Mapping Highly Energetic Messengers throughout the Universe

Prof. Sara Buson

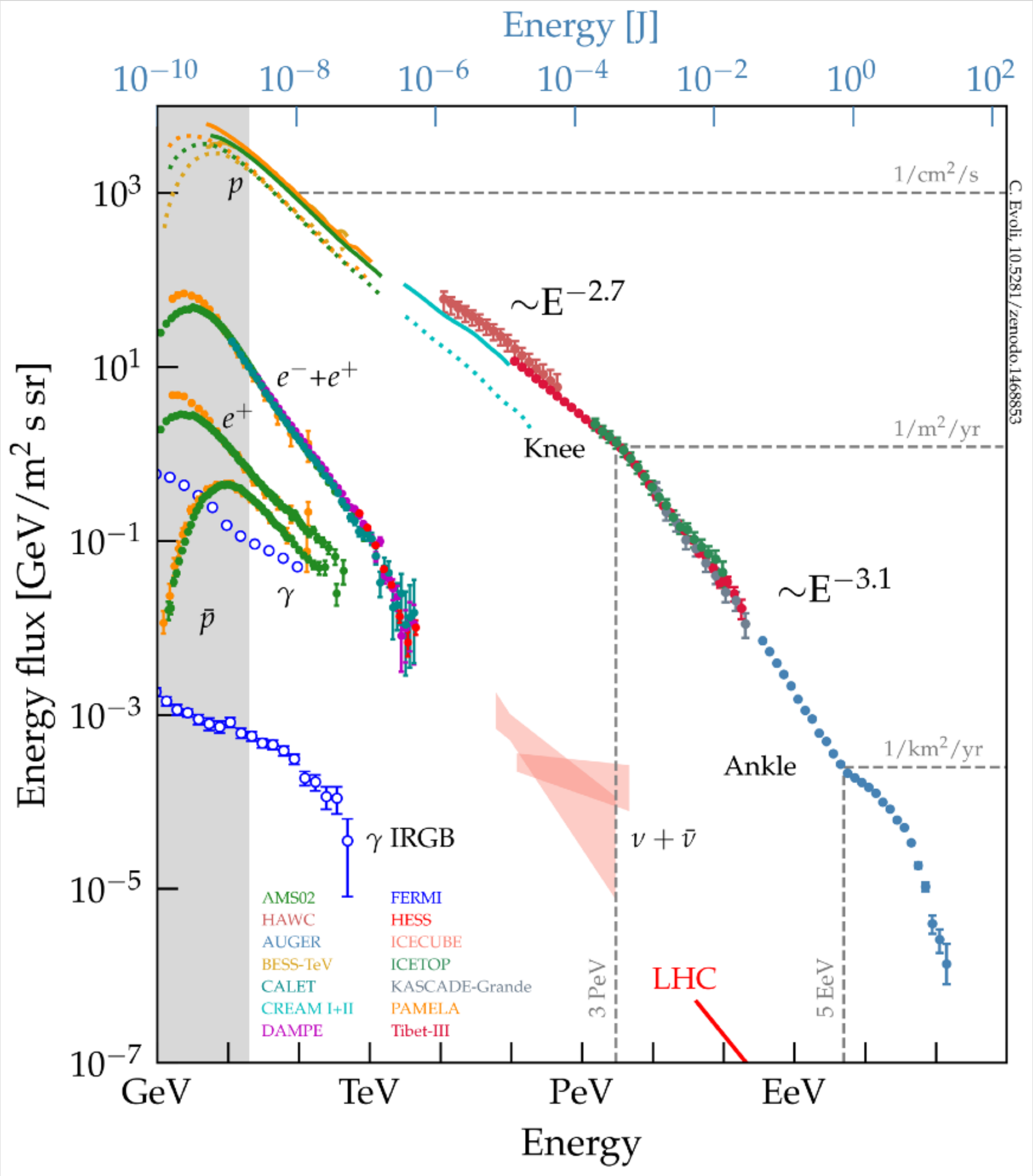
DPG Spring Meeting; Gießen 2024

Cosmic rays

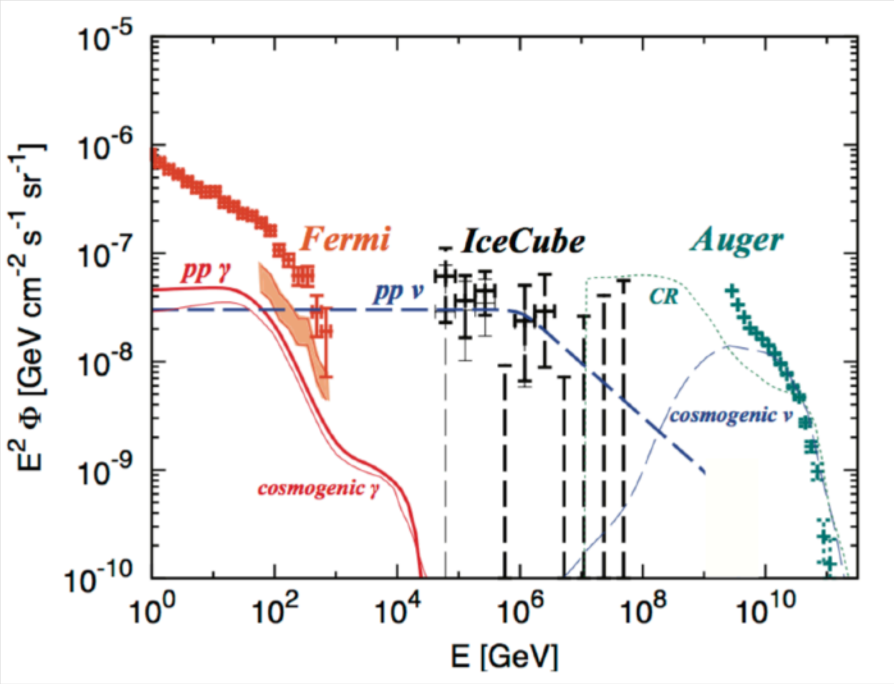
Origin

Composition

Propagation



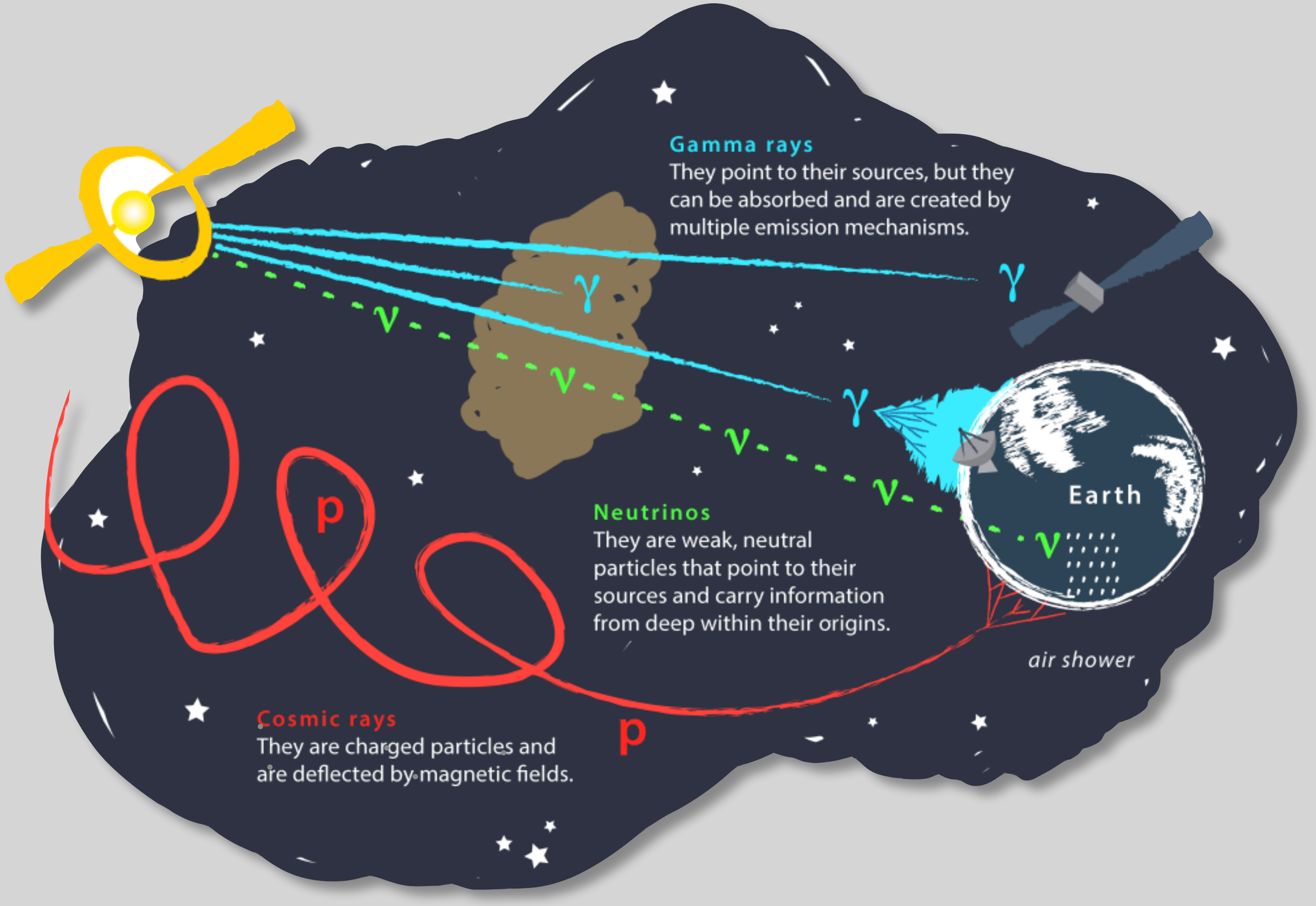
Energy density in the Universe in γ rays, ν, cosmic rays is similar



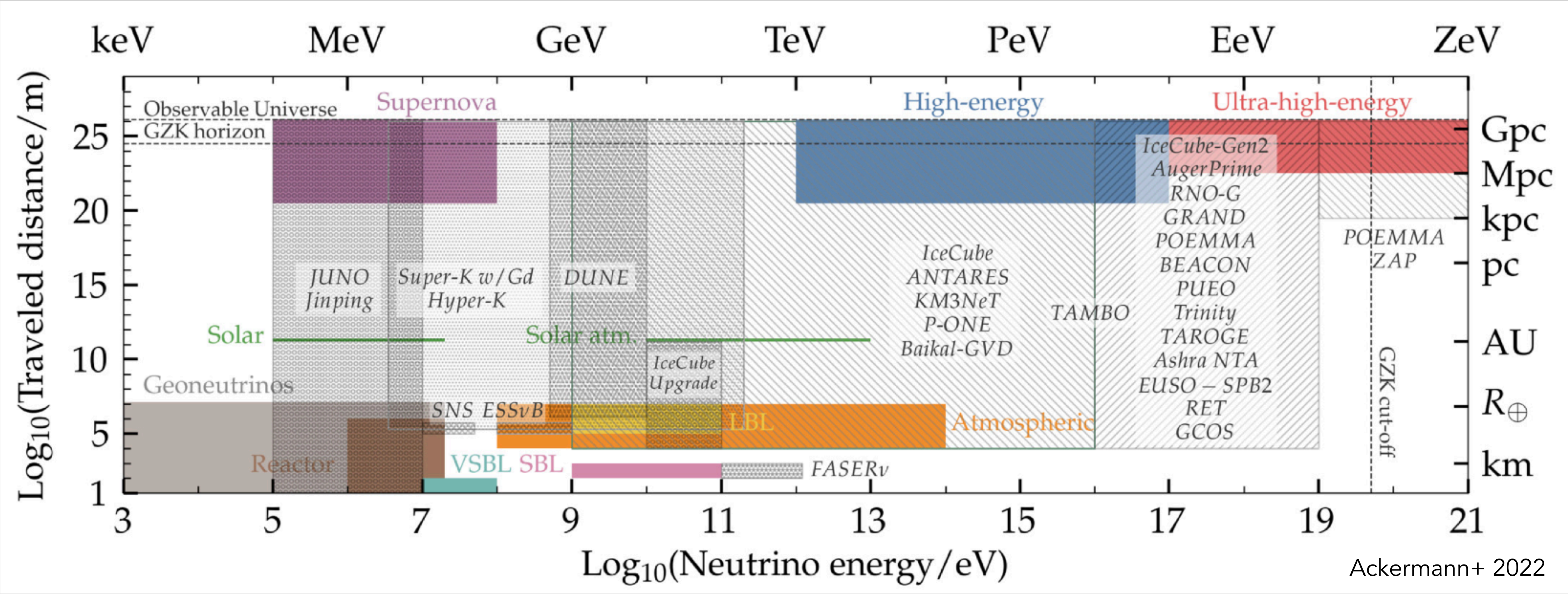
Murase & Waxam 2016

Diffuse energy fluxes of sub-TeV γ rays, PeV neutrinos, and UHECRs are all comparable, while particle energy spans over ten orders of magnitude.

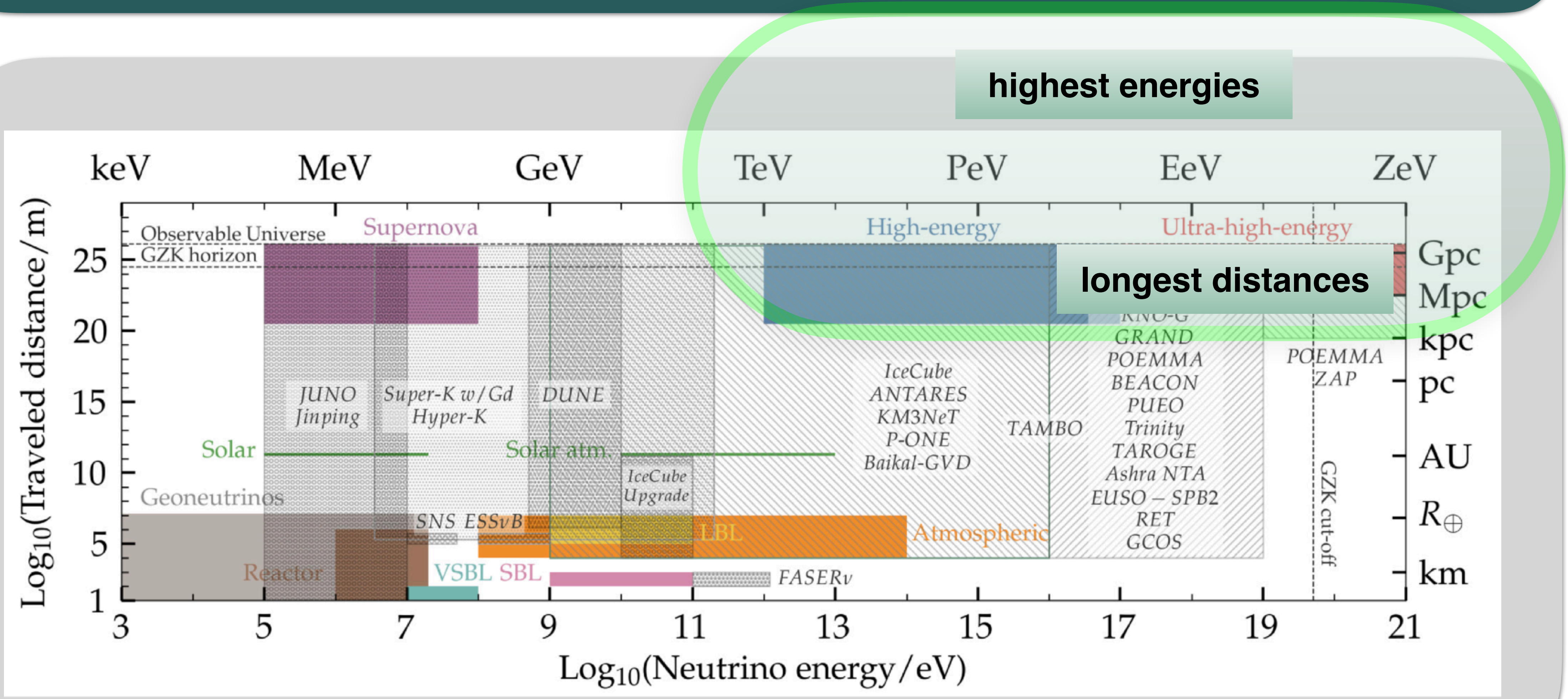
Cosmic rays, γ rays, ν Propagation



Neutrinos


keV
MeV
GeV
TeV
PeV
EeV
ZeV
Observable Universe
GZK horizon
Supernova
High-energy
Ultra-high-energy
Gpc
Mpc
kpc
pc
AU
$R_\oplus$
km
JUNO
Jinping
Super-K w/Gd
Hyper-K
DUNE
Solar
Solar atm.
IceCube Upgrade
IceCube
ANTARES
KM3NeT
P-ONE
Baikal-GVD
TAMBO
IceCube-Gen2
AugerPrime
RNO-G
GRAND
POEMMA
BEACON
PUEO
Trinity
TAROGE
Ashra NTA
EUSO – SPB2
RET
GCOS
POEMMA
ZAP
GZK cut-off
Geoneutrinos
SNS ESSνB
LBL
Atmospheric
Reactor
VSBL SBL
FASERν
Log10(Traveled distance/m)
Log10(Neutrino energy/eV)
Ackermann+ 2022

Neutrinos


highest energies
longest distances
keV MeV GeV TeV PeV EeV ZeV
Observable Universe
GZK horizon
Supernova
High-energy
Ultra-high-energy
JUNO
Jinping
Super-K w/Gd
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Solar
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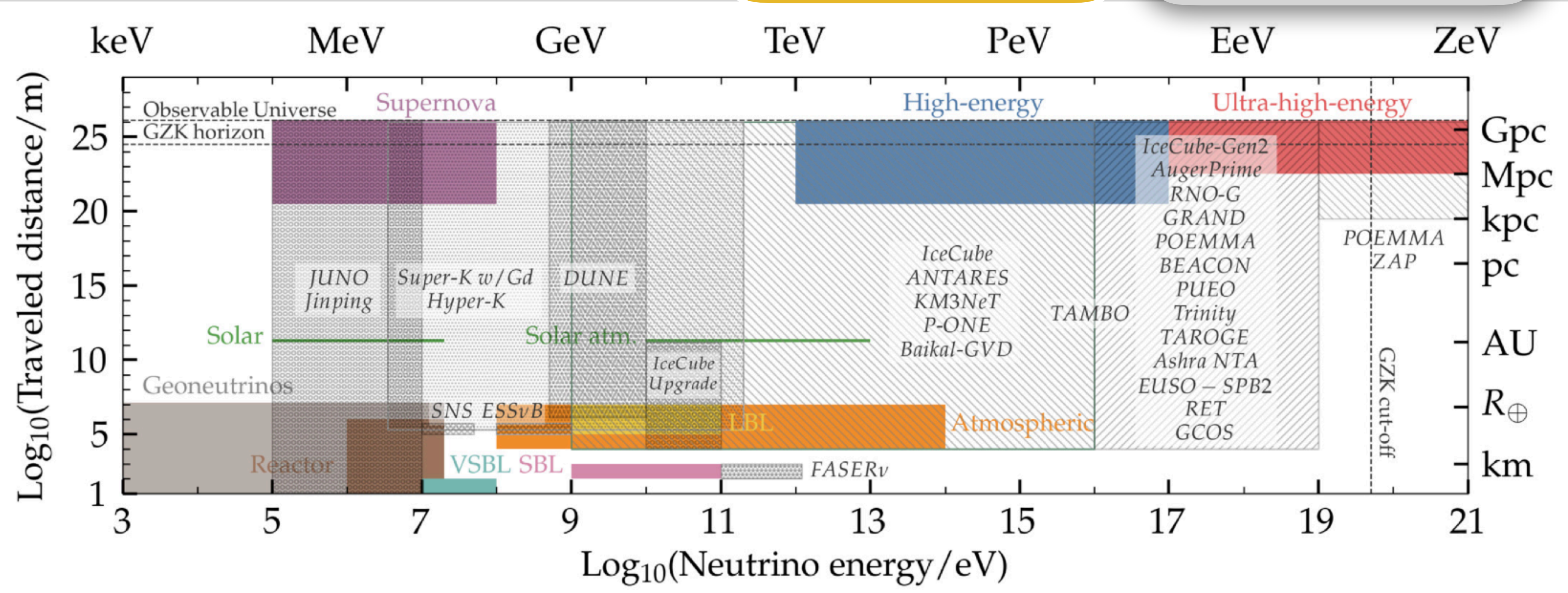
km
Log$_{10}$(Traveled distance/m)
Log$_{10}$(Neutrino energy/eV)

Neutrinos

discovered in 2013
(IceCube coll.)

predicted
(Berezinksy+1969)



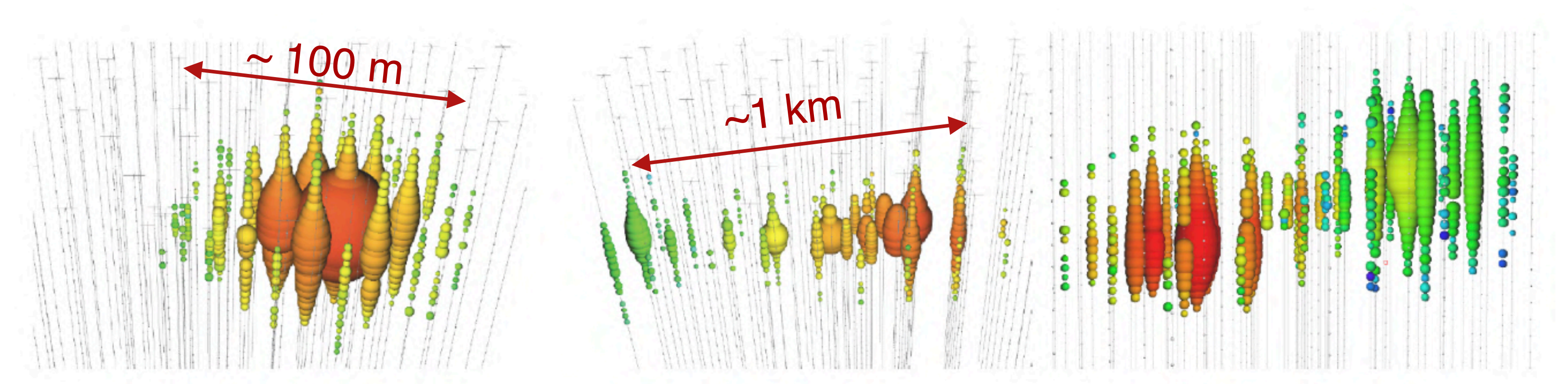
Astrophysical TeV–PeV neutrino detectors

Astrophysical TeV–PeV neutrino: detection

Detection of neutrinos primarily via neutrino deep-inelastic scattering (DIS) on nucleons, N.

- A DIS interaction can be:
  - Charged-current (CC): $\nu_\alpha + \mathrm{N} \rightarrow l_\alpha + \mathrm{X}$ (X final-state hadrons)
  - Neutral-current (NC): $\nu_\alpha + \mathrm{N} \rightarrow \nu_\alpha + \mathrm{X}$
- At these energies (>100 GeV), DIS cross sections of ν_α and $\bar{\nu}_\alpha$ are nearly equal, and events are not distinguishable
- Charged final-state particles initiate high-energy showers; which, in turn, emit Cherenkov light that propagates through the ice/water and is detected by the PMTs.
- From the event morphology of the deposited light pattern, infer the energy and direction of the original interacting neutrino.

High-energy neutrino event topologies



(a) *Cascade* (b) *Track* (c) *Double bang*

Poor angular resolution: **~10°**

Angular resolution: **< 1°**

Rarely observed

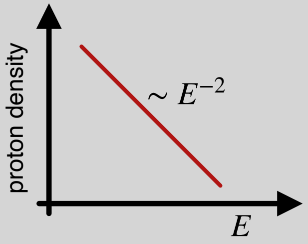
Shower
(mainly from ν_e and ν_τ)

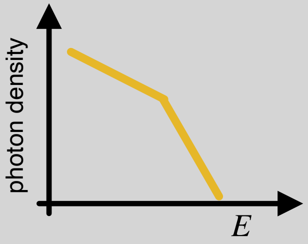
Track
(mainly from ν_μ)

Double bang
(from ν_τ)

Production of high-energy cosmic neutrinos

$$p + \gamma_{target} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, br = 2/3 \\ n + \pi^+, br = 1/3 \end{cases}$$





(or *p + p*)

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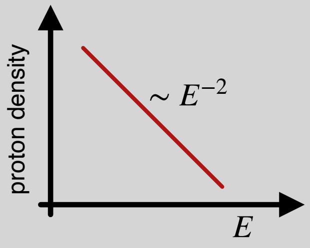

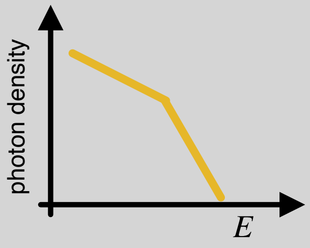

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+$$

$$n_{(escapes)} \rightarrow p + e^- + \nu_e$$

$$E_\gamma = E_p/10$$
$$E_\nu = E_p/20$$

(or $p + p$)

Note: v and v are (so far) indistinguishable in neutrino telescopes

Astrophysical Scenarios

Cosmic-ray Accelerators

Neutrinos produced within the CR source, mesons are typically produced by interactions of CRs with radiation

Cosmic-ray Reservoirs

Neutrinos produced by inelastic hadronuclear collisions while confined within the environment surrounding the CR source

Astrophysical Scenarios

Cosmic-ray Accelerators

Neutrinos produced within the CR source, mesons are typically produced by interactions of CRs with radiation

- Gamma-ray bursts (e.g. Waxman & Bahcall 97, Murase et al. 06, Cholis & Hooper 13, Liu & Wang 13, Murase & Ioka 13, Winter 13, Senno, Murase & Meszaros 16)
- Active Galactic Nuclei (e.g. Mannheim et al. 98, Stecker et al. 91, Mannheim 93/95, Reimer 2012, Kalashev, Kusenko & Essey 13, Stecker 13, Murase, Inoue & Dermer 14, Dermer, KM & Inoue 14, Tavecchio et al. 14, Kimura, Murase & Toma 15, Padovani et al. 15, Wang & Li 1, Lamastra 2017)

Cosmic-ray Reservoirs

Neutrinos produced by inelastic hadronuclear collisions while confined within the environment surrounding the CR source

- Starburst galaxies (e.g., Loeb & Waxman 06, Thompson+ 07; Murase, Ahlers & Lacki 13, Katz et al. 13, Liu+ 14, Tamborra, Ando & Murase 14, Anchordoqui+ 14, Senno+ 15)
- Galaxy groups/clusters (e.g., Berezinsky+ 97, KM et al. 08, Kotera+ 09, Murase, Ahlers & Lacki 13, Fang & Olinto 16)

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Neutrino Searches: Status of Art

Main approaches:

— diffuse astrophysical flux studies

— time dependent studies (variable point sources)

— time integrated studies (steady point sources)

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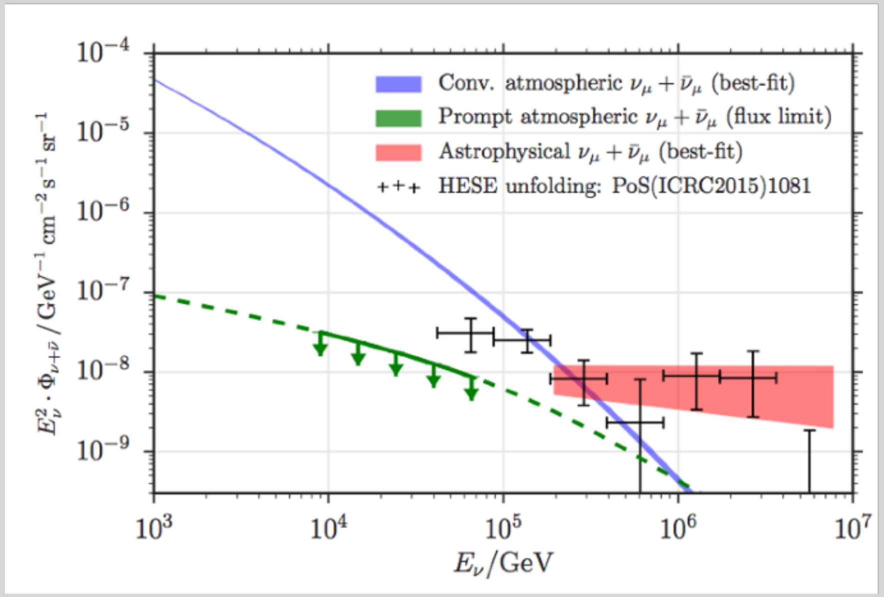
Neutrino Searches: Status of Art

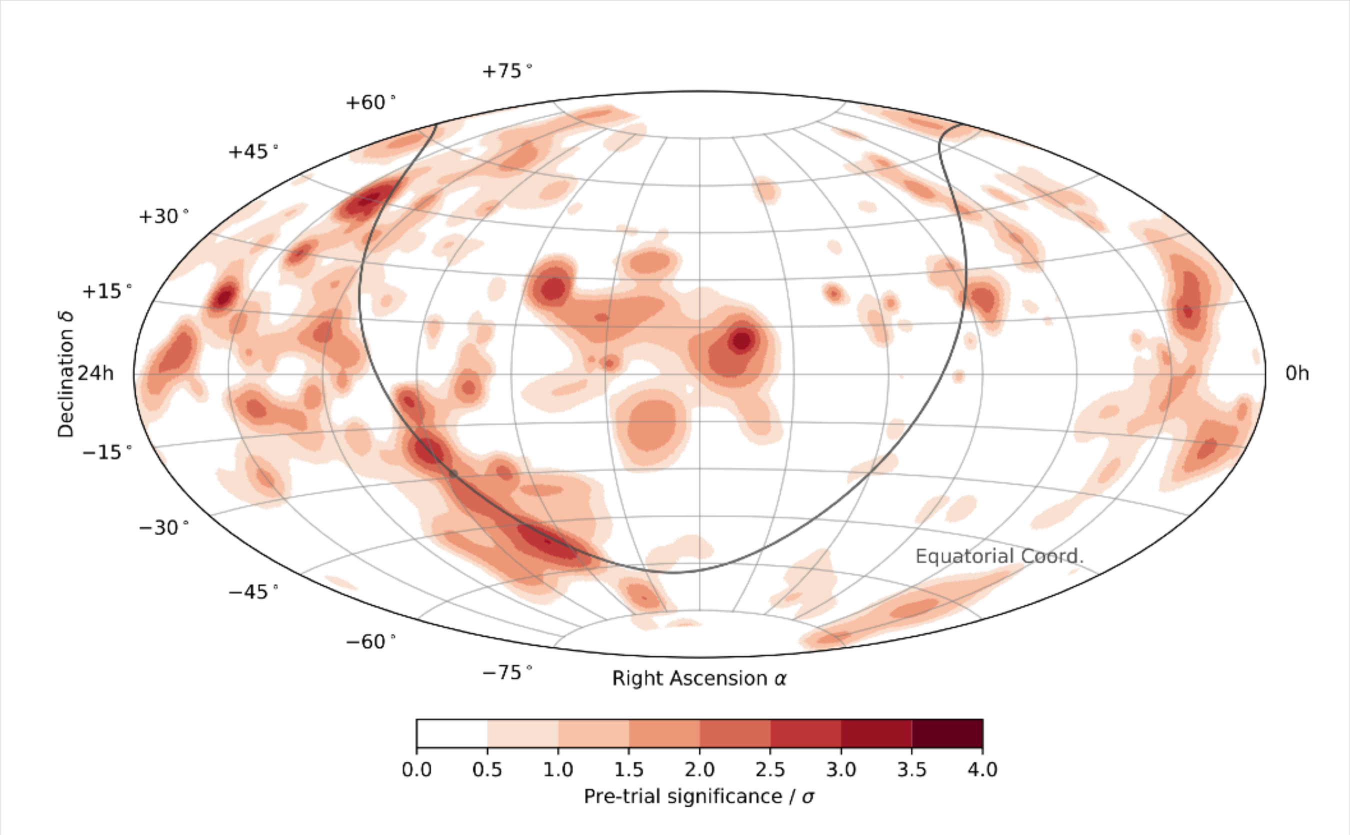
Diffuse flux

- A significant astrophysical contribution is observed, it dominates at the highest neutrino energies, ≳100 TeV
- Break in the diffuse energy spectrum, harder at highest energies
- It may suggest different populations contributing to the astrophysical neutrino spectrum



IceCube coll. 2016; ICRC2023

Milky Way: Evidence of neutrino emission

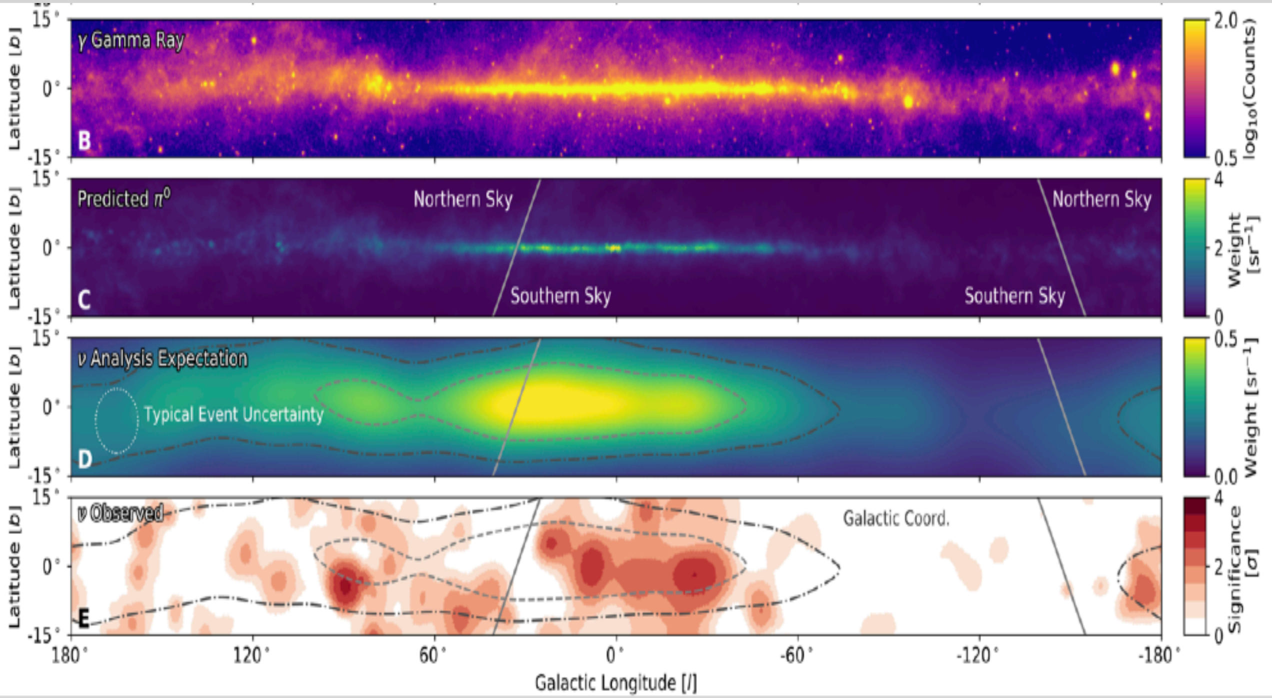


IceCube coll. 2024

Milky Way: Evidence of neutrino emission

Analysis based on theoretical model of the expected distribution of star-forming regions and supernova remnants in the Galactic plane

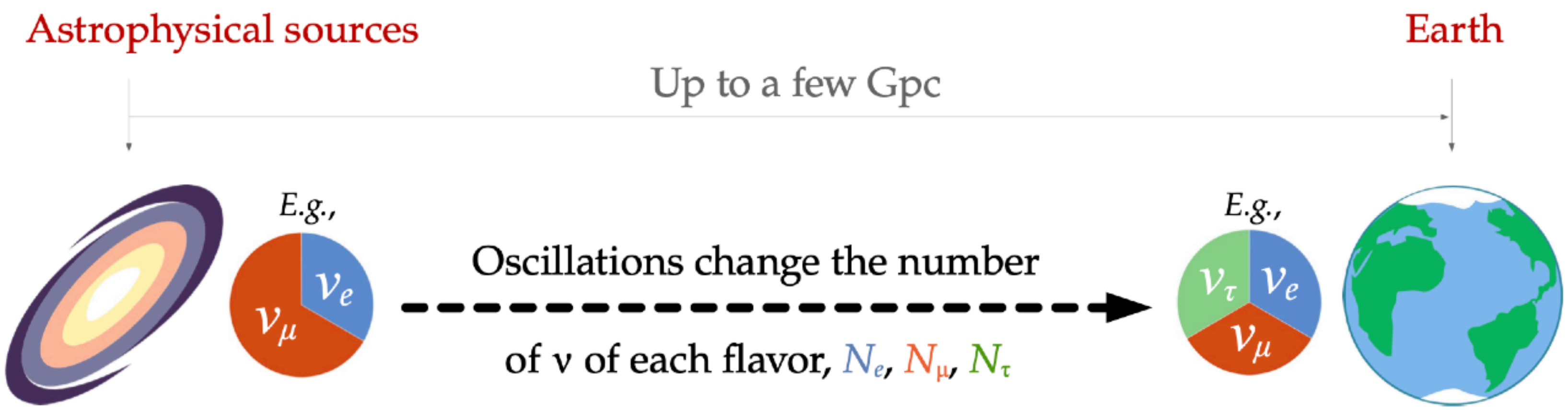
- Galactic γ-ray emission (*Fermi*-LAT)
- The predicted neutrino emission is derived from a π^0 template* that matches the diffuse γ-ray emission
- Predicted neutrino map obtained upon convolving the template with IceCube sensitivity
    - Expected angular distribution of neutrino events
- Evidence for emission from the Galactic plane (4.5 σ)



*Gaggero et al. 2015

IceCube coll. 2024

Neutrino flavor composition



Different production mechanisms yield different flavor ratios:

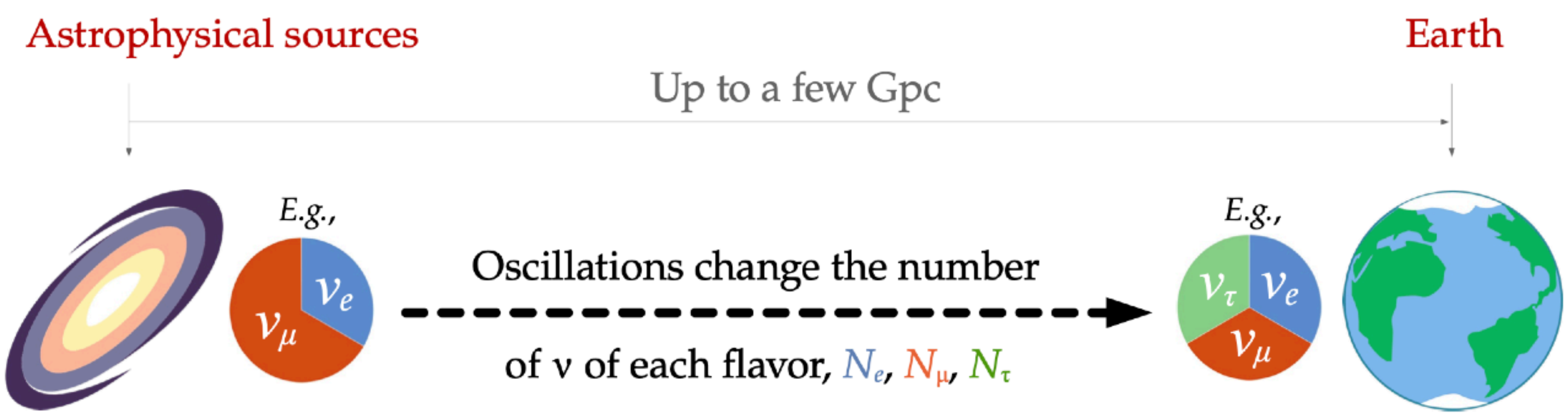
$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$$

Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$$

Credit: Bustamante

Neutrino flavor composition



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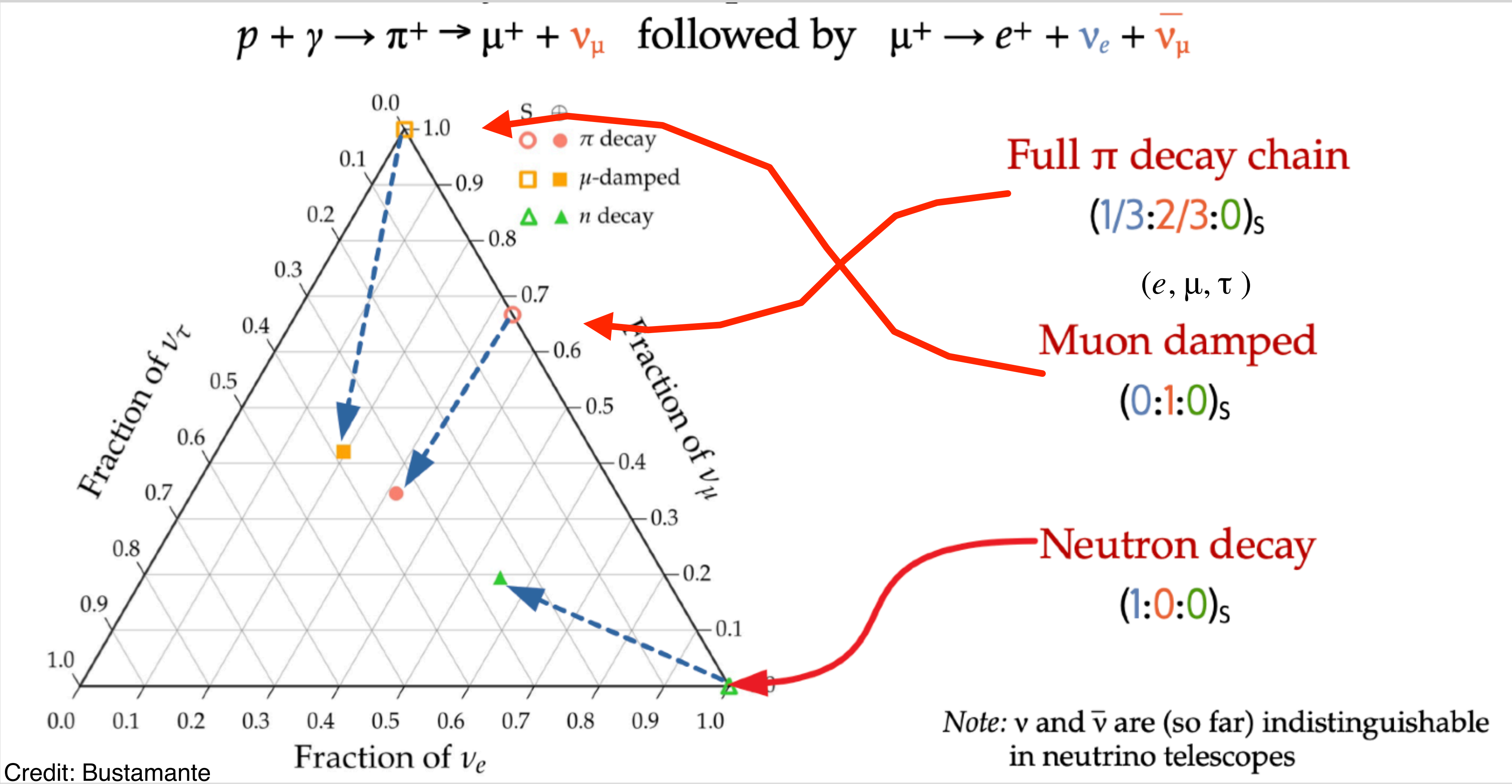
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$

Standard oscillations
or
new physics

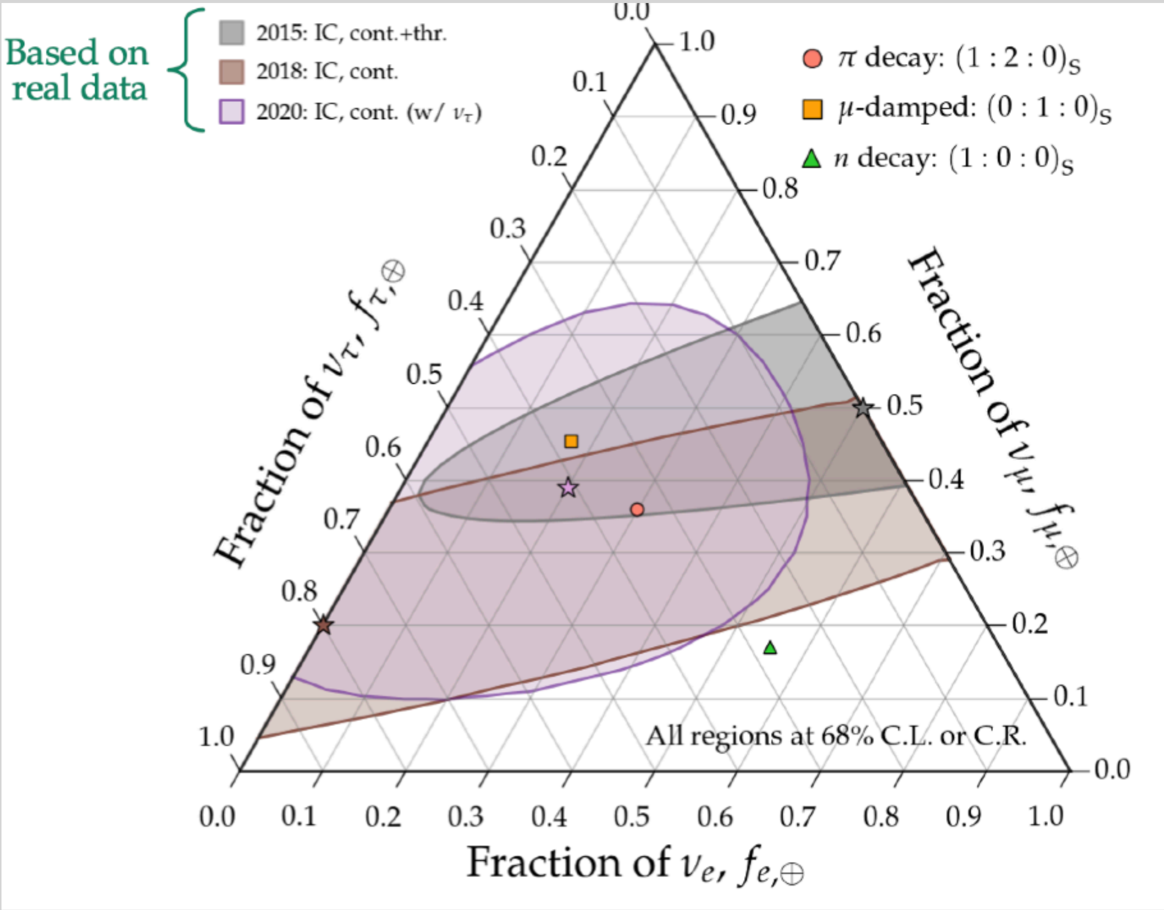
Credit: Bustamante

Neutrino flavor composition (2015–2020)



Neutrino flavor composition (2015–2020)

Astrophysical flavor ratio can probe sources and new physics



IceCube Collab., EPJC 2022: PRD 2019; ApJ 2015

Neutrino Searches: Status of Art

Main approaches:

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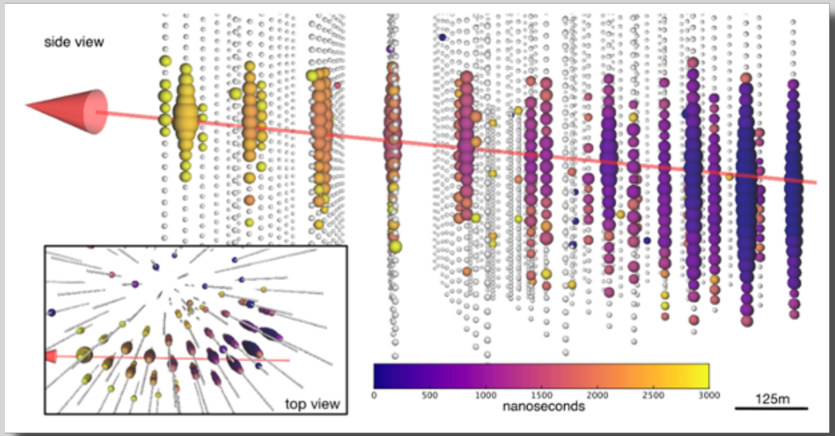
The first extragalactic candidate neutrino emitter : TXS 0506+056

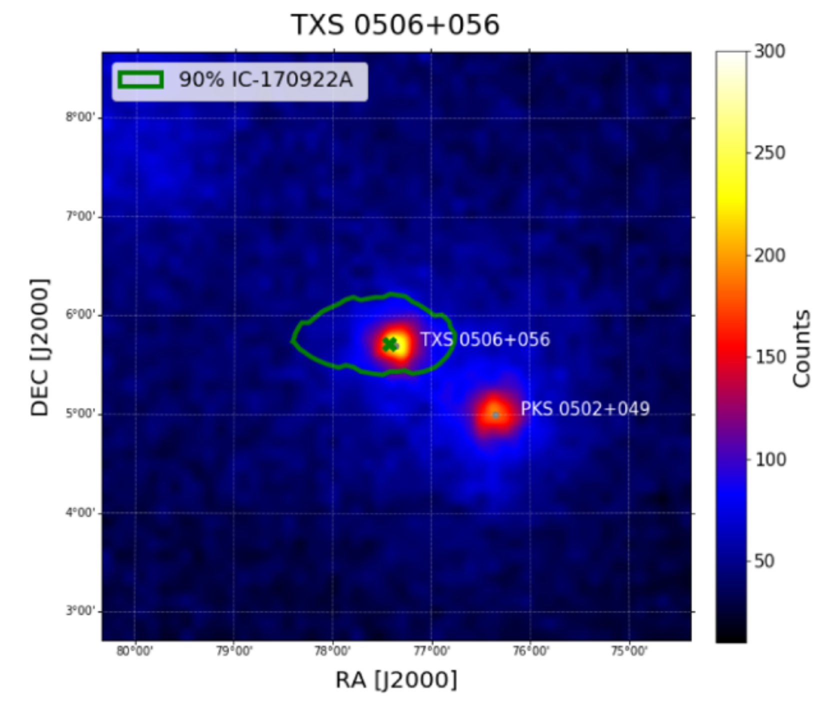
Time dependent studies : IC170922A

IceCube high-energy candidate, neutrino event



Fermi-LAT detection of candidate counterpart

(Tanaka, SB+ 2017)



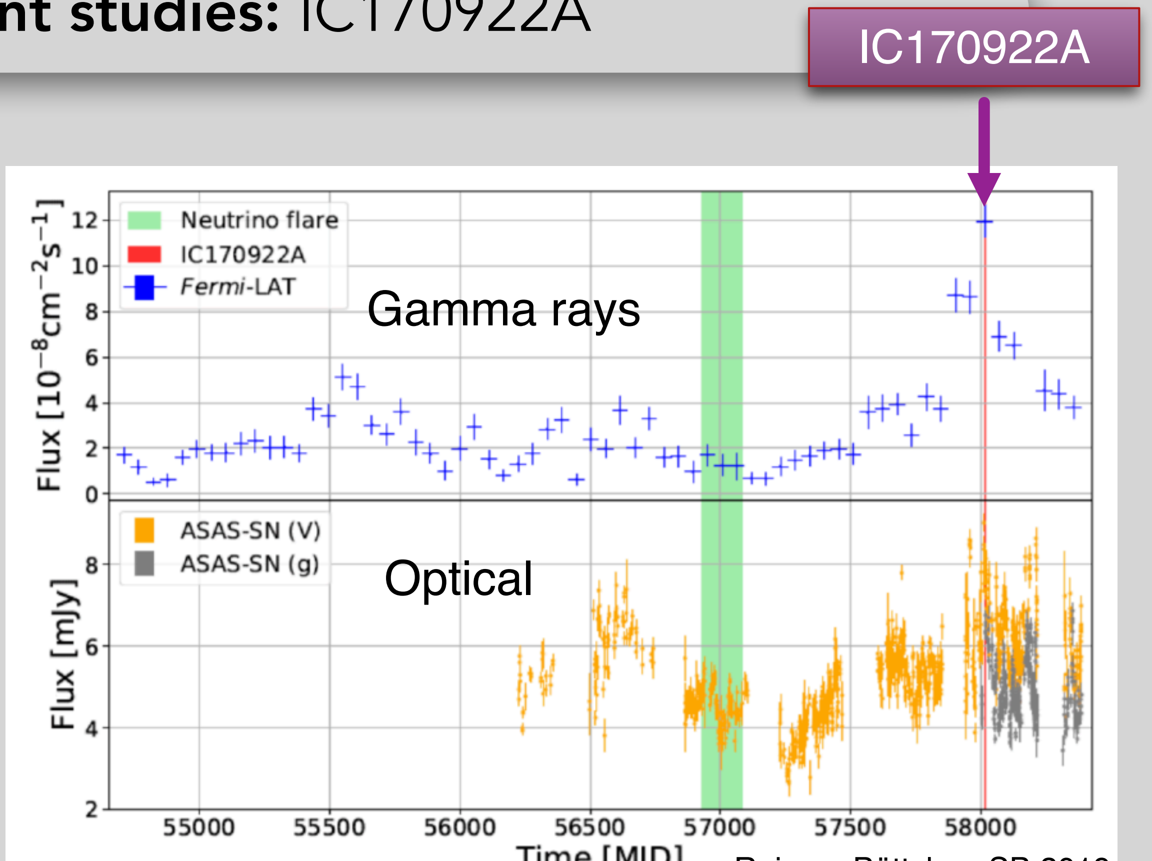
The first extragalactic candidate neutrino emitter : TXS 0506+056

Time dependent studies: IC170922A

Intriguing high-energy neutrino/flaring blazar association

- High-energy neutrino event with E >183TeV
- Flaring γ–ray blazar
- ~3σ post-trial chance coincidence

Lepto-hadronic models can explain the observations (IC170922A), but bulk of γ rays and neutrinos not correlated



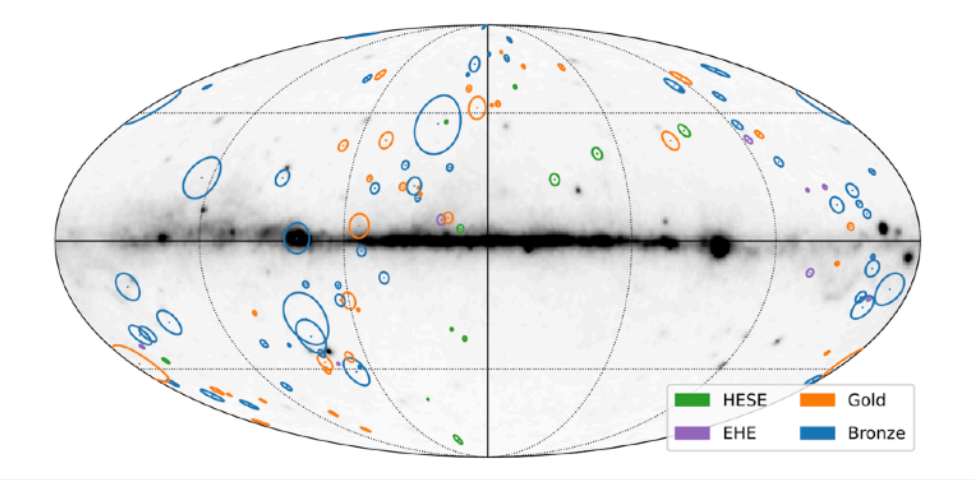
Reimer, Böttcher, SB 2019

Patterns in the behaviour of γ-ray-candidate neutrino blazars?

Time dependent studies: high-energy events

Archival sample of candidate-high-energy neutrino events: since 2011, ~200 events

Testing other γ-ray blazars positionally consistent



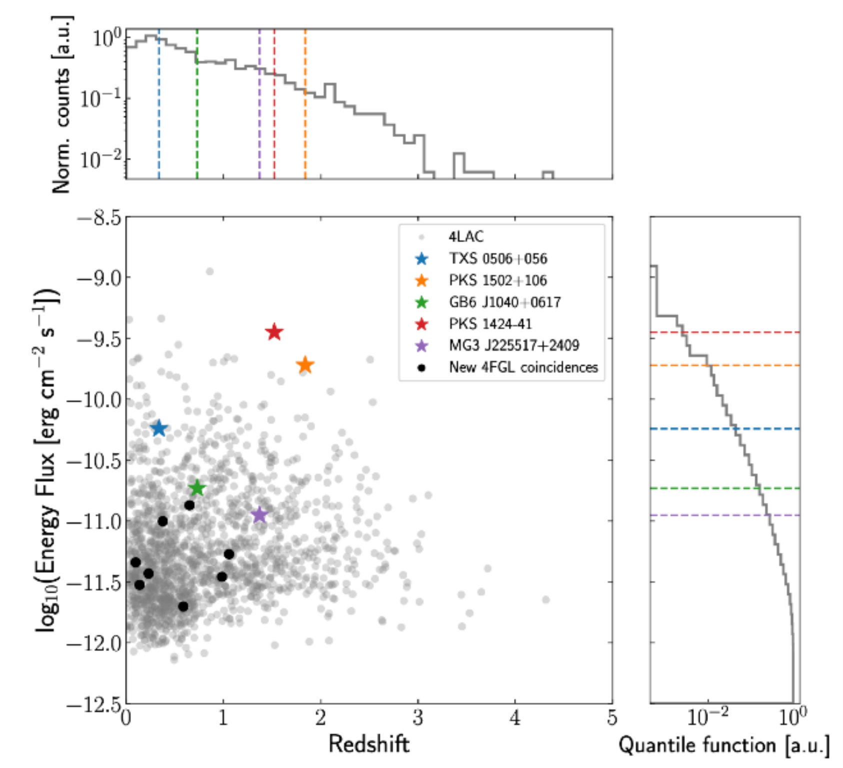
Patterns in the behaviour of γ-ray-candidate neutrino blazars?

Time dependent studies: high-energy events

Archival sample of candidate-high-energy neutrino events: since 2011, ~200 events

Inconclusive:

Neutrino-emitting blazar candidates are statistically compatible with hypotheses of both a linear correlation and no correlation between neutrino and gamma-ray energy flux.



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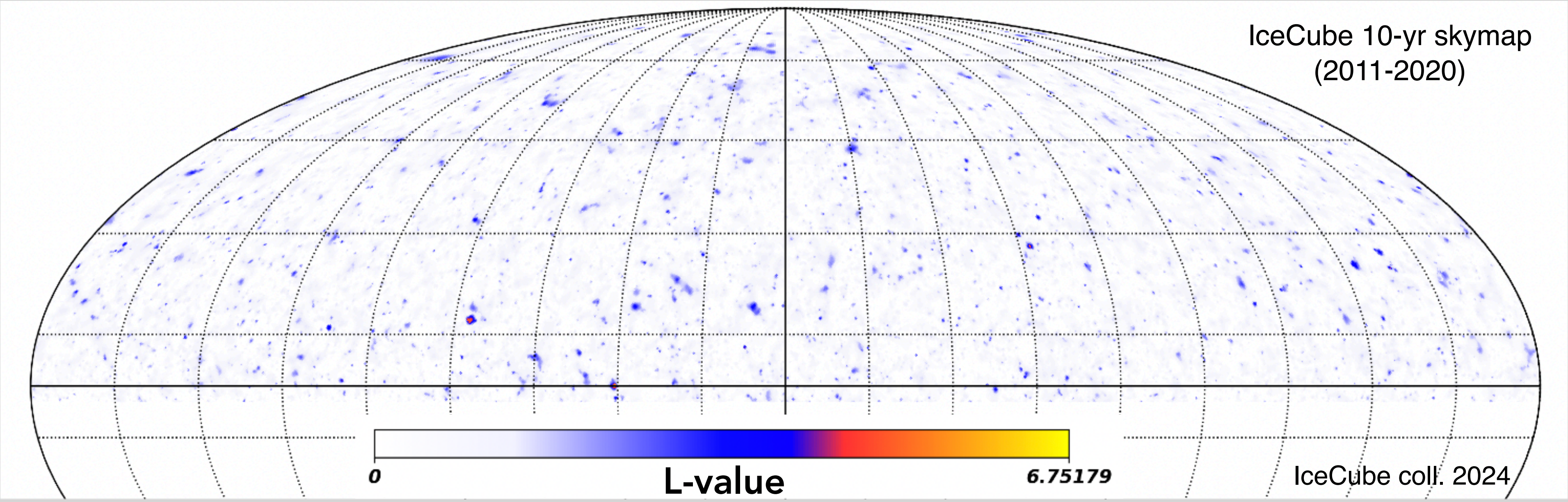
IceCube Neutrino (p-value) sky-map

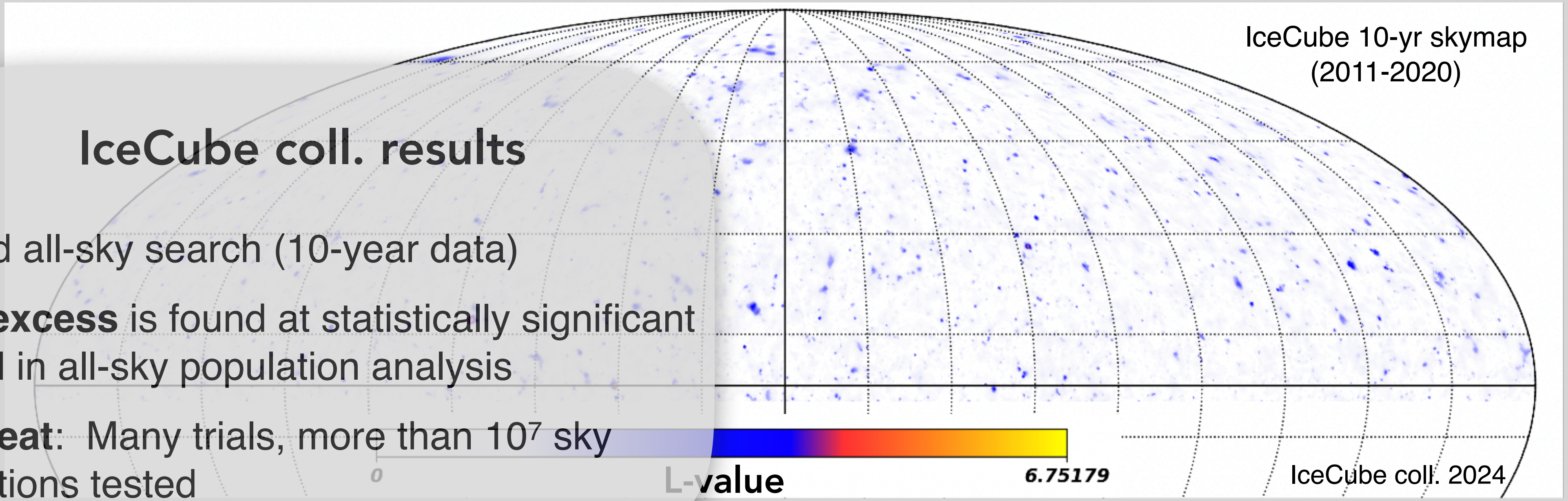
Time integrated studies (steady point sources)

Skymap informs about the level of anisotropy in the event spatial distribution



IceCube Neutrino (p-value) sky-map

Events largely isotropically distributed, favouring extragalactic origin

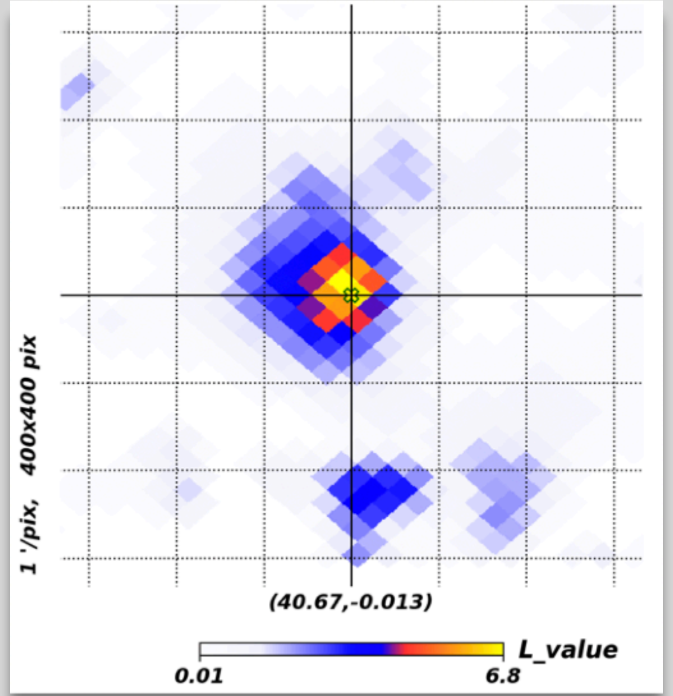


IceCube coll. results

- Blind all-sky search (10-year data)
- **No excess** is found at statistically significant level in all-sky population analysis
- **Caveat**: Many trials, more than 10^7 sky locations tested

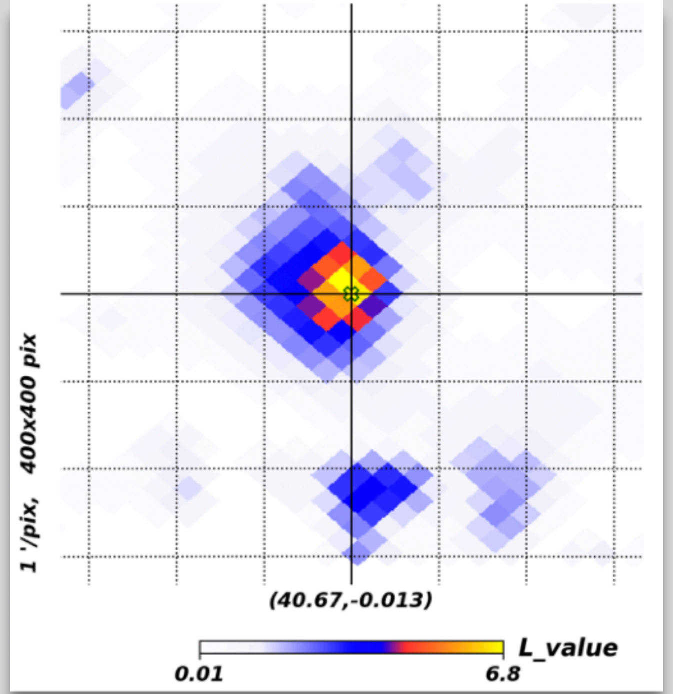
NGC 1068: Evidence of neutrino emission

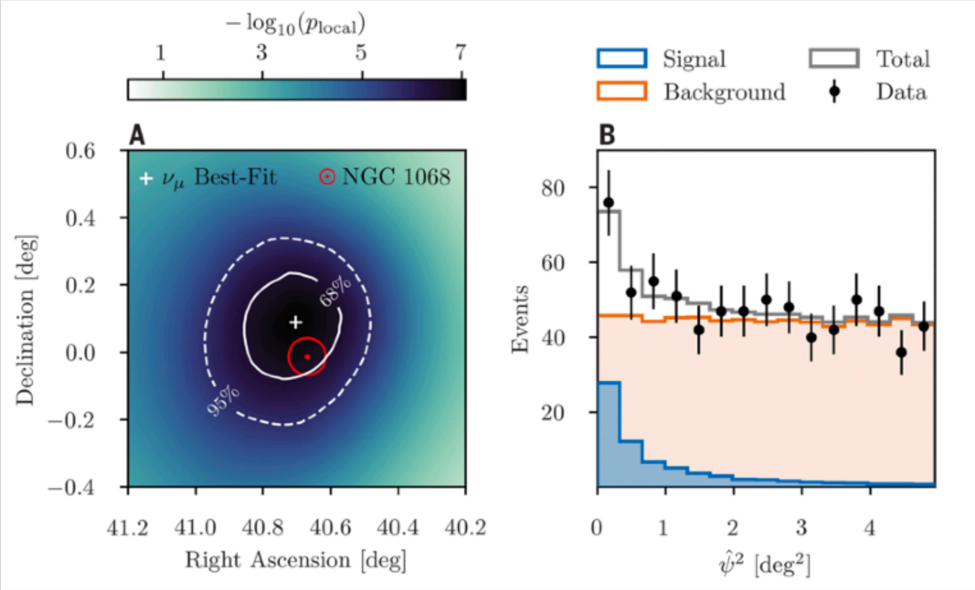
Most significant excess in the IceCube 10-yr skymap, “hotspot”



NGC 1068: Evidence of neutrino emission

Most significant excess in the IceCube 10-yr skymap, “hotspot”,
positionally consistent (68% CL) with a known astrophysical object: NGC 1068





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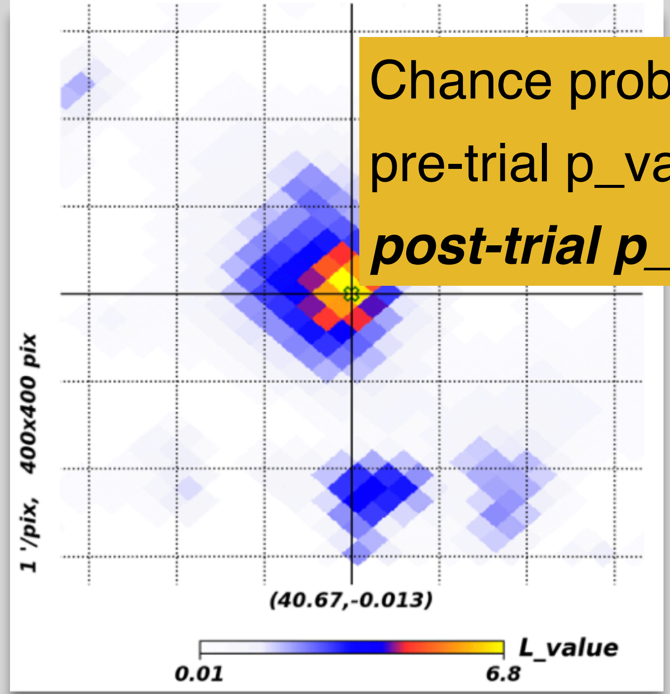
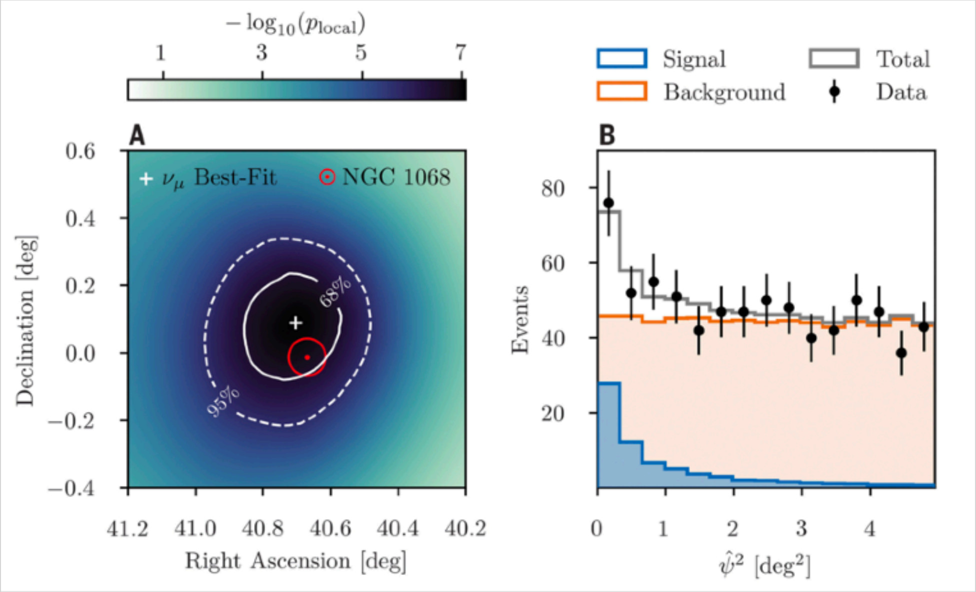


Chance probability*:

pre-trial p_val = 10^{-7} (~5.2σ)

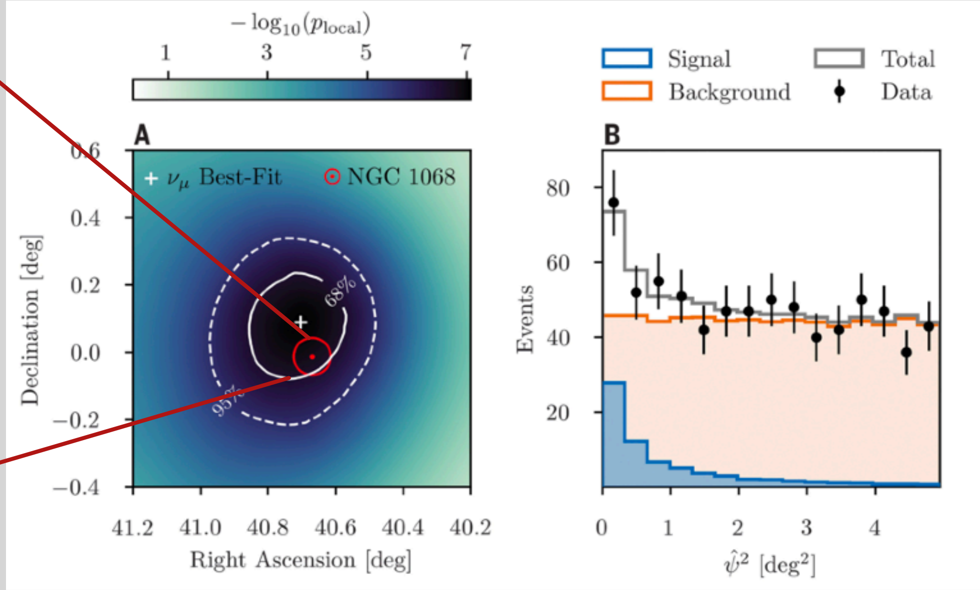
post-trial p_val = 10^{-5} (~4.2σ)



*Note: based on a list of 110 astronomical objects tested

NGC 1068: Evidence of neutrino emission

Active starburst spiral galaxy, close-by (~10 Mpc)



NGC 1068: Evidence of neutrino emission

AGN powered by a SMBH with mass ~10^8 $M_\odot$.

Looking at the nucleus edge-on, through the torus.

- Heavily obscured by dust and gas

Intrinsically the brightest Seyfert galaxy in the X-ray band.

NGC 1068: Evidence of neutrino emission

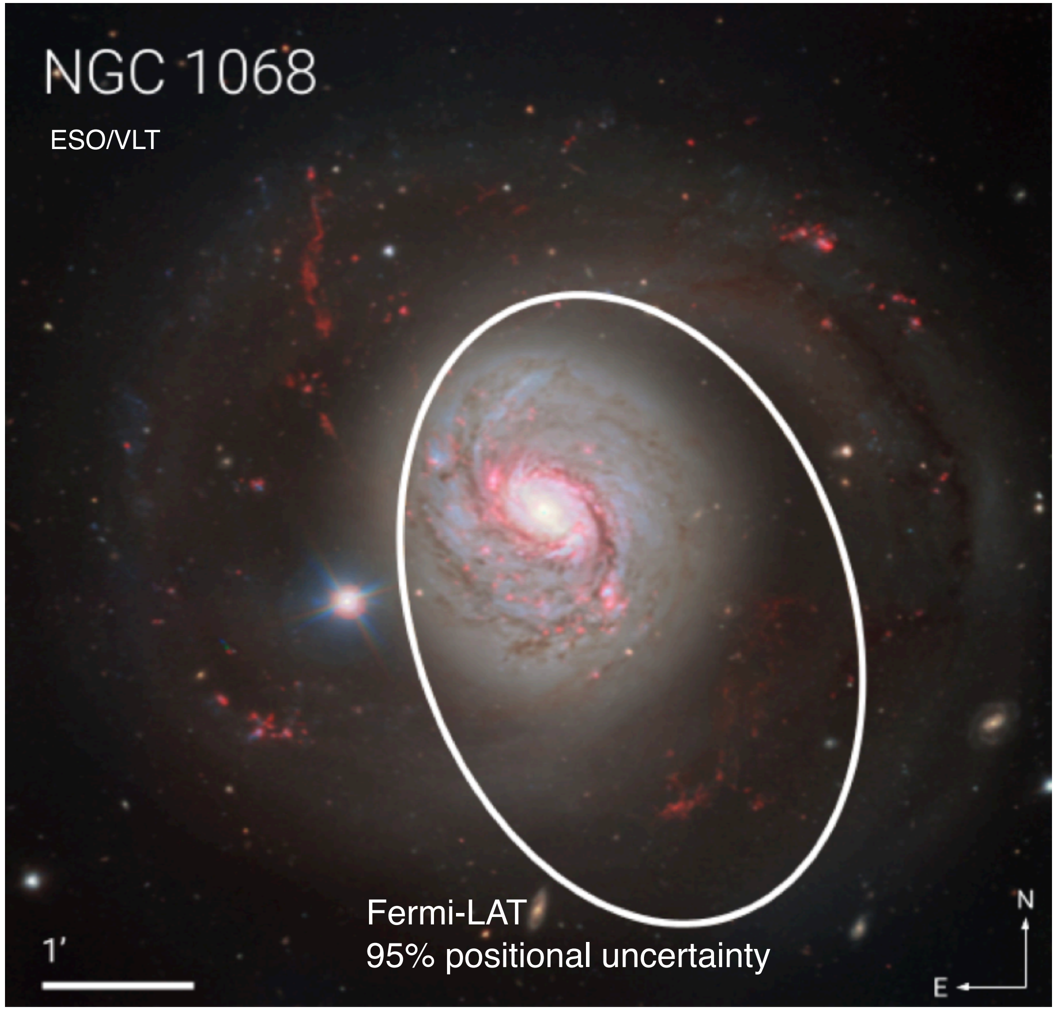
AGN powered by a SMBH with mass $\sim 10^8 M_\odot$.

Looking at the nucleus edge-on, through the torus.

- Heavily obscured by dust and gas

Intrinsically the brightest Seyfert galaxy in the X-ray band.

Fairly bright at γ rays



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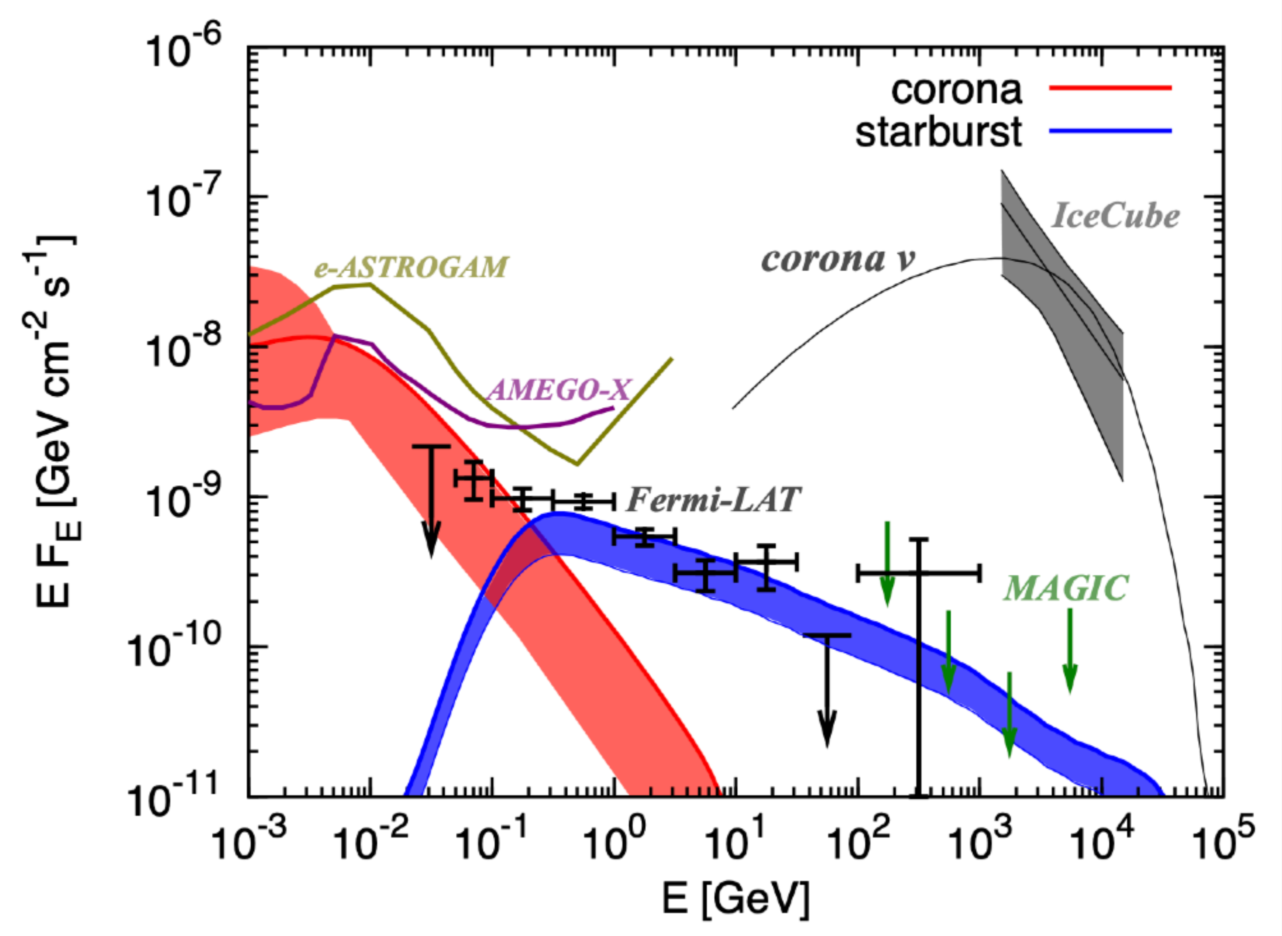


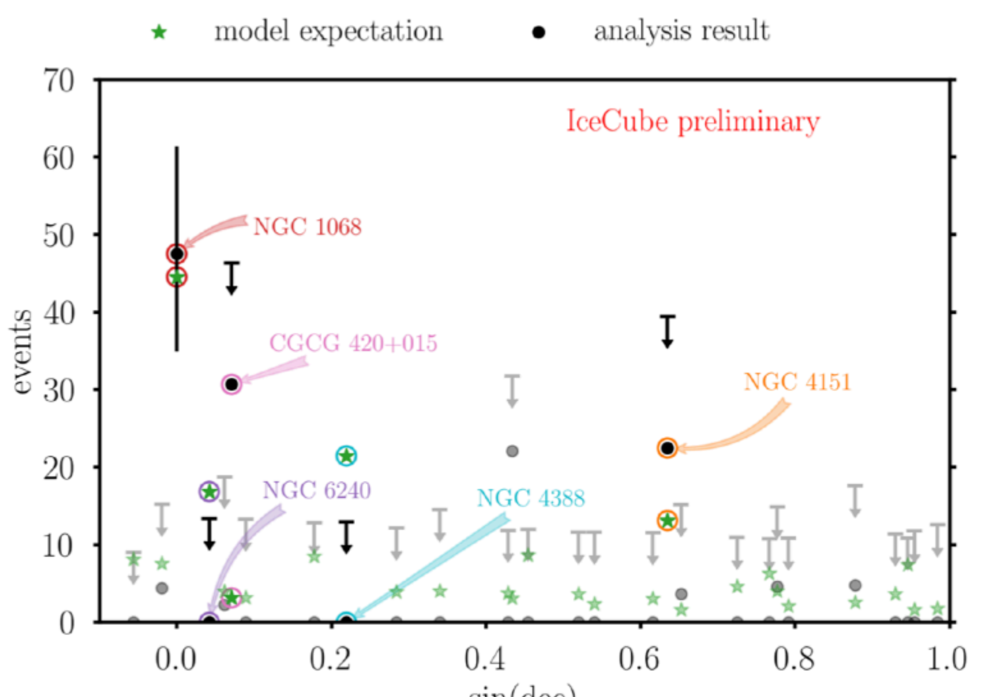
Unexpected:

Neutrino flux considerably higher than the observed γ-ray flux.

—> different origin for the bulk of MeV-GeV photons and neutrinos

Ajello+ 2023; AGN corona (Murase et al. 2020; Murase 2022); starburst model (Ajello et al. 2020)

Neutrinos from Seyfert galaxies?



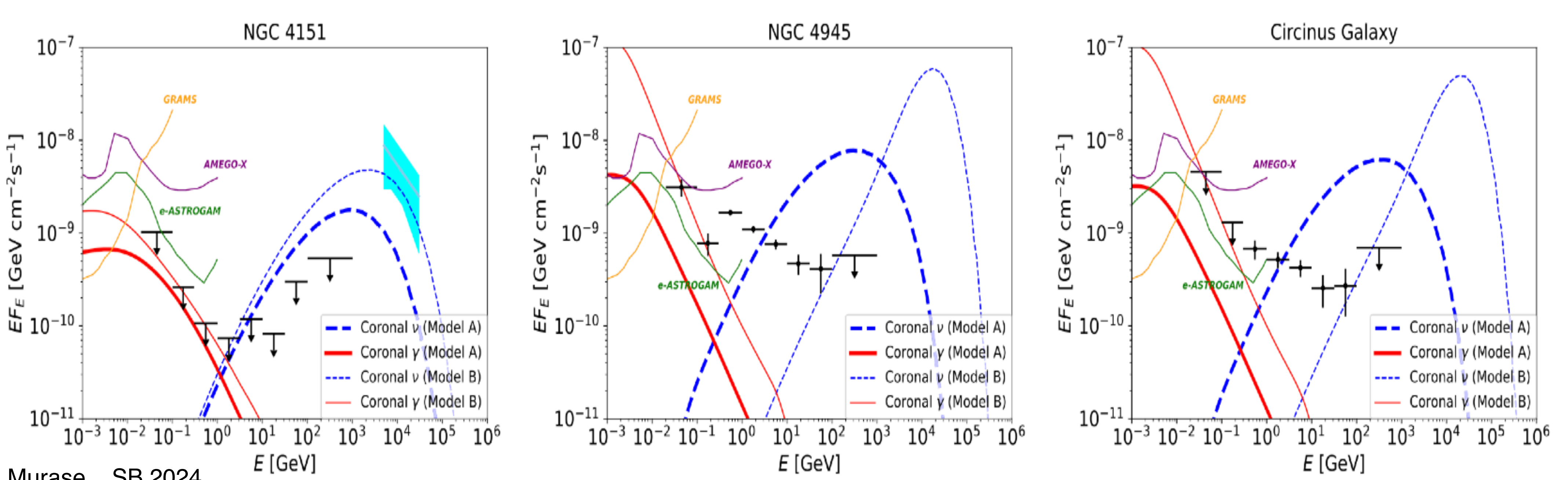
IceCube coll. 2023

Catalog search:

- 2.3σ from CGCG 420-015 assuming the disk-corona model
- Binomial test: 2.7σ from 2/27 sources in the disk-corona model
- Stacking: no detection

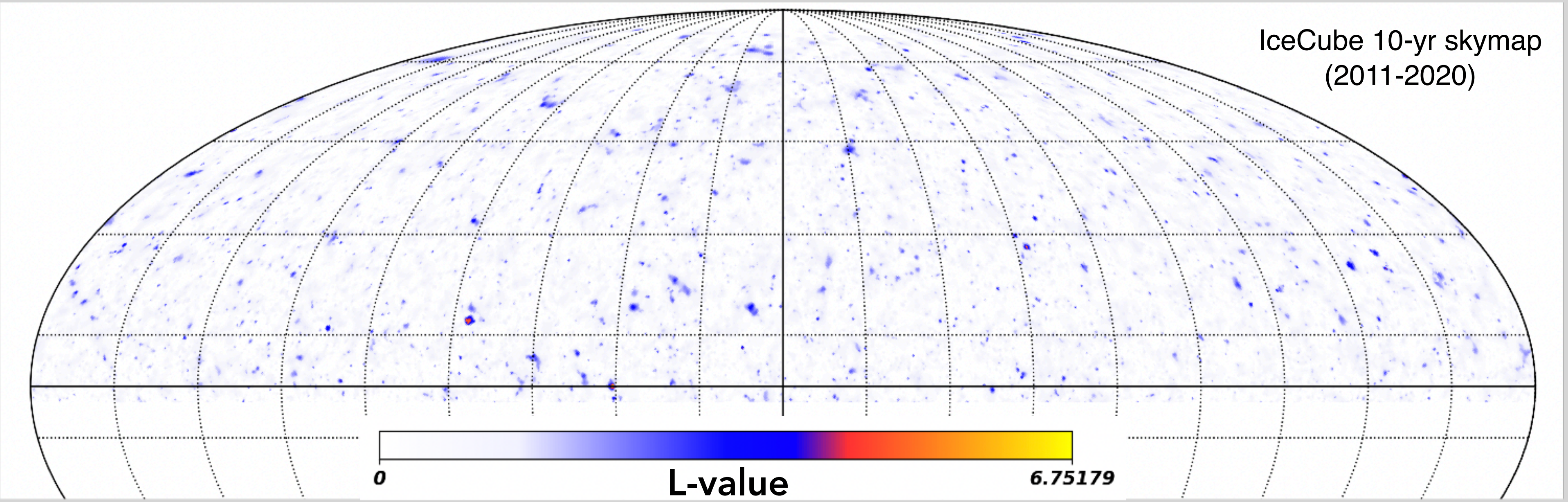
The NGC 1068 model does not describe most sources in the sample

Neutrinos from Seyfert galaxies, predictions



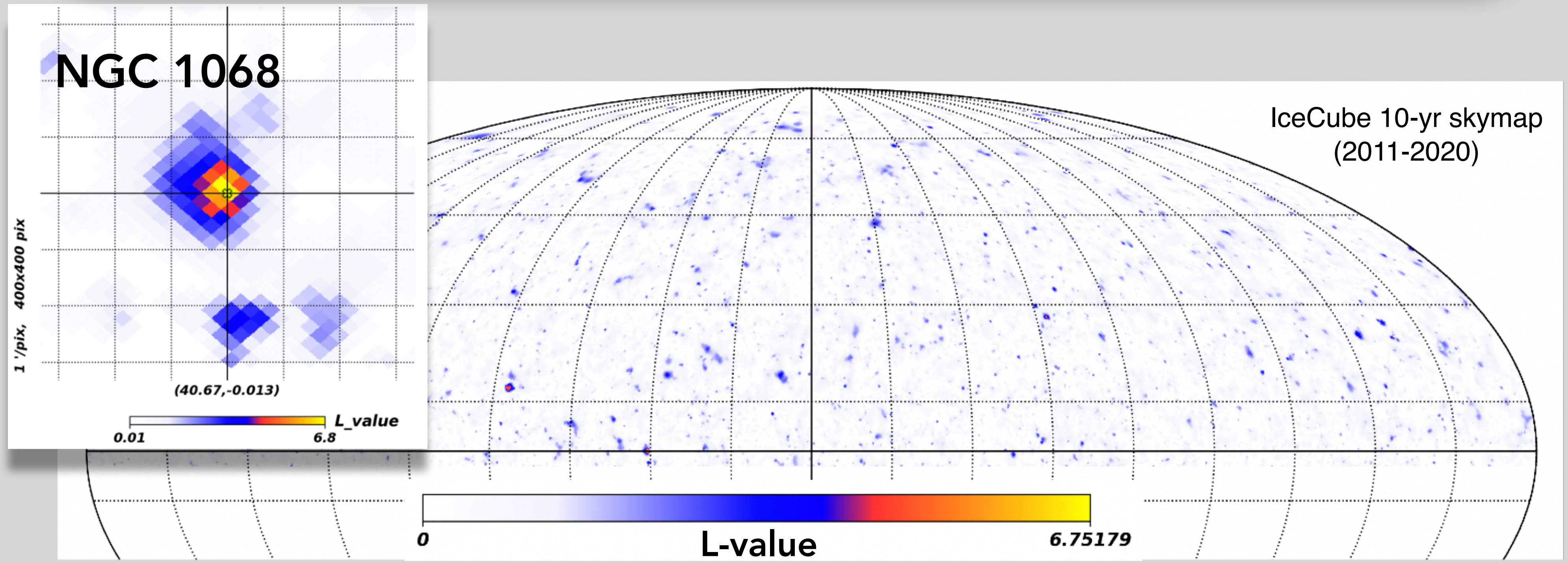
Murase,.. SB 2024

IceCube skymaps: sensitive to comic sources



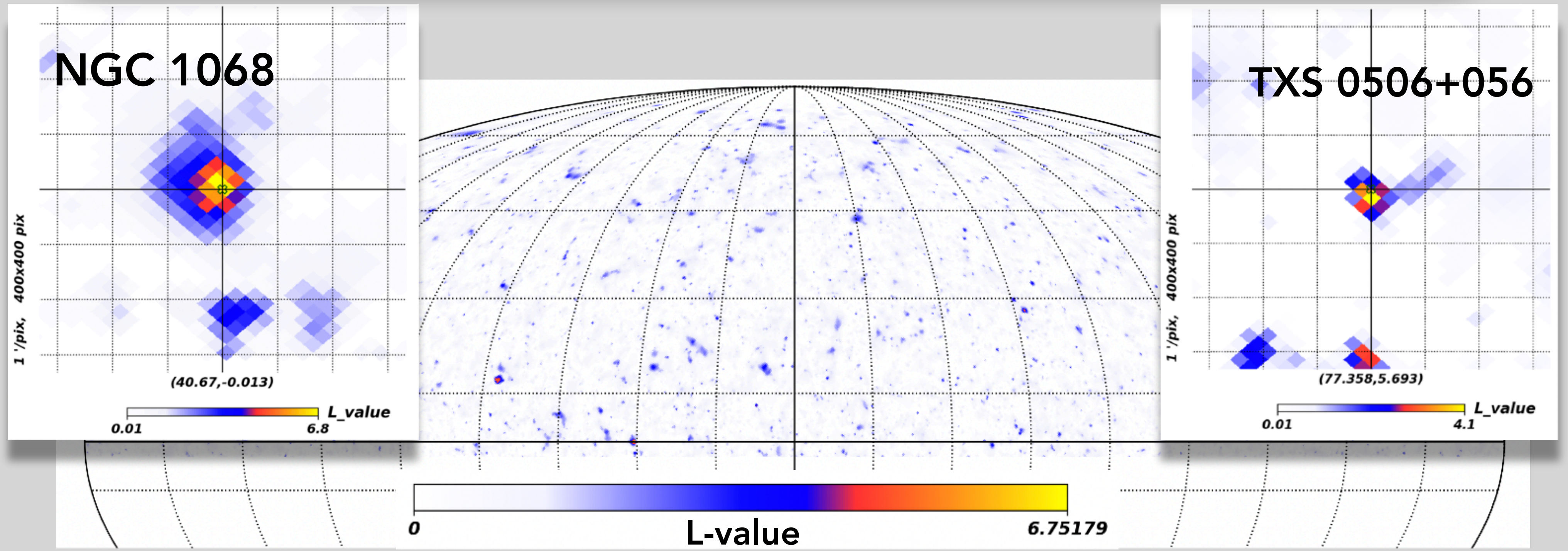
IceCube skymaps: sensitive to comic sources

Hotspot consistent with NGC 1068



IceCube skymaps: sensitive to comic sources

Hotspots consistent with NGC 1068 and TXS 0506+056



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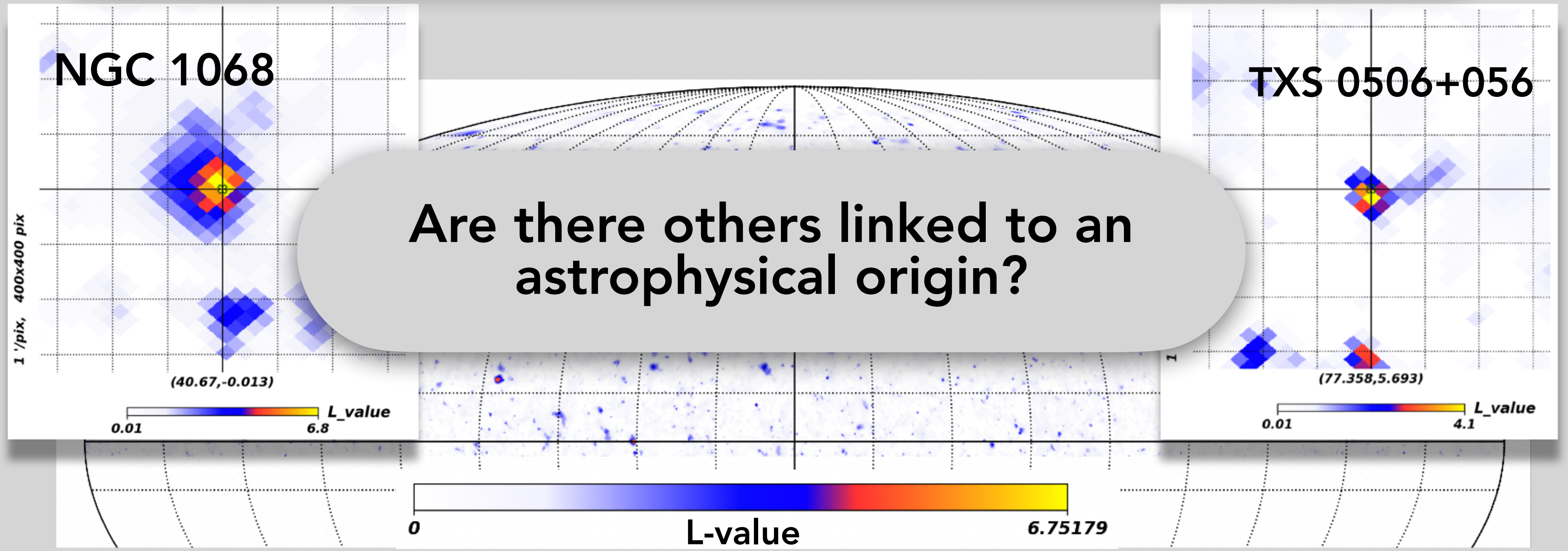


Are there others linked to an astrophysical origin?

Skymap: Cross-correlation analysis

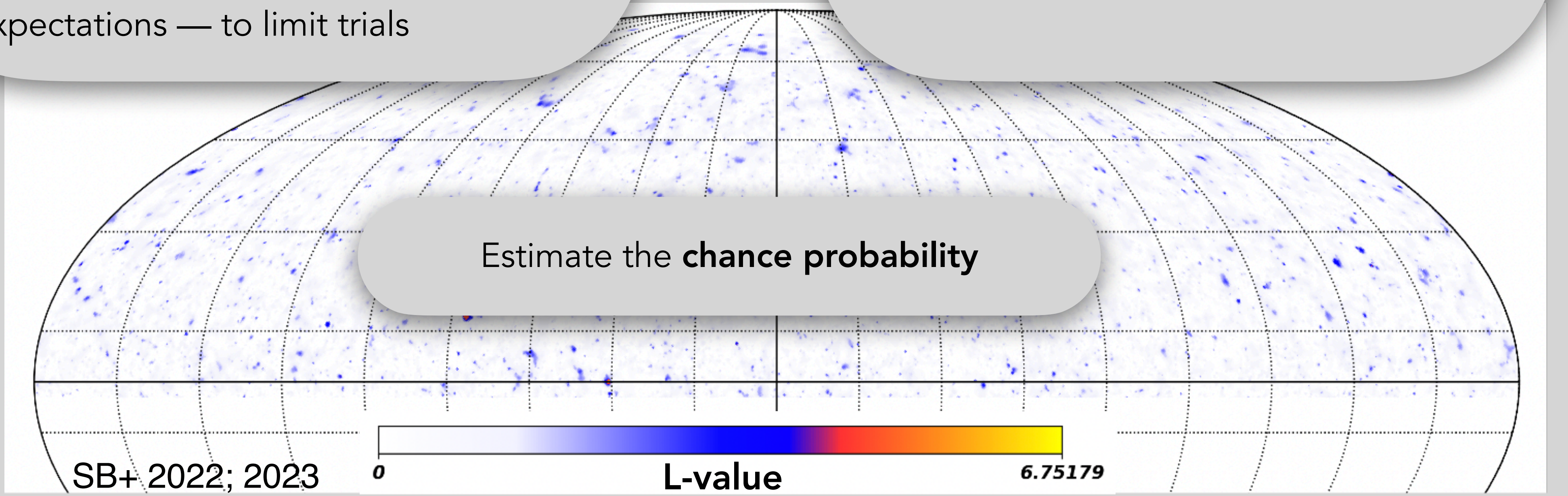
Sky-map : 10^7 pixels (sky locations)

—> **Focus** on the clusters (spots) with **strongest deviation from background** expectations — to limit trials

Positional crossmatch

with a catalog of **known blazars**

Estimate the **chance probability**



SB+ 2022; 2023

Skymap: Cross-correlation analysis

Summary of findings

Perform positional cross-correlation analysis, between blazar sample and neutrino spot sample.

Combining the (independent) north and south analysis, the global post-trial p-value for the chance correlation is 2.59 x 10^{-7}.

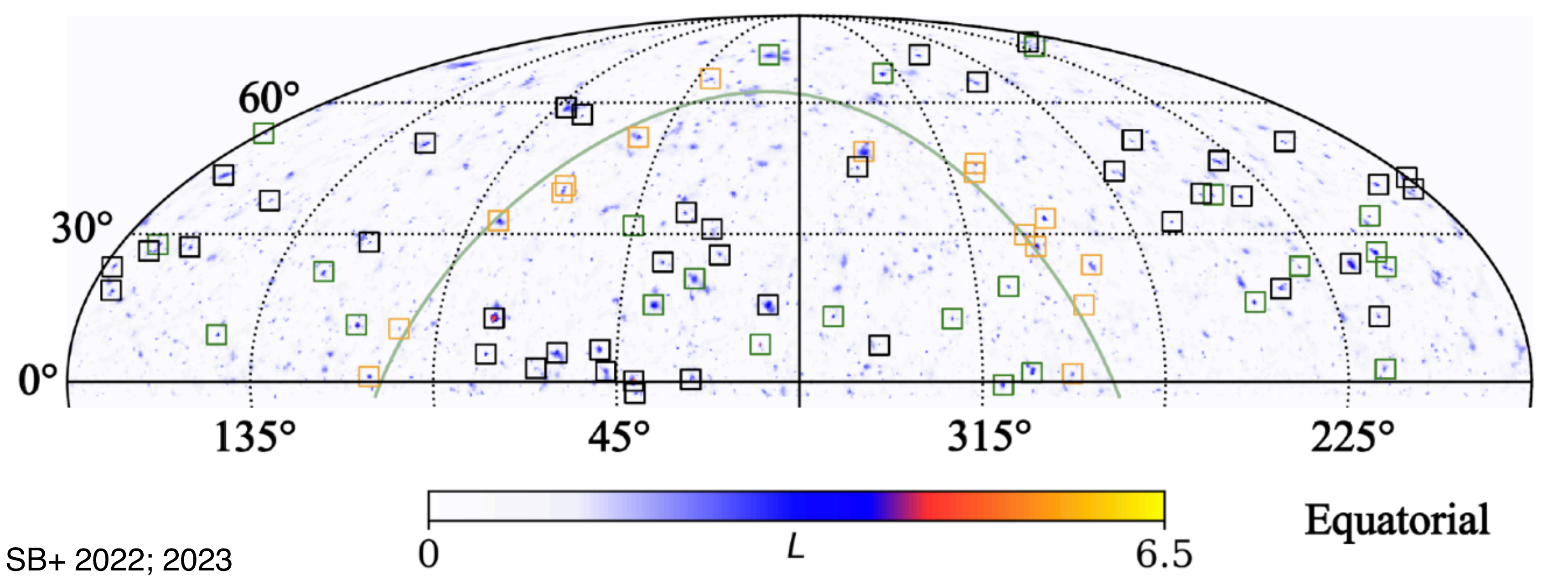
Sky region	Dataset (energies)	5BZCat	Hotspots	Matches	Pre-trial p-value	Post-trial p-value
North ($-3^\circ \leq \delta \leq 81^\circ$)	9 yr data ($\sim$TeV/$\lesssim$ 0.1 PeV)	2130	66	42	5.12×10^{-4} (3.28σ)	6.79×10^{-3} (2.47σ)
South ($-85^\circ < \delta < -5^\circ$)	7 yr data ($\gtrsim$ 0.1 PeV)	1177	19	10	3×10^{-7} (4.99σ)	2×10^{-6} (4.5σ)
					$p_{\rm pre}^{\rm global}$	$p_{\rm post}^{\rm global}$
North + South		–	–	–	3.62×10^{-9} (5.78σ)	2.59×10^{-7} (5.02σ)

SB+ 2022; 2023; see also Bellenghi+2023

Candidate neutrino-emitter blazars

Pushing forward a small set of blazars as neutrino counterparts

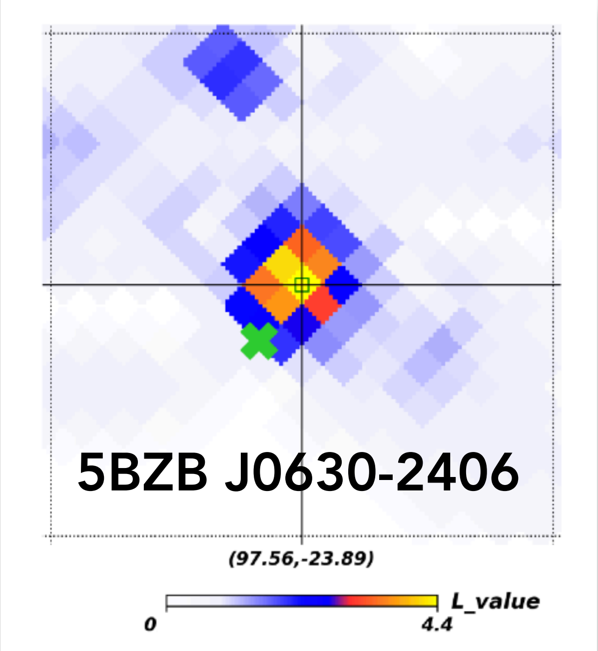
— and PeVatron accelerators —

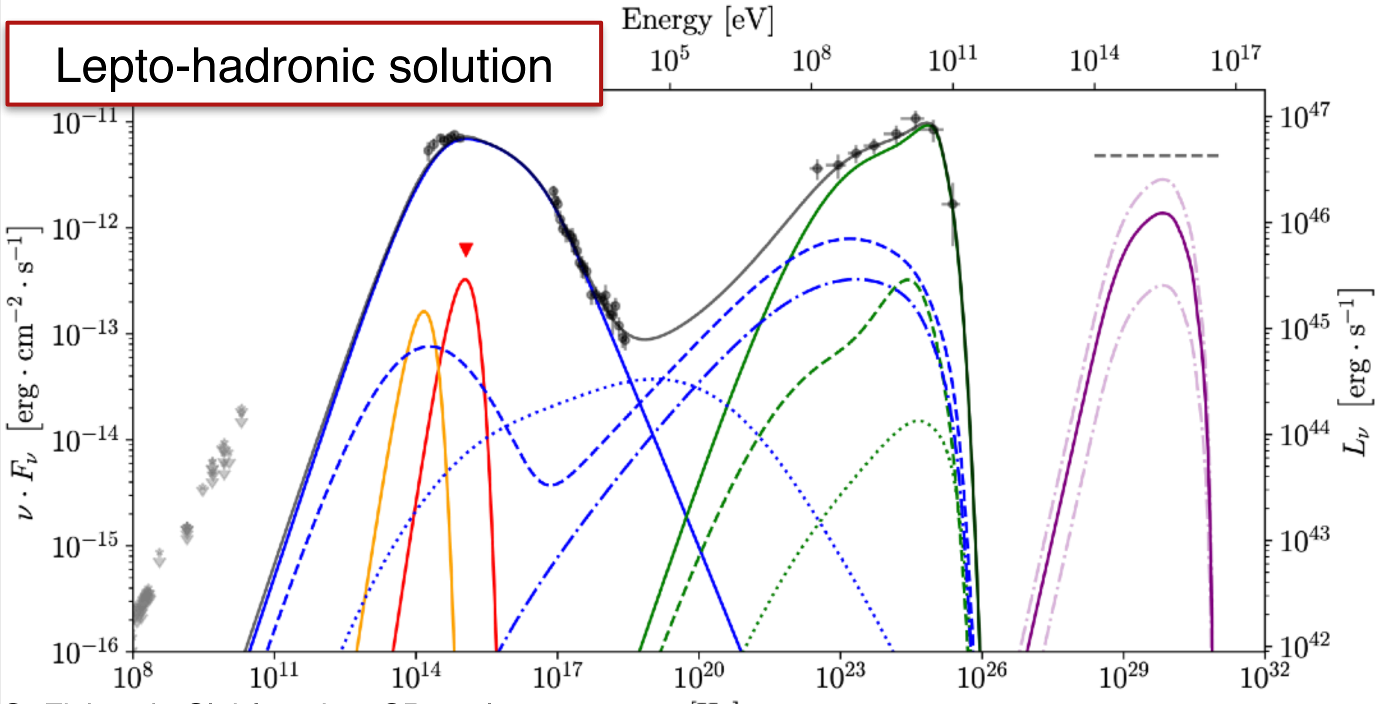


SB+ 2022; 2023

Candidate neutrino-emitter blazars

Plausible counterparts from the physical perspective

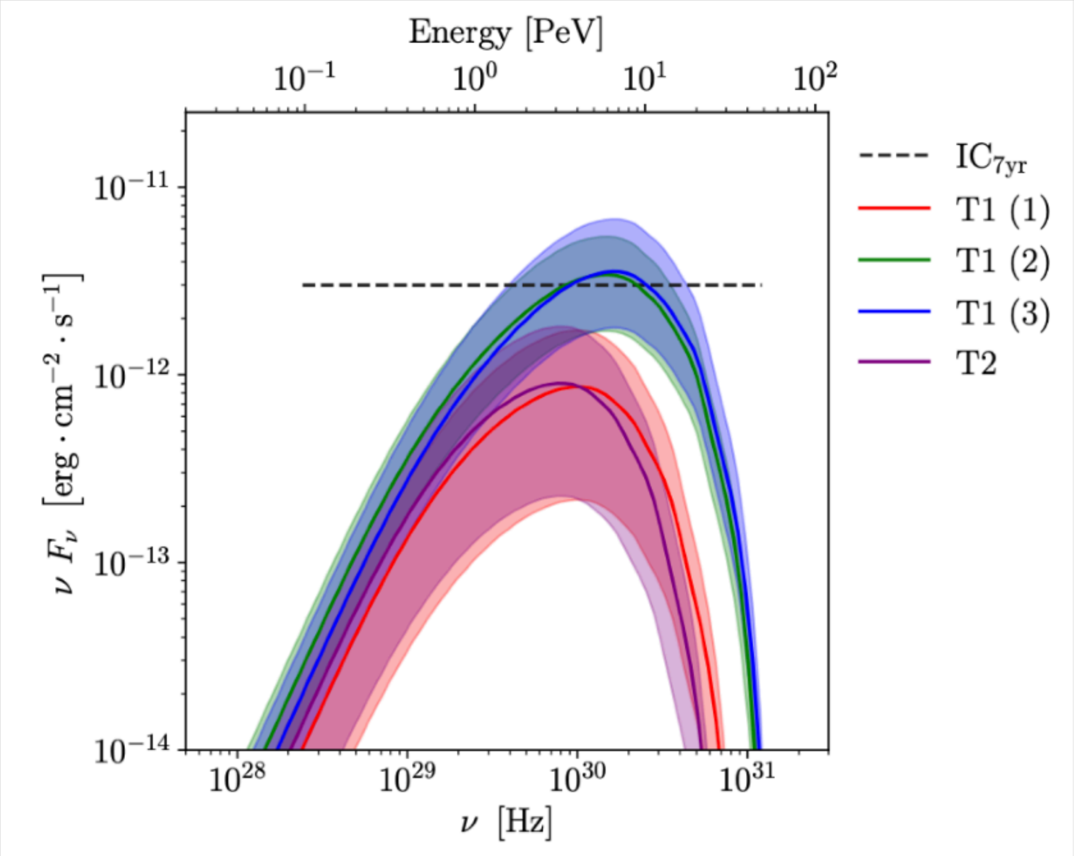




G. Fichet de Clairfontaine, SB et al. 2023

Candidate neutrino-emitter blazars

- Overall properties similar to TXS 0506+056
- Contributing up to 1% to the diffuse neutrino flux
- Predicted neutrino flux variable



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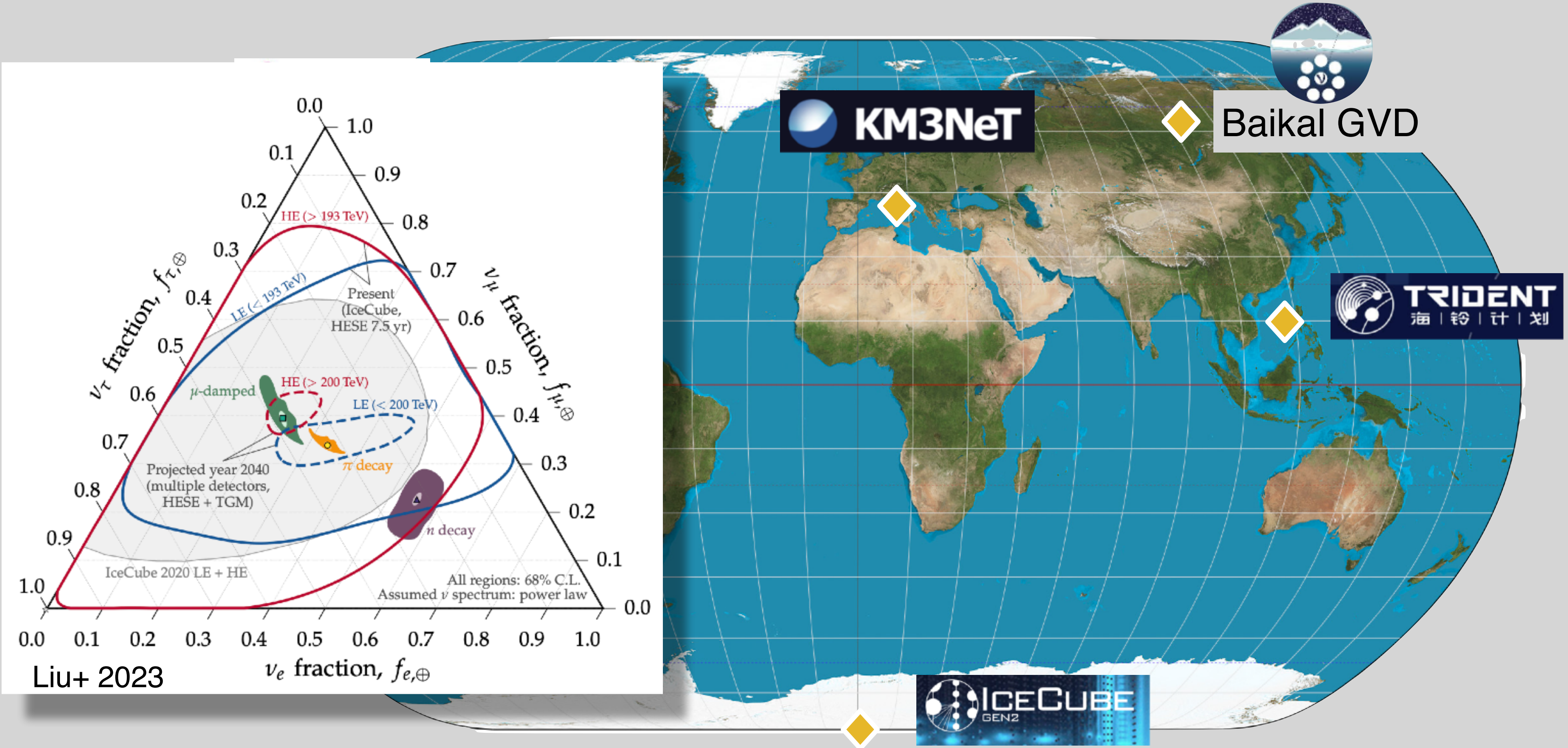
TeV–PeV neutrino detectors: forthcoming decade

TeV–PeV neutrino detectors: forthcoming decade



Summary

- Energy density of neutrinos and cosmic rays in the non-thermal Universe are at the same order of magnitude as that in γ rays, hinting toward a common origin.
- A variety of astrophysical sources for TeV-PeV neutrinos proposed, no firm association yet. Encouraging prospects for the future detection of astrophysical neutrino sources:
  - Seyfert galaxy NGC 1068, Milky Way, blazar TXS 0506+056
- Evidence for non-uniformity in the IceCube skymap
  - A subsample of (PeVatron) blazars proposed as associated with IceCube hotspots
    - Broad implications: *indirect detection of extragalactic cosmic-ray factories*
    - In situ acceleration of cosmic rays to PeV energies and, possibly, up to the EeV regime
    - '*Tip of the iceberg*' : other individual sources may be already detectable in the 15-yr IceCube datasets
- Next generation neutrino observatories, along with γ-ray observatories will provide incredible boost in sensitivity and statistics (e.g. IceCube-Gen2, KM3NeT, Baikal-GVD, P-ONE, GRAND, ARIANNA, RNO…; CTA, AMEGO+...) with great discovery potential ahead.