Cosmic Accelerators:

Gamma Rays, Neutrinos and The Dawn of Multimessenger Astrophysics

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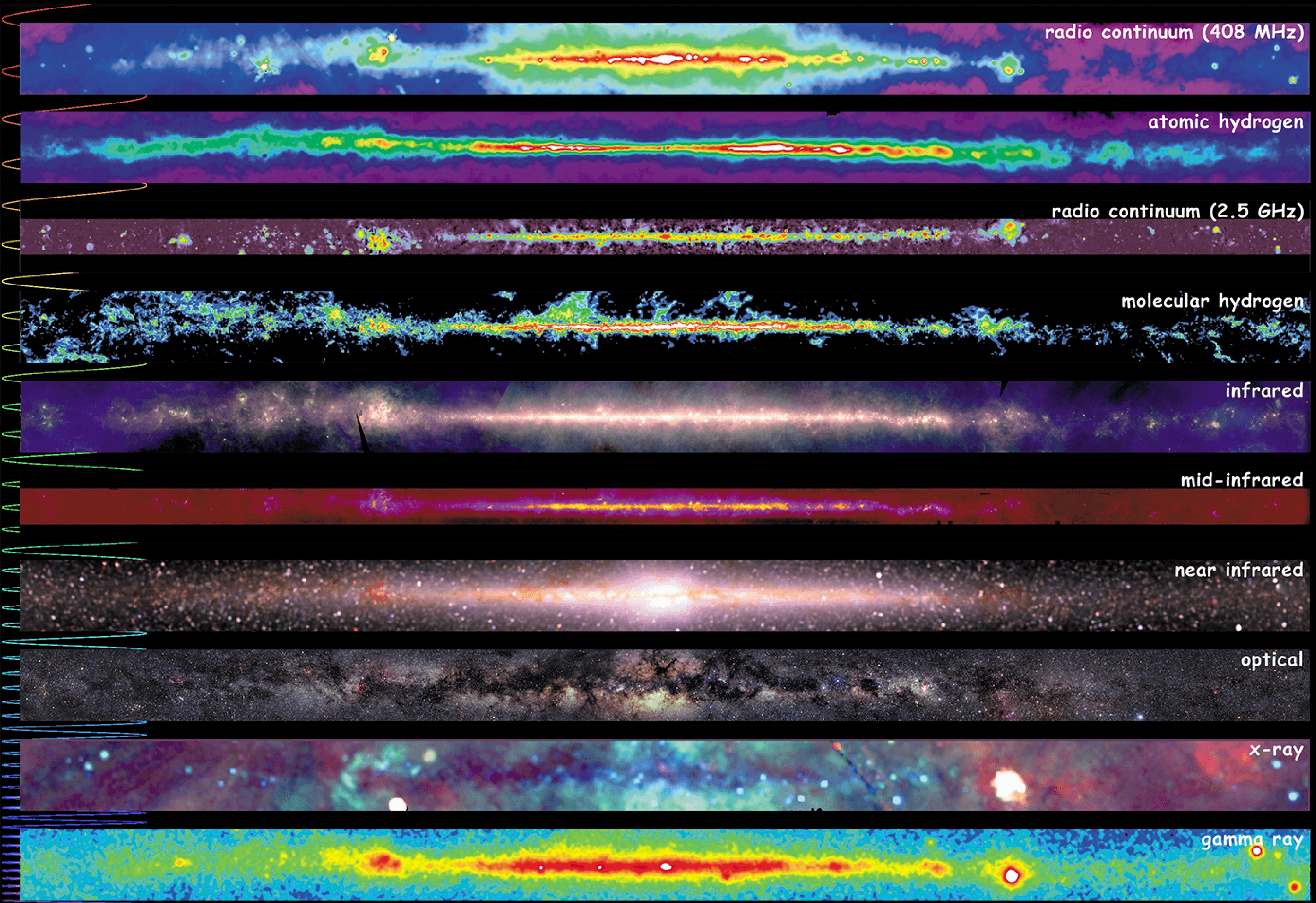
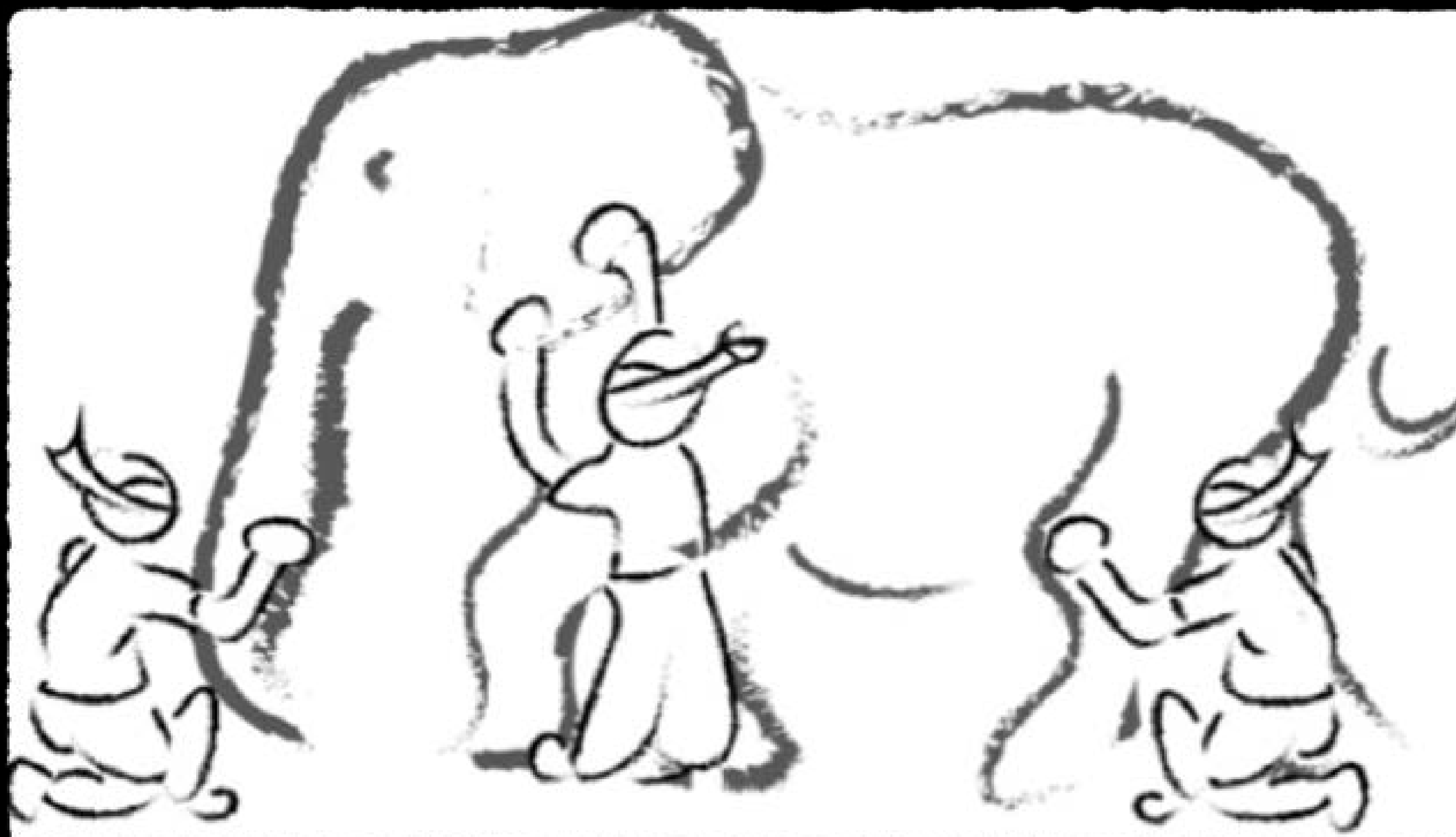


NASA

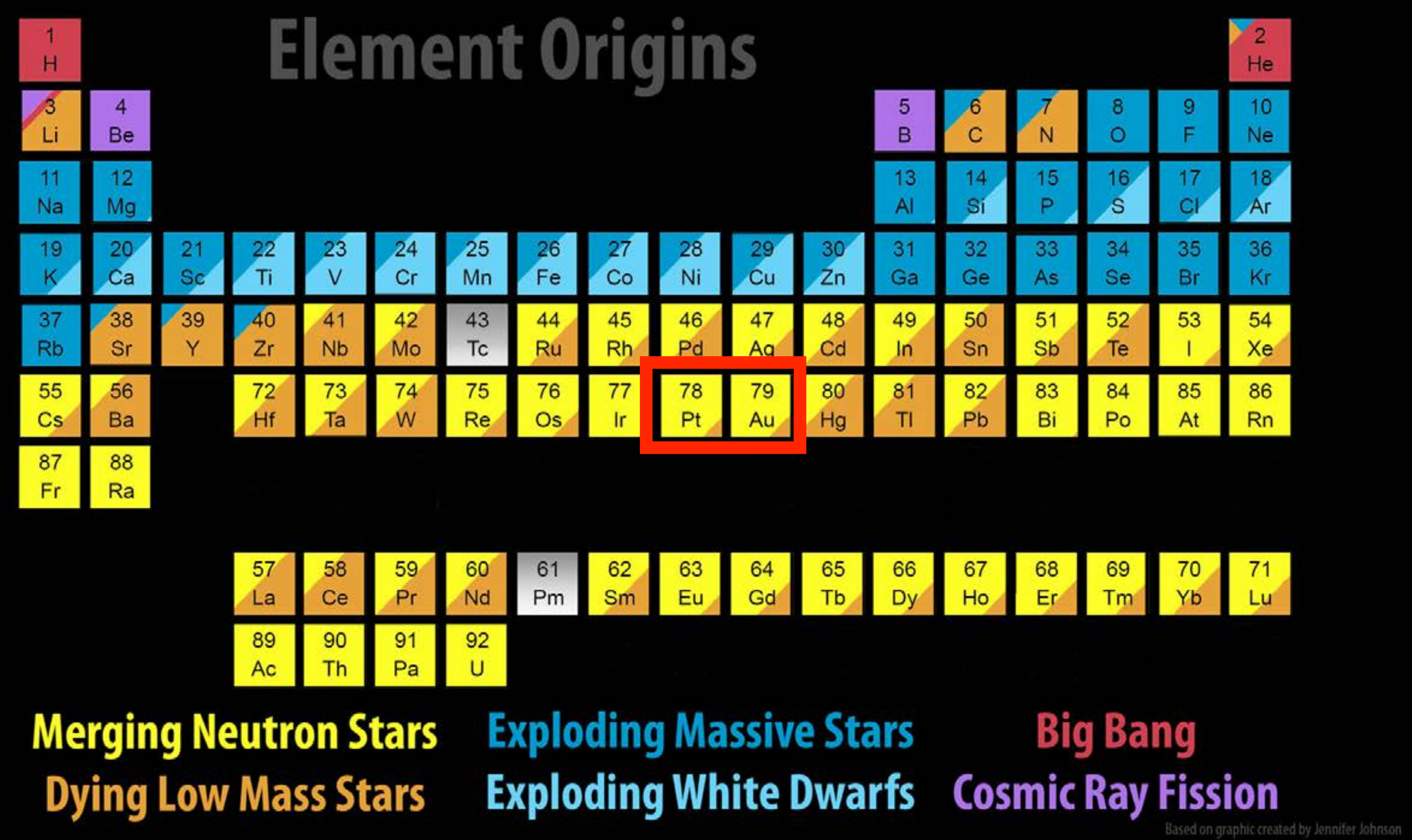
The Multiwavelength Milky Way

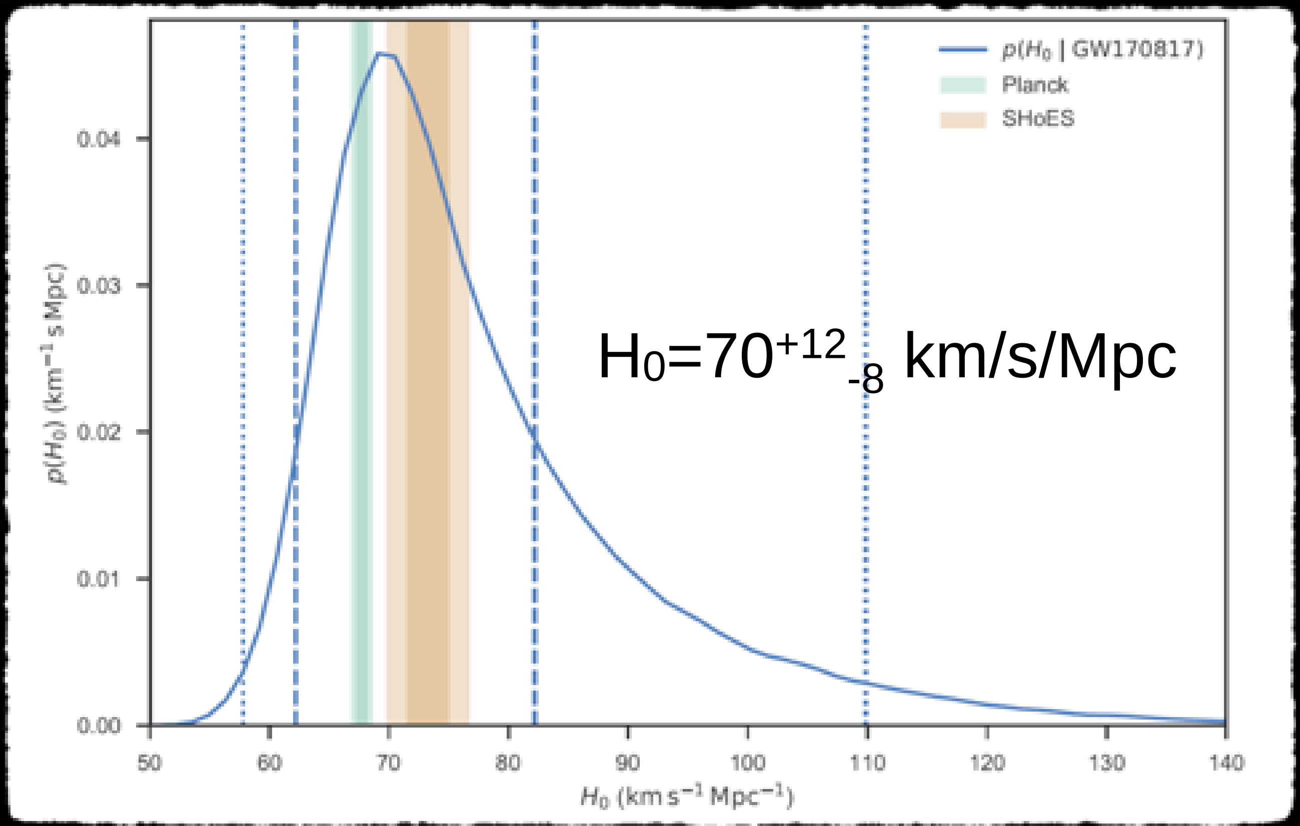
The Universe in Multiwavelength Light



August 17, 2017

What did we learn?





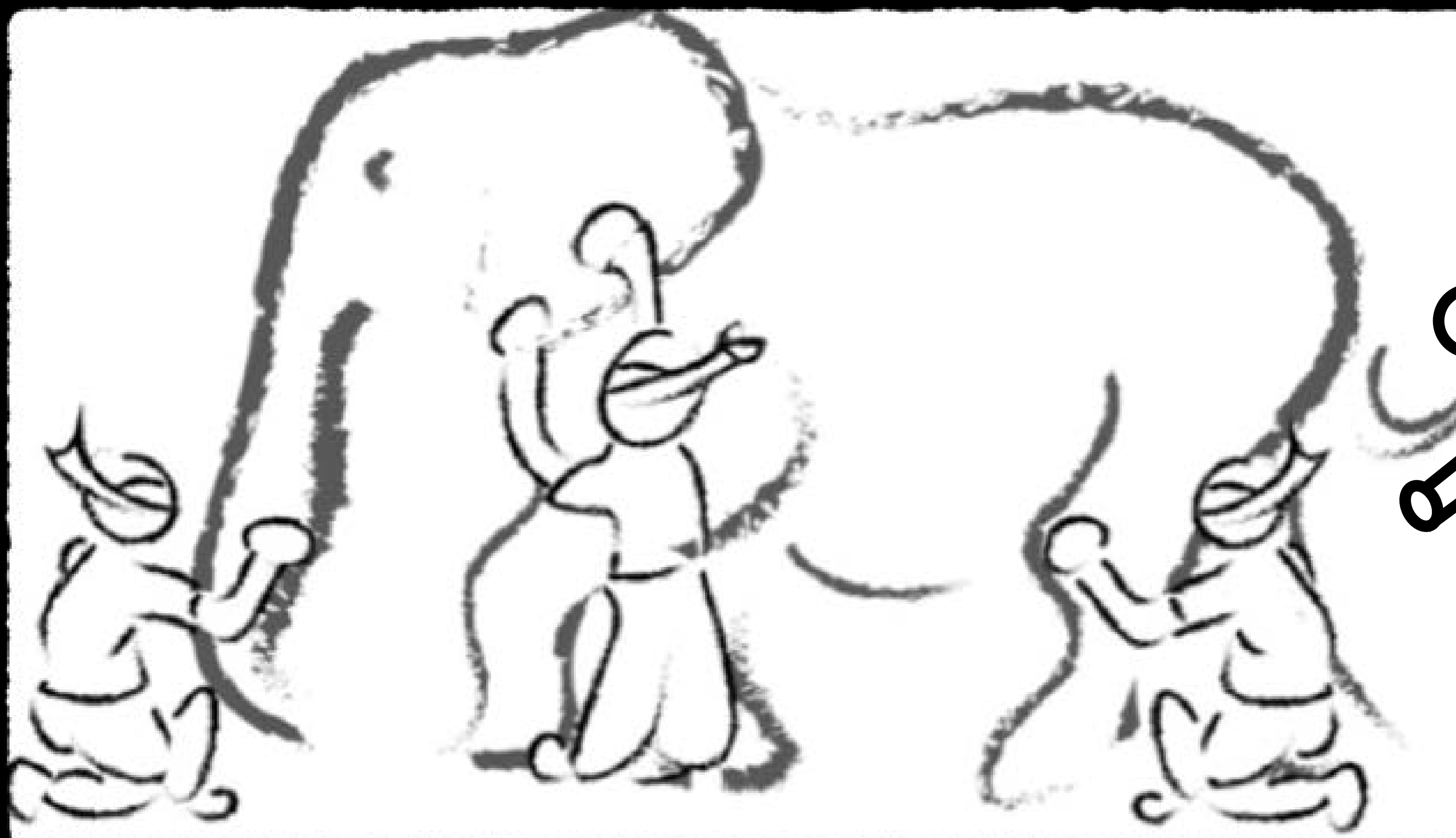
$H_0 = 70^{+12}_{-8}$ km/s/Mpc

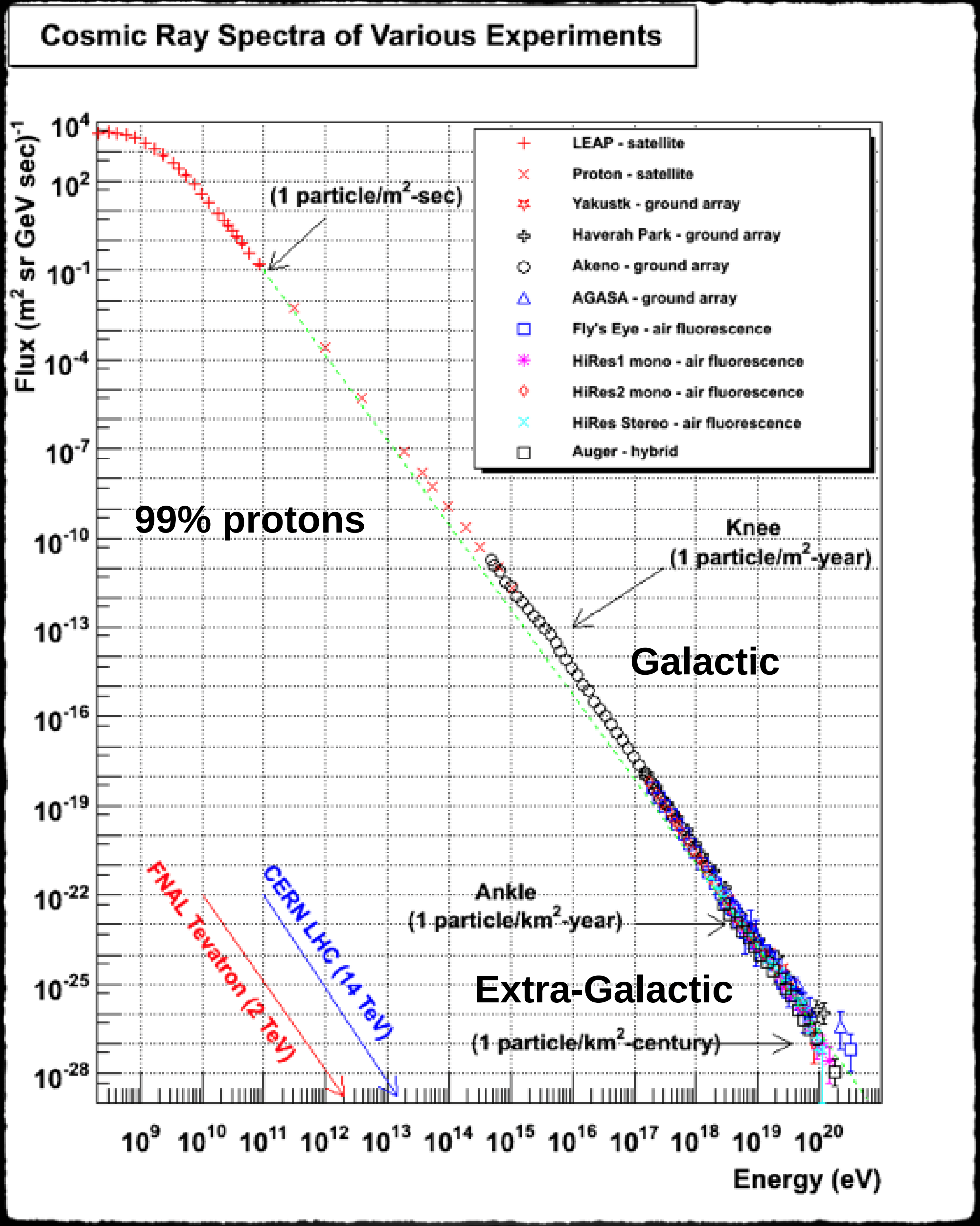
Speed of Gravity

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

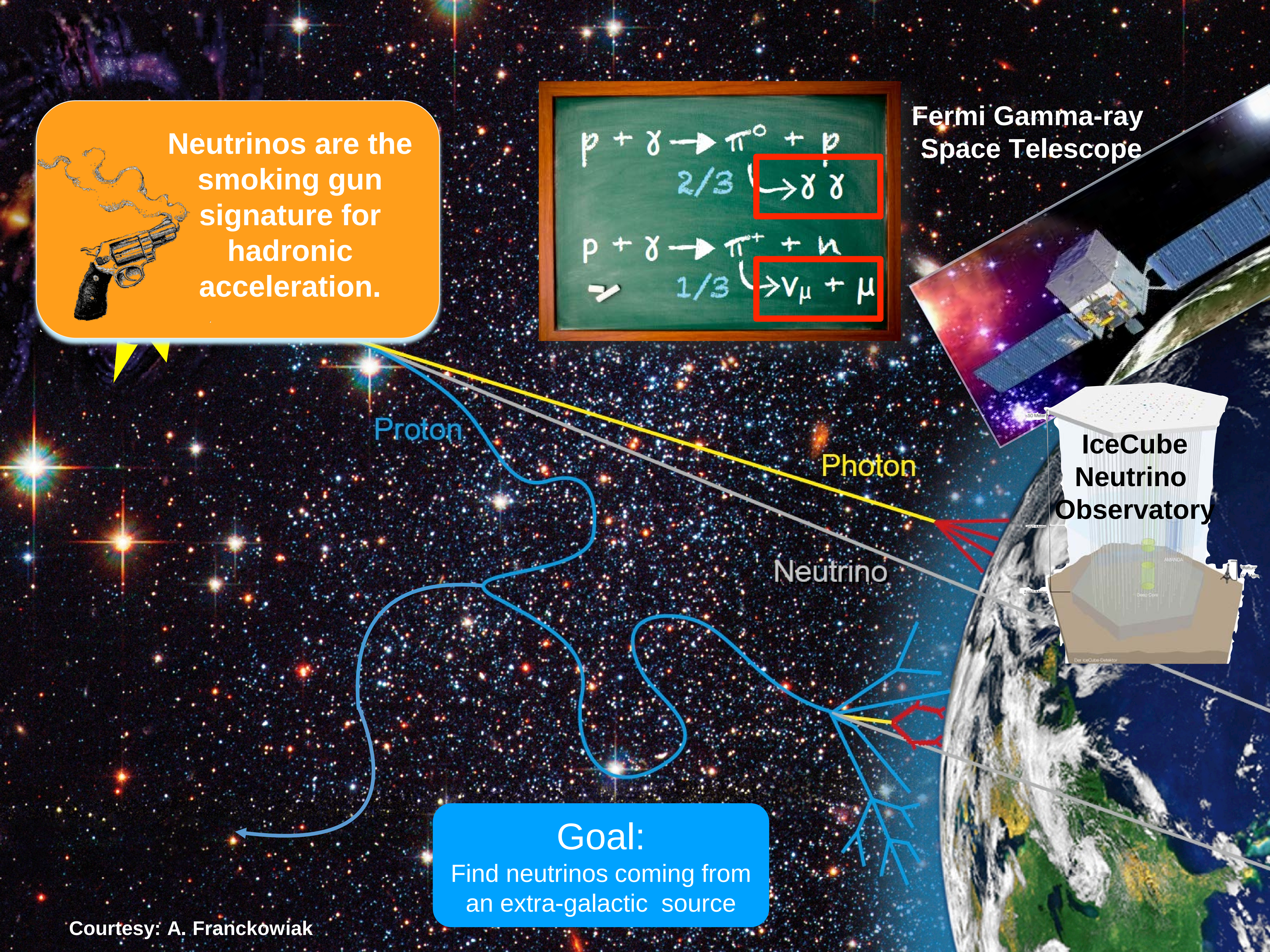
Tested Equivalence Principle of Gravity:
Ruled out many theories of modified gravity to explain dark matter

The Multimessenger Universe



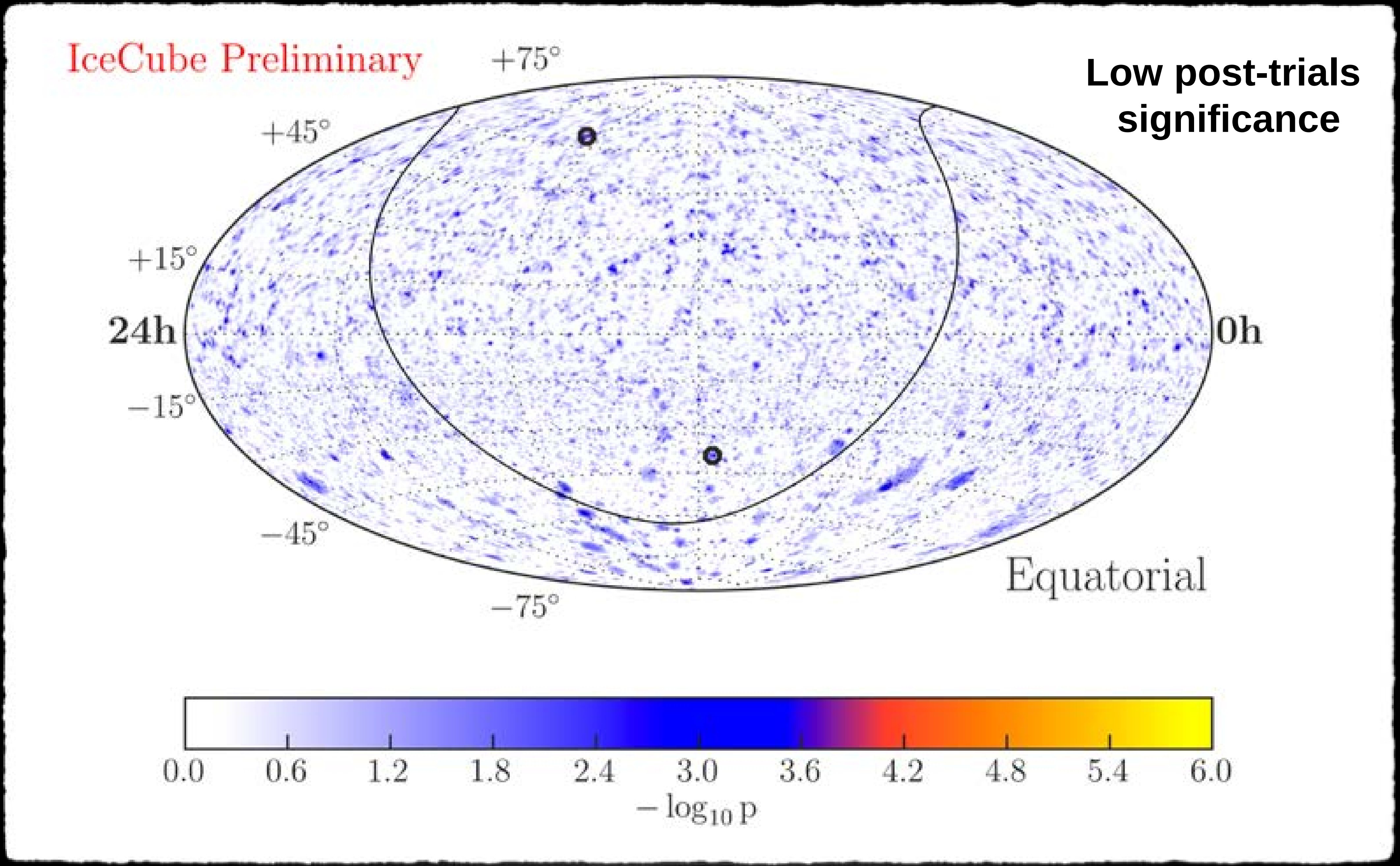


What is creating these ultra-high energy particles?



Neutrinos are the smoking gun signature for hadronic acceleration.
$p + \gamma \rightarrow \pi^0 + p$
2/3 $\rightarrow \gamma\gamma$
$p + \gamma \rightarrow \pi^+ + n$
1/3 $\rightarrow \nu_\mu + \mu$
Fermi Gamma-ray Space Telescope
Proton
Photon
Neutrino
IceCube Neutrino Observatory
Goal:
Find neutrinos coming from an extra-galactic source
Courtesy: A. Franckowiak

Searching for Neutrino Sources



Large trials factor when looking only at neutrinos, multiwavelength data can identify potential sources!

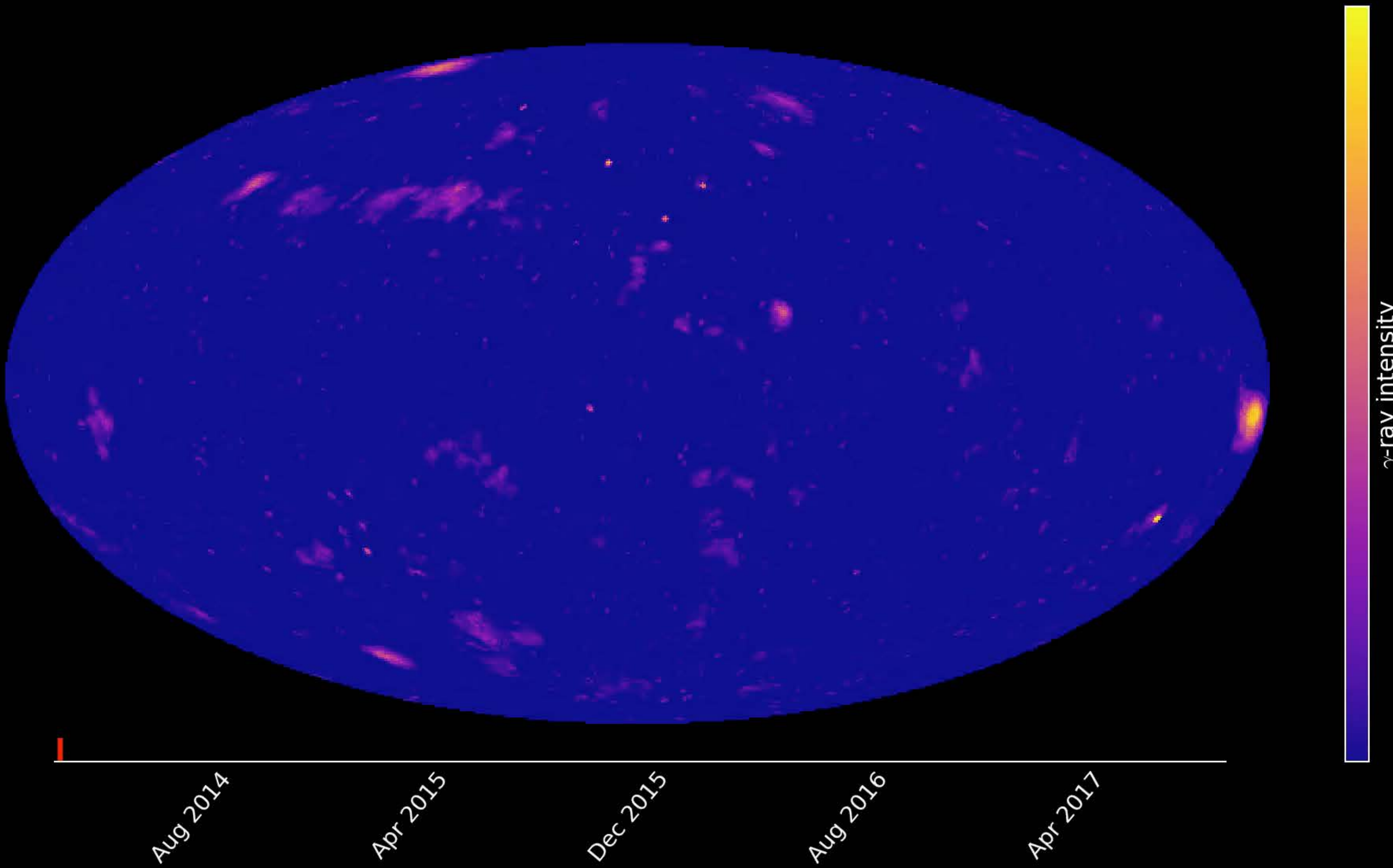
IceCube Coll. ApJ, 835 (2017)

Sources that produce high-energy photons

Fermi observes over 2000 blazars

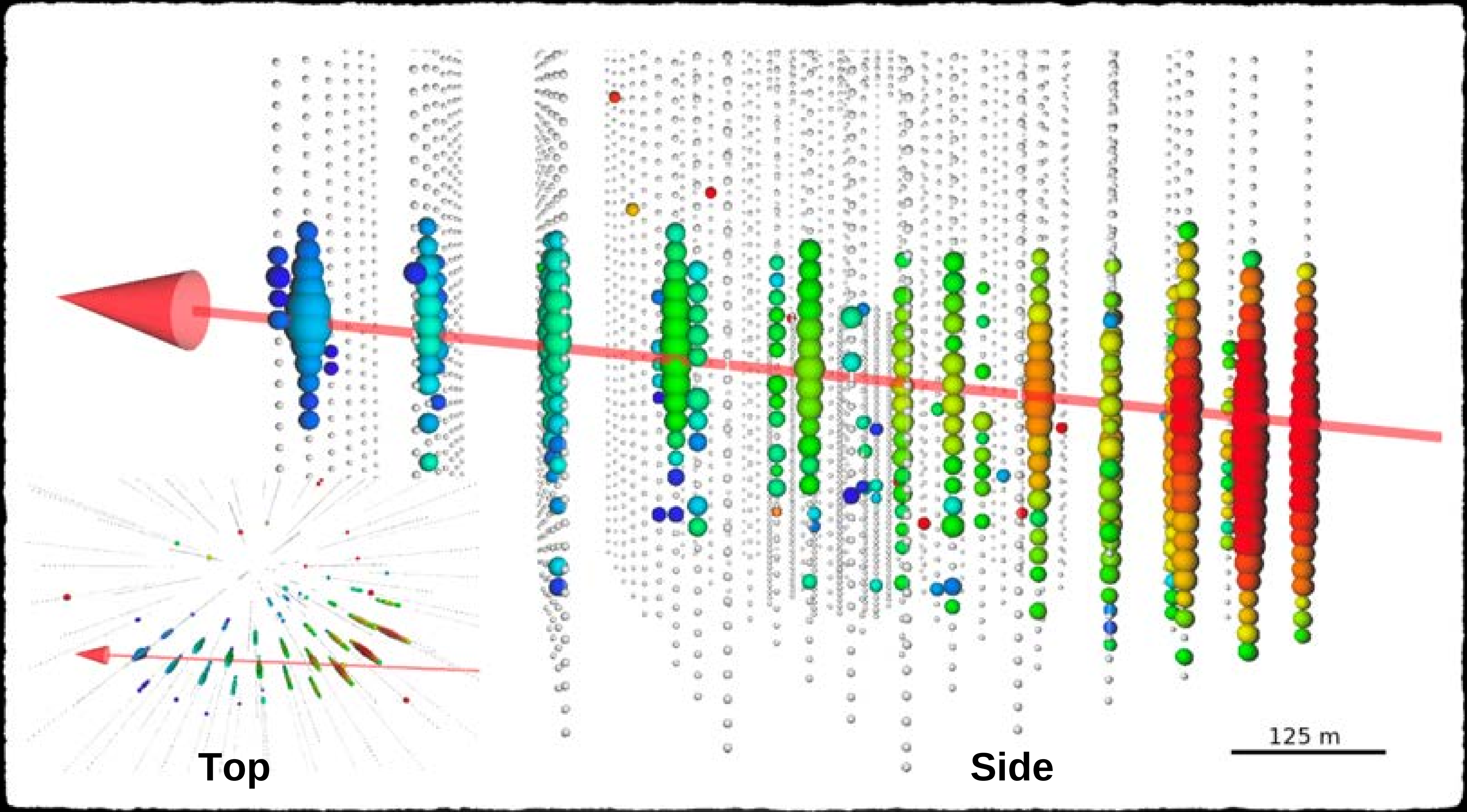
>300 MeV over 3 months in 2008

IceCube: Alerts starting in April 2016



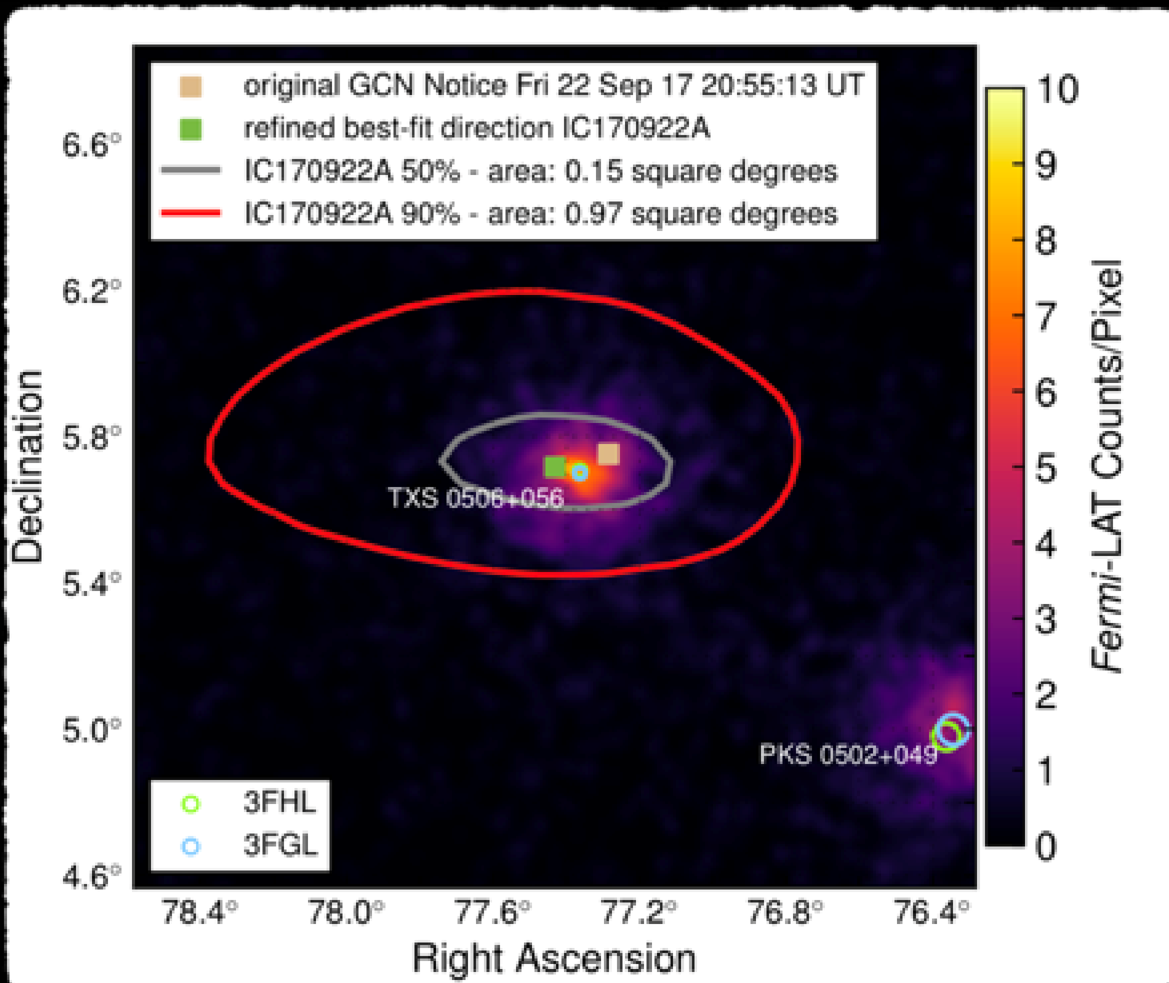
Fermi-LAT Coll., ApJ 846, 2017, Video credits: Matteo Giomi, Fermi-LAT Collaboration

IC-170922A: 290 TeV Neutrino

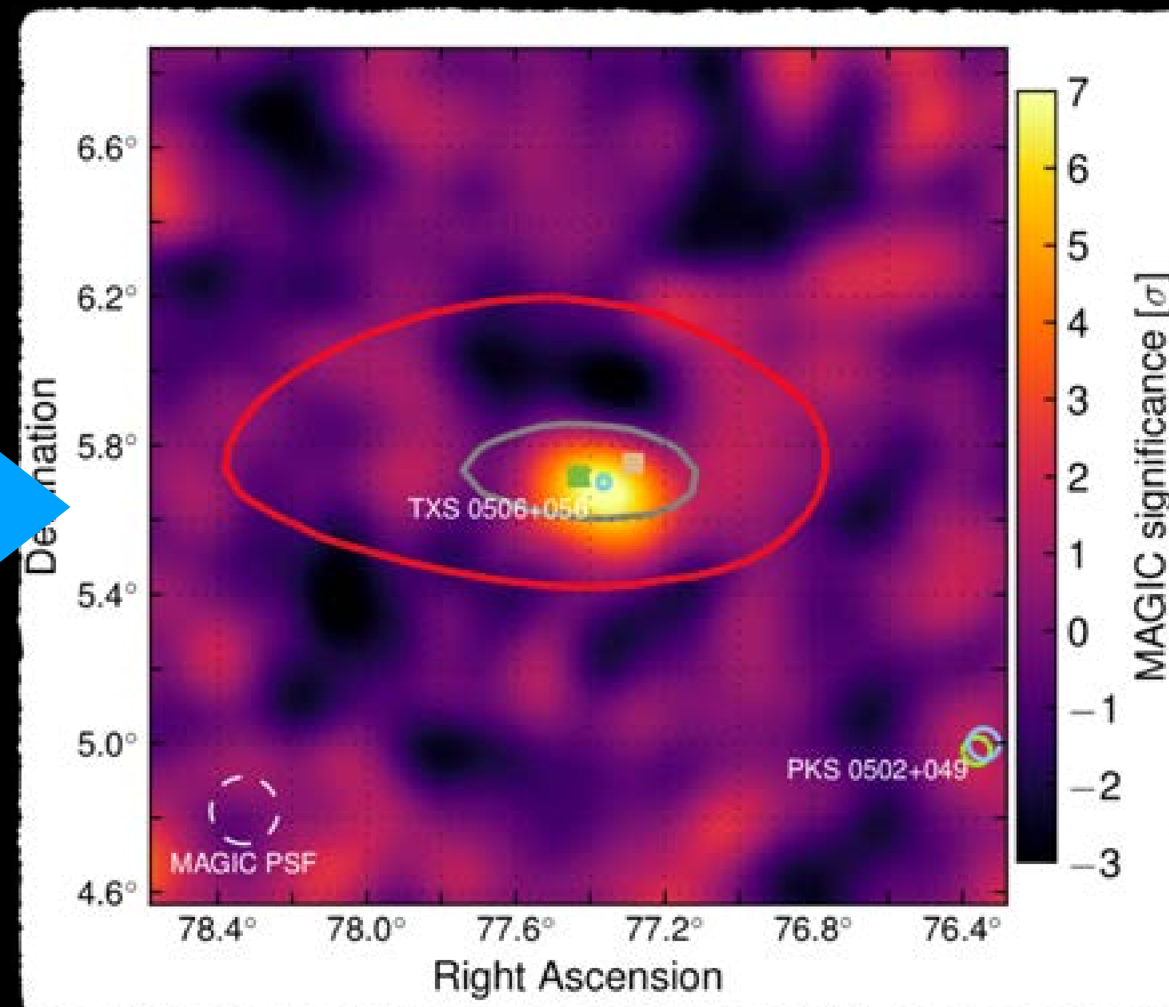


IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018


IceCube
September 22
Swift
September 26
Fermi, ASAS-SN
September 28
Liverpool, AGILE
September 29
MAGIC
October 4
SALT, Kapteyn
October 7
Kanata, NuSTAR
October 12
VLA
October 17
Subaru
October 25

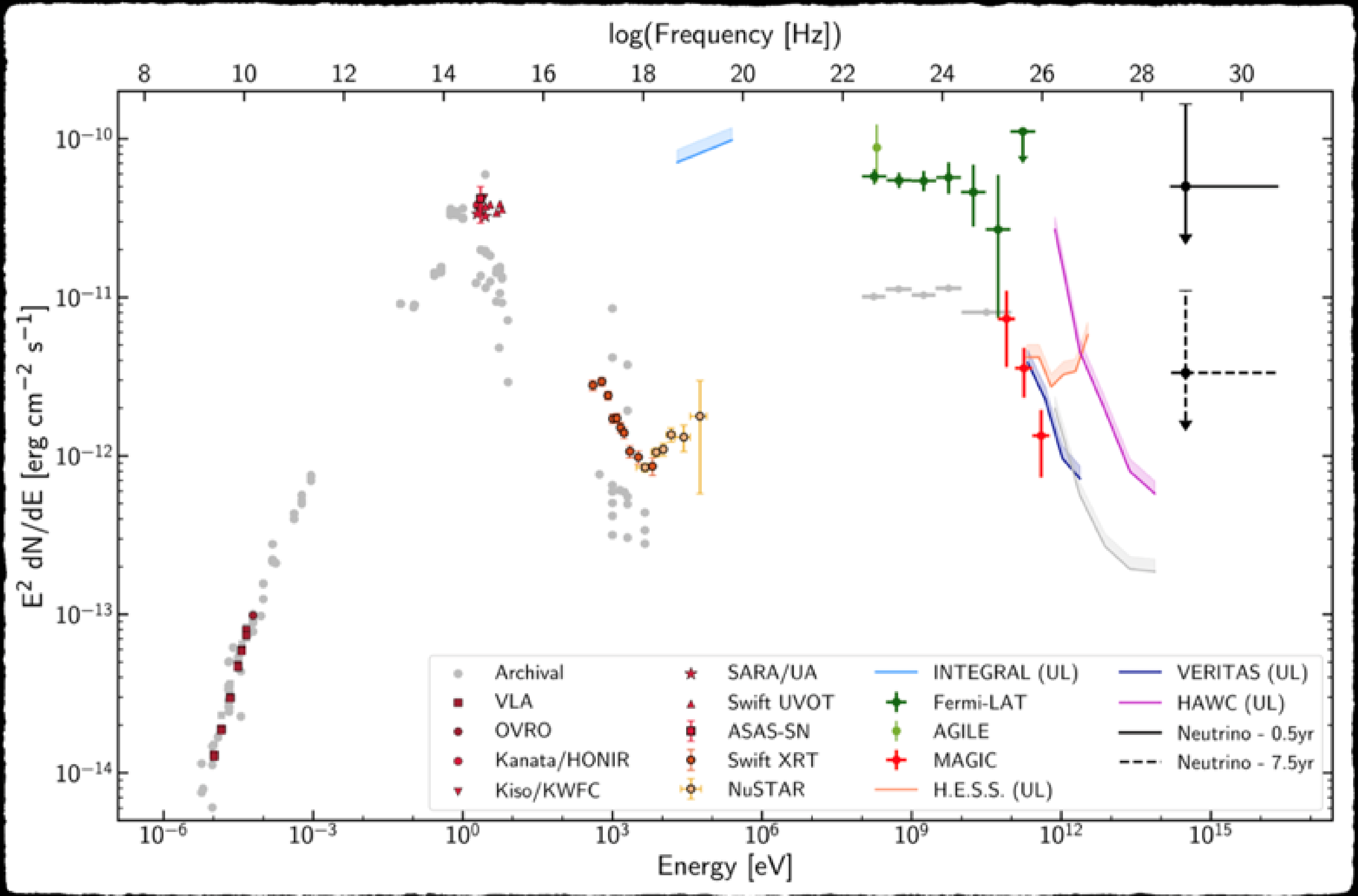


Fermi-LAT Counts Map with IceCube Sky position

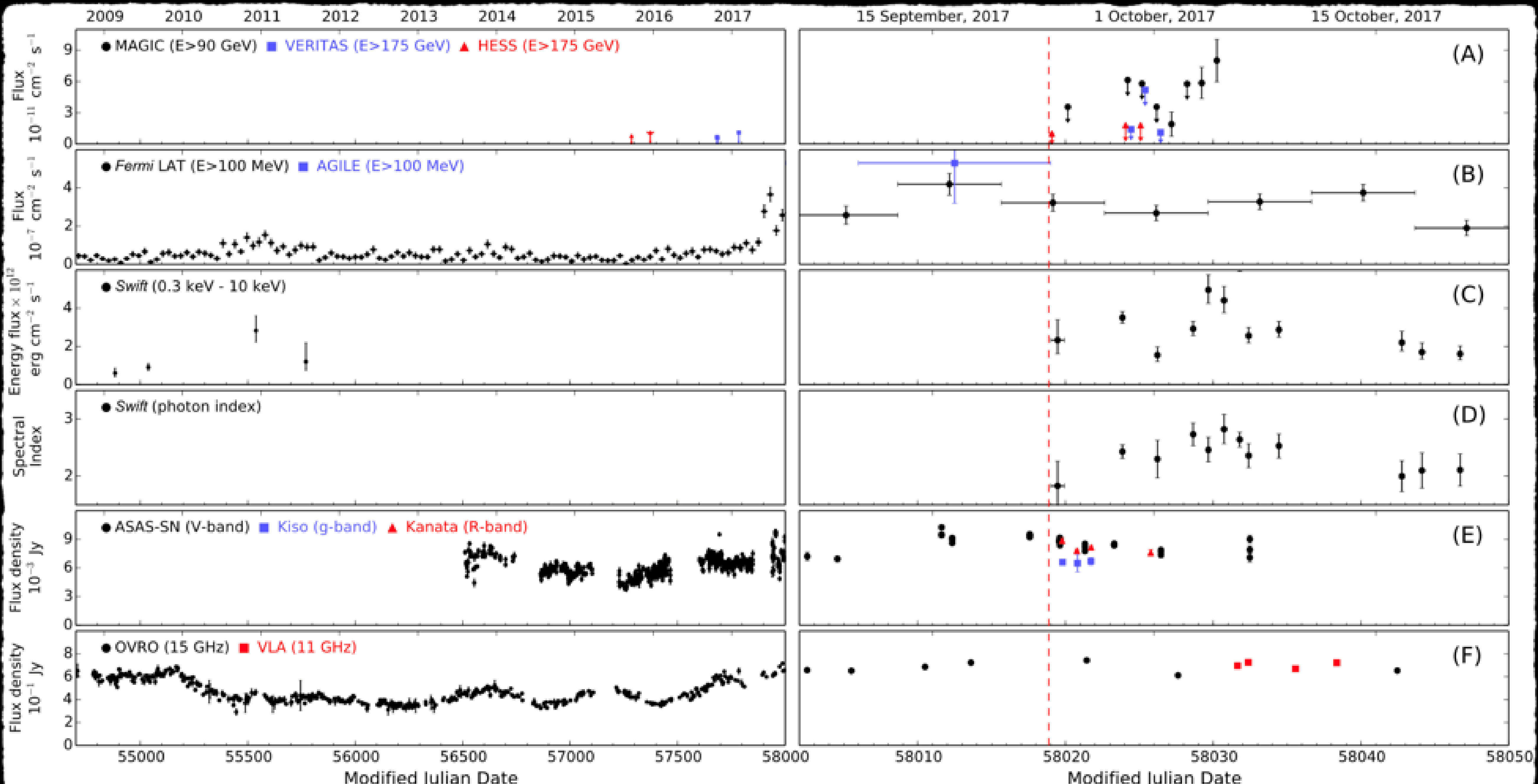


MAGIC Counts Map with IceCube Sky position

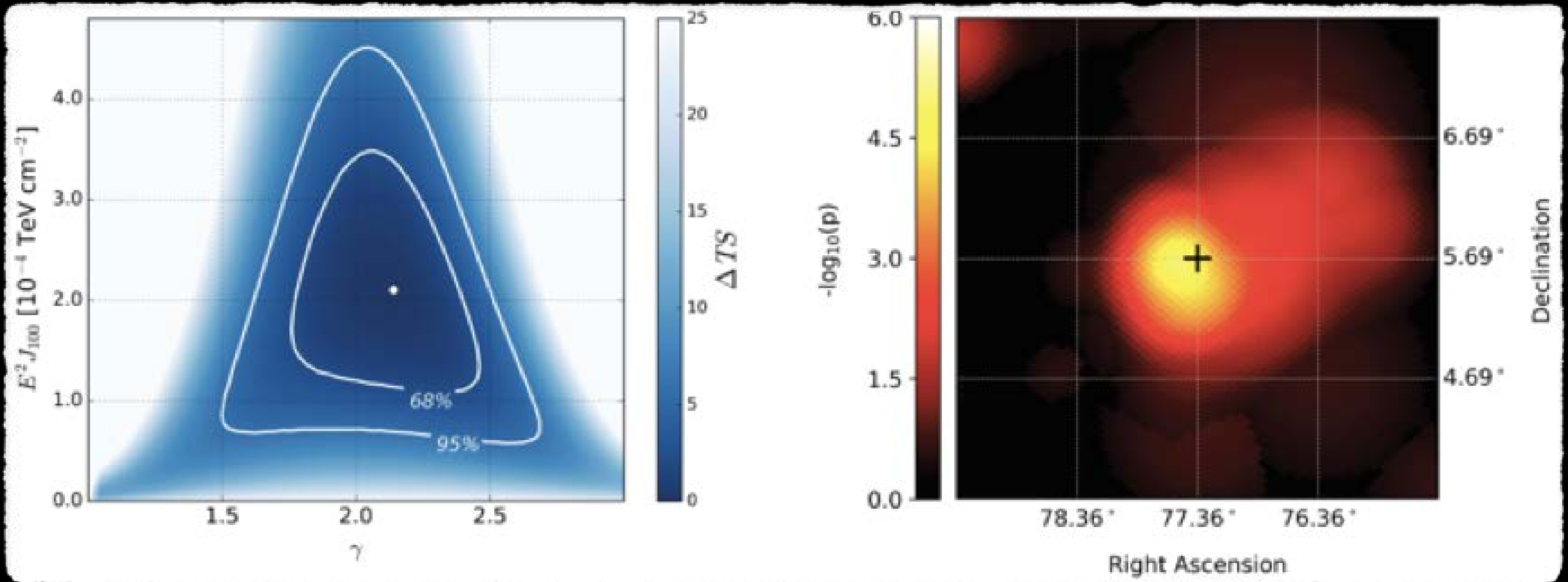
Spectra of TXS 0506+56 across all wavelengths and messengers



Light Curve of TXS 0506+56 across all wavelengths and messengers



Looking back at the IceCube data



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

Modeling the Multimessenger Universe

- "Interpretation of the coincident observation of a high energy neutrino and a bright flare", Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275
- "A multiwavelength view of BL Lacs neutrino candidates", Righi, Tavecchio, Pacciani, arXiv::1807.04299
- "The blazar TXS 0506+056 associated with a high-energy neutrino: insights into extragalactic jets and cosmic ray acceleration", MAGIC Collaboration, arXiv:1807.04300
- "Lepto-hadronic single-zone models for the electromagnetic and neutrino emission of TXS 0506+056", Cerruti, Zech, Boisson, Emery, Inoue, Lenain, arXiv:1807.04335
- "A Multimessenger Picture of the Flaring Blazar TXS 0506+056: implications for High-Energy Neutrino Emission and Cosmic Ray Acceleration", Keivani, Murase, Petropoulou et al., arXiv:1807.04537
- "Blazar Flares as an Origin of High-Energy Cosmic Neutrinos?" Murase, Oikonomou, Petropoulou, arXiv:1807.04748

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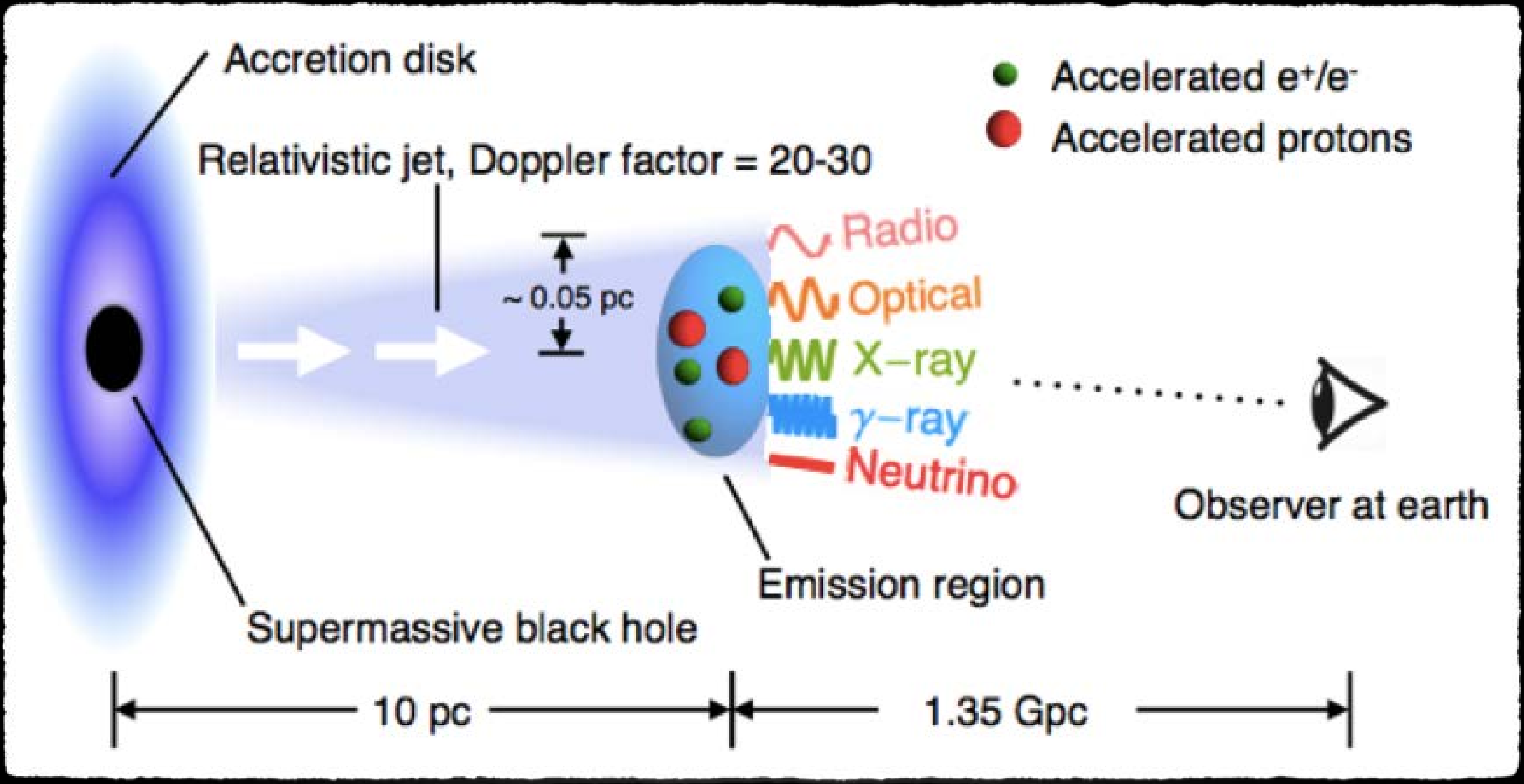
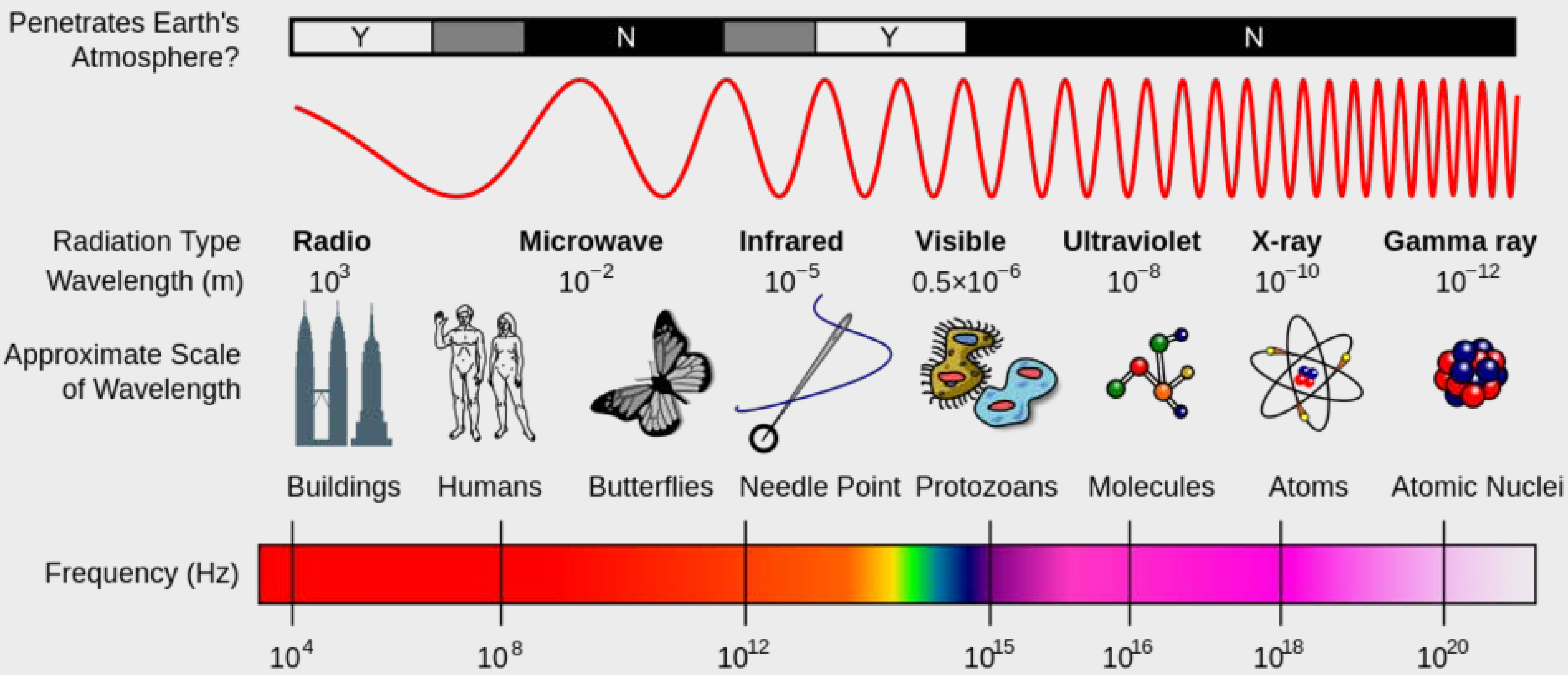
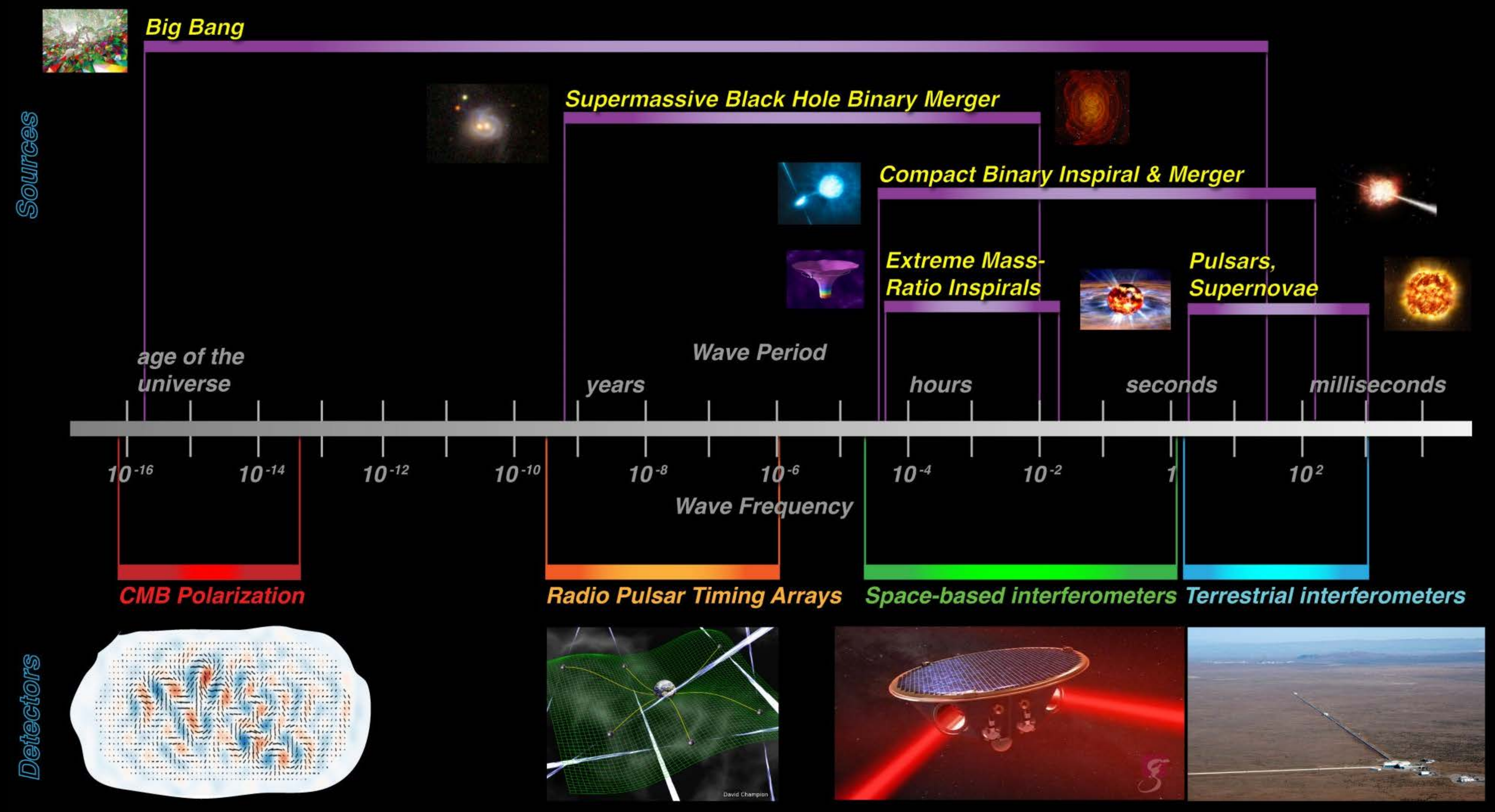


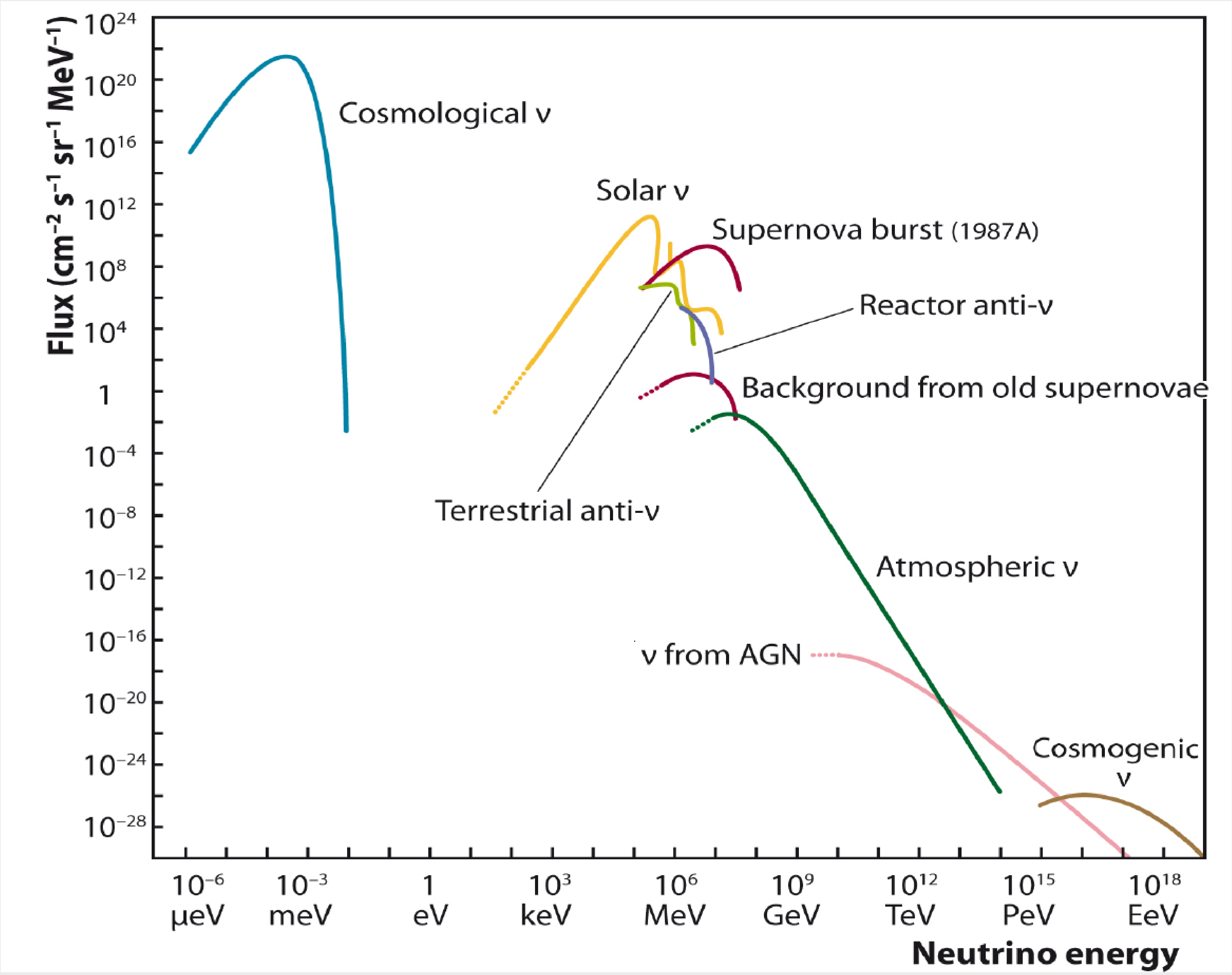
Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275



Electromagnetic Spectrum

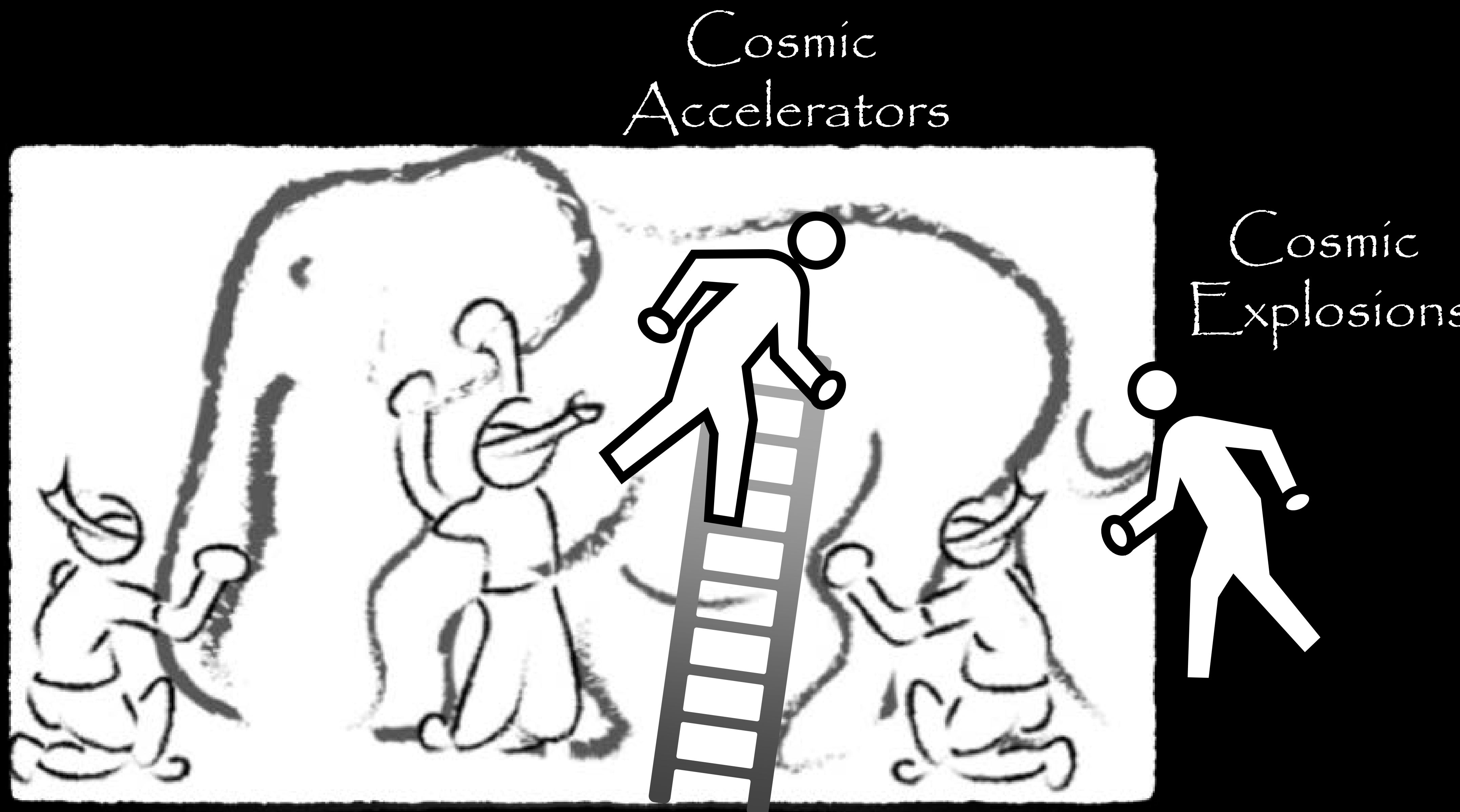


Gravitational Wave Spectrum



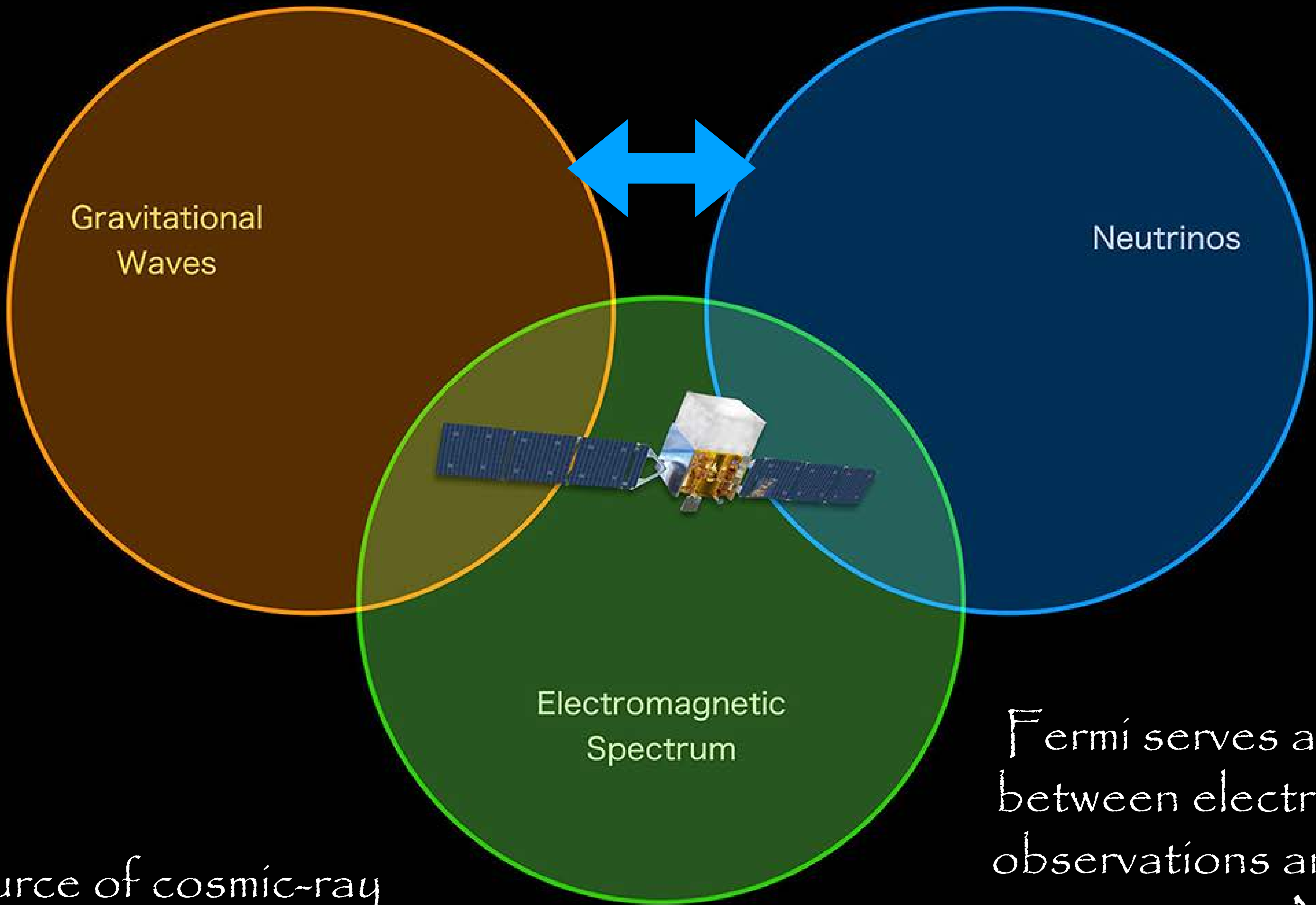
Neutrino Spectrum

The Multimessenger Universe



Summary

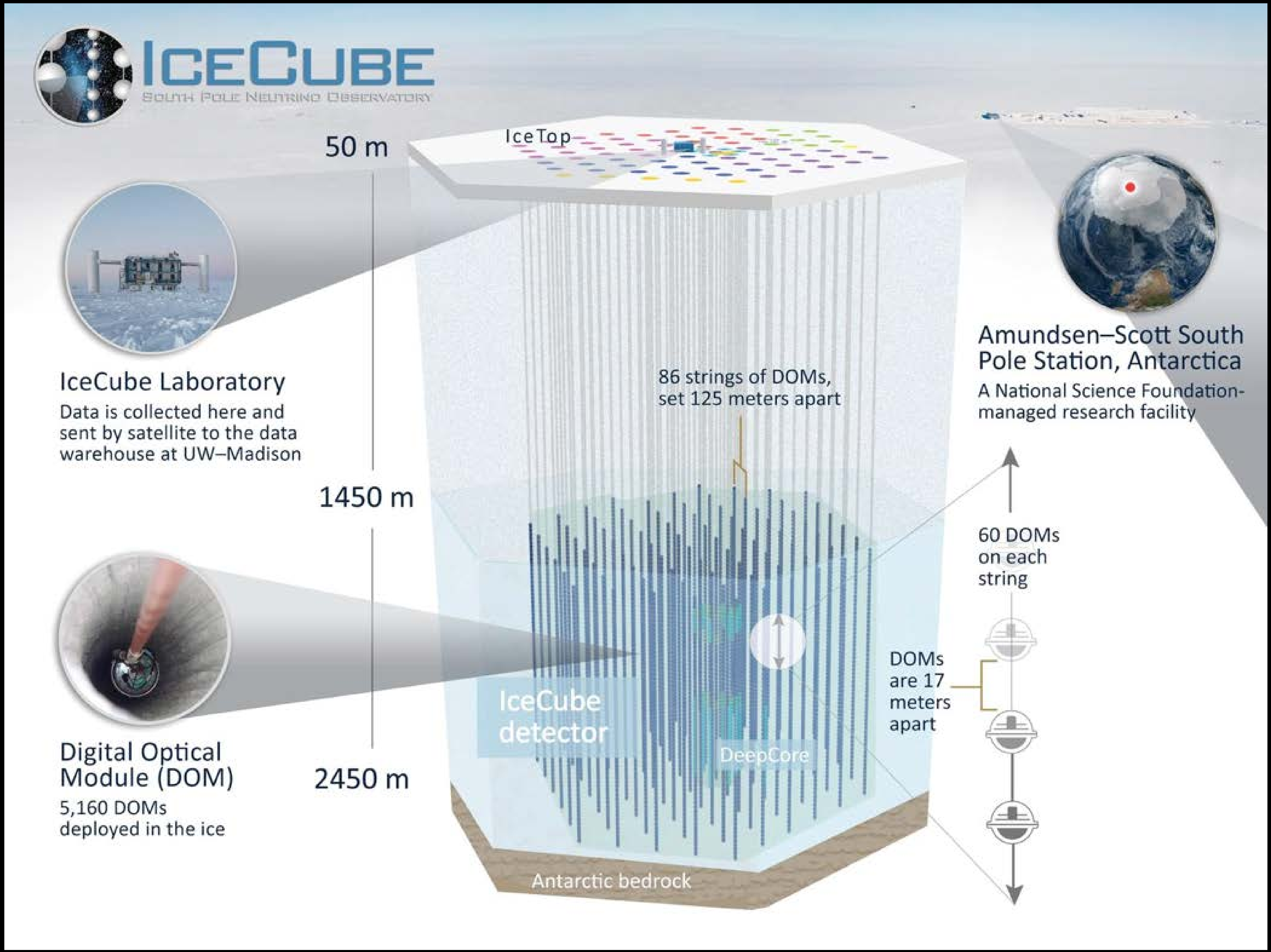
Era of Multimessenger Astrophysics!



A source of cosmic-ray acceleration has been identified

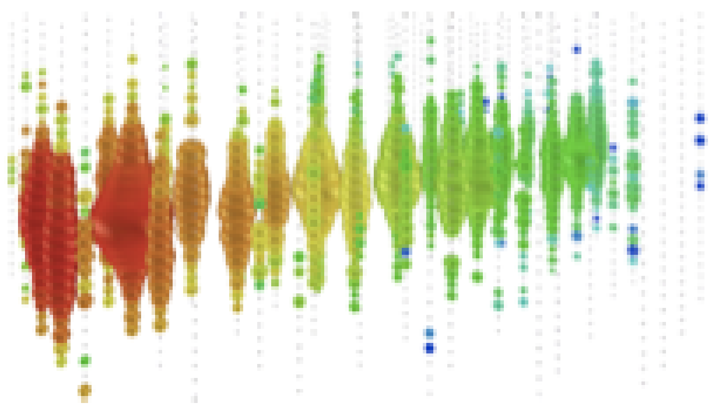
Fermi serves as a bridge between electromagnetic observations and the new messengers: Neutrinos and gravitational waves

Thank you

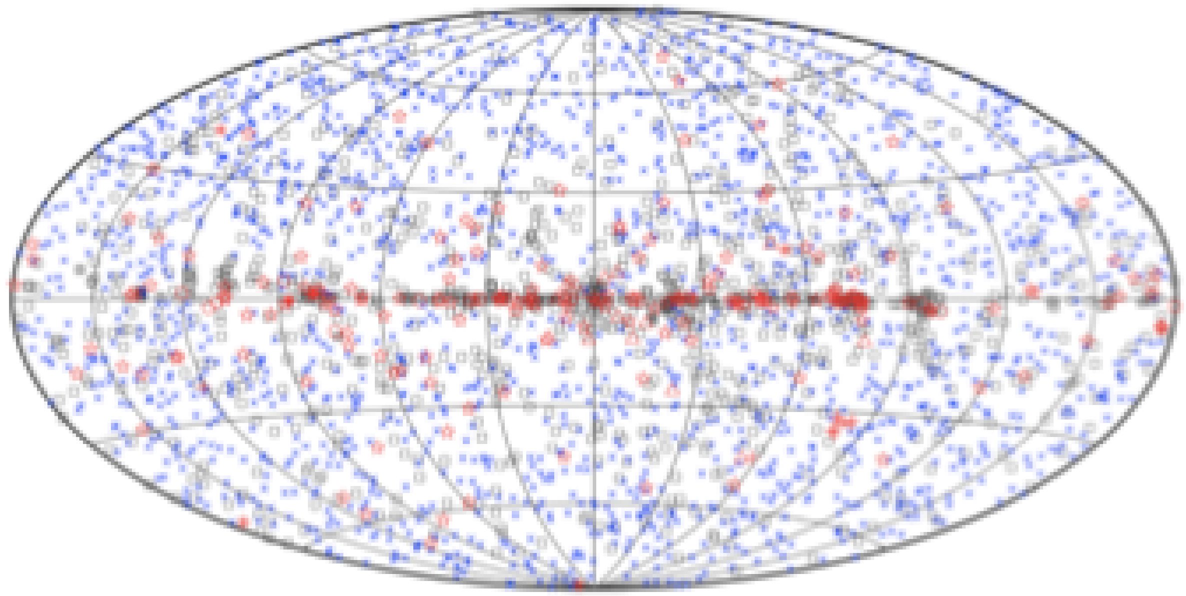


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart

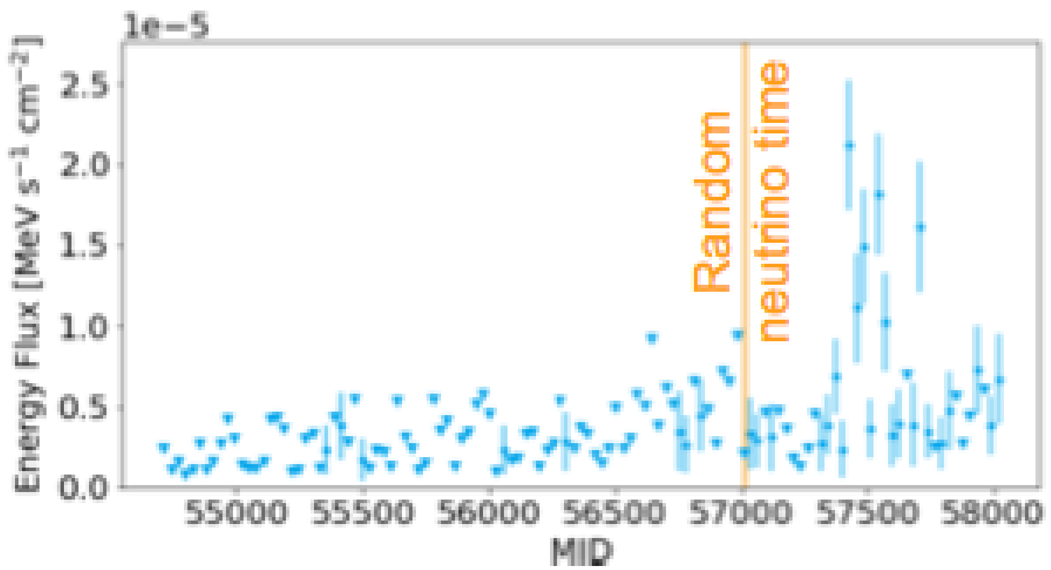
How Likely is it a Chance Probability?



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



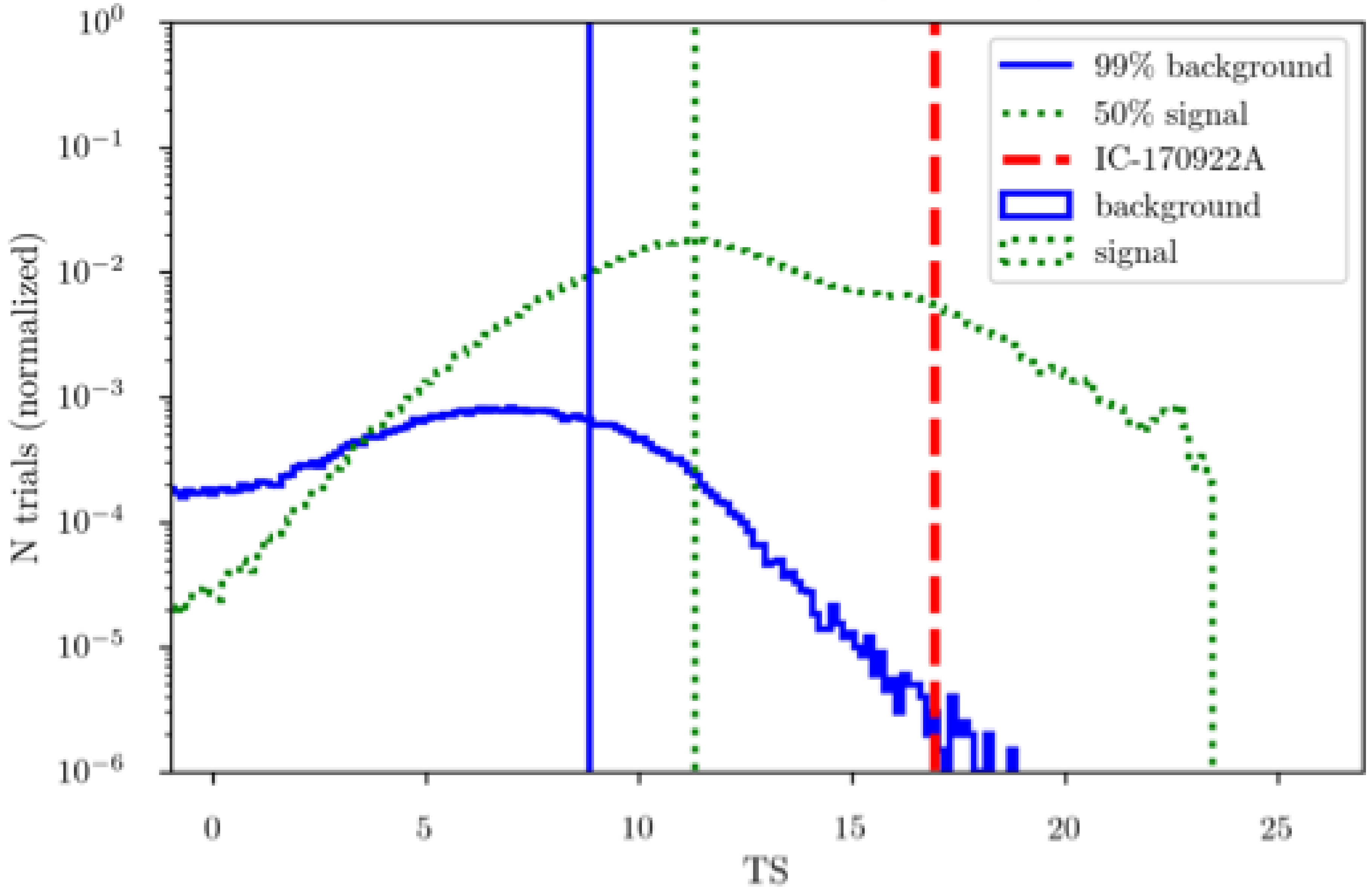
Step II: Are there any extra-galactic Fermi sources close in space to the neutrinos?



Step III: What is the gamma-ray energy flux in the time bin when the neutrino arrives?

How Likely is it a Chance Probability?

$$TS = 2\log\frac{\mathcal{L}(n_s=1)}{\mathcal{L}(n_s=0)} = 2\log\frac{\mathcal{S}}{\mathcal{B}}$$



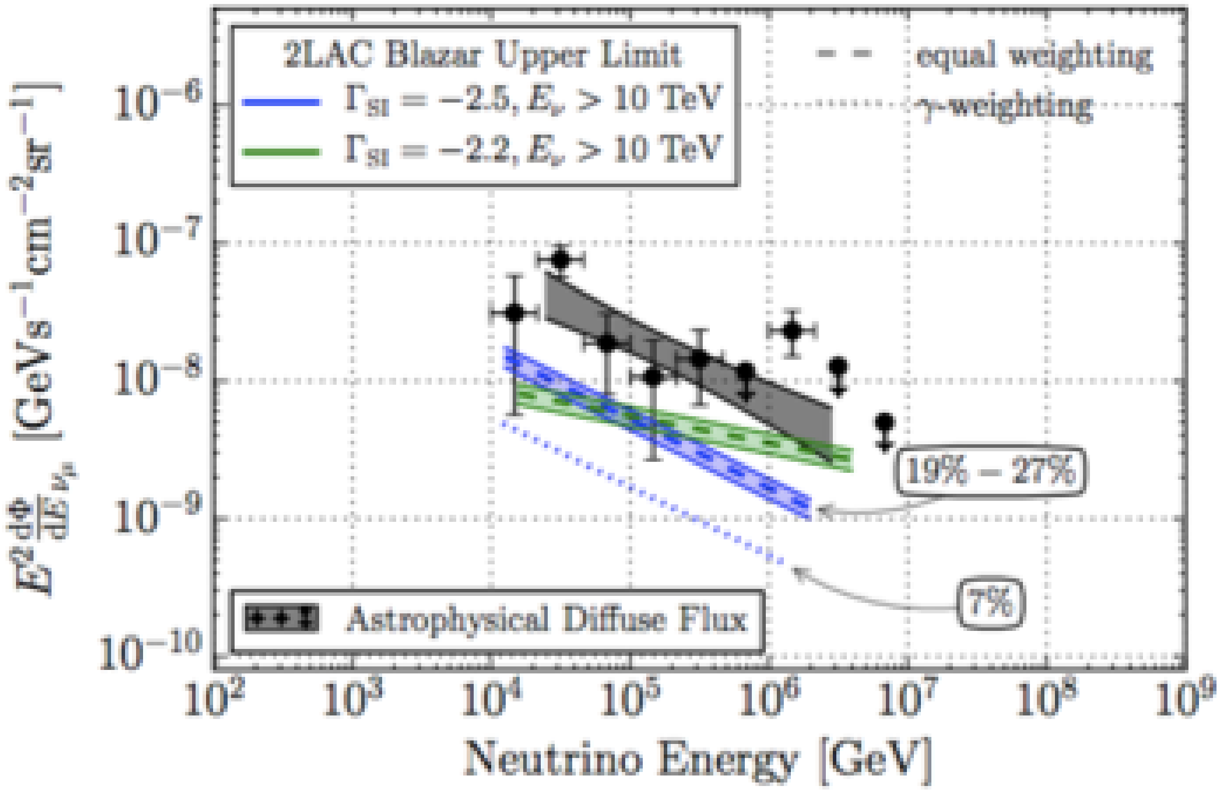
Pre-trials p-value: 4.1σ

Post-trials p-value: 3.0σ

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

How does this compare to stacking limit?

- **Stacking**:
  - Upper limit of 27% of the diffuse flux fit between 10 TeV and 100 TeV with a soft $E^{-2.5}$ spectrum
  - Upper limit of 40% and 80% for an E^{-2} spectrum (compatible with the diffuse flux fit > 200TeV)



- Allowed contribution by blazars as a population is larger, because it would include the contribution of unresolved blazars
- Averaged over 9.5 years, the neutrino flux of TXS 0506+056 by itself corresponds to 1% of the astrophysical diffuse flux, and is fully compatible with the blazar catalog stacking results