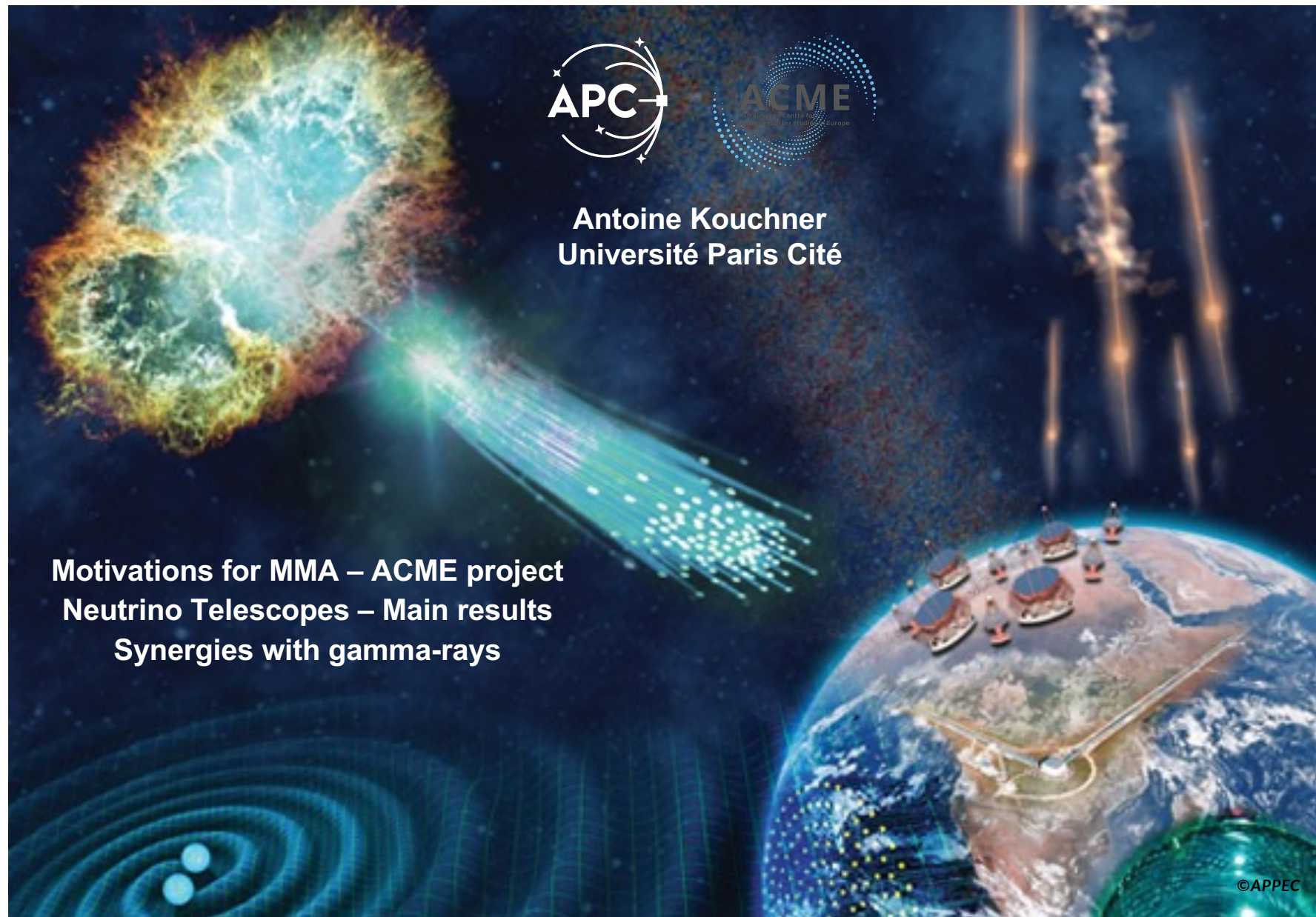
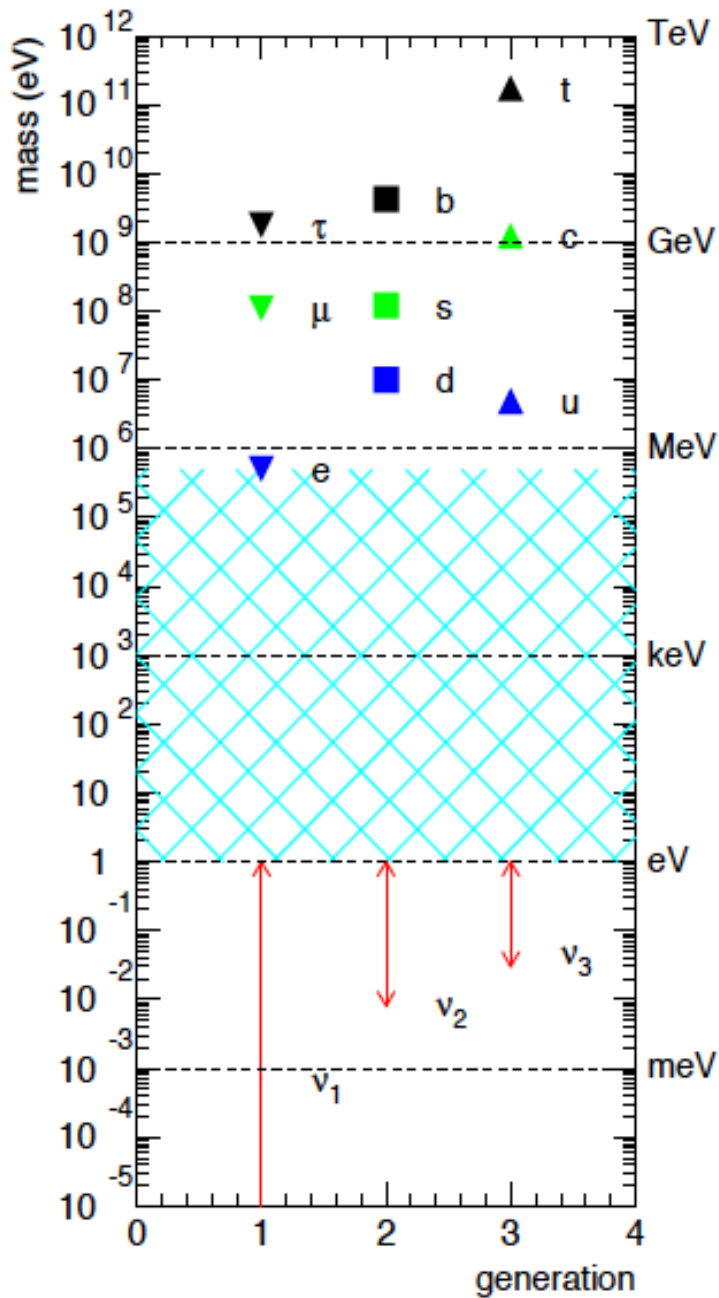


Neutrino astronomy as part of a multi-messenger approach

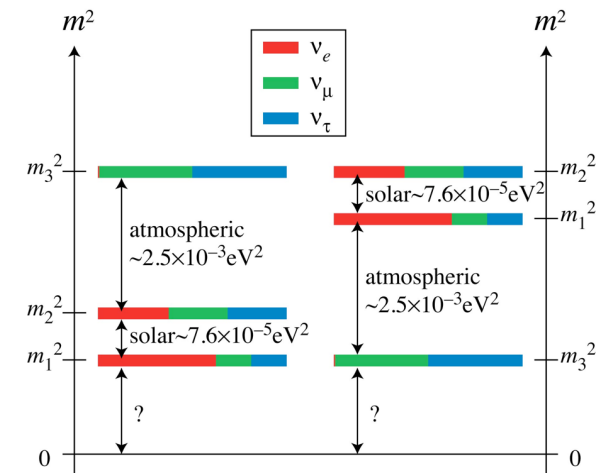


Neutrinos ?

2



- Weak interactions
- Anti-particle ?
 - Majorana or Dirac ?
 - Higgs Mechanism ?
- Sterile Neutrinos ?
- Oscillations - Flavor mixing along propagation
- CP violation ?
- **Mass ordering ?**



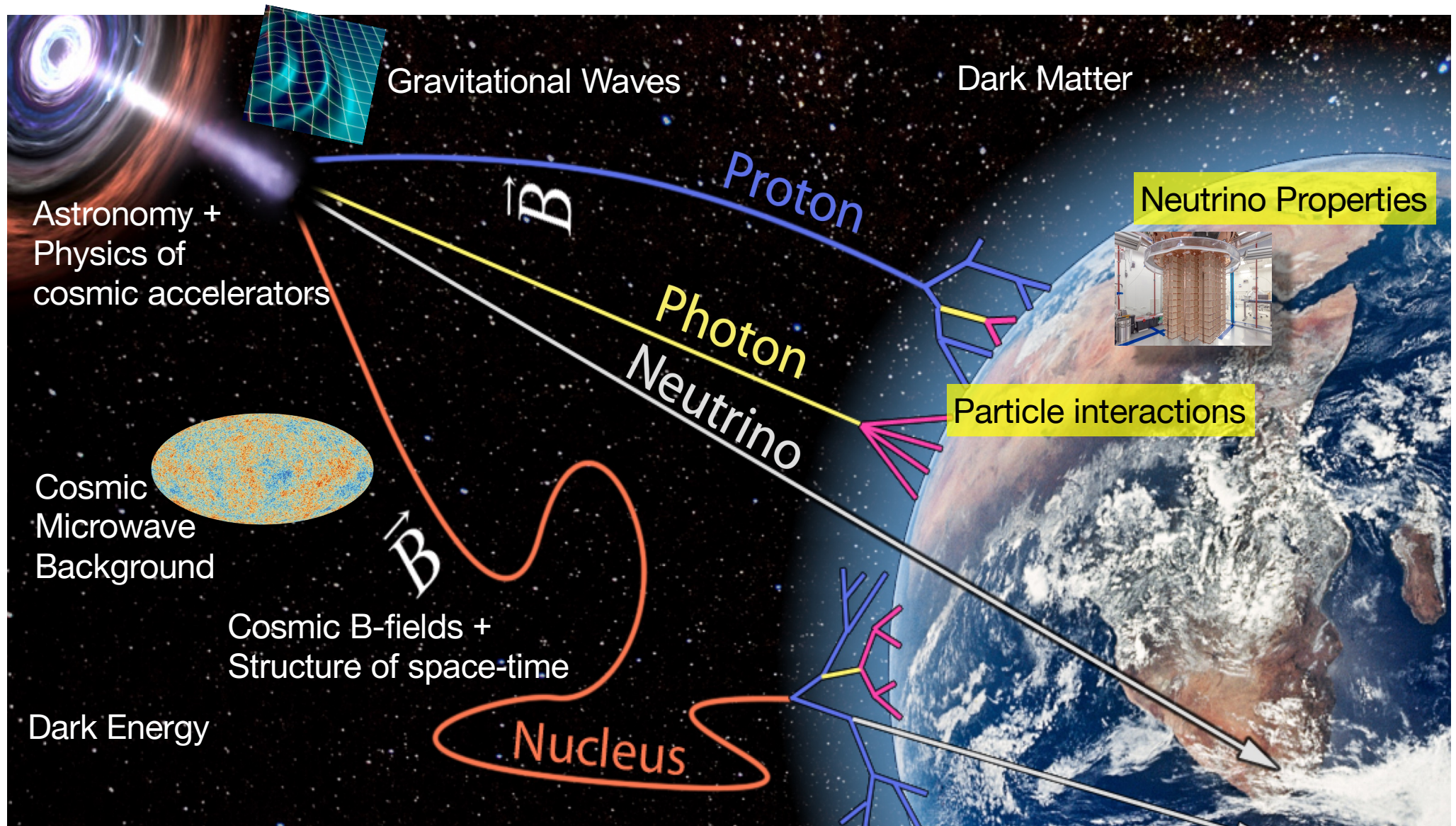
(Pontecorvo–Maki–Nakagawa–Sakata)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Diagram illustrating neutrino mixing with rotation angles θ_{12} , θ_{23} , and θ_{13} .

Multi-Messenger Astroparticle Physics

3

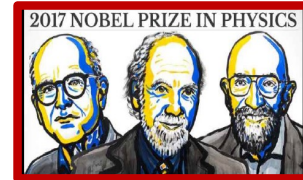
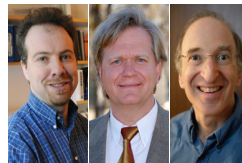


A very large Scientific Scope

A Nobel Prize Field

[21st century]

4

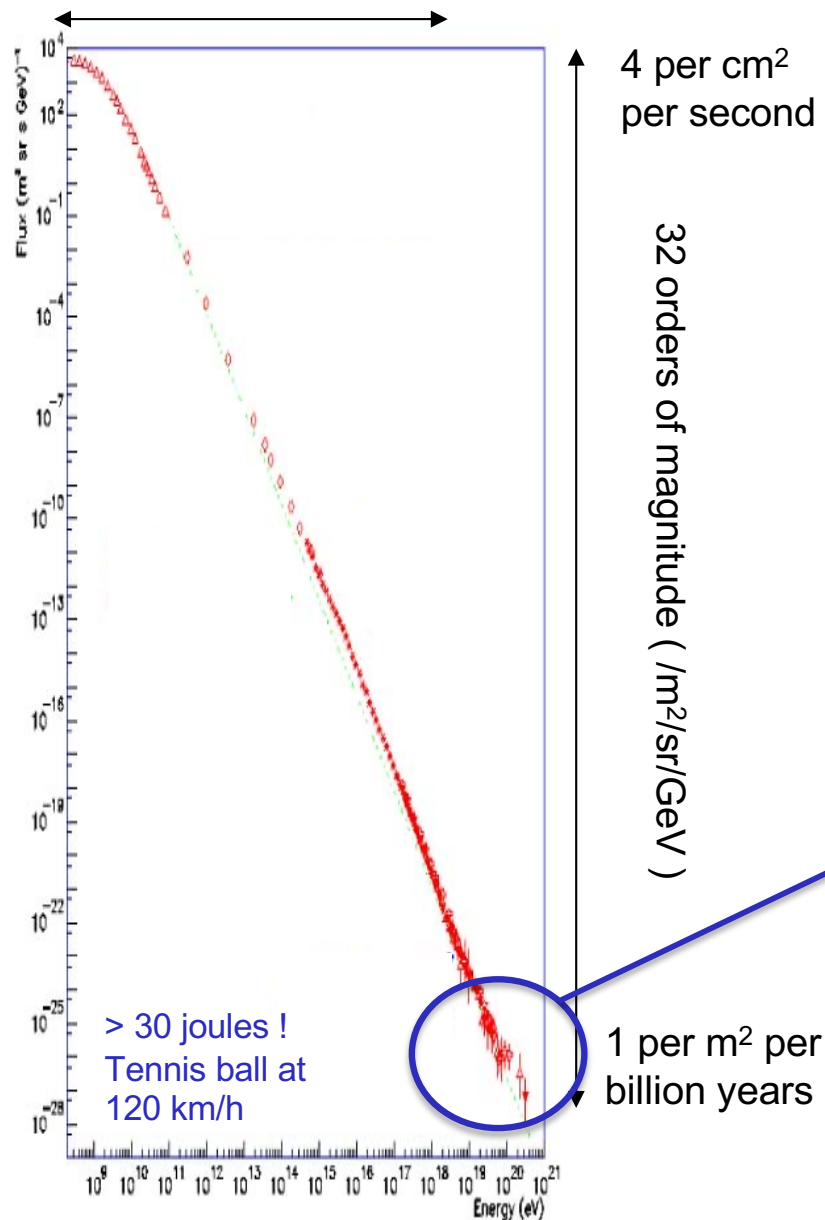


"for decisive contributions to the IceCube Neutrino Observatory and the discovery of high-energy neutrinos of astrophysical origin"

Cosmic rays, challenging since 1900

5

> 12 orders of magnitude!



✧ Major role in Galactic ecosystem !

- ✧ Energy density ~ star light, thermal, B field
- ✧ Regulate the equilibrium between the different phases of the interstellar medium
- ✧ Control ionisation, heating
- ✧ Regulate star formation
- ✧ Produce Li, Be and B!

✧ Main unknowns

- ✧ Which sources (Galactic and Extragalactic)
- ✧ Acceleration processes are uncertain

✧ How does Nature proceed ? to produce them

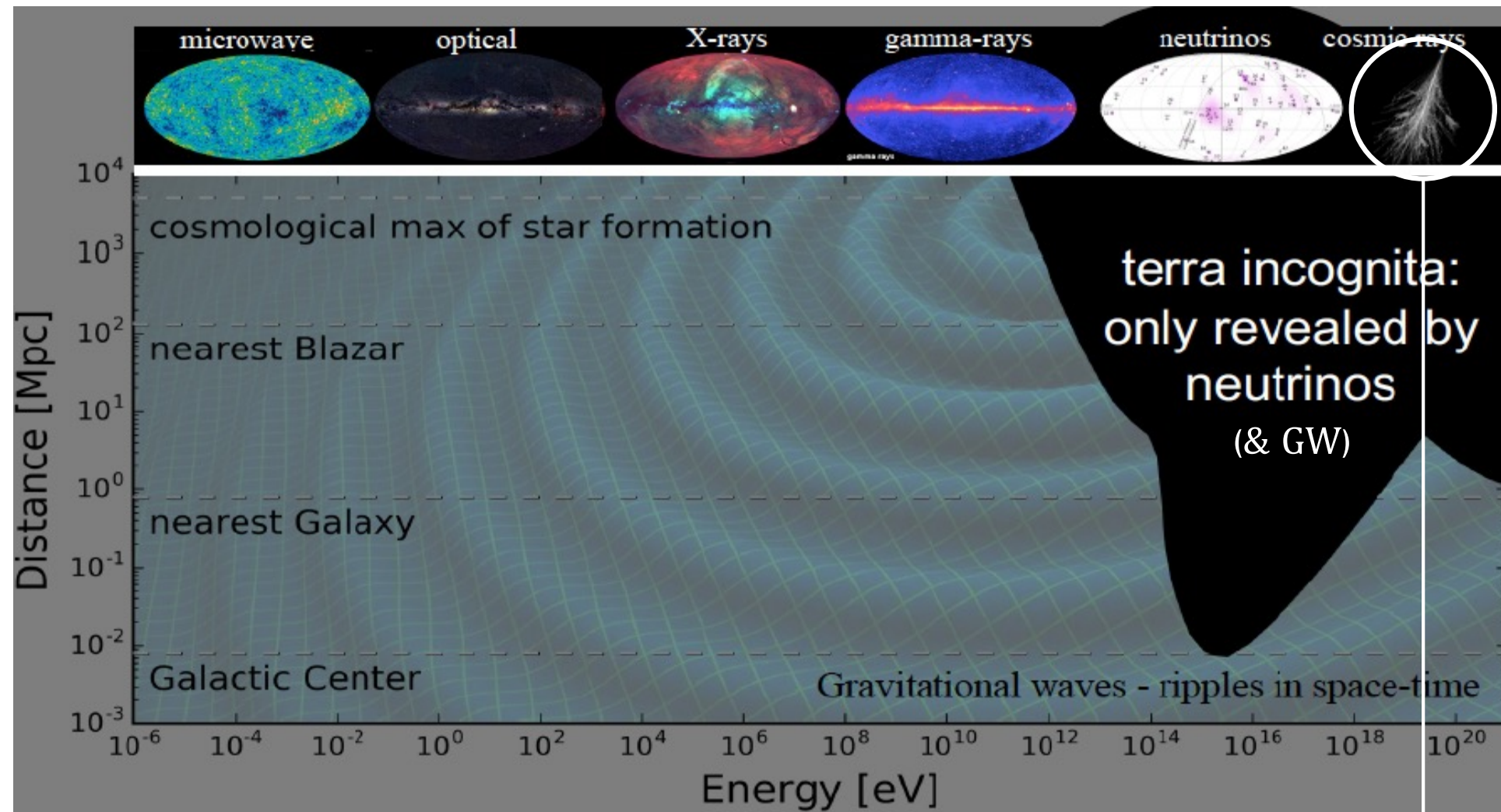
- ✧ What, where and how ?

✧ How does Nature behave ? at such energies

- ✧ Lorentz factors beyond all tests of Relativity
- ✧ Cross section beyond LHC reach

Rationale for HE Neutrino Astronomy

6



Neutrinos

✓ Transient sources

✓ Core of astrophysical bodies

✓ Point source

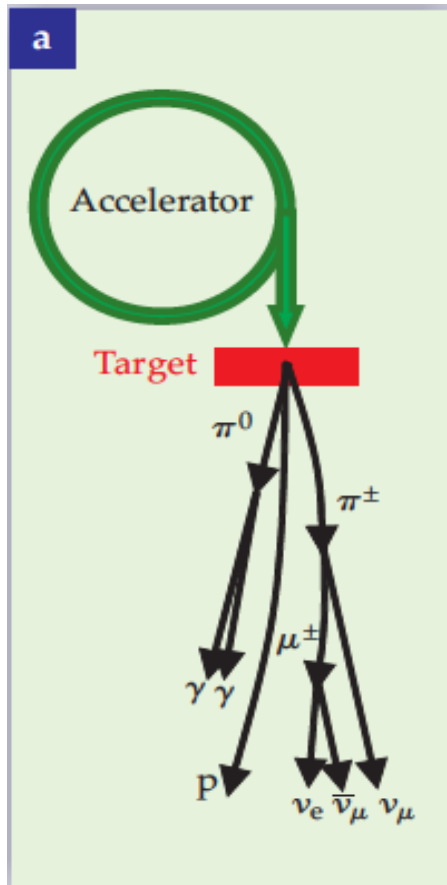
✓ Cosmological distance

⇒ Signature of hadronic acceleration

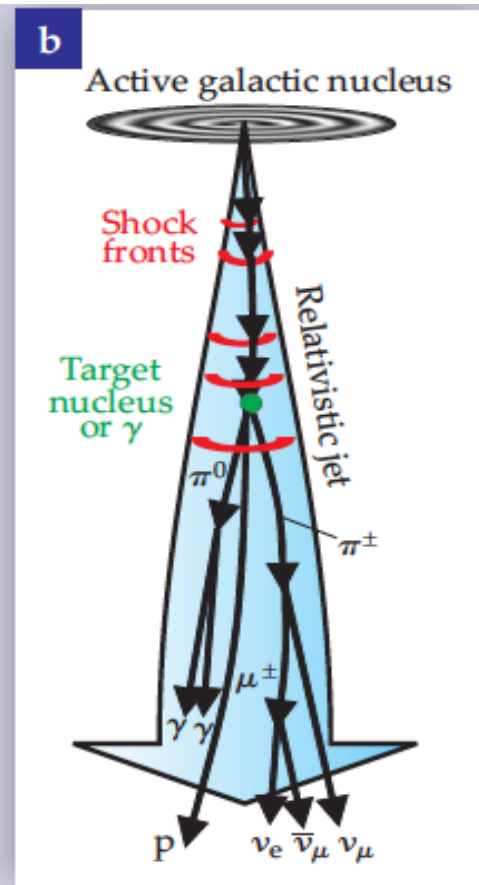
Common production mechanism

7

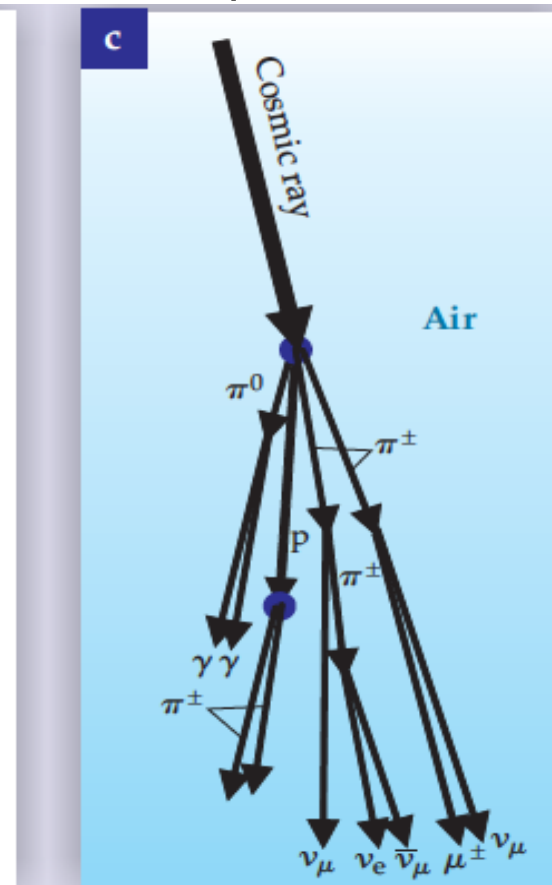
Neutrino beam



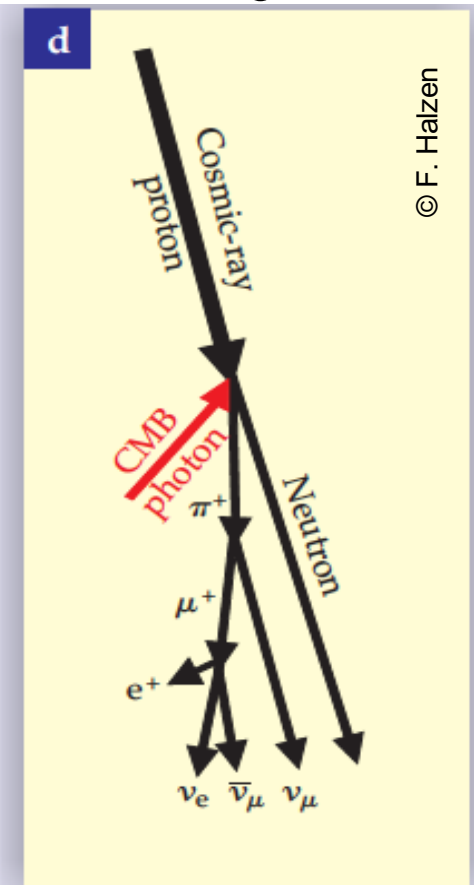
Cosmic neutrinos



Atmospheric neutrinos



Cosmogenic ν



© F. Halzen

$$pp \rightarrow \pi^+ + \pi^- + \pi^0 + X$$

$$N_{\pi^+} \approx N_{\pi^-} \approx N_{\pi^0}$$

$$\Phi_\nu \approx \Phi_\gamma$$

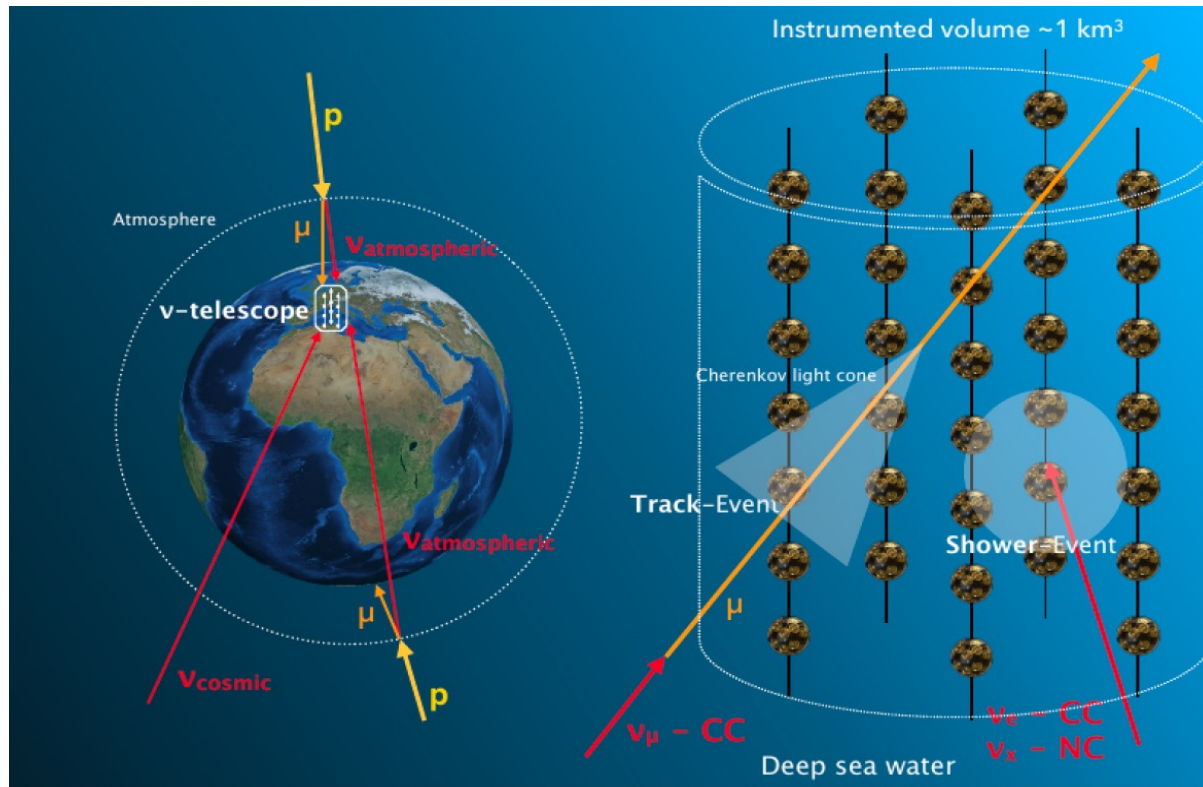
$E_\gamma/E_p = \sim 0.10 \rightarrow 100 \text{ TeV gamma-rays are produced by 1 PeV protons!}$

$E_\nu/E_p = \sim 0.05 \rightarrow 50 \text{ TeV neutrinos are produced by 1 PeV protons!}$

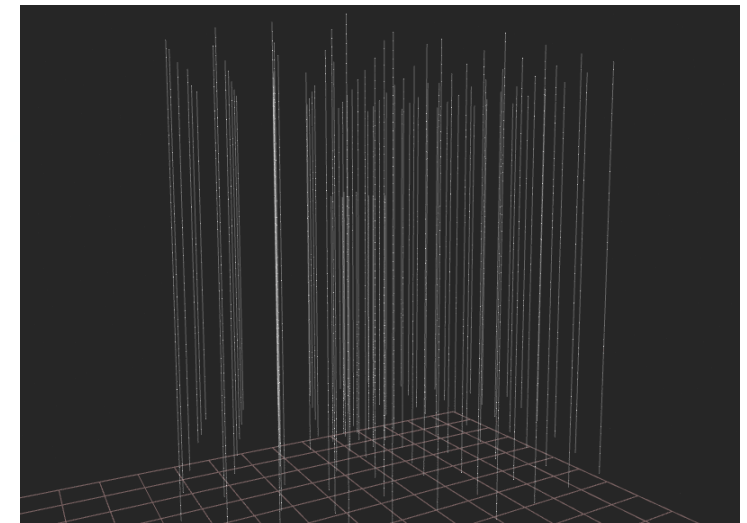
Gamma-ray morphology can indicate target material while neutrinos test hadronic emission

In short

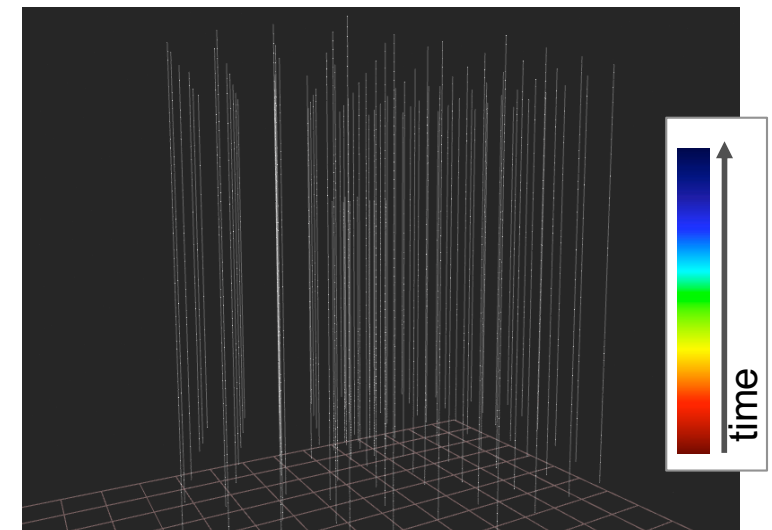
8



Sea



Tracks : $\sim 0.5^\circ$ $\sim 0.1^\circ$
Cascades : $\sim 10^\circ$ $\sim 1^\circ$

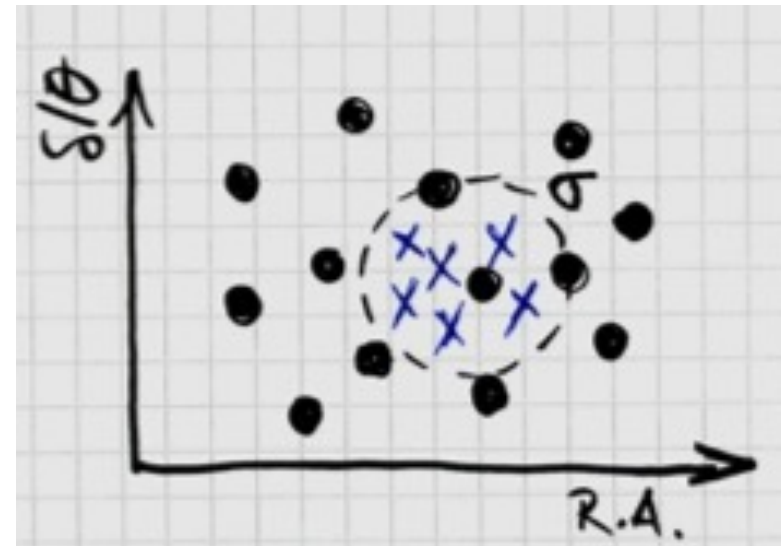
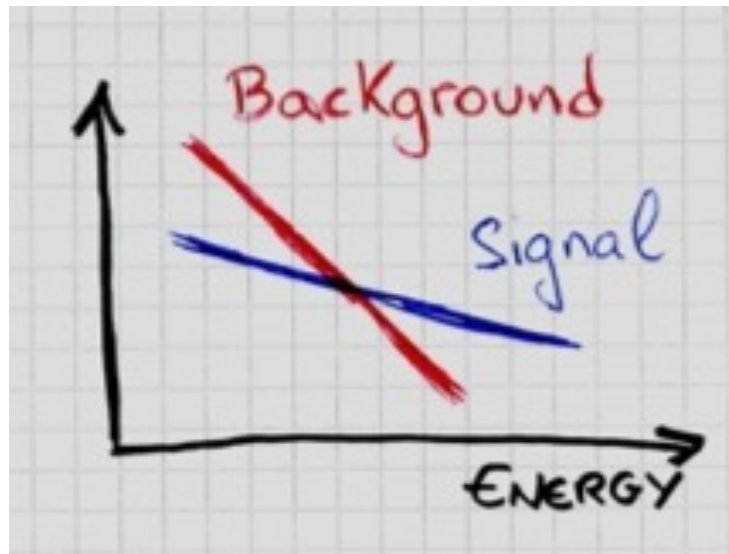


Ice

Atmospheric background vs cosmic ν 's

9

Atmospheric muons: **shield detector & define signal as upward muons**



Atmospheric neutrinos: **search for**

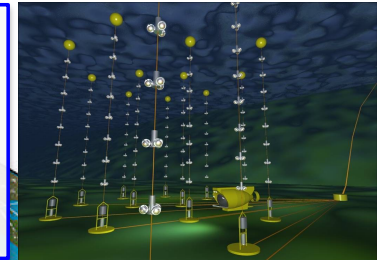
- An excess at High Energy
- Anisotropies
- Time / space coincidence with other cosmic probes

The neutrino telescope world map

+ Prototypes in Canada (P-ONE)
and China (TRIDENT, HUNT, NEON)



ANTARES
Deep water
0.01 km³
2008 – 2022



KM3NeT
Deep water
1 + 0.006 km³
Construction



Baikal/GVD
Deep water
~1 km³
Construction



ICECUBE

IceCube
Deep ice
1 km³
2011 –
Upgrade
with a lower
energy threshold
2025-2026
(5 strings)



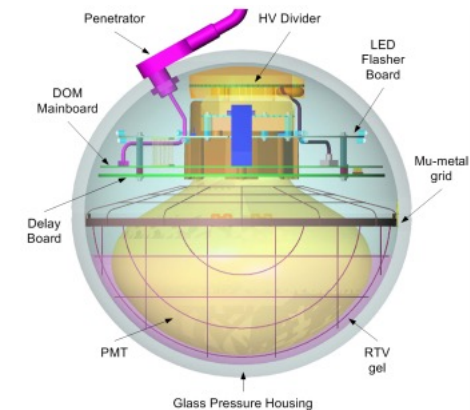
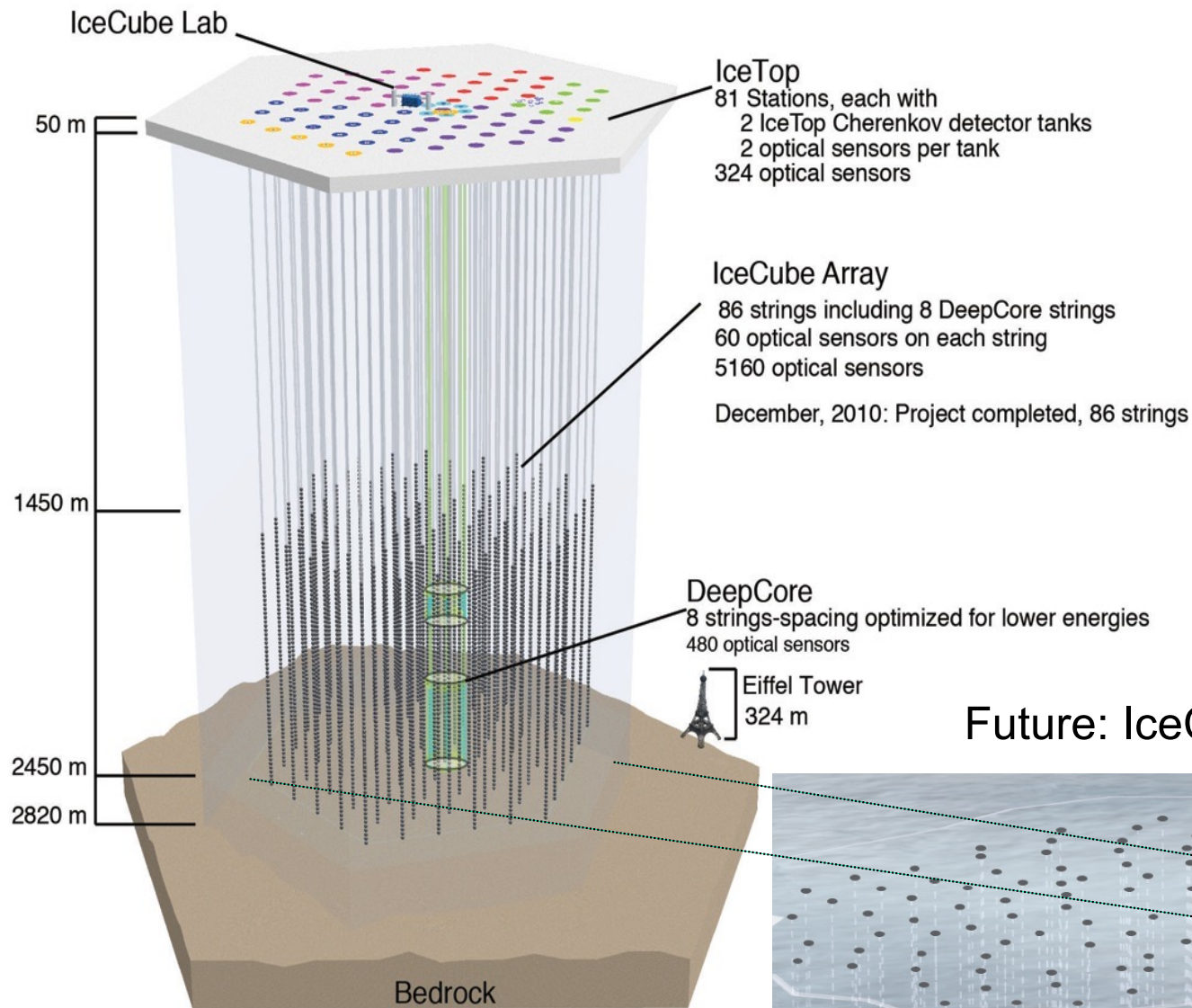
www.globalneutrino.org

Frame for enhanced cooperation

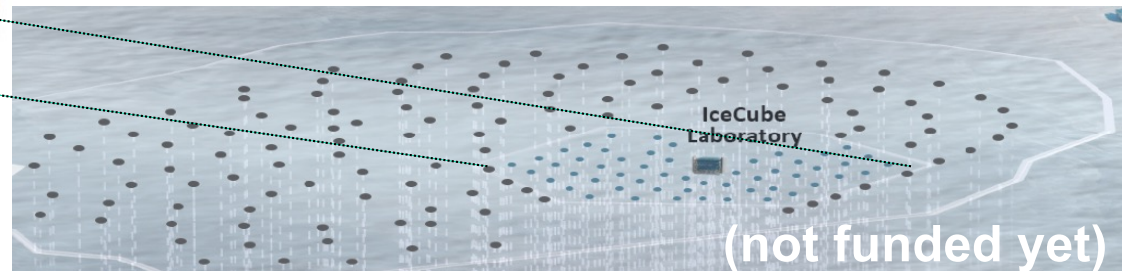
IceCube : the biggest NT in the world

11

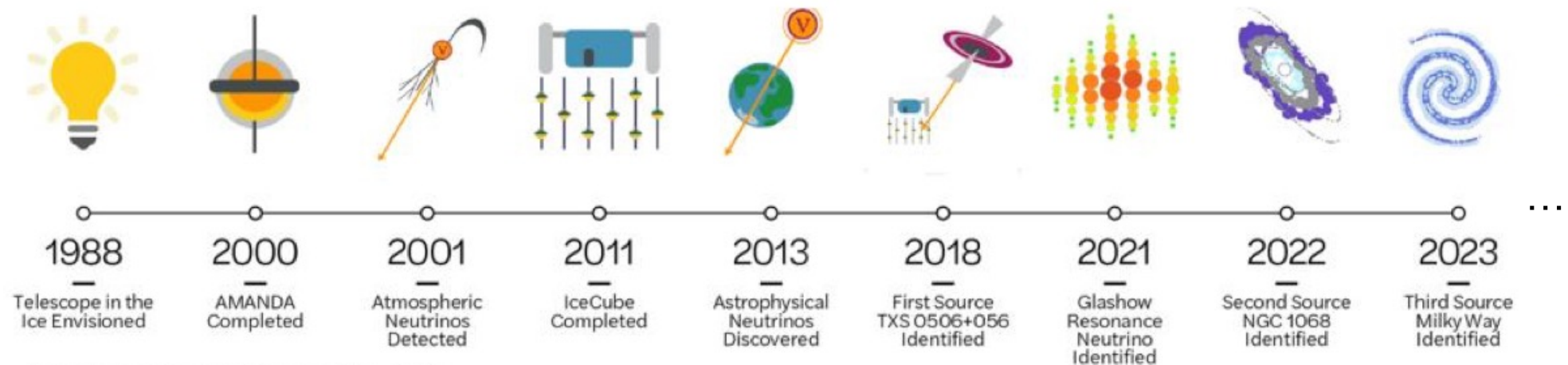
Completed since December 2010.



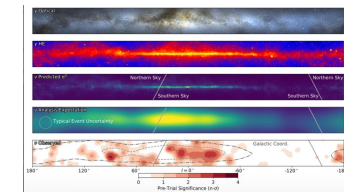
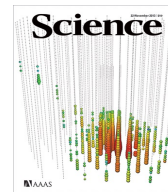
Future: IceCube Gen-2 (10 km^3)



Historical major steps in Antarctica

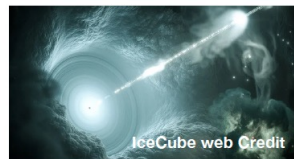


Credit: IceCube Collaboration/NSF



During the last decade few discoveries thanks to the IceCube observations

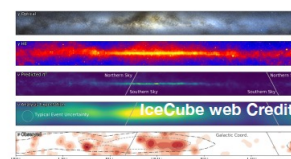
TXS0506+056 +
few other blazars



Seyfert galaxy
NGC1068

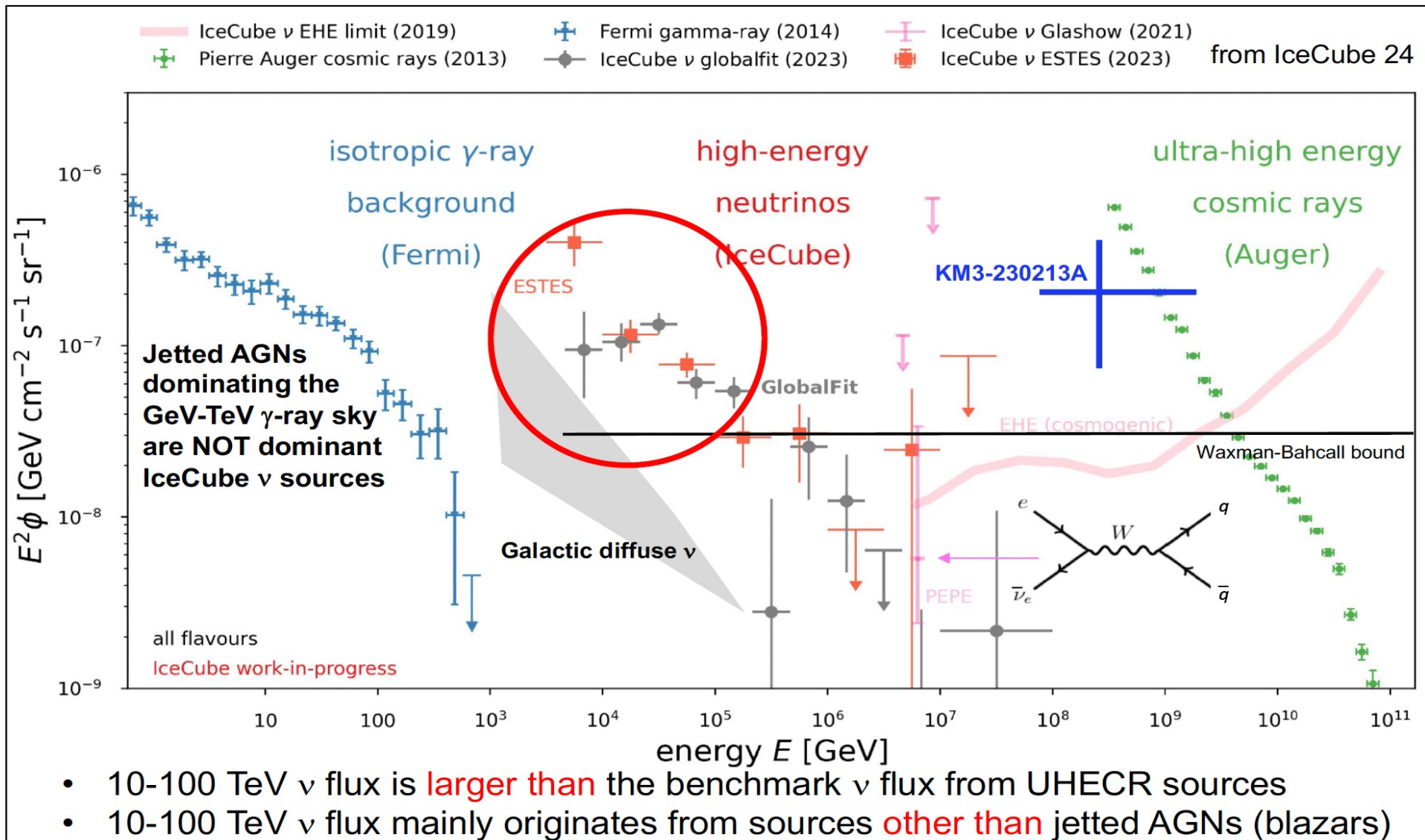


Galactic neutrino
Excess



Hundreds of TeV-PeV
Astrophysical neutrinos
+
Non associated with
known sources

Diffuse Neutrino Spectrum



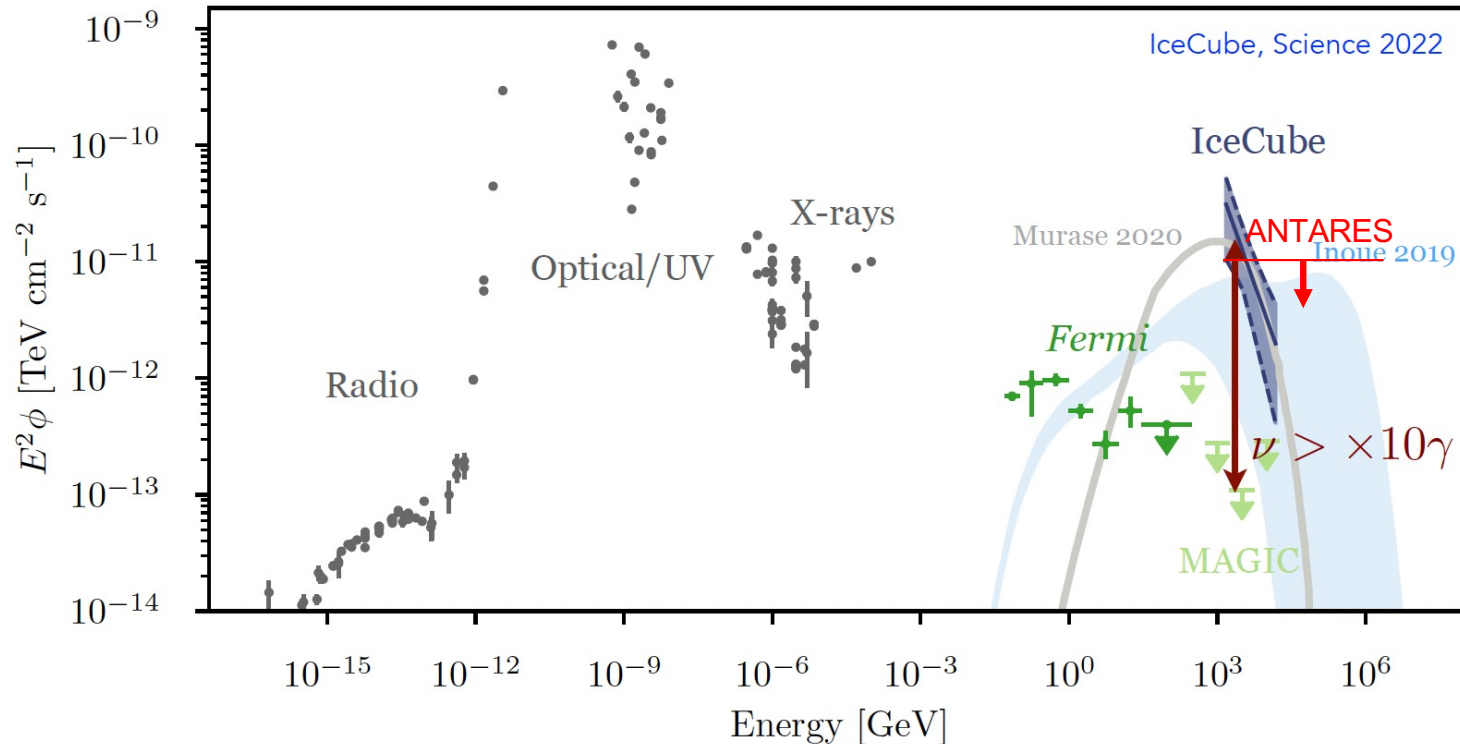
© K. Murase

Current Status: Evidence for spectral break ~ 30 TeV
 (supported by ANTARES diffuse flux search: JCAP 08 (2024) 038)

Neutrinos from γ -ray opaque sources ?

NGC 1068 Spectrum

5,1 σ 13 years of data



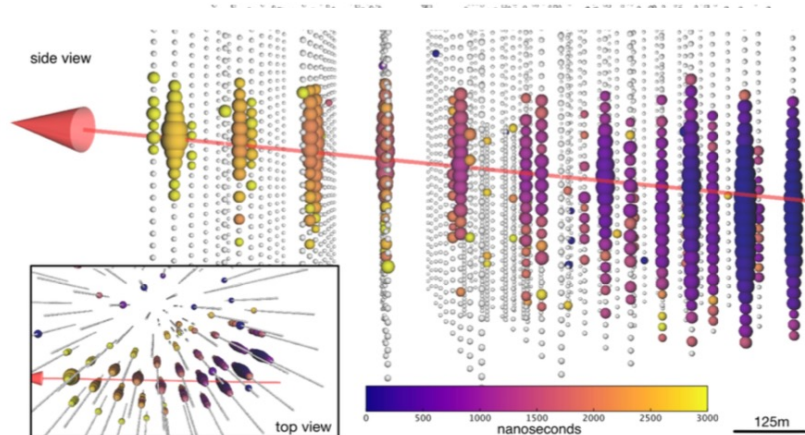
- ▶ The neutrino flux much higher than the measured γ -ray flux.
- ▶ Models built on Fermi γ -ray flux cannot accommodate the neutrino flux.
- ▶ **Obscuring** necessary to absorb the pionic γ -ray accompanying neutrinos.
- ▶ The high opacity indicates that the neutrinos are produced in dense environment in the vicinity of AGN core ($< 100 R_s$) → Consistent with the multimessenger picture for the HE cosmic neutrino flux

Neutrinos from blazar TXS0506+056

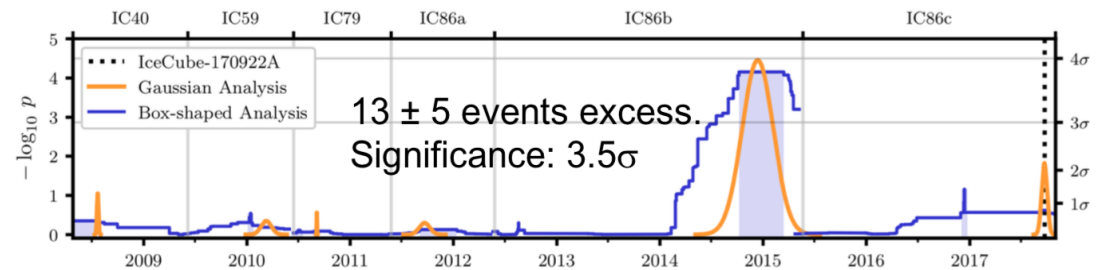
15

Sept. 22, 2017:

A neutrino in coincidence with a blazar flare

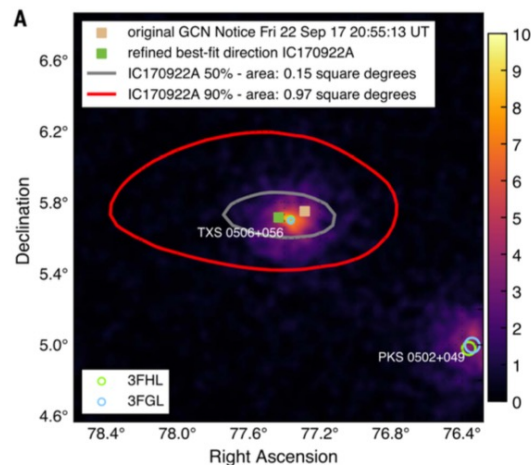


2014-2015: A (orphan) neutrino flare found from the same object in historical data



Science 361 (2018) no. 6398, eaat2890

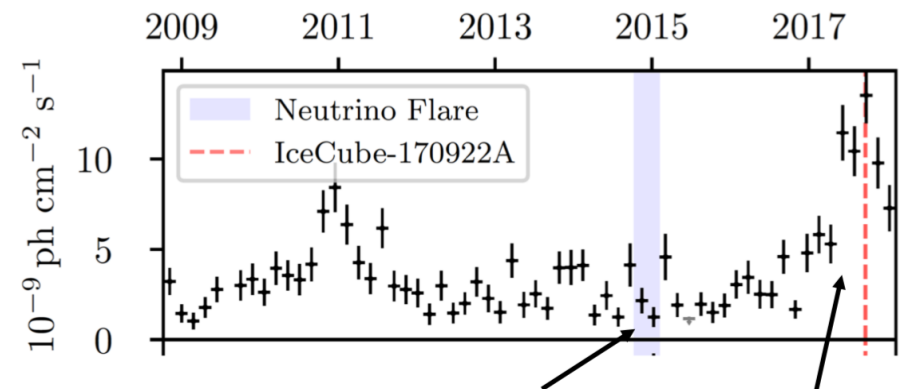
Fermi-LAT data; Padovani et al, MNRAS 480 (2018) 192



Observed by
Fermi-LAT
and MAGIC

Significance for
correlation: 3σ

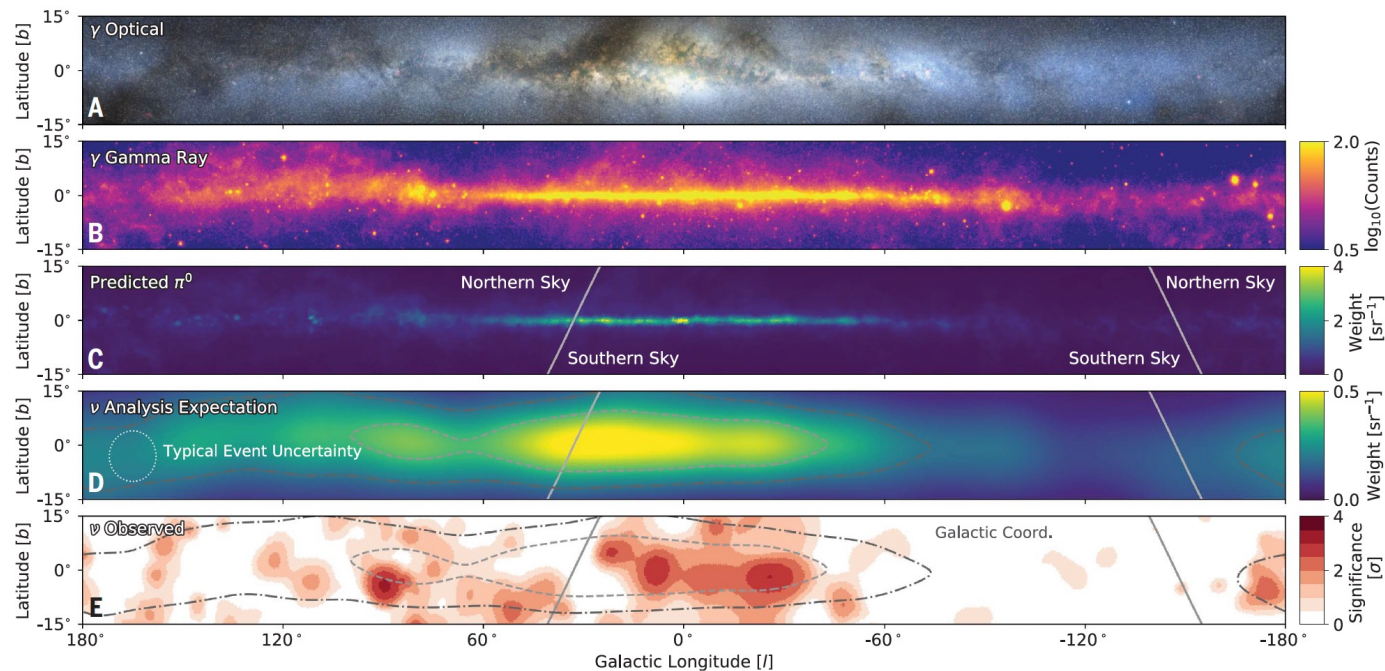
Science 361 (2018) no. 6398, eaat1378



At 2014-15 neutrino flare The 2017 flare Page 2

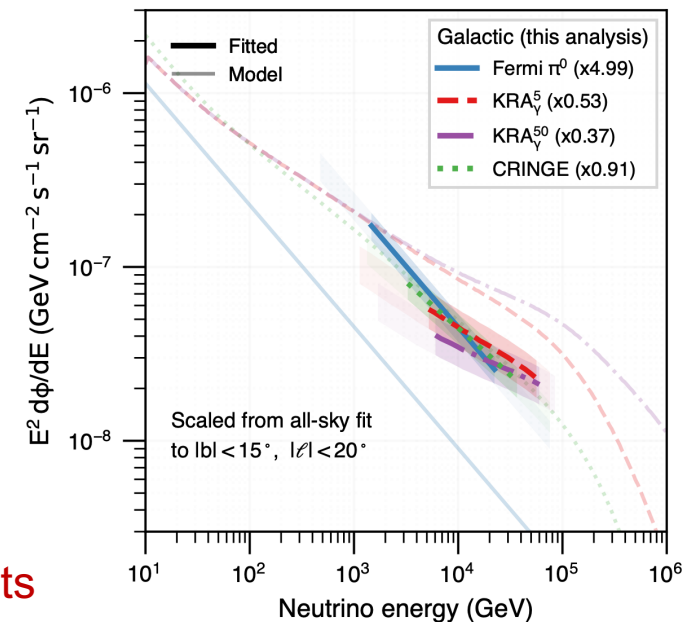
IceCube conclusion: **Compelling evidence of a HE ν from a blazar**

Neutrinos from the Milky Way



10 years of cascade data identified neutrino emission from the Milky Way at 4.5σ

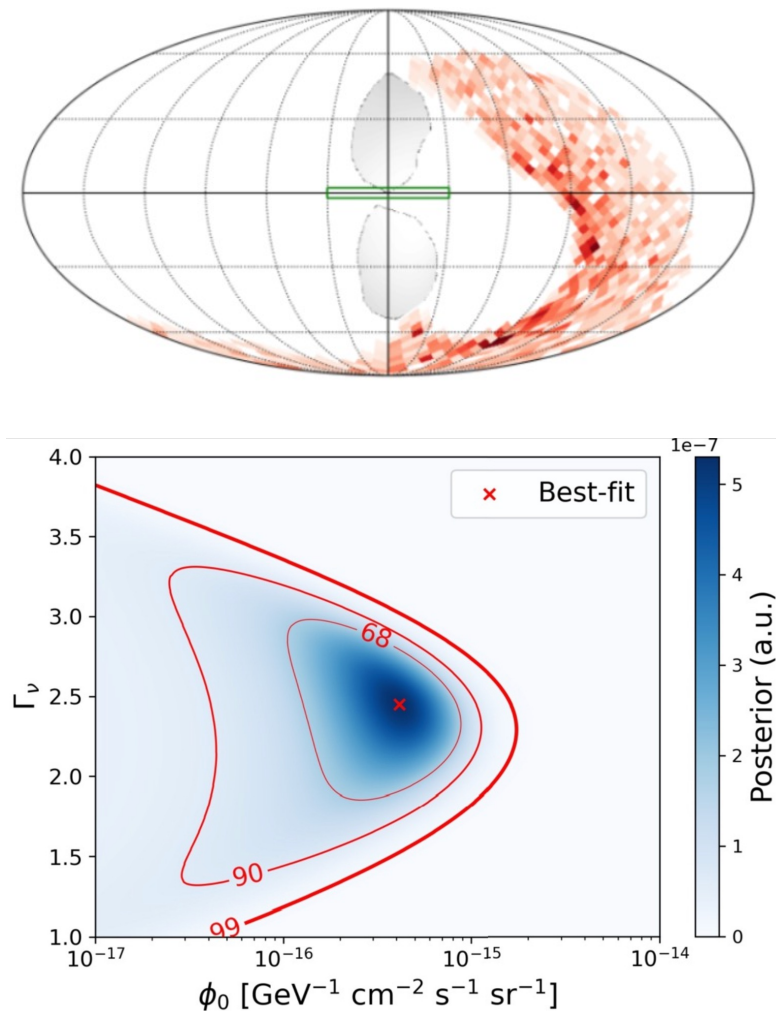
- Various **galactic diffuse emission models** tested.
- Only normalization of modeled emission fitted.
- Null hypothesis for all models rejected at $> 5\sigma$.



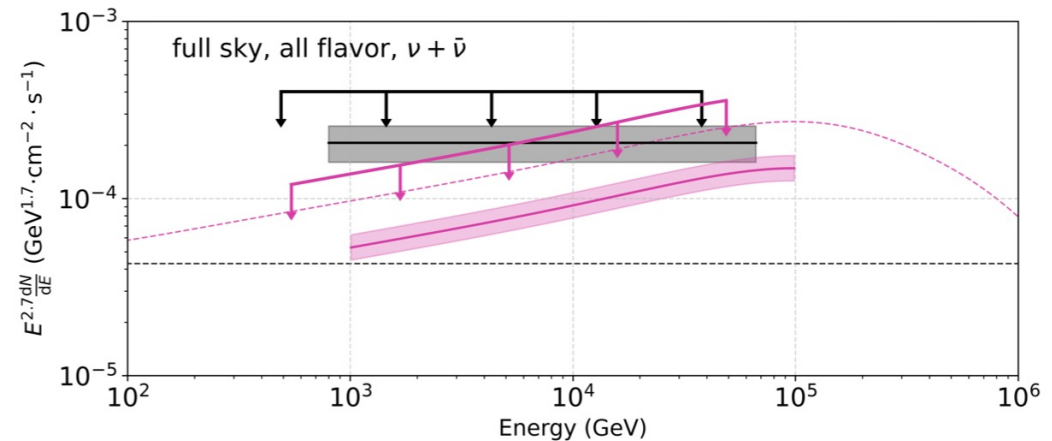
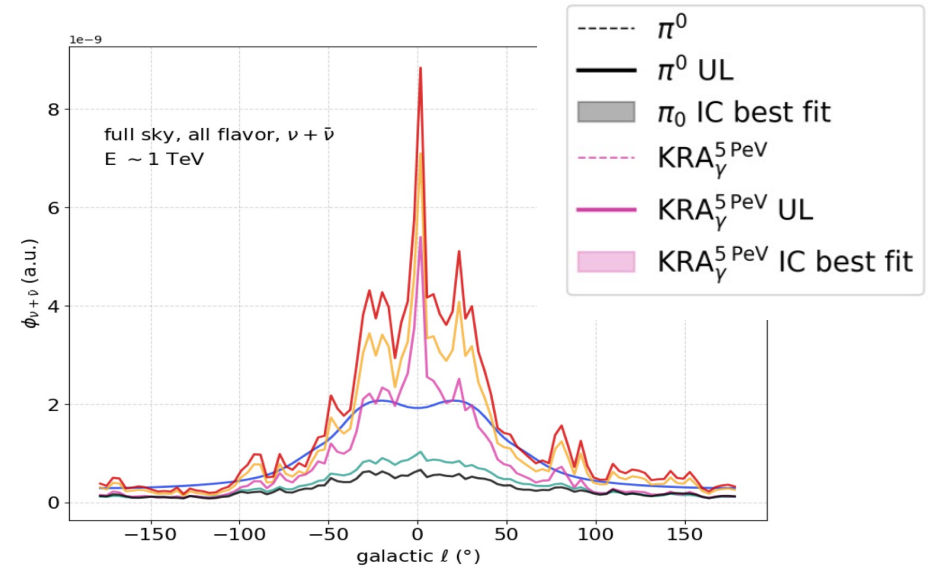
→ Clarification will come from Northern Hemisphere Instruments

Antares Focus on the Galactic Plane

17



96% C.L. hint of a galactic signal



No excess → KM3NeT well suited to discriminate models

ANTARES Main Legacy Paper



Physics Reports

Volumes 1121–1124, 5 June 2025, Pages 1–46



Review Article

The ANTARES detector: Two decades of neutrino searches in the Mediterranean Sea

A. Albert^{1 2}, S. Alves³, M. André⁴, M. Ardid⁵, S. Ardid⁵, J.-J. Aubert⁶, J. Aublin⁷, B. Baret⁷, S. Basa⁸, Y. Becherini⁷, B. Belhorma⁹, F. Benfenati^{10 11}, V. Bertin⁶, S. Biagi¹², J. Boumaaza¹³, M. Bouta¹⁴, M.C. Bouwhuis¹⁵, H. Brânzaș¹⁶, R. Bruijn^{15 17}, J. Brunner⁶...J. Zúñiga³

Show more ▼

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<https://doi.org/10.1016/j.physrep.2025.04.001> ↗

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<https://antares.in2p3.fr/>

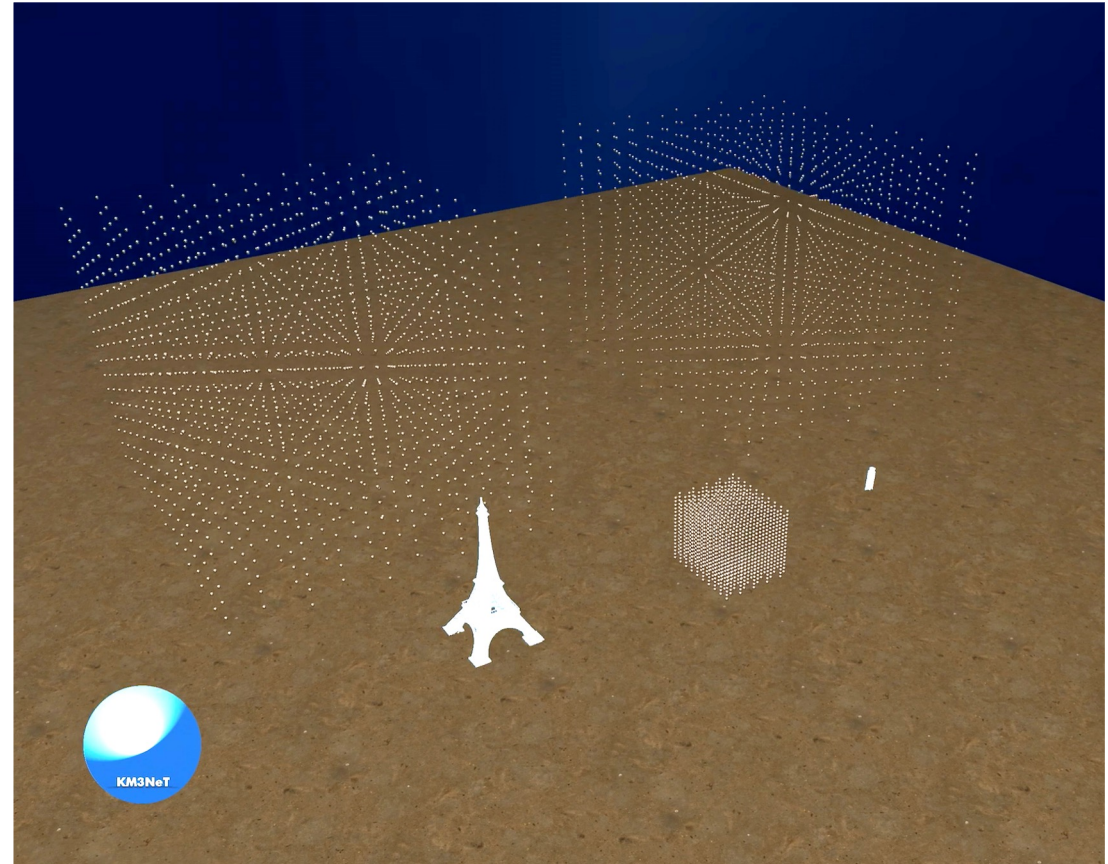
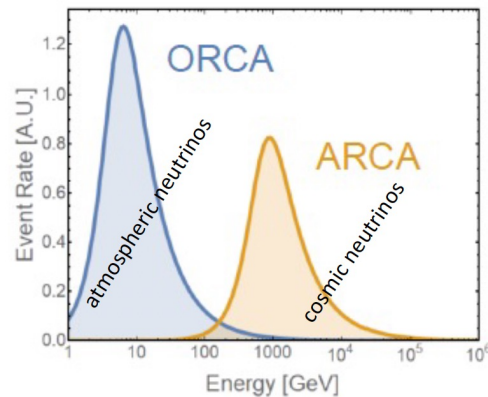
The KM3NeT Infrastructure



19

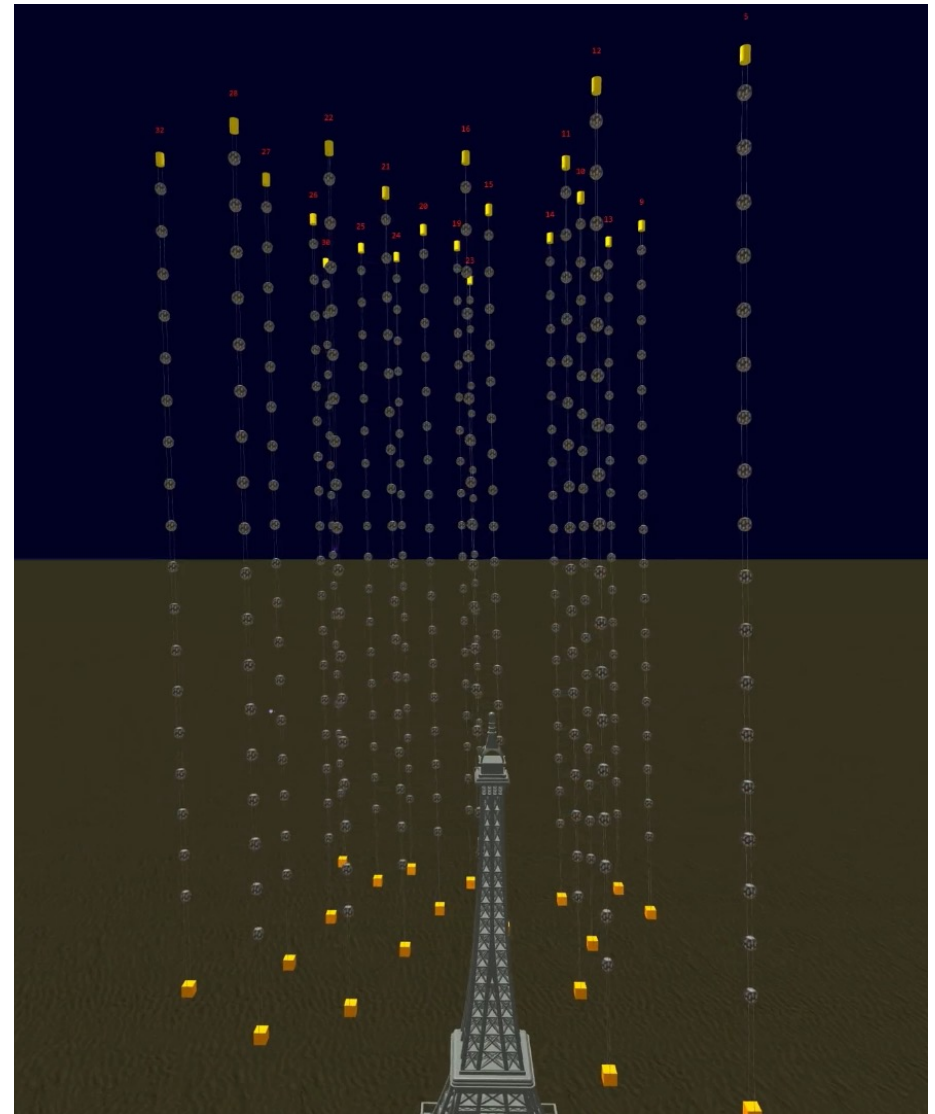
ORCA (France): 108 detection units, dense spacing (20m between lines), 6.5 Mton fiducial mass

ARCA (Italy): 198 detection units, sparse layout (90m between lines), 1 Gton

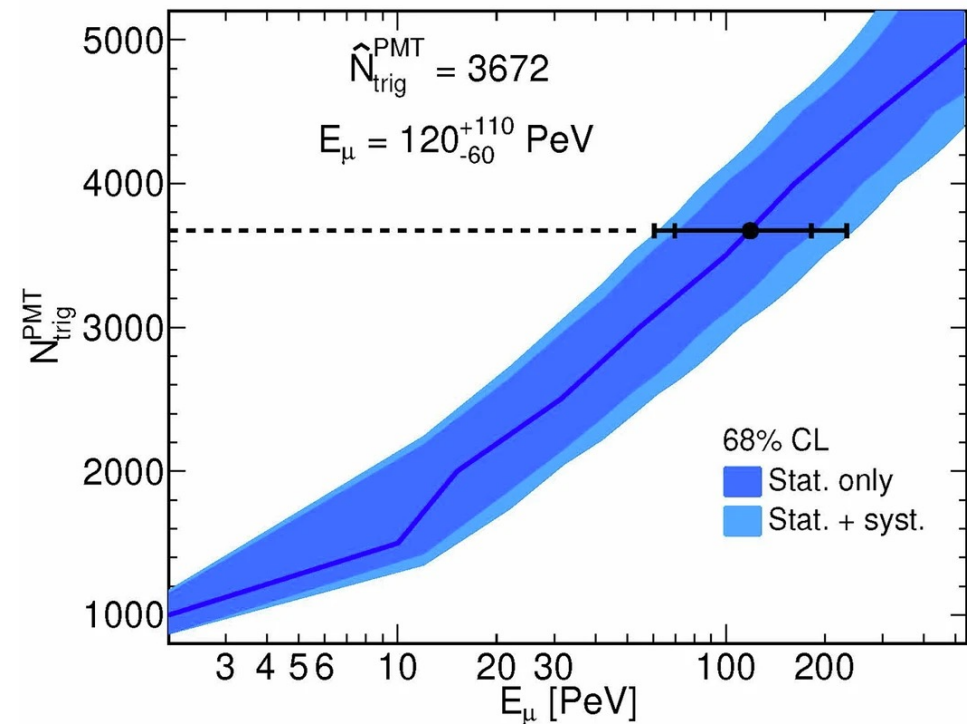
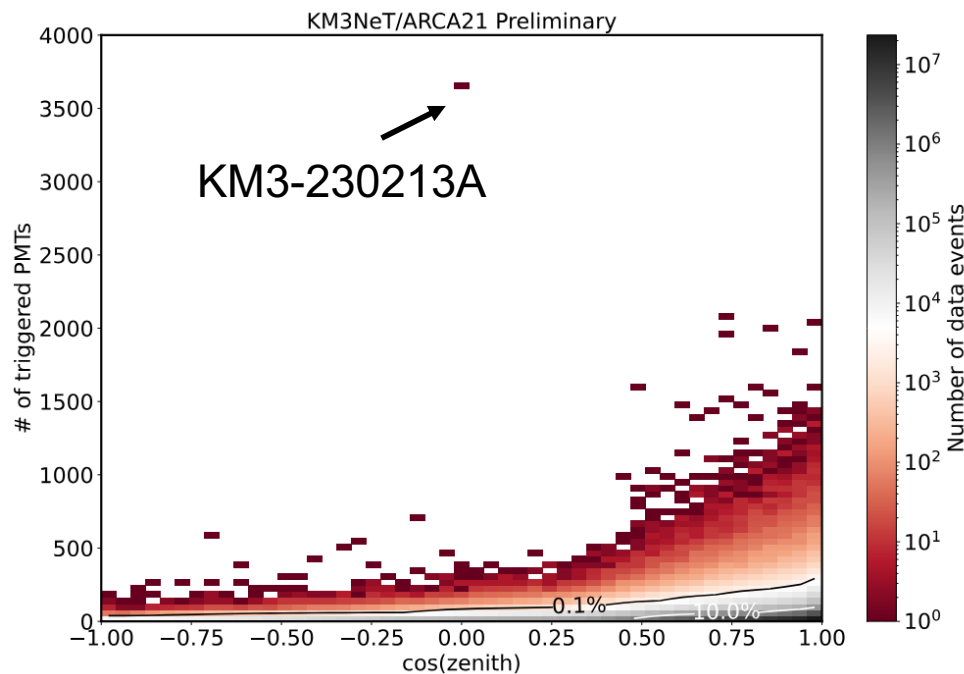


The construction goes on...





- High-energy muon seen on 13 February 2023, 21-DU ARCA configuration
- 3,672 PMTs (35%) triggered during the event

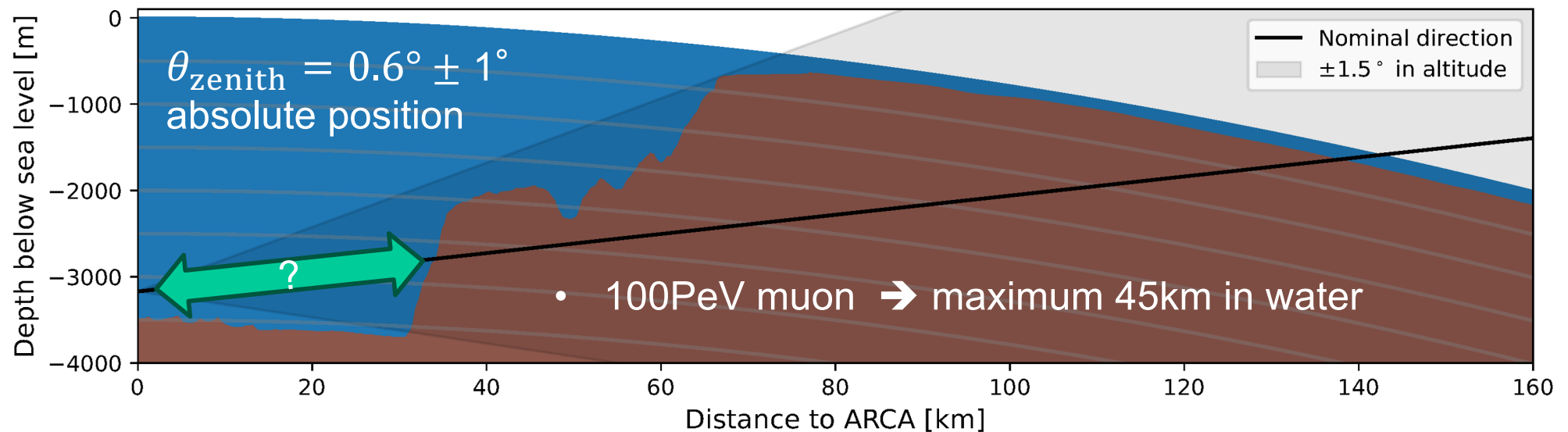
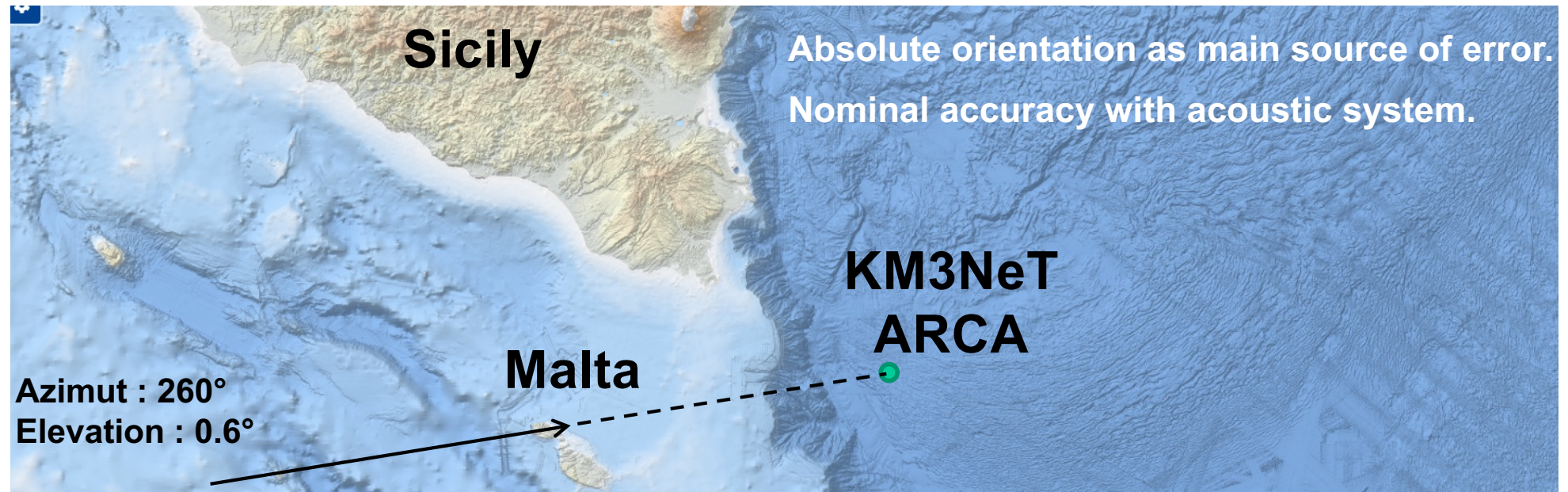


- Energy is measured from light amount:

$$E_{\mu} = 120_{-60}^{+110} \text{ PeV} \xrightarrow{E^{-2}} E_{\nu} = 220_{-100}^{+570} \text{ PeV}$$

KM3-230213A: incoming direction

22



- Exceedingly unlikely for atm. muon to travel that much column depth $\rightarrow$ neutrino

KM3-230213A: Origin ?

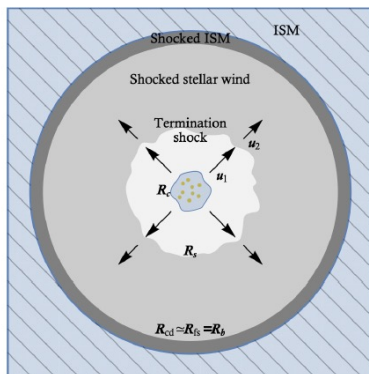
© Alberto Manfreda

Origin	Likely?	MM expectation	What would we learn?
Galactic	Not much	γ -ray counterpart unless hidden/transient; possible radio/X-ray transient counterpart; nearby gas clouds can act as targets	Galactic EeVatron; new hard CR/ ν population
Blazars	Plausible	Variable radio/X-ray/ γ activity may accompany the ν flare; γ rays can be absorbed and EM/ ν activity need not be simultaneous	Blazars can accelerate hadrons to multi-EeV energies; evidence for a rare, strongly hadronic/UHE-peaked blazar population
GRB / other transient	Theoretically possible, no counterpart	Prompt/delayed X/optical/radio/ γ counterpart if visible; hidden/obscured transients possible	UHECR acceleration in explosive sources; baryon loading/environment; population of rare or hidden transients
Cosmogenic	Plausible	No individual counterpart expected; constraints come from UHECR spectrum/composition and diffuse γ -ray cascades	UHECR proton fraction; cosmological source evolution; UHECR accelerators beyond the local horizon

- ✓ On the Potential Cosmogenic Origin of the Ultra-high-energy Event KM3-230213A, ApJL 984(2025) L41
- ✓ On the Potential Galactic Origin of the Ultra-High-Energy Event KM3-230213A, ApJ 1003 (2026) 157.
- ✓ Blazars as a Potential Origin of the KM3-230213A Event, JCAP03(2026)033.
- ✓ The ultra-high-energy event KM3-230213A within the global neutrino landscape, Phys. Rev. X 15 (2025) 031016
- ✓ Constraining gamma-ray burst parameters with the first ultra-high-energy neutrino KM3-230213A, A&A, 710 (2026) A168
- ✓ Characterising Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A, *accepted* to Astron. J., arXiv:2502.08484
- ✓ Testing Heavy Dark Matter Decay as the Origin of KM3-230213A. arXiv:2606.09986 *submitted* to JCAP

Gamma-ray & neutrino sources ?

- Most Galactic sources are optically thin
 - Example Stellar Cluster



© Condorelli

- ▶ As SNR $\rightarrow$ shock wave $\rightarrow$ Fermi acceleration but in the reverse shock.
- ▶ Very slow acceleration $\rightarrow$ stationary object.
- ▶ They can explain the GCR mass composition above ^{20}Ne .
- ▶ Theoretically, capable to reach PeV acceleration.
- ▶ Experimentally, observed in VHE gamma rays by LHAASO $\rightarrow$ Candidate galactic PeVatrons.

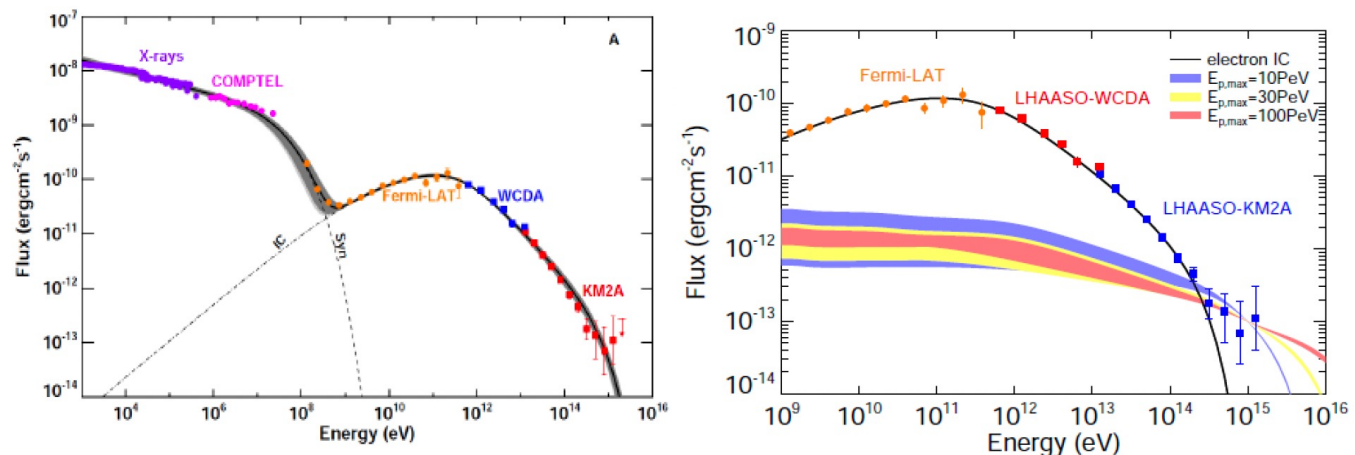
▶ Tension in literature: hadronic or leptonic?

Combined gamma-neutrino observation can solve this degeneracy!

Gamma-ray & neutrino sources ?

- Most Galactic sources are optically thin
 - Example Crab Nebula

The first Galactic PeVatron: Crab Nebula



- Detection of PeV photons! Regardless of leptonic or hadronic origin, PeV particles should be there!
- This also marks the beginning of PeV astronomy.
- Possible spectral hardening at PeV energies, may be an indication of a second component (lepton + hadron/lepton).
- One of the promising interpretation is the PeV emission from underlying hadronic component interacting with dense photon environments within the pulsar region via photohadronic interactions.
- Puzzle can only be solved with multi-messenger observations (neutrinos).

Gamma-ray & neutrinos sources ?

- Most Galactic sources are optically thin
 - Example of tool :



© Condorelli

- ❖ Starting from "Prospects for combined analyses of hadronic emission from γ -ray sources in the Milky Way with CTA and KM3NeT", *Eur.Phys.J.C* 84 (2024) 2, 112
- ❖ Milestone for many ongoing works within KM3NeT.
- ❖ How does the combination of gamma-ray and neutrino data at the event level compare to separate analyses with respect to the emission scenario of galactic sources and what can these measurements say about hadronic or leptonic contributions to the emission?
- ❖ Analysis with **ARCA full detector**.

Gamma-ray & neutrinos sources ?

- Most Galactic sources are optically thin
 - Example of tool :



© Condorelli

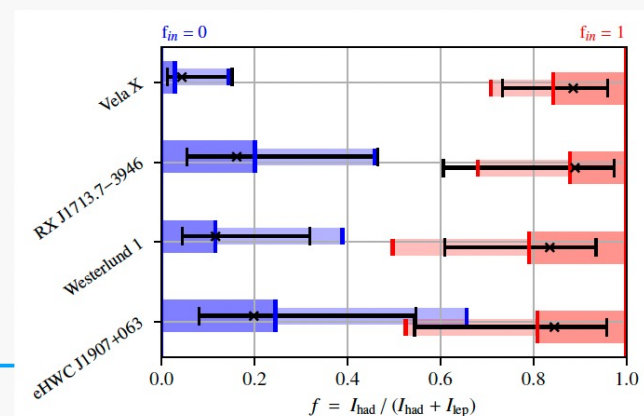
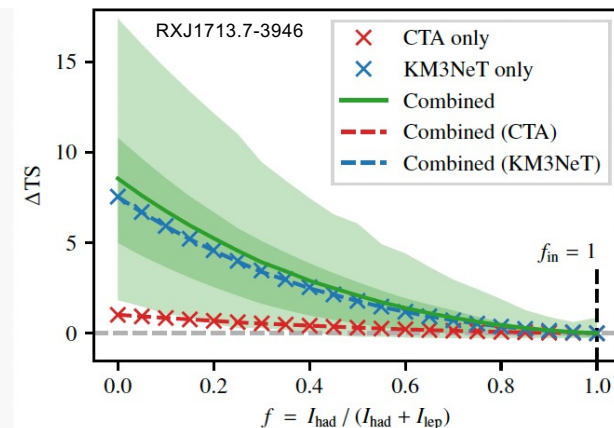
- Profile likelihood provides confidence intervals on f .
- Combined analysis generally improves discrimination.

$$TS_{\text{joint}} = TS_{\text{CTA}} + TS_{\text{KM3NeT}}$$

- Sensitivity depends on:

- similarity of hadronic vs leptonic models
- neutrino statistics

- Combined framework ensures consistent modeling and shared treatment of systematics.



Just a beginning ...

28



Astrophysics Center for Multimessenger studies in Europe

Gravitational waves, Cosmic rays, Neutrinos
VHE gamma-rays, X-rays, Optical, Radio



**Funded by
the European Union**

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or of the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them. The ACME project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101131928.

...Towards optimal Multi-Messenger Astronomy

From landmark discoveries to routine multi-messenger science

- **Coordinate globally**

Align observatories, scientific communities and ground- and space-based facilities.

- **Optimize observing strategies**

Prioritize targets, share resources and coordinate follow-up observations.

- **Enable real-time multi-messenger science**

Invest in low-latency alerts, interoperable data systems and shared infrastructure.

- **Maximize scientific return**

Strengthen theoretical modelling, joint data analyses and AI-driven methods.

- **Secure long-term capabilities**

Sustain space missions, next-generation observatories and dedicated expertise.

Multi-messenger astronomy will reach its full potential only through coordinated facilities, shared data and sustained investment.

Outlook

- The **origin of Galactic and extragalactic cosmic rays** remains an open question.
 - Need to identify the sources capable of accelerating hadrons to **multi-PeV energies**.
- **Gamma-ray** and **neutrino** observations are complementary.
 - A multi-messenger approach is essential to distinguish hadronic from leptonic scenarios and to overcome source confusion and absorption effects.
- **CTAO** and **KM3NeT** are **key and complementary instruments**.
 - CTAO**: unrivalled sensitivity and angular resolution in **gamma rays** to identify and characterise sources.
 - KM3NeT**: high sensitivity to **cosmic neutrinos** to confirm the hadronic origin and probe hidden sources.
- **Synergies** between **Gamma-ray** and **Neutrinos** will enable major advances.
 - Joint analyses, source correlations and coordinated observations are crucial to unveil the most powerful cosmic accelerators and explore new physics. [e.g. ACME]
- The **next decade** is really exciting.
 - Will we move from detecting high-energy particles to **identifying their cosmic origins**.



THANK YOU !

« Let's make great science together ! »