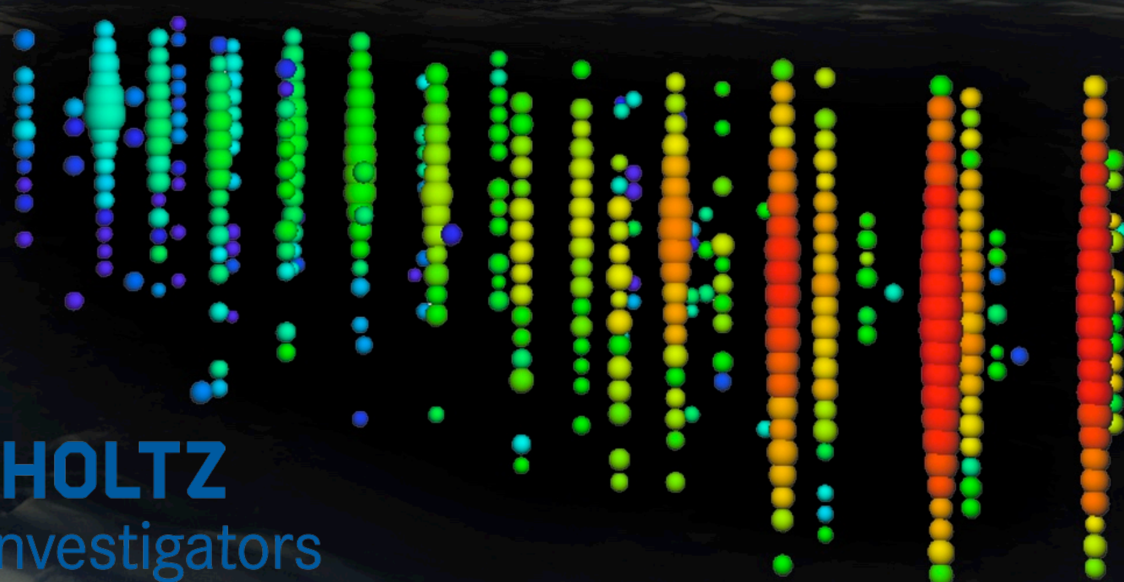
Multi-messenger Astronomy with high-energy Neutrinos

Anna Franckowiak for the
IceCube Collaboration

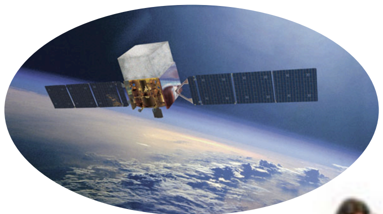


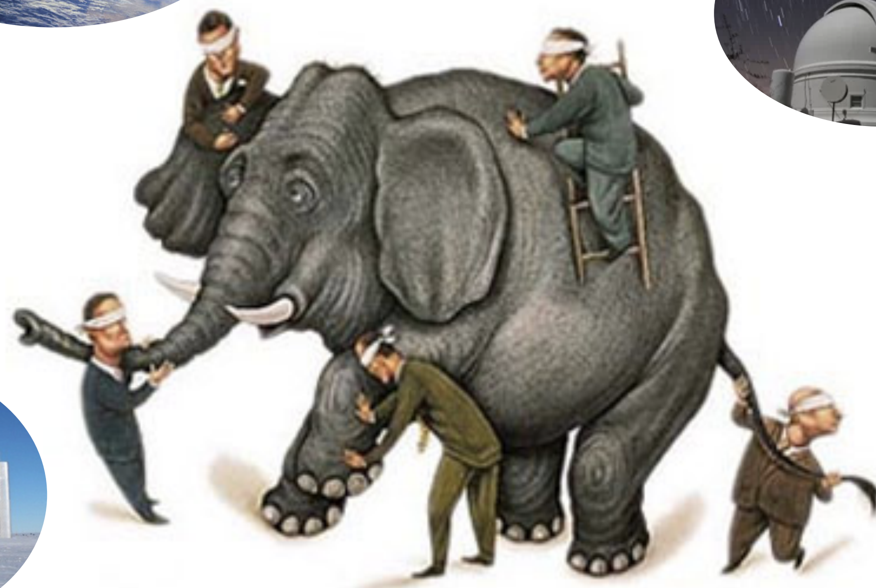
HELMHOLTZ
Young Investigators

DESY.

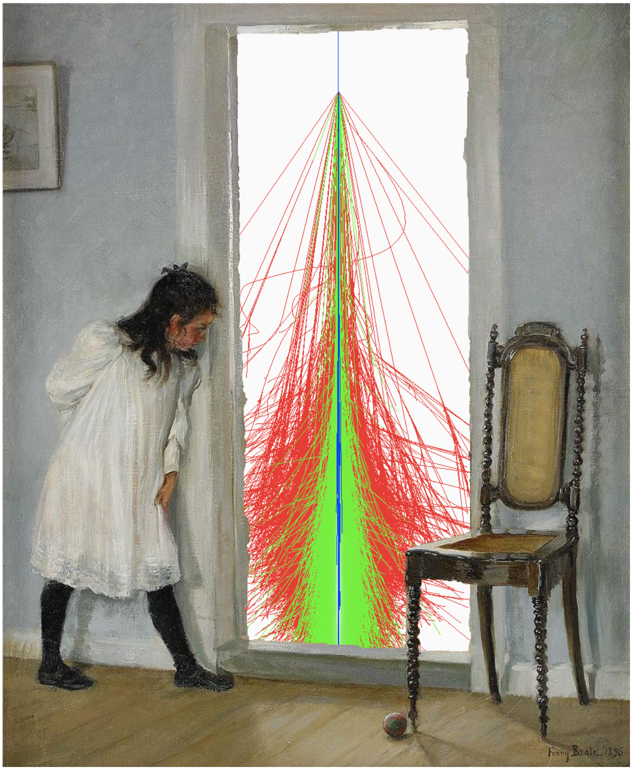
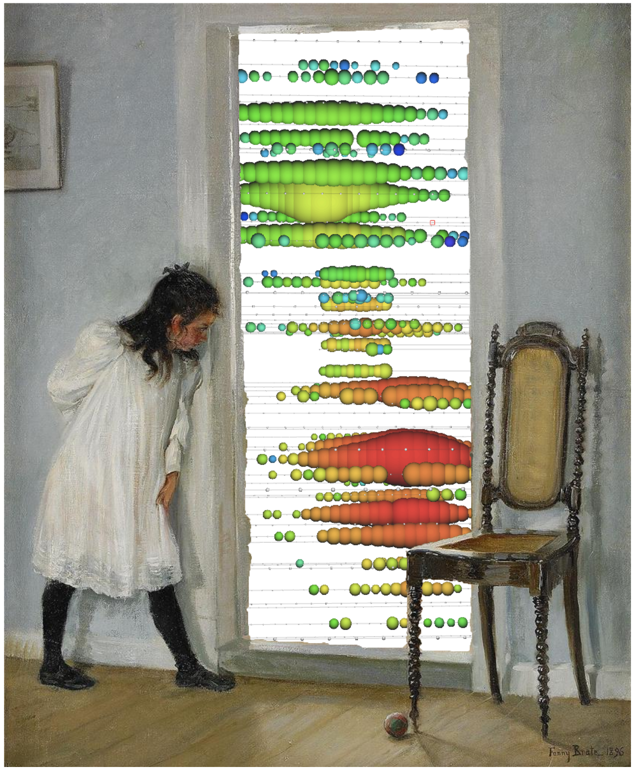
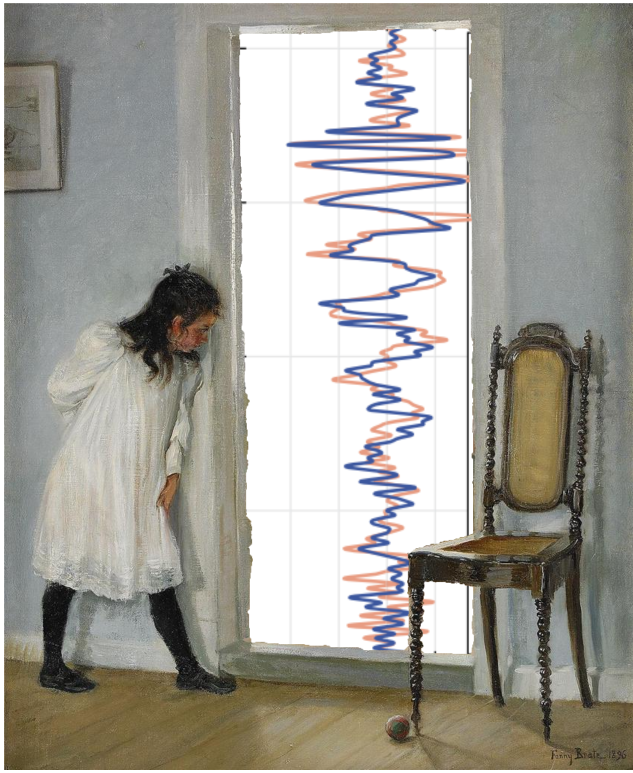
“Invisibles18 Workshop” Karlsruhe, September 4, 2018

The Multi-Messenger Picture

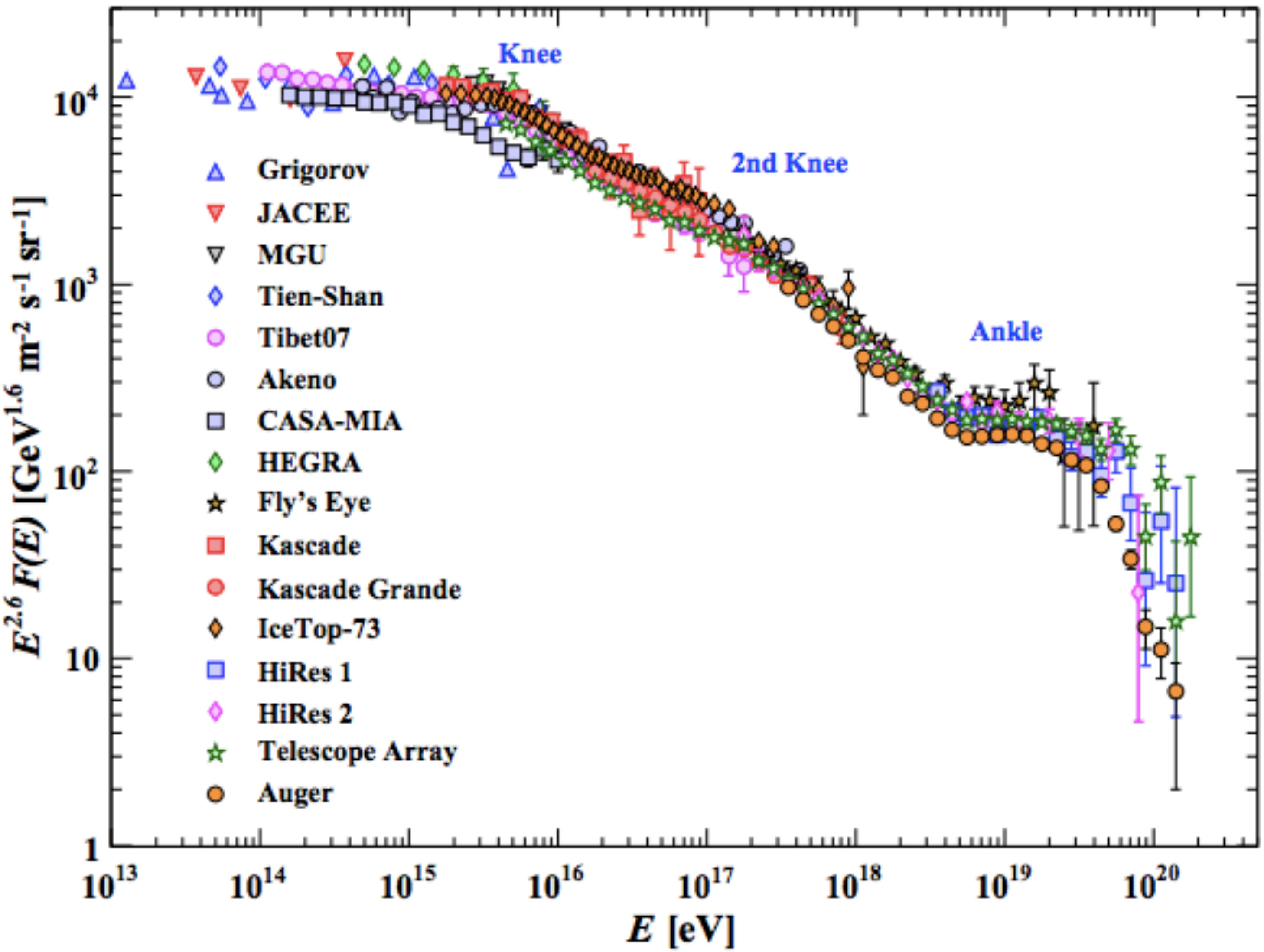




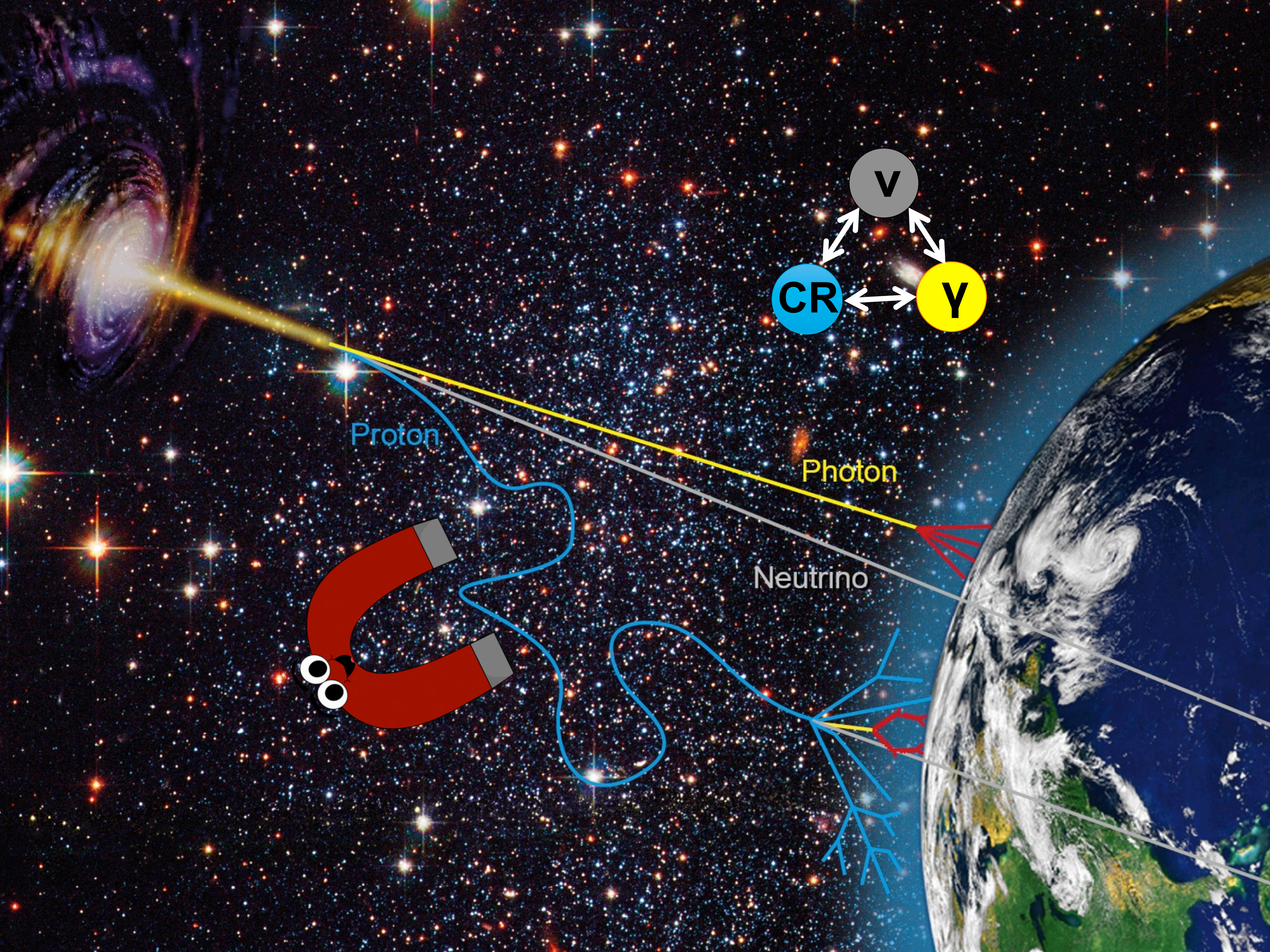
New Windows to the Universe

Cosmic rays reach 10^{20}eV



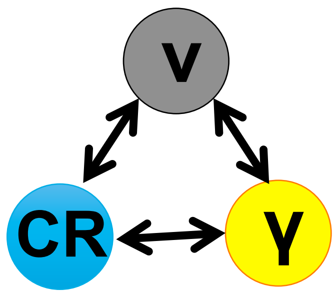
M. Tanabashi et al. (Particle Data Group), PRD 98, 2018


ν
CR
γ
Proton
Photon
Neutrino

Neutrino Production Processes

Hadronuclear (e.g. star burst galaxies and galaxy clusters)

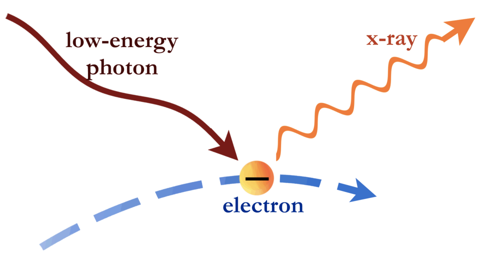
$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\, \gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e\, \nu_\mu\, \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e\, \bar{\nu}_\mu\, \nu_\mu \end{cases}$$

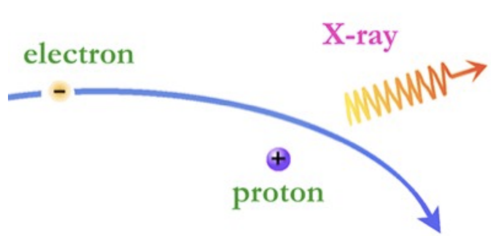


Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\, \pi^0 \rightarrow p\, \gamma\, \gamma \\ n\, \pi^+ \rightarrow n\, \mu^+ \nu_\mu \rightarrow n\, e^+ \nu_e\, \bar{\nu}_\mu\, \nu_\mu \end{cases}$$

Gamma-rays are not exclusively produced in hadronic processes





Neutrino Production Processes

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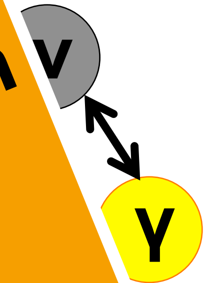
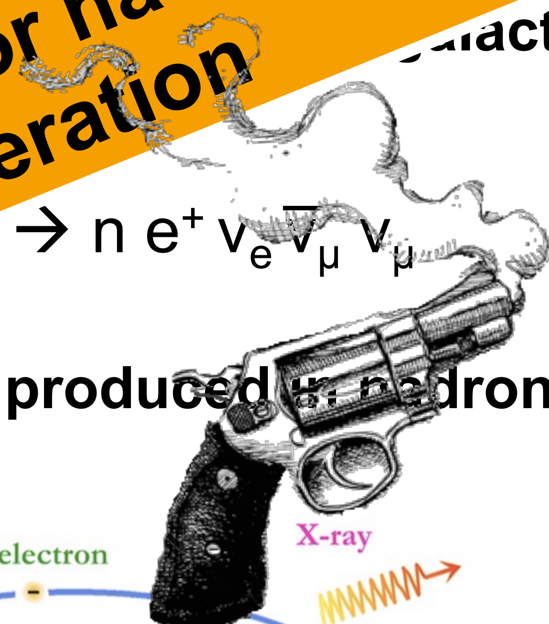


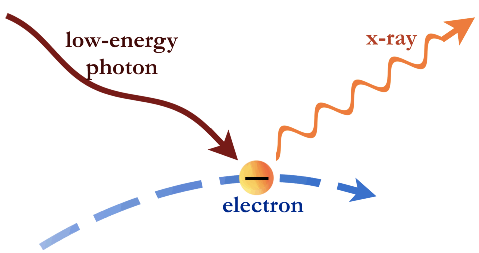
Neutrinos are the smoking gun signature for hadronic acceleration

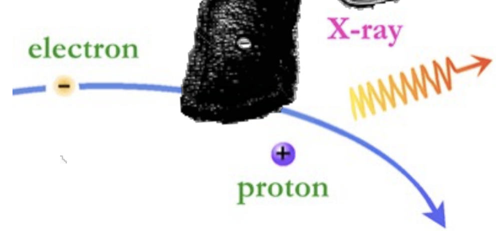
Photohadronic (e ... alactic nuclei)

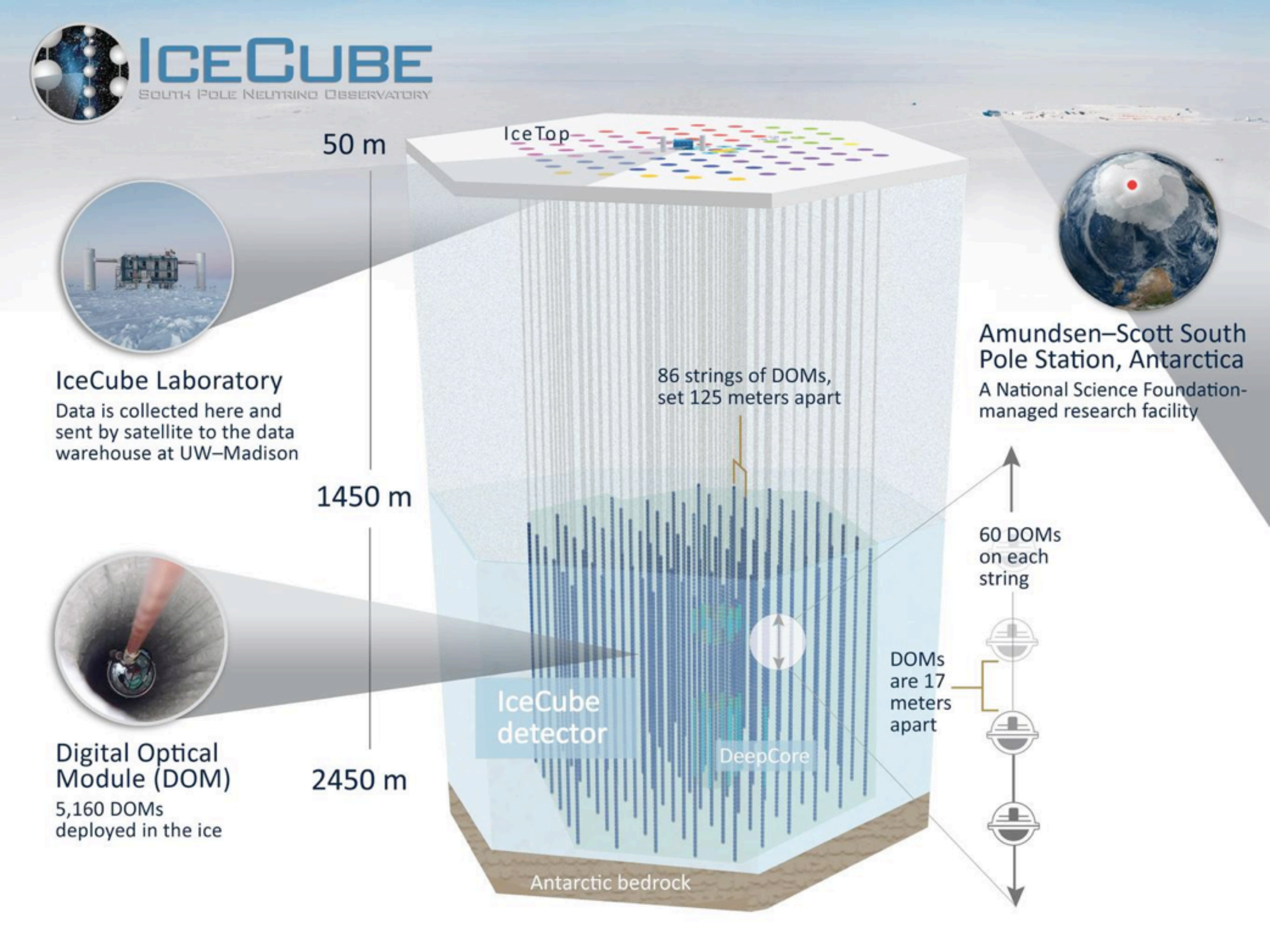
$$p\gamma \rightarrow \ldots \nu_\mu \rightarrow n\, e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$



Gamma-ray ... not exclusively produced in hadronic processes

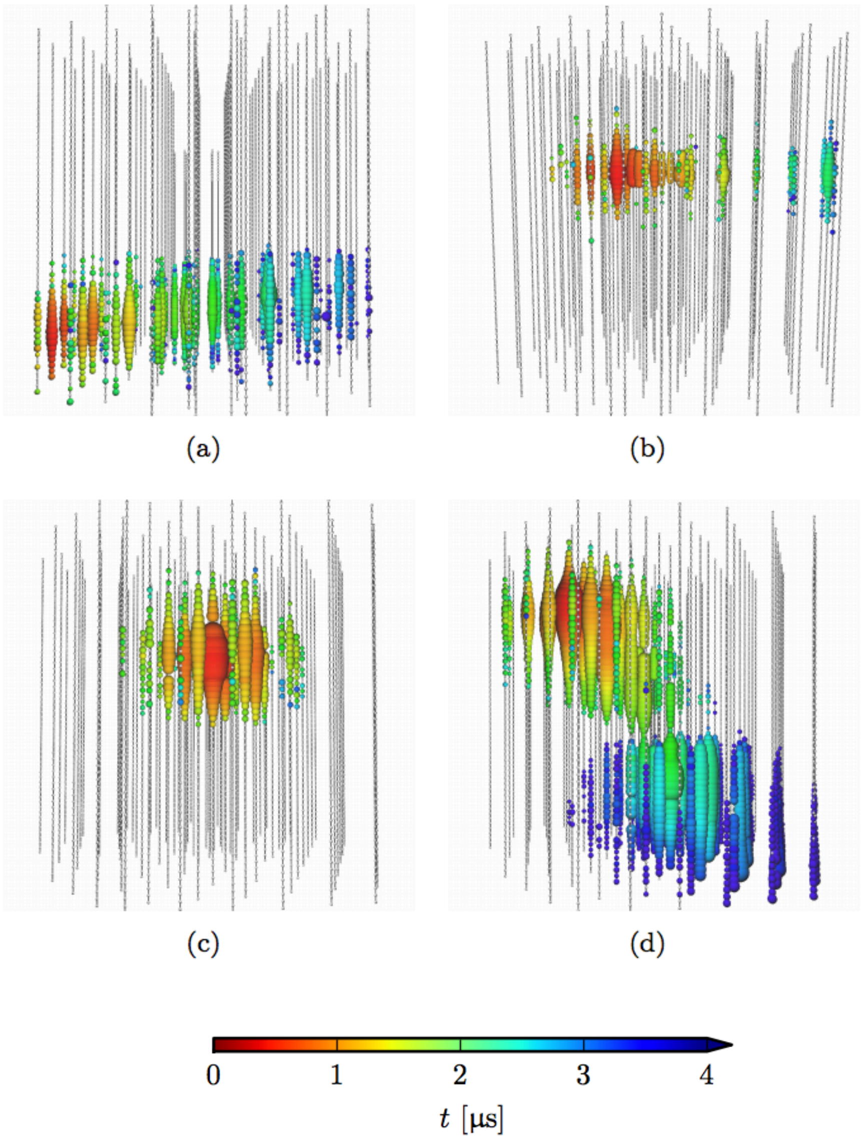






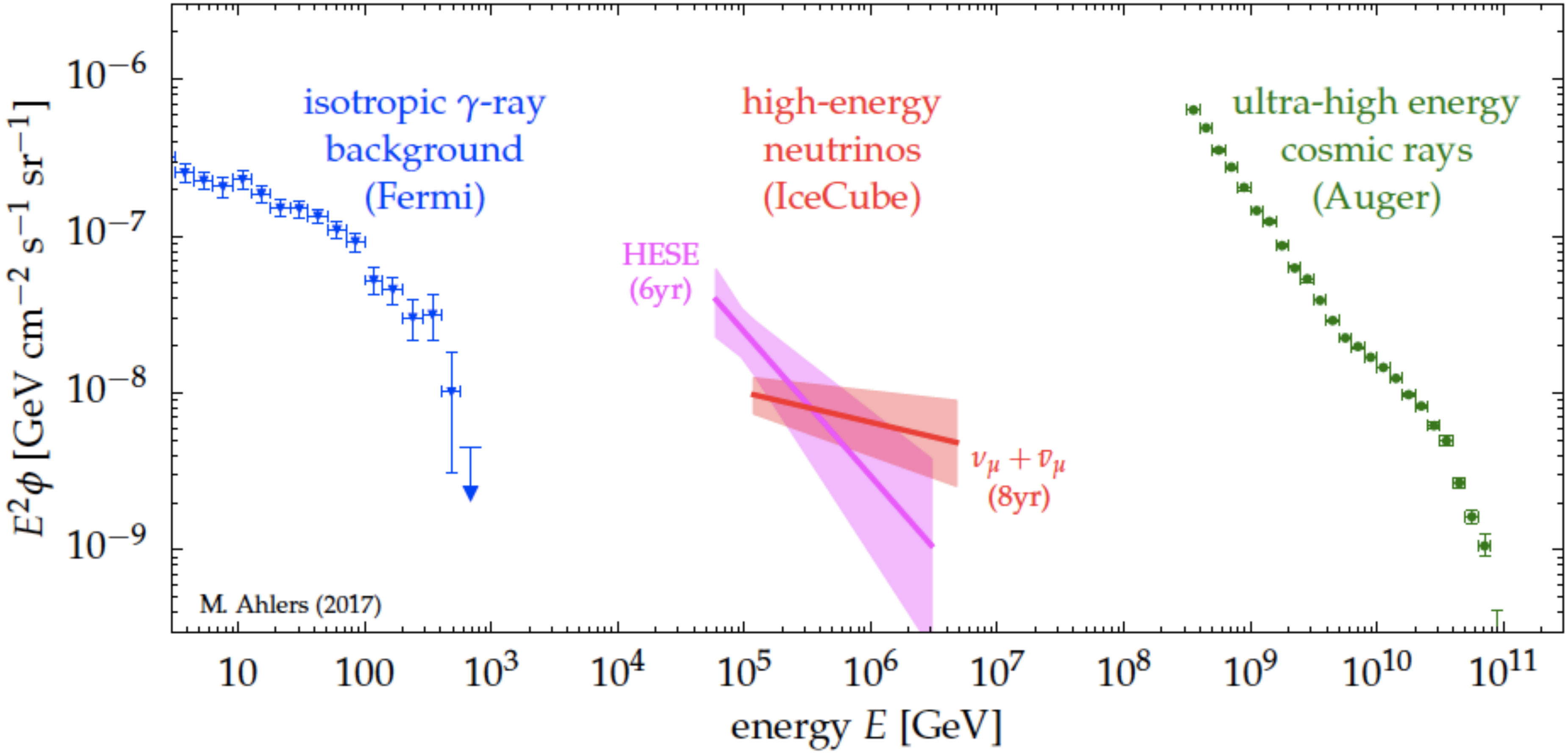
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic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

Event Signatures



a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV
c) Shower event E ~ 1 PeV
d) “double bang” event E ~ 200 PeV

Diffuse Neutrino Flux detected!



Similar energies in gamma rays, neutrinos & cosmic rays injected into our Universe!

Flavor composition: what do we expect?

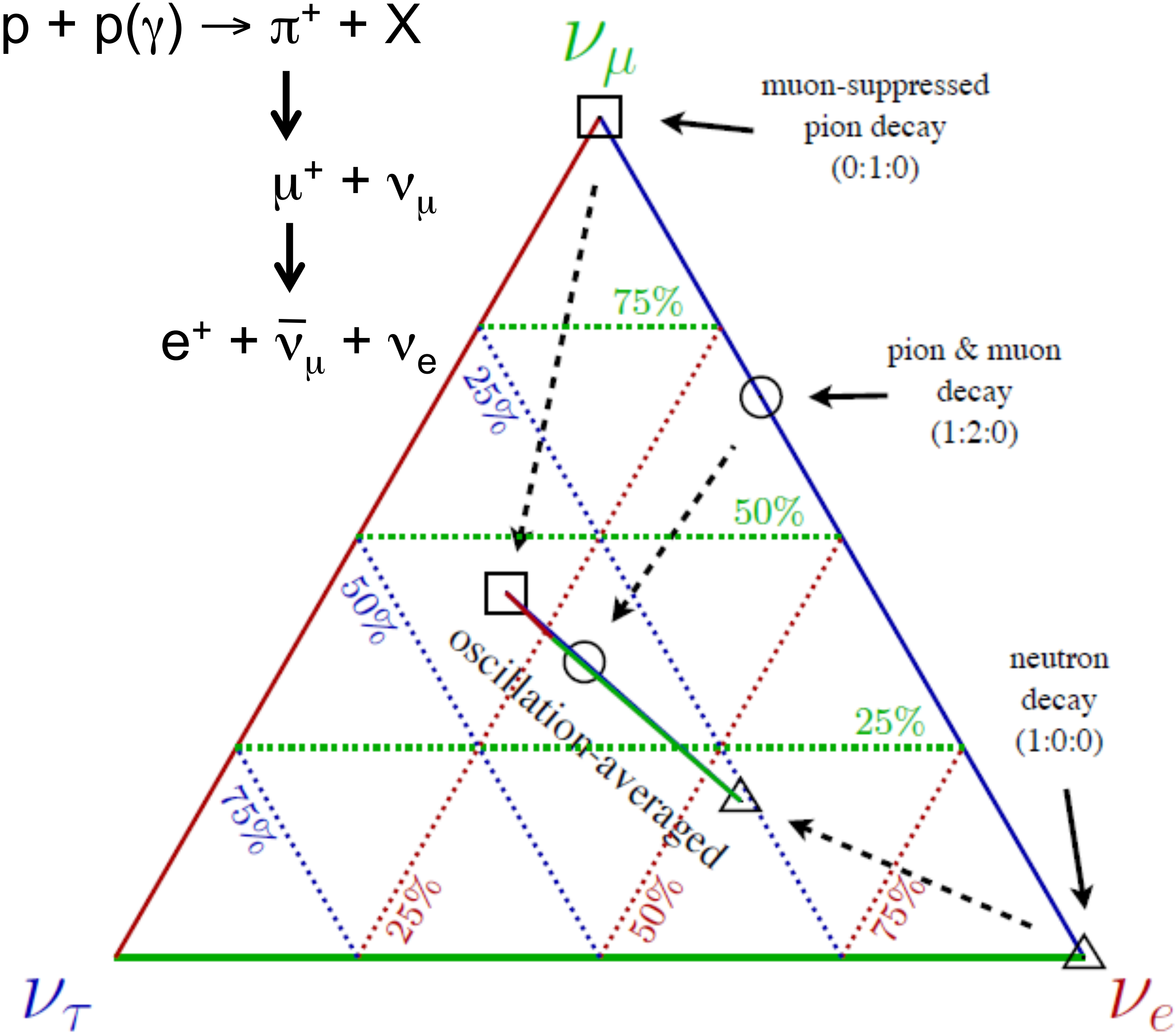
$p + p(\gamma) \rightarrow \pi^+ + X$

$\downarrow$

$\mu^+ + \nu_\mu$

$\downarrow$

$e^+ + \bar{\nu}_\mu + \nu_e$

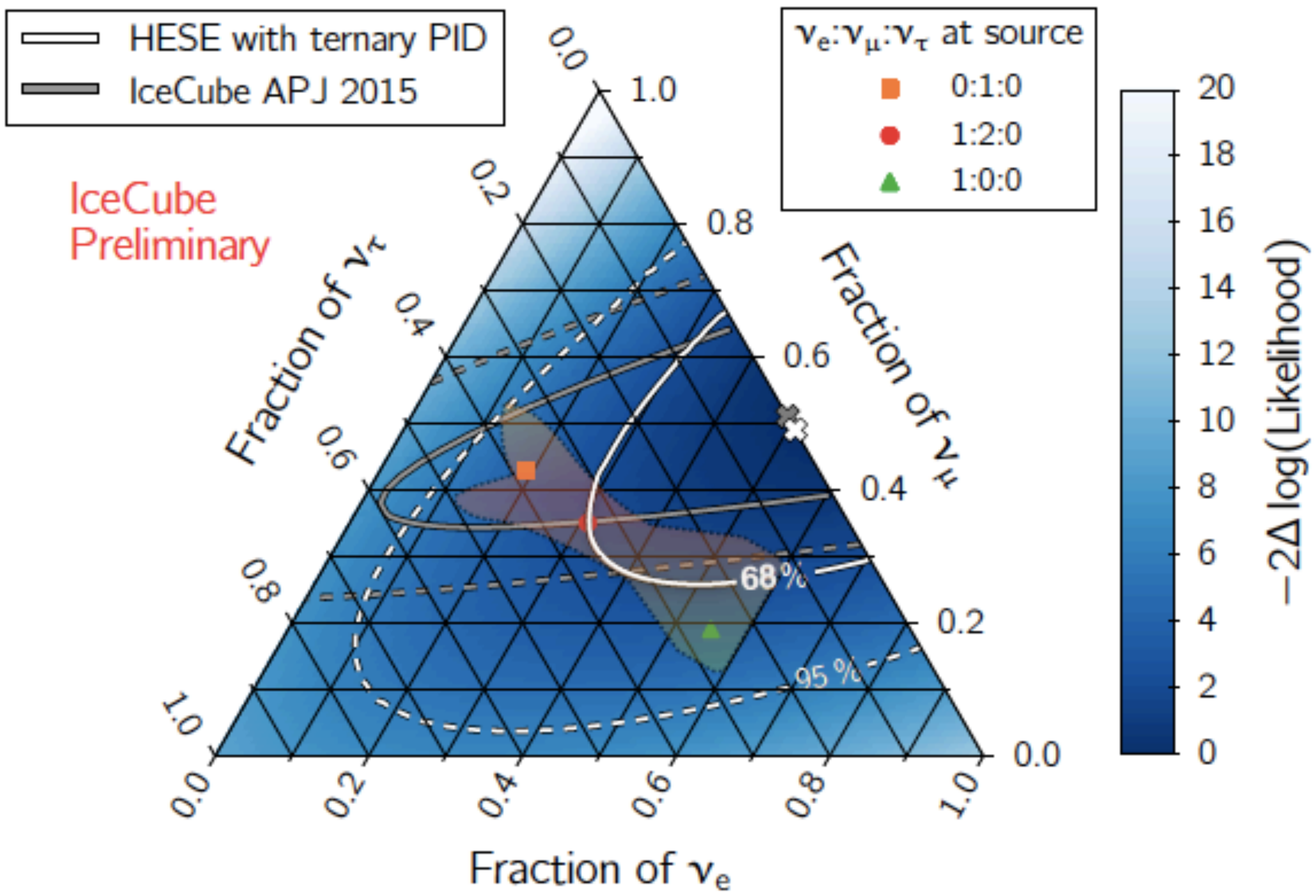


Muon loses energy before it decays due to large magnetic fields

"standard" scenario, pion decay

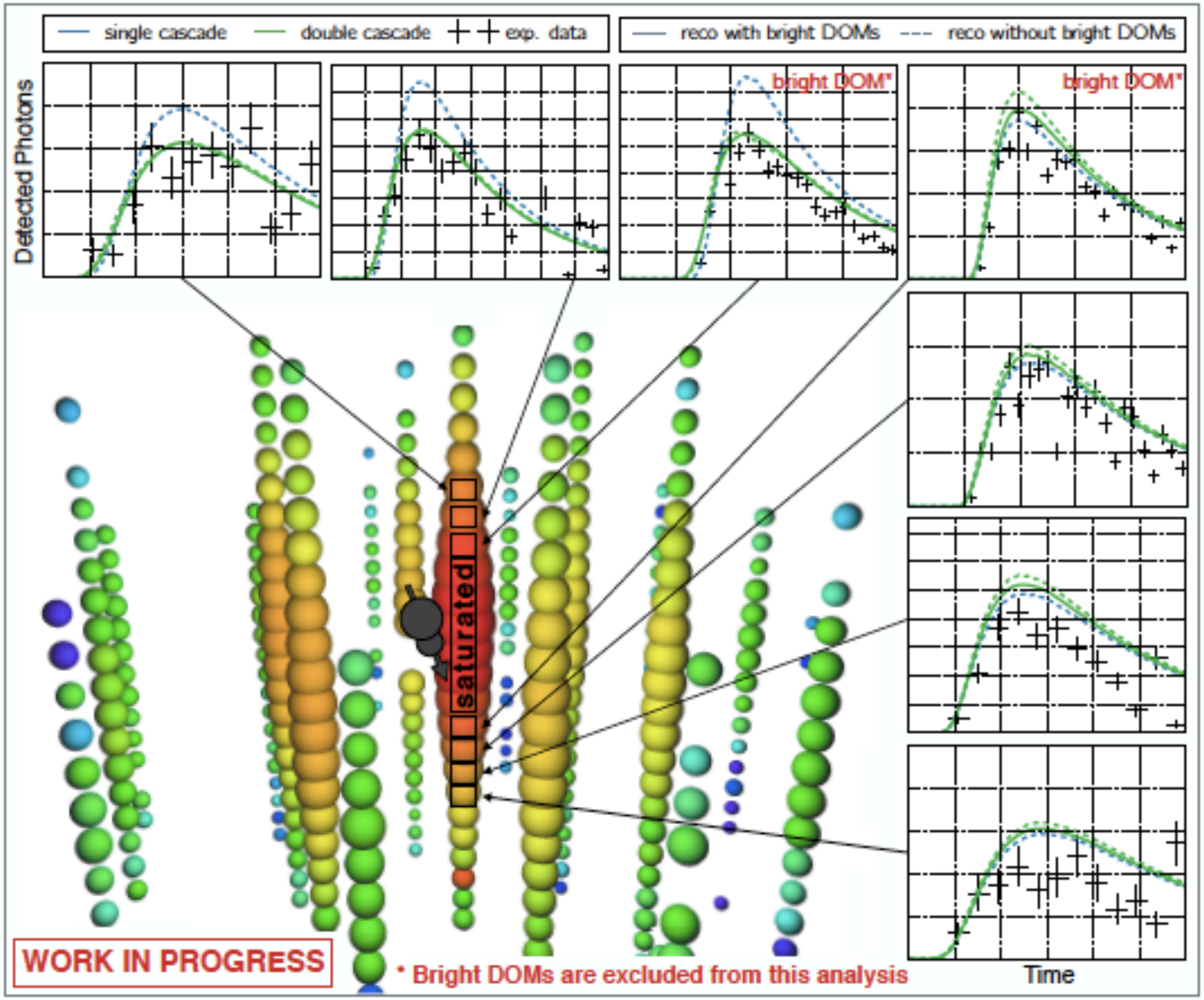
Neutron sources

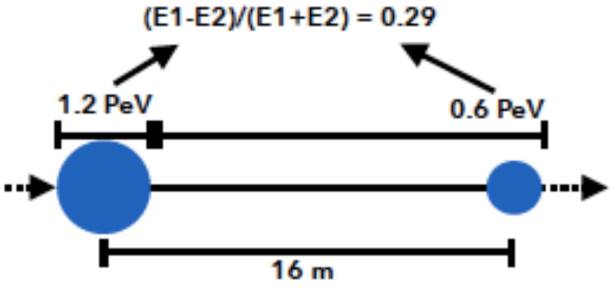
Flavor Ratio



M. Usner, PoS(ICRC2017)974

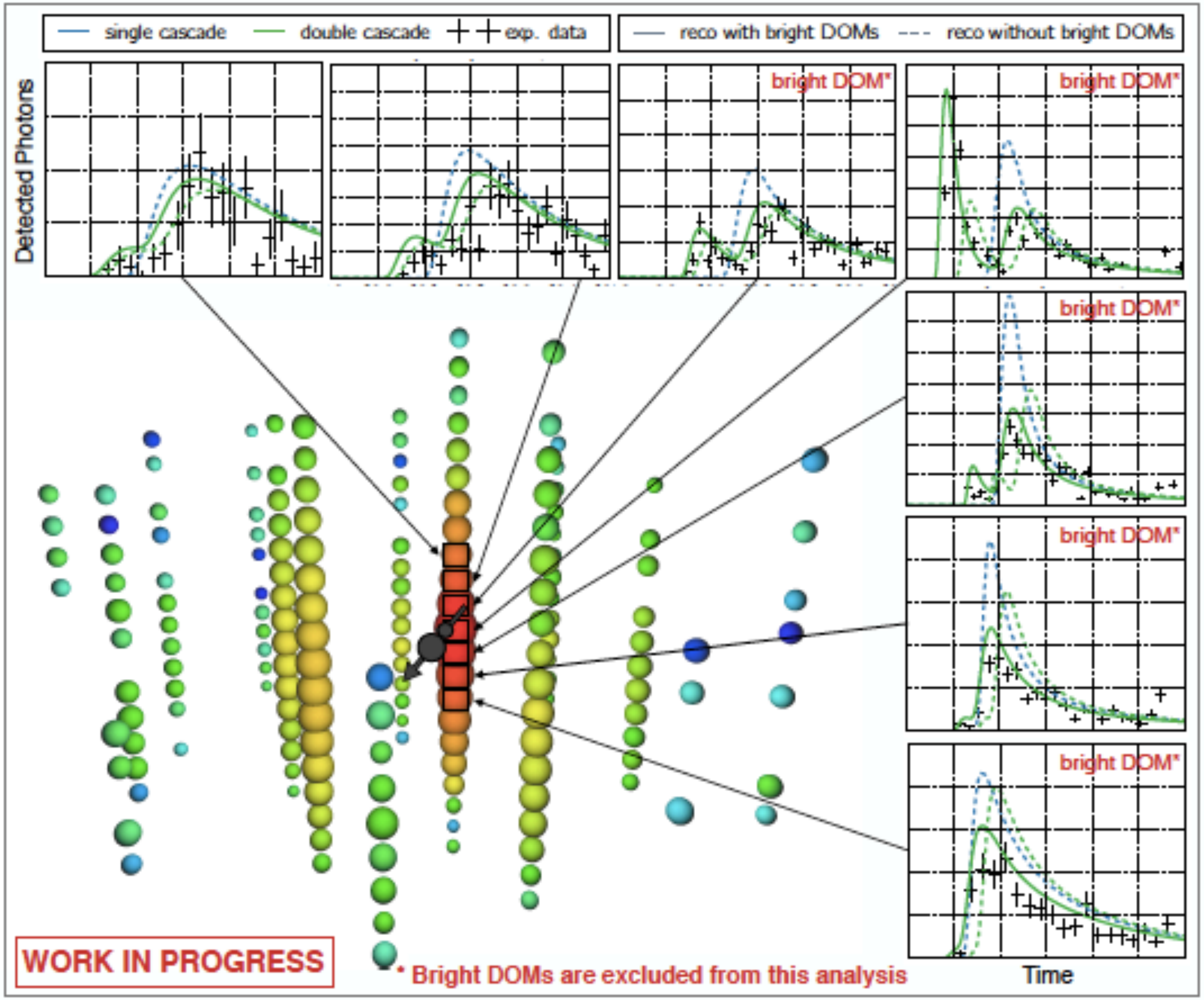
First Tau Neutrino Candidates – Event 1

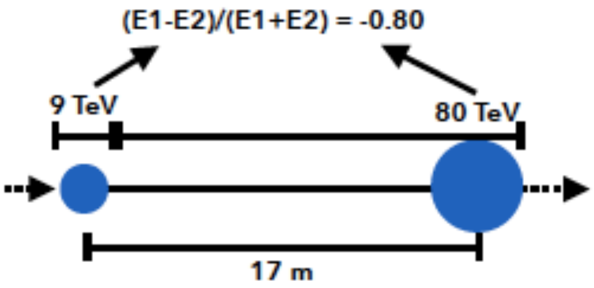




- Observed 2012
- Shows no clear preference between a single cascade and double cascade hypothesis

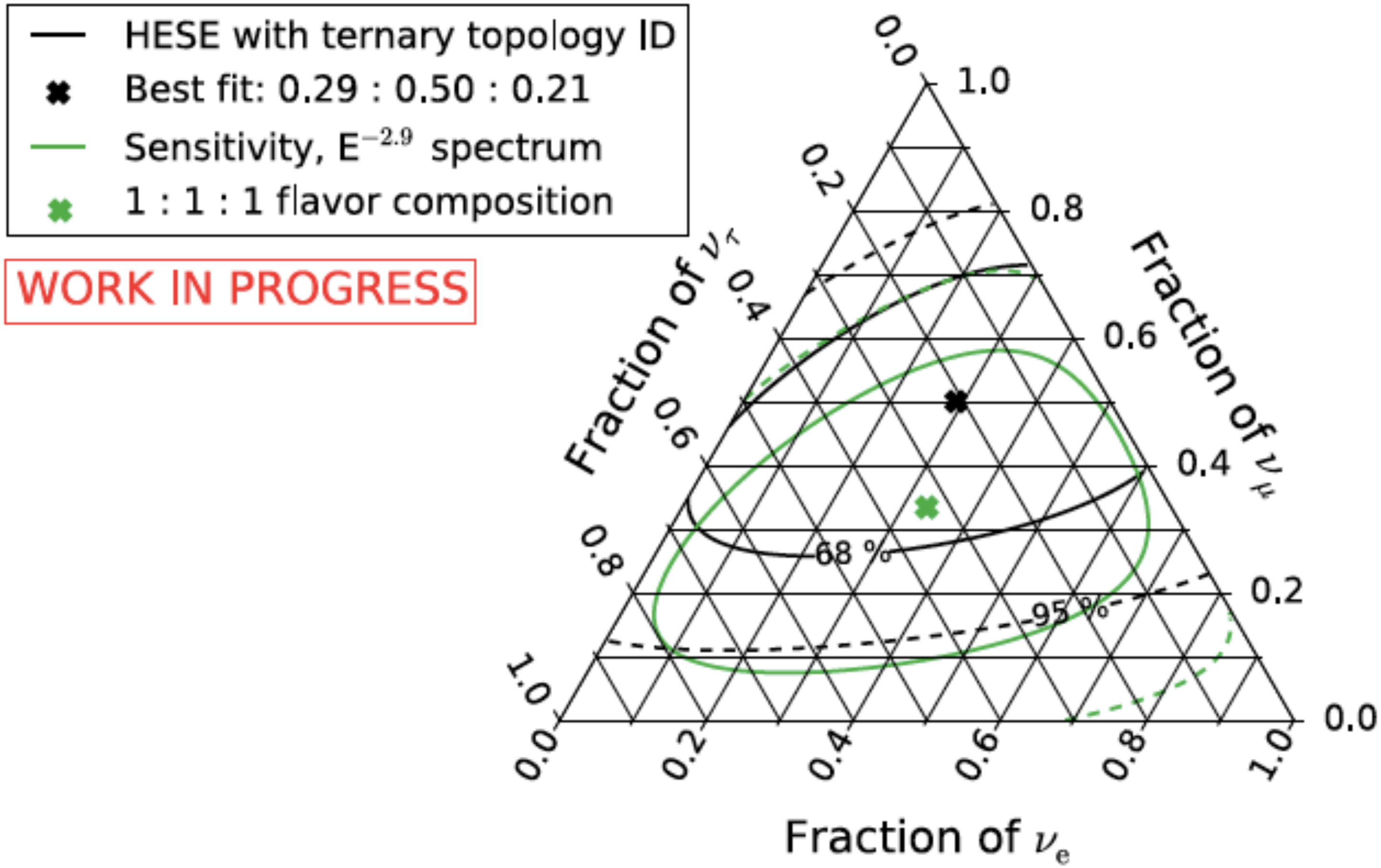
First Tau Neutrino Candidates – Event 2





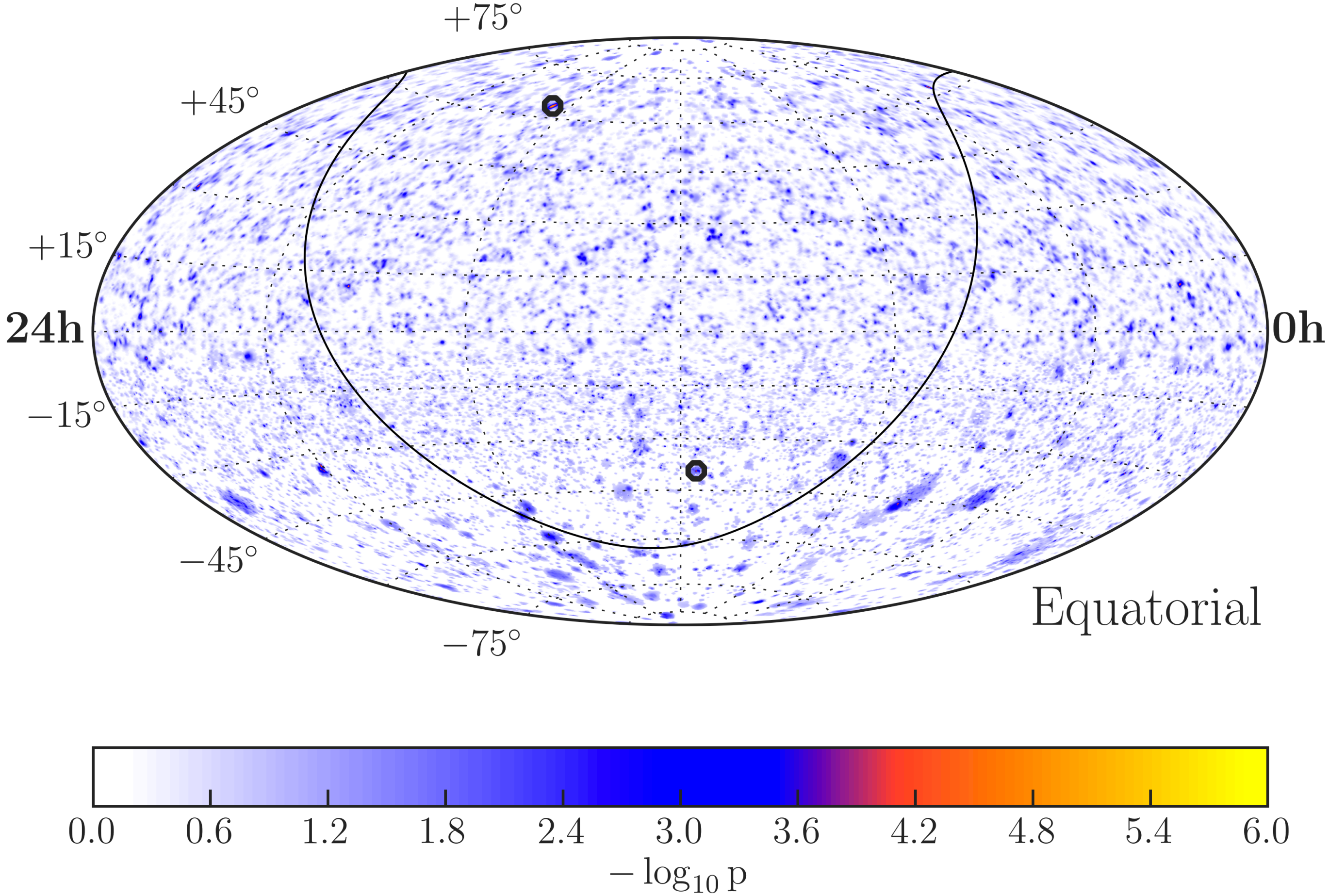
- Observed 2014
- Observed light arrival pattern clearly favors double cascade hypothesis

Flavor Ratio – Update!



Search for Neutrino Point Sources

Search for statistical excess of neutrinos from a direction in the sky



IceCube Coll. ApJ, 835 (2017)

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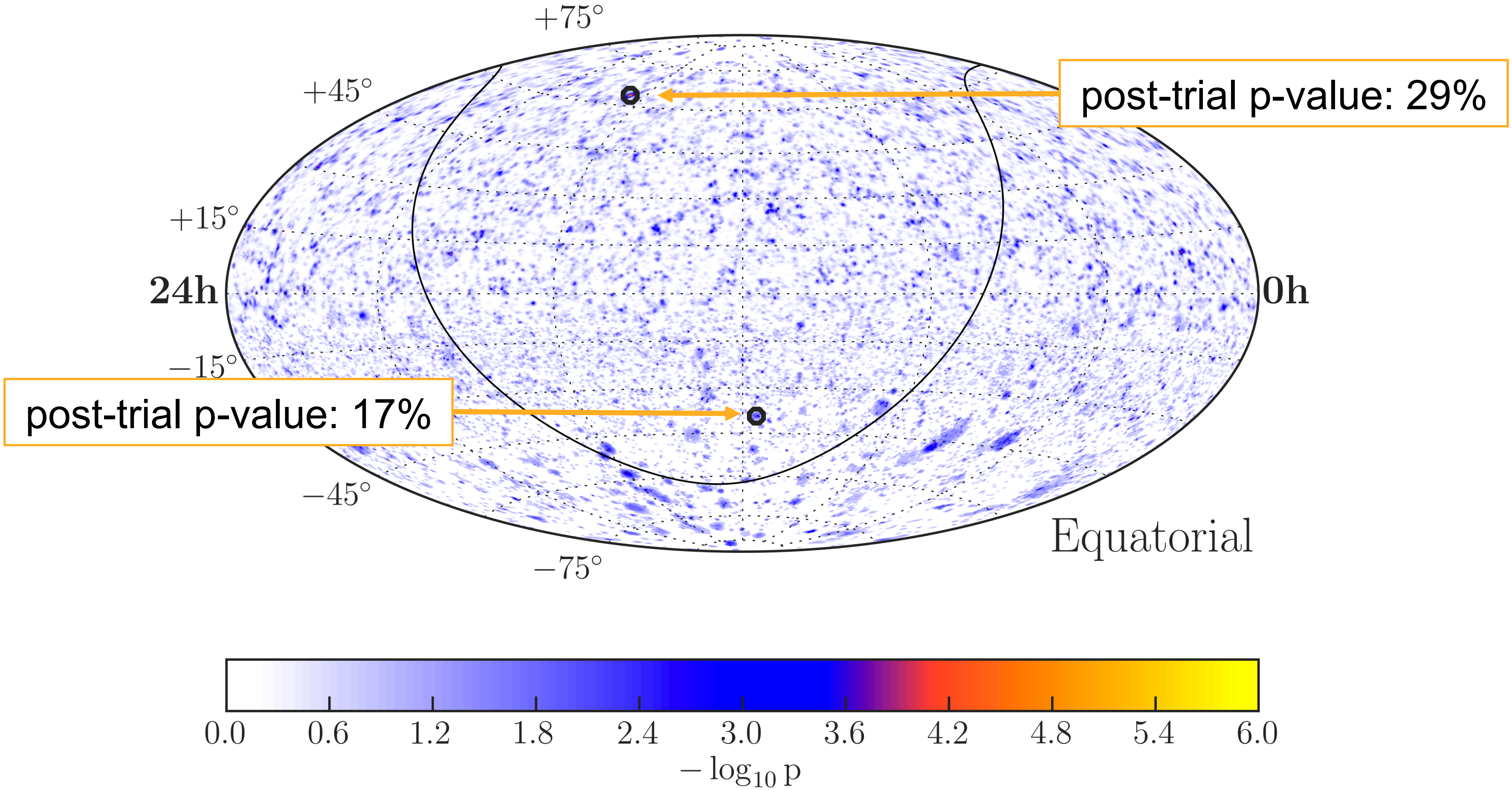

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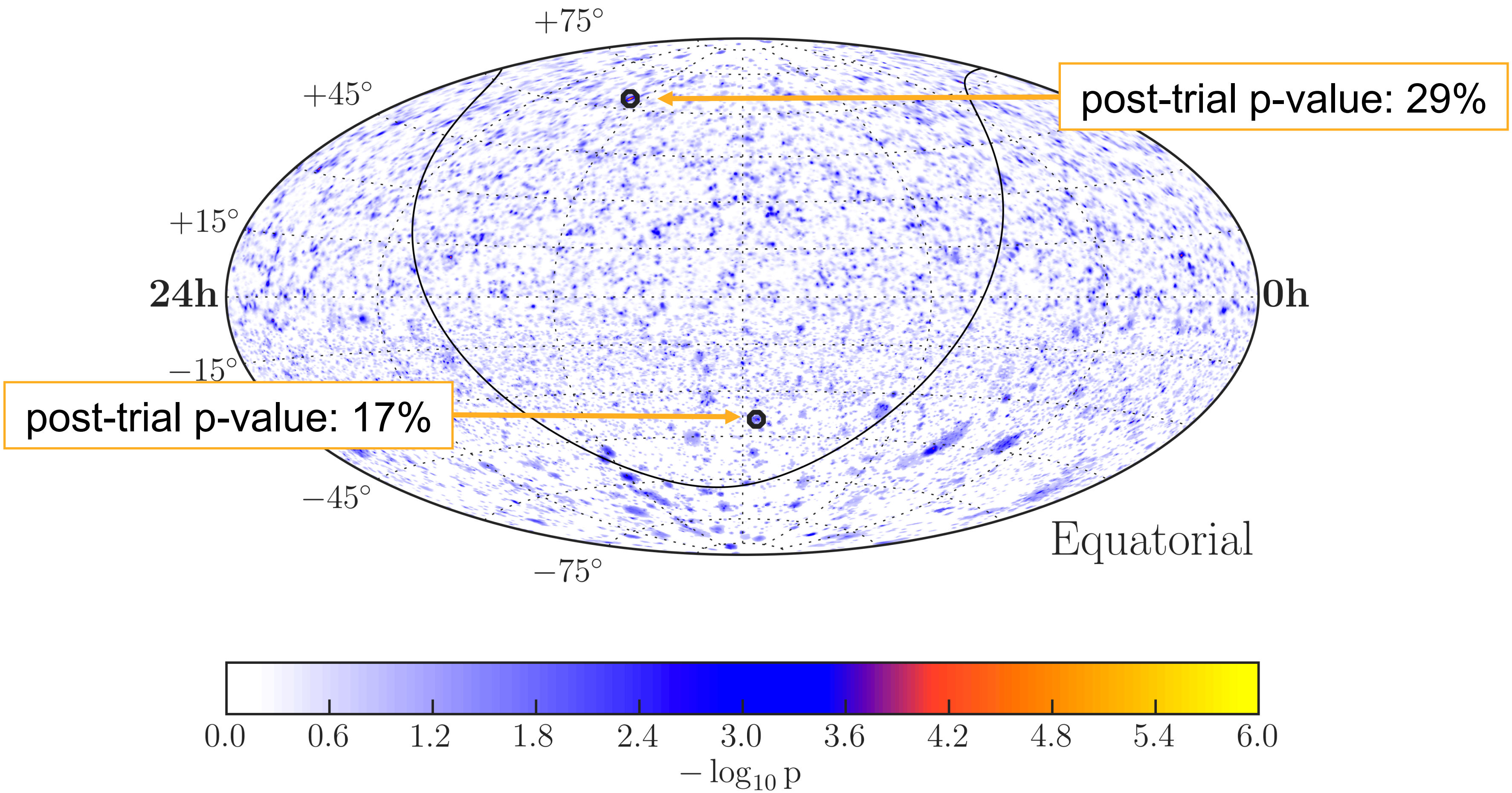
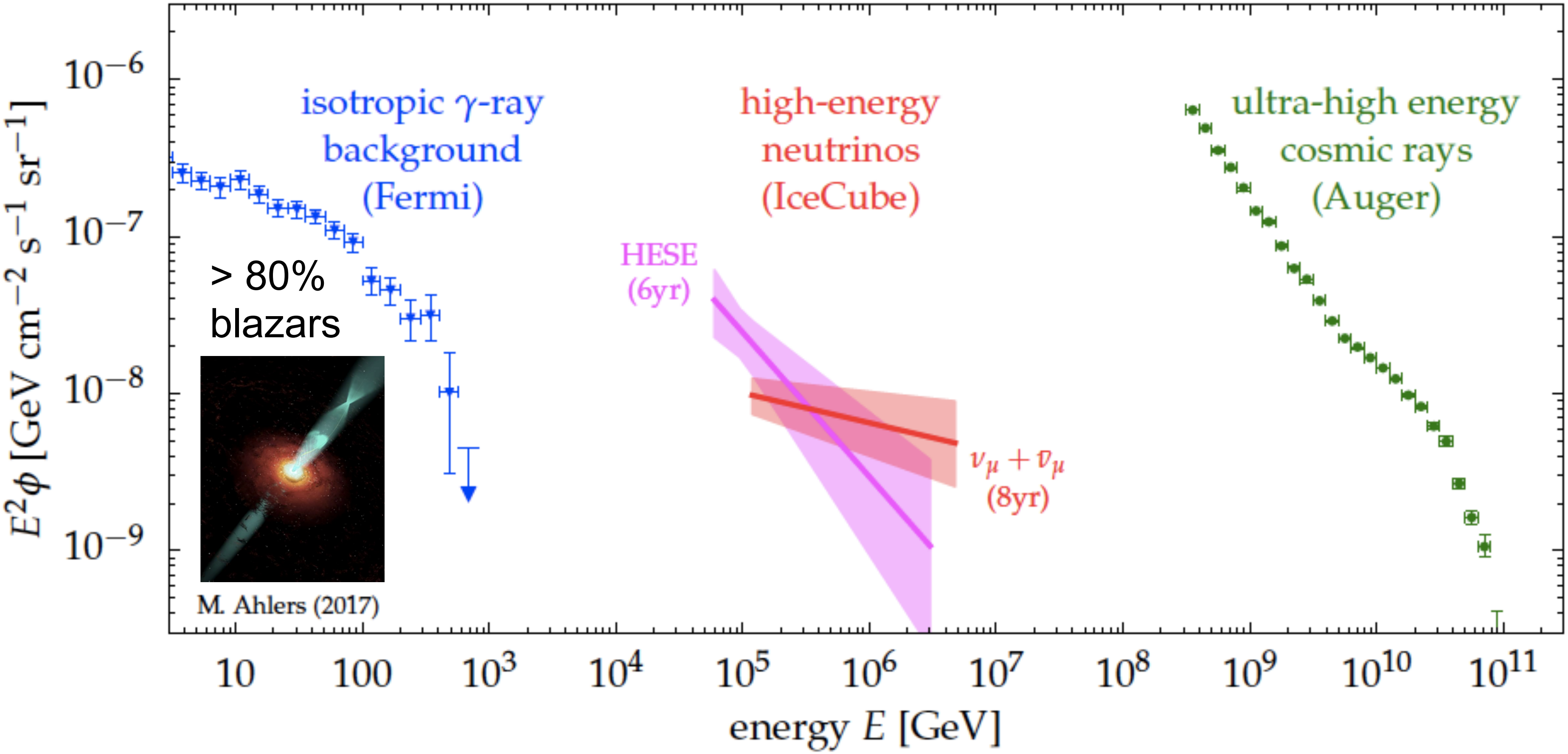
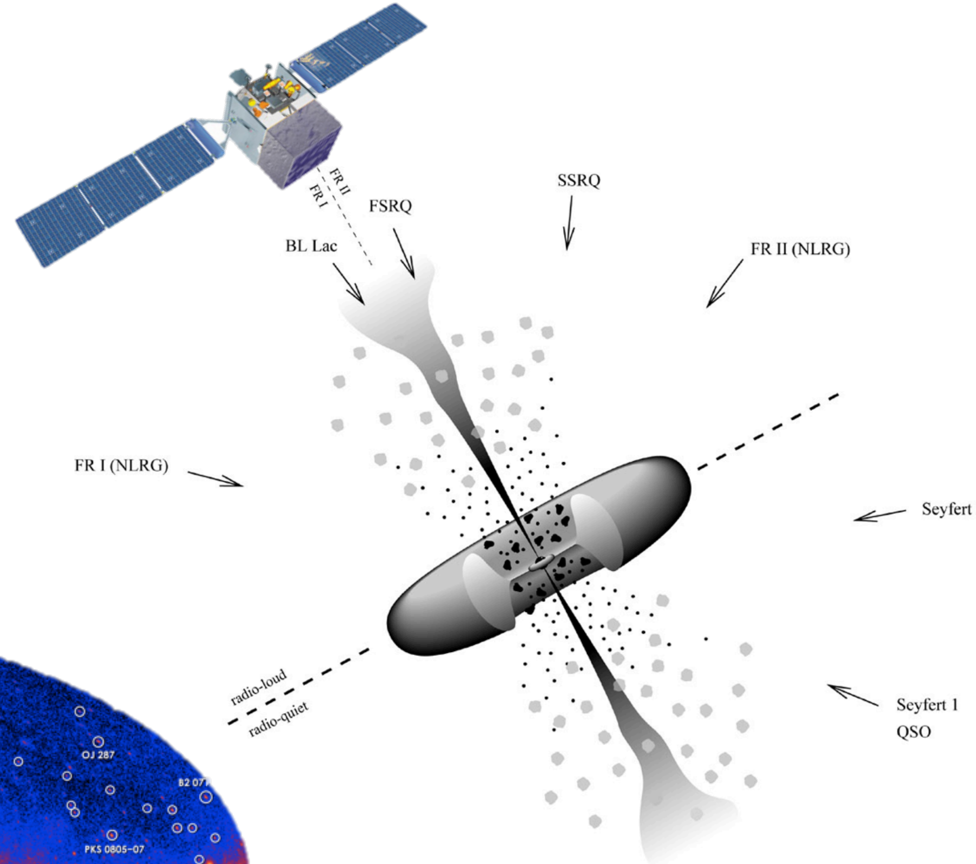


Large trials factor → Multiwavelength data can tell us where and when to look for neutrinos

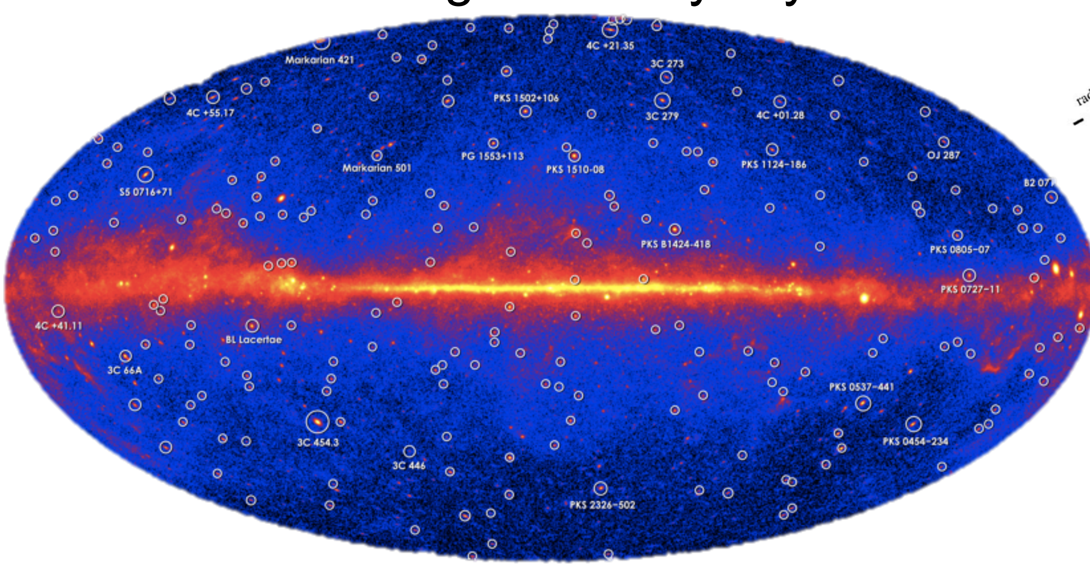
Diffuse Neutrino Flux detected!



Blazars

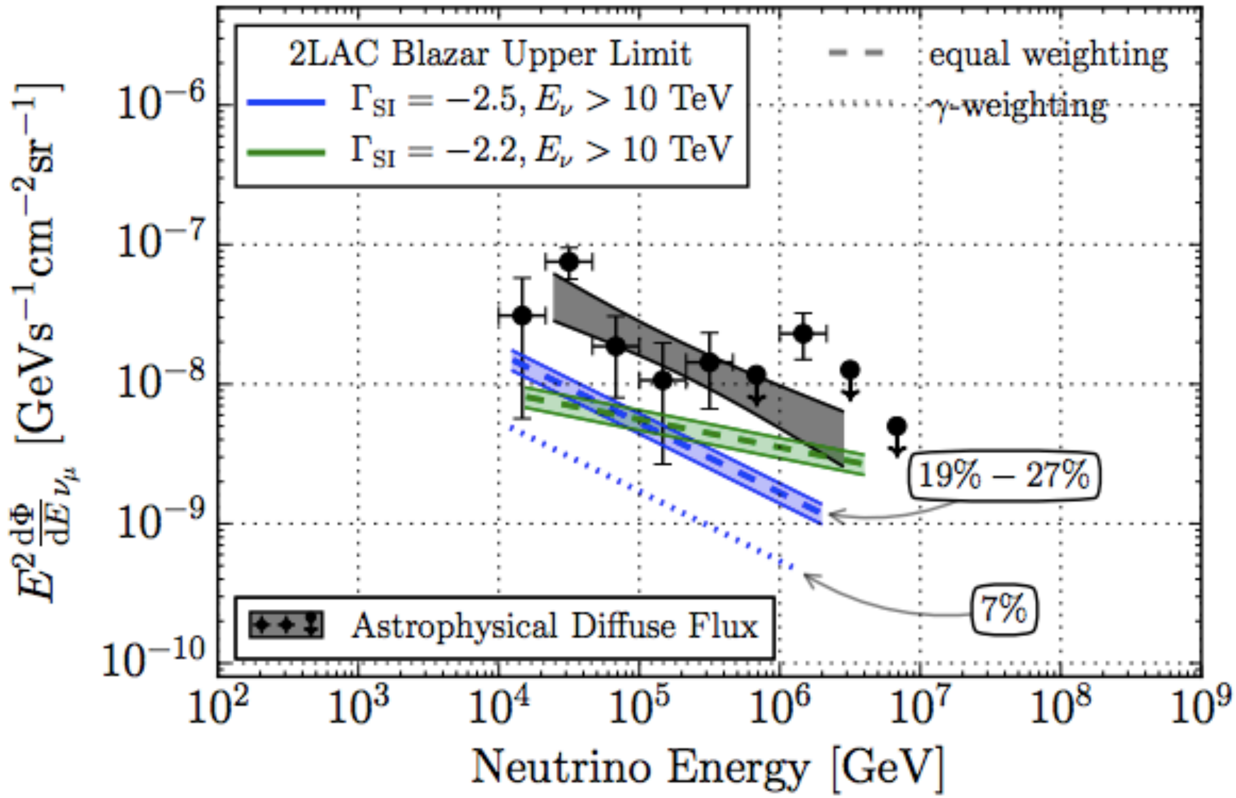


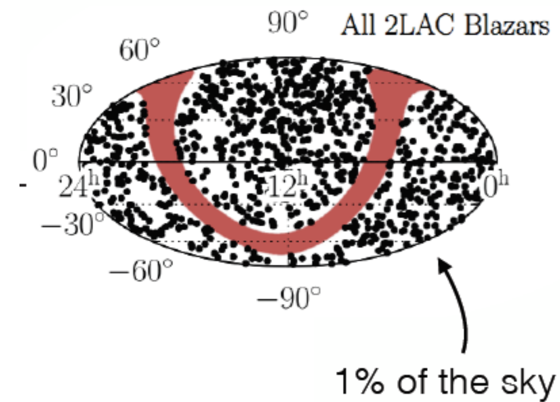
Fermi gamma-ray sky



IceCube Collaboration, ICRC 2017
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45

Blazars





Correlation study of 3 years of IceCube data and 862 Fermi-LAT blazars

2LAC blazars contribute >80% to the gamma-ray background but less than 30% to the diffuse neutrino flux

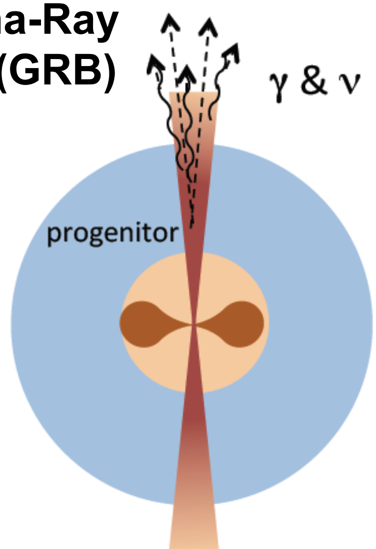
IceCube Collaboration, ICRC 2017
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45

IceCube Target of Opportunity Program

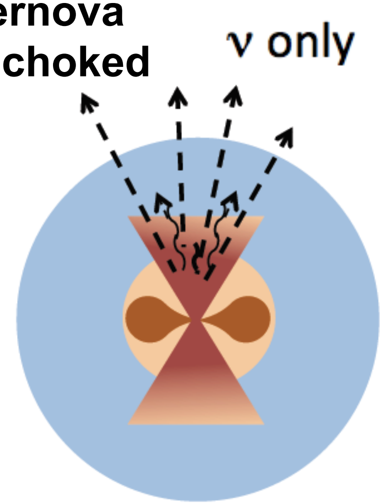
Public alerts since April 2016

- Single high-energy muon track events (> ~100TeV)
- 8 / yr, ~3 / yr of cosmic origin
- Median latency: 30 sec

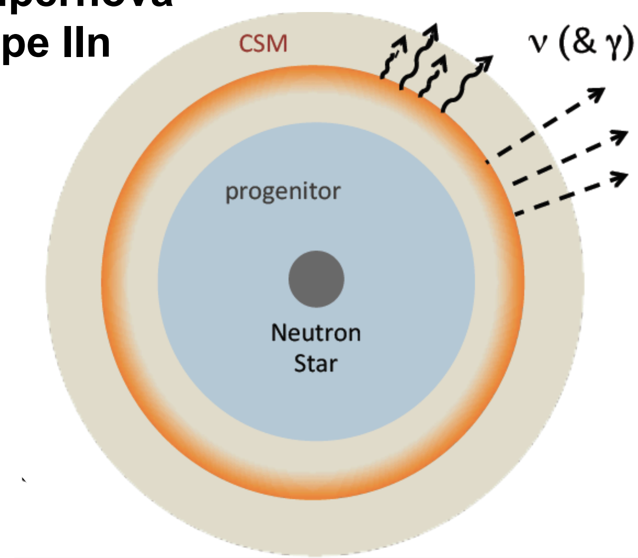
Gamma-Ray Burst (GRB)



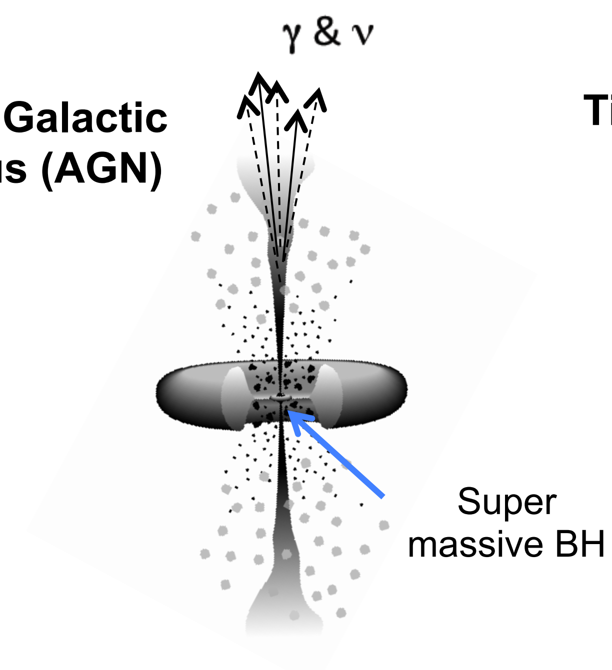
Supernova with choked jets



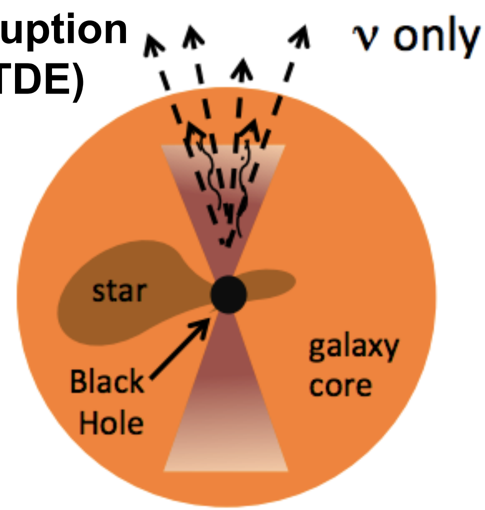
Supernova Type IIn



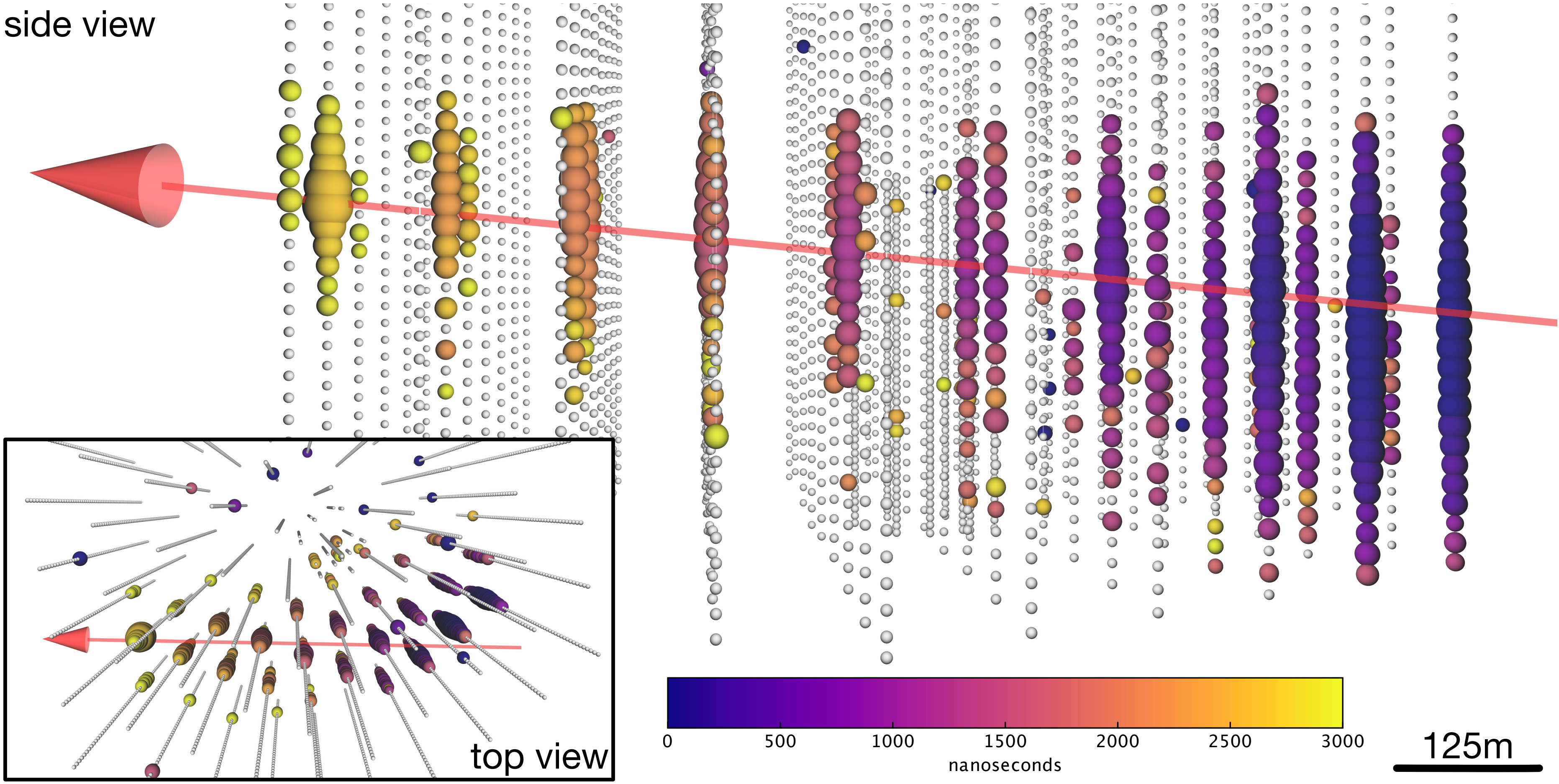
Active Galactic Nucleus (AGN)



Tidal Disruption event (TDE)



IC-170922A – a 290 TeV Neutrino



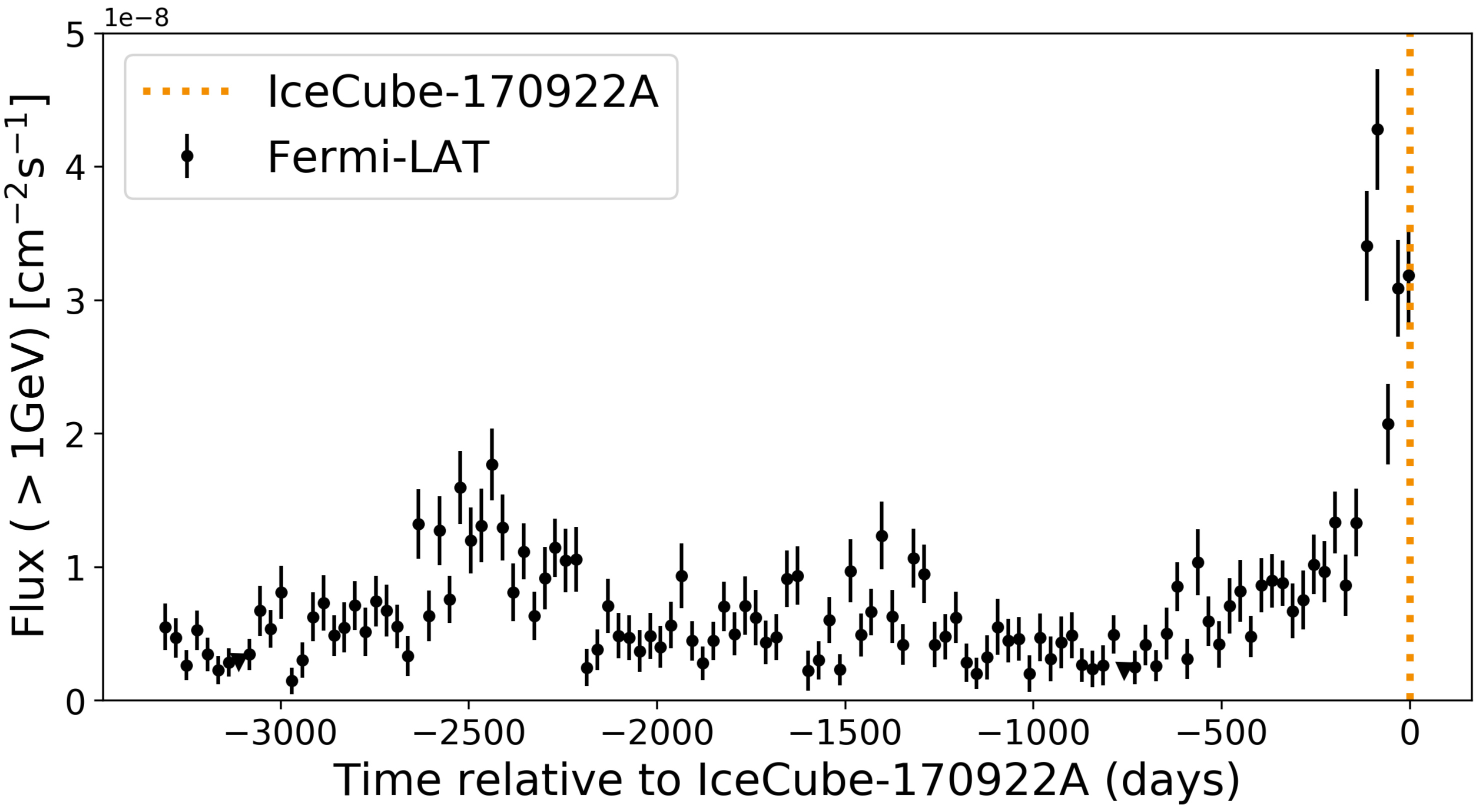
Signalness: 56.5%

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

Fermi-LAT finds Flaring Blazar

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

Fermi-LAT finds Flaring Blazar



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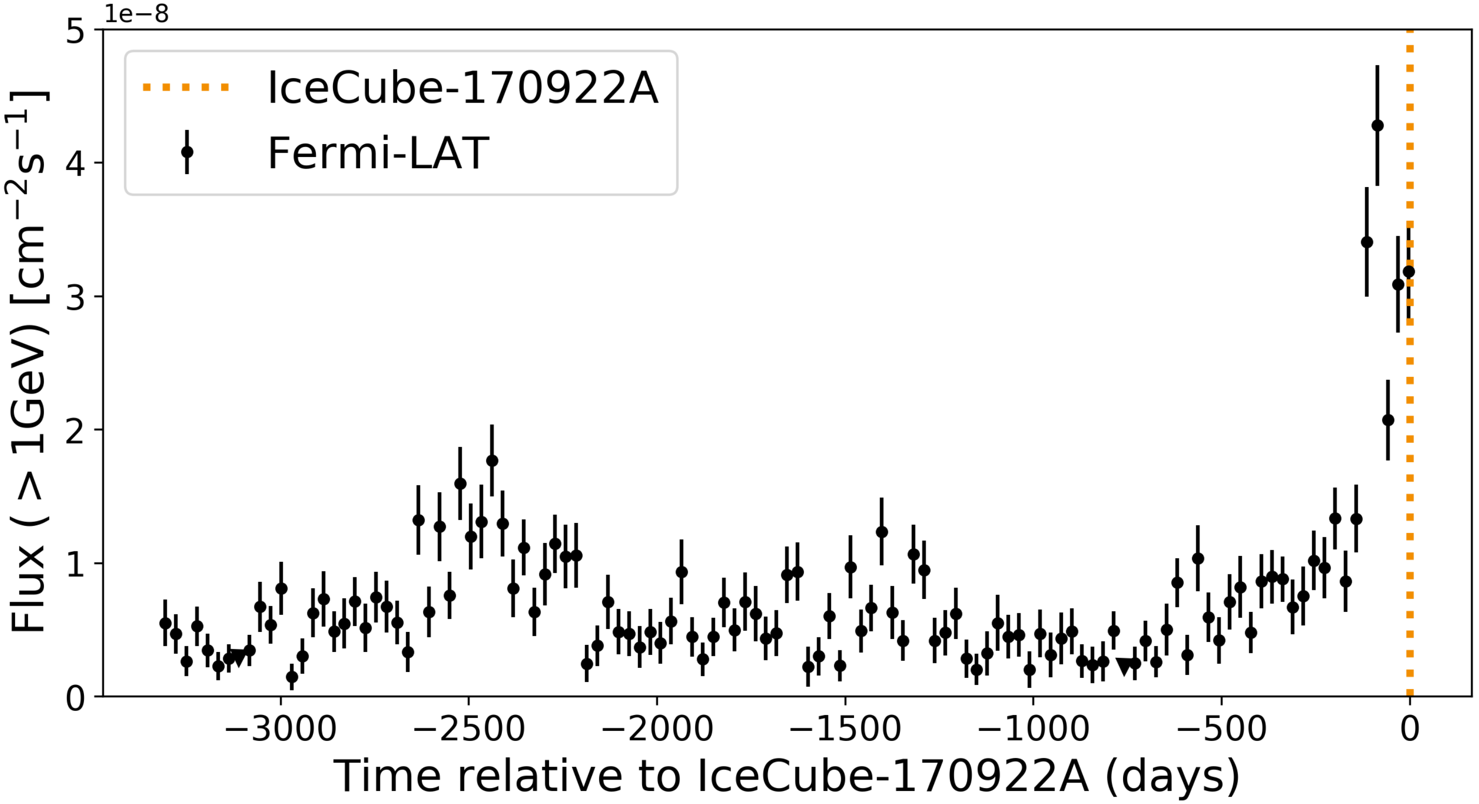
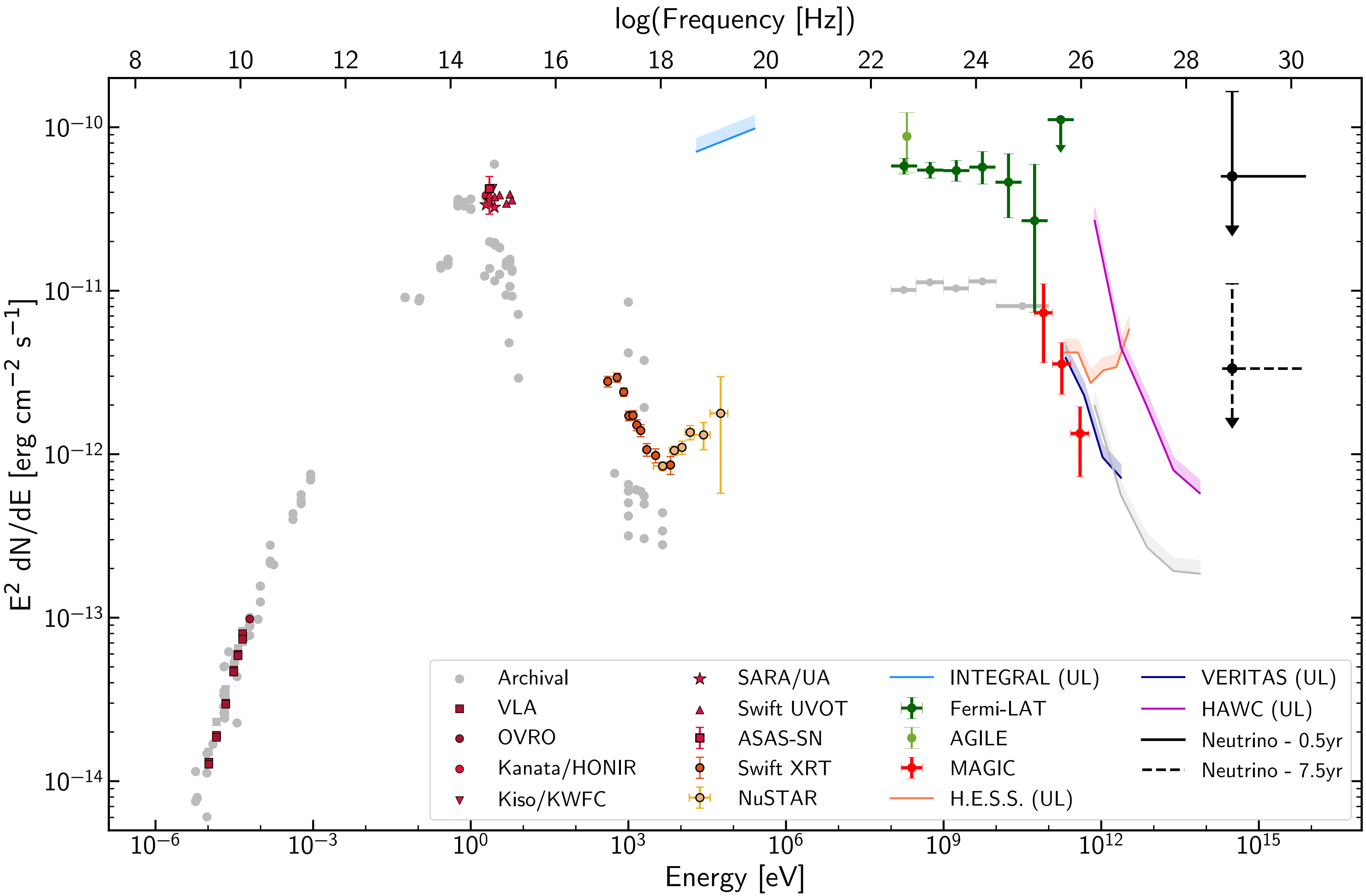


Pre-trials p-value: 4.1σ

10 public alerts and 41 archival events
→Post-trials p-value: 3.0σ

The Multi-Messenger SED



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

The Source: TXS 0506+056

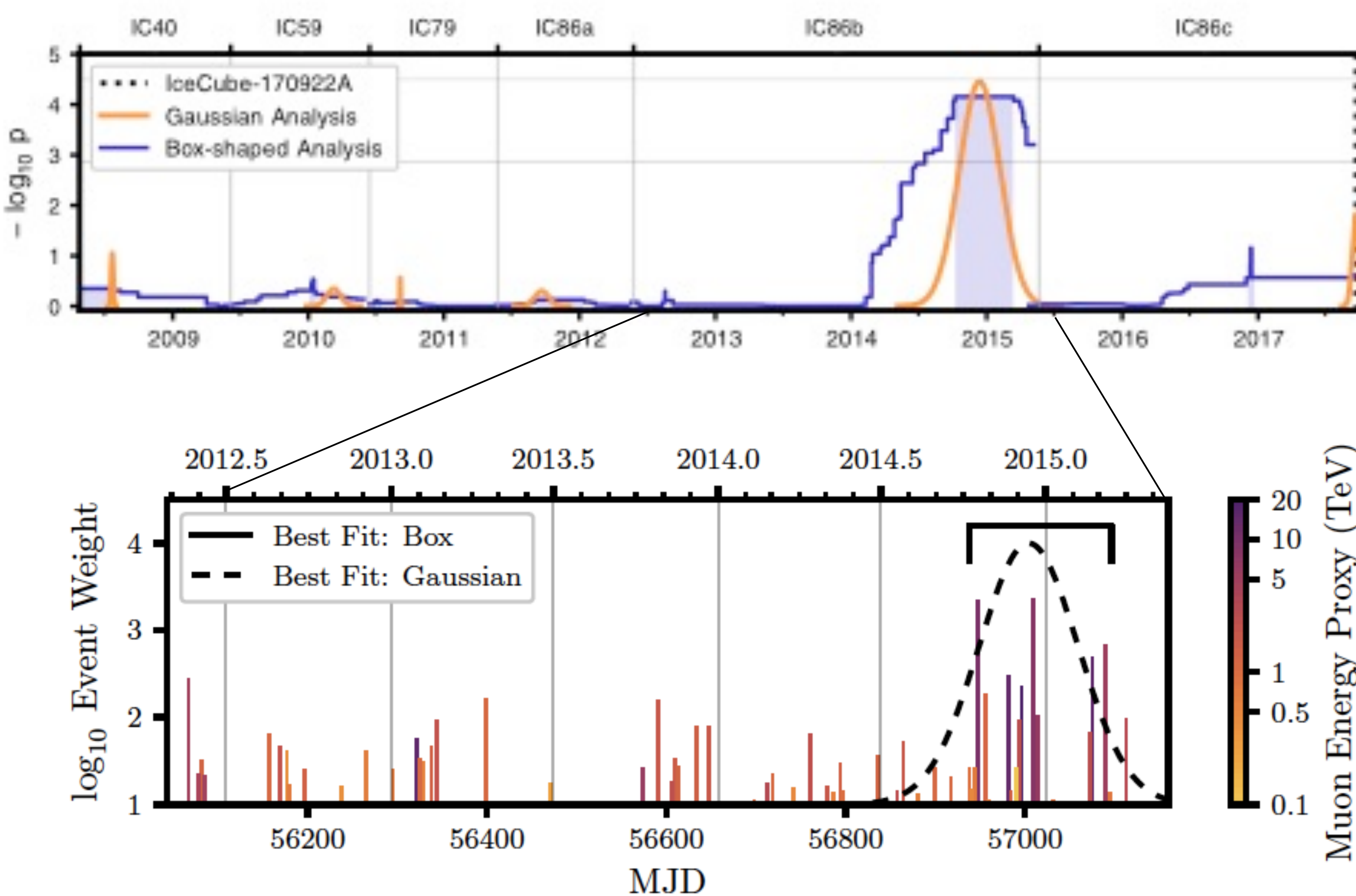
- Redshift 0.3365±0.0010 (S. Paiano et al. 2018)
- Among 50 brightest blazars in 3LAC
- Gamma-ray luminosity: 3×10^{46} erg/s

Are there more Neutrinos from this Source?

IceCube Coll.,Science 2018

Are there more Neutrinos from this Source?

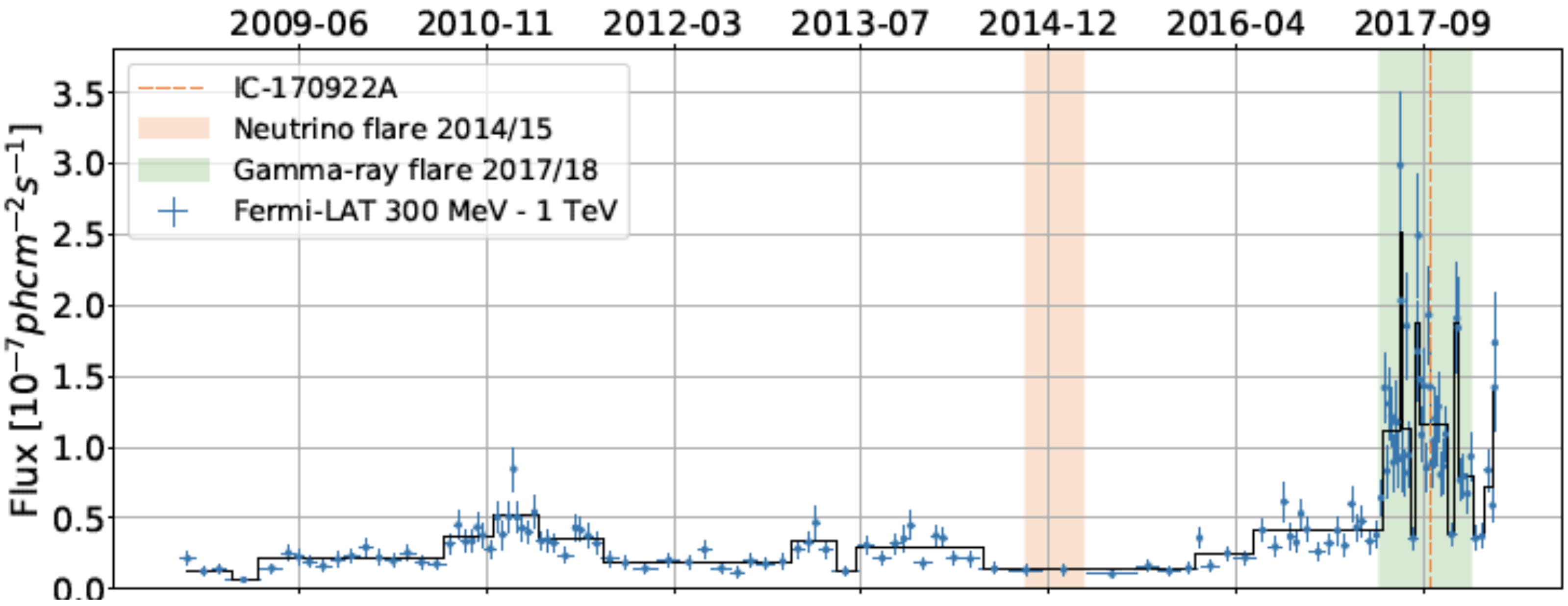
13±5 above the background of atmospheric neutrinos, 3.5σ



Neutrino luminosity (averaged over 158 days): $(1.2^{+0.6}_{-0.4}) \times 10^{47}$ erg s^{-1}

IceCube Coll.,Science 2018

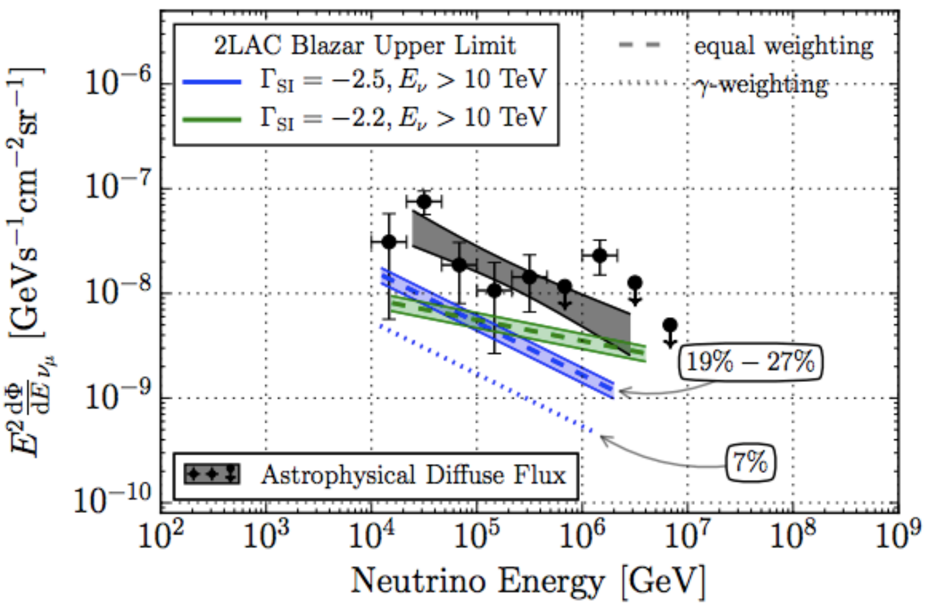
Is there also a Gamma-ray Flare?



No gamma-ray activity during 2014/15 neutrino flare

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)



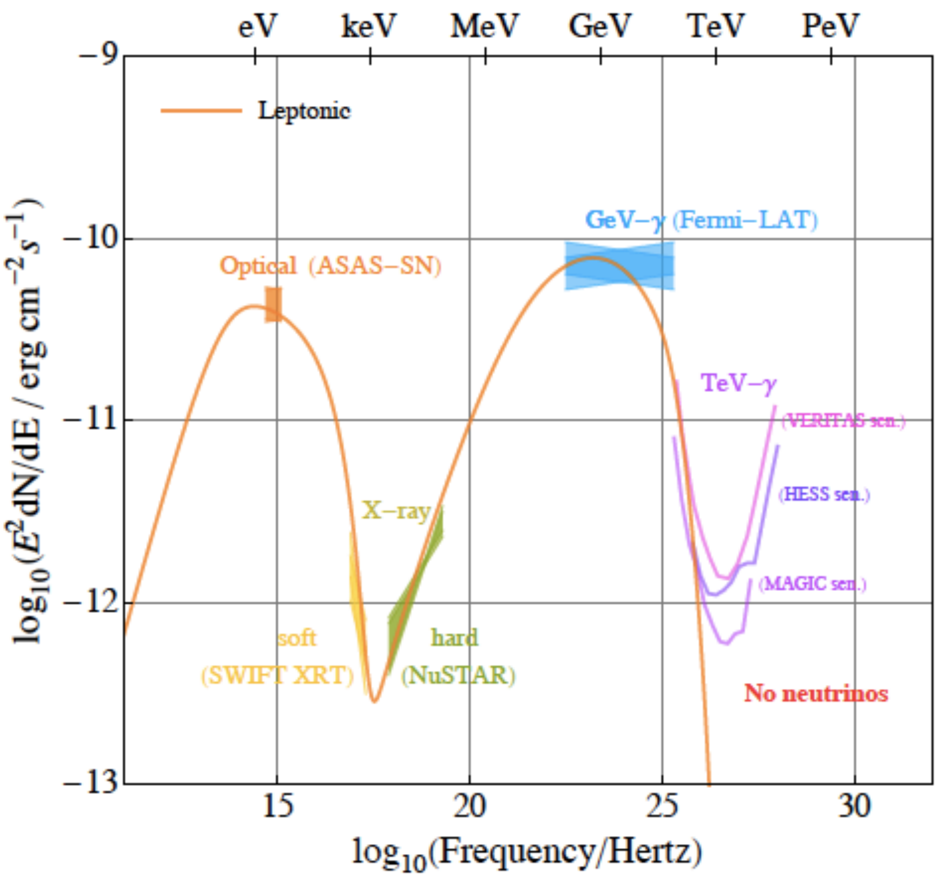
- Averaged over 9.5 years, the neutrino flux of TXS 0506+056 by itself corresponds to 1% of the astrophysical diffuse flux
- 40 high-energy neutrinos, 20 signal neutrinos, 1-2 neutrino blazar coincidences → 10% blazar contribution

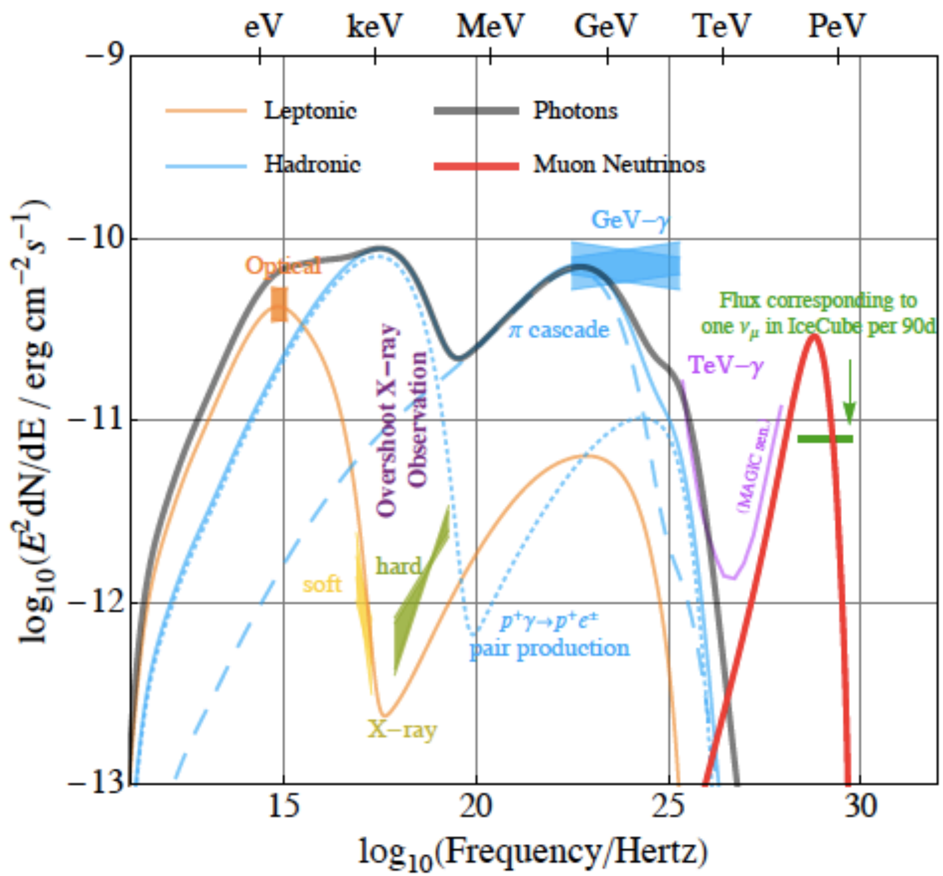
Fully compatible with blazar catalog stacking results

Modeling Papers on the arXiv on July 12

- “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

Modeling – leptonic vs. hadronic



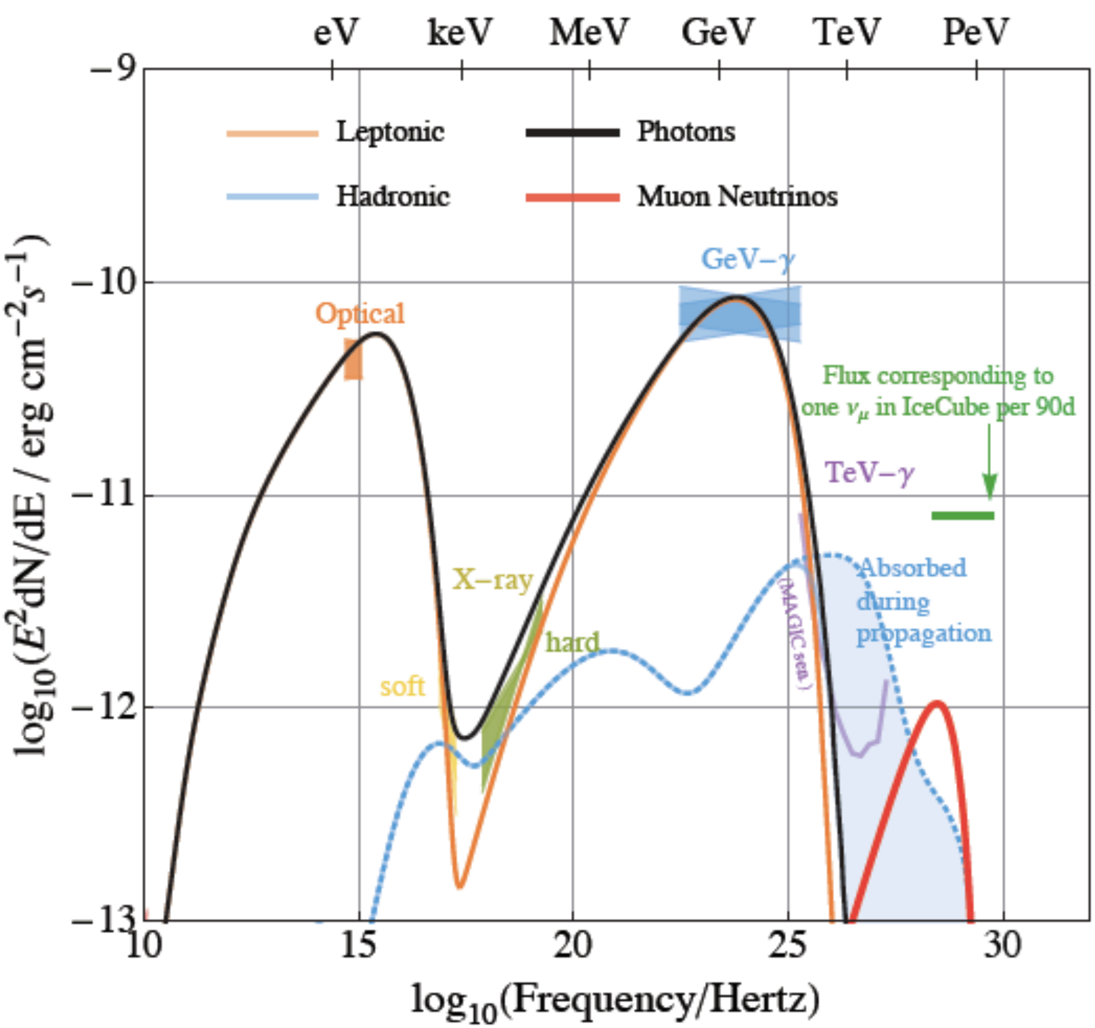


Pure hadronic models violate X-ray constraints

Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275

Modeling – leptonic, hadronic, Gin & Tonic

2017 neutrino + gamma flare:



2014/15 neutrino flare:

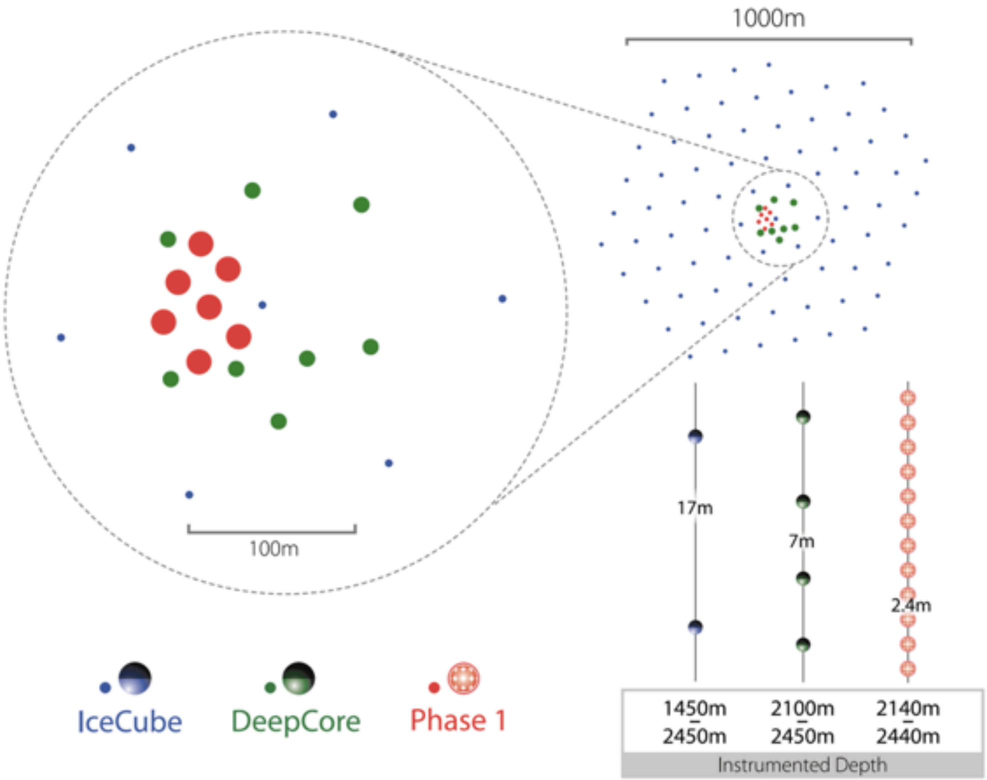
neutrino luminosity is ~5 times higher than gamma-ray luminosity

→ **challenge for models**

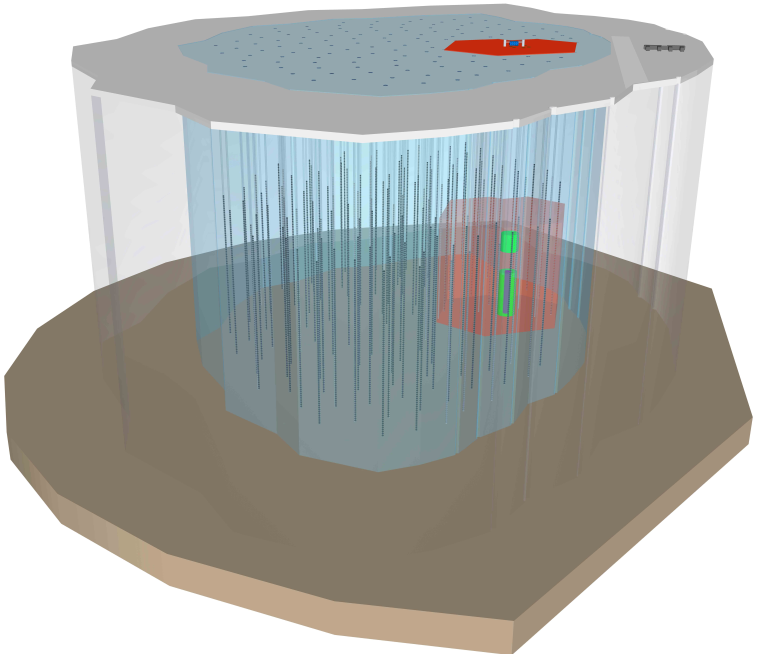
Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275

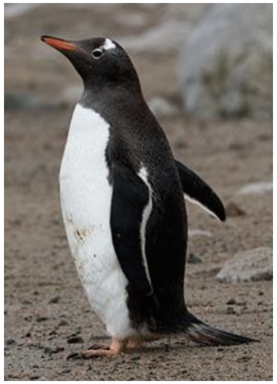
What's Next?

Phase I



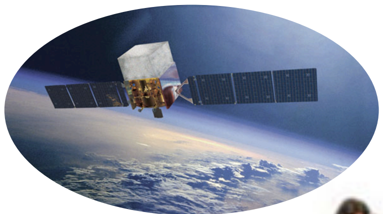
IceCube Gen2



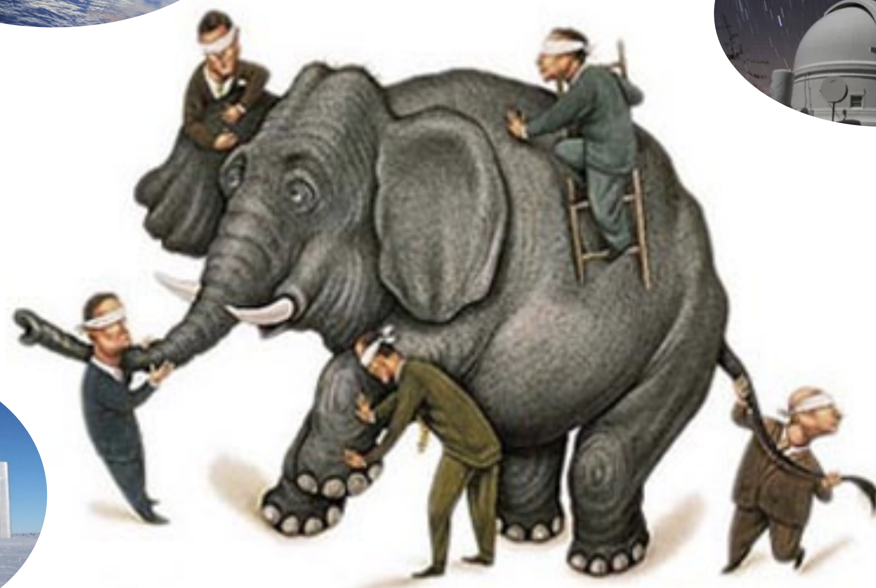


Summary

gamma-rays



visible light



gravitational waves

neutrinos

cosmic rays

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gamma-rays

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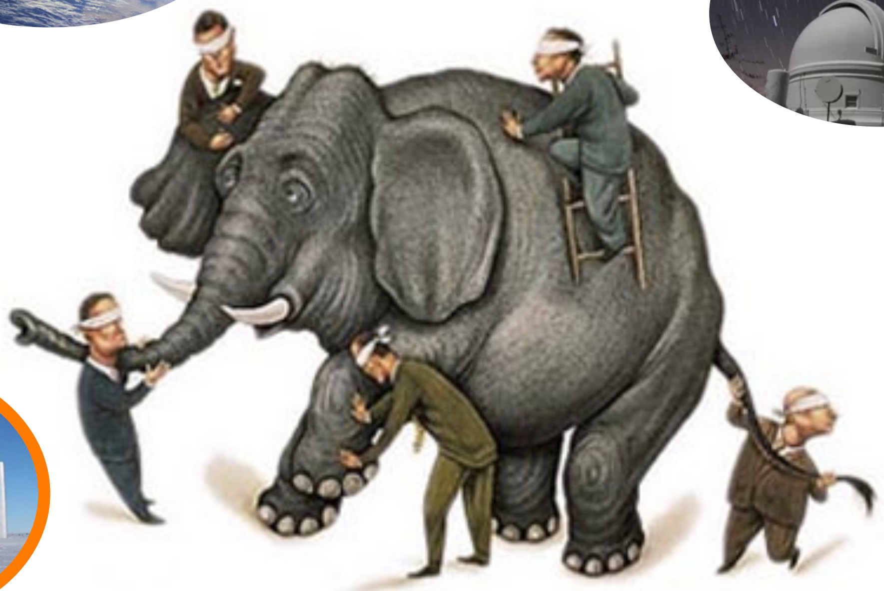


gravitational waves

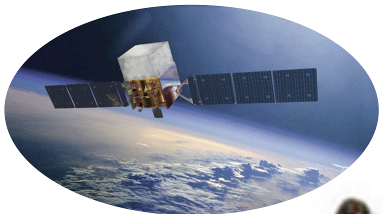
neutrinos

unique messengers from the high-energy Universe

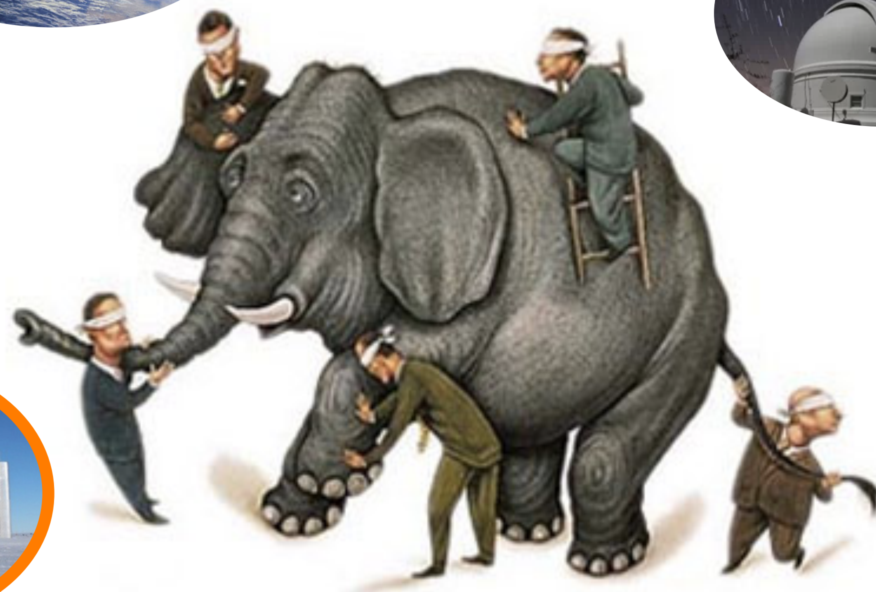
cosmic rays

Summary

gamma-rays



visible light



gravitational waves

neutrinos

Neutrinos can reveal the sources of high-energy cosmic rays

cosmic rays

Summary

Sources still unknown → Electro-magnetic counterparts are crucial to identify the sources
First compelling candidate found!

gamma-rays

visible light

gravitational waves

neutrinos

cosmic rays

Summary

Neutrino could help to better localize gravitational wave events and understand their environments