Neutrino Telescopes

Sergio Navas
University of Granada, Spain
UNIVERSIDAD DE GRANADA

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(IMFP22)

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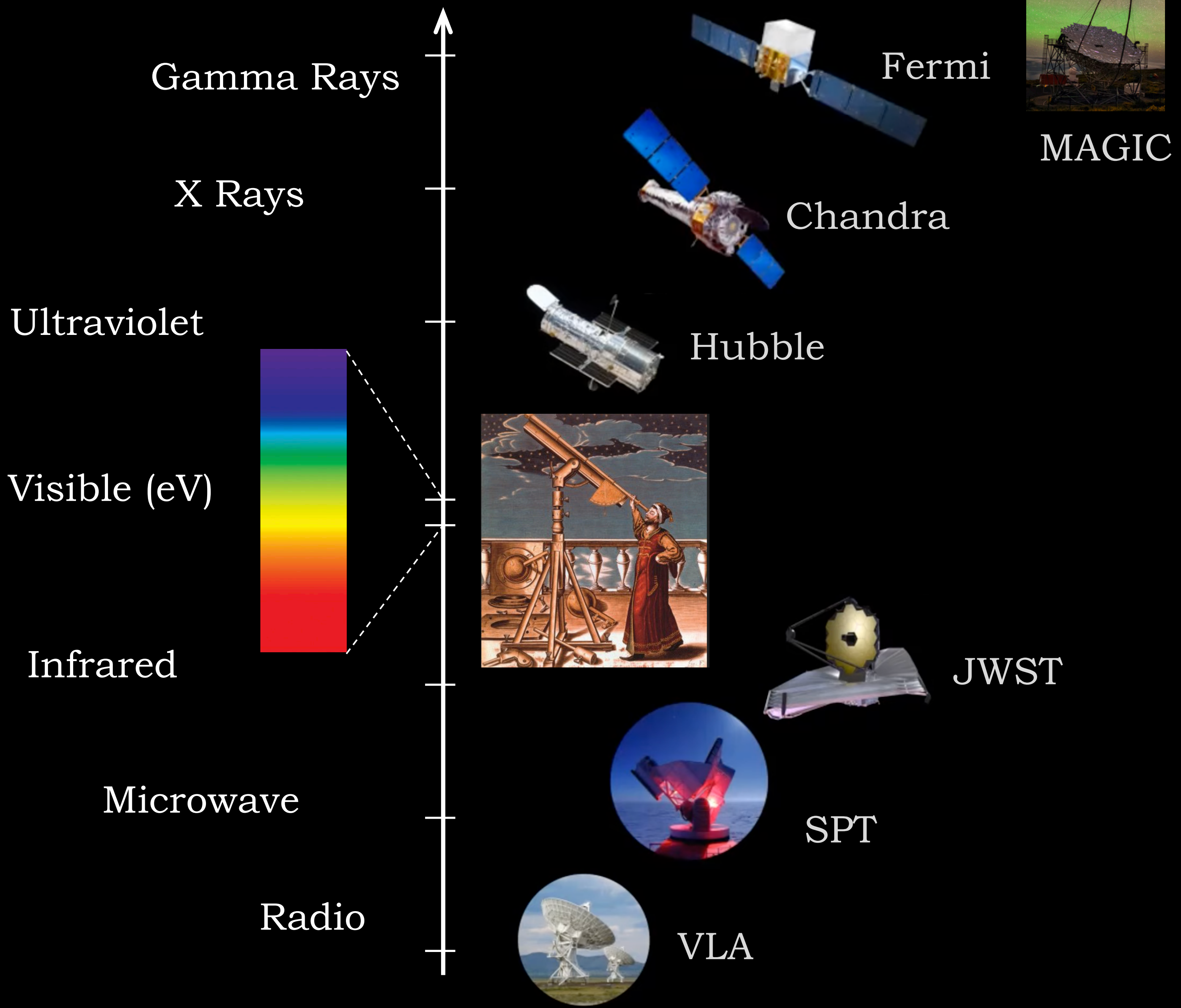
Neutrino Telescopes:

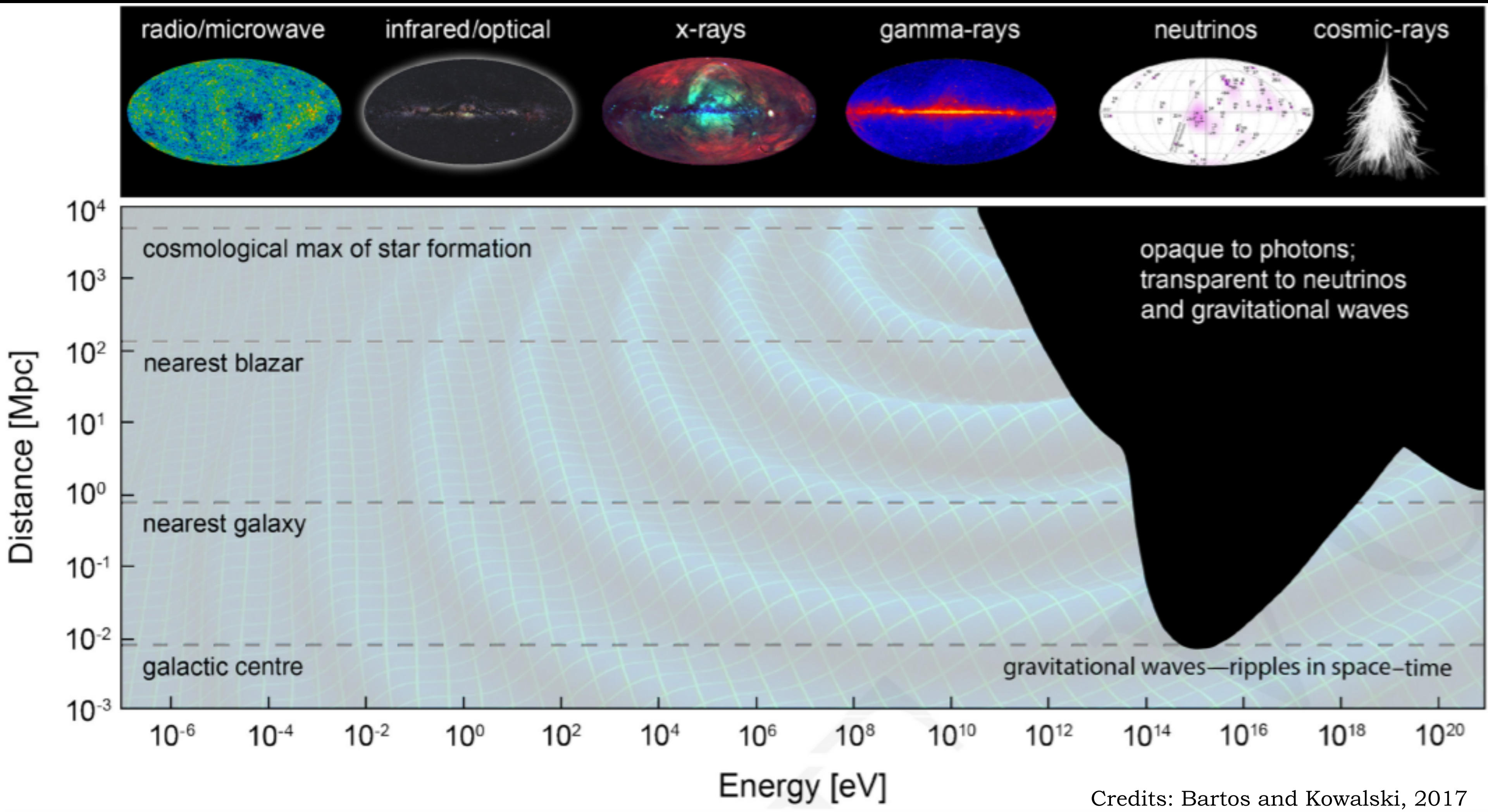
- ✓ Why ?
- ✓ How ?
- ✓ Who ?
- ✓ What ? → Astrophysical ν / Atmospheric ν

Why

Looking at the sky ...

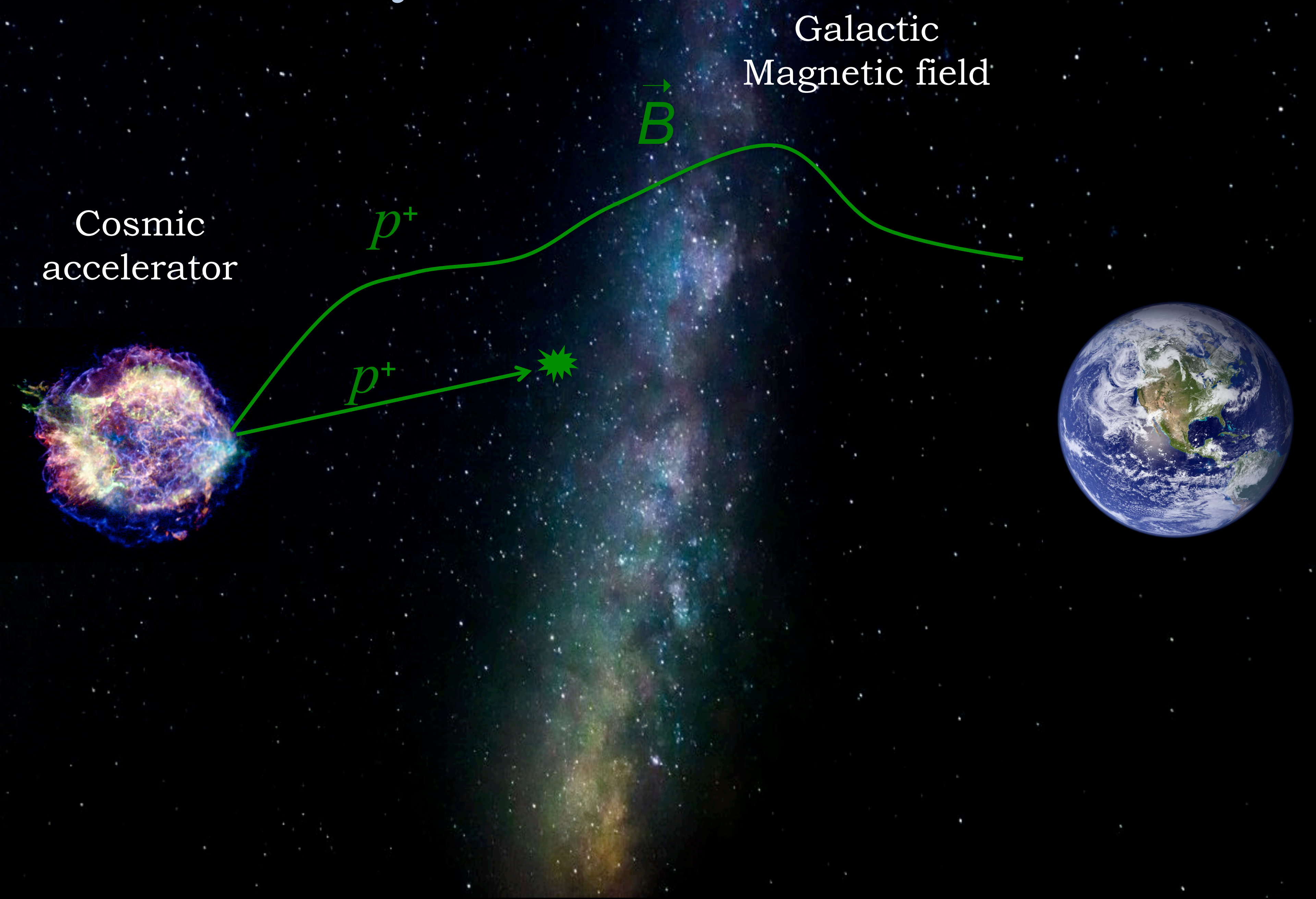


Deep Universe Opaque to High Energy photons



Credits: Bartos and Kowalski, 2017

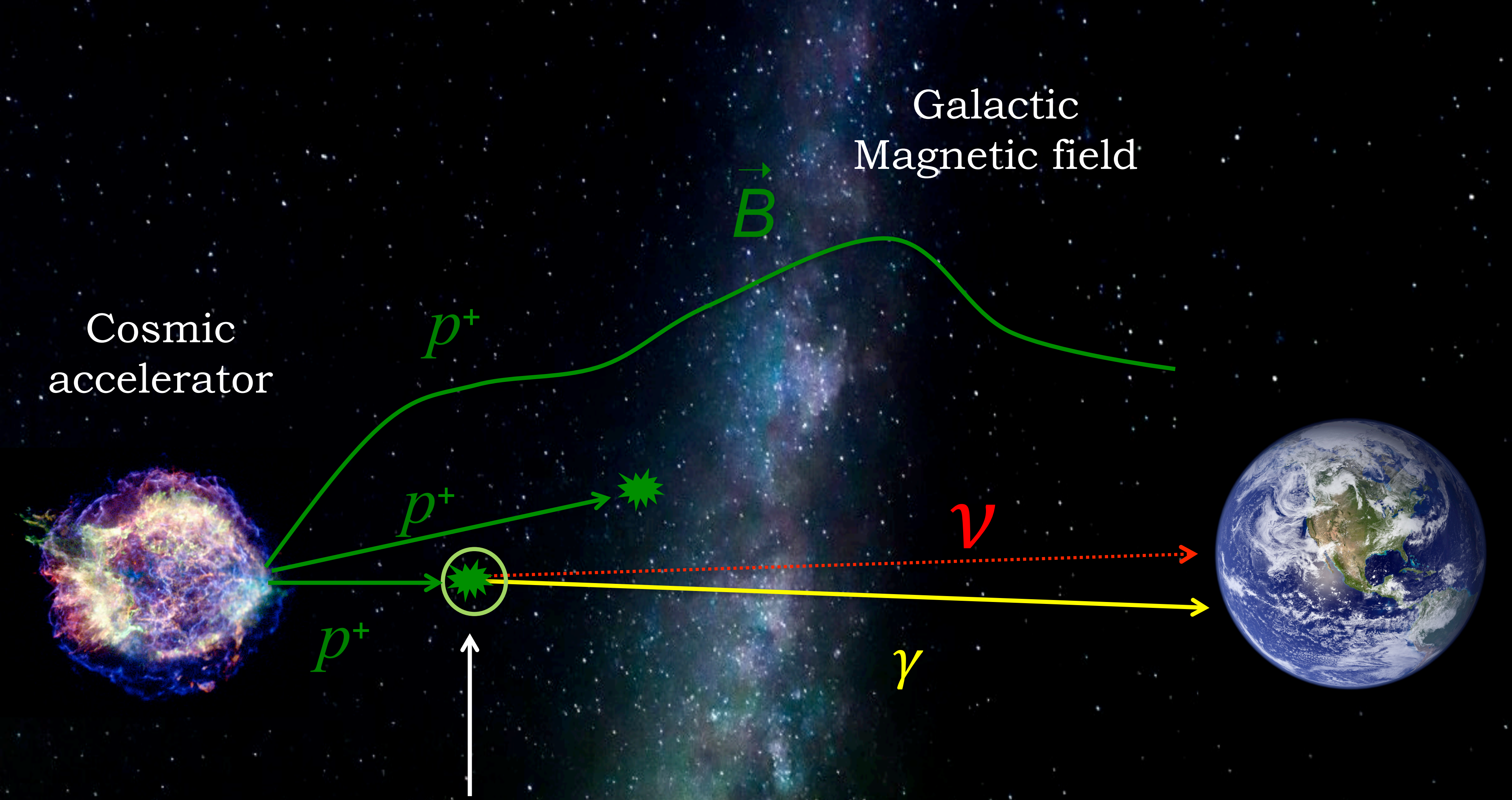
The Cosmic Rays



Neutrinos as messengers from deep Universe

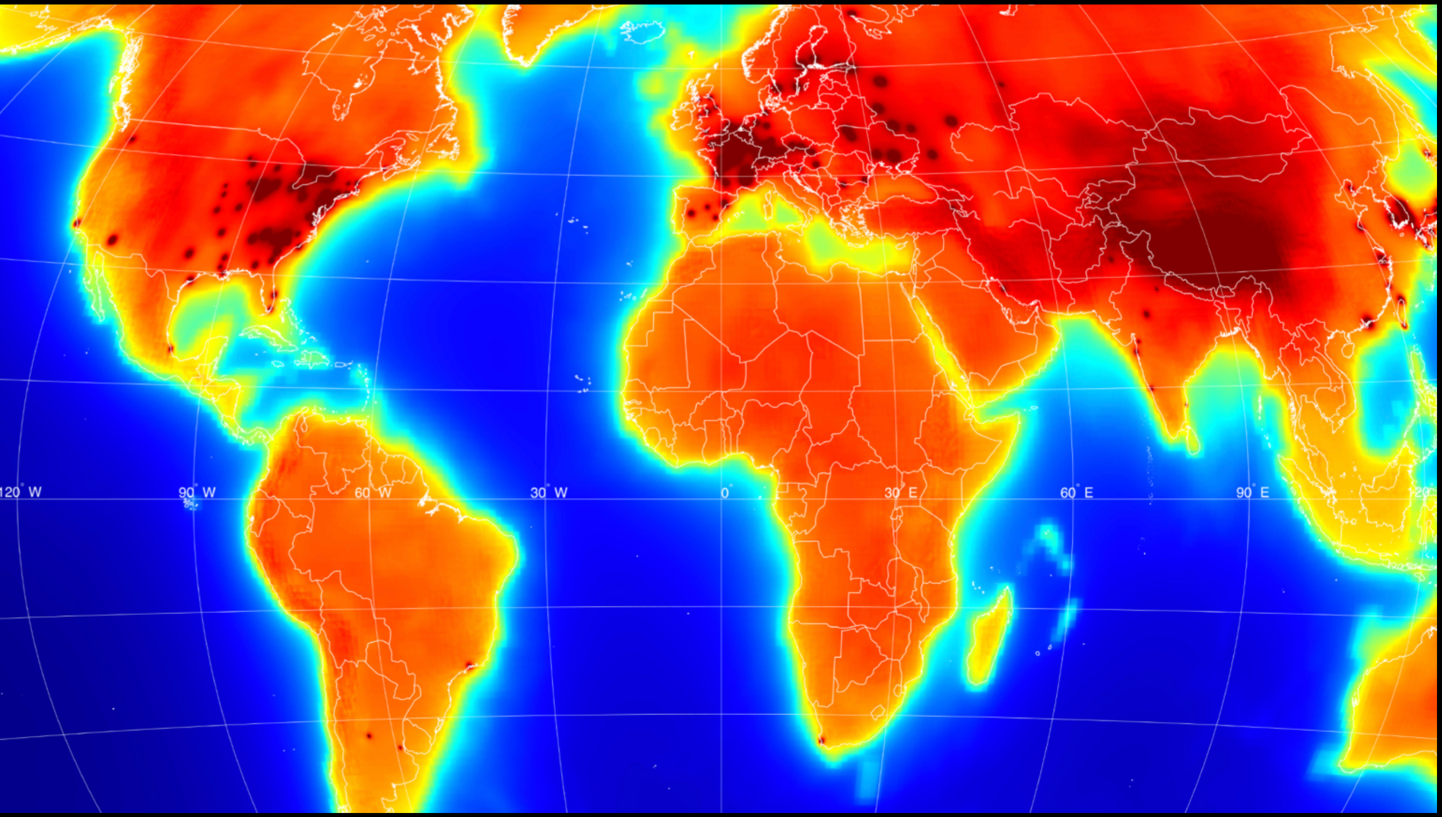
- First proposed by Pauli (1930) ⇦ E conservation desperate solution
- First detected by Cowan & Reines (1956) ⇦ 25 years later!
- Electrically Neutral ⇦ no electric charge
- “Weak interaction” only ⇦ barely interact with matter
- Stable ⇦ do not decay
- Very light ⇦ so light that we do not know their mass
- 3 flavours ⇦ oscillate

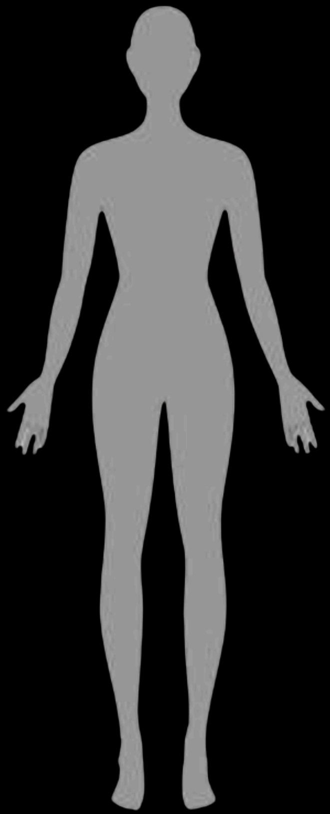
- Neutrinos trace nuclear and hadronic processes



$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\rightarrow \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Neutrinos are everywhere on Earth …



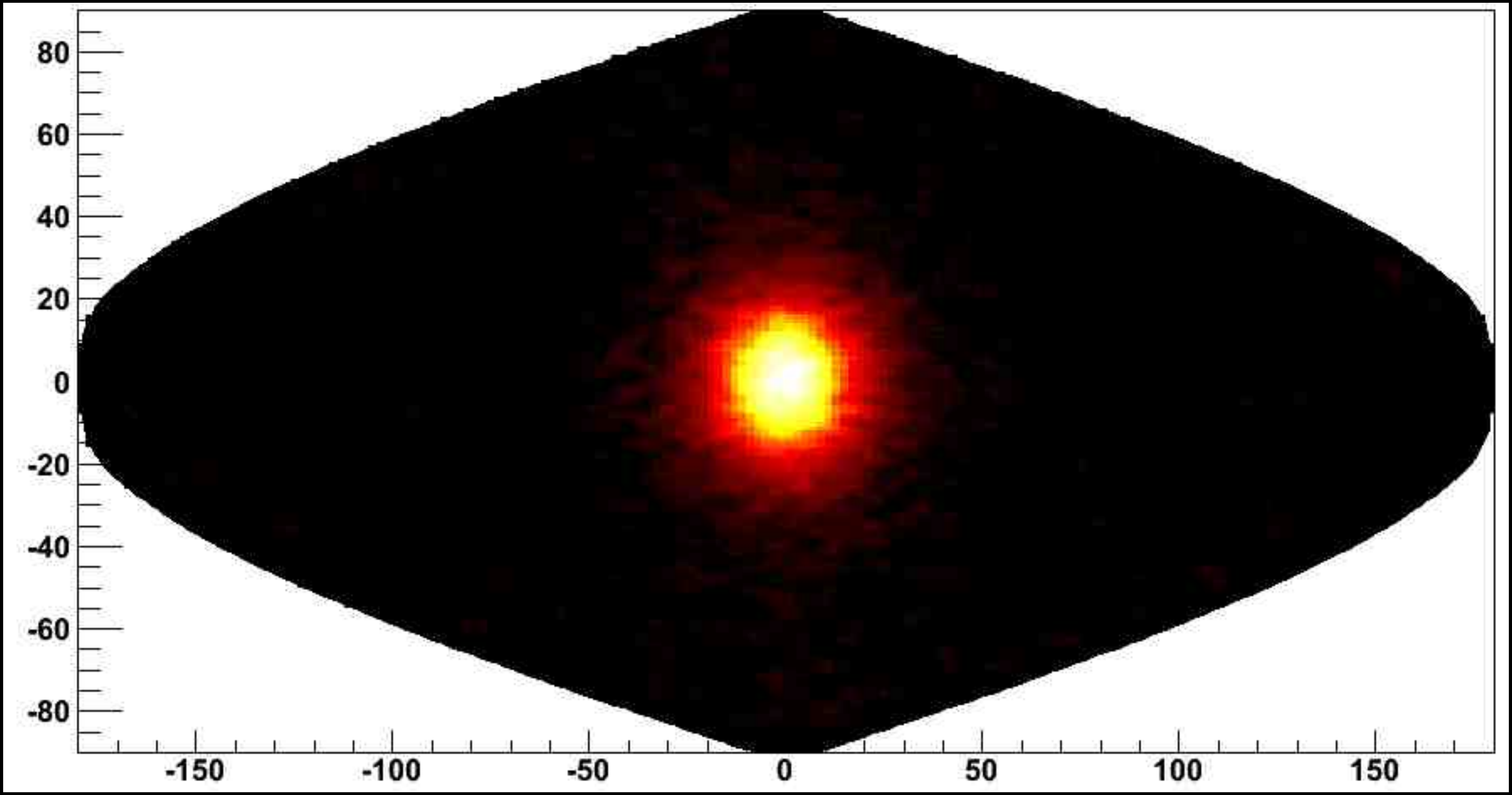


Radioactive decays from Earth’s mantle and from nuclear reactors

Our body emits $\sim$4000 neutrinos/s from ^{40}K decays

… and out there!

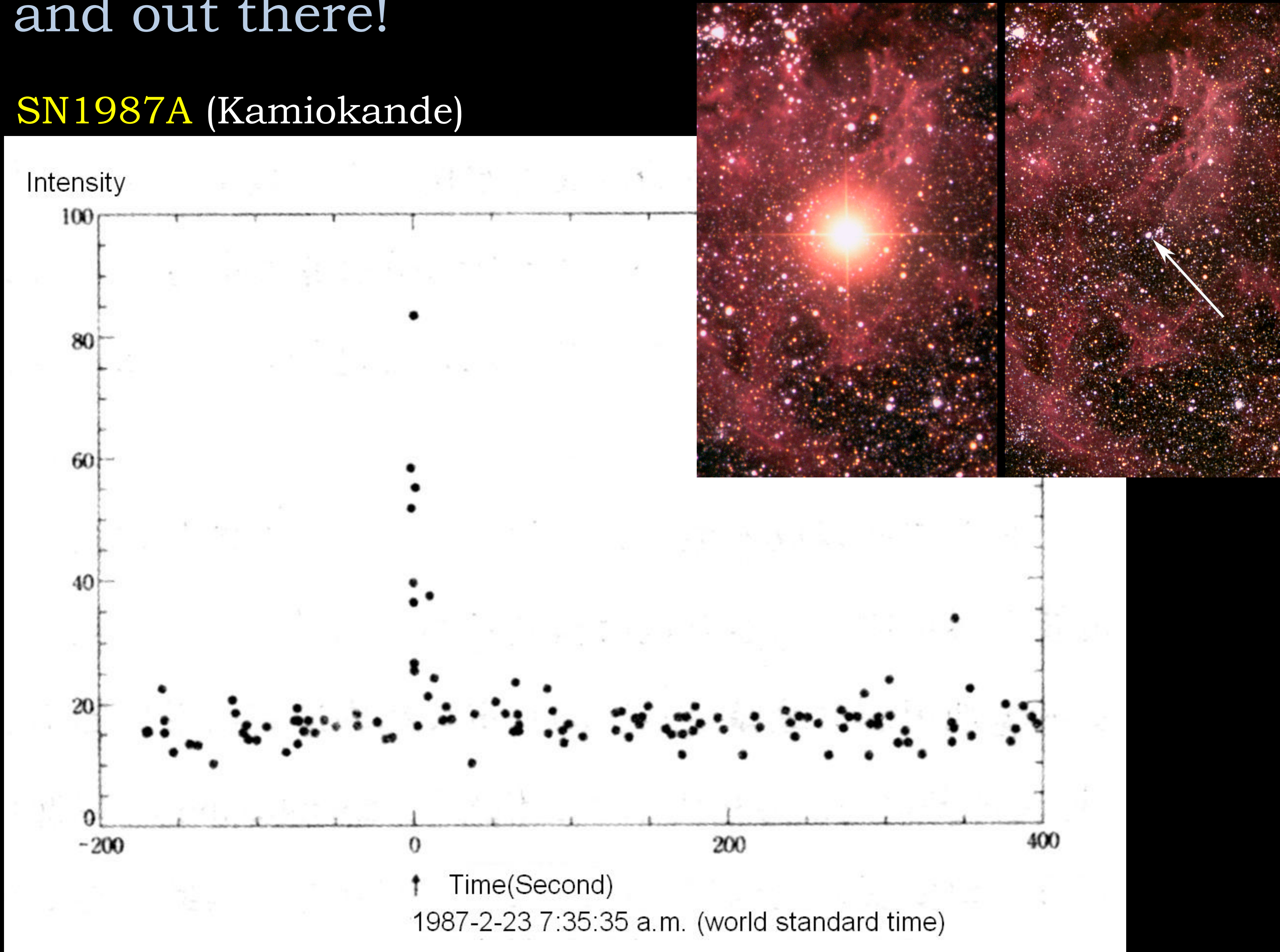
The Sun in neutrinos by SuperKamiokande (1996 – 2018)



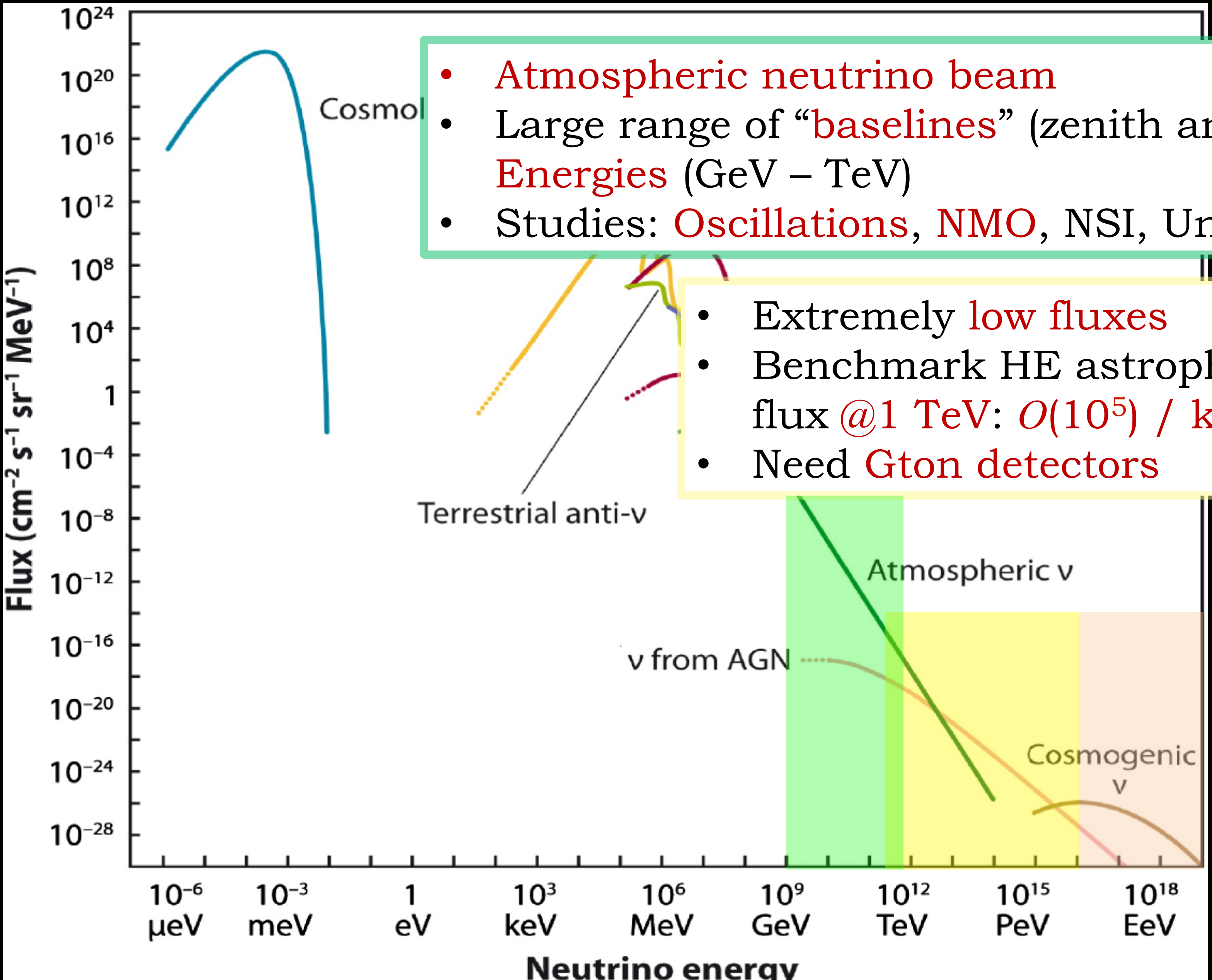
$\sim 10^{11}$ neutrinos/cm^2/s at Earth

… and out there!

SN1987A (Kamiokande)



The neutrino flux

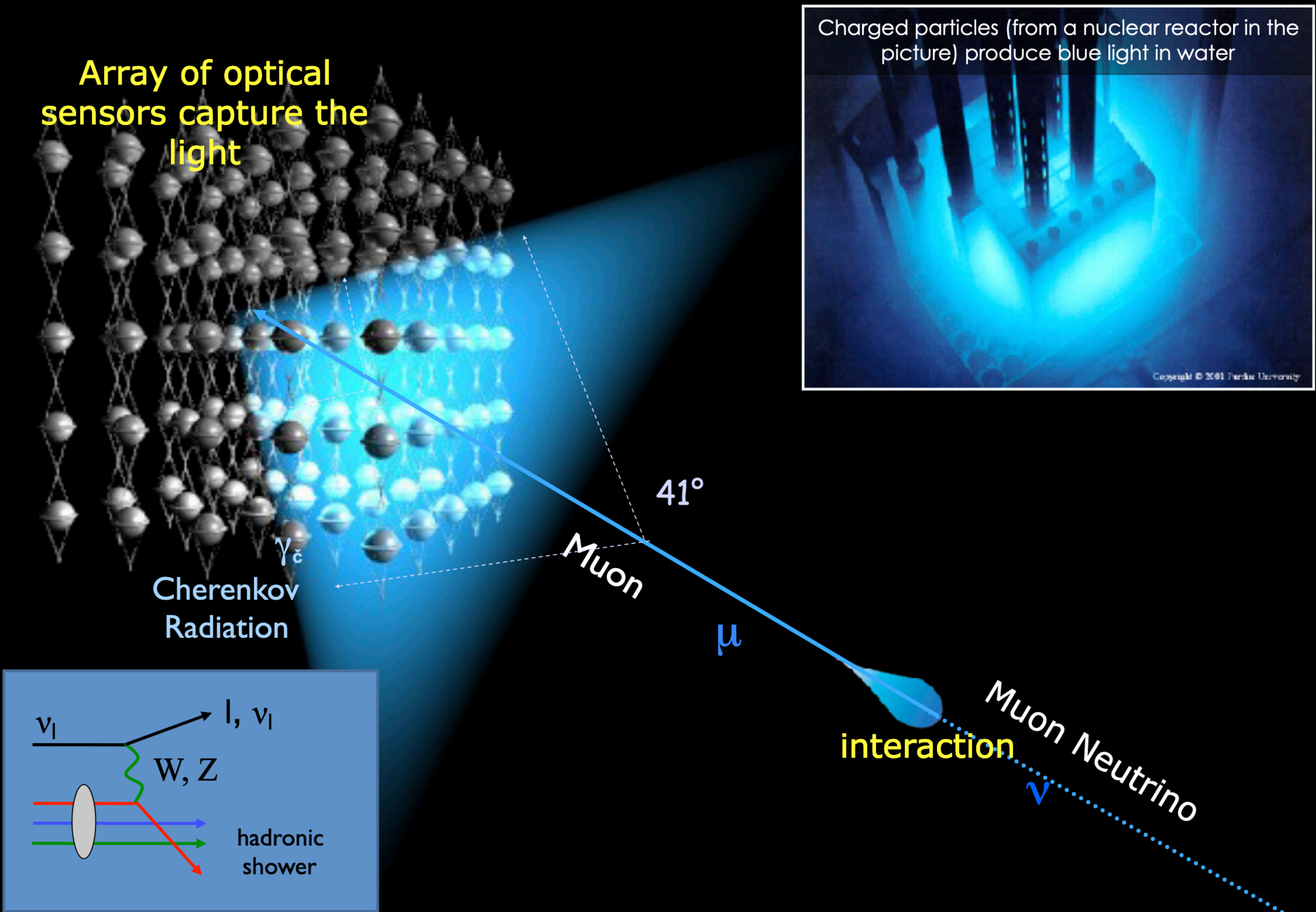


- Atmospheric neutrino beam
- Large range of "baselines" (zenith angles) and Energies (GeV – TeV)
- Studies: Oscillations, NMO, NSI, Unitarity …

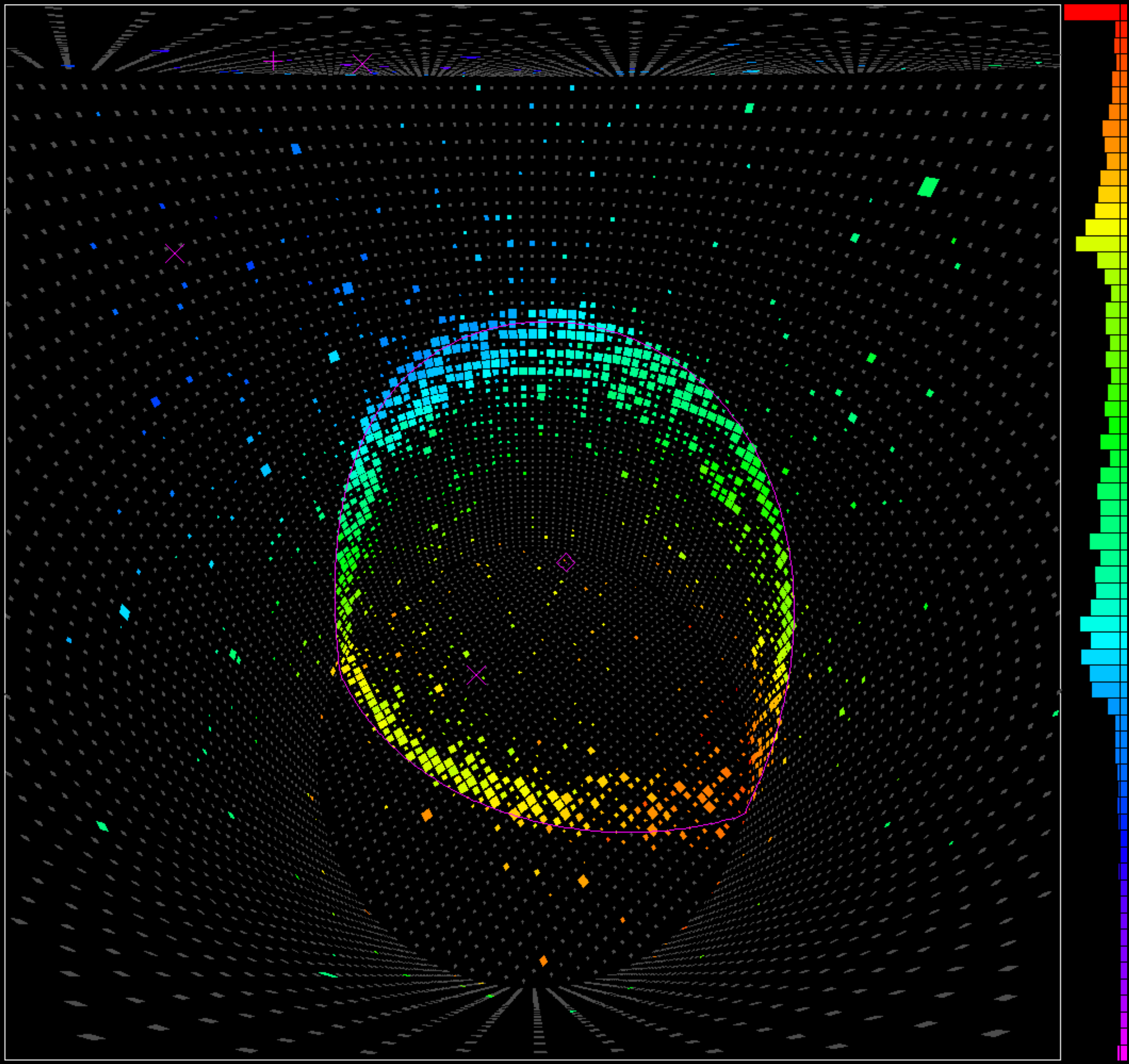
- Extremely low fluxes
- Benchmark HE astrophysical flux @1 TeV: $O(10^5)$ / km^2 / year
- Need Gton detectors

How

The Cherenkov effect

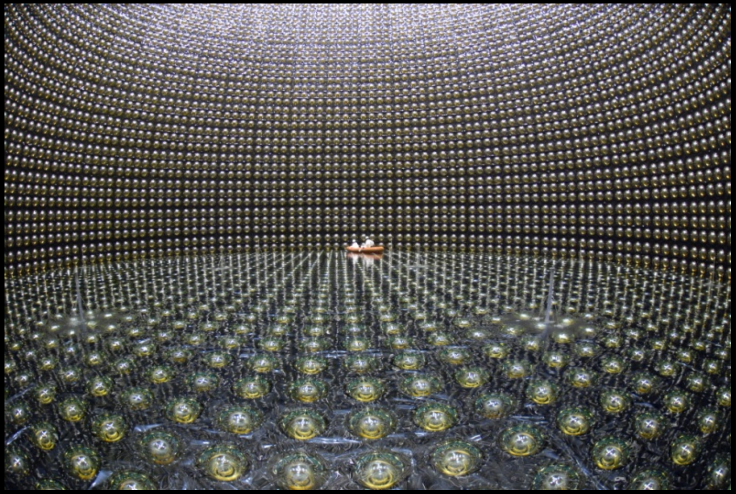


SuperKamiokande



- ~41 m height × ∅39 m
- ~13,000 phototubes
- 365 – 24/7 detector

- 50 ktons of pure water
- ~10^6 ktons needed !



ON HIGH ENERGY NEUTRINO PHYSICS

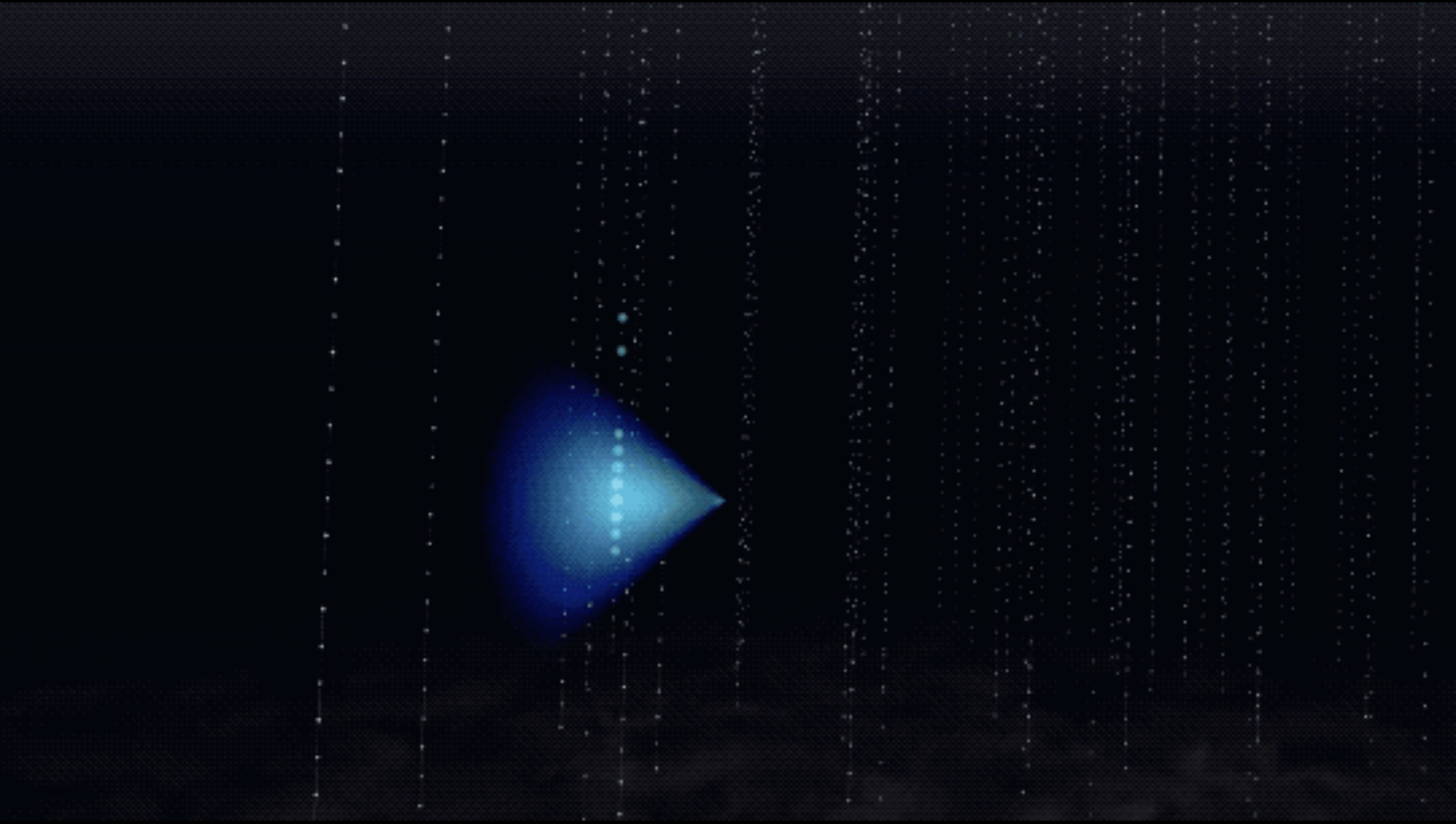
10th ICHEP (1960)

M. A. Markov

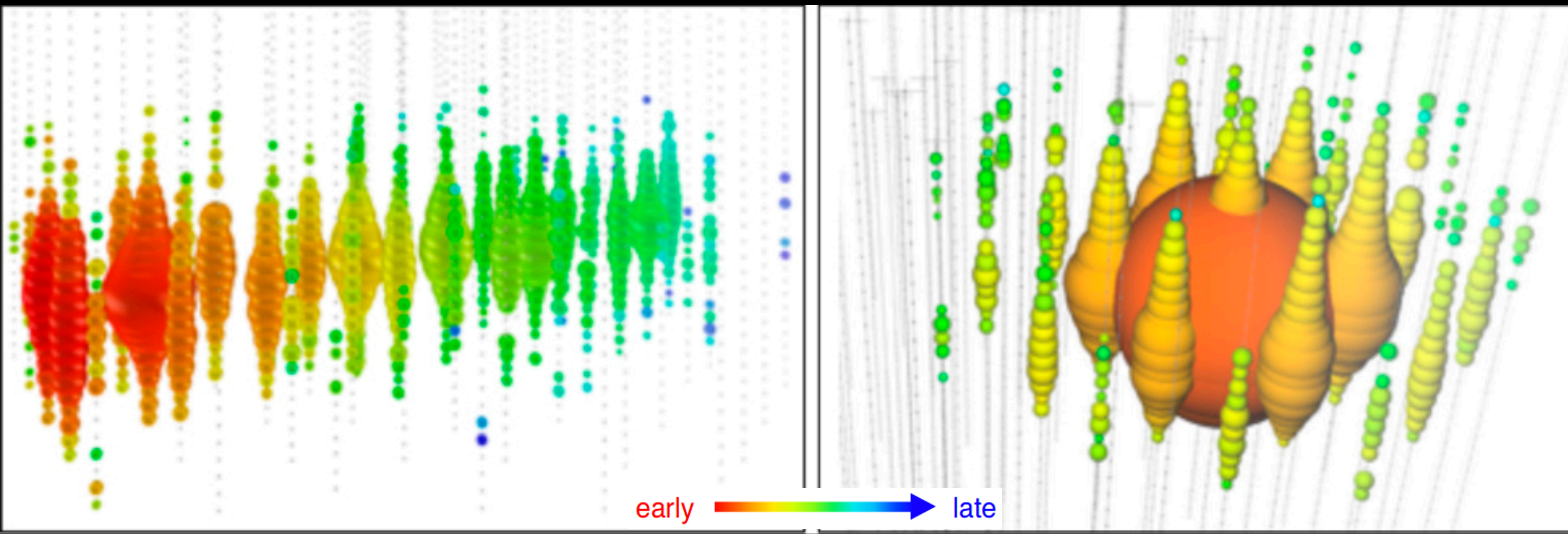
Joint Institute for Nuclear Research, Dubna, USSR

In the papers by Zheleznykh and myself (1958, 1960) possibilities of experiments with cosmic ray neutrinos are analyzed. We have considered those neutrinos produced in the earth's atmosphere from pion decay. From the known μ spectrum the neutrino energy spectrum is reconstructed. We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Čerenkov radiation. We consider μ mesons

A gigantic dark volume filled with photosensors



Neutrino Event Topologies



"tracks"

- CC ν_μ interactions
- Ideal tool for astronomy
- Excellent angular resolution + Large effective volume
- Larger atmospheric backgr.

"showers"

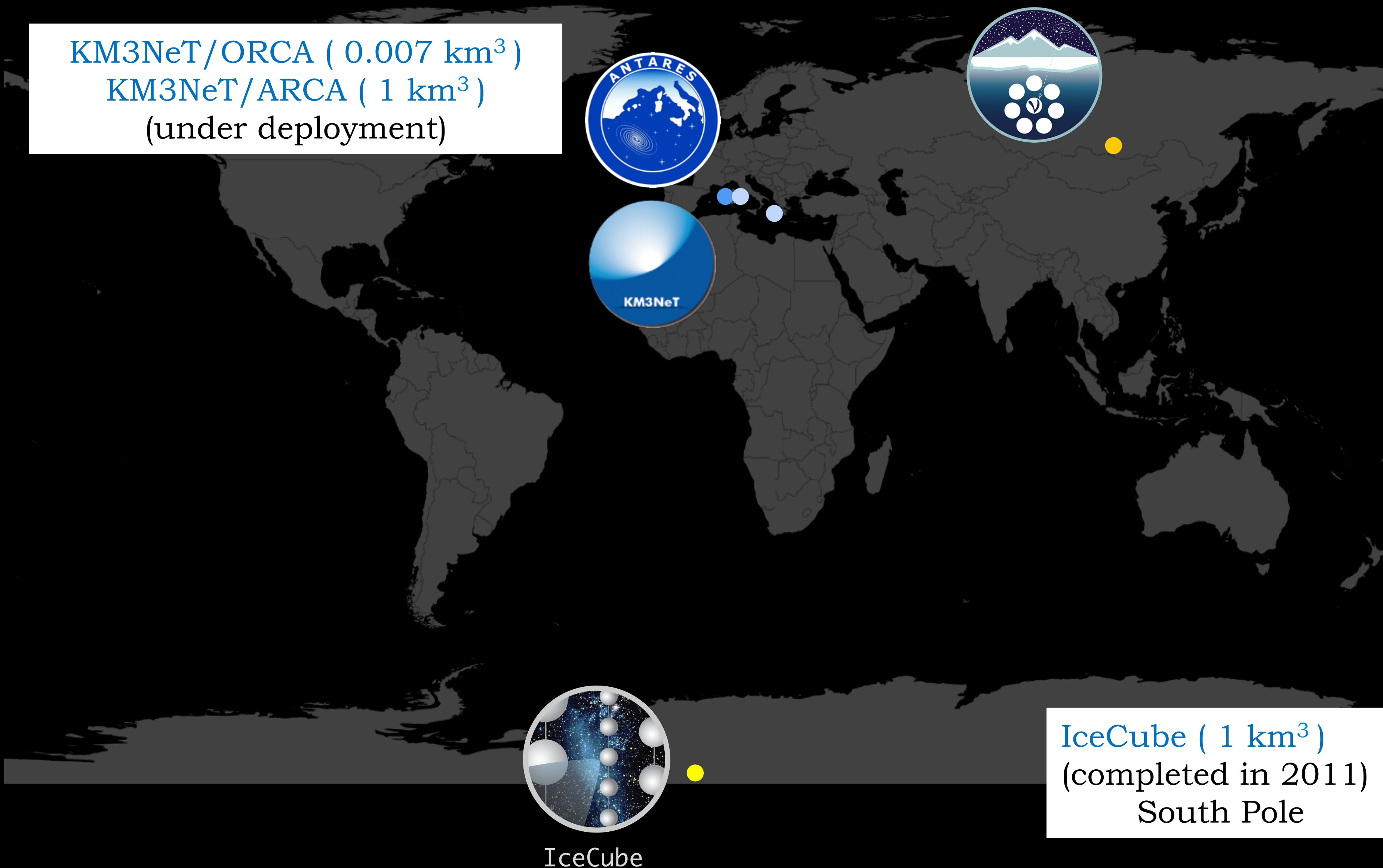
- NC / CC ν_e interactions, most ν_τ
- Contained events → Better energy resolution
- Almost no atmospheric backgr.

Who

ANTARES (0.01 km^3)
(2007 – 2022)
Mediterranean Sea

Baikal-GVD (0.4 km^3)
(1998 + upgrading)
Lake Baikal (Russia)

KM3NeT/ORCA (0.007 km^3)
KM3NeT/ARCA (1 km^3)
(under deployment)



IceCube (1 km^3)
(completed in 2011)
South Pole

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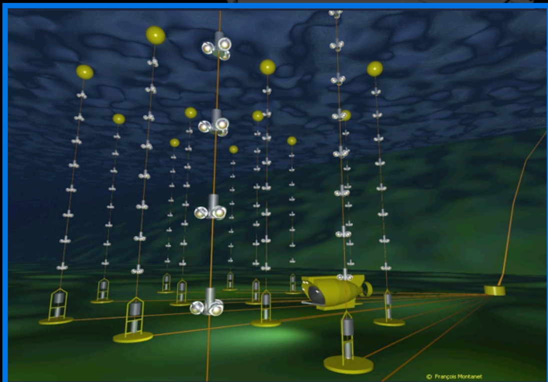

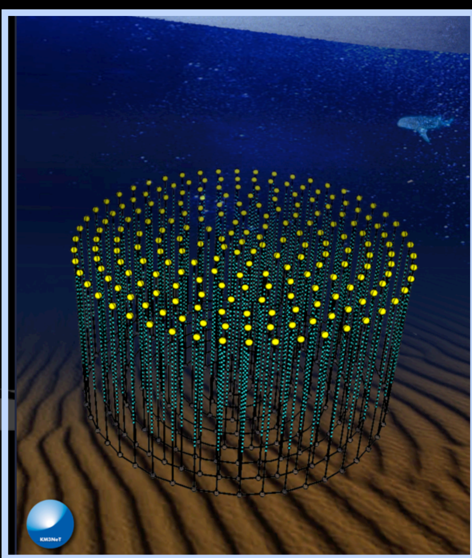

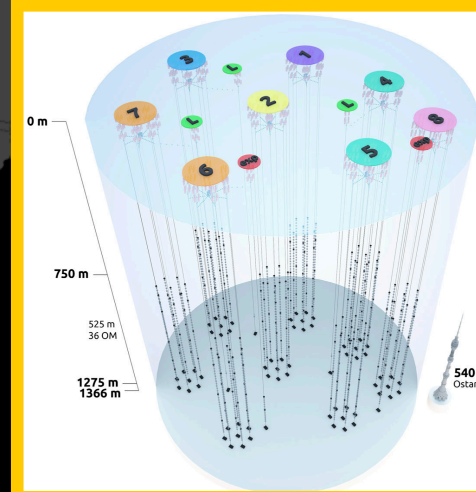

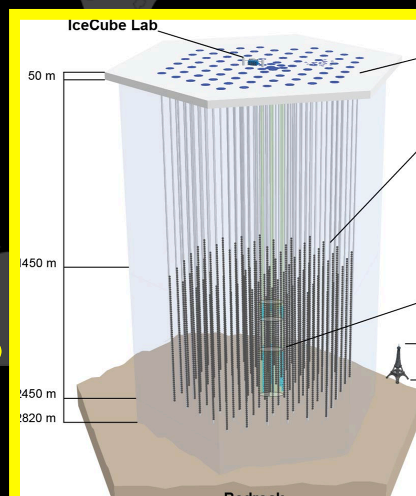

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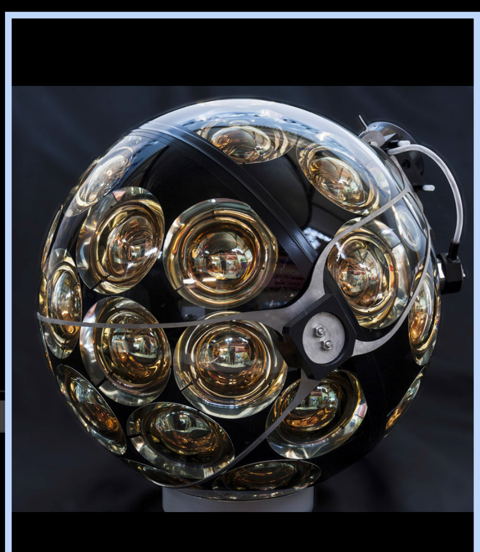
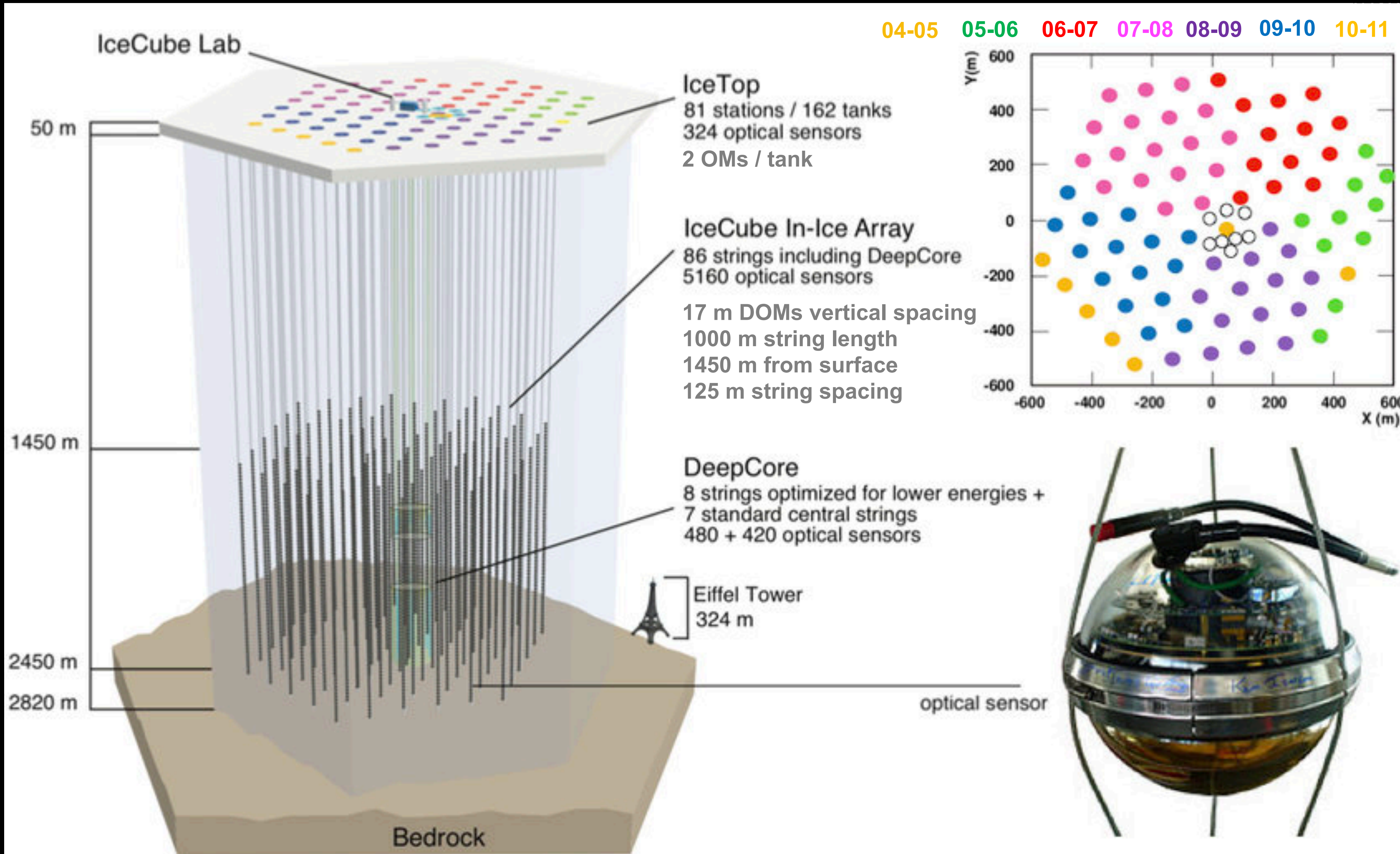


IceCube (1 km^3)
(completed in 2011)
South Pole

Antarctica : IceCube (1 km^3)

JINST 12 P03012 (2017)

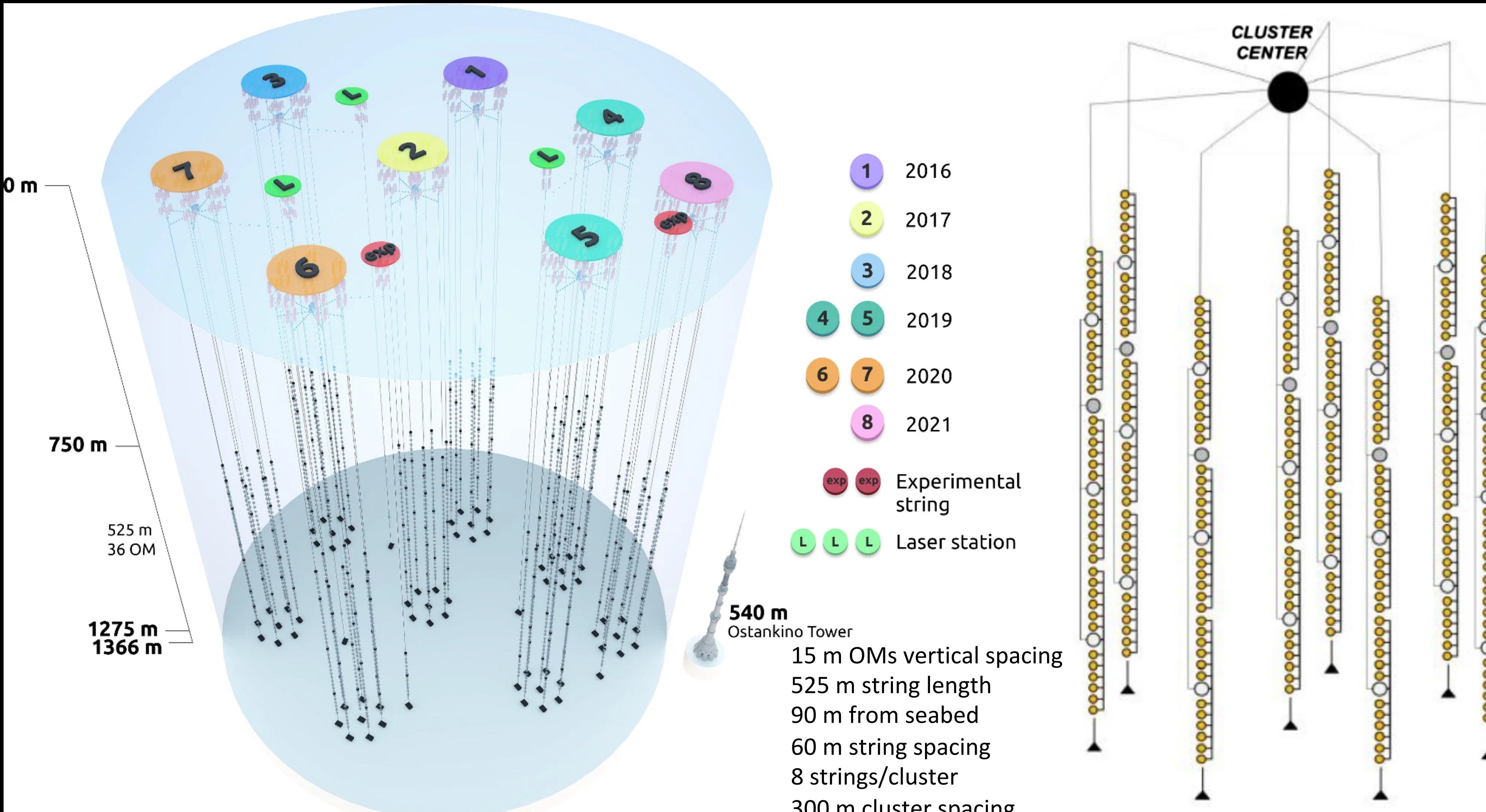


2820 m depth

5160 OMs | 60 DOMs/string | 17 m DOM vertical spacing | 125 m string spacing

GVD-Baikal (0.4 km^3 in 2021)

DOI: 10.22323/1.395.0002

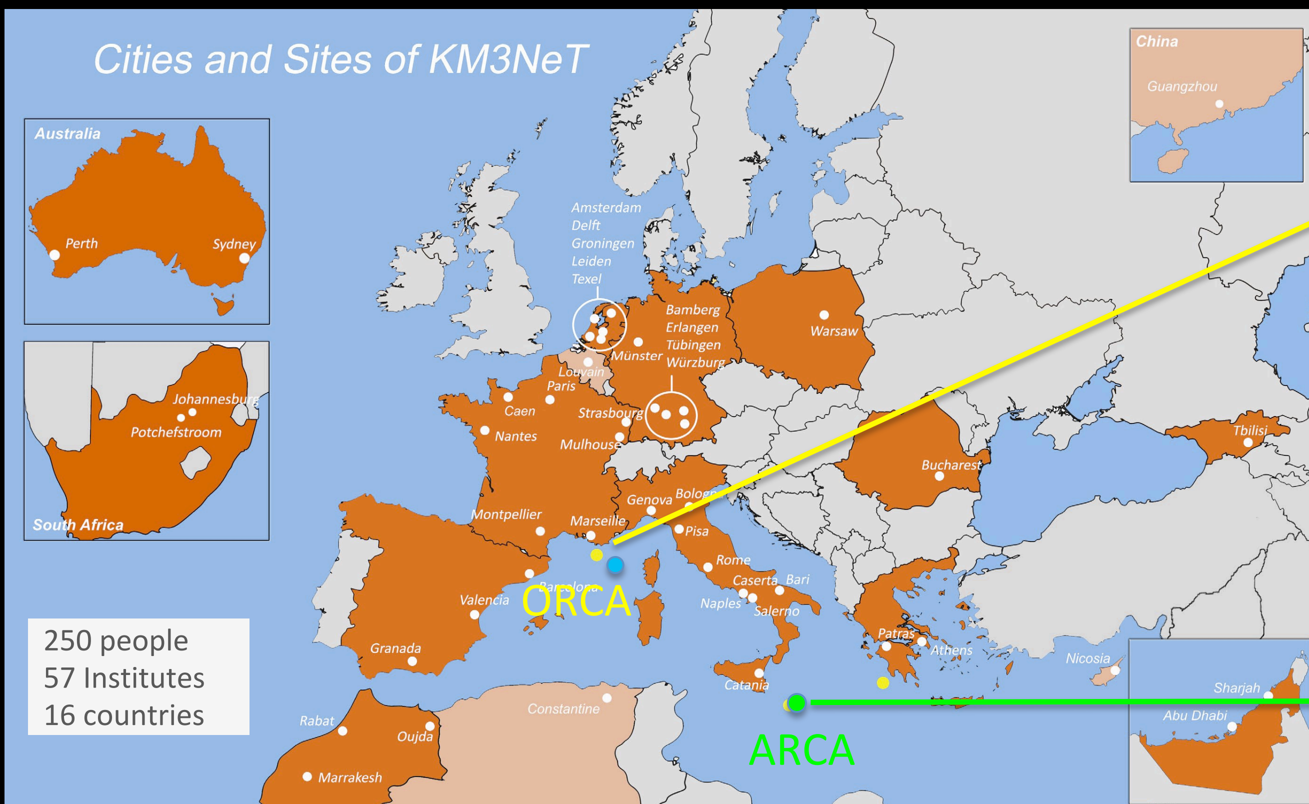


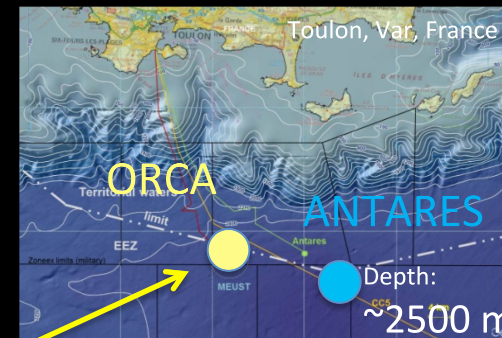
1366 m depth
36 OMs/string | 8 strings / cluster | 8 clusters deployed = 2304 PMTs (10-inch) |
6 more clusters by 2025

Mediterranean Sea: ANTARES and KM3NeT

ANTARES: ~10 Mt instrumented mass. Completed in 2008

KM3NeT: A distributed research infrastructure with
<u>2 main physics topics</u>: ORCA & ARCA

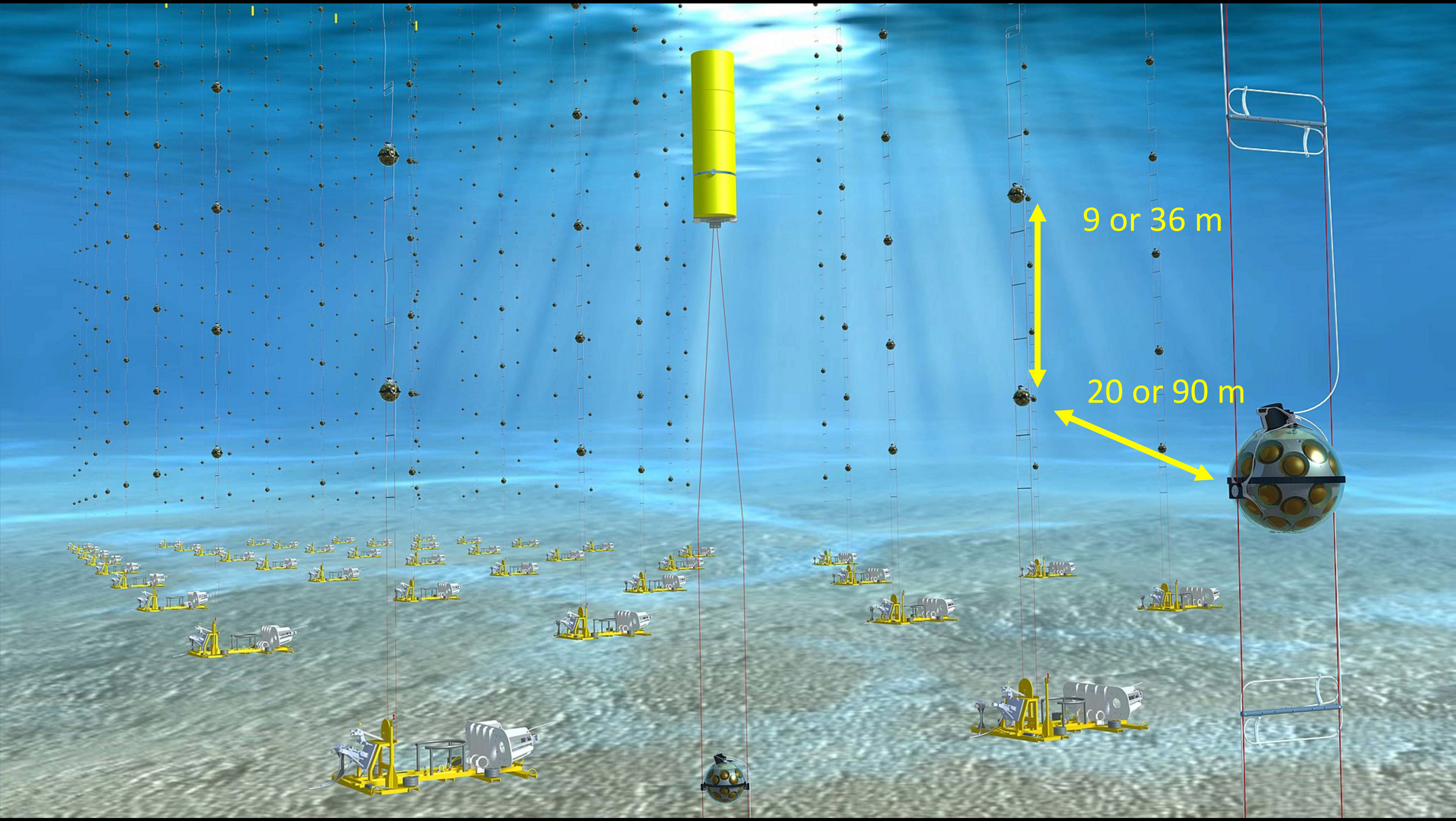




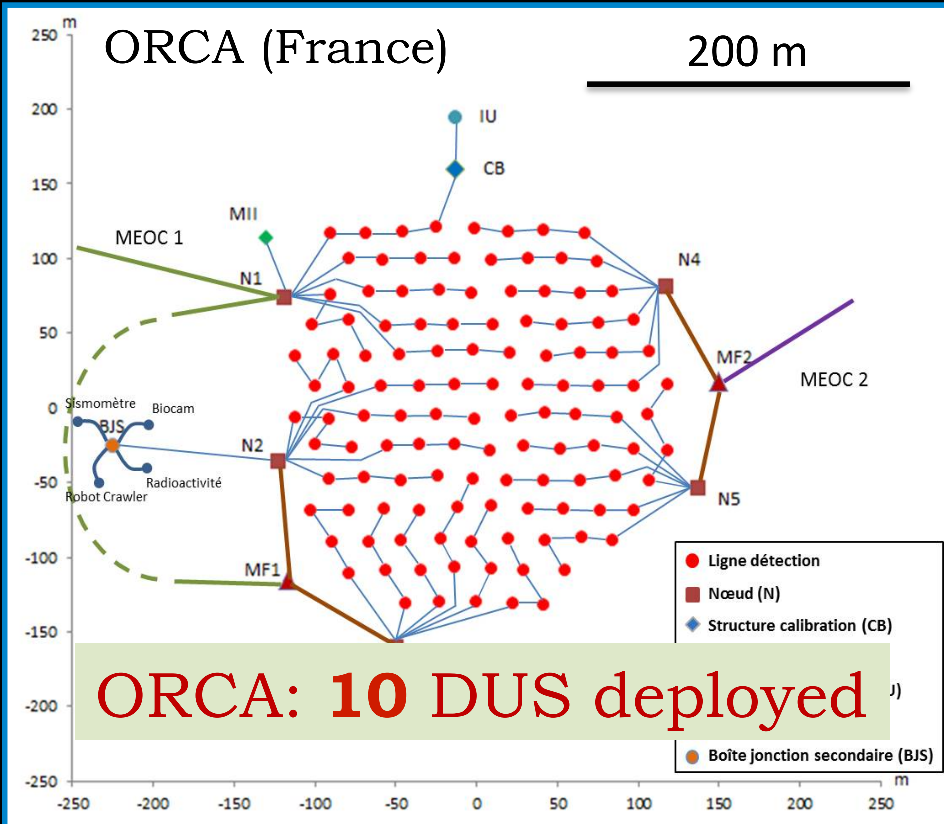
Low-energy (~GeV) studies of atmospheric neutrinos

High-energy (TeV-PeV) neutrino astrophysics

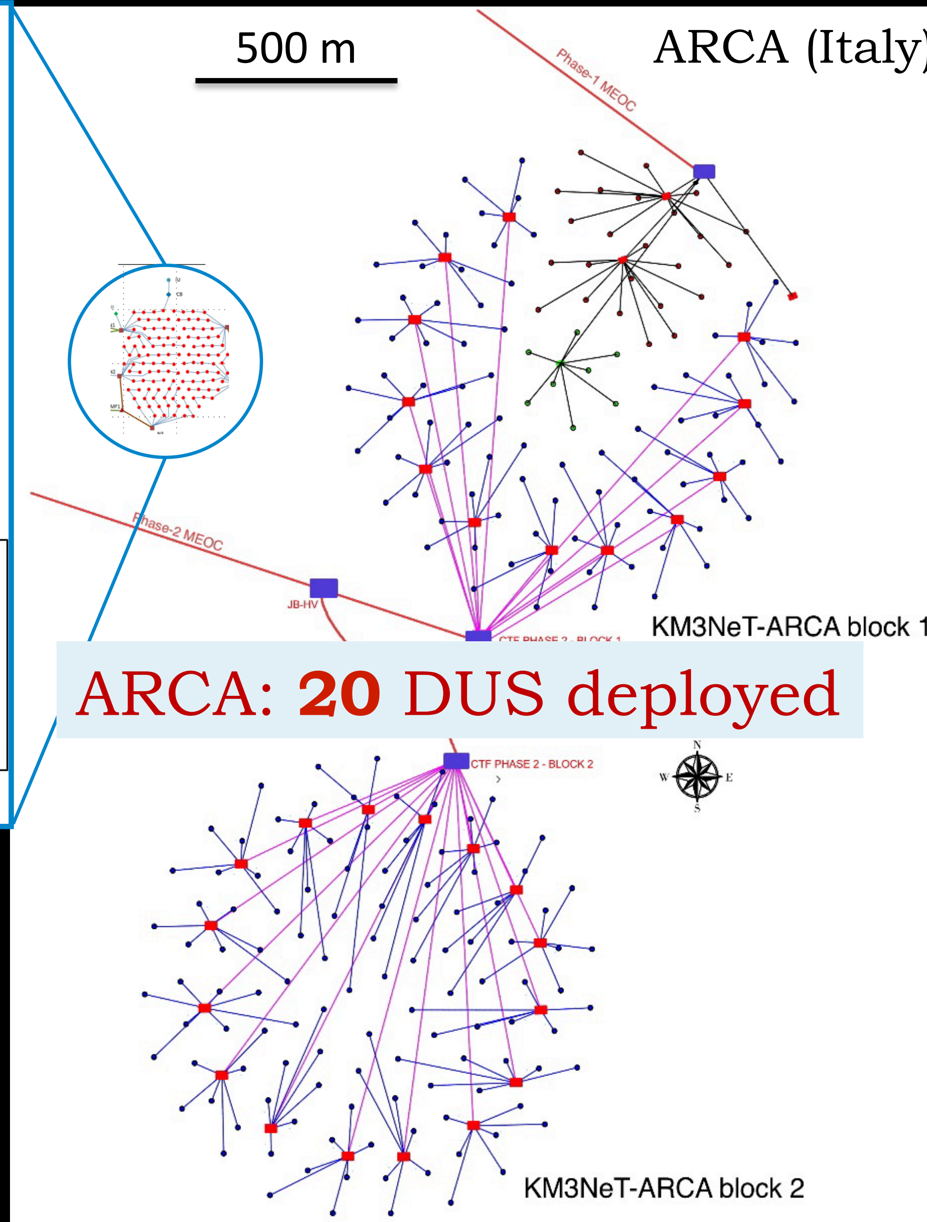
KM3NeT: ORCA and ARCA



KM3NeT: Building Blocks



ORCA: 10 DUS deployed

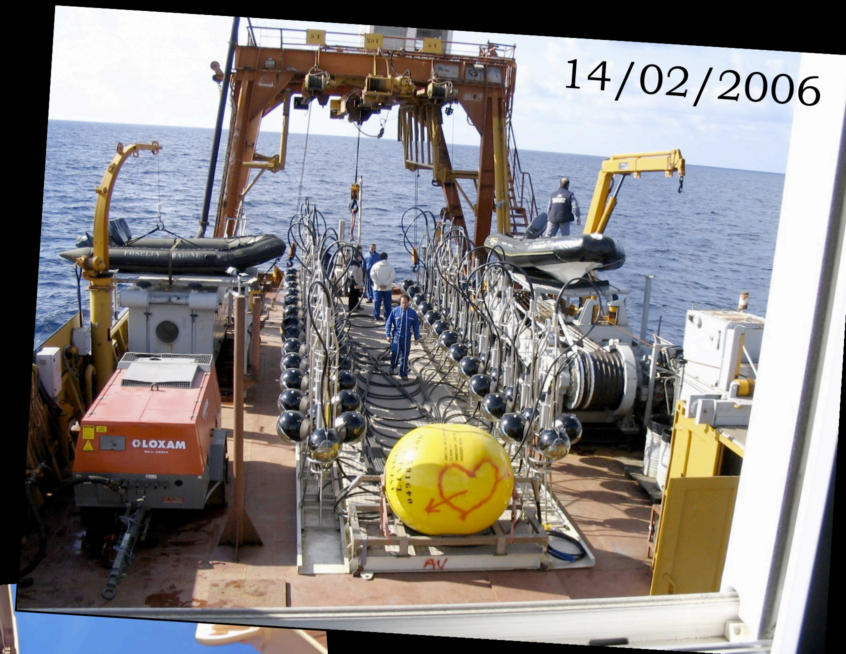


ARCA: 20 DUS deployed

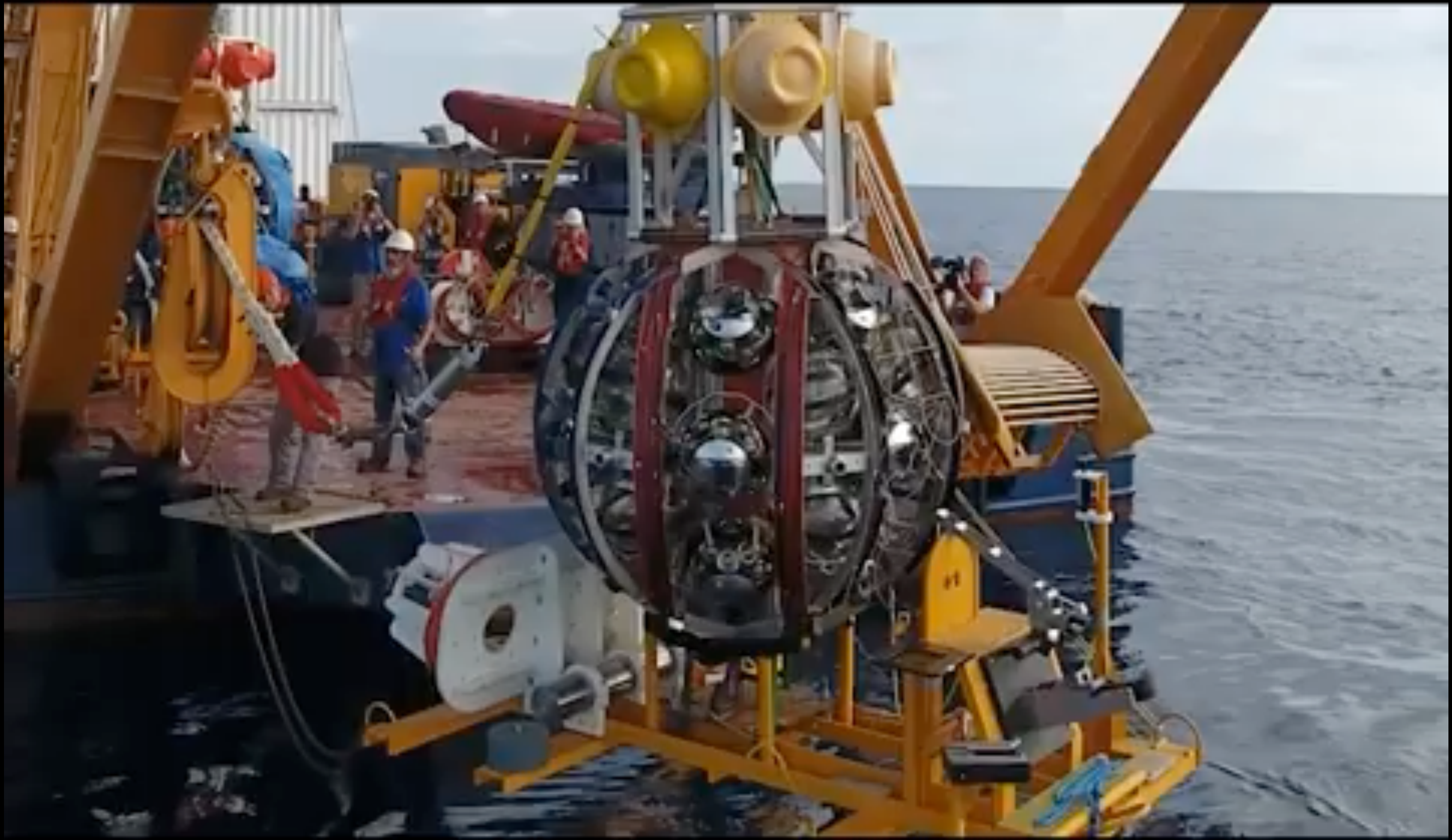
	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
DU length	200 m	700 m
Instrumented mass	7 Mton	~ 2 × 0.5 Gton

ANTARES: decommissioned on May 2022

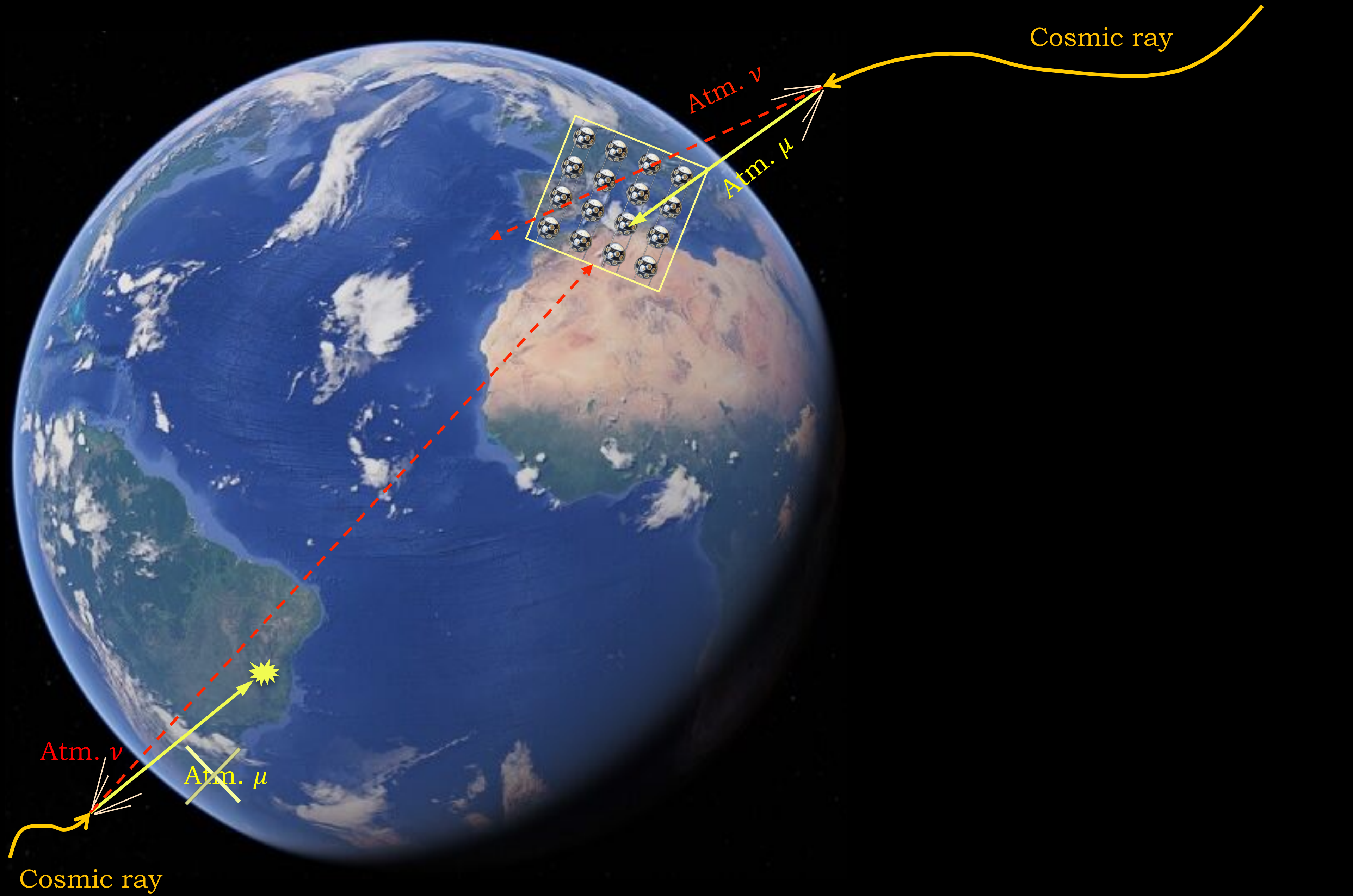
- First Under-Sea neutrino telescope
- Precursor to KM3NeT
- Competitive results
  - Northern hemisphere
  - Galactic plane
  - Dark matter
- Decommissioned after14 years of operation.



KM3NeT-ORCA Detector Unit Deployment



Signal and Background in Neutrino Telescopes



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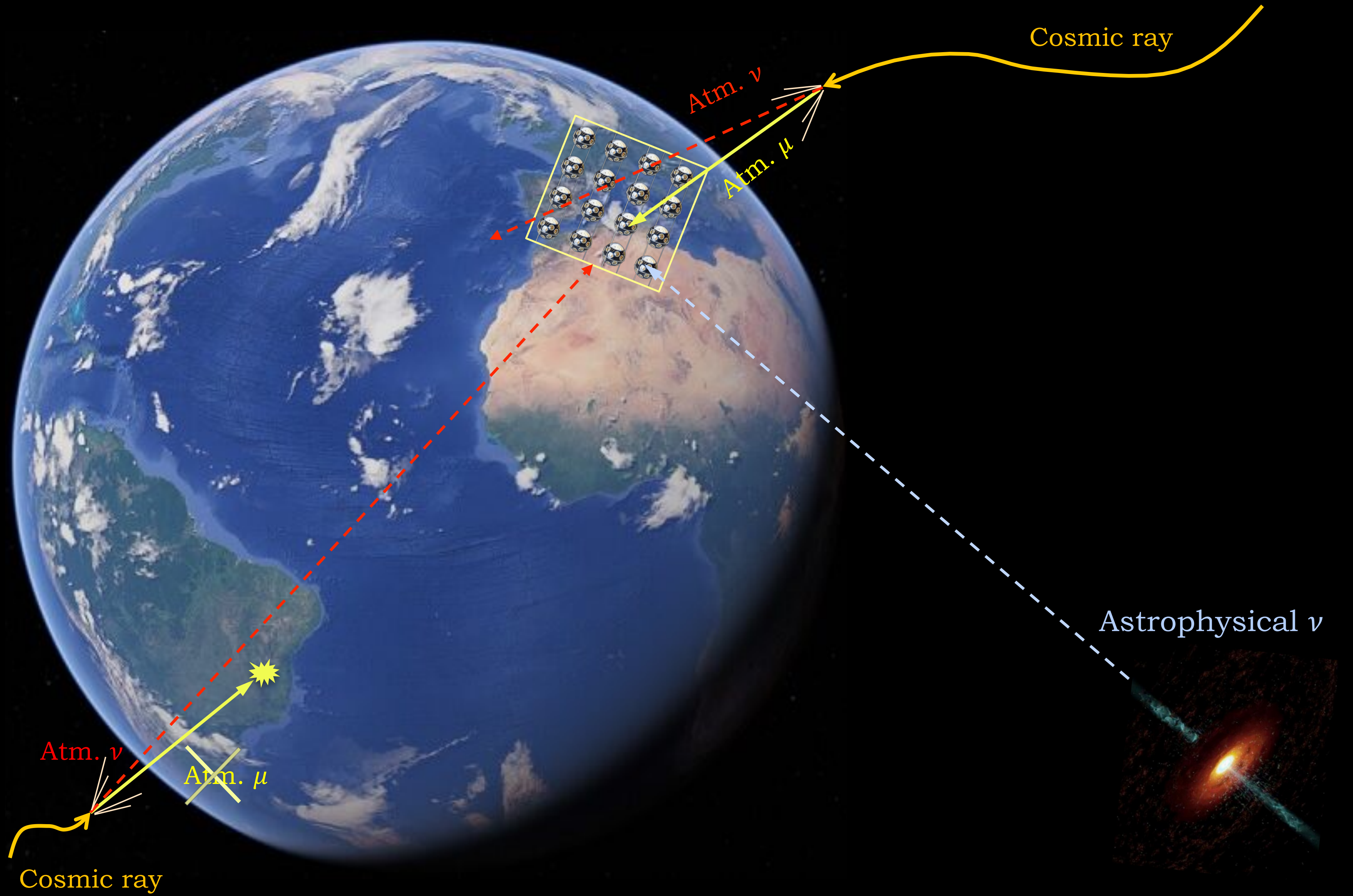
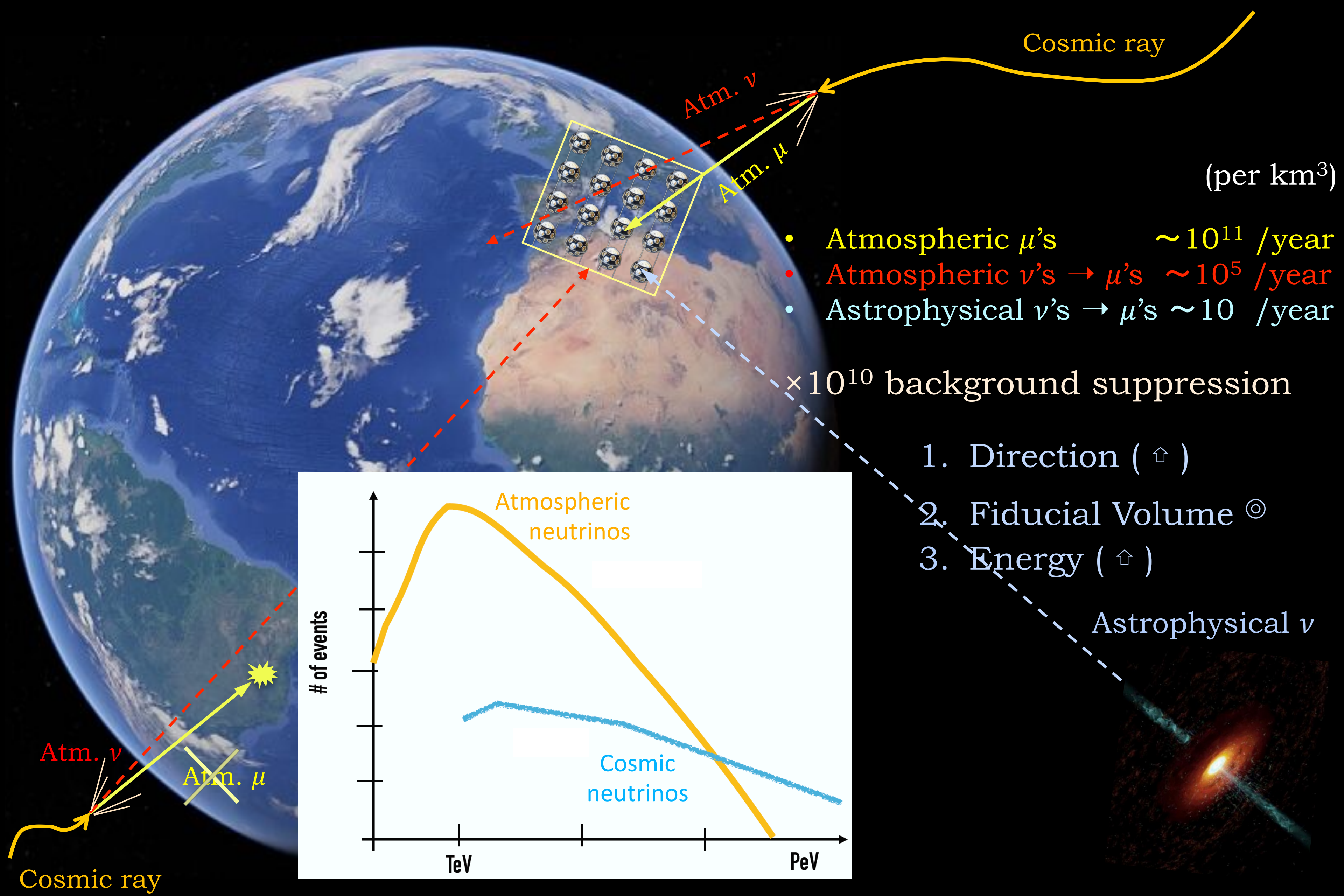
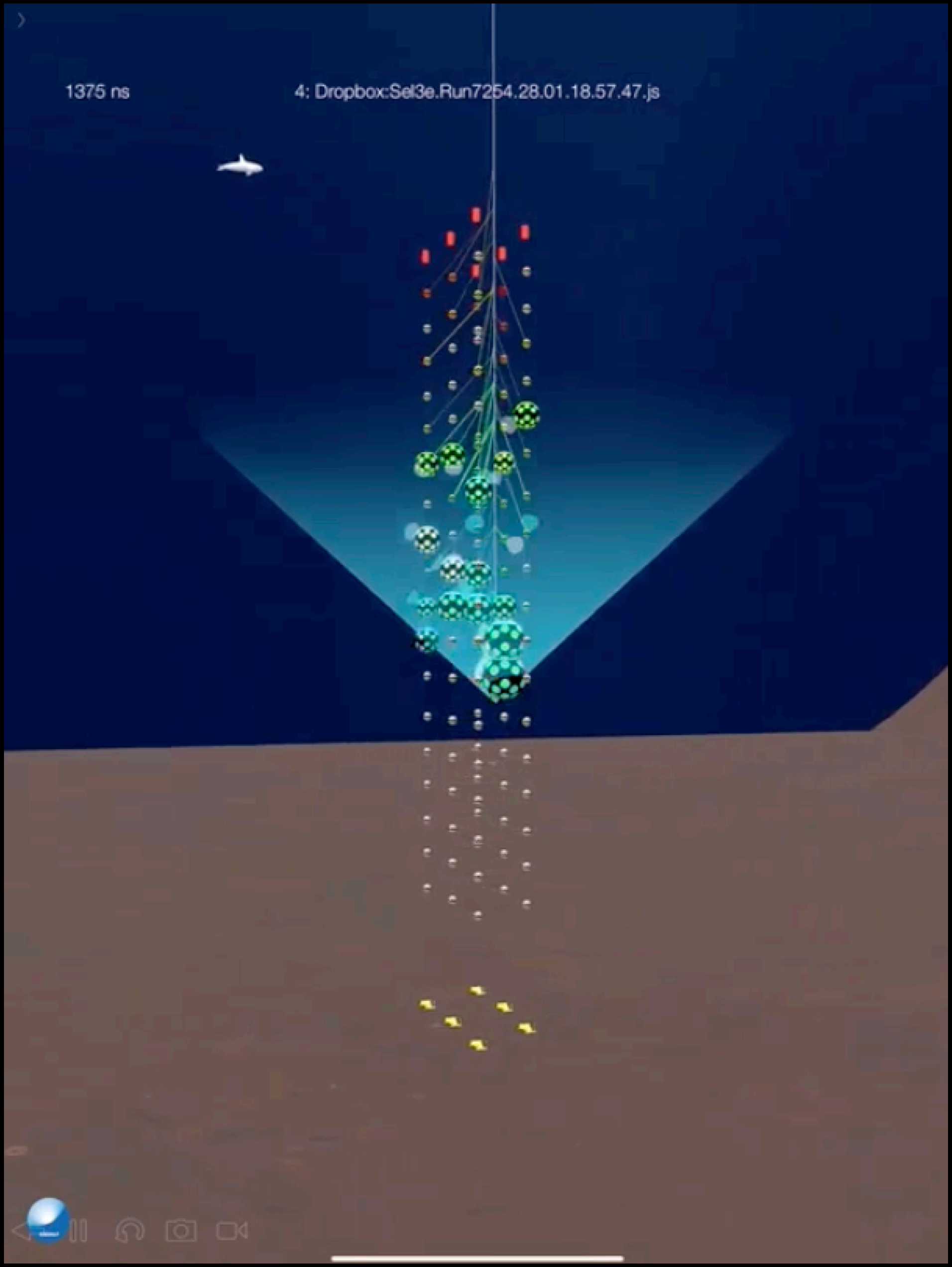


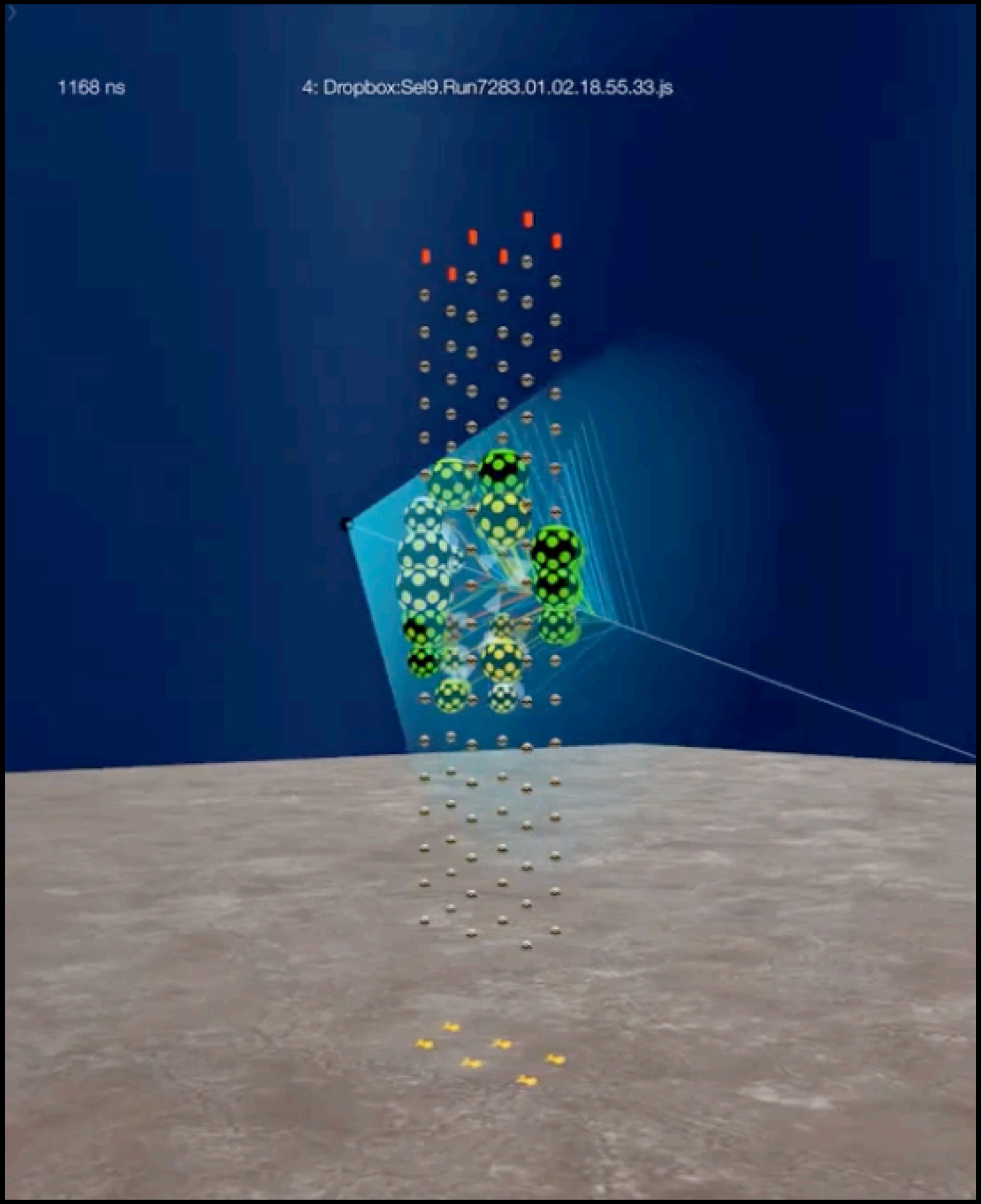
Signal and Background in Neutrino Telescopes



KM3NeT/ORCA-6 atmospheric muons



KM3NeT/ORCA-6 neutrino candidates

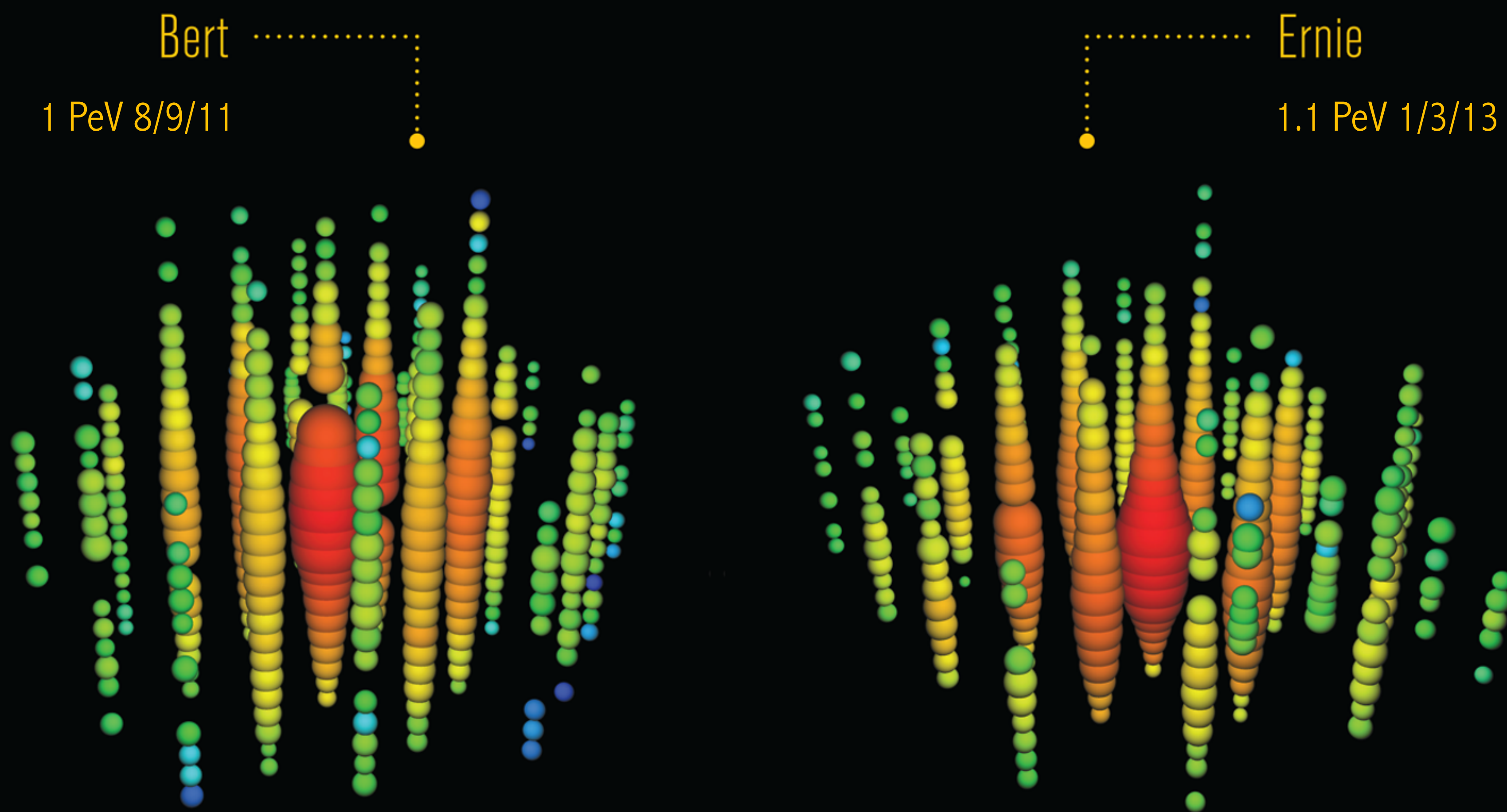


What

- Astrophysical ν
- Atmospheric ν beam

First Detection of Astrophysical Neutrinos

IceCube



- PeV neutrinos observed for the first time (IC, PRL 111 (2013), 021103)
- Are there more?

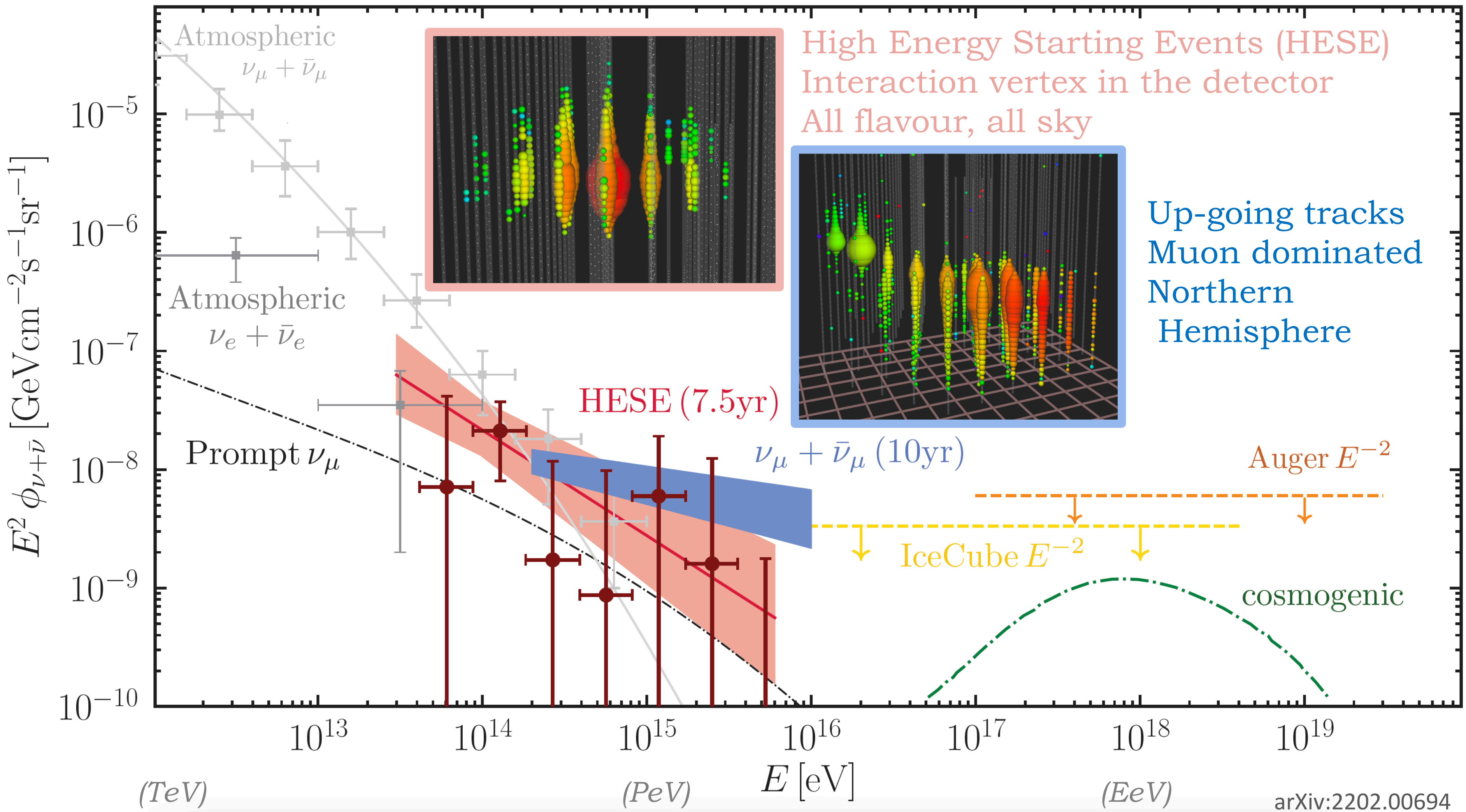
I. Astrophysical Diffuse Flux: solid confirmation

IceCube

Baseline spectral model for astrophysical flux:

$$\frac{d\Phi}{dE} = \Phi_{astro} \times \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma_{astro}}$$

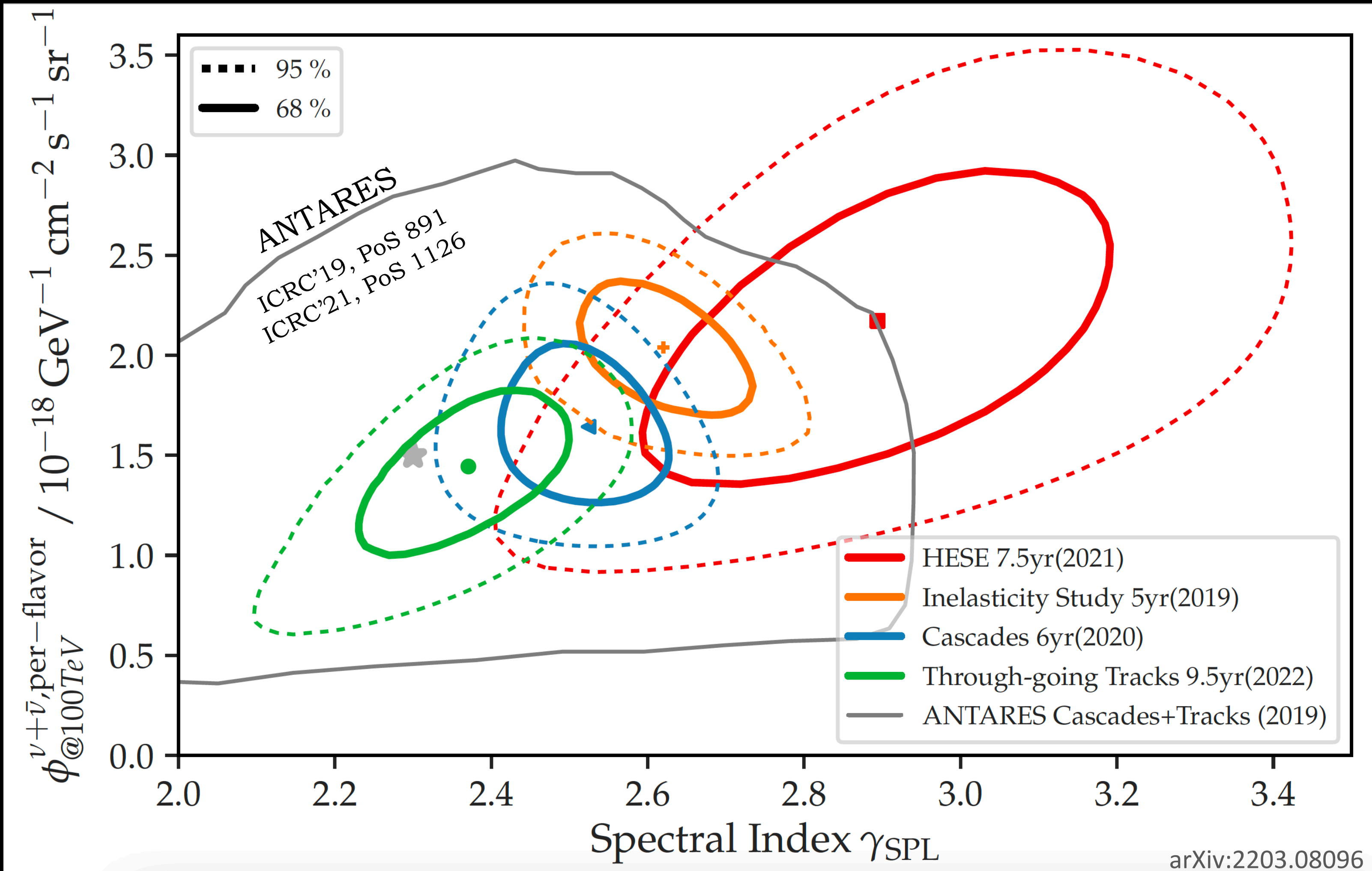
(single power law with normalization and slope)



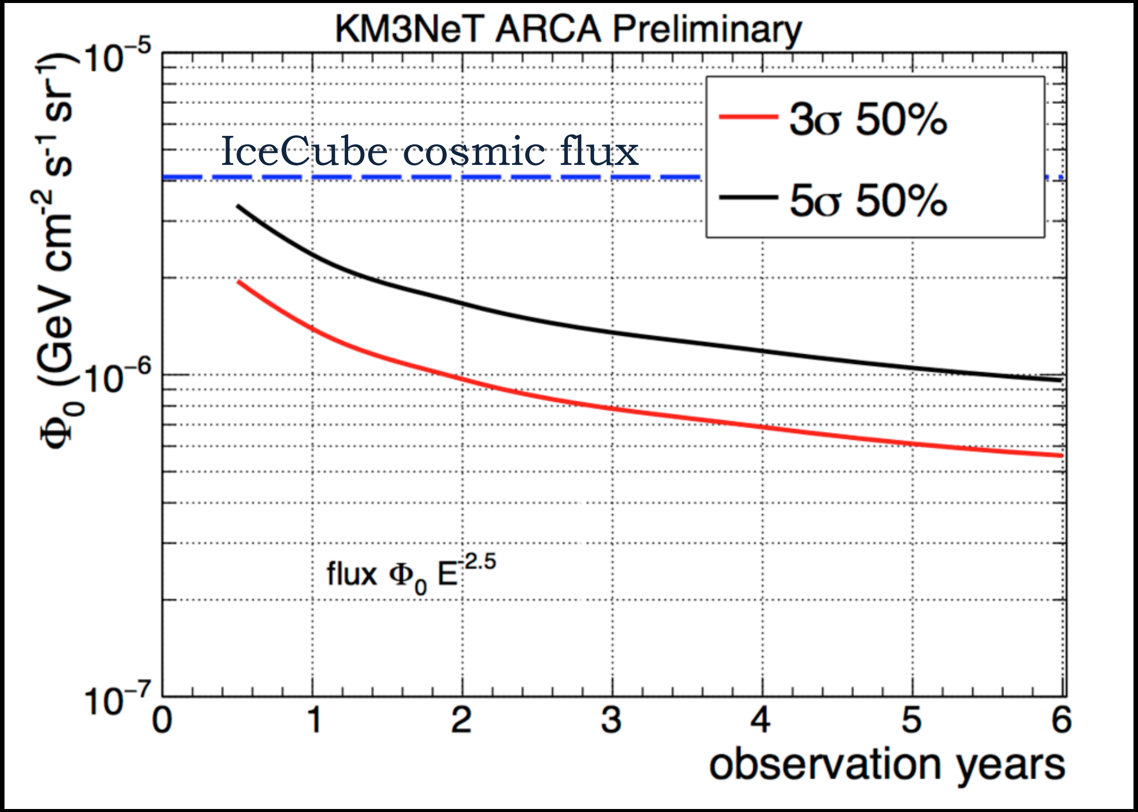
arXiv:2202.00694

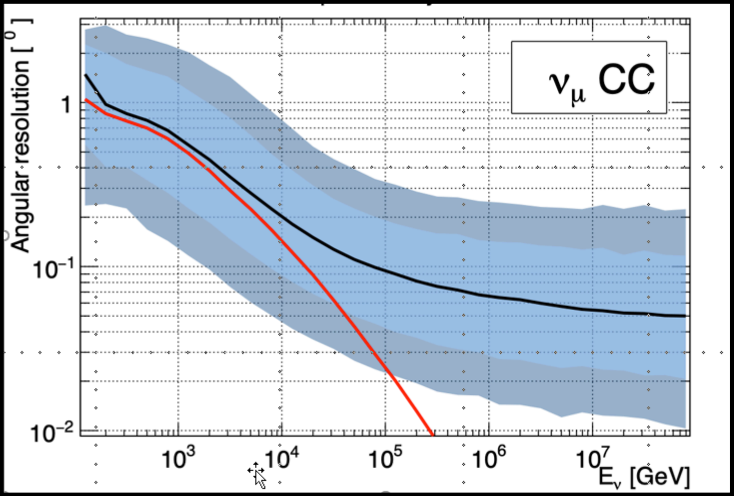
I. Astrophysical Diffuse Flux

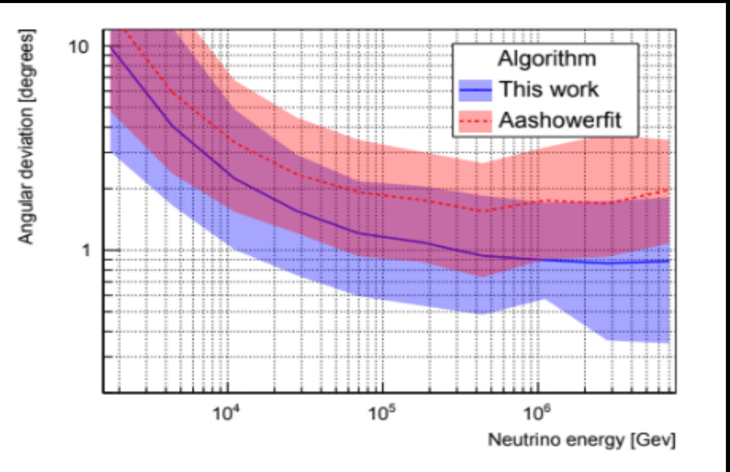
- Measured with multiple independent analyses/selections
- Global agreement on Flux & Index (assuming single power-law distribution)
- Slight tension may be caused by differences in flavour composition, energy range, background, …



I. ARCA: Astrophysical Diffuse Flux







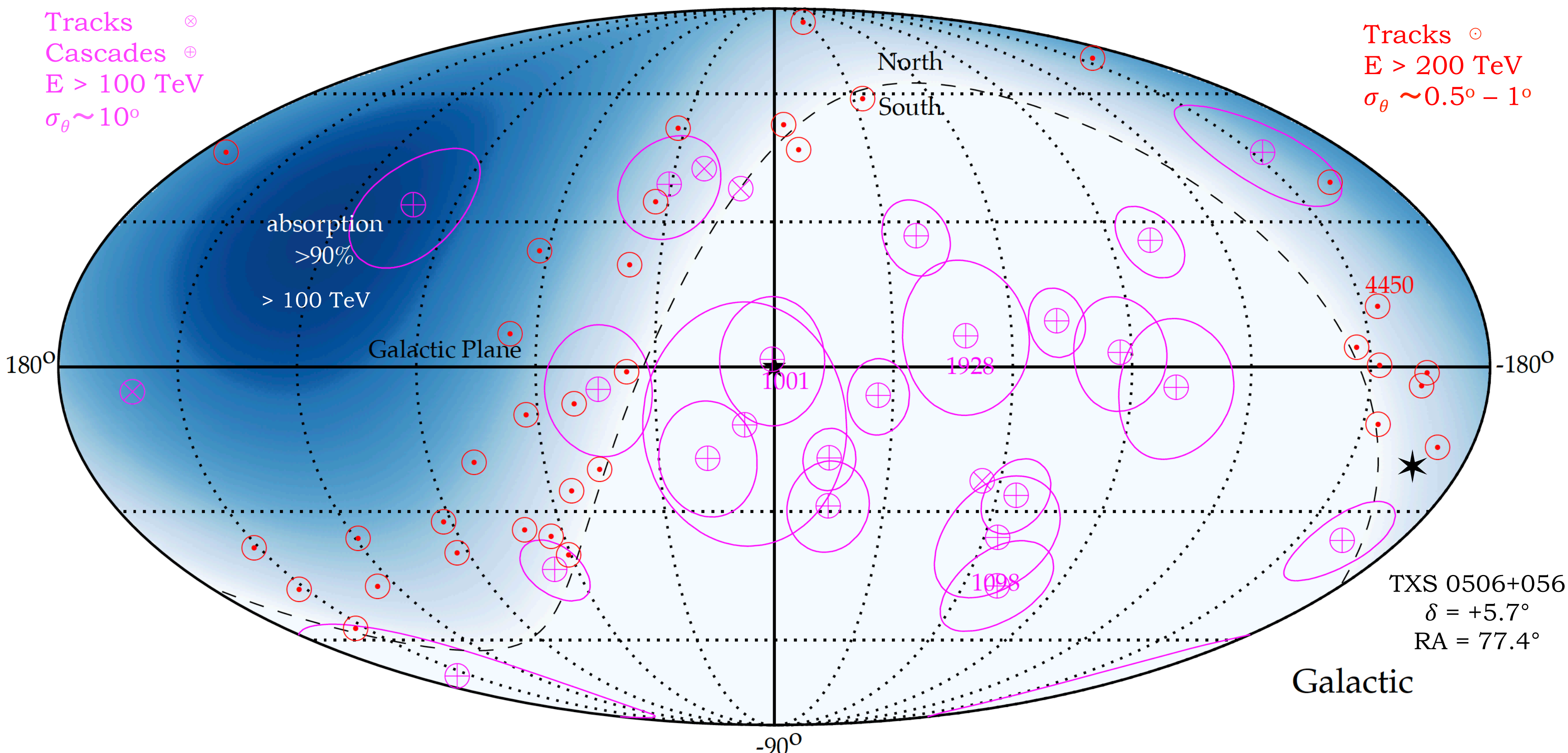
- ARCA can confirm the IceCube diffuse flux within 1 year of data taking (full detector)
- With a much better angular resolution for both tracks and cascades

Which is the origin of the observed neutrinos?

IceCube

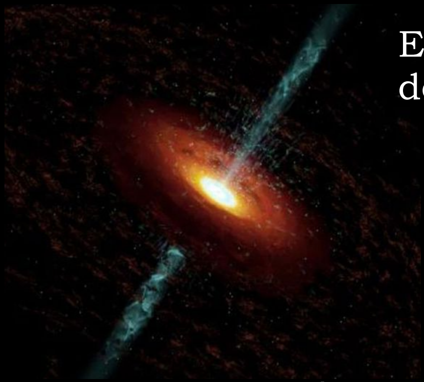
- Consistent with isotropic distribution ⇨ favours extra-galactic origin
- No dominant contribution from the Galactic Plane ⇨ contribution < 10%

Arrival directions of most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))



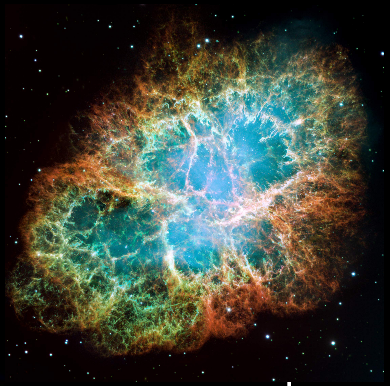
arXiv:2202.00694

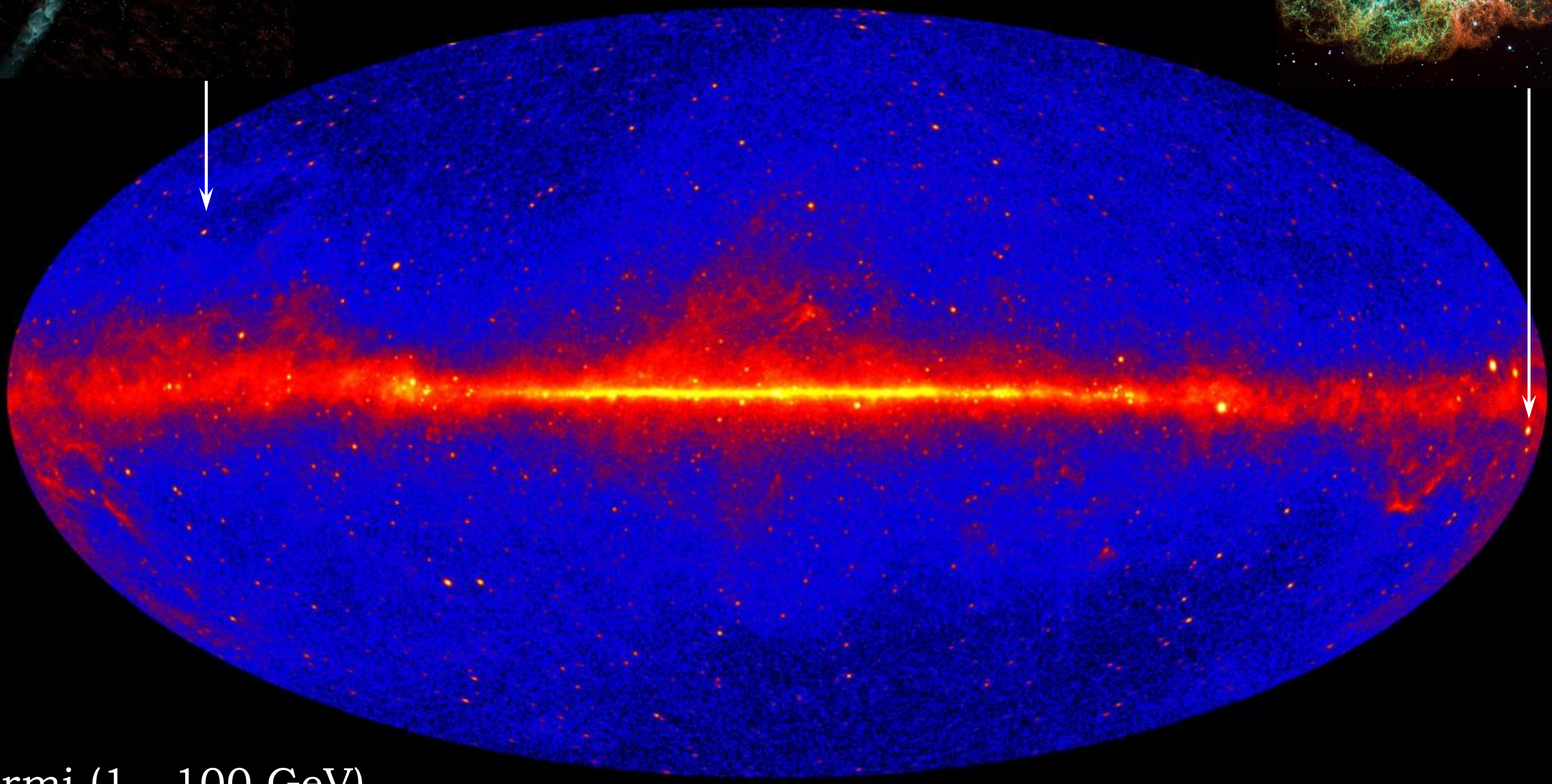
Gamma–rays as tracers of neutrinos



Extragalactic sky
dominated by Blazars

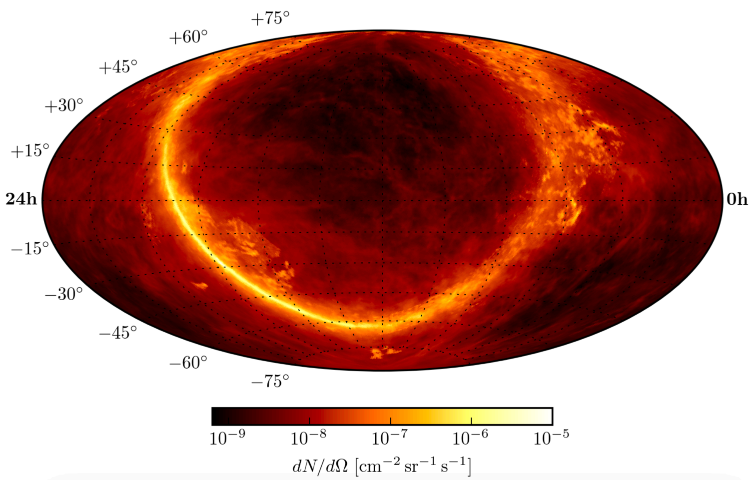
Galactic gamma-rays from
diffuse emission and discrete
sources (SNRs, PWNs, ...)



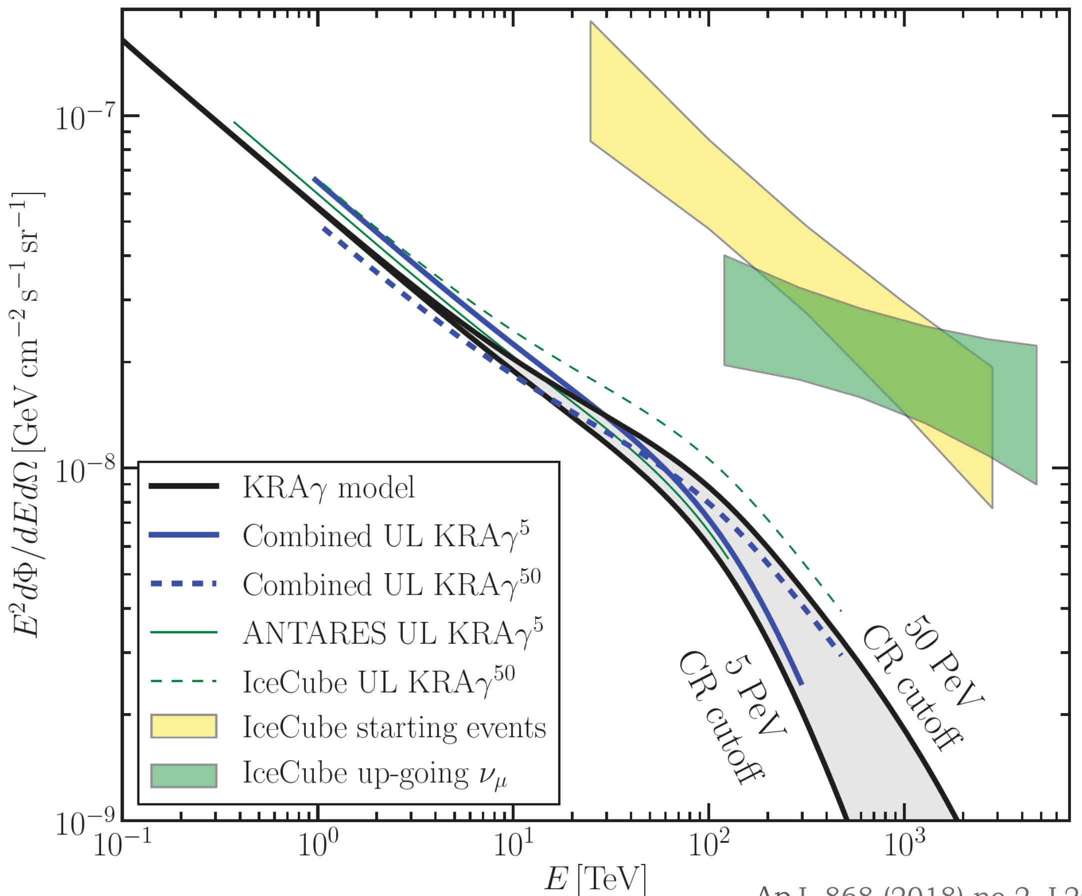


Fermi (1 - 100 GeV)

Galactic Neutrinos (from the Milky Way) ?



IceCube + ANTARES combined



ApJ. 868 (2018) no.2, L20

- No significant correlation with Galactic Plane so far ⇨ contribution < 8.5% of the astrophysical flux.
- Multimessenger motivation: correlation with potential hadronic γ-ray signals

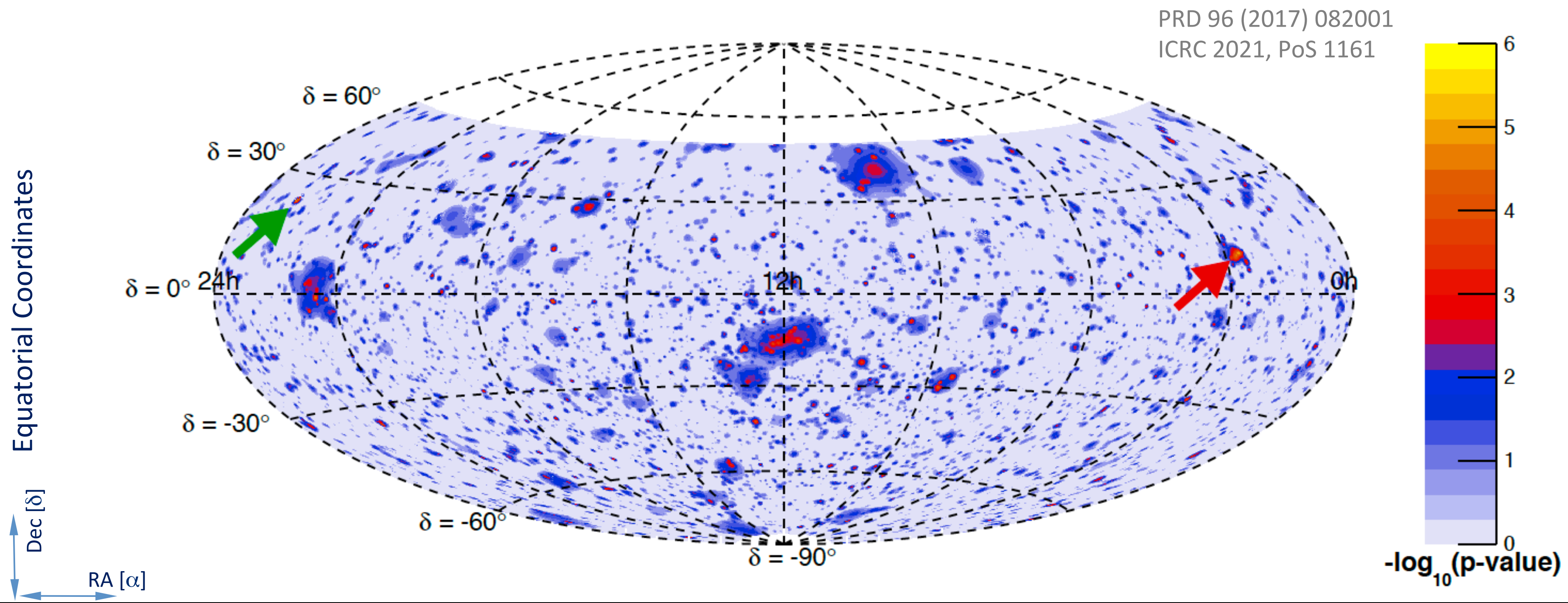
Clusters of Neutrinos ? All-Sky Search

ANTARES Data: 2007 – 2020 (3845 days) → 10162 tracks + 225 showers

- Full sky (no source assumption)
- No significant evidence of cosmic neutrino sources found

(RA, δ) = (343.7º, 23.6º) close to Radio Blazar J0242+1101
(RA, δ) = (39.6º, 11.1º) close to Blazar MG3 J225517+2409

PRD 96 (2017) 082001
ICRC 2021, PoS 1161

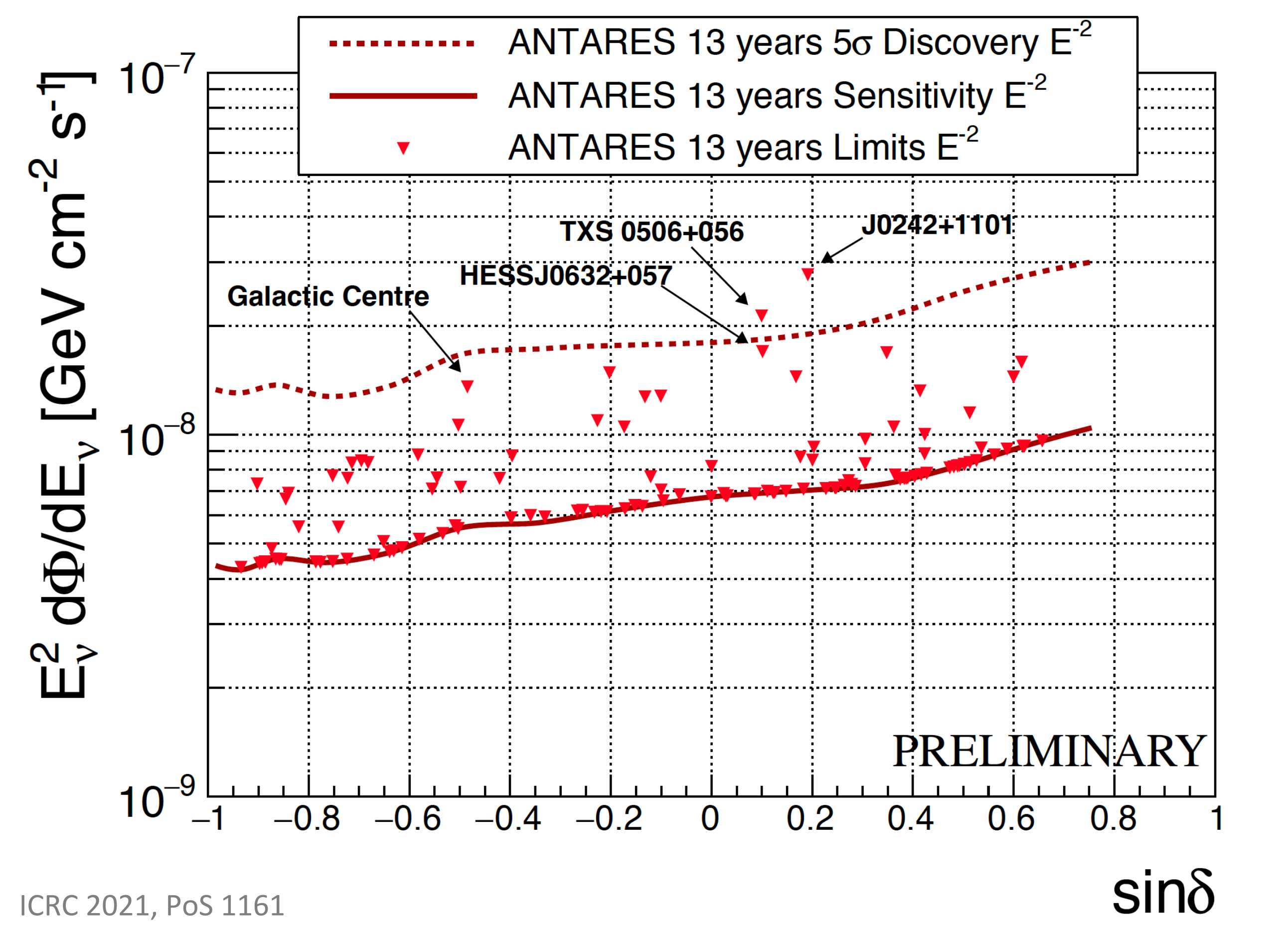


Full sky search: pre-trial *p-values* for a point-like source of the ANTARES visible sky.

Point Sources of Neutrinos: Catalogue Search

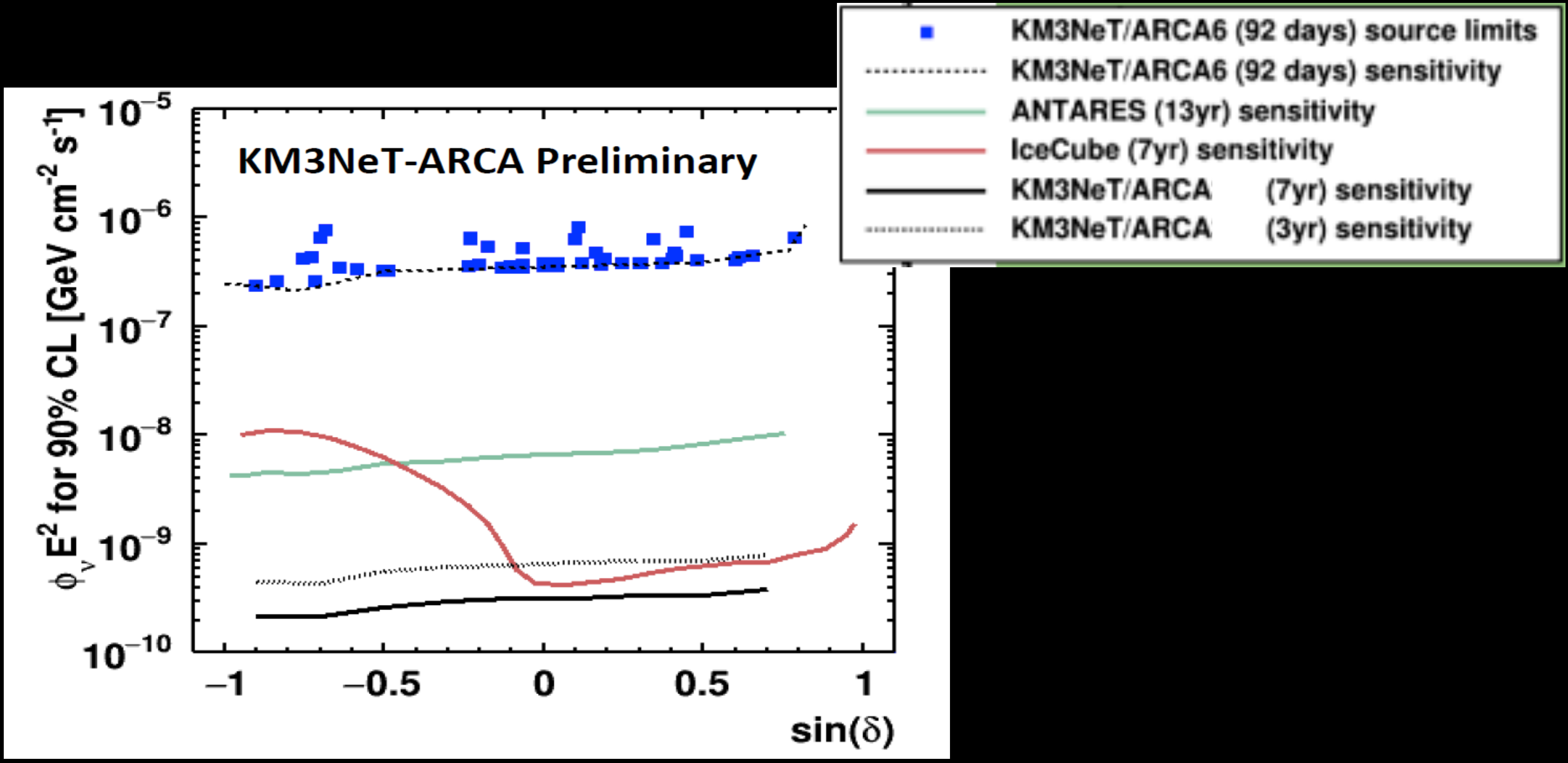
ANTARES Data: 2007 – 2020 (3845 days) → 10162 tracks + 225 showers

- 121 Catalogue sources investigated (galactic + extragalactic)
- No significant evidence of cosmic neutrino sources found



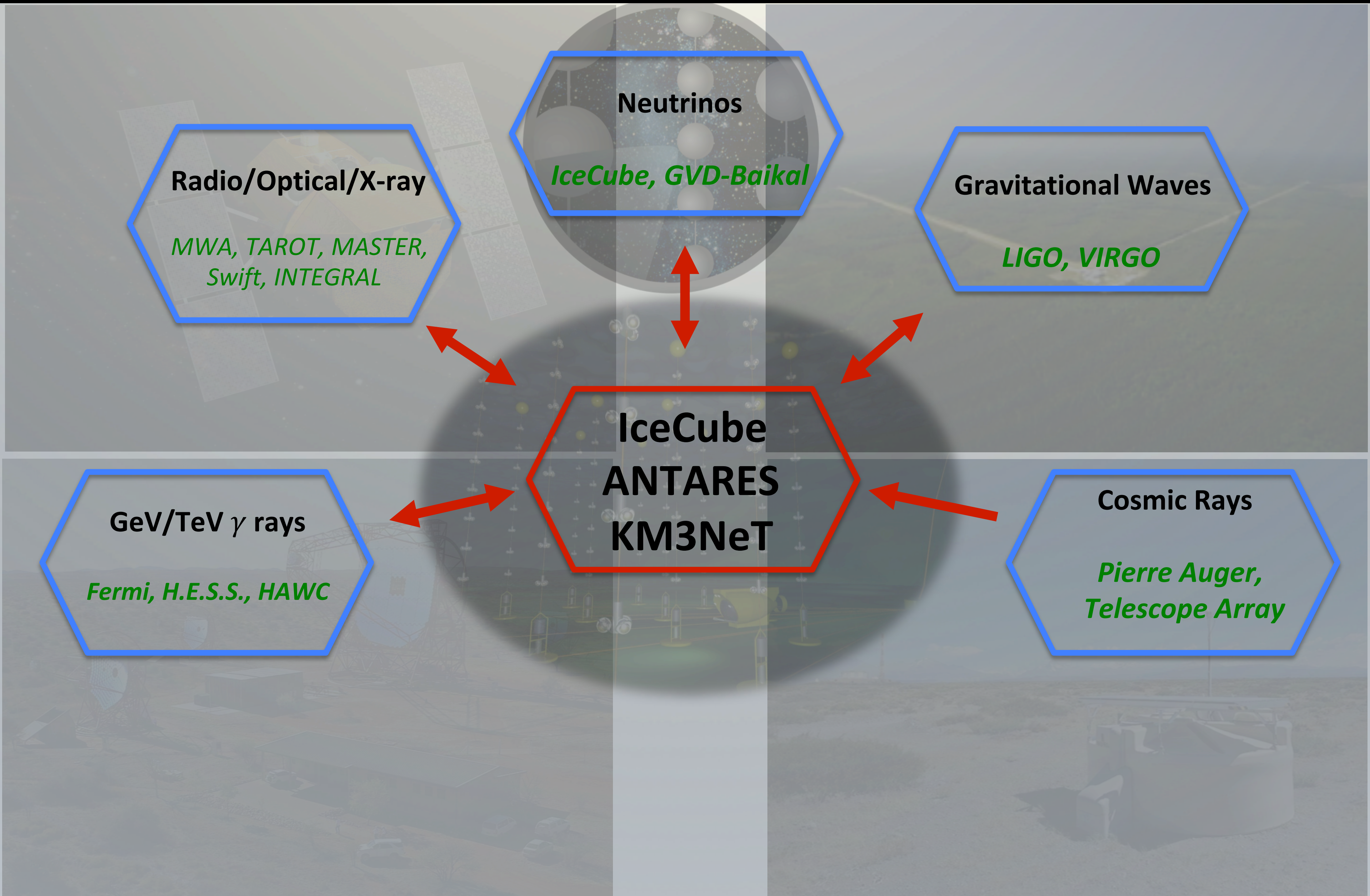
ICRC 2021, PoS 1161

II. ARCA: Search for Point-like Sources

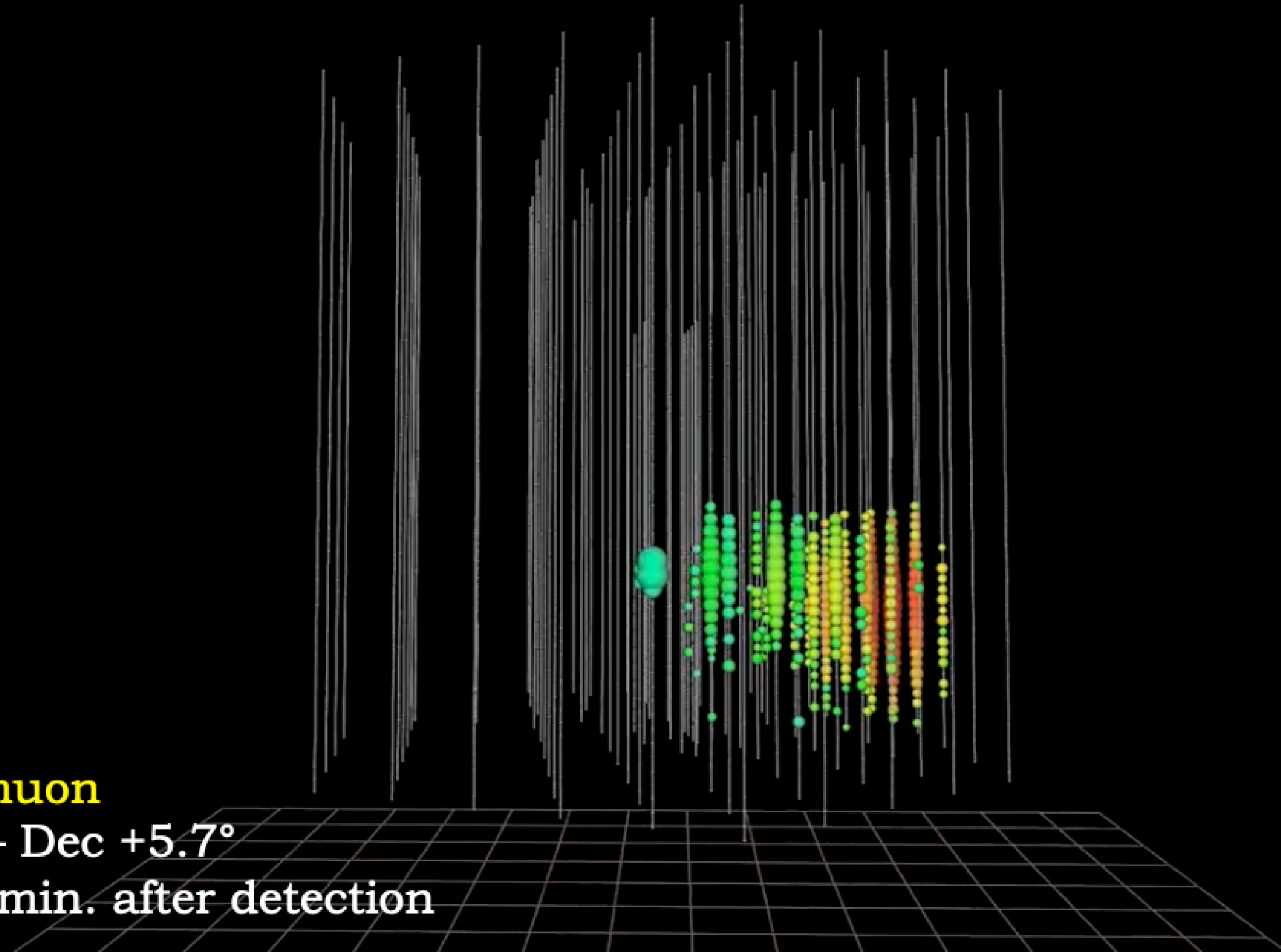


- ARCA6 DUs for 100 days: First point-like source search results
- Time integrated source search
- Angular resolution ∼1.3° for E^{-2}
- No significant excess observed ➪ No competitive results yet.

V. Real-Time Alert System

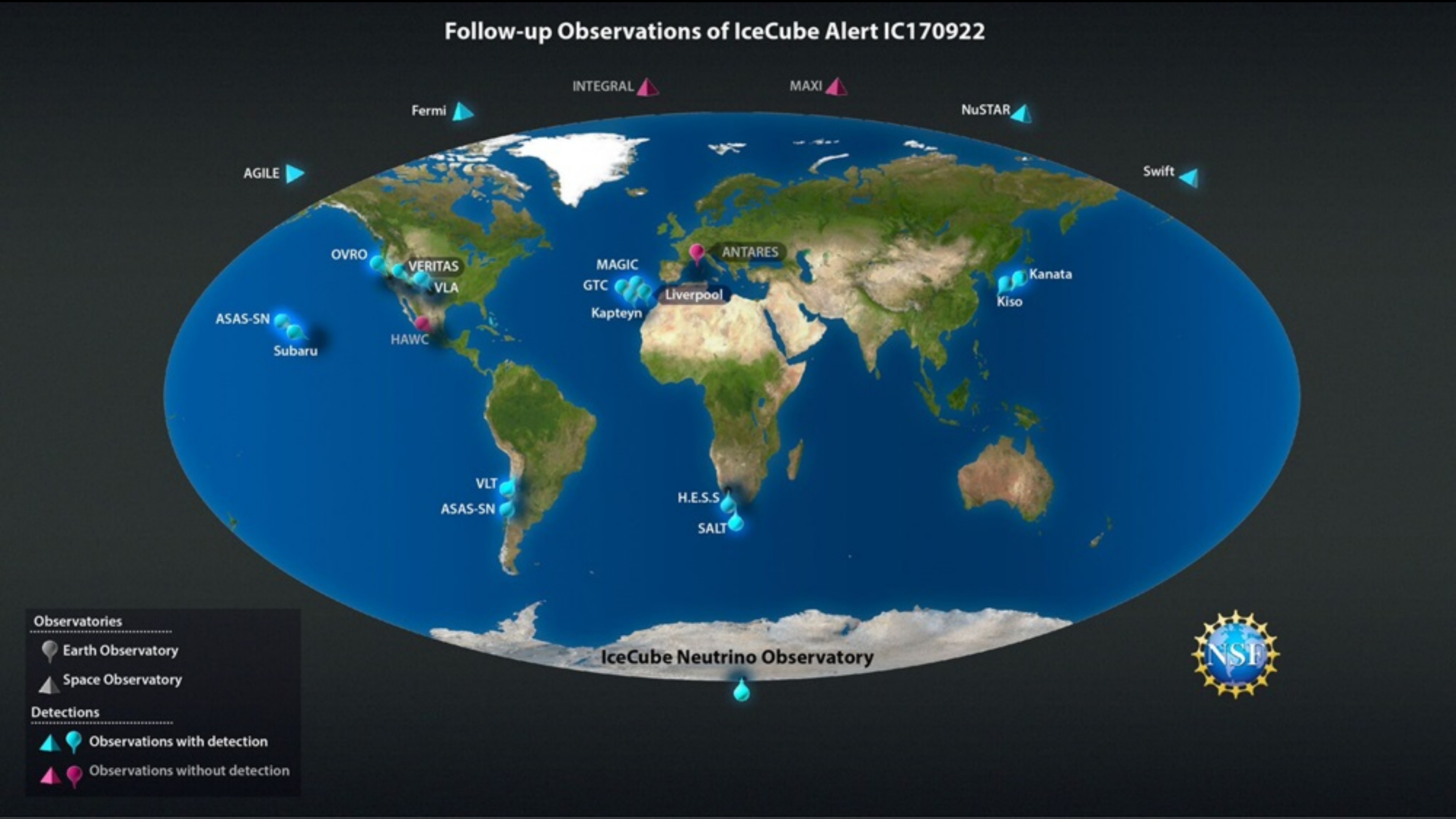


The discovery of HE cosmic neutrinos: IC170922A



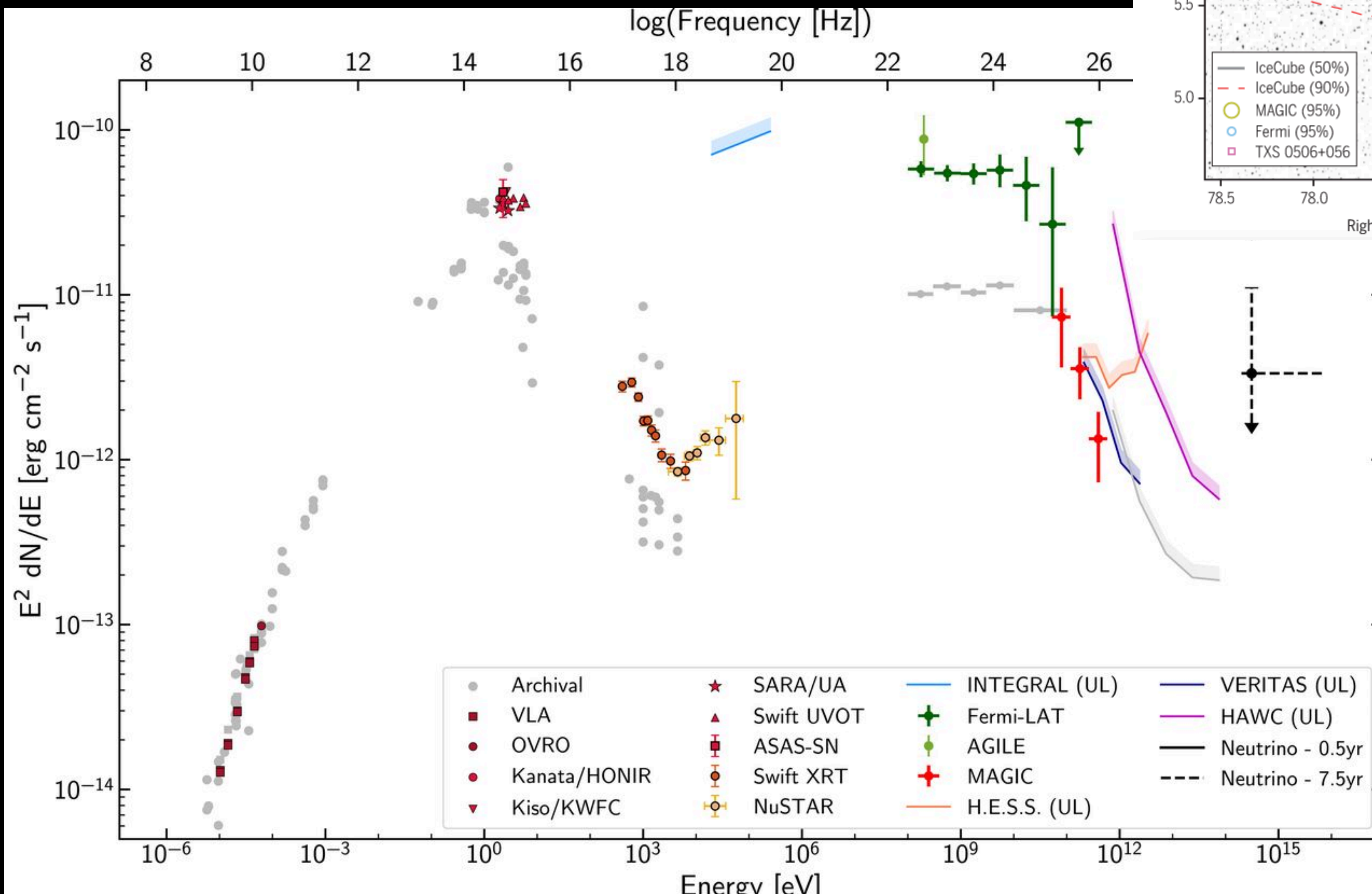
Extreme high energy neutrino alert from IceCube followed by detection of very high energy photons from Flaring Blazar TXS 0506+056

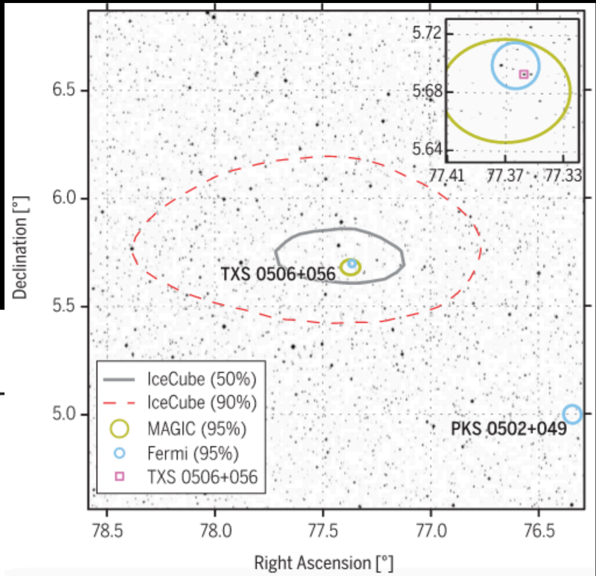
IC170922A Alert Follow-up



Photons from TXS 0506+056

- 3 σ chance coincidence correlation ("evidence")

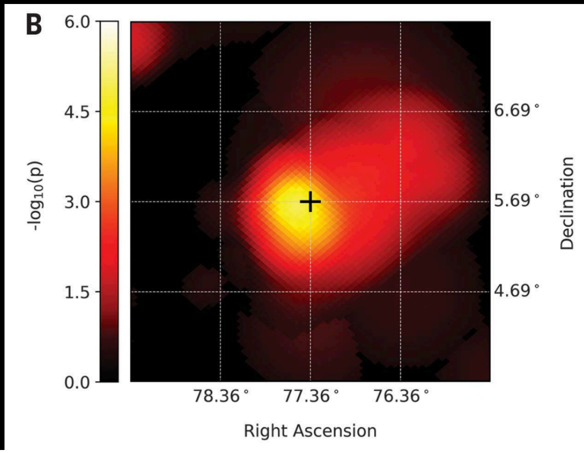


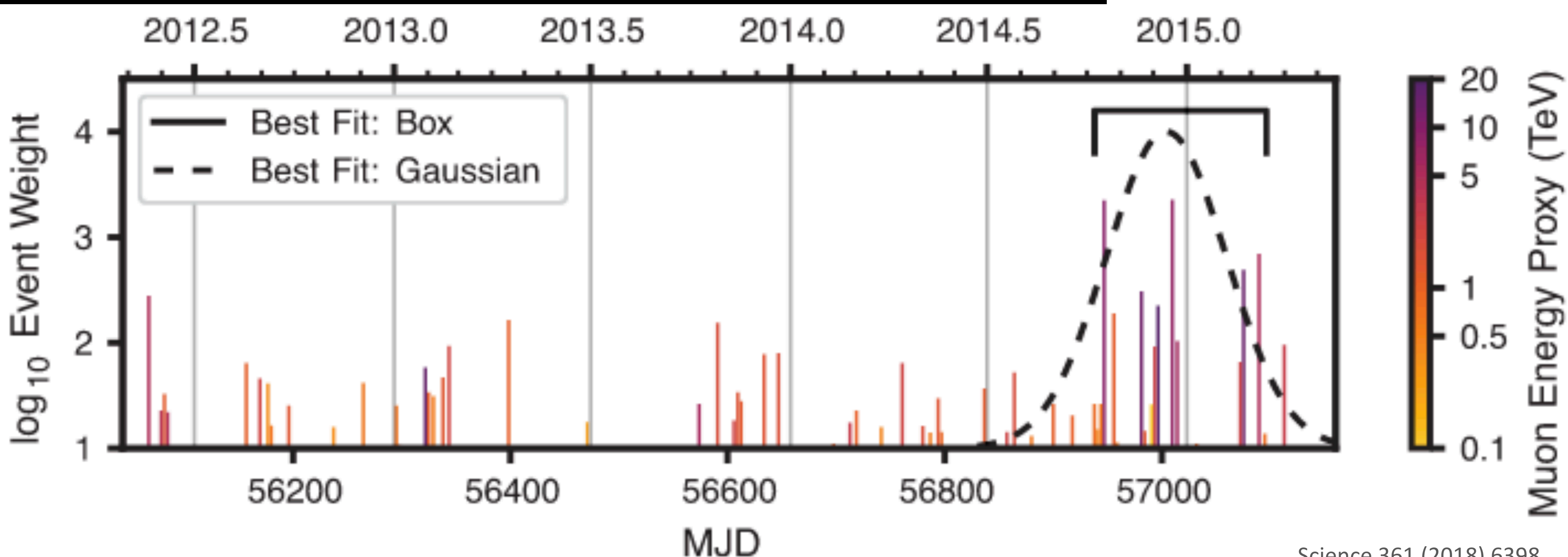


Science 361 (2018) 6398

Archival neutrino searches around TXS 0506+056

- Archival data revealed a 13 ± 5 neutrino excess (3.5 σ) in 2014 – 2015 over 110 days
- No evidence of EM activity from the source during this period





Science 361 (2018) 6398

ANTARES TXS 0506+056 follow-up

Three searches performed:

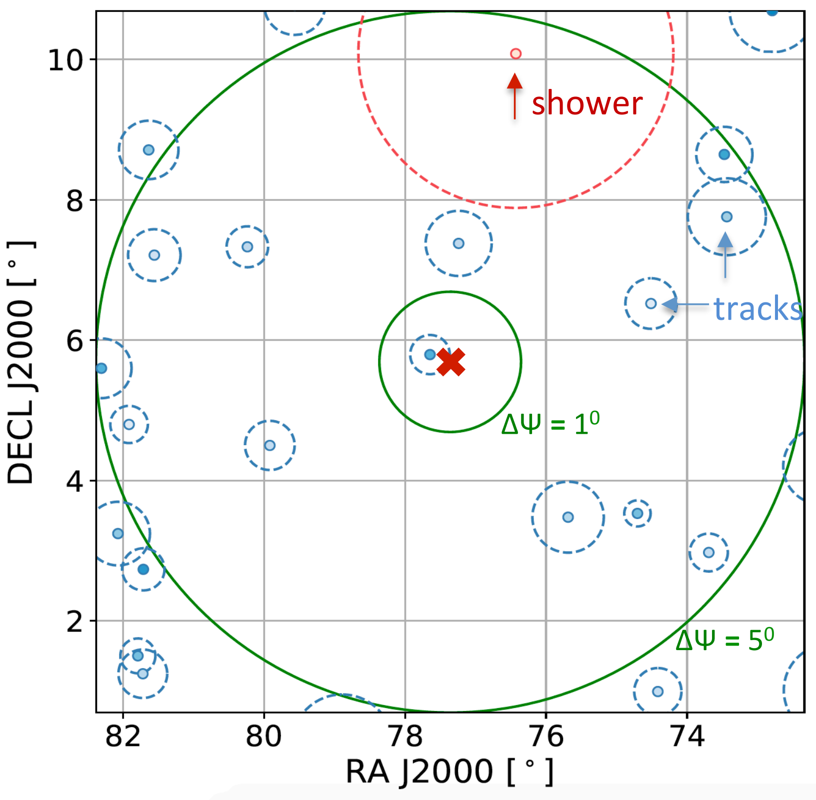
I. Online prompt search for neutrinos associated with IC170922A

II. Time-dependent search in TXS 0506+056 historical bursting periods

III. Time-integrated search from TXS 0506+056

- No counterpart events seen in ANTARES data
- No significant evidence of cosmic ν 's → upper limits

Equatorial Coord. $(\alpha, \delta) = (77.36^o, 5.69^o)$



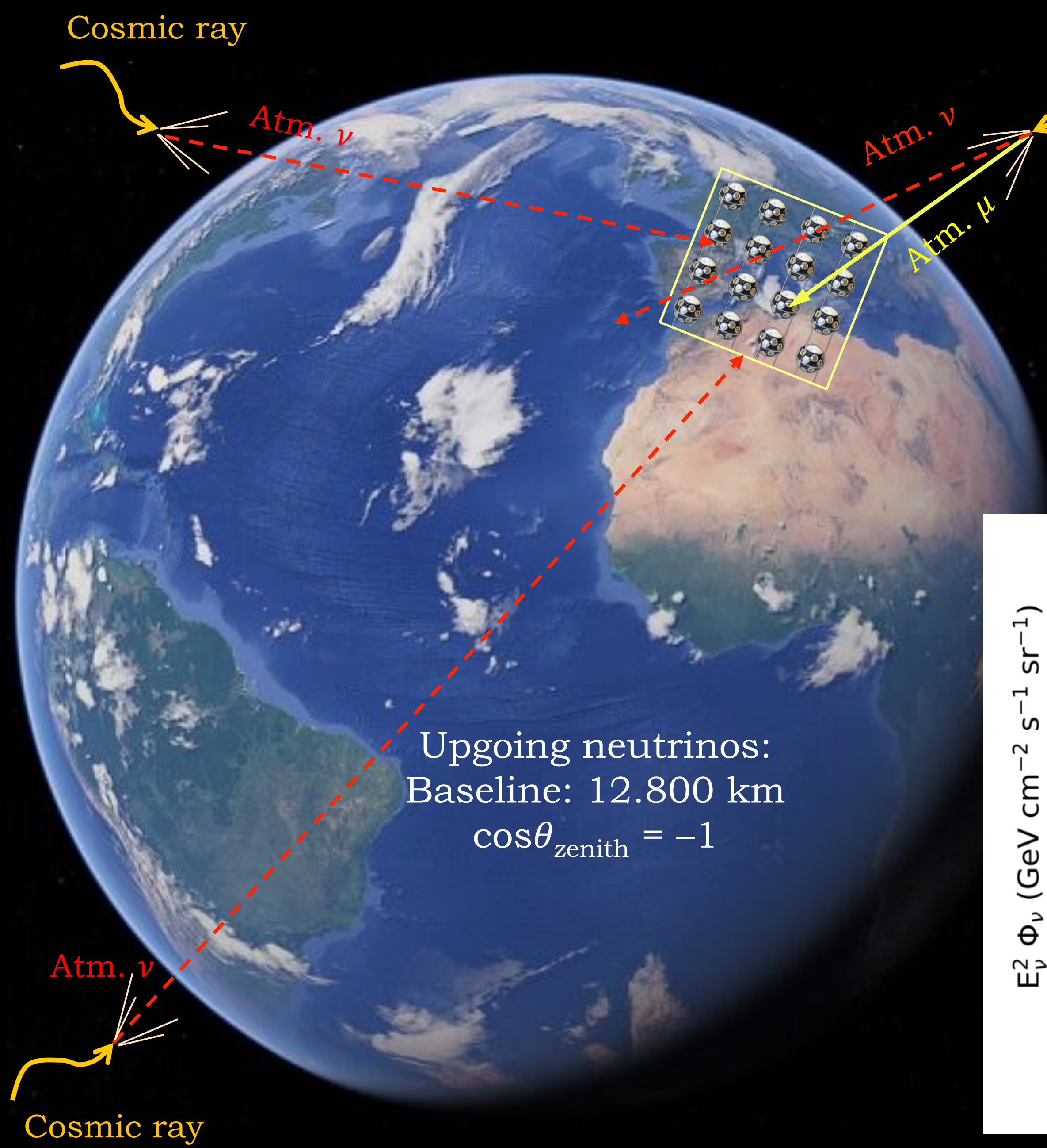
ApJ Lett. 863 (2018) L30 , PoS (ICRC2019) 920

KM3NeT/ORCA

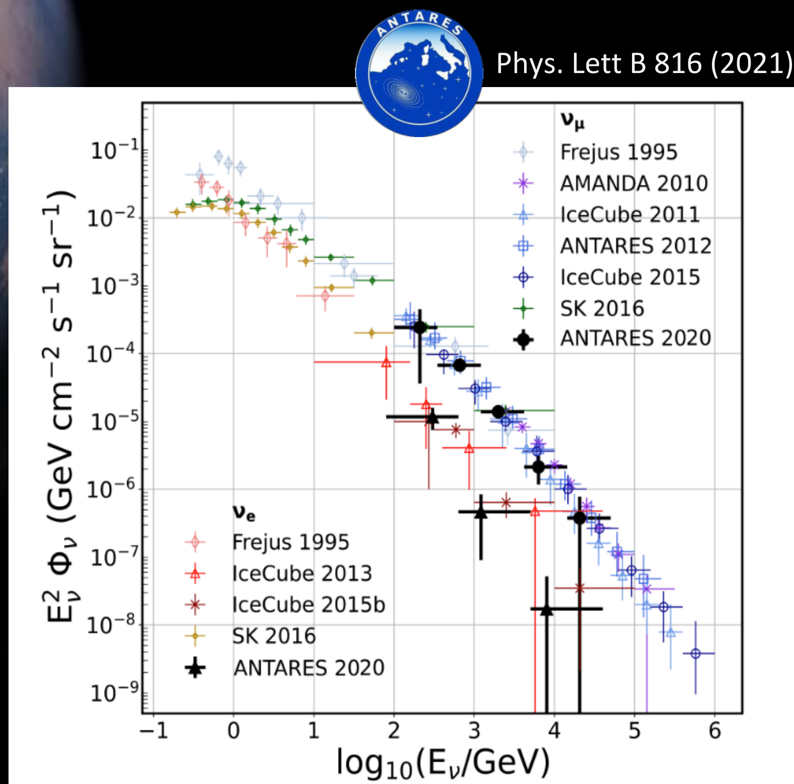
ORCA6: 1 year of data

- Atmospheric ν beam

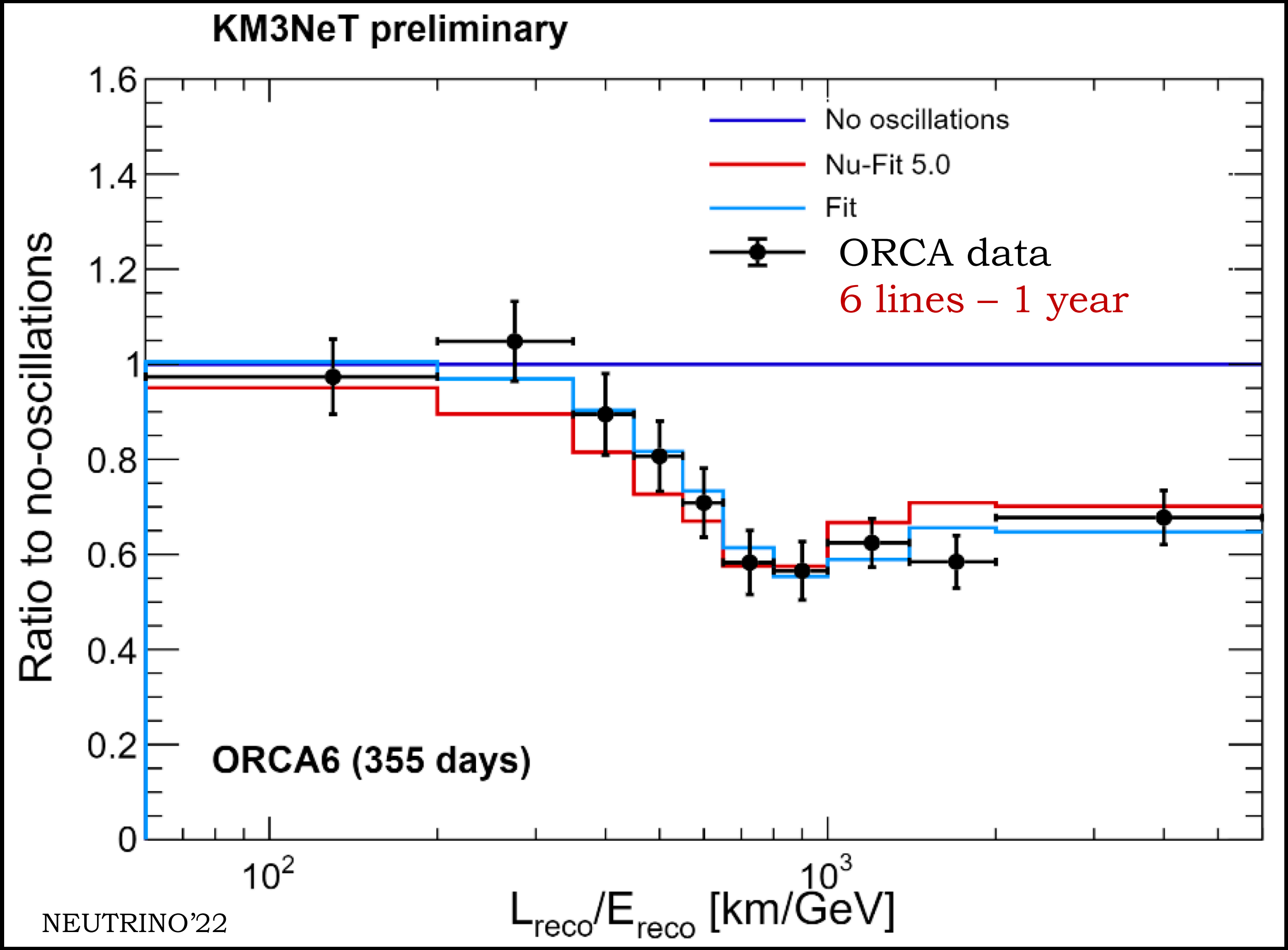
Physics with Atmospheric neutrinos



Phys. Lett B 816 (2021)



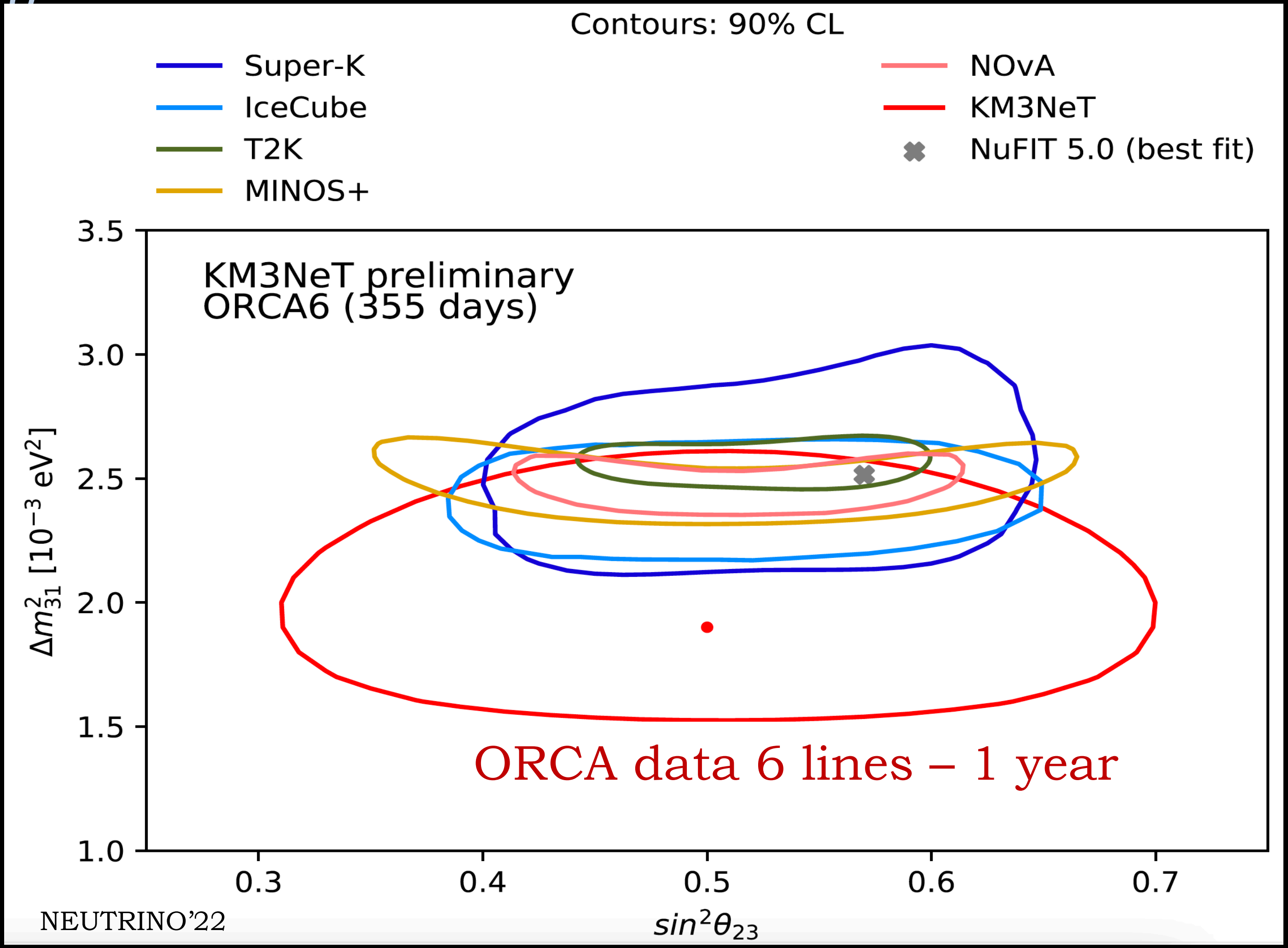
ORCA-6 1 year: Neutrino Oscillations L/E



Atmospheric neutrinos traversing the Earth: sensitive to Δm^2_{31}

Clear effect of oscillations seen with 6 ORCA lines in 1 year

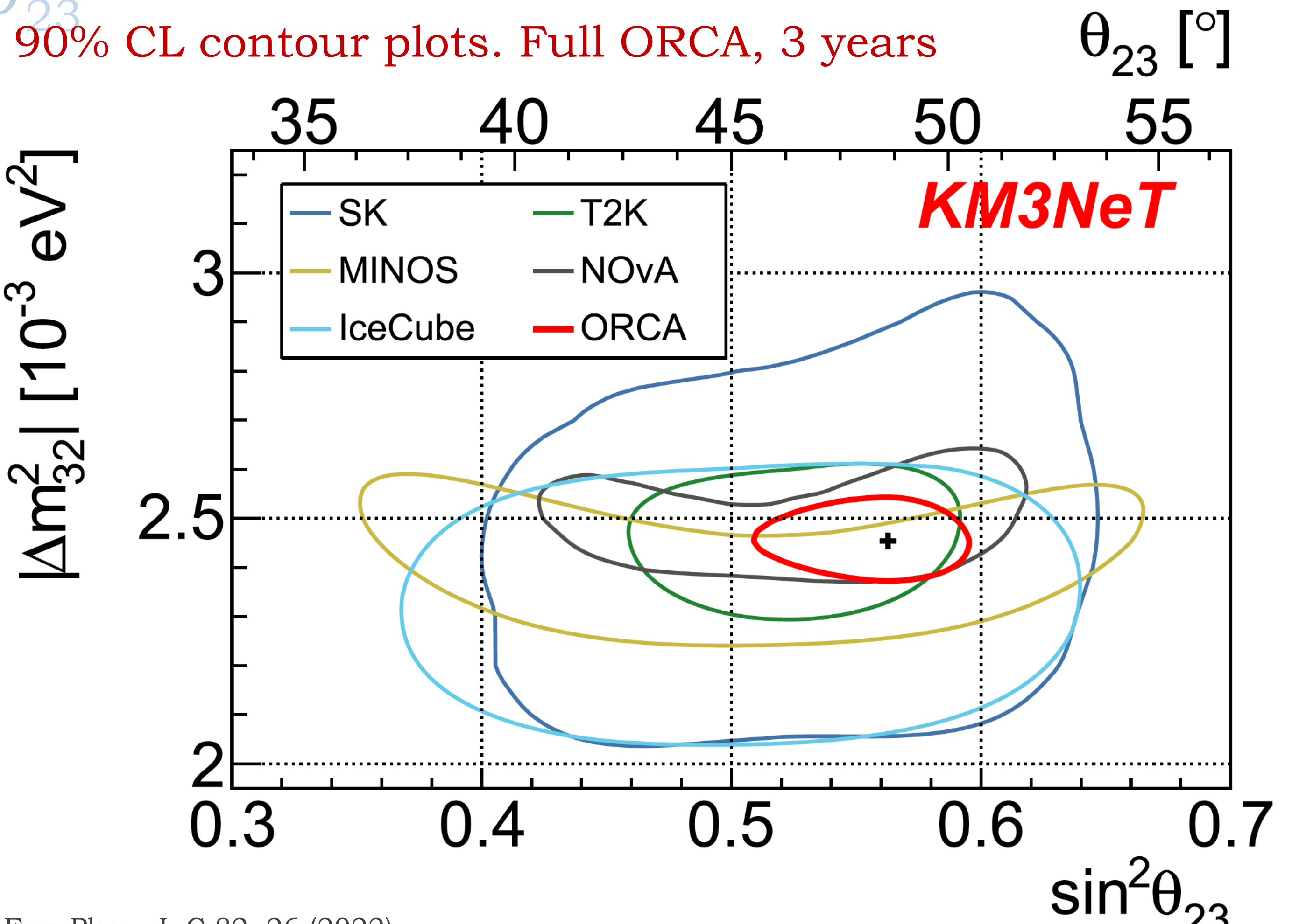
ORCA-6 1 year: Neutrino Oscillations Δm^2_{31} & θ



With full ORCA: very precise measurement of neutrino oscillation parameters.

Full ORCA Neutrino Oscillations: Δm^2_{32} & θ_{23}

90% CL contour plots. Full ORCA, 3 years



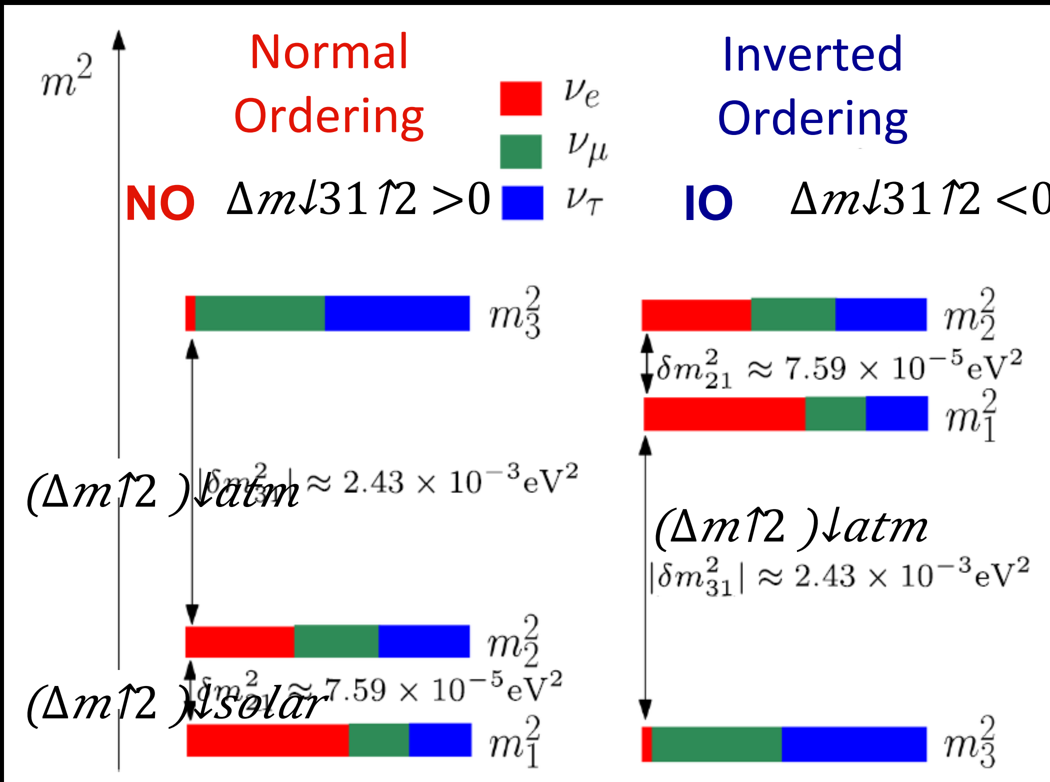
Eur. Phys. J. C 82, 26 (2022)

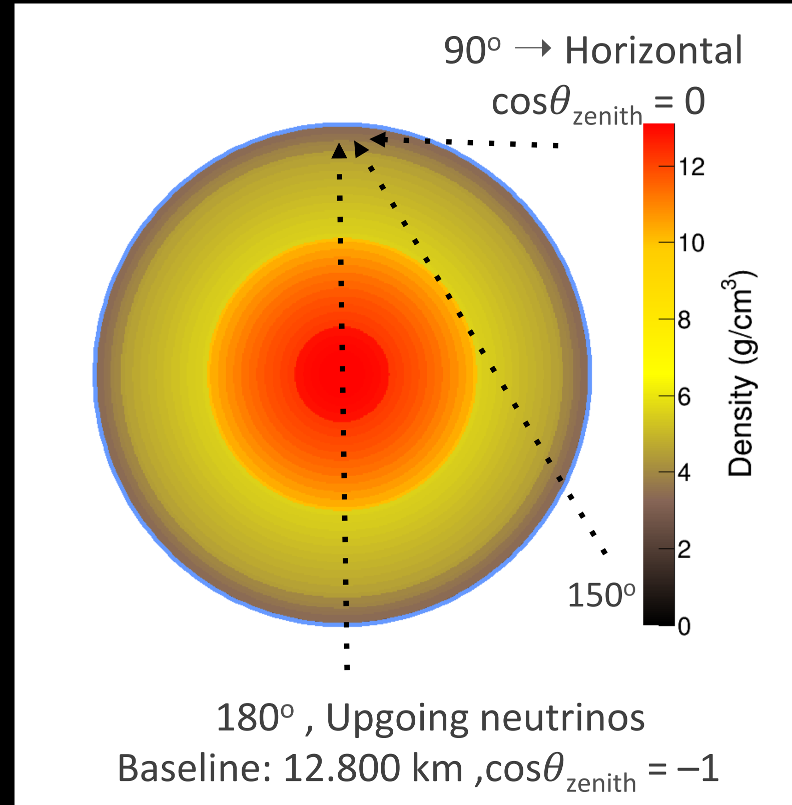
Full ORCA, 90% CL interval for Δm^2_{32} and θ_{23}:

NO: 85×10^{-6} eV^2 and $\left(^{+1.9}_{-3.1}\right)^\circ$

IO : 75×10^{-6} eV^2 and $\left(^{+2.0}_{-7.0}\right)^\circ$

ORCA Neutrino Mass Ordering (NMO)





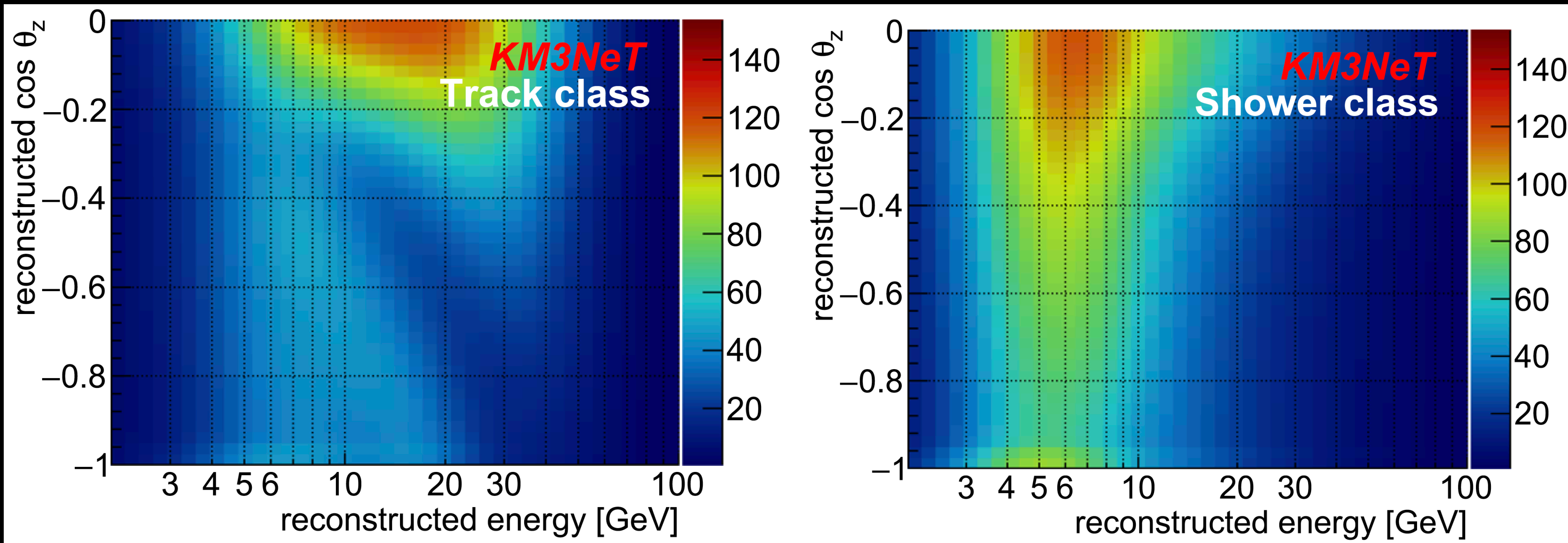
Sign of Δm_{31}^2 sensitive to matter effects in the oscillation patterns

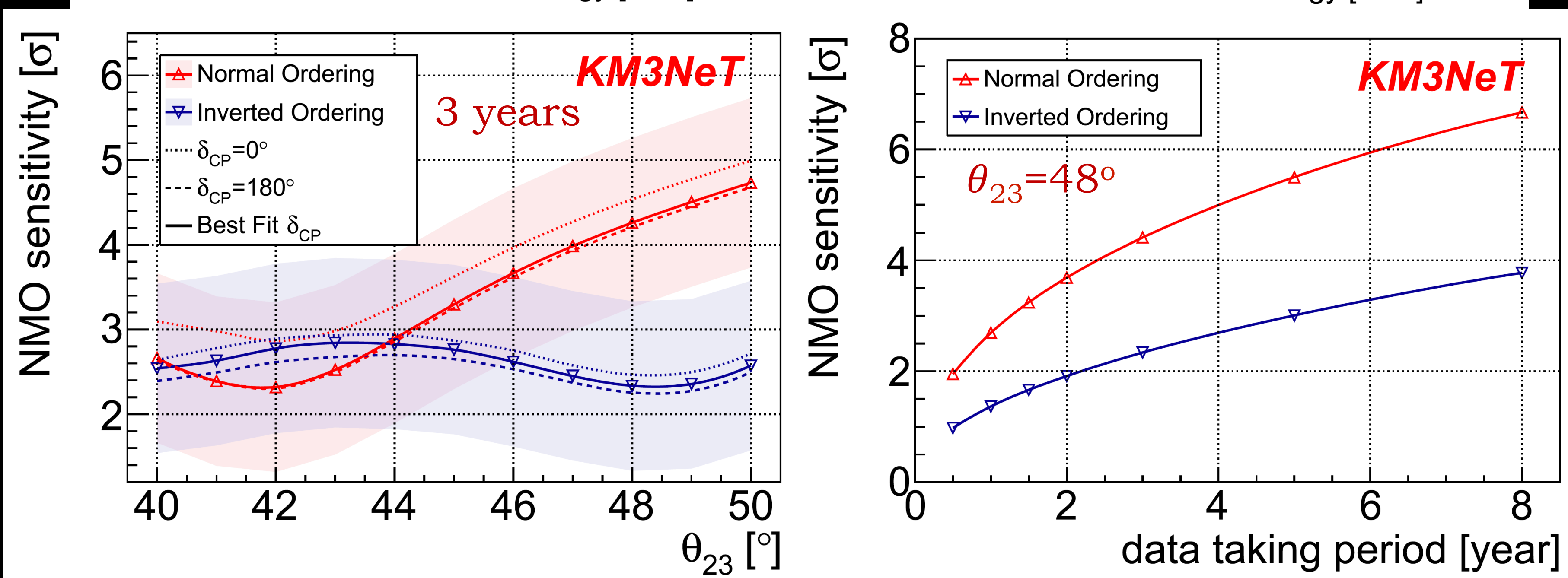
- ✓ NO (ν_e appear. ⇧) ≡ IO (anti-ν_e appear. ⇧)
- ✓ E_{res} ~7 GeV (3 GeV) in Mantle (Core)

σ_ν ~ 2 $\sigma_{anti\text{-}\nu}$
ϕ_ν ~ 1.1 $\phi_{anti\text{-}\nu}$

NMO affects oscillograms : ($\cos\theta$ – E_{reco}) plots

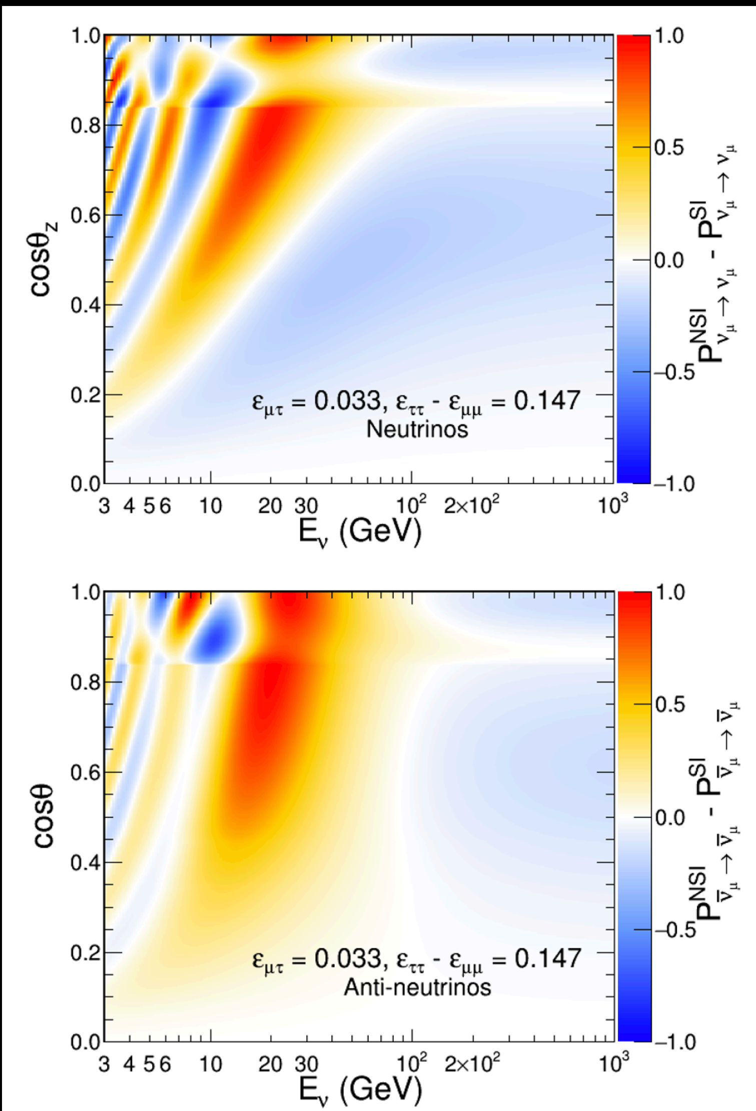
ORCA Neutrino Mass Ordering (NMO)



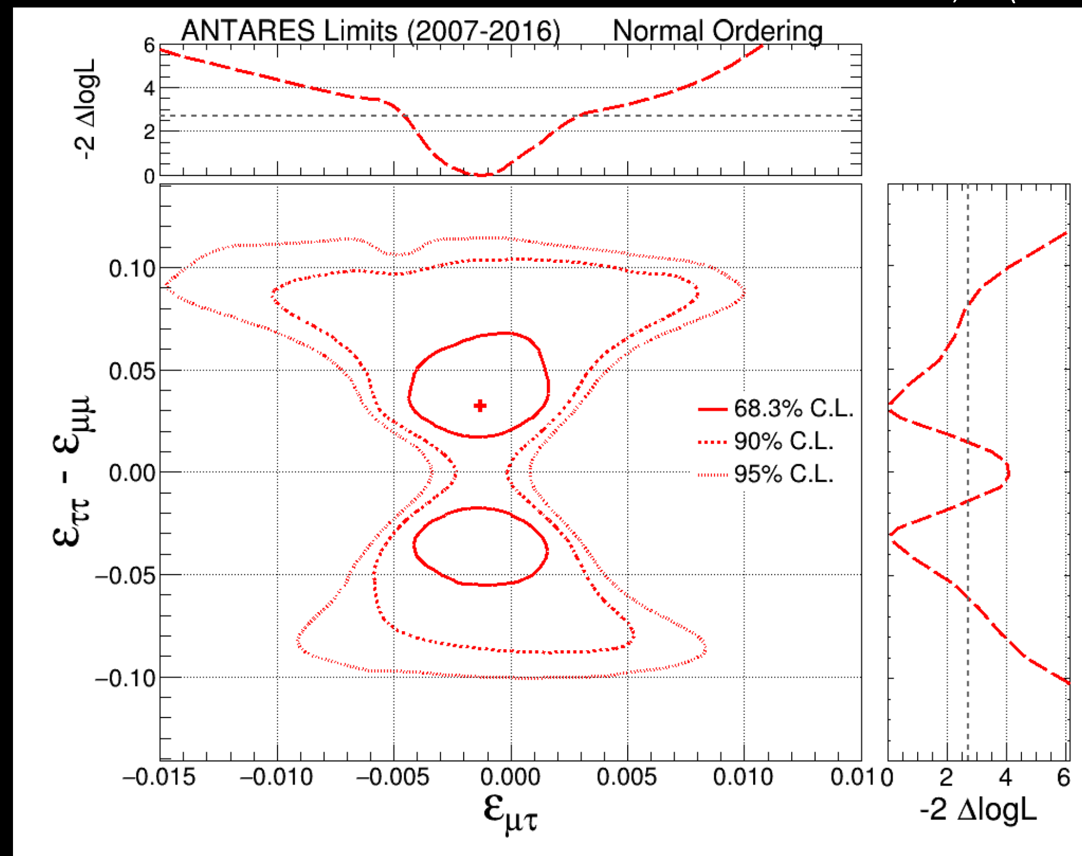


Non-Standard Interactions (NSI): ANTARES

NSIs would distort the standard MSW effects → oscillograms modified w.r.t. SM predictions (shifts in minima and changes in amplitudes)



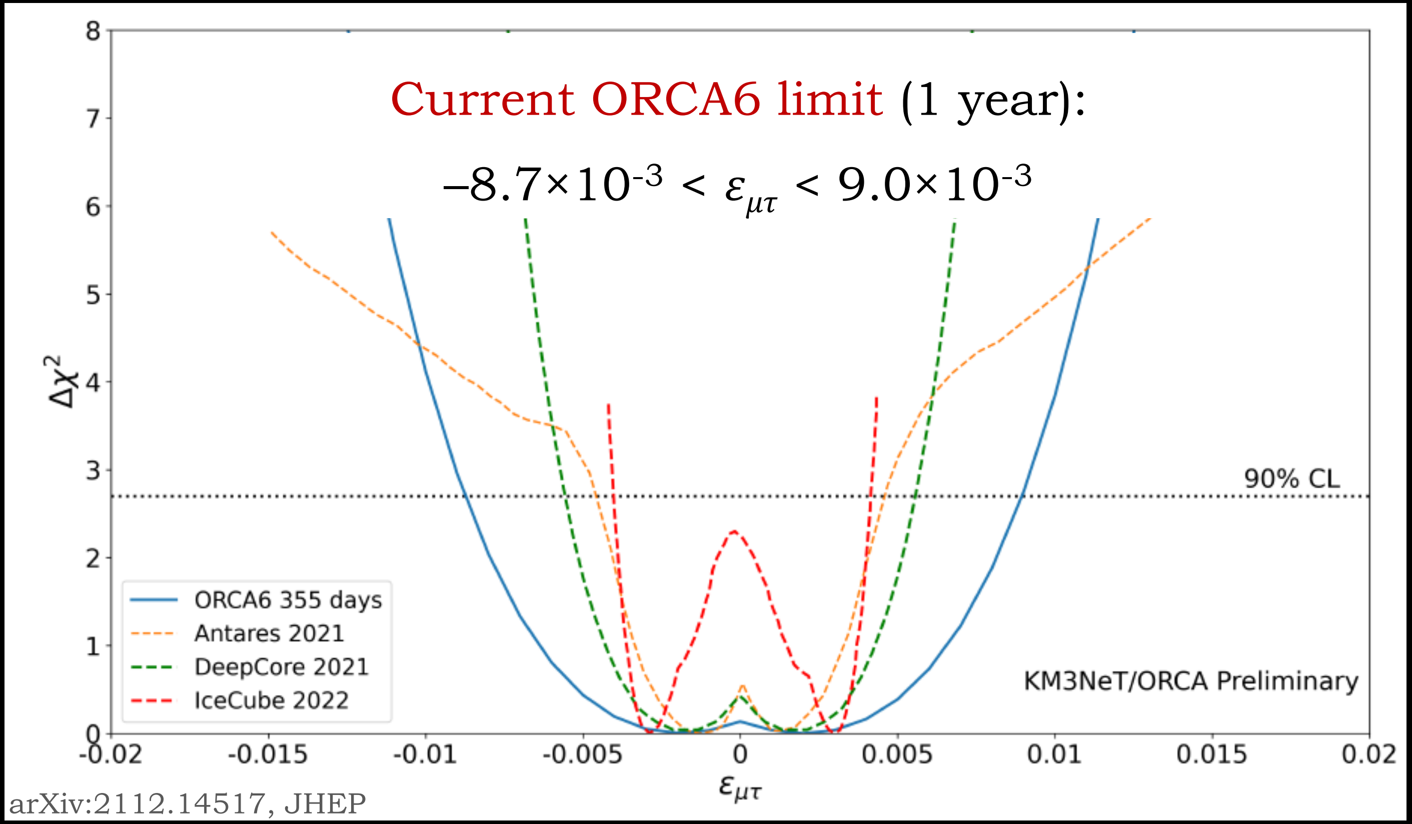
JHEP 2022, 48 (2022)



- ANTARES 10 years of data analysed
- Compatible with no NSIs : 1.7σ/1.6σ effect (NO/IO)
- Among the most restrictive to date ($\varepsilon_{\mu\tau}$)

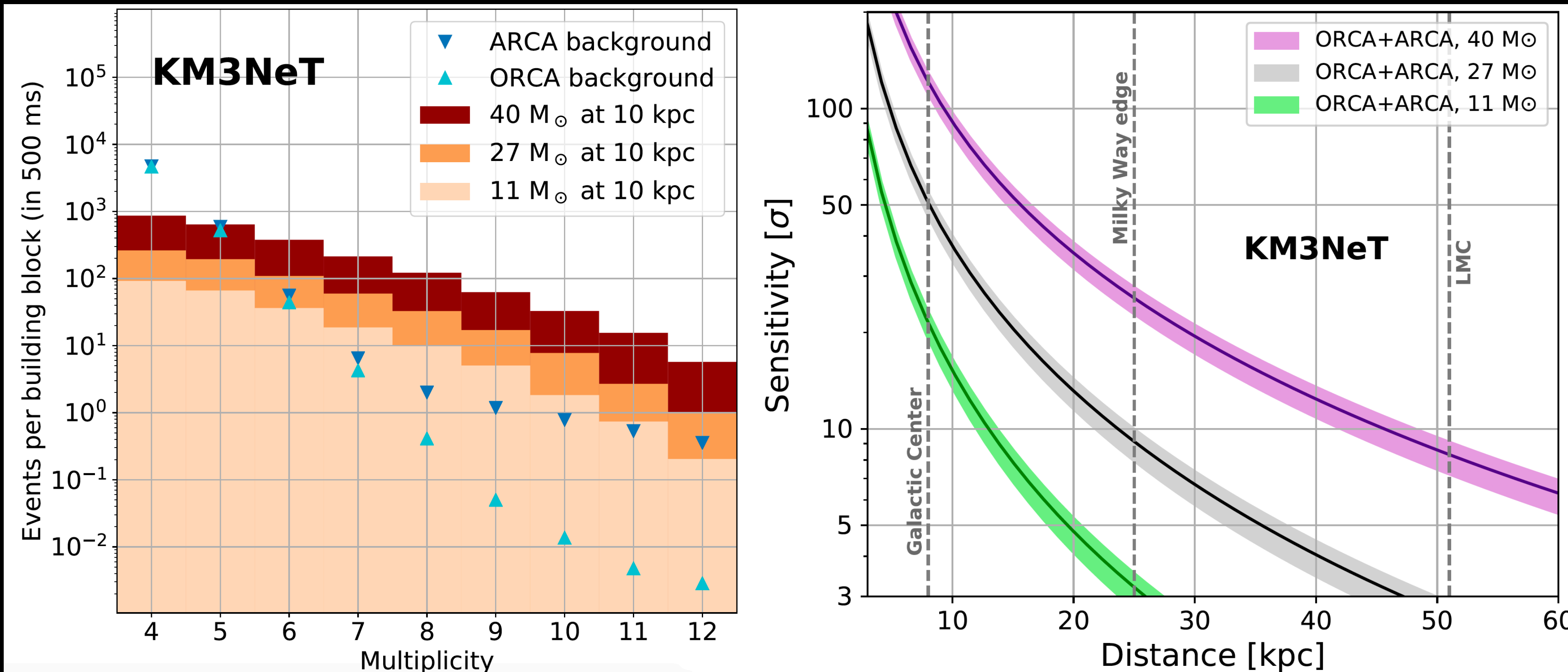
Non-Standard Interactions (NSI)

NSIs would distort the standard MSW effects → oscillograms modified w.r.t. SM predictions (shifts in minima and changes in amplitudes)



- ORCA6 limits: Less than a factor 3 from best world limits!
- Full ORCA in 3 years: constraints by one order of magnitude better than current experimental limits

ORCA+ARCA: Core Collapse Supernovae

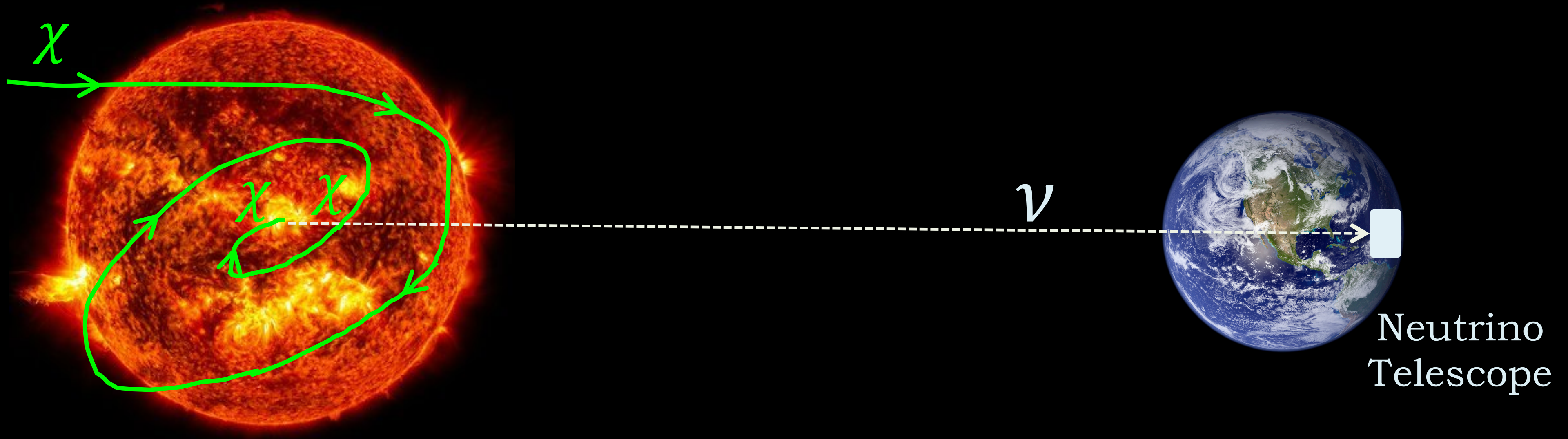


Eur. Phys. J. C 81, 445 (2021)

- Supernova MeV neutrinos ➜ collective excess of multi-fold coincidences on all DOMs
- Real time monitoring activity
- A trigger for CCSN already implemented ⇦ integrated in SNEWS

Search for Dark Matter in the Sun & Galactic Center

Relic WIMPS gravitationally bound in celestial massive objects
(Galactic Center, Sun ...)
They would accumulate and annihilate yielding HE neutrinos

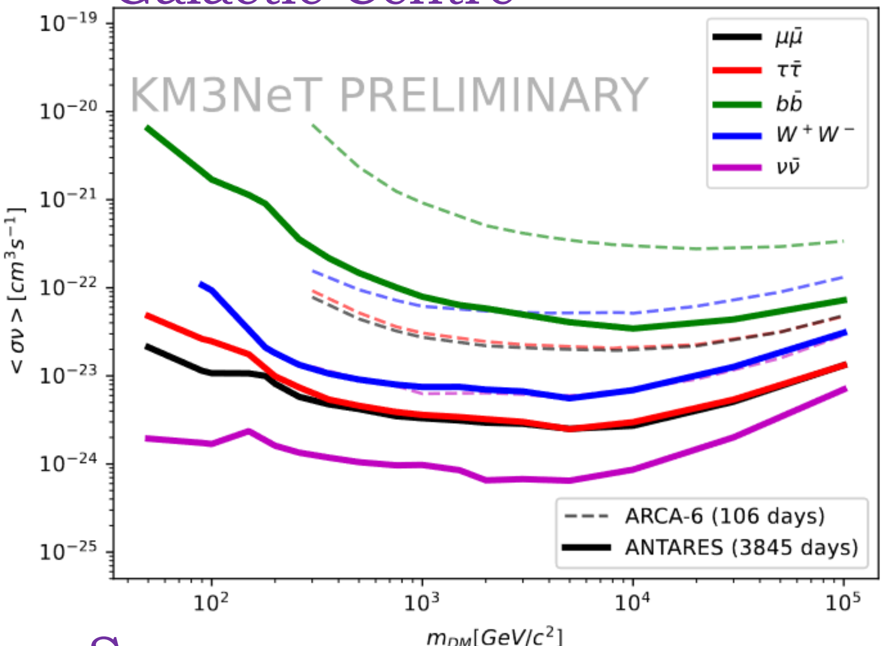


Searches for a possible ν_μ excess from these objects due to DM annihilation ⇒ very clean signature with no significant astrophysical background expected.

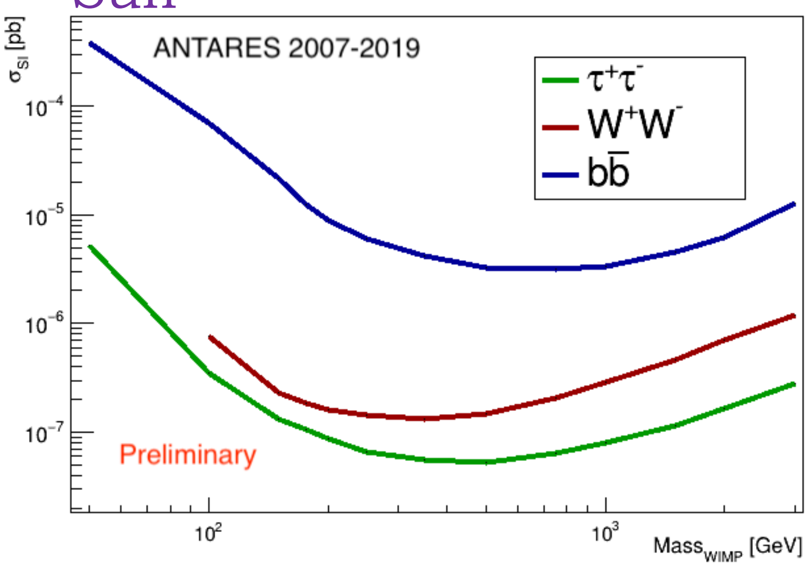
Explored channels: WIMP + WIMP → $b\bar{b}$, W^+W^- , $\tau^+\tau^-$, $\mu^+\mu^-$, $\nu_\mu\bar{\nu}_\mu$

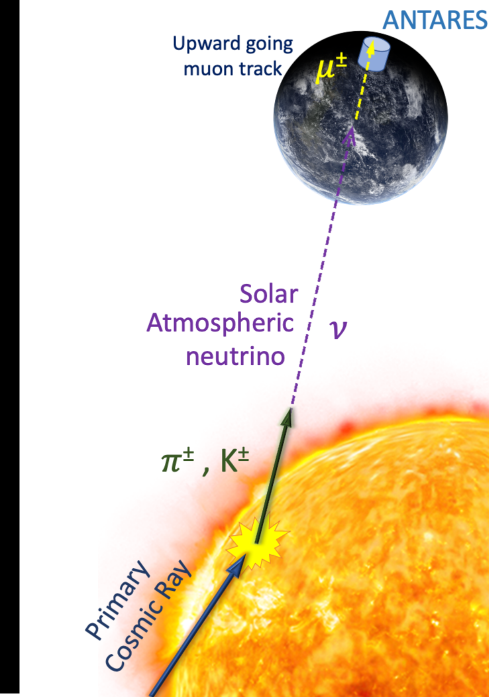
The Galactic Center and the Sun

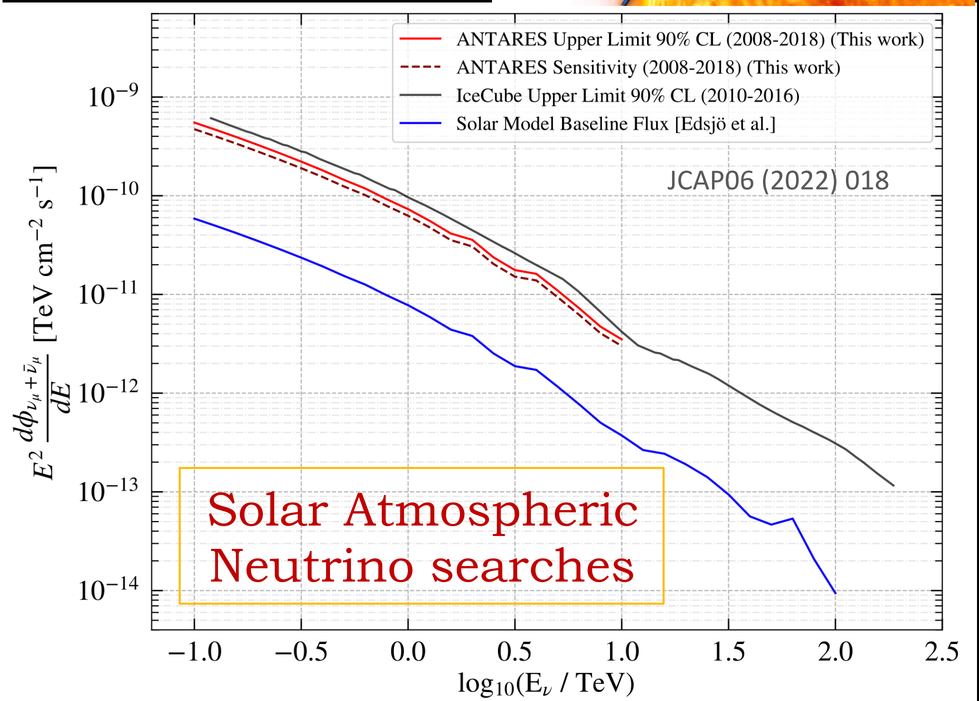
Galactic Centre



Sun





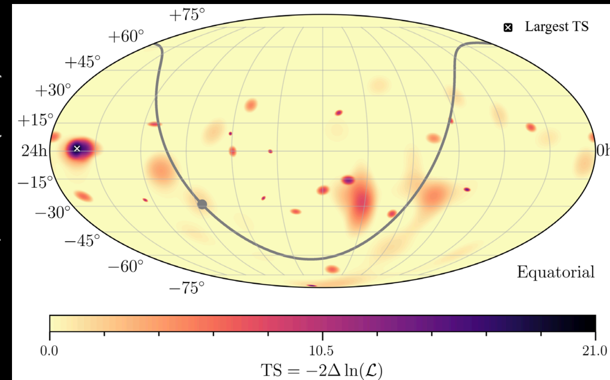


Solar Atmospheric Neutrino searches

Summary

Today

PRD 104, 022002 (2021)



2030 – 2040

First EeV neutrinos

Precision PeV ν tests

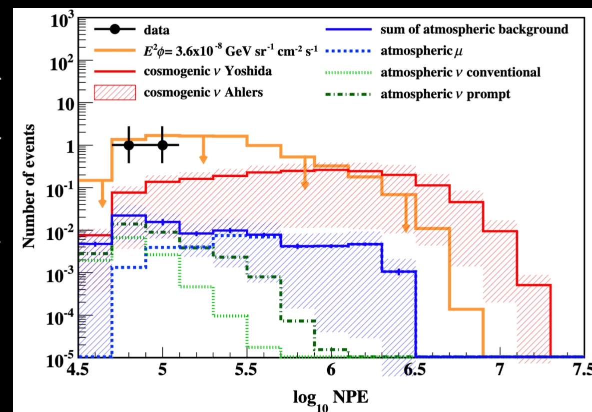
2020's

Hints of sources

Firsts ν physics tests

Juan de la Cosa (Cádiz 1510)

PRL 111, 021103 (2013)



2013

First Observation of PeV neutrinos

Martellus (Florence 1489)

astro-ph: 0209556

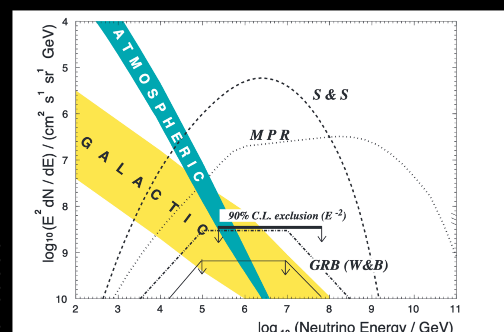
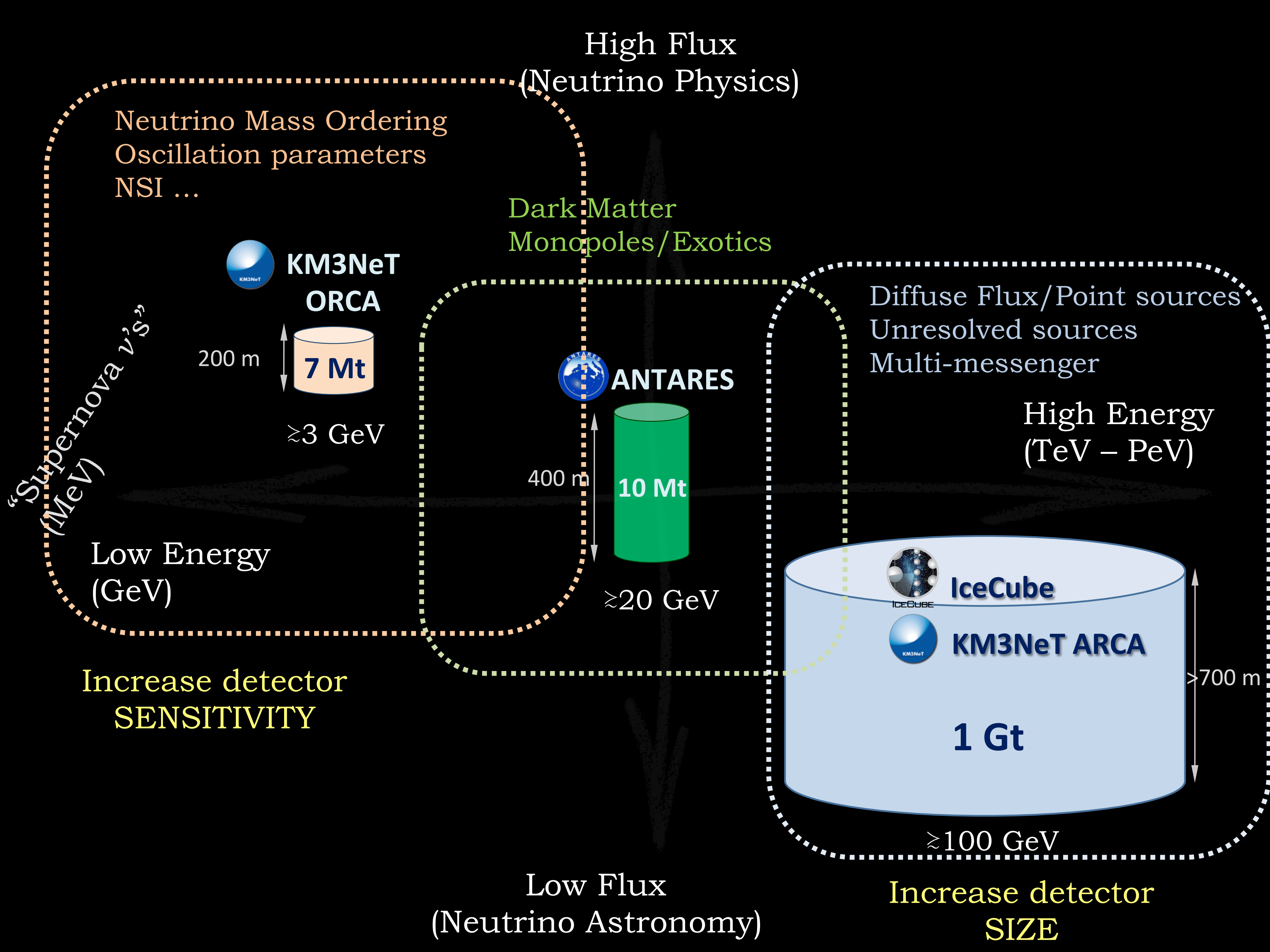


Figure 6. Expected sensitivity of the Ice-Cube detector. The thick solid line indicates the 90% c.l. limit setting potential for an E^{-2} type spectrum for a time period of three years (see

2000's

Predictions



High Flux
(Neutrino Physics)
Neutrino Mass Ordering
Oscillation parameters
NSI …
Dark Matter
Monopoles/Exotics
KM3NeT
ORCA
200 m
7 Mt
≳3 GeV
"Supernova ν's"
(MeV)
ANTARES
400 m
10 Mt
≳20 GeV
Diffuse Flux/Point sources
Unresolved sources
Multi-messenger
High Energy
(TeV – PeV)
Low Energy
(GeV)
IceCube
KM3NeT ARCA
>700 m
1 Gt
≳100 GeV
Increase detector
SENSITIVITY
Low Flux
(Neutrino Astronomy)
Increase detector
SIZE

Neutrino Telescopes

Sergio Navas
University of Granada, Spain

XLIX International Meeting on Fundamental Physics

Centro de Ciencias de Benasque Pedro Pascual, Benasque (Spain) September 5–10, 2022

Thanks!