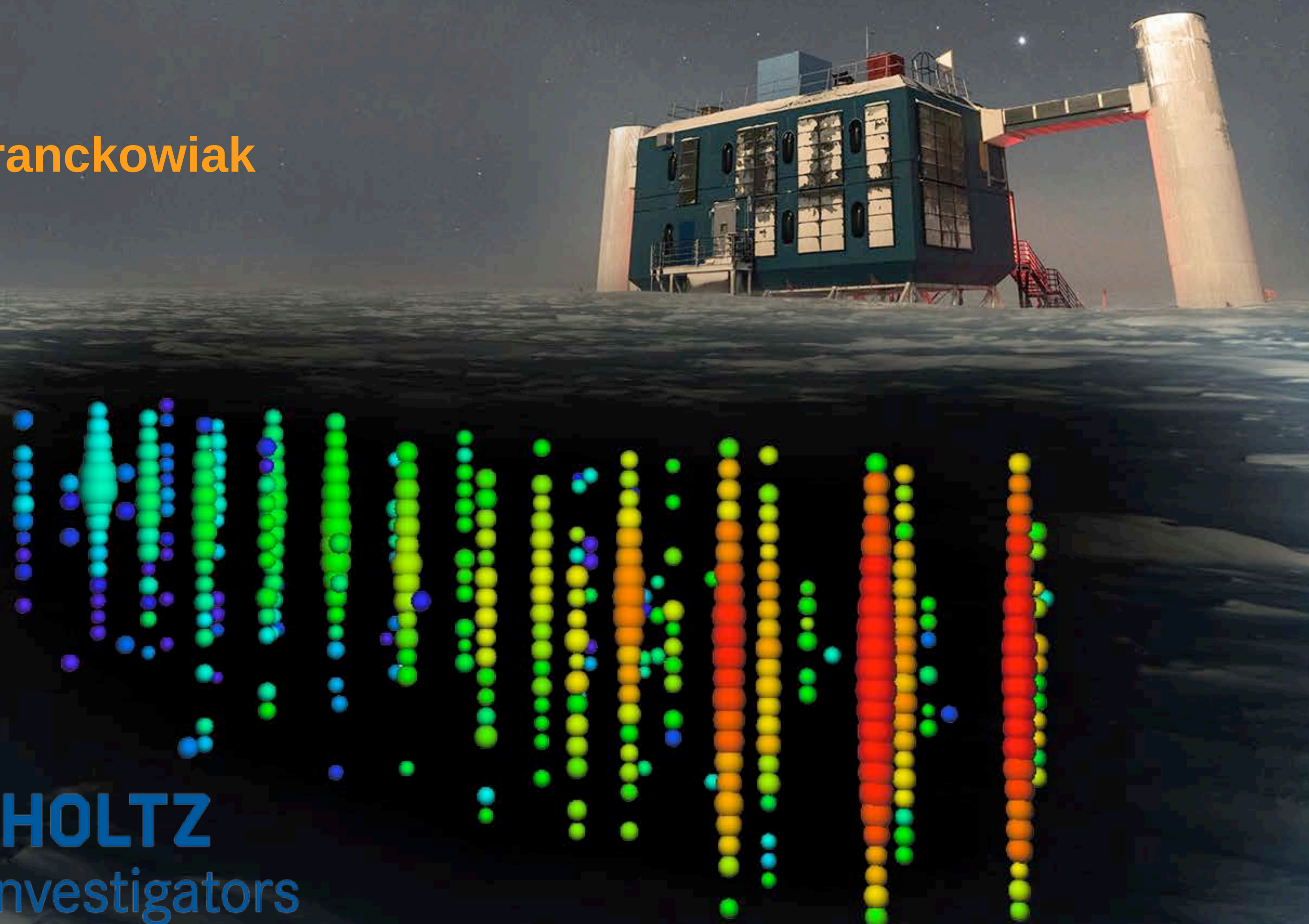
Multi-messenger Astronomy with high-energy Neutrinos

Anna Franckowiak

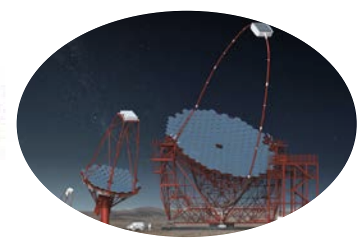


HELMHOLTZ
Young Investigators

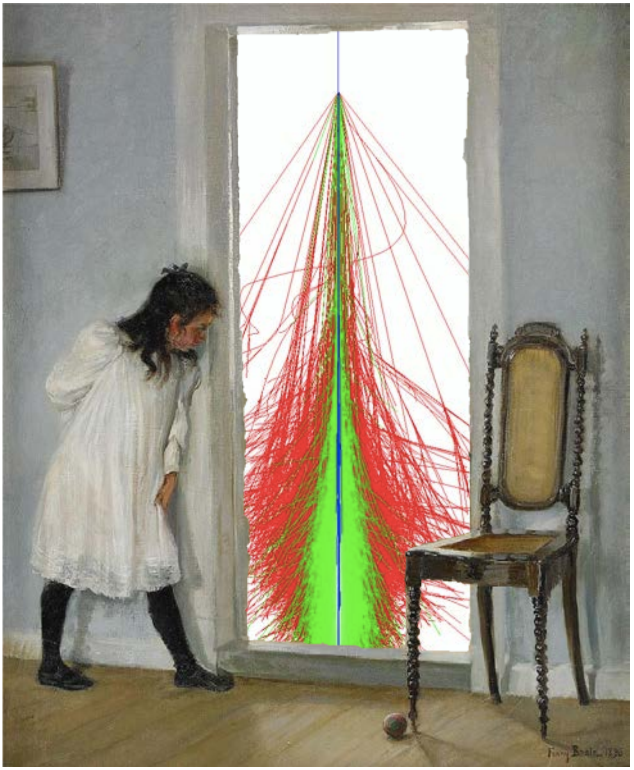
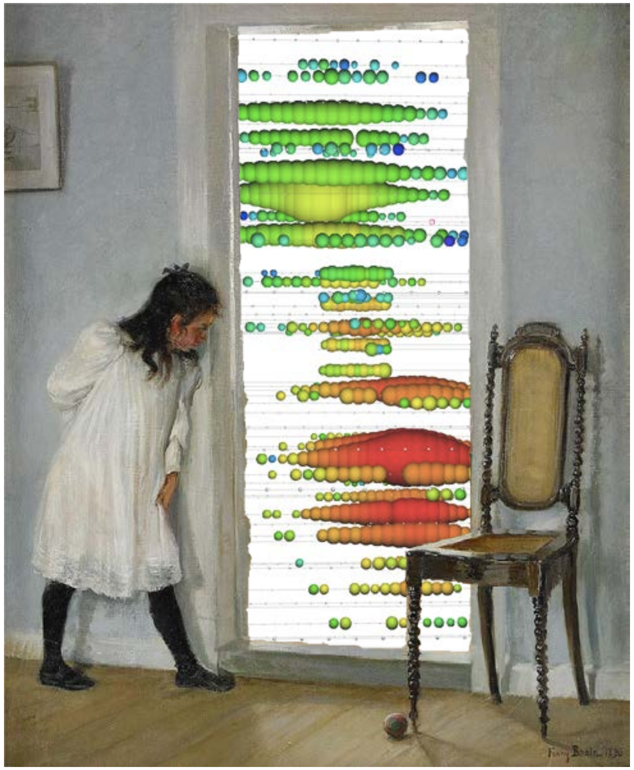
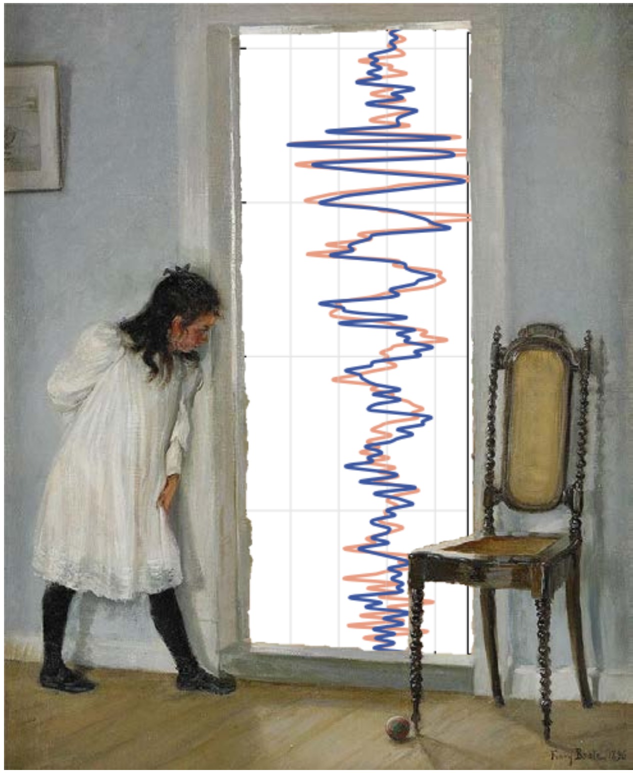
Paul Scherrer Institut, February 28, 2019

DESY.

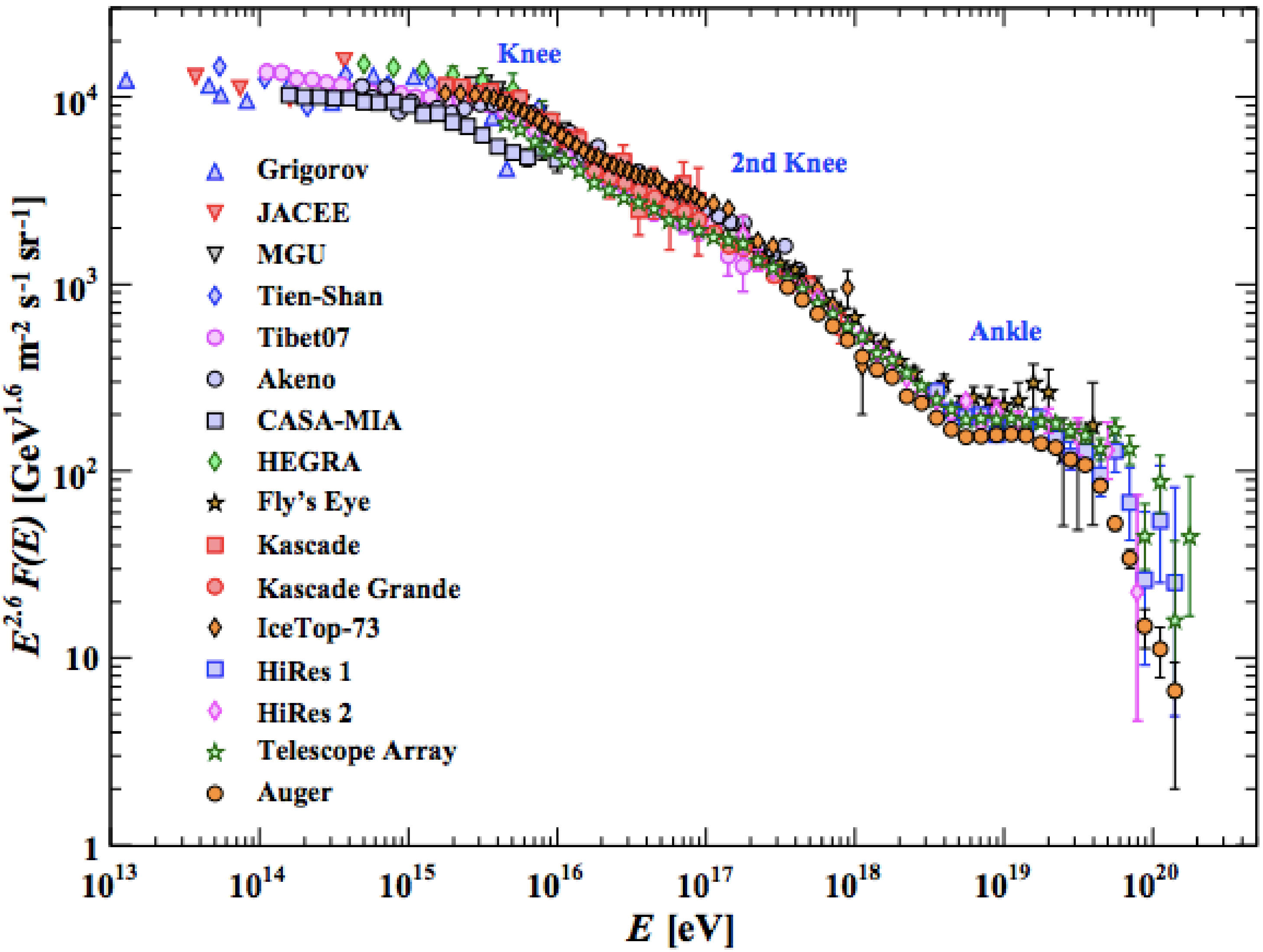
The Multi-Messenger Picture



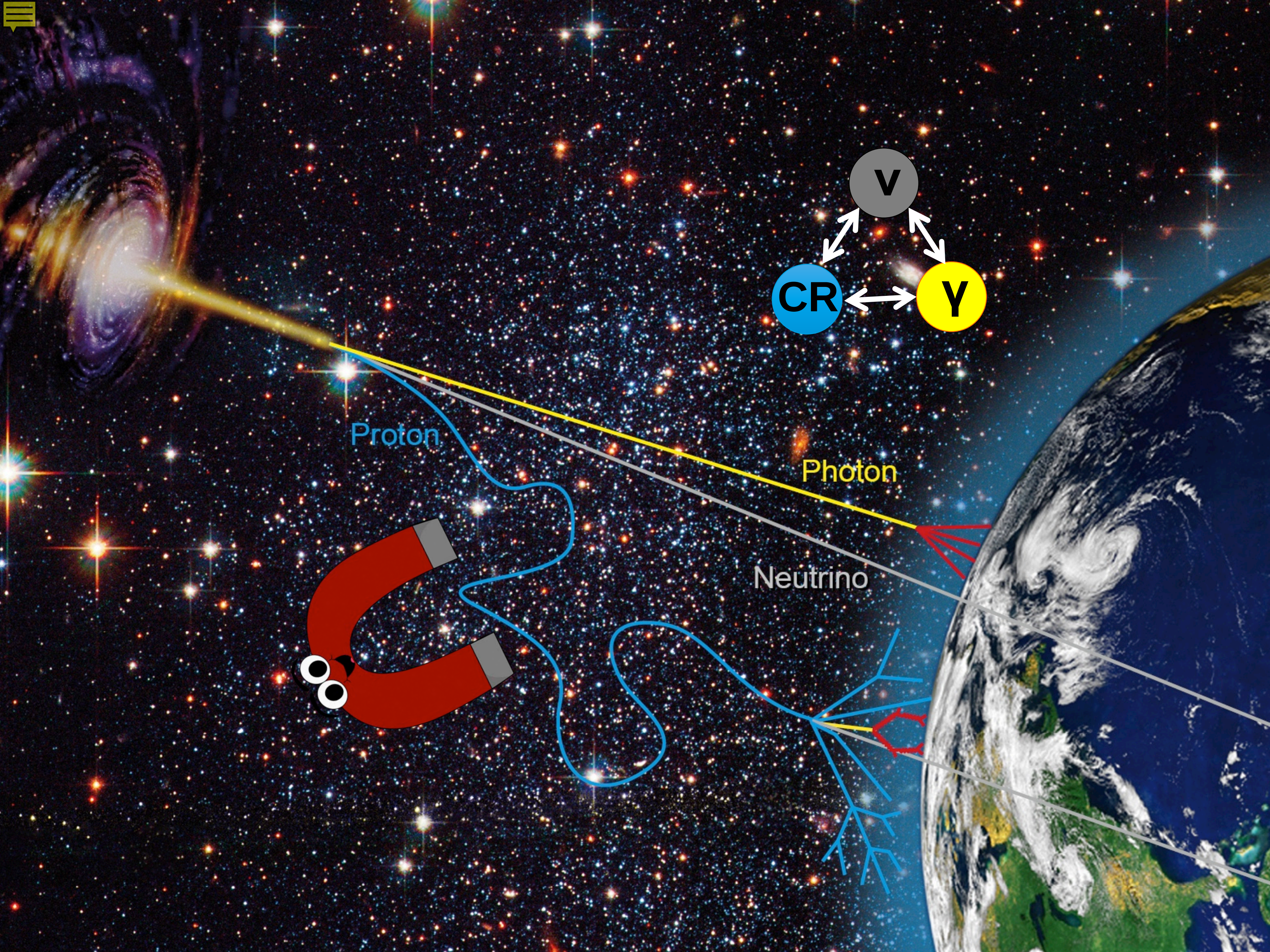
New Windows to the Universe

Cosmic rays reach 10^{20}eV



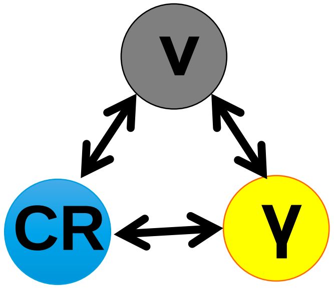
M. Tanabashi et al. (Particle Data Group), PRD 98, 2018


ν
CR
γ
Proton
Photon
Neutrino

Neutrino Production Processes

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

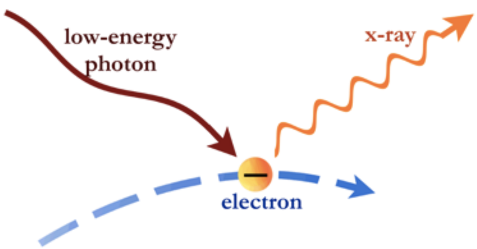
$$pp \rightarrow \begin{cases} X + \pi^0 \rightarrow \gamma\,\gamma \\ X + \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu \\ X + \pi^- \rightarrow \mu^- \nu_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu \end{cases}$$

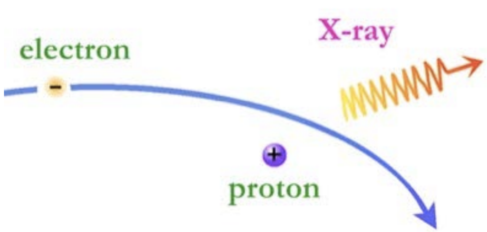


Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

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

Gamma-rays are not exclusively produced in hadronic processes

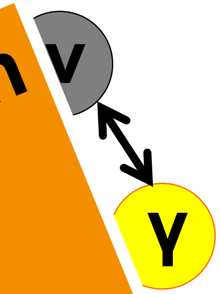




Neutrino Production Processes

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

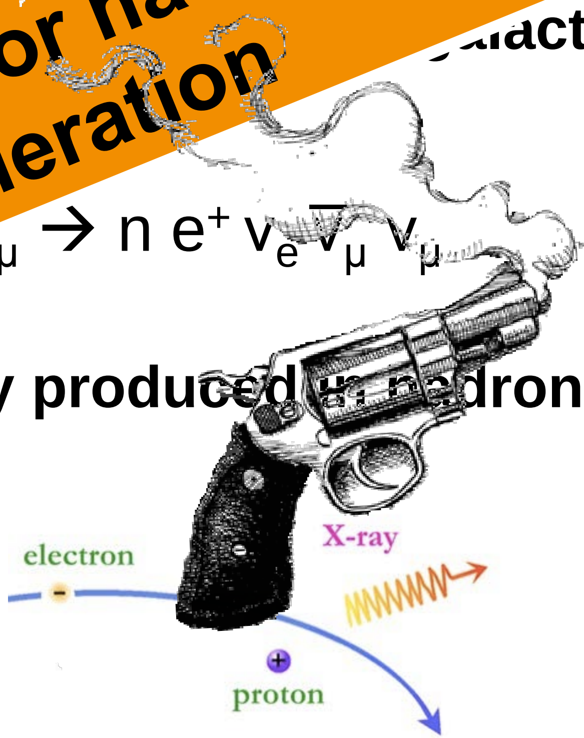
$$pp \rightarrow \begin{cases} X + \pi^0 \rightarrow \gamma\,\gamma \\ X + \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu \\ X + \pi^- \rightarrow \mu^- \nu_\mu \rightarrow e^- \bar{\nu}_e \nu \ldots \end{cases}$$



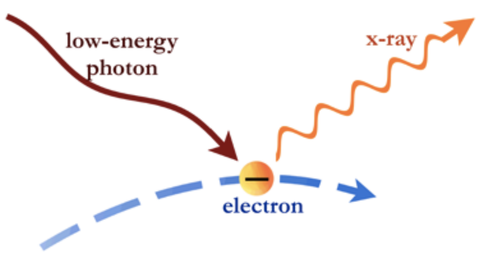
Neutrinos are the smoking gun signature for hadronic acceleration

Photohadronic (e... ...alactic nuclei)

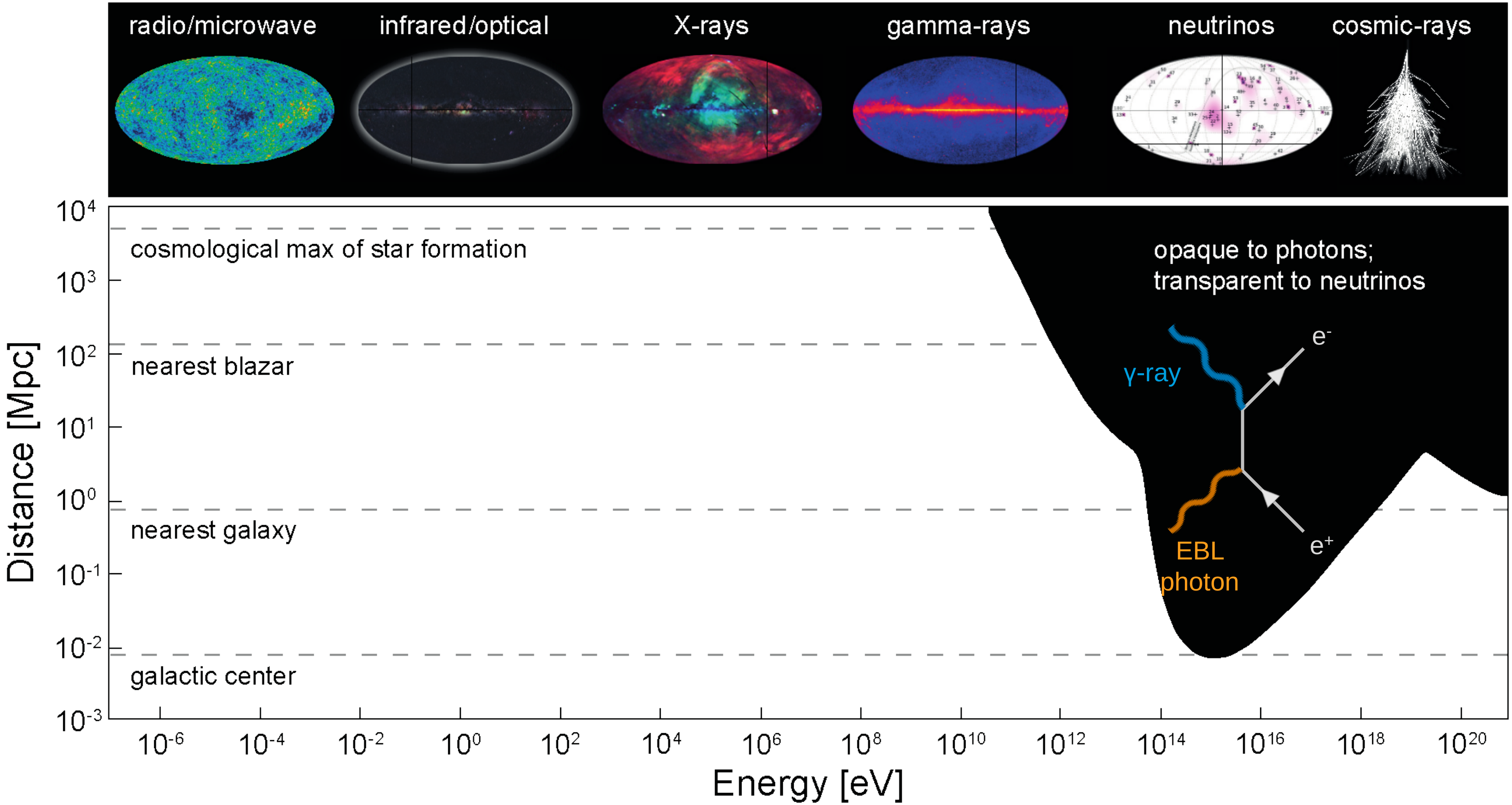
$$p\gamma \rightarrow \ldots \nu_\mu \rightarrow n\, e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

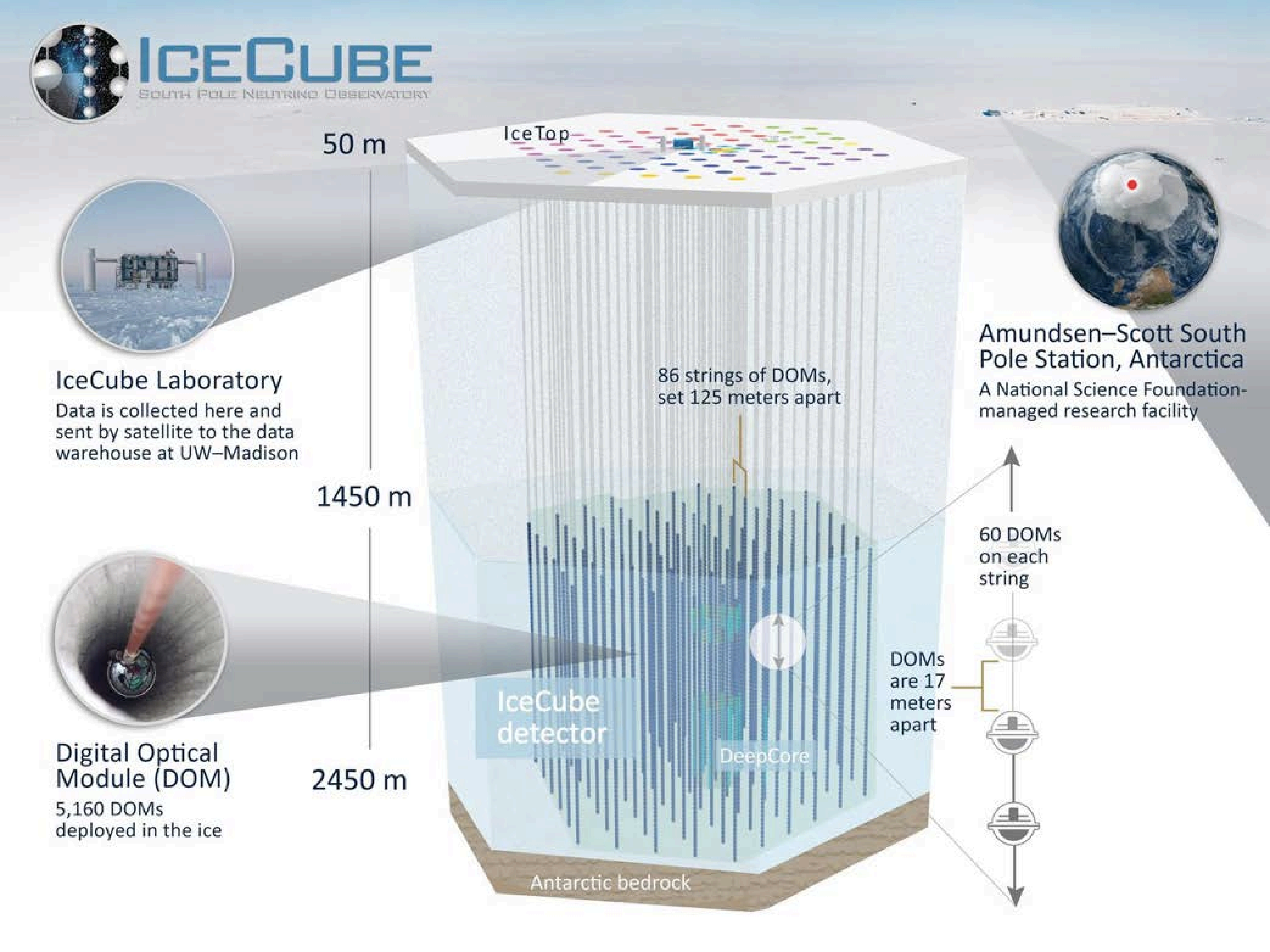


Gamma-ray ... not exclusively produced ... hadronic processes



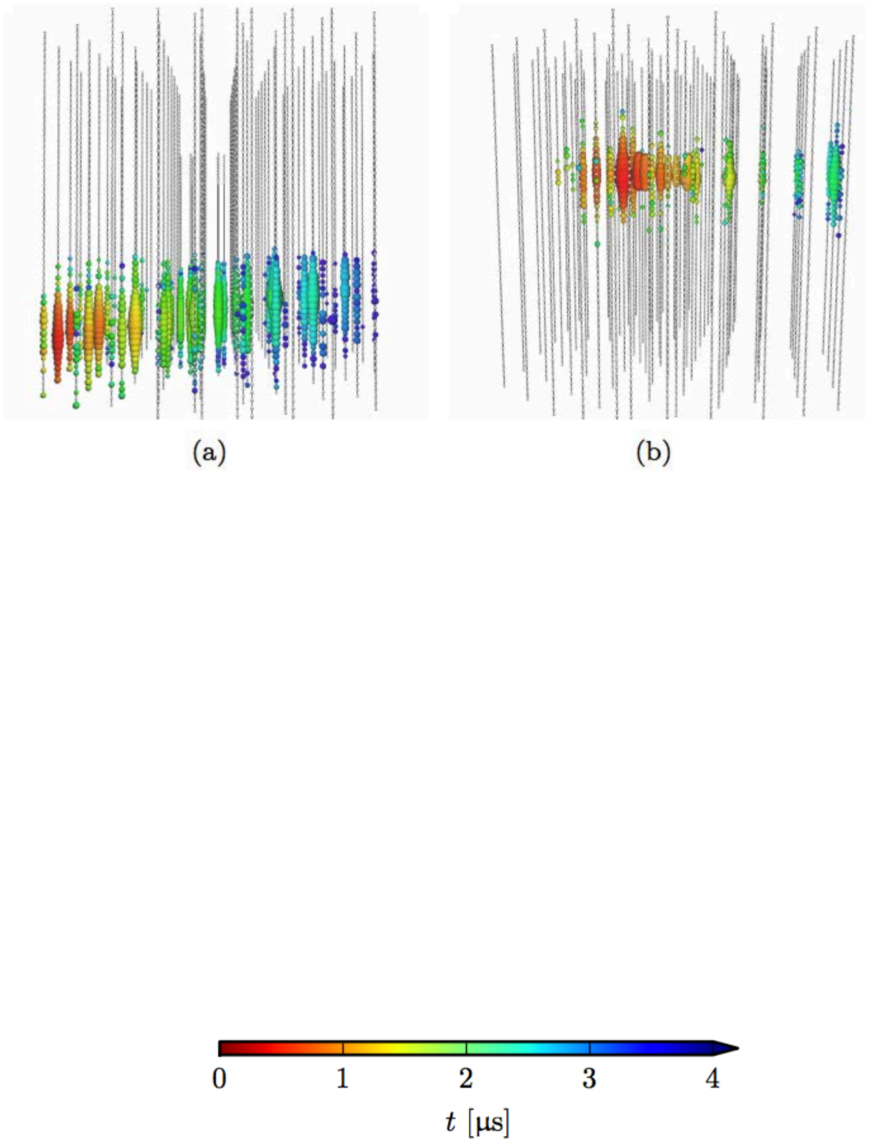
Where Can We Look?





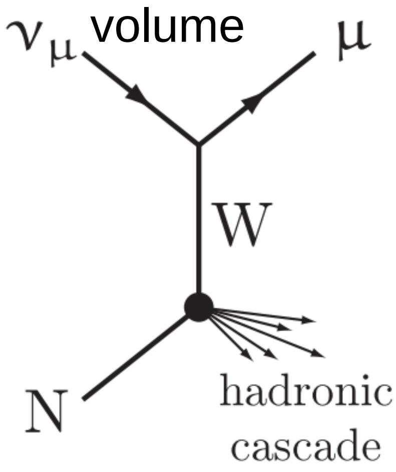
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic 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

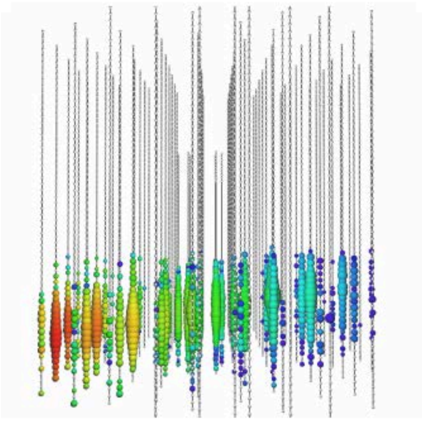


a) **through-going muon track E ~ 140 TeV**
b) **Starting muon track E ~ 70 TeV**

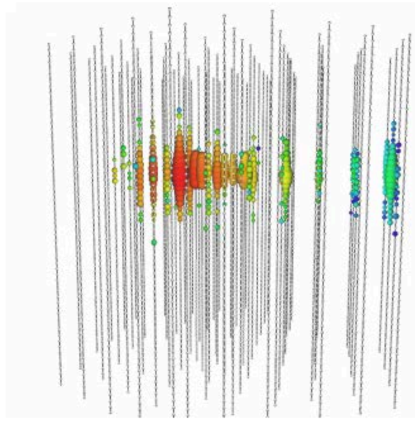
Charged current interaction of muon neutrino outside / inside the detector volume



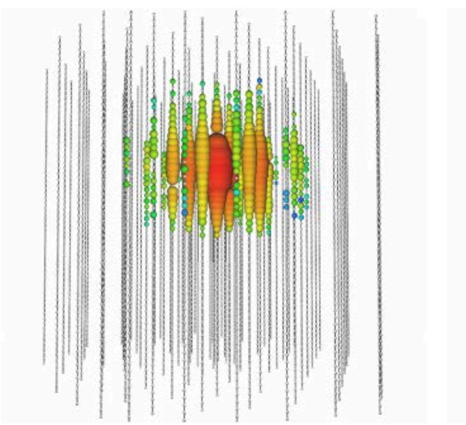
Event Signatures



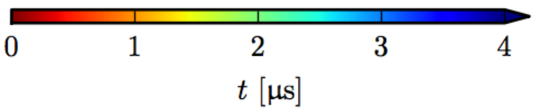
(a)



(b)

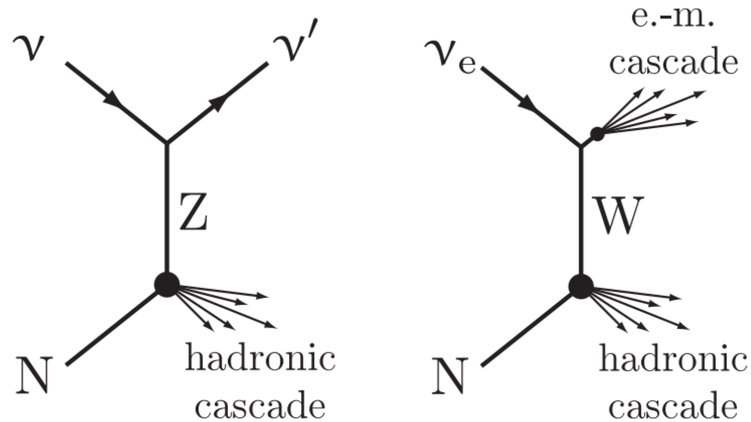


(c)



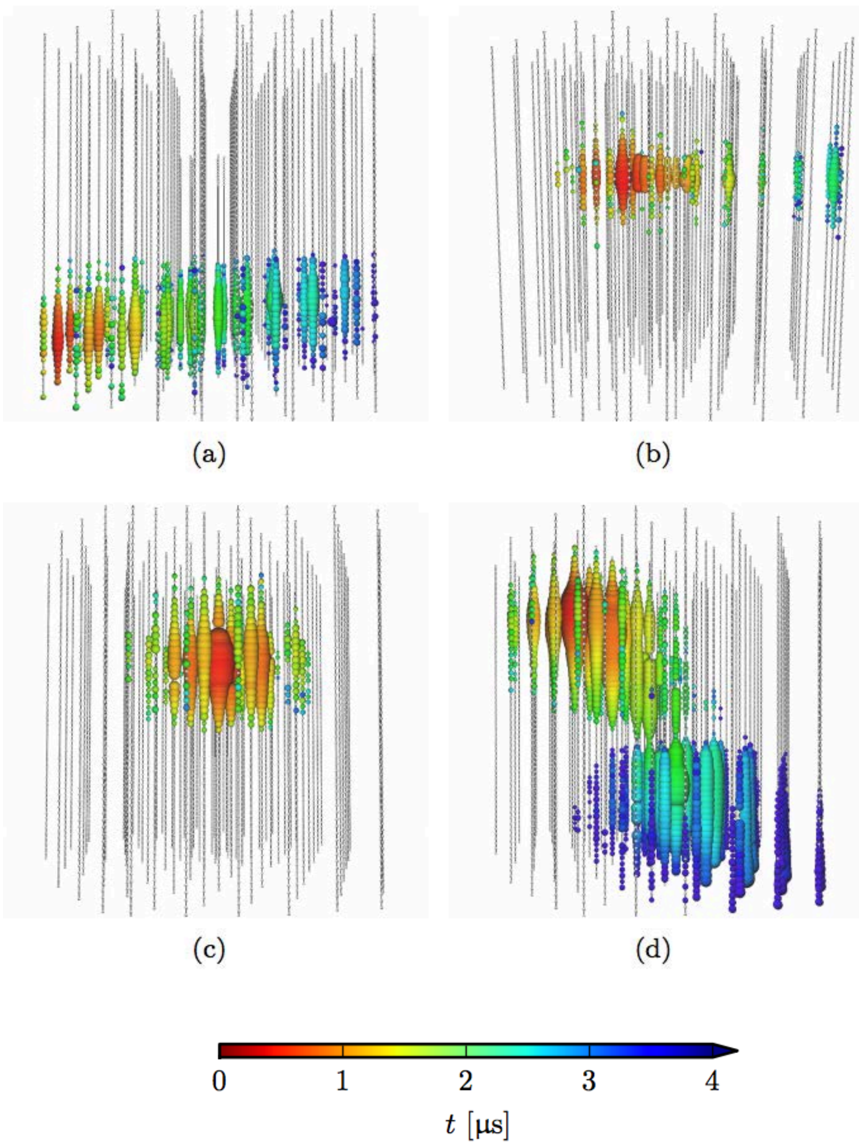
a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV
c) Shower event E ~ 1 PeV

Neutral current or electron neutrino charged current interaction



Cannot distinguish between showers (size few meters)

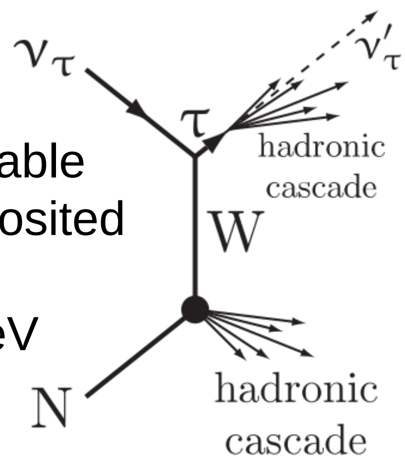
Event Signatures



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 (simulated)

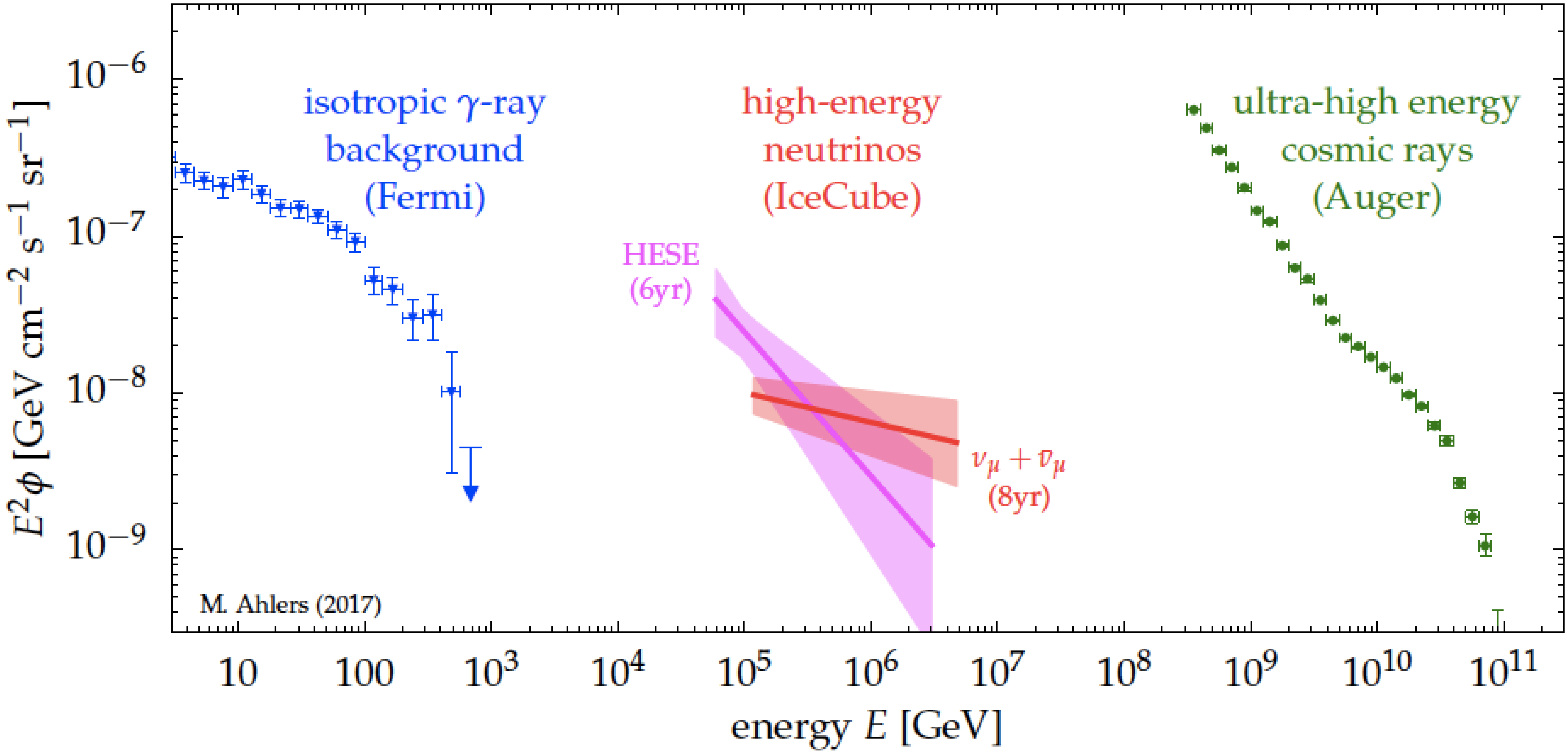
Tau neutrino charged current interaction

Resolvable for deposited energy >100TeV



Only for very large energies the two showers can be separated (otherwise signature c)

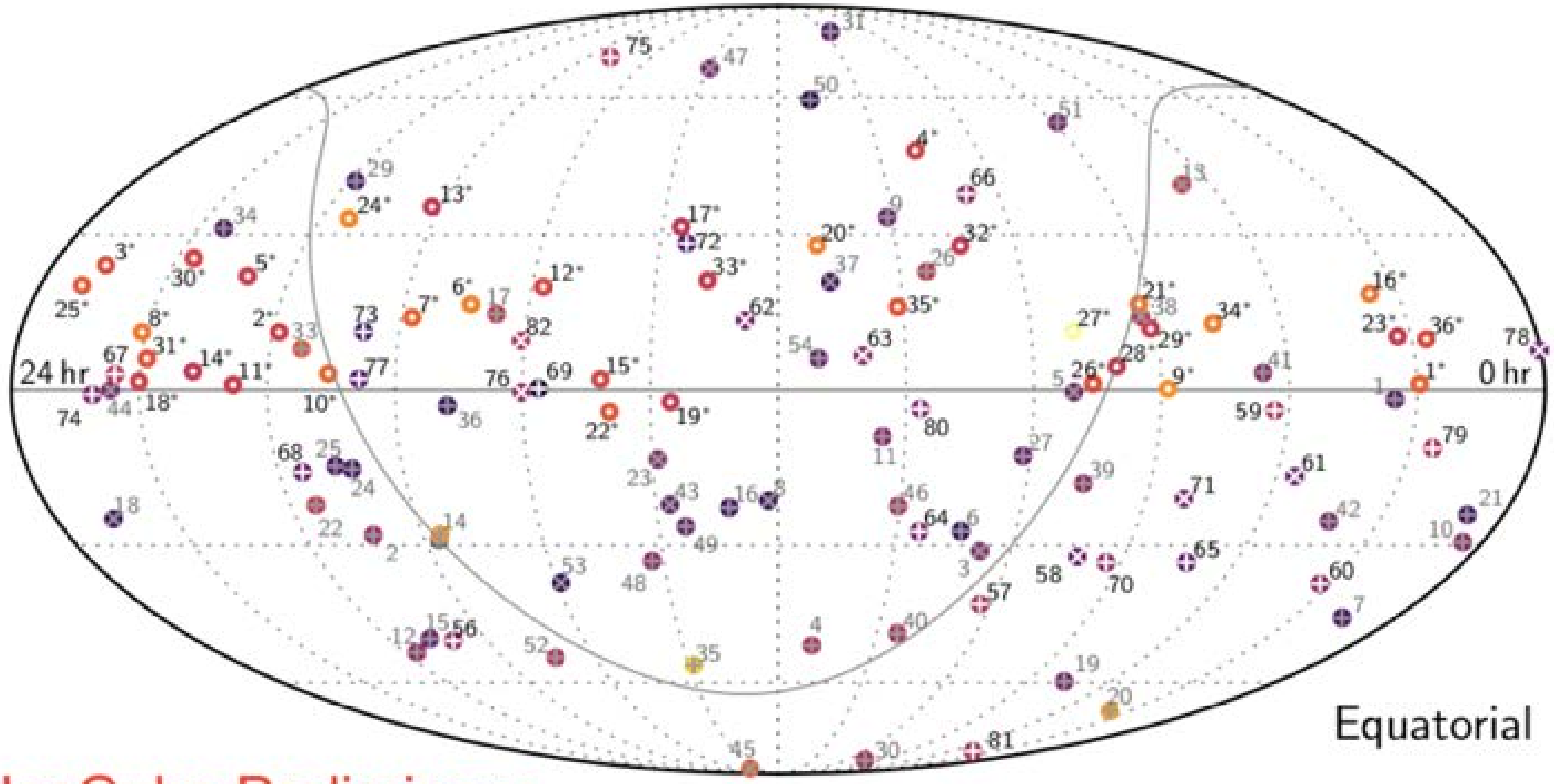
Diffuse Neutrino Flux detected!



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

Where do the Neutrinos come from?

IceCube high-energy events > 30 TeV (2010 - 2016)



IceCube, ICRC 2017

Compatible with an isotropic distribution

→ extragalactic origin of cosmic neutrinos

IceCube Target of Opportunity Program

Public alerts since April 2016

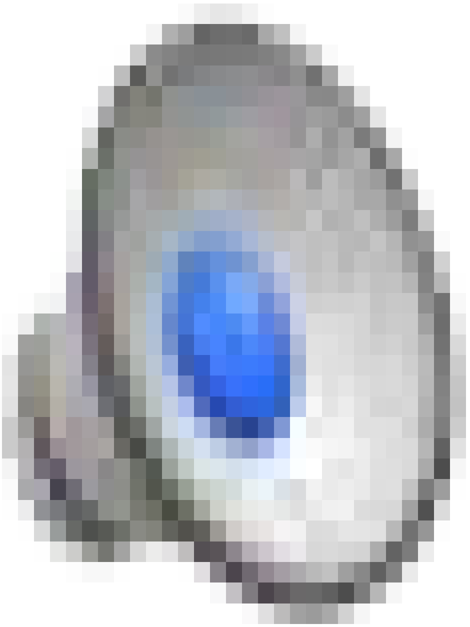
- Single high-energy muon track events (> ~100TeV)
- 8 / yr, ~3 / yr of cosmic origin
- Median latency: 30 sec

IC-170922A – a 290 TeV Neutrino

Signal

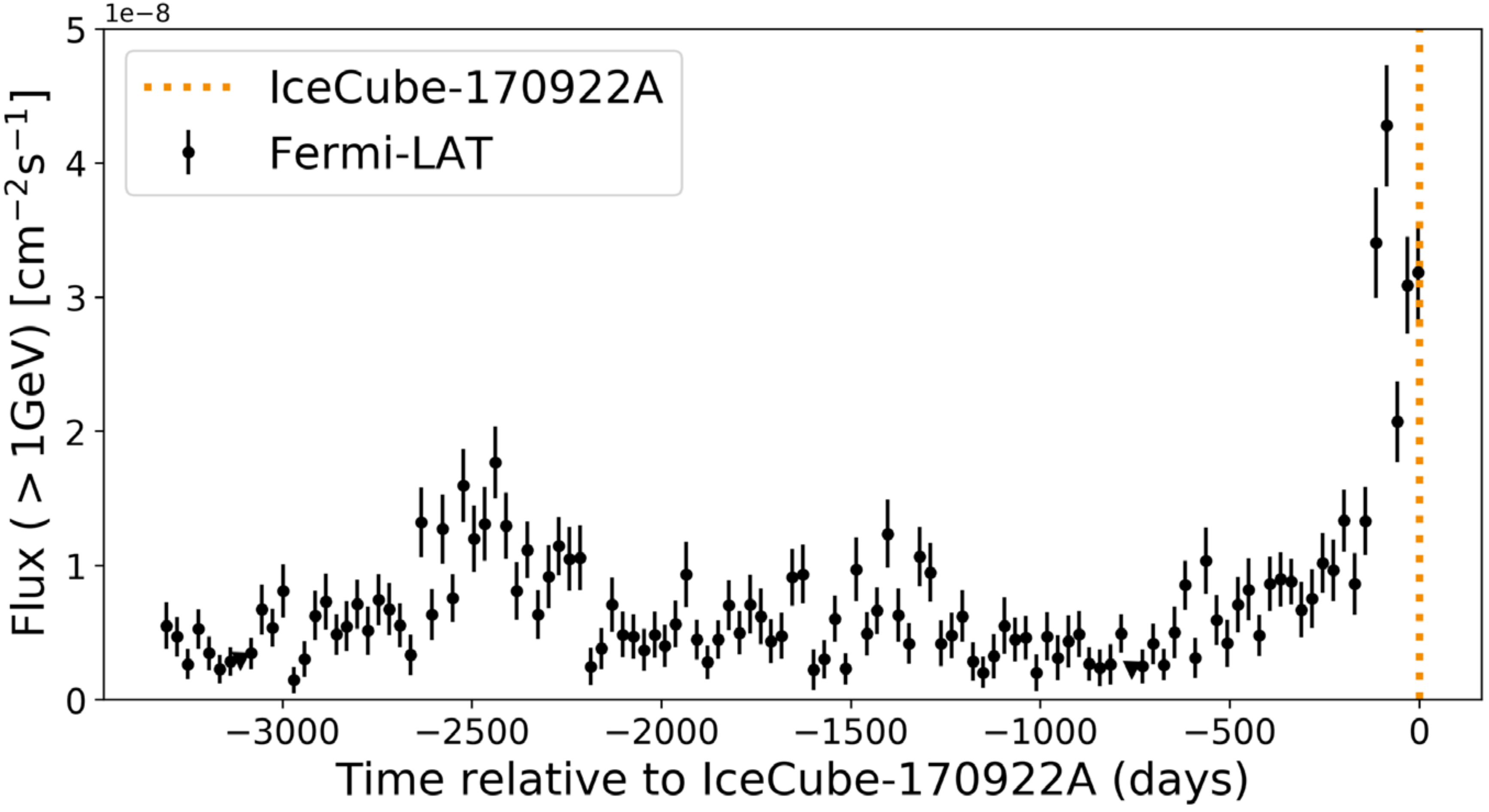
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Fermi-LAT finds Flaring Blazar

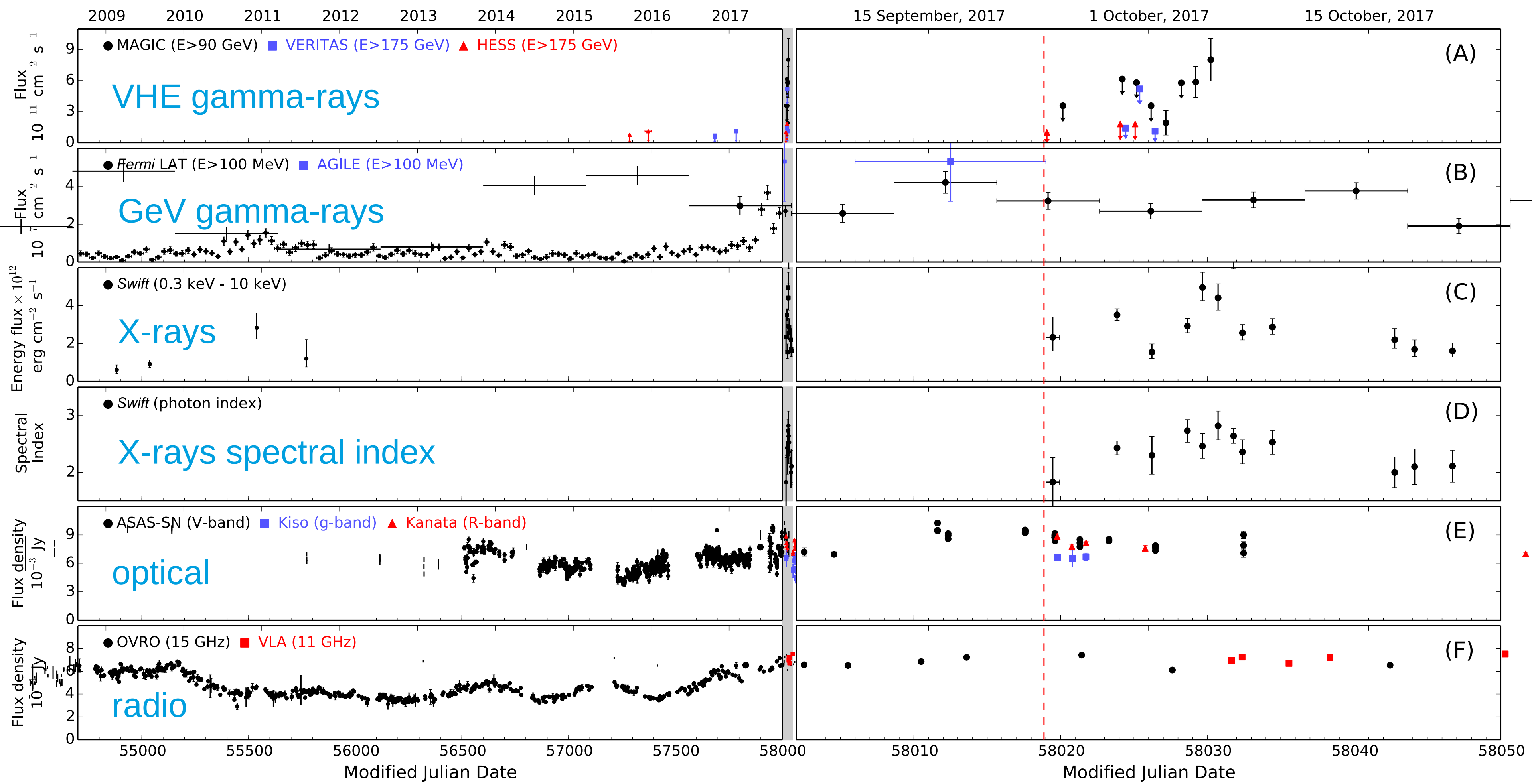


Fermi-LAT Coll., ApJ 846, 2017, Video credits: Matteo Giomi, Fermi-LAT Collaboration

Fermi-LAT finds Flaring Blazar, TXS 0506+056

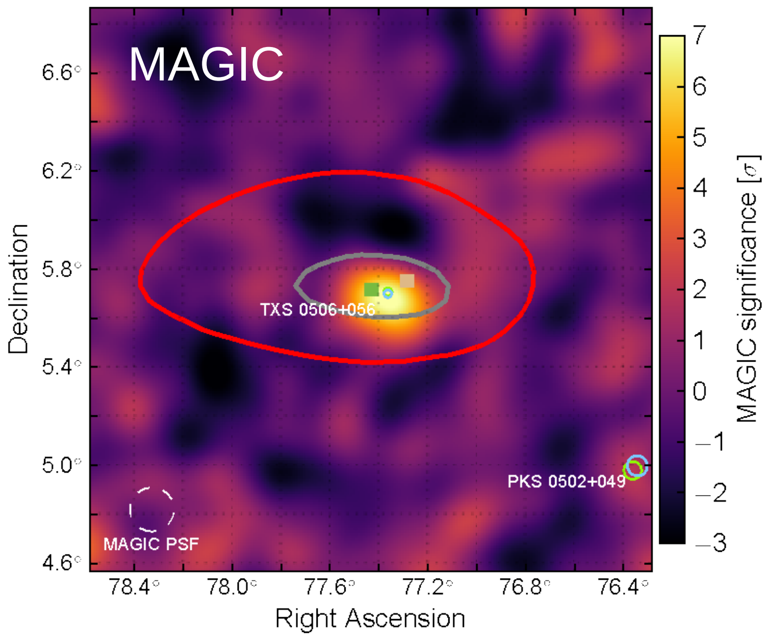


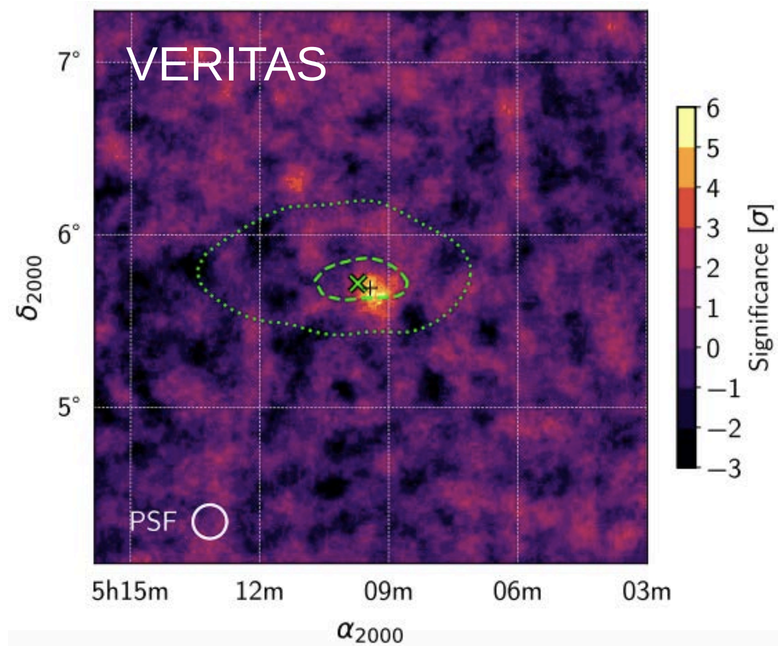
The Multi-Messenger Light Curve



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

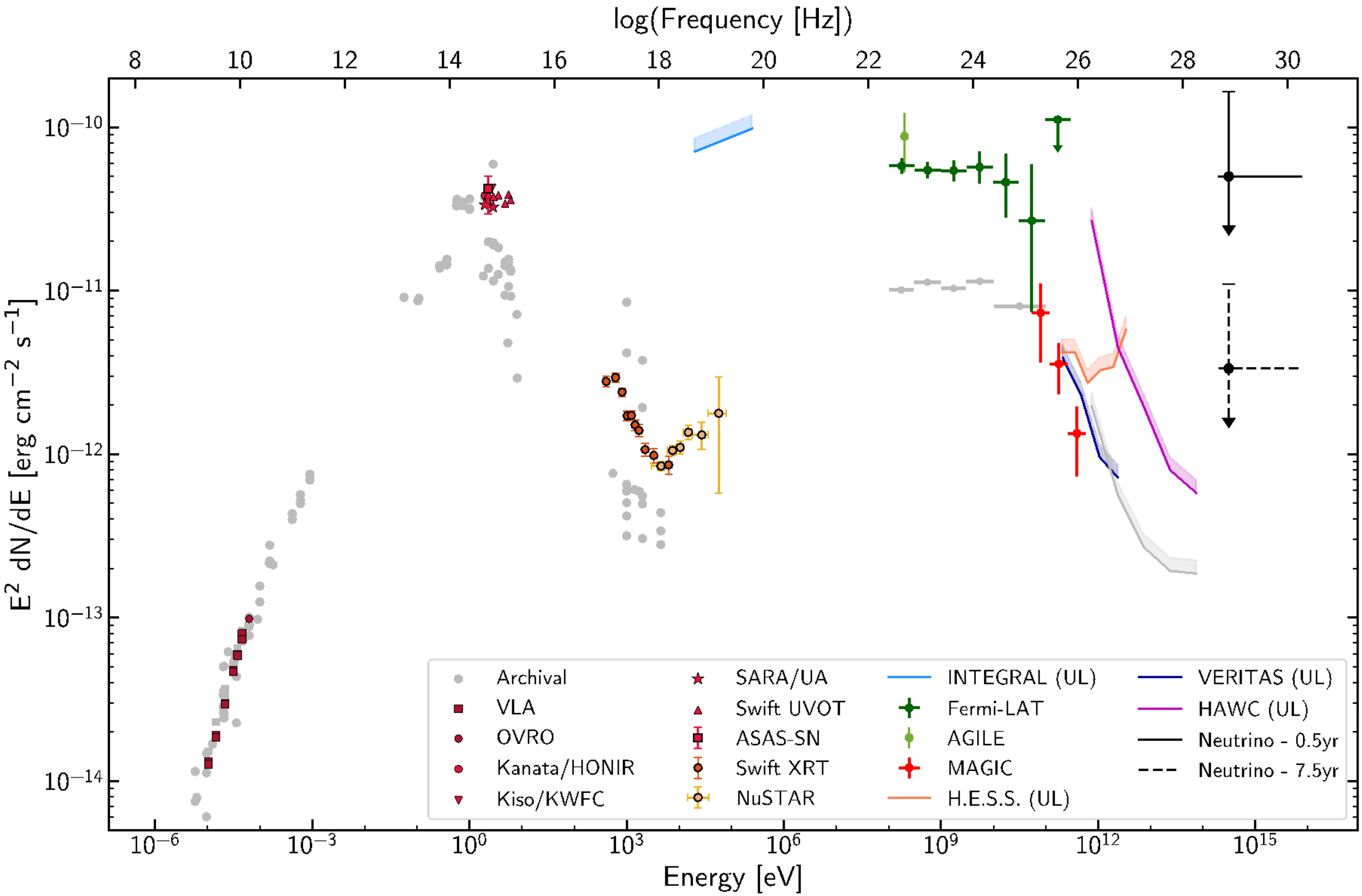
First observation at >100 GeV gamma rays





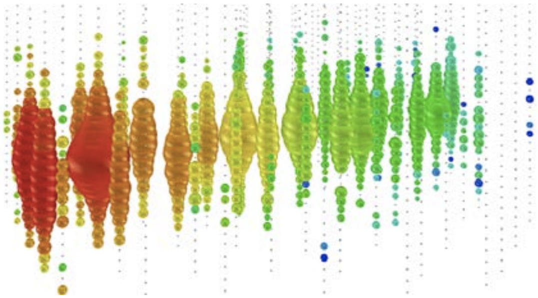
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018, VERITAS ApJL 2018

The Multi-Messenger SED

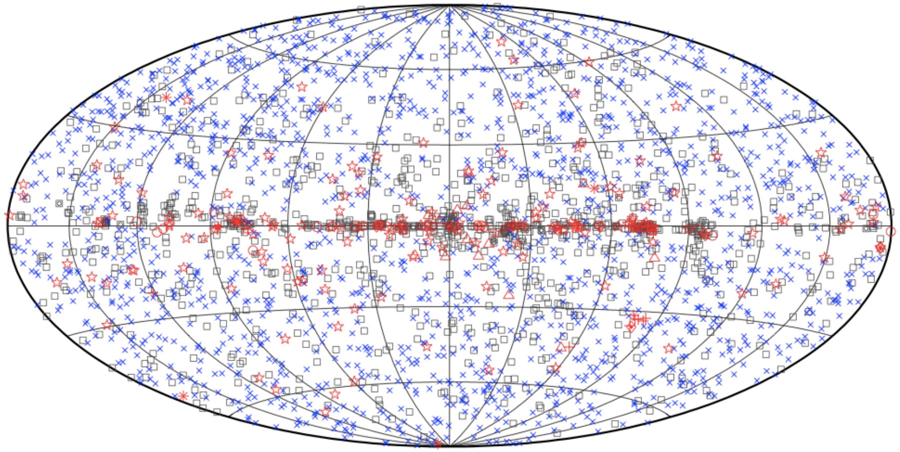


IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

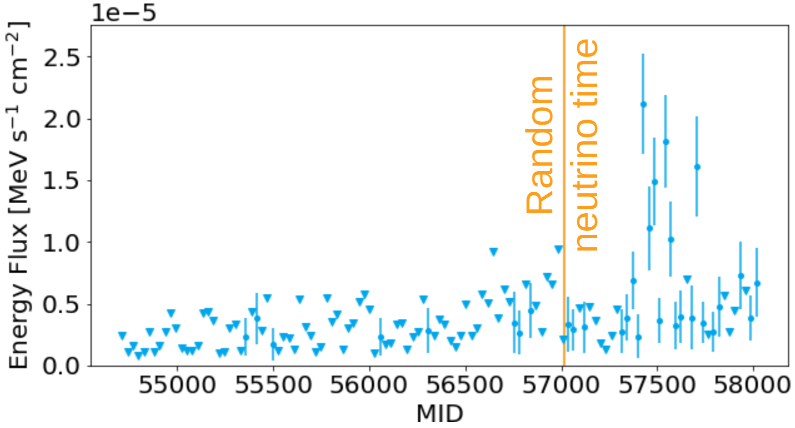
How Likely is it a Chance Probability?



Step I: Draw a random neutrino from a representative Monte-Carlo 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?

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

Background PDF

$$\mathcal{B}(\vec{x}) = \frac{\mathcal{P}_{BG}(\sin\theta)}{2\pi}$$

Signal PDF

$$\mathcal{S}(\vec{x},t) = \sum_s \frac{1}{2\pi\sigma^2} e^{-|\vec{x}_s-\vec{x}|^2/(2\sigma^2)}\, w_s(t)\, w_{\rm acc}(\theta_s)$$

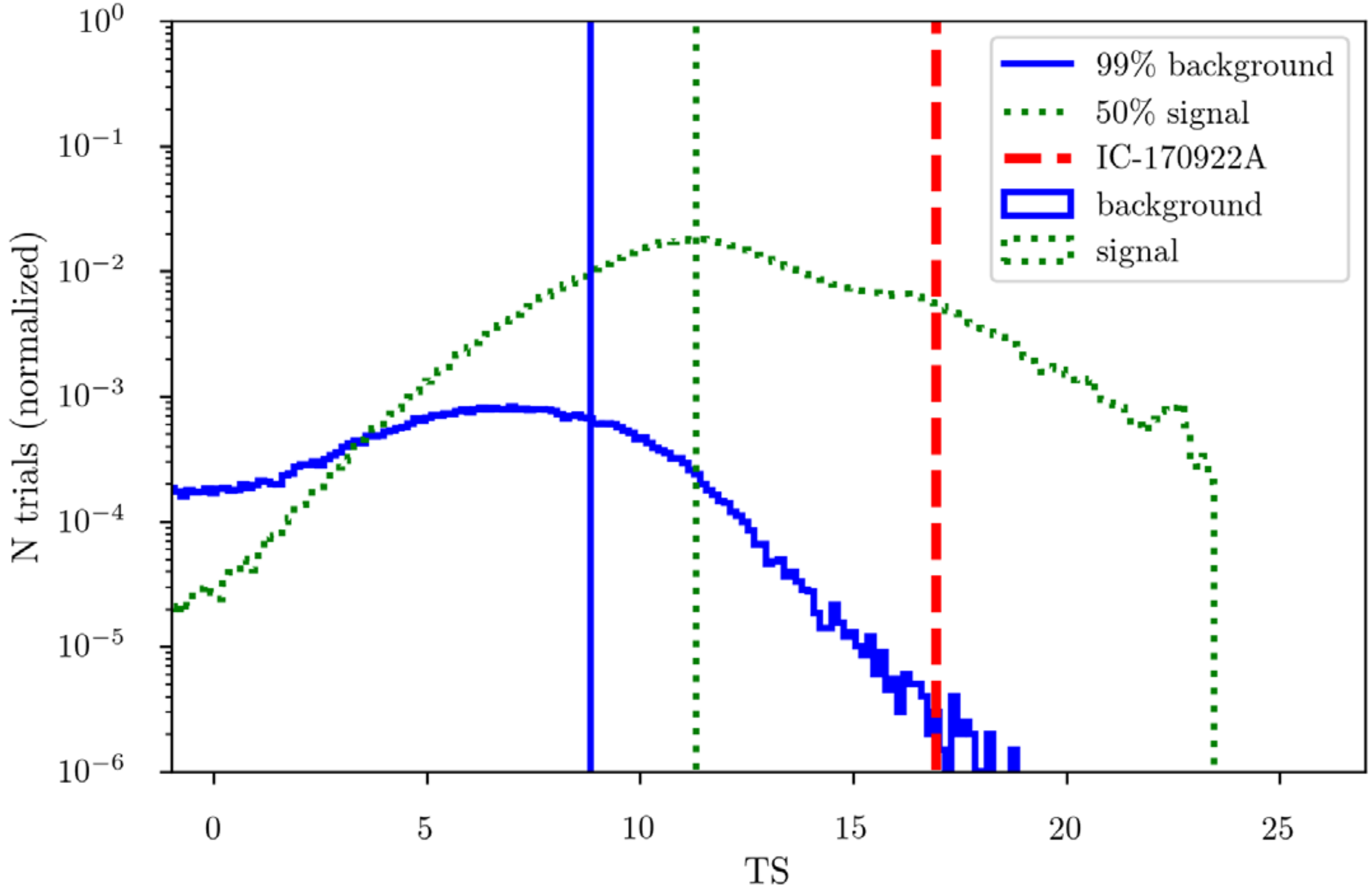
Spatial term

gamma-ray energy flux at time t

acceptance

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

10 public alerts and 41 archival events → 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

Three models tested

Neutrino emission correlates with

$$\mathcal{S}(\vec{x},t) = \sum_s \frac{1}{2\pi\sigma^2} e^{-|\vec{x}_s - \vec{x}|^2/(2\sigma^2)} w_s(t) w_{\rm acc}(\theta_s)$$

1. gamma-ray energy flux in the range 1-100 GeV

$$w_s(t) = \phi_E(t) = \int_{1\ \rm GeV}^{100\ \rm GeV} E_\gamma \frac{d\phi_\gamma(t)}{dE_\gamma} dE\gamma$$

2. relative gamma-ray flux variations in the range 1-100 GeV

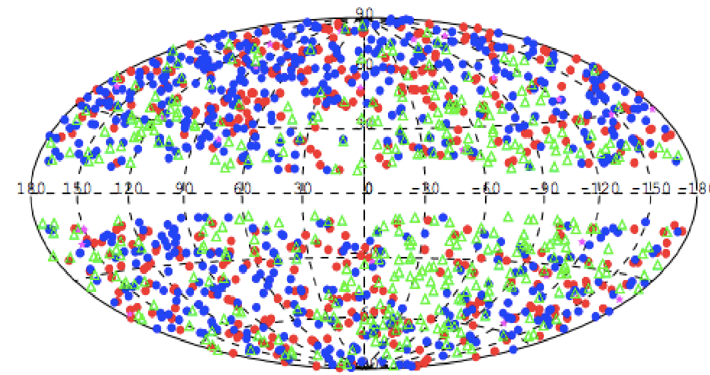
$$w_s(t) = \phi_\gamma(t) / \langle \phi_\gamma \rangle$$

3. very high-energy gamma-ray energy flux in the range 100GeV-1TeV (extrapolated from Fermi energy range)

$$w_s(t) = \phi_E(t) = \int_{100\ \rm GeV}^{1\ \rm TeV} E_\gamma \frac{d\phi_\gamma(t)}{dE_\gamma} dE\gamma$$

All tested models yield similar p-values

TXS 0506+056 in 3LAC



Redshift 0.3365±0.0010, Paiano et al. 2018

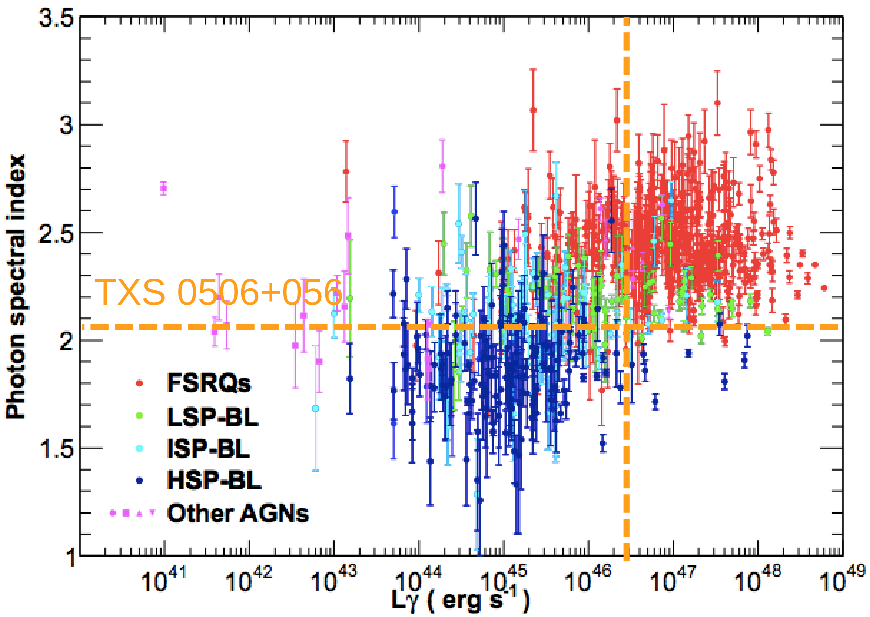
Among 50 brightest blazars (3%) in 3LAC

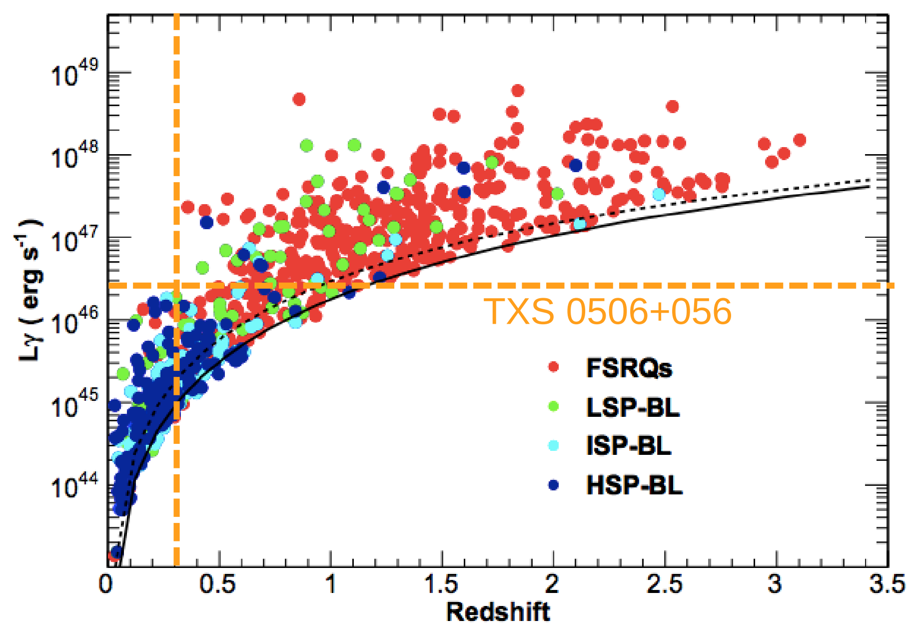
bright radio sources (0.3%), Padovani et al. 2018

Intermediate synchrotron peak (ISP), BL Lac, if classified by line width

"masquerading BL Lac" , Padovani et al. 2019

based on radio and O II luminosities, emission line ratios, Eddington ratio



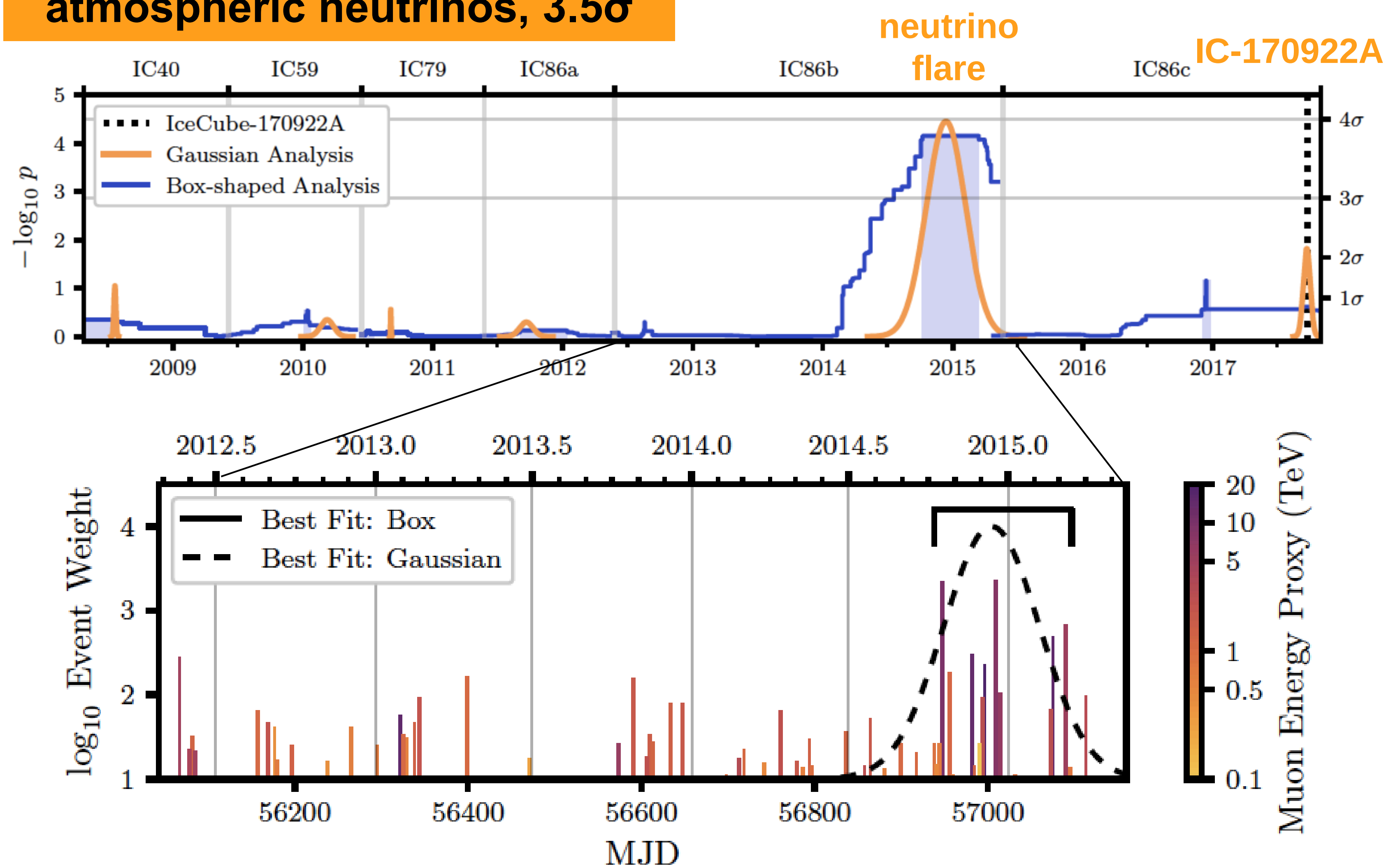


Fermi-LAT Collaboration, ApJ 810 (2015)

Are there more Neutrinos from this Source?

Are there more Neutrinos from this Source?

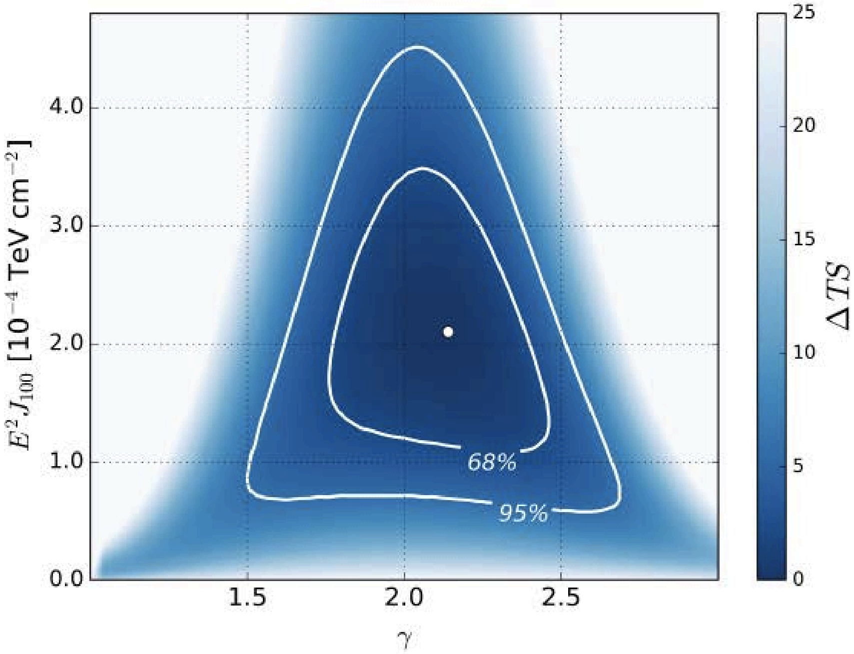
13±5 above the background of atmospheric neutrinos, 3.5σ

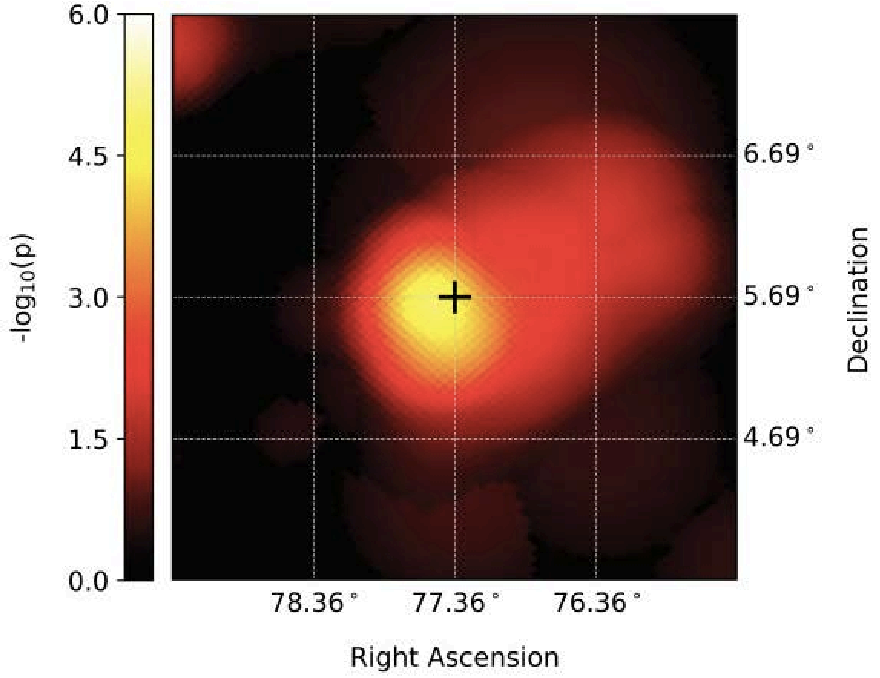


IceCube Coll.,Science 2018

Neutrino Flare Properties

neutrino spectral
parameter fit



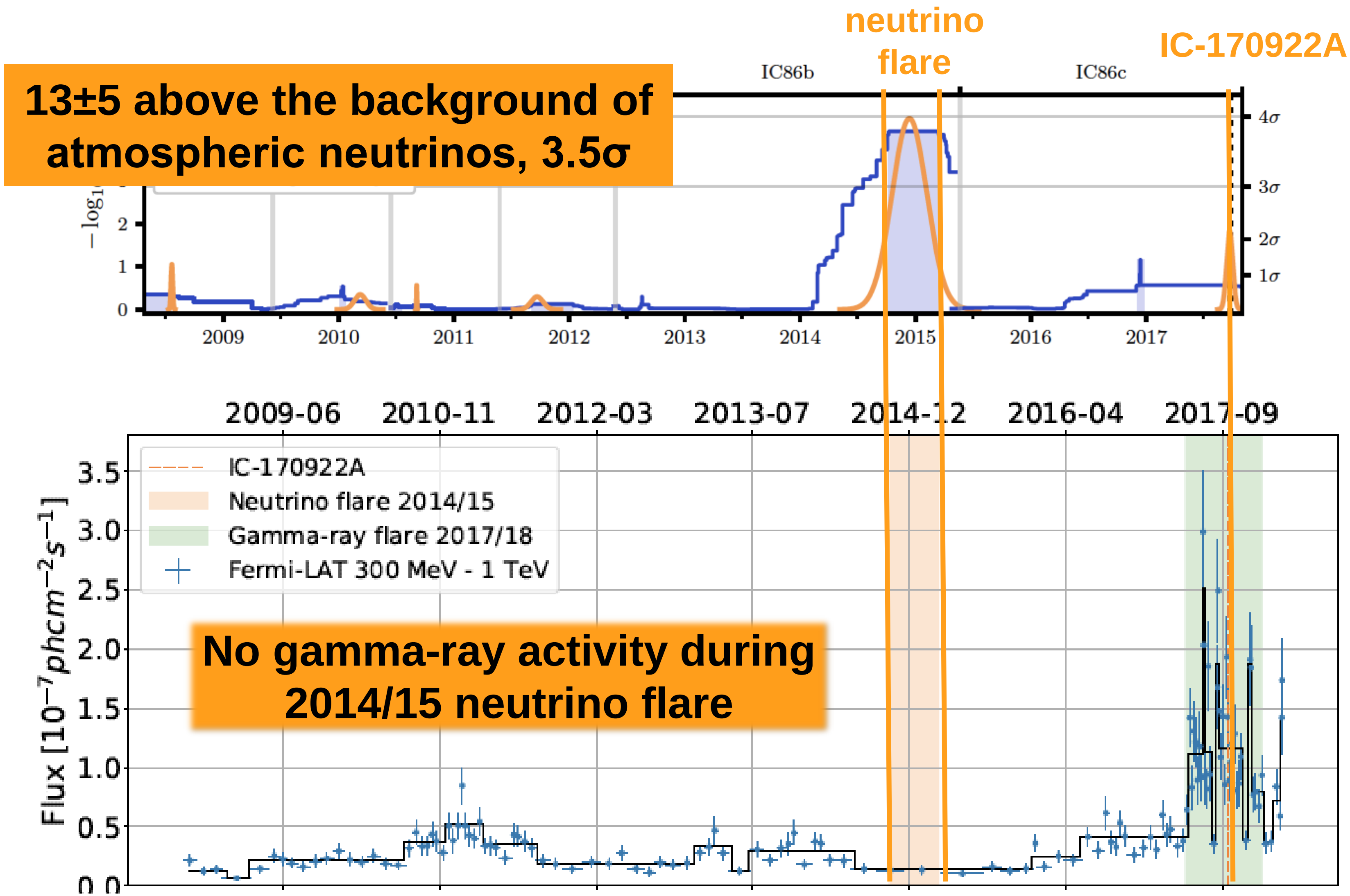


Neutrino luminosity (averaged over 158 days): $(1.2^{+0.6}_{-0.4}) \times 10^{47}$ erg s^{-1}

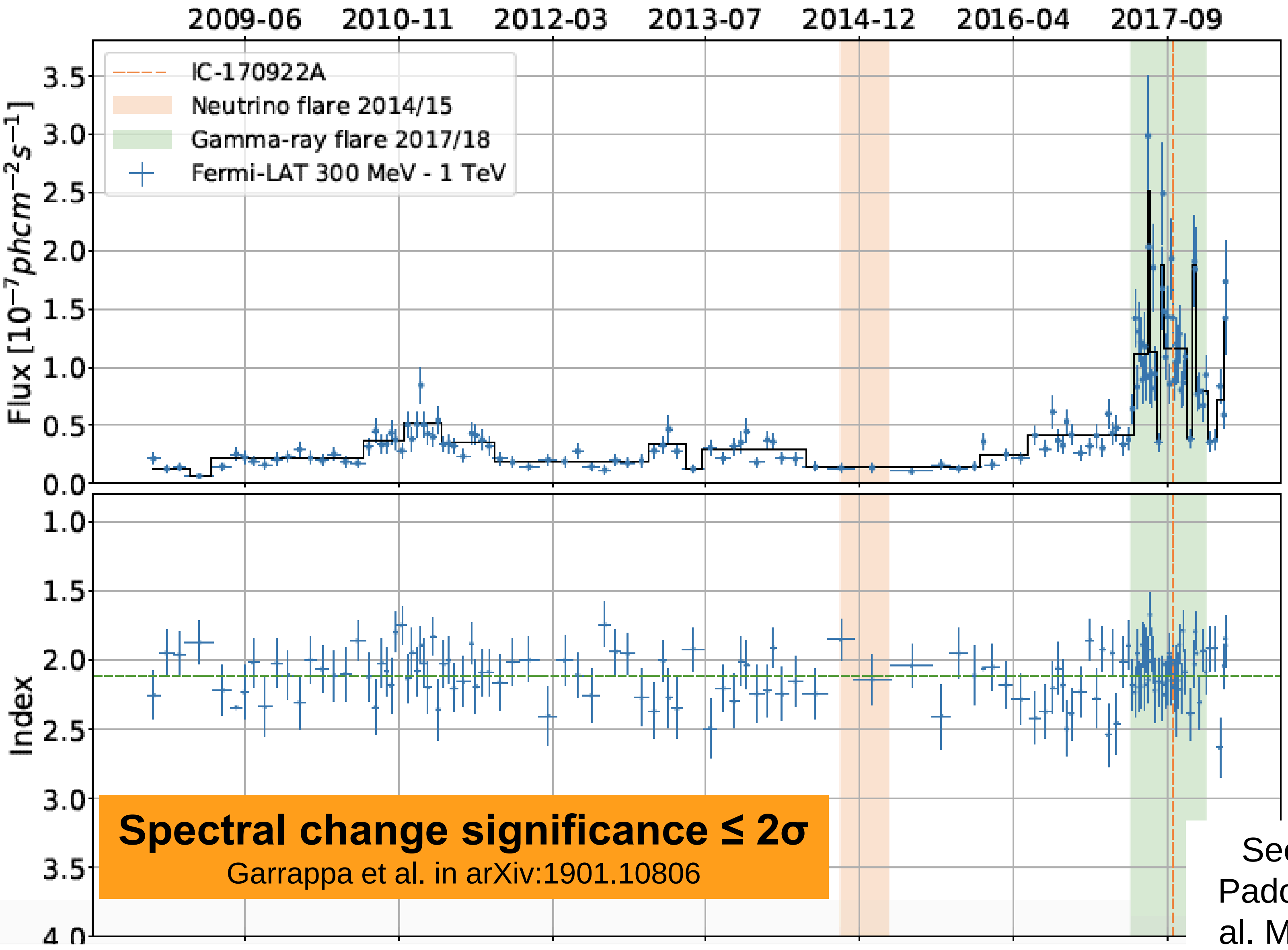
4 times larger than average gamma-ray luminosity!

IceCube Coll.,Science 2018

Is there also a Gamma-ray Flare?



Spectral Change?

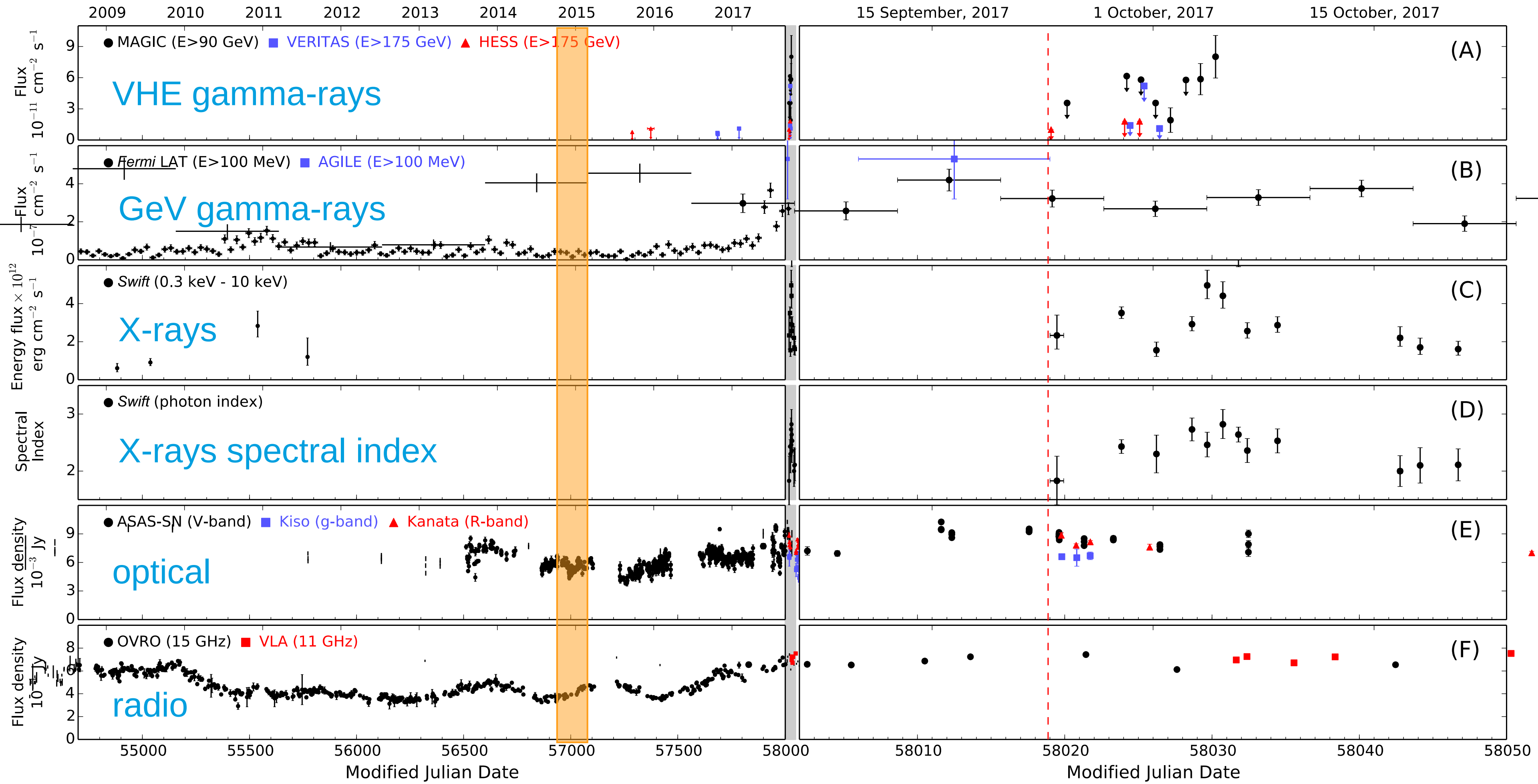


Spectral change significance ≤ 2σ

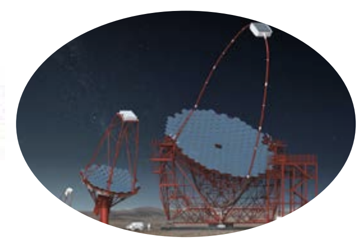
Garrappa et al. in arXiv:1901.10806

See also Padovani et al. MNRAS, 2018

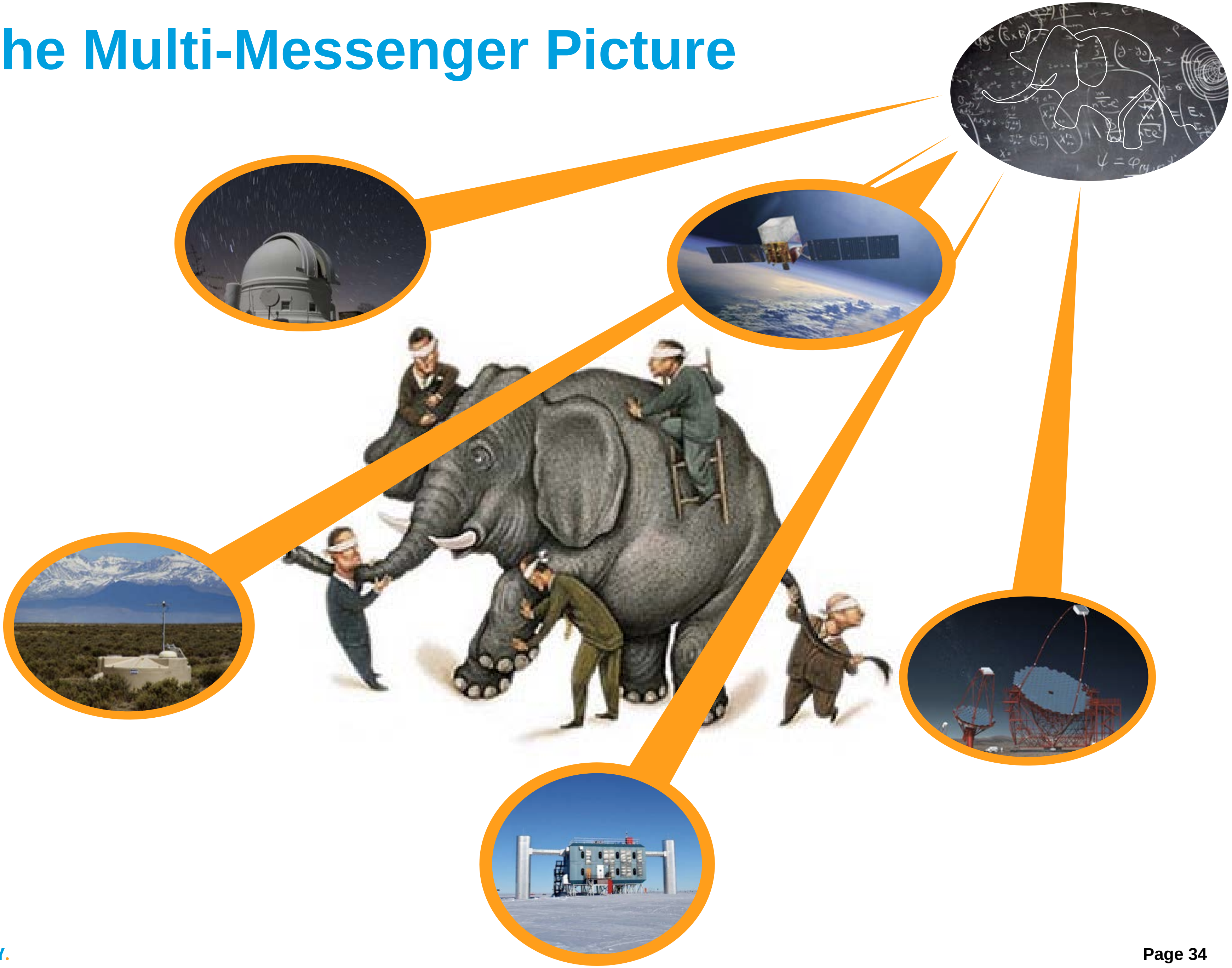
The Multi-Messenger Light Curve

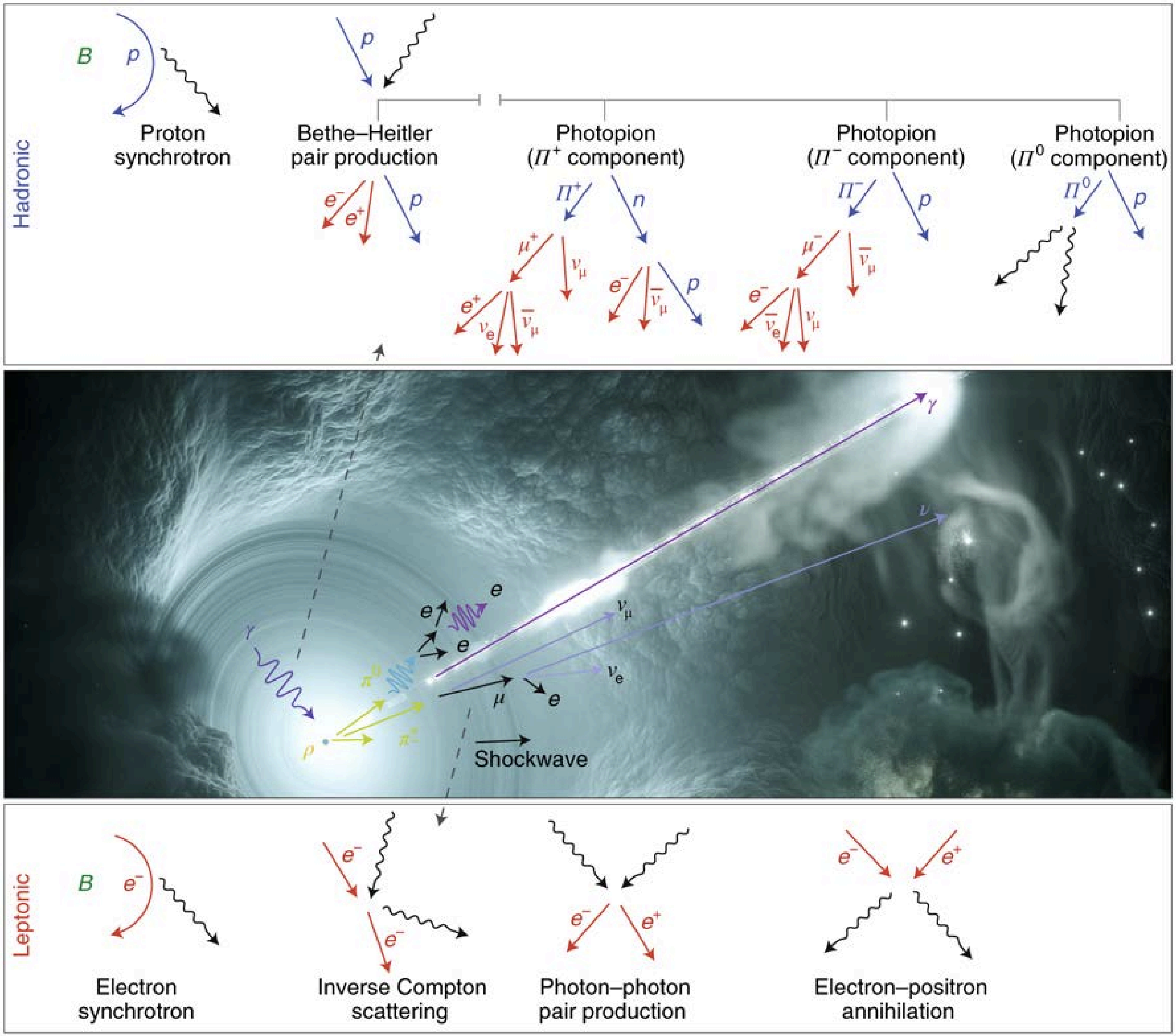


The Multi-Messenger Picture



The Multi-Messenger Picture



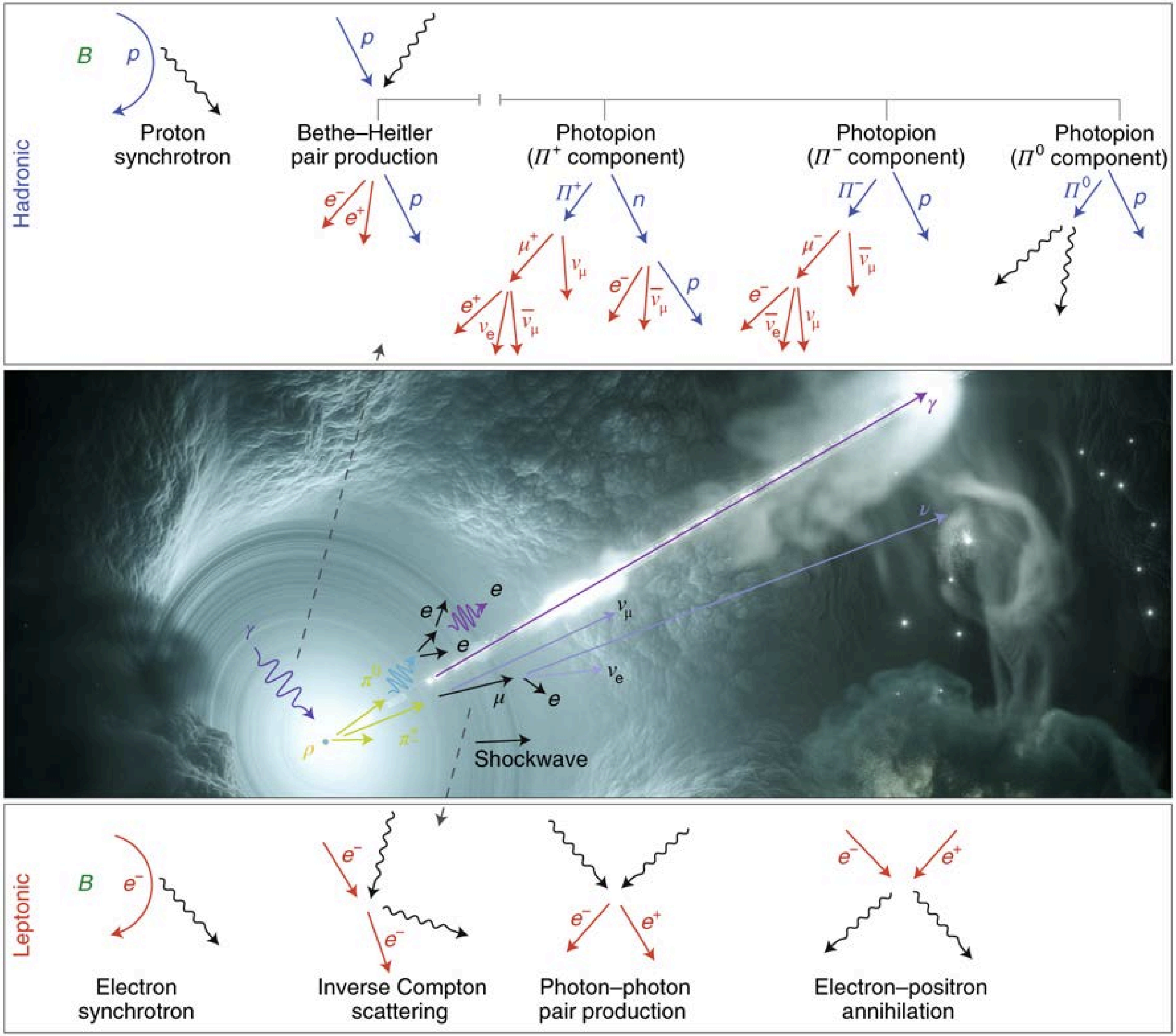


Production of ~300 TeV neutrinos need

- ~PeV protons
- photon target

Photon target

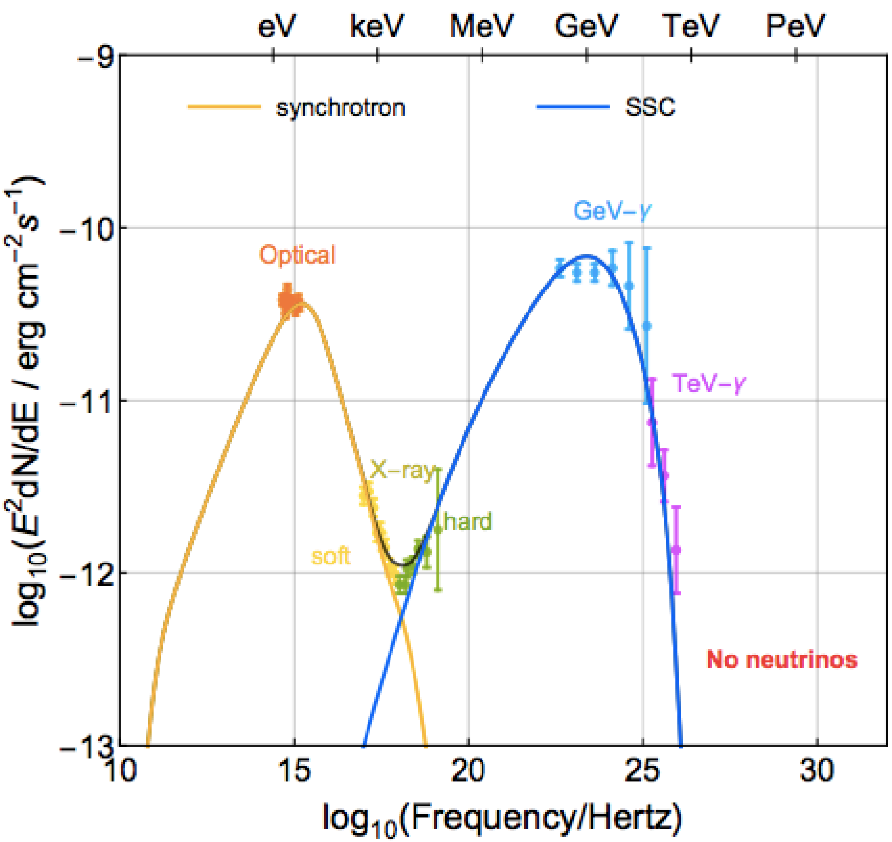
- observed in X-rays (~keV) if moving with the jet
- observed in UV (~10eV) if stationary



Electromagnetic cascade dominated by synchrotron or inverse Compton emission

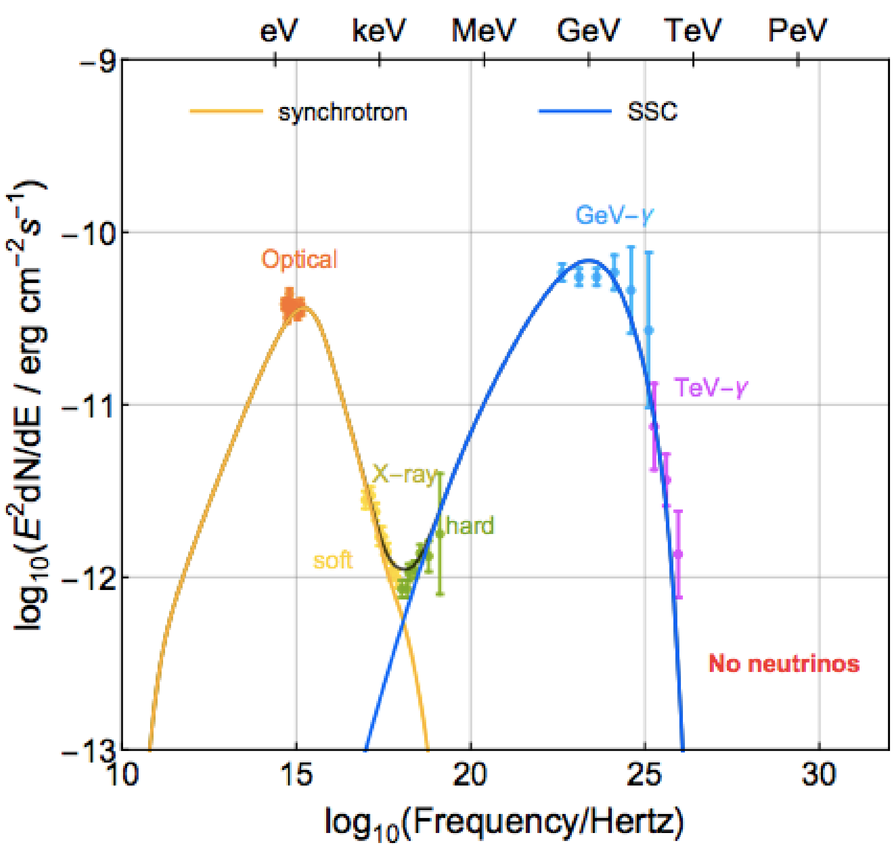
- Broadband EM emission from radio to γ-rays
- Absorption of high-energy γ-ray emission
- Additional target for p-γ interactions

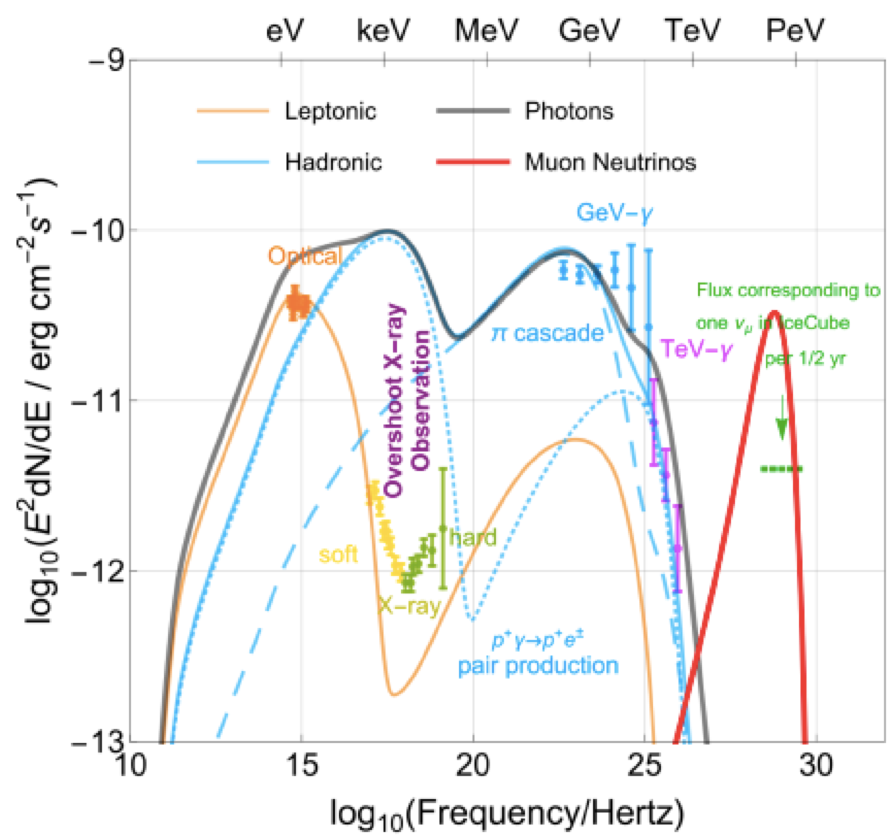
Modeling – leptonic



Gao et al., Keivani et al., Murase et al.

Modeling – leptonic, hadronic



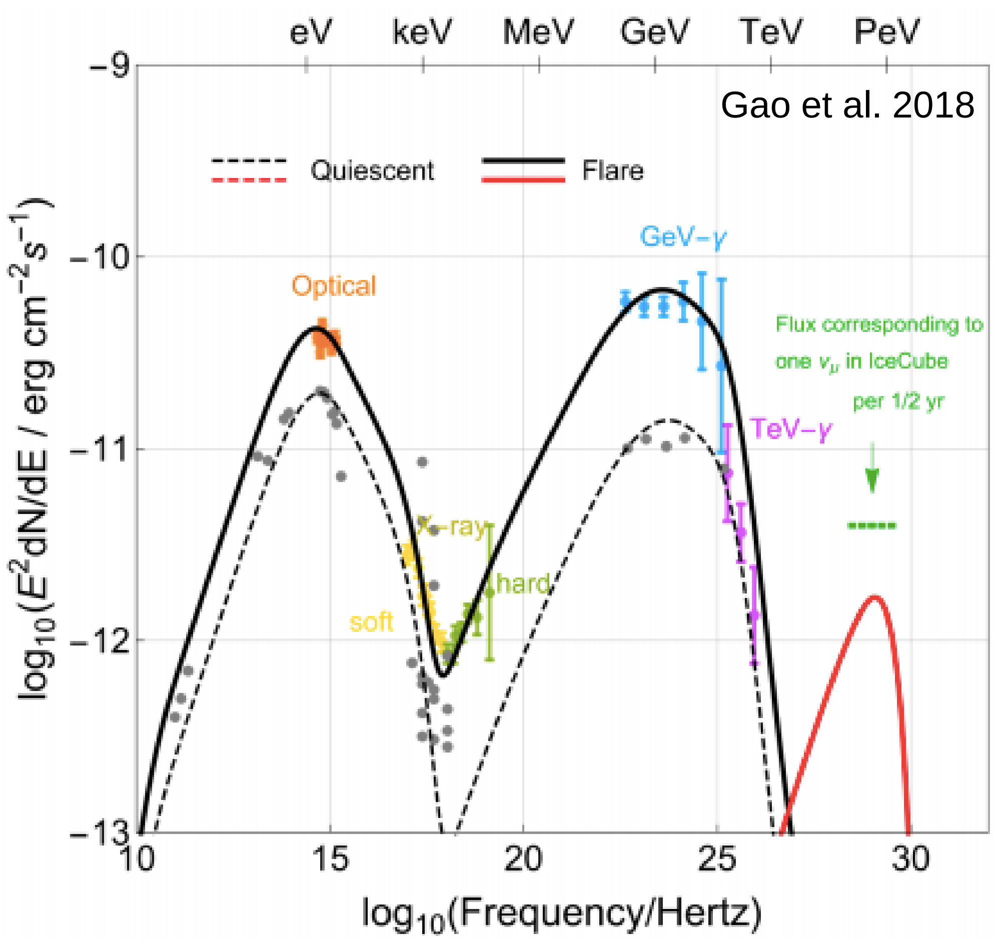


Simple one-zone hadronic models violate X-ray constraints
→ More complex models needed

Gao et al., Keivani et al., Murase et al.

Modeling – leptonic, hadronic, Gin & Tonic

2017 neutrino + gamma flare:



Gao, Fedynitch, Winter, Pohl, Nature Astronomy 2018, Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018 …

2014/15 neutrino flare:

neutrino luminosity is ~4 times higher than gamma-ray luminosity

→ challenge for models

see e.g.
Rodrigues et al. arXiv:1812.05939
A. Reimer et al. arXiv:1812.05654,
F. Halzen et al., arXiv:1811.07439

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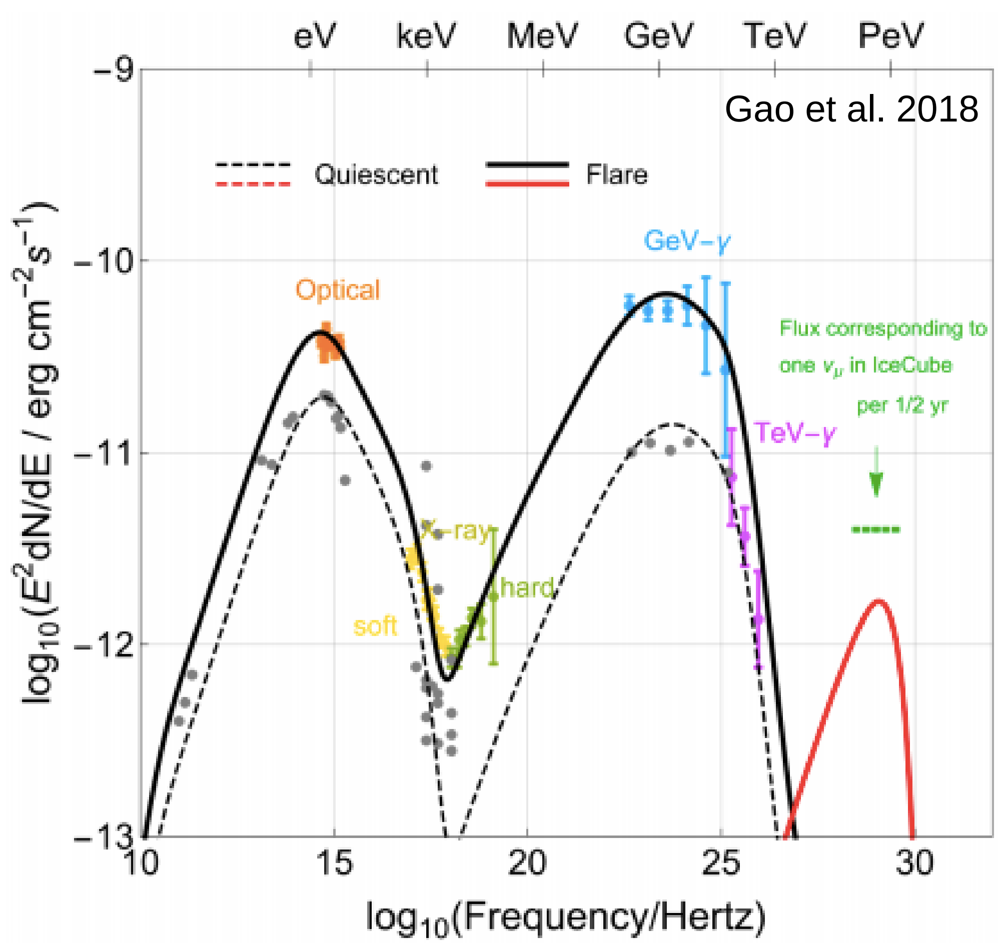

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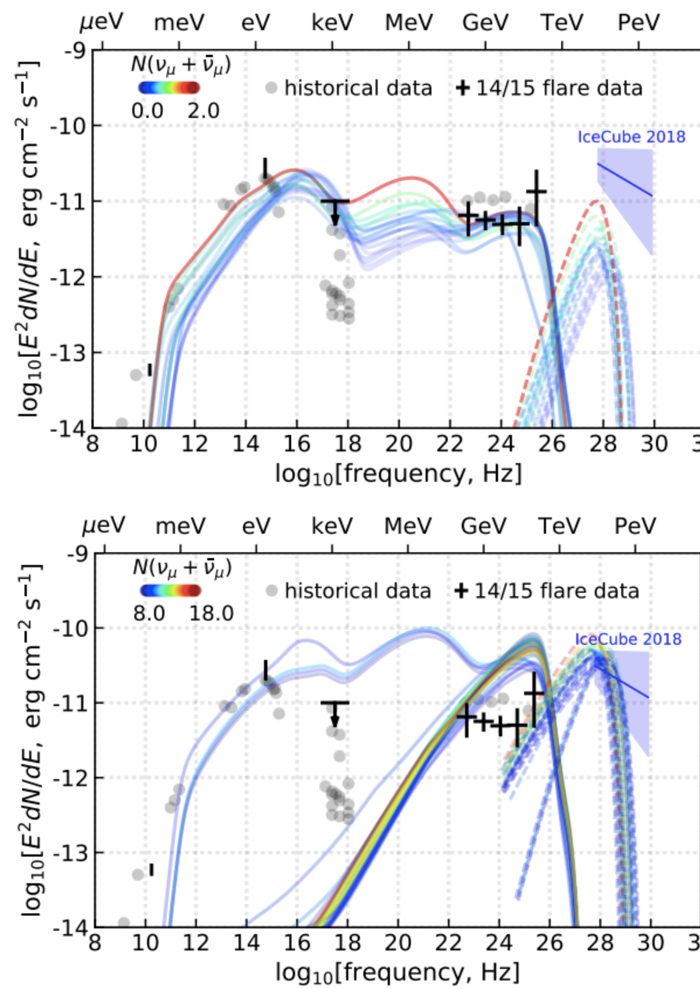
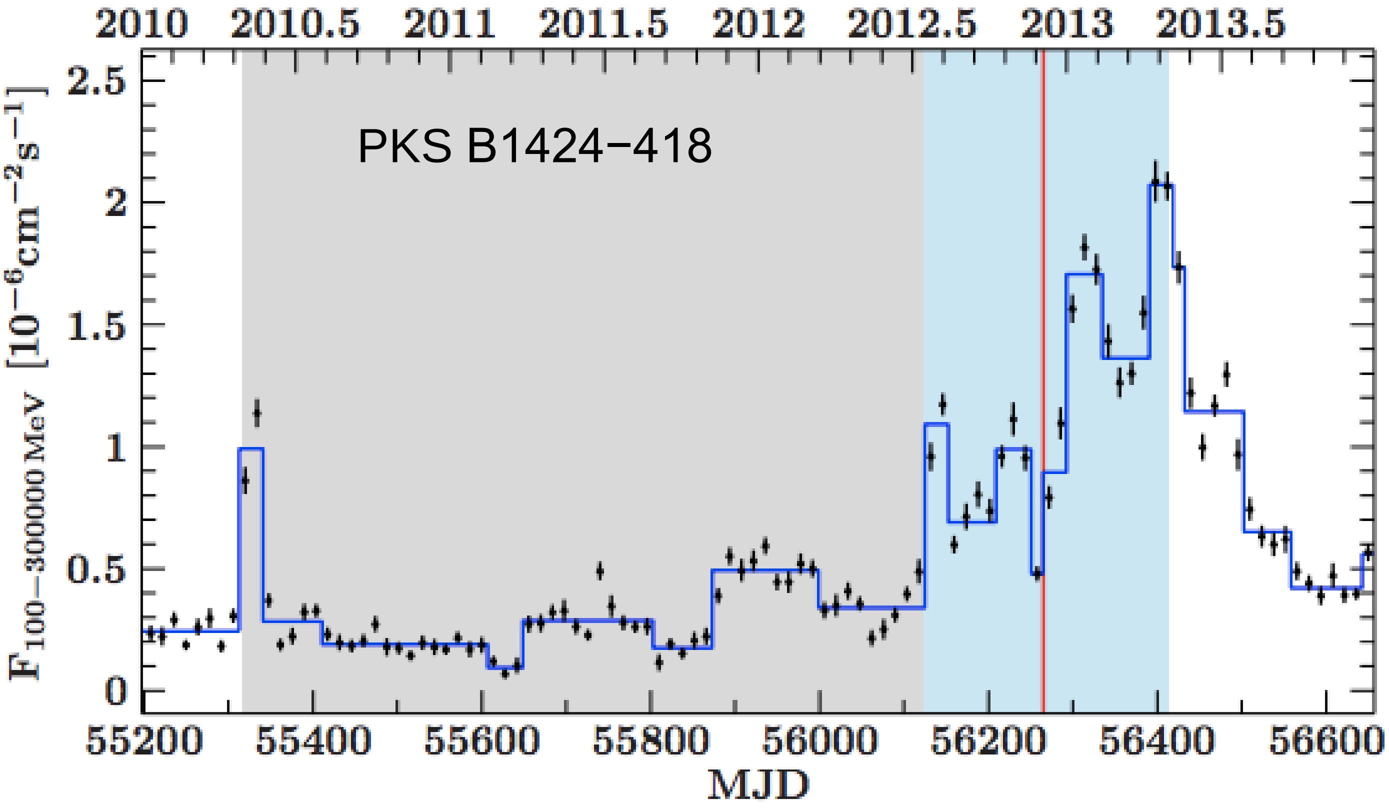


Rodrigues et al. arXiv:1812.05939

Other interesting candidates

Blazar + high-energy cascade

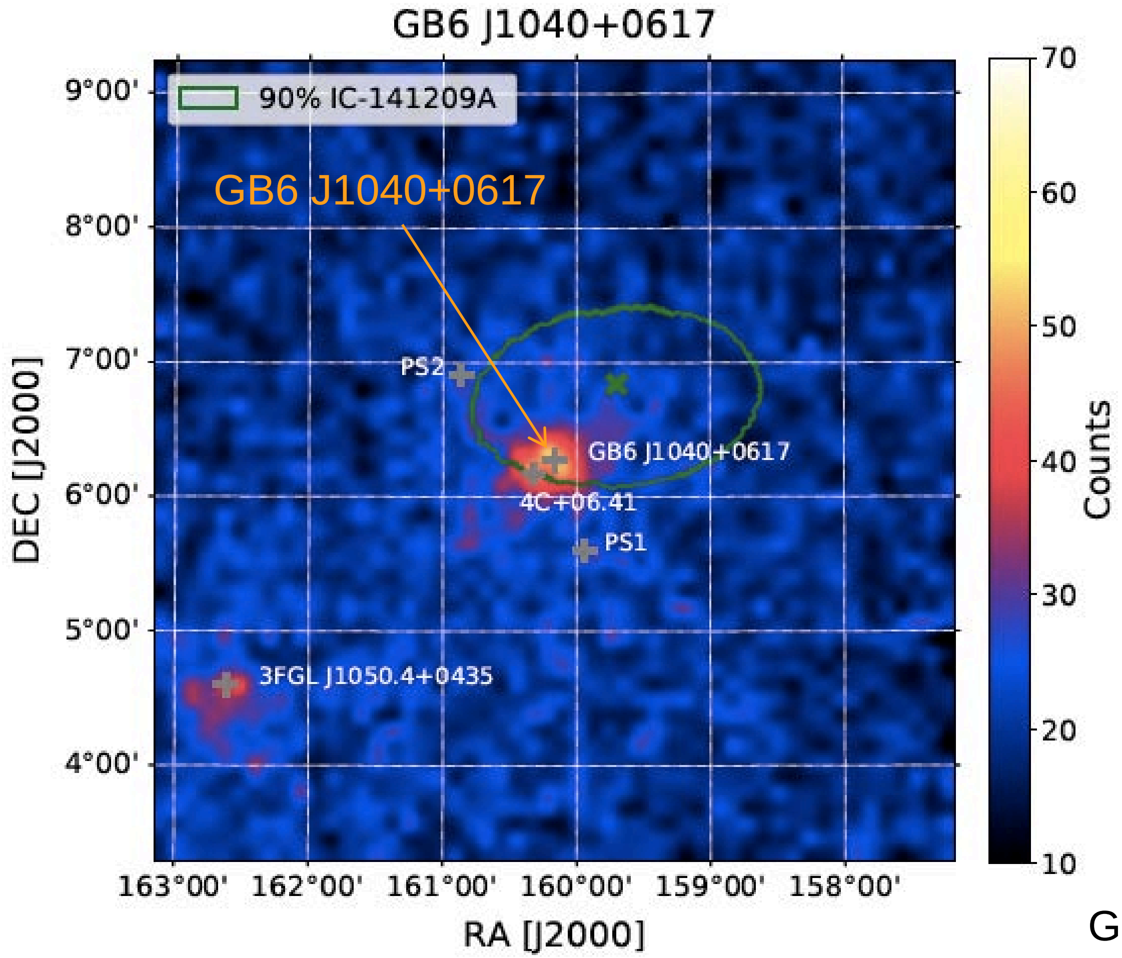


5% chance coincidence

Kadler et al., Nature Physics 2016

Other interesting candidates

Systematic search for Fermi-LAT catalogued counterparts (3FHL, 3FGL) to 37 well-reconstructed IceCube real-time alerts and archival events revealed on more coincidence. Chance coincidence ~30%

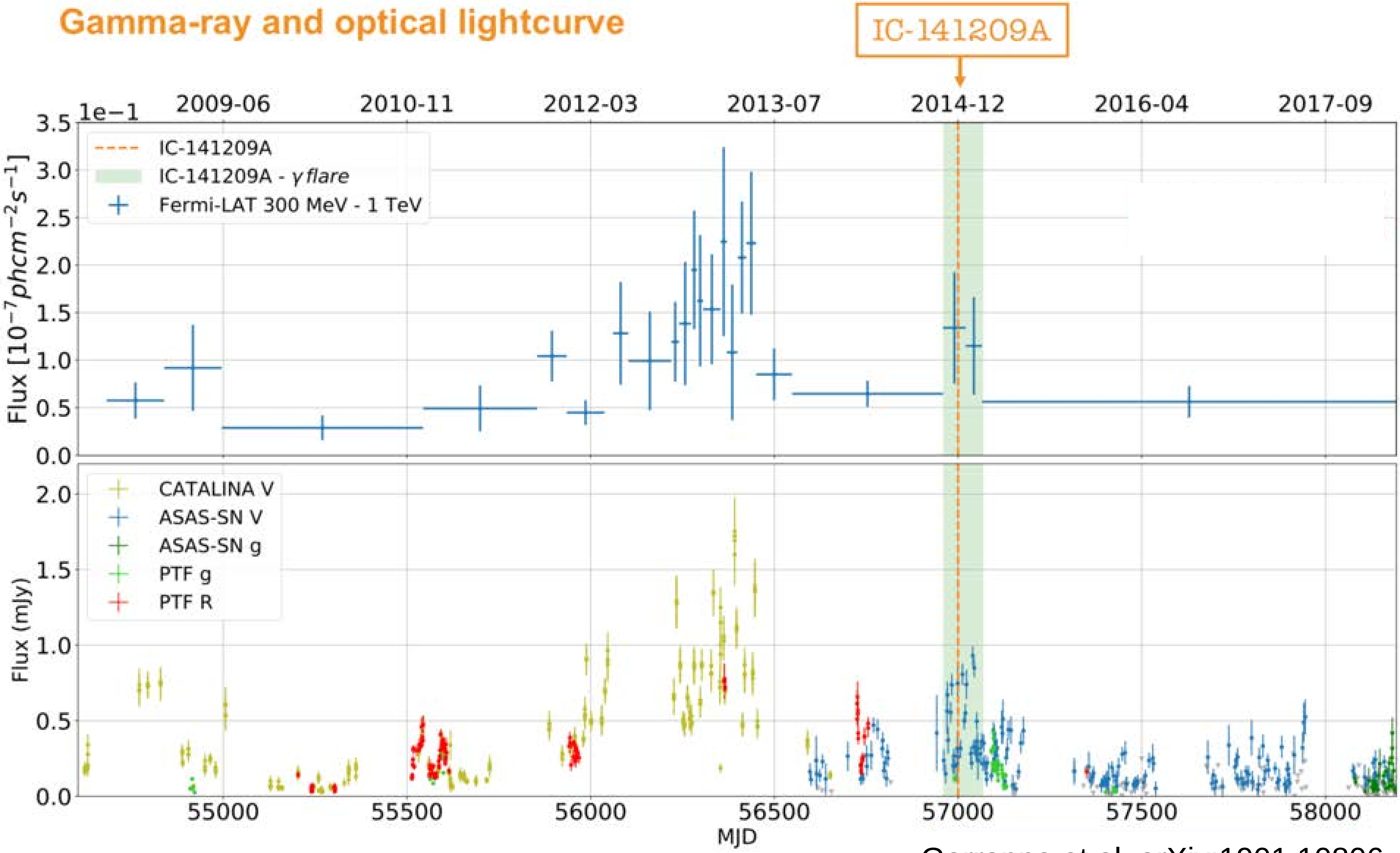


Garrappa et al. arXiv:1901.10806

Other interesting candidates

Not significant if weighted with gamma-ray energy flux

Gamma-ray and optical lightcurve



Garrappa et al. arXiv:1901.10806

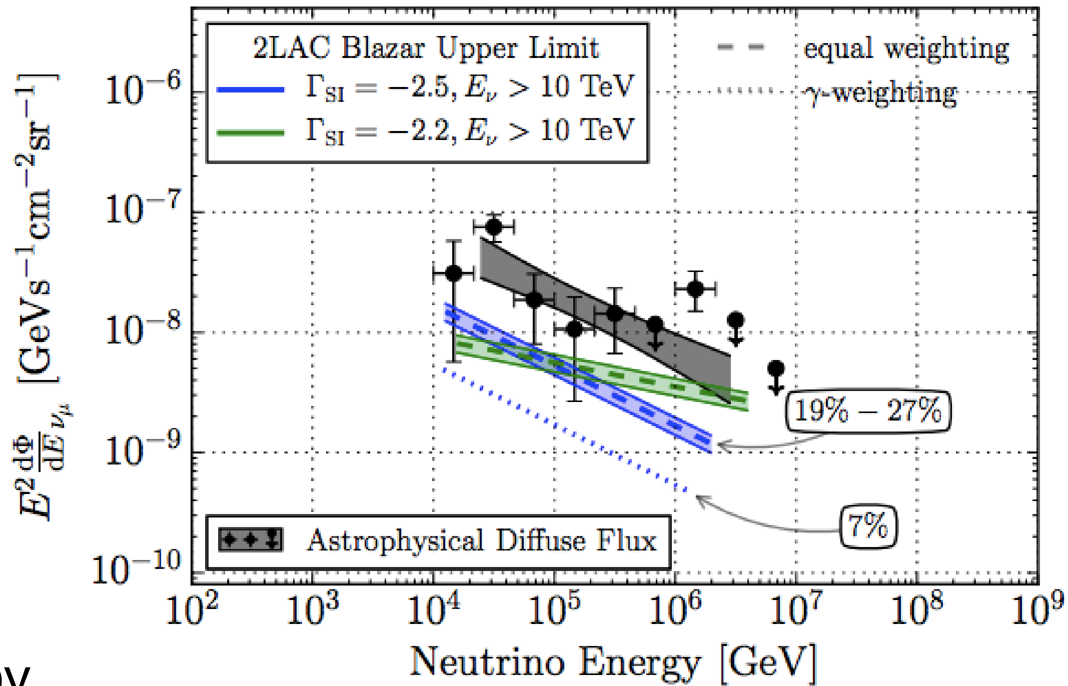
Do blazars produce all IceCube neutrinos?

- 40 well-reconstructed track events, 20 signal events, 1-2 blazar/neutrino coincidences → ~10% contribution

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)

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



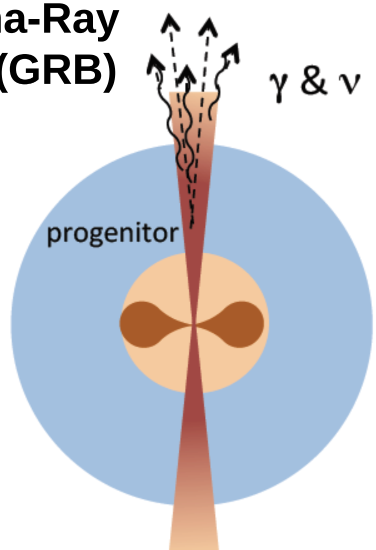
Averaged over 9.5 years, the neutrino flux of TXS 0506+056 by itself corresponds to 1% of the astrophysical diffuse flux

Fully compatible with blazar catalog stacking results

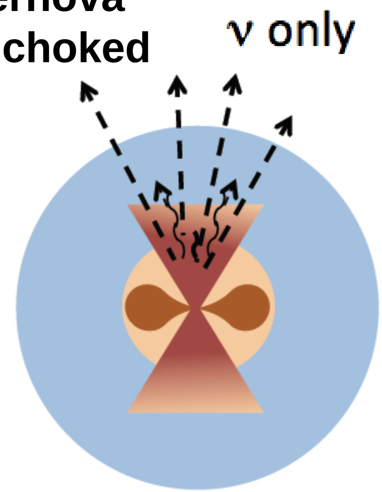
IceCube, ApJ, 835 (2017)

Other neutrino source candidates

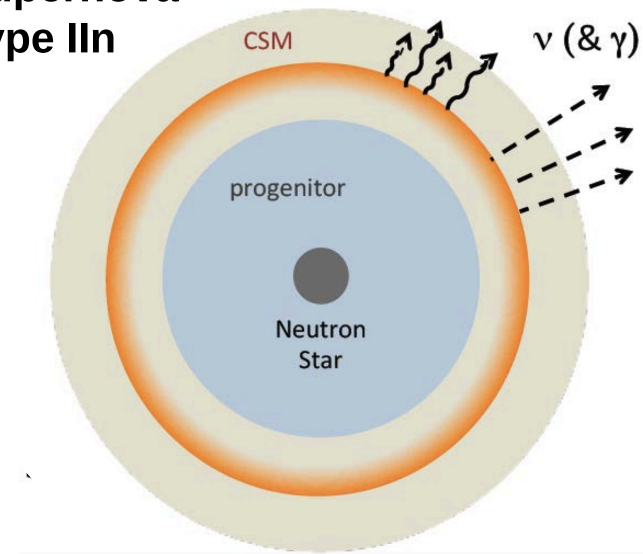
Gamma-Ray Burst (GRB)



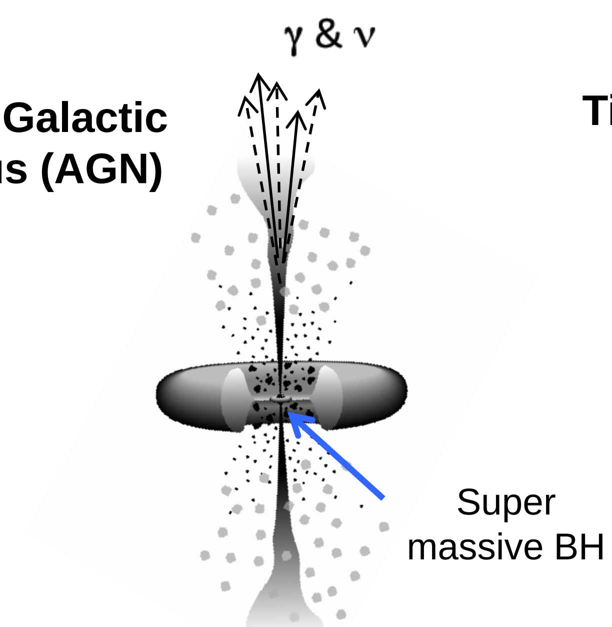
Supernova with choked jets



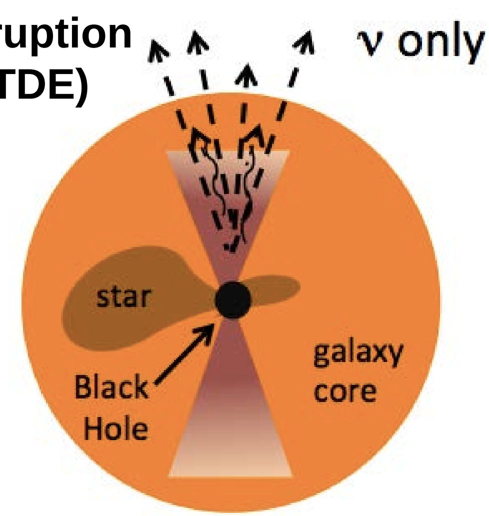
Supernova Type IIn



Active Galactic Nucleus (AGN)



Tidal Disruption event (TDE)



Other neutrino source candidates

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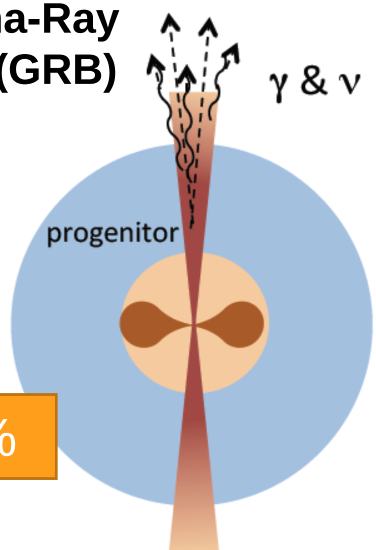
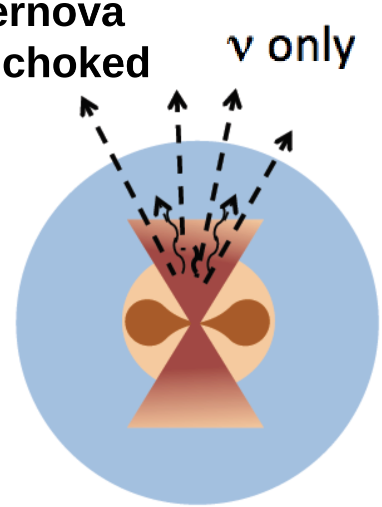


<1%

Supernova with choked jets



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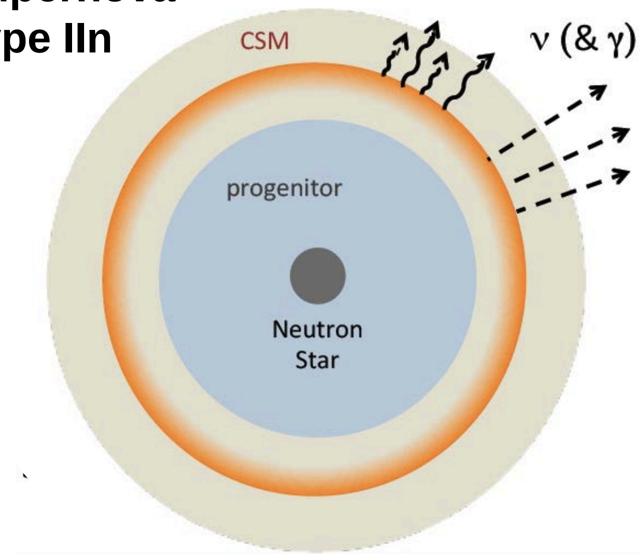

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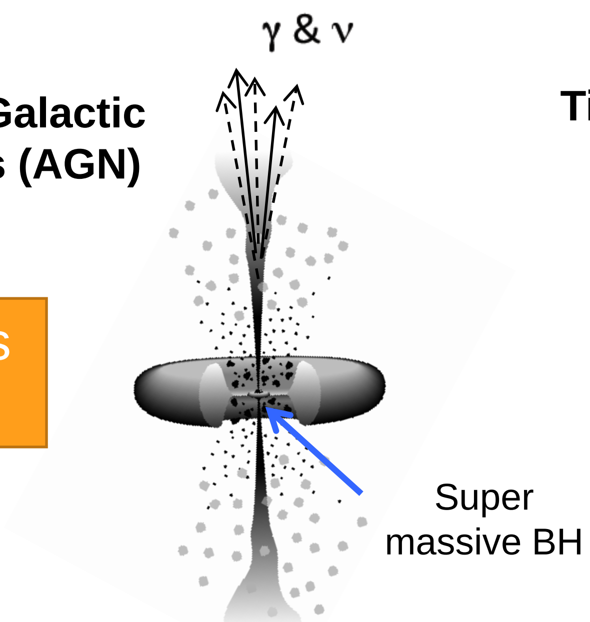
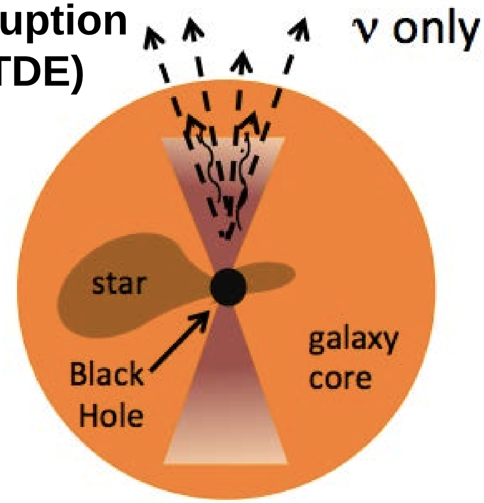
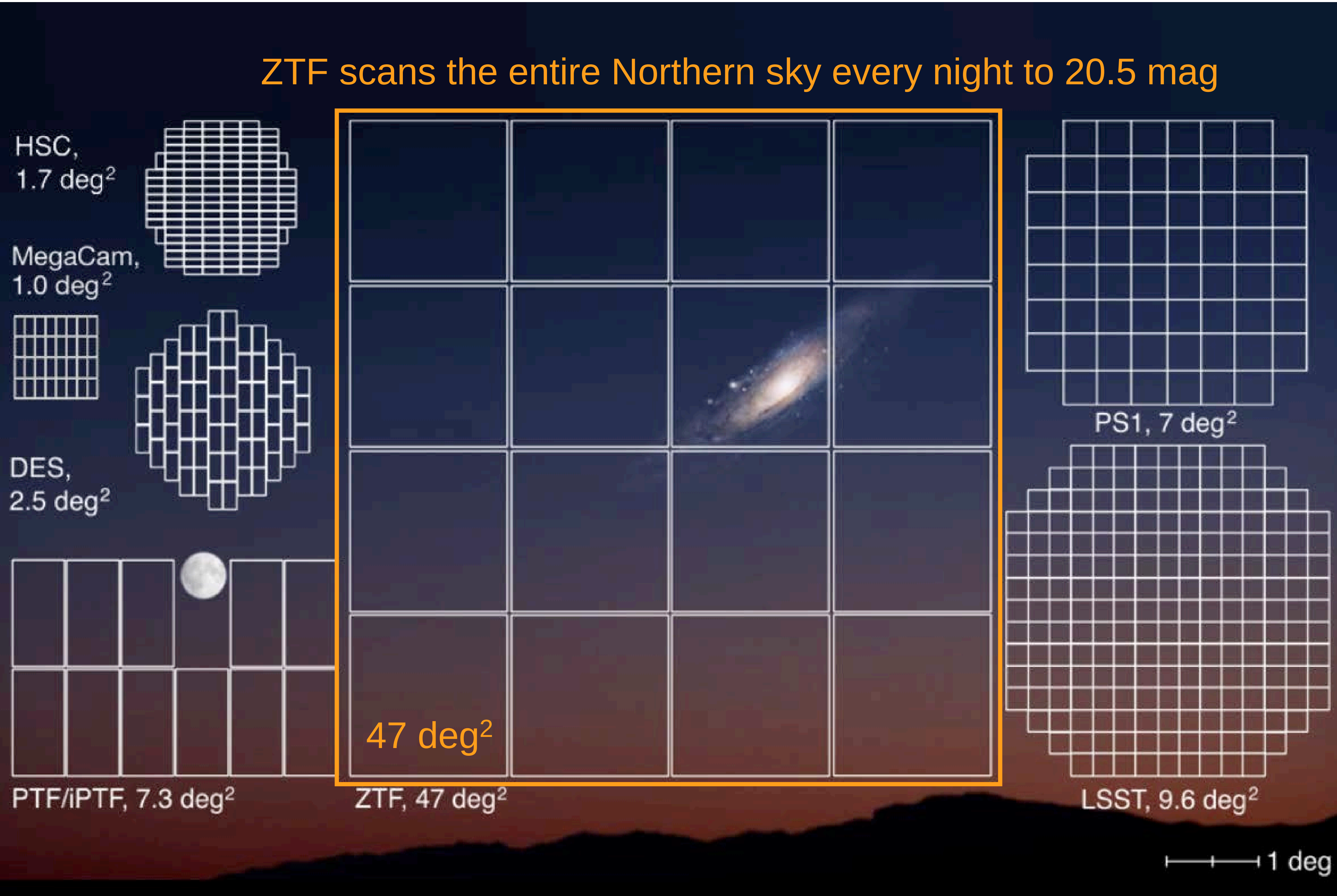


blazars <30%

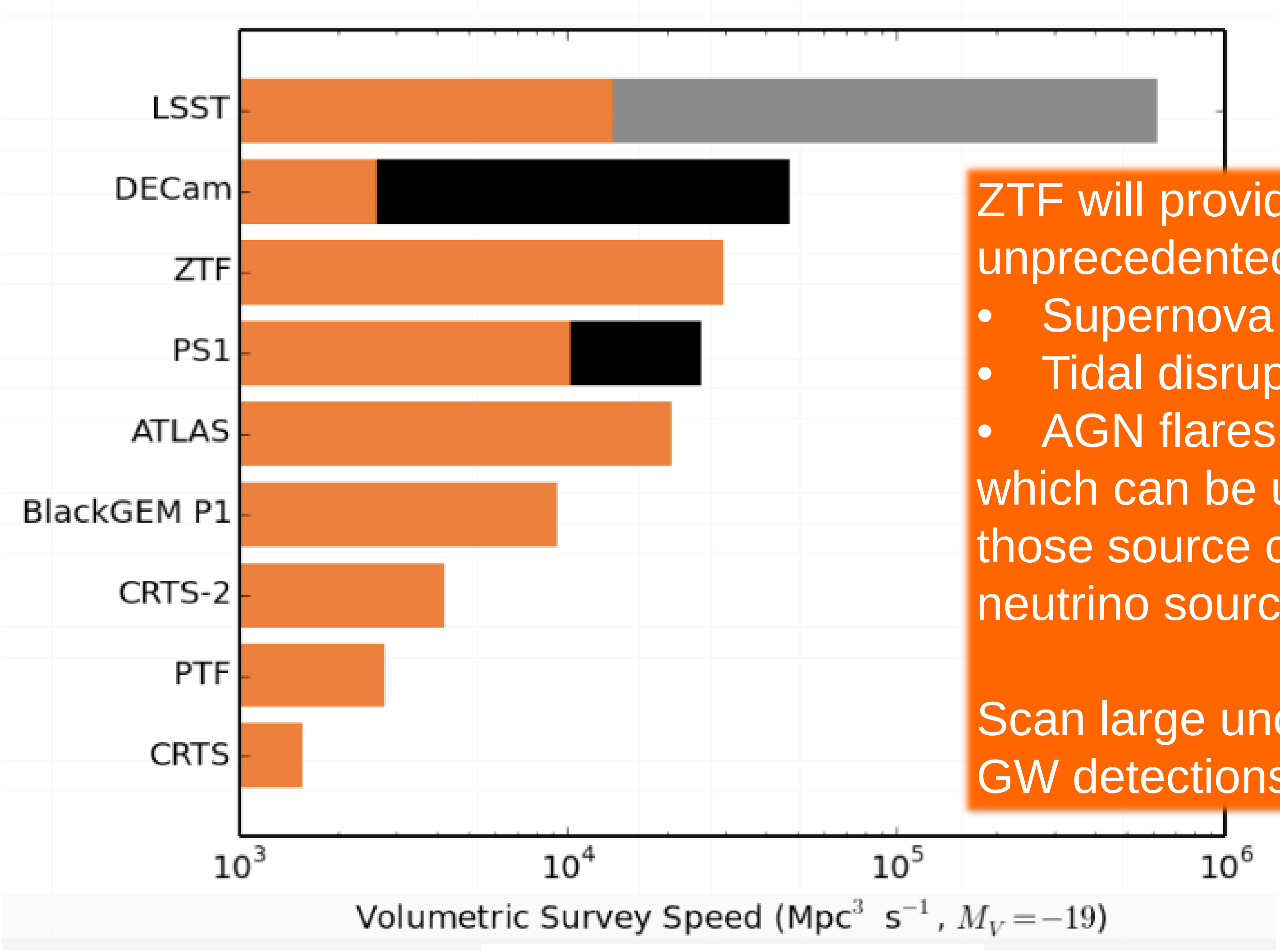
Tidal Disruption event (TDE)



Zwicky Transient Facility



ZTF will reach world-leading speed in finding spectroscopically-accessible transients



ZTF will provide an unprecedented catalog of

- Supernova
- Tidal disruption events
- AGN flares

which can be used to probe those source classes as neutrino sources

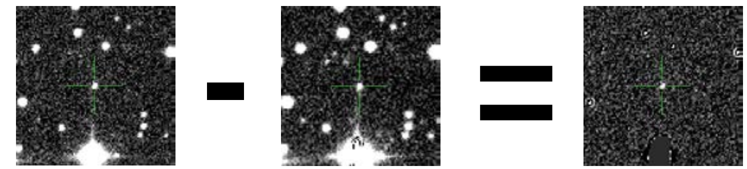
Scan large uncertainties of GW detections

$$\dot{V}_M = \frac{\Omega_{\rm fov}}{4\pi} \frac{V_{\rm c}(z_{\rm lim}(M, t_{\rm exp}))}{t_{\rm exp} + t_{\rm OH}}$$

AMPEL

Alert Management, Photometry and Evaluation of Light curves

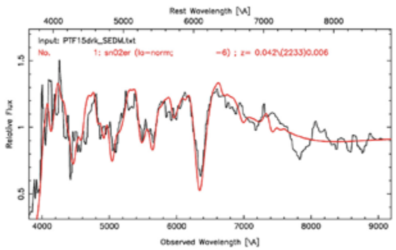
NEW - REF = SUB



ZTF

alert stream

Spectroscopy



trigger

Event selection

Real-time analysis tools:
Photometric redshift
Catalog matching
Light curve fitting

Archival analysis tools:
Reproducibility
Cross correlation of data sets

Storage

Farm

real-time ν-stream

IceCube

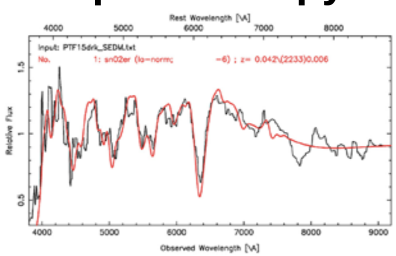
AMPEL – Towards a MM real-time center

Alert Management, Photometry and Evaluation of Light curves

ZTF ASAS-SN LSST SKA

alert stream

Spectroscopy



trigger

γ-ray light curve

IACT follow-up

Event selection

Real-time analysis tools:
Photometric redshift
Catalog matching
Light curve fitting

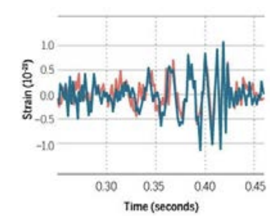
Archival analysis tools:
Reproducibility
Cross correlation of data sets

Storag e

Farm

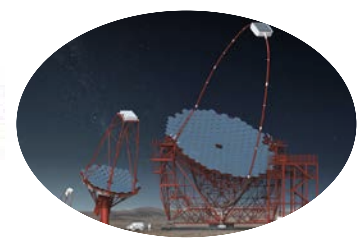
real-time ν-stream

ICECUBE



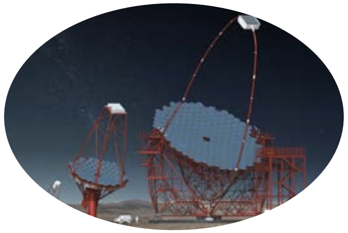
gravitational wave triggers

Summary



unique messengers from the
high-energy Universe

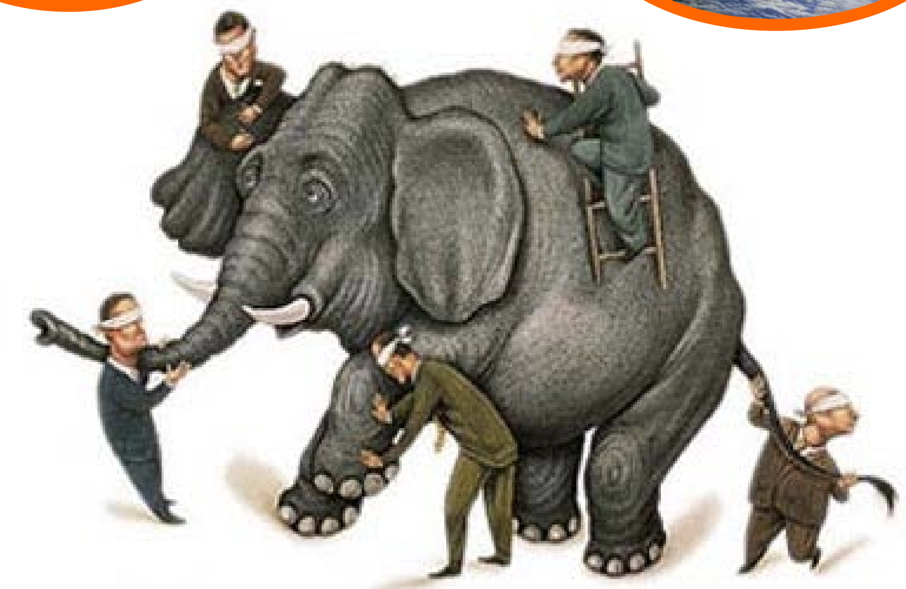
Summary

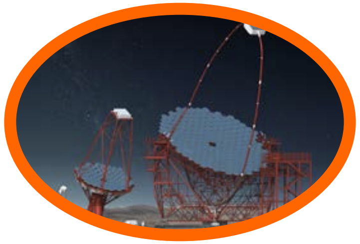


Neutrinos can reveal the sources of high-energy cosmic rays

Summary

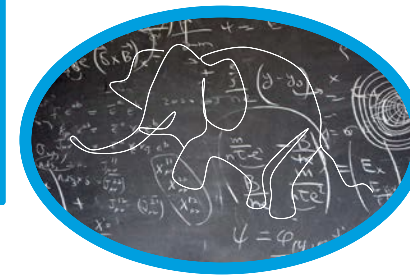
Sources still unknown → Electro-magnetic counterparts are crucial to identify the sources
First compelling candidate found!

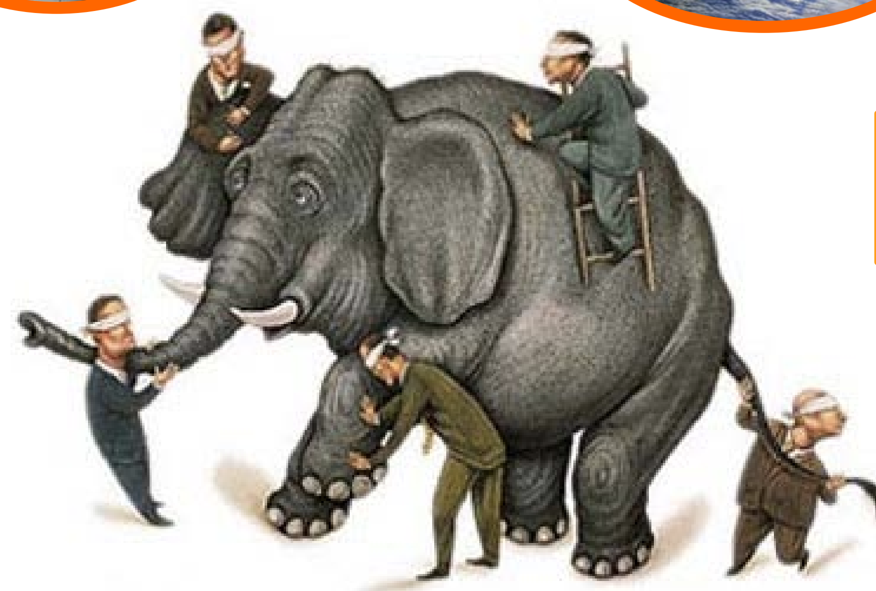




Summary

Development of models describing **all** multi-messenger data in a consistent way.





Probe other source classes.