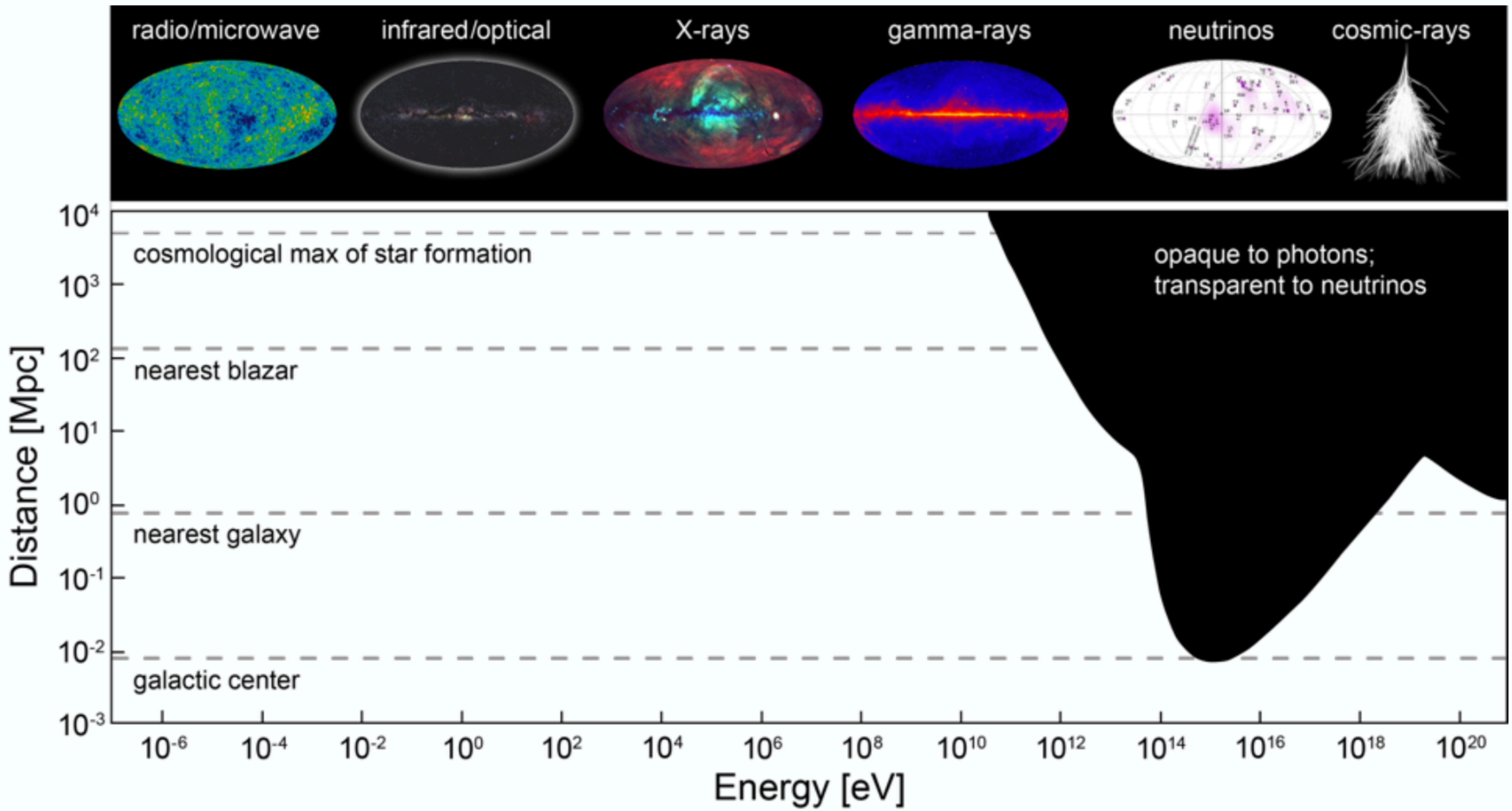
Neutrinos in 2030s

D. Dornic (CPPM)

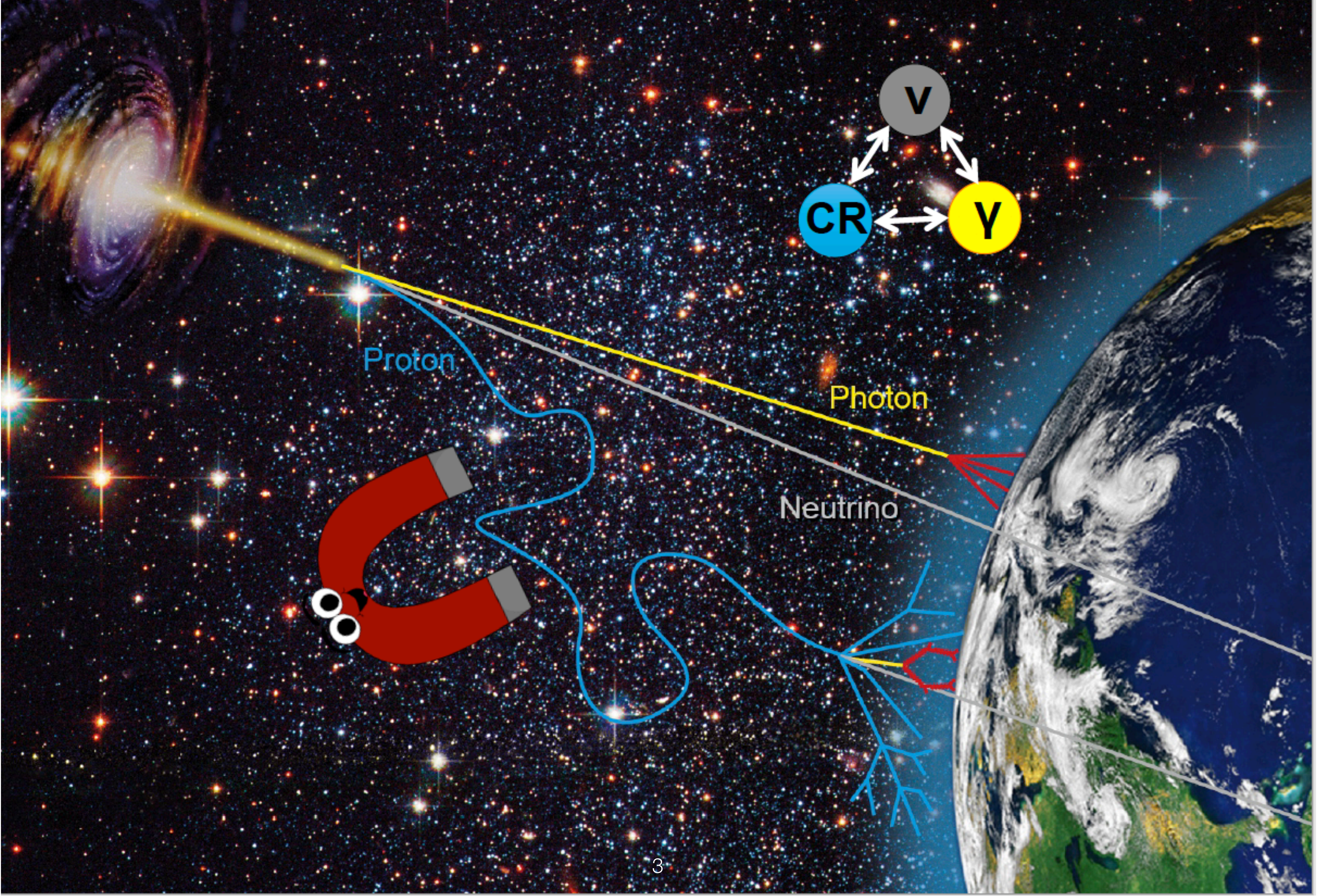
Journée THESEUS France - Sept. 2019

The promise land



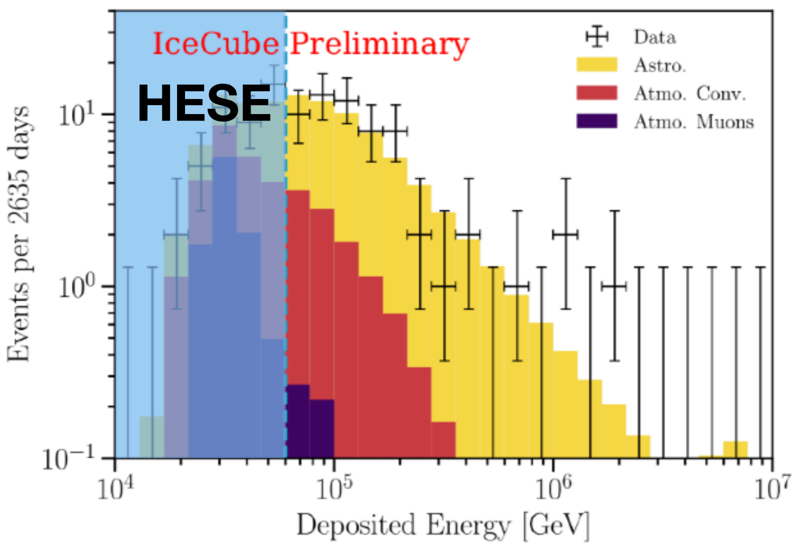
The Universe is opaque to EM radiation for ¼ of the spectrum,
i.e. above 10-100 TeV where IceCube sees cosmic neutrinos.

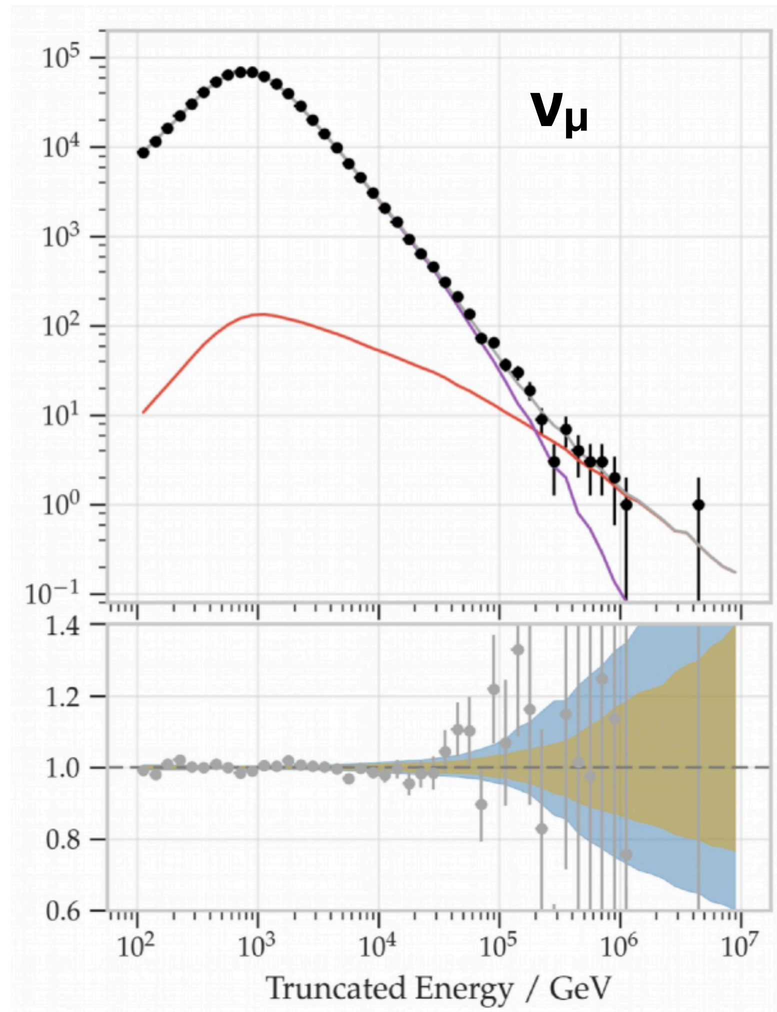
Multi-messenger context

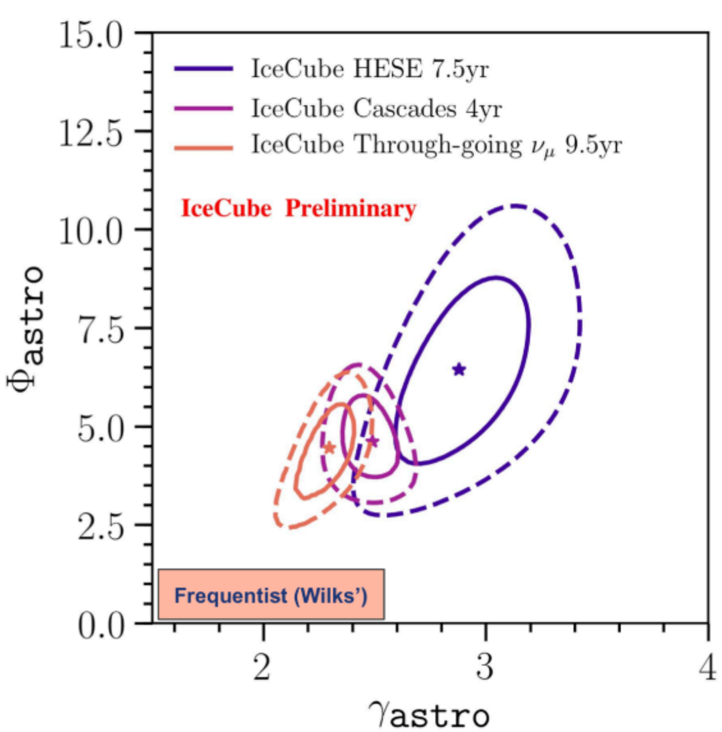


So far, HE ν diffuse fluxes detected

IceCube 7-10 yrs

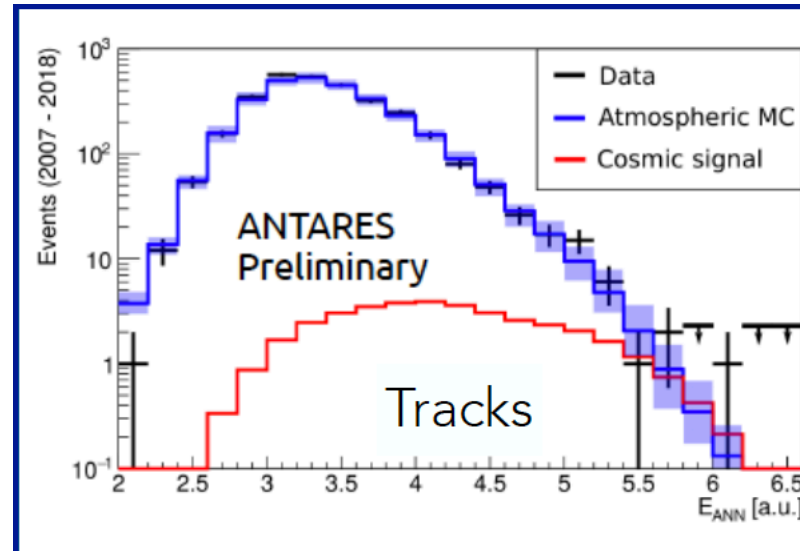


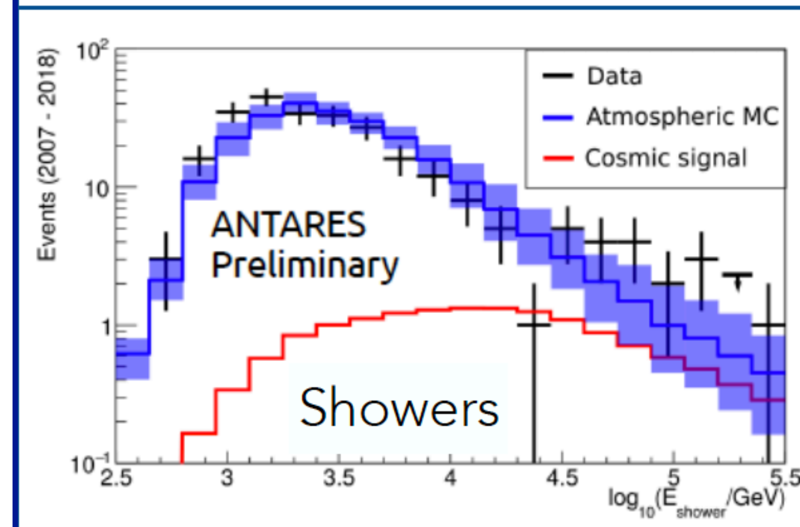


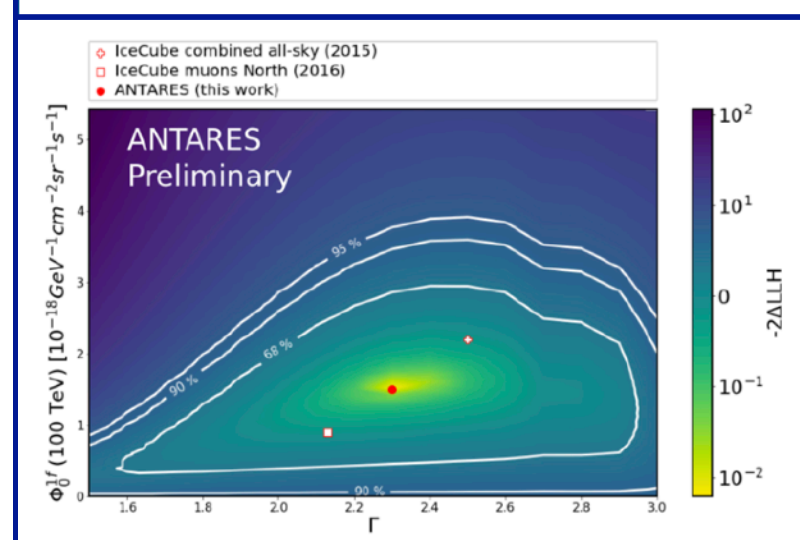


Name	Approx. Neutrino Energy	Direction	Dominant Flavor	Unbroken Spectral Index
HESE	50 TeV - 5 PeV	All-sky	e, μ, τ	2.89
Cascades	5 TeV - 5 Pev	All-sky	e, τ	2.48
NuMu	50 TeV - 10 PeV	Northern sky	μ	2.28

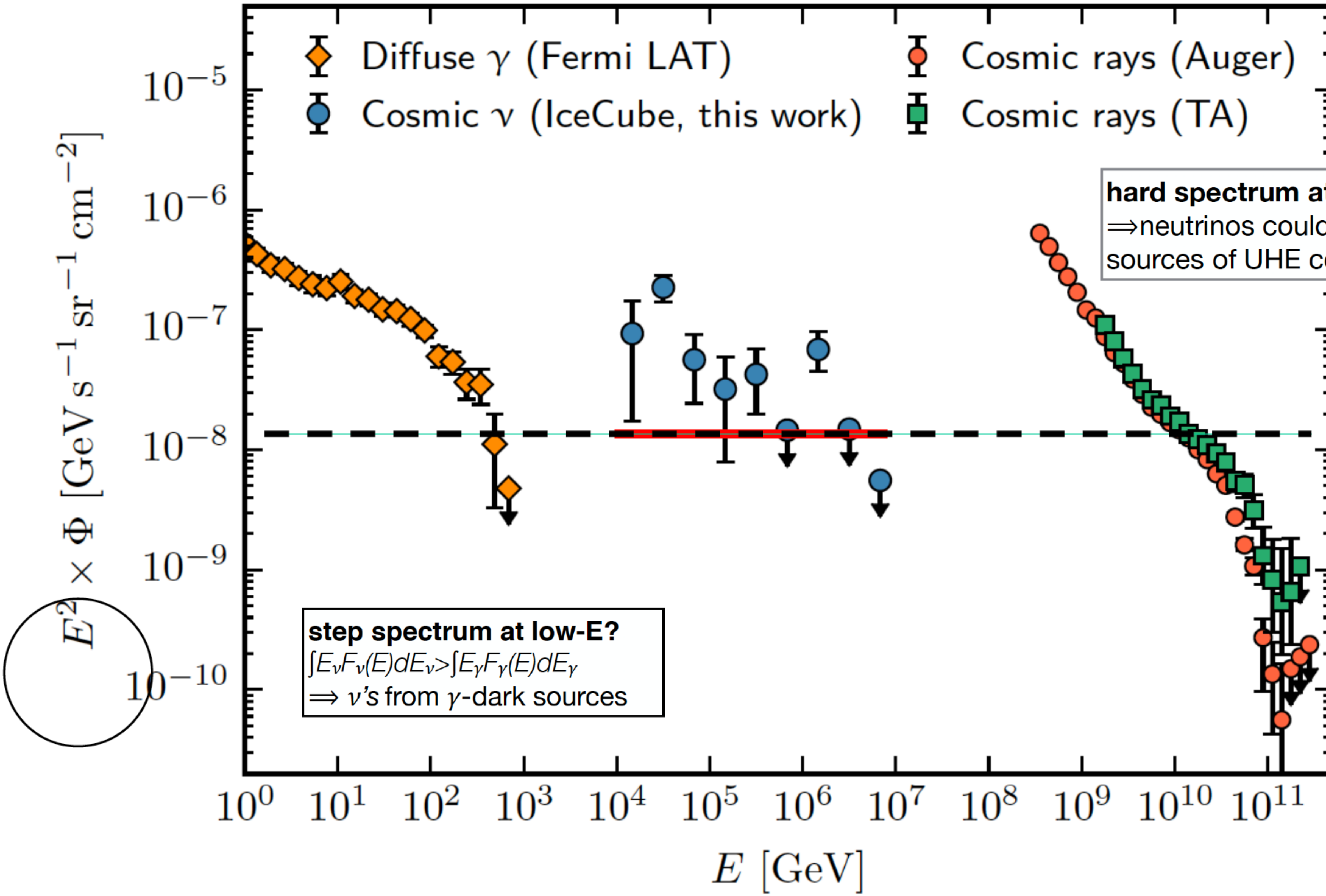
ANTARES 11 yrs







Multi-messenger context



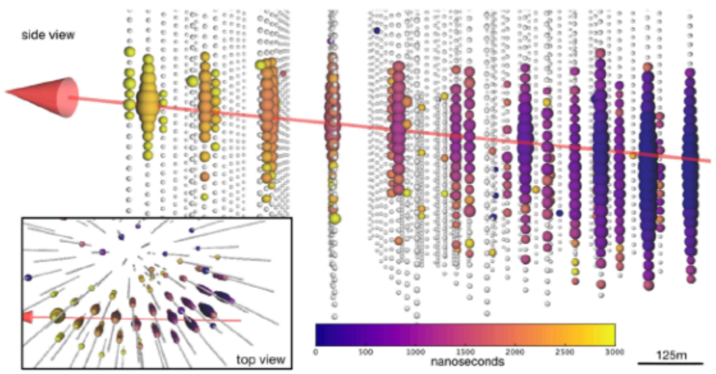
hard spectrum at high-E?
⟹neutrinos could point to sources of UHE cosmic rays

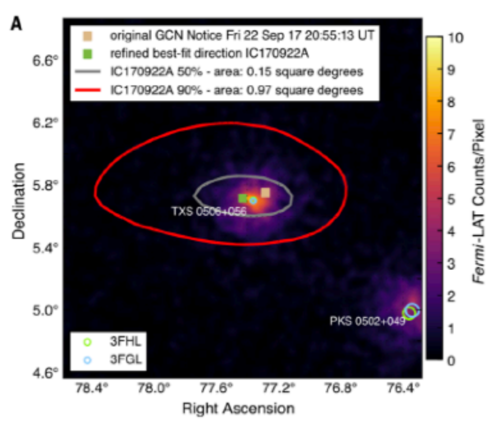
step spectrum at low-E?
$\int E_\nu F_\nu(E) dE_\nu > \int E_\gamma F_\gamma(E) dE_\gamma$
⟹ ν's from γ-dark sources

So far, may be 1 source identified

Neutrinos from the AGN blazar TXS 0506+056

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



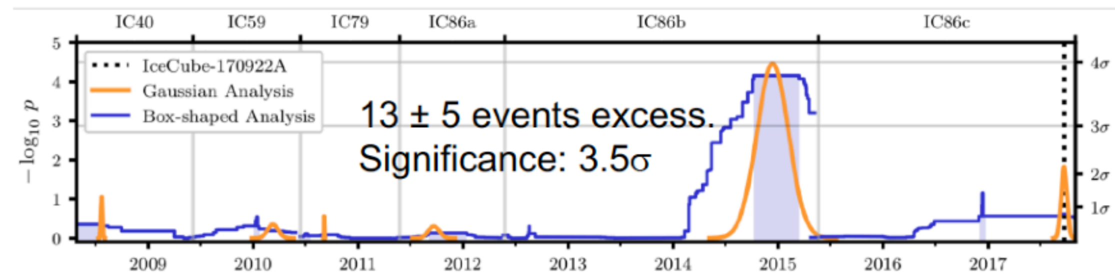


Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

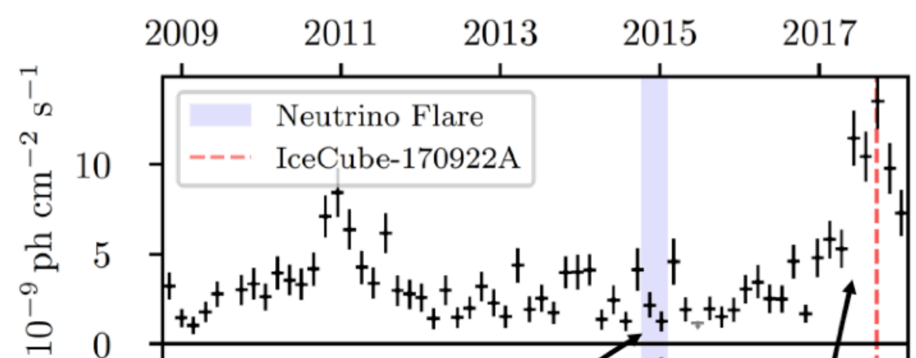
Science 361 (2018) no. 6398, eaat1378

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



Science 361 (2018) no. 6398, eaat2890

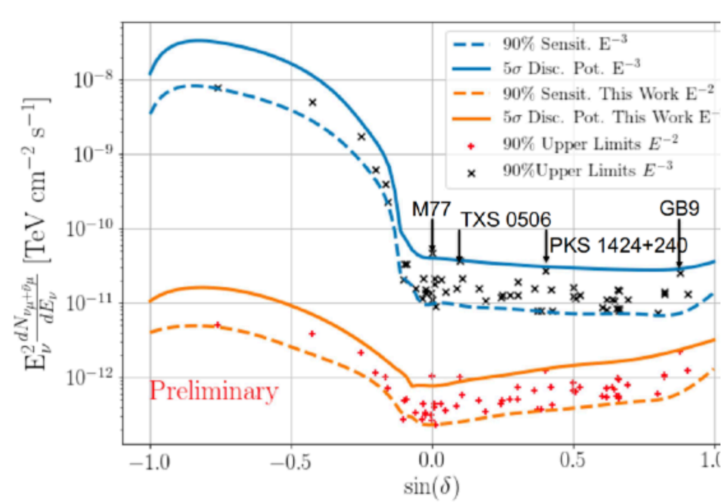
Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192

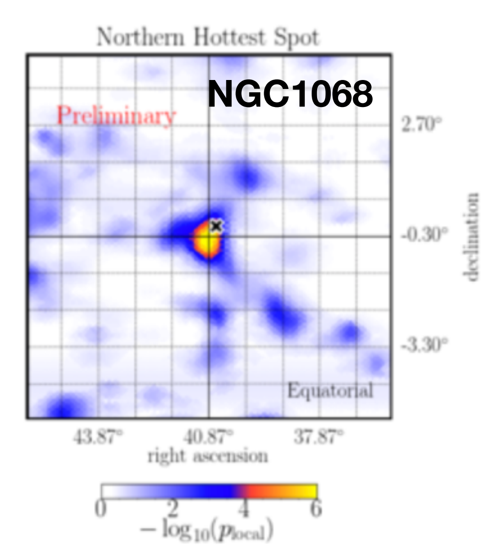


At 2014-15 neutrino flare

The 2017 flare

Few additional hints in the most recent dataset:





Still a lot to do for HE neutrino astrophysics

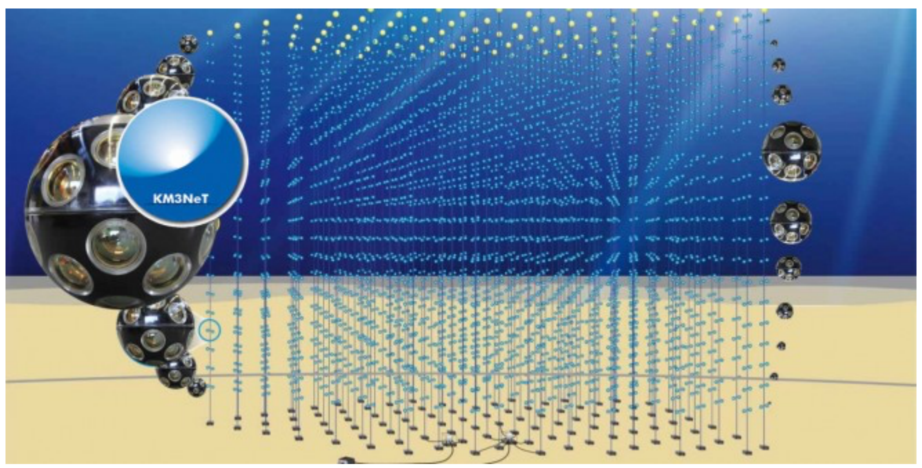
- **Identify the high-energy astrophysical neutrinos**
- **Identify the sources of the highest energy cosmic rays**
- **Constrain the production mechanisms of high-energy cosmic particles**
- **Obtain a unique multi-messenger view into the explosion of stars and the evolution of stellar remnants**
- **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

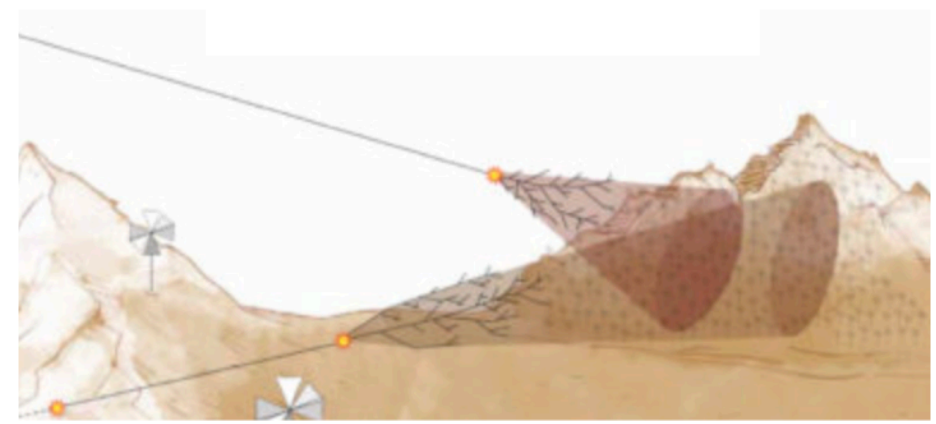
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
ANTARES
ANITA
PIERRE AUGER OBSERVATORY

Precision Frontier

Energy Frontier



Intensity Frontier

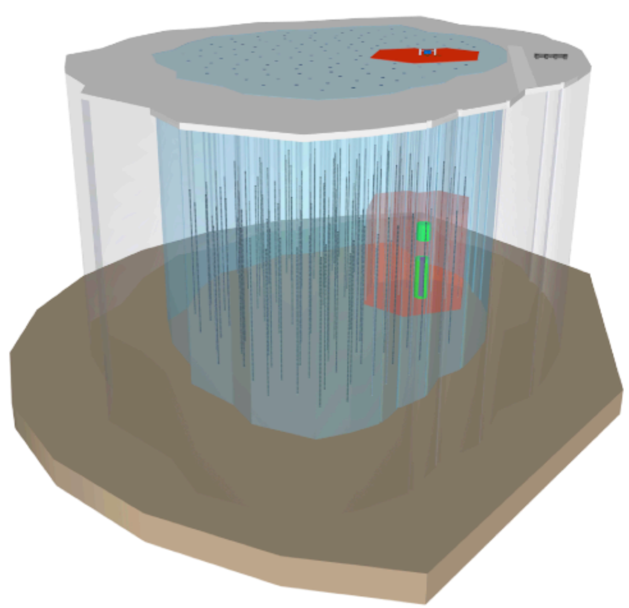


GRAND, ARA, ARIANNA, POEMMA

Tracking cosmogenic ν at UHE

KM3NeT, GVD

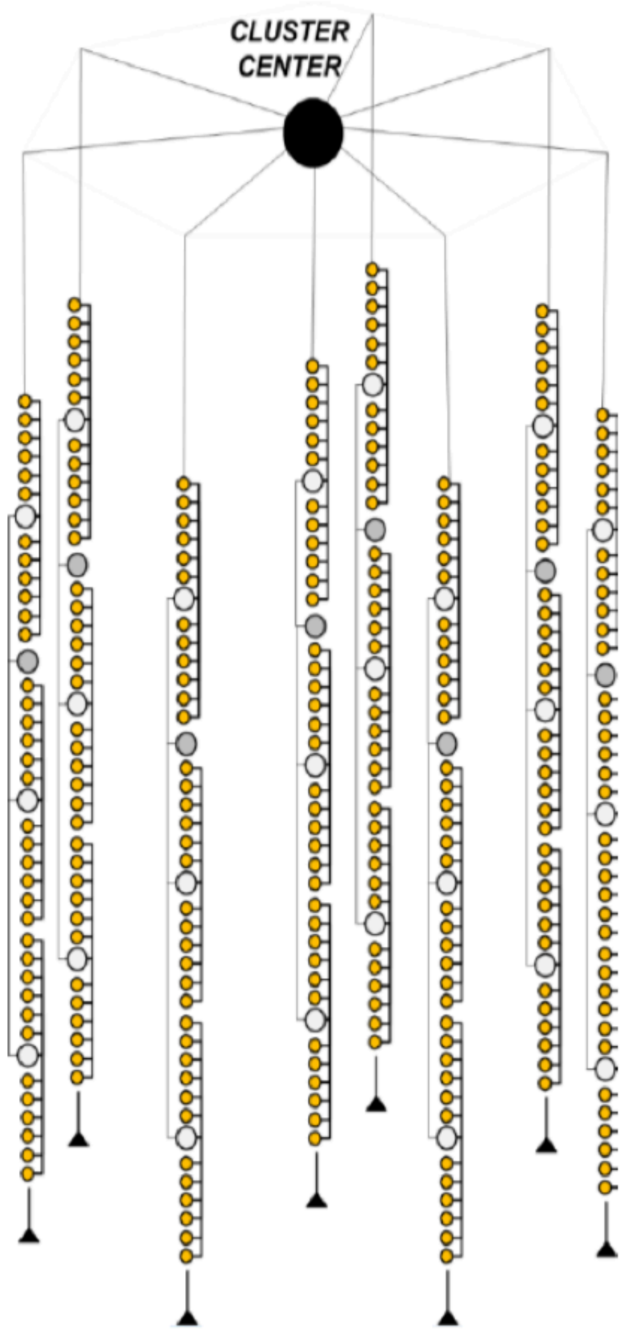
Having the best angular resolution with a reasonable instrumented volume



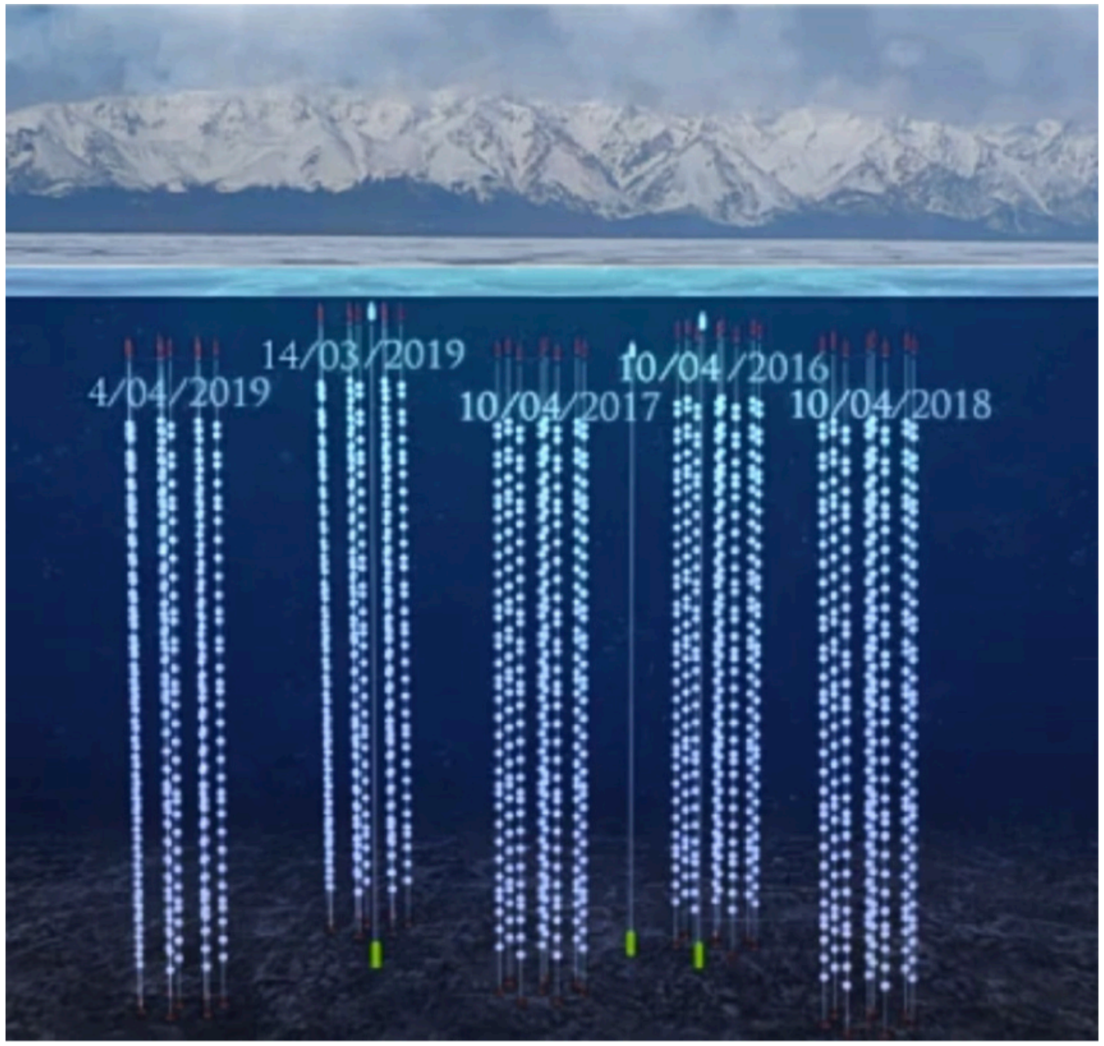
IceCube Gen2

Having the largest statistics with reasonable precision

GVD Baikal



Cluster: 8 strings, 288 OMs
Radius 60 m, Clusters distance 300 m



In 2019, 5 clusters in operation
<=> 40 strings of 1440 OMs with an instrumented volume of 0.25 km³
(Phase 1 end in 2021 with 0.4 km³)

⇒ Full GVD will contain 20 clusters with an instrumented volume of 1.5 km³

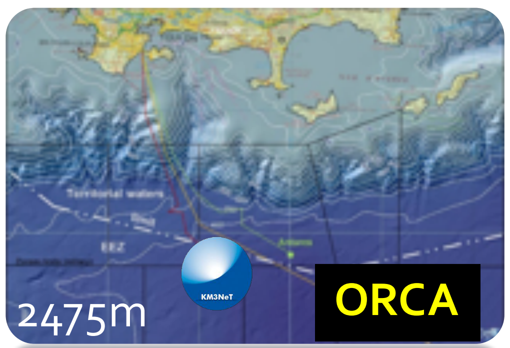
⇒ Limited performances despite the large volume due to the quality of the water

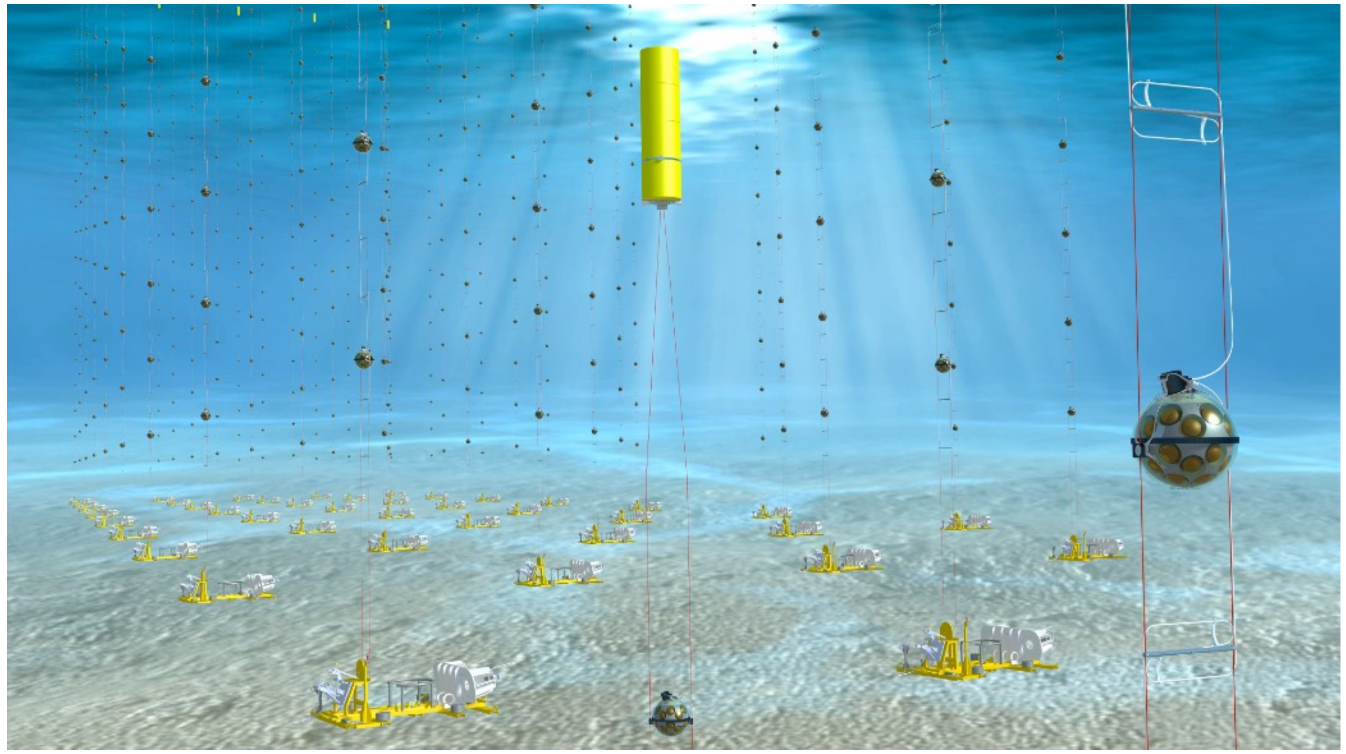
KM3NeT

KM3NeT is the neutrino research infrastructure in the deep Mediterranean Sea

Oscillation
Research
with **C**osmics
In the **A**byss

ORCA: off shore
Toulon, France





Astroparticle
Research
with **C**osmics
In the **A**byss

ARCA: off shore
Capo Passero, Italy

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

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

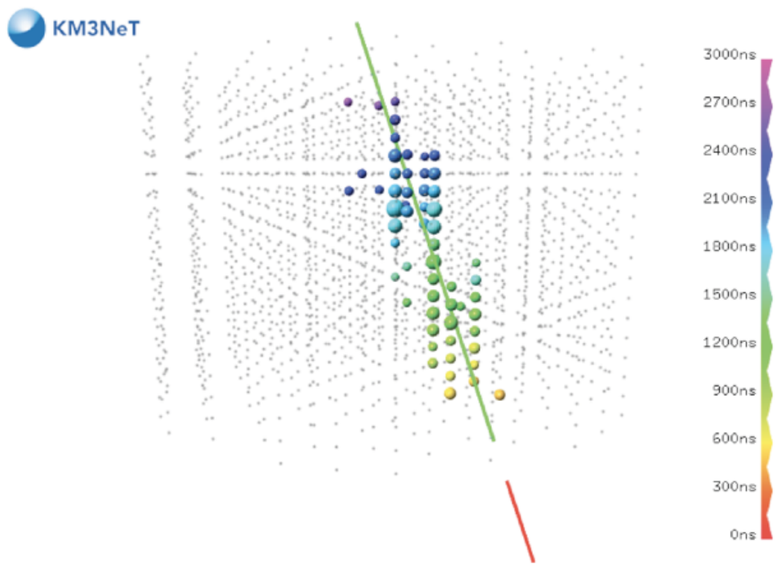
Main characteristics:

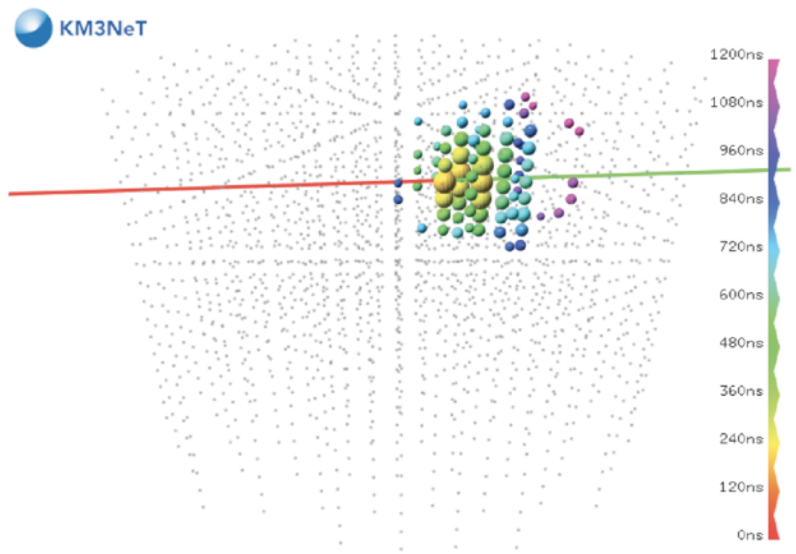
- Extended energy range: 10 MeV → >10 PeV
- Full sky coverage with the best sensitivity for the galactic sources
- High duty cycle (> 90-95%)
- All-flavour neutrino detection
- Best angular resolutions

⟹ Construction on-going: 2 DU working in ARCA & ORCA + 4 DUs ready for deployment in ORCA (+300 DOMs builded)

⟹ Construction on-going, by mid 2020, better sensitivities than ANTARES in the whole energy range. Current plan, finish the construction of ORCA (2024) and ARCA (2029)
+ Phase 3: 1 detector in Greece, + other sites in discussion.

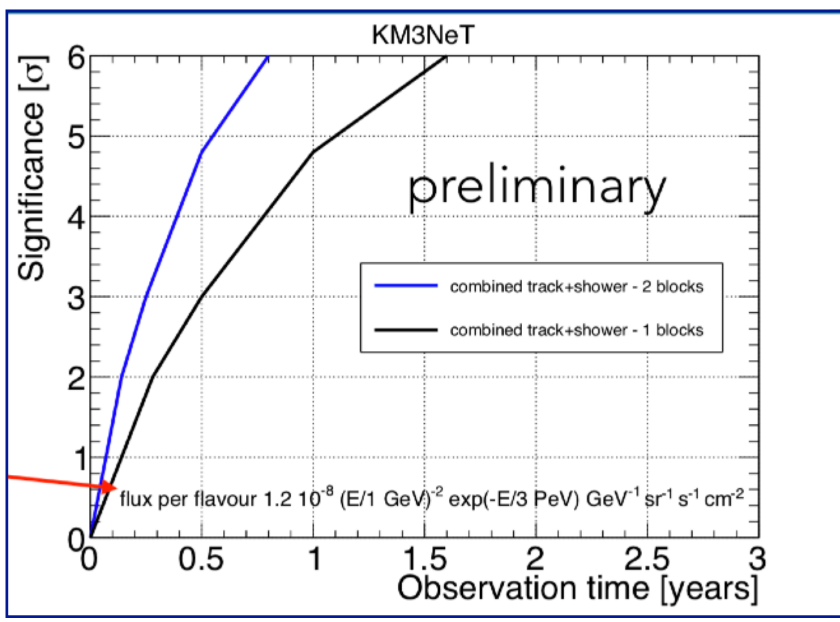
KM3NeT



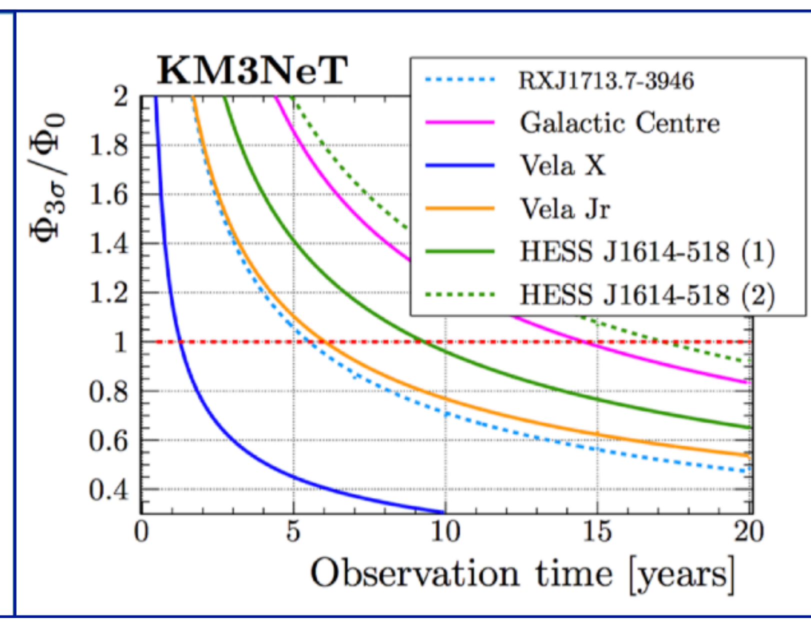


Tracks:
ARCA: < 0.1° (>100 TeV)
ORCA: 1 - 2° (100 GeV - 1 TeV)

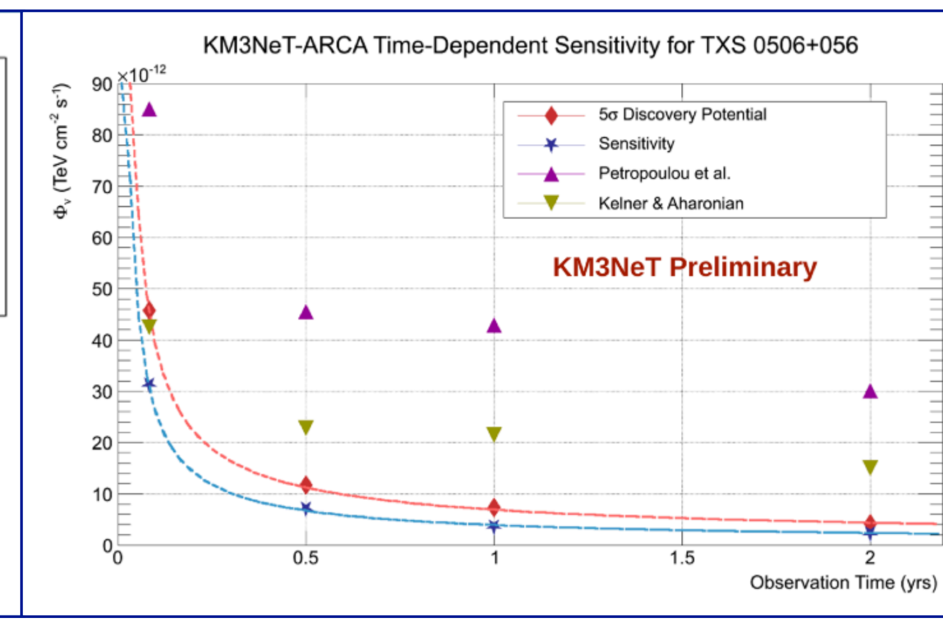
Cascades:
ARCA: < 1.5° (>100 TeV)
ORCA: ~4 - 5° (100 GeV - 1 TeV)



Diffuse ν flux

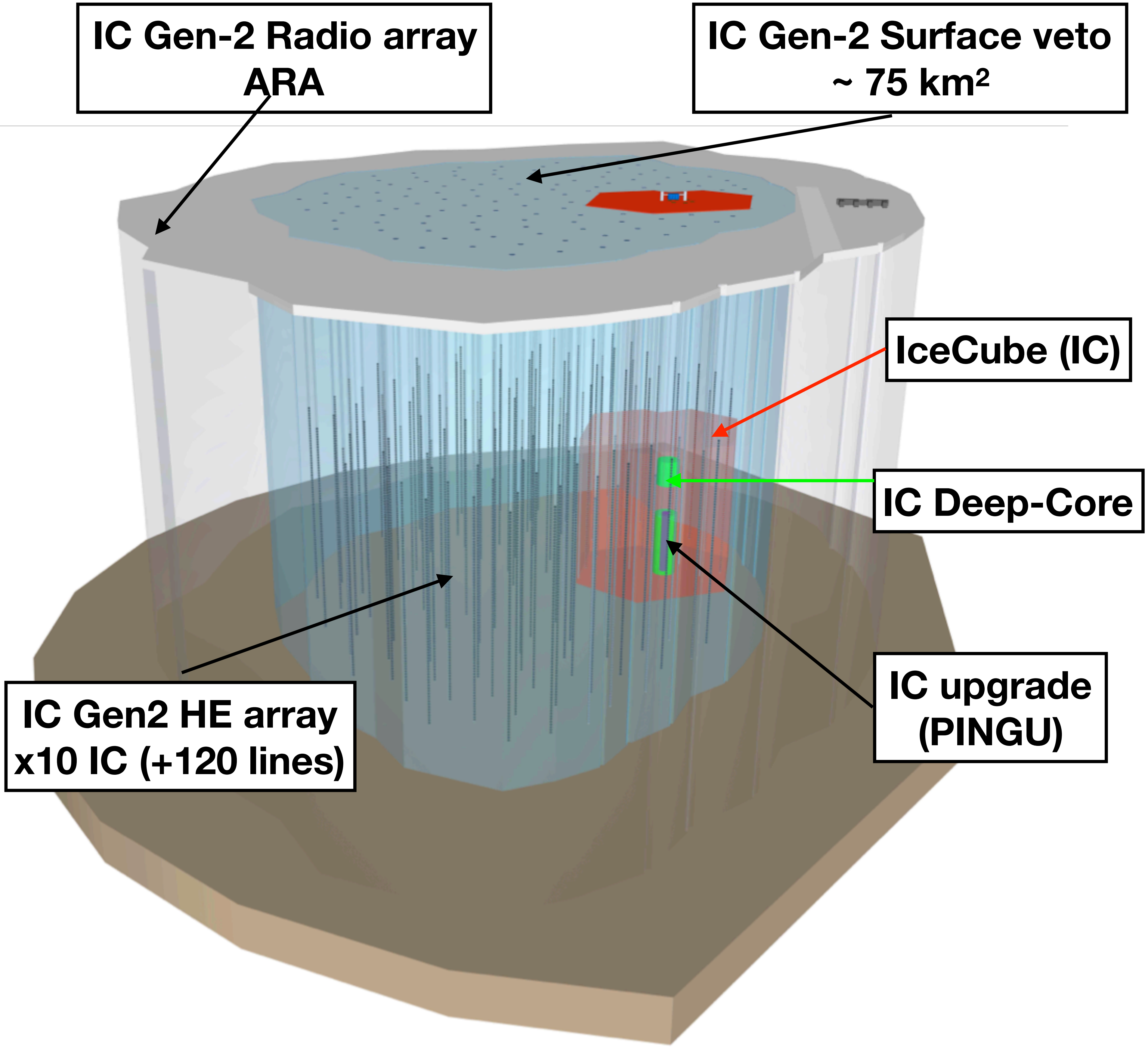


Galactic sources



Extragalactic sources

IceCube Gen2



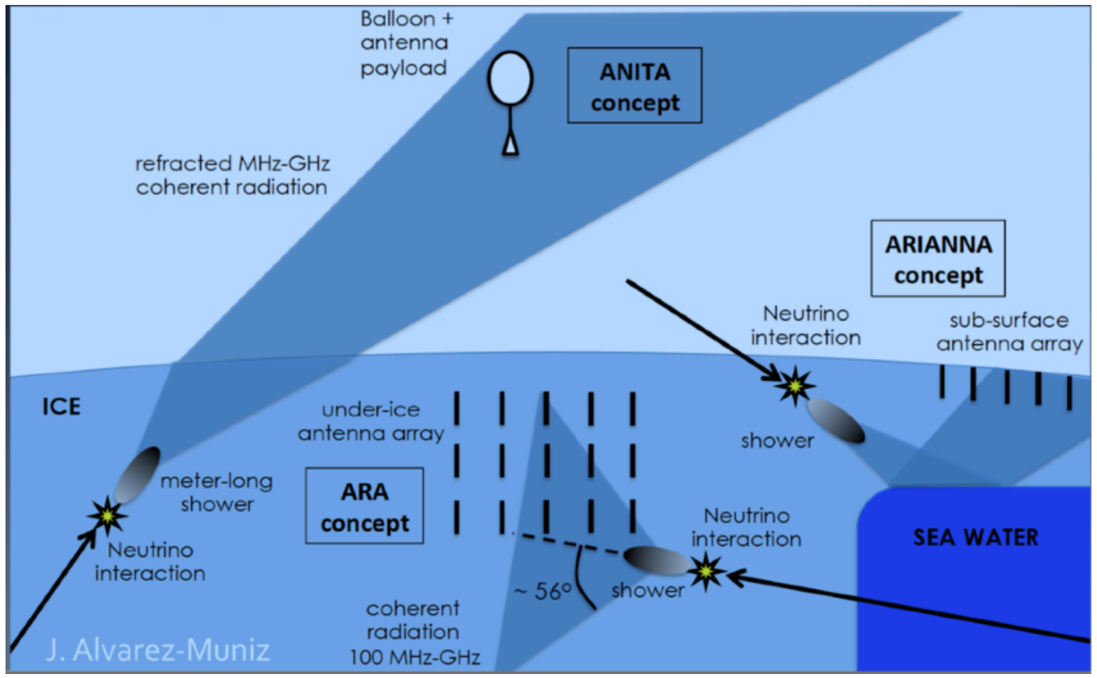
IceCube is taking continuously data since more than 10 yrs.

$\Longrightarrow$ The project IceCube Gen2 is submitted but not yet funded. Full construction in 2030s.

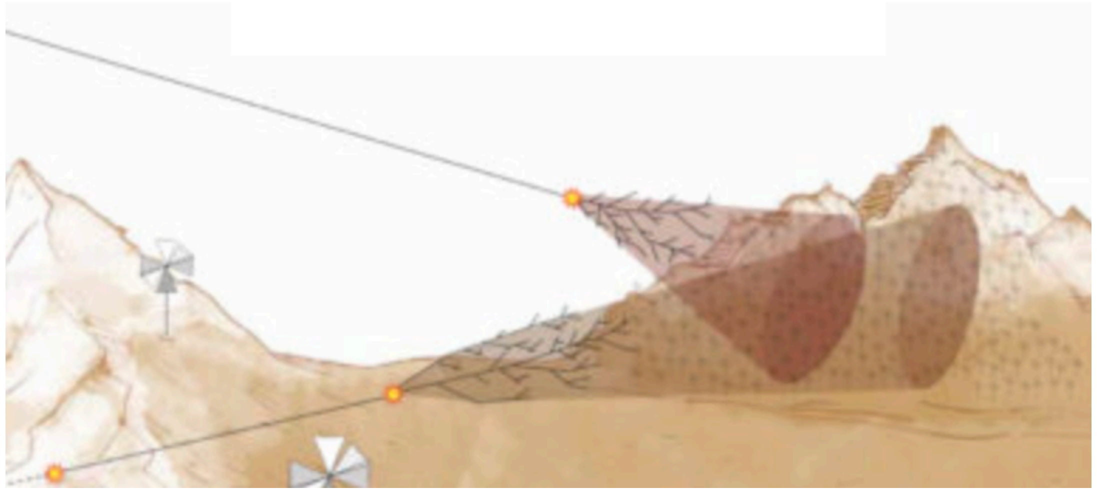
$\Longrightarrow$ IceCube-upgrade is financed: 7 new lines to test the new technos (+LE ν physics). Deployment 2023-2024

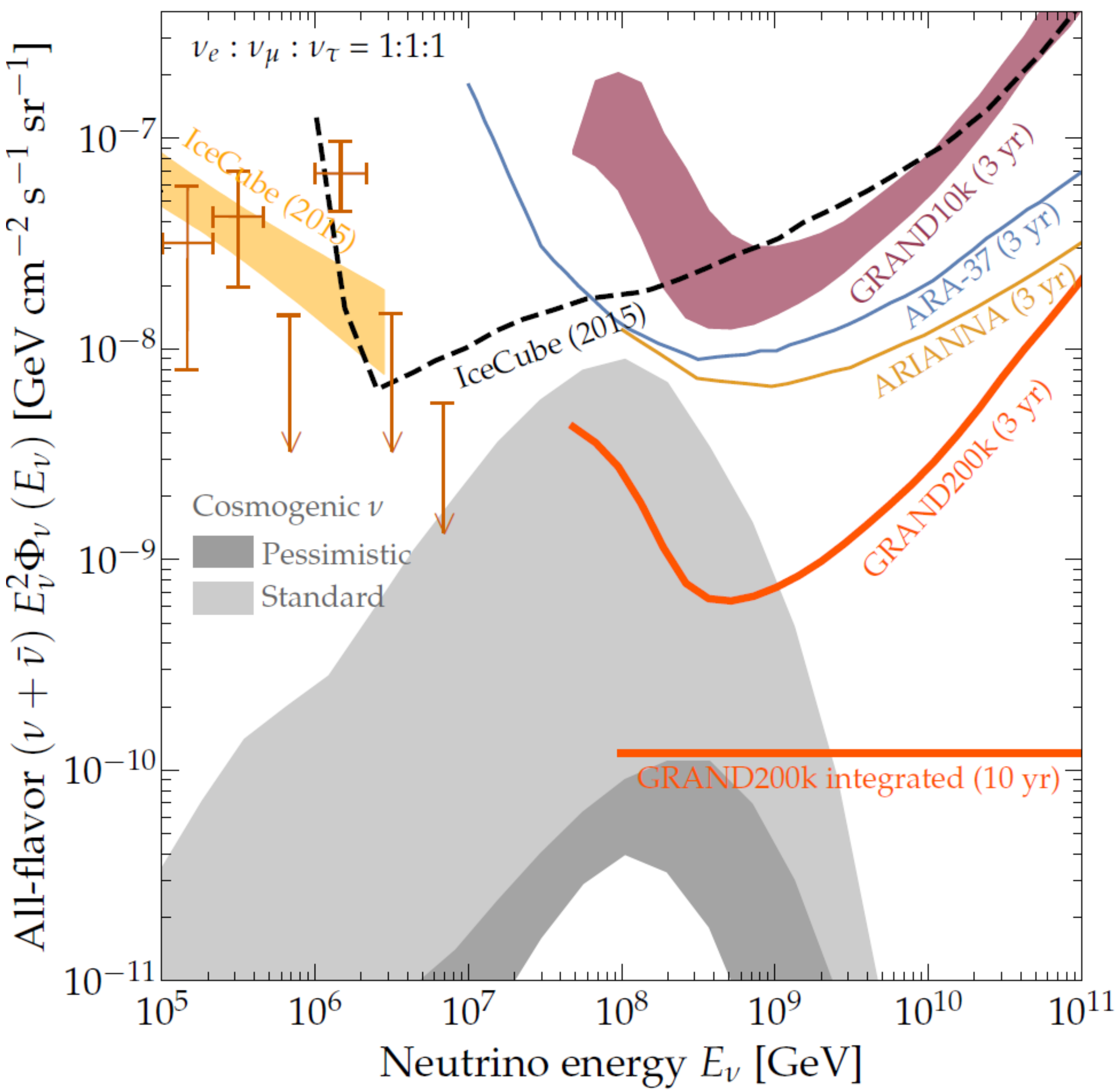
Radio UHE ν detectors

ARA / ARIANNA / ANITA / RNO (Antartica)



GRAND (China)





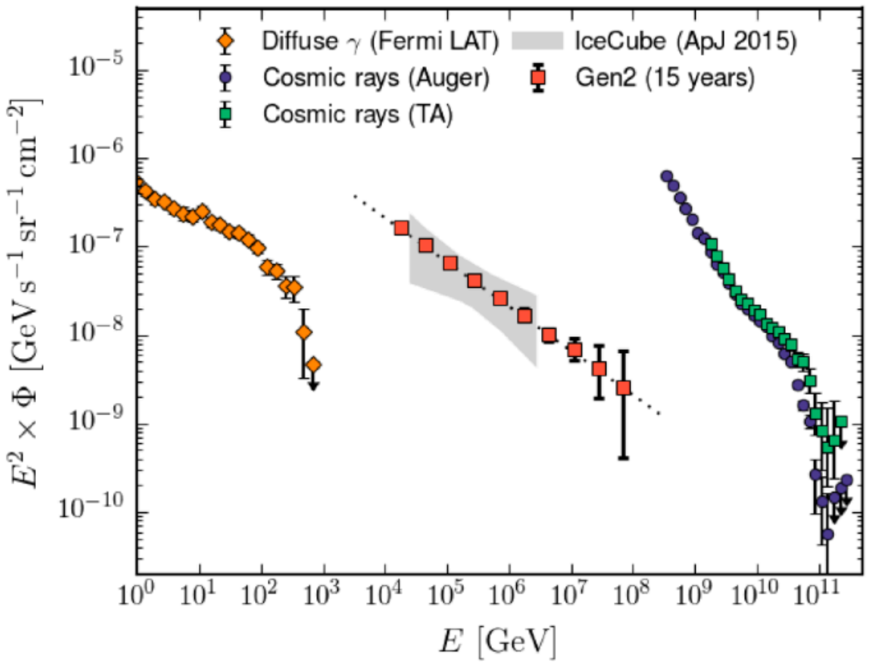
Sciences with the future generation

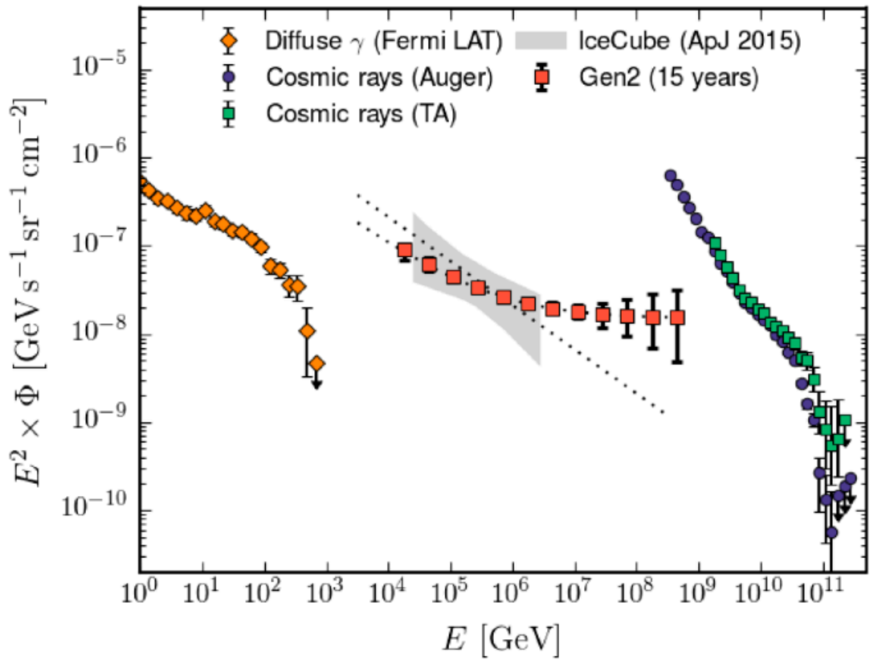
<u>Astronomy with the future generation neutrino detectors:</u>

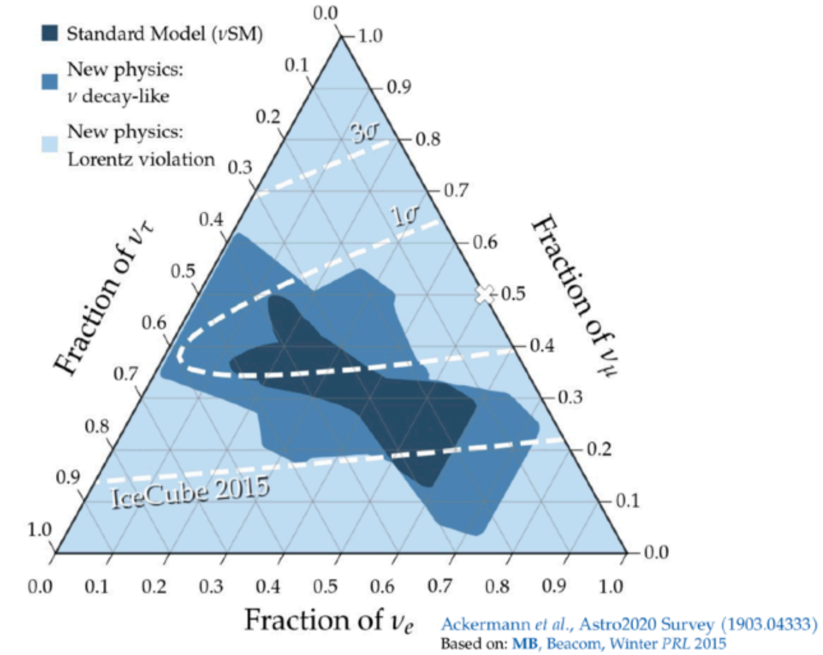
- Identify the **sources** responsible for high energy neutrinos diffuse flux
- Measure features in the **diffuse** spectrum and extend it to higher energy → connection **UHECR** ?
- Neutrino **flavour ratio** and its indication of the source properties
- **Cosmogenic** neutrinos

- Also:

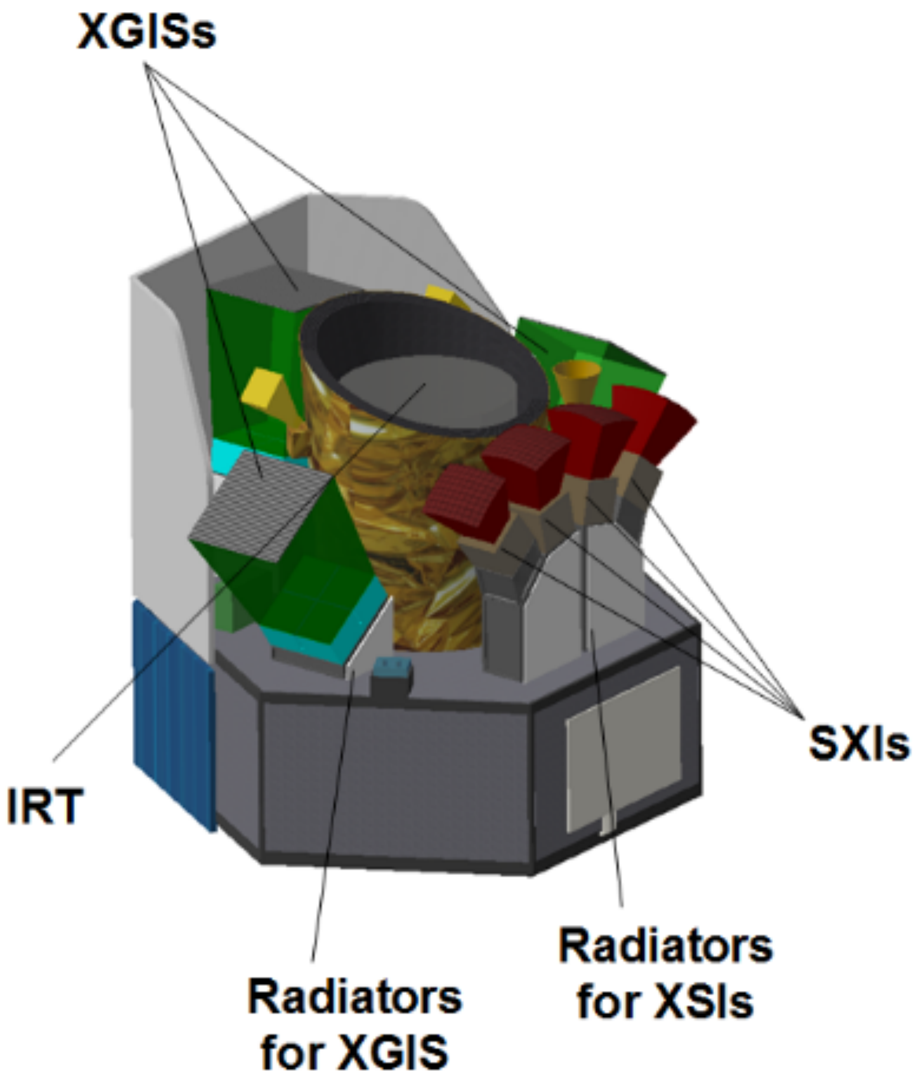
Hadronic interaction models, cosmic-ray composition, charm production, exotic searches, PeV photons, high PT muons, elasticity and cross-section measurements …



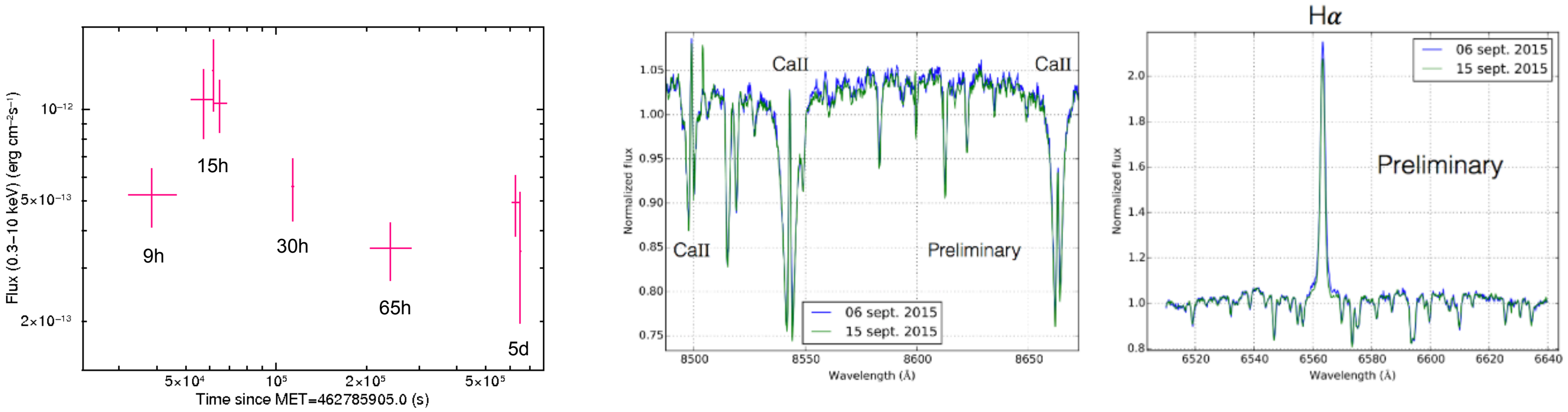




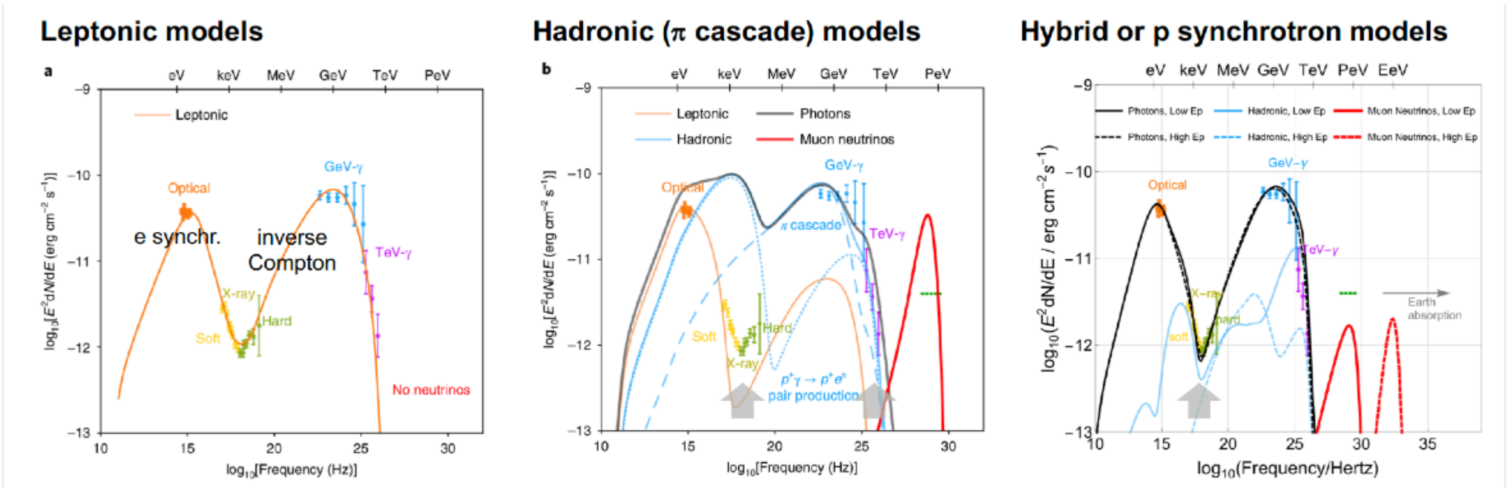
Neutrino - THESEUS



ANT150901A: XRT follow-up + Shooter spectroscopy



TXS0506+056 modélisation (1D model)



<u>Synergies THESEUS-KM3NeT:</u>

- Simultaneous MWL coverage
- X-ray time-dependent survey
- Very large field of view

$\Longrightarrow$ Potential neutrino source identification, localisation and classification

- Fast trigger dissemination (underluminous / obscured GRBs)
- ToO program

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. THESEUS can be very important partner.