The multi-wavelength and multi-messenger context II

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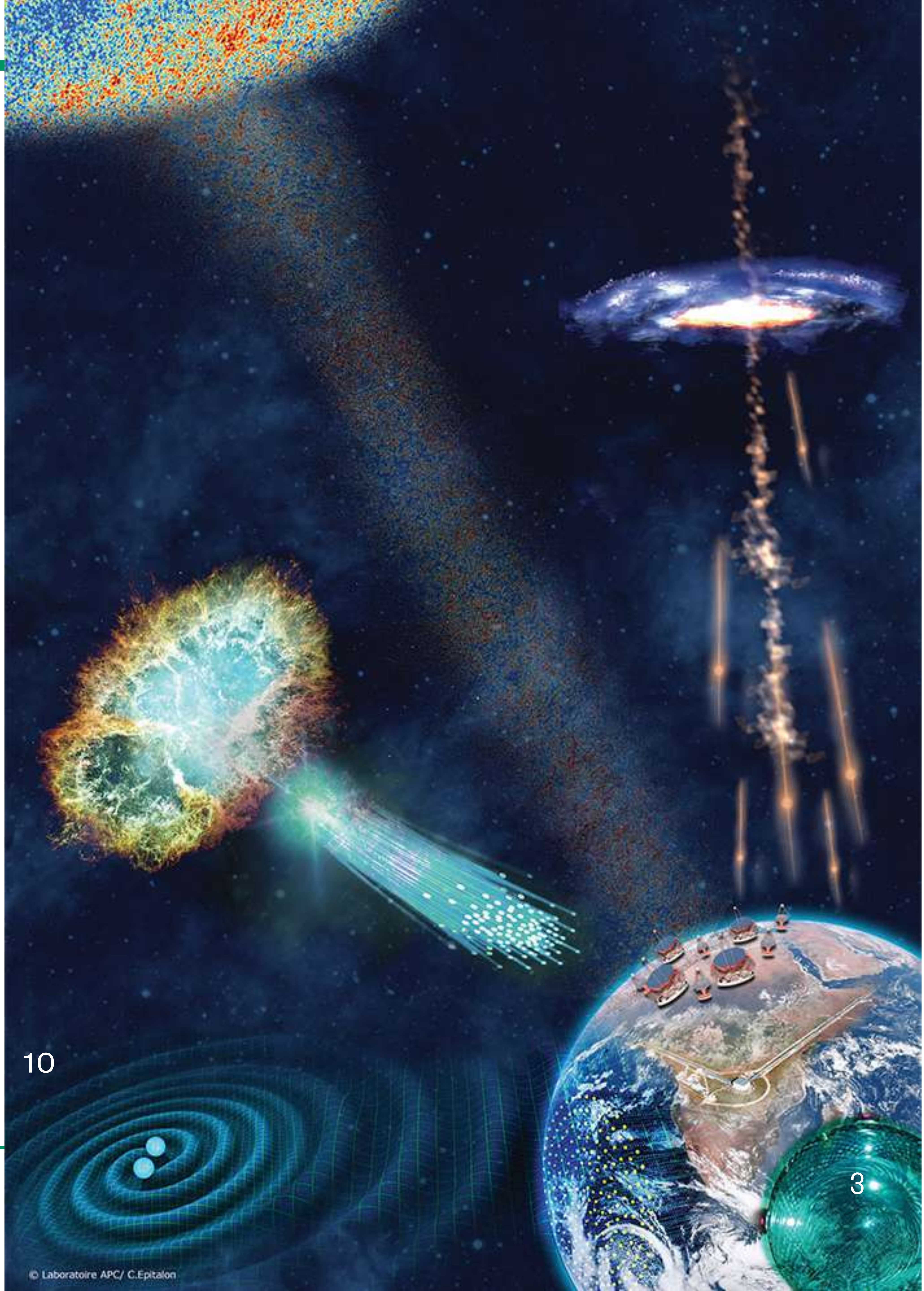
with thanks to **Marcos Santander**

ICTP-SAIFR Advanced School 2023

- The Neutrino - Gamma connection
- A primer on neutrino astronomy
- Overview of recent results
- The MM context of neutrinos
- CTA coordination activities

The neutrino - gamma connection



Connecting the puzzle

All messengers are connected and relate back to the same sources: logic behind the multi-messenger astrophysics

p^+, He, Fe,.... $\xrightarrow{\text{Interactions with matter and photon-fields}}$ **$\pi^{+/-}$** $\longrightarrow$ **$\mu^{+/-}$ ν_μ**

π^0 $\rightarrow$ **$\gamma\gamma$**

$\mu^{+/-}$ $\rightarrow$ **$e^{+/-}$** **ν_e ν_μ**

Intense radiative losses => hadronic hard X-rays or soft-gamma signature

p^+,e^- $\rightarrow$ **MWL**

Only charged particle are accelerated in EM fields

Synchrotron in B-fields, inverse-Compton… p^+, inefficient

Easy detection

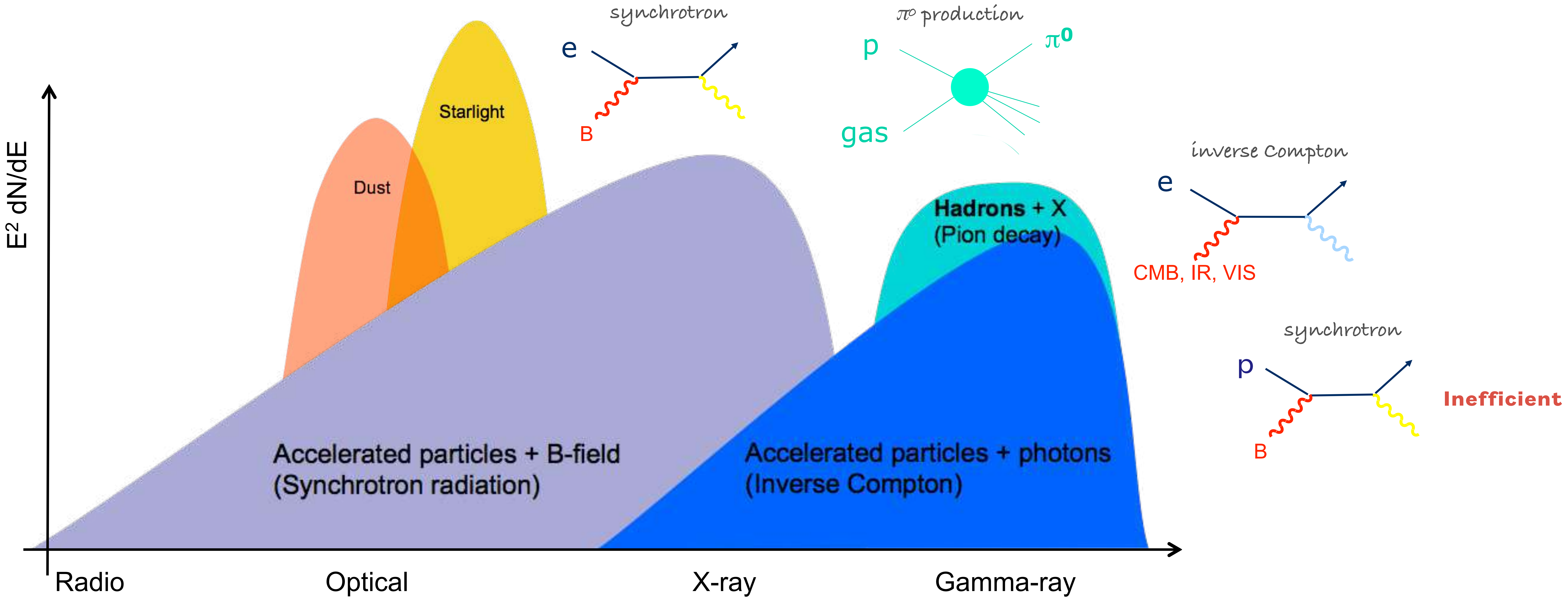
Difficult detection

MM Astronomy : Directionality information preserved, but strong backgrounds.

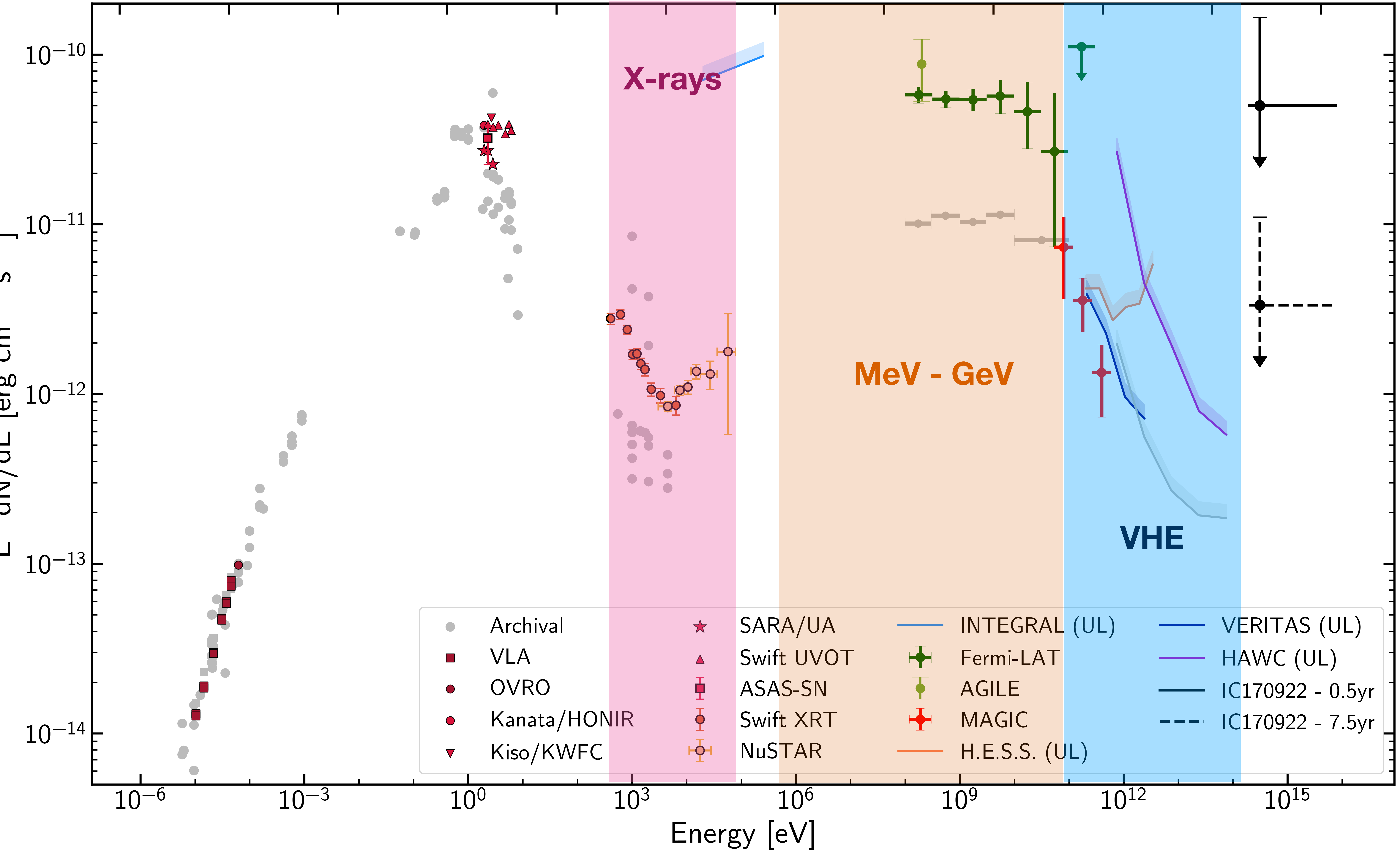
Gamma-rays are the cornerstone of multi-messenger astrophysics

© adapted from a slide by Johannes Knapp

Anatomy of a relativistic astrophysical source



© plot by Christian Stegmann, DESY, MG XIV Meeting 2015 (modified)



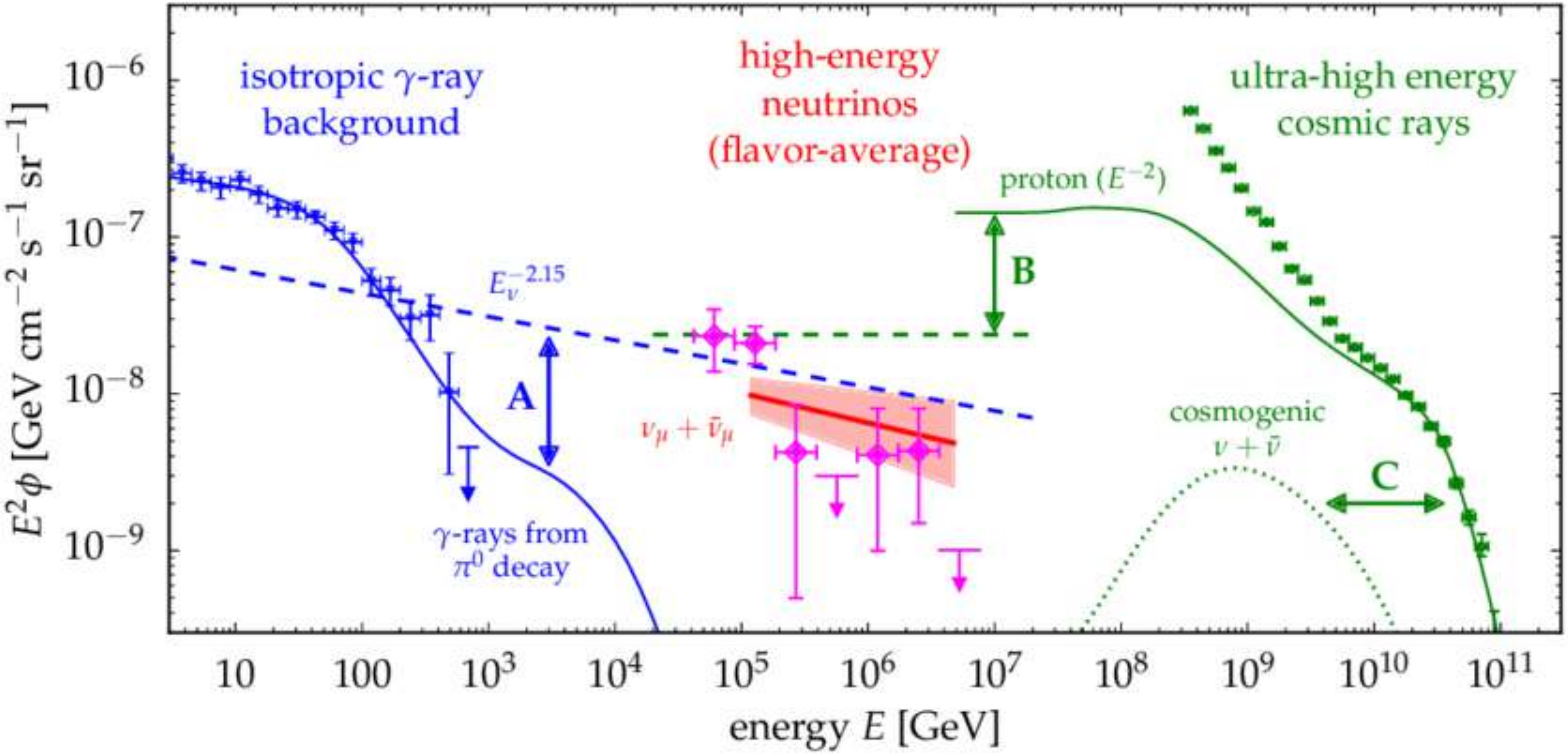
Towards the first MM SED

MWL / MM spectral energy distribution of TXS 0506+056

(IceCube, Fermi-LAT, MAGIC et al. Science 2018)

Connecting the puzzle

ASTRO 2020 - High-energy Cosmic Neutrinos - Science White Paper



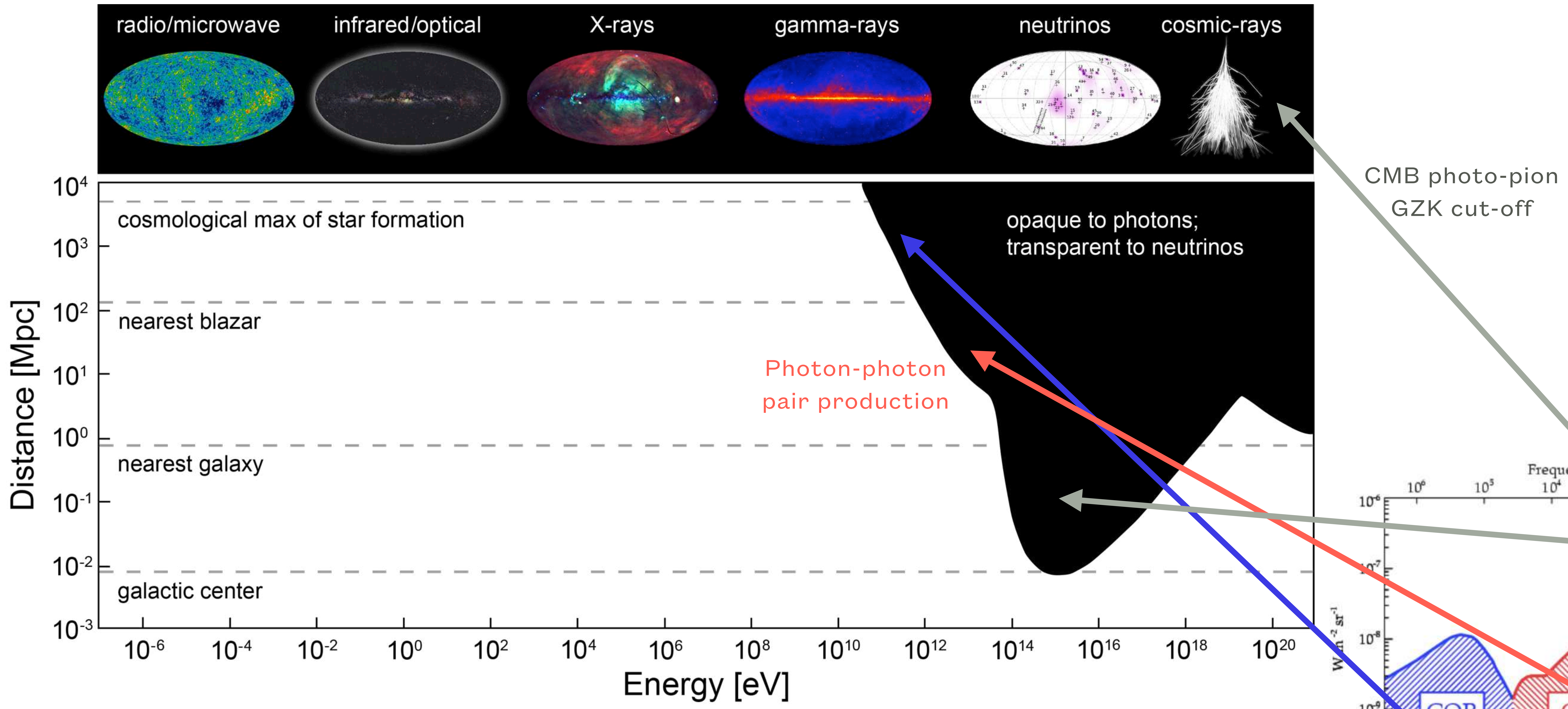
Neutrino limit A - π-production in CR interactions suggest potential links between neutrino and TeV-PeV gamma-ray sources. V

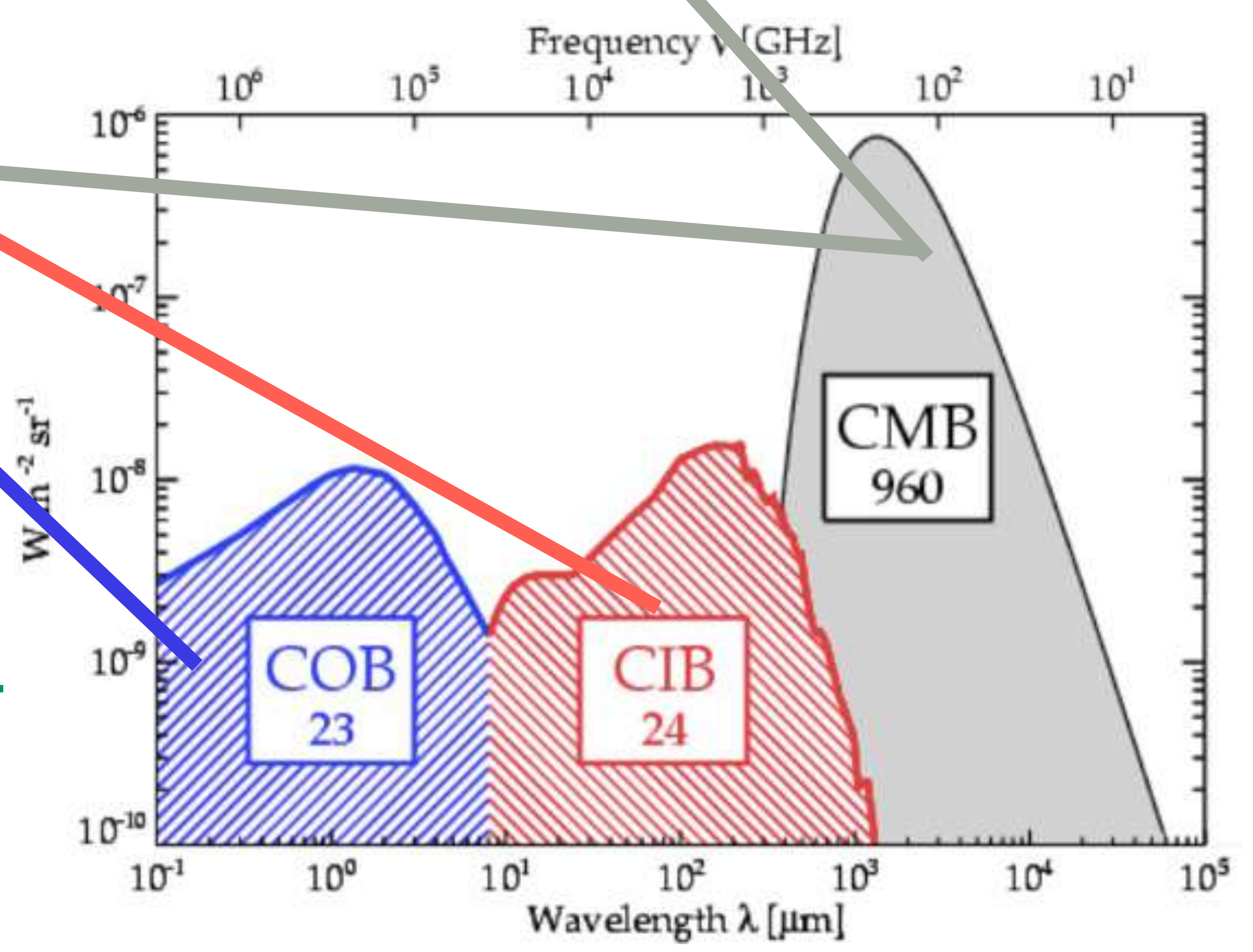
Neutrino limit B - If neutrino fluxes are related to UHECR, UHE neutrino limits could be higher, from large “cosmic-ray reservoirs"

Cosmogenic neutrinos - Attenuation of CRs by the CMB (GZK cut-off) supress CRs above EeV and if detected would impose important constraints on UHECR physics.

Astroparticle Physics

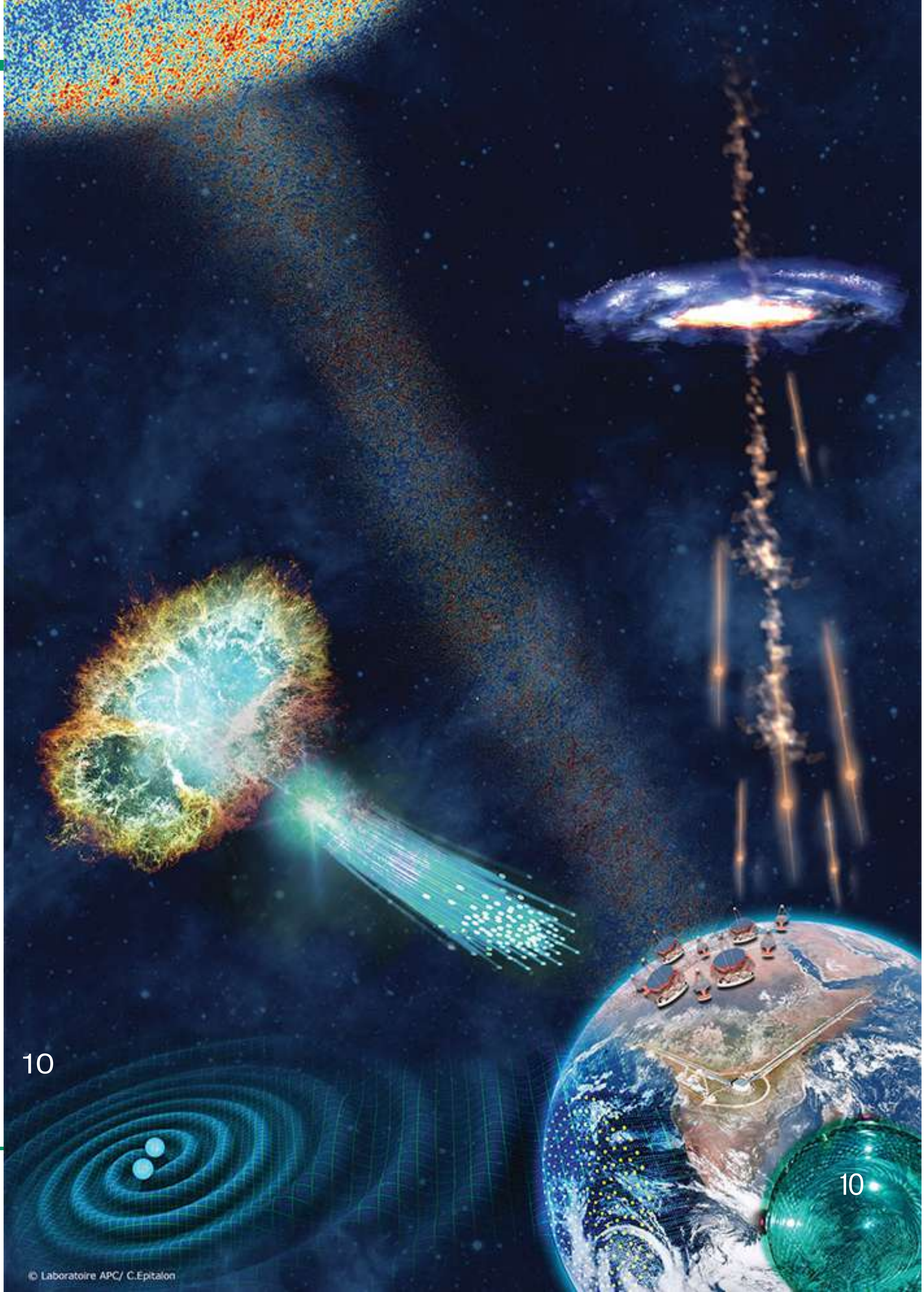
Neutrinos : probe of deeper horizon, denser environments





A primer on neutrino astronomy

ULISSES BARRES DE ALMEIDA - ICTP-SAIFR - MARCH 2023



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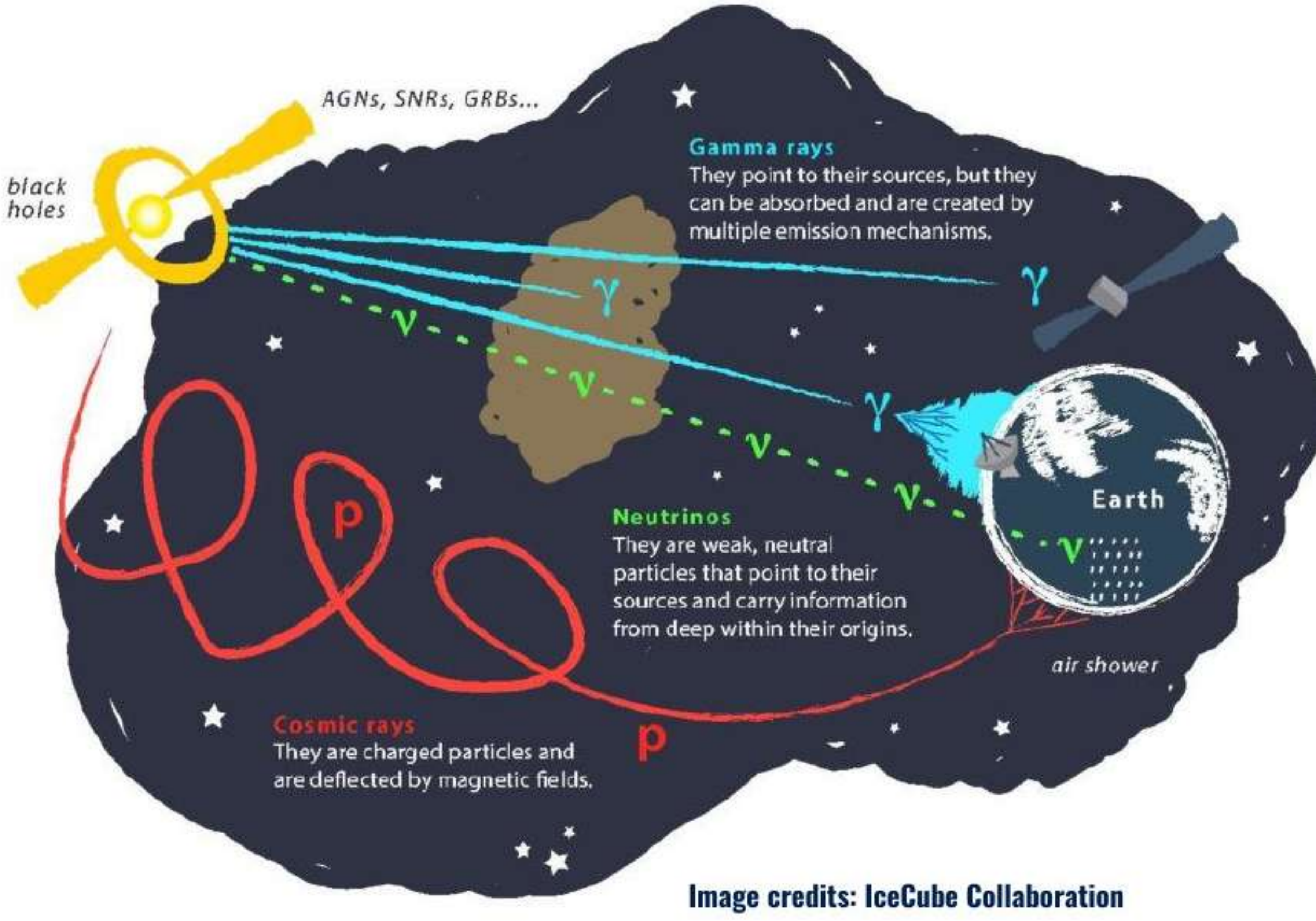
The MM context of neutrinos

Neutrinos interact via weak interaction (rare, hard to detect). The basic reactions are:

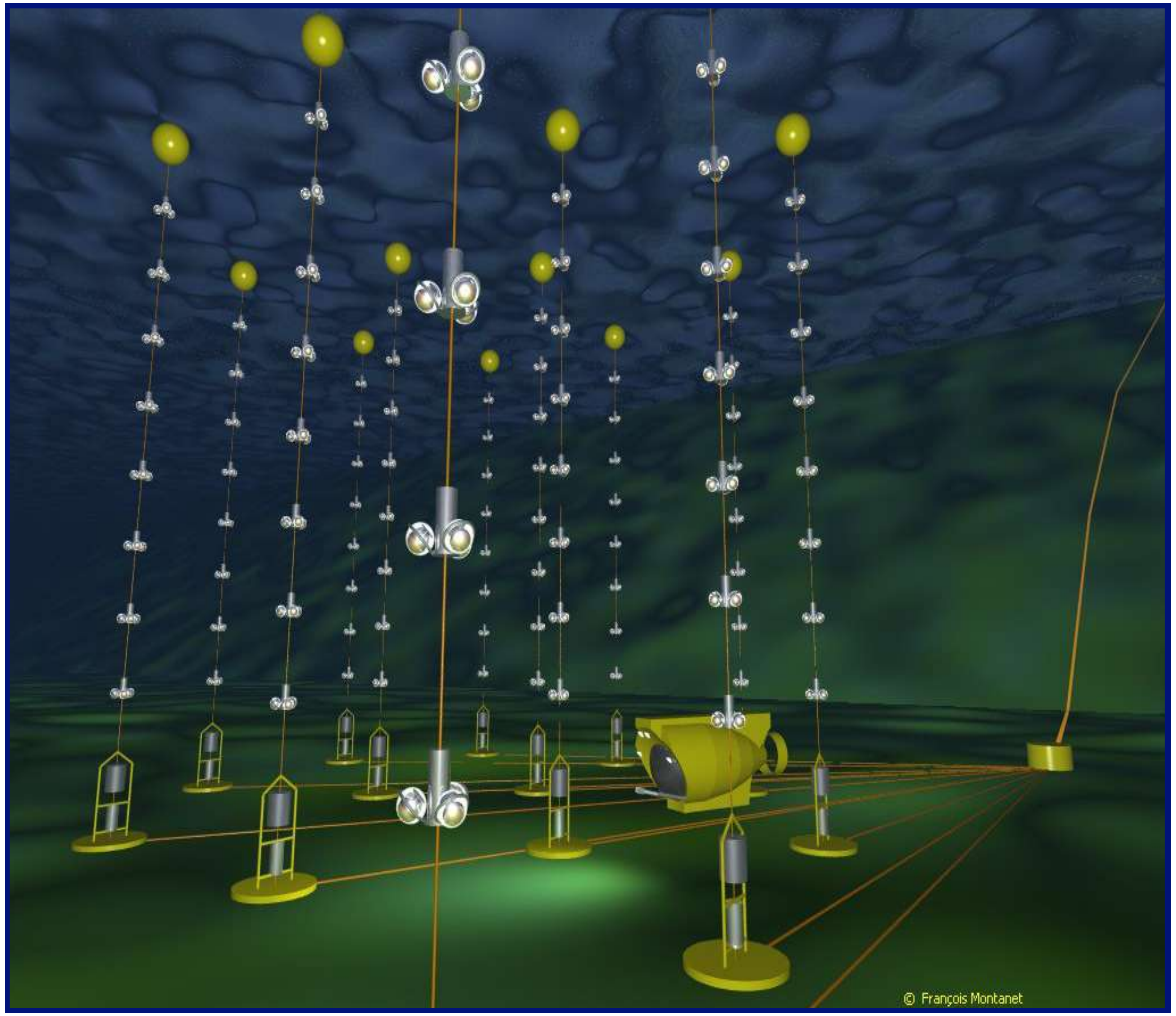
- $n \longrightarrow p^+ + e^- + \nu_e$ typically in nuclear reactors where neutron-rich fragments from Uranium fission stabilize by neutron decay
- $p^+ \longrightarrow n + e^+ + \nu_e$ typically for Solar Neutrinos where 4 protons fuse to produce ^4He (2p, 2n), i.e. 2 p converted into 2 n
- $p^+ + e^- \longrightarrow n + \nu_e$ typically in Supernovae, where protons and electrons fuse to produce neutrons.



But VHE (IceCube) neutrinos (also the case of accelerator neutrinos) originate in decay process from mesons produced in hadronic interactions:

- $\pi^+ \longrightarrow \mu^+ + \nu_\mu$ or $\pi^- \longrightarrow \mu^- + \nu_\mu$ from pion decay.
- $\mu^+ \longrightarrow e^- + \nu_\mu + \nu_e$ or $\mu^- \longrightarrow e^- + \nu_e + \nu_\mu$ from muon decay.

Astrophysics with TeV neutrinos



The technique is based on the use of km³ volumes of water or ice to detect neutrino interaction signals

Effective area : despite gigantic volumes of detectors, effective areas are low due to difficulty of detection (between 10-100 m^2 in the range 10-100 TeV)

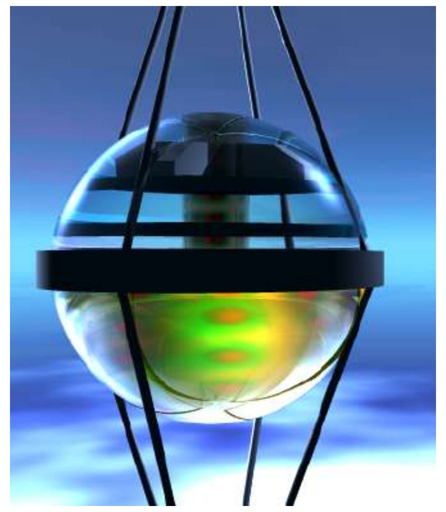
Cf. Gamma-ray detectors : In space (Fermi-LAT) effective areas are relatively low, 1 m^2 @ 100 GeV, but fluxes are high; whereas in ground-based observatories effective areas reach 10^5 m^2 in the TeV range (and compensate for the lower fluxes).

In principle, efective areas are sufficient to detect several events from a "1 Crab" TeV source, if emission is hadronic… (but beware of heavily absorbed sources, e.g. in binaries where intrinsic luminosities could be up to 100x brighter).

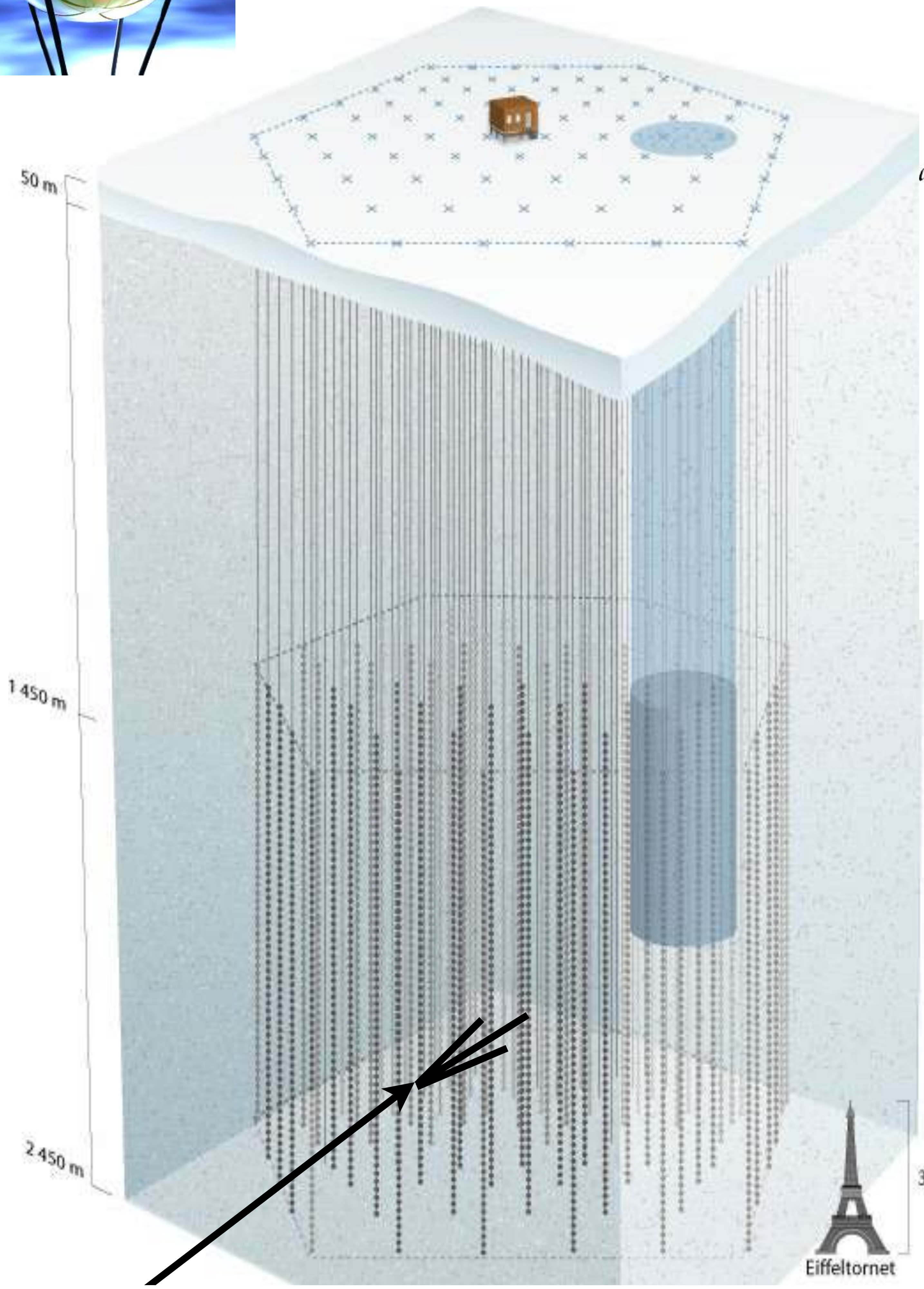
km³ detectors

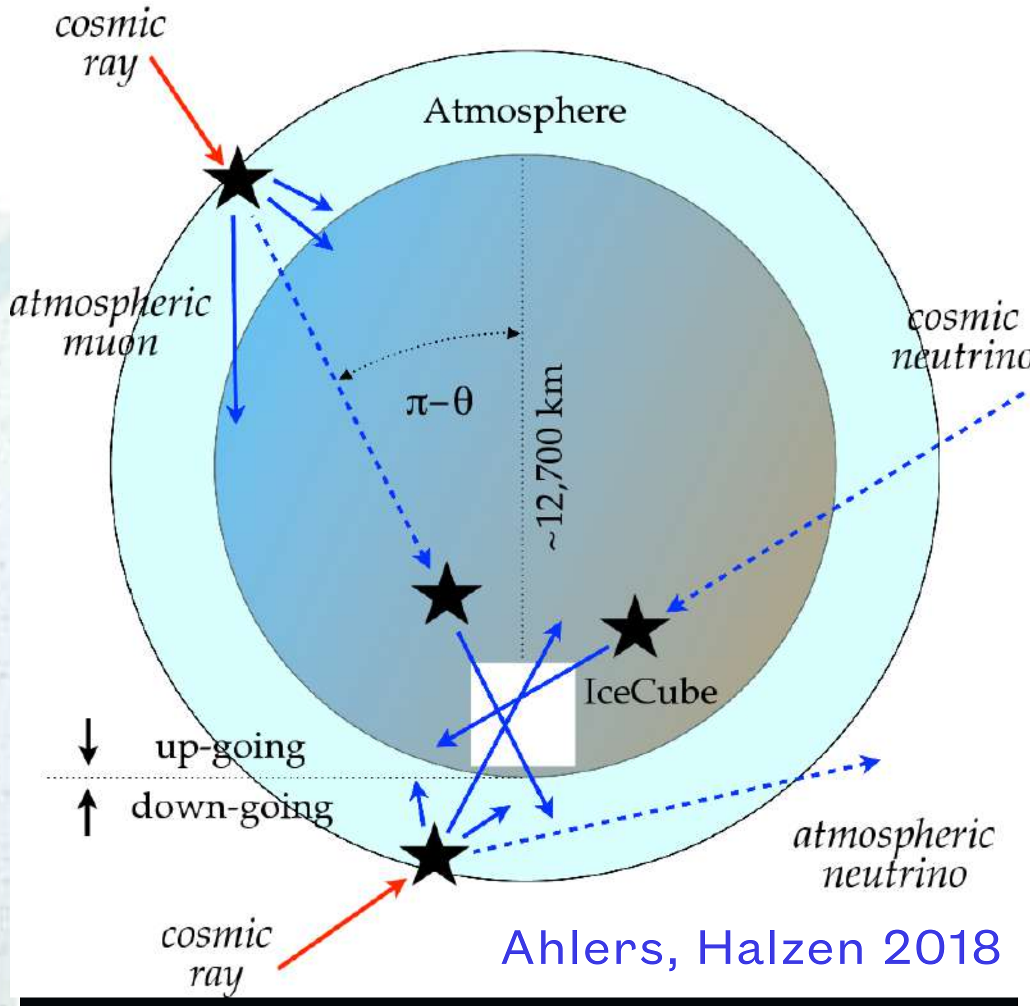
Antares & KM3Net: in the Mediterranean Sea (1999 -)
Amanda & IceCube: in the South Pole (1995 -)

2010 - 1 km^3! Currently in activity

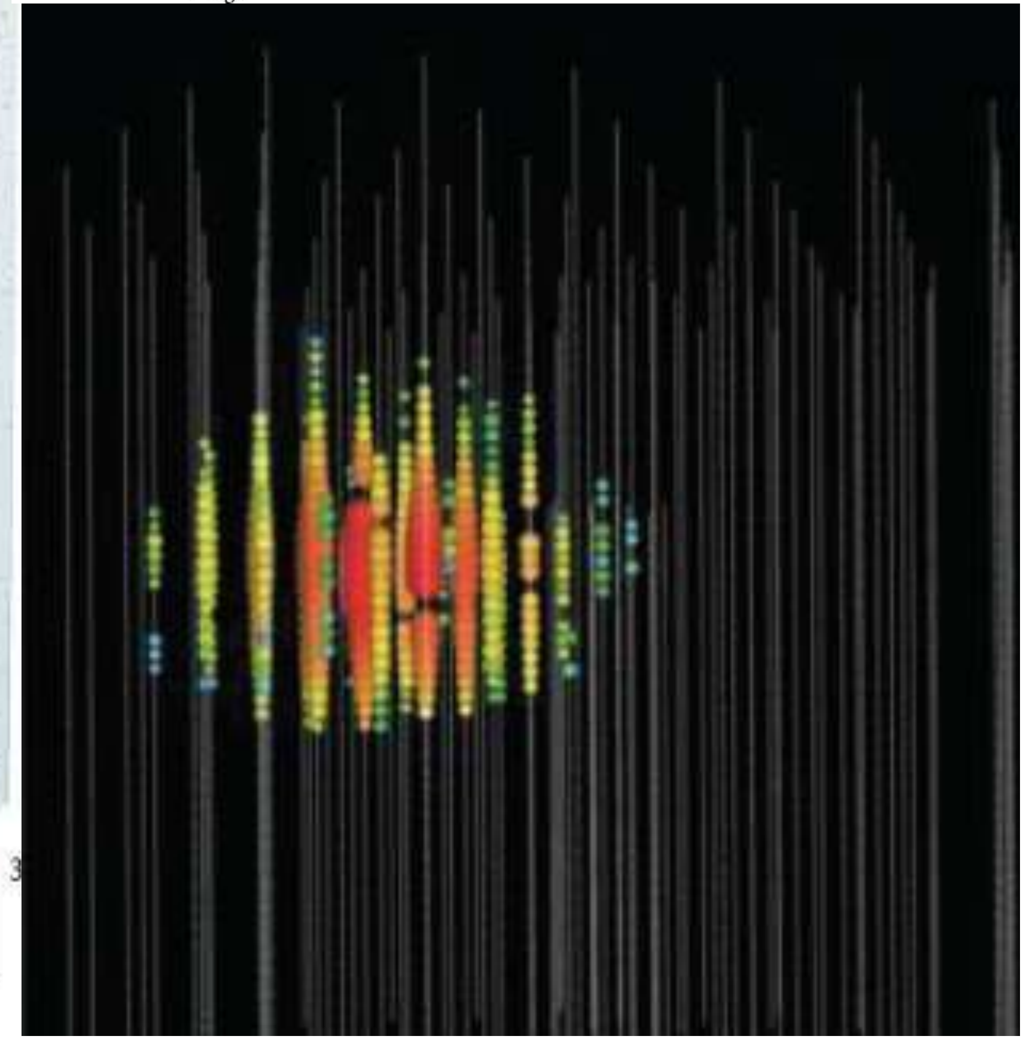


80 lines
60 optical modules / each





Ahlers, Halzen 2018



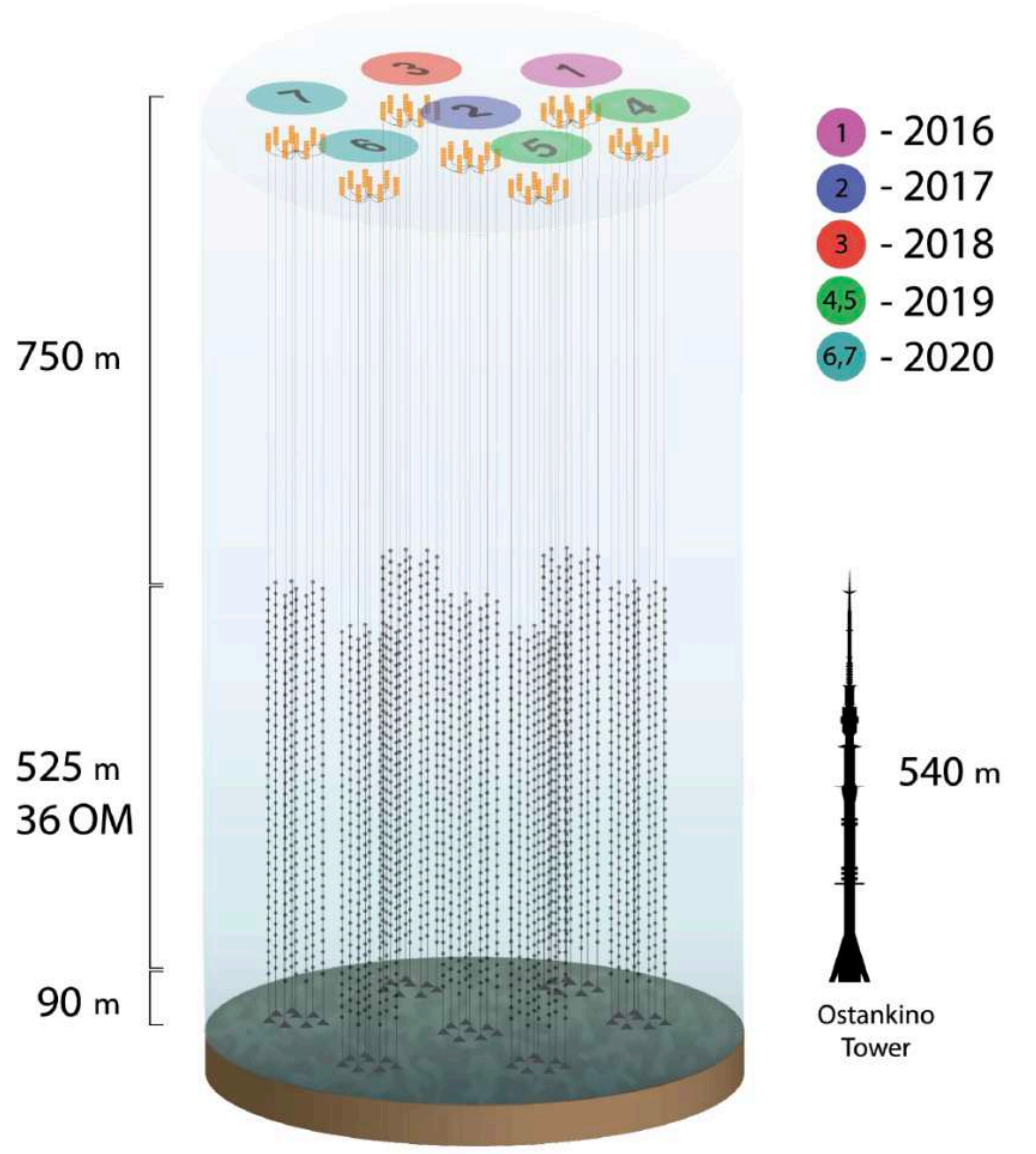
1 km^3 5200 sensors, ~2 km deep in the ice

Astrophysical VHE neutrinos are detected after traversing the Earth ($E \approx 10^{11}$–10^{15} eV)

How to distinguish signal astrophysical / background shower atmospheric neutrinos? Down vs. up-going

At energies $> 10^{15}$ eV astrophysical neutrinos dominate the flux…

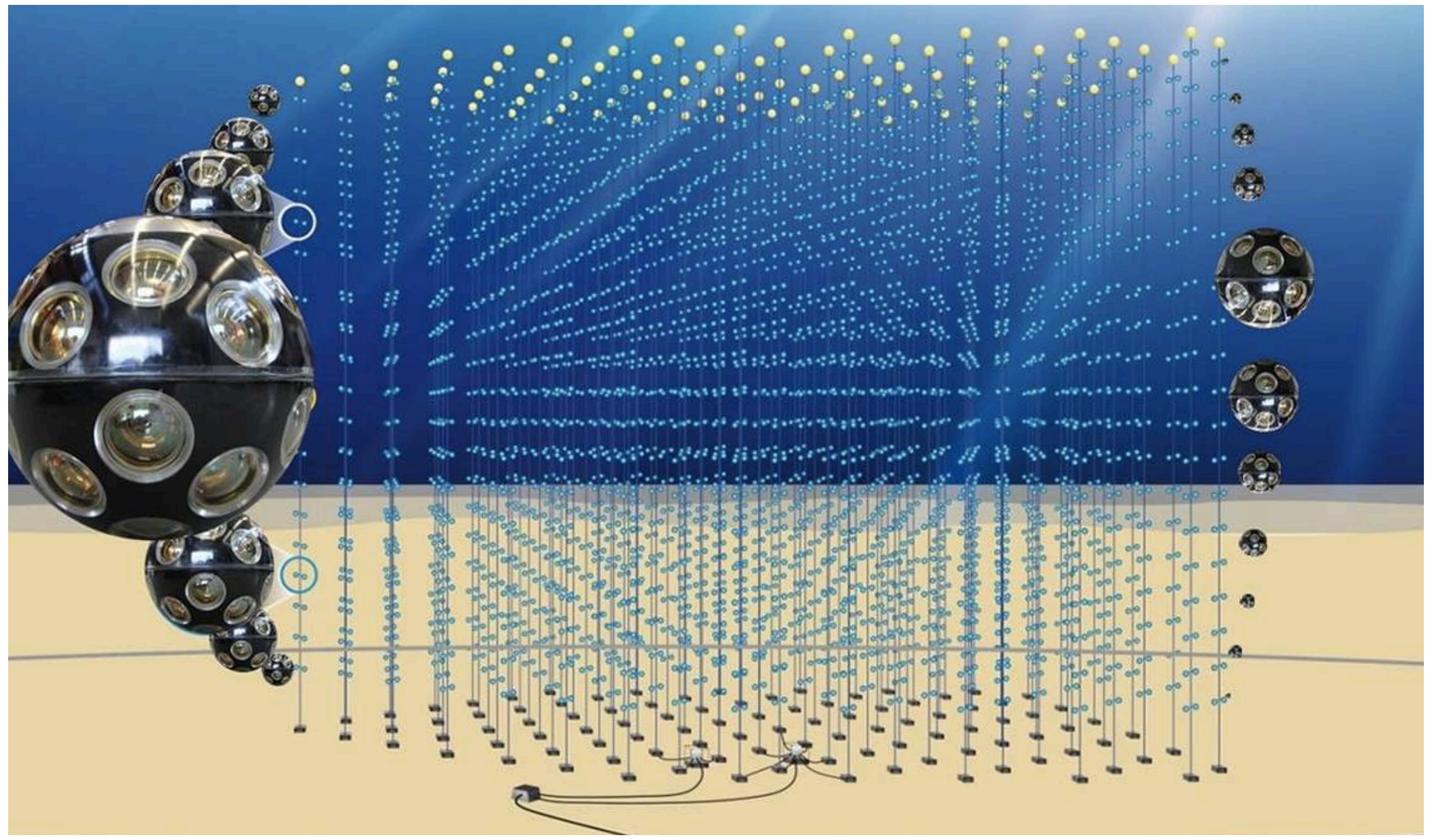
The next Generation



Baikal GVD

Km3-detector with 10,000 sensors.

In construction, Siberia, Lake Baikal

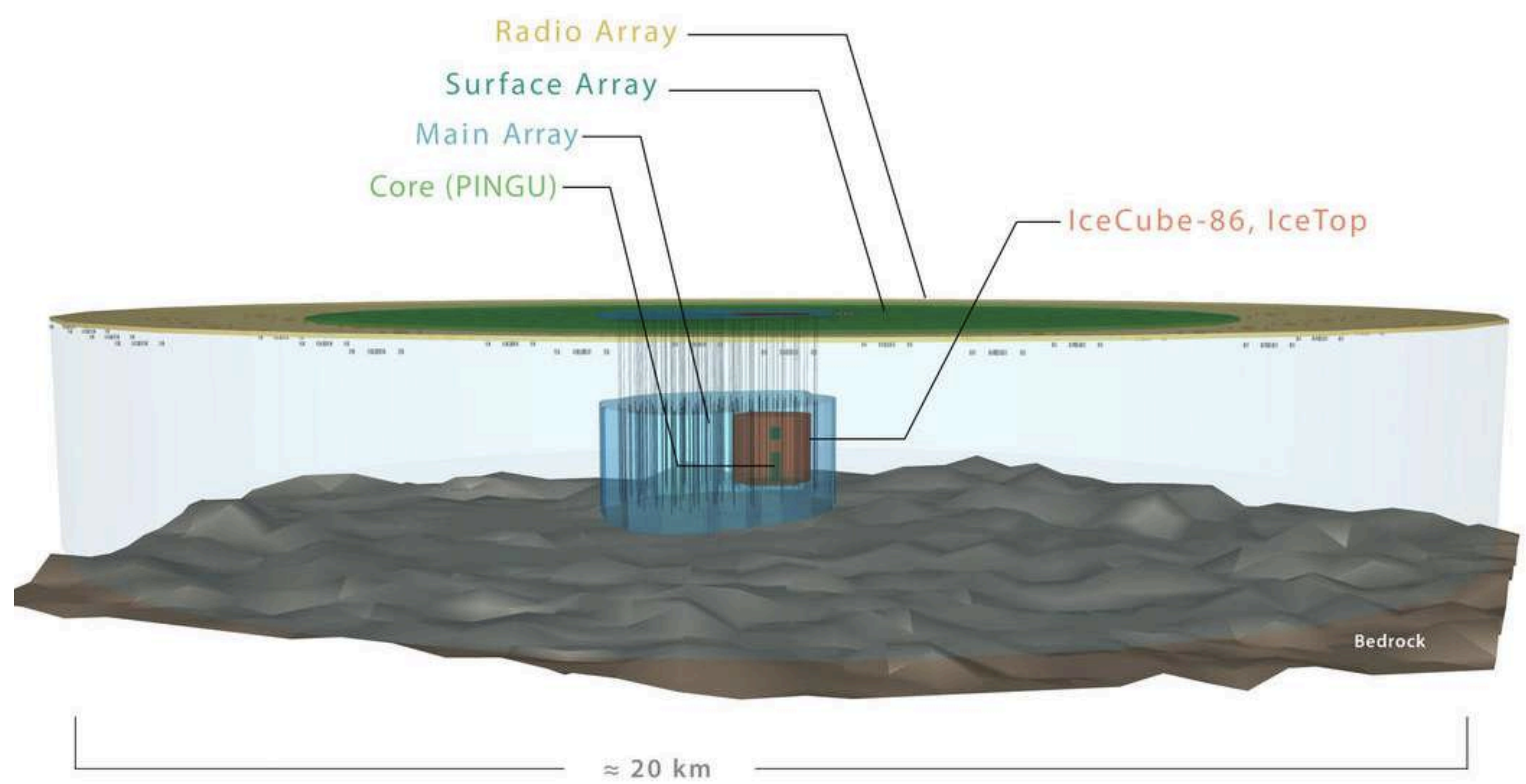


Km3Net

km3-detector with 4,000 sensors

0.1º angular resolution (better than ice)

IceCube GEN-2



Approaching 10 km3 in volume

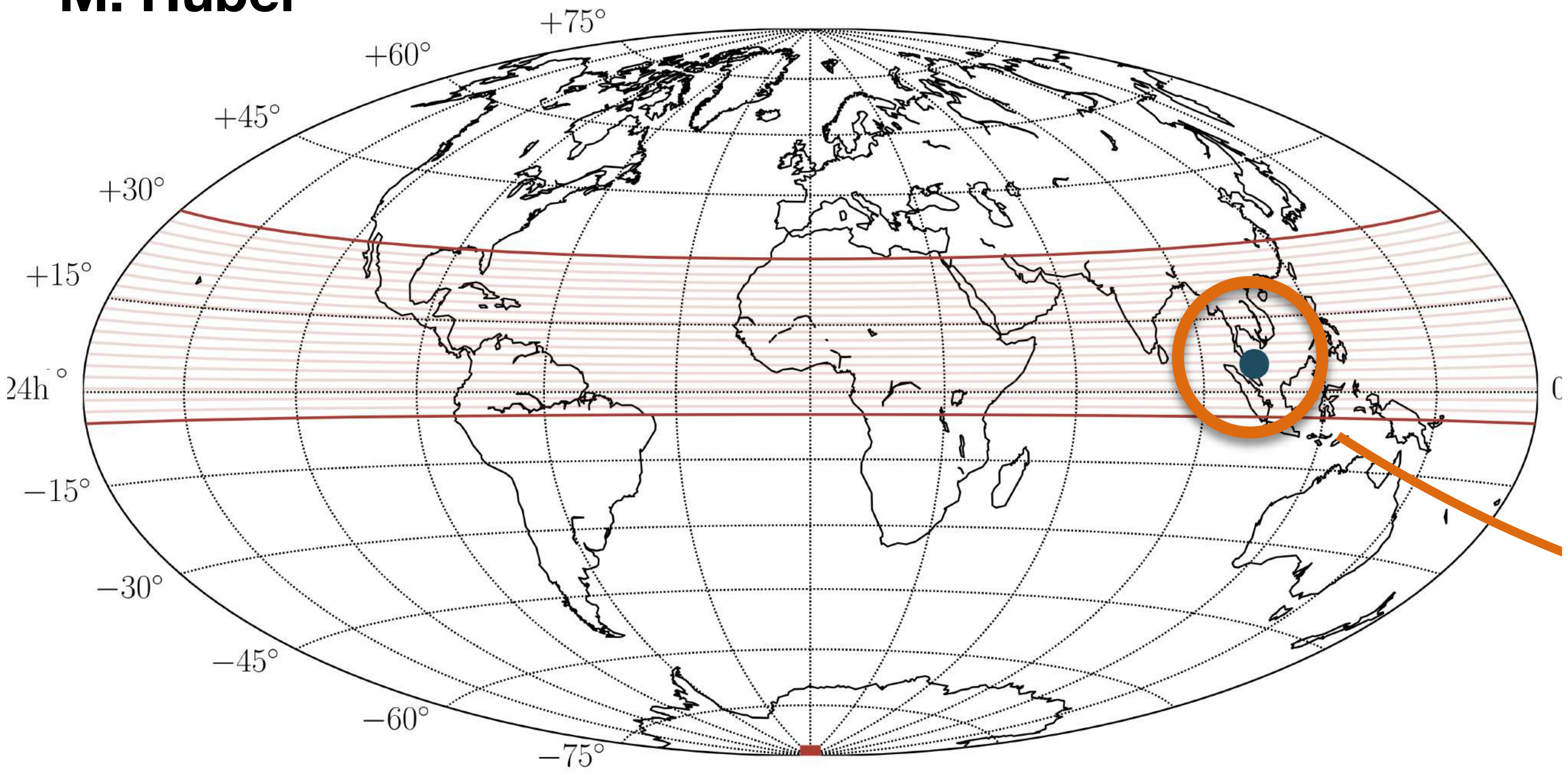
=> 5x sensitivity improvement

0.2º angular resolution

<u>Deployment ongoing</u>

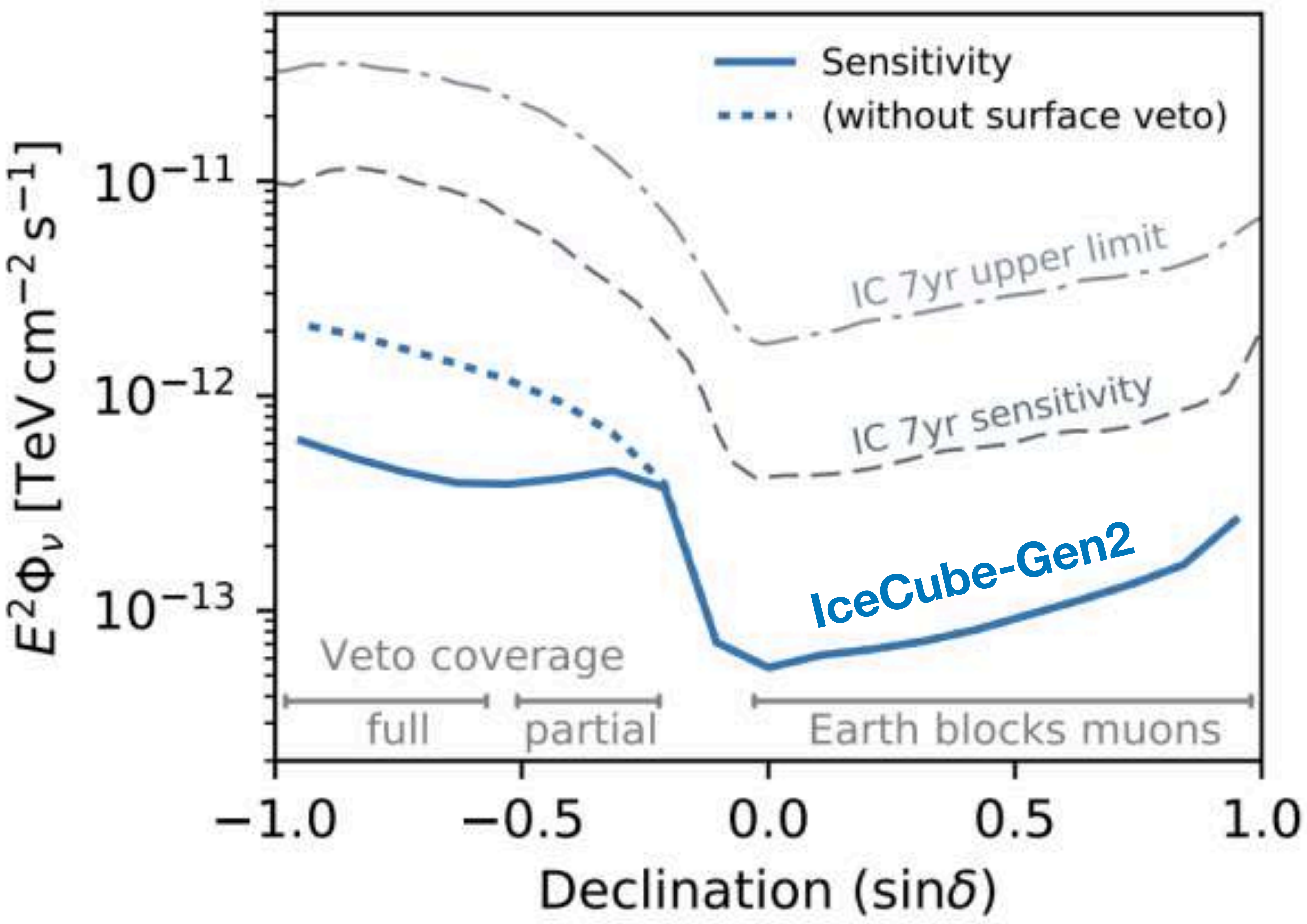
Future global network of neutrino observatories

M. Huber



~30% sky coverage from IceCube

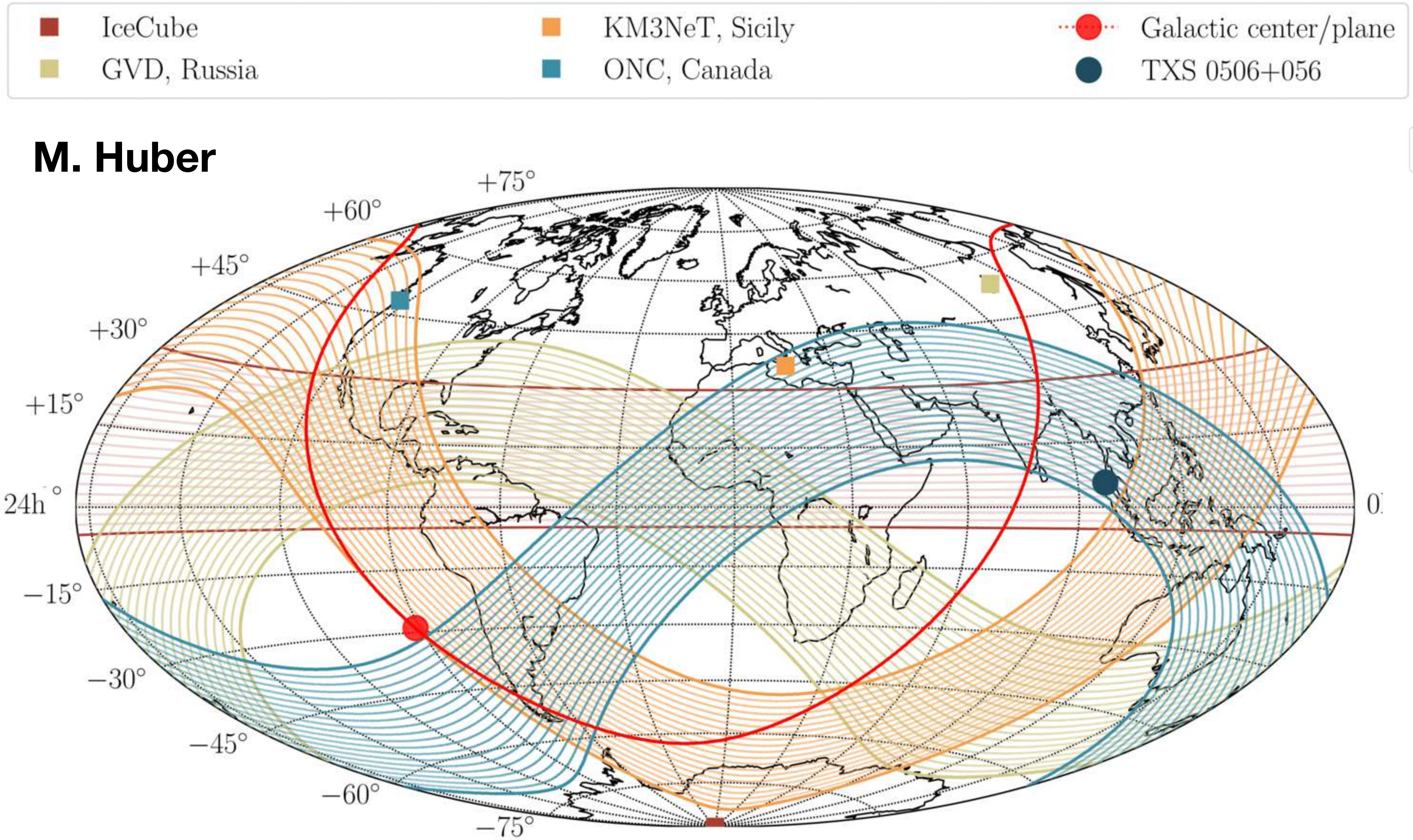
IceCube-Gen2 arXiv/2008.04323

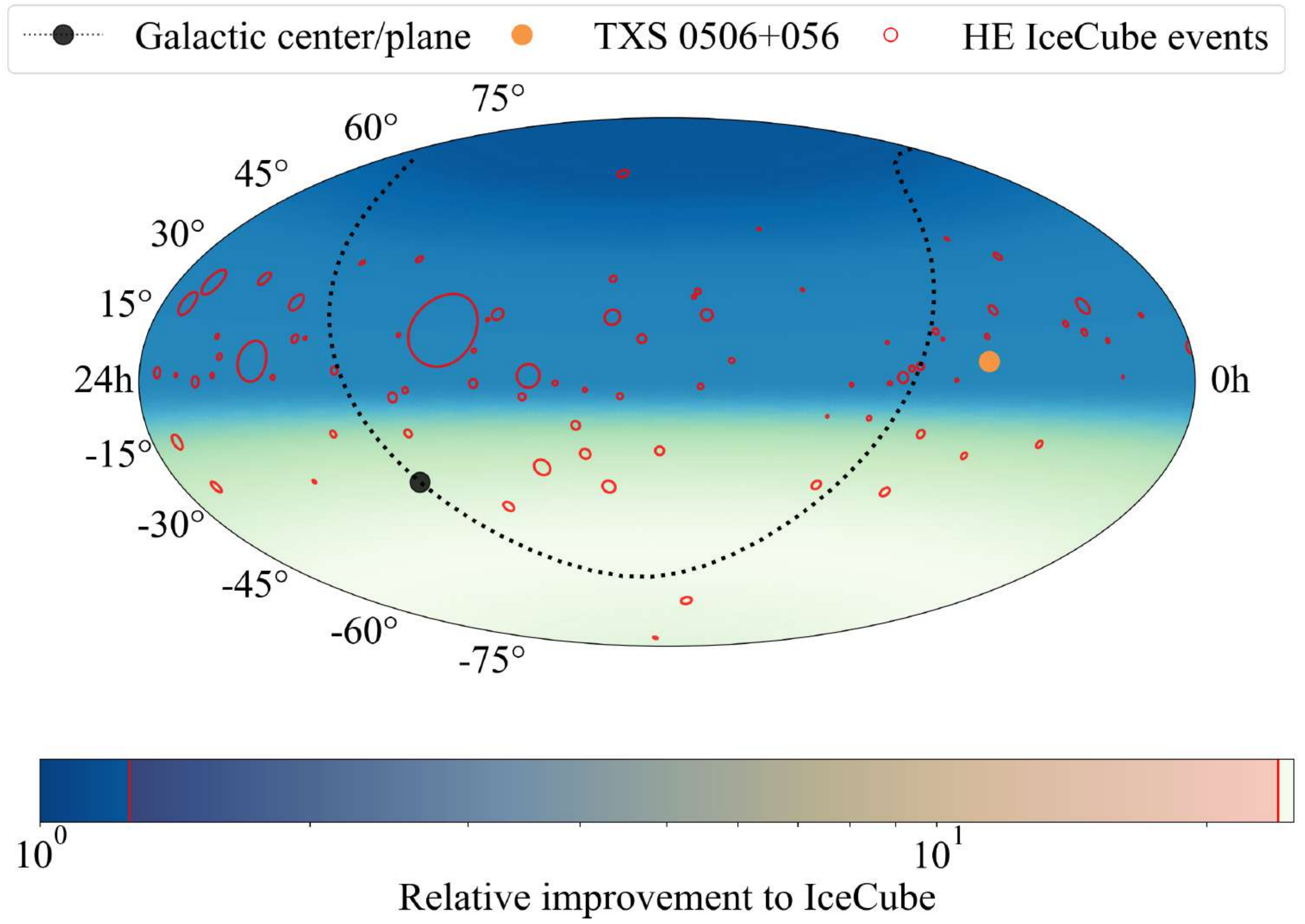


- IceCube is most sensitive near the celestial equator.

Future global network of neutrino observatories

M. Huber

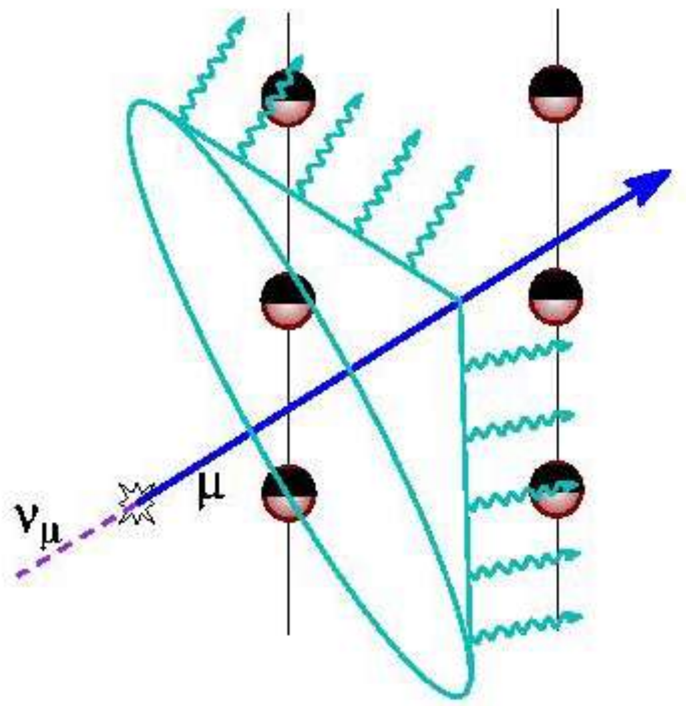




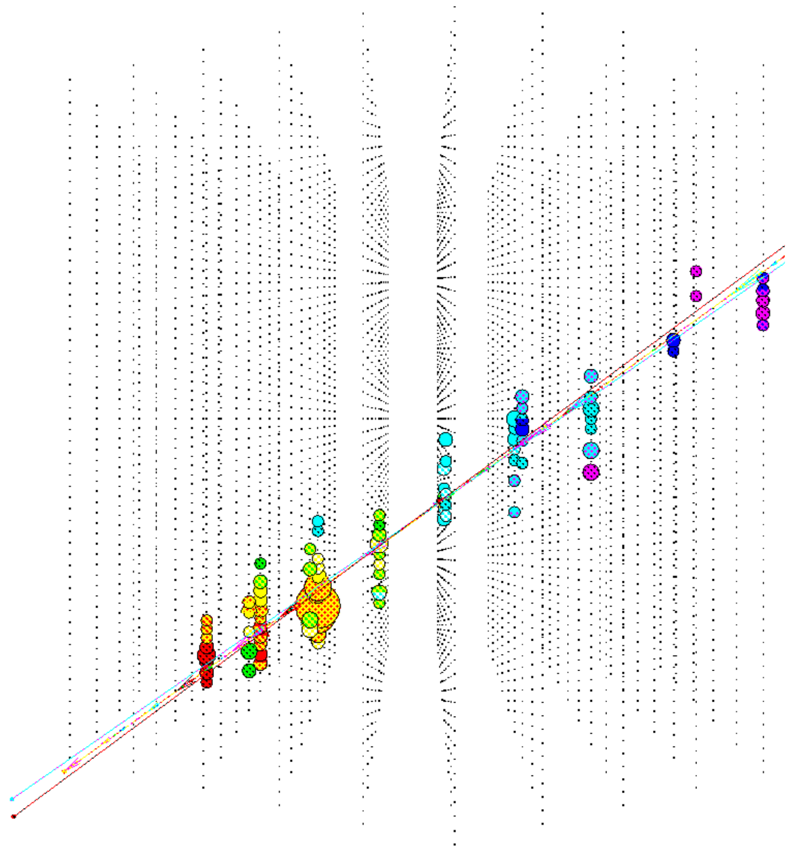
Sensitive to spectral index

Detection Principle

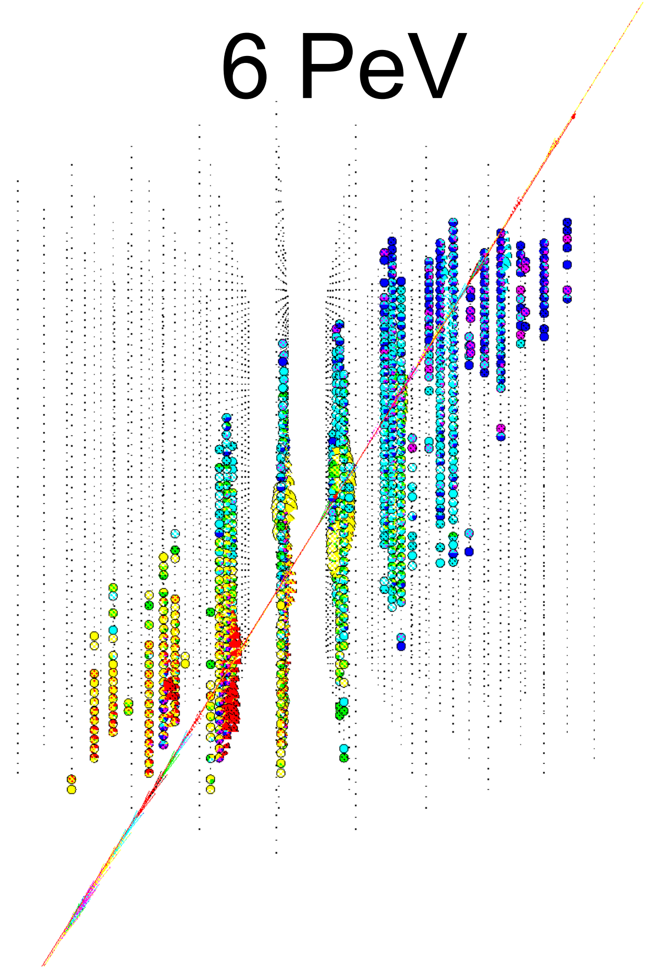
signature of ν_μ



10 TeV



6 PeV

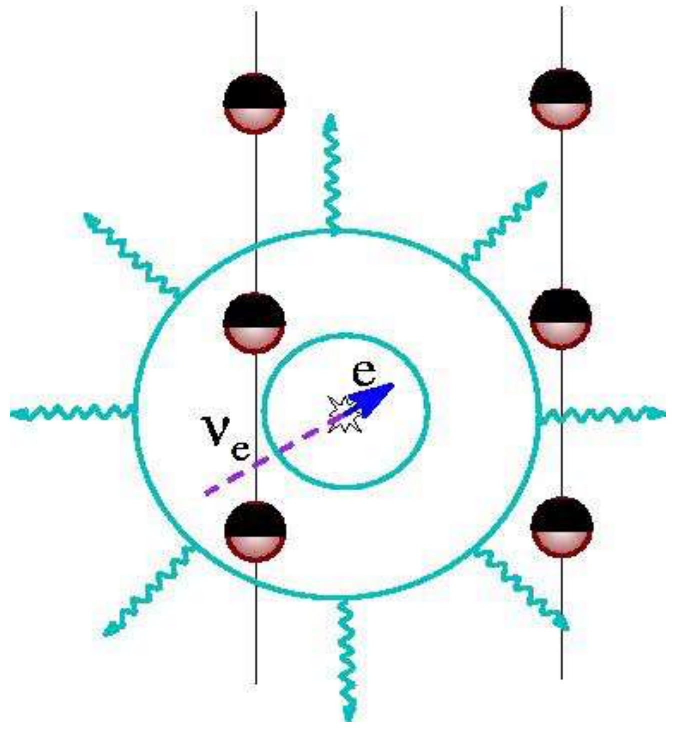


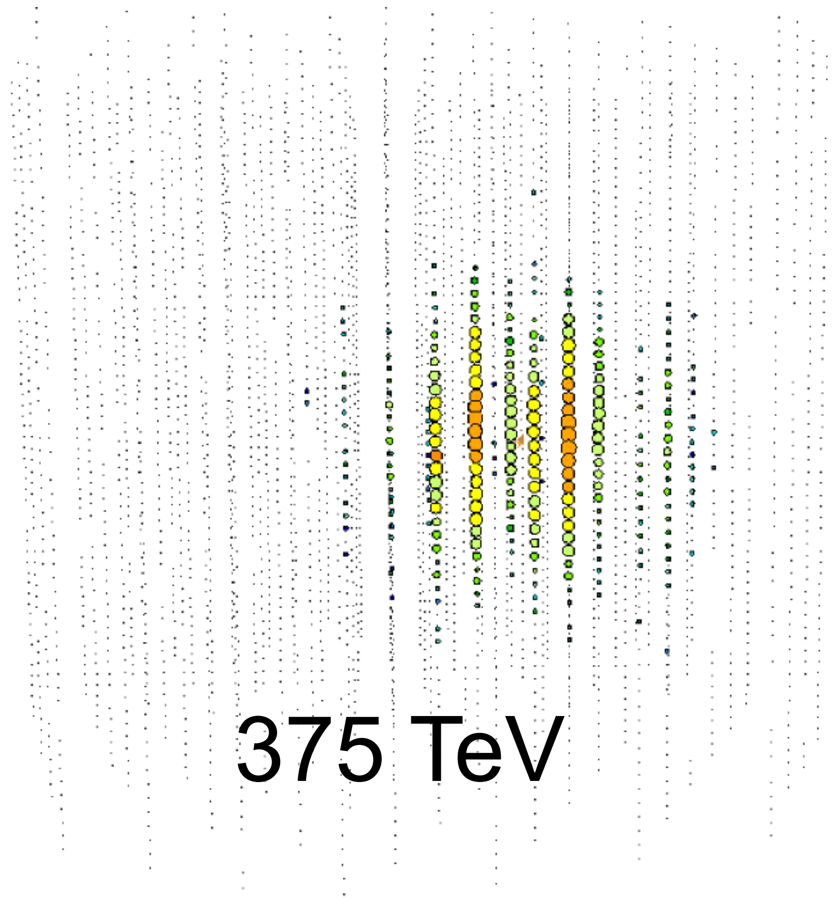
Neutrinos create charged particles in interactions, which then produce the Cherenkov radiation detected.

Muon-tracks

better type of event for astronomy, with good localization (< 1°)

most common type of event, thanks to the long trajectories which cross the detector.





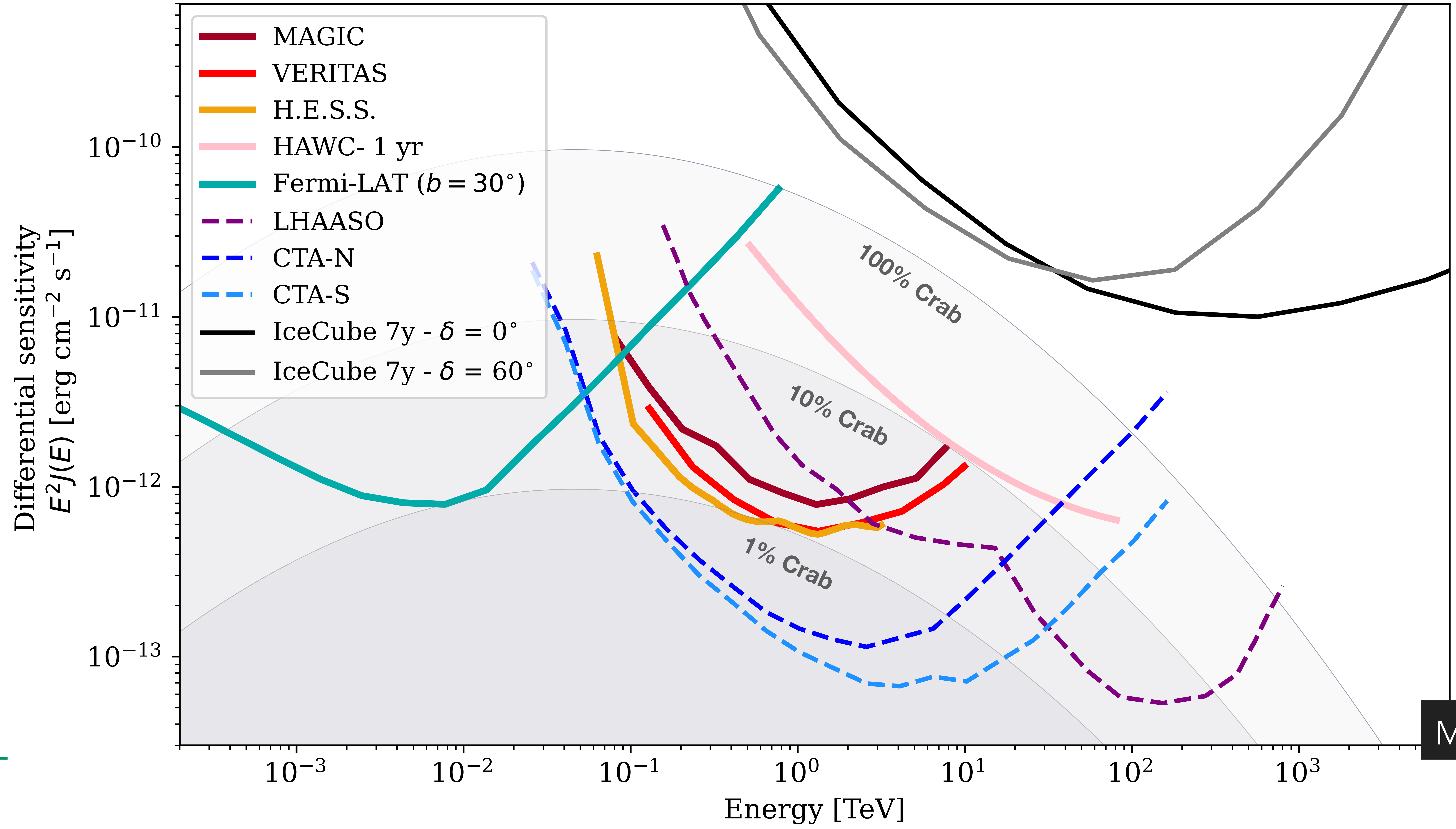
signature of ν_e

Cascade events

results from electron and tau neutrino interactions

Event has poor localization but good energy resolution and lower background

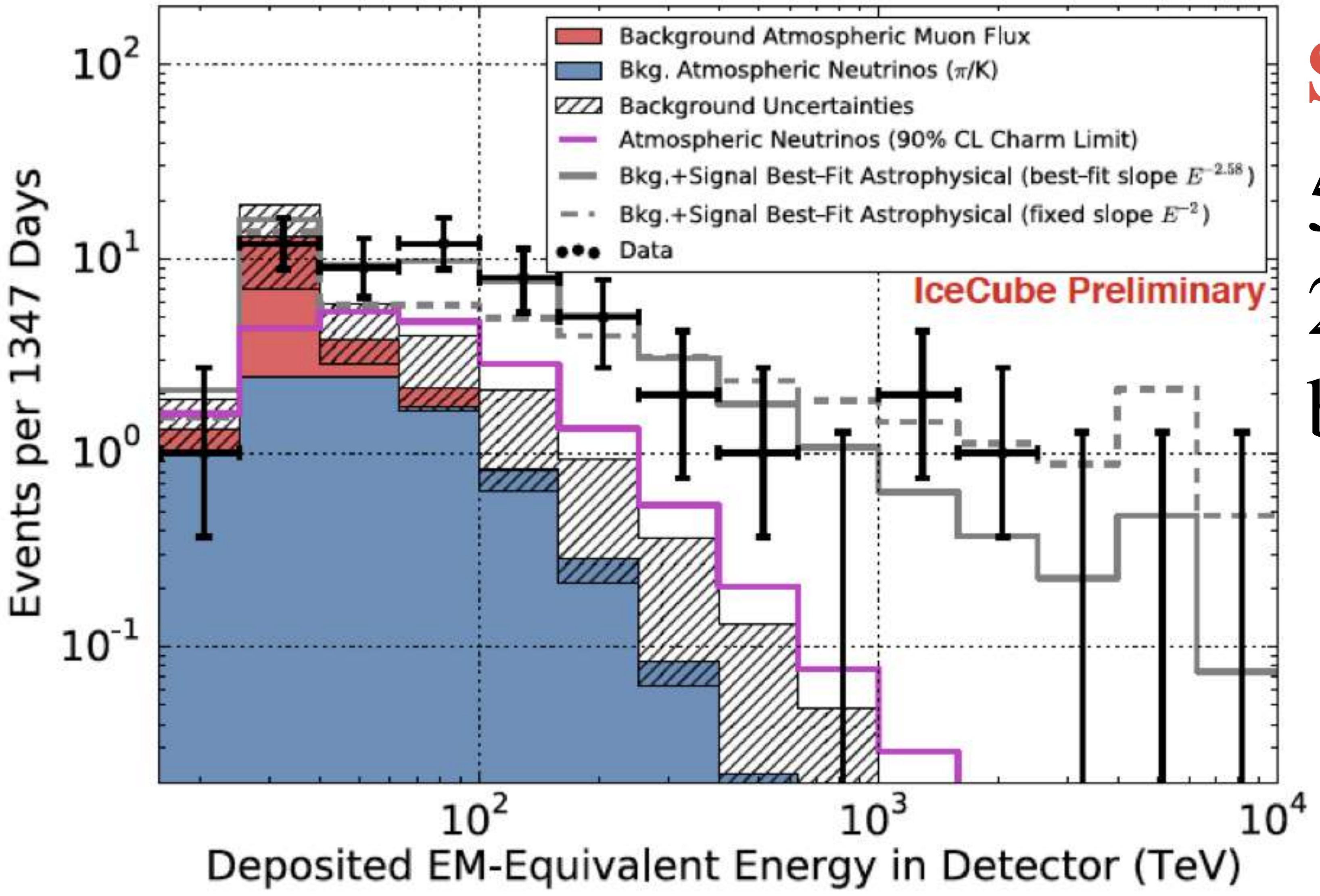
IceCube Point source sensitivity



M. Santander

Phenomenology : Neutrinos

1 **In 2013, IceCube detected the first set of 28 excess high-energy neutrinos of clear astrophysical (non-atmospheric) origin.**



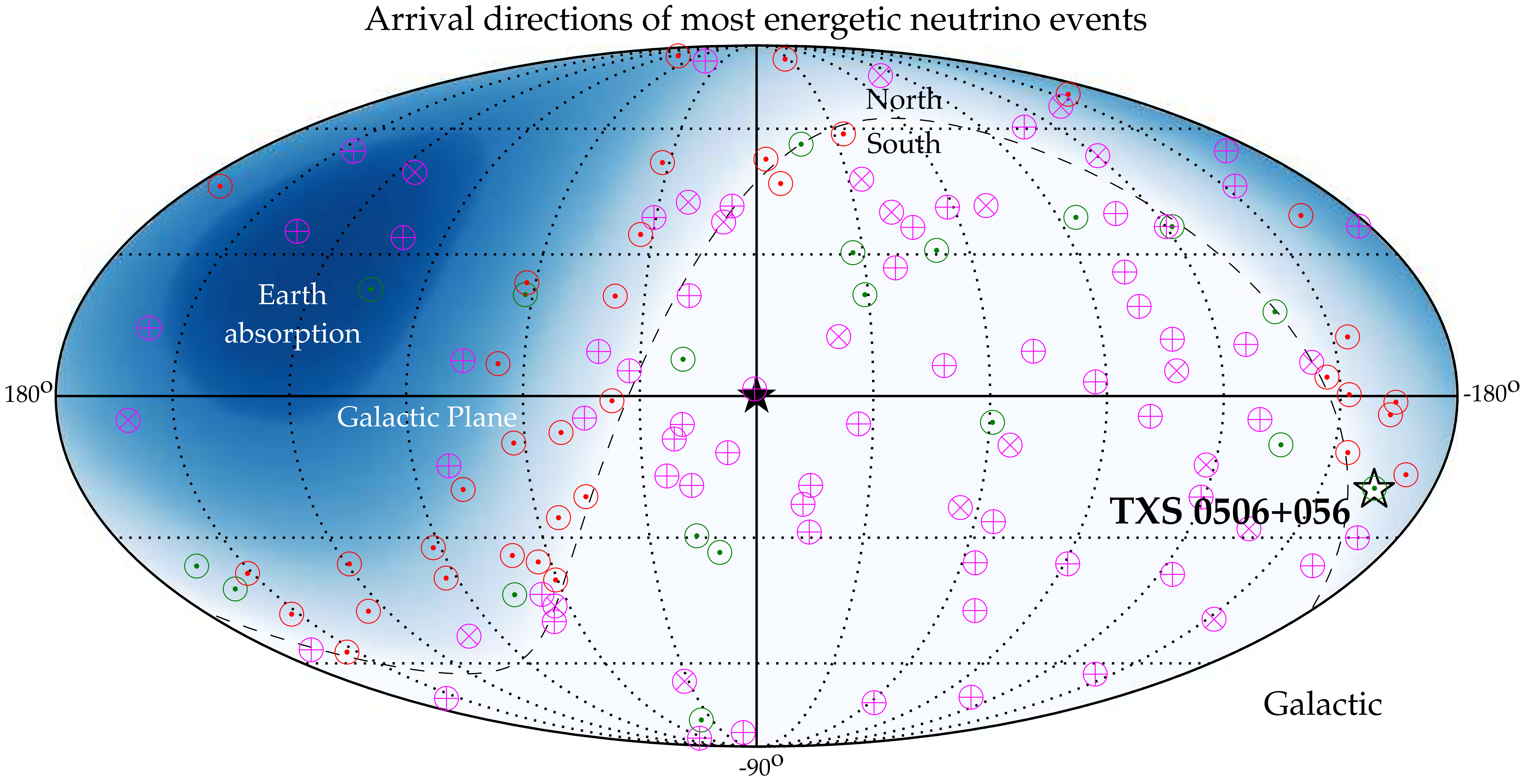
Spectrum

54 observed events,
20 ± 6 expected atmospheric background

2 In 2017, first evidence (tentative) of a correlated photon-ν emission from a blazar: **TXS 0506+056** (IceCube Coll. Science 2018)

- month-long gamma-ray high-state with 2 UHE neutrinos in coincidence at 3σ level
- 3.5σ neutrino high-state in 2014-2015, with no electromagnetic counterparts
- TXS 0506+056 is a blazar sequence outlier (Padovani+2019)

The neutrino sky



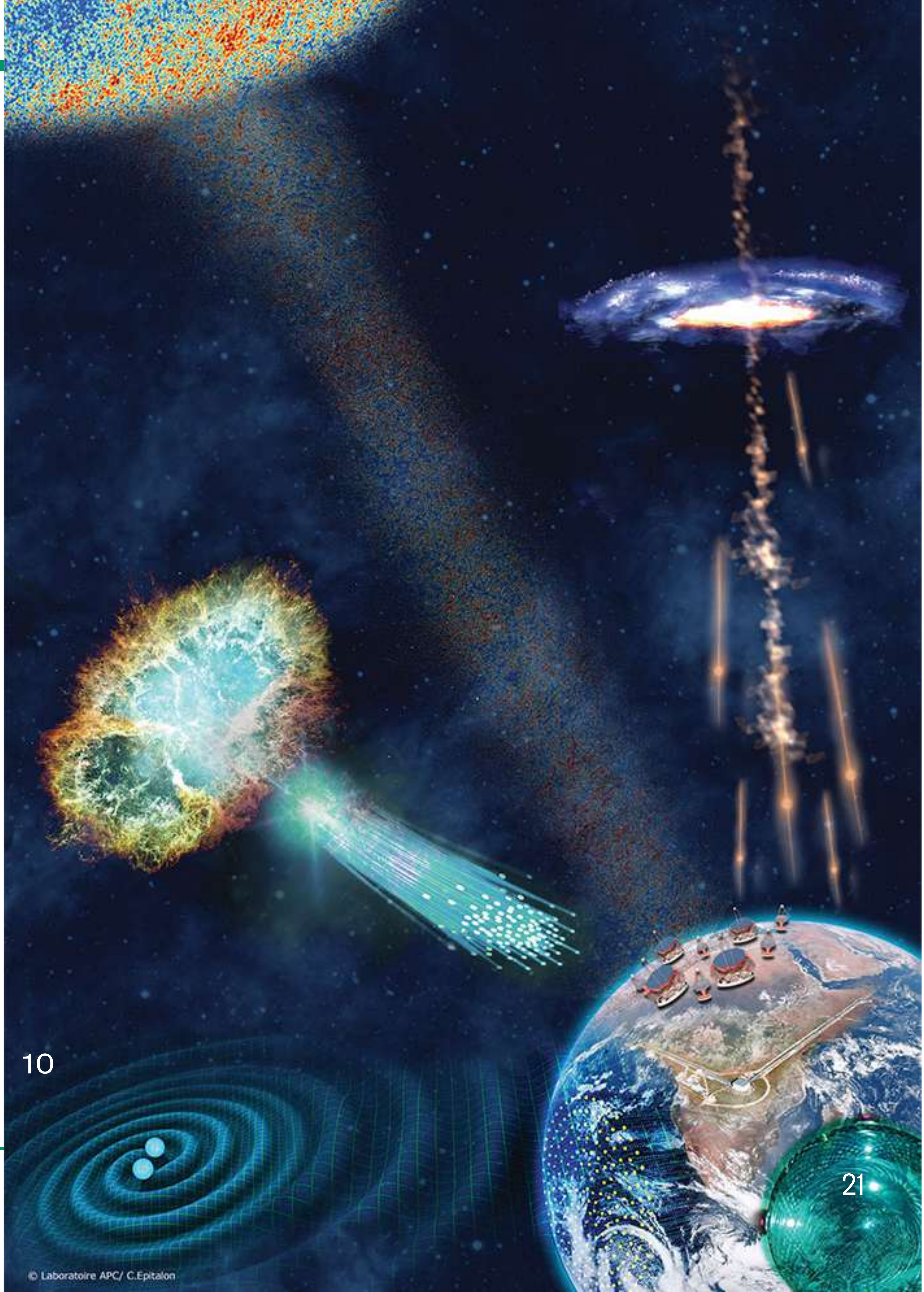
ASTRO 2020 - High-energy Cosmic Neutrinos - Science White Paper

No evidence of clustering in high-energy neutrino direction, pointing towards an extragalactic origin (mostly)

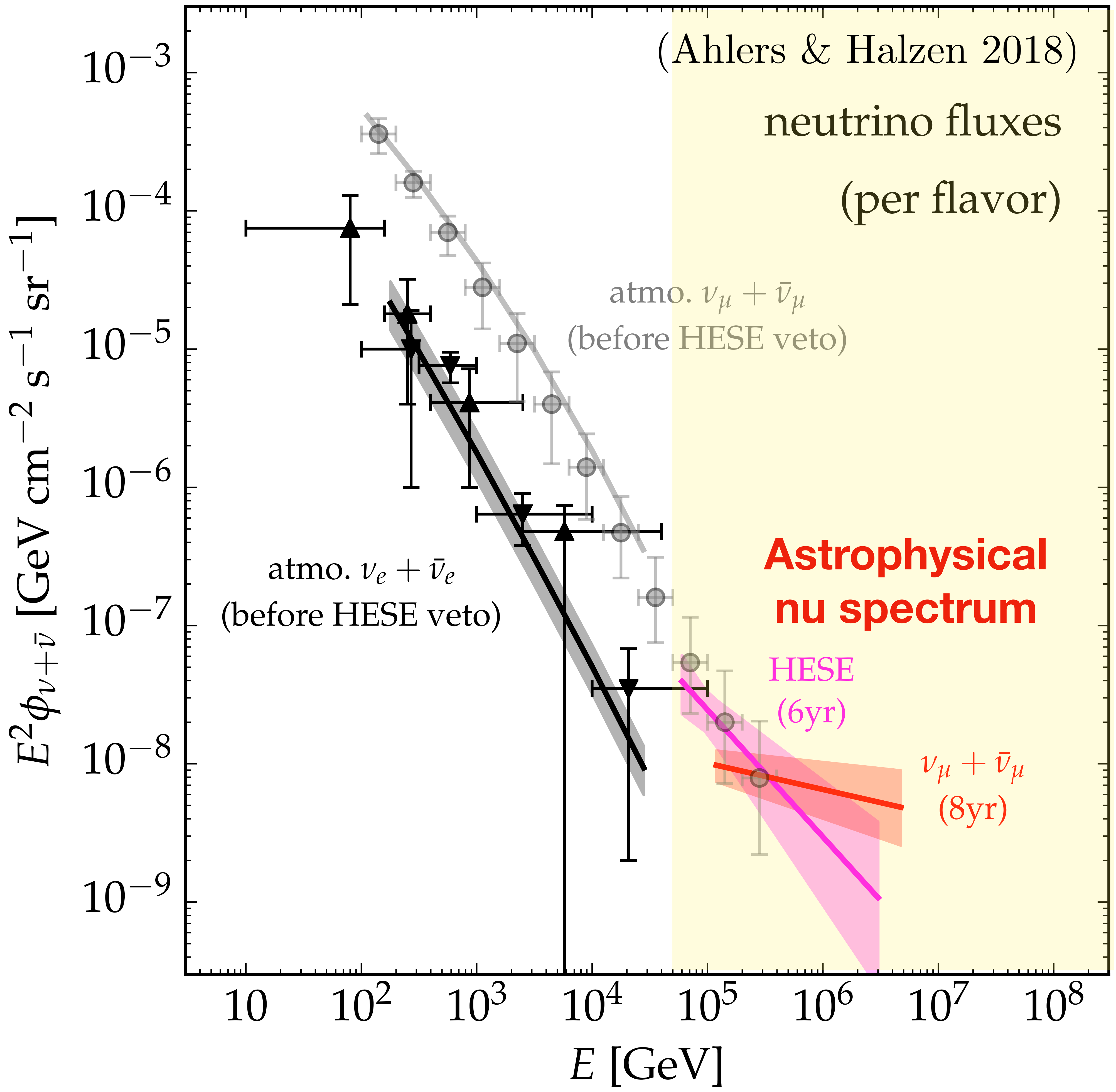
km³-class detectors could in principle detect neutrino fluxes from TeV sources with flux superior to 1 Crab ($2x10^{-11}$ /cm^2.s) - Crab Nebula, Vela X, + a couple of Supernovae...

Blazars have been considered the potential sources if their gamma-ray flux is from hadronic origin, and potentially attenuated by absorption (intrinsic flux >> observed flux)

Overview of current status



High-energy Astrophysical neutrinos



IceCube measured the 10 TeV - 10 PeV astrophysical neutrino flux

Atmospheric origin excluded > 8sigma

Flux > 200 TeV follows a power law of index 2.2 - 2.8

Searches for astrophysical origin

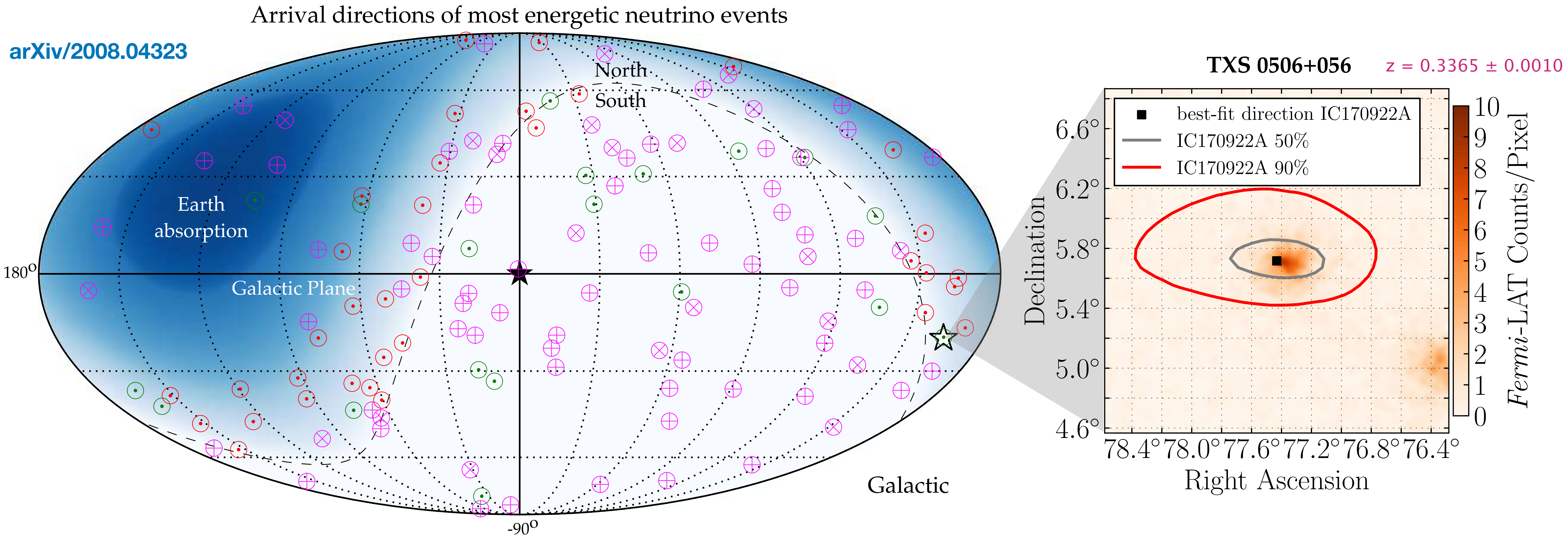
Astrophysical correlations with individual sub-PeV events

Astrophysical ID of lower-energy neutrino clusters

*Preferential use of cascade events

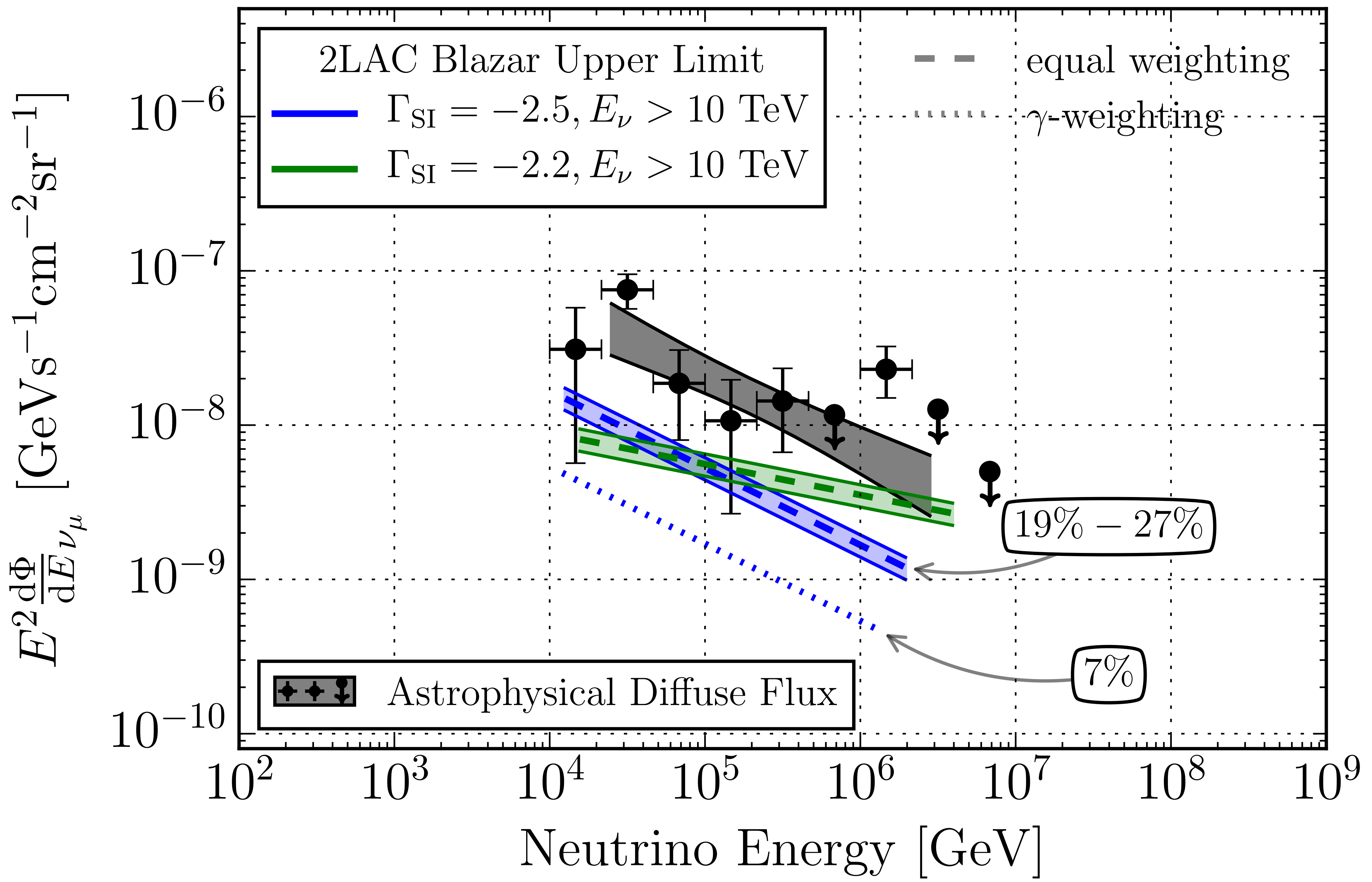
High-energy Astrophysical neutrinos

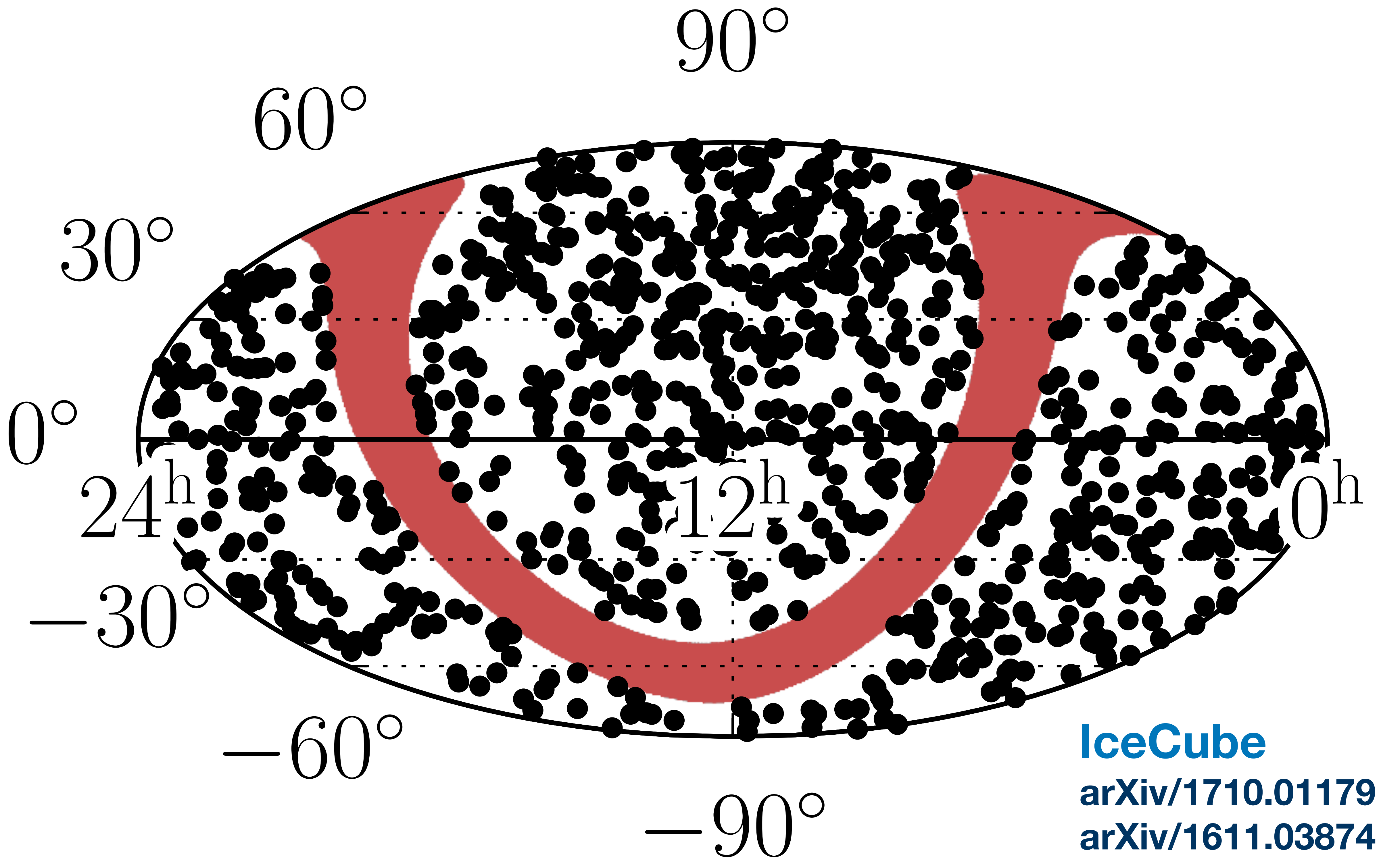
arXiv/2008.04323



The near-isotropic neutrino distribution favors an extragalactic origin

PeV neutrinos and Fermi Blazars



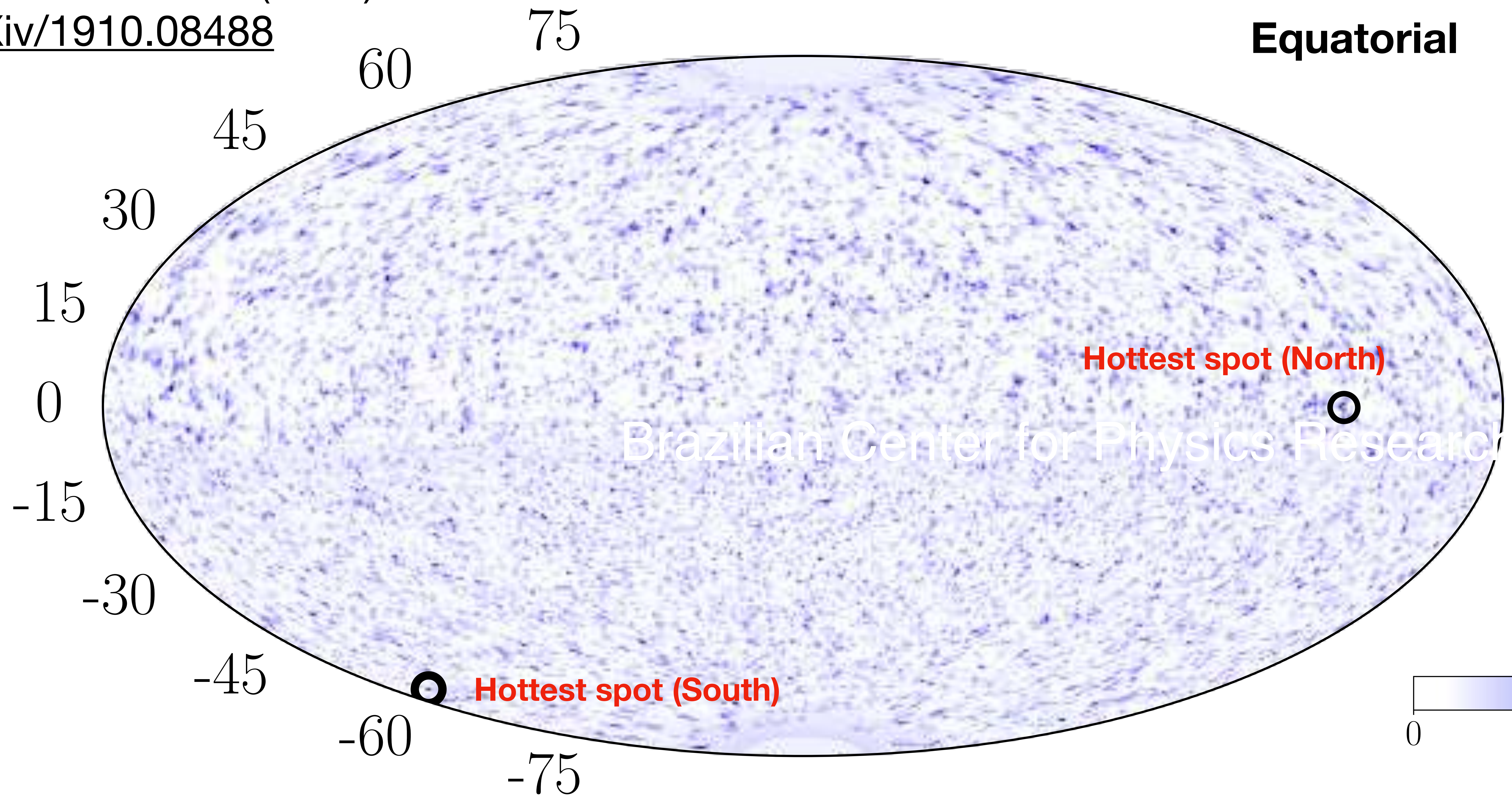


IceCube
arXiv/1710.01179
arXiv/1611.03874

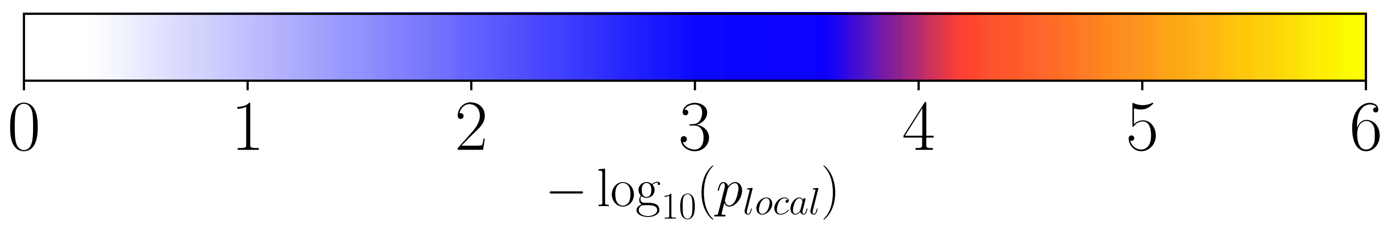
The population of LAT GeV-emitting blazars is not the astrophysical counterpart, as derived from limits from stacked signal estimations.

Neutrino point sources?

IceCube Collab. (2019)
arXiv/1910.08488



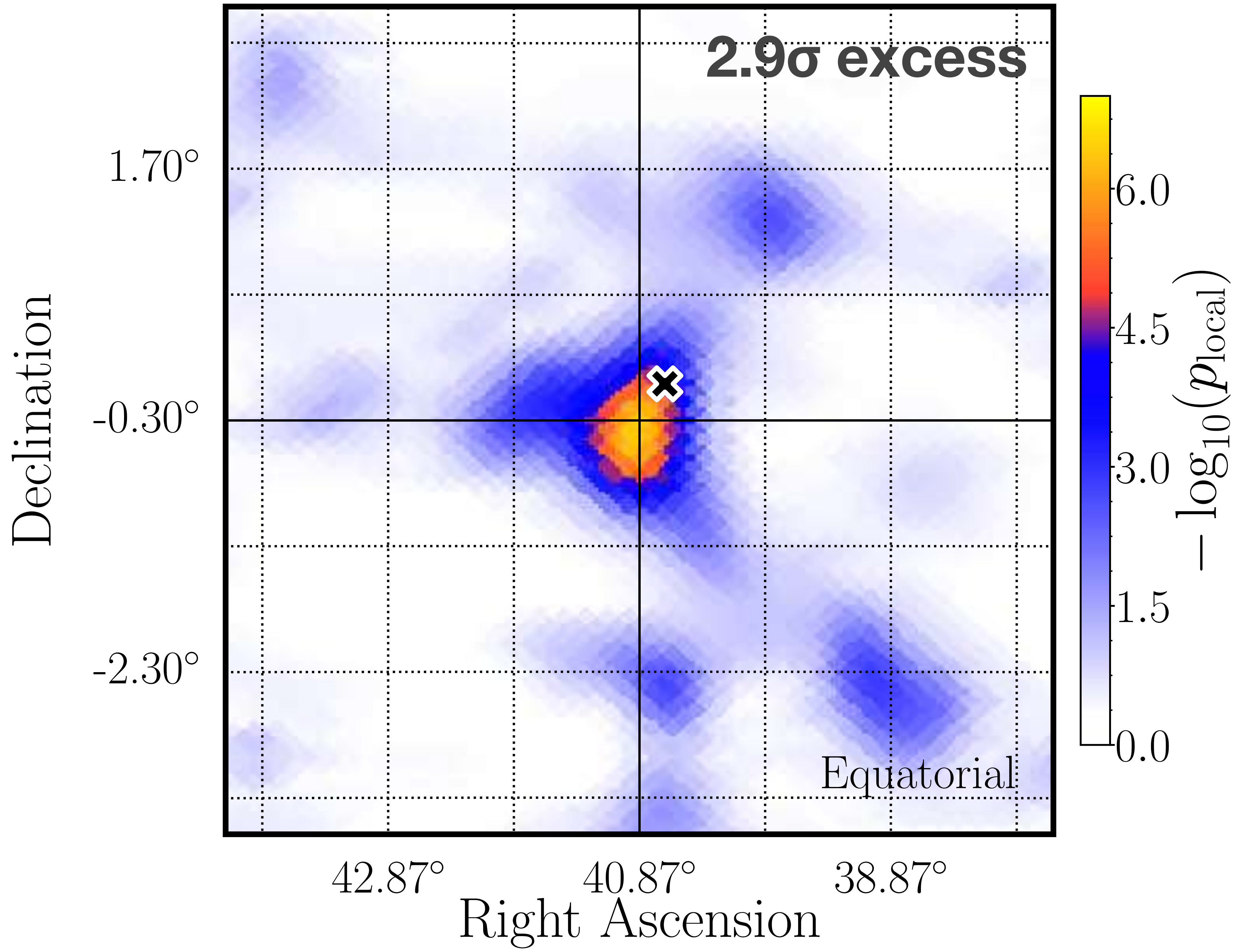
Analysis	Category	Pre-trial significance (p_{local})	Post-trial significance
All-Sky Scan	North	3.5×10^{-7}	9.9×10^{-2}
	South	4.3×10^{-6}	0.75
Source List	North	1.8×10^{-5}	2.0×10^{-3} ($2.9\,\sigma$)
	South	5.9×10^{-2}	0.55
Catalog Population	North	3.3×10^{-5}	4.8×10^{-4} ($3.3\,\sigma$)
	South	0.12	0.36
Stacking Search	SNR	–	0.11
	PWN	–	1.0
	UNID	–	0.4

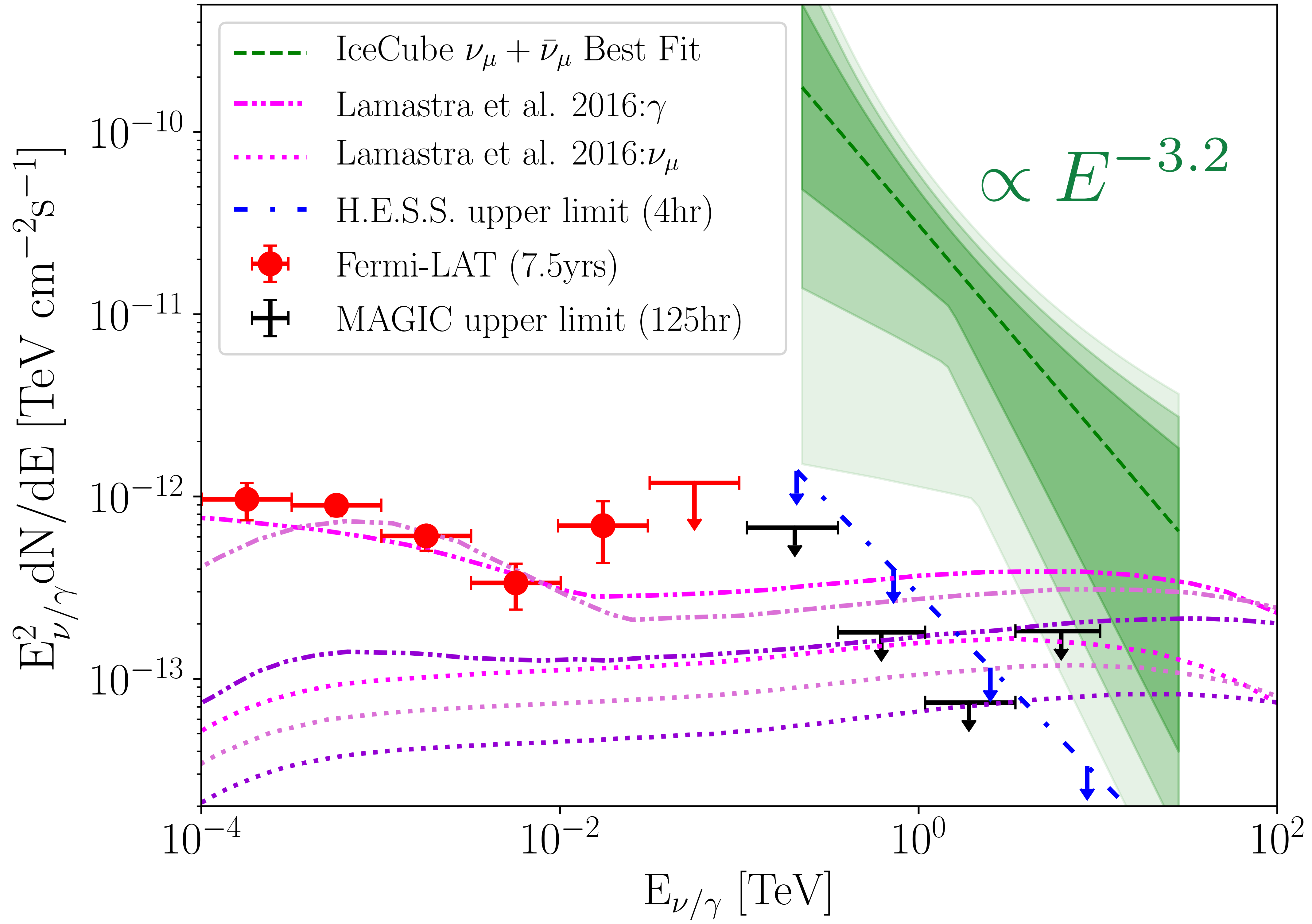


First 10 years of data, circa 1 million candidate neutrino events, following multiple tests: clustering, population cross-matching, stacking analysis.

Hotspot in the Northern sky

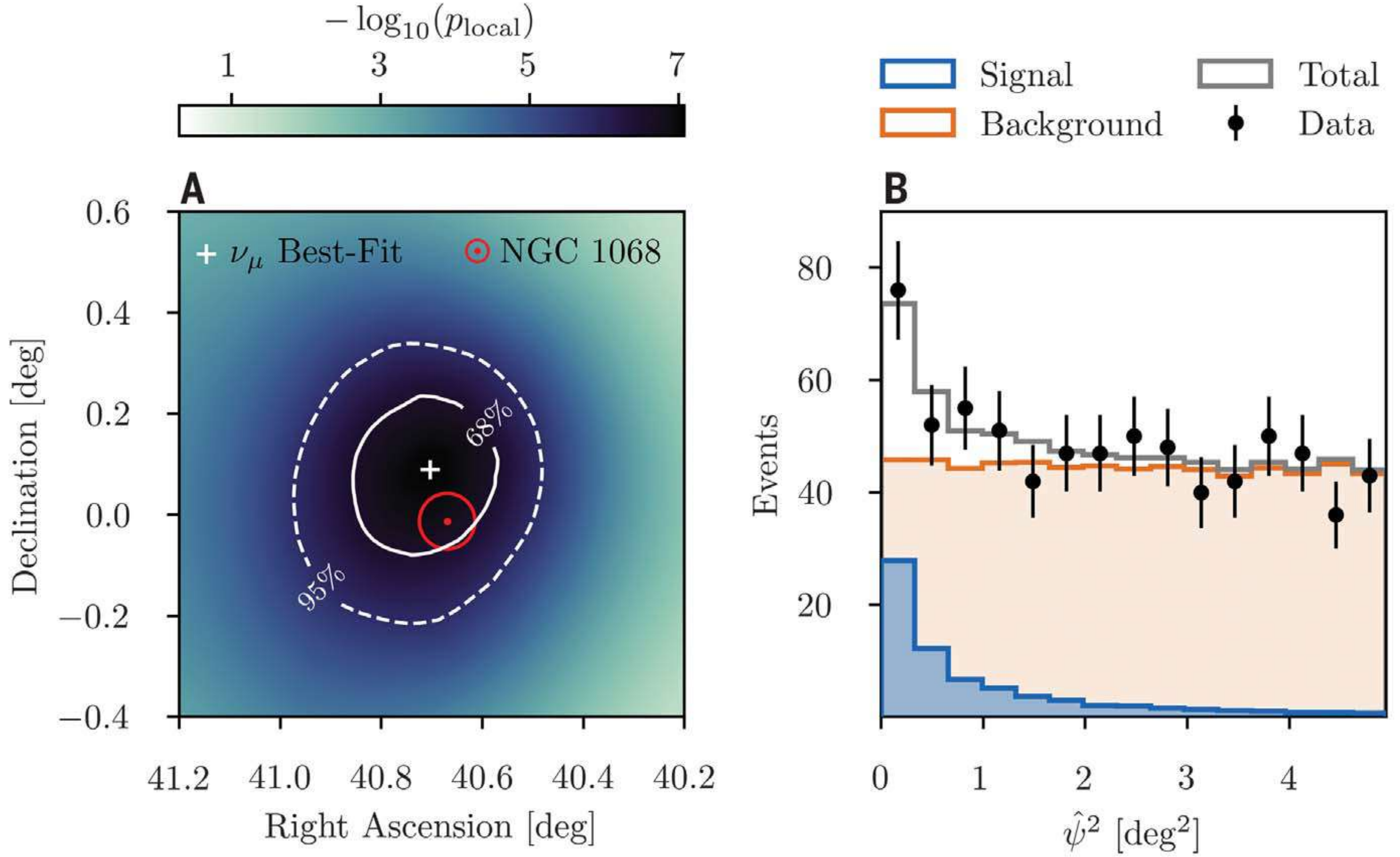
IceCube Collab. (2019)
arXiv/1910.08488





Seyfert Galaxy NGC 1068, with heavily obscured nucleus which is Compton thick for gamma-ray emission.

Current hottest spot



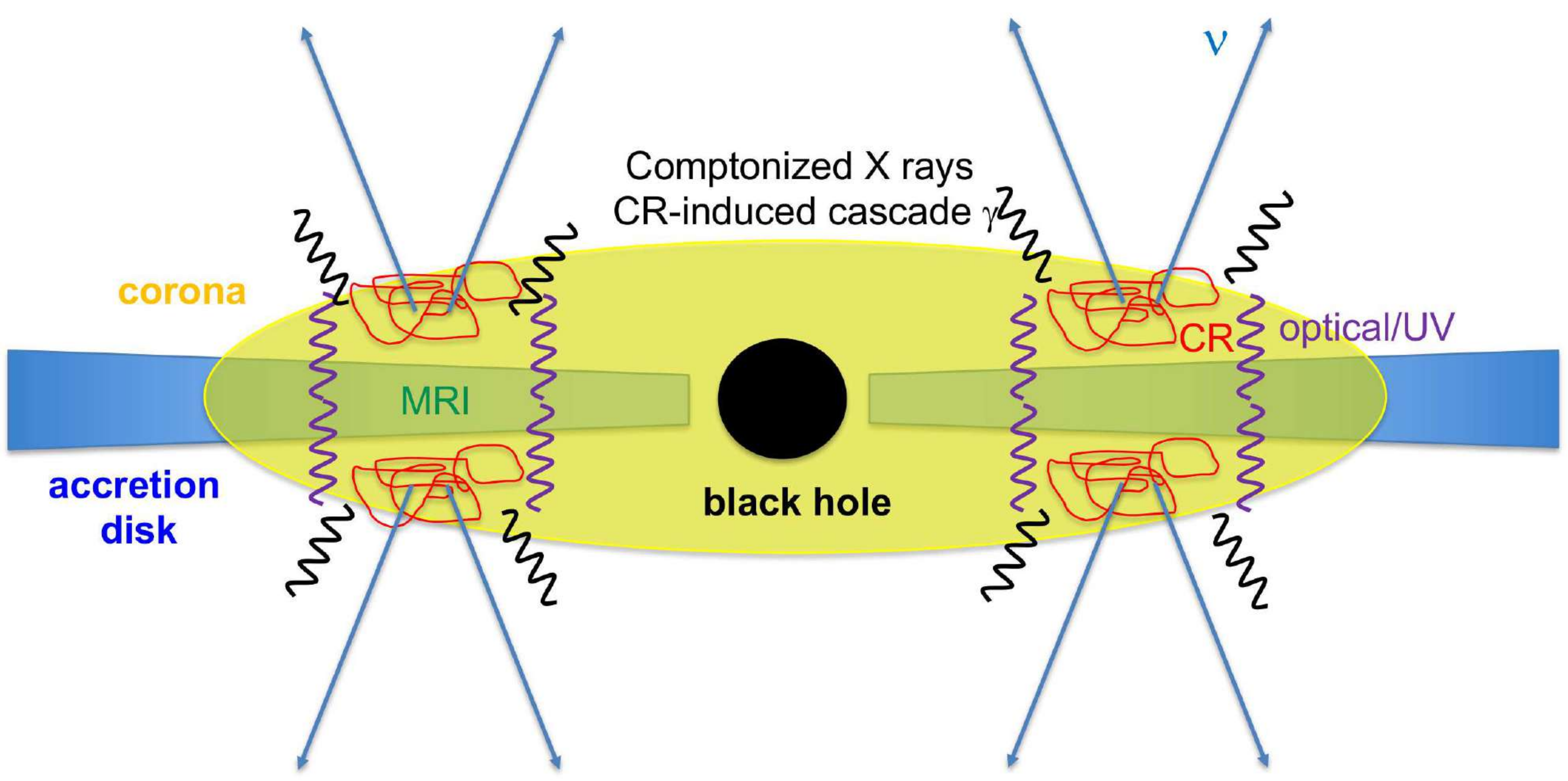
NGC 1068 remains standing out as hottest source with **4.2 sigma**

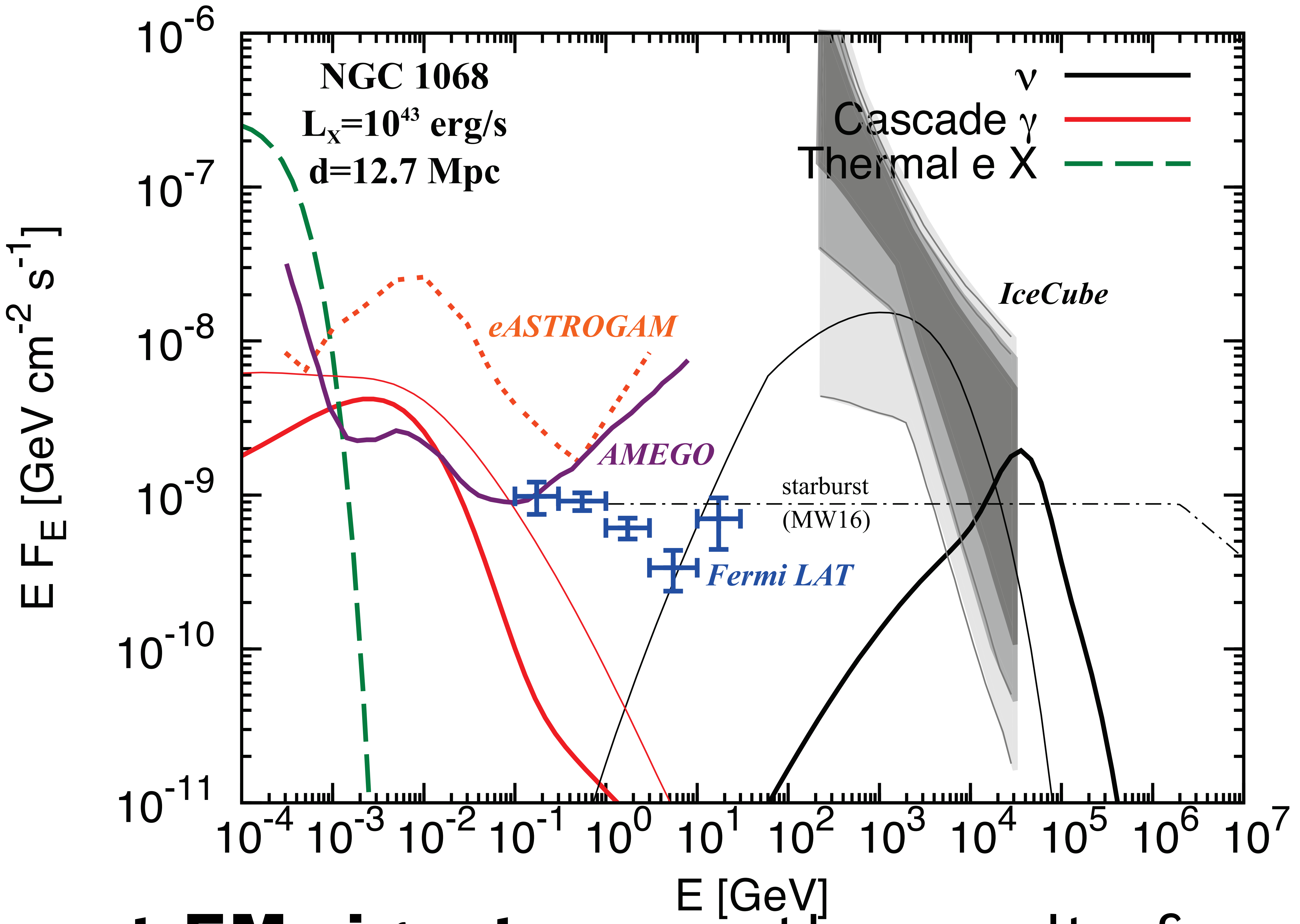
Test type	Pretrial P value, P_{local} (local significance)	Posttrial P value, P_{global} (global significance)
Northern Hemisphere scan	5.0×10^{-8} (5.3σ)	2.2×10^{-2} (2.0σ)
List of candidate sources, single test	1.0×10^{-7} (5.2σ)	1.1×10^{-5} (4.2σ)
List of candidate sources, binomial test	4.6×10^{-6} (4.4σ)	3.4×10^{-4} (3.4σ)

Other sources which are dominating correlations are, TXS 0506+056, PKS 1424+240, GB6 J1542+6129, NGC 1068, with combined **3.3 sigma.**

Beware of opaque EM sources!

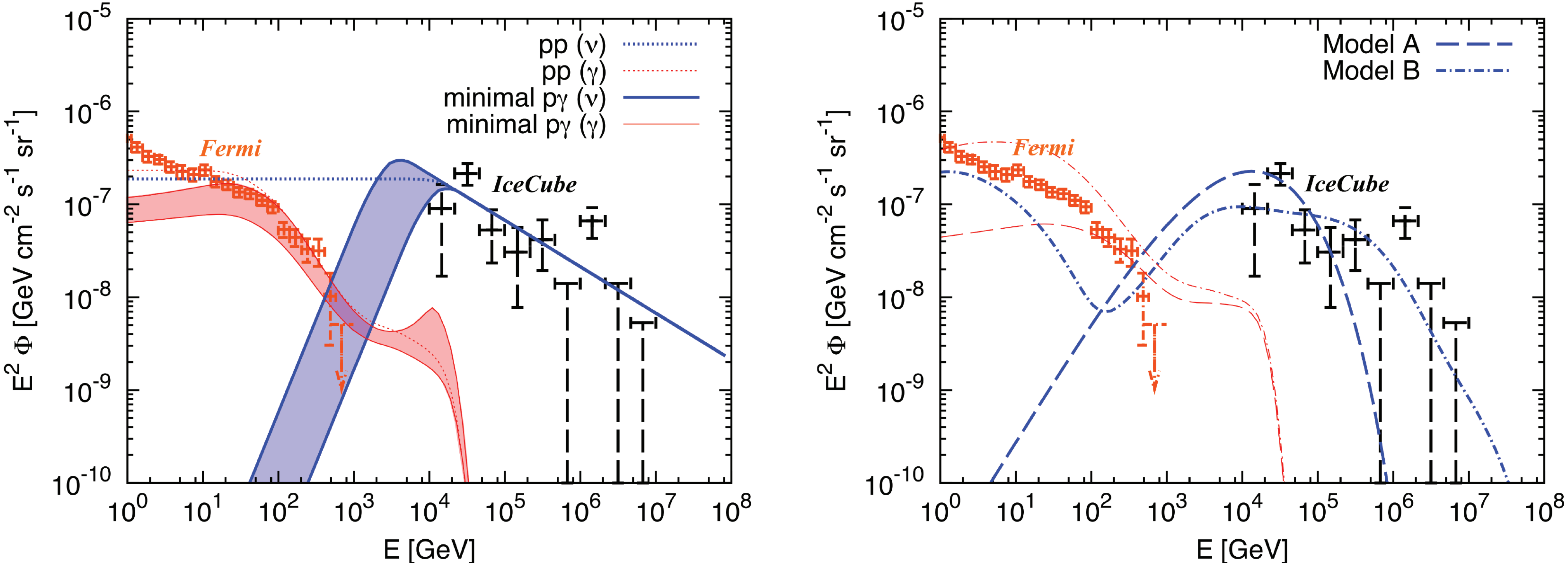
K. Murase, S. Kimura, P. Meszaros, PRL 125 (2020) 011101
arXiv/1904.04226





Hard X-rays represent a potential counterpart EM signature, as the result of cascading gamma-rays that give off hard X-rays by Compton scattering.

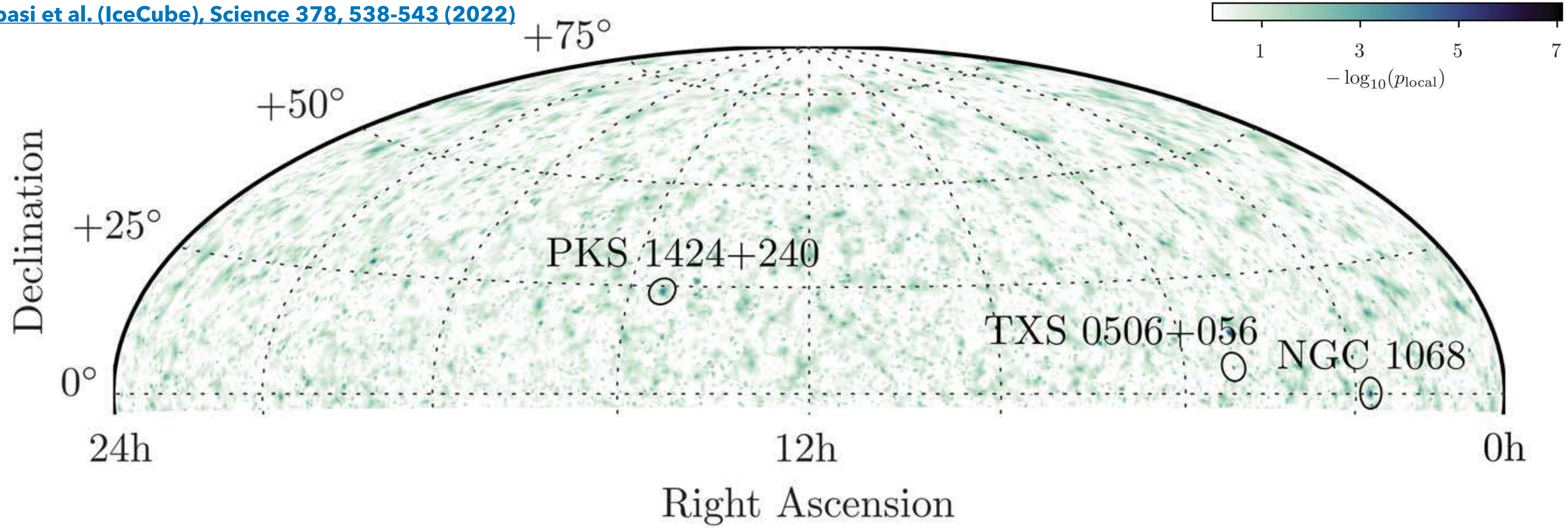
Beware of opaque EM sources!



Isotropic neutrino flux is higher than the Gamma-ray Background, pointing to a potential dark EM origin of the neutrino flux

Recent all-sky search results

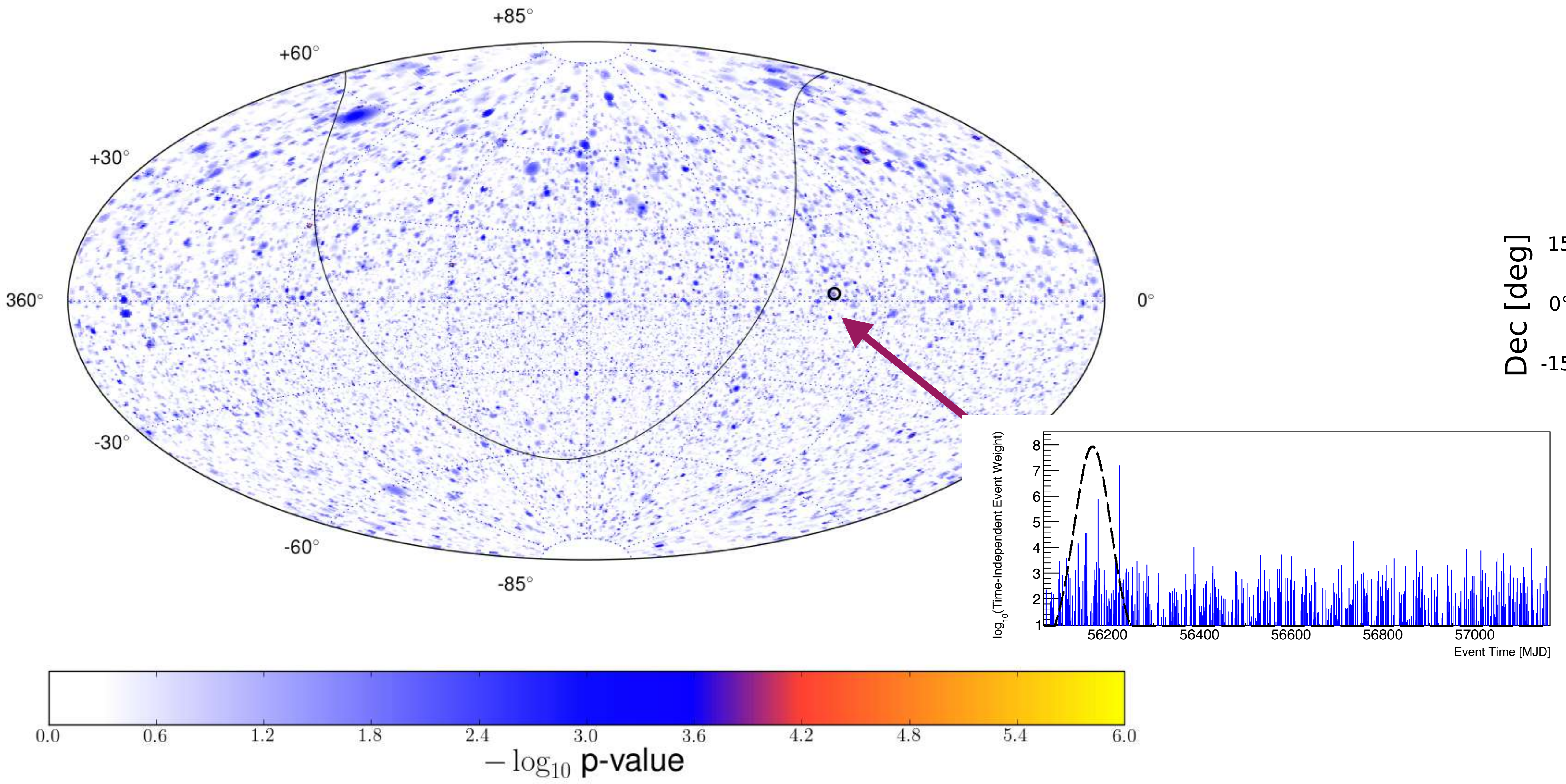
[Abbasi et al. (IceCube), Science 378, 538-543 (2022)]



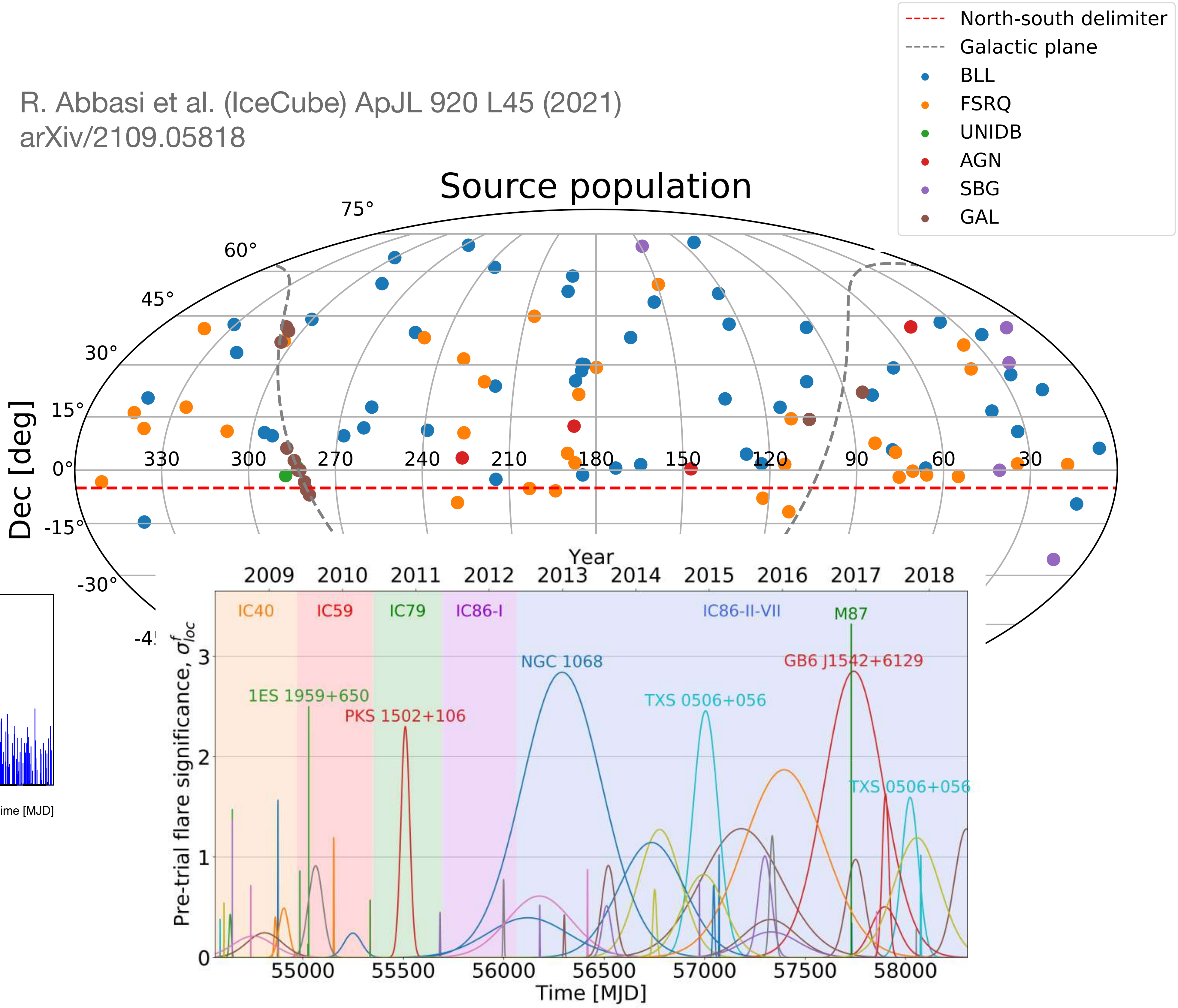
Nearly 1 million events from Northern sky only, and searches of clusters, population cross-matching and signal stacking analysis.

Time-dependent searches

R. Abbasi et al. (IceCube) ApJ 911 (2021) 1, 67
arXiv/2012.01079



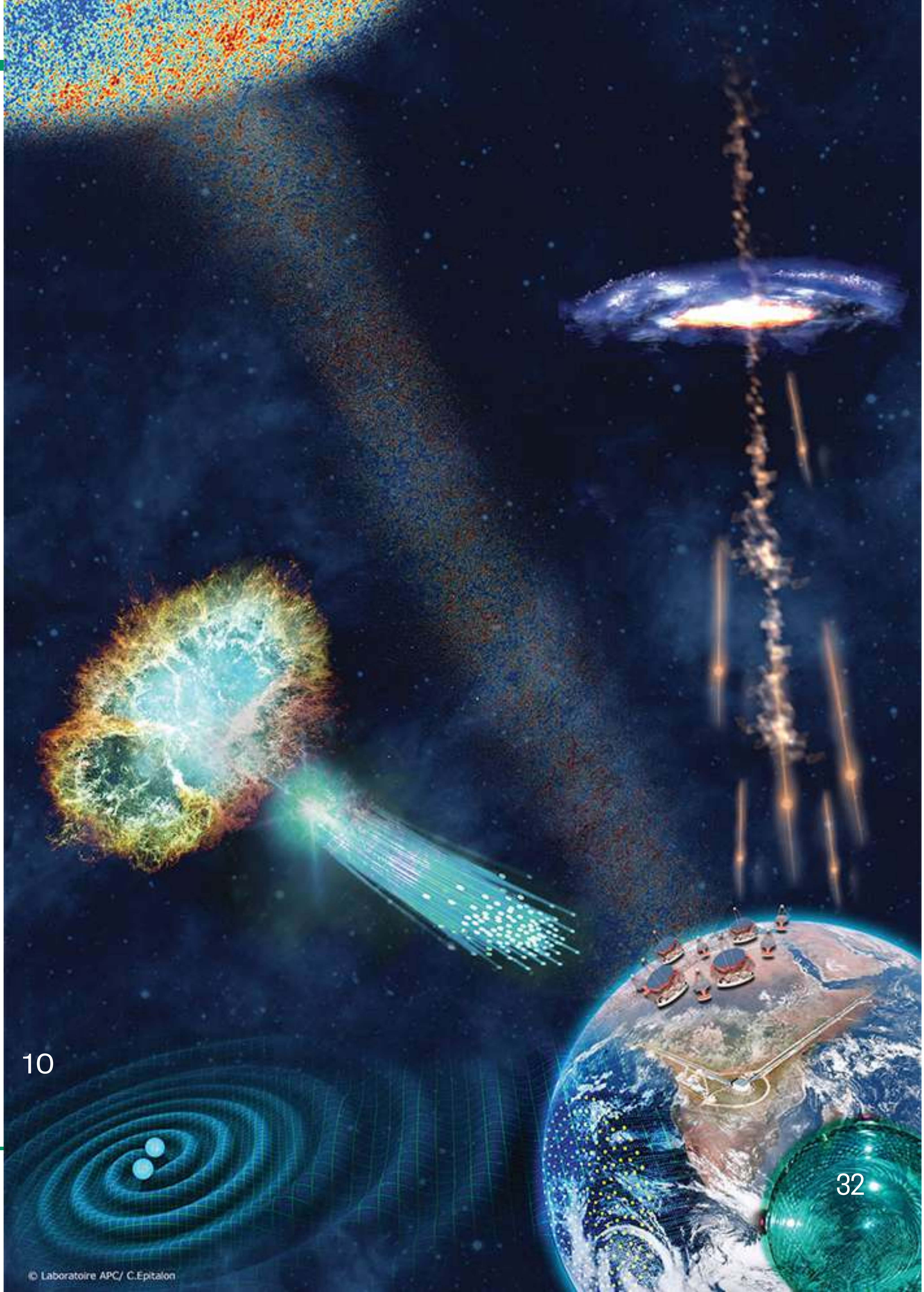
R. Abbasi et al. (IceCube) ApJL 920 L45 (2021)
arXiv/2109.05818



No significant spatial-temporal clusters found in 5 year all-sky data (2012-17)

+ searches from flares from selected source catalogue of AGNs (3σ w/ 4 sources)

The Gamma-MM context of neutrinos



High-energy neutrino counterparts

Relativistic astrophysical sources are natural cosmic-ray accelerators and therefore expected to be multi-messenger sources

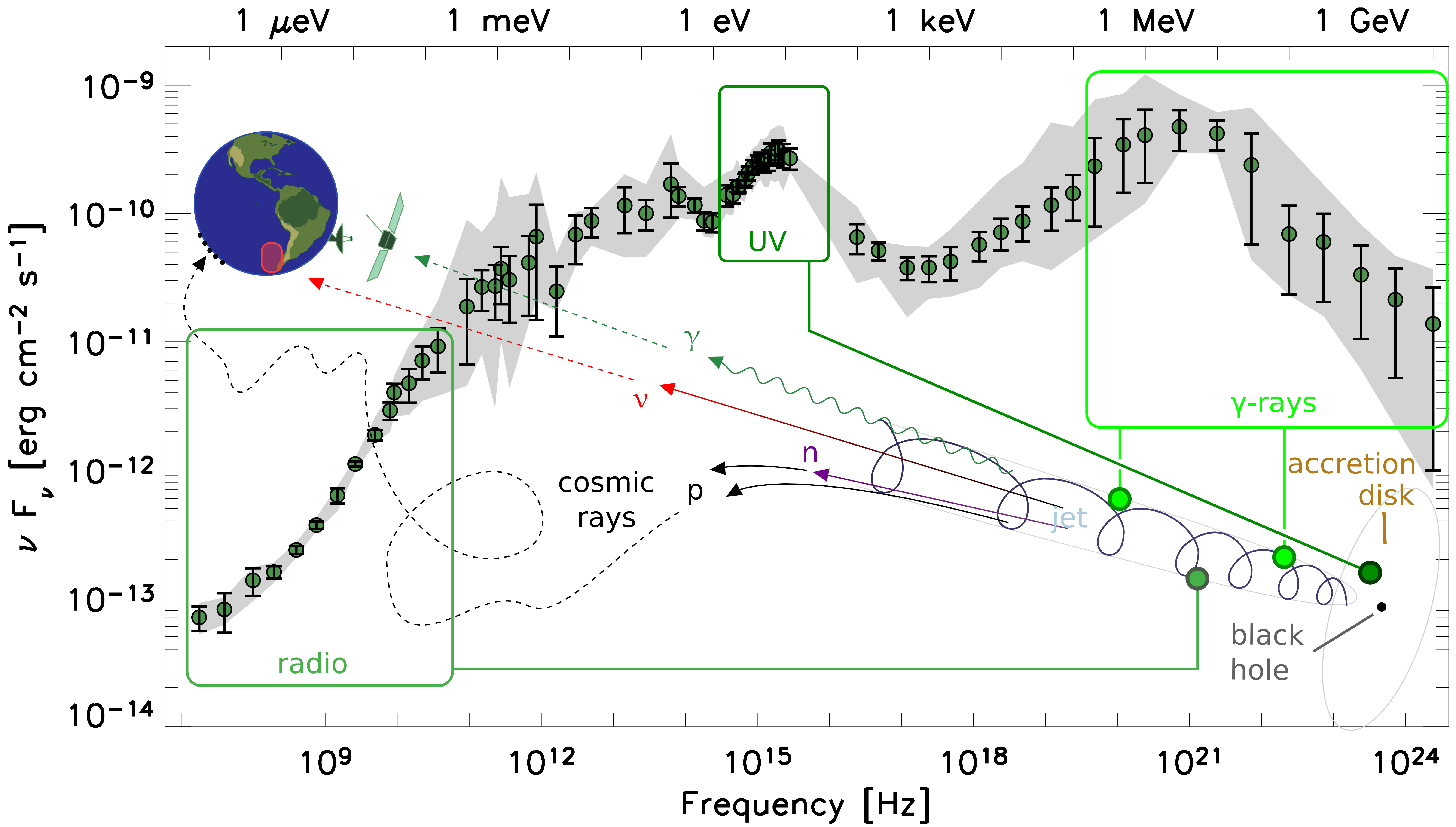
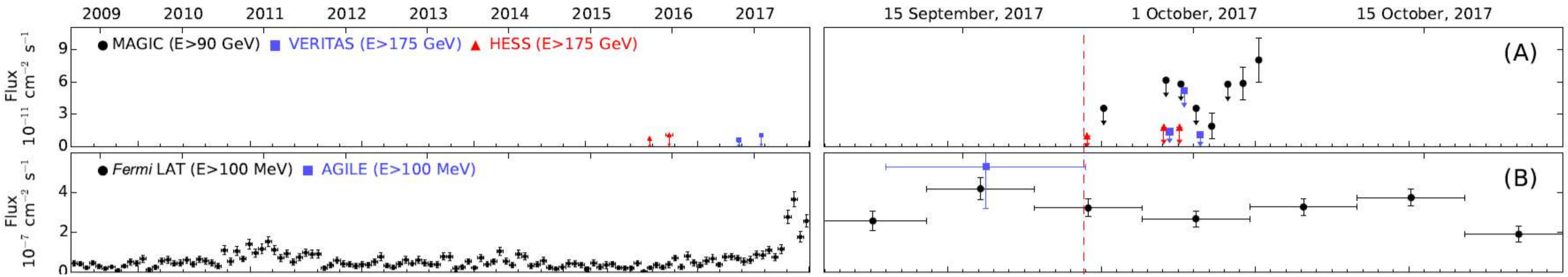


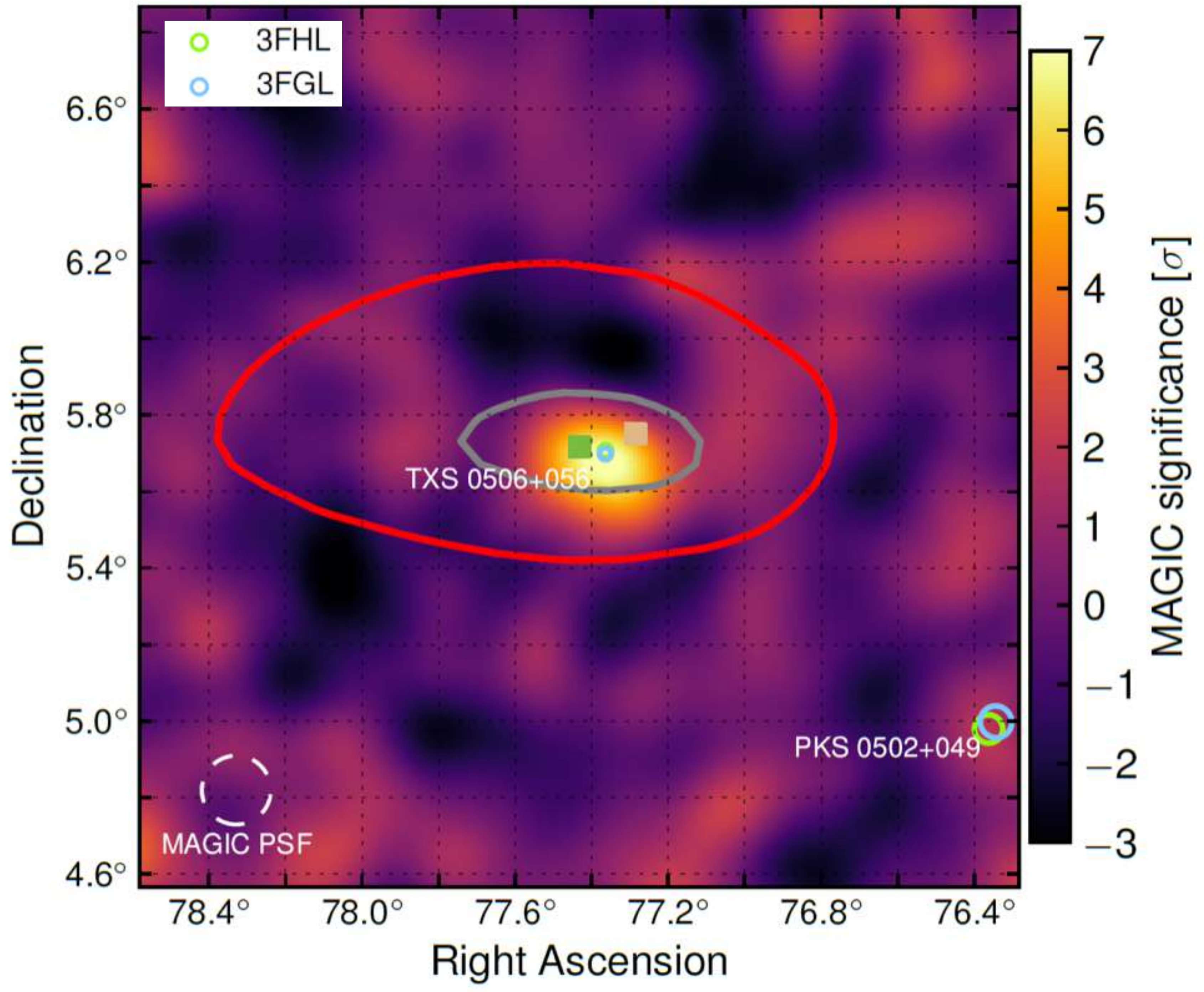
illustration adapted from arXiv:1903.04504

IceCube 170922A - TXS 0506+056



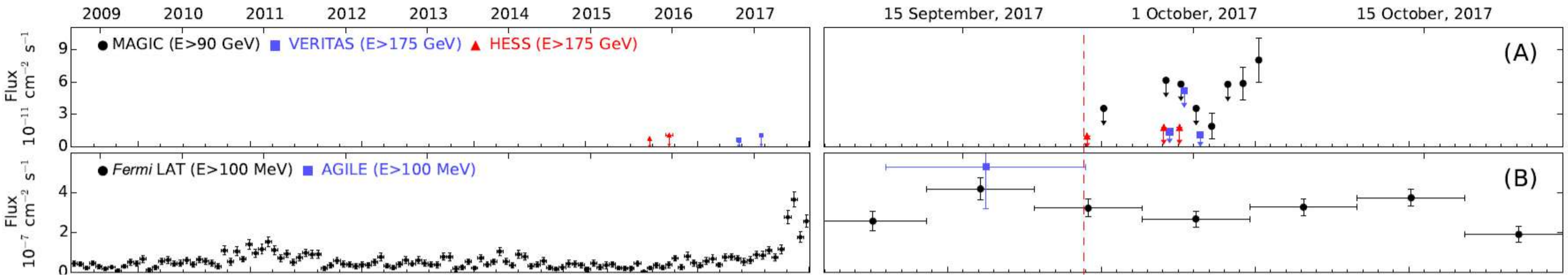
IceCube et al. 2018

The 290 TeV neutrino event detected by IceCube coincided with an increased activity of the blazar as recorded by Fermi-LAT and a first follow-up detection by MAGIC in the VHEs (3σ association).



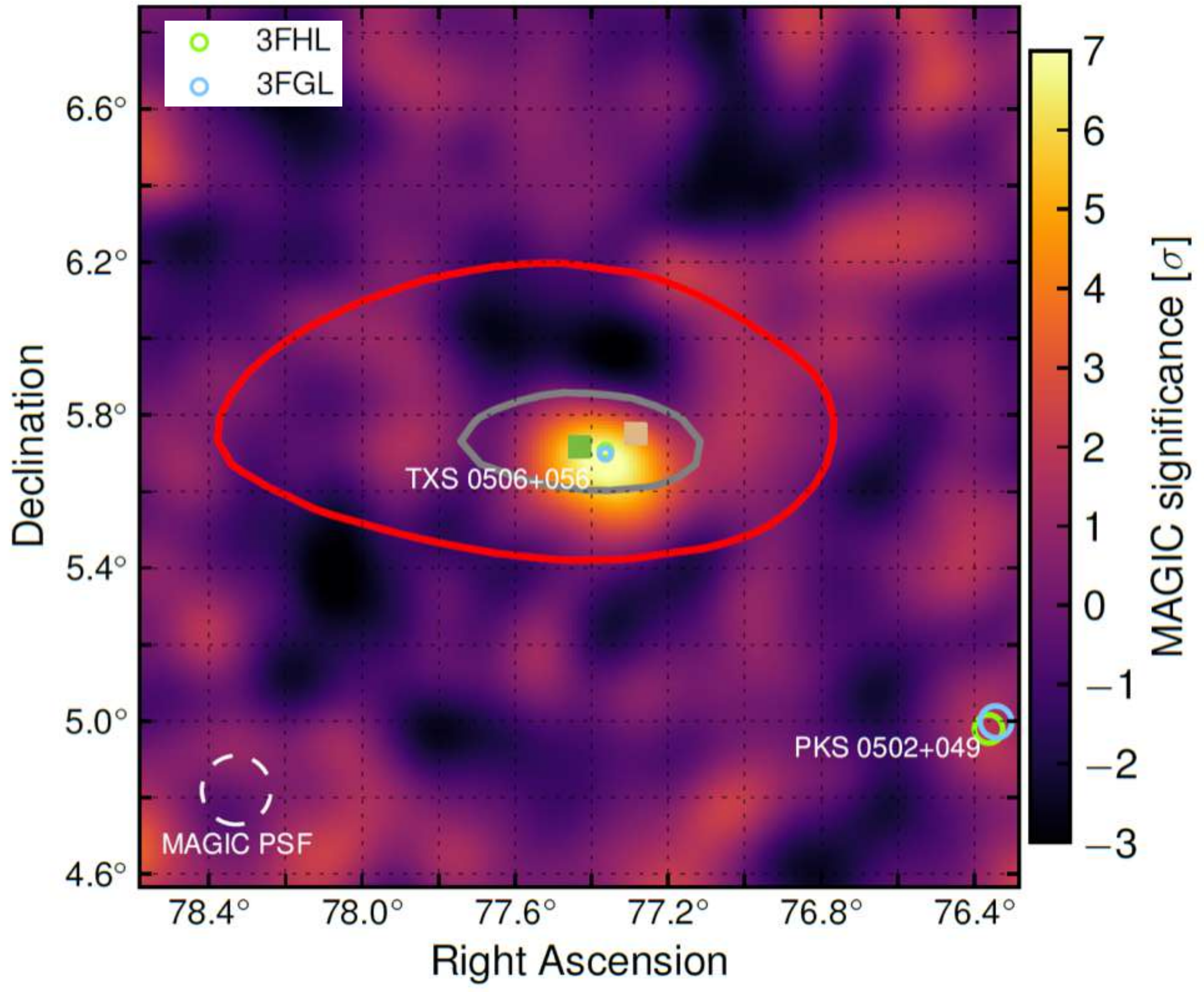
IceCube 170922A - TXS 0506+056

CBPF Centro Brasileiro de Pesquisas Físicas
UNIDADE DE PESQUISA DO MCTI

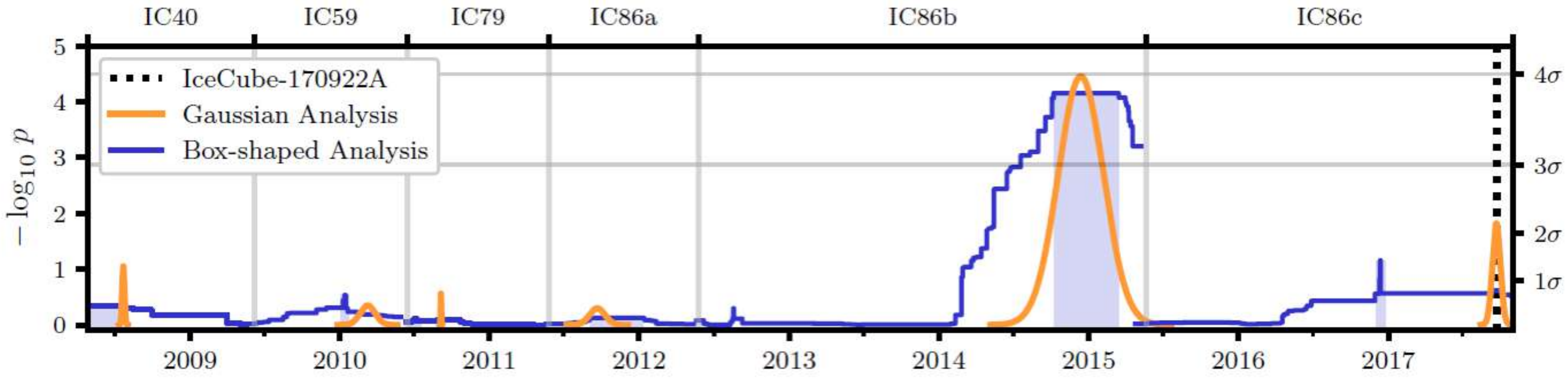


IceCube et al. 2018

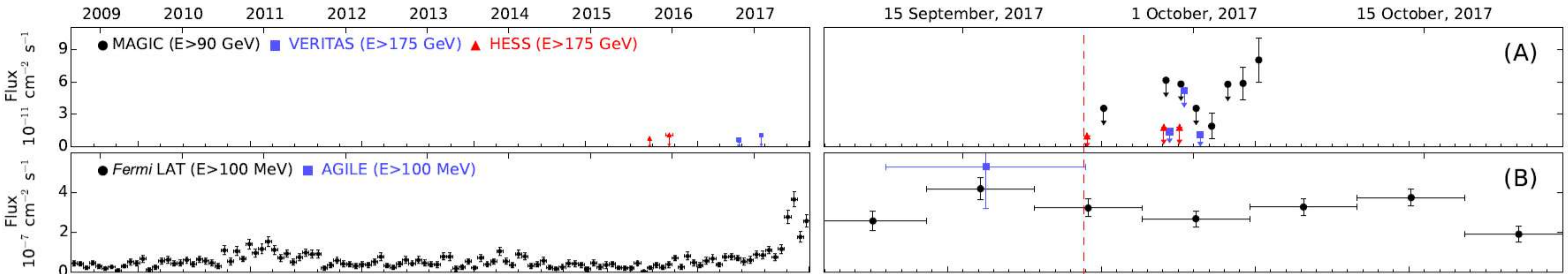
The 290 TeV neutrino event detected by IceCube coincided with an increased activity of the blazar as recorded by Fermi-LAT and a first follow-up detection by MAGIC in the VHEs (3σ association).



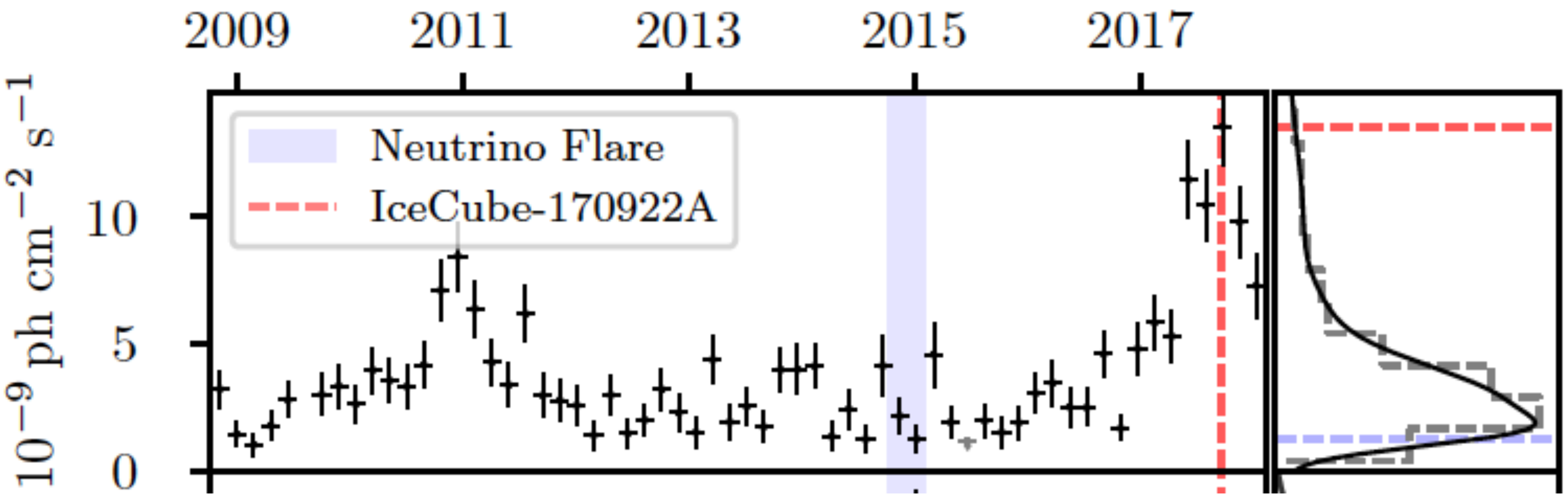
Additionally, search through archival data revealed evidence for 13 +/- 5 excess events from the direction of TXS during for months in 2014-15, without counterpart gamma-ray flare

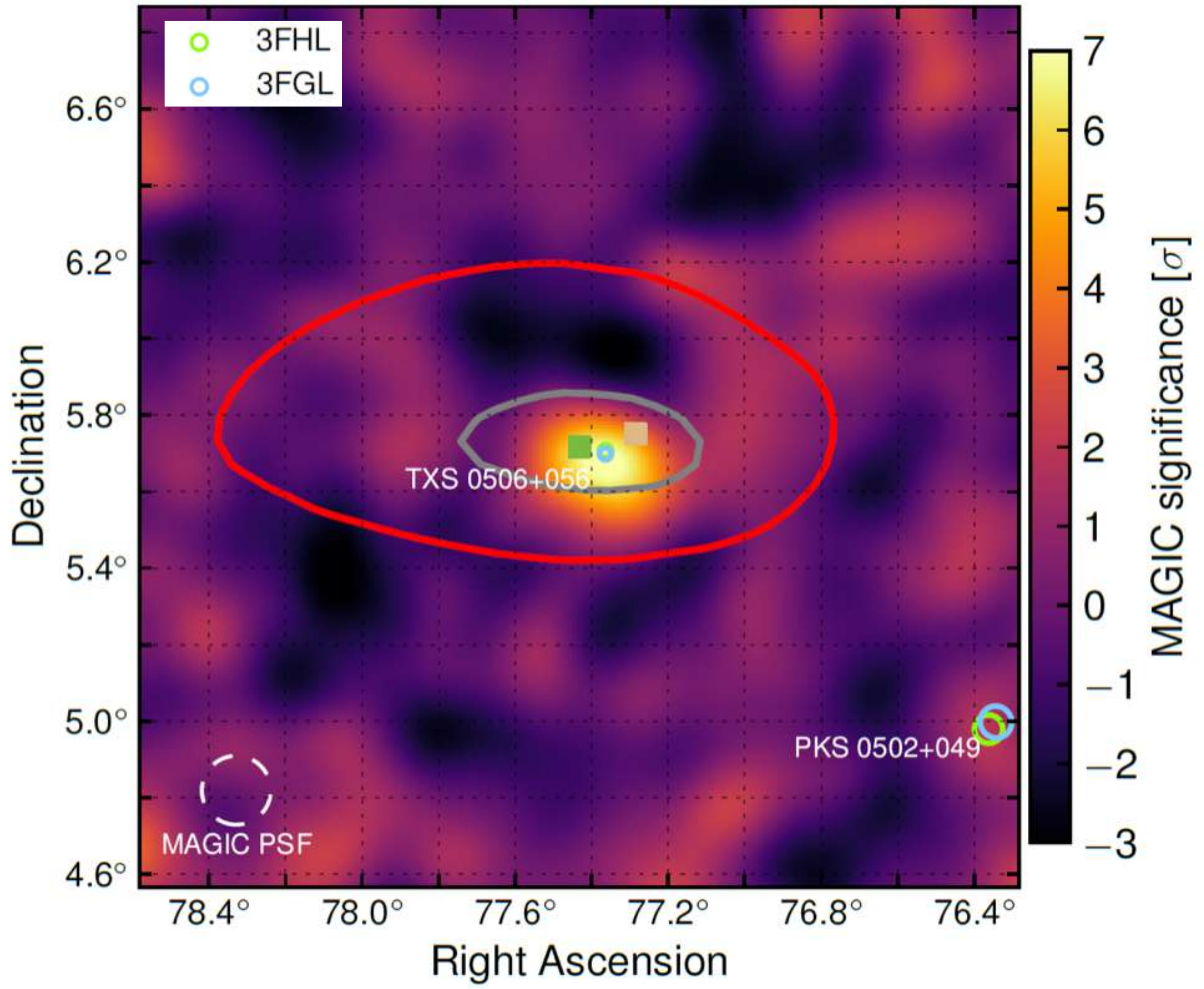


IceCube 170922A - TXS 0506+056



IceCube et al. 2018





IceCube 170922A - TXS 0506+056

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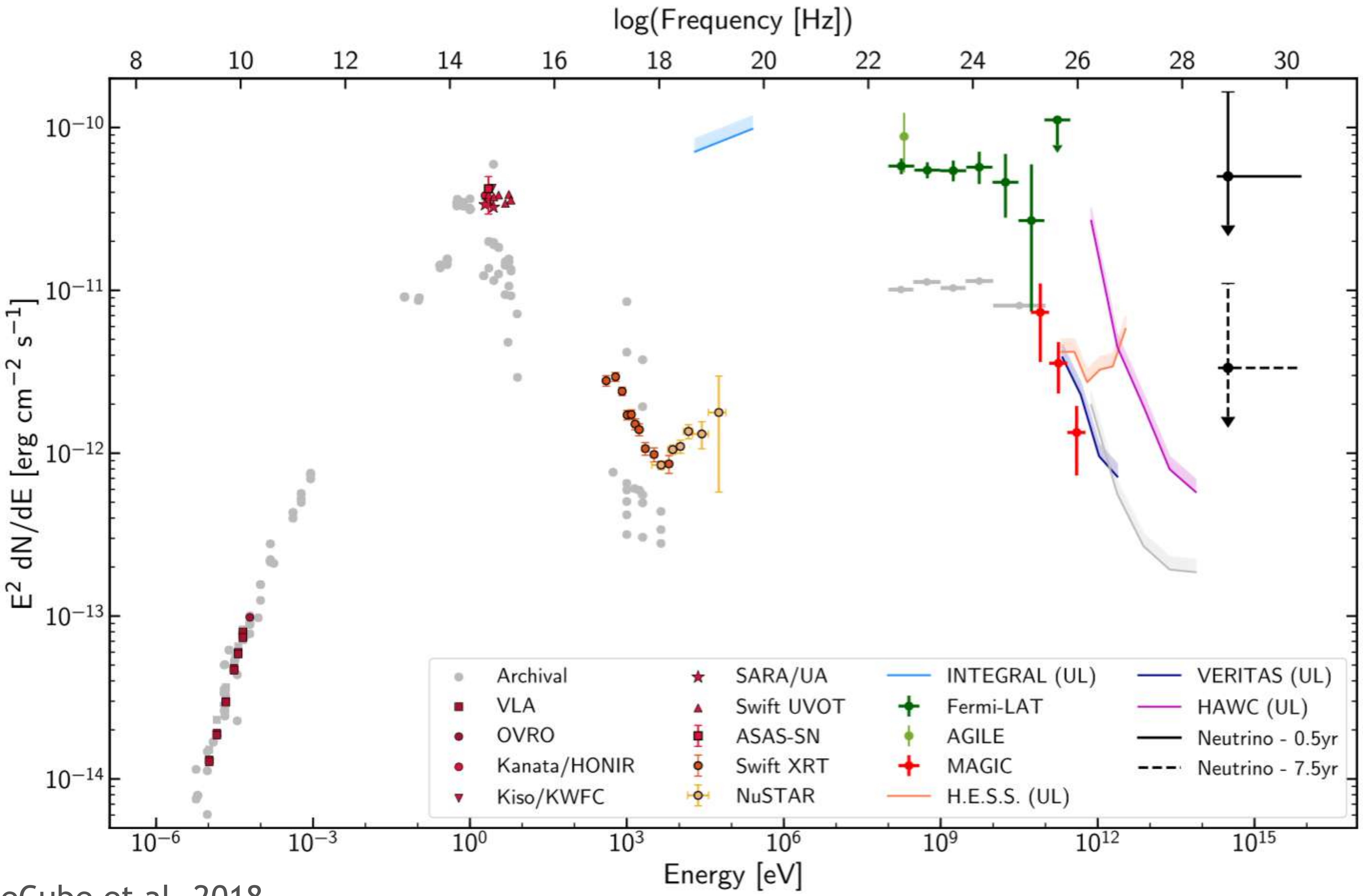
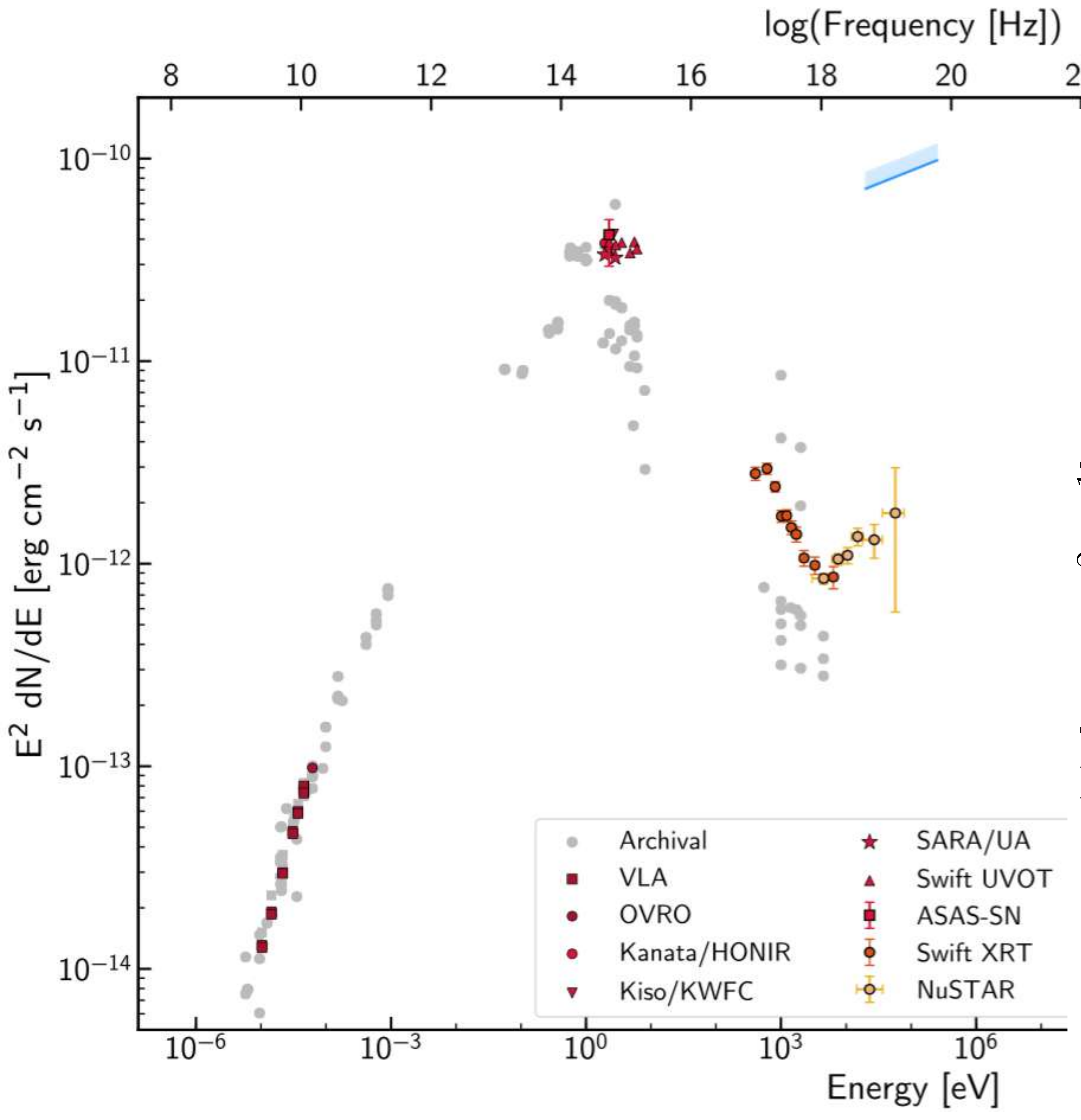
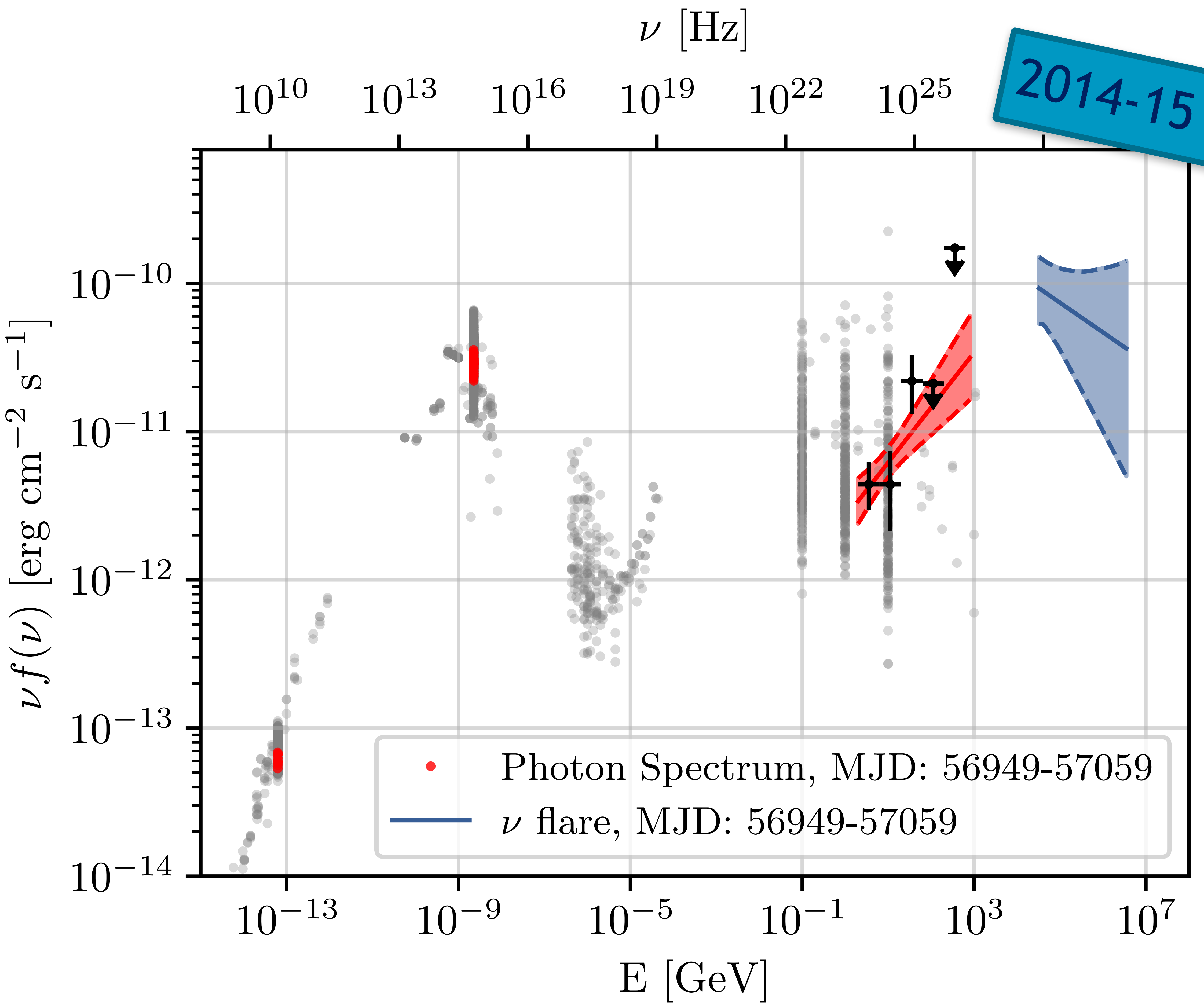


IceCube et al. 2018

IceCube 170922A - TXS 0506+056



IceCube et al. 2018

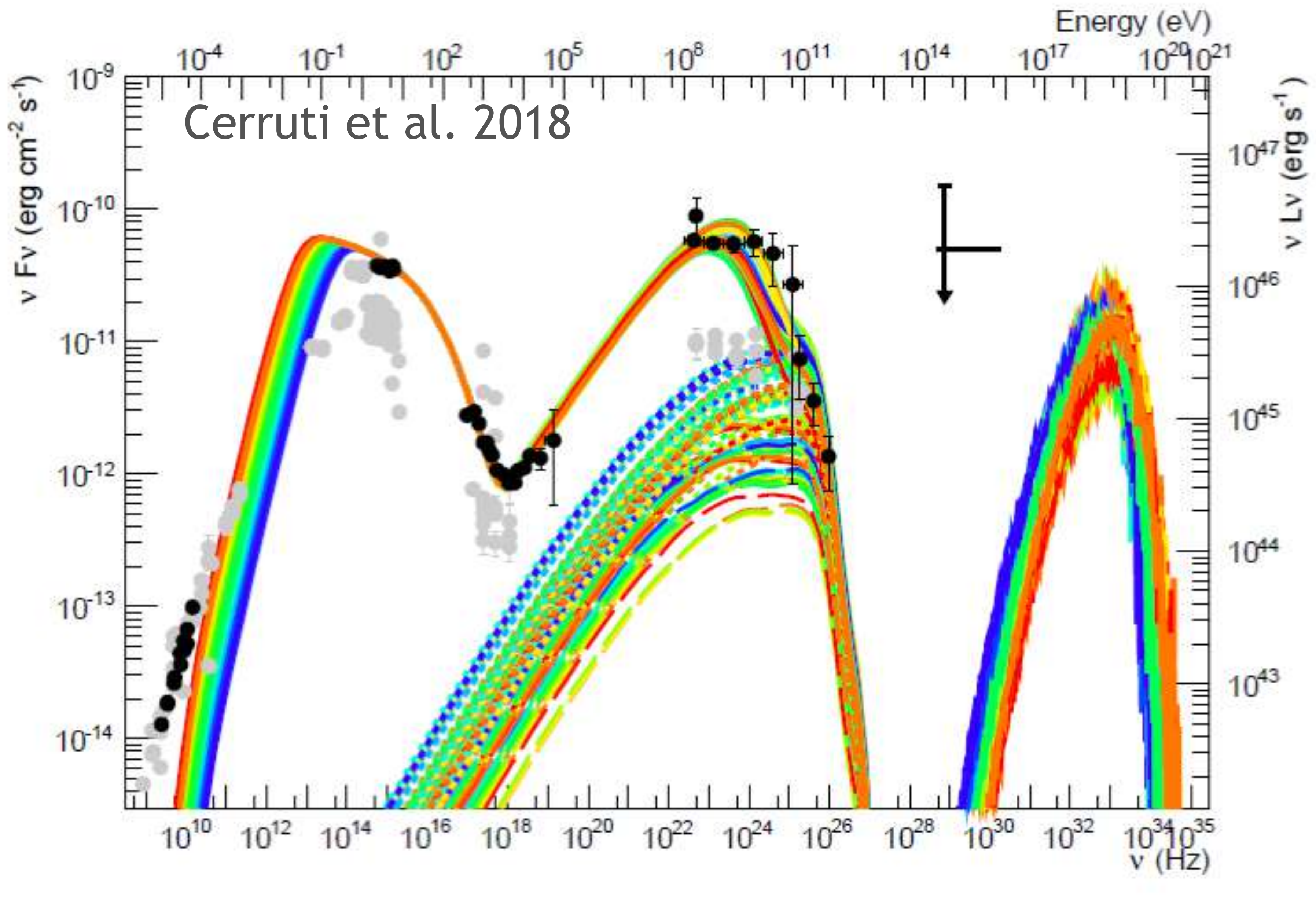


2014-15 ν flare

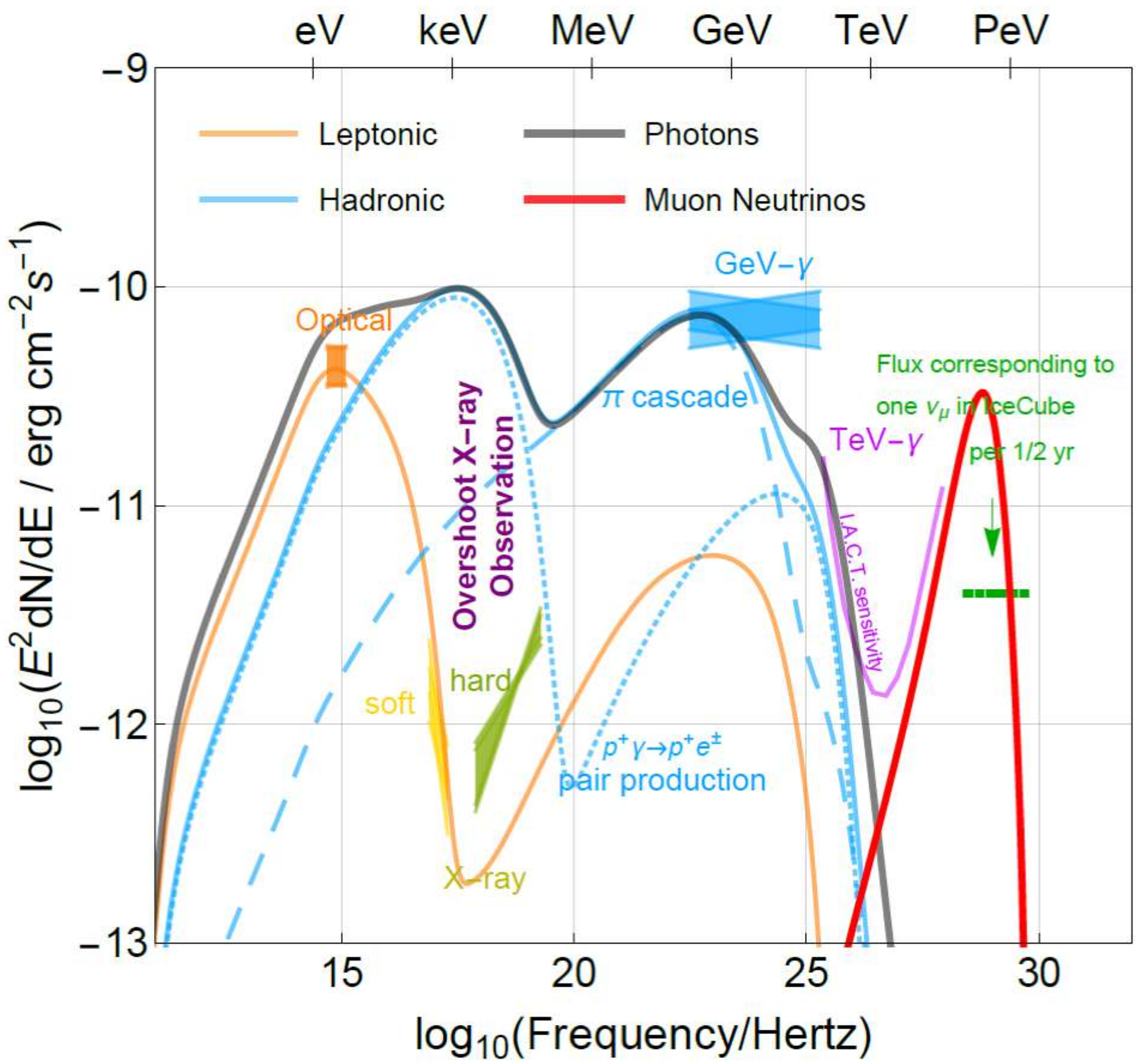
Energetics of the SED

No straightforward theoretical explanation for the photon SED - neutrino association.

- General scenario would be photo-pion production
  - For $\nu \sim 100$ TeV, need $E_p \sim 200E_{14}\delta_1^{-1}$ TeV and $E_{ph} \sim 1.6E_{14}^{-1}\delta_1$ keV (X-rays)
- But the model fits to SED either **overestimate the X-ray photon component** (e.g., Gao et al. 2018) or predict **too high neutrino energies** (e.g., Cerruti et al. 2018)



(a) Proton synchrotron modeling of TXS 0506+056



Gao et al. 2018

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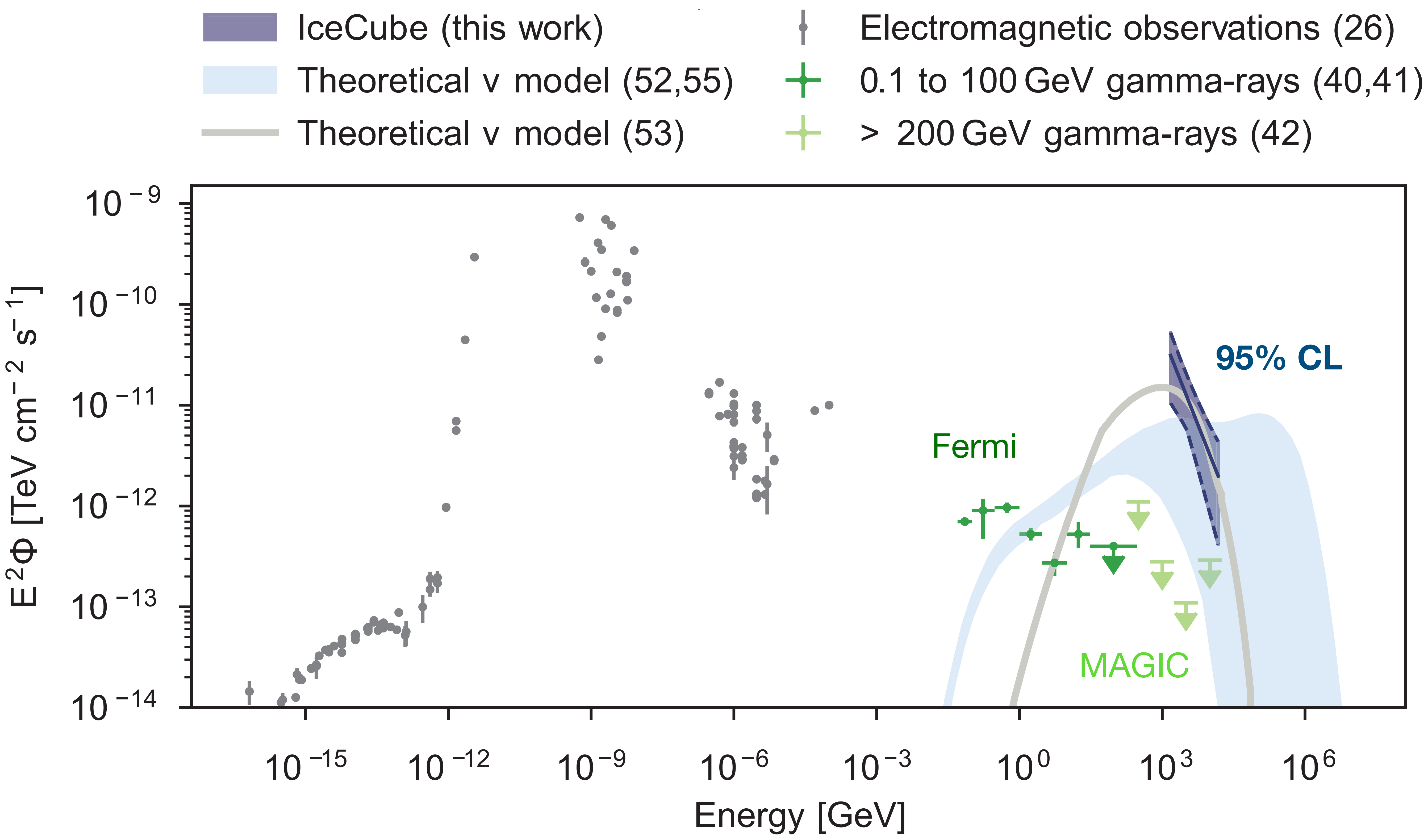
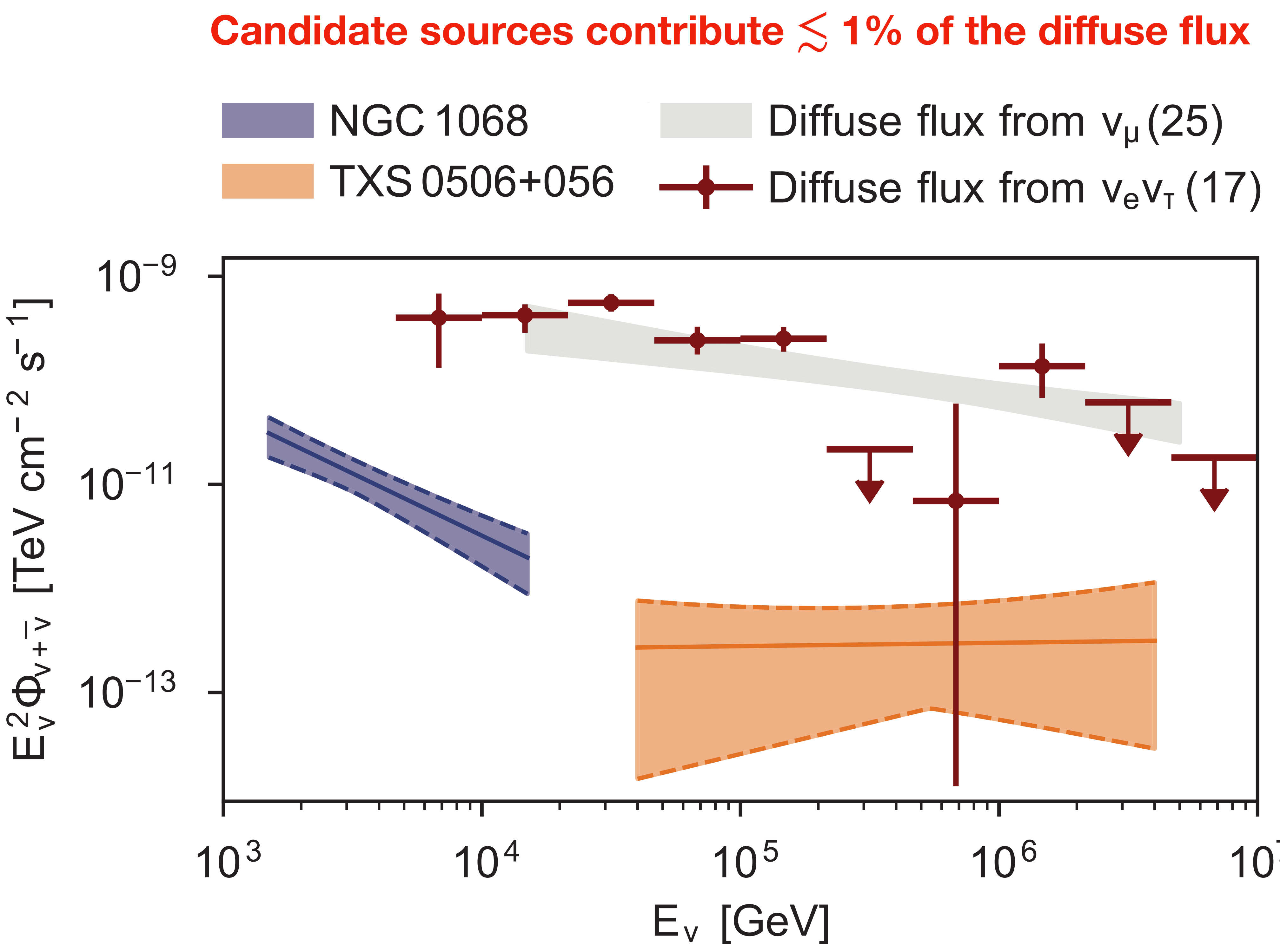
- But, the model fits to SED either **overestimate the X-ray photon component** (e.g., Gao et al. 2018) or **predict too high neutrino energies** (e.g., Cerruti et al. 2018)
- Detailed analysis by Reimer et al 2019 suggested that the 2014-15 neutrino flare and the gamma-ray emission from TXS 0506+056 **could not have originated in the same process**, from constraints derived on the development of photo-hadronic initiated EM cascades.
- **More individual source coincidences are necessary** to reinforce the statistical connection and provide further observational elements to guide and constrain theoretical modelling.

MM view of NGC 1068

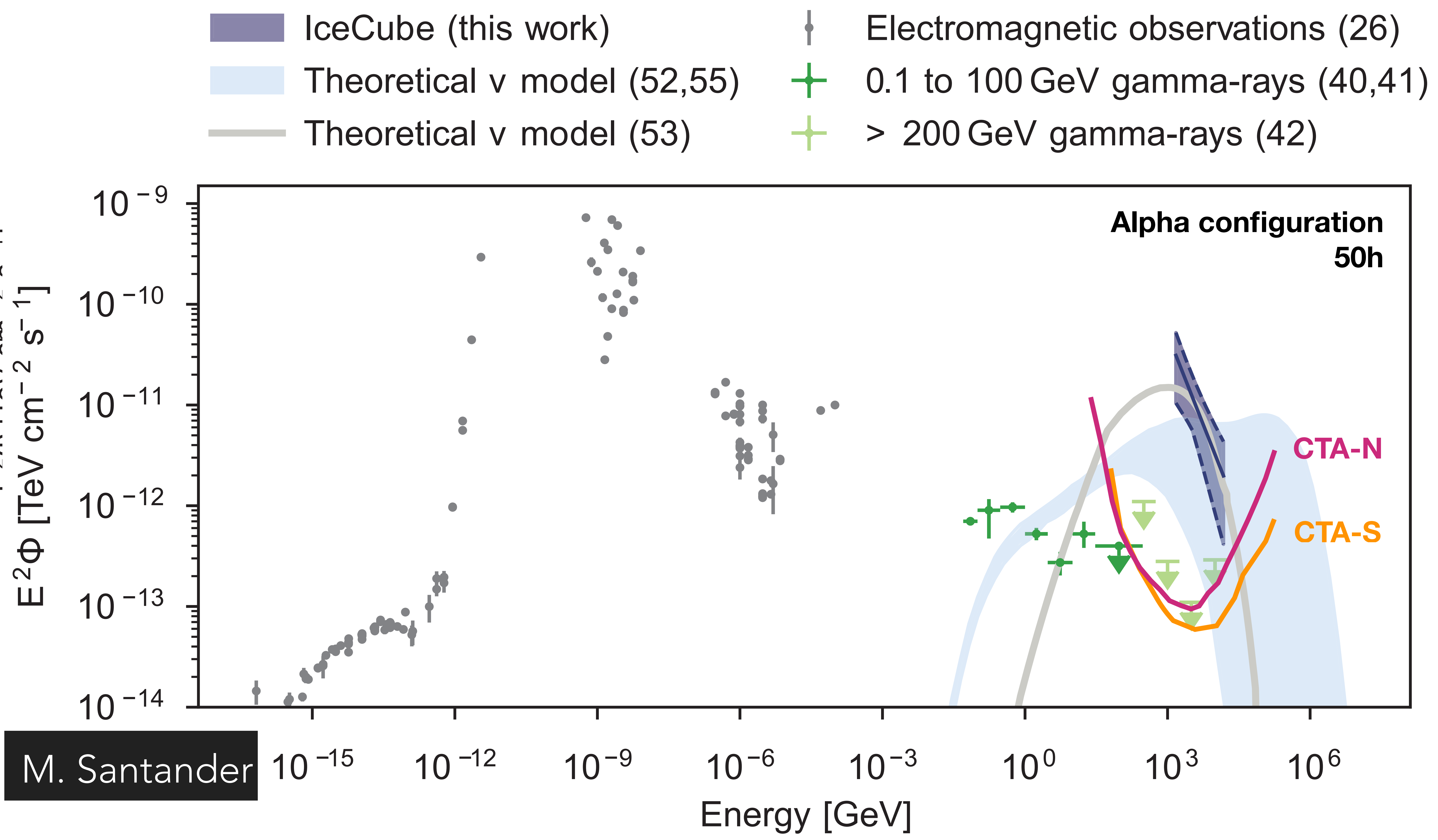




Gamma-ray opaque neutrino emitting region is favoured (20x more gamma flux expected).

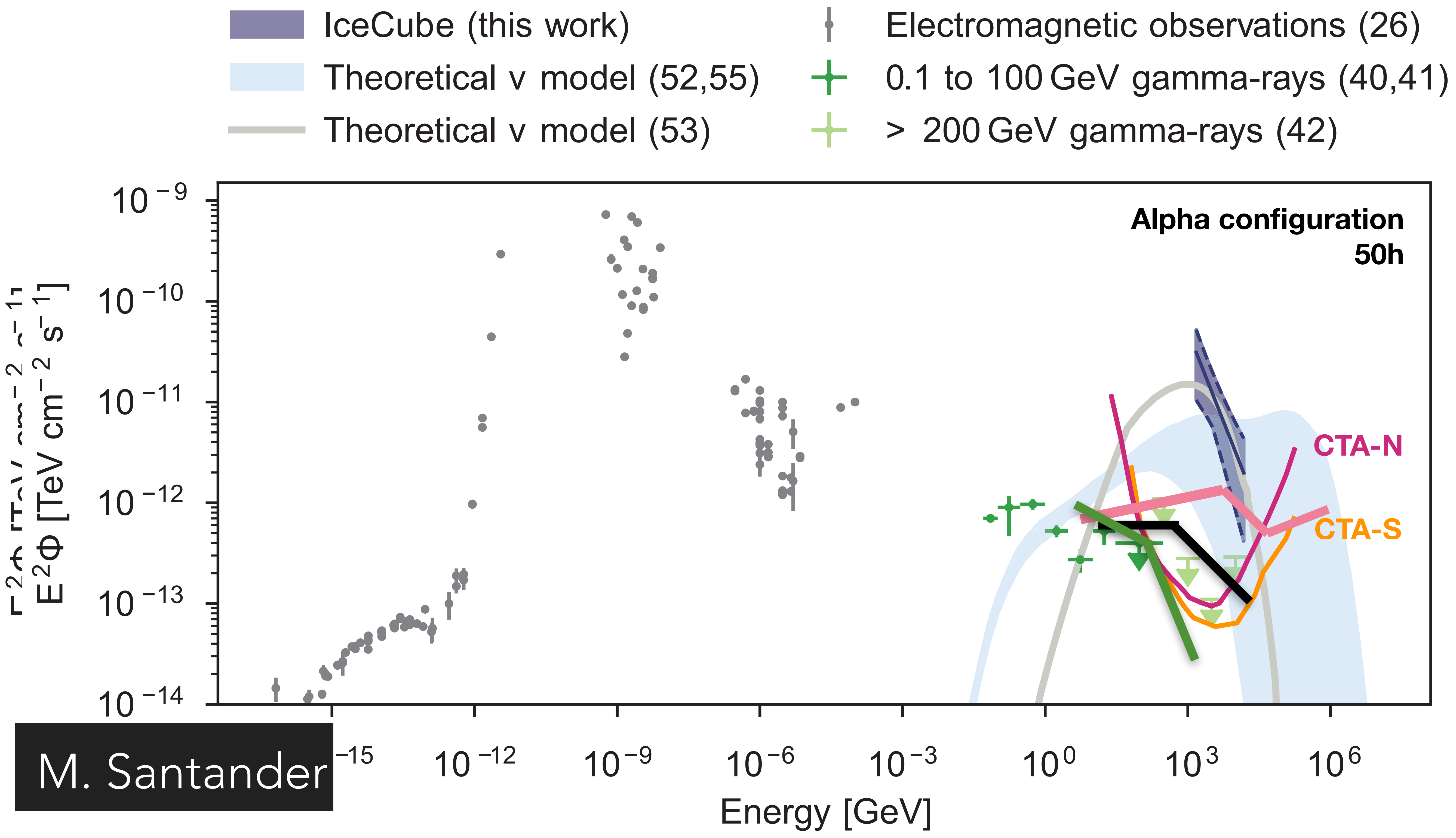
X-ray bright excess?

How can CTA contribute?

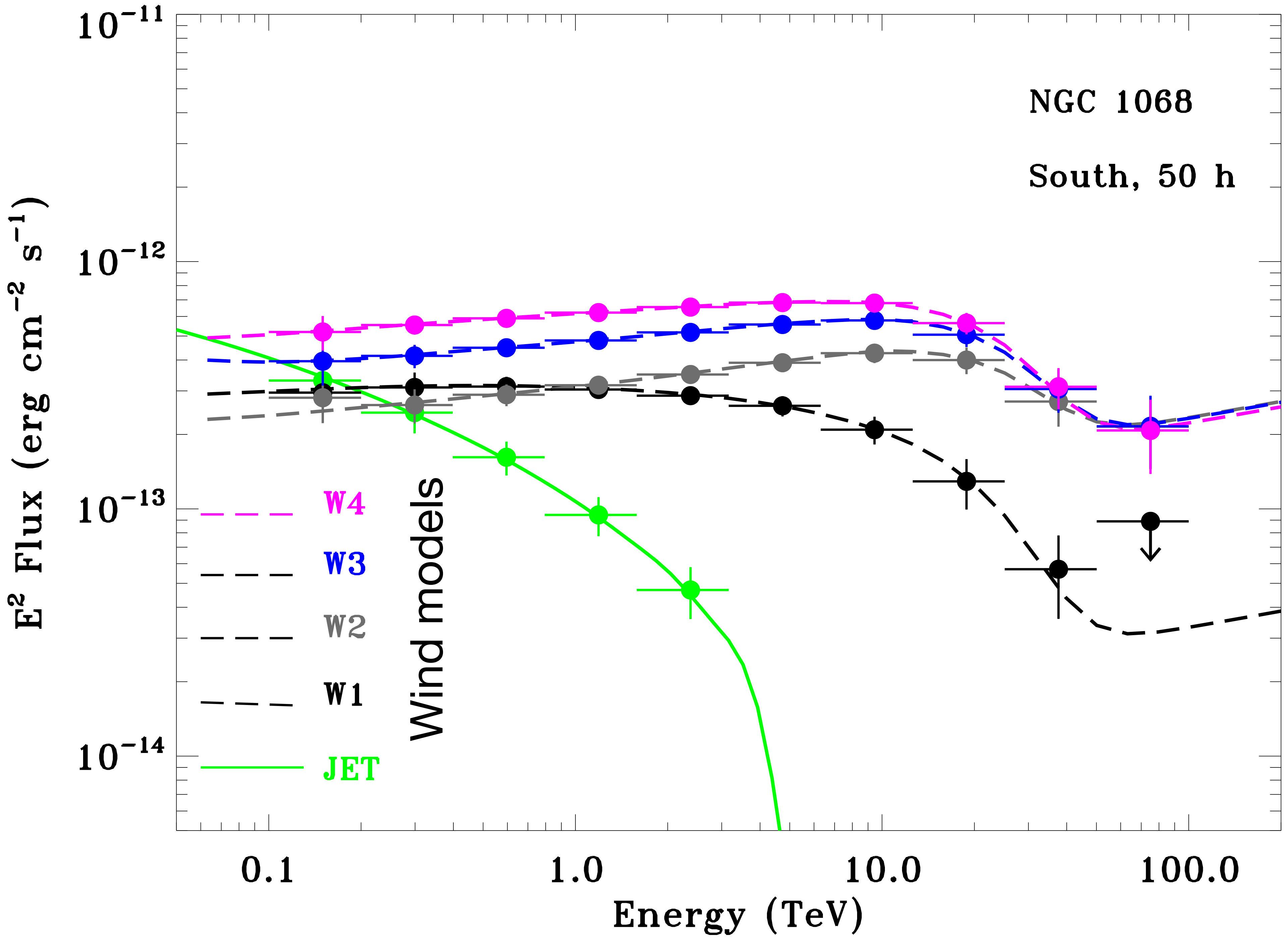


M. Santander

How can CTA contribute?



Lamastra et al. 2019

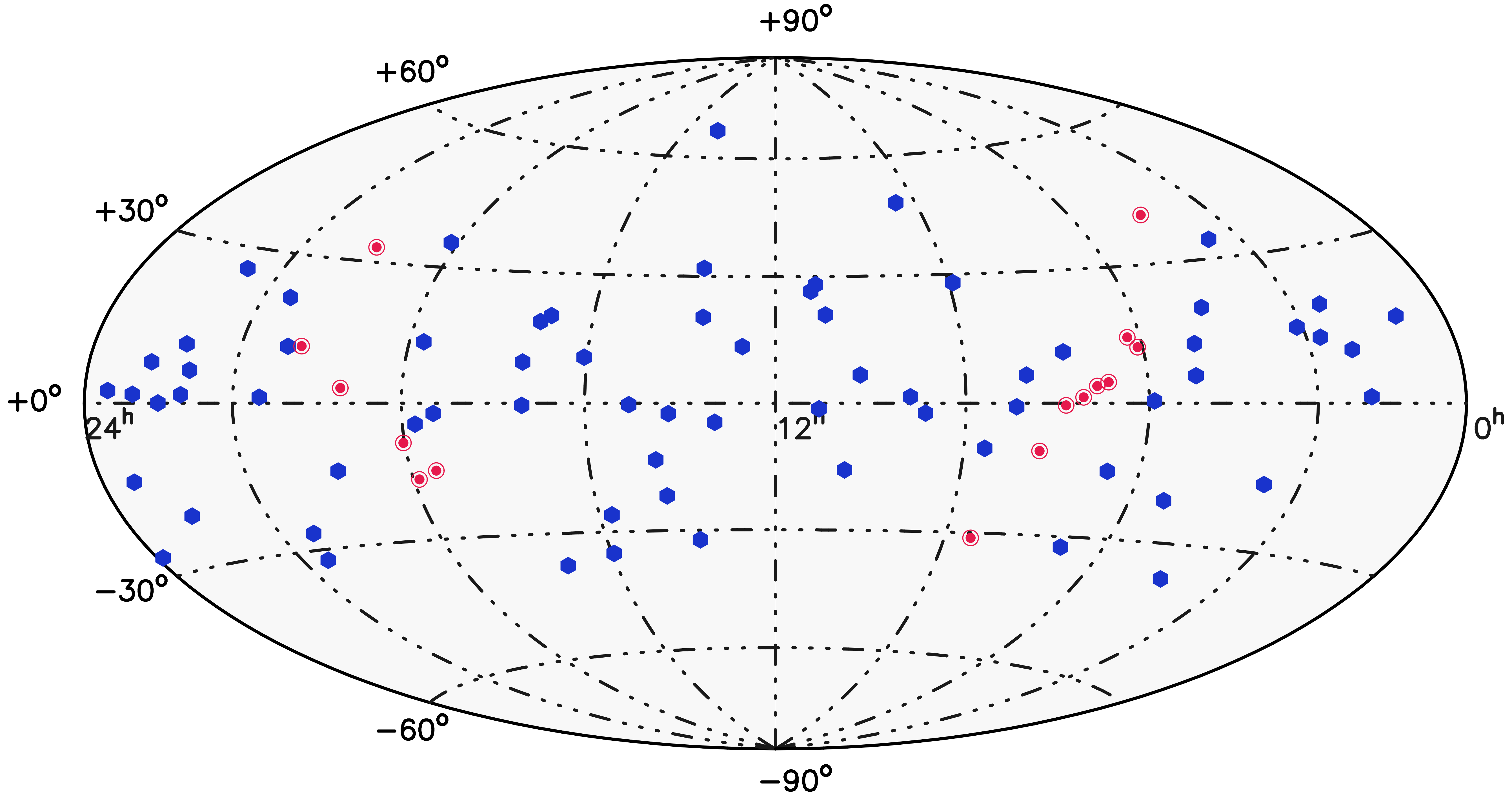


CTA will have sufficient sensitivity to probe the wind / jet emission of NGC 1068

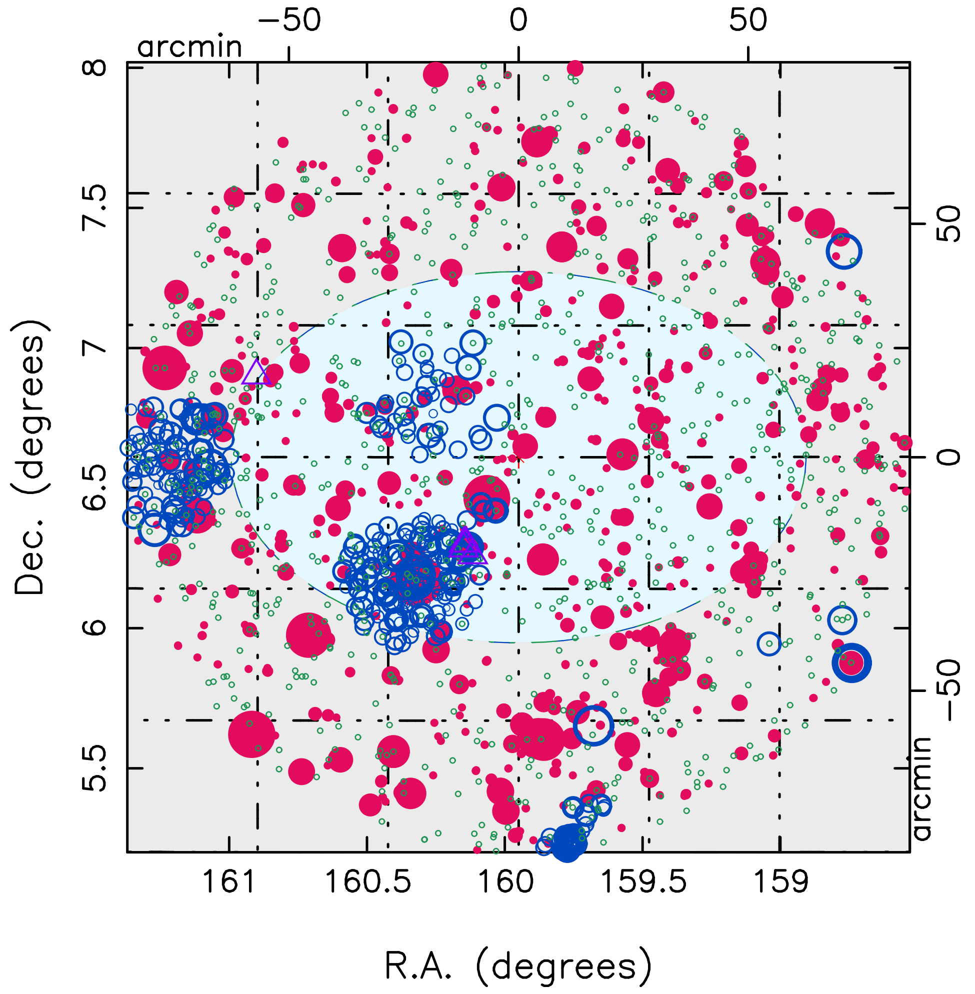
Leading to constraints to the source most likely origin of the neutrino flux

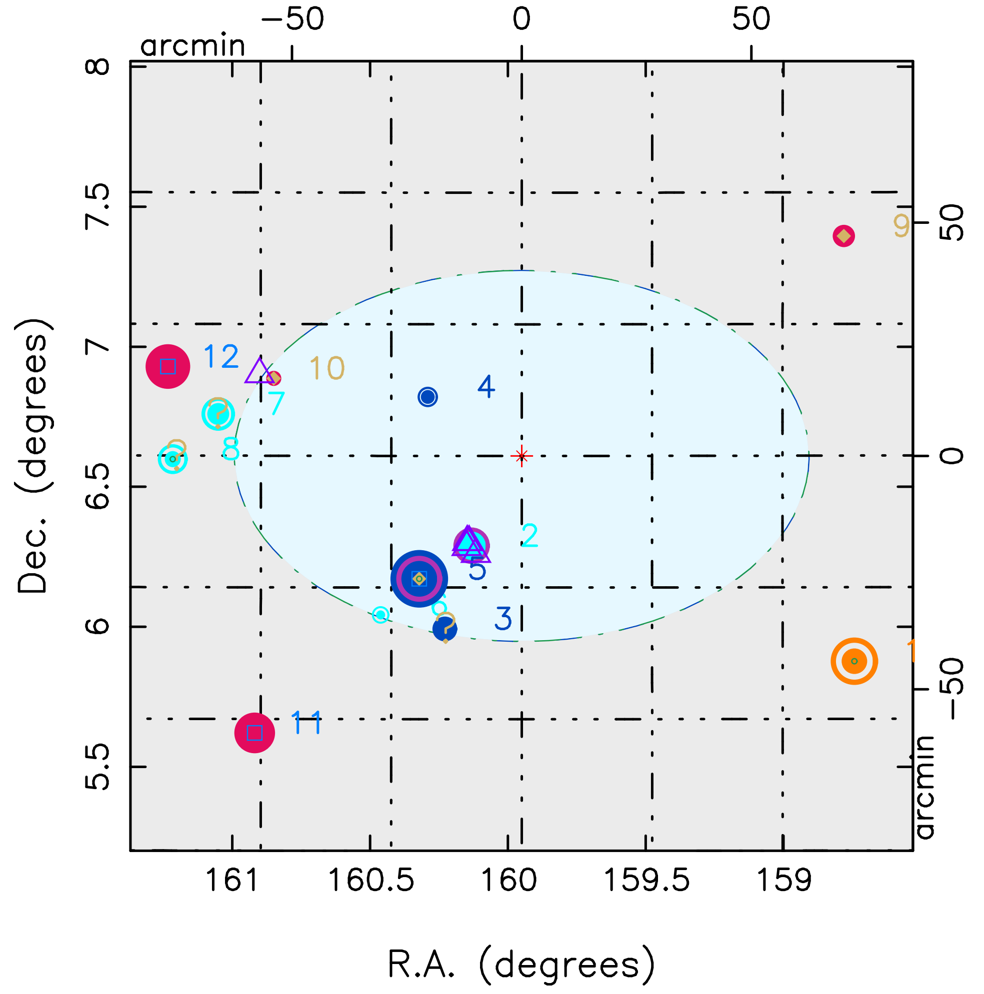
A closer look at the neutrino sky

An alternative approach is to look for population correlations between neutrino events and candidate blazar sources.



Sky distribution of high-energy IceCube neutrinos
P. Giommi et al. 2019



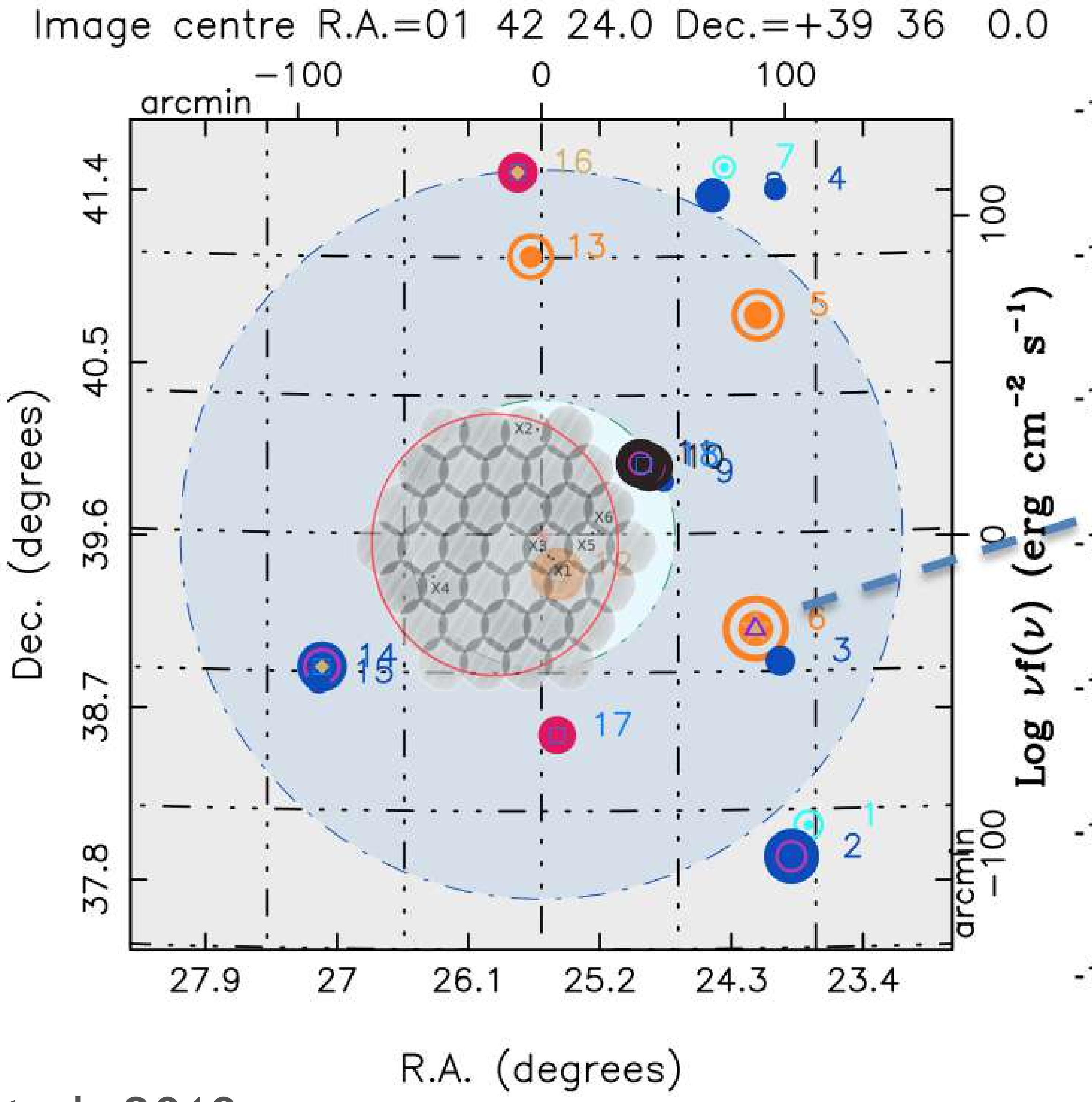


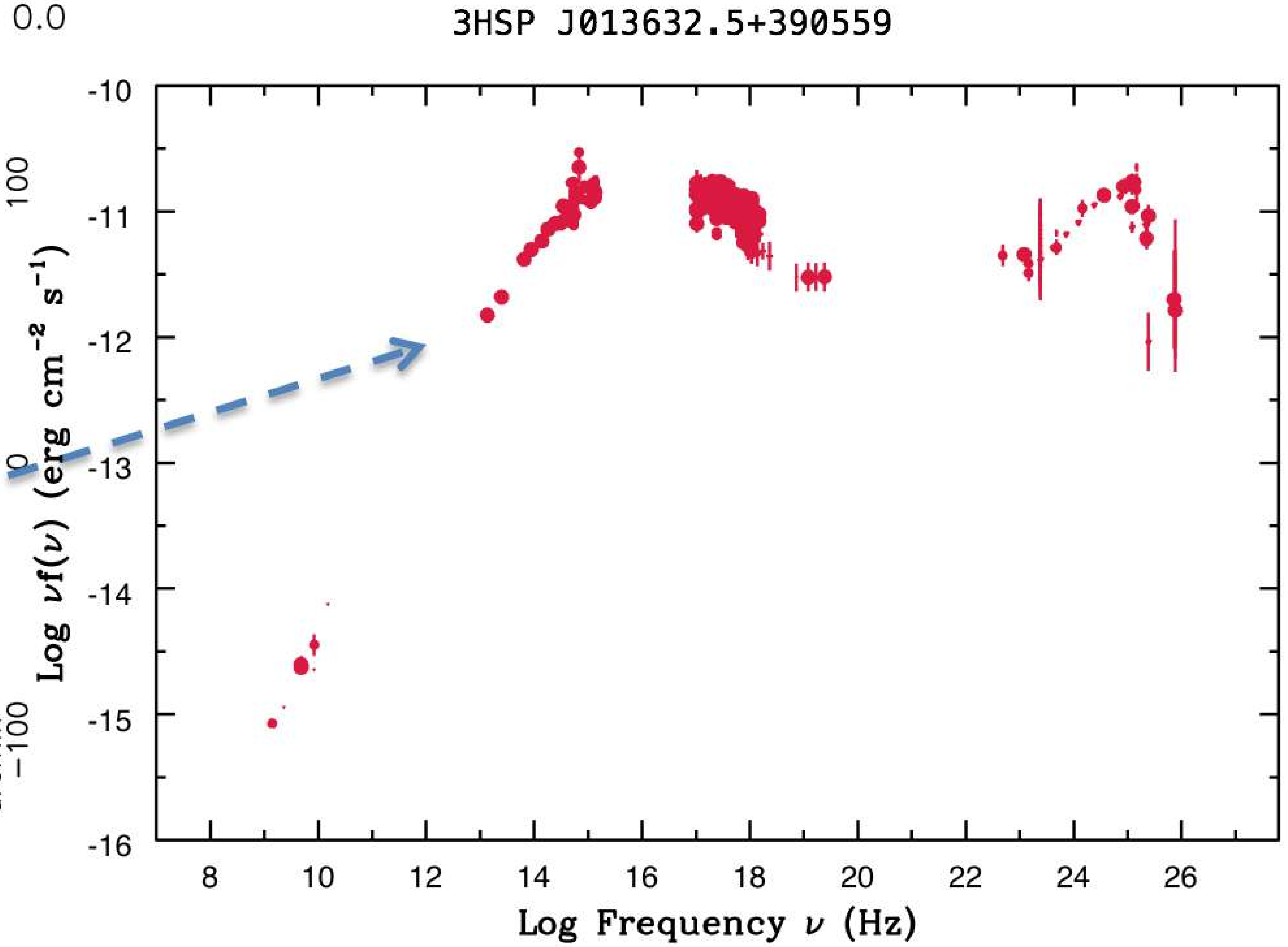
Top: Multi-wavelength counterpart candidates in a sample neutrino region.

Bottom: blazar counterparts

Virtual Observatory Data Tools

Cross-matching between blazar and neutrino catalogues VO tools, is a promising avenue — allows for a selection of best candidate counterparts by providing complete SED information on the sources.





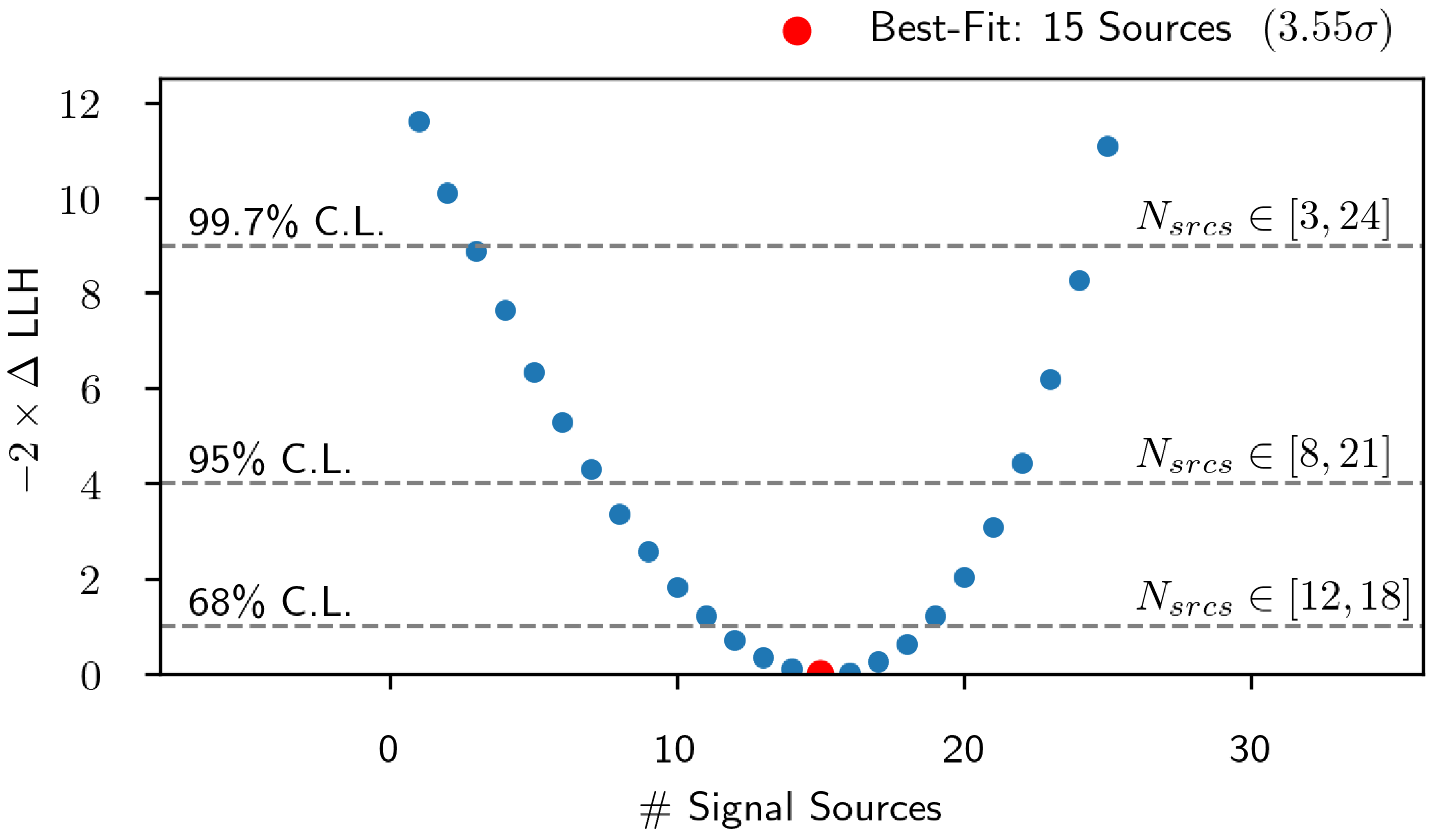
Left: In this case showing the error regions and candidate counterparts for the 2016 triplet 1 TeV neutrino event (< 100s)

Right: and the corresponding SED for one of the 3HSP blazar counterpart candidates.

P. Giommi et al. 2019

Most promising results in blazar-neutrino cross-match

A marginal 2.8σ excess on the positional coincidence between good localisation neutrinos events and the blazars from the 3HSP

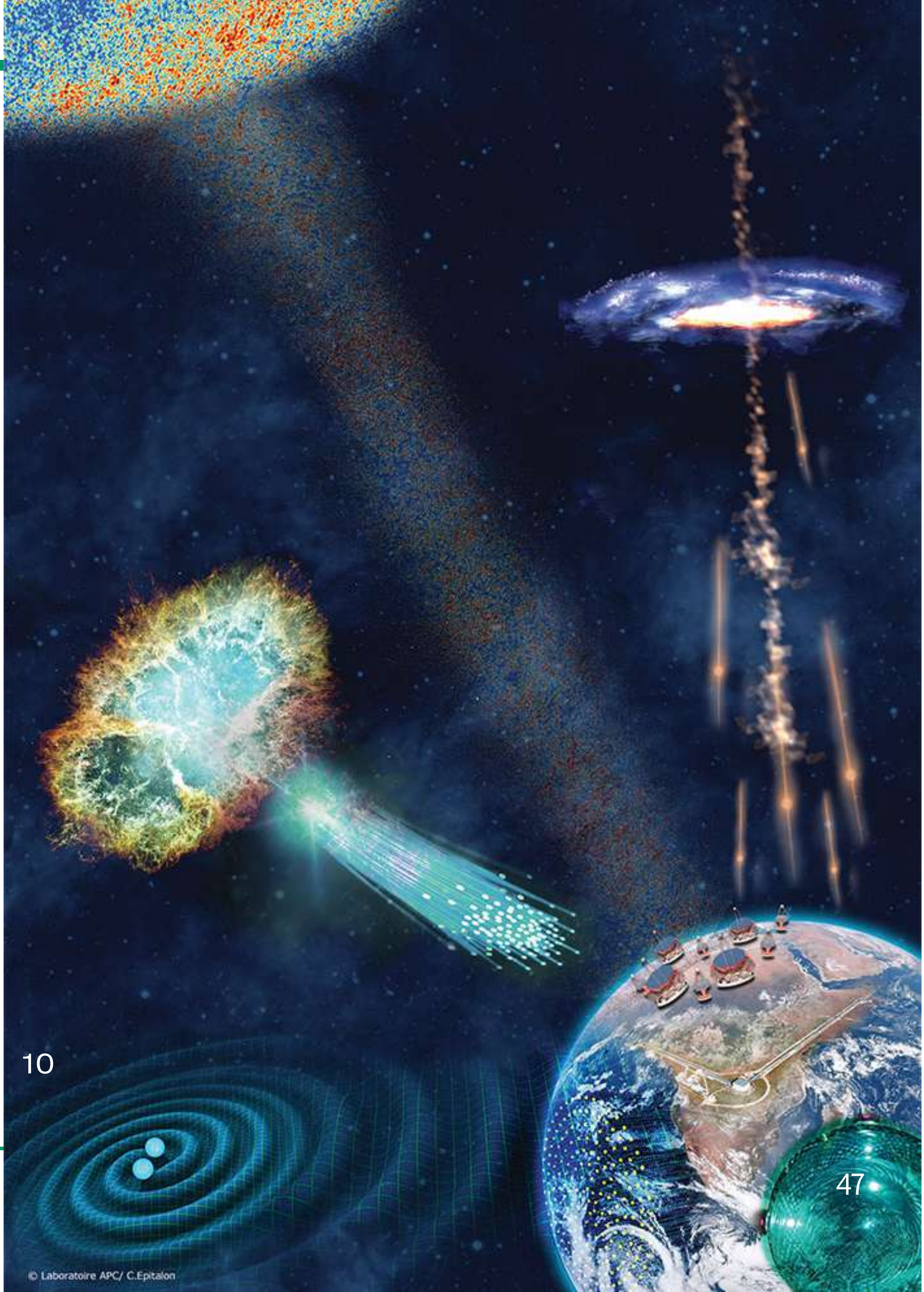


Excess HBL coincidences between neutrino and 3HSP blazars.

Excess for gamma-ray detected HBLs in neutrino positions (1.3x 90% containment region), at the 3.6σ level, = 15 excess HBLs with respect to chance coincidence.

P. Giommi et al. 2019

CTA coordination activities



MM Neutrino Studies with CTA

Extragalactic / transient studies

- Follow-up of sub-PeV astrophysical neutrino events
- Real-time correlation studies with active gamma-ray sources

Galactic Searches

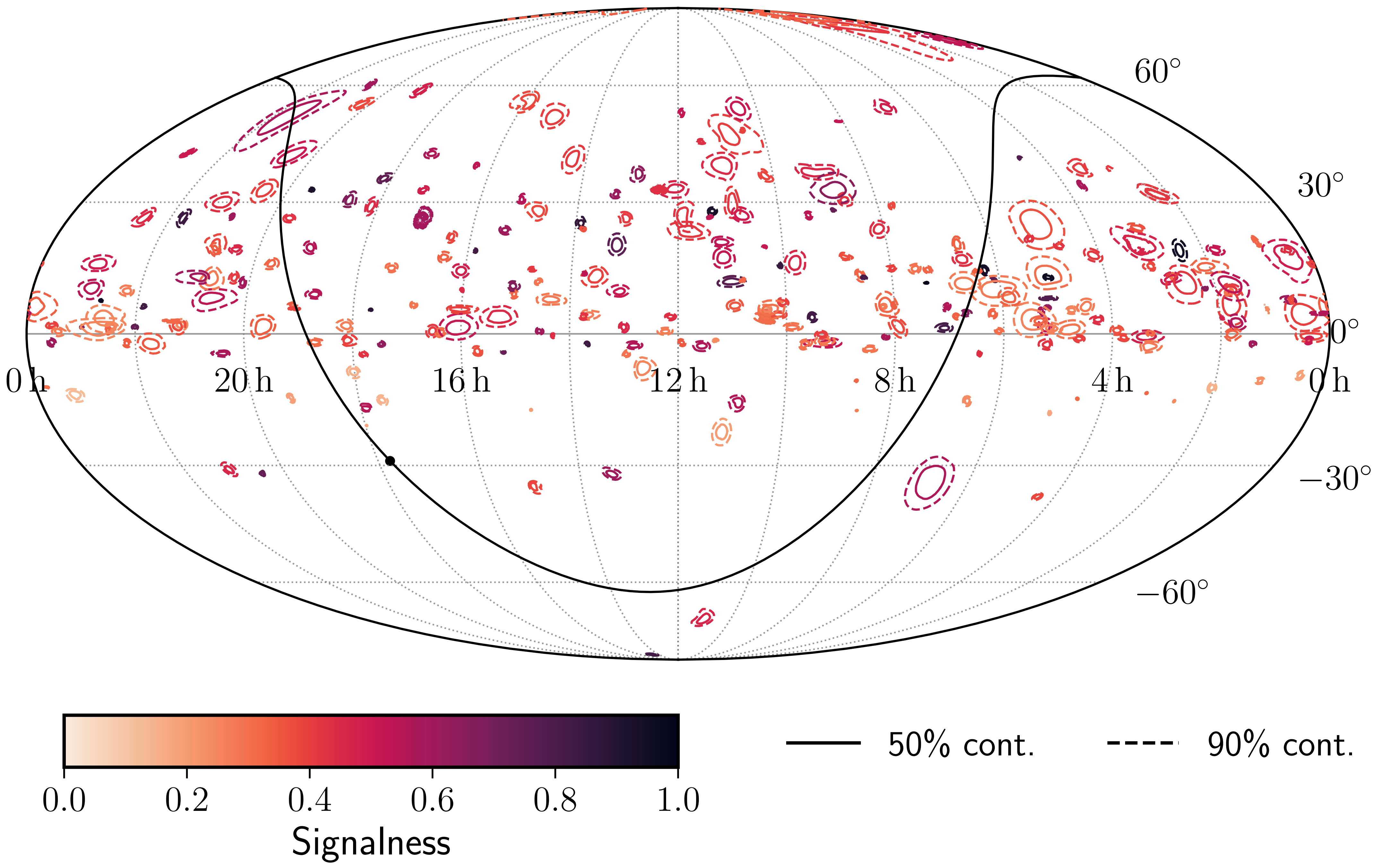
- Focus on hadronic emitters such as SNR, Novae, > 100 TeV
- And searches for correlations in diffuse emission

The Unknown Unknowns

- Dark sources or unidentified sources
- New types of objects like tidal disruptions

Deep astrophysical view of candidate sources

IceCube neutrino alerts



Neutrino FIRESONG (Tung et al. 2021)

https://github.com/ChrisCFTung/FIRESONG

CTA strategy: Neutrino Target of Opportunity (NToO):

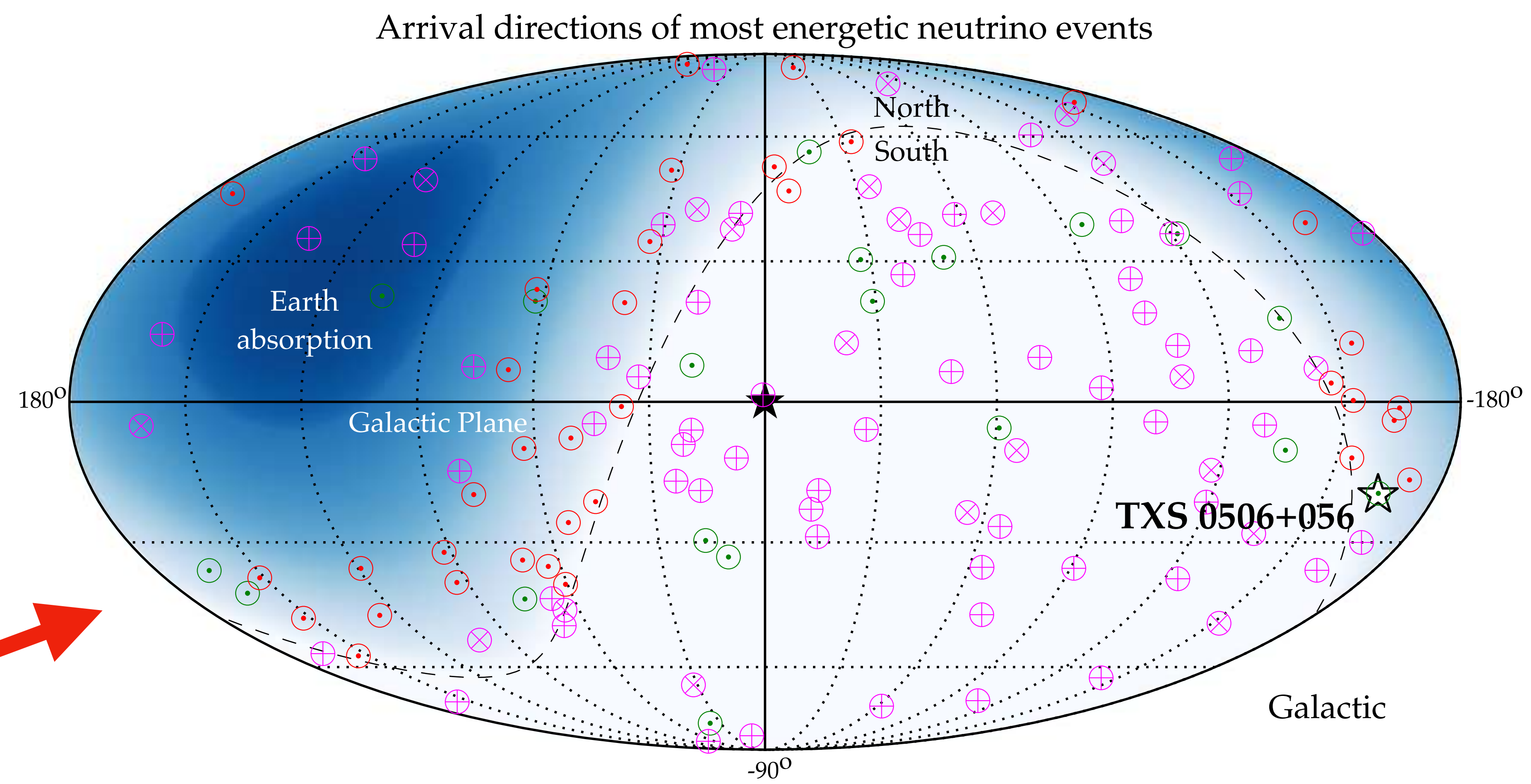
- Transients: CTA search for gamma-ray counterpart from a neutrino alert
- Steady sources: monitor hotspots exceeding IceCube sensitivity

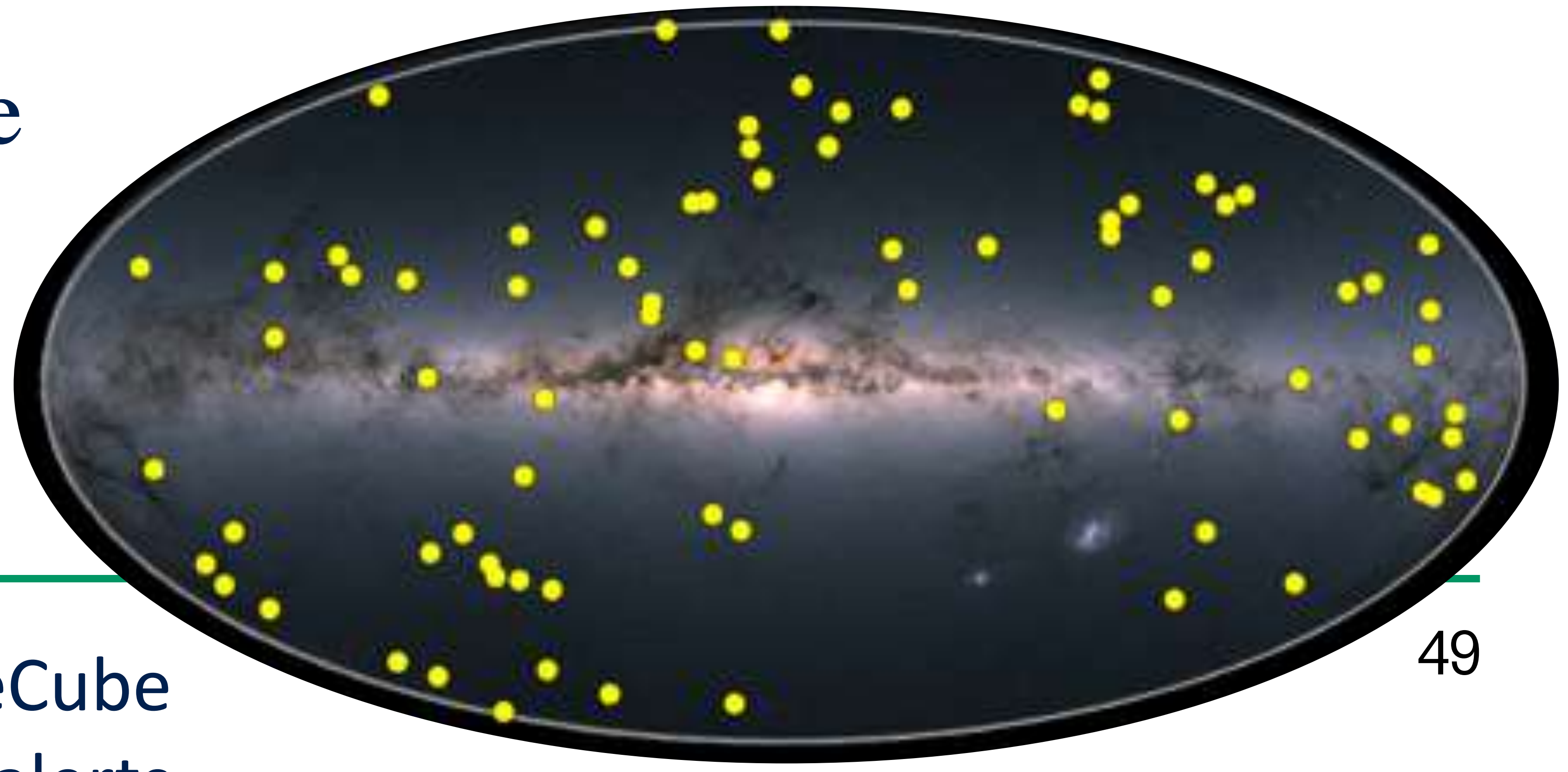
FIRESONG

- Simulate a neutrino population according to source evolution and luminosity function

Density vs. Luminosity plot

- Steady sources: sources/Mpc^3 vs. neutrino luminosity
- Transient sources: burst rates/Mpc^3 (%flaring blazars) vs. neutrino flare luminosity





IceCube neutrino alerts

- **IC-170922A:** TXS 0506+056 (z = 0.3365) *IceCube Collab. 2018*
- **IC-190730A:** PKS 1502+106 (z = 1.84) *IceCube Collab. 2019*
- **IC-200107A:** 3HSP J095507.9+355101 (z = 0.557) *IceCube Collab. 2020*
- **IC-141209A:** GB6 J1040+0617 (z = 0.7351) *Garappa et al. 2019*

Neutrino FIRESONG (Tung et al. 2021)

https://github.com/ChrisCFTung/FIRESONG

Steady Sources

Standard candles, follow the SFR evolution model of Madau & Dickinson (2014)

Local density $\rho = 10^{-12}$ to 10^{-5} Mpc^{-3}
Luminosities: $L_\nu = 5\times10^{47}$ to 10^{57} erg/year

Gamma-ray flux parametrised assuming $p\gamma$ interactions
Ahlers & Halzen (2018)

Sources exceeding the IceCube sensitivity (Aartsen et al., IceCube Collaboration, (2019)) are used as seeds of the NToO for CTA

Assuming all the sources are always observable by CTA

Transient Sources

Standard candles and the flat cosmological evolution

Based on the neutrino flare model of TXS 0506+056 in 2014-2015
Halzen et al., ApJ 874 (2019)

Only a fraction **F** (1%, 5% and 10%) of all blazars is responsible for the astrophysical neutrino flux

All the sources are assumed to have the same flare duration in their reference frame (110 days @z TXS)

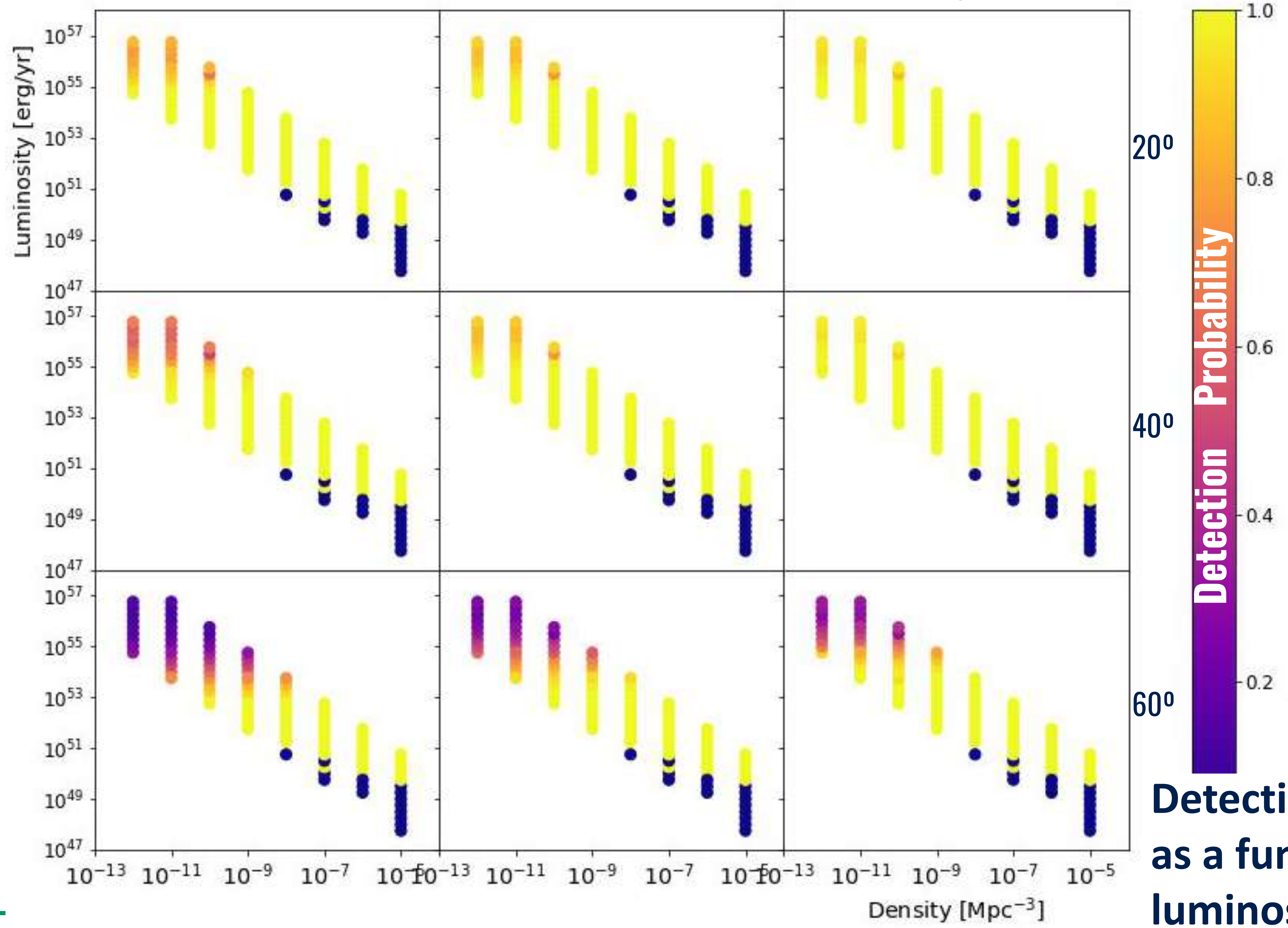
Assuming IC Gold alerts and events always observable by CTA

O. Sergijenko

Neutrino FIRESONG (Tung et al. 2021)

https://github.com/ChrisCFTung/FIRESONG

CTA-N; 30 min obs; SFR evolution



Detection probability as a function of source luminosity and local density of sources, for 30 exposure

PoS(ICRC2021)975

Steady Sources

Assuming these sources will be always observable by CTA:

At low-mid zeniths (20º-40º) CTA-N detects all sources up to ρ= 10^{-9} Mpc^{-3}

Drastic performance loss, up to 65%, at high zeniths (60º)

Magnetic field effect: 10-30% difference for low to high zeniths

For sources with flat redshift evolution the trends are similar, but less pronounced

O. Sergijenko

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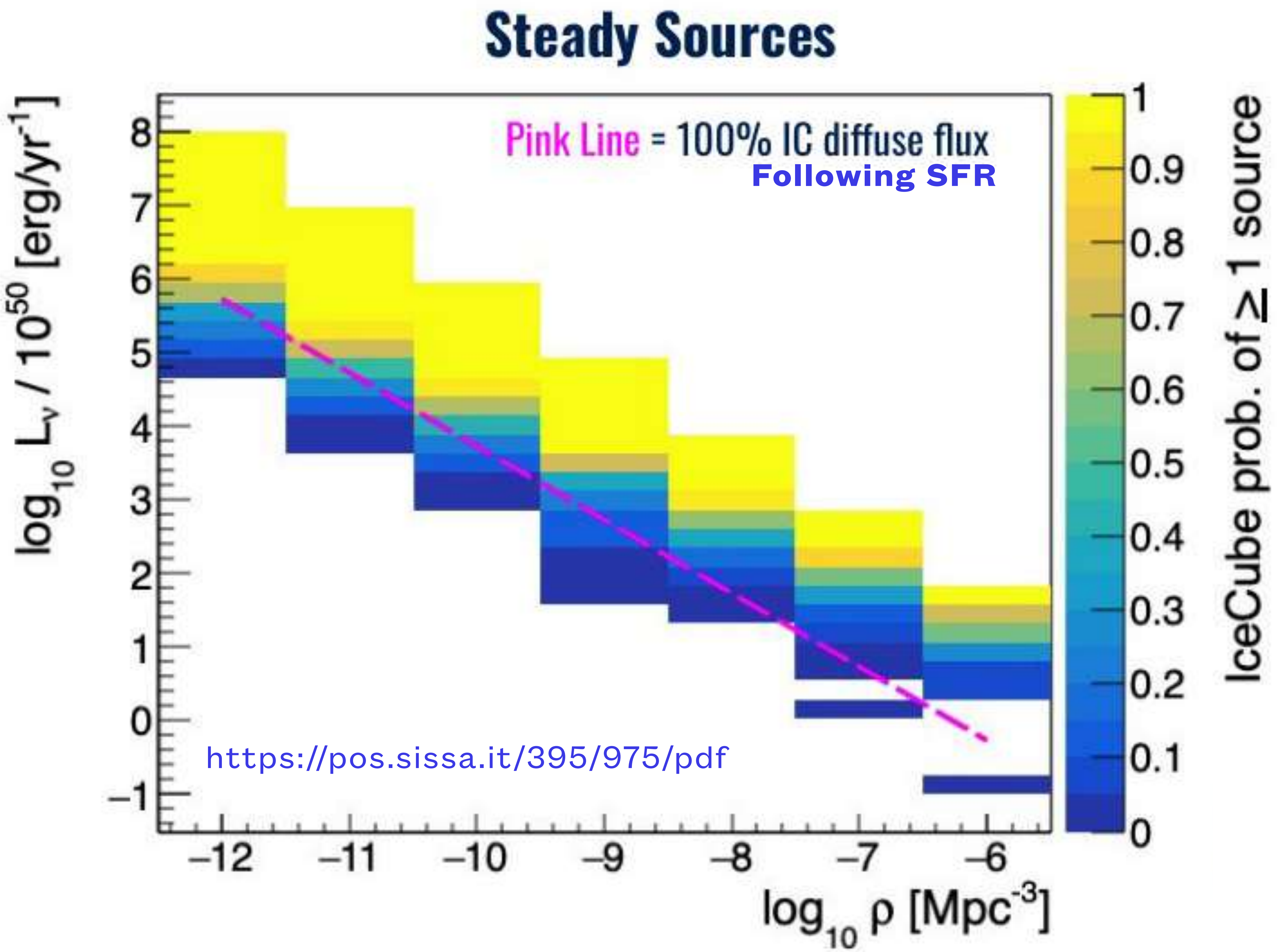

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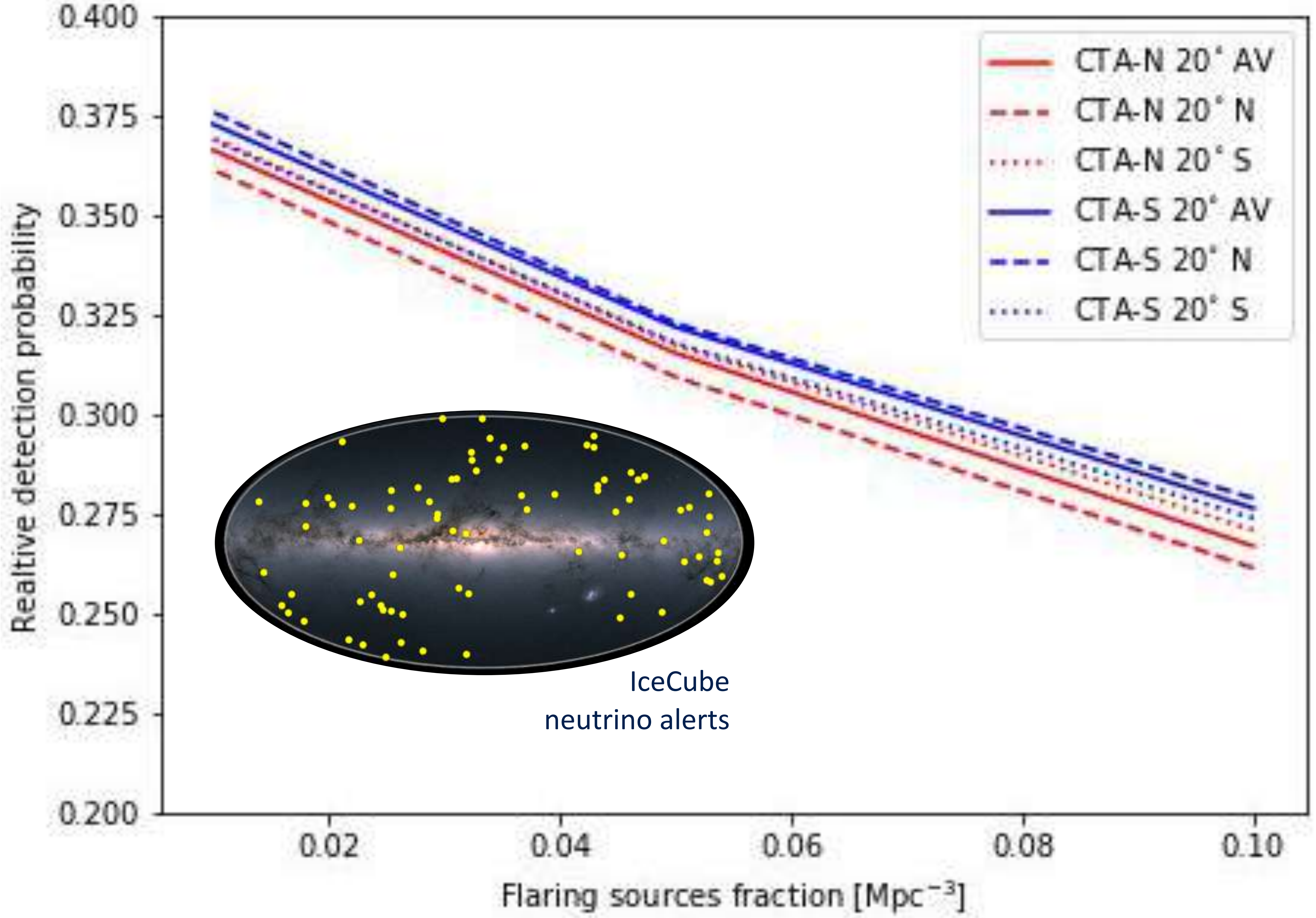
CTA 30 mins obs; Flaring blazars



Transient Sources (Flaring blazars)

Selecting IC Gold alerts (>50 %) and assuming observable conditions by CTA:

CTA detection probability grows while **F** decreases (as expected: flux of each flare is increasing)

Detection probability is almost identical for 20º and 40º zenith IRFs (difference < 1%), decreases by 4% for 60º

Influence of magnetic field is minimal: <0.5% for CTA-S and up to 2% for CTA-N

O. Sergijenko

Thank you for the attention!

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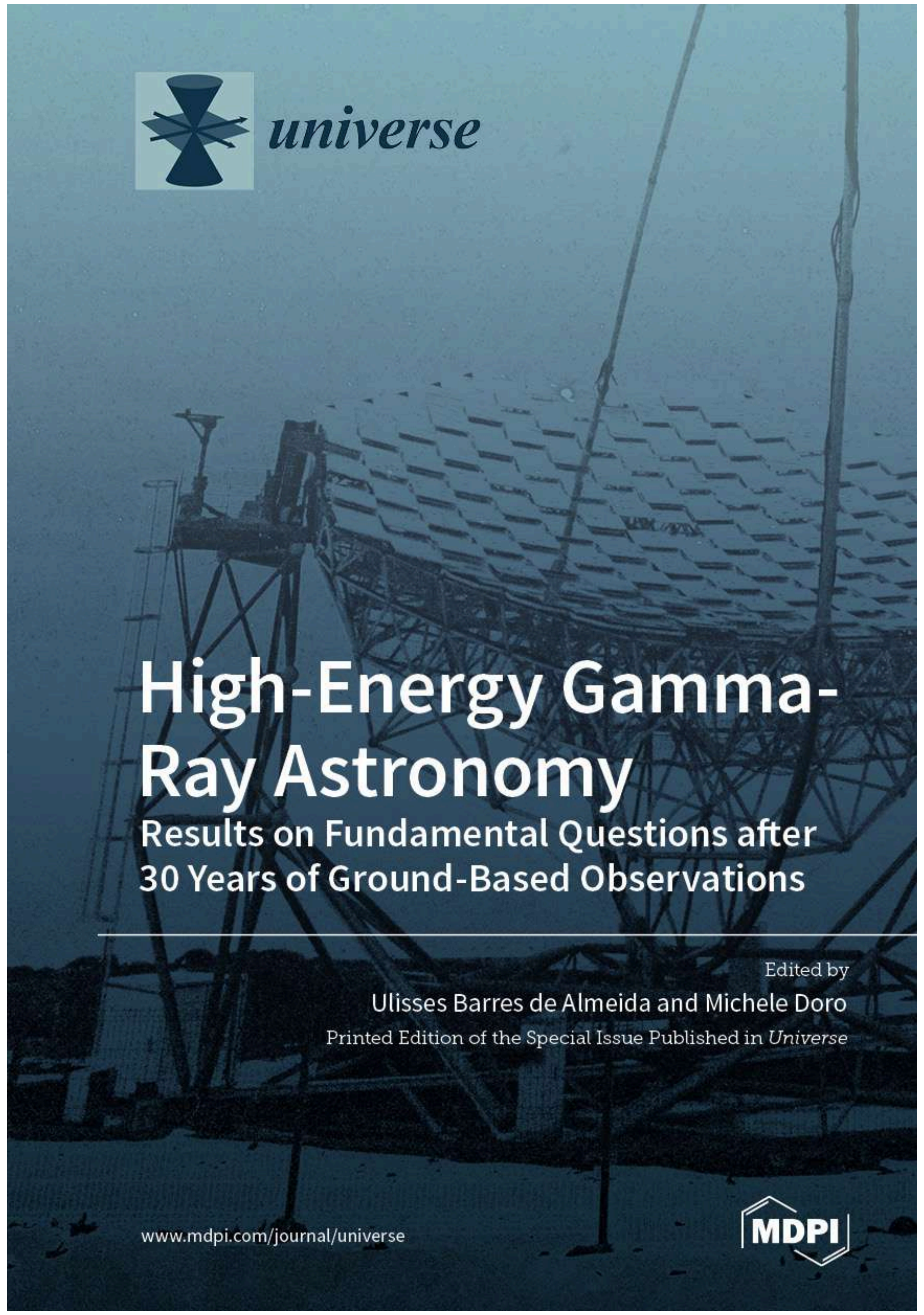

https://www.mdpi.com/books/book/6514