Dark Matter Searches with Neutrino Telescopes

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Cosmic messengers and Dark Matter

	radio	IR	X	gamma
	WIMP non WIMP		WIMP non WIMP	WIMP
Photons	radio	IR	X	gamma

Cosmic rays

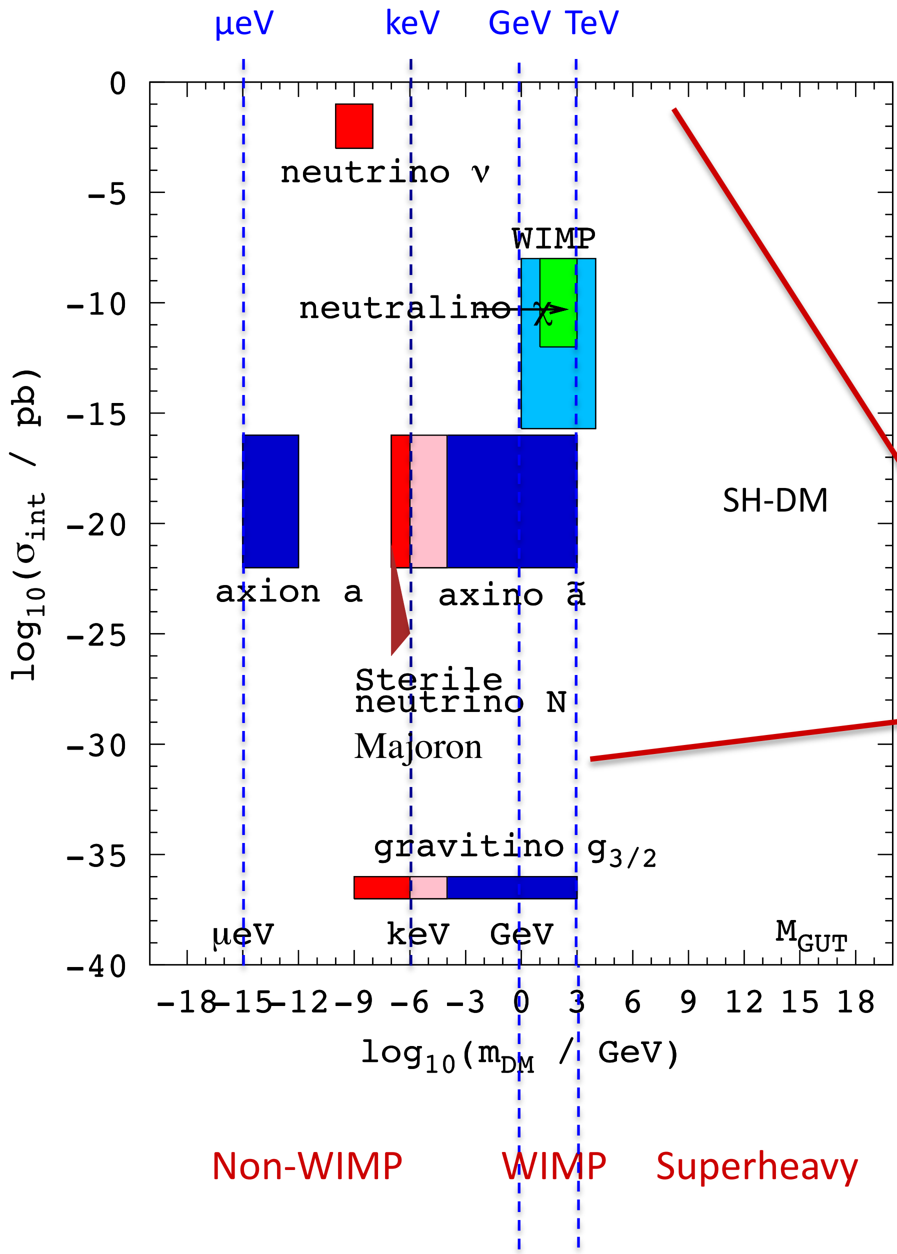
electrons/positrons — WIMP, non WIMP

antiprotons, antideuterium, antinuclei — WIMP

Neutrinos — WIMP, non WIMP

Gravitational waves — non WIMP (DM = primordial BH)

Particle physics scales



"Strong (-ish)"

Self-interacting

Technicolor DM

…

"EM (-ish)"

Millicharged DM

Electric/magnetic dipole

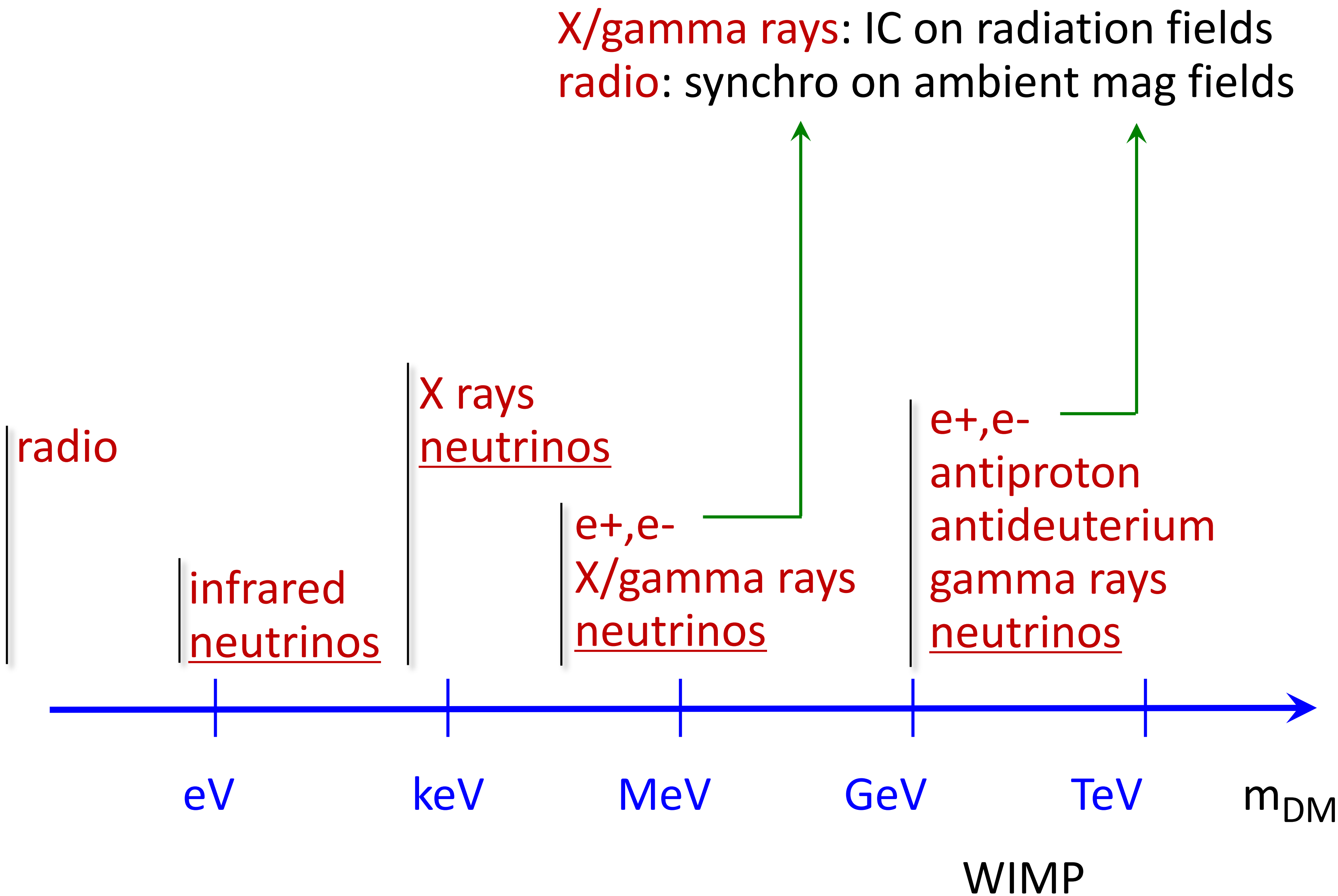
…

<u>Weak</u>

WIMP

Gravitational

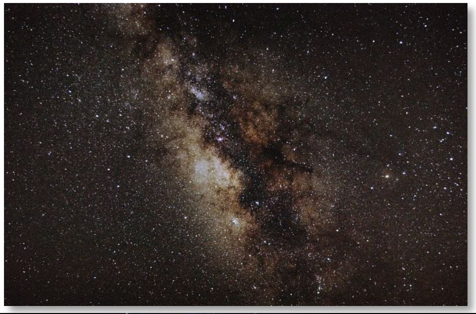
The Multimessenger Landscape

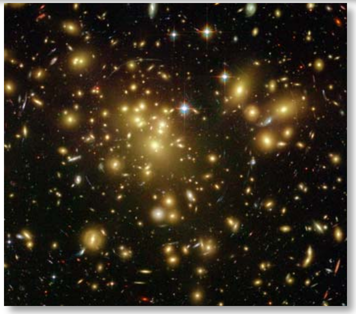


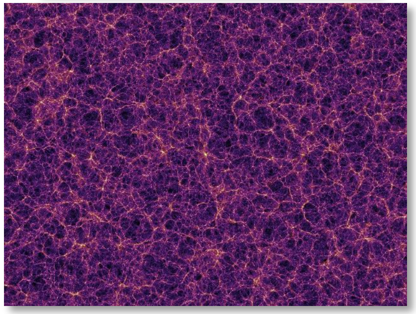
Where to search for a signal

DM is present in:

- Our Galaxy
  - smooth component
  - subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - smooth component
  - individual galaxies
  - galaxies subhalos
- "Cosmic web"

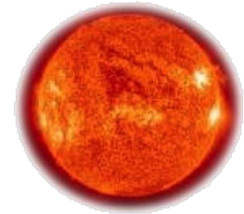






Targets

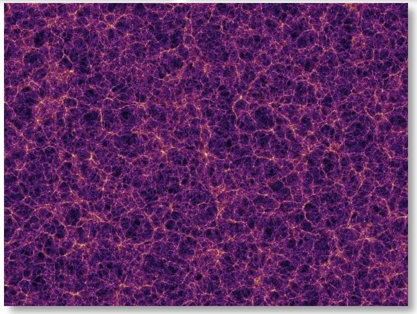
- Earth and Sun




- Milky Way halo

- Nearby Galaxies and Clusters


- Diffuse background



Targets and DM probes

- Earth and Sun

  Local DM

  Shares features with DM direct detection

- Milky Way

  Galactic center, halo

  Galactic DM halo

  Shares features with galactic indirect detection signals (gamma rays, antimatter; radio)

- Nearby Galaxies and Clusters

  As specific targets

  Inner DM halo

  Shares features with gamma ray and radio signals

- Diffuse background

  As cumulative emission

  Large scale structure

  Shares features with extra galactic gamma ray and radio signals

Targets and particle probes

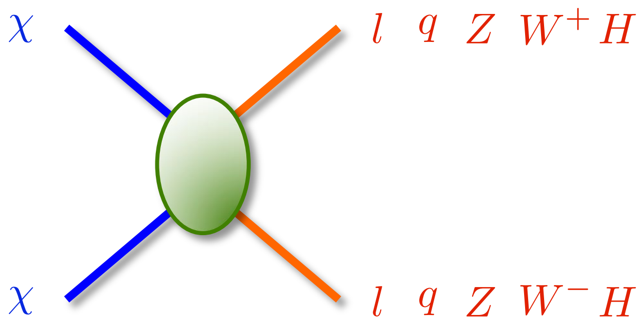
- Earth and Sun
- Milky Way
- Nearby Galaxies and Clusters
- Diffuse background

Scattering with nuclei
Self annihilation

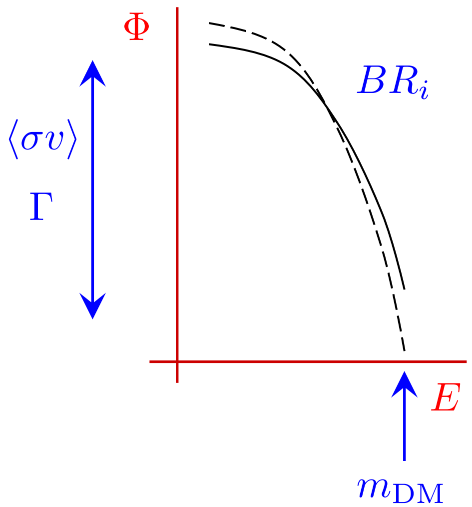
Self annihilation
or
Decay

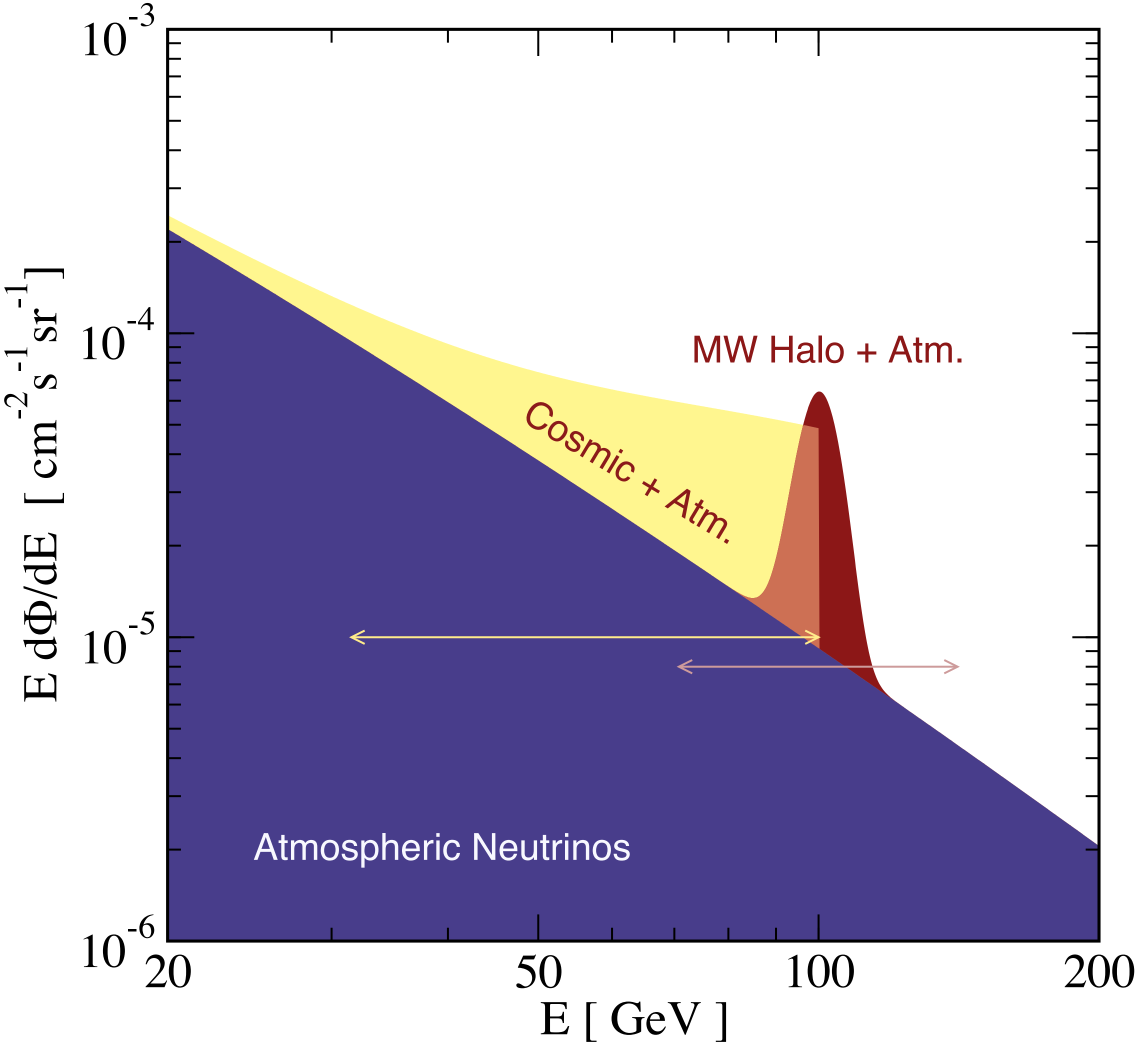
Spectral features

- Continuum
- Line



- Features: size, endpoint, shape
- Oscillations from source:
  - Earth and Sun: vacuum, matter, absorption
  - Milky Way and cosmological: VLBaseline

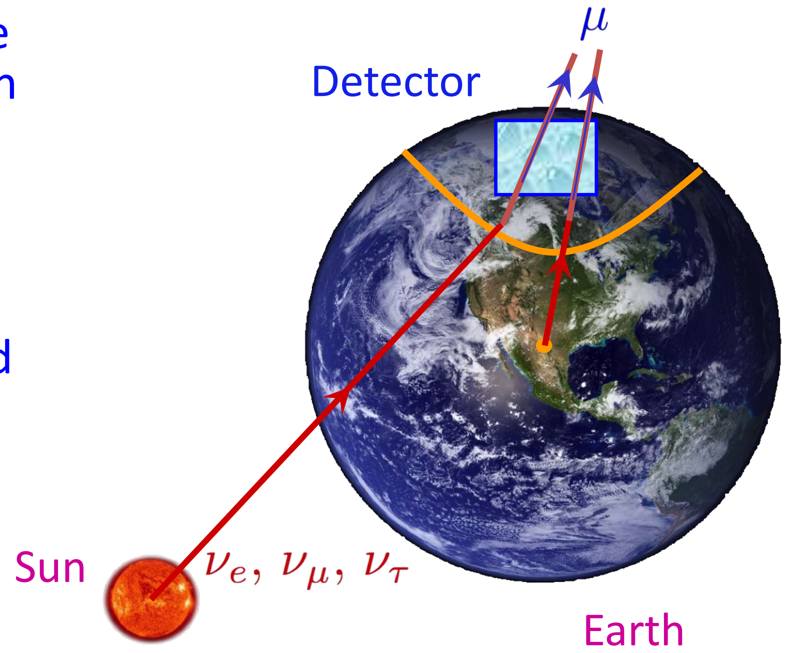




MW Halo + Atm.
Cosmic + Atm.
Atmospheric Neutrinos
10^{-3}
10^{-4}
10^{-5}
10^{-6}
20
50
100
200
E [GeV]
E dΦ/dE [cm^{-2} s^{-1} sr^{-1}]

Neutrinos from Earth and Sun

- Capture
  - Galactic DM particles that cross the Earth and the Sun, can interact with the nuclei in these bodies and loose enough energy to remain gravitationally captured
- Accumulation
  - After subsequent interactions they tend to drop into the innermost parts of the Earth and the Sun, where they accumulate
- Annihilation
  - When the energy density in the inner parts of the Earth and the Sun increases enough, they may start to annihilate



neutrino signal

Capture Rate

- Elastic scattering of the DM particle with a nucleus *i* in a spherical shell at a distance *r* from the center of the Earth (or Sun)
- In order to be captured, the velocity of the DM particle after the interaction must be smaller than the escape velocity at the shell

$$v_{\rm esc}^{\rm Sun} = 618 \ {\rm Km \ s^{-1}}$$
$$v_{\rm esc}^{\rm Earth} = 11.2 \ {\rm Km \ s^{-1}}$$

at the surface

$$\langle v \rangle \sim 300 \ {\rm Km \ s^{-1}}$$

mean DM particle velocity

DM-nucleus cross section

DM density

DM velocity dispersion

$$C = \sum_i \left(\frac{8}{3\pi}\right)^{1/2} \left[\frac{\sigma_i \rho_\chi \bar{v}}{m_\chi}\right] \left[\frac{M_i}{m_i}\right] \left[\frac{3v_{esc}^2}{2\bar{v}^2}\langle\phi\rangle_i\right] \xi(\infty) S_i$$

interaction rate of a flux of DM particle with a nucleus in free space

number of nuclei of type *i* in the body

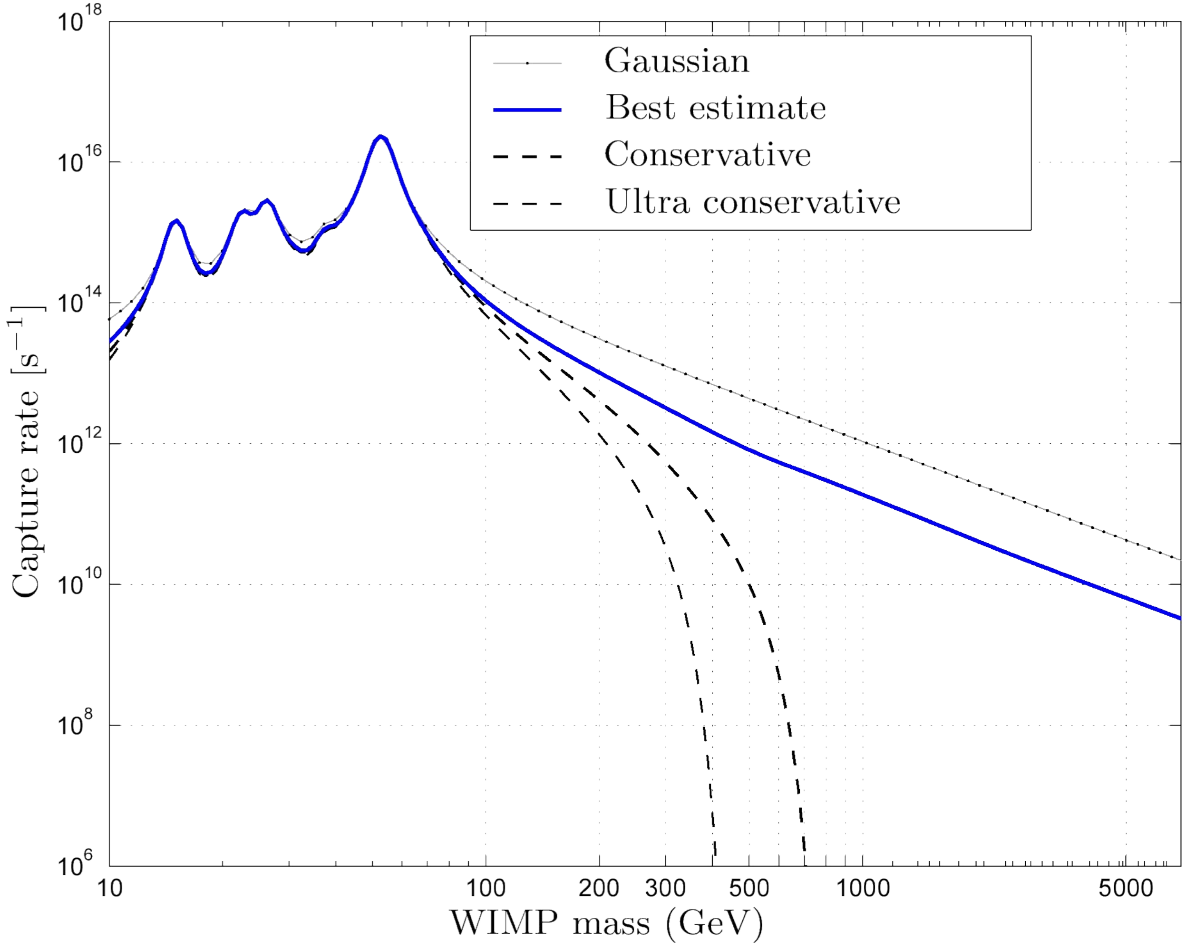
“focusing factor” which determines the maximum capture rate of the body

suppression factor due to the motion of the body (~0.75)

suppression factor due to kinematics (mainly mass mismatch)

M_i	Total mass in terms of element *i*
$\langle\phi\rangle_i$	Gravitational potential averaged over the mass distribution of element *i*

Capture rate on the Earth



Lundberg, Edsjo, PRD 69 (2004) 123505

Solar bound orbits

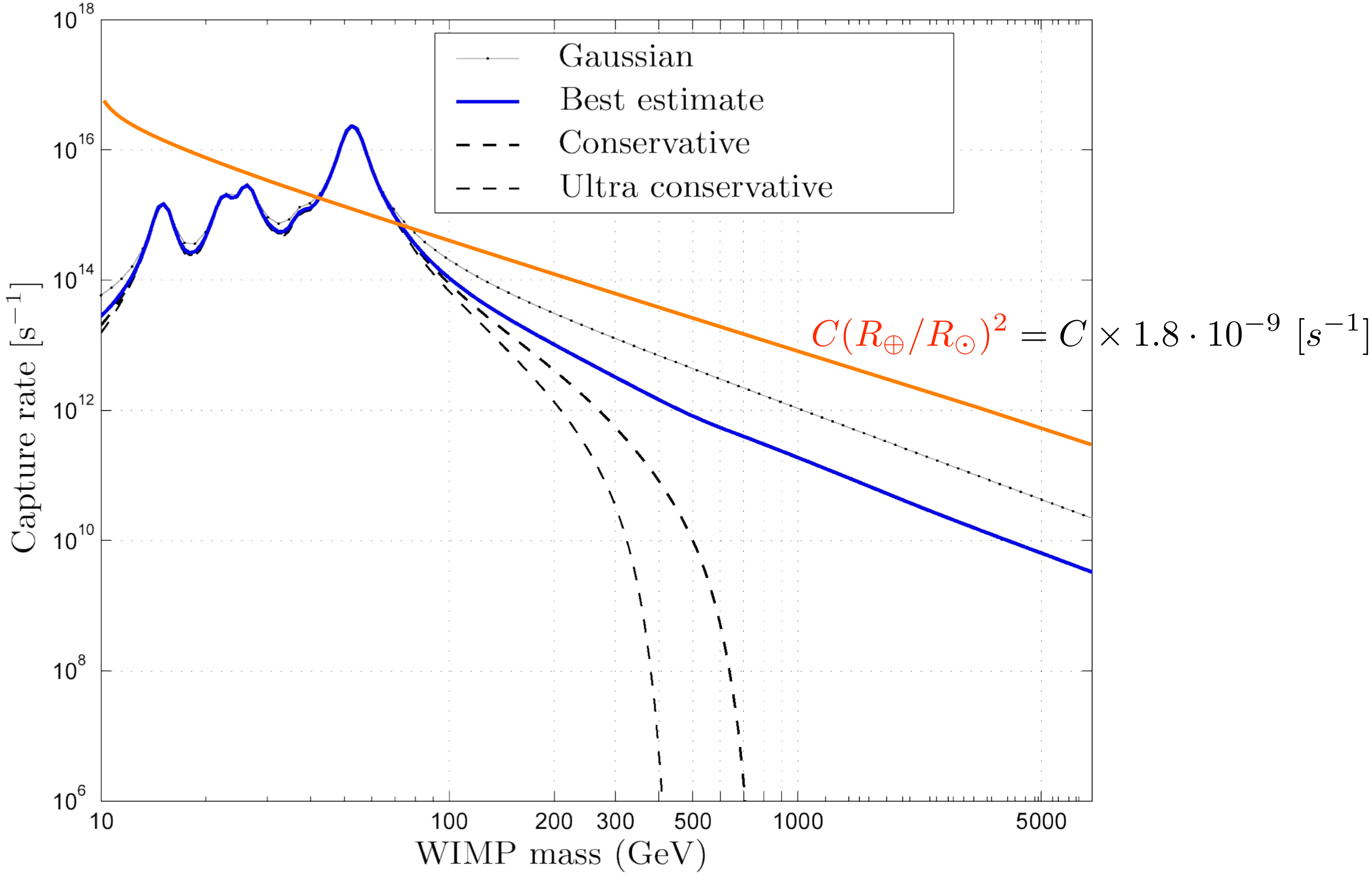
- Numerical simulation of Near Earth Asteroids show that many of these have life times in the solar system less than 2 Myr

- After that, they are either:
  - Driven into the Sun
  - Escape the solar system

- If this would occur also to the DM particles, this would significantly reduce the number of these particles bound to the solar system, and therefore reduce the capture rate on Earth

and consequently the neutrino signal

Capture rate on the Sun



Annihilation rate

Evolution equation

$$\frac{dN}{dt} = C - 2\Gamma_A$$

Annihilation rate

$$\Gamma_A = \frac{C}{2}\tanh^2\left(\frac{t_0}{\tau_A}\right)$$

Neutrino Flux

$$\frac{dN_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi R^2}\sum_{\mathcal{F}} \mathrm{BR}(\chi\chi \to \mathcal{F})\frac{dN_\nu^{\mathcal{F}}}{dE_\nu}$$

Capture rate C

Age of the body $t_0 = 4.6\ \mathrm{Gyr}$

Relaxation time $\tau_A = [C C_A]^{-1/2}$

$$C_A = \langle \sigma_{\mathrm{ann}} v\rangle_0 V_2/V_1^2$$

$$V_j = c_B (j m_\chi / 10\ \mathrm{GeV})^{-3/2}\ \mathrm{cm}^3$$

Effective volumes of DM concentrations

More concentrated for larger masses

$$c_B = 1.8 \cdot 10^{25}\ /\ 6.6 \cdot 10^{28}$$

Earth Sun

Neutrino flux at production

$$\chi\chi \rightarrow \nu\nu,\, l\bar{l},\, q\bar{q},\, W^+W^-,\, ZZ,\, \text{Higgses},\, \text{Higgs} + \text{gauge}$$

Productions in Earth

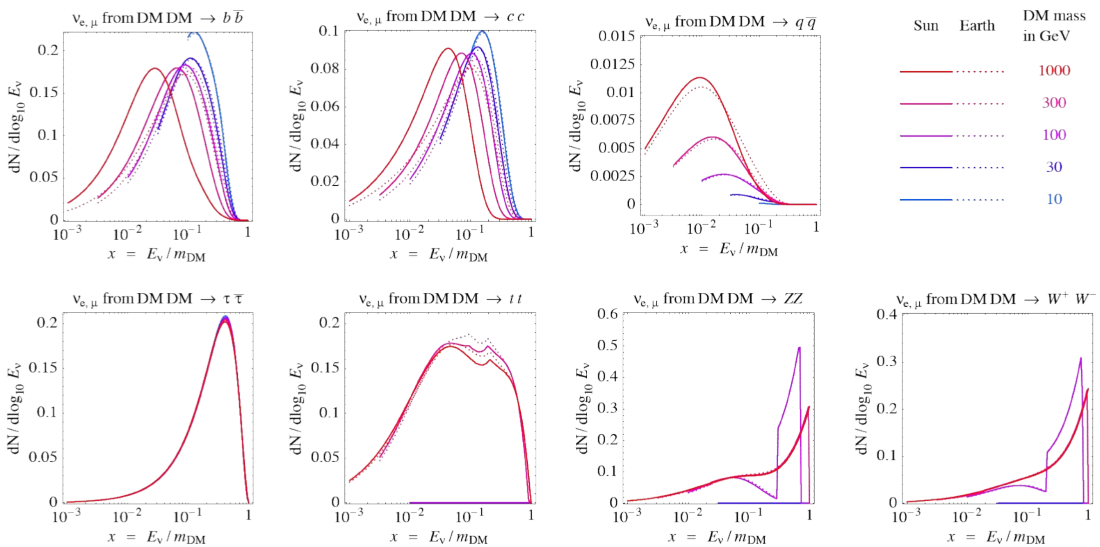
- Muons: stopped before decay $\rightarrow$ neutrinos below typical thresholds
- Taus: decay almost as in vacuum
- Light hadrons: typically stopped before decay
- Heavy hadrons: typically decay before loosing significant energy

Production in Sun

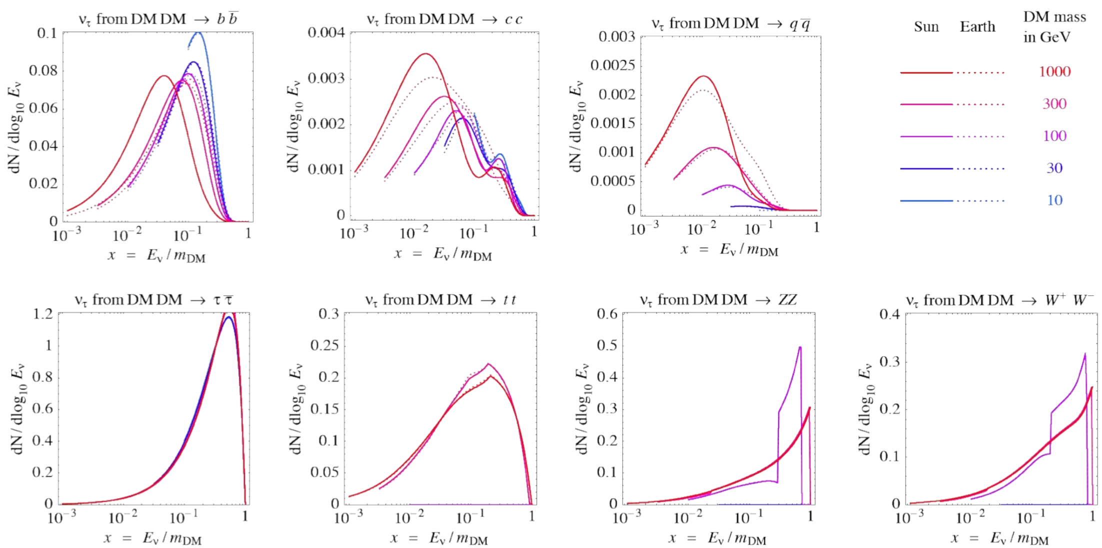
- Leptons: stopping power of medium is stronger $\rightarrow$ softer neutrino spectra
- Light hadrons: typically stopped before decay
- Heavy hadrons: energy losses important, need modeling

Spectra at production

ν_e, ν_μ

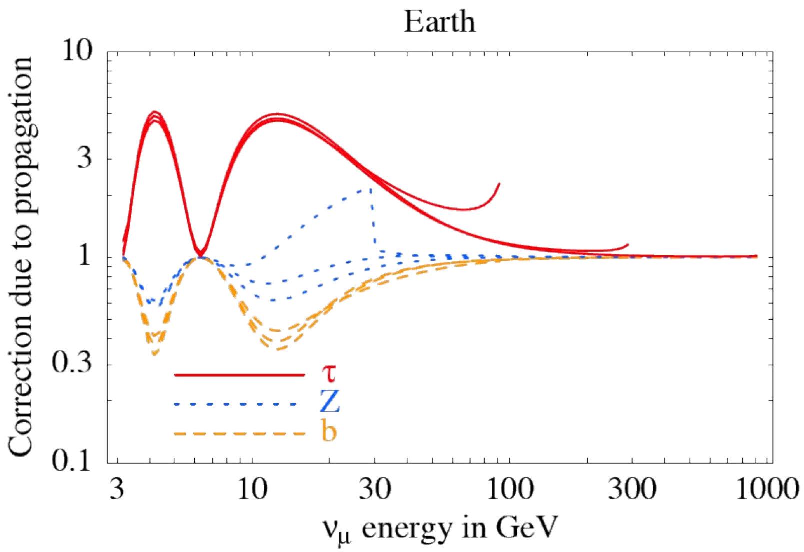


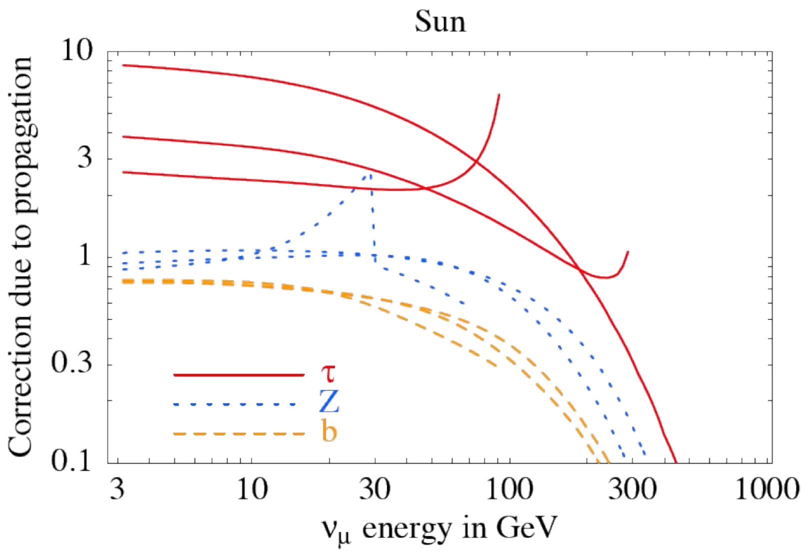
ν_τ



M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

Oscillations and absorption





Earth:

– Affected only by "atmospheric" oscillation $\nu_\mu \leftrightarrow \nu_\tau$ at E < 100 GeV

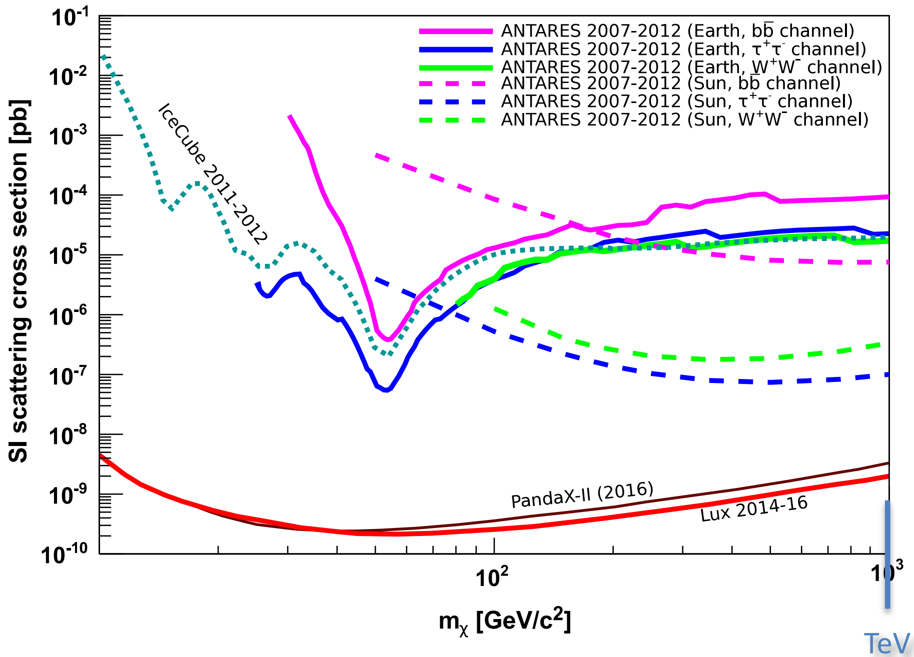
Sun:

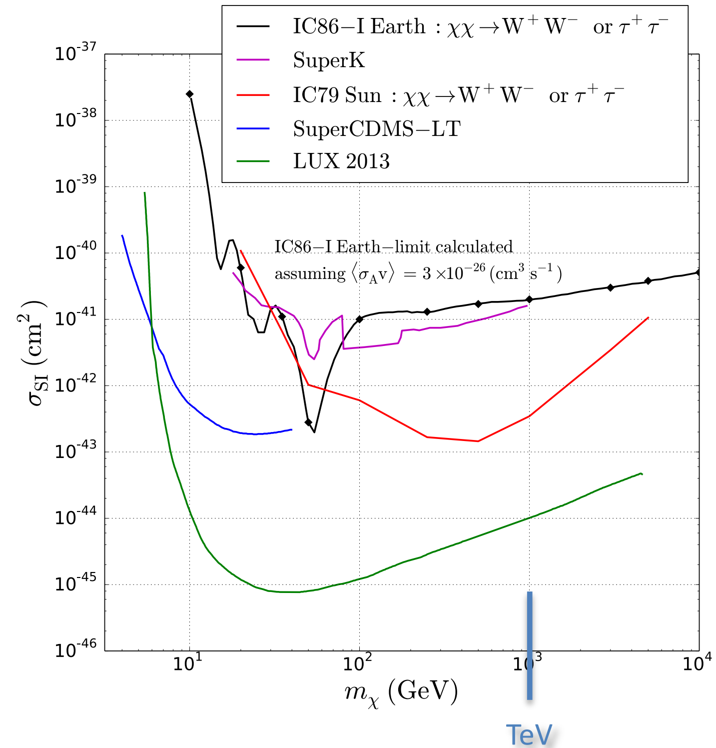
– Affected by average "solar" and "atmospheric" oscillations
– Absorption suppresses neutrinos for E > 100 GeV (partially converted to lower energy neutrinos (by NC and regeneration)

M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

Neutrinos from the Earth

Spin-independent cross section



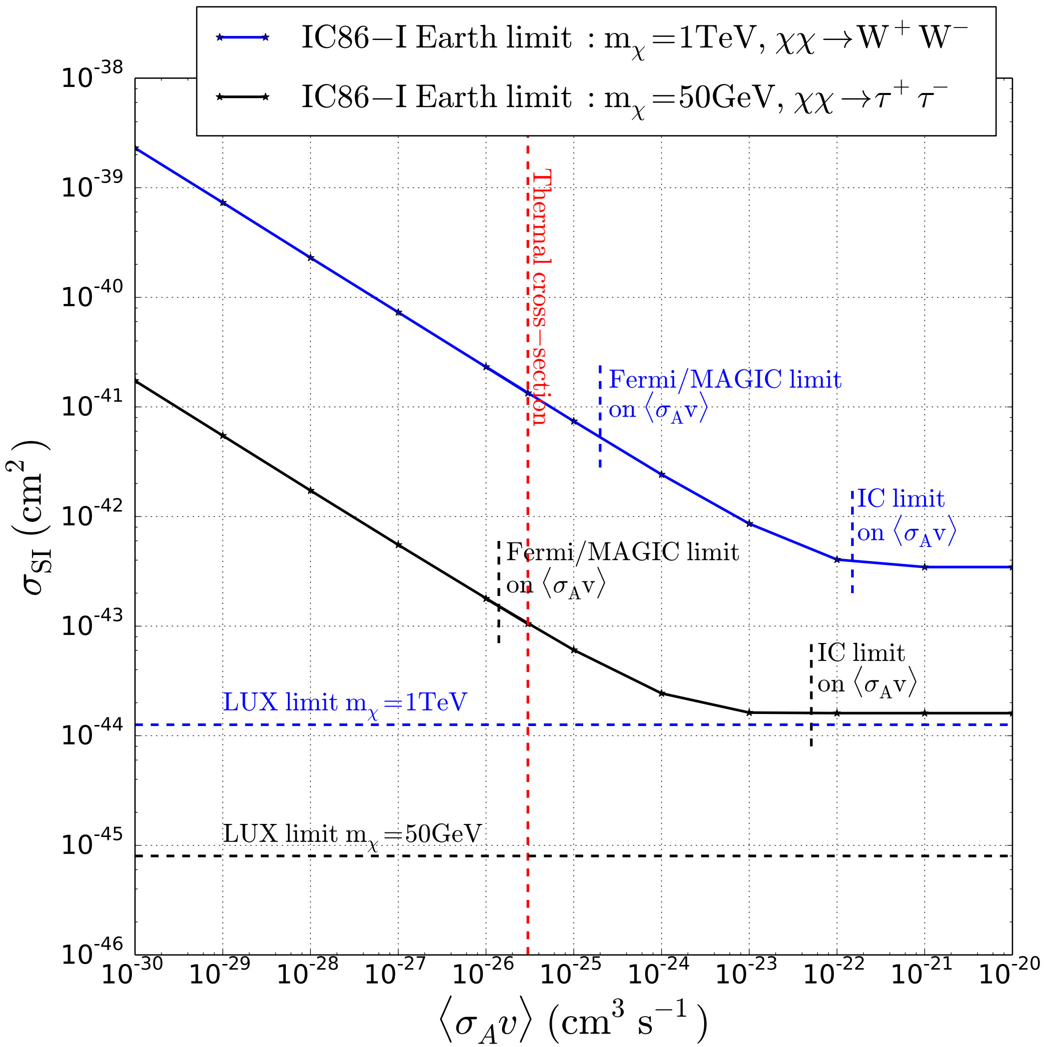


ANTARES
(assuming thermal annihilation cross section)

IceCube
(assuming thermal annihilation cross section)

Albert et al (ANTARES Collab), Phys Dark U 16 (2017) 41

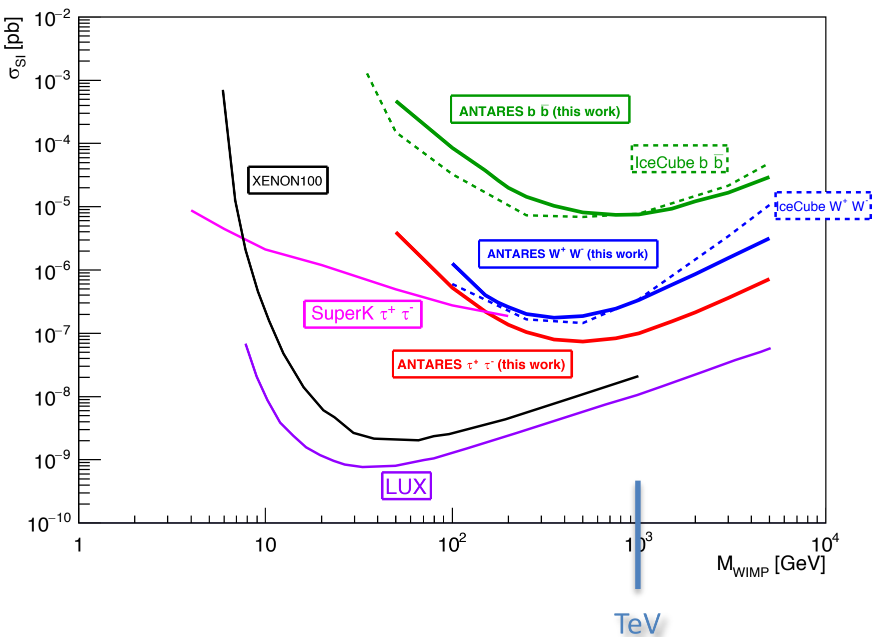
Aartsen et al (IceCube Collab), 1609.01492



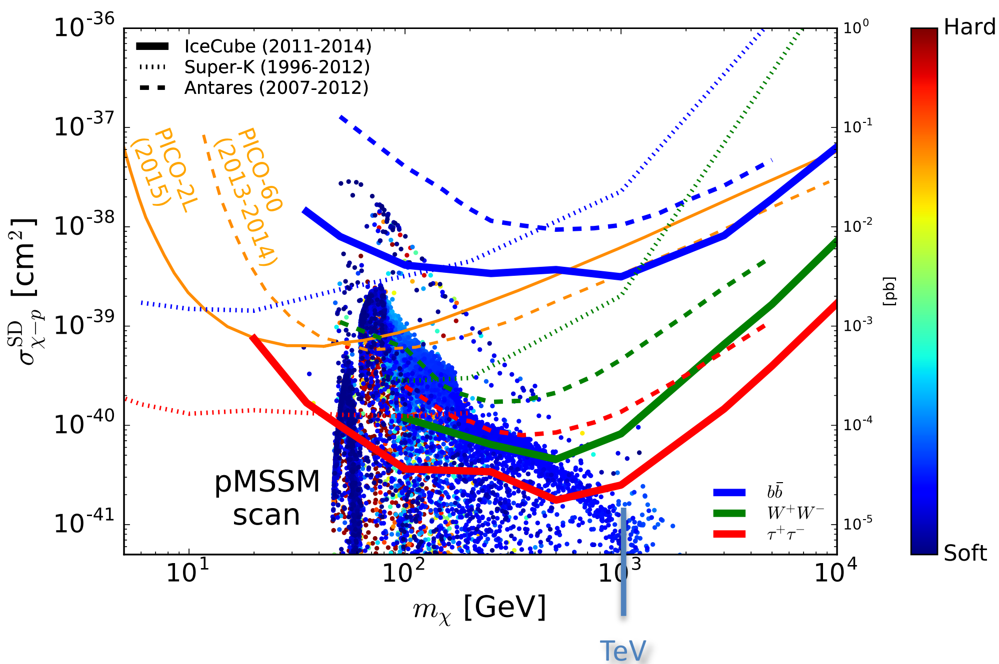
Aartsen et al (IceCube Collab), 1609.01492

Neutrinos from the Sun

Spin-dependent cross section



ANTARES

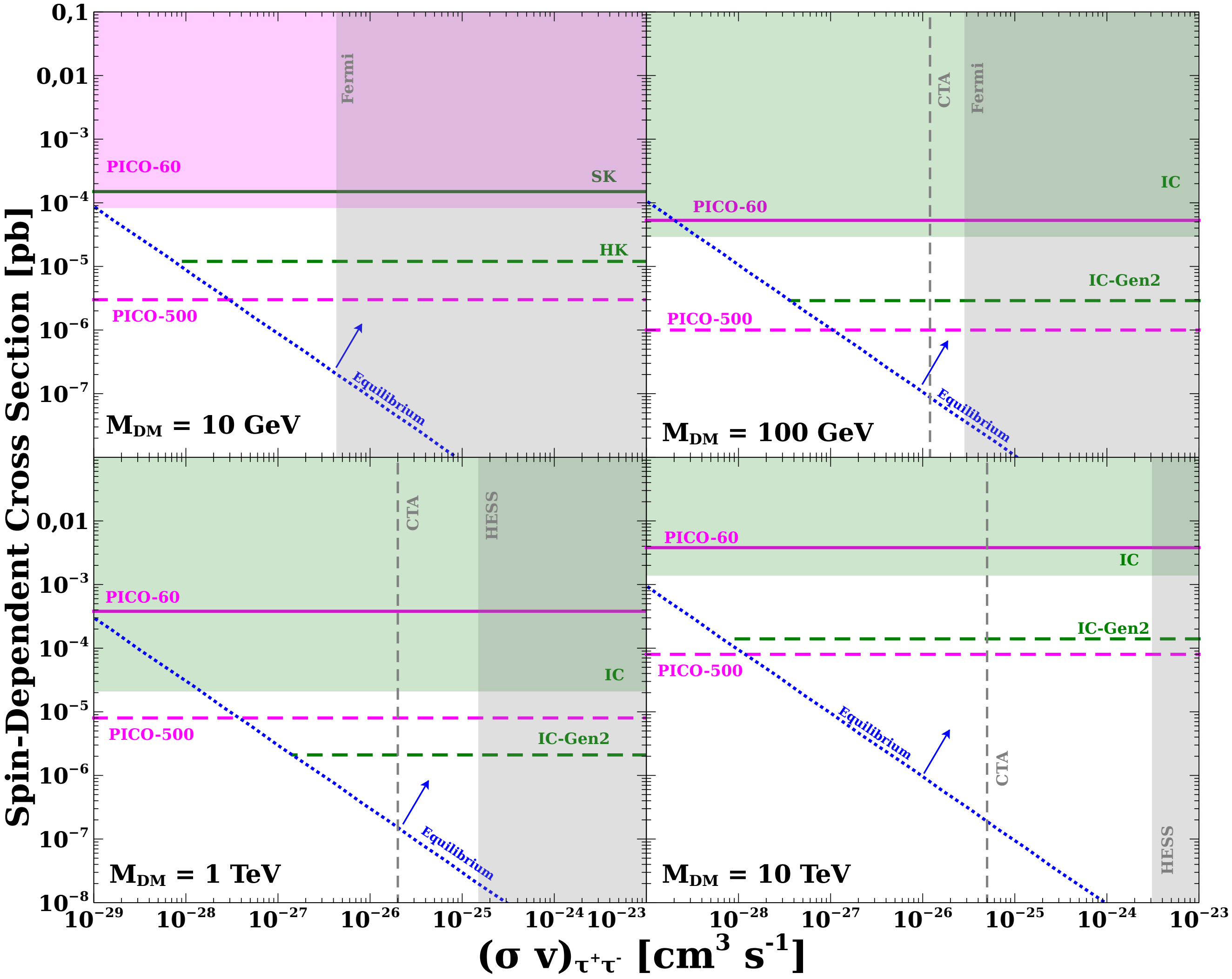


IceCube

Adrian-Martinez et al (ANTARES Collab), 1603.02228

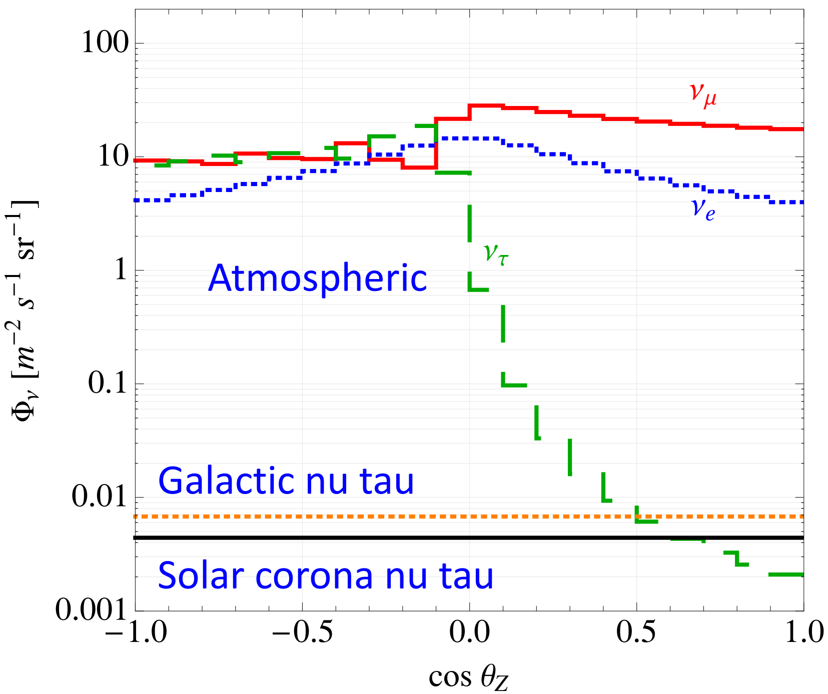
Aartsen et al (IceCube Collab), 1612.05949

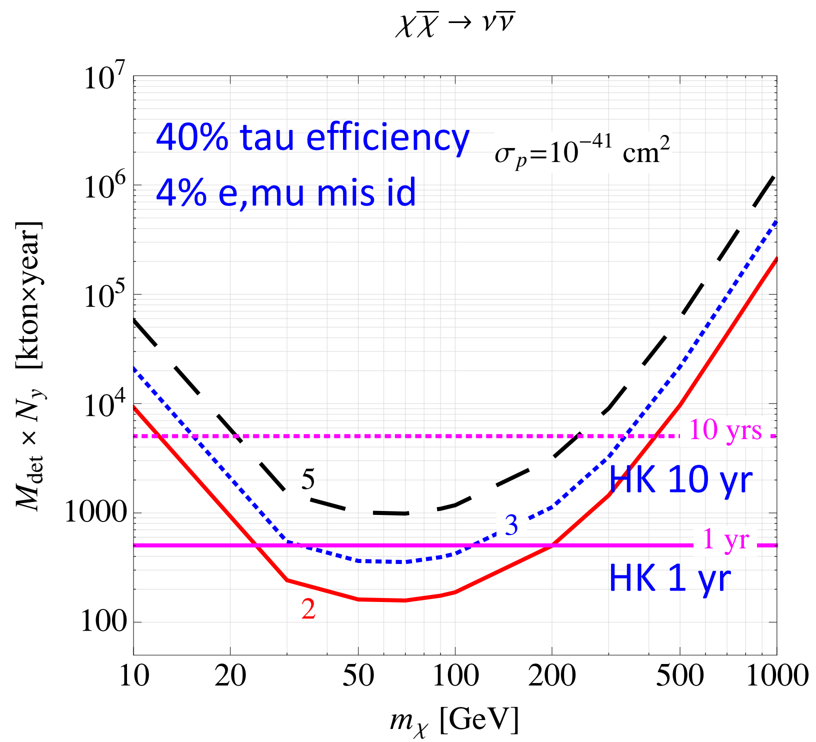
Complementarity with DD



NF, Masiero, Queiroz, Yaguna, 1710.02155

Down-going tau neutrinos?





Significance in sigma

NF, Niro, 1108.2630

Neutrinos from the Milky Way

Flux

$$\frac{d\Phi_{\Delta\Omega}}{dE} = \frac{\langle \sigma_A v \rangle}{2} \mathcal{J}_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

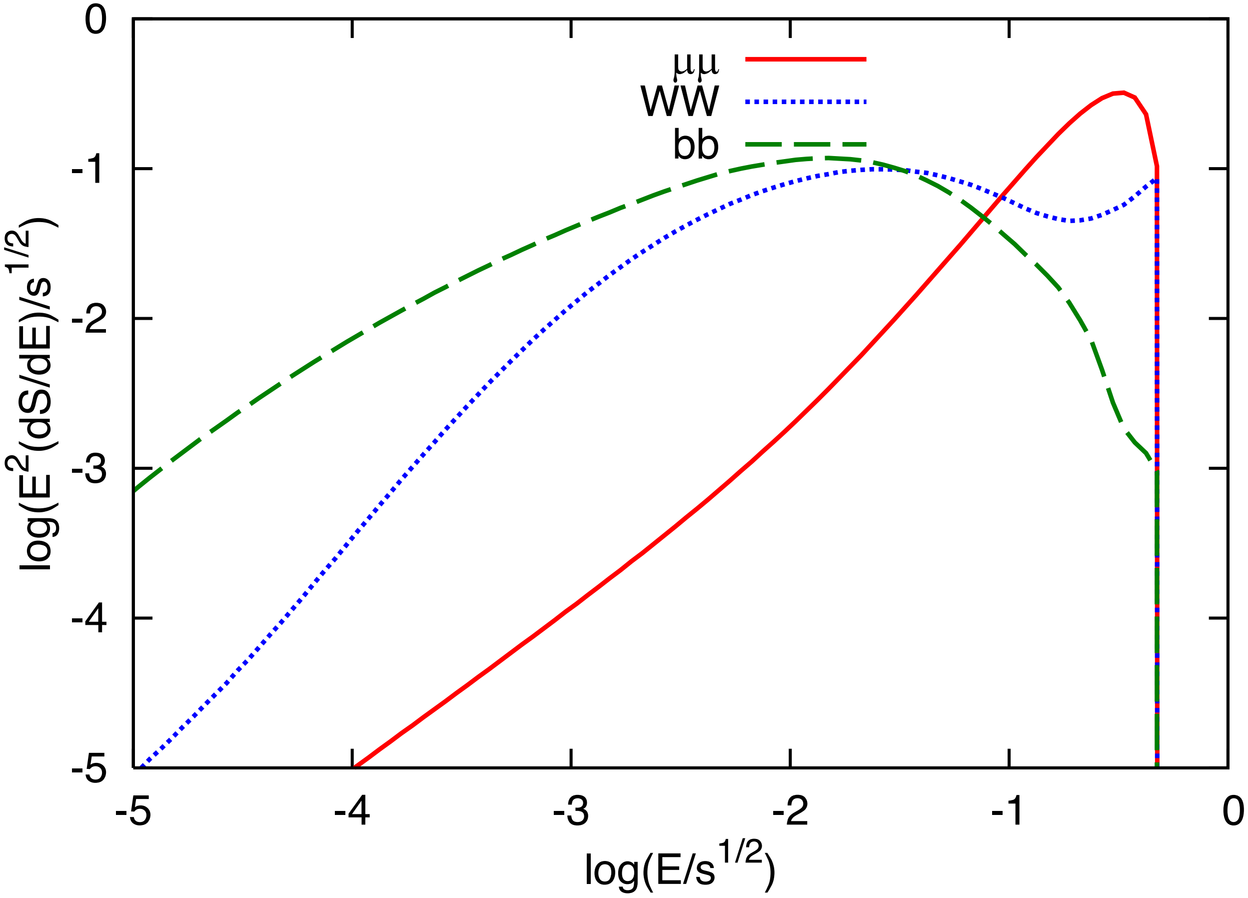
Line-of-sight integral

$$\mathcal{J}(\psi) = \frac{1}{R_{sc}\rho_{sc}^2} \int_0^{\ell_{max}} \rho^2 (\sqrt{R_{sc}^2 - 2\, l\, R_{sc} \cos\psi + l^2})\, d\ell$$

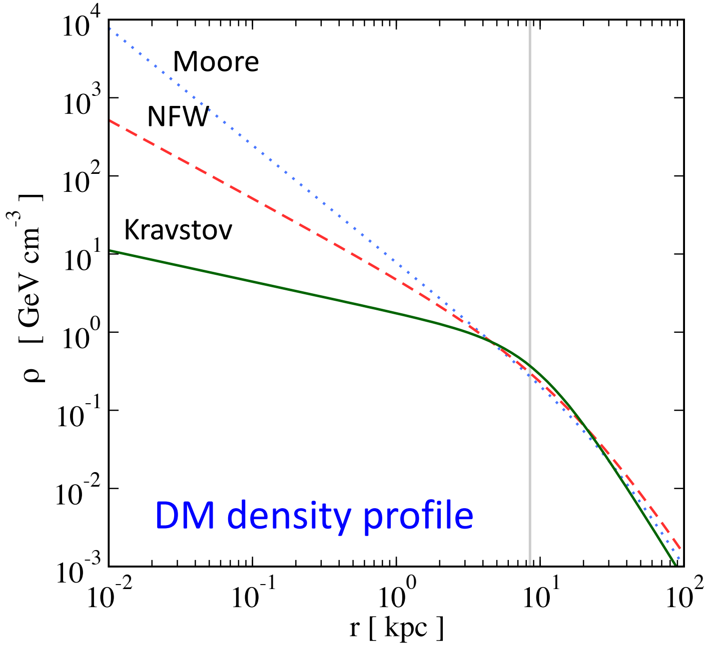
Angle-averaged LOS

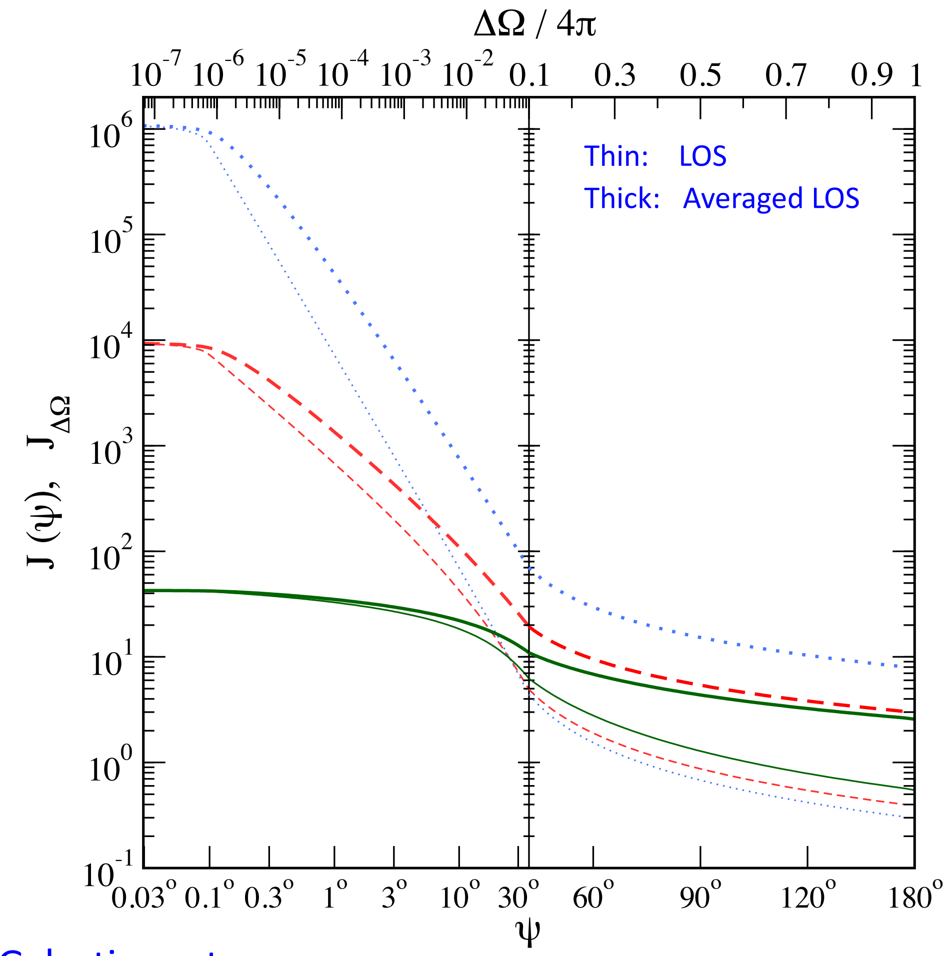
$$\mathcal{J}_{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_{\cos\psi}^{1} \mathcal{J}(\psi')\, 2\pi\, d(\cos\psi')$$

Spectra



Line of sight integral



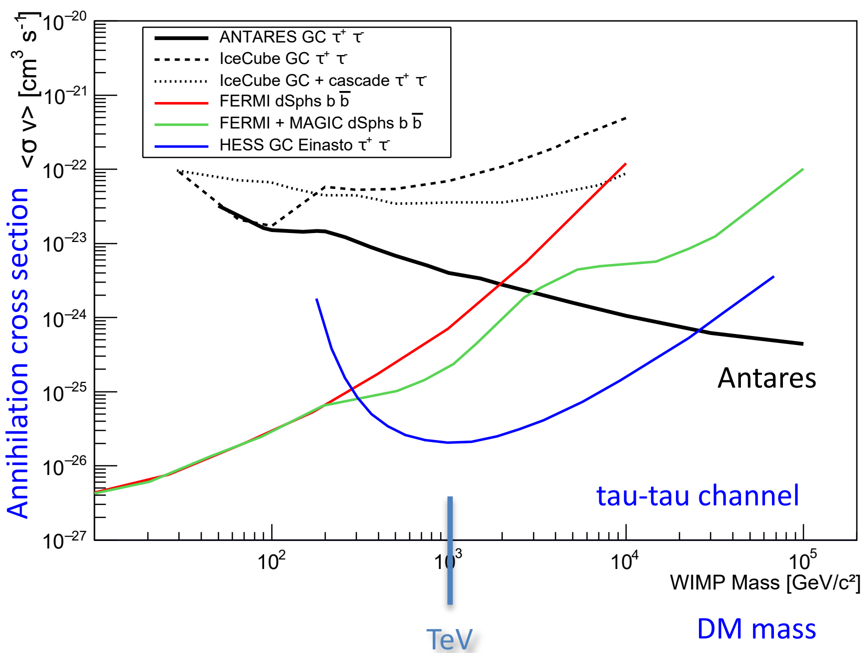


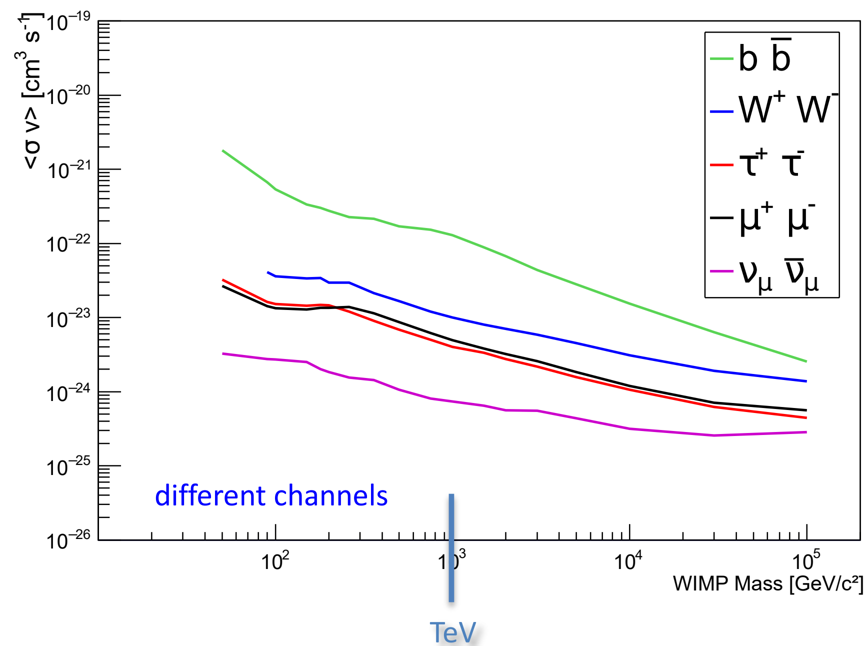
Galactic center

Yuksel et al, 0707.0196

Milky Way Halo

Antares

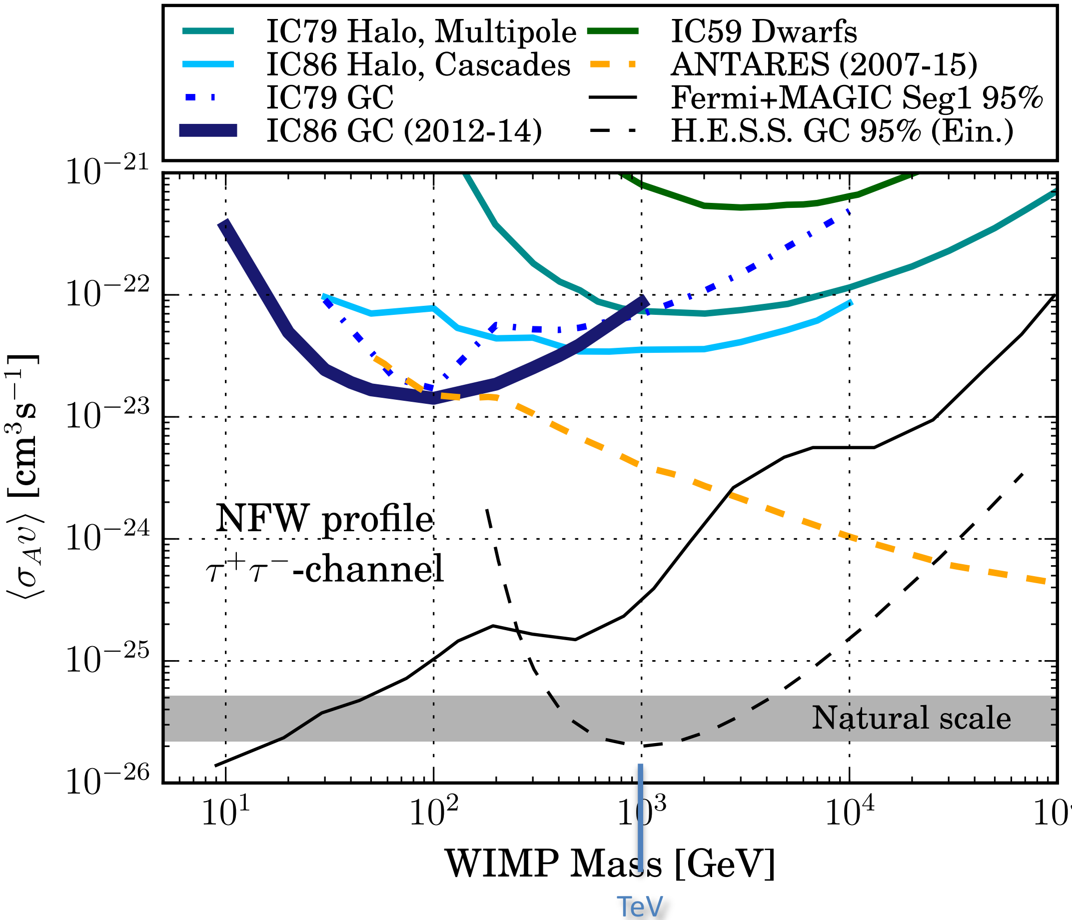




Albert et al (Antares Collab), 1612.04595

Milky Way Halo

IceCube



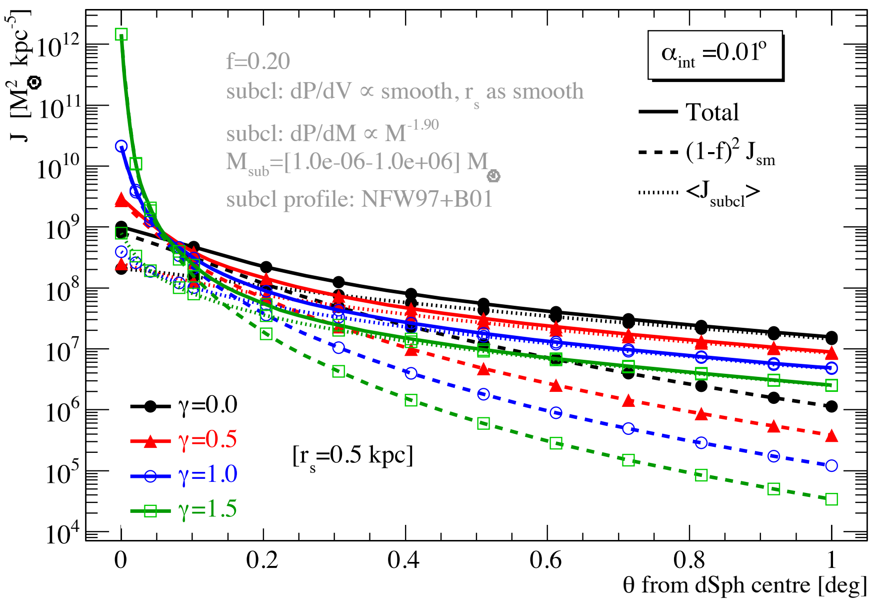
Aartsen et al (IceCube Collab), 1606.00209

Neutrinos from Nearby Galaxies and Galaxy Clusters

$$\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_A v \rangle}{4\pi \cdot 2m_\chi^2} \frac{dN_\nu}{dE} \times J(\Delta\Omega)$$

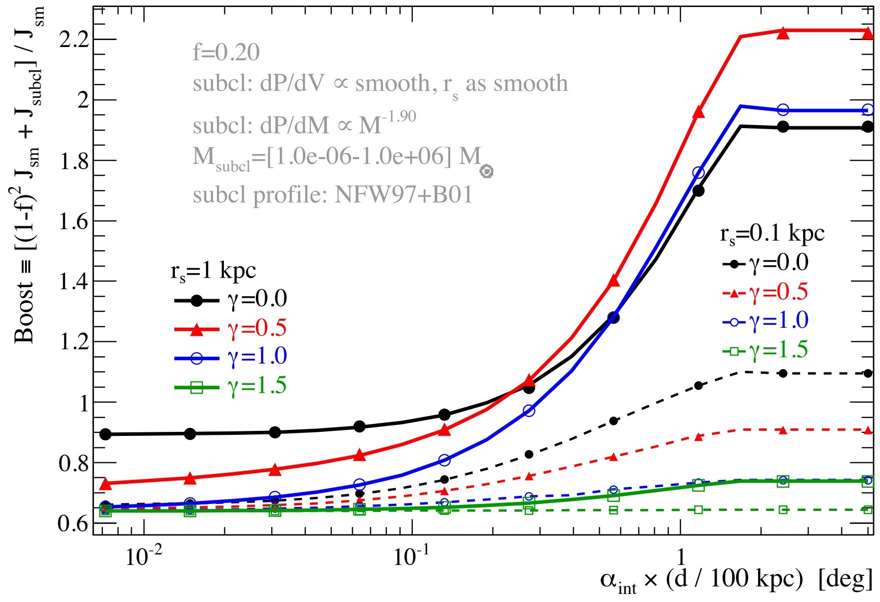
$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho(l)^2 dl$$

Astro-Factors: Nearby Galaxies



J factor

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int \rho^2_{\rm DM}(l, \Omega)\, dl d\Omega.$$

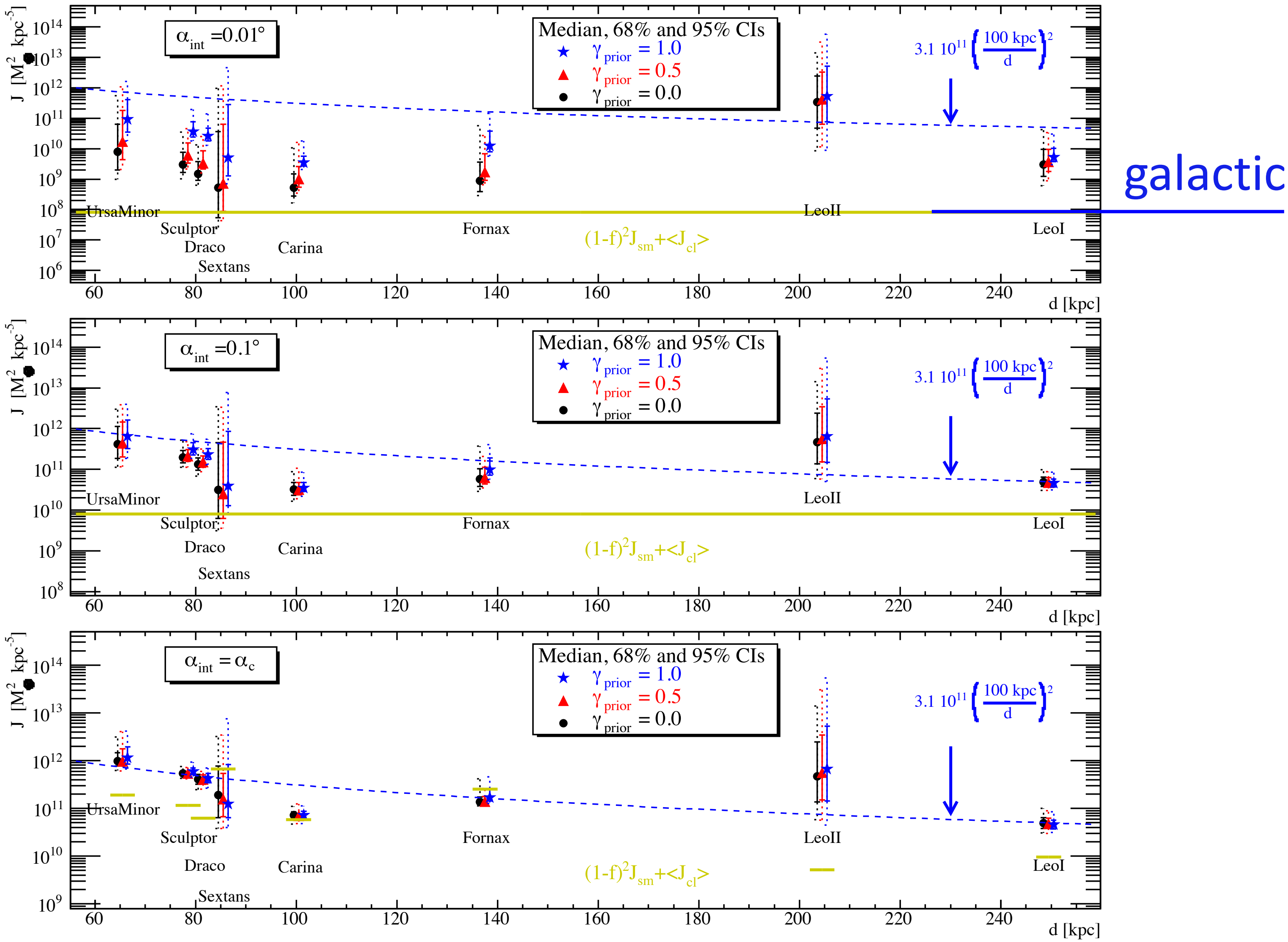


Boost factor

due to substructures

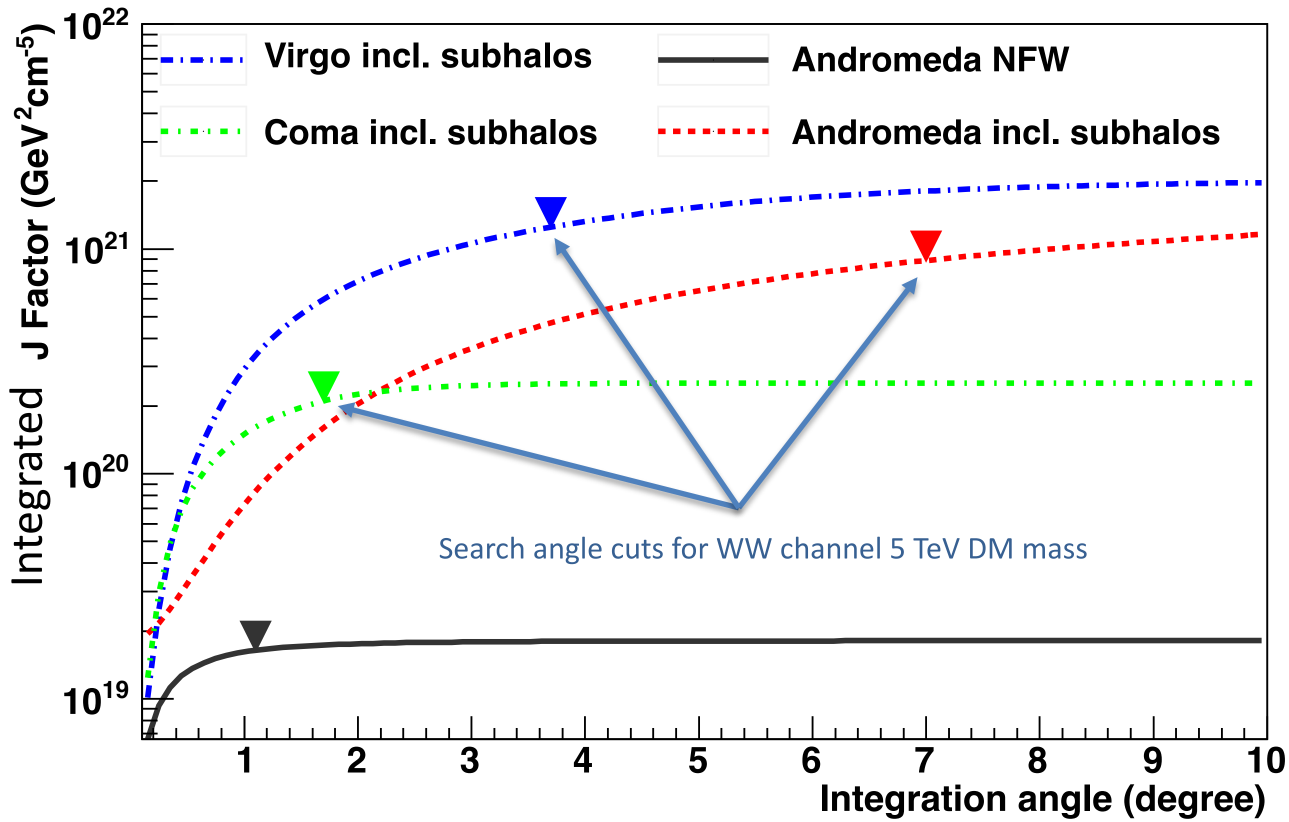
Charbonnier et al, MNRAS 418 (2011) 1526

J Factor: Nearby Galaxies



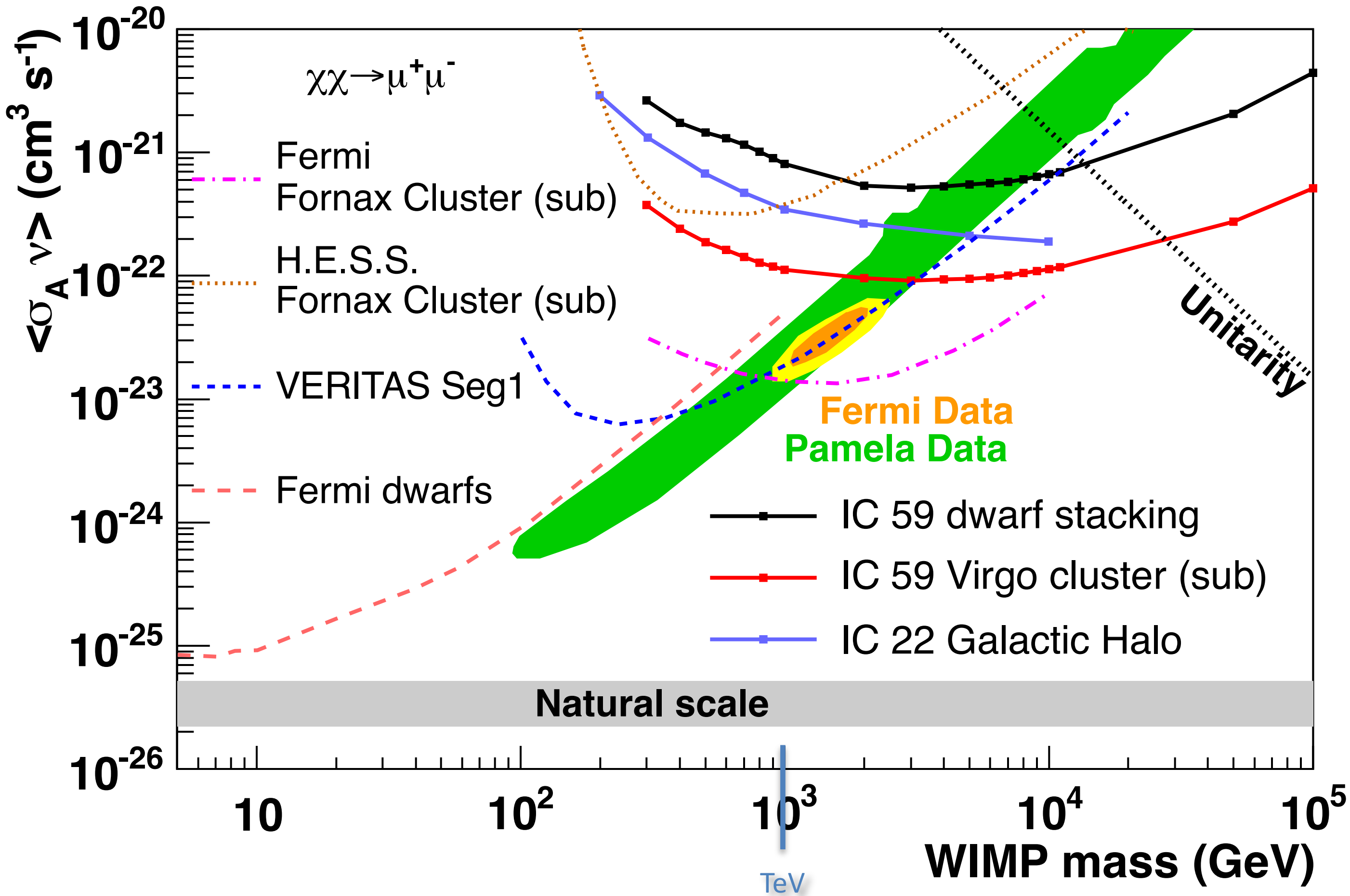
Charbonnier et al, MNRAS 418 (2011) 1526

J-Factor: Galaxy Clusters



Aartsen et al (IceCube Collab.), 1307.3473

IceCube Summary



Aartsen et al (IceCube Collab.), 1307.3473

Diffuse Neutrino Background

Decaying DM

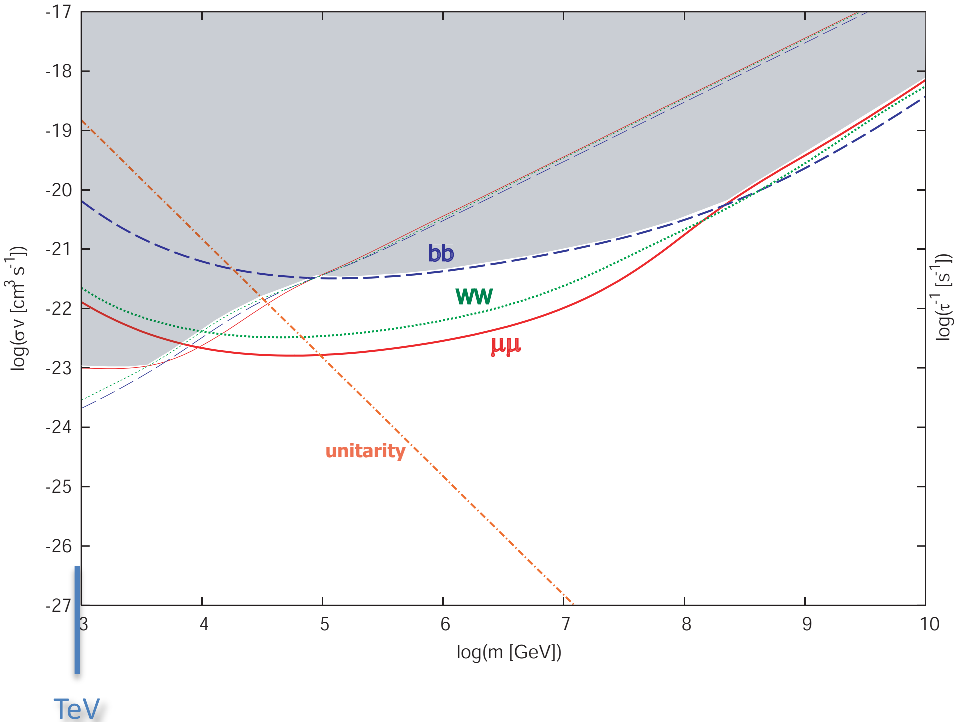
$$\Phi = \frac{c}{4\pi H_0} \int dz \; \frac{1}{\sqrt{\Omega_\Lambda + (1+z)^3 \Omega_m}} \; \frac{\rho_{\rm dm}}{m_{\rm dm} \tau_{\rm dm}} \frac{dS}{dE'}$$

Annihilating DM

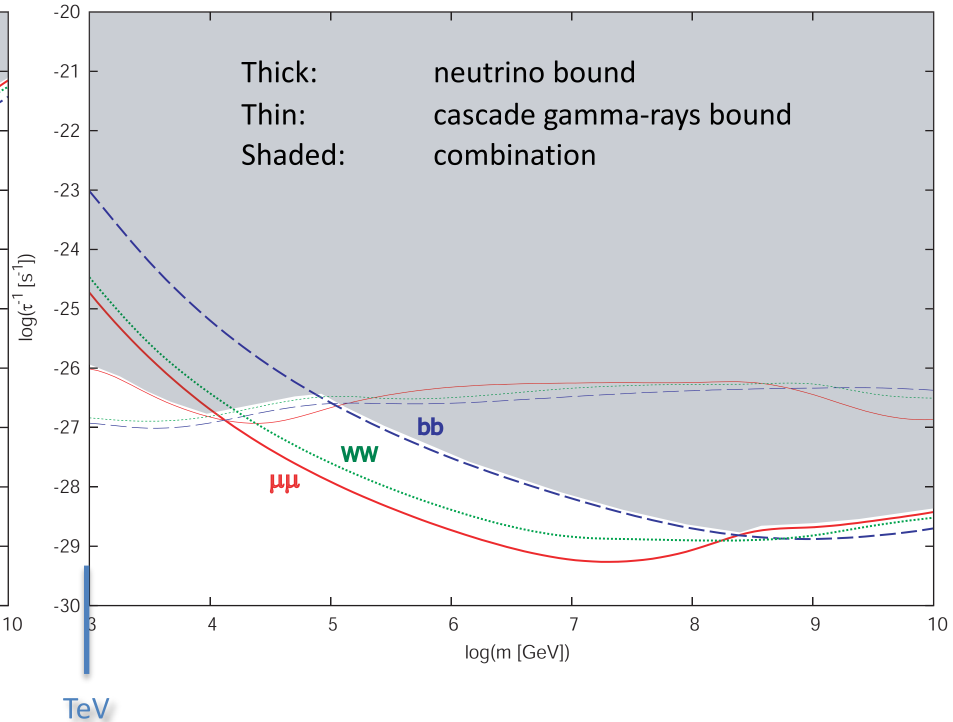
$$\Phi = \frac{c}{4\pi H_0} \int dz \; \frac{g(z)(1+z)^3}{\sqrt{\Omega_\Lambda + (1+z)^3 \Omega_m}} \; \frac{< \sigma v >_{\rm dm} \rho_{\rm dm}^2}{2 m_{\rm dm}^2} \frac{dS}{dE'}$$

$$g(z) = \int dM \; \frac{dn_{\rm halo}}{dM} g(c(M,z)) \frac{M}{\rho_{\rm dm}} \frac{\Delta_c}{\Omega_{\rm dm}}$$

Diffuse Neutrino Background



Annihilation



Decay

Murase, Beacom, 1206.2595

PeV Neutrinos

- PeV neutrinos observed by IceCube triggered discussion about their origin

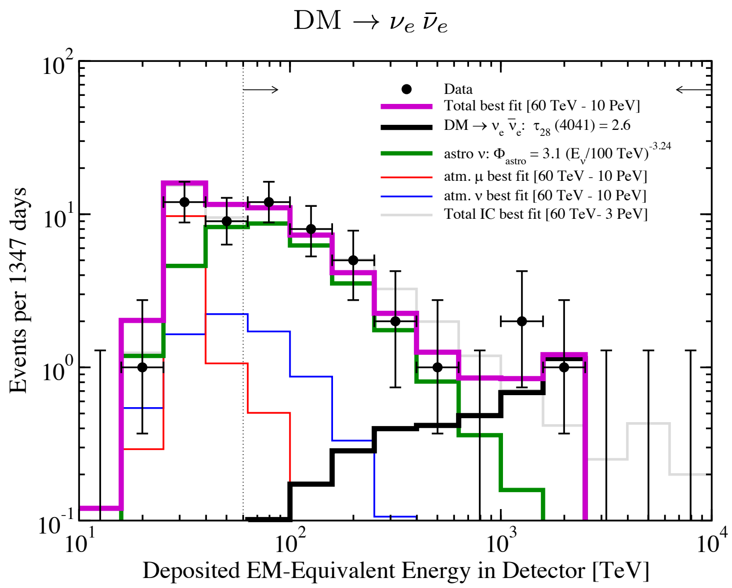
- An excees at these energies can be related to very heavy (PeV mass scale) decaying DM

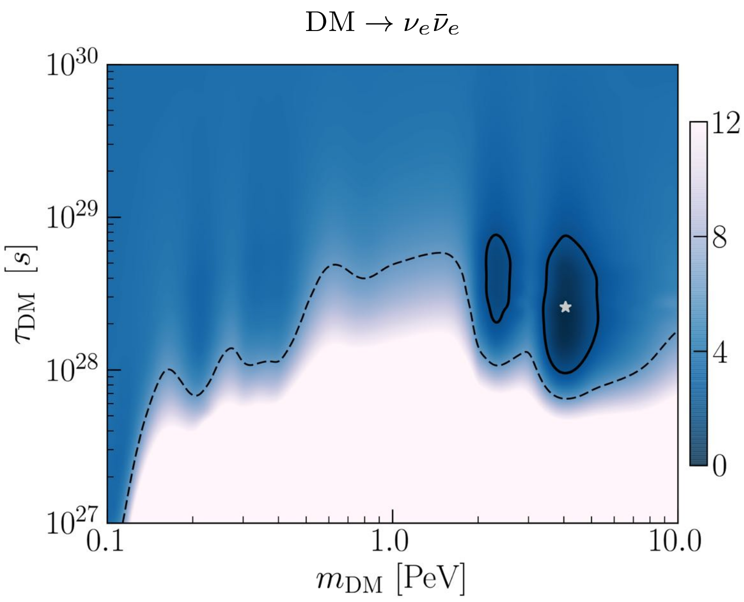
- Alternative to the standard WIMP scenario

PeV Neutrinos

IceCube 4 years

- 54 high-energy events (HESE: 20 TeV – 2 PeV)
- Expected atmospheric background: 20 events below 100 TeV



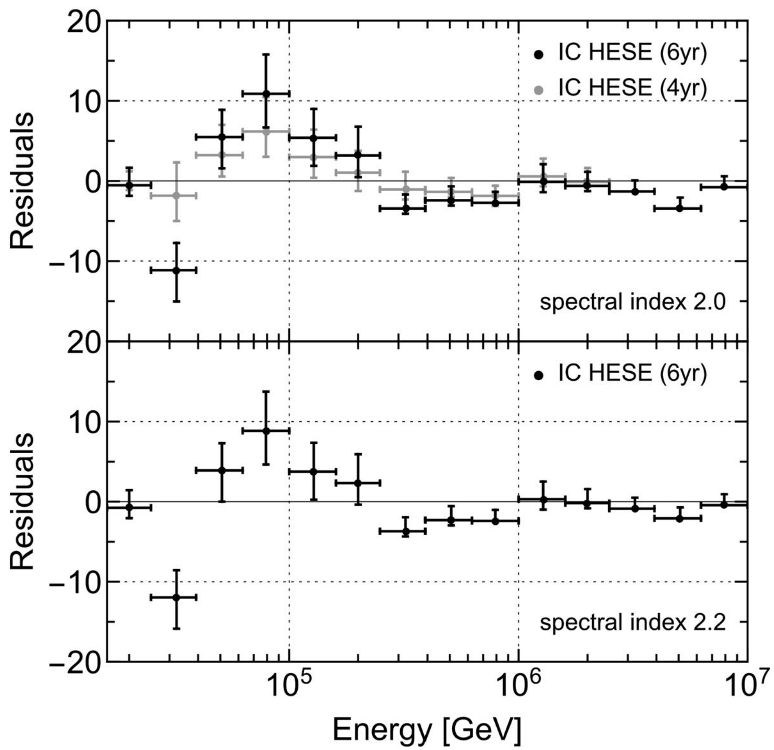


Bhattacharia et al, 1706.05746

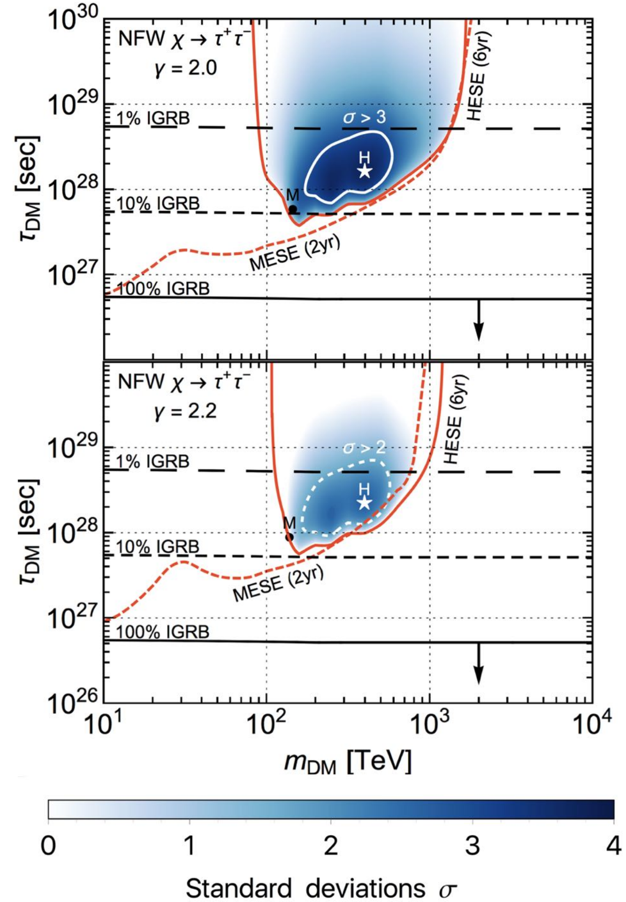
PeV Neutrinos

IceCube 6 years

- HESE interpretation with astro sources lead to a large spectra index, likely in tension with gamma rays and 6yrs muon neutrino data
- Adopting a spectra index in (2.0,2.2): 2.6sigma excess



Chianese et al, 1707.05241



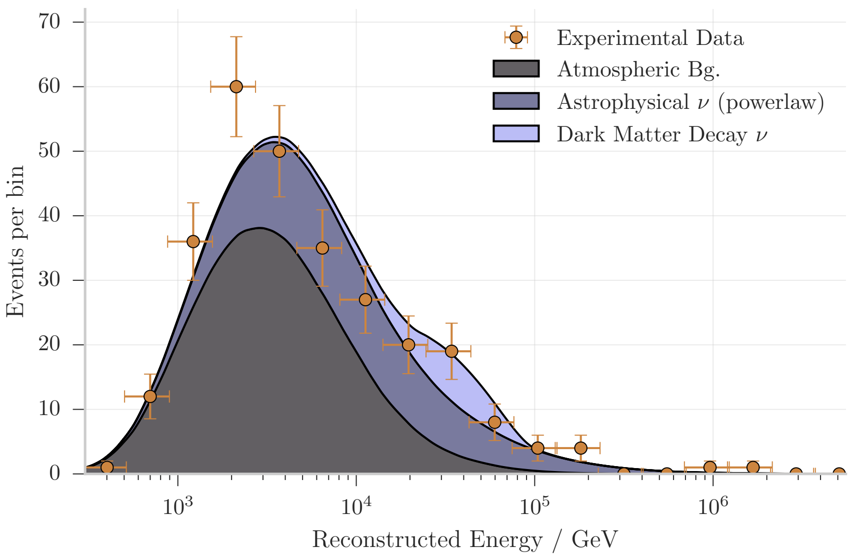
PeV Neutrinos

IceCube analysis combining:

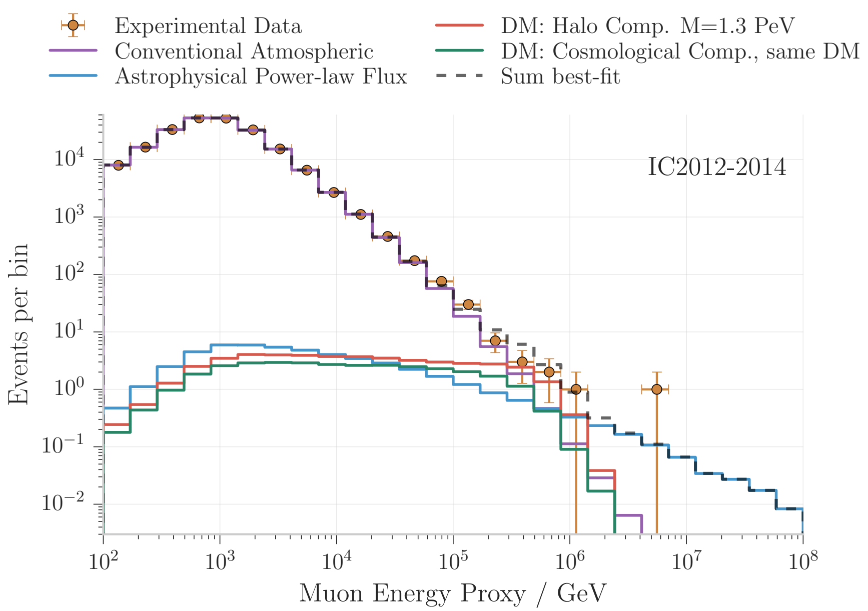
6 yrs muon neutrino tracks from North hemisphere

2 yrs cascade events from full sky

No preference for DM signal over backgrounds



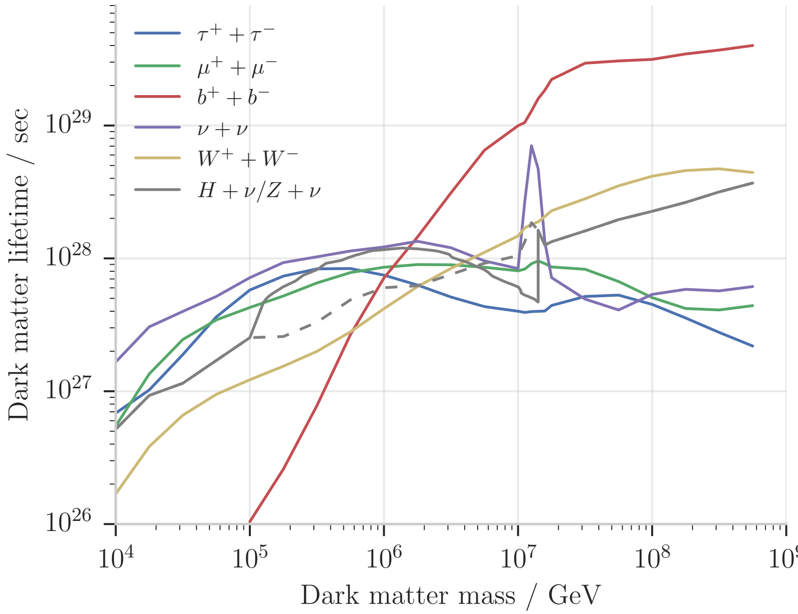
Cascade analysis

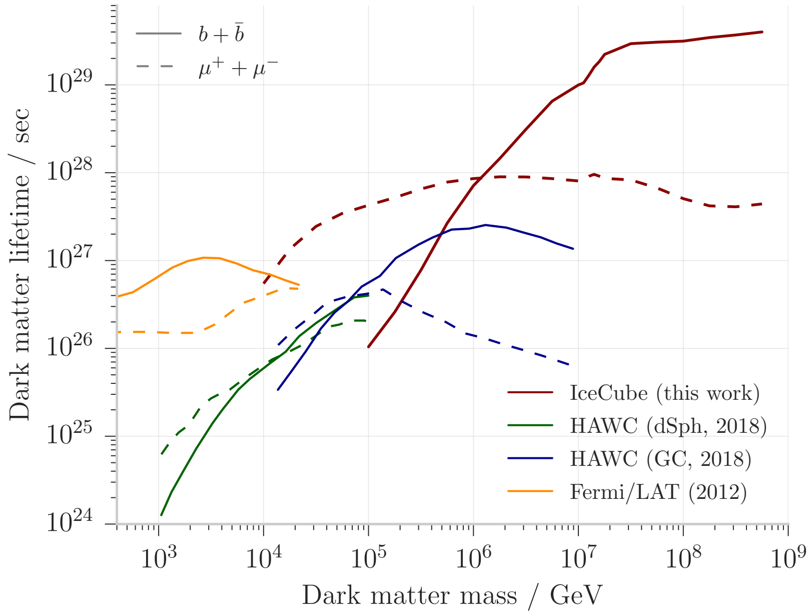


Track Analysis

Aartsen et al (IceCube Collab) 1804.03848

PeV Neutrinos





Aartsen et al (IceCube Collab), 1804.03848

PeV Neutrinos

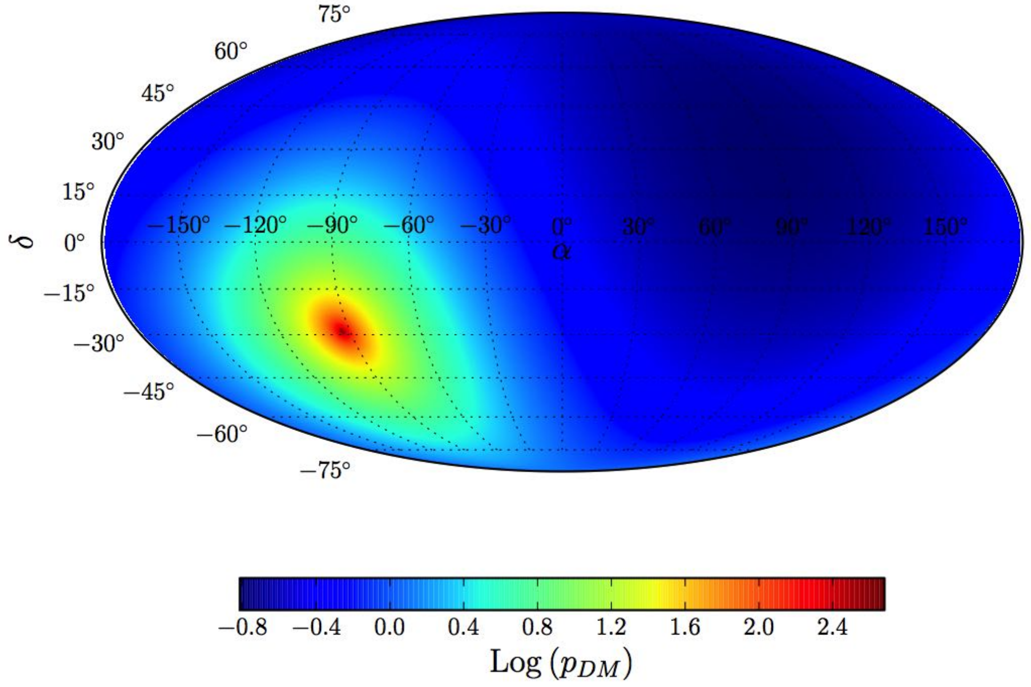
See also:

Feldstein, Kusenko, Matsumoto, Yanagida, 1303.7320
Esmaili, Serpico, 1308.1105
Ema, Jinno., Moroi, 1312.3501
Zavala et al, 1404.2932
Higaki,Kitano, Sato, 1405.0013
Rott, Kohri, Park, 1408.4575
Fong, Minakata, Panes, Zukanovich Funchal, 1411.5318
Dudas, Mambrini, Olive, 1412.3459
Murase, Laha, Ando, Ahlers, 1503.04663
Anchordoqui et al, 1506.08788
Boucenna et al, 1507.01000
Re Fiorentin, NF, Niro, 1606.04445
Hiroshima, Kitano, Kohri, Murase, 1705.04419
(...)

The PeV neutrino DM interpretation has connections with neutrino mass models, leptogenesis and cosmological reheating

Anisotropies

Due to the DM halo profile, a level of anisotropy in the arrival distribution is expected



Bai et al, 1311.5864

Anisotropies

Multipole decomposition

$$f(\theta,\phi) = \sum_{\ell} \sum_{m=-\ell}^{m=\ell} a_\ell^m \cdot Y_\ell^m(\theta,\phi)$$

Combination of the power and phase into a single coefficient

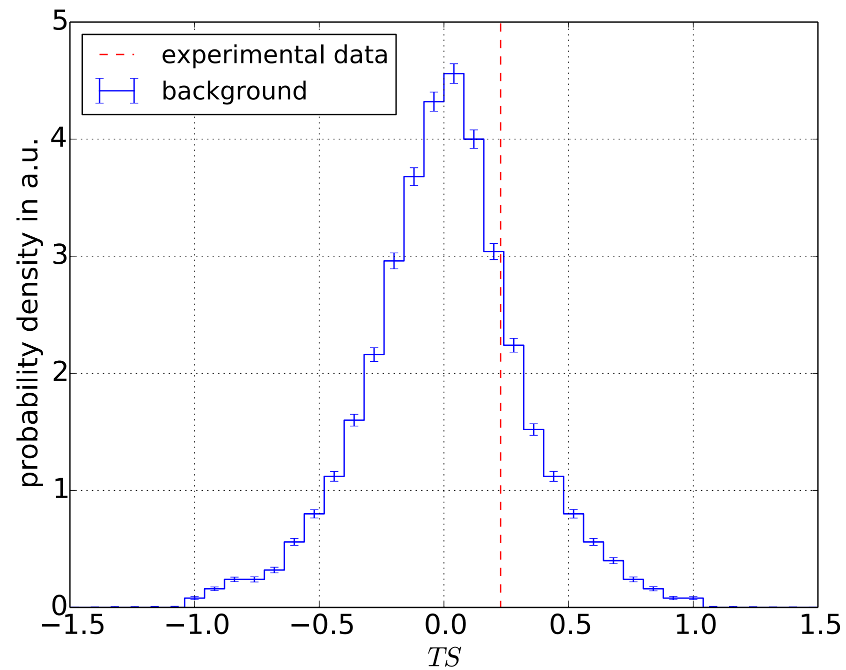
$$\mathcal{A}_\ell^m = \|a_\ell^m\| \cos\left(\arg\left(a_\ell^m\right) - \left\langle \arg\left(a_{\ell,\mathrm{sig}}^m\right)\right\rangle\right)$$

Test statistics

$$TS = \frac{1}{\sum w_\ell^m} \sum_{\ell=1}^{\ell_{\max}} \sum_{m=1}^{\ell} \mathrm{sig}\left(\mathcal{A}_\ell^m\right) w_\ell^m \left(\frac{\mathcal{A}_\ell^m - \left\langle \mathcal{A}_{\ell,\mathrm{bgd}}^m \right\rangle}{\sigma\left(\mathcal{A}_{\ell,\mathrm{bgd}}^m\right)}\right)^2$$

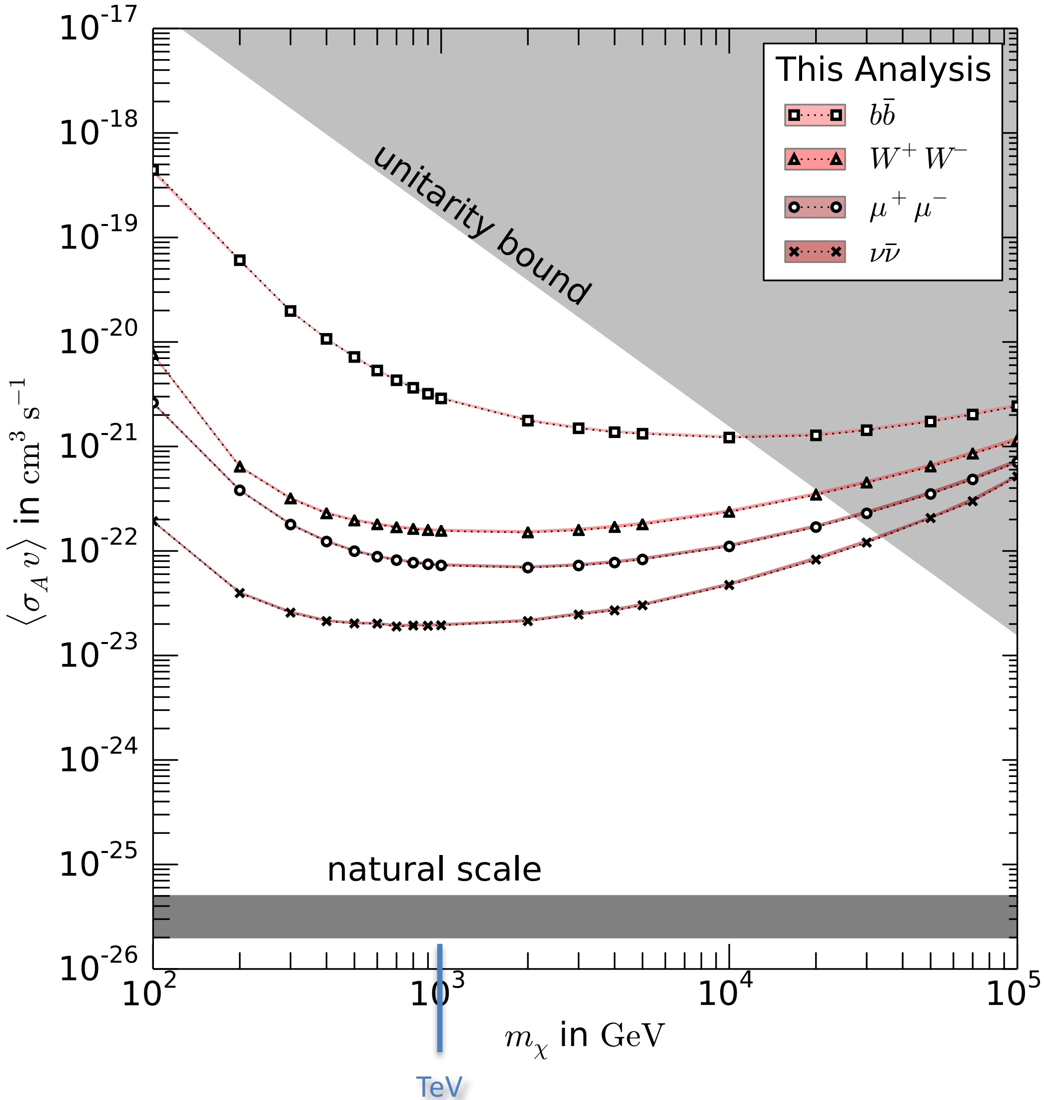
High purity sample from North hem.

Result compatible with null hyp.



Aartsen et al (IceCube Collab), 1406.6868

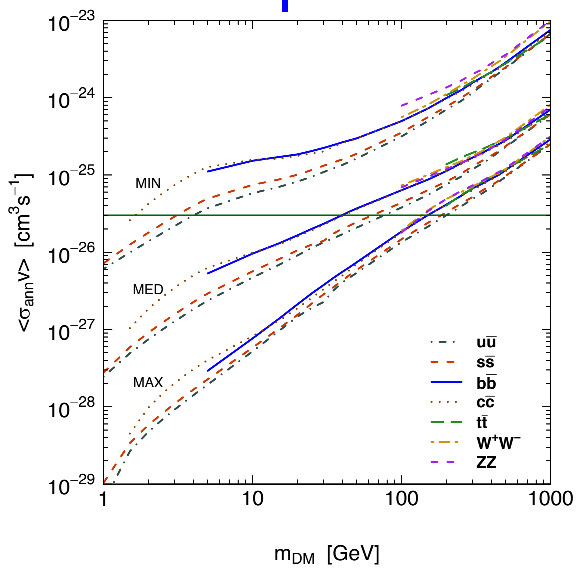
Anisotropies



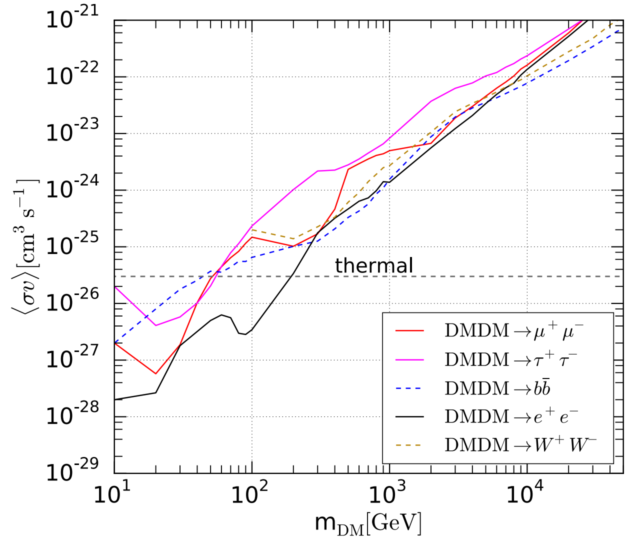
Aartsen et al (IceCube Collab), 1406.6868

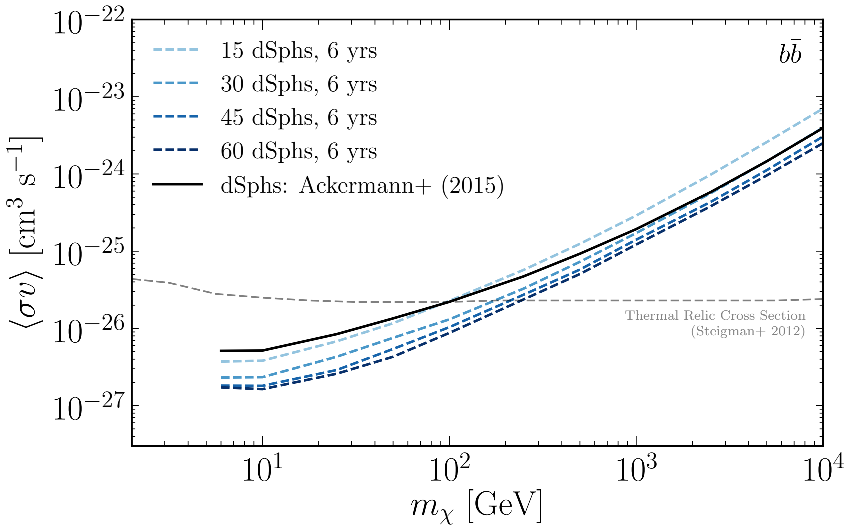
Link to Multimessenger

Antiprotons

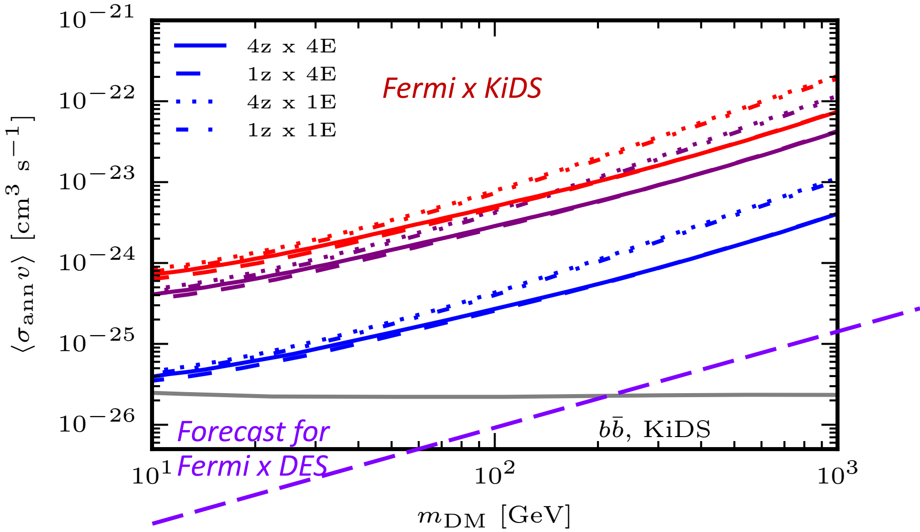


Positrons



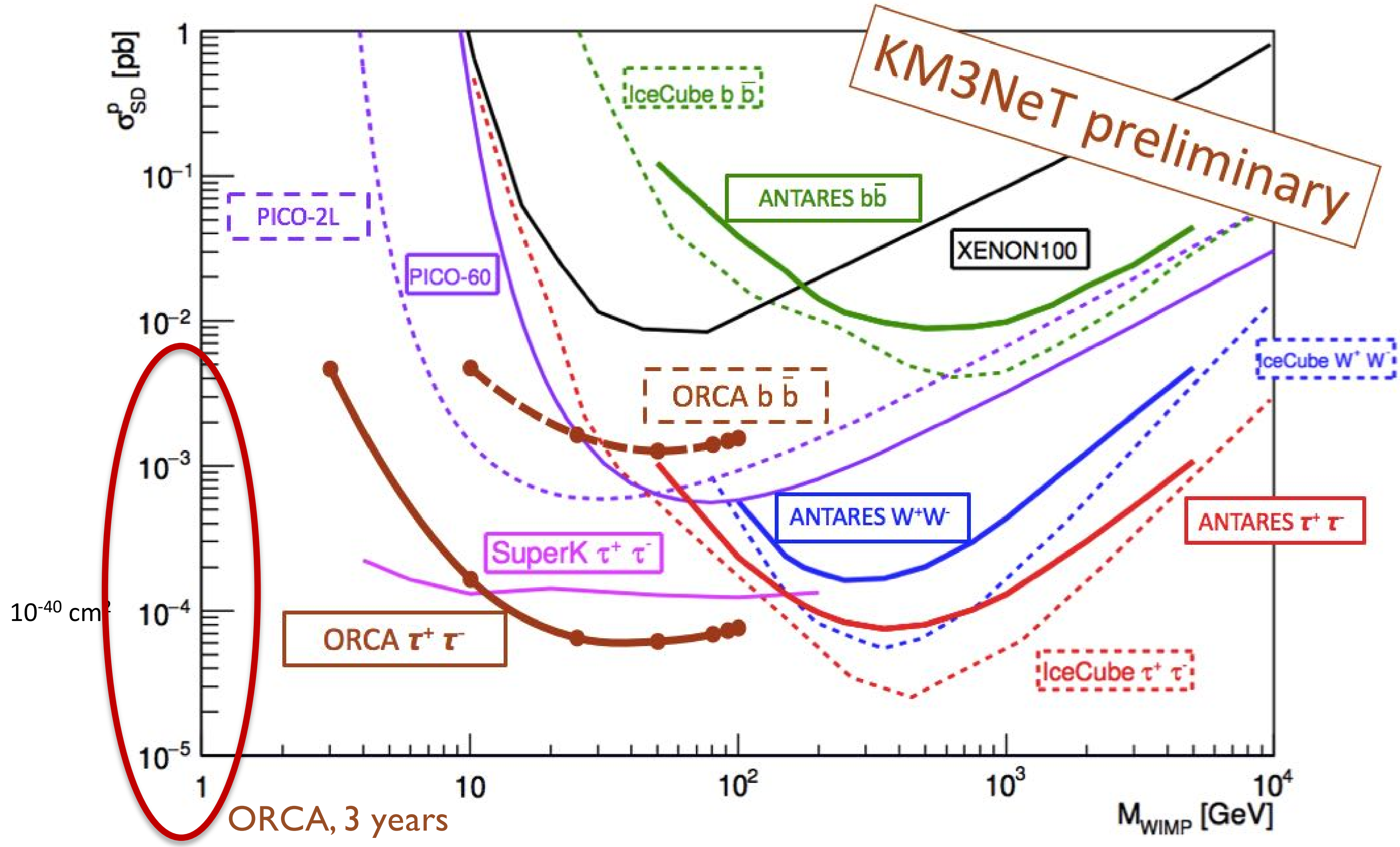


Gamma rays from dwarfs



Cross-correlations

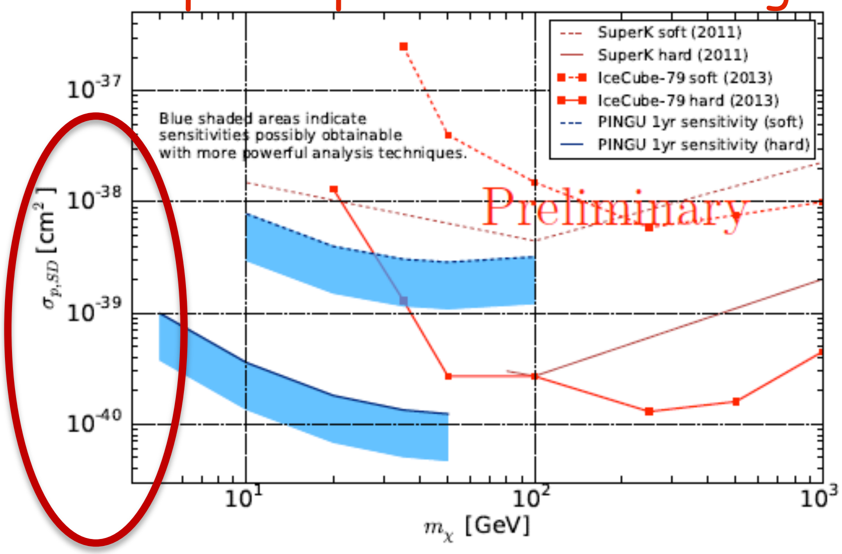
Future – KM3NeT



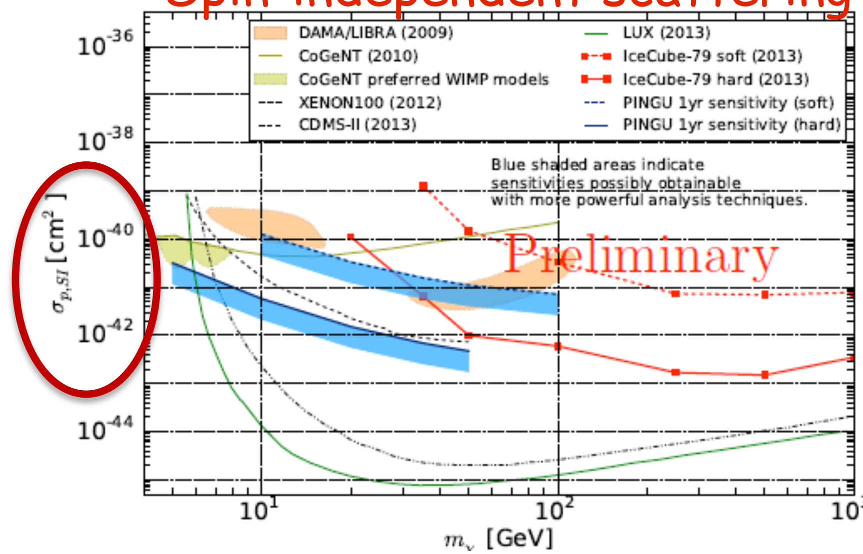
Kulikowskiy (Km3NeT Collab), Nuovo Cim 40 C (2017) 141

Future – IceCube/PINGU

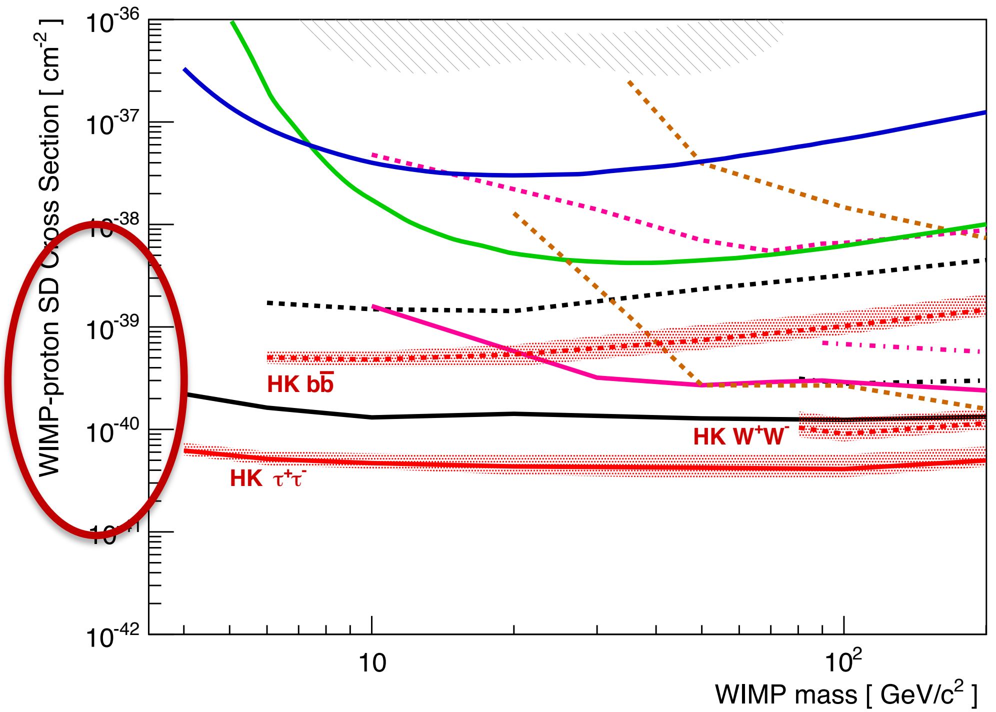
Spin-dependent scattering

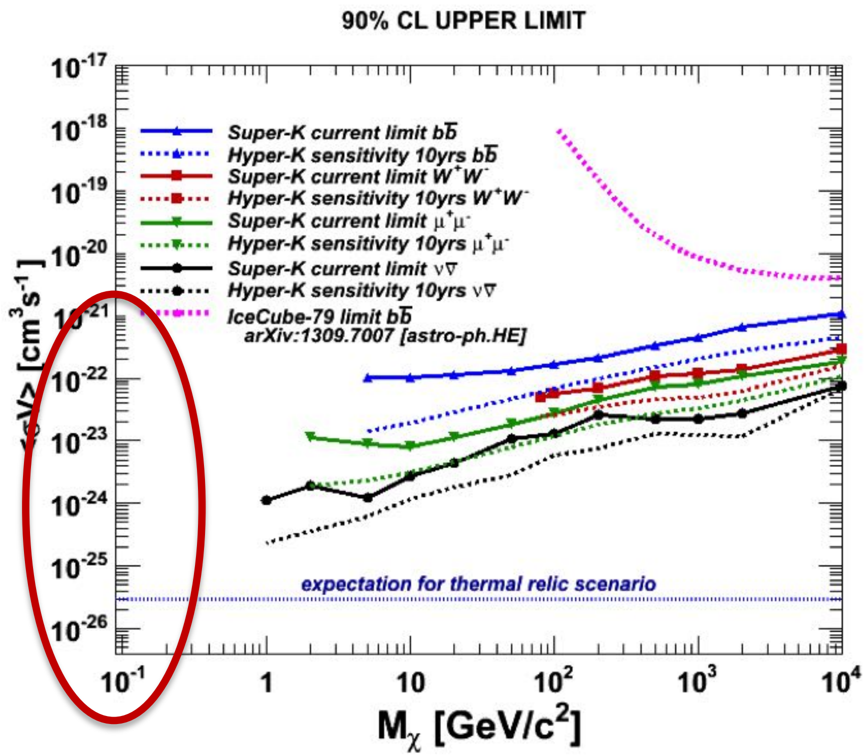


Spin-independent scattering



Future - HyperK





Sun – spin dependent

Galactic center

Baikal: see O. Souvorova's talk

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