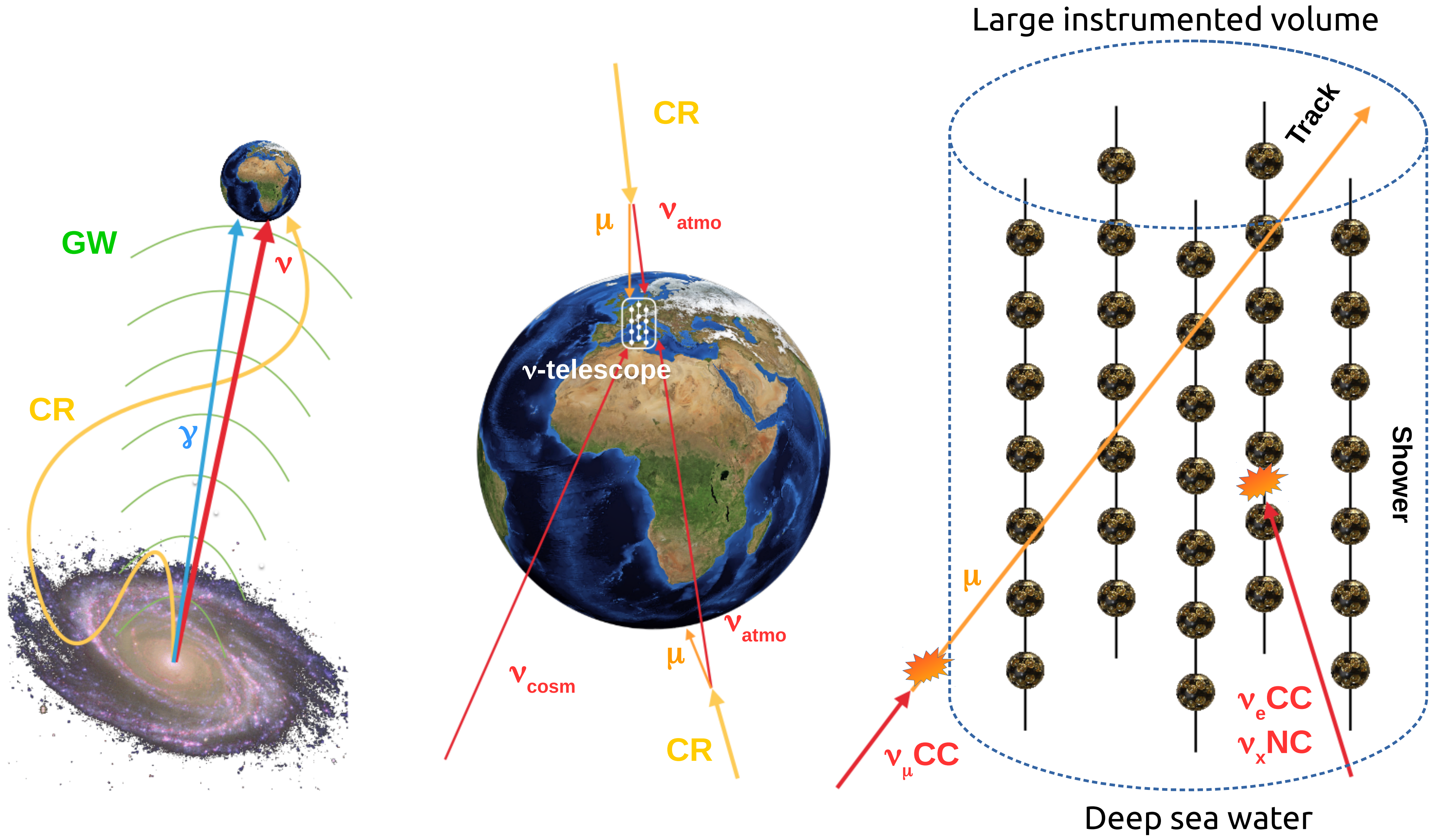
Status and overview of neutrino (astro)physics with neutrino telescopes

Luigi Antonio Fusco – Università di Salerno

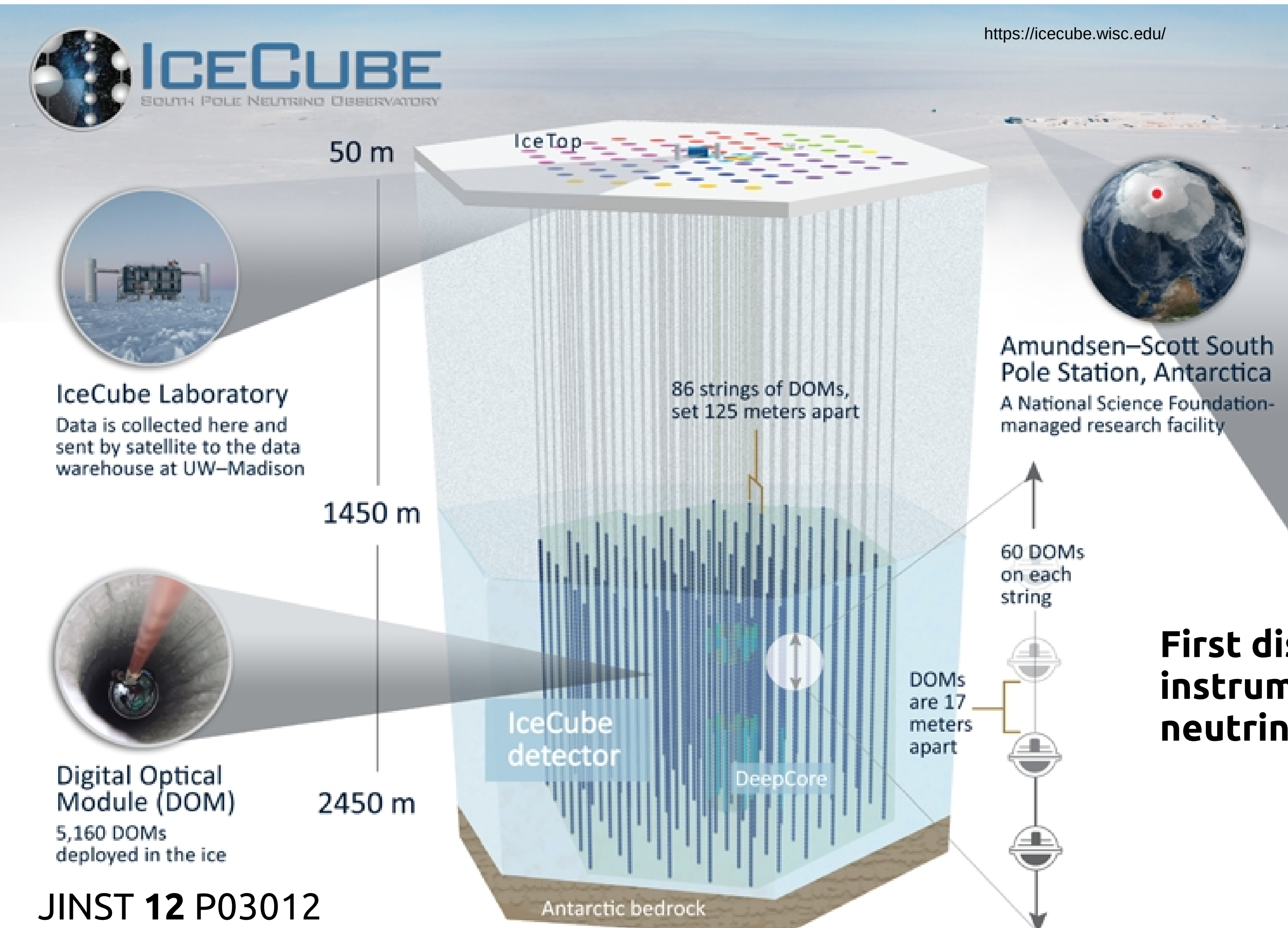
8th Workshop on Theory, Phenomenology and Experiments in Flavour Physics Neutrinos, Flavor Physics and Beyond

Anacapri, 11-13th June 2022

Neutrino telescopes in a nutshell



The current generation of neutrino telescopes



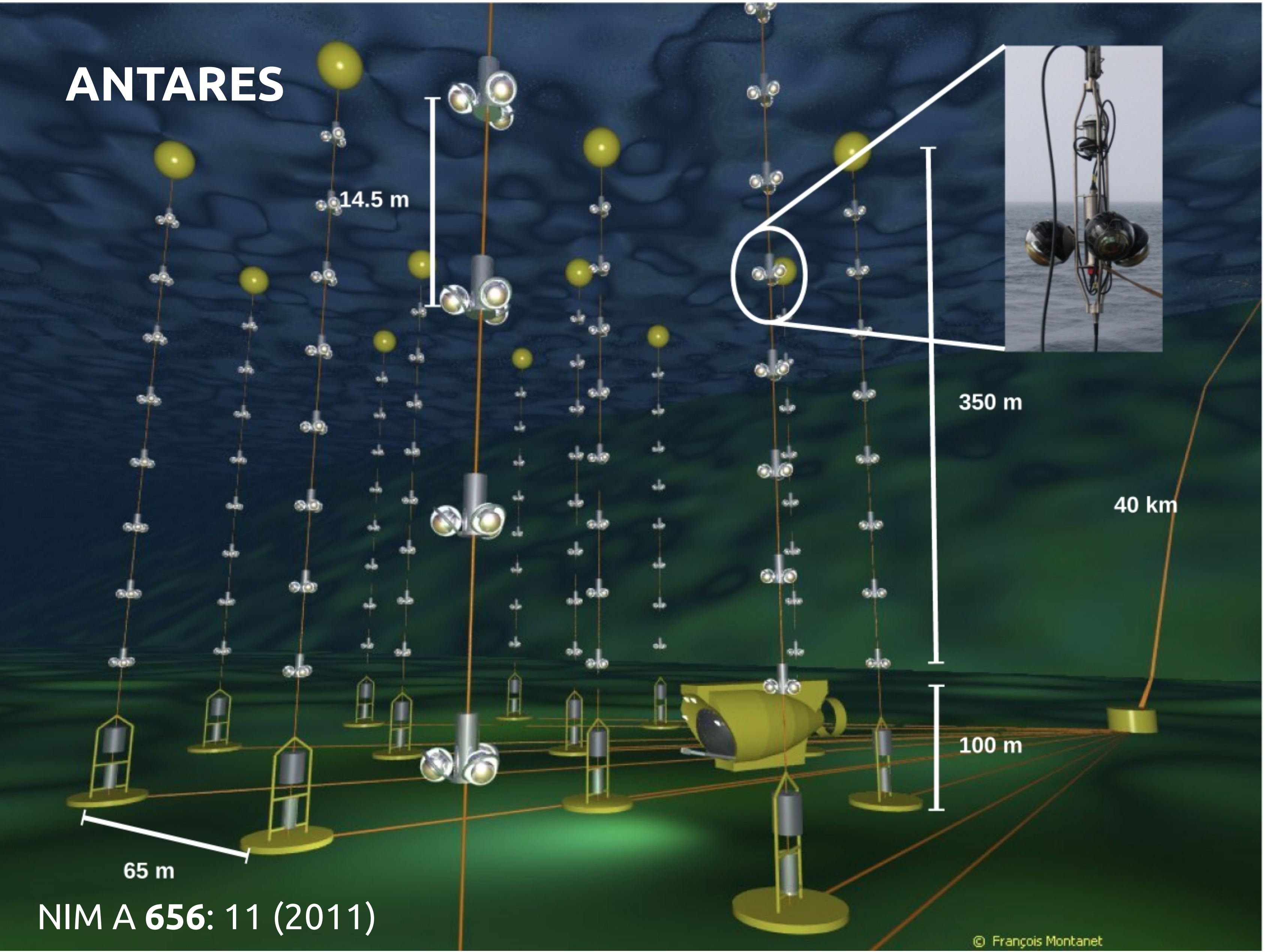
A Gton neutrino telescope

10+ years of data taking at the South Pole

First discovery instrument for HE neutrino astronomy

JINST **12** P03012 (2017)

The current generation of neutrino telescopes



NIM A **656**: 11 (2011)

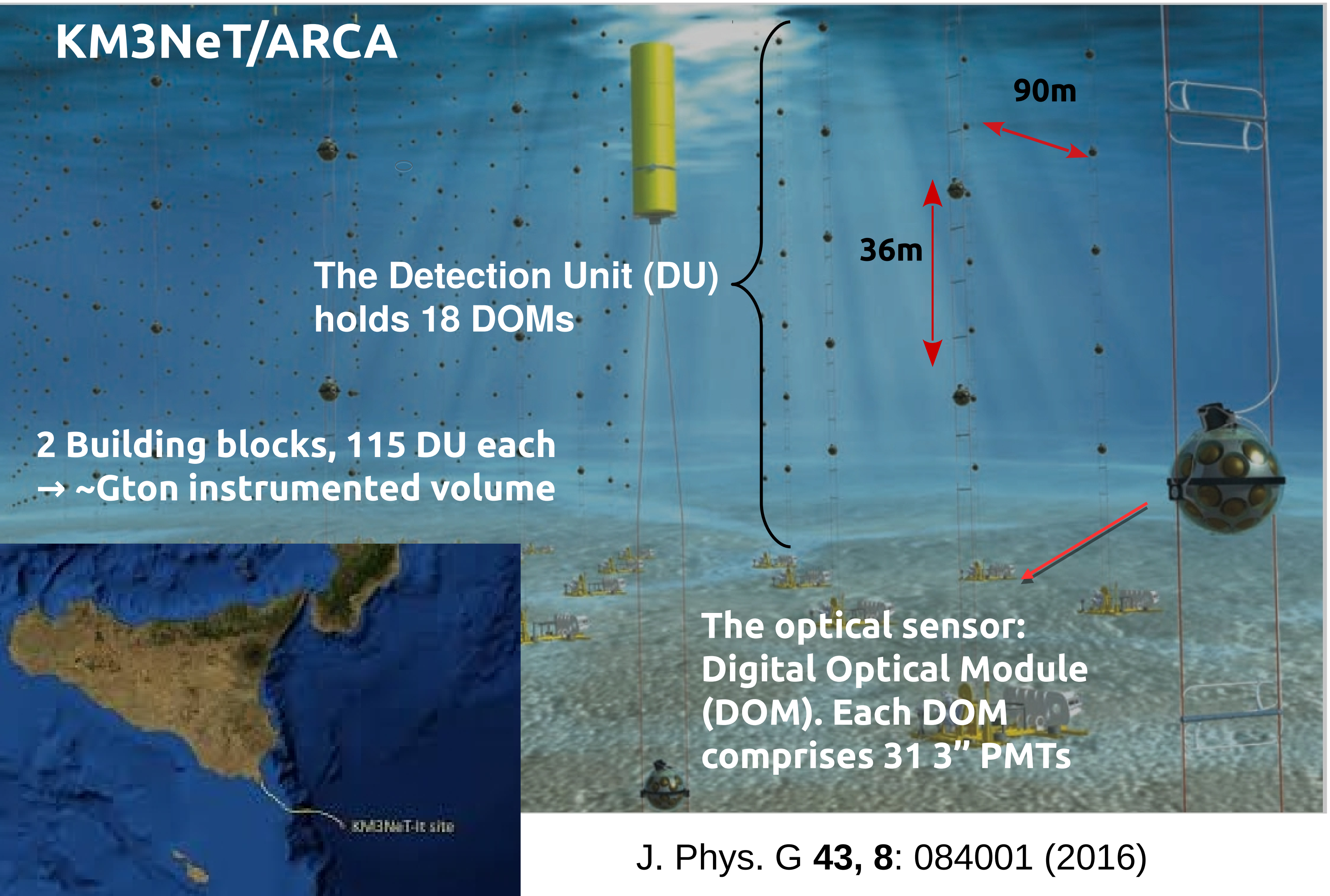
0.01 Gton neutrino telescope

15 years of data taking in the Mediterranean Sea (France)

Switched off Feb 2022

In de-commisioning stage

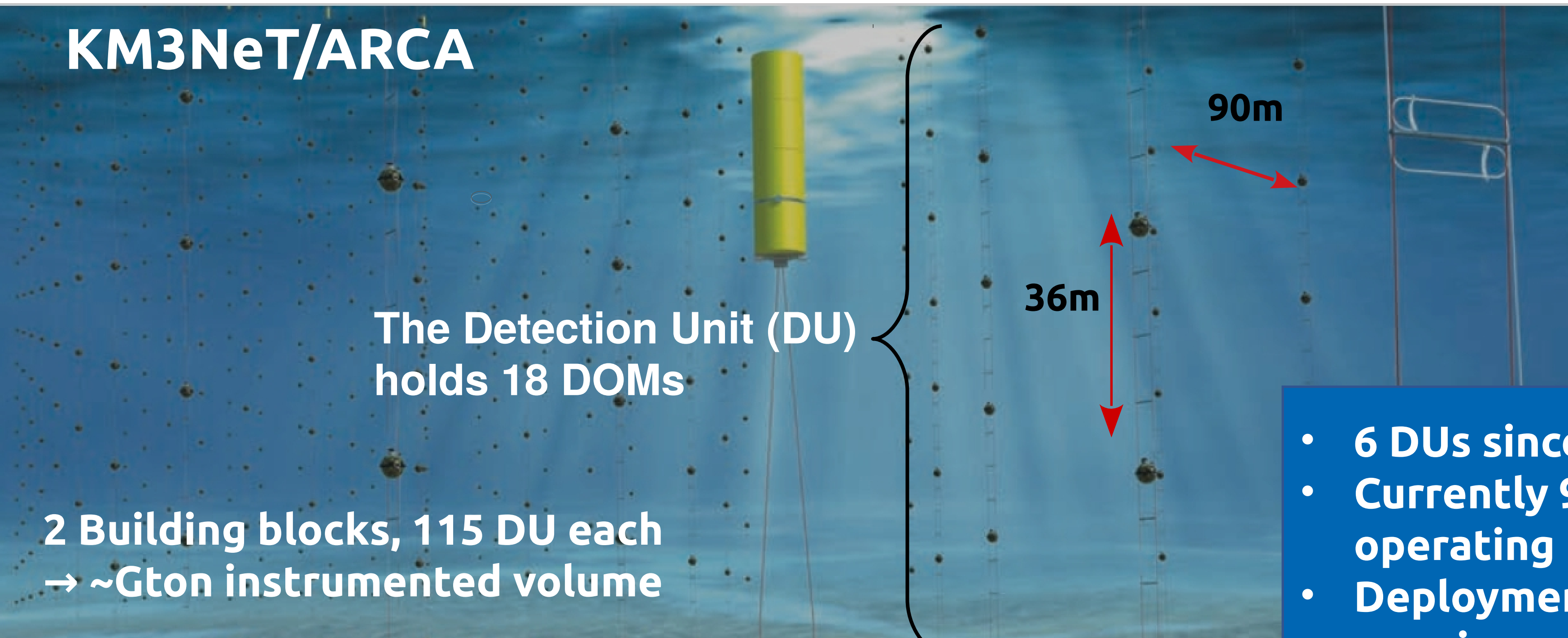
The current generation of neutrino telescopes



Construction and first data

J. Phys. G **43, 8**: 084001 (2016)

The current generation of neutrino telescopes



The Detection Unit (DU) holds 18 DOMs

2 Building blocks, 115 DU each
→ ~Gton instrumented volume

The optical sensor: Digital Optical Module (DOM). Each DOM comprises 31 3" PMTs

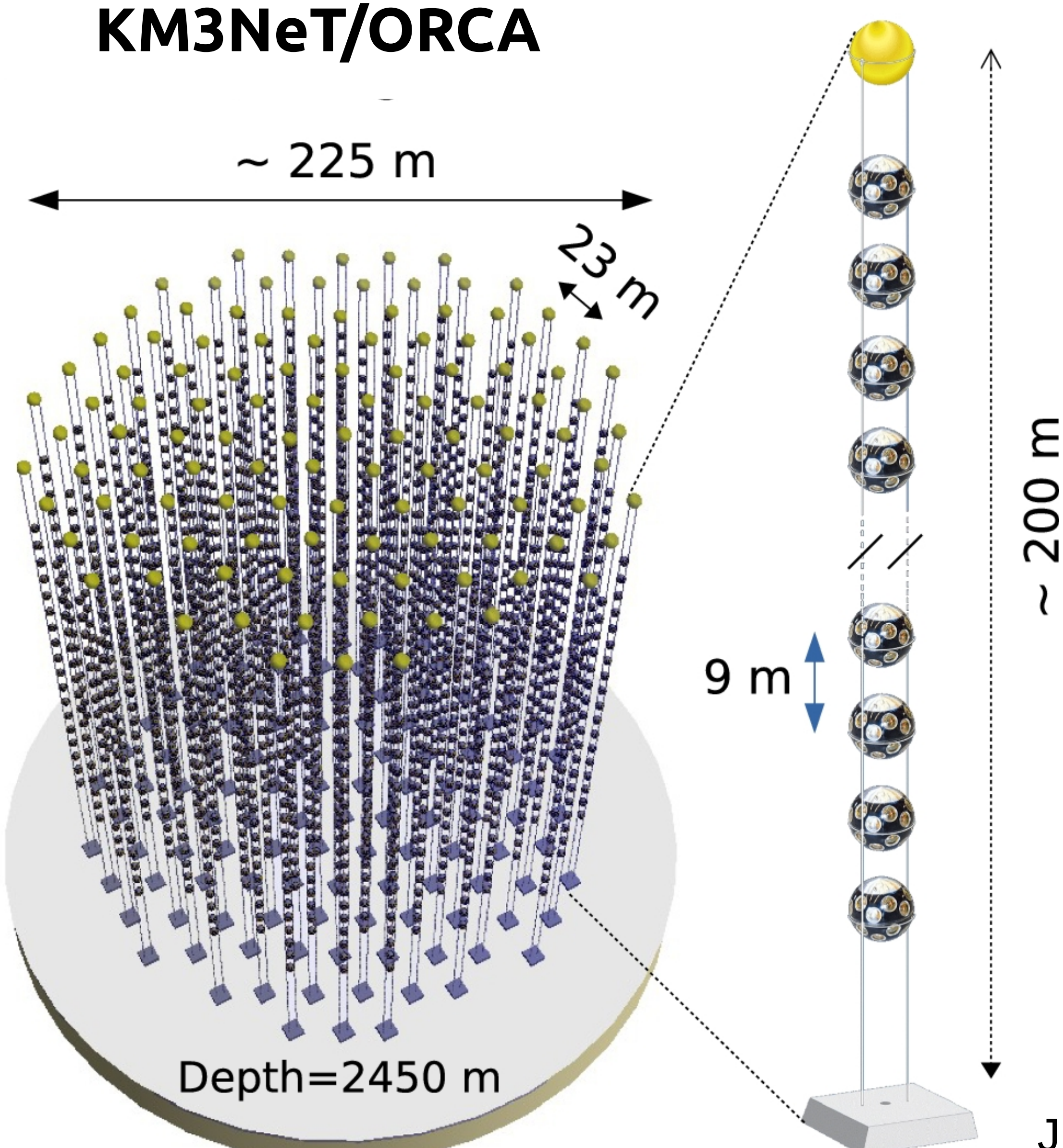
Construction and first data

- 6 DUs since April-Sept '21
- Currently 9 deployed 7 operating
- Deployment of 11 DU ongoing now!

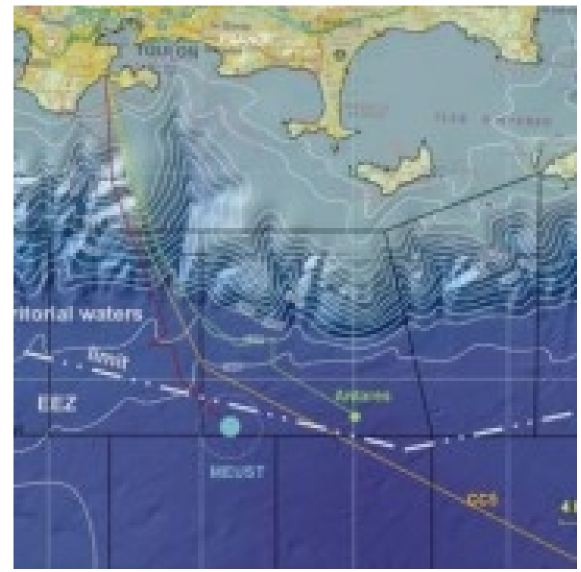
J. Phys. G **43, 8**: 084001 (2016)

The current generation of neutrino telescopes

KM3NeT/ORCA



7 Mton volume



Construction and first data

Uniform KM3NeT detector design

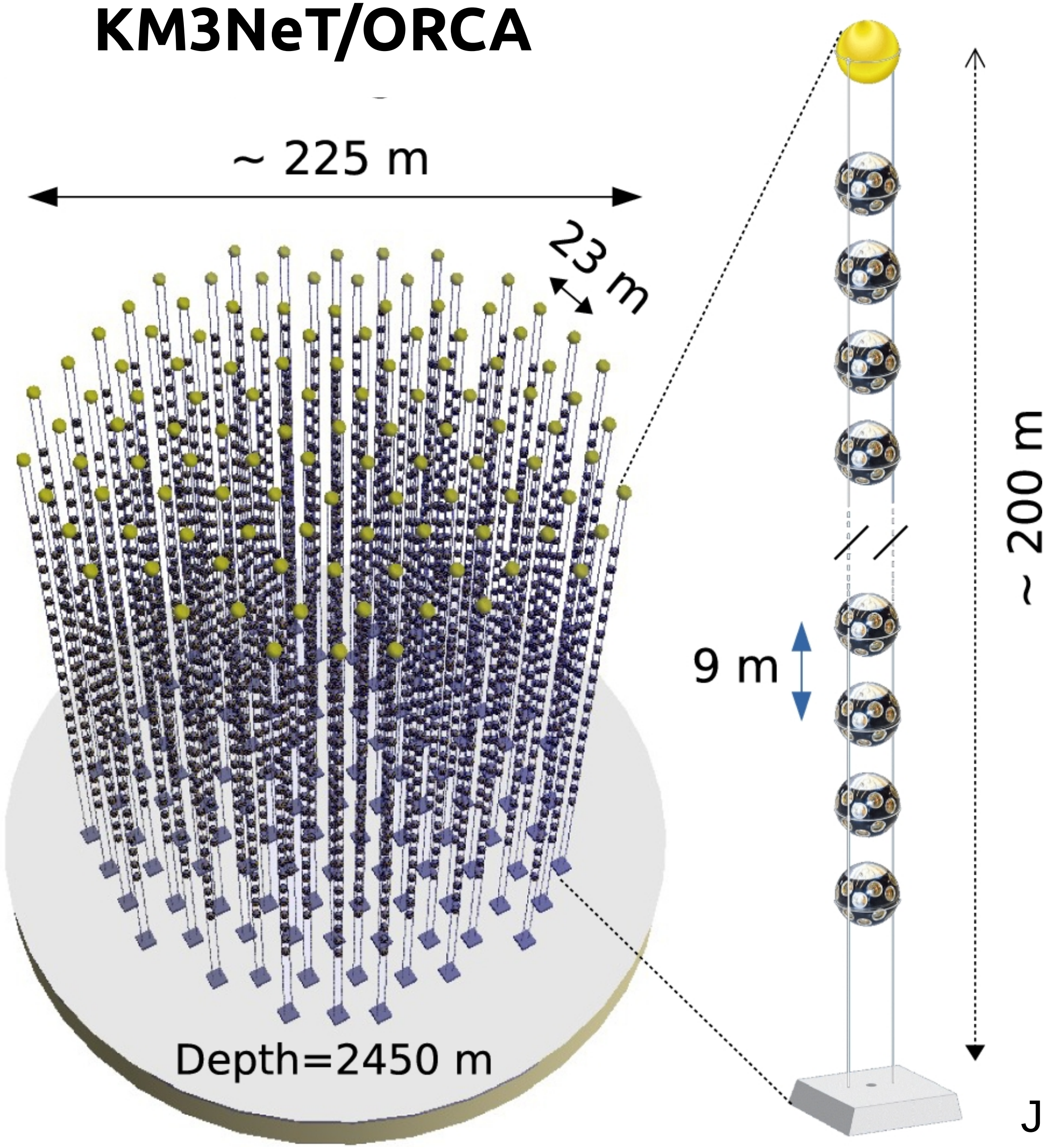
Designed to assess **Neutrino Mass Ordering** with atmospheric neutrinos

See e.g.
POS(ICRC2019)857
POS(ICRC2019)934

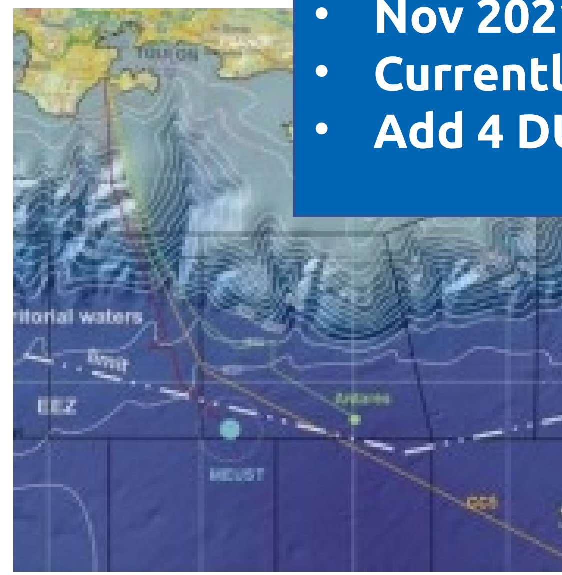
J. Phys. G **43, 8**: 084001 (2016)

The current generation of neutrino telescopes

KM3NeT/ORCA



- **6 DUs since Feb 2020**
- **Nov 2021: 10 DUs**
- **Currently operating 7**
- **Add 4 DUs in Summer**



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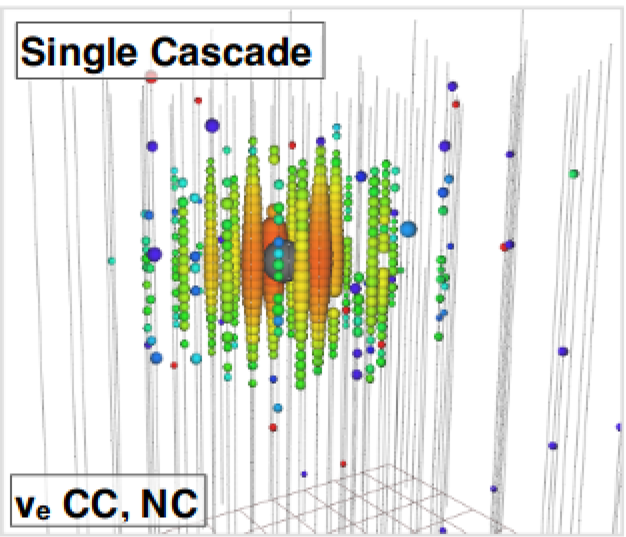
J. Phys. G **43, 8**: 084001 (2016)

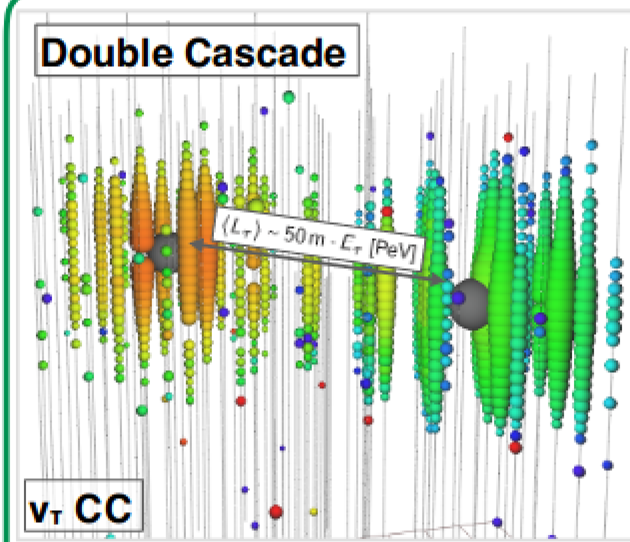
Event topologies in a neutrino telescope

early → late



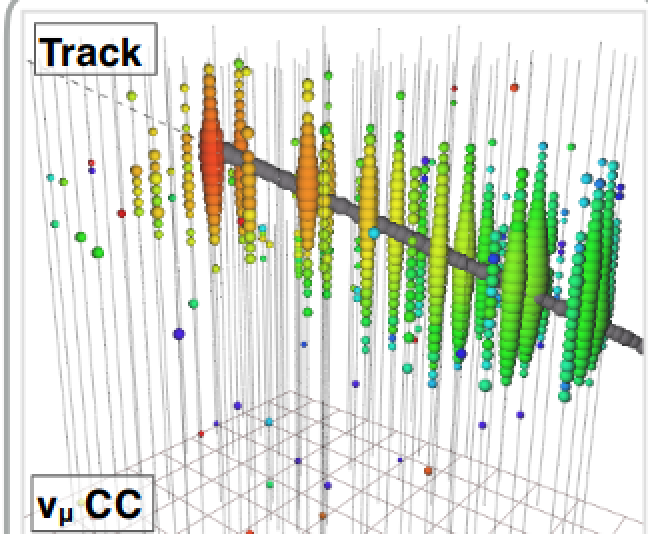
All NC interactions
ν_e CC interactions

Good energy resolution
Limited precision for the direction reconstruction



ν_τ CC interactions with hadronic / electronic tau decay

Good energy resolution
Angular resolution gets better with larger lengths



ν_μ CC interactions
Atmospheric μ
ν_τ CC interactions with muonic tau decay

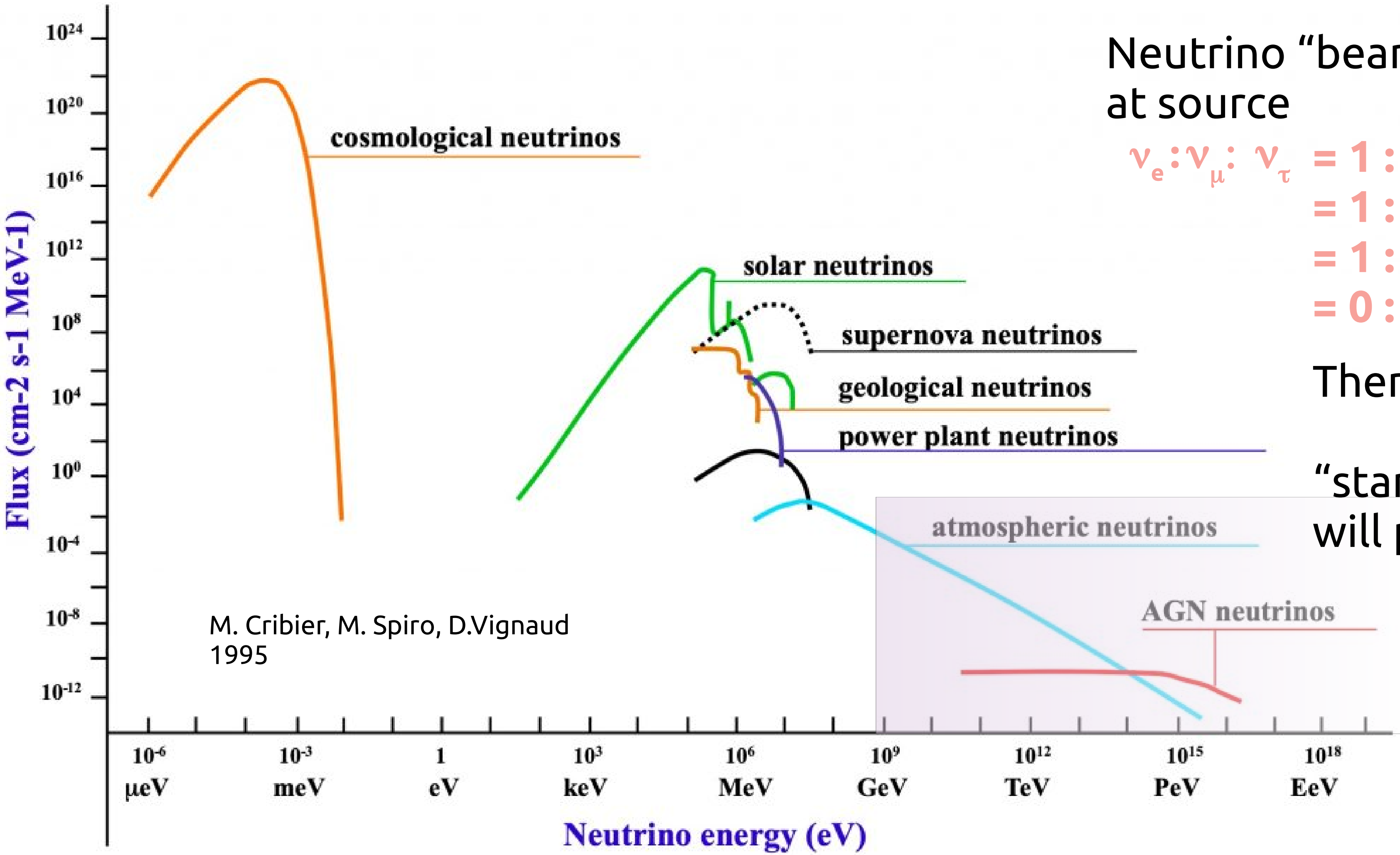
Good angular resolution
Limited precision for the energy reconstruction

Simulated event displays in the IceCube detector

Targets for neutrino telescopes

Target GeV to PeV energies with the same instruments

Allow the study of all-flavour neutrino fluxes



M. Cribier, M. Spiro, D.Vignaud
1995

Neutrino "beam" flavour ratio at source

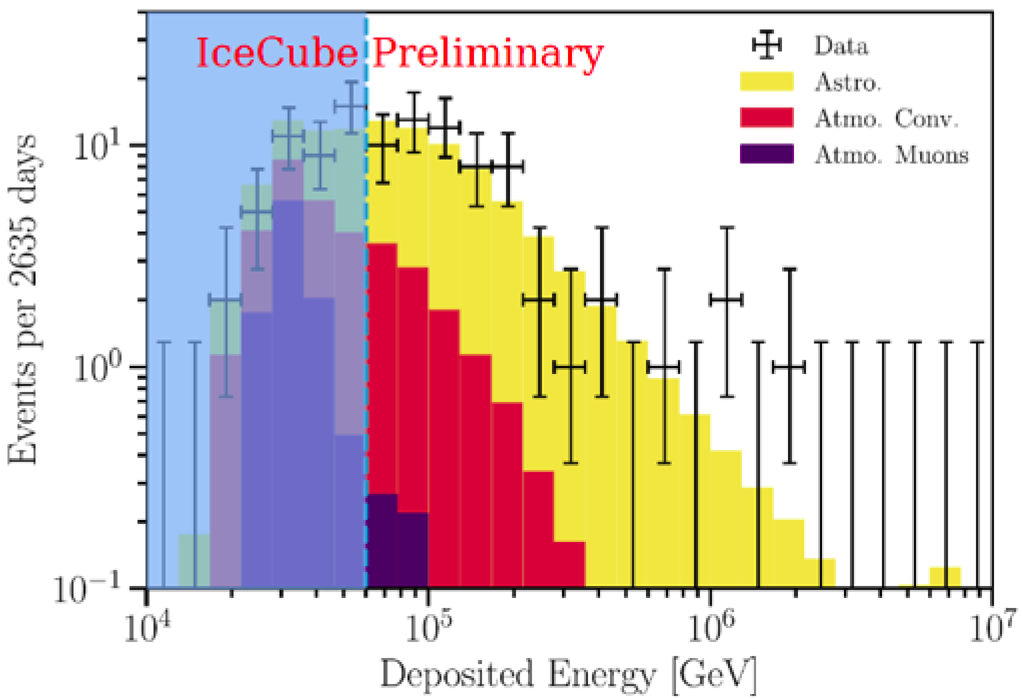
$\nu_e : \nu_\mu : \nu_\tau$ = 1 : 2 : 0 or
= 1 : 1 : 0 or
= 1 : 0 : 0 or
= 0 : 1 : 0

Then oscillations!

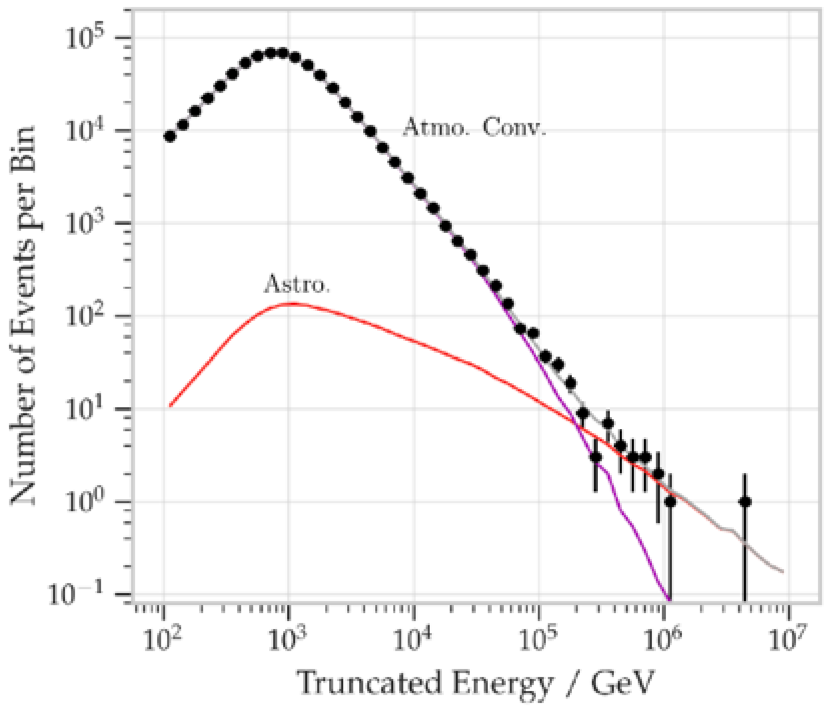
"standard model" will produce 1:1:1 at Earth

The discovery of HE cosmic neutrinos

Diffuse flux from astrophysical objects observed by IceCube in all-flavour analyses



High Energy Starting Events
IceCube 7.5 yr



Through-going muons
IceCube 9 yr

The discovery of HE cosmic neutrinos

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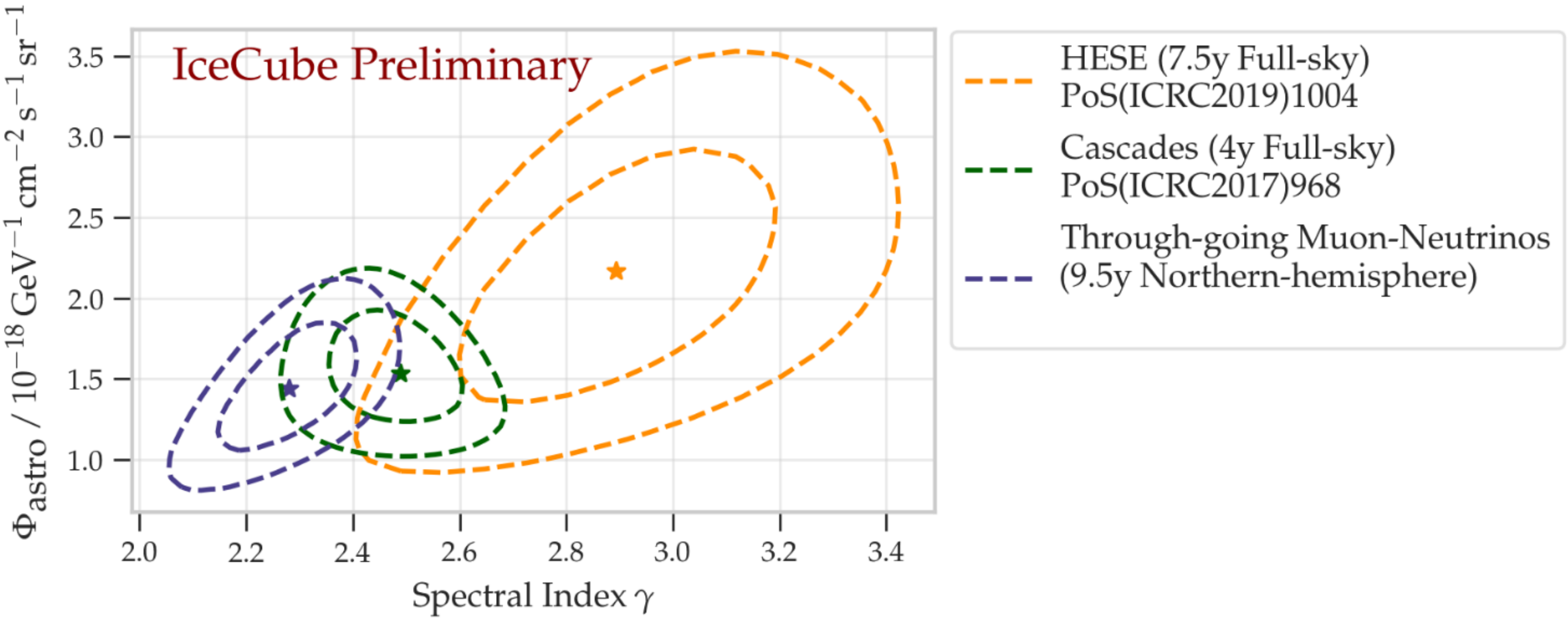
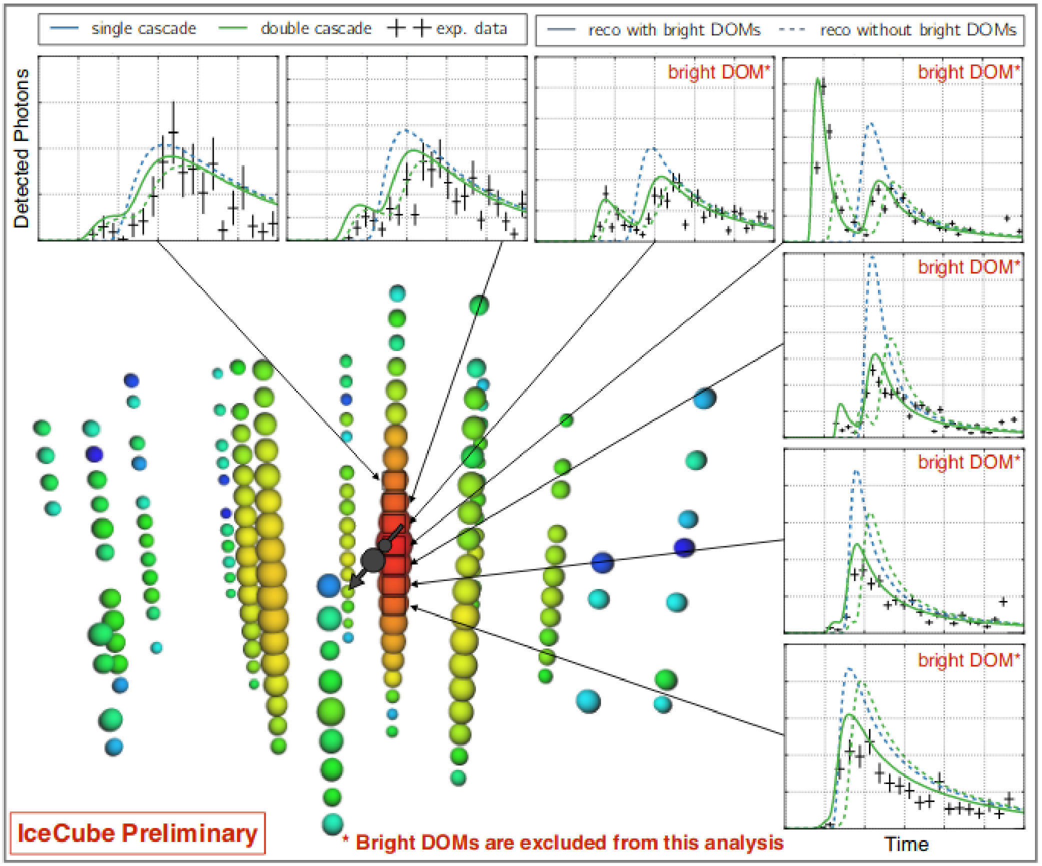
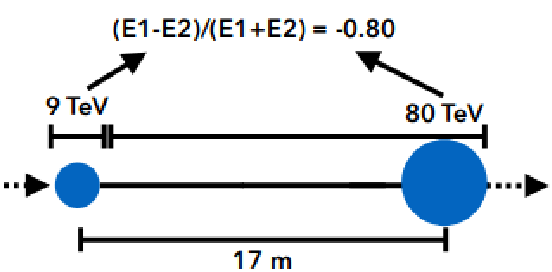


Some tension between different channels: “HESE” and “Cascades” are electron neutrino dominated, muon neutrinos show a different behaviour

Astrophysics or **Neutrino Physics**?

HE tau neutrinos in IceCube





https://arxiv.org/abs/2011.03561

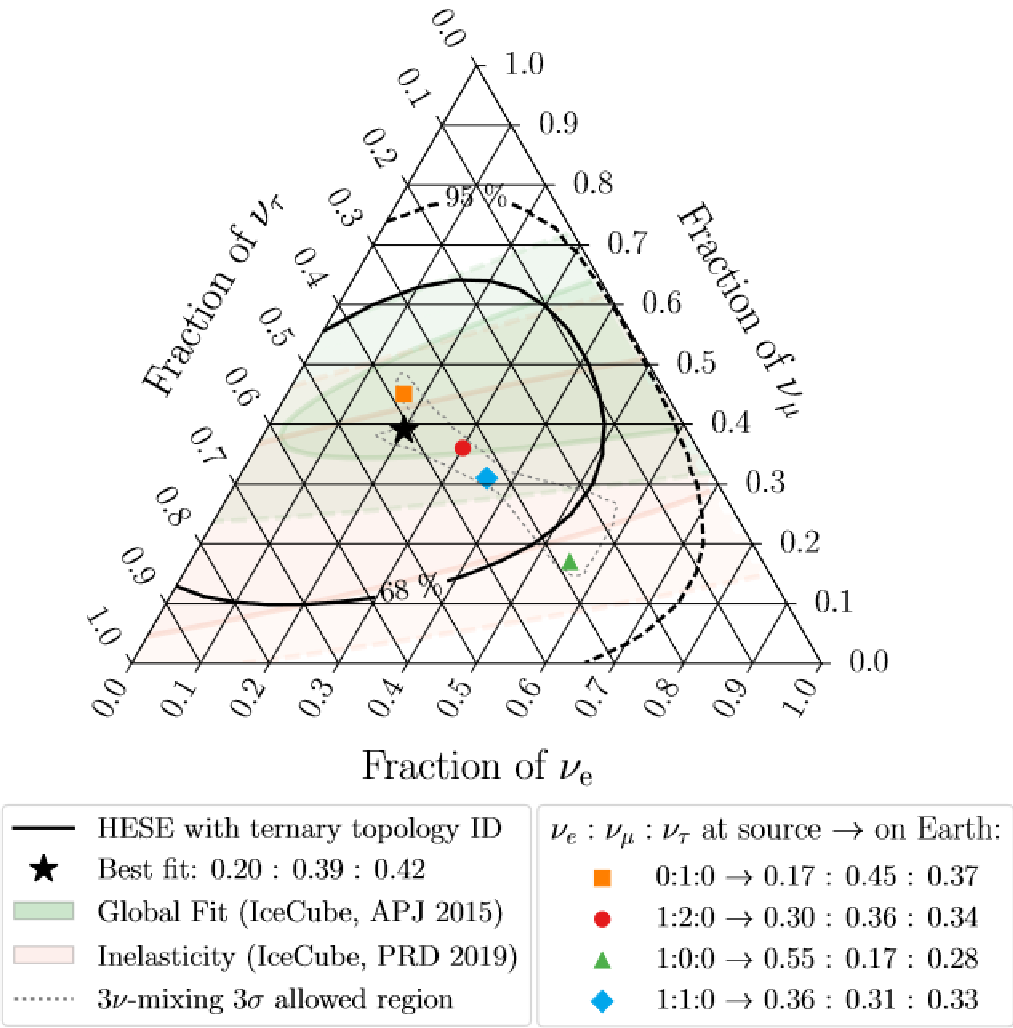
No atmospheric background → tau flux can only be of cosmic origin

2 candidate events in 10 years of IceCube data

Tau observation
→ **constrain flavour ratio @Earth and thus @source**

Propagation effects? Beyond Standard Model?

HE tau neutrinos in IceCube



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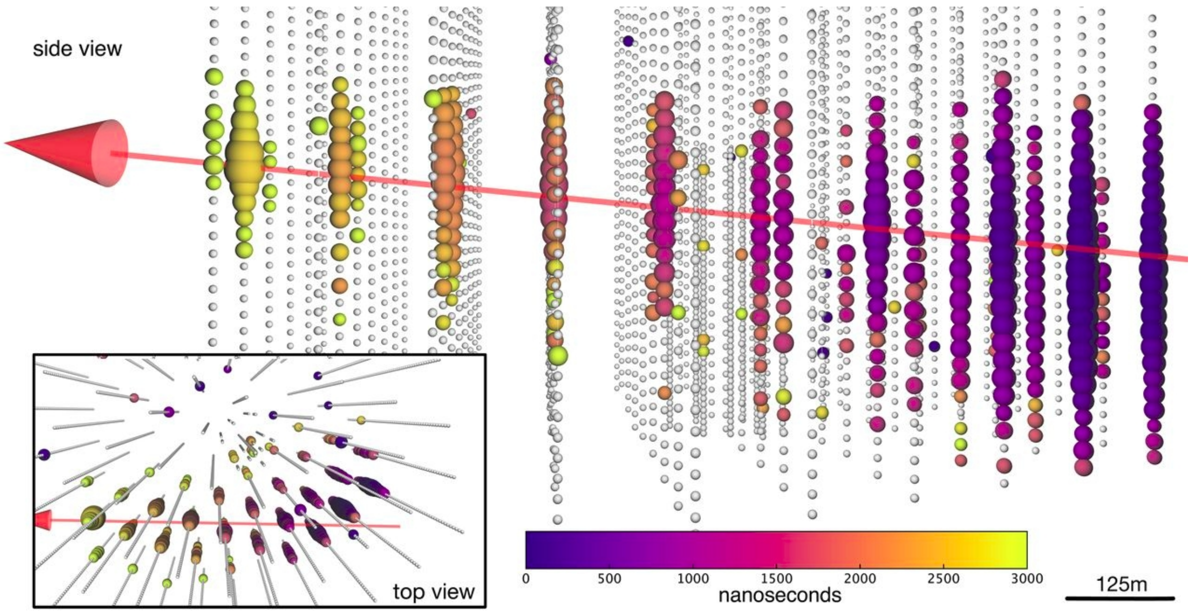
The discovery of HE cosmic neutrinos



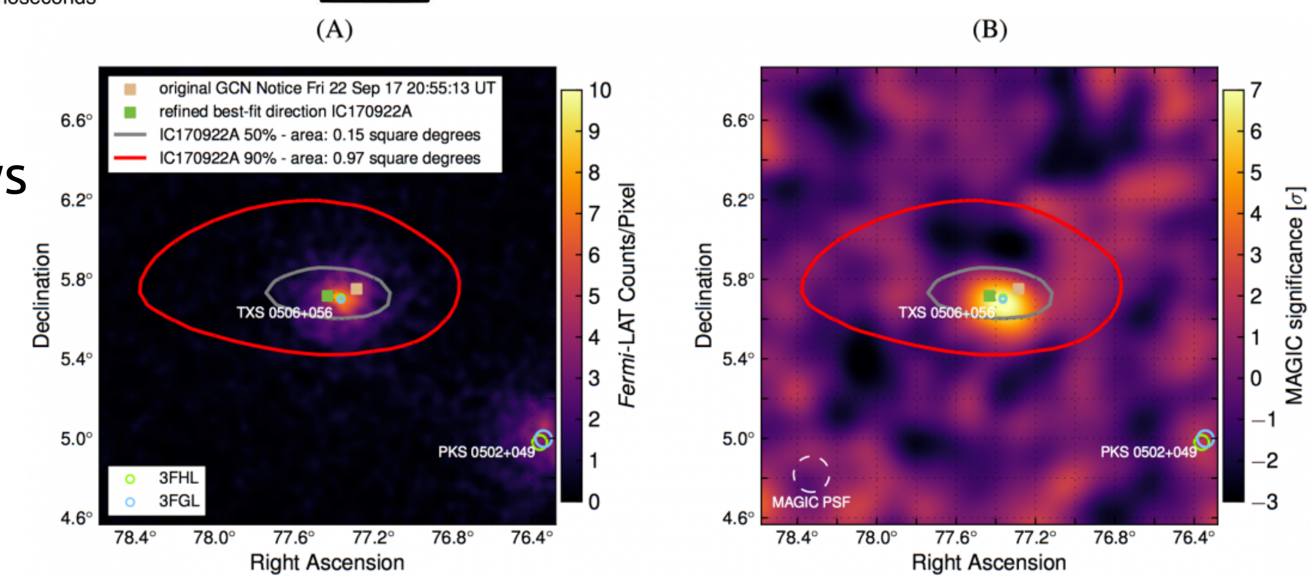
270 TeV muon
On 22 September 2017 at 20:54:30.43 UTC

RA 77.4° and Dec +5.7°

Close to the Flaring Blazar
TXS 0506+056

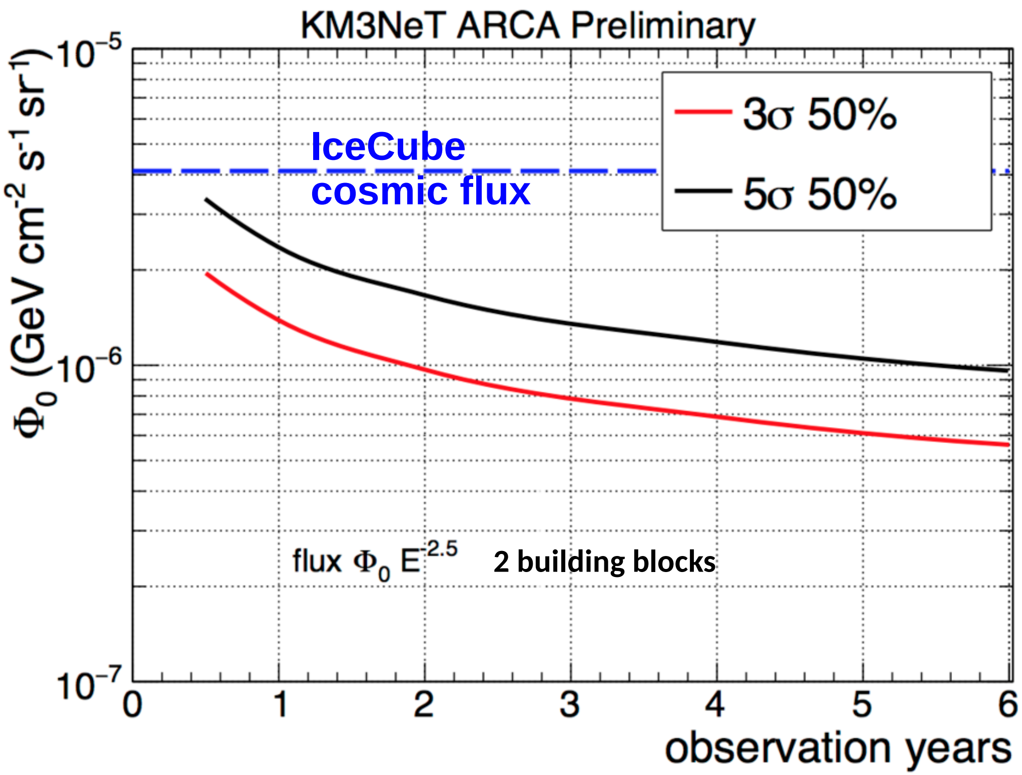
Fermi-LAT and MAGIC prompt follow-up in gamma rays
>3σ significance

Not really compatible with other close-by emitters



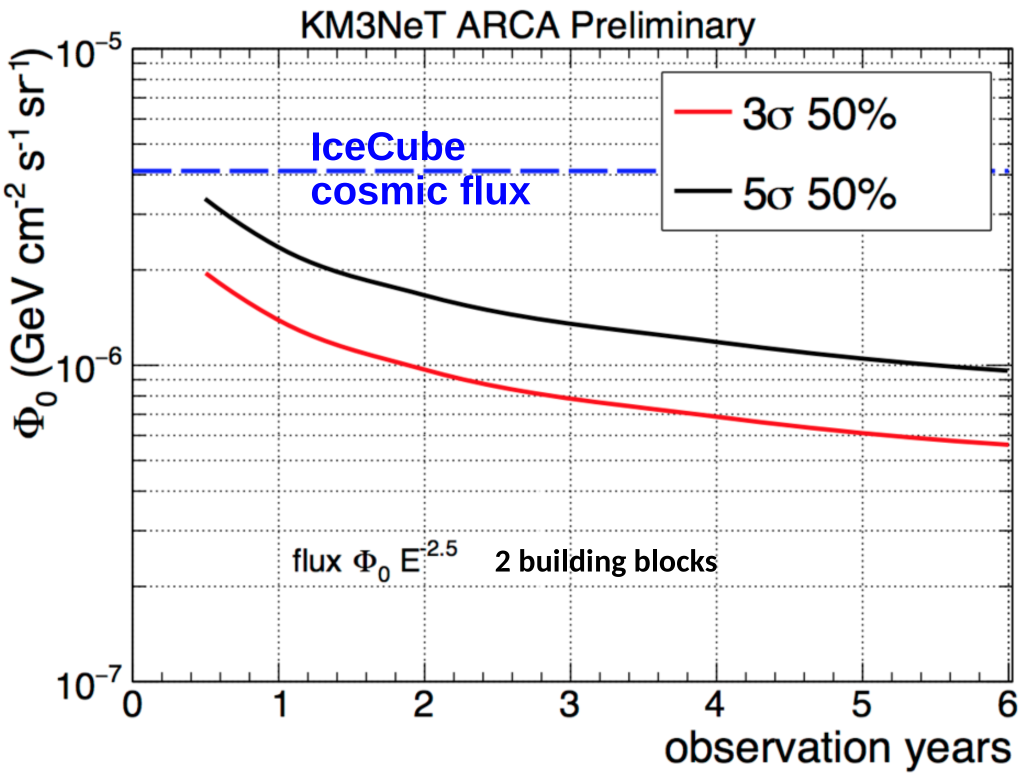
Science **361, 6398**, eaat1378
DOI: 10.1126/science.aat1378

The future of cosmic neutrinos searches



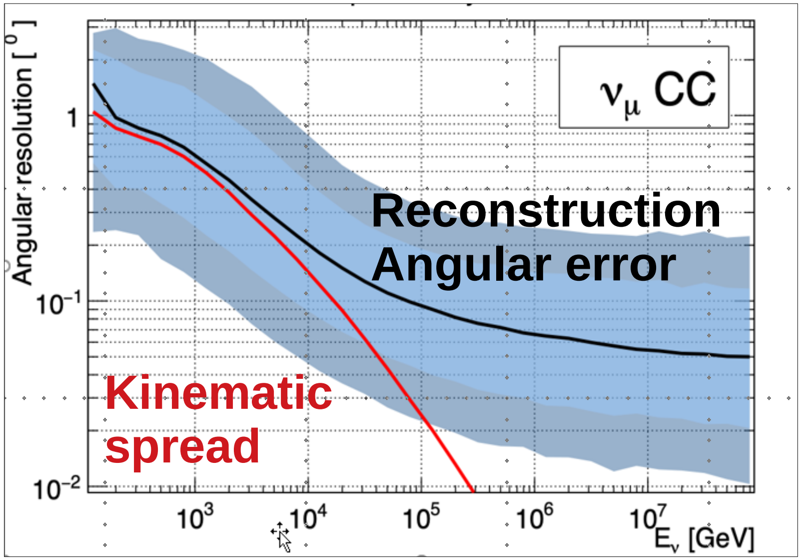
ARCA can confirm the IceCube diffuse flux within 1 year of data taking with the full planned detector

The future of cosmic neutrinos searches

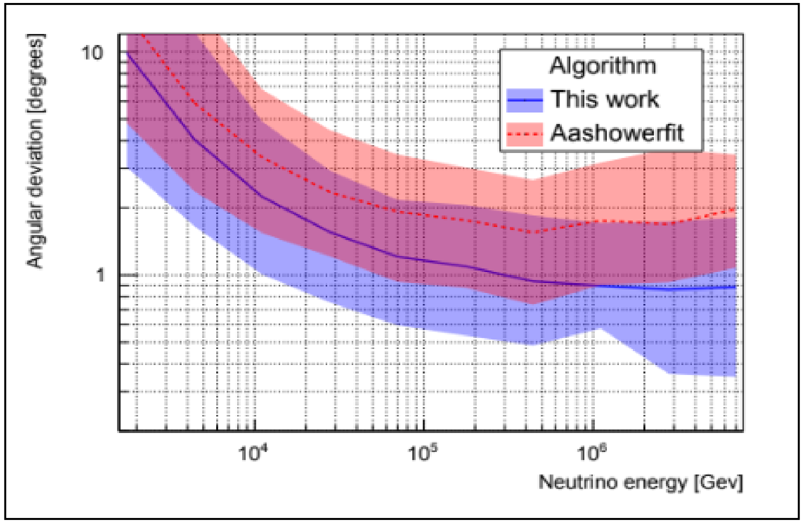


With a much better angular resolution
for both tracks and cascades

Track Reconstruction



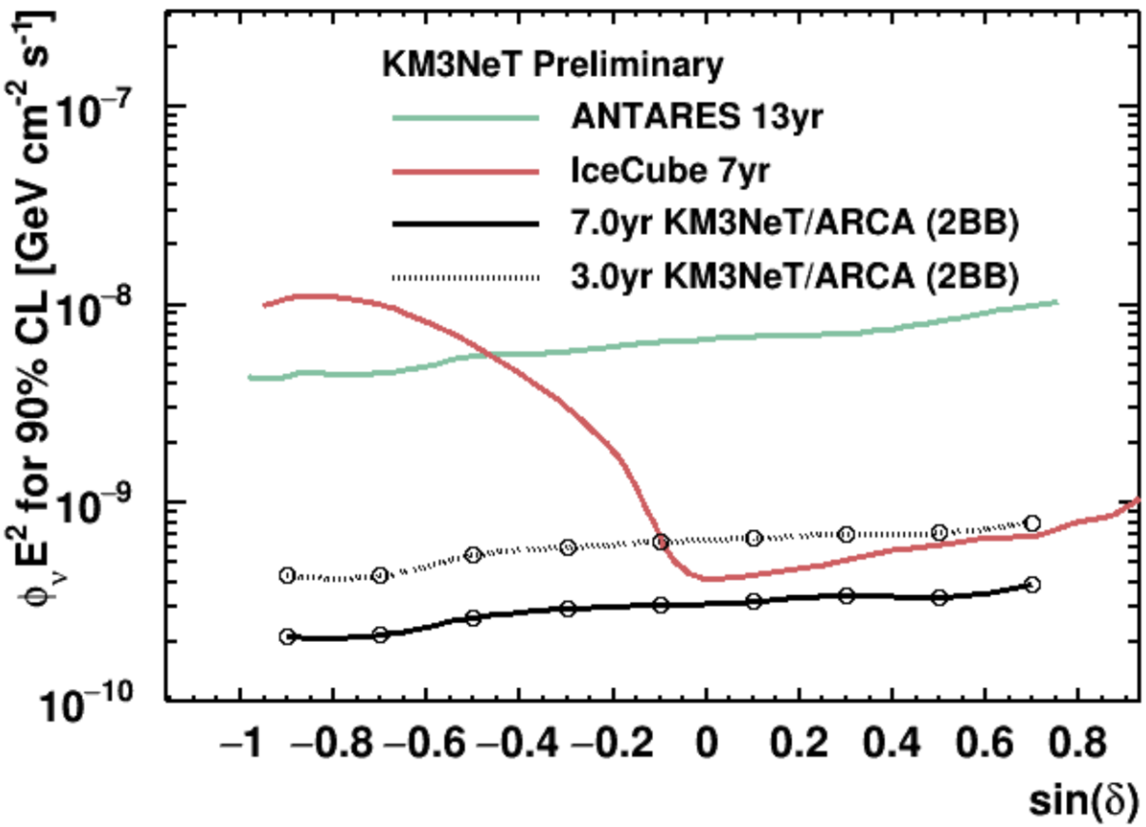
Cascade Reconstruction



KM3NeT

The future of cosmic neutrinos searches

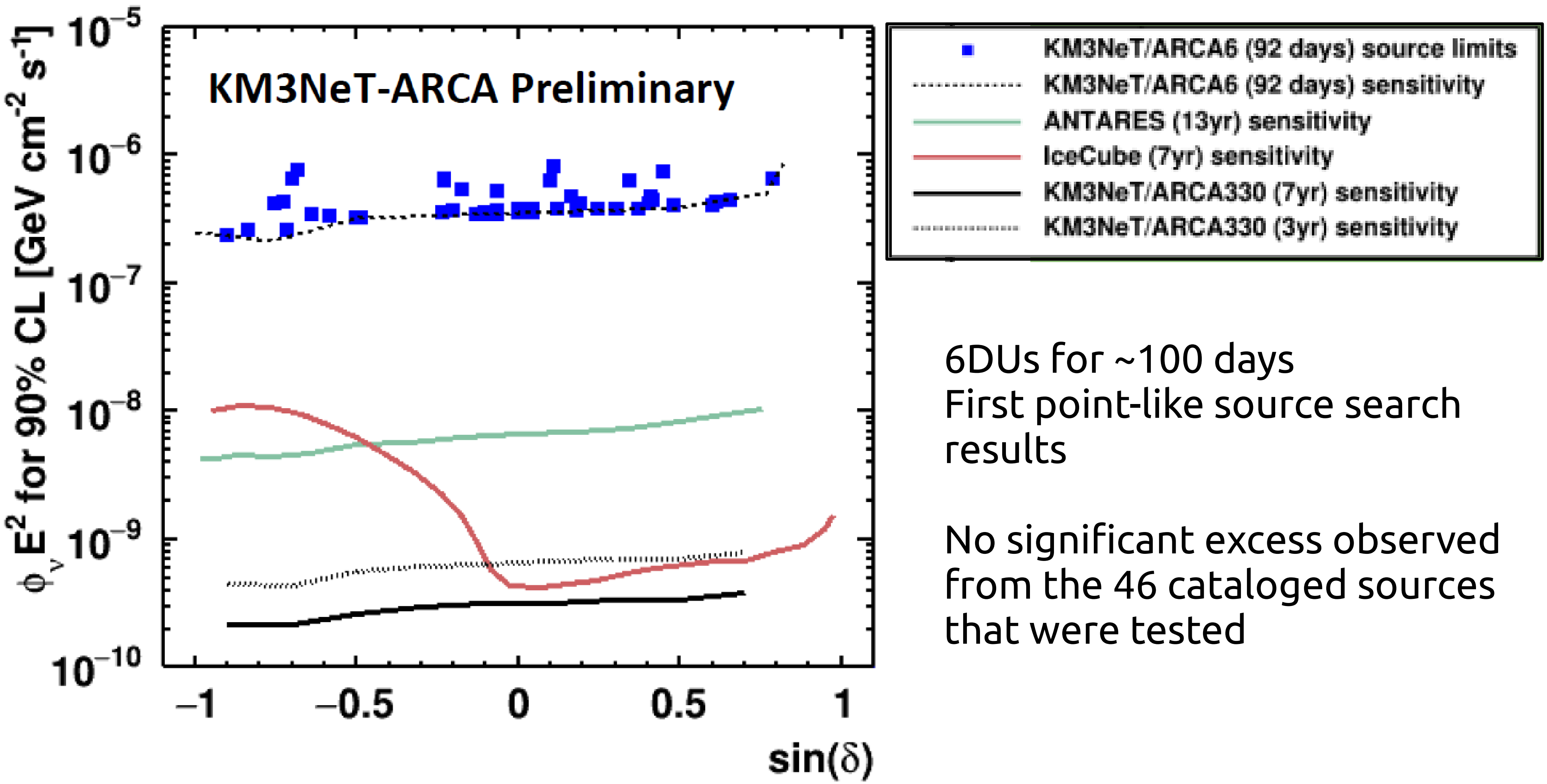
Point-source sensitivities



Improvement in searches for point-like sources mainly in the Southern Celestial Hemisphere

B. Caiffi et al, ICRC 2021

The future of cosmic neutrinos searches

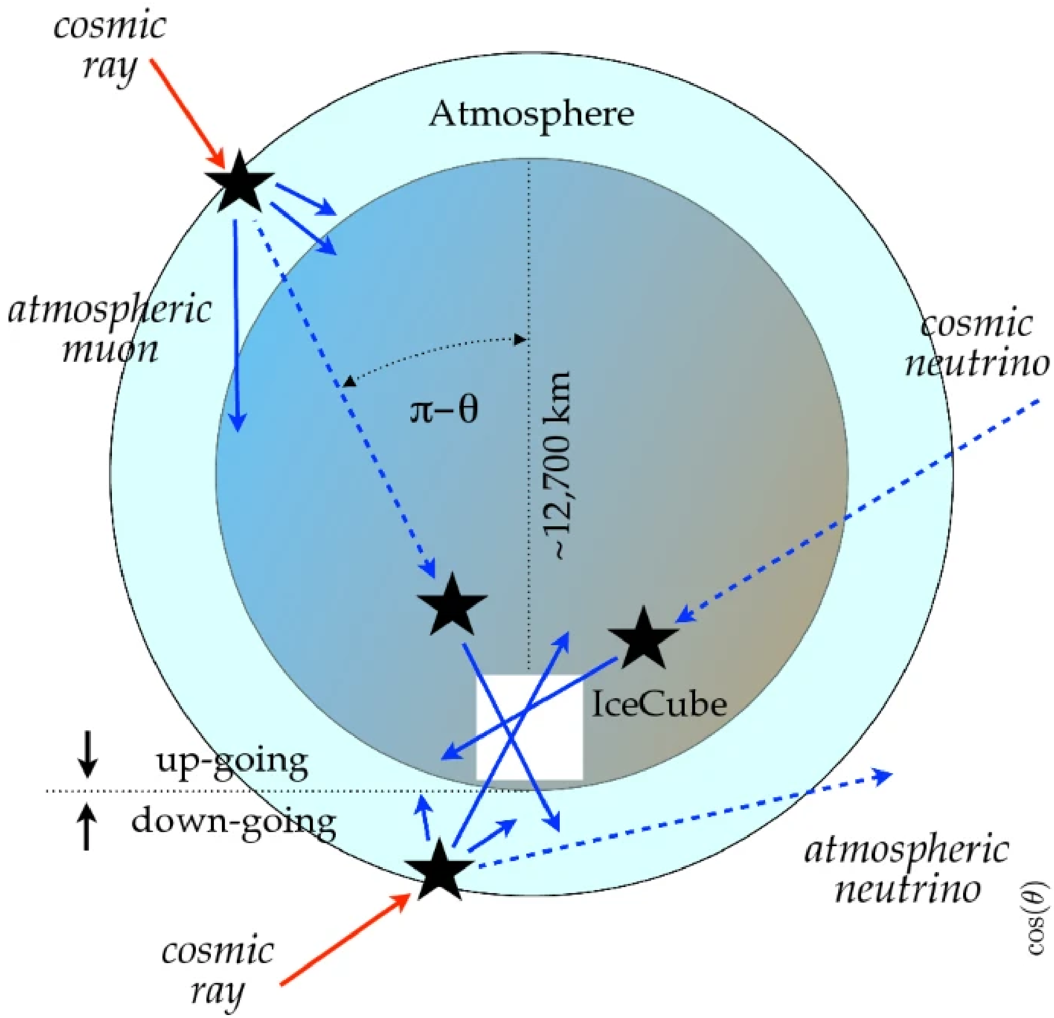


6DUs for ~100 days
First point-like source search results

No significant excess observed from the 46 cataloged sources that were tested

R. Muller et al, Neutrino2022

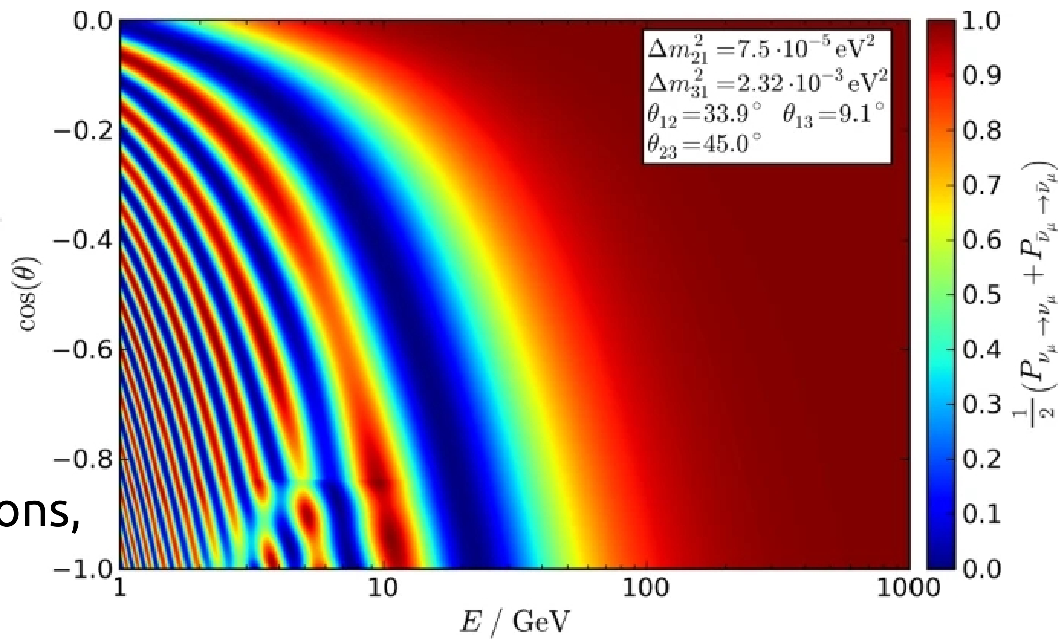
Neutrino physics with the atmospheric beam



A wide range of energies and lengths can be studied

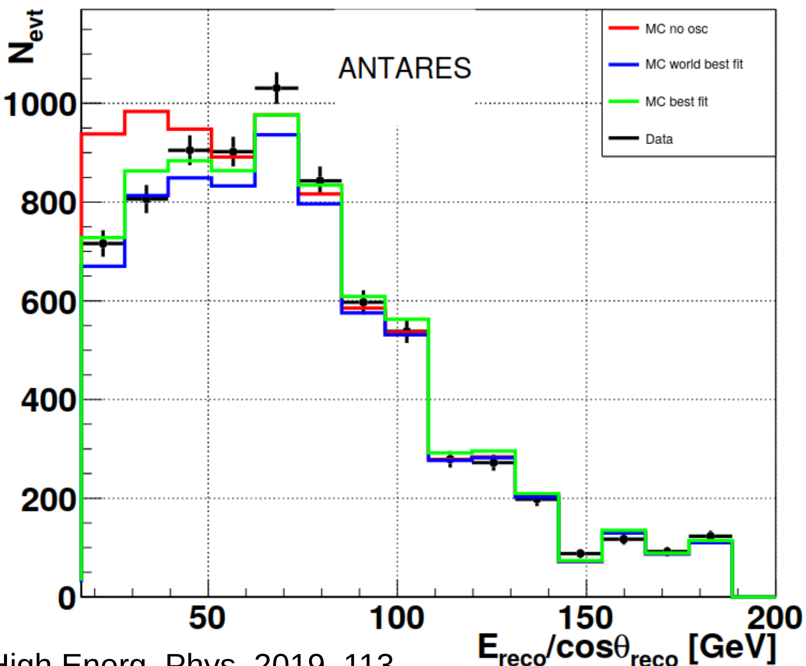
Zenith and energy dependent oscillation patterns at the detector

Muon neutrino survival probability

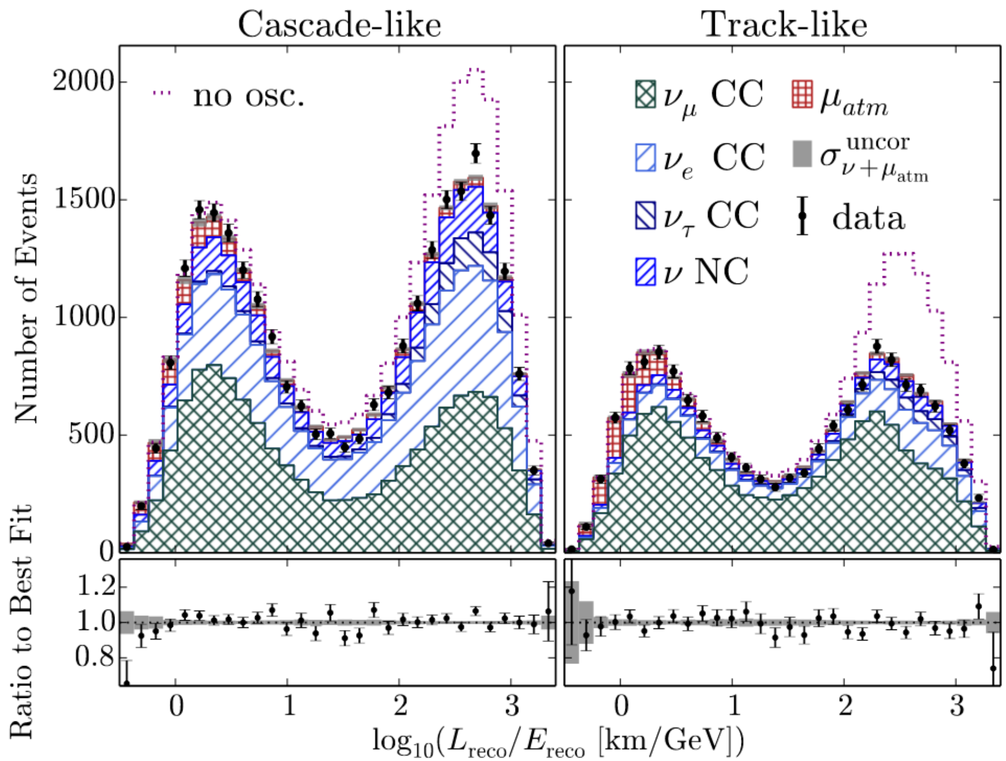


Also, anomalies can show up
e.g. Sterile Neutrinos, Non-standard Interactions, Lorentz Invariance Violation...

Neutrino physics with the atmospheric beam



J. High Energ. Phys. 2019, 113 (2019)

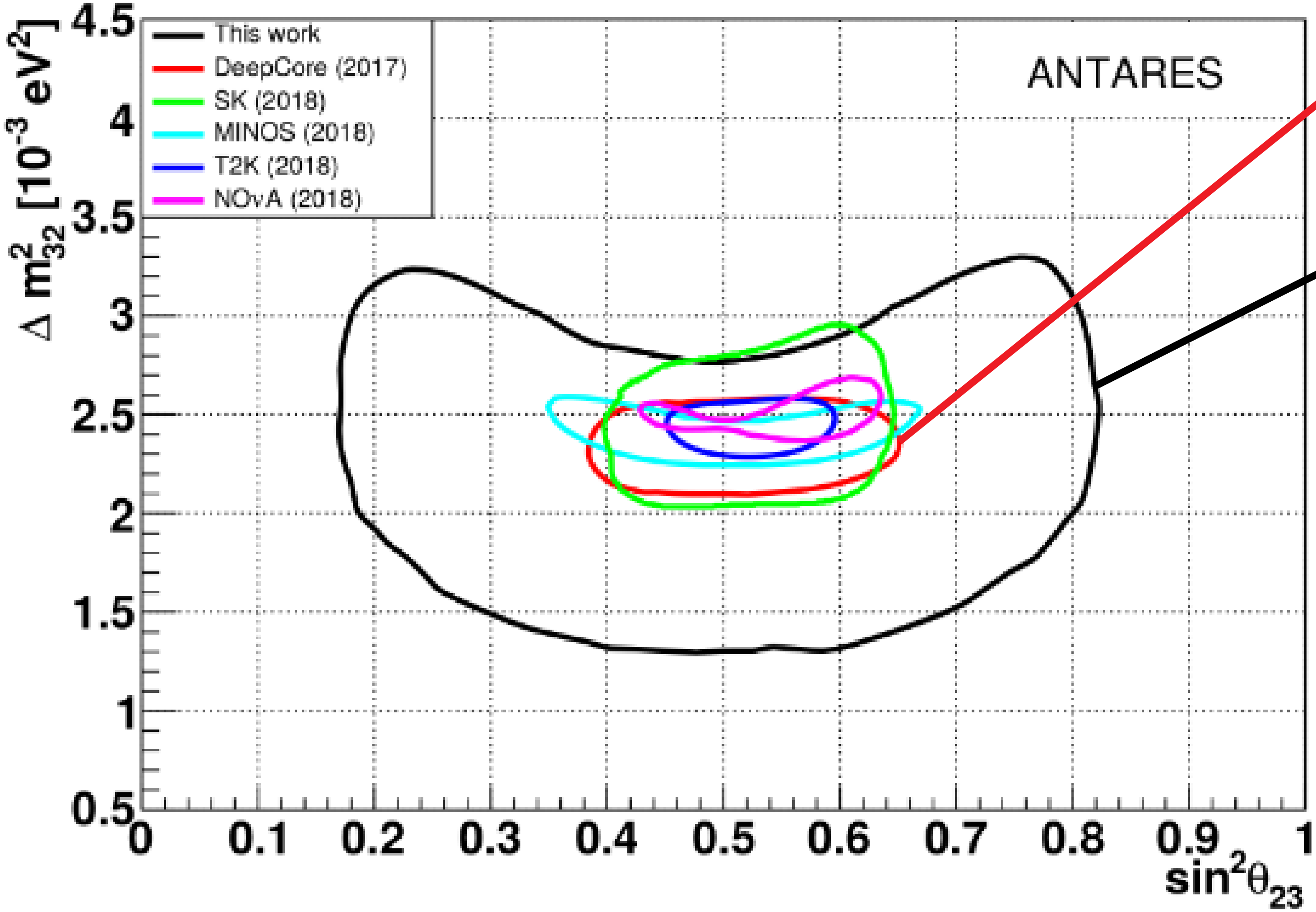


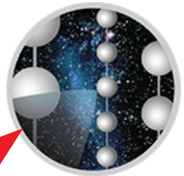
Phys. Rev. Lett. 120, 071801 (2018)

Muon neutrino disappearance from the atmospheric beam

– tau appearance is difficult to see
– neutral current contribution affect the “cascade” sample

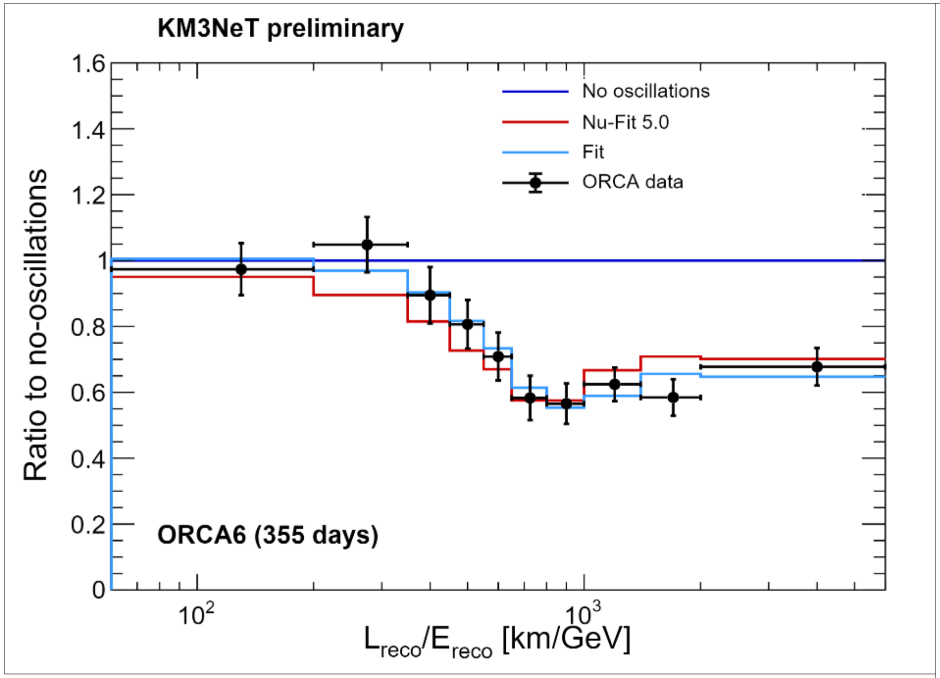
Neutrino physics with the atmospheric beam

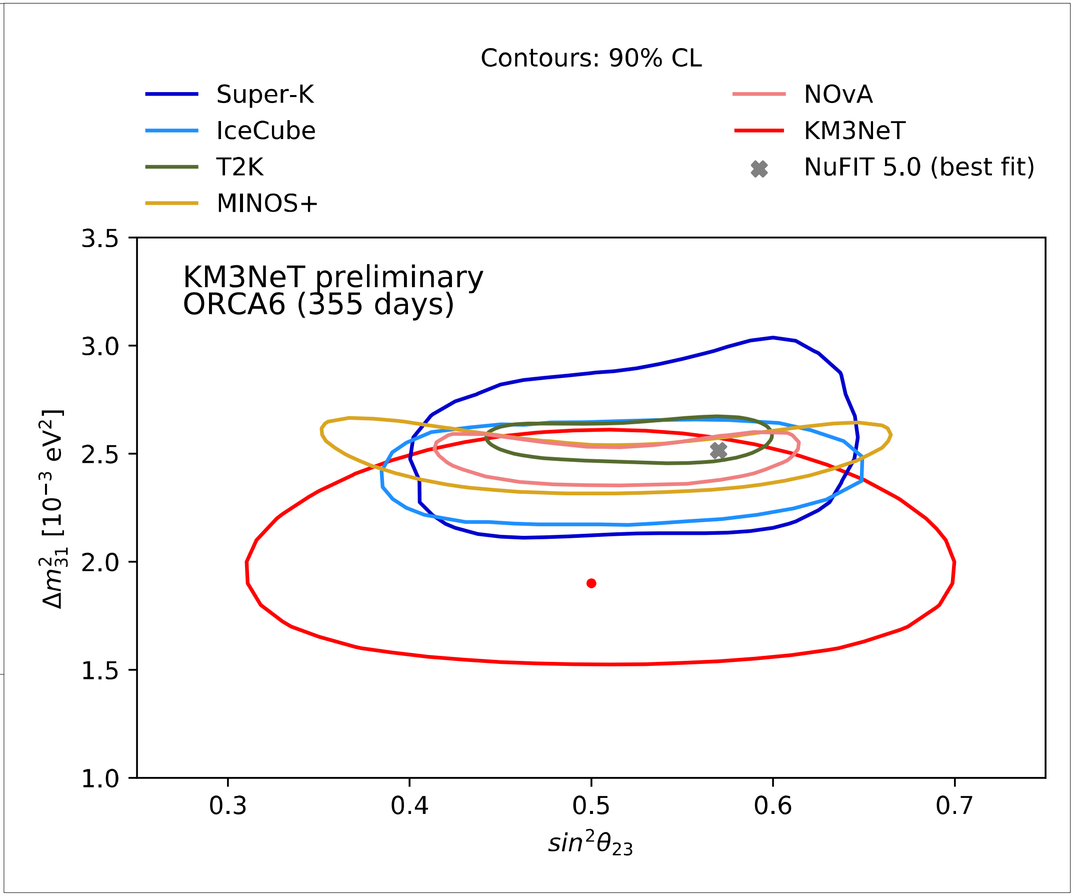




J. High Energ. Phys. 2019, 113 (2019)

Neutrino oscillations in KM3NeT/ORCA

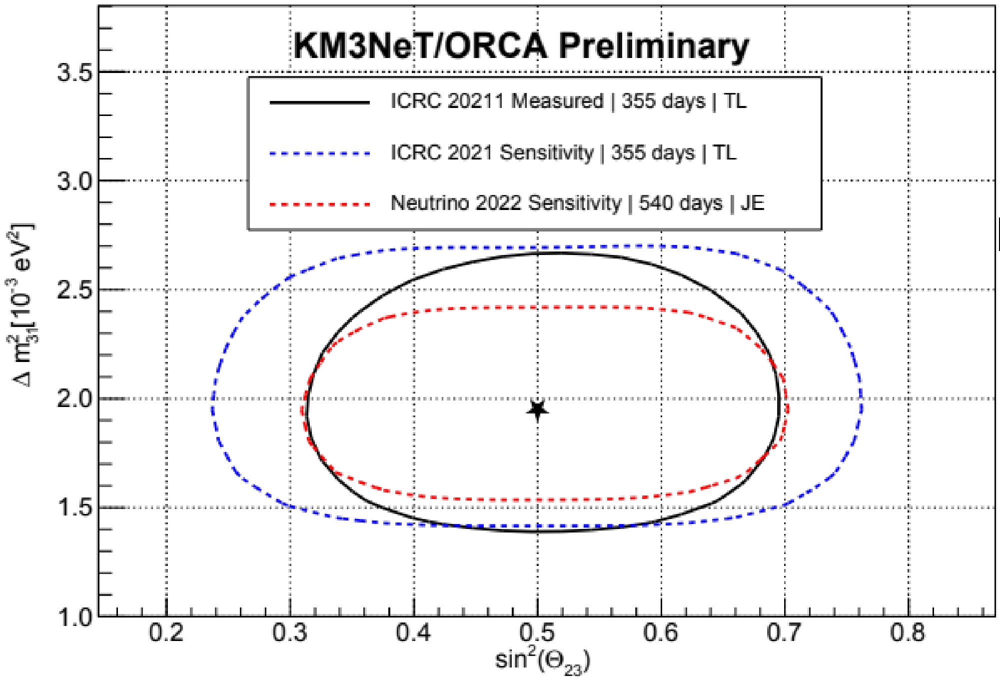




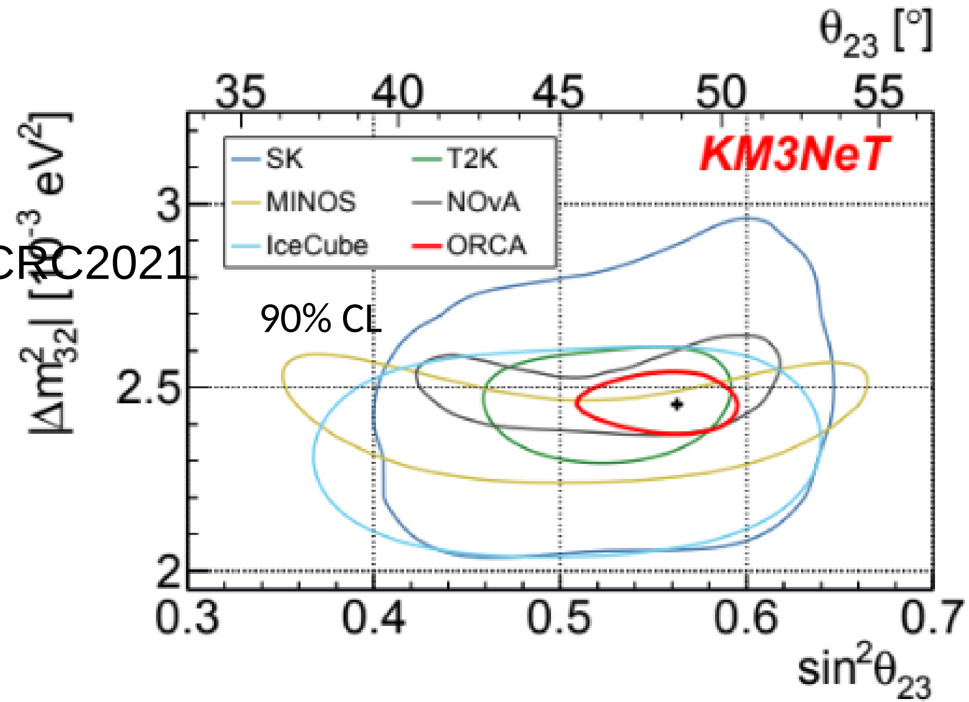
1 year of data with 6 lines of ORCA

Neutrino oscillations in KM3NeT/ORCA

Neutrino2022



ICRC2021



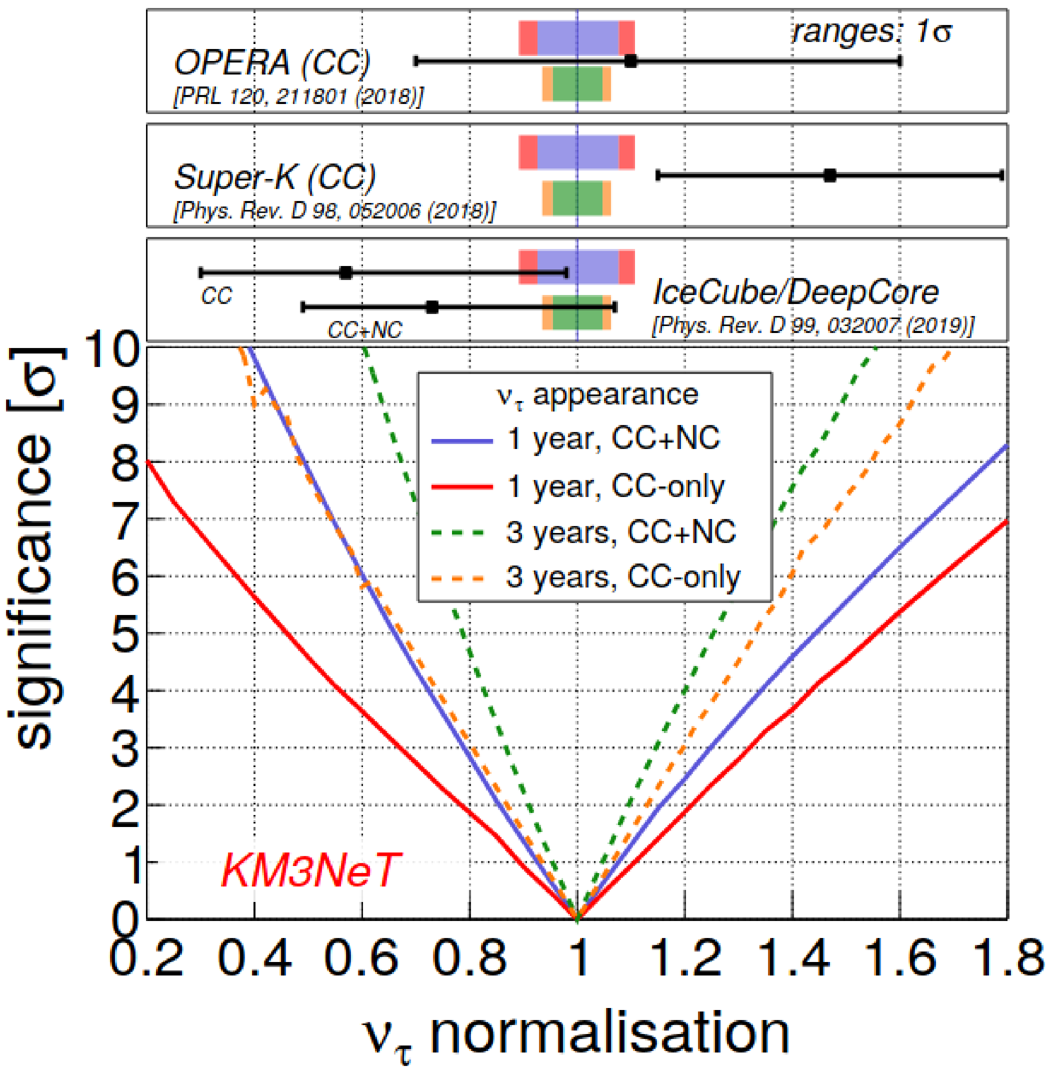
Coming soon

- More data 355 -> 540 days
- Better selection & particle identification
- Sample increased by a factor 5
- Unblinding to come in the next months

And then ...

3 years of full ORCA operations will give unprecedented sensitivity to oscillation parameters

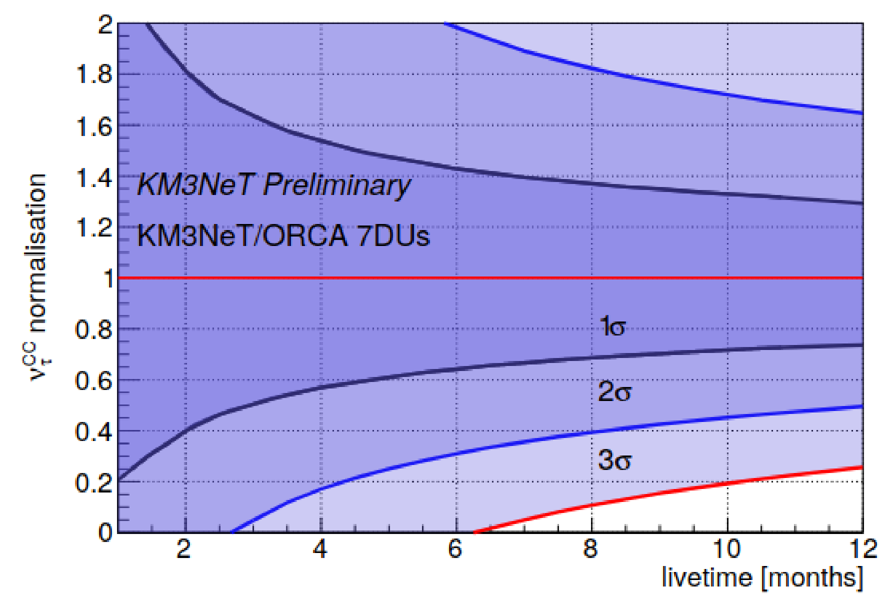
Tau appearance in KM3NeT/ORCA



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

The full KM3NeT/ORCA detector should measure few thousands of tau neutrinos from oscillation

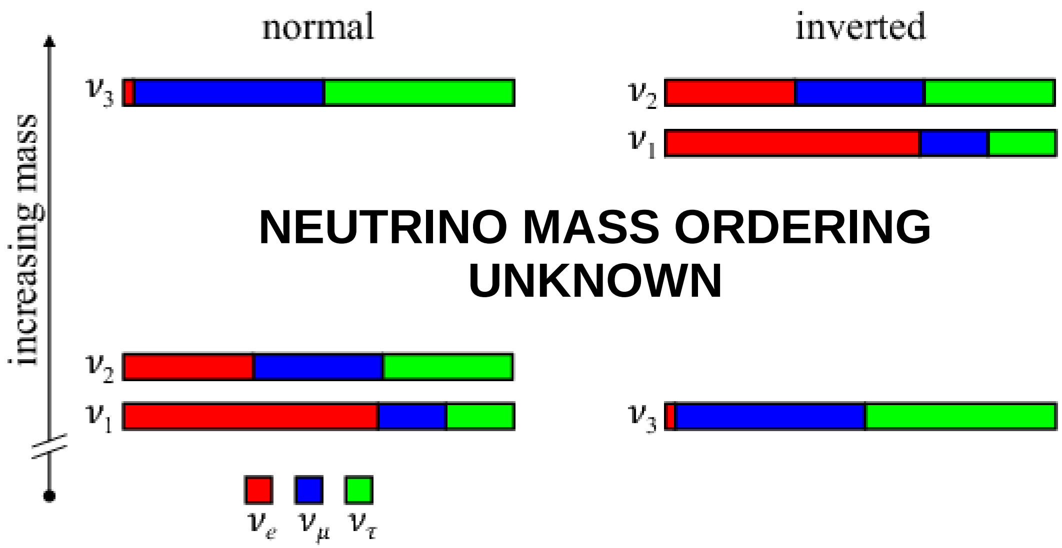
→ strong constraints on unitarity

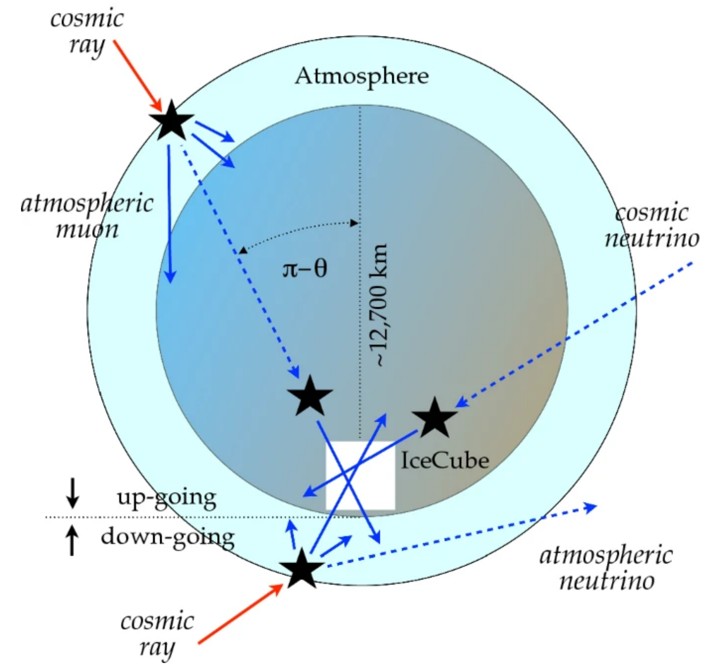


First studies ongoing
Good estimated sensitivity

PoS ICRC2019, 1019 (2019)

Neutrino mass ordering with atmospheric neutrinos

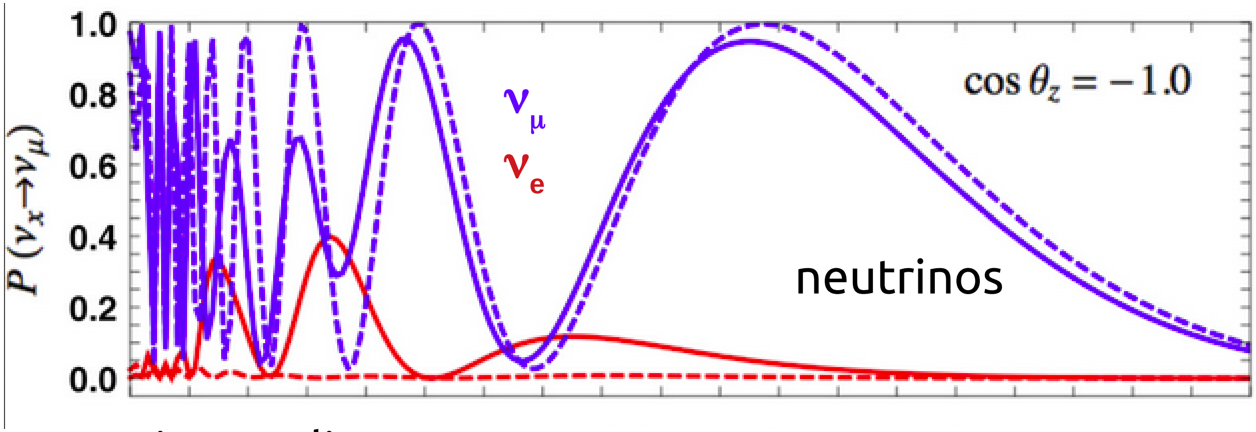




Matter effects for neutrinos through the Earth → NMO accessible

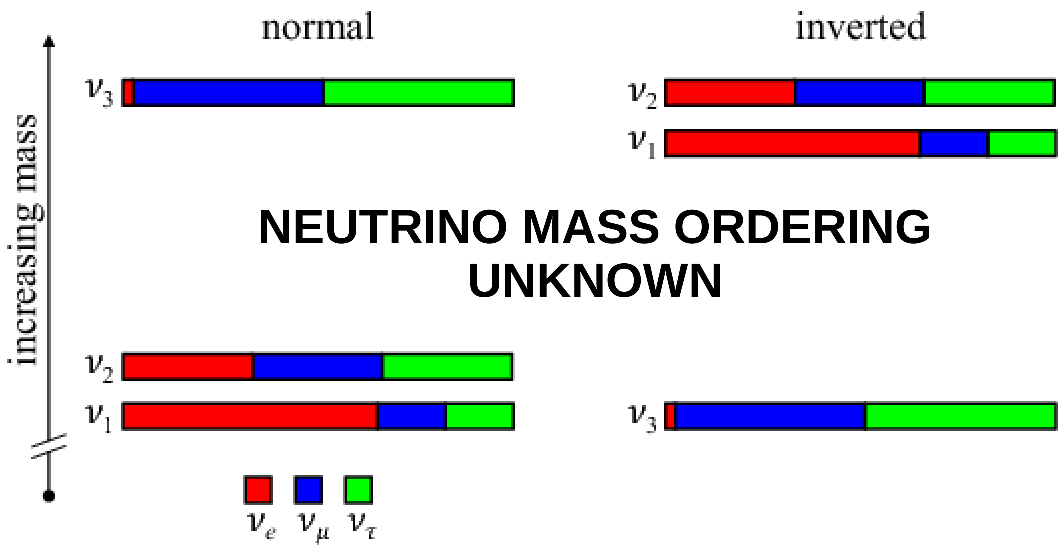
Measurable effects at ~10 GeV in 10 Mton water Cherenkov detector

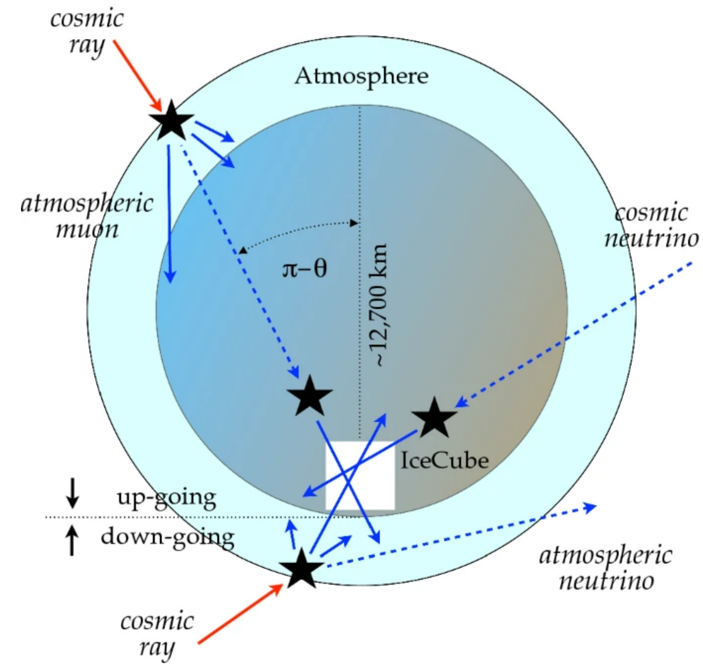
Huge detector → large statistics

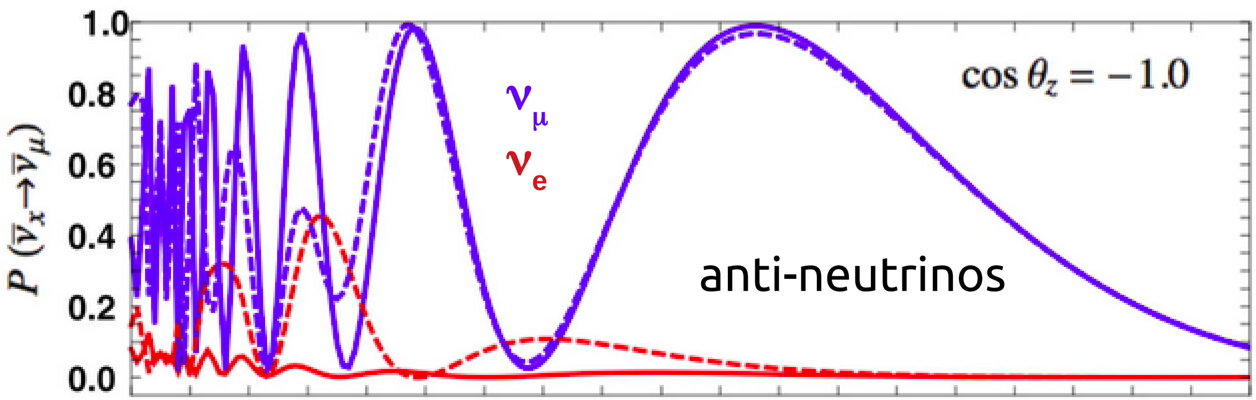


Continuous line → NO
Dashed line → IO

Neutrino mass ordering with atmospheric neutrinos







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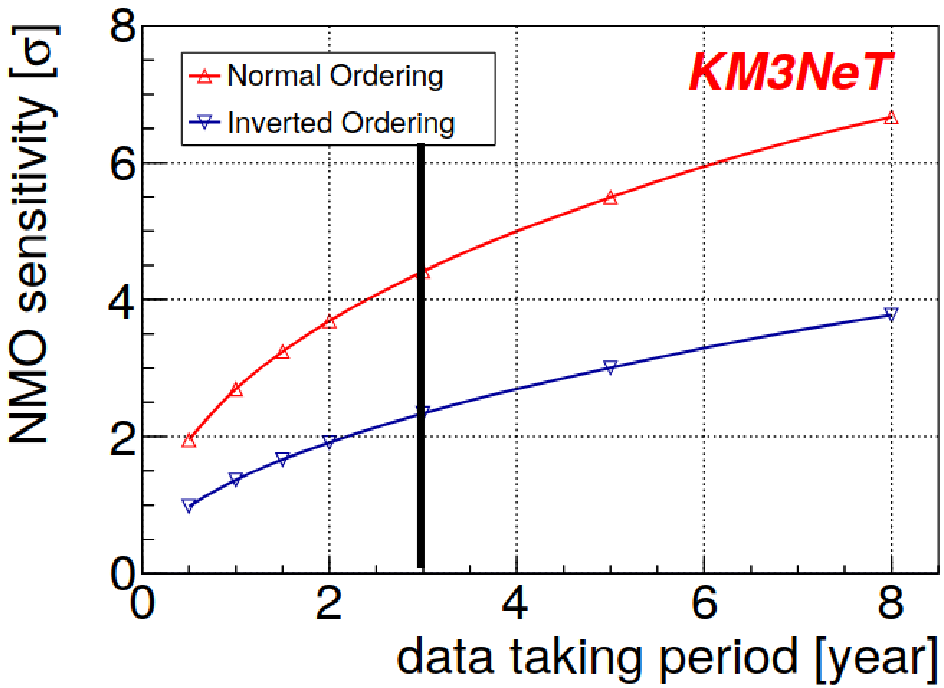
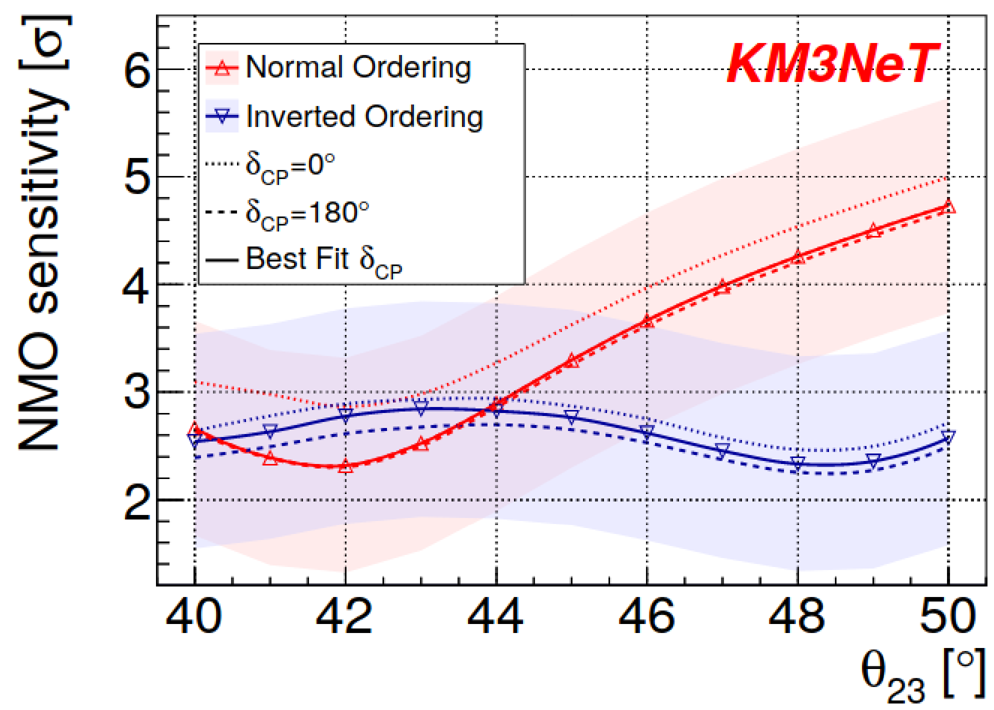
NMO in KM3NeT/ORCA





NMO determination at 3 sigma level within 3 years of detector completion

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

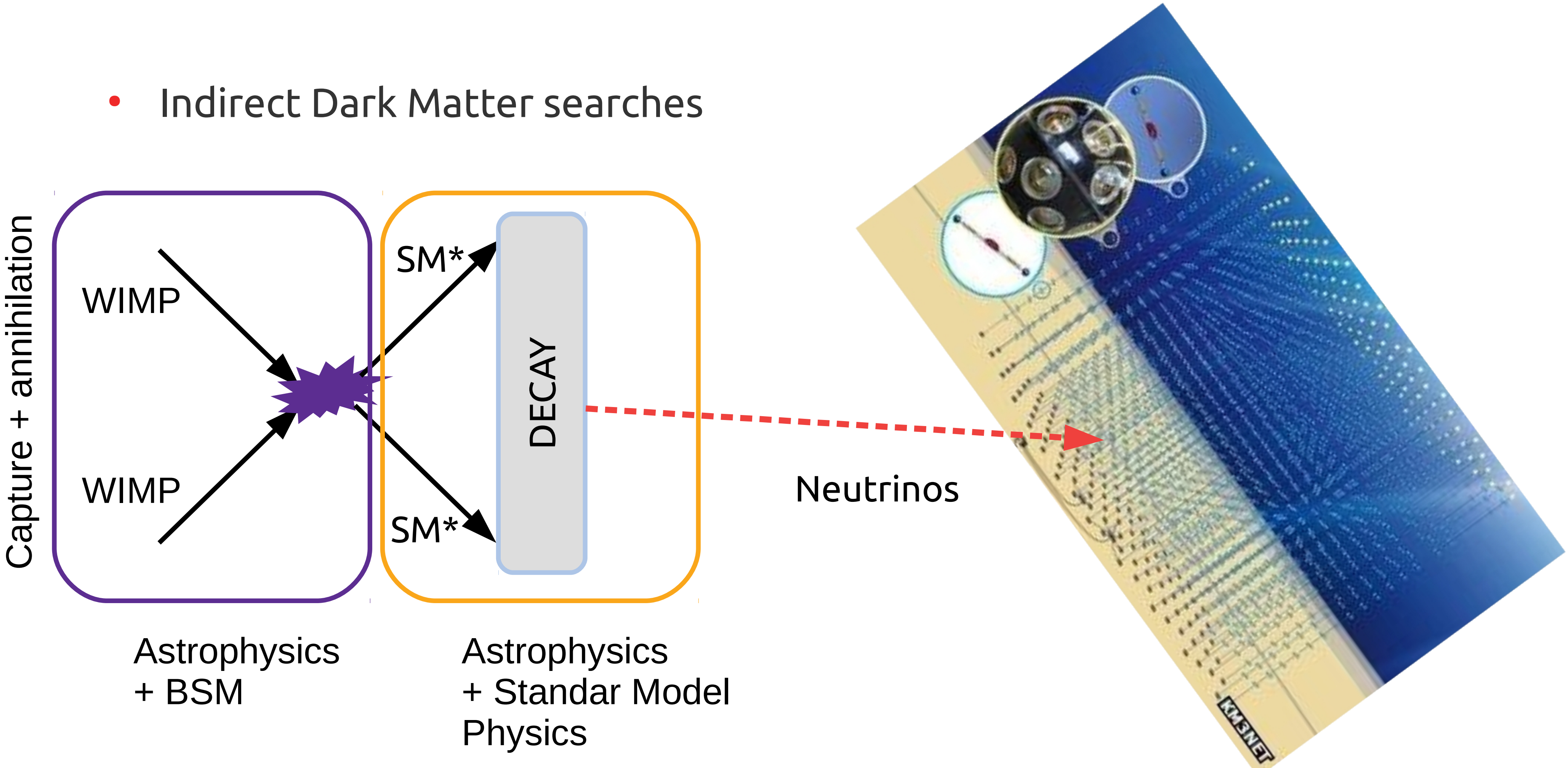
Beyond Standard Model searches with neutrino telescopes

- Indirect Dark Matter searches
- Non-standard interactions in neutrino oscillations*
- Sterile neutrinos*
- ...*

*(in the backup slides)

Dark matter searches with neutrino telescopes

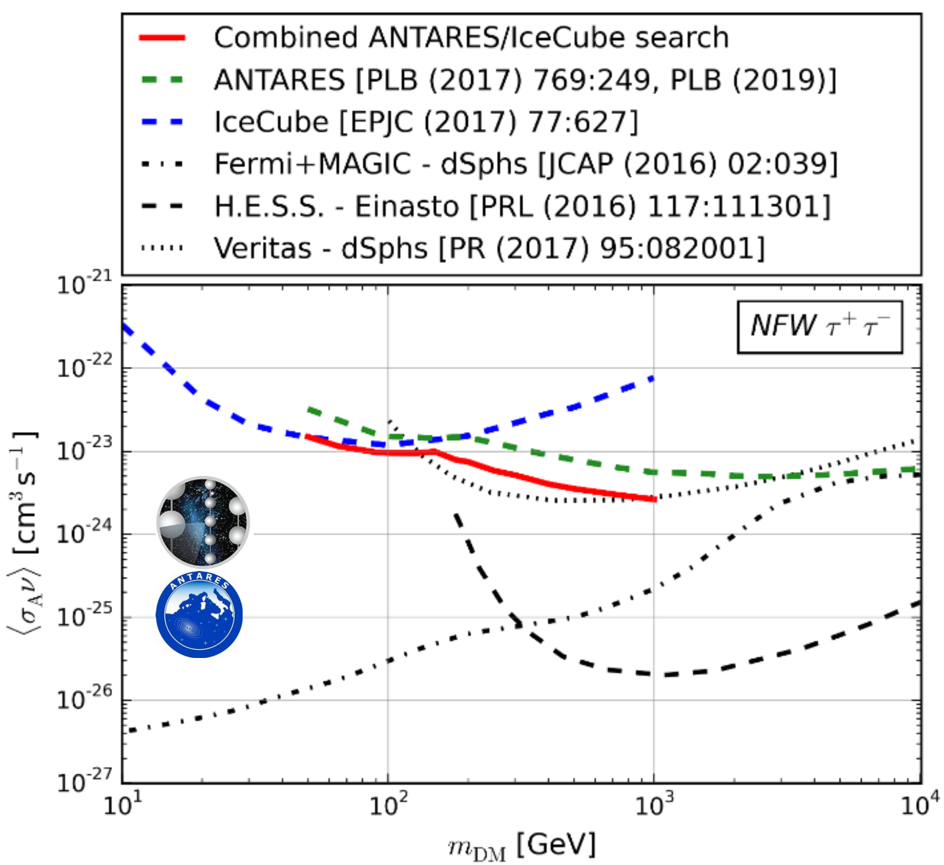
- Indirect Dark Matter searches



* fermions or bosons

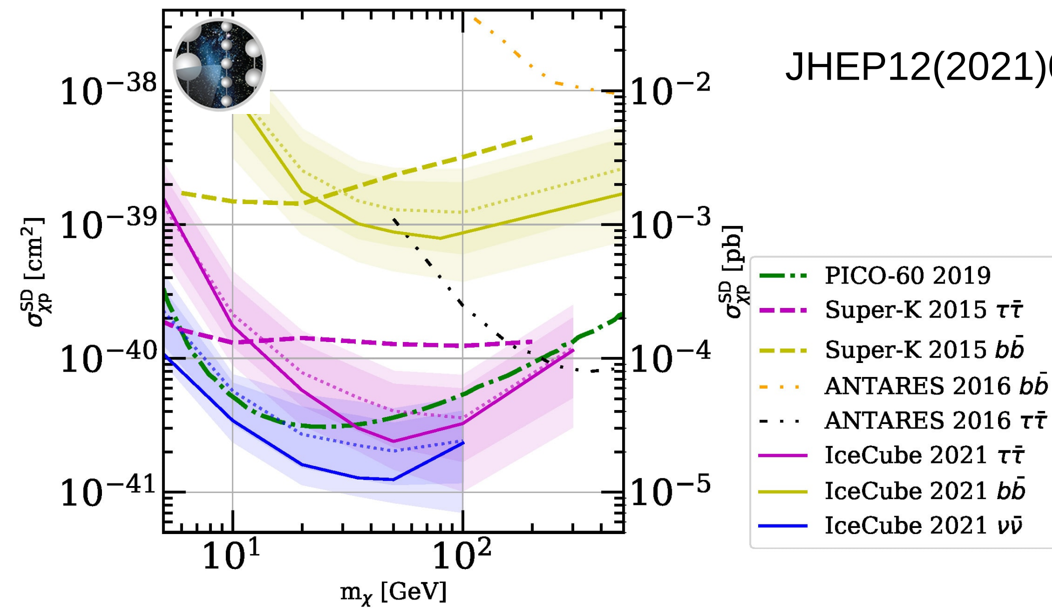
Dark matter searches with neutrino telescopes

Galactic Centre
→ annihilation cross-section

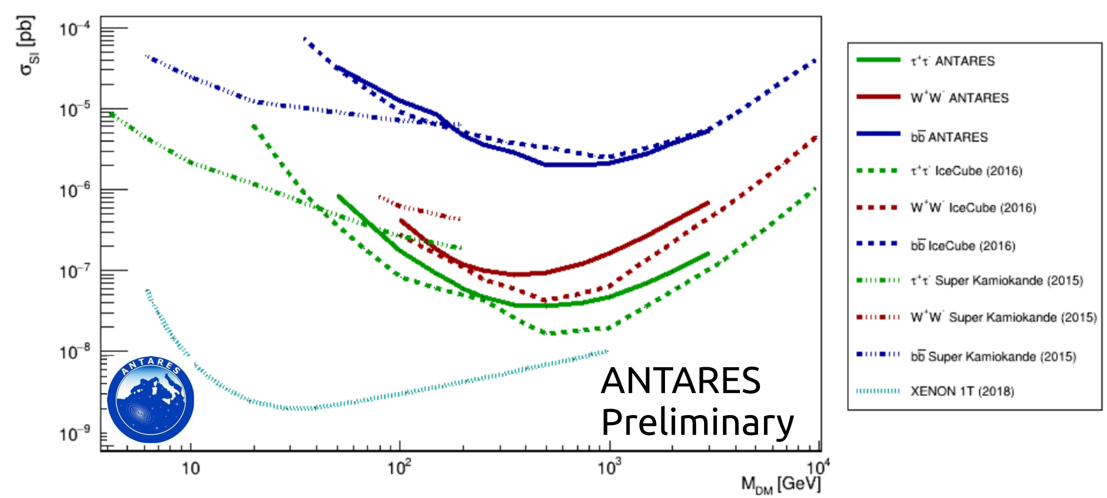


Phys. Rev. D 102, 082002 (2020)

Sun → scattering cross section
(spin dependent or independent)



JHEP12(2021)035



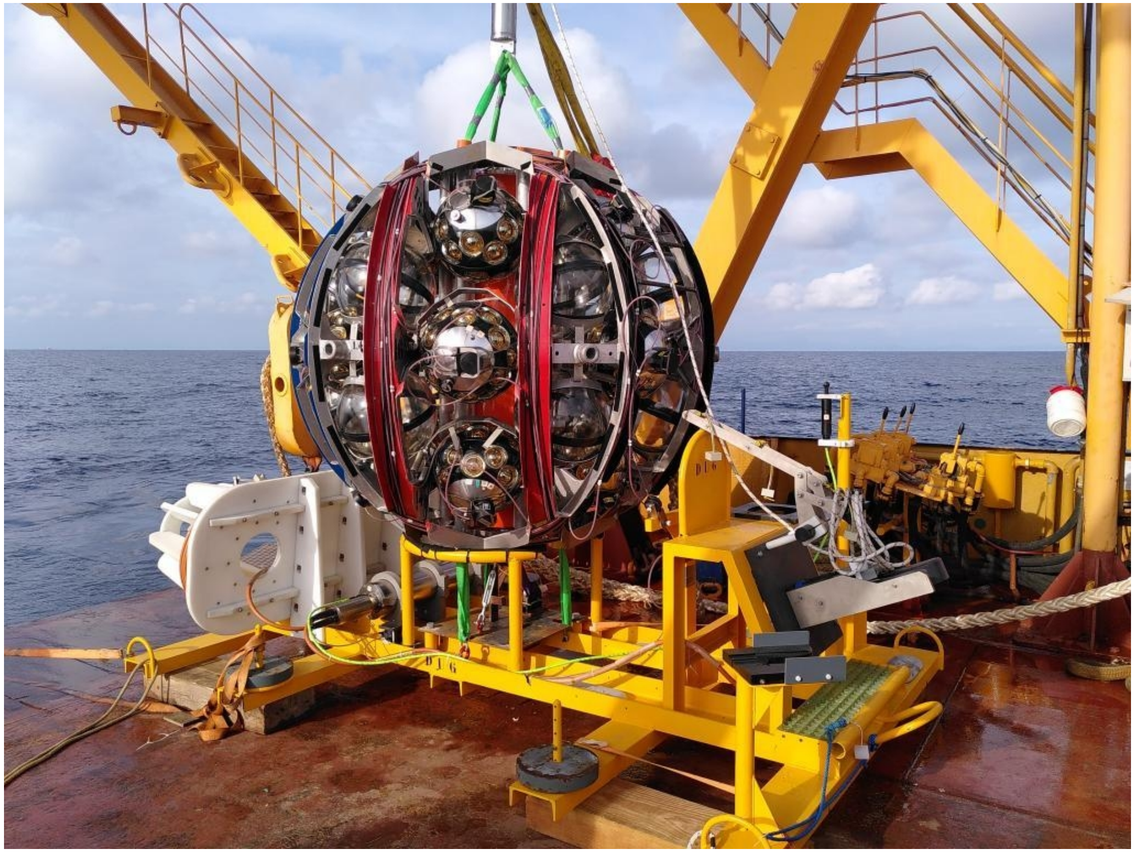
C. Poiré, Neutrino 2022

Conclusions

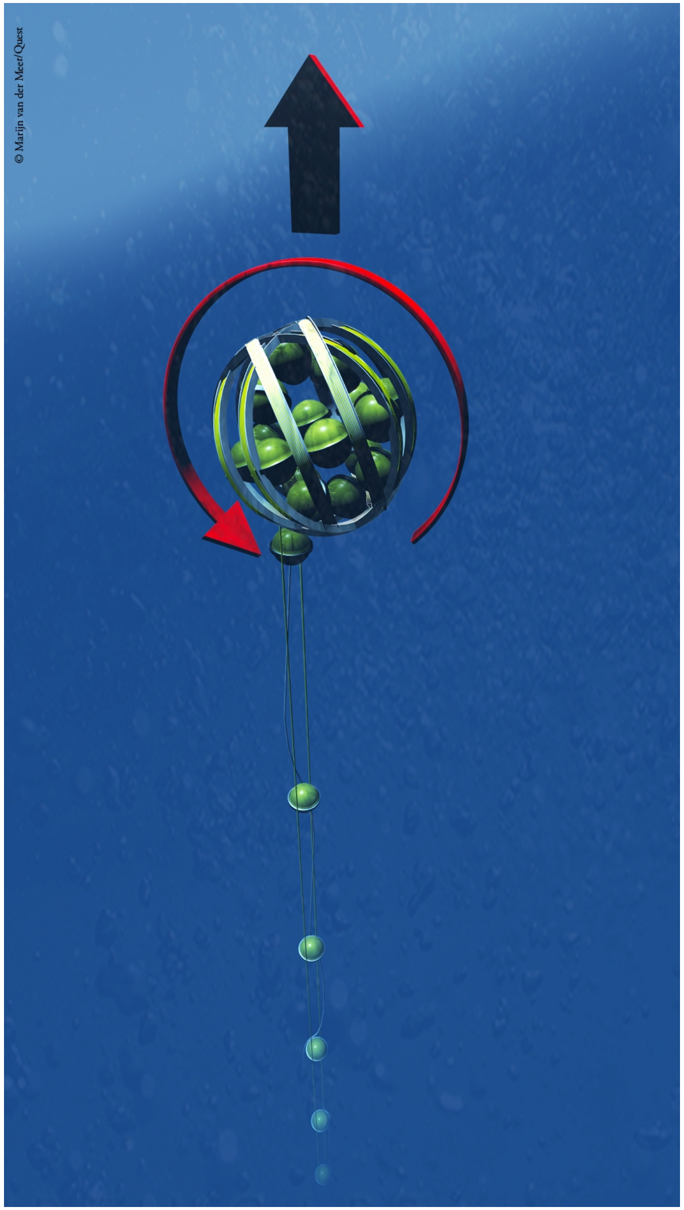
- Neutrino telescopes are showing how lively the field is
- IceCube has already produced discoveries
  - Diffuse neutrino flux
  - First neutrino candidate sources
  - Phenomenology of atmospheric neutrinos
- KM3NeT on the rise, with first physics results on their way
  - Quickly confirm IceCube discoveries thanks to its improved sensitivity
  - Complete the observation of the sky fully opening the Southern Hemisphere to neutrino astronomy
  - Full neutrino oscillation physics program ← already started!

Backup

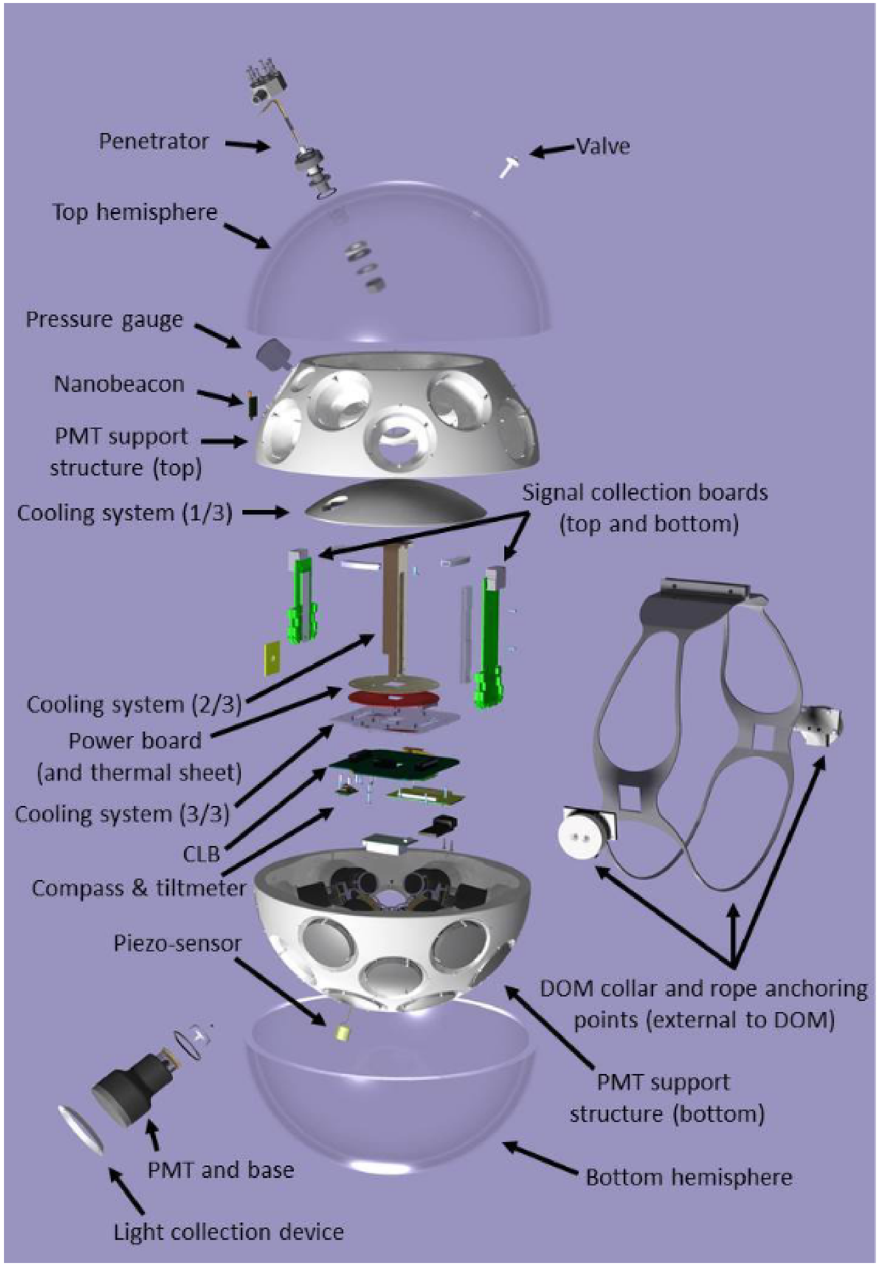
The KM3NeT Deployment



2020 JINST 15 P11027

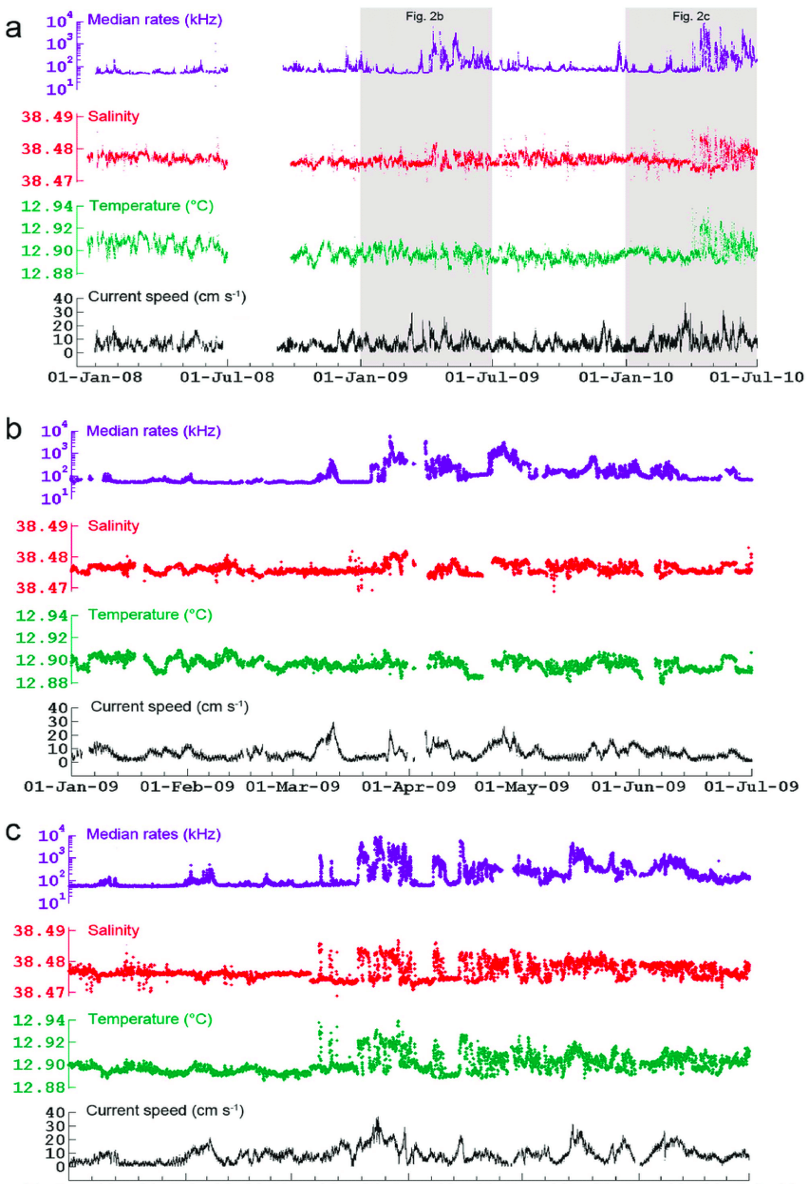


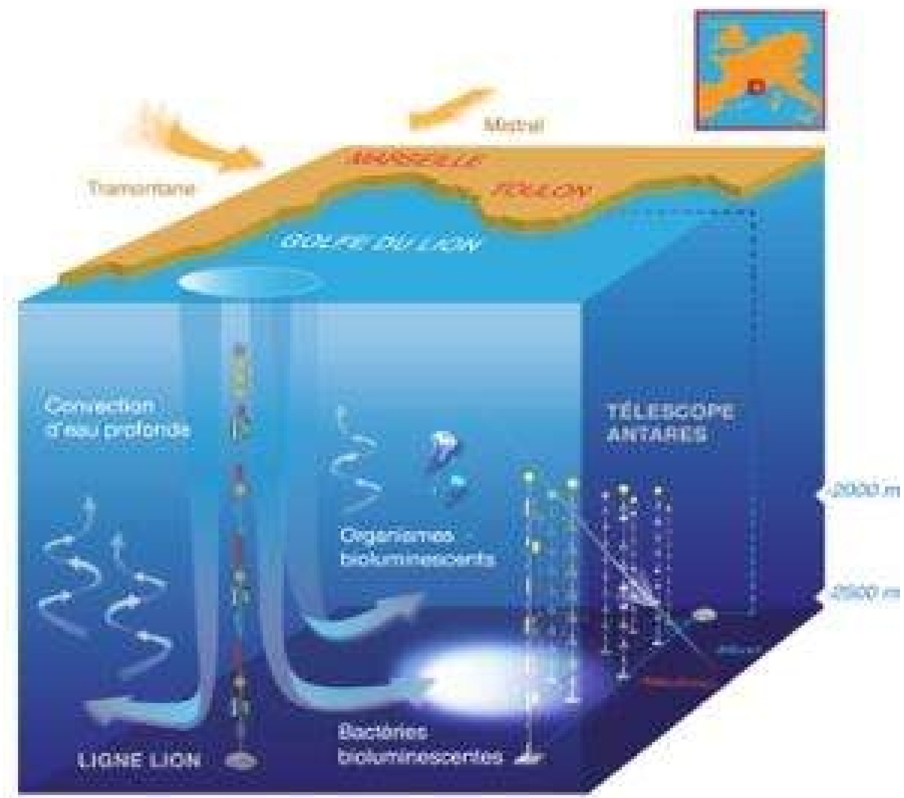
The KM3NeT Digital Optical Module



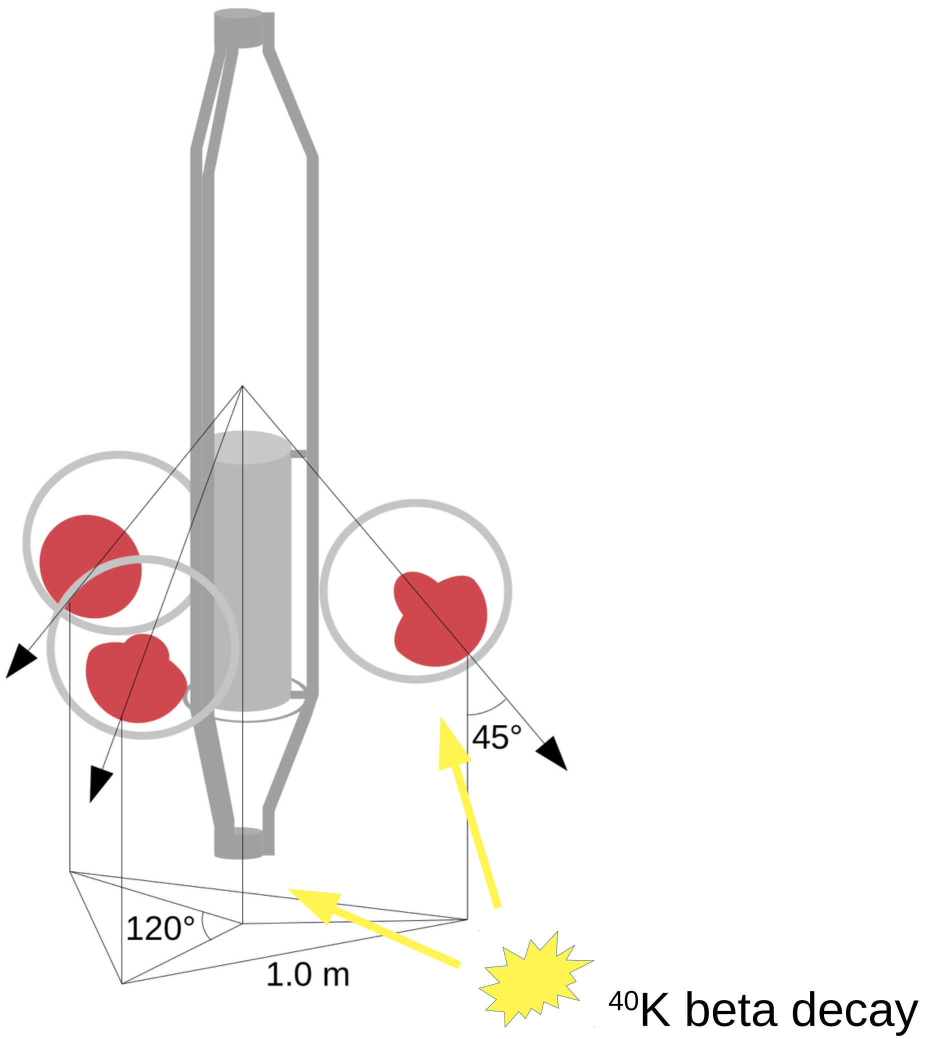
https://doi.org/10.48550/arXiv.2203.10048

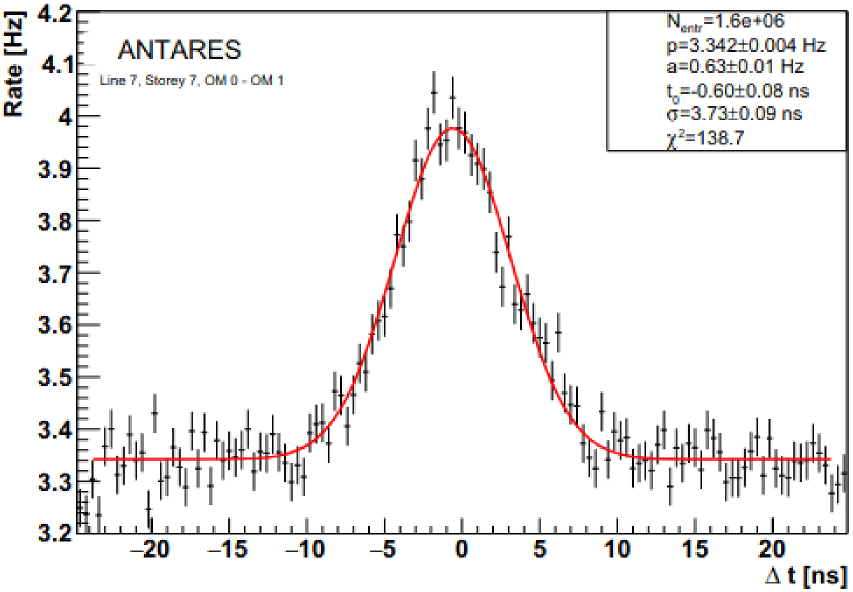
Mediterranean waters

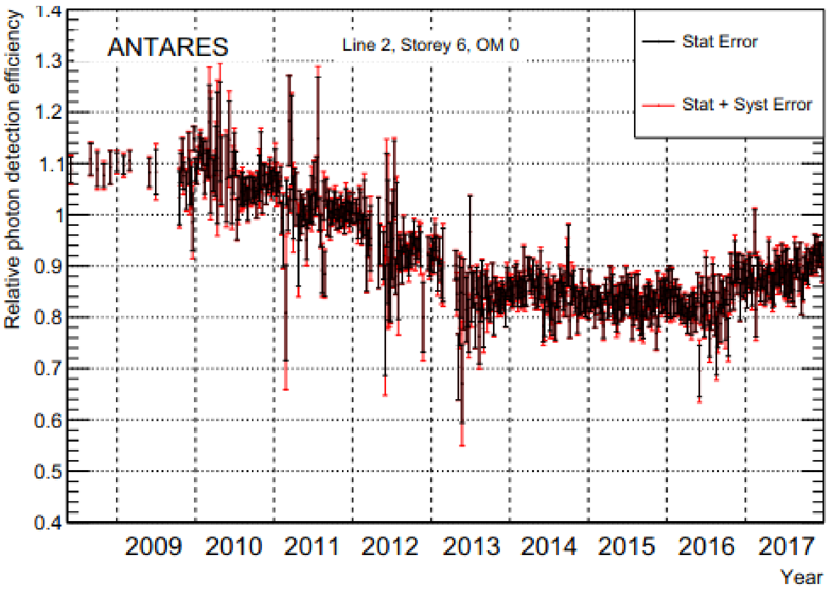




Mediterranean waters







Antarctic ice

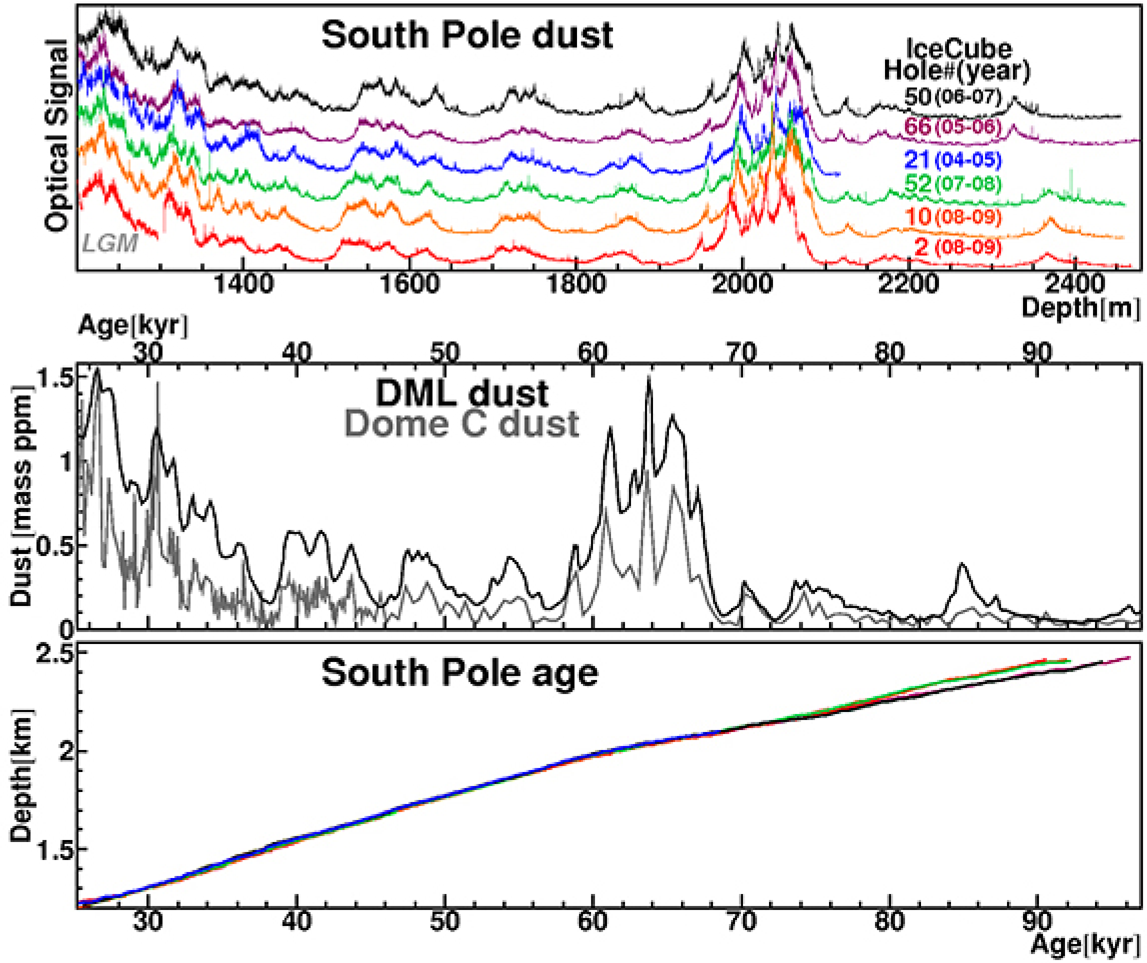
Ice shells formed over 100k yrs from snowfall

→ ice collects impurities + air bubbles

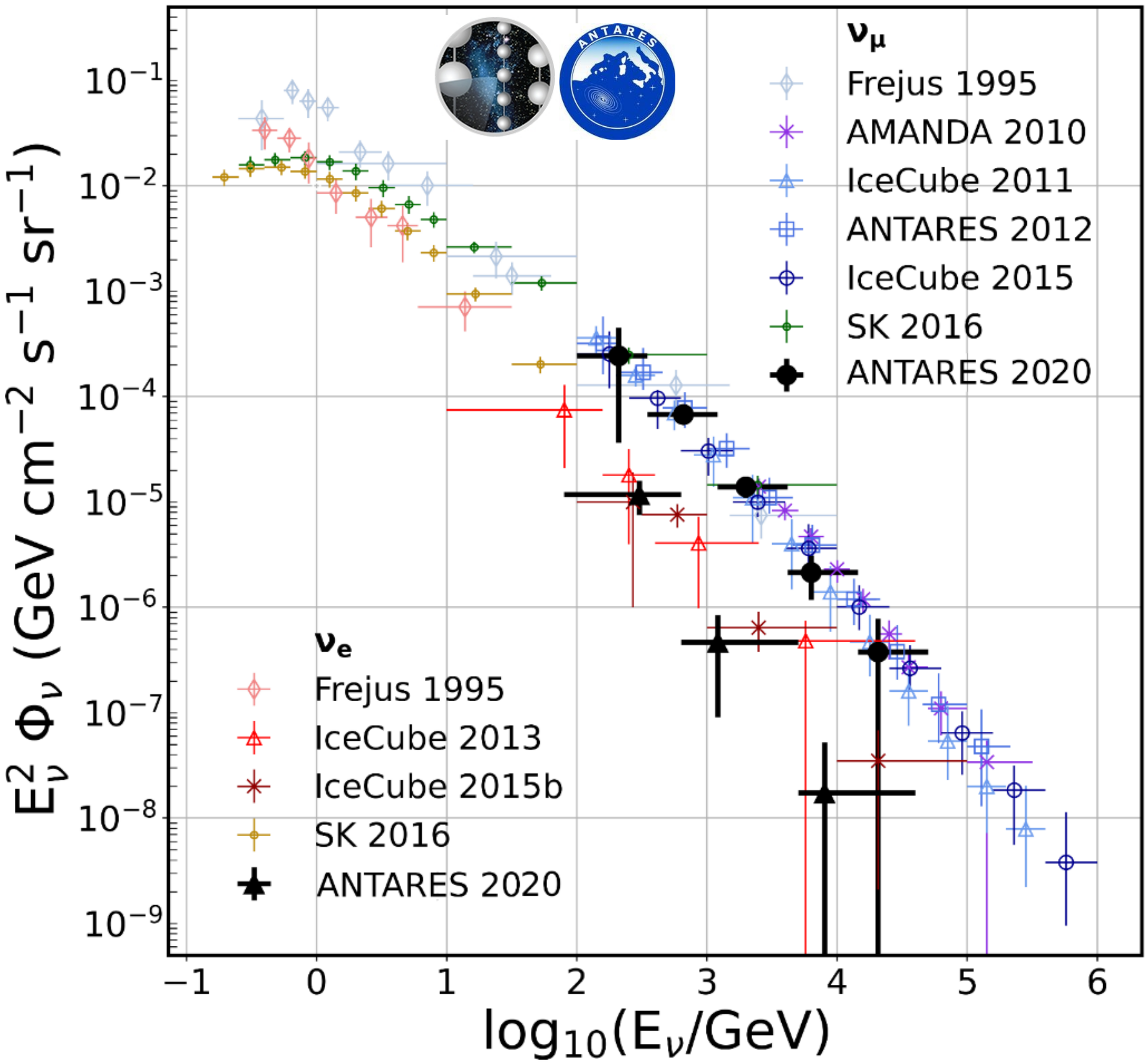
These represent scattering centres for light in the ice

→ scattering length changes with depths

– needs to be taken into account when reconstructing Cherenkov light



The atmospheric neutrino “beam”

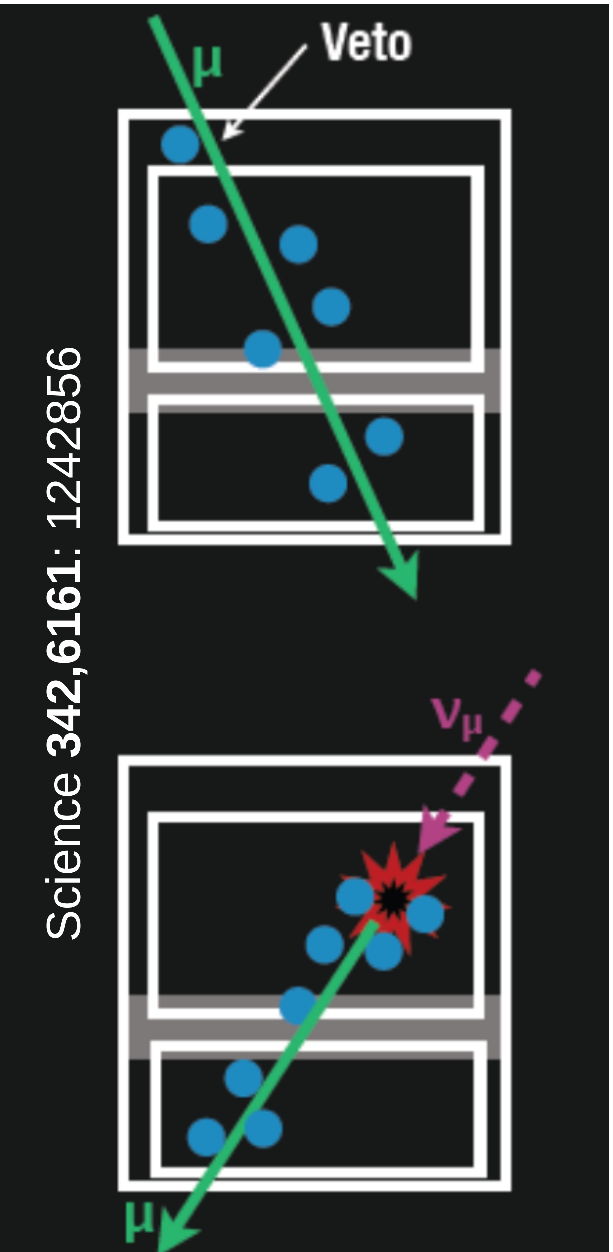


Muon and electron neutrino energy spectra in the atmosphere can be measured

– energy estimation
– detector systematics

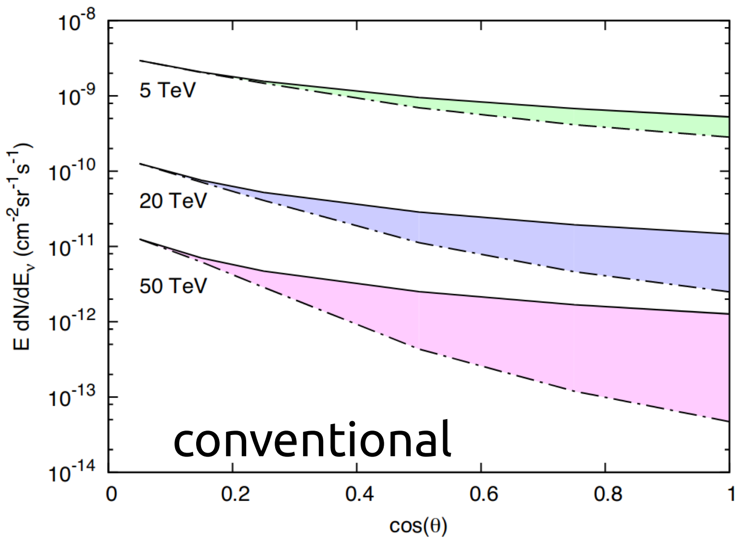
+ physics of cosmic rays in the atmosphere (composition, interactions)

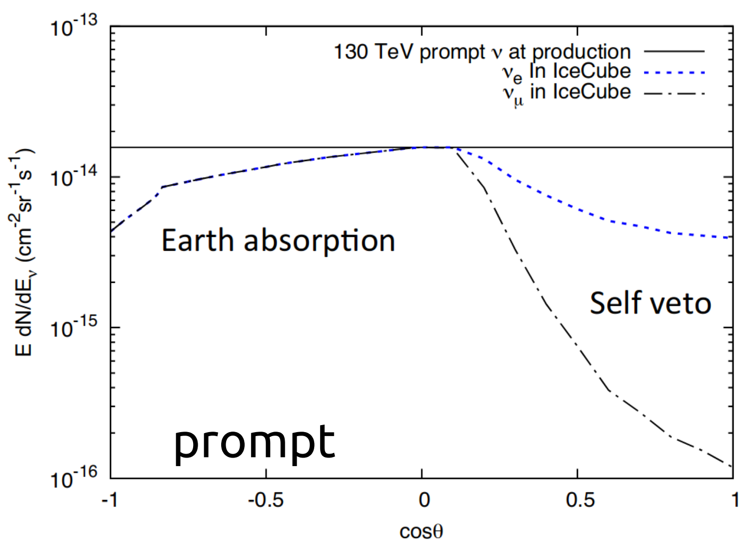
The IceCube High Energy Starting Events



Vetoing downward-going passing-through events
→ **rejection of accompanied atmospheric neutrinos**

High Energy Starting Events





Opens the sky to downward-going neutrino events → **highest energies**

Dependent on the proper modelisation of:

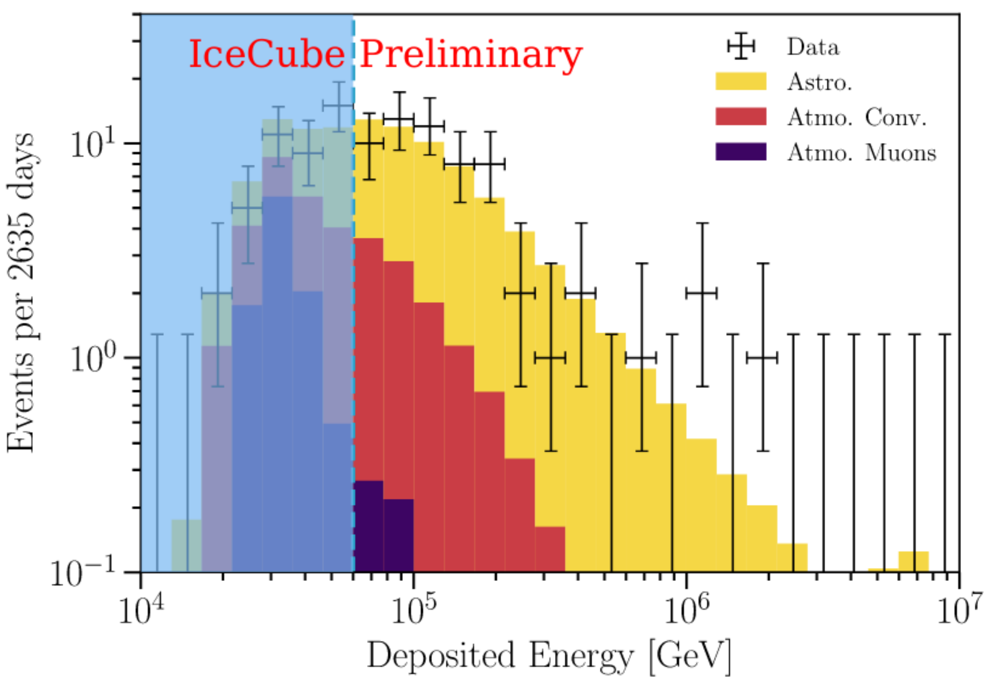
– *CR muon flux at the detector*
– *CR muons in the detector*

The IceCube High Energy Starting Events

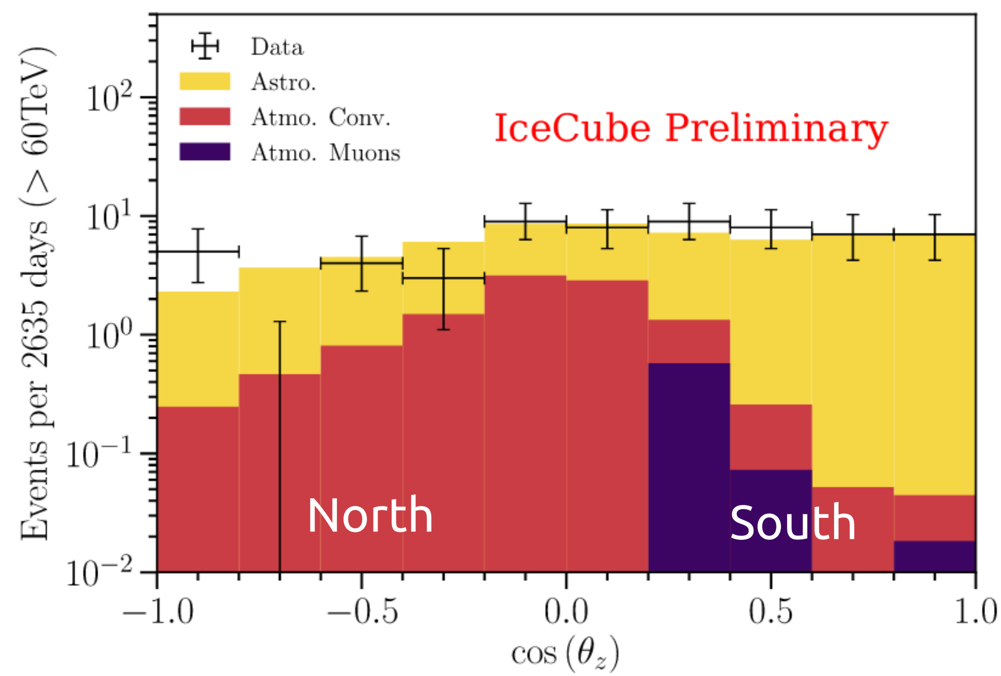
High-energy starting events above 60 TeV
– Southern sky accessible (veto)
– Northern sky more opaque (absorption)

$\Phi^{1f}(100\ \text{TeV}) = (2.15^{+0.5}_{-0.15})\ 10^{-18}\ (\text{GeV cm}^2\ \text{s sr})^{-1}$
$\Gamma = 2.9 \pm 0.2$

Too soft?



Compatible with isotropy



Not really compatible with any reasonable atmospheric assumption; however a **null-prompt** is fitted

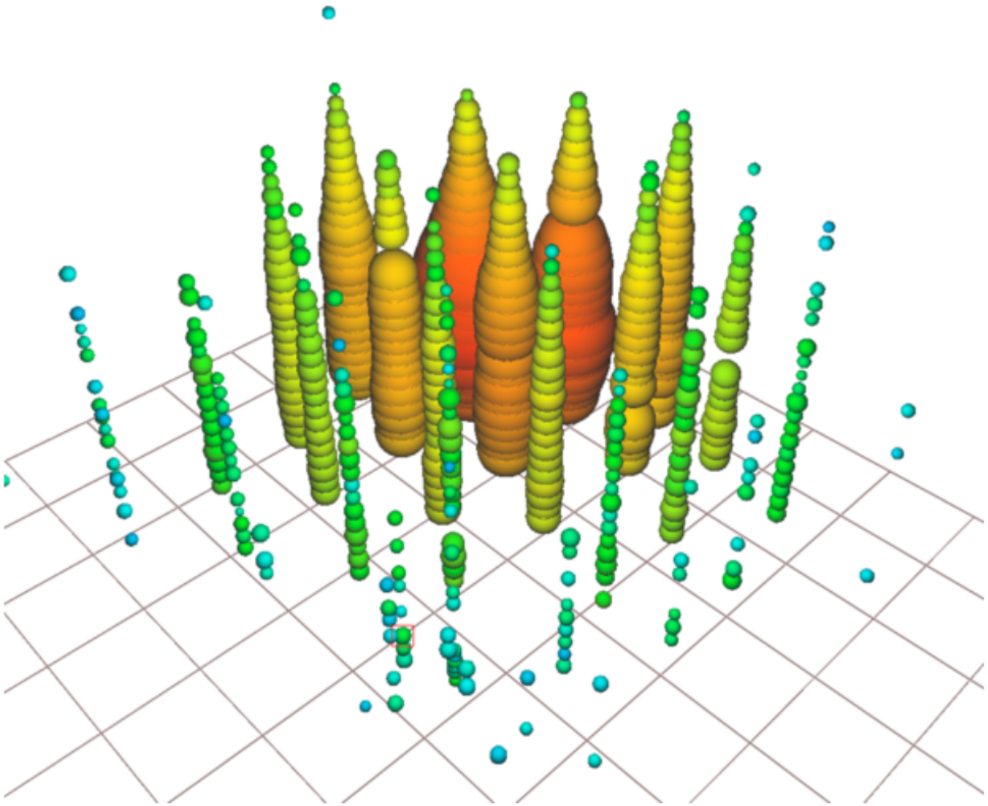
The highest-energy cascade event

Partially contained events
→ allow for higher energies
→ need more sophisticated analysis
to reject backgrounds

6 PeV cascade: candidate found in data
→ candidate Glashow-resonance event

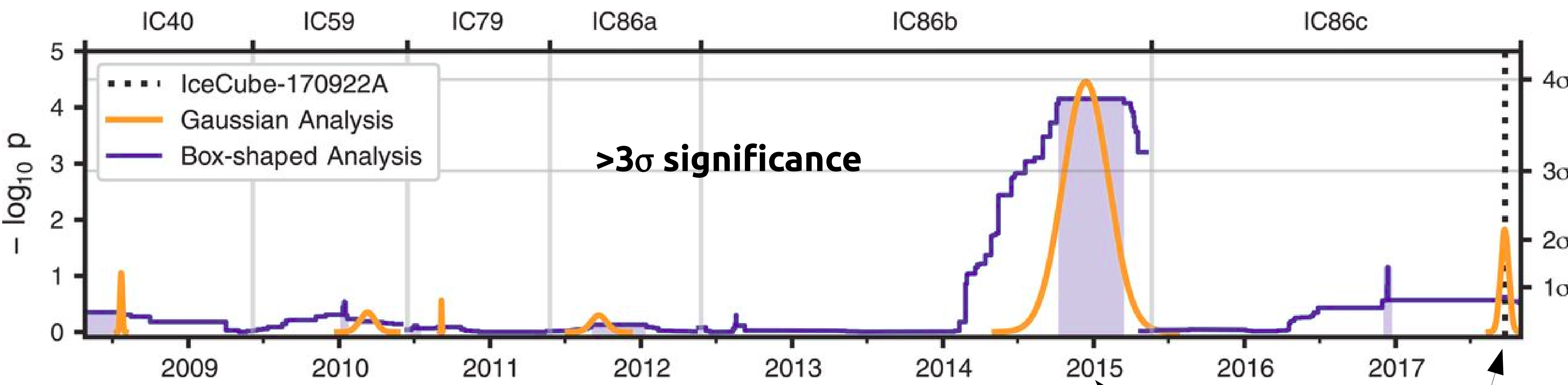
Direct identification of an anti-electron
neutrino ← flavour studies

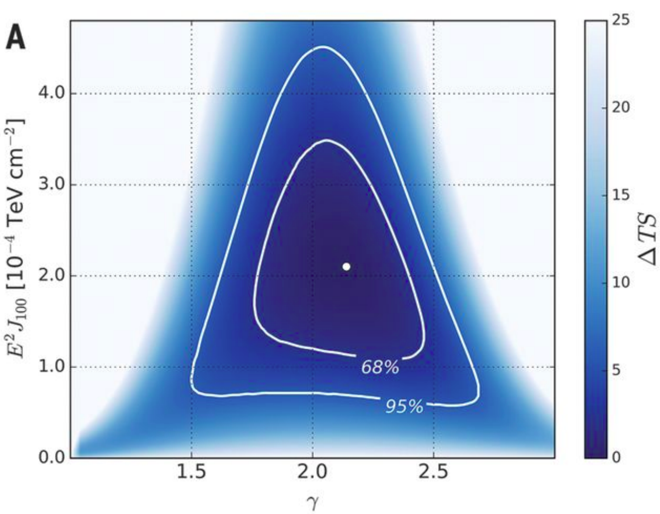
+ study of the W production at resonance

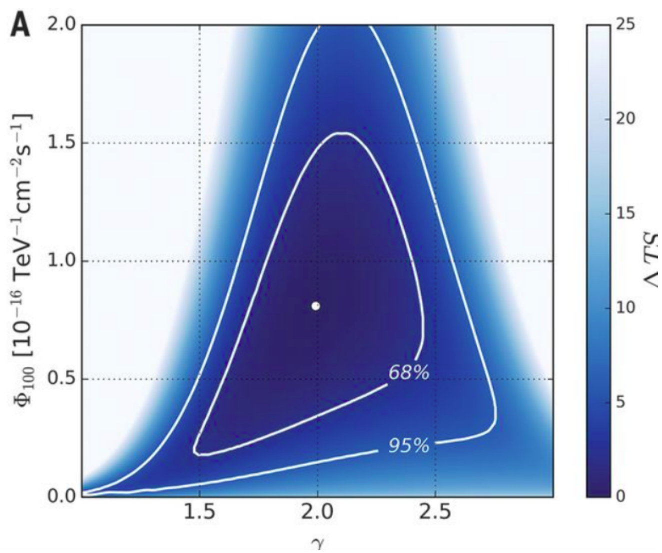


PoS(ICRC2019)945

TXS 0506+056







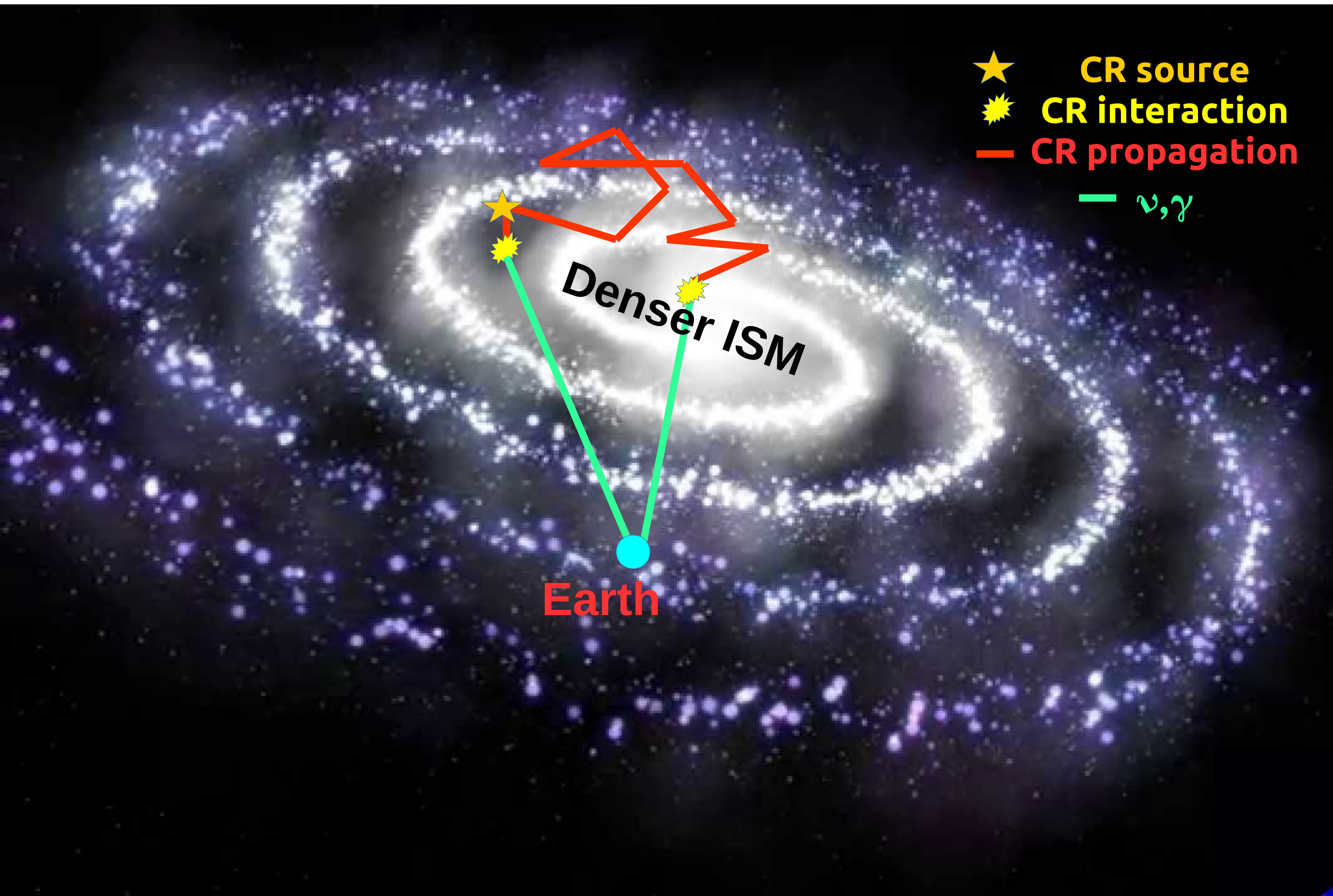
13 neutrinos
in excess
No gammas

gamma flare
+ IC170922A

Some ambiguities in the interpretation are still there (no flare in 2015? is it a peculiar source? ...)

Science **361, 6398**, pp. 147-151
DOI: 10.1126/science.aat2890

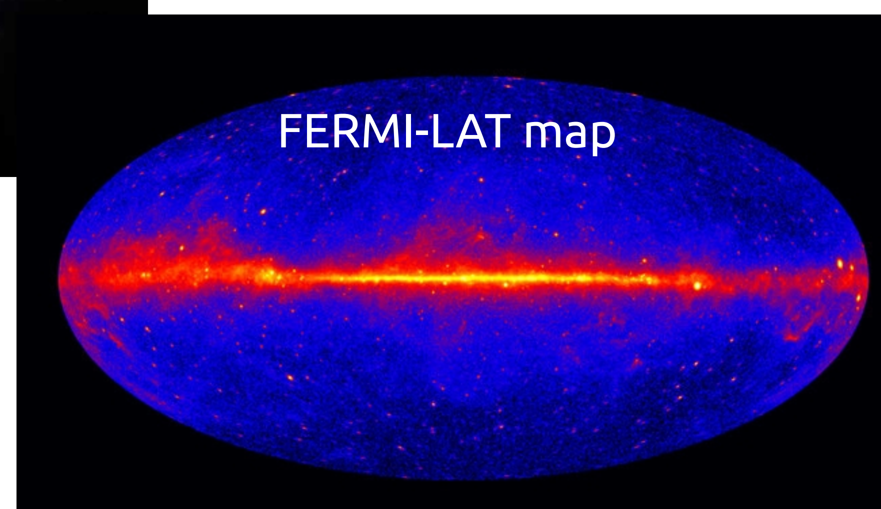
γ and ν: CR propagation in the Milky Way



Neutrinos carry direct information on CR propagation. e.g.:

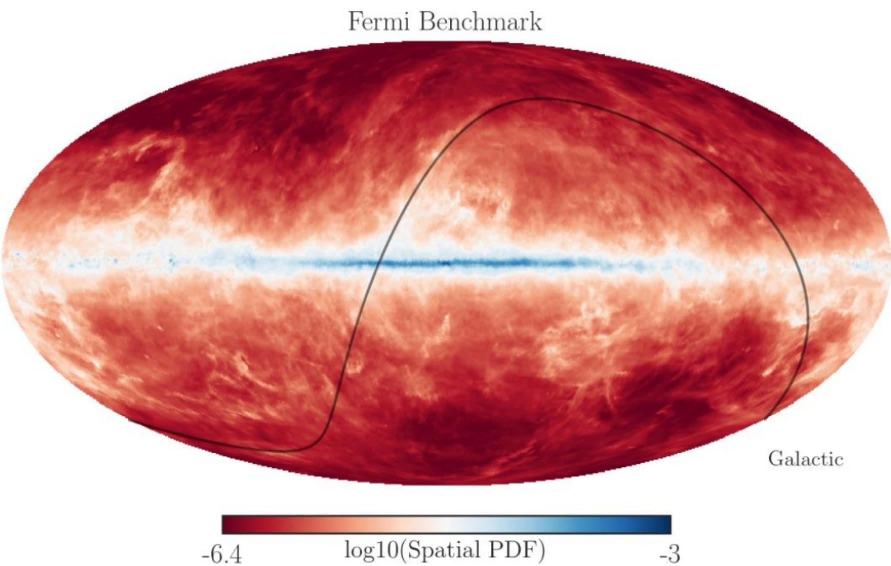
- Non-homogeneous diffusion can enhance γ and ν emission

- Molecular clouds/dense environments boost γ and ν fluxes



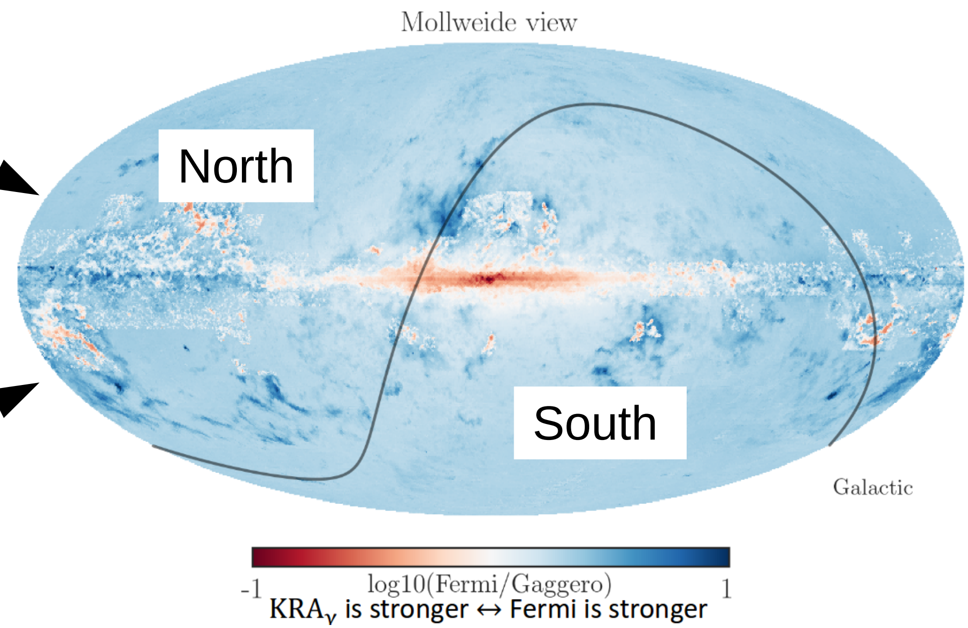
* ApJ. **750:** 3, 2012
** ApJ Lett. **815**: L25, 2015

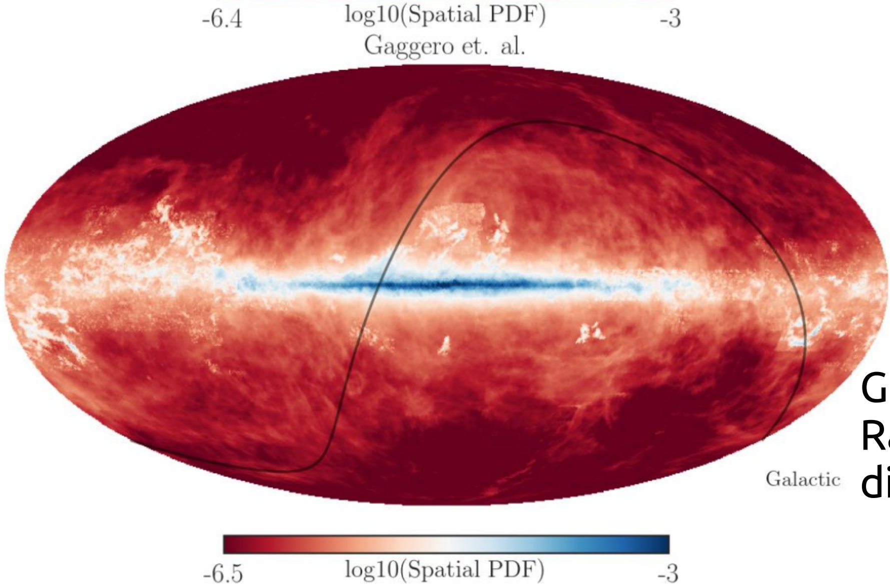
ν models from GCR and γ



Standard model*

Ratio of the two





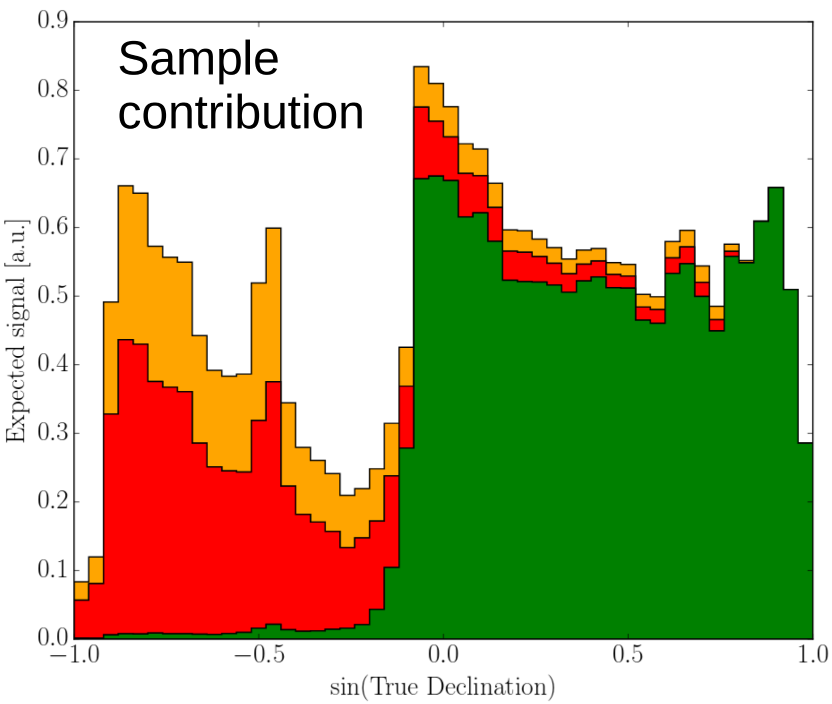
Gaggero et al.**
Radially dependent diffusion – data tuned

Harder/stronger in the centre
Softer/lower in the periphery
→ different fields of view can test differently the model

Plots by C.Haack, for the IceCube Collaboration

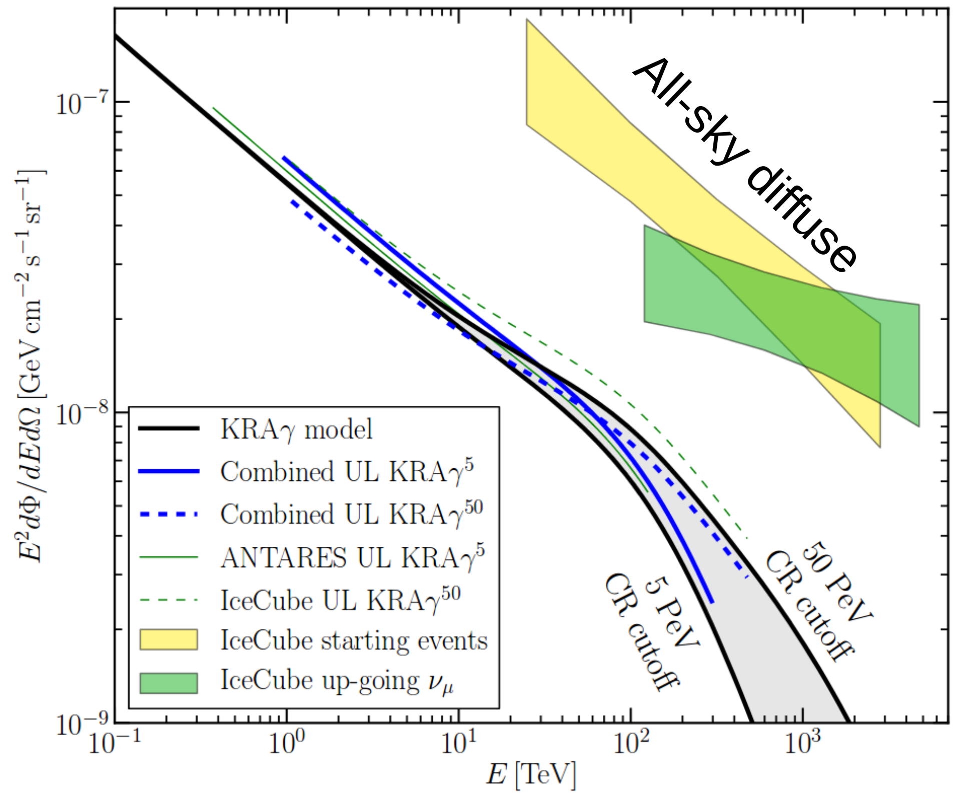
νs from the GP

Joint analysis ANTARES (tracks + cascades) and IceCube (tracks)



+ spectral energy distributions are different in the model

No significant excess observed



Low latitude Galactic contribution constrained to 8% of the all-sky flux

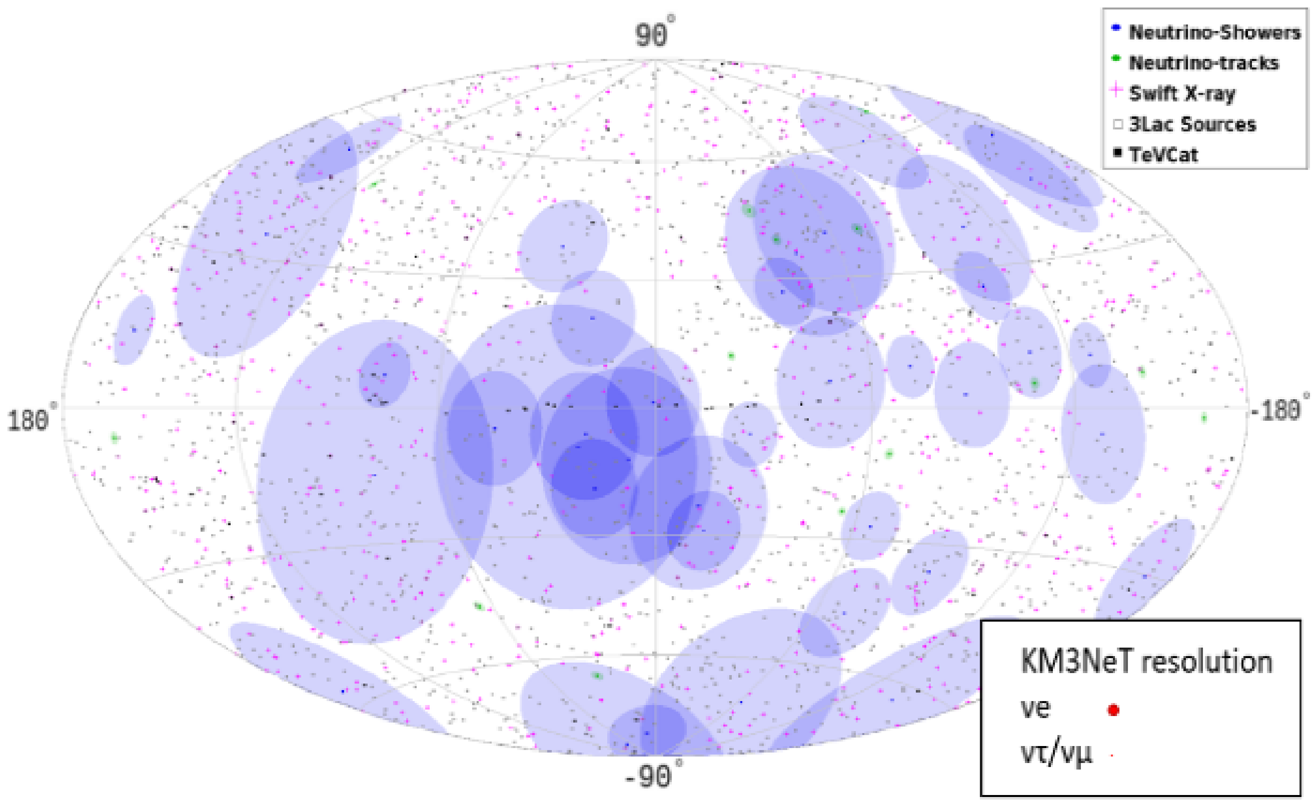
ApJ Lett **868**: L20 (2018)

New IC cascade analysis:
ApJ **886**: 1, 2019 (see backup)

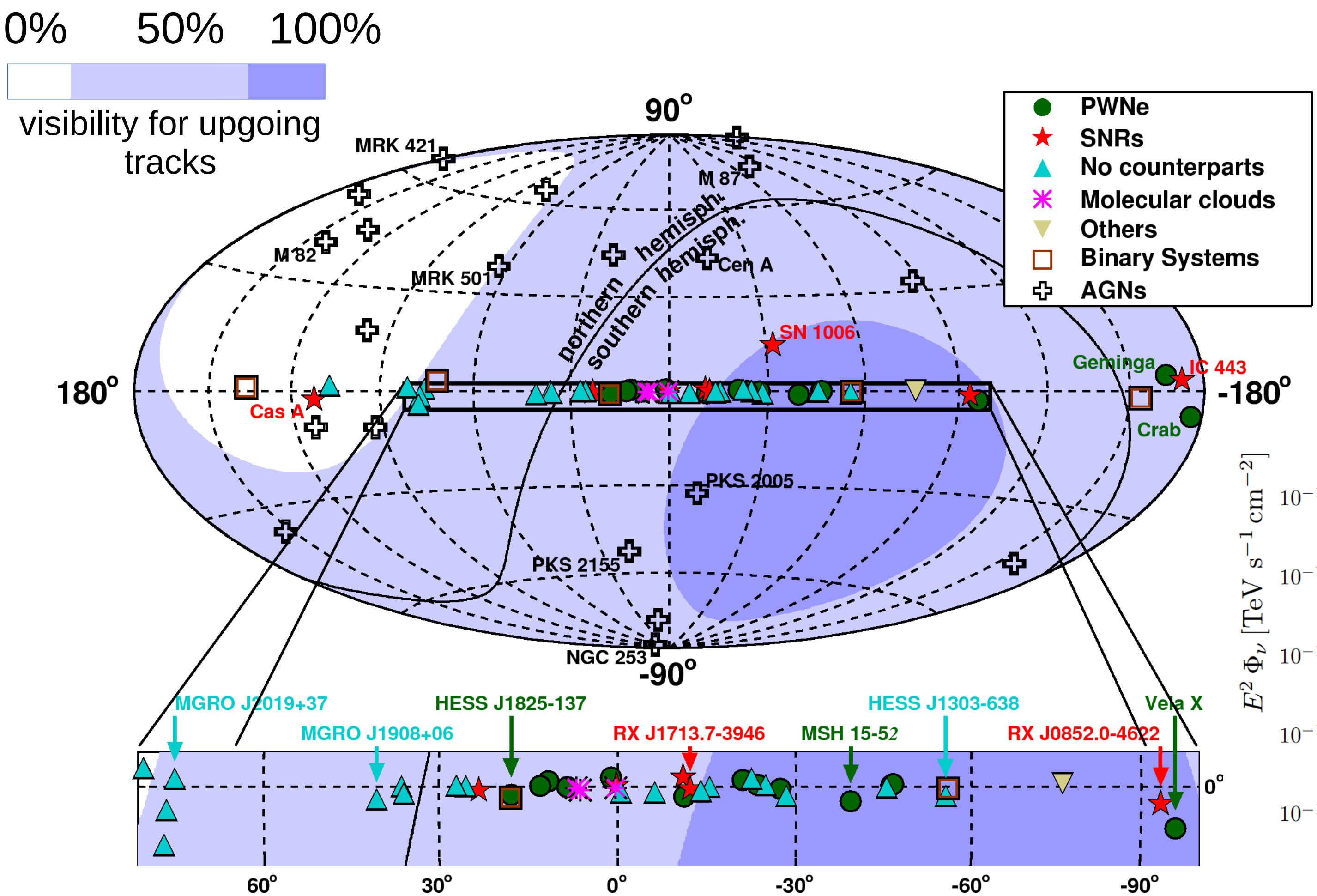
Why a km³ detector in the Northern Hemisphere

- Water is optimal for light
  - Limited scattering → direct photons
  - Homogeneous medium → easy to simulate, less systematic effects

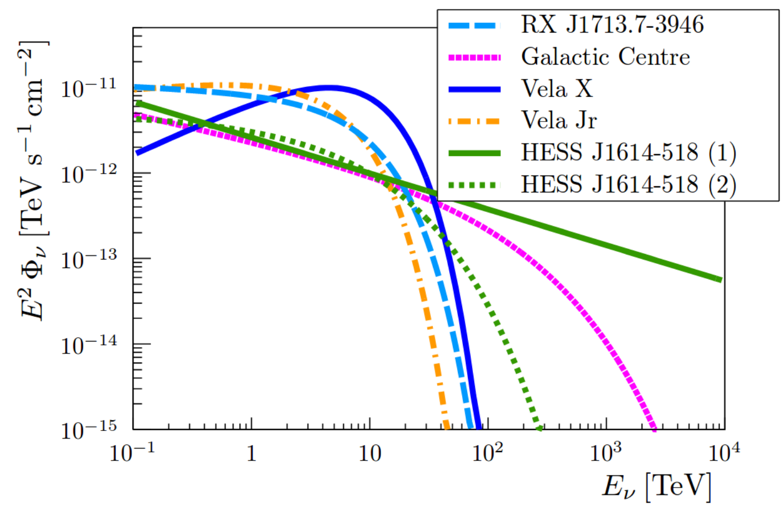
→ **0.1 degree angular reconstruction accuracy**



Why a km³ detector in the Northern Hemisphere



High visibility with 0.1° angular resolution

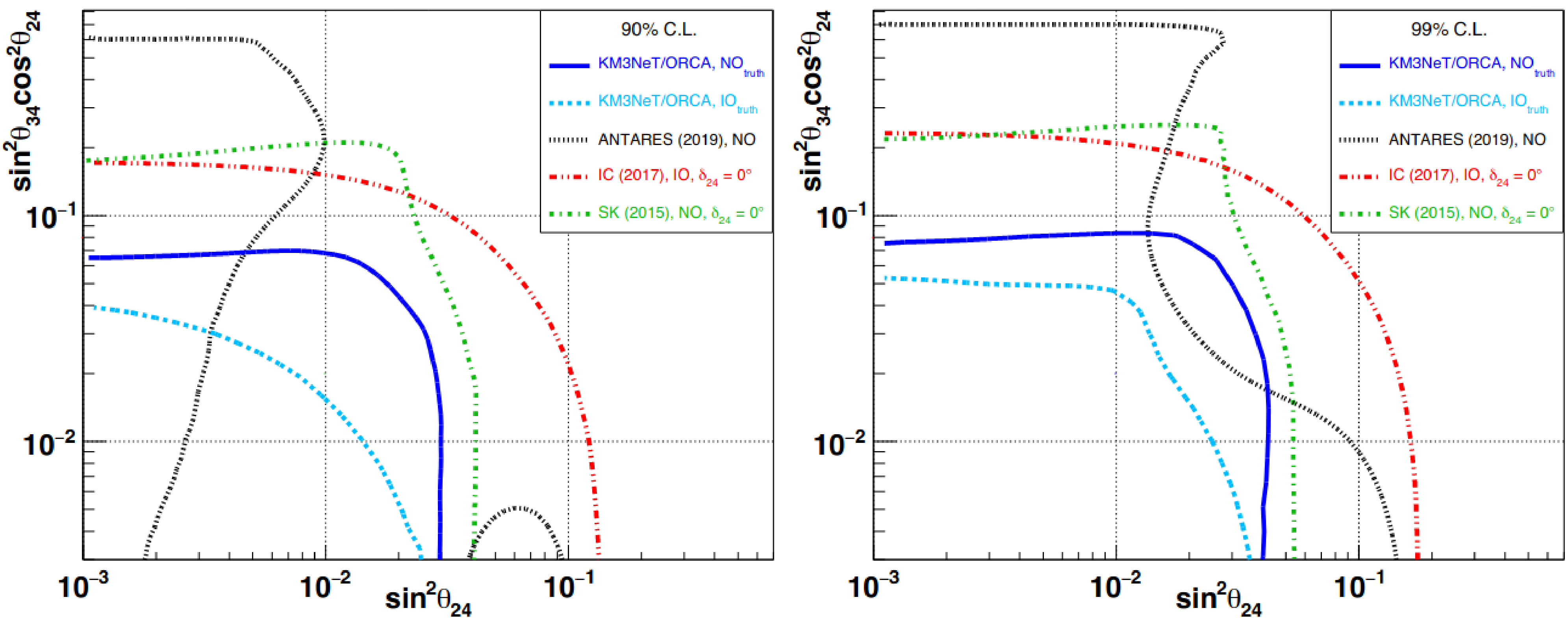


Soft spectra from γ obs.
→ lowE threshold analysis

Sterile neutrino searches

4th sterile neutrino added into oscillations
→ atmospheric oscillograms are modified

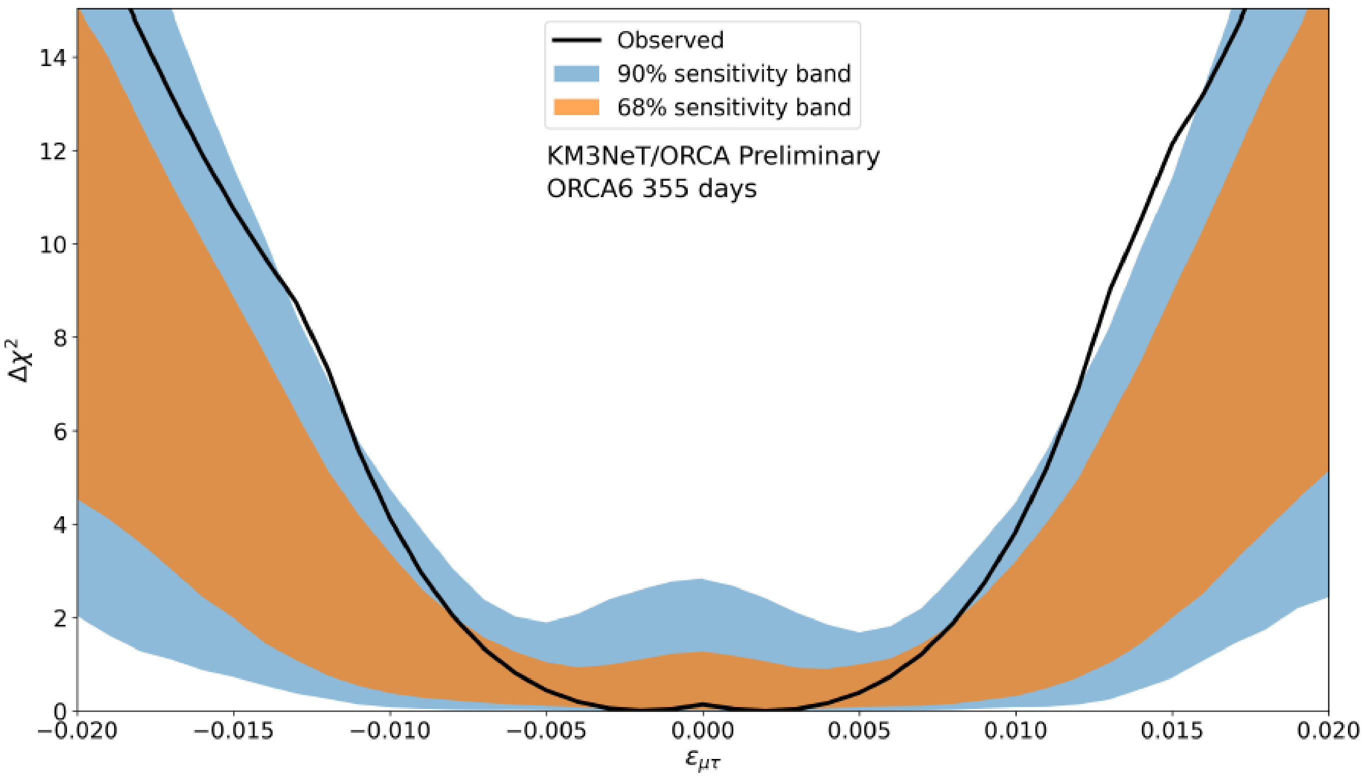
$$\Delta m^2_{41} = 1\,\mathrm{eV}^2$$



J. High Energ. Phys. 2021, 180 (2021).

Non-standard interactions

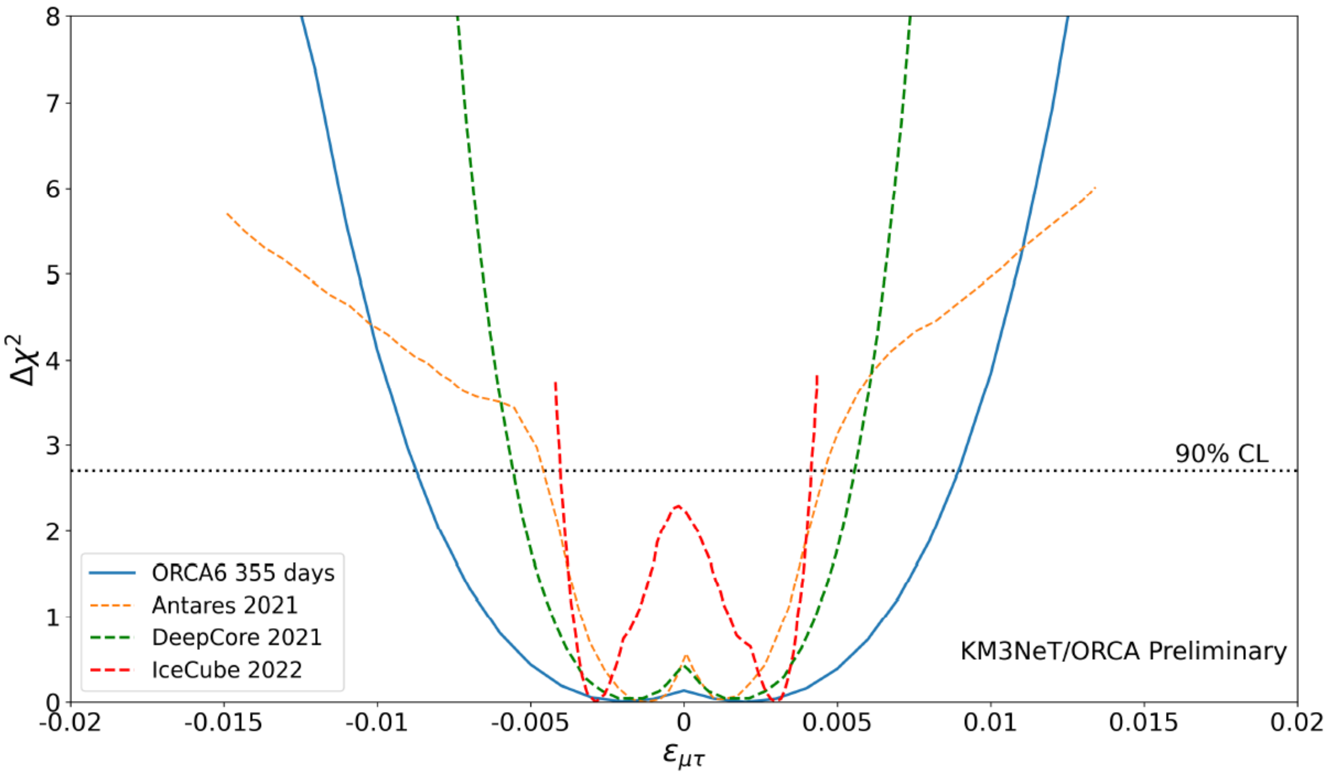
$$H_{eff} = \frac{1}{2E} U_{PMNS} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U^\dagger_{PMNS} + V_{CC} \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix},$$



J. Manzak
Neutrino2022

Non-standard interactions

$$H_{eff} = \frac{1}{2E} U_{PMNS} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{bmatrix} U_{PMNS}^\dagger + V_{CC} \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{bmatrix},$$



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Quantum Decoherence

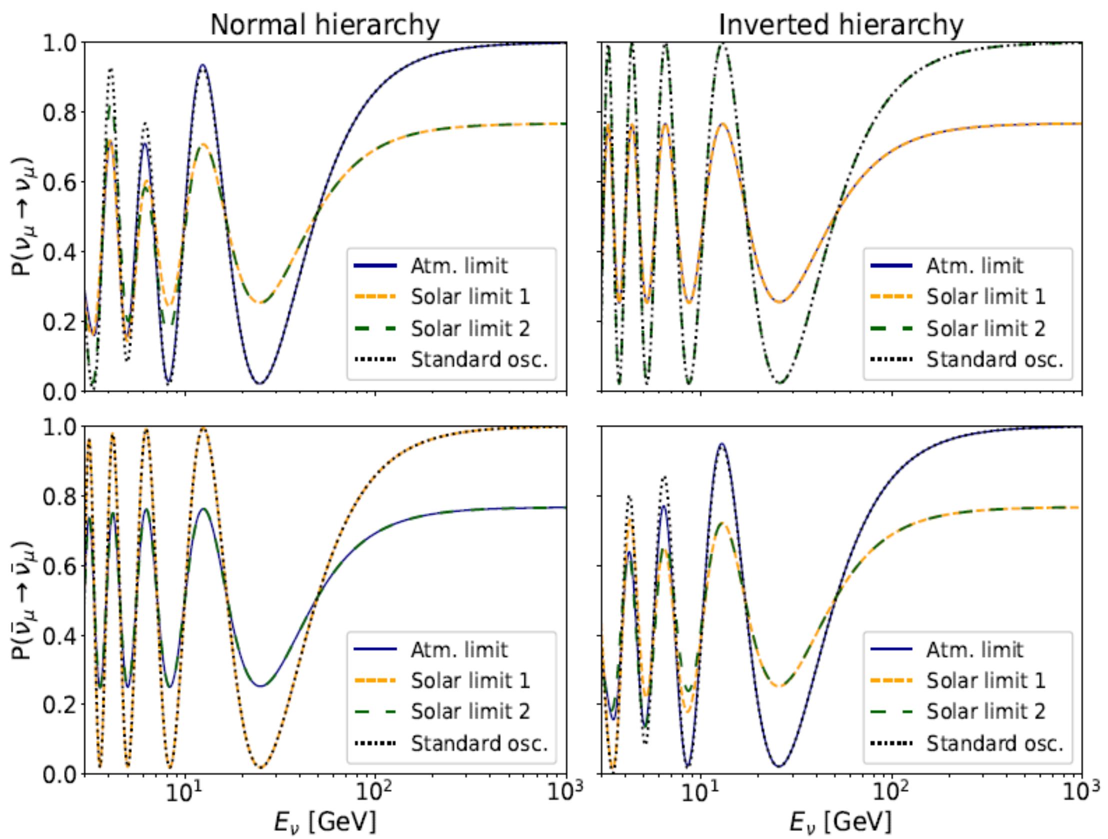
$$\frac{d}{dt}\rho = -i[H,\rho] - \sum_m [\{\rho, D_m D_m^\dagger\} - D_m \rho D_m^\dagger].$$

The solution is given by

$$\rho_{ij} \sim e^{-i\Delta E_{ij} t - \gamma_{ij} t}.$$

The decoherence parameter γ determines the strength of the damping. Three limiting cases can be considered, where one of the parameters is zero, and the other two are equal:

- Atmospheric limit: $\gamma_{21} = 0 \Leftrightarrow (\gamma_{32} = \gamma_{31})$
- Solar limit 1: $\gamma_{32} = 0 \Leftrightarrow (\gamma_{21} = \gamma_{31})$
- Solar limit 2: $\gamma_{31} = 0 \Leftrightarrow (\gamma_{21} = \gamma_{32})$



N. Lessing
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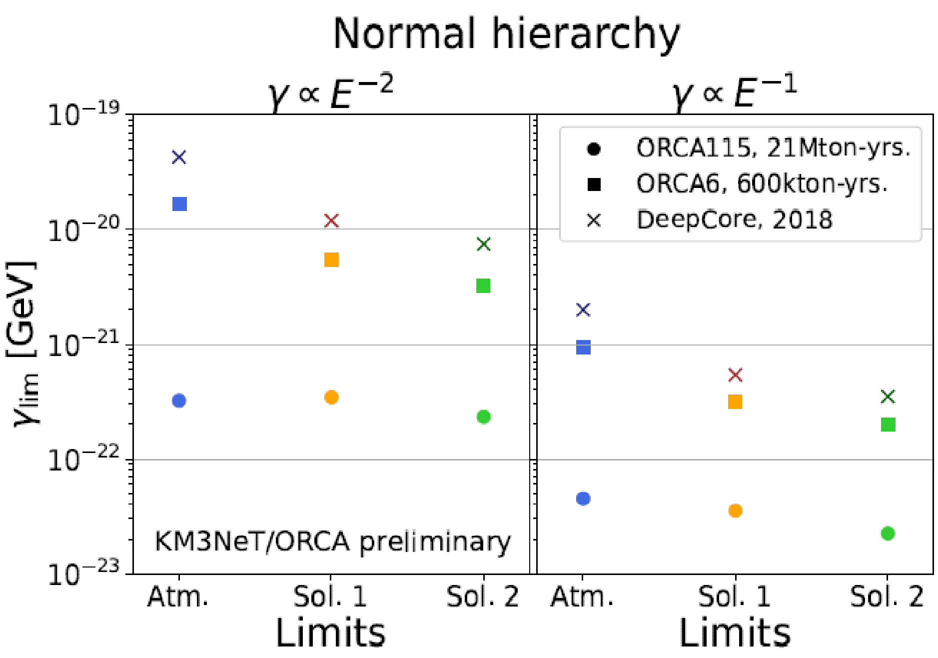
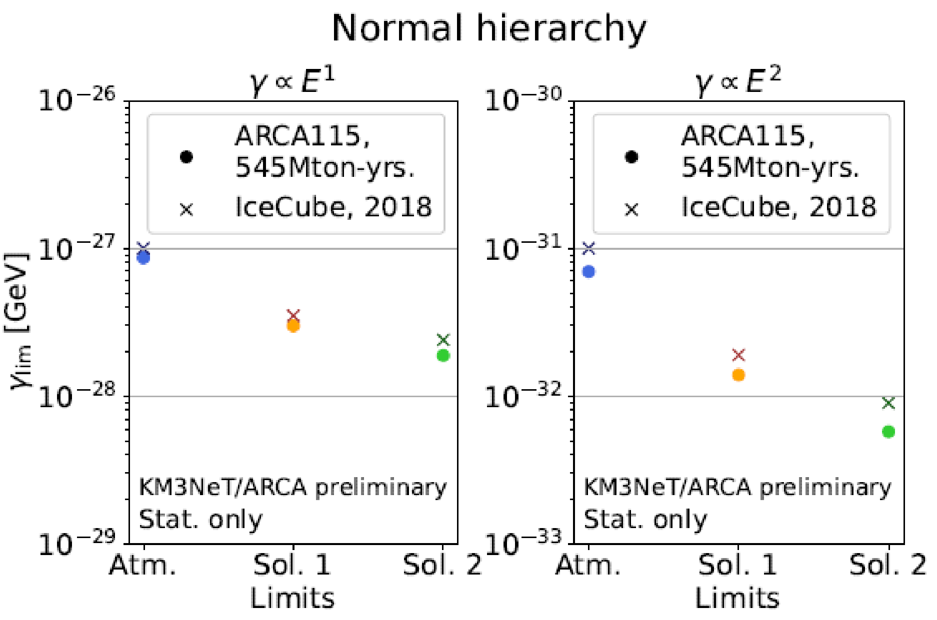
Quantum Decoherence





N. Lessing
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