The Niels Bohr International Academy

Neutrinos from Dark Matter

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3rd August 2016

NBIA PHD SCHOOL : NEUTRINOS UNDERGROUND AND IN THE HEAVENS

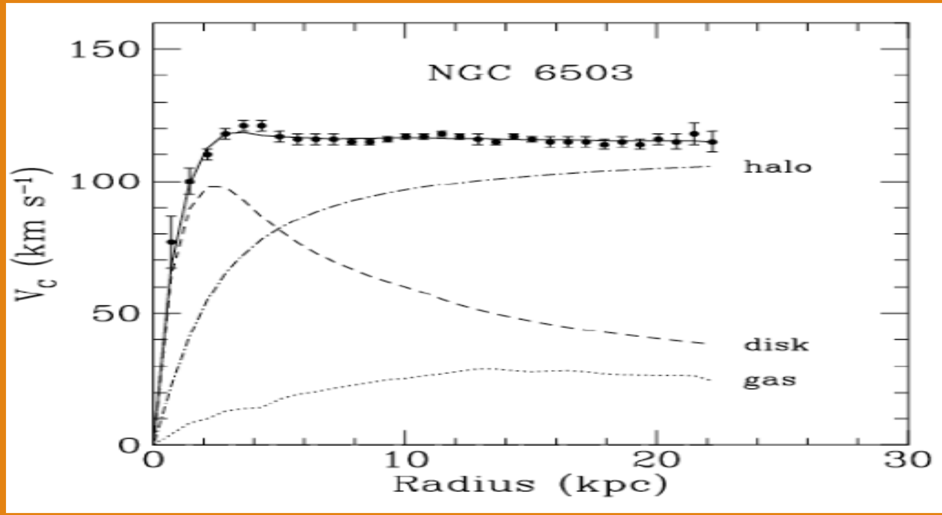
Outline

- Dark Matter
  - Evidence, Candidates
  - The WIMP Paradigm
- Dark Matter detection
- Indirect detection
  - The targets
  - The fluxes
  - DM Distributions and J factors
  - Neutrino fluxes from DM
- The instruments
- The backgrounds
- Constraints on $\langle\sigma_{ann}v\rangle$
  - Monochromatic neutrino lines
- Constraints on $\sigma_{\chi-P}$
- Complementarity
- DM interpretations of the astrophysical ν flux
- The future of ν DM searches

Dark Matter

Galactic Rotation Curves :

$$\Omega_{dm} \geq 0.1$$



- **Gravitational Lensing**

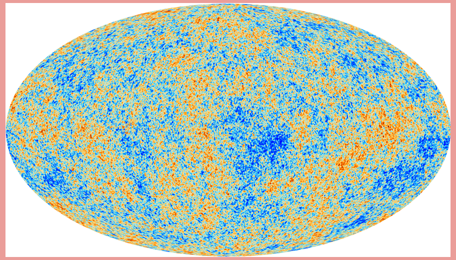
  due to galaxy Clusters:

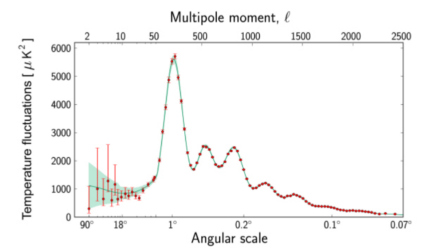
  Bullet Cluster :

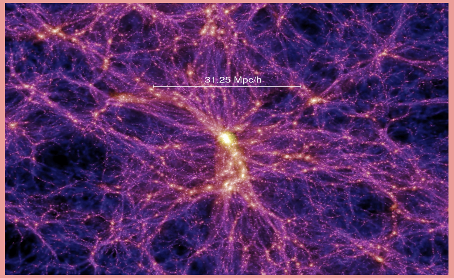
  astro-ph/0608247

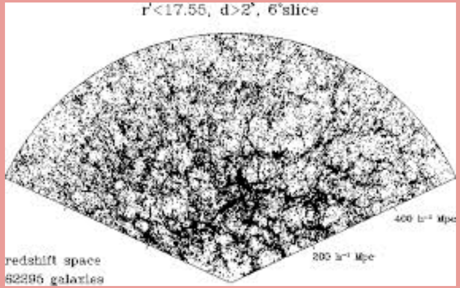
$$\Omega_{dm} \sim 0.2 - 0.4$$

Contstraint on DM self interaction









- **Precision Cosmology**
  - Planck CMB Measurements
  - Cold DM simulations such as Millenium reproduce observed LSS

$$\Omega_{dm} = 0.268 \pm 0.02$$

The DM candidates

Particle (or particle-like)

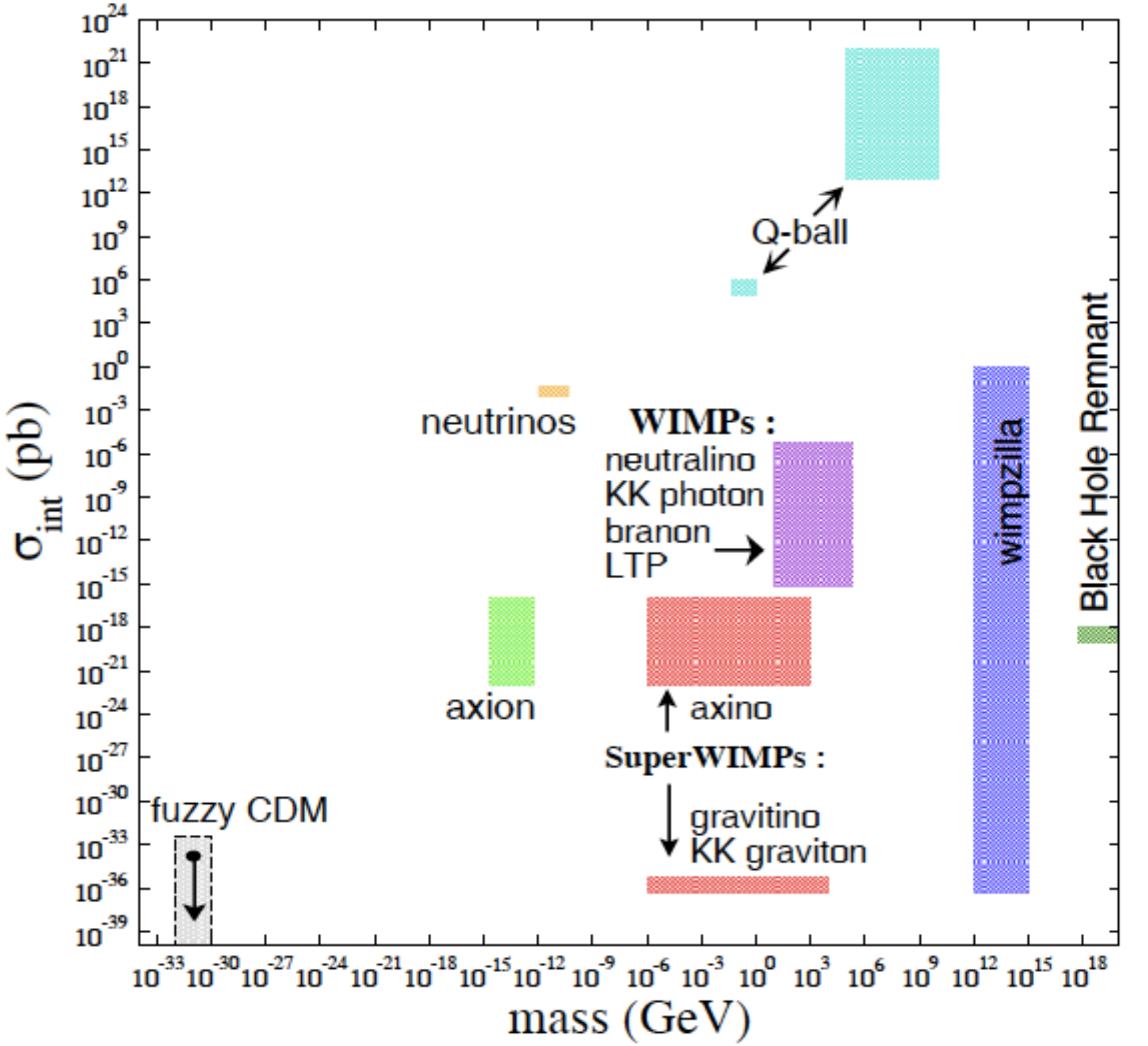
Very feebly interacting with SM particles

Stable (~ age of the universe)

(Mostly) Cold

Unknowns:

- Mass
- Spin
- Interaction cross section

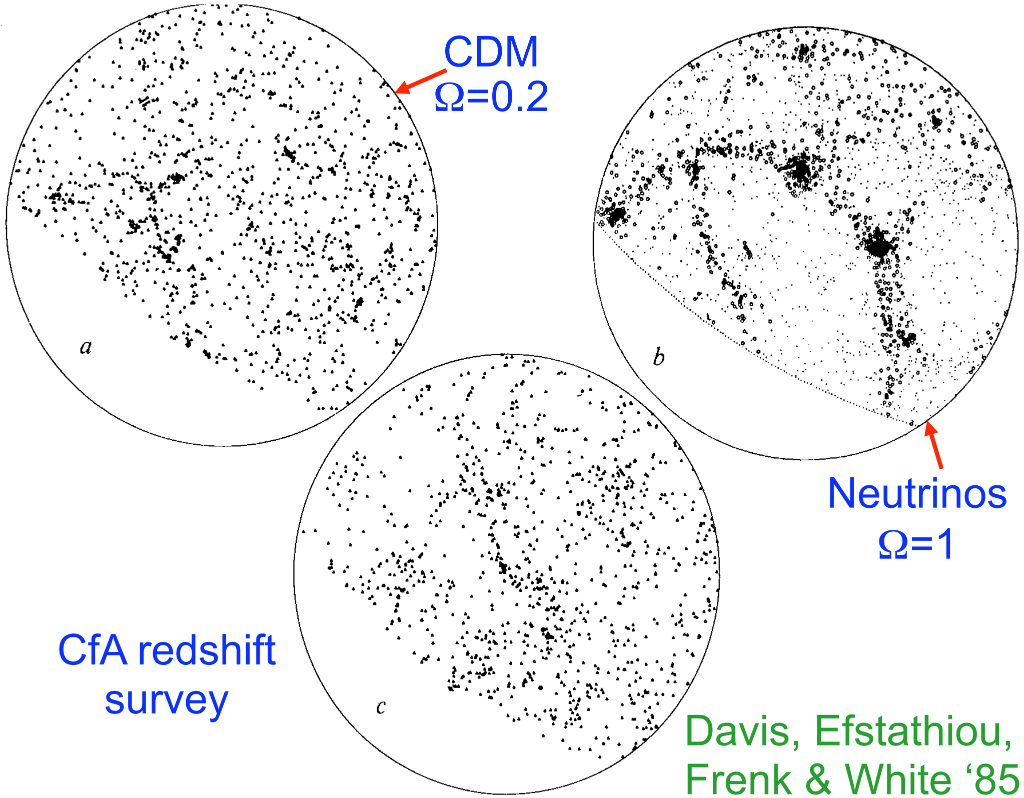


Neutrinos ~~from~~ as Dark Matter?

- 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



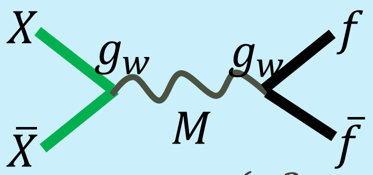
Heavy sterile neutrinos could be DM candidates

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 $\Omega_{DM} \sim 0.27$

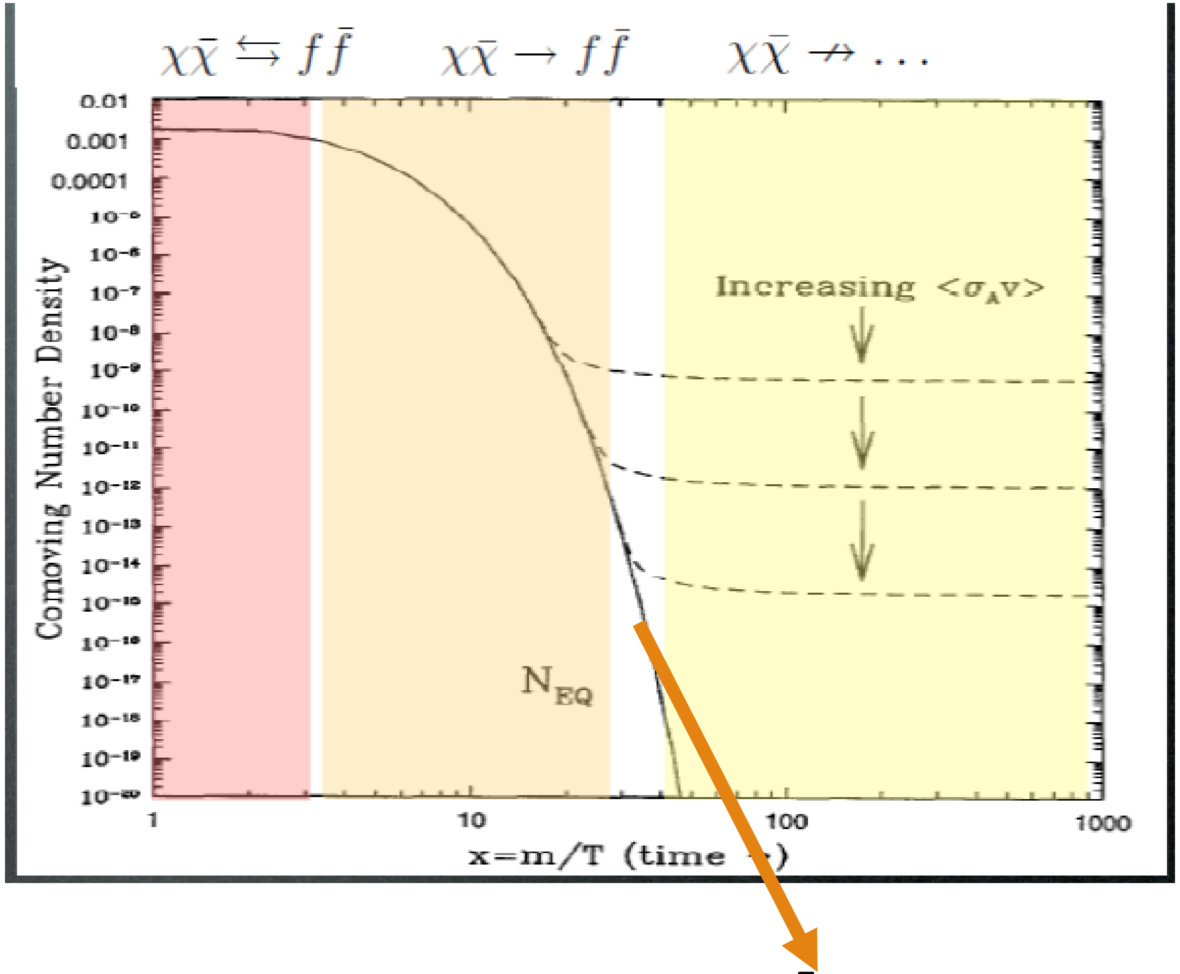
  For $\langle\sigma_{ann}v\rangle = 3\,.\,10^{-26}\ cm^3/s$



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

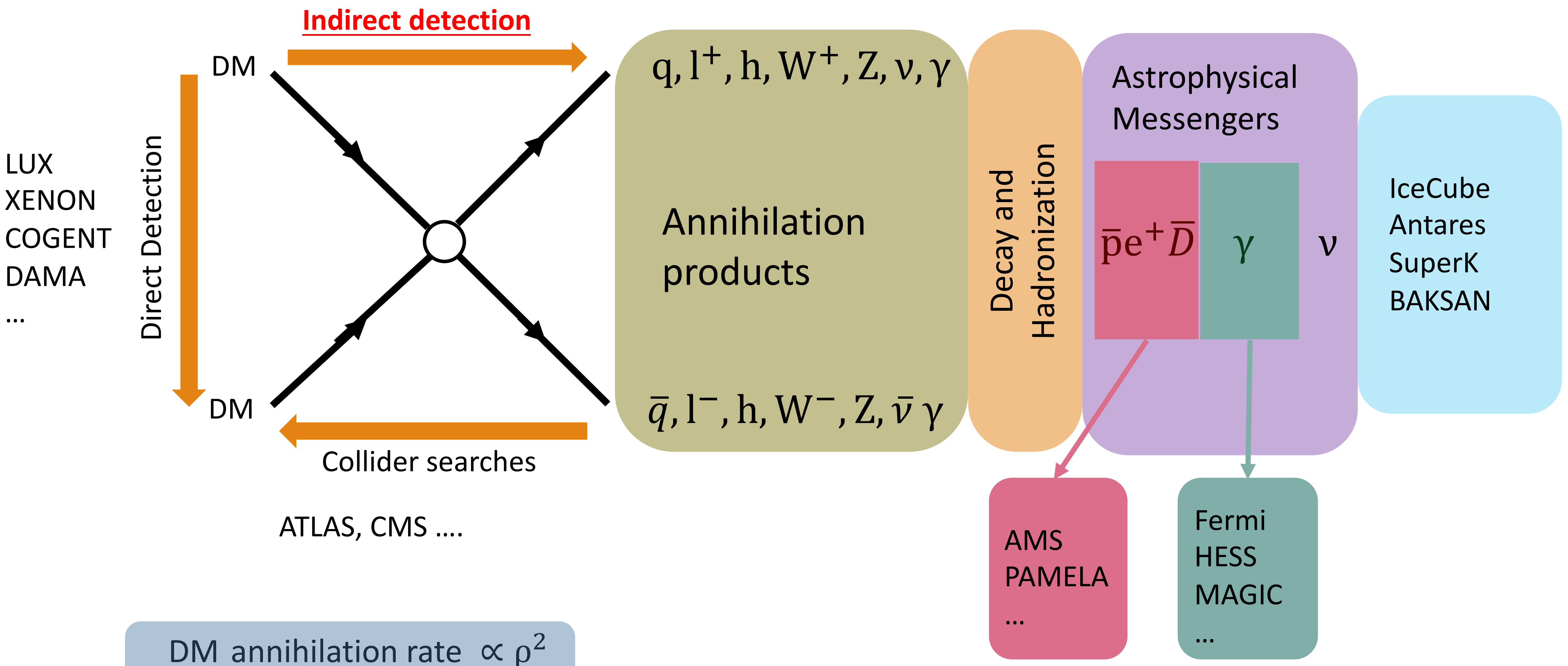
WIMP Miracle

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



Freeze out

Dark Matter Detection



DM annihilation rate $\propto \rho^2$

decay rate $\propto \rho$

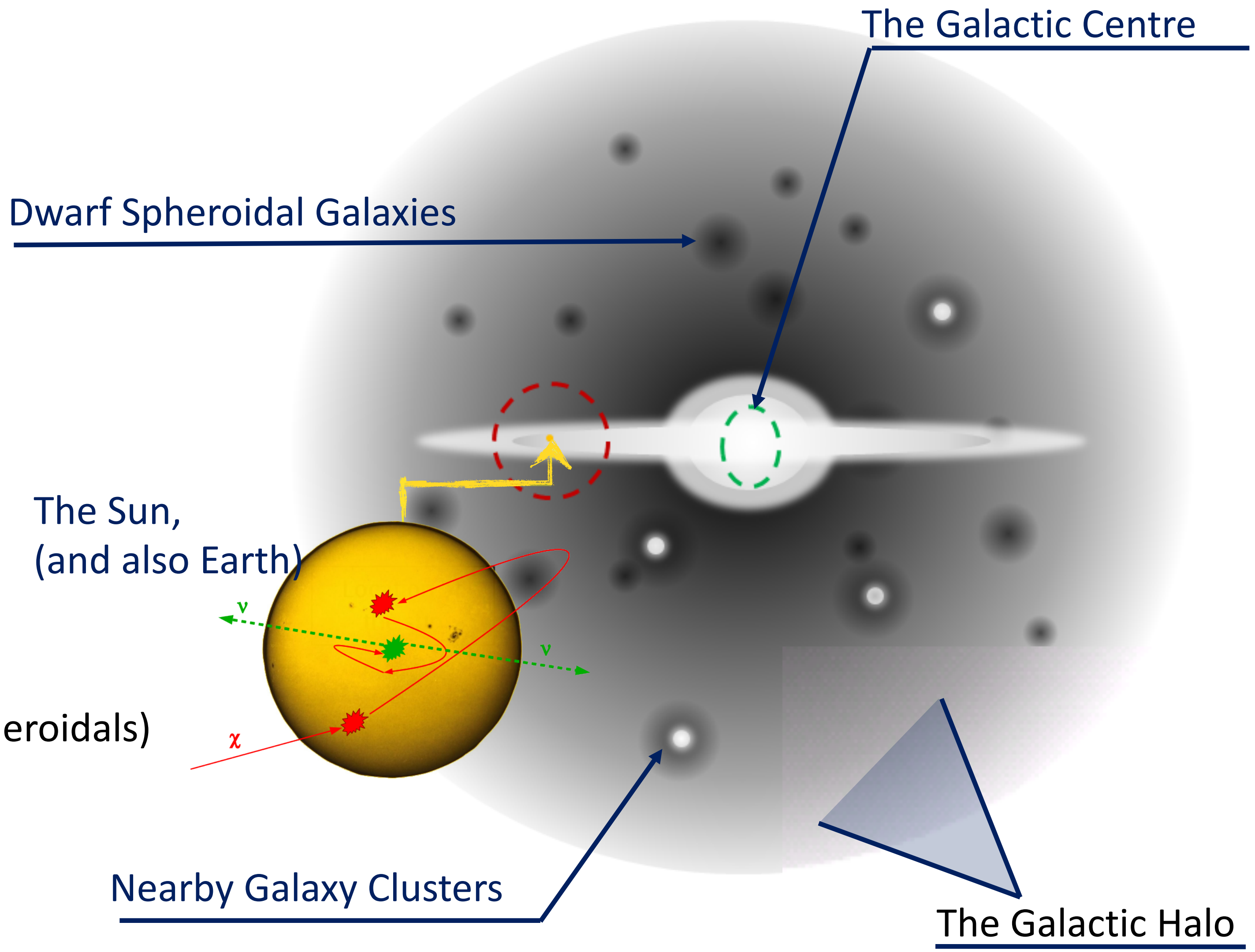
Indirect Searches – The Targets

Well understood/low astrophysical backgrounds

Also regions of high dark matter Density

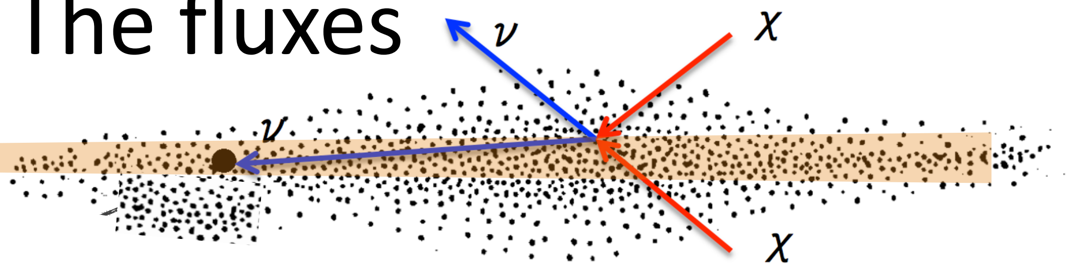
Search for:

- 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

Detector



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

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)

$$\mathrm{J} = \iint \rho^2\,(\mathrm{l},\Omega)\mathrm{dld}\Omega$$

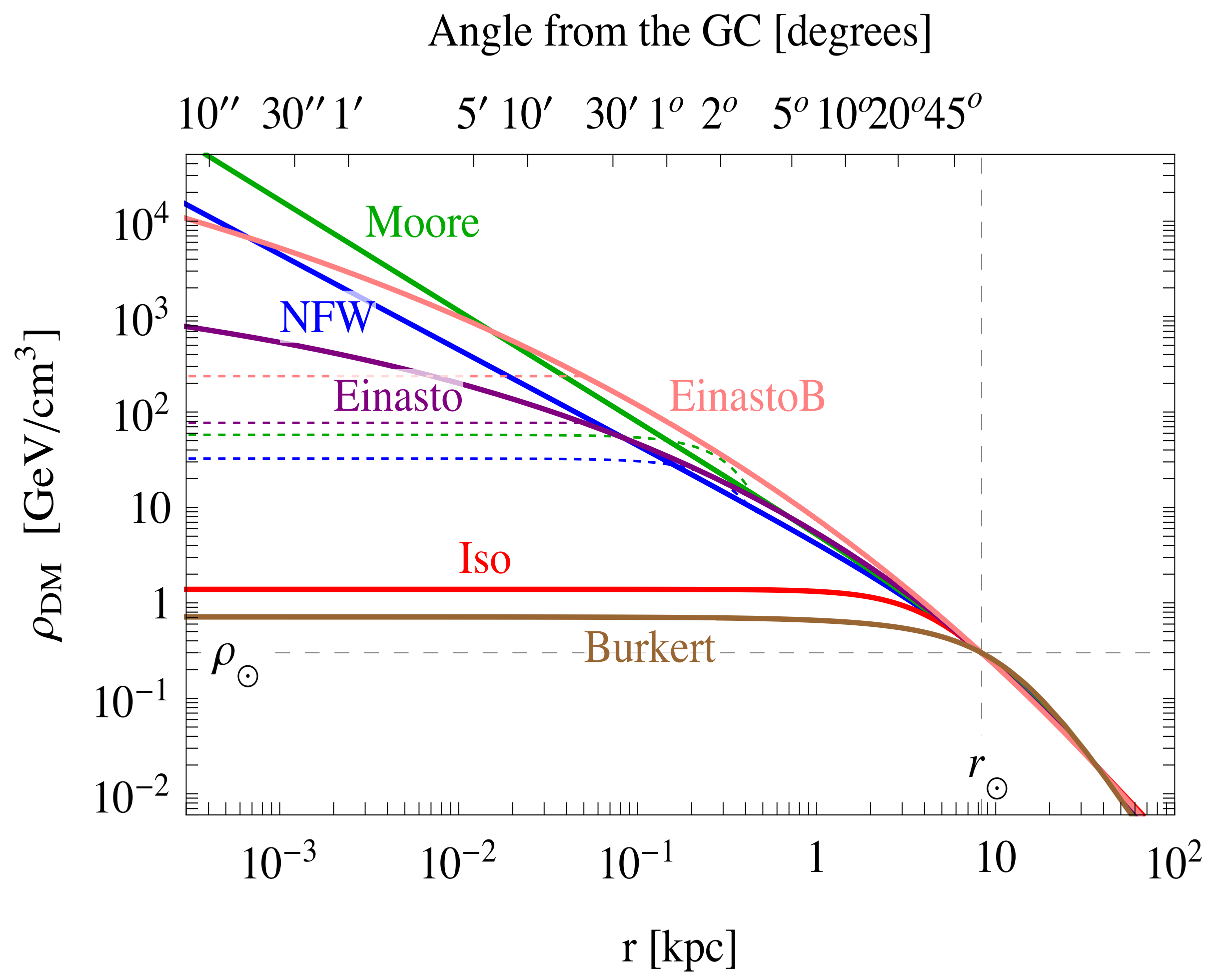
For annihilating DM

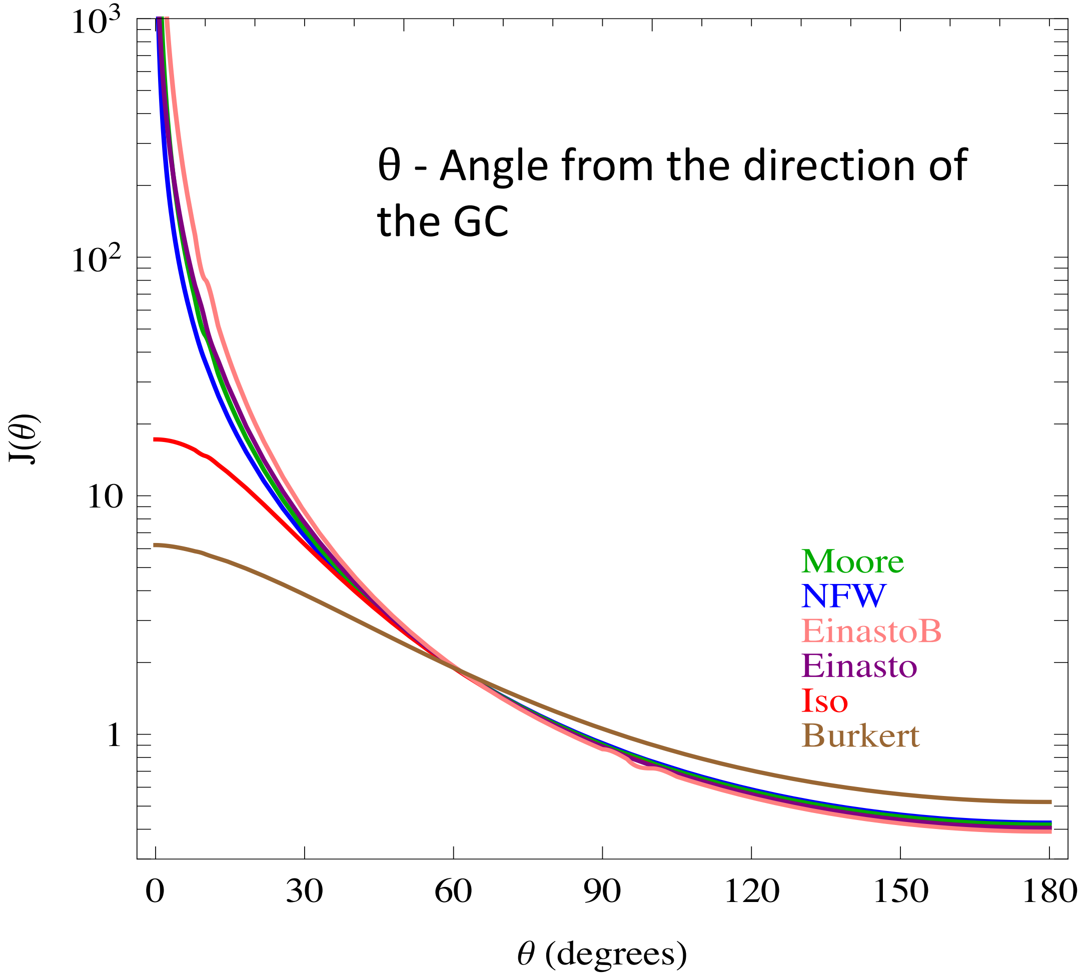
$$\mathrm{D} = \iint \rho\,(\mathrm{l},\Omega)\mathrm{dld}\Omega$$

For decaying DM

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

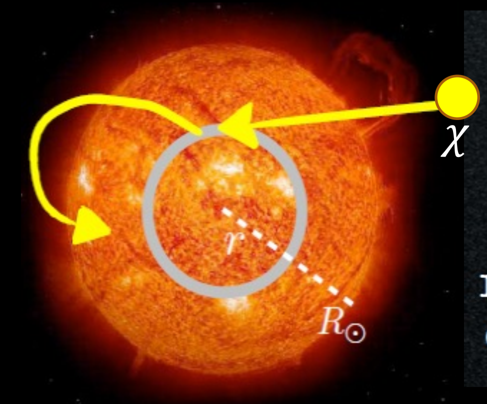
DM distributions and J factors





θ - Angle from the direction of the GC

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

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

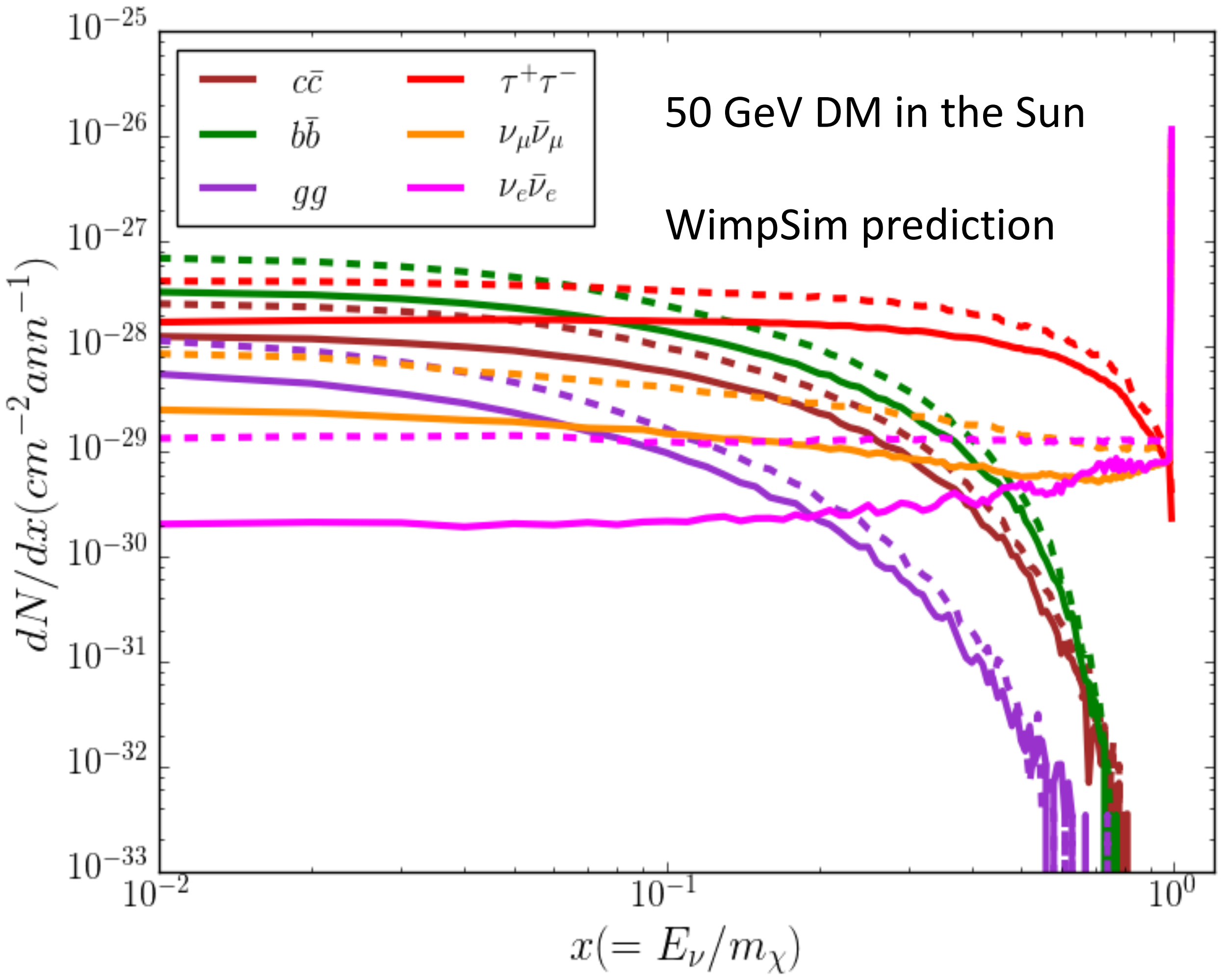
The secondary annihilation products can interact in the dense baryonic environment inside the Sun

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

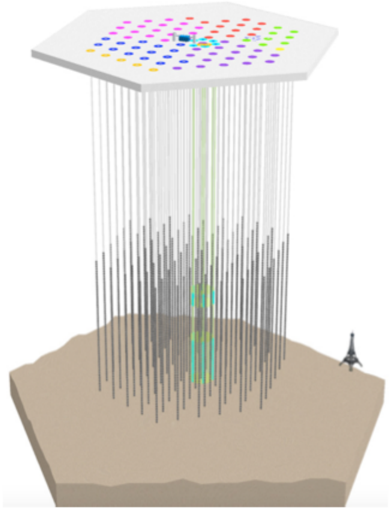


- 'Hard' channel : $\tau^+\tau^-$, W^+W^-,$\nu\bar{\nu}$
    - Produces many neutrinos at energies close to DM mass.
- 'Soft' channel: gg, $b\bar{b}$
    - Produces neutrinos at lower energies

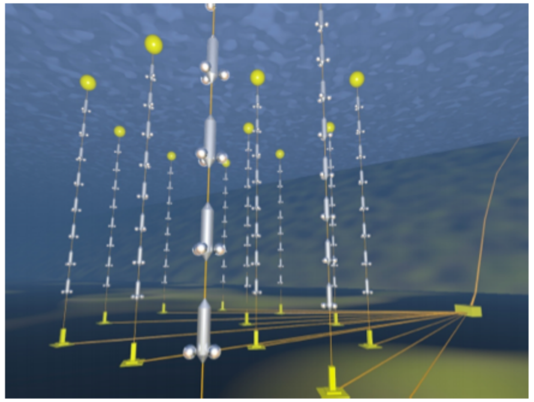
$\nu - nucleon$ cross sections (and hence effective areas of the detectors) also increase with energy, compounding the effect

Indirect Searches with ν - The instruments

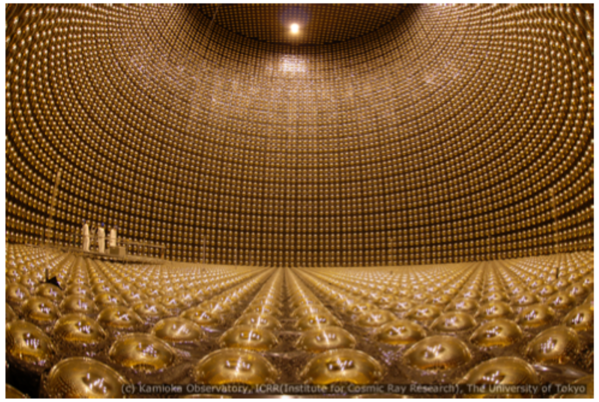
IceCube/DeepCore



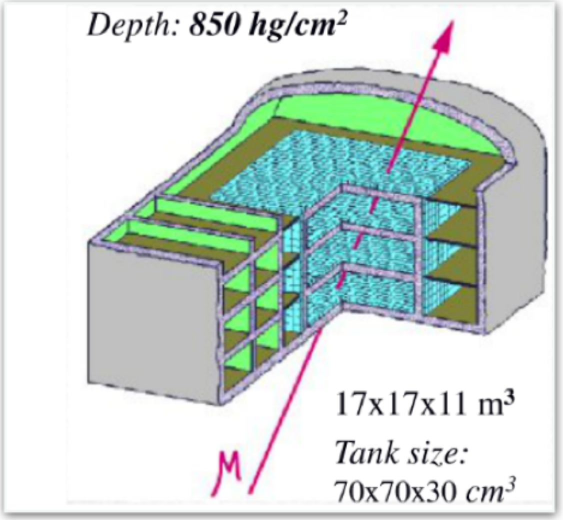
ANTARES



Super-K



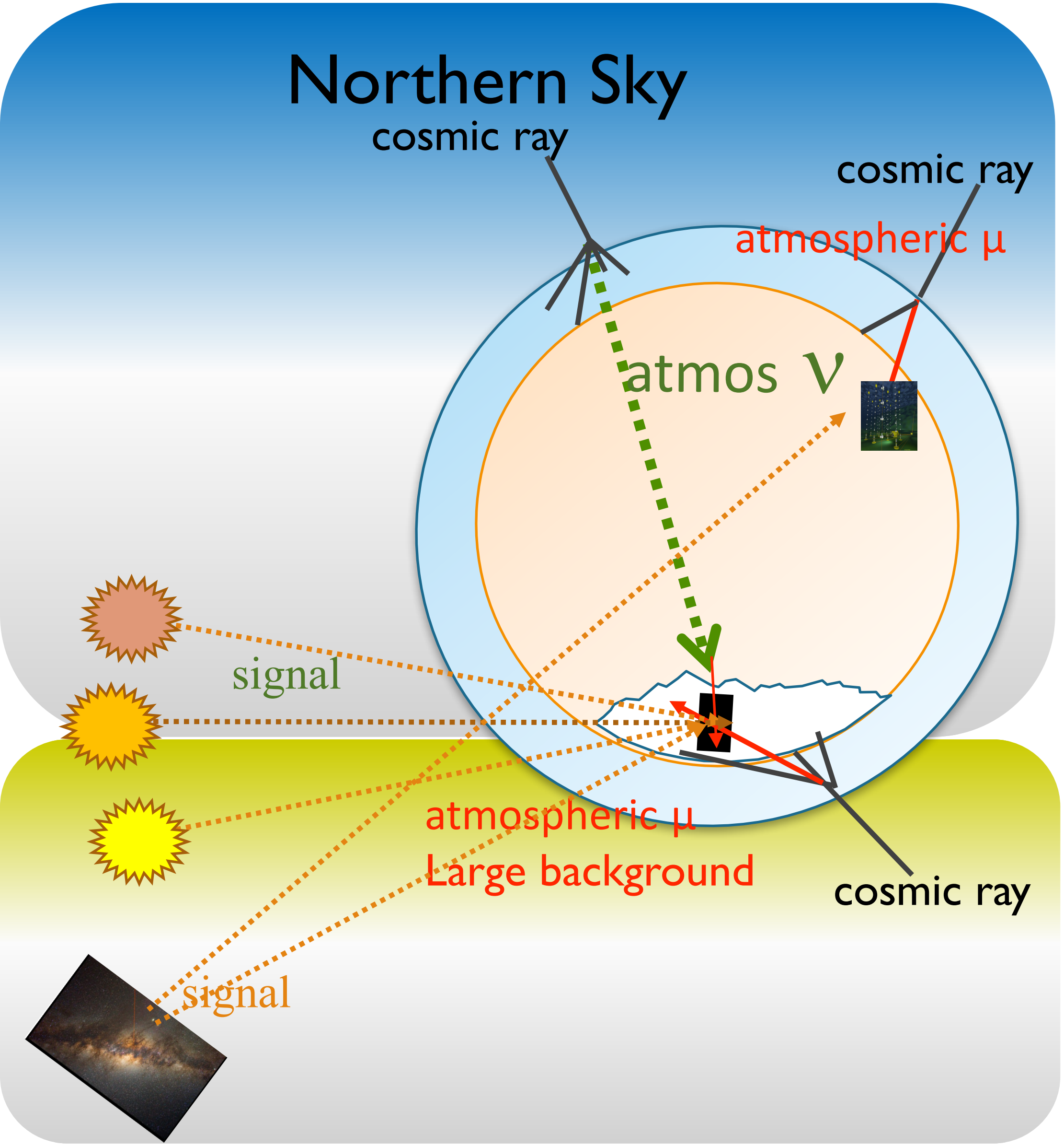
Baksan



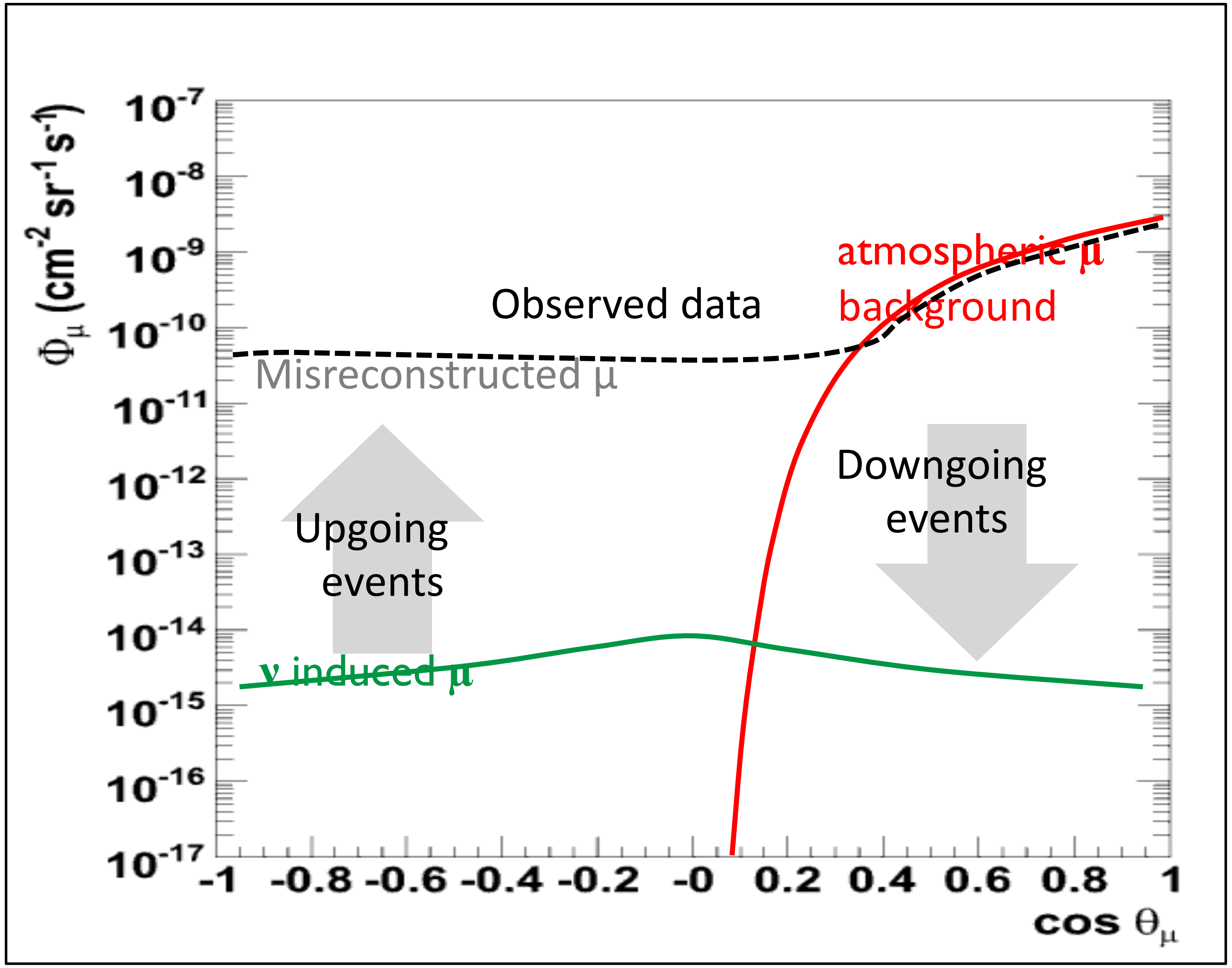
	E_ν-range (GeV)	Instrumented volume (ton)	$\overline{\Theta}$ (°) at E_ν 25 / 100 / 1000 GeV
IceCube	$\gtrsim 10^*$	~1 Gton	13 / 3.2 / 1.3
ANTARES	$\gtrsim 10$	~20 Mton	6 / 3.5 / 1.6
Super-K	$\gtrsim 0.1$	~50 kton	1-1.4‡
Baksan	$\gtrsim 1$‡	~3 kton	1.5‡ (tracks > 7 m)

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

The backgrounds

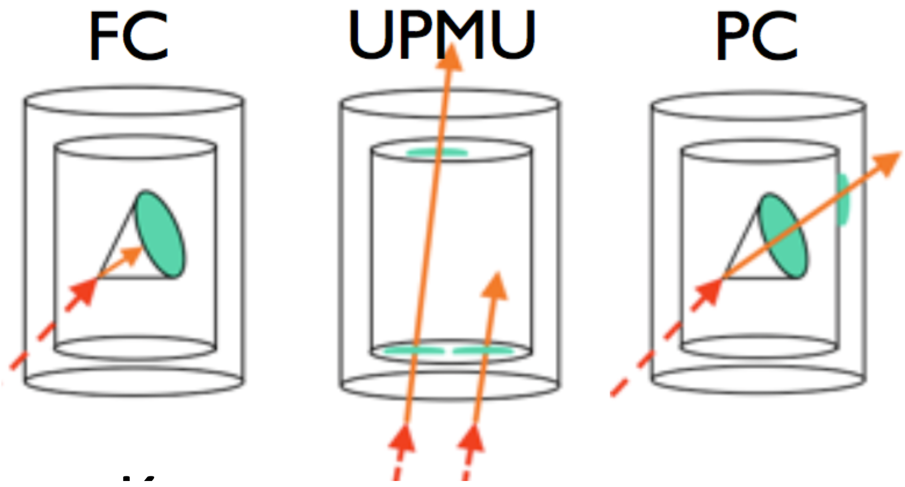


Example : IceCube



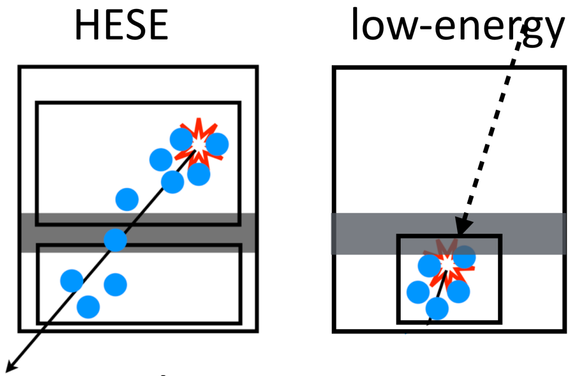
Indirect Searches with νs- Improvements in Analysis methods

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 ~3 years, sensitivities have improved by ~an order of magnitude in most searches

No signal yet.

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

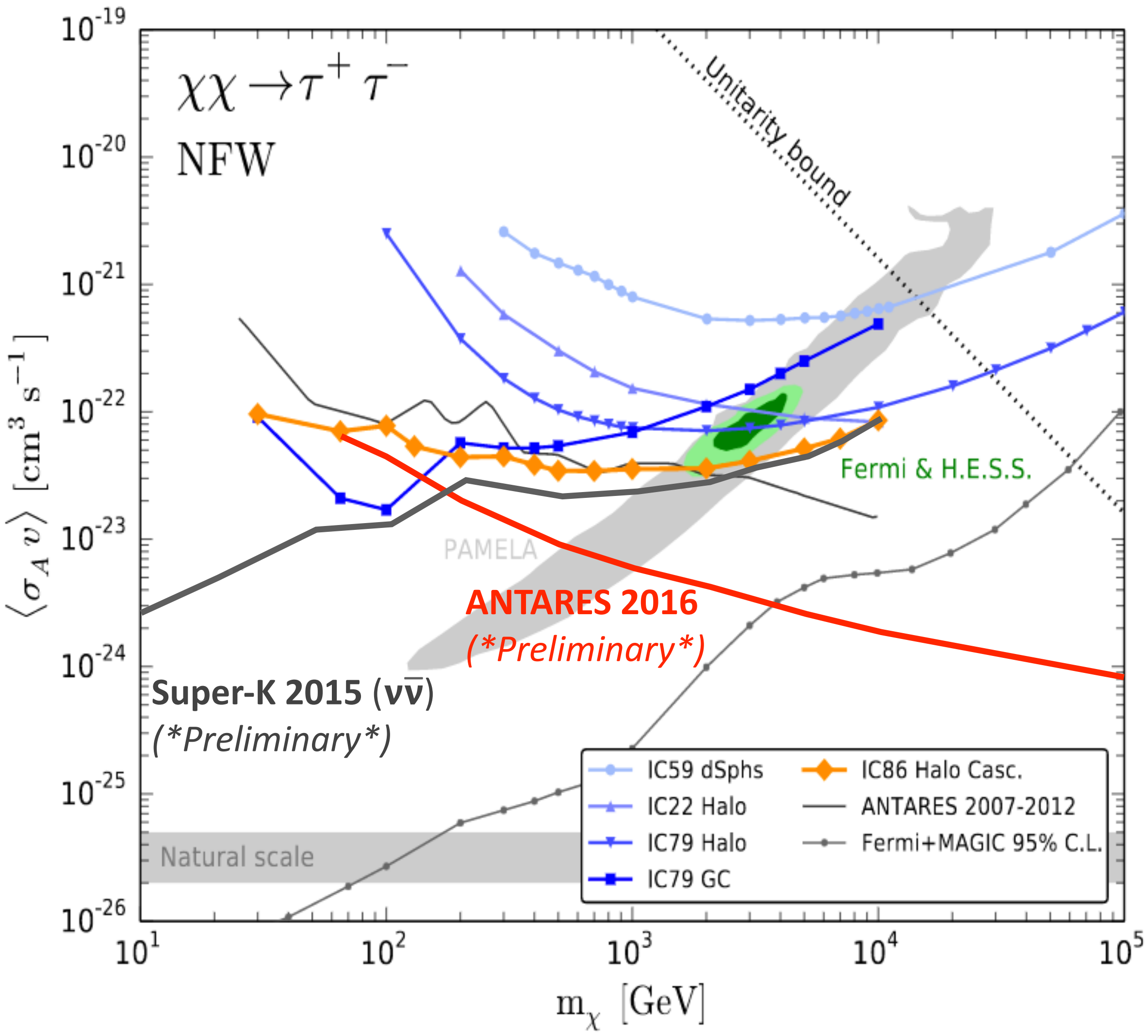
Searches targeting the GC, Halo, Dwarf Spheroids or Galaxy Clusters

Can test parameter space favoured by the DM interpretation of the rise in e^+/e^- fraction as measured by PAMELA and AMS

Antares constraints are better (it can see the GC through Earth)

GC is above the horizon for IceCube

SuperK constraints go down to 1 GeV WIMP mass

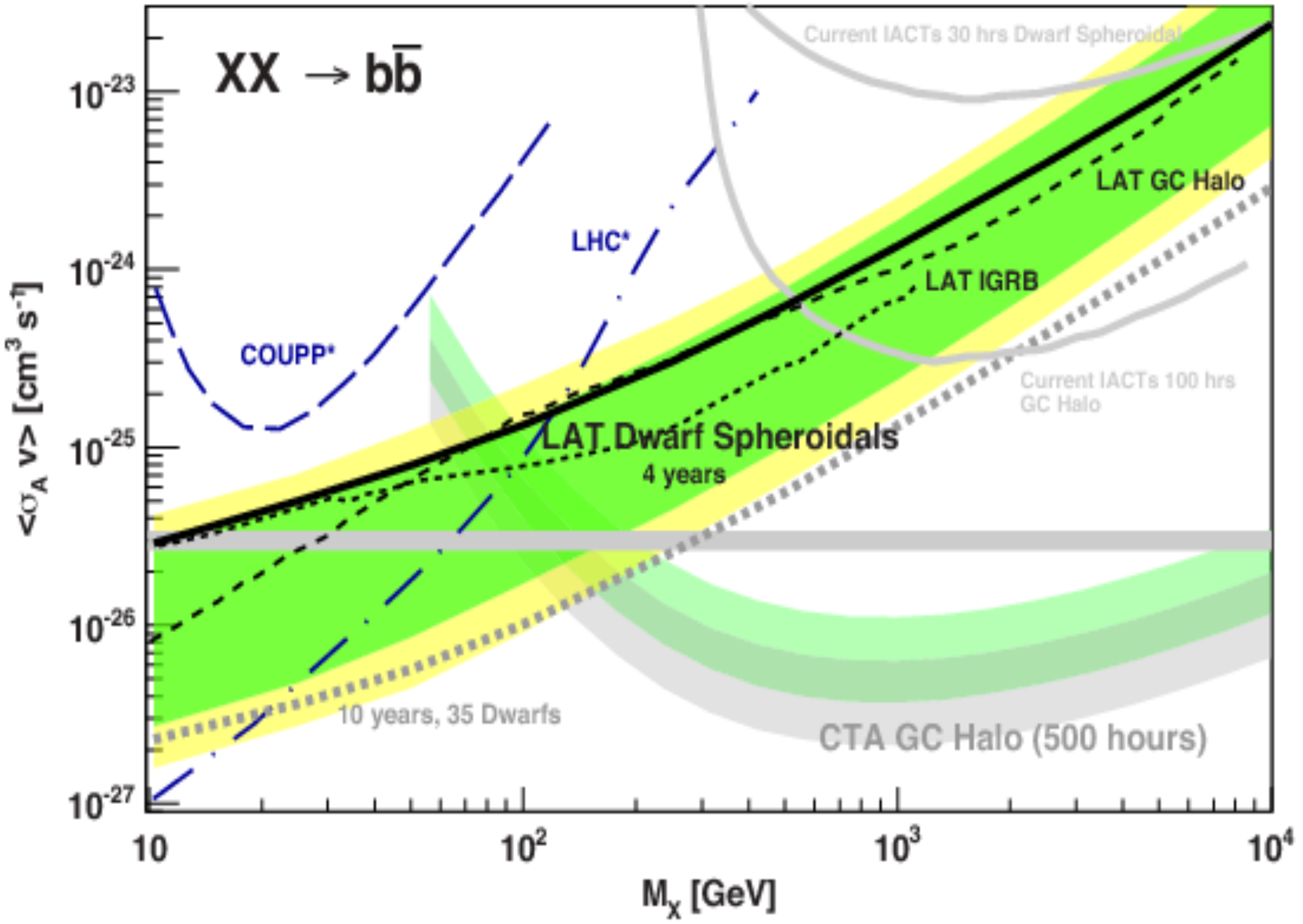


Constraints on $\langle \sigma_{ann} v \rangle$

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.

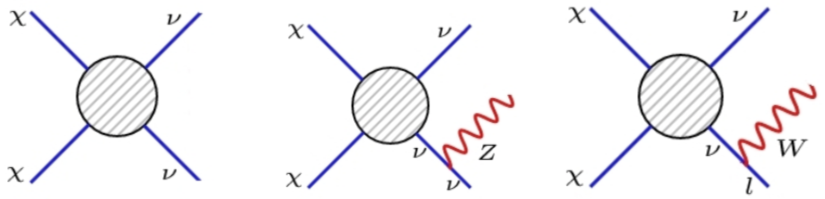
ν searches have lower astrophysical uncertainties and foregrounds



Monochromatic Neutrino Lines

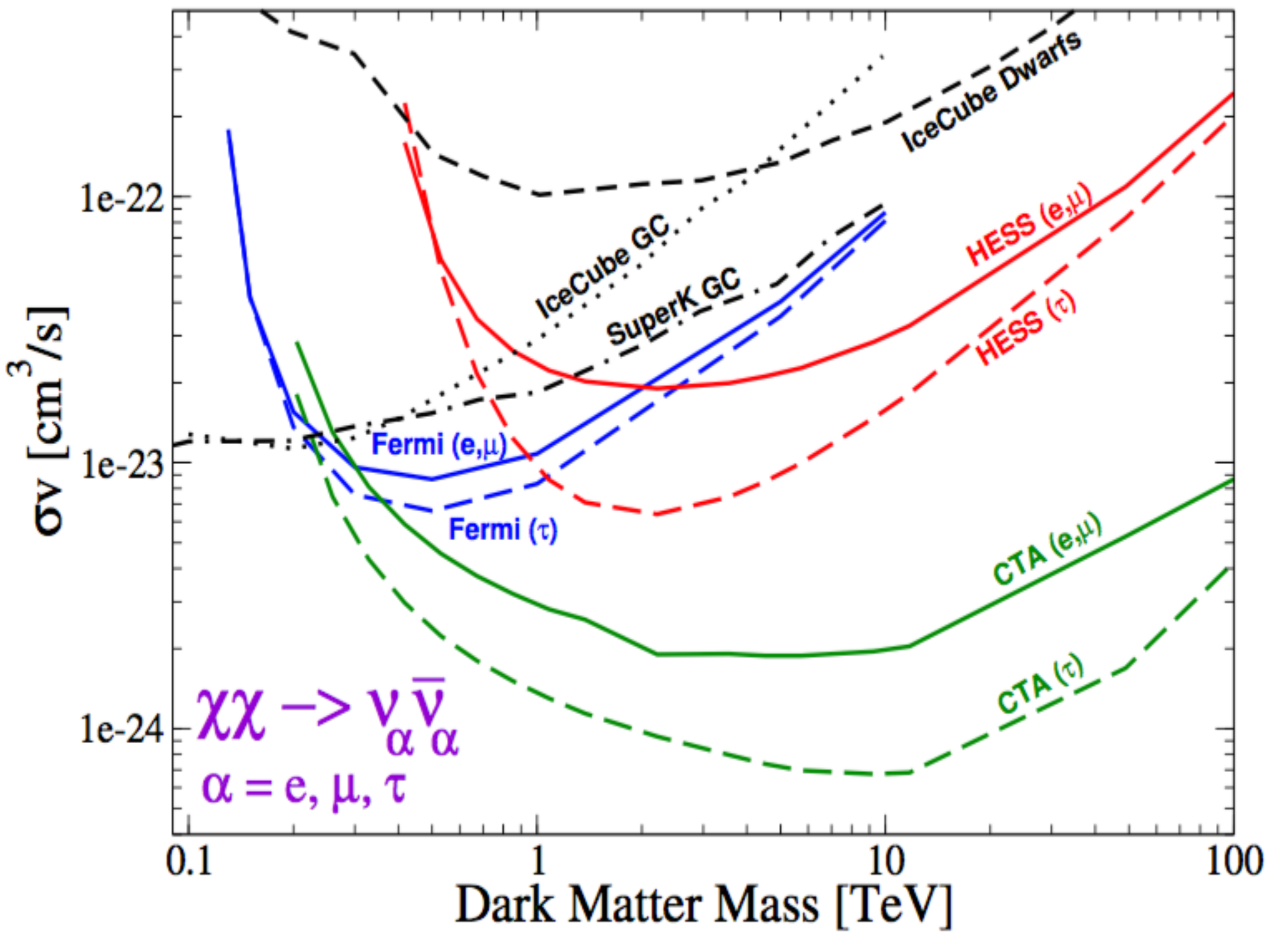
$\chi\chi \to \nu\nu$, a neutrino line at the DM mass.

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



γ-ray constraints are still stronger

JCAP 05 (2016) 050



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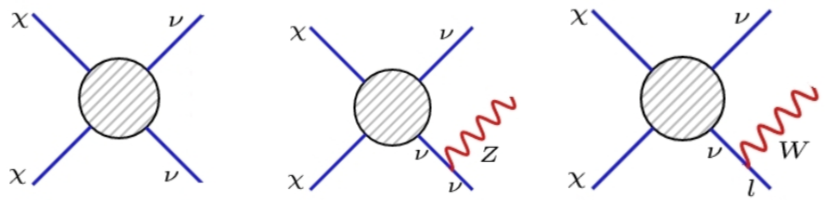


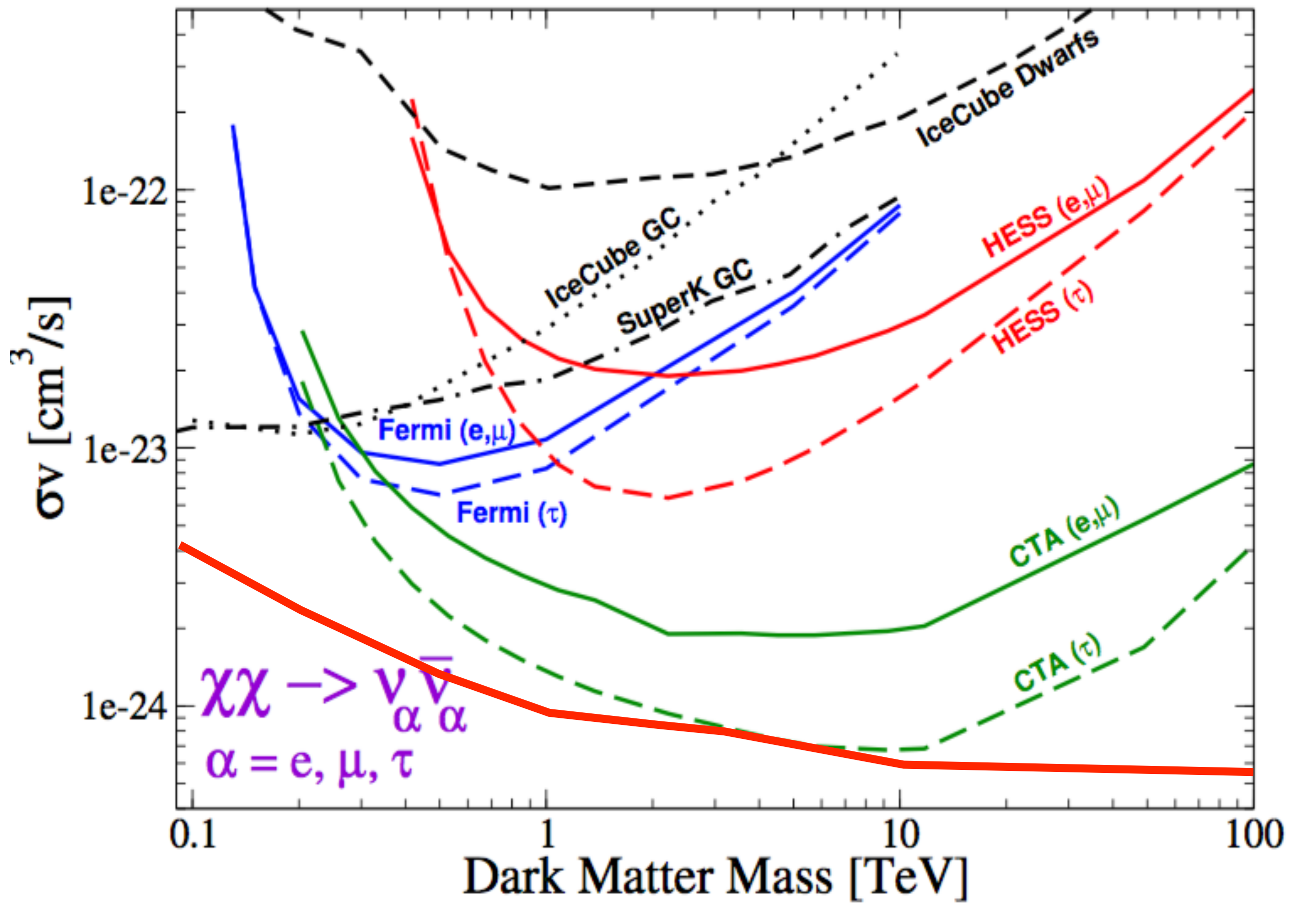
Recent Antares analysis might have better constraints

Only ν telescopes can really identify a ν line

Danninger, Neutrino 2016

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

JCAP 05 (2016) 050



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

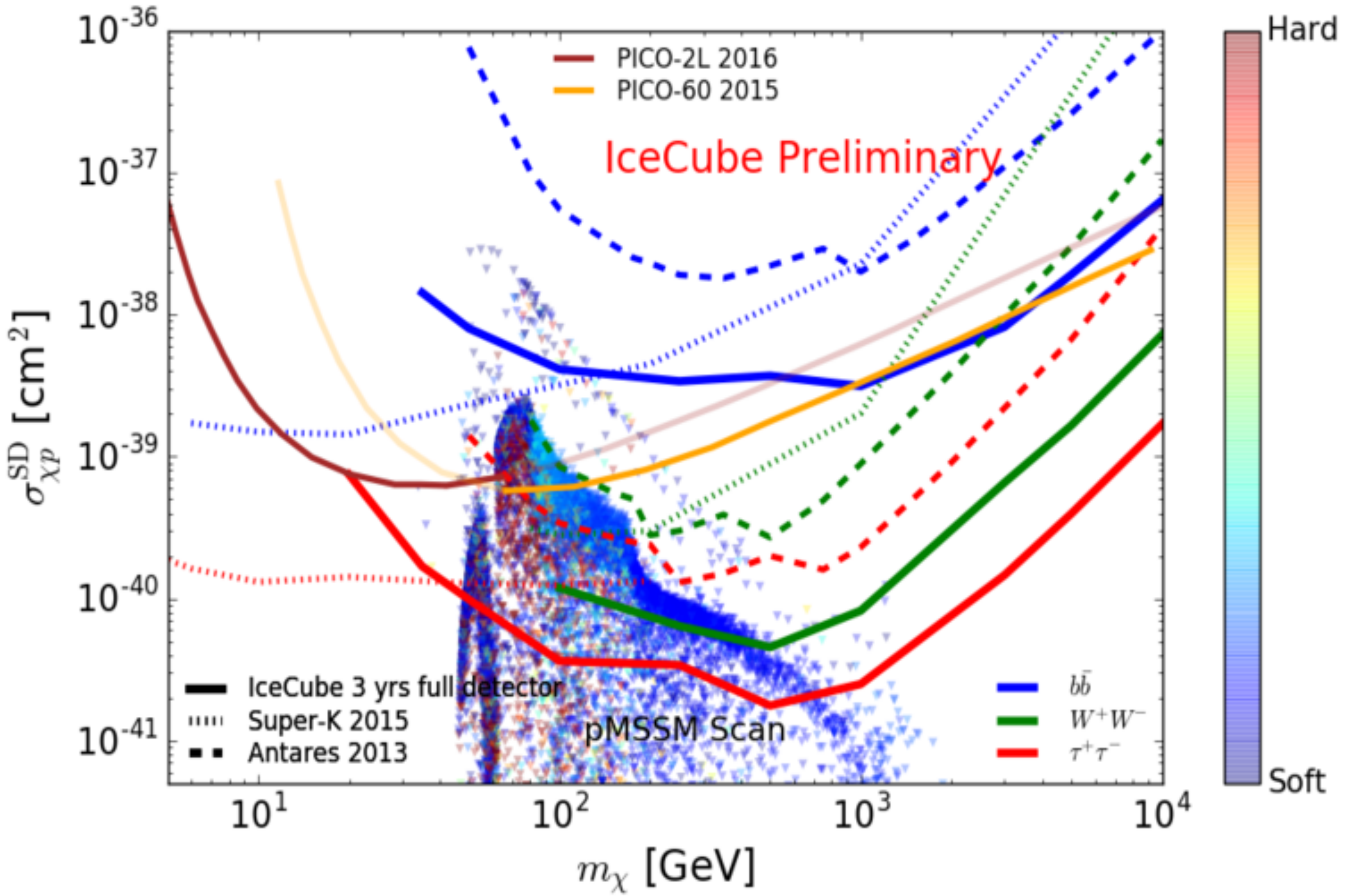
For spin dependent scattering, where

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

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/cm³



pMSSM models colour coded by hardness of predicted neutrino spectrum

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

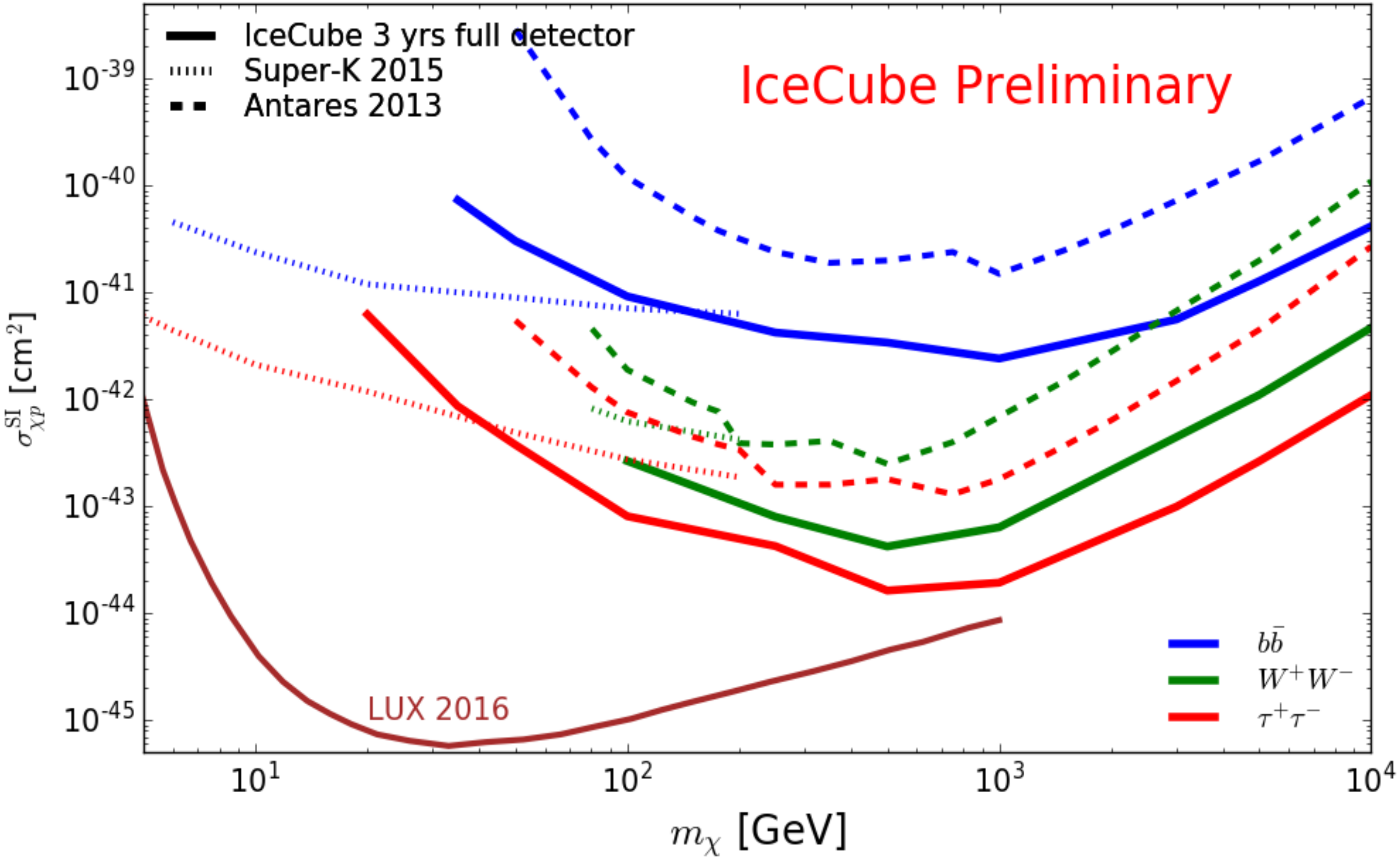
DD experiments have more stringent constraints for Spin Independent scattering:

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

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)**

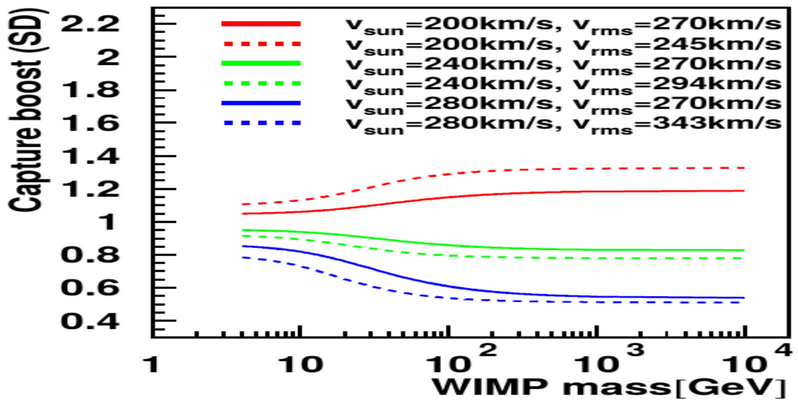


Apart from SD and SI, velocity and momentum suppressed interactions possible at the NR limit. **JCAP 1504 (2015) no.04, 052**

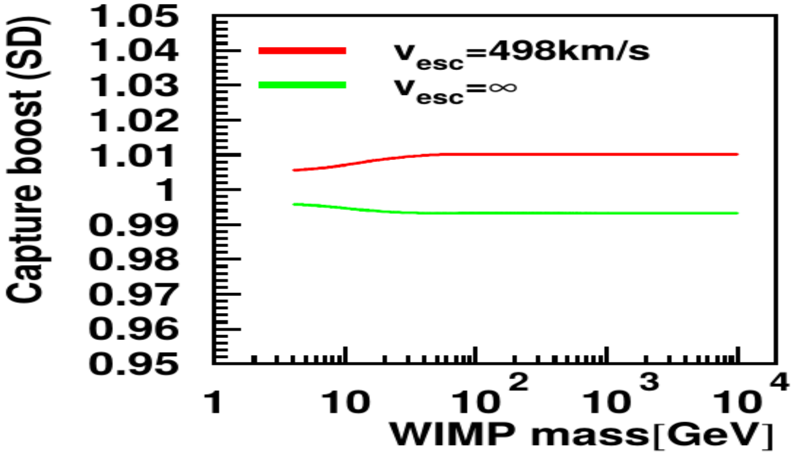
Astrophysical Uncertainties

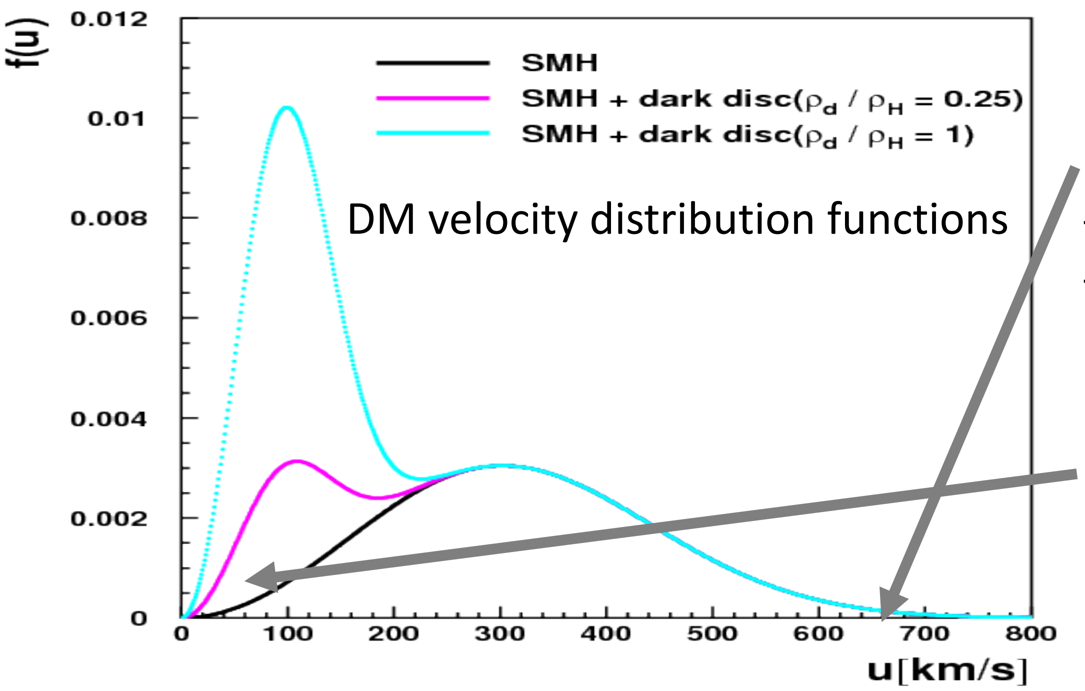
There are uncertainties on:

- 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

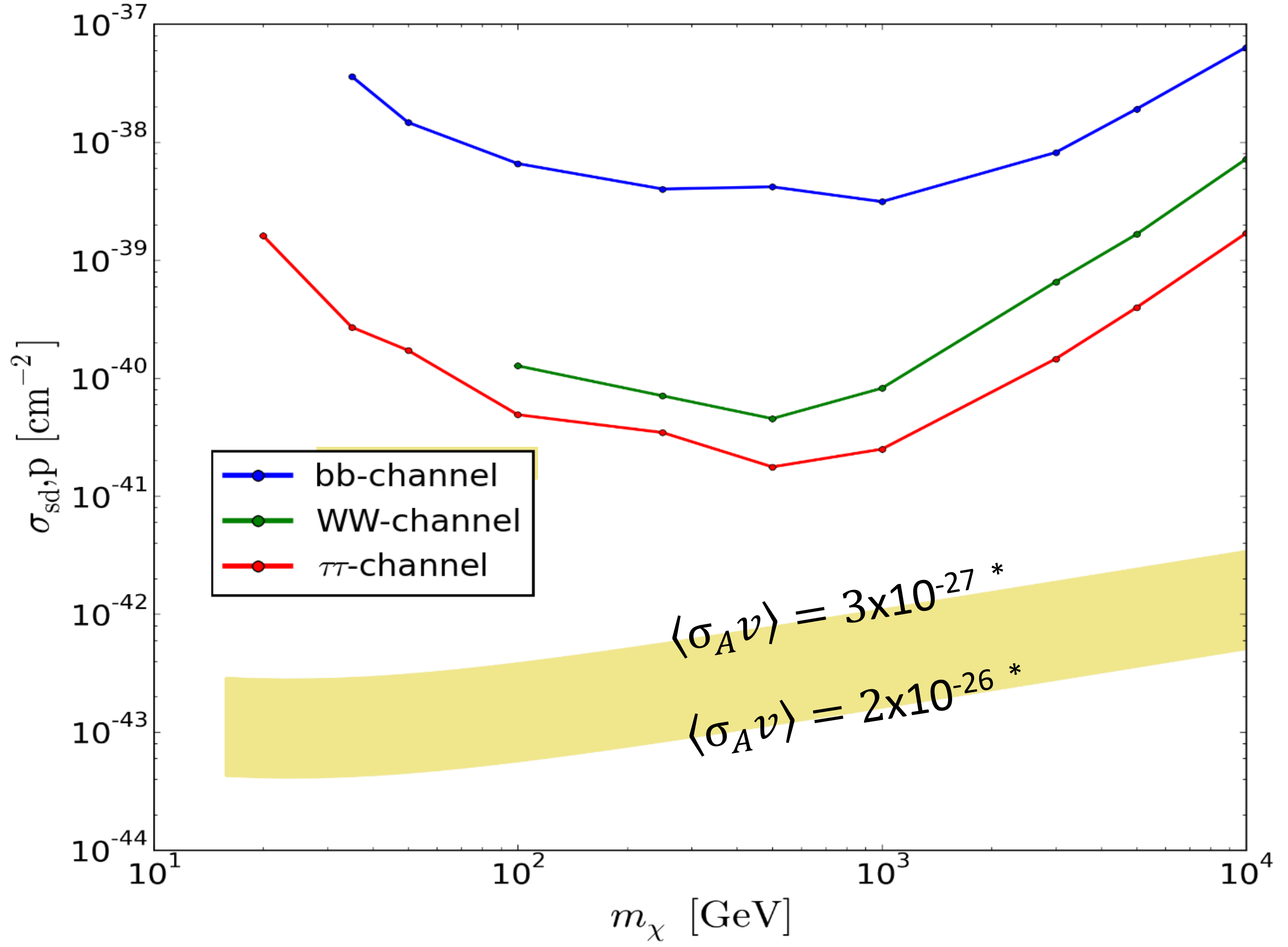
Solar capture is more likely for slower particles

C. Rott et al. JCAP05 (2014) 049

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

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

Capture Annihilation Equilibrium in the Sun



Our limits will remain above this threshold for a long time to come

Assuming $\langle\sigma_A v\rangle\sim$ natural scale.

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

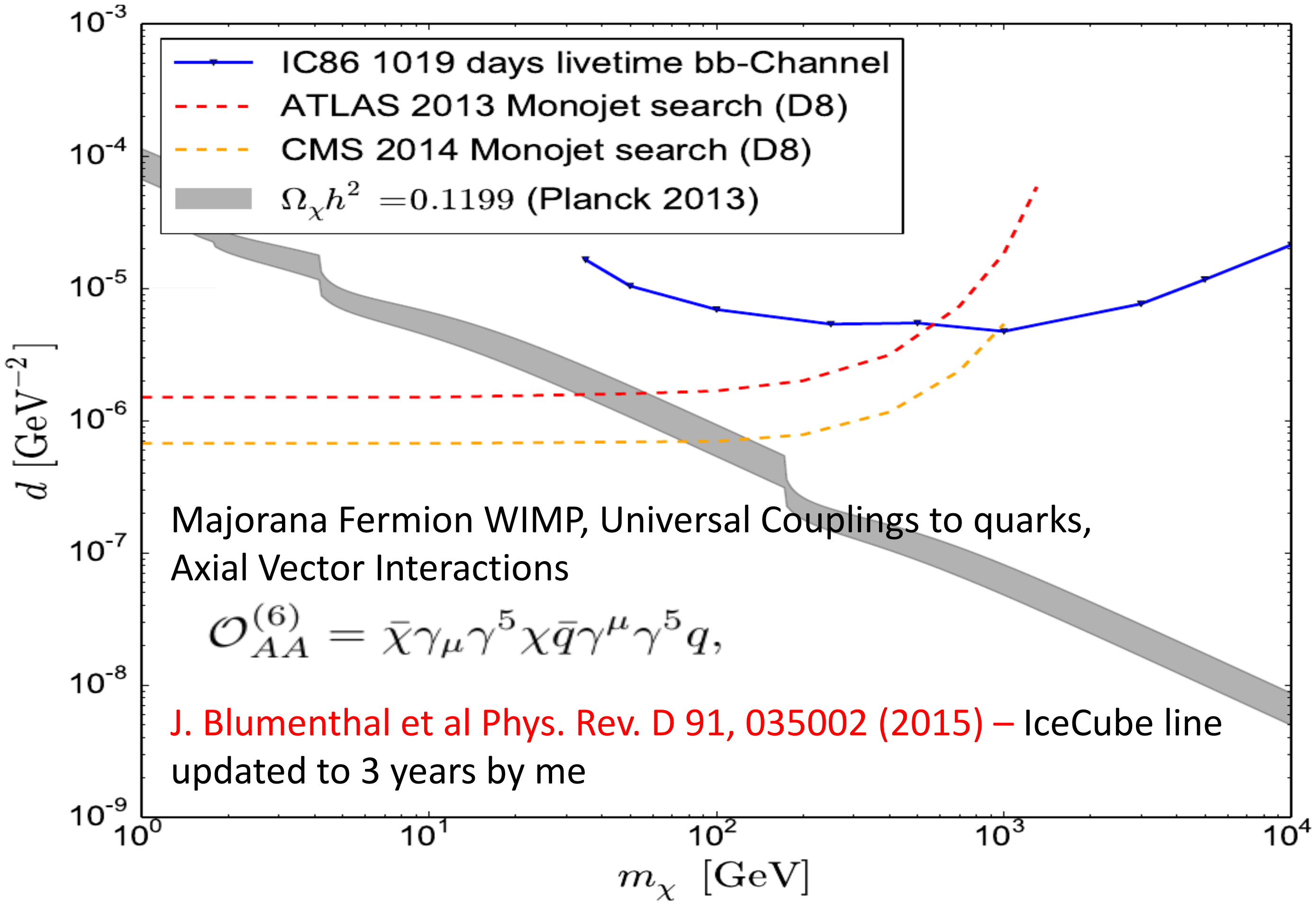
$$\frac{t_\odot}{\tau_\odot} = 330\left(\frac{C_\odot}{\mathrm{s}^{-1}}\right)^{1/2}\left(\frac{\langle\sigma_A v\rangle}{\mathrm{cm}^3\ \mathrm{s}^{-1}}\right)^{1/2}\left(\frac{m_\chi}{10\ \mathrm{GeV}}\right)^{3/4},$$

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

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



EFT

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

Complementarity : LHC Motivated DM models - the 750 GeV Diphoton excess

A pseudoscalar, P of mass 750 GeV:

- Scattering is SD at the NR limit

750 GeV > Ewk Scale

- Lagrangian is $SU(2)_L$ invariant, P couples to B.
- Guarantees annihilation to ZZ and Zγ

P also couples to gluons and/or quarks

- Run 1 constraints

DM χ (fermion) or ϕ (scalar) stable under Z_2 symmetry.

3 scenarios.

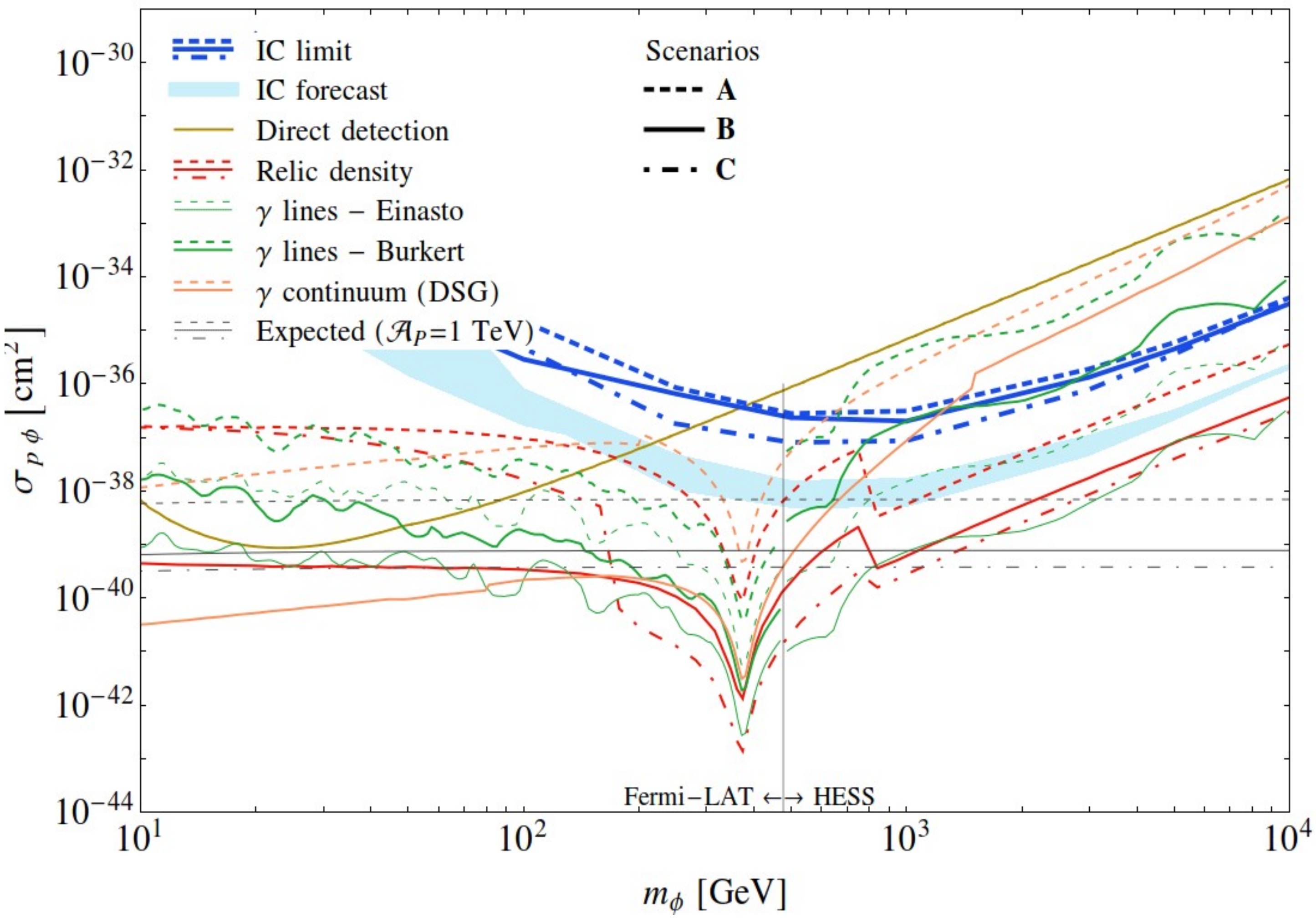
P couples to :

- B, g, u, χ
- B, g, u, χ, b
- B, g, u, χ, t

WIMP-proton scattering in the NR limit

$i(\hat{S}_N.\frac{\hat{q}}{m_N})$ for scalar DM and

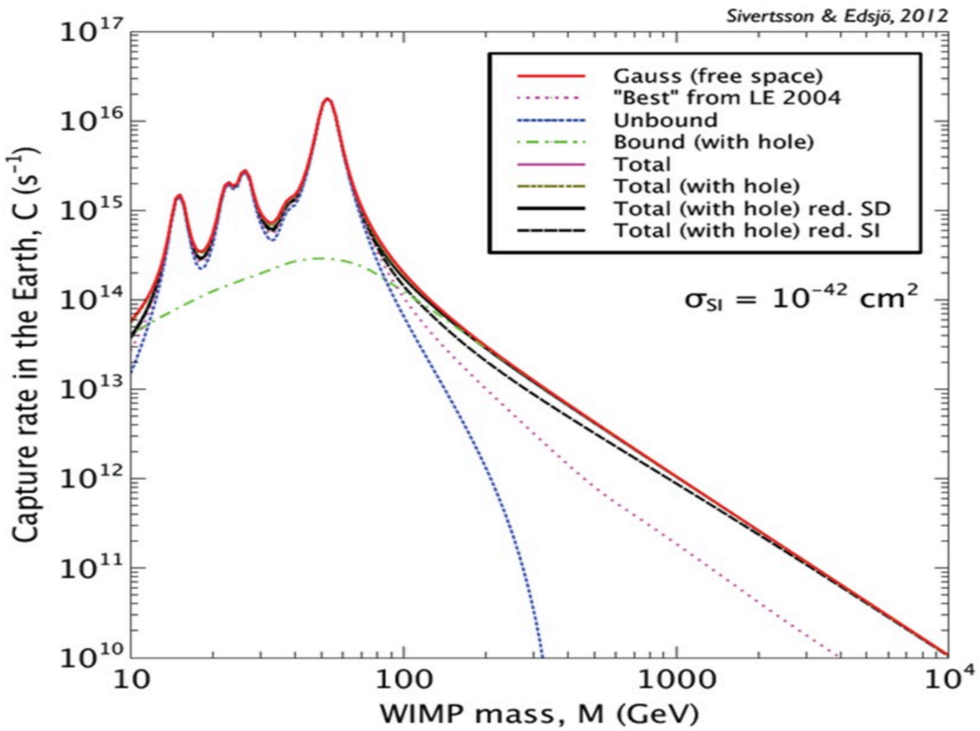
$(\hat{S}_\chi.\frac{\hat{q}}{m_N})\ (\hat{S}_N.\frac{\hat{q}}{m_N})$ for fermionic DM



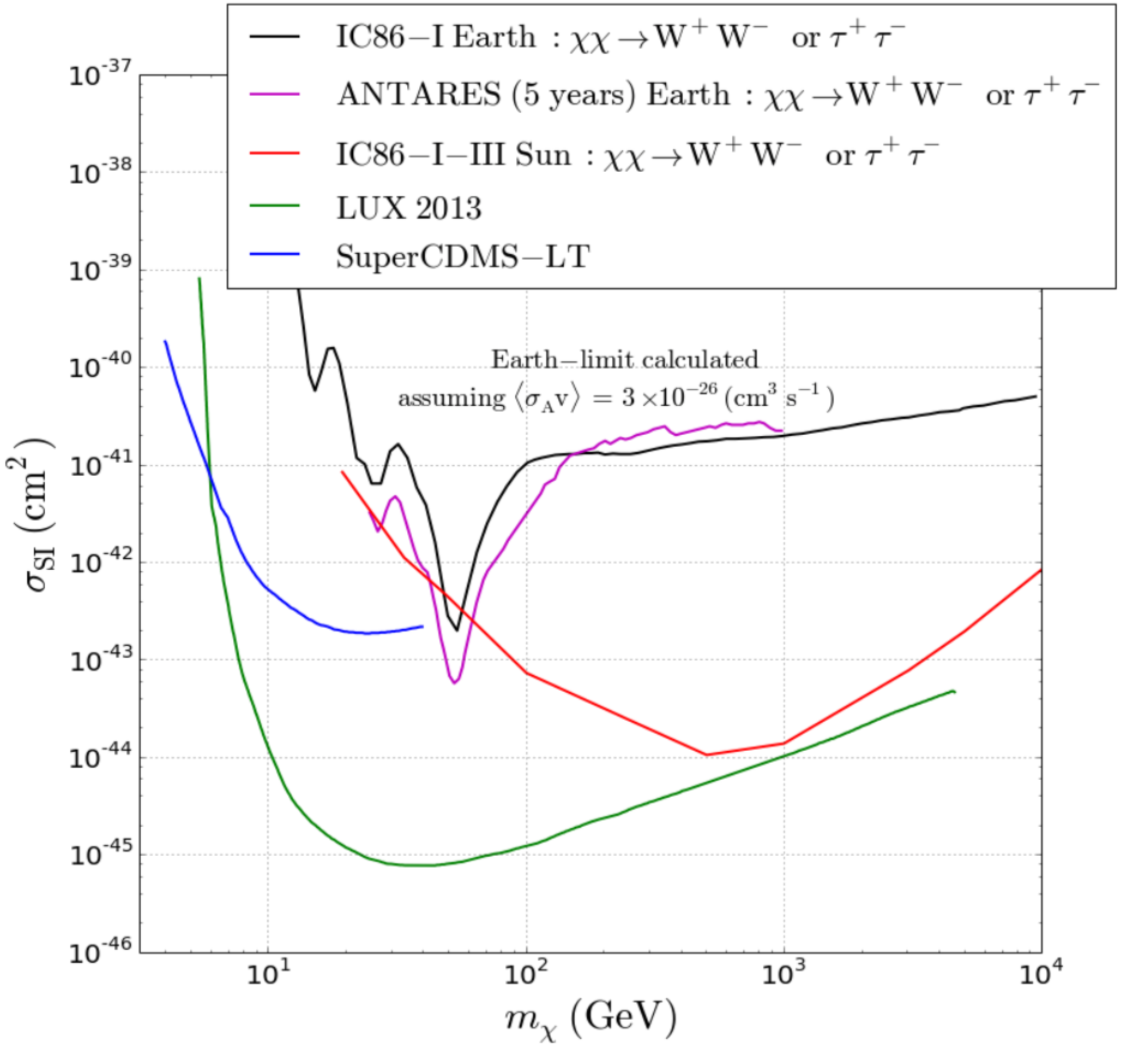
arXiv:1603.05592

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



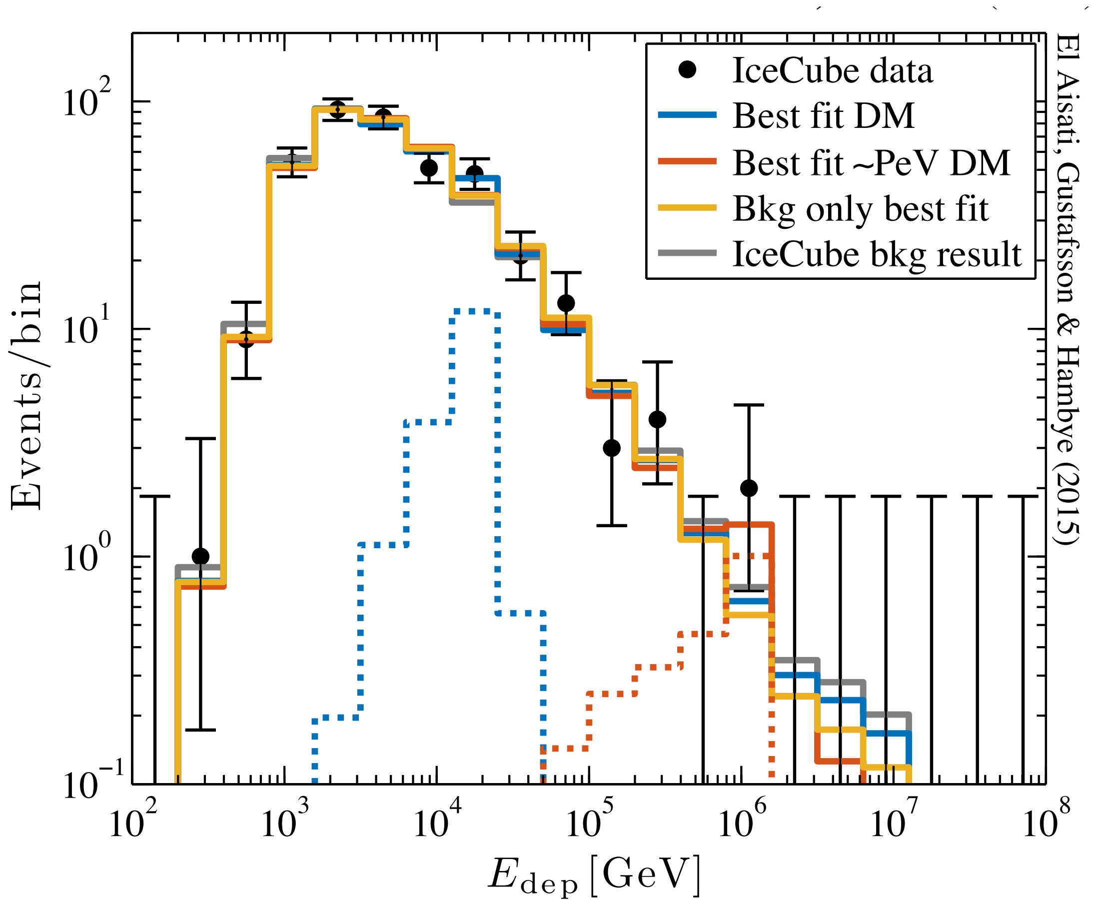
PhD thesis: J.Kunnen (VUB Oct.2015)



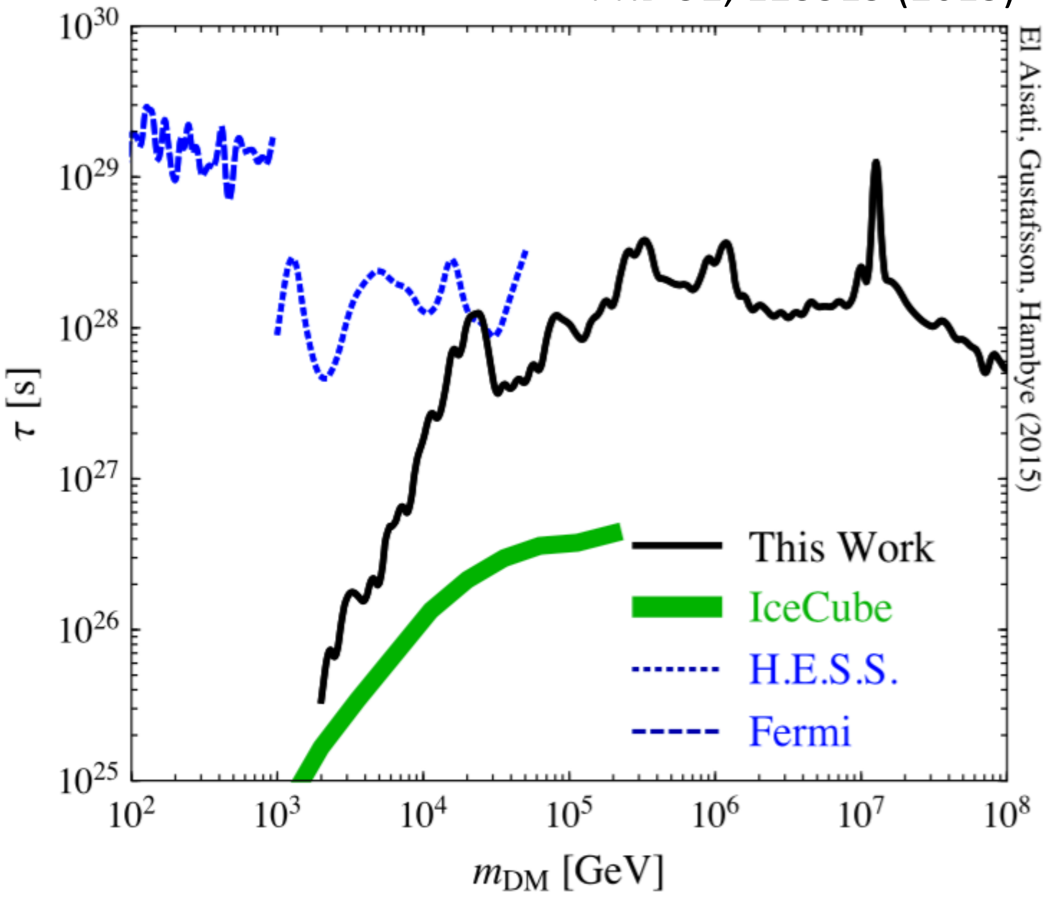
Heavy DM decay

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

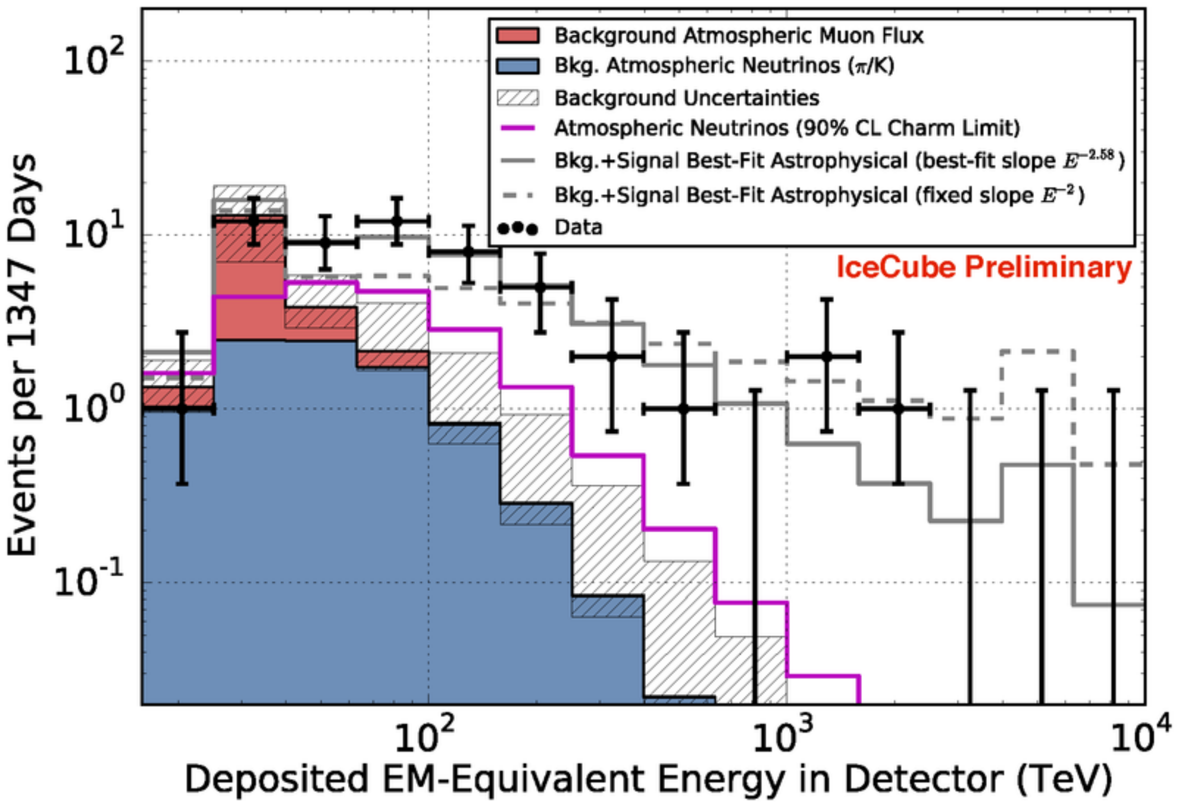
ν –telescopes are the most sensitive, since 100TeV-PeV γ-rays don't travel beyond ~10s of kPc

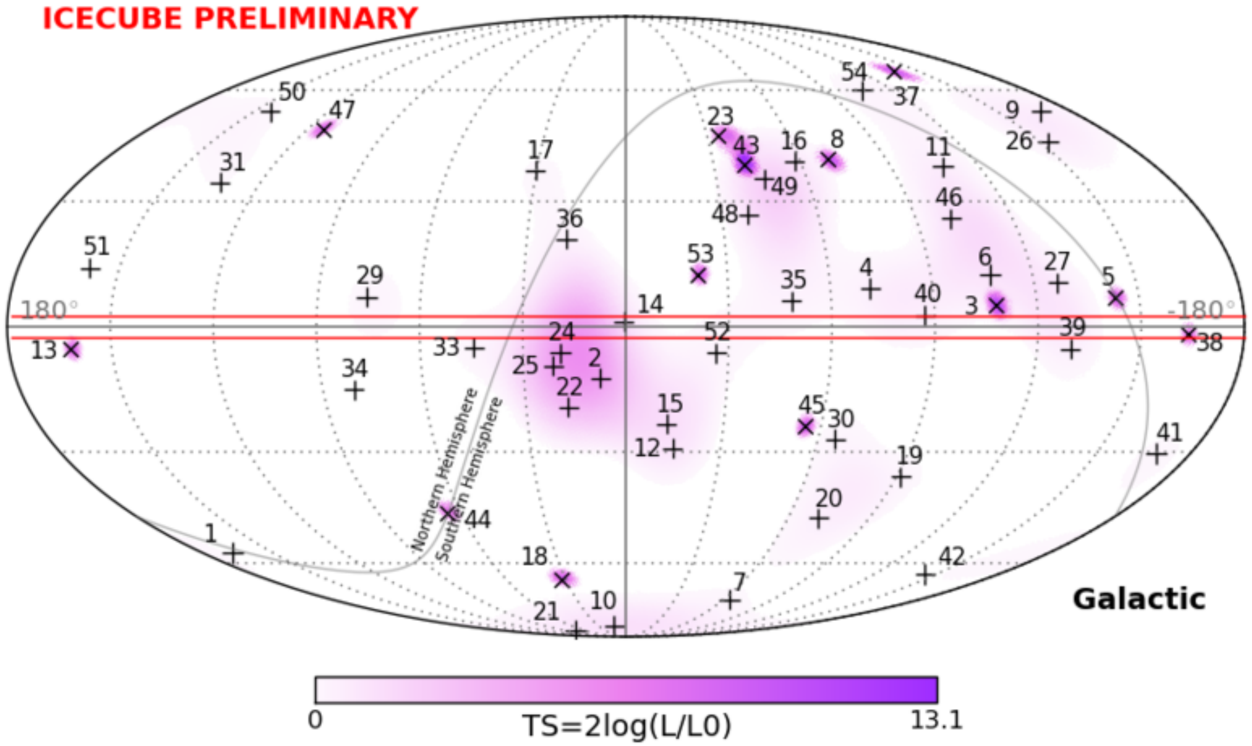


PRD 92, 123515 (2015)



The IceCube astrophysical flux





54 events seen on an expected background of $12.6 \pm 5.1\ \mu$ and $9.0^{+8.0}_{-2.2}\ \nu$. Atmospheric only origin rejected at $> 6\sigma$

No statistically significant clustering

Compatible excess also seen in other channels (upgoing μ) global best fit $E^{-2.52}$

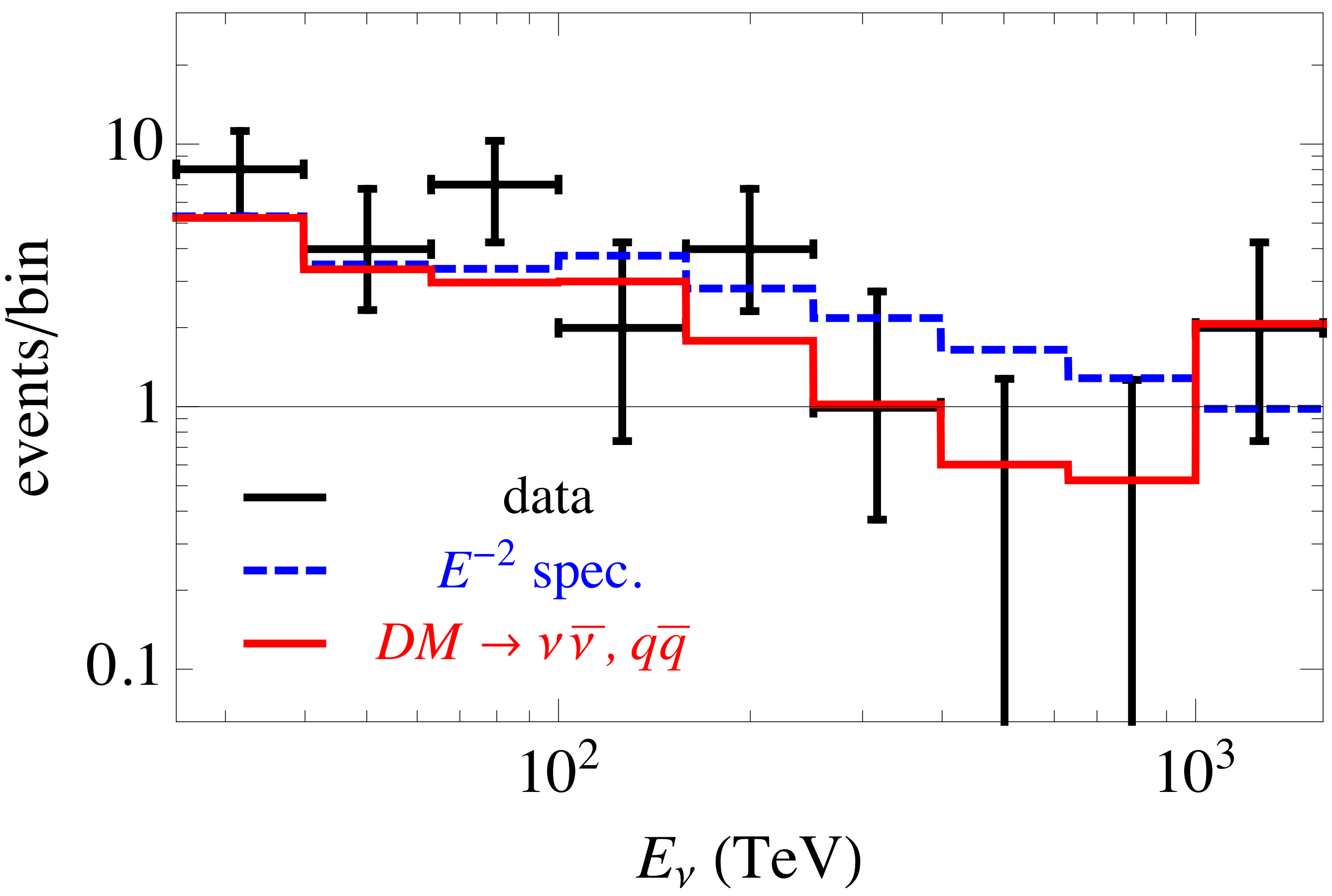
The IceCube astrophysical flux : PeV Decaying Dark Matter?

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

$$M_{DM} = 3.2\text{PeV}$$
$$\tau_{DM} = 2\times10^{27}\text{s}$$

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

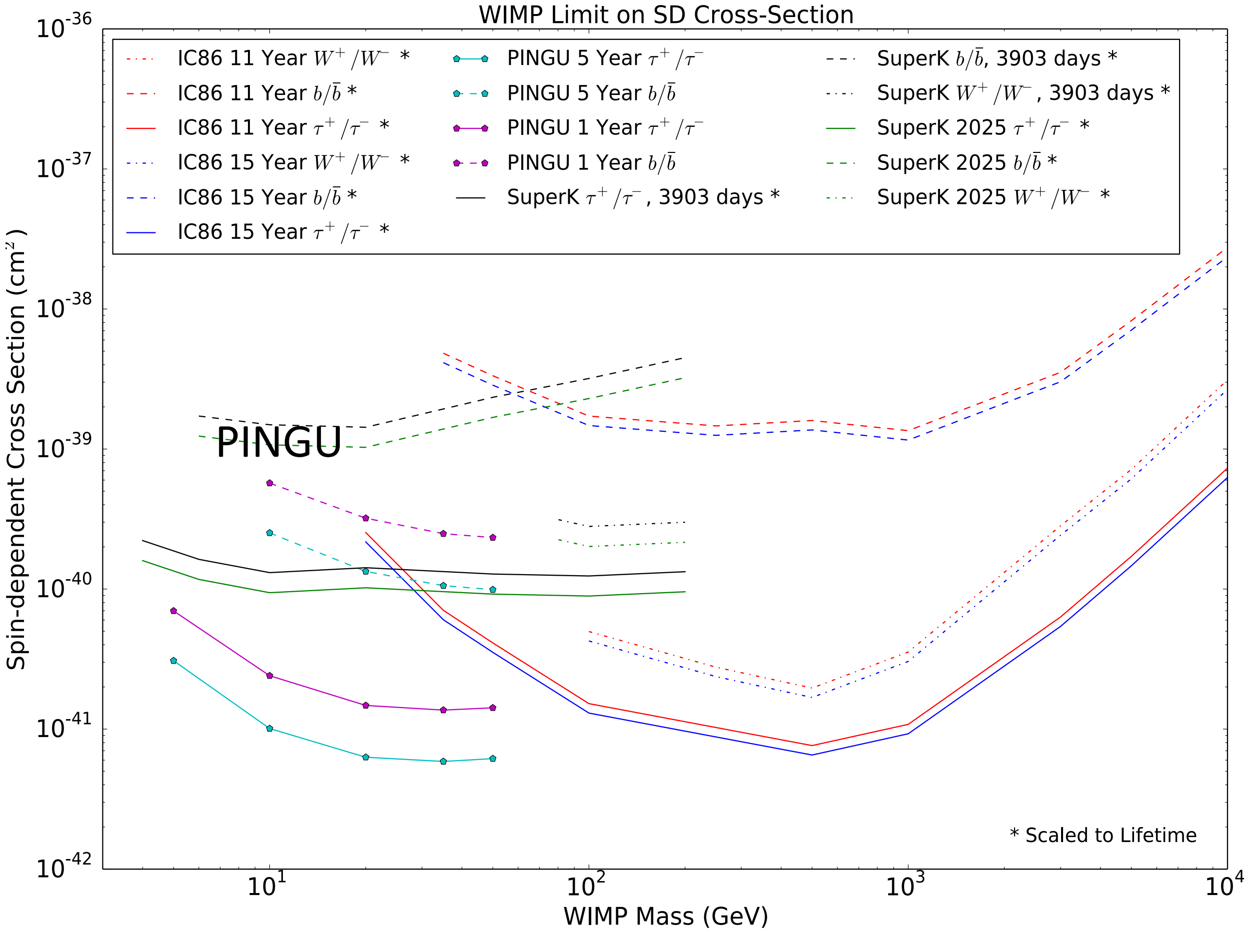
A. Esmaili et al. JCAP 1311 (2013) 054

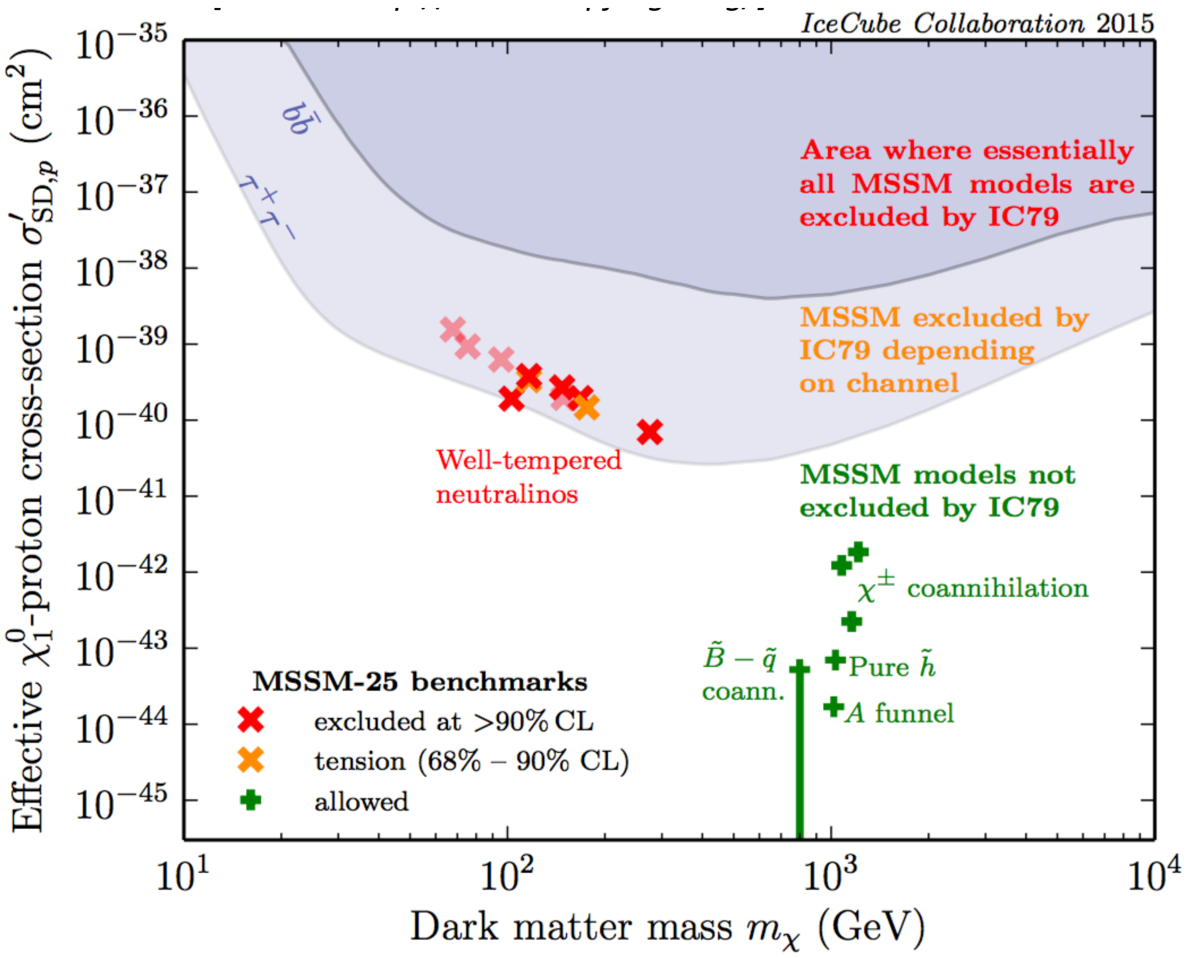


More data required

The Future of ν searches for DM

Solar Searches

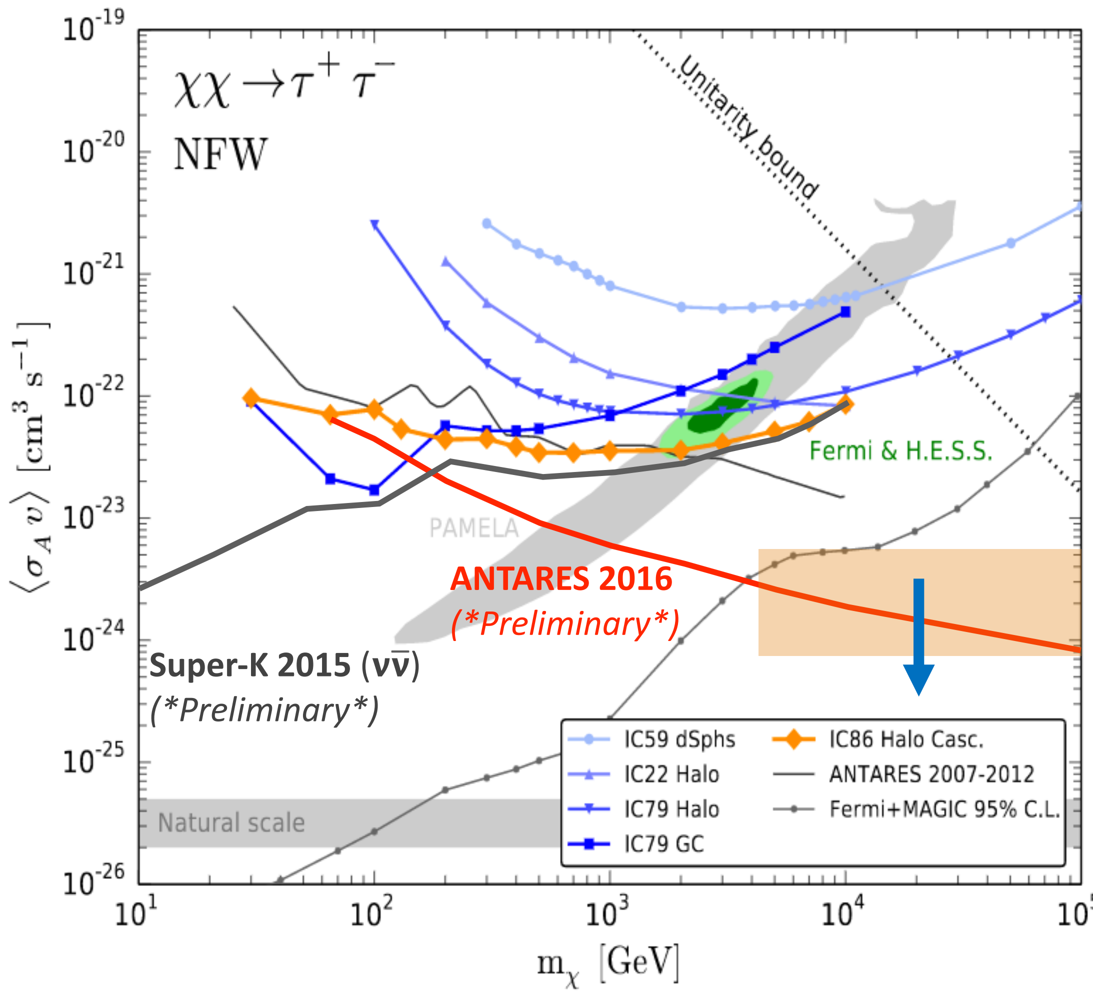




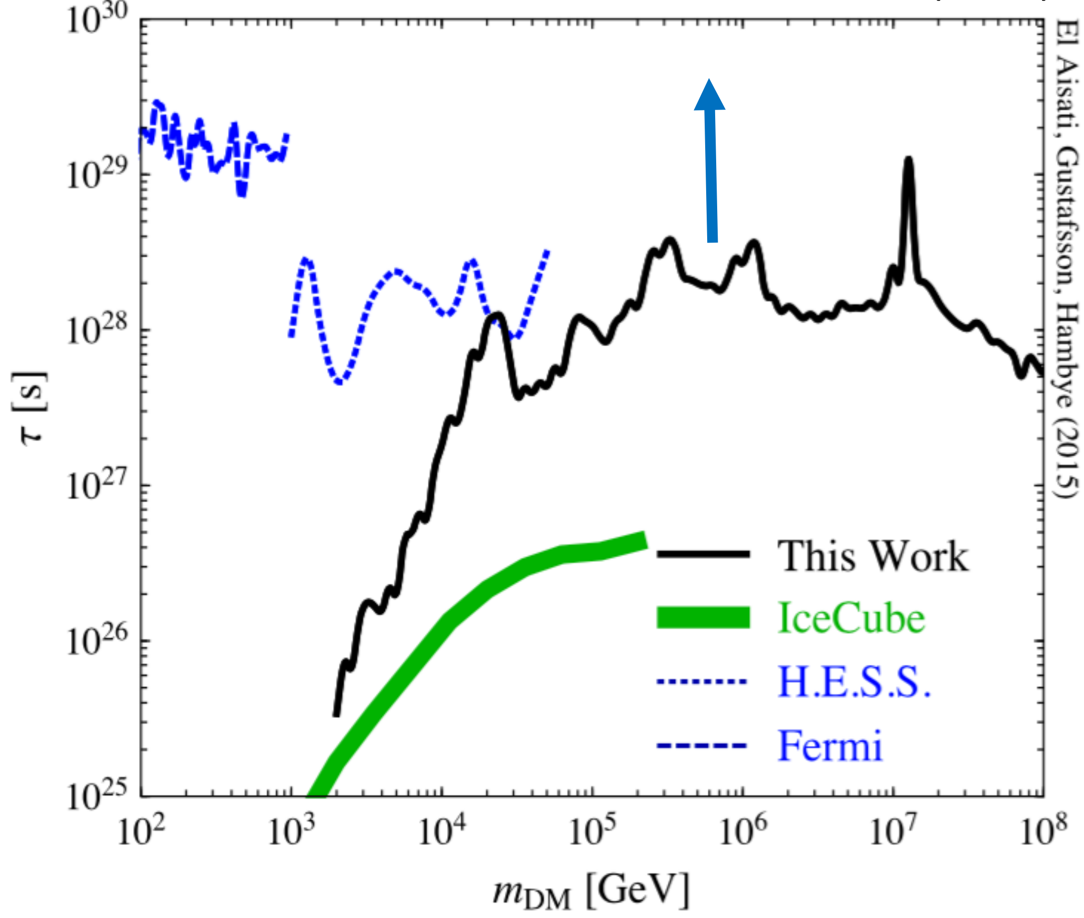
Also see HyperK and ORCA

The Future of ν searches for DM

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



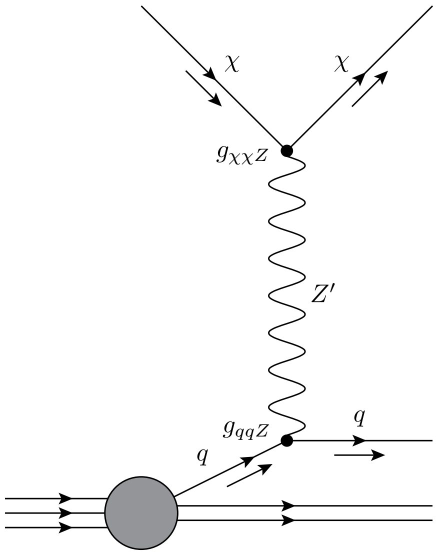
PRD 92, 123515 (2015)



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

Backups

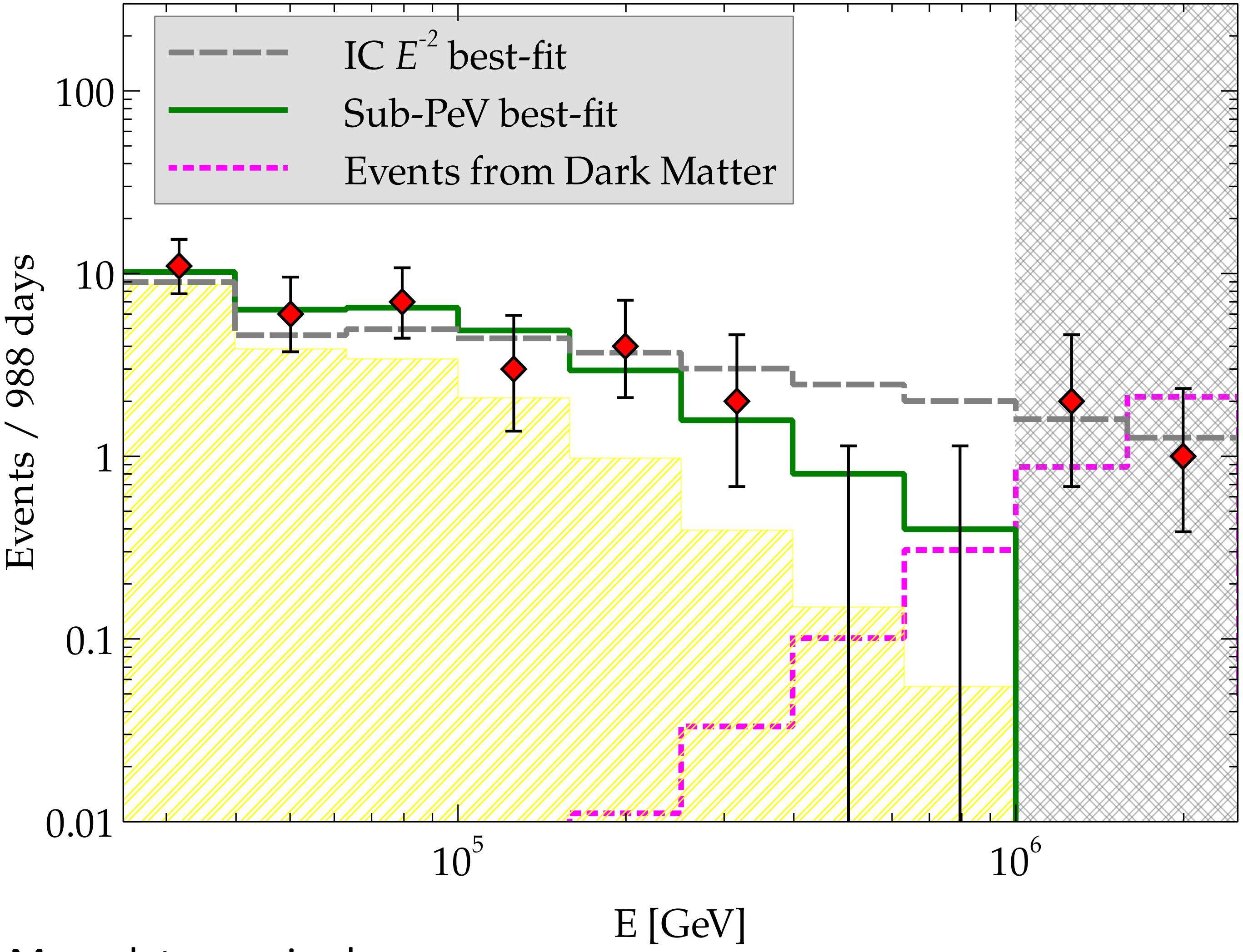
The IceCube astrophysical flux : from PeV Dark Matter Φ decaying to Fermionic DM χ



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

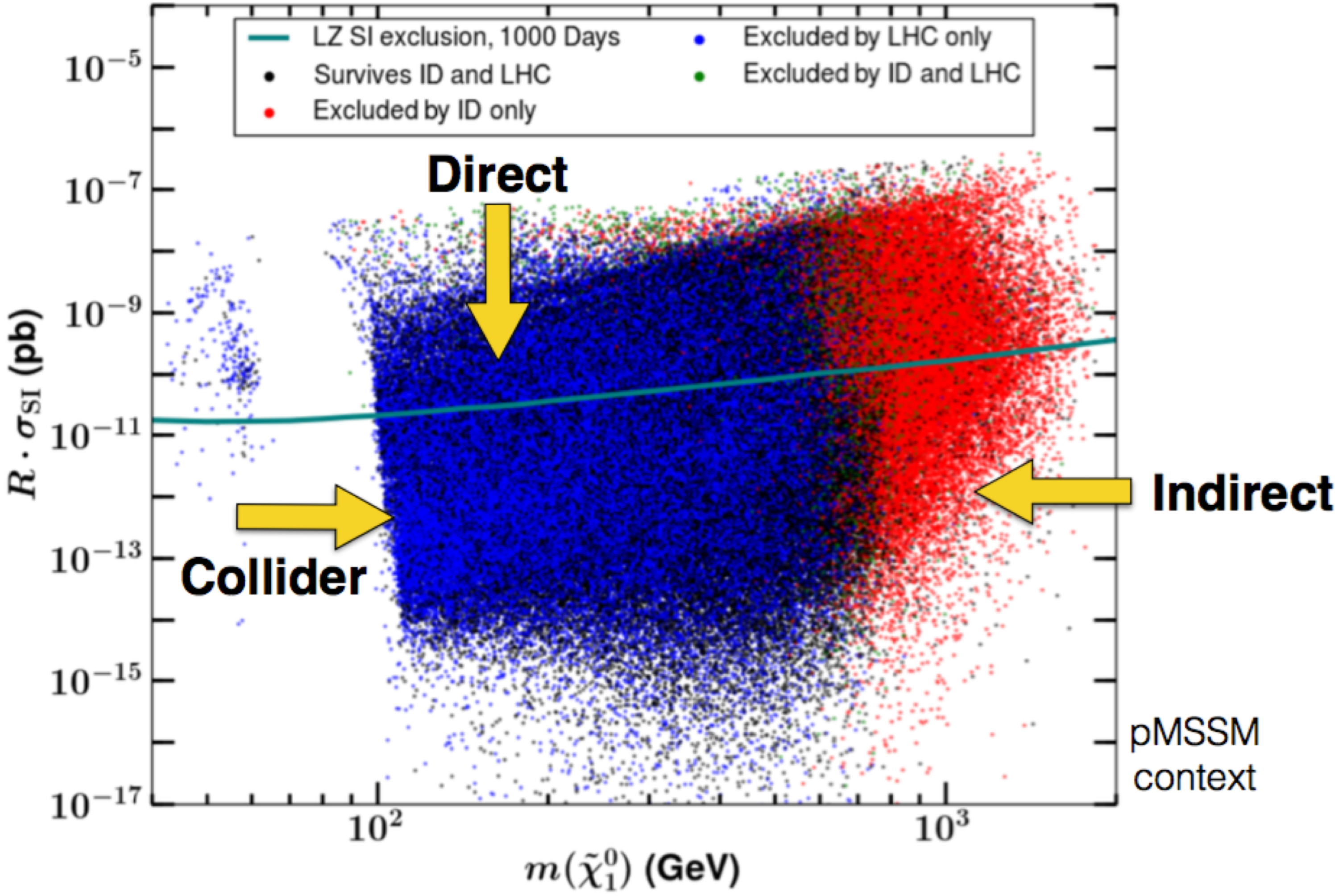


Motivated by the fact that there are no events between 400 TeV and 1 PeV, and so a fit of only events below PeV produces a softer spectrum

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