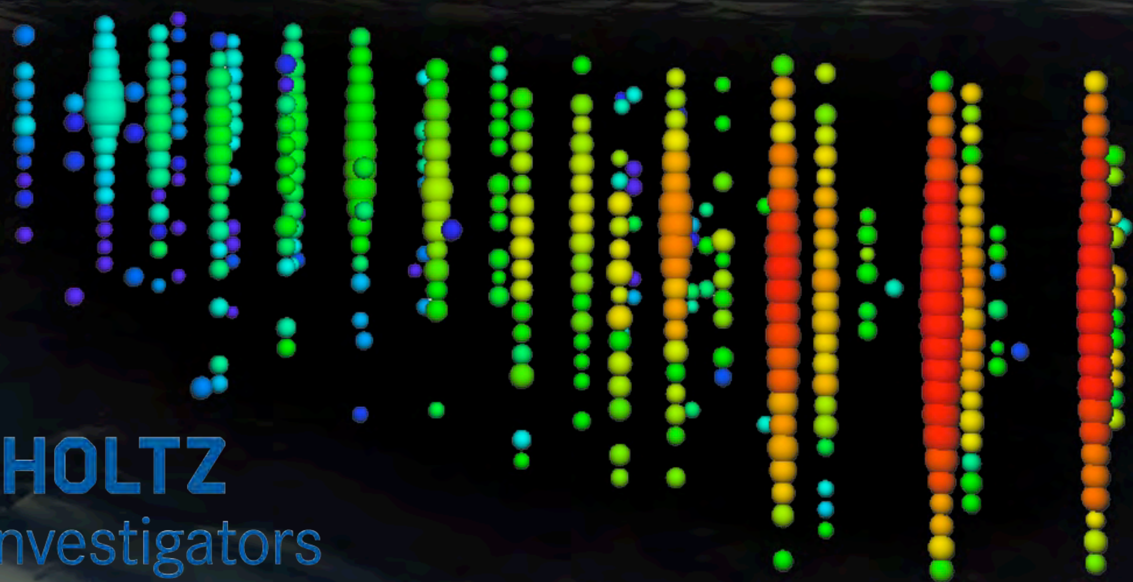
Multi-messenger Astronomy with high-energy Neutrinos

Anna Franckowiak



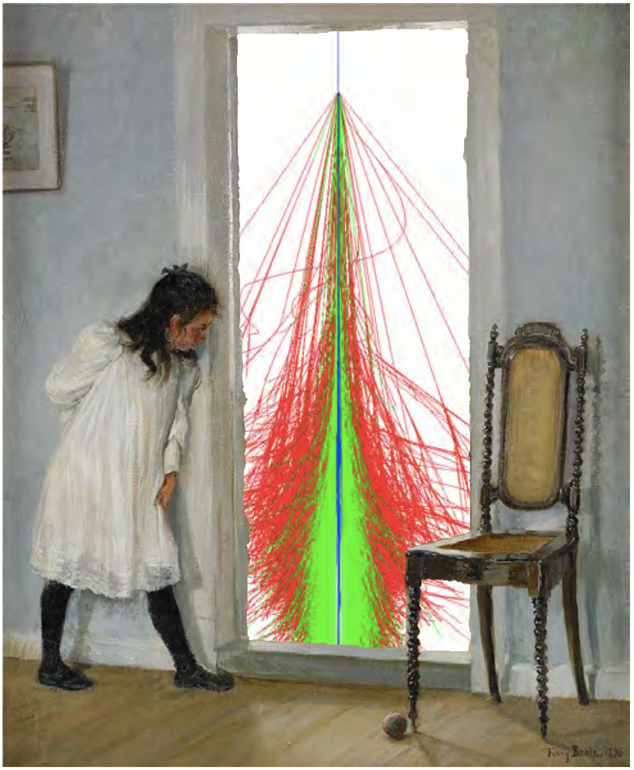
HELMHOLTZ Young Investigators

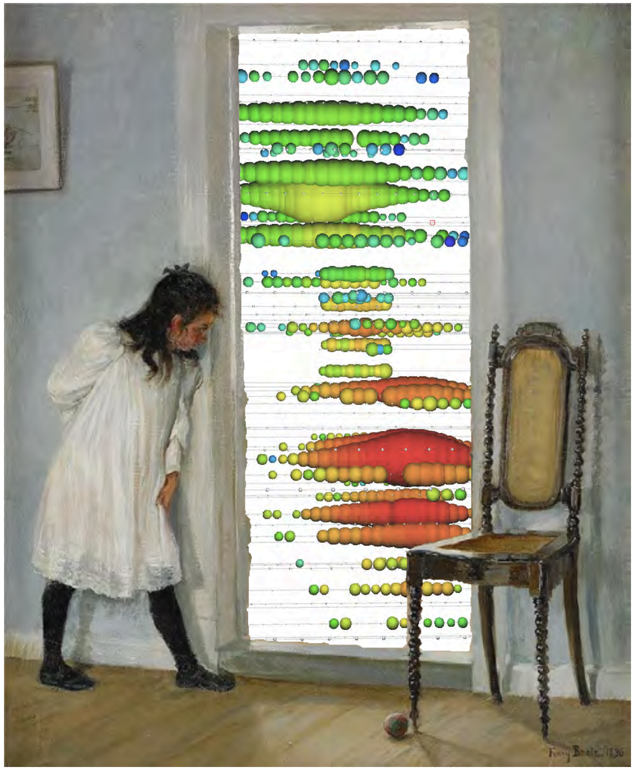
DESY.

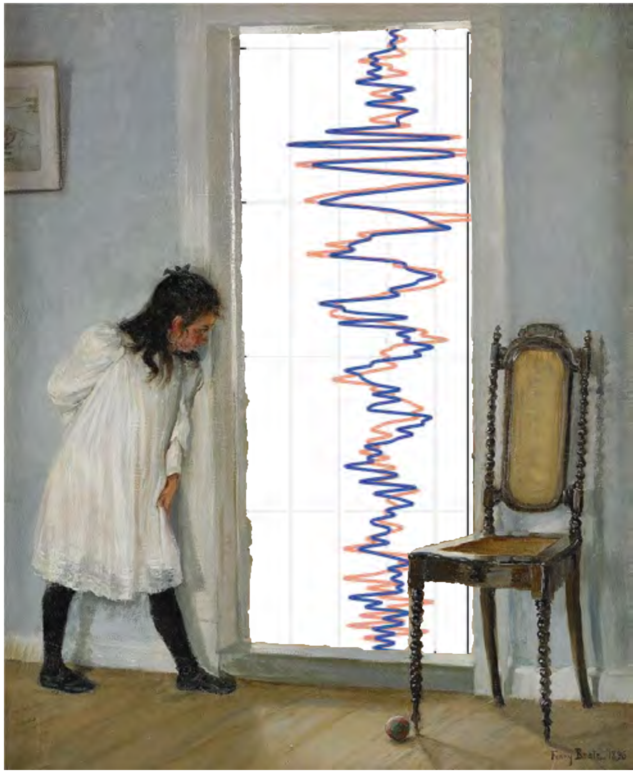
DESY, Zeuthen, November 26, 2018

The Multi-Messenger Picture

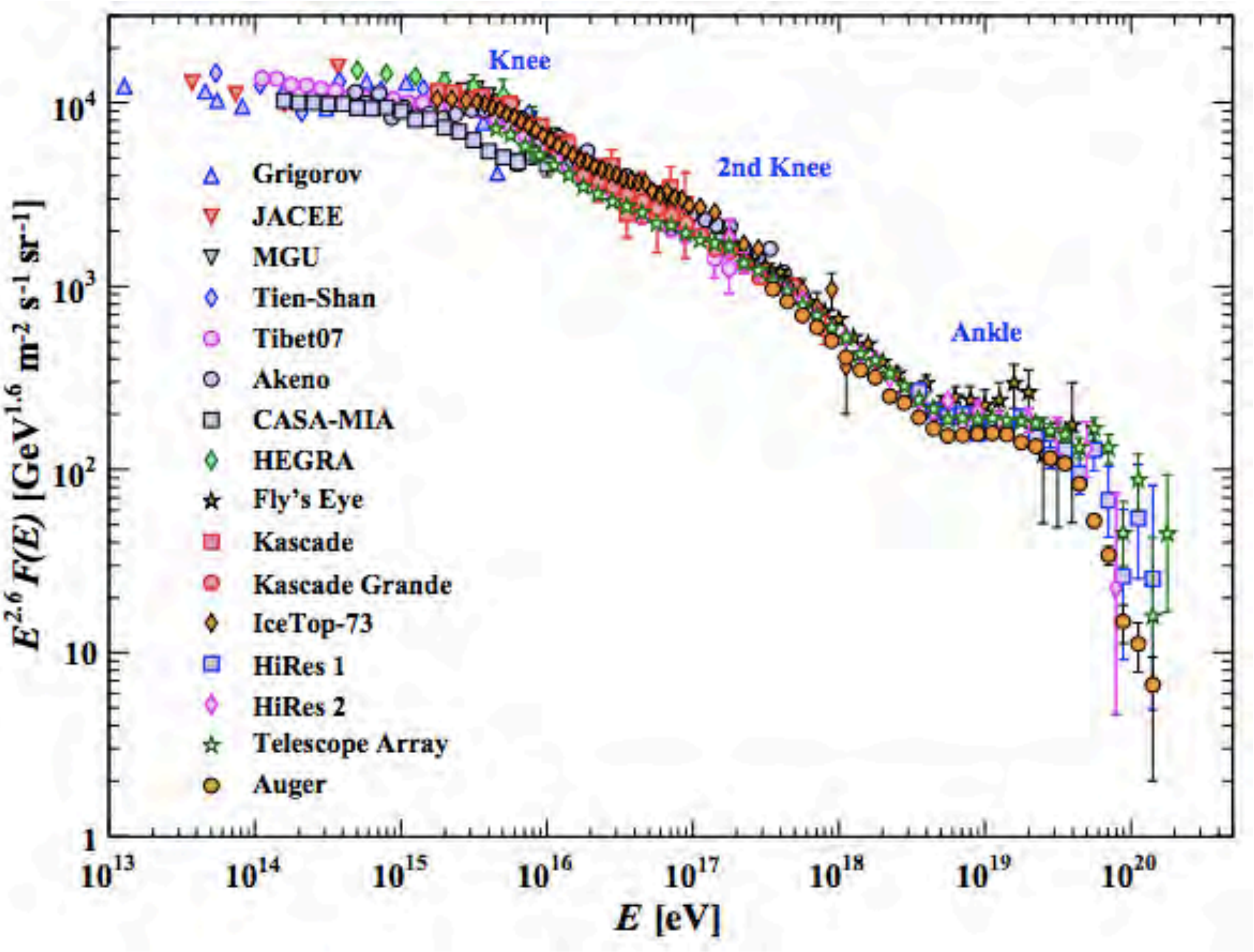
New Windows to the Universe



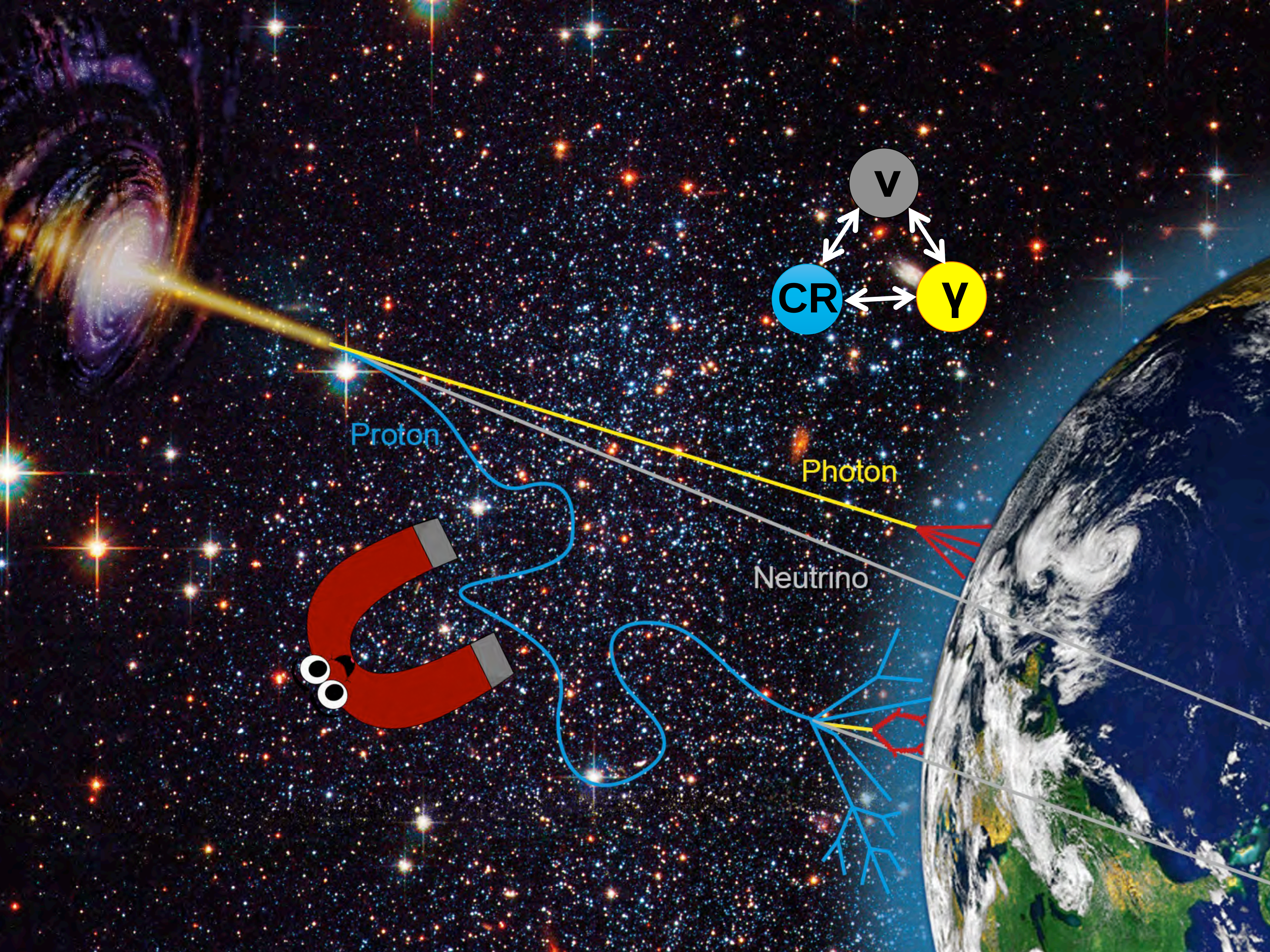




Cosmic rays reach 10^{20}eV



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

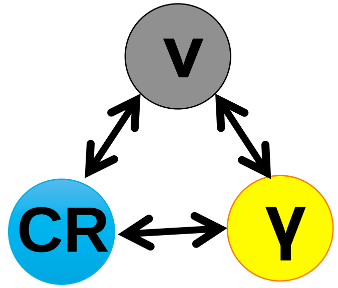


ν
CR
γ
Proton
Photon
Neutrino

Neutrino Production Processes

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

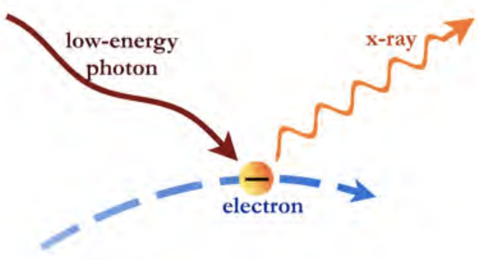
$$pp \rightarrow \begin{cases} X + \pi^0 \rightarrow \gamma\,\gamma \\ X + \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu \\ X + \pi^- \rightarrow \mu^- \nu_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu \end{cases}$$

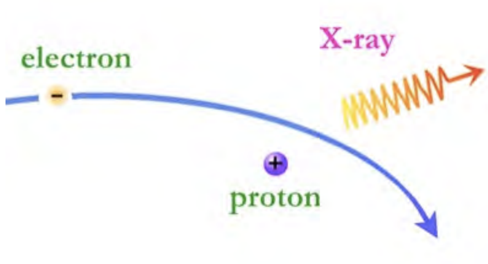


Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

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

Gamma-rays are not exclusively produced in hadronic processes





Neutrino Production Processes

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

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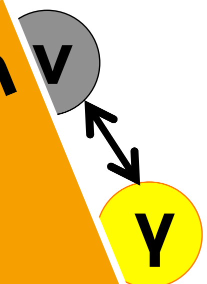
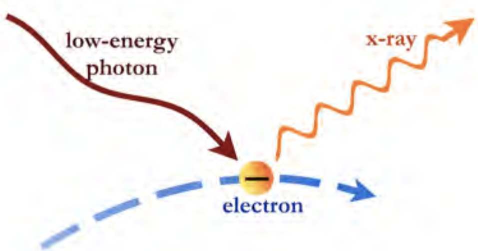


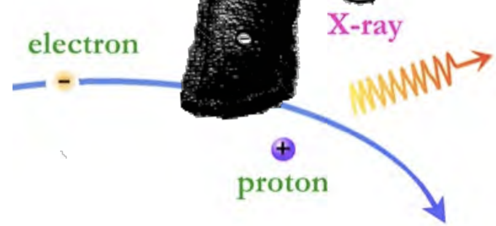
Photohadronic (e… …galactic nuclei)

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

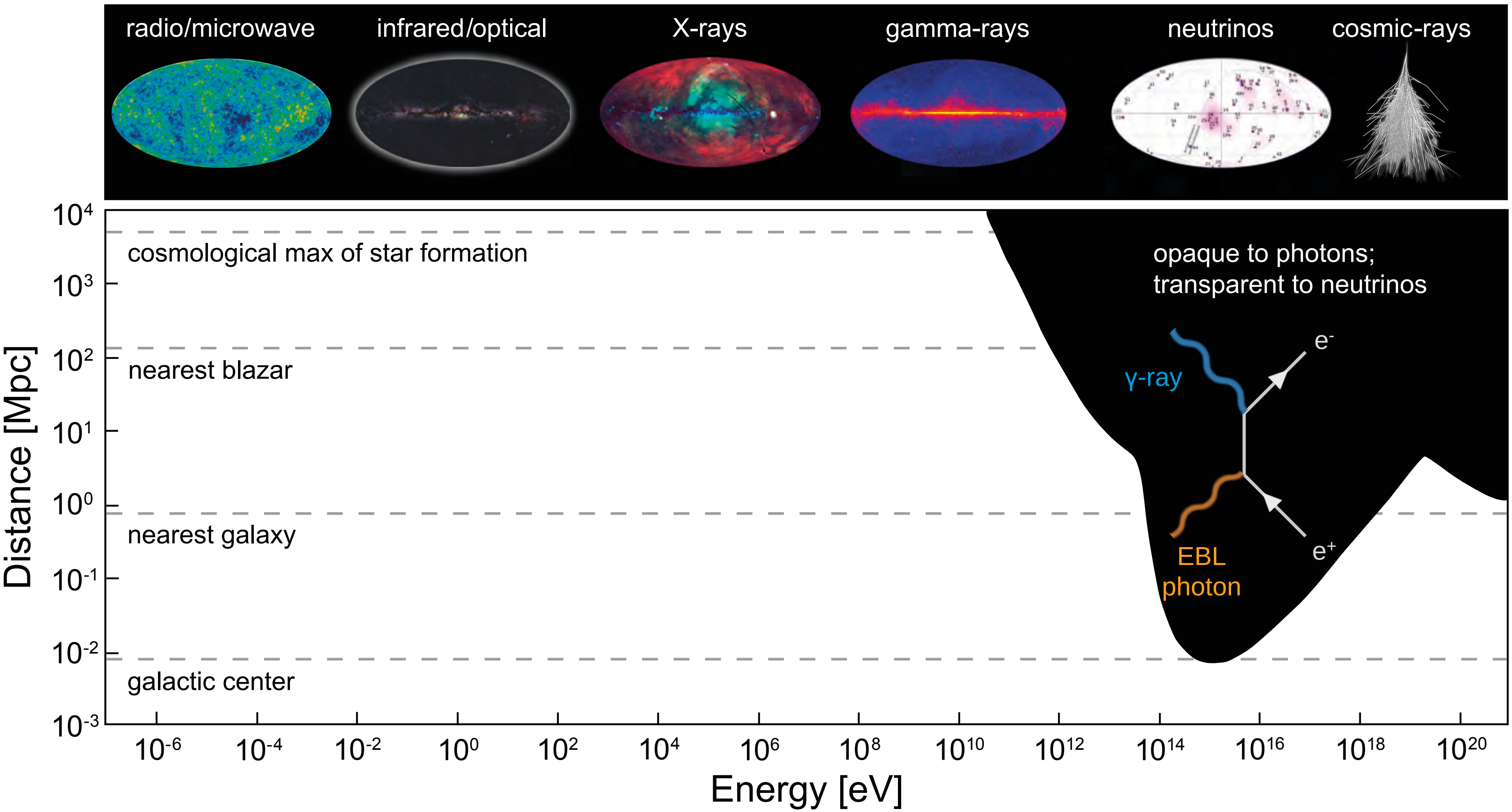
Neutrinos are the smoking gun signature for hadronic acceleration

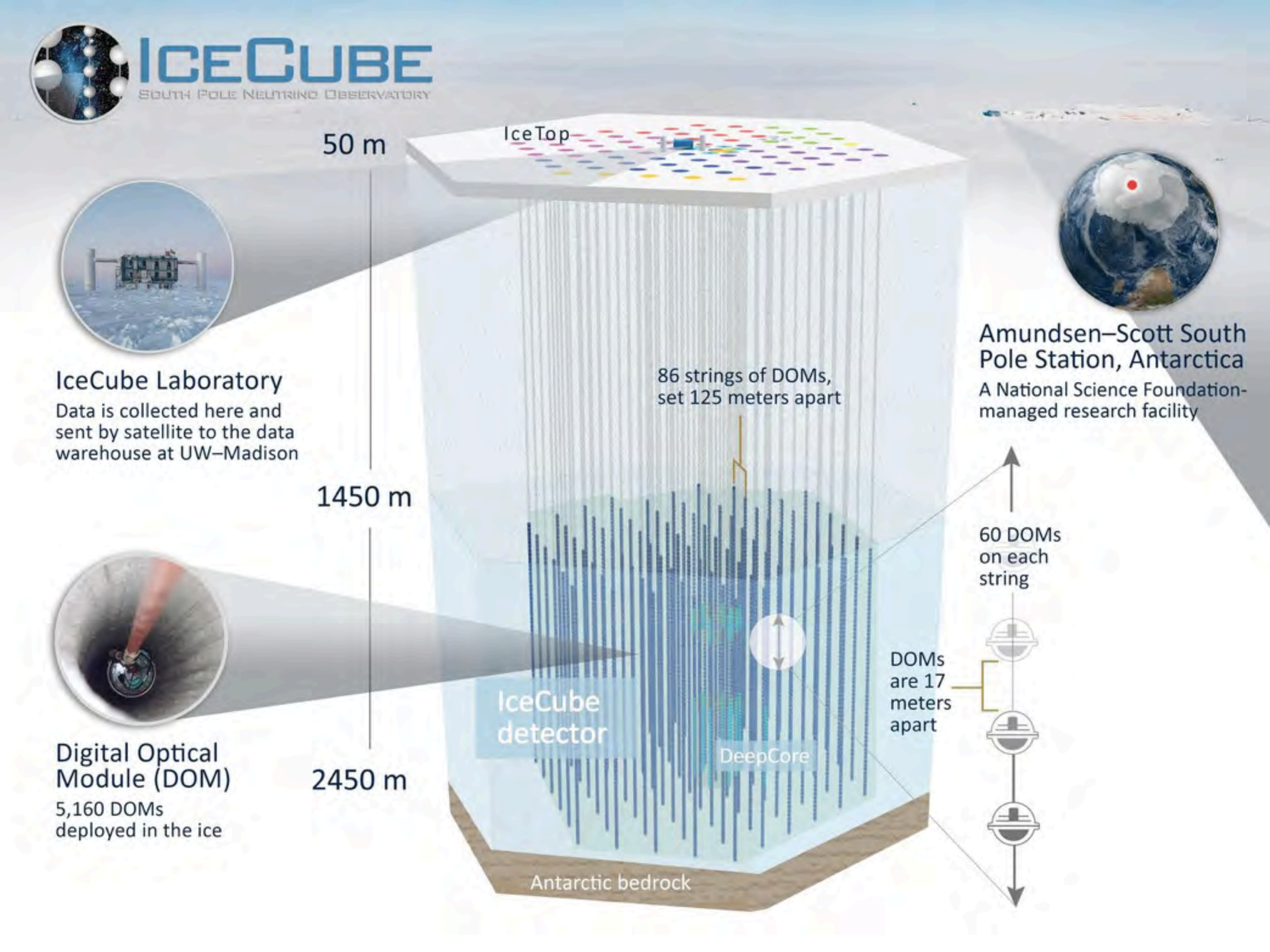
Gamma-ray … not exclusively produced … adronic processes





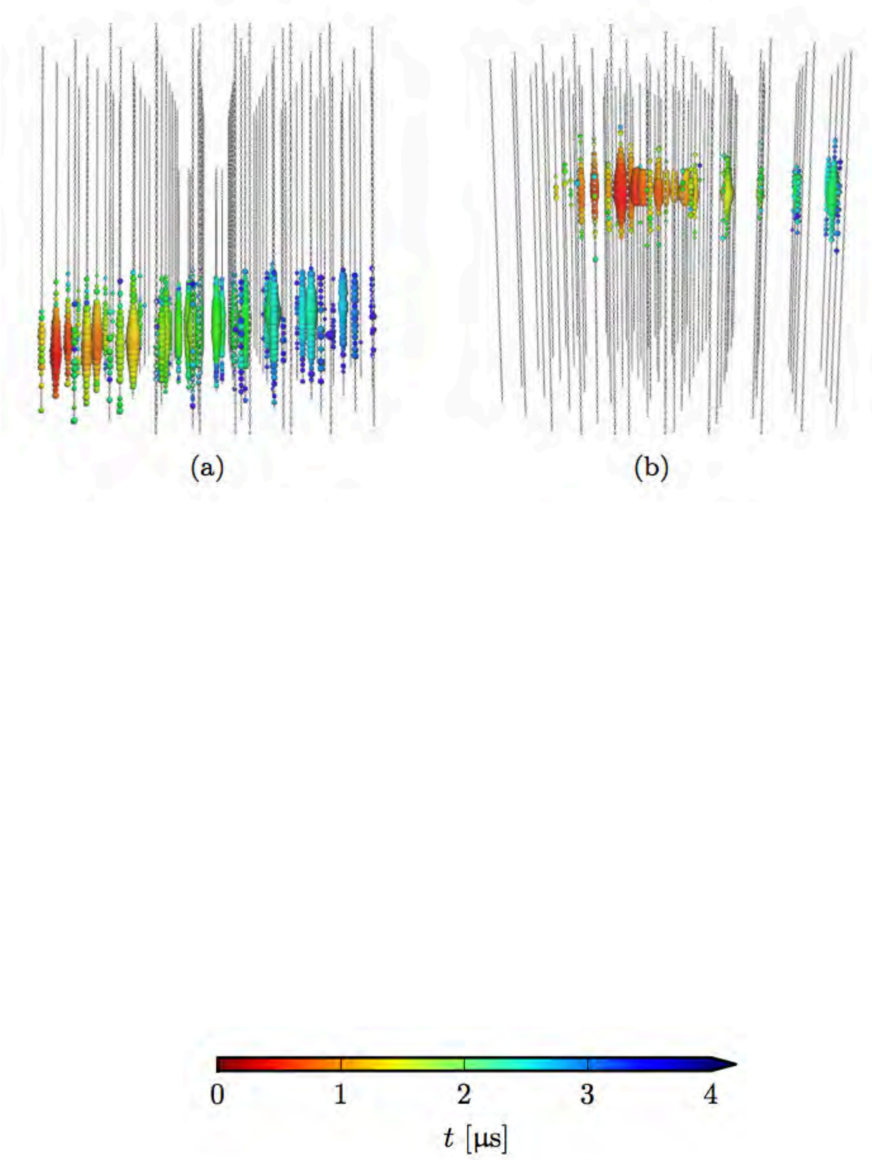
Where Can We Look?





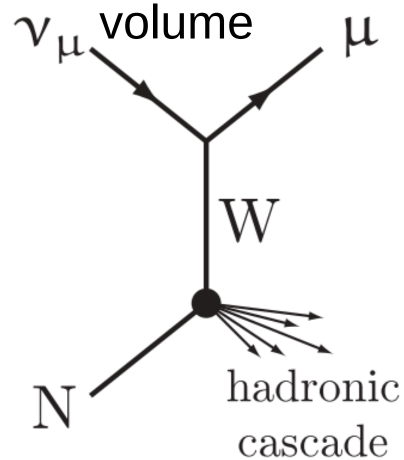
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility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

Event Signatures

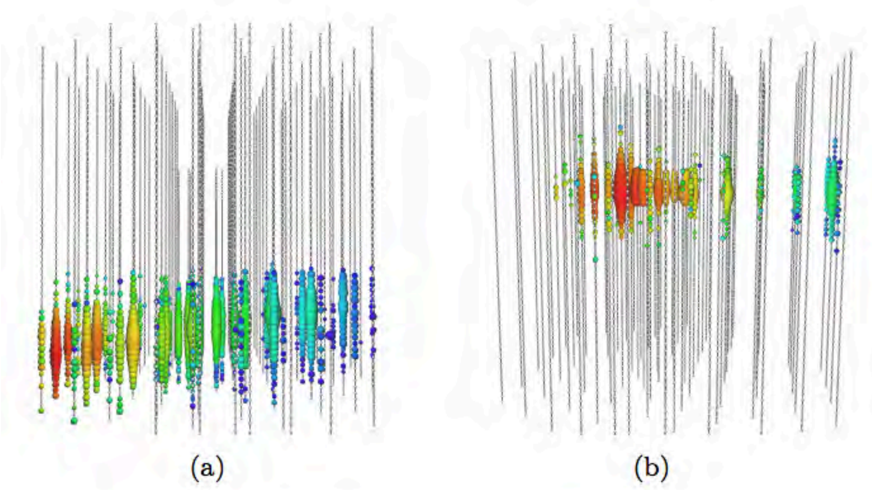


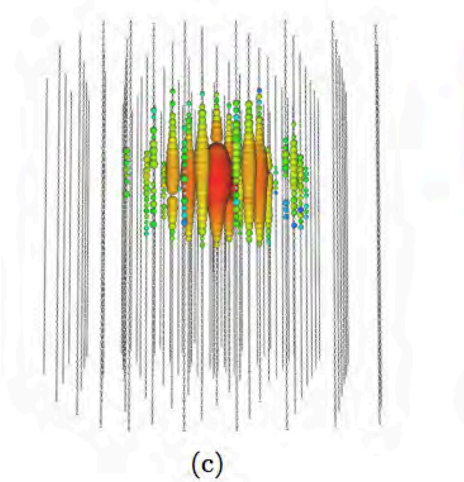
a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV

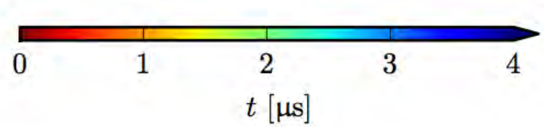
Charged current interaction of muon neutrino outside / inside the detector volume



Event Signatures

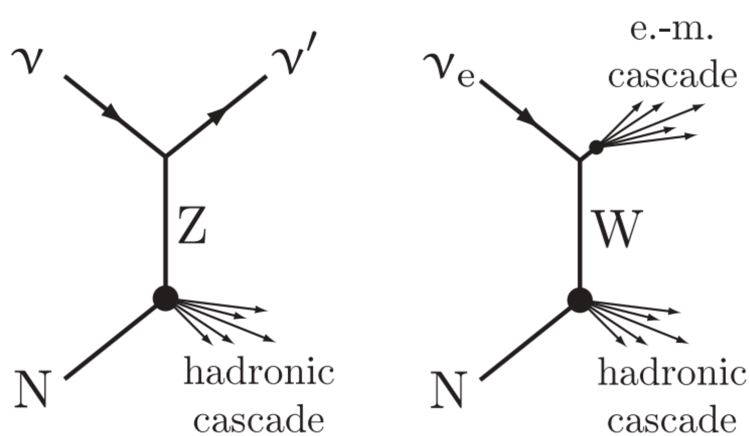






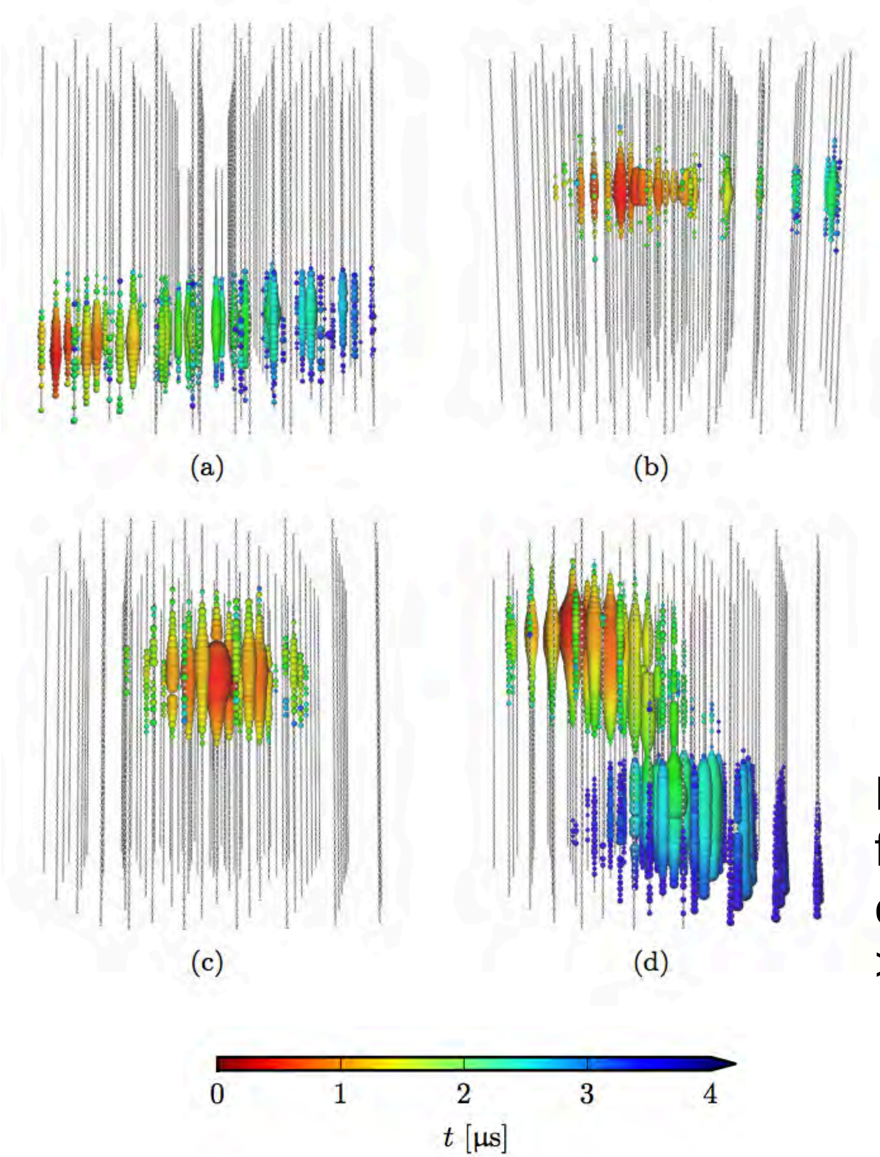
a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV
c) Shower event E ~ 1 PeV

Neutral current or electron neutrino charged current interaction



Cannot distinguish between showers (size few meters)

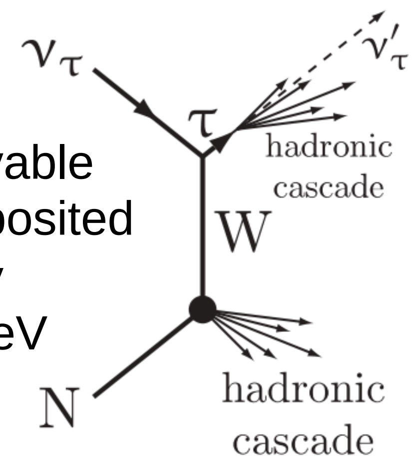
Event Signatures



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)

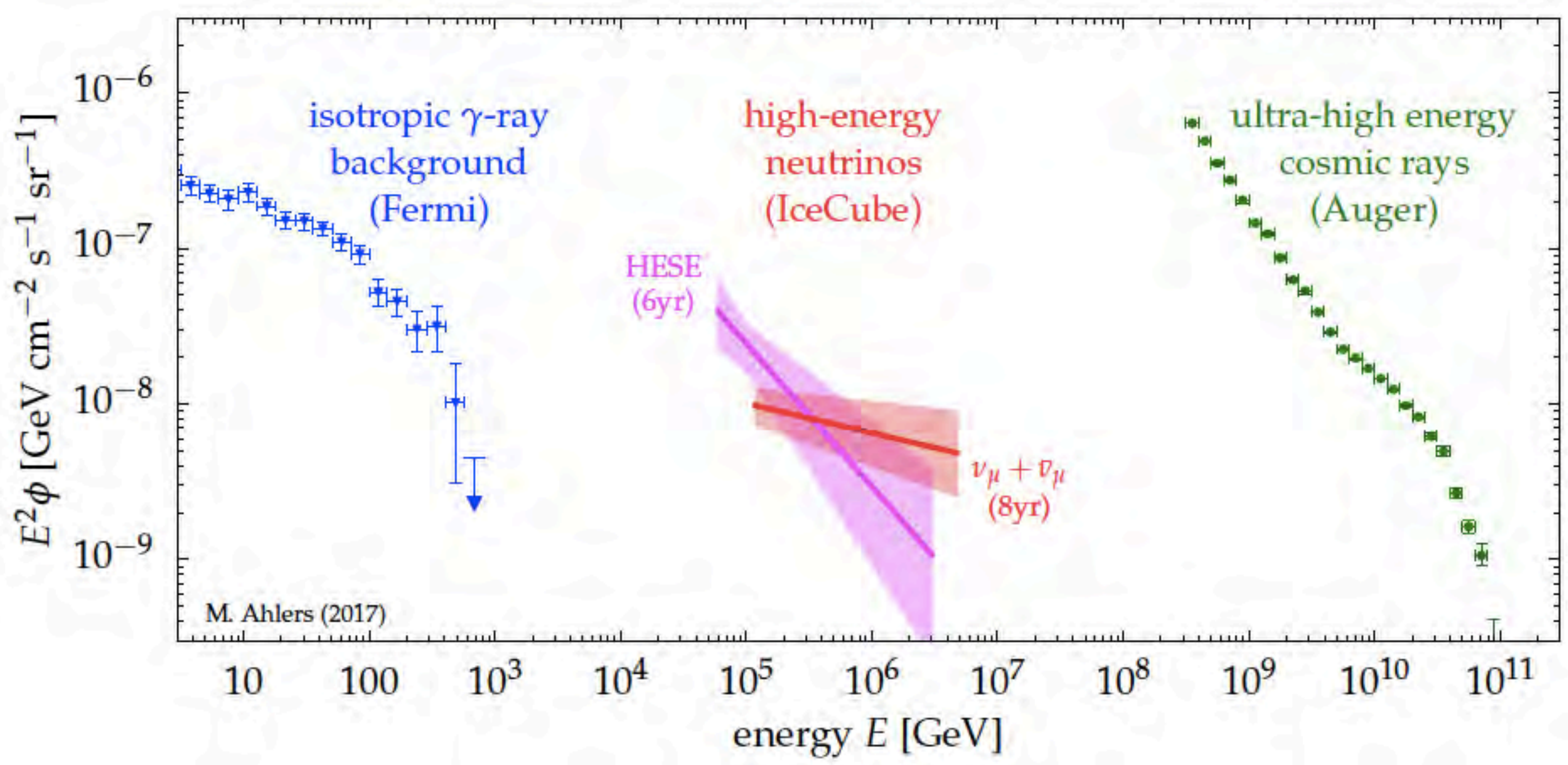
Tau neutrino charged current interaction

Resolvable for deposited energy >100TeV



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

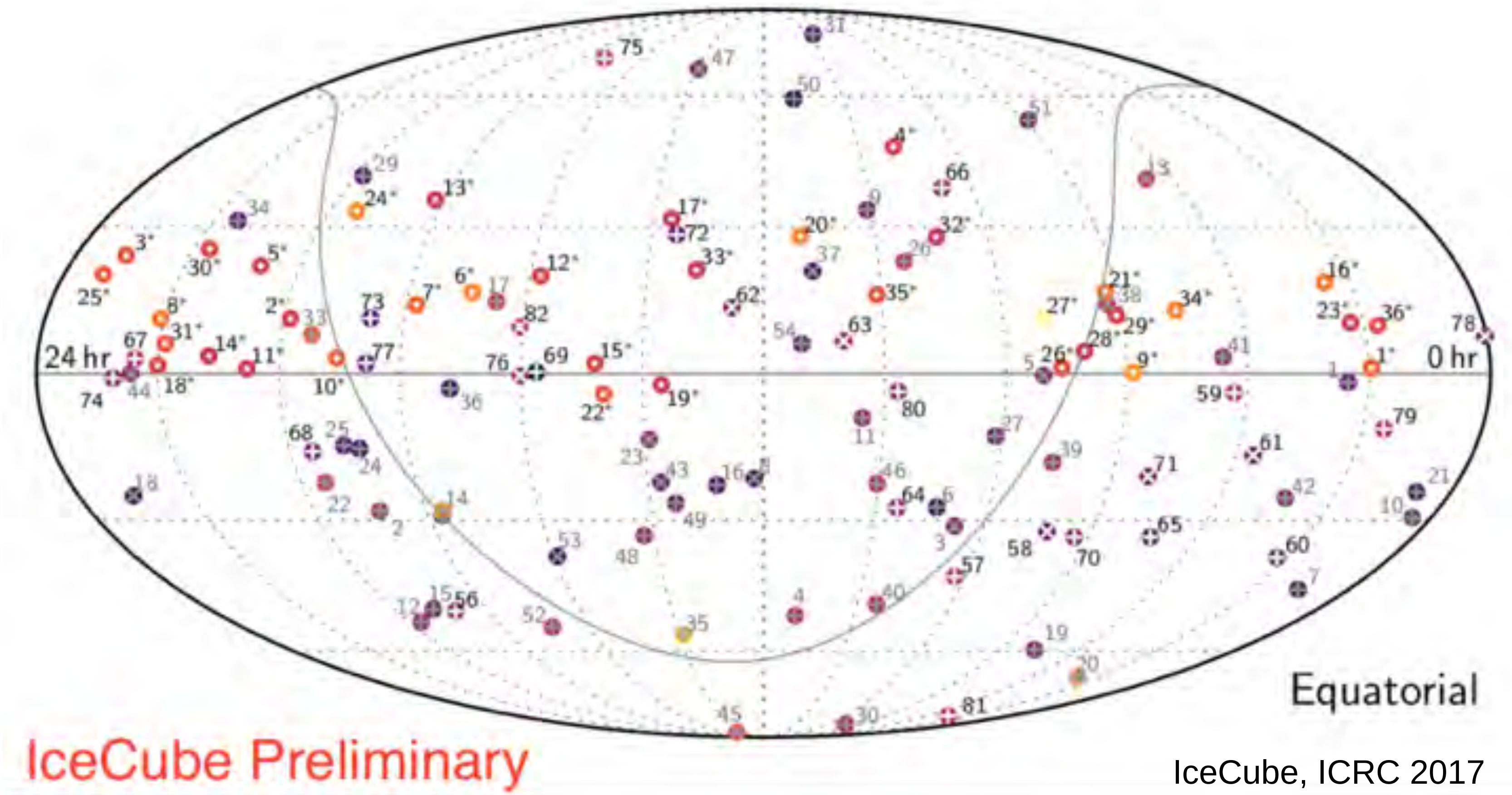
Diffuse Neutrino Flux detected!



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)



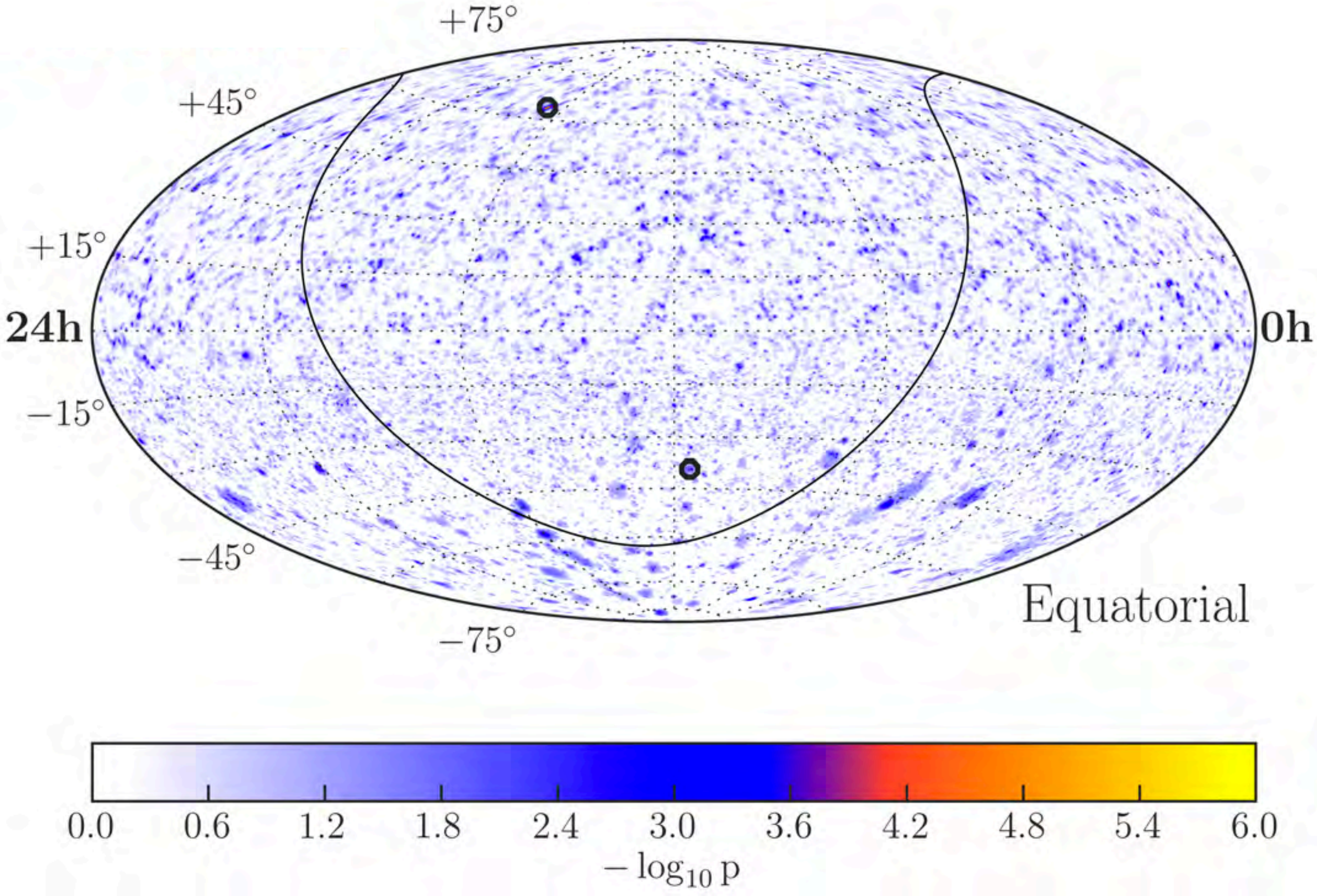
IceCube, ICRC 2017

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)

Search for Neutrino Point Sources

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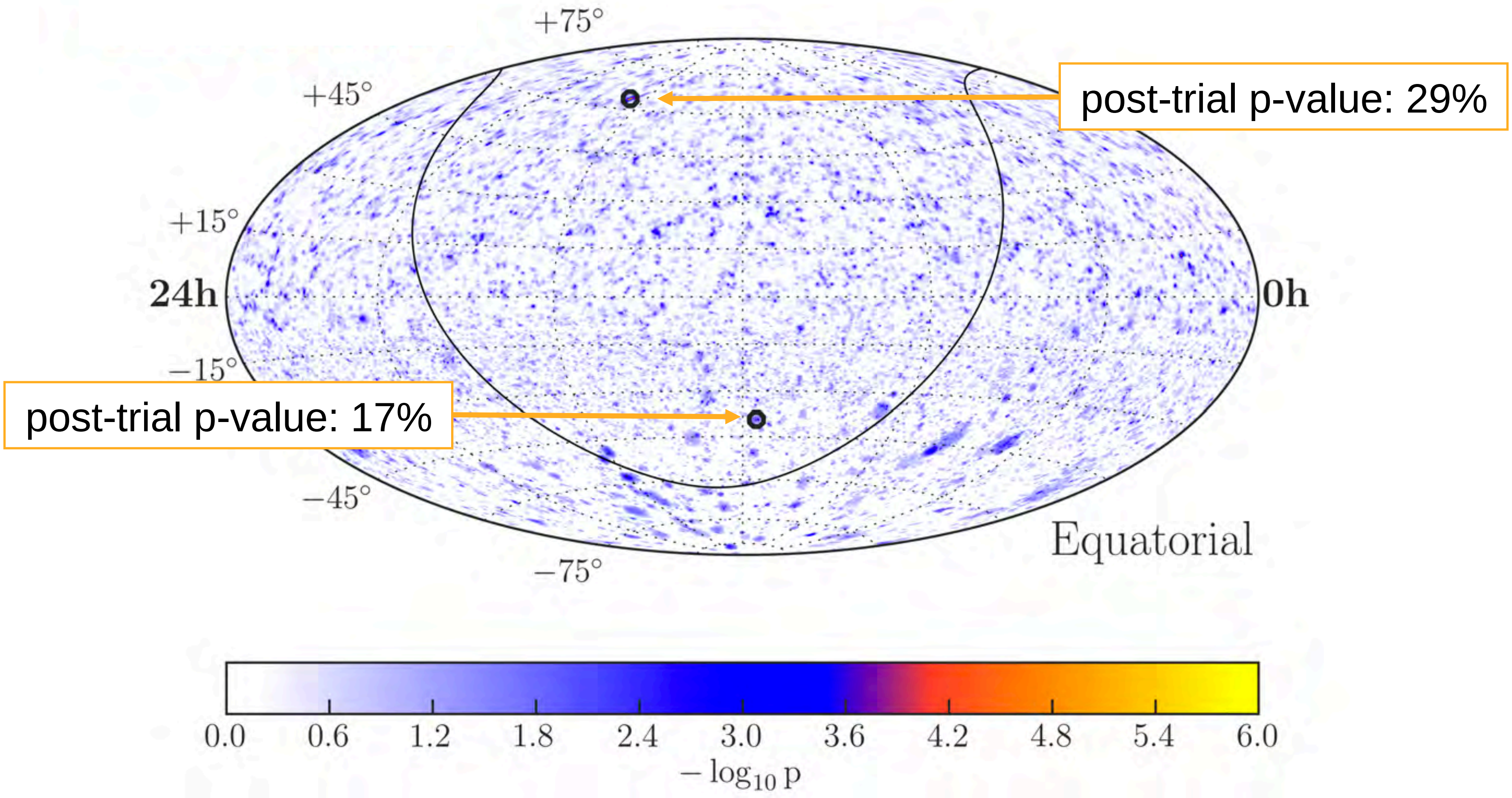

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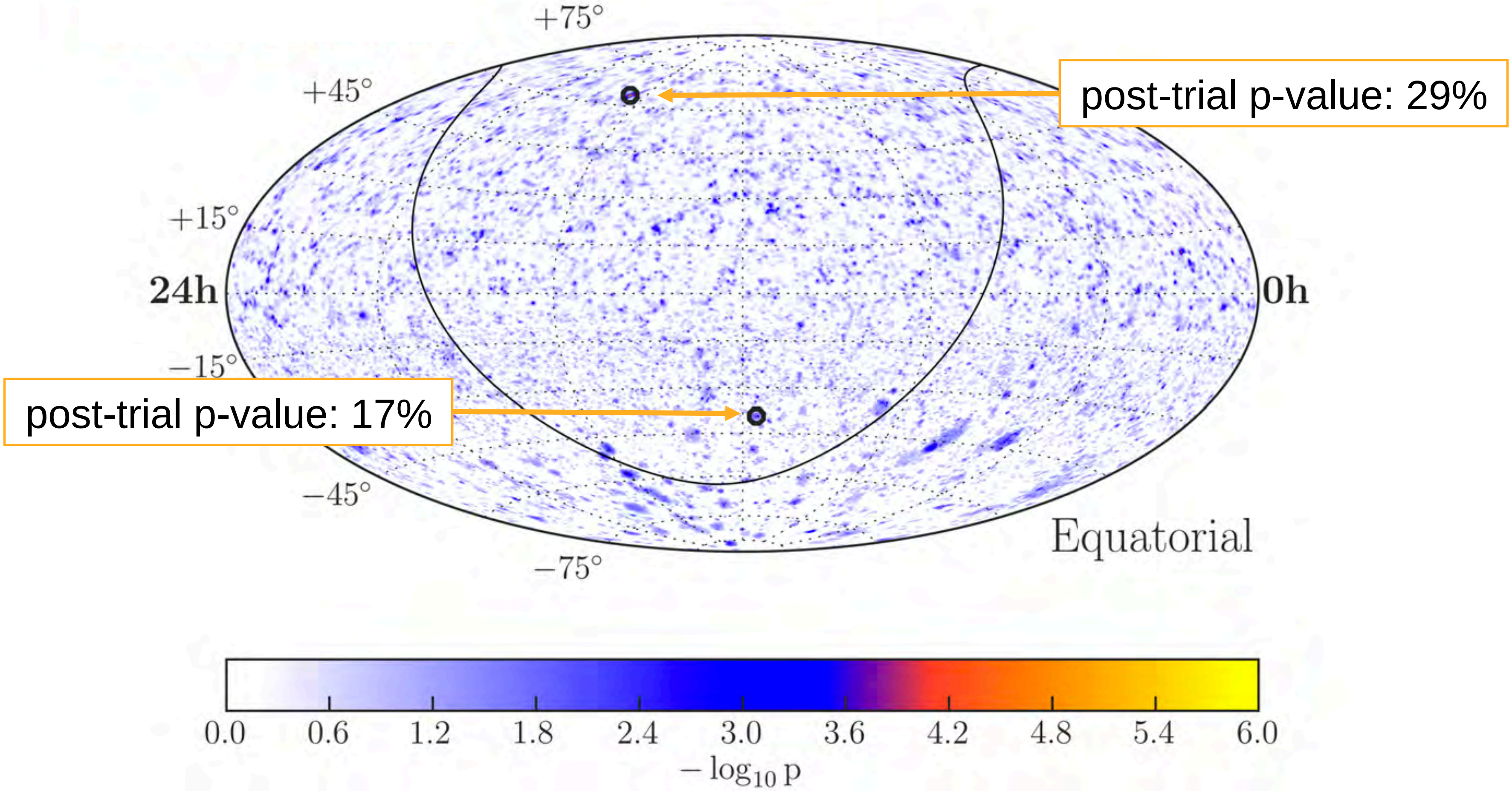


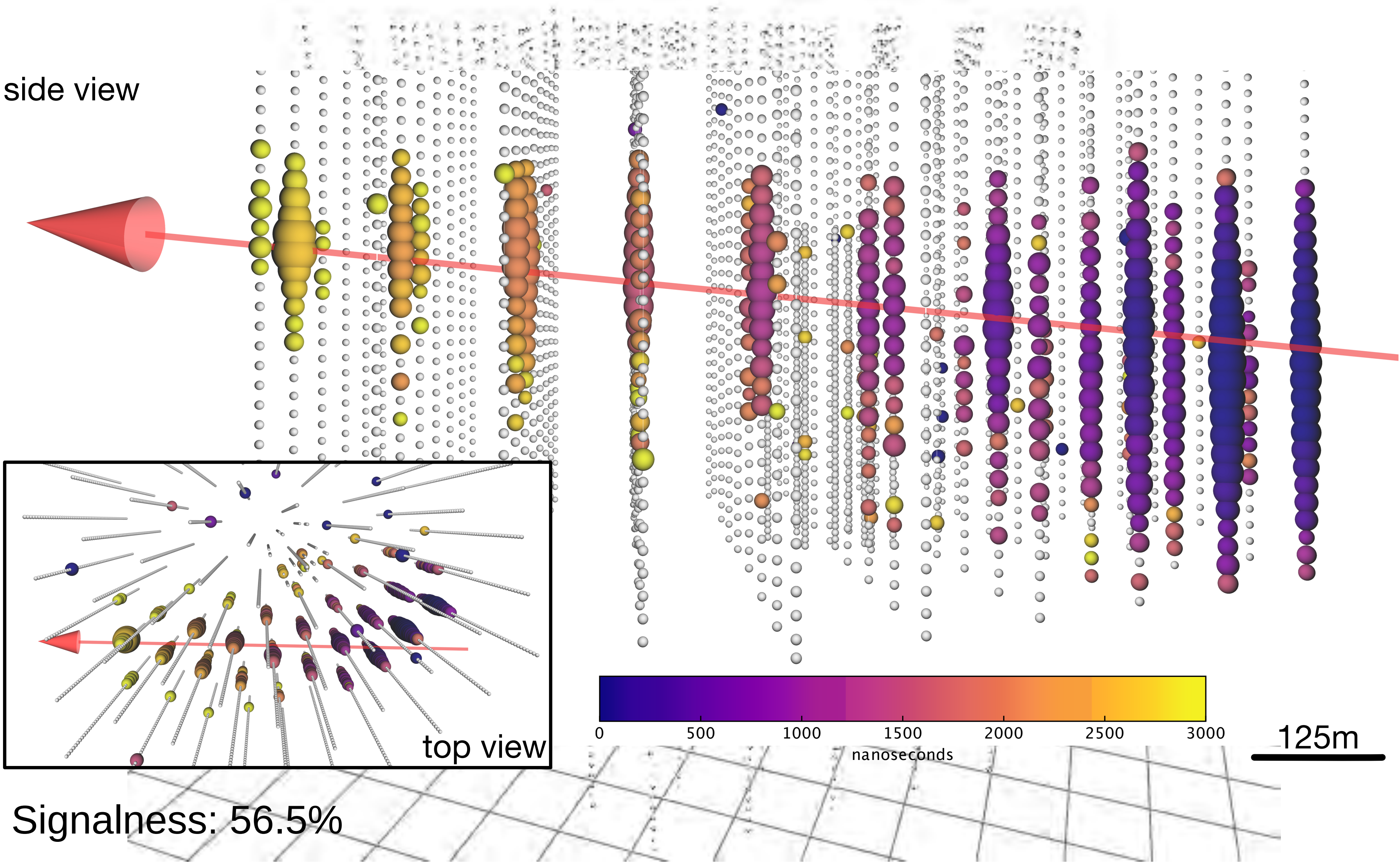
Large trials factor → Multi-wavelength data can tell us where and when to look for neutrinos

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



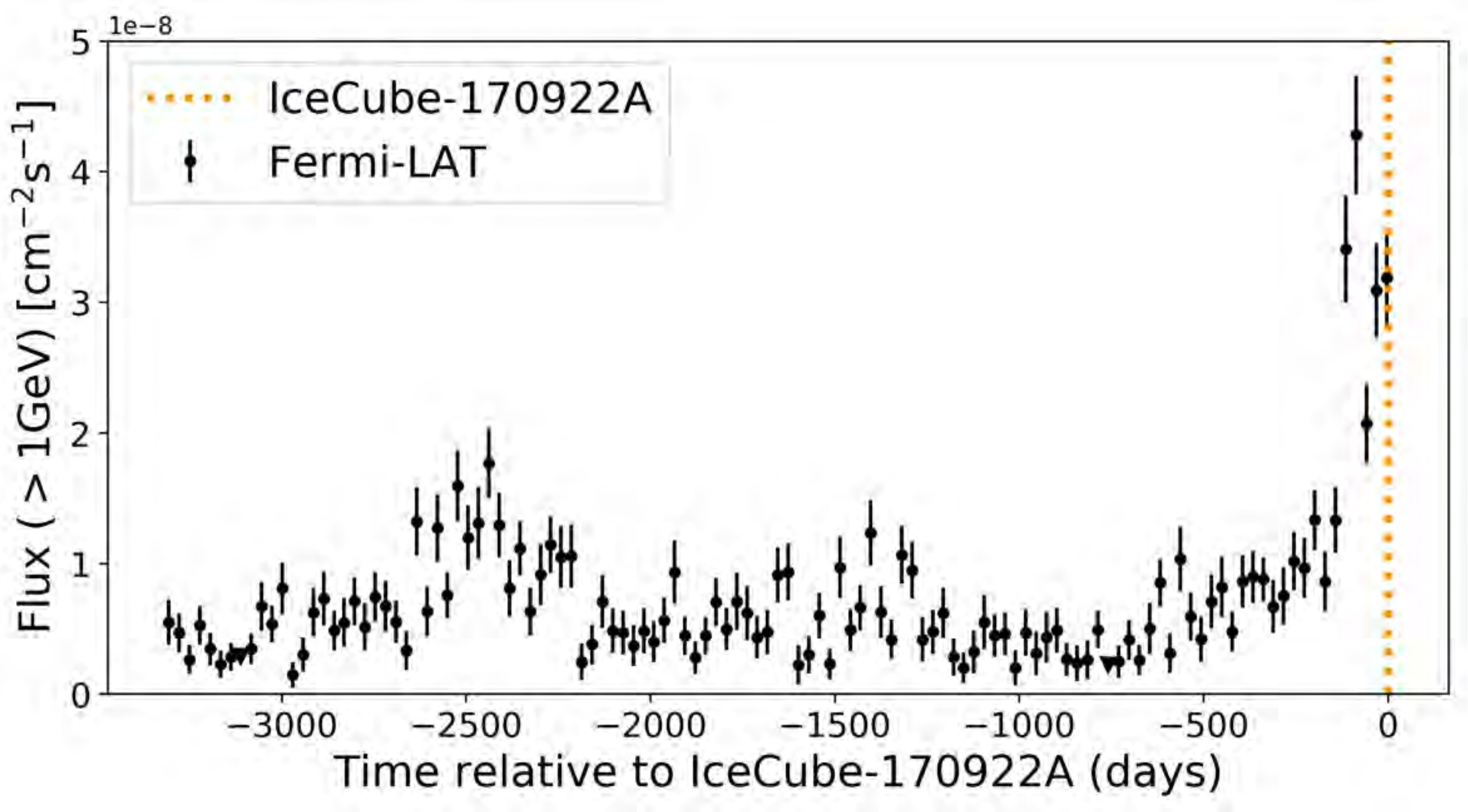
Signalness: 56.5%

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

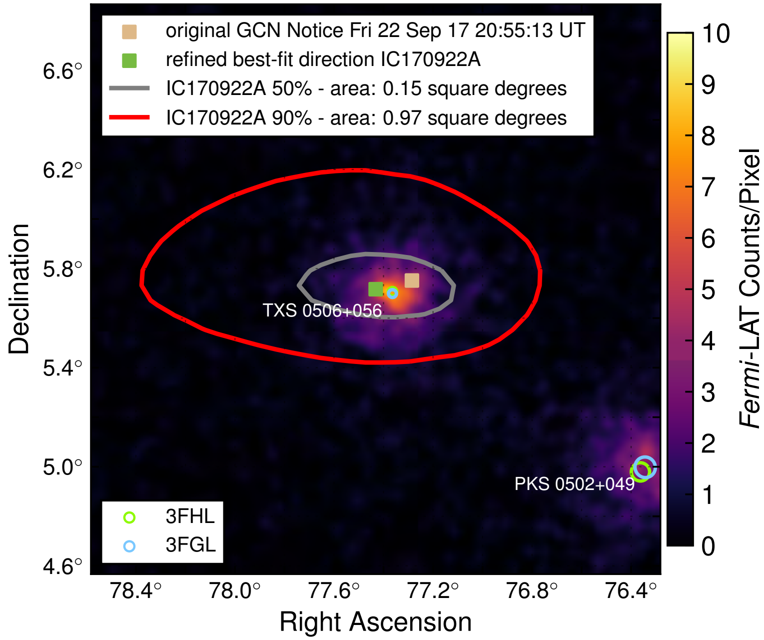
Fermi-LAT finds Flaring Blazar, TXS 0506+056

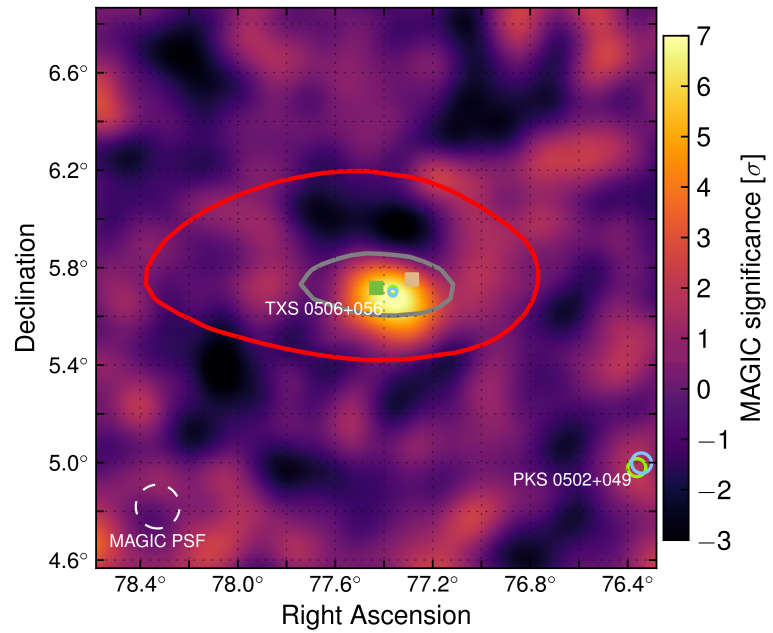


Pre-trials p-value: 4.1σ

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

MAGIC observes >100 GeV gamma rays





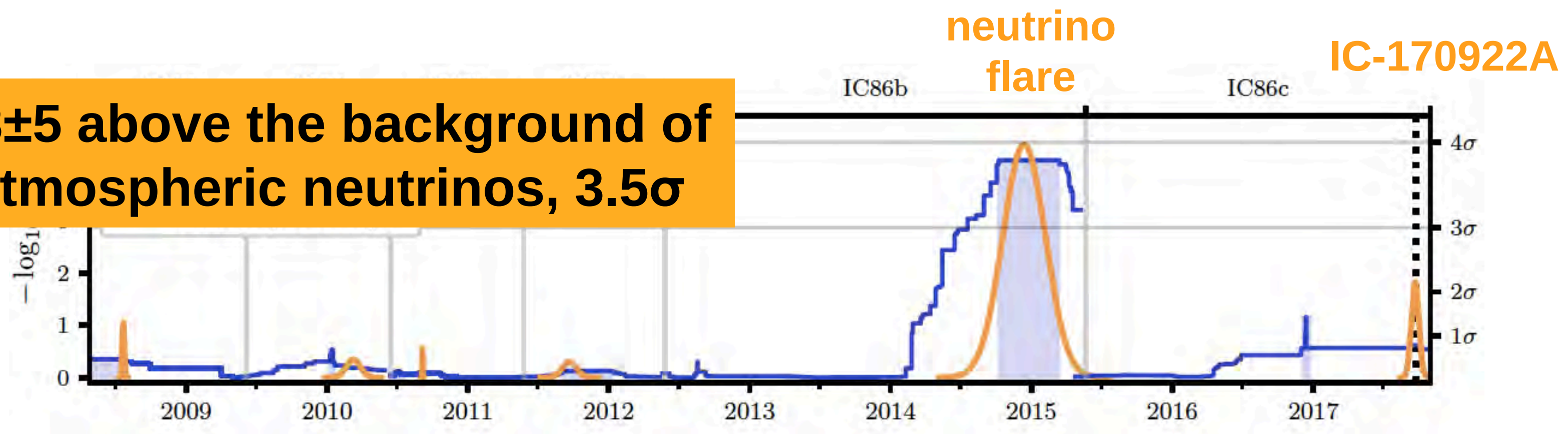
Flux increase observed also in optical, X-ray and radio

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?

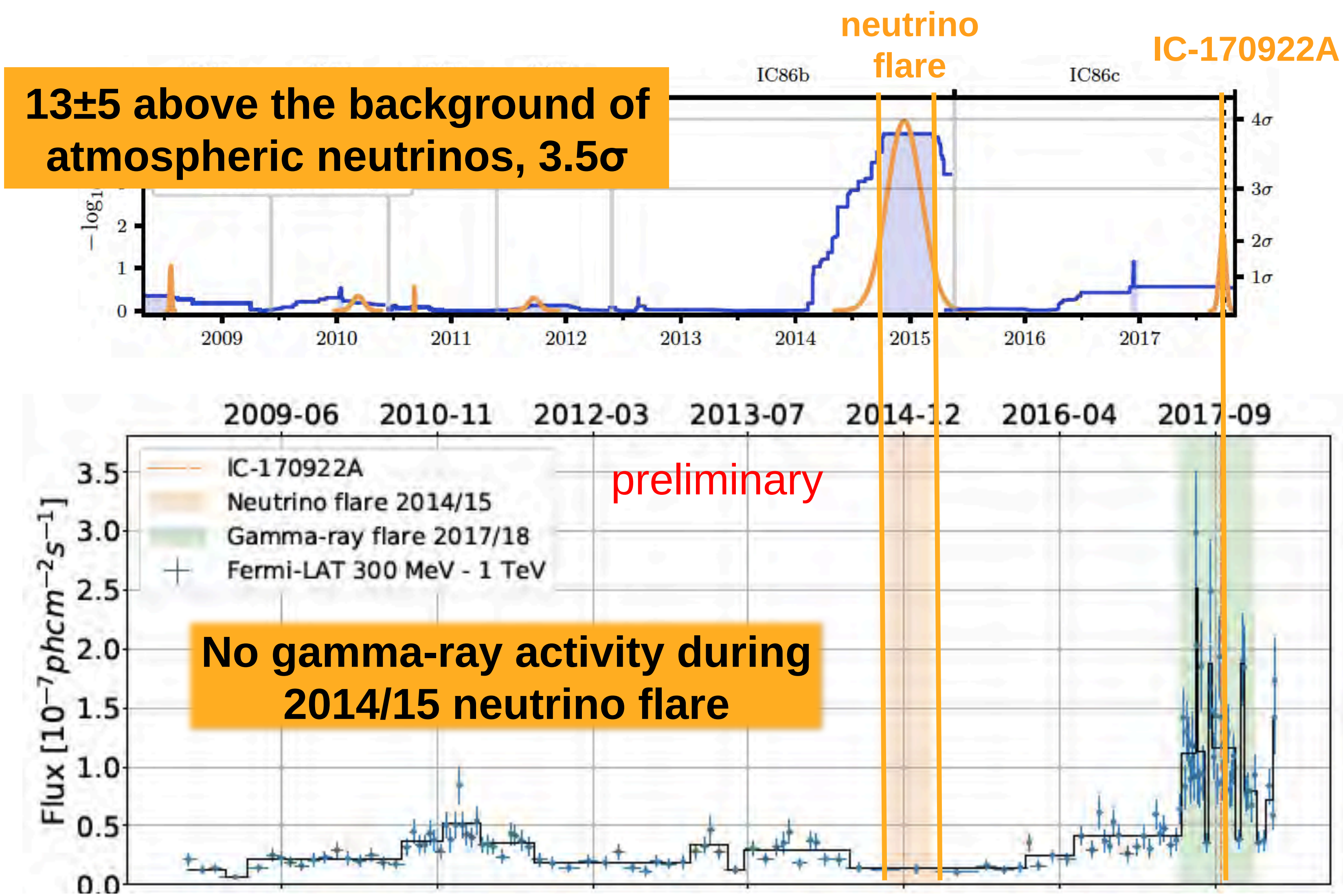
Are there more Neutrinos from this Source?

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



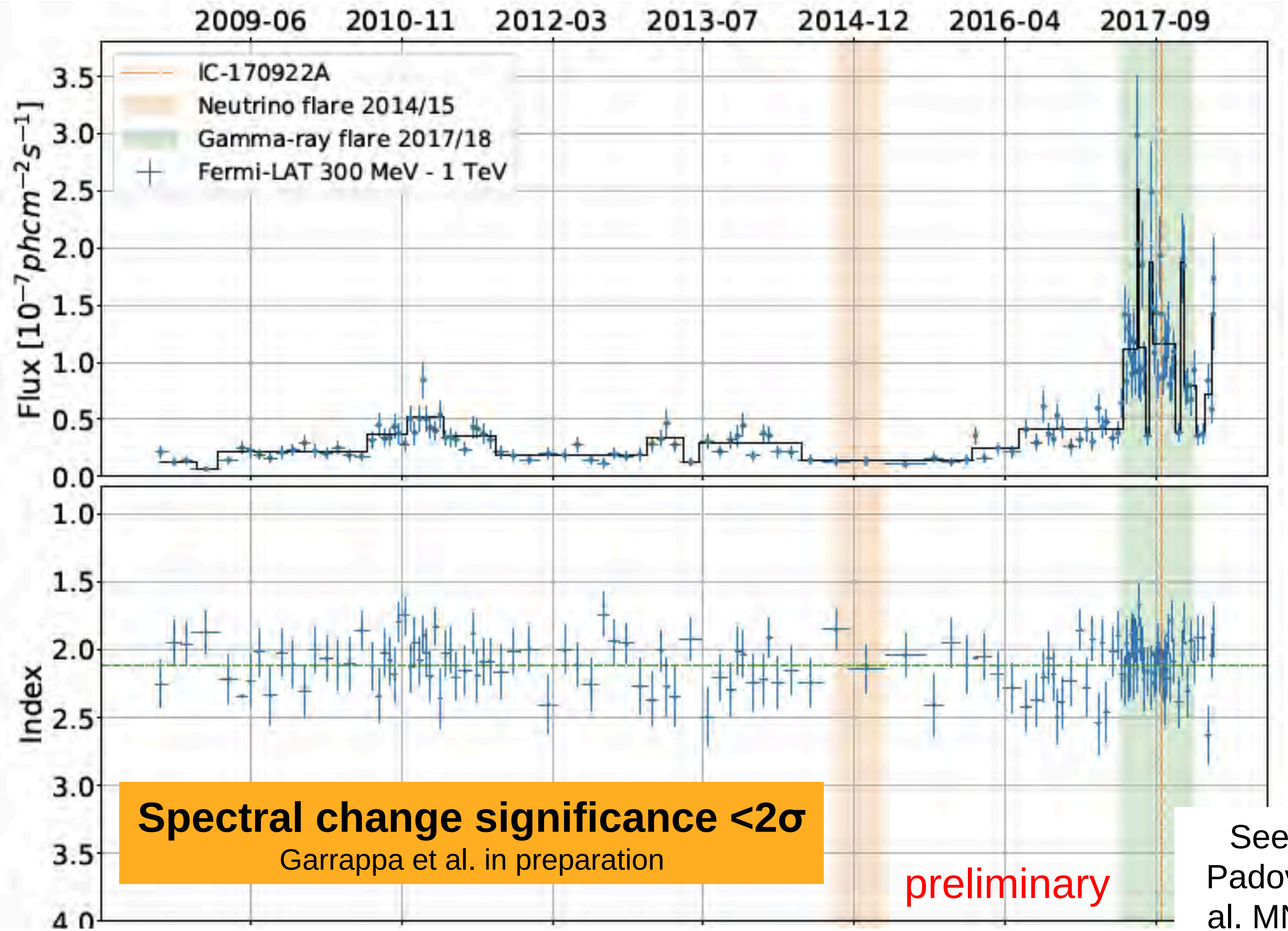
Neutrino luminosity (averaged over 158 days): $(1.2^{+0.6}_{-0.4}) \times 10^{47}$ erg s^{-1}

Is there also a Gamma-ray Flare?



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

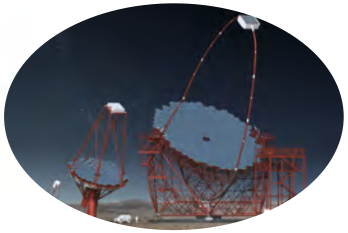
Spectral Change?



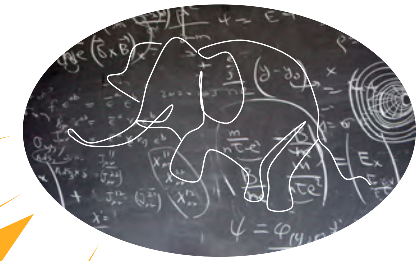
Spectral change significance <2σ
Garrappa et al. in preparation

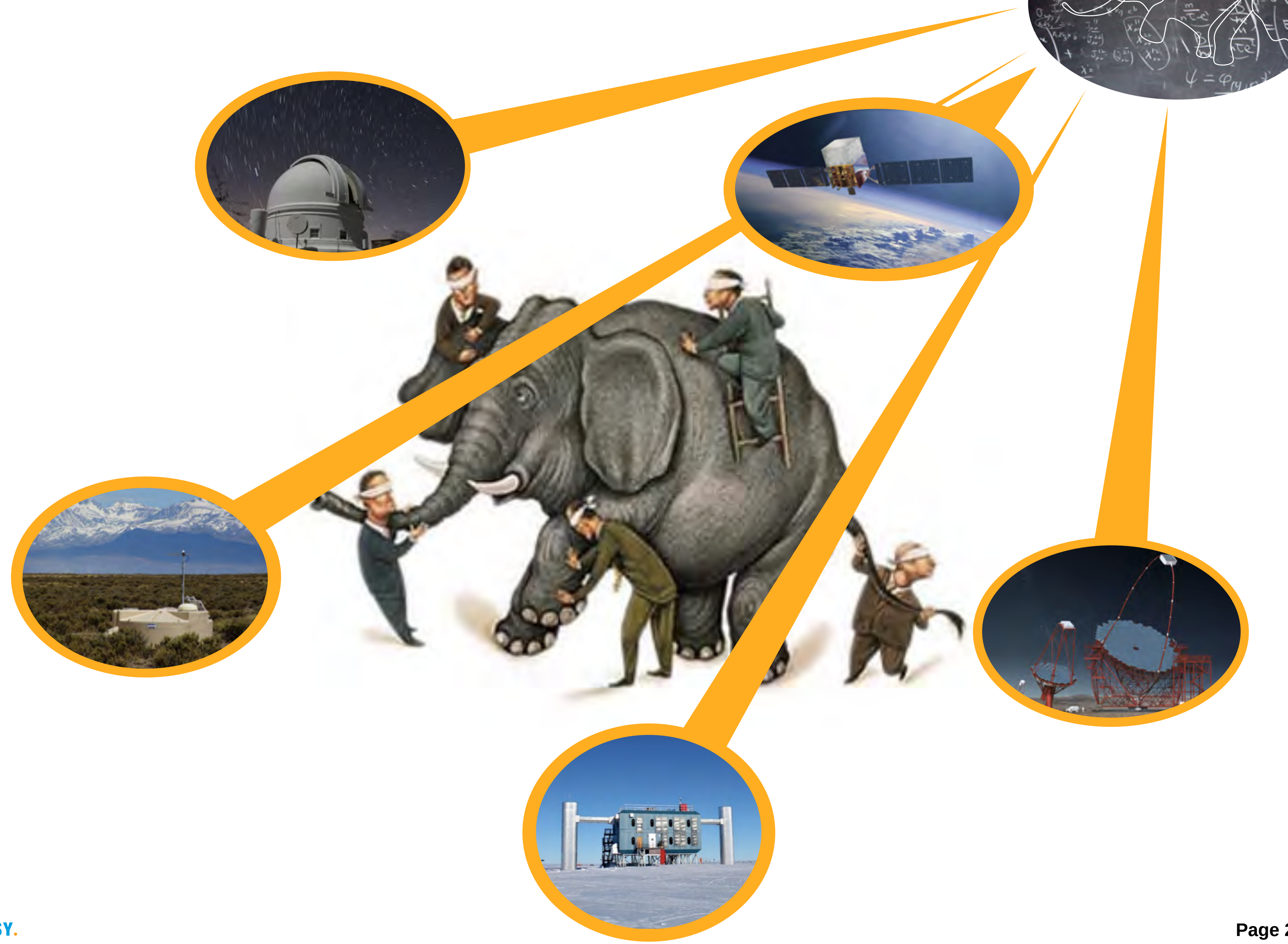
See also Padovani et al. MNRAS, 2018

The Multi-Messenger Picture

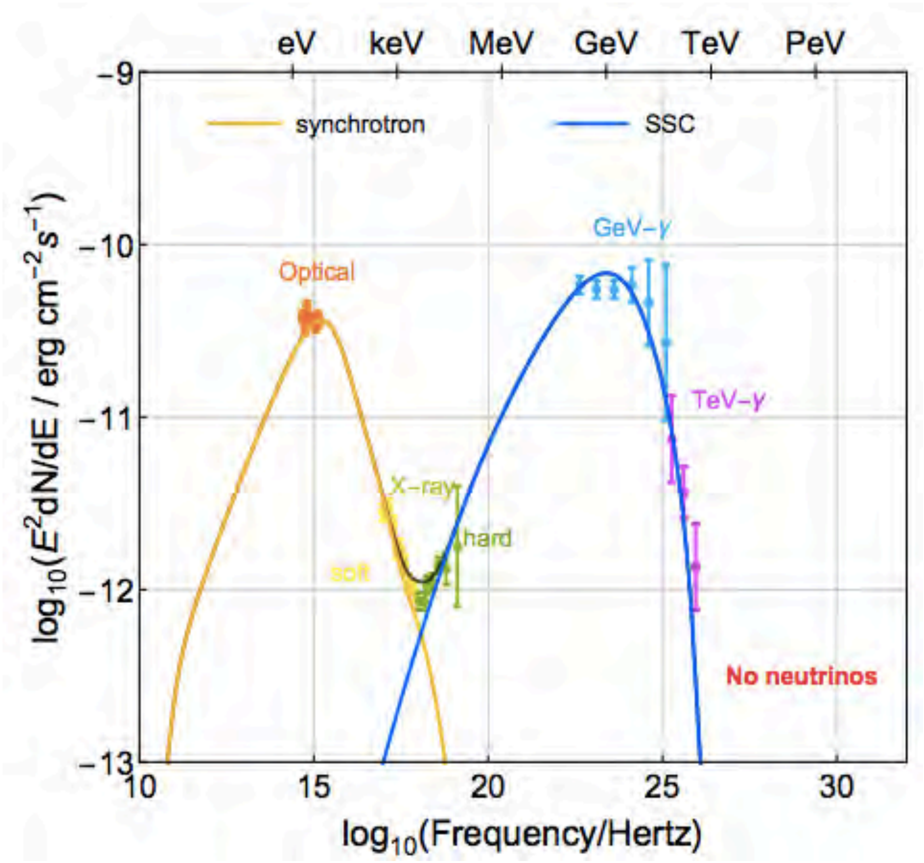


The Multi-Messenger Picture



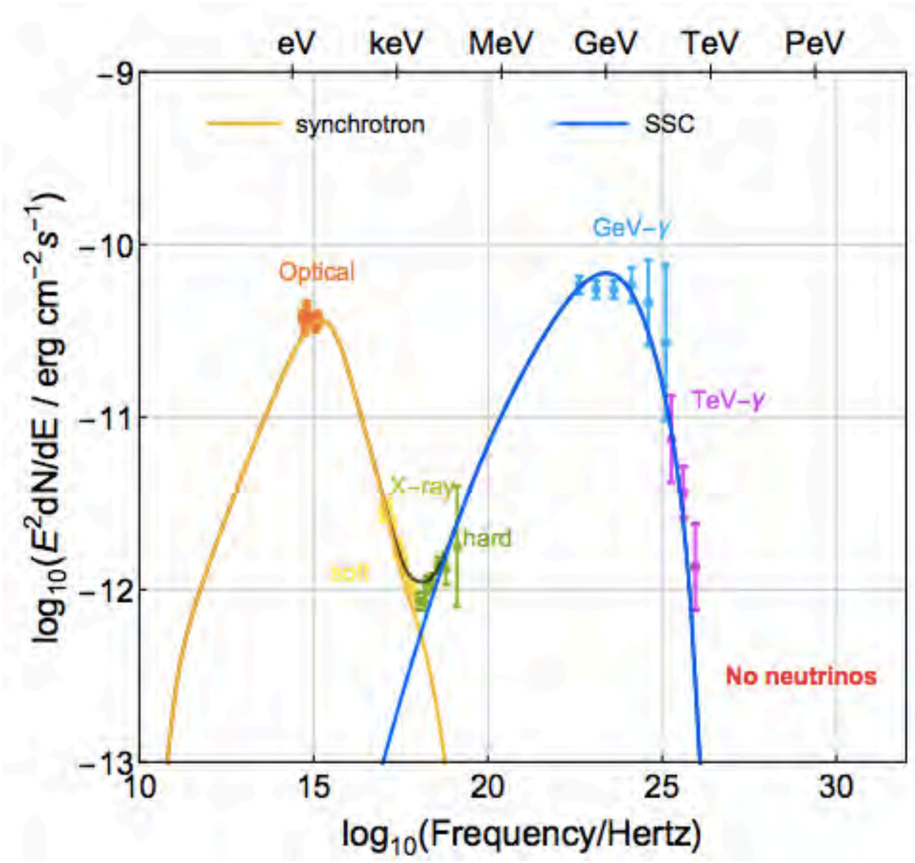


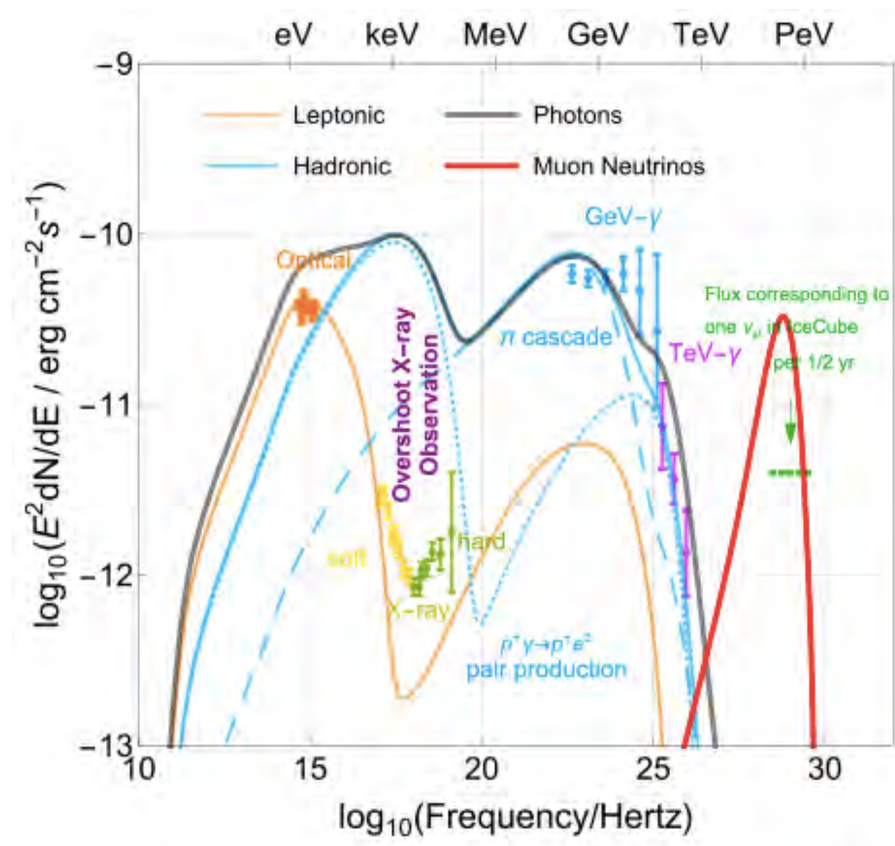
Modeling – leptonic



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

Modeling – leptonic, hadronic

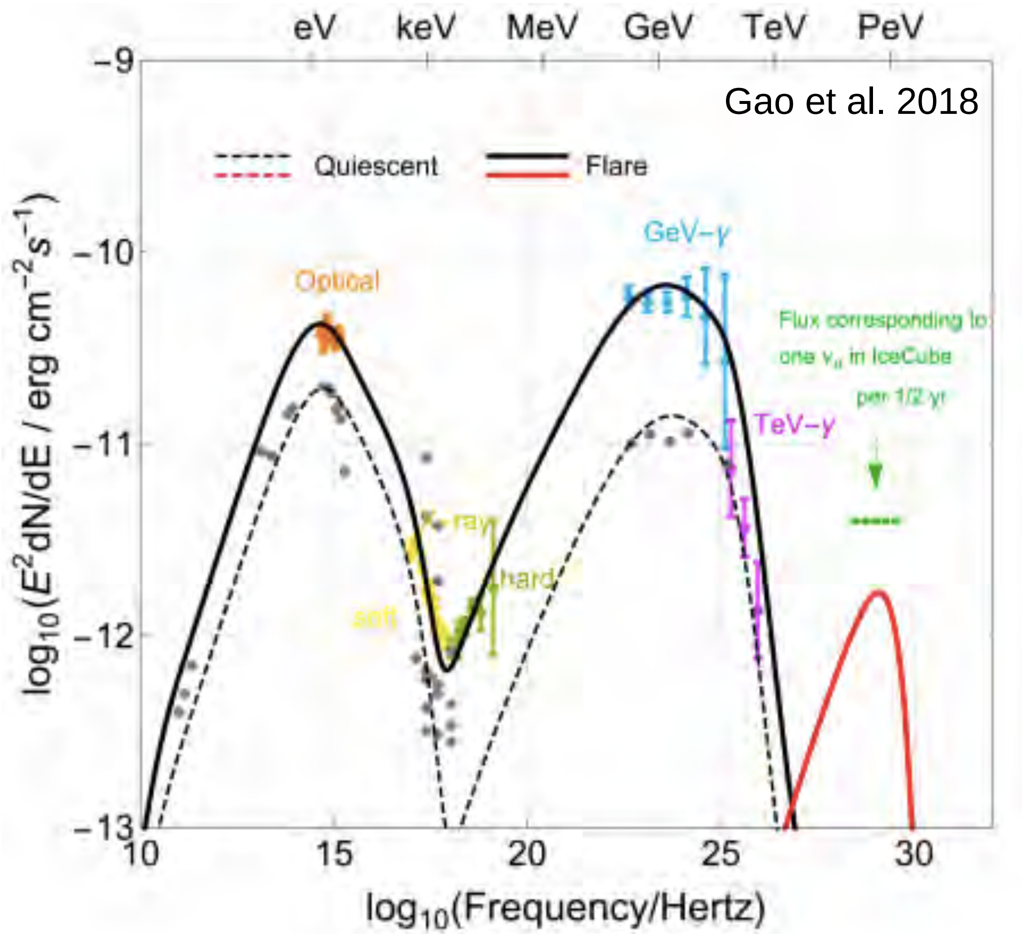




Simple one-zone hadronic models violate X-ray constraints
→ More complex models needed

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:

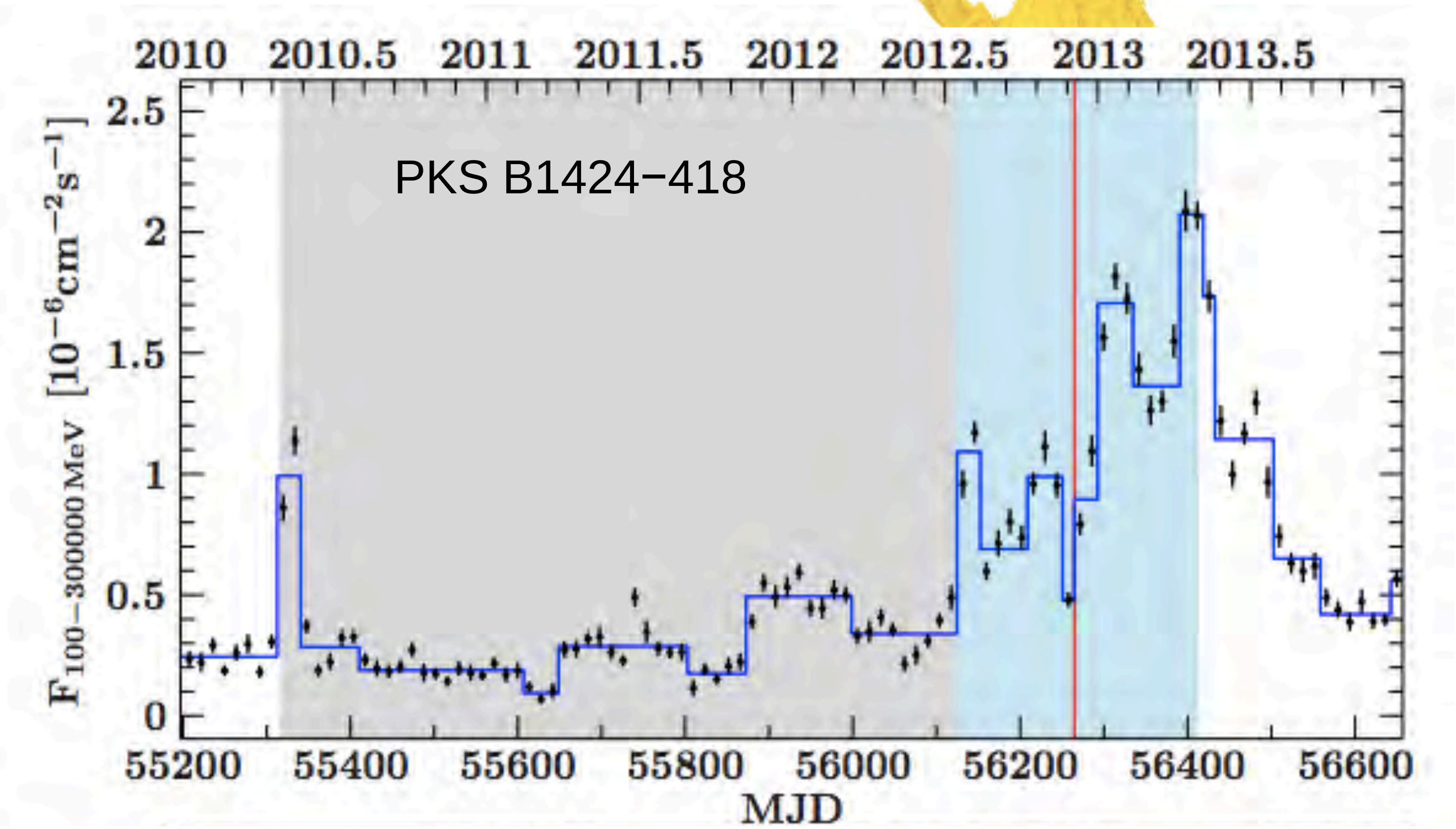
neutrino luminosity is ~4 times higher than gamma-ray luminosity

→ 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

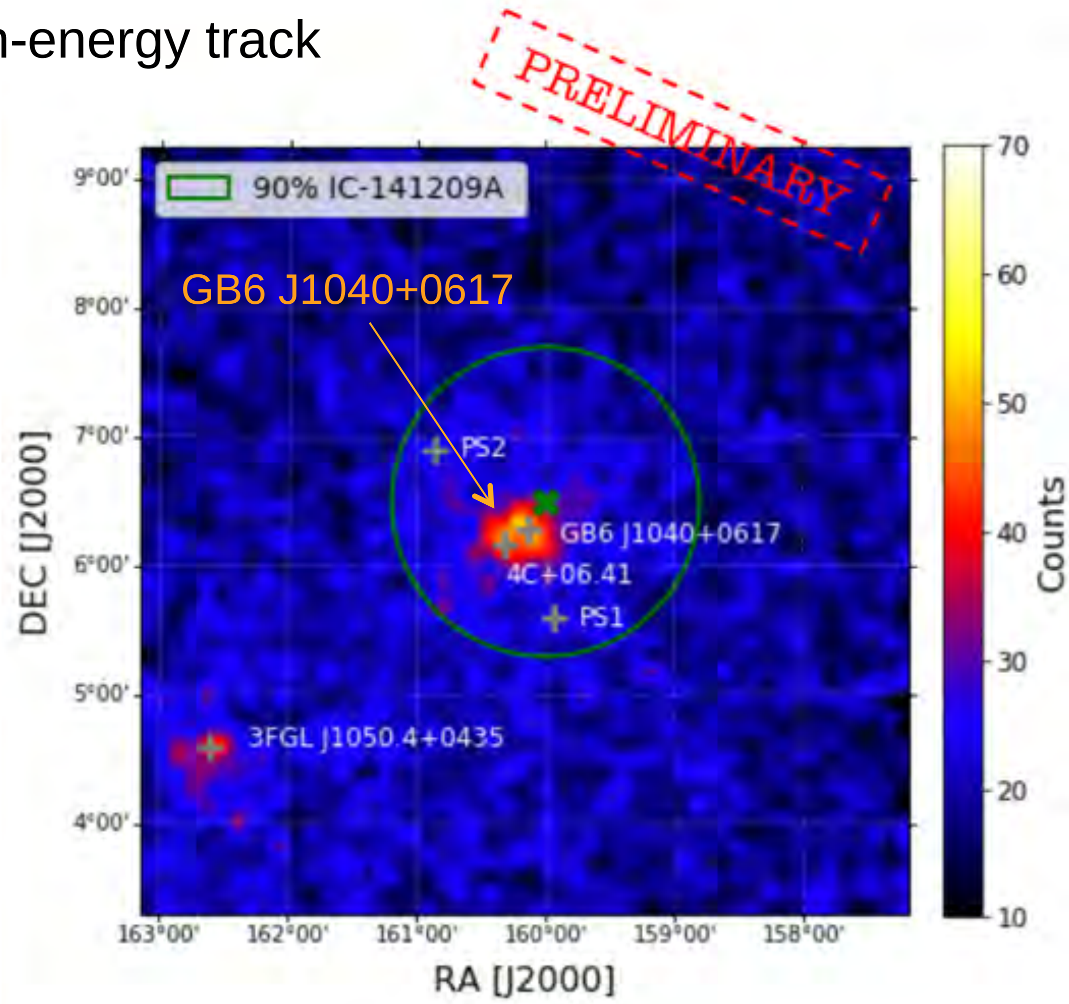


5% chance coincidence

Kadler et al., Nature Physics 2016

Other interesting candidates

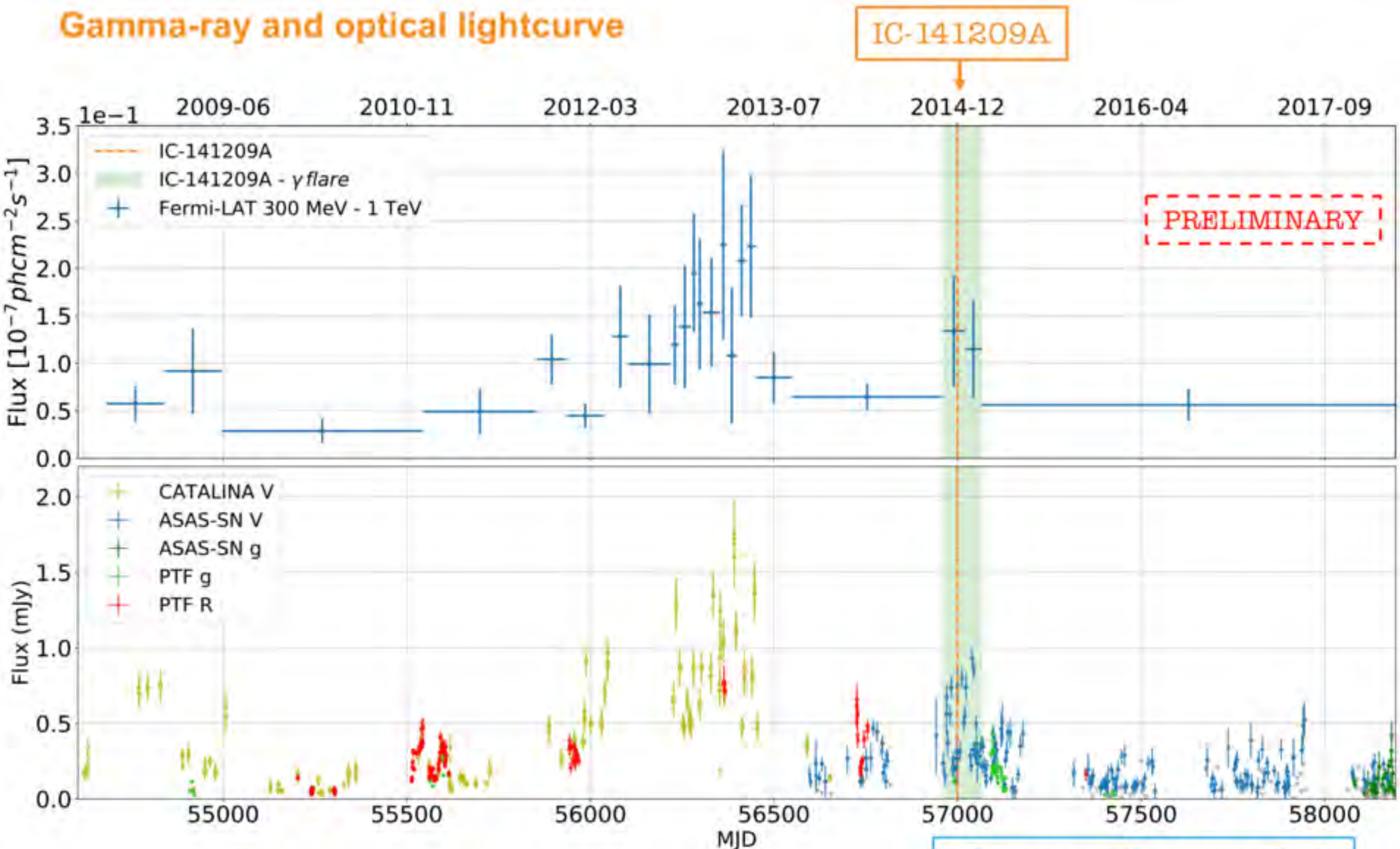
Blazar + high-energy track



Garrappa+ (in preparation)

Other interesting candidates

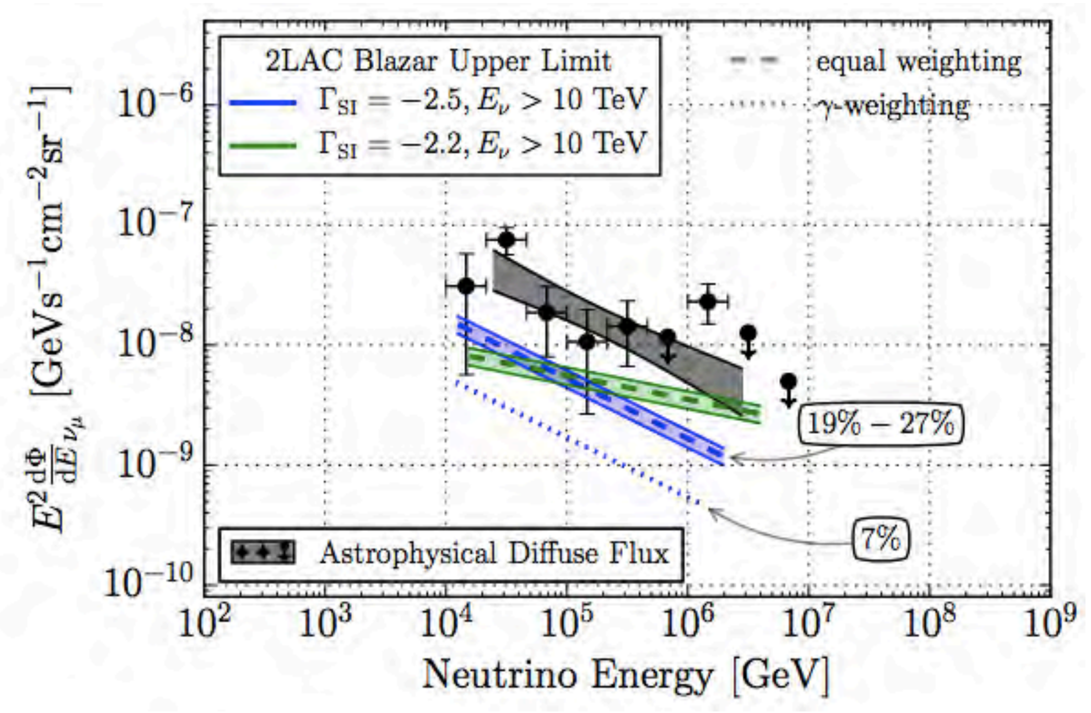
Not significant if weighted with gamma-ray energy flux



Garrappa+ (in preparation)

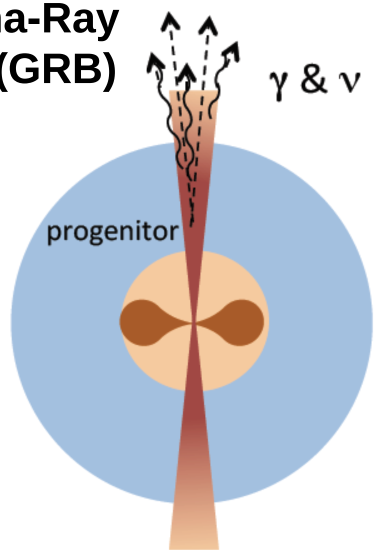
Do blazars produce all IceCube neutrinos?

- 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%

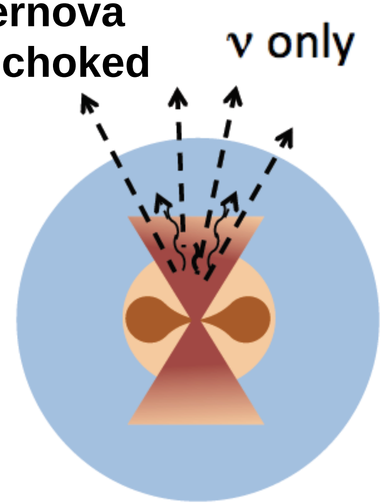


Other neutrino source candidates

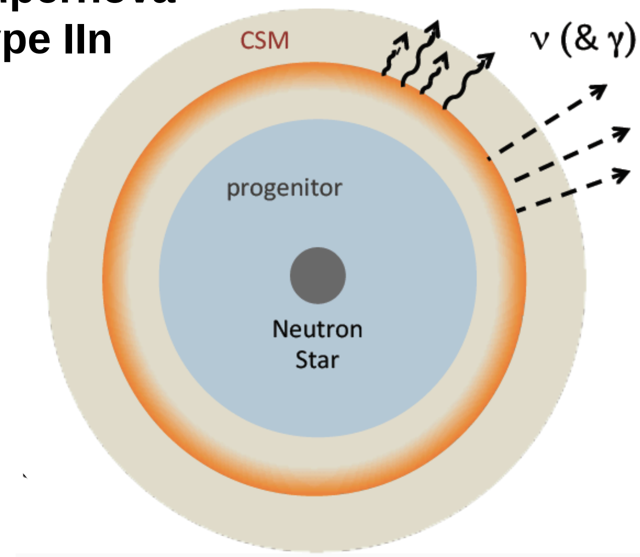
Gamma-Ray Burst (GRB)



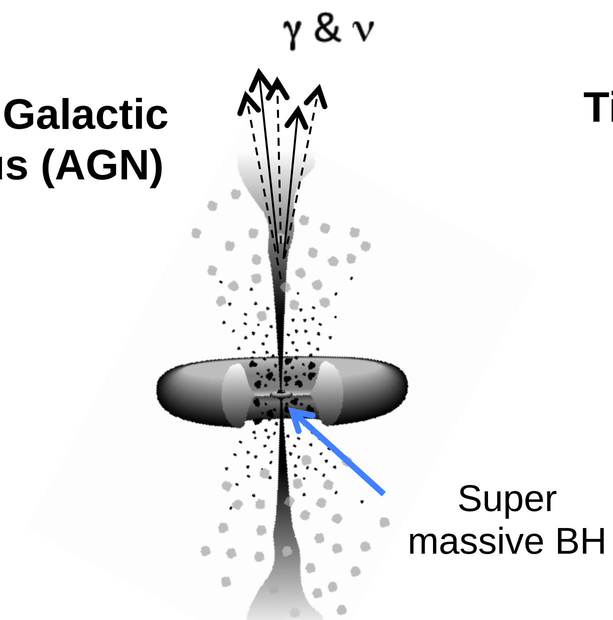
Supernova with choked jets



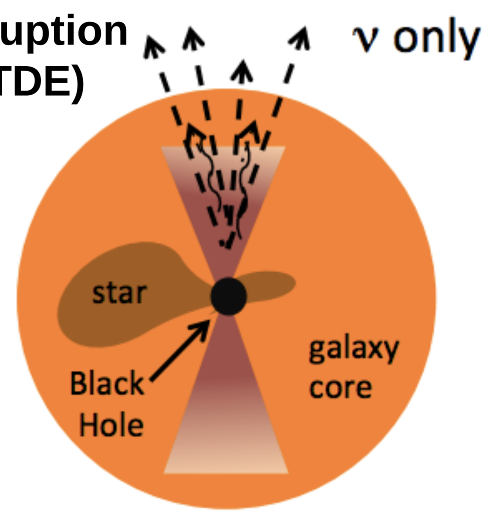
Supernova Type IIn



Active Galactic Nucleus (AGN)

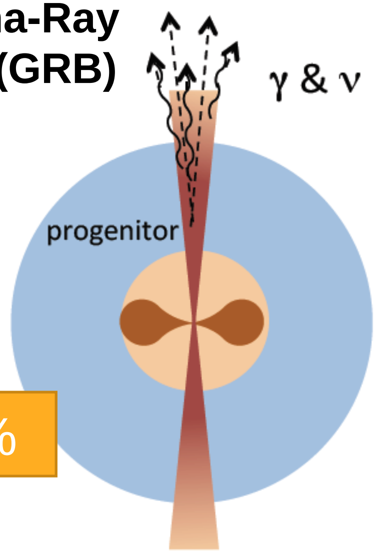


Tidal Disruption event (TDE)



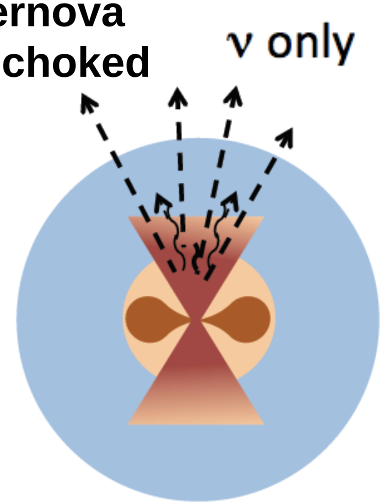
Other neutrino source candidates

Gamma-Ray Burst (GRB)



<1%

Supernova with choked jets



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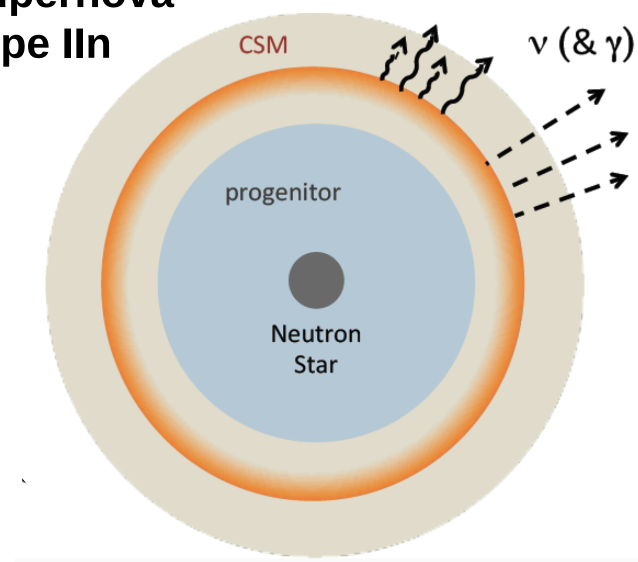
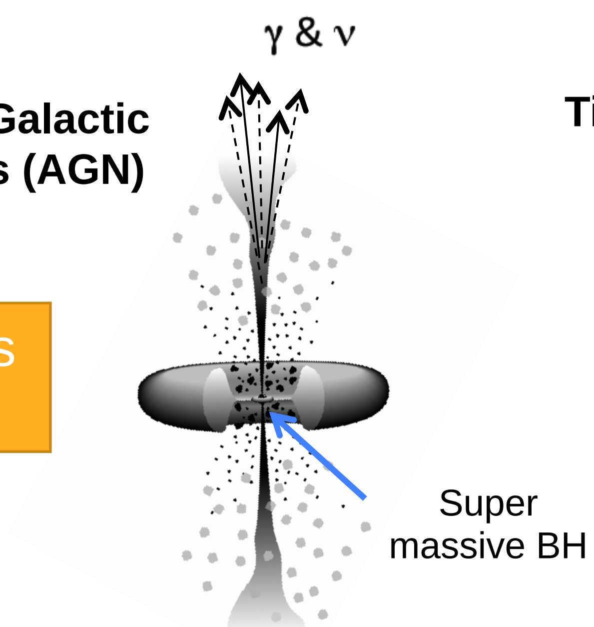
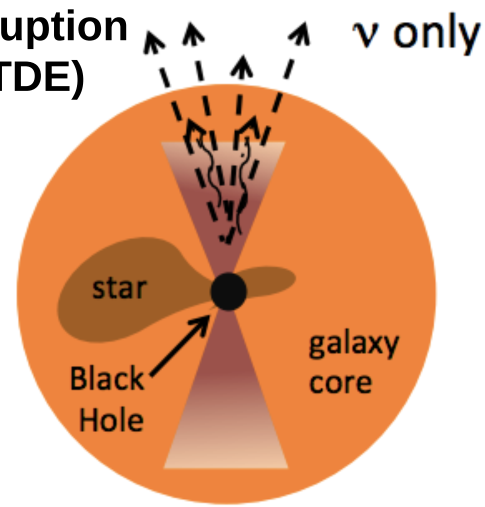


Active Galactic Nucleus (AGN)



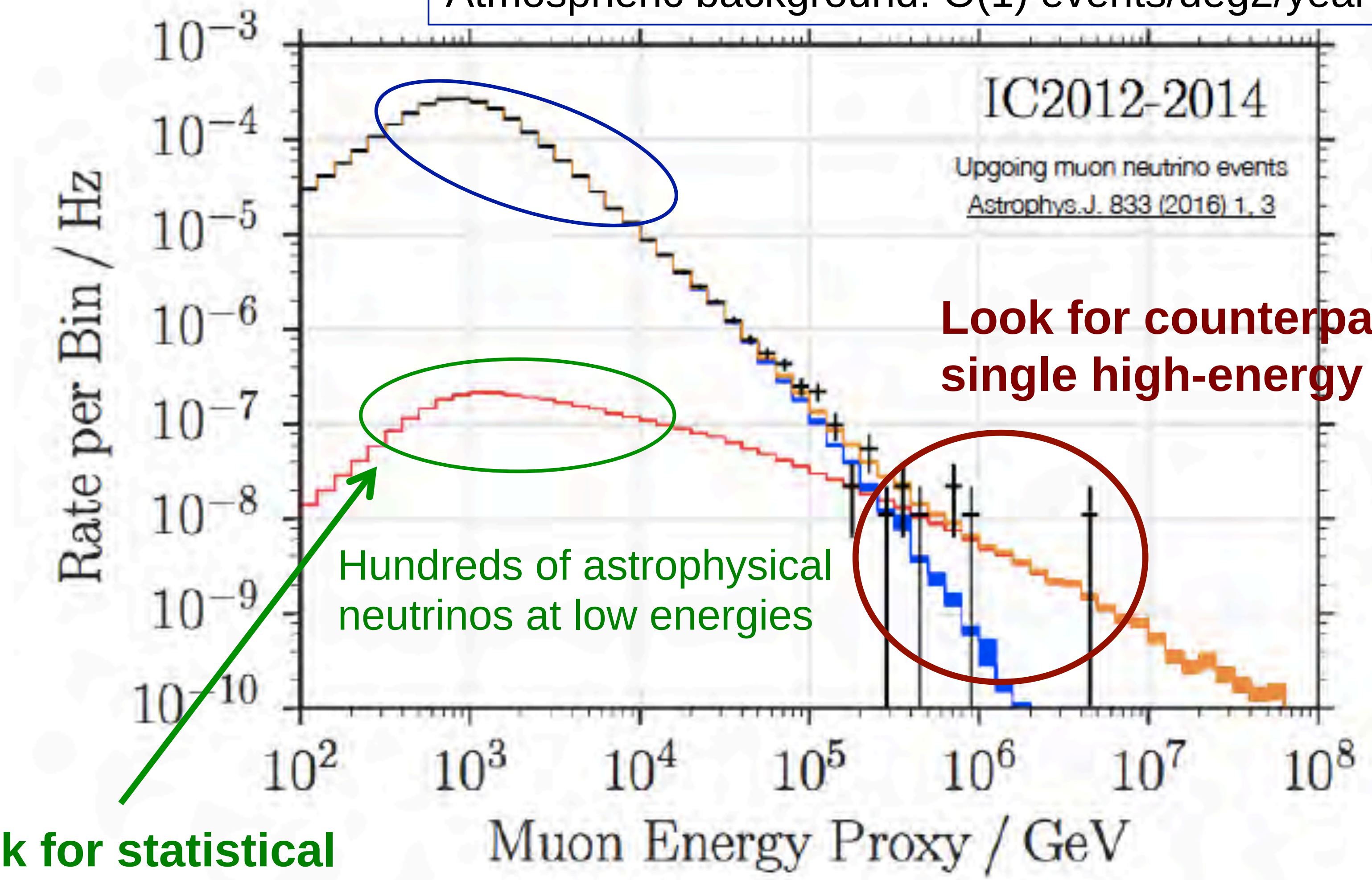
blazars <30%

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

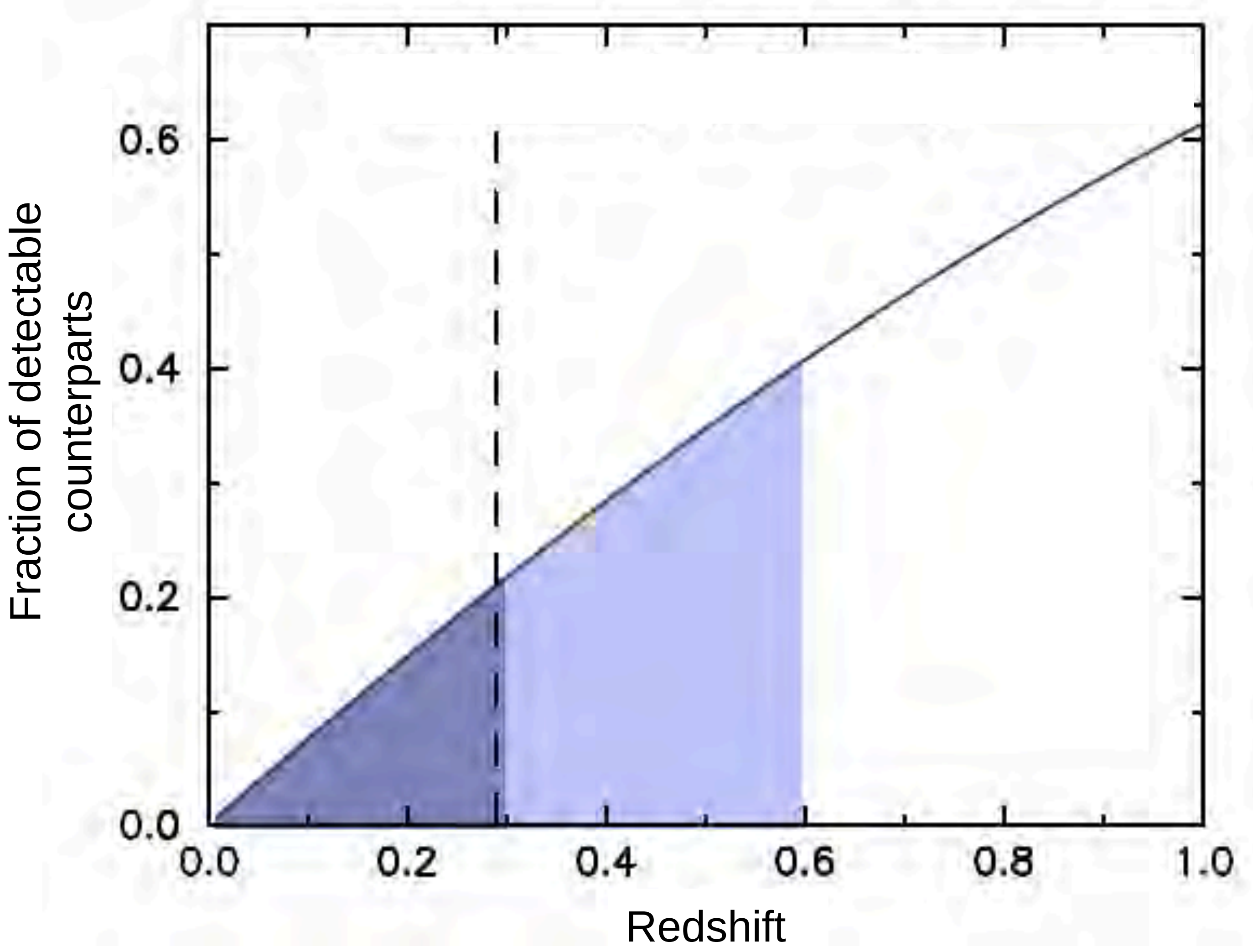
Look for statistical excess

Deep Optical Follow-up

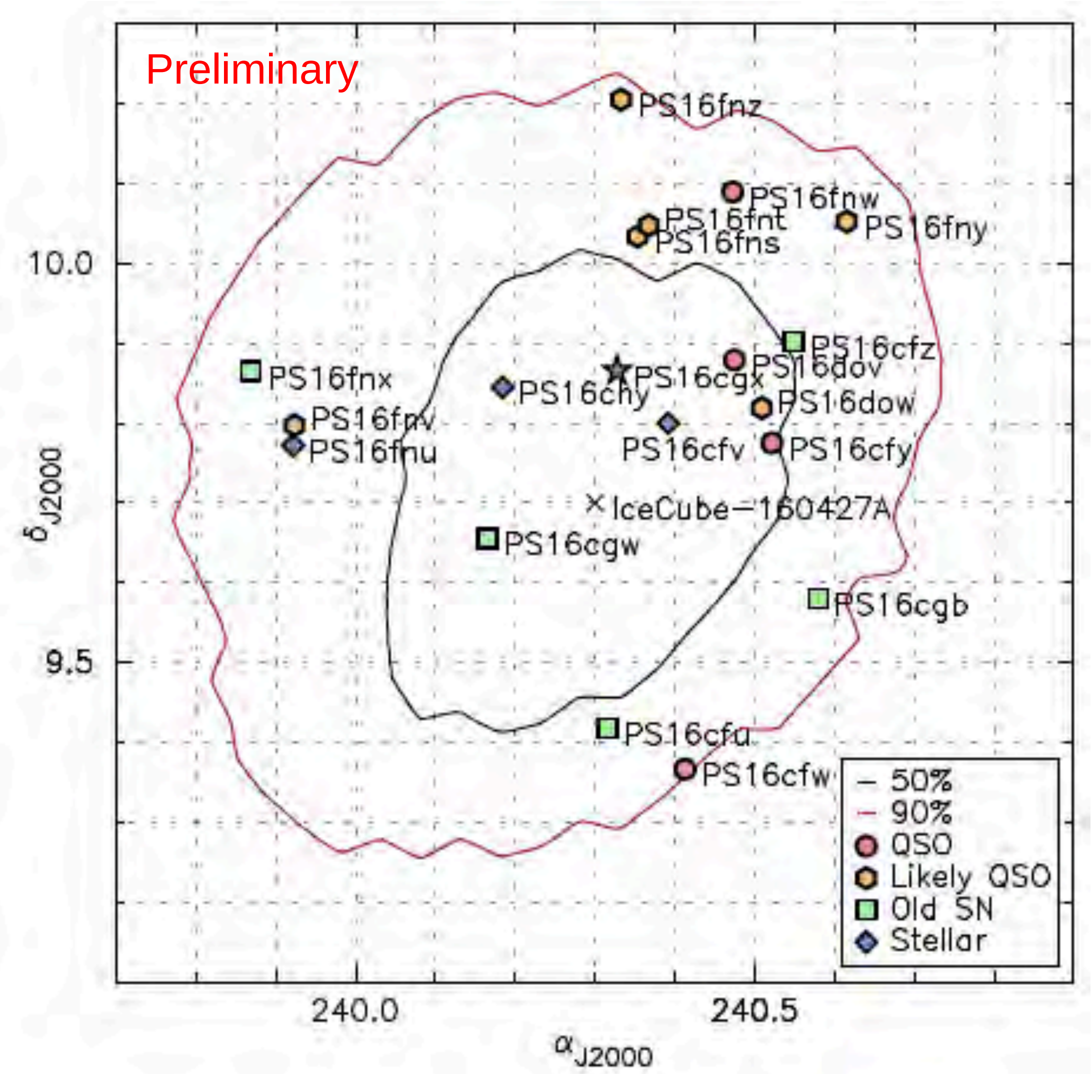
Pan-STARRS, 1.8m telescope, Hawaii

Dark-energy survey, 4m telescope, Chile

Deep Optical Follow-up



Pan-STARRS follow-up of IC-160427A



Type	Number
QSO	10
Stellar	3
Old SNe	5
Young SN	1
Total	**19**

Young SN found:
PS 16cgx

Chance probability:

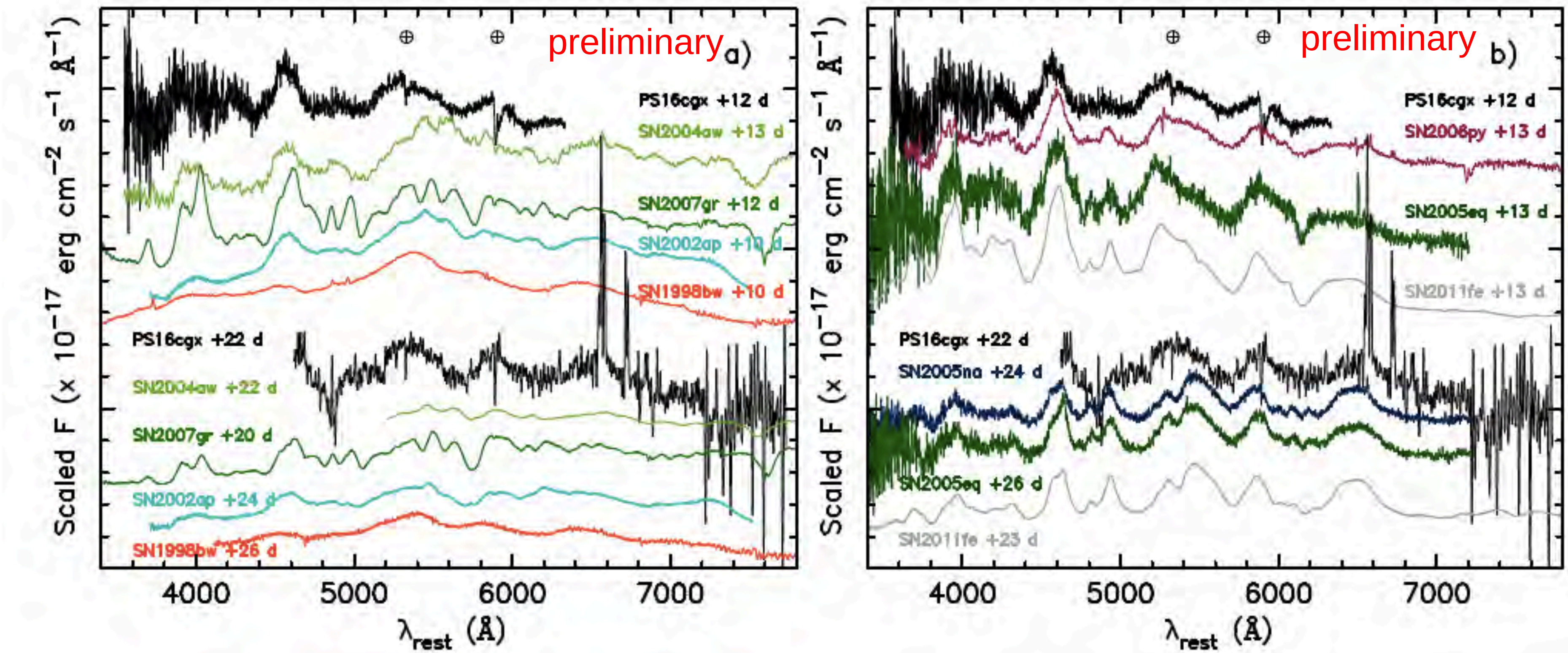
- if **type Ic** (associated with GRBs): **~2%**
- if **type Ia** (no HE neutrinos exp.): **~15%**

What type of SN is PS 16cgx?

Spectra

Comparison with core-collapse (type Ic), candidates for choked jets and neutrino emitters

Comparison with thermonuclear explosions (type Ia), no neutrino emitters

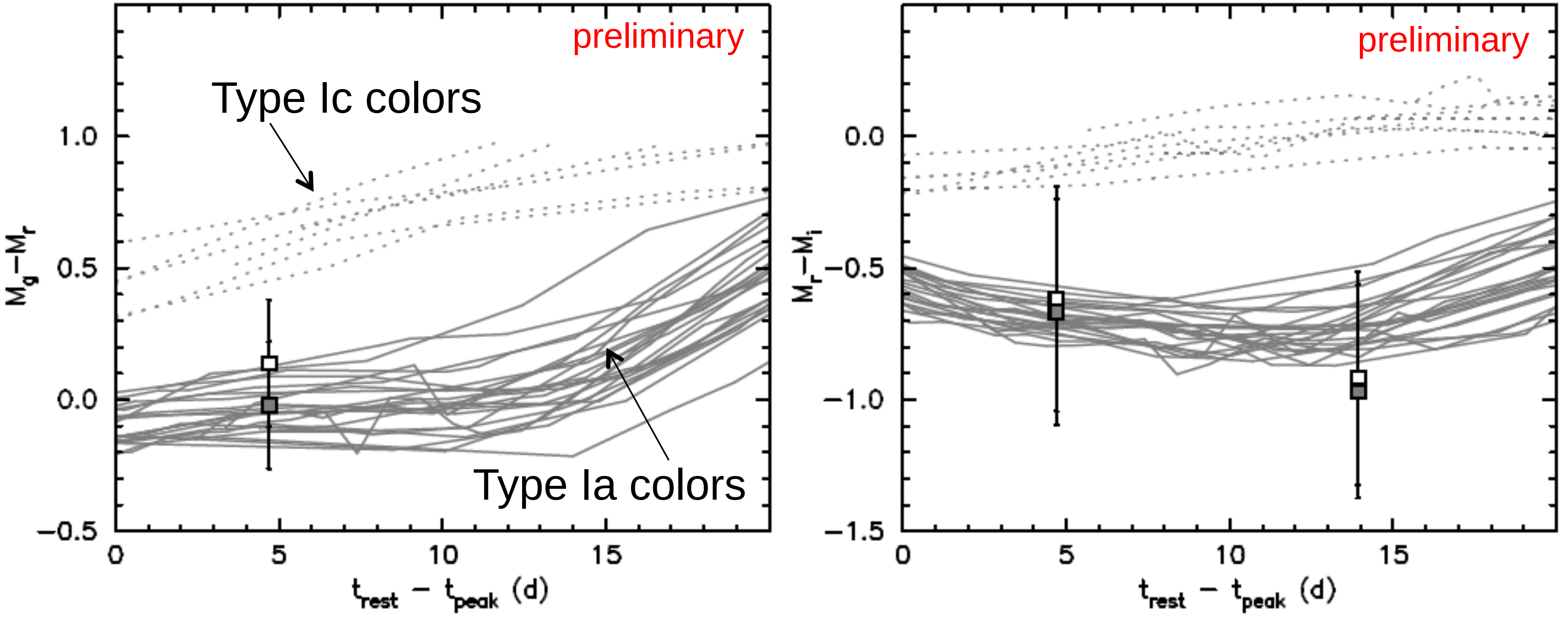


Pan-STARRS + IceCube in preparation

What type of SN is PS 16cgx?

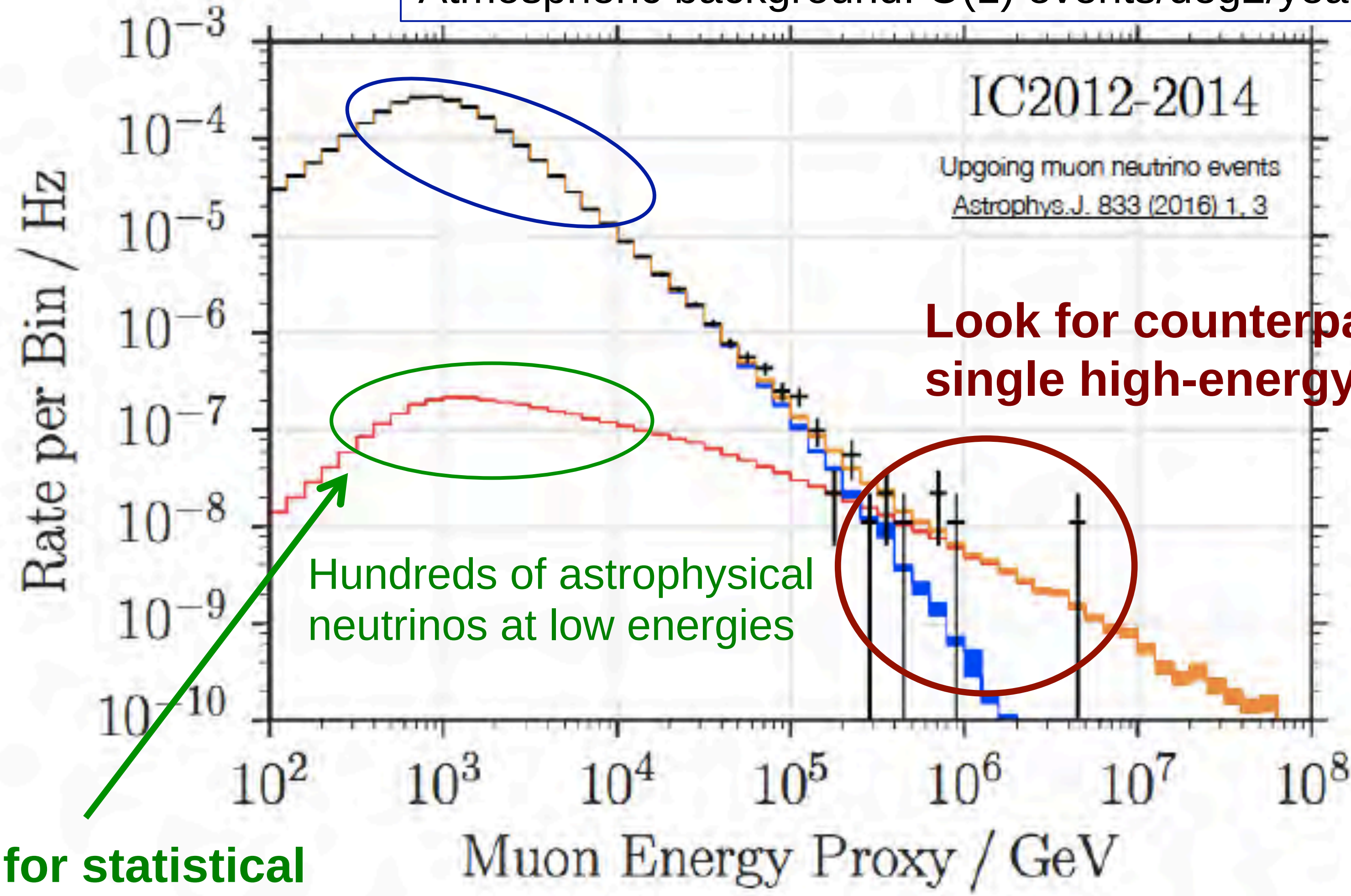
Colors

PS 16cgx is more likely of type Ia → not a high-energy neutrino emitter



Two Strategies

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



Hundreds of astrophysical neutrinos at low energies

Look for counterpart of single high-energy events

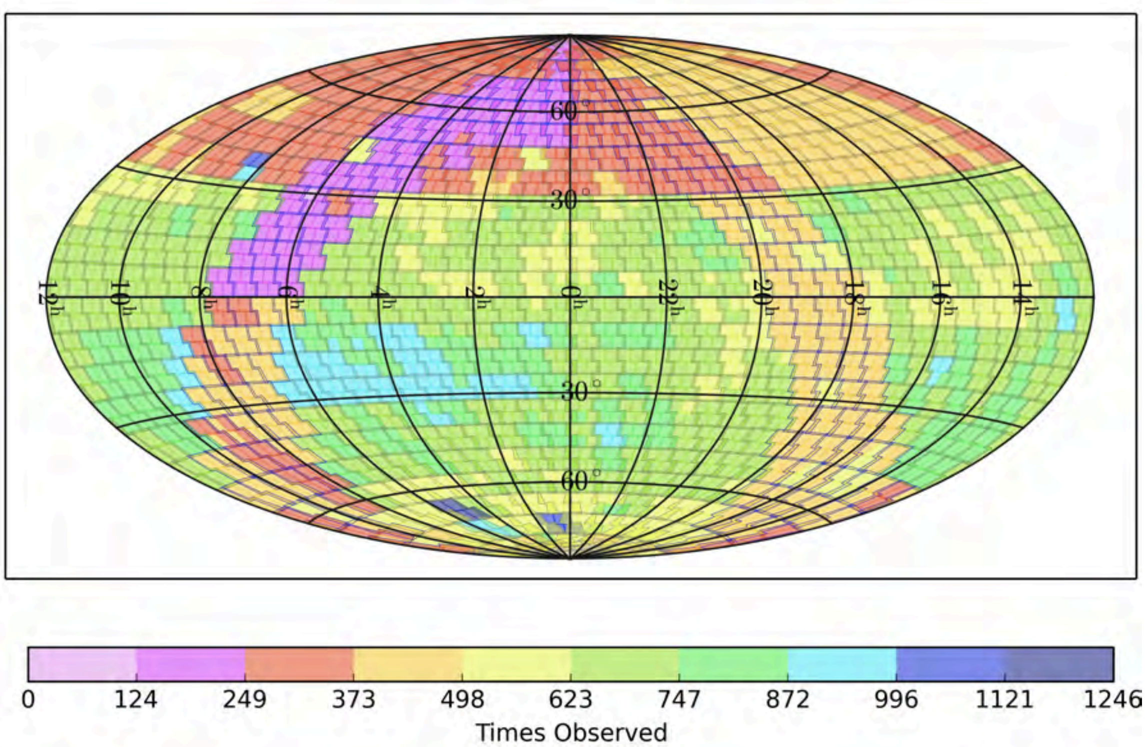
Look for statistical excess

Search for Generic Optical Counterparts

With ASAS-SN

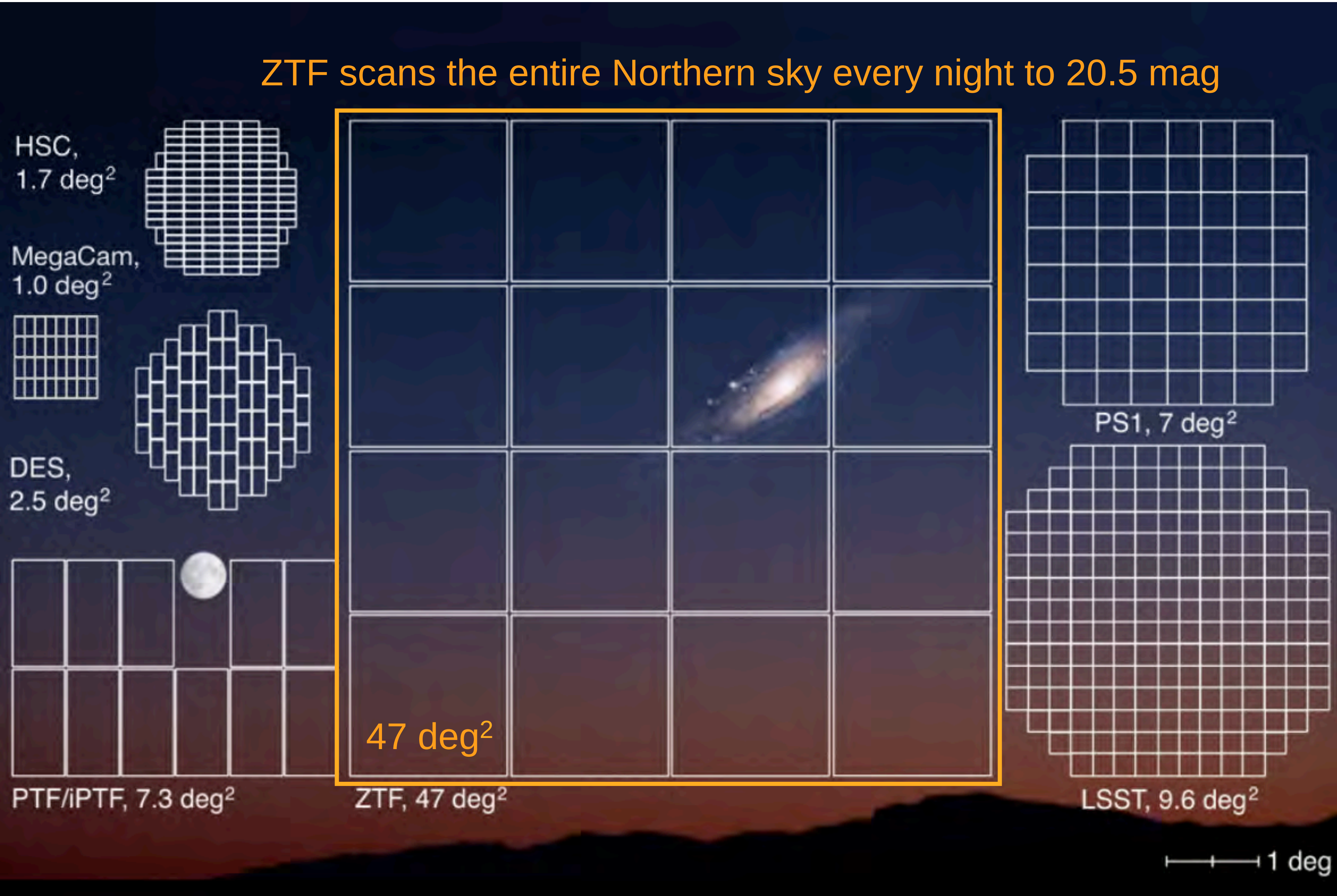
For sides in: Chile, Hawaii, Texas, South Africa

All-sky coverage to 17th magnitude

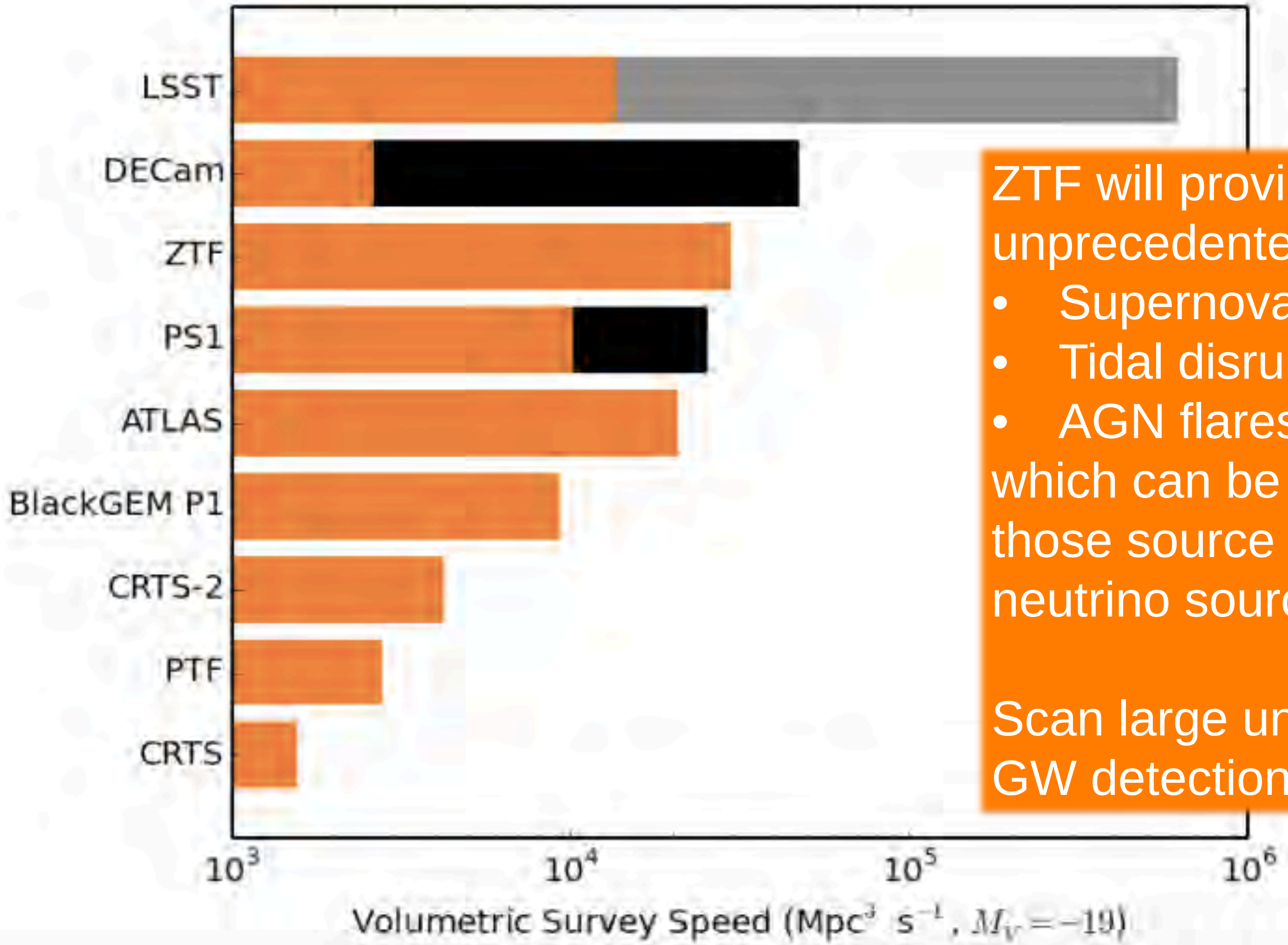


Planned cross-correlation analysis with IceCube data → generic constraints on bright optical counterparts

Zwicky Transient Facility



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



ZTF will provide an unprecedented catalog of

- Supernovae
- Tidal disruption events
- AGN flares

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

Scan large uncertainties of GW detections

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

Stacking Analysis of Various Source Types

Based on (optical) source catalogs

- Choked-jet Supernovae
- Interacting Supernovae

First paper in preparation

R. Stein

A. Stasik

Improved analysis with ZTF/ASAS-SN source in preparation

L. Rauch

- Tidal disruption events

First paper in preparation and follow-up analysis planned

R. Stein

- Blazar flares

Analysis in preparation

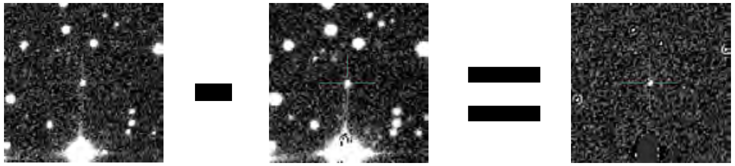
S. Garrappa

V. Paliya

AMPEL

Alert Management, Photometry and Evaluation of Light curves

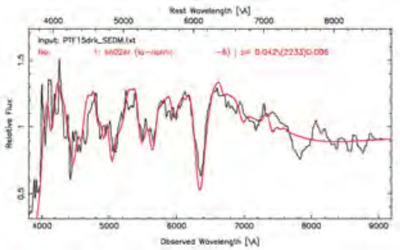
NEW - REF = SUB



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

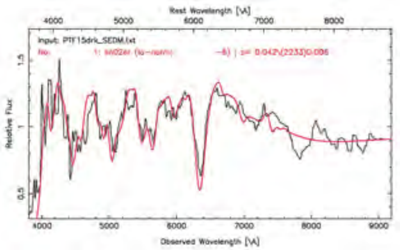
AMPEL – Towards a MM real-time center

Alert Management, Photometry and Evaluation of Light curves

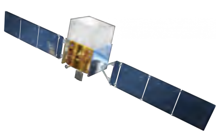
ZTF ASAS-SN LSST SKA SQUARE KILOMETRE ARRAY

alert stream

Spectroscopy



trigger



γ-ray light curve

IACT follow-up

Event selection

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

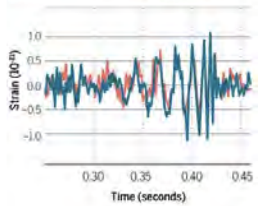
Archival analysis tools:
Reproducibility
Cross correlation of data sets

Storage

Farm

real-time ν-stream

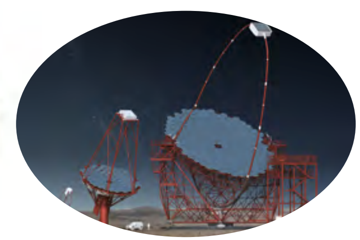
ICECUBE



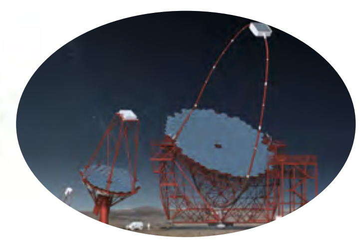
gravitational wave triggers

DESY is well positioned with its contributions to many experiments and access to large computing facilities

Summary

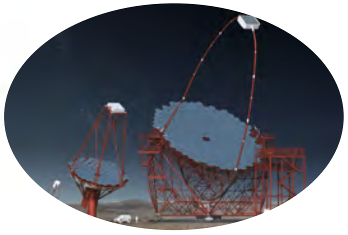


Summary



unique messengers from the
high-energy Universe

Summary



Neutrinos can reveal the sources of high-energy cosmic rays

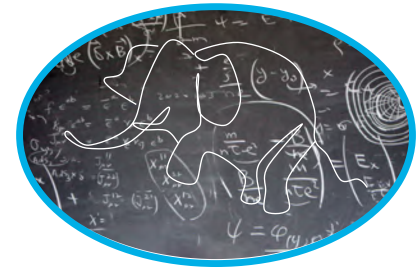
Summary

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.