XVII Marcel Grossmann Meeting

Pescara, July 7th-12th 2024

Physics beyond the standard model with the ANTARES neutrino telescope

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on behalf of the ANTARES collaboration

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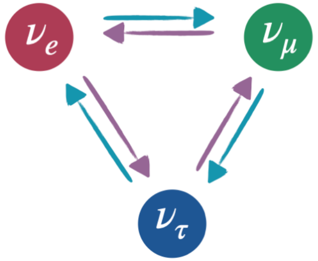
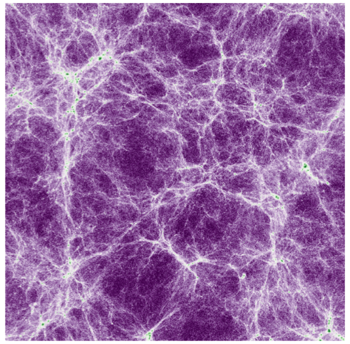
Physics motivations

Supernovae Explosions — **MeV**

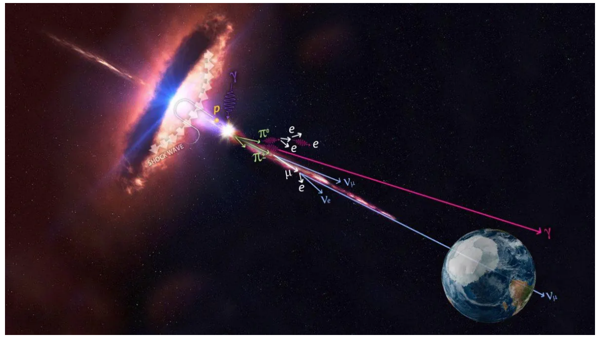
Neutrino Physics — **GeV**



Dark Matter & Exotics searches — **TeV**



Cosmic neutrinos Multi-Messenger program — **PeV**



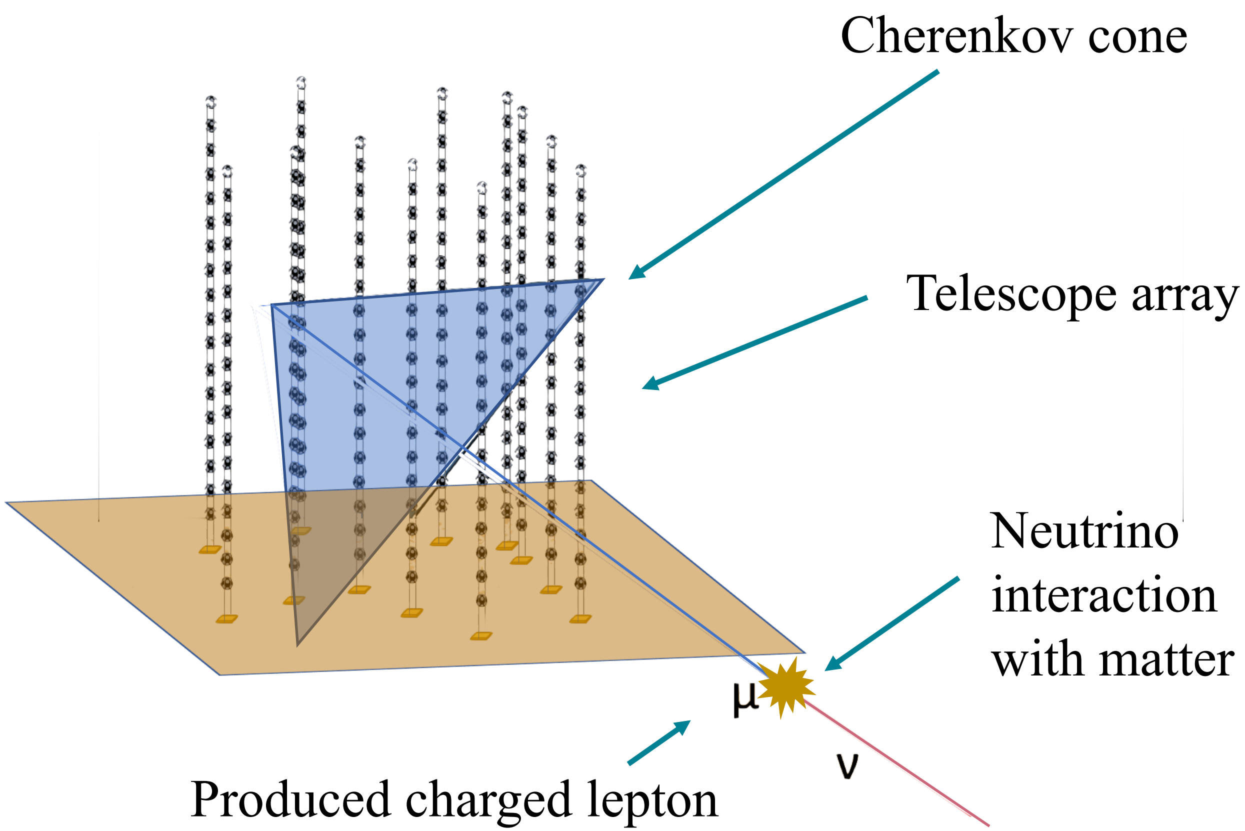
ANTARES

+ Not only physics: Environmental research (Earth & Sea Science).

Characteristics of neutrino telescopes

- Large volume: offers a large number of free target nucleons for neutrino interactions.
- Great depth: provides shielding against secondary particle produced by CRs.
- Transparent medium: allows propagation of Cherenkov photons emitted by relativistic charged particles produced by neutrino interactions

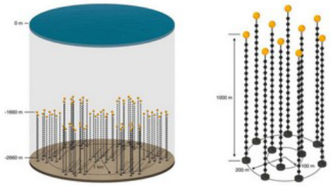
Sensitive from few GeV to few PeV

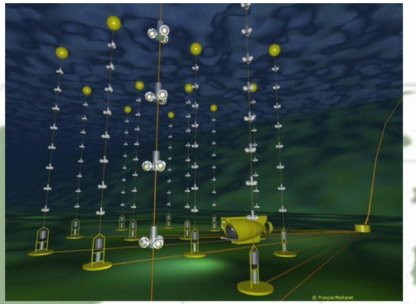


Time and position of photons to reconstruct the Cherenkov cone → neutrino incoming direction

Neutrino telescopes around the world

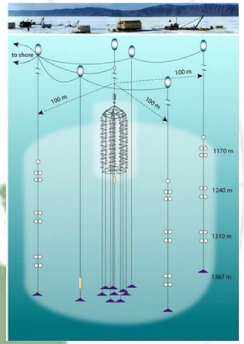
P-ONE
R&D phase



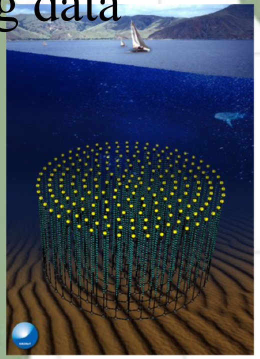


ANTARES , 0.01 km^3
2007 – Feb 2022

Baikal/GVD,
Under construction,
taking data

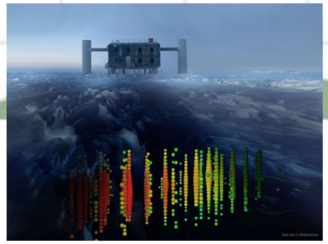


KM3NeT/ORCA,
Under construction,
taking data



KM3NeT/ARCA,
Under construction,
taking data

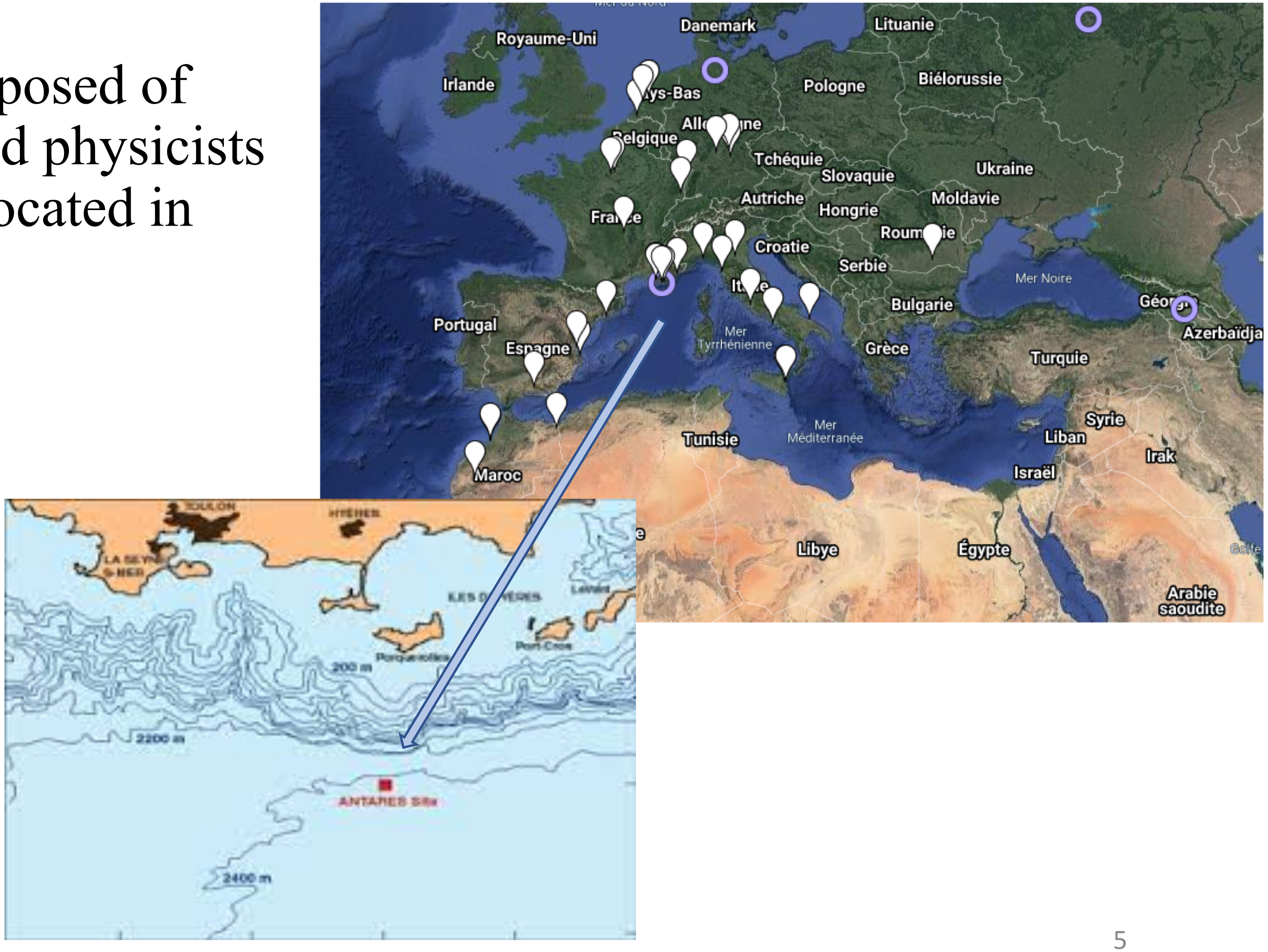
IceCube, 1Km^3



IceCube Gen 2,
Projected

The ANTARES Collaboration

The ANTARES collaboration is composed of around 150 engineers, technicians and physicists from different institutes principally located in Europe.
The collaboration was born in 1997.

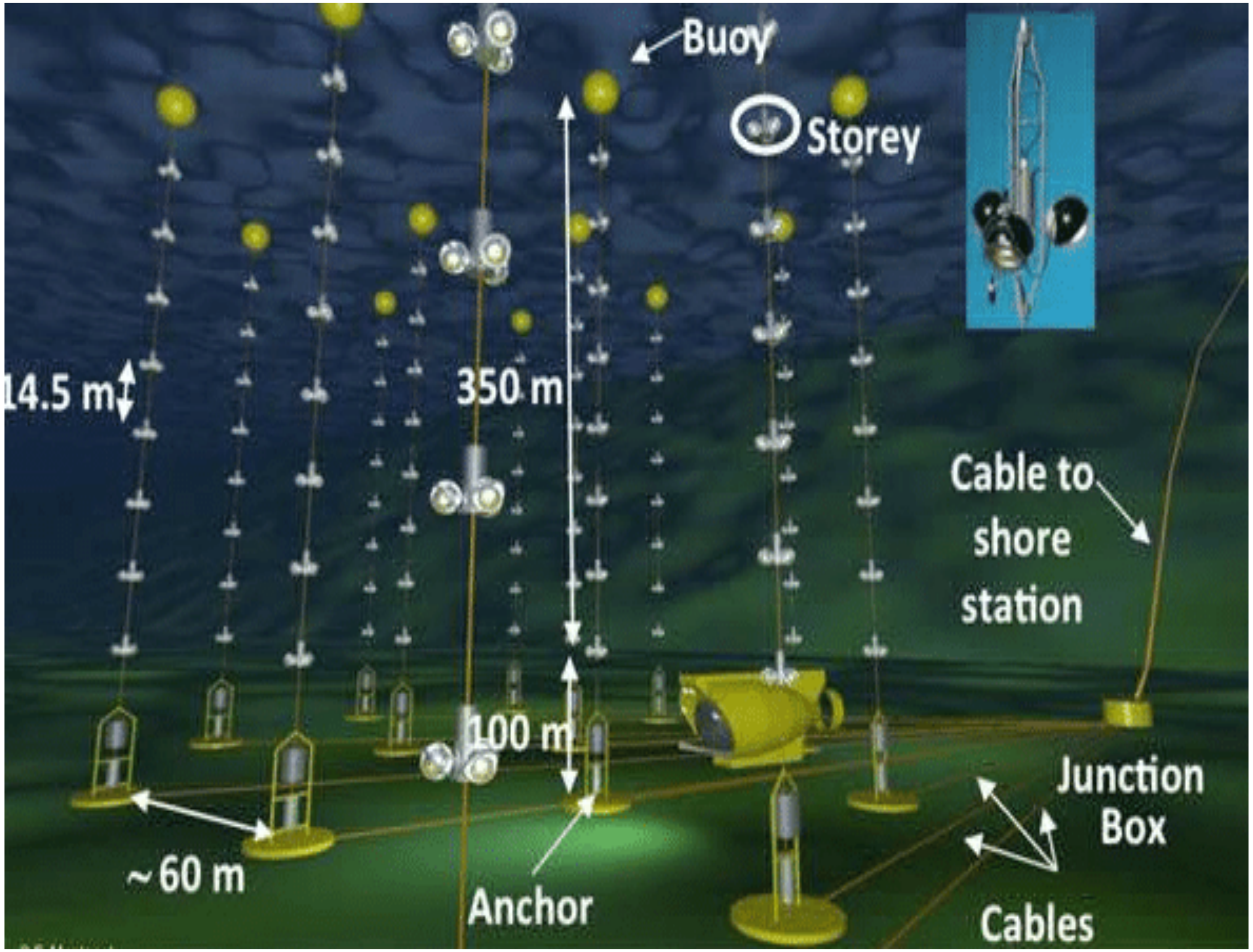


The ANTARES neutrino telescope

- Toulon, France
- ~2500 m depth
- Data taking: 2007-> February 2022💜

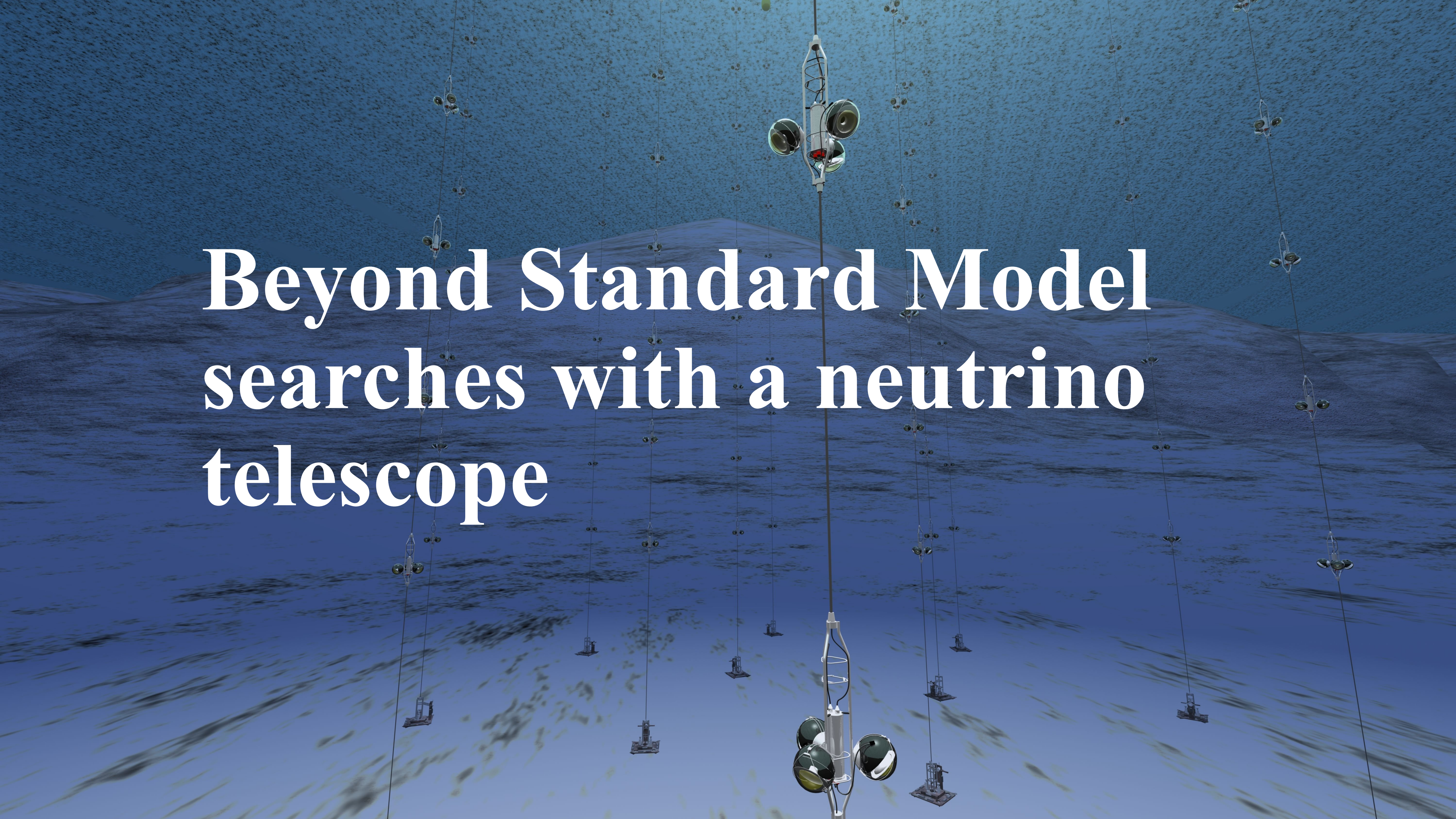
Array infrastructure:

- 12 lines
- 25 storeys (3 OM x storey)
- ~900 PMTs
- Volume = 0.01 km^3



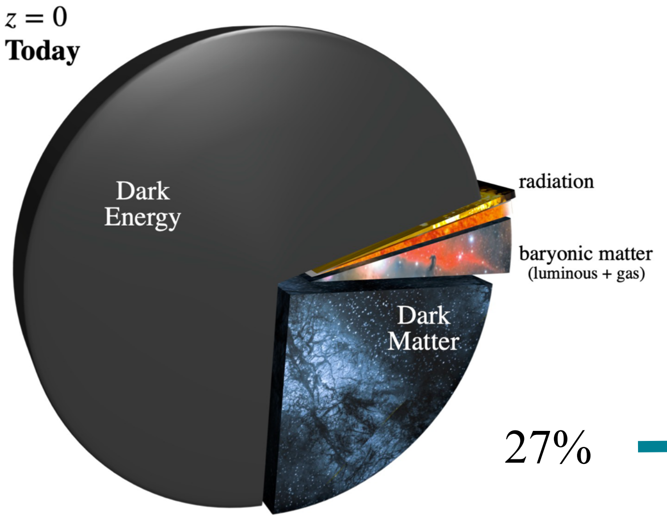
→ > 10000 neutrinos recorded

→ ~100 publications in the field of neutrino physics and astrophysics



Beyond Standard Model searches with a neutrino telescope

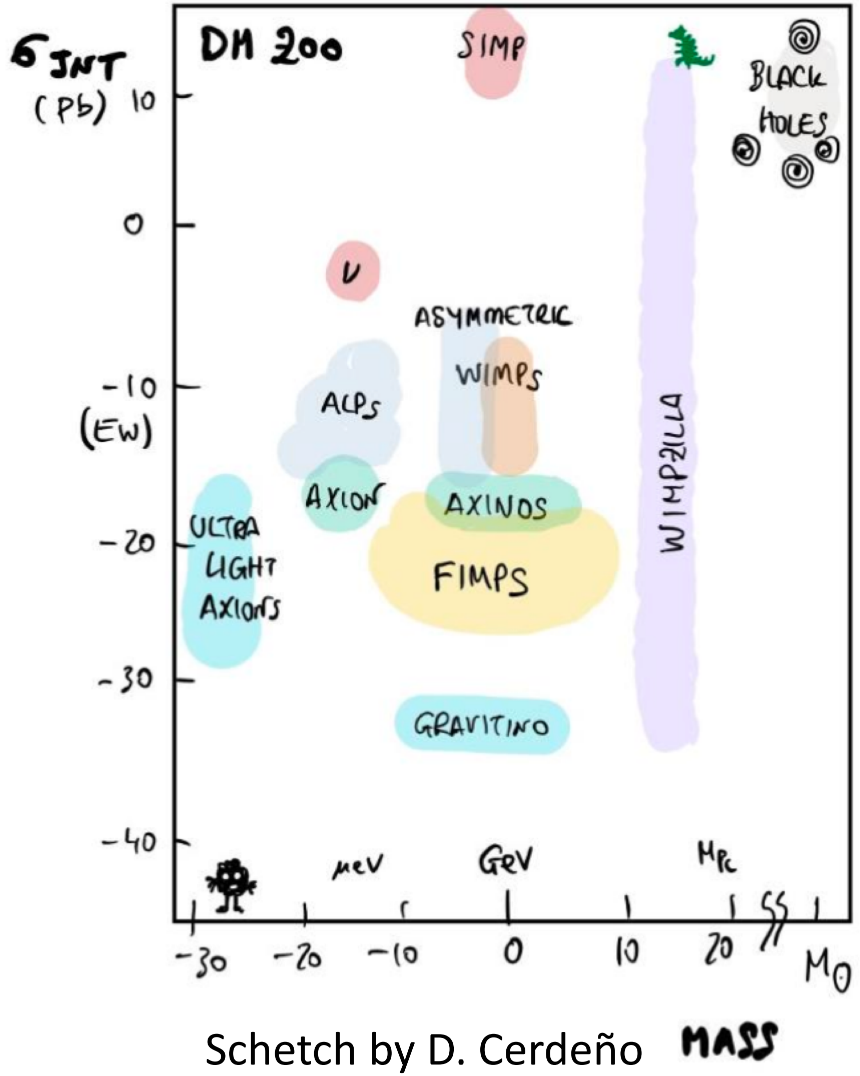
Beyond standard model: dark matter



27% → New elementary particle?

- In the early Universe they were in thermal equilibrium with the ordinary matter plasma
- Electrically neutral
- Very weakly interactions with ordinary matter
- Stable on cosmological scales
- Non-relativistic

} WIMP-like particle



Schetch by D. Cerdeño

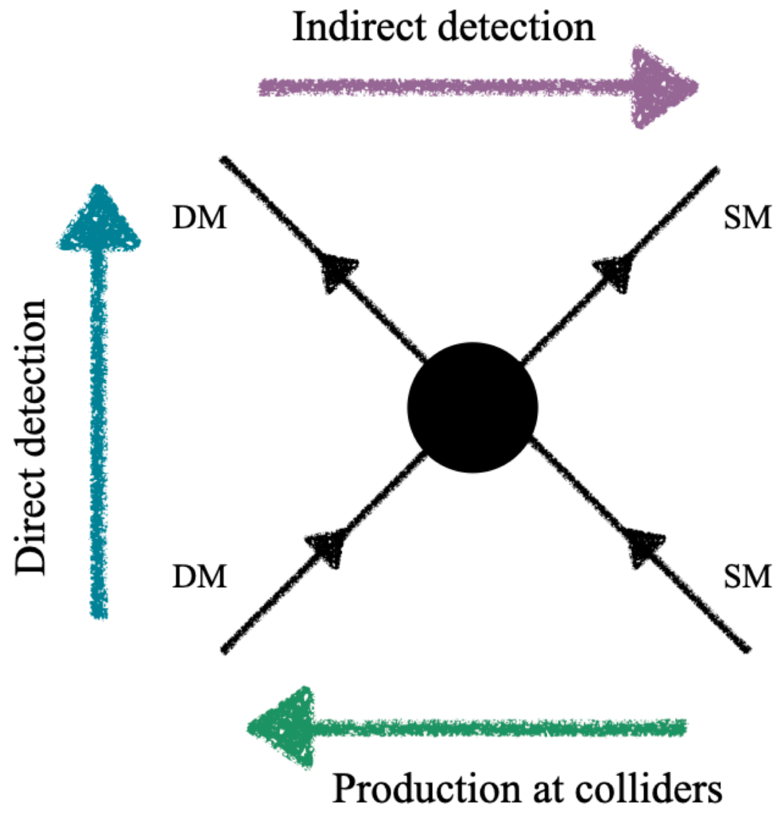
Dark matter searches with a neutrino telescope

Neutrinos give:

- Directional information
- Spectral information
- Propagation unaffected by absorption, nor deflection

But

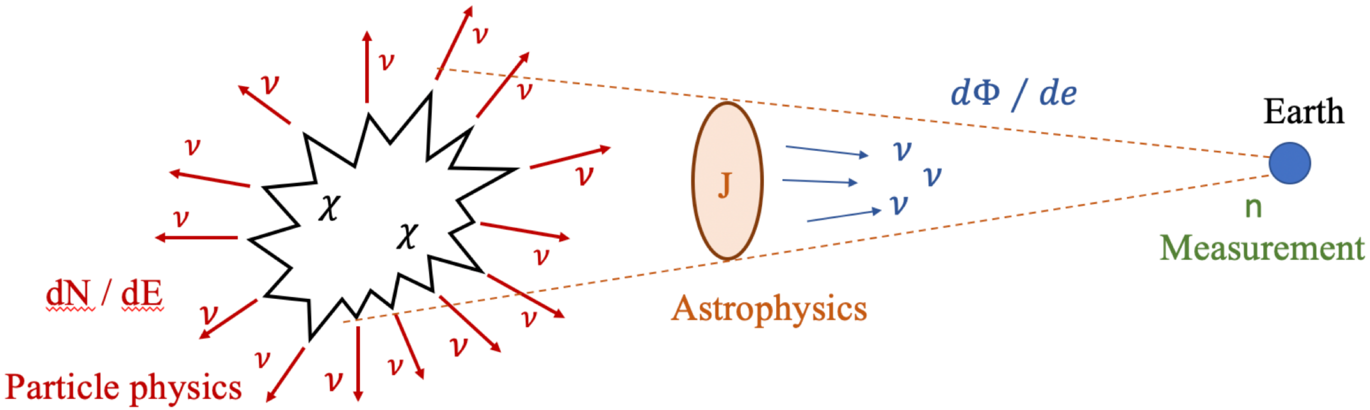
- The method is subject to astrophysical uncertainties
- Sensitive to scattering or annihilation cross sections depending on the object being analysed



Possible candidate sources: *Sun, Galactic Center, Earth,* Dwarf Spheroidal Galaxies

Dark matter searches in the Galactic Center

Dark matter searches from Galactic centre



$$J = \int_{\Omega} d\,\Omega \int_{l.o.s.} \rho^2\, ds$$

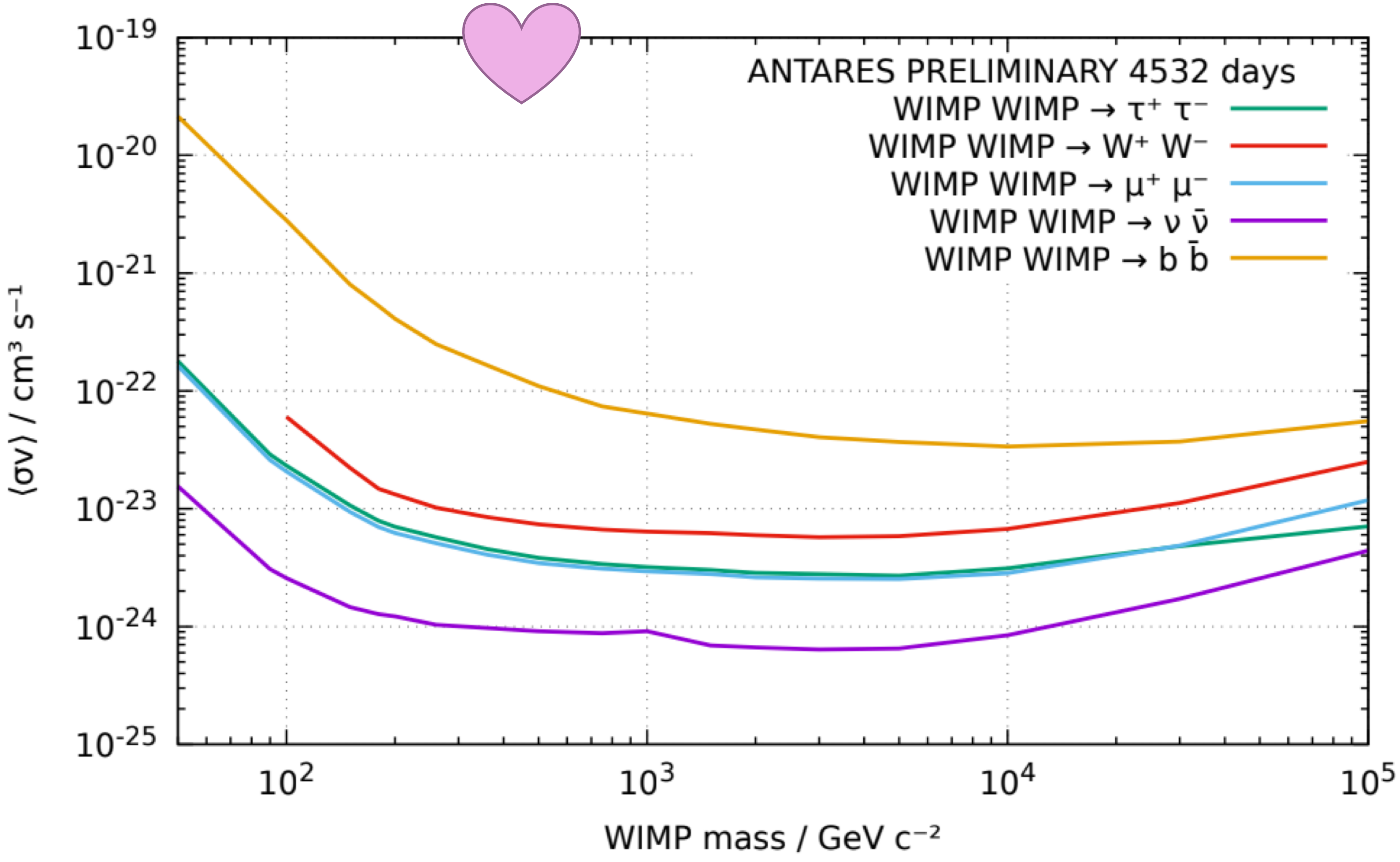
J factor,
depending on the density model

$$\phi = \frac{n}{A(M_\chi)t} = \frac{1}{4\,\pi}\frac{1}{M_\chi^2}\frac{\langle\sigma v\rangle}{2}\int_0^M \frac{dN}{dE}\,dE\; J$$

Flux = number of observed events / Acceptance * lifetime = annihilation rate * average number of particle per collision * source geometry

Dark matter searches from Galactic centre

- Limits on $< \sigma v >$ from WIMP annihilation in galactic center
- ANTARES **2007-2022**, 4532 days
- 11850 tracks, 235 showers
- Assuming NFW halo profile with 100% branching ratio for each annihilation channel



PoS ICRC 2023 (1375)

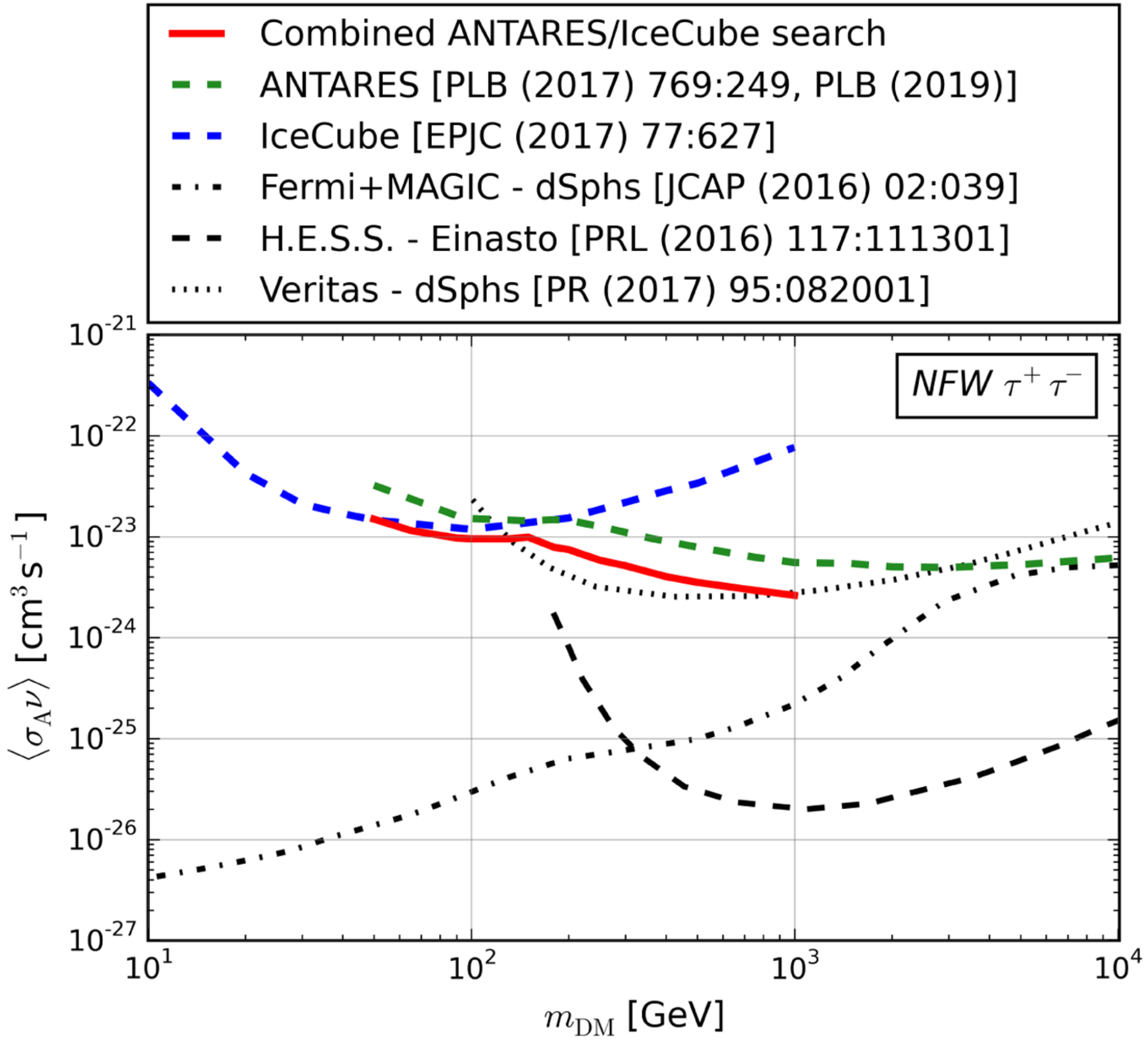
Multiple-experiment combination

ANTARES and IceCube have conducted a combined-likelihood search for dark matter searches from the Galactic Center

Limits for NFW, tau channel

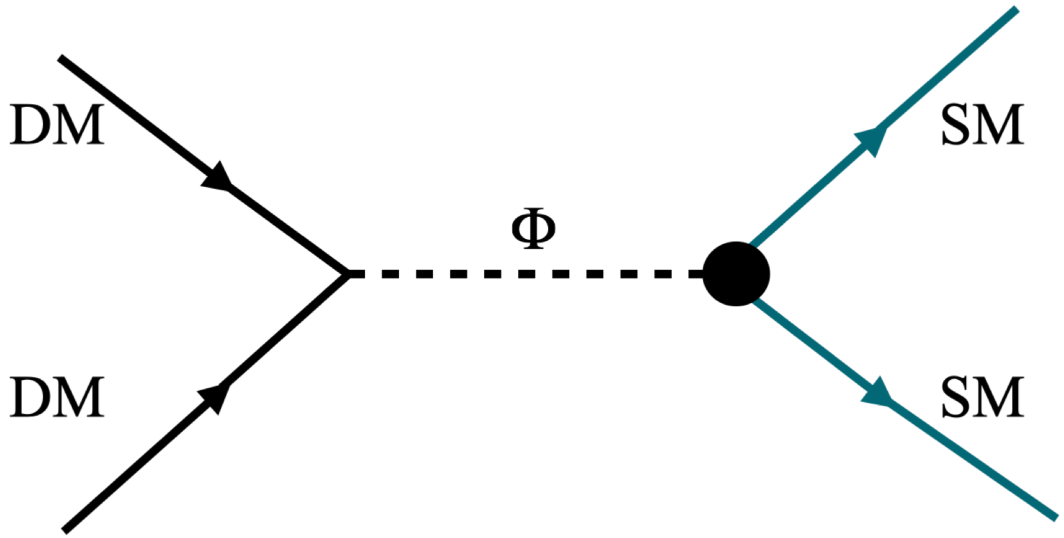
ANTARES 2101.6 days
IceCube 1007 days

[Phys. Rev. D 102, 082002 (2020)]



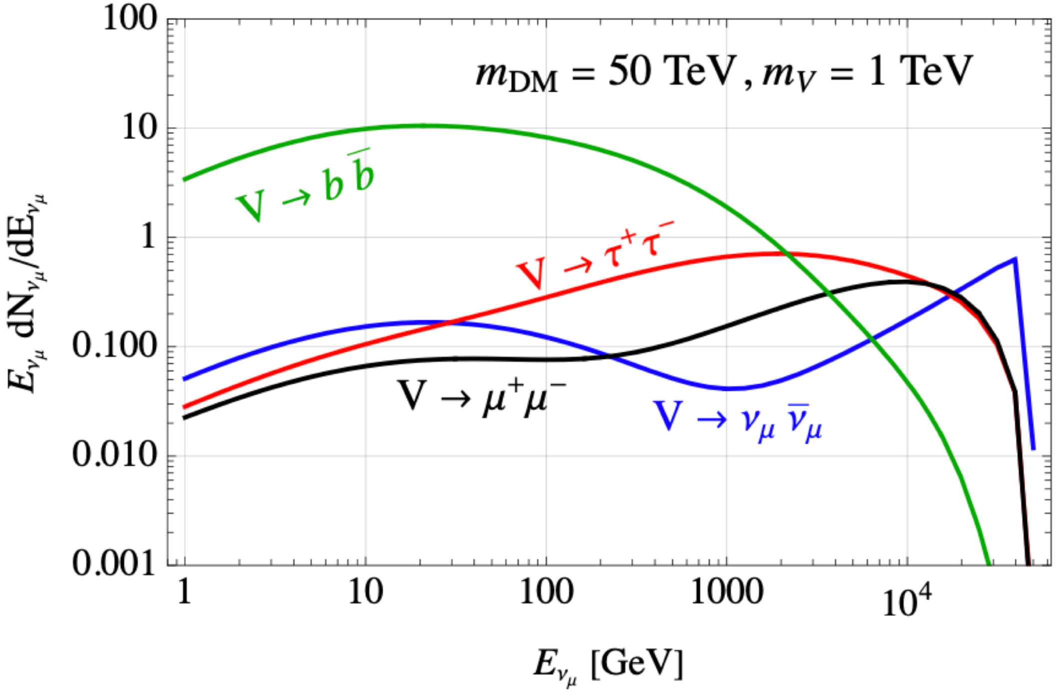
Secluded dark matter

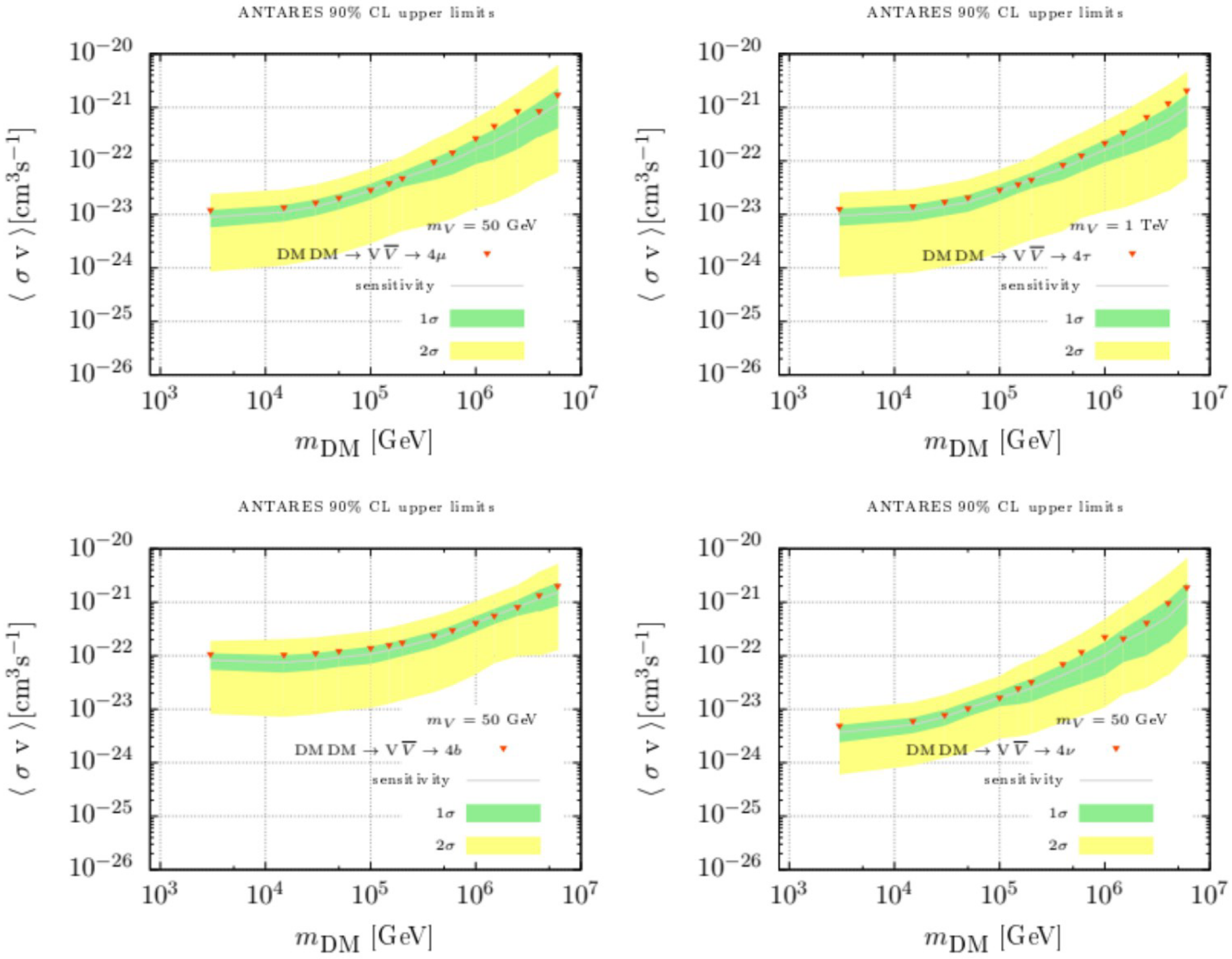
- Since WIMP models has not provide results
- New models, according to the searches at colliders, can be investigated
  - Modified cosmological evolution: Universe at freeze-out is smaller
  - Same amount of dark matter but more diluted
  - Dark matter decay by a mediator
  - The cross section is smaller and the dark matter is heavier



Secluded dark matter: from the Galactic Center

ANTARES 2007 -2015

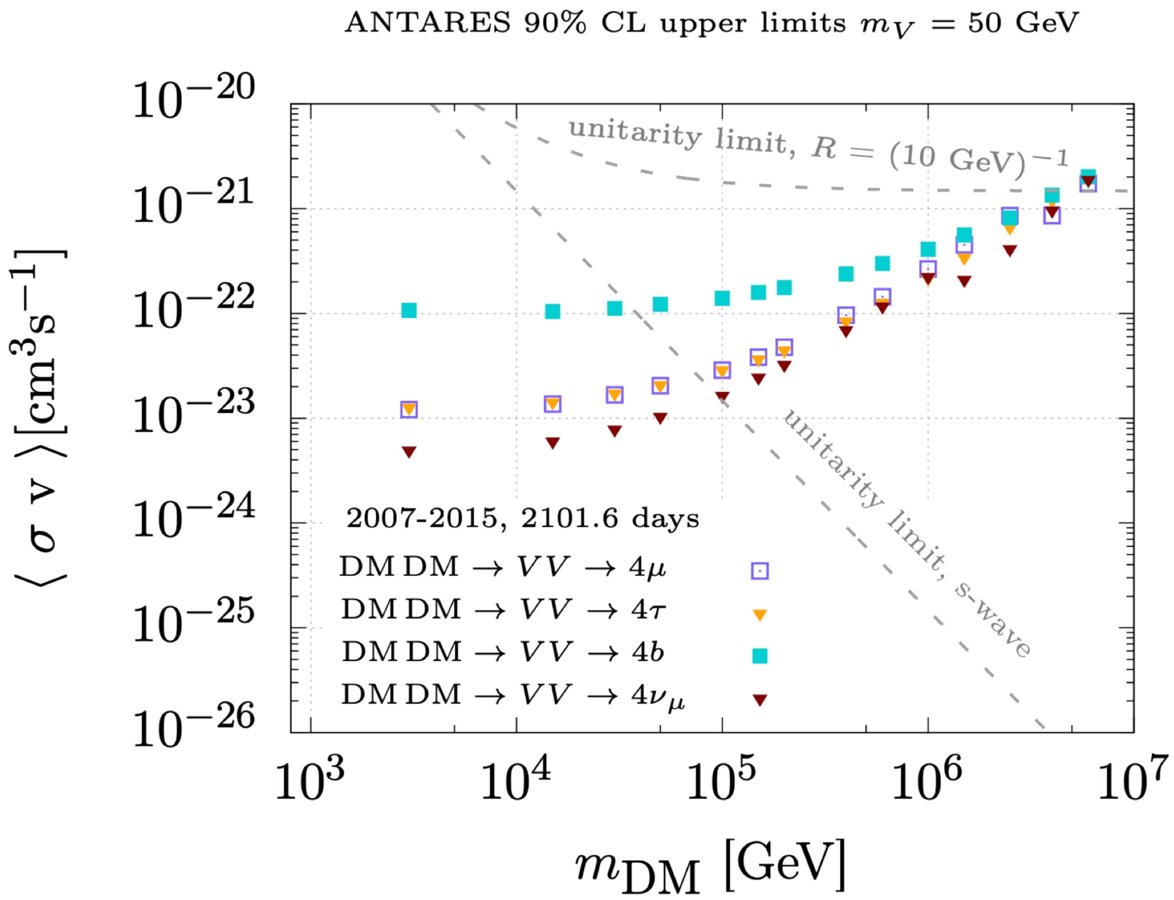


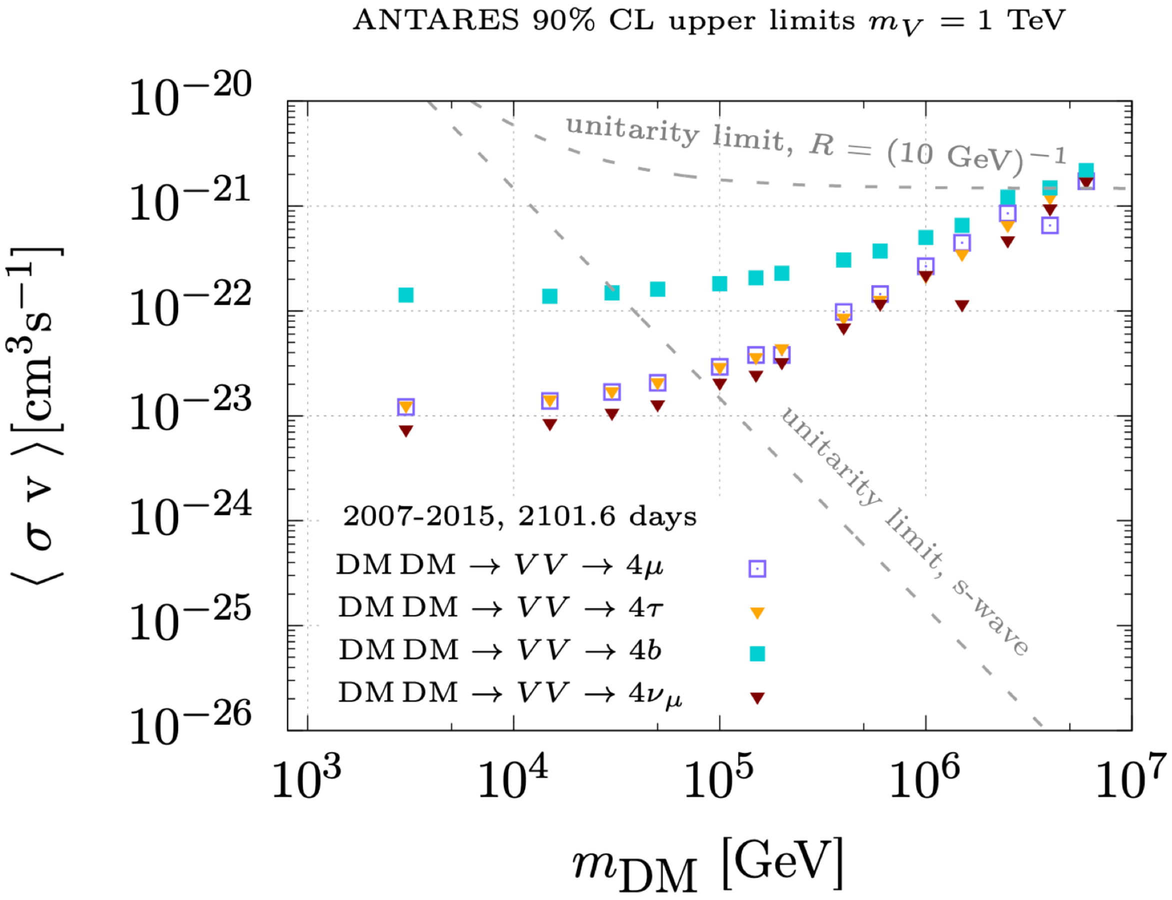


JCAP06(2022)028

Secluded dark matter: from the Galactic Center

ANTARES 2007 -2015



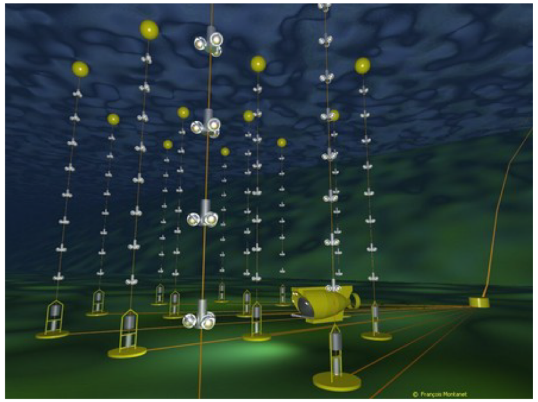


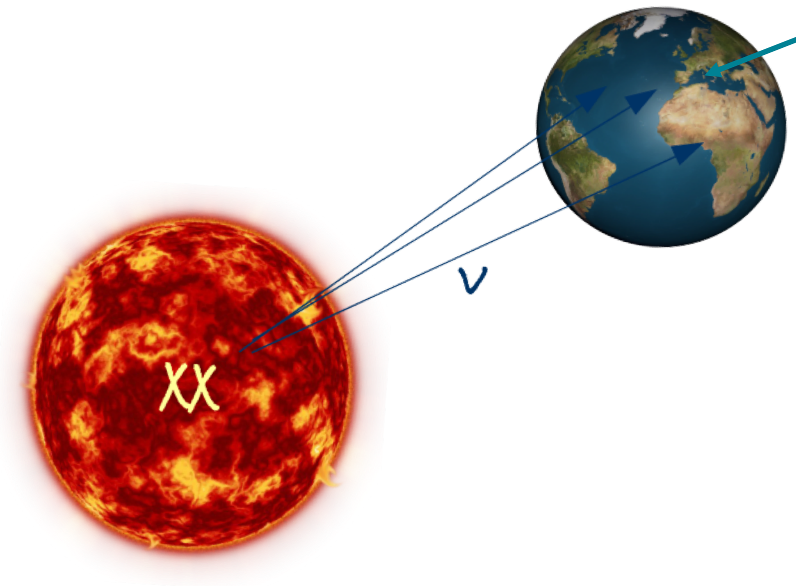
JCAP06(2022)028

Dark matter searches towards the Sun

Dark matter towards the Sun using neutrinos

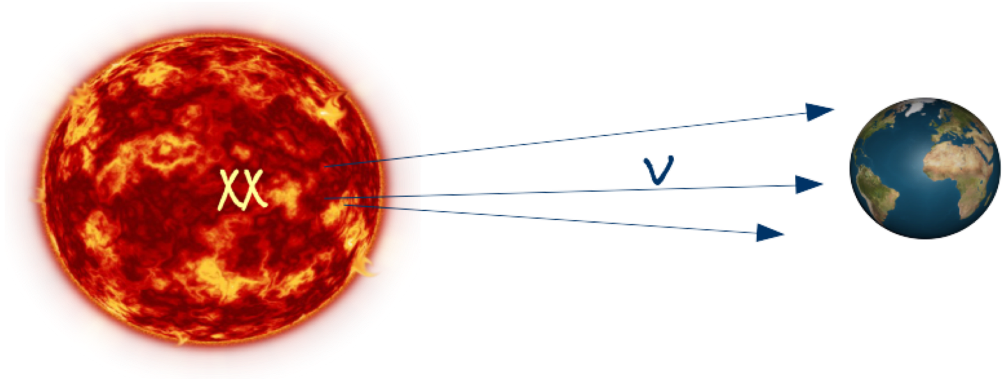
- Neutrinos and anti-neutrinos, all flavours, with energy < few TeV
- Neutrinos are detected through Cherenkov light emitted by the products (relativistic charged particles) of the neutrino interaction





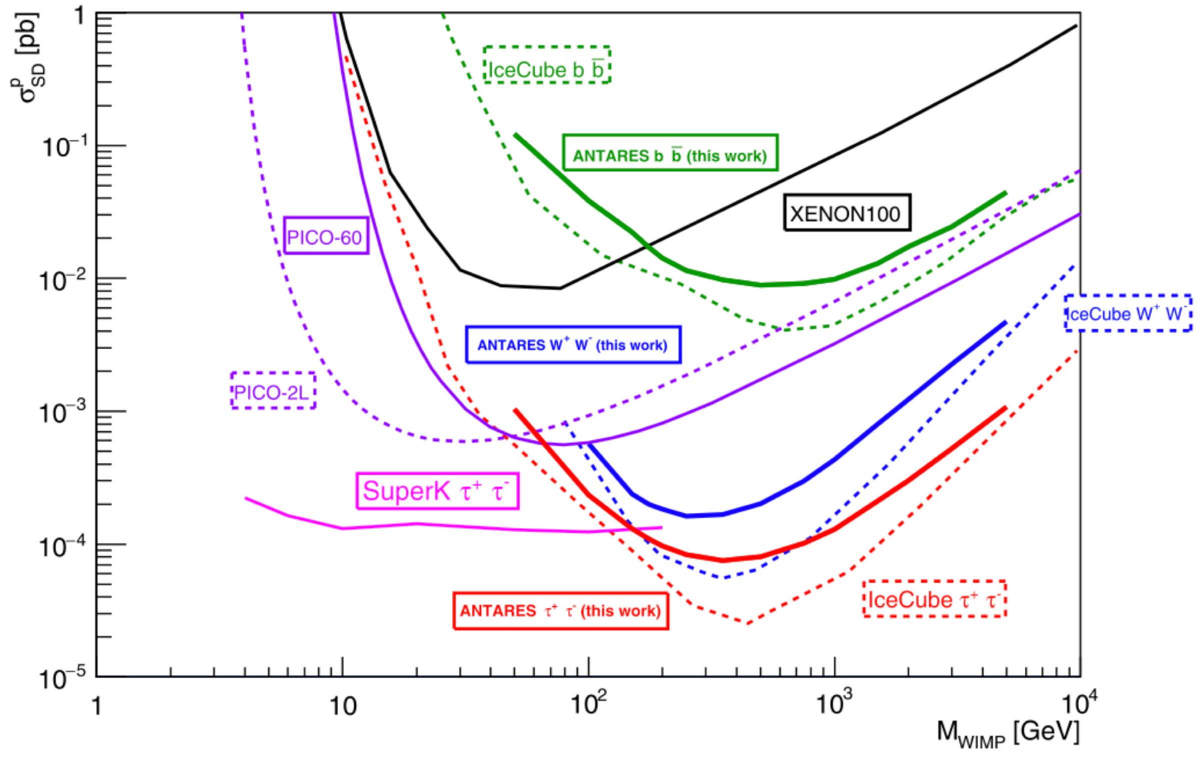
- DM can be captured by massive bodies, such as the Sun
- Inside these bodies, DM can annihilate into Standard Model particles
- These SM particles yield neutrinos

Dark matter towards the Sun



- Differential neutrino flux related to the annihilation rate $\frac{d\Phi}{dE_\nu} = \frac{\Gamma}{4\pi d^2}\frac{dN_\nu}{dE_\nu}$
- In equilibrium between capture and annihilation $\Gamma = C/2$ where C is the capture rate
- Neutrino flux is sensitive to DM-nucleon scattering cross-section, both spin-dependent and spin-independent
- Negligible Astrophysical background:
  Very clean signal → DM interpretation

Dark matter towards the Sun



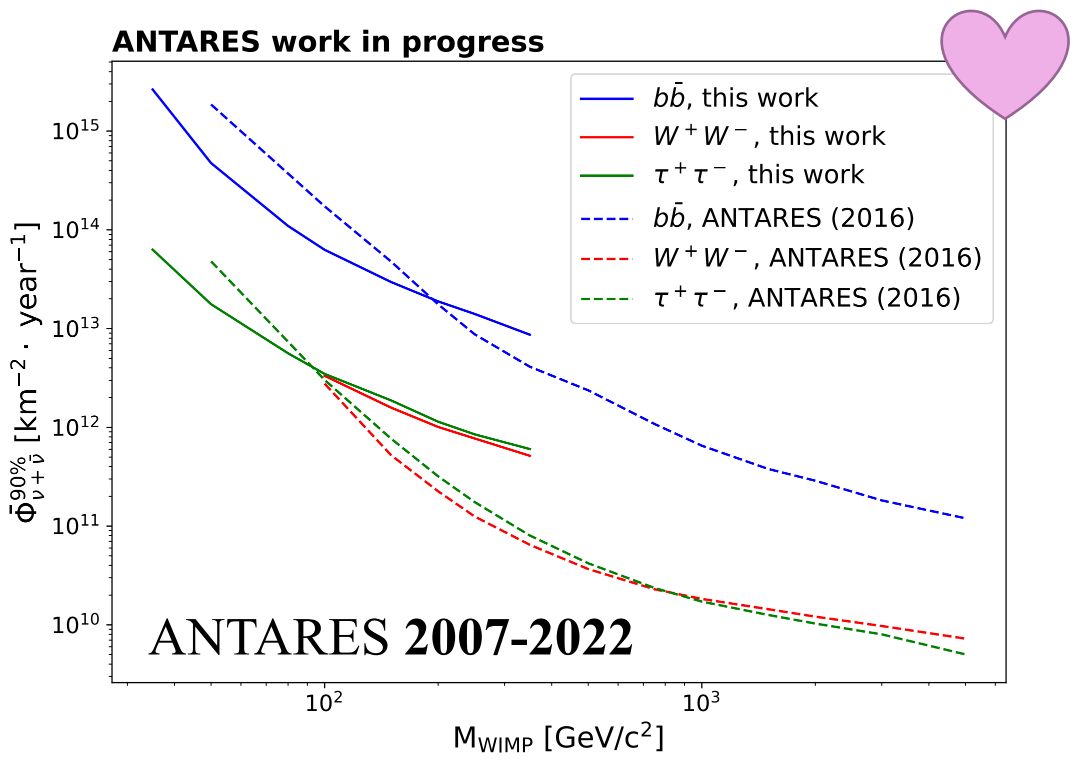
[Physics Letters B 759 (2016) 69–74](#)

ANTARES 2007-2012

Annihilation channels: $b\bar{b}$, W^+W^- , $\tau^+\tau^-$

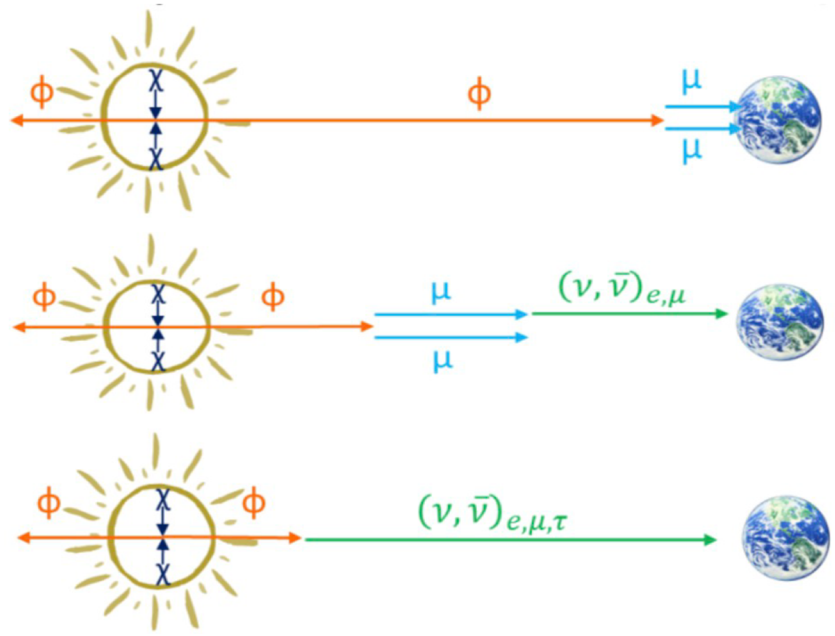
New work in progress!

Presented at Neutrino2024

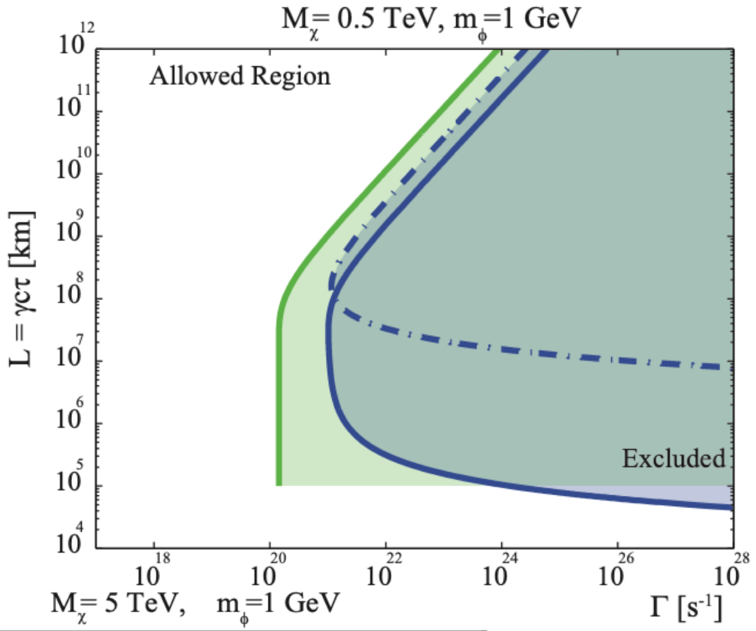


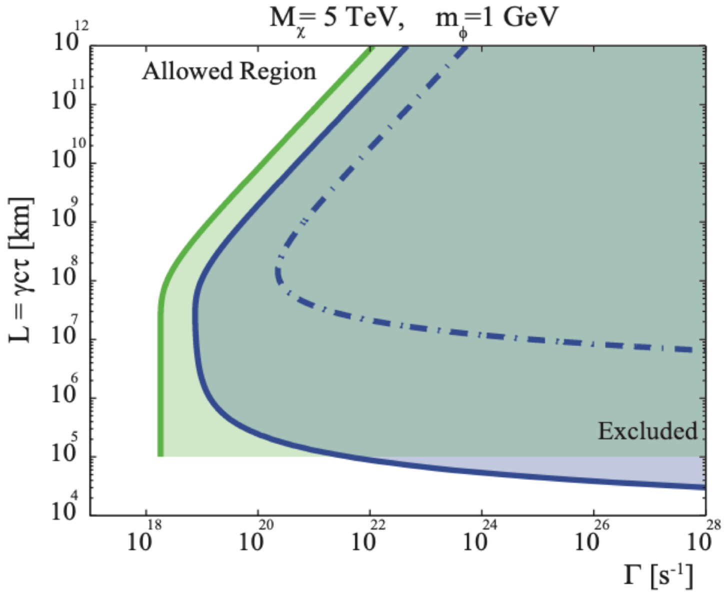
Secluded dark matter: towards the Sun

Assuming that DM can be annihilated through a mediator that has a long lifetime, three different situations have been considered:



Limits depending on the lifetime of the mediator and the dark matter mass



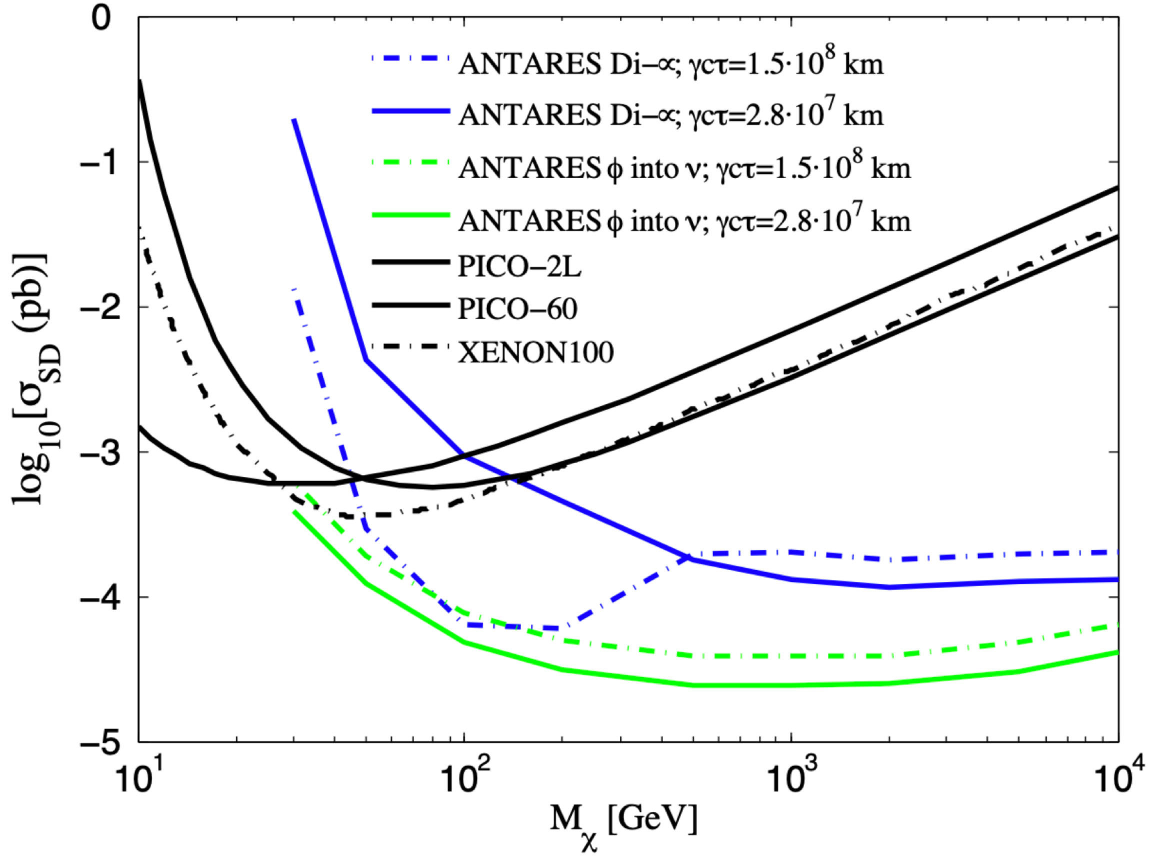


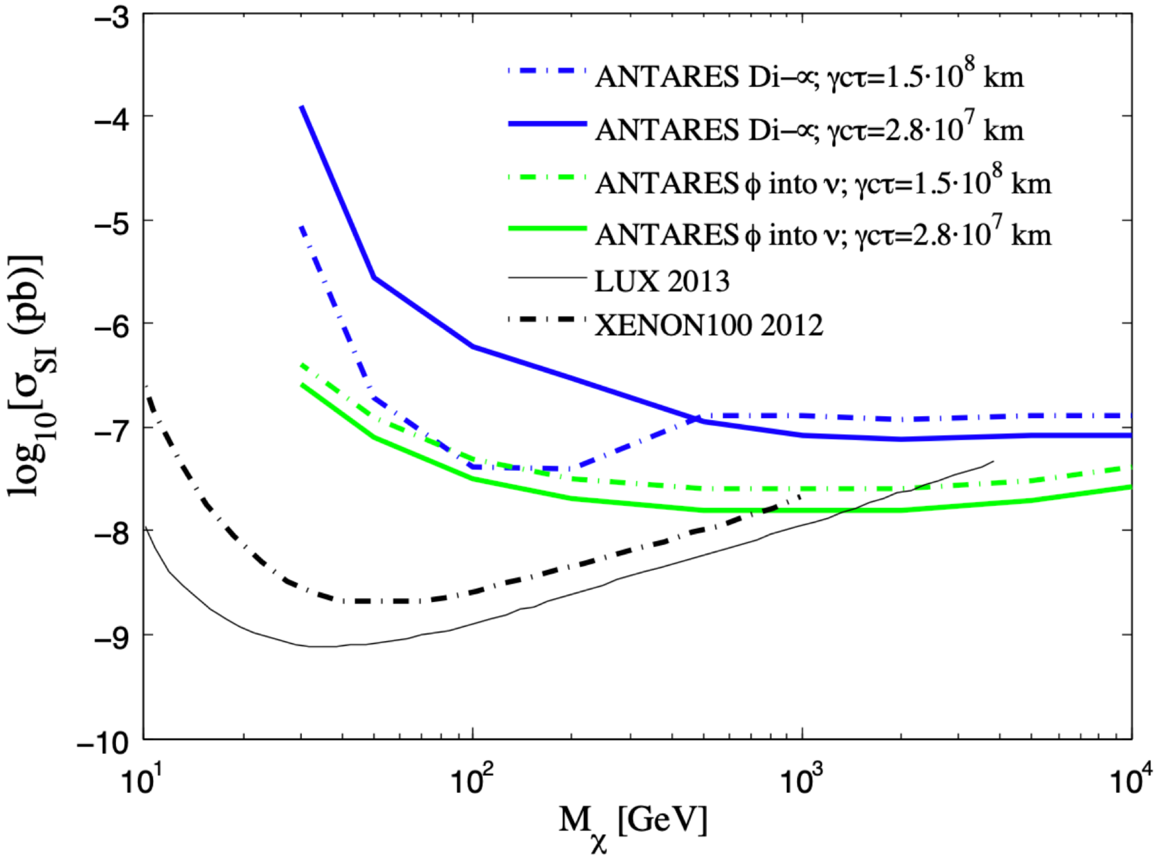
ANTARES 2007 -2012

JCAP05(2016)016

Secluded dark matter: towards the Sun

ANTARES 2007 -2012





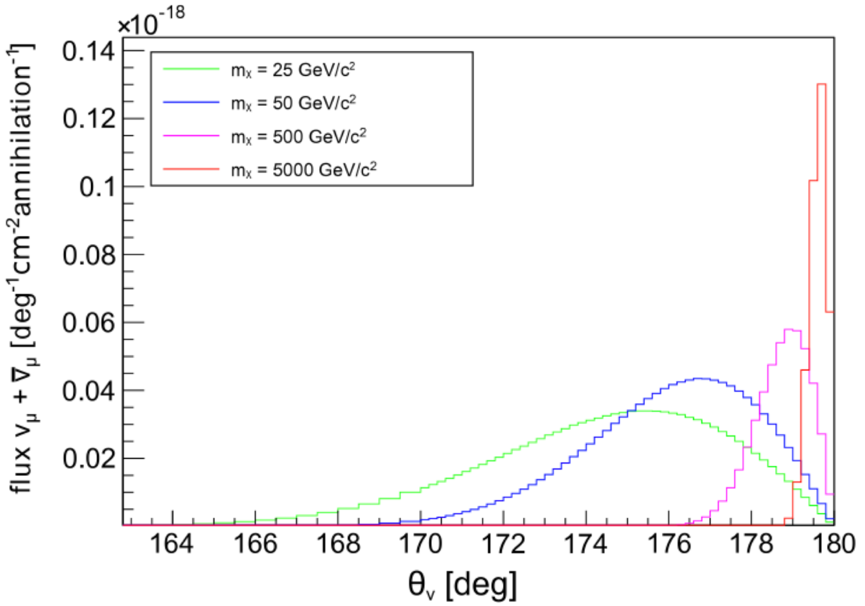
JCAP05(2016)016

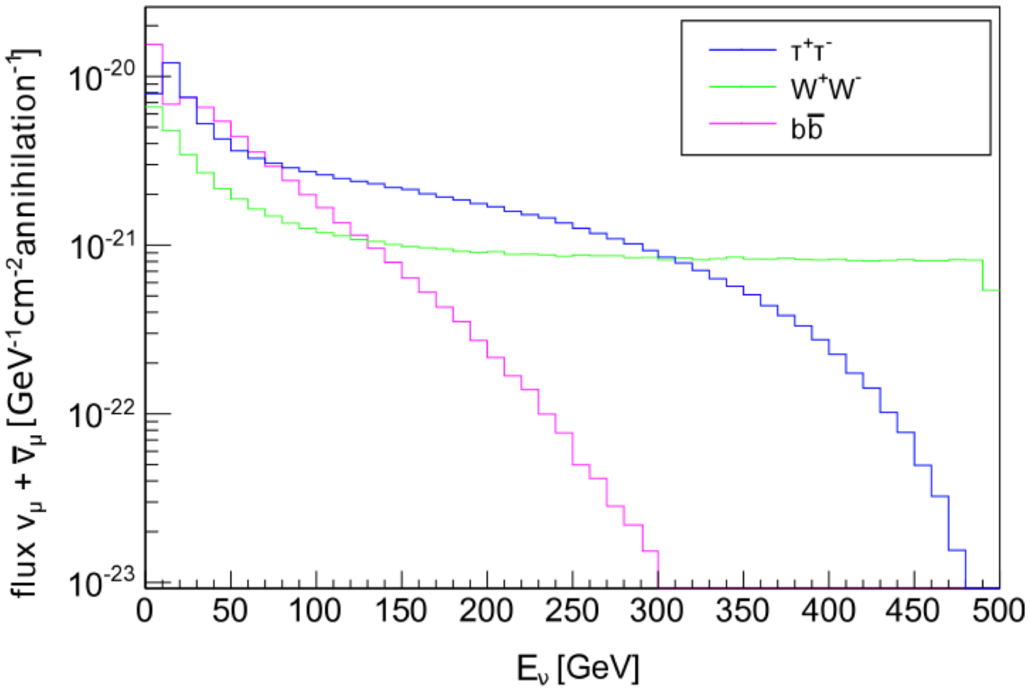
Dark matter searches in the center of the Earth

Dark matter searches in the centre of the Earth

Conditions:

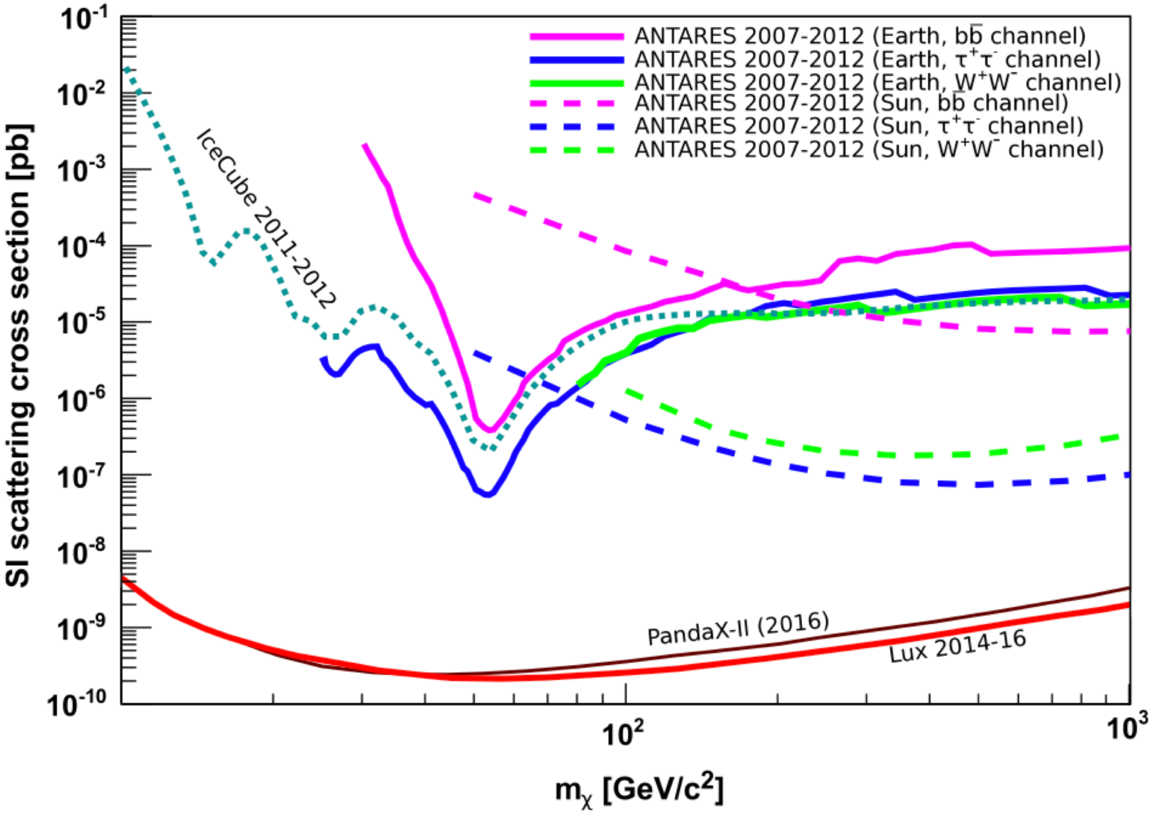
- WIMP velocity (270 km/s) < Earth escape velocity (11-14 km/s)
- large difference between the mass of the WIMP and the mass of the nucleus the particle is scattering on
- Spin-Independent elastic scattering (Iron, nickel)
- Same channels used for Sun analysis: $b\bar{b}$, W^+W^- , $\tau^+\tau^-$

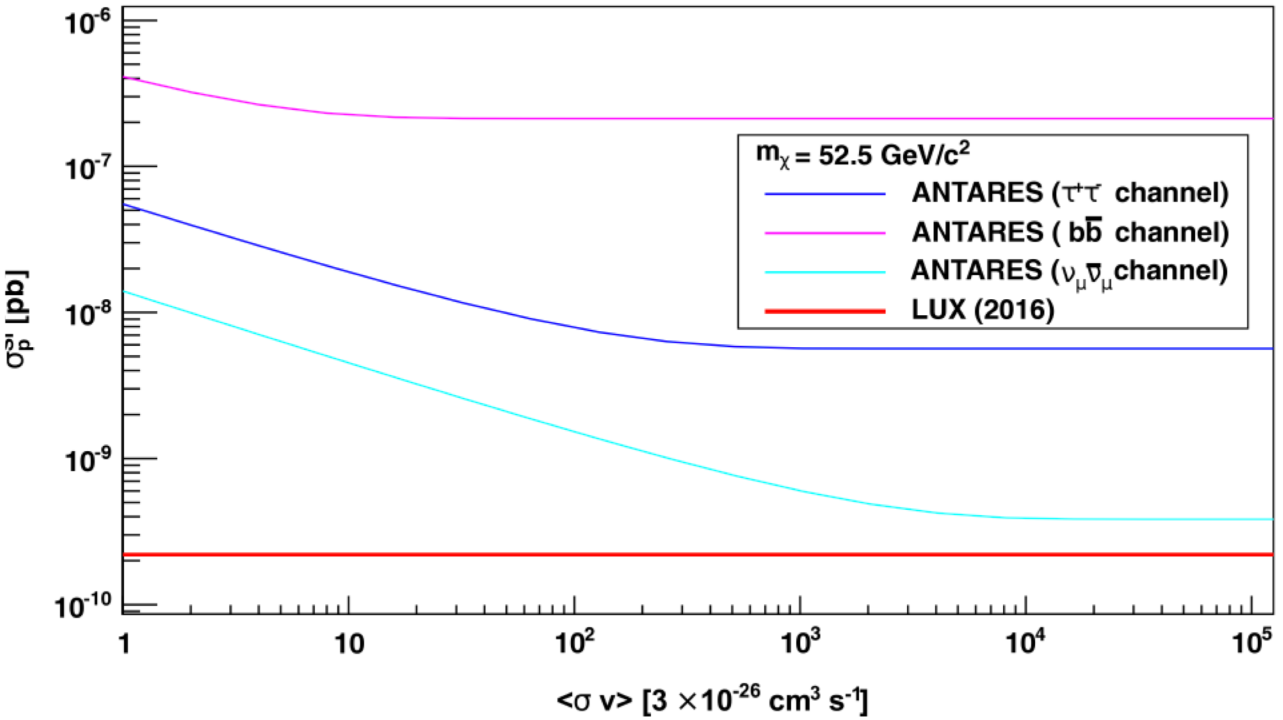




Dark matter searches in the Earth

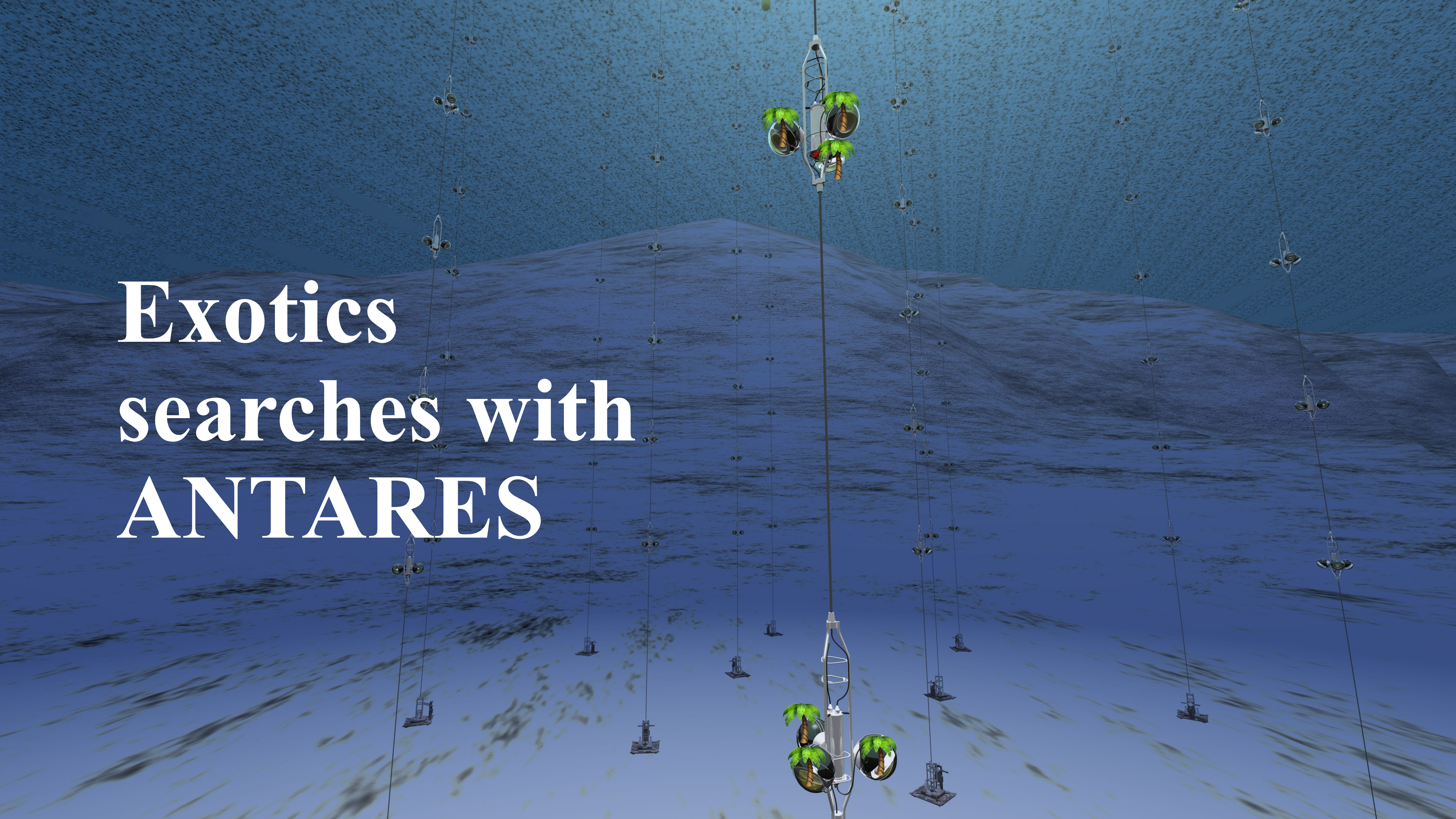
ANTARES 2007 -2012





[Physics of the Dark Universe 16 (2017) 41–48]

Exotics searches with ANTARES



Beyond standard model: new physics

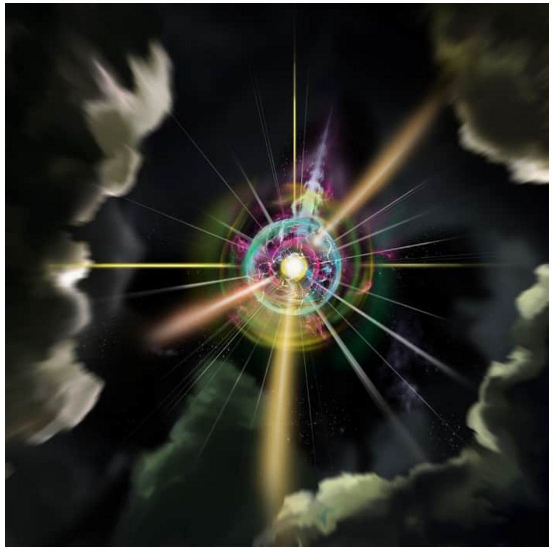
In addition to dark matter, different searches for new physics beyond standard model can be performed with a neutrino telescope:

- Magnetic monopoles
- Very massive nuclearites
- Lorentz Invariance Violation (LIV)
- Sterile neutrinos
- Non standard neutrino oscillations
- Quantum decoherence
- …

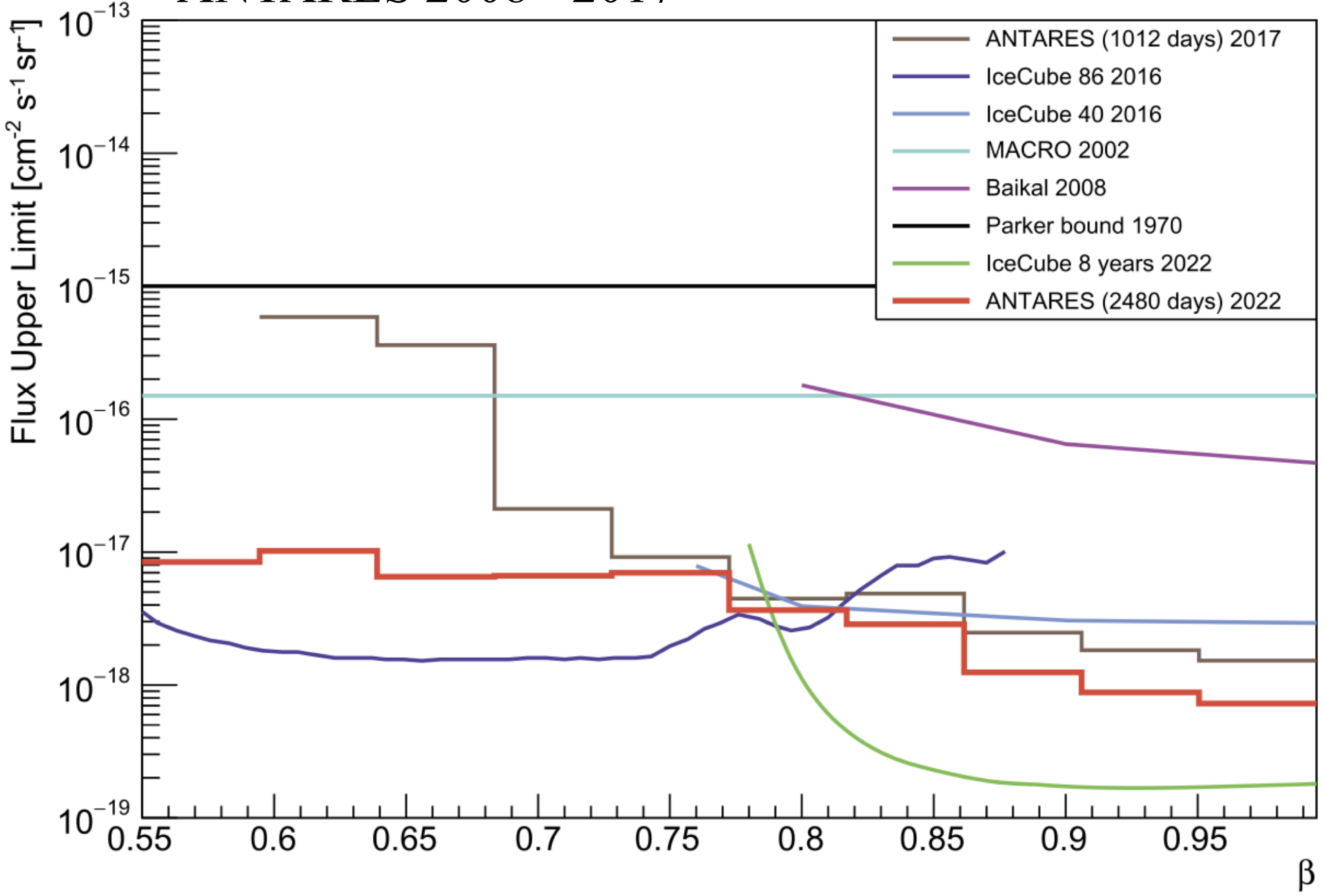
} This presentation (first three items)

Magnetic monopoles

Created during early phase of Universe
Magnetic monopoles can be accelerated at large velocities and emit a large amount of Cherenkov light.



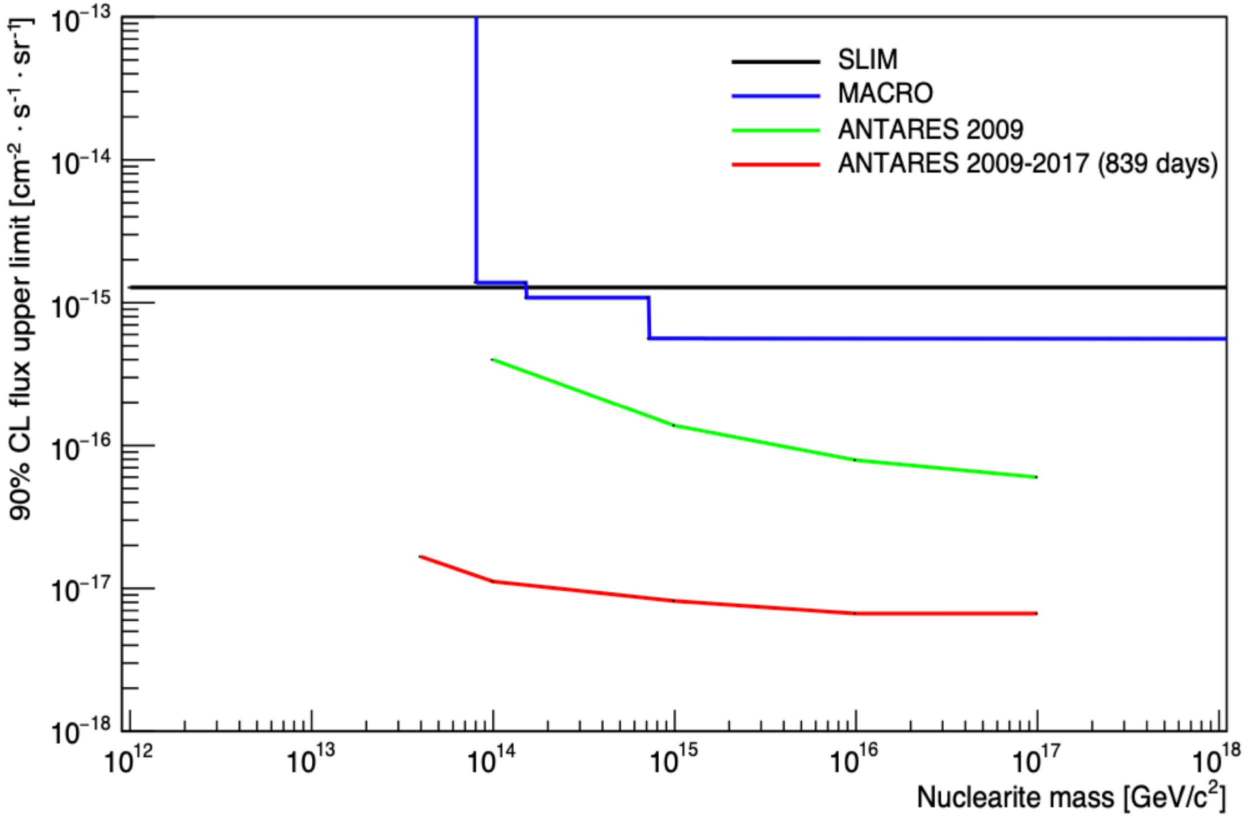
ANTARES 2008 - 2017



JHEAp 34 (2022)

Very massive nuclearites

Massive strange matter
Produced in violent astrophysical processes
Reaching the Earth in the cosmic radiation
→ black body radiation



ANTARES 2009 – 2017 (red line)
Down-going cosmic nuclearites arriving on the Earth with velocities $\beta = 10^{-3}$

JCAP01(2023)012

Lorentz Invariance Violation (LIV)

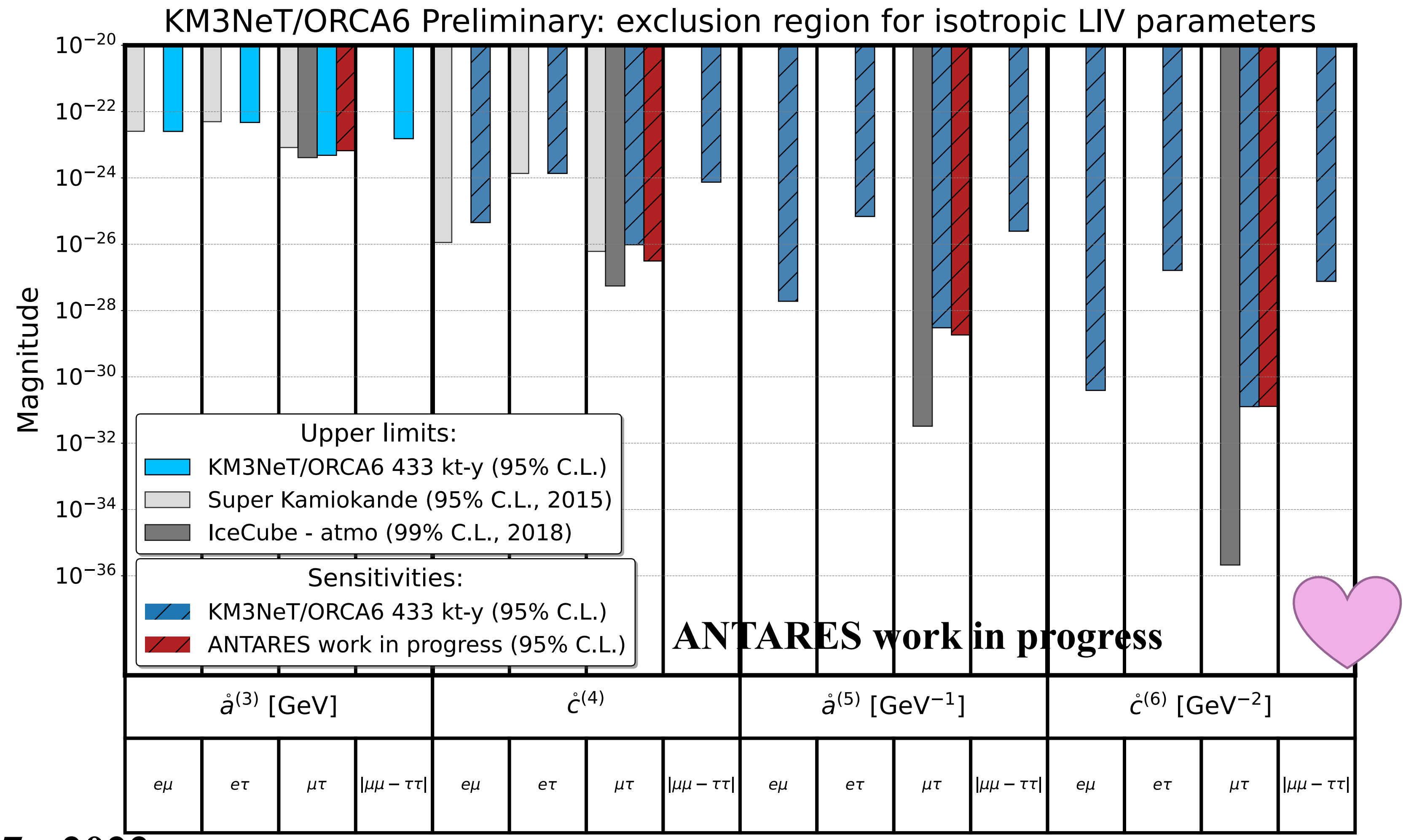
Lorentz invariance states that the outcome of an experiment is:

- the same for two inertial observers watching the same experiment
- independent of the inertial laboratory in which it is performed

- LIV is allowed in many theories attempting to unify the Standard Model and general relativity
  - Standard Model Extension (effective field theory):
    - isotropic LIV models → ANTARES focus
    - Nonzero LIV coefficient implies deviations from standard oscillations
    - Mass dimension determines oscillation dependence on baseline L and energy E
    - Focus on mass dimension up to six

$$H_{LIV} = \begin{pmatrix} \mathring{a}^{(3)}_{ee} & \mathring{a}^{(3)}_{e\mu} & \mathring{a}^{(3)}_{e\tau} \\ \mathring{a}^{(3)*}_{e\mu} & \mathring{a}^{(3)}_{\mu\mu} & \mathring{a}^{(3)}_{\mu\tau} \\ \mathring{a}^{(3)*}_{e\tau} & \mathring{a}^{(3)*}_{\mu\tau} & \mathring{a}^{(3)}_{\tau\tau} \end{pmatrix} - \frac{4}{3}E \begin{pmatrix} \mathring{c}^{(4)}_{ee} & \mathring{c}^{(4)}_{e\mu} & \mathring{c}^{(4)}_{e\tau} \\ \mathring{c}^{(4)*}_{e\mu} & \mathring{c}^{(4)}_{\mu\mu} & \mathring{c}^{(4)}_{\mu\tau} \\ \mathring{c}^{(4)*}_{e\tau} & \mathring{c}^{(4)*}_{\mu\tau} & \mathring{c}^{(4)}_{\tau\tau} \end{pmatrix} + E^2\mathring{a}^{(5)} - E^3\mathring{c}^{(6)} + E^4\mathring{a}^{(7)} - E^5\mathring{c}^{(8)} + \ldots$$

Lorentz Invariance Violation (LIV)

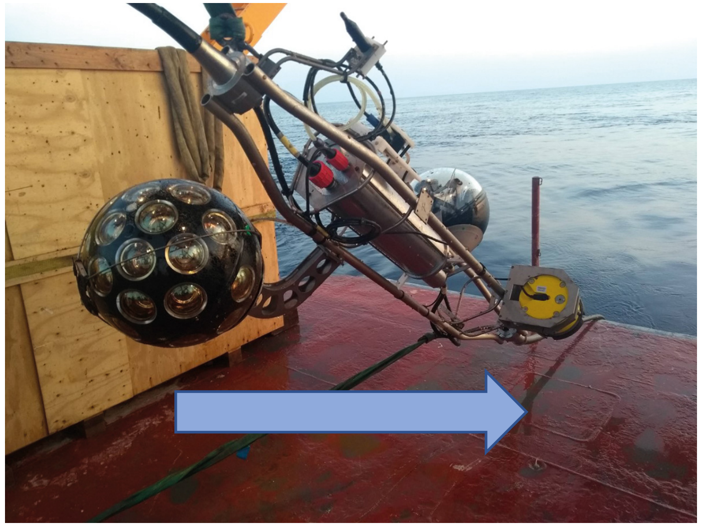


ANTARES **2007 - 2022**

What is next?

- The next generation neutrino telescope KM3NeT is under construction and is already taking data
- KM3NeT has an improved design, with two detectors (ARCA & ORCA) sensitive from MeV to PeV energies.
- Expected to become complete by 2028

ANTARES



KM3NeT

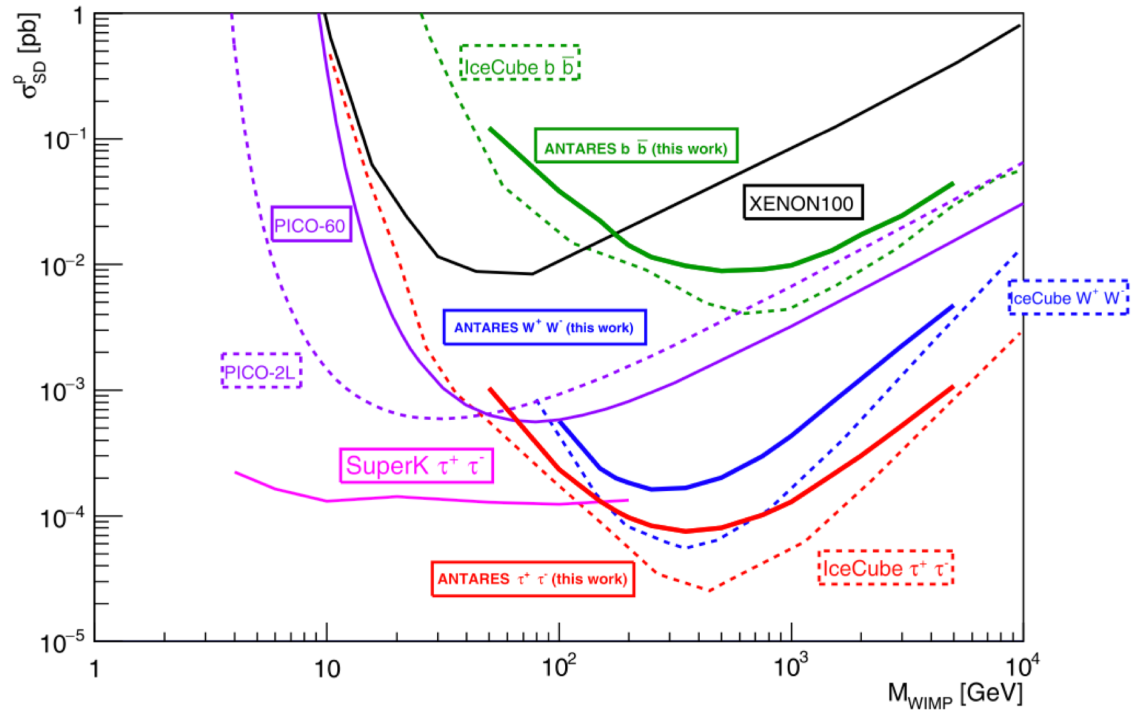
Conclusions

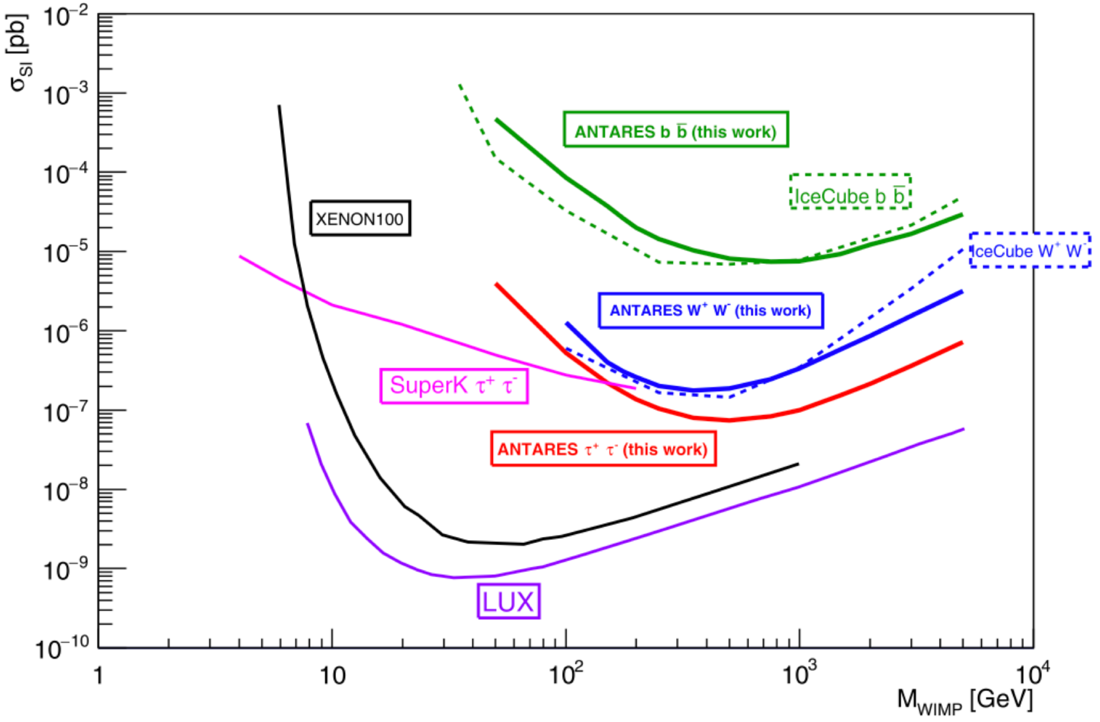
- ANTARES has taken data from 2007 to early 2022
- More than 100 papers have been published in peer-review journals in the field of neutrino searches
- ANTARES was part of the multi-messenger world collaborating with other experiments
- Final legacy analysis are ongoing and will be finalized in 2024


Thanks for the attention!

Back - up

Dark matter towards the Sun

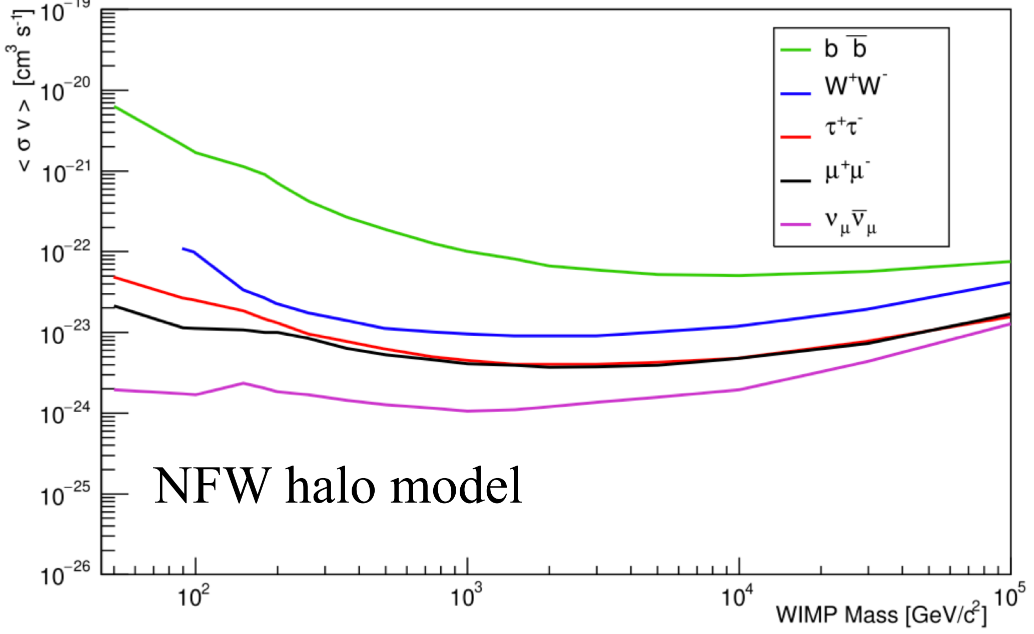


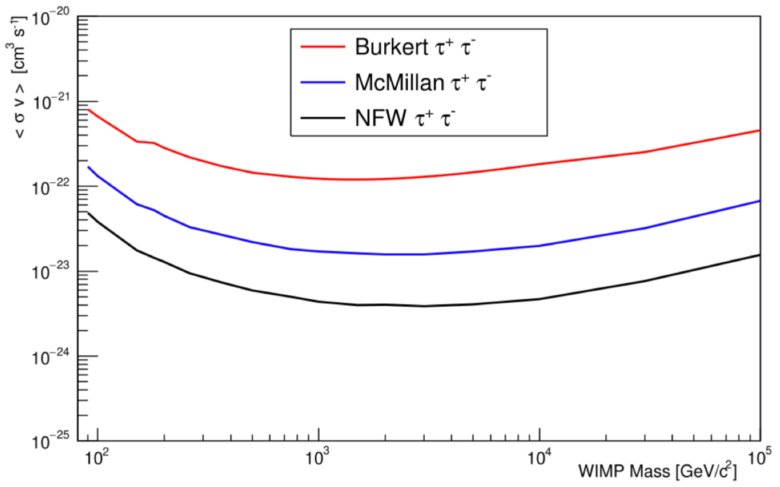


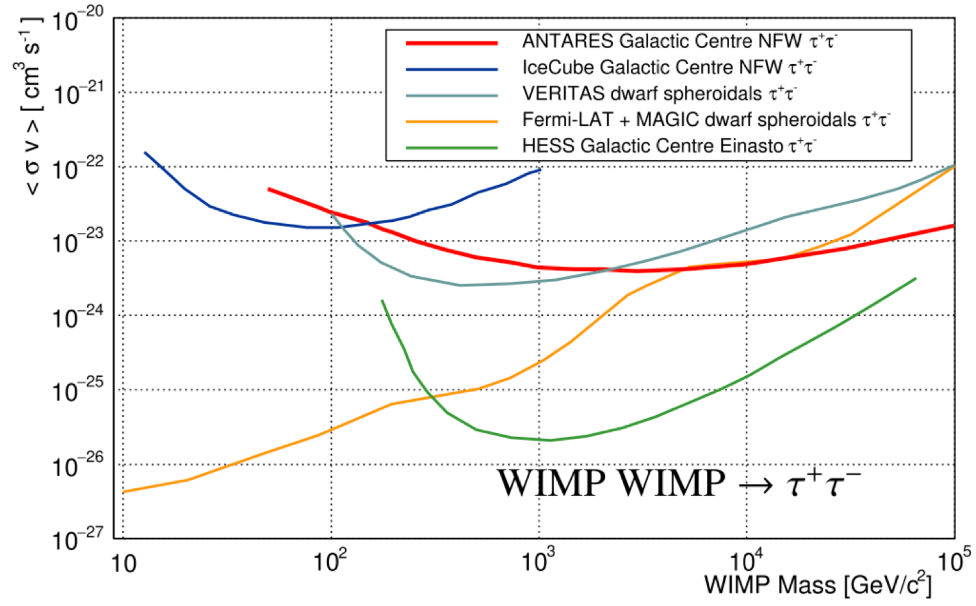
Physics Letters B 759 (2016) 69–74

Dark matter searches from Galactic centre

ANTARES 2007-2017

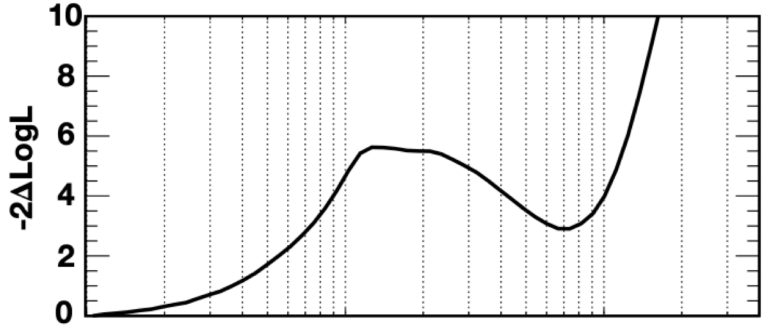






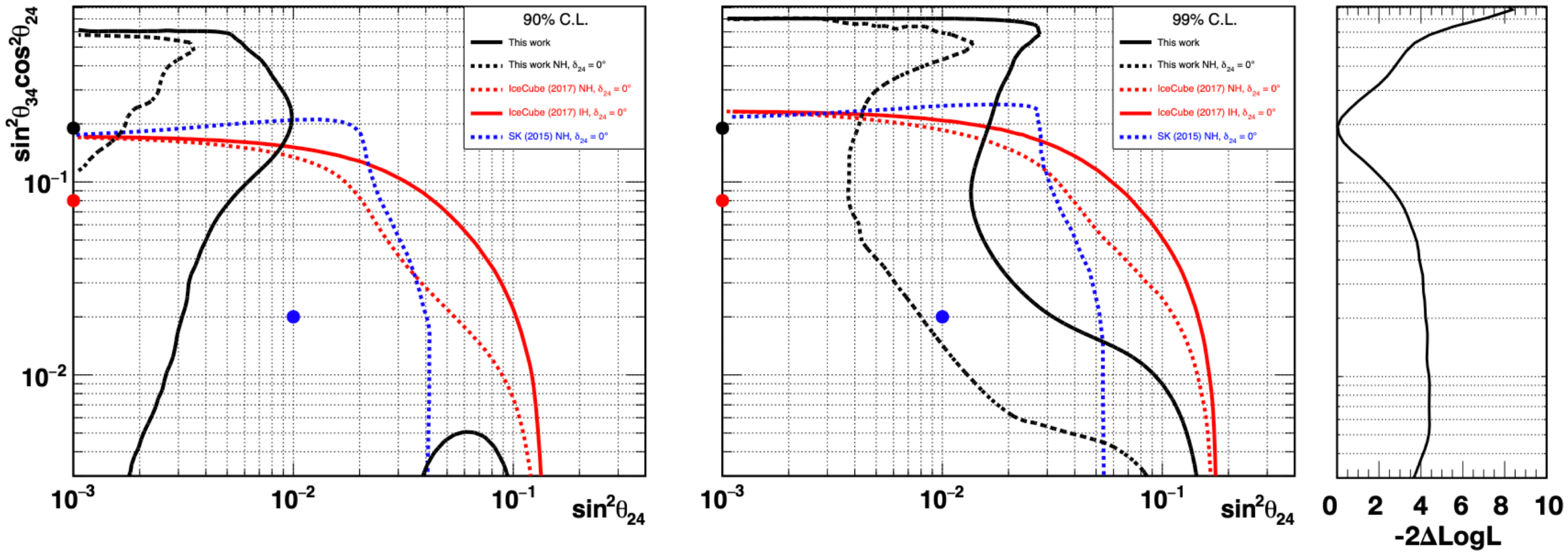
Physics Letters B 805 (2020) 135439

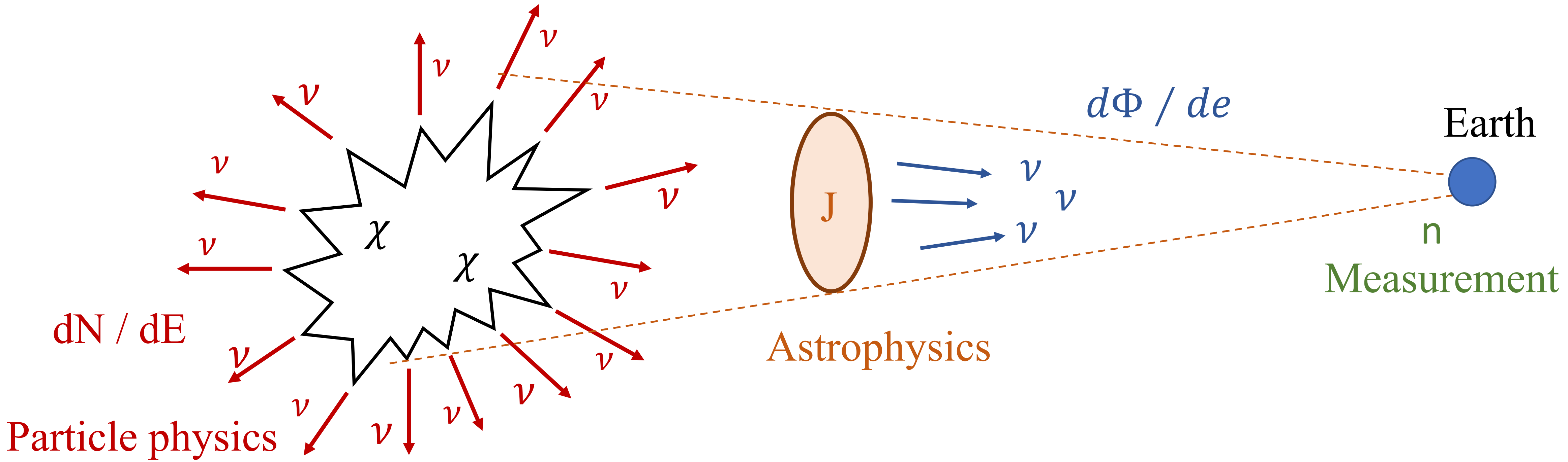
Sterile neutrinos



3+1 neutrino model
ANTARES 2007-2016

JHEP06(2019)113





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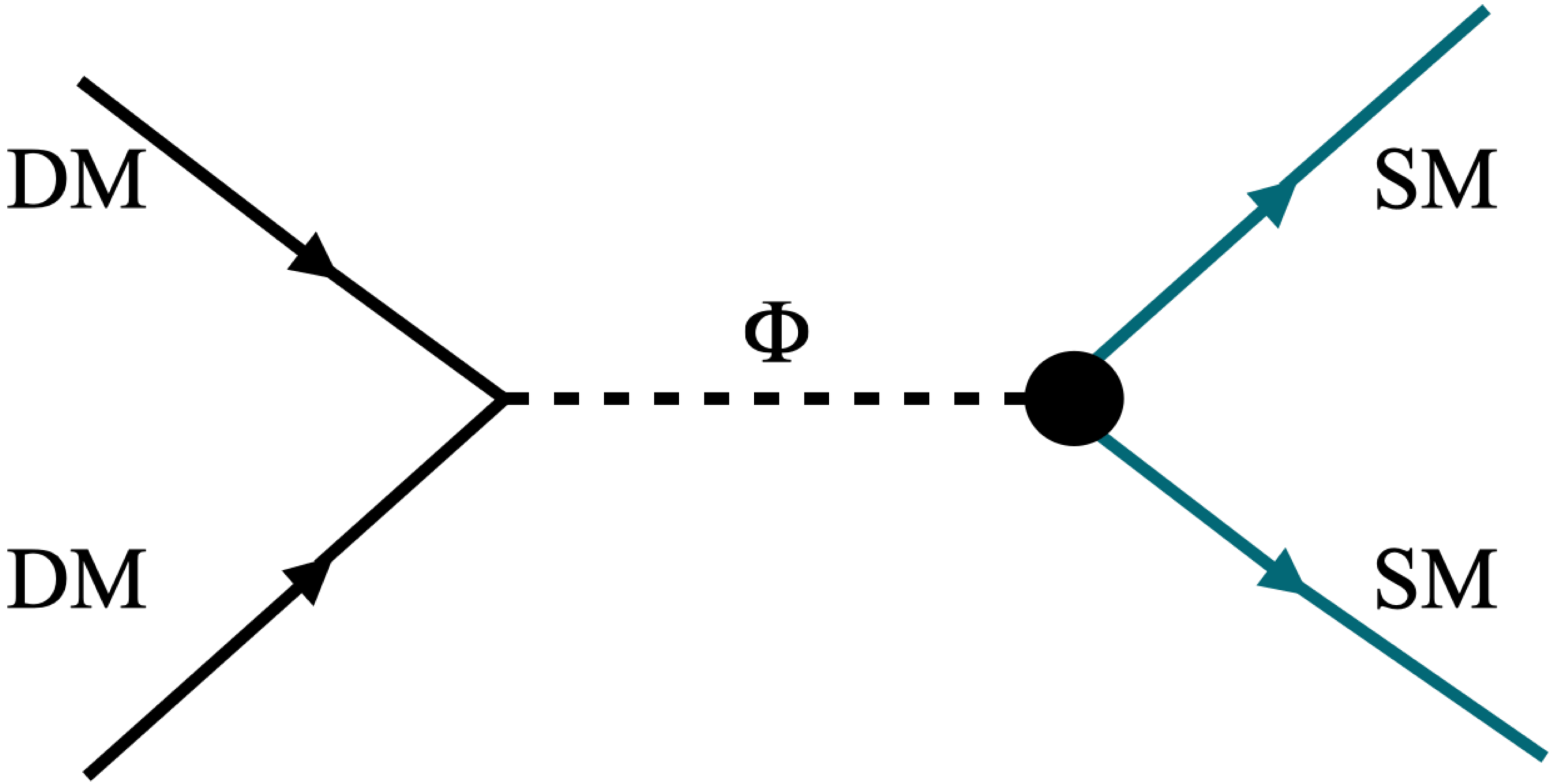
Measurement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