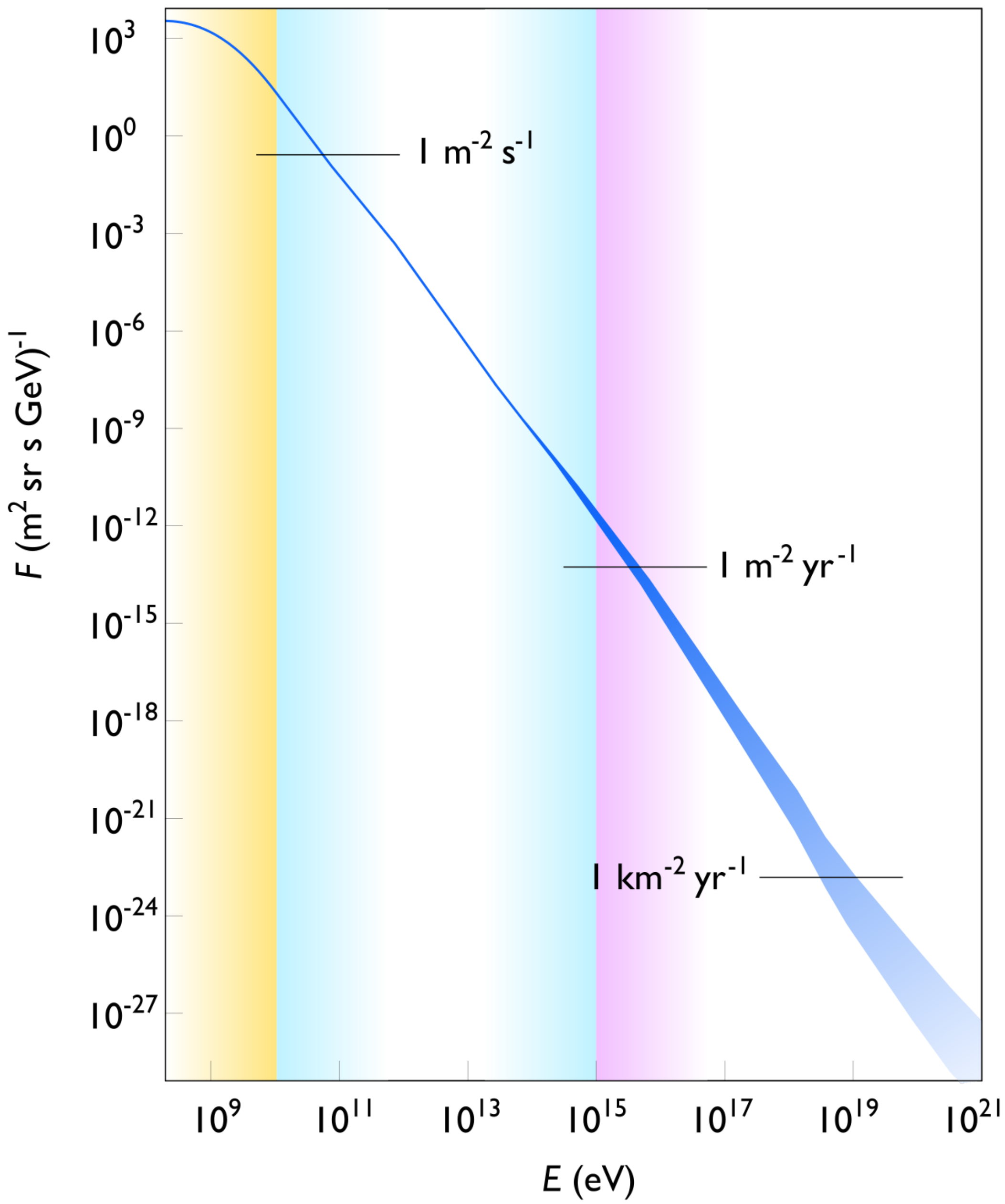
Neutrinos in 2020-2030

D. Dornic (CPPM)
On behalf KM3NeT France groups

Journée Prospectives IN2P3 - Nov. 2019

Why doing neutrino astronomy ?

Main question: what is the origin and the role of the cosmic rays in the Universe ?

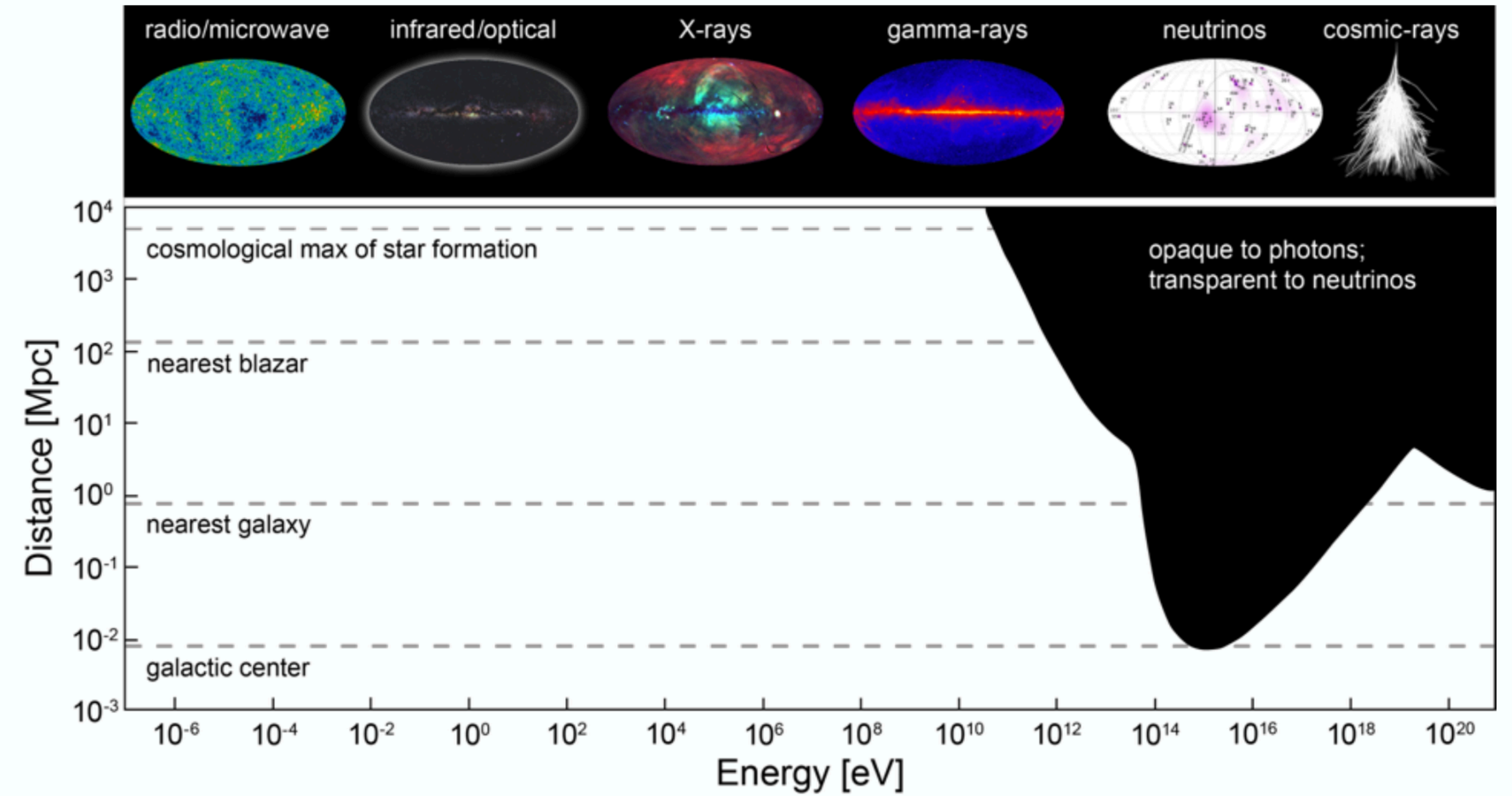


→ Discover ~100 years ago but still unknown origin
→ Spectrum coherent over 32 orders of magnitude, non equilibrium (constant CR injection)

→ Mysteries at the ultra high energies > 10^{20} eV, which acceleration mechanism ? Which sources ? Which cosmic evolution ?

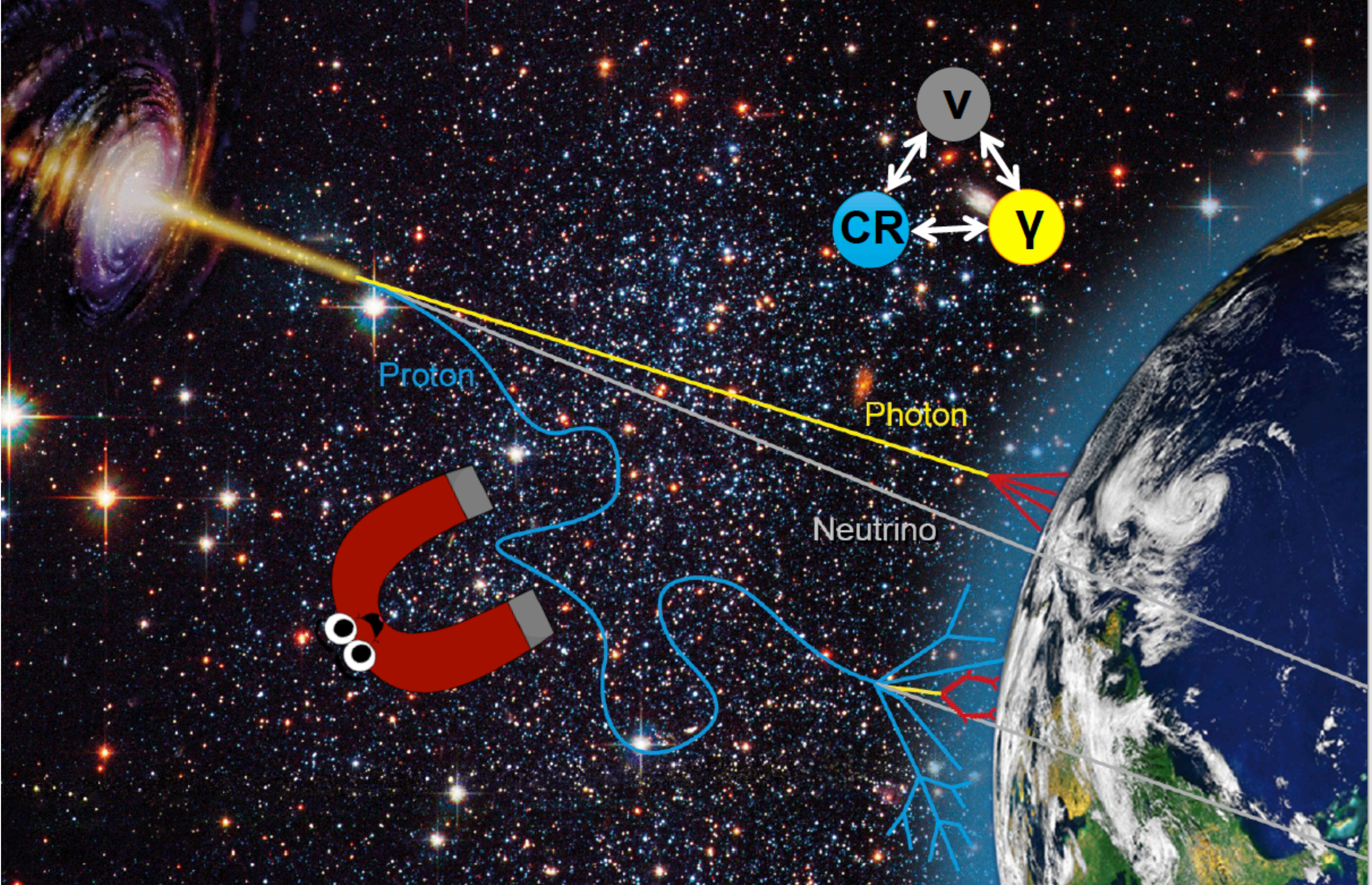
→ Interaction with the other messengers (ν, γ, GW)
→ At the heart of the non-thermal astronomy
→ Important roles in the Universe (ionisation, regulation of the star formation, astrochemistry, heating, turbulent magnetic field, galactic winds, Cosmic evolution of light elements Li, Be, B etc)
→ …

The promised land



The Universe is opaque to EM radiation for ¼ of the spectrum, i.e. above 10-100 TeV where IceCube sees cosmic neutrinos.

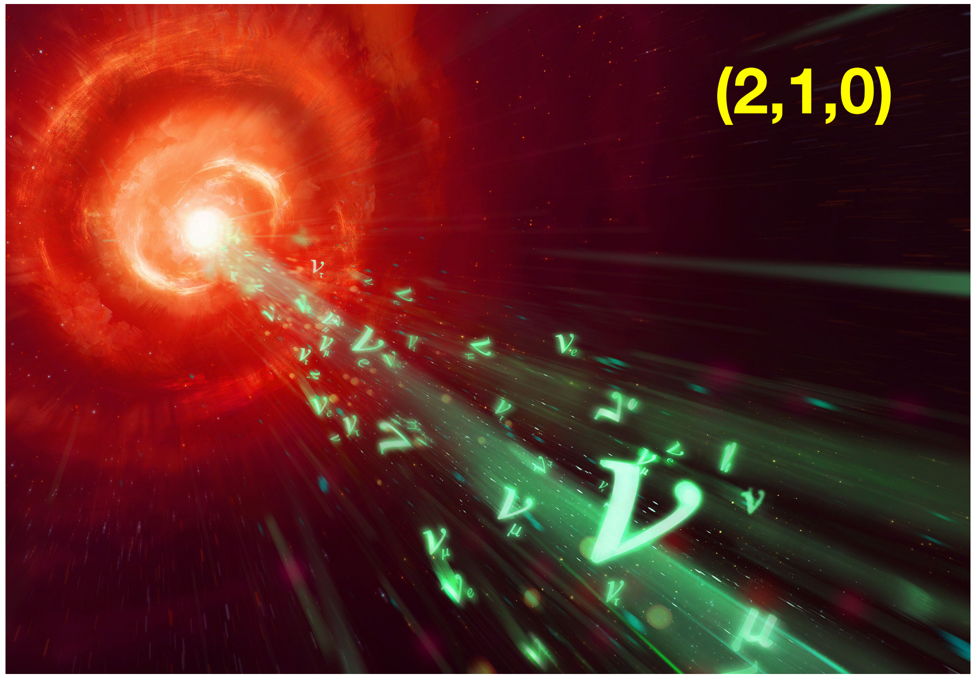
Multi-messenger context



Neutrino is the smoking gun of hadronic sources…

All-flavour neutrino detection

ν_e ν_μ ν_τ

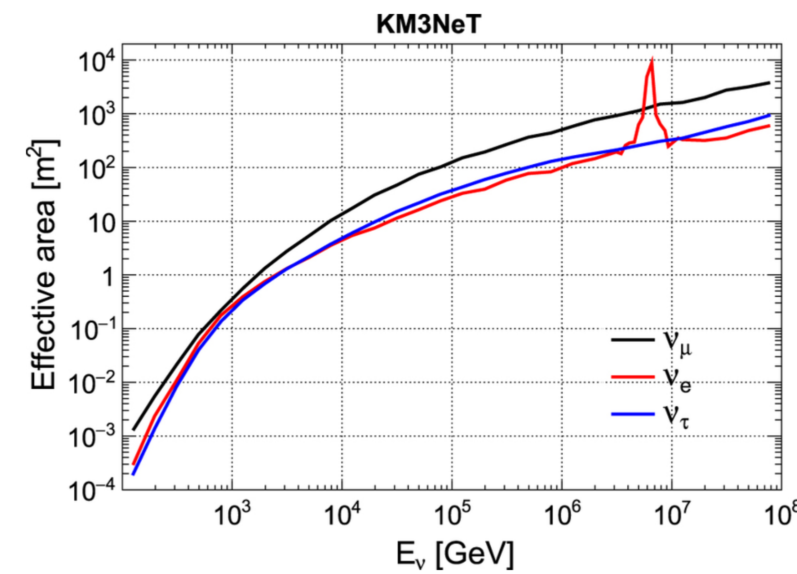


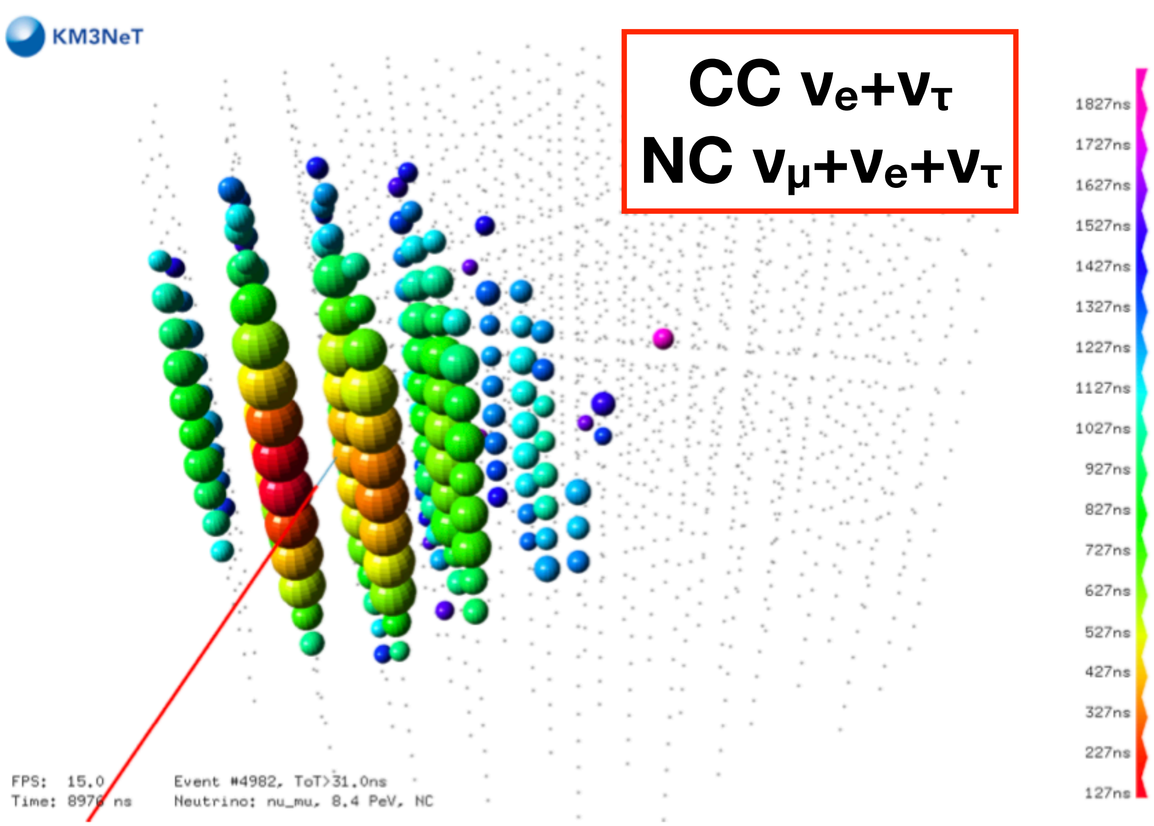
New physics ?

Oscillation

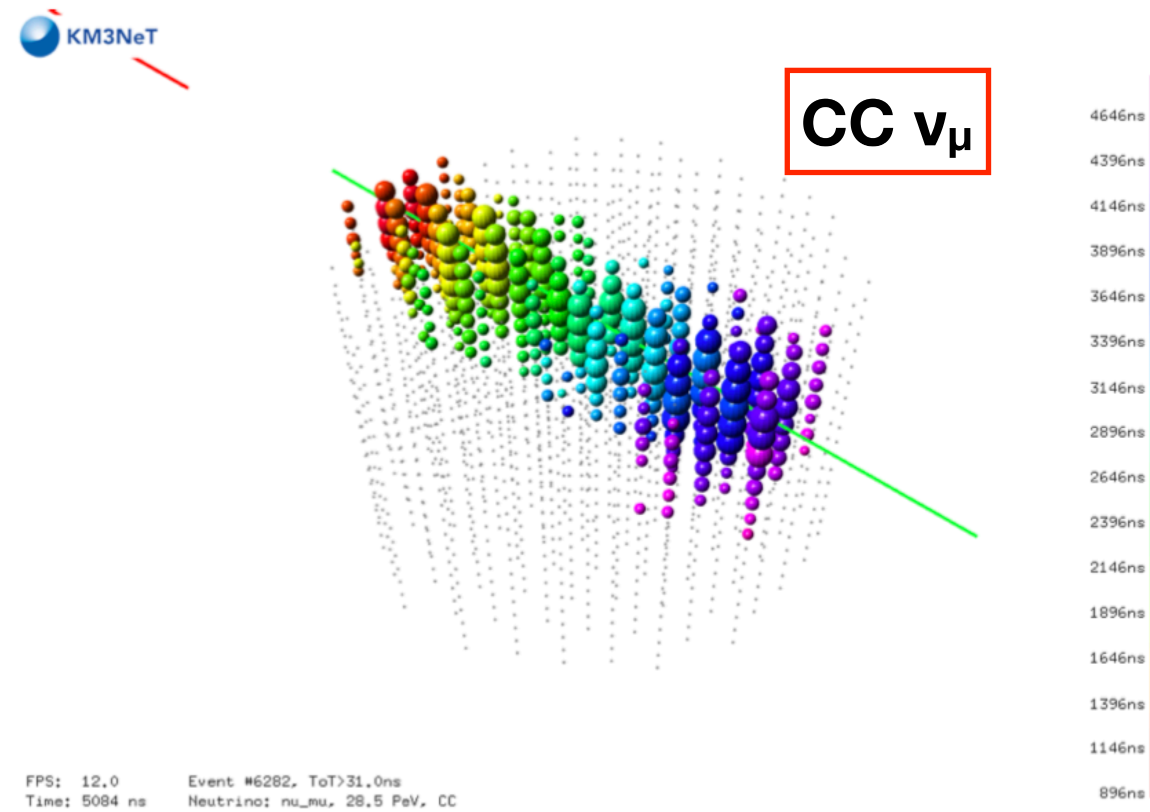
(1,1,1)

Each neutrino flavour brings information
$\Longrightarrow$ All-flavour astronomy



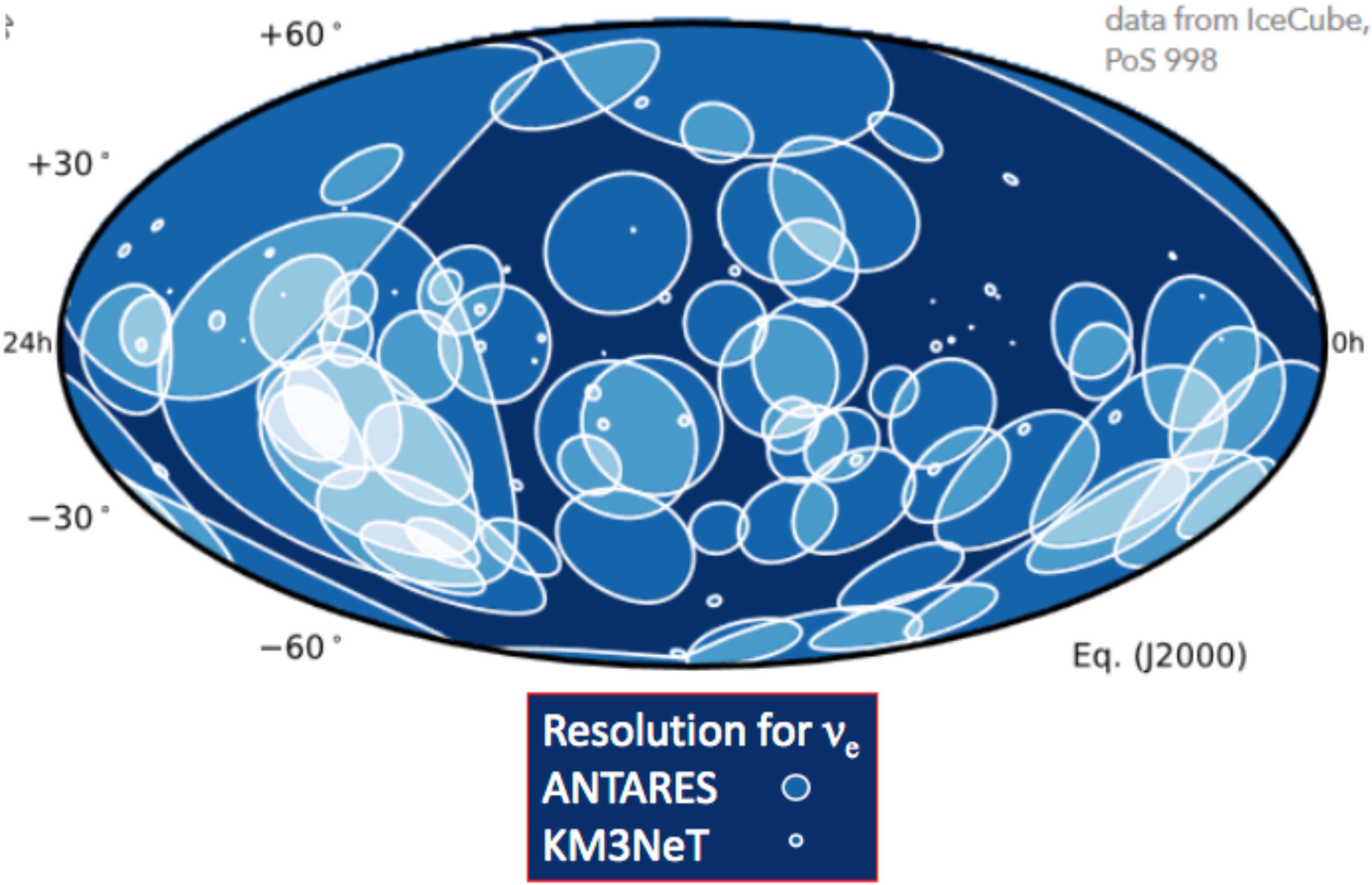


CC $\nu_e+\nu_\tau$
NC $\nu_\mu+\nu_e+\nu_\tau$

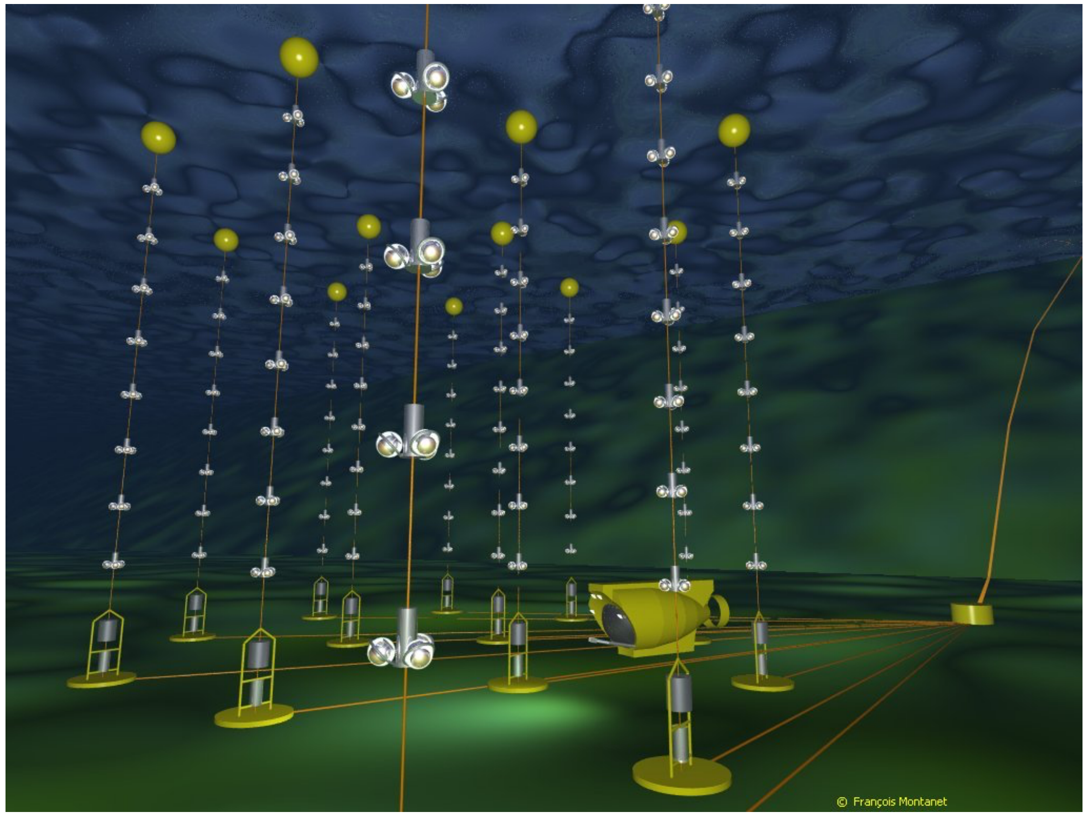


CC ν_μ

Neutrino sky



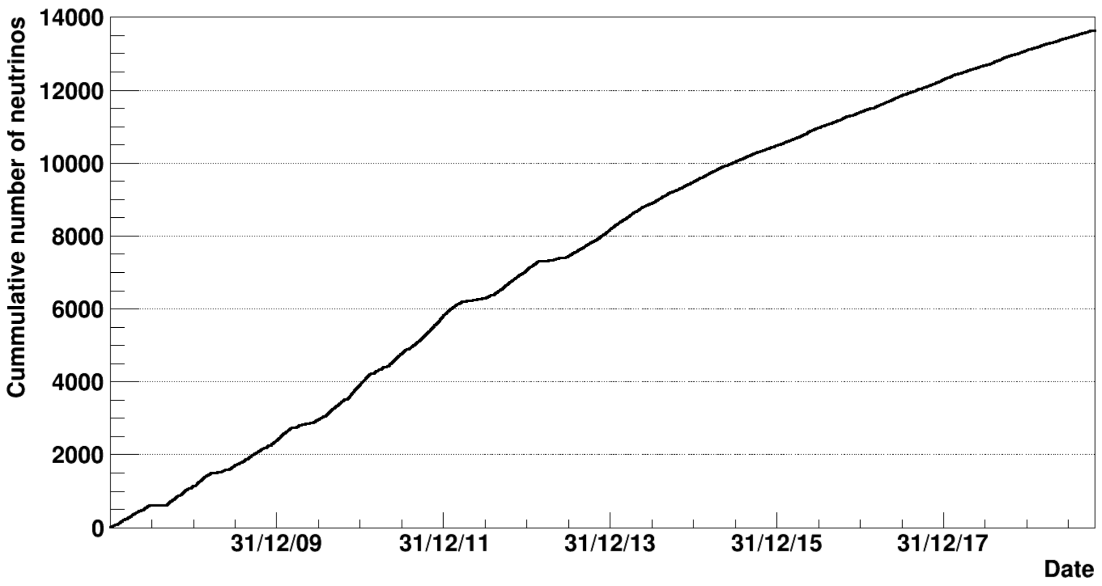
ANTARES: more than 5000 days of operation

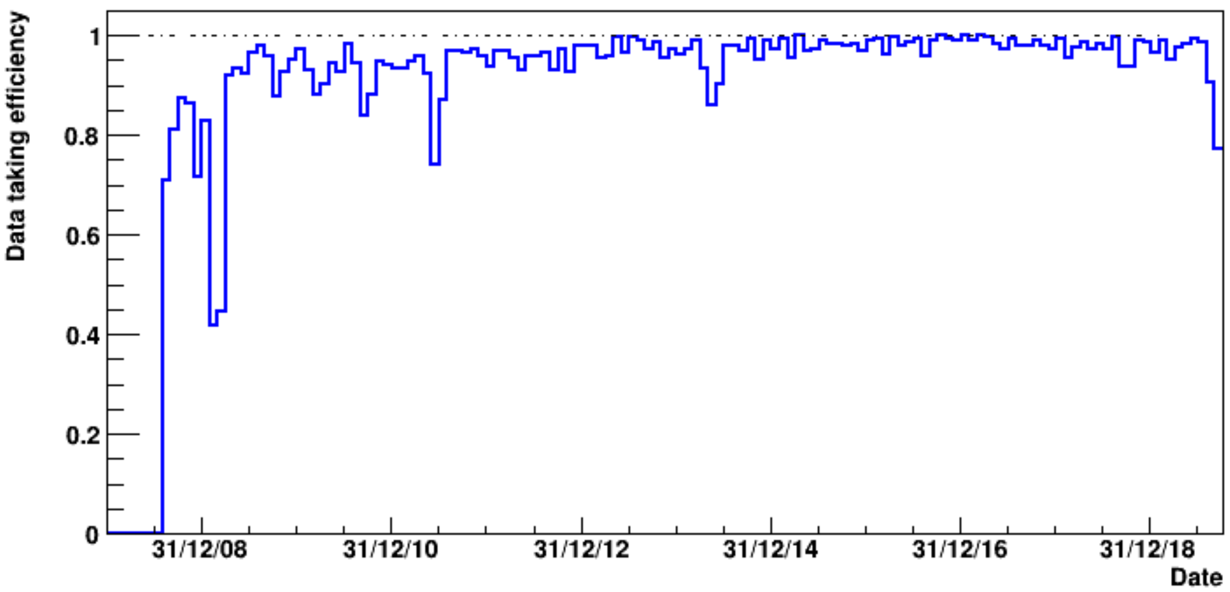


ANTARES has started doing physics in 2007.
with a probable dismantlement mid 2020.

⟹ We have demonstrated that we can operate such detector with a very high duty cycle (~96%)

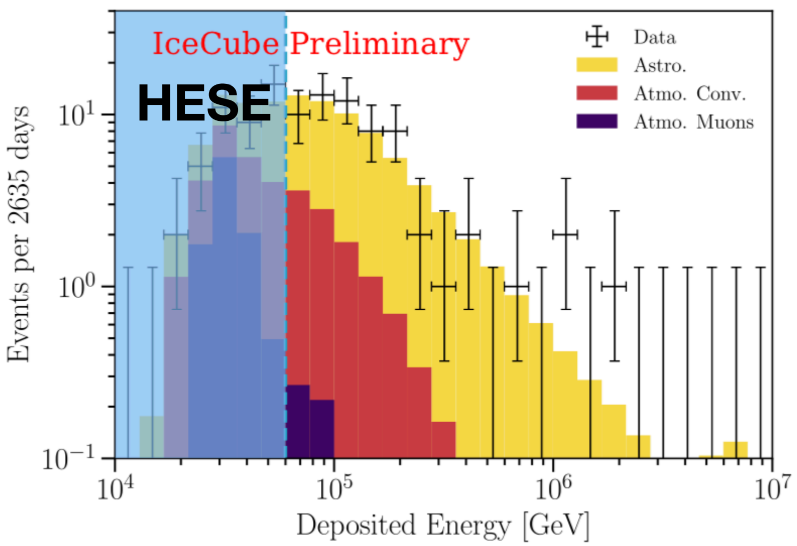
⟹ Very complete scientific programs, especially very wide multi-messenger analysis.

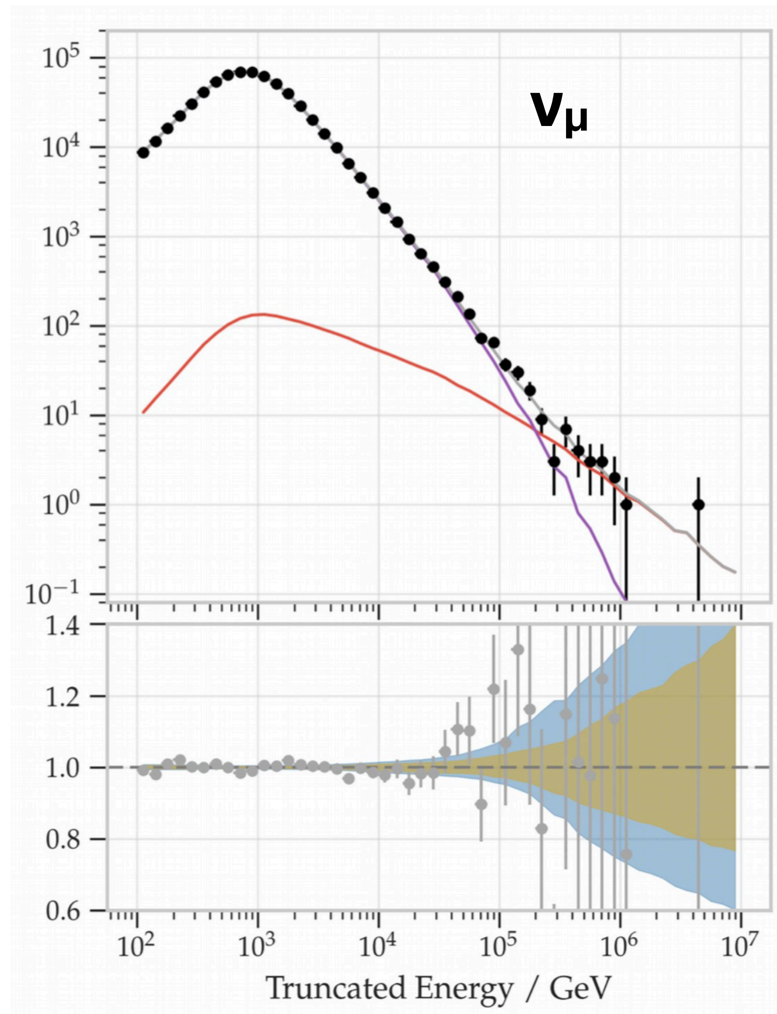


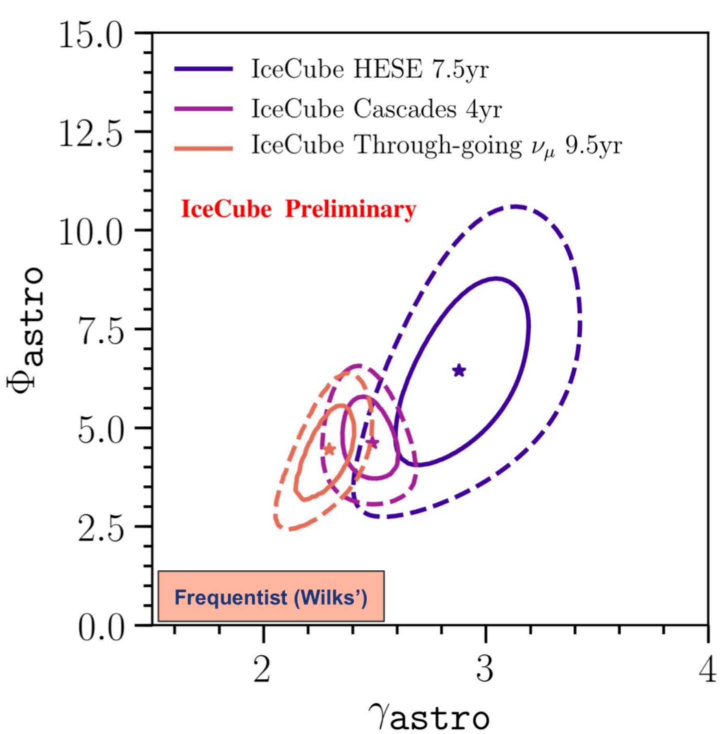


So far, HE ν diffuse fluxes detected

IceCube 7-10 yrs

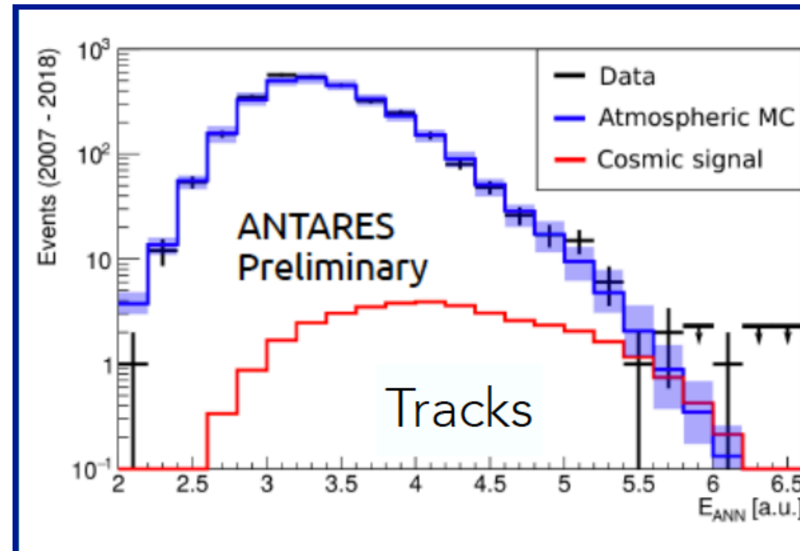


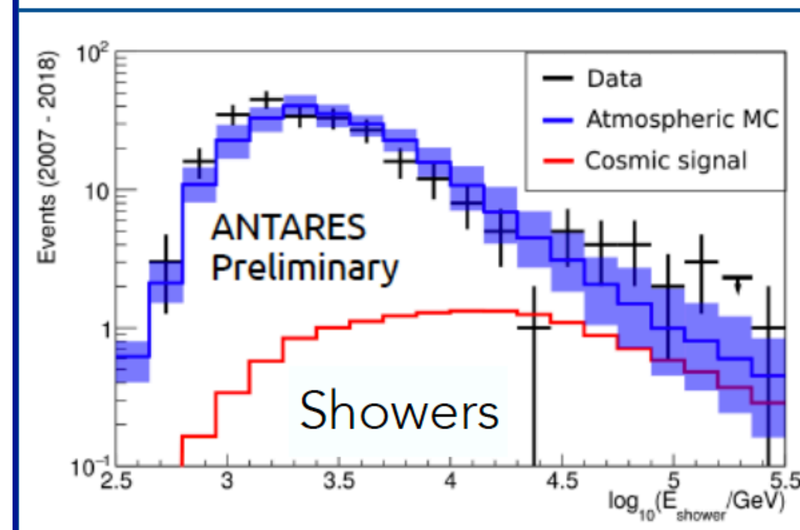


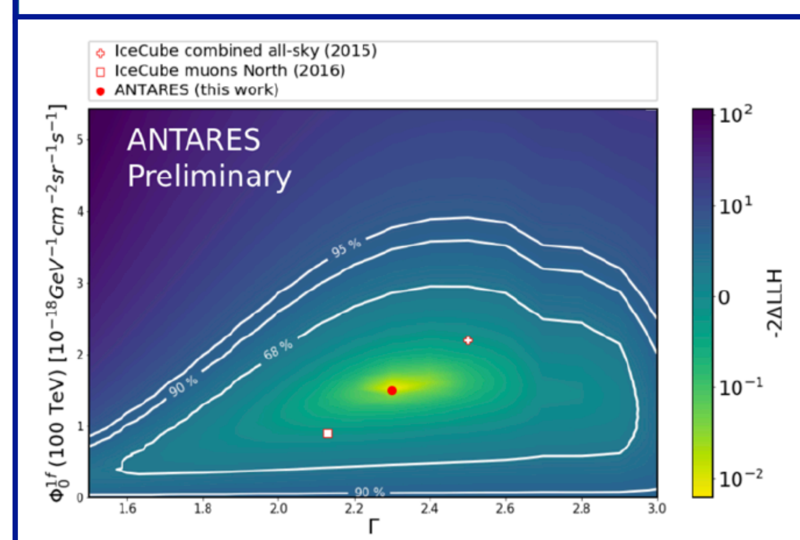


Name	Approx. Neutrino Energy	Direction	Dominant Flavor	Unbroken Spectral Index
HESE	50 TeV - 5 PeV	All-sky	e, μ, τ	2.89
Cascades	5 TeV - 5 Pev	All-sky	e, τ	2.48
NuMu	50 TeV - 10 PeV	Northern sky	μ	2.28

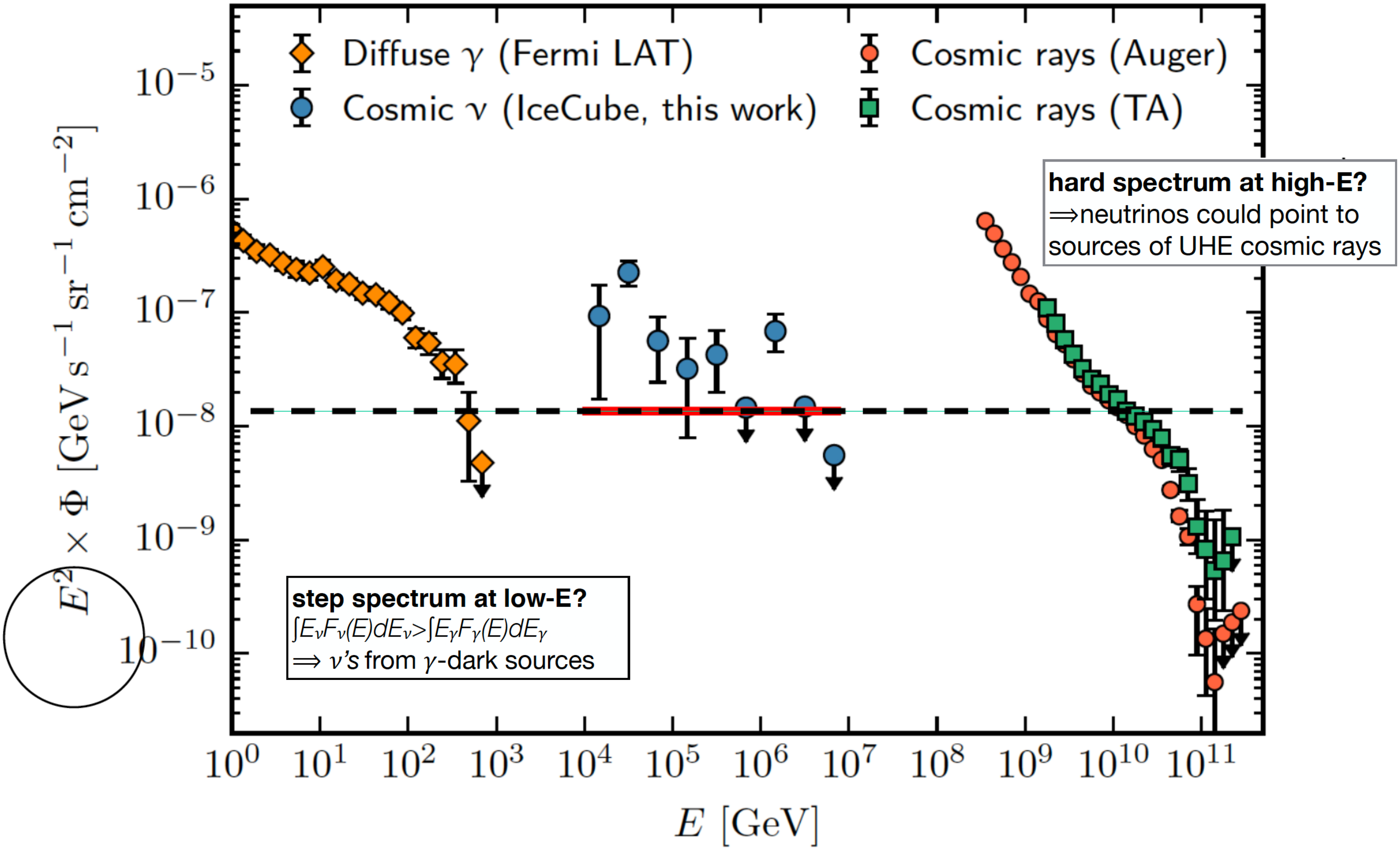
ANTARES 11 yrs







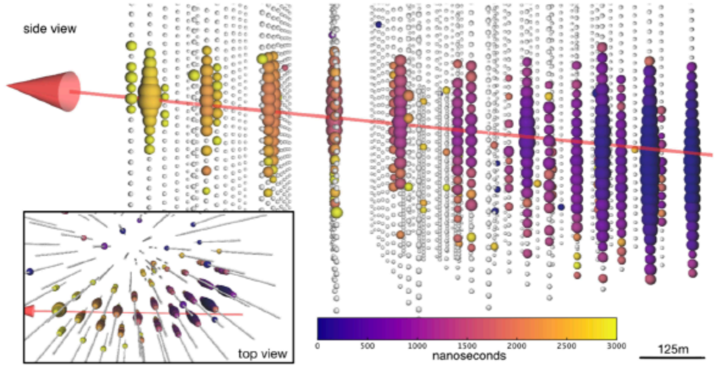
Multi-messenger context



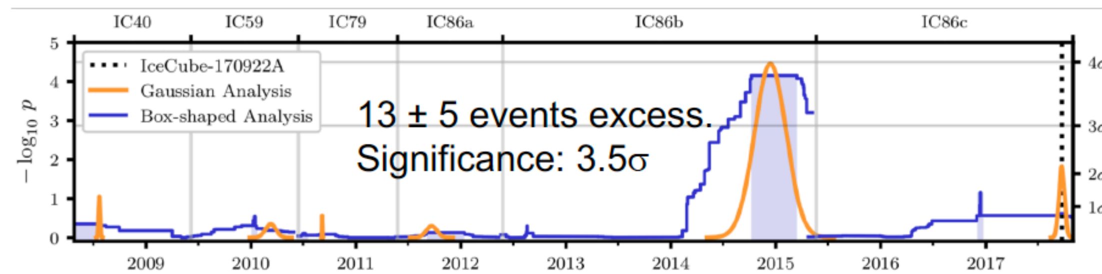
So far, may be 1 identified source

Neutrinos from the AGN blazar TXS 0506+056

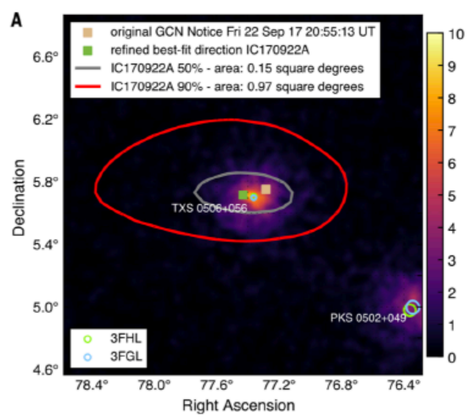
Sept. 22, 2017:
A neutrino in coincidence with a blazar flare



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



Science 361 (2018) no. 6398, eaat2890

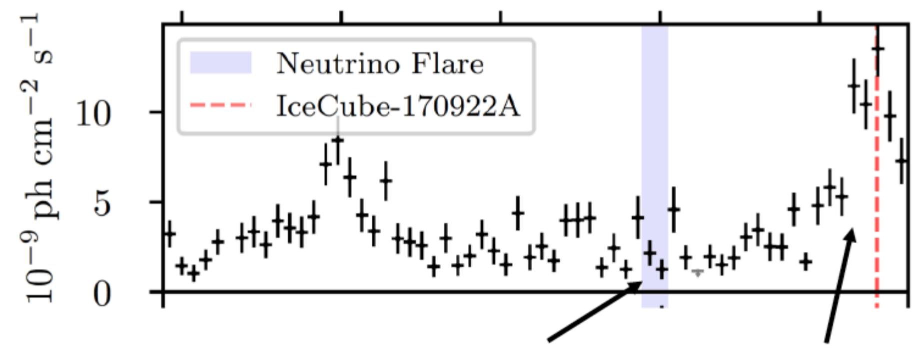


Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

Science 361 (2018) no. 6398, eaat1378

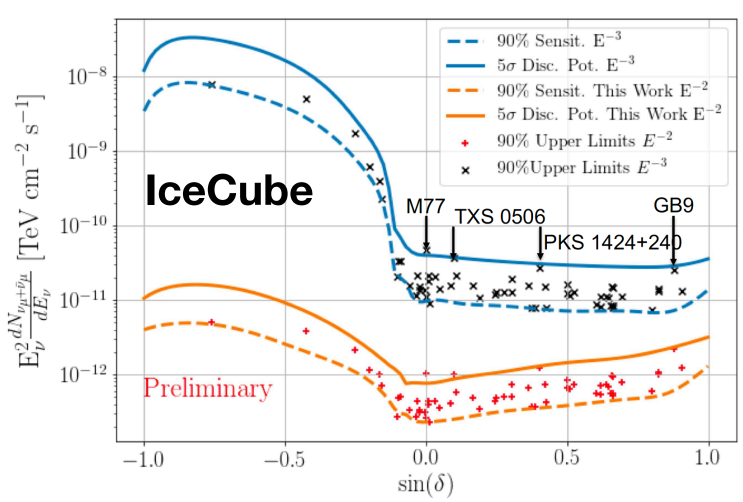
Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192

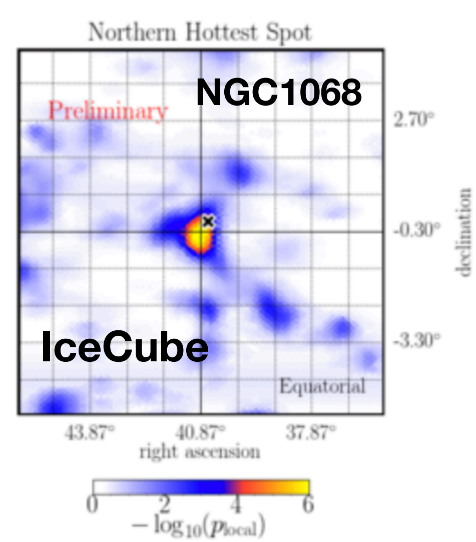


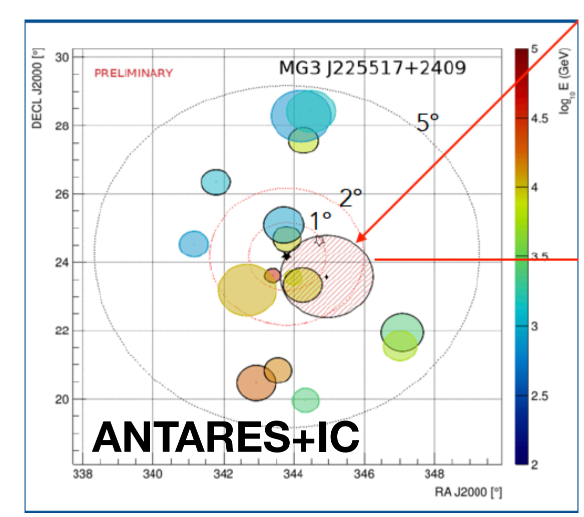
At 2014-15 neutrino flare   The 2017 flare

DESY. | ICRC 2019 | Winter Walter, July 25, 2019, Madison, USA   Page 2

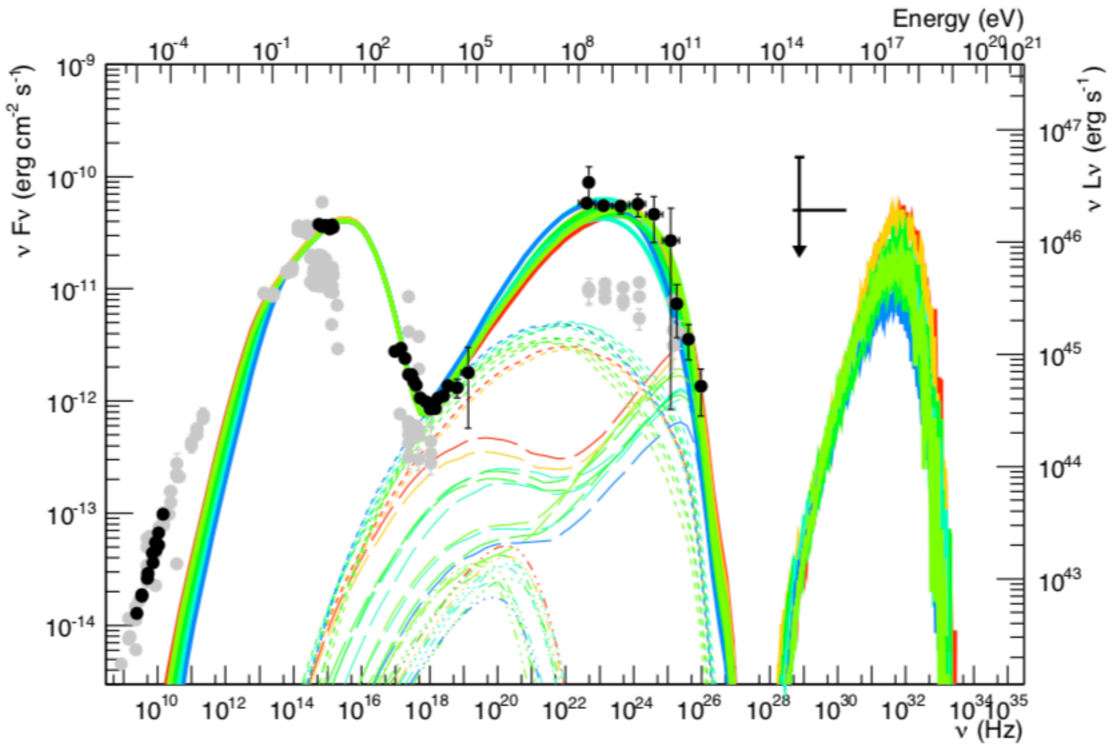
Few additional hints in the most recent dataset:



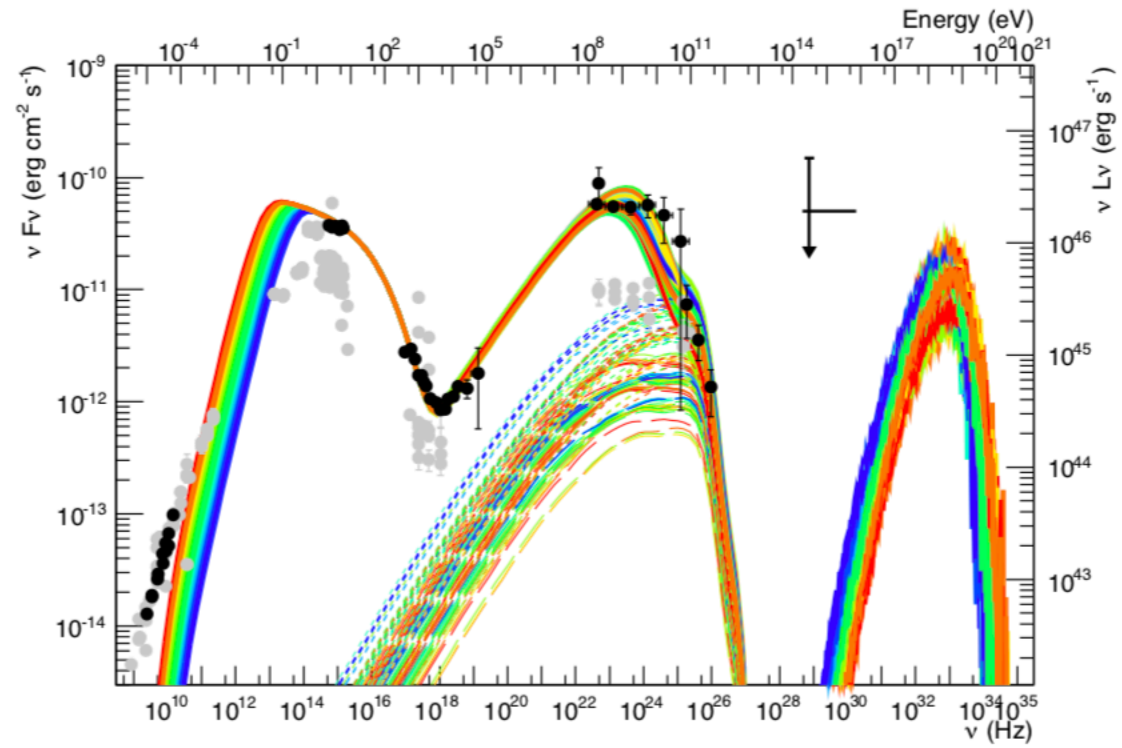




Difficult modélisation of TXS 0506+056

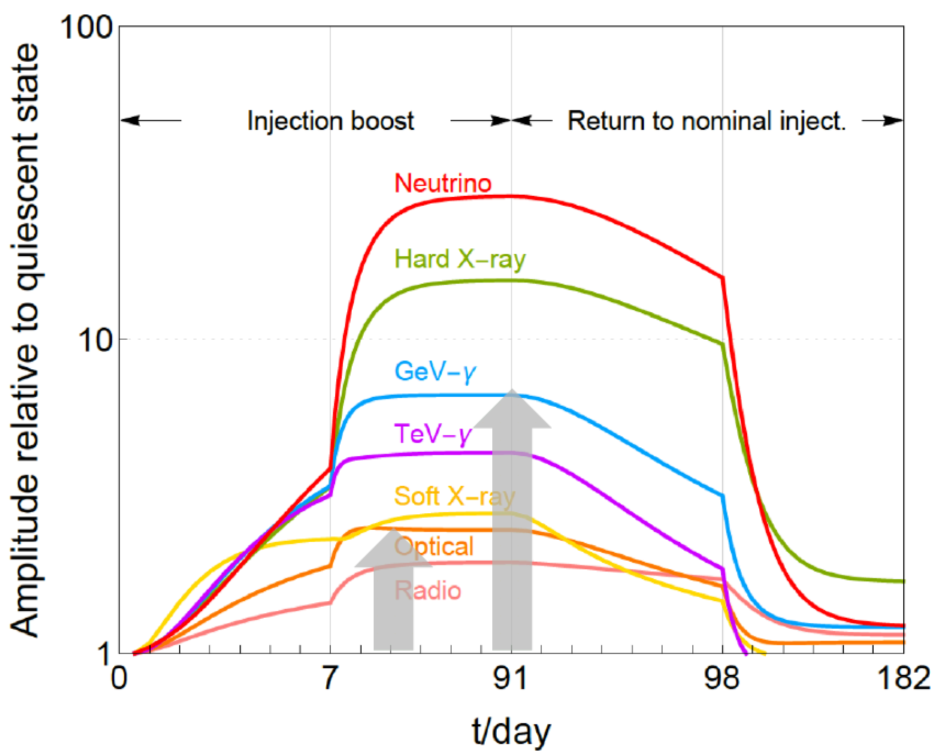


(b) Lepto-hadronic modeling of TXS 0506+056



(a) Proton synchrotron modeling of TXS 0506+056

(Cerruti et al, 2018)



(Winter et al, 2018)

- **Simple 1-zone models are not working properly**
- **More sophisticated multi-zone models on the market to satisfy the energetic problem: interaction with external field (Sikora 2016), jet-cloud interaction (Liu 2018), formation of a compact core (Gao 2019)…**

$\Longrightarrow$ Simultaneous X-ray data are extremely important for the modeling, even more important than the very high energy

Still a lot to do for HE neutrino astrophysics

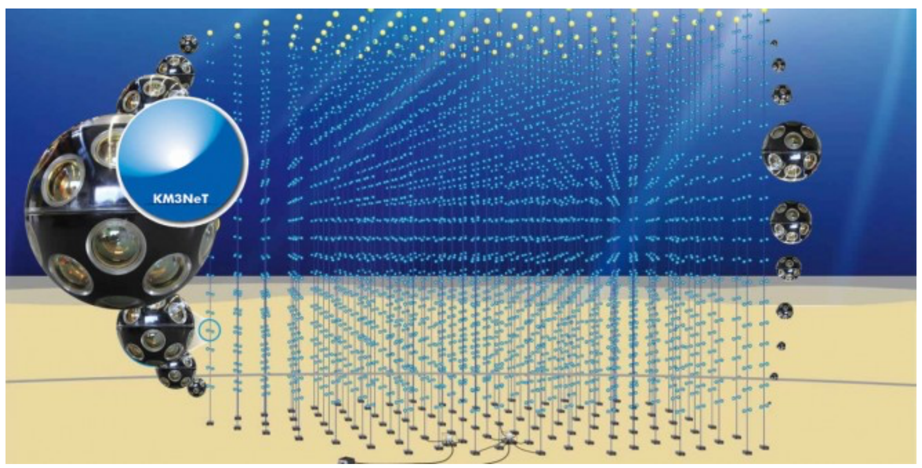
- **Identify the high-energy astrophysical neutrinos**
- **Identify the sources of the highest energy cosmic rays**
- **Where are the PeVatrons ?**
- **Constrain the production mechanisms of high-energy cosmic particles**
- **Obtain a unique multi-messenger view into the explosion of stars and the evolution of stellar remnants**
- **Explore active galaxies and the very high-energy Universe when it was most active**
- **Study of galactic and extra galactic propagation of CR with neutrinos as tracers**
- **Test nuclear, neutrino and BSM physics**

Present HE ν detectors

Precision Frontier

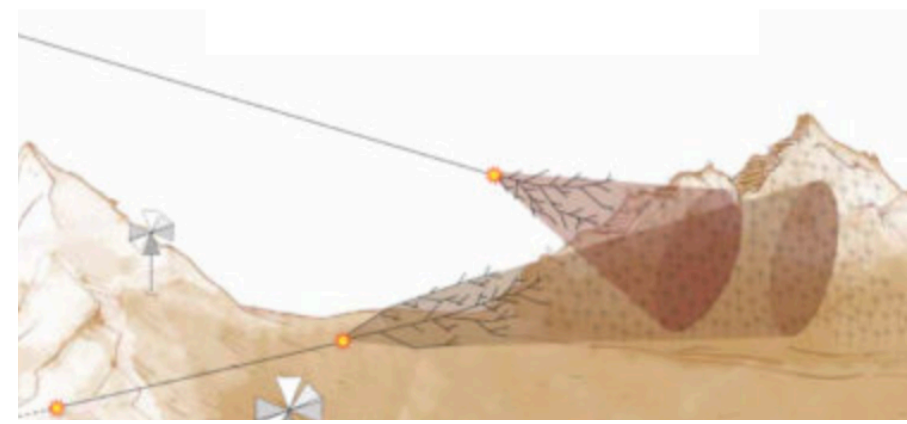
Intensity Frontier

Energy Frontier



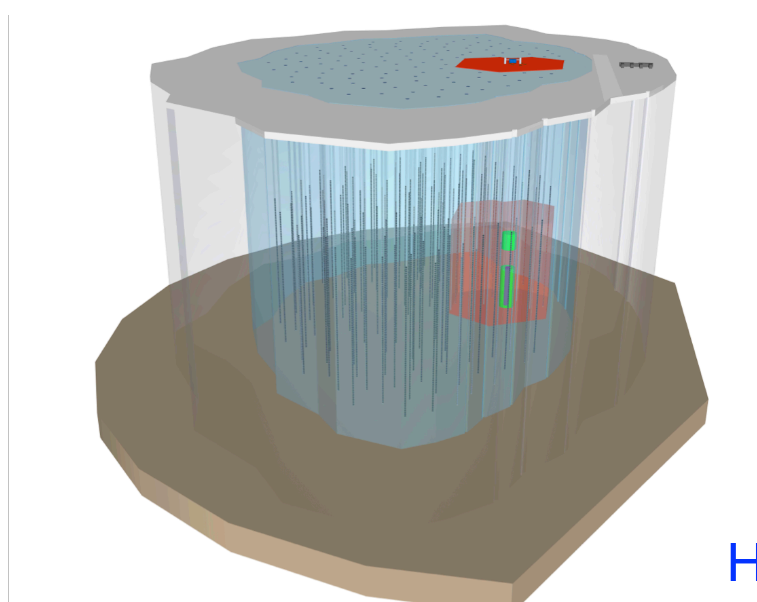
KM3NeT, GVD

Having the best angular resolution with a reasonable instrumented volume



GRAND, ARA, ARIANNA, POEMMA

Tracking cosmogenic ν at UHE



IceCube Gen2

Having the largest statistics with reasonable precision

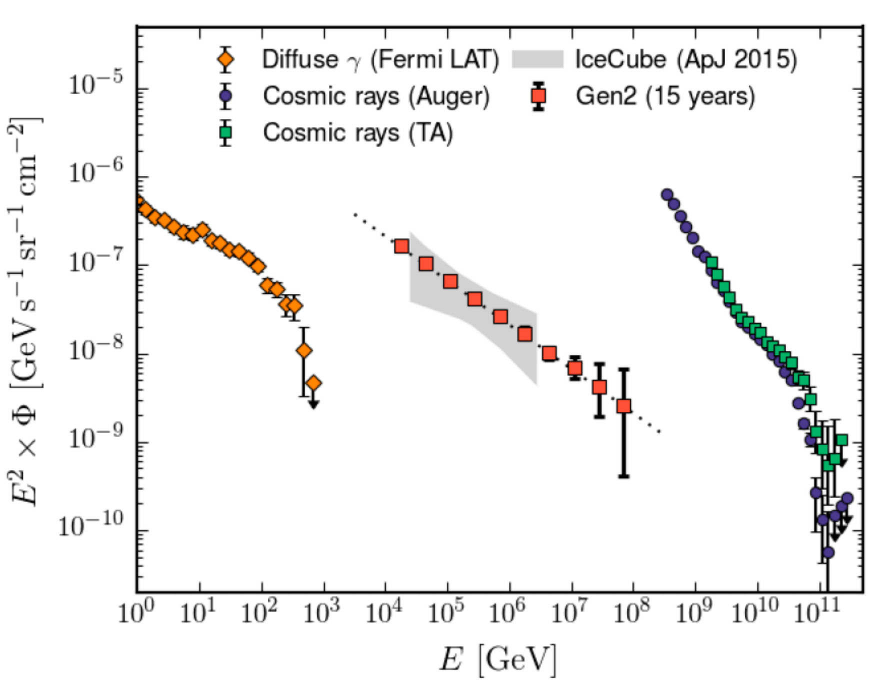
Sciences with the future generation

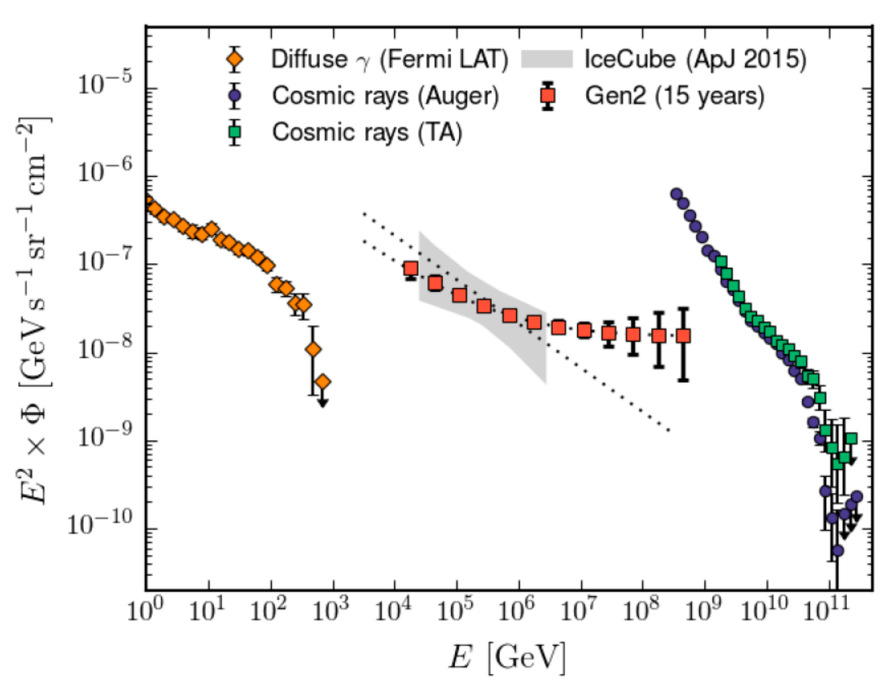
Astronomy with the future generation neutrino detectors:

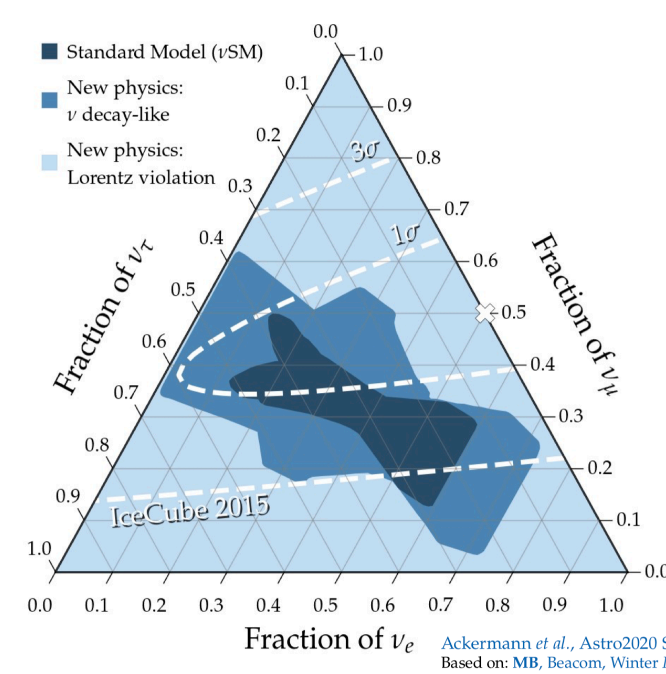
- Identify the **sources** responsible for high energy neutrinos diffuse flux
- Measure features in the **diffuse** spectrum and extend it to higher energy → connection **UHECR** ?
- Neutrino **flavour ratio** and its indication of the source properties
- **Cosmogenic** neutrinos

- **Also**:

Hadronic interaction models, cosmic-ray composition, charm production, exotic searches, PeV photons, high PT muons, elasticity and cross-section measurements …







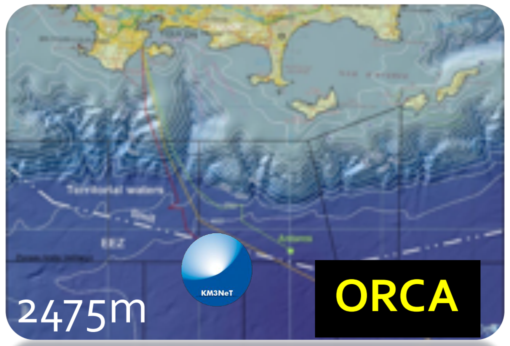
Ackermann *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

KM3NeT

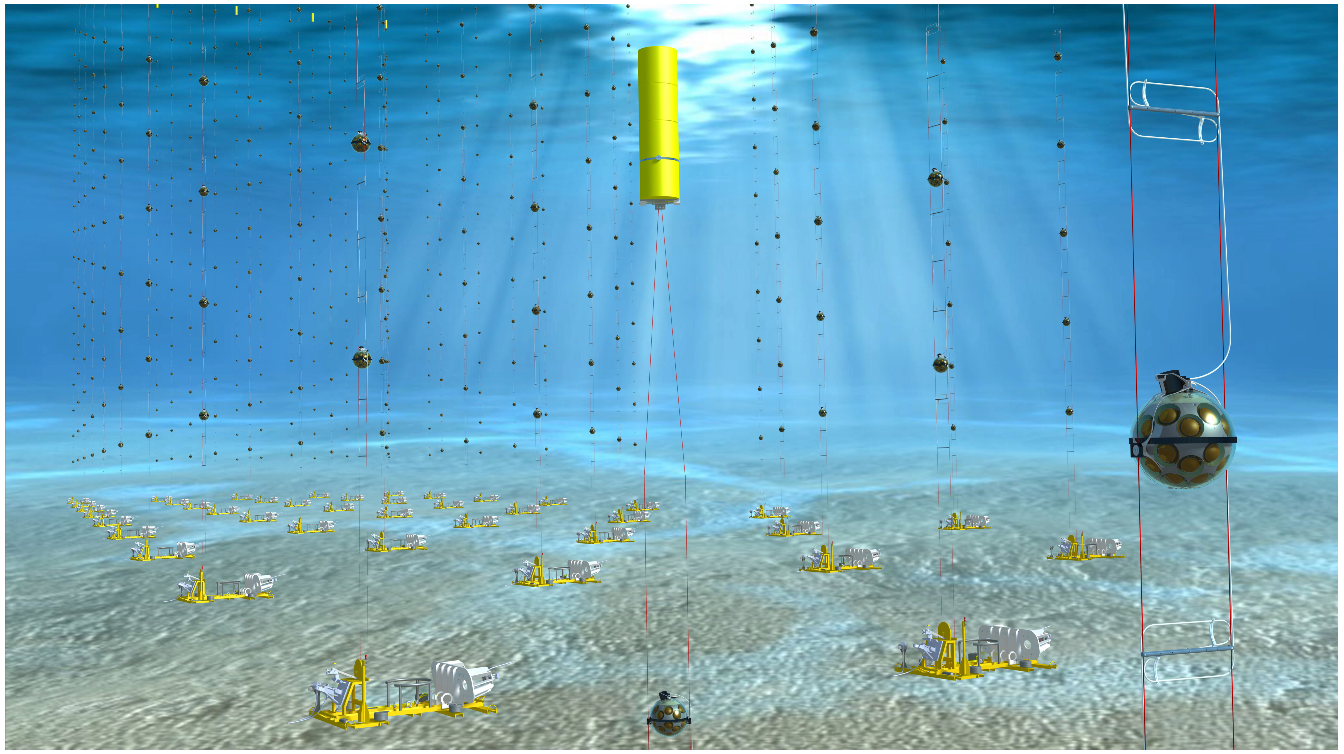
KM3NeT is the neutrino research infrastructure in the deep Mediterranean Sea

Oscillation Research with Cosmics In the Abyss

ORCA: off shore Toulon, France



115 lines of 18 DOMs (L~20m, H~9m)



Astroparticle Research with Cosmics In the Abyss

ARCA: off shore Capo Passero, Italy

230 lines of 18 DOMs (L~90m, H~36m)

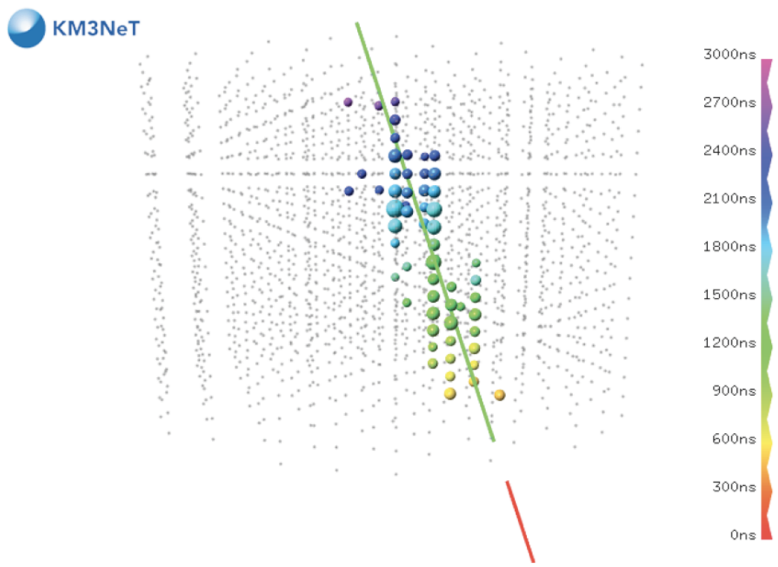
Main characteristics:

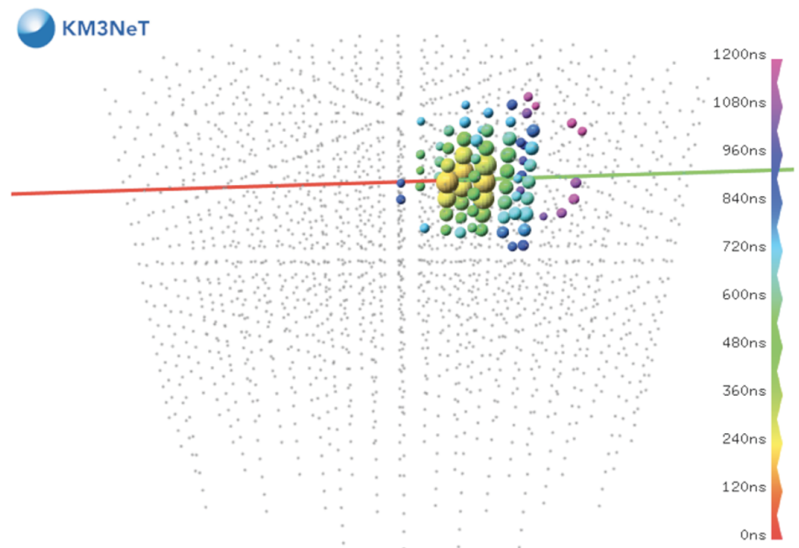
- Extended energy range: 10 MeV → >10 PeV
- Full sky coverage with the best sensitivity for the galactic sources
- High duty cycle (> 90-95%)
- All-flavour neutrino detection
- Best angular resolutions

⟹ Construction on-going: 6 (1) DU working in ORCA (ARCA) +300 DOMs builded

⟹ By end 2020, better sensitivities than ANTARES in the whole energy range. Current plan, finish the construction of ORCA (2024) and ARCA (2026)
+ Phase 3: 1 detector in Greece, + other sites in discussion.

KM3NeT





Tracks:

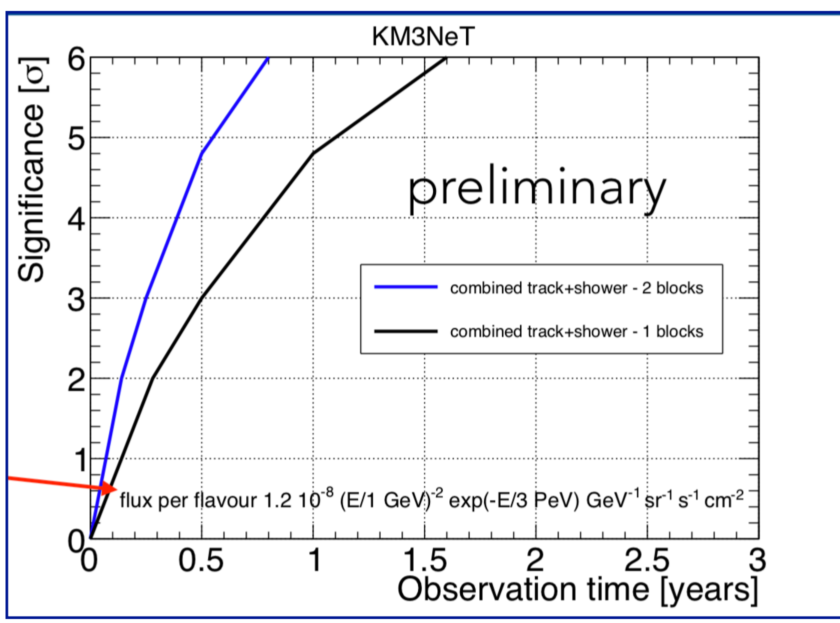
ARCA: < 0.1° (>100 TeV)

ORCA: 1 - 2° (100 GeV - 1 TeV)

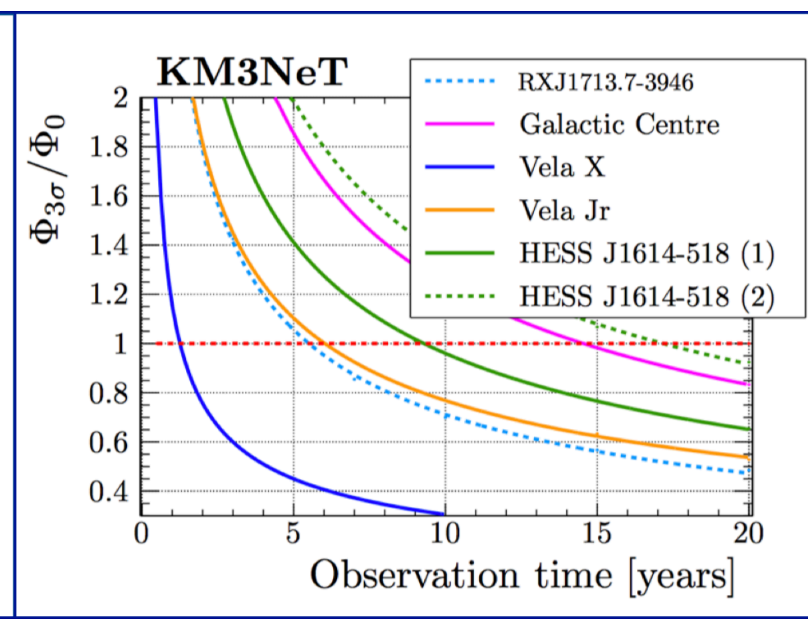
Cascades:

ARCA: < 1.5° (>100 TeV)

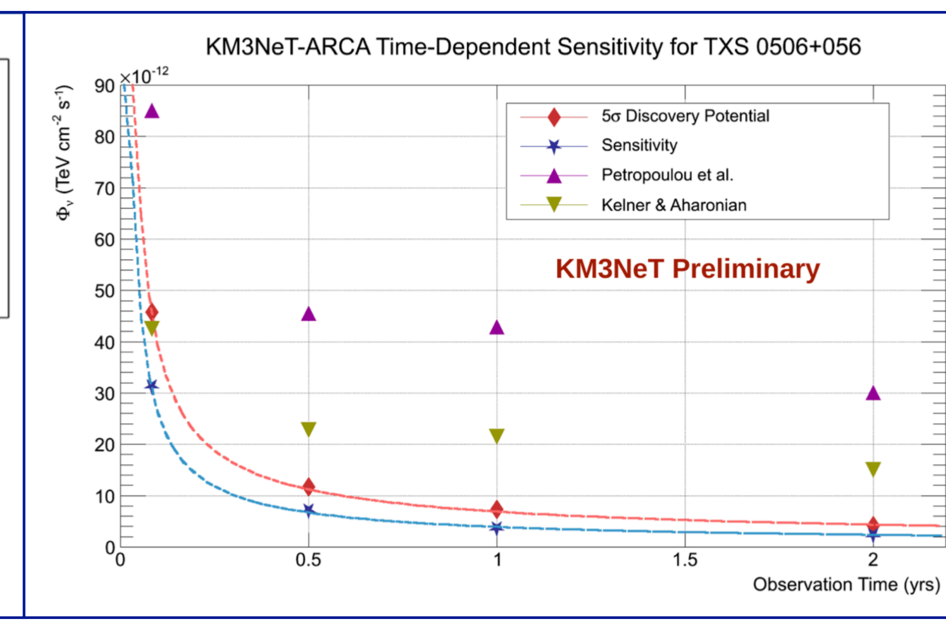
ORCA: ~4 - 5° (100 GeV - 1 TeV)



Diffuse ν flux



Galactic sources

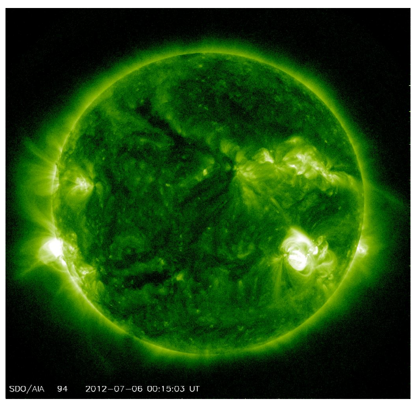


Extragalactic sources

At low energy, KM3NeT can do astronomy

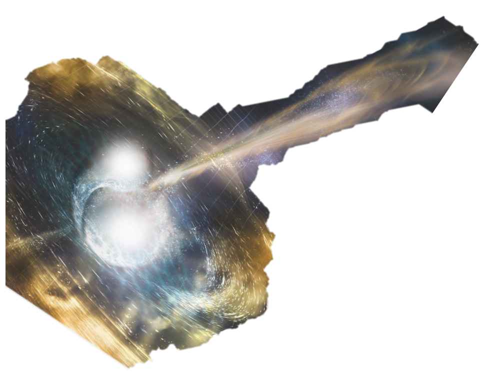
<u>Core-collapse supernova</u>: (see MAB's talk)

- MeV neutrino detection via IBD
- Sensitivity for the next galactic CCSN detection
- Large number of expected neutrinos: detailed study of the LC + T0 estimation
- Offline and online analyses ready and running



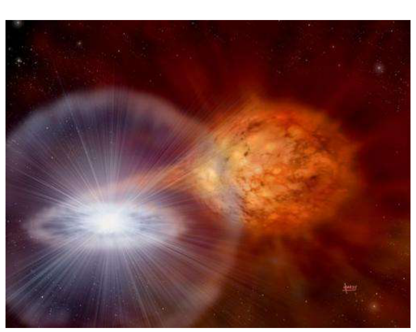
<u>Solar flare neutrinos</u>: up to 5 GeV neutrinos

- Produced by proton accelerated towards the solar atmosphere via magnetic reconnection
- Constraints on hadronic acceleration in solar flares (e.g., upper cutoff of the proton spectrum)
- Complementary to gamma rays and solar energetic particles



<u>Gamma Ray Bursts</u>: 1–100 GeV neutrinos

- Emitted below the photosphere after proton-neutron decoupling or in dense environment
- Potentially precursor to the EM signal
- Searches based on EM and/or GW detection



<u>Many other transients</u>: MeV-GeV range?

- Fast Radio bursts
- Novae
- Unknown transients based on LE neutrino monitoring

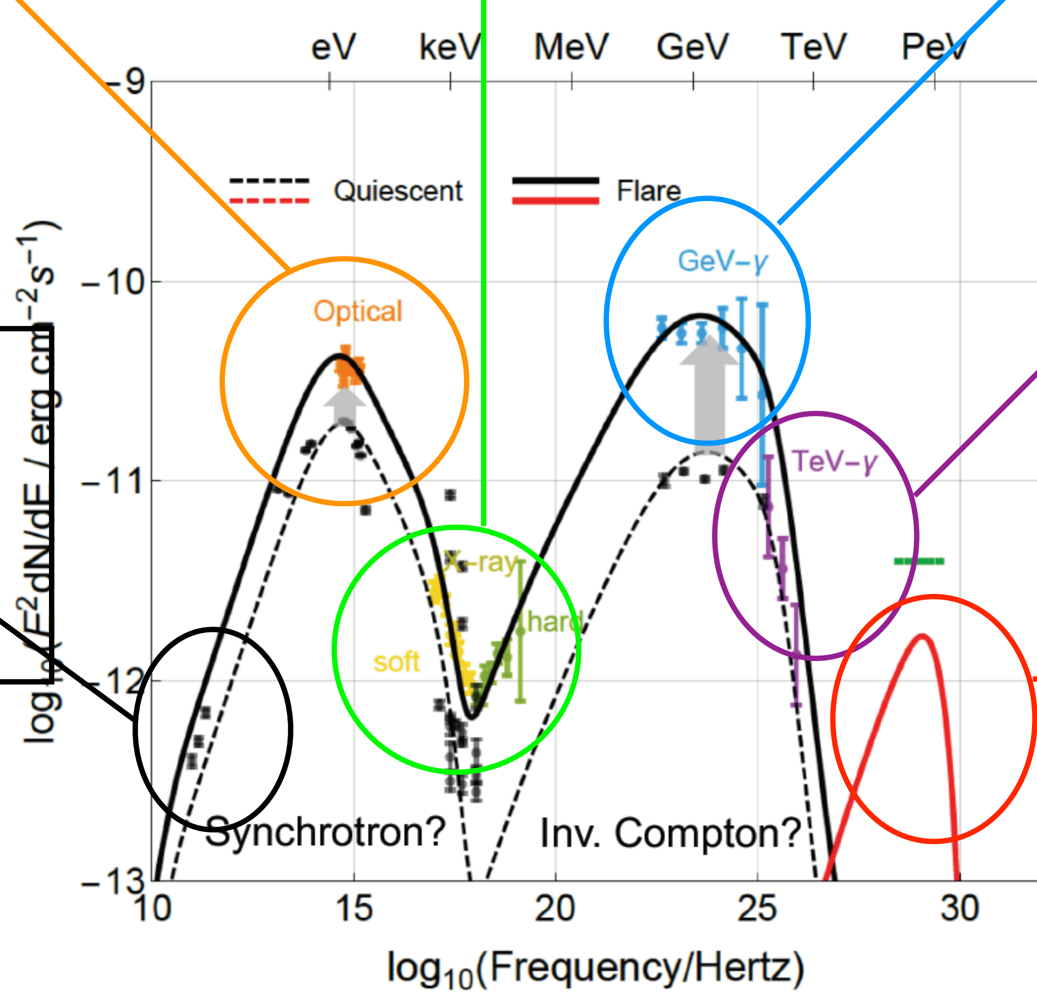
Multi-messenger synergies

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

X-ray telescopes: Swift, INTEGRAL, SVOM, THESEUS, ATHENA…
- Very clean sky
- Provide transient triggers (GRB, AGN, Novae…)
- ToO program (not so easy access)

γ-ray telescopes: Fermi-LAT
- All-sky complete monitoring
- Provide transient triggers (GRB, AGN…)

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



VHE γ-ray telescopes: HESS, MAGIC, CTA…
- Most natural common science case
- Follow-up (not easy access)

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

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

+ link with LIGO/VIRGO
+ SK, SNEWS

Summary

In 2030s, 3 major high-energy neutrino telescopes should run with full sensitivities:

- **KM3NeT in the Mediterranean Sea with the best angular precision**
- **IceCube Gen2 in the South Pole with the highest statistics**
- **GVD in the Lake Baikal**

+ Several UHE neutrino experiments (ARA, ARIANNA, GRAND…)

With all these facilities, we want to identify the population sources of HE neutrinos, pinpoint the sources of the UHECR and identify the main CR production and acceleration mechanisms occurring in these sources.

The multi-messenger approach is the key of success to reach this goal, combining in real-time MWL information with neutrino, CR and GW data. The synergies with EM telescopes are essential to be organized and facilitated.