Searching for Dark Matter at Neutrino Experiments

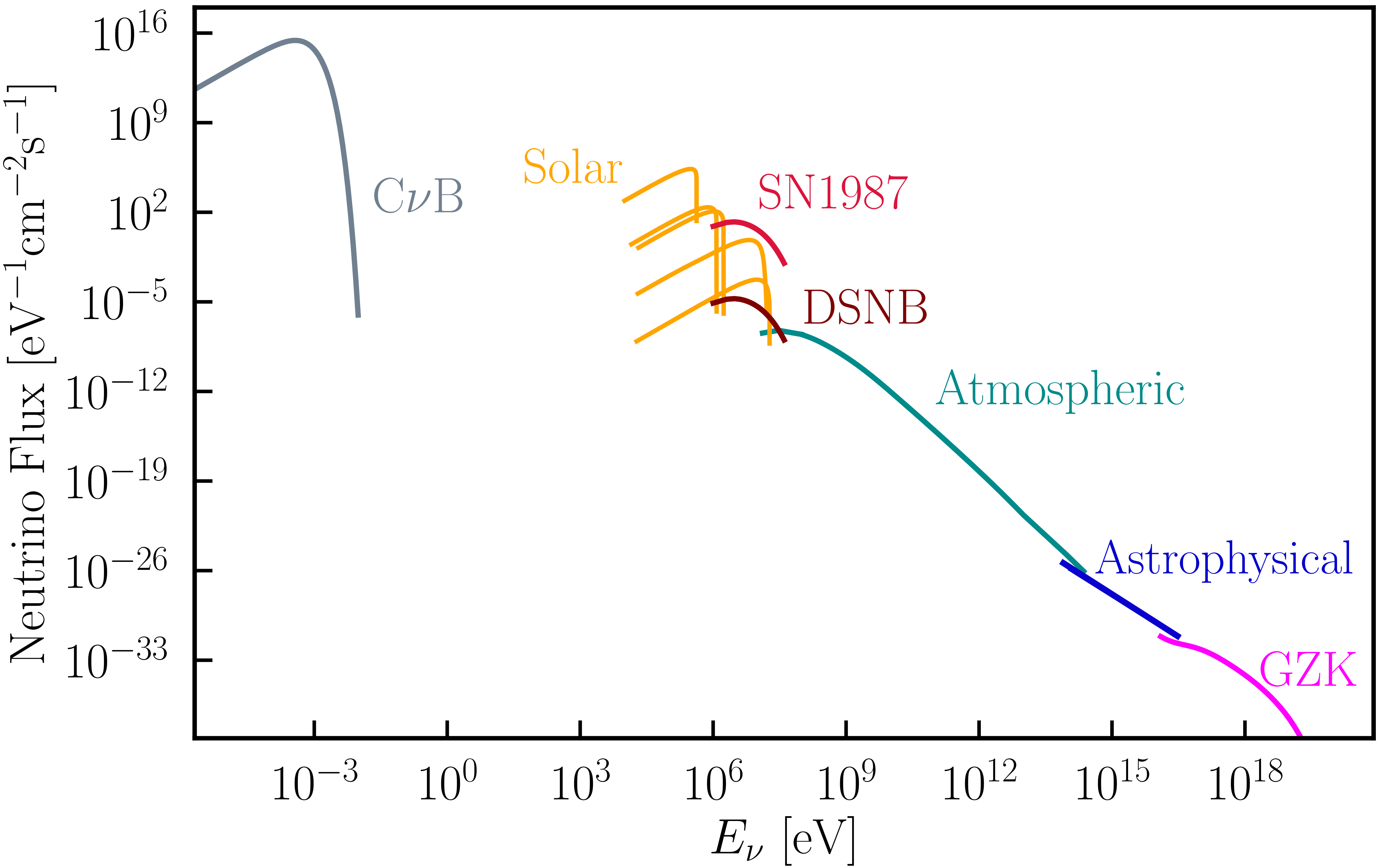
Ali Kheirandish for the IceCube Collaboration
Pennsylvania State University

The 2022 Conference on Flavor Physics and CP Violation (FPCP2022)
University of Mississippi

PennState

IceCube

The Universe in Neutrinos



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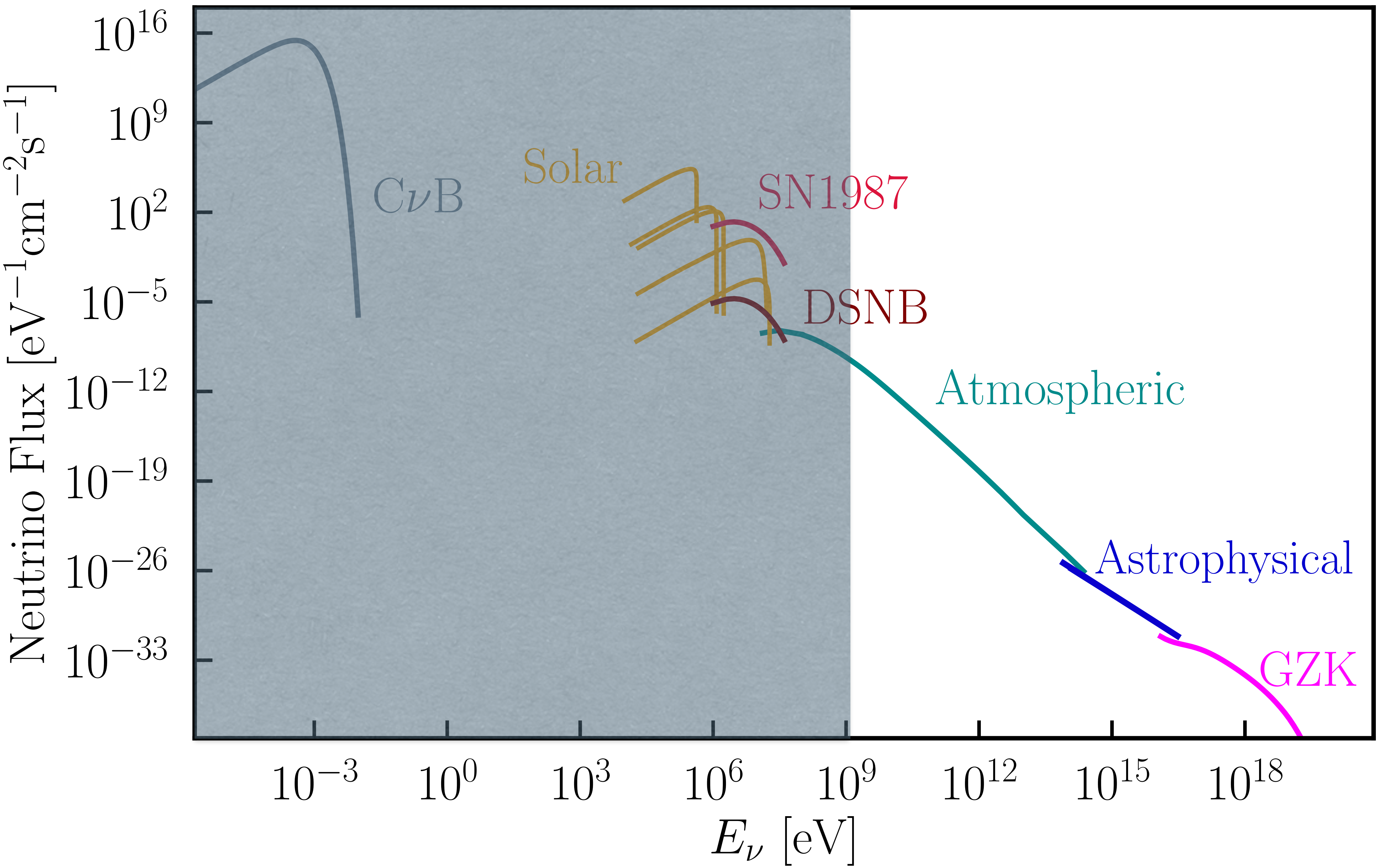

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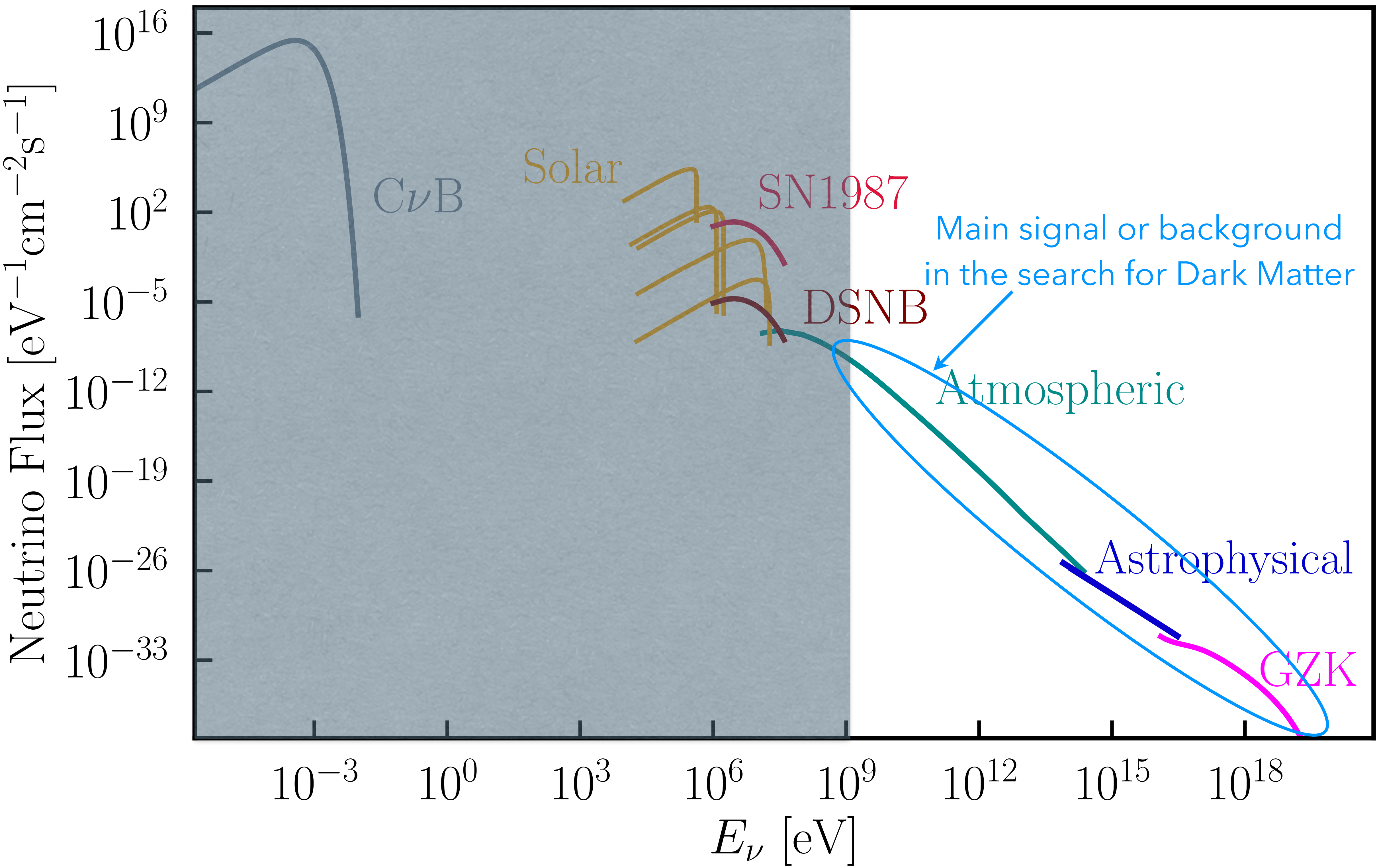
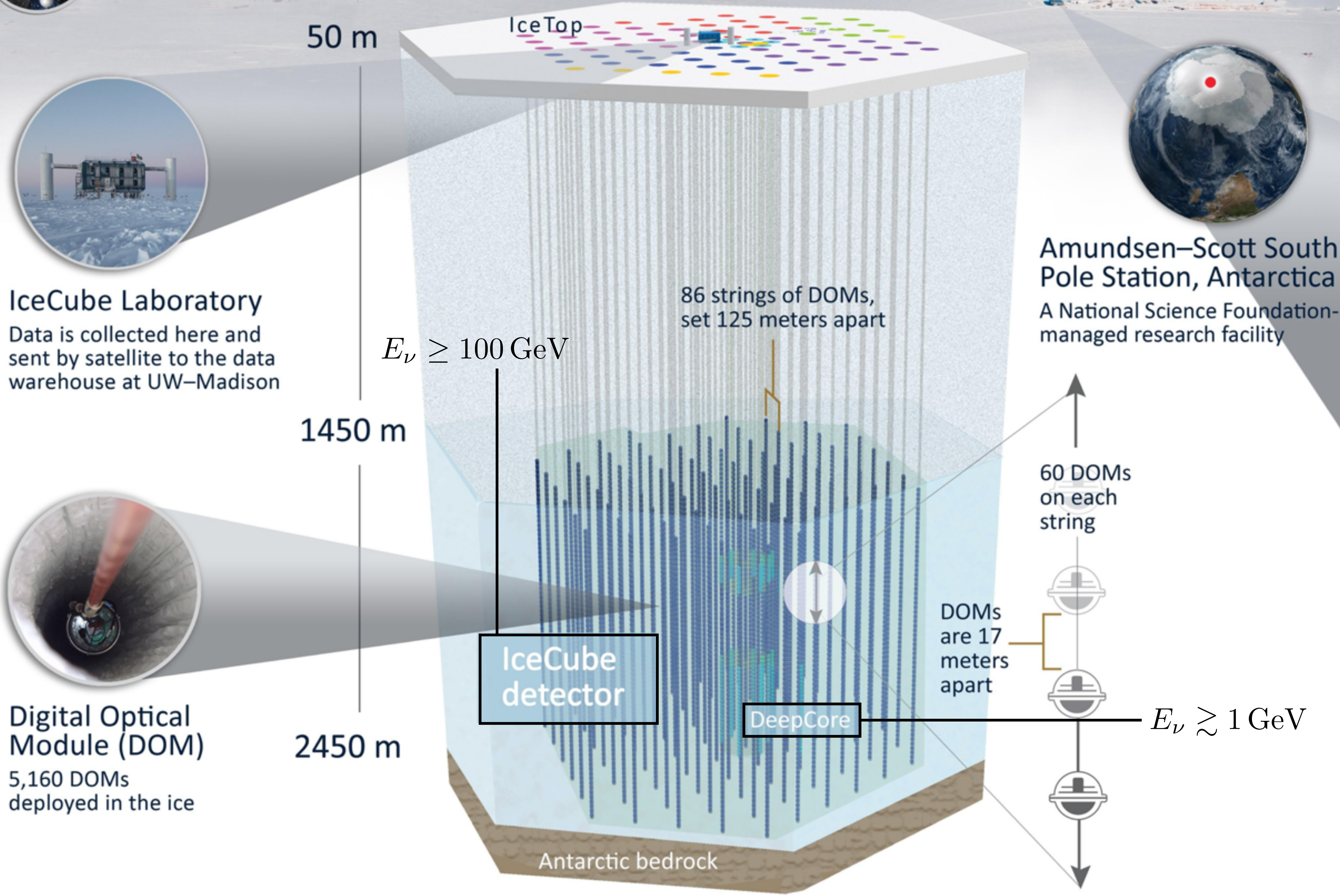
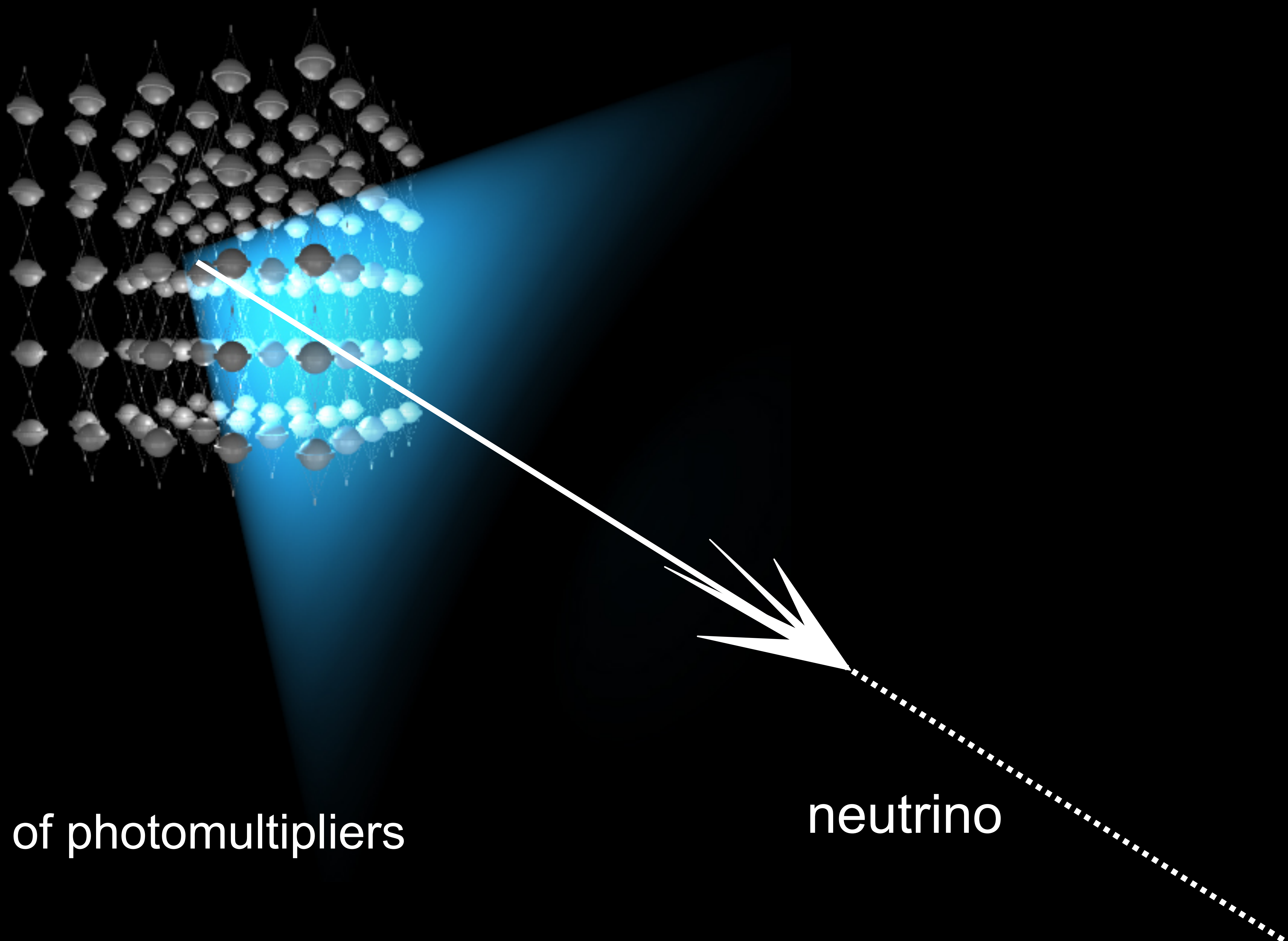


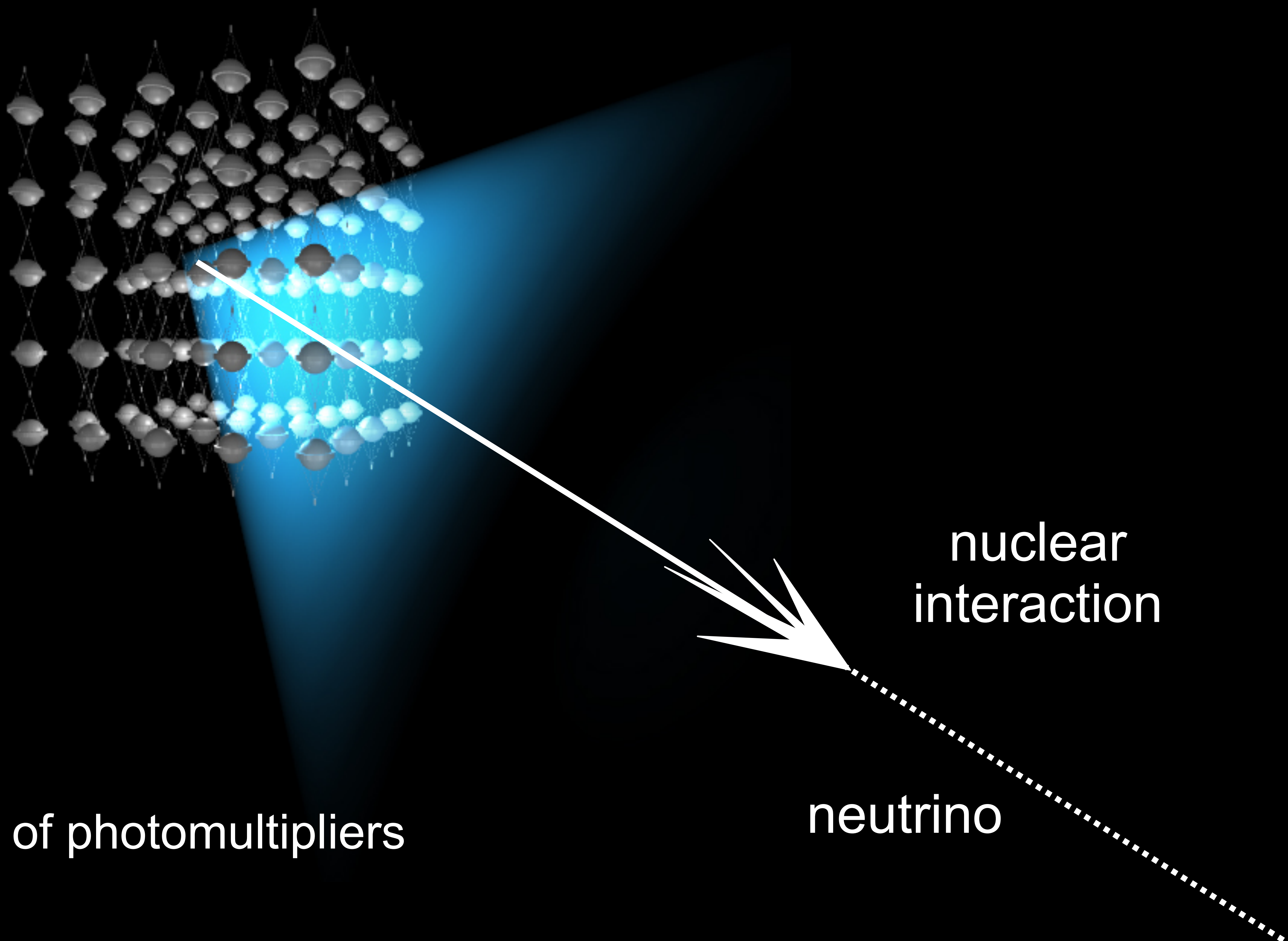
IceCube : the 1st km^3 neutrino telescope

South Pole Neutrino Observatory





- lattice of photomultipliers



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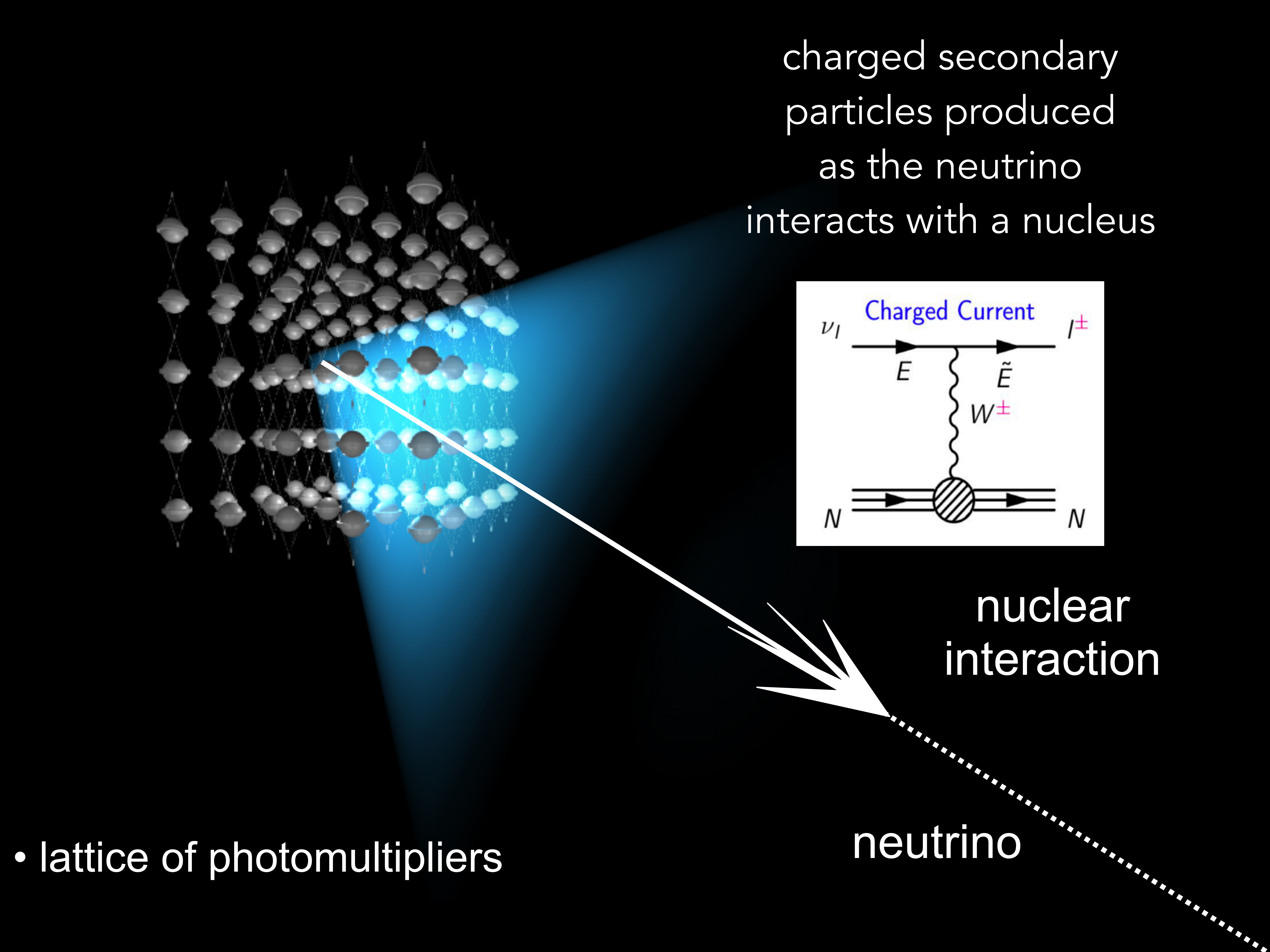
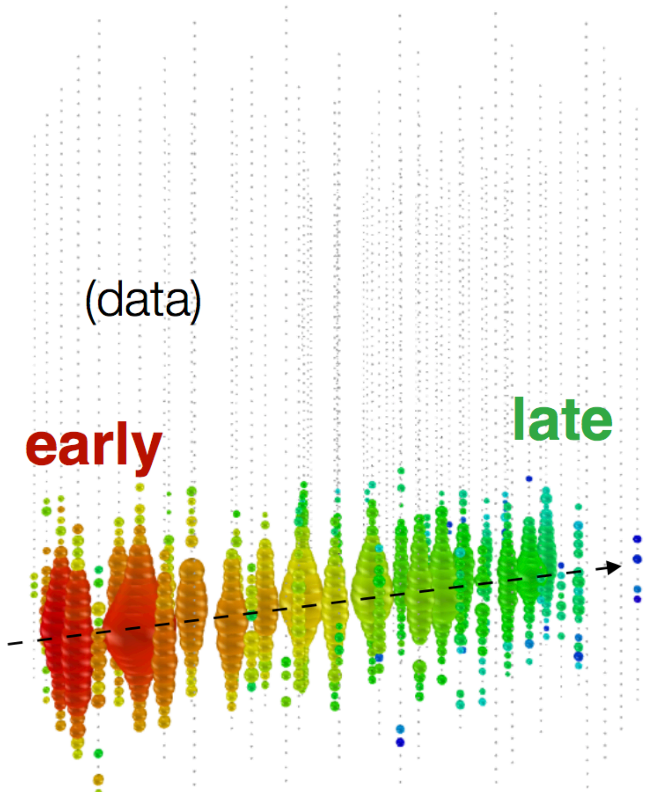

charged secondary
particles produced
as the neutrino
interacts with a nucleus
Charged Current
ν_l
$l^{\pm}$
E
$\tilde{E}$
$W^{\pm}$
N
N
nuclear
interaction
neutrino
• lattice of photomultipliers

Detection Principle

High-energy charged particles produce Cherenkov light in the ice.

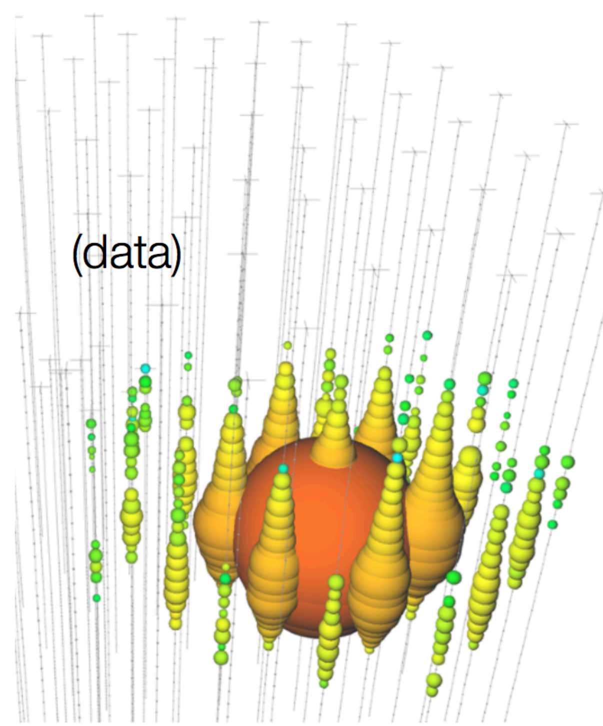
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

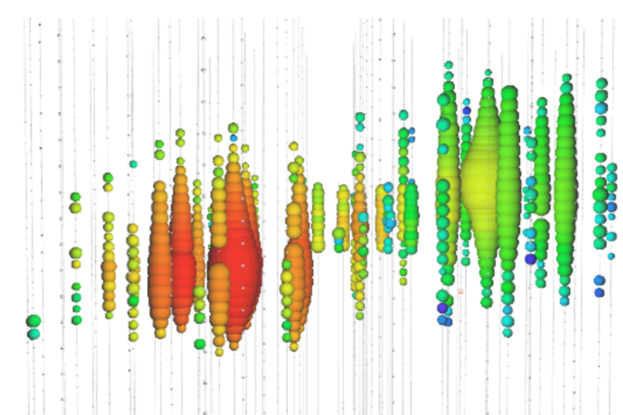


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

Charged-current ν_τ

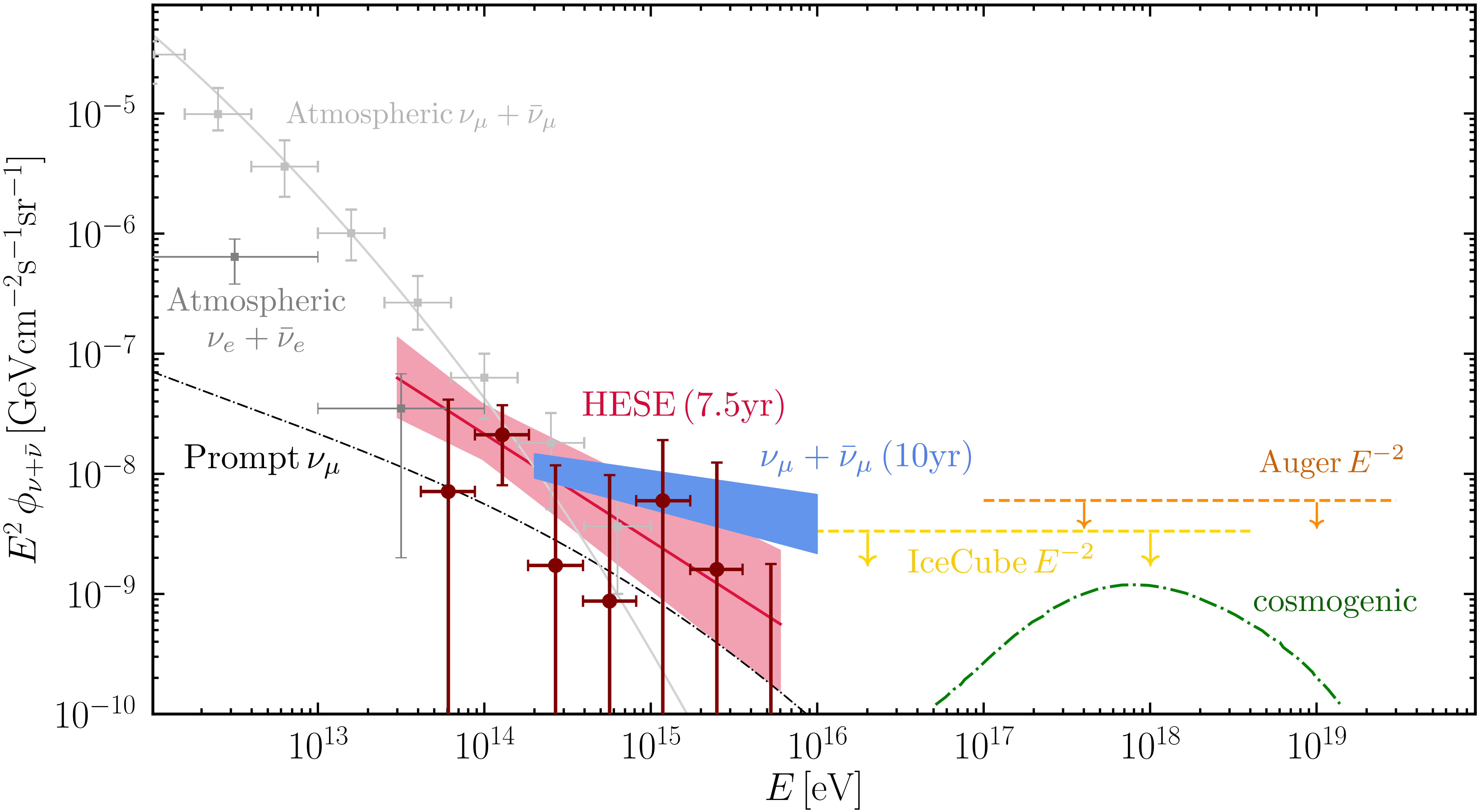
(simulation)



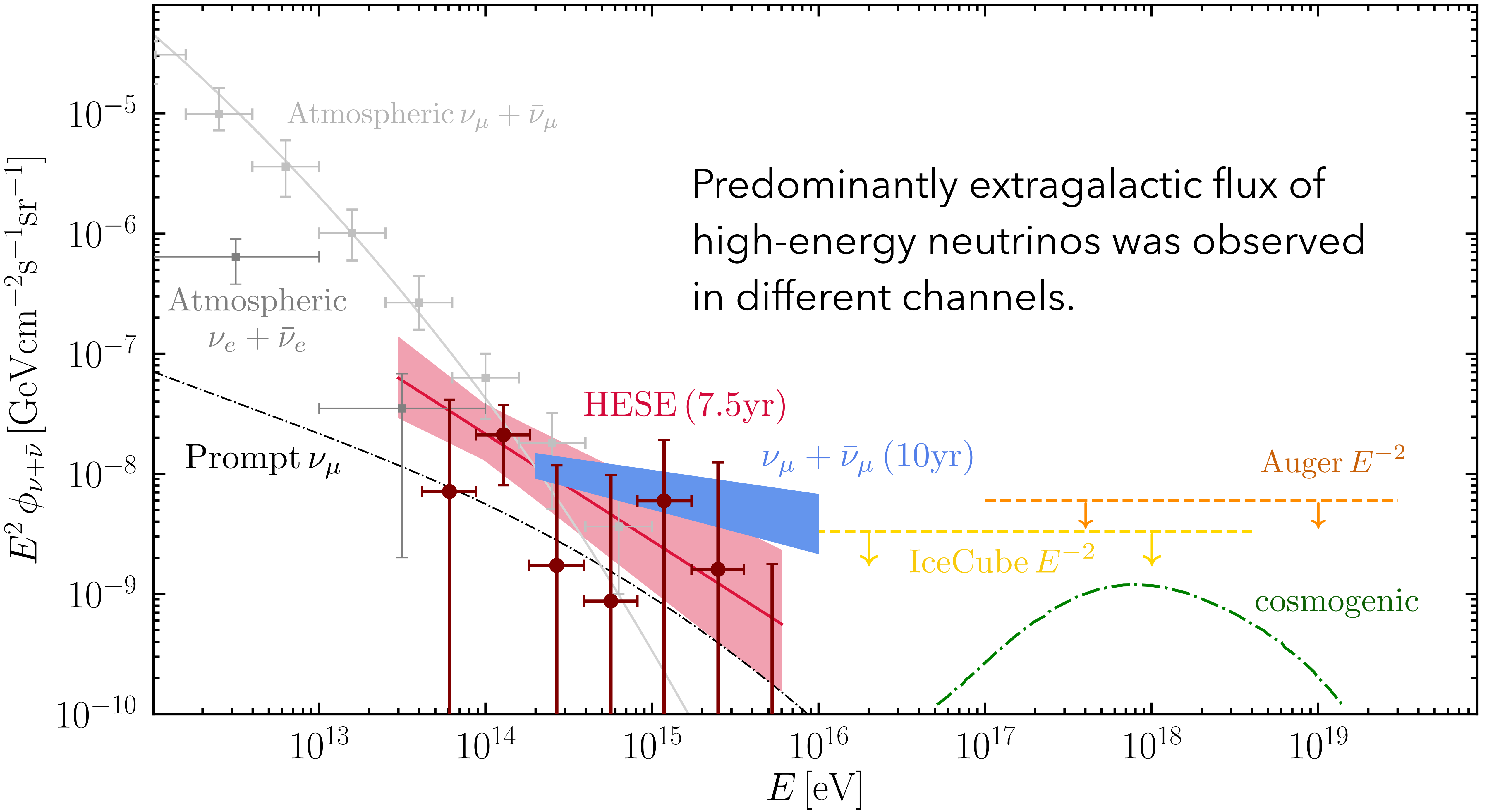
Double cascade

(resolvable above ~100 TeV deposited energy)

High-Energy Neutrino Flux

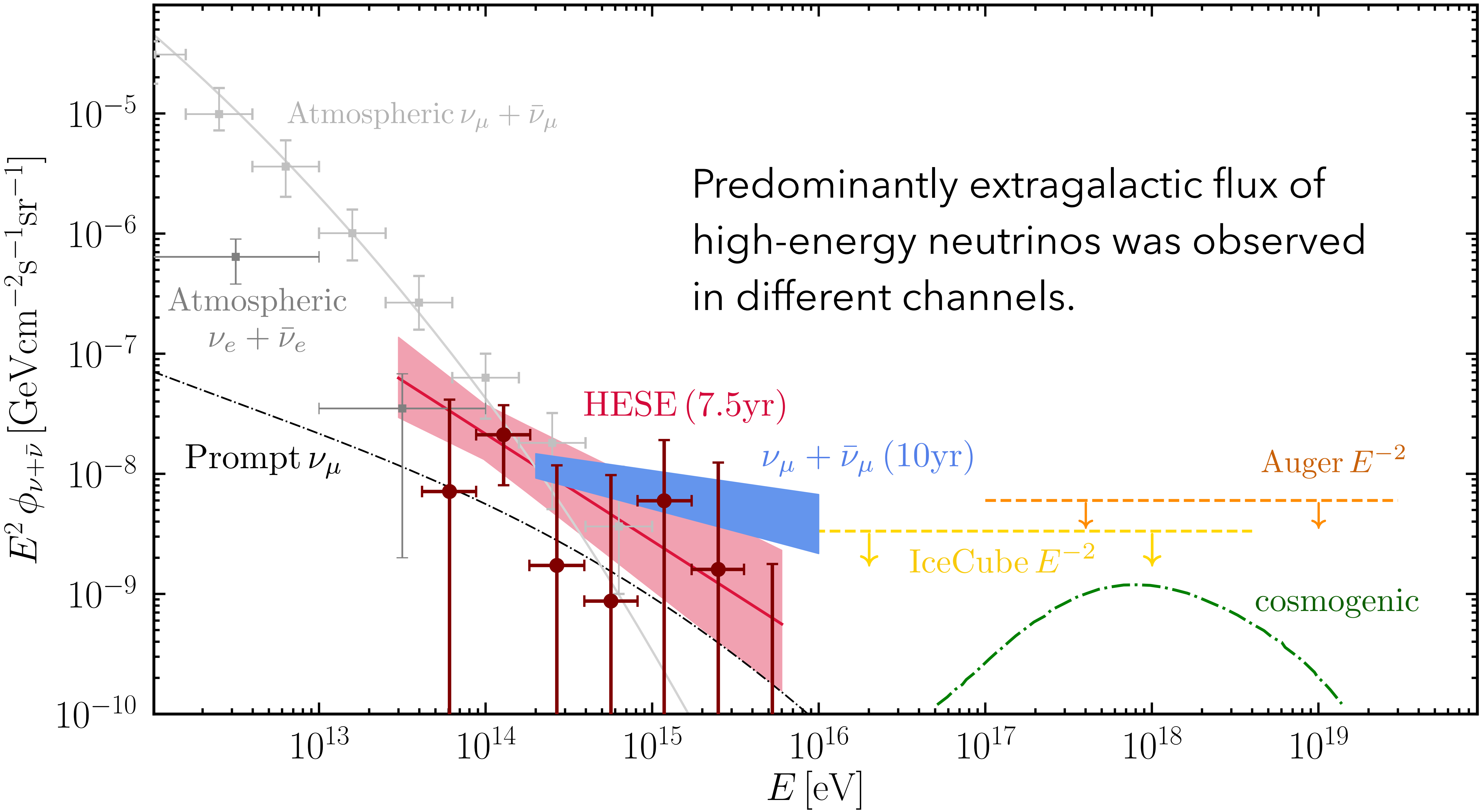


High-Energy Neutrino Flux



Predominantly extragalactic flux of high-energy neutrinos was observed in different channels.

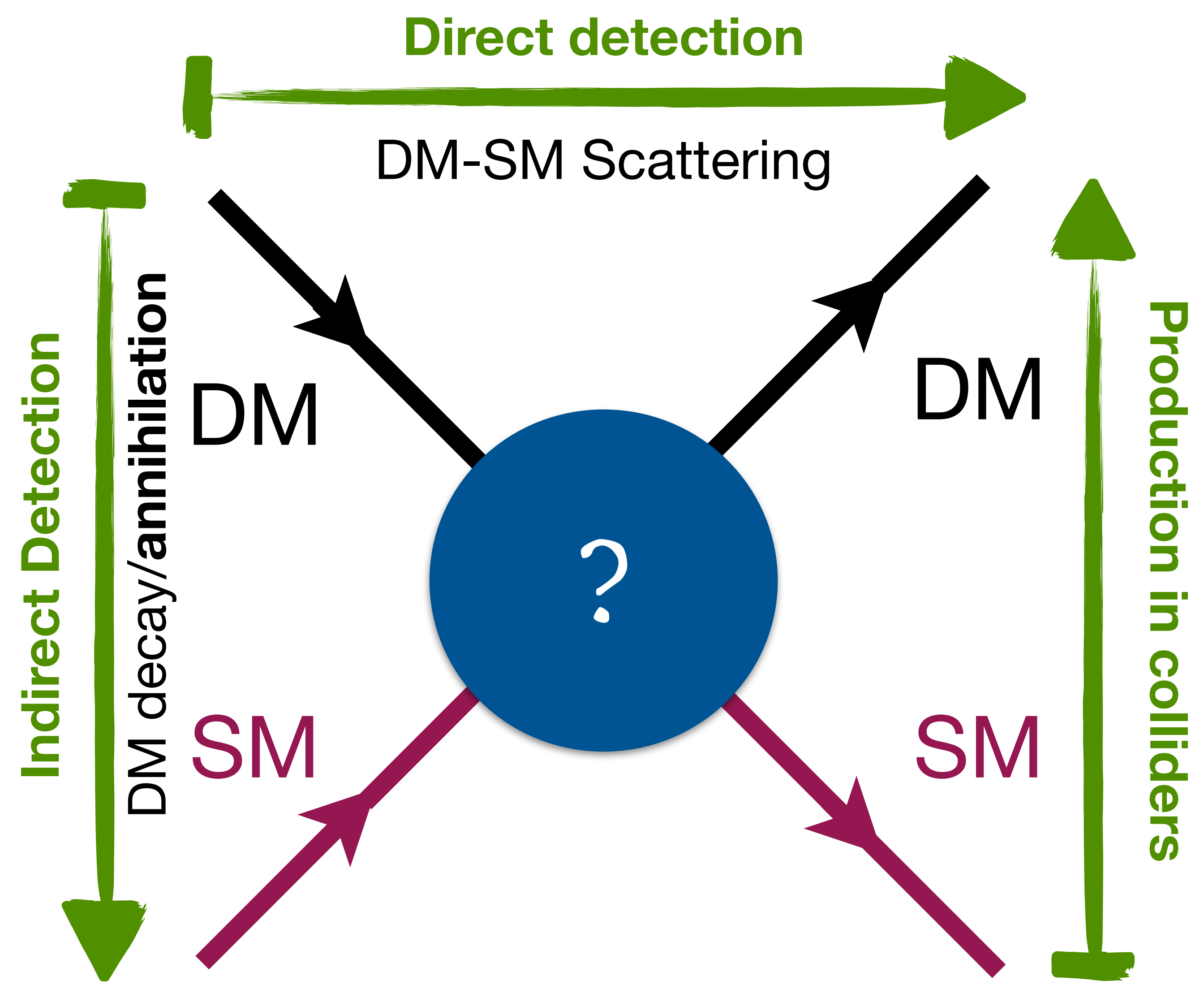
High-Energy Neutrino Flux



- Features in high-energy neutrino flux can reveal new physics phenomena.
- The upper limits on yet to be seen fluxes impose limits on BSM scenarios.

Search for Dark Matter

- Q. What is dark matter (DM)?
- Q. What SM particles does DM interact with?
- Q. How does it interact?



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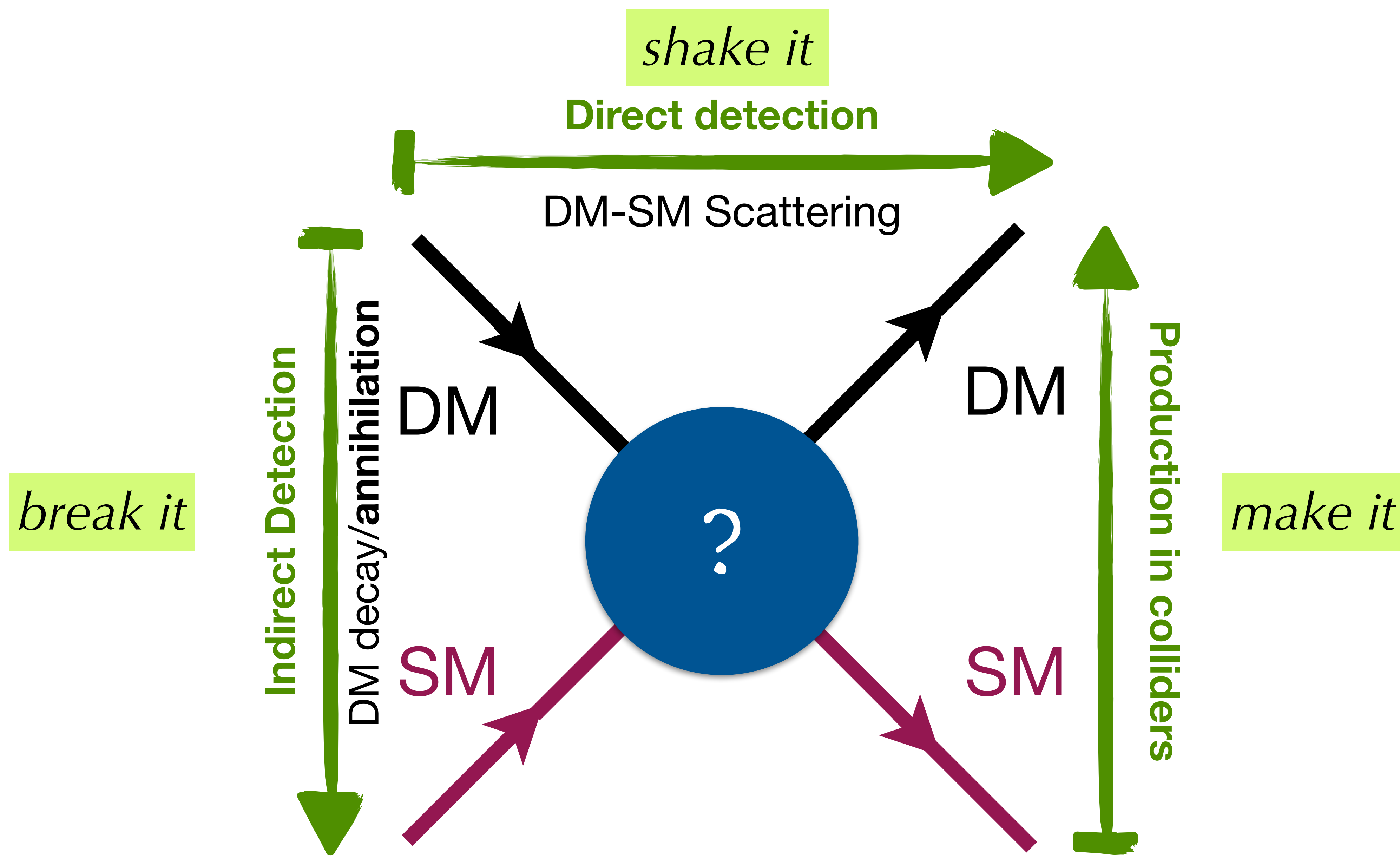


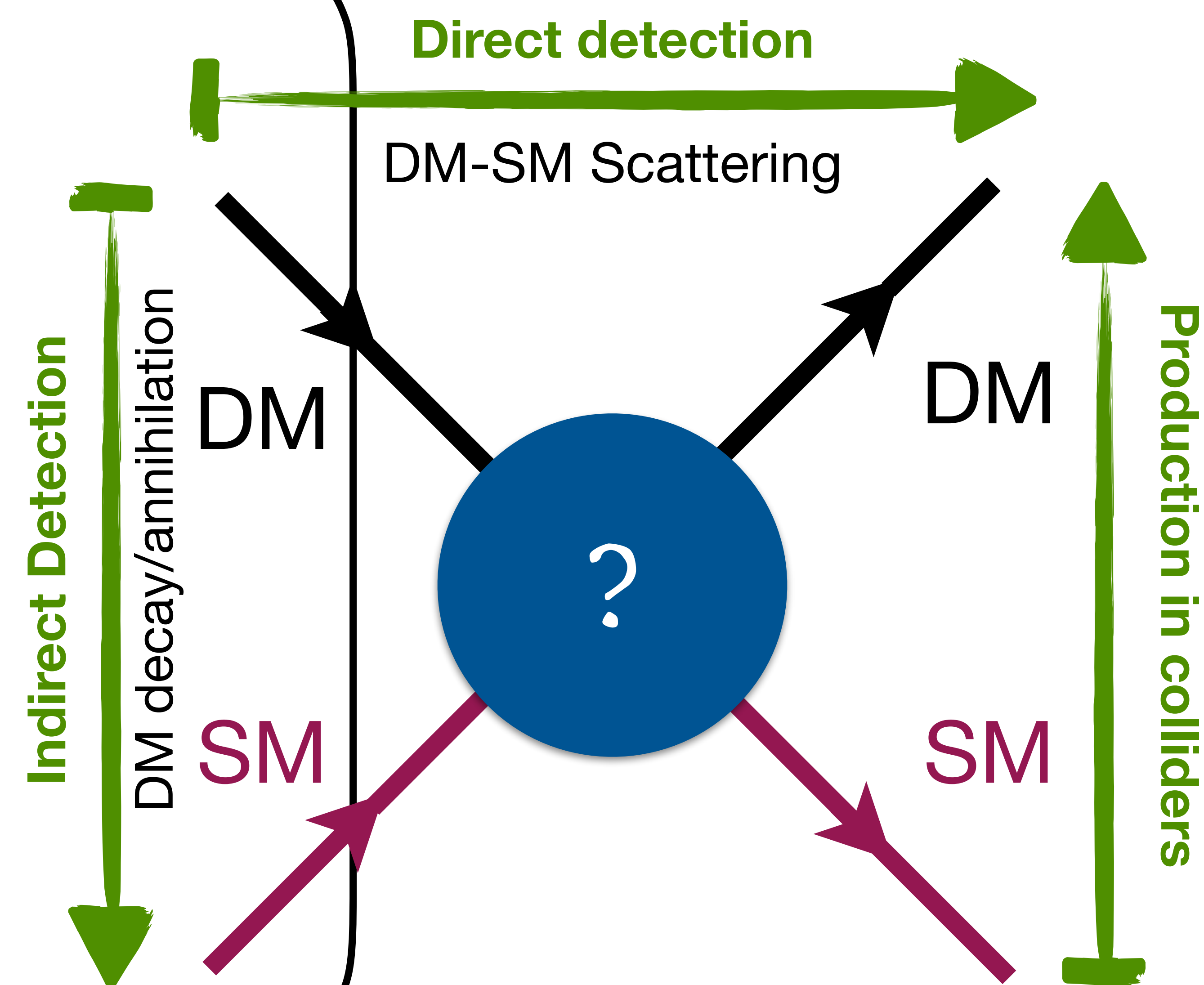
Neutrino portal to Dark Matter

Neutrinos may be the principal portal to the dark sector.

- Motivated by the *scotogenic* models
- Can explain the MiniBooNE anomaly

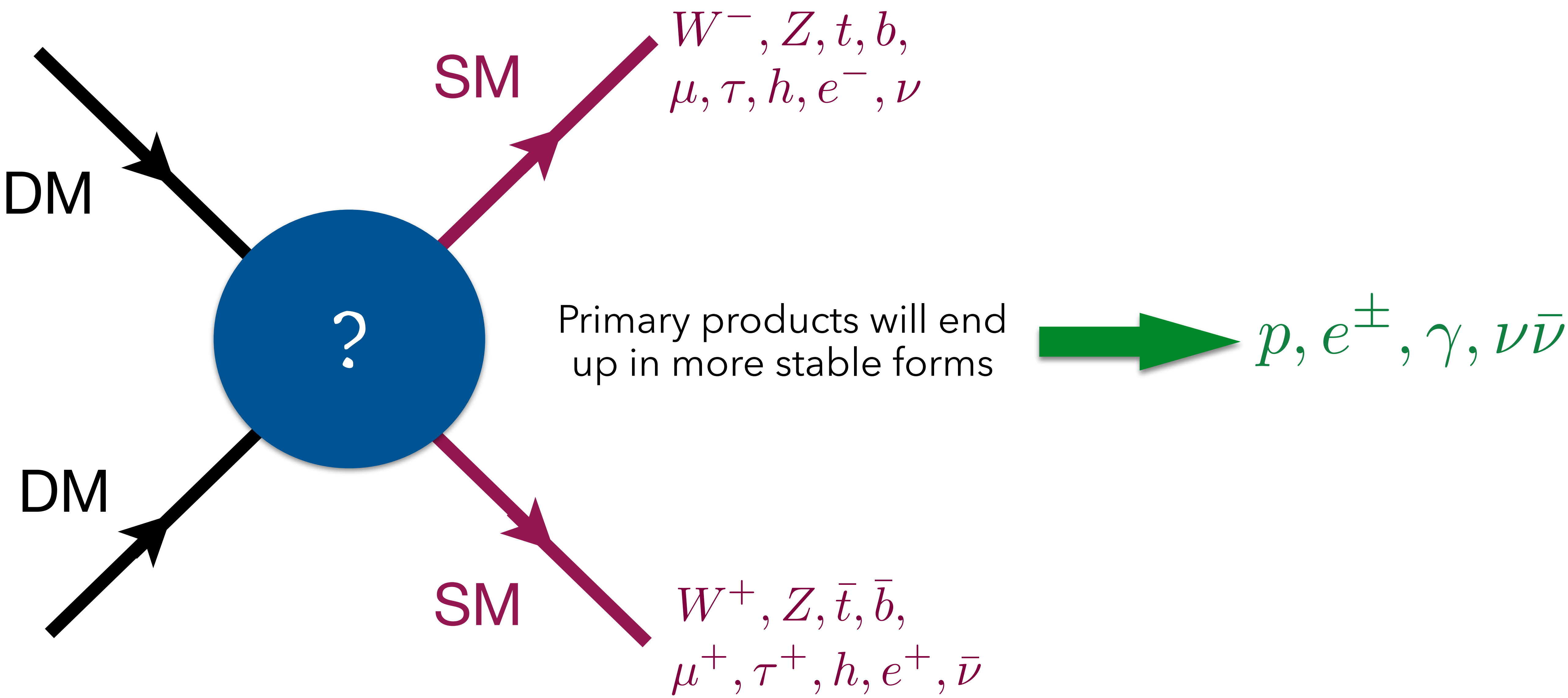
Indirect dark matter signatures in the neutrino sector:

- Features in geo, solar, atmospheric, and cosmic neutrino spectra
- Anisotropies in high-energy neutrinos from local dense regions or due to DM-Neutrino interaction.
- Features in the diffuse SN neutrino background.



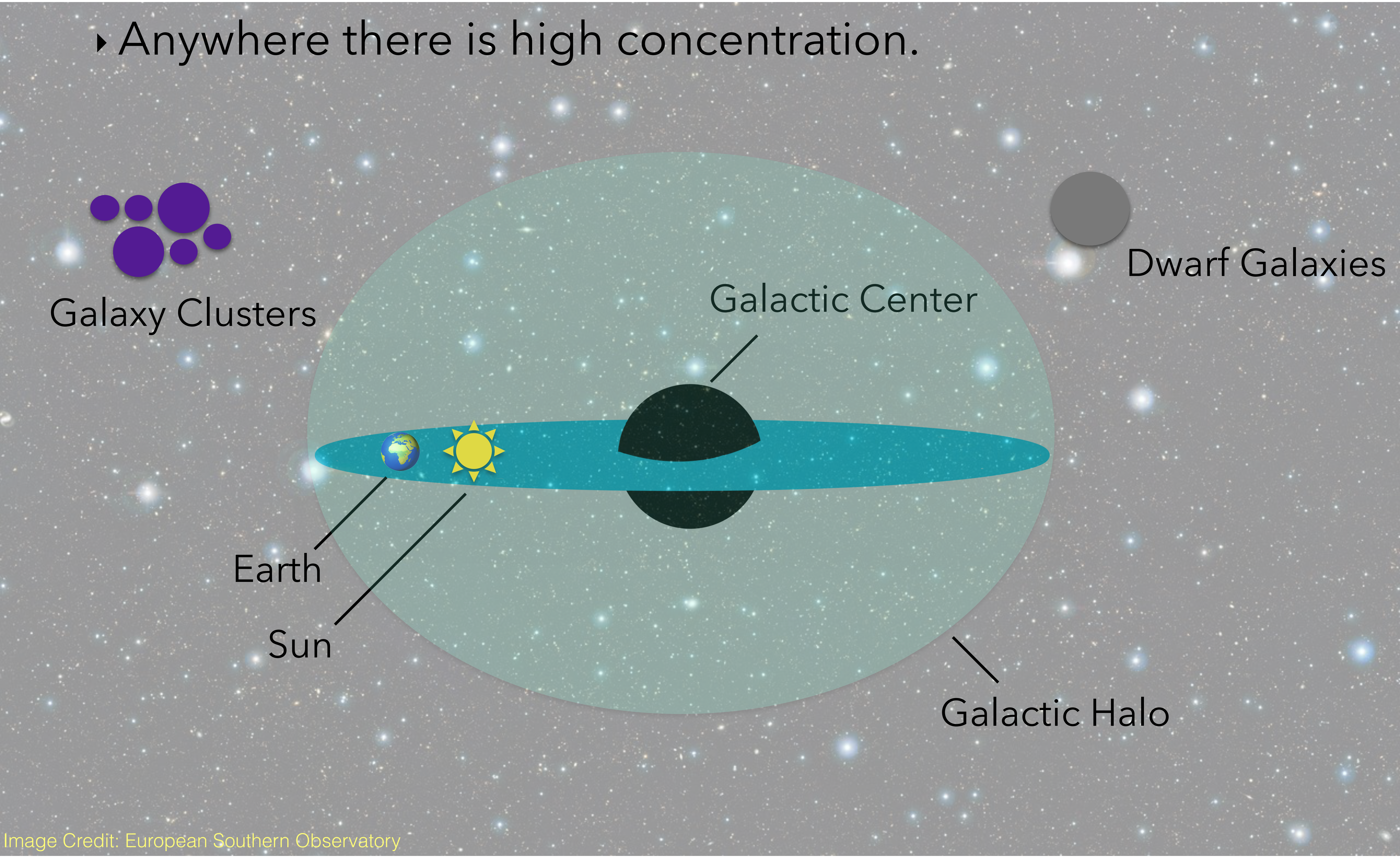
Dark Matter Annihilation (Decay)

- Weakly Interacting Massive Particles (WIMPs) are the leading candidate for DM.
- DM annihilation near the weak scale can produce the relic abundance in current Universe (aka WIMP Miracle).
- Thermal production of WIMPs in early Universe implies possible ongoing self-annihilation of DM.

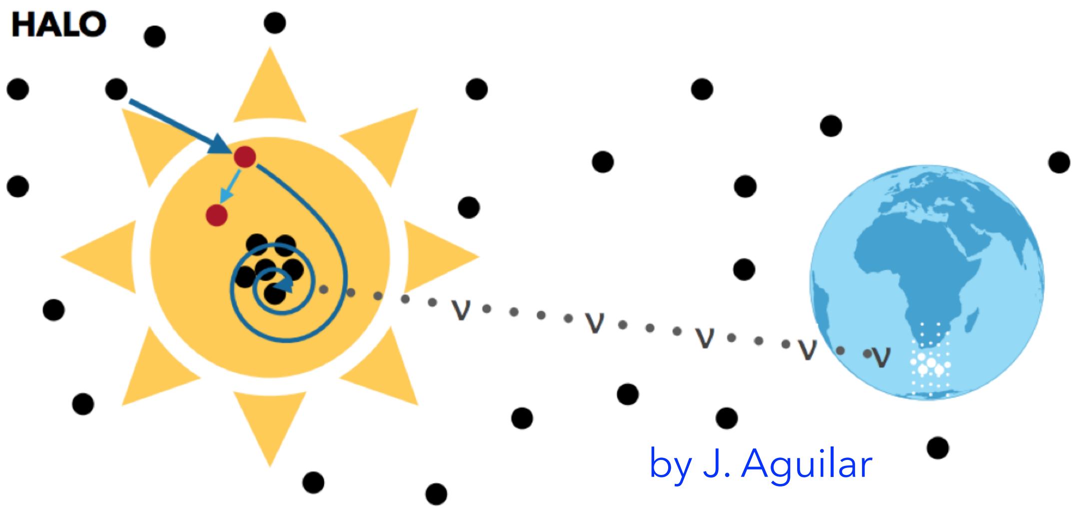


Where to look for Dark Matter?

- Anywhere there is high concentration.

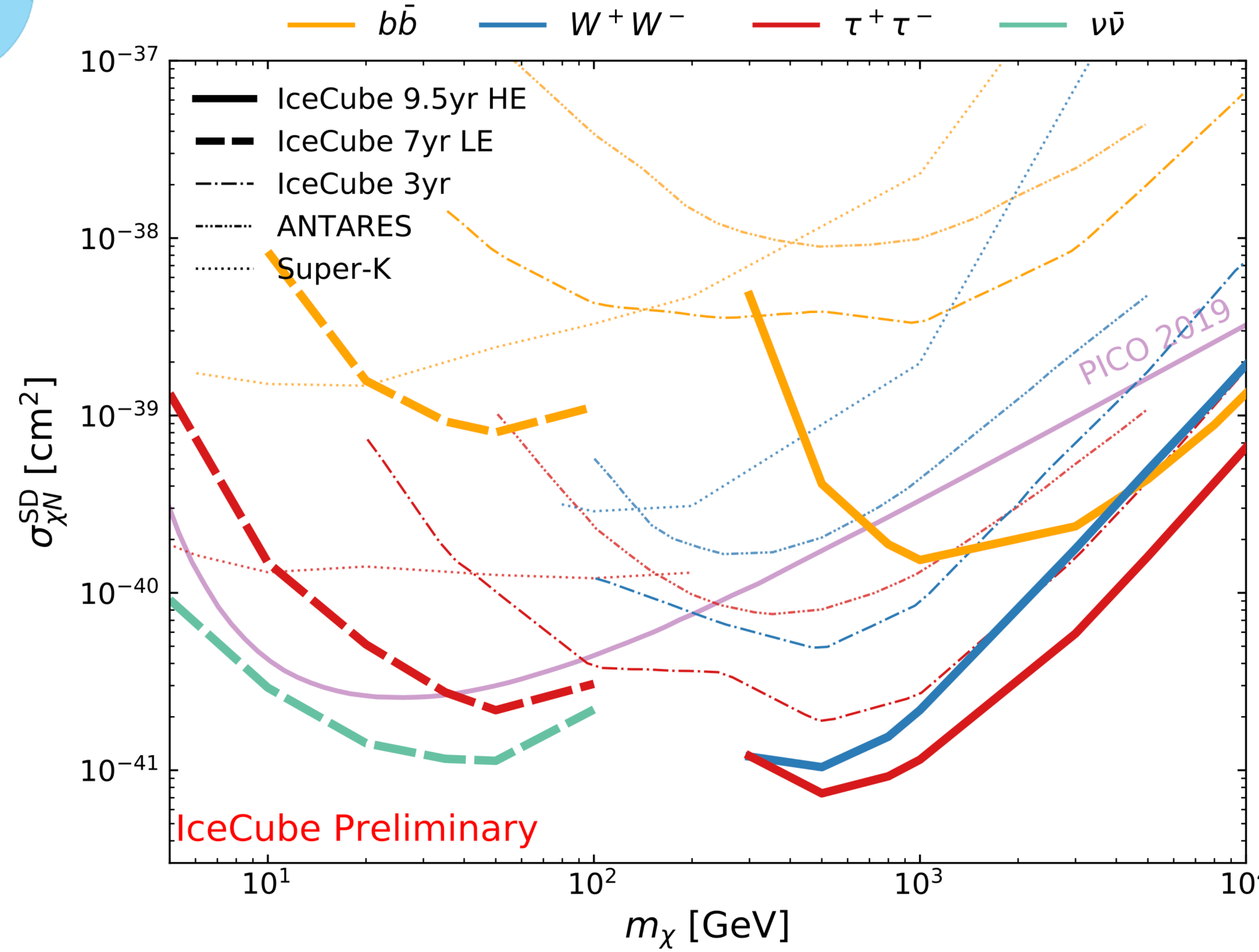


Search for Dark Matter in the Sun



- 7 years of IceCube-DeepCore data (LE)
- 9 years of muon track data (HE)
- Searching for annihilation signatures with neutrinos in full detector

IceCube PRD 2022,
J. Lazar, ICRC 2021

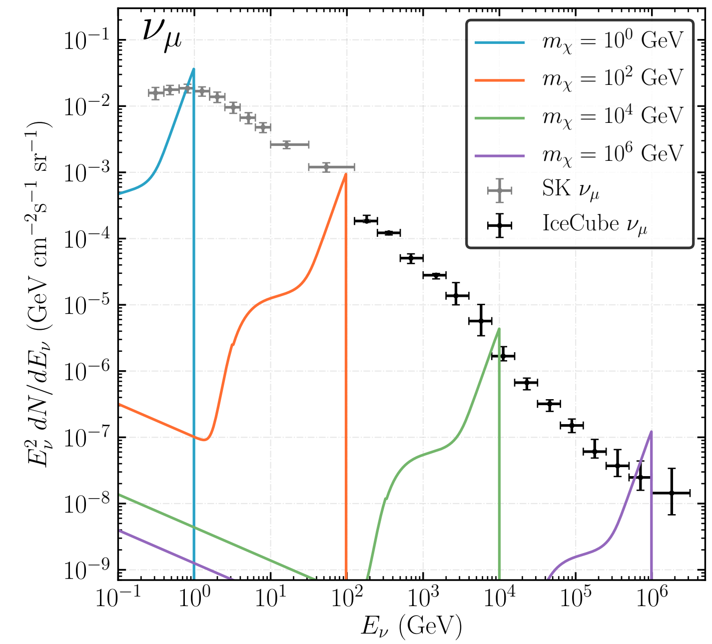


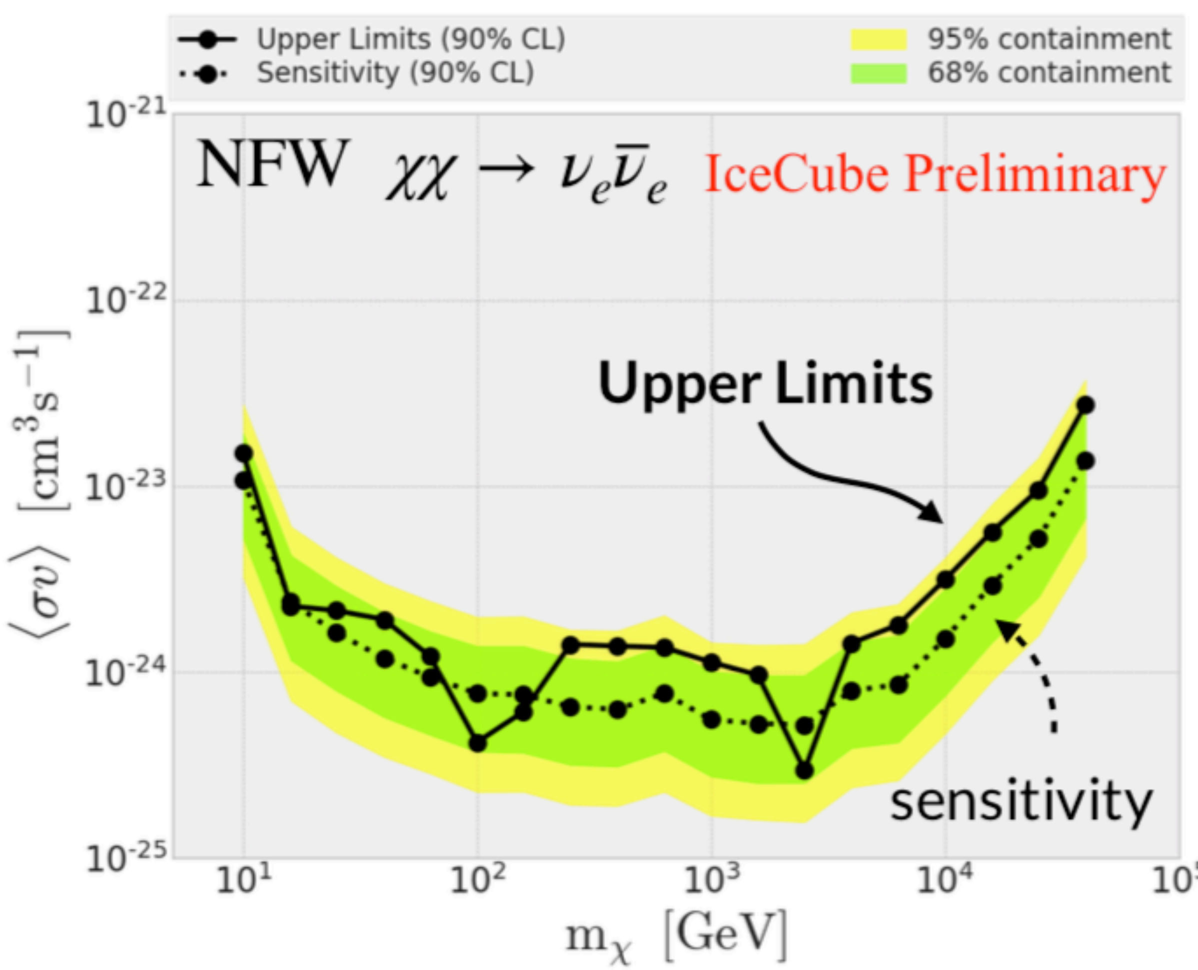
- Strongest limits on the spin-dependent cross section!

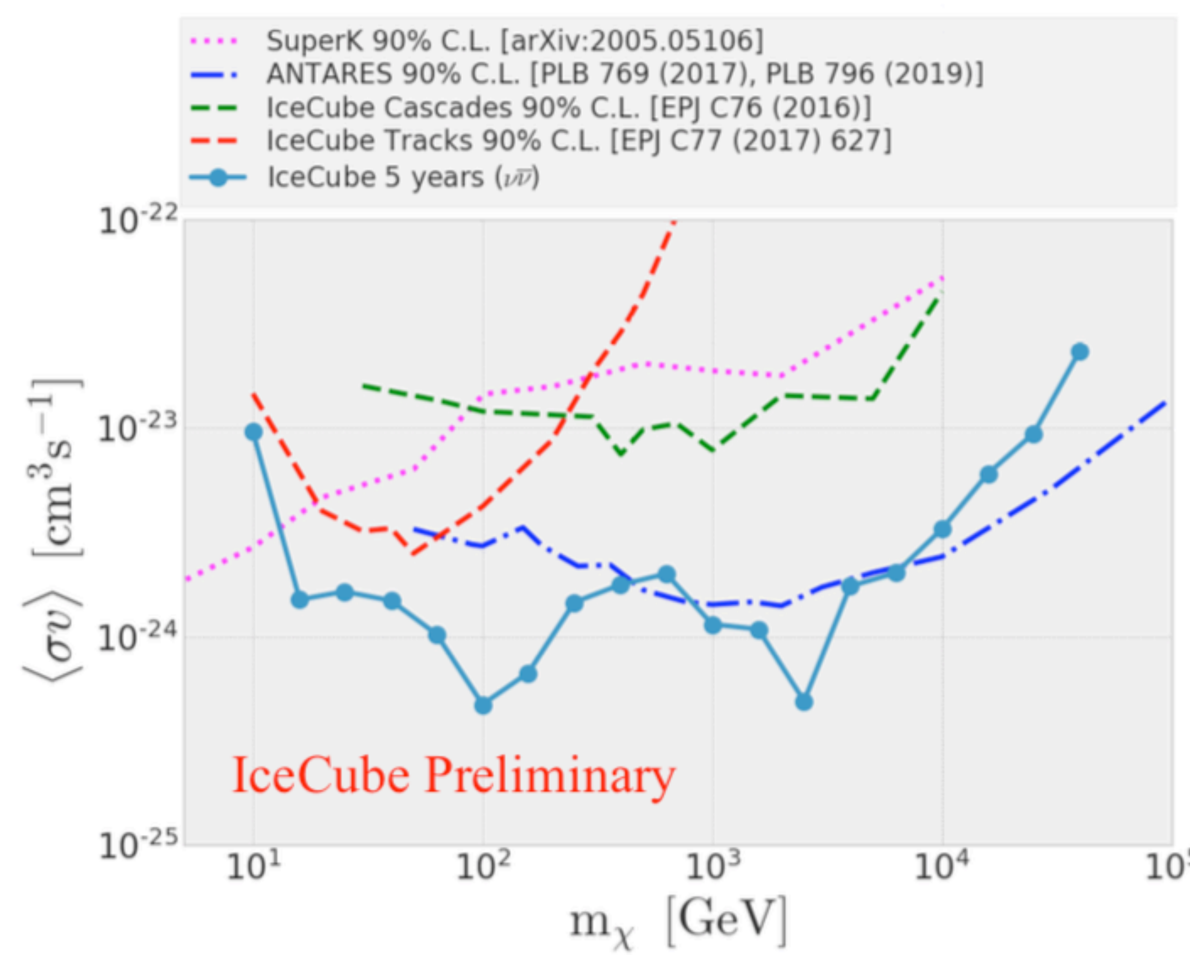
Galactic Center Dark Matter Search

Annihilation

- 5 years of IceCube data
- Looking for the neutrino lines as a unique spectral feature

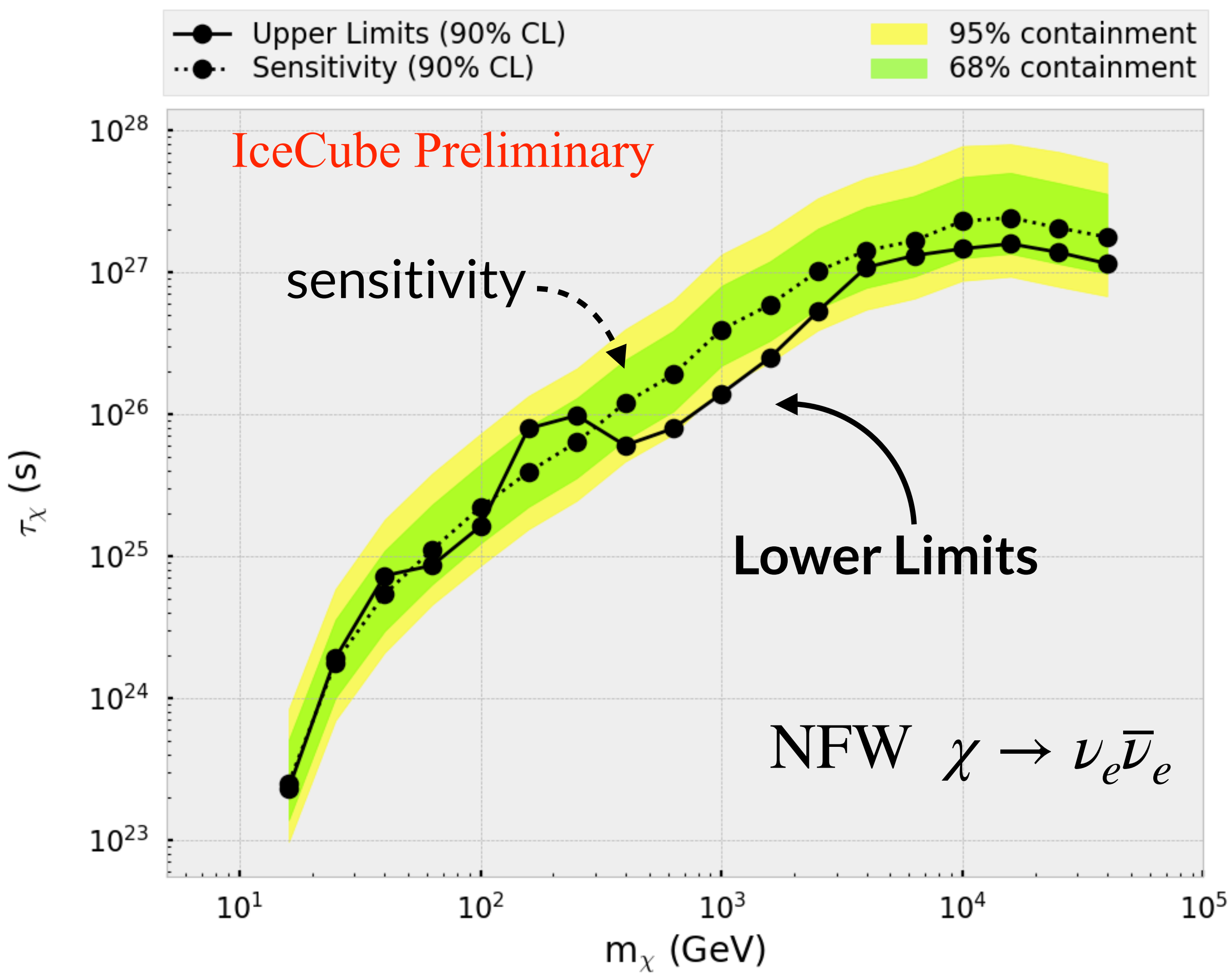


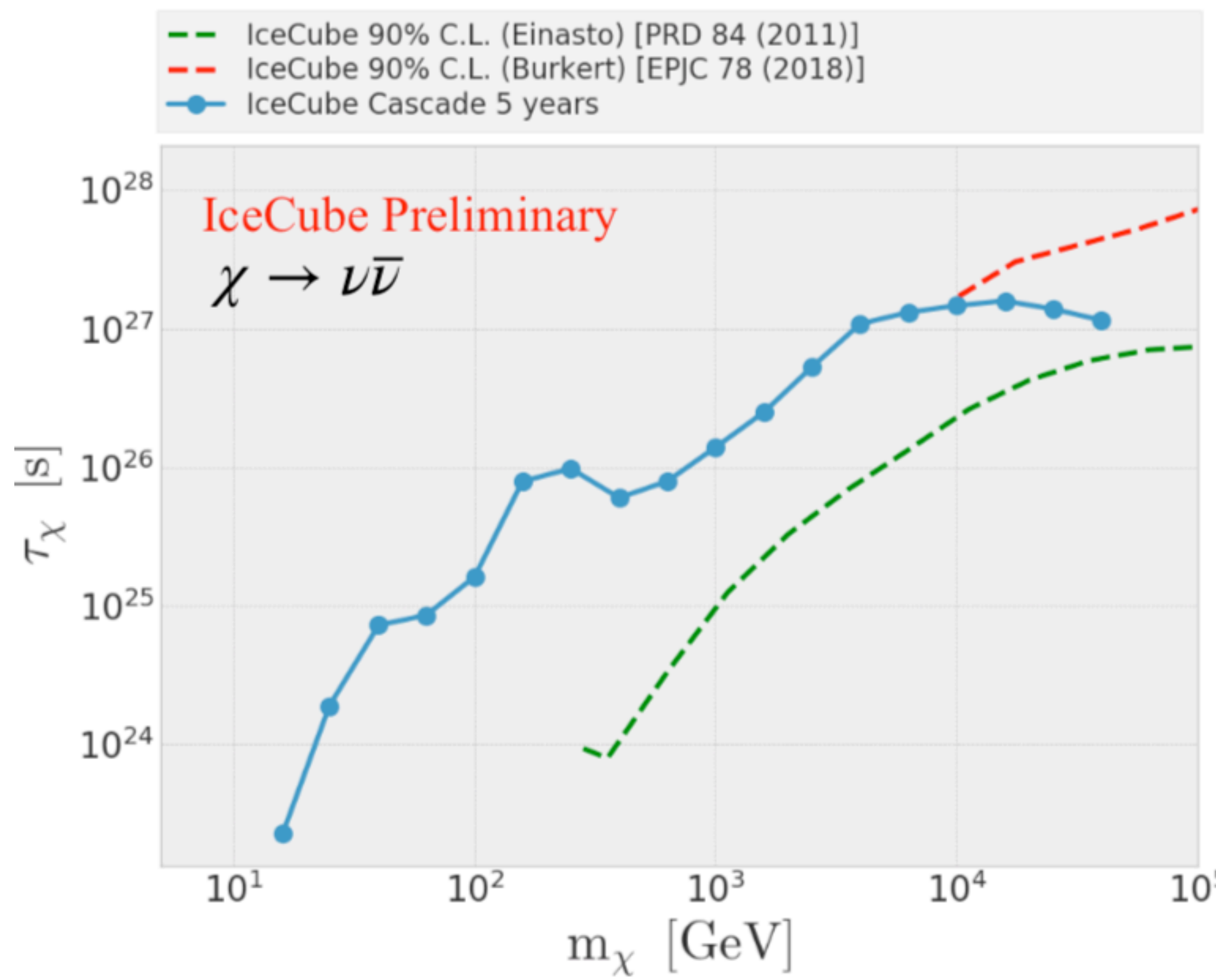




Galactic Center Dark Matter Search

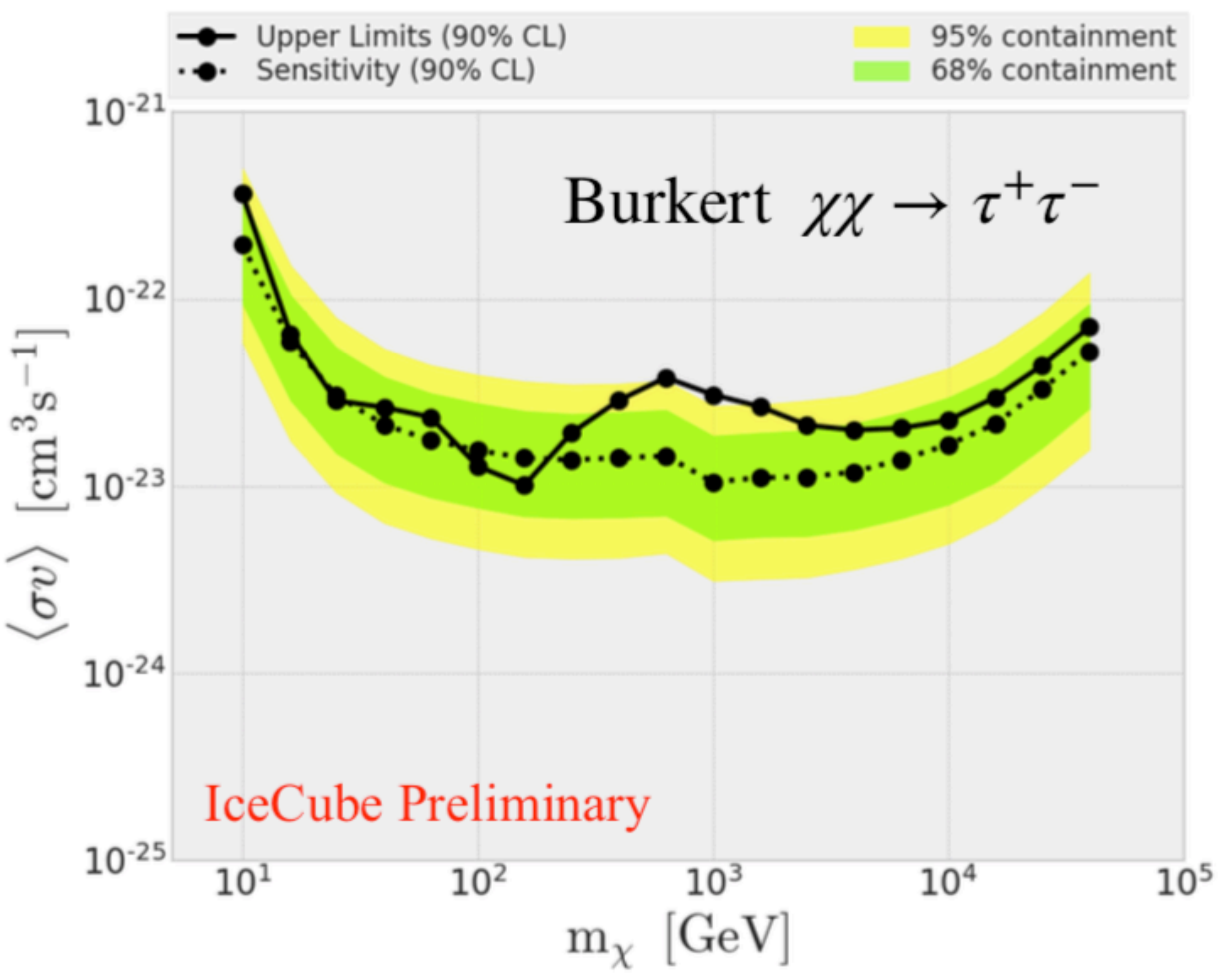
- Decay

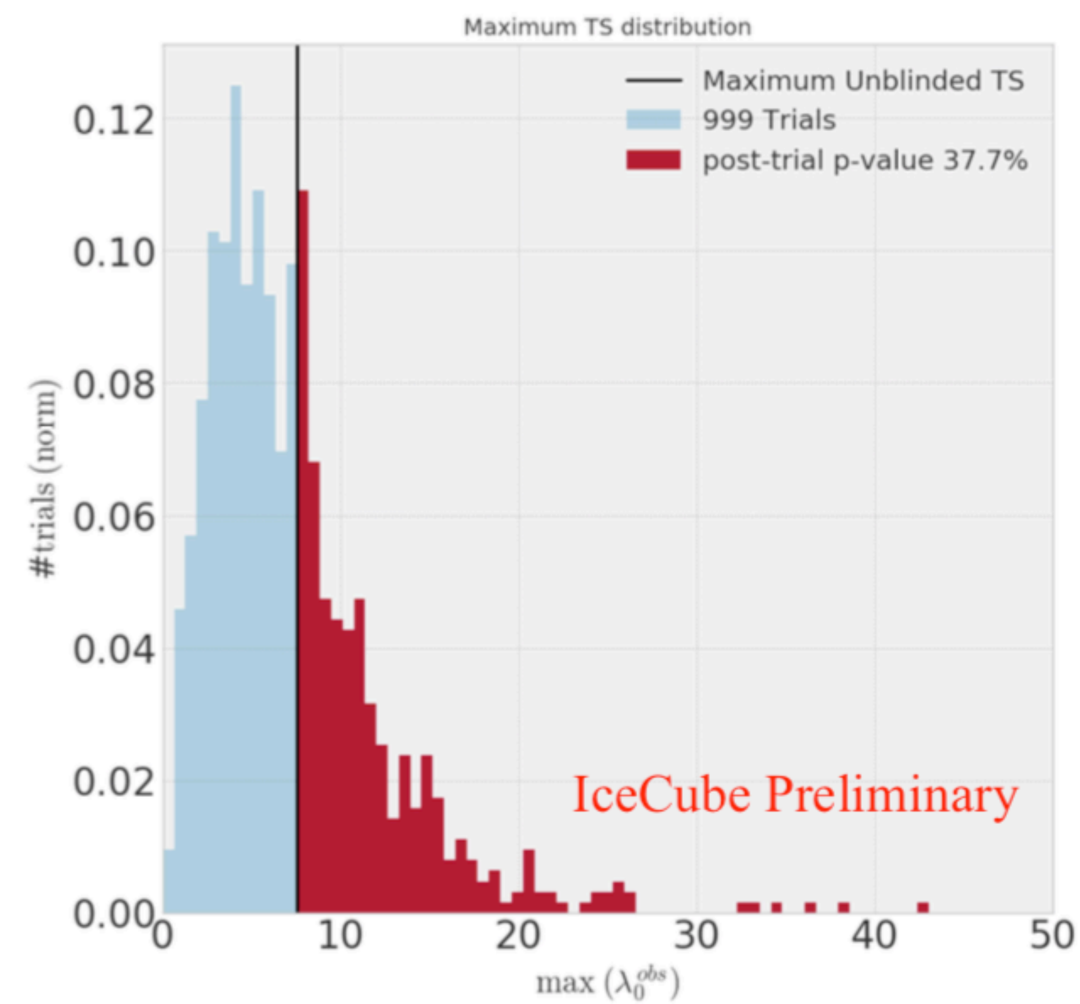




Galactic Center Dark Matter Search

- other channels for annihilation

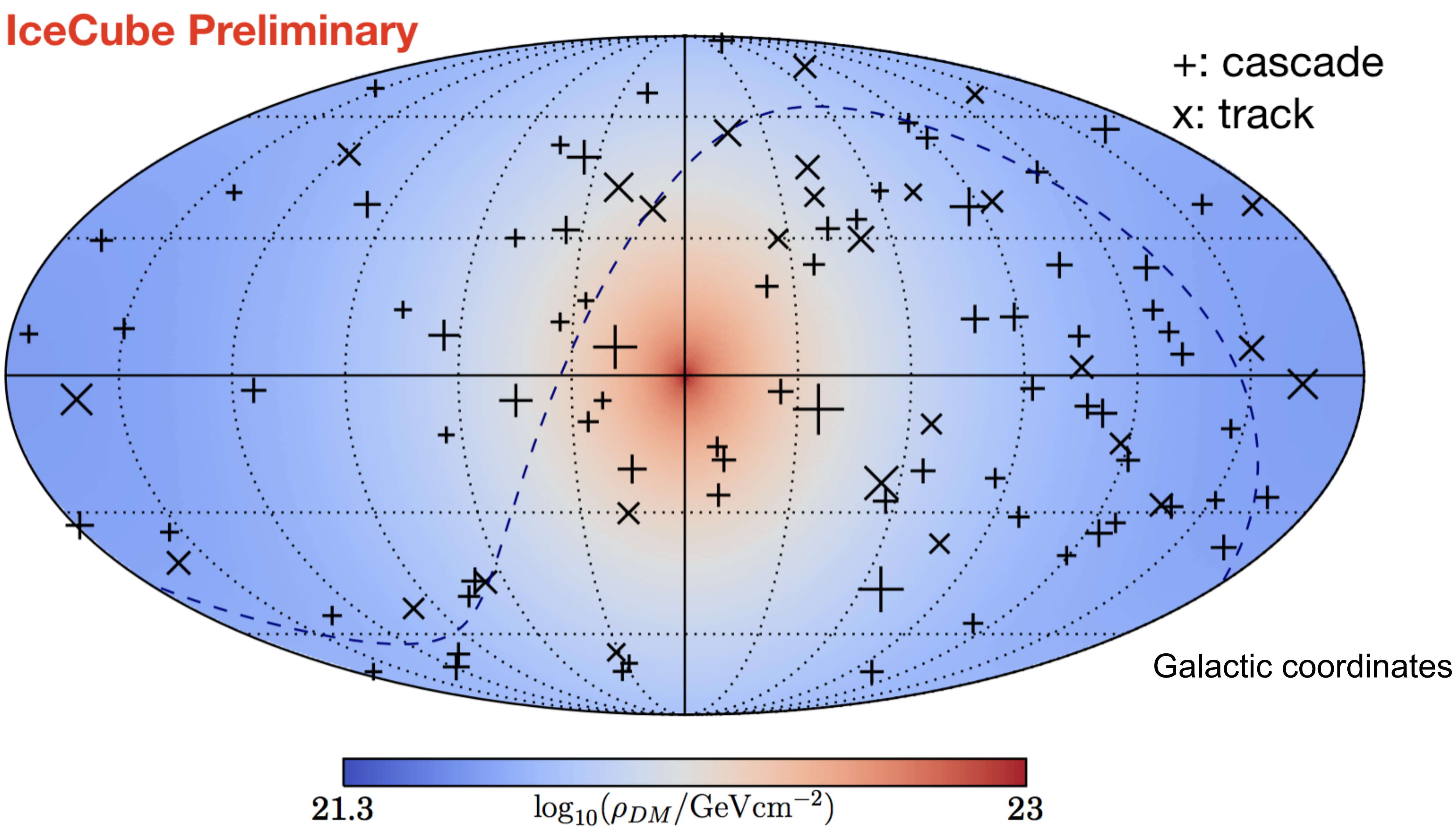




- The most significant result is found at 1 TeV, with a post(pre)-trial p-value of 38%(0.3%)

Dark Matter Search at High Energies

High-Energy Starting Events



IceCube 2022

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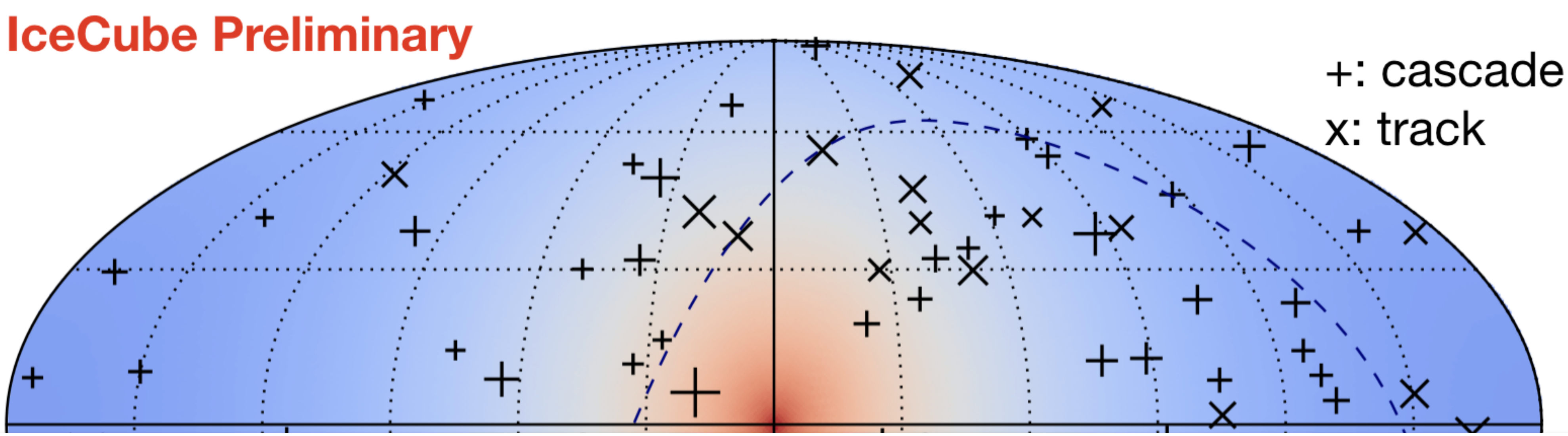
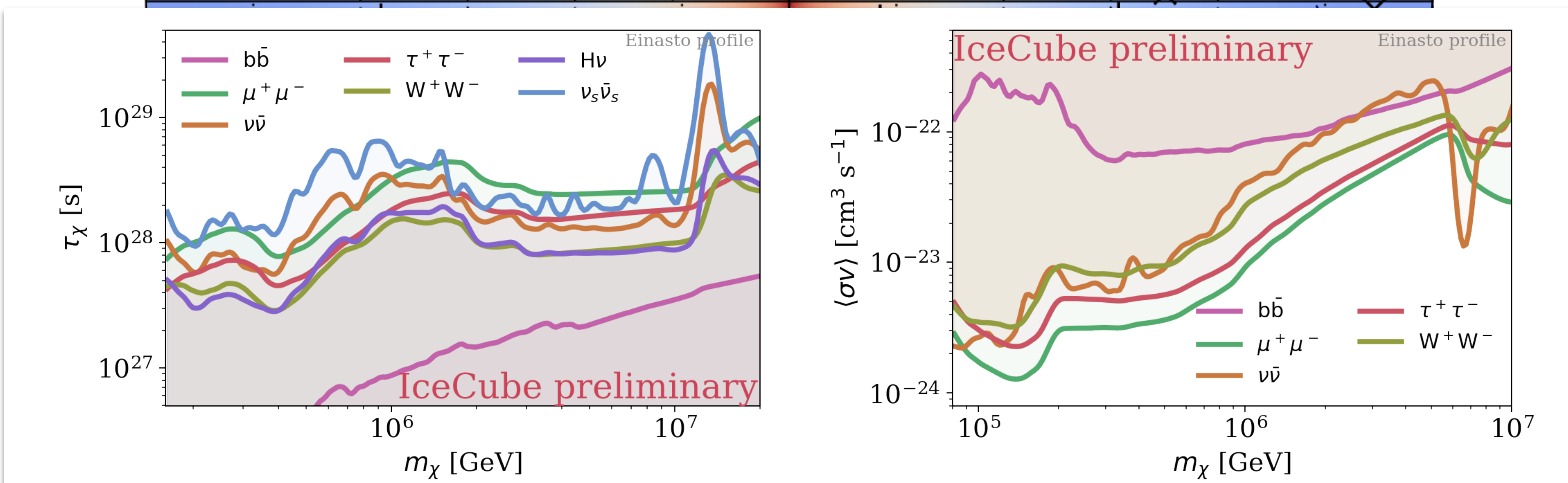
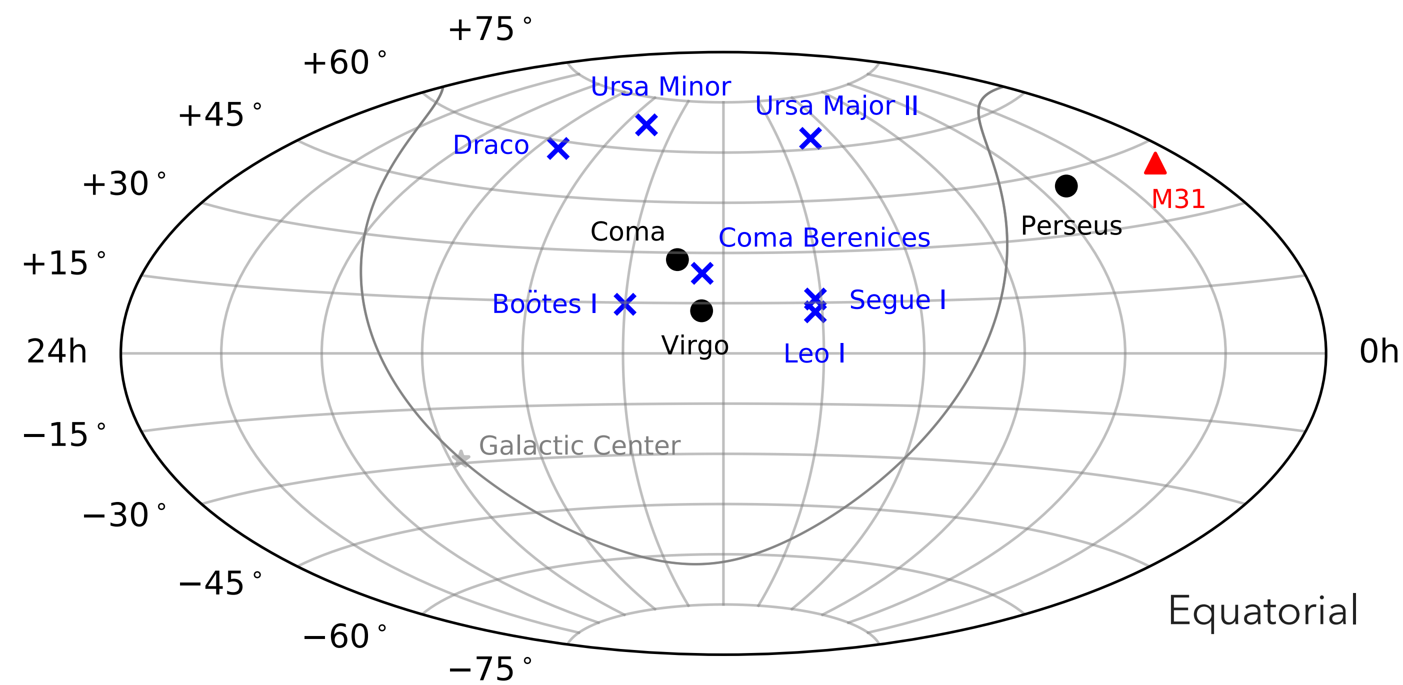




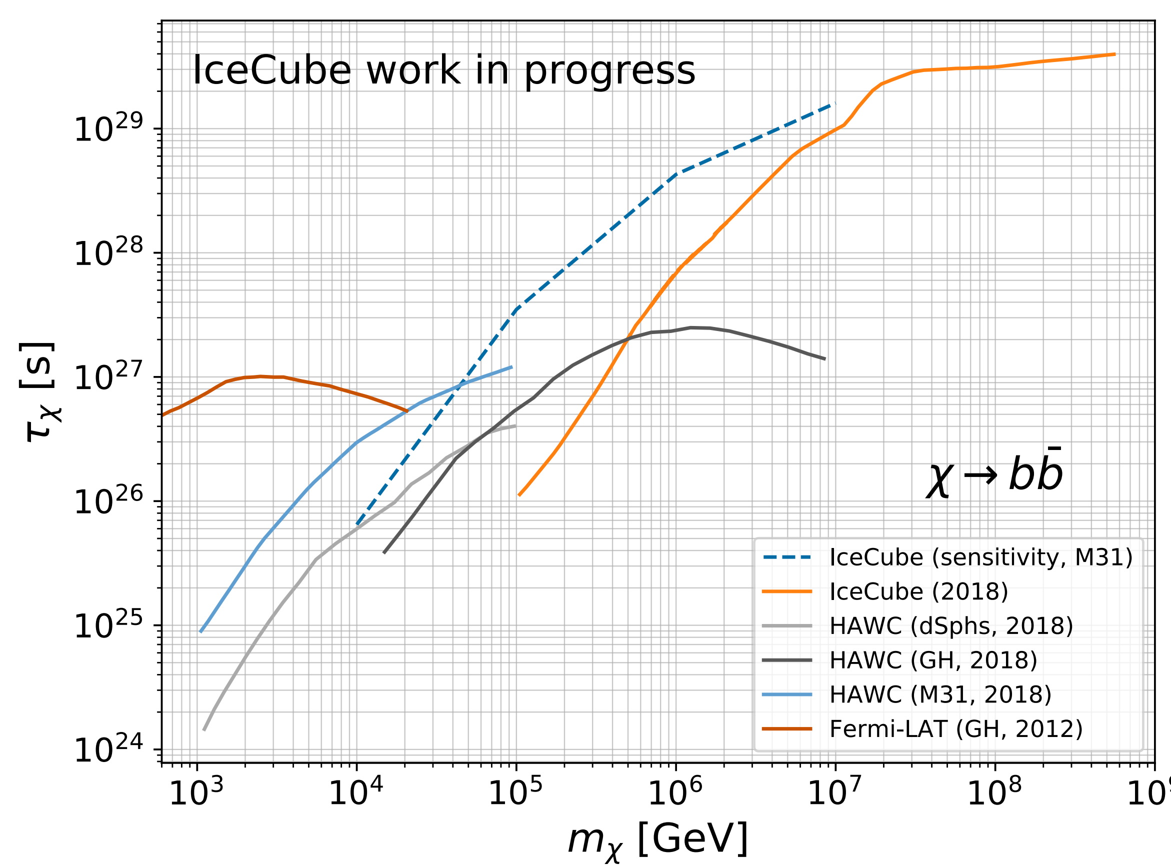
IceCube 2022

Galaxy Clusters

- Searching for neutrino emission from Galaxy Clusters and dwarf spheroidal galaxies
- Targeting heavy dark matter decay signatures to different channels
- Nearby cluster such as Virgo can provide a strong probe dark matter decay
- Sensitivity will enhance with better understanding of the origin of the cosmic neutrino flux

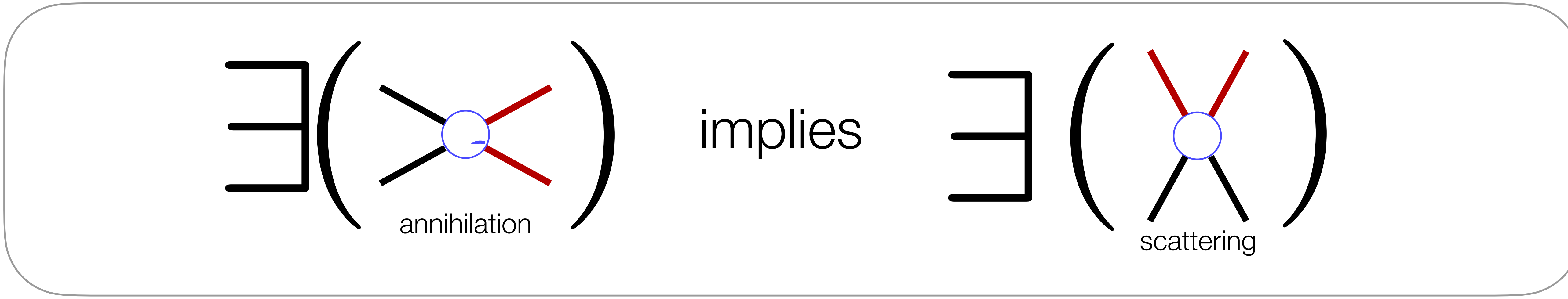


M. Jeong ICRC 2021

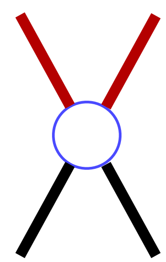


Dark Matter-Neutrino Interaction?

Thermal production of WIMPs in early Universe implies possible ongoing self-annihilation of DM.



if = quarks, then

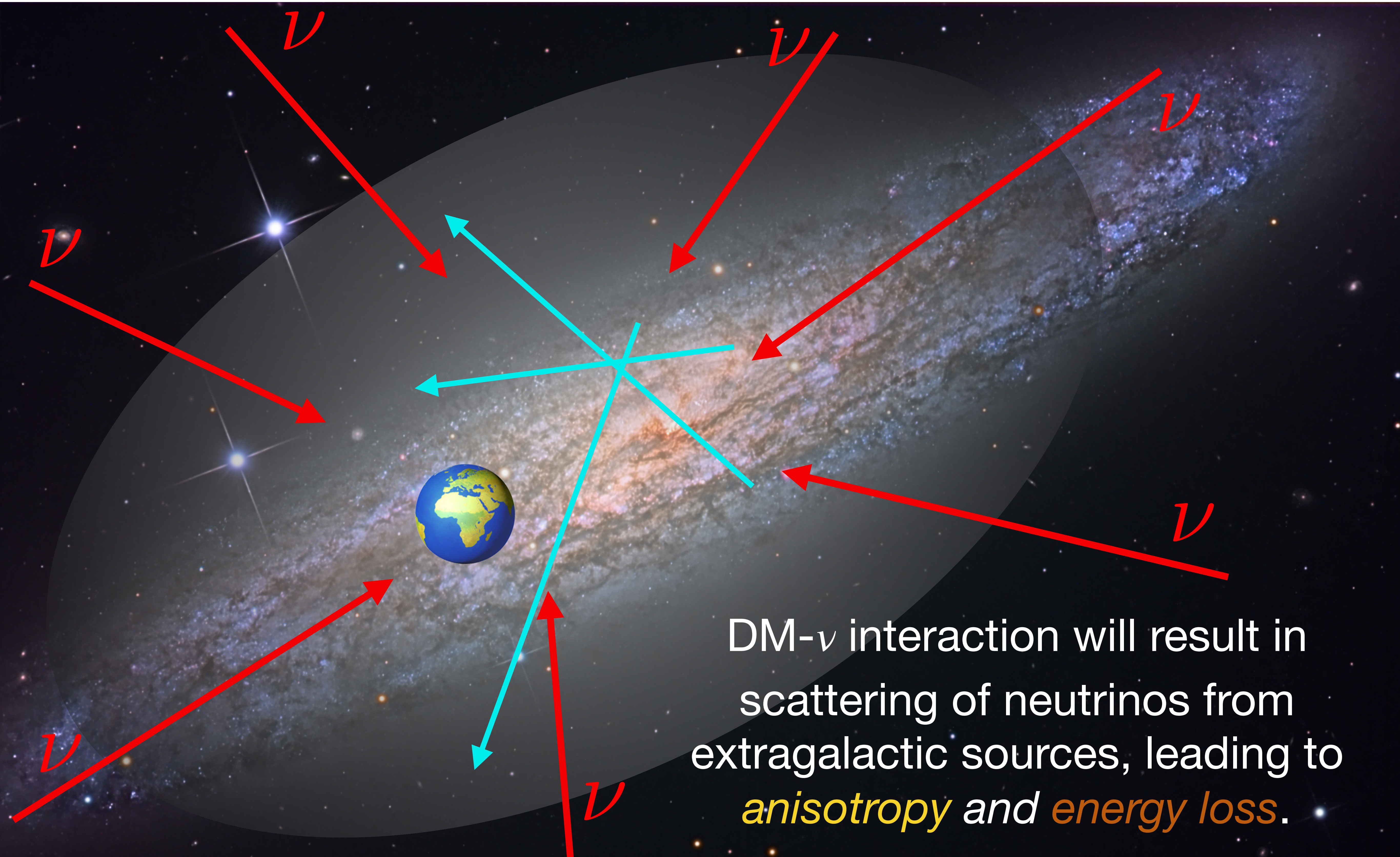


= direct detection (LUX, LZ, SuperCDMS, …)

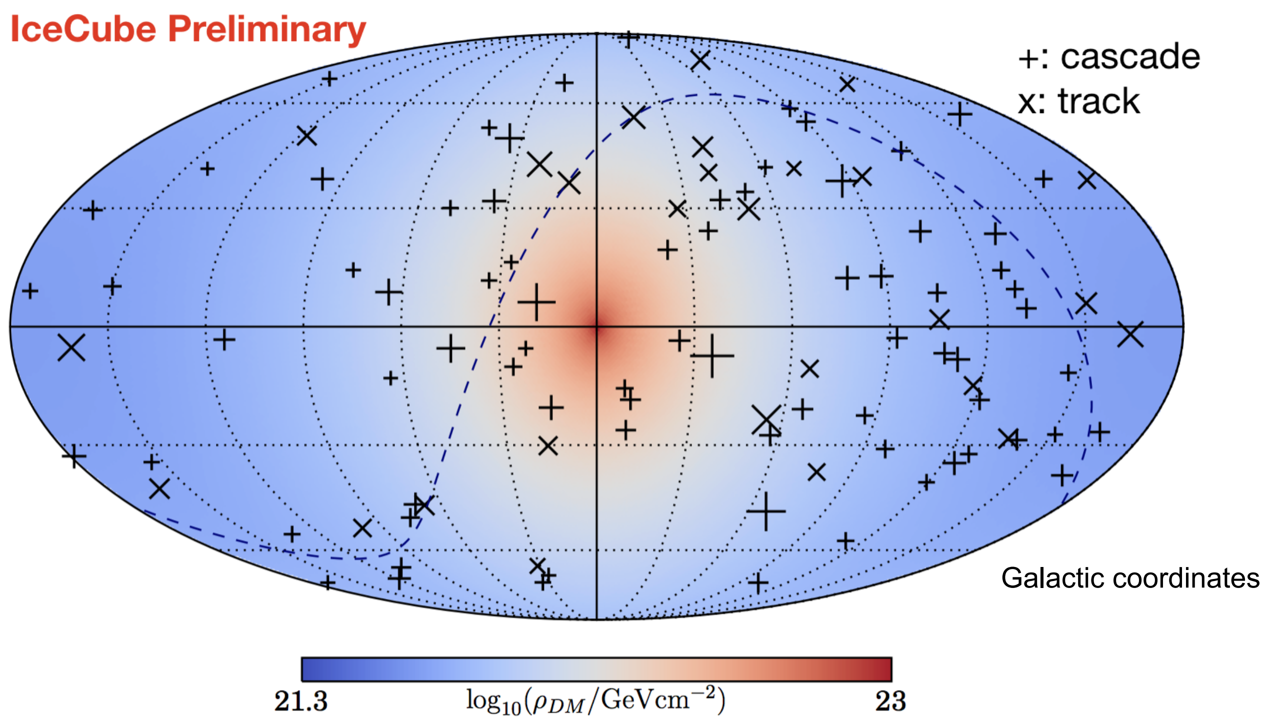
But if too light, or ? does not talk to quarks, then could be neutrinos

[Boehm+ 01, 02, 05, 14–Bertschinger+ 06– Mangano+ 06–Serra+ 10–Wilkinson+ 14 –van den Aarssen+ 12–Farzan+ 14–Cherry+ 14–Bertoni+ 15–Chewtschenko+ 15]

Dark Matter–Neutrino Scattering



Dark matter column density* seen from Earth



* *Einasto*

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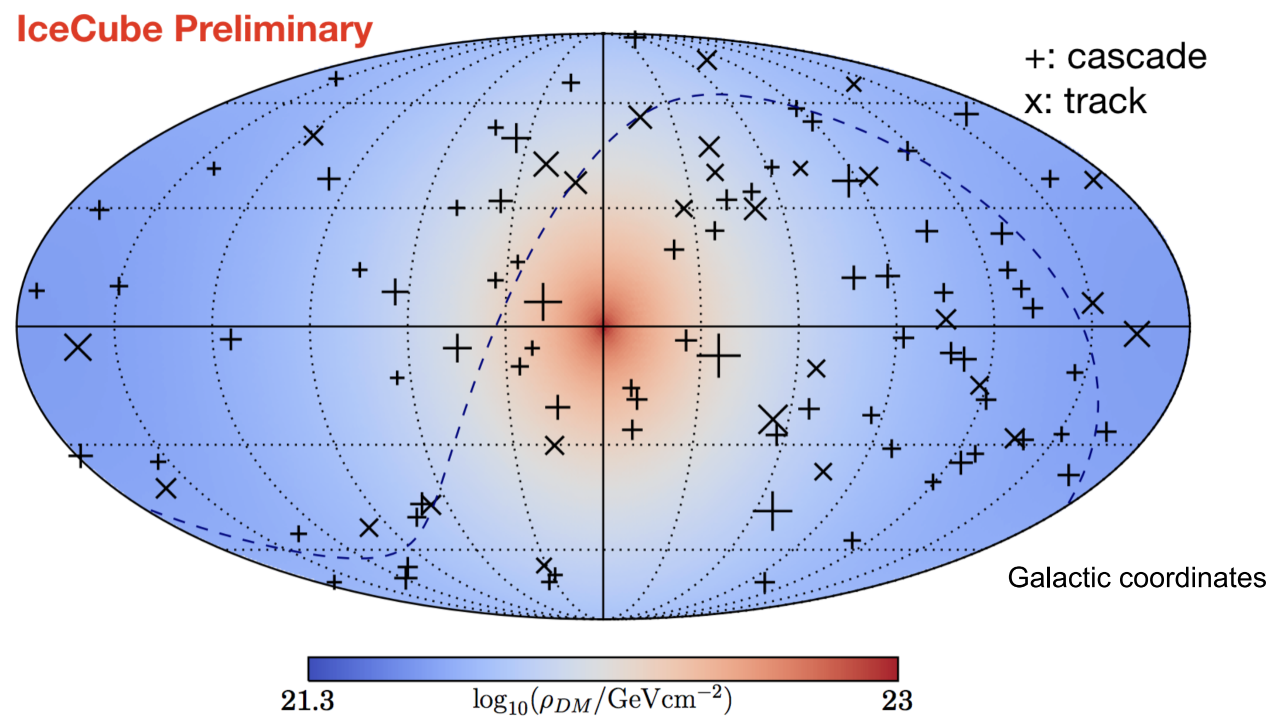

Simulation including effects of detector, Earth

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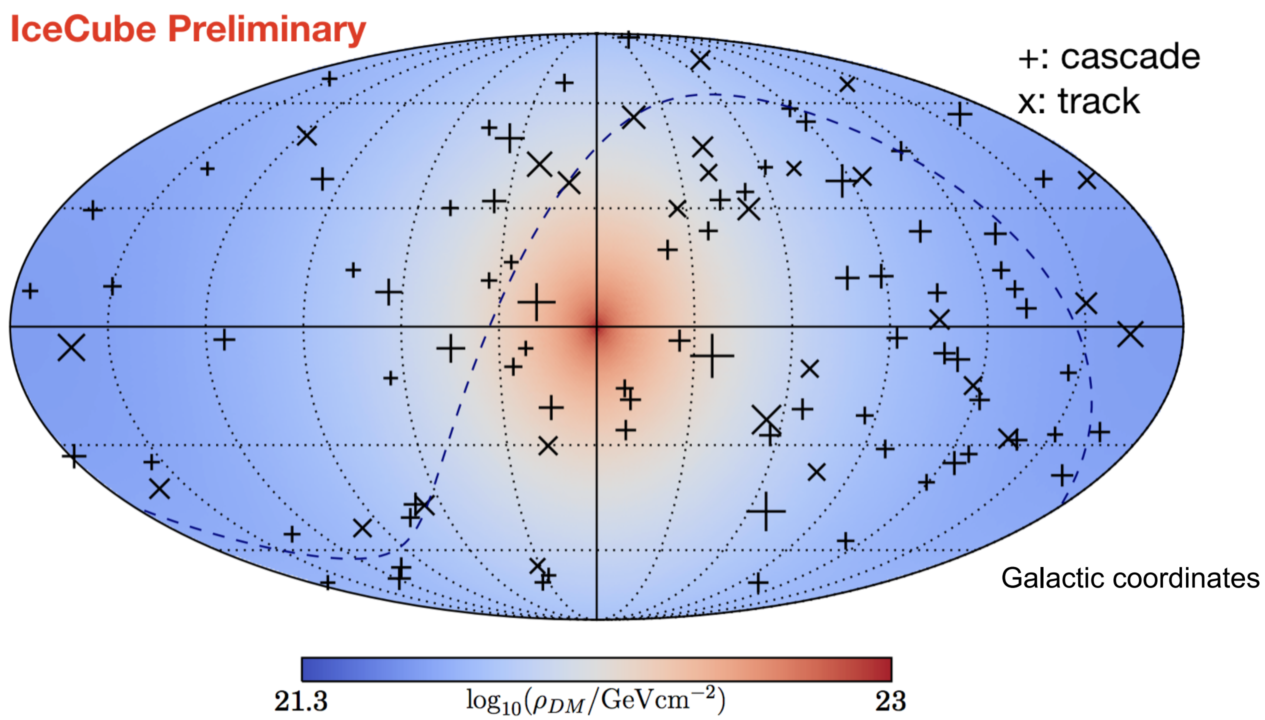

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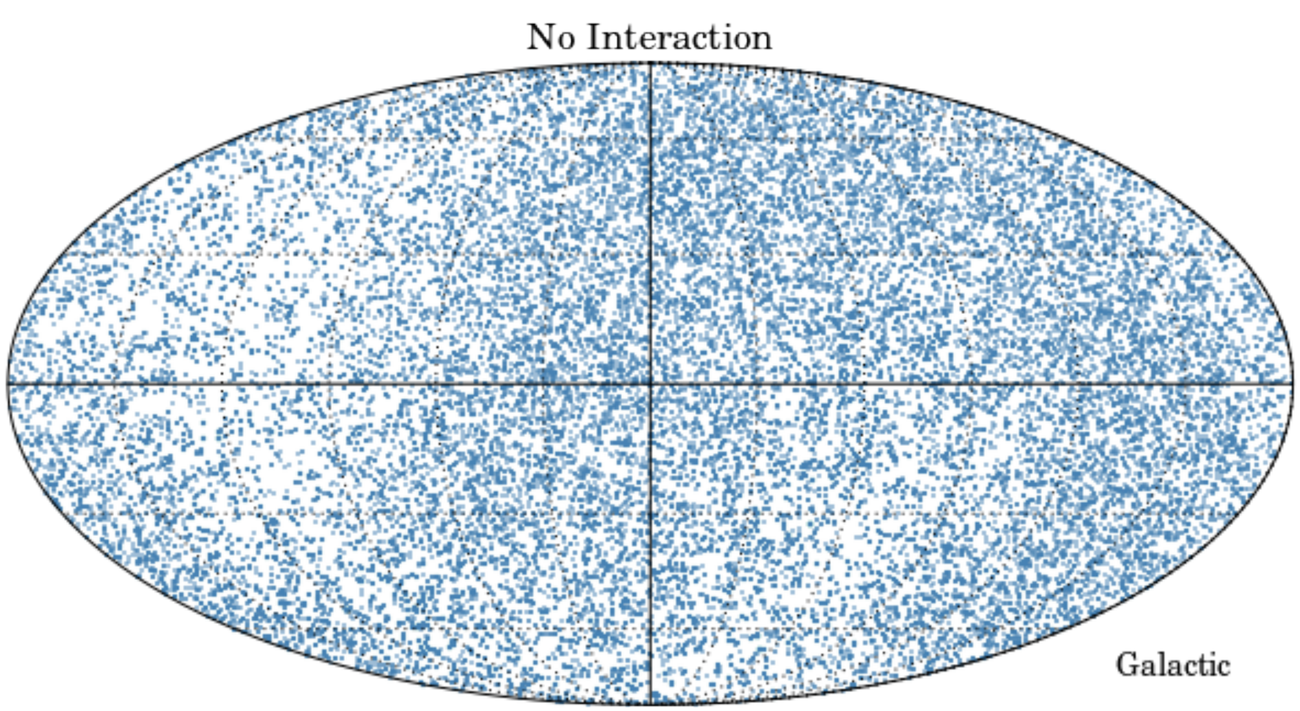

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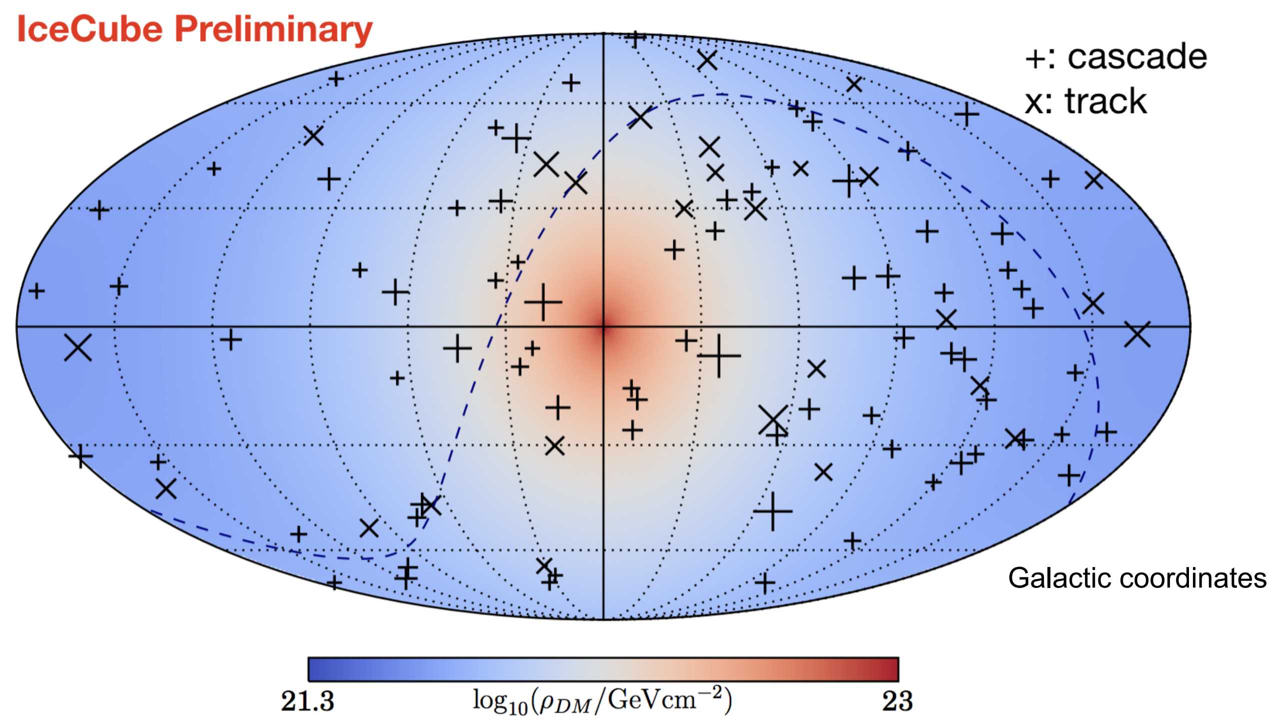

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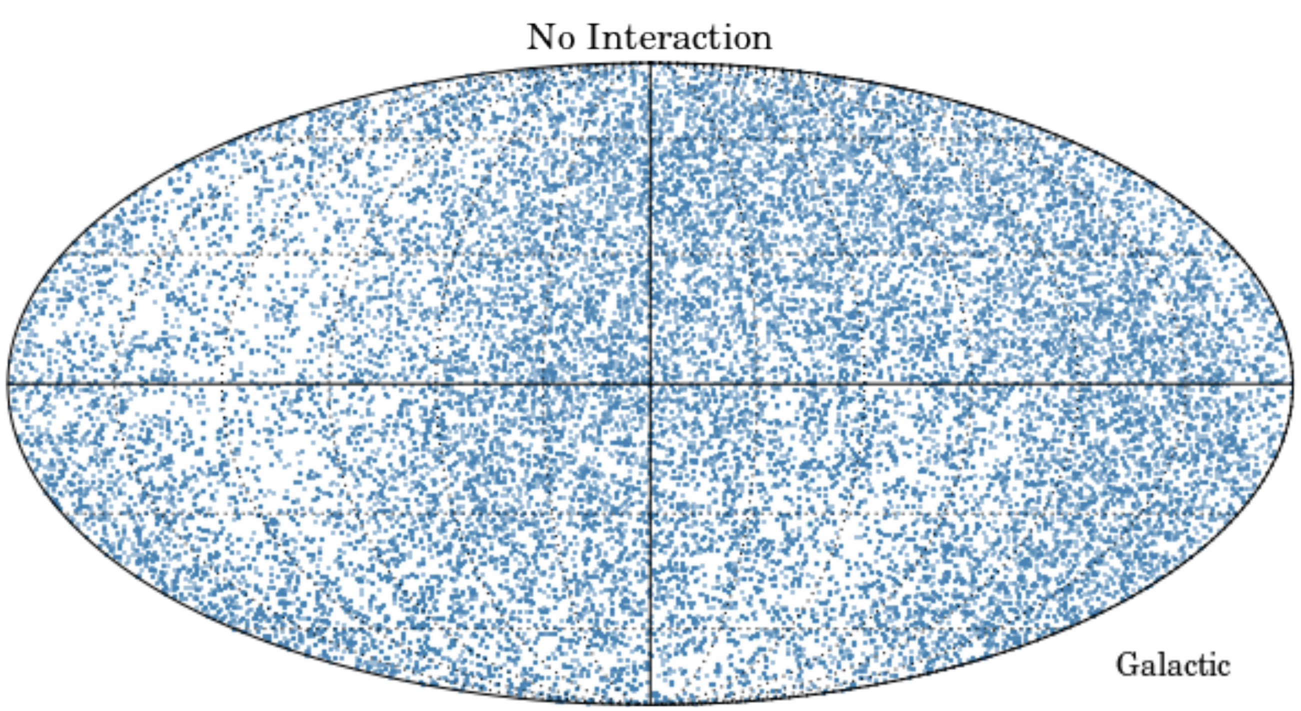
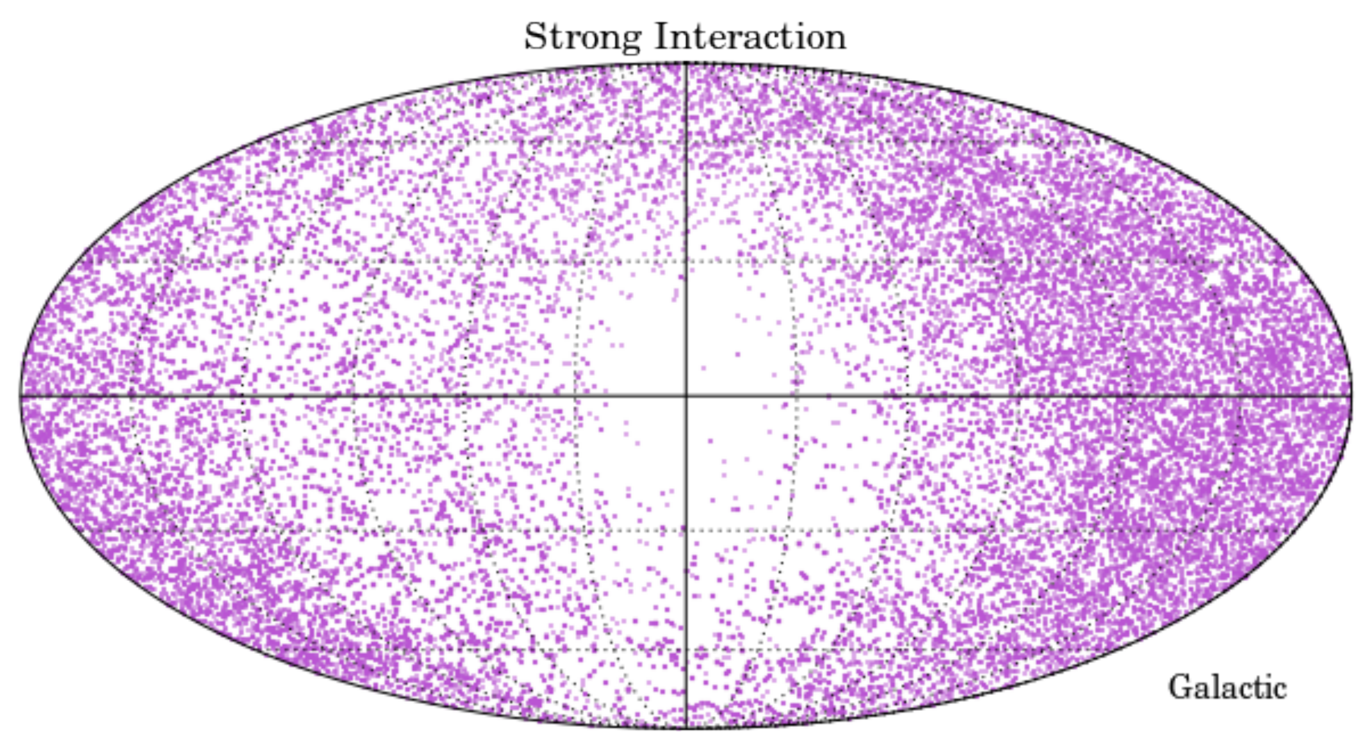
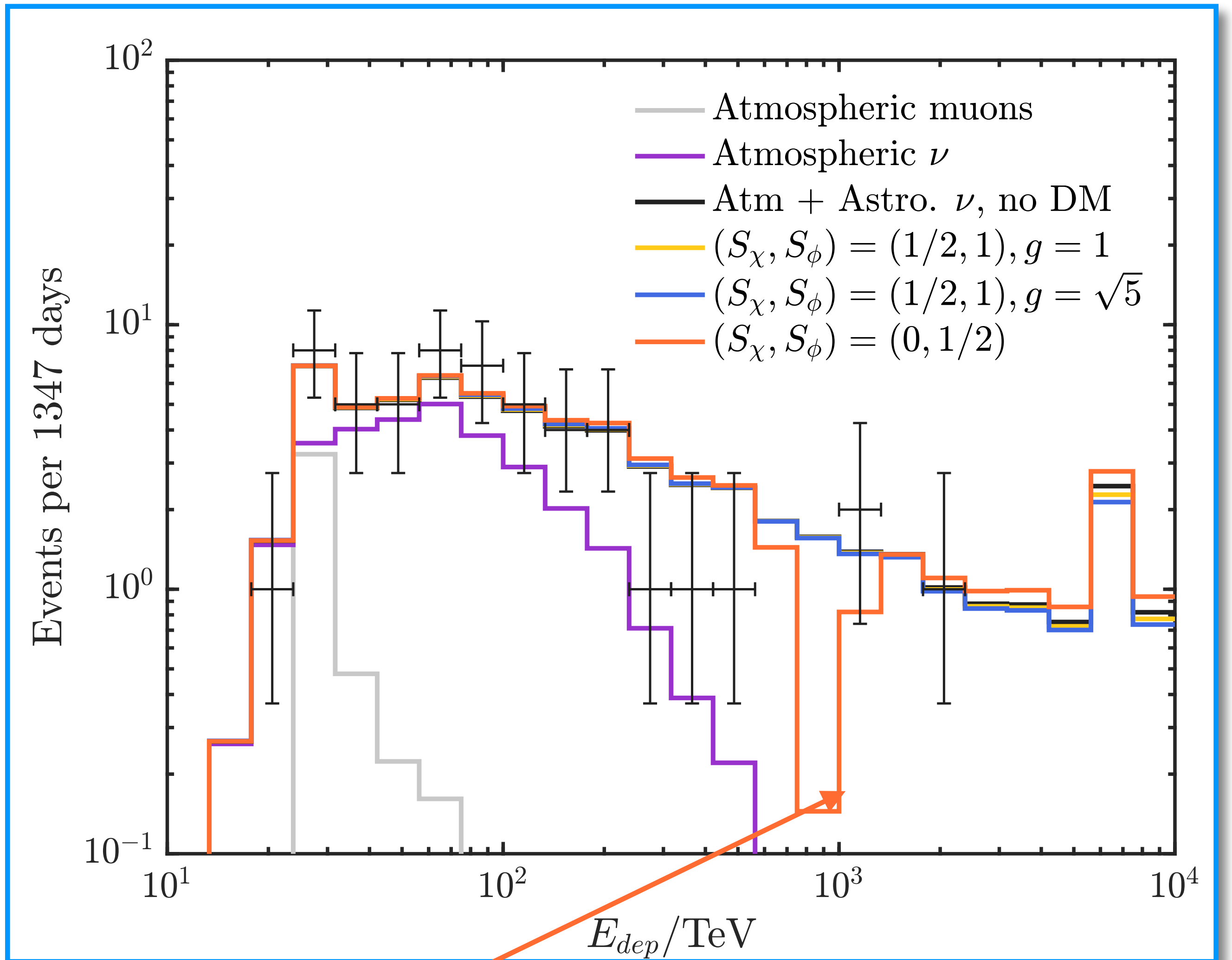




* *Einasto*

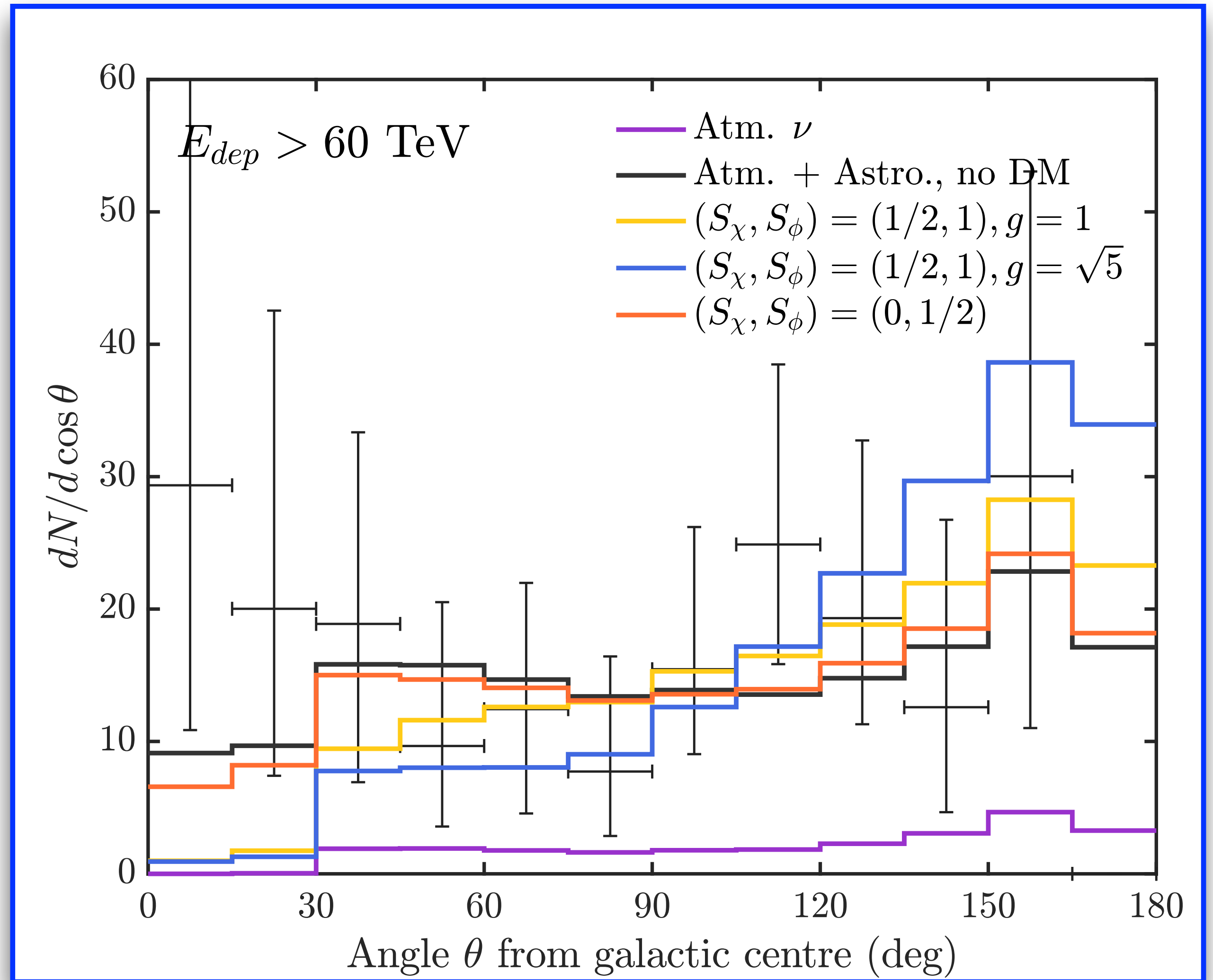
Energy & Morphology

Energy Distribution



Resonance @ 810 TeV

Angular Distribution



Argüelles, AK, Vincent, PRL 2017

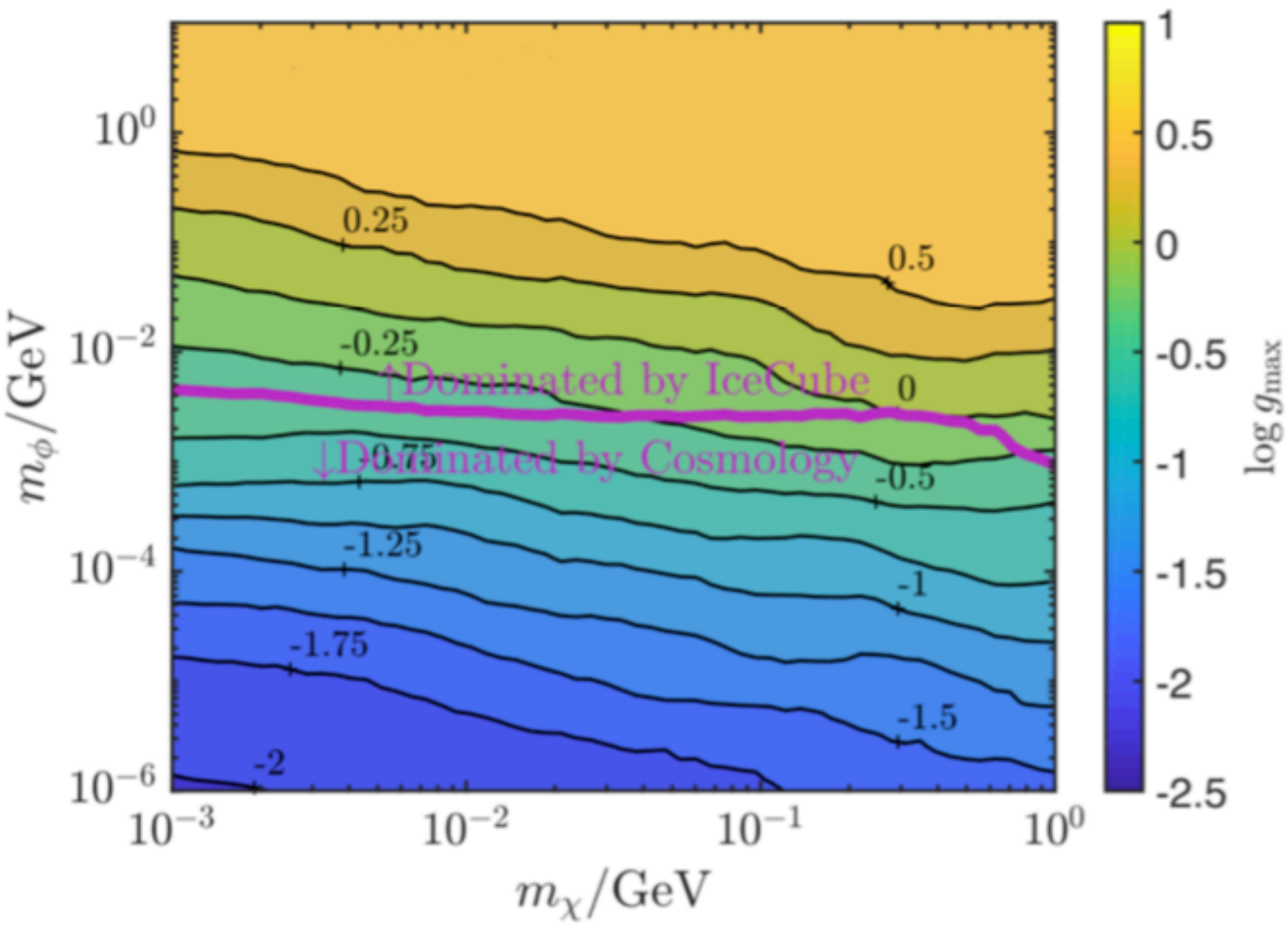
IceCube HESE

Neutrino-DM interactions creates features in the energy spectrum (e.g. Dips, cut-off, softening)

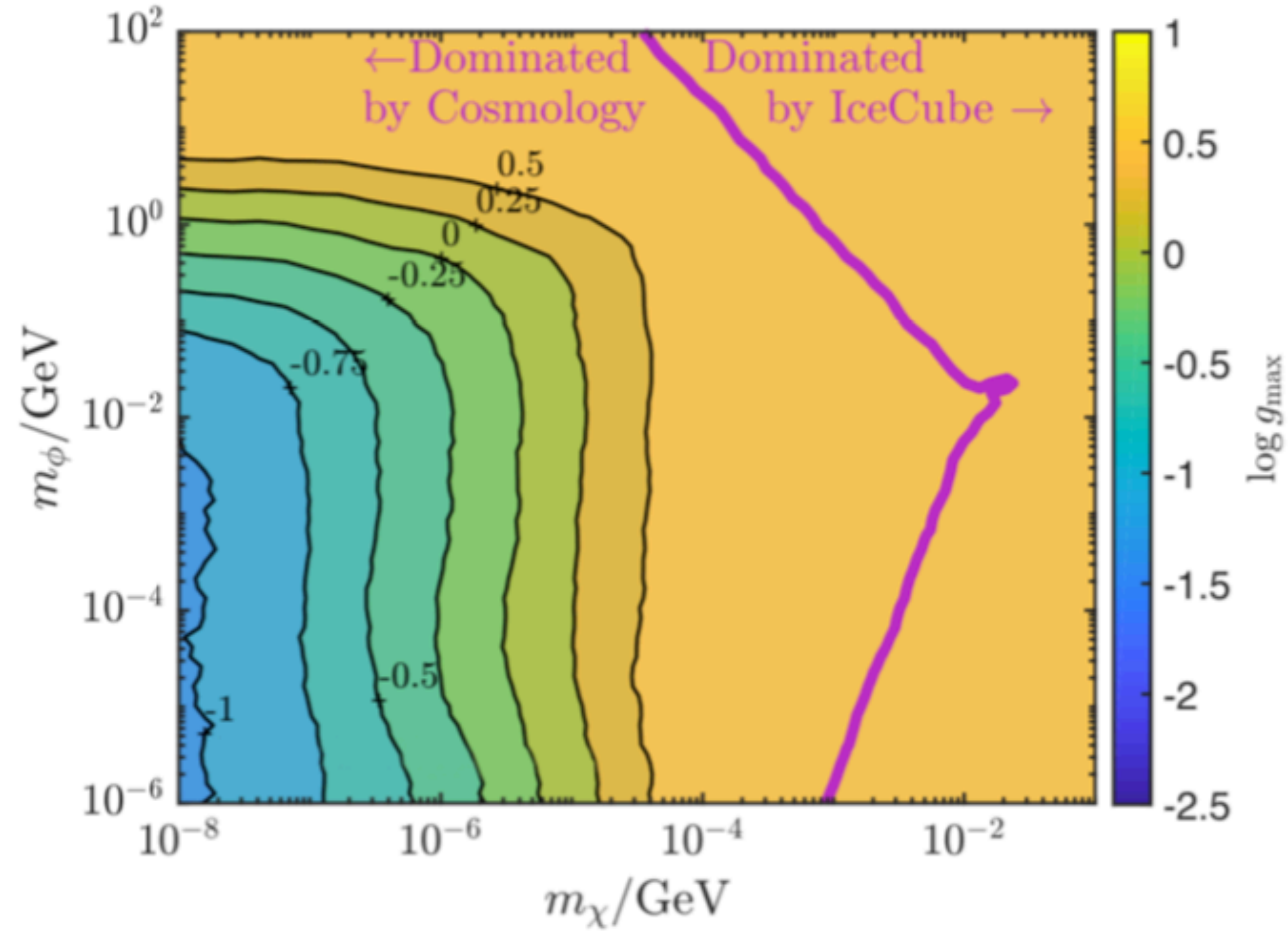
Neutrino-DM interaction leads to the deficit towards Galactic center

Constraints on DM-Nu Interaction

Fermionic DM
Vector Mediator



Scalar DM
Fermionic Mediator



Competitive limits compared to cosmological constraints!

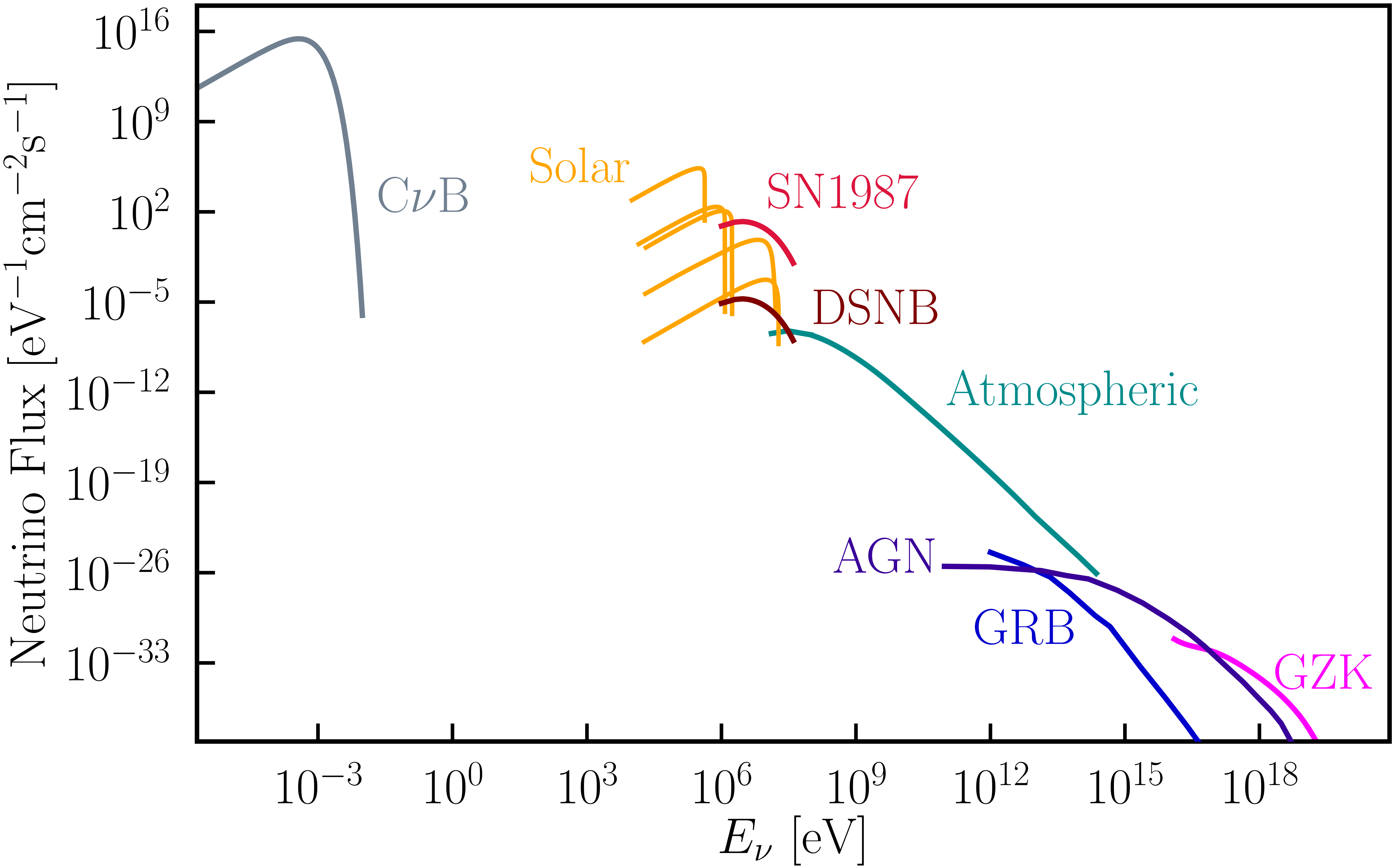
Argüelles, AK, Vincent, PRL 2017, IceCube 2022

Landscape of Dark Matter Searches with Neutrinos

- Broader energy ranges
- Next Generation of experiments

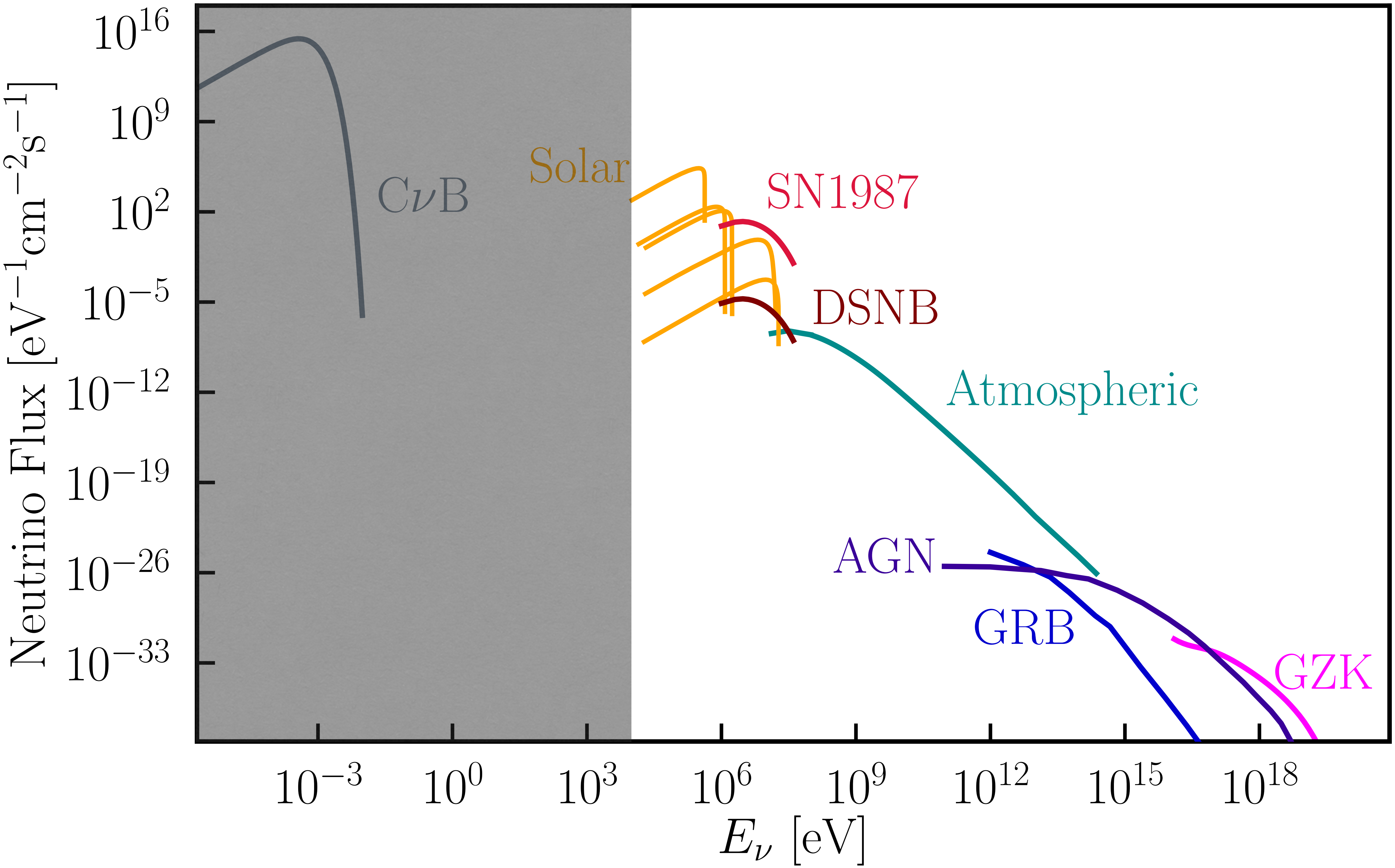
Upper limit on DM annihilation to neutrinos serves as an upper bound to DM annihilation to SM.

The Universe in Neutrinos



An uninterrupted measurement is available across a wide range of energy; near 14 orders of magnitude!

The Universe in Neutrinos



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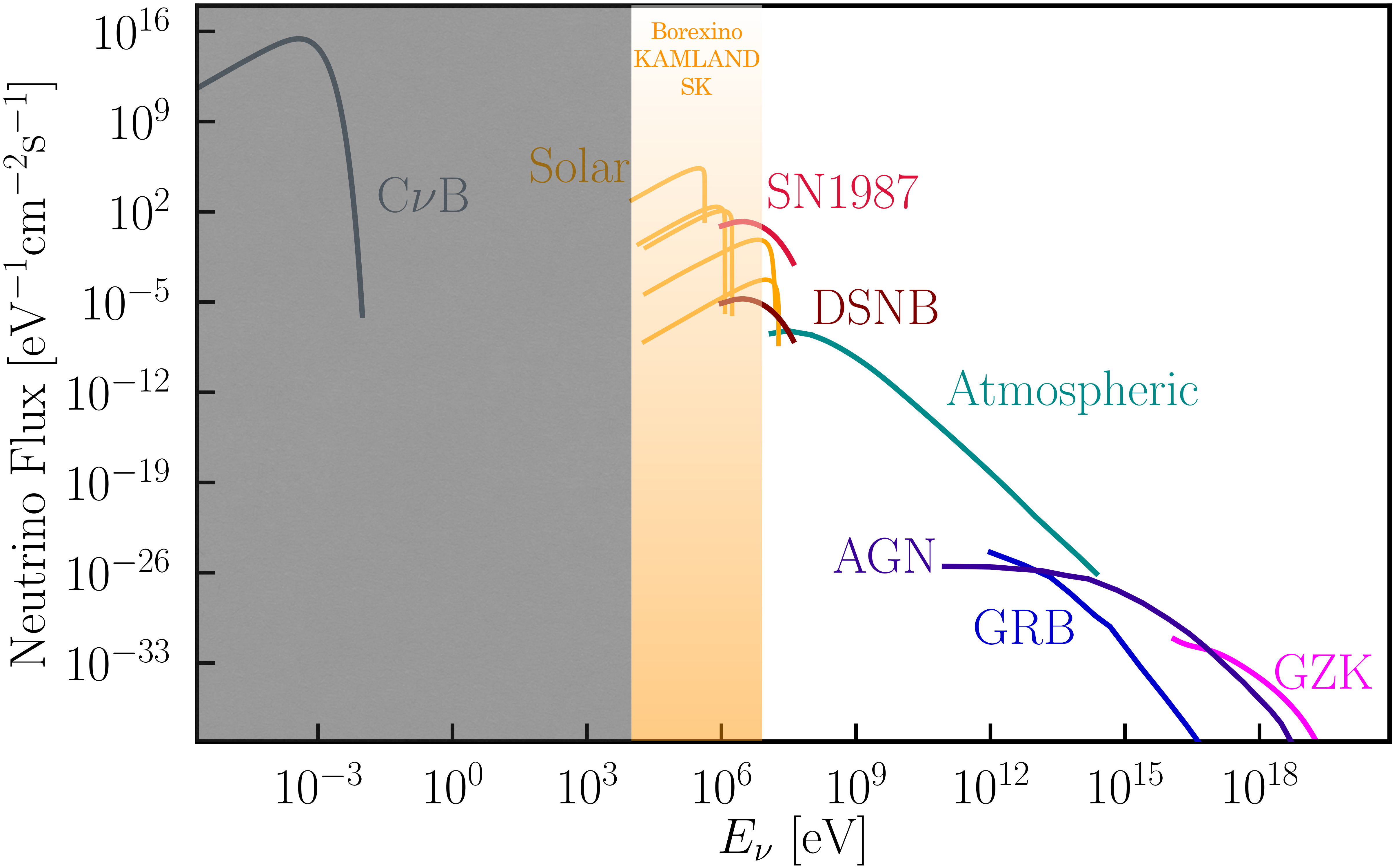

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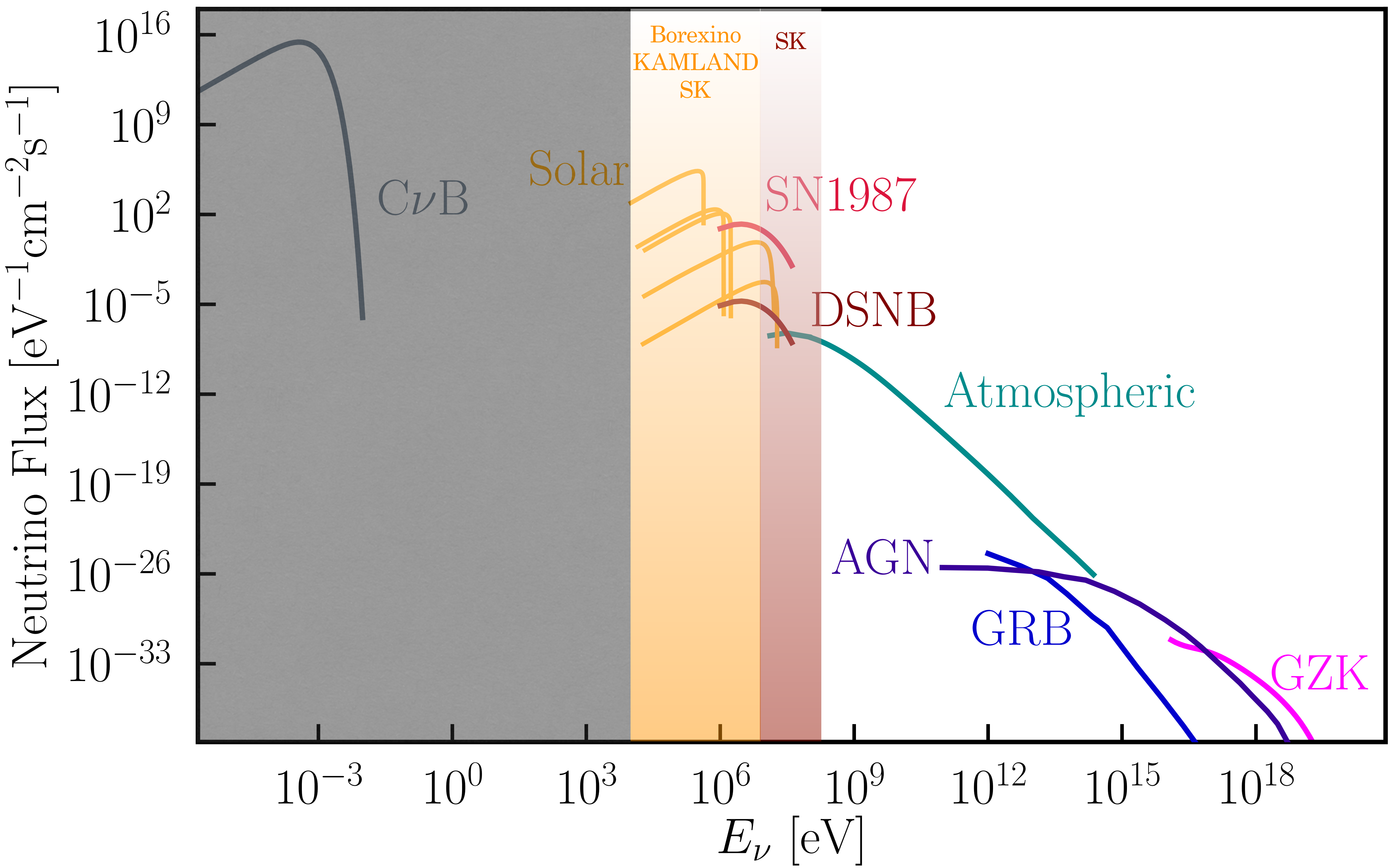

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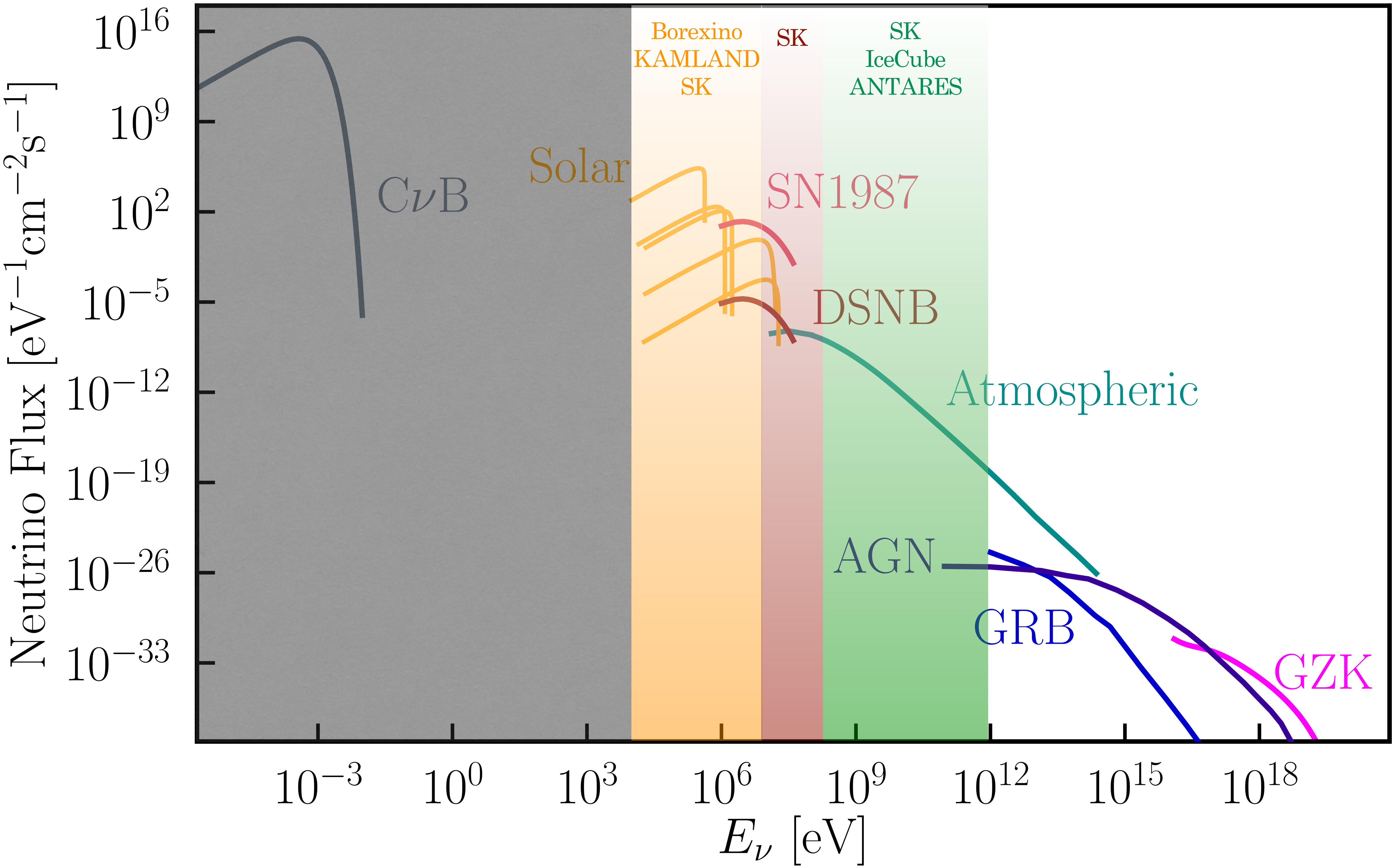

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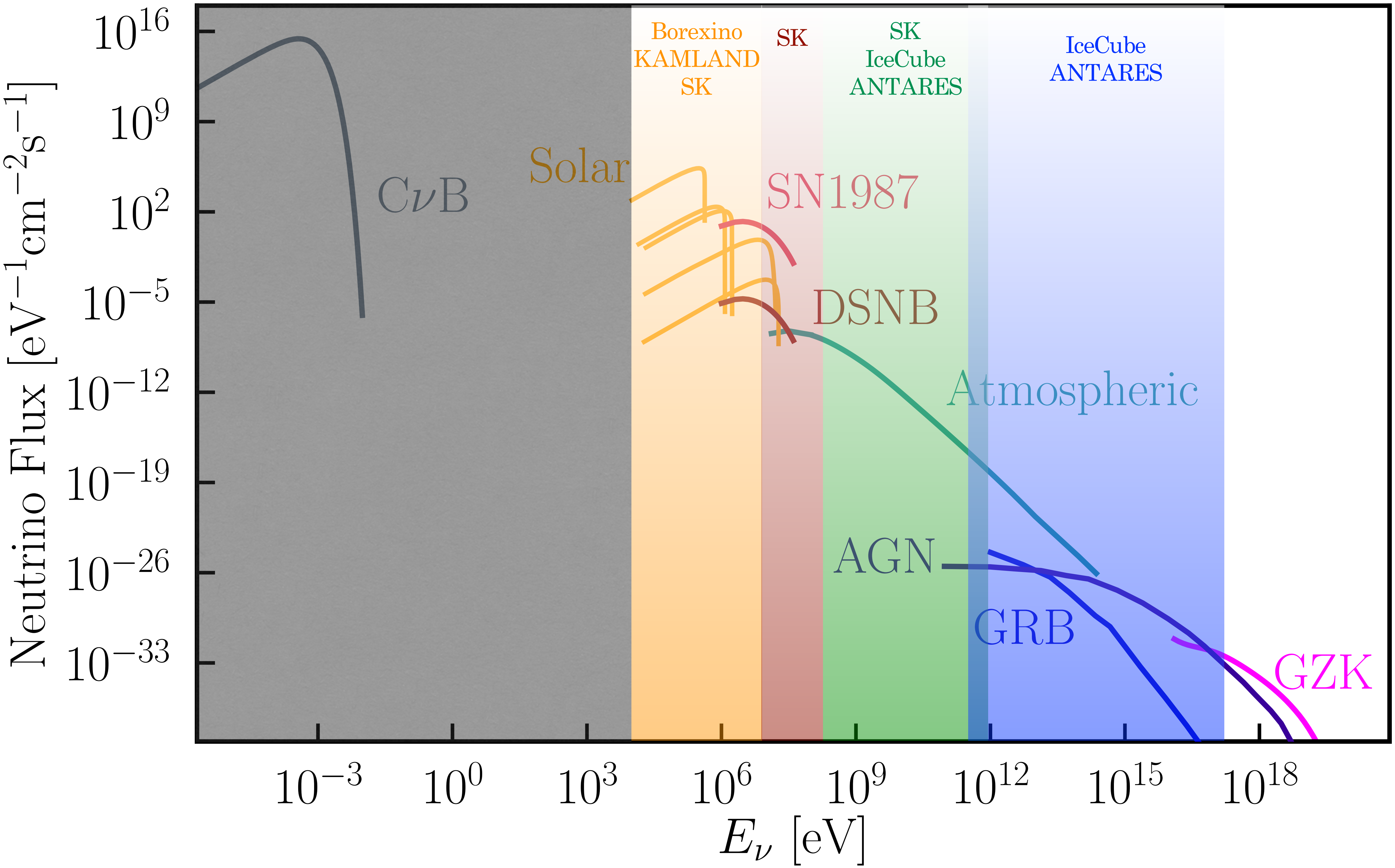

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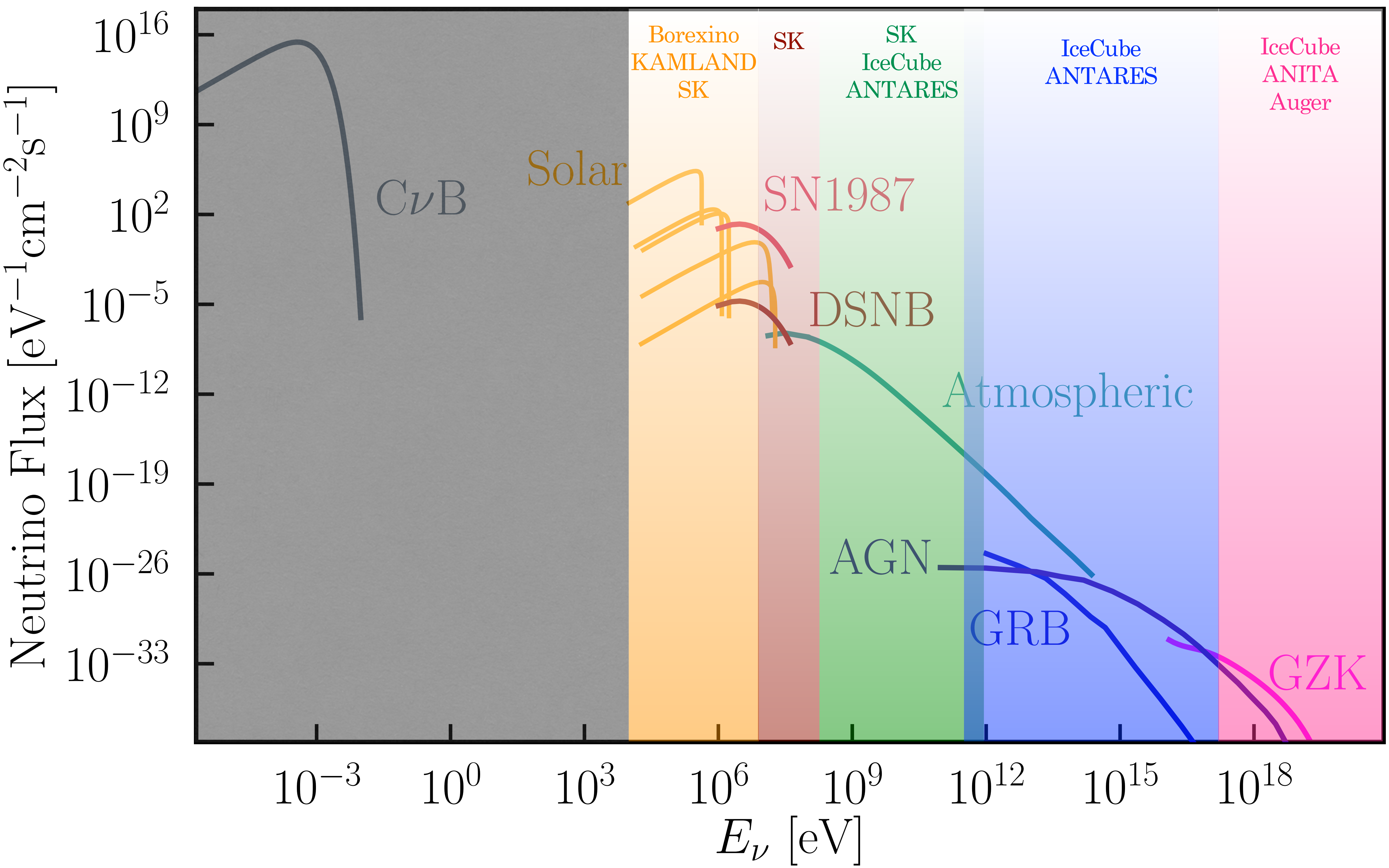
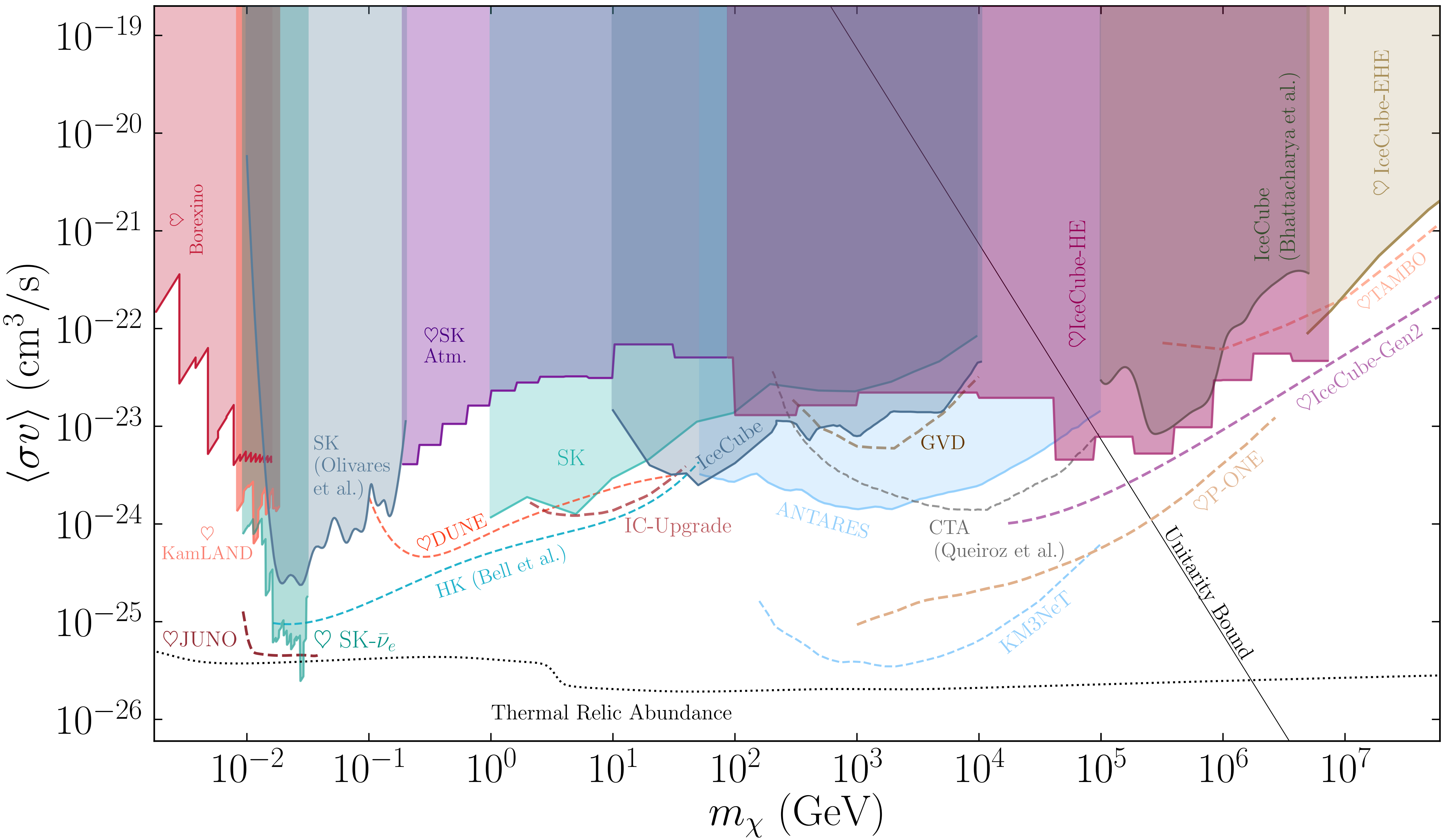


An uninterrupted measurement is available across a wide range of energy; near 14 orders of magnitude!

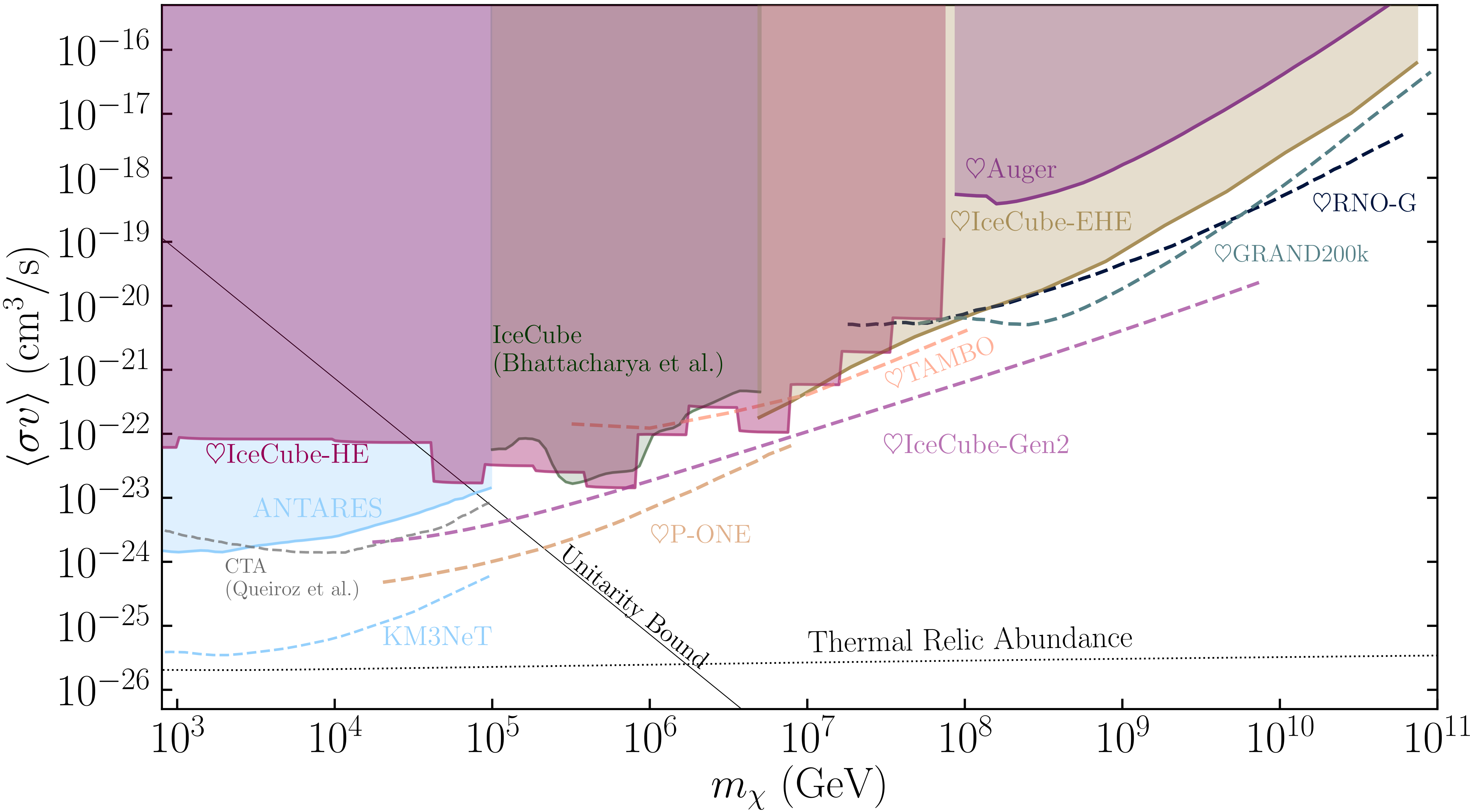
Limit on DM Annihilation to Neutrinos

Argüelles, Diaz, AK+, Rev. Mod. Phys 2021



Constraining the DM parameter space
‣ High Mass (only accessible to neutrinos)

Argüelles, Diaz, AK+, Rev. Mod. Phys 2021



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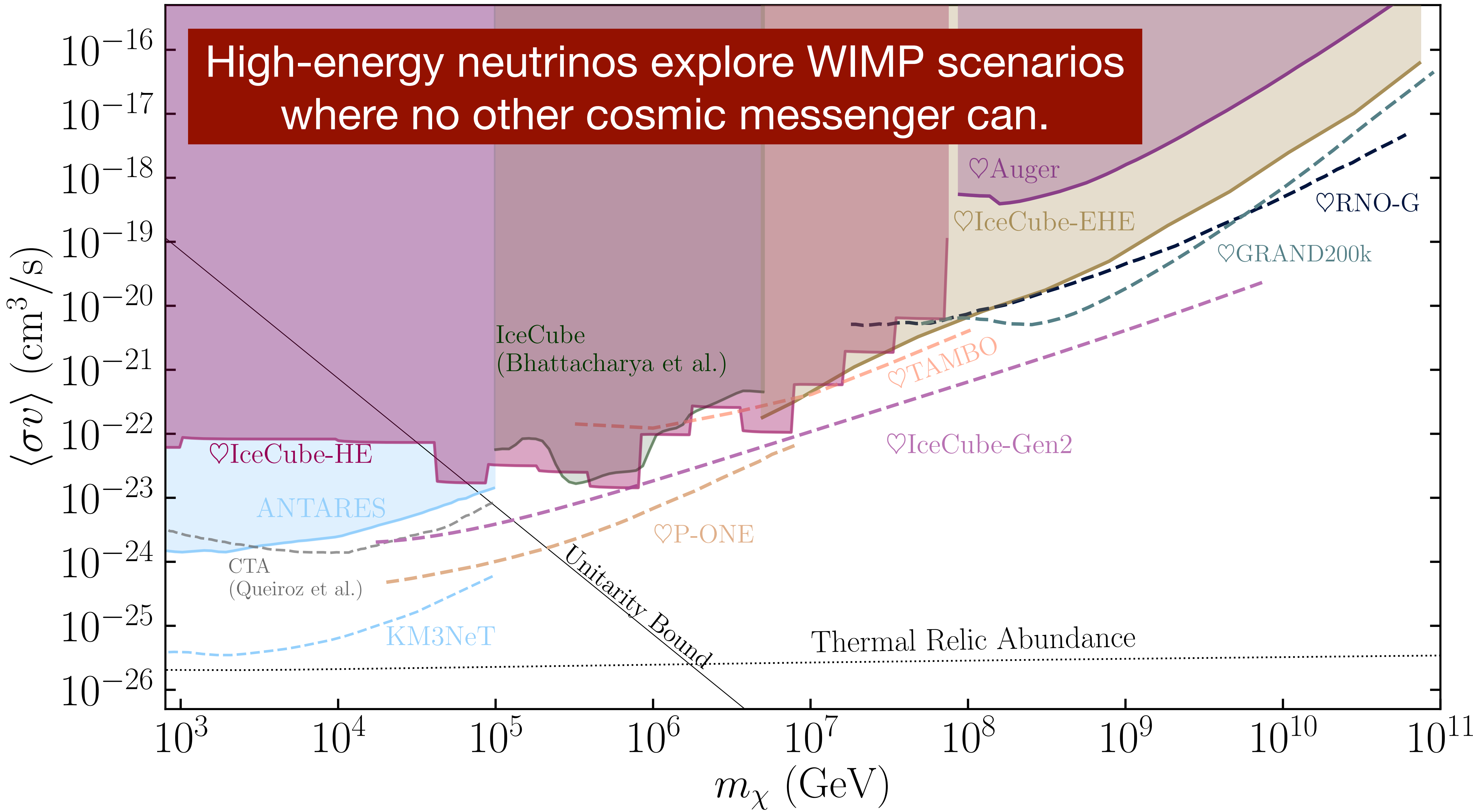

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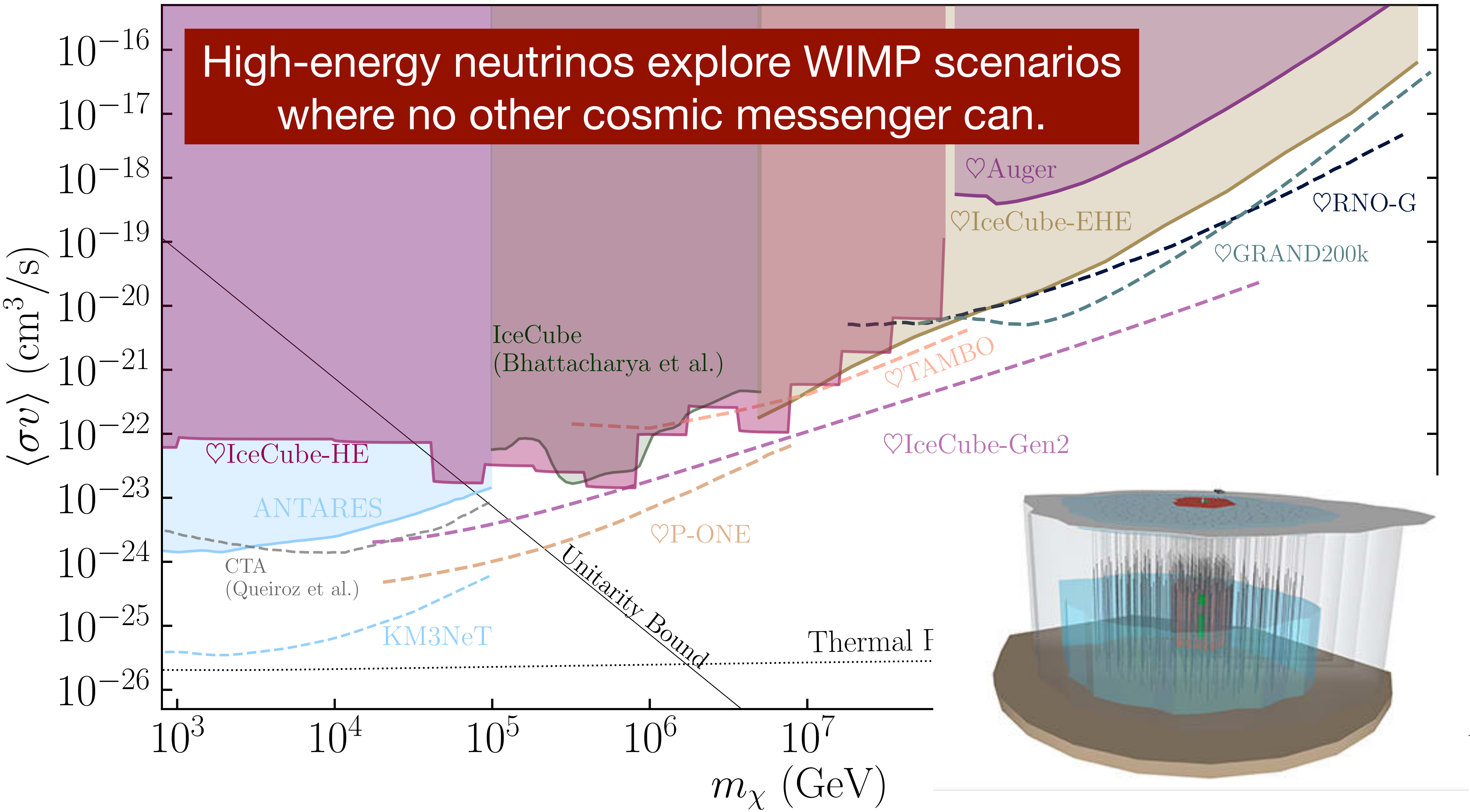

Summary

- High-energy neutrinos can expose the footprints of the physics beyond the Standard Model and provide an insight unattainable by other cosmic messengers.
- High-energy neutrinos are at the intersection of particle physics, astrophysics, and cosmology, presenting an unprecedented opportunity to probe new physics, especially dark matter.
- Neutrinos could present the key portal from Standard Model to the dark sector.
- Future neutrino experiments will be closing in on the parameter space of direct dark matter annihilation to neutrinos.
- Identification of the origin of IceCube neutrinos can provide an unprecedented opportunity for probing dark matter – neutrino interactions.

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen
Technische Universität Dortmund
Technische Universität München
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ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Thanks!

Back up Slides

DM Annihilation to Neutrinos
Galactic component

Flux of neutrinos from dark matter annihilation in the Milky Way:

$$\frac{d\Phi_\nu}{dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{1}{3}\frac{dN_\nu}{dE}J(\Omega)$$

thermally averaged DM annihilation cross section

The neutrino production spectrum for direct annihilation of DM to neutrinos

$$= \delta(m_\chi - E_\nu)$$

J-facror: 3d integral over the target solid angle in the sky and the line of sight

$$J \equiv \int d\Omega \int_{\mathrm{l.o.s.}} \rho_\chi^2(x)dx,$$

DM Annihilation to Neutrinos
Extragalactic component

An isotropic neutrino signal is also expected from DM annihilation in every other halo in the universe:

$$\frac{d\Phi_\nu}{dE} = \frac{c}{4\pi}\frac{\Omega_{DM}^2\rho_{crit}^2\langle\sigma v\rangle}{2m_x^2}\int_0^{z_{up}} dz \frac{\big(1+G(z)\big)(1+z)^3}{H(z)}\frac{dN_\nu(E')}{dE}$$

Production spectrum

$$\frac{2}{3E}\delta\left[z-\left(\frac{m_\chi}{E}-1\right)\right]$$

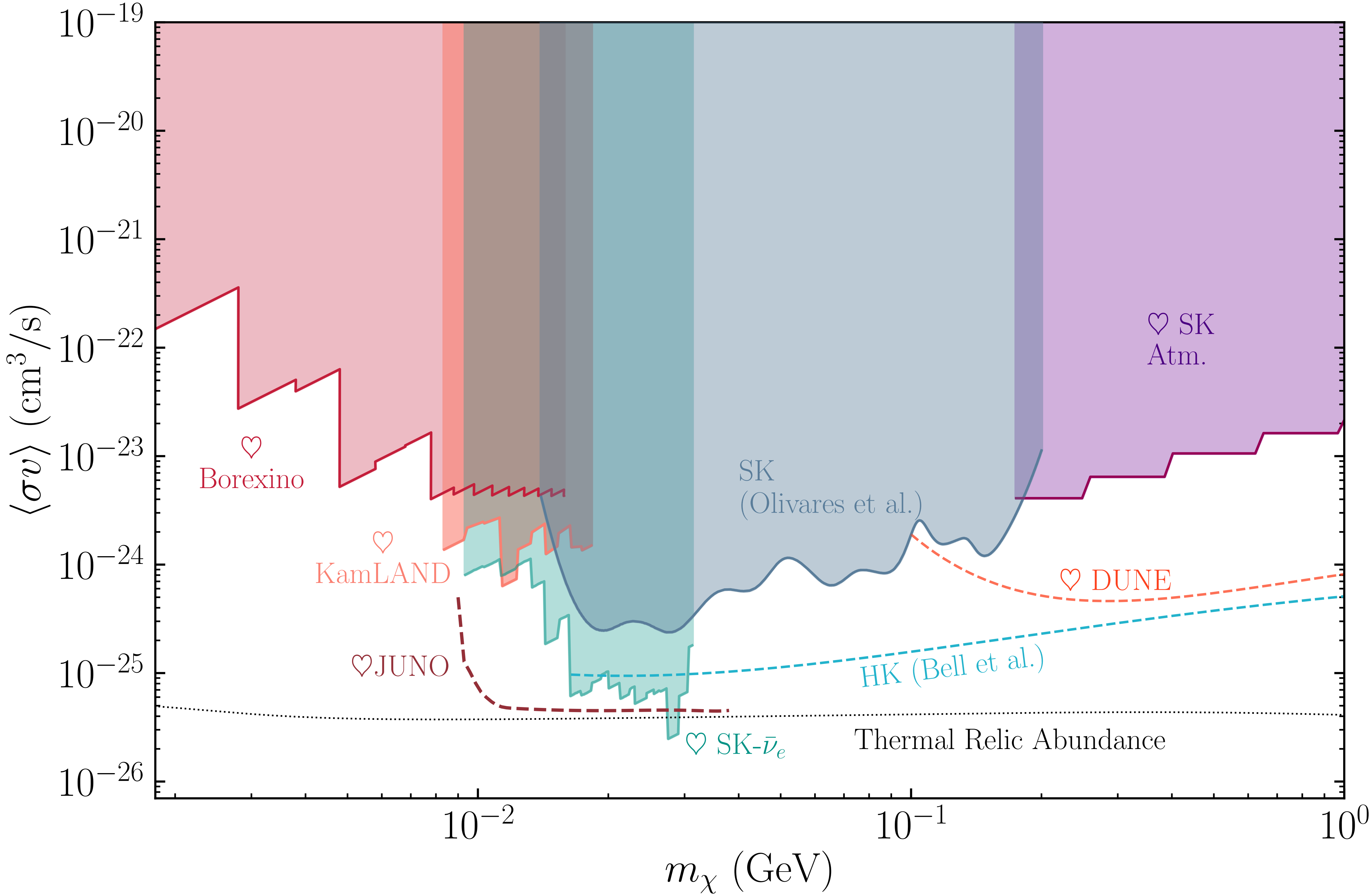
Halo boost

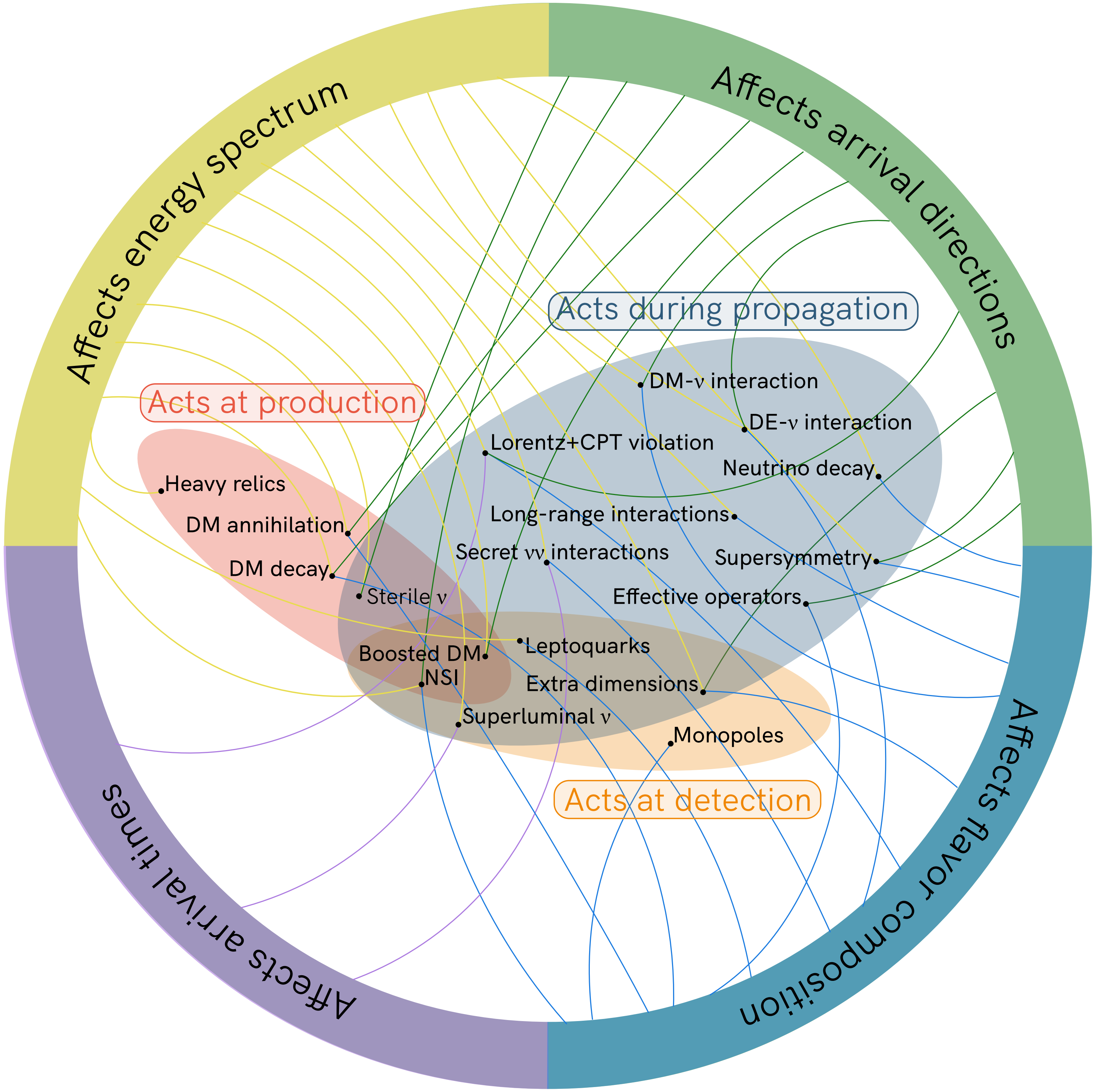
$$G(z) = \frac{1}{\Omega_{DM,0}^2\rho_c^2}\frac{1}{(1+z)^6}\int dM \frac{dn(M,z)}{dM}\int dr\ 4\pi r^2\ \rho_{\rm halo}^2(r)$$

Time-dependent Hubble parameter

$$H(z) = H_0\left[(1+z)^3\Omega_{DM}+\Omega_\Lambda\right]^{1/2}$$

Constraining the DM parameter space
‣ Low Mass





Argüelles, Bustamante, AK, Palomares-Ruiz, Vincent, 2019