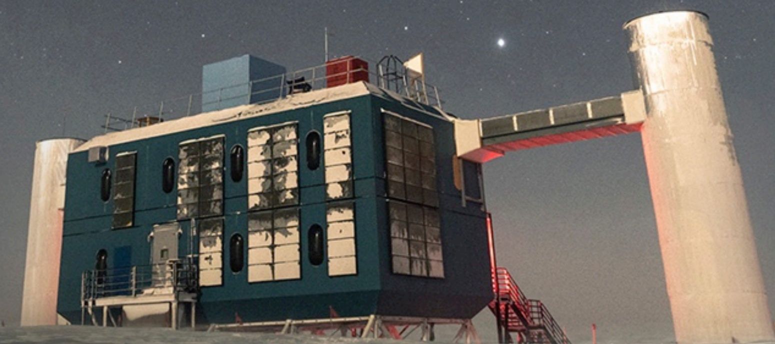
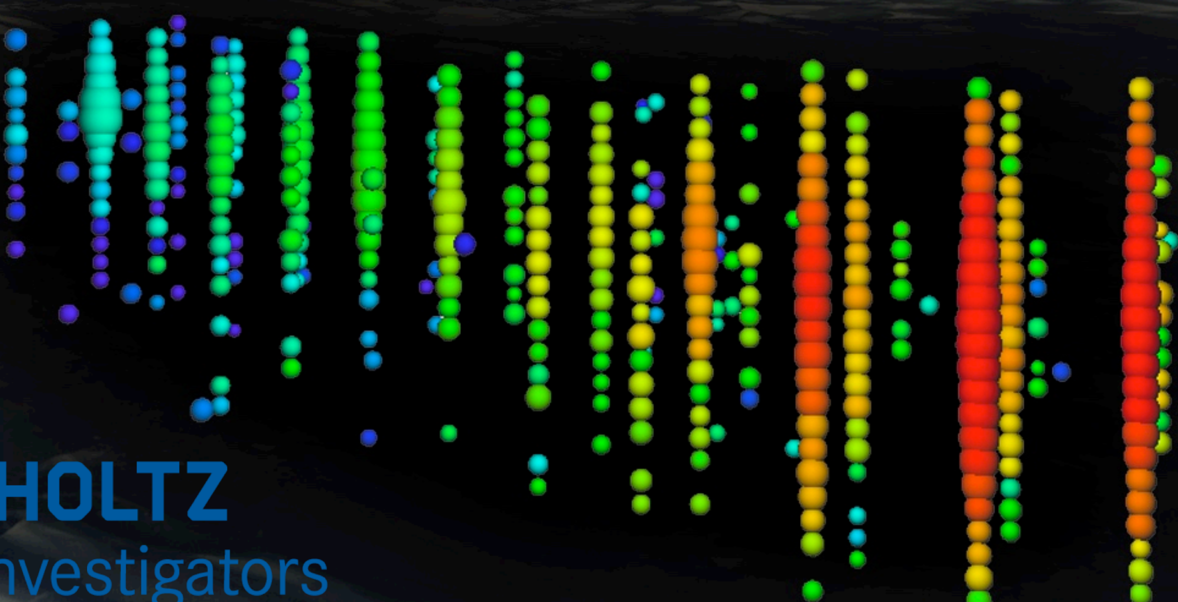
Multimessenger observations of the flaring gamma-ray blazar TXS 0506+056 coincident with the high-energy neutrino IceCube-170922A



Anna Franckowiak

for the IceCube and Fermi-LAT Collaborations

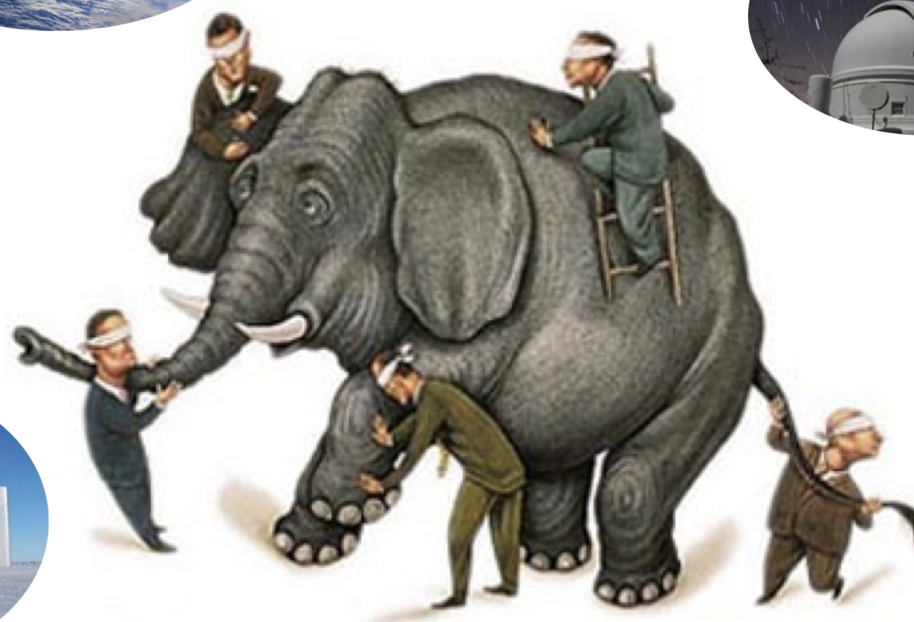


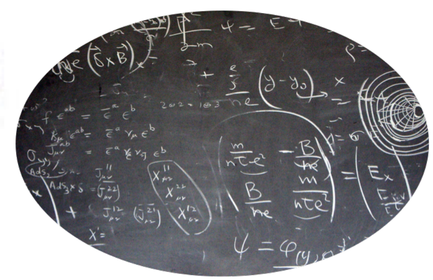
HELMHOLTZ Young Investigators

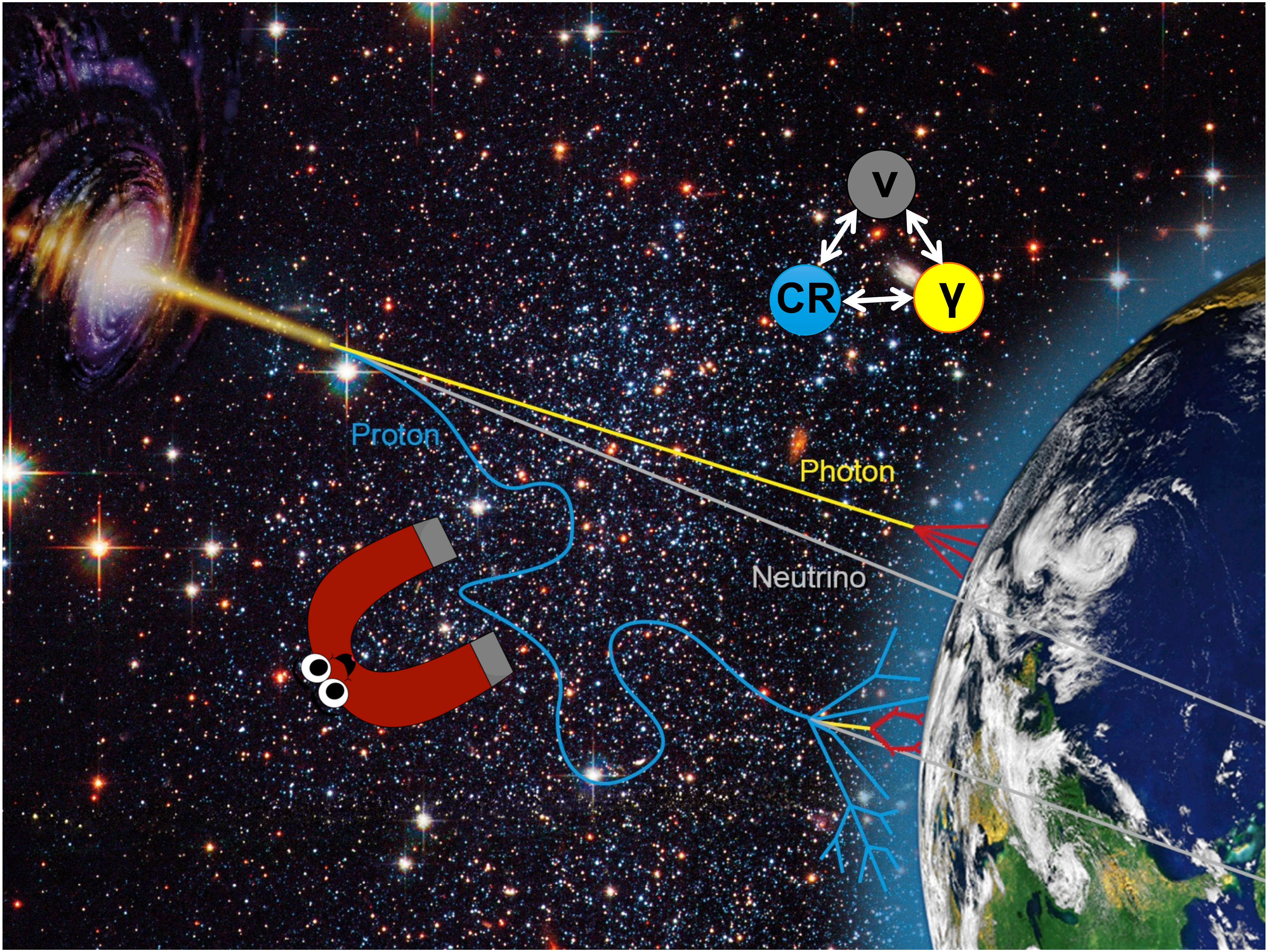
DESY.

Fermi Symposium 2018, Baltimore, October 15, 2018

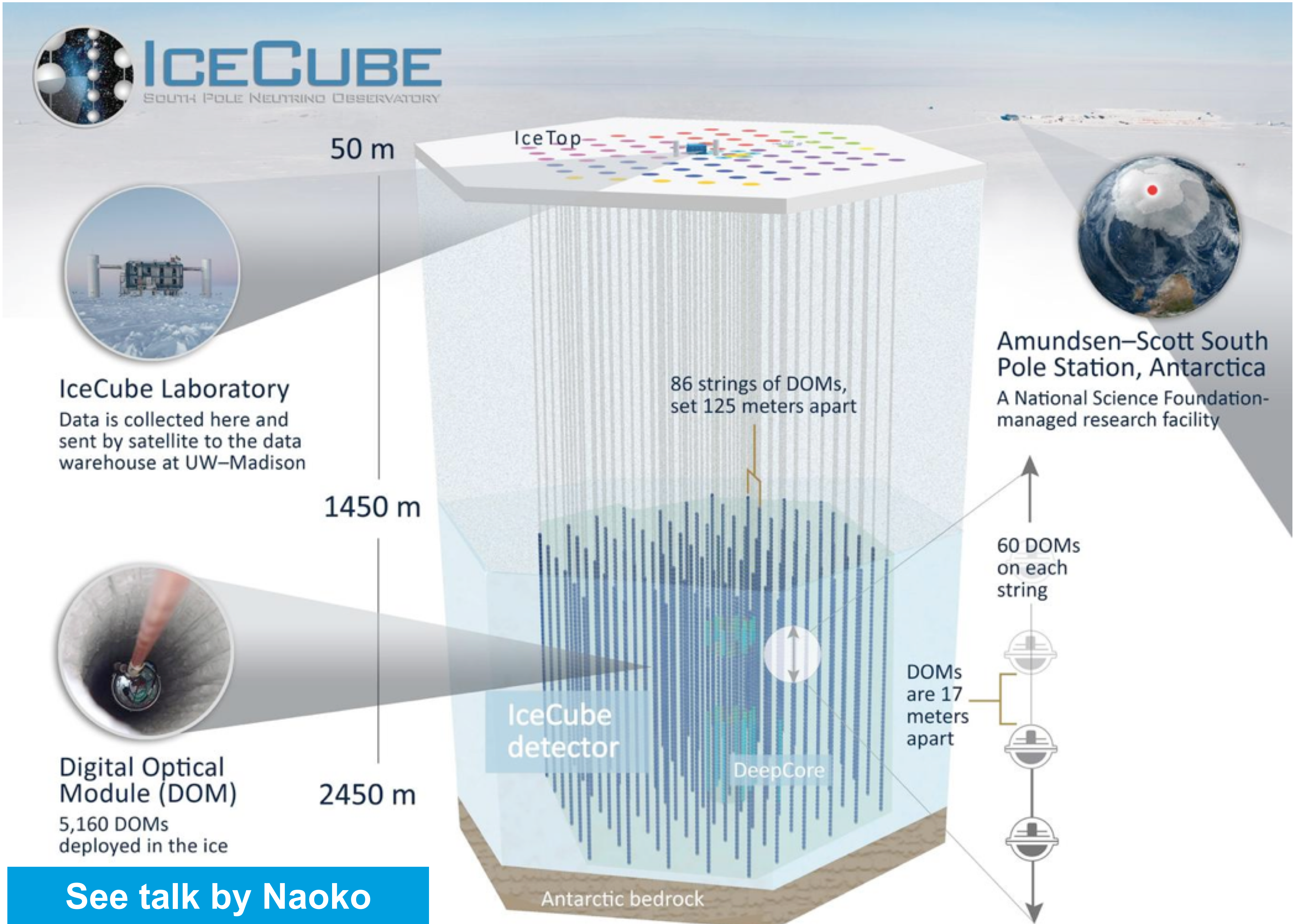
The Multi-Messenger Picture







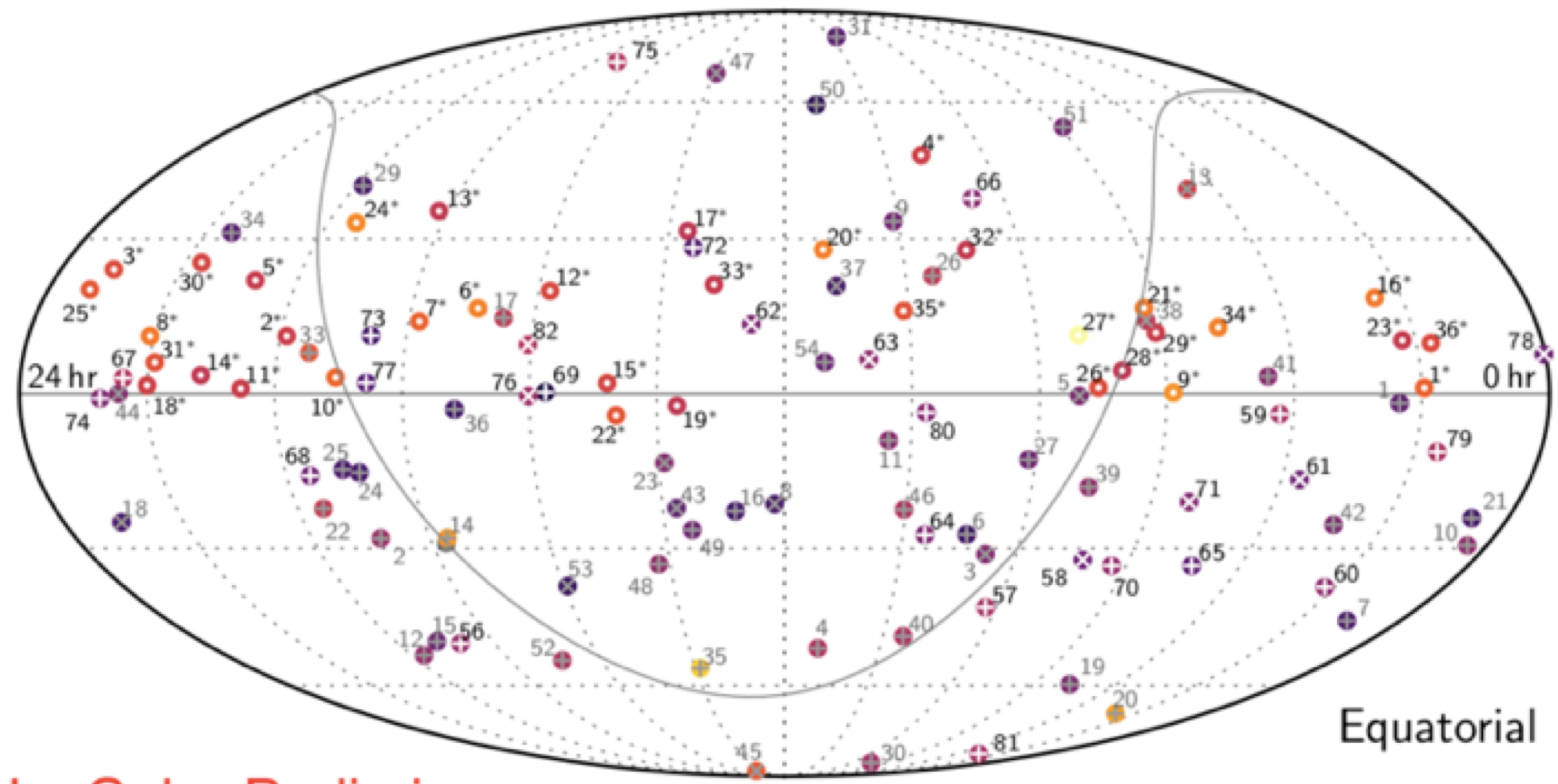
ν
CR
γ
Proton
Photon
Neutrino



See talk by Naoko Kurahashi Neilson

Diffuse Neutrino Flux detected, but where do the Neutrinos come from?

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



IceCube, ICRC 2017

Compatible with an isotropic distribution

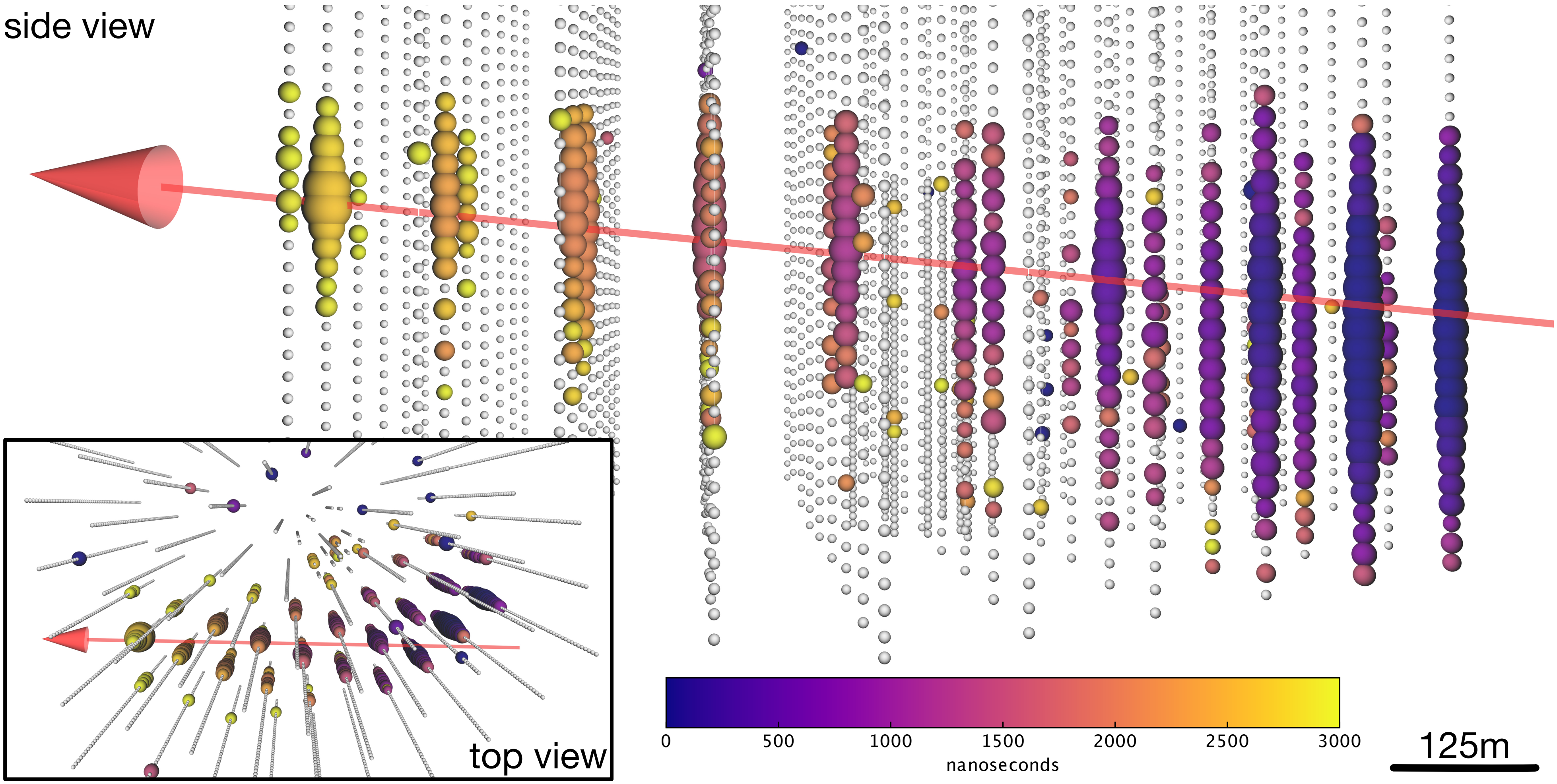
→ extragalactic origin of cosmic neutrinos

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



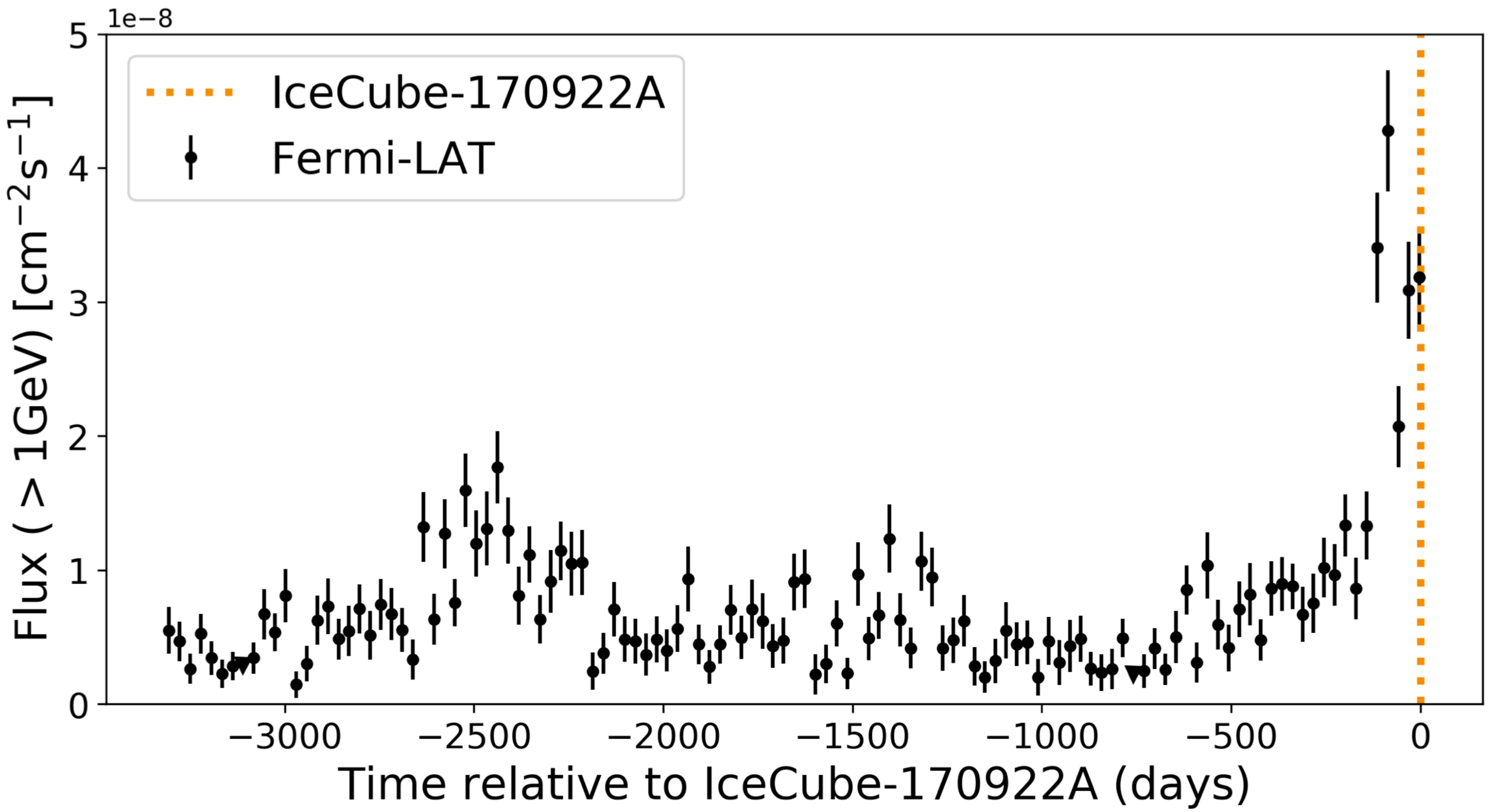
Signalness: 56.5%

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

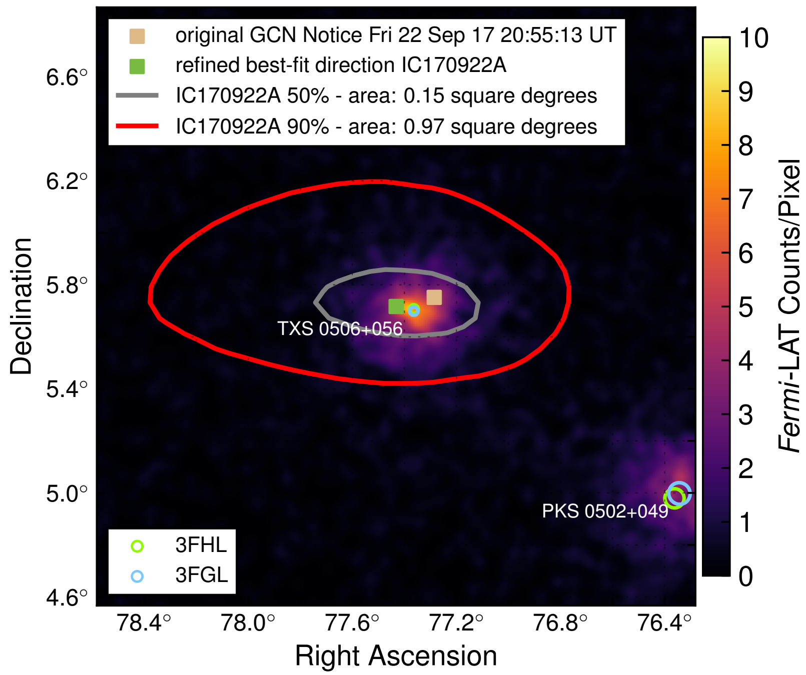
Fermi-LAT finds Flaring Blazar

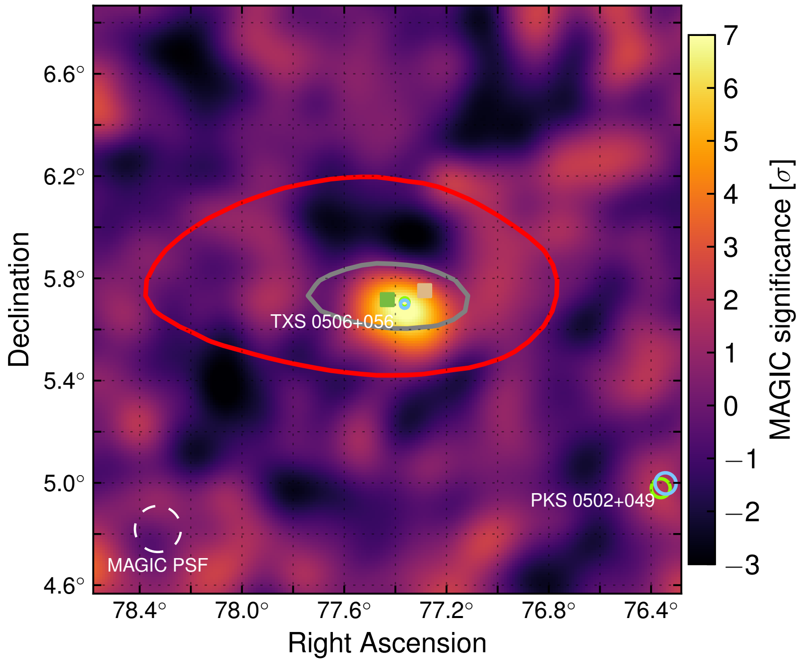
Fermi-LAT Coll., ApJ 846, 2017, Video credits: Matteo Giomi, Fermi-LAT Collaboration

Fermi-LAT finds Flaring Blazar: TXS 0506+056



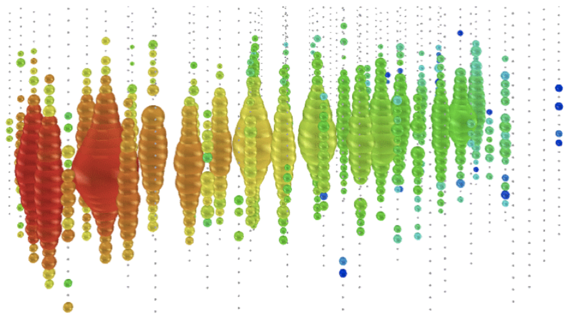
MAGIC observes >100 GeV gamma rays



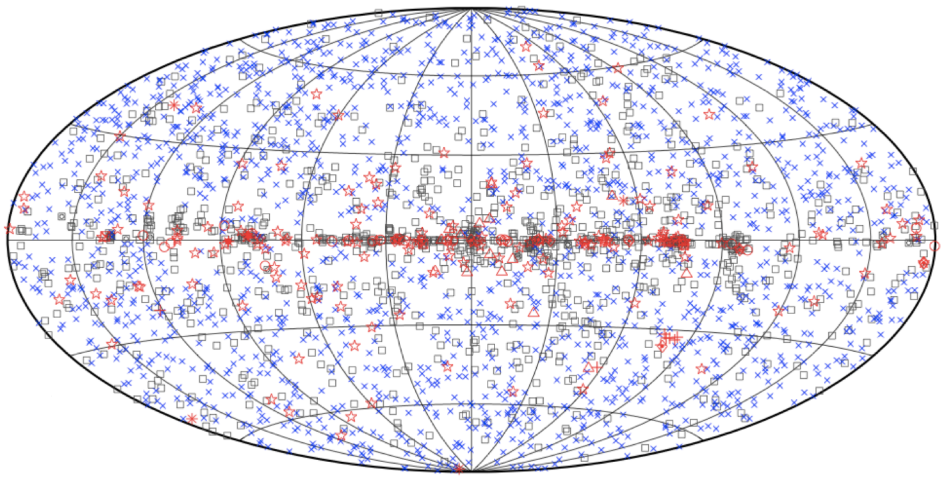


IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

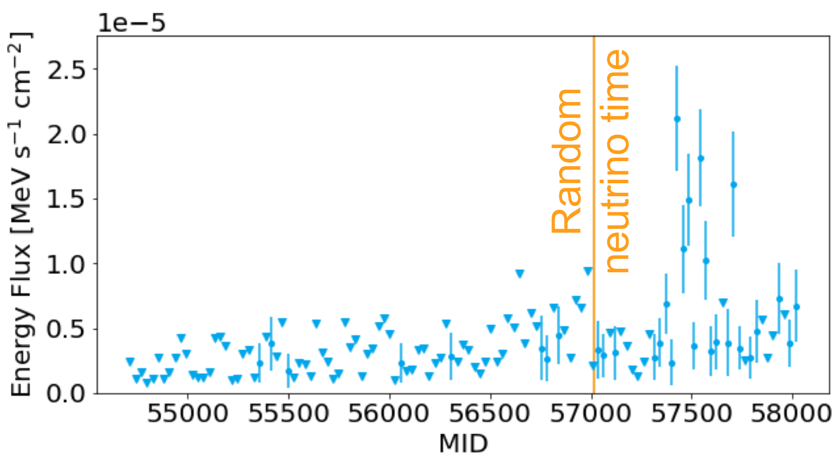
How Likely is it a Chance Probability?



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



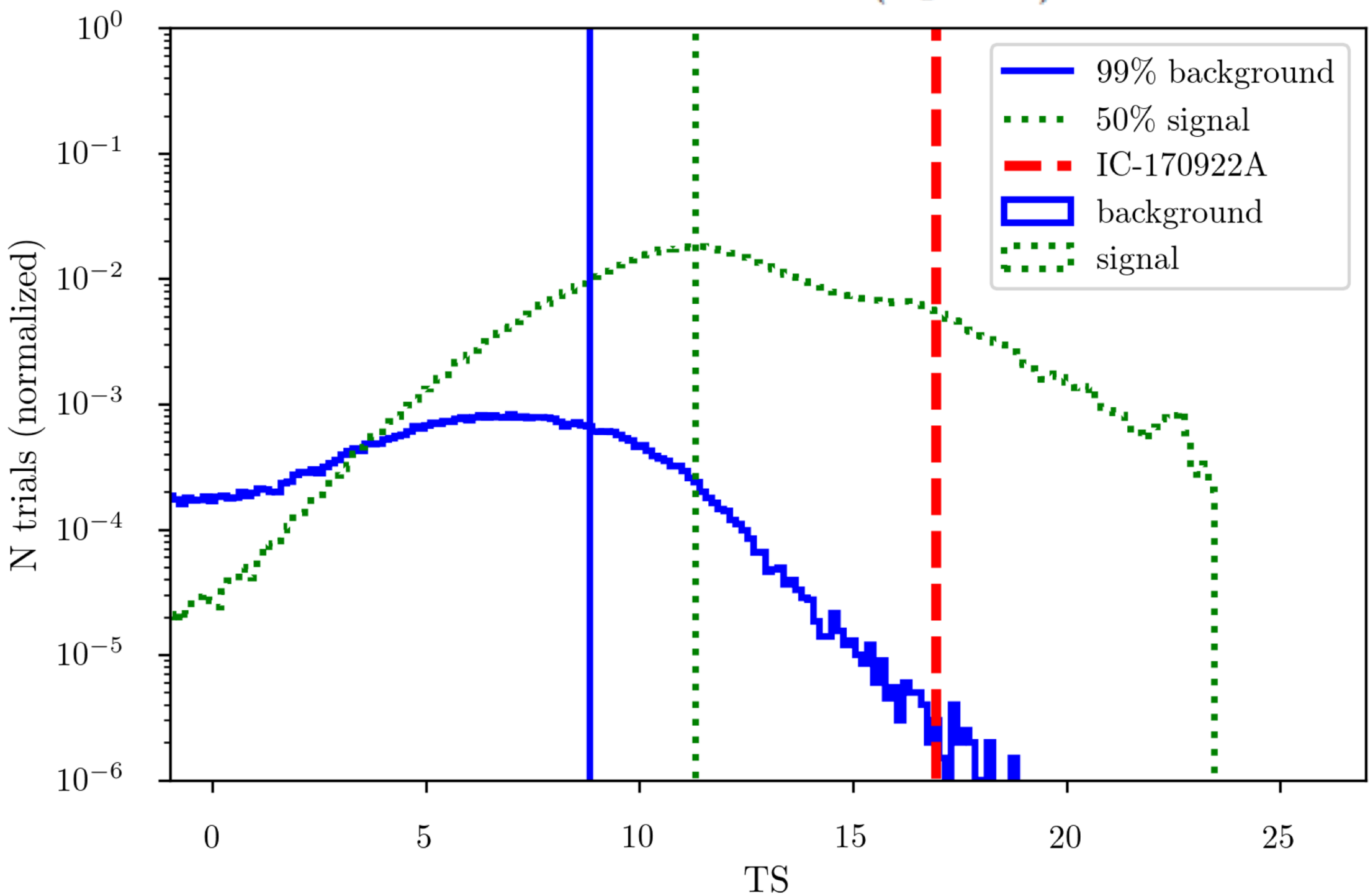
Step II: Are there any extra-galactic Fermi sources close in space to the neutrinos?



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

How Likely is it a Chance Probability?

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



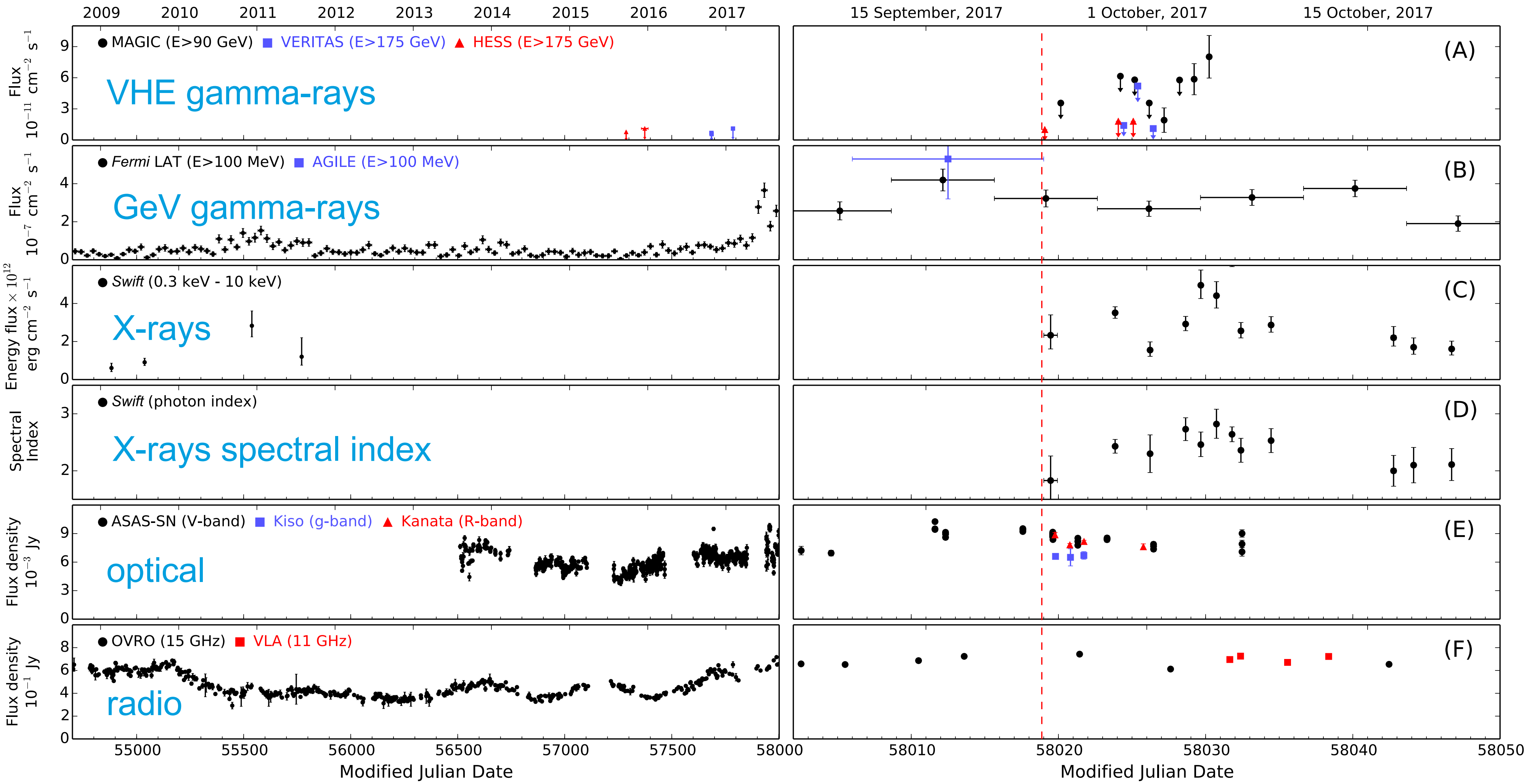
Pre-trials p-value: 4.1σ

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

Three tested models yield similar p-values

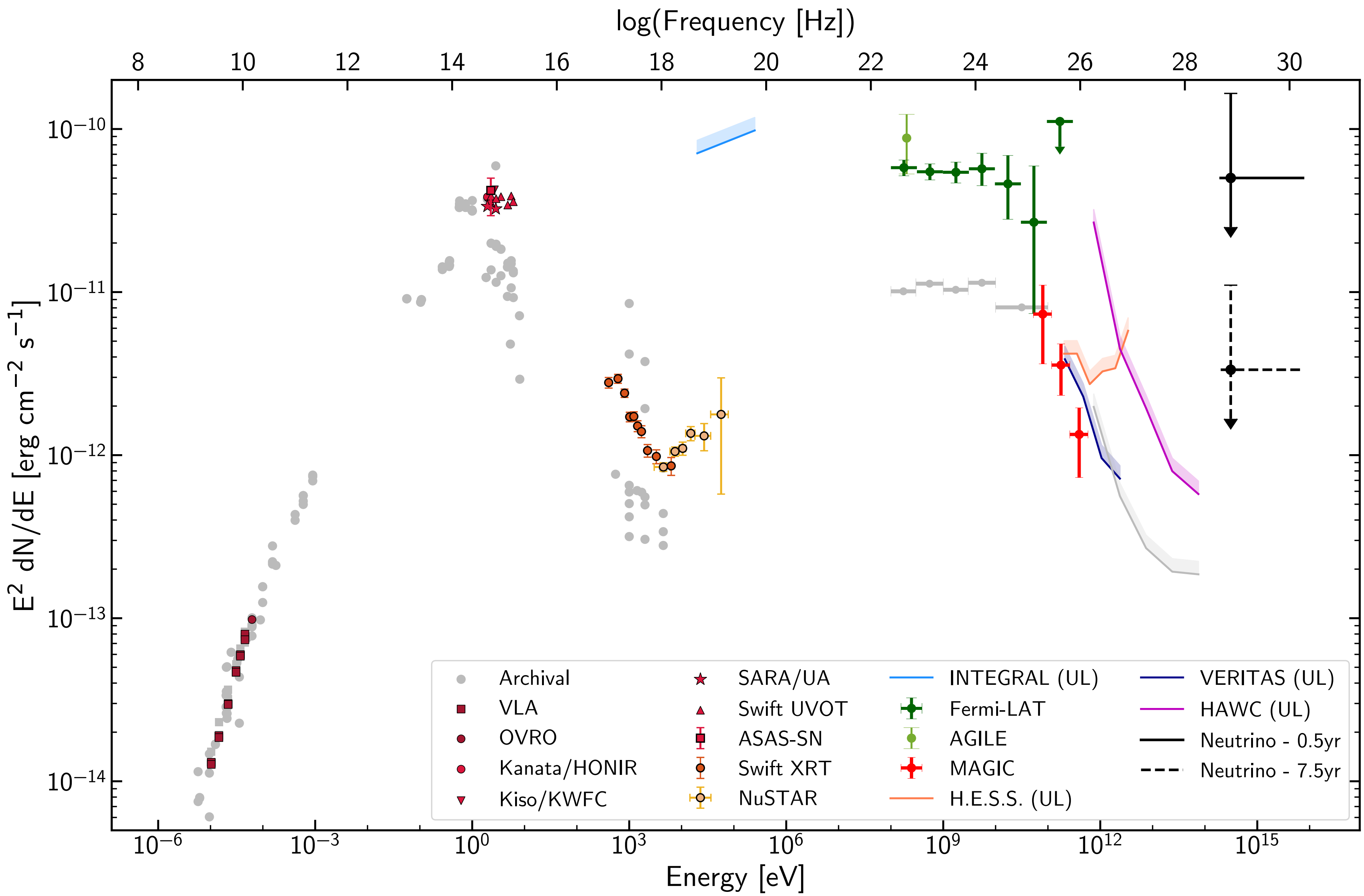
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

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

The Multi-Messenger SED



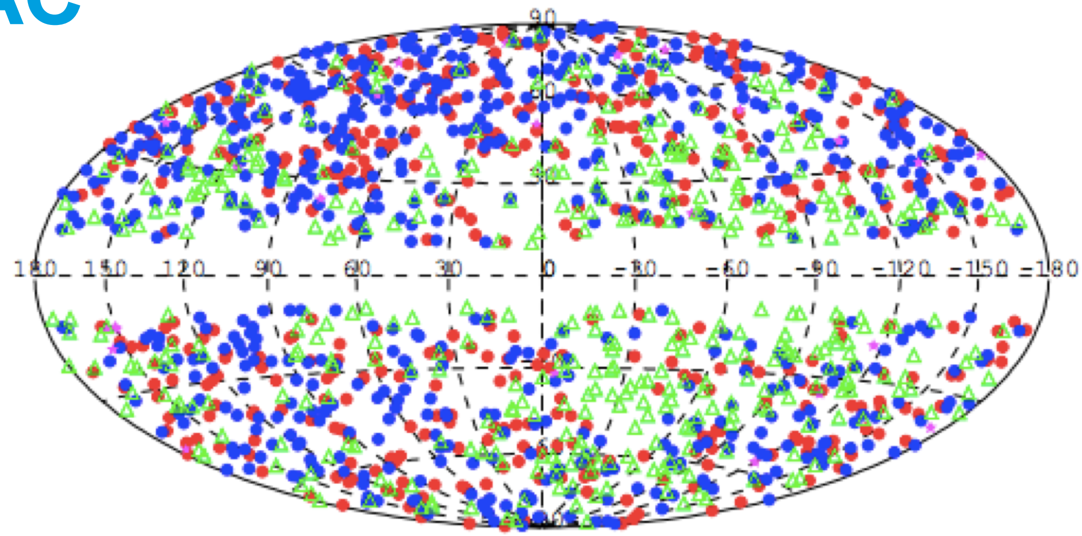
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

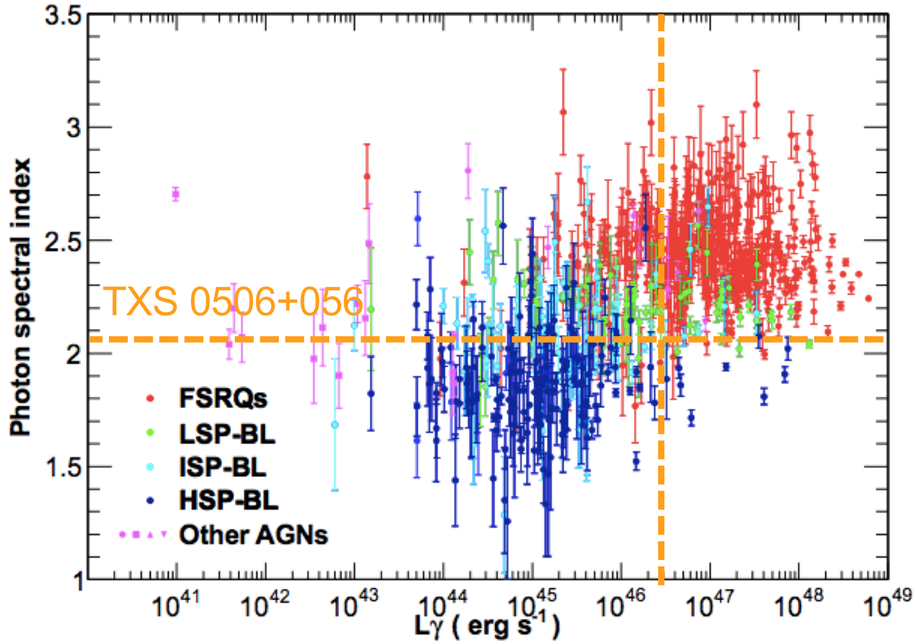
TXS 0506+056 in 3LAC

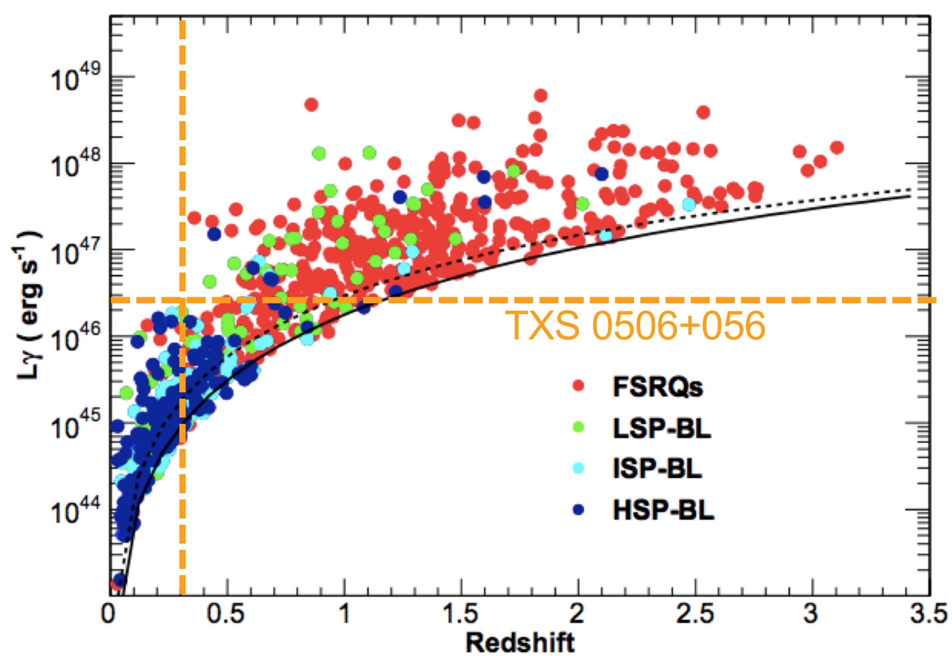
Among 50 brightest blazars (3%) in 3LAC

ISP

Redshift 0.3365±0.0010 (S. Paiano et al. 2018)





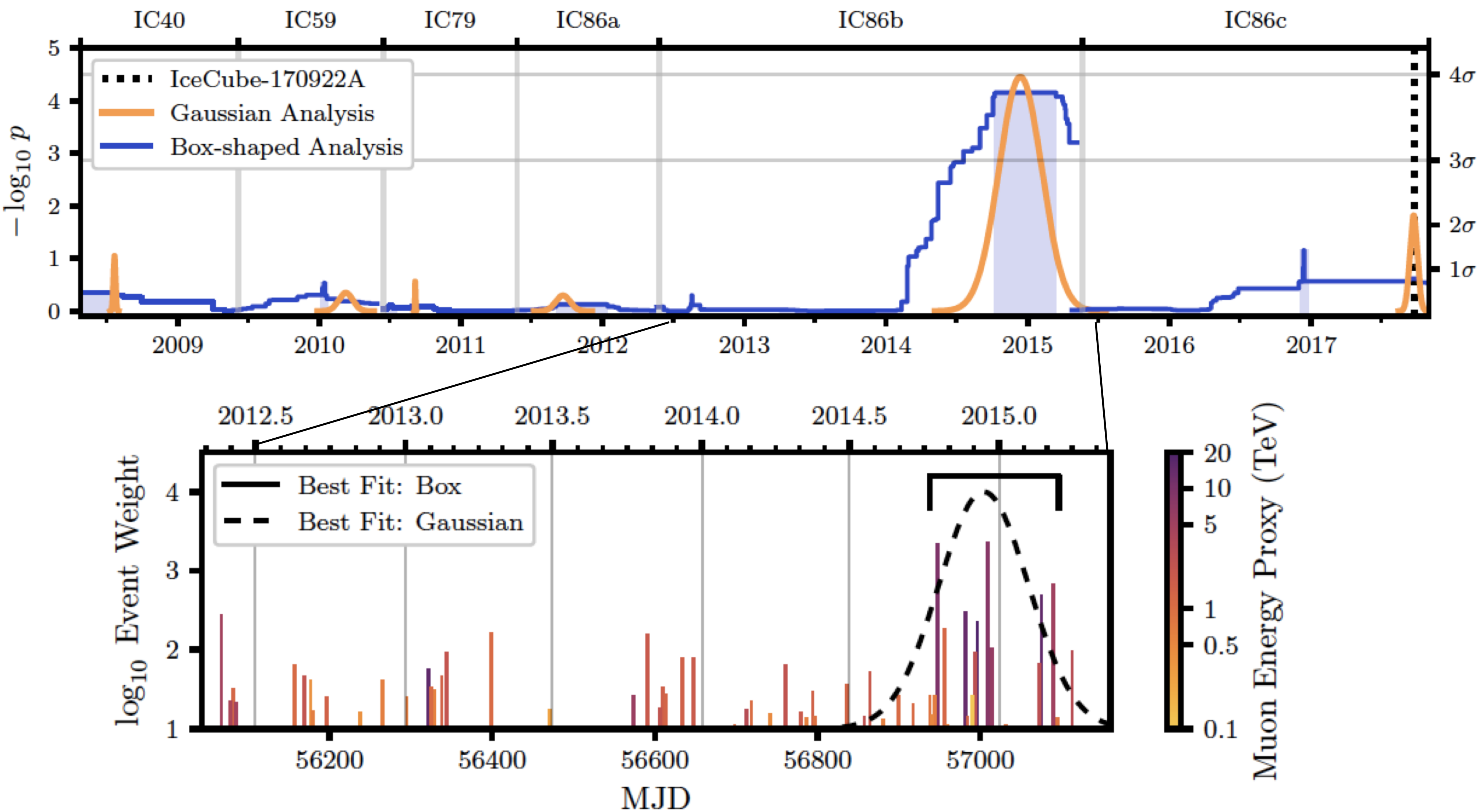


Fermi-LAT Collaboration, ApJ 810 (2015)

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

Are there more Neutrinos from this Source?

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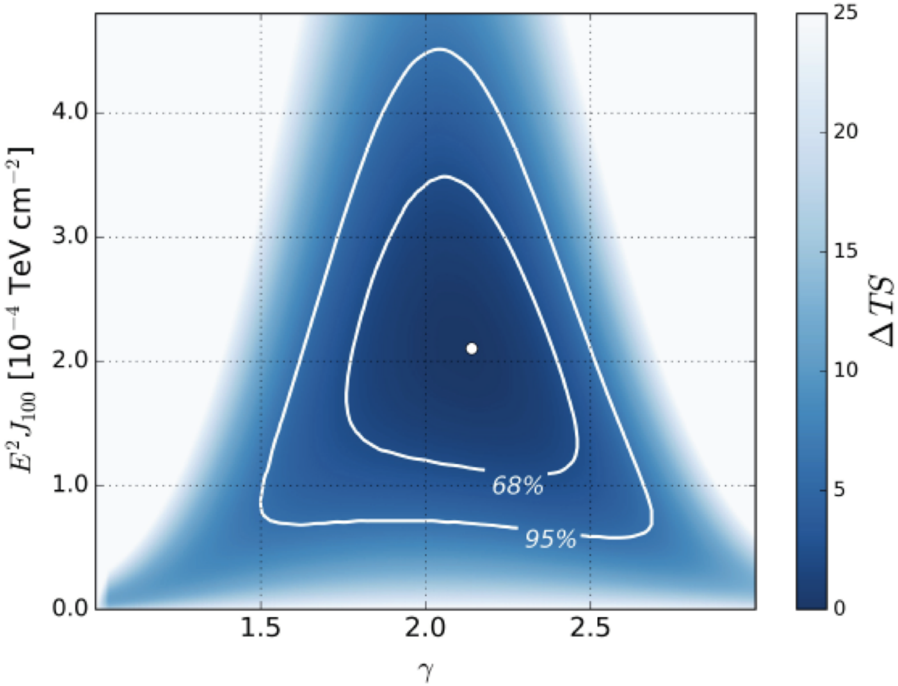
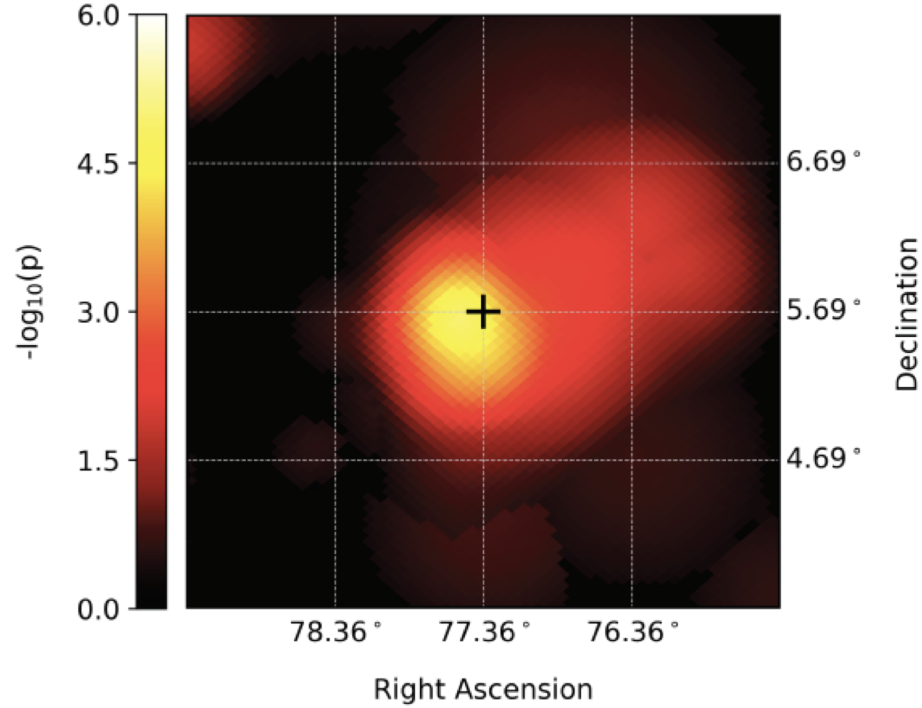


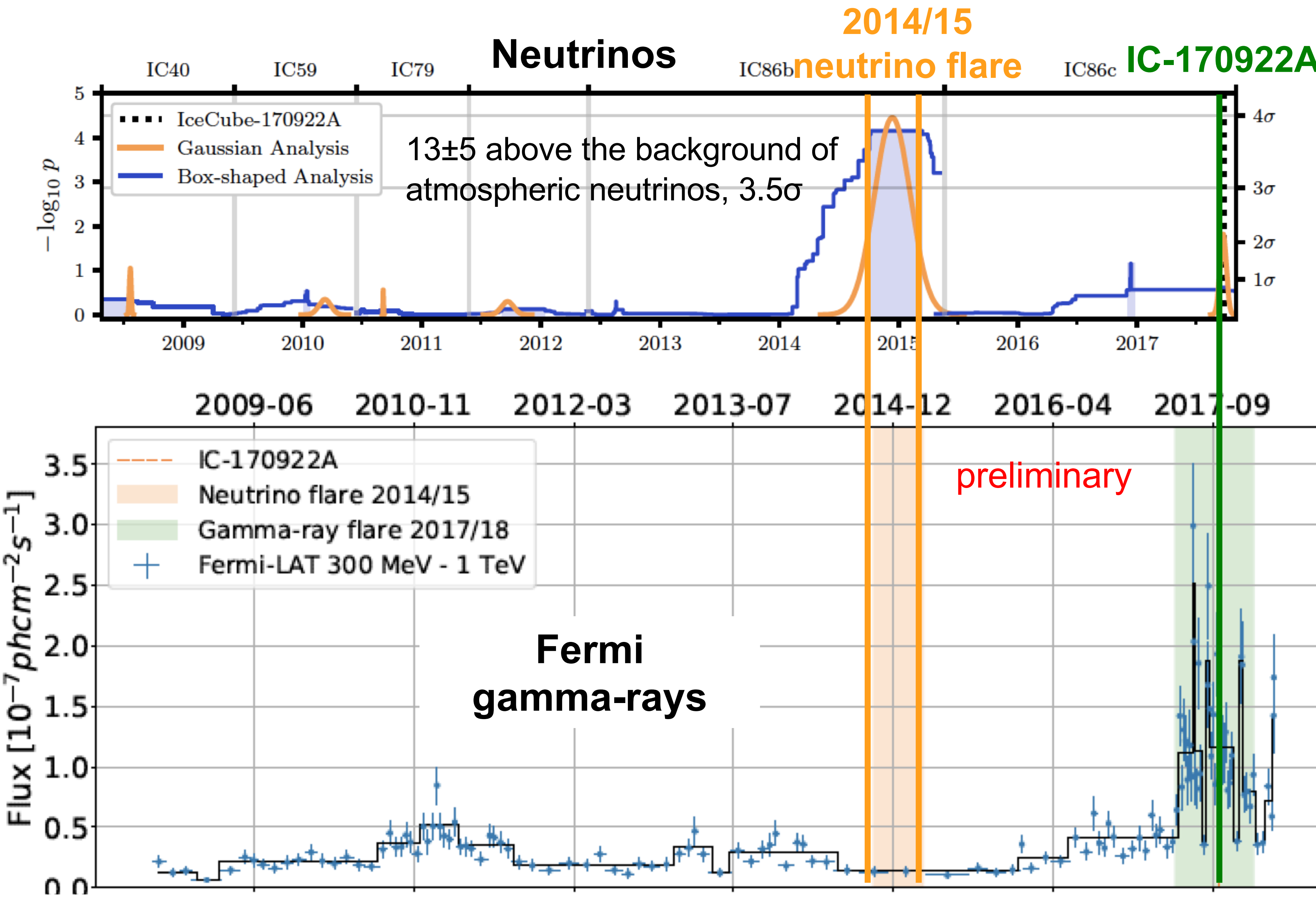


Neutrino luminosity (averaged over 158 days): $(1.2^{+0.6}_{-0.4}) \times 10^{47}$ erg s^{-1}

4 times larger than average gamma-ray luminosity!

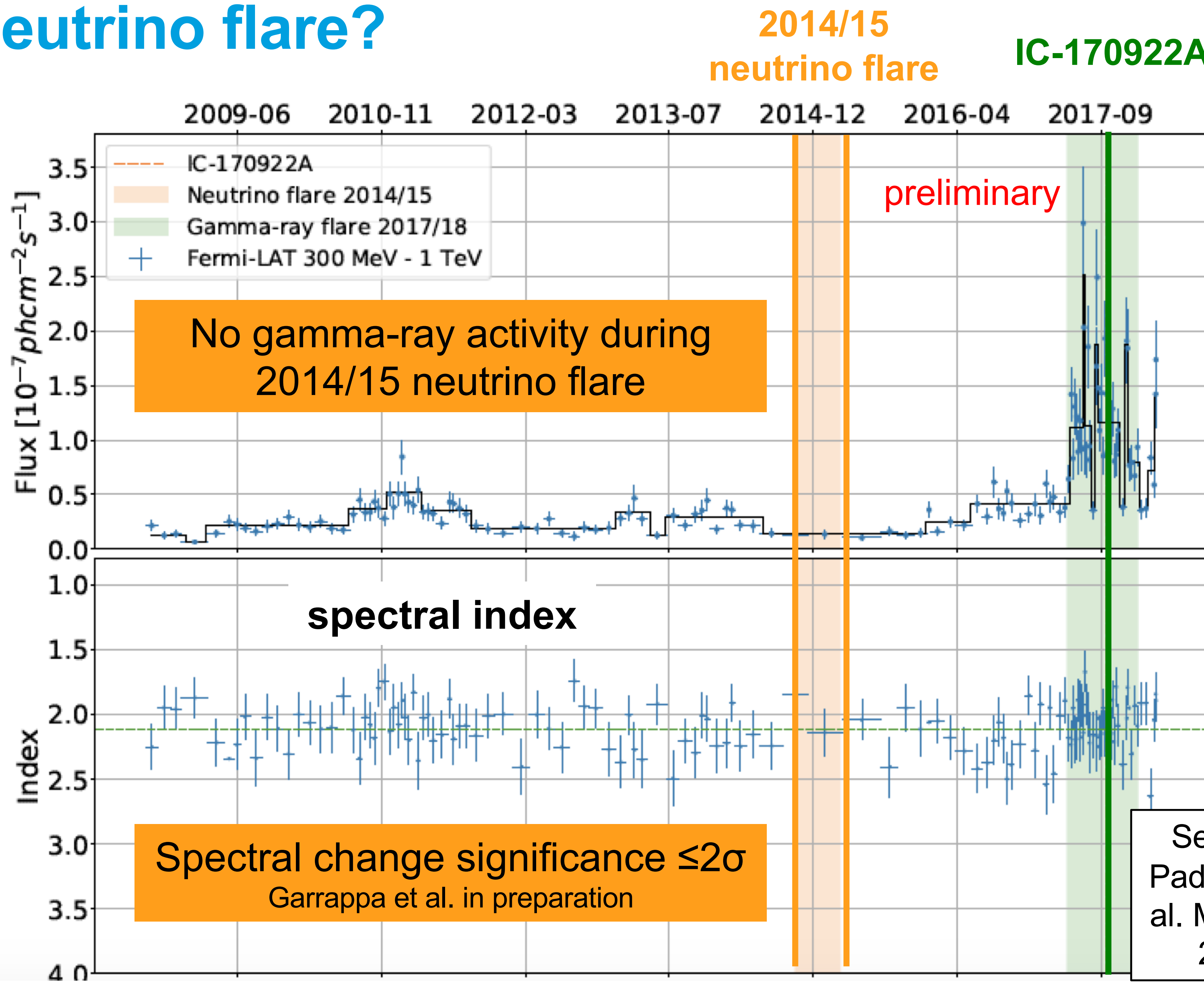
IceCube Coll.,Science 2018

Is there also a Gamma-ray Flare?



IceCube Coll.,Science 2018, Garrappa et al. in preparation

Gamma-ray Spectral Variations during neutrino flare?



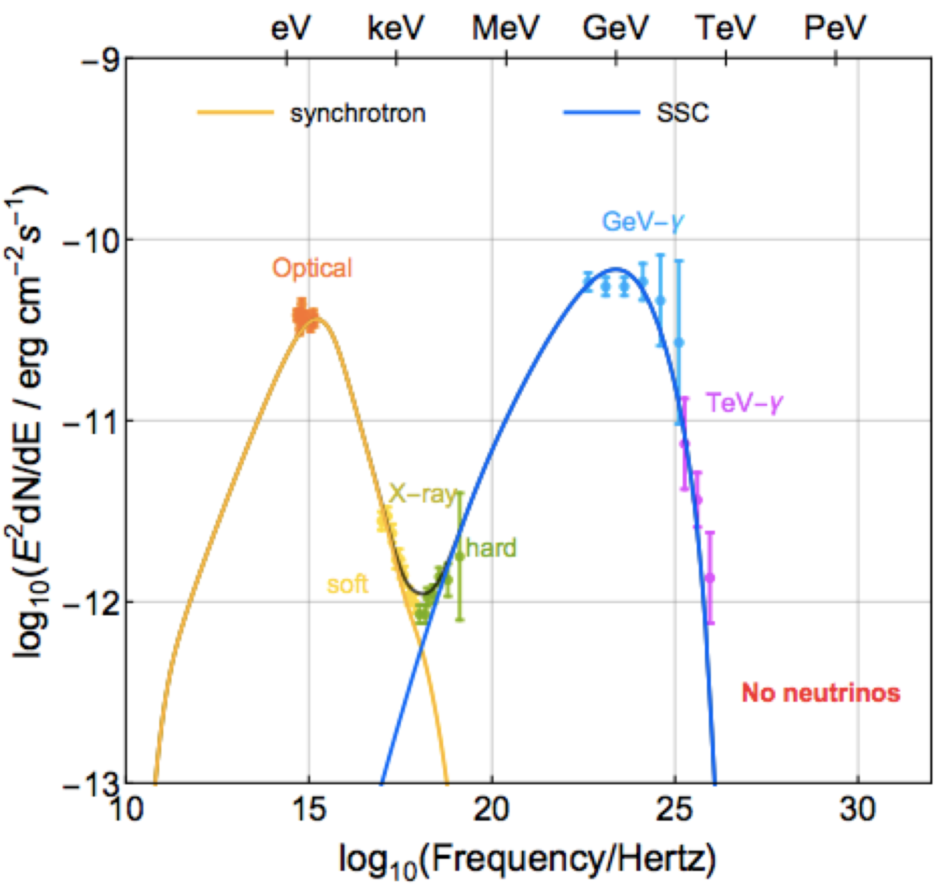
See also Padovani et al. MNRAS, 2018

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

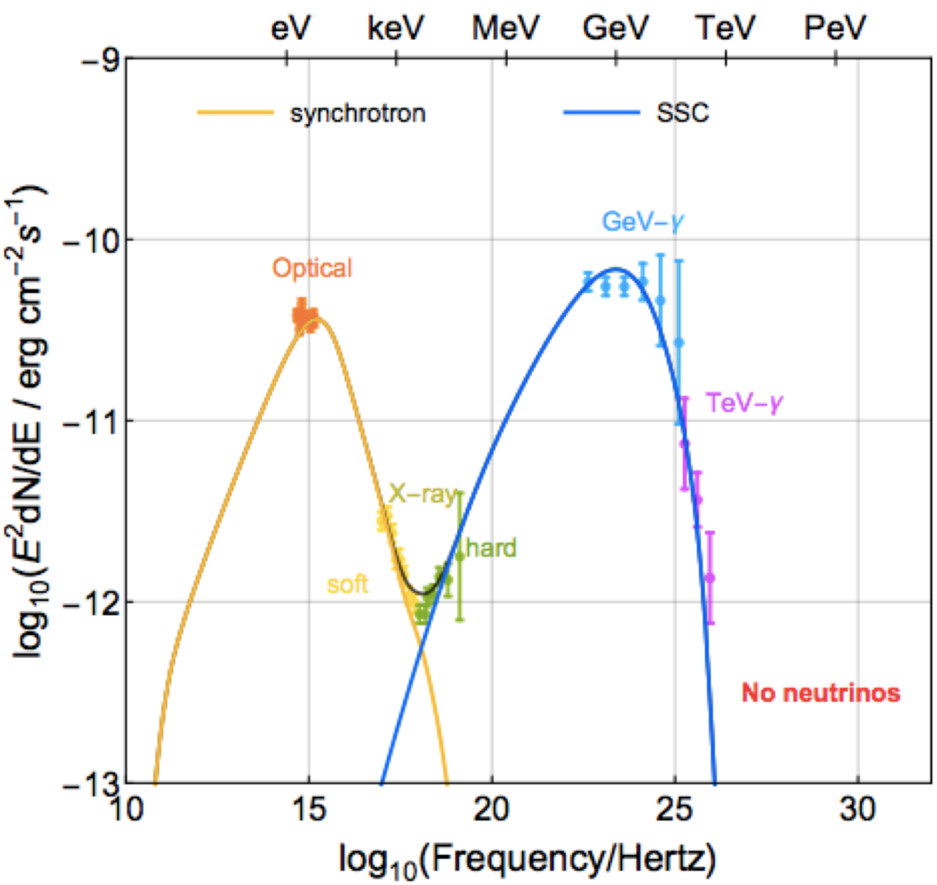
See talk by Azadeh Keivani

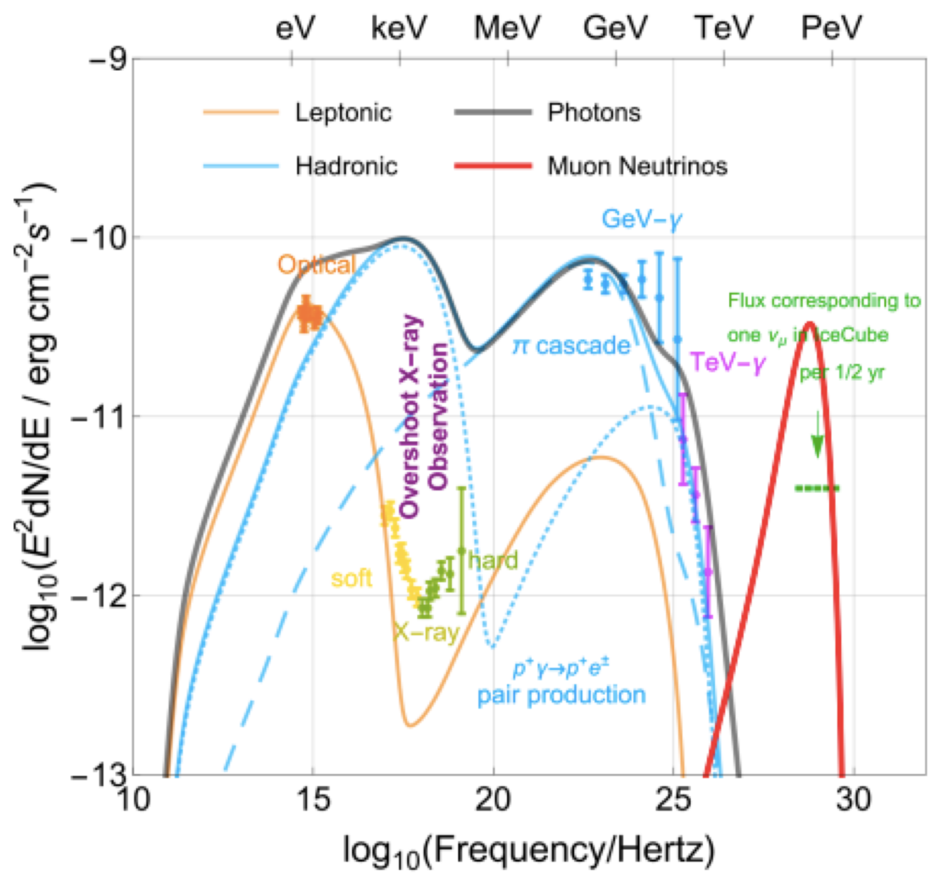
Modeling – leptonic



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

Modeling – leptonic, hadronic



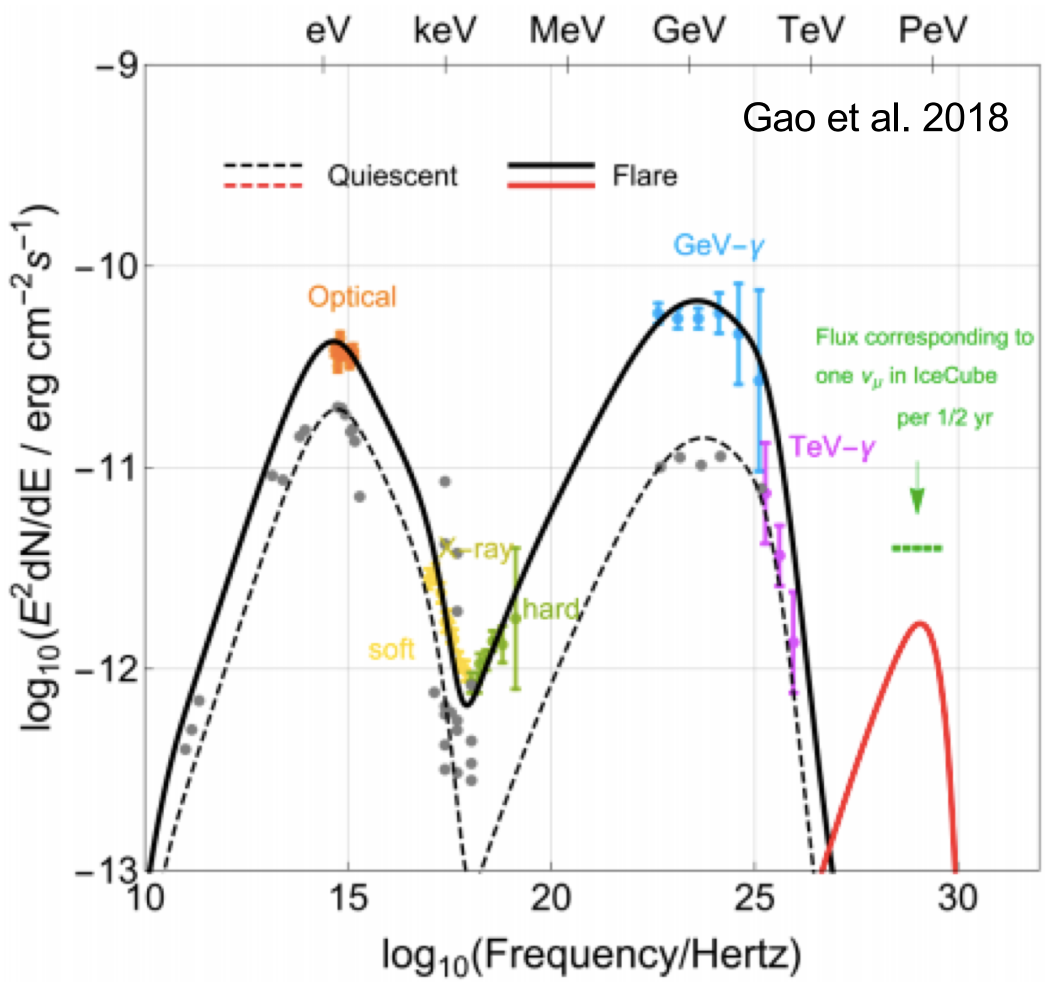


Simple one-zone hadronic models violate X-ray constraints
→ More complex models needed

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

Modeling – leptonic, hadronic, Gin & Tonic

2017 neutrino + gamma flare:



Two zone-model with dense blob (Gao+ 2018)
or structured jet (MAGIC Coll. 2018)

2014/15 neutrino flare:

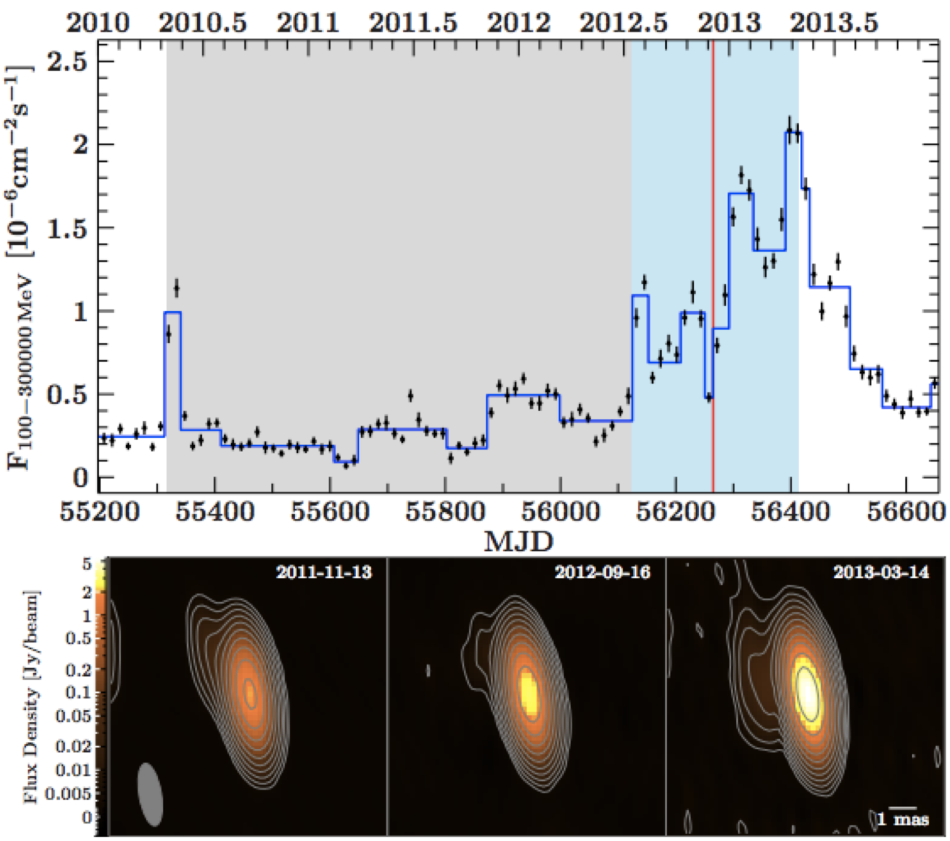
neutrino luminosity is ~4 times higher than gamma-ray luminosity

→ challenge for models

Reimer et al. in preparation, M. Boettcher at TeVPA 2018

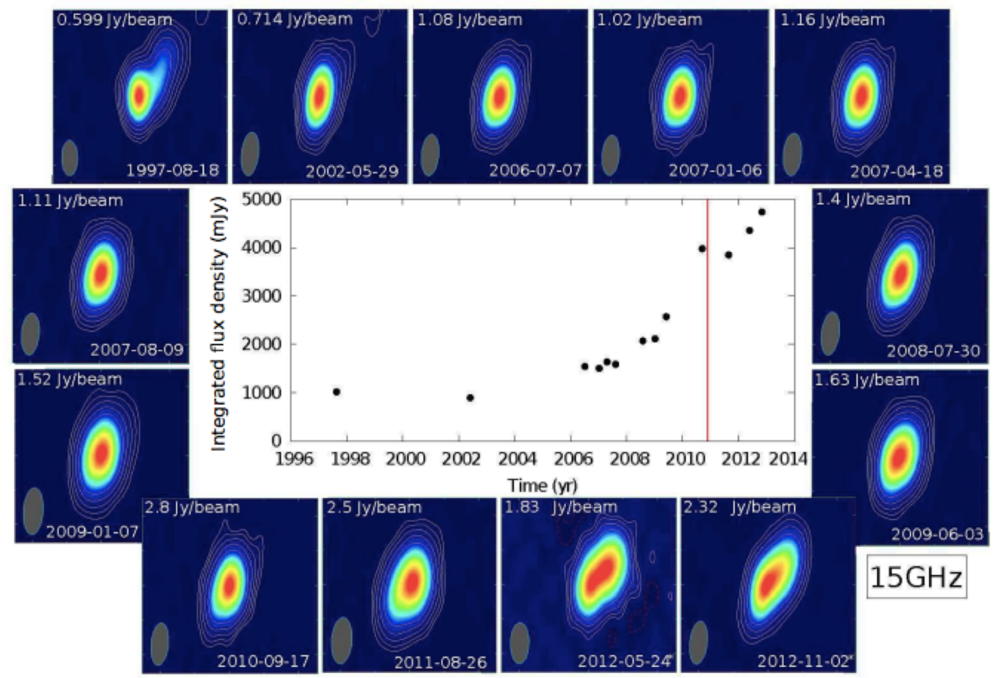
Other interesting candidates

PKS B1424−418 + cascade event
5% chance coincidence



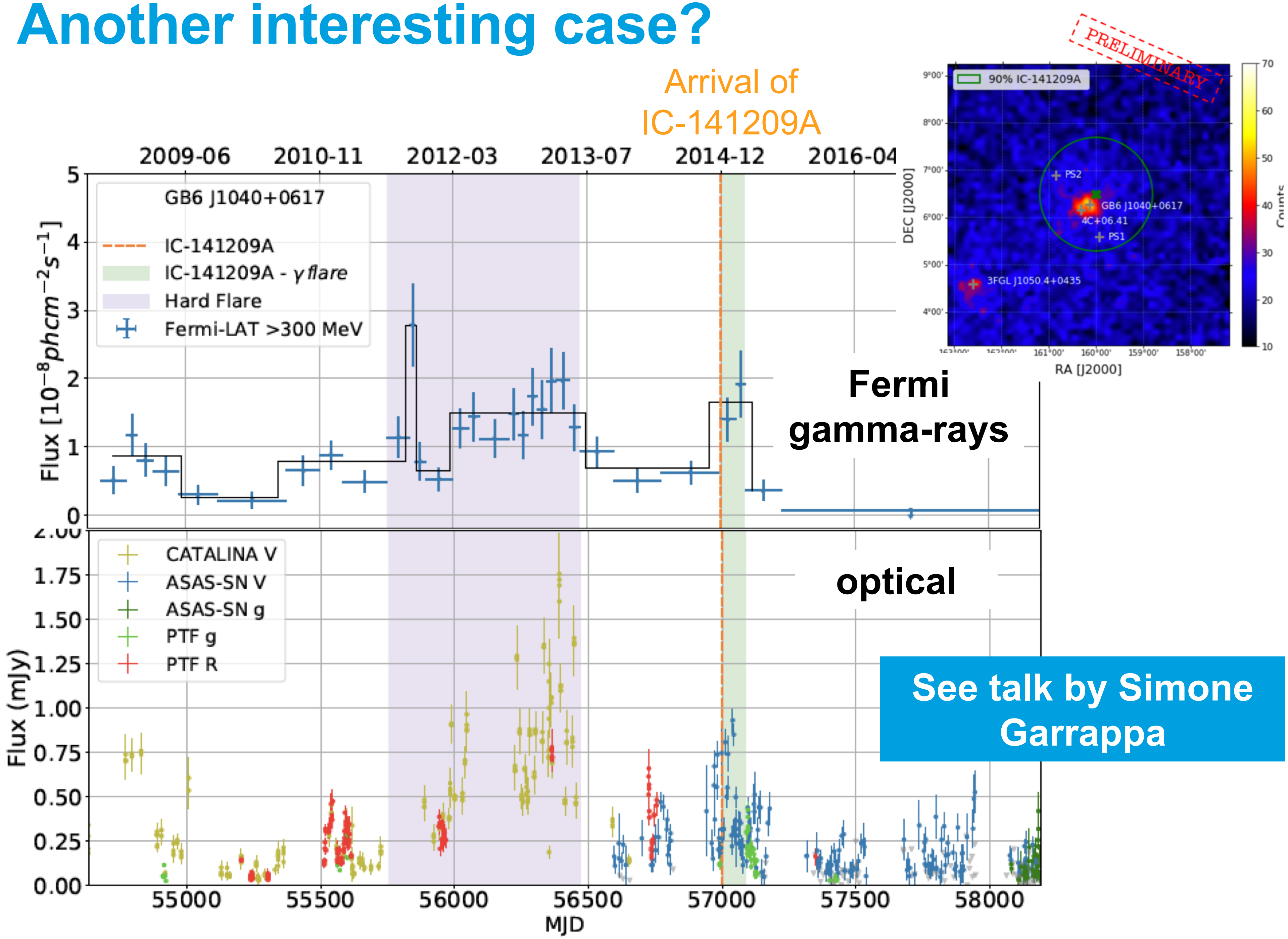
Kadler et al. 2016

PKS 0723-008 + track event,
Barely outside 90% error circle,
dim gamma-ray source



Kun et al. 2017

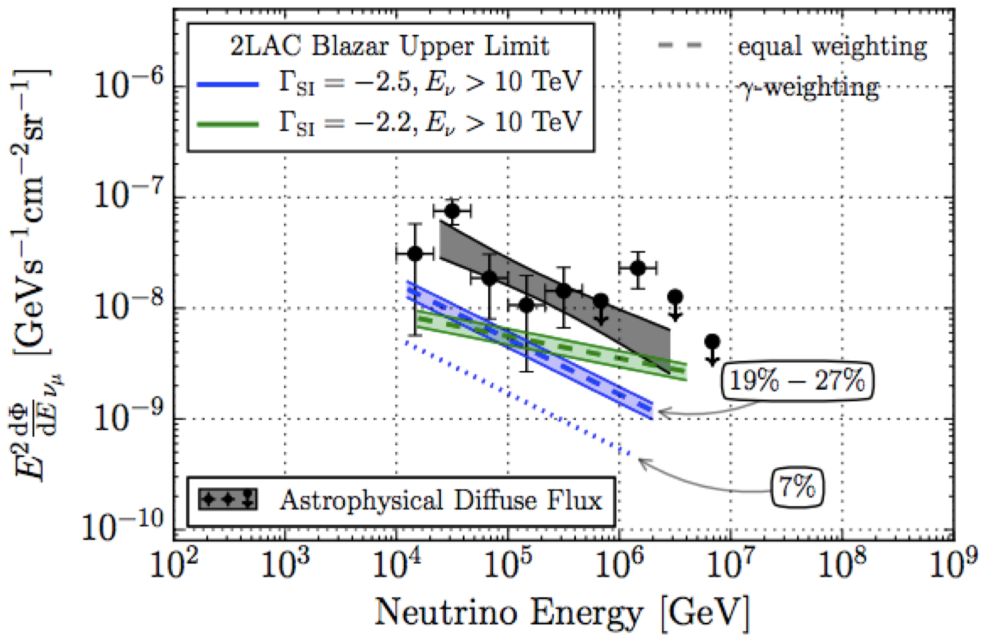
Another interesting case?



Garrappa et al. in preparation

Do gamma-ray blazars produce all diffuse neutrinos?

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



IceCube, ApJ 835 (2017)

Fully compatible with blazar catalog stacking results

What can we improve in the Future?

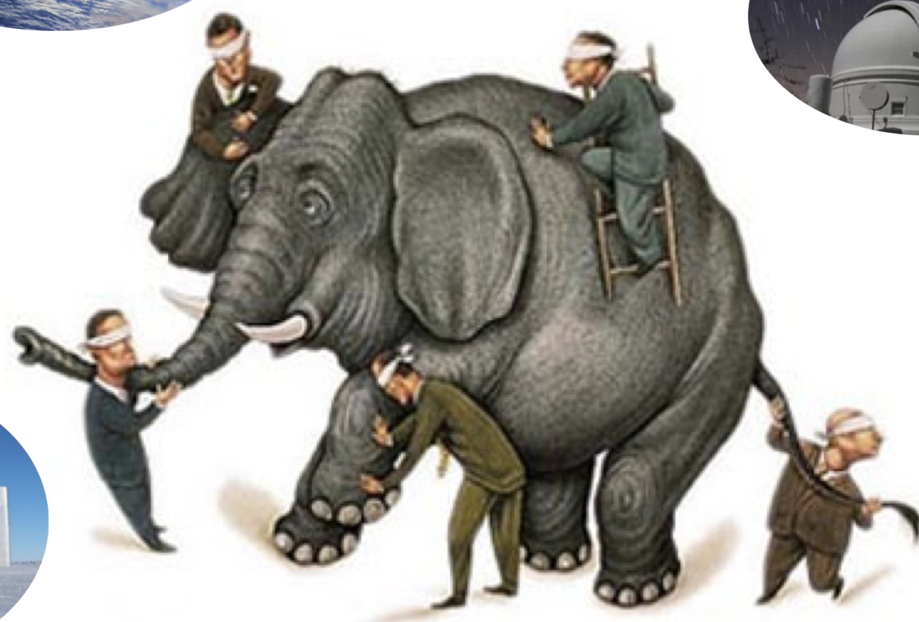
- **Archival Data**: Carefully check for more candidates in archival IceCube and Fermi data
- **Blazar Stacking**: Preselection of Fermi blazars / flares
- **Realtime Program**: Upgrade of IceCube realtime stream will deliver higher rate with higher purity
- **Detector Upgrade**: IceCube upgrade will improve angular uncertainty due to ice systematics

Fermi data is crucial input!

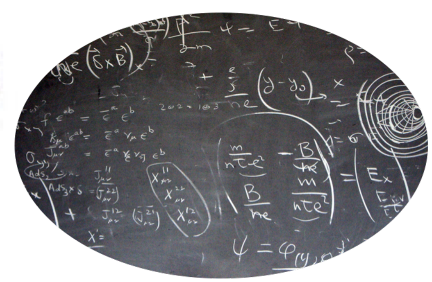
Summary

gamma-rays

visible light



theory



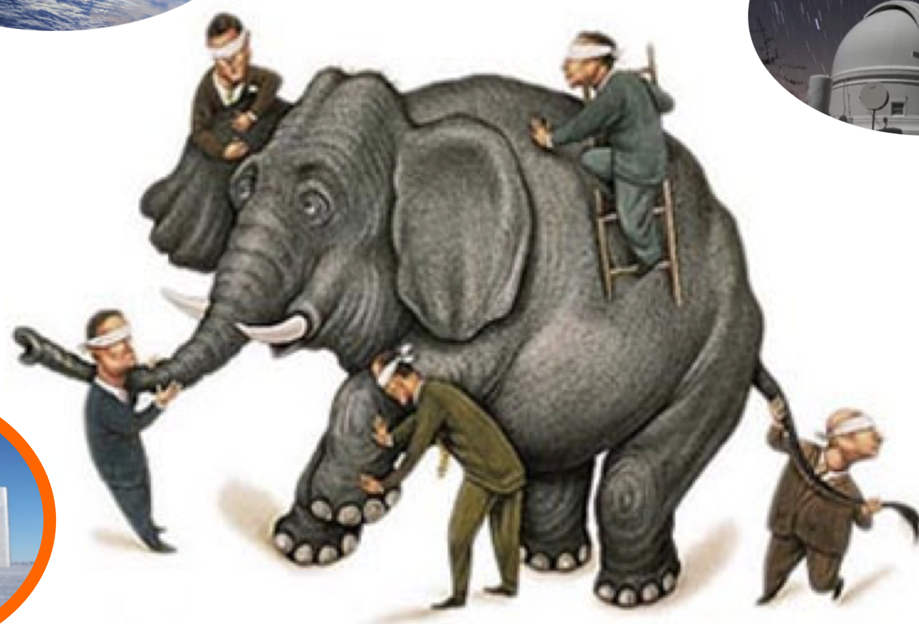
neutrinos

cosmic rays

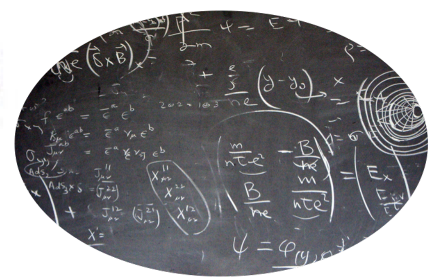
Summary

gamma-rays

visible light



theory



neutrinos

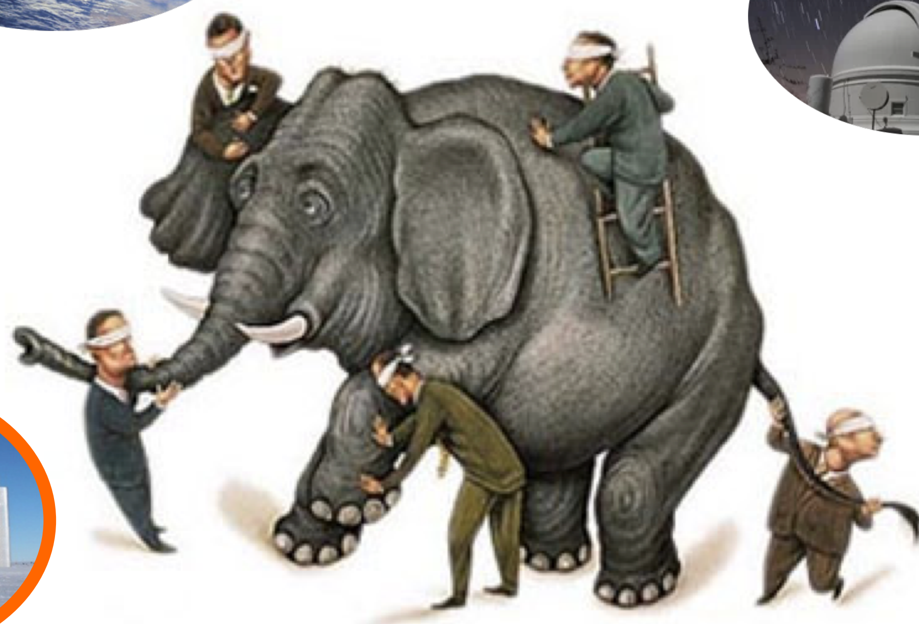
unique messengers from the high-energy Universe

cosmic rays

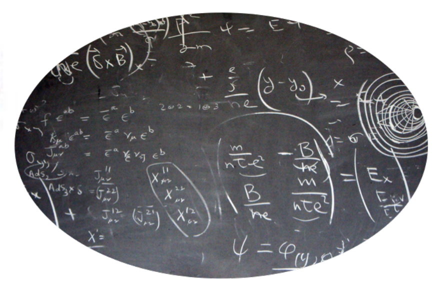
Summary

gamma-rays

visible light



theory



neutrinos

Neutrinos can reveal the sources of high-energy cosmic rays

cosmic rays

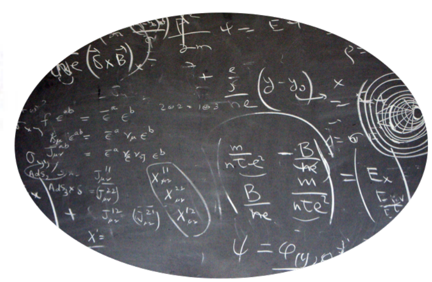
Summary

Electro-magnetic counterparts are crucial
to identify the sources.
First compelling candidate found!
IC170922A + TXS flare: 3σ
2014/15 neutrino flare (13 events): 3.5σ

gamma-rays

visible light

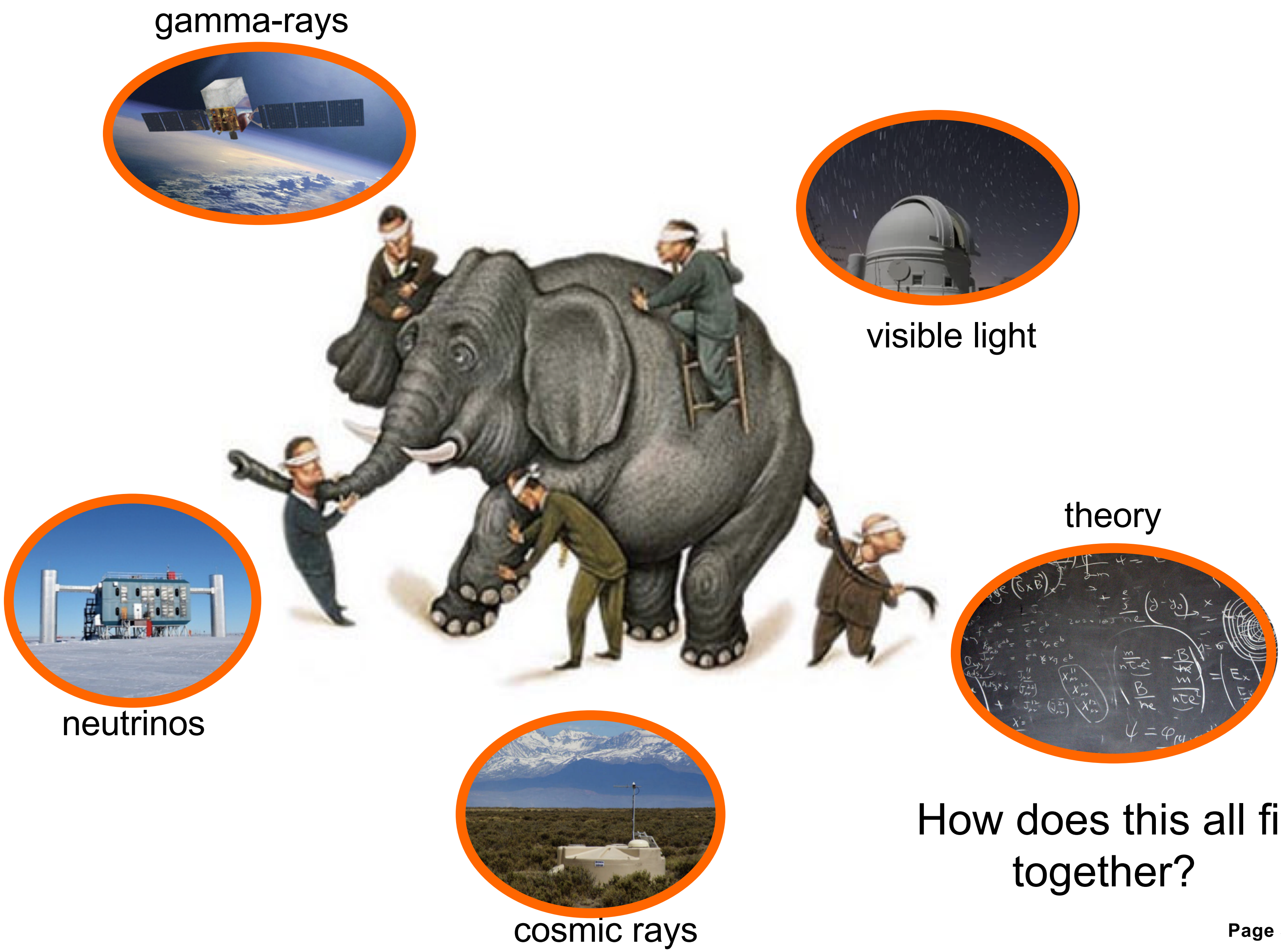
theory



neutrinos

cosmic rays

Summary

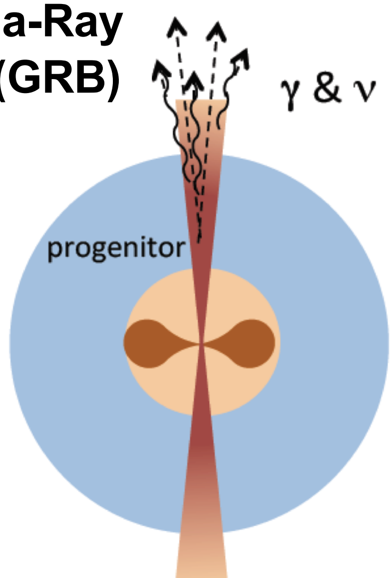


How does this all fit together?

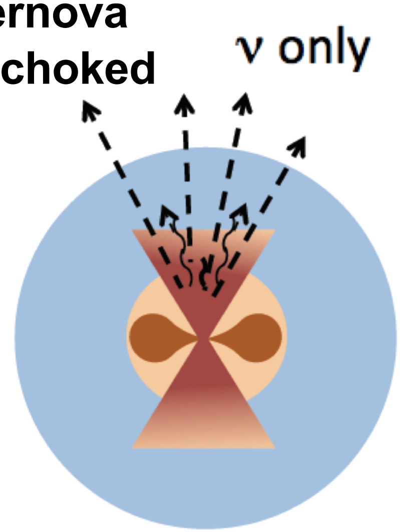

Stay tuned!

Back-up

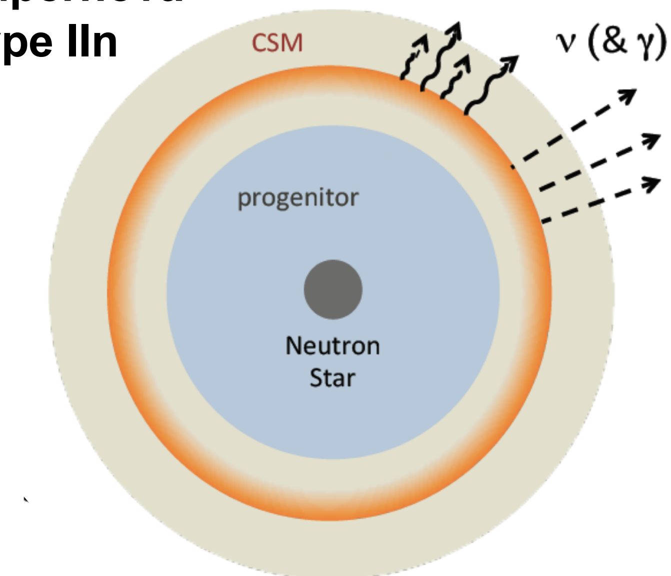
Gamma-Ray Burst (GRB)



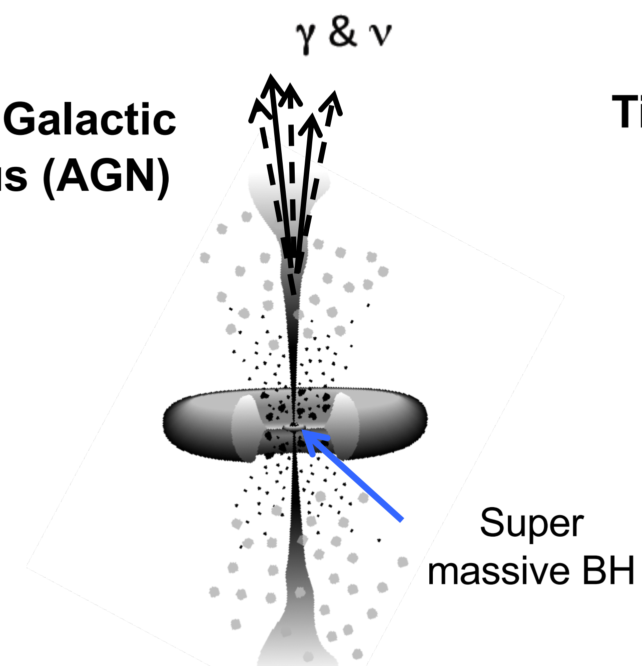
Supernova with choked jets



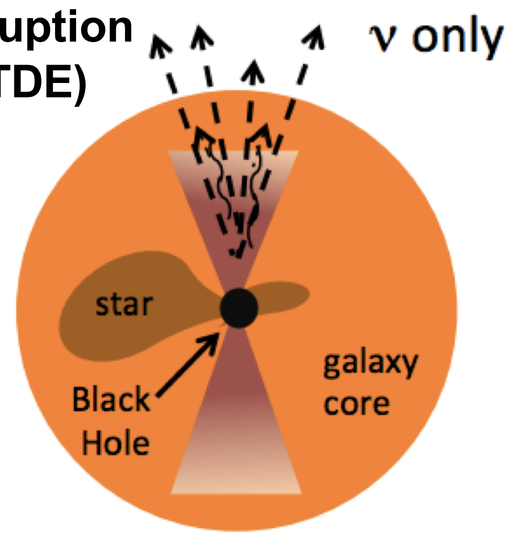
Supernova Type IIn



Active Galactic Nucleus (AGN)

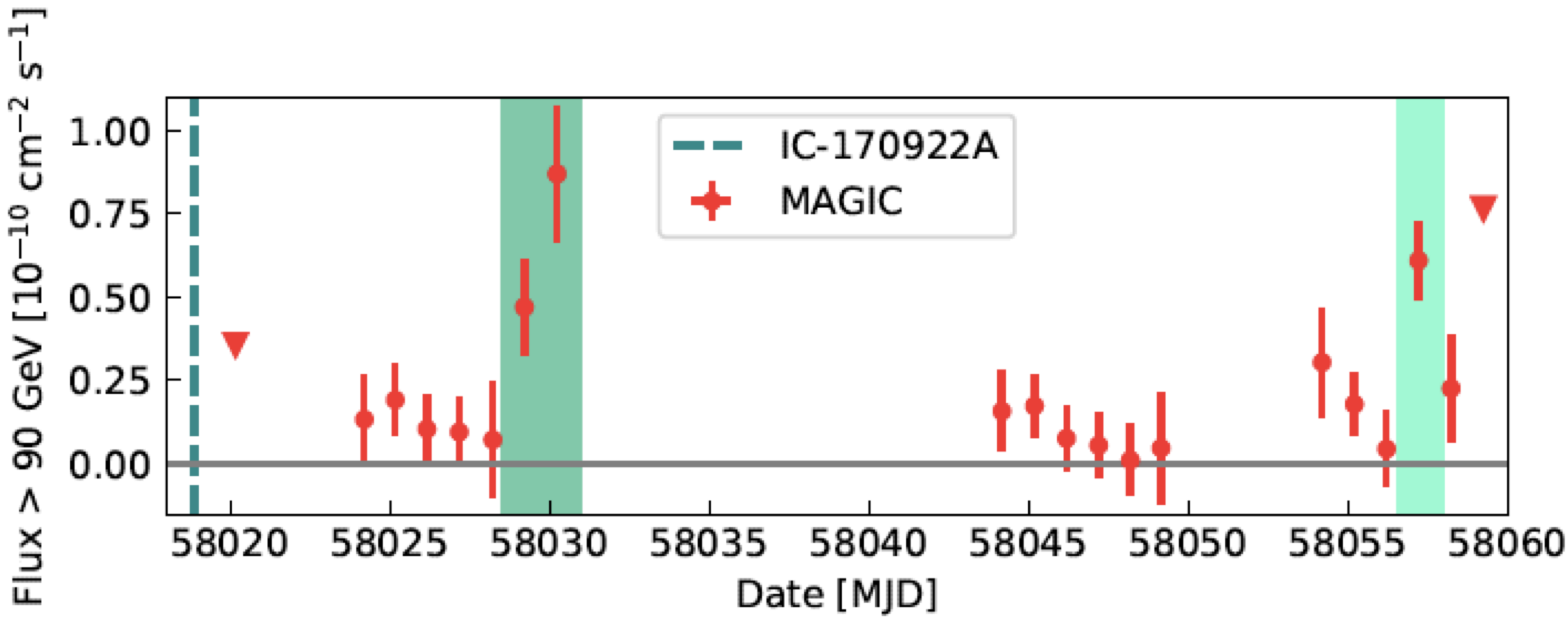


Tidal Disruption event (TDE)



All have distinct electro-magnetic counterparts

MAGIC finds variability on 1-day scale



Compact emission region

MAGIC Coll. ApJL, 2018

How Likely is it a Chance Probability?

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

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

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

Three models tested

Neutrino emission correlates with

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

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

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

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

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

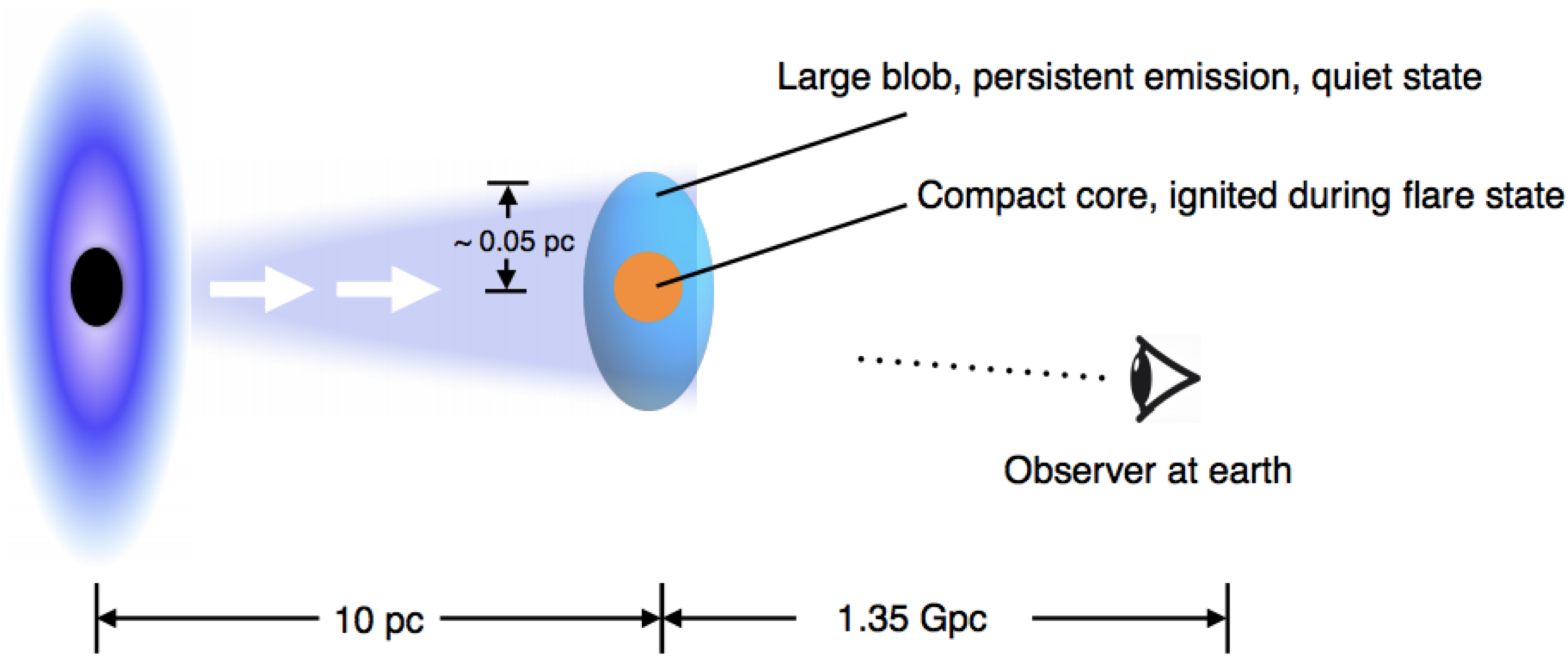
3. very high-energy gamma-ray energy flux in the range 100GeV-1TeV (extrapolated from Fermi energy range)

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

All tested models yield similar p-values

Modeling – leptonic, hadronic, Gin & Tonic

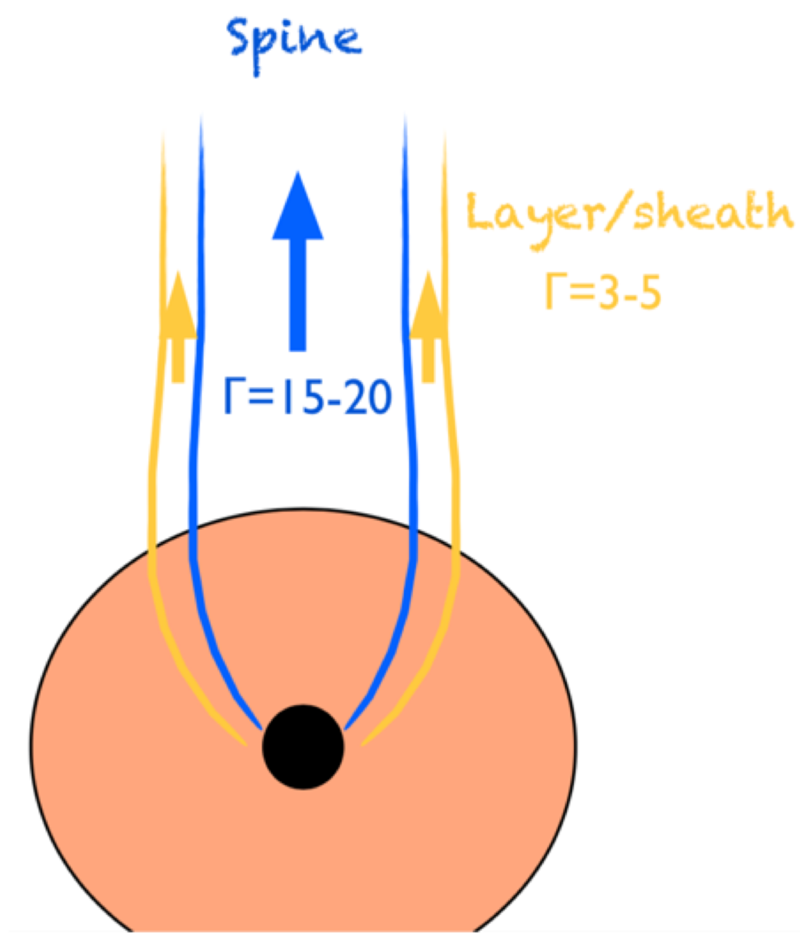
Solution: two-zone models



Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275

Modeling – leptonic, hadronic, Gin & Tonic

Alternative two-zone model: spine sheath



Taveccio, TeVPA 2018

Blazar Spine Sheath Model
(by Ghisellini & Tavecchio 2005)

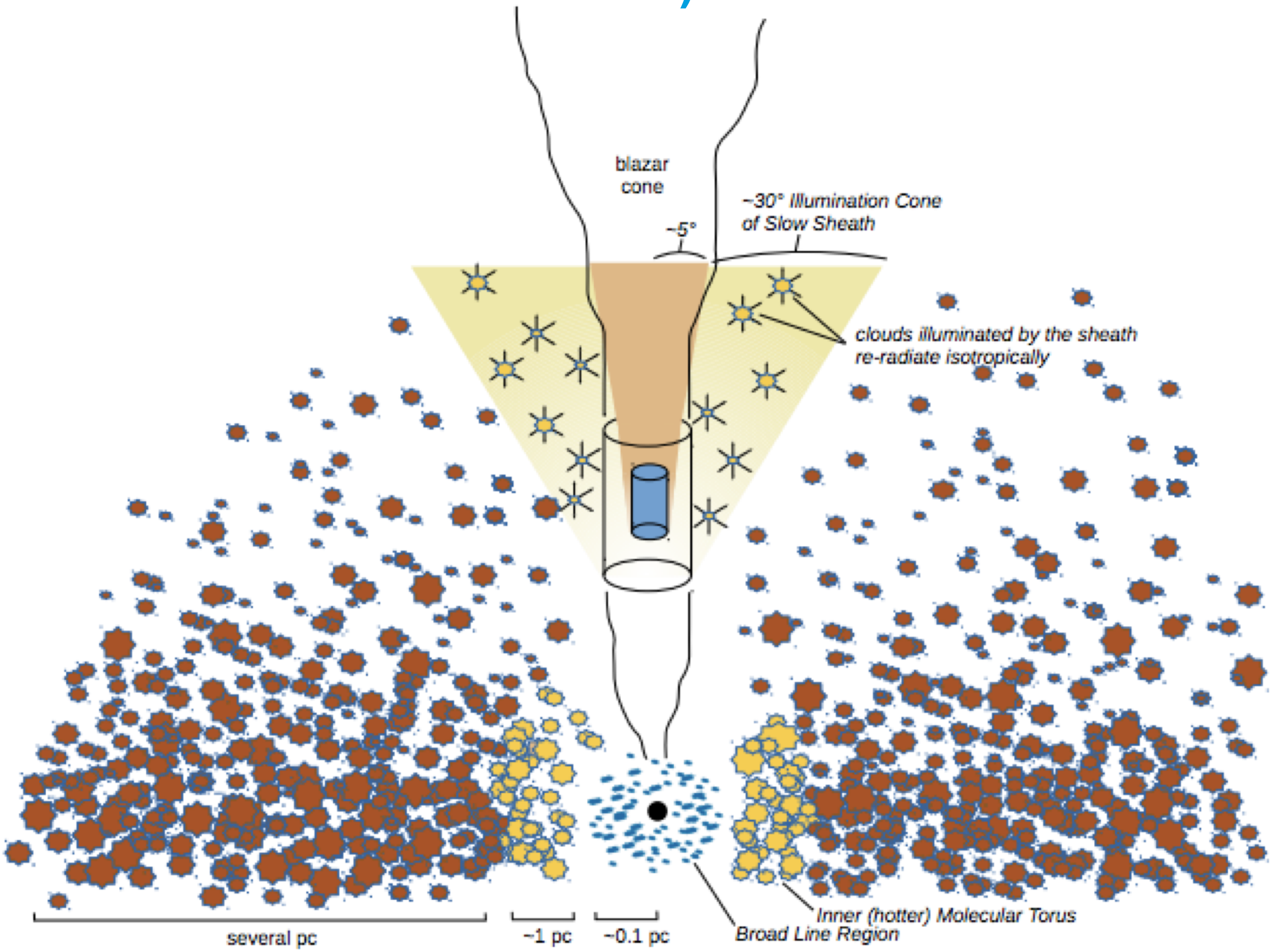
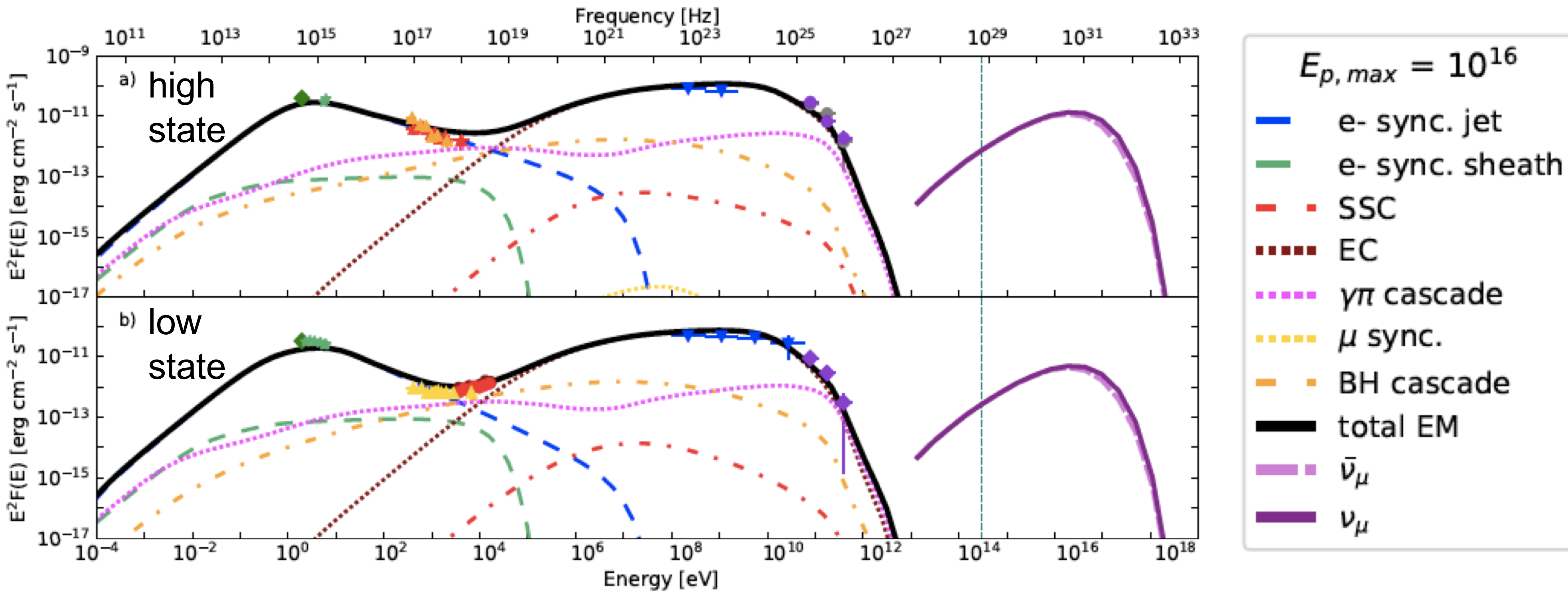


Illustration from Breiding, Georganopoulos, Meyer, 853, ApJ, 2018

Table 3. Parameters for the jet-sheath model for $E_{\rm p,max}$=10^{16}.

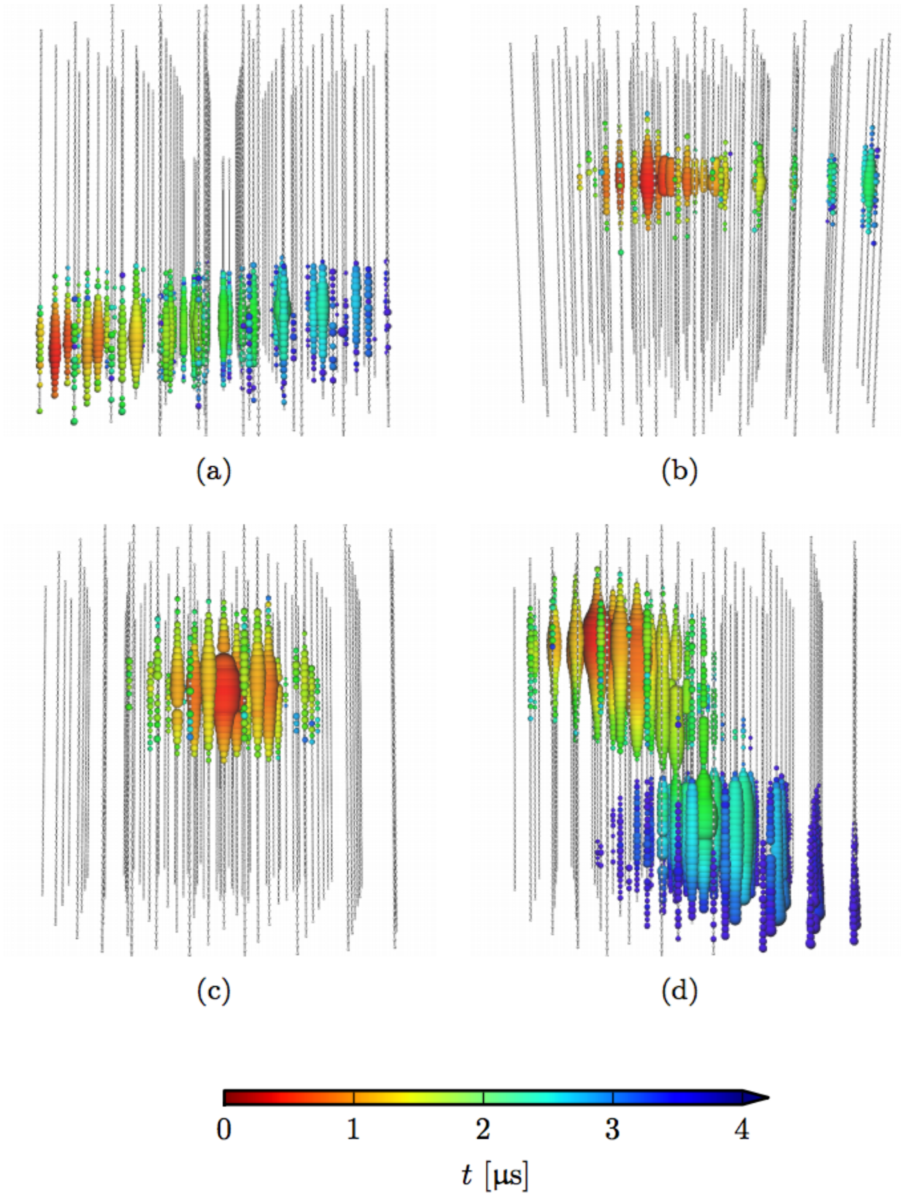
State	MJD 58029-30	Lower VHE
B [G]	2.6	2.6
$E_{\rm min}$ [eV]	3.2×10^8	2.0×10^8
$E_{\rm br}$ [eV]	7.0×10^8	9.0×10^8
$E_{\rm max}$ [eV]	8×10^{11}	8×10^{11}
n_1	2	2
n_2	3.9	4.4
U_e [erg cm^{-3}]	4.4×10^{-4}	3.6×10^{-4}
U_B [erg cm^{-3}]	0.27	0.27
U_p [erg cm^{-3}]	1.8	0.7
P_e [erg s^{-1}]	2×10^{42}	1.6×10^{42}
P_p [erg s^{-1}]	8×10^{45}	3×10^{45}
P_B [erg s^{-1}]	1.2×10^{45}	1.2×10^{45}

Blazar Spine Sheath Model – applied to TXS
(by Ghisellini & Tavecchio 2005)



MAGIC Coll., 1807.04300

Event Signatures

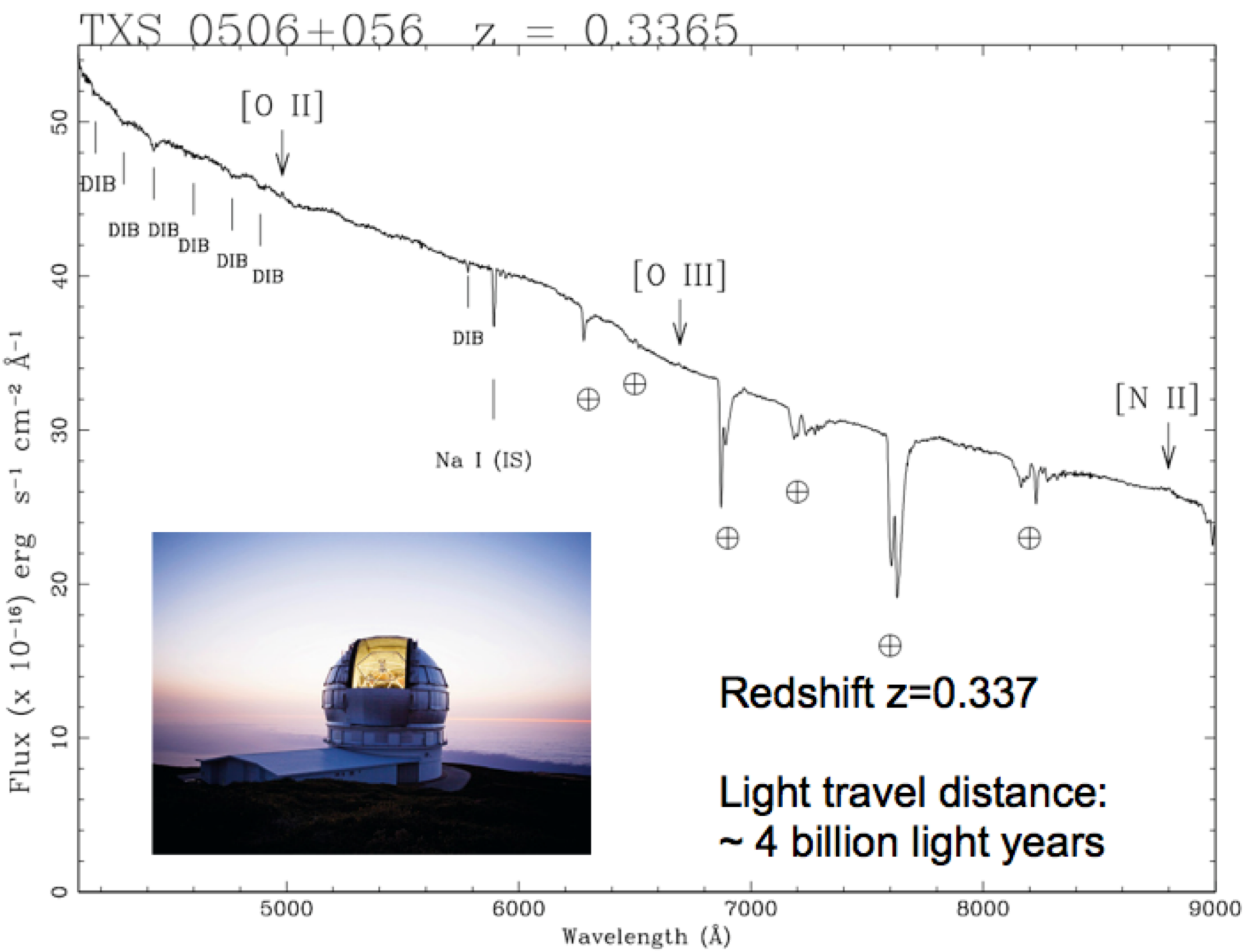


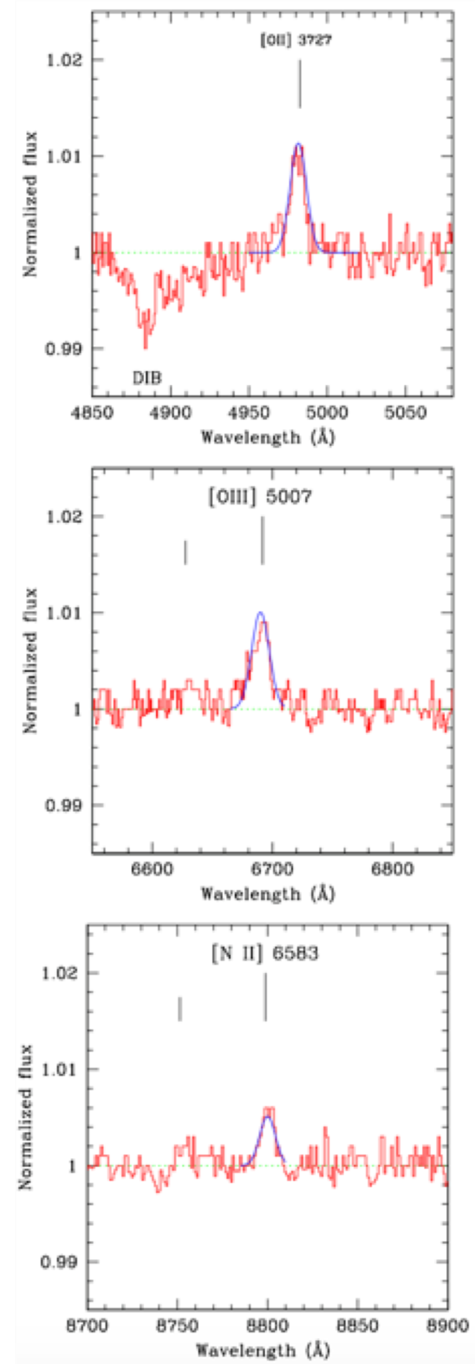
a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV
c) Shower event E ~ 1 PeV
d) "double bang" event E ~ 200 PeV (simulated)

Resolvable for deposited energy >100TeV

The Redshift

From the 10.4m Gran Telescopio Canarias





S. Paiano et al. 2018