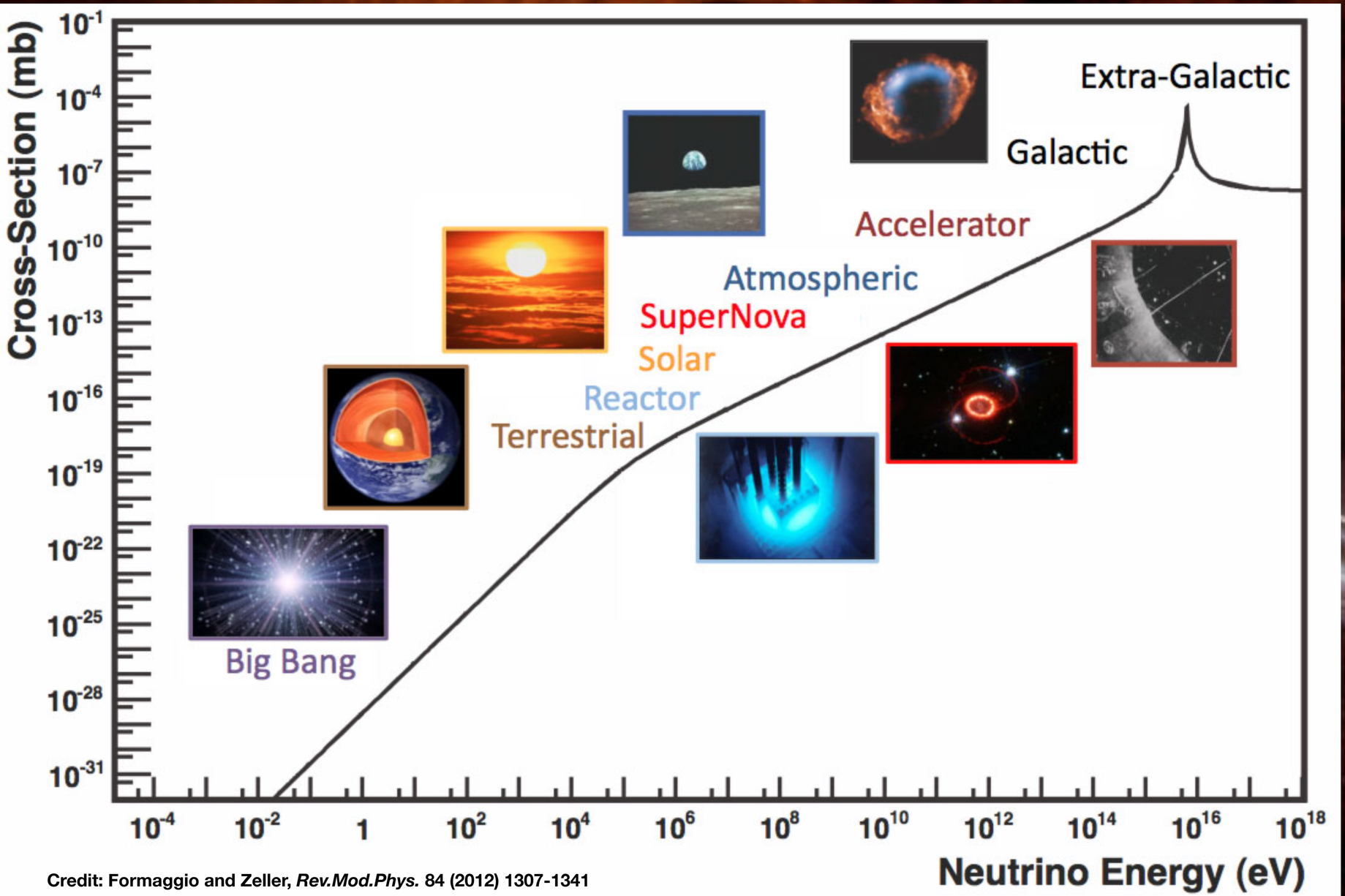
BSM Physics: Perspectives and Recent Results from IceCube

Mehr Un Nisa
Michigan State University

CIPANP 2025

Why Cosmic Neutrinos



Credit: Formaggio and Zeller, *Rev.Mod.Phys.* 84 (2012) 1307-1341

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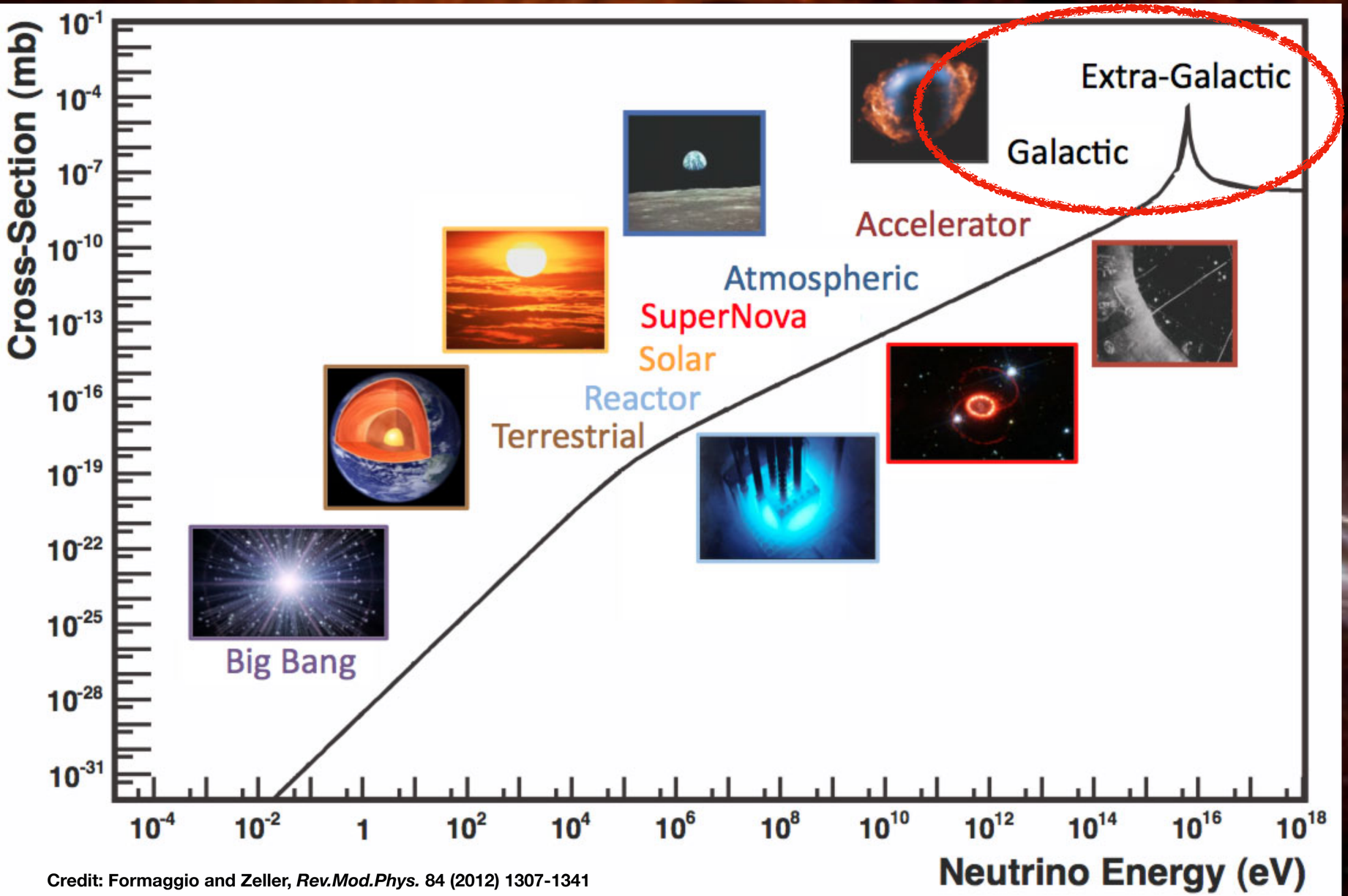

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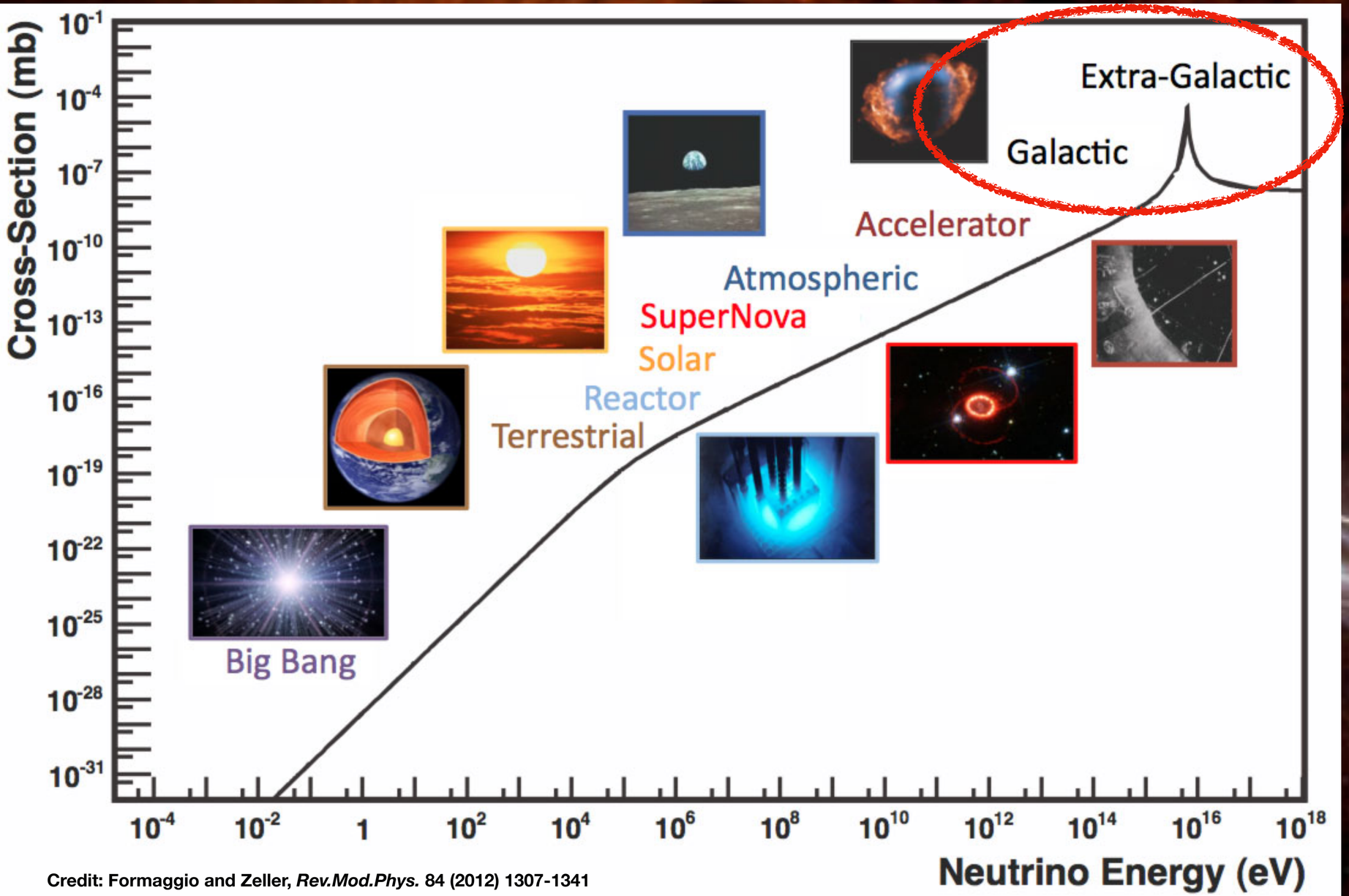

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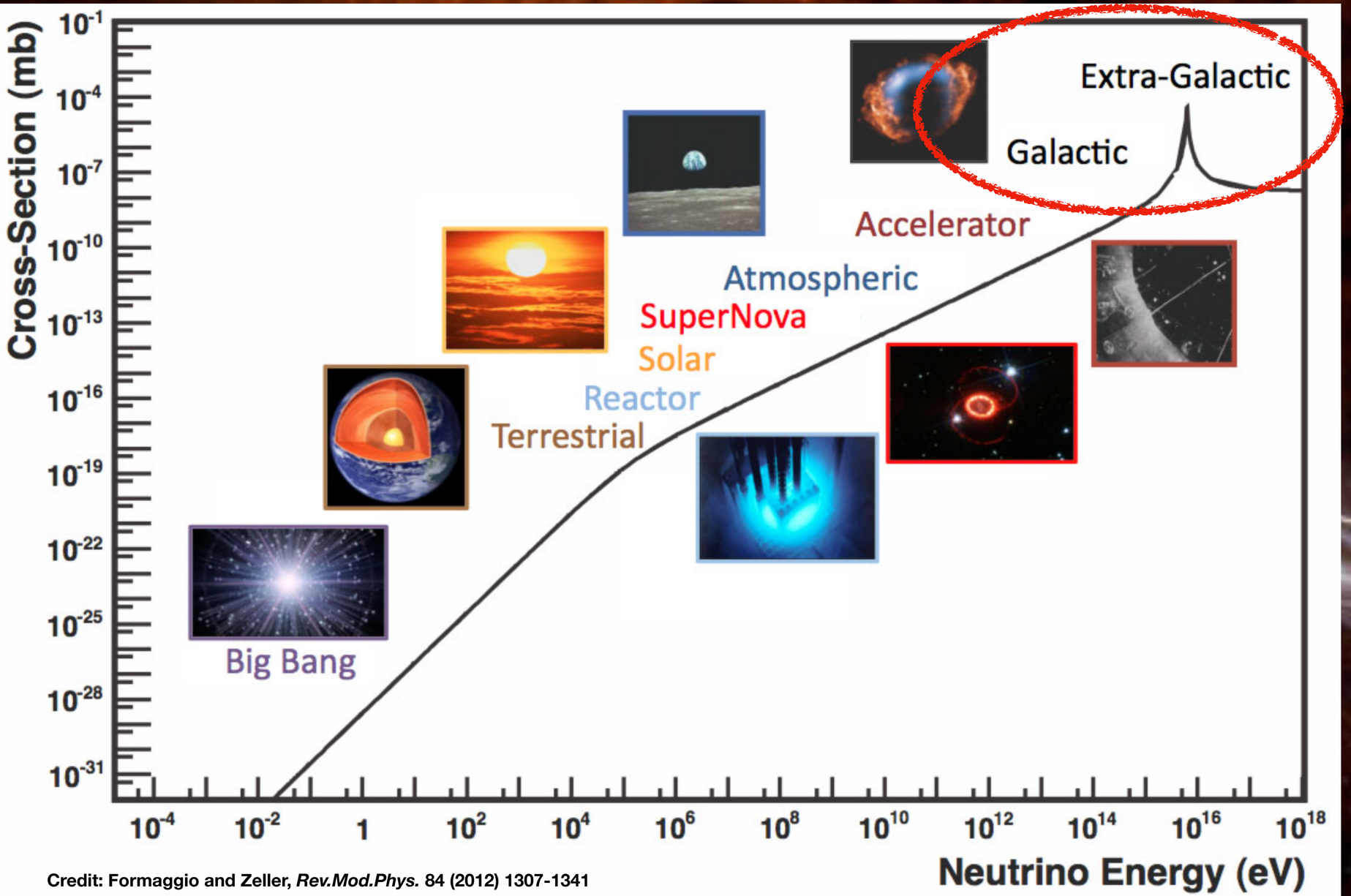
- **Probe a parameter space in particle physics (GeV—PeV) that is not accessible in other experiments (beam dump/ accelerators) .**

Why Cosmic Neutrinos



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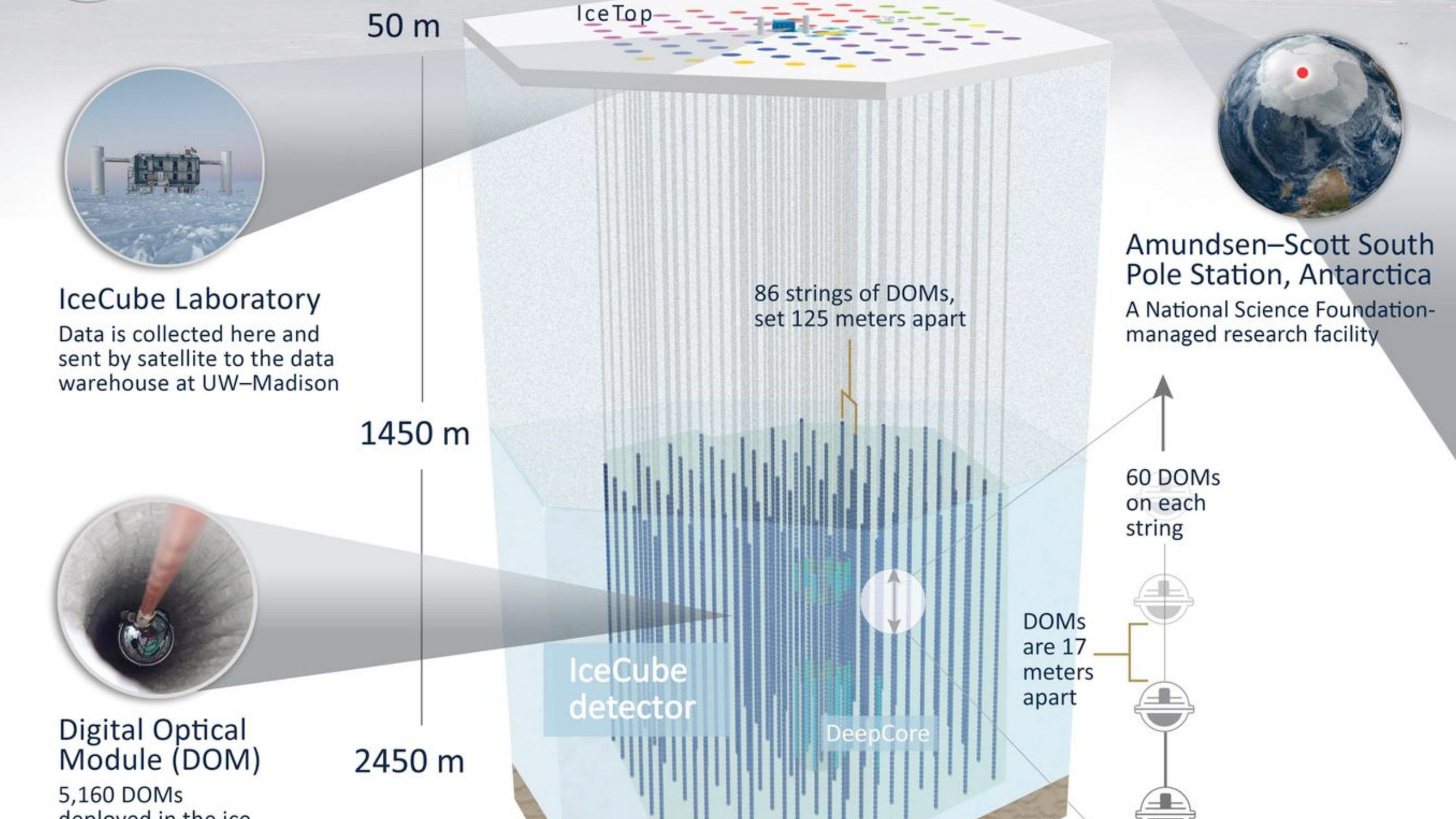
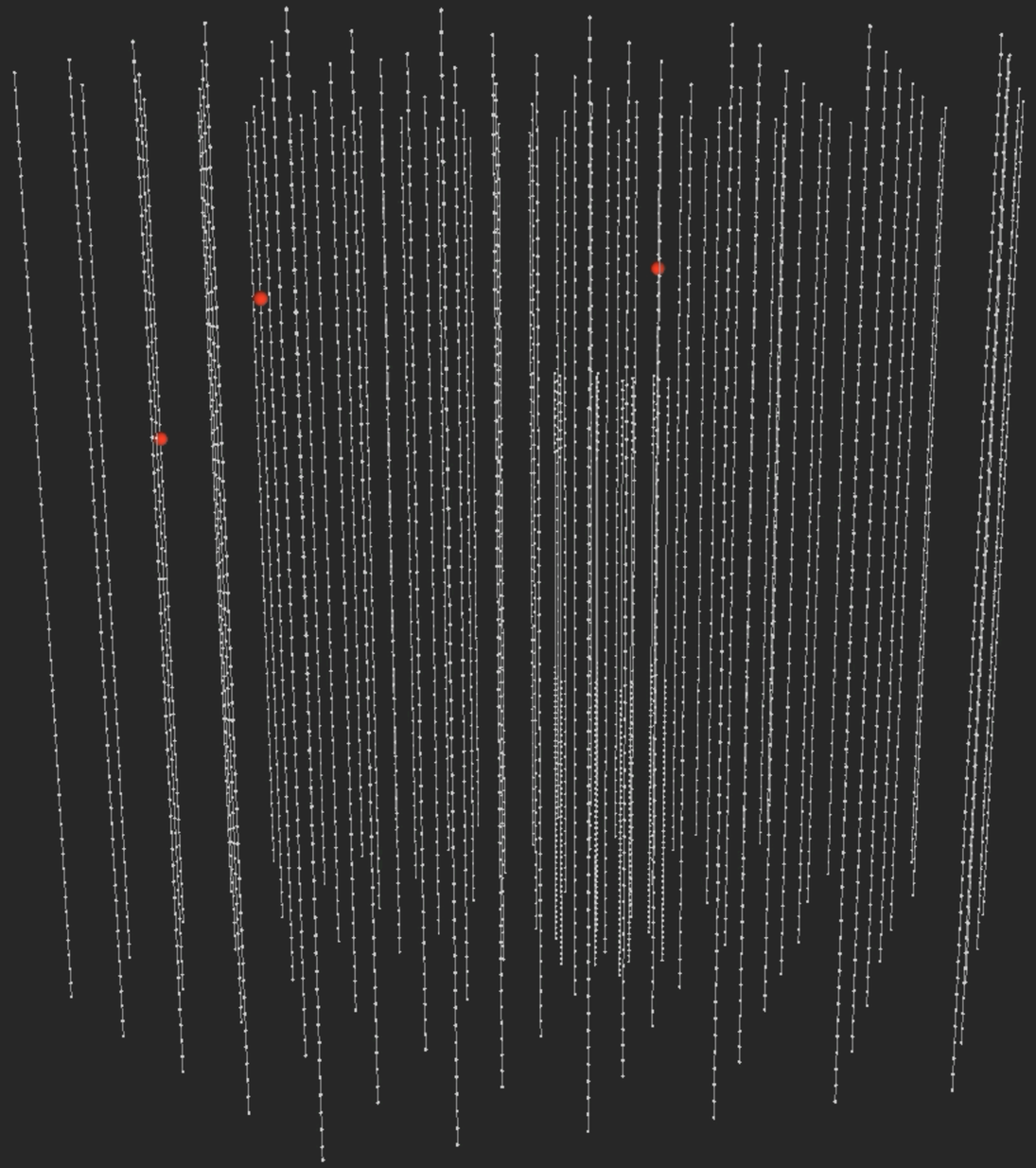
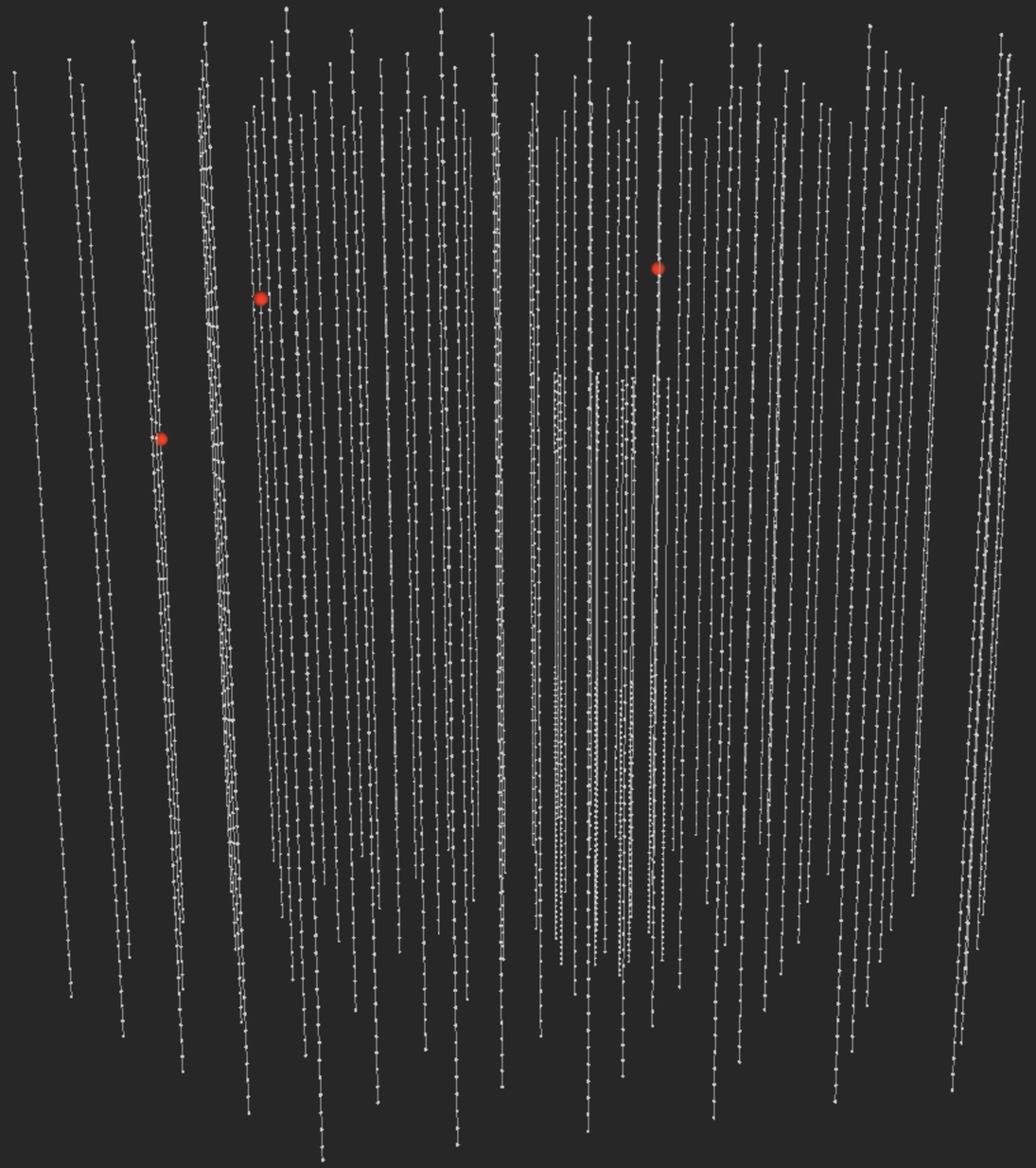
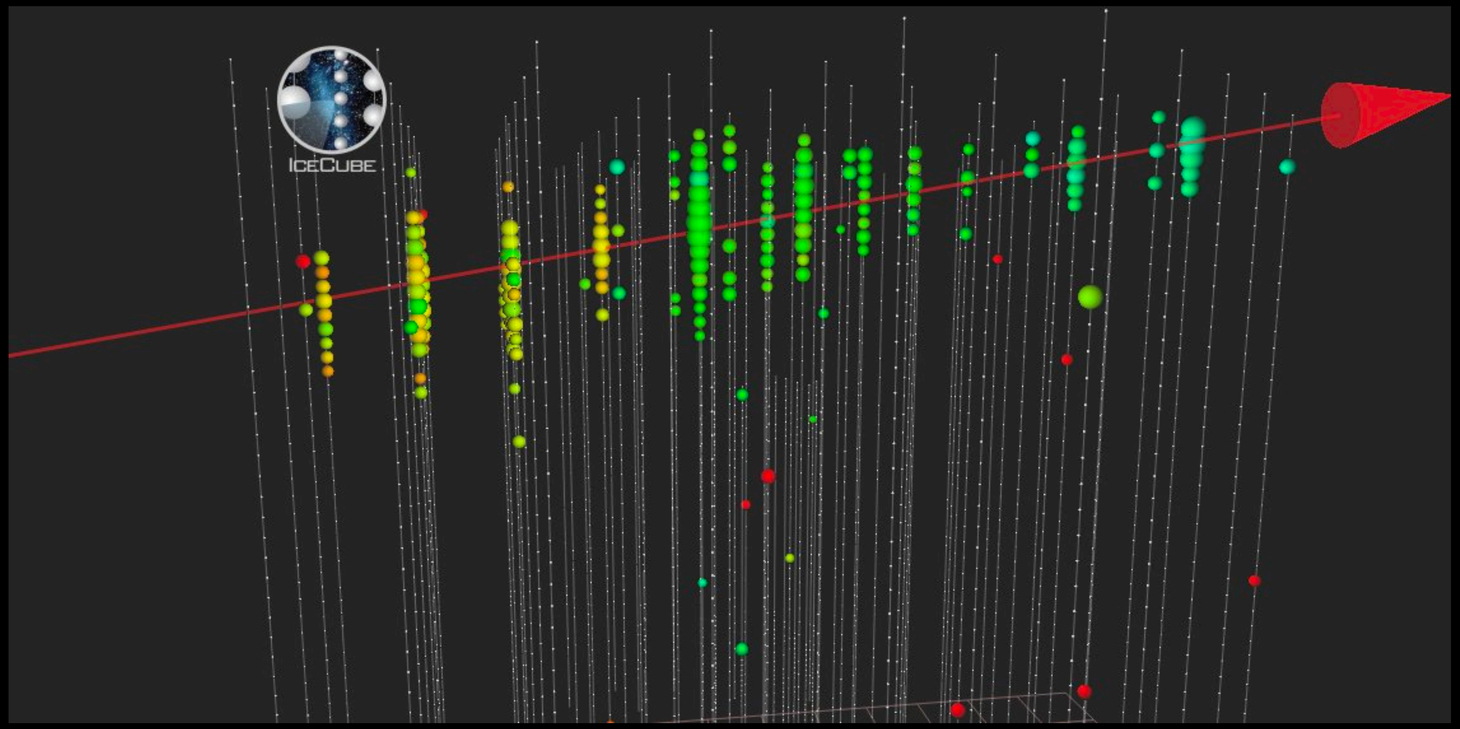
- Probe a parameter space in particle physics (GeV—PeV) that is not accessible in other experiments (beam dump/ accelerators) .
- Observe the universe where it is opaque in other wavelengths.


50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs
2450 m



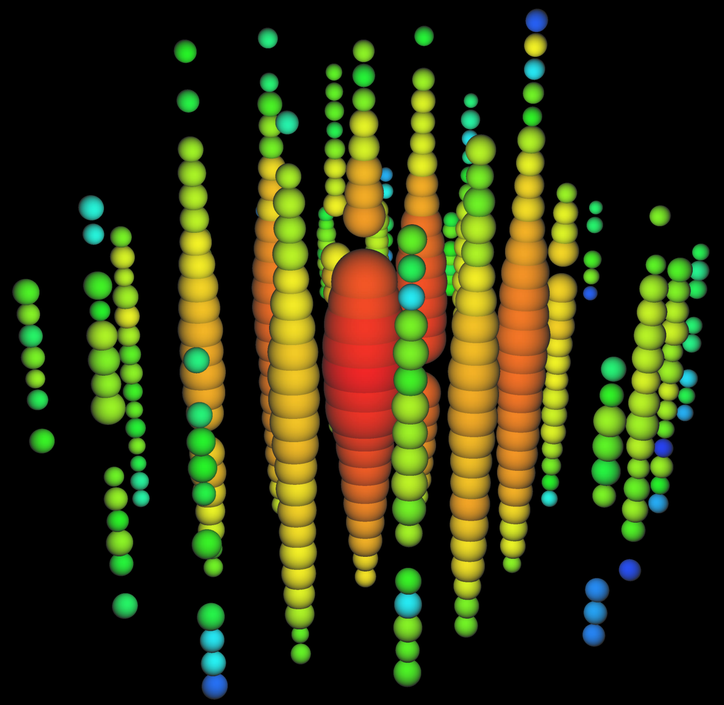


Typical Event Signatures



Track-like

ν_μ



Cascade

ν_e CC, ν_x NC, low-E ν_τ

Data and Background

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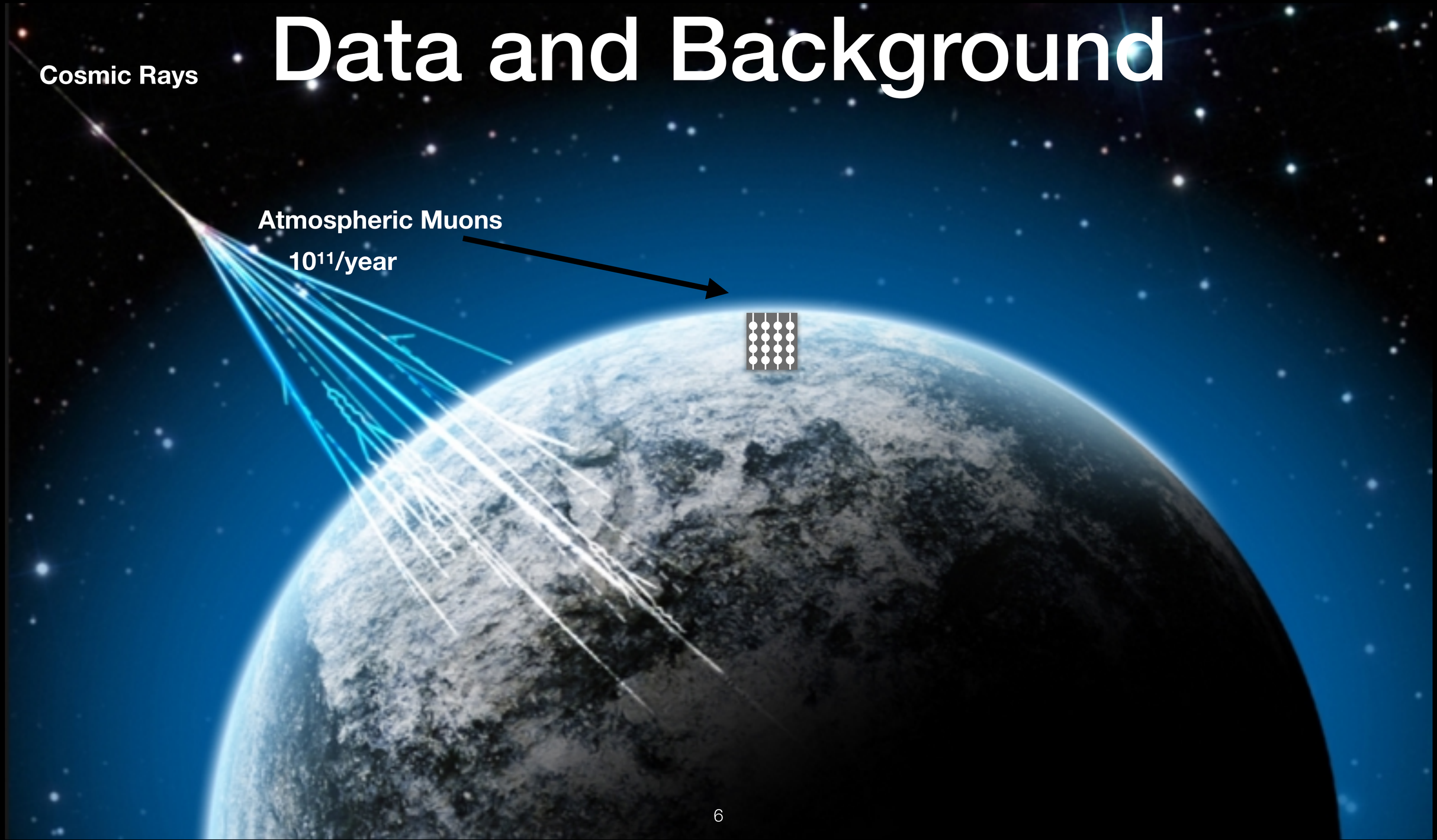

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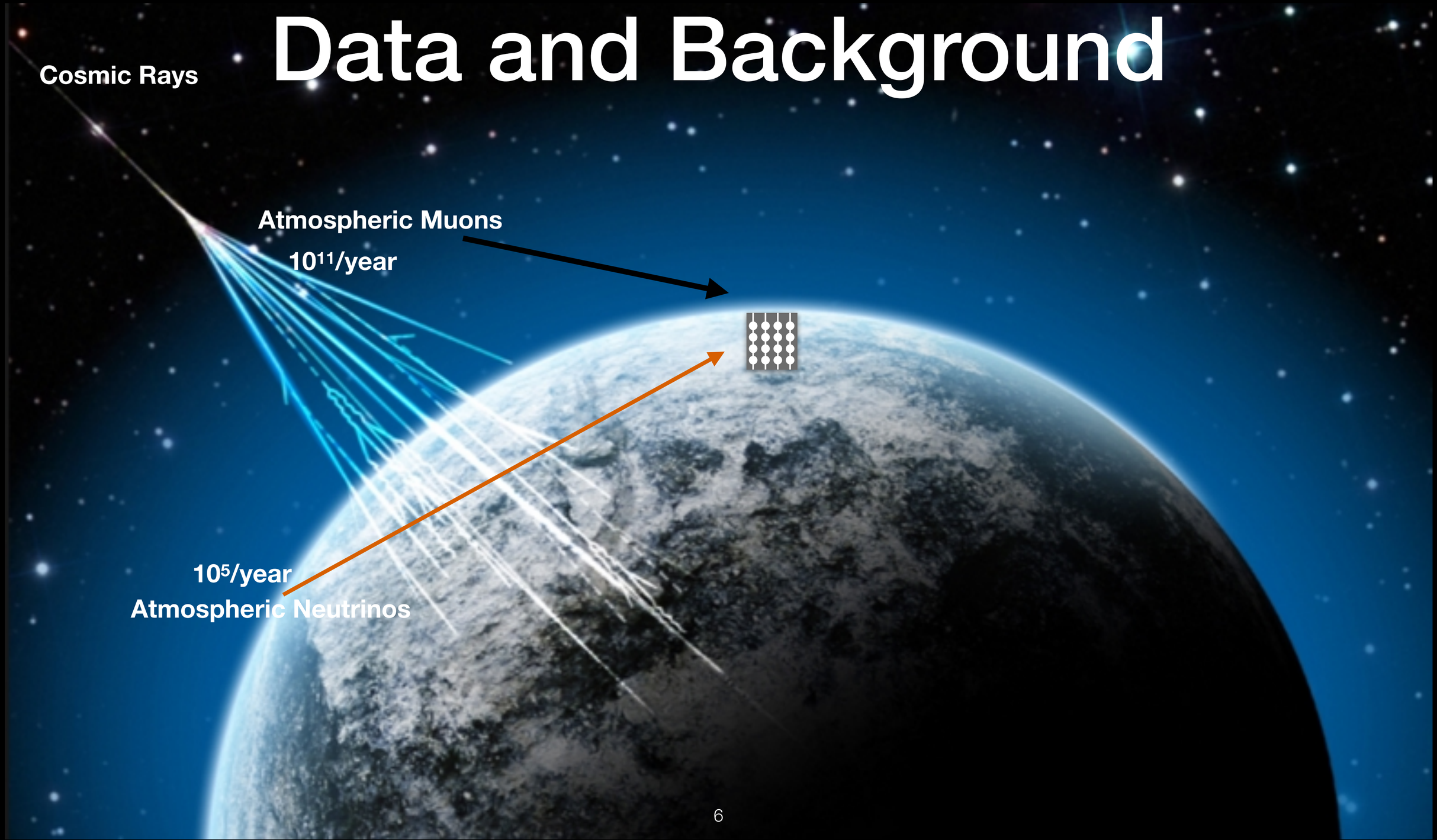

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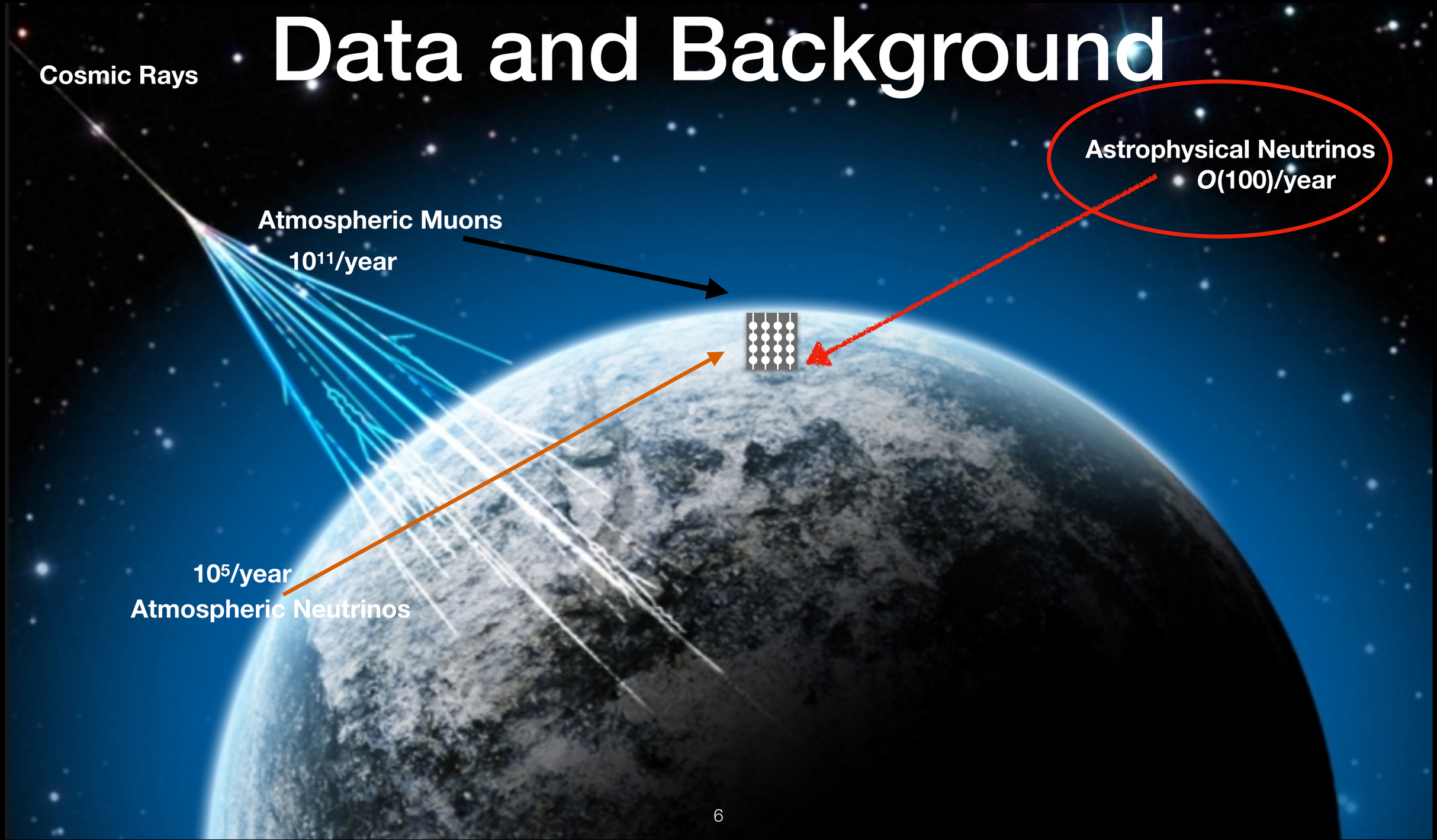
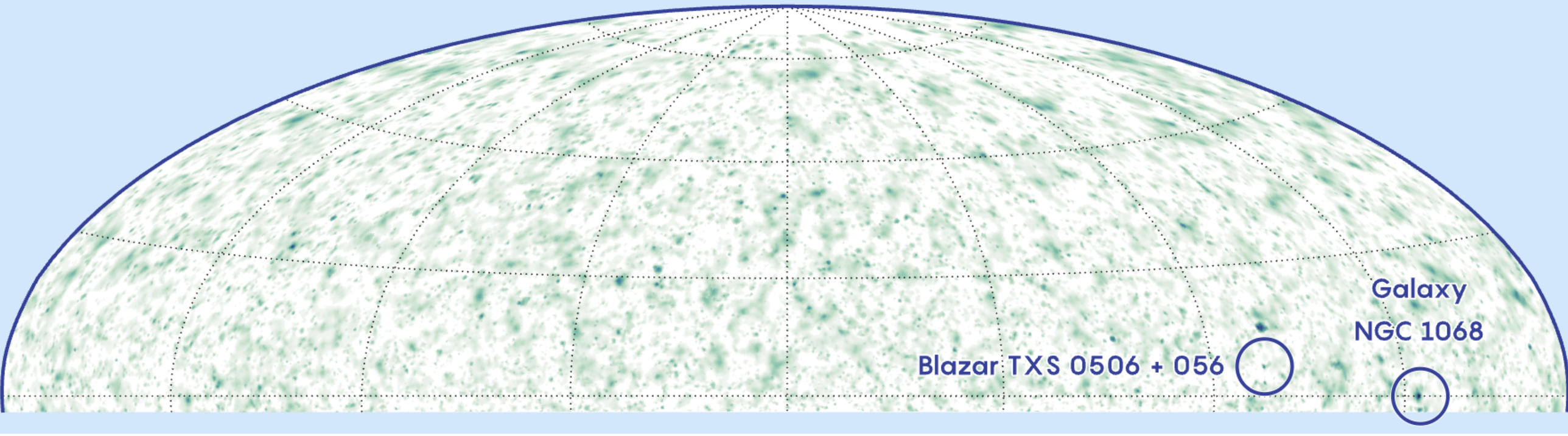
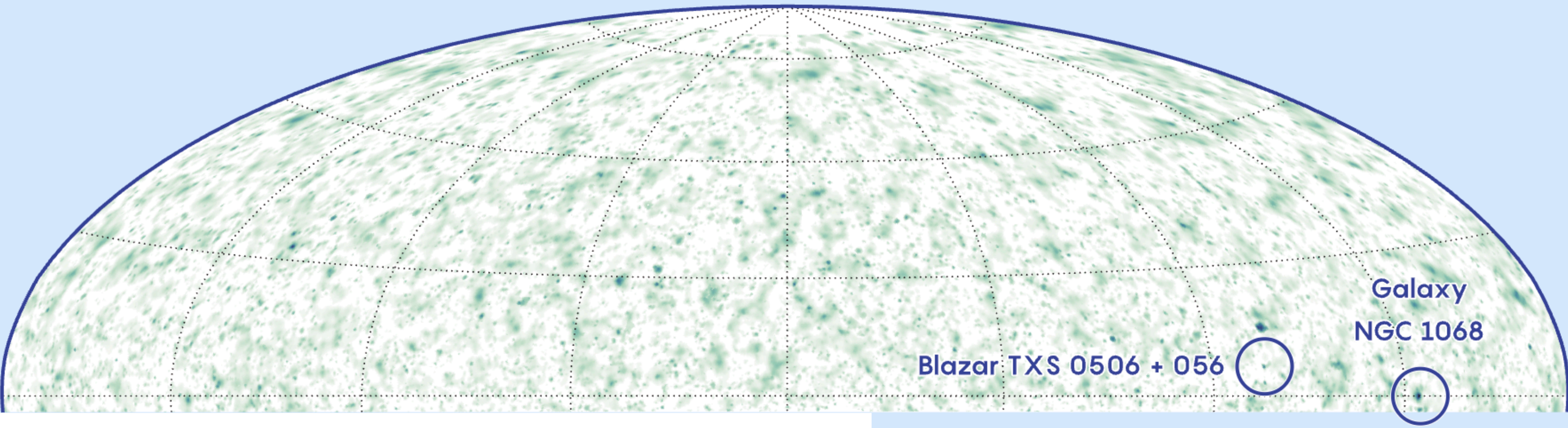


The Neutrino Sky


Galaxy
NGC 1068
Blazar TXS 0506 + 056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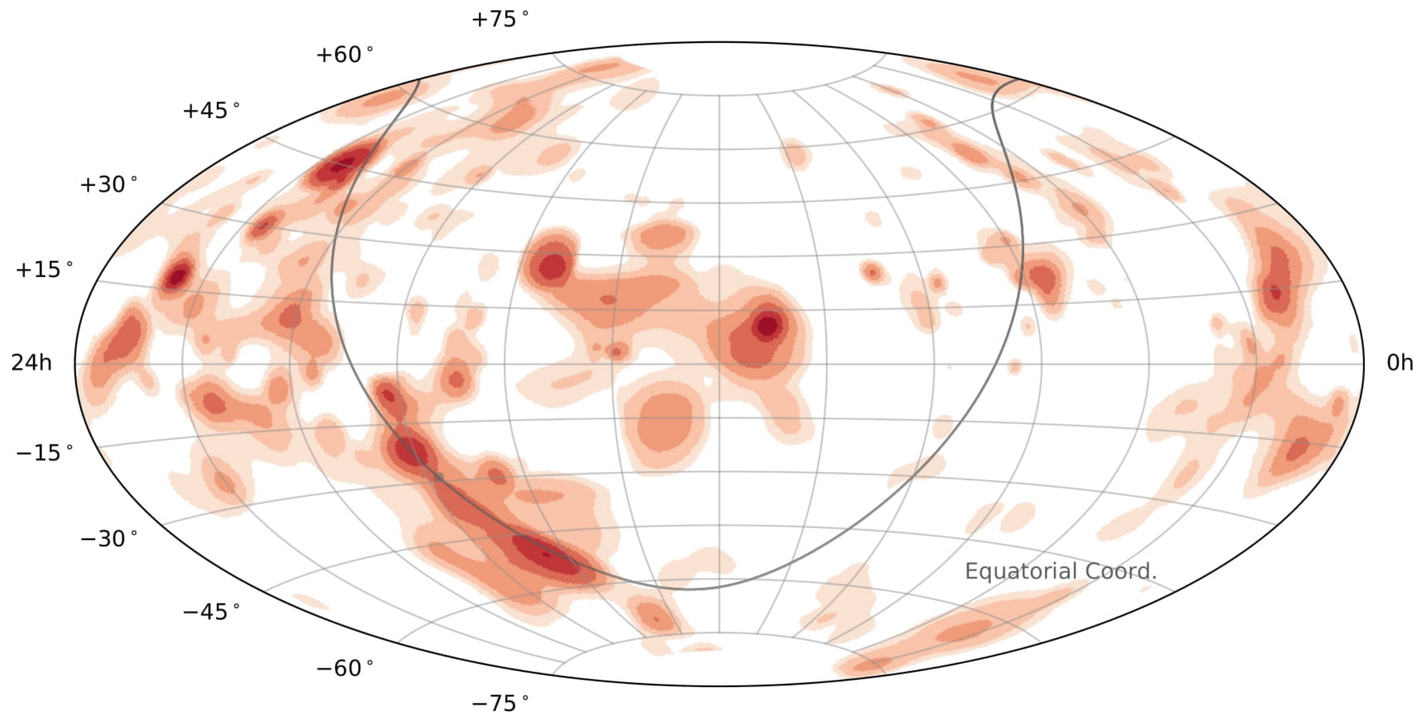
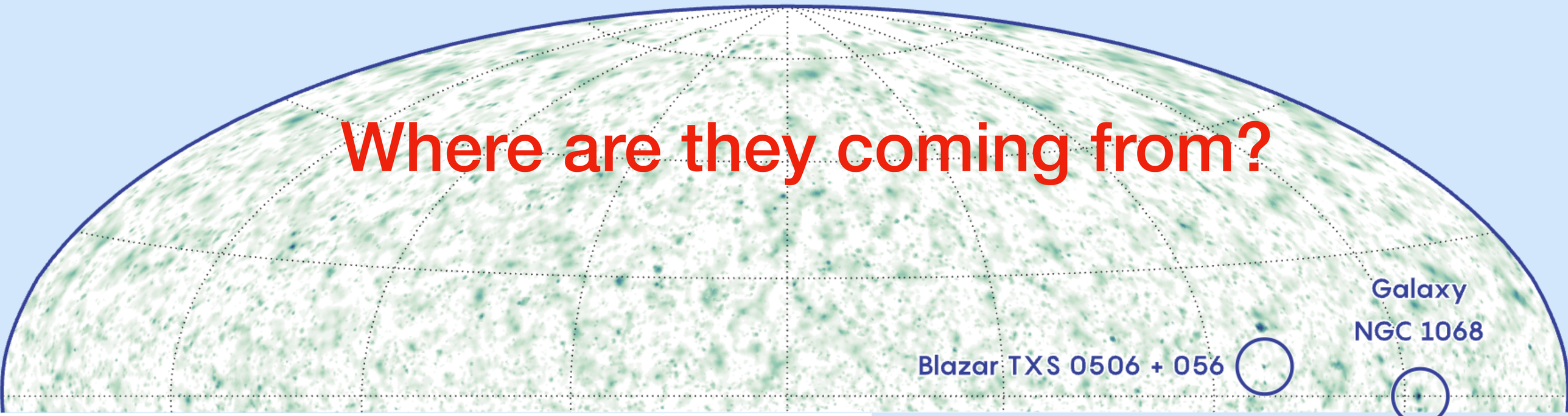
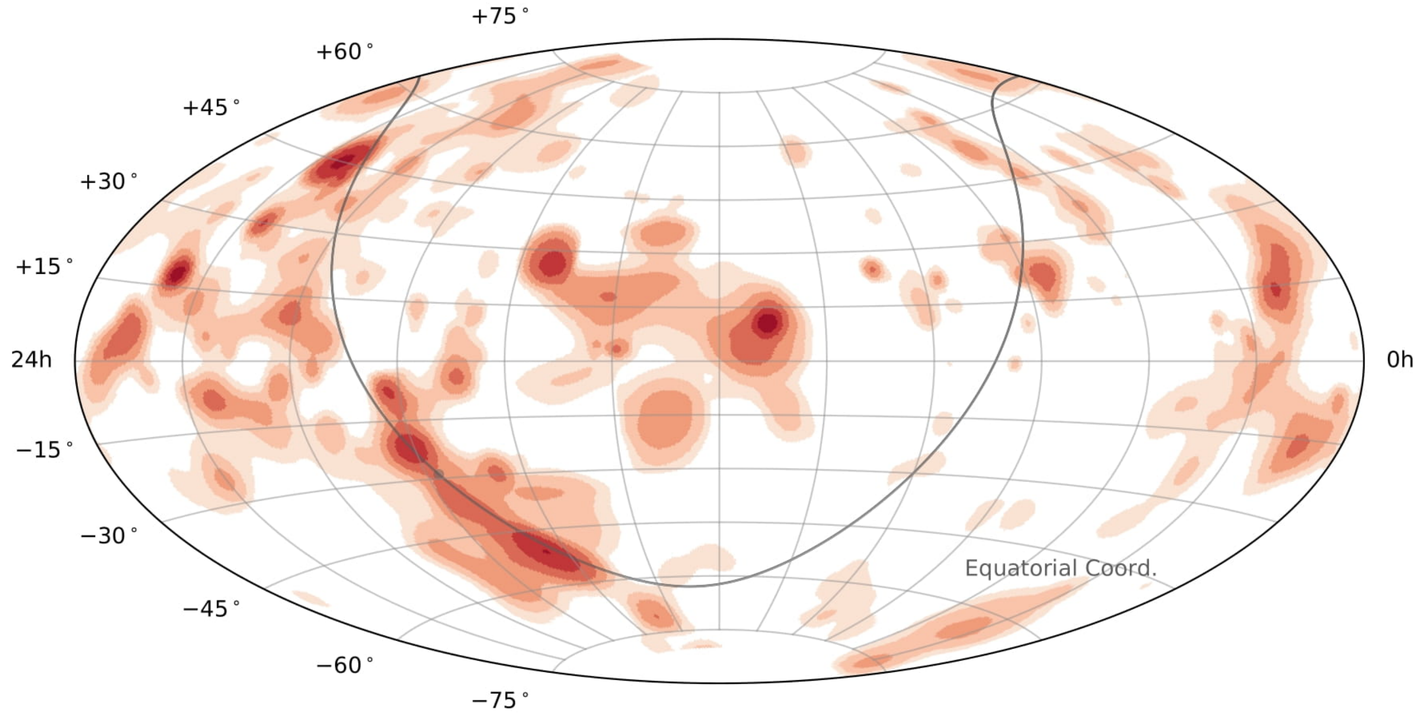

+75°
+60°
+45°
+30°
+15°
24h
0h
−15°
−30°
−45°
−60°
−75°
Equatorial Coord.

Where are they coming from?





Where are they coming from?

ν Astronomy

- Recent PS Results (Ali Kheirandish)
- Recent Diffuse Measurements (Vedant Basu)
- Supernova Prospects (Segev BenZvi)
- Galactic Plane Flavor Ratio (John Hardin)

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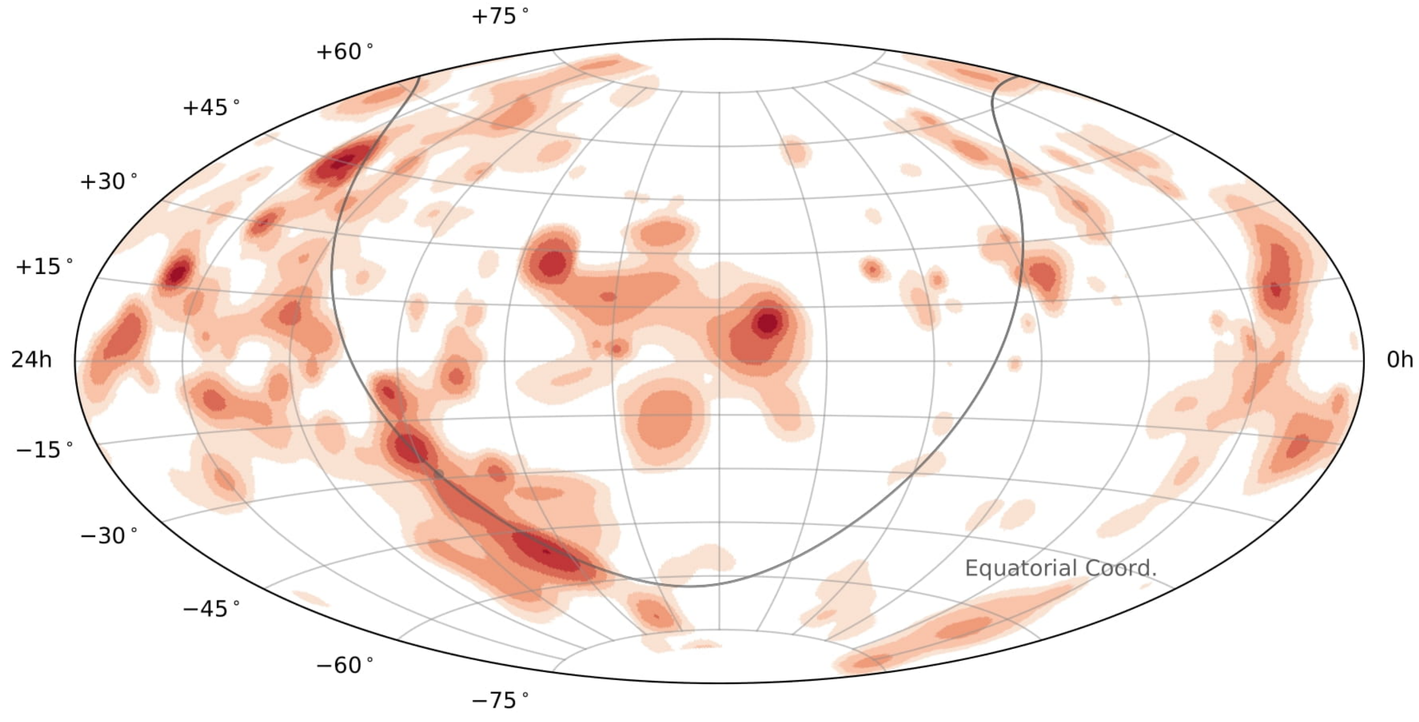

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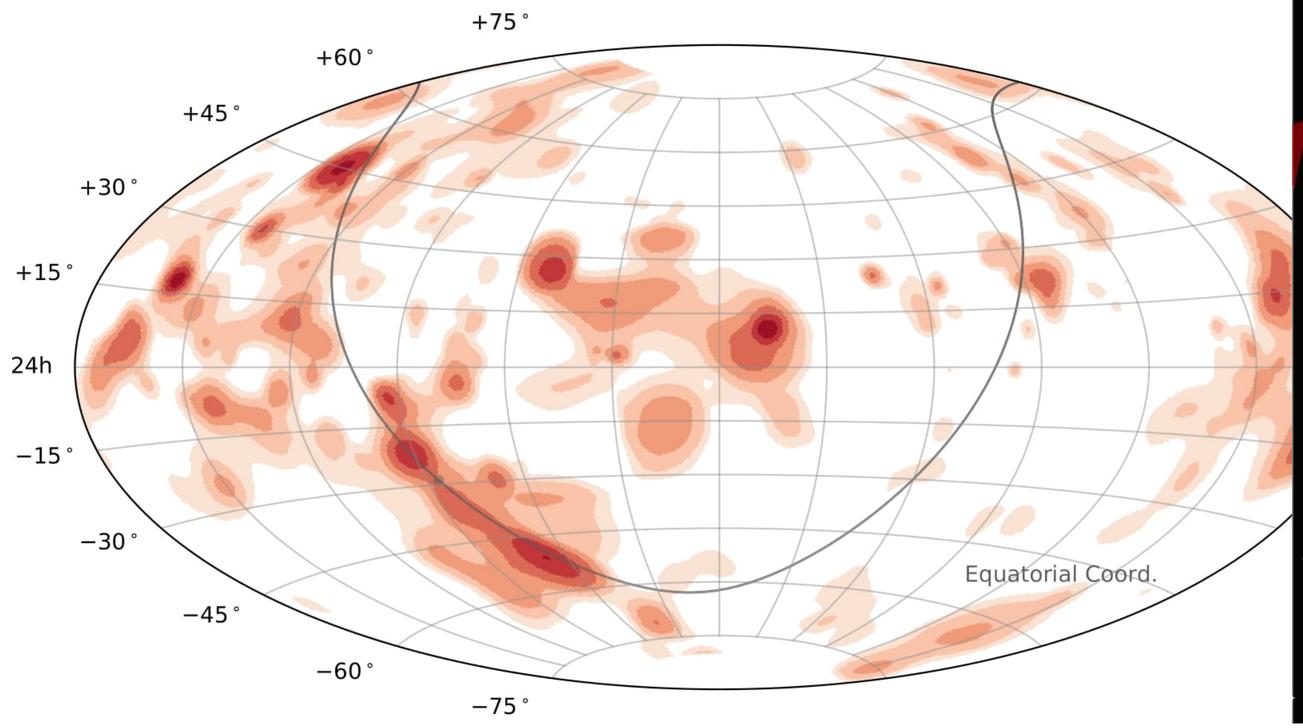

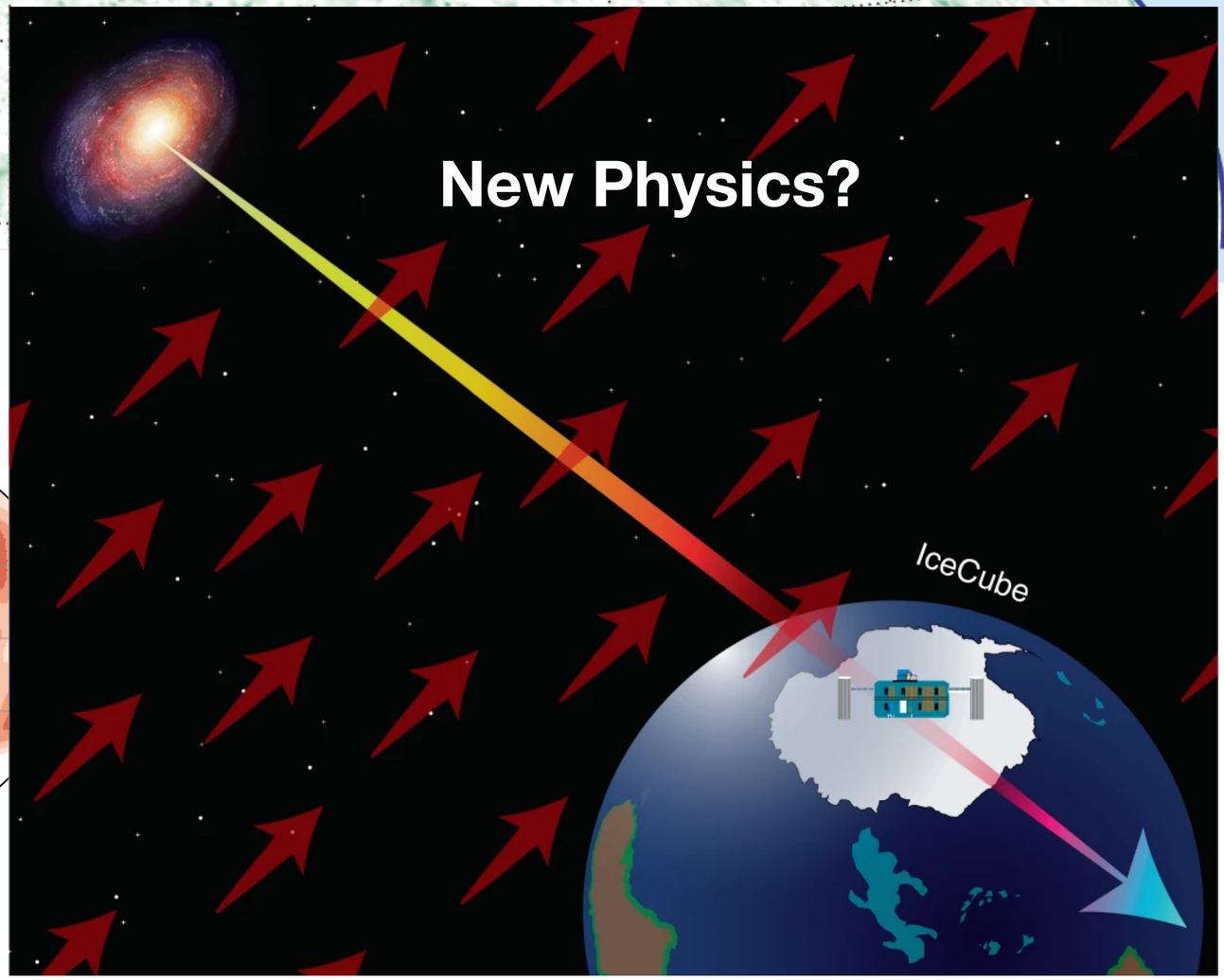

IceCube Beyond Astronomy: Neutrinos as a portal to New Physics

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Look for interactions between the “dark sector” and the Standard Model
Signatures of new physics could show up in neutrinos’

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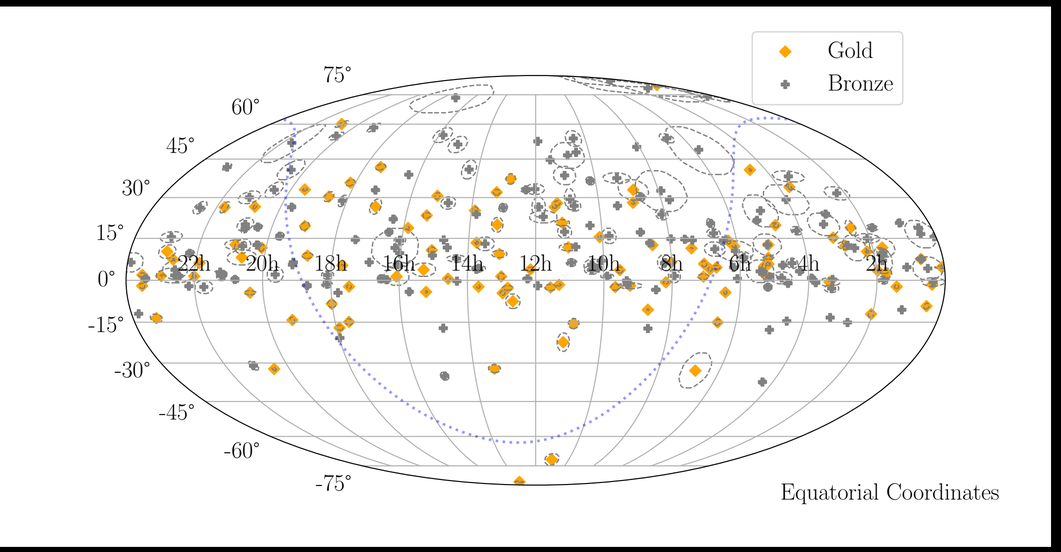
Directions



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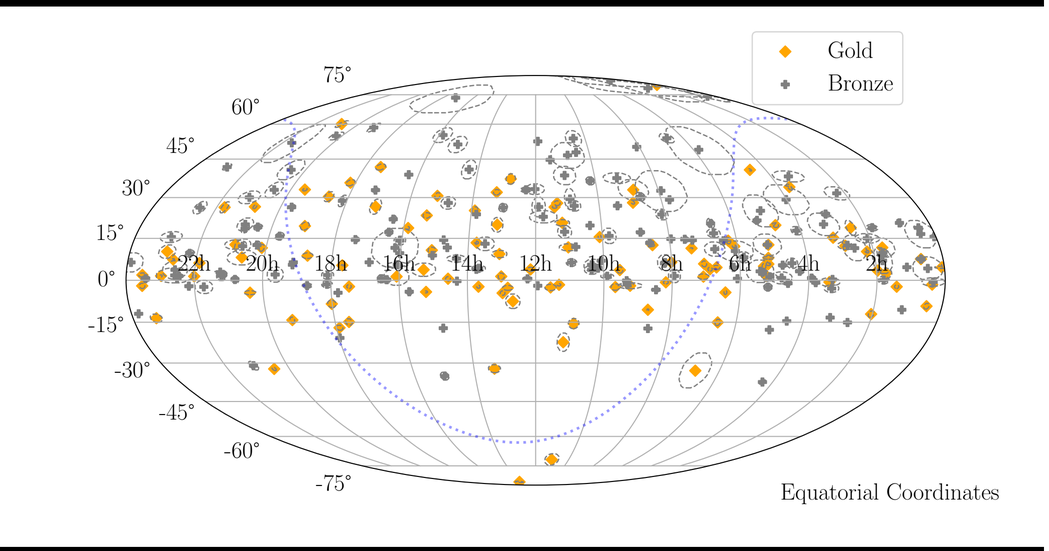
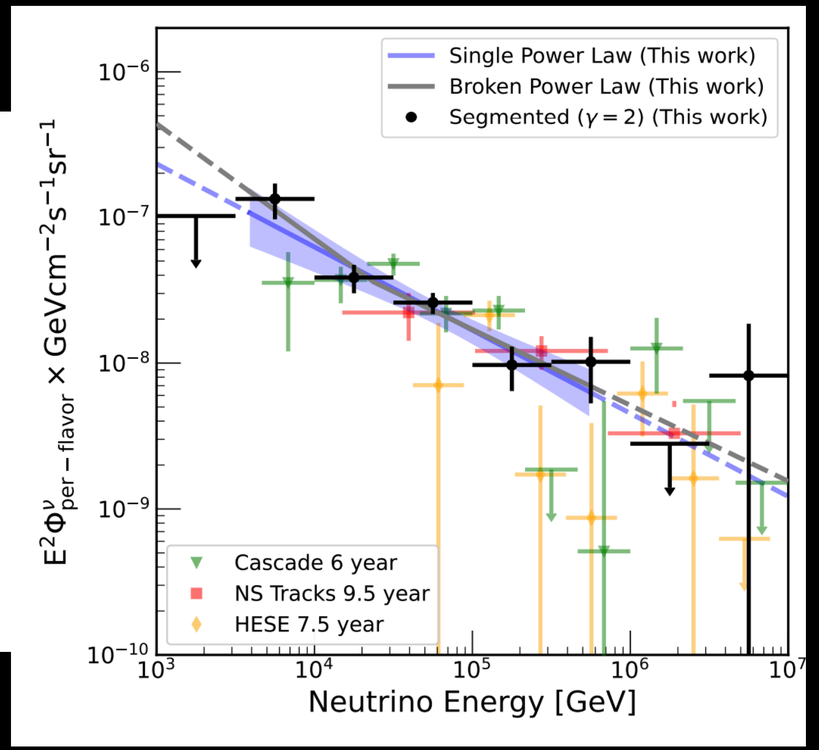


Spectrum



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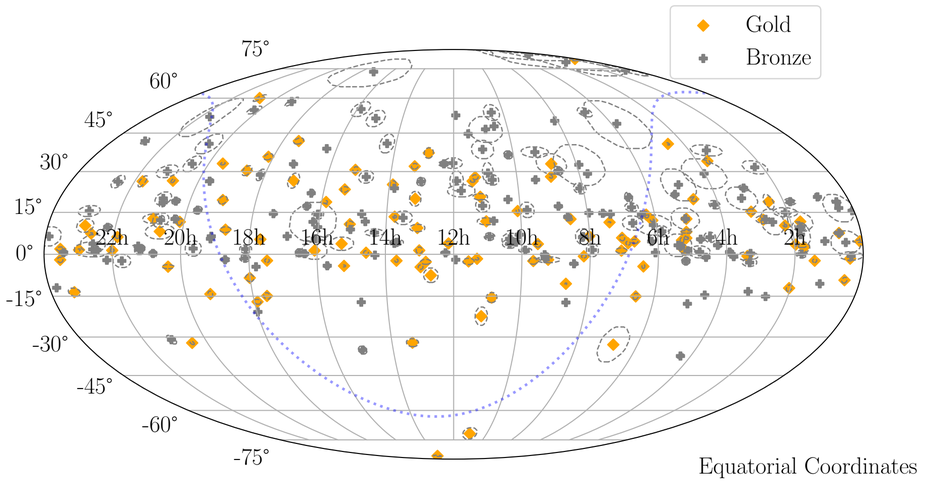
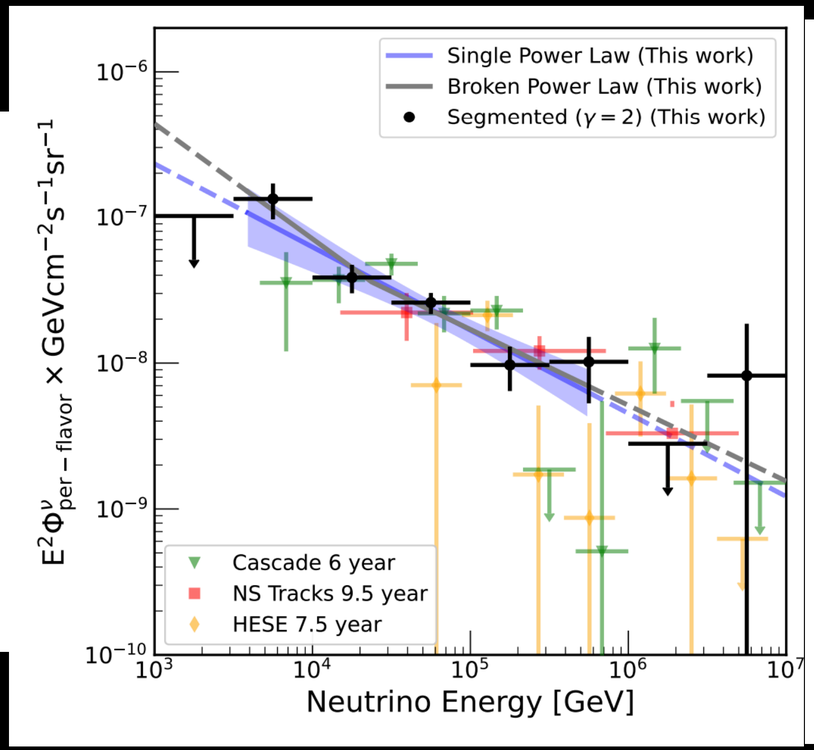
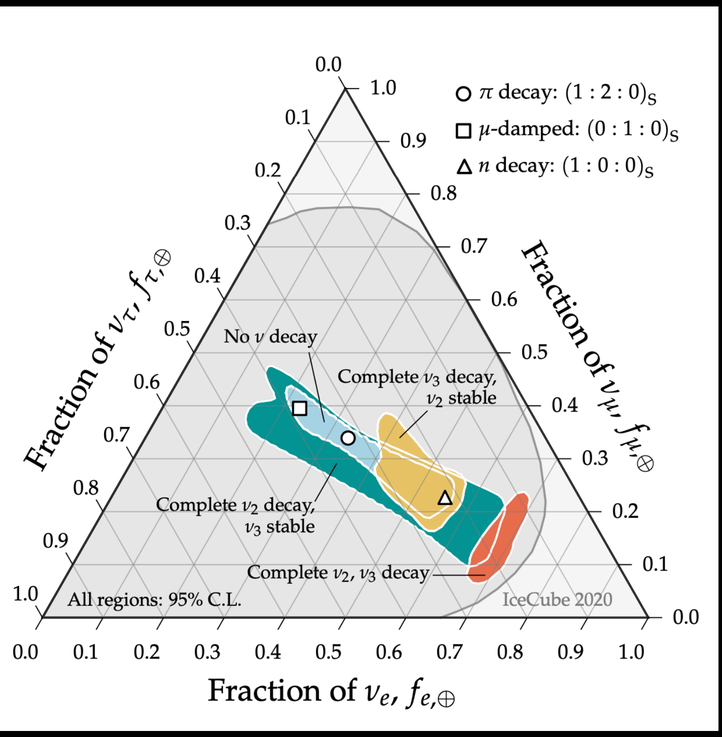


Spectrum

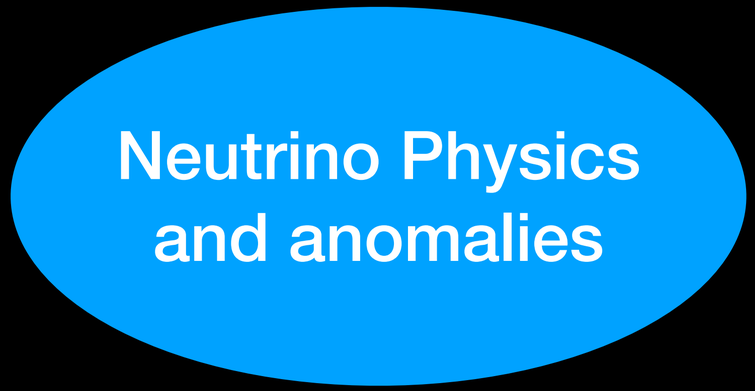


Flavor



IceCube Neutrinos Probing BSM Physics

Today



Indirect Dark Matter Searches

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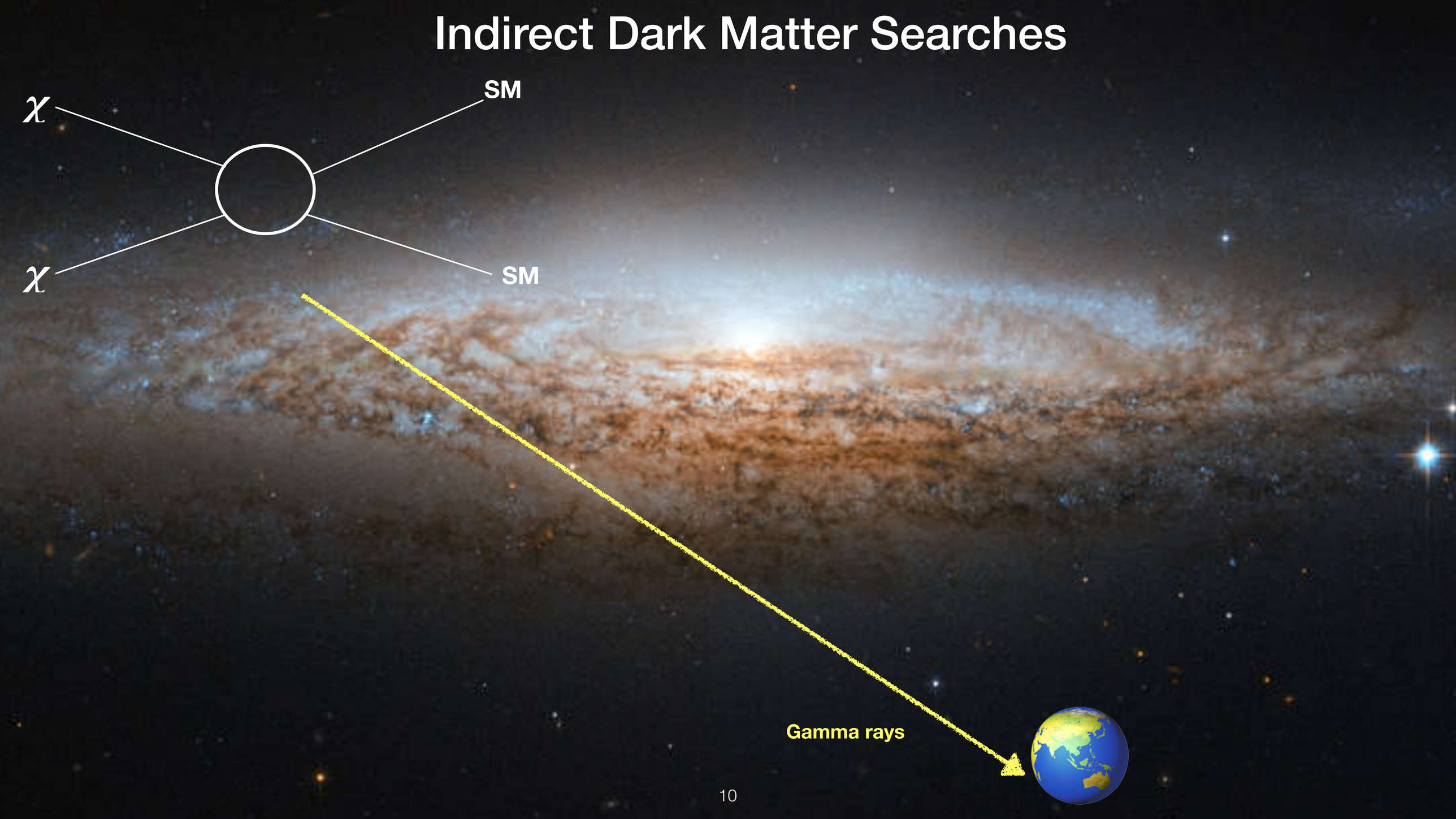
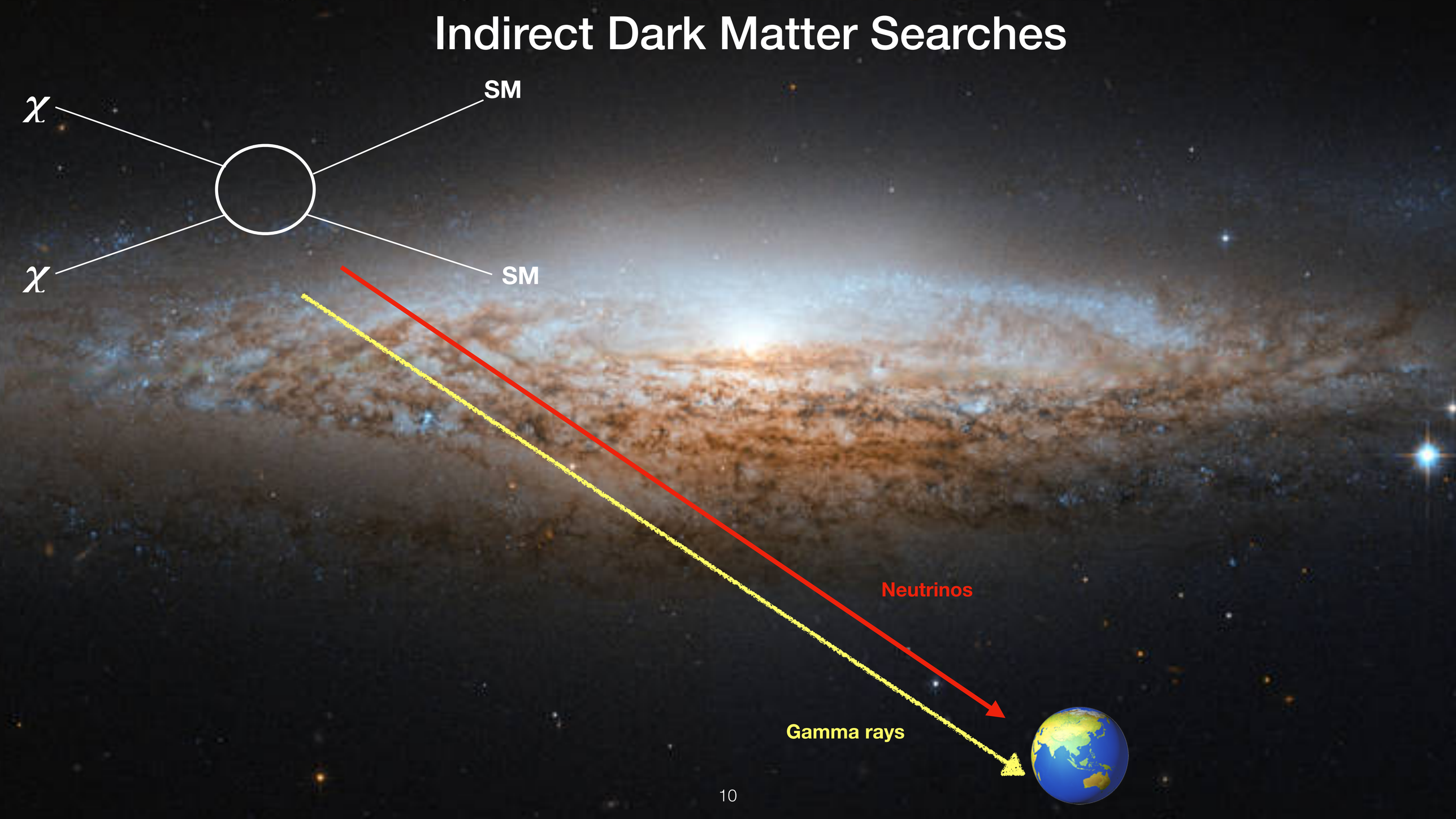
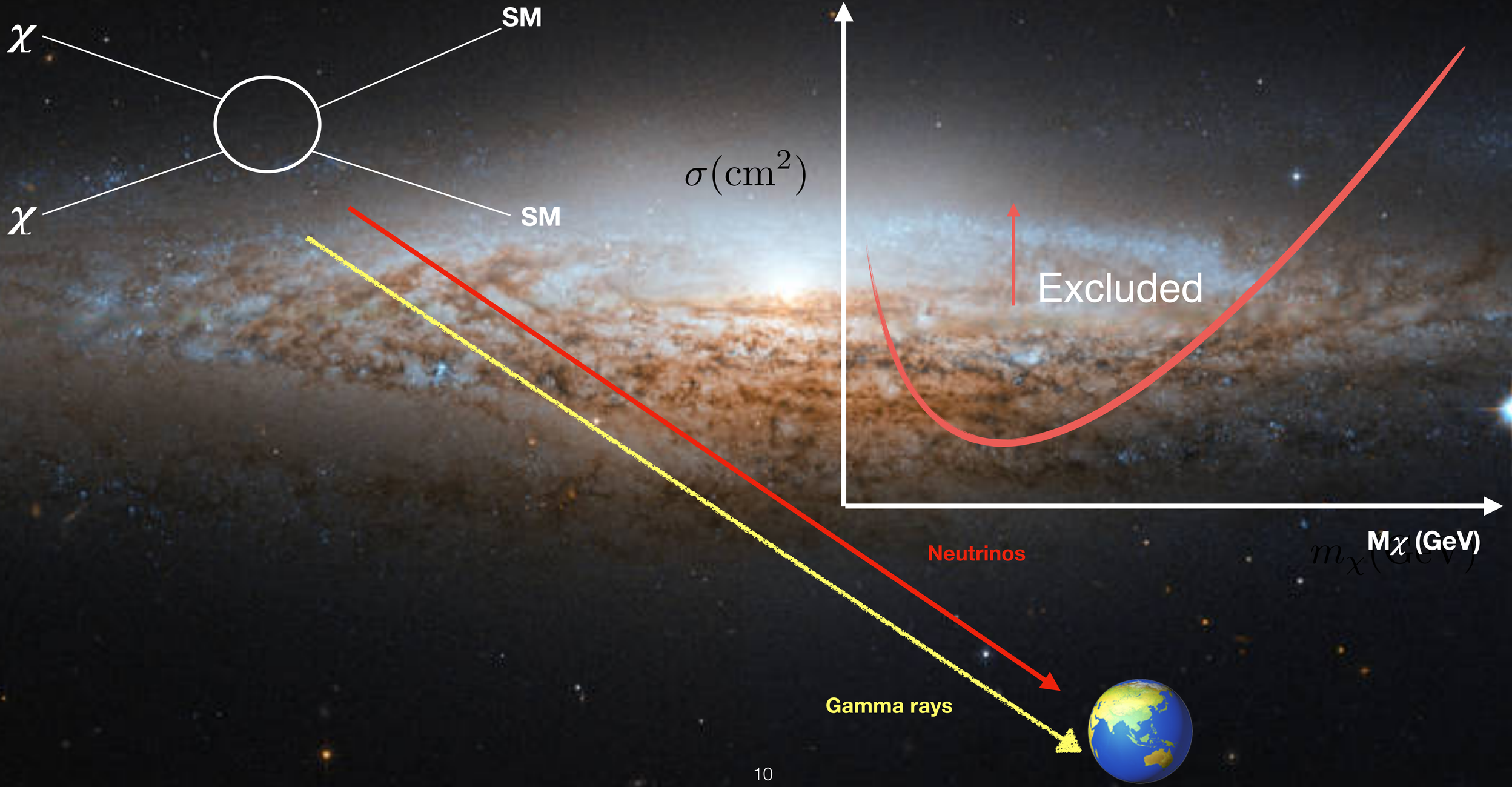


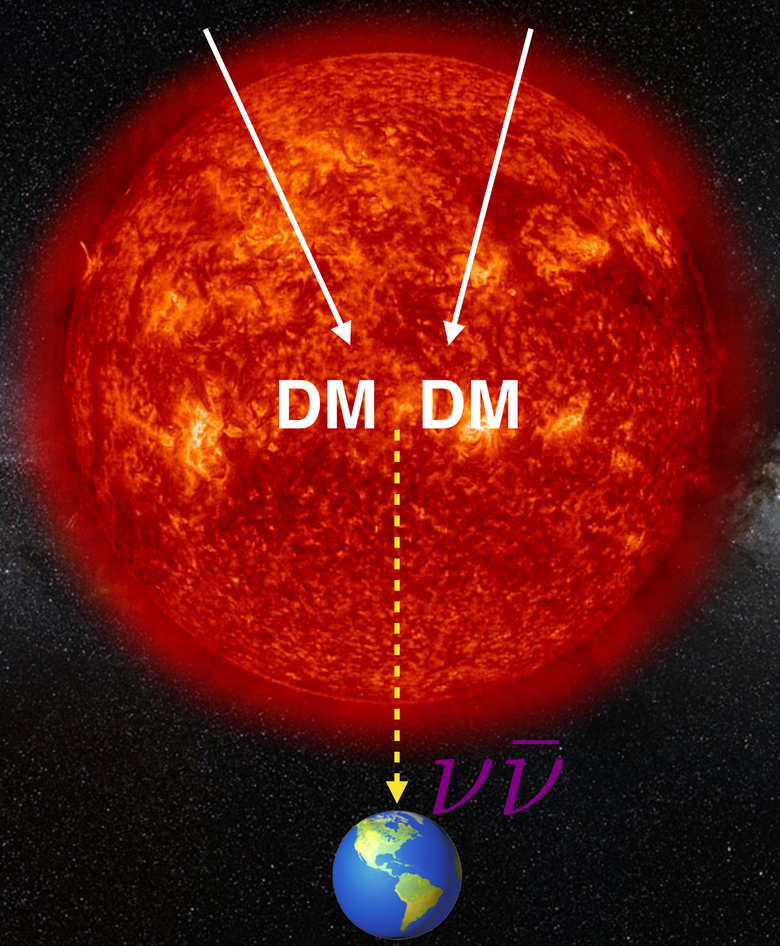
Indirect Dark Matter Searches



Indirect Dark Matter Searches

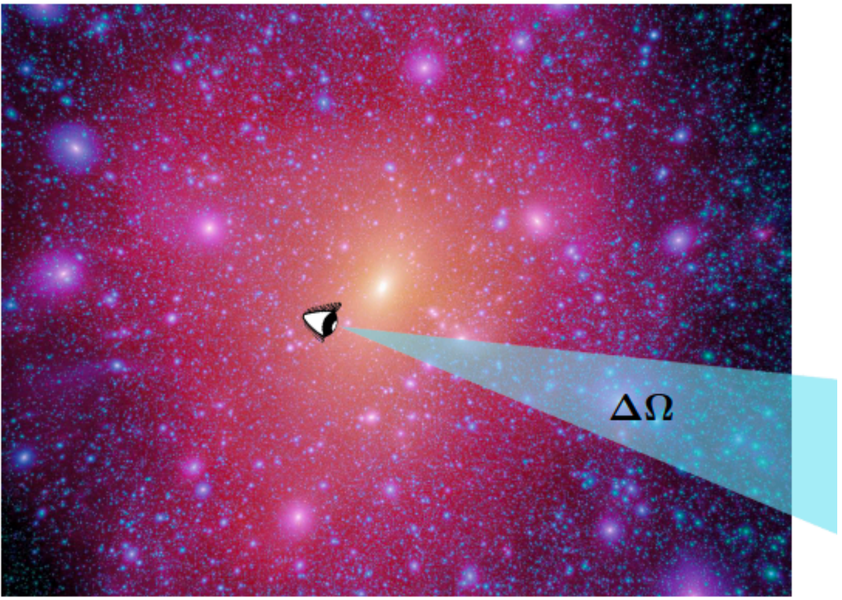


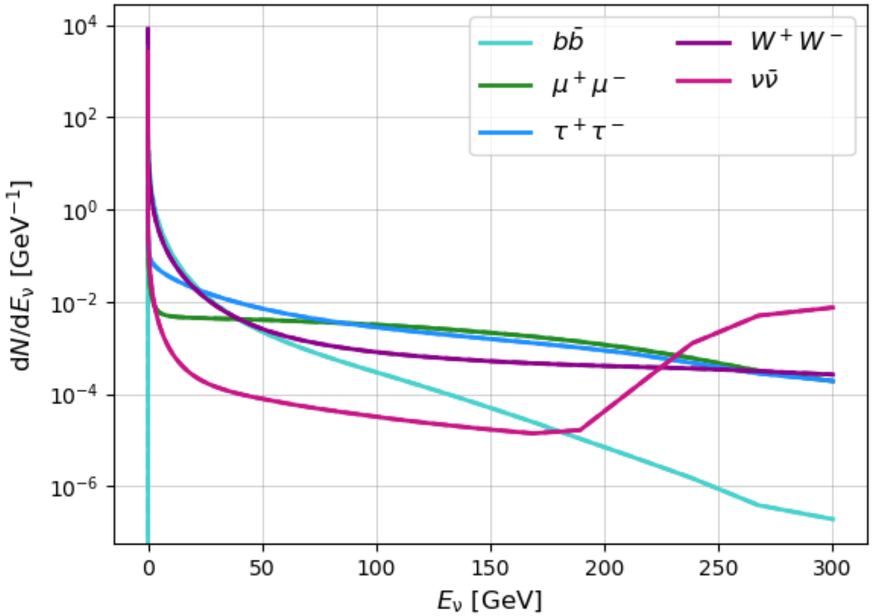
Astrophysical Targets

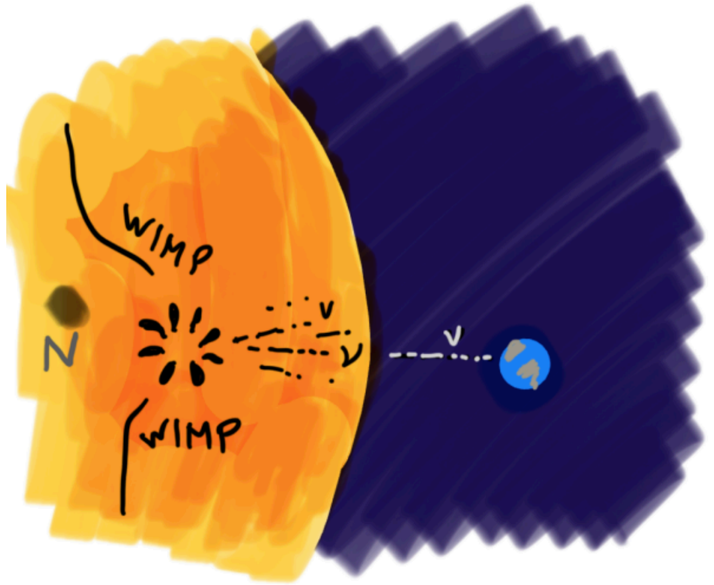


- Earth
- Sun
- Galactic Center
- Dwarf Galaxies
- Galactic Halo
- Diffuse Cosmological DM
- Galaxy Clusters

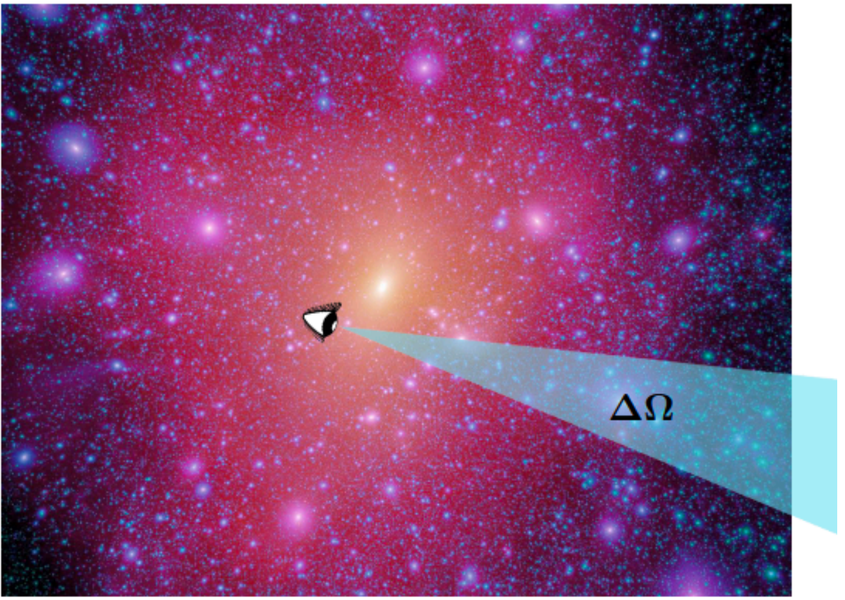
Assumptions

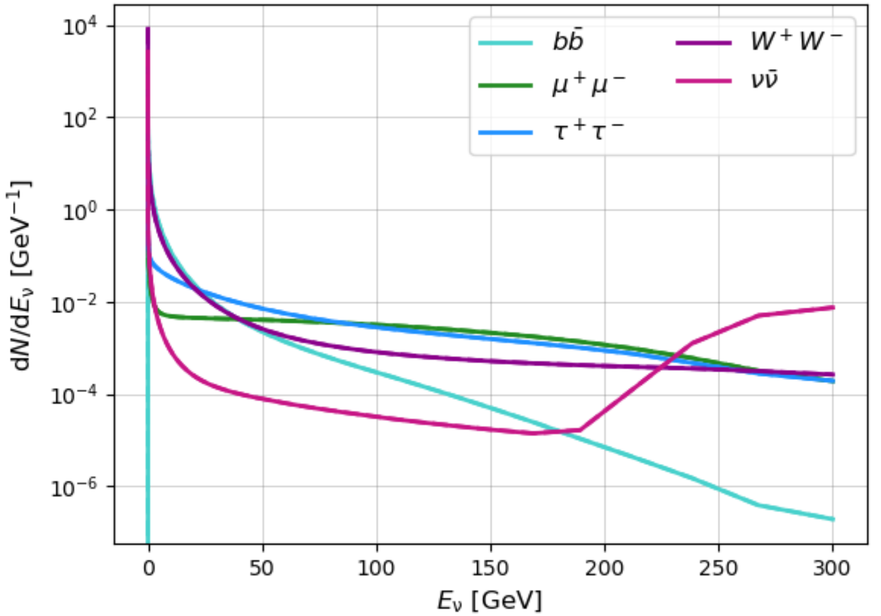


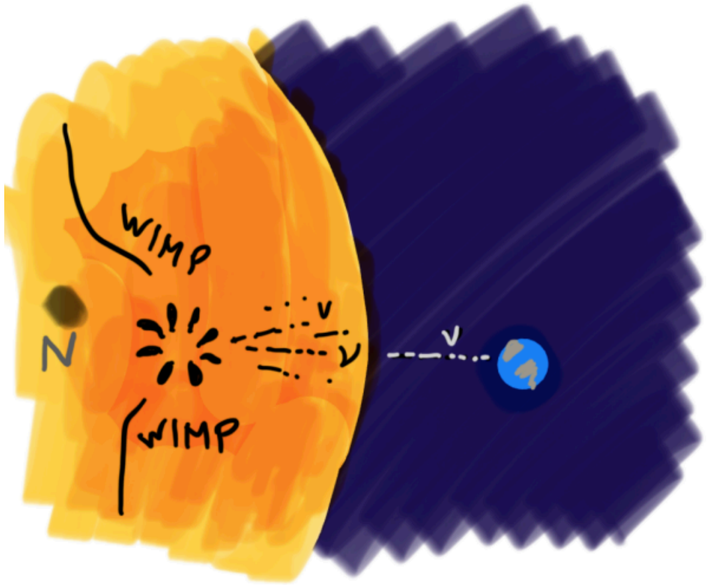




Assumptions

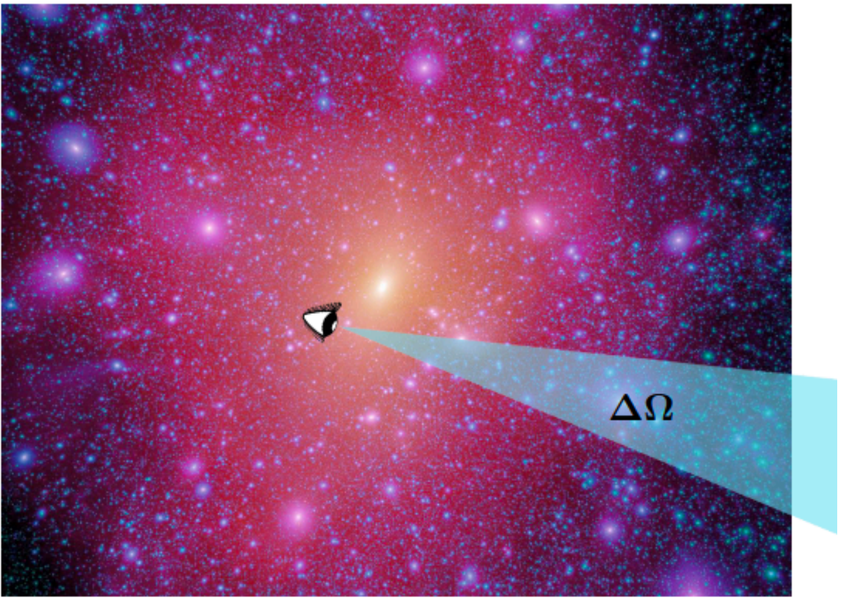


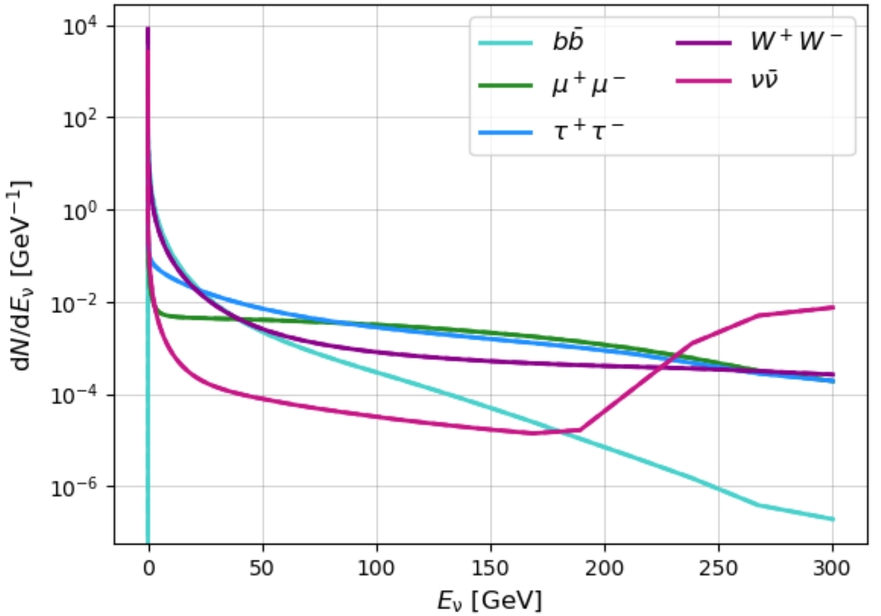


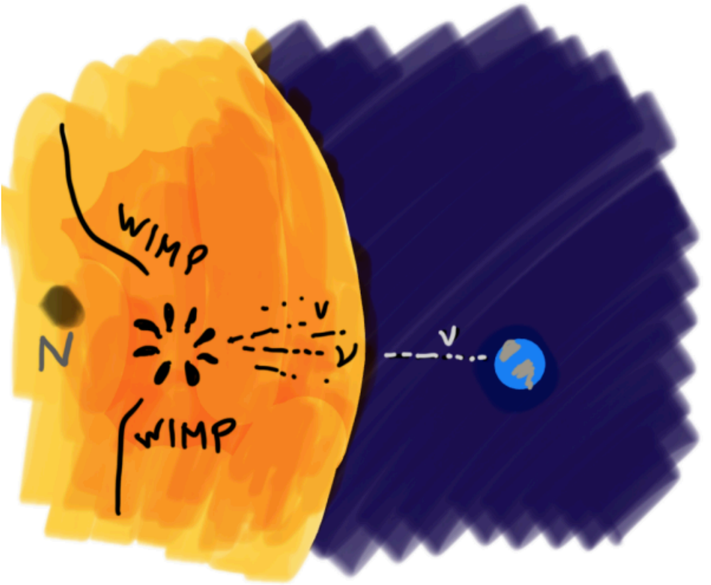


$$J_{\mathrm{ANN}} = \int_{\Omega} d\Omega \int_{l} \rho^2(r(\theta,\phi))dl \quad \text{or}$$

Assumptions







$$J_{\mathrm{ANN}} = \int_{\Omega} d\Omega \int_{l} \rho^2(r(\theta,\phi))dl \quad \text{or}$$

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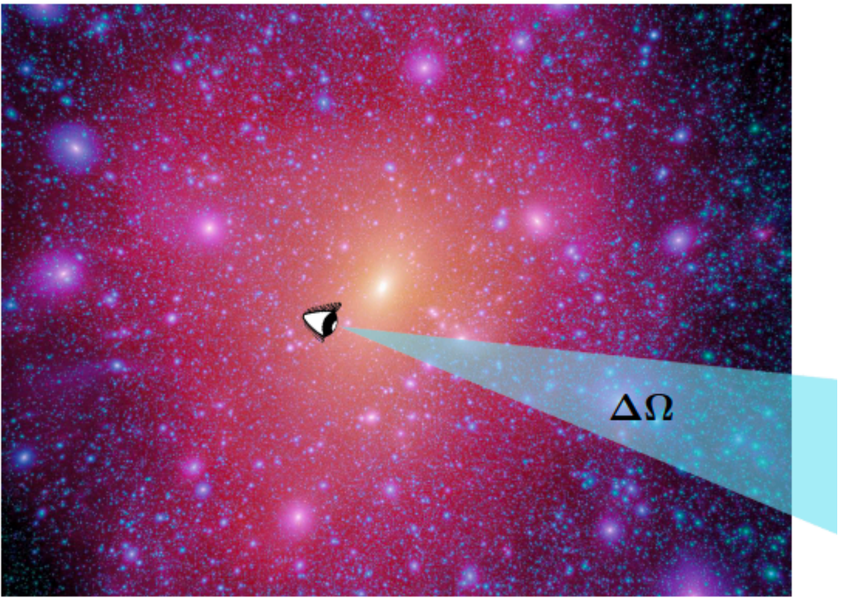
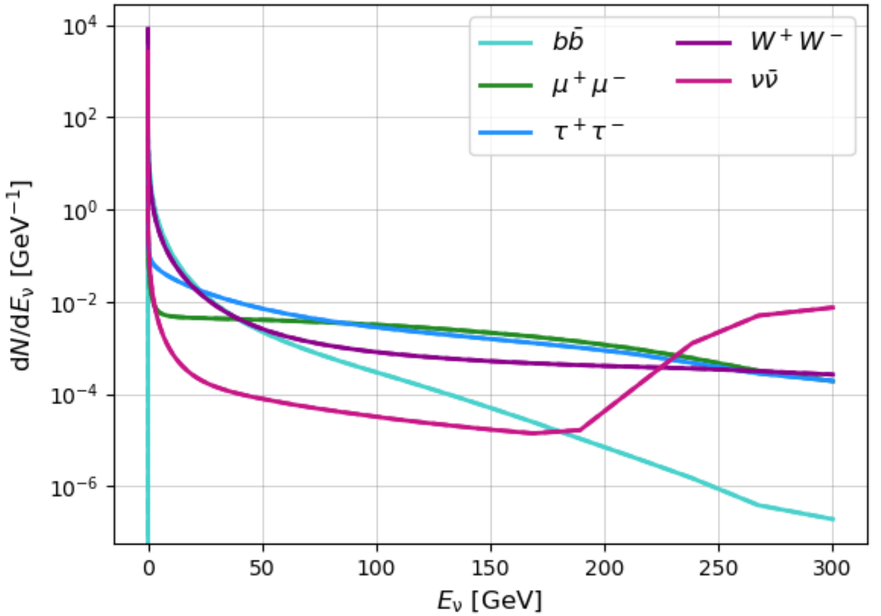
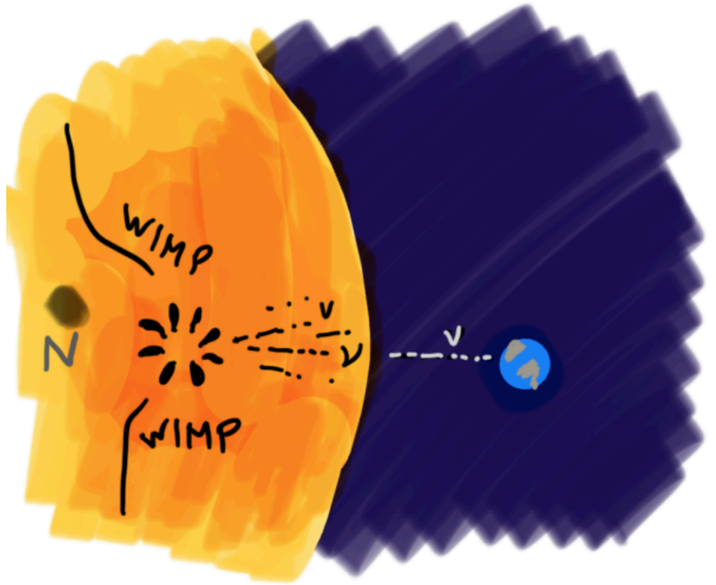
Assumptions







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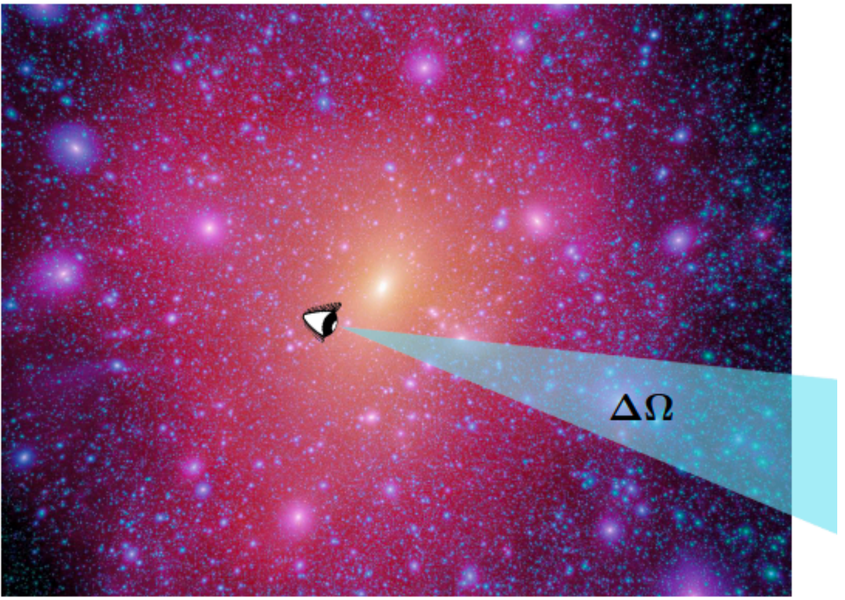
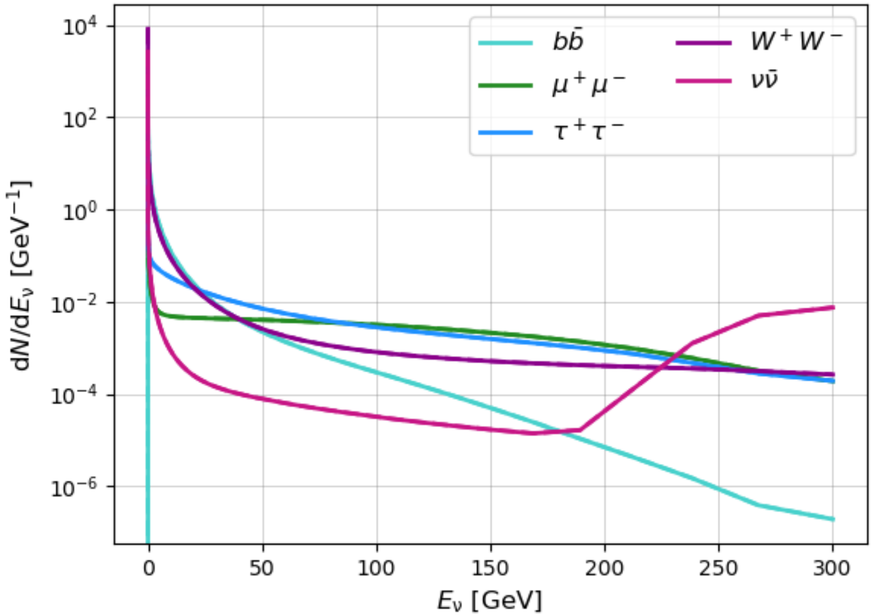
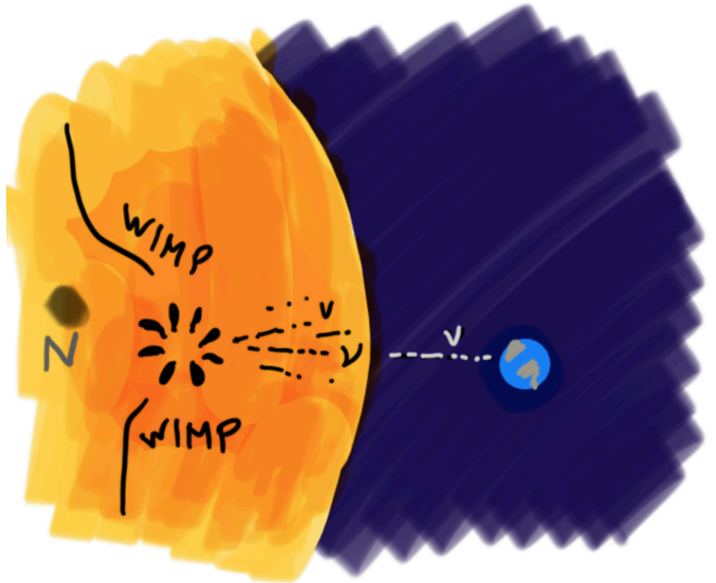
For dark matter density ρ in source at sky coord. (θ,ϕ), seen of size Ω over line of sight *l*

Assumptions







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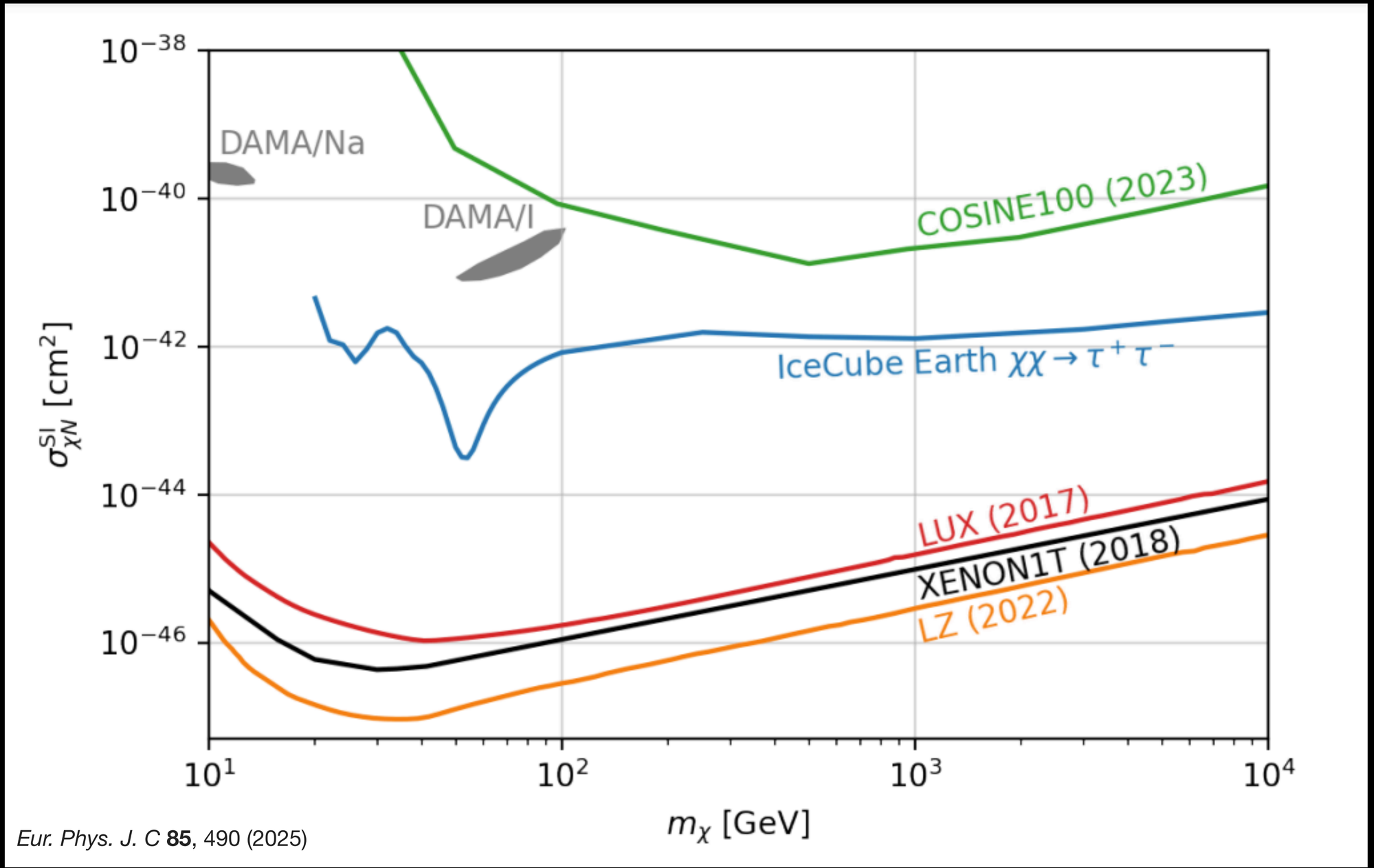
$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma_{ann}}{4\pi\, d^2}\frac{dN_\nu}{dE_\nu}$$

d= distance source-detector

Γ_{ann}= annihilation rate

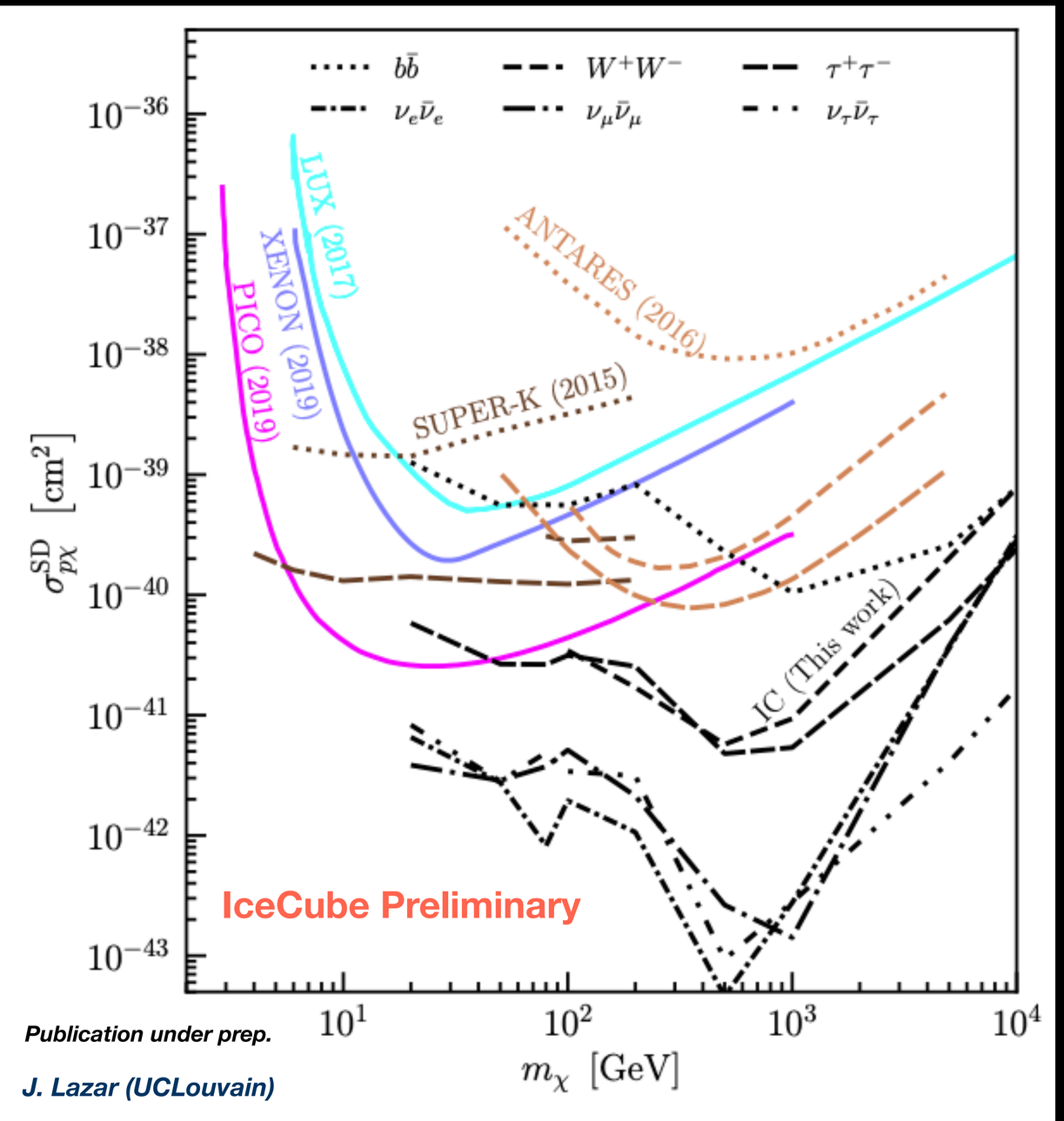
For dark matter density ρ in source at sky coord. (θ,ϕ), seen of size Ω over line of sight *l*

Recent Results: DM Capture and Annihilation in Earth



Eur. Phys. J. C **85**, 490 (2025)

Recent Results: Sun

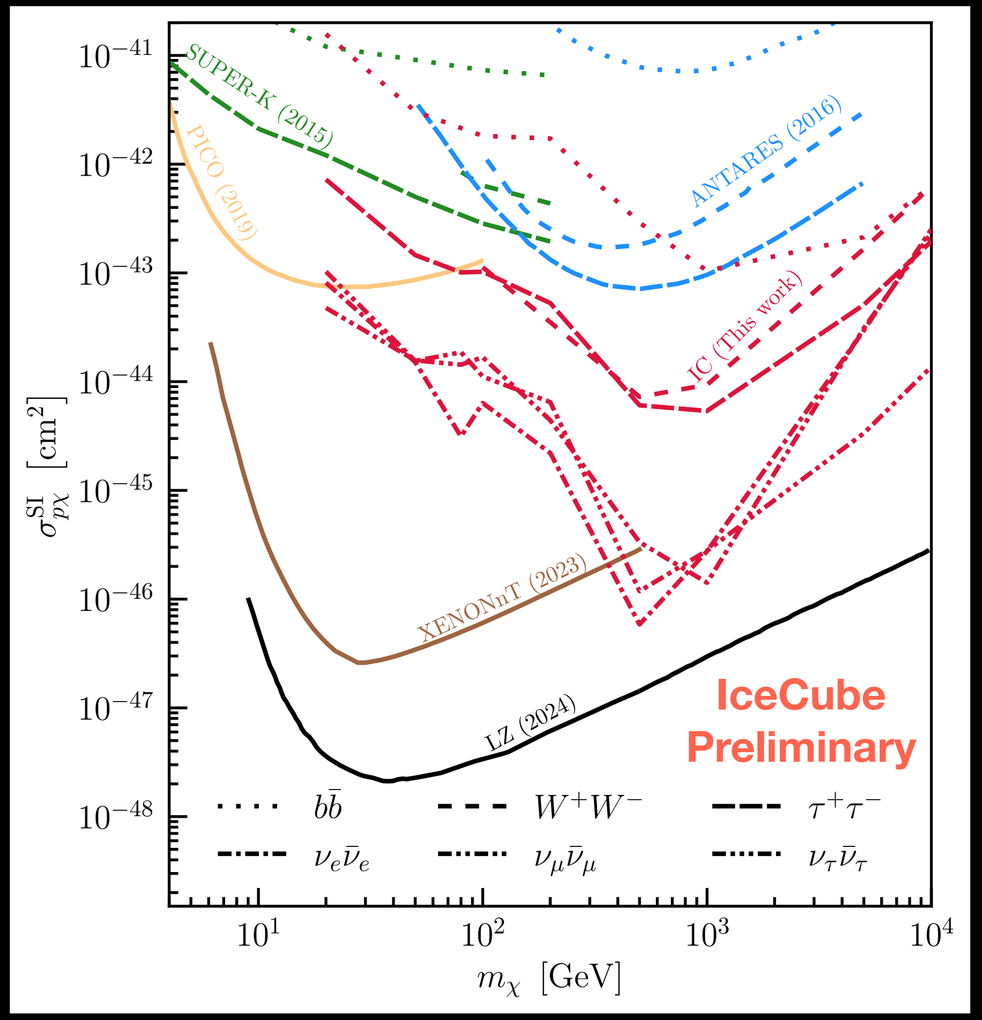


Publication under prep.

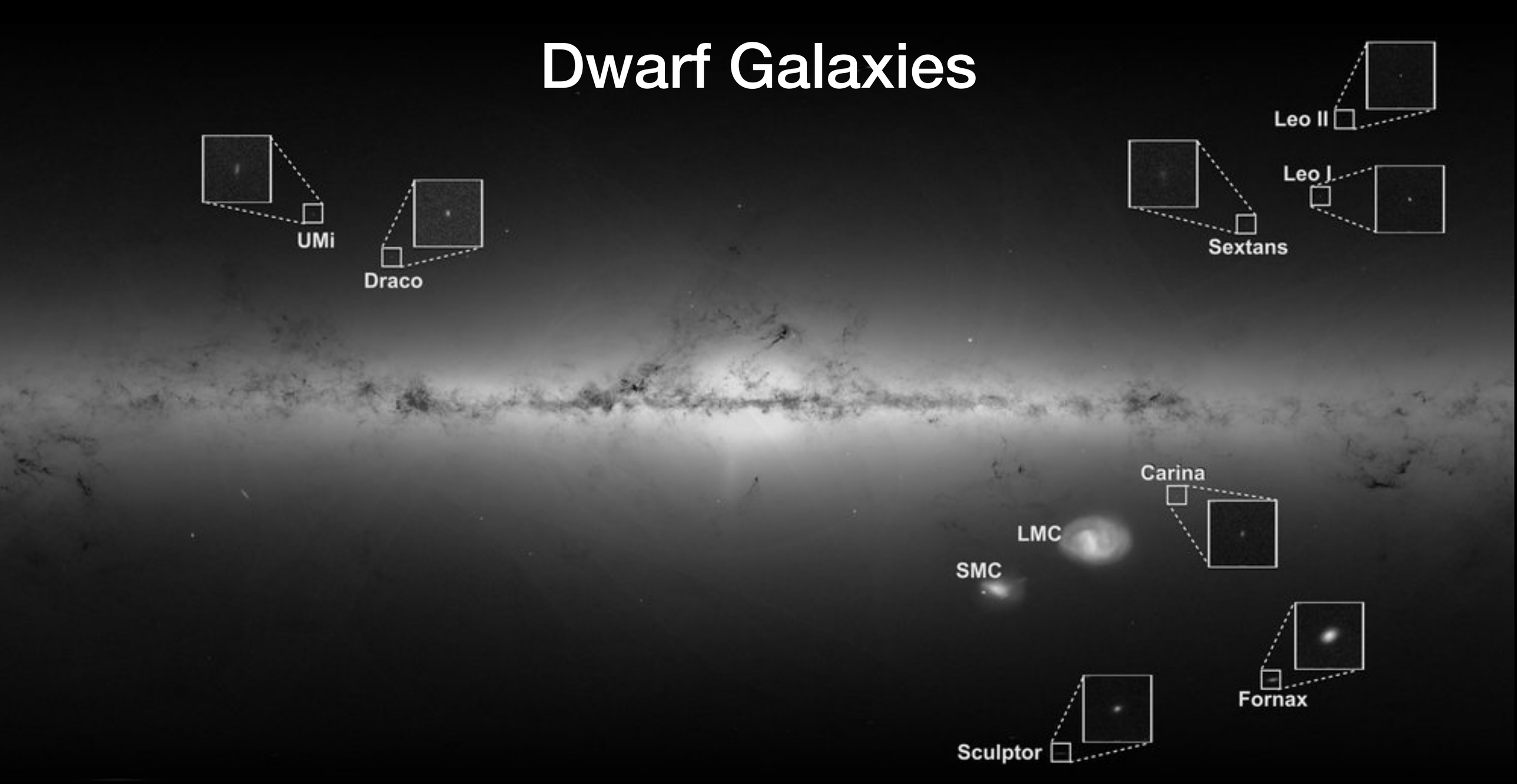
J. Lazar (UCLouvain)

$\chi\chi \rightarrow \nu\bar{\nu}$

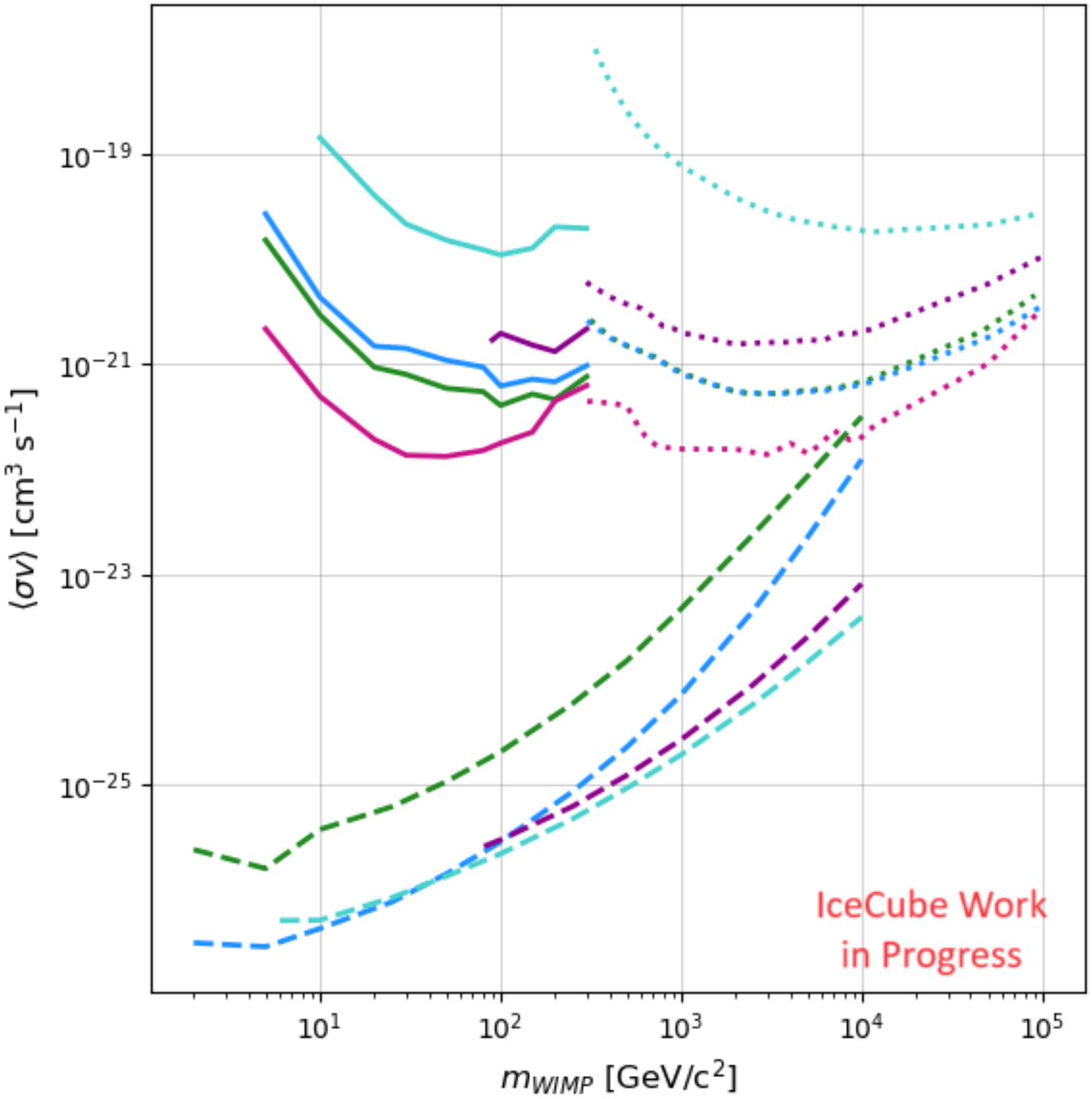
Orders of magnitude stronger than direct detection constraints for spin-dependent scattering

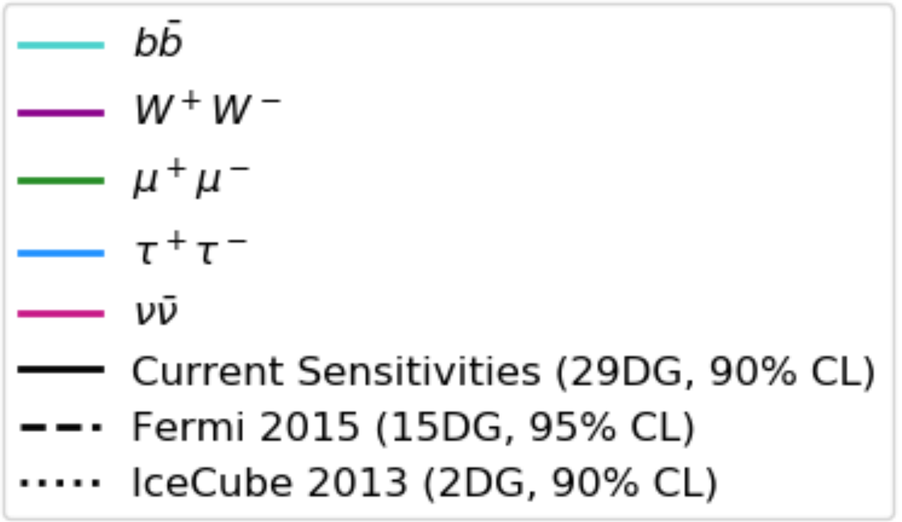


Dwarf Galaxies



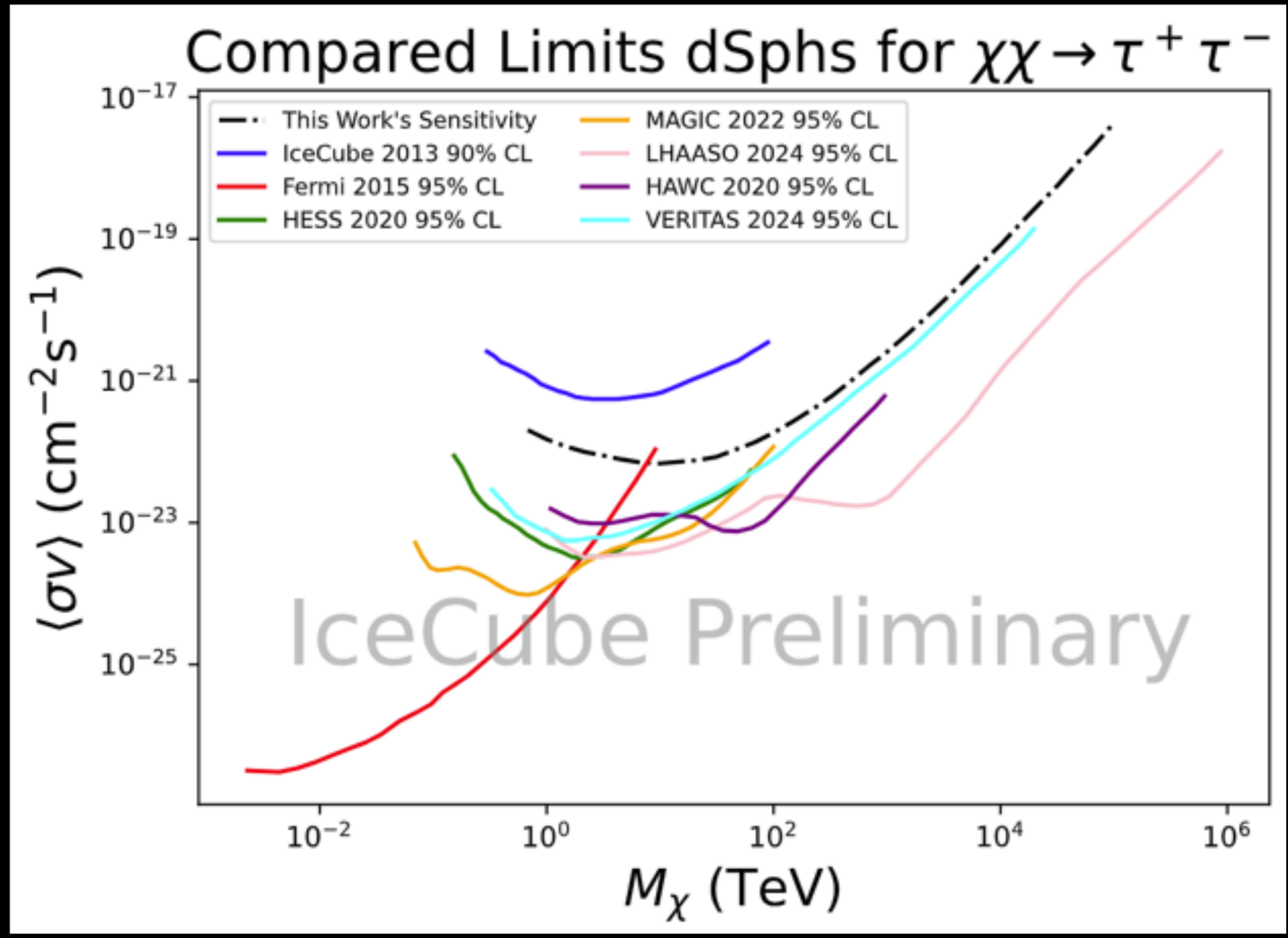
GeV scale DM in dwarfs





Constraints from Dwarf Galaxies

TeV—PeV DM



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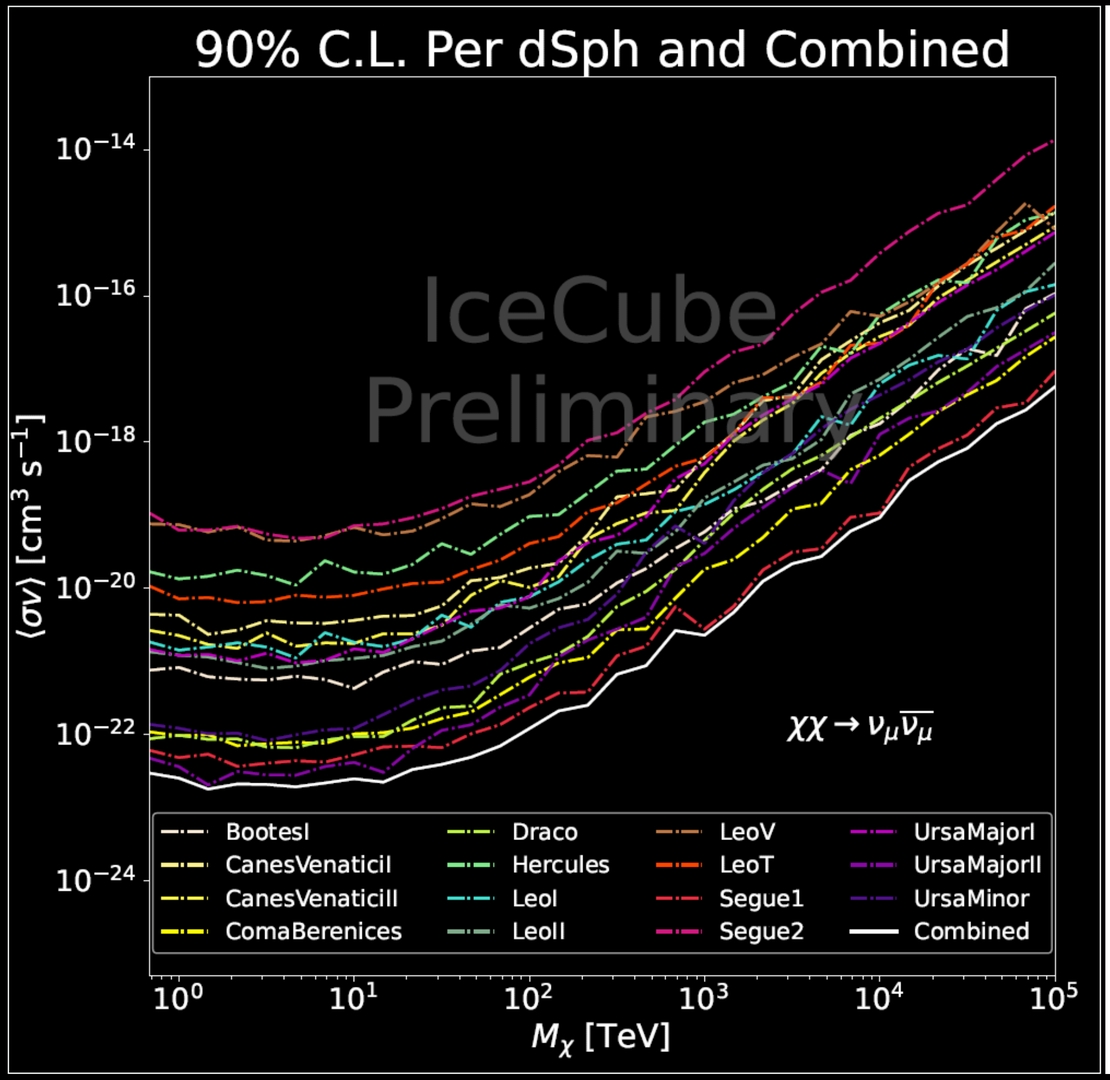
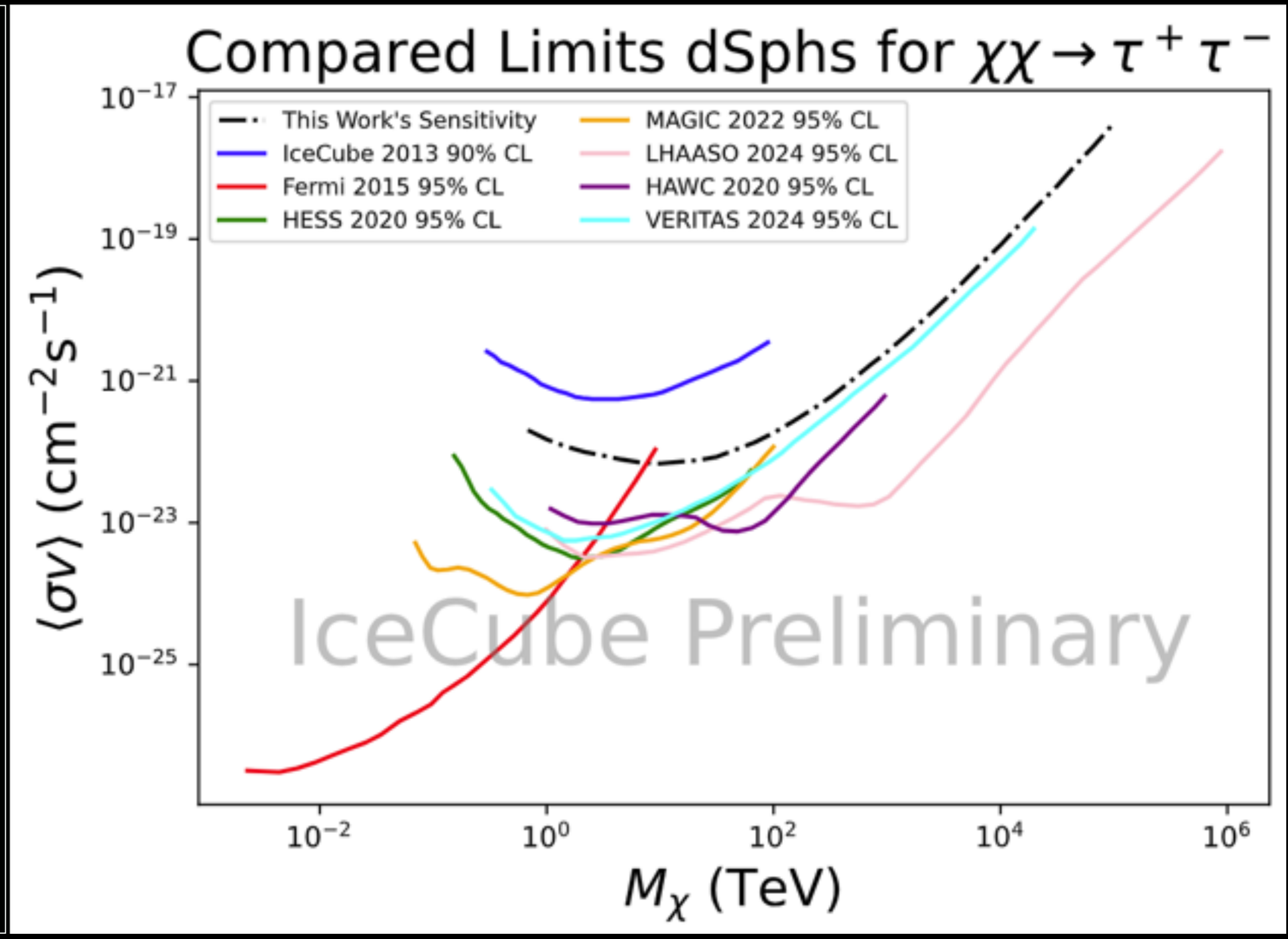
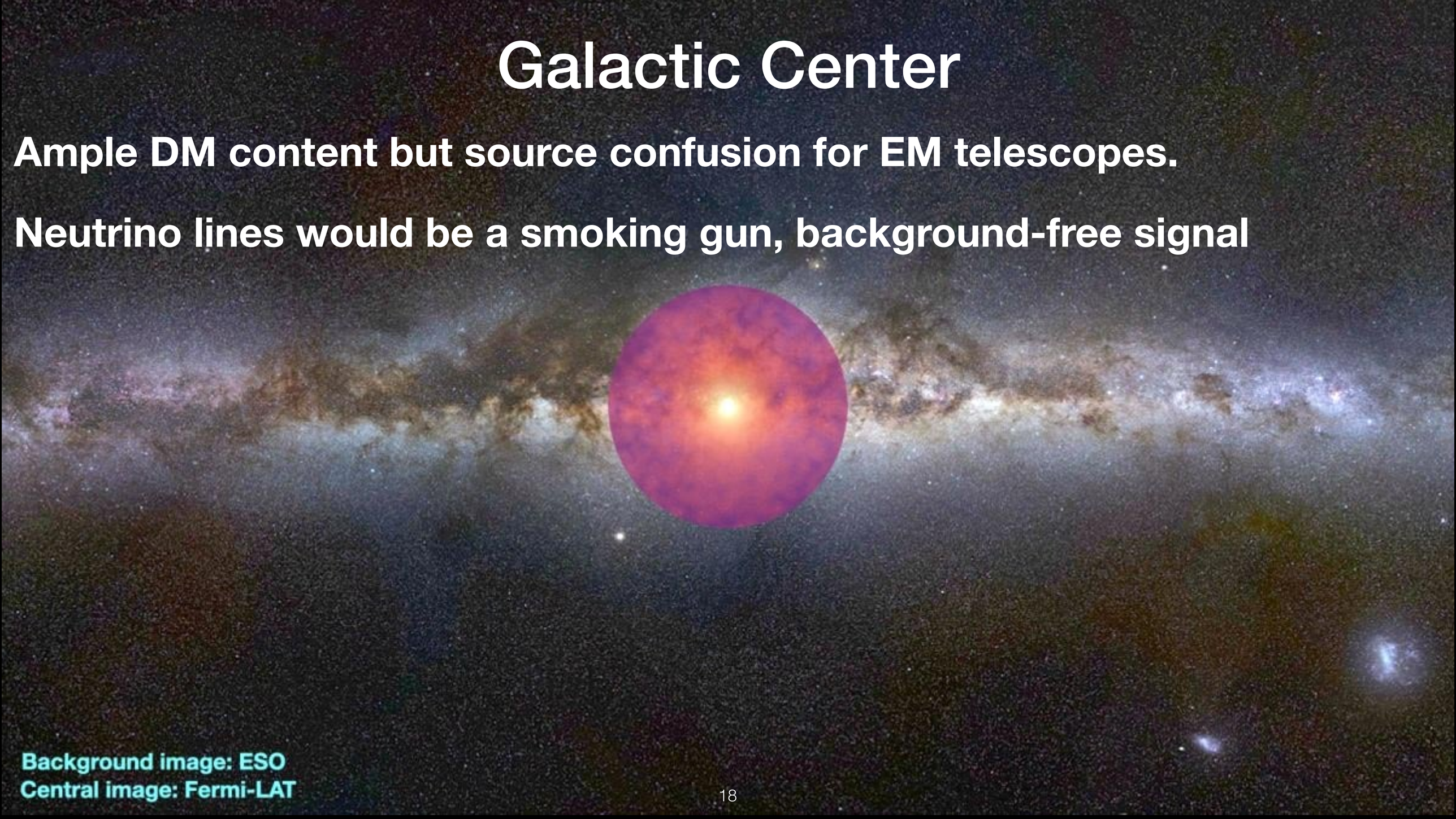




Galactic Center

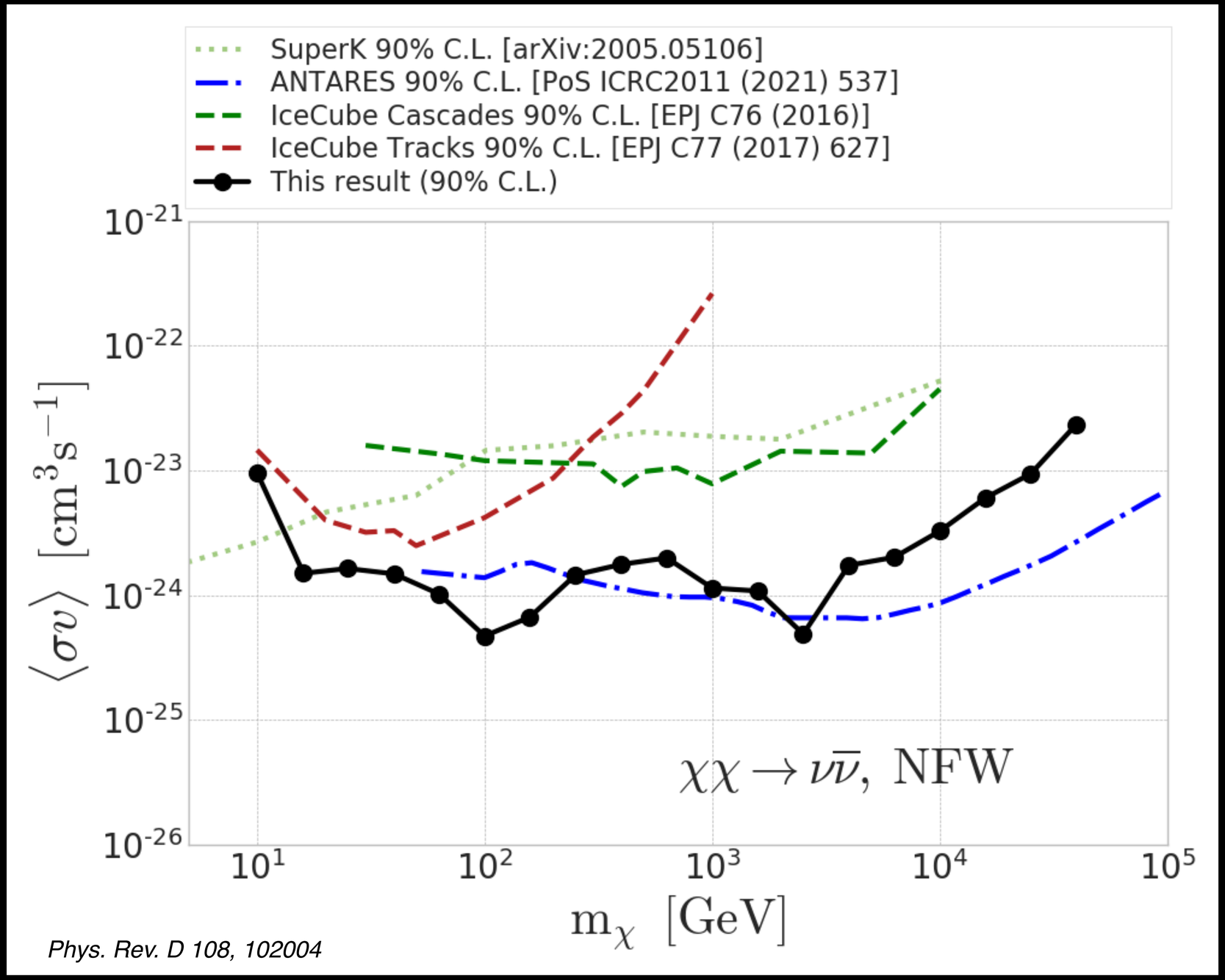
Ample DM content but source confusion for EM telescopes.

Neutrino lines would be a smoking gun, background-free signal



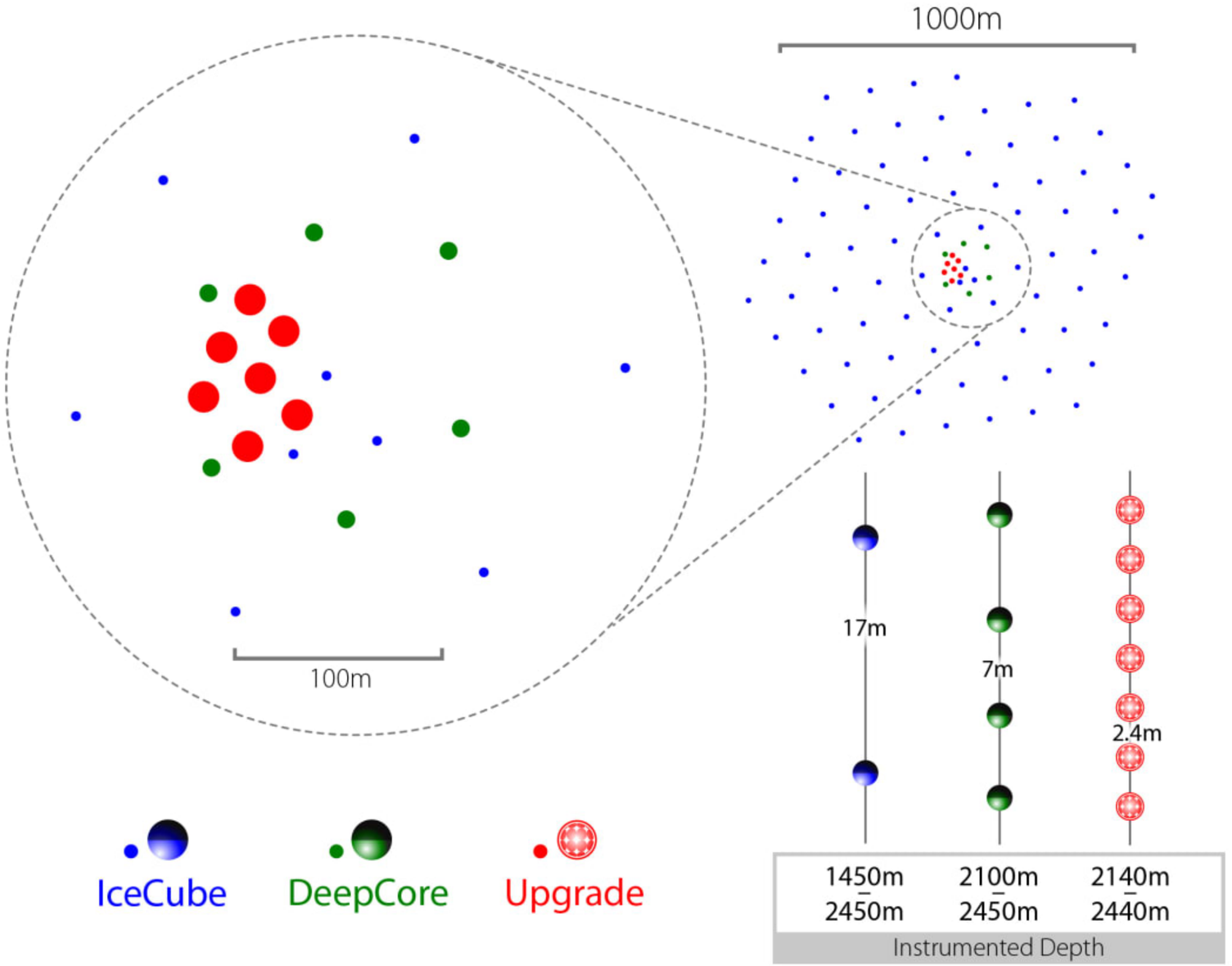
Background image: ESO
Central image: Fermi-LAT

Recent Results: Galactic Center



Phys. Rev. D 108, 102004

Looking Ahead: IceCube Upgrade



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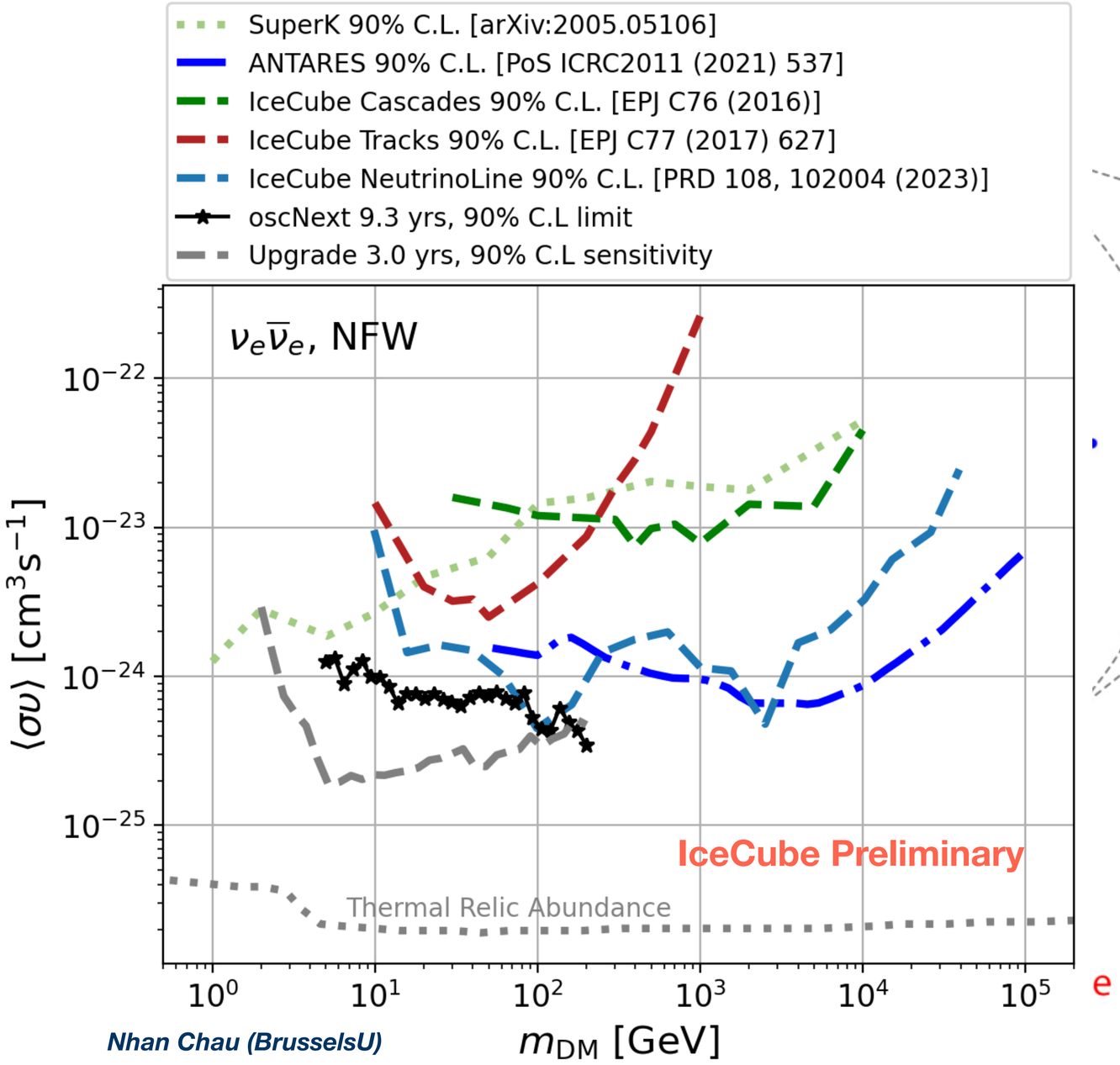

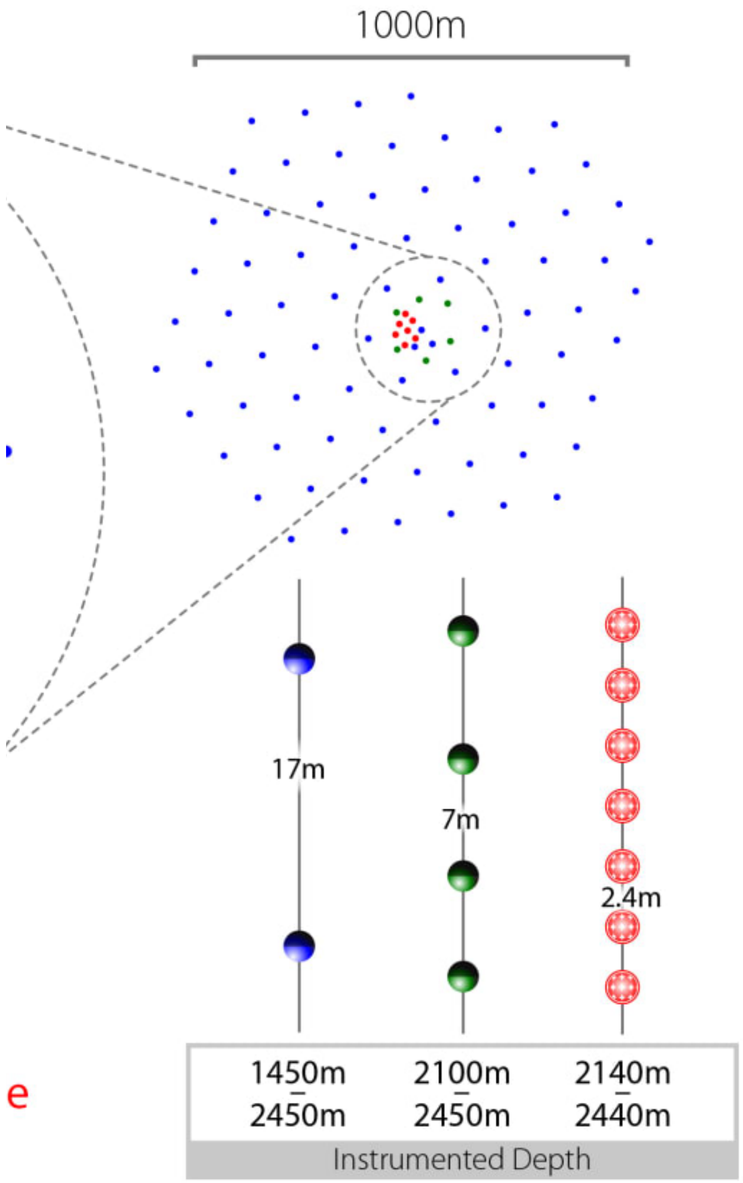

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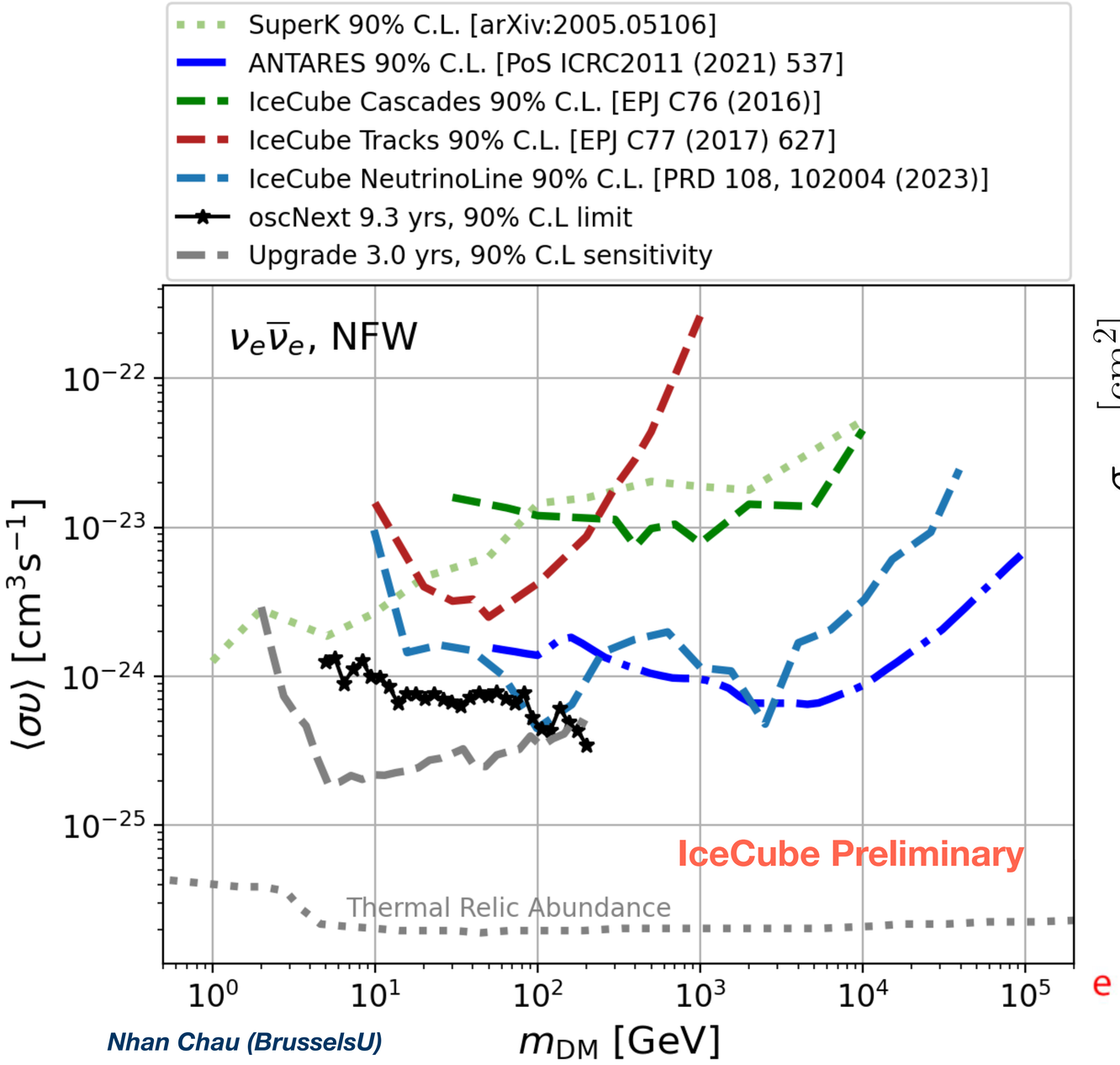
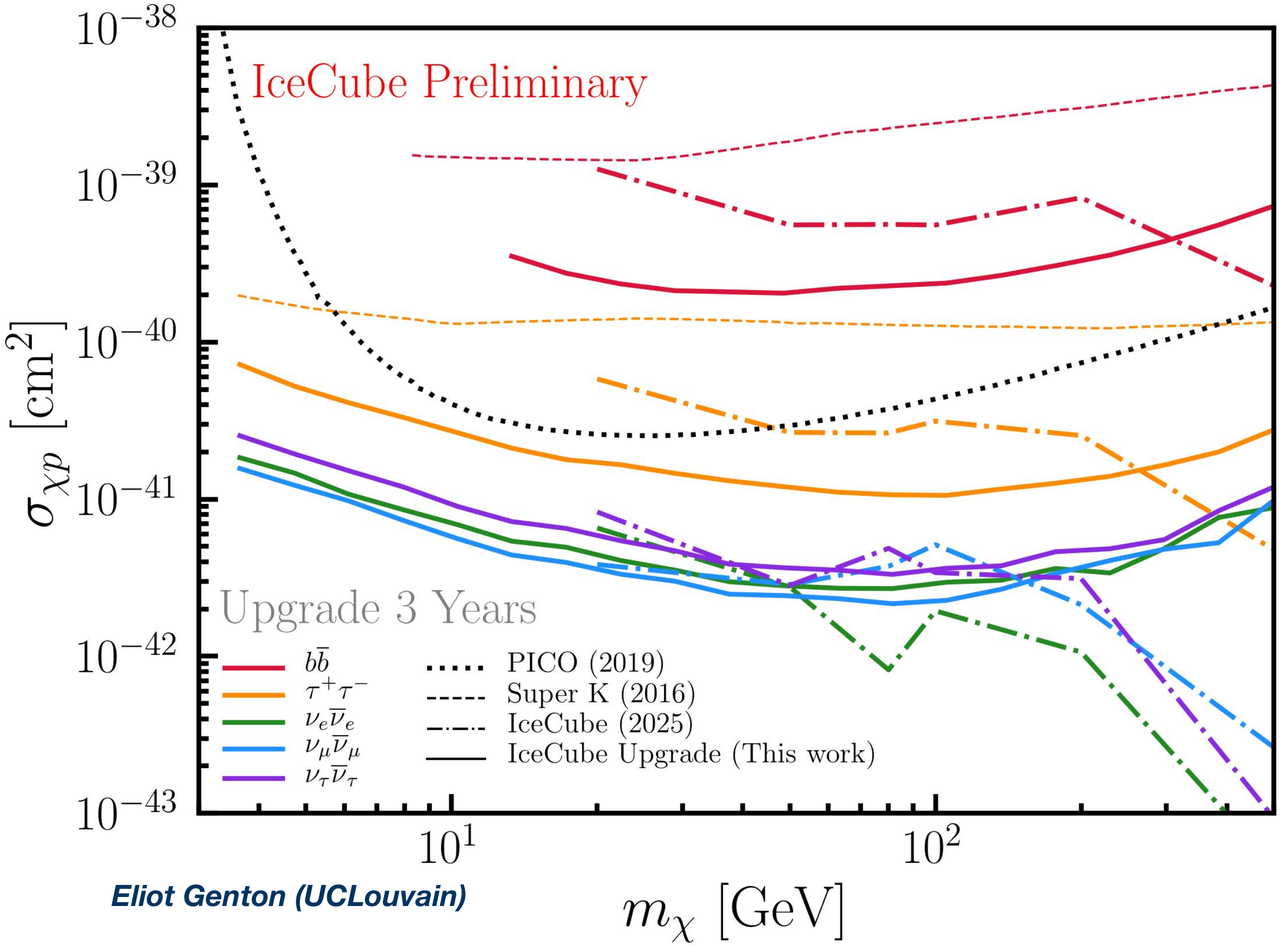
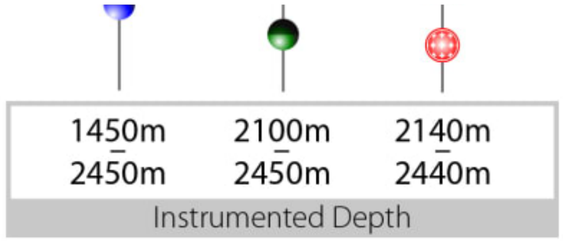


Nhan Chau (BrusselsU)



Eliot Genton (UCLouvain)



IceCube Neutrinos Probing Particle Physics

Signatures of new physics could show up in neutrino directions, spectrum and flavor…

Dark Matter

Neutrino Physics

Search for Exotics

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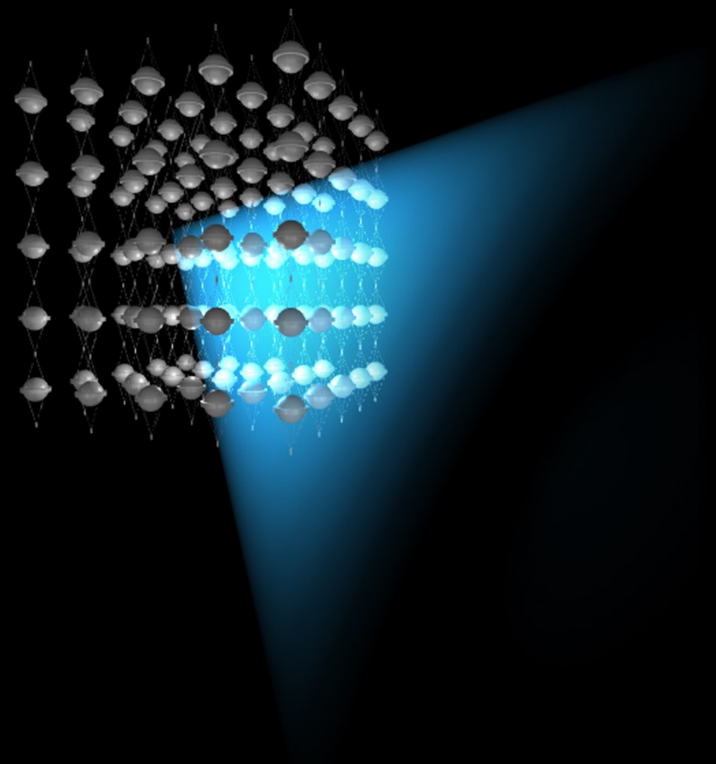

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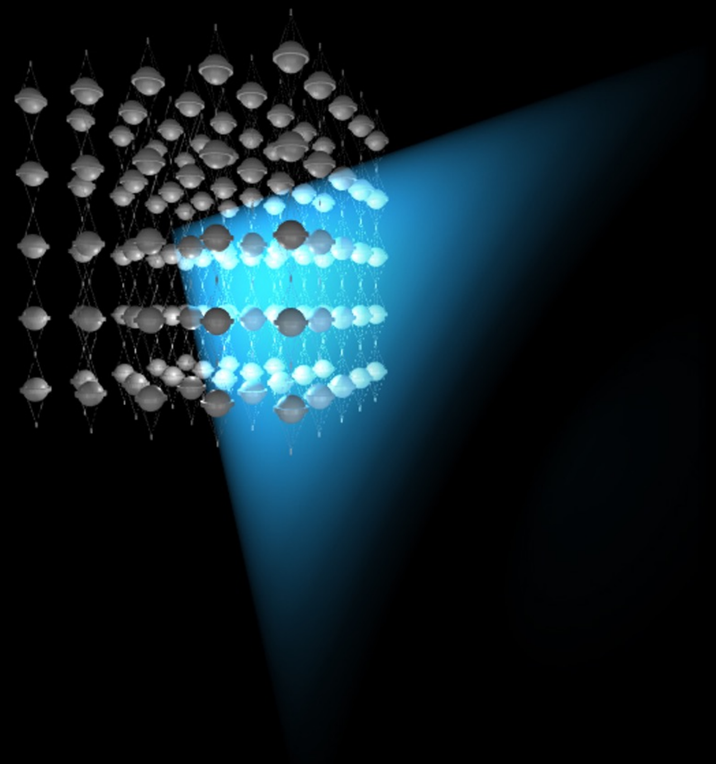


Or in the form of rare event topologies…

Upcoming Works from IceCube

- **Heavy Neutral Leptons**
- **Multi-messenger DM searches (Combined ν+γ search with dwarf-spheroidals)**
- **Neutrino-DM Interactions in point sources**
- **Search for Lorentz Invariance Violation**
- **Neutrino Trident Production**
- **Long-lived particles**
- **Fractionally charged particles**
- **Sterile Decay**
- **Magnetic Monopoles**

Stay Tuned

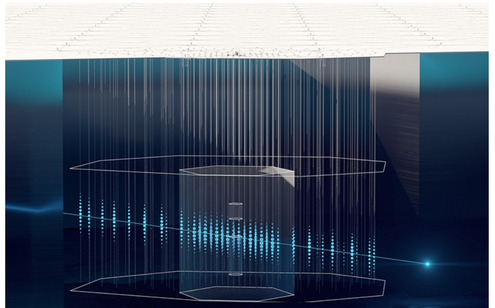
Future

- **IceCube has completed nearly 15 years of successful operations with robust measurements of a TeV—PeV neutrino flux.**

- **Neutrinos offer a unique window into extensions of the SM.**

- **Recent searches have placed some world-leading constraints on various BSM parameters.**

- **Low energy upgrade will extend these searches to unprecedented sensitivity in the coming years. Highly complementary to terrestrial beam-dump, and photon-based astrophysical detectors.**



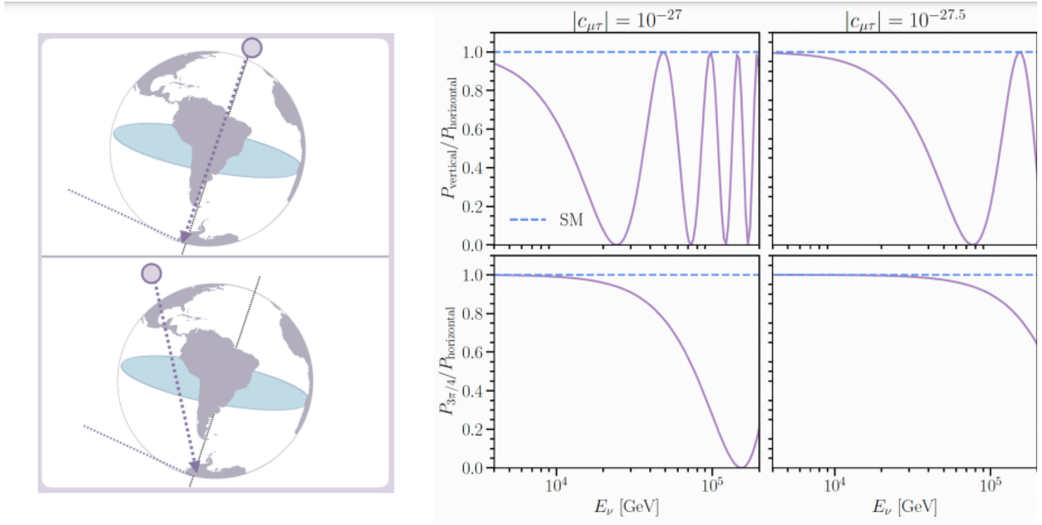
SWGO
The Southern Wide-field Gamma-ray Observatory

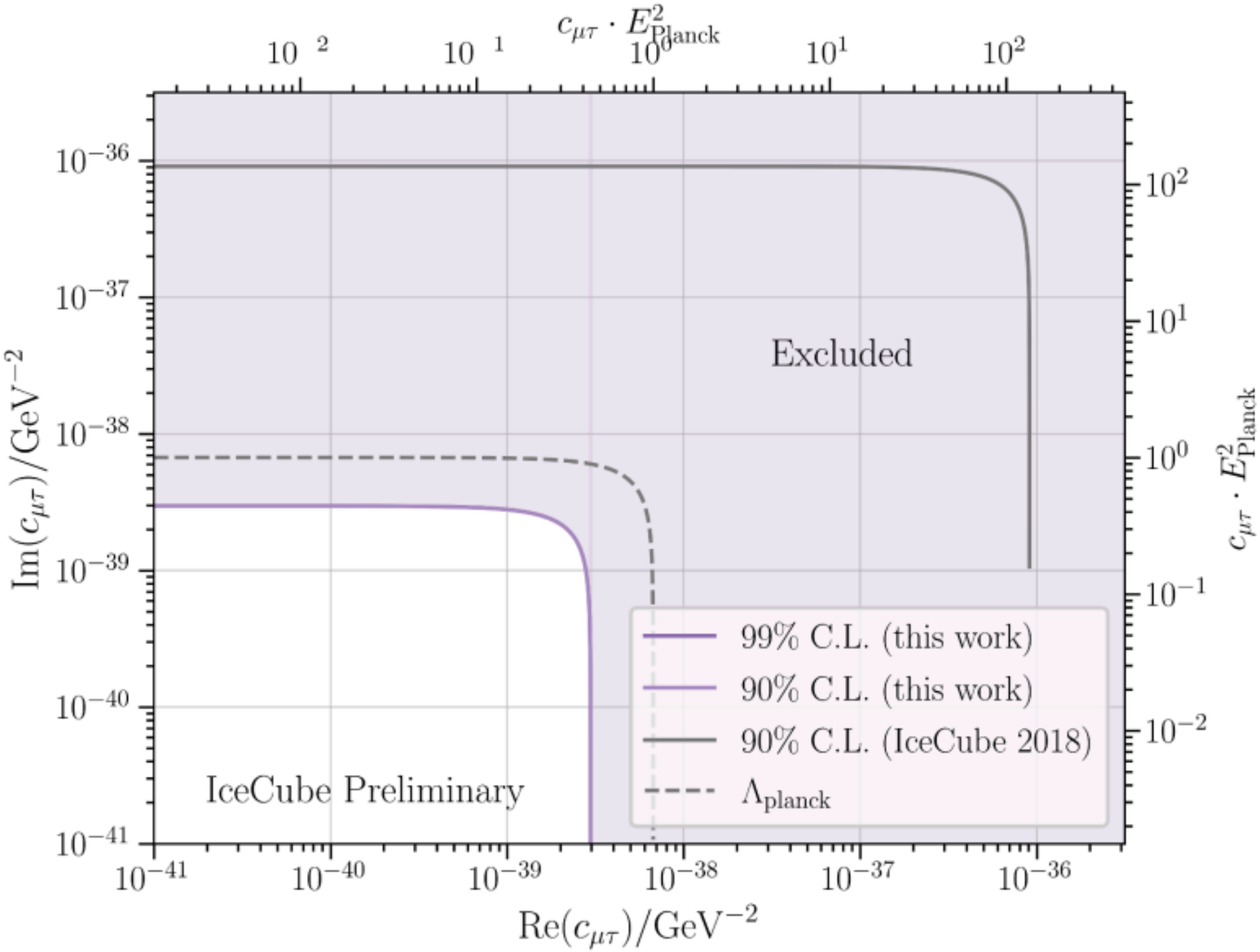
KM3NeT

P-ONE

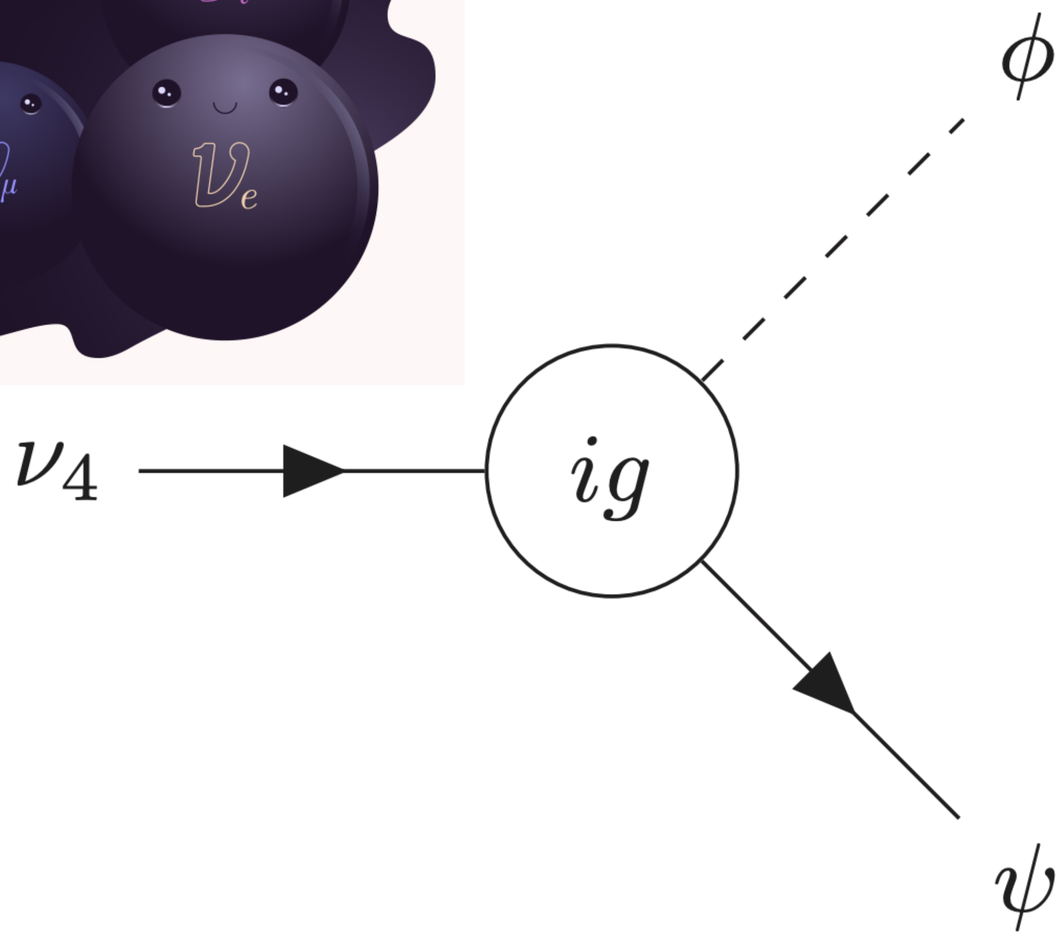
Back Up

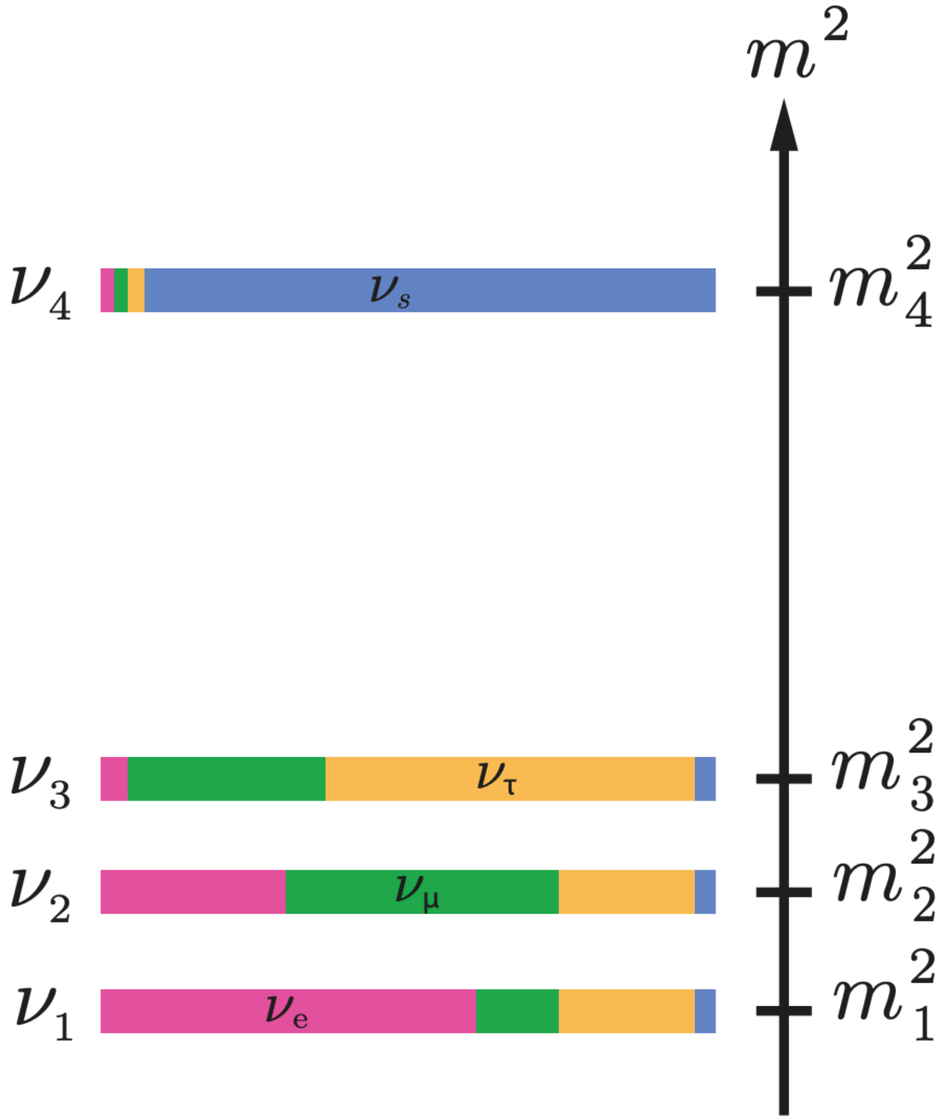
Probing Standard Model Extensions





Constraining Sterile Decay





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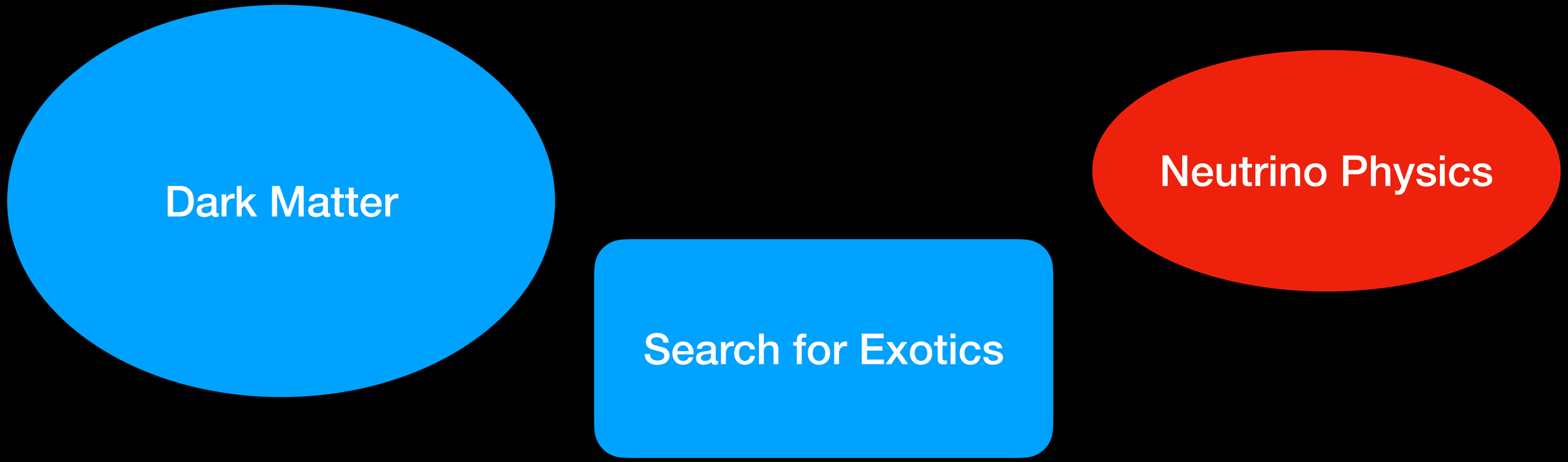
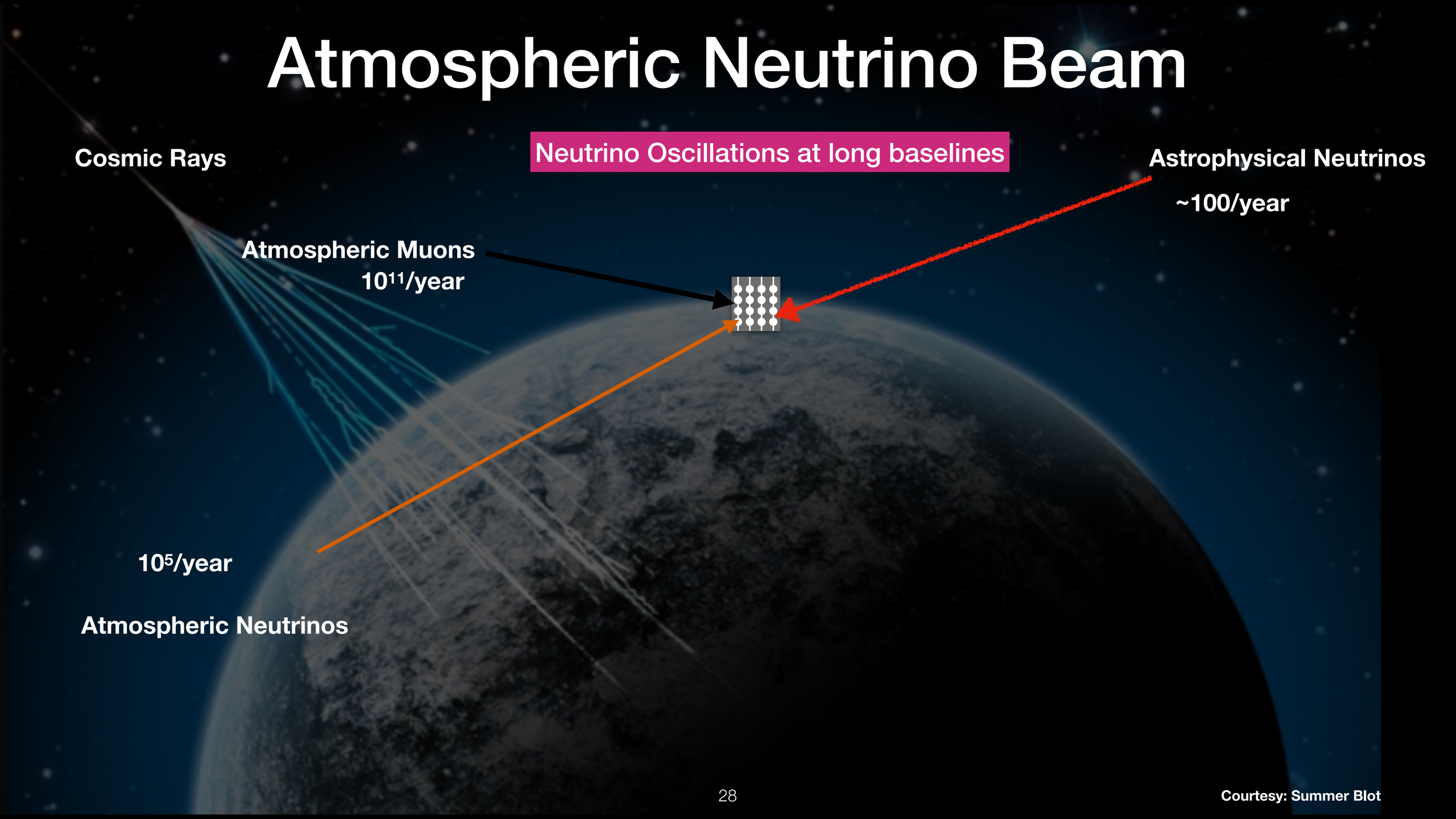
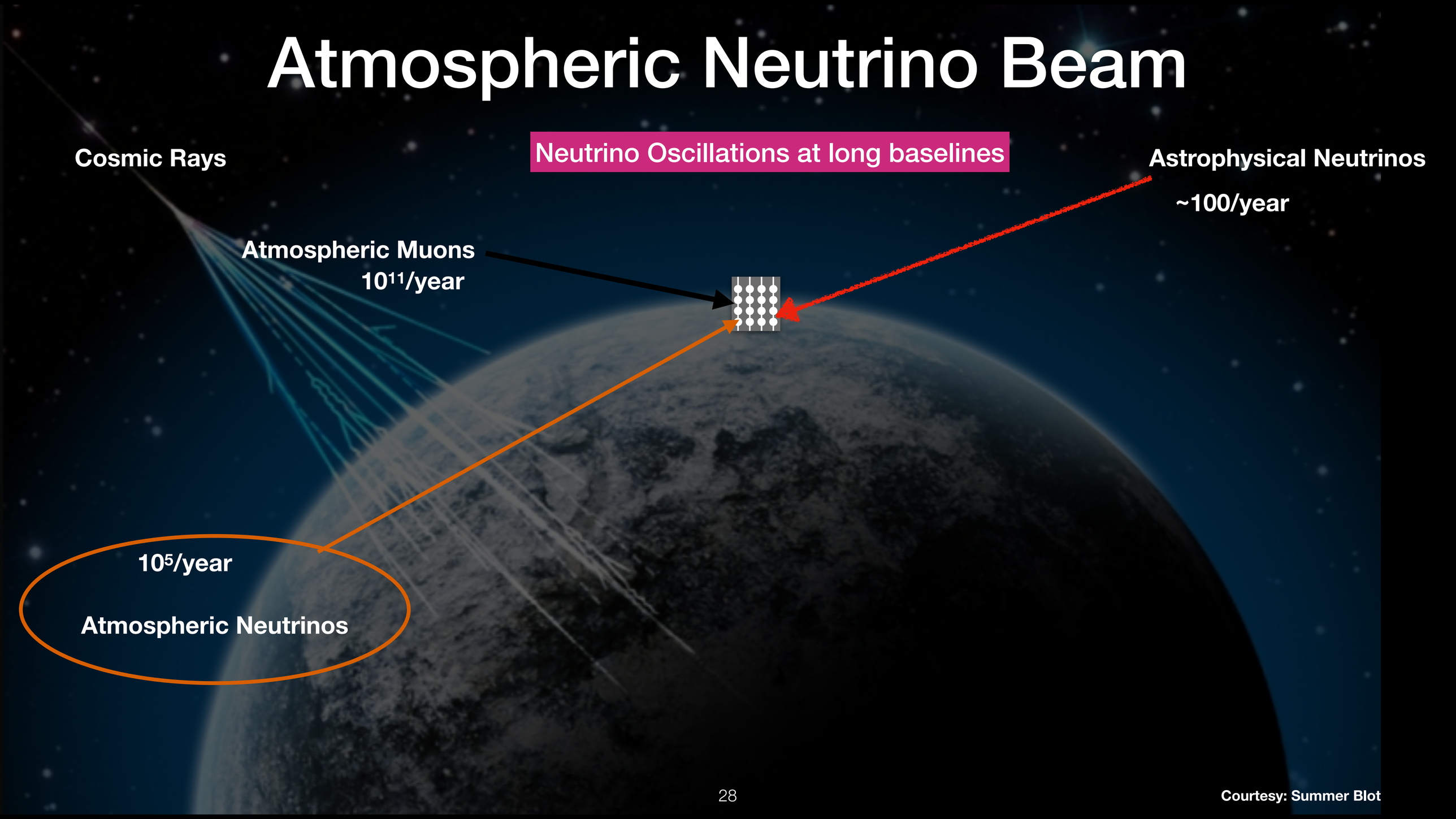


Atmospheric Neutrino Beam



Courtesy: Summer Blot

Atmospheric Neutrino Beam



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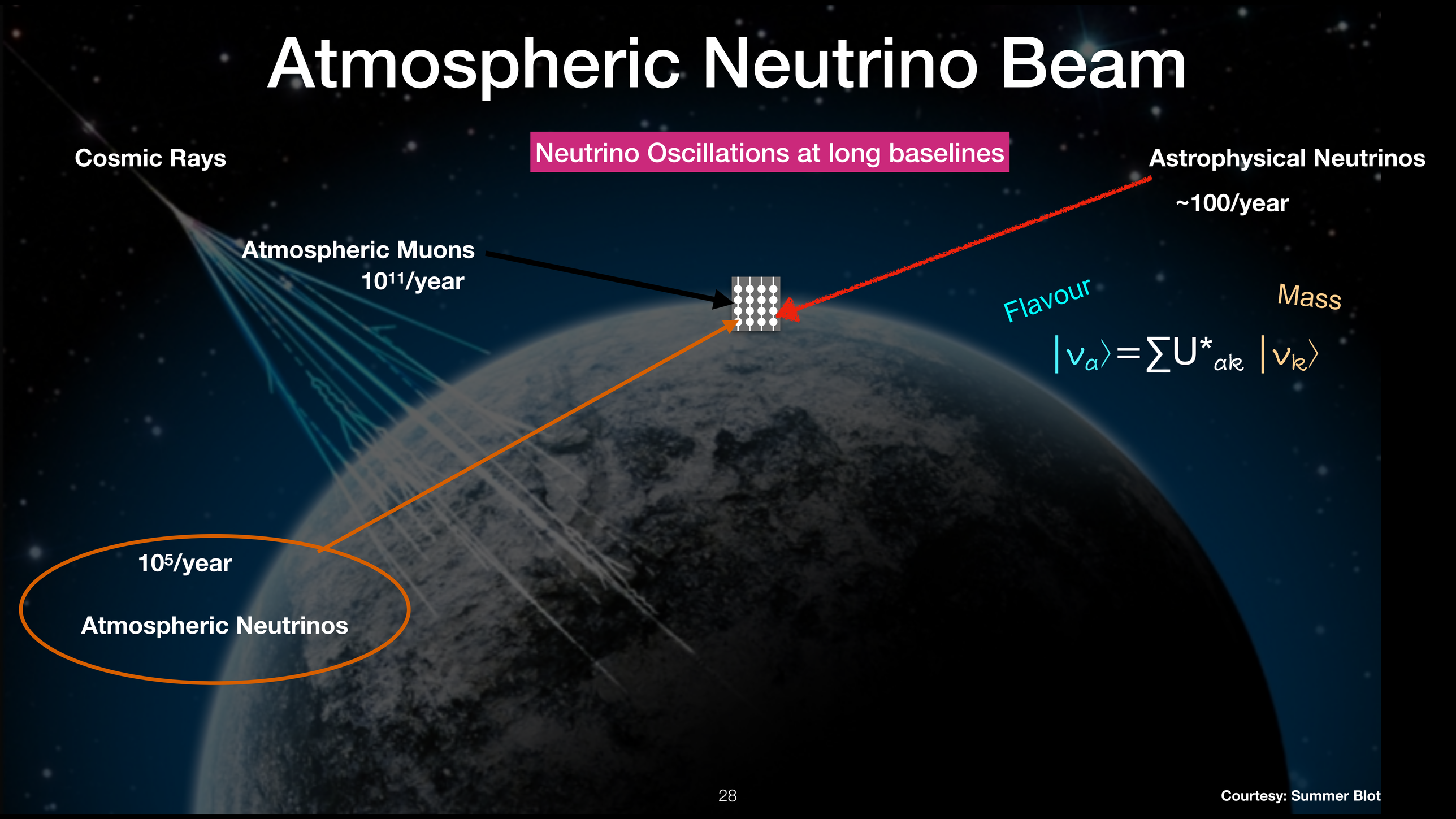

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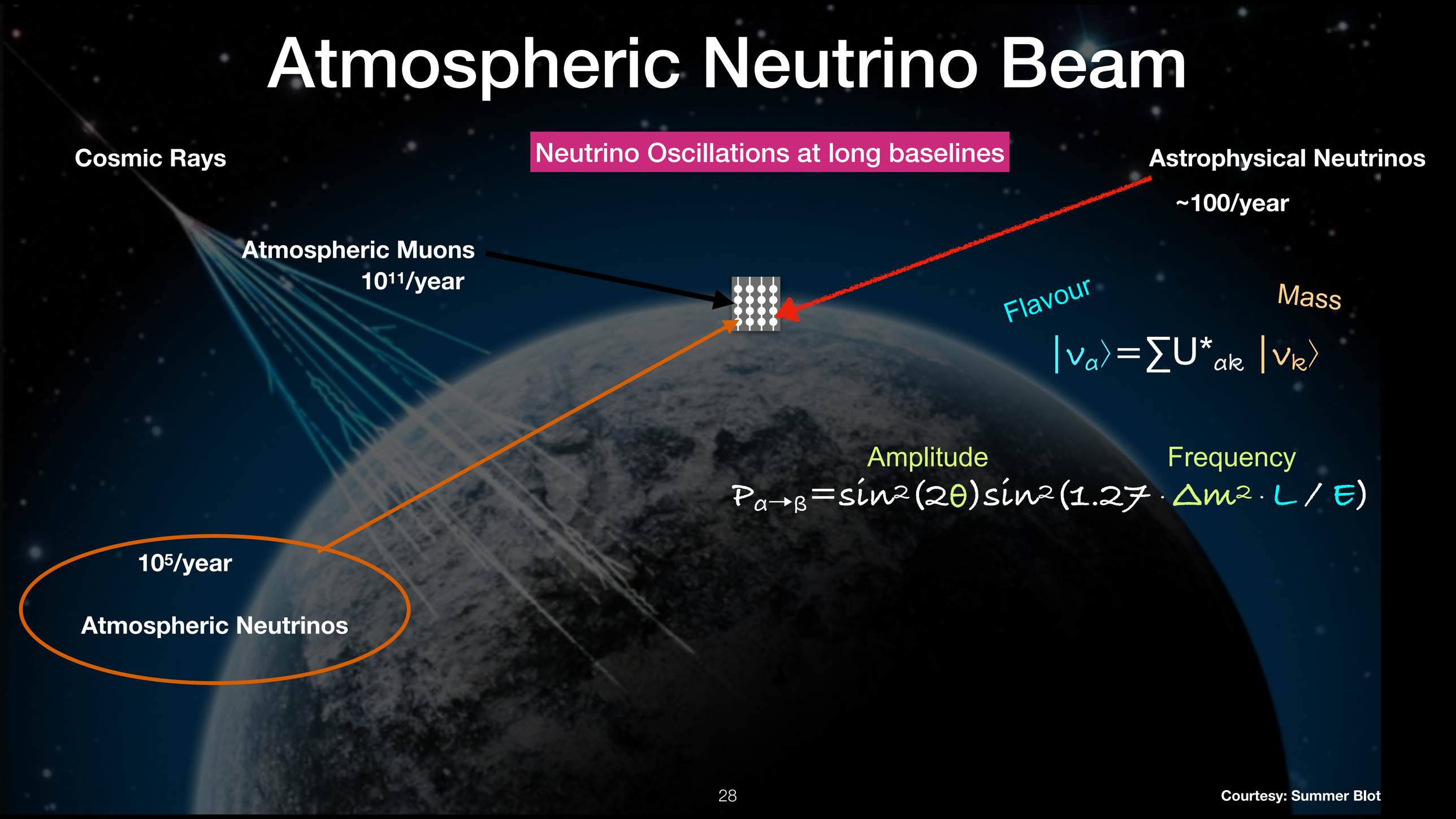


Courtesy: Summer Blot

Atmospheric Neutrino Beam

Cosmic Rays

Neutrino Oscillations at long baselines

Astrophysical Neutrinos

~100/year

Atmospheric Muons

10^{11}/year

Flavour

Mass

$$|\nu_\alpha\rangle = \sum U^*_{\alpha k} \, |\nu_k\rangle$$

Amplitude

Frequency

$$P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2(1.27 \cdot \Delta m^2 \cdot L / E)$$

10^5/year

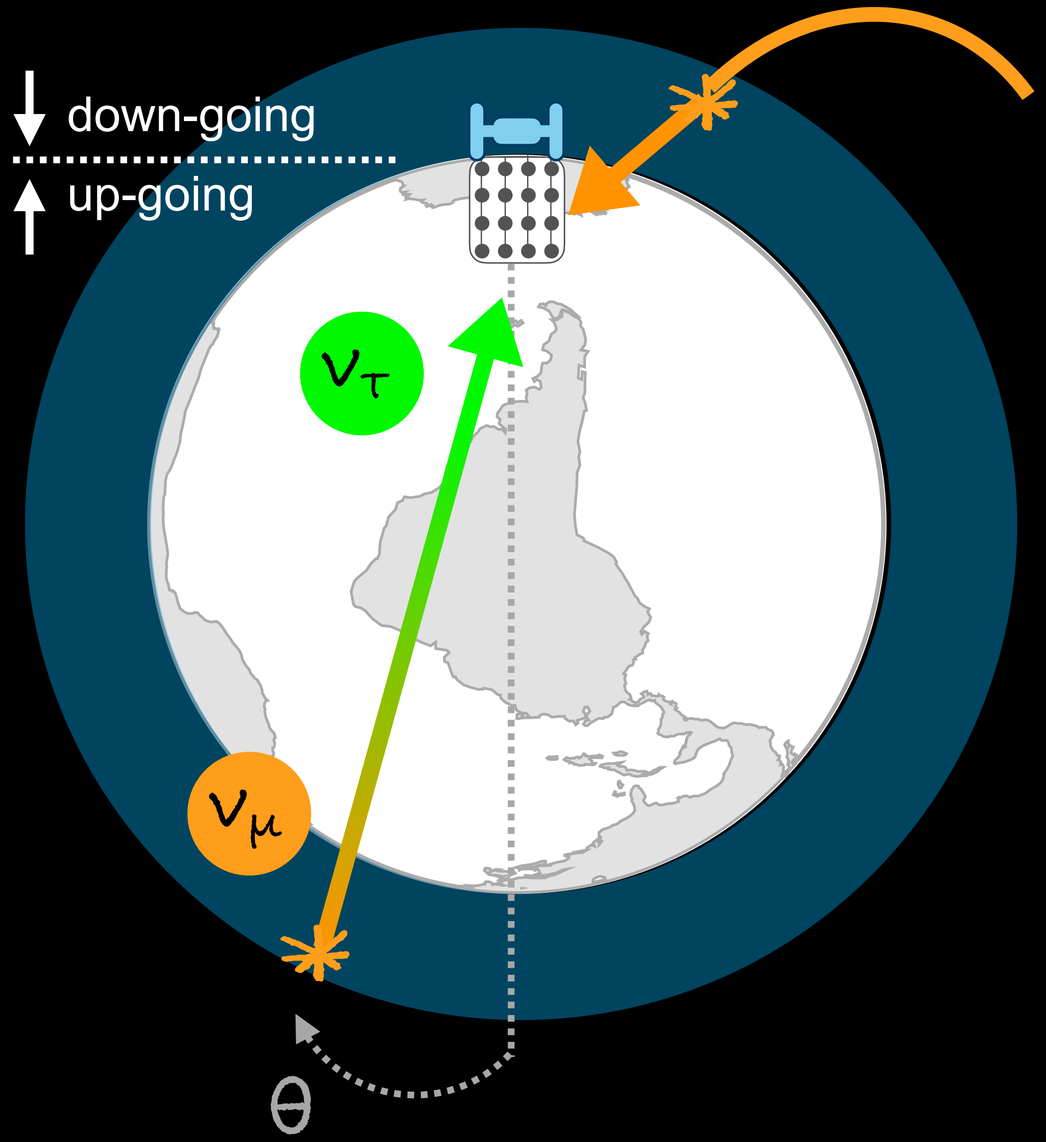
Atmospheric Neutrinos

IceCube measures the energy and zenith angle of neutrinos, with the zenith angle as a proxy for baseline distance traveled.

Courtesy: Summer Blot

Probing BSM Physics with Neutrino Oscillations

To first order, DeepCore is sensitive to Δm_{32}^2 and θ_{23}



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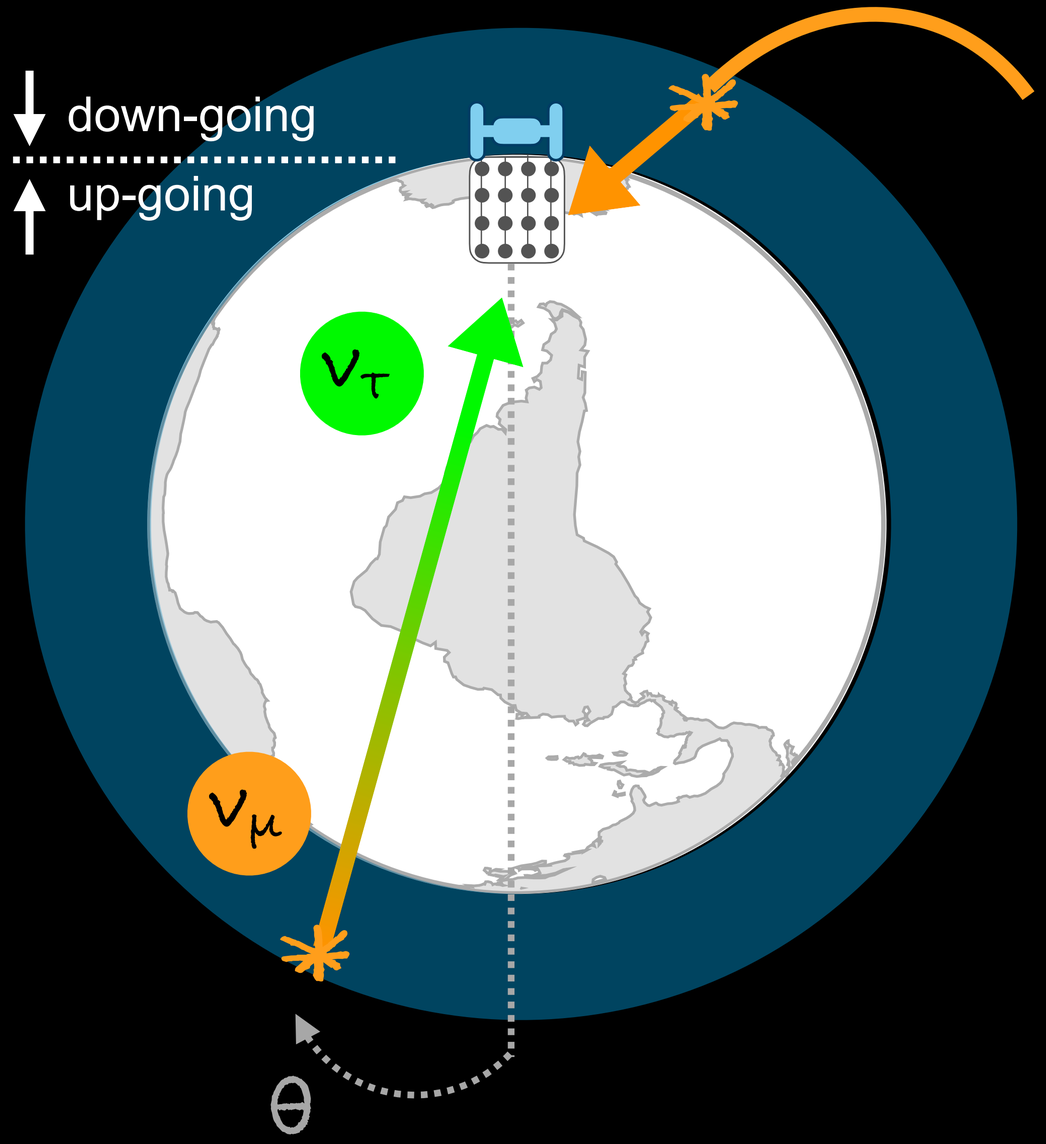
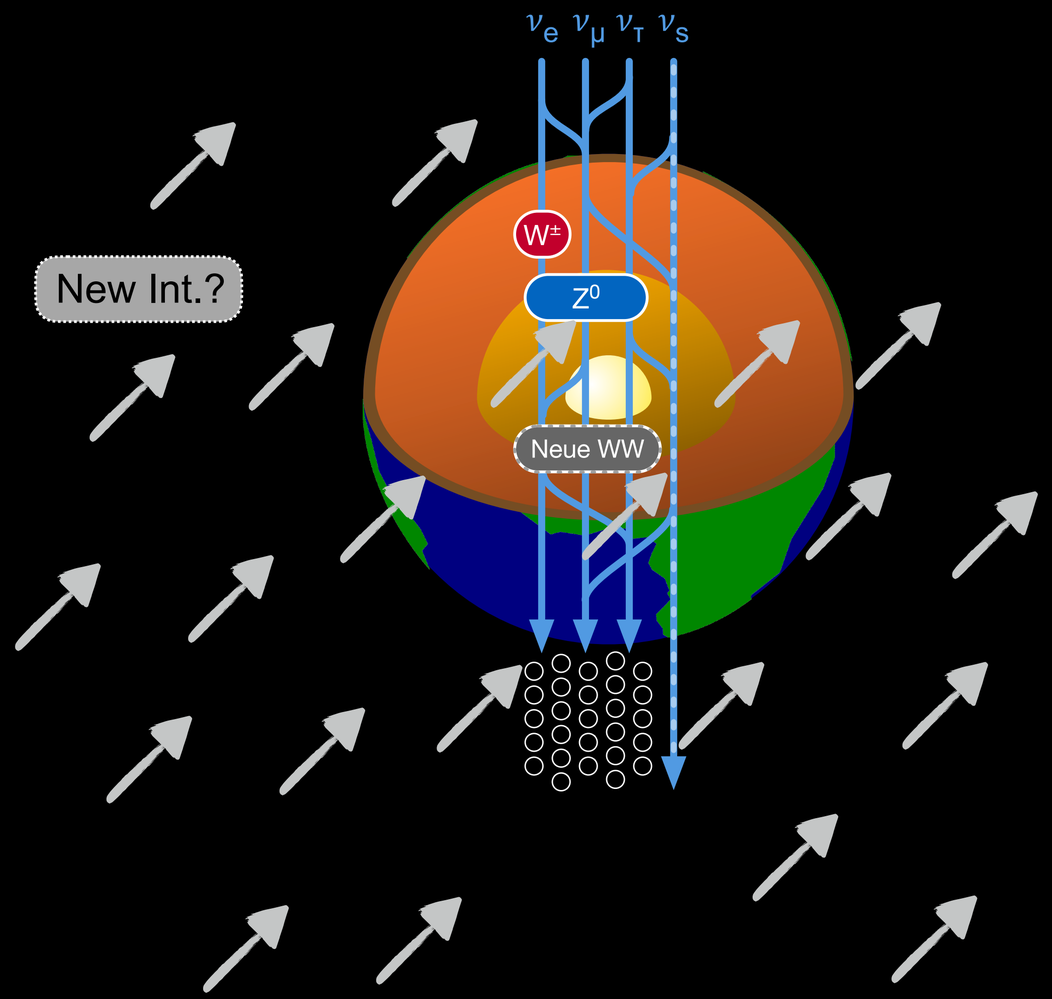
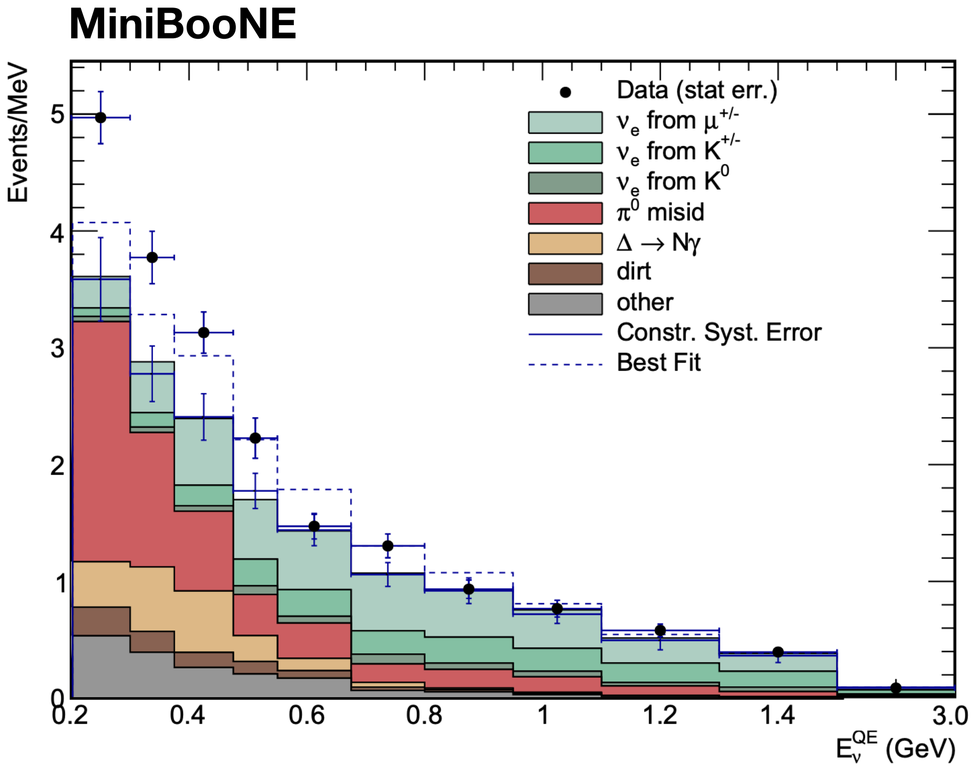
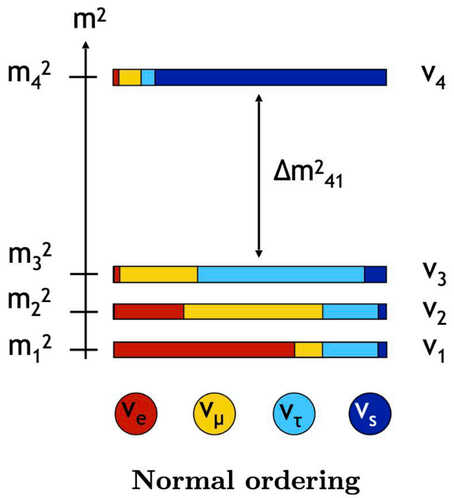




Non-standard oscillations modify mixing matrix

Going After the Sterile Neutrino



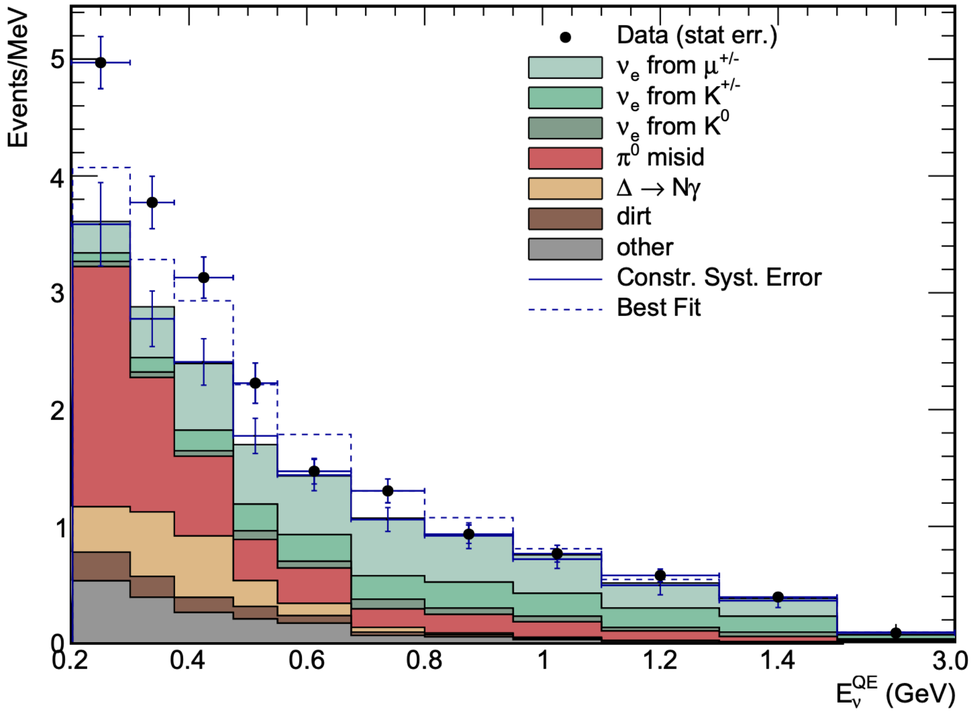


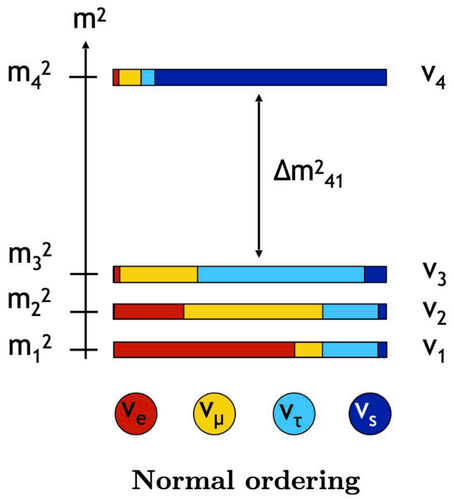
Proposed as a resolution to various experimental anomalies in short-baseline oscillation experiments.

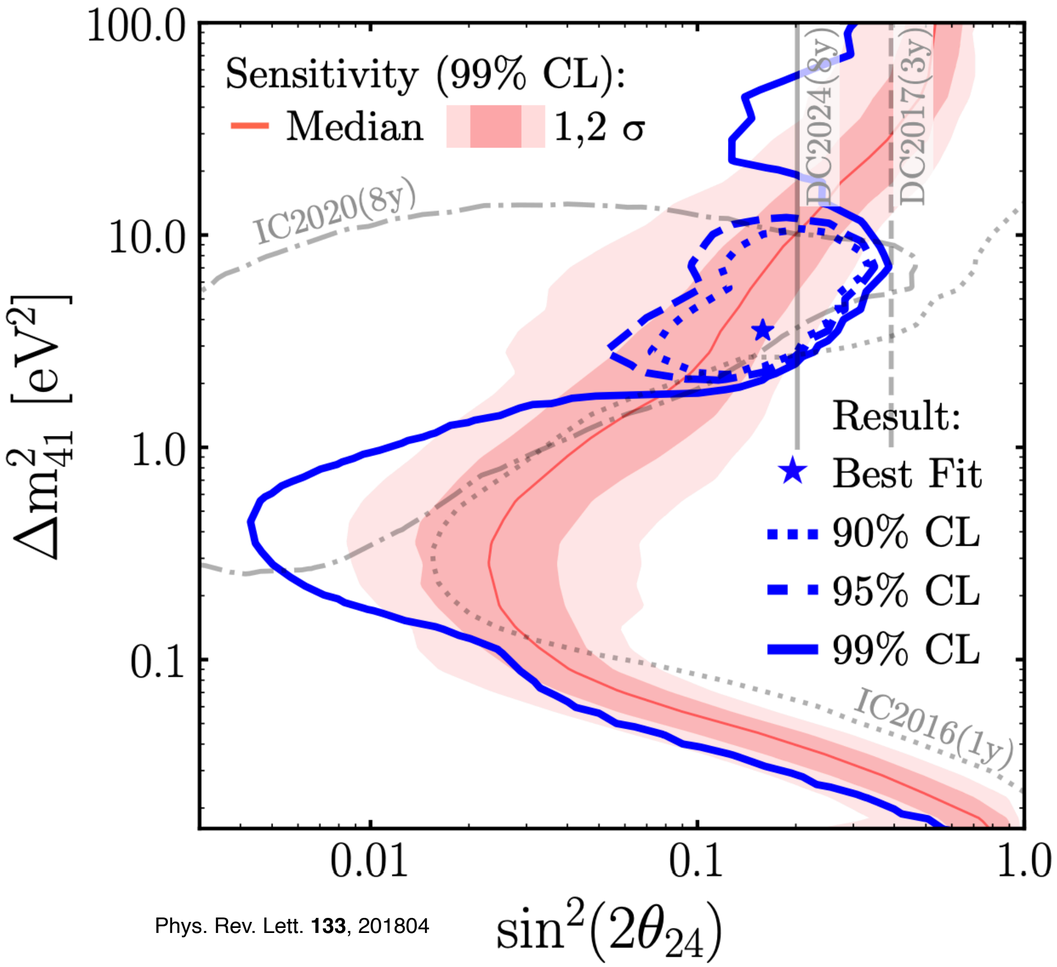
Candidate DM particle

Going After the Sterile Neutrino

MiniBooNE







Phys. Rev. Lett. **133**, 201804

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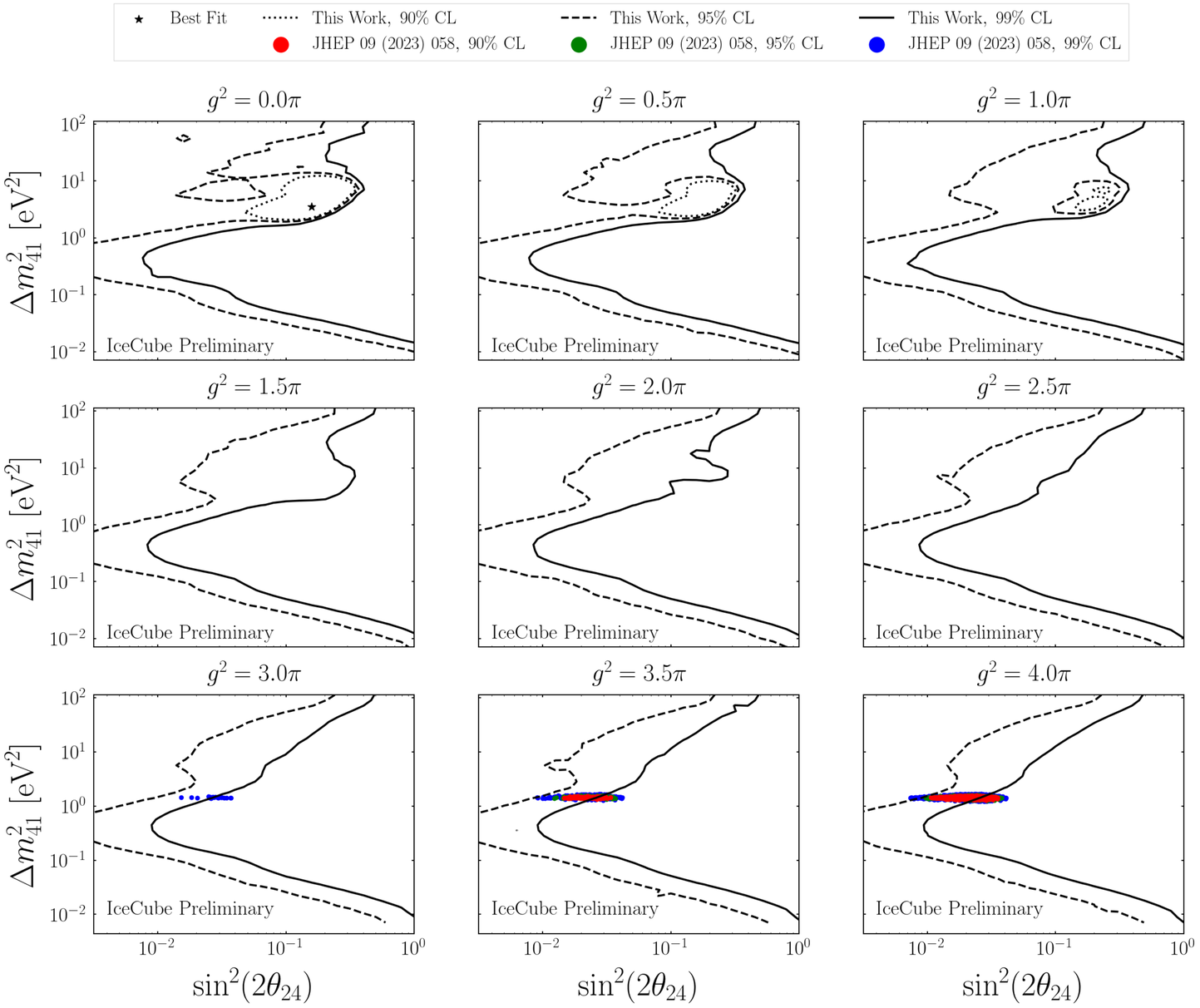
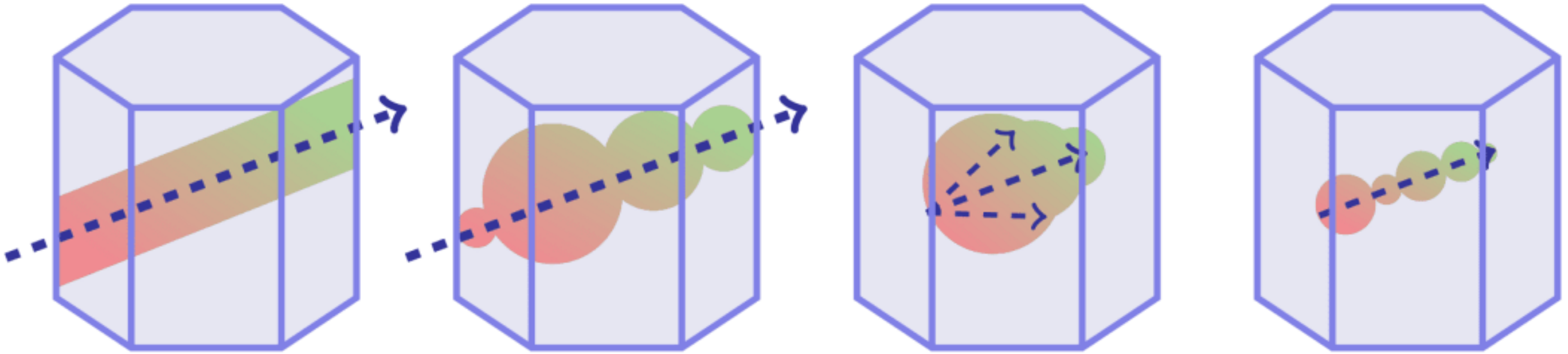
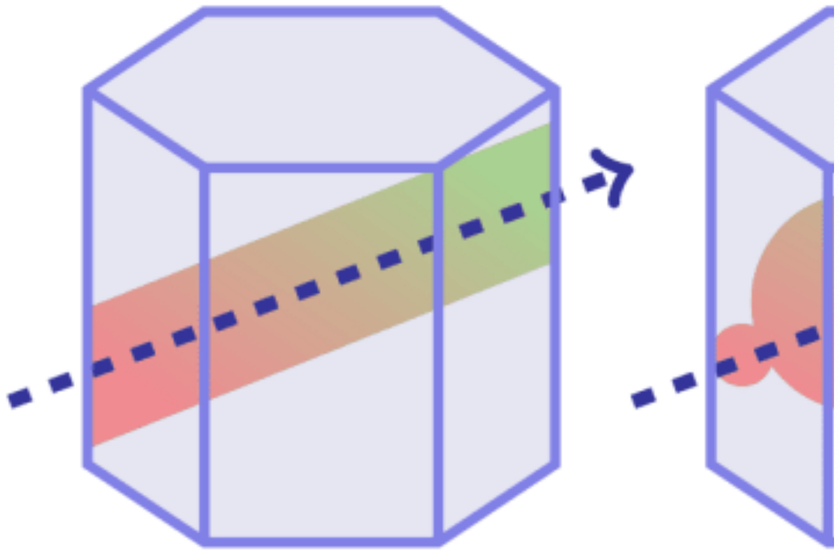


Relativistic Monopoles



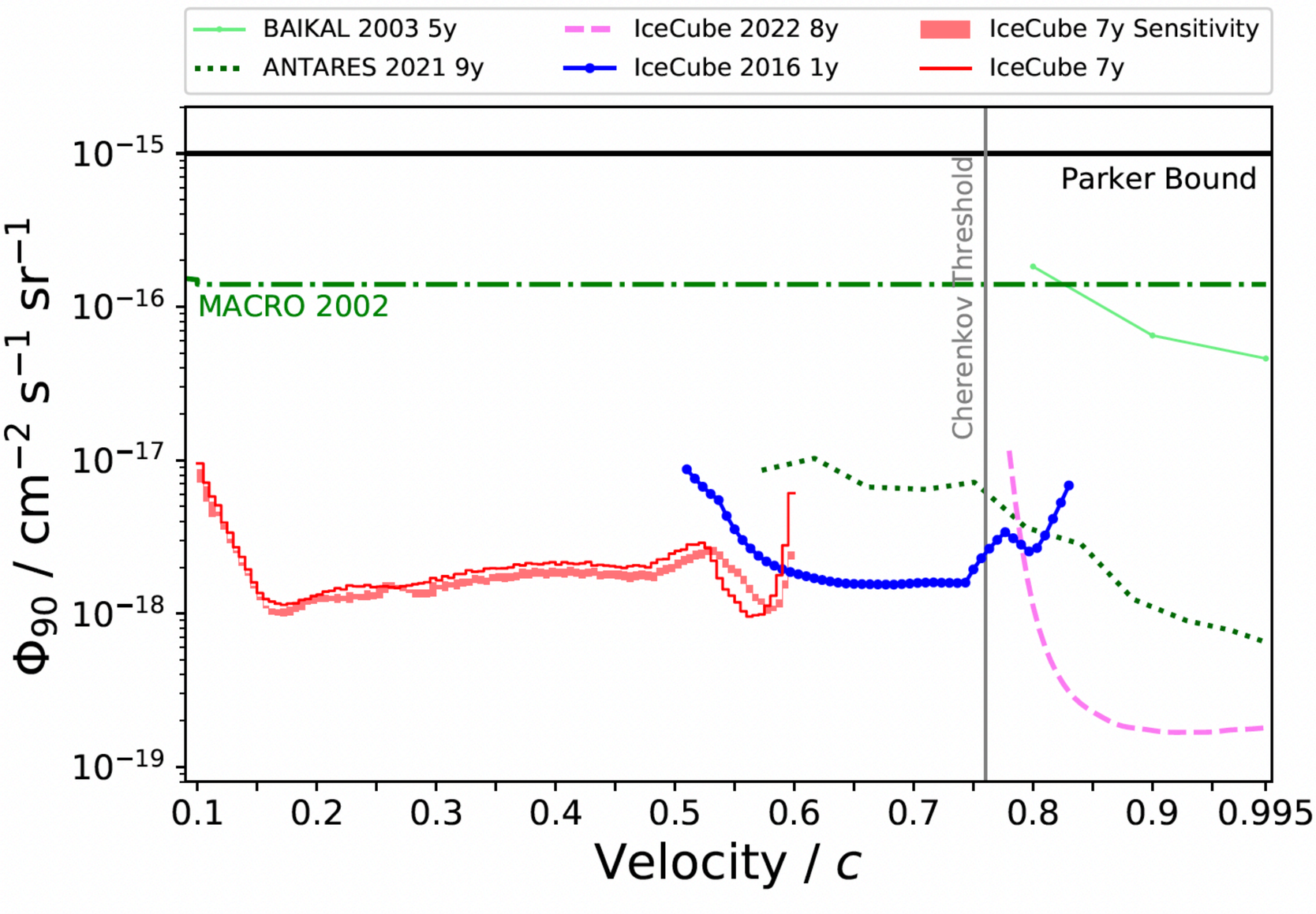
Credit: Alexander Burgman

Relativistic Monopoles



Magnetic monopole

Thr



Credit: Alexander Burgman