Neutrino telescopes in the context of multimessenger astrophysics

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ALMA MATER STUDIORUM
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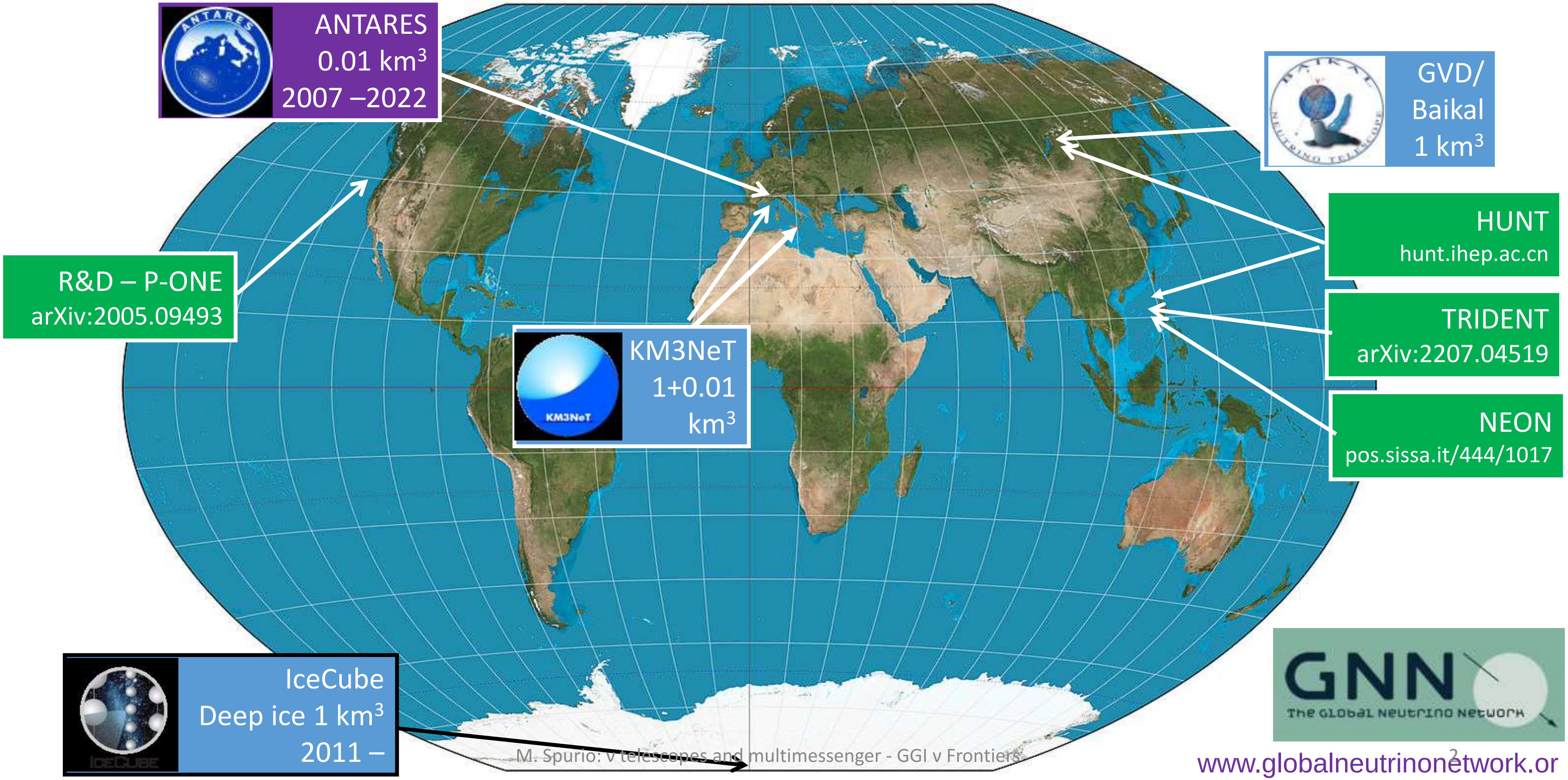
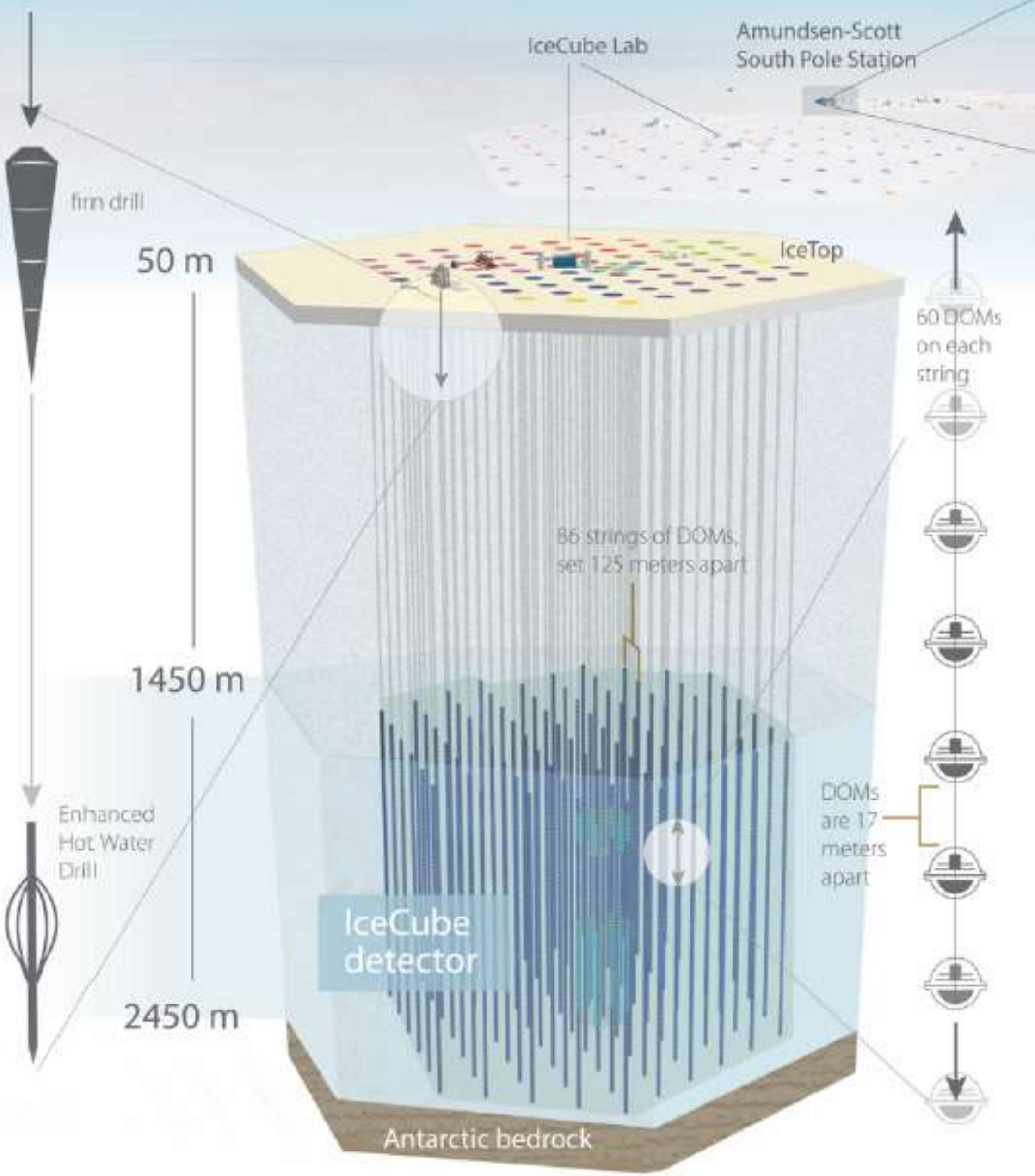
The neutrino telescope world map 202*



www.globalneutrinonetwork.org

IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)

86 string with 60 DOMs each

6 denser strings called **DeepCore**

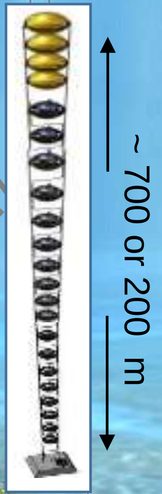
1 km² surface array with 324 DOMs: **IceTop**

Completion in December 2010

KM3NeT in the Mediterranean sea

https://www.youtube.com/watch?v=tzxHlLgAahE https://www.youtube.com/watch?v=omlFkdCKbYk&t=3s

Digital Optical Module (DOM)
- Multi-PMT : 31 x 3” PMTs
- Gbit/s on optical fiber
- Positioning & timing



Detection Unit (DU)
- 18 DOMs
- Low-drag design

- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reusable

Baikal-GVD

Presently detector consists of 110 strings arranged into 14 independent detectors - **clusters**

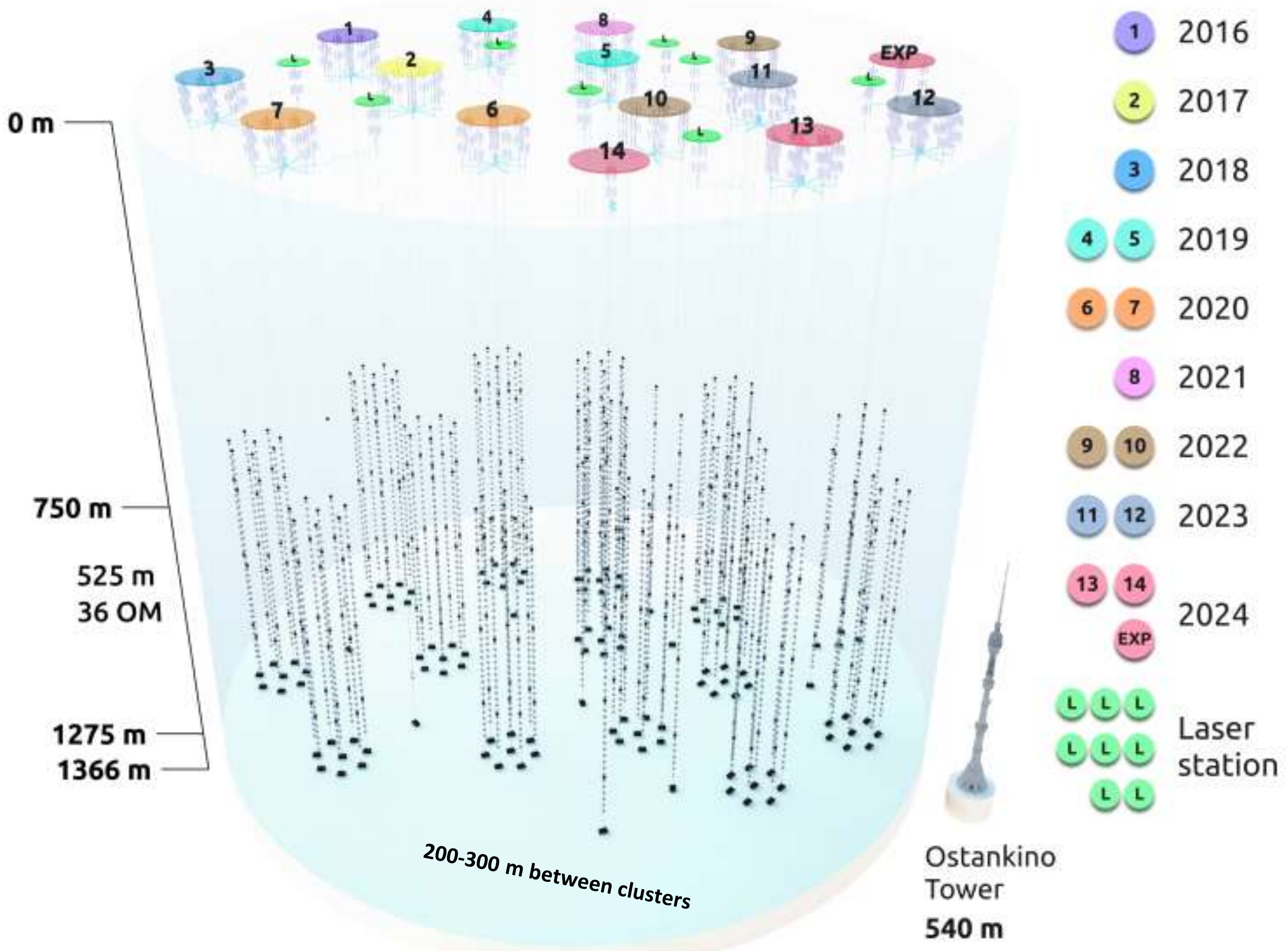
- 3960 OMs in total

Baikal-GVD cluster:

- 8 regular strings, 525 m instrumented with OM
- 60m radius
- Inter-cluster string carrying lasers, some instrumented with OMs
- Has its own control, trigger and readout systems

Additional cluster “EXP”:

- 4 strings with experimental high-speed DAQ



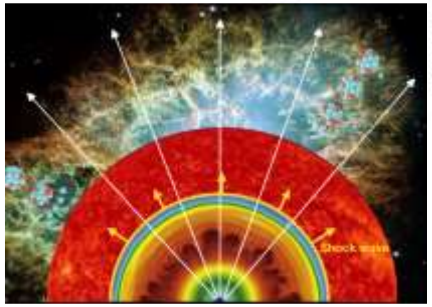
Physics with neutrino telescopes

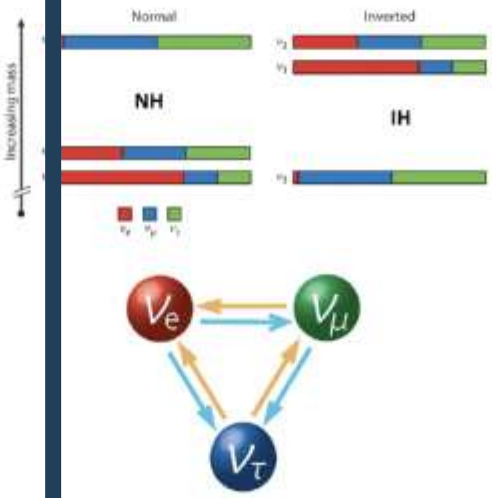
Supernovae Explosion

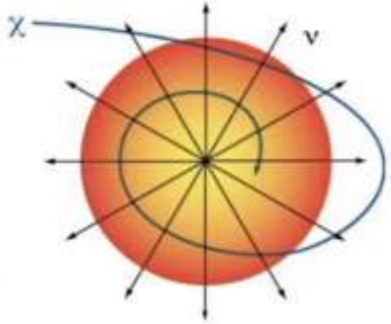
Neutrino Physics

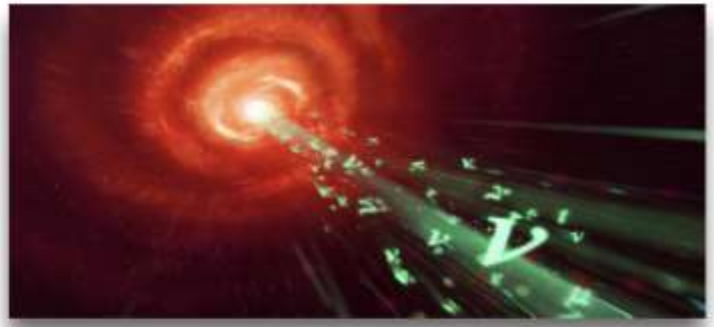
Dark Matter & Exotic searches

Cosmic neutrinos

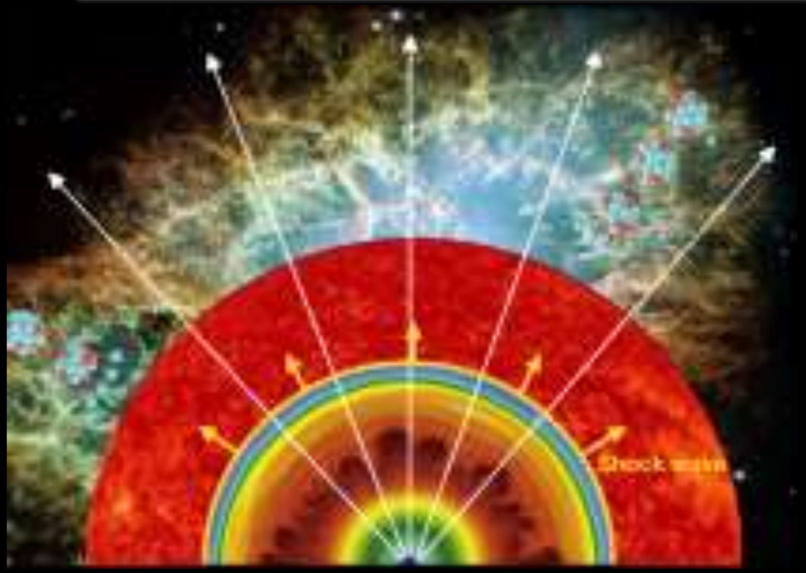


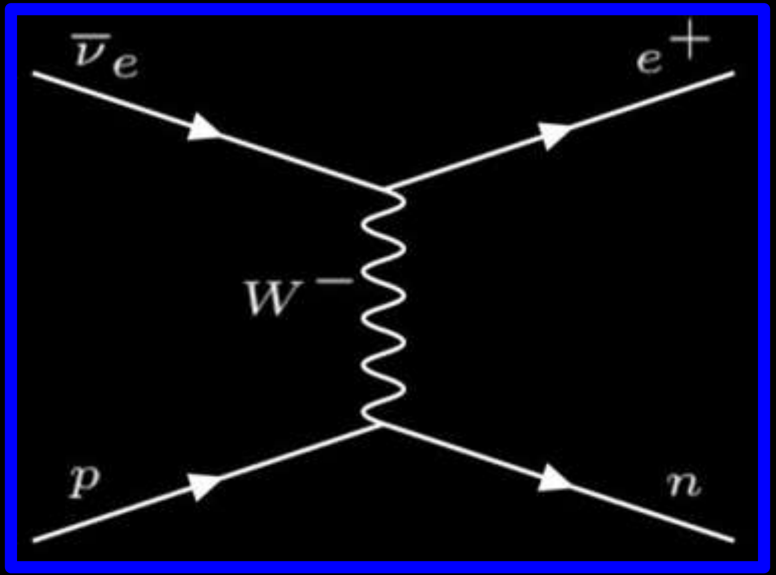




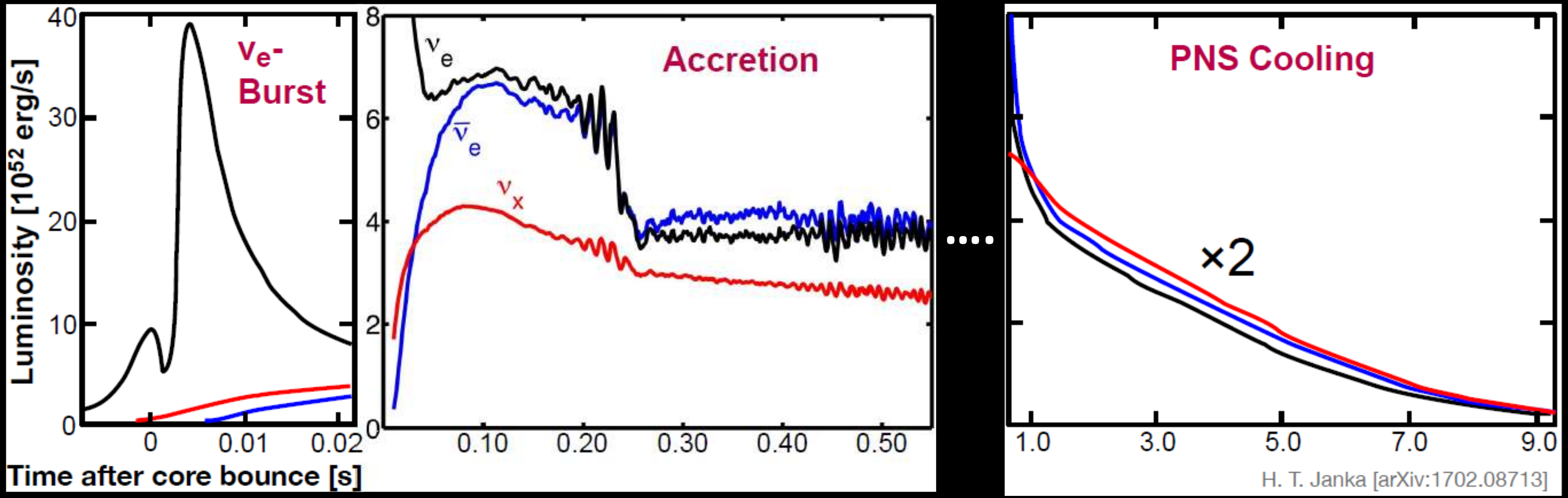


ν from core-collapse supernovae





- **Signal Model:** Neutrino Emission from SNe: H.-Th. Jank arXiv:1702.08713
- Accretion phase: 0.5 s
- **Signal in the detector**: 90% due to CC $\overline{\nu_e}$ interaction
- 10 MeV electron release its energy in about 5 cm of water
- Coherent increase of the "light" in the detector.

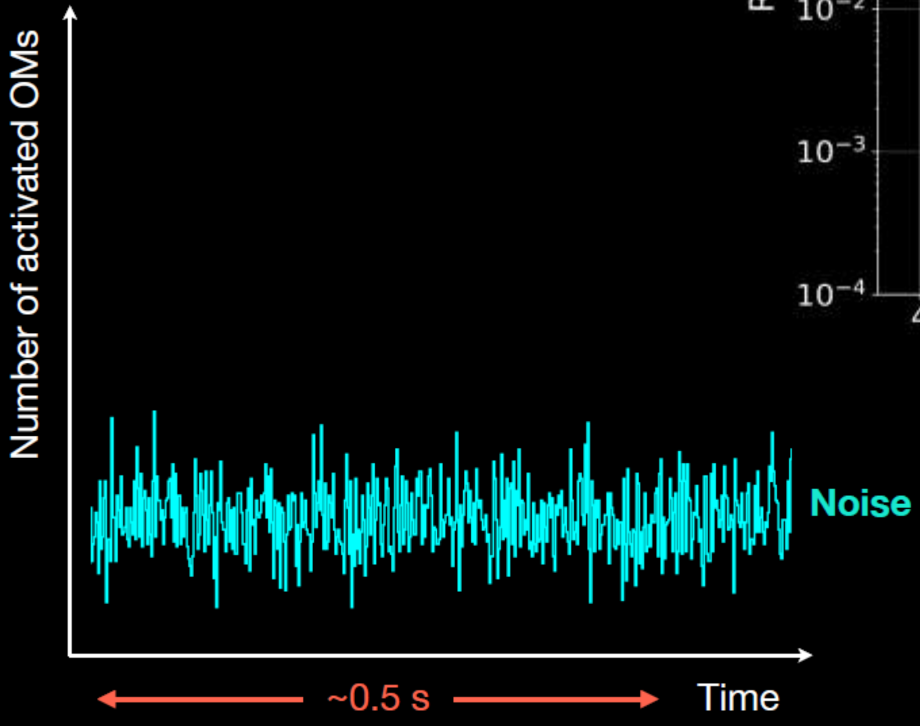


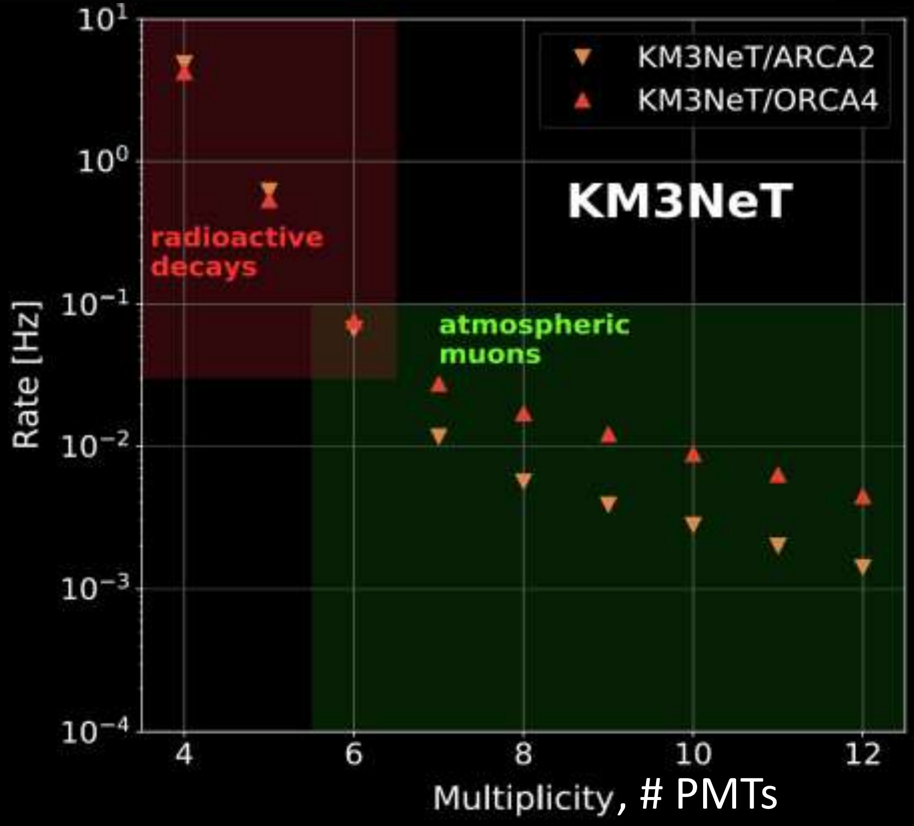
ν from core-collapse supernovae: background

- 2070 DOMs in one detector building block
- Each DOM is a detector, each with 31 small PMTs

β-decay: 1-2 PMTs in 20 ns

Muons: > 3 PMTs in many DOMSs within few μs





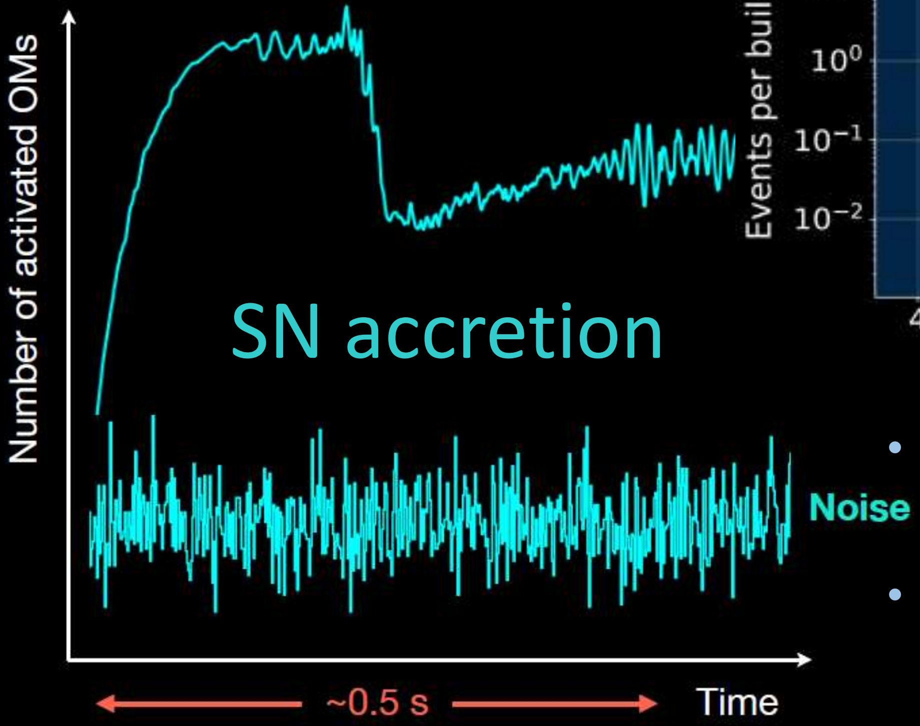
KM3NeT: EPJ. C (2021) 81:445

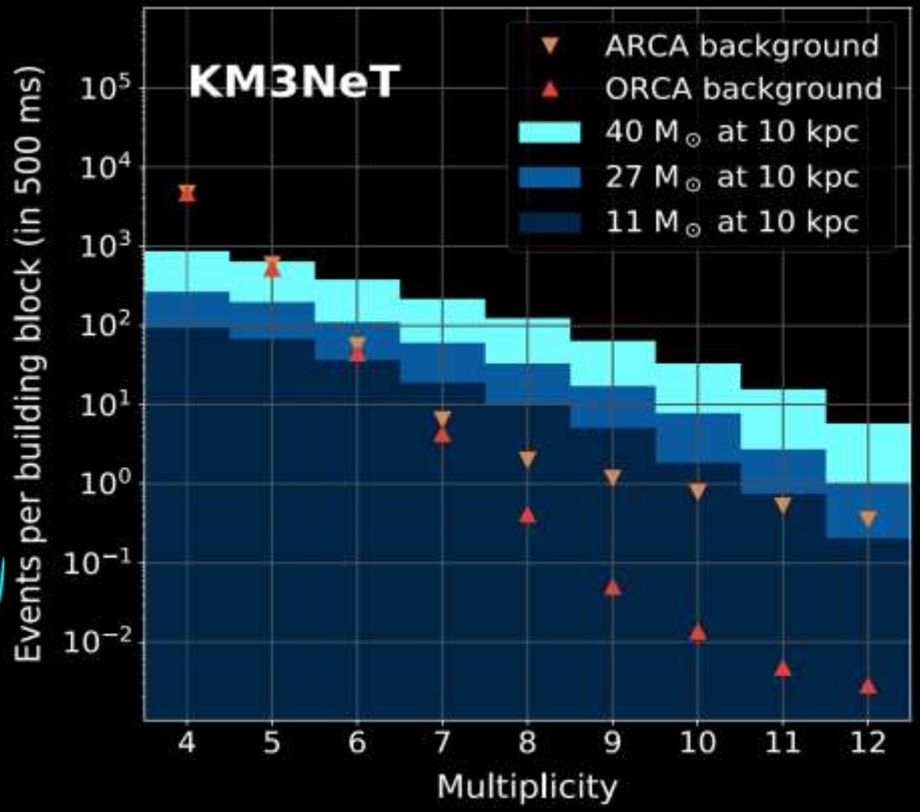
ν from core-collapse supernovae: signal

- 2070 DOMs in one detector building block
- Each DOM is a detector, each with 31 small PMTs

KM3NeT: EPJ. C (2021) 81:445

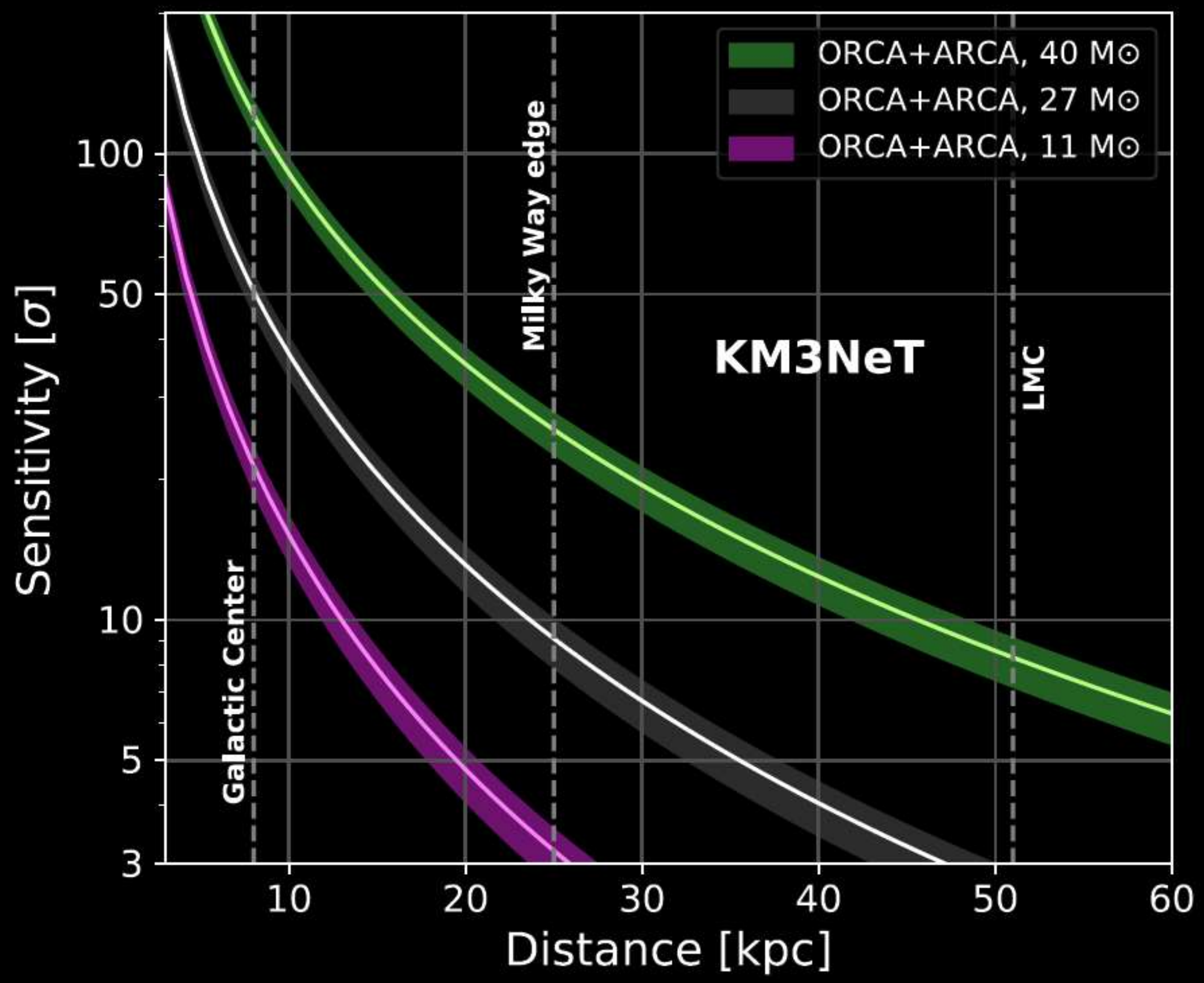
10 MeV electron: > 4 PMTs





- Number of **signal +bck** events within **0.5 s** in **2070 DUs**
- Multiplicity distribution used as proxy of the SN ν's energy spectrum.

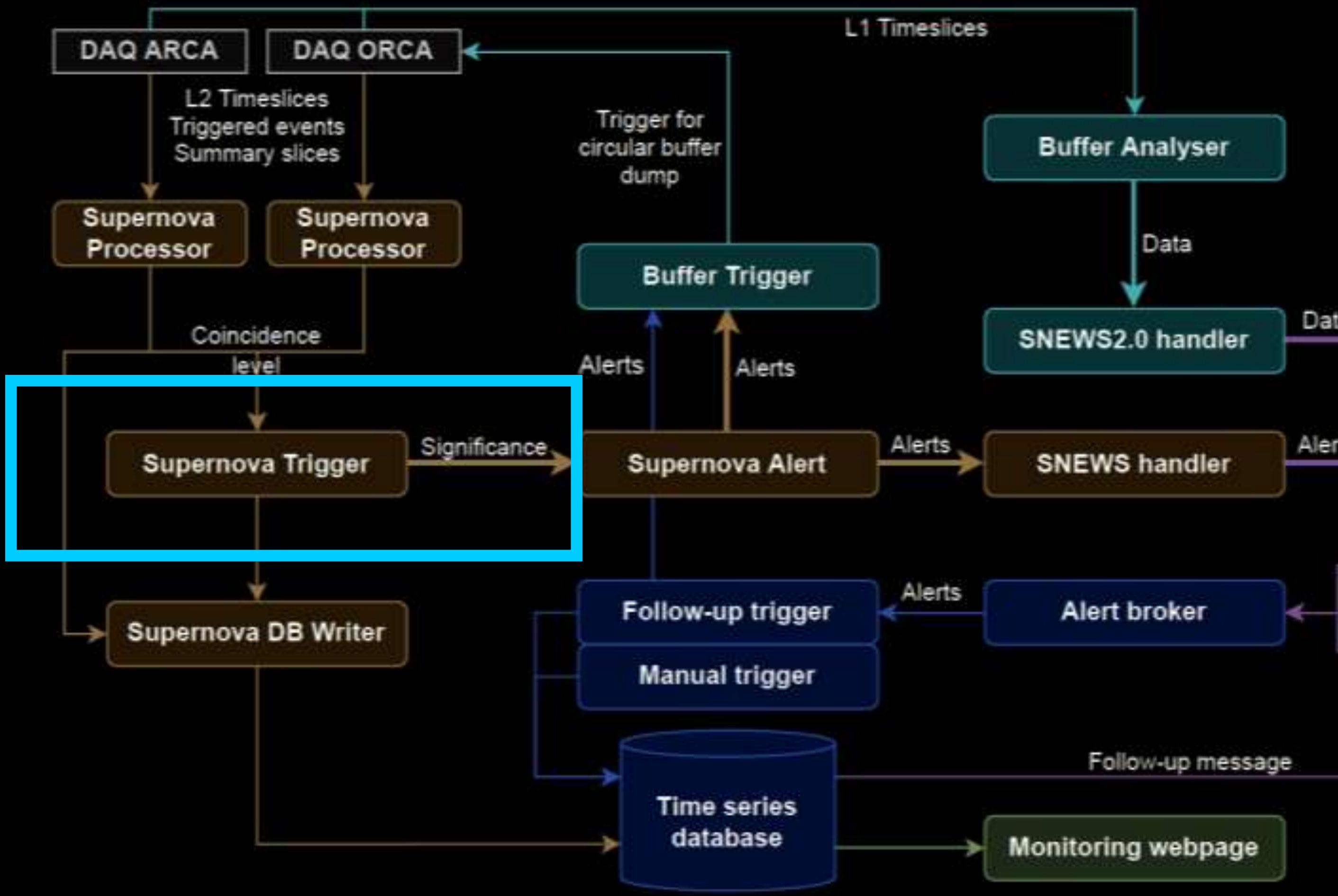
ν from core-collapse supernovae: sensitivity



- KM3NeT detection sensitivity as a function of the distance to the CCSN for the three progenitors considered.
- The error bars include the systematic uncertainties

KM3NeT: EPJ. C (2021) 81:445

KM3NeT supernovae alert (online pipeline)



- Alert system: 20 s latency time
- Trigger threshold: adapt to background level 1 fake event/week
- Buffer 10 min of data
- Timing of the SN detection for triangulation with other experiments.

PoS(ICRC2023)1223

HE astrophysics with neutrino telescopes

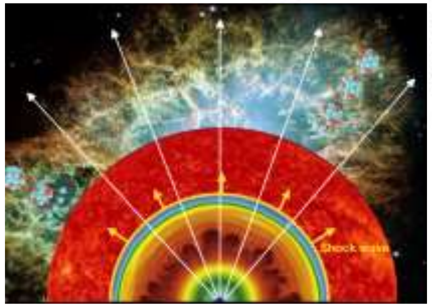
Supernovae Explosion

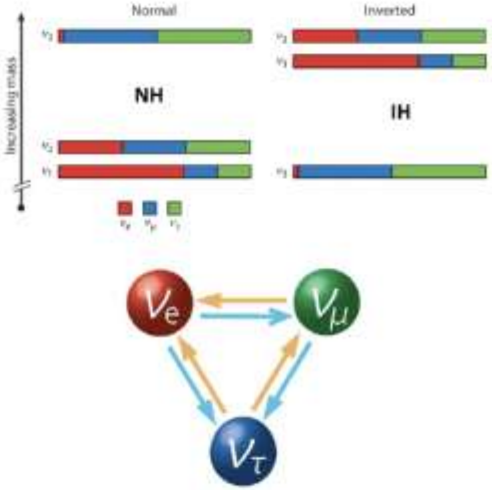
Neutrino Physics

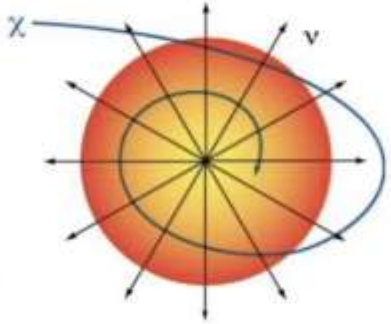
Dark Matter & Exotic searches

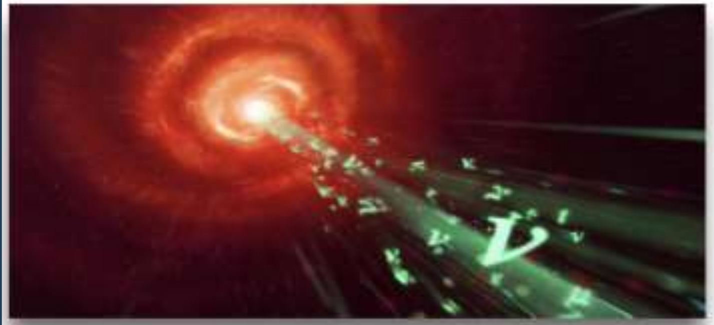
Cosmic neutrinos

MeV GeV TeV PeV



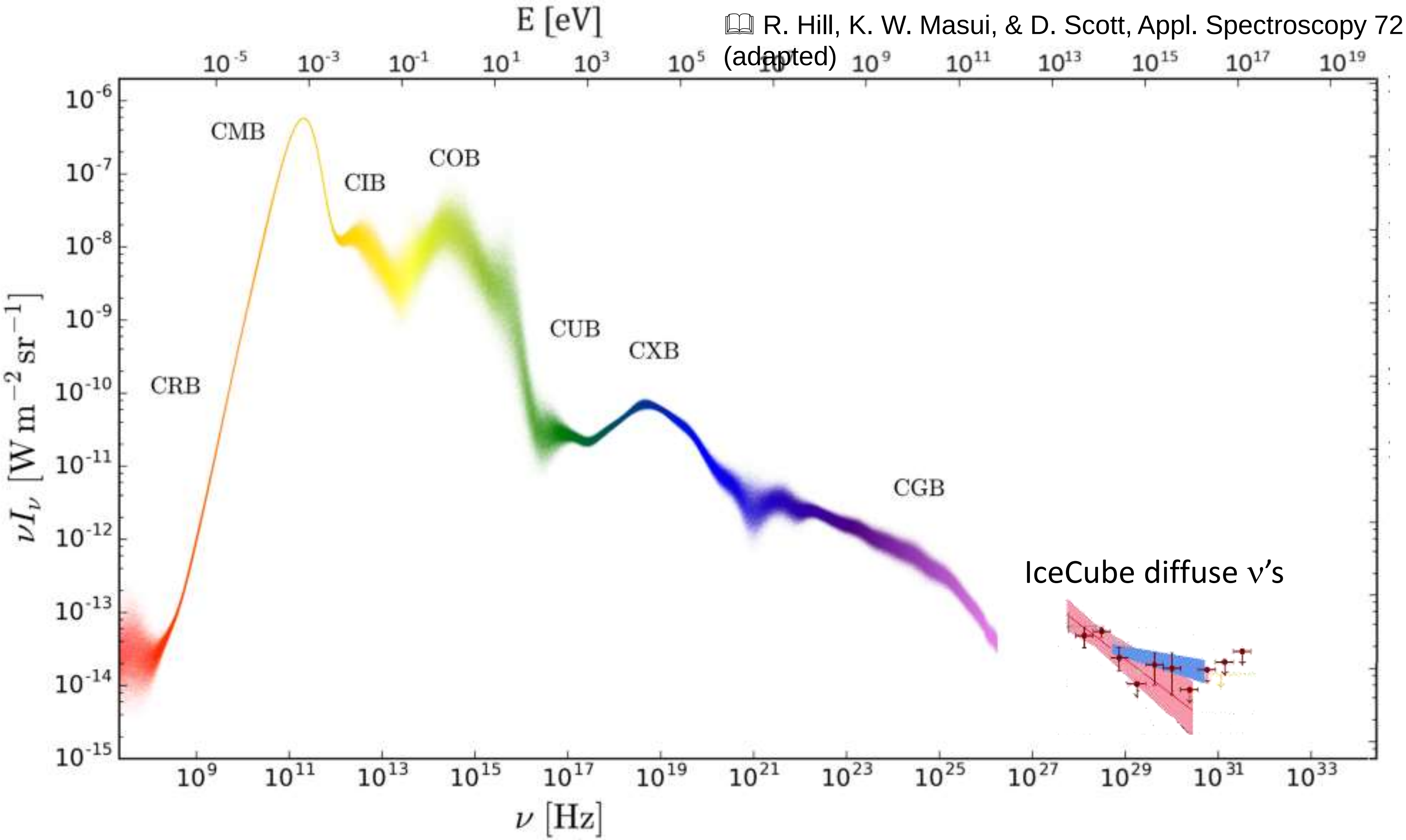






Energy density of the extragalactic radiation

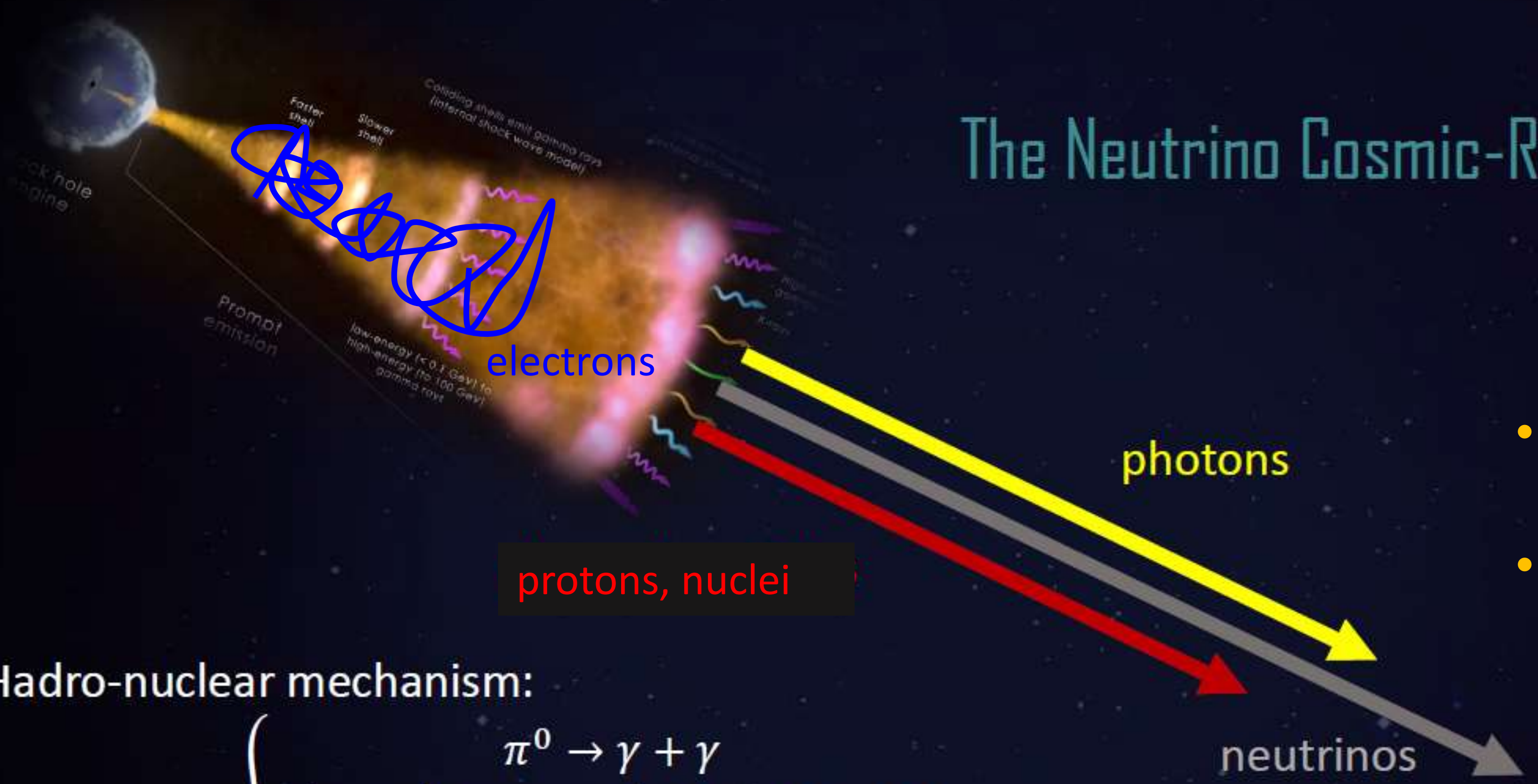
📖 R. Hill, K. W. Masui, & D. Scott, Appl. Spectroscopy 72, (2018) 663 (adapted)



Adapted from M. Taiuti

📖 Palladino+, Universe 2020, 6,30

The Neutrino Cosmic-Ray Connection



- The **leading pion** carries (on average) 1/5 of the proton E_K.
- The 4 light (anti)leptons in $\pi^\pm$ decay carries ¼ of its energy:

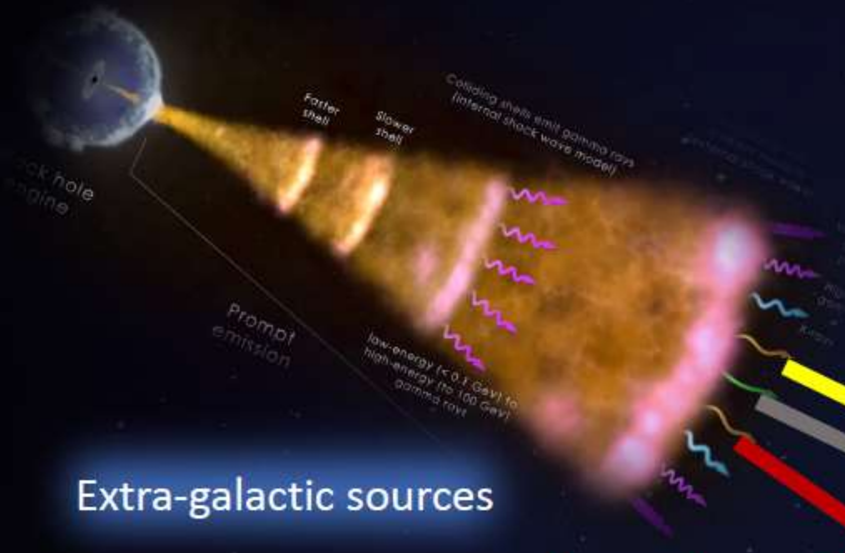
$$E_\nu \sim \frac{E_\gamma}{2} \sim \frac{E_\pi}{4} \sim \frac{E_p}{20}$$

Hadro-nuclear mechanism:

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

Adapted from M. Taiuti

The Neutrino Cosmic-Ray Connection



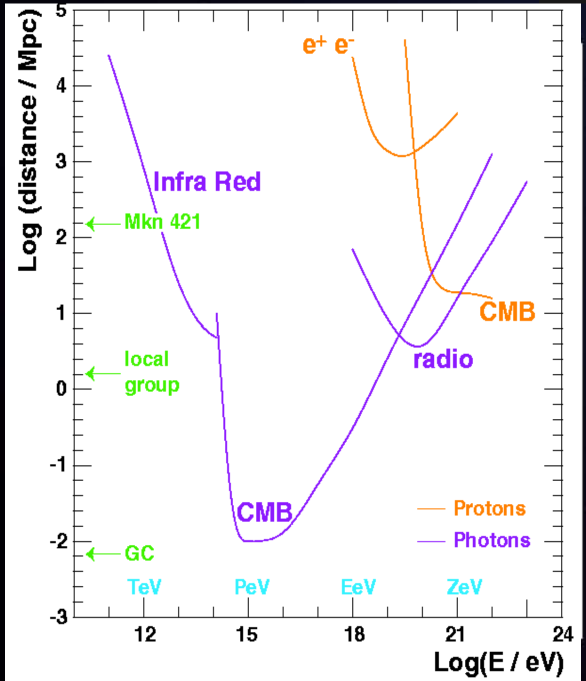
I) Sources may not be γ-ray transparent. In photo-hadronic collisions, the dense target of is also a target for $\gamma\gamma$ interaction and subsequent cascading

photons

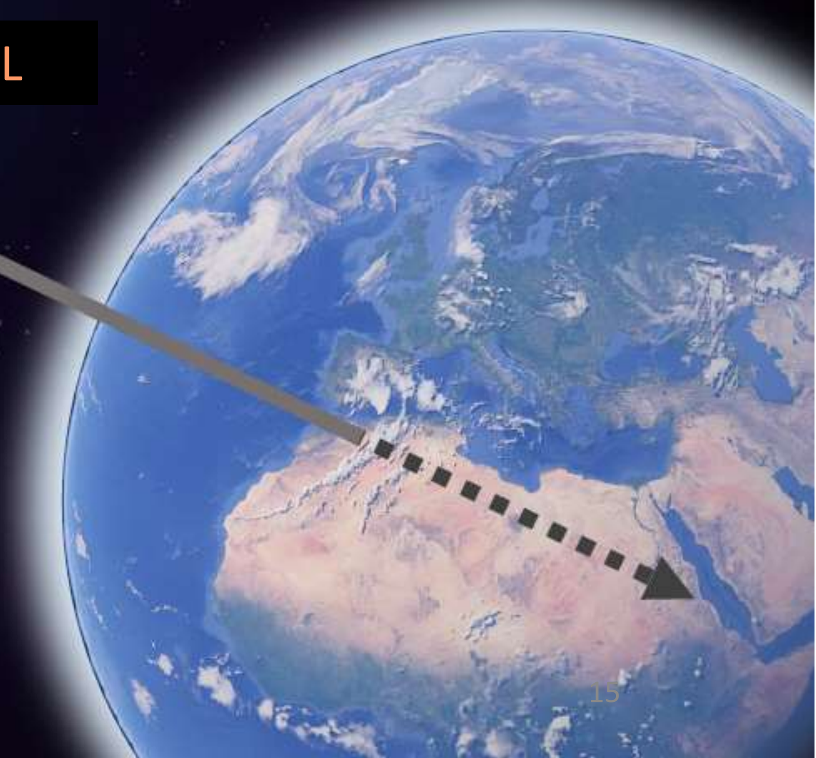
protons, nuclei

CMB, EBL

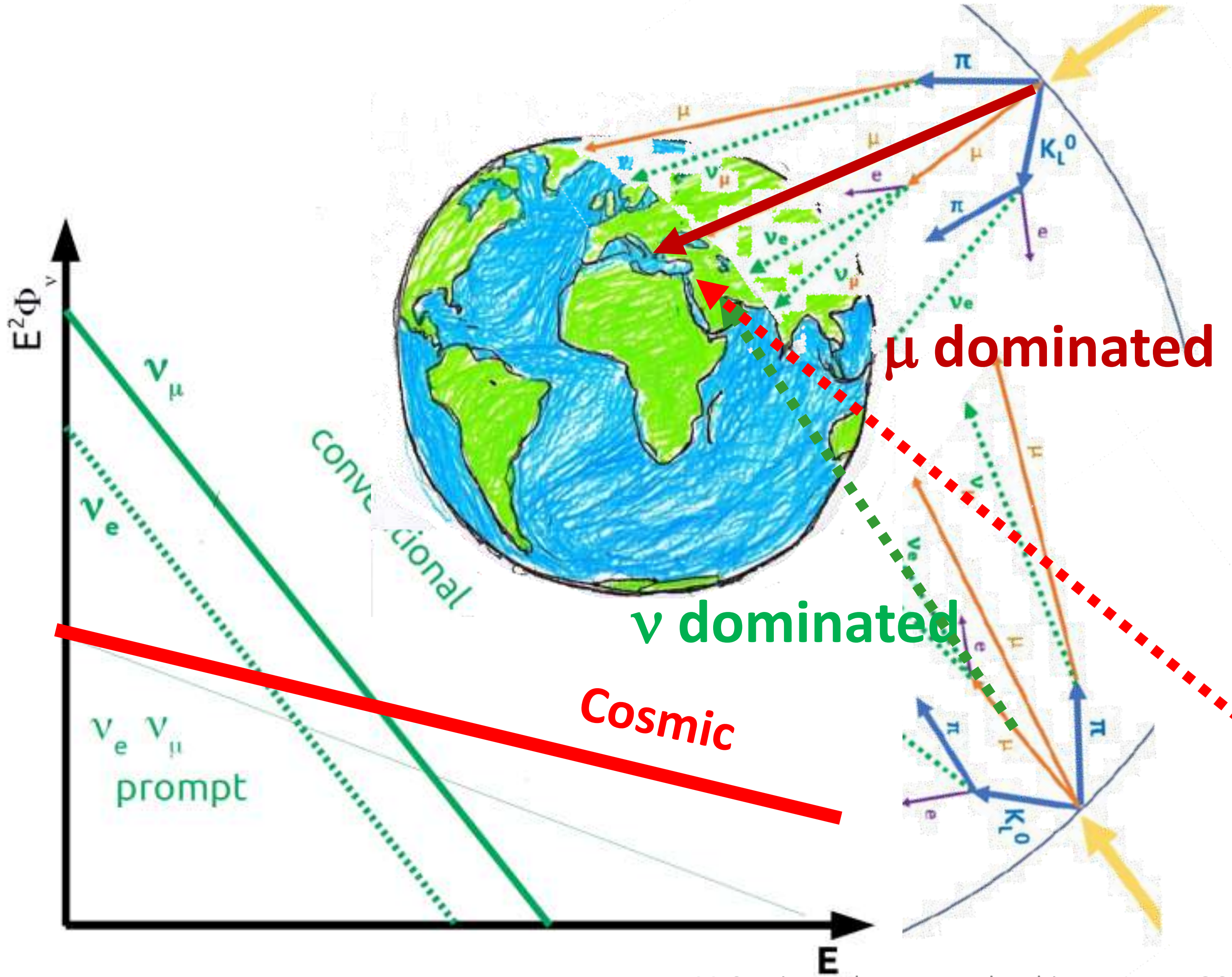
neutrinos



II) If γ-rays escape the source, at $E_\gamma \gtrsim 1$ TeV are strongly attenuated by γγ interaction with the CMB and the Extragalactic Background Light (EBL).



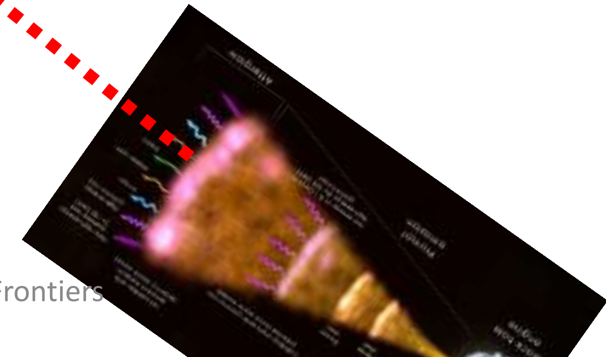
Background of atmospheric μ and ν



- **Atmospheric μ** dominates the down flux
- **Atmospheric ν** is irreducible background
- HE cosmic neutrino may originate from the **sources** or from CRs interacting during **propagation**.
- Single power-law (SPL) parameterization

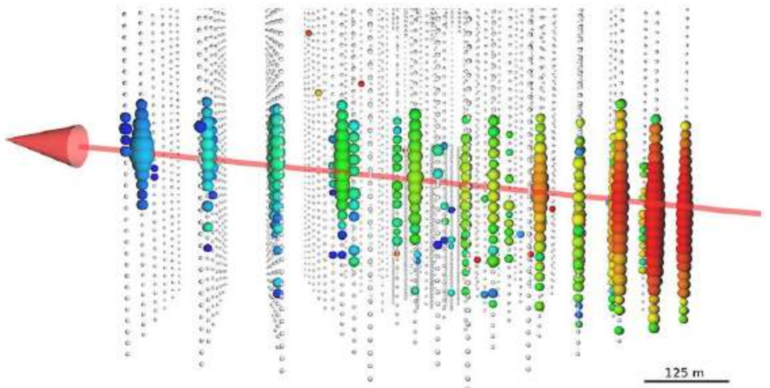
$$\Phi_\nu = \Phi_{astro}\left(\frac{E}{E_0}\right)^{-\gamma}$$

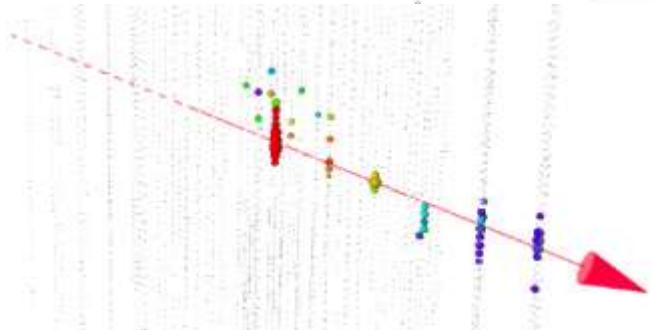
- **Neutrino oscillations:** equipartition between 3 flavors at Earth (if π→νμ).

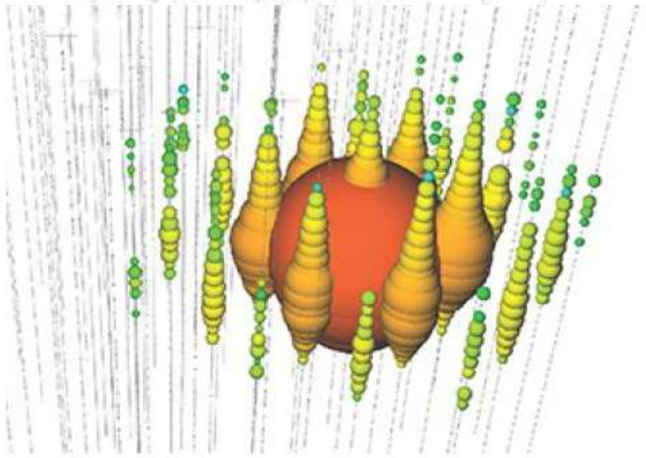


Neutrino event topologies (E>1 TeV)

Real IceCube events







Tracks ($\nu_\mu + N \rightarrow \mu + X$)

- Good angular resolution 0.1°-1°
- Vertex can be outside the detector
  - Muon range in water/ice >5 km @ E_μ>1 TeV
- Challenging energy estimation

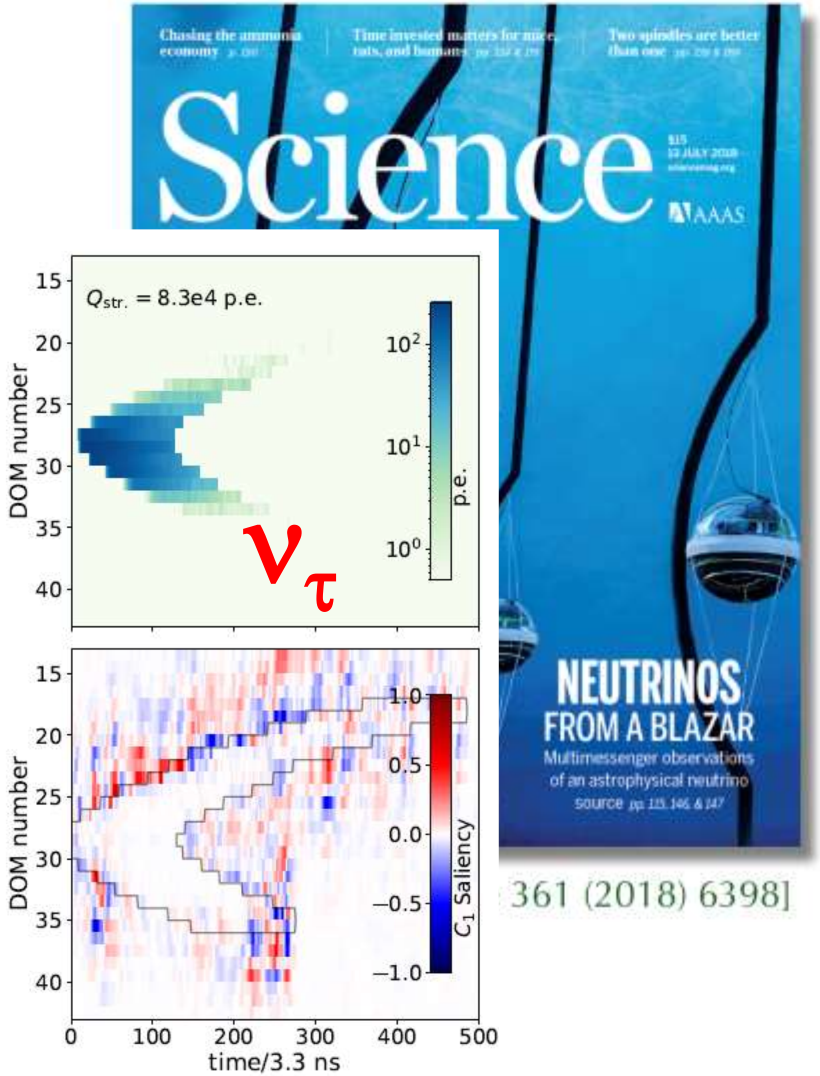
- Vertex inside the detector (**starting tracks**)
  - Use of self-veto

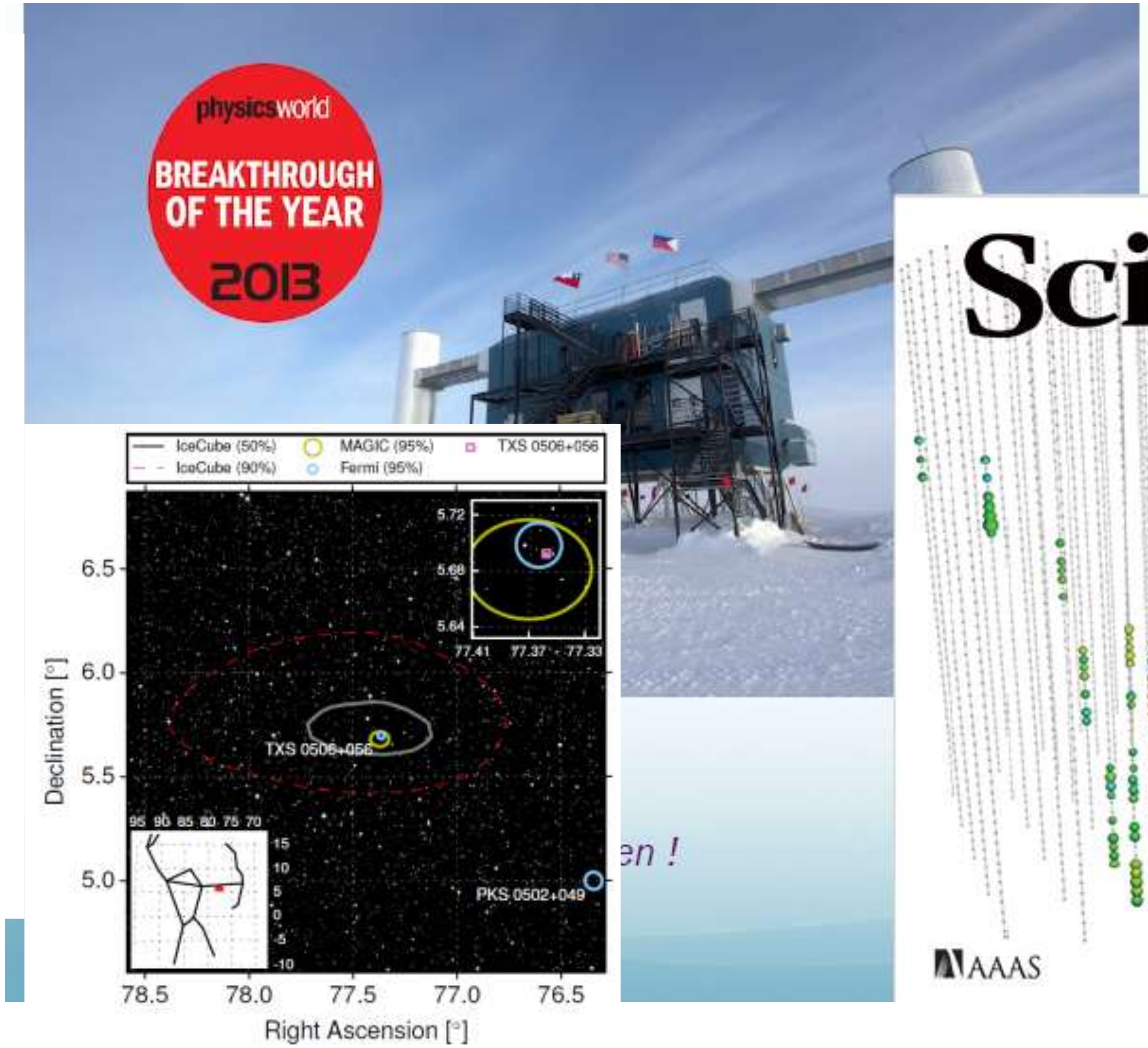
Warning: some event properties (energy, direction,…) depends on medium (sea or lake water, ice)

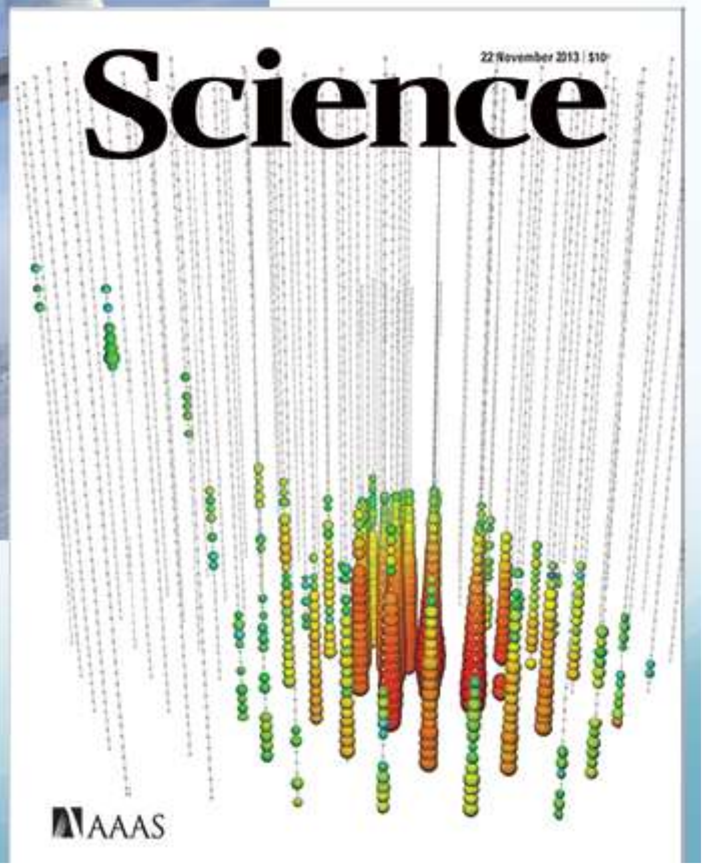
Cascades or Showers ($\nu_e + N \rightarrow e + X$ + N.C.)

- Vertex inside the detector
  - EM cascade develops in 10 m in water
- Fully active calorimeter
  - better E determination
- Limited angular resolution (few to 15°)
- All flavors for NC

The IceCube discovery of cosmic neutrinos





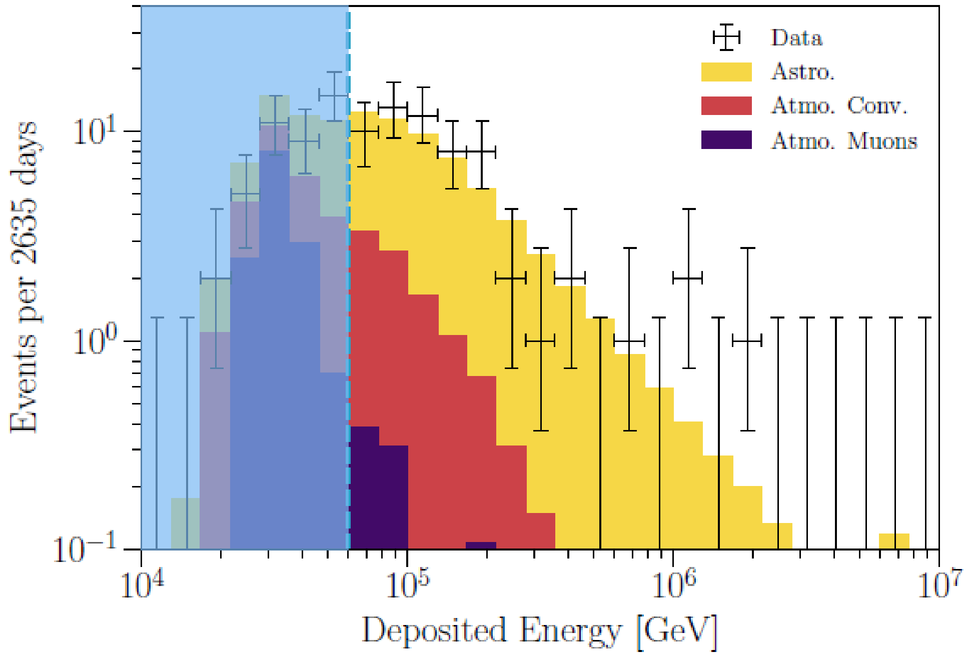


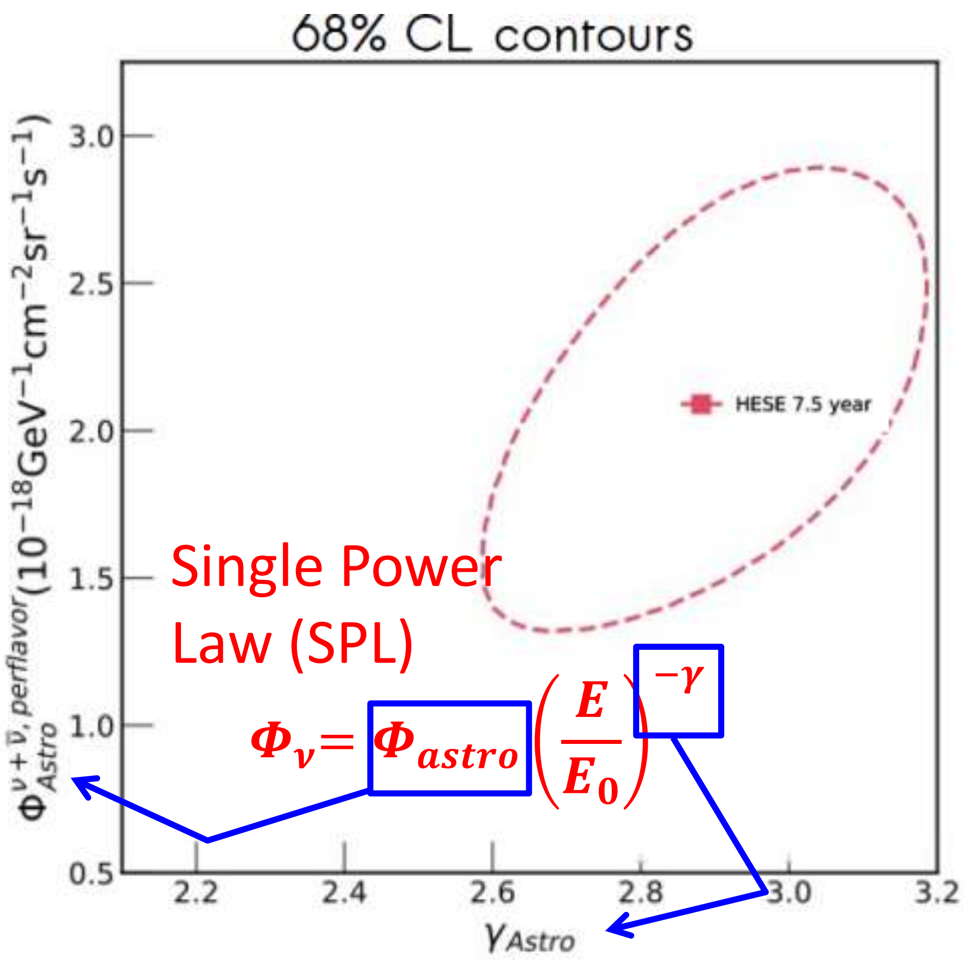
📖 IceCube arXiv:2403.02516v3

IceCube High Energy Starting Events

📖 IceCube PRD 104 (2021), 022002

- Mostly **cascades** with poor angular resolution (>10°)
- Selection criteria favor events from **Southern sky**
- Excess of events (>60 TeV) w.r.t. atmospheric background.



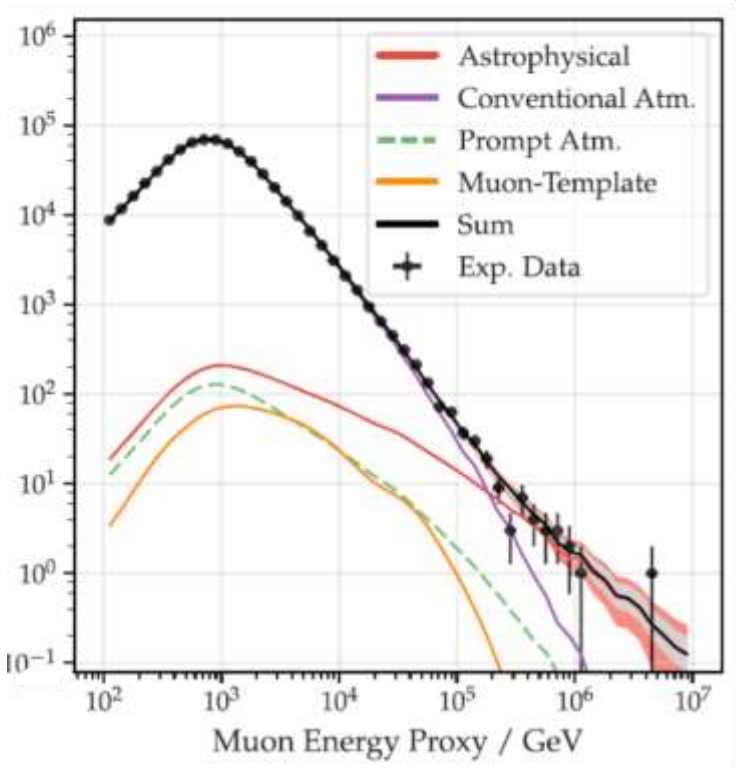


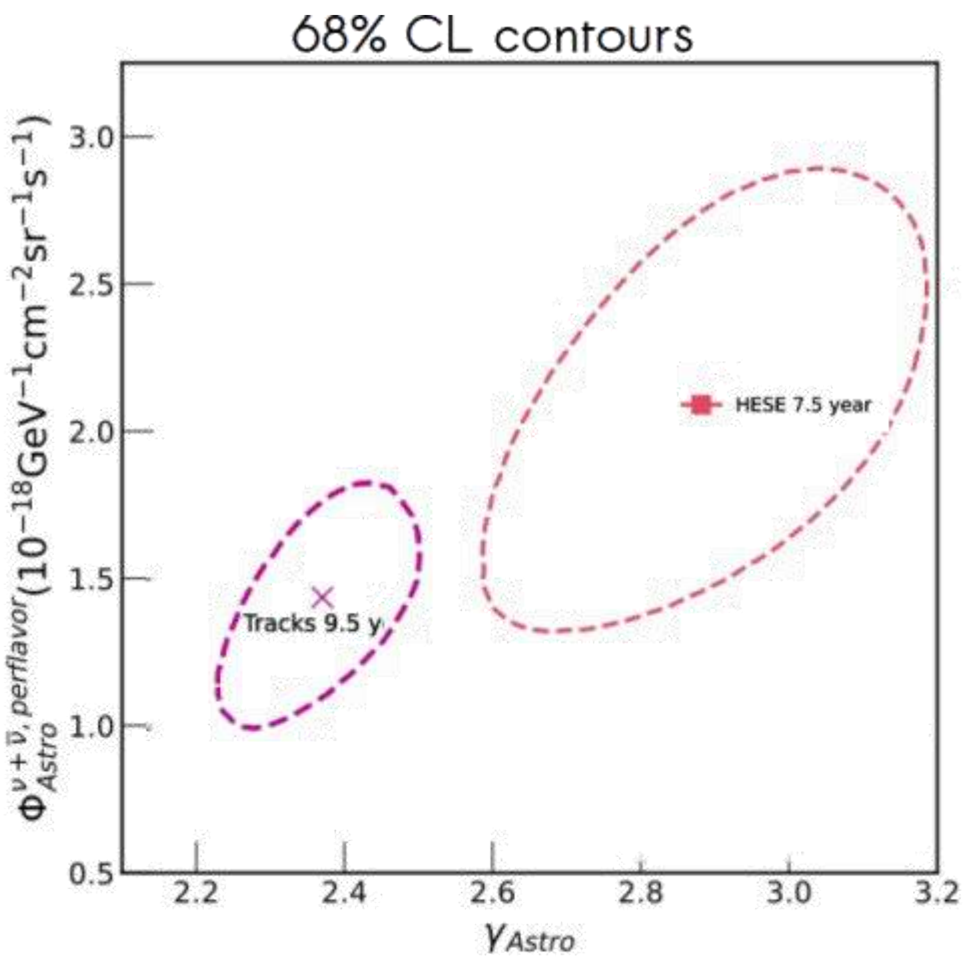
- The astrophysical origin deduced mainly from their high energies
- A SPL assumed to fit the entire energy range, due to the limited statistics.

Upward throughgoing tracks

📖 IceCube ApJ 928 50 (2022)

- Upgoing tracks by ν_μ interactions, 9.5 y of data → **Northern sky**
- Relatively poor (good) energy (direction) estimate
- Excess (E>100 TeV) over the expected distribution for background events using an **unfolding method**

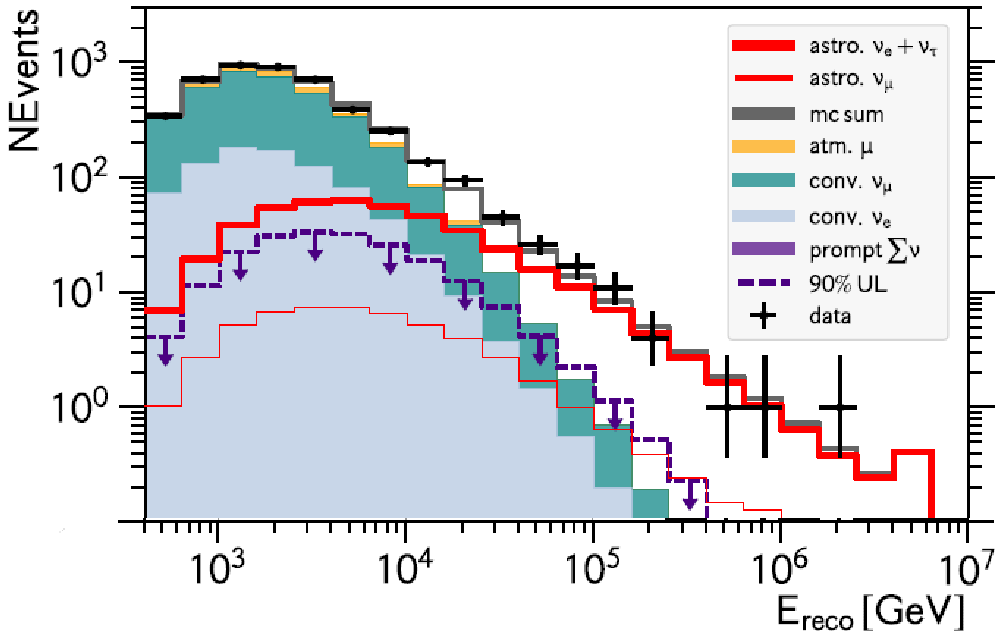


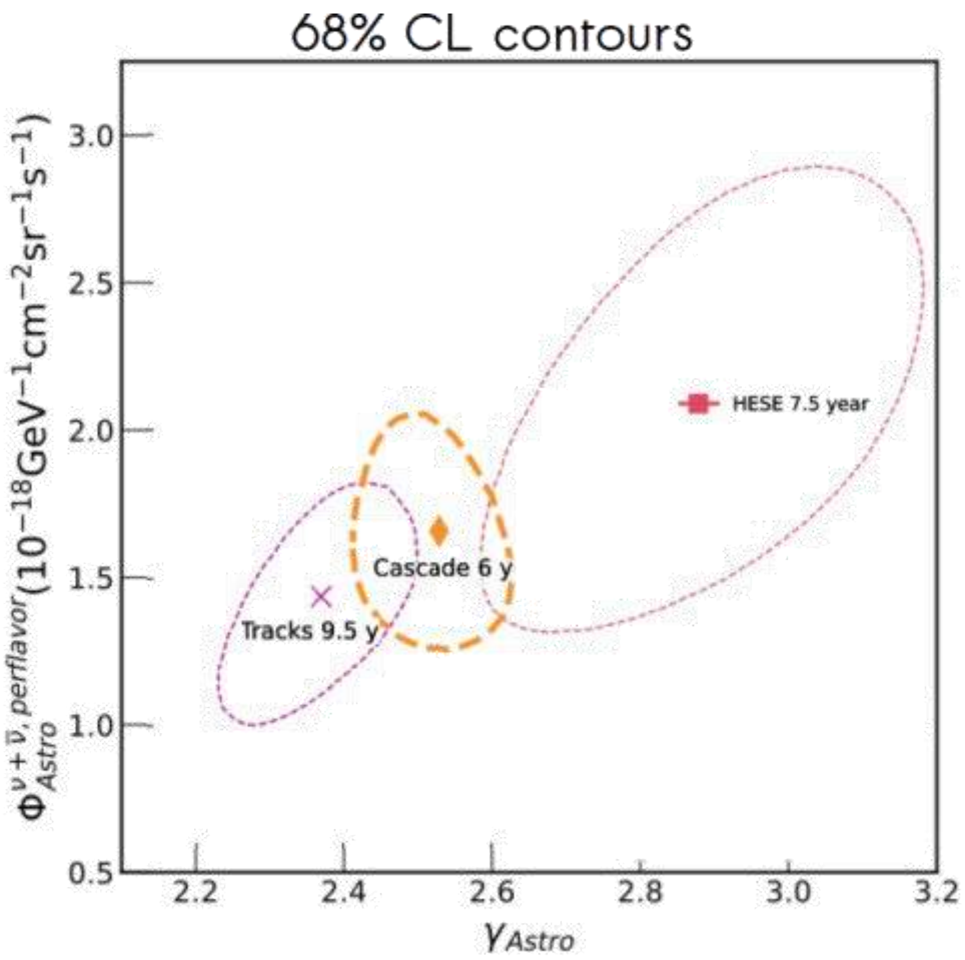


Cascades: ν_e ν_τ CC+NC interactions

IceCube PRL. 125, 121104 (2020)

- Showers produced by ν_e **and** ν_τ interactions, 6.0 y of data
- Relatively poor (good) direction (energy) estimate
- Energy range from **16 TeV to 2.6 PeV, all-sky**
- Boosted Decision Tree based rejection of muons

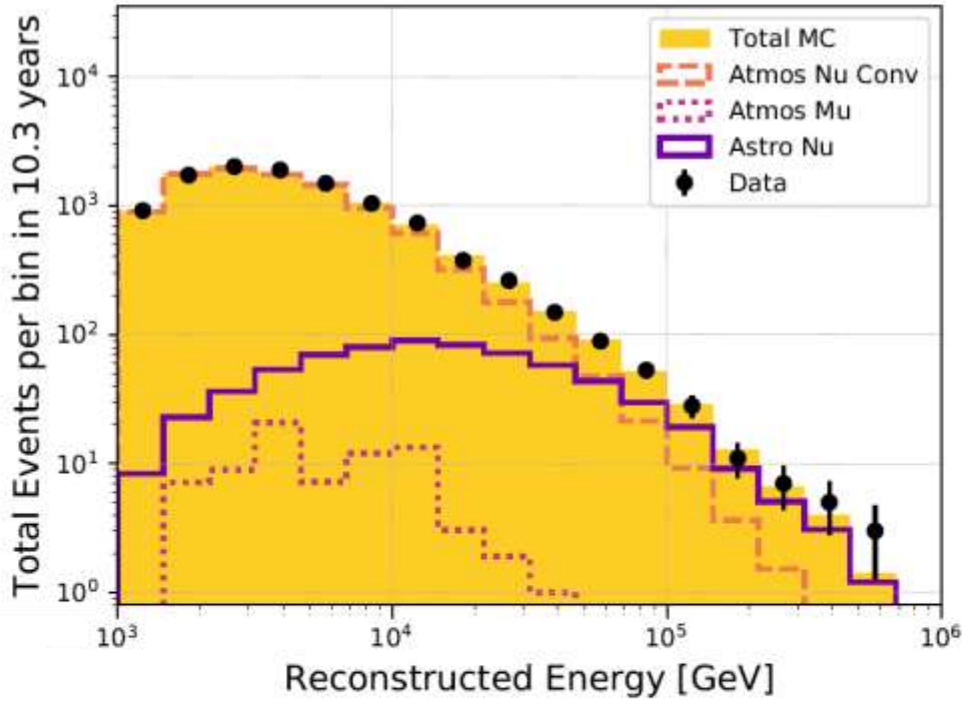


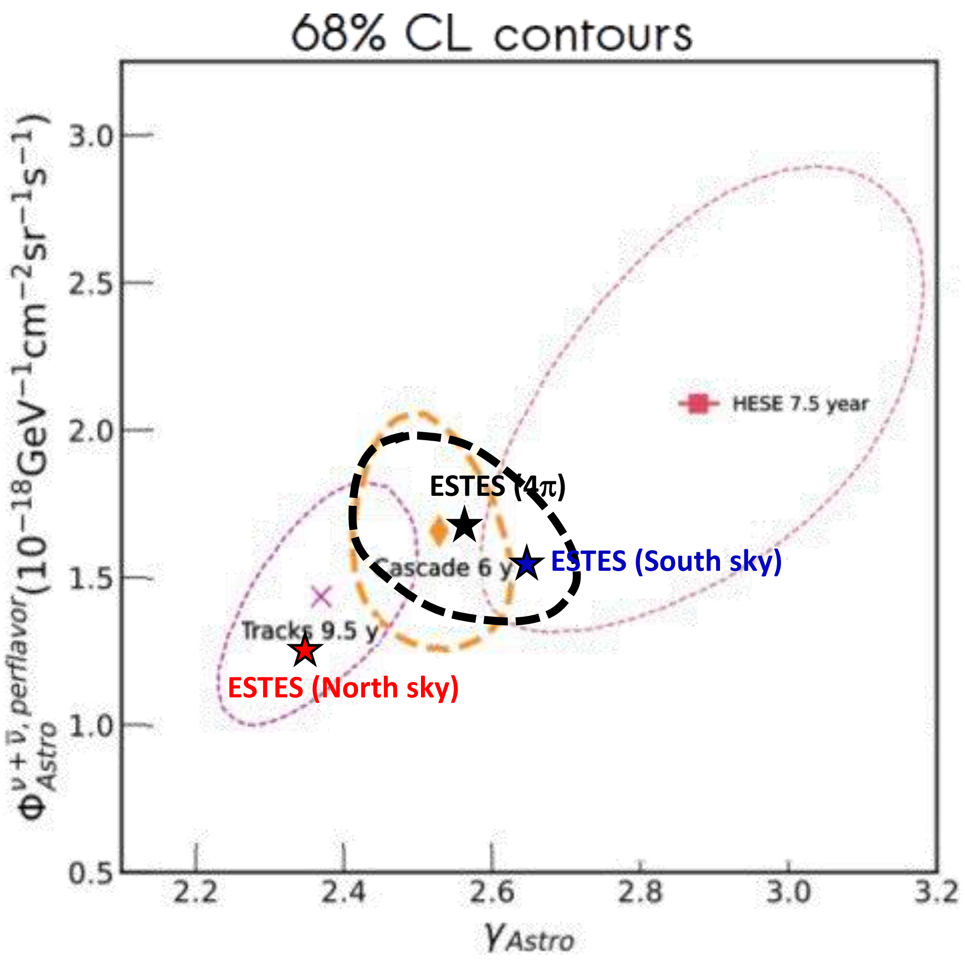


Enhanced Starting Track Events (ESTES)

📖 IceCube: arXiv:2402.18026

- Selection of **starting tracks (ν_μ CC)** based on a BDT,.
- Energy range from 3 to 500 TeV
- SPL slightly different from North and South sky

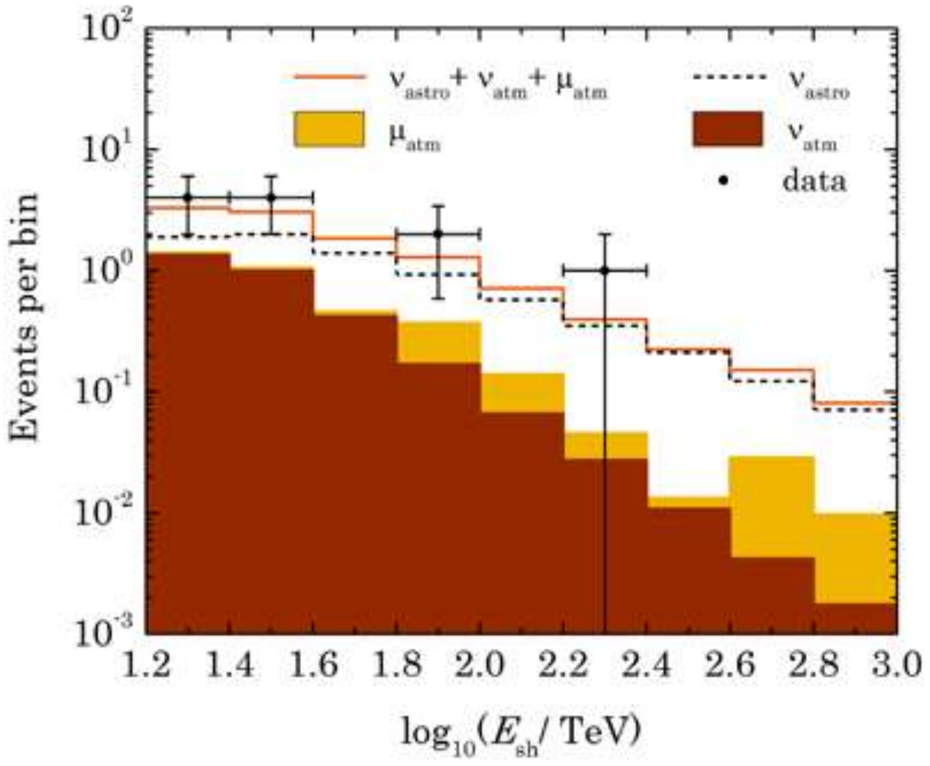


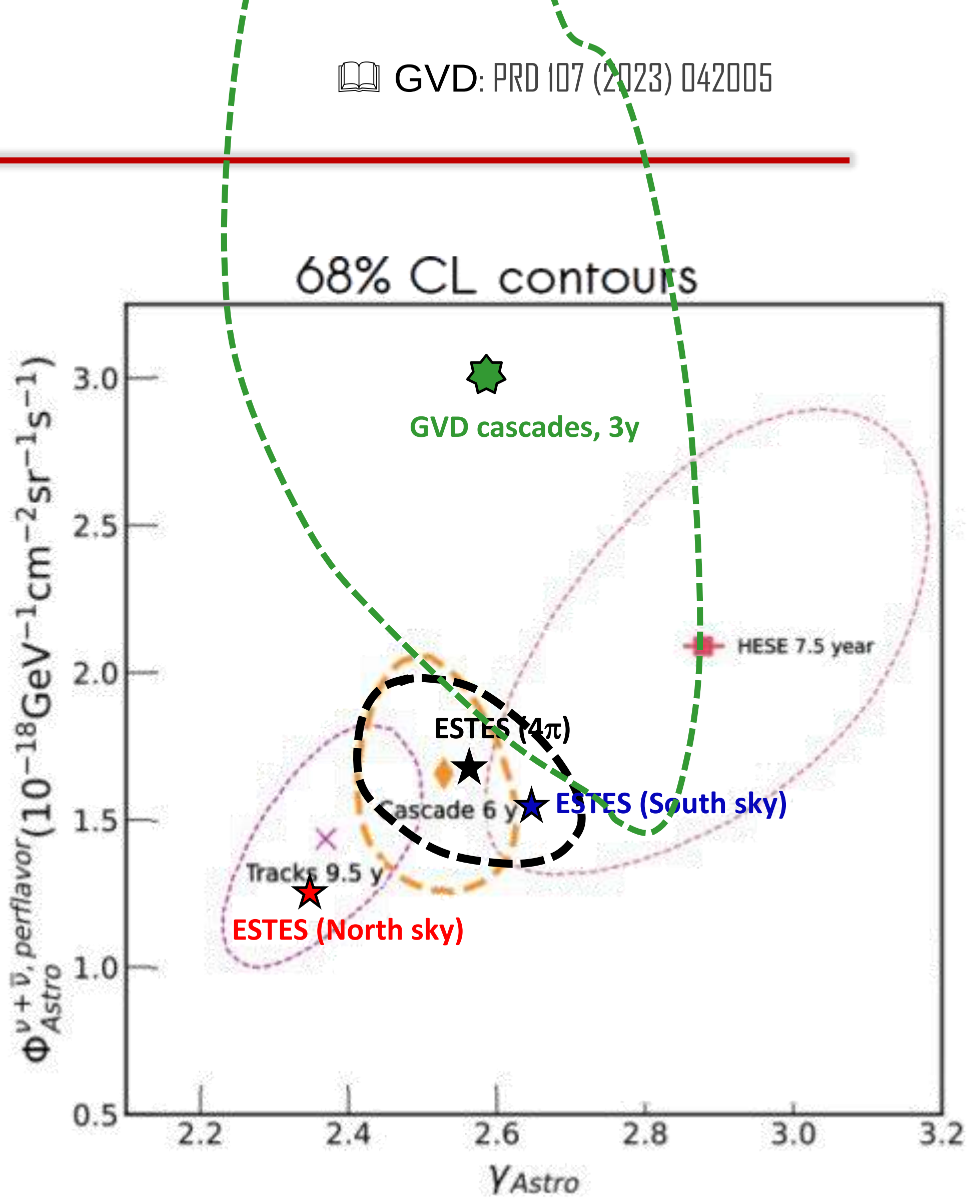


Baikal-GVD cascades

📖 GVD: PRD 107 (2023) 042005

- Selection of **cascades,** events from all sky
- To remove the background of atmospheric muons, upgoing events selected (mostly South sky)
- Excess w.r.t. atmospheric ν's **> 15 TeV**





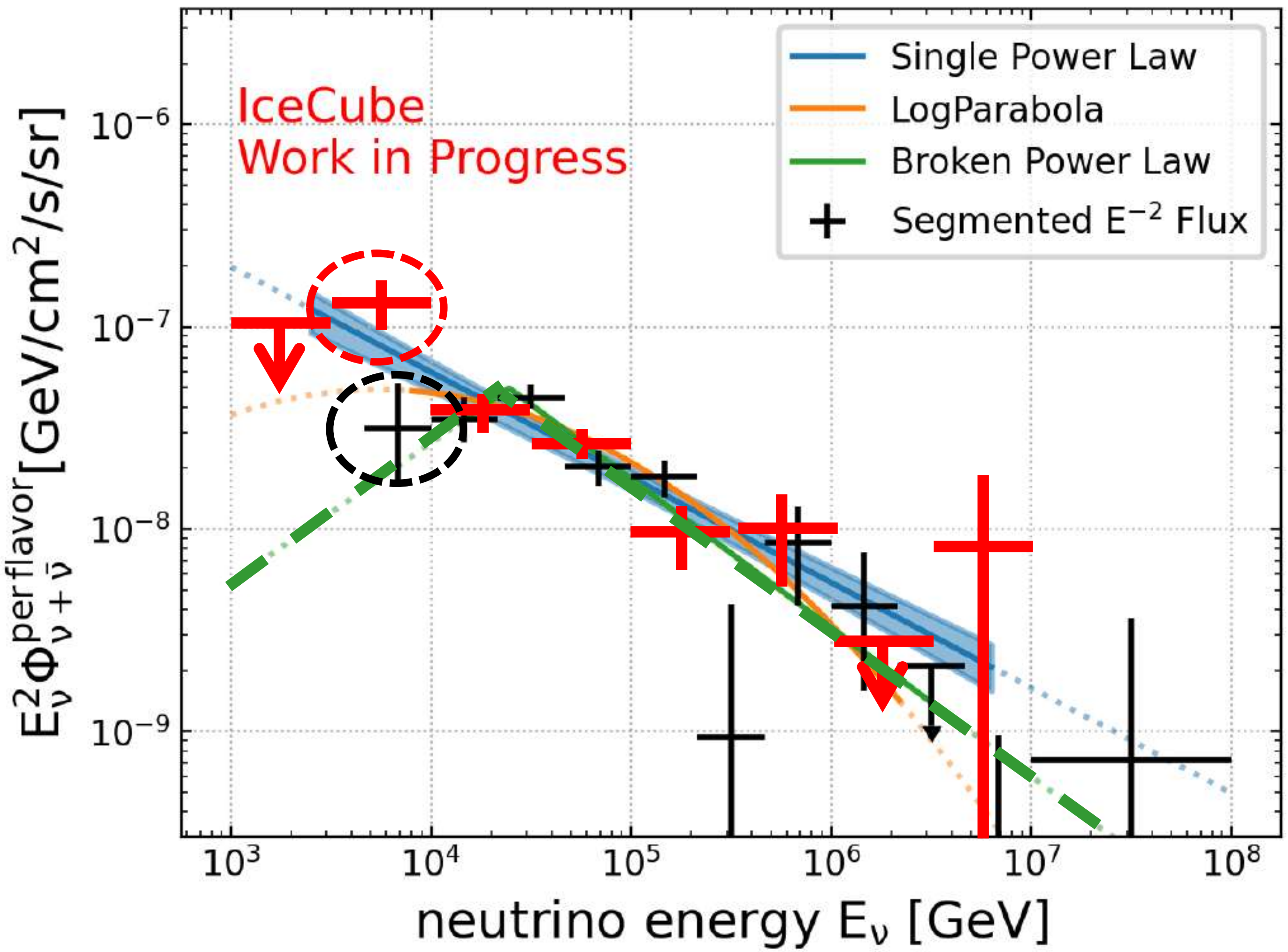
Diffuse flux: no a Single Power Law

📖 IceCube: PoS(ICRC23)1064
📖 IceCube: arXiv:2402.18026

- No clear agreement with SPL from different samples, in particular below few tens of TeV.
- This could be attributed to:
  - different **energy range** of samples
  - the different **flavor** in the samples;
  - (most) of **Galactic Plane** in South Sky.
- A **segmented fit** of the IceCube data (tracks+ cascades) seems represent data better: **spectral features visible** (between 20-30 TeV)

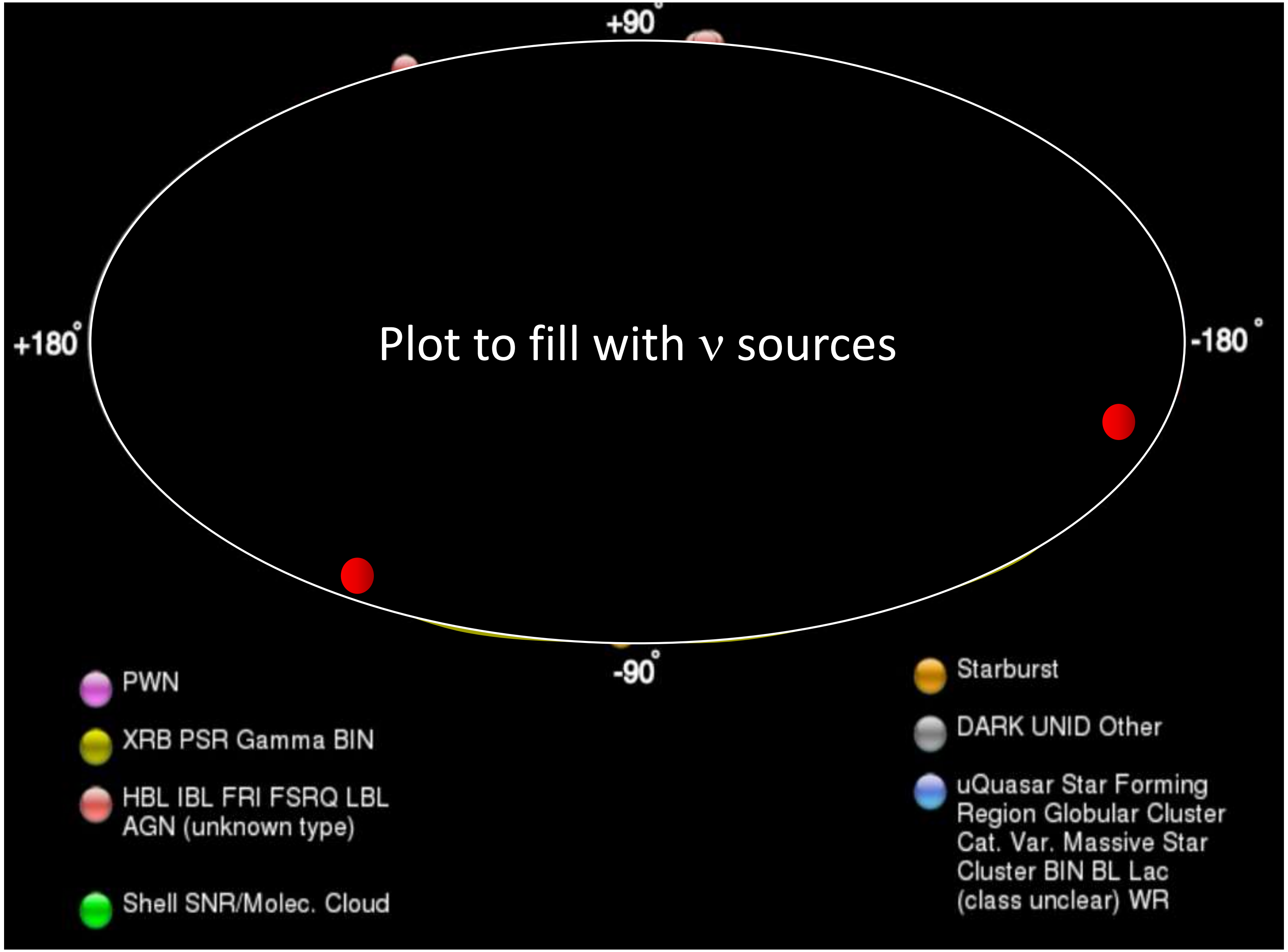
- The **starting tracks sample** (new) agrees with segmented fit above the 30 TeV feature
- ANTARES data also are more compatible with some change of slope at 20-30 TeV. See:

📖 ANTARES arXiv:2407.00328



Point Sources: catalog of >0.1 TeV γ-rays

http://tevcat.uchicago.edu/



Today: 336 objets

- 94 Galactic (<15 kpc)

Out of the Galactic Plane: AGN

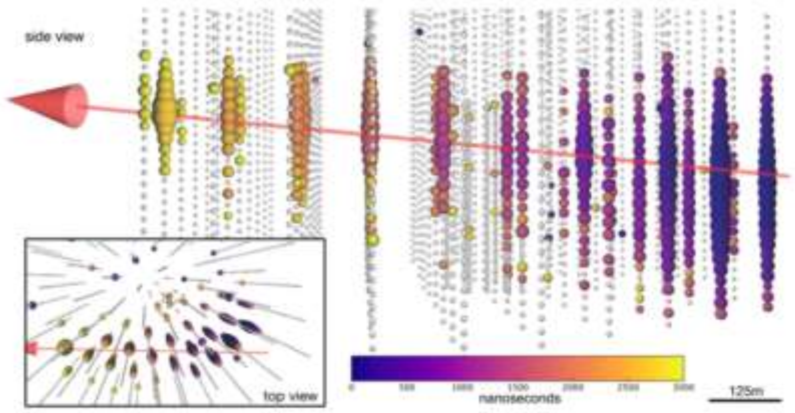
- 8 AGN with 0.5<z<1
- 18 AGN with 0.2<z<0.5
- 28 AGN with 0.1<z<0.2
- 23 AGN with 0.001<z<0.1
- 7 GRBs (transient)

- ***Blazars** are powerful AGN with relativistic jets directed at the Earth.*
- *Not all blazars are γ-ray sources, but they constitute the dominant population*
- ***Seyfert** are visible galaxies with active nuclei (unusually bright core regions).*

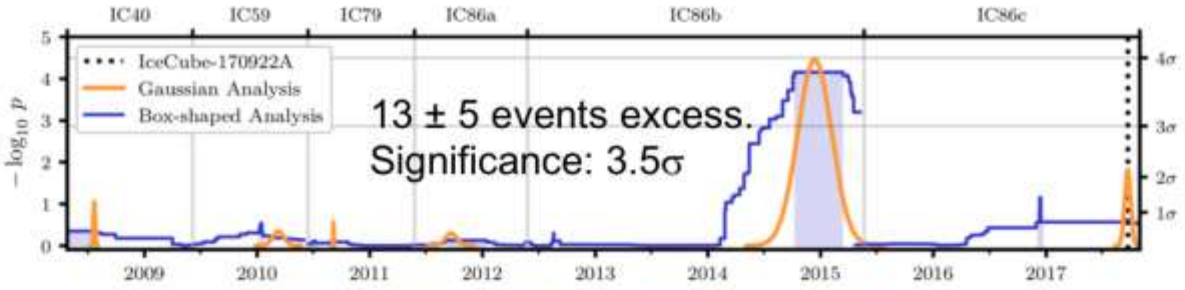
ν_μ from the blazar TXS 0506+056 (I)

📖 IceCube:Science 361 (2018)eaat1378
📖 IceCube:Science 361 (2018)eaat2890

Sept. 22, 2017:
A neutrino in coincidence with a blazar flare



2014-2015: A (orphan) neutrino flare found from the same object in historical data

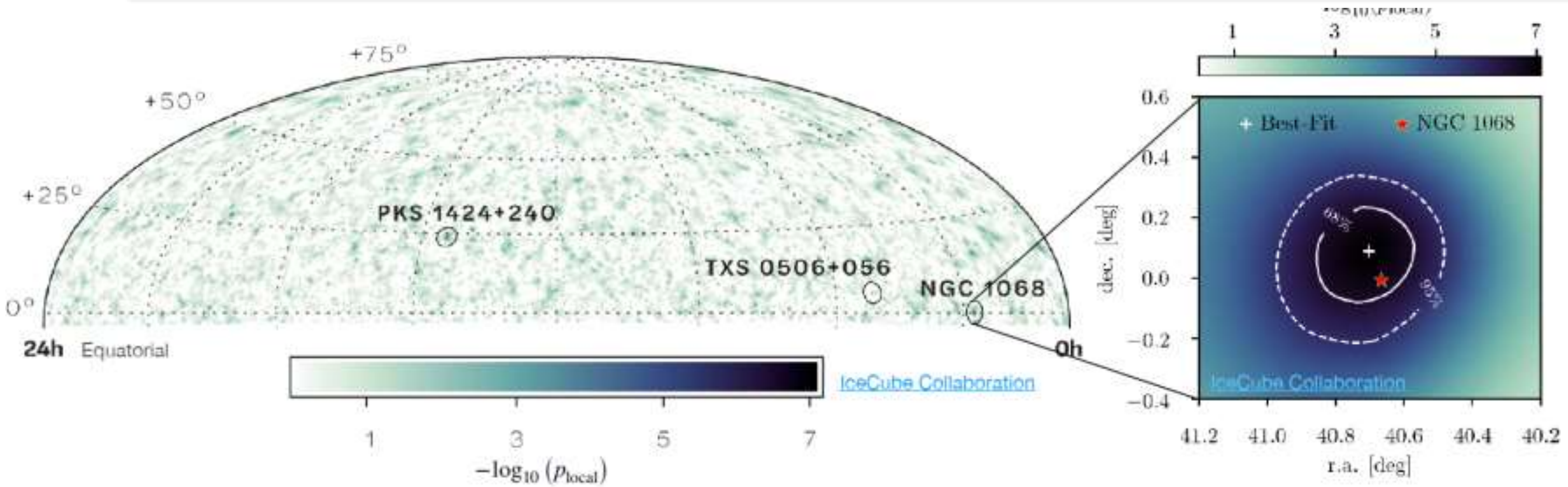


Science 361 (2018) no. 6398, eaat2890

- An **electromagnetic follow-up** campaign followed the IC ν_μ event (angular resolution < 1°)
- **FERMI-LAT** and **MAGIC** observations indicate that this event correlate with the blazar (BL Lac object or FSRQ?) TXS 0506+056 at redshift z=0.3365
- After the coincident event, a ν-flare but without associated γ–rays found in **archival IceCube data**.
- A further analysis of archival IceCube data revealed a precedent ν burst with excess of **(13±5)** events.
- No significant EM flaring activity during the ν burst
- Two potential ν flares of very different nature
- Not simple theoretical interpretation

IceCube 2π sr sky survey

📖 IceCube:[DOI 10.1126/science.abg3395](https://doi.org/10.1126/science.abg3395) (2022)

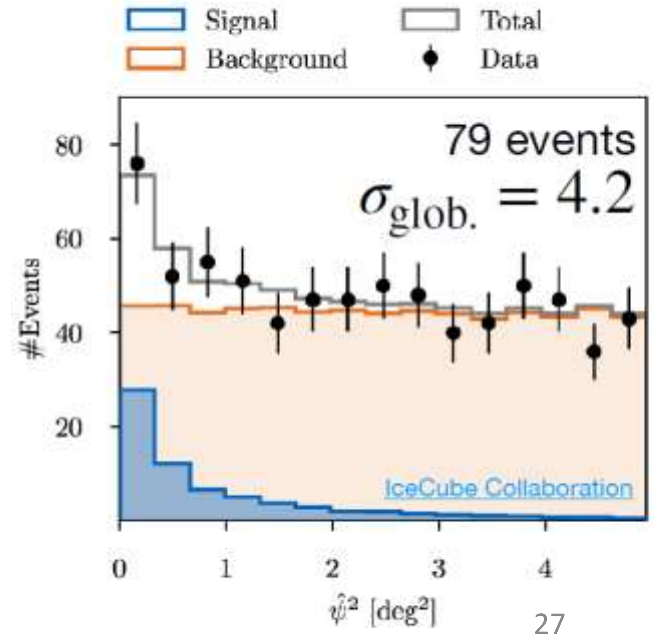


NGC-1068

- Neutrino candidates vs. (angular distance)^2 from source.
- **79±22** events in excess

- **110 selected sources**. Found 3 sources with > 3σ pre-trial.
- Use of up-going muon tracks
- The astrophysical origin of the ν excess deduced mainly from directional clustering, not from their high energies

- NGC 1068 (M77), close AGN (**10-14 Mpc**), not TeV γ-rays
- [TXS 0506+056](), z=0.336 (**1.8 Gpc**), γ-rays from 80 to 400 GeV
- [PKS 1424+240](), z=?



Results of neutrino sky map

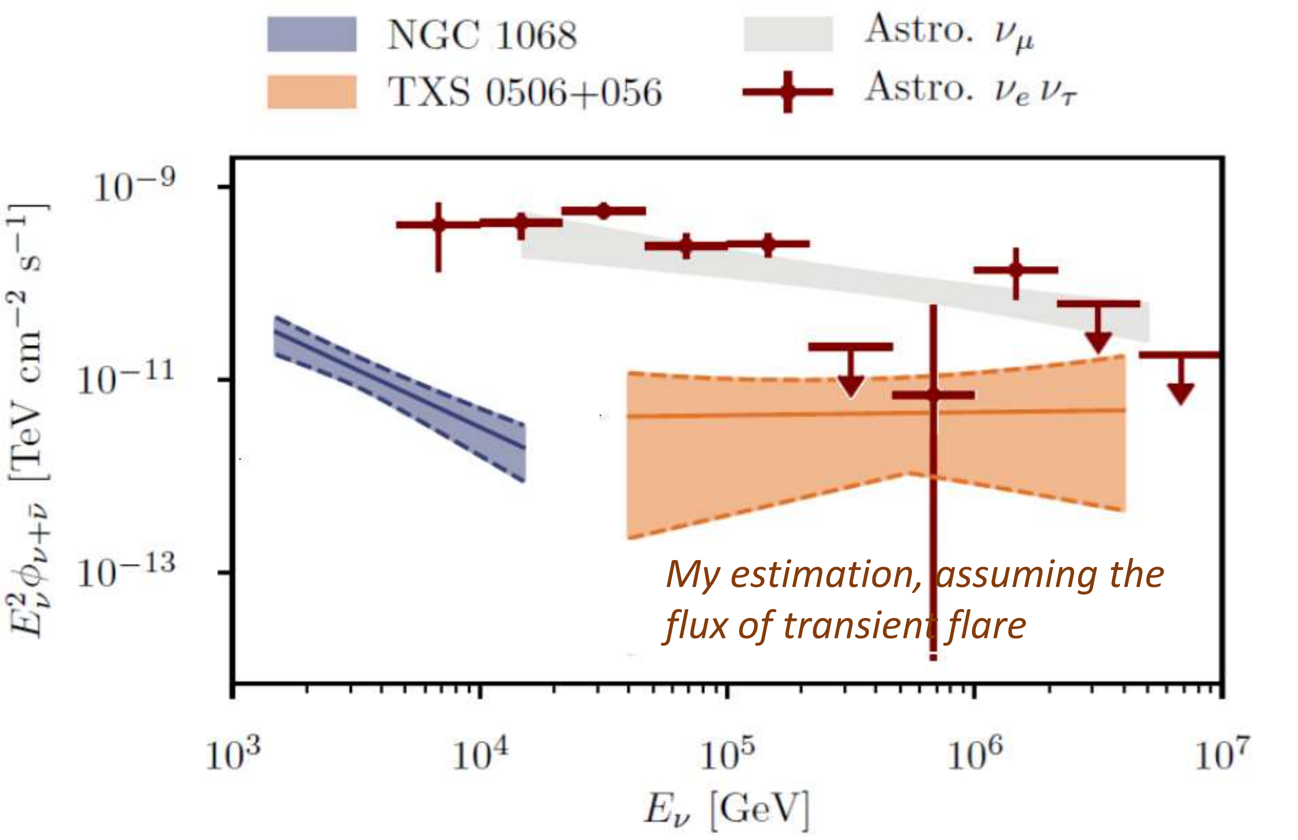
IceCube: DOI 10.1126/science.abg3395 (2022)

- **NGC 1068:** neutrino energies in a range not well measured with the diffuse flux.
- Best-fit spectral index of γ = 3.2±0.2, softer than the diffuse flux

- **TXS 0506+056** is >100 times farther away than the near NGC 1068: there are at least **two populations of neutrino sources** that differ in luminosity by orders of magnitude.

- The TXS 0506+056 time-integrated emission in 10 y has pre-trial of 3.5 σ (i.e. n_s=5).
- The *Science 2018* result provided evidence for transient emission with n_s = **13±5** in 6 months.

- If the TXS 0506+056 findings are both corrects, the population of HE (100 TeV range) ν's could be significantly influenced by transients



Spectral Energy Distribution of IC diffuse flux and of NGC and TXS sources.

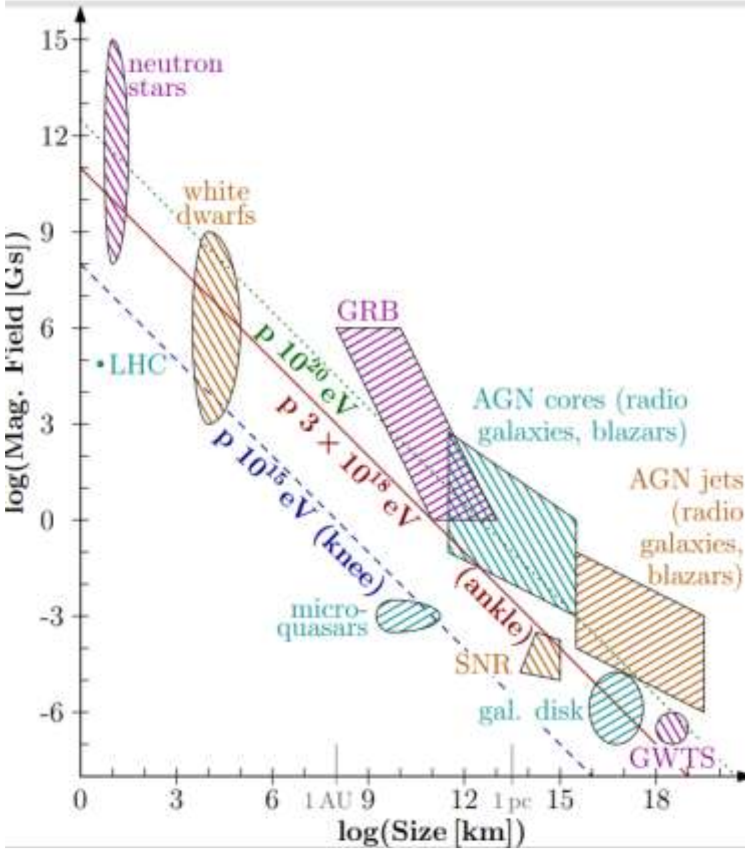
Origin of the (diffuse) extragalactic ν's

For a recent review: see the **377 refs** in
📖 Fiorillo, Universe 2024, 10, 149

To identify ν sources, different strategies are adopted in IceCube, ANTARES, Baikal-GVD and KM3NeT:

- searches for multiplets of events from close directions in the sky
- searches for temporal and spatial correlations with transients
- cross-correlation of ν angular distribution with catalogs
- the analysis of the neutrino angular power spectrum

📖 Becker Tjus, Merten, Phys. Rep. 872 (2020) 1



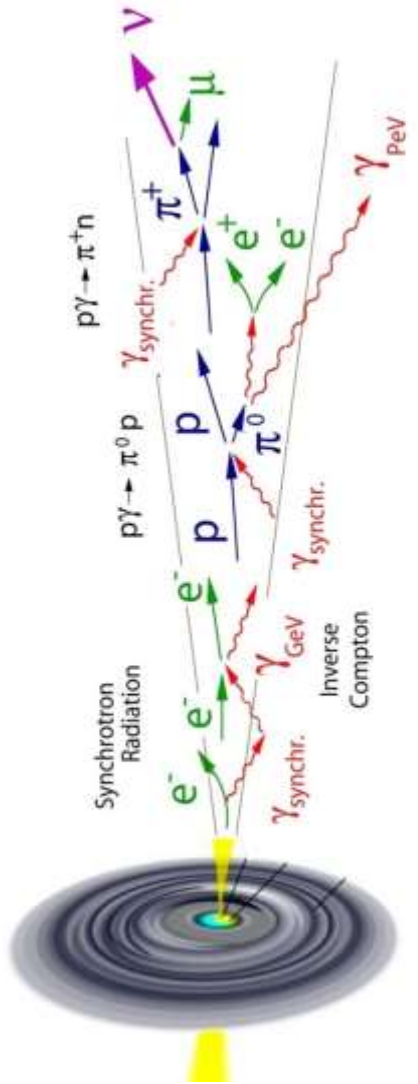
Sources candidates

- AGNs jets: about 1-10% of the AGNs. Blazars=jets towards the Earth. **TXS 0506+056**
- AGNs cores (Seyfert,…): ν produced in an optically thick region that absorbs γ–rays. **NGC 1068**
- GRBs (or choked/low-luminosity GRBs)
- Starburst galaxies
- Tidal Disruption Events (TDEs)
- Clusters of galaxies
- Galaxy & Galaxy Cluster mergers
- Beyond the Standard Model (BSM)
- …

Open problems with the identification of sources

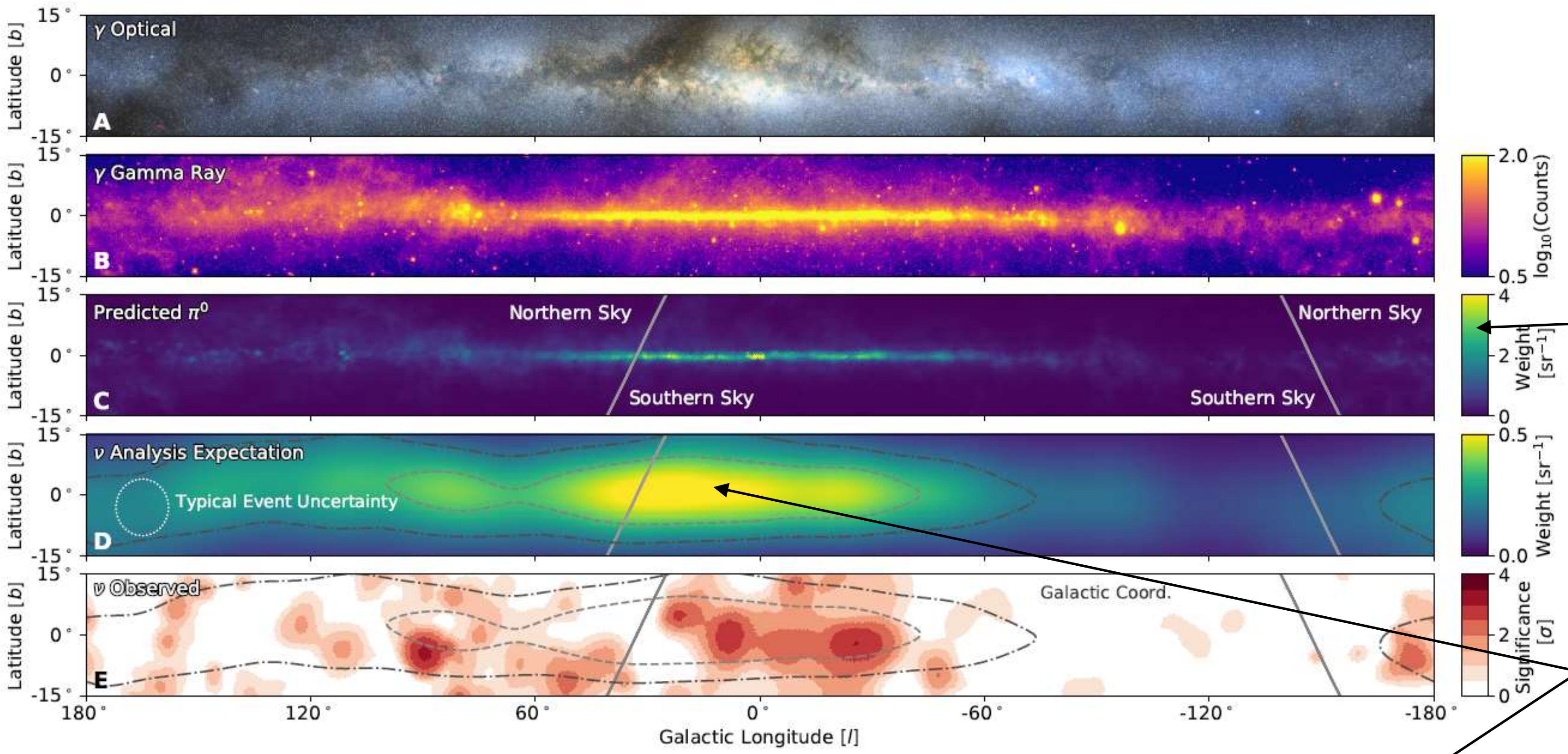
- Public catalogues have also been used by many authors in >>377 refs
- Positive correlations (also >3σ) between ν and selected catalogues have disappeared or significantly reduced after a new release of ν candidates appears.
- The ν catalogs released by Collaborations are “work in progress” as they can be improved in the future
- The accuracy of reconstruction of the ν properties is limited by systematics: new refined statistical analysis, improved reconstruction/ calibration can lead to a significant improvements in ν direction/energy.
- The reduction of “>3σ” is true also for the TXS 0506+056 burst (arXiv:2307.14559)
- Analysis of data of independent experiments, with uncorrelated systematic errors, could be recommended to reduce incorrect associations

- **Warning for young researchers**: the machine learning involves a training dataset with characteristics based on MC simulations can be affected by the medium properties (water is more homogeneous that ice, but it needs calibrations)



The Galaxy is not a neutrino desert

IceCube: DOI: 10.1126/science.adc9818



The model predictions depend on:

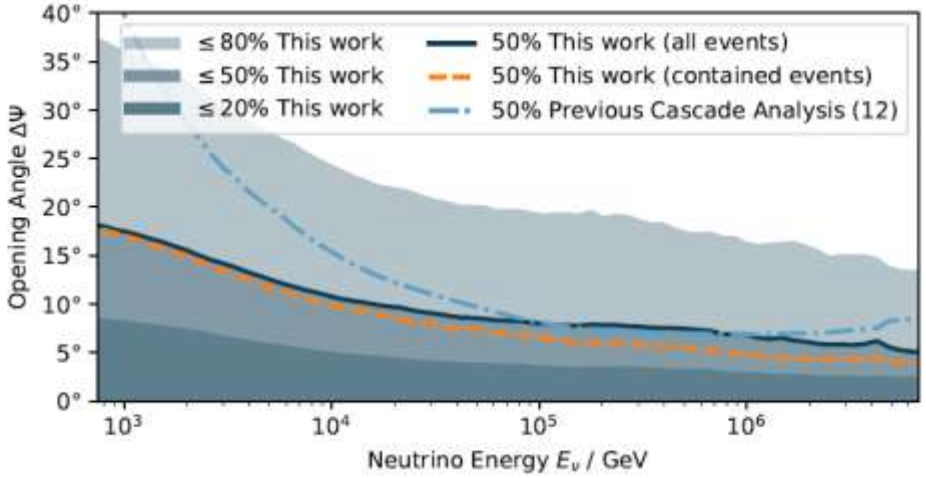
- *distribution and emission spectrum of cosmic-ray (CR) sources in the Galaxy,*
- *the properties of CR diffusion in the interstellar medium,*
- *the spatial distribution of target gas.*

- *Each neutrino emission model converted to a spatial template and convolved with the detector acceptance and the angular uncertainty, to produce a specific spatial PDF*

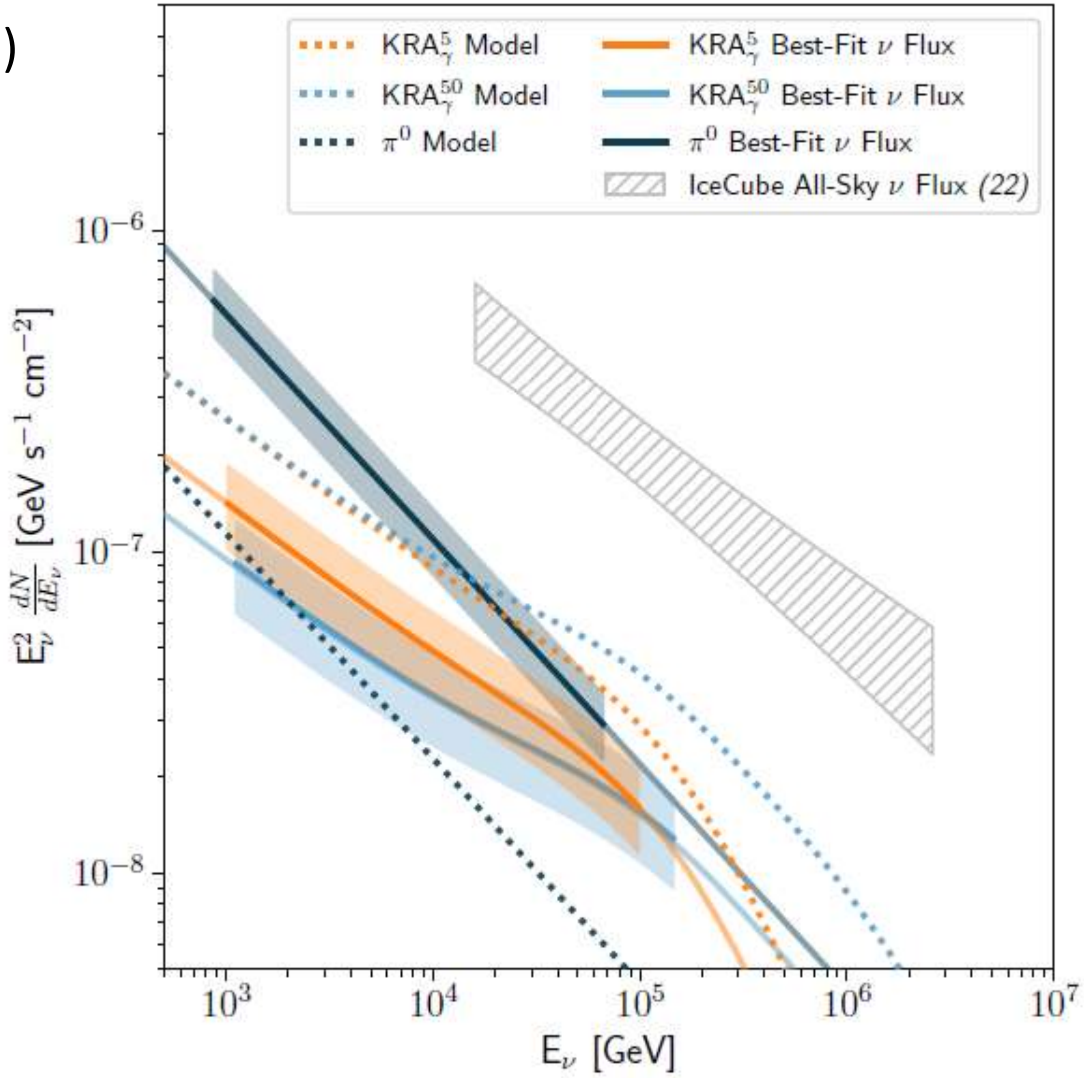
The Galaxy is not a neutrino desert

IceCube: DOI: 10.1126/science.adc9818

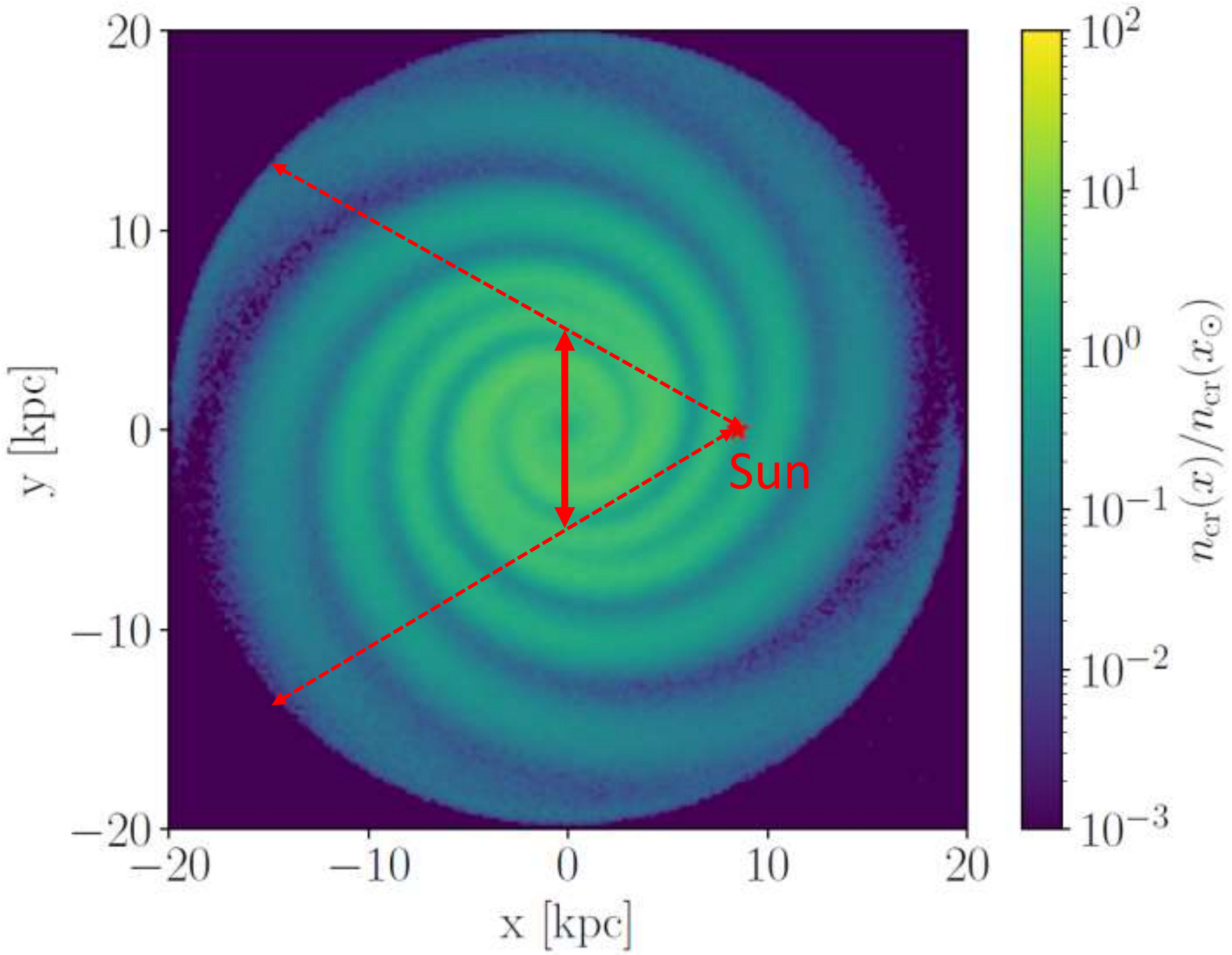
- IceCube compared three diffuse emission models (based on ν production associated with CRs and γ-rays) from the Galactic plane to a background-only hypothesis
- (

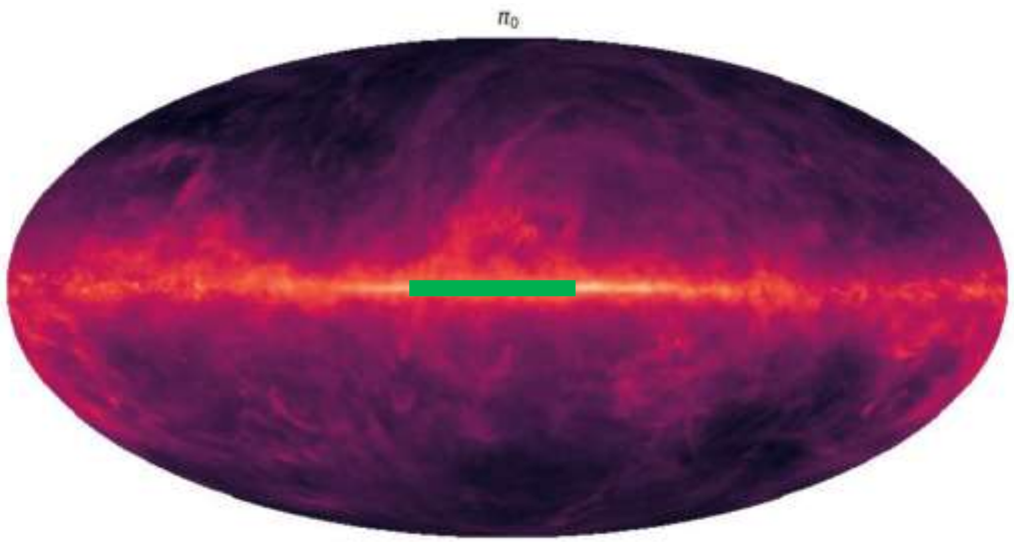


- Model-dependent result, due to the impossibility to evaluate the background using data.
- Three *results* produced on the **flux integrated over the whole sky**: a factor of x 4-6 difference @1 TeV.



The Galactic ridge





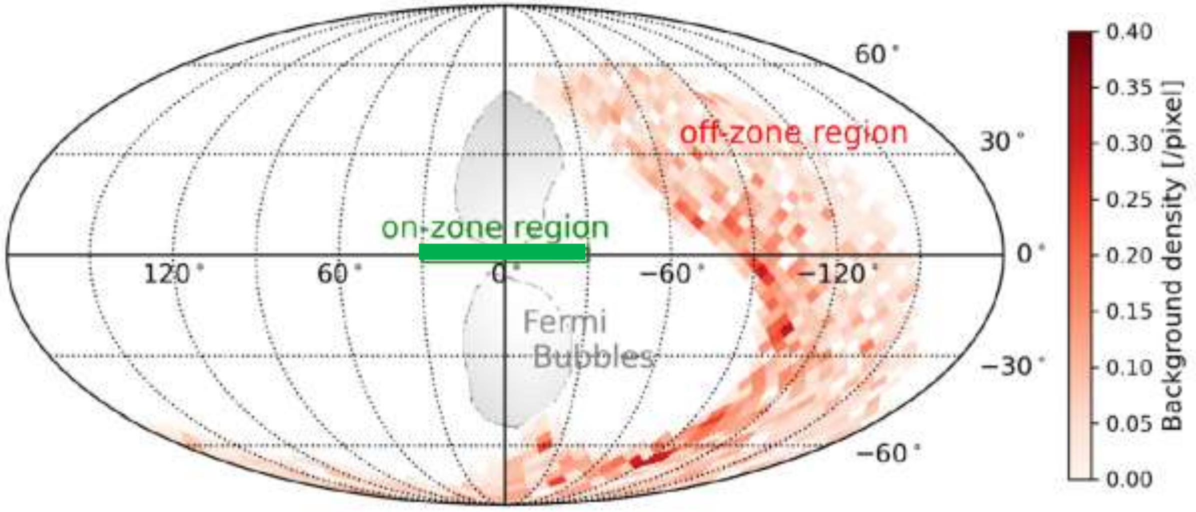
Most of the signal from the Galactic Ridge $|b|<2^o$ and $|l|<30^o = \frac{1}{172} \times 4\pi$ sr

Each model yields a different signal contribution in this region

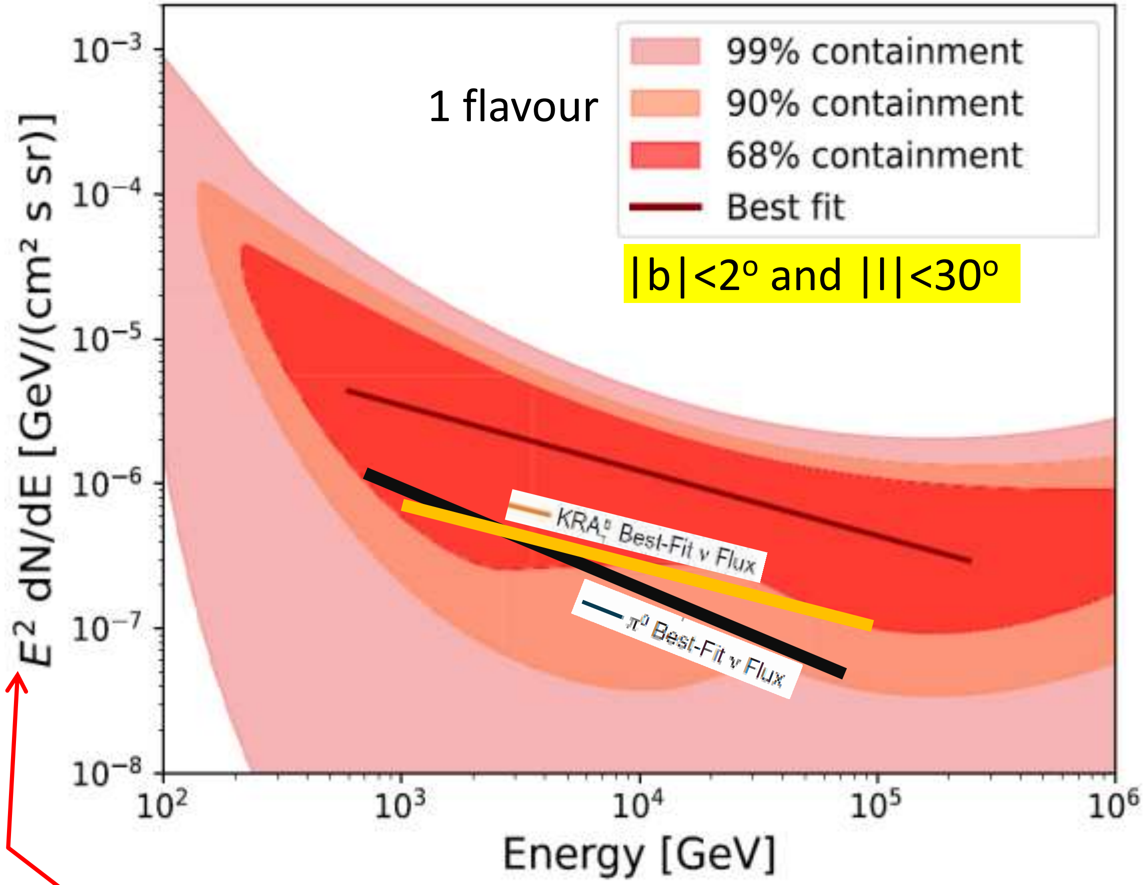
- 12% of the total signal by π^0 model
- 30%-40% in the KRAγ .

ANTARES as a «telescope»

📖 ANTARES: PLB841 (2023) 137951
📖 ANTARES PoS(ICRC2023)1084/1103



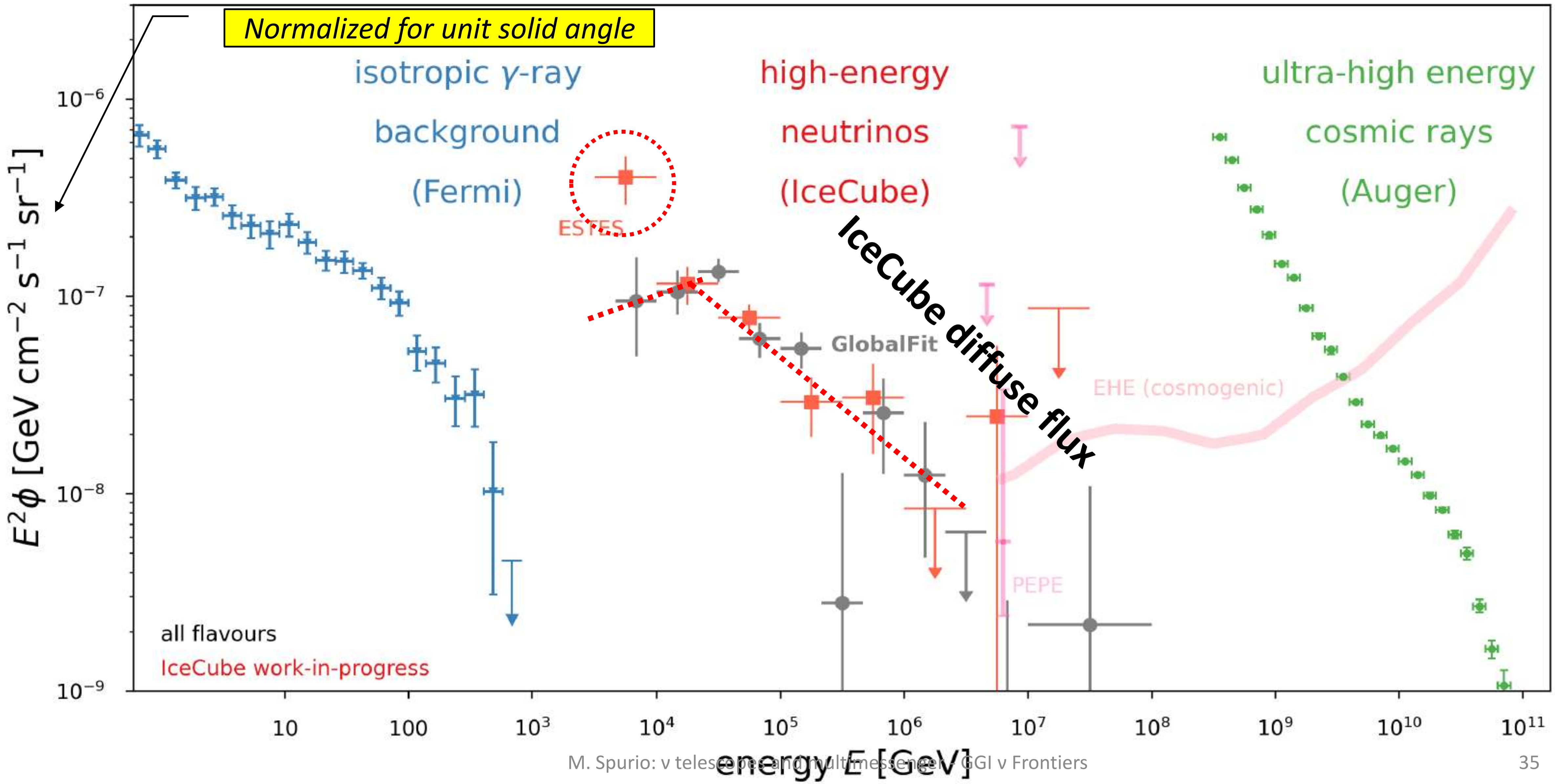
- Robust and model-independent measurement (**On-Off method)** possible due to the Earth rotation
- Use upgoing track-like events (better direction)
- Observed a 2.2σ excess from signal region
- IceCube signal from the Ridge (ϵ_{ridge} model-dependent)



$$\Phi_{ridge}(\mathrm{GeV\ cm^{-2}s^{-1}sr^{-1}}) = \Phi_{all\ sky} \cdot \epsilon_{ridge}/\Delta\Omega$$

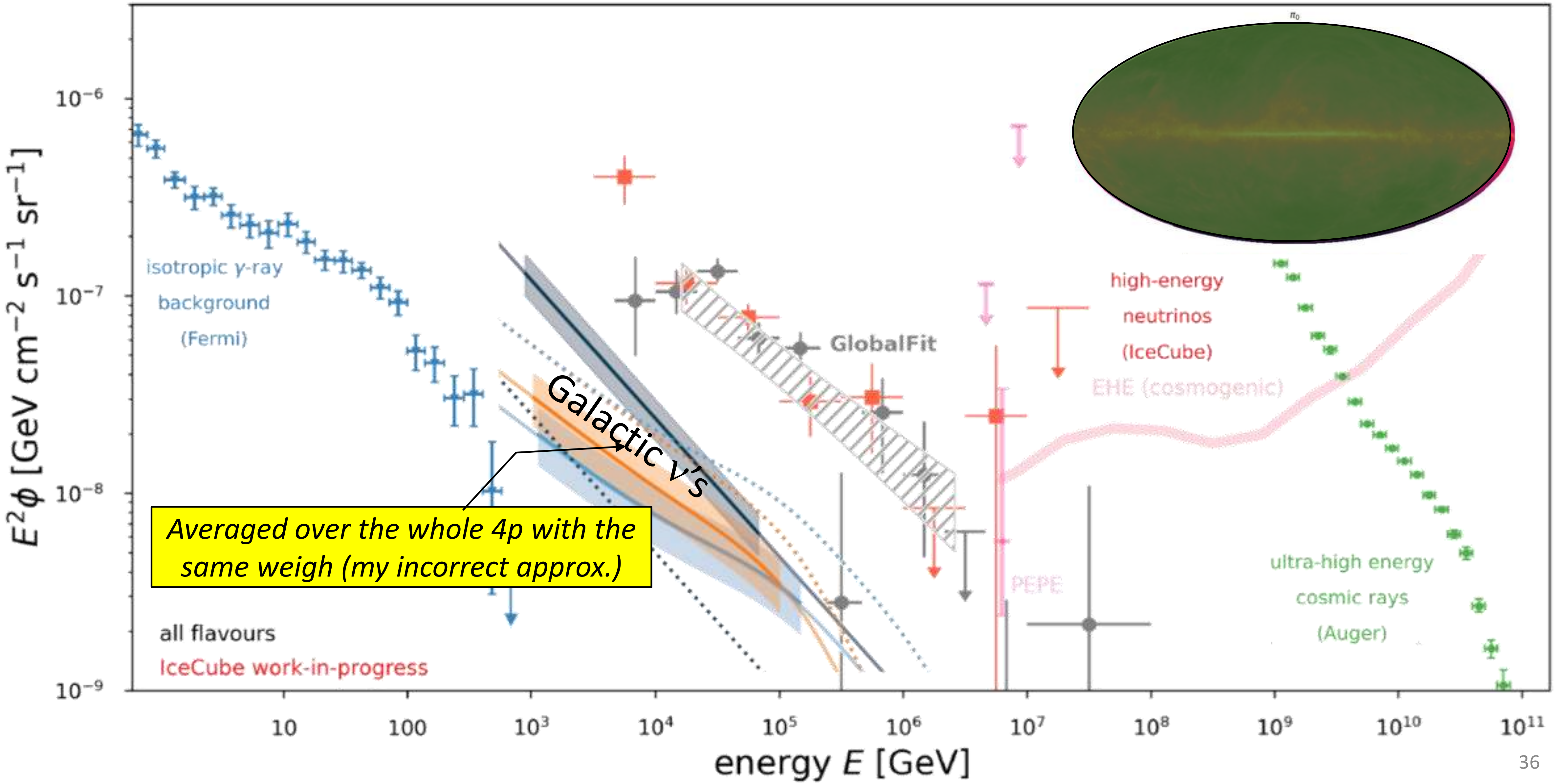
Galactic and extragalactic neutrinos (I)

📖 IceCube: PoS(ICRC2023)017



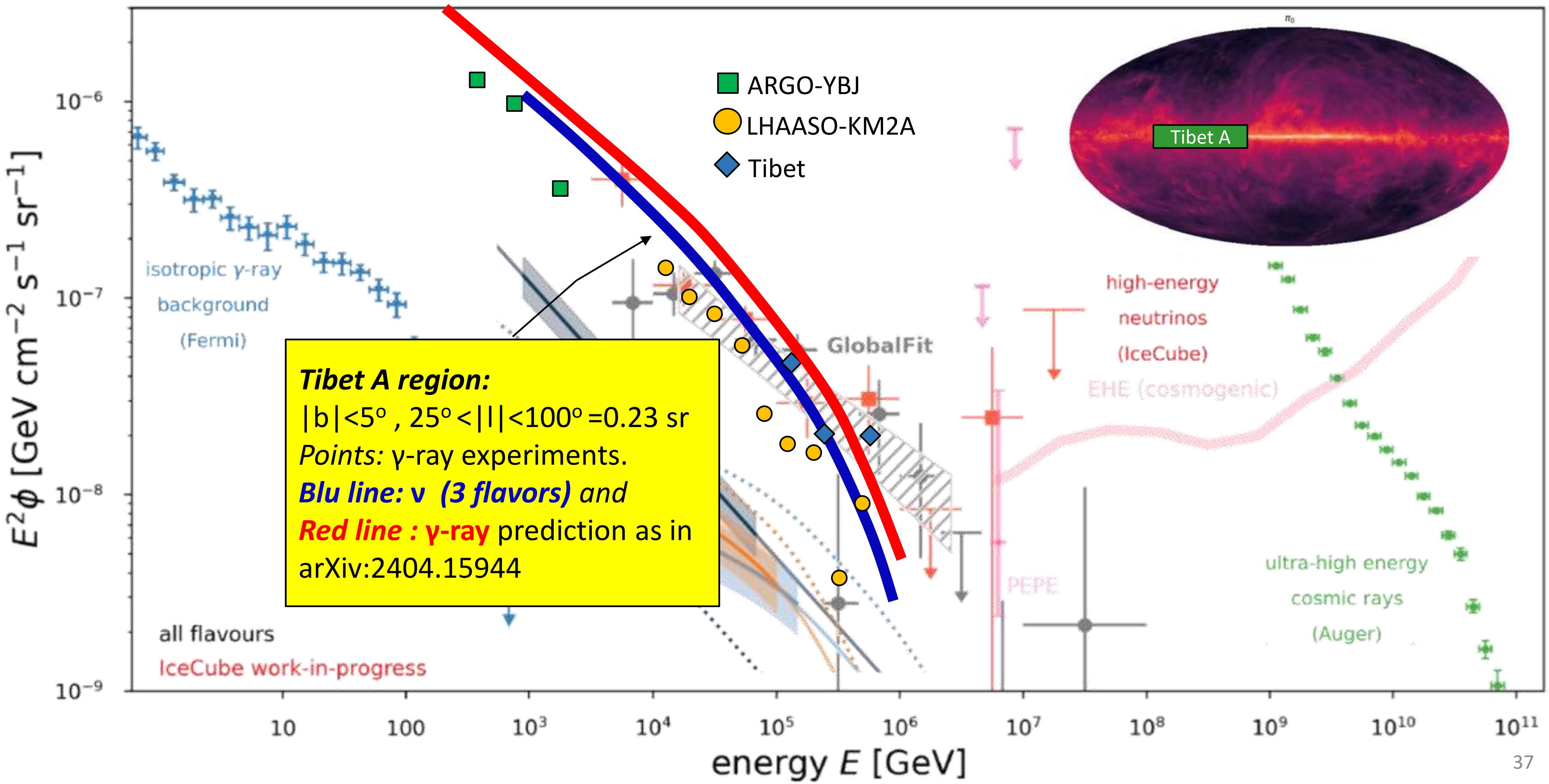
Galactic and extragalactic neutrinos (II)

📖 IceCube: PoS(ICRC2023)017
📖 IceCube: science.adc9818

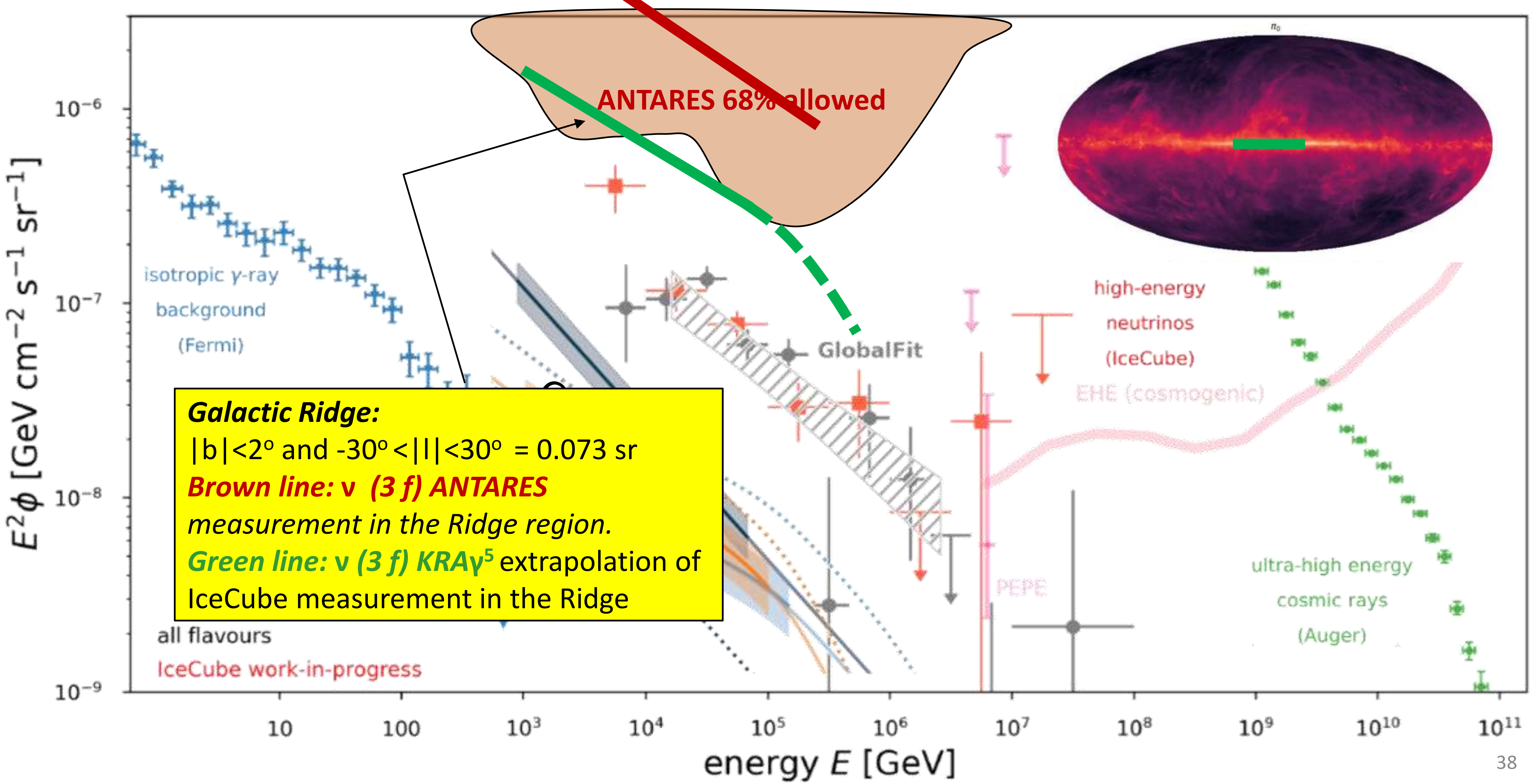


Galactic and extragalactic neutrinos (III)

📖 IceCube: PoS(ICRC2023)017
📖 Fang, Halzen-arXiv:2404.15944



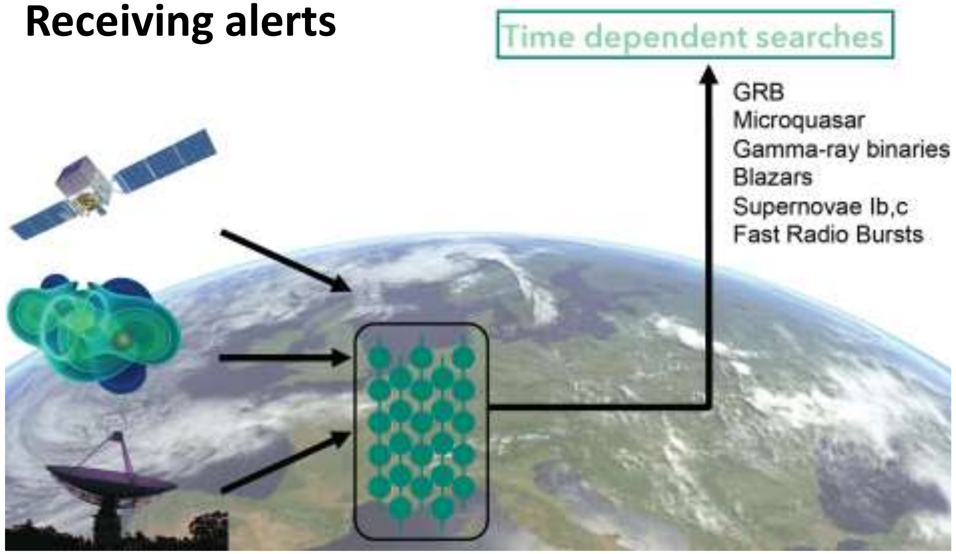
Galactic and extragalactic neutrinos (IV)



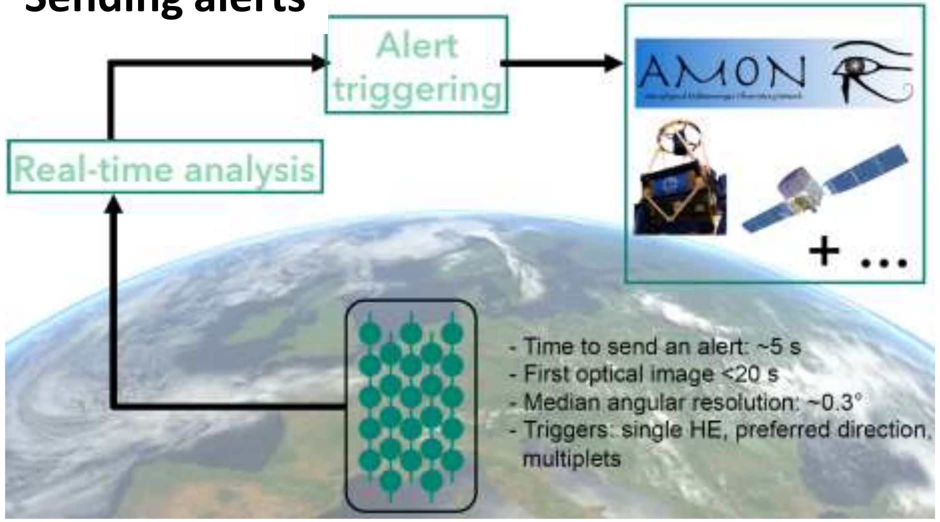
Galactic Ridge:
|b|<2° and -30°<|l|<30° = 0.073 sr
Brown line: ν (3 f) ANTARES measurement in the Ridge region.
Green line: ν (3 f) KRAγ[5] extrapolation of IceCube measurement in the Ridge

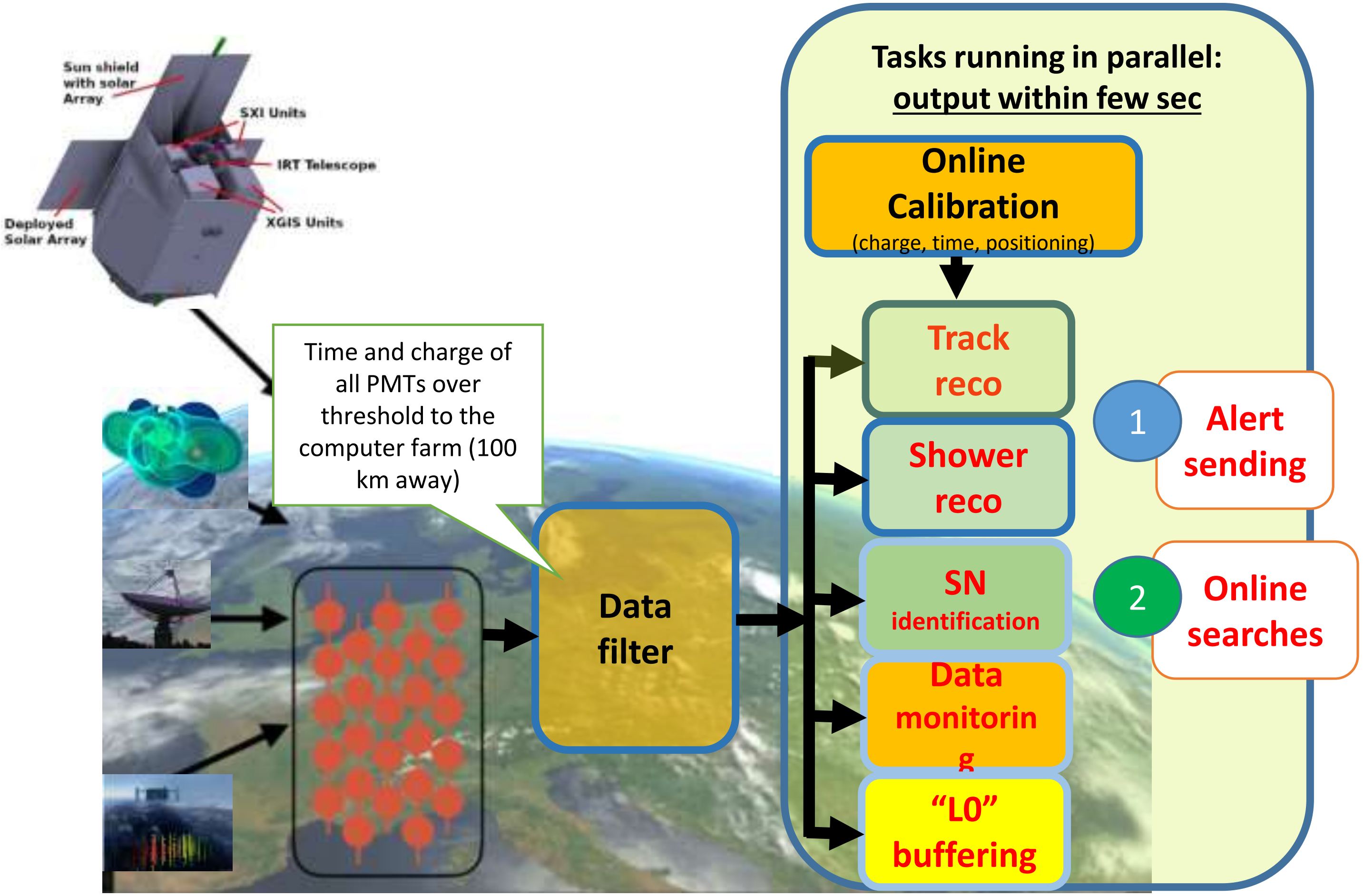
The “multimessenger” online alert system

Receiving alerts

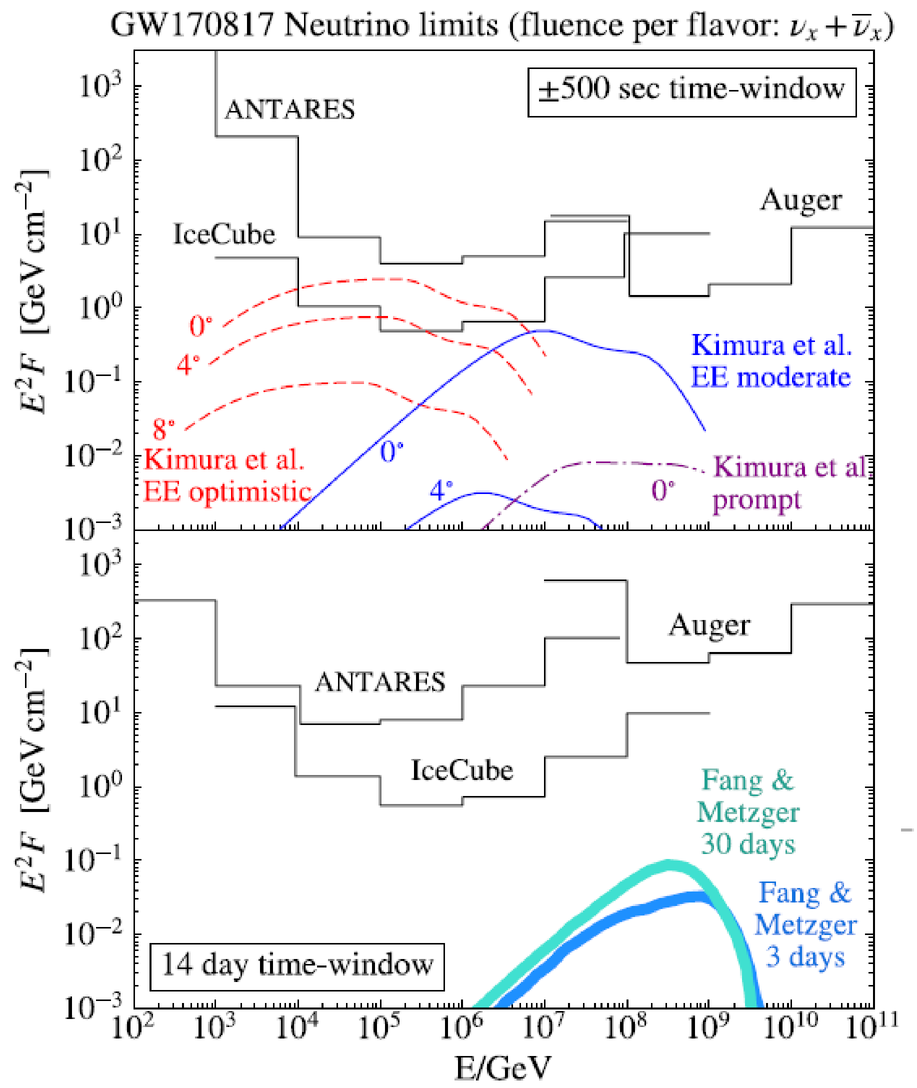


Sending alerts

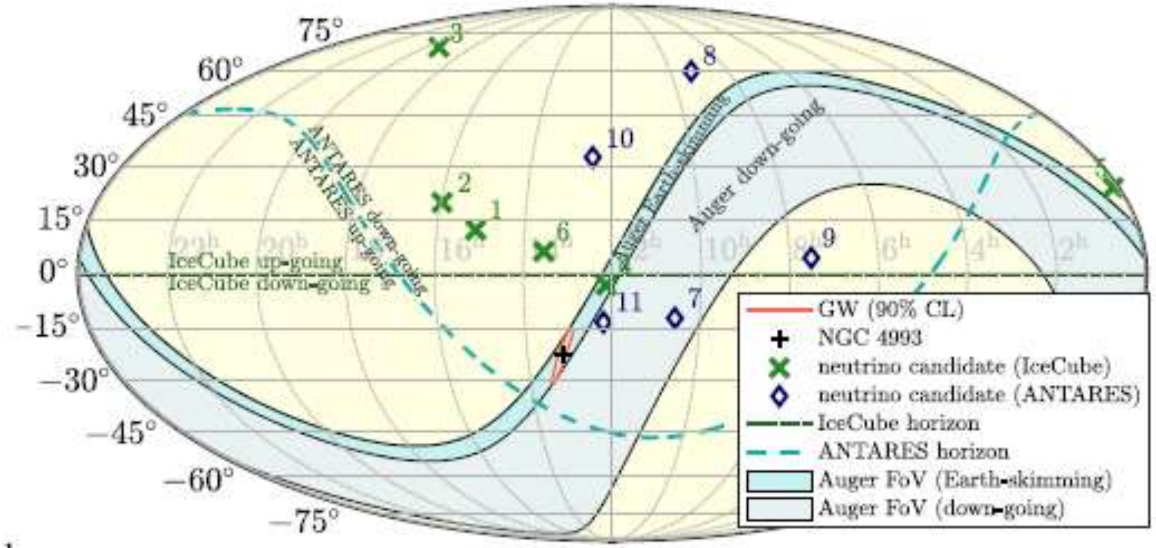




Limits on ν correlated with GW170817

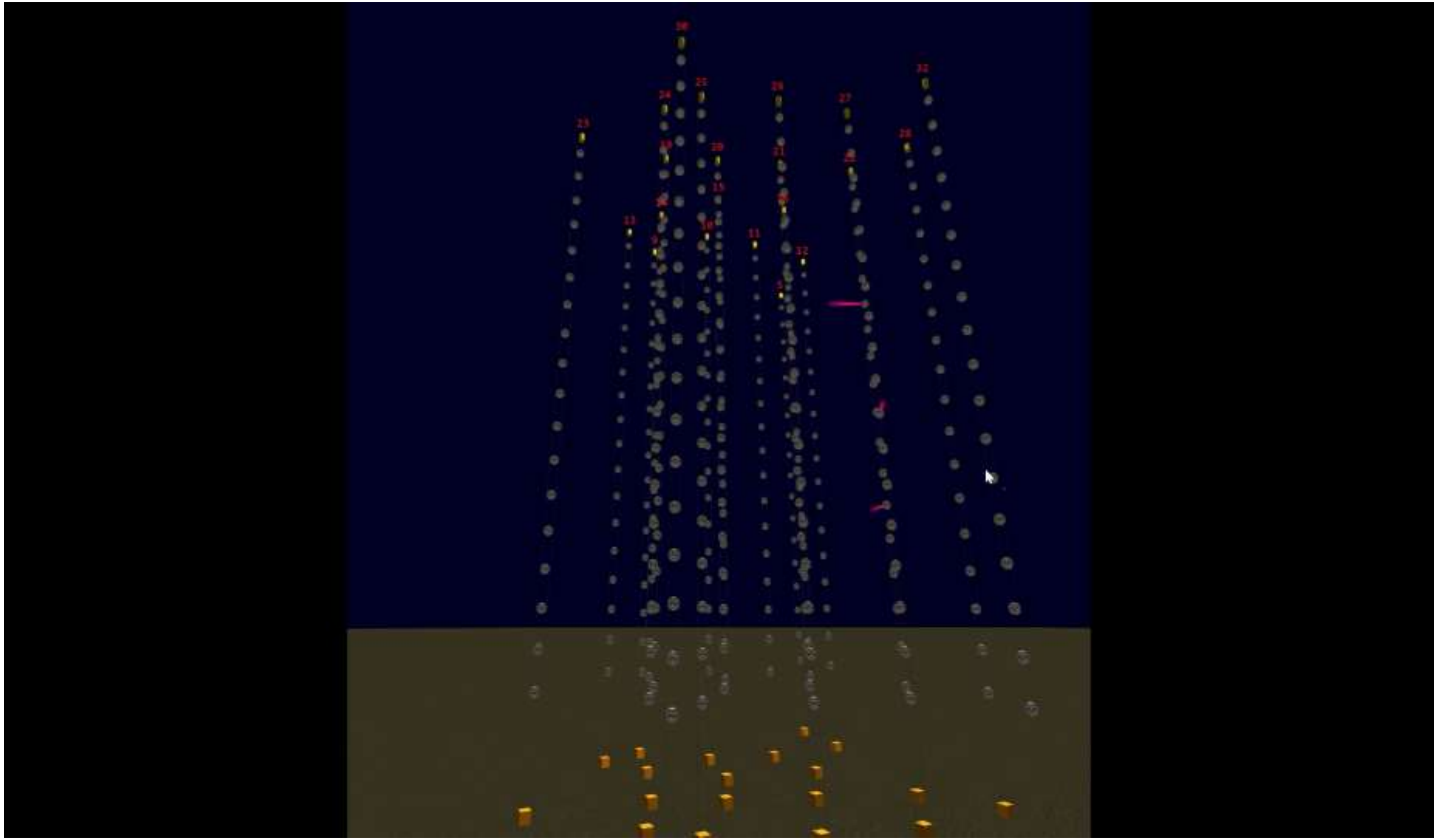


- No coincident neutrinos observed by IceCube, ANTARES or Auger.
- Consistent with predicted neutrino flux from internal shocks and **off-axis viewing angle**

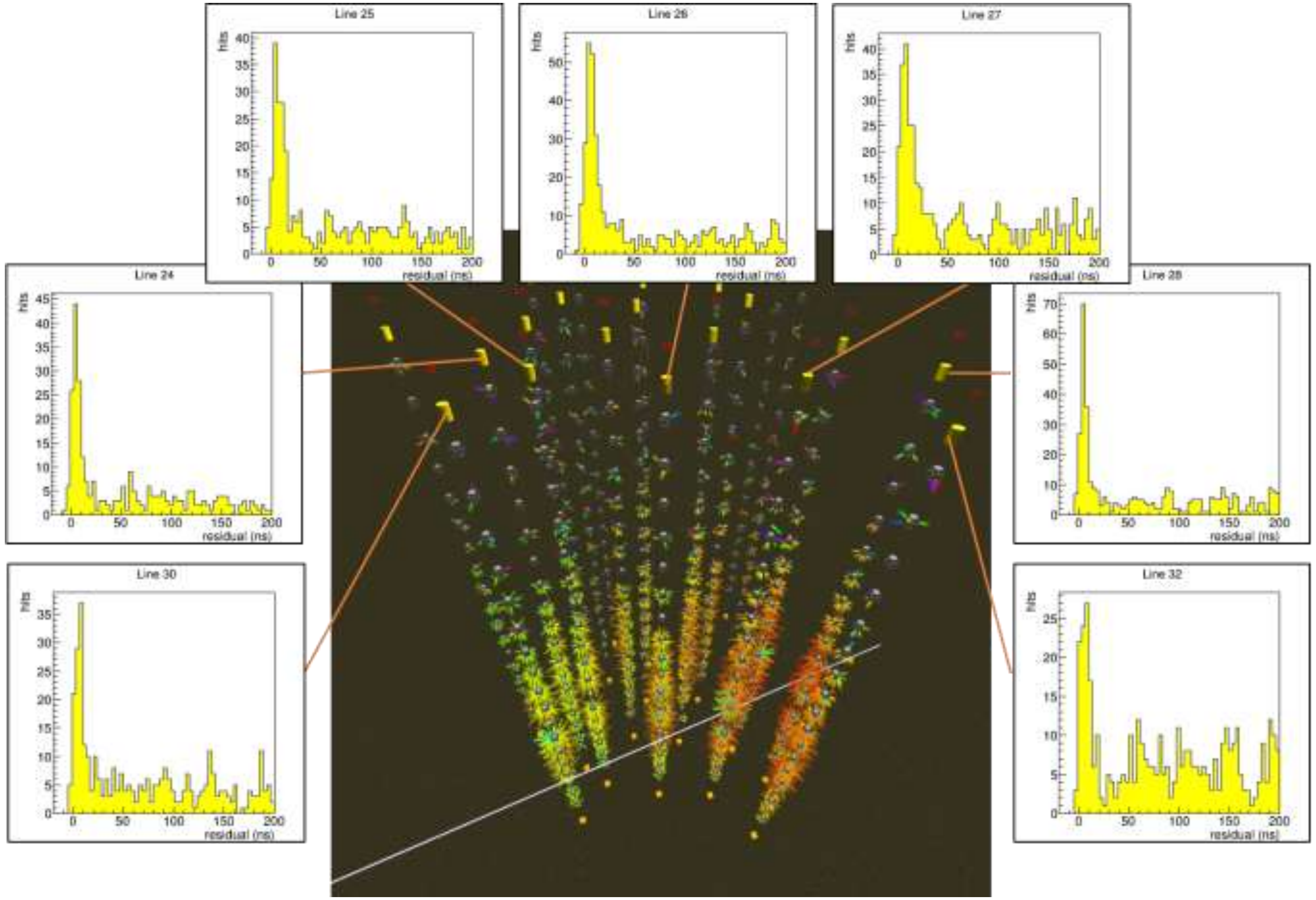


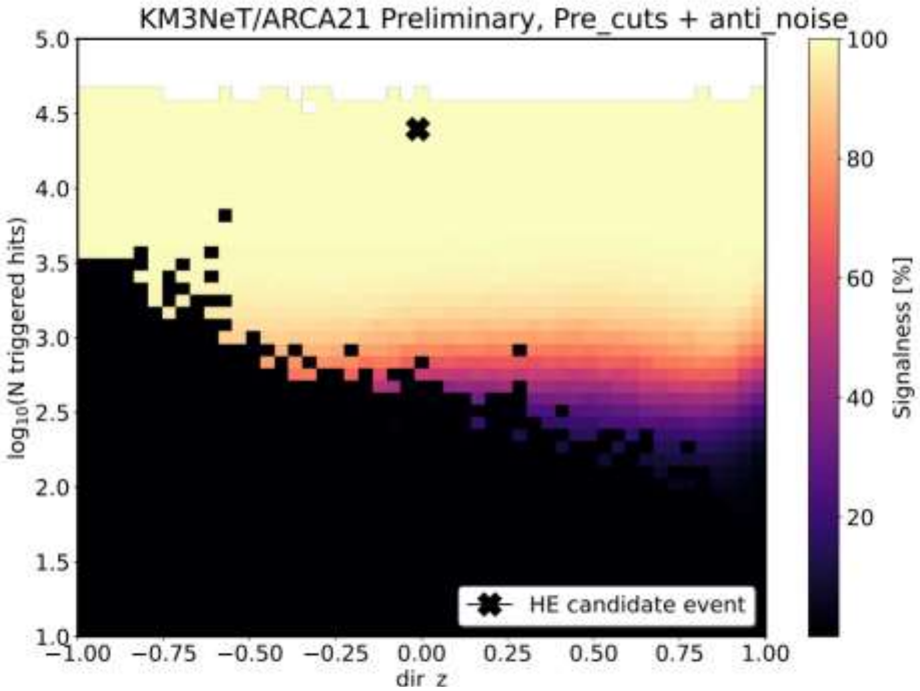
ANTARES, IceCube, Auger & LVC, ApJ 850 (2017) 2

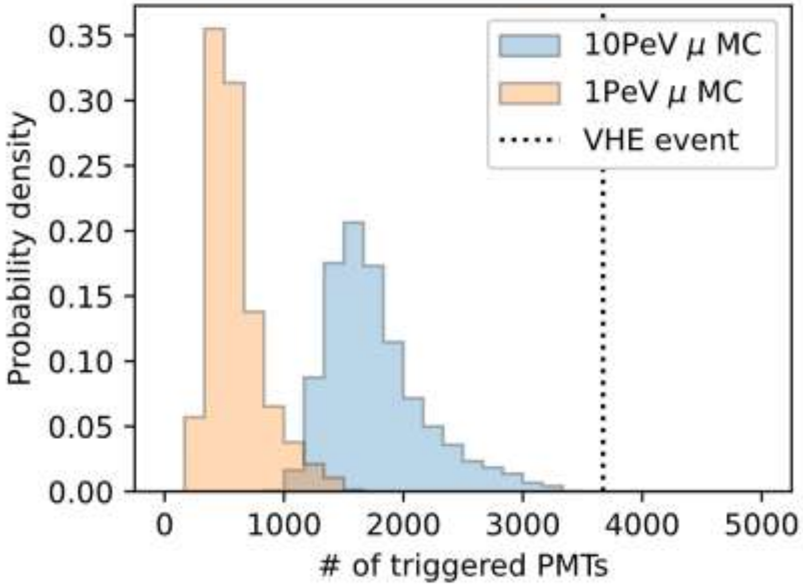
The KM3NeT highest energy event



A >10 PeV event in KM3NeT

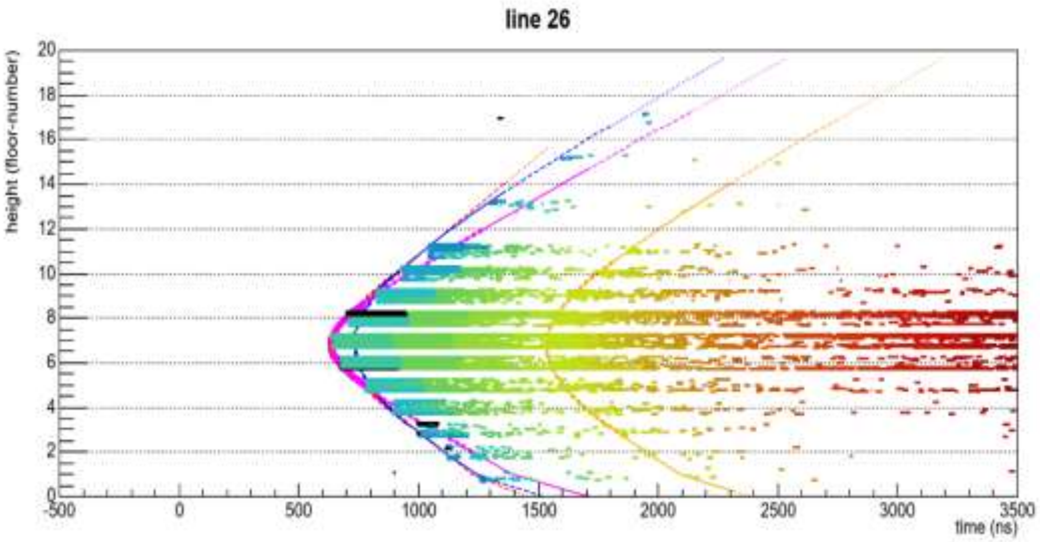


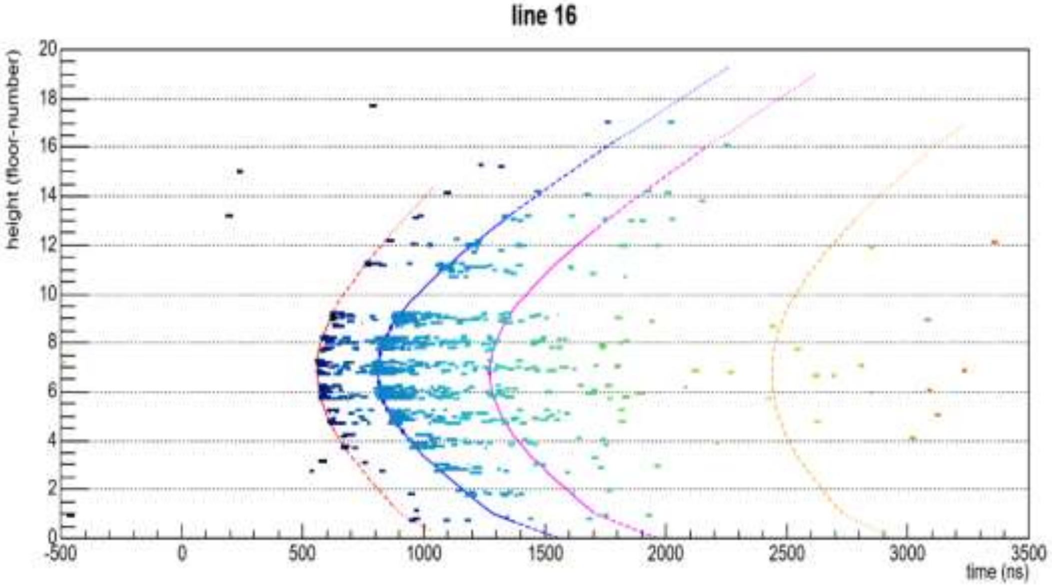




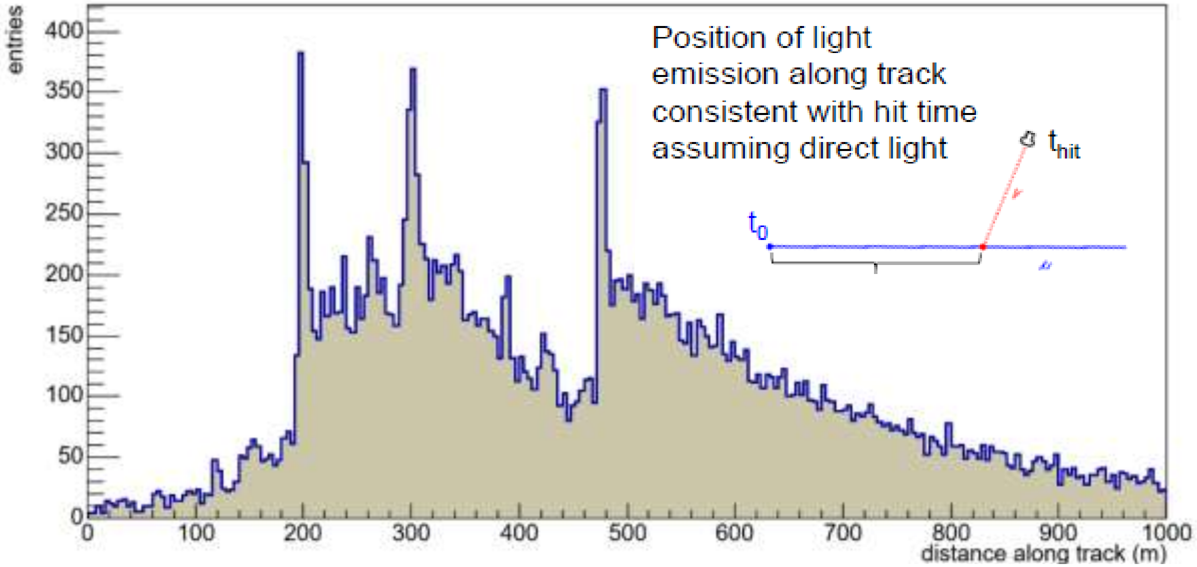
- Event 1°above horizon, as expected since earth opaque to PeV ν's;
- 3672 / 10630 PMTs (35%) triggered
- Muons simulated at 10 PeV almost never generate this much light

Cascades along the trajectory





- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons
- Space-time distribution of light consistent with shower hypothesis associated with these energy depositions



Summary

- A **diffuse flux of cosmic ν's** firmly established by IceCube. A simple power law seems not represent all data samples. Good news, i.e.: statistics increases
- Below few tens of TeV, small tension in the data. Still insufficient precision/sensitivity

- Two sources significantly detected, but **extragalactic sources**/class of sources still **not identified**.
- Caveat: the sources of >100 TeV ν's could be dominated by transients, if TXS orphan flare correct

- **Existence of galactic neutrinos** with $1<E<100$ TeV established.
- Impossible to disentangle the contribution of CR diffusion from that of sources. More precise results from Northern telescopes using upgoing ν_μ tracks.

- The ongoing activities (IceCube, KM3NeT, Baikal-GVD) and in the future IceCube Gen2 and (may be) other telescopes in the North will contribute to clarify these fundamental aspects for HE astrophysics.
- NT are discovery experiments: surprises are always possible

Conclusions

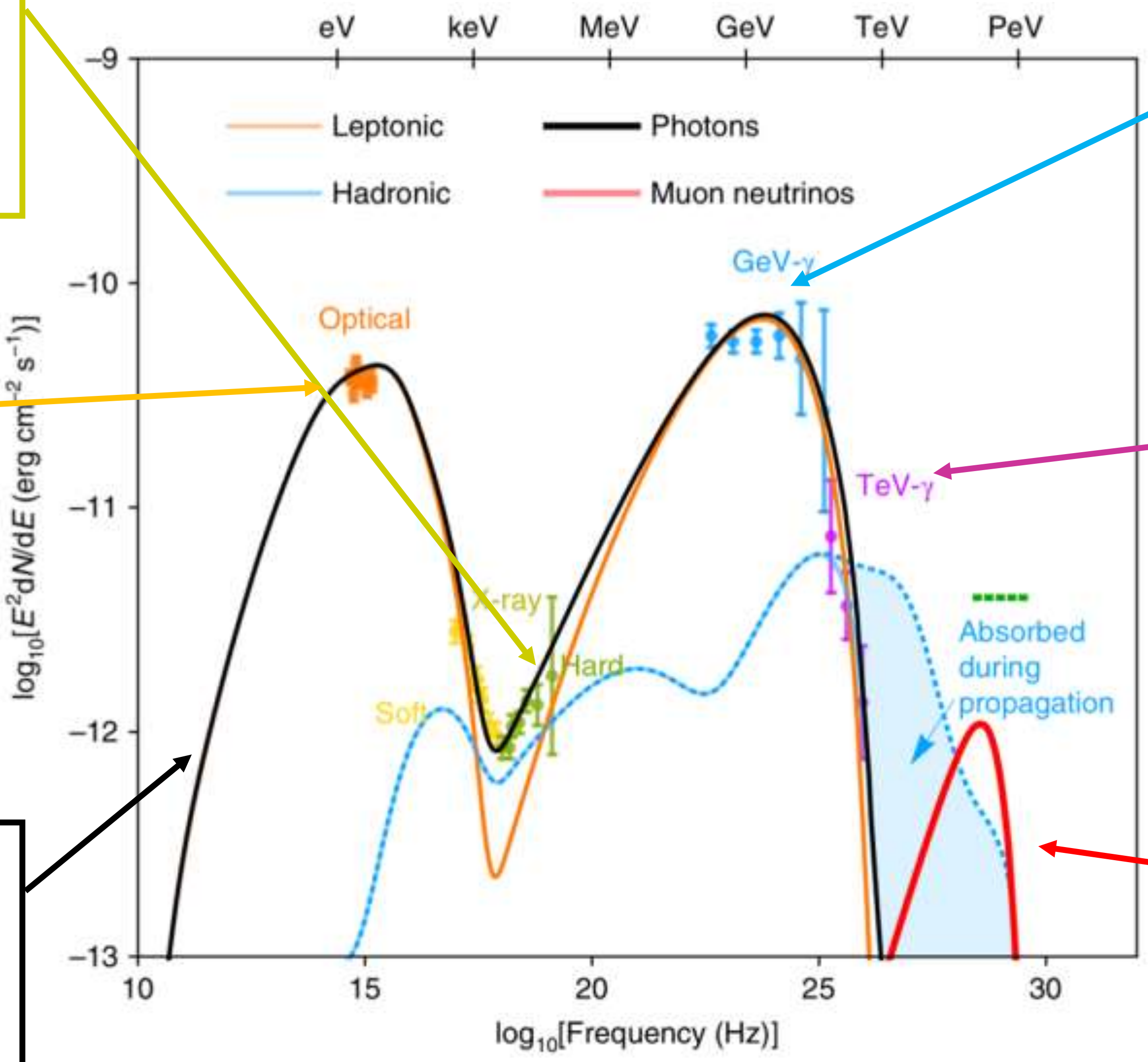
- **Multimessenger astrophysics** is the joint effort to understand HE phenomena using CRs, γ-rays, neutrinos, gravitational waves, in addition to EM radiation.
- Multimessenger is a difficult task due to the differences in the experiments (visibility, duty cycles, sensitivity, time response,…). **Information brokers** are of fundamental importance.
- **Electrons** and **hadrons** are at the origin of EM radiation and ν's, respectively.
- In the extreme universe more energy seems to be emitted in ν's than in γ-rays
- A significant fraction of extragalactic IceCube ν's seems to be produced in sources obscured to HE γ-rays: this is unexpected and represents a great opportunity for a "new" astronomy.
- New actors (LHAASO, CTA,KM3NeT, IceCubeGen2,…) will play a fundamental role for this
- IceCube and ANTARES started to observe Galactic ν's: the Galaxy is NOT a neutrino desert
- Today, astroparticle physics with multimessenger probes is paving the way for the **future of particle physics**, after the next generation of collider.
- Only knowing the beams (=accelerators and space medium), we will have the opportunity to study the underlying properties of particles and interactions

Multimessenger synergies

X-ray telescopes: Swift, INTEGRAL, SVOM, ATHENA…
- Provide transient triggers (GRB, AGN, Novae…)
- ToO program

Optical telescopes: TAROT, MASTER, LCOGT, ZTF, LSST…
- Easy access follow-up
- large error box
- Characteristation of potential counterpart with spectroscopy (nature, redshift…)

Radio telescopes: Parkes, MWA, Lofar, Nenufar, ASKAP, SKA, VLBI…
- Provide triggers (FRB…)
- Follow-up



γ-ray telescopes: Fermi-LAT
- All-sky complete monitoring
- Provide also transient triggers

VHE γ-ray telescopes: HAWC, LHAASO…
- All-sky monitoring
- Provide triggers

HESS, MAGIC, CTA…
- Follow-up (not easy access)

Neutrino telescopes: ~~ANTARES~~, IceCube, KM3NeT, GVD…
- Mutual follow-up
- Confirmation of sources, improve significance