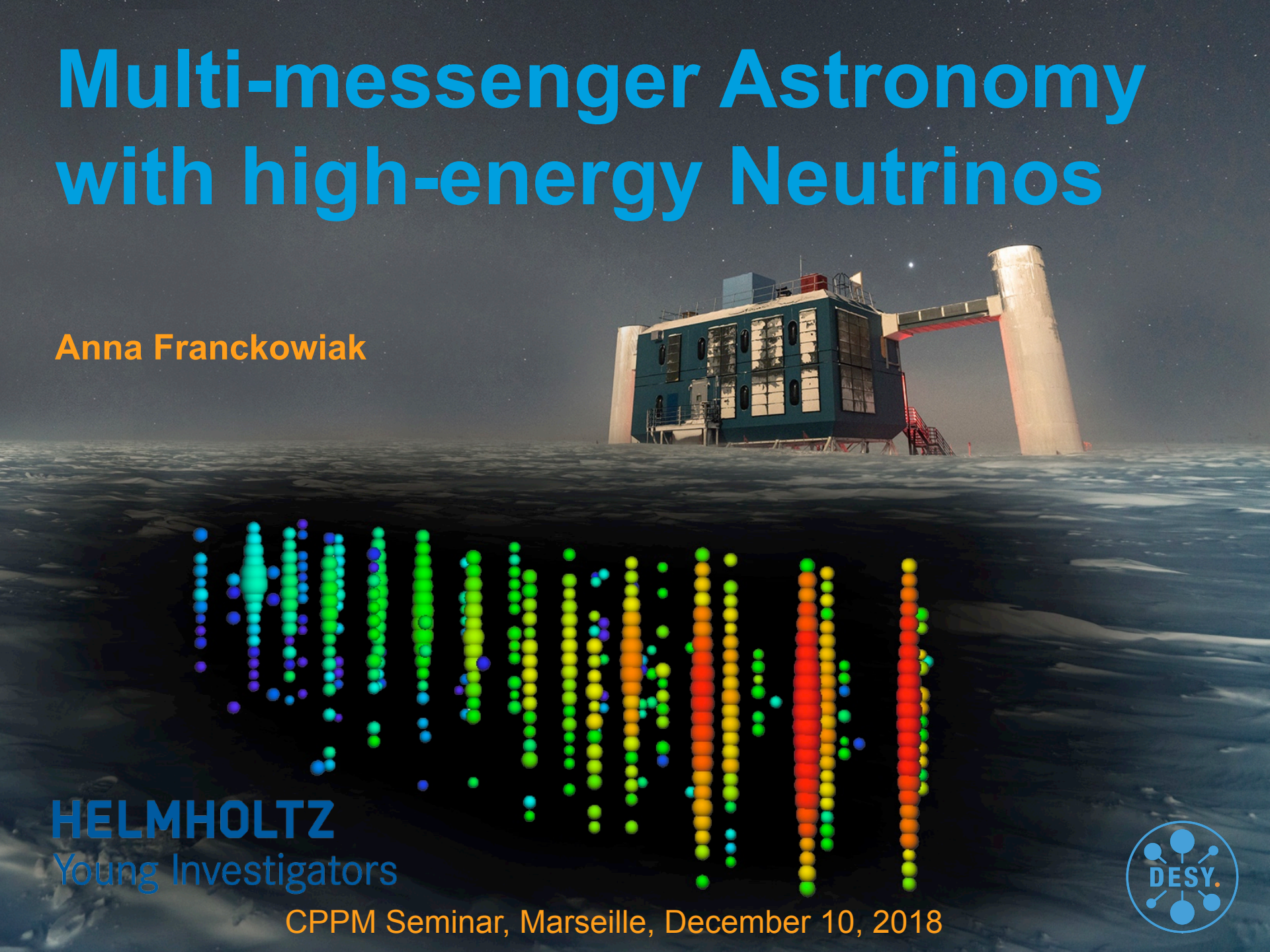
Multi-messenger Astronomy with high-energy Neutrinos

Anna Franckowiak

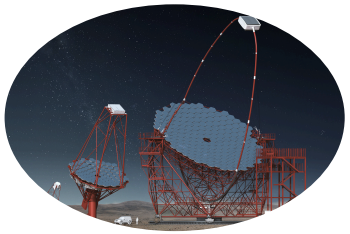


HELMHOLTZ
Young Investigators

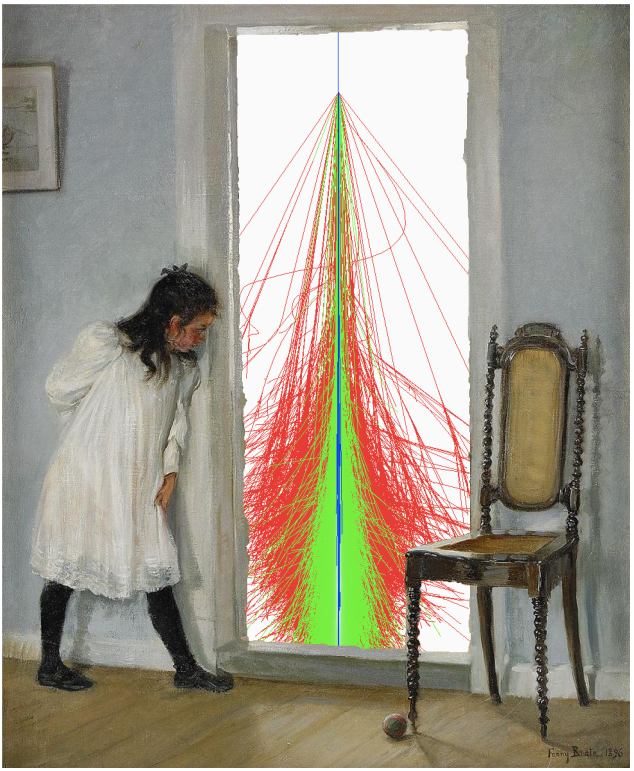
CPPM Seminar, Marseille, December 10, 2018

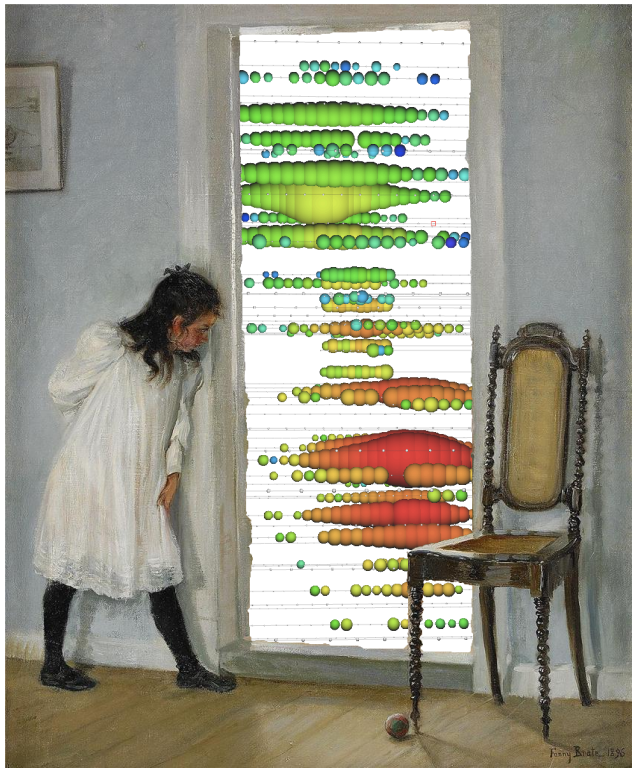
DESY.

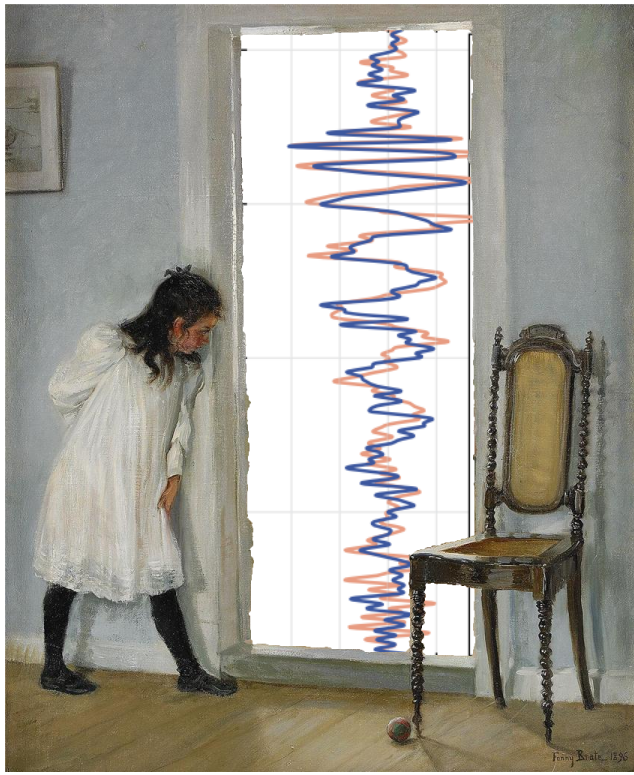
The Multi-Messenger Picture



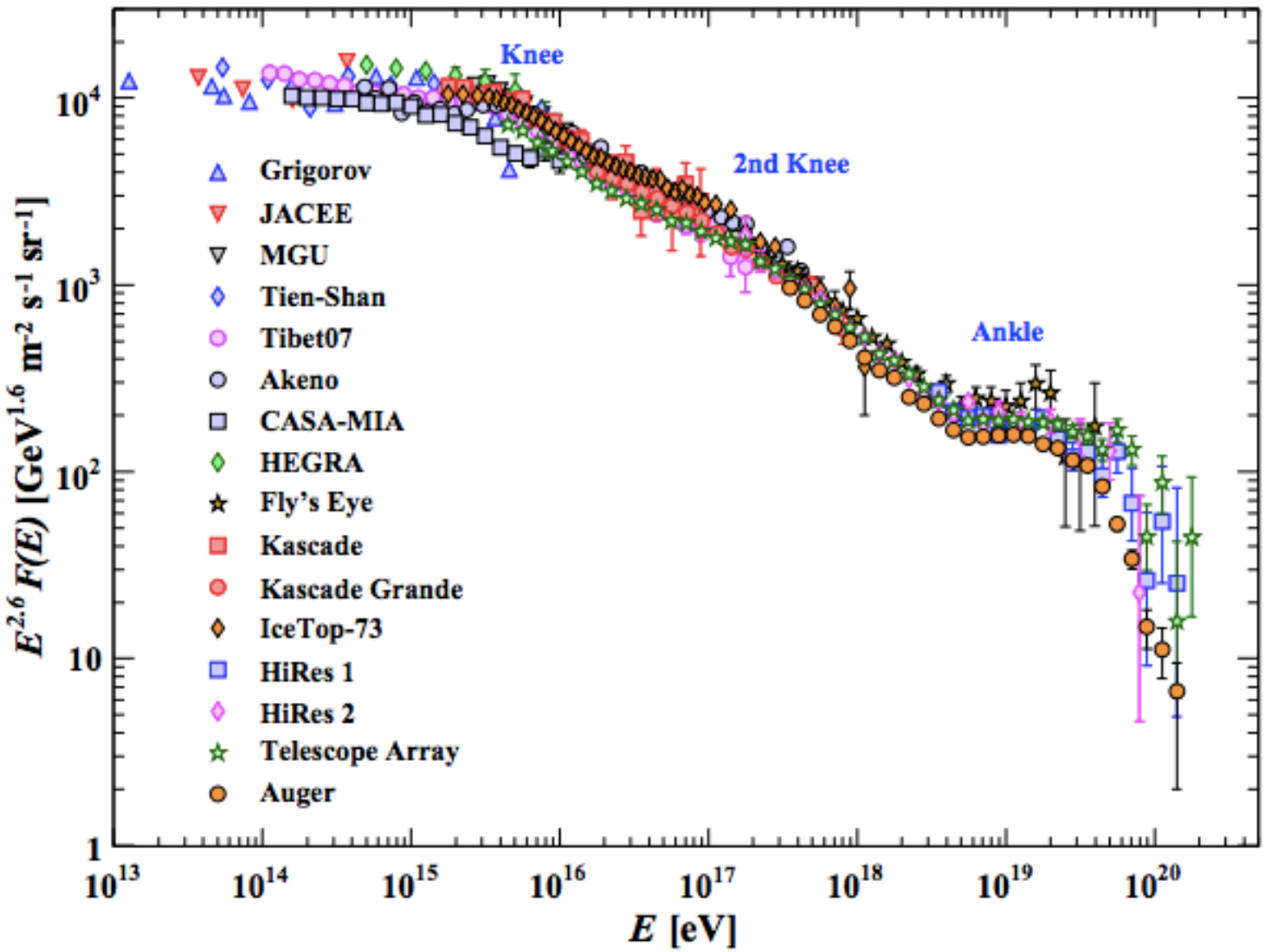
New Windows to the Universe



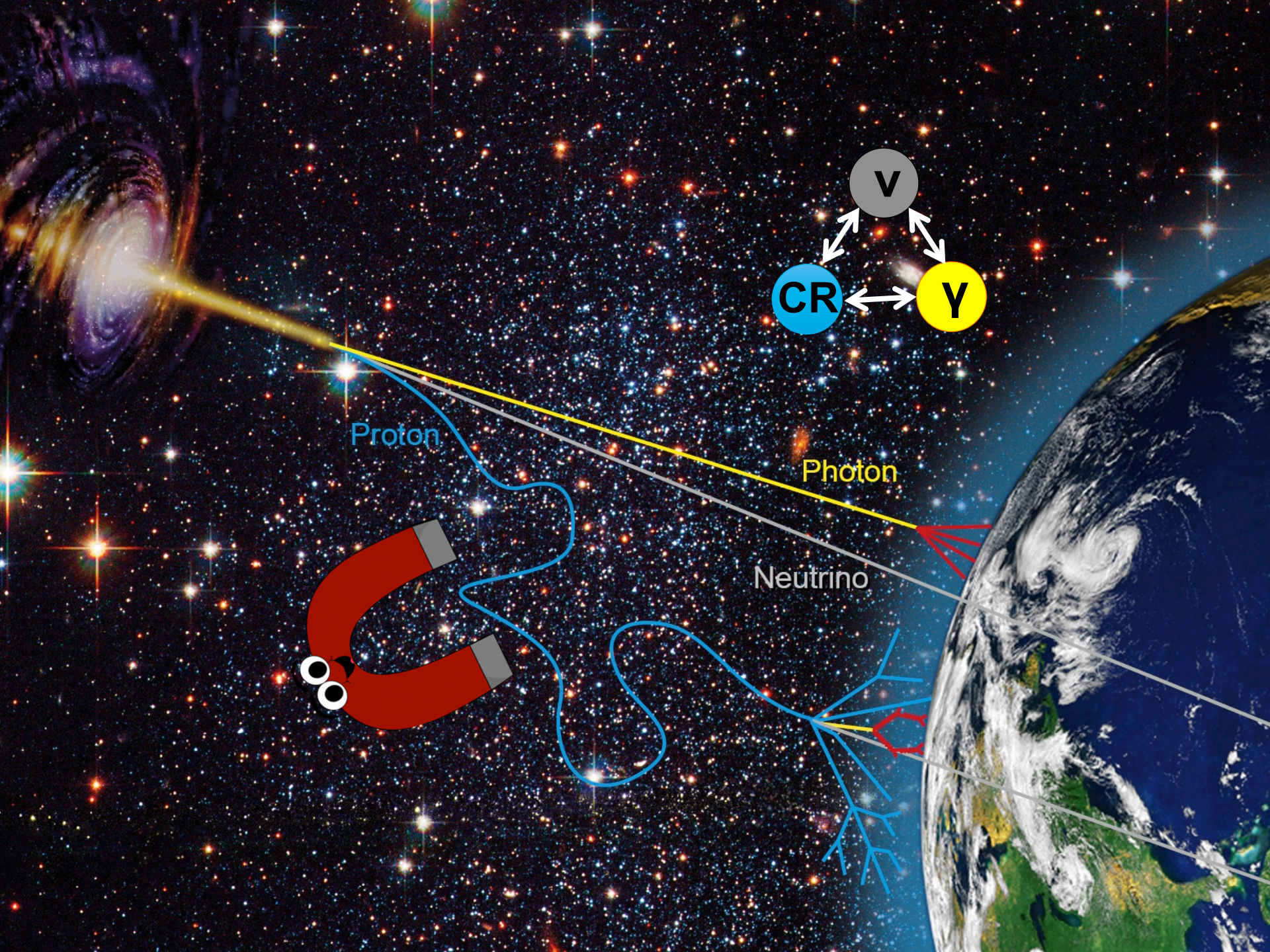




Cosmic rays reach 10^{20}eV



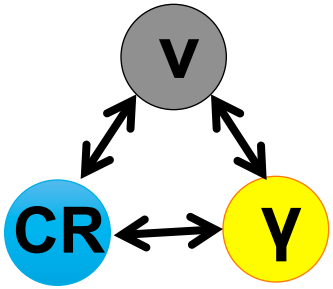
M. Tanabashi et al. (Particle Data Group), PRD 98, 2018


ν
CR
γ
Proton
Photon
Neutrino

Neutrino Production Processes

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

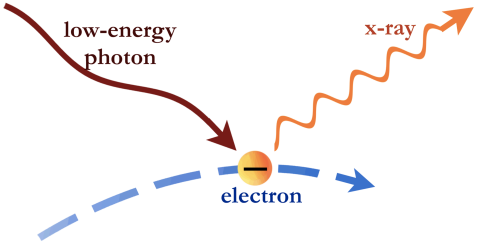
$$pp \rightarrow \begin{cases} X + \pi^0 \rightarrow \gamma\,\gamma \\ X + \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu \\ X + \pi^- \rightarrow \mu^- \nu_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu \end{cases}$$

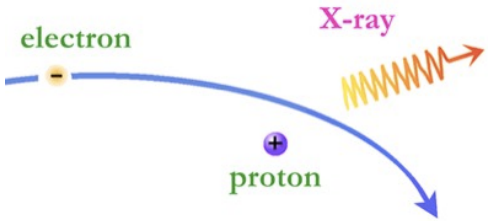


Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

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

Gamma-rays are not exclusively produced in hadronic processes

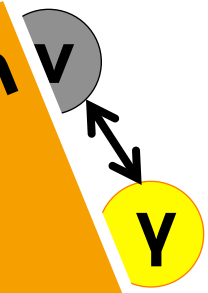




Neutrino Production Processes

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

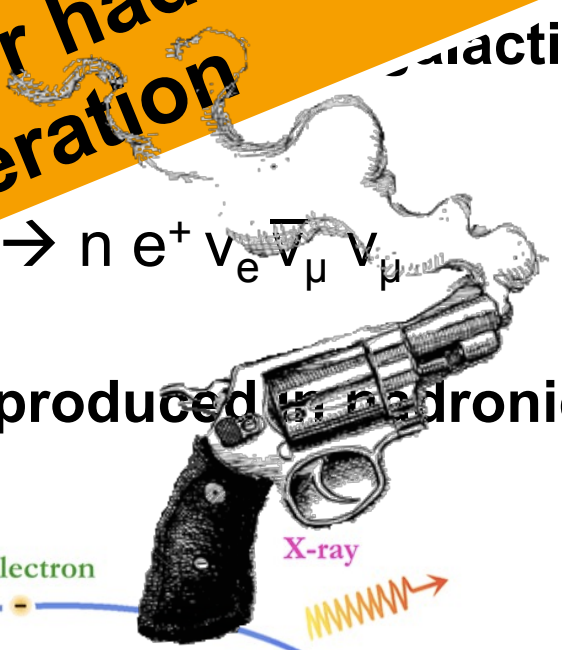
$$pp \rightarrow \begin{cases} X + \pi^0 \rightarrow \gamma\,\gamma \\ X + \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu \\ X + \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \end{cases}$$



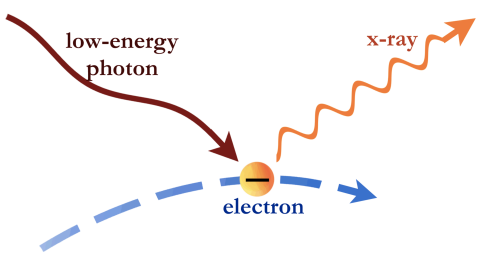
Photohadronic (e… …actic nuclei)

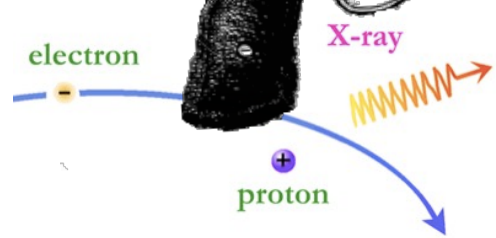
$$p\gamma \rightarrow \ldots \nu_\mu \rightarrow n\, e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

Neutrinos are the smoking gun signature for hadronic acceleration

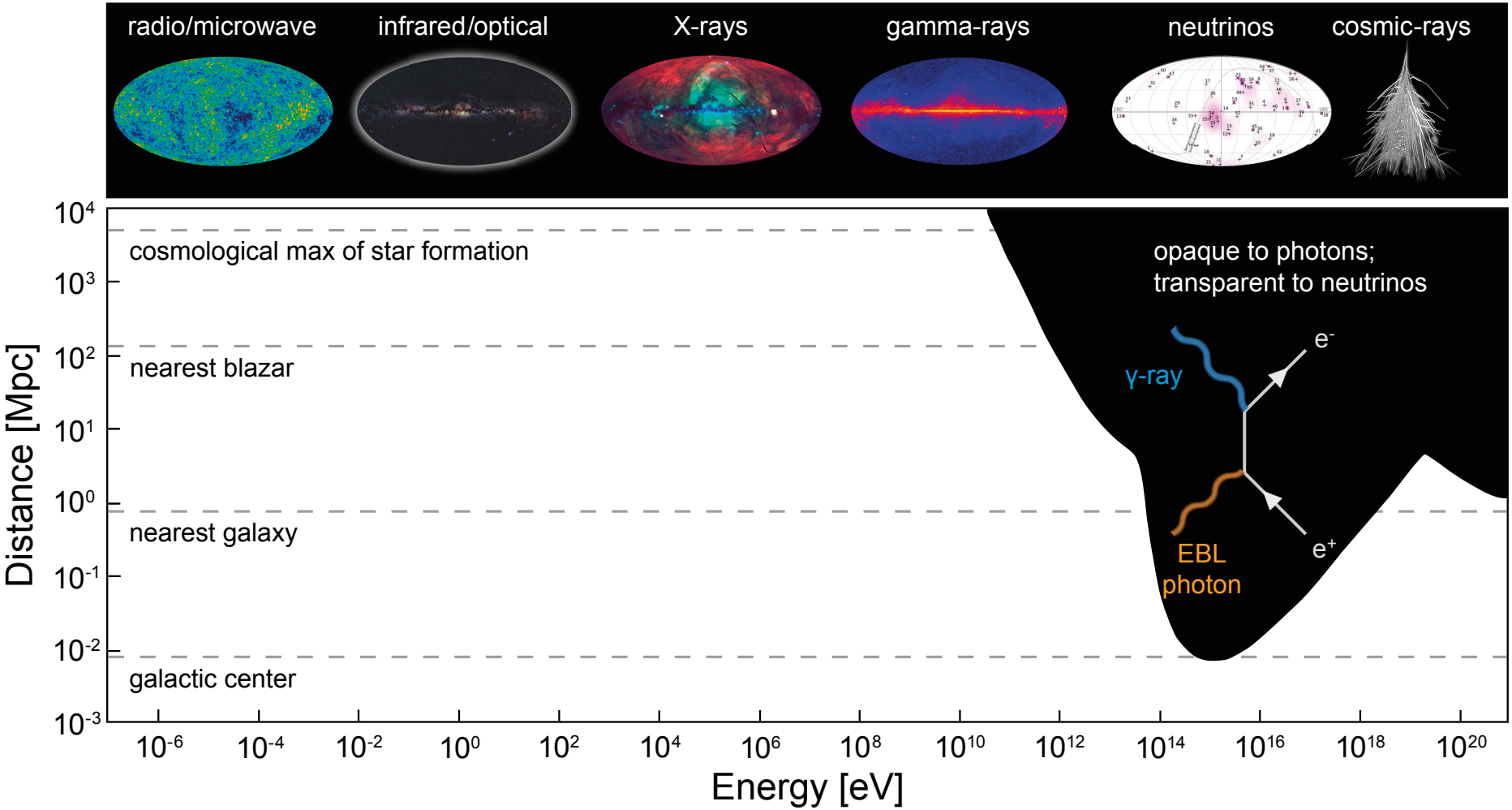


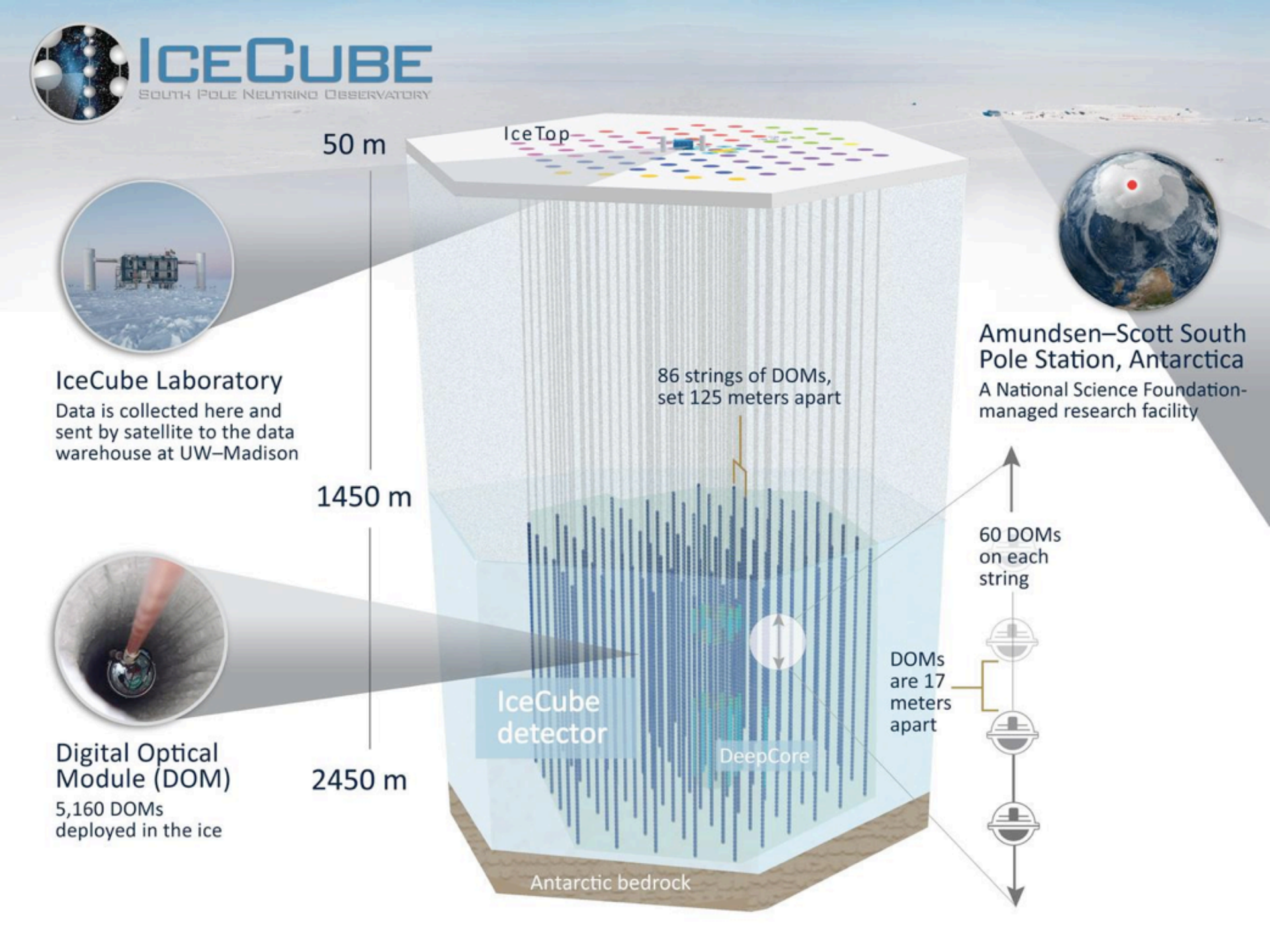
Gamma-ray … not exclusively produced in hadronic processes



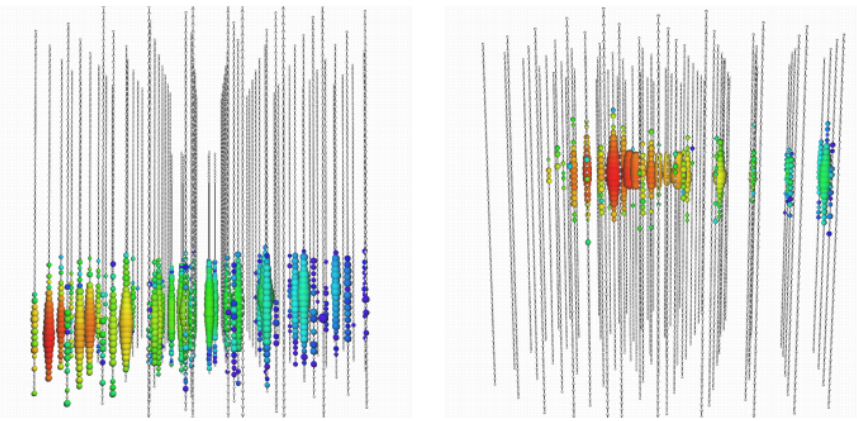


Where Can We Look?



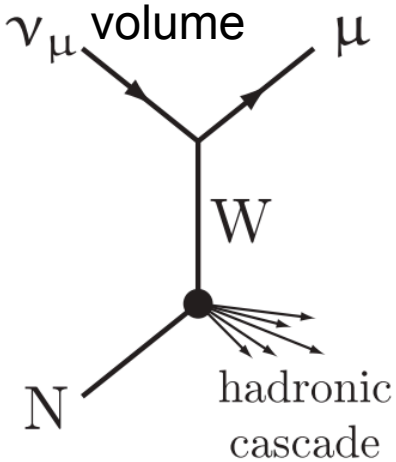

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility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

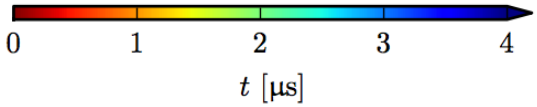
Event Signatures



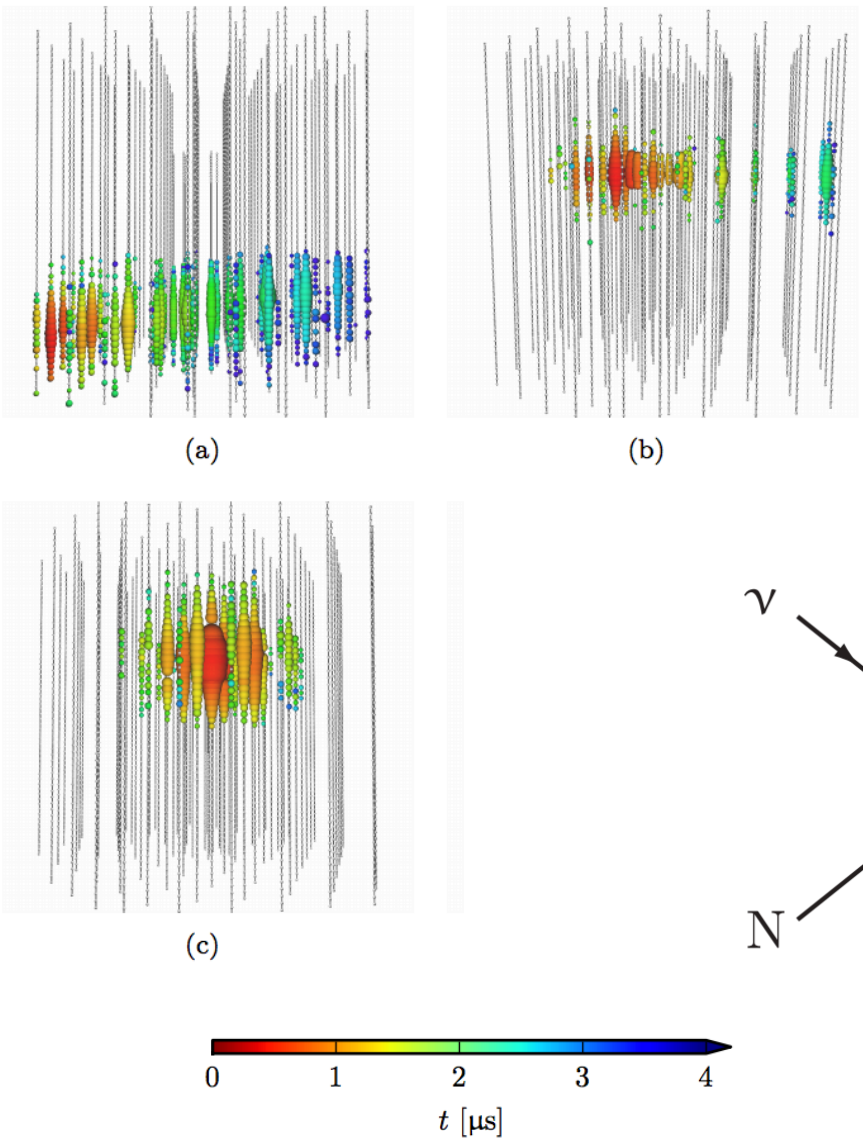
a) **through-going muon track E ~ 140 TeV**
b) **Starting muon track E ~ 70 TeV**

Charged current interaction of muon neutrino outside / inside the detector



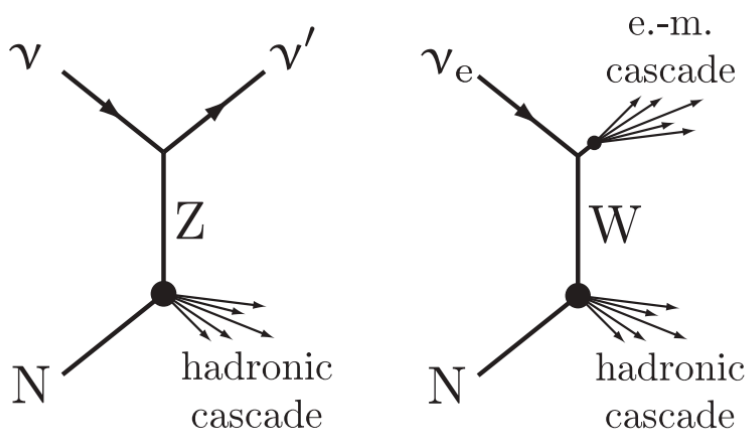


Event Signatures



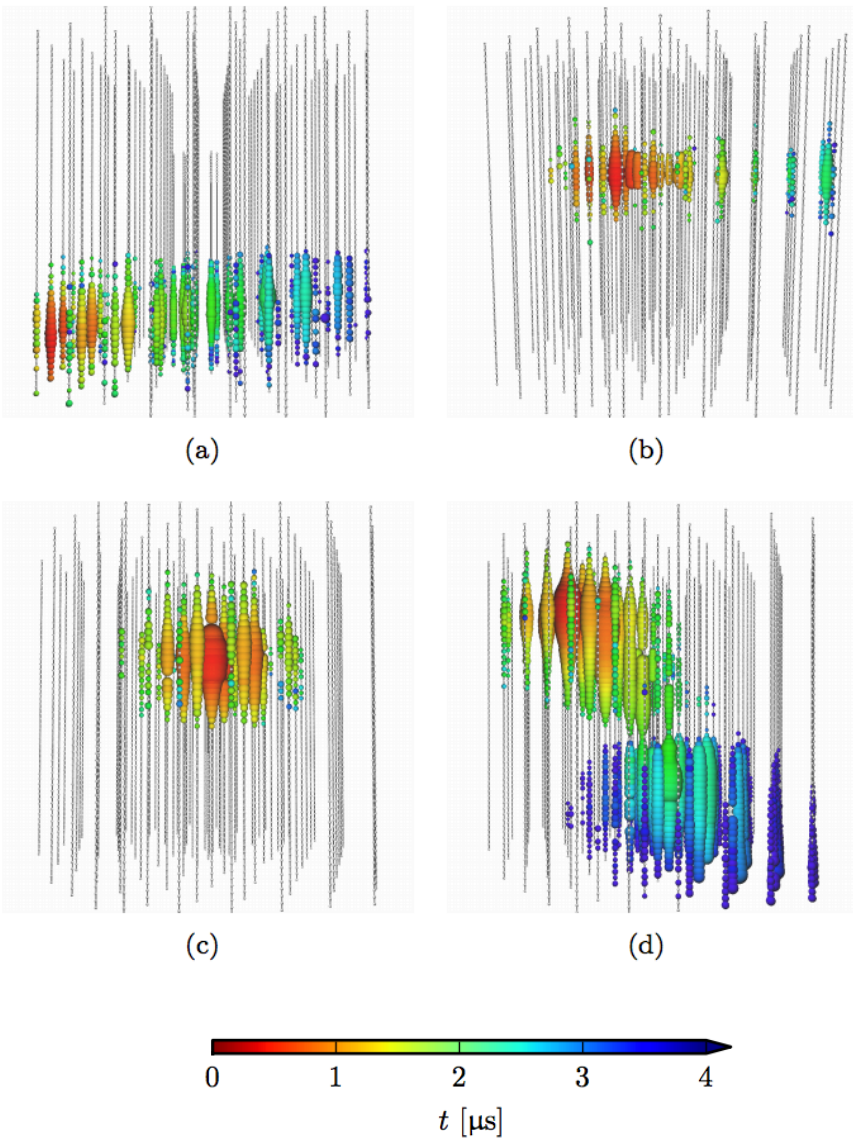
a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV
c) Shower event E ~ 1 PeV

Neutral current or electron neutrino charged current interaction



Cannot distinguish between showers (size few meters)

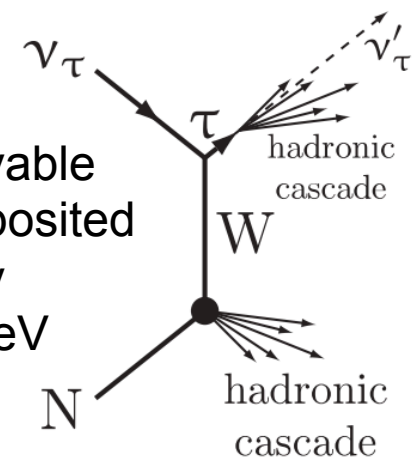
Event Signatures



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)

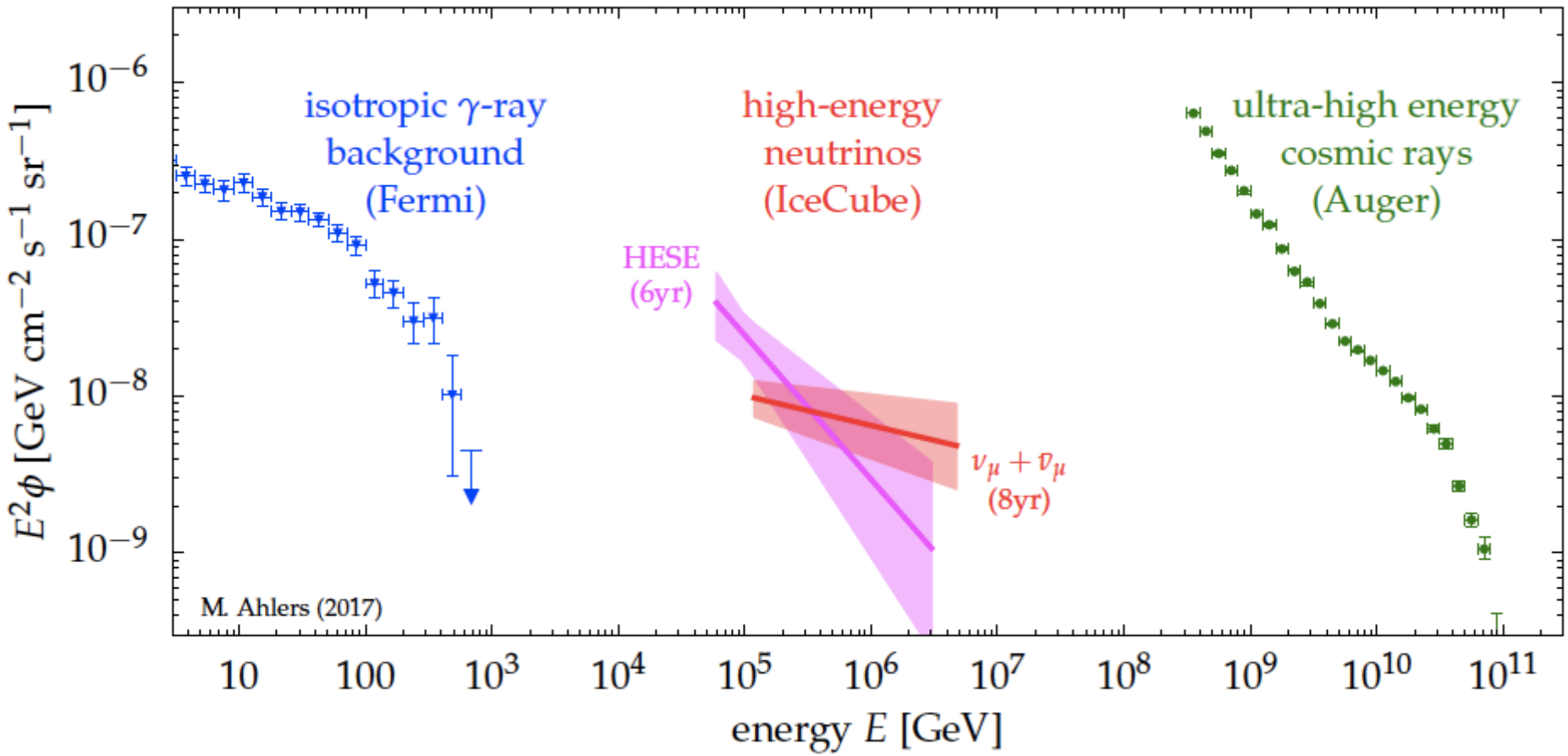
Tau neutrino charged current interaction

Resolvable for deposited energy >100TeV



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

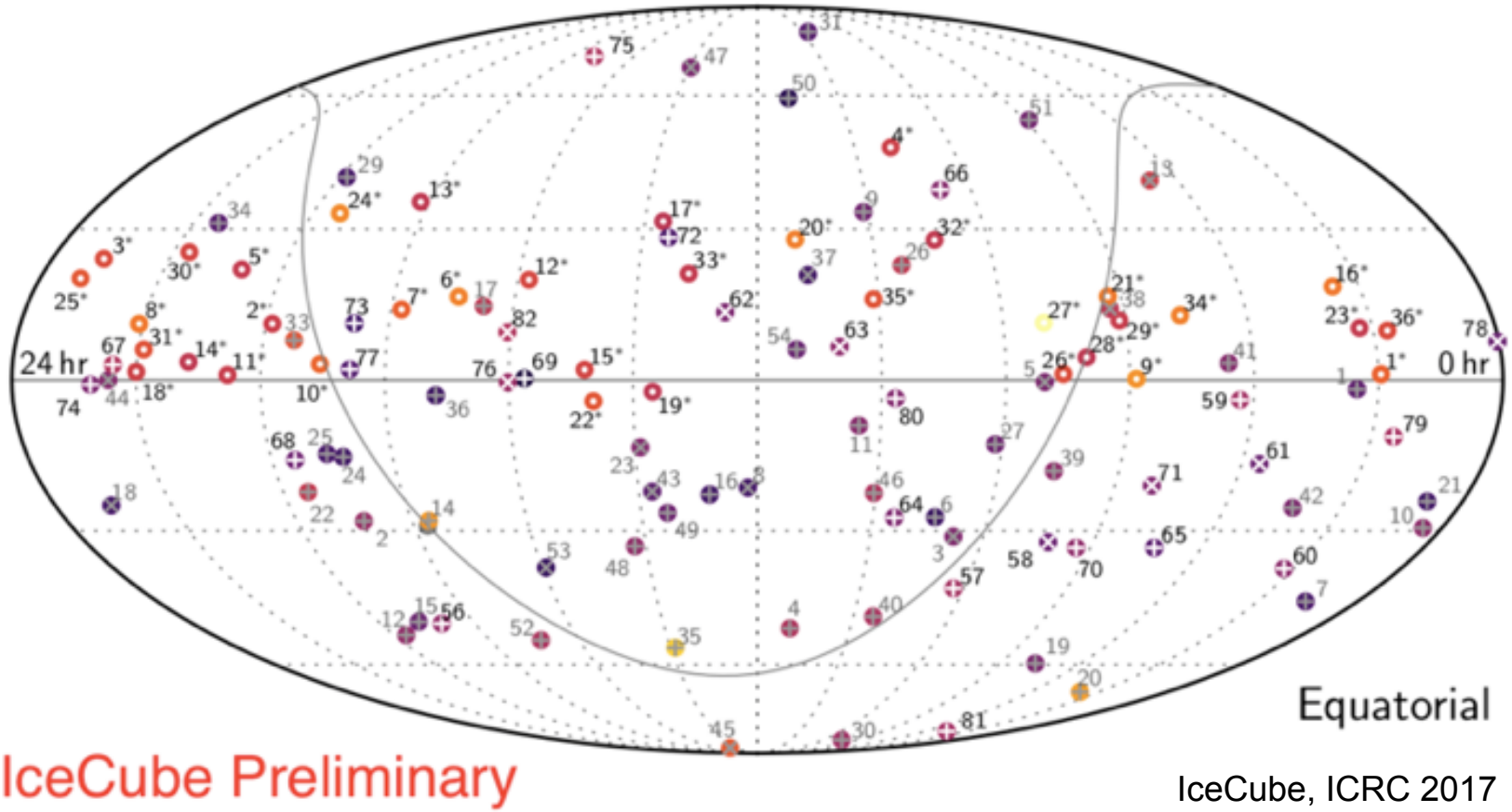
Diffuse Neutrino Flux detected!



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)



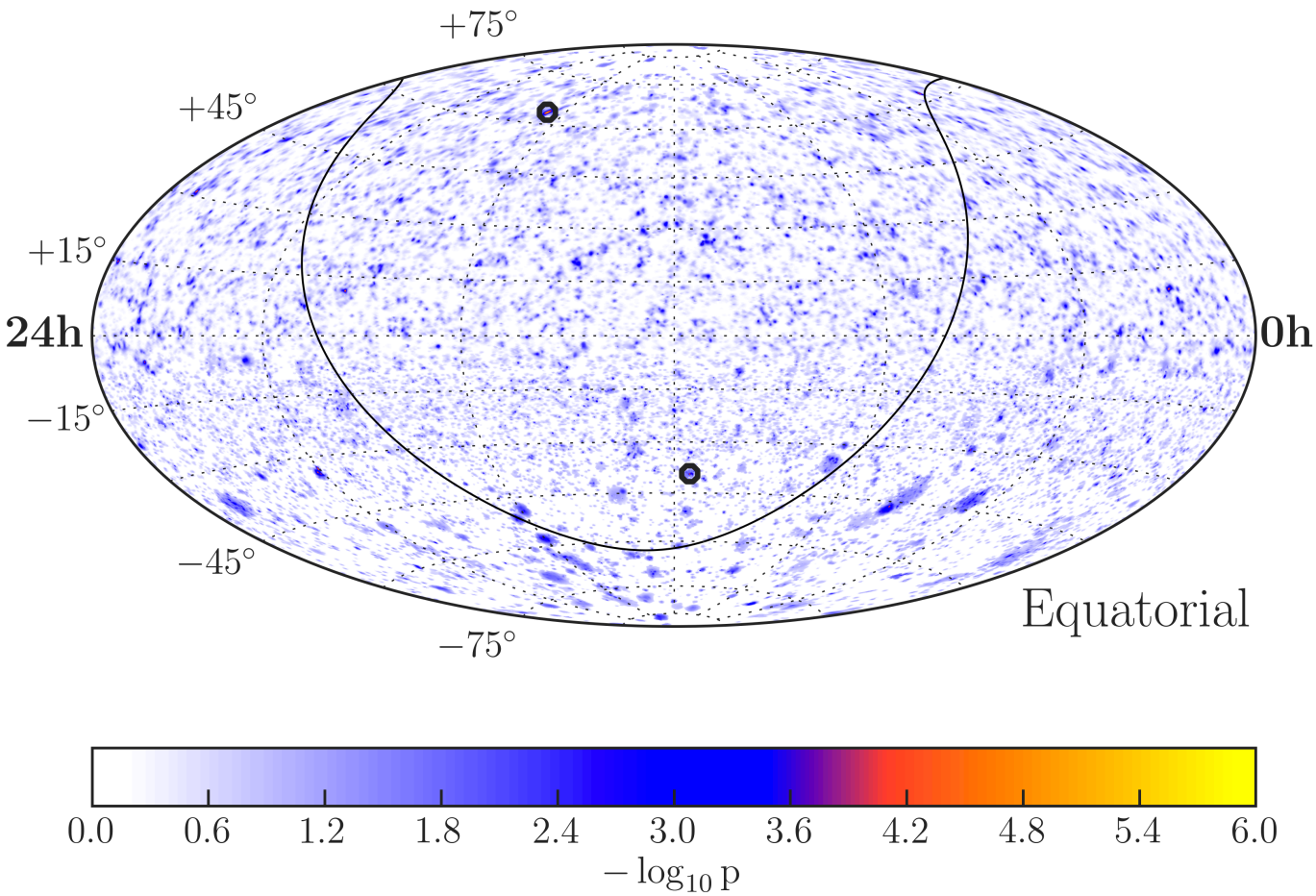
IceCube, ICRC 2017

Compatible with an isotropic distribution

→ extragalactic origin of cosmic neutrinos

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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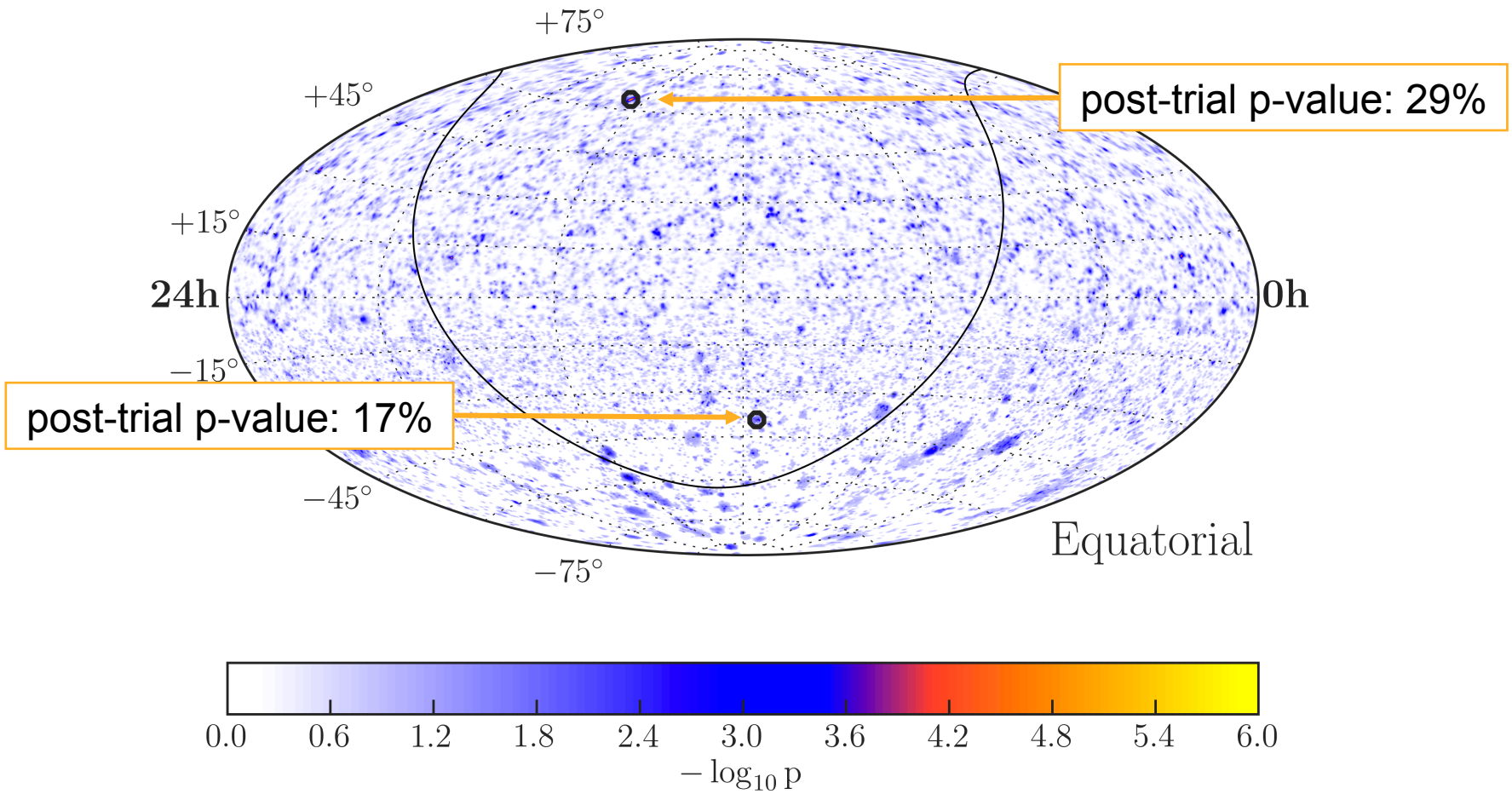

IceCube Coll. ApJ, 835 (2017)

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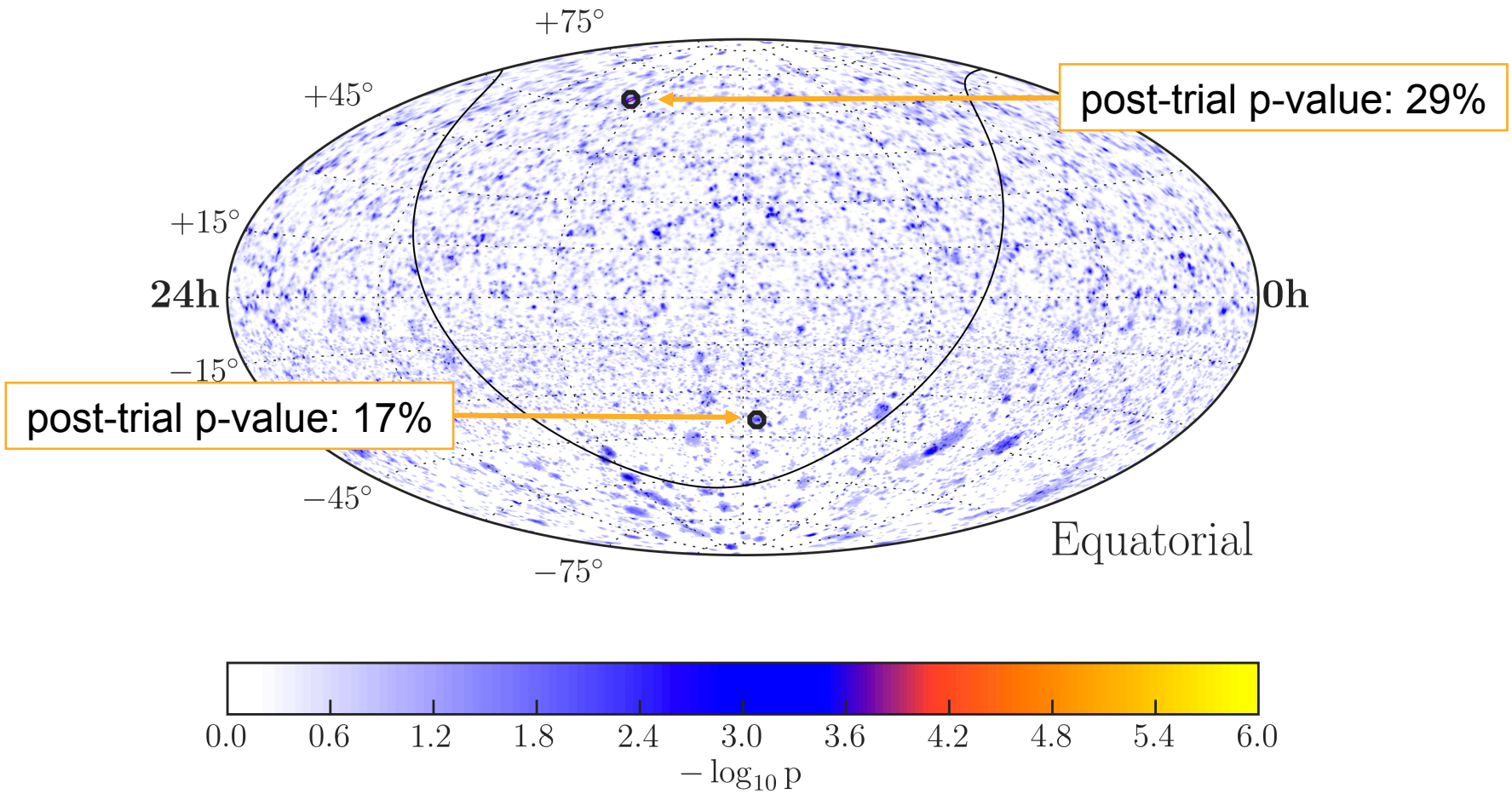


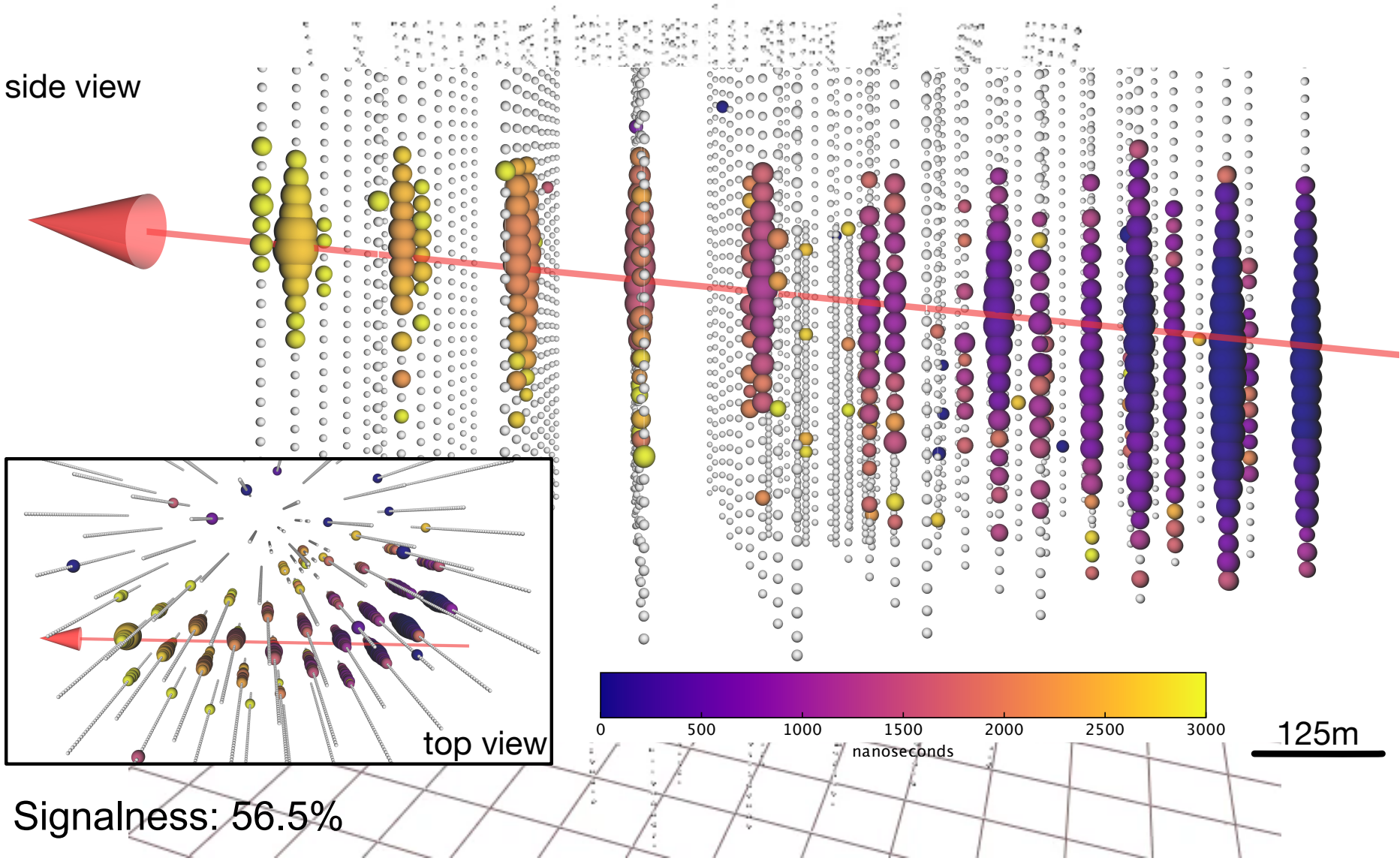
Large trials factor → Multi-wavelength data can tell us where and when to look for neutrinos

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



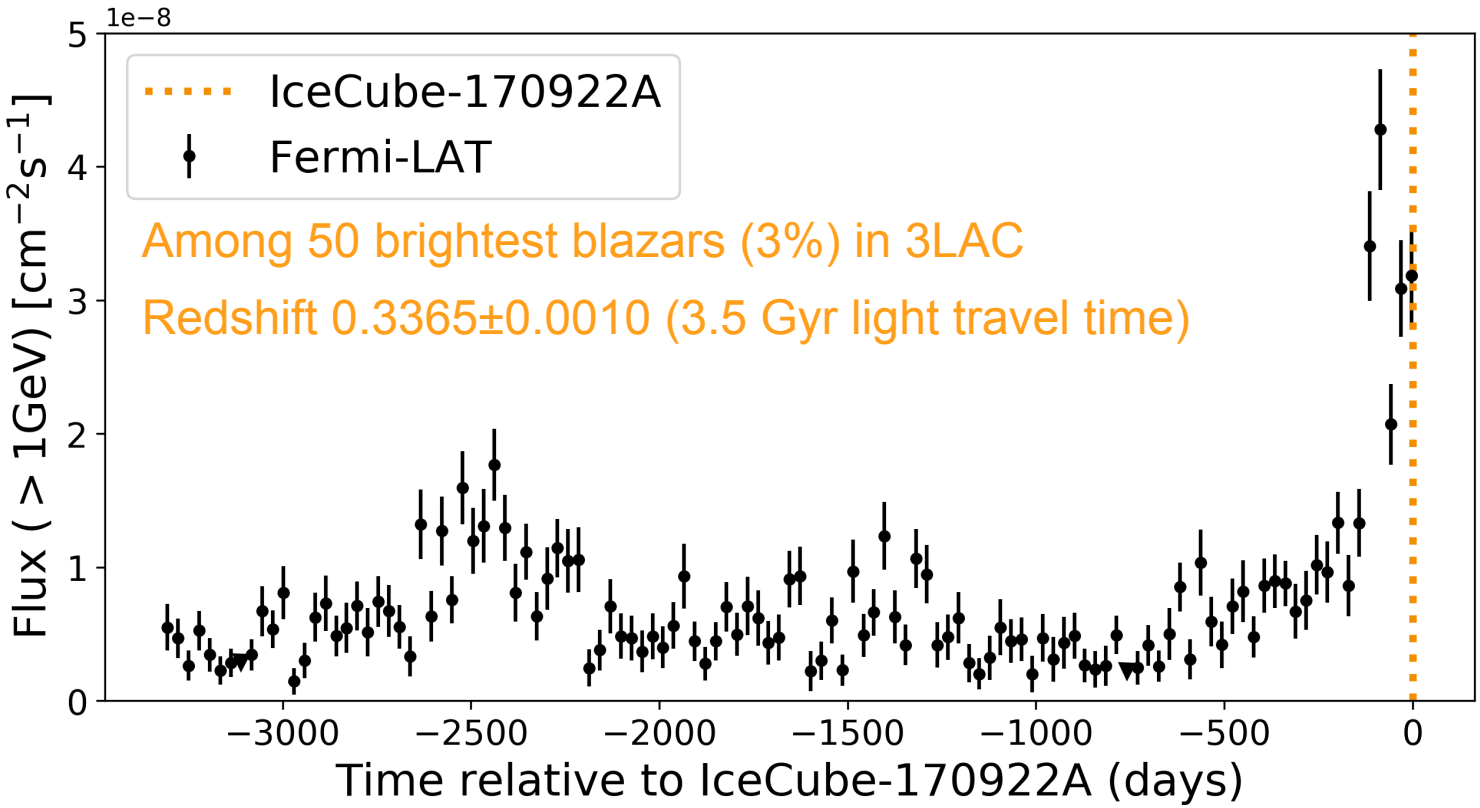
Signalness: 56.5%

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

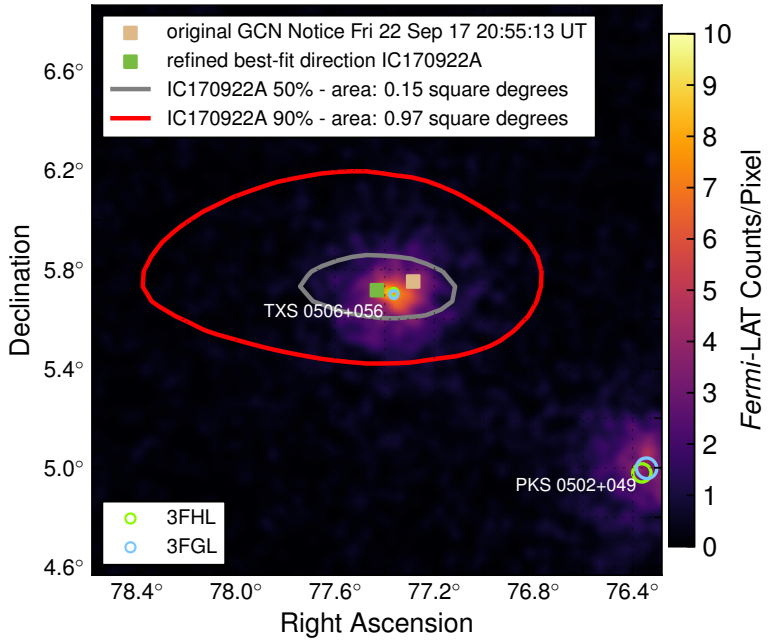
Fermi-LAT finds Flaring Blazar, TXS 0506+056

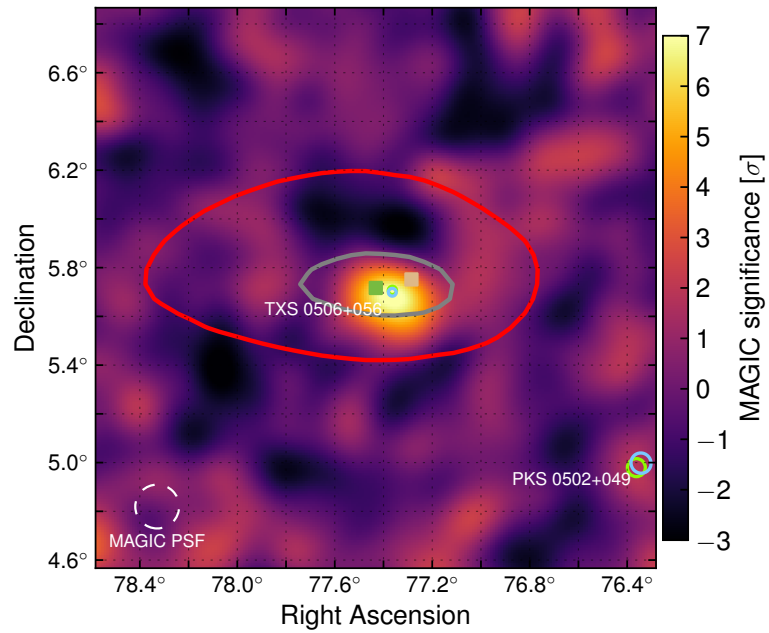


Pre-trials p-value: 4.1σ

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

MAGIC observes >100 GeV gamma rays



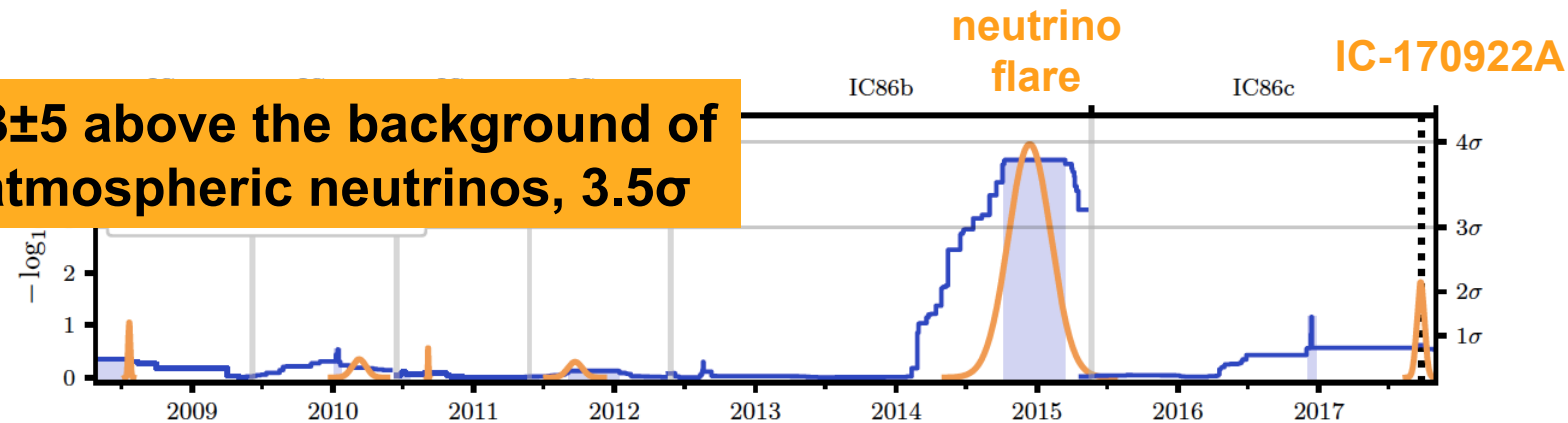


IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Are there more Neutrinos from this Source?

Are there more Neutrinos from this Source?

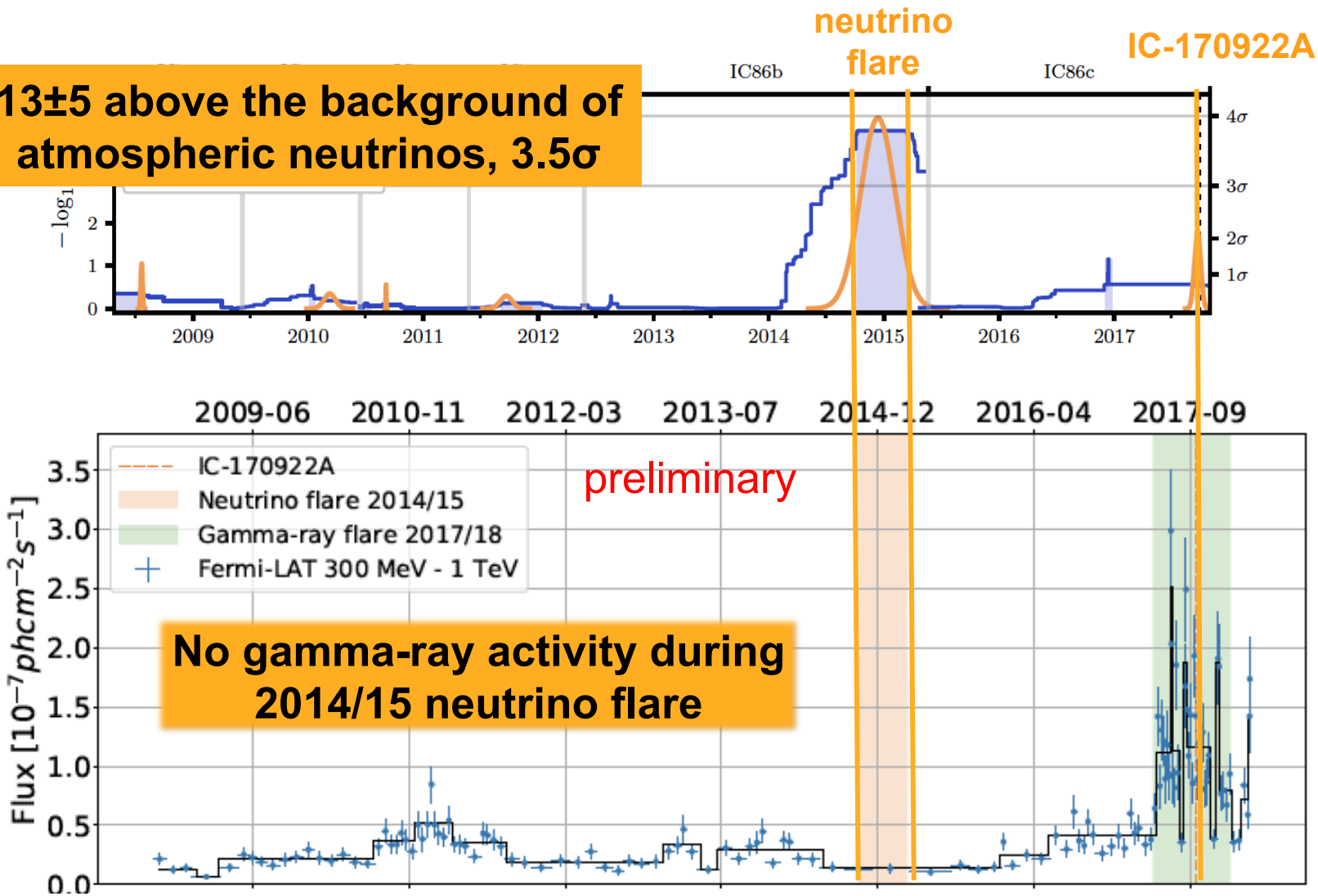
13±5 above the background of atmospheric neutrinos, 3.5σ



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

Is there also a Gamma-ray Flare?

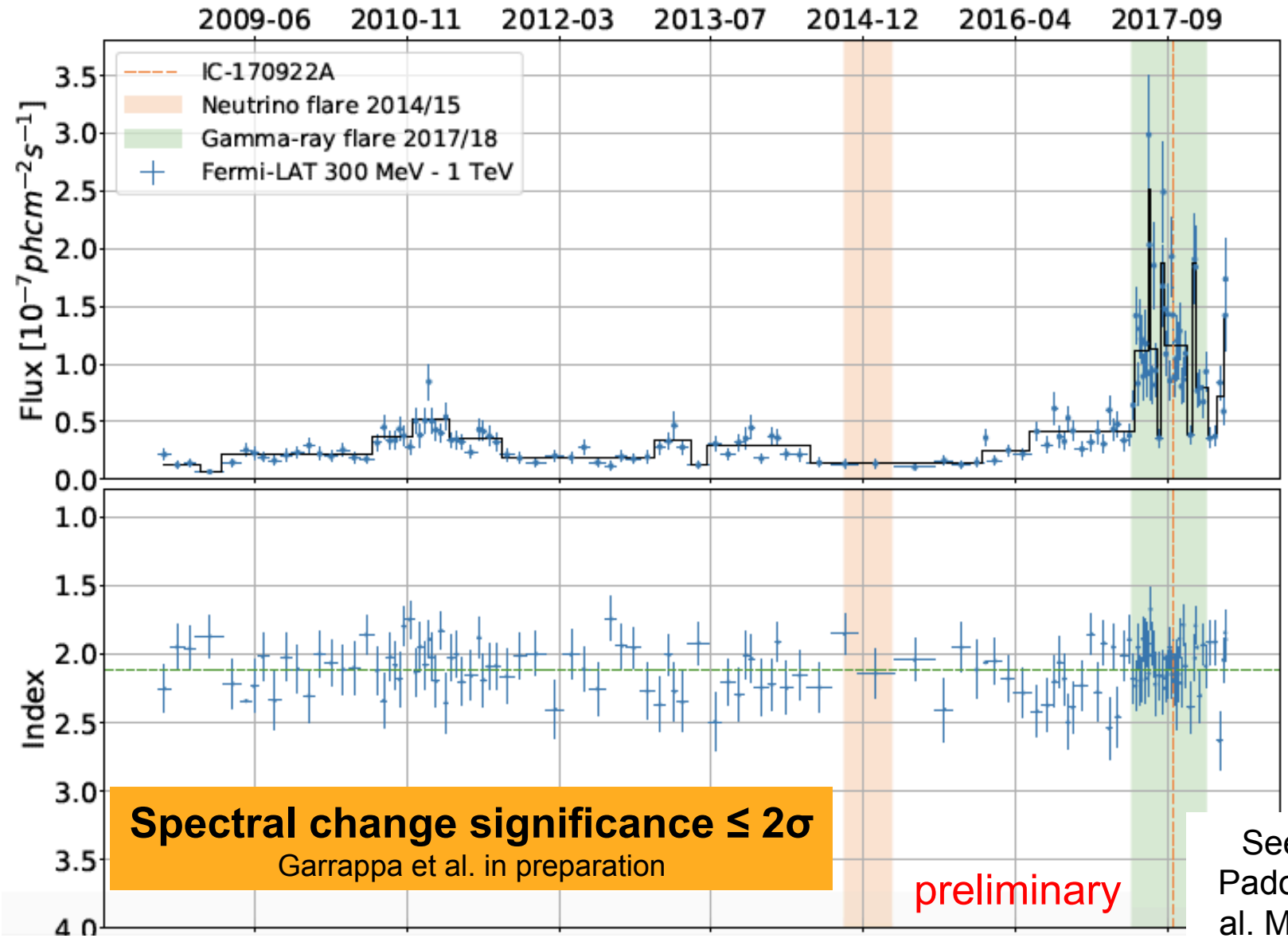
13±5 above the background of atmospheric neutrinos, 3.5σ



No gamma-ray activity during 2014/15 neutrino flare

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

Spectral Change?

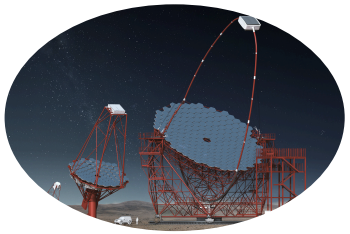


Spectral change significance ≤ 2σ

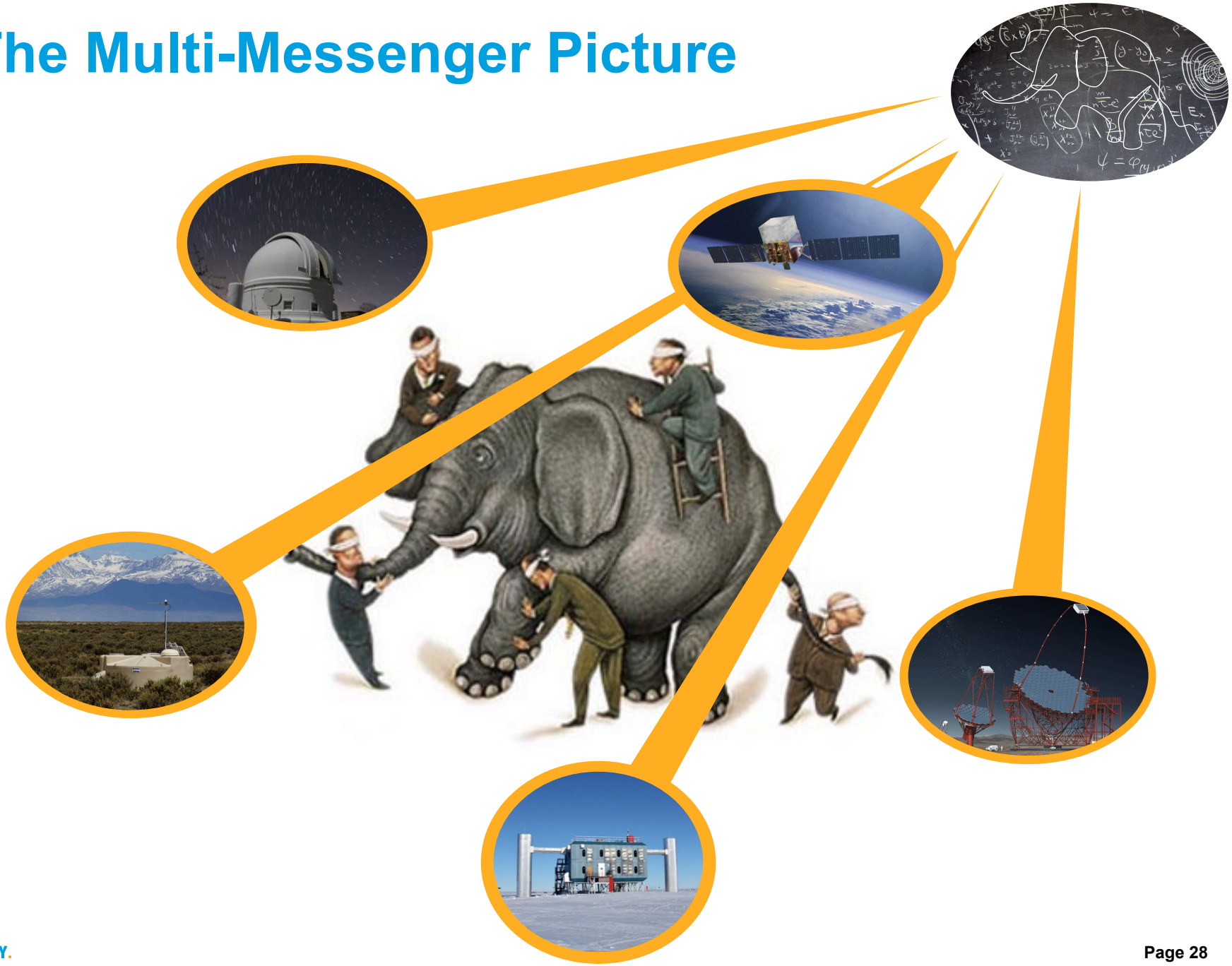
Garrappa et al. in preparation

See also Padovani et al. MNRAS, 2018

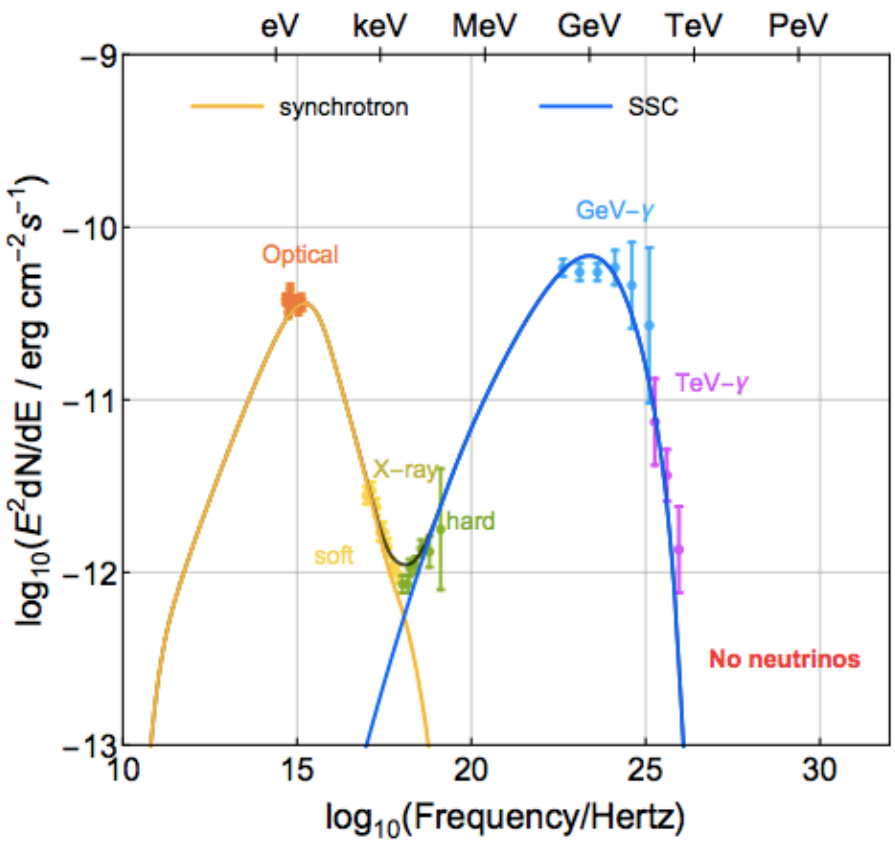
The Multi-Messenger Picture



The Multi-Messenger Picture

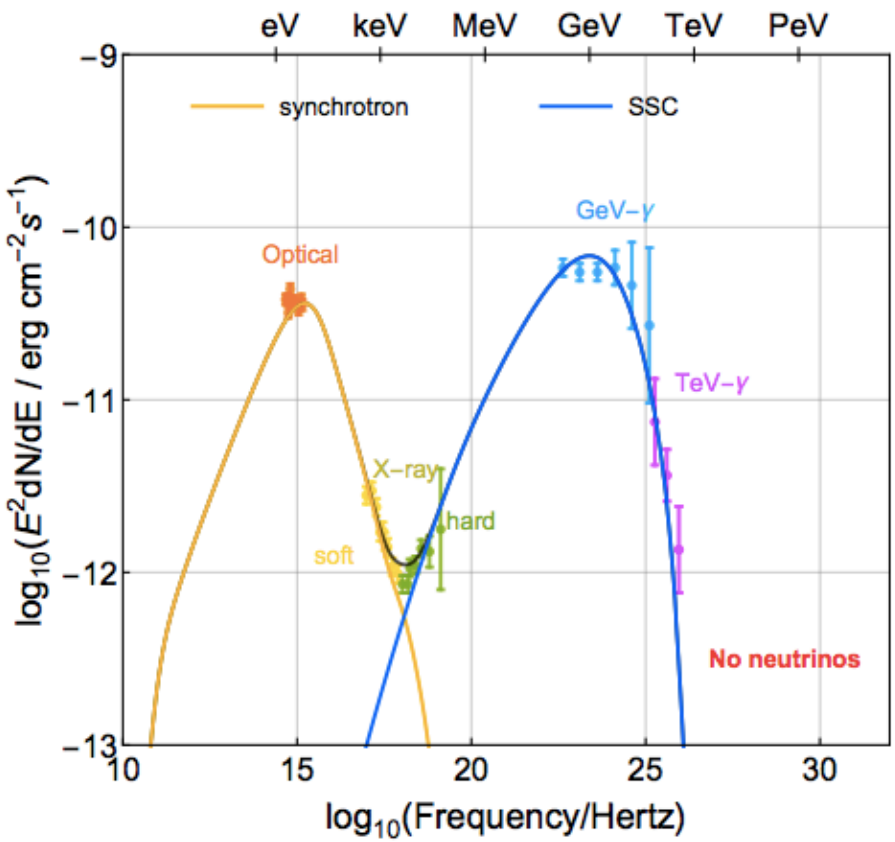


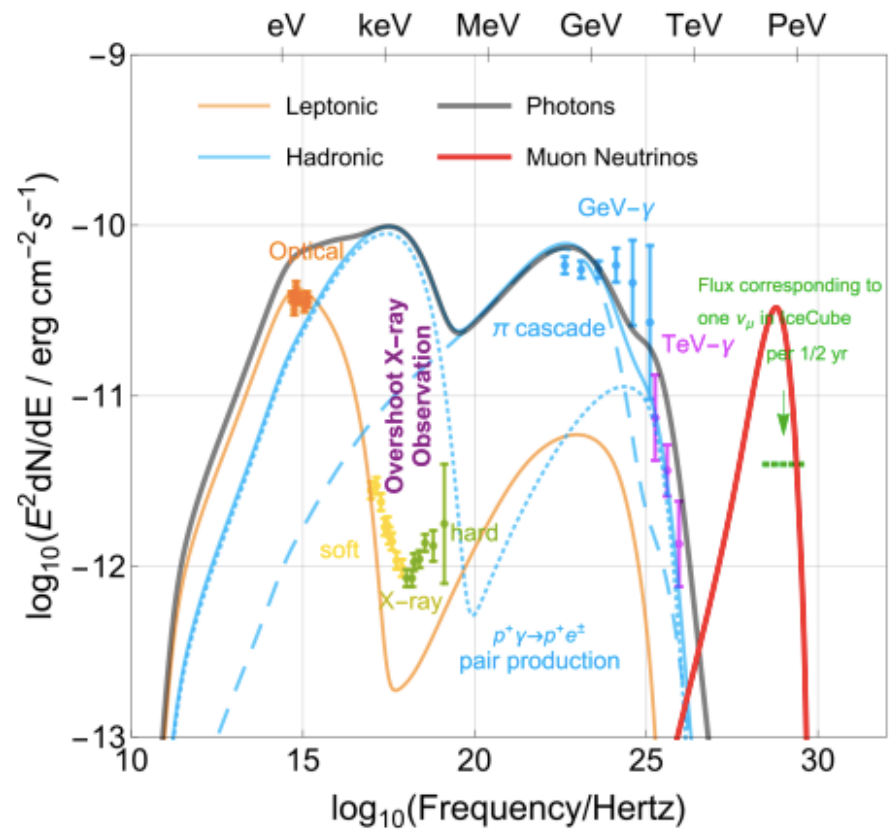
Modeling – leptonic



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

Modeling – leptonic, hadronic



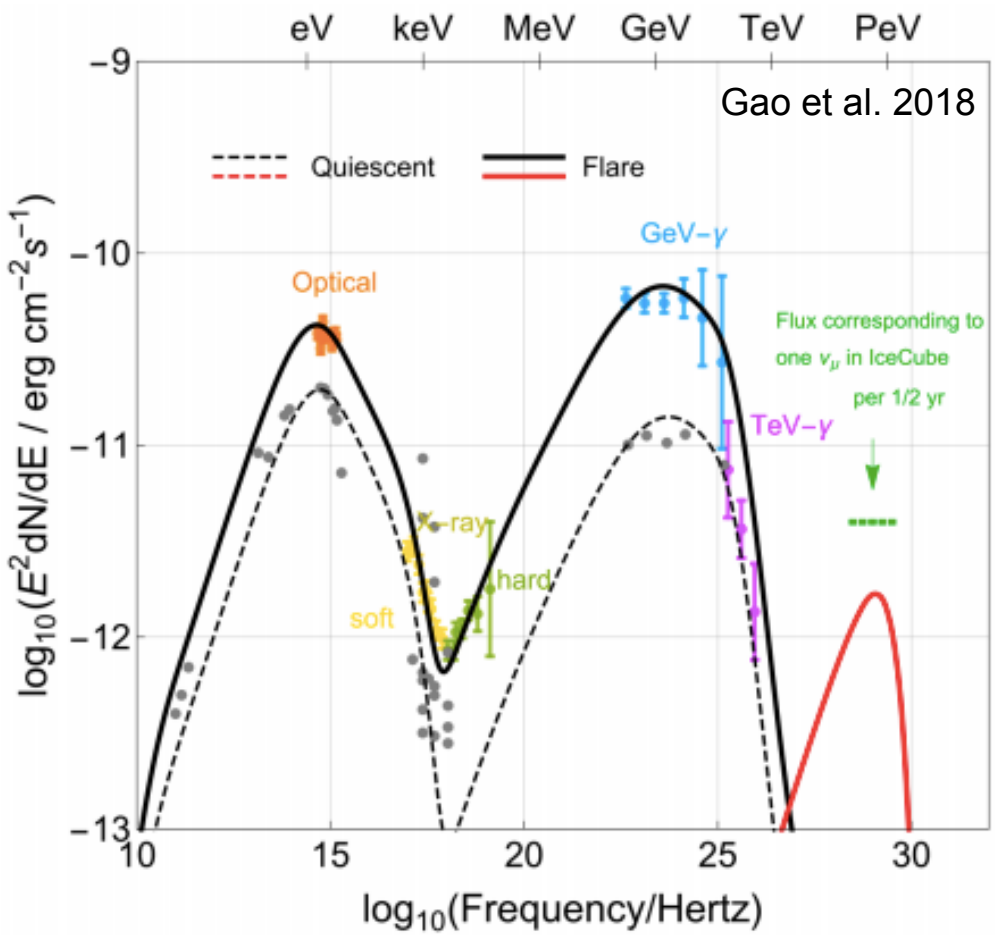


Simple one-zone hadronic models violate X-ray constraints
→ More complex models needed

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:

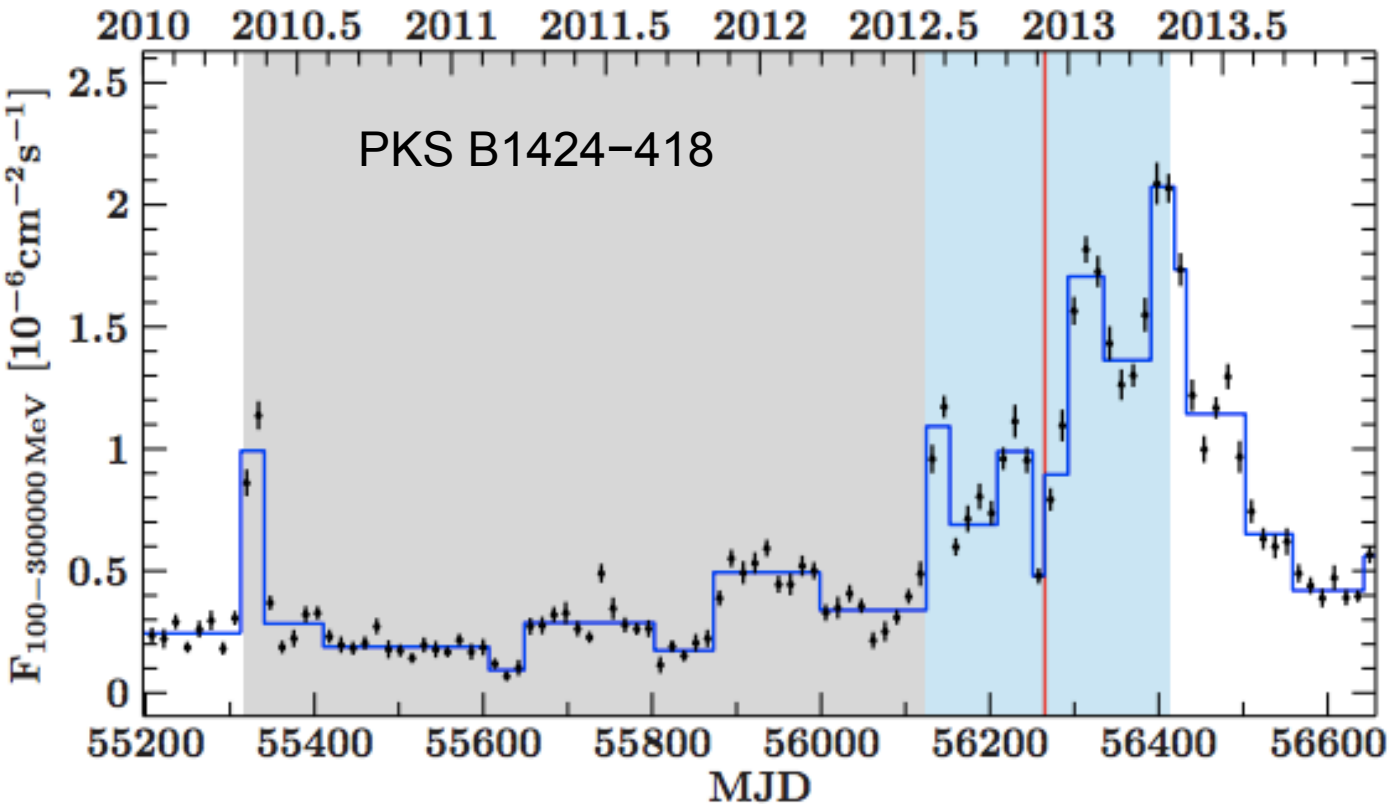
neutrino luminosity is ~4 times higher than gamma-ray luminosity

→ challenge for models

see e.g. M. Boettcher, A. Reimer,
S. Gao @ TeVPA 2018,
F. Halzen et al., 2018

Other interesting candidates

Blazar + high-energy cascade

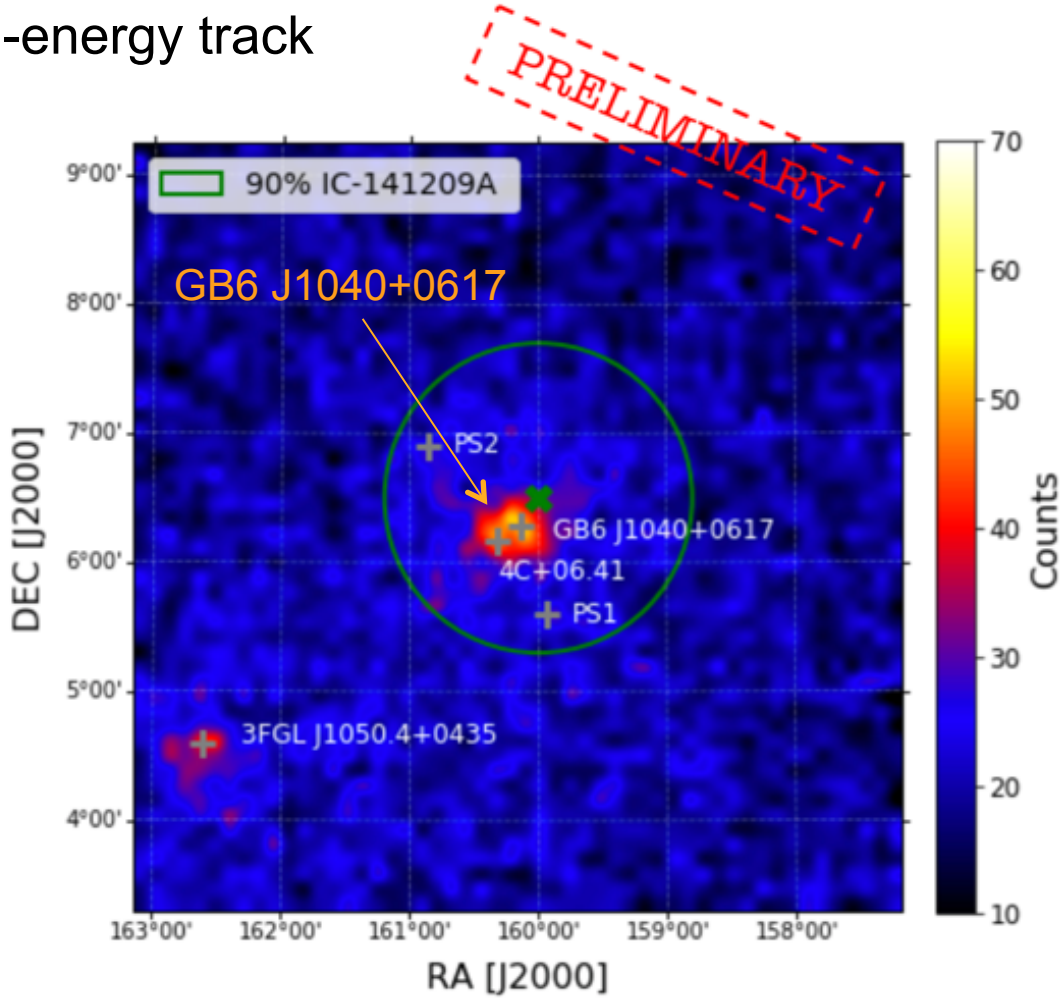


5% chance coincidence

Kadler et al., Nature Physics 2016

Other interesting candidates

Blazar + high-energy track

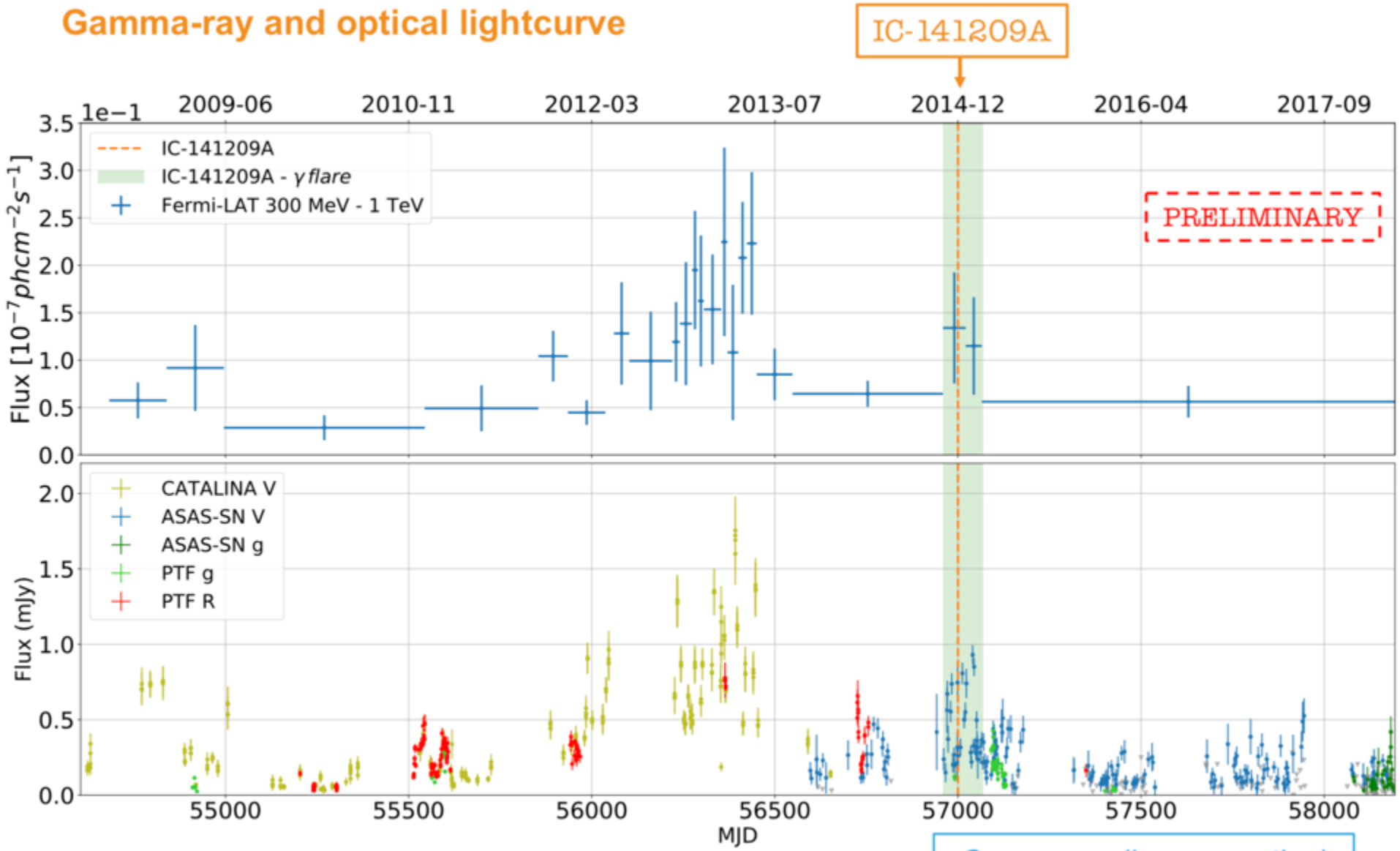


Garrappa+ (in preparation)

Other interesting candidates

Not significant if weighted with gamma-ray energy flux

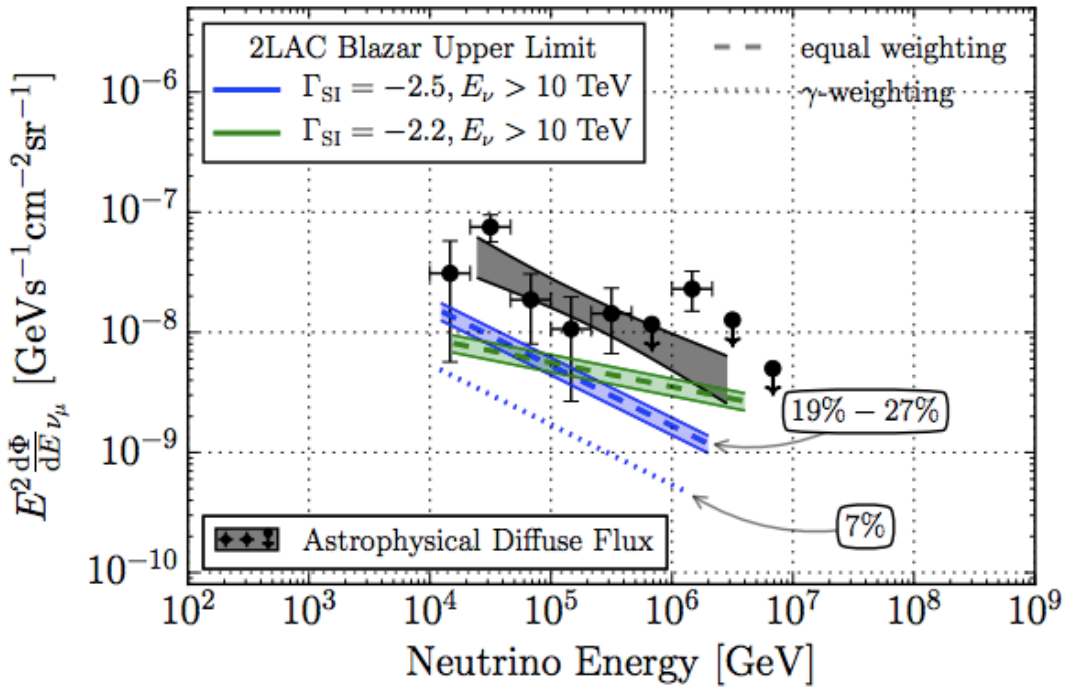
Gamma-ray and optical lightcurve



Garrappa+ (in preparation)

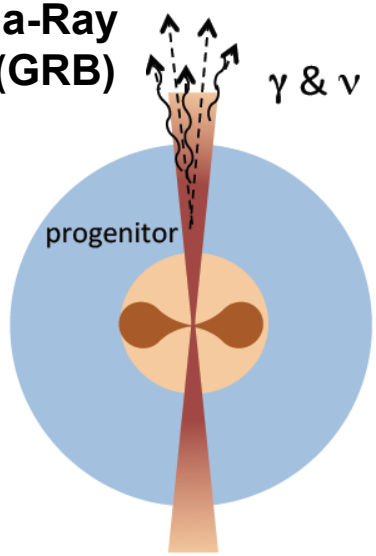
Do blazars produce all IceCube neutrinos?

- 40 well-reconstructed track events, 20 signal events, 1-2 blazar/neutrino coincidences → ~10% contribution
- No significant excess from the directions of cataloged Fermi blazars
  → contribution < 30%

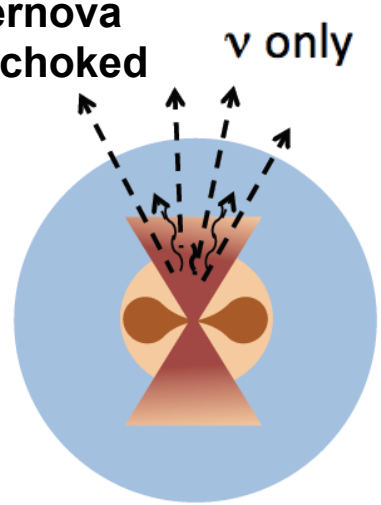


Other neutrino source candidates

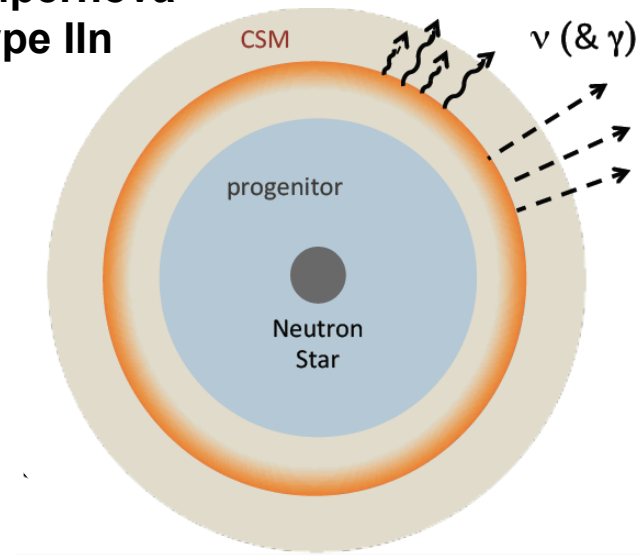
Gamma-Ray Burst (GRB)



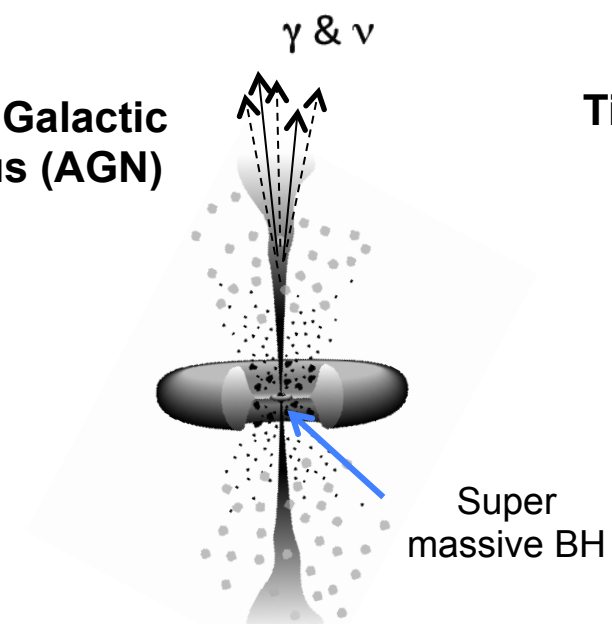
Supernova with choked jets



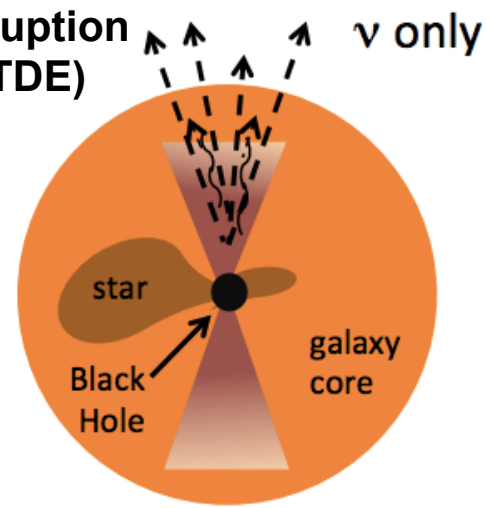
Supernova Type IIn



Active Galactic Nucleus (AGN)

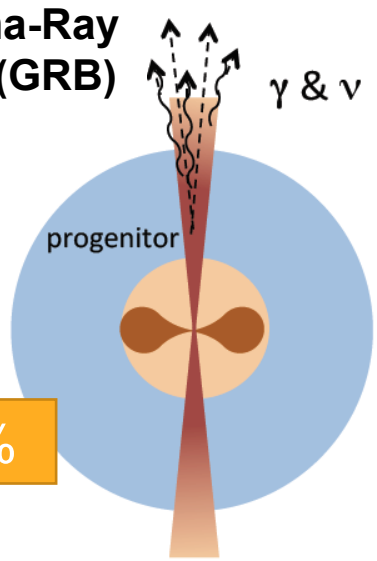


Tidal Disruption event (TDE)



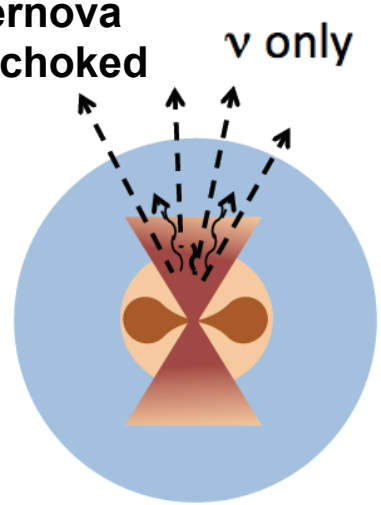
Other neutrino source candidates

Gamma-Ray Burst (GRB)

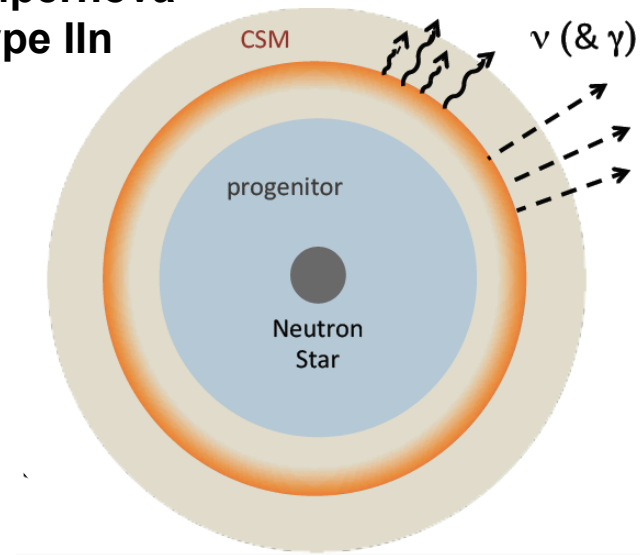


<1%

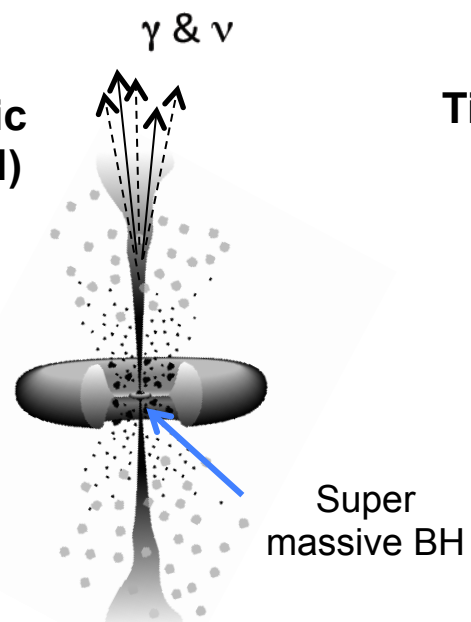
Supernova with choked jets



Supernova Type IIn

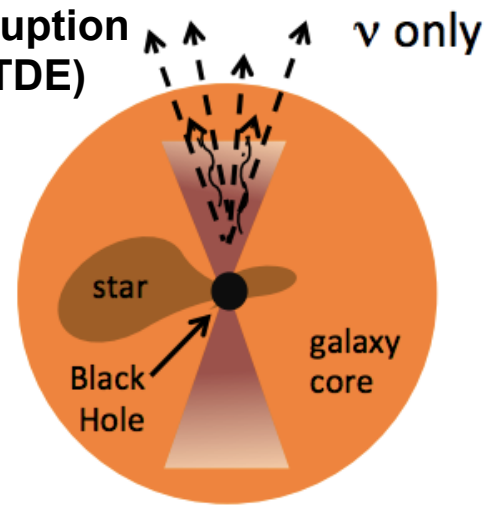


Active Galactic Nucleus (AGN)



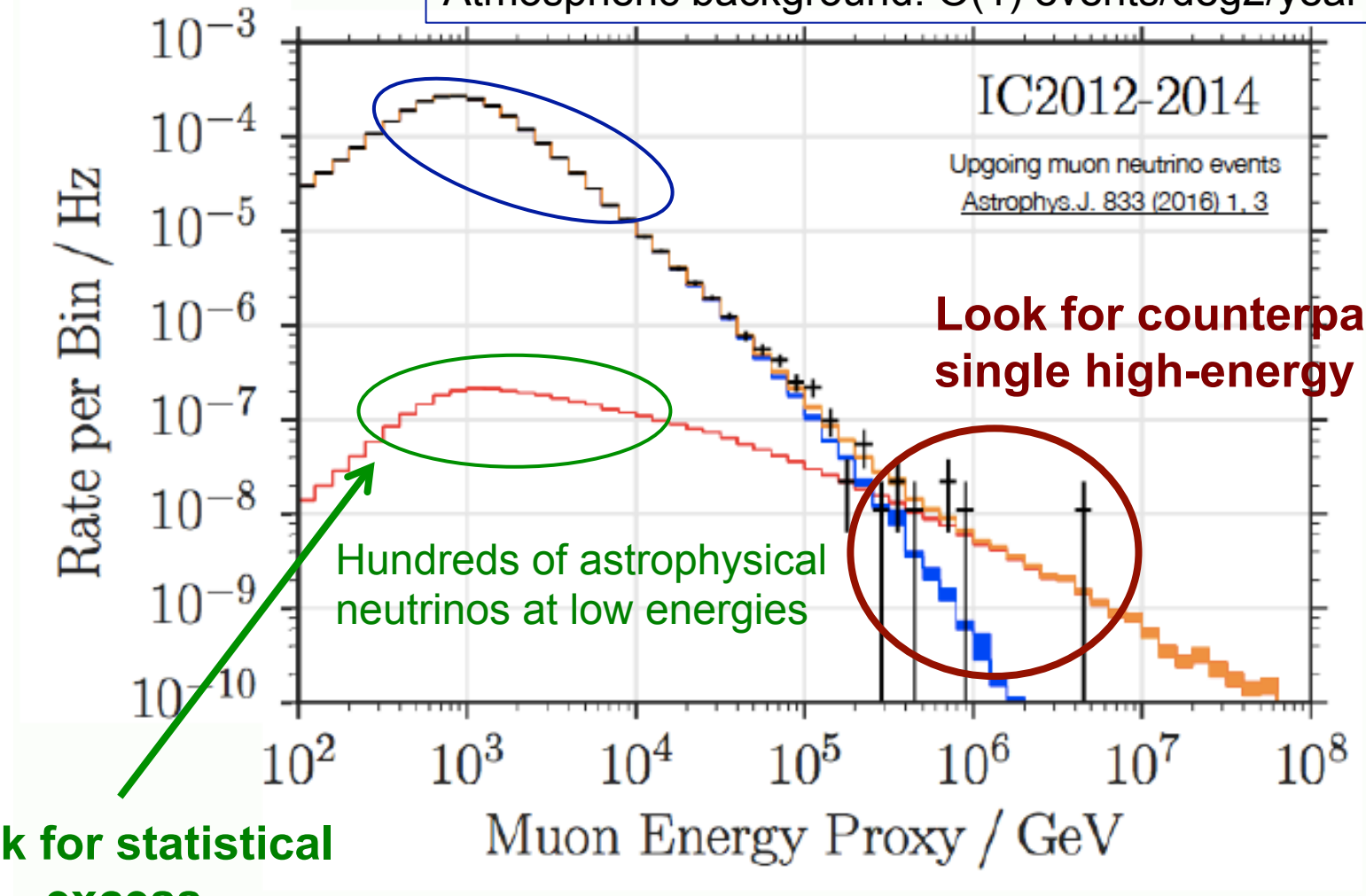
blazars <30%

Tidal Disruption event (TDE)



Two Strategies

Atmospheric background: O(1) events/deg2/year



Look for counterpart of single high-energy events

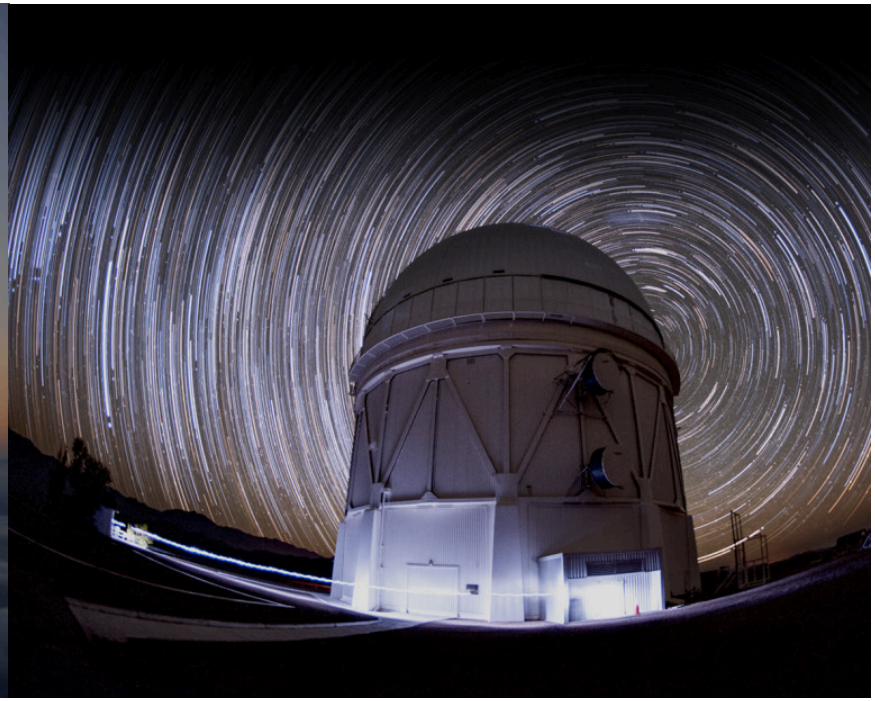
Hundreds of astrophysical neutrinos at low energies

Look for statistical excess

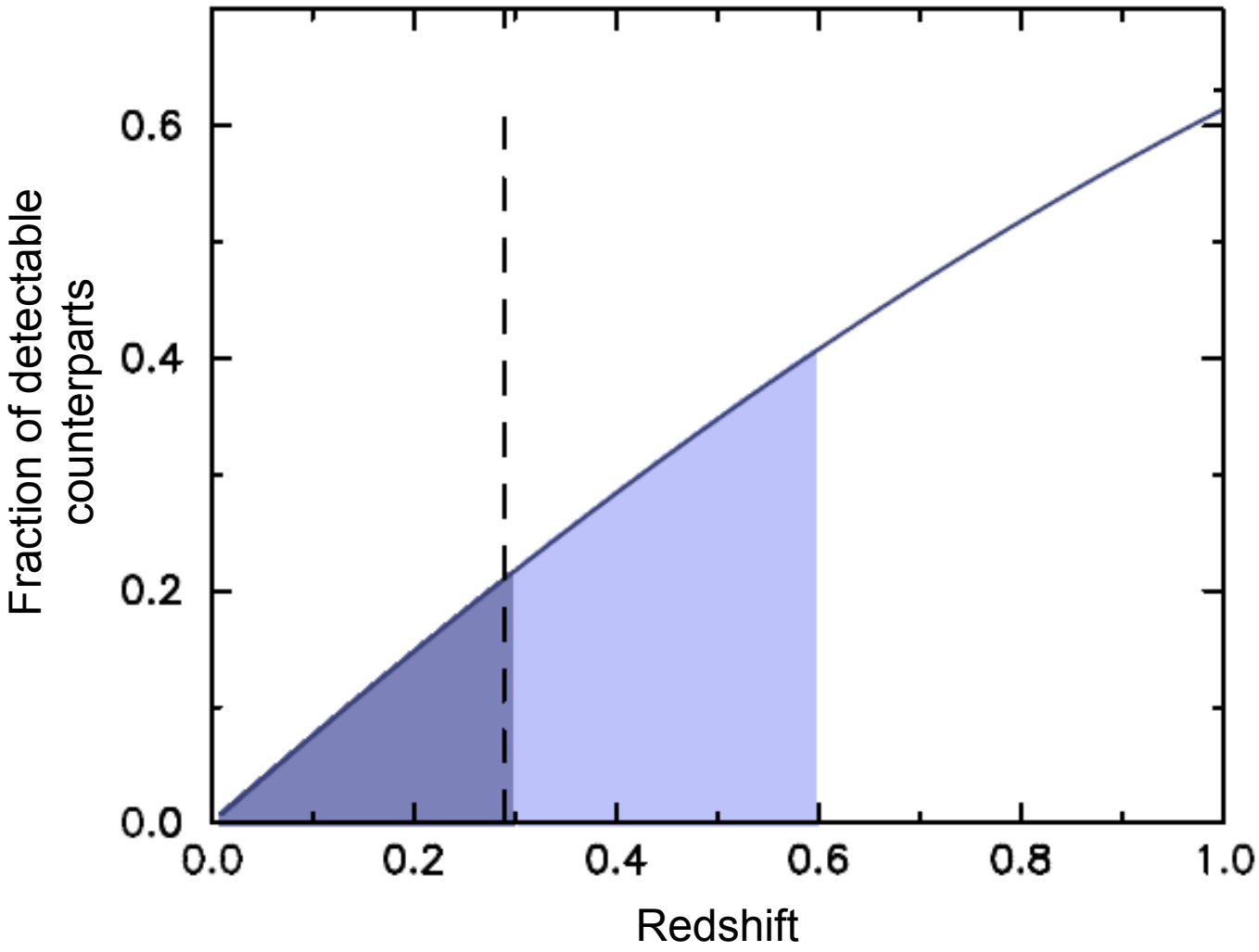
Deep Optical Follow-up

Pan-STARRS, 1.8m telescope, Hawaii

Dark-energy survey, 4m telescope, Chile



Deep Optical Follow-up



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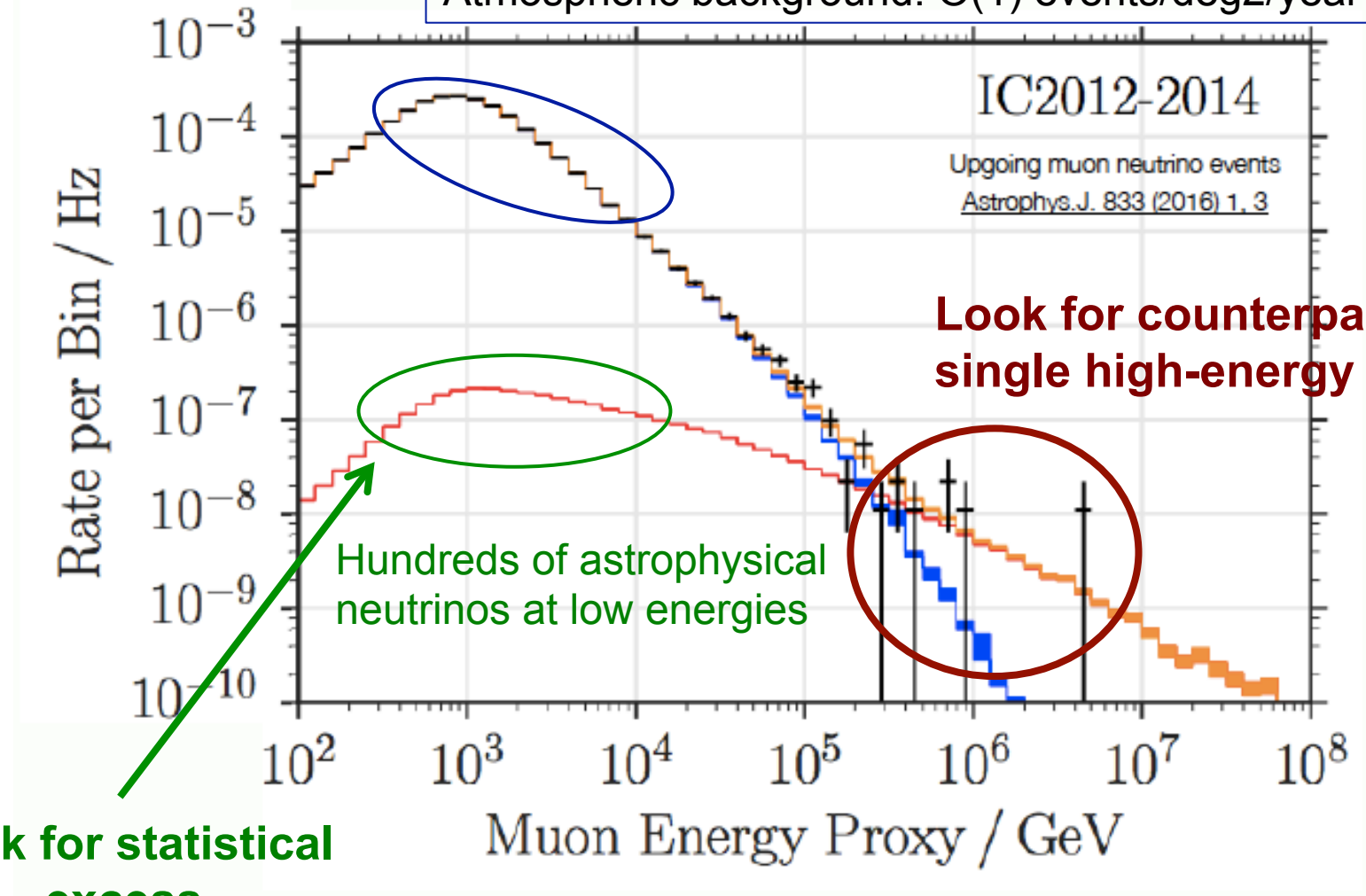


Look for counterpart of single high-energy events

Hundreds of astrophysical neutrinos at low energies

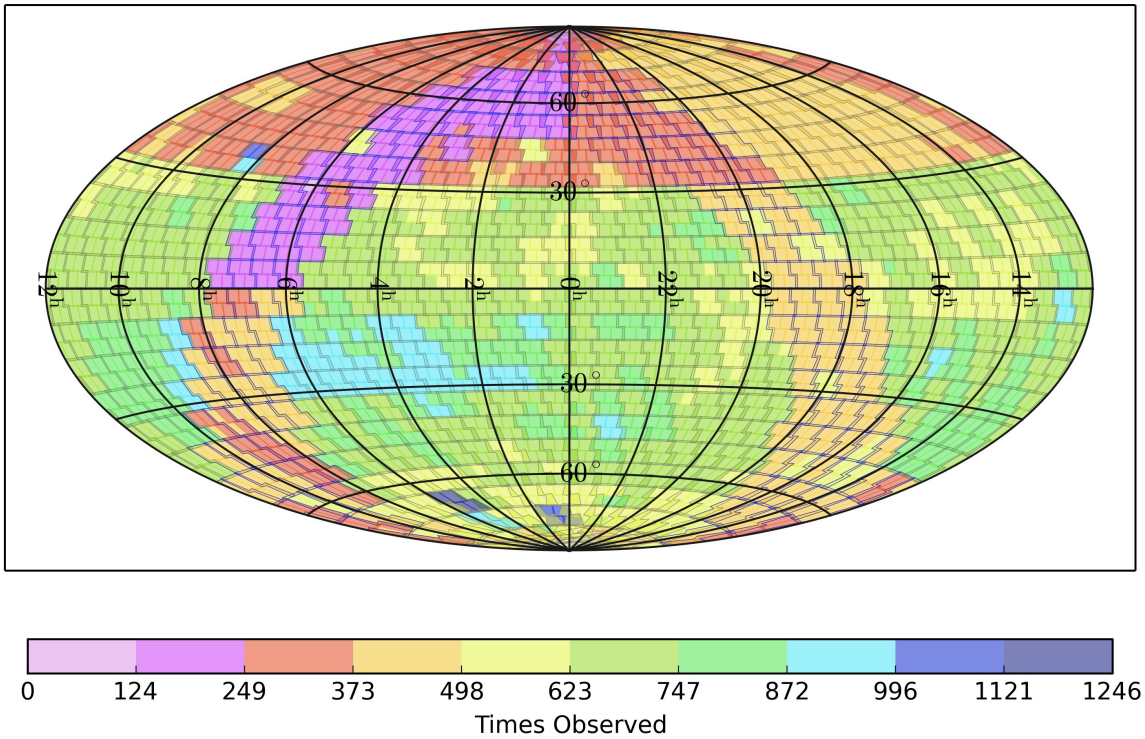
Look for statistical excess

Search for Generic Optical Counterparts

With ASAS-SN

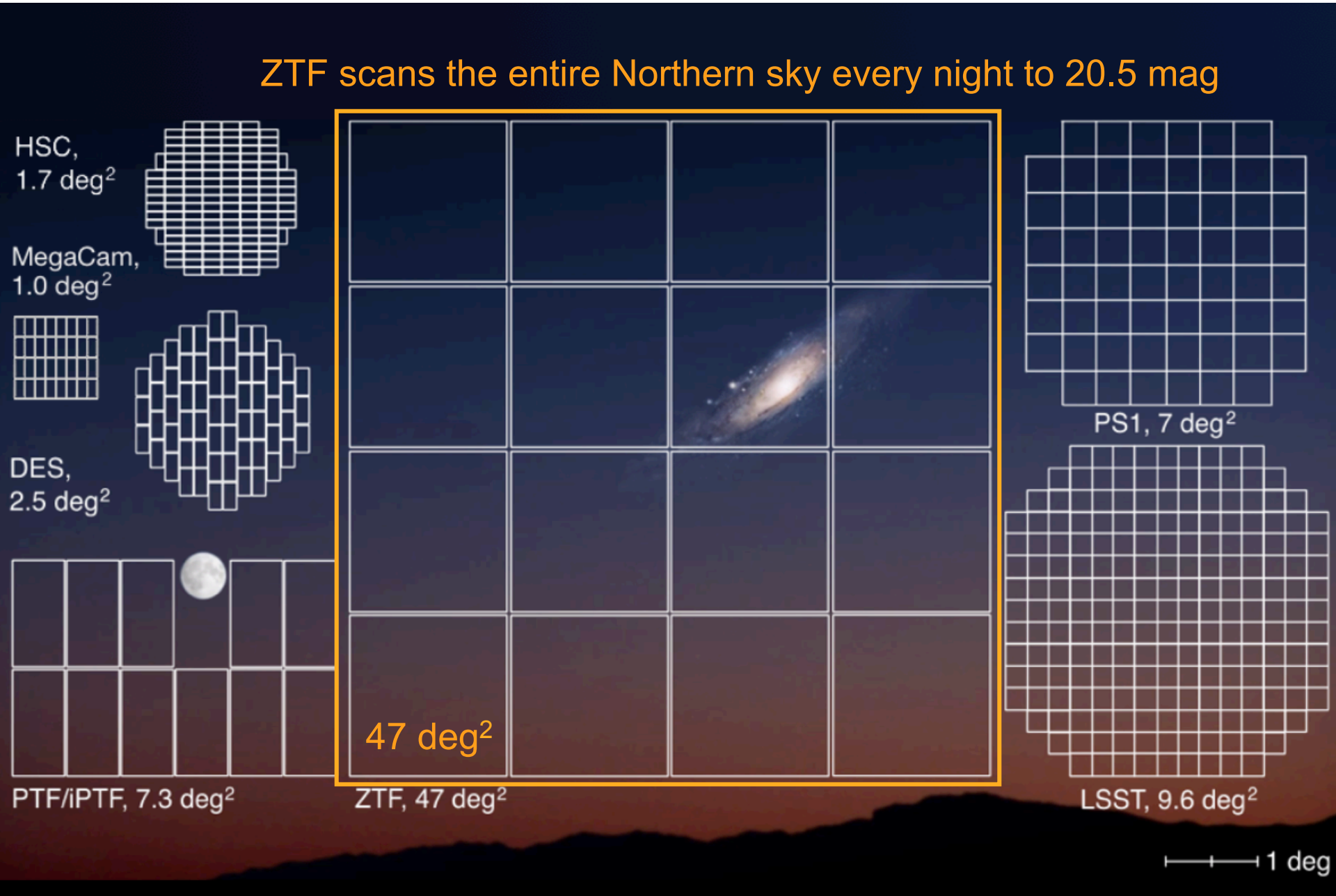
Four sides in: Chile, Hawaii, Texas, South Africa

All-sky coverage to 17th magnitude

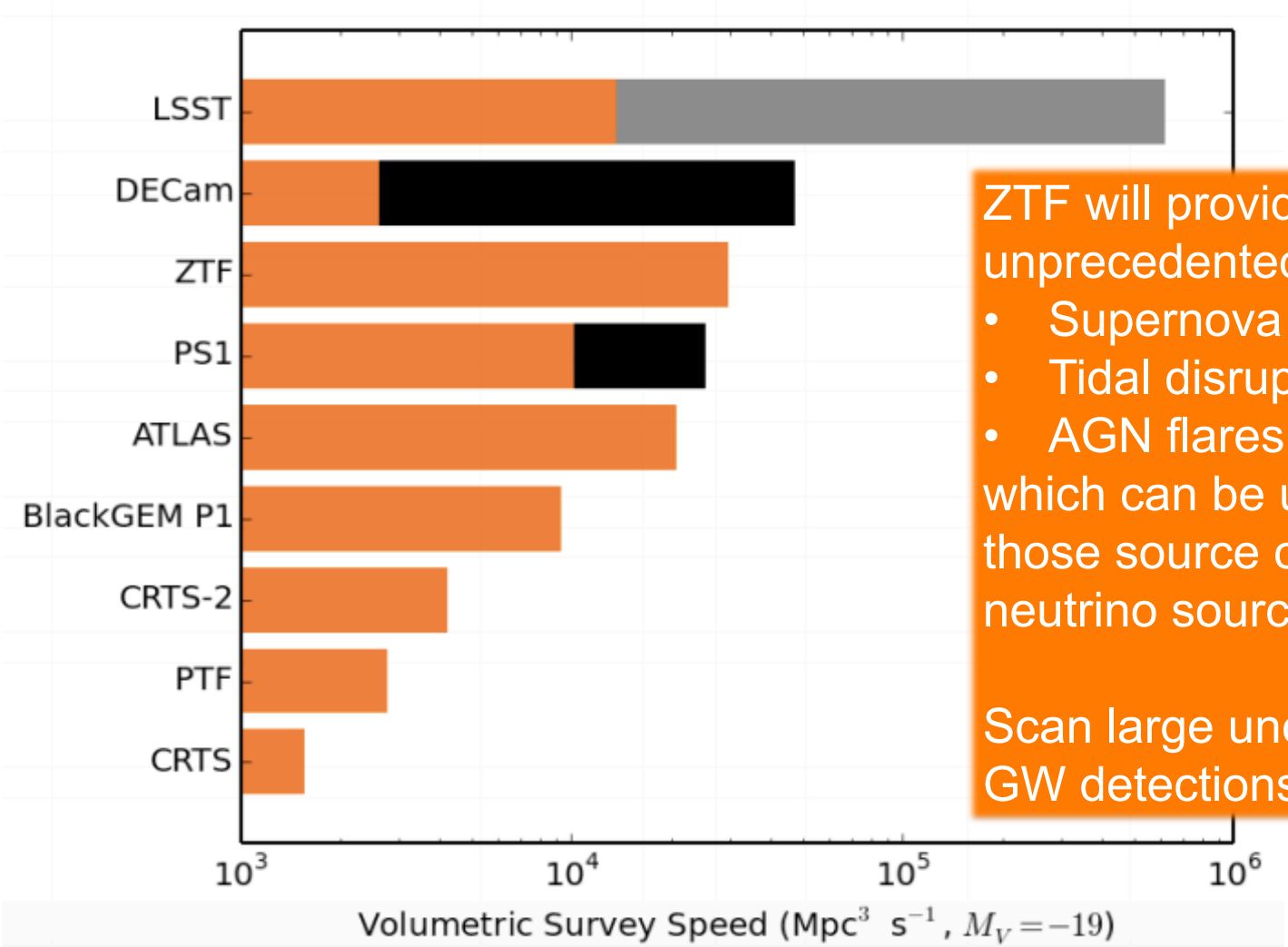


Planned cross-correlation analysis with IceCube data → generic constraints on bright optical counterparts

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

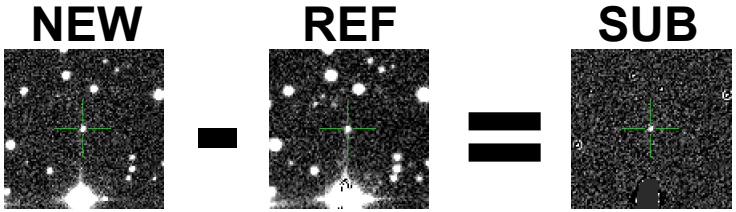
which can be used to probe those source classes as neutrino sources

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

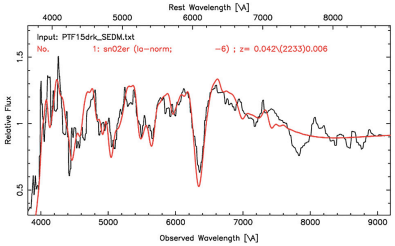
Alert Management, Photometry and Evaluation of Light curves



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 v-stream

ICECUBE

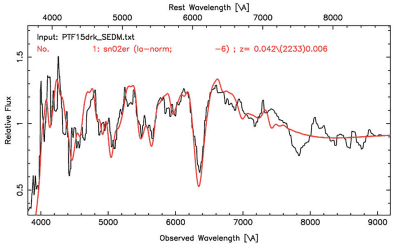
AMPEL – Towards a MM real-time center

Alert Management, Photometry and Evaluation of Light curves

ZTF ASAS-SN LSST SKA SQUARE KILOMETRE ARRAY

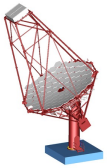
alert stream

Spectroscopy



trigger

γ-ray light curve



IACT follow-up

Event selection

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

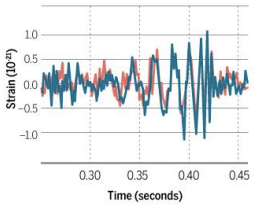
Archival analysis tools:
Reproducibility
Cross correlation of data sets

Storage

Farm

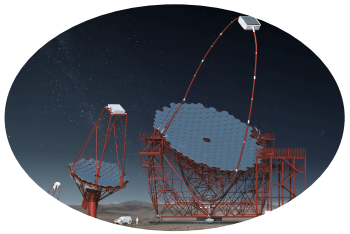
real-time ν-stream

ICECUBE



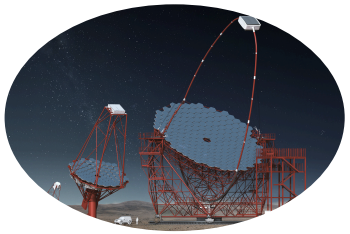
gravitational wave triggers

Summary



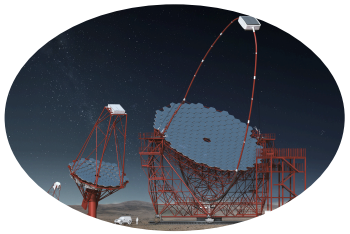
unique messengers from the high-energy Universe

Summary



unique messengers from the high-energy Universe

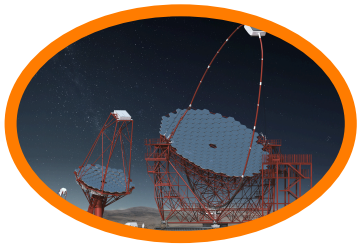
Summary



Neutrinos can reveal the sources of high-energy cosmic rays

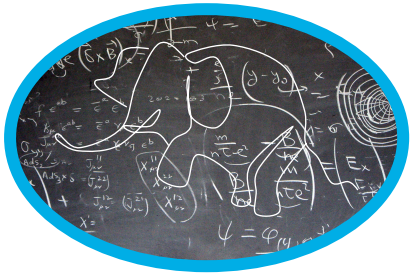
Summary

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



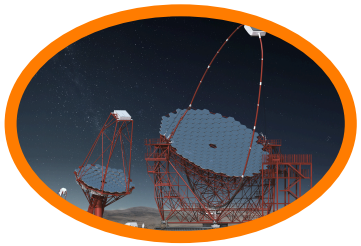
Summary

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



theory

Probe other source classes.



Stay tuned!