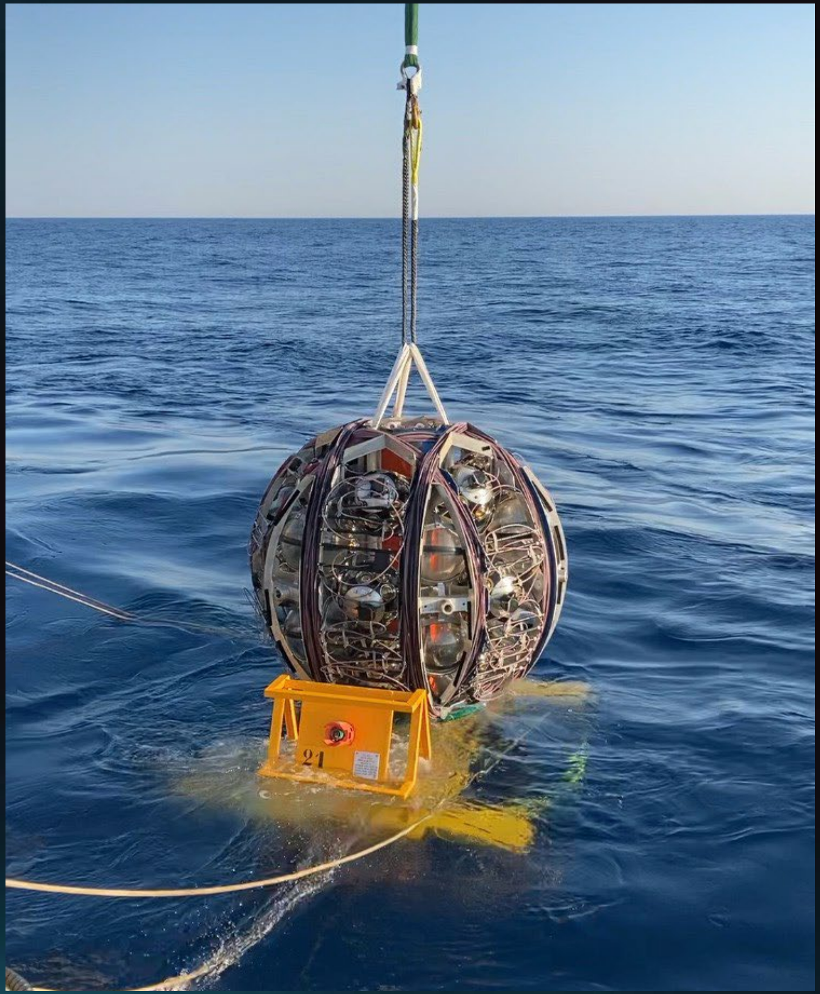
Searches for Dark Matter with Neutrino Telescopes

Juande Zornoza (IFIC, Univ. Valencia-CSIC)

VEGA Valencia Experimental Group of Astroparticles
IFIC INSTITUT DE FÍSICA CORPUSCULAR 75 aniversari
CSIC
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
UNIÓN EUROPEA FONDO EUROPEO DE DESARROLLO REGIONAL "Una manera de hacer Europa"
AGENCIA ESTATAL DE INVESTIGACIÓN
GENERALITAT VALENCIANA Conselleria d'Educació, Investigació, Cultura i Esport

Outline

- Introduction
  - Detection strategy
  - Neutrino telescopes
- Results
  - Galactic Centre / Halo
  - Sun
  - Other sources
- Summary



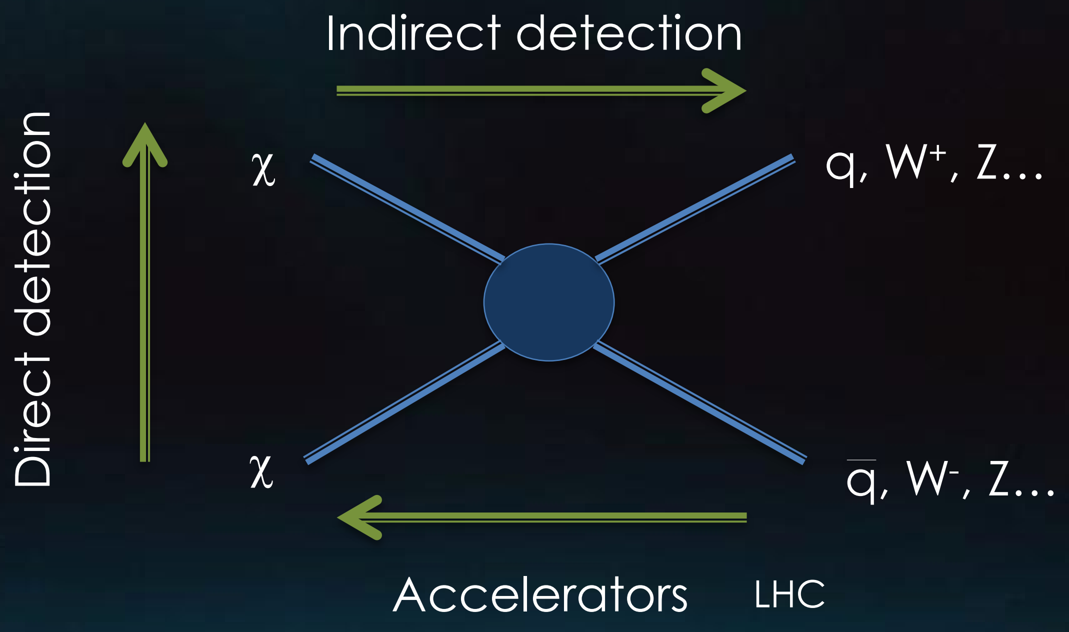
Introduction

Detection strategies

- We do not know what is dark matter, so it is hard to say which is the winning strategy: **multi-front attack**!

AMS, FERMI, HESS, CTA, KM3NeT, IceCube…

XENON
CDMS
DAMA
ANAIS
PandaX
DEAP
DarkSide
…



+astrophysical probes (self-interaction of DM affecting dark matter densities in galaxies…)

In any case:
-we want more than one "detection"
-results (constraints) of each strategy are input for the others
Also: that DM interact with normal matter (beyond gravity) is an *assumption*.

Indirect searches

χ

Annihilation

χ

$W^+ \; Z \; \bar{b} \; \tau^+ \; \bar{t} \; h \ldots$

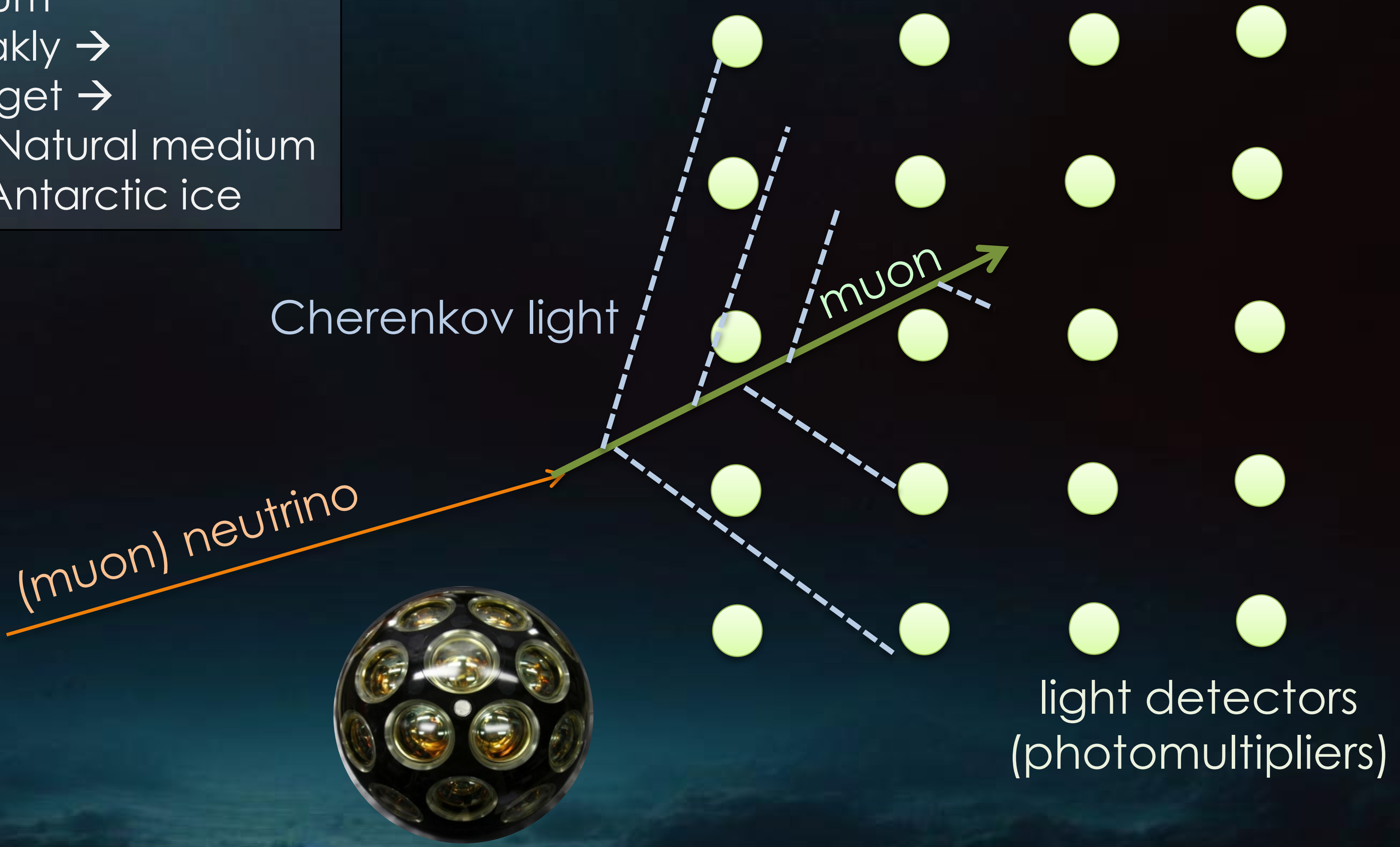
$W^- \; Z \; b \; \tau^- \; t \; h \ldots$

$\nu \; \gamma \; e^+ \; p$

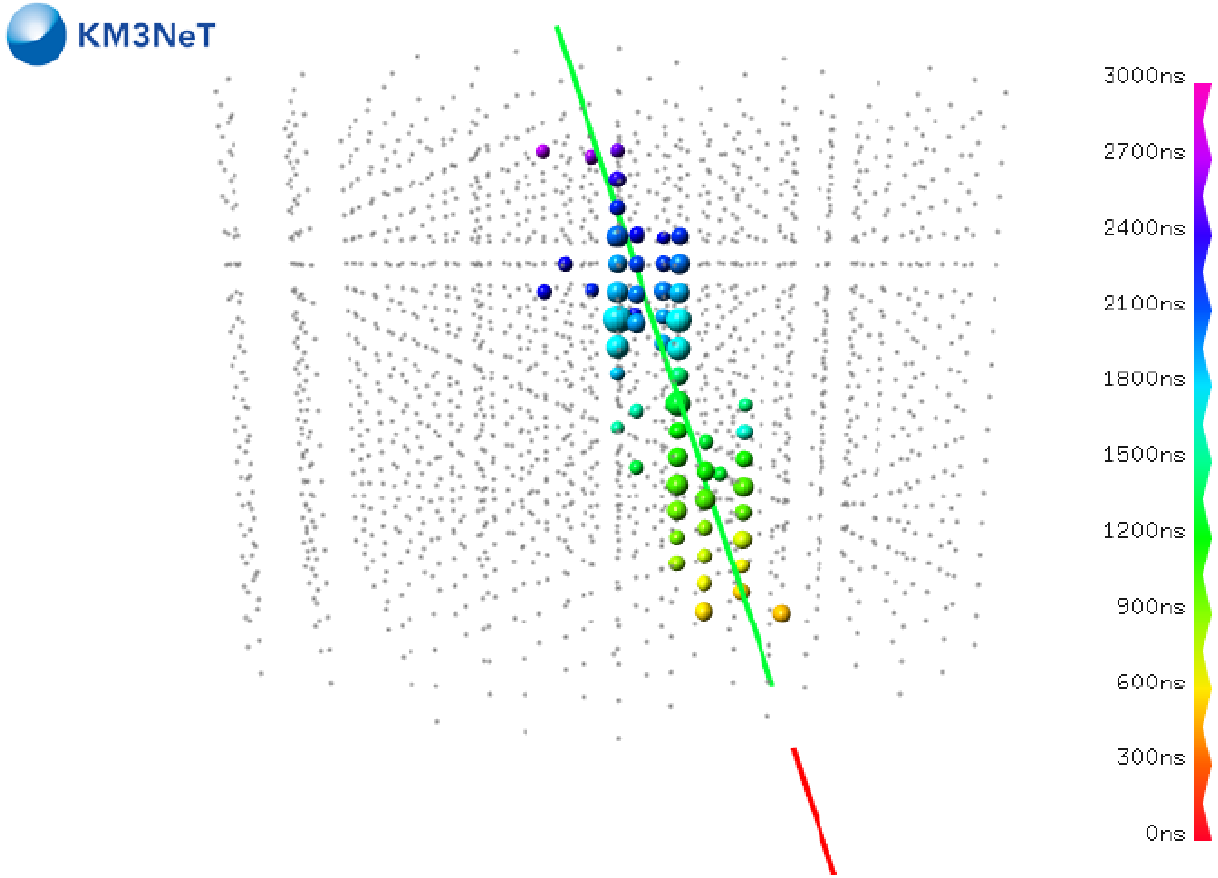
$\bar{\nu} \; \gamma \; e^- \; \bar{p}$

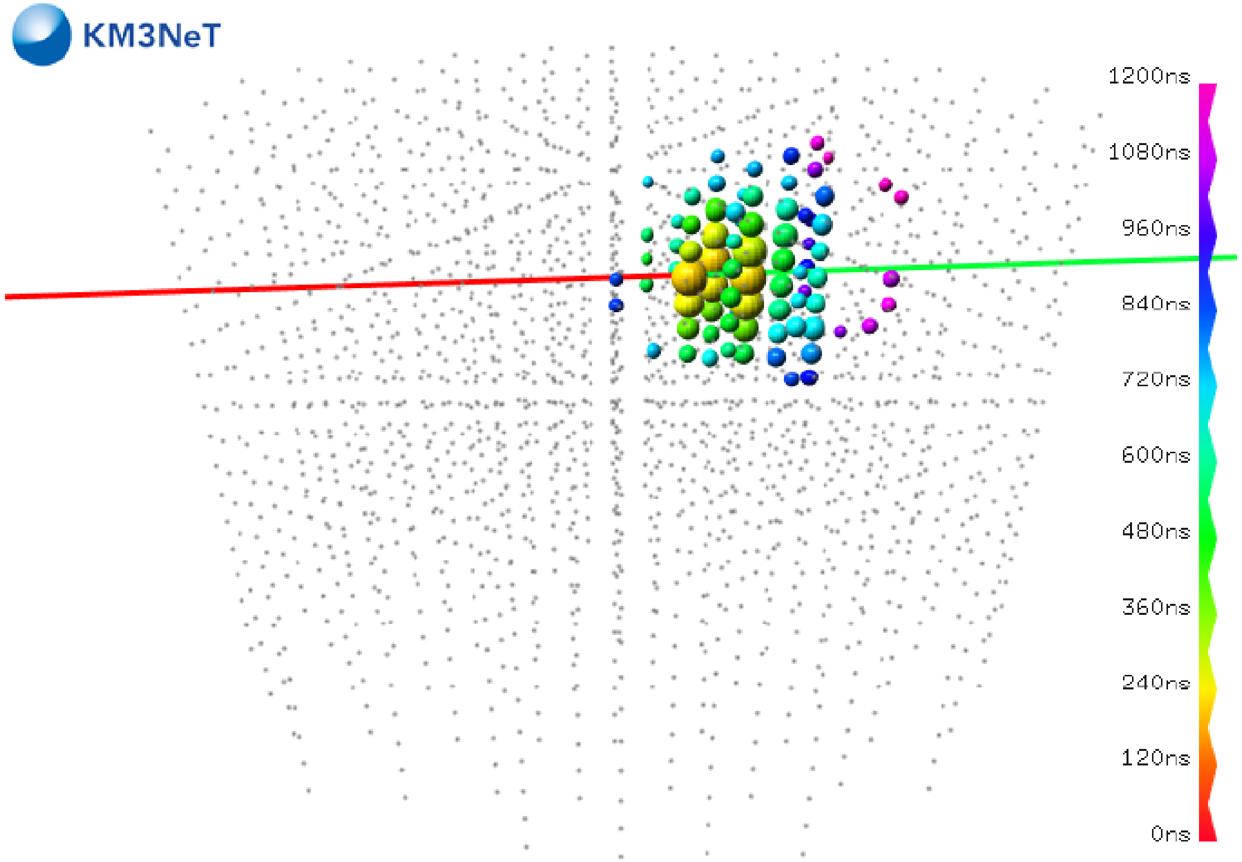
Detection Principle

Where to put the detector?
1) In a transparent medium
2) Neutrinos interact weakly →
→ We need a LARGE target →
→ It has to be cheap → Natural medium
→ Oceans (or lakes) or Antarctic ice



Tracks vs showers





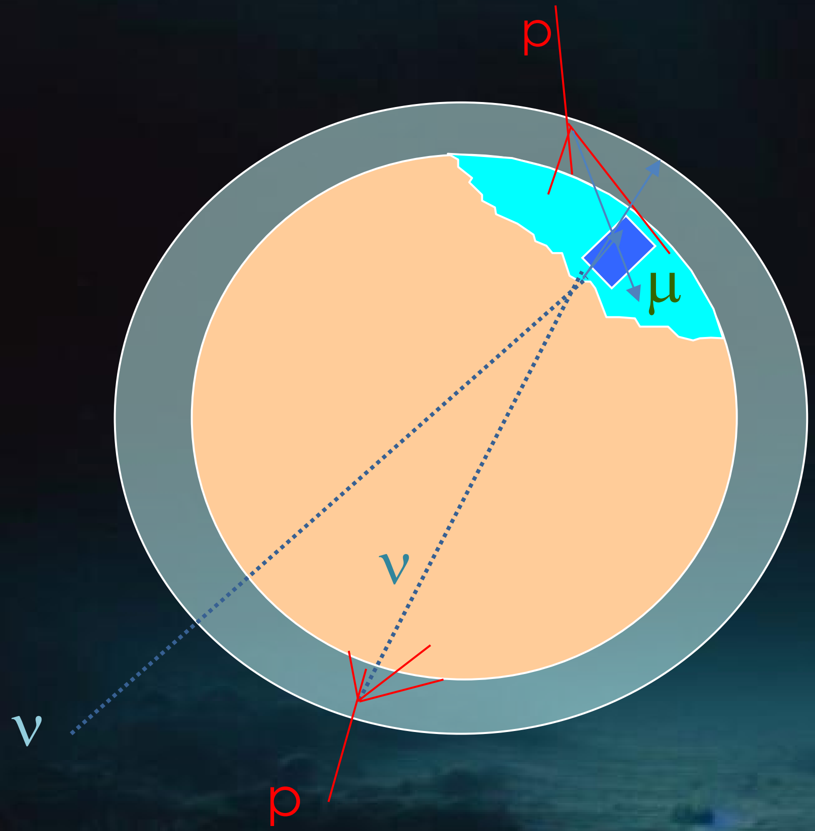
Tracks: CC ν_μ

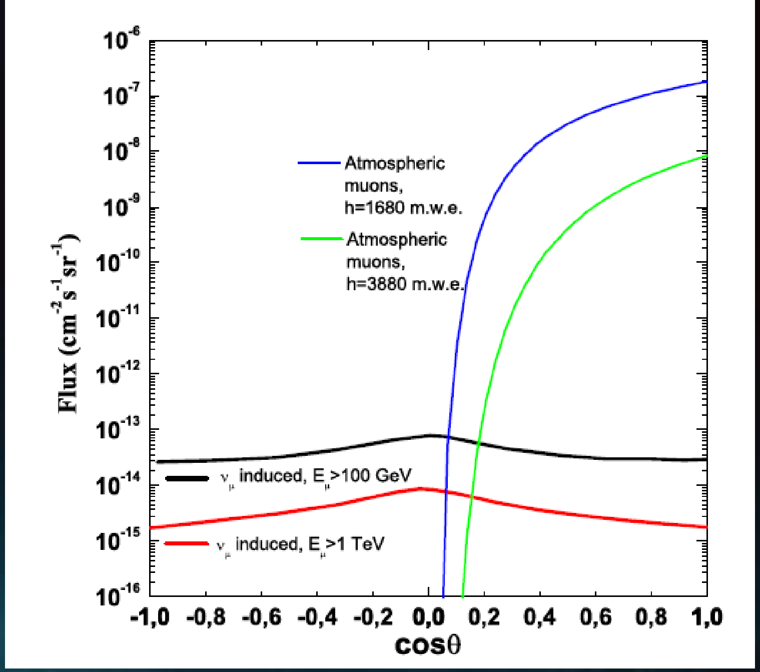
Showers: CC ν_e, ν_τ and NC

Physical Background (but also beam!)

- There are two kinds of background:
  - Muons produced by cosmic rays in the atmosphere (→ detector deep in the sea and selection of up-going events)
  - Atmospheric neutrinos (cut in the energy)

$$p \to \pi^+(+K^+ ...) \to \mu^+ + \nu_\mu$$
$$\mapsto e^+ + \bar{\nu}_\mu + \nu_e$$

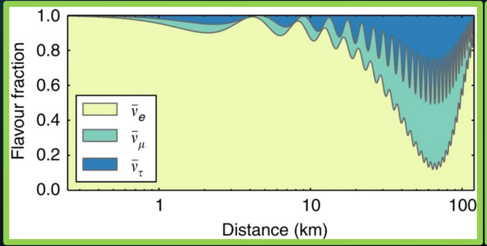


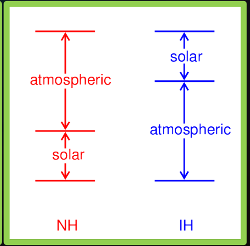


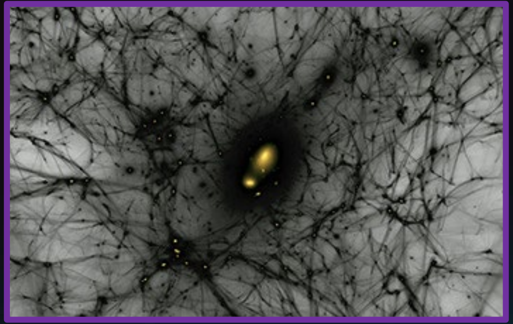
Scientific scope

Supernovae

Neutrino properties







Dark matter

Astrophysical neutrinos

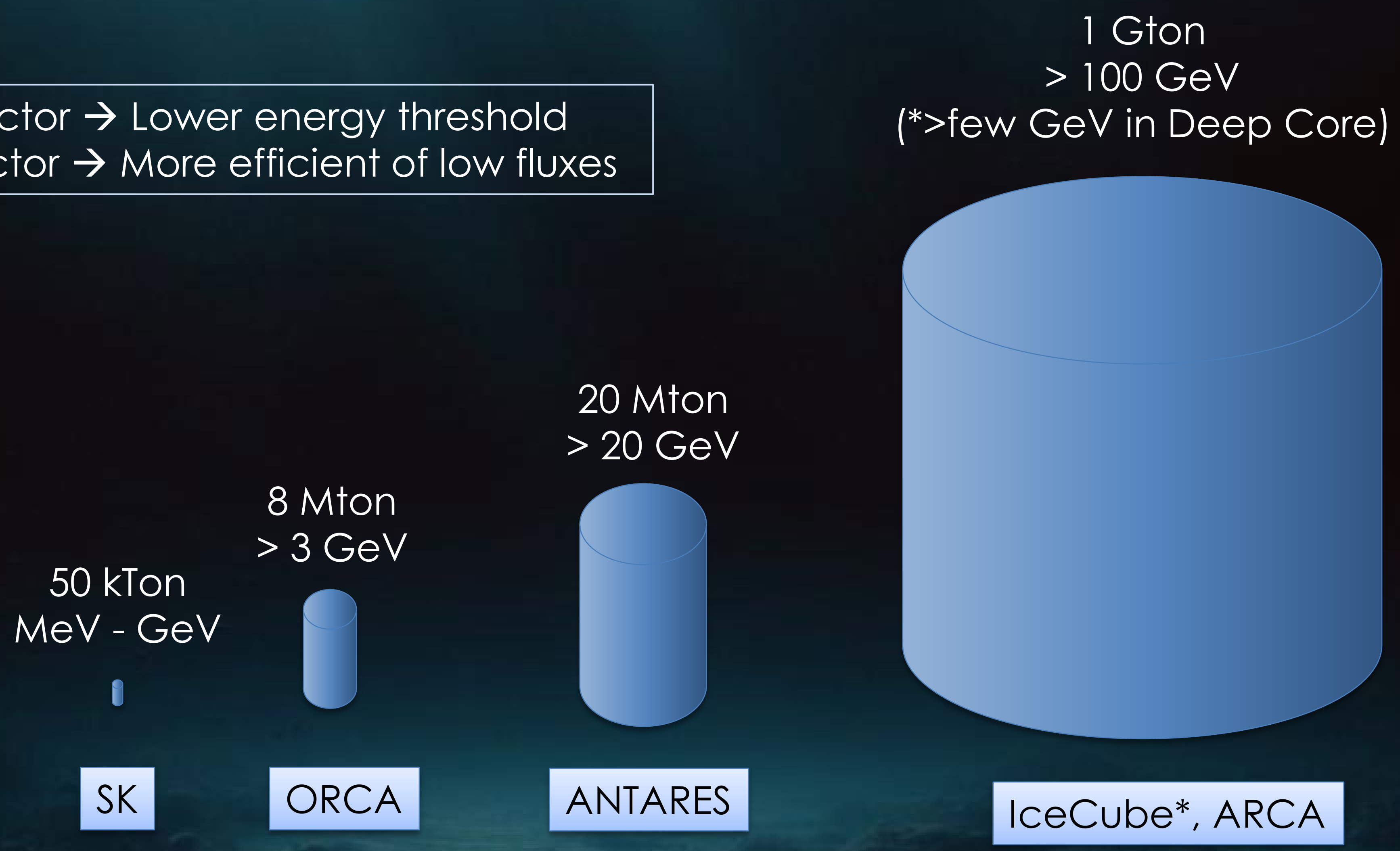
GZK

MeV GeV TeV PeV EeV

Other physics: NSIs, nu decay, monopoles, nuclearites, Lorentz invariance...

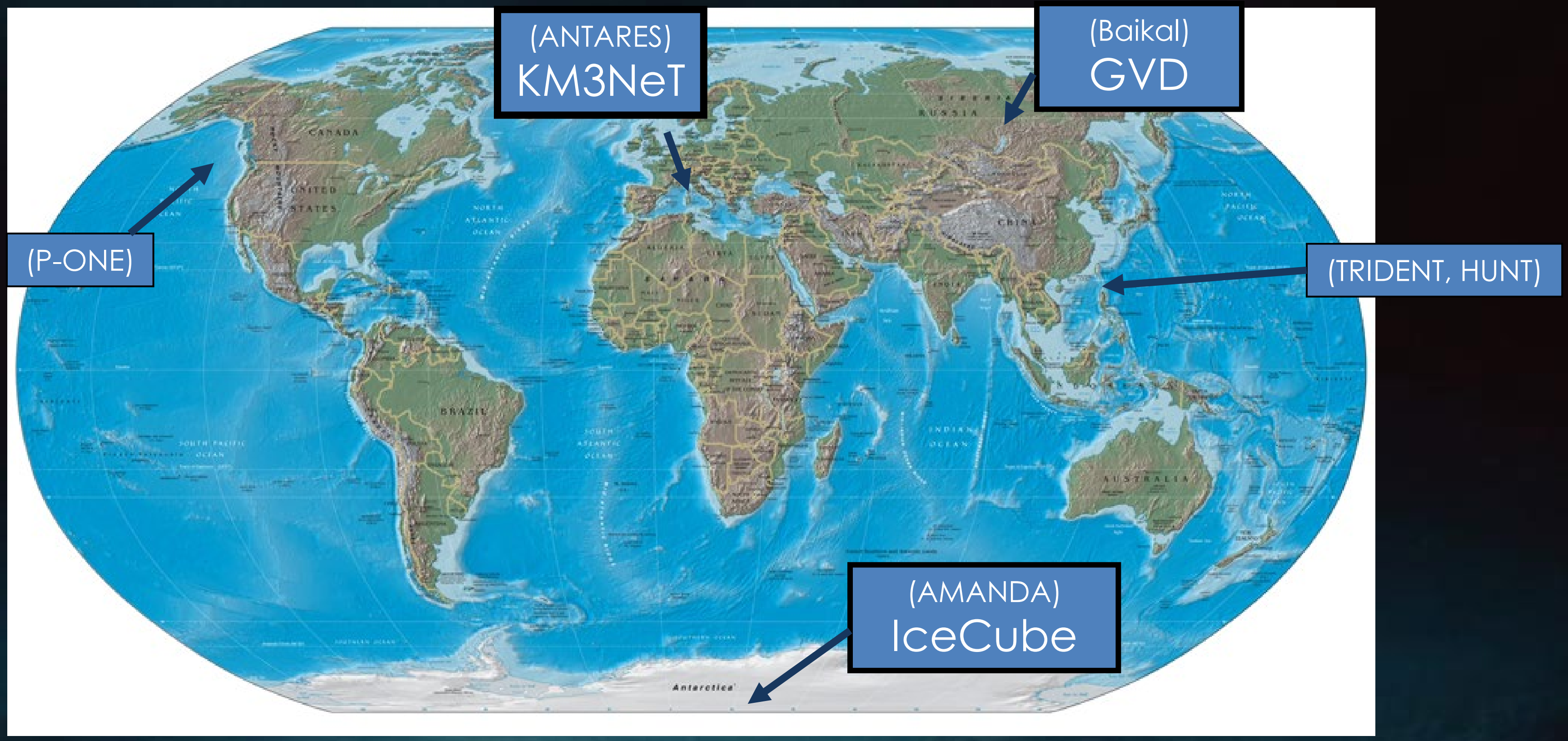
Detector size vs energy threshold

Denser detector → Lower energy threshold
Larger detector → More efficient of low fluxes

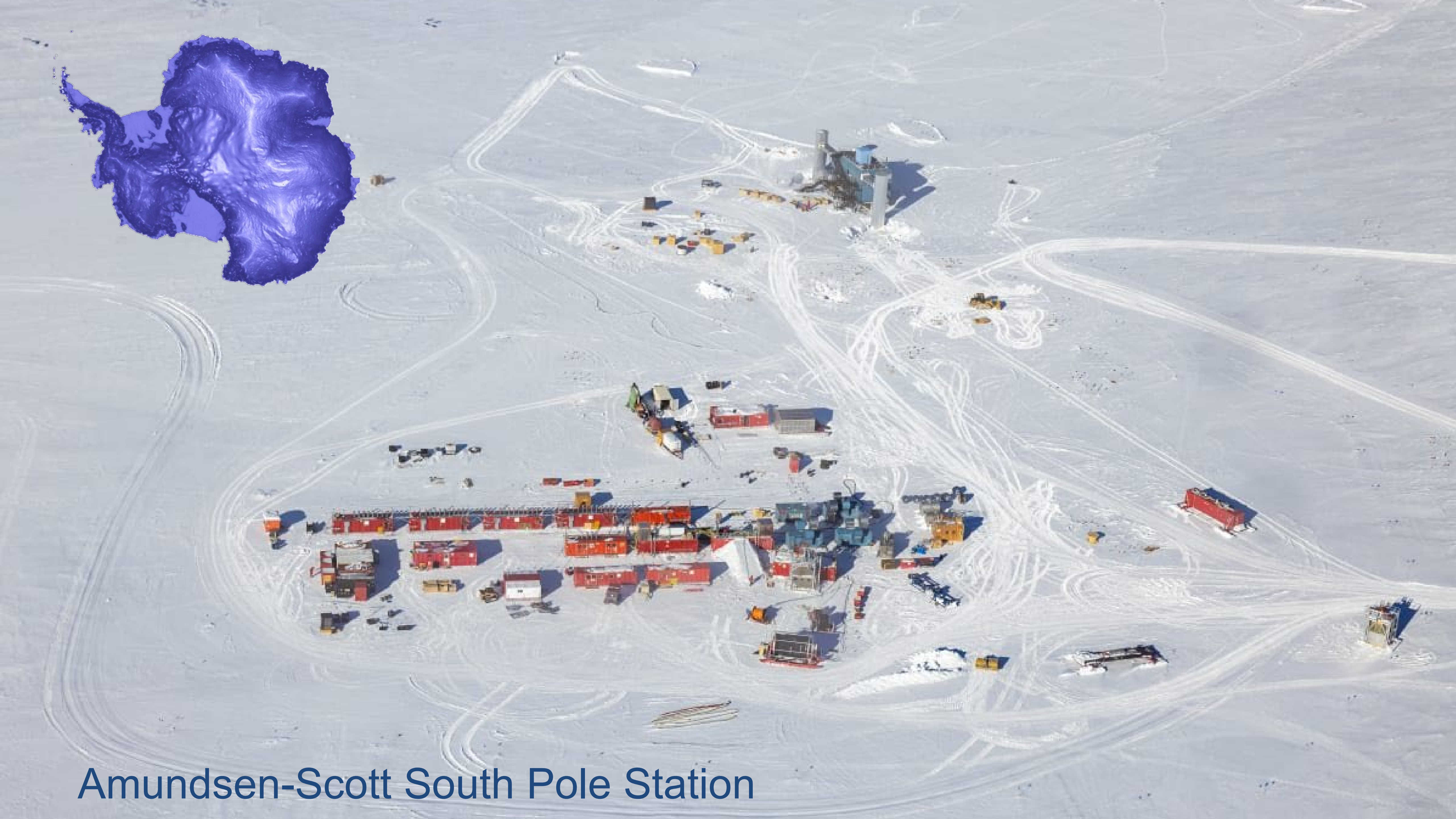


NTs in the world

- Several projects are working/planned (and decommissioned), both in ice and ocean and lakes.



IceCube



Amundsen-Scott South Pole Station

IceCube

IceTop

80 pairs of ice Cherenkov tanks
Threshold ~ 300 GeV

Deep Core

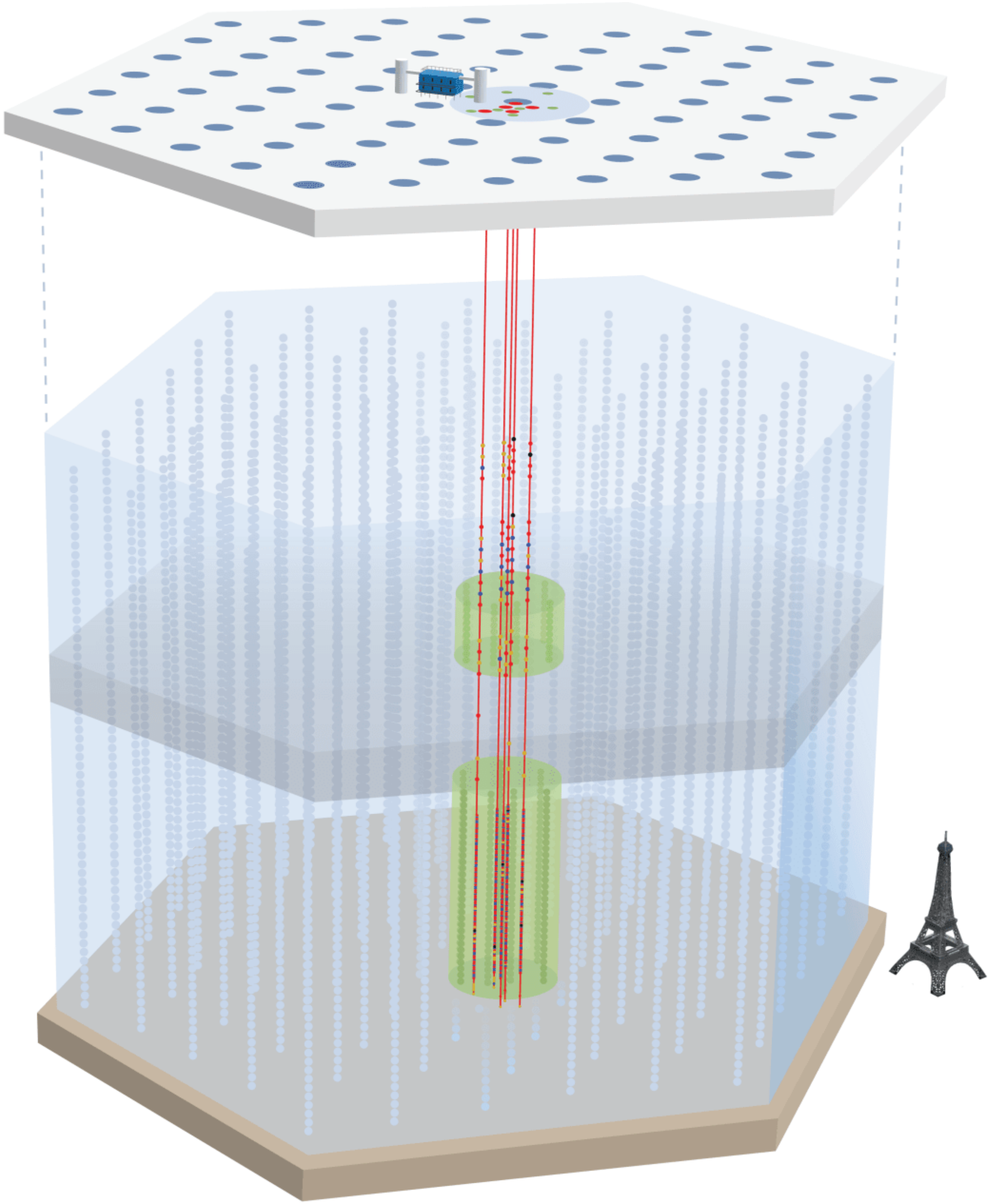
6 strings with 60 HQE OMs
Inner part of the detector

IceCube Array

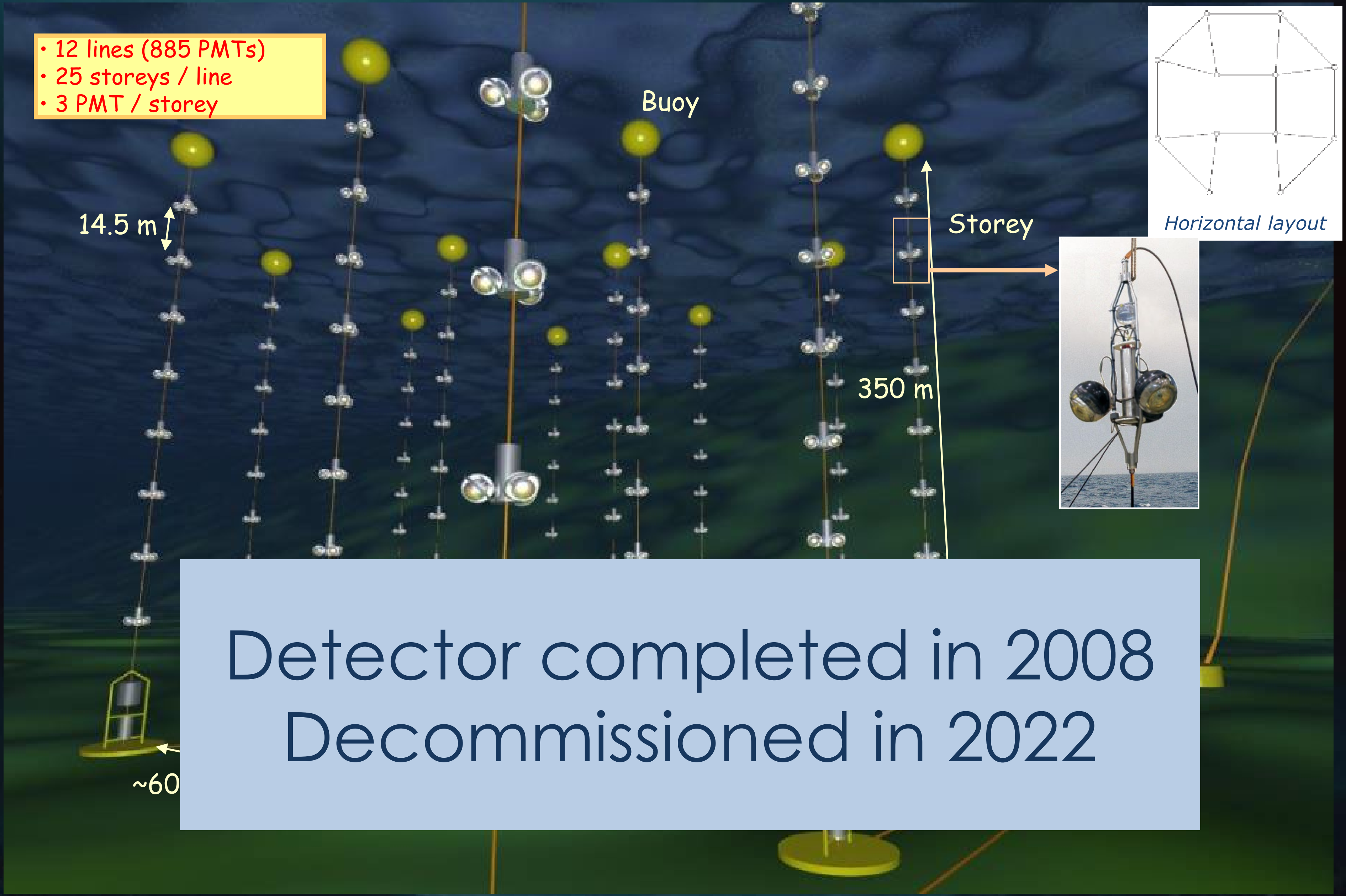
80 strings with 60 OMs
17 m between OMs
125 m between strings
1 km^3. A 1-Gton detector

Upgrade New!

5 strings, 600 advanced photodetectors and calibration devices
Inner part of the detector



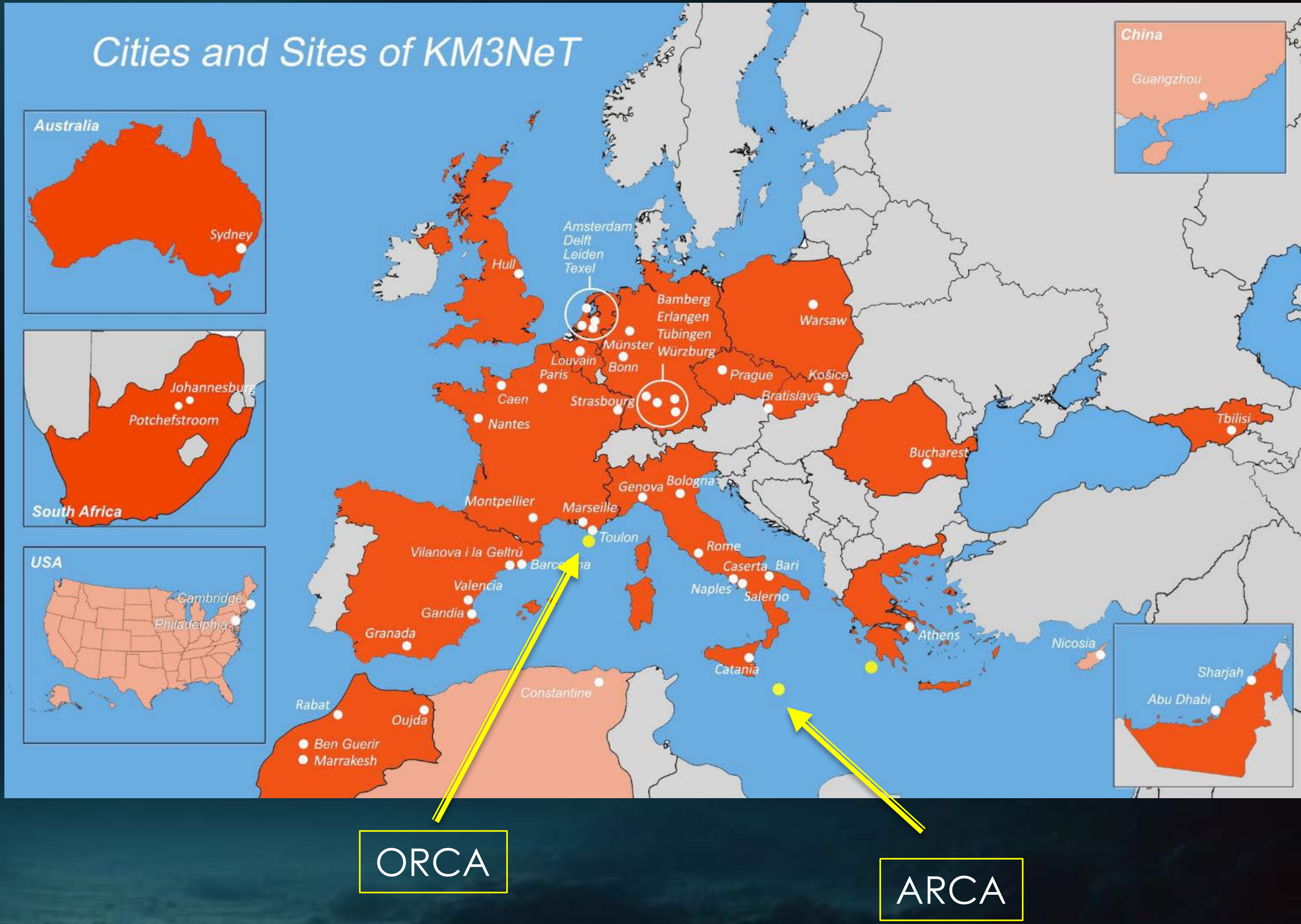
The ANTARES Detector



Detector completed in 2008
Decommissioned in 2022

KM3NeT

- KM3NeT is a common project to construct neutrino telescope in the Mediterranean with an instrumented volume > 1 km^3
- It will also be a platform for experiments on sea science, oceanography, geophysics, etc.
- 250+ scientists and engineers, 50+ institutes and groups of Astroparticle Physics and Sea Science



Letter of Intent: J. Phys. G: Nucl. Part. Phys. 43 084001 (2016)

KM3NeT

DU=Detector Unit (aka line)

ARCA
230 DUs
18 DOMs / DU
inter-DU distance: 90 m
inter-DOM distance: 36 m

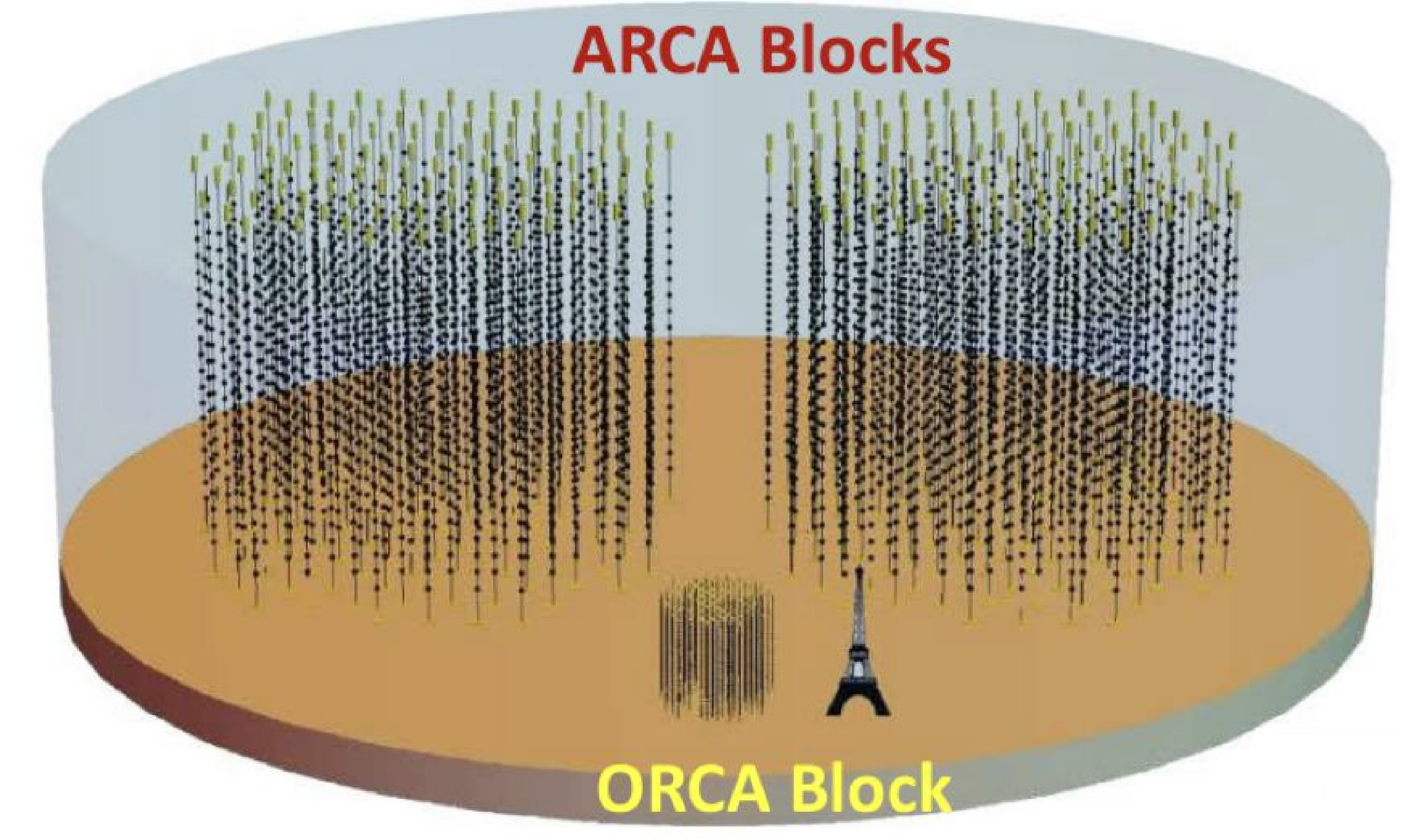
ORCA
115 DUs
18 DOMs / DU
inter-DU distance: 20 m
inter-DOM distance: 9 m

ARCA
51 DUs deployed

ORCA
33 DUs deployed

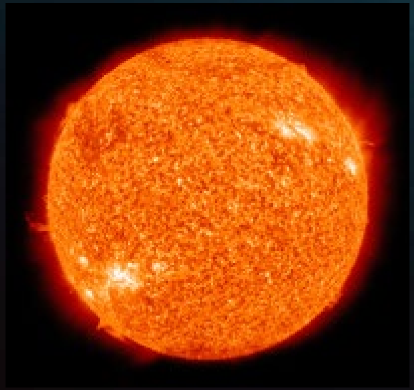
Physics starts as soon as a few lines are deployed… = some years ago!

ARCA vs ORCA



Sources for DM searches

Sun



$\sigma_{SD/\,SI}$

Earth

Galactic Centre

Galactic Halo

$\langle \sigma_{ann} v \rangle$

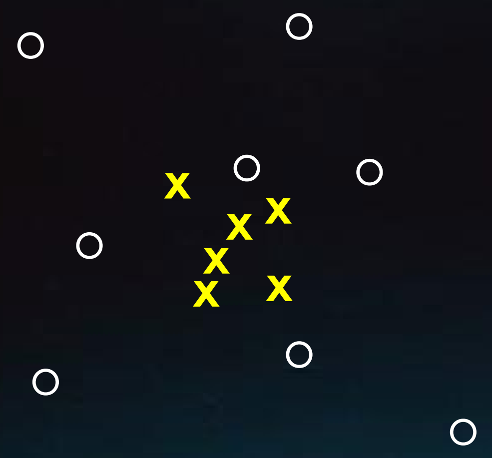
Dwarf galaxies

$\langle \sigma_{ann} v \rangle$

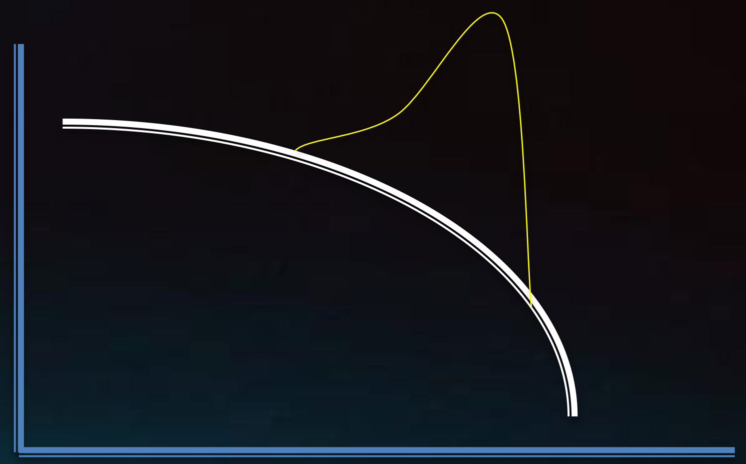
Galaxy clusters

DM features in NTs

Spatial distribution:
concentrated in DM
sources (also “shadows”)



Energy distribution:
spectral shape, peaks?



Results

Galactic Centre / Halo

Galactic Centre: Rate calculation

- Annihilation:

$$\frac{d\Phi}{dE}(E\;,\psi,\theta,\Delta\Omega)=\boxed{\frac{1}{4\pi}\,\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\,\frac{dN^i}{dE}}\,\boxed{\int_0^{\Delta\Omega}d\Omega\int_{\mathrm{l.o.s}}\rho^2(r(s,\psi,\theta))ds.}$$

Particle Physics

Dark matter distribution (J-factor)

- Decay:

$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu)=\boxed{\frac{1}{4\pi m_\chi\tau_\chi}\,\frac{dN_\nu}{dE_\nu}(E_\nu)}\,\boxed{\int_0^{\Delta\Omega}d\Omega\int_0^{\infty}\rho_\chi(l\hat{n})dl,}$$

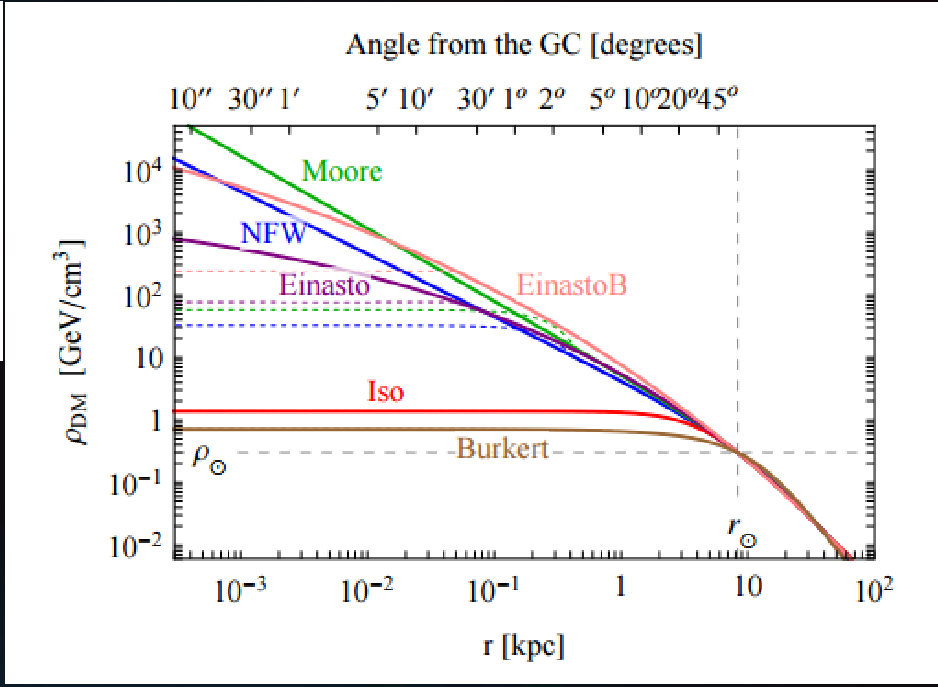
Halo density profiles

- Several profiles available on the market

Cirelli et al., 1012.4515v4

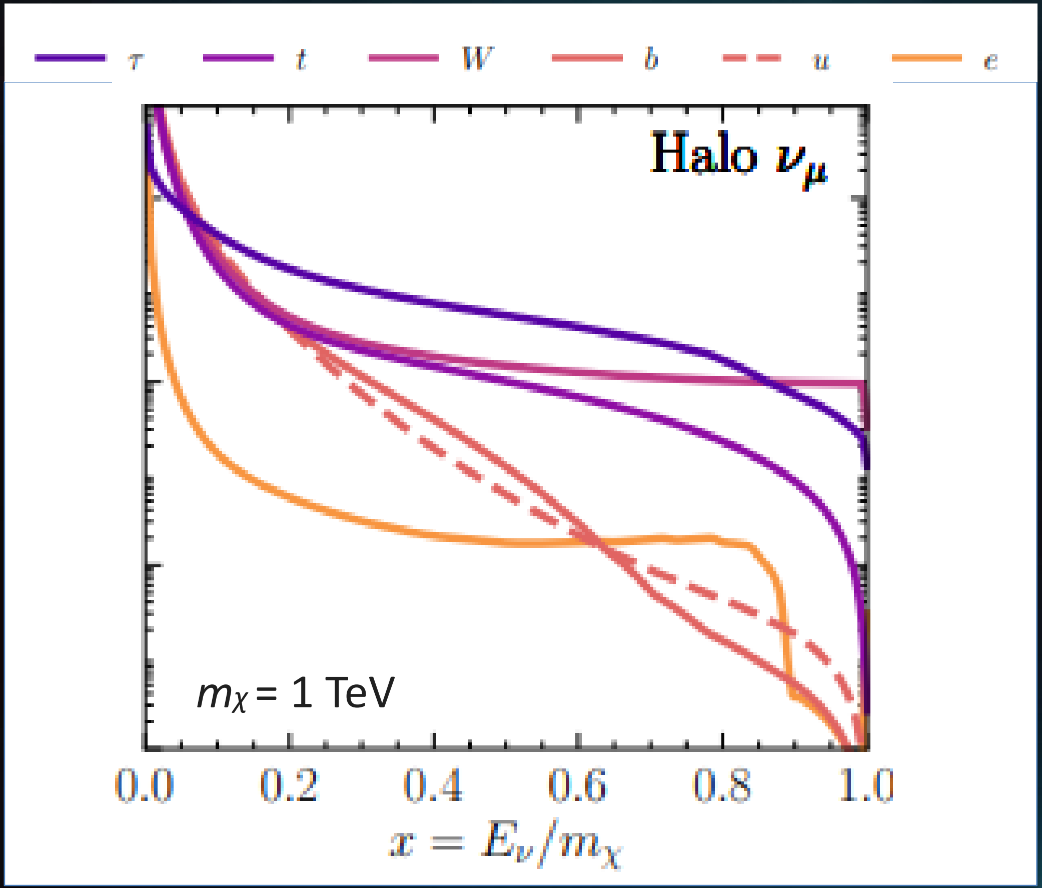
$$
\begin{aligned}
\text{NFW}: \quad \rho_{\rm NFW}(r) &= \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2} \\
\text{Einasto}: \quad \rho_{\rm Ein}(r) &= \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\} \\
\text{Isothermal}: \quad \rho_{\rm Iso}(r) &= \frac{\rho_s}{1+(r/r_s)^2} \\
\text{Burkert}: \quad \rho_{\rm Bur}(r) &= \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)} \\
\text{Moore}: \quad \rho_{\rm Moo}(r) &= \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}
\end{aligned}
$$

DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105



- NFW, Einasto (cuspy) vs Burkert (cored)
- Effect of baryons unknown
- Maybe not spherical (triaxial)
- Clumps? → boost
- Dark disk: very good for NTs

Neutrino spectrum

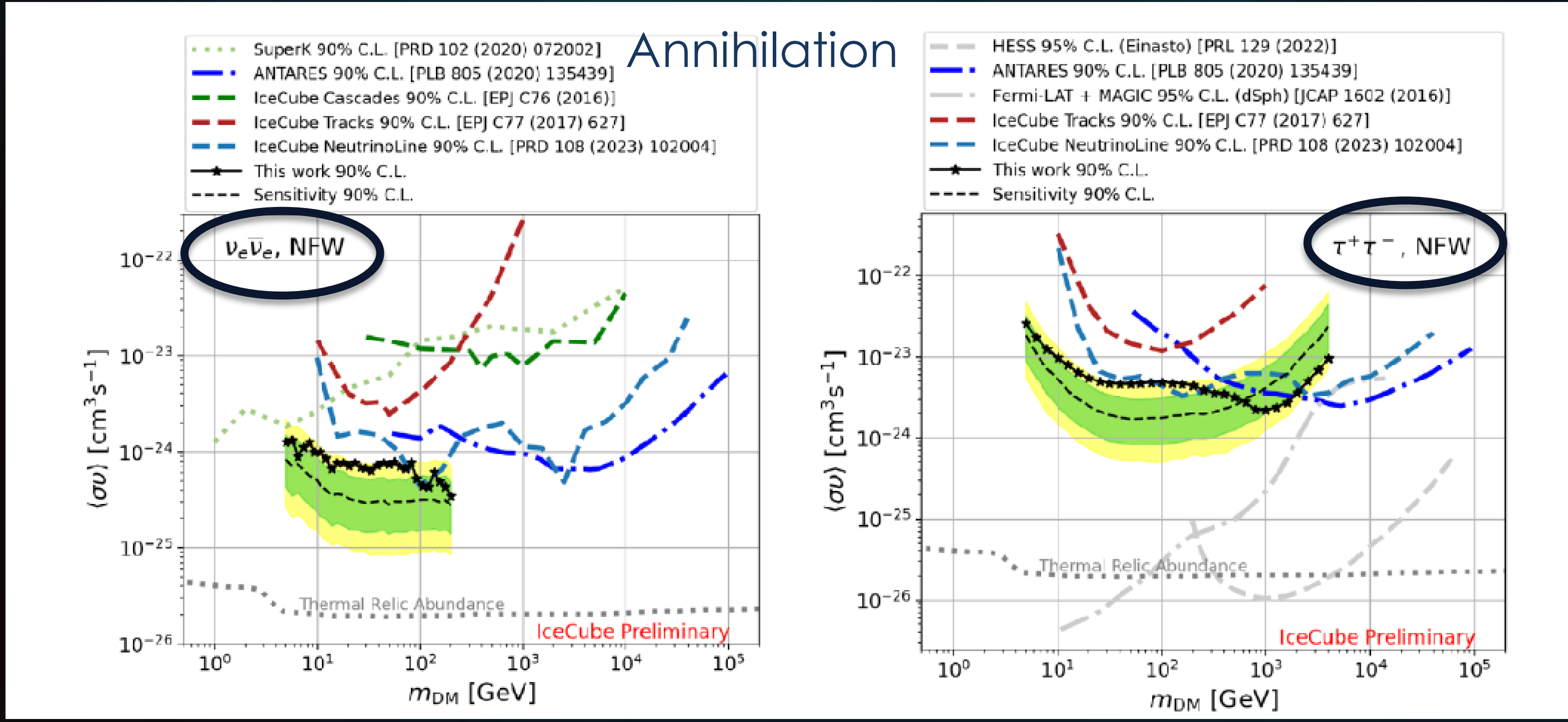


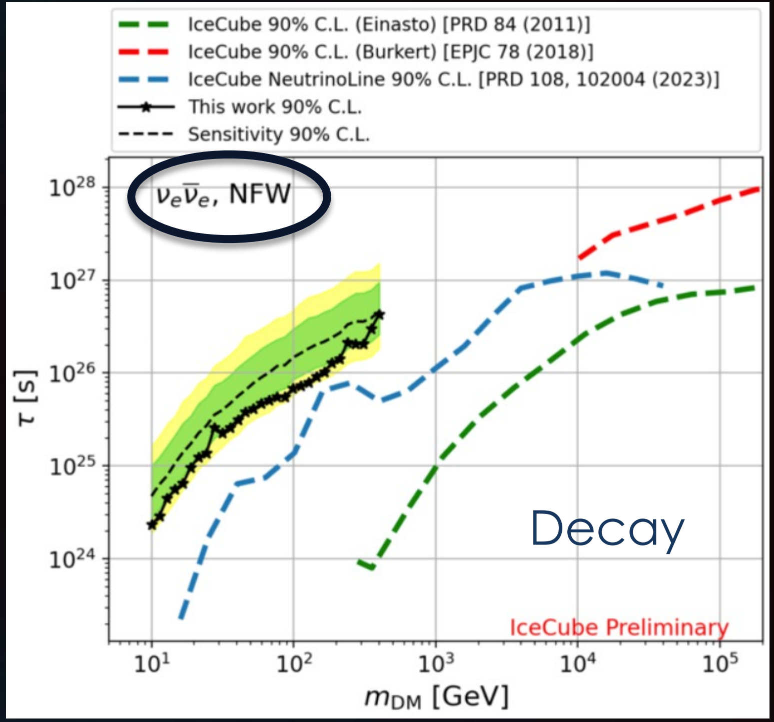
arxiv:2007.15010

- 100% branching ratio is assumed to include optimistic and pessimistic scenarios
- Electro-weak corrections have to be taken into account

IceCube: Galactic Centre

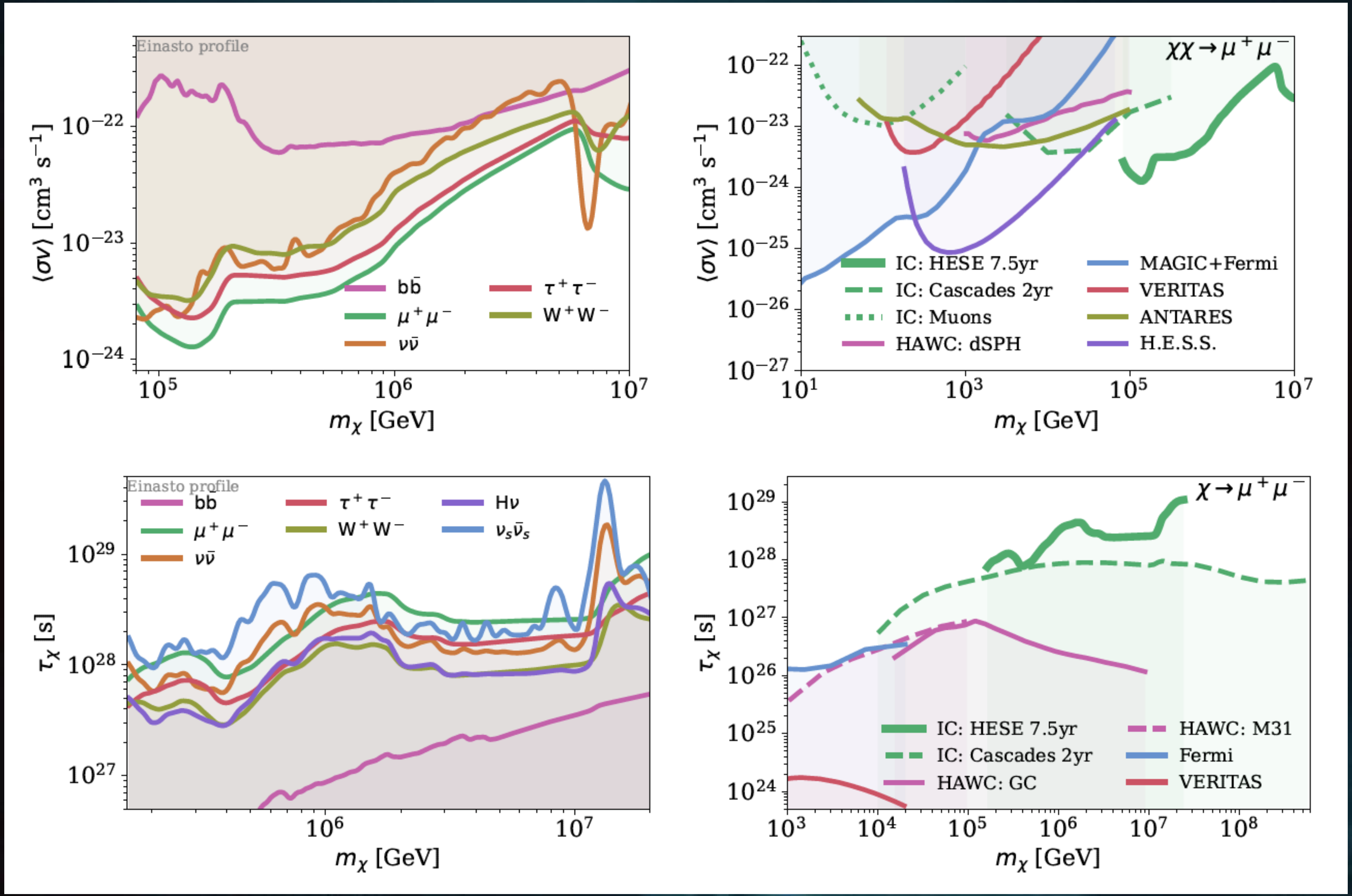
arxiv:2511.00918





- 9.28 y of IceCube + DeepCore
- World-leading limits on neutrino line signal for DM masses from several tens of GeV up to 100 GeV

IceCube: high energies

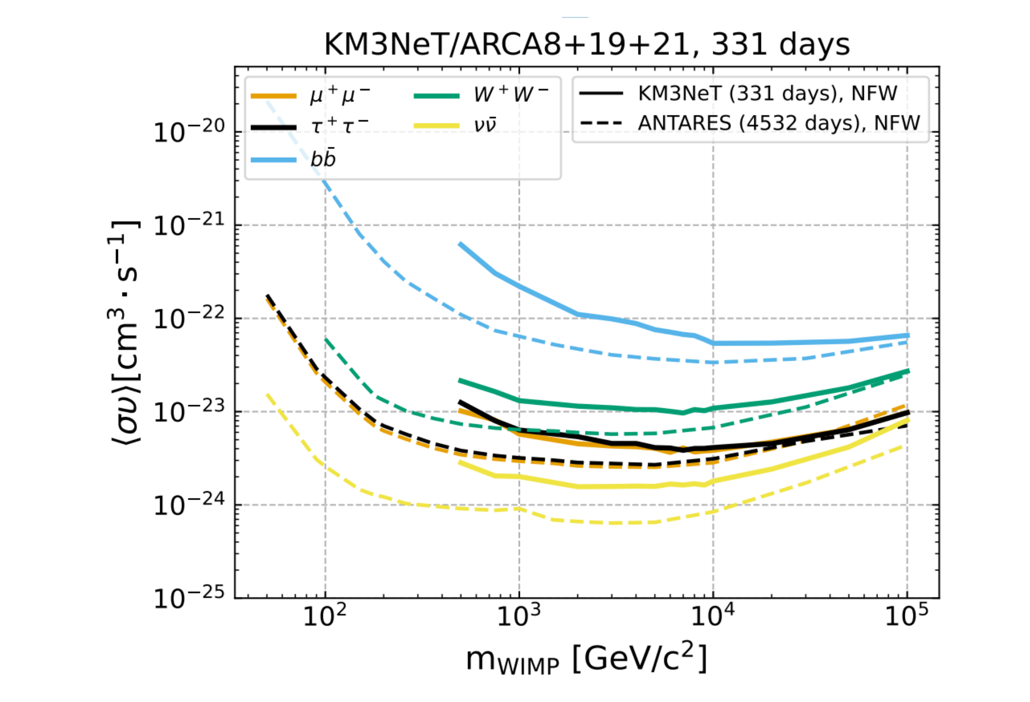


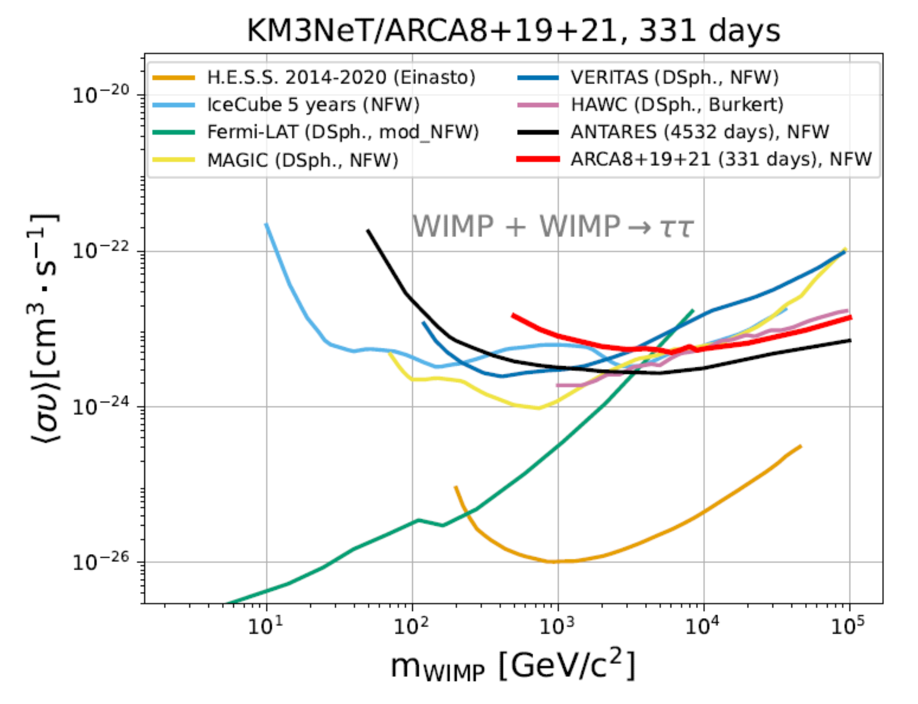
JCAP10(2023)003

- HESE sample (7.5 years)
- DM models fitted on top of a diffuse astrophysical neutrino flux and atmospheric backgrounds
- Particularly relevant at high masses

KM3NeT, Galactic Centre

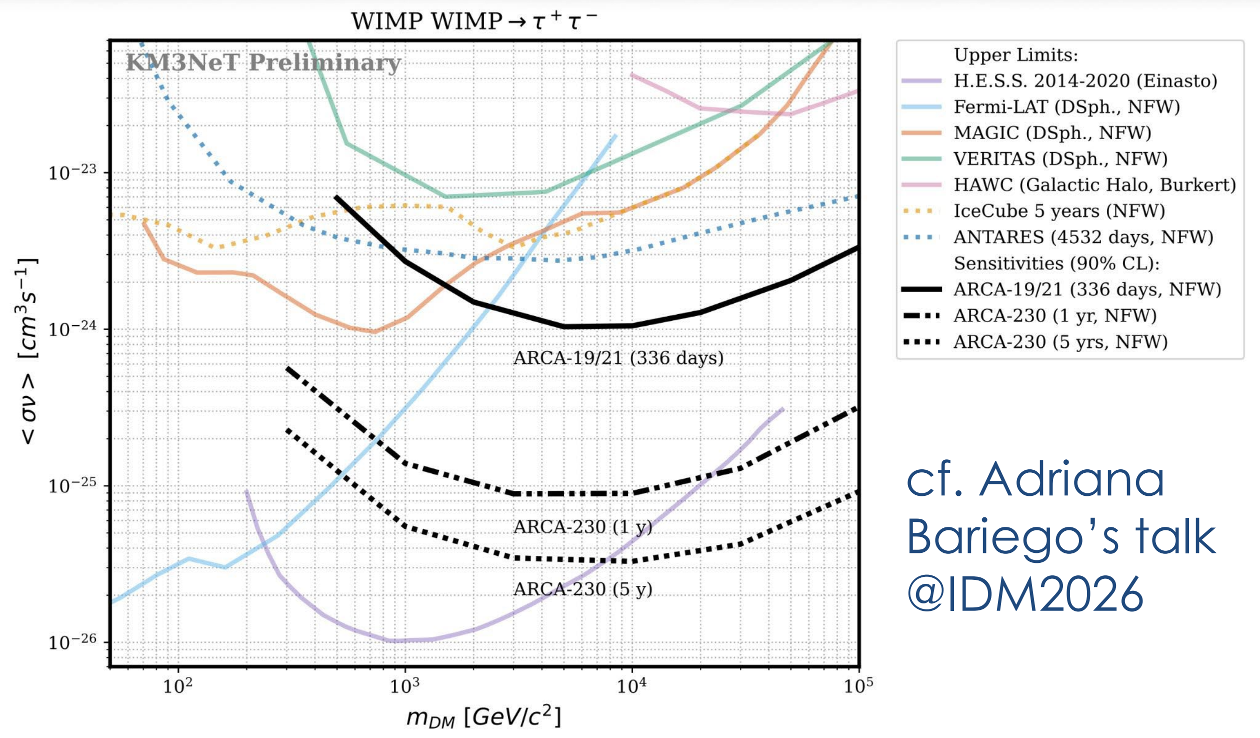
- Good visibility (70%) of the Galactic Centre from the Mediterranean (atmospheric background shielded)
- Limits with one year of live time with ARCA8-21 are comparable (although less stringent) to those obtained with the full ANTARES sample (4500+ days)



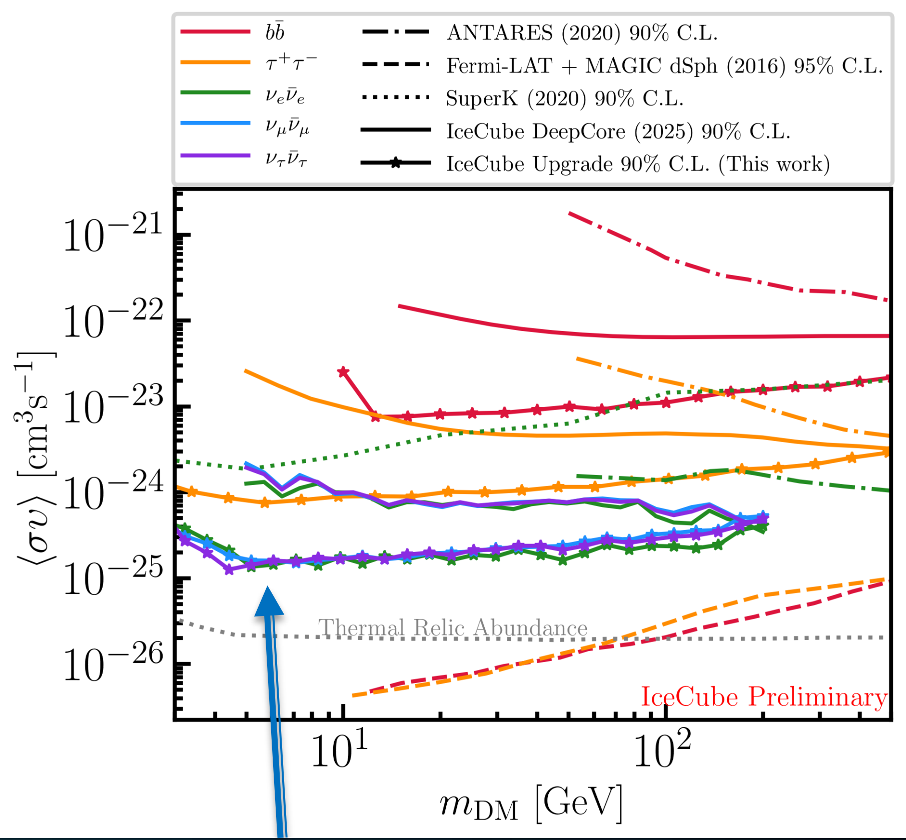


Phys. Lett. B 805 (2020), JCAP03(2025)058

Galactic Halo/Centre: prospects



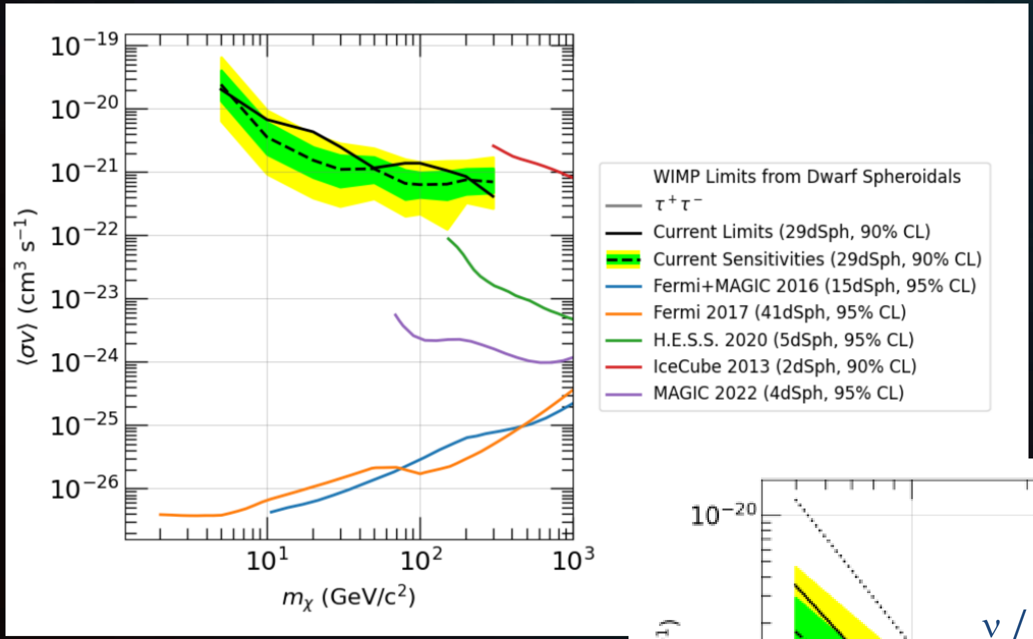
cf. Adriana Bariego's talk @IDM2026

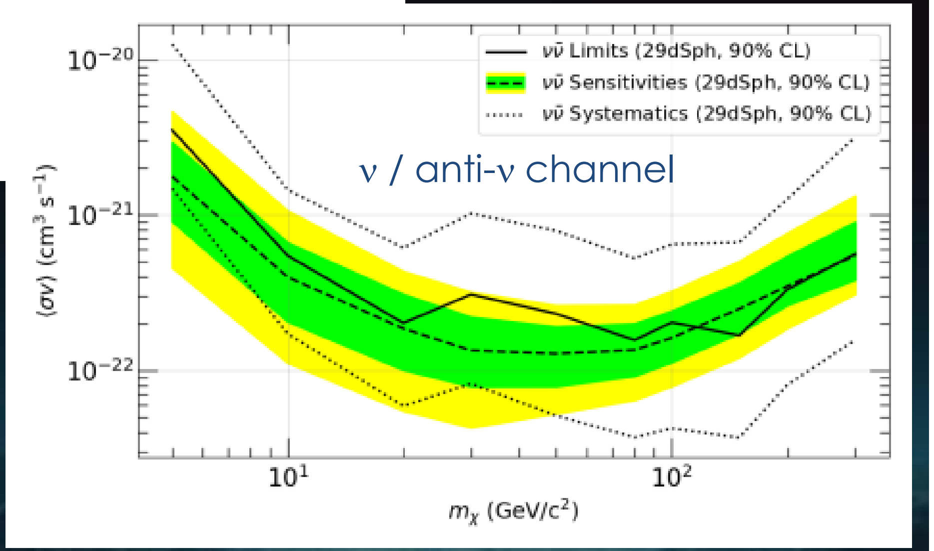


- Full ARCA will lead results in the high mass region
- The IceCube upgrade will allow to improve sensitivity <50 GeV by one order of magnitude
- In three years, it will reach sensitivity of 9 years of DeepCore at 100 GeV

IceCube on Dwarf Spheroidals

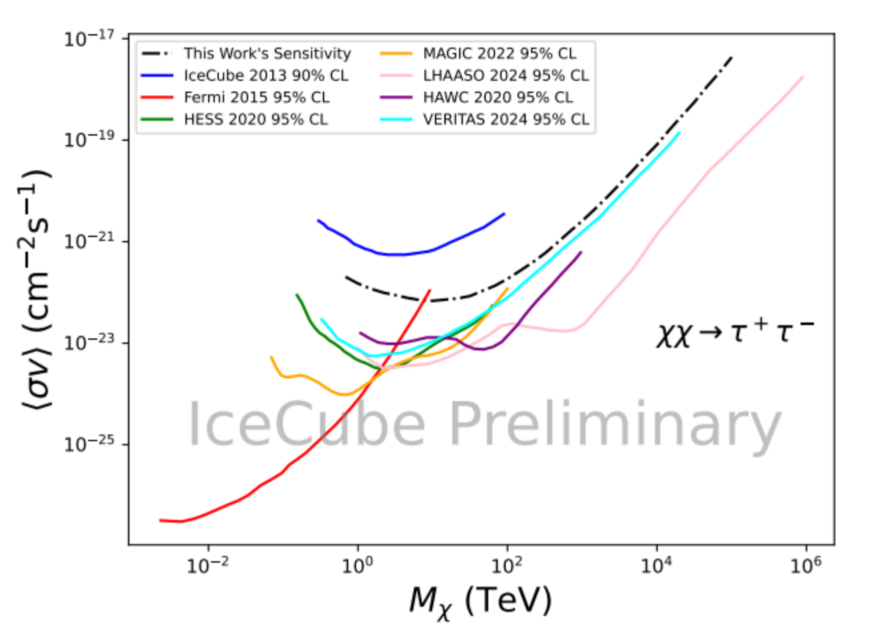
arxiv: 2511.19385





- DSphs are the most DM-dominated structures known, with vey little high energy astrophysical activity
- Mass range <300 GeV
- Seven years of IceCube livetime
- 29 dSphs used
- Strongest limits on <σ_{ann}v> (O(10^{-22} cm^3 s^{-1})) for ν / anti-ν channel
- Also, recent analysis for larger masses (up to 100 PeV)

PoS(ICRC2025)523



Results

Sun and Earth

Credit: D. Cerdeño

Sun: $\sigma_{\chi N}$

annihilation

$$\frac{dN}{dt} = C_C - C_A N^2 - \cancel{C_E N}$$

capture

~~evaporation~~

Differential neutrino flux is related with the annihilation rate as

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi d^2}\frac{dN_\nu}{dE_\nu}$$

If we assume equilibrium between capture and annihilation in the Sun:

$$\Gamma \simeq \frac{C_\otimes}{2}$$

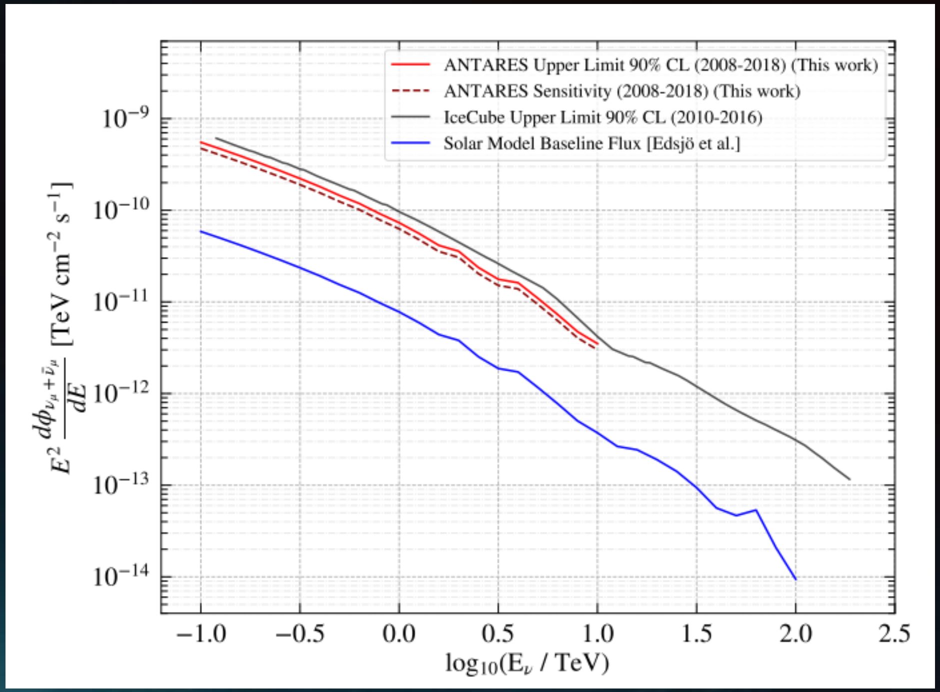
where the capture rate can be expressed as

$$C_\otimes \simeq 3.35 \times 10^{18}\mathrm{s}^{-1} \times \left(\frac{\rho_{\mathrm{local}}}{0.3\,GeV \cdot cm^{-3}}\right) \times \left(\frac{270\,\mathrm{km}\cdot\mathrm{s}^{-1}}{v_{\mathrm{local}}}\right) \times \left(\frac{\sigma_{H,SD}}{10^{-6}\,\mathrm{pb}}\right) \times \left(\frac{TeV}{M_{\mathrm{WIMP}}}\right)^2$$

DM at the Sun with NTs

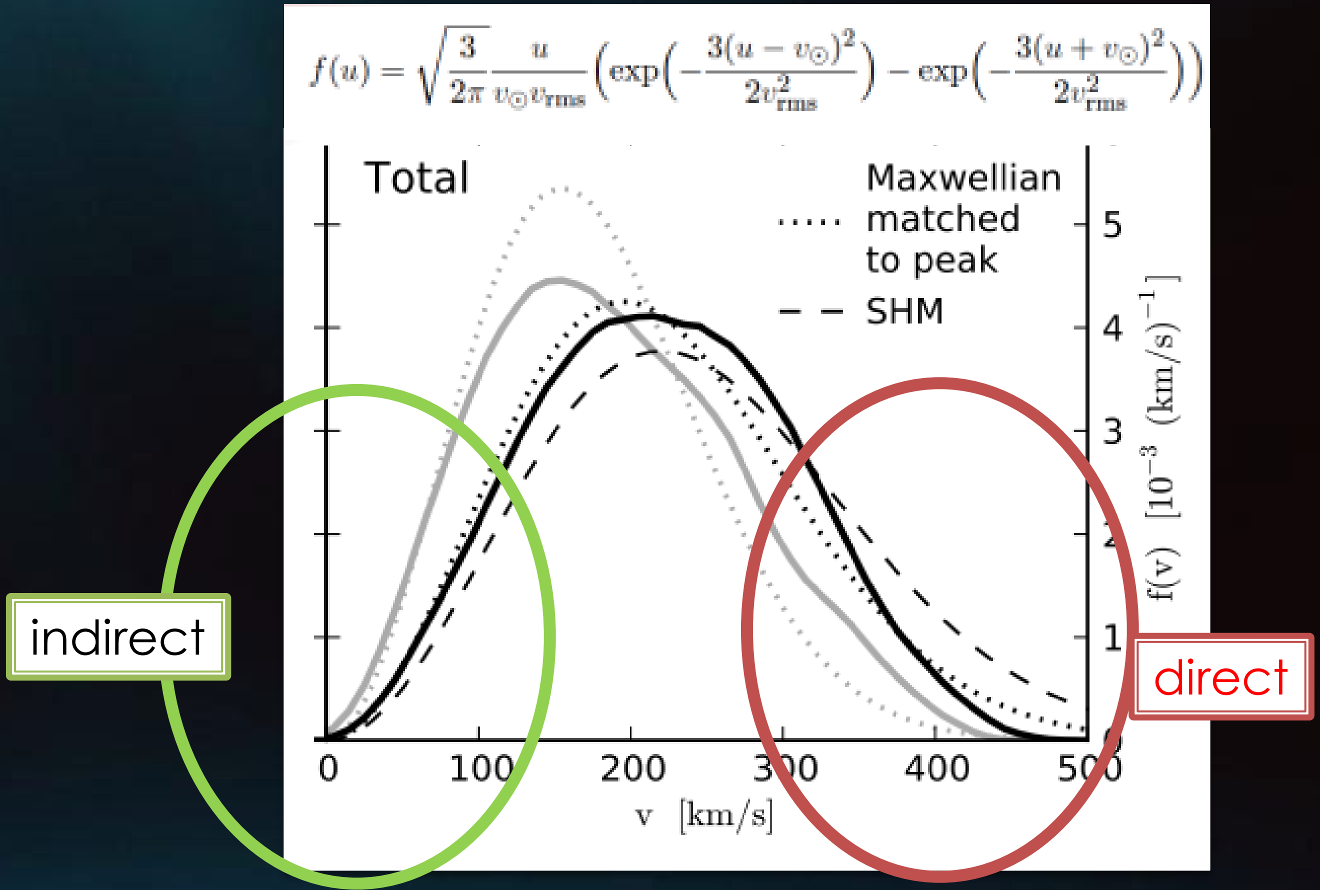
- An important advantage of NTs when looking for DM in the Sun is that the background is well known:
  - Atmospheric background: measured
  - Astrophysical background (cosmic rays interacting in the Sun, aka solar atmospheric neutrinos): smaller than present sensitivities and known
- An excess of high energy neutrinos from the Sun would be a "smoking gun"

ANTARES, JCAP06 (2022) 018



Velocity distributions in the Galactic Halo

- Neutrino telescopes (for searches in the Sun) complementary to direct searches
  - low velocity: easier to capture in the Sun
  - high velocity: large recoils easier at high velocities

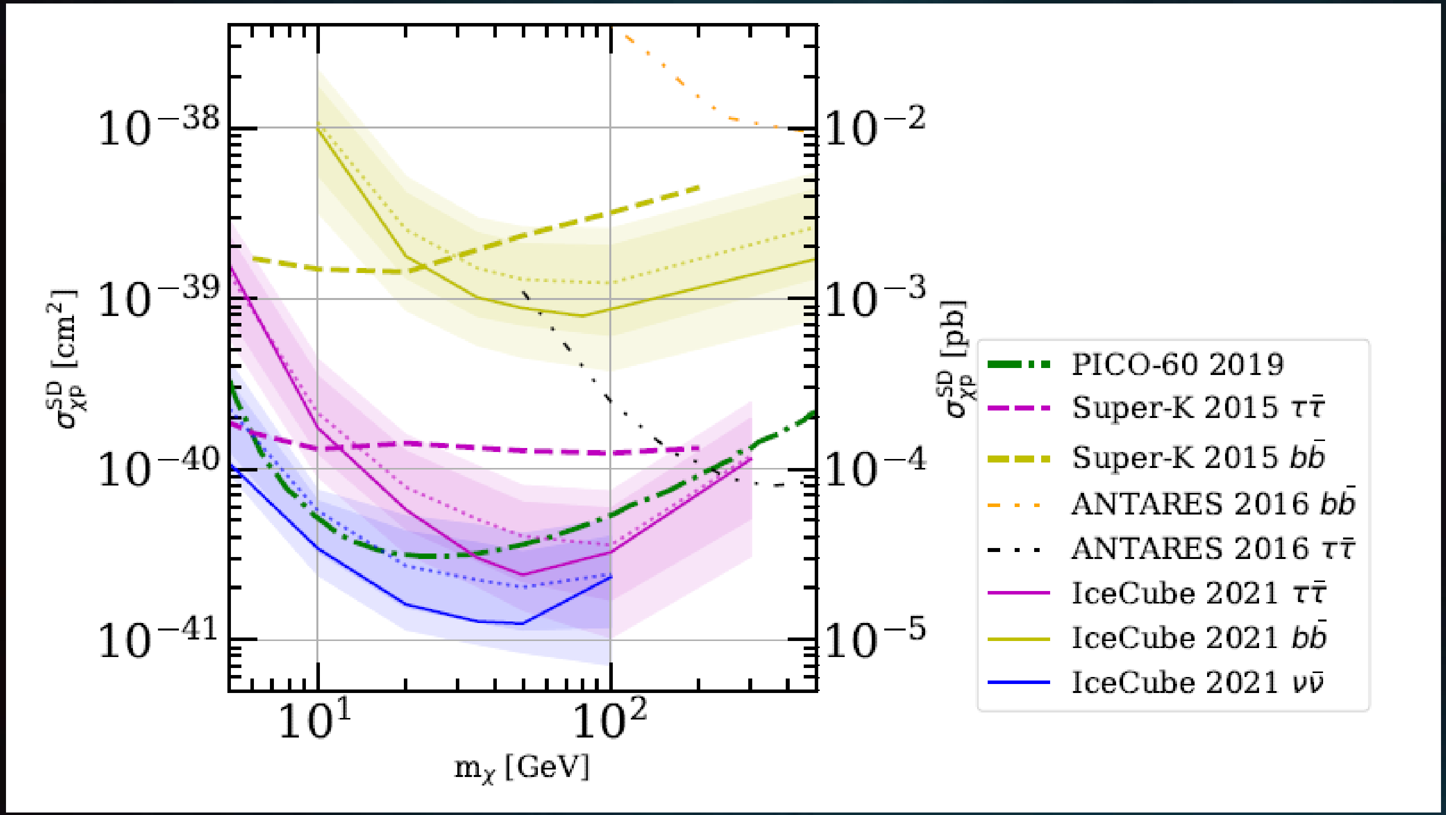


arxiv:1308.1703

Simplest assumption: Maxwell distribution

Other v distributions: <20% change in C
Choi et al. JCAP 1405 (2014) 049

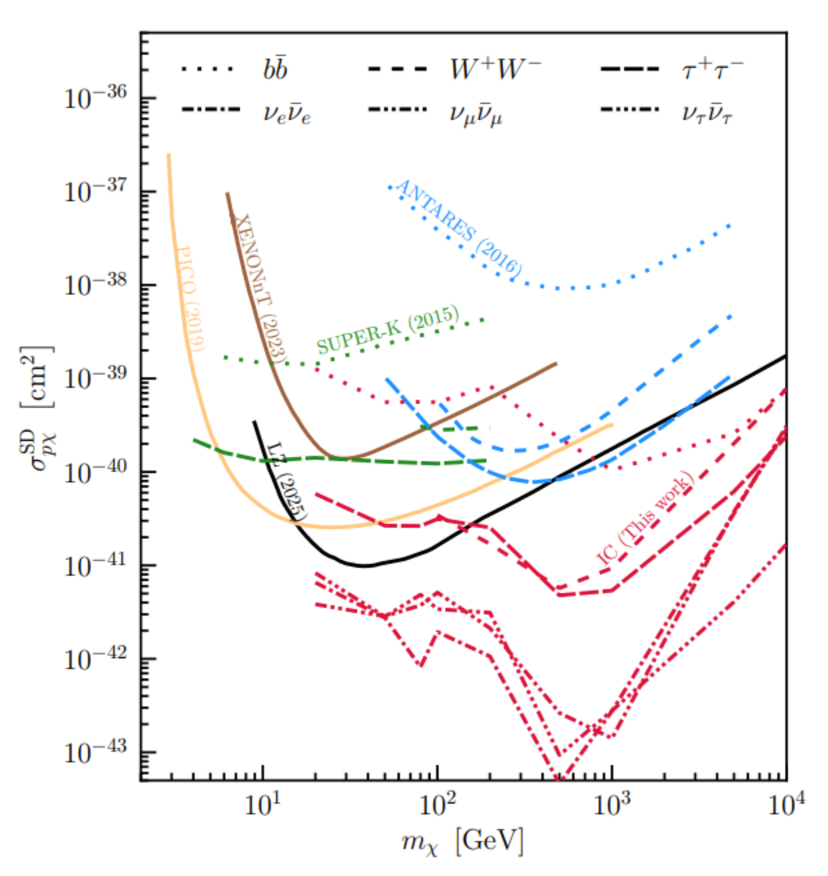
IceCube: Sun, low energies



Phys. Rev. D 105, 062004

- 7 years of IceCube and Deep Core
- Optimized cuts to reach m_{WIMP}~5 GeV (evaporation still negligible)
- Limits up to < 100 GeV
- Strongest constraints at GeV energies for dark matter annihilation directly to neutrinos.

IceCube: Sun, high energies

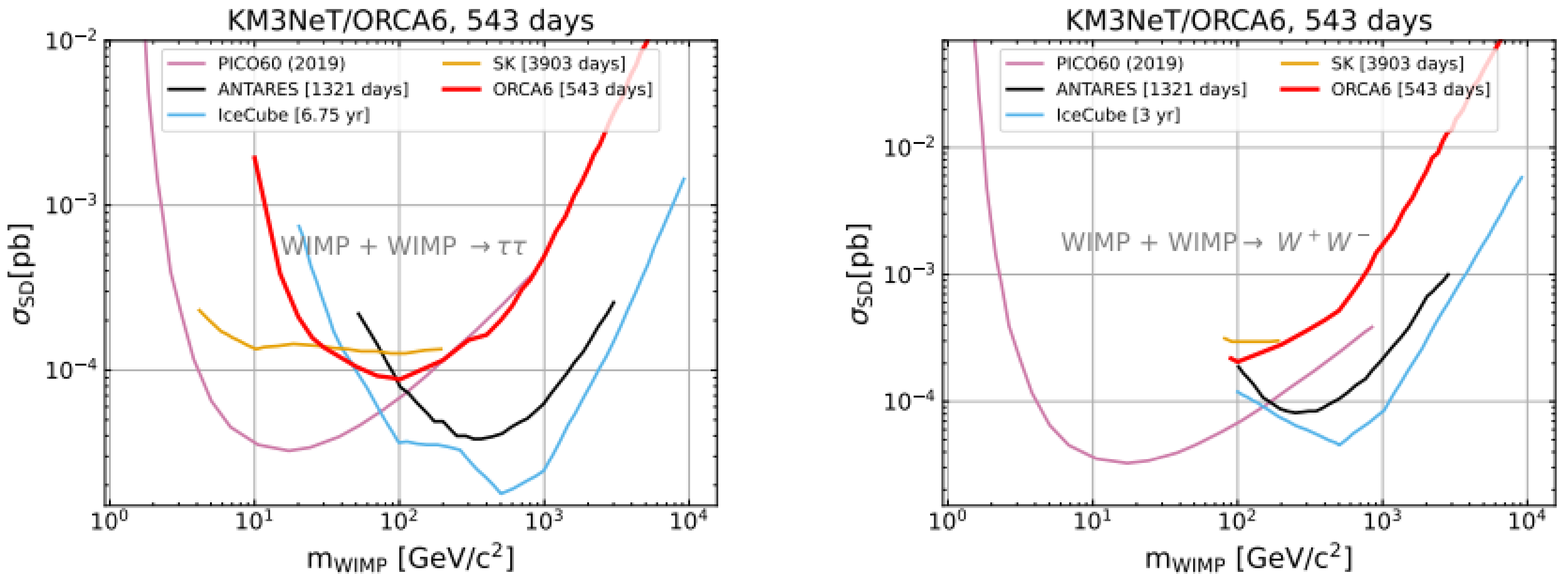


arXiv:2507.08457

- 9.3 y DeepCore + 10,4 y IceCube
- Range: tens of GeV- tens of TeV
- Also constraints on solar atmospheric neutrinos
- World-best limits for spin dependent DM-nucleon interactions

KM3NeT, Sun

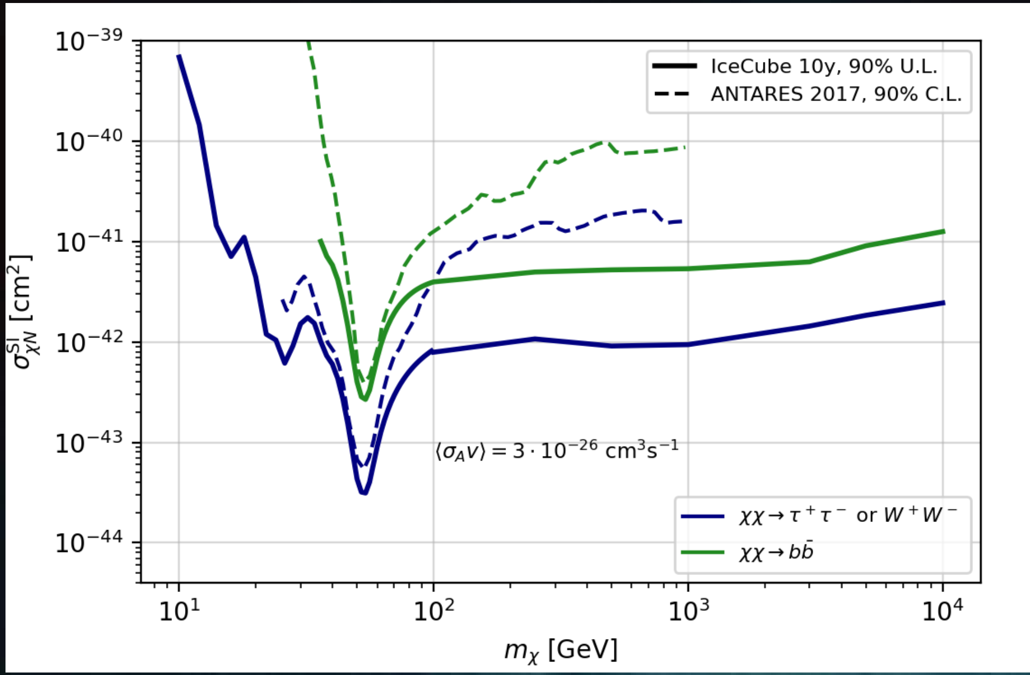
- ORCA6, 543 days
- Mass range: 10 GeV to 5 TeV
- Still limited sensitivity, but already better than ANTARES for low masses in some channels

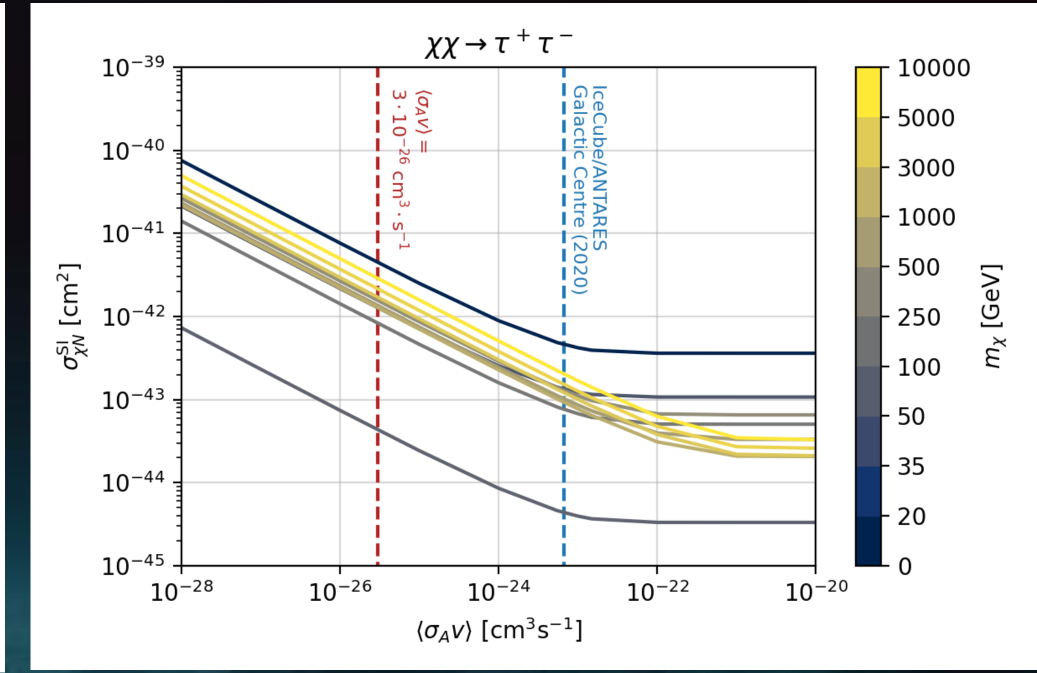


JCAP03(2025)058

Earth

- Capture – annihilation equilibrium is not expected → Particular value of annihilation cross section has to be assumed: $\langle\sigma_A v\rangle = 3 \times 10^{-26} cm^3\, s^{-1}$
- Results on spin ***independent*** DM-nucleon cross section
- More efficient for **masses** close to those of **Fe and Si**
- Backgrounds more complicated to estimate
- Not competitive with direct searches (but complementary: probing low velocities)
- Significant improvement expected with IceCube Upgrade

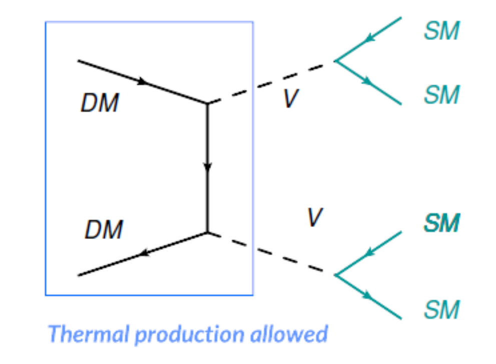


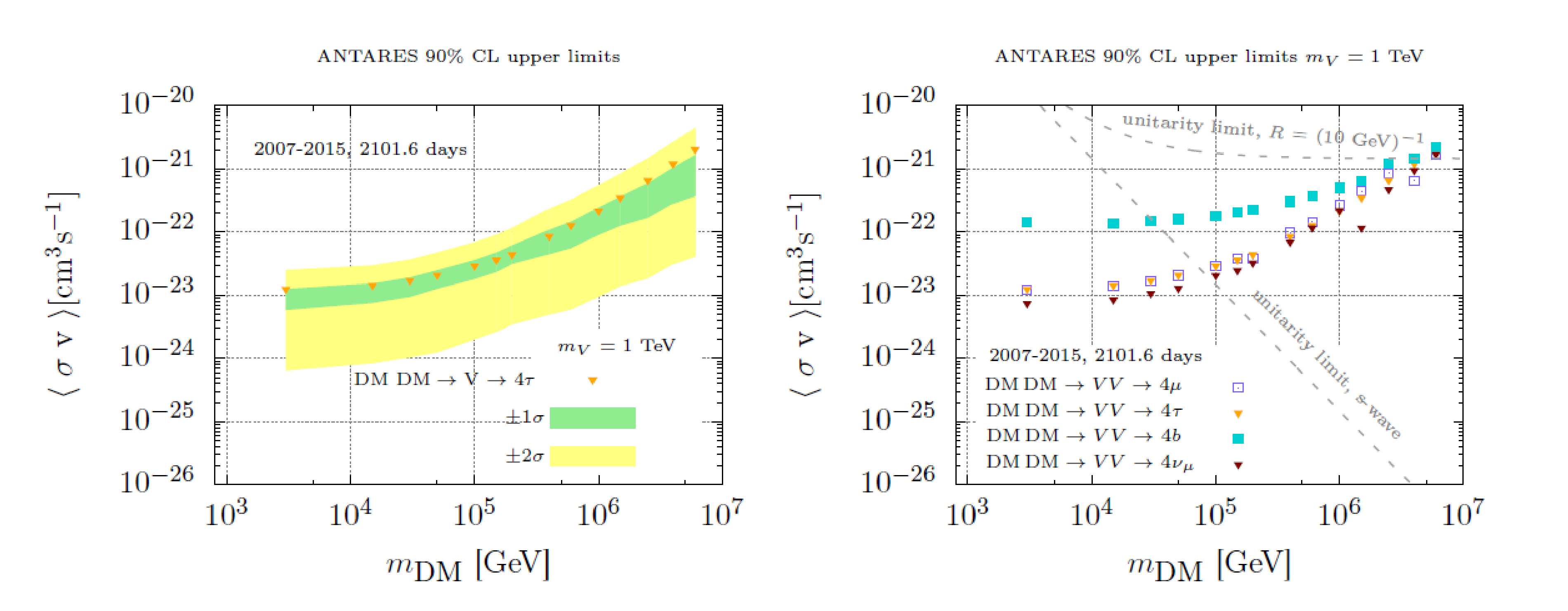


EPJC C85:490 (2025)

GC: Secluded DM

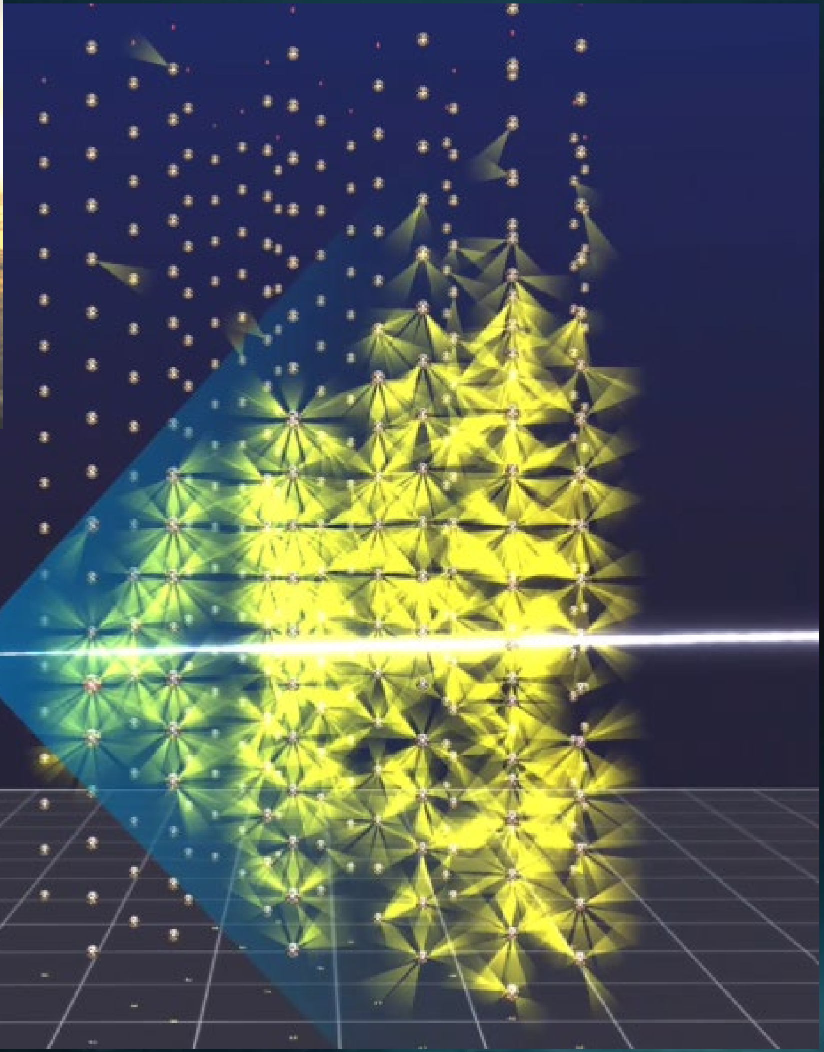
JCAP, 06(2022)028



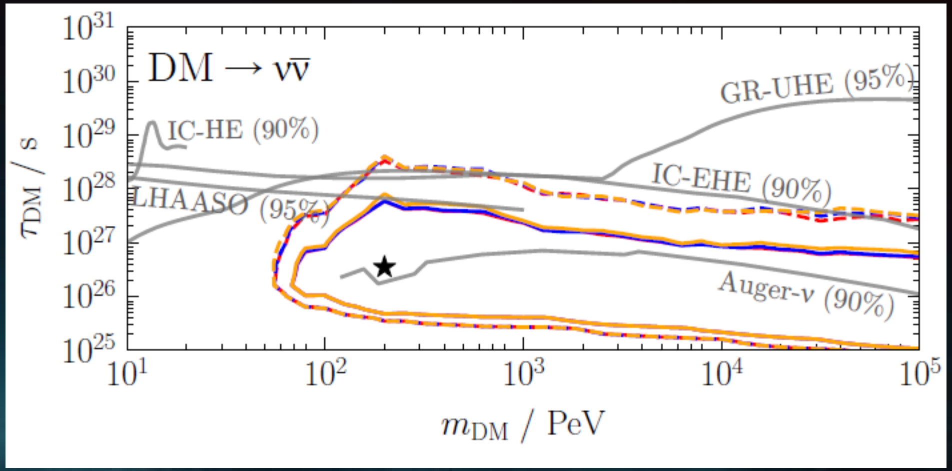


Secluded models are particularly interesting since these models can evade WIMP constraints at ~100 GeV (unitarity limit)

KM3-230213A as heavy DM decay



- On Feb. 13th 2023, ARCA21 observed the highest energy neutrino ever detected (Eμ~120 PeV)
- It can be interpreted as decay of decaying dark matter with mass larger than 10^7 GeV
- Preferred regions in tension with existing limits from other NTs and gamma-ray observatories
- See Alfonso García-Soto's presentation yesterday



Summary

- Neutrino astronomy is an extraordinary tool for both Astroparticle and Particle Physics
- DM is one of the most relevant topics for NTs. IceCube, ANTARES, Baikal and KM3NeT have shown the feasibility of the technique and have produced rich set of results for several sources
- There is complementarity between NTs and other DM searches
  - Sun: large, almost free of astrophysical background and probe of low velocities
  - Galactic Centre: strong limits at large DM masses
  - Models with special DM connections to neutrinos
- Deployment/upgrade of detectors continue (and other new instruments also coming!), along with more data taking
- The quest goes on…

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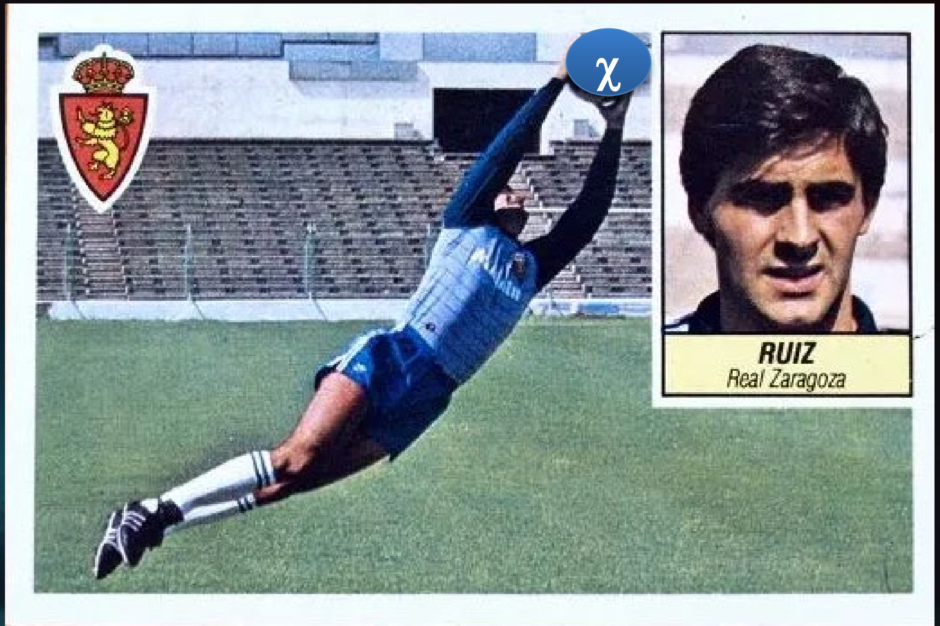
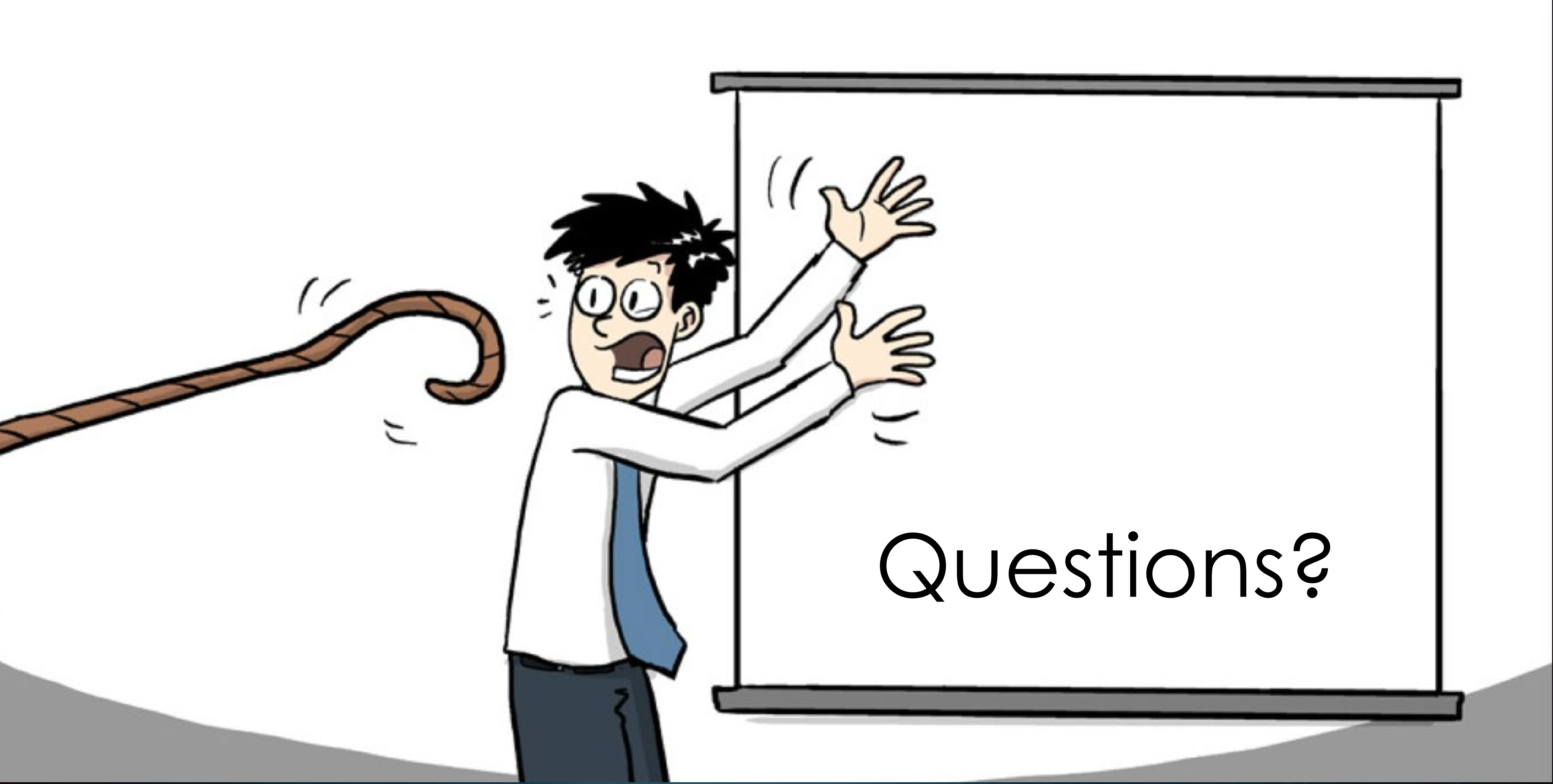
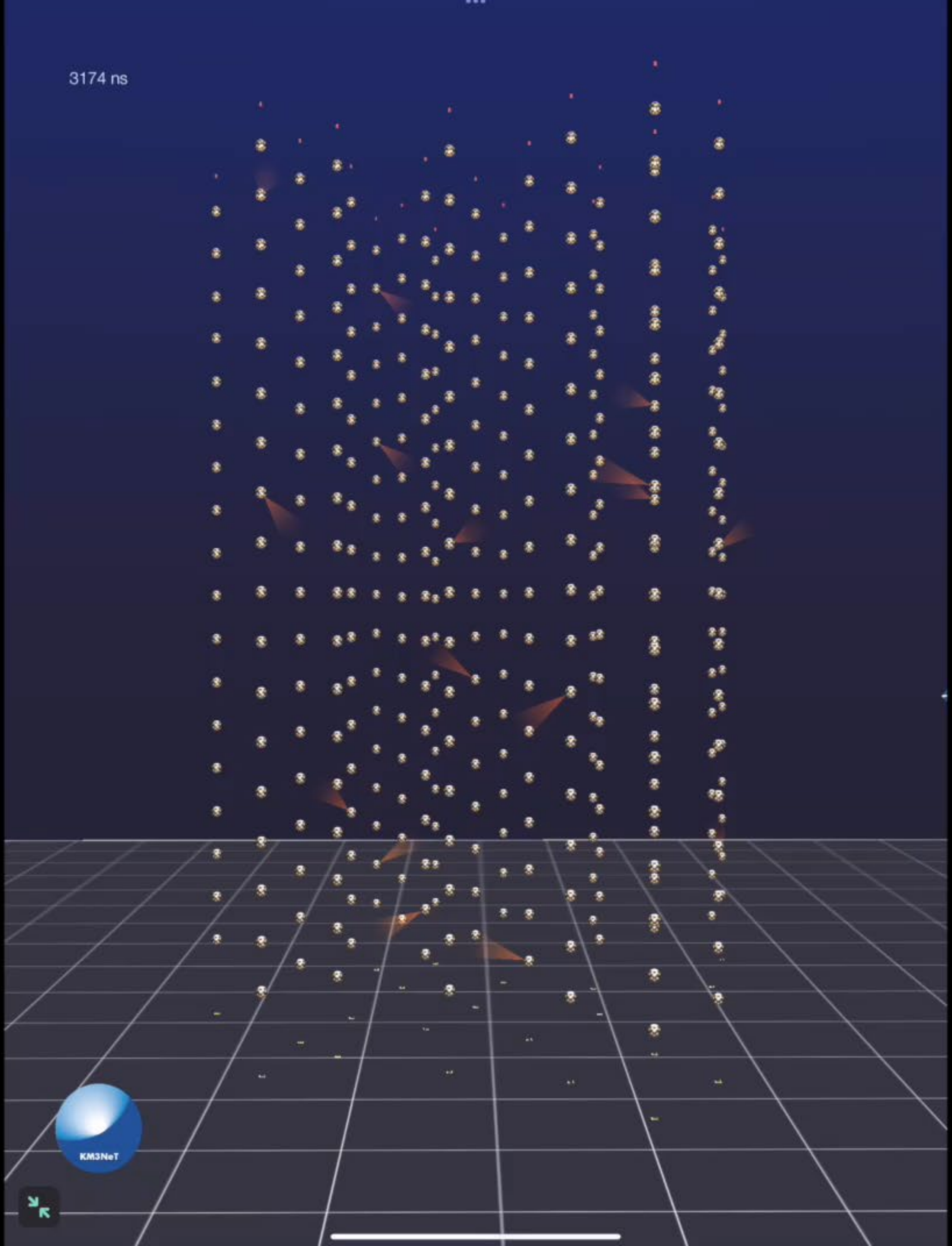
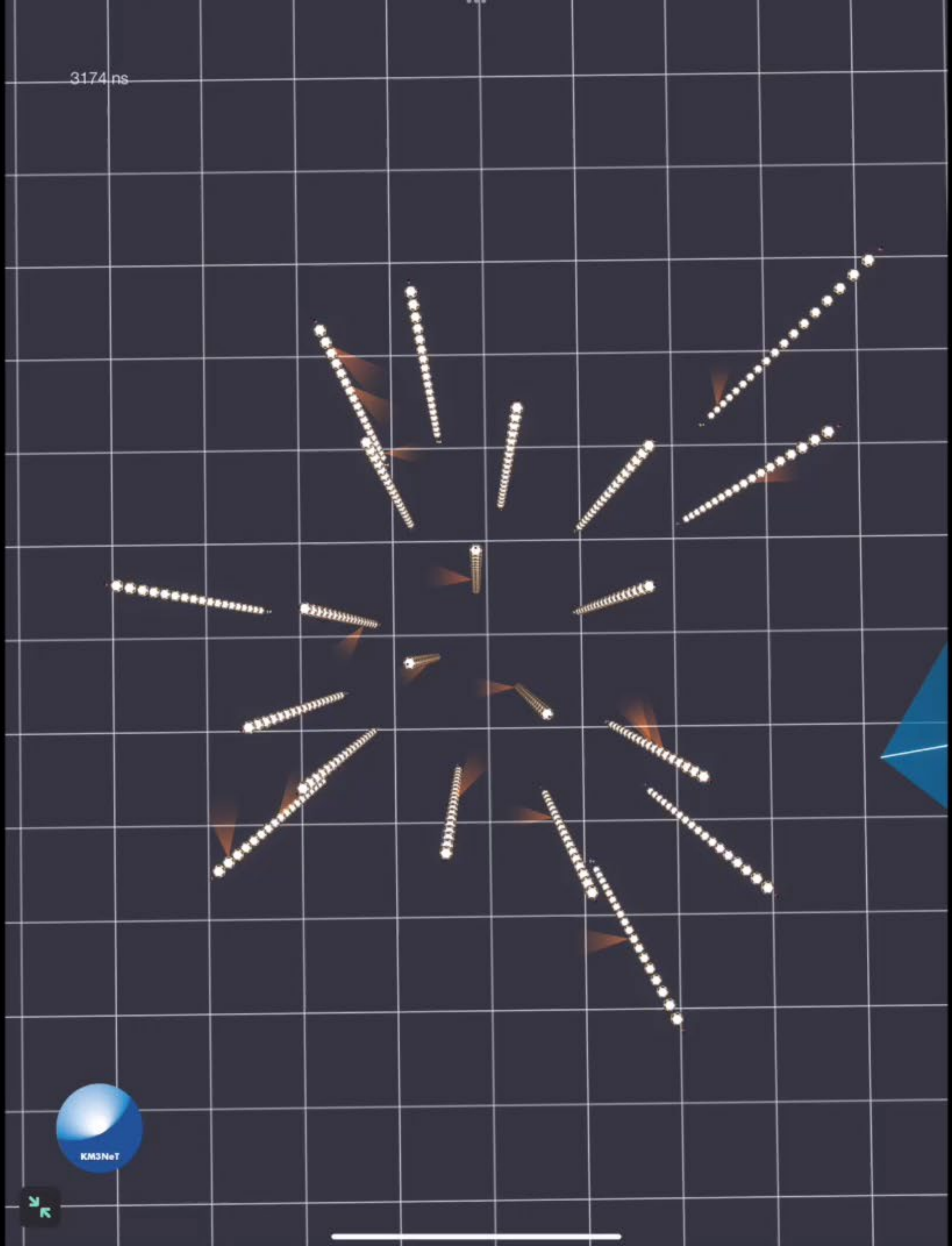
- DM is one of the most relevant topics for NTs. IceCube, ANTARES, Baikal and KM3NeT have shown the feasibility of the technique and have produced rich set of results for several sources
- There is complementarity between NTs and other DM searches
  - Sun: large, almost free of astrophysical background and probe of low velocities
  - Galactic Centre: strong limits at large DM masses
  - Models with special DM connections to neutrinos
- Deployment/upgrade of detectors continue (and other new instruments also coming!), along with more data taking
- The quest goes on…





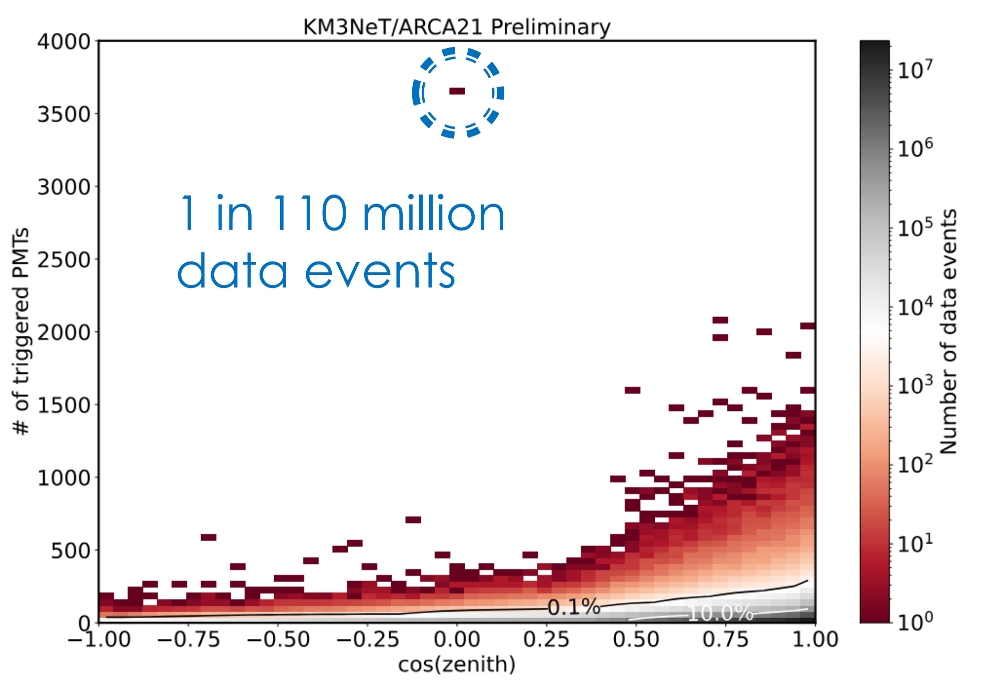
source: https://phdcomics.com/comics.php?f=1553

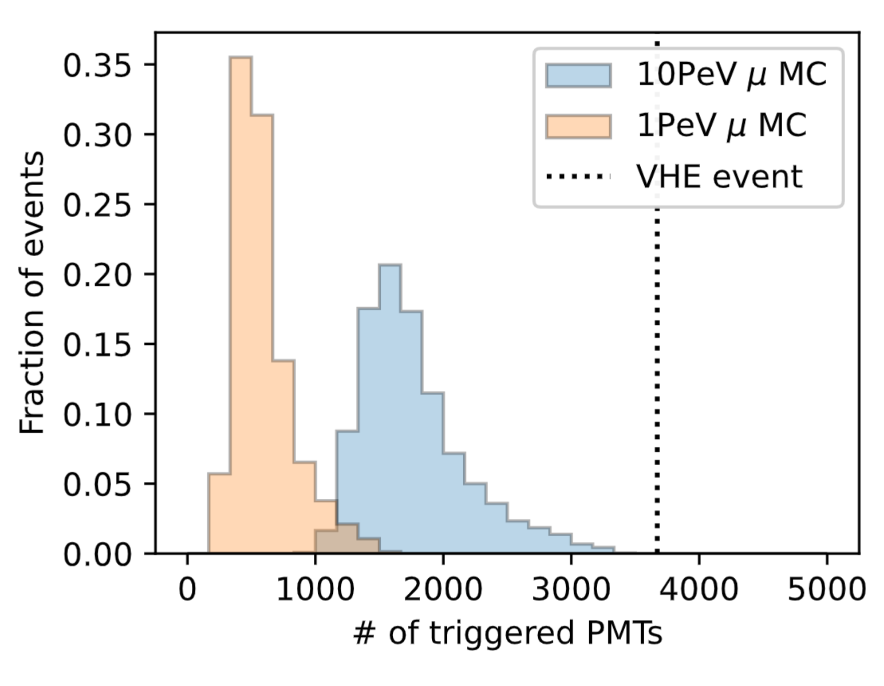
Backup


3174 ns
KM3NeT

3174 ns
KM3NeT

VHE Event

- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV

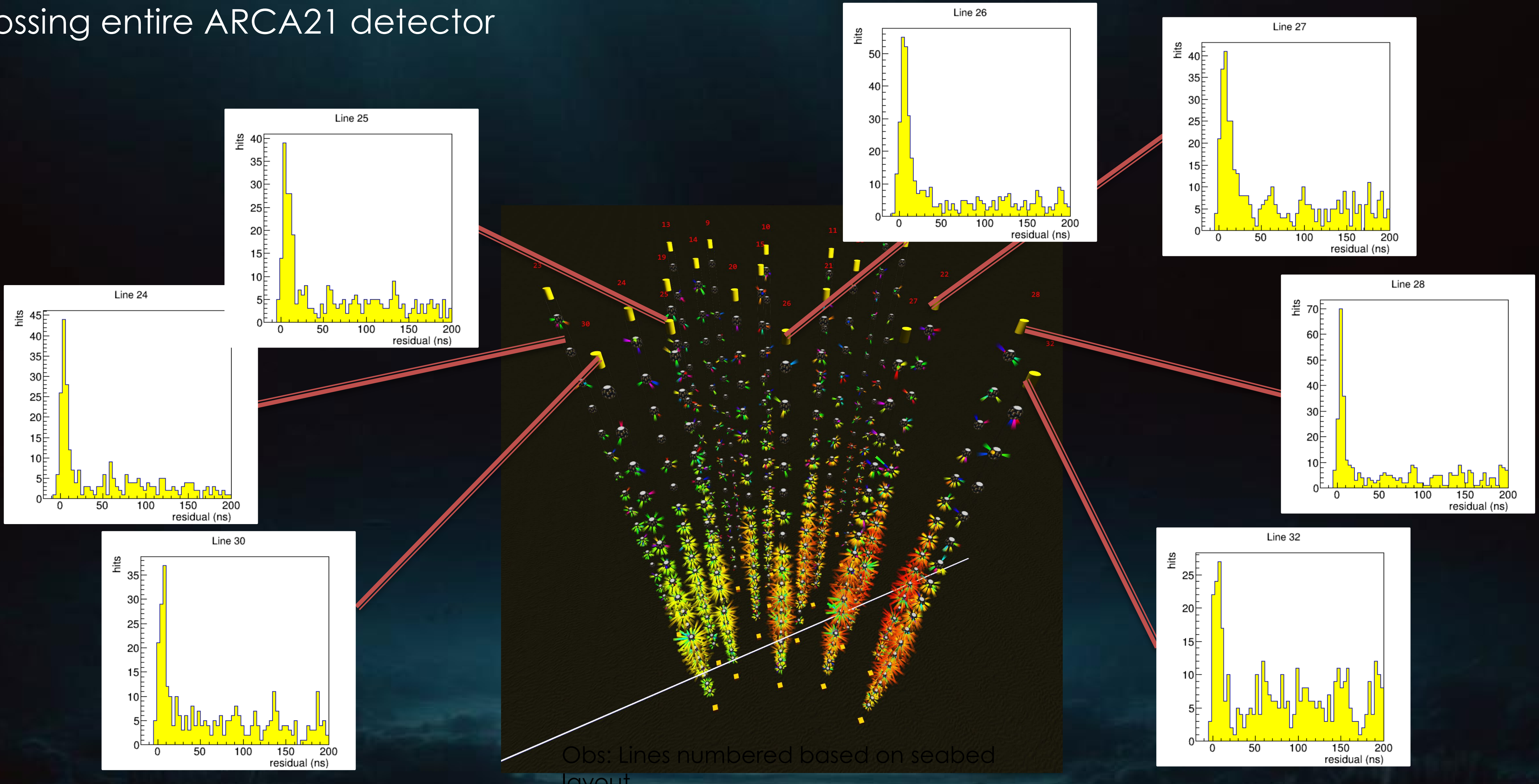




J. Coelho
@Neutrino2024

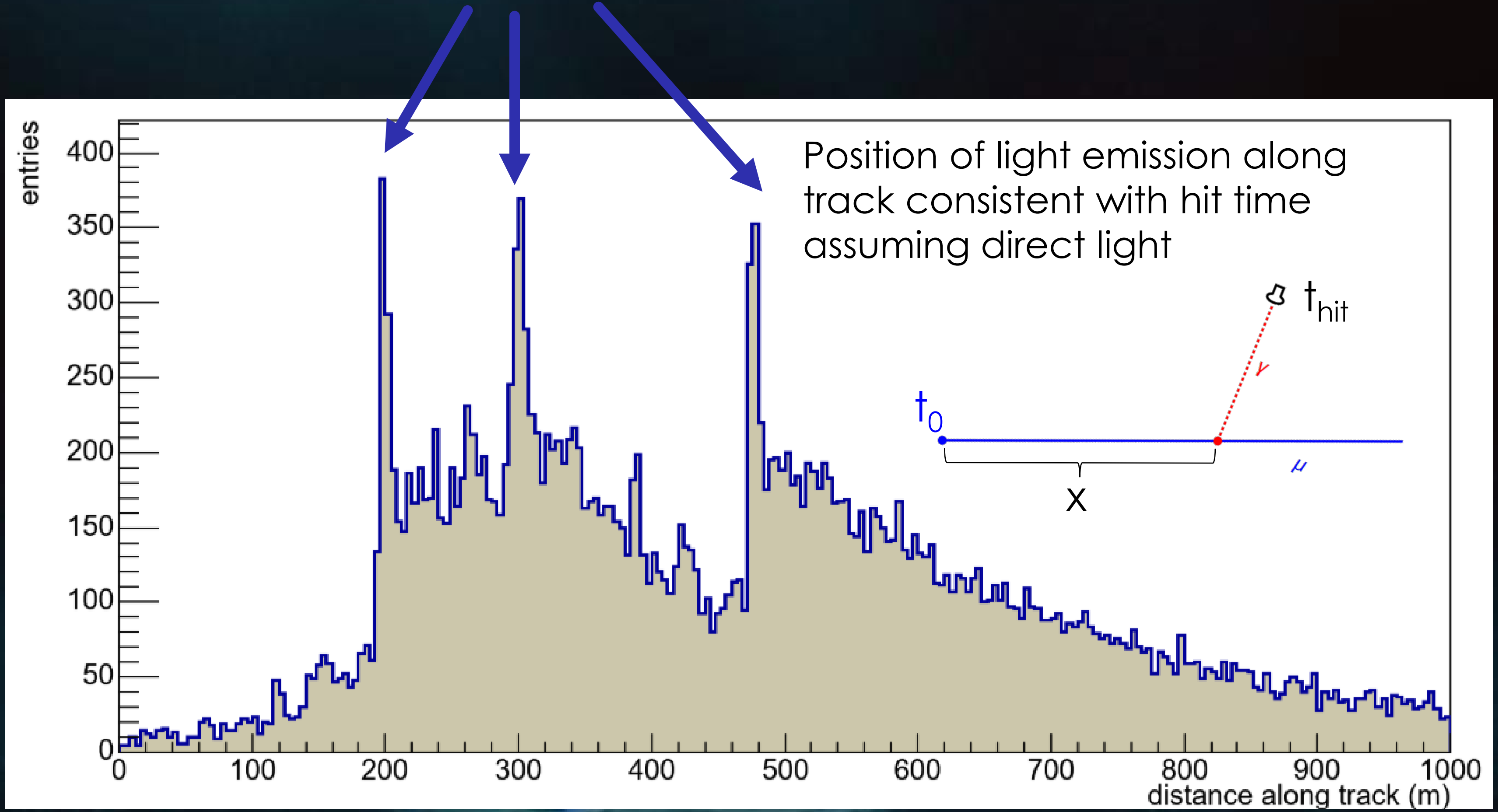
VHE Event

- The event is well reconstructed as a high energy muon crossing entire ARCA21 detector

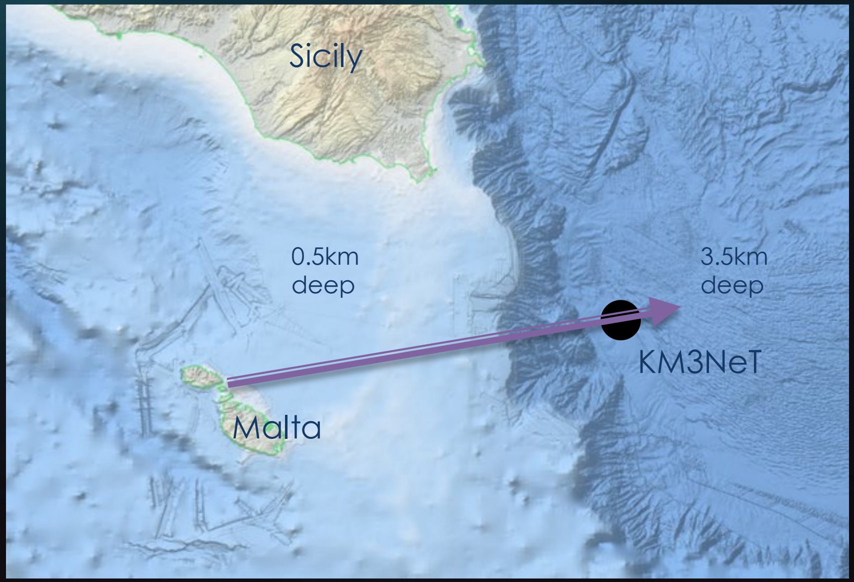


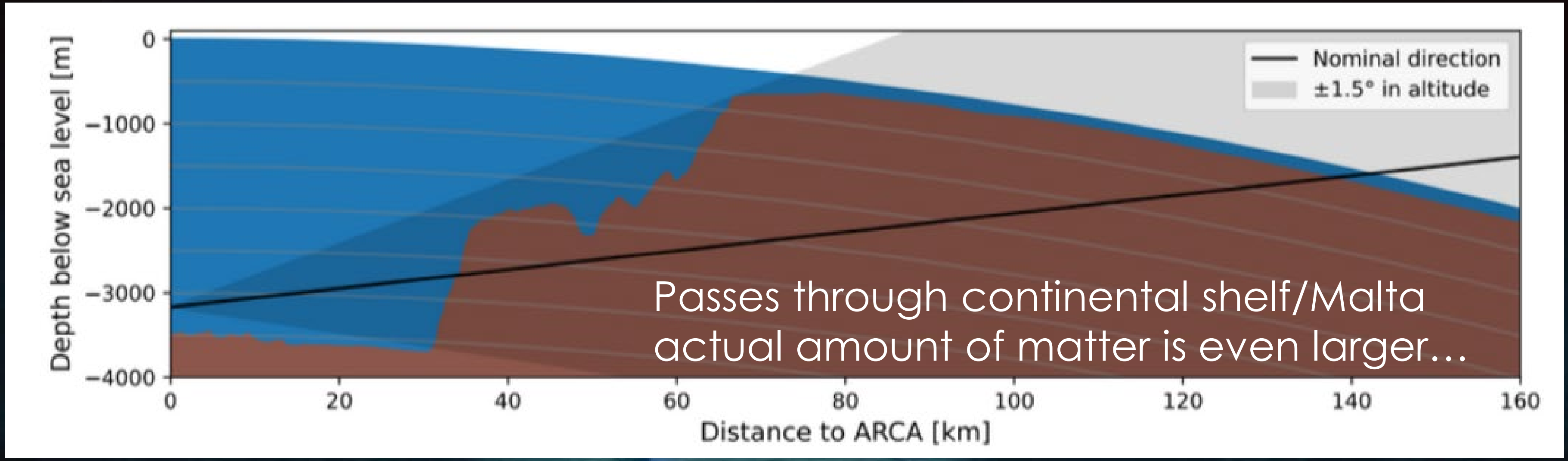
VHE Event

- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons



VHE Event


Sicily
0.5km deep
3.5km deep
KM3NeT
Malta


Nominal direction
±1.5° in altitude
Depth below sea level [m]
0
−1000
−2000
−3000
−4000
0
20
40
60
80
100
120
140
160
Distance to ARCA [km]
Passes through continental shelf/Malta
actual amount of matter is even larger…