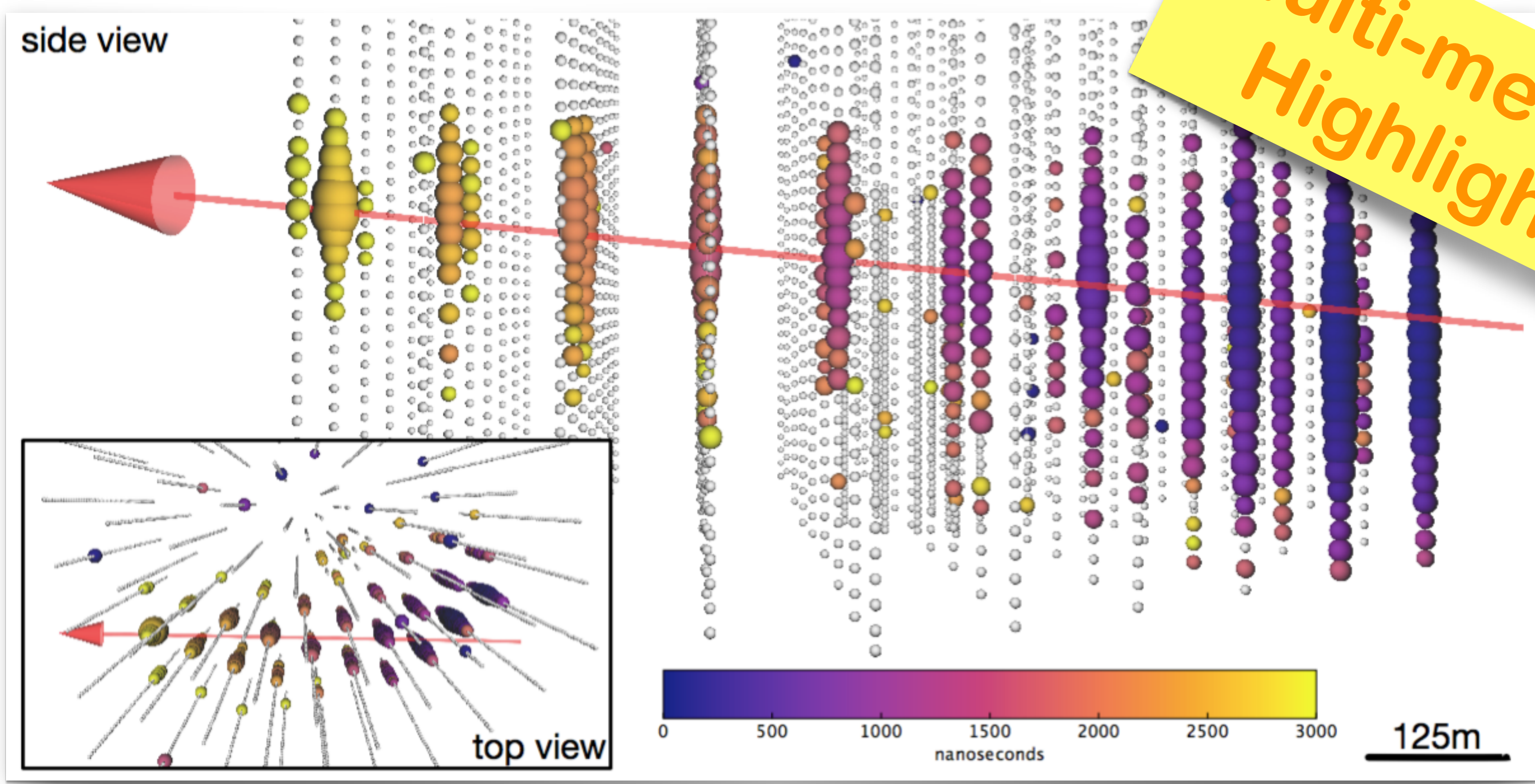
M. Ackermann, E.B., et al., Neutrino Triggered Target of Opportunity (NToO) test run with AMANDA-II and MAGIC, arXiv:0709.2640 (2007)

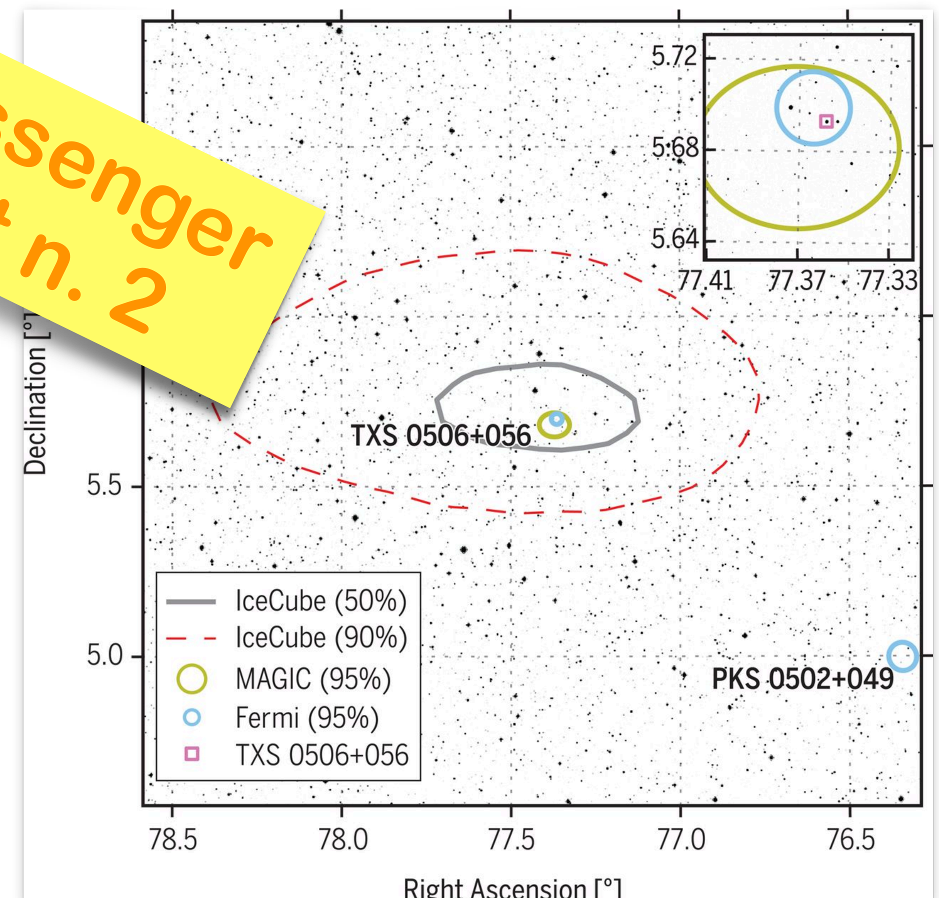
M. G. Aartsen, et al., Very High-Energy Gamma-Ray Follow-Up Program Using Neutrino Triggers from IceCube, JINST 11 (2016), arXiv:1610.01814

IceCube-170922A

Compelling evidence for neutrino emission from the **Blazar TXS 0506+056.**
Identification of a cosmic hadron accelerator with >PeV energies!

Multi-messenger Highlight n. 2





- Publicly distributed 43 seconds after trigger, refined direction 4 hr later
- At 6 arc-minutes from the direction of TXS 0506+056
- Most probable energy between 250 and 300 TeV and probability of astrophysical origin 56.6%

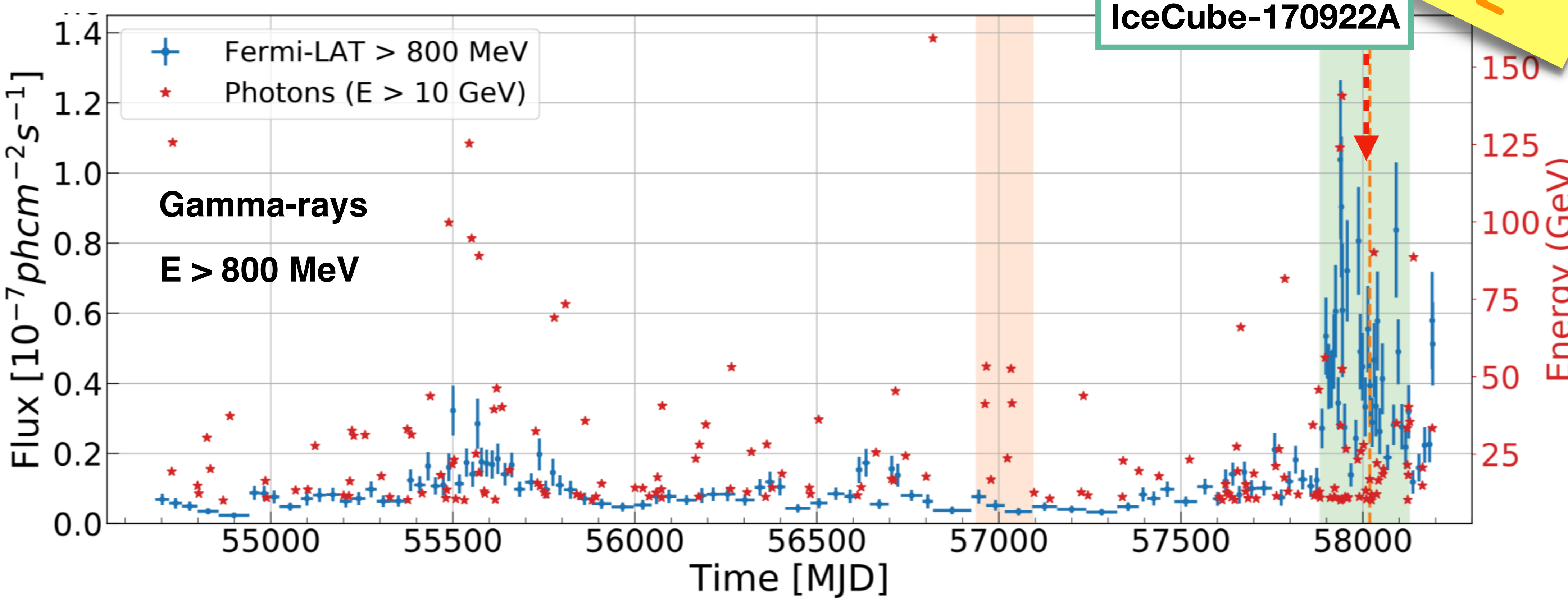
Follow-up detections of IC170922 based on public telegrams

~1000 astronomers / 18 observatories!
(~3000 astronomers / 70 observatories was for GW170817)

IceCube-170922A

Multi-messenger Highlight n. 2

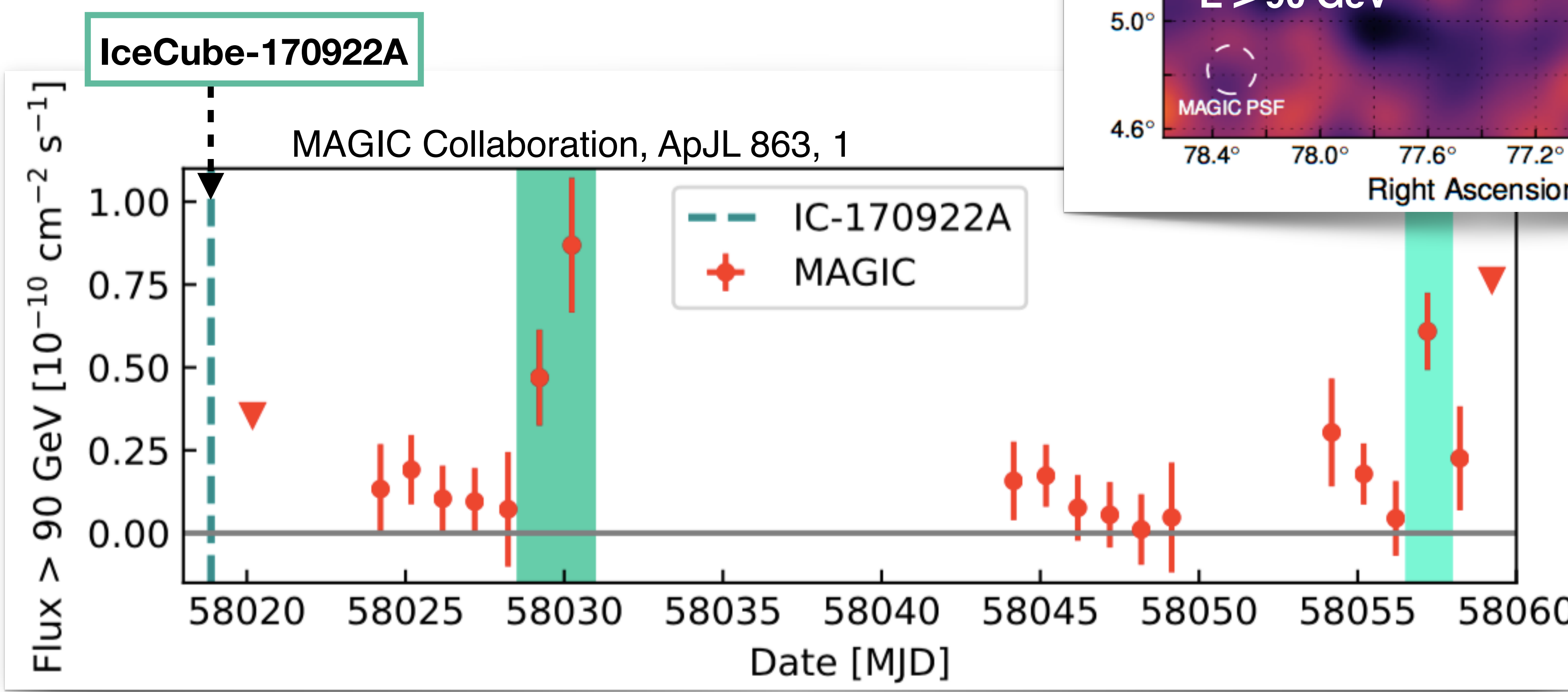
Compelling evidence for neutrino emission from the B… …6+056.
Identification of a cosmic hadron accelerator with >PeV en…

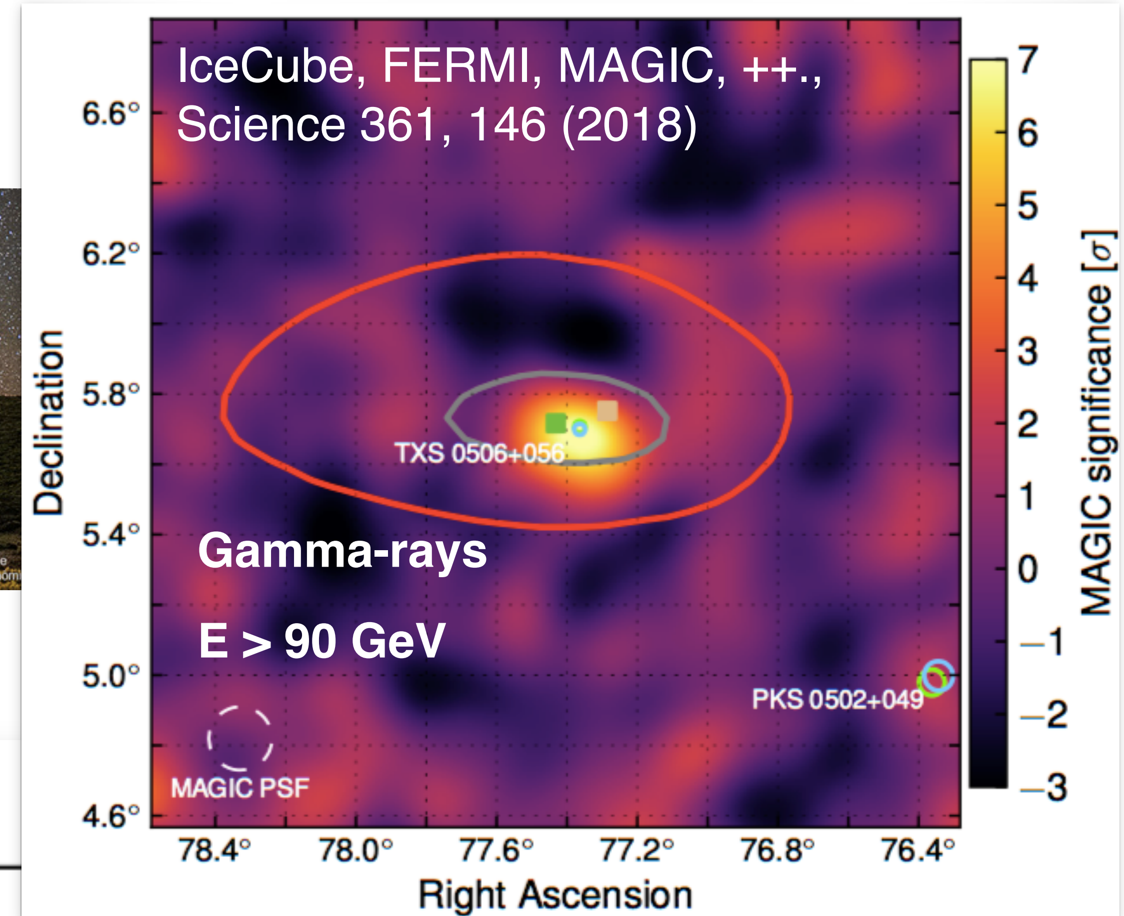


- Consistent with the direction of IceCube-170922A there is the Blazar TXS 0506+056
- The source was found in a state of enhanced gamma-ray activity lasting several months
- Coincidence probability after trials (10 public alerts and 40 archival events): 3 σ

Very high energy gamma-rays from TXS 0506+056

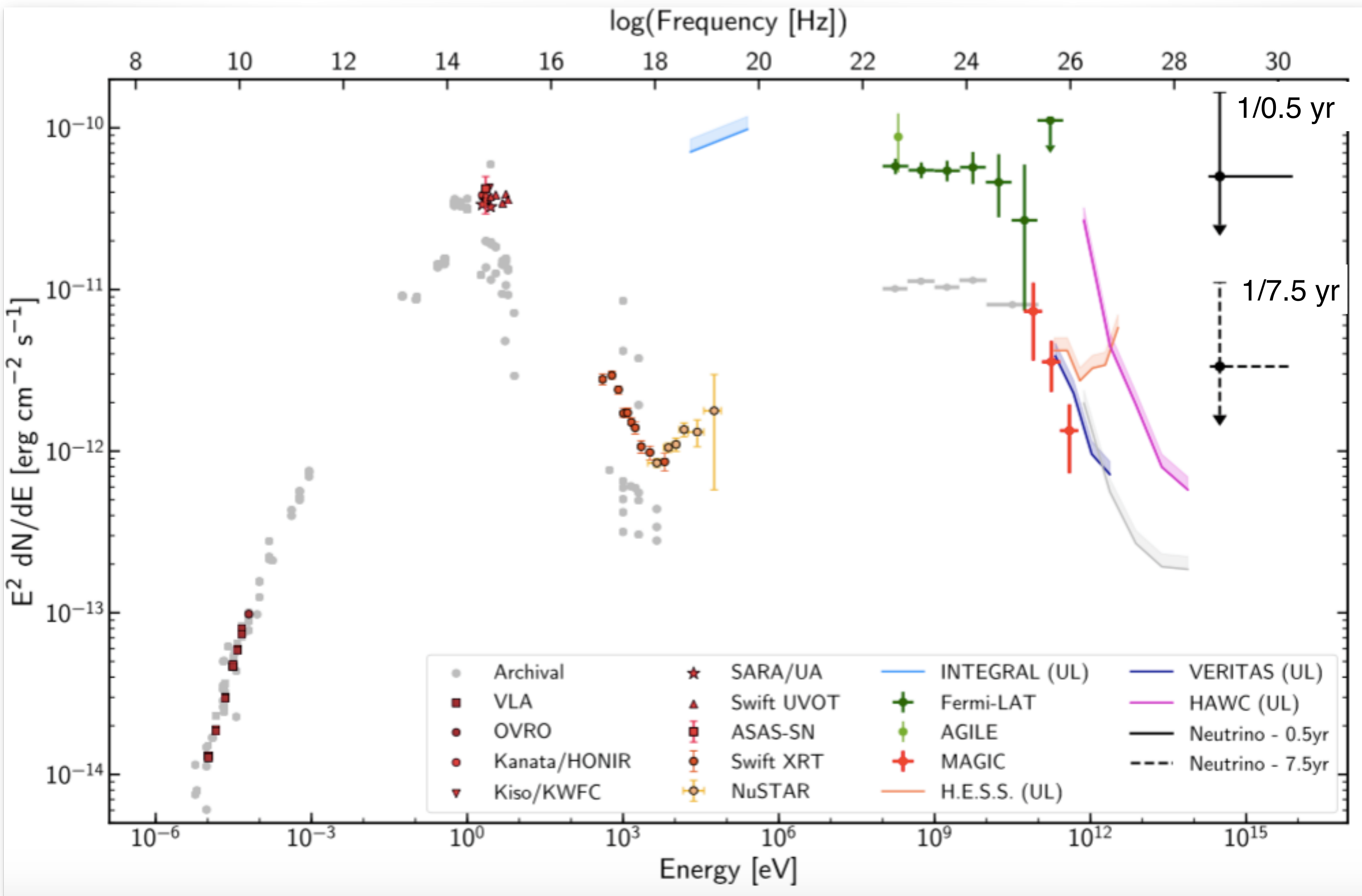
MAGIC detected ɣ-rays with energies up to about 400 GeV with strong day-to-day variations





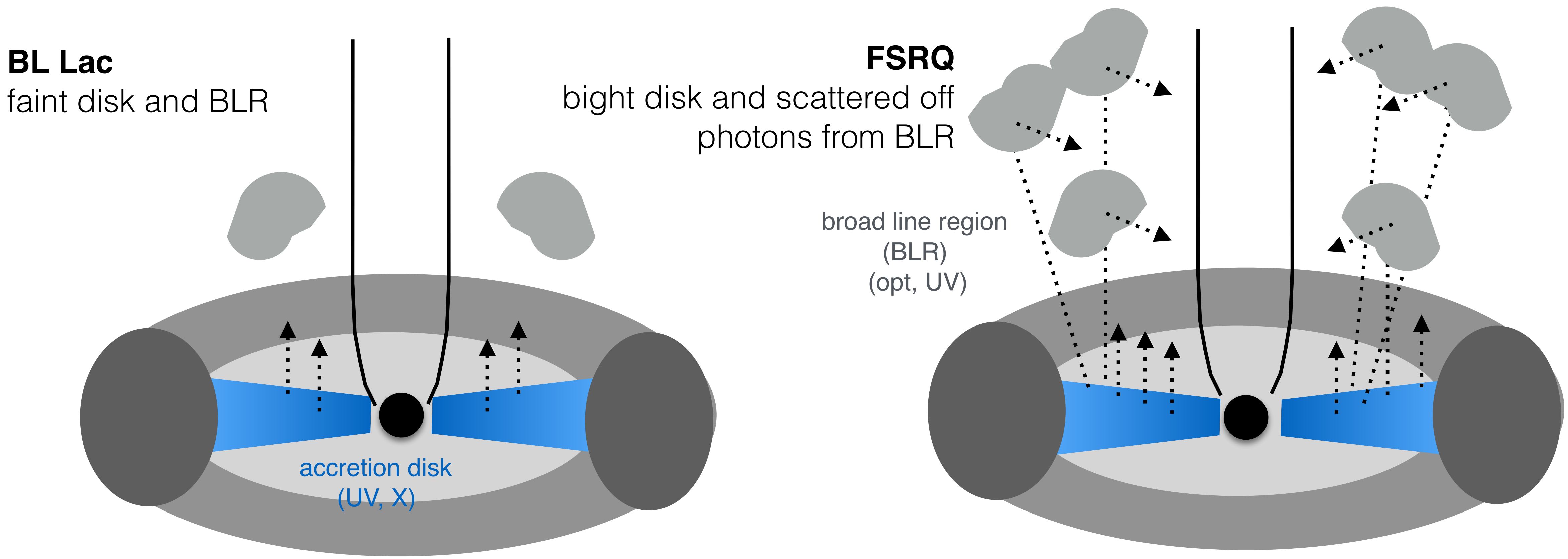
Does it all fit together?

IceCube, FERMI, MAGIC, ++., Science 361, 146 (2018)



Interpreting the multi-messenger data in a nutshell

Most Blazar emission models assume that high-energy particles (electrons, protons, nuclei) are injected into the jet where they encounter target radiation (non-thermal emission by the high-energy particles, or external photons from the accretion disk, clouds or dust torus.



A neutrino emitter?

For $E_\nu \sim 300$ TeV, **interacting protons shall have energies $E_p \geq 6$ PeV** and must interact with photons with energies in the UV to soft X-ray range. Getting all the elements of this puzzle to fit together is not easy. Blazars seem to contain important clues on the origin of cosmic neutrinos and cosmic rays.

C. Righi, F. Tavecchio, and S. Inoue. Neutrino emission from BL Lac objects: the role of radiatively inefficient accretion flow

S. Ansoldi et al. The Blazar TXS 0506+056 Associated with a High-energy Neutrino: Insights into Extragalactic Jets and Cosmic

M. Cerruti, A. Zech, C. Boisson, G. Emery, S. Inoue, and J. P. Lenain. Leptohadronic single-zone models for the electromagnetic and neutrino emission of TXS 0506+056. *Mon.*

Shan Gao, Anatoli Fedynitch, Walter Winter, and Martin Pohl. Modelling the coincident observation of a high-energy neutrino and a bright blazar flare. *Nature Astronomy*, 3:88–92, 2019.

A. Keivani et al. A Multimessenger Picture of the Flaring Blazar TXS 0506+056: Implica- tions for High-energy Neutrino

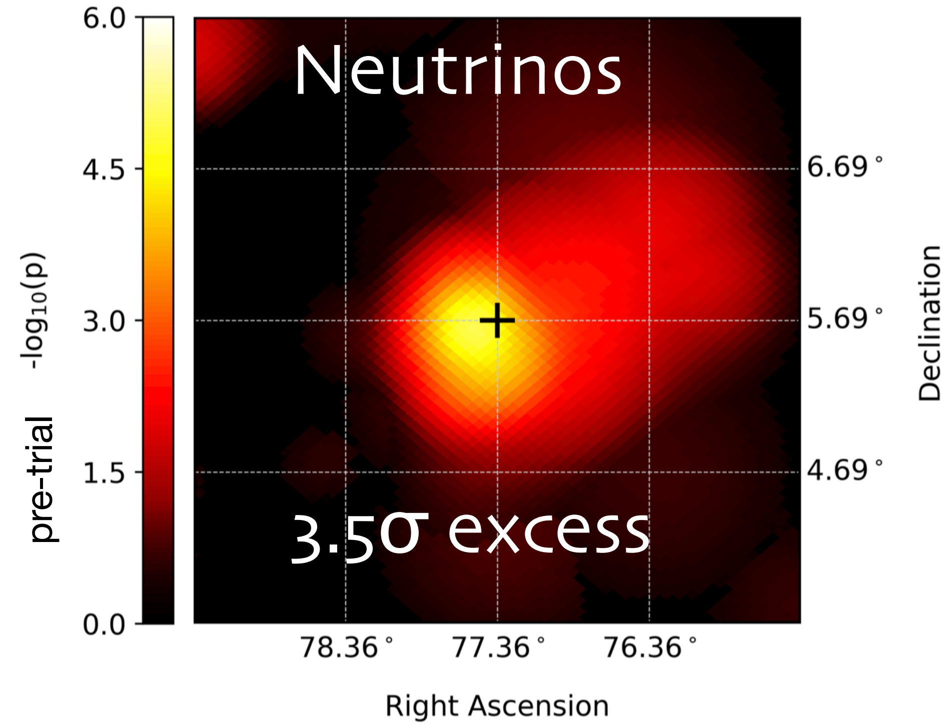
A. Gokus, S. Richter, F. Spanier, M. Kreter, M. Kadler, K. Mannheim, and J. Wilms. Decom- posing blazar spectra into lepto-hadronic emission components. *Astron. Nachr.*, 339:331, 2018.

Ruo-Yu Liu, Kai Wang, Rui Xue, Andrew M. Taylor, Xiang-Yu Wang, Zhuo Li, and Huirong Yan. Hadronuclear interpretation of a high-energy neutrino event coincident with a blazar flare. *Phys. Rev.*, D99(6):063008,

N. Sahakyan. Lepto-hadronic γ-ray and neutrino emission from the jet of TXS 0506+056. *Astrophys. J.*, 866(2):109, 2018.

IceCube archival data on TXS 0506+056

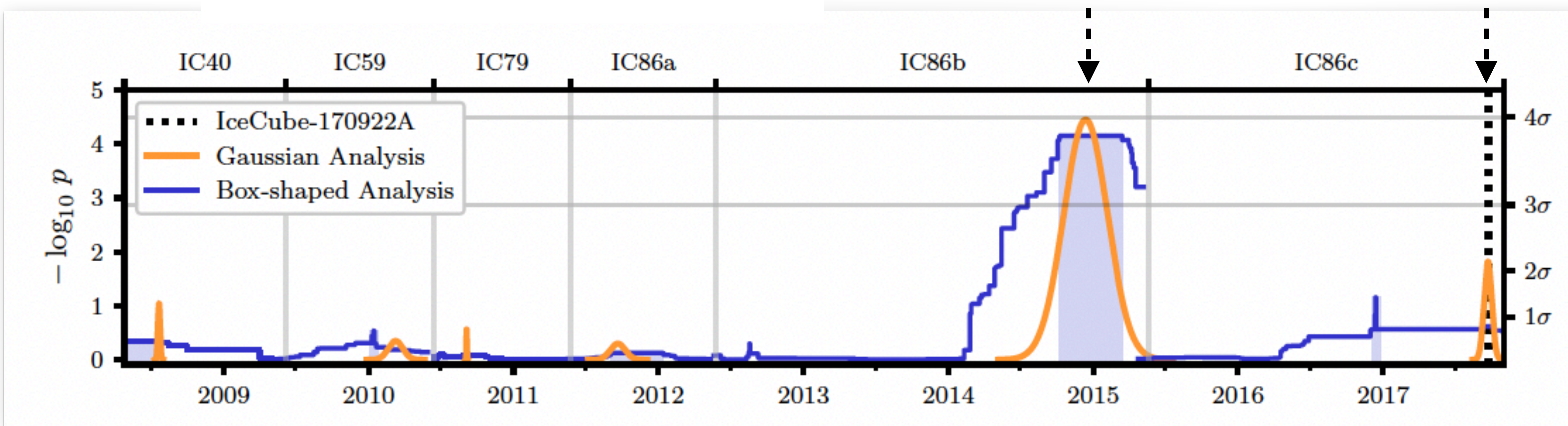
The observation of an excess of neutrino events in ~5 months (2014-2015) together with IceCube-170922A in coincidence with a flaring state provides a strong evidence against the background hypothesis



~110-150 days
Spectral index ~2

~20 days
Spectral index ~1.7

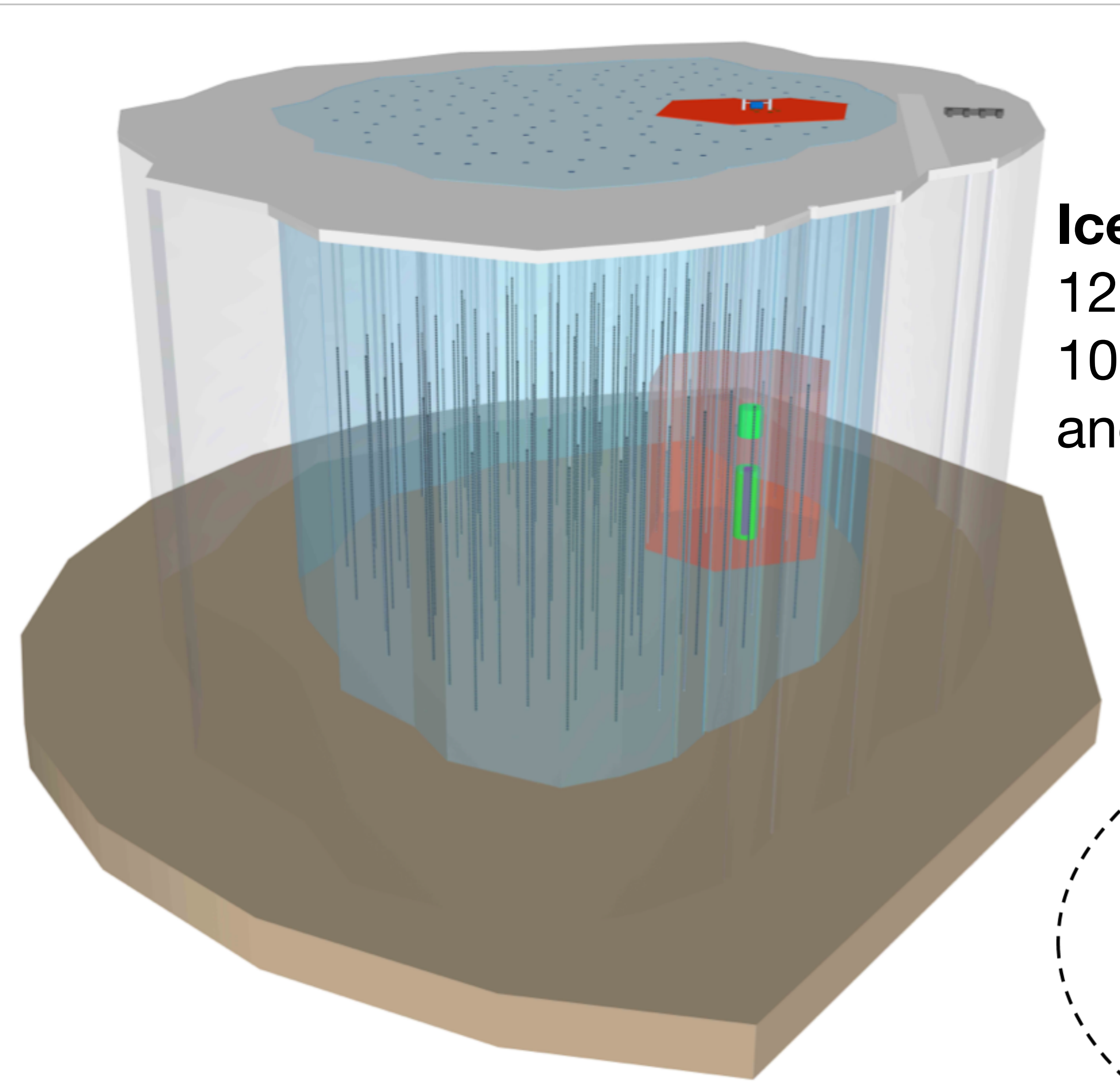
IceCube Coll. Science 361, eaat1378 (2018)



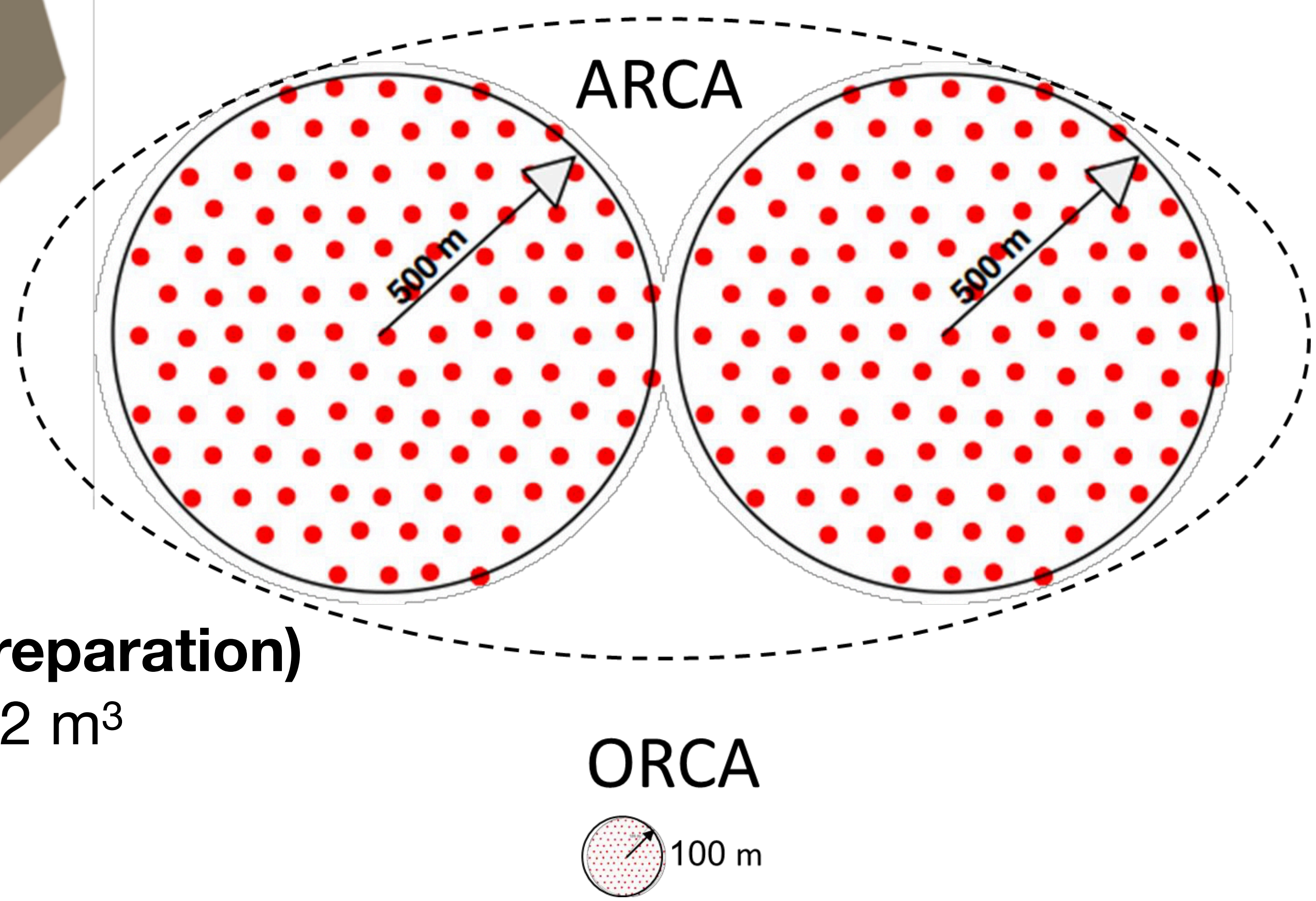
In Summary

- High Energy Neutrinos **opened a new window into the Universe**:
  - Diffuse cosmic neutrinos well established (more than 8 sigma by two channels)
  - Compelling evidence for the first non-stellar neutrino source: a Blazar
- **Multimessenger studies are essential for identification of sources**
- State of the art is limited by too few photons and too few neutrinos Better (theoretical) understanding of the potential sources and relevant data can help the way to new breakthroughs
- Looking forward to upcoming ten times more sensitive instruments

Future



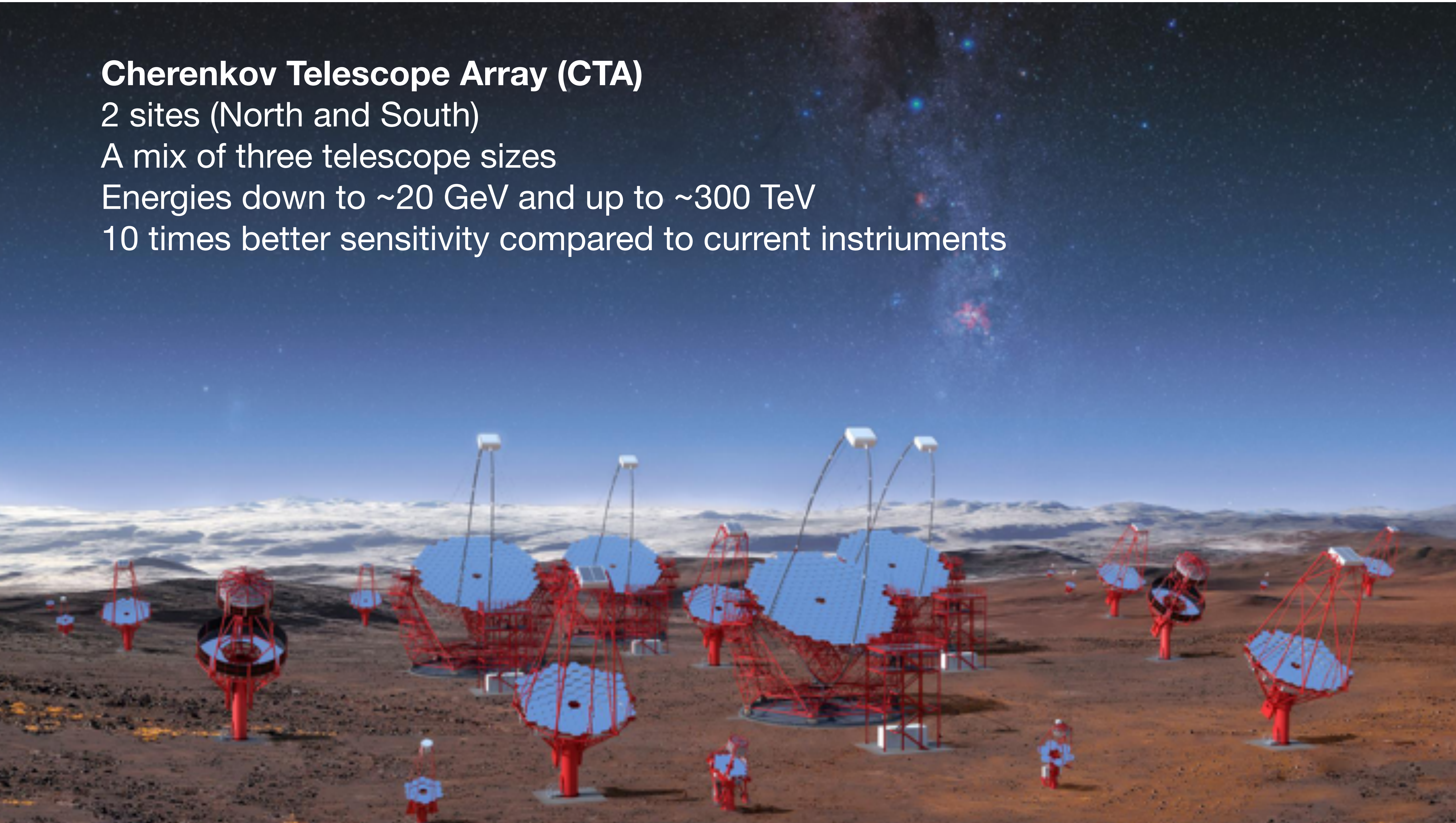
IceCube-Gen 2 (in preparation)
120 strings with 80 DOM/string, 1.35 to 2.7 km deep
10 times the instrumented volume of IceCube, better angular resolution



KM3NeT Phase 2 (in preparation)
2 x 115 ARCA strings 1.2 m^3
1 x 115 ORCA strings

Future

Cherenkov Telescope Array (CTA)
2 sites (North and South)
A mix of three telescope sizes
Energies down to ~20 GeV and up to ~300 TeV
10 times better sensitivity compared to current instriuments



Extras

Neutrinos from astrophysical beam dump

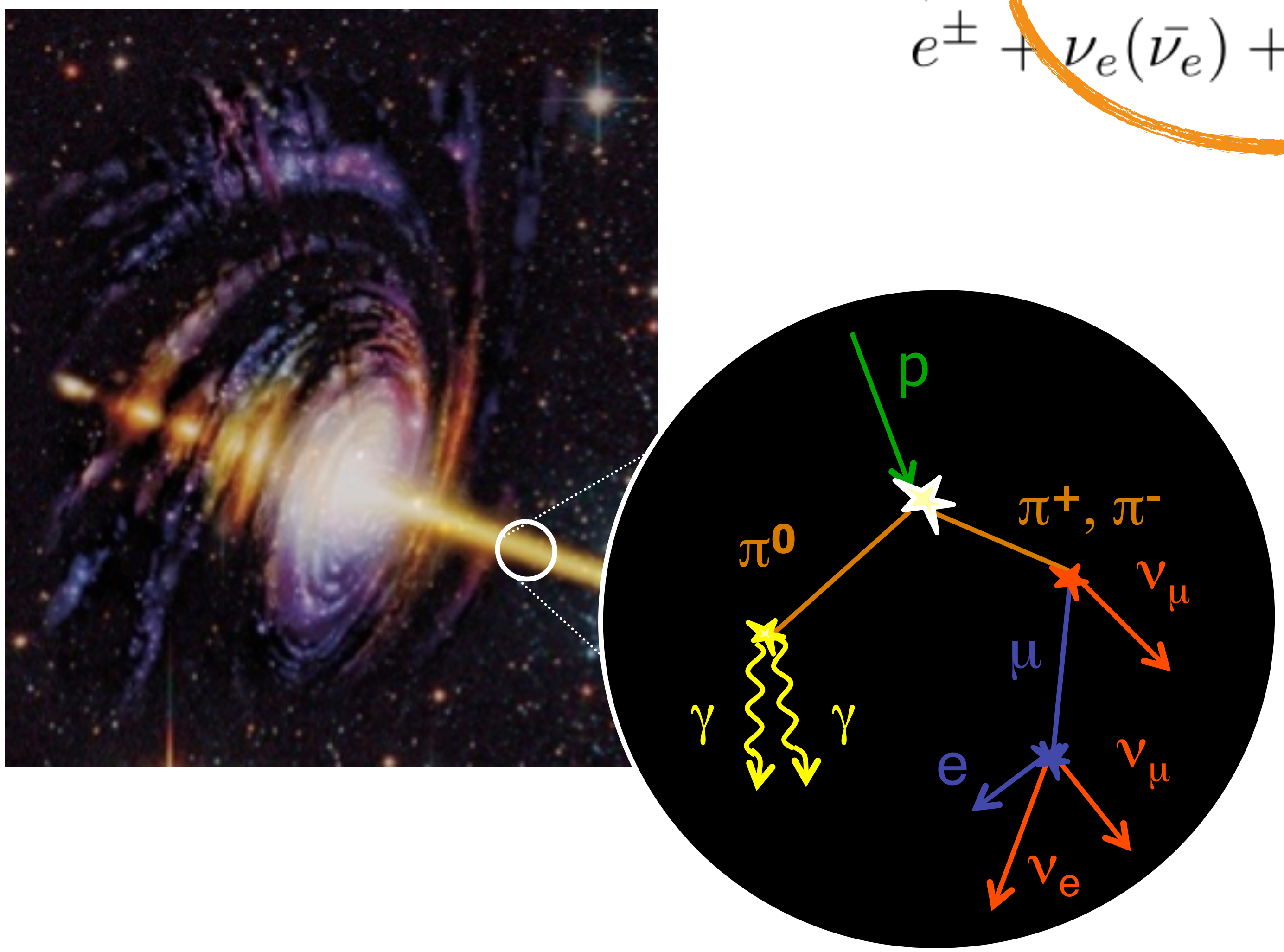
If neutrinos are produced by cosmic accelerators, two scenarios are possible leading to different predicted spectra

Case 1: proto-proton

$$pp \rightarrow pp(np, nn) + \quad n_1\pi^{\pm} + \quad n_2\pi^0 + \quad (n_3K^{\pm} + n_4K^0 + ...)$$

$$n_1\pi^{\pm} \downarrow \mu^{\pm} + \nu_\mu(\bar{\nu_\mu}) \downarrow e^{\pm} + \nu_e(\bar{\nu_e}) + \bar{\nu_\mu}(\nu_\mu)$$

$$n_2\pi^0 \downarrow \gamma\gamma$$



Case 2: photo-hadronic

$$p\gamma \rightarrow \Delta \rightarrow \begin{array}{l} p + \pi^0 \ [2/3] \\ n + \pi^+ \ [1/3] \end{array}$$

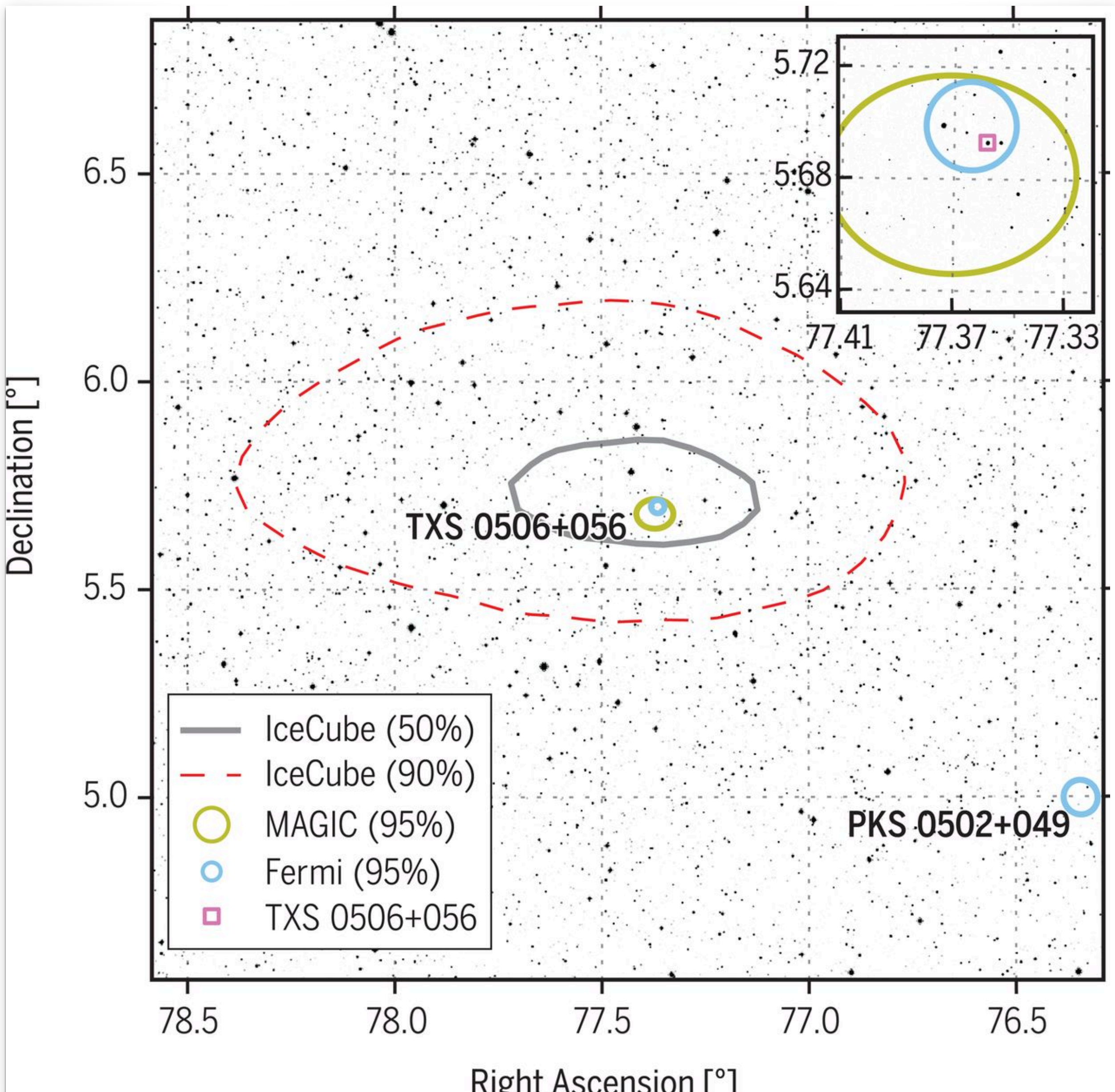
- In all cases:

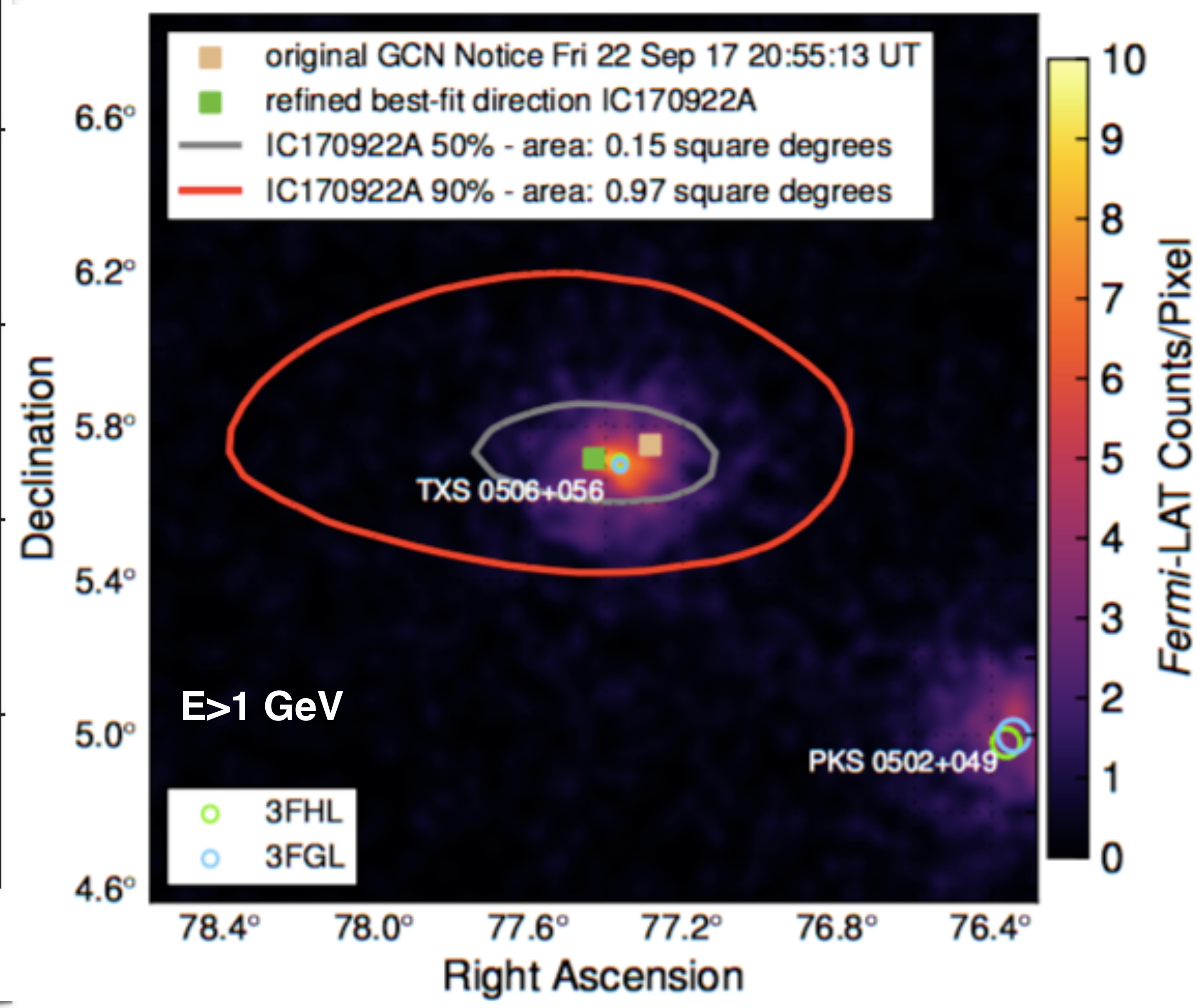
$$\int_{E_\gamma^{\min}}^{E_\gamma^{\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_\nu^{\min}}^{E_\nu^{\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu$$

The Blazar TXS 0506+056

Probability to observe by chance a flaring Fermi-LAT Blazar in the error circle of a high energy neutrino after trials (10 public alerts and 40 archival events): 3 σ

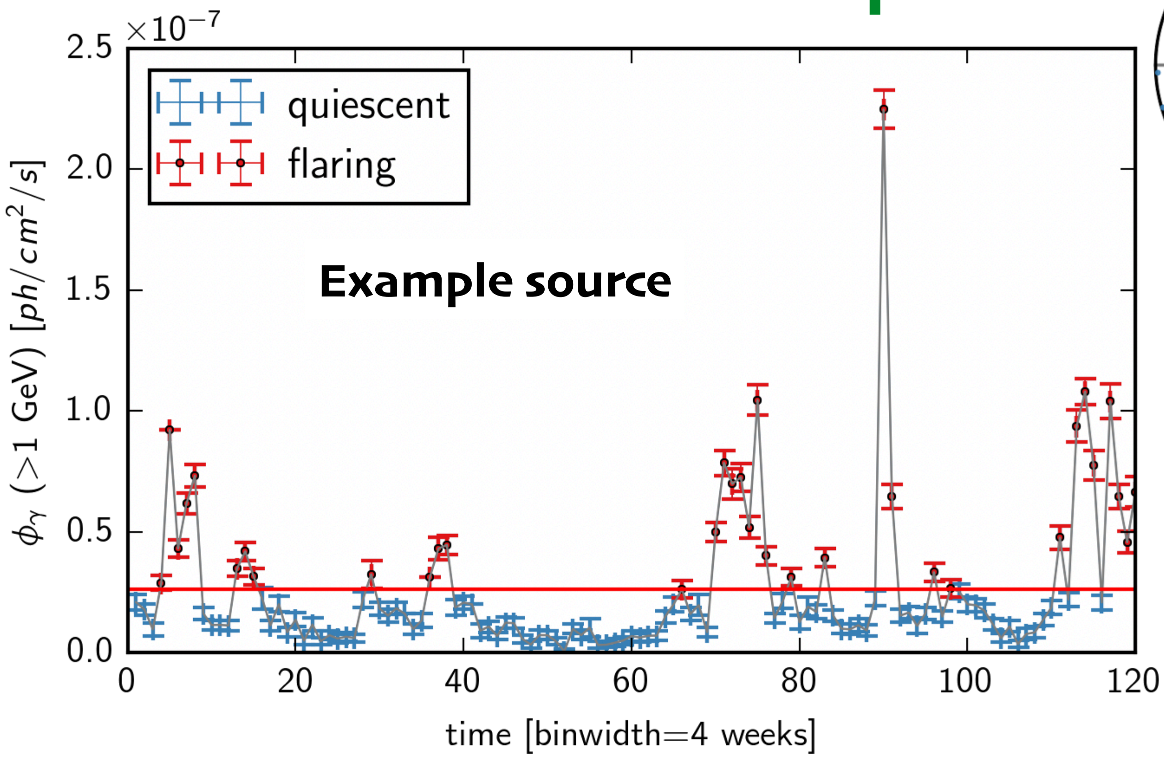
IC+Fermi+MAGIC++., Science 361, 146 (2018), arXiv:1807.08816

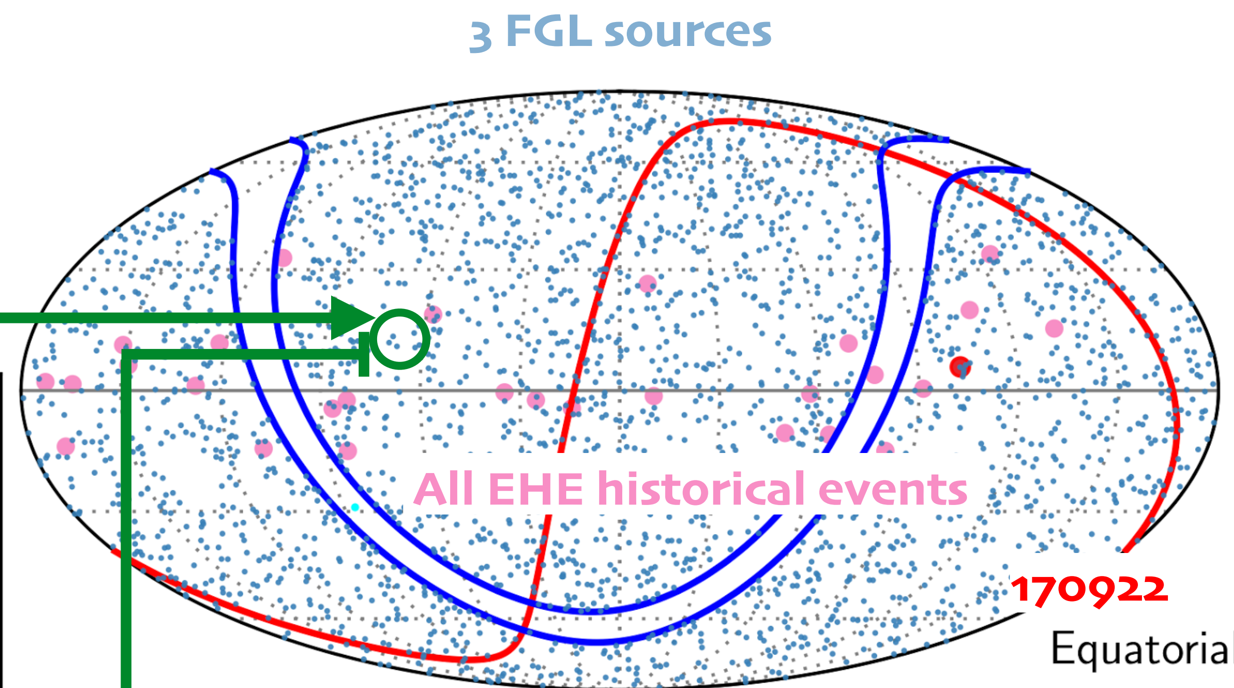




Spatial + temporal coincidence

Step 1: Draw many times a random neutrino from a representative sample of high-energy muon-track events





Step 2: Check for existence of a F Blazar in neutrino error circle and **Step 3:** check its GeV γ-ray flux at the same time bin

Probability to observe by chance a flaring Fermi-LAT Blazar in the error circle of a high energy neutrino:

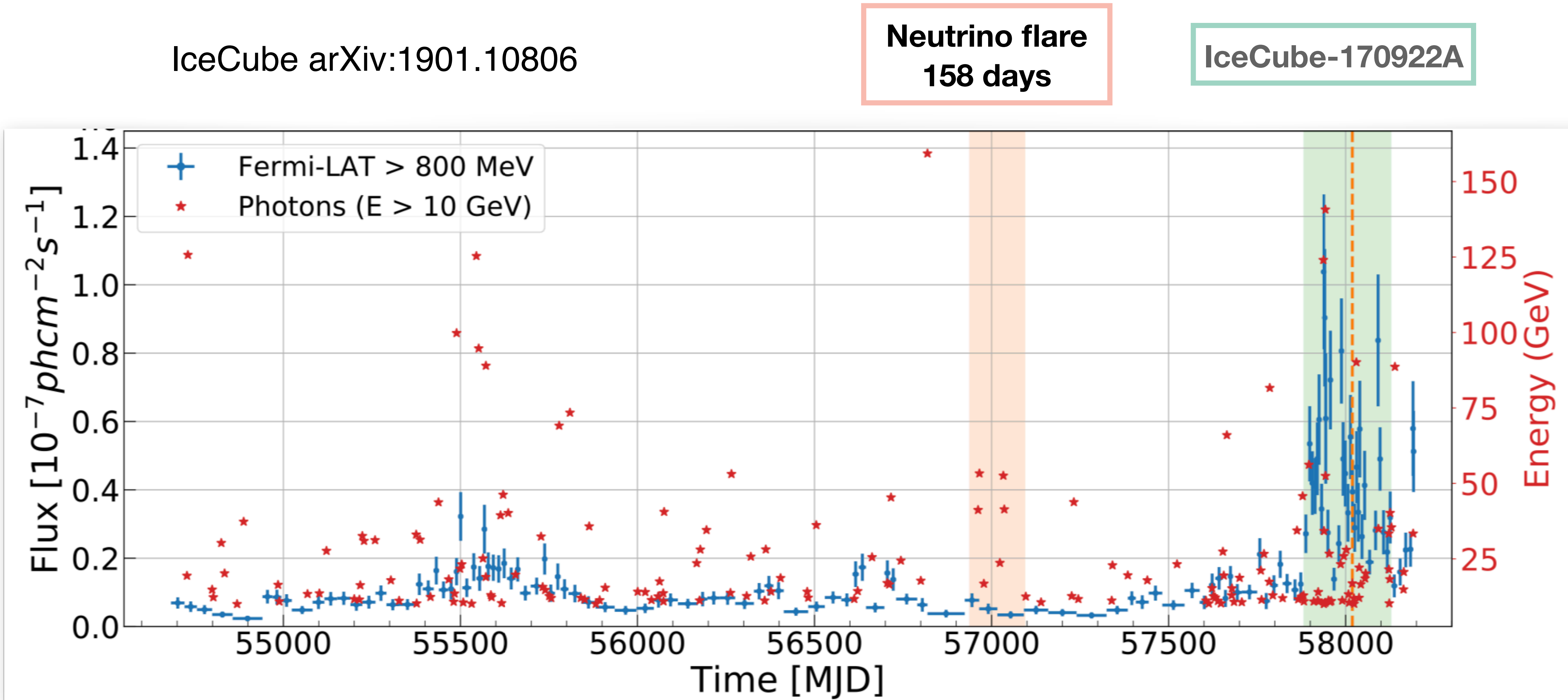
Pre-trials p-value: 4.1 σ

Post-trials p-value (10 public alerts and 40 archival events): **3 σ**

and FERMI archival data on TXS 0506+056

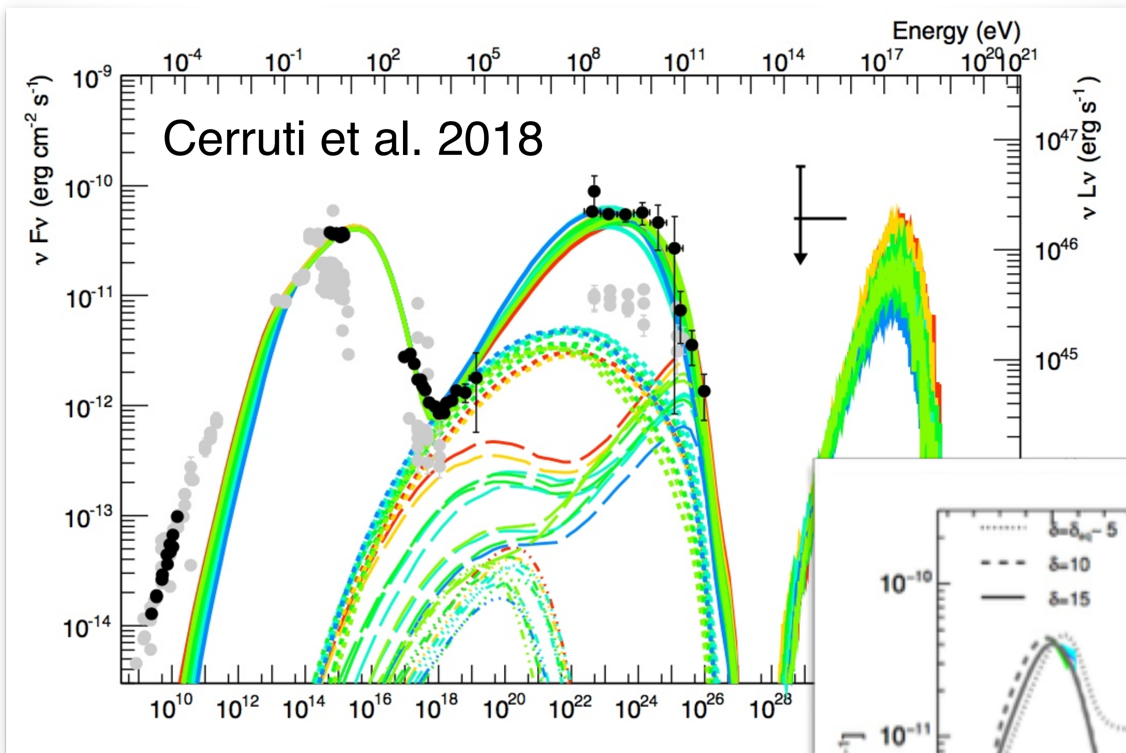
During the earlier (2014/15) neutrino flare no significant gamma-ray flaring activity or spectral change have been observed, few authors report a possible hint of hardening (P. Padovani, et al. MNRAS 2018)

IceCube arXiv:1901.10806

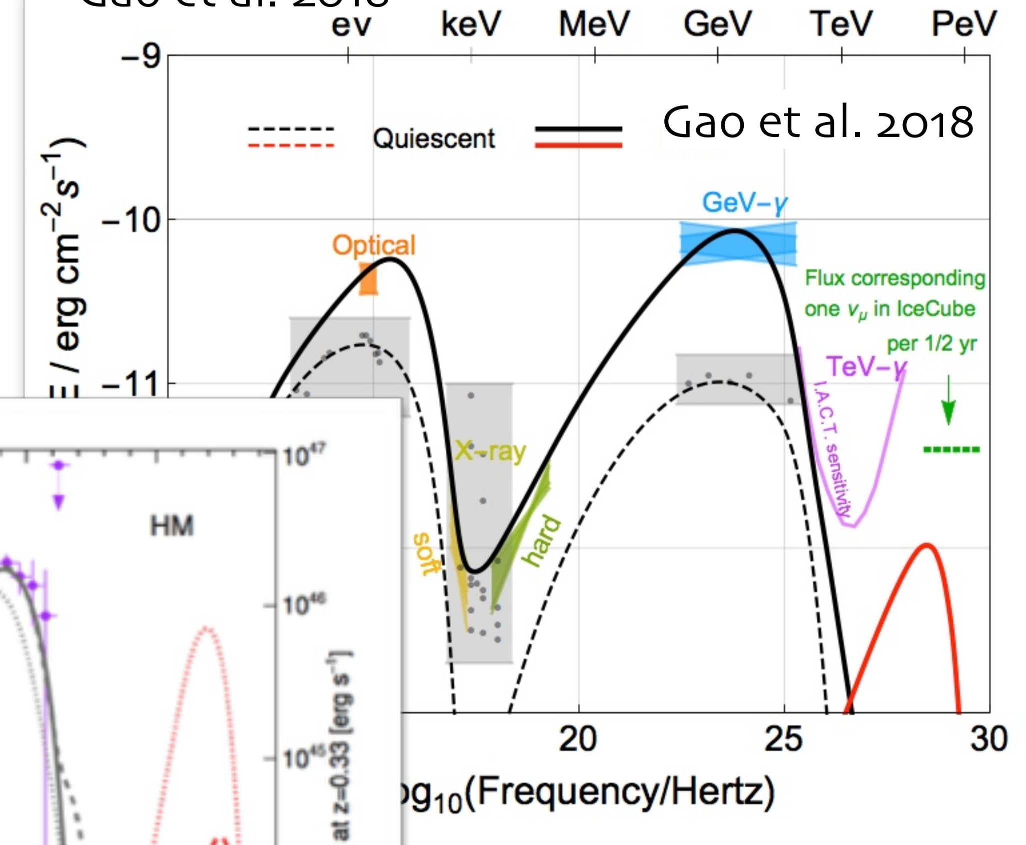


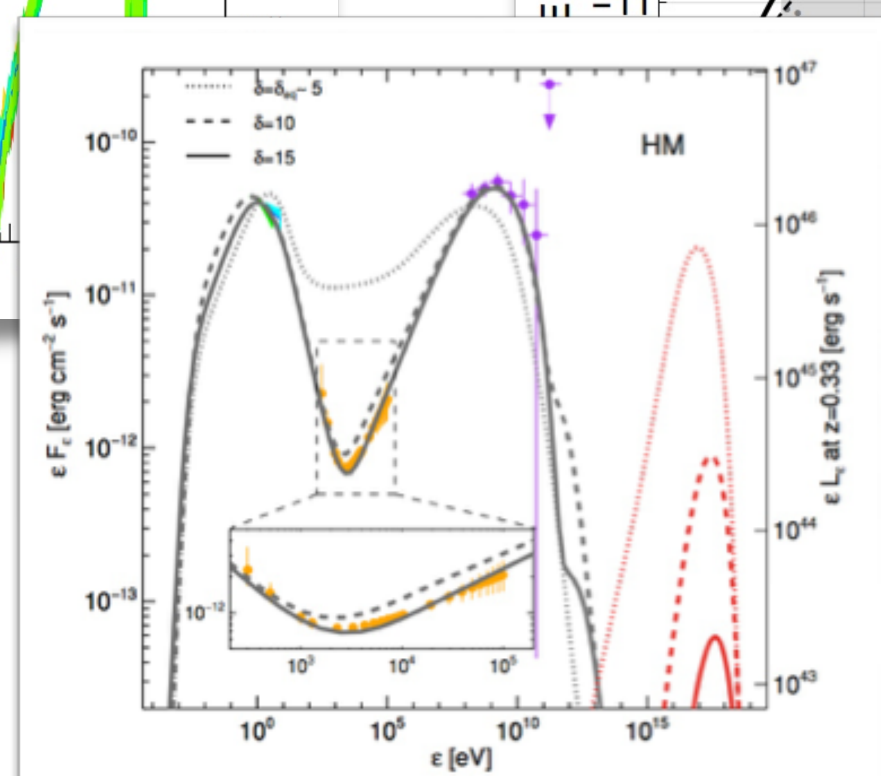
Interpretation

Getting all the elements of this puzzle to fit together is not easy. Blazars seem to contain important clues on the origin of cosmic neutrinos and cosmic rays.



Gao et al. 2018

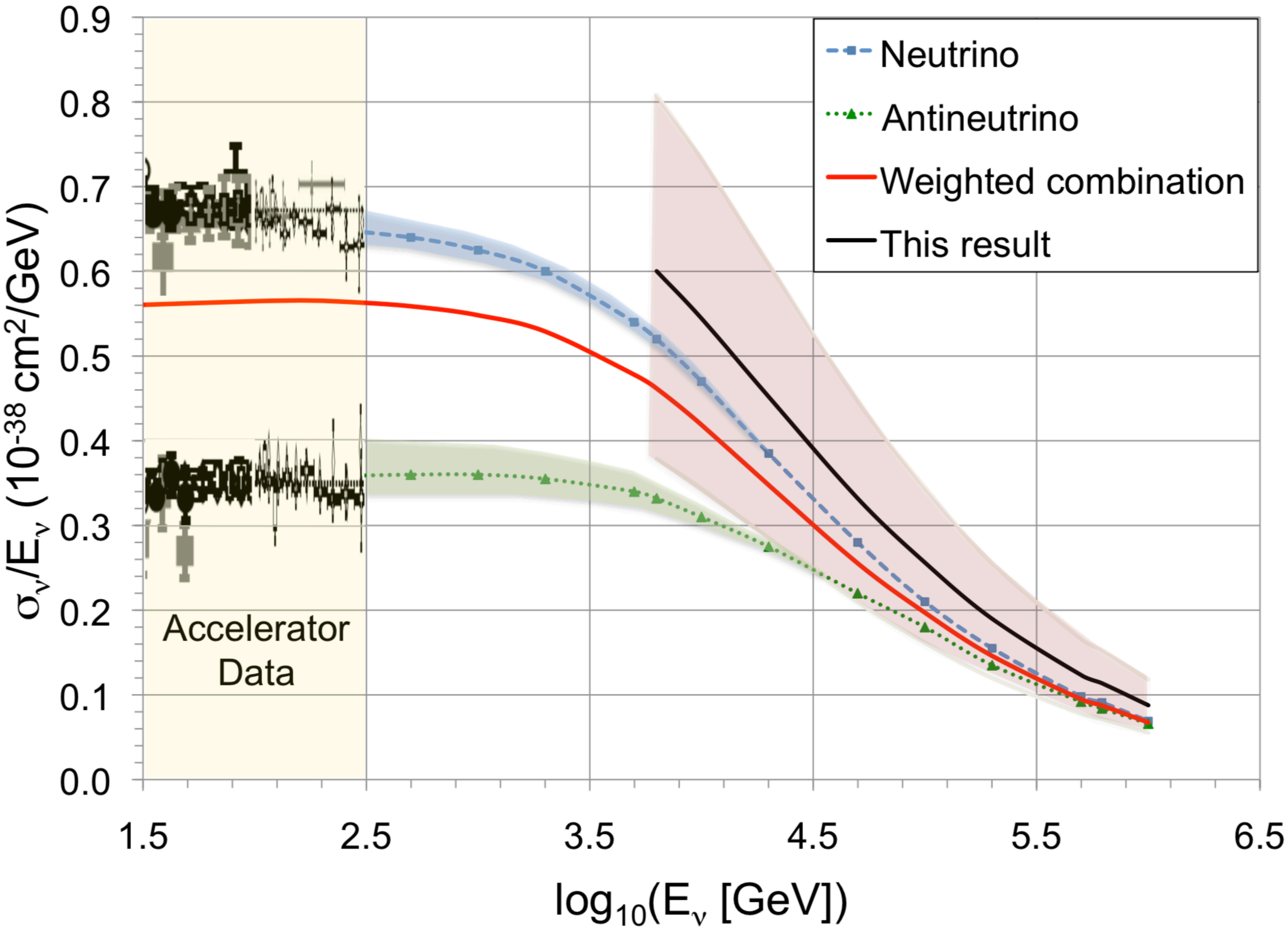




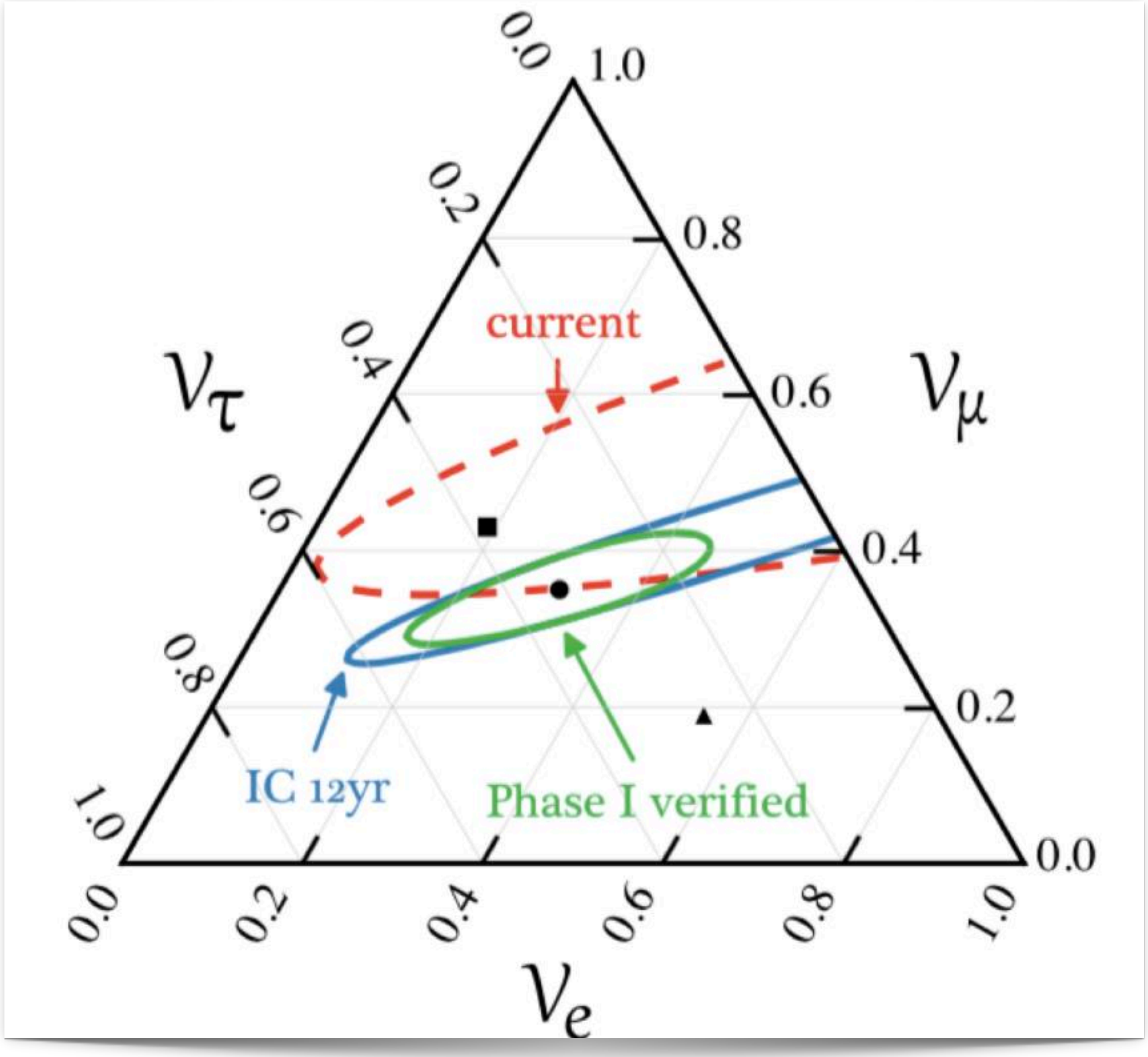
Keivani et al. 2018

Also Reimer at al. 2018

Cross sections



Neutrino flavour



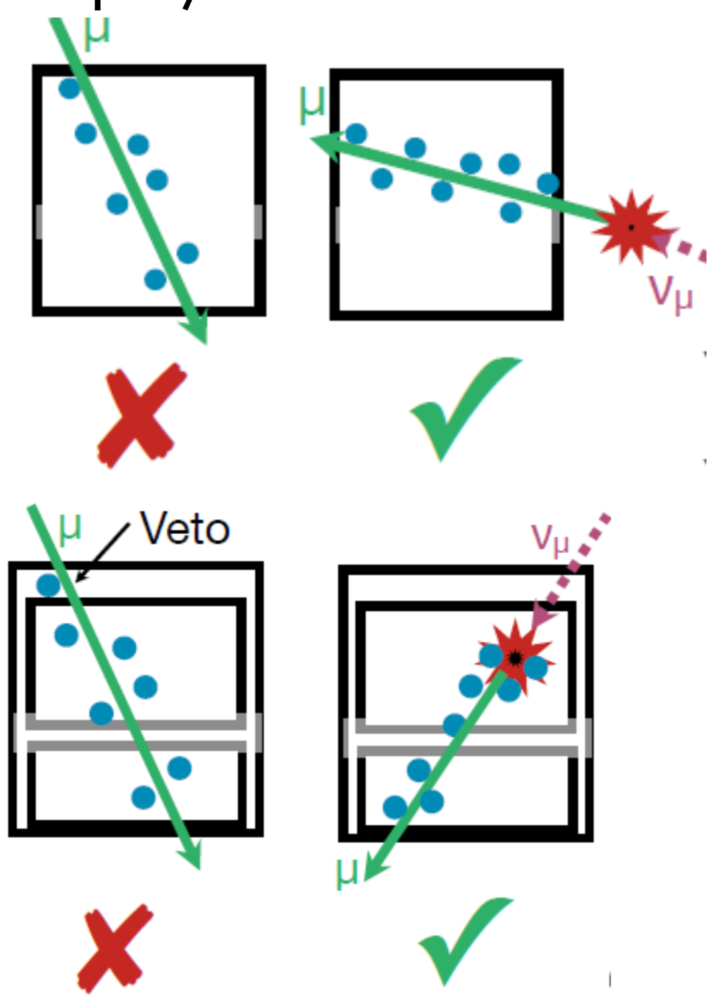
Signals and backgrounds

Event rates in IceCube are:

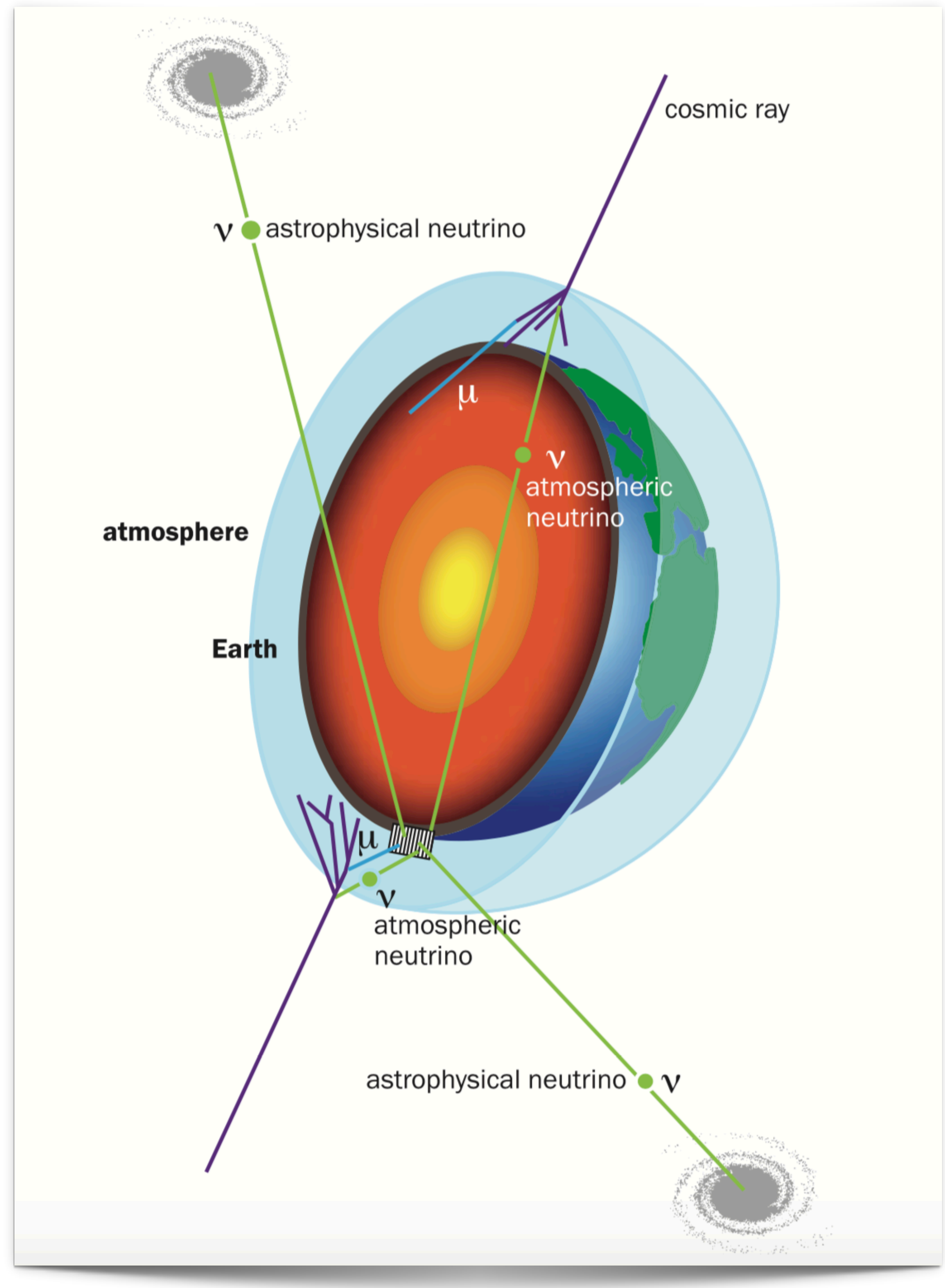
~3000 atmospheric muons per second (7×10^{10} year^{-1})

1 atmospheric neutrino every 6 minutes (8×10^{4} year^{-1})

O(10) astrophysical neutrinos year^{-1}



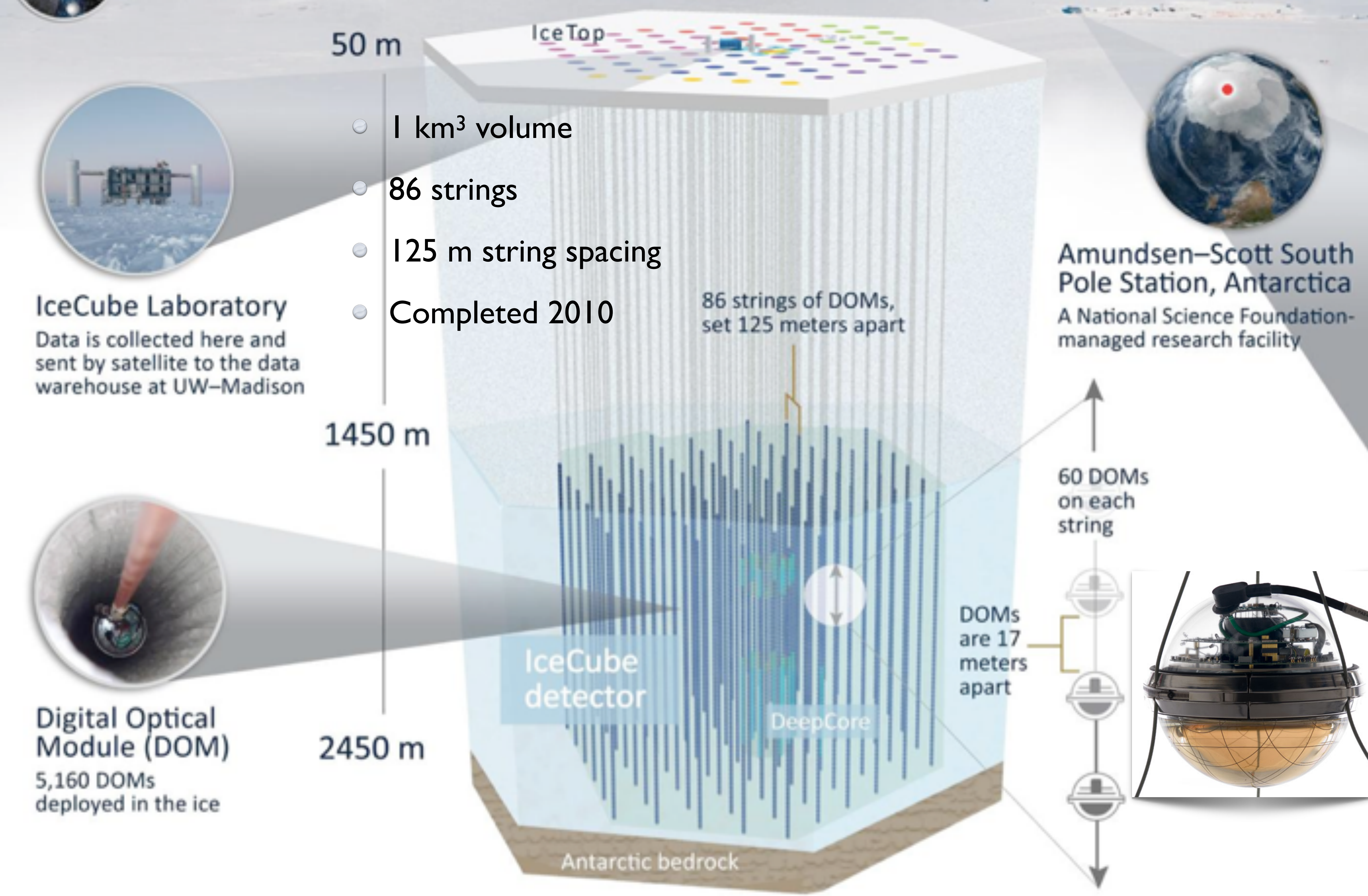
E. Bernardini, Asimmetrie n. 18 (2015)



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Featuring in this talk

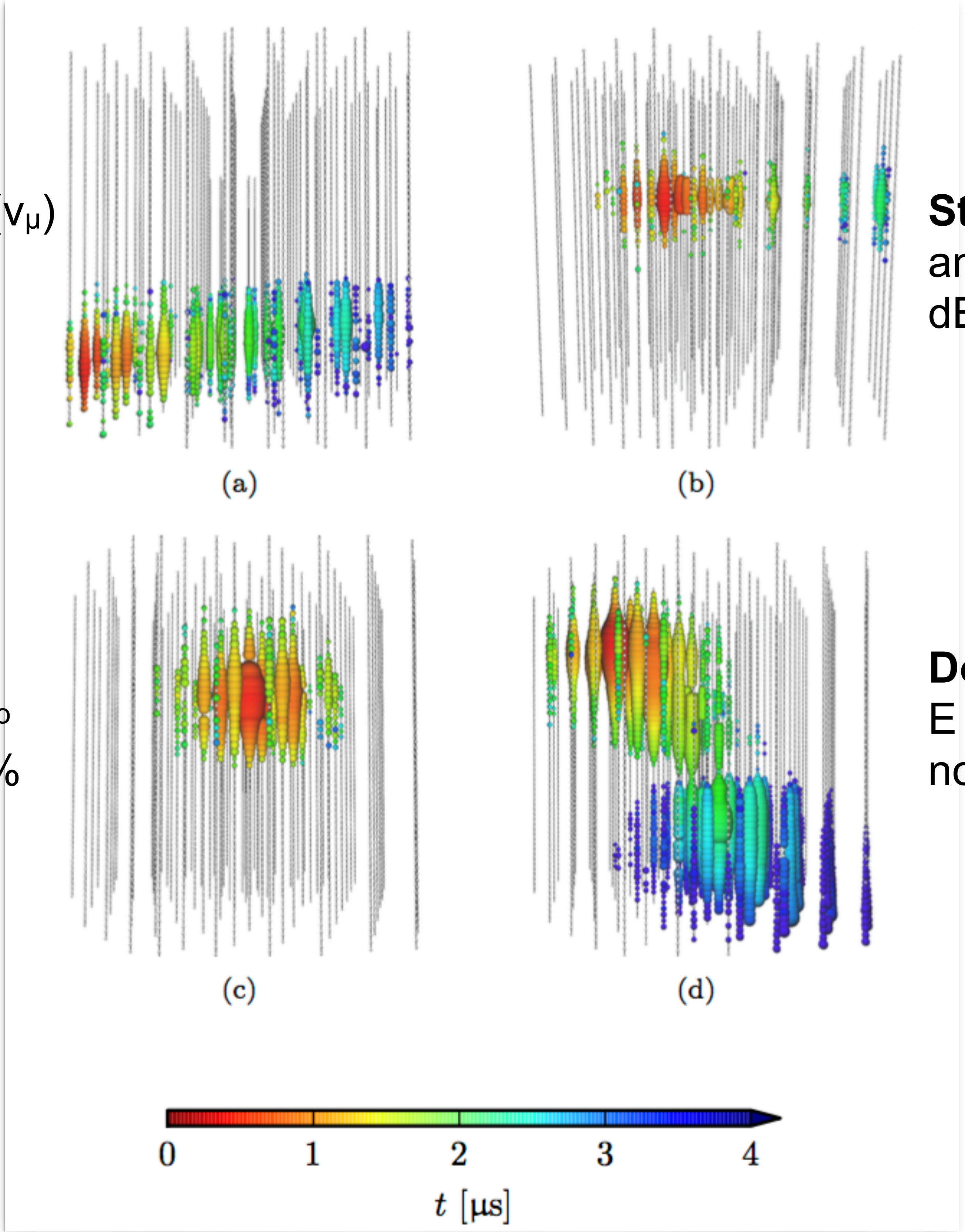
- 1 km^3 volume
- 86 strings
- 125 m string spacing
- Completed 2010



Event signatures

Through-going track (ν_μ)
angular resolution < 1°
only dE/dx

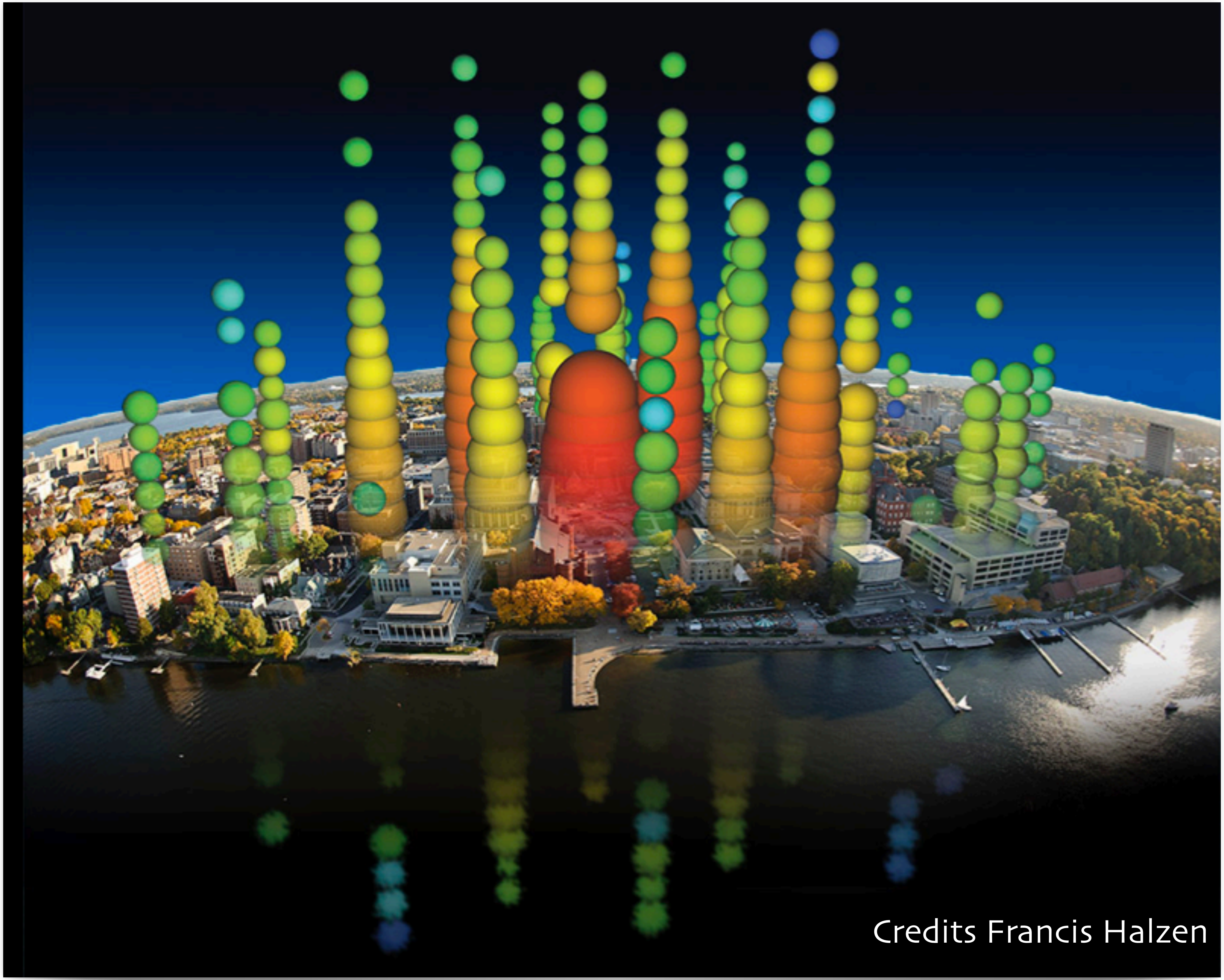
Starting track (ν_μ)
angular resolution < 1°
dE/dx + energy at vertex



Cascade (ν_e, ν_μ, ν_τ)
angular resolution > 10°
energy resolution ~ 15%

Double-Bang (ν_τ)
E > *O*(PeV)
not observed yet!

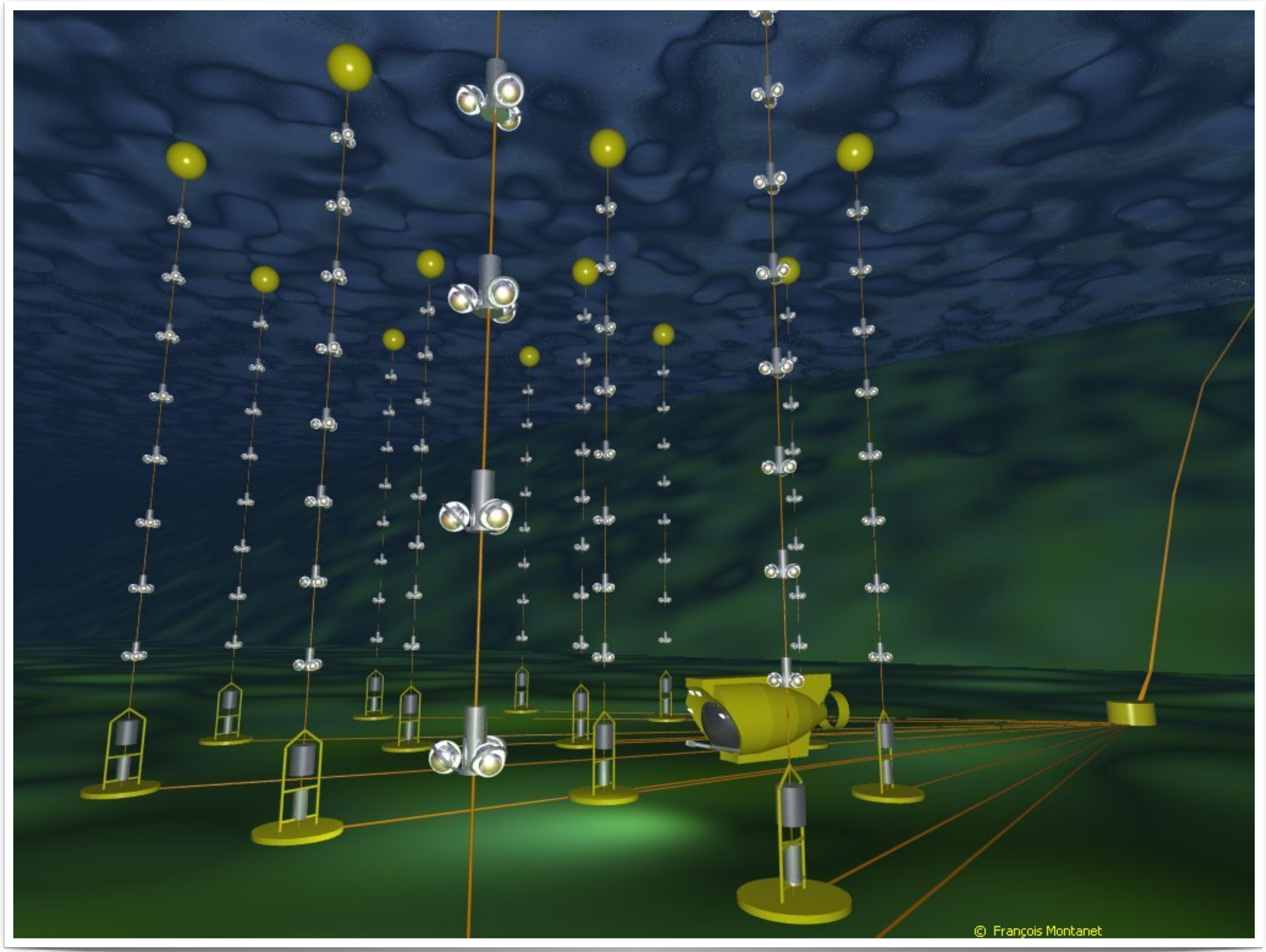
One of the highest energy particle ever observed



Comparing to LHC

ANTARES

Consisting of 885 PMTs deployed in the Mediterranean sea at depths between 2.01 km and 2.47 km below sea level, it instruments a volume of ~1% of IceCube



Merger of two neutron stars

GW170817 - first binary Neutron- Star merger detected via GW and electro magnetic emission
3000 astronomers / 70 observatories

Multi-messenger Highlight n. 1

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