The future of dark matter searches at neutrino telescopes

International Conference on High Energy
Particle & Astroparticle Physics (ICHEPAP2023)
Saha Institute of Nuclear Physics

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13th December 2023

The DM candidates

Particle (or particle-like)

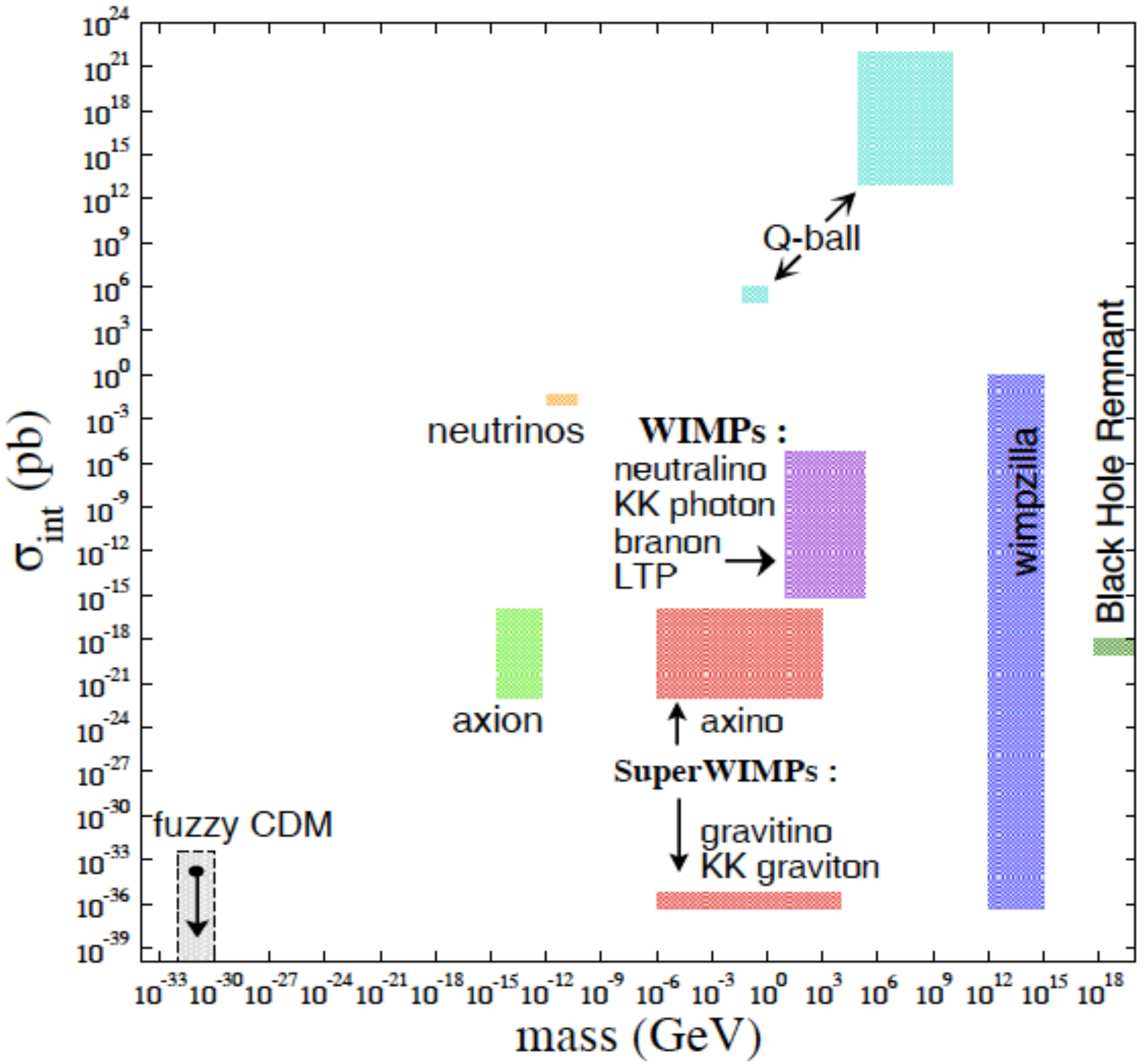
Very feebly interacting with SM particles

Stable (~ age of the universe)

(Mostly) Cold

Unknowns:

- Mass
- Spin
- Interaction cross section

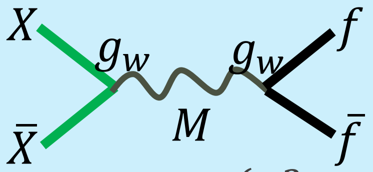


Weakly Interacting Massive Particles

Dark Matter as a thermal relic of the Early universe.

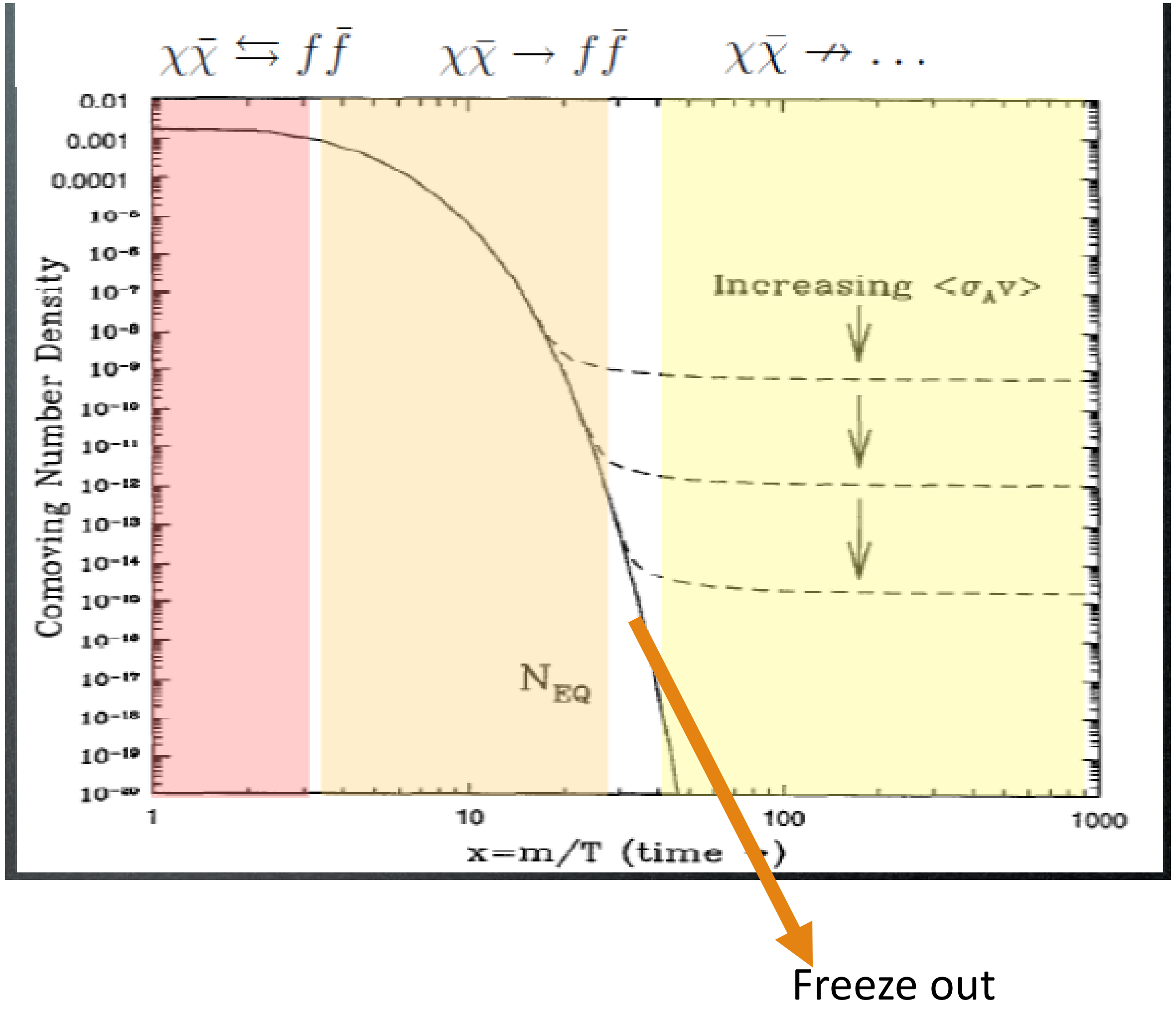
- Boltzmann equation of the early universe
  - $$\frac{dn_X}{dt} + 3Hn_X = -\langle\sigma_{ann}v\rangle[n_X^2 - n_{eq\,X}^2]$$
- Relic $\Omega_{DM} \sim 0.27$

  For $\langle\sigma_{ann}v\rangle = 3\,.\,10^{-26}\,cm^3/s$



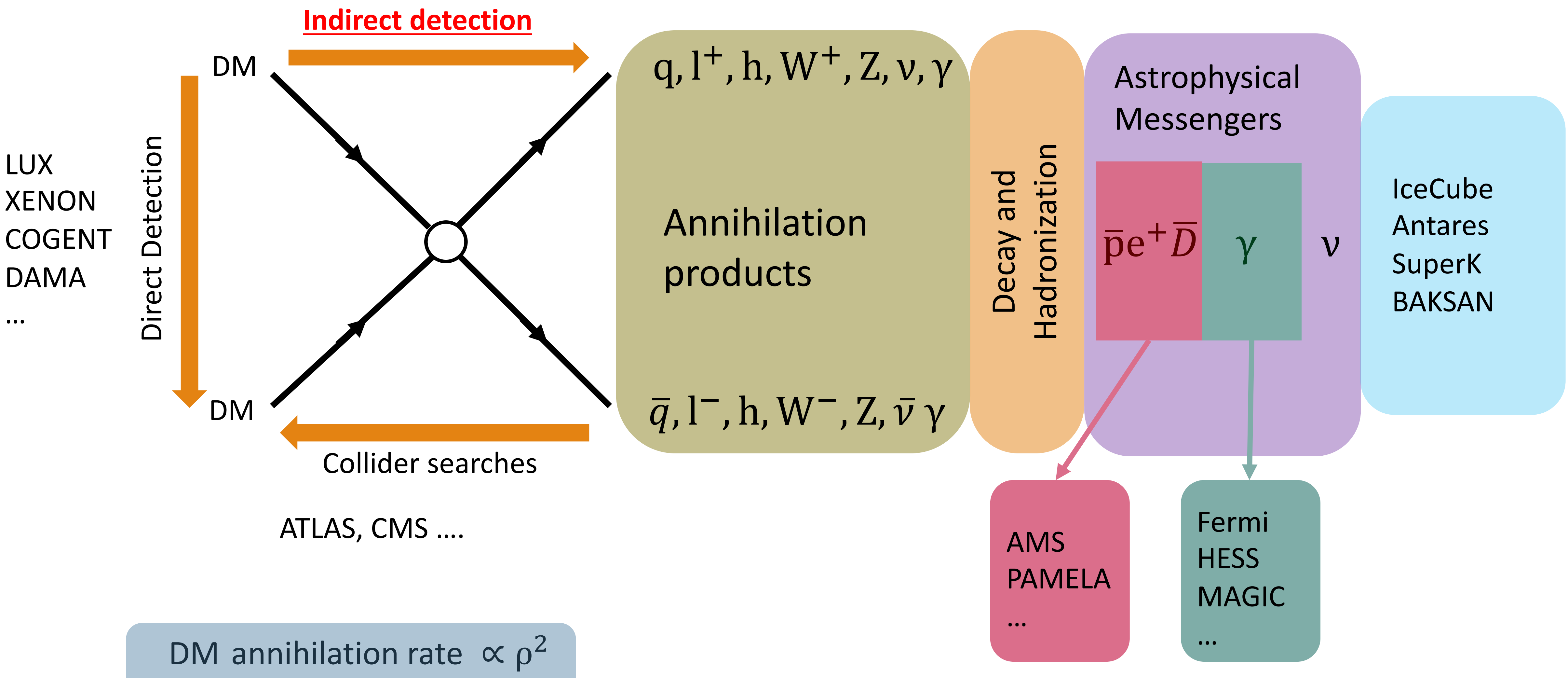
$$\langle\sigma_{ann}v\rangle \approx \frac{(g_W^2/4\pi)^2}{M^2} \approx 3\,.\,10^{-26}\,cm^3/s$$

WIMP Miracle



- Stable WIMPS present in various theories
  - Neutralino in SUSY theories
  - Kaluza Klein photons.

Dark Matter Detection



DM annihilation rate $\propto \rho^2$
decay rate $\propto \rho$

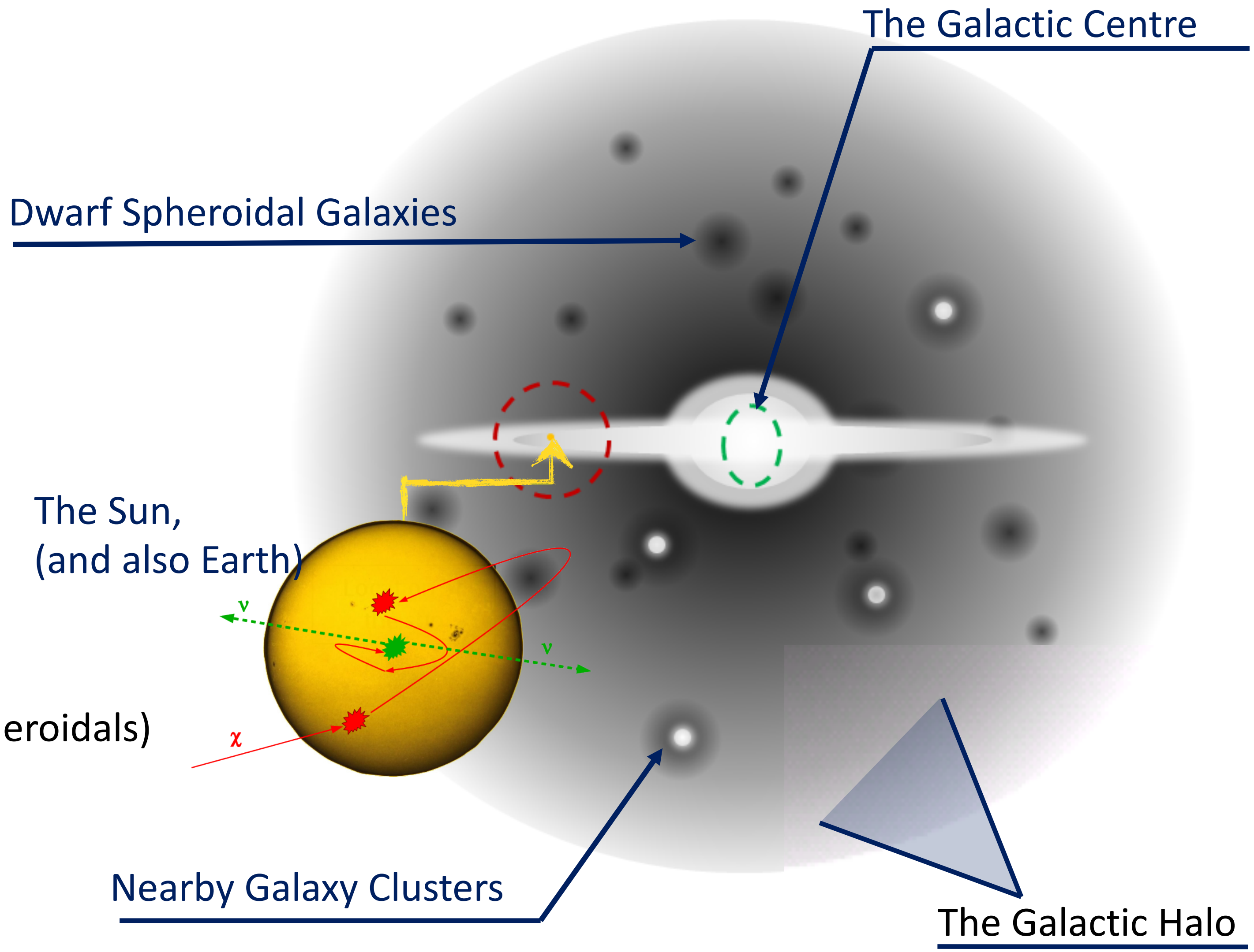
Indirect Searches – The Targets

Well understood/low astrophysical backgrounds

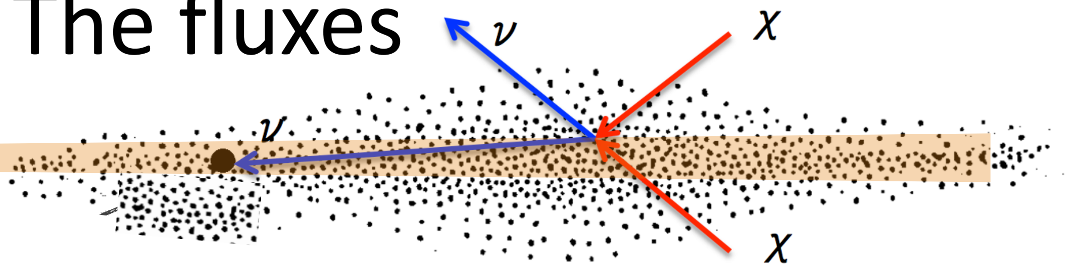
Also regions of high dark matter Density

Search for:

- Point-like excess of neutrinos (the Sun)
- Extended emission (Galactic Centre)
- Multipole expansion (Galactic Halo)
- Stacking searches (Galaxy clusters and Dwarf Spheroidals)
- Zenith dependent upgoing excess (Earth)



Indirect Searches : The fluxes



$$\frac{d\Phi_\nu}{dE}(\Omega) = \frac{dN_\nu}{dE} \int \int_\Omega \frac{1}{4\pi} \frac{\rho^2}{{m_\chi}^2} dl d\Omega \frac{\langle \sigma_{ann} v \rangle}{2}$$

Neutrino Flux at the detector, within a solid angle Ω depends on:

- The neutrino yield per annihilation $\frac{dN_\nu}{dE}$ - (from particle physics)
- The annihilation cross section of DM, averaged over its velocity distribution $\langle \sigma_{ann} v \rangle$ - (to be measured)
- The line integral of the DM density ρ^2 along the line of sight, J, - (from astrophysics)

$$J = \iint \rho^2 (l, \Omega) dl d\Omega$$

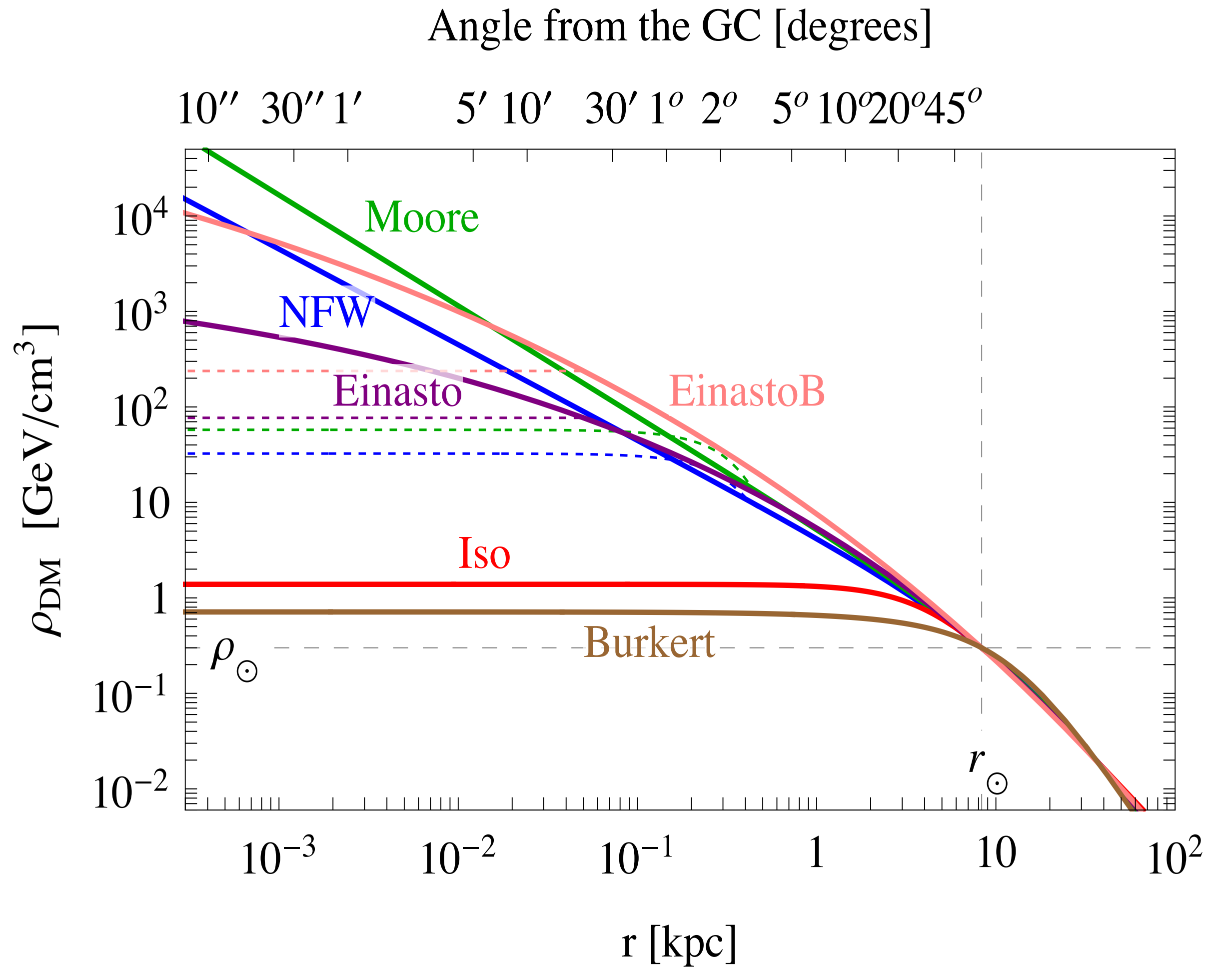
For annihilating DM

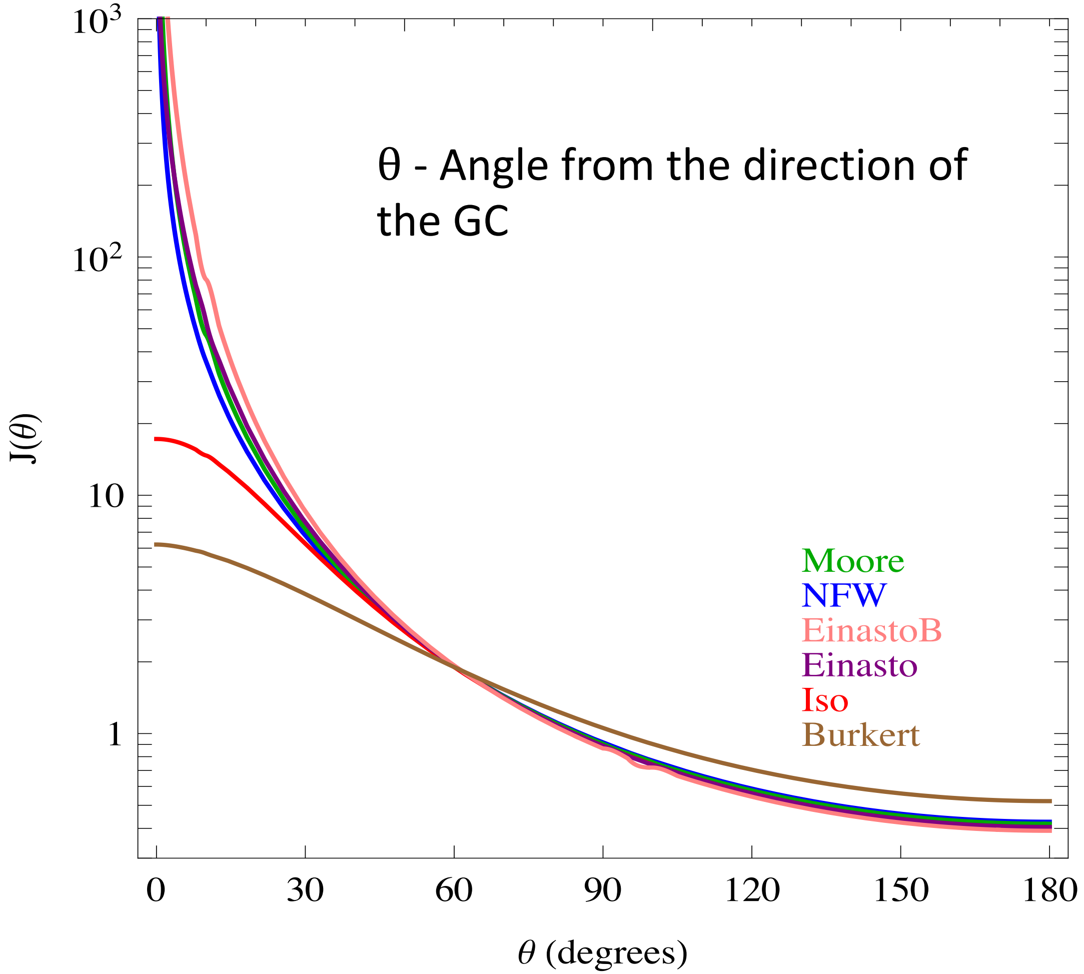
In practice also account for neutrino oscillations over long baselines – flux predictions are made using MC codes such as WimpSim, PPPC4DMnu -

$$D = \iint \rho (l, \Omega) dl d\Omega$$

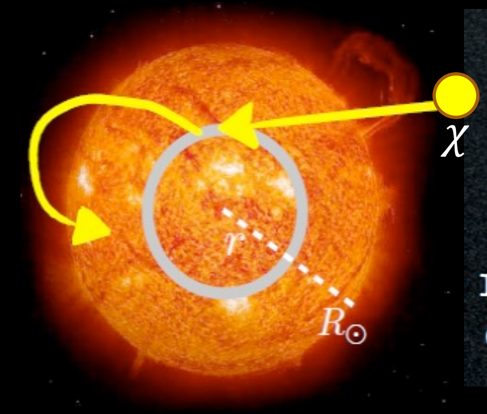
For decaying DM

DM distributions and J factors





DM Capture and Annihilation in the Sun



$$\Gamma_{\text{capt}} = \frac{\rho_{\text{DM}}}{M_{\text{DM}}} \sum_i \sigma_i \int_0^{R_\odot} dr\; 4\pi r^2\, n_i(r) \int_0^\infty dv\; 4\pi v^2 f_\odot(v)\, \frac{v^2 + v_{\odot\text{esc}}^2}{v}\, \wp_i(v, v_{\odot\text{esc}})$$

DM number density

Scattering Cross Section
$\sigma_{SD} \propto J(J+1)$
$\sigma_{SI} \propto A^2$

Number density of element i -> Solar Model

velocity distribution (in solar frame, without Sun's gravity)

effect of solar gravity

Capture

Equilibrium → $\Gamma_A^{equi} = \frac{1}{2} C_c$

Annihilation

Spin Dependent scattering

- Only the hydrogen in the Sun contributes significantly.
- Lower event rates in direct detection experiments
- More interesting for IceCube

Spin Independent scattering

- Heavier nuclei contribute more due to $\propto A^2$ enhancement.
- Better sensitivity using direct detection experiments such as LUX, XENON etc

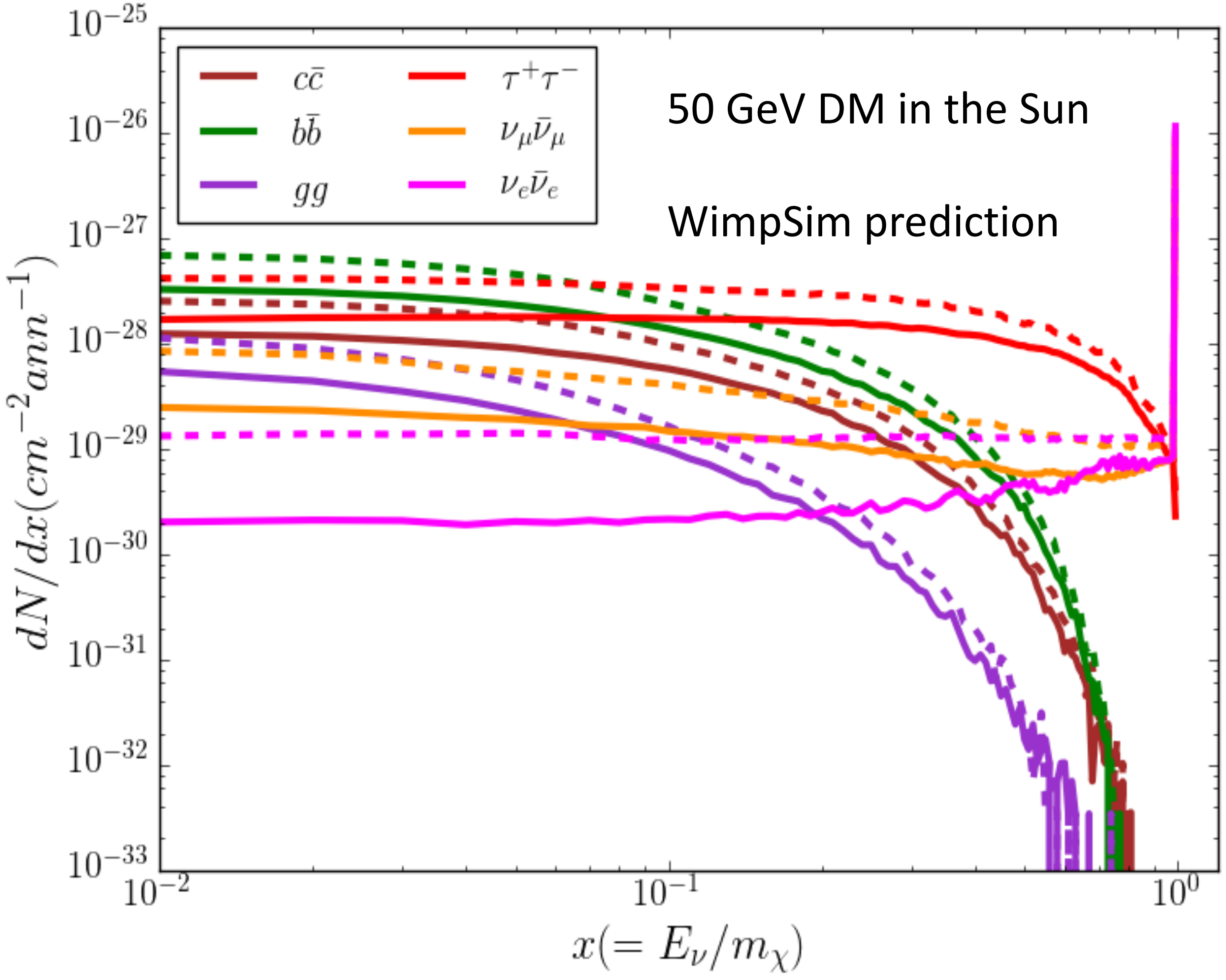
The secondary annihilation products can interact in the dense baryonic environment inside the Sun

Neutrinos are the only messengers that can get out

GeV neutrinos from the Sun- Smoking gun for DM

Sun opaque to neutrinos above ~1 TeV (Exercise)

Neutrino fluxes from DM

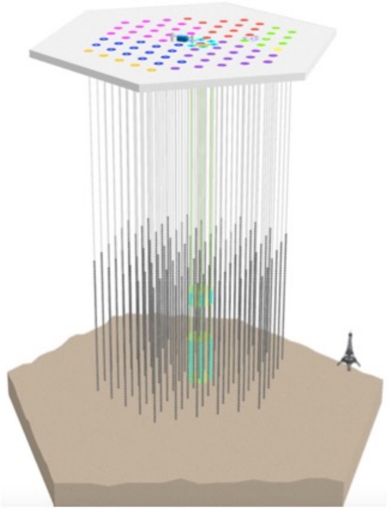


- 'Hard' channel : $\tau^+\tau^-$, W^+W^-,$\nu\bar{\nu}$
  - Produces many neutrinos at energies close to DM mass.
- 'Soft' channel: gg, $b\bar{b}$
  - Produces neutrinos at lower energies

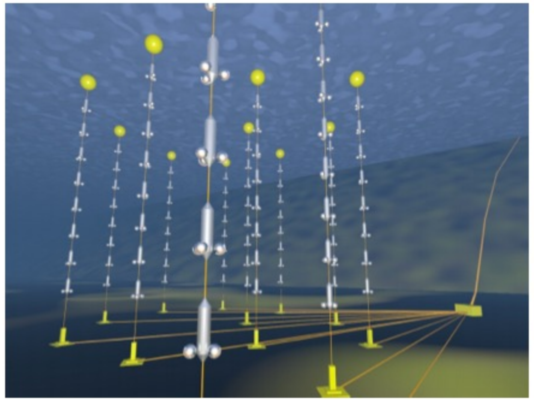
$\nu - nucleon$ cross sections (and hence effective areas of the detectors) also increase with energy, compounding the effect

Indirect Searches with ν - The instruments

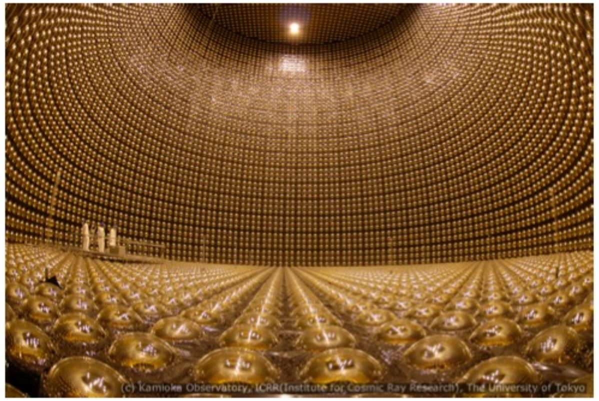
IceCube/DeepCore



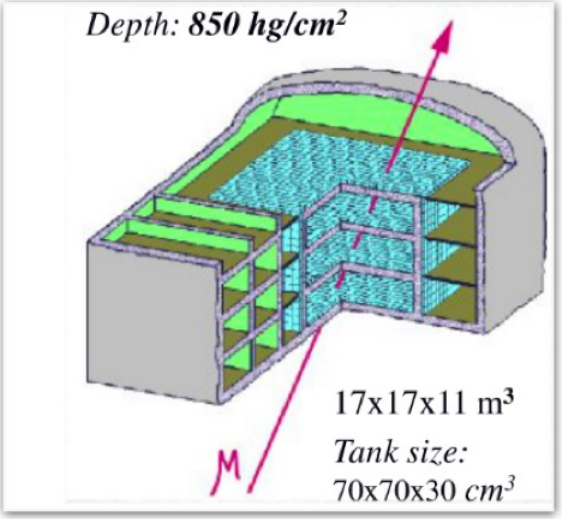
ANTARES



Super-K



Baksan



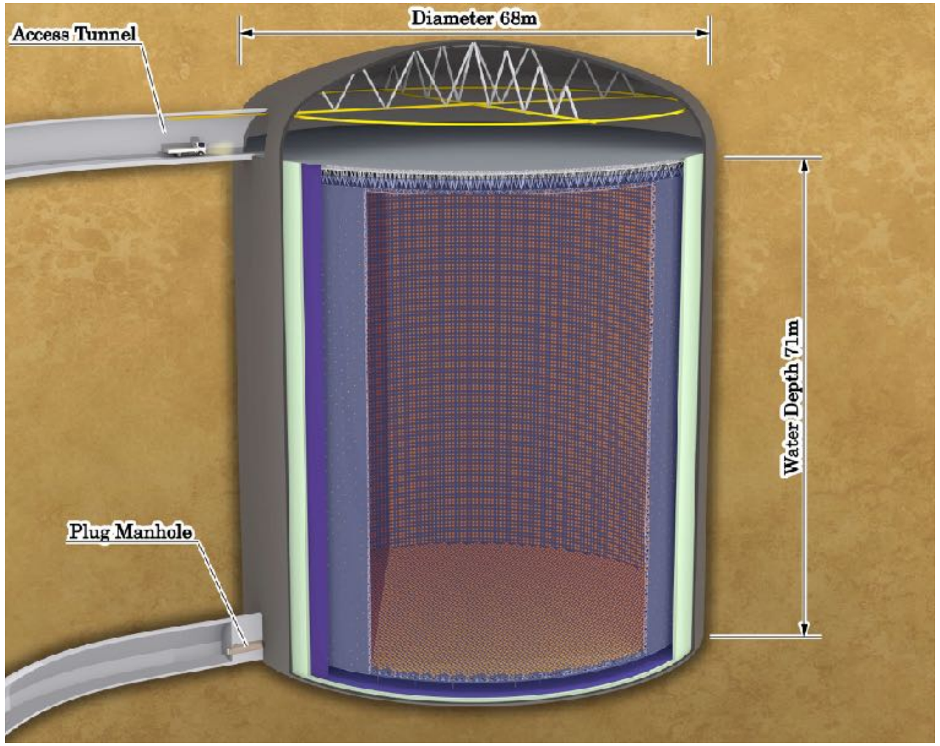
	E_ν-range (GeV)	Instrumented volume (ton)	$\overline{\Theta}$ (°) at E_ν 25 / 100 / 1000 GeV
IceCube	$\gtrsim 10^*$	~1 Gton	13 / 3.2 / 1.3
ANTARES	$\gtrsim 10$	~20 Mton	6 / 3.5 / 1.6
Super-K	$\gtrsim 0.1$	~50 kton	1-1.4‡
Baksan	$\gtrsim 1$‡	~3 kton	1.5‡ (tracks > 7 m)

‡ Values are given at muon level (E_μ); $\overline{\Theta}$ dominated by kinematic scattering angle.

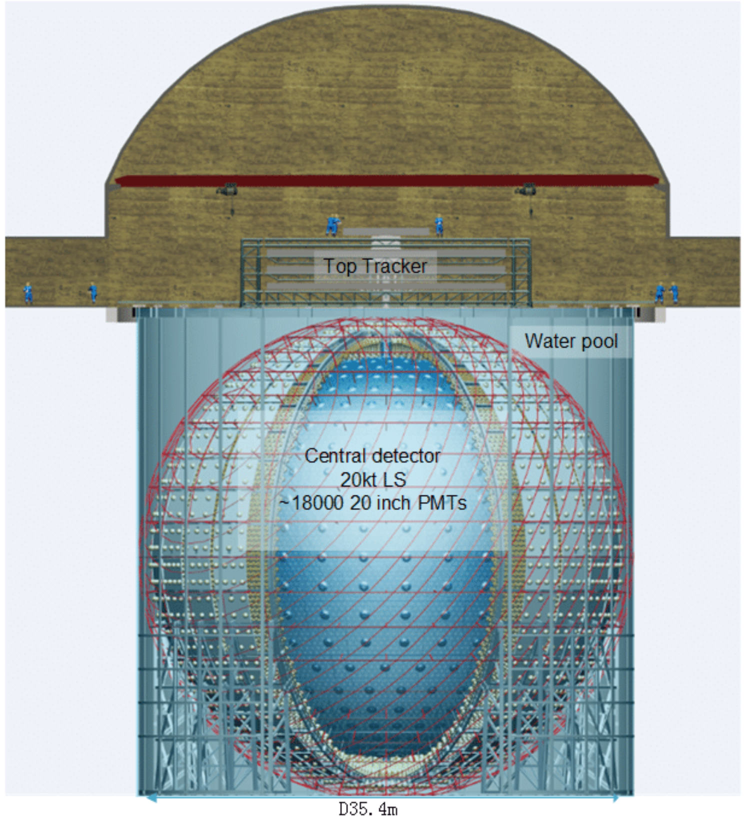
Future instruments

Hyper-Kamiokande detector in Japan;
total detector mass = 258 kton (currently under construction)
water Cherenkov detector

JUNO detector in China;
total detector mass = 20 kton (expected to take data from 2024)
liquid scintillator detector arXiv: 2103.11939

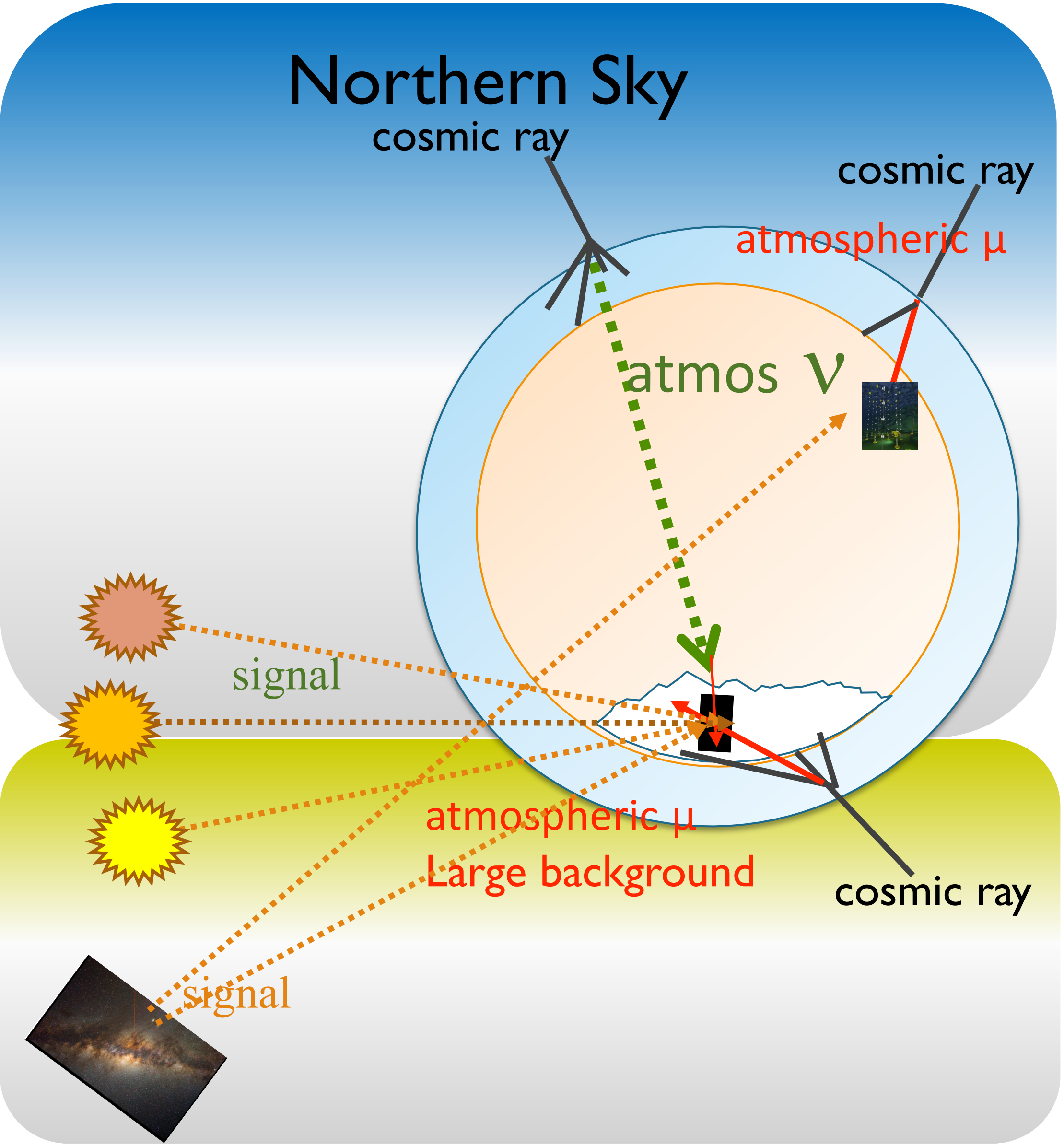


Hyper-Kamiokande website

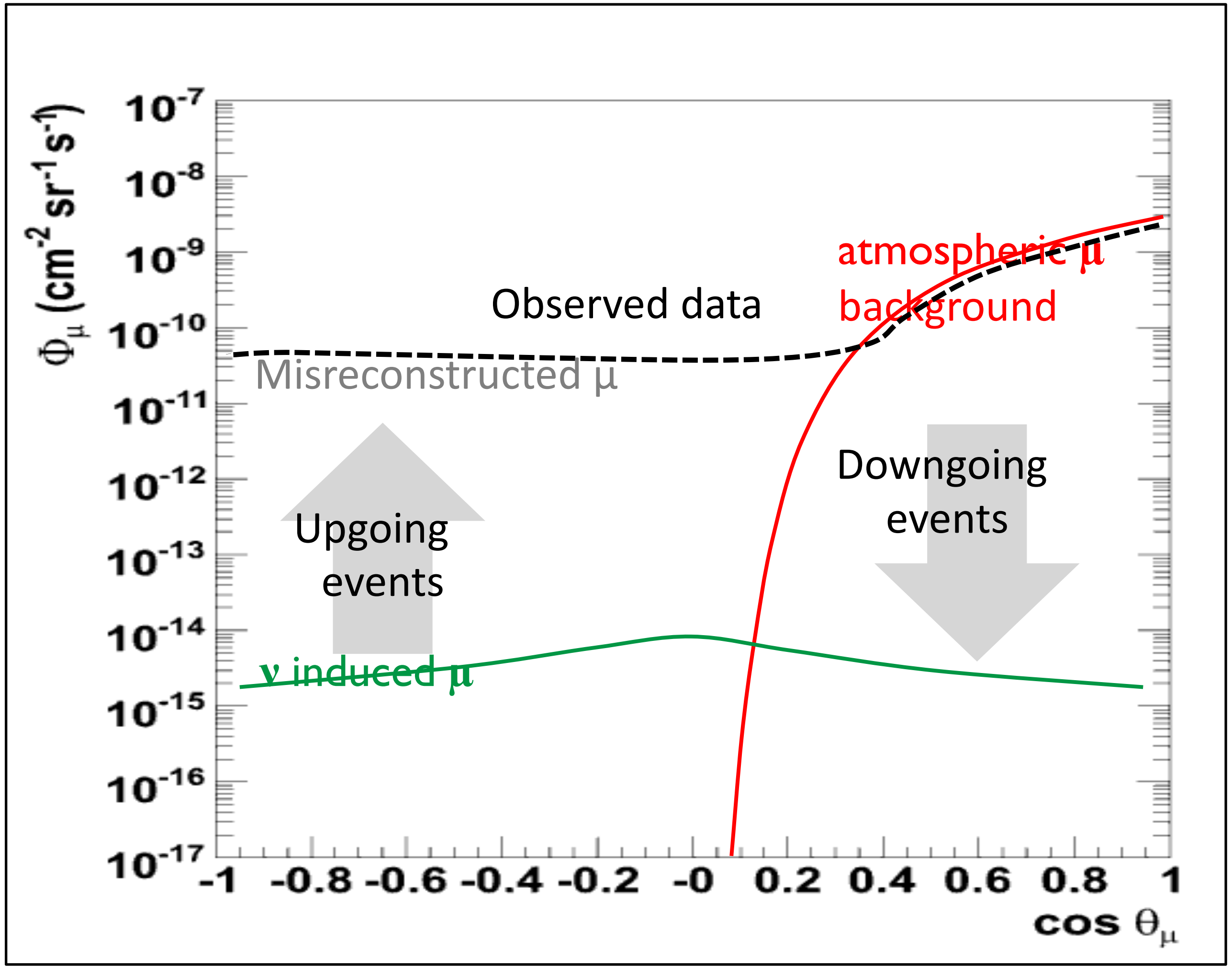


Other planned neutrino detectors (DUNE, KM3NeT, IceCube Gen-2, and others) are also important

The backgrounds

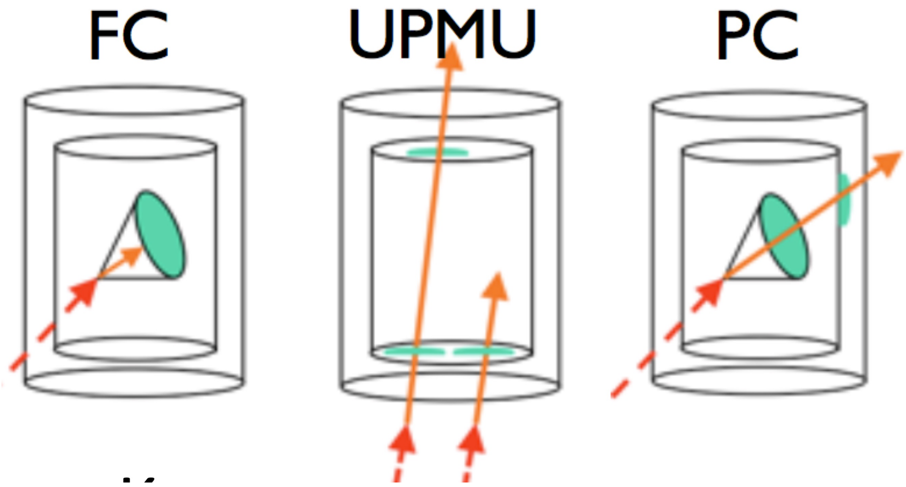


Example : IceCube



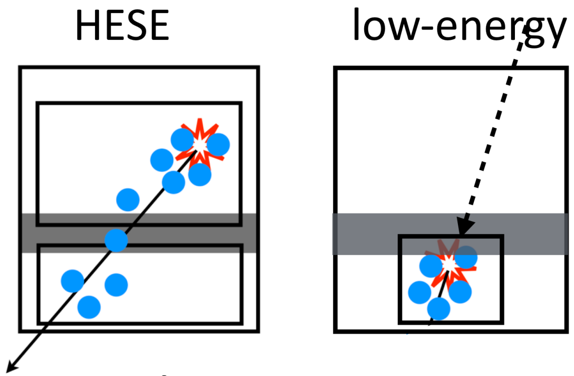
Indirect Searches with νs- Improvements in Analysis methods

A few years back
- Count number of events from the direction of the target
- Compare against off source



Better event selections improved acceptance of ~3 GeV neutrinos by factor of ~50

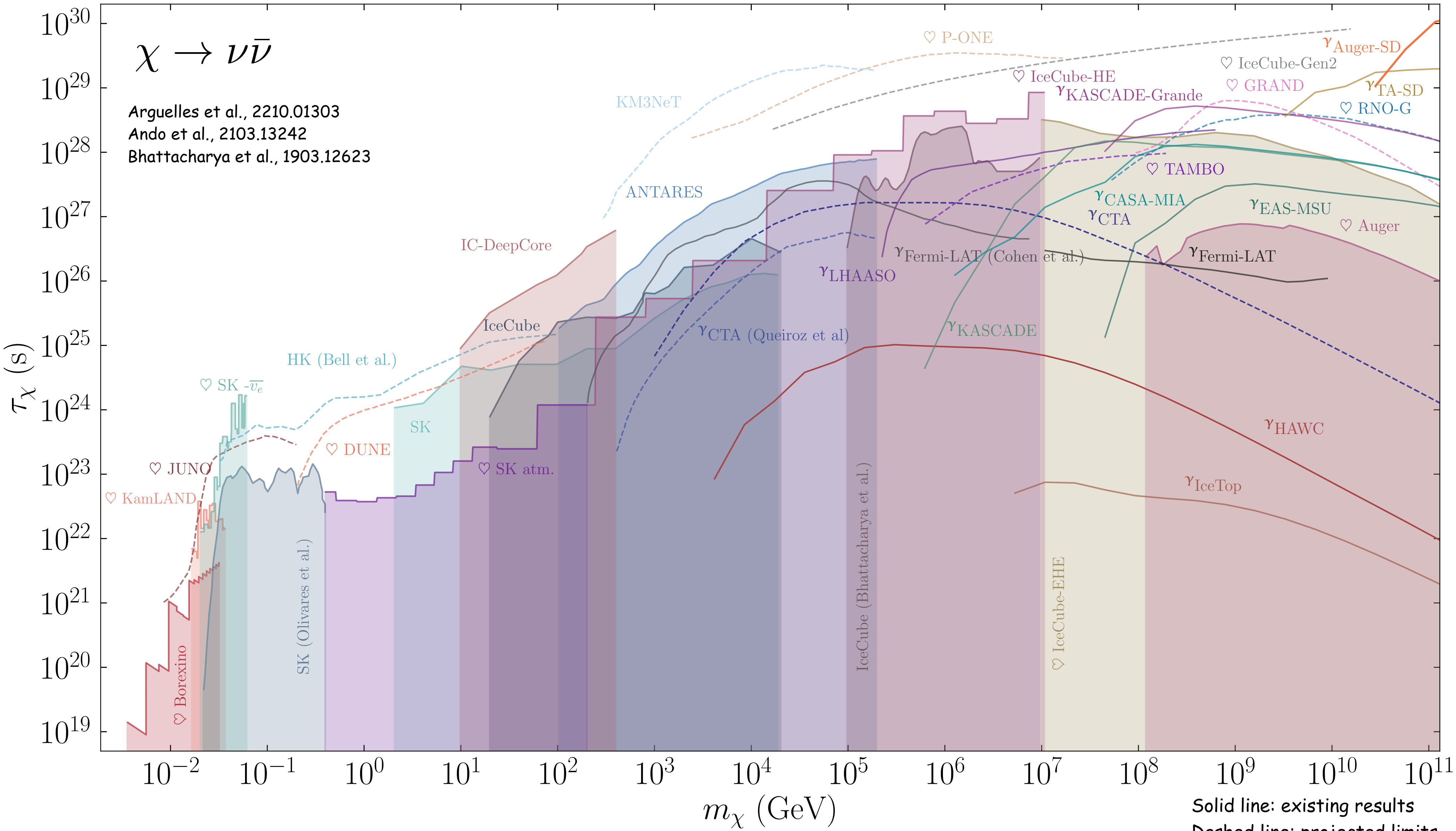
Now:
- Different event topology selections for different energies
- Use vetos to reject muon background better
- Energy proxies to resolve spectral features
- Use both ν_μ and ν_e signal events
- Unbinned methods
- Better handle on systematics.



IceCube/DeepCore:
- Veto techniques make Galactic Centre searches possible

In the last ~10 years, sensitivities have improved by more than order of magnitude in most searches

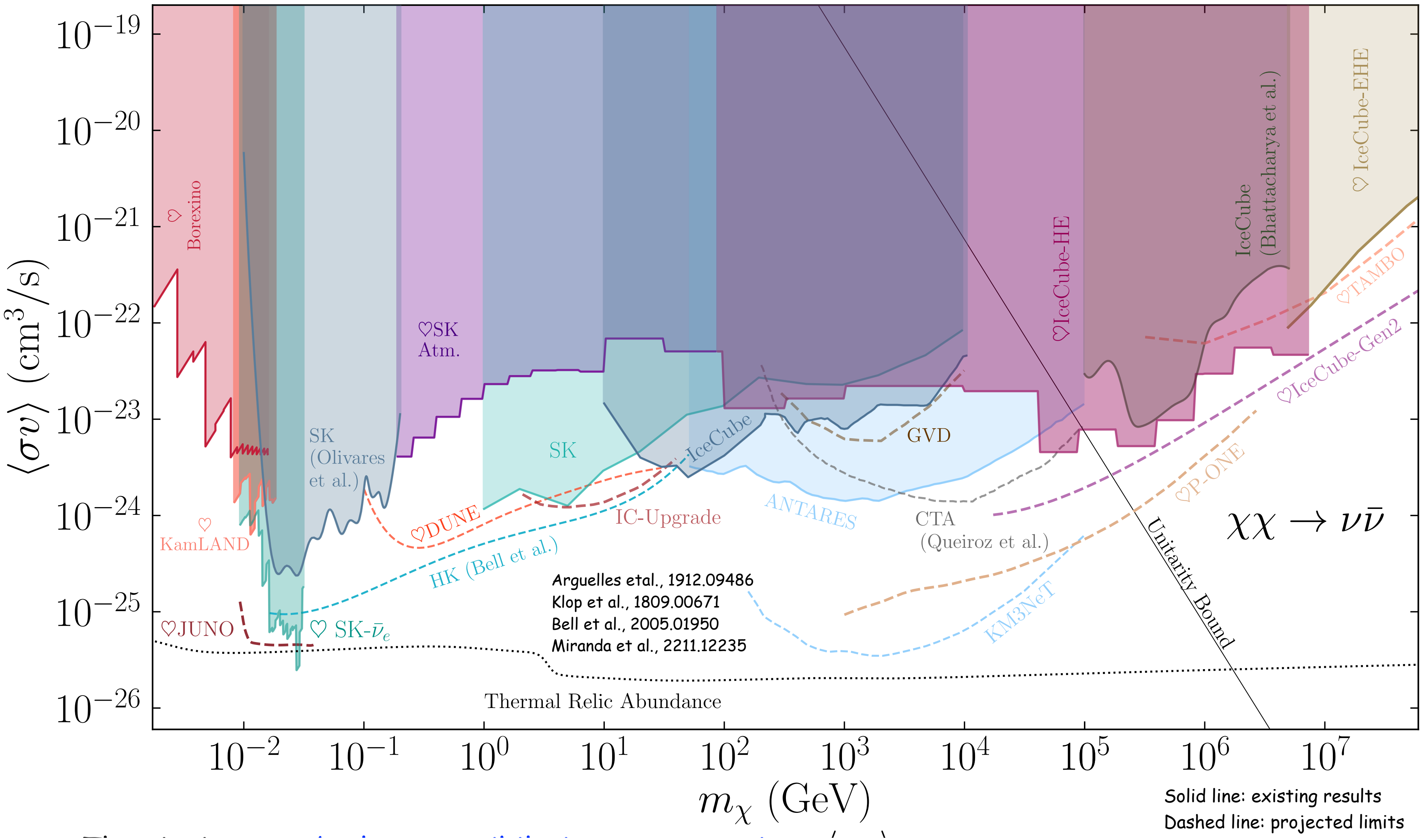
No signal yet.



Solid line: existing results

Dashed line: projected limits

Constraints on $\langle\sigma_{ann}v\rangle$



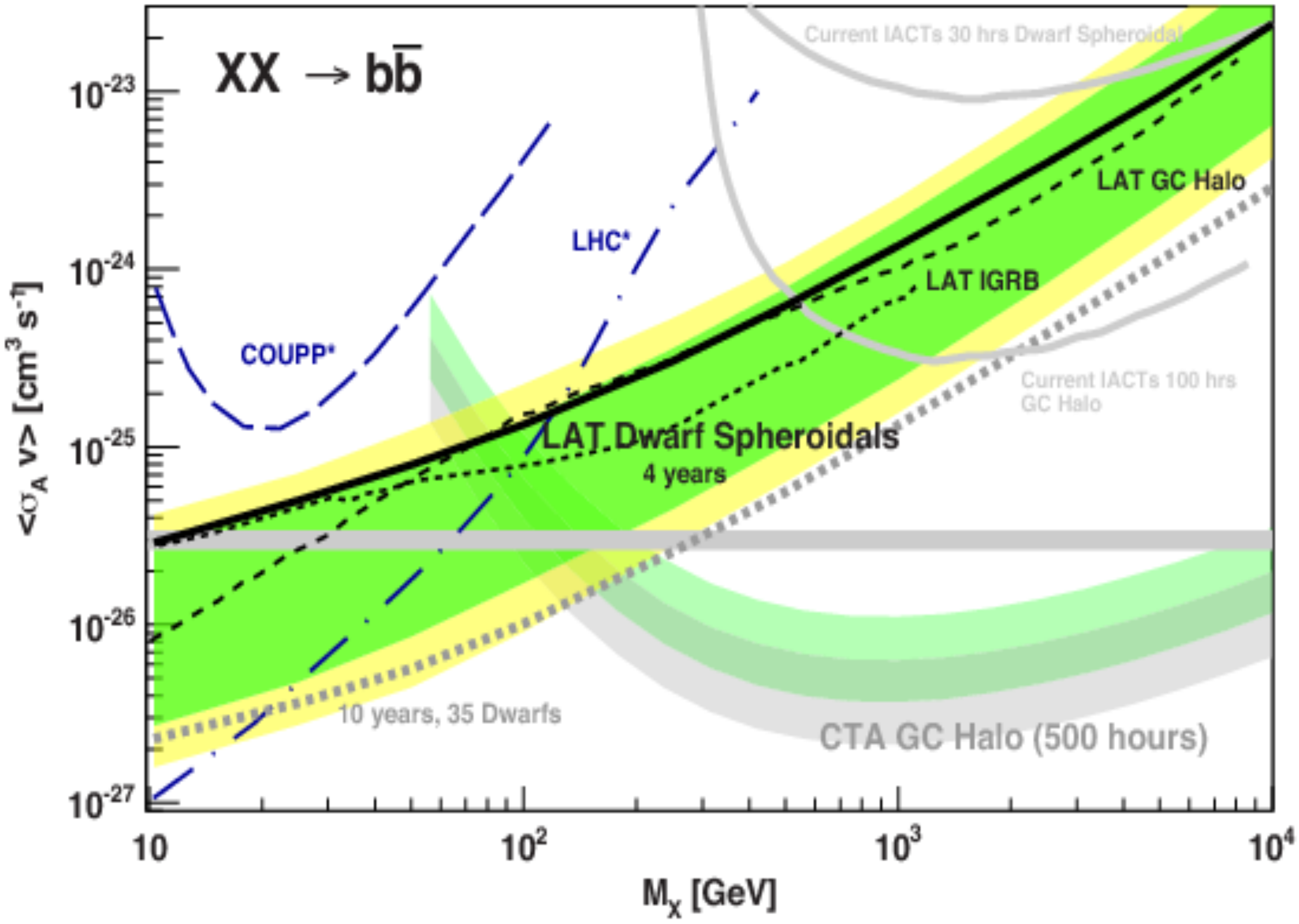
Solid line: existing results
Dashed line: projected limits

Constraints on $\langle\sigma_{ann} v\rangle$

In general, constraints on $\langle\sigma_{ann} v\rangle$ from γ ray searches are more powerful than the ν constraints.

A comparable number of ν and γ are produced per DM annihilation but γ-rays are much easier to detect.

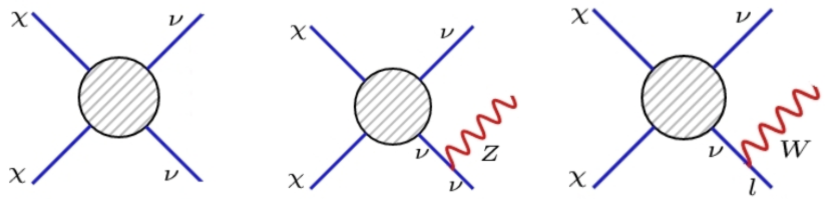
ν searches have lower astrophysical uncertainties and foregrounds



Monochromatic Neutrino Lines

$\chi\chi \rightarrow \nu\nu$, a neutrino line at the DM mass.

However, γ-rays are also produced, through Ewk FSR



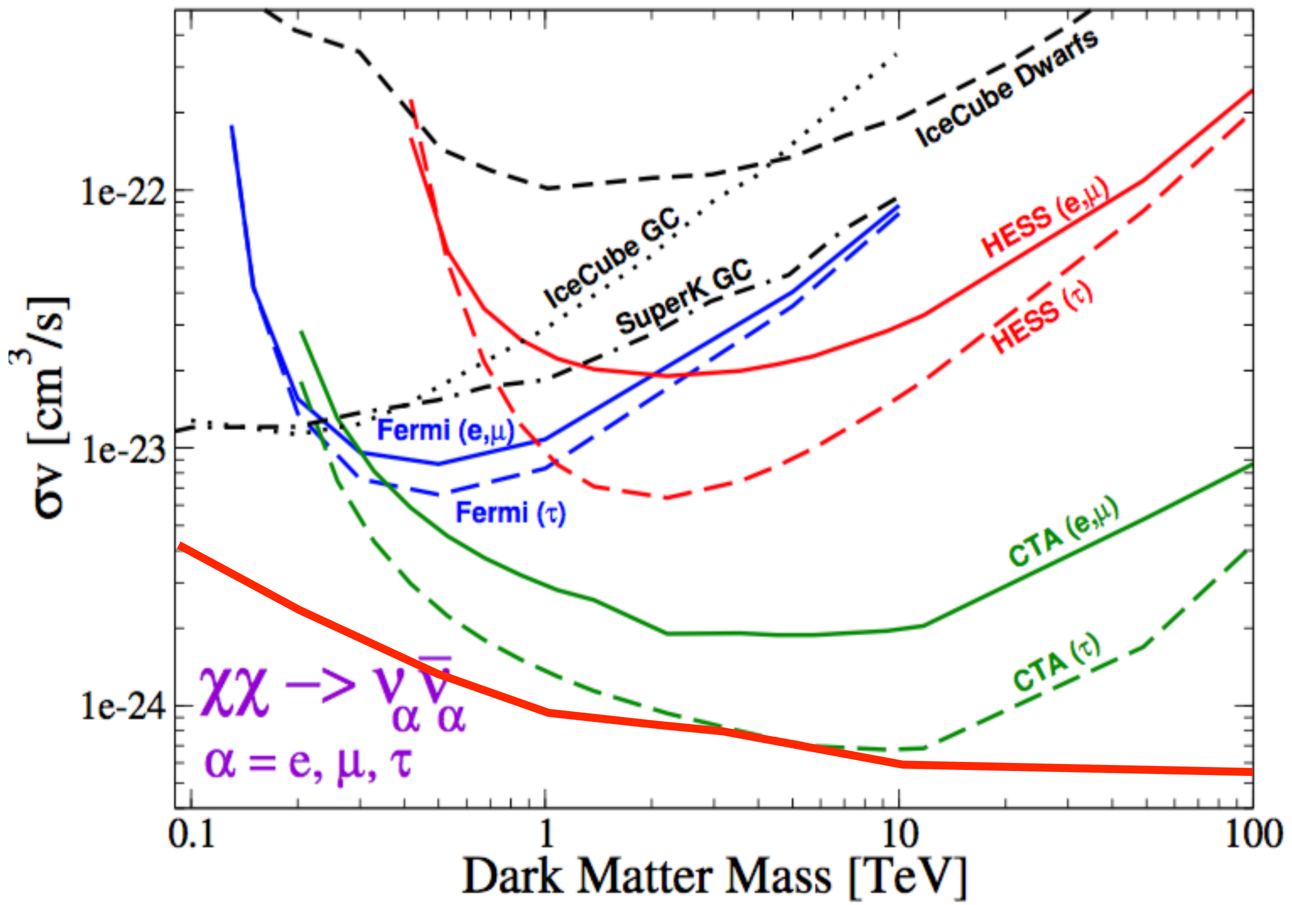
Recent Antares analysis might have better constraints

Only ν telescopes can really identify a ν line

Danninger, Neutrino 2016

ANTARES 2016 $(\nu\nu)$ *(*Preliminary*)*

JCAP 05 (2016) 050



Constraints on $\sigma_{\chi-P}$

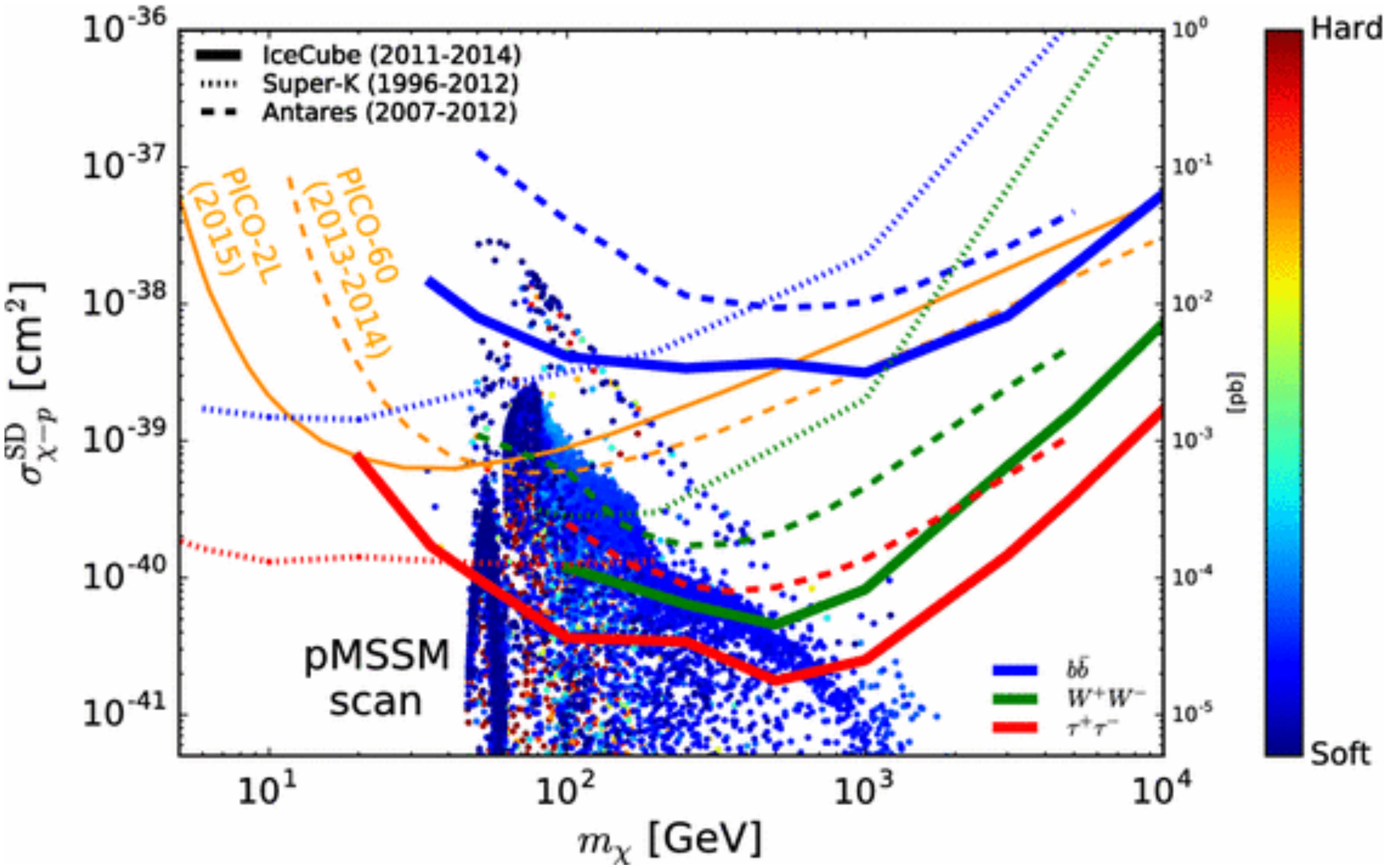
For spin dependent scattering, where

$$\sigma_{\chi-N} \propto \vec{S}_{\chi}.\vec{S}_{N}$$

Constraints from searches looking for GeV neutrinos from the Sun are the most stringent. IceCube above ~80 GeV, and SuperK below.

Constraints derived by assuming:

- equilibrium
- Maxvellian velocity distribution
- local DM density of 0.3 GeV/cm^3



pMSSM models colour coded by hardness of predicted neutrino spectrum

DD experiments have more stringent constraints for Spin Independent scattering:

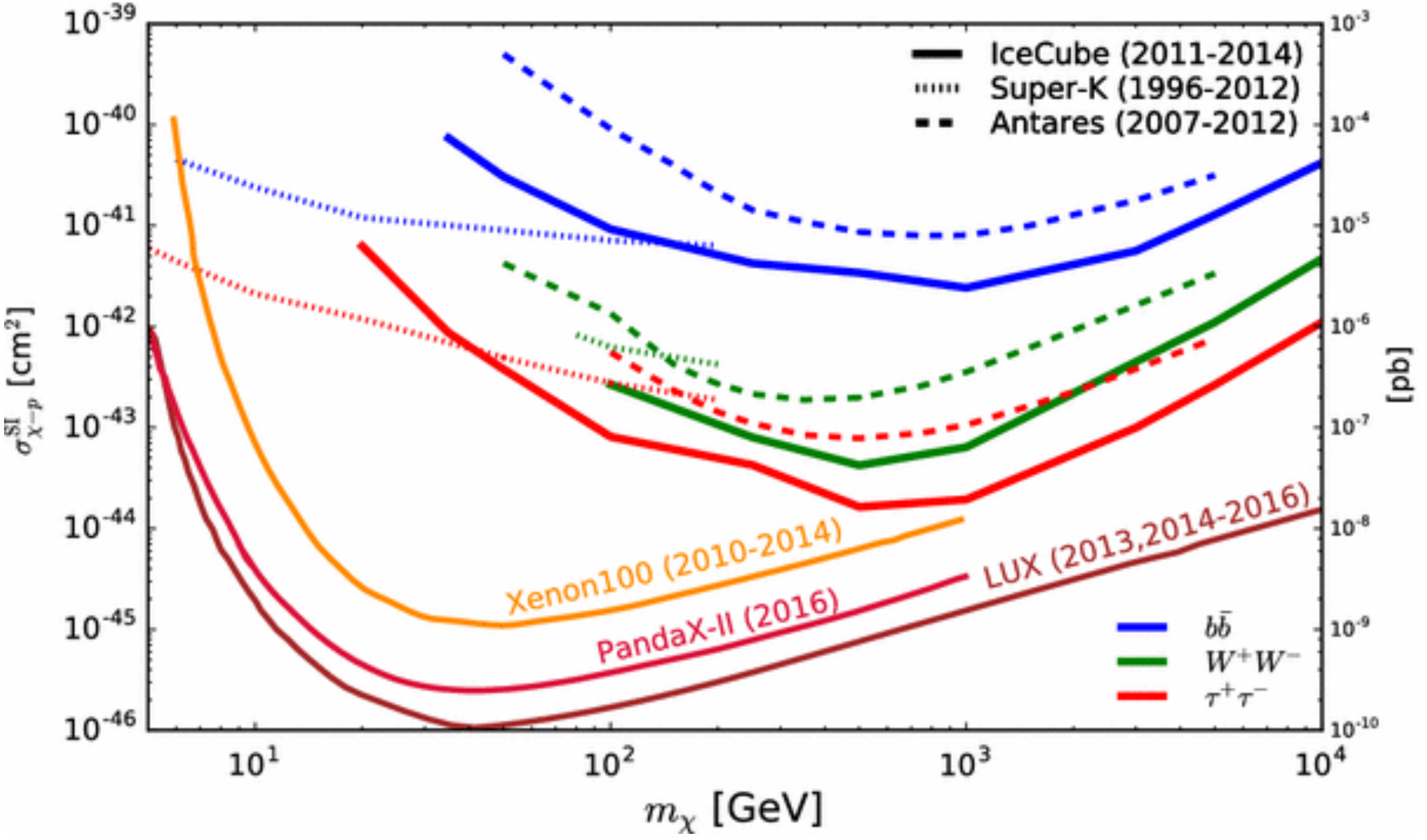
$$\sigma_{\chi-N} \propto A^2$$

Target nuclei are large, in XENON, Argon etc.

These limits are derived assuming the interaction is isoscalar , DM interacts equally strongly with neutrons and protons.

Neutrino telescope constraints are more robust against Isospin violation than DD constraints **Phys. Rev. D 84, 031301(R)**

Constraints on $\sigma_{\chi-P}$

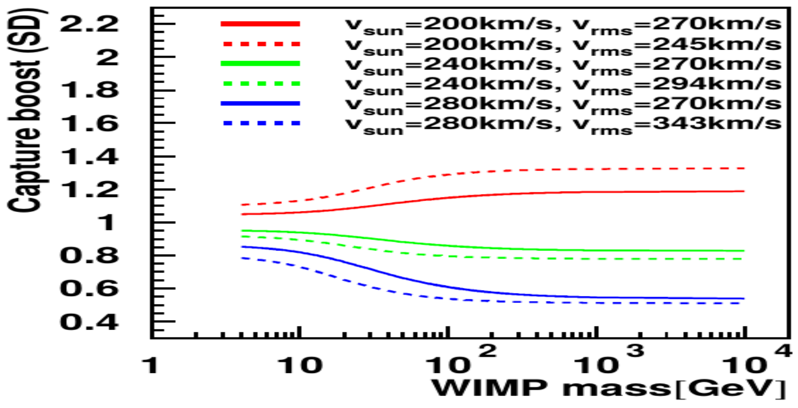


Apart from SD and SI, velocity and momentum suppressed interactions possible at the NR limit. **JCAP 1504 (2015) no.04, 052**

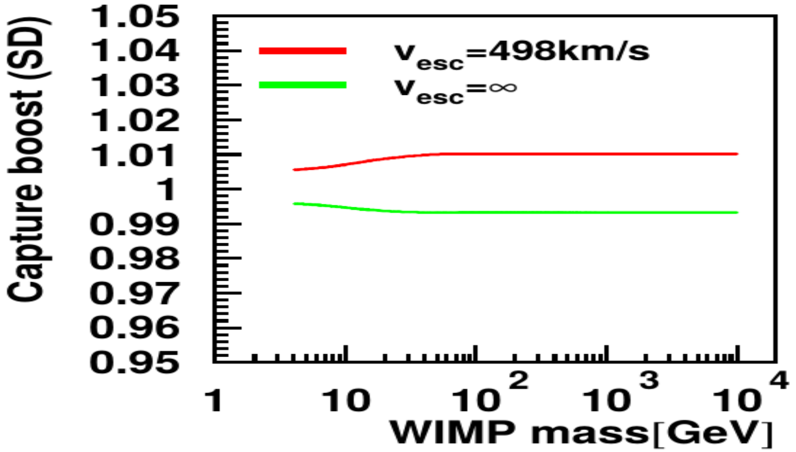
Astrophysical Uncertainties

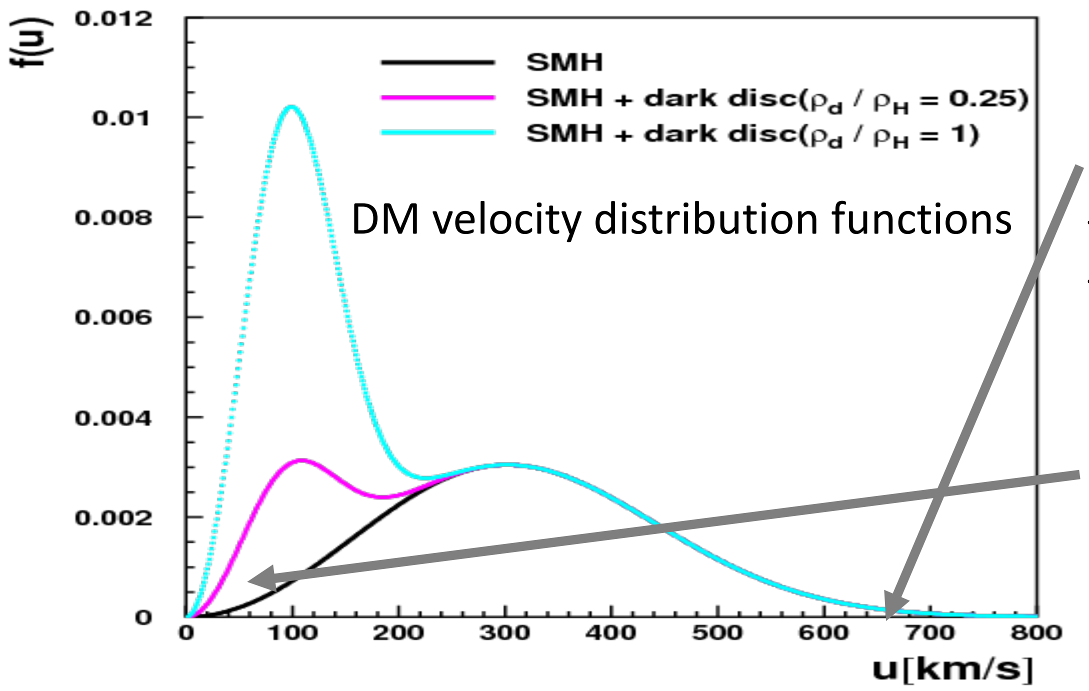
There are uncertainties on:

- The velocity of the Sun w.r.t the halo



- The fraction of DM in a co-rotating dark disk
- The galactic escape velocity





DD experiments are sensitive to the high velocity tail

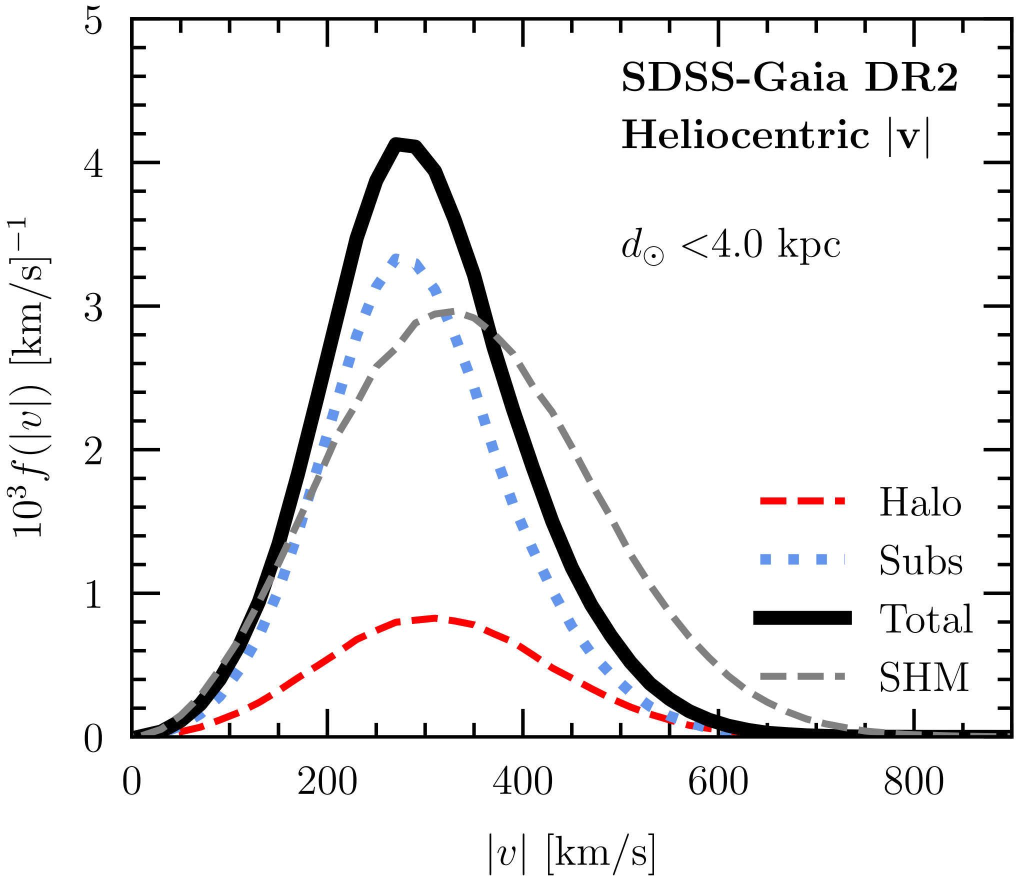
Solar capture is more likely for slower particles

K Choi **et al. JCAP05 (2014) 049**

The uncertainties are **20% (50%) at low (high) WIMP masses.**

Conservative w.r.t. the dark disk fraction.

All’s not well with the SMH



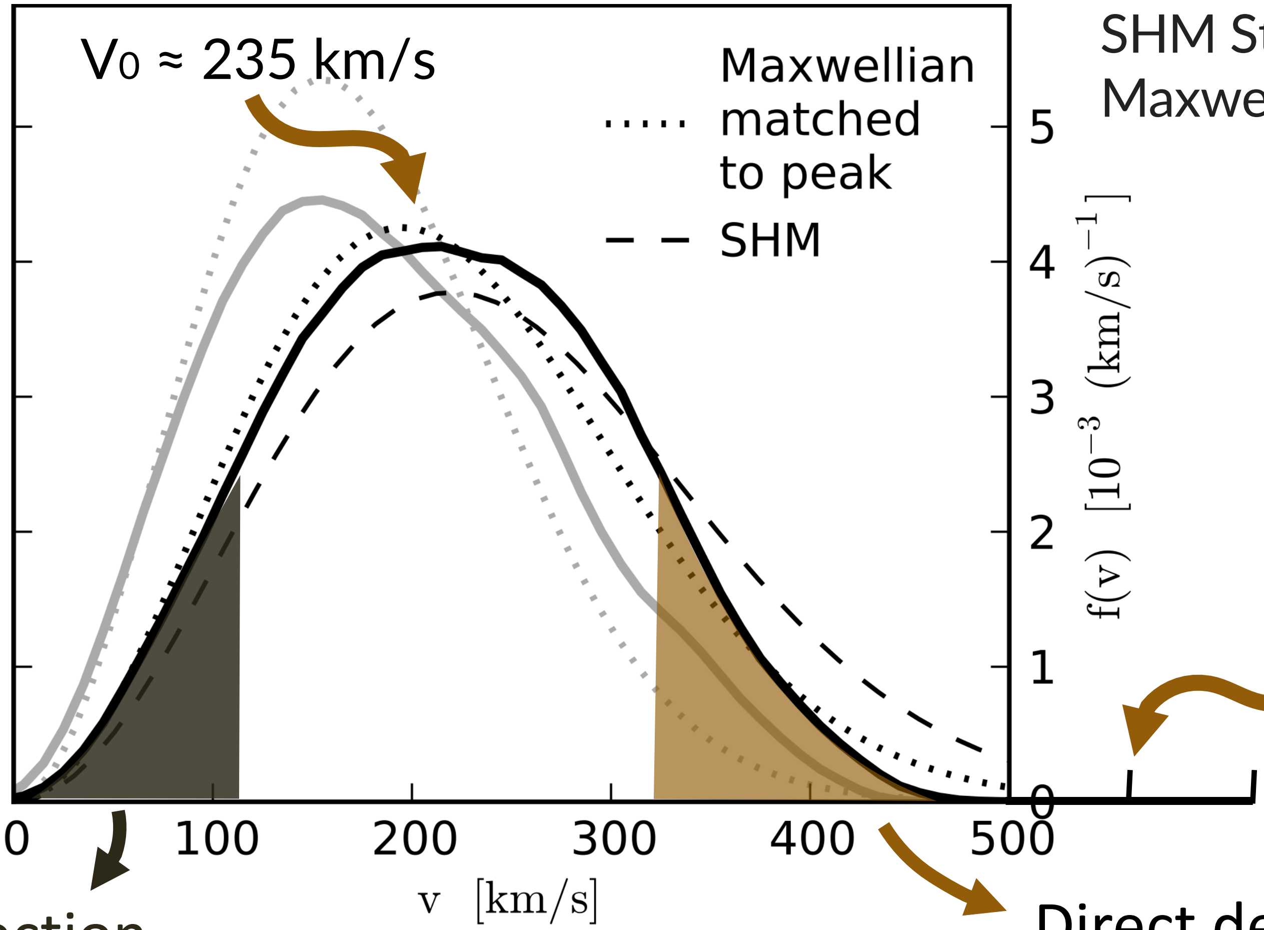
Necib, Lisanti and Belokurov 1807.02519
|Z coord| < 2.5 kpc
4 kpc sphere around the Sun

“the debris from the youngest mergers may be in position and velocity substructure. Referred to as tidal streams, these cold phase-space features tend to trace fragments of a progenitor’s orbit (Zemp et al. 2009; Vo- gelsberger et al. 2009; Diemand et al. 2008; Kuhlen et al. 2010; Maciejewski et al. 2011; Vogelsberger & White 2011; Elahi et al. 2011). ”

Celestial Bodies Velocity Distribution

Heavy dark matter particles can only be captured at low velocities

Figure from https://arxiv.org/pdf/1308.1703.pdf



SHM Standard Halo Model = Maxwellian with v_{esc}

Dark Shards: velocity substructure from Gaia and direct searches for dark matter [arXiv:1909.04684v1]

$V_{esc} \approx 544$ km/s

Indirect detection

Direct detection

Velocity Independent PICO and IceCube

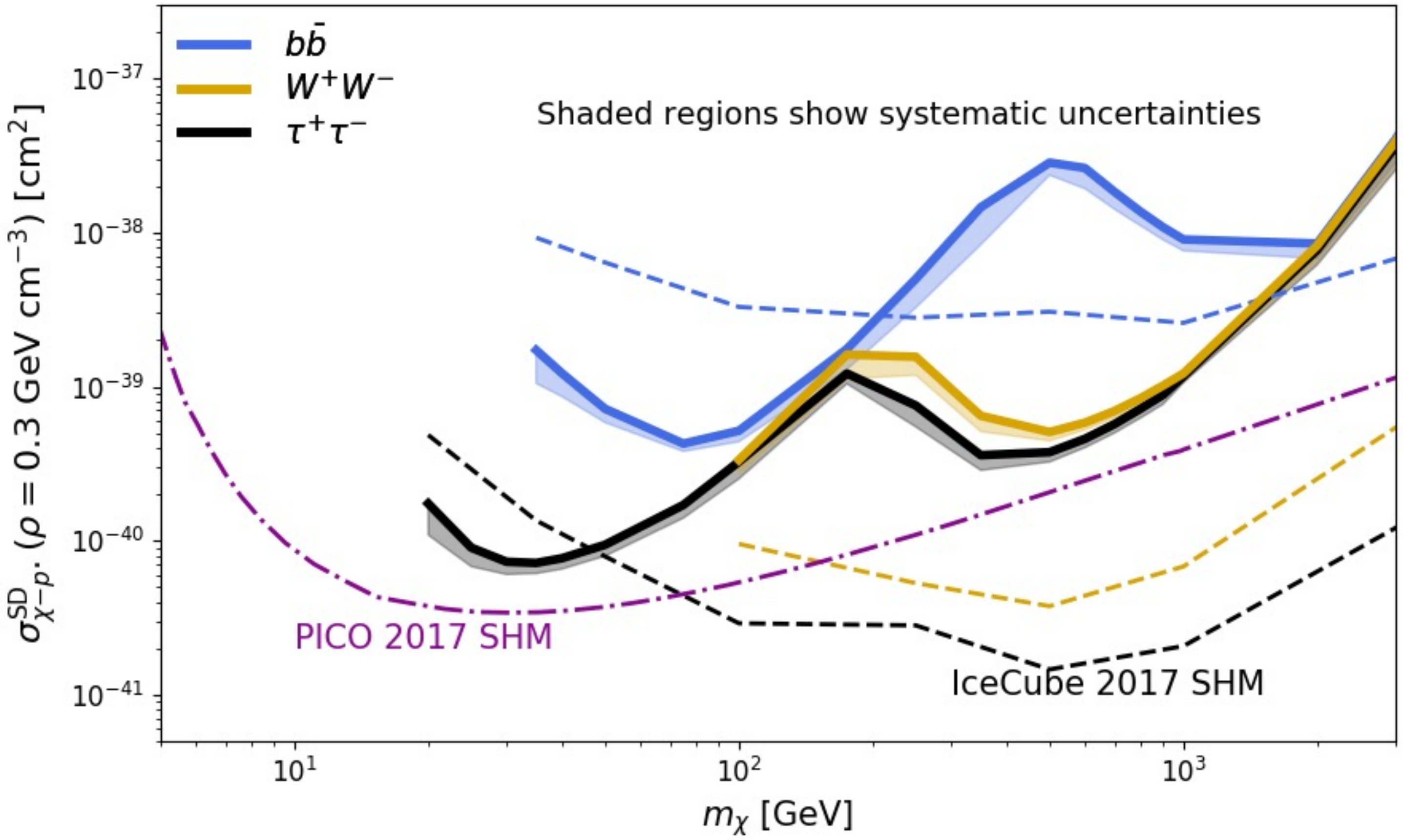
Limits assuming the superposition of **streams with fixed velocity**.

Only the velocity stream with the highest allowed scattering cross-section is selected:

Conservative limits

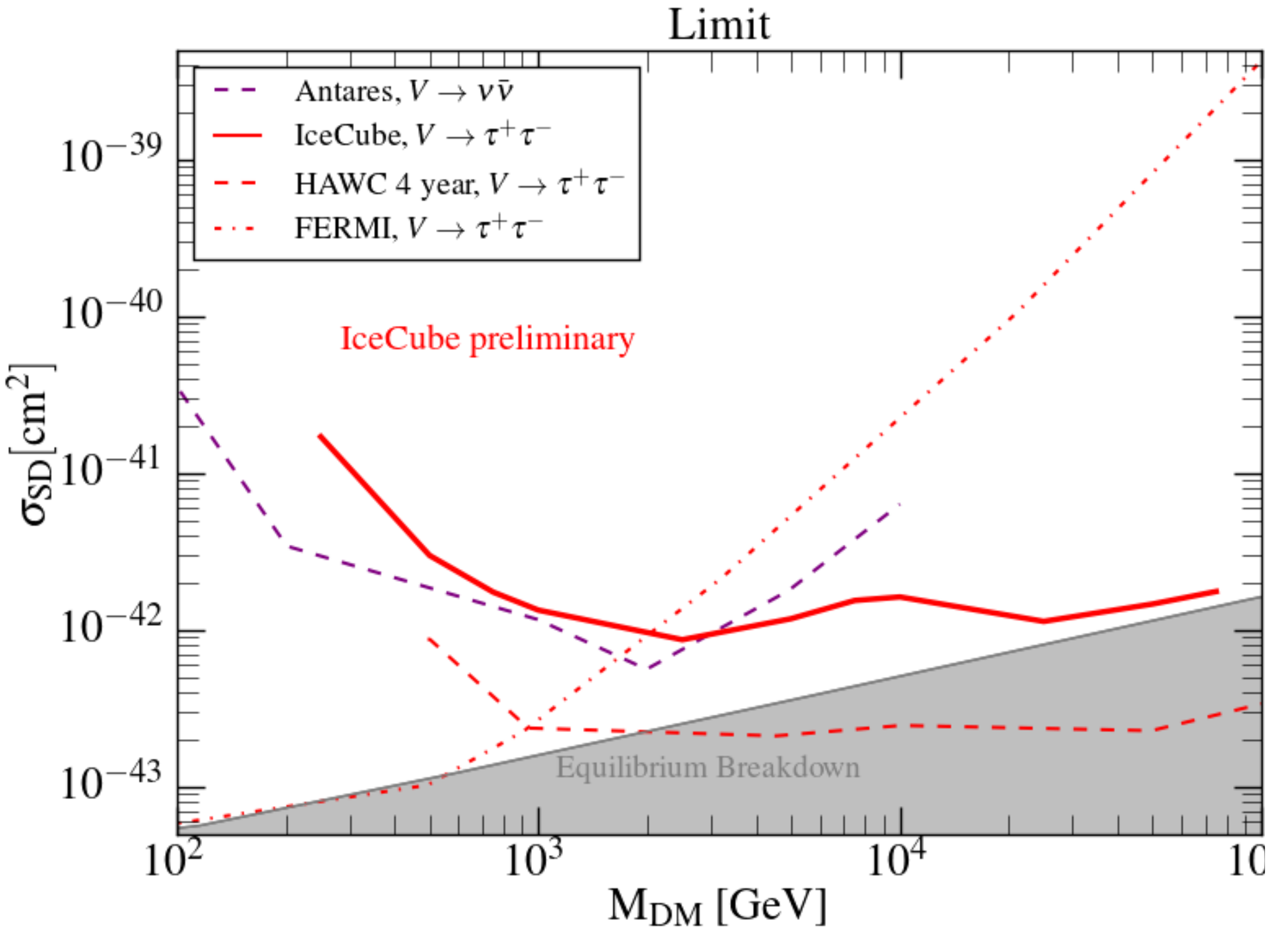
equilibrium!

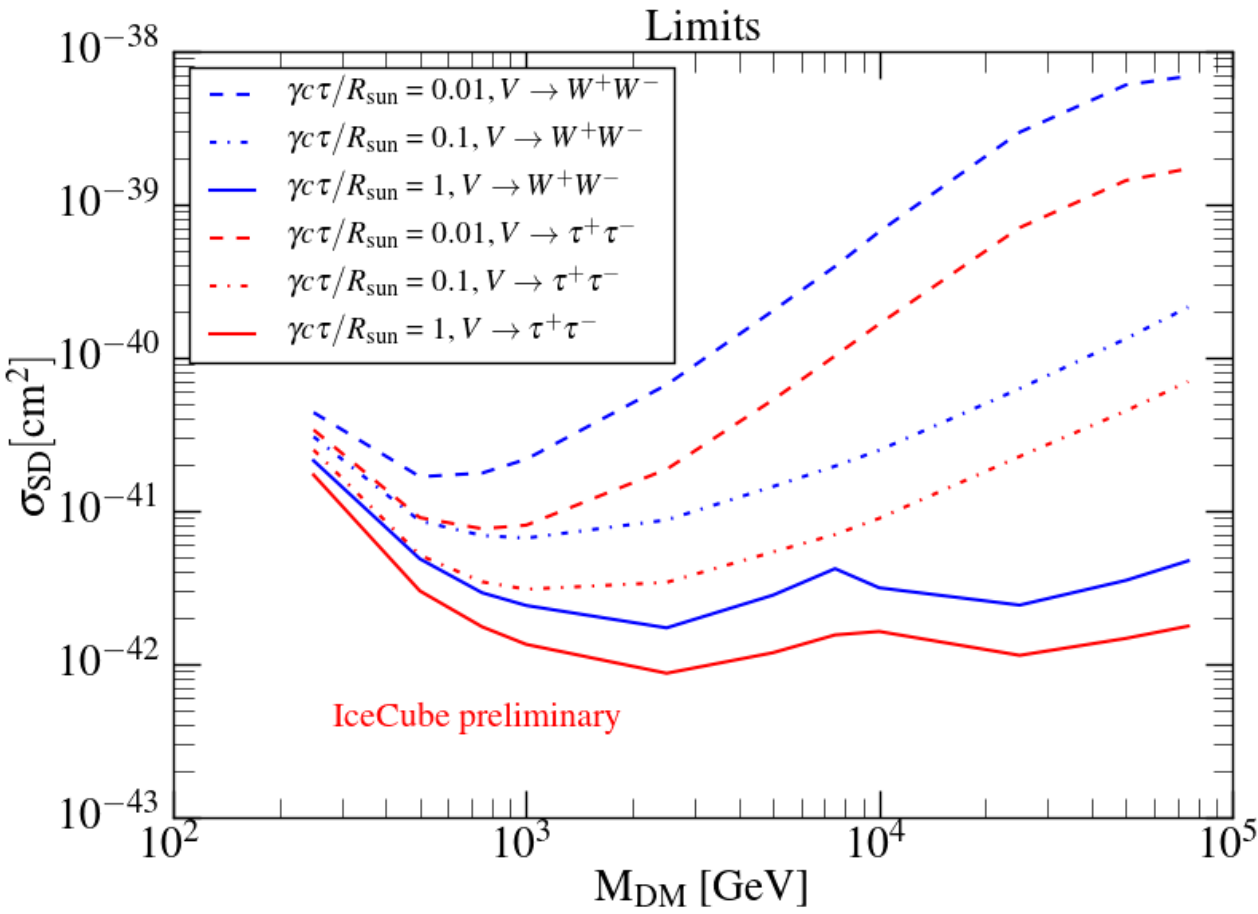
$$\Phi_\nu \rightarrow C_A \Rightarrow C_c \rightarrow \sigma_{\chi N}$$



Eur.Phys.J.C 80 (2020) 9, 819

Secluded Dark matter

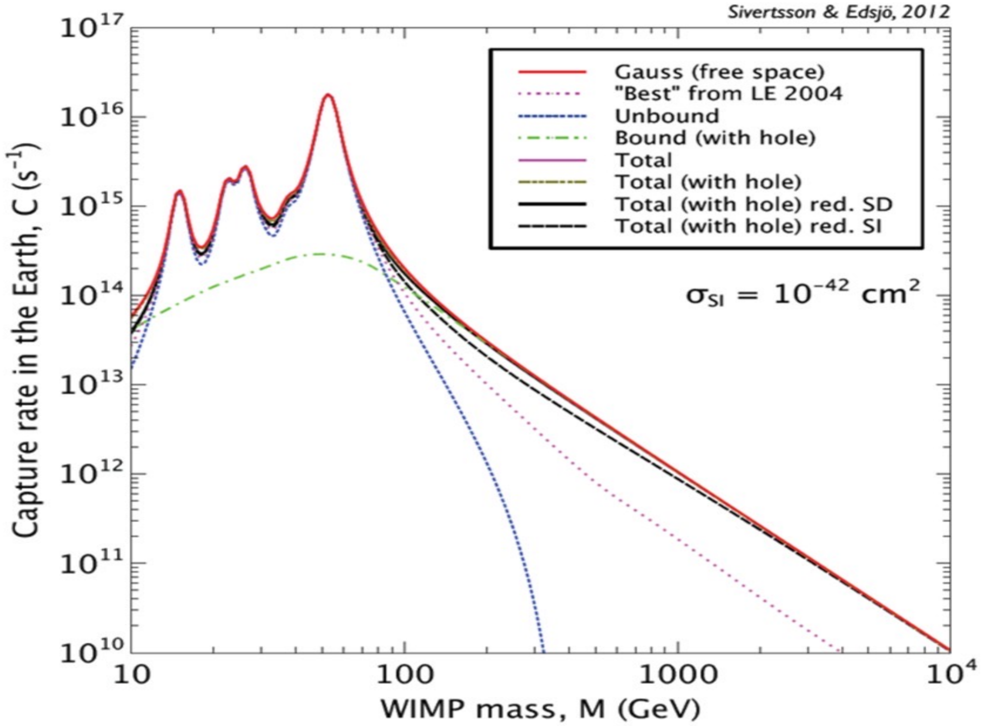




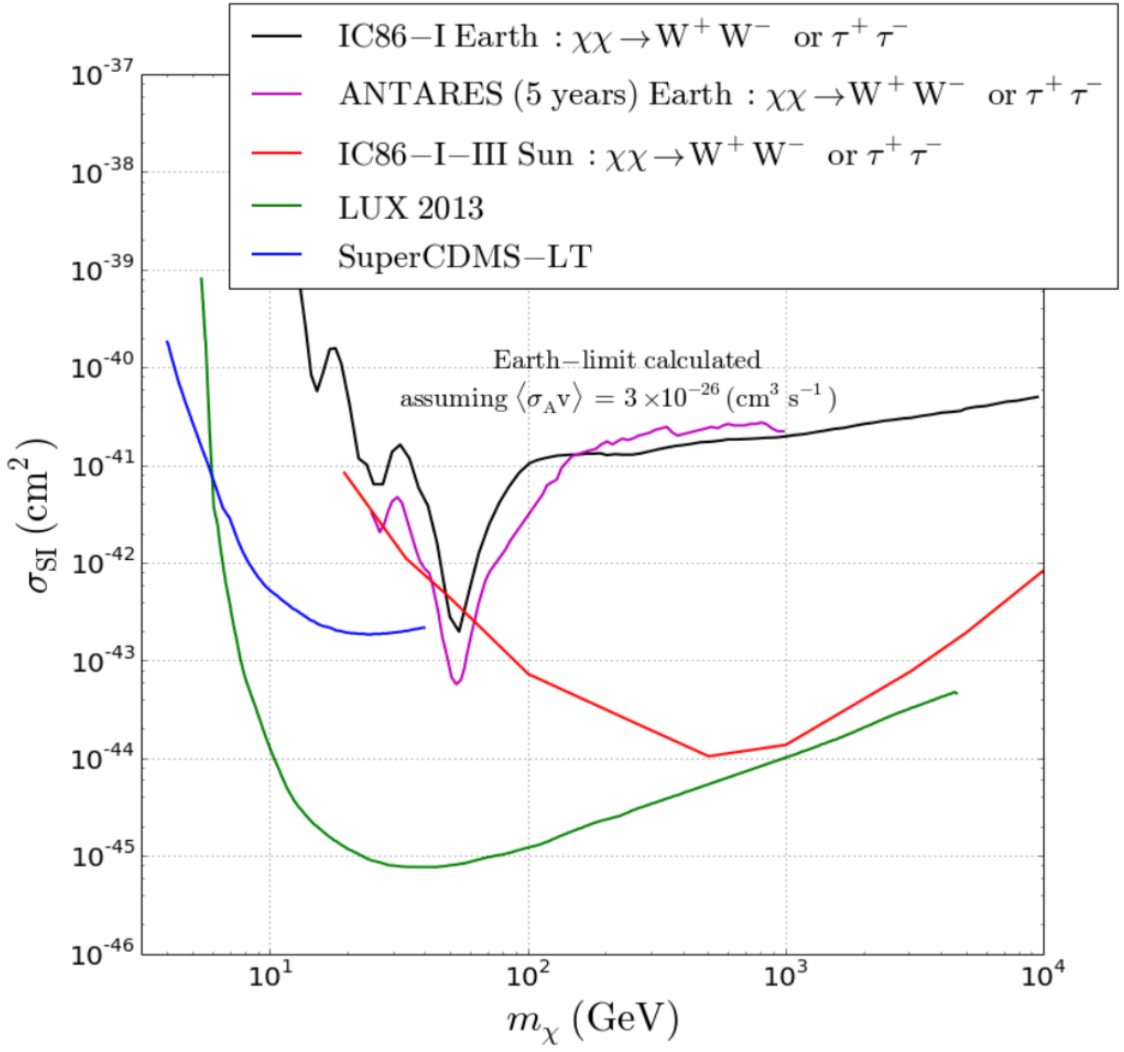
PoS(ICRC2021)521

Constraints on $\sigma_{\chi-P}$ from Earth DM searches

- Just like in the Sun, DM can be also captured in the Earth
- Capture Annihilation equilibrium unlikely – Earth is too light
- Signal : Vertically upgoing ν excess.
- No off source region. Background estimation is challenging

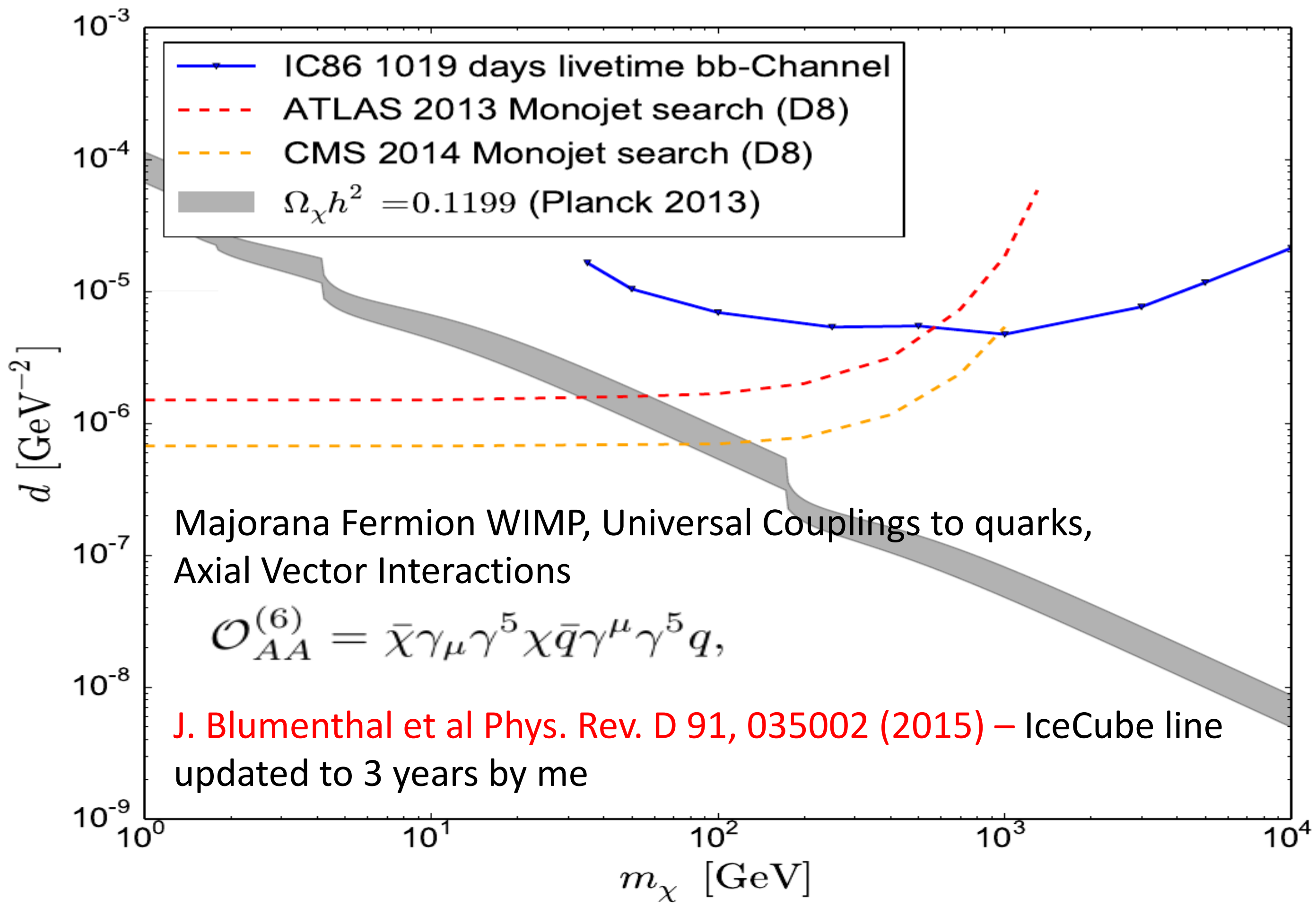


PhD thesis: J.Kunnen (VUB Oct.2015)



Complementarity - EFTs

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	7	SI
D2	$\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	7	N/A
D3	$\frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	7	N/A
D4	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	7	N/A
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D6	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	SD
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	6	N/A
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A



Majorana Fermion WIMP, Universal Couplings to quarks, Axial Vector Interactions

$$\mathcal{O}^{(6)}_{AA} = \bar{\chi}\gamma_\mu\gamma^5\chi\bar{q}\gamma^\mu\gamma^5 q,$$

J. Blumenthal et al Phys. Rev. D 91, 035002 (2015) – IceCube line updated to 3 years by me

EFT

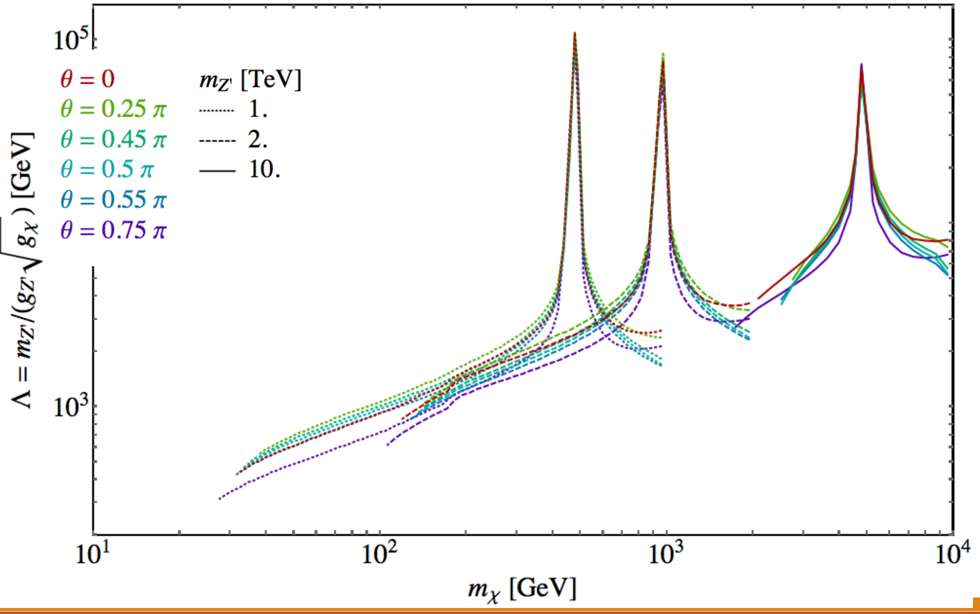
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{n>4}\frac{f^{(n)}}{\Lambda^{n-4}}\mathcal{O}^{(n)}.$$

Jacques, Katz, Morgante, Racco, MR and Riotto *JHEP* 10 (2016) 071

Complementarity – UV complete consistent theory

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-L}$	$U(1)'$
$\begin{pmatrix}\nu_L^{\ell_i}\\ \ell_L^i\end{pmatrix}$	**1**	**2**	$-\frac{1}{2}$	-1	$-\frac{1}{2}\cos\theta - \sin\theta$
$(\ell_R^i)^C$	**1**	**1**	1	$+1$	$\cos\theta + \sin\theta$
$\begin{pmatrix}u_L^i\\ d_L^i\end{pmatrix}$	**3**	**2**	$\frac{1}{6}$	$+\frac{1}{3}$	$\frac{1}{6}\cos\theta + \frac{1}{3}\sin\theta$
$(u_R^i)^C$	$\overline{\mathbf{3}}$	**1**	$-\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}\cos\theta - \frac{1}{3}\sin\theta$
$(d_R^i)^C$	$\overline{\mathbf{3}}$	**1**	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}\cos\theta - \frac{1}{3}\sin\theta$
$\Phi = \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}$	**1**	**2**	$\frac{1}{2}$	0	$\frac{1}{2}\cos\theta$

Table 1. Charges of the SM matter content under the gauge symmetries of the SM and the gauge $U(1)'$ with the generator (2.3). i stands for the family index.



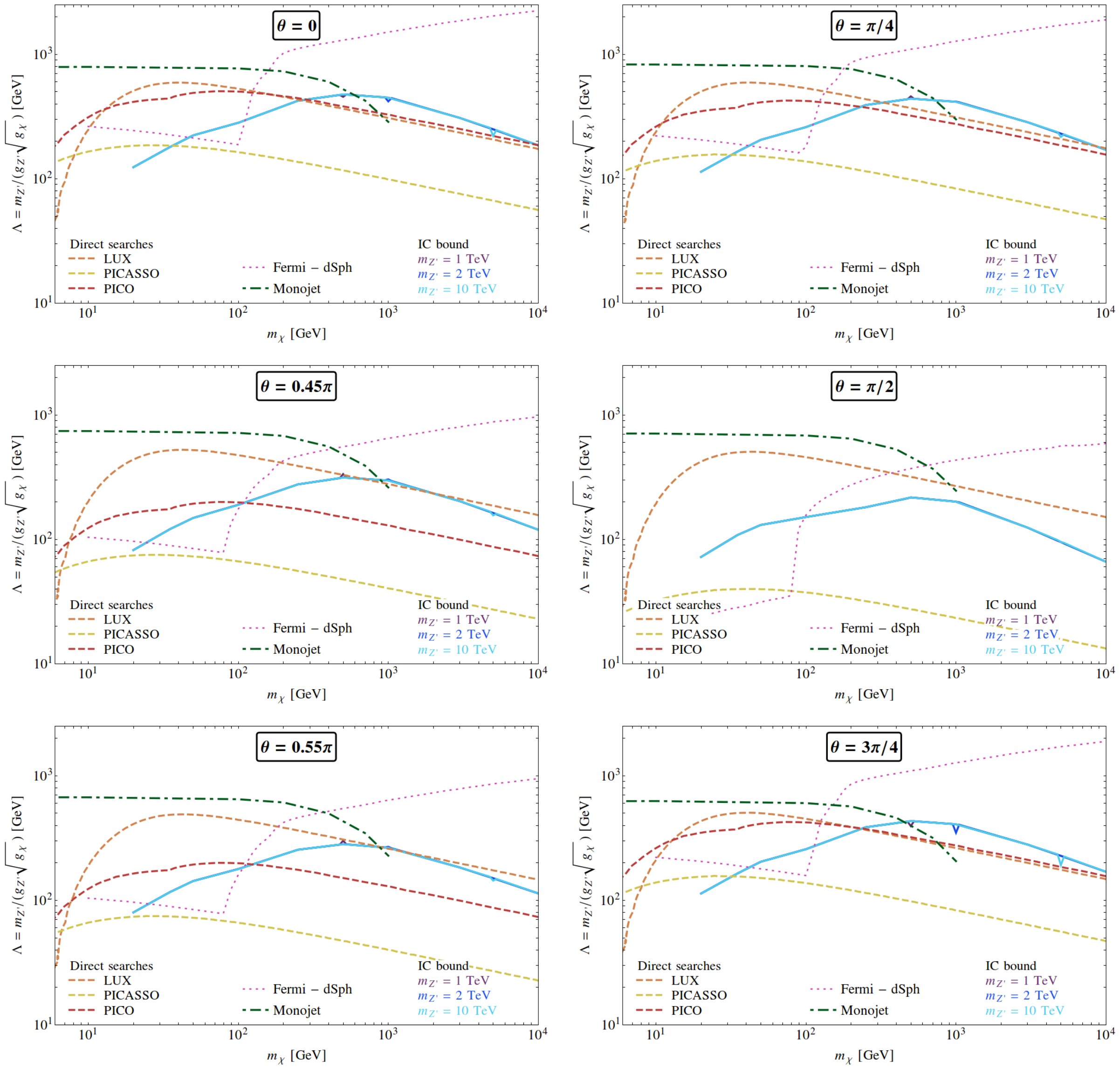
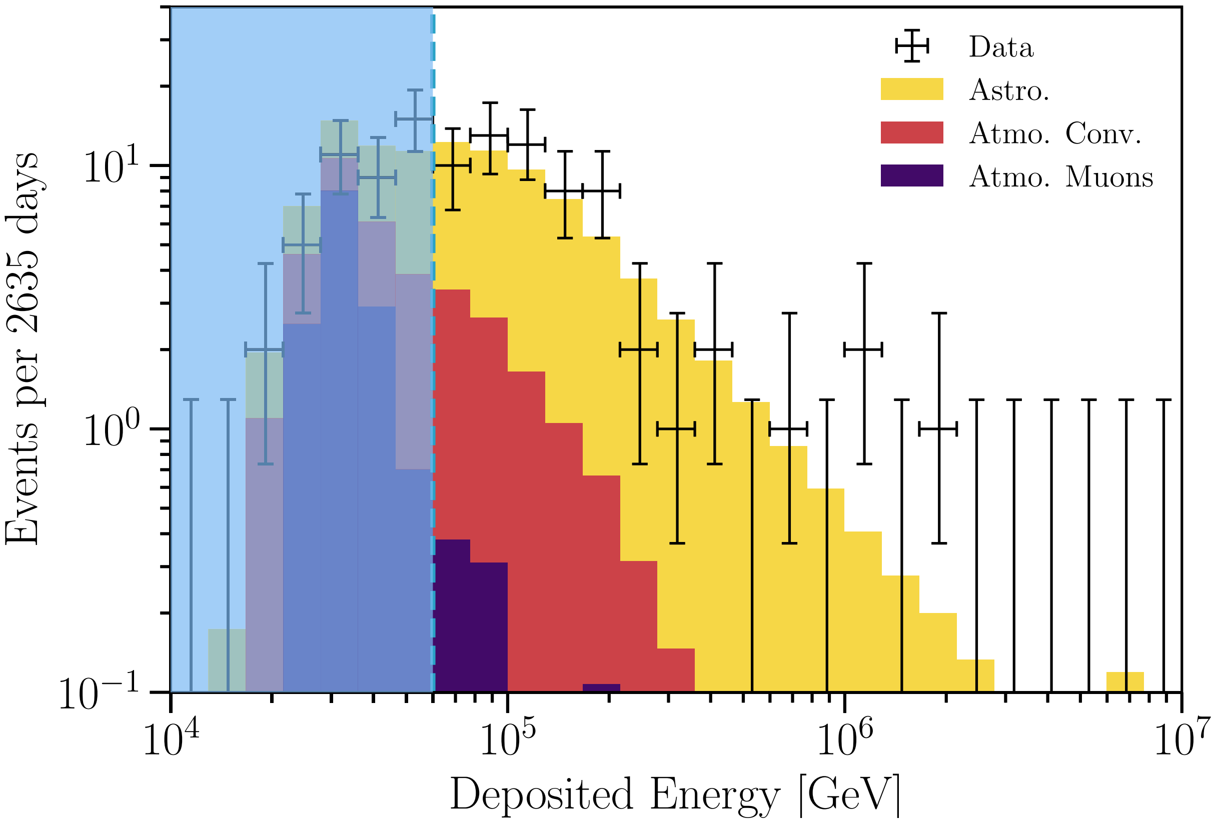


Figure 8. Bound on $\Lambda = m_{Z'}/(g_{Z'}\sqrt{g_\chi})$ from direct detection, LHC's monojet analysis, IceCube and Fermi-LAT, for different values of θ.

The IceCube astrophysical flux



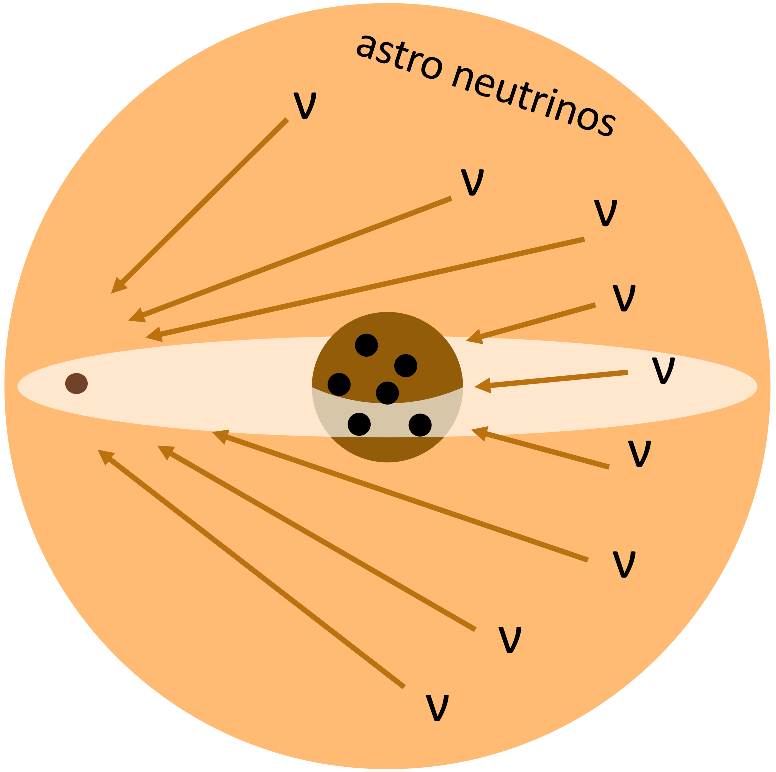
Phys.Rev.D 104 (2021) 022002

Neutrino Astronomy achievements

Identification of the first TeV and extragalactic source of neutrinos with the help of realtime alerts – TXS0506+056
Science 361 (2018) 6398, 147-151
Science 361 (2018) 6398, eaat1378

Evidence for neutrino emission from nearby active galaxy NGC1068
Science 378 (2022) 6619, 538-543

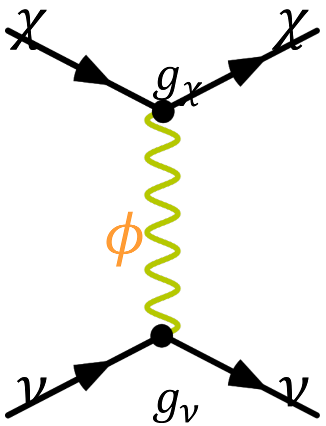
Neutrino-Dark Matter Scattering



- Astrophysical neutrinos assumed to be extra-Galactic:
  - Isotropic distribution of arrival directions.
- Scattering of high energy cosmic neutrinos on DM:
  - Deficit in the direction of Galactic Center
- Two simplified models tested:

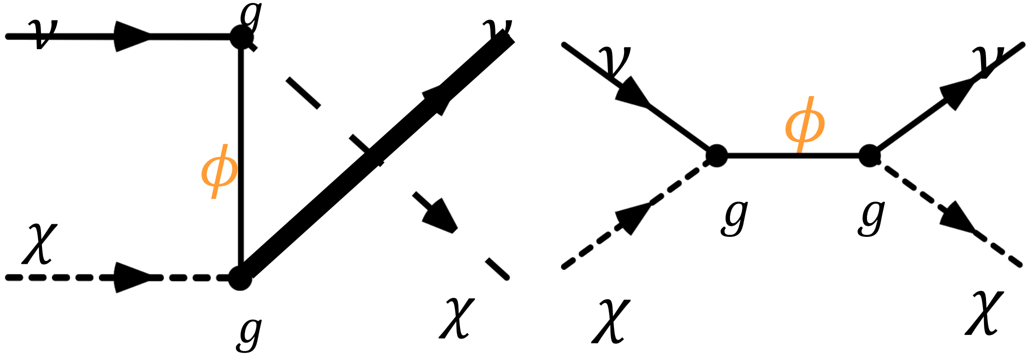
Fermion—vector

$(S_\chi, S_\phi) = (1/2, 1)$



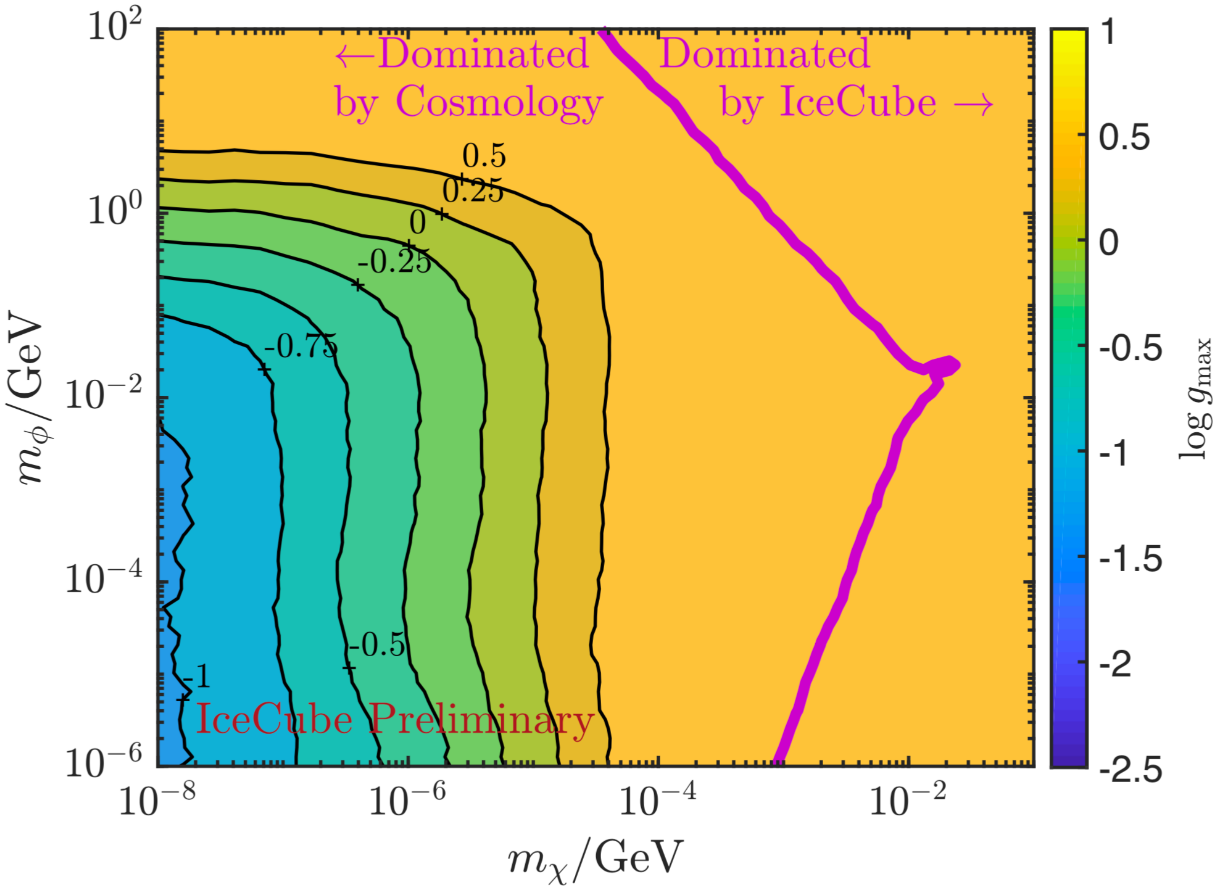
Scalar—Fermion

$(S_\chi, S_\phi) = (0, 1/2)$

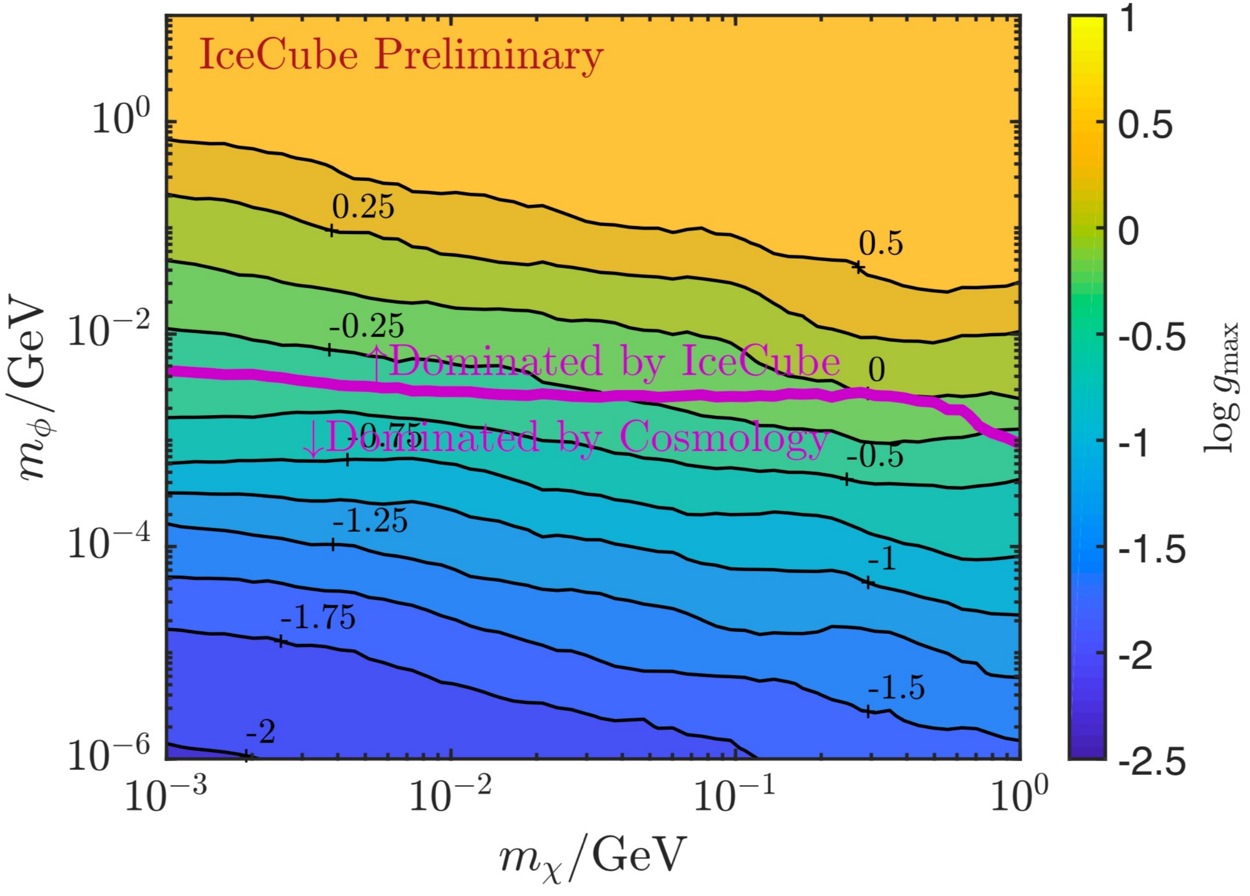


Neutrino-Dark Matter Scattering

Scalar—Fermion



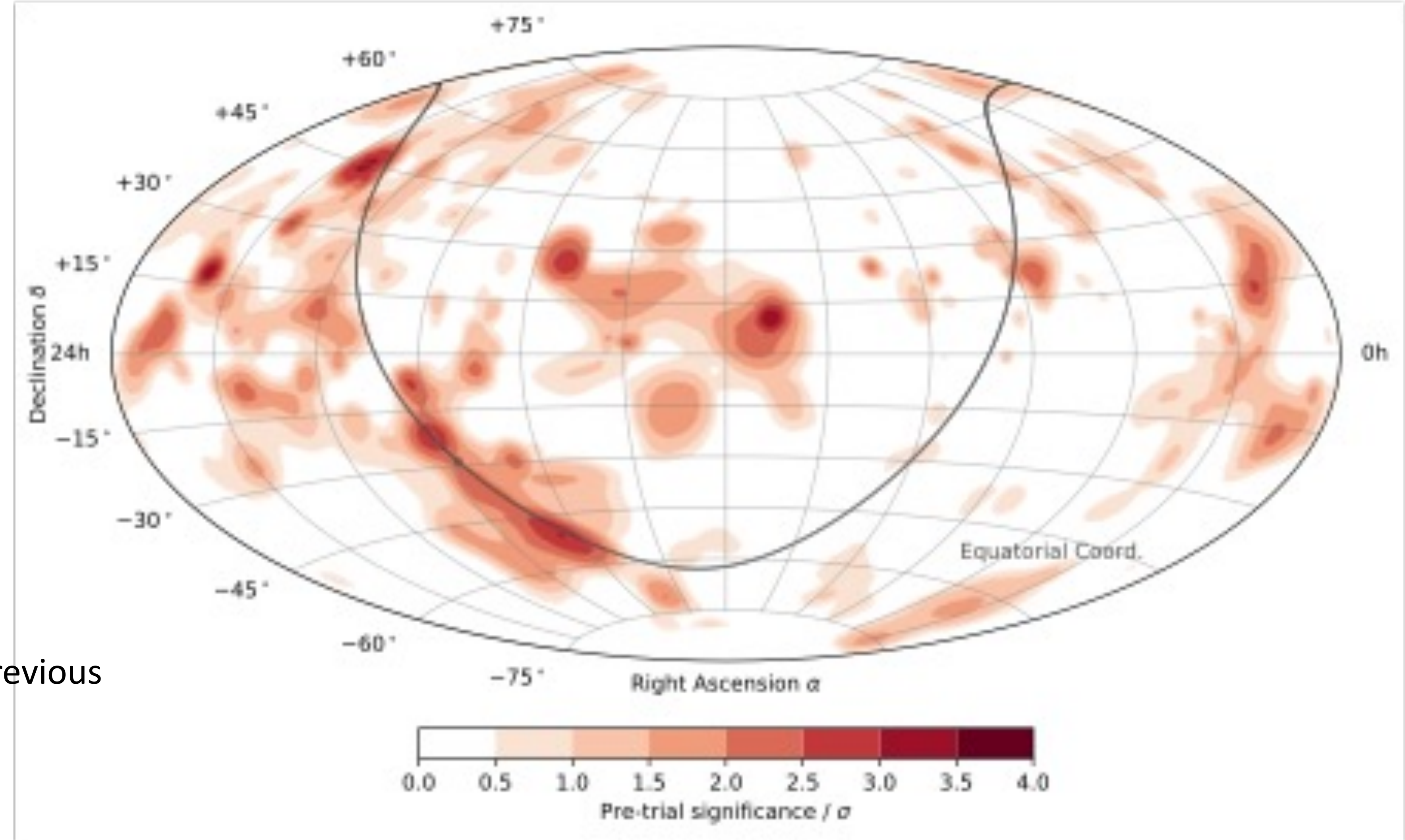
Fermion—vector



T Yuan

doi:10.5281/zenodo.1300506

Observation of high-energy neutrinos from the Galactic plane
Science 380 (2023) 6652, adc9818



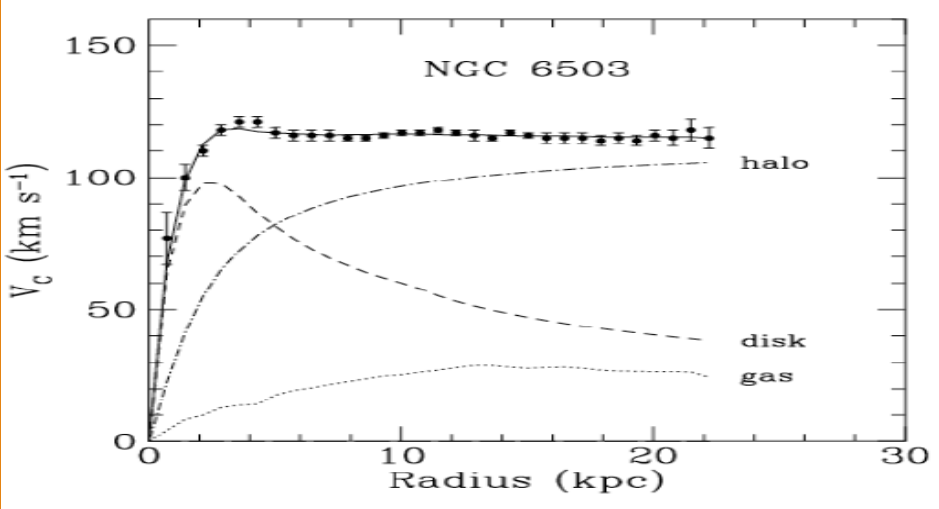
Key assumption going into the previous constraints is wrong

Is there really any actual evidence for Dark Matter?

We know DM exists from:

Galactic Rotation Curves : Newtonian

Mon.Not.Roy.Astron.Soc. 496 (2020) 2, 2107-2122 (see subsequent debate)

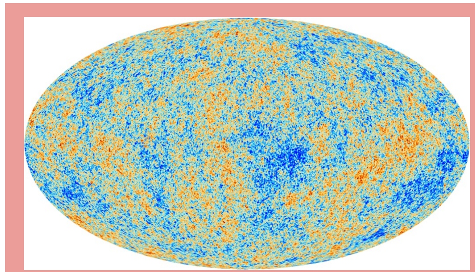


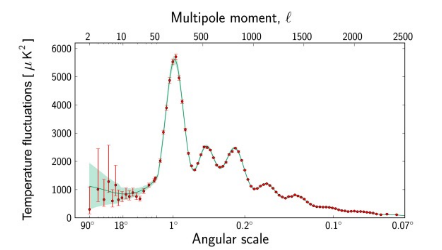
- **Gravitational Lensing**

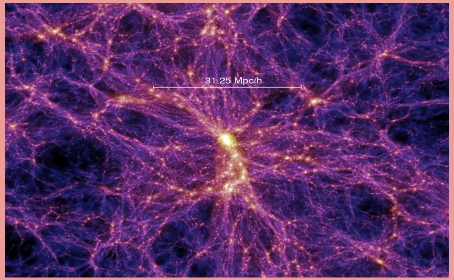
  Circular Logic

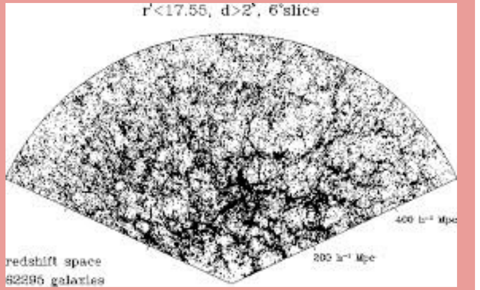
  See essay by Jenny Wagner (The cosmological Cheshire cat)

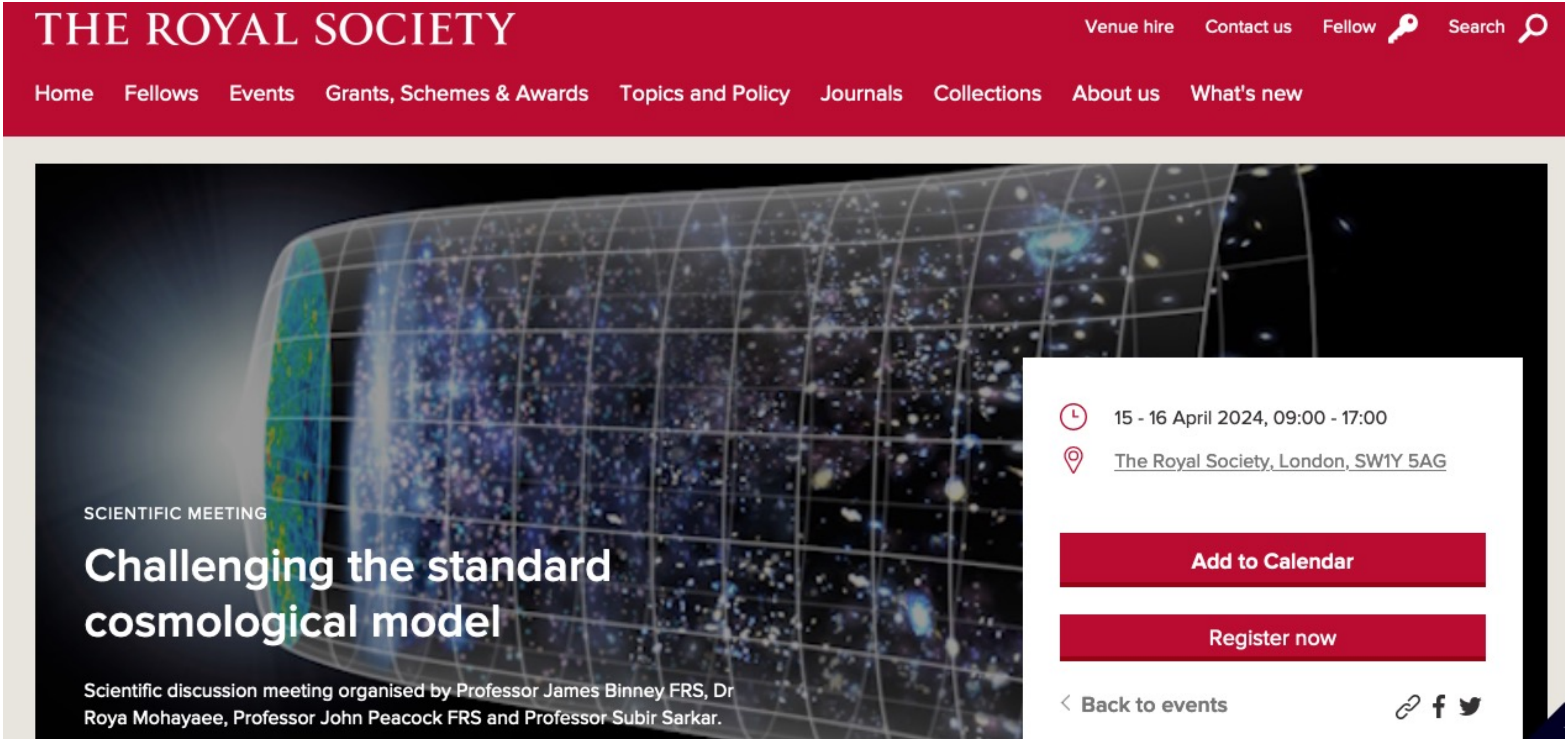
- **Precision Cosmology (In Crisis)**
  - Hubble tension
  - Cosmic Dipole Anomaly *Astrophys.J.Lett.* 908 (2021) 2, L51







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Challenging the standard cosmological model
Scientific discussion meeting organised by Professor James Binney FRS, Dr Roya Mohayaee, Professor John Peacock FRS and Professor Subir Sarkar.
15 - 16 April 2024, 09:00 - 17:00
The Royal Society, London, SW1Y 5AG
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Register now
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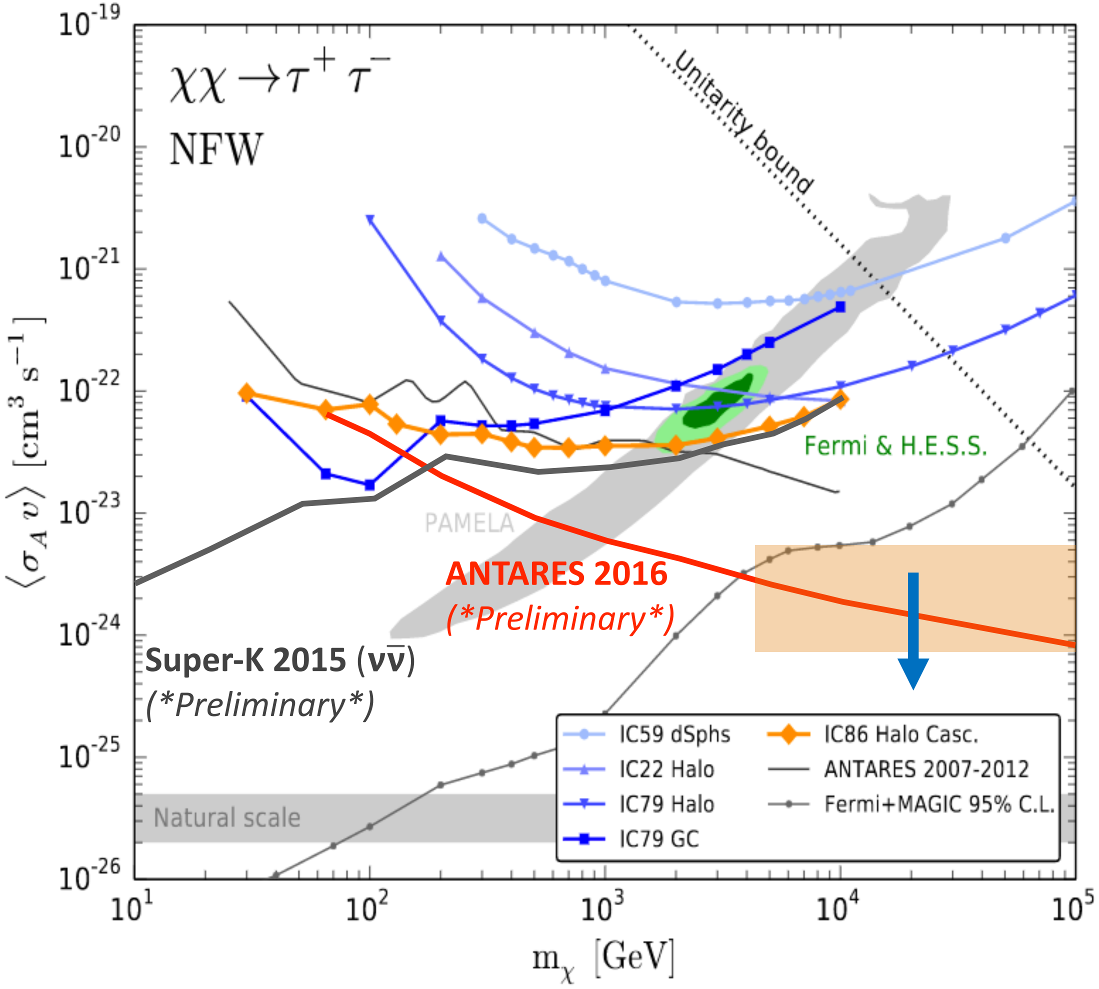
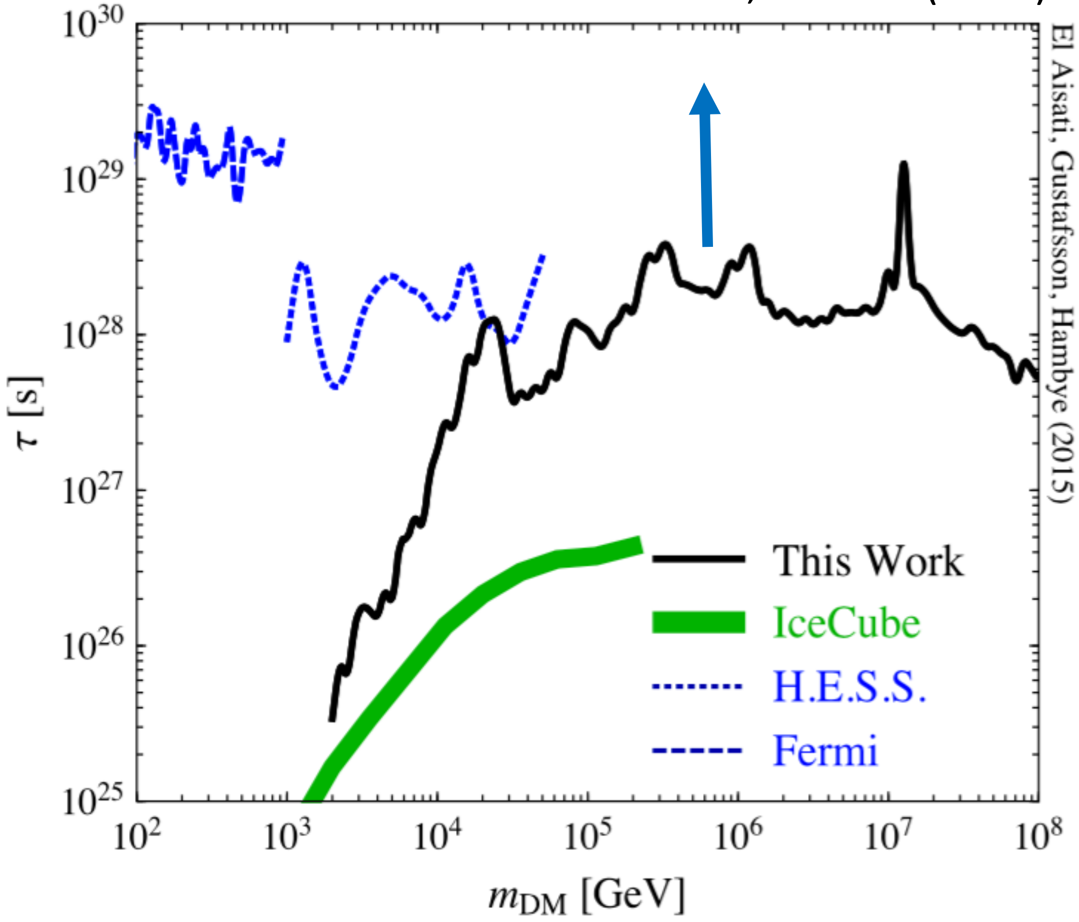
Backups

The Future of ν searches for DM

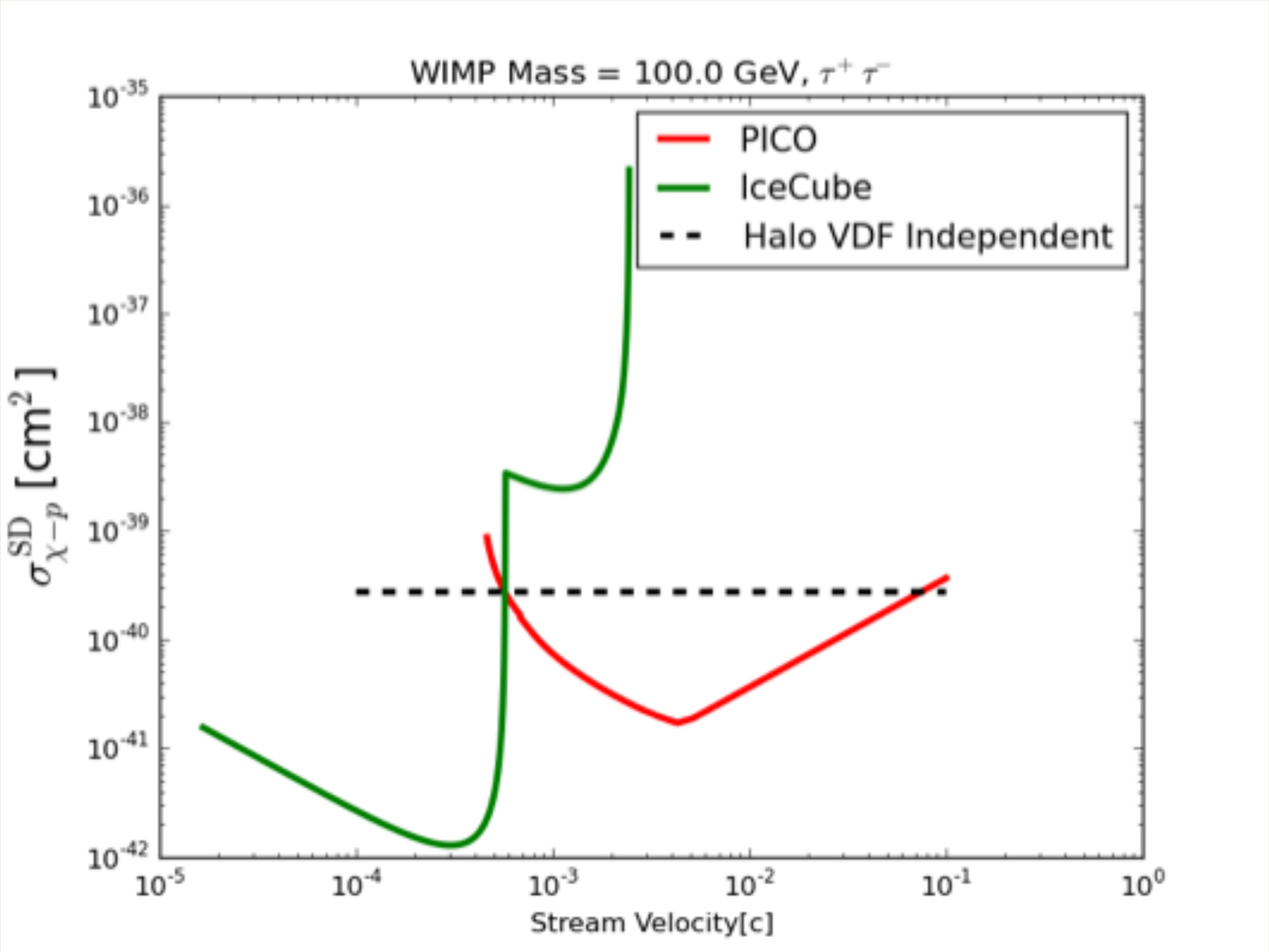
Searches from Galactic center, halo, dwarf spheroidals, galaxy clusters etc



PRD 92, 123515 (2015)



Neutrinos are the best at high energies: prospects for ARCA and IceCube Gen2



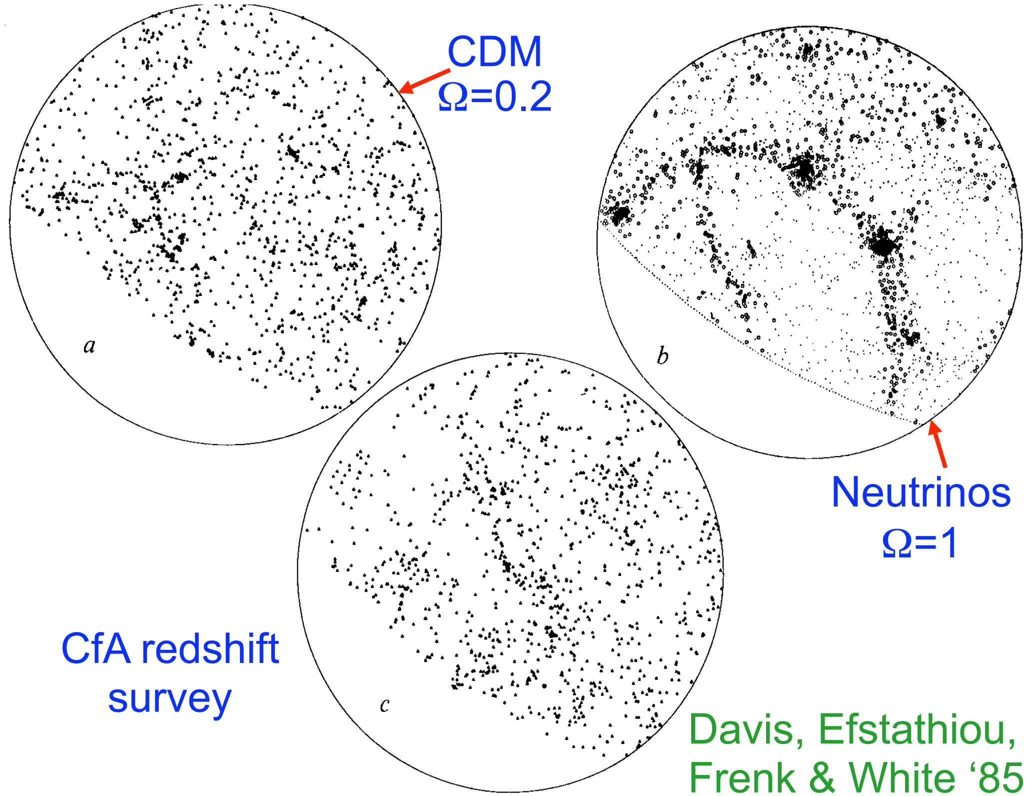
WIMP Mass = 100.0 GeV, $\tau^+ \tau^-$
PICO
IceCube
Halo VDF Independent
$\sigma^{SD}_{\chi-p}$ [cm^2]
Stream Velocity[c]
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

Neutrinos ~~from~~ as Dark Matter?

- Already detected
- They have mass
  - $\Sigma m_\nu < 0.23\ eV$ from the CMB
- Electrically neutral

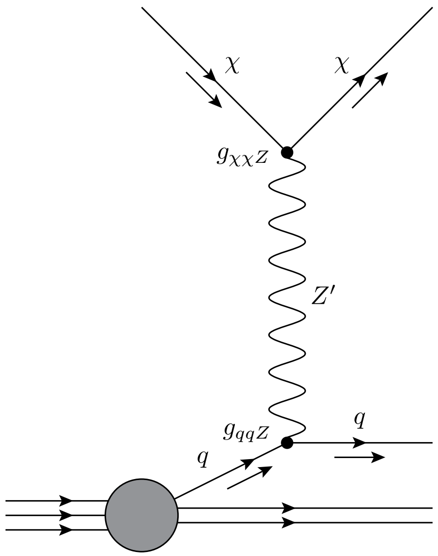
- Not enough of them
  - $\Omega_\nu h^2 \sim (m_\nu/93eV) \sim 2.5\times10^{-3} \ll 0.12$
- Number of neutrinos in the Galactic Halo is limited:
  - Pauli's exclusion principle
- Neutrinos would make 'hot' dark matter.
  - $E_{kin} >\sim m_\nu$ (relativistic)
  - Incompatible with structure formation

Light neutrinos not abundant enough to be the dominant component of Dark Matter



Heavy sterile neutrinos could be DM candidates

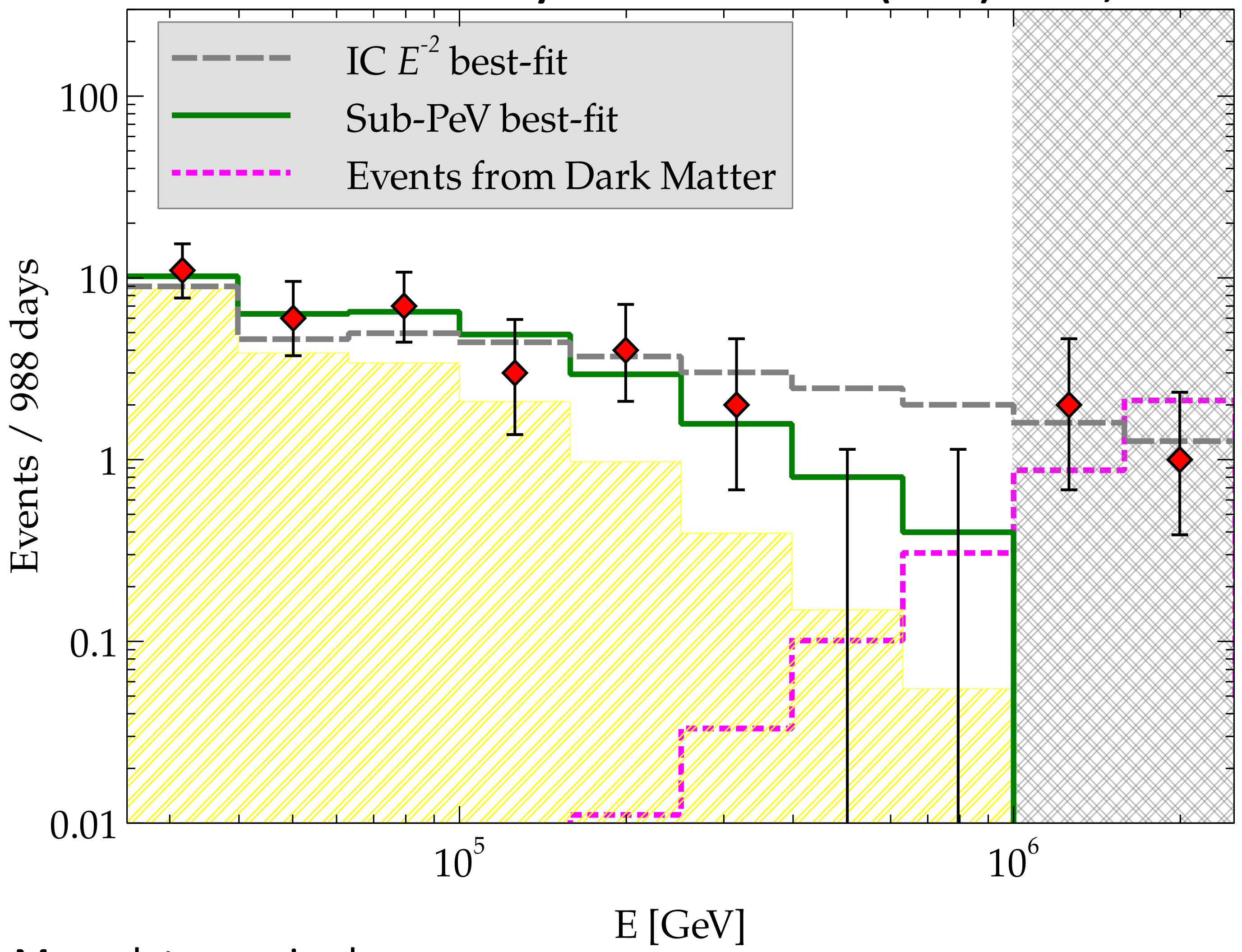
The IceCube astrophysical flux : from PeV Dark Matter Φ decaying to Fermionic DM χ



χ interacts with nuclei inside IceCube - signature similar to ν induced cascade

Best fit $m_\phi = 5.06\ PeV$

A. Bhattacharya et al. JCAP 1503 (2015) no.03, 027

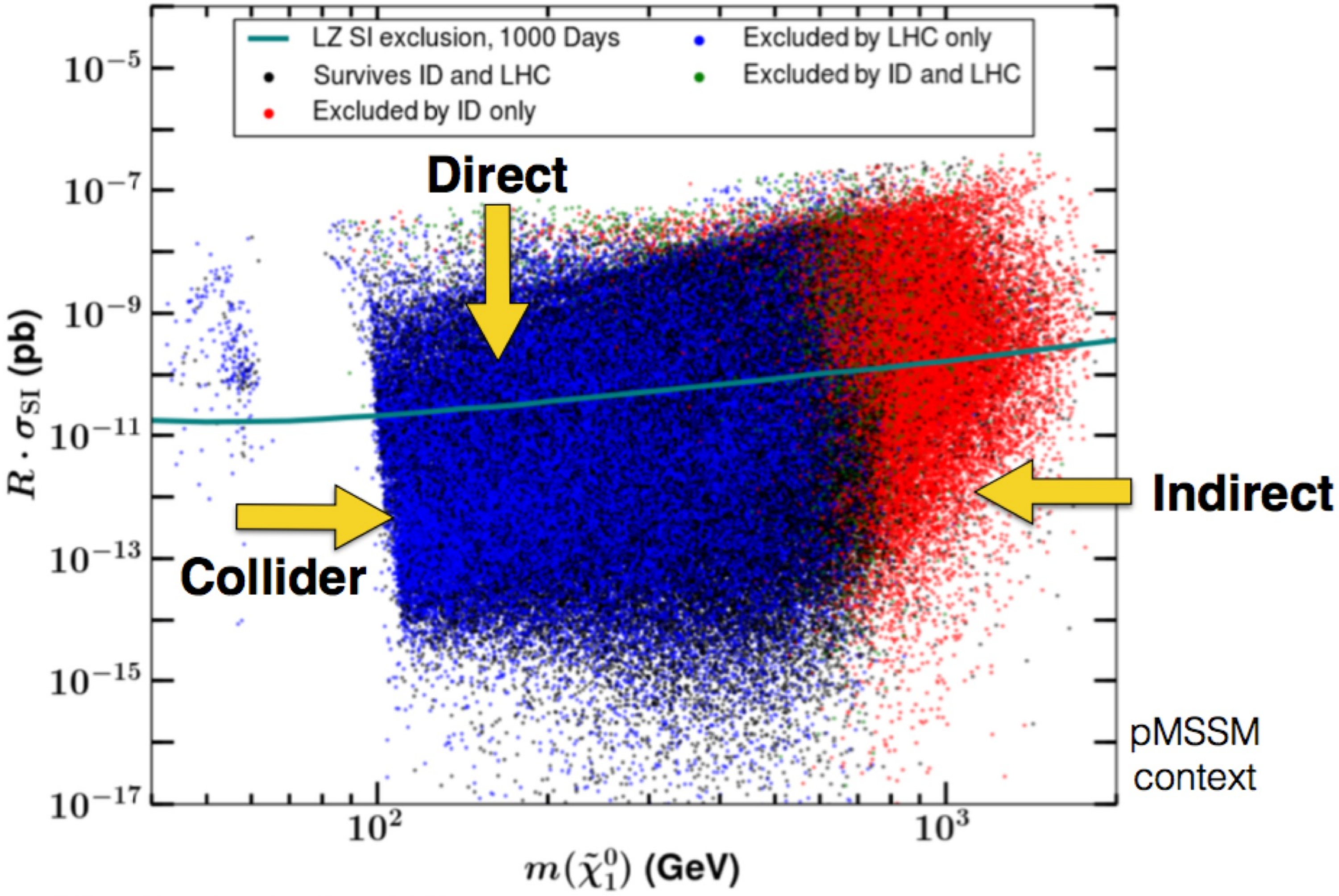


Motivated by the fact that there are no events between 400 TeV and 1 PeV, and so a fit of only events below PeV produces a softer spectrum

43% of all simulations with IC fitted unbroken powerlaw have no events between 400 TeV and 1 PeV

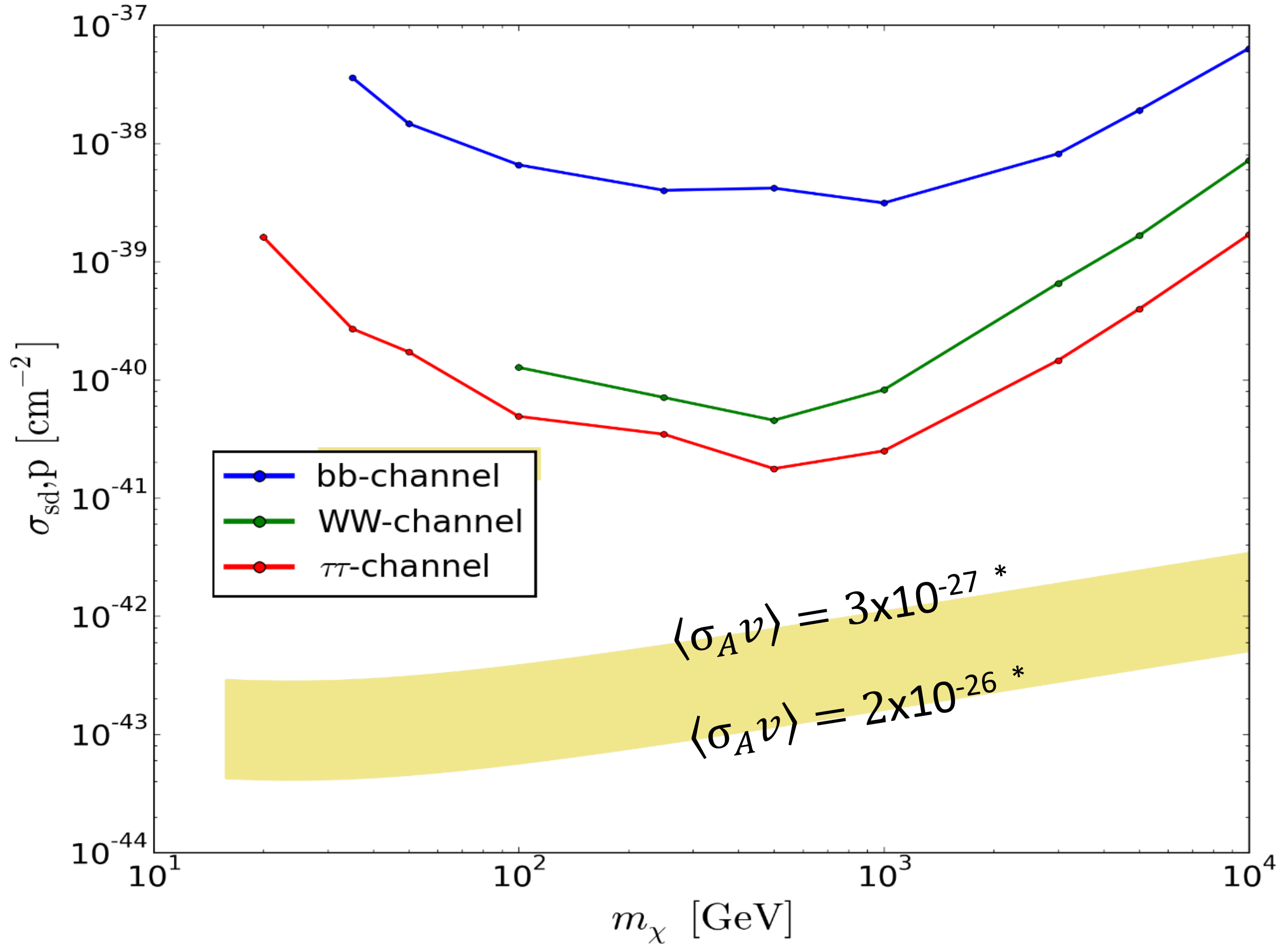
More data required

Complementarity



Cahill-Rowley et al. 2015, Phys. Rev. D, 91, 055011

Capture Annihilation Equilibrium in the Sun



There's a threshold σ_{SD} below which the equilibrium condition is not a valid assumption

$$\frac{t_\odot}{\tau_\odot} = 330\left(\frac{C_\odot}{\mathrm{s}^{-1}}\right)^{1/2}\left(\frac{\langle\sigma_A v\rangle}{\mathrm{cm}^3\ \mathrm{s}^{-1}}\right)^{1/2}\left(\frac{m_\chi}{10\ \mathrm{GeV}}\right)^{3/4},$$

Jungman and Kamionkowsky (1996)

Upcoming experiments like CTA have sensitivity towards DM $\langle\sigma_A v\rangle$ below the natural scale even at high WIMP masses

Our limits will remain above this threshold for a long time to come
Assuming $\langle\sigma_A v\rangle\sim$ natural scale.

Heavy DM decay

$DM \rightarrow \nu + \gamma$, decaying PeV DM (Gravitino for eg)

ν −telescopes are the most sensitive, since 100TeV-PeV γ-rays don't travel beyond ~10s of kPc

PRD 92, 123515 (2015)