Dark Matter annihilation to neutrinos: New limits and future prospects

Ibrahim Safa in collaboration with:

Carlos Argüelles, Alejandro Diaz, Ali Kheirandish, Andrés Olivares Del-Campo, and Aaron Vincent

Coming soon: 1910.XXXX

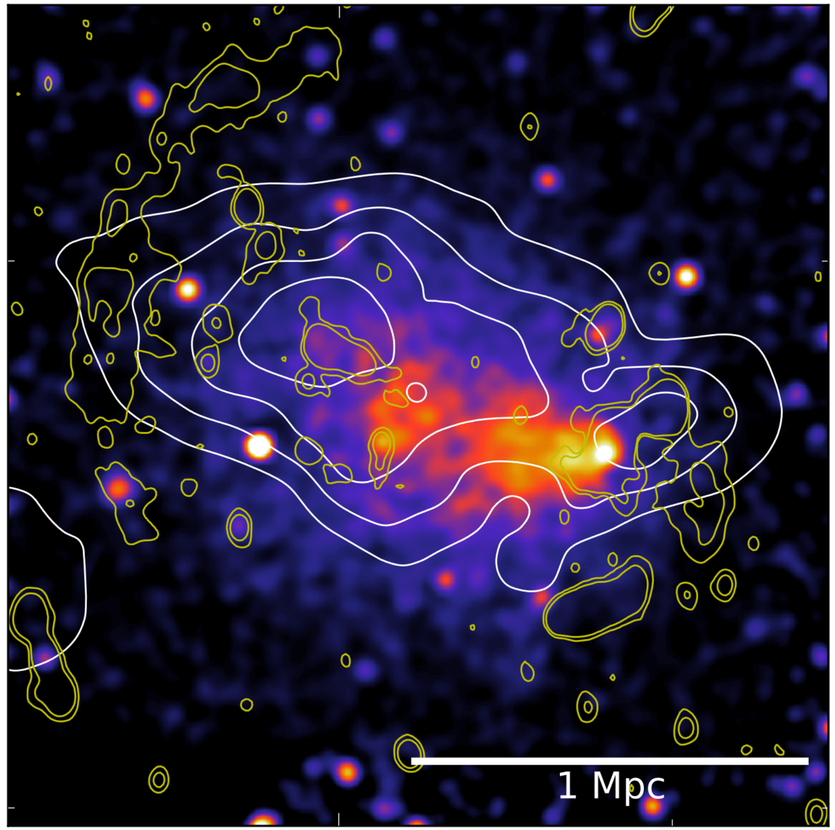
Motivation

- Dark matter gravitational effects unambiguously observed.

- Merging halos (bullet cluster) hint at a particle nature of DM.

- Gauge invariant models where neutrinos are the dominant SM product have been proposed (1903.00006).

- Neutrinos are our only evidence of new physics Beyond the SM and could be the link to the dark sector.



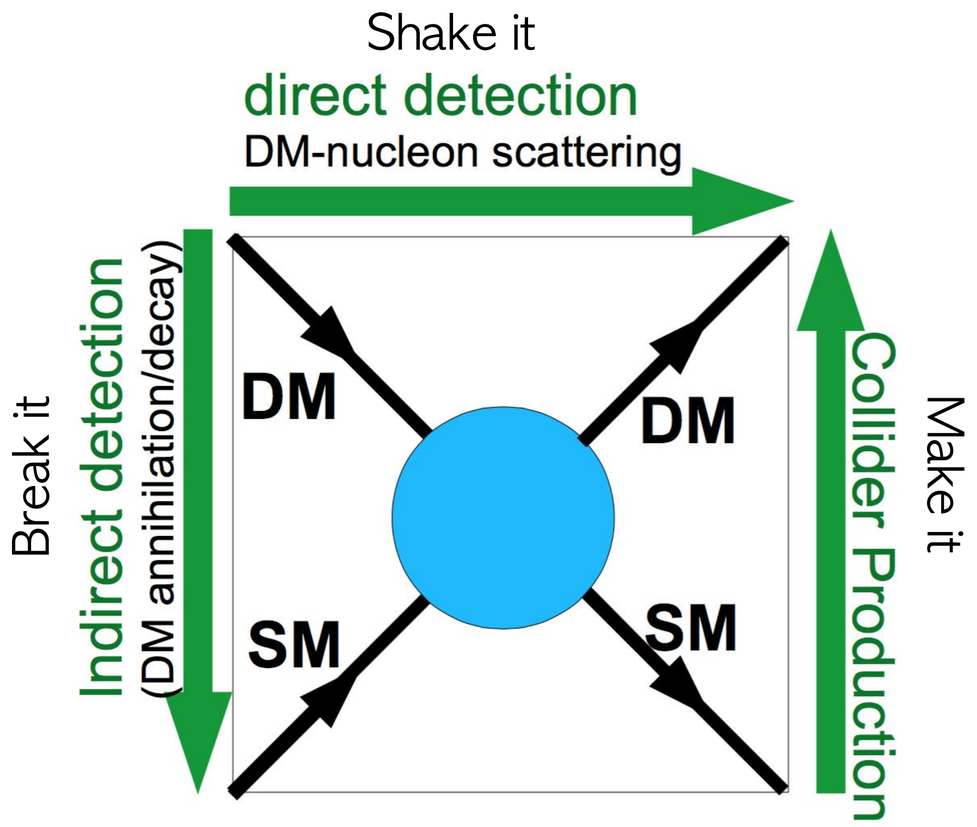
Indirect Detection

- Indirect signatures in the neutrino sector include:

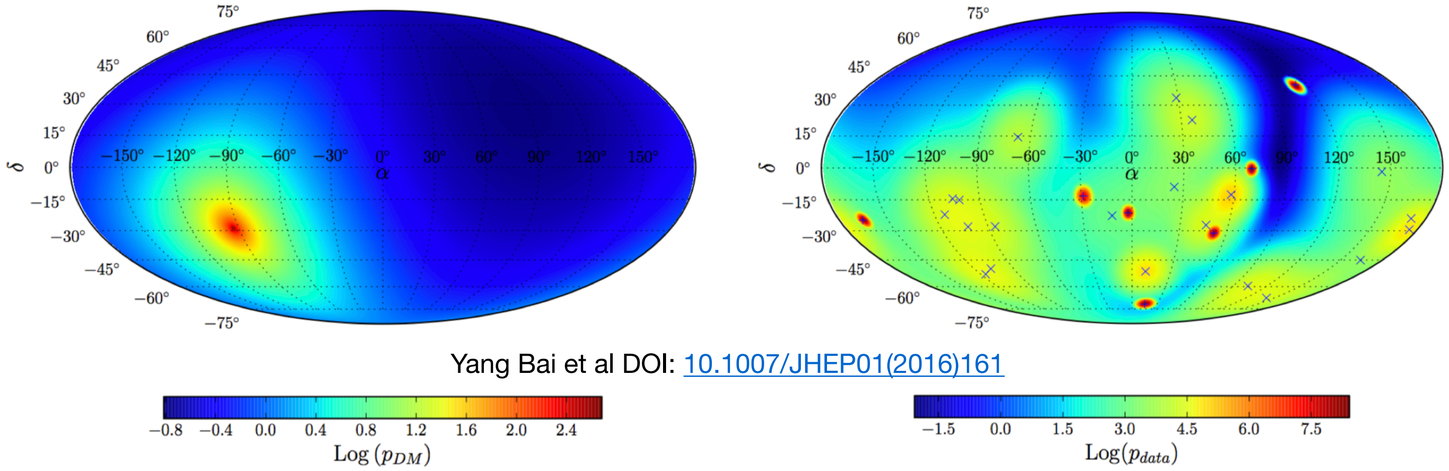
  - Features in geo, solar, atmospheric, and astrophysical neutrino spectra due to annihilation/ decay.

  - Anisotropies in the angular distributions of high-energy neutrinos due to DM-nu scattering.

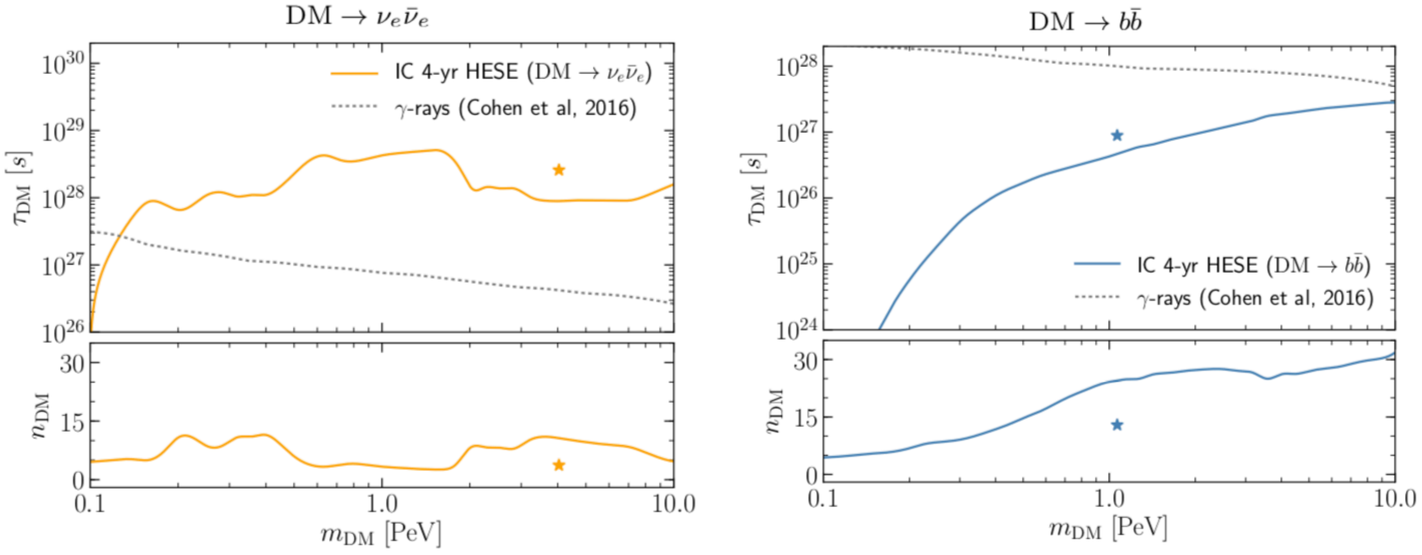
  - Features in the diffuse supernova neutrino background.



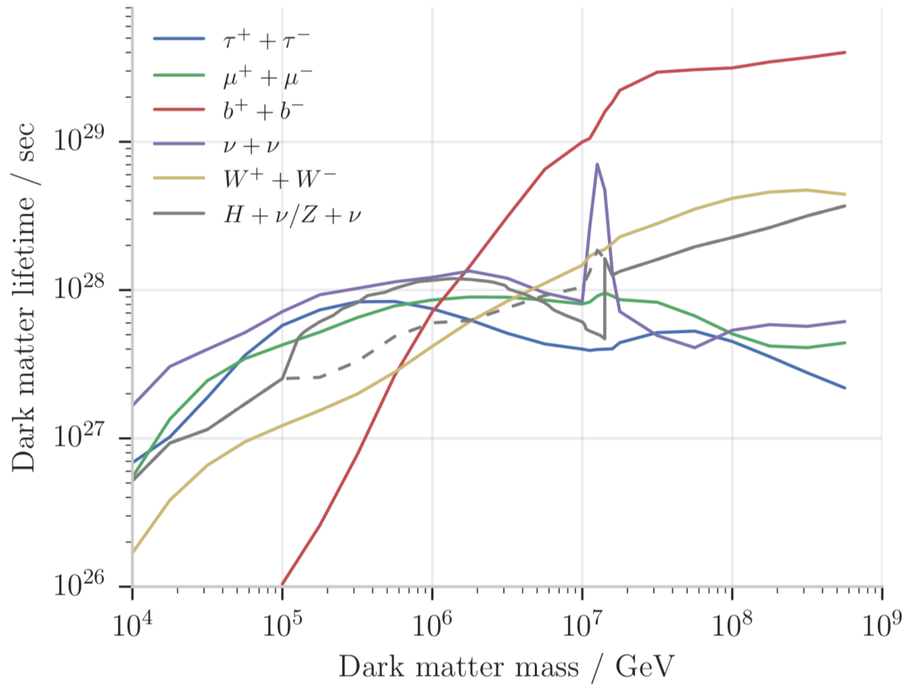
Decay



Yang Bai et al DOI: 10.1007/JHEP01(2016)161

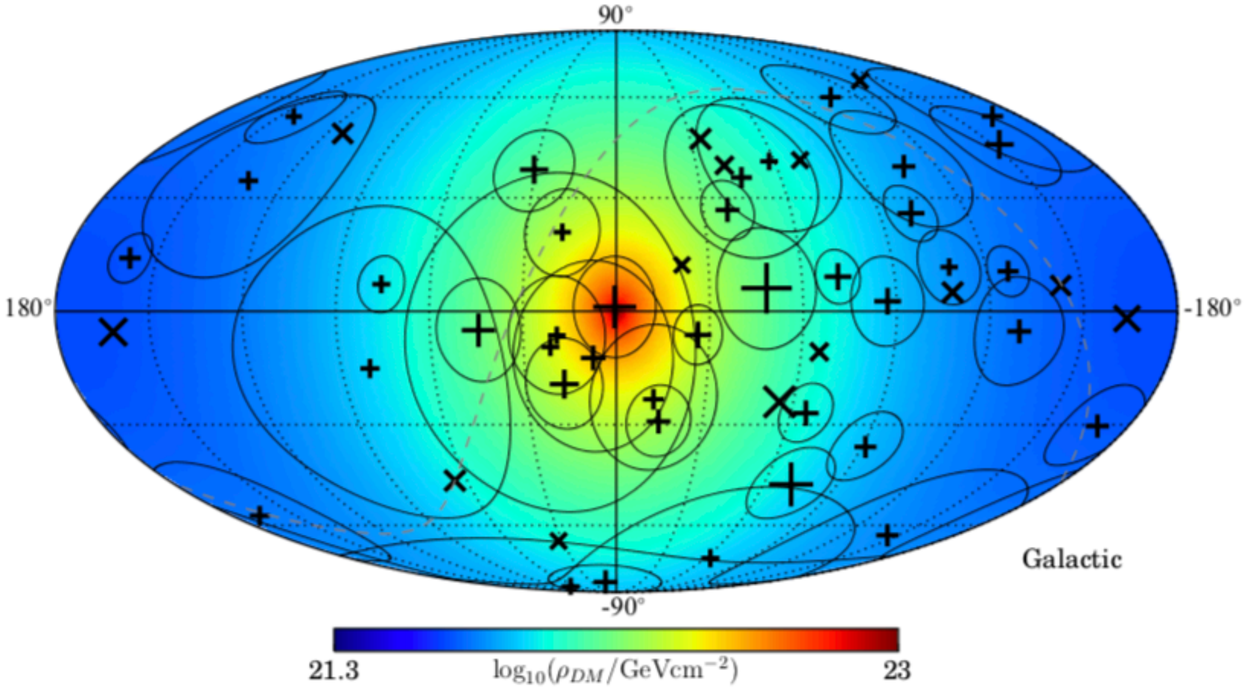


Atri Bhattacharya et al JCAP07(2017)027

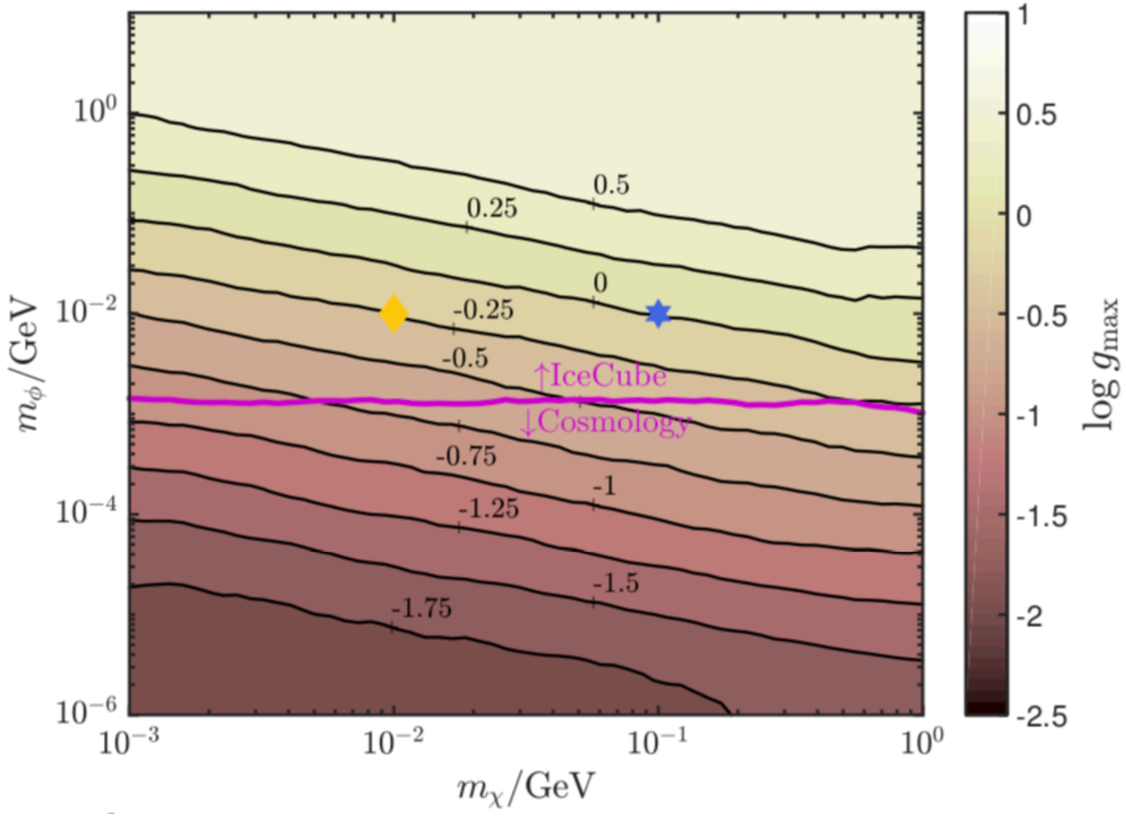


IceCube Collaboration DOI: 10.1140/epjc/s10052-018-6273-3

Scattering



DOI: 10.1103/PhysRevLett.119.201801



See also: Kelly & Machado JCAP 1810 (2018) 048
Murase and Shoemaker arXiv:1903.08607

Annihilation: Galactic contribution

Flux of neutrinos from Dark matter annihilation in our very own galaxy is

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

$\langle\sigma v\rangle$ & m_χ Are the thermally averaged annihilation cross section, and the dark matter mass, respectively.

$\frac{dN_\nu}{dE} = \delta(m_\chi - E_\nu)$ is the neutrino production spectrum. In this work, we study direct annihilation to neutrinos.

$J \equiv \int d\Omega \int_{\text{l.o.s.}} \rho_\chi^2(x)dx,$ is a three-dimensional integral over the target solid angle in the sky dΩ and the line of sight and is referred to as the 'J-factor'.

Dark Matter Profile

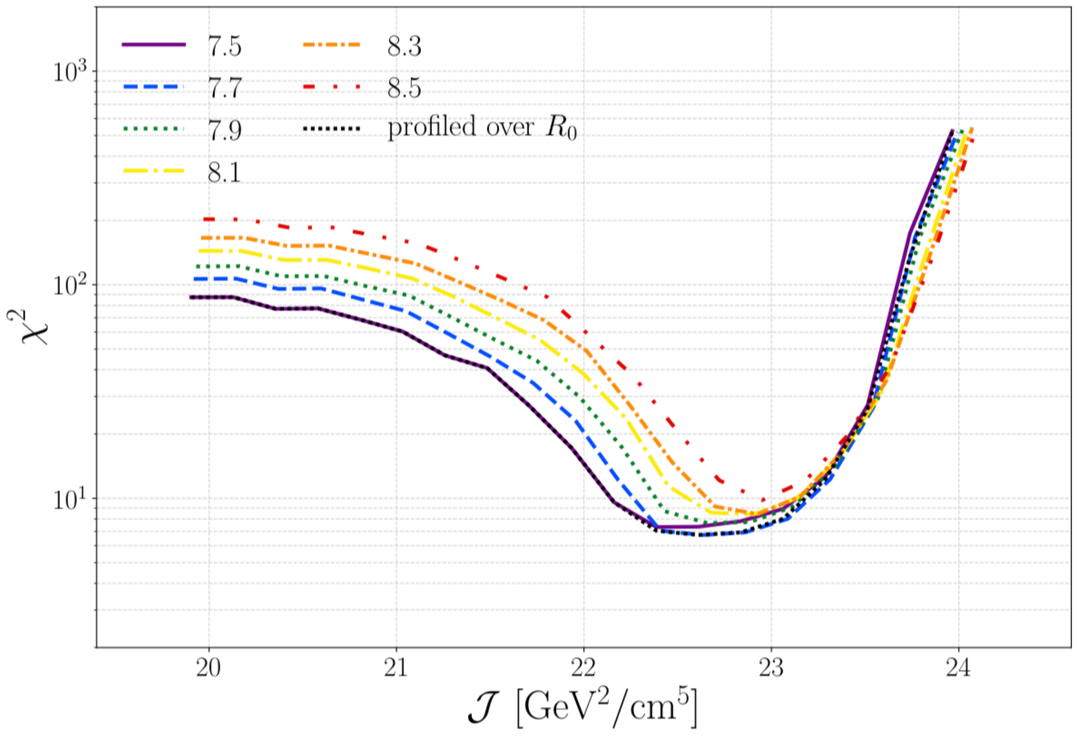
- We use a generalized NFW profile:

$$\rho = \frac{2^{3-\gamma}\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$

- 1901.02460 fits for the above free parameters using the "Rotation Curve" method.

- Limits here use the best-fit parameters and uncertainties are accounted for.

Plot from: 1901.02460



Extragalactic contribution

An isotropic neutrino signal is also expected due to annihilation of dark matter in every other galactic halo, and is given by

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

Production spectrum

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

Halo boost

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

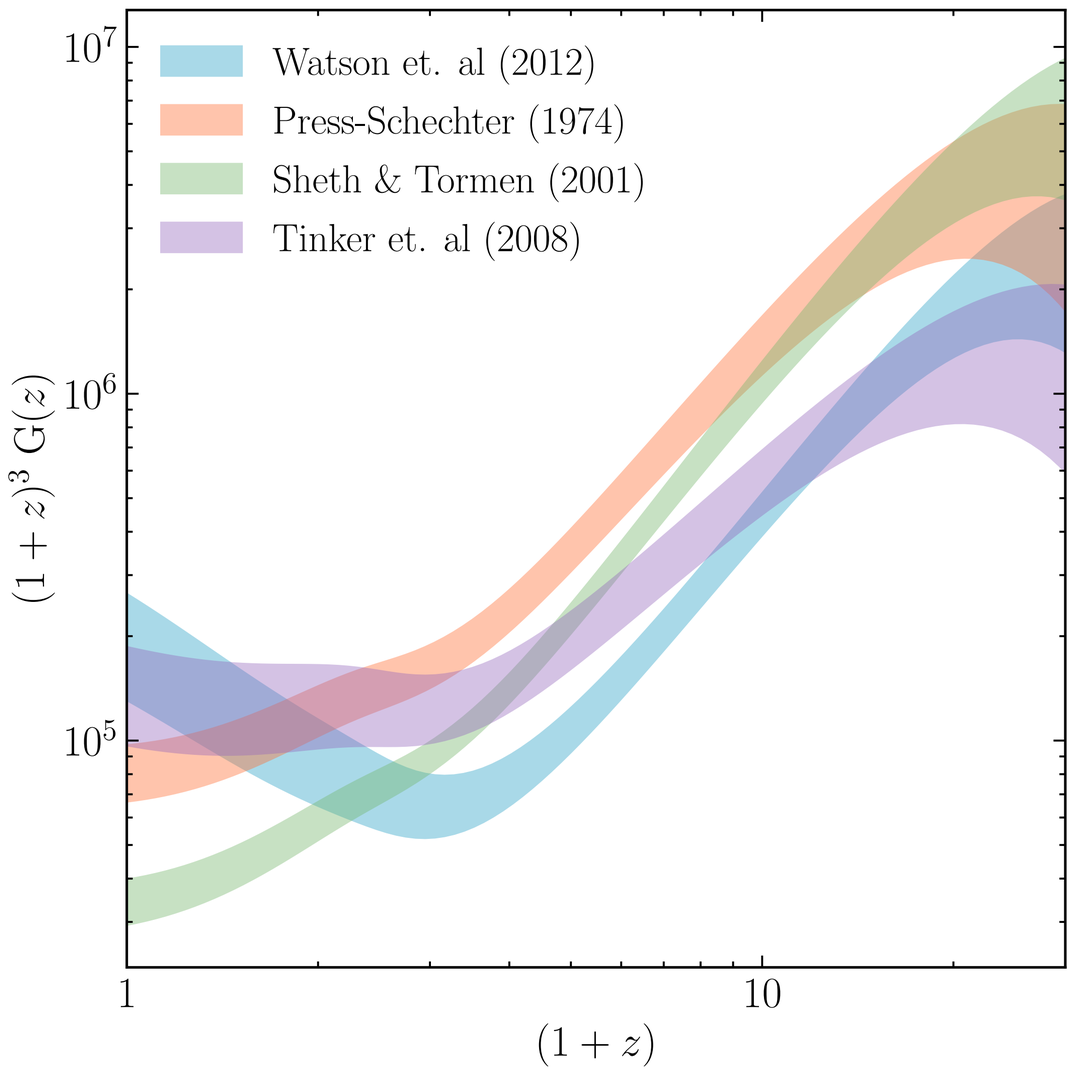
Time-dependent Hubble parameter

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

See also: Beacom et al. DOI: 10.1103/PhysRevLett.99.231301

Halo Uncertainties

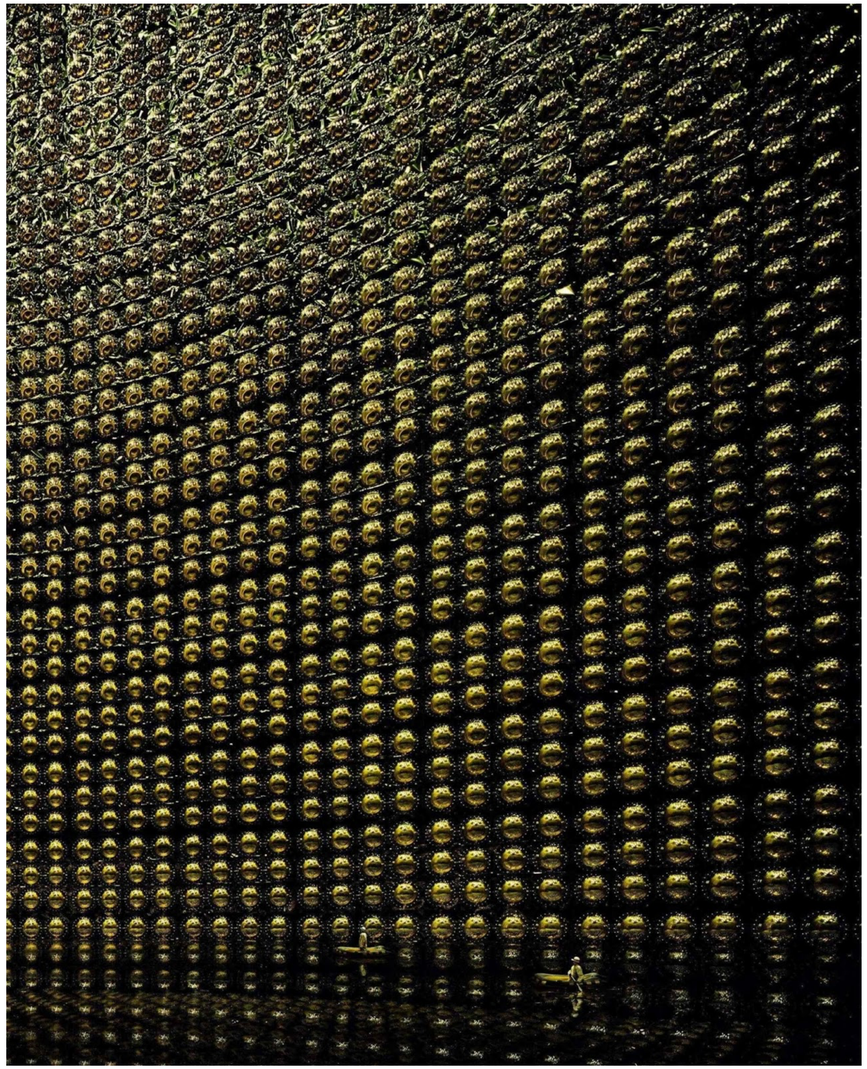
- We adopt four halo mass function (hmf) parameterizations.
- The band shows the uncertainty from the choice of minimum halo mass from 10^{-9} to 10^{-3} M_{sun}
- Limits shown in this work use Watson et. al (calibrated using N-body simulations) and a conservative choice of minimum mass (M_{min} = 10^{-3} M_{sun}).



Super-Kamiokande

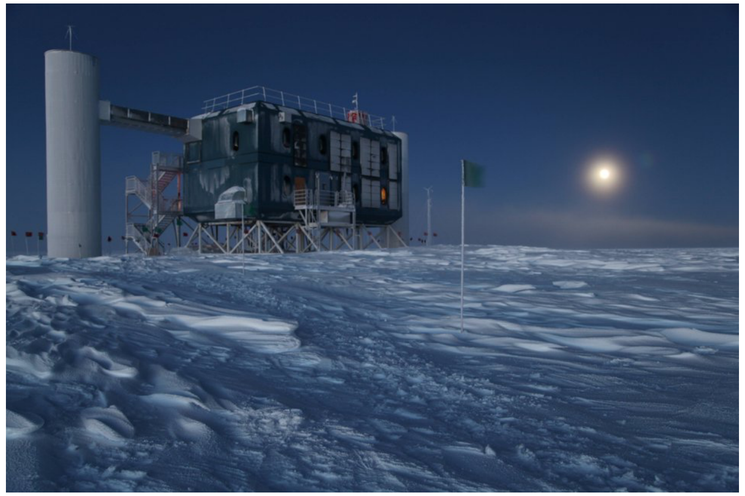
- 50K ton water Cherenkov detector located in the Kamioka mine, Japan.

- Dark Matter annihilation signatures can be found by looking for:
  - Excess in the direction of the galactic center above ν_e and ν_μ atmospheric neutrinos in the 1 GeV-10 TeV range.
  - Excess in the diffuse atmospheric flux from the extragalactic contribution.
  - Excess above the Diffuse Supernova Neutrino Background in the 15-10^3 MeV range.

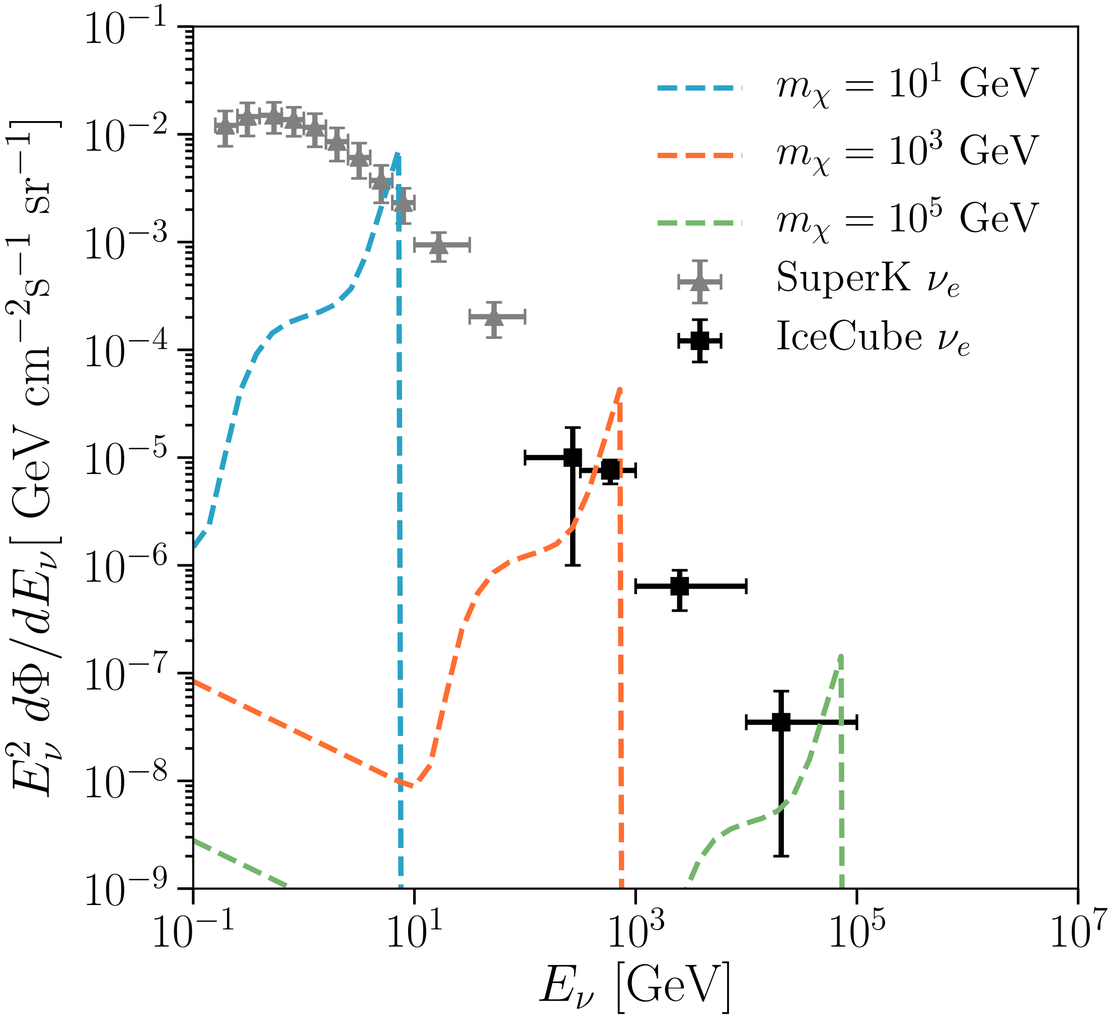


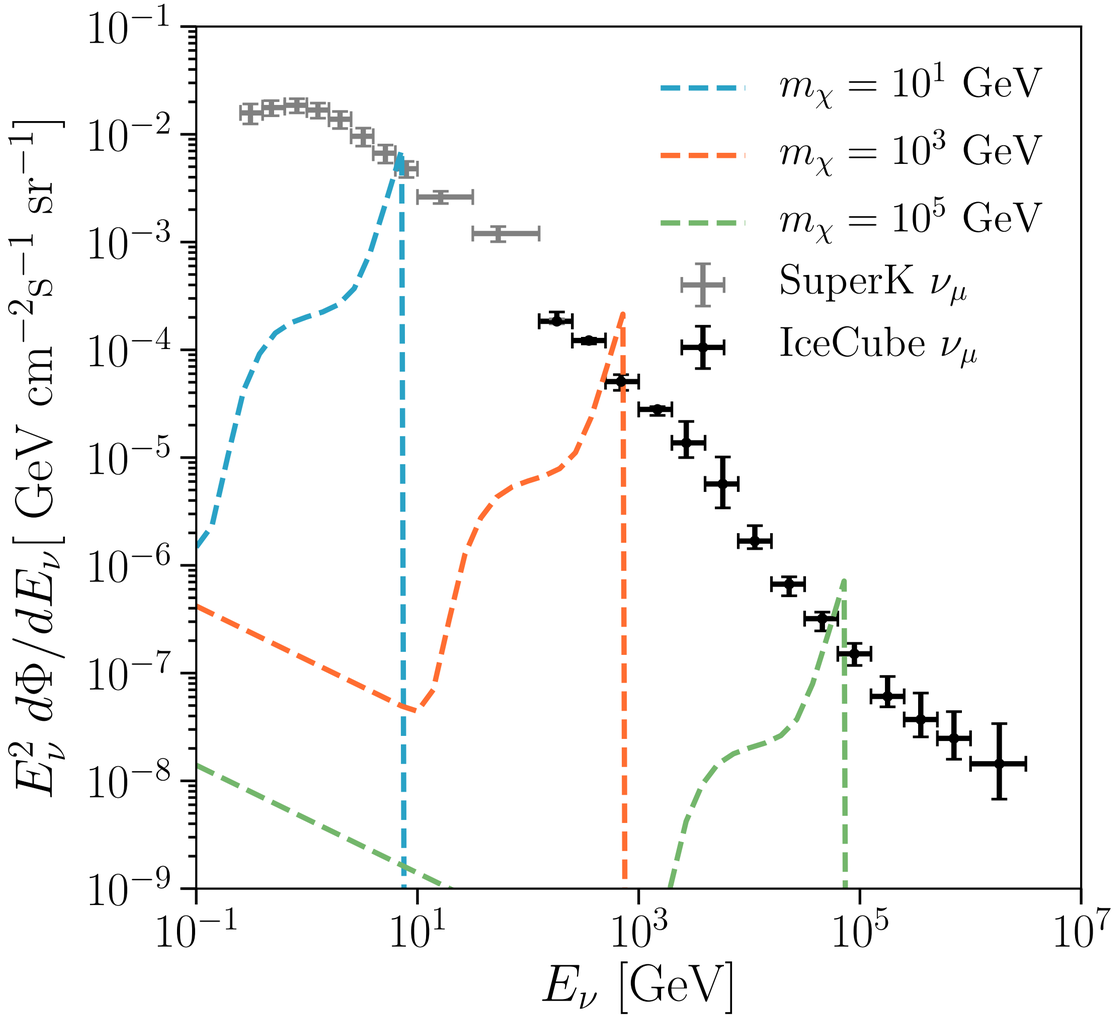
IceCube

- 1 Gton of antarctic ice instrumented with 5180 PMTs.
- IceCube has measured a diffuse astrophysical neutrino flux in the TeV-10PeV range.
- Atmospheric neutrinos measured by DeepCore and IceCube in the GeV - 100 TeV range.
- Competitive limits on the cosmogenic neutrino flux.
- Dark matter - neutrino connections manifest as features in the above measured spectra.



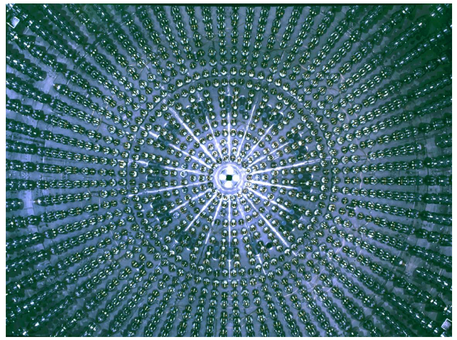
Expected neutrino flux





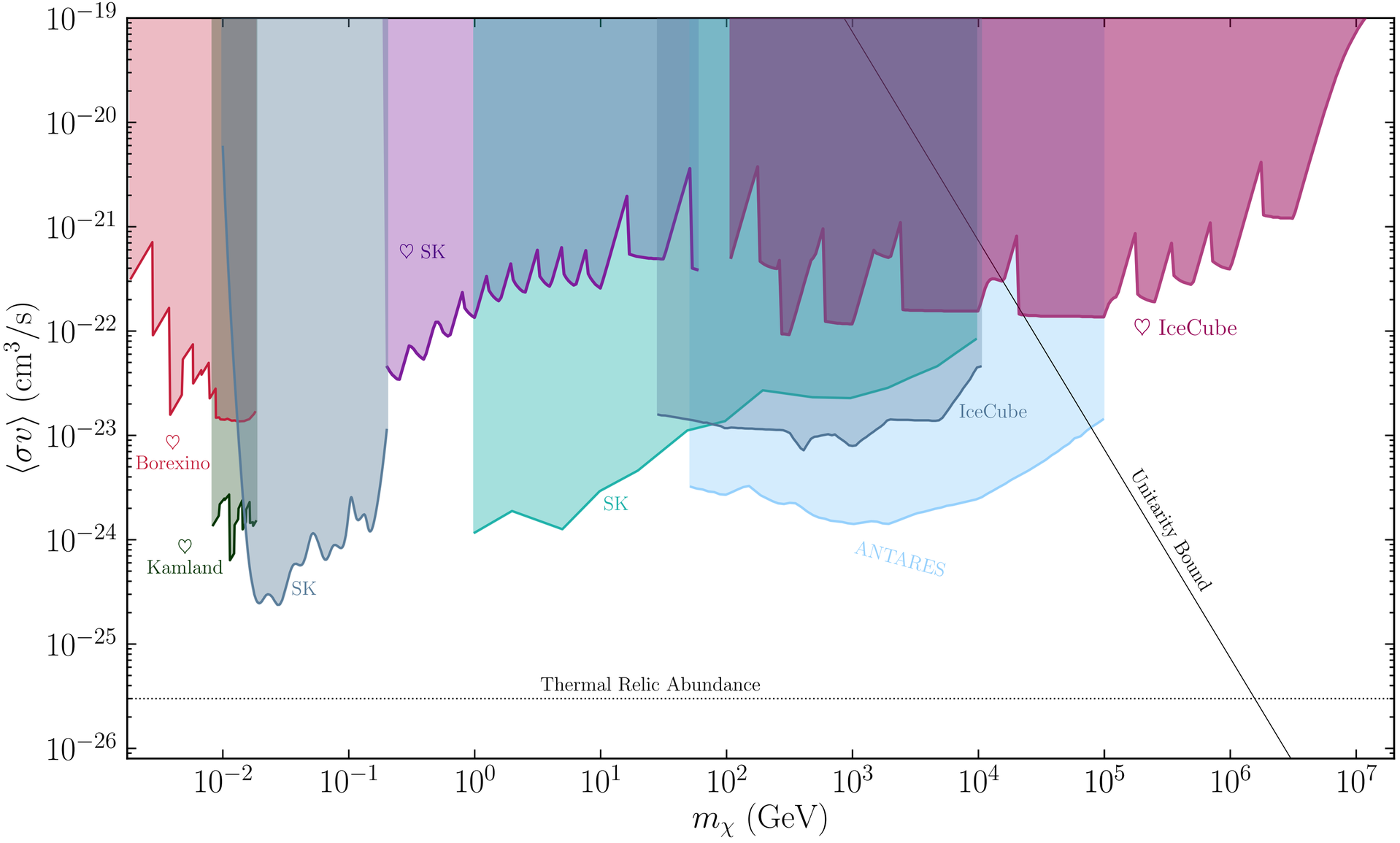
And many, many more

- Borexino: Organic liquid scintillator experiment in Gran Sasso, Italy. Measures solar neutrinos (MeV).
- ANTARES: Water Cherenkov detector in the Mediterranean Sea. Has measured atmospheric neutrinos (GeV-TeV).
- CTA: Air Cherenkov telescope array. Designed for high energy gamma-rays. Will have sensitivity to VHE gamma-rays(TeV).
- Auger: Water Cherenkov surface array. Detects Ultra High Energy Cosmic Rays. Has also set competitive limits on cosmogenic neutrinos (EeV).
- ANITA: Radio balloon flying above Antarctica. Has set limits on the cosmogenic neutrino flux (EeV).
- GRAND: Proposed radio array that will (hopefully) detect mountain-skimming tau-neutrinos (EeV).



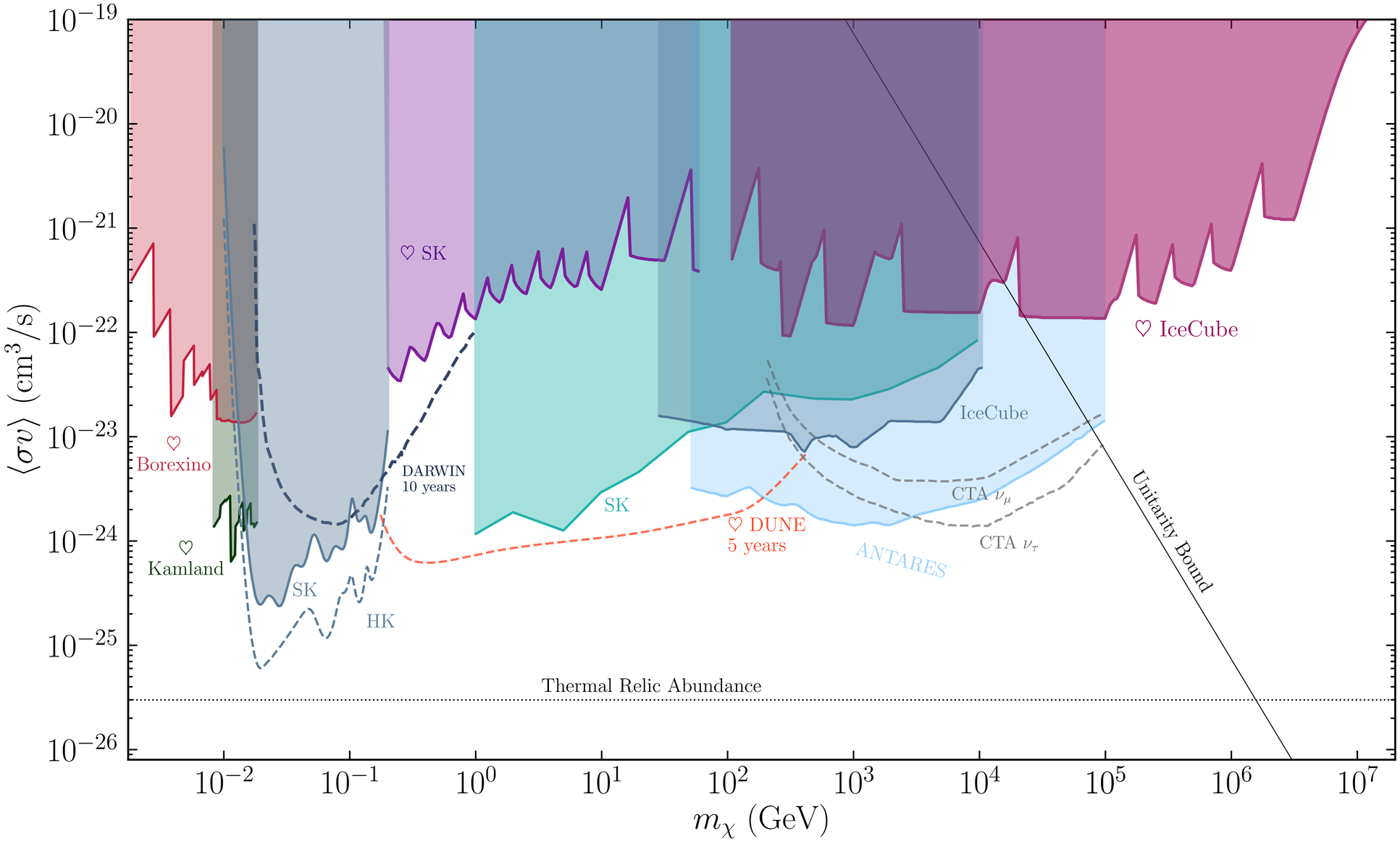
Results: s-wave

$\langle \sigma v \rangle \propto k$



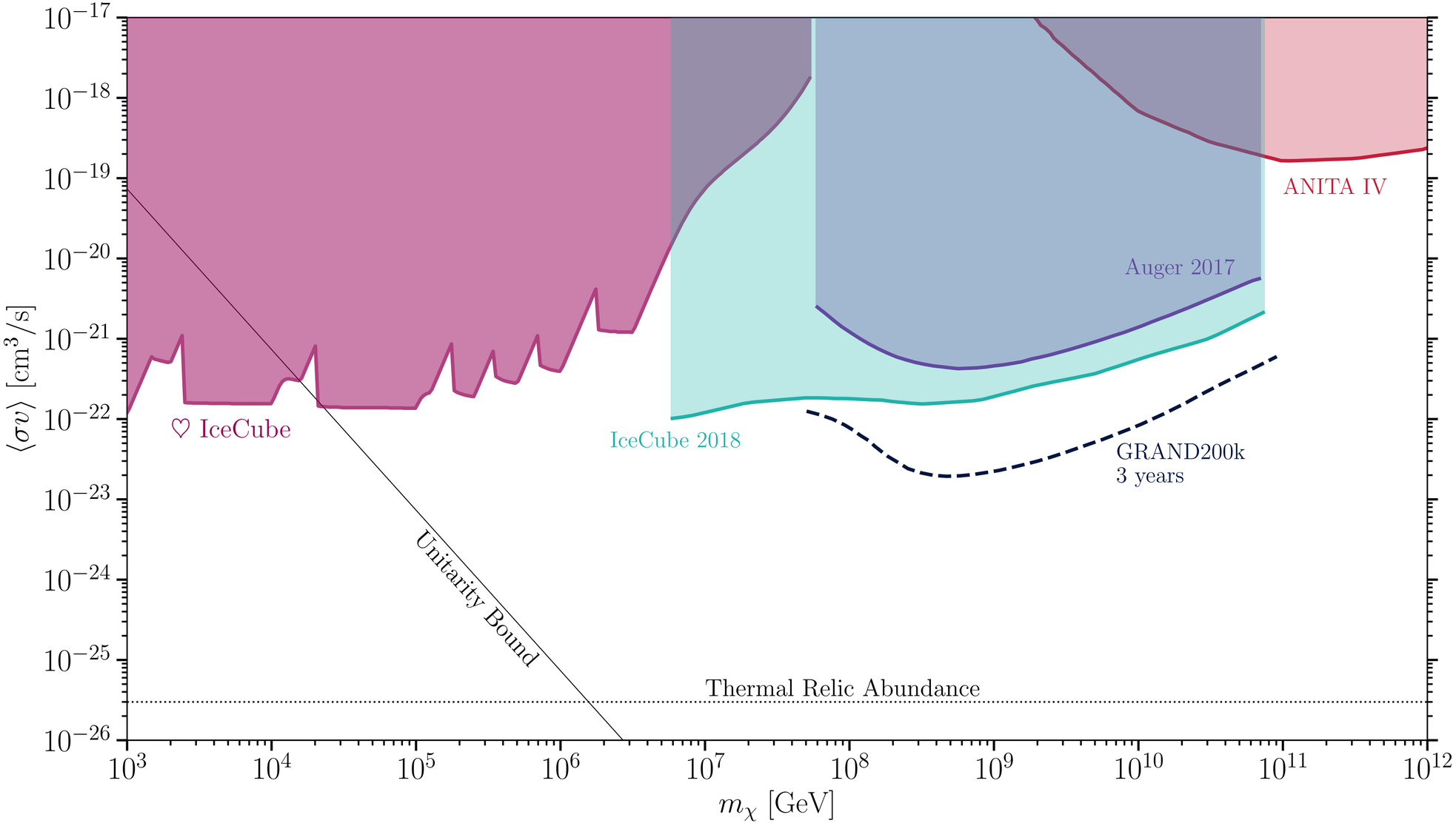
Results: s-wave

$\langle \sigma v \rangle \propto k$



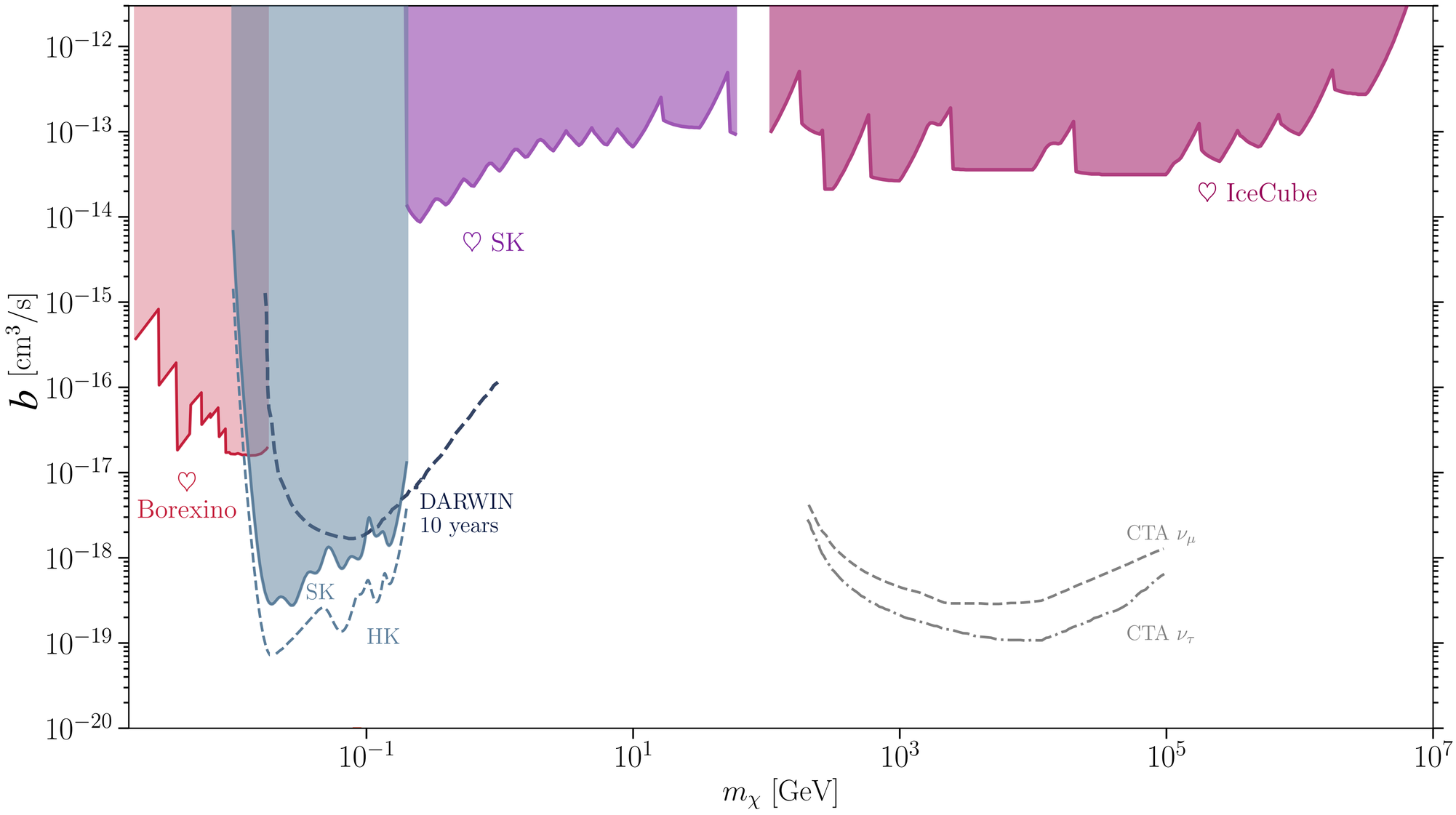
Results: s-wave (High-Mass region)

$\langle \sigma v \rangle \propto k$



Results: p-wave

$\langle \sigma v \rangle \propto b(v/c)^2$



Summary

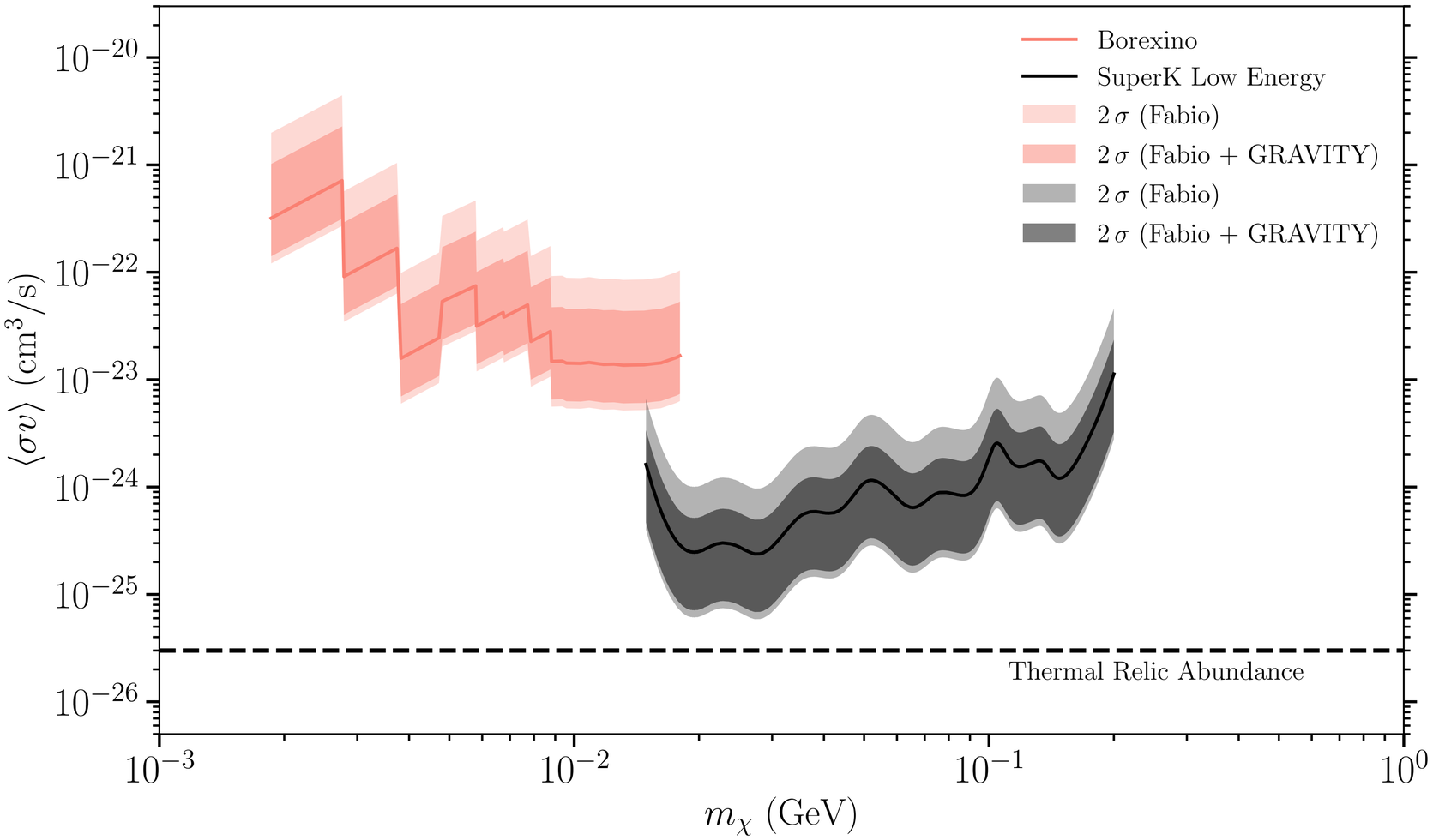
- Both the nature of Dark Matter and its connection to the Standard Model are still open questions.
- Neutrinos are the first chink in the SM armor. New physics in the neutrino sector is inevitable.
- Indirect detection of Dark Matter in the neutrino channel is a necessary complement to searches via charged particles.
- We have updated existing limits and derived new ones in the MeV to EeV range, this work will appear soon.
- Next-generation experiments will dip their toes in the thermal relic abundance region.
- Lots of work to do!

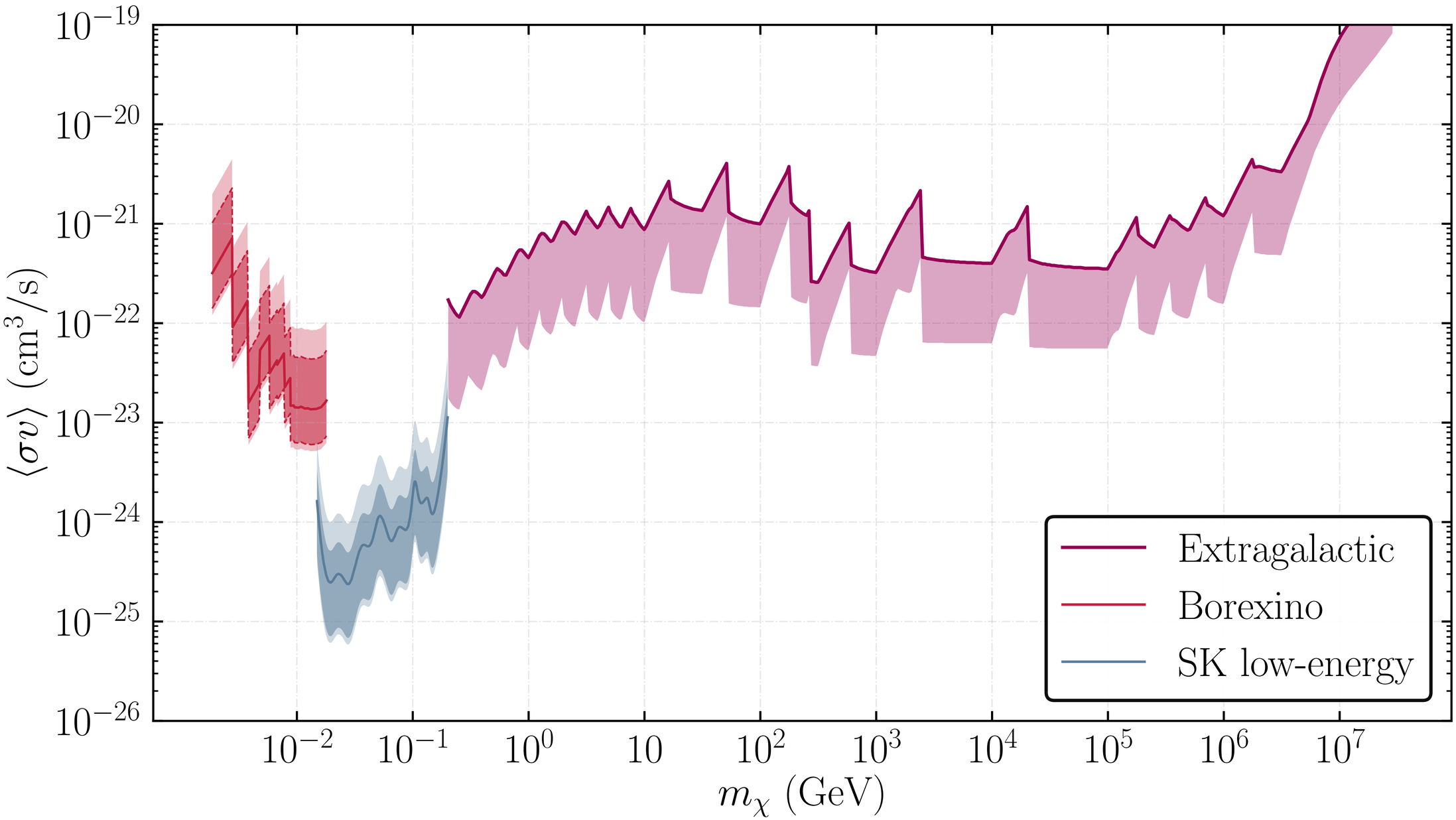
Backups

ANTARES

- ANTARES: Roughly 10% of IceCube volume in the Mediterranean Sea.
- Photon scattering length in the Mediterranean is much longer than in ice. ANTARES has, on average, better angular resolution.
- Galactic center is below the horizon more than 50% of the time. Earth can be used as a veto to cosmic-ray muons.

Dark Matter Profile Uncertainties




10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
$\langle \sigma v \rangle$ (cm^3/s)
10^{-2}
10^{-1}
10^{0}
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
m_χ (GeV)
Extragalactic
Borexino
SK low-energy

Velocity-dependent J-factors

$$\langle v^n \rangle = \int d^3v v^n f(v, r),$$

f is the normalized dark matter phase space distribution

$$\langle v^2 \rangle = 3v_0^2(r),$$

For p-wave

$$\langle v^4 \rangle = 15v_0^4(r)\,.$$

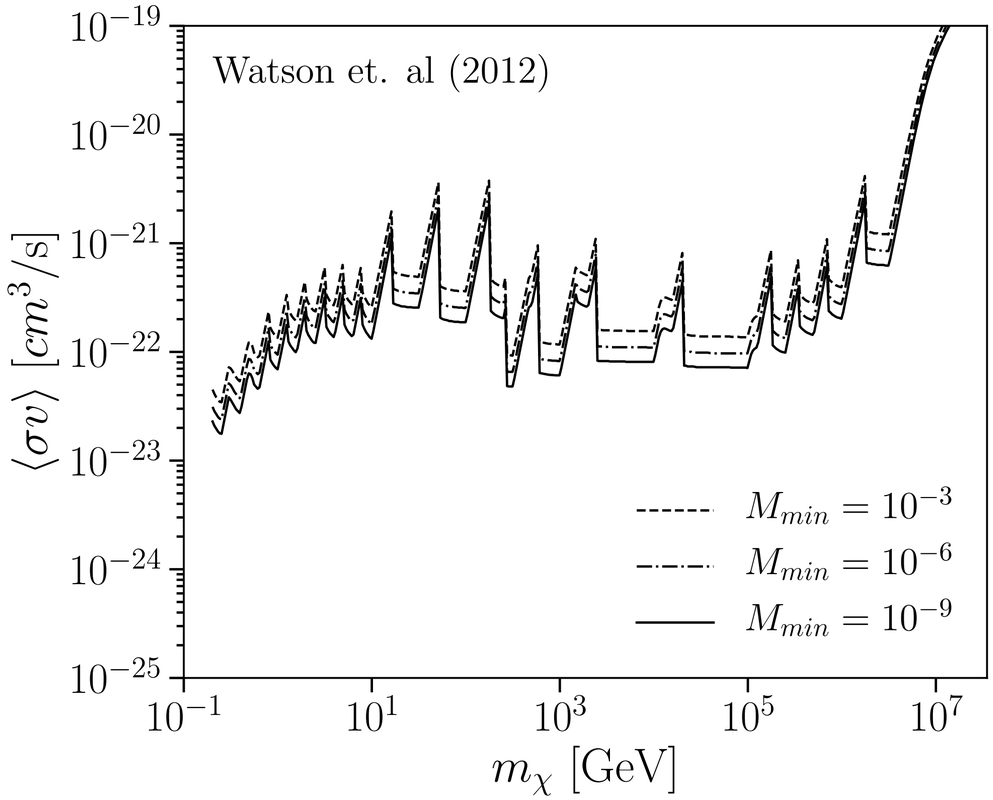
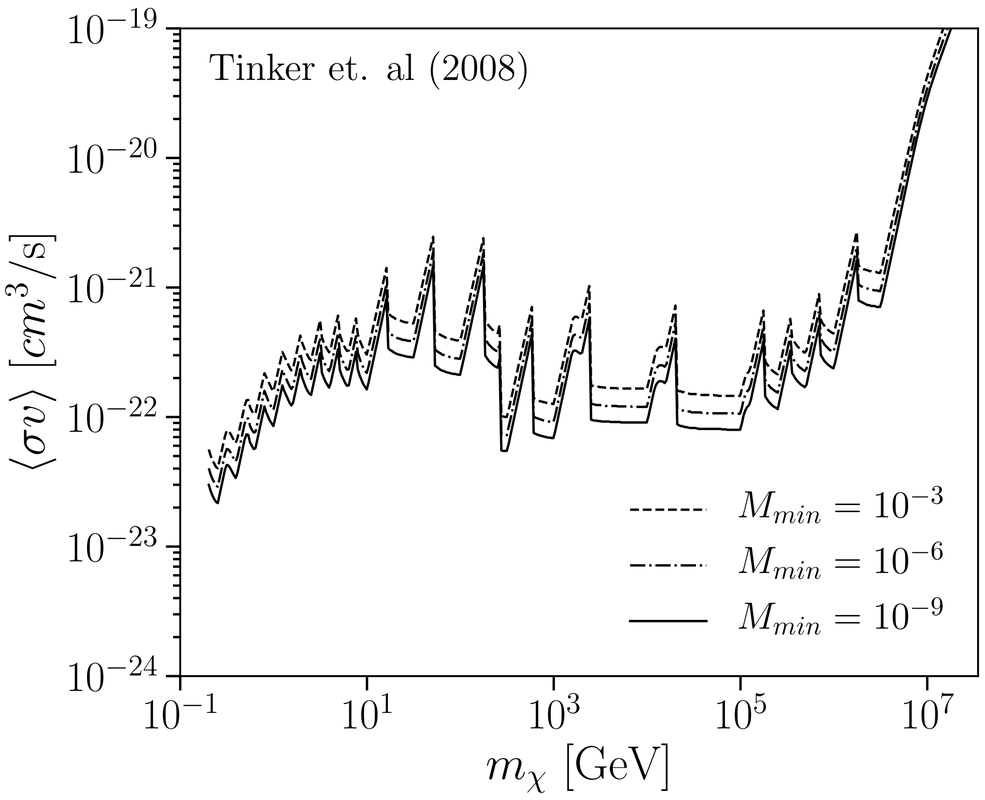
For d-wave

v_0 can be found by solving the spherical Jeans equation, assuming isotropy:

$$\frac{d(\rho(r)v_0^2(r))}{dr} = -\rho(r)\frac{d\phi(r)}{dr}$$

\phi here is the gravitational potential and includes the halo, bulge and disk contributions

$$J_{v^n} = \int d\Omega \int_{\text{l.o.s.}} \langle (v/c)^n \rangle (r) \rho_\chi^2(r) dx\,.$$

Modified J-Factor

Uncertainties from choice of minimum halo mass