Dark Matter Searches with the IceCube detector

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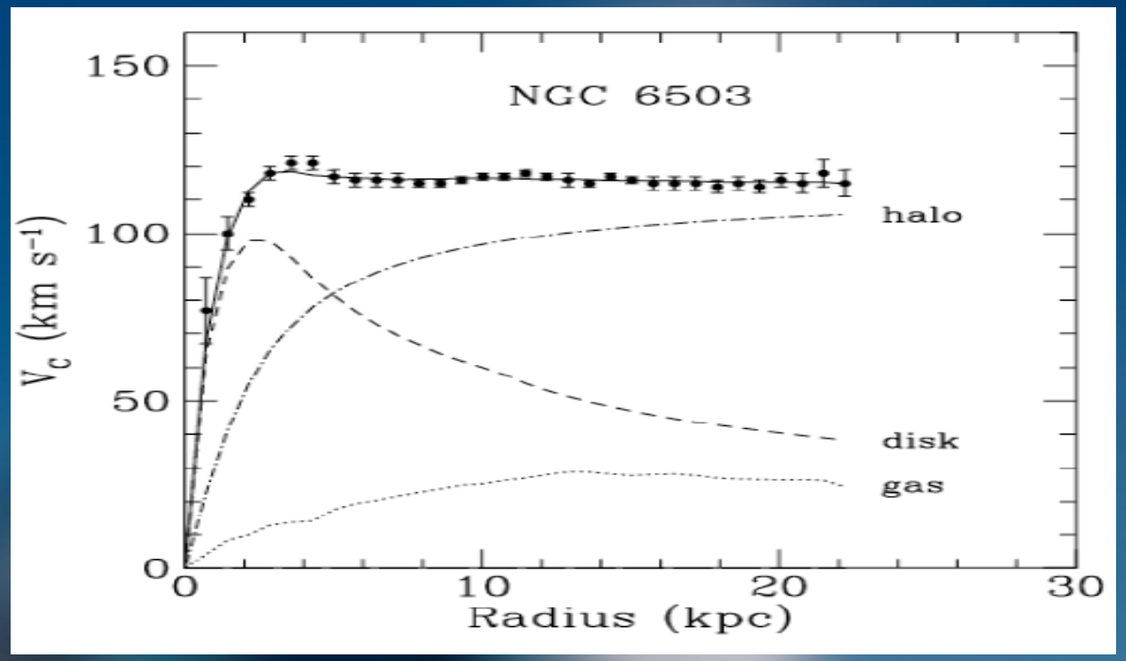
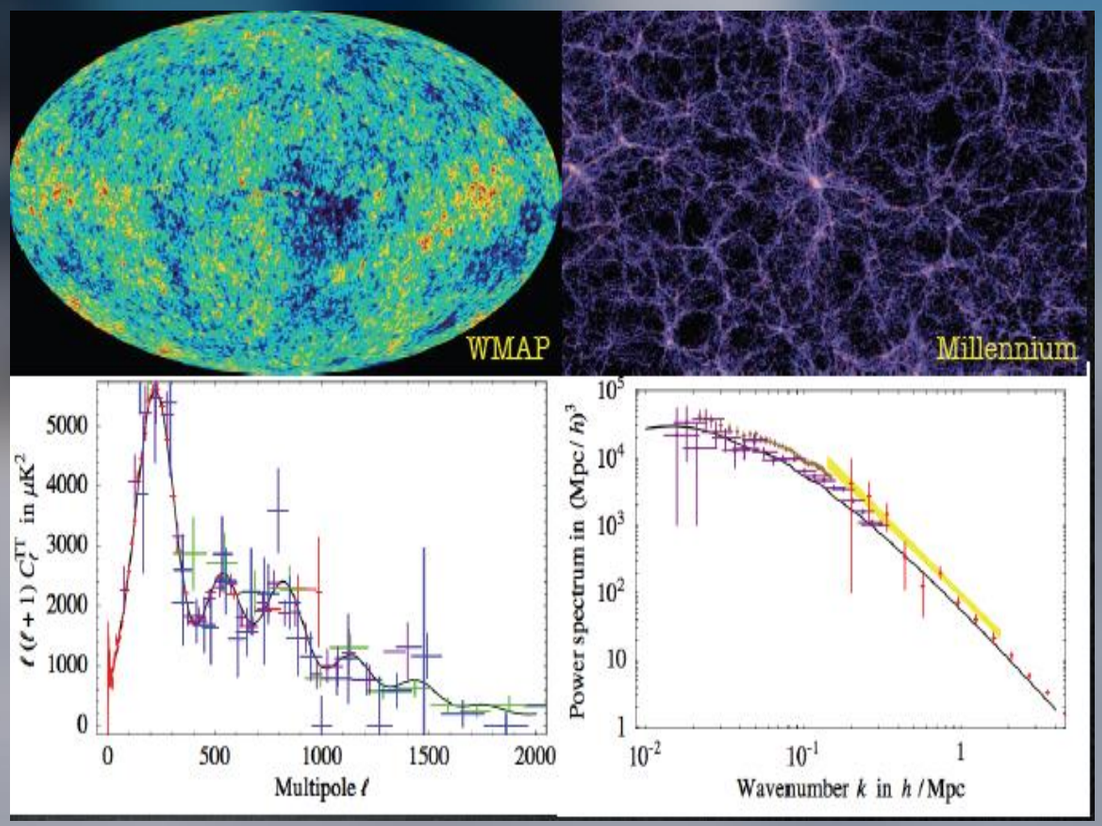
Dark Matter Exists

Galactic Rotation Curves :



:Weak Lensing (Bullet Cluster)



CMB Anisotropy and LSS Simulations of the Universe:

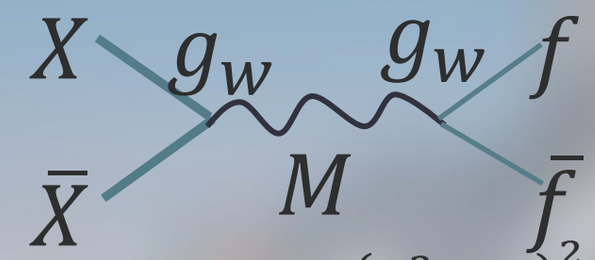
Dark Matter could be WIMPs

Dark Matter as a thermal relic of the Early universe.

Boltzmann equation of the early universe

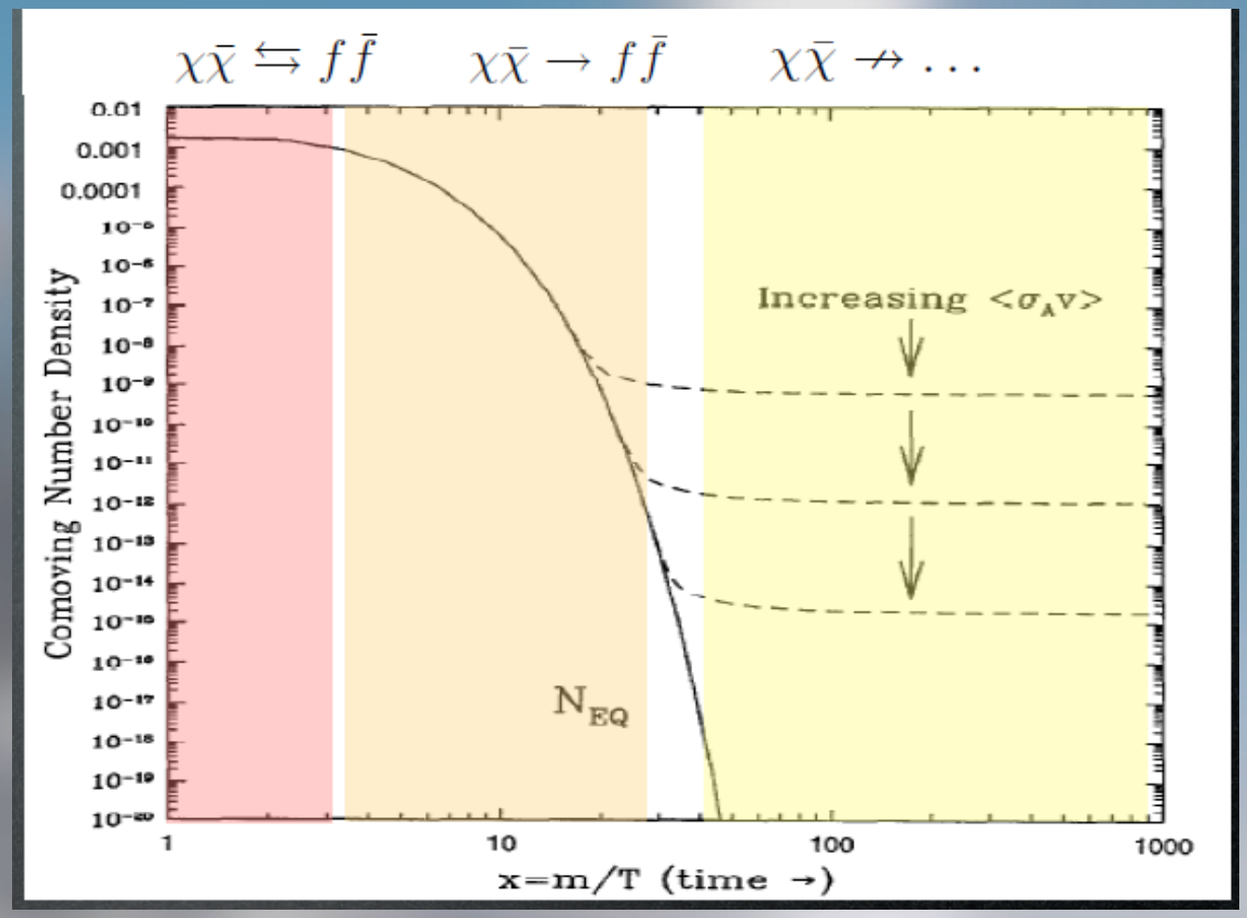
$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{ann} v \rangle \left[n_X^2 - n_X^{eq} \right]$$

Relic $\Omega_{DM} \sim 0.23$



$$\langle \sigma_{ann} v \rangle \approx \frac{\left(g_w^2/4\pi\right)^2}{M^2}$$

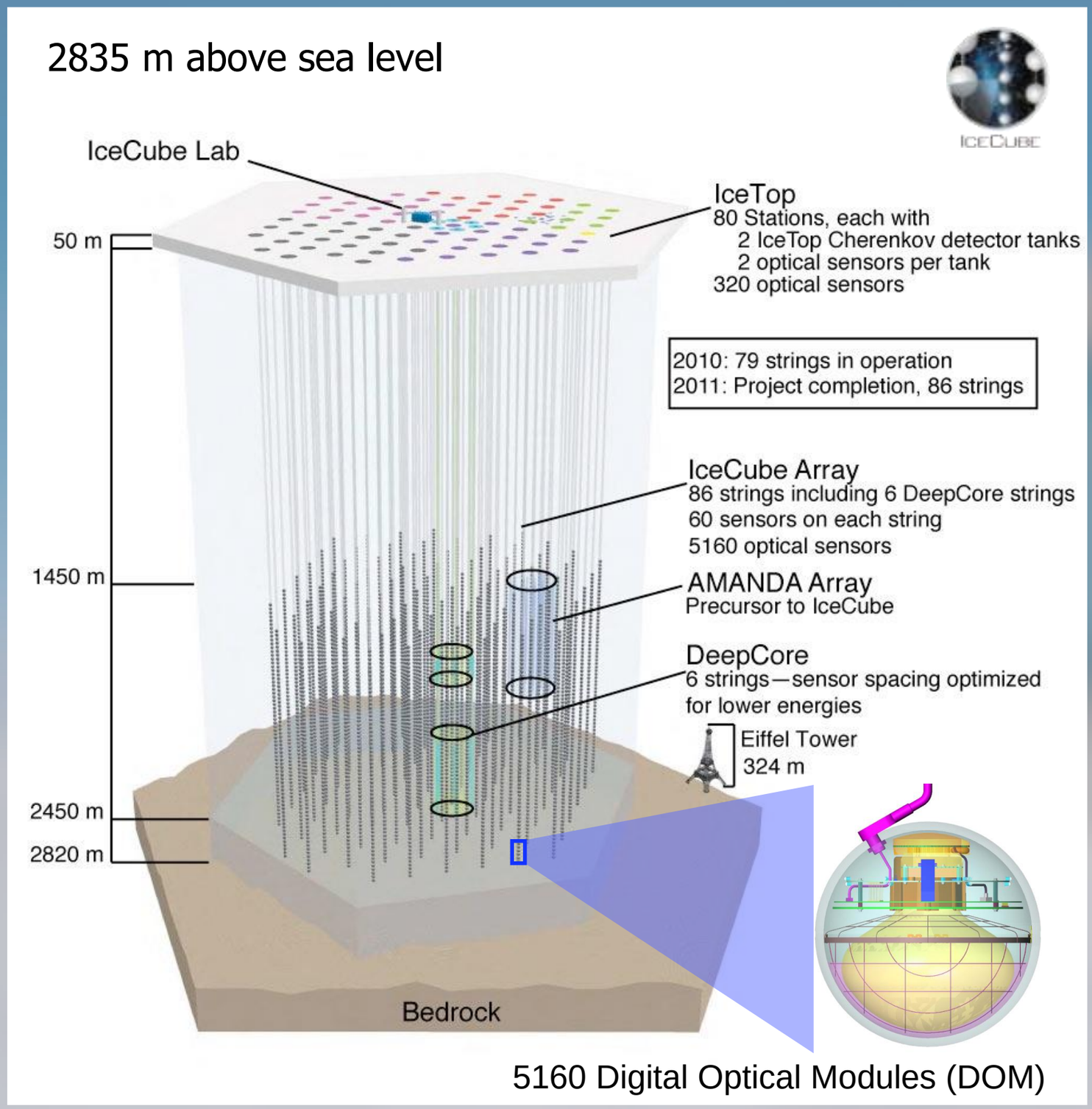
$$\approx 3.10^{-26}\ cm^3/s$$



WIMP Miracle!

Correct Abundance

IceCube Neutrino Observatory



5160 Digital Optical Modules (DOM)

20 years of construction from AMANDA to IceCube

<u>IceCube phases:</u>

IceCube 1 (2004-5)

⋮

IceCube 40 (2008-9)

IceCube 59 (2009-10)

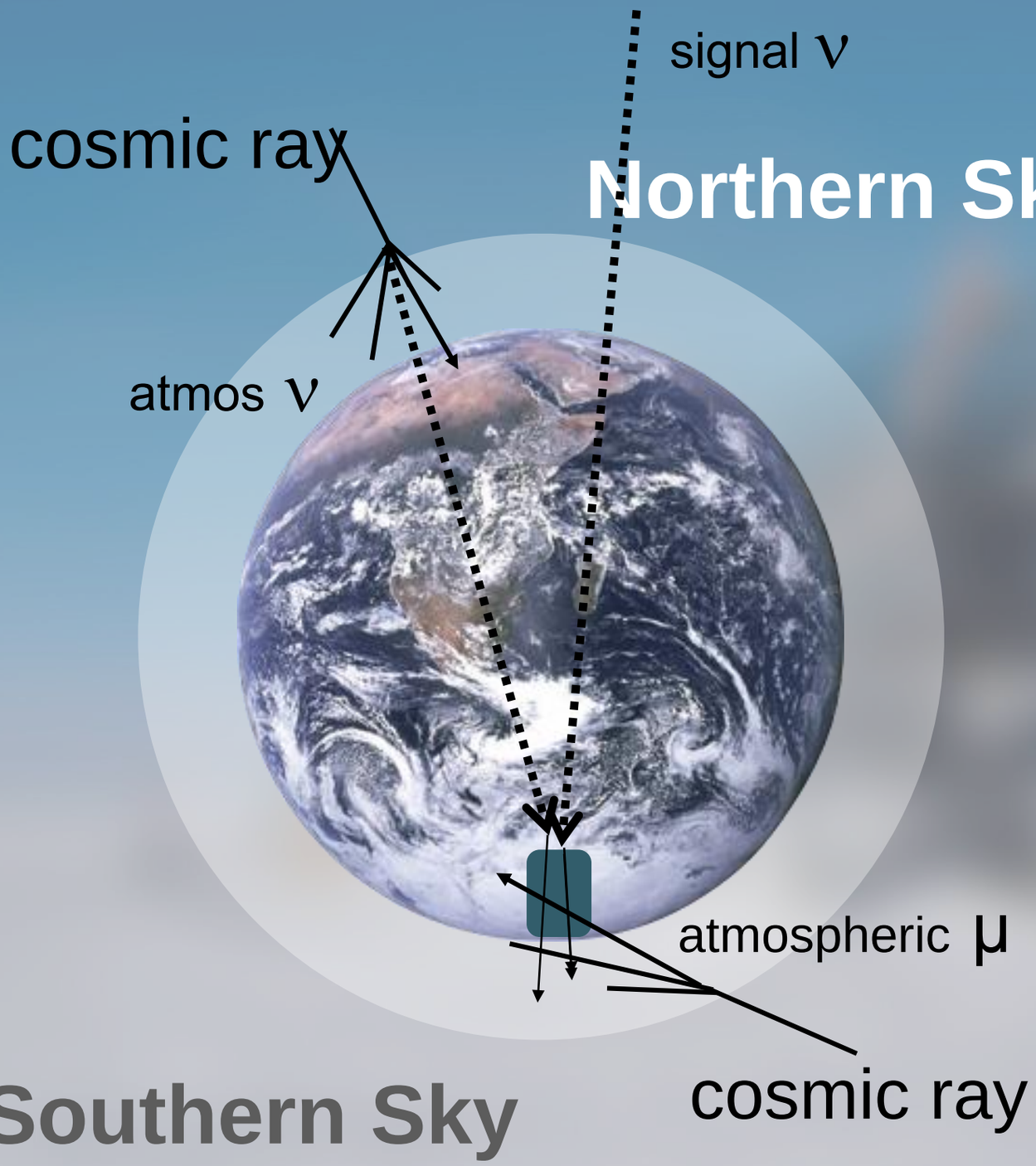
IceCube 79 (2010-11)

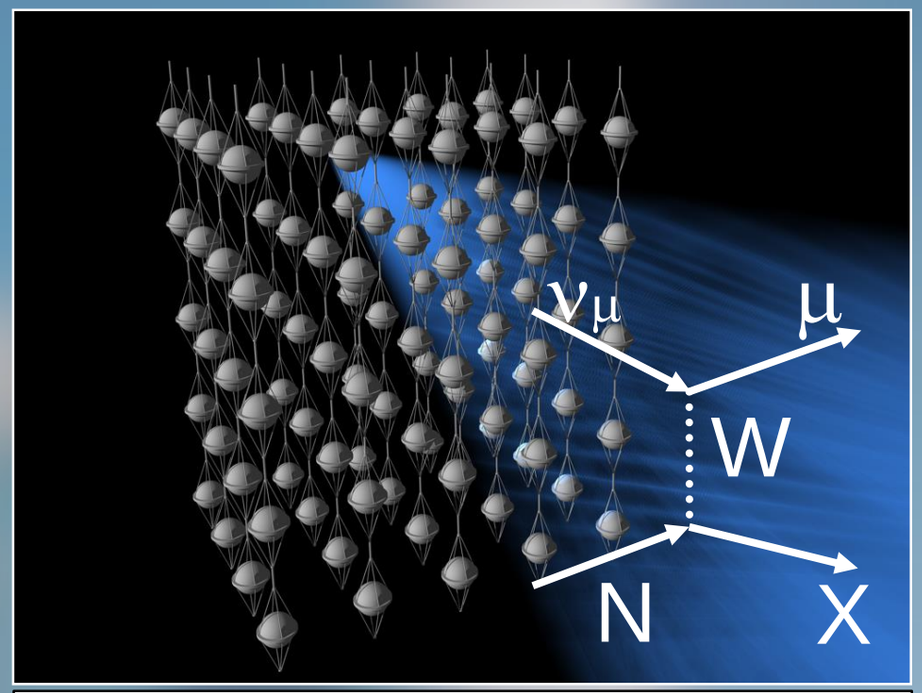
Completion with 86 strings in December 2010

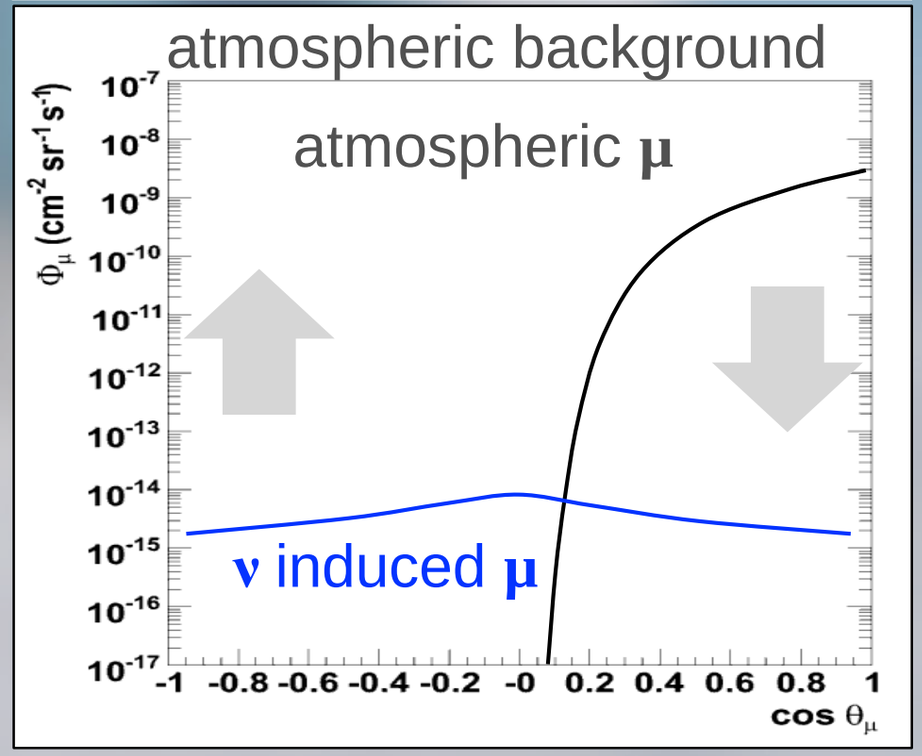
IceCube 86-I (2011-12)

⋮

Detection Principle

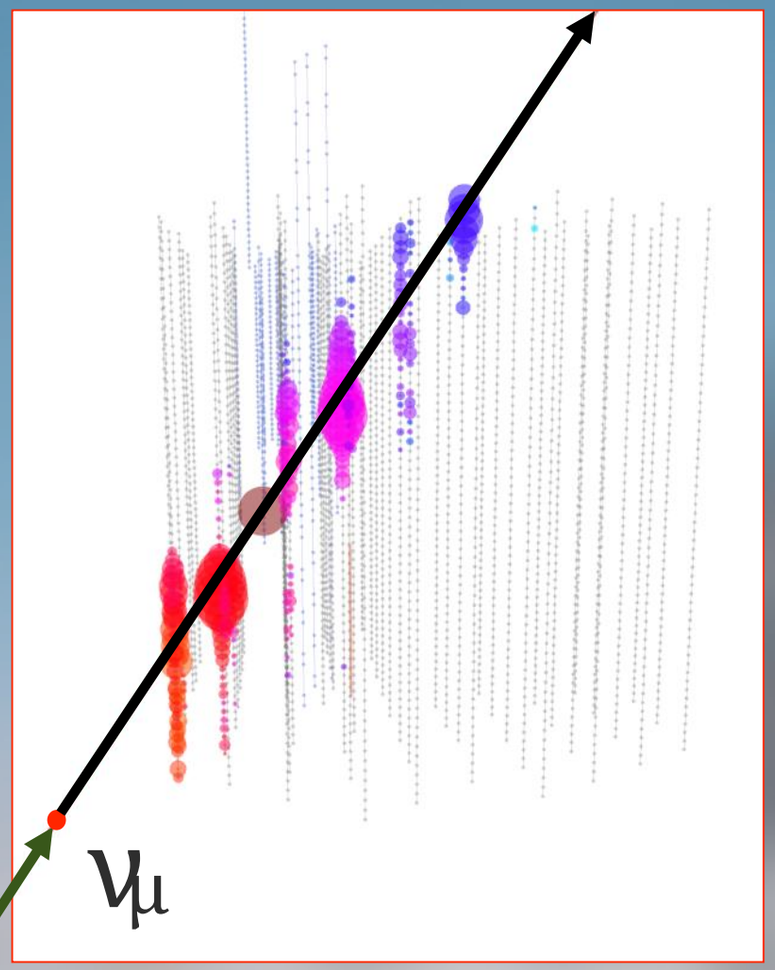






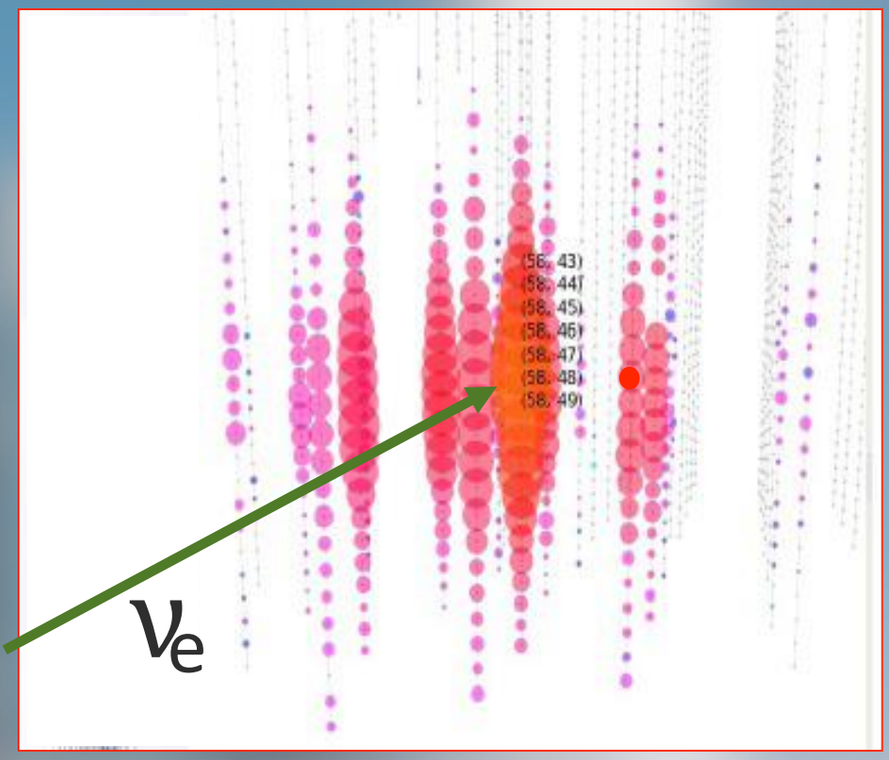
In-ice Signatures

tracks→ ν_μ (or ν_τ above few PeV)



- Good angular resolution (< 1º): **Points back to the source**
- Vertex can be outside the detector: **Increased effective volume!**

cascade → ν_e, ν_τ & all flavor NC



- ν_e, ν_τ and all-flavor neutral current
- Fully active calorimeter: **High energy resolution (~10%)**
- Angular reconstruction above ~50 TeV (~ 10º)

Dark Matter Searches in IceCube

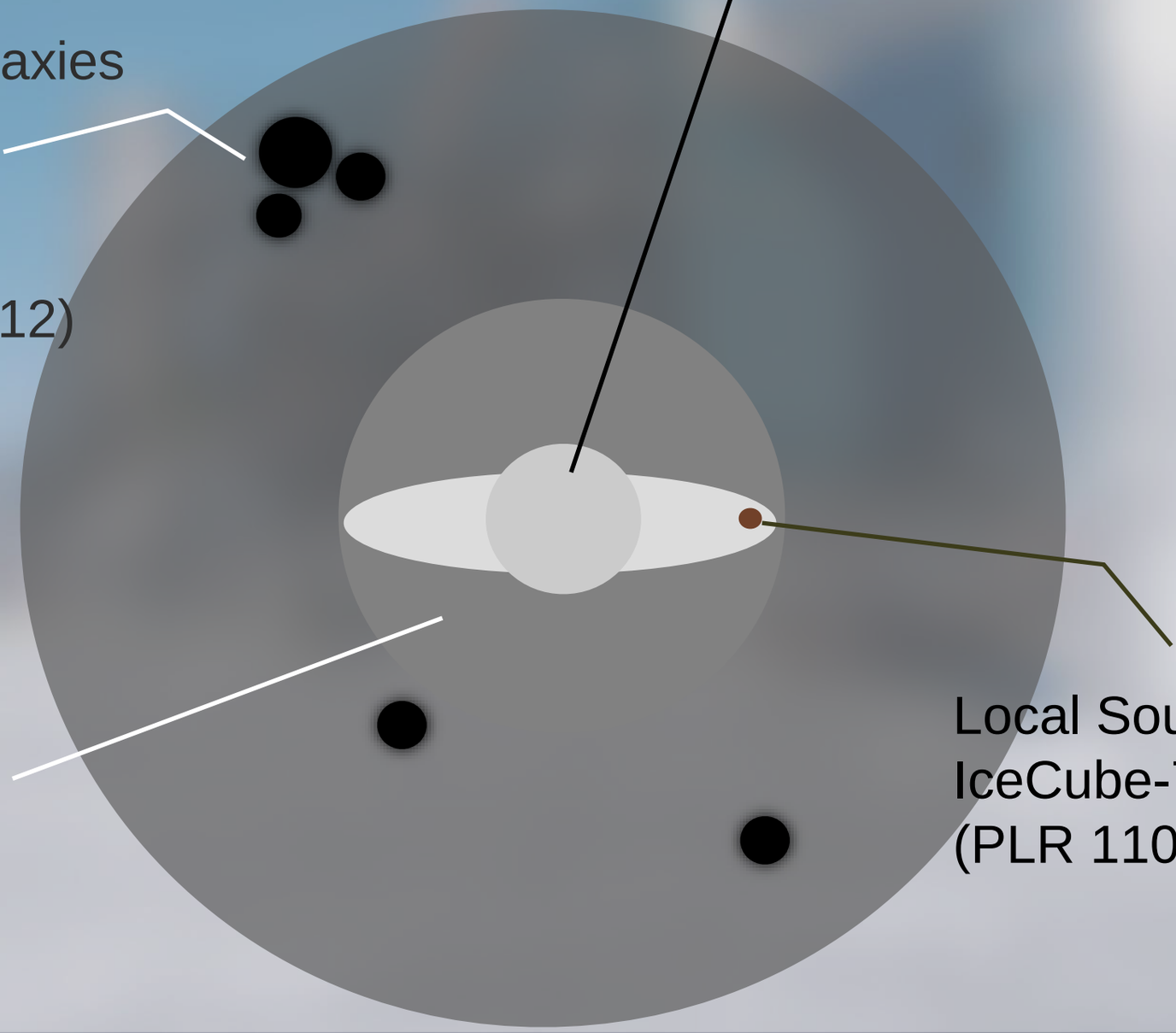
Indirect Searches

Galactic Center
IceCube-40 limits
(arXiv:1210.3557 2012)
IceCube-59 sens.

σ_{ann}

Dwarf spheroidal Galaxies
IceCube-59 limits
Cluster of Galaxies
IceCube-59 limits
(arXiv: 1210.3557 2012)

σ_{ann}



Galactic Halo
IceCube-22 limits
(PDR 84 (2011)
022004)

σ_{ann}

Local Sources (Sun, Earth)
IceCube-79 limits
(PLR 110 (2013) 131302)

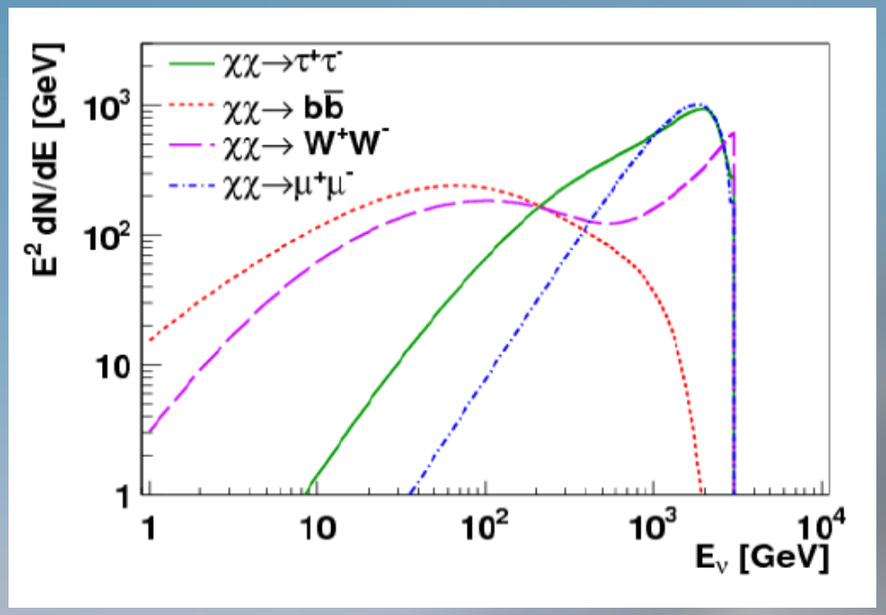
σ_{sc}!

Galactic Centre, Halo & Distant Halo Searches

Neutrinos from pairwise annihilation of dark matter:

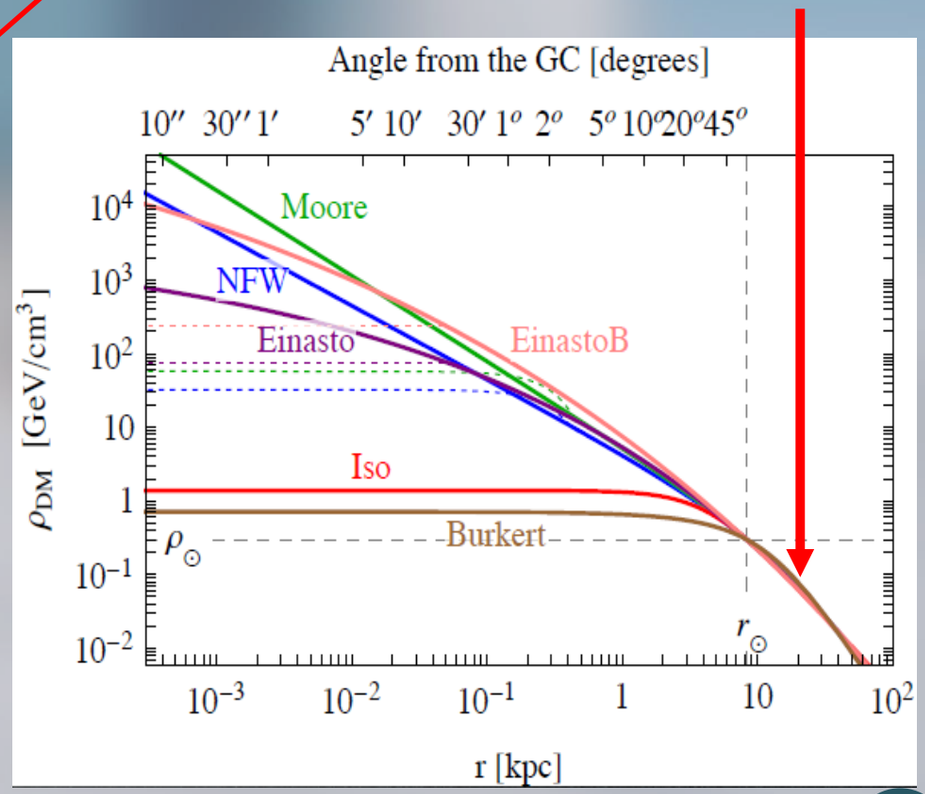
$$\frac{d\Phi(\Delta\Omega)}{dE} = \frac{\langle\sigma_A v\rangle}{4\pi.2m_\chi^2}\frac{dN}{dE}J(\Delta\Omega)$$

Velocity averaged annihilation cross section



Neutrino spectrum per annihilation : Depends on Wimp Mass and Channel: DarkSusy

<- ν_μ from 3000 GeV WIMP annihilating at GC: After oscillations at earth



'J factor' : line of sight integral over squared mass density:

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{l.o.s} \rho_\chi^2(s)ds$$

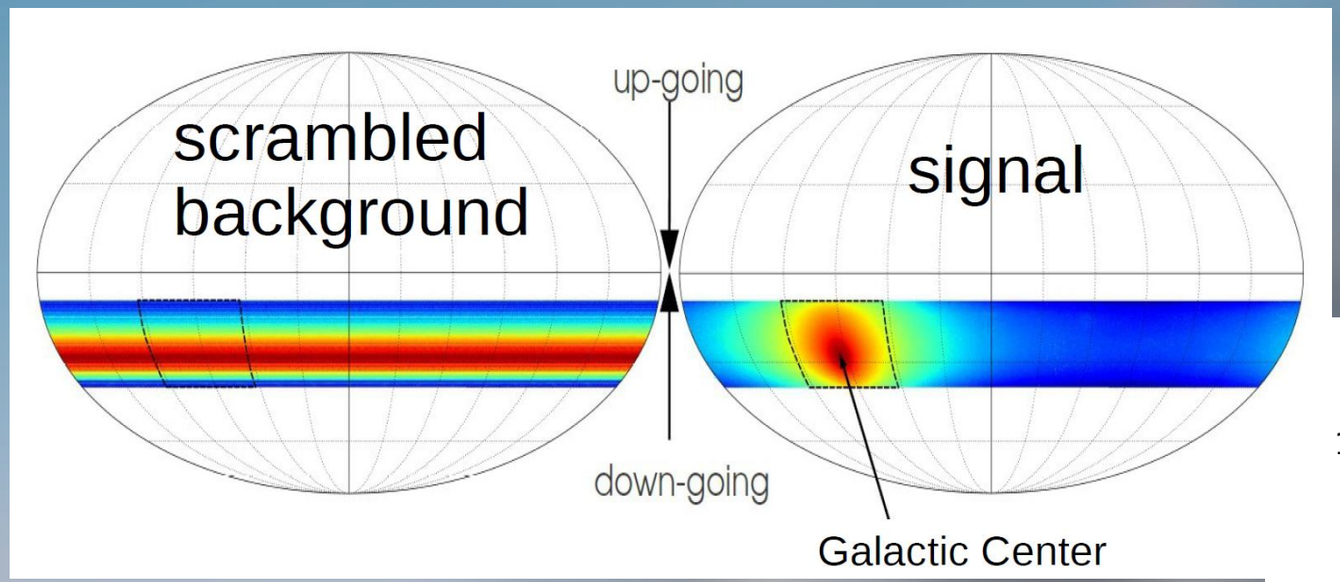
Subclusters can:

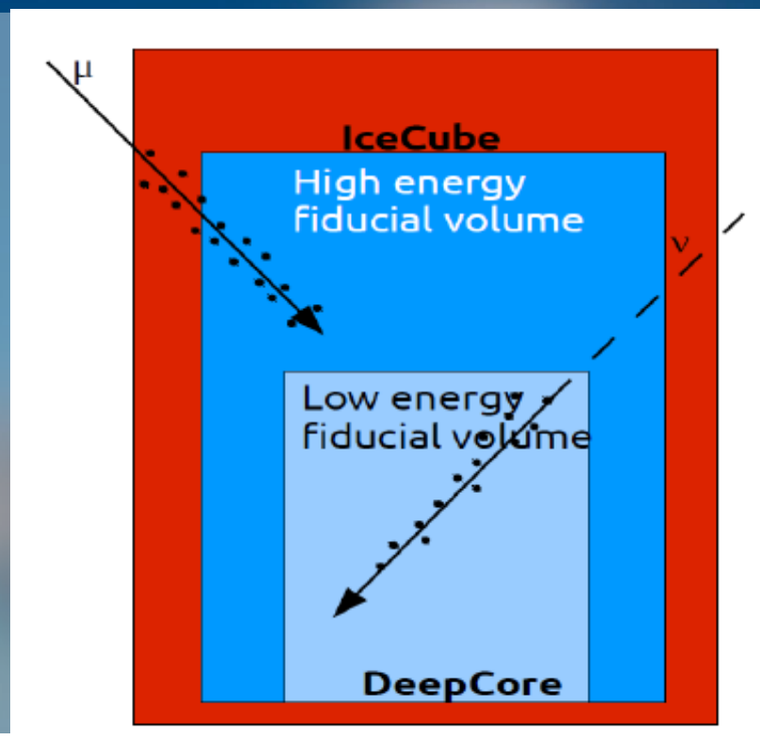
1. Boost Signal
2. Create Larger non point like target region.

Galactic Centre

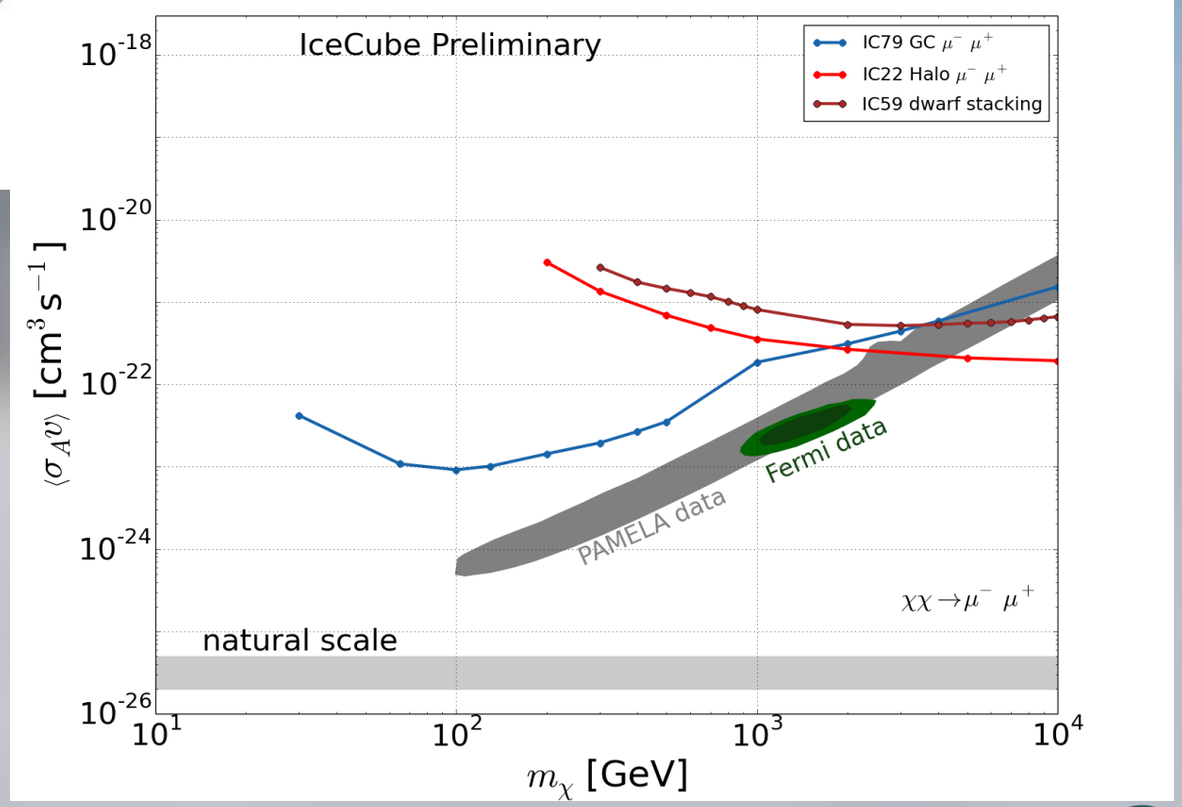
GC is in the Southern Hemisphere

- Data dominated by Muon Back-ground
- Define different fiducial volumes for differ ent Energy levels and Veto Muons





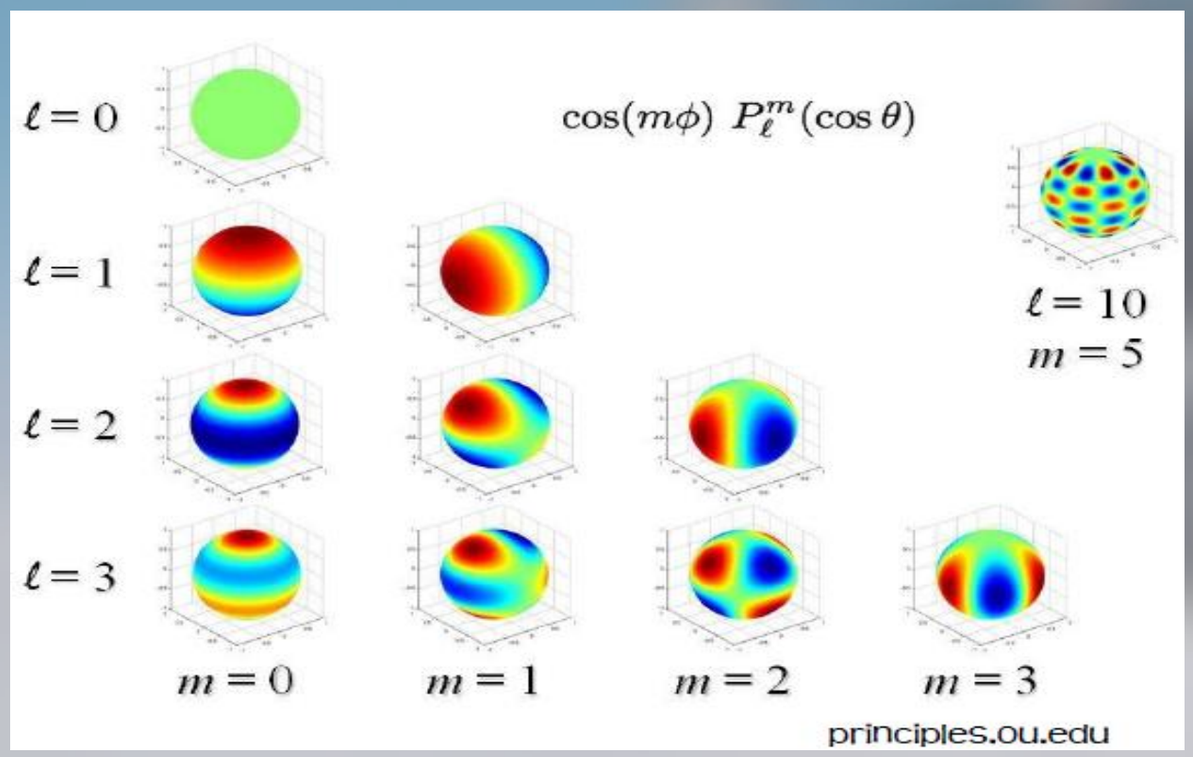
Upper Limits (without systematics) for the $\mu^+\mu^-$ channel assuming the NFW profile :

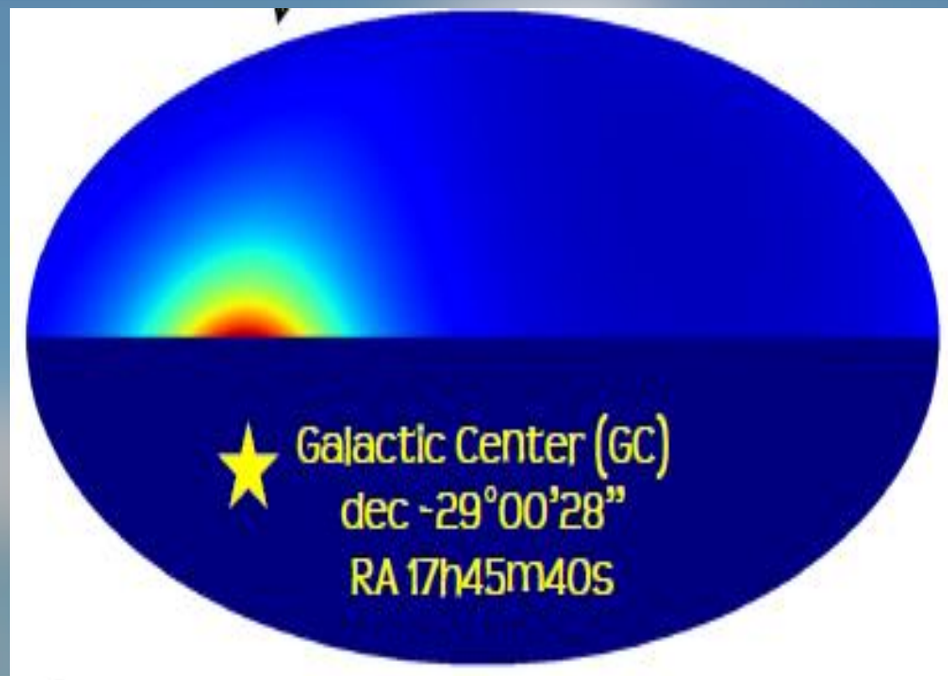


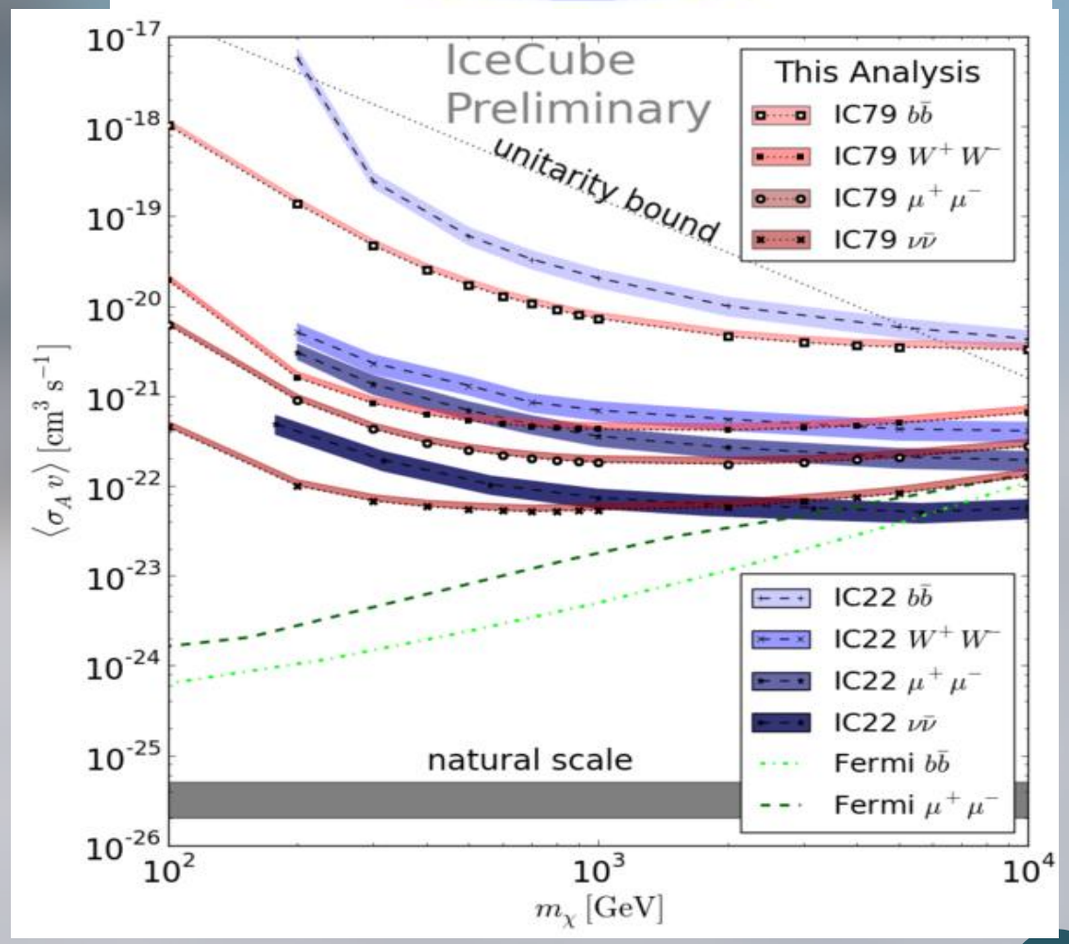
Galactic Halo

Look only in the Northern Hemisphere
Look for an anisotropy due to the Galactic HALO

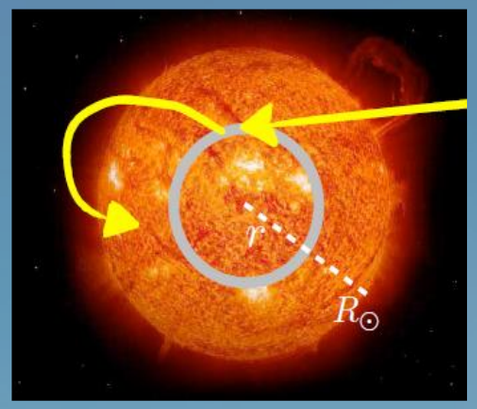
Multipole Analysis:





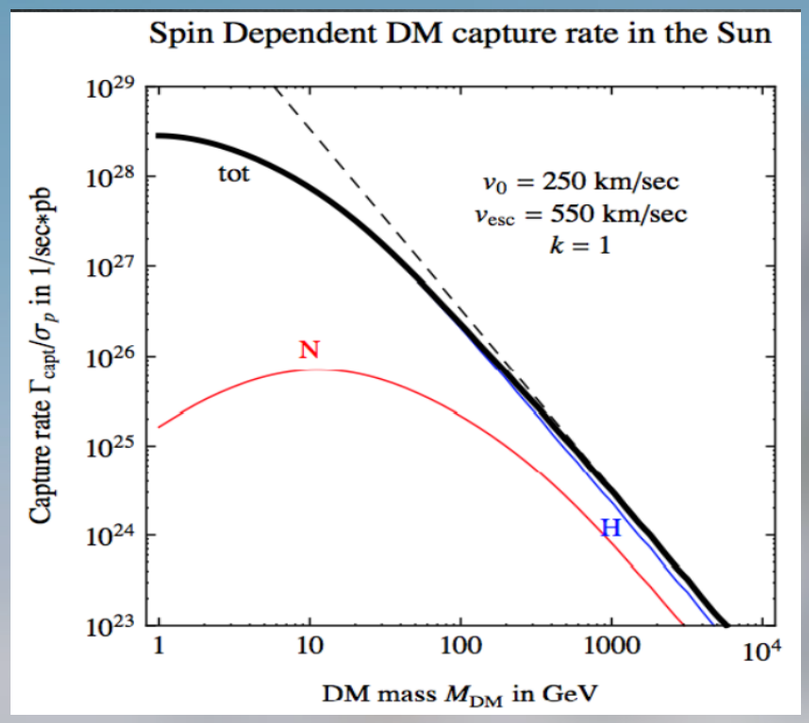


WIMP Capture in the Sun



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

- $\frac{\rho_{\rm DM}}{M_{\rm DM}}$: DM number density
- σ_i: scattering cross section on element **i**
- $n_i(r)$: number density of element **i**
- $f_\odot(v)$: velocity distribution (in solar frame, without Sun's gravity)
- $\frac{v^2 + v_{\odot\rm esc}^2}{v}\, \wp_i(v, v_{\odot\rm esc})$: effect of solar gravity



scattering probability:

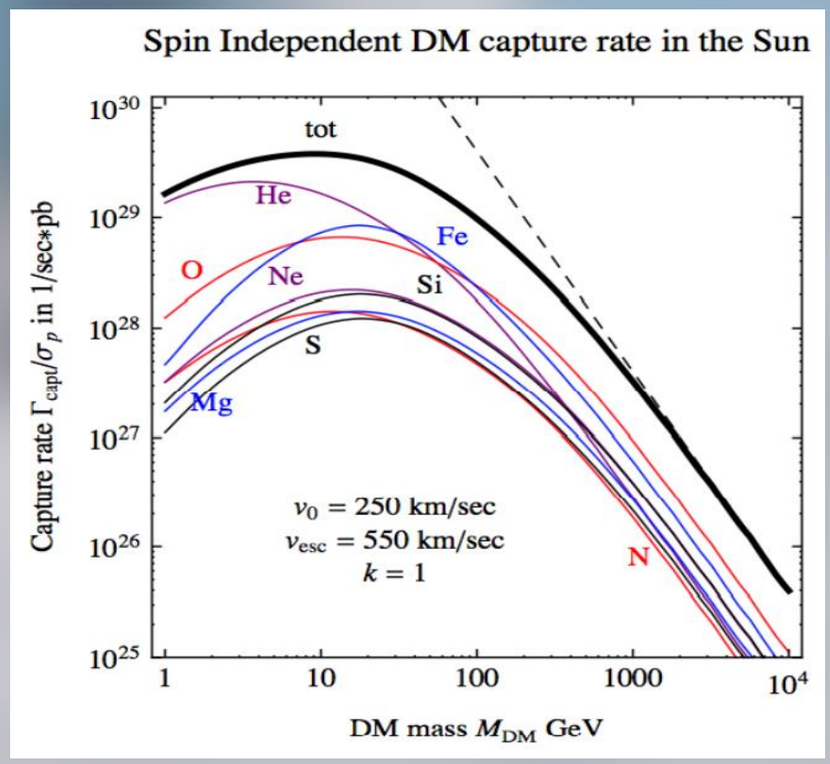
$$\wp_i(v, v_{\odot\rm esc}) = \max\left(0, 1 - \frac{\Delta_{\rm min}}{\Delta_{\rm max}}\right) \qquad \Delta_{\rm max} = \frac{4 m_i M_{\rm DM}}{(M_{\rm DM} + m_i)^2} \qquad \Delta_{\rm min} = \frac{v^2}{v^2 + v_{\odot\rm esc}^2}$$

$$\wp_i(v, v_{\odot\rm esc}) = \frac{1}{E\,\Delta_{\rm max}} \int_{E\,\Delta_{\rm min}}^{E\,\Delta_{\rm max}} {\rm d}(\Delta E)\, |F_i(\Delta E)|^2 \qquad |F_i(\Delta E)|^2 = e^{-\Delta E/E_0} \qquad E_0^{\rm SI} = 5/2 m_i r_i^2 \qquad E_0^{\rm SD} = 3/2 m_i r_i^2$$

G. Jungman et.al. (1996)

$\sigma_{SD} \propto J(J+1)$

$\sigma_{SI} \propto A^2$



Annihilation

$$\frac{dN}{dt} = C_c - C_A N^2$$

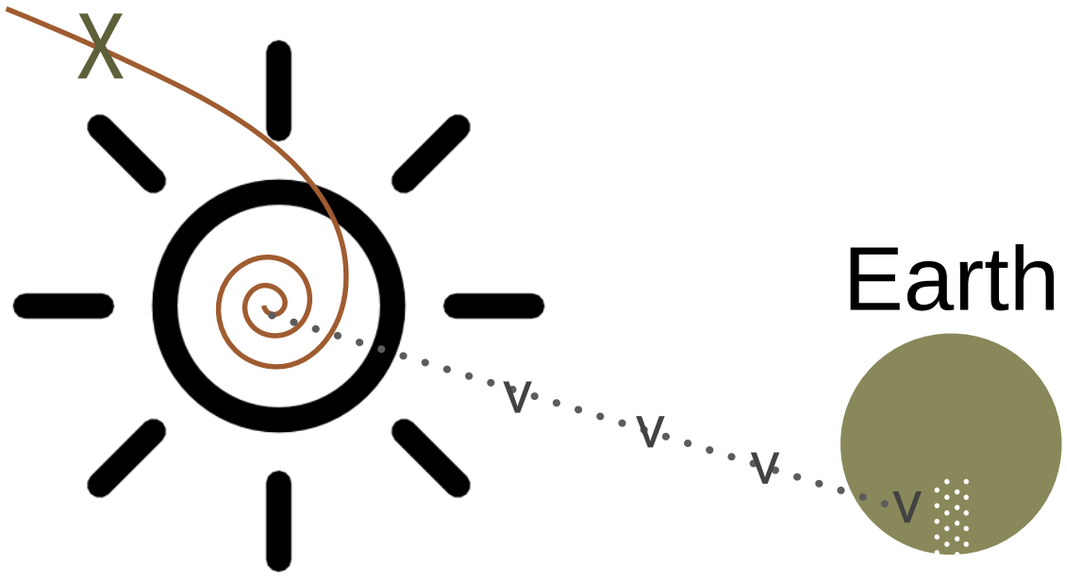
$$\Gamma_A = \frac{C_C}{2} \tanh^2\left(t/\tau\right)$$

$$\tau = (C_C C_A)^{-1/2}$$

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

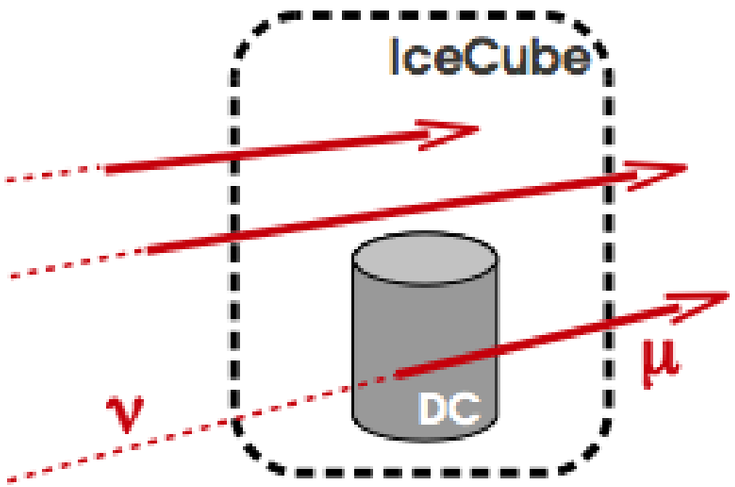
At equilibrium, neutrino flux is proportional to σ_{sc}

Neutrinos from WIMP annihilations in the Sun

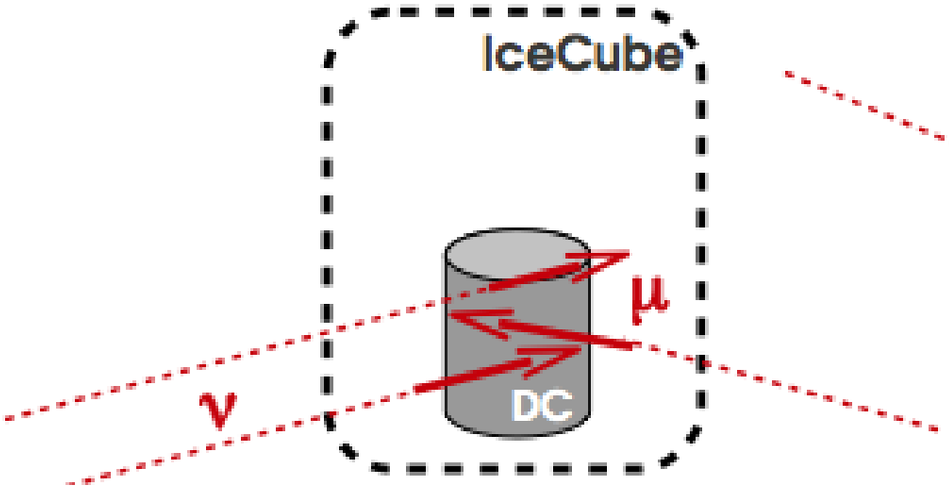


- Sun is a **down-going** source during austral summer
- Sun is an **up-going** source during austral winter

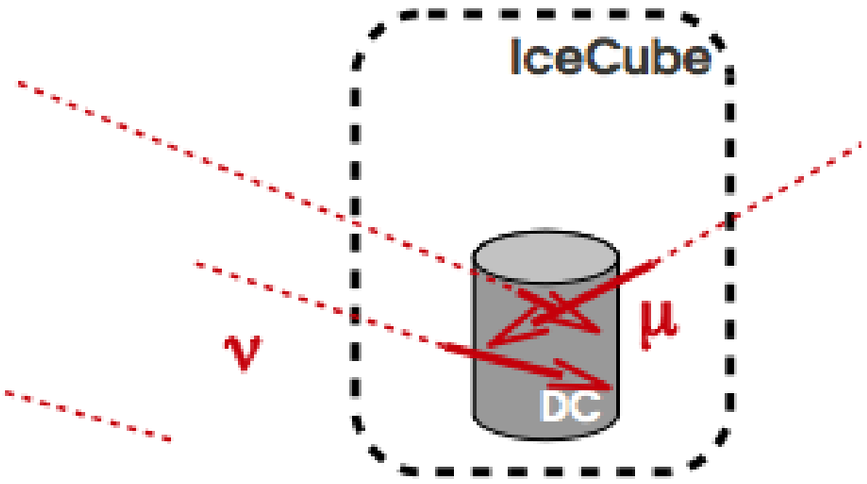
- ***Up-going*** ①
  - No containment



- ***Up-going*** ②
  - strong containment

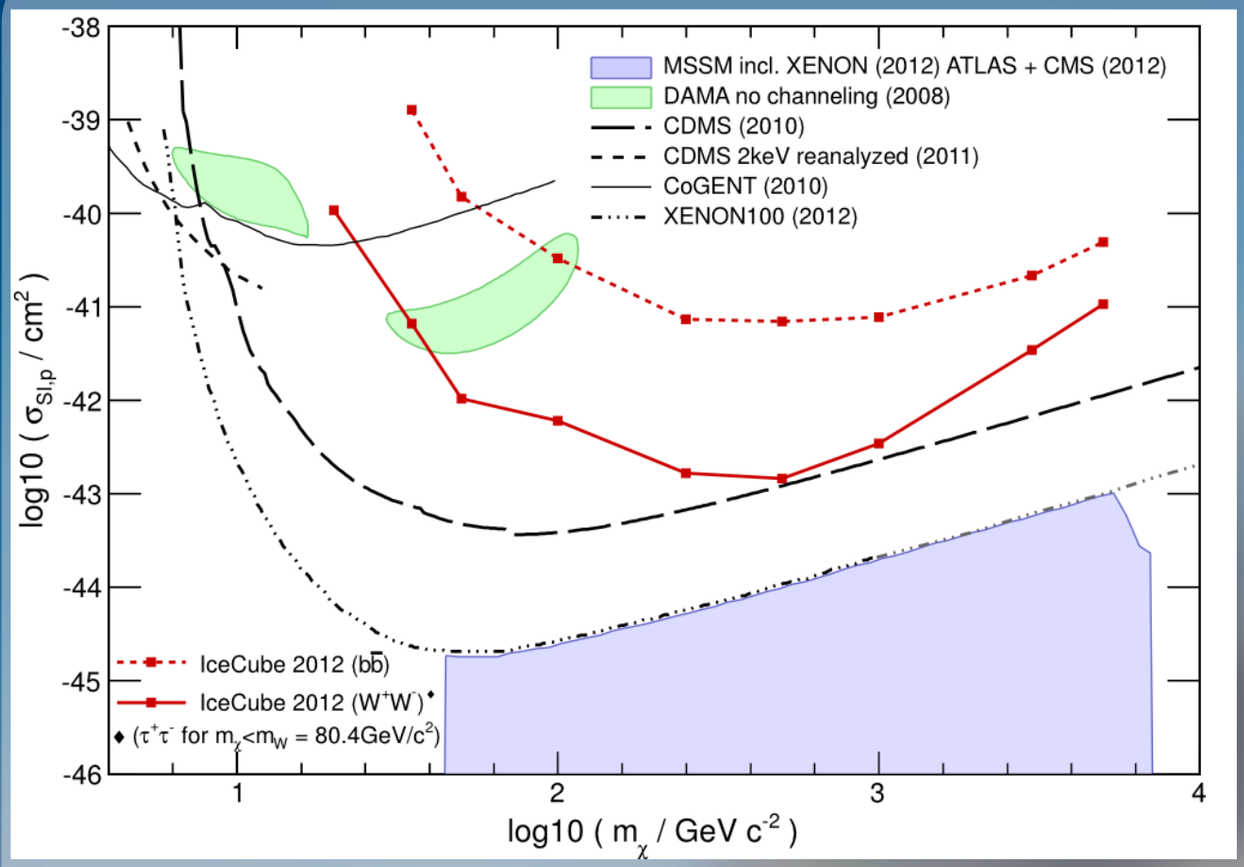


- ***Down-going*** ③
  - strong containment

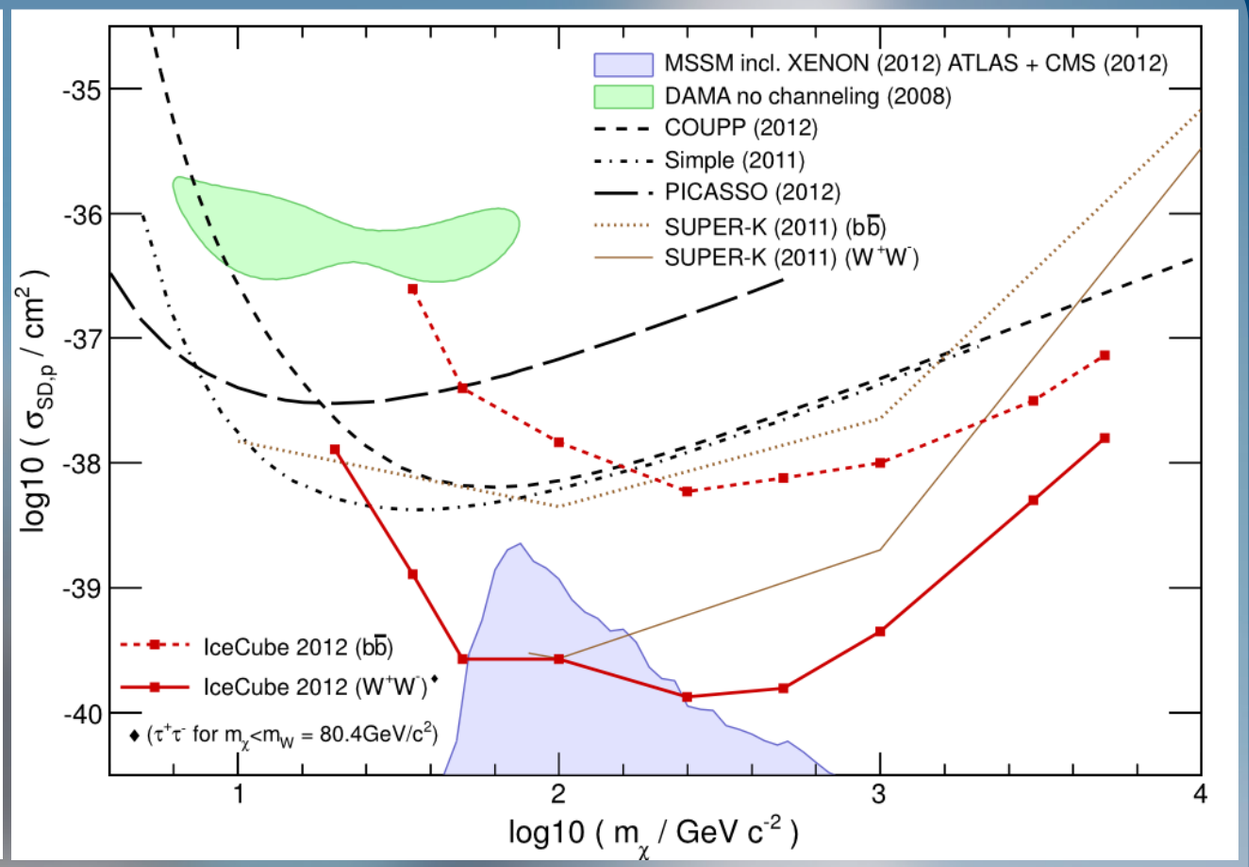


317 days of livetime, down to neutrino energies of ~10GeV!

Neutrinos from WIMP annihilations in the Sun



90% CL χ-p cross-section (spin-independent)



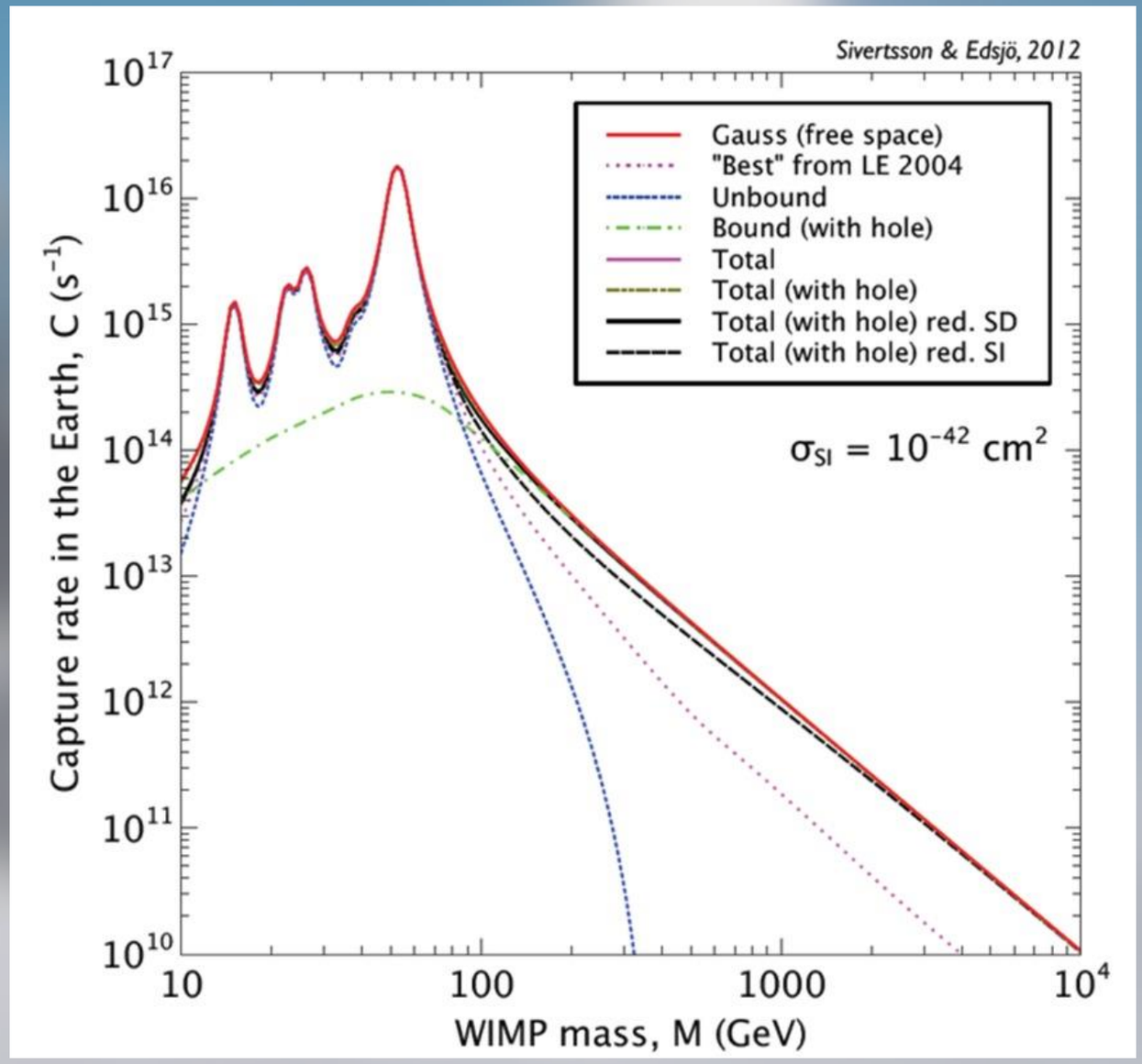
90% CL χ-p cross-section (spin-dependent)

- Assume : Capture and annihilation have reached equilibrium in the Sun -> Set limits on WIMP-nucleon scattering cross section
- Complementary to direct detection search efforts
  - fills out WIMP picture by testing other properties
- Most stringent SD cross-section limit for most models

WIMPs in Earth

- Search for vertical up-going tracks
- Capture rate dominated by heavy elements
- Capture and annihilation not in equilibrium

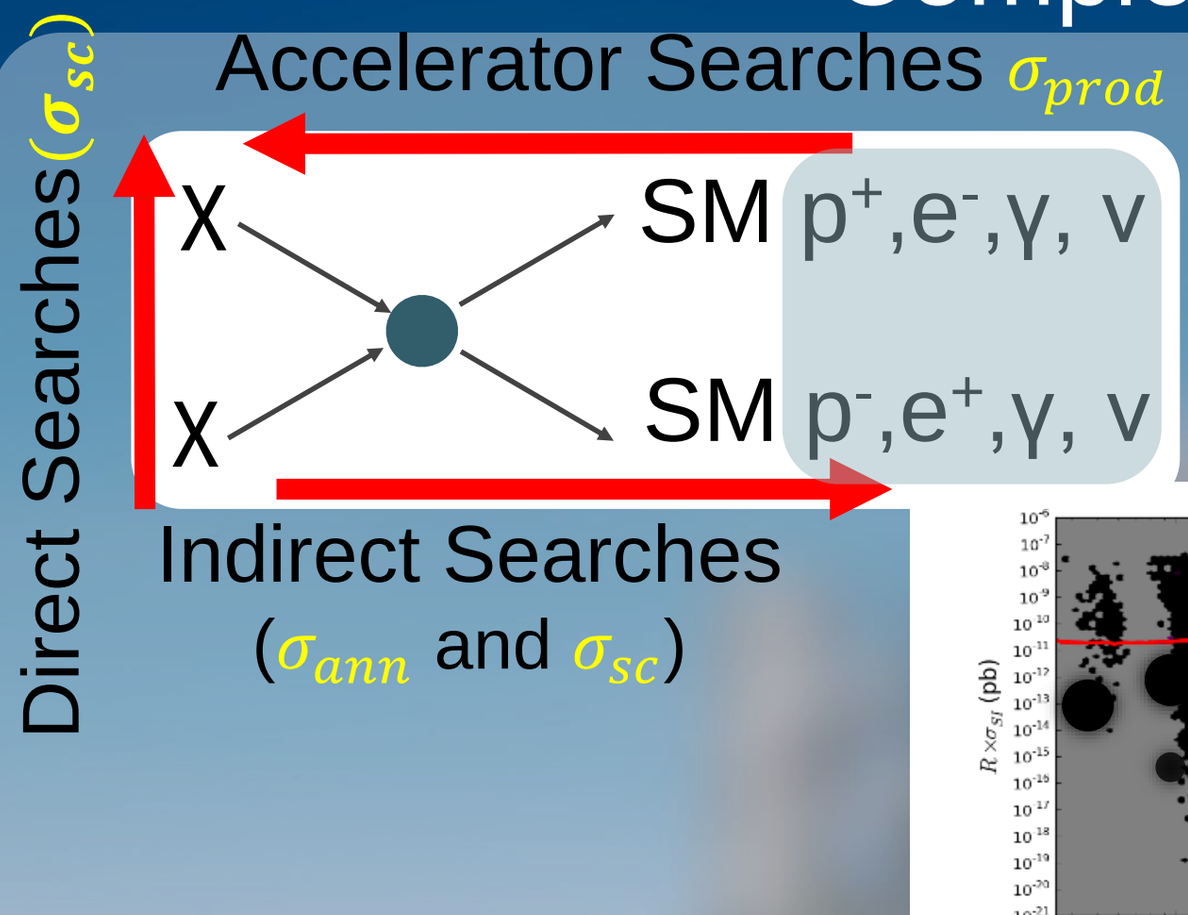
WIMP Capture rate in Earth



Resonant peaks correspond to O, Mg, Si, & Fe respectively

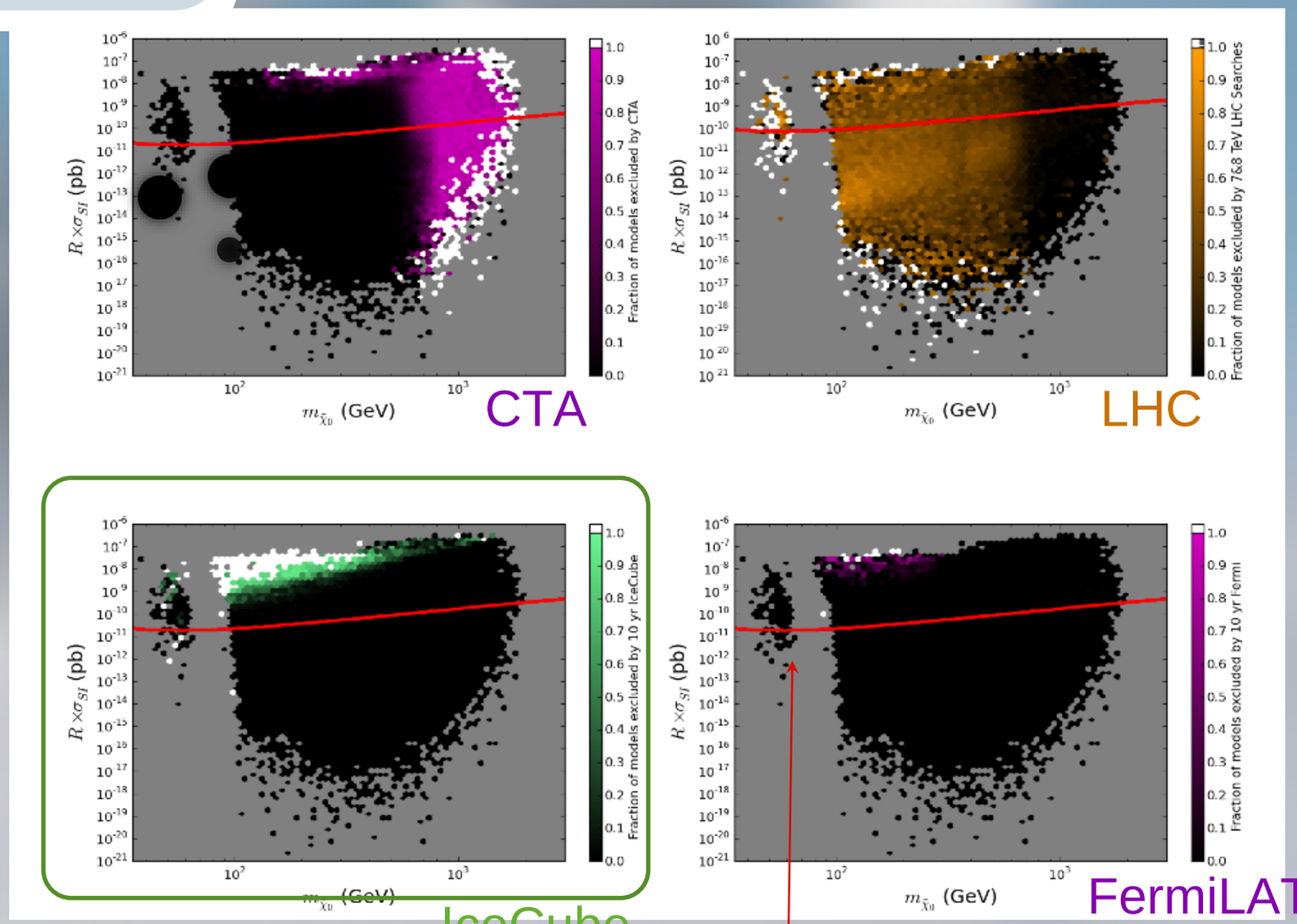
Analysis in Progress!

Complementarity



Fraction of excluded pMSSM models

arxiv:1305.6921v2

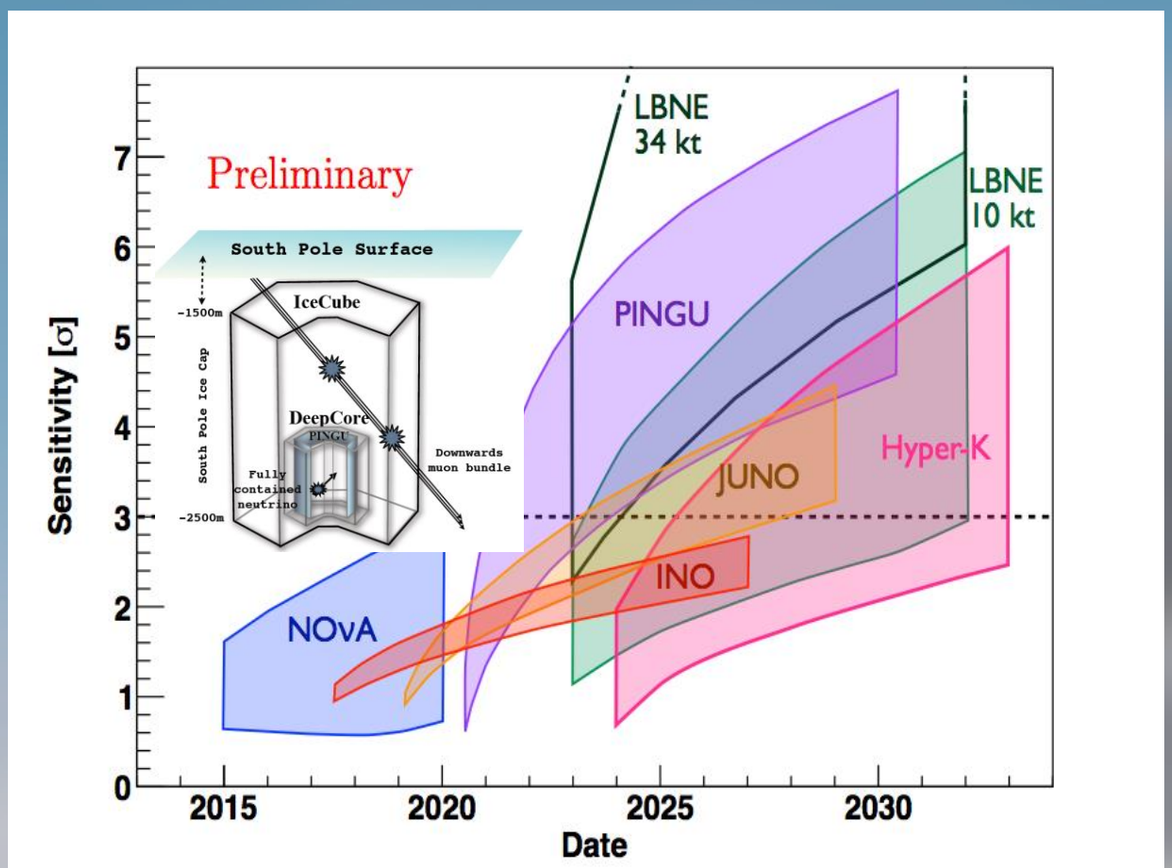


Combining different strategies is important

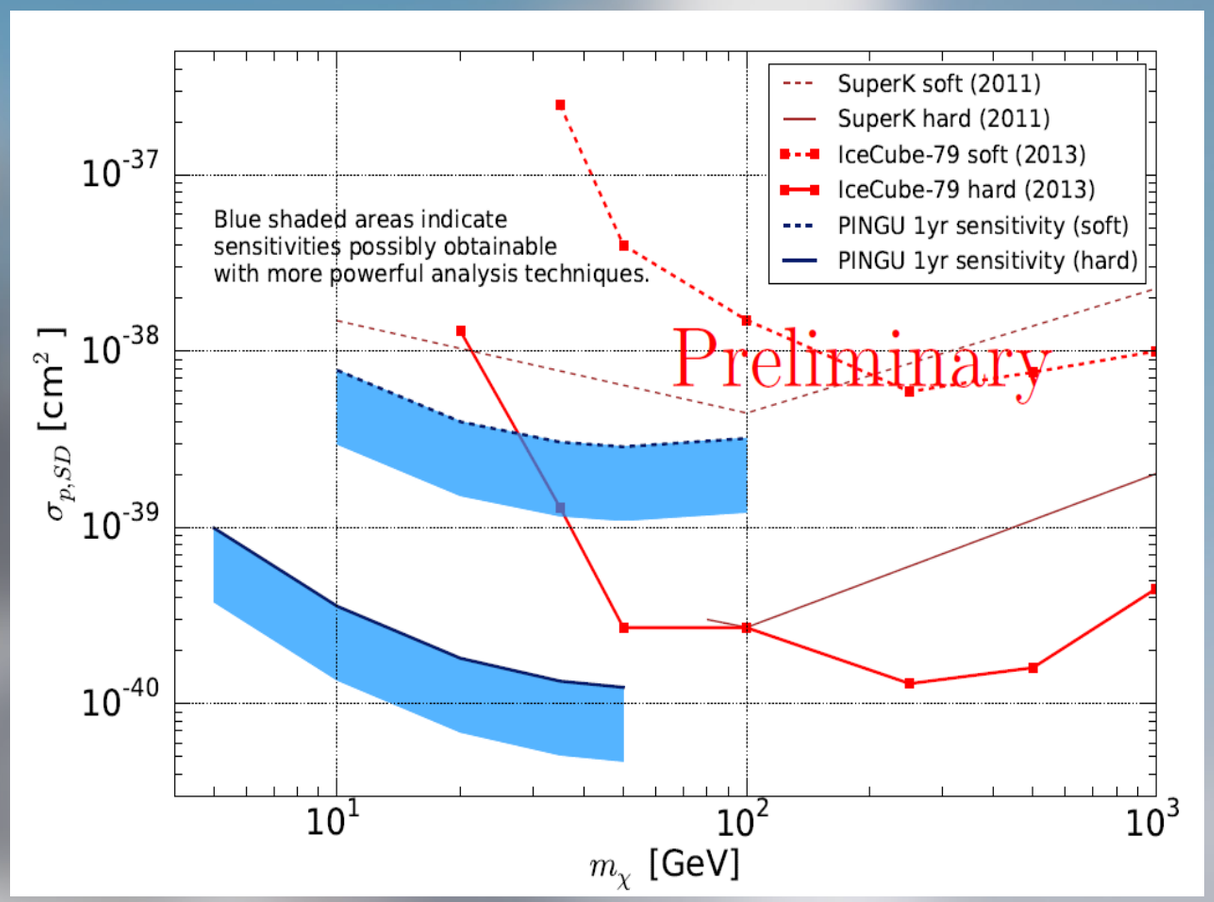
- Pin down DM properties in case of a signal

The FUTURE : PINGU

Further in-fill of deep core.
Lower the energy threshold few GeV : Sensitivity for WIMP masses down to 5 GeV
Oscillations and Neutrino Mass Hierarchy



Mass Hierarchy Sensitivity



Spin Dependent WIMP-nucleon cross section sensitivity from WIMP Annihilations in the Sun.

Conclusions

- Dark Matter exists and WIMPs are excellent DM candidates.
- IceCube can look for neutrinos produced by WIMP Annihilations in various targets.
- When looking at targets in which WIMPs get gravitationally captured, IceCube can set limits on σ_{sc}, comparable to Direct Detection Experiments. The spin dependent limits set by IceCube are the most stringent for WIMP Masses above 35 GeV.
- IceCube can also look for WIMP annihilations in the GC, the Galactic Halo and Dwarf Spheroidal Galaxies.
- The parameter space of certain Dark Matter models can be studied in entirety only by the combined efforts of Direct and Indirect detection experiments.
- PINGU will Increase IceCube sensitivity to lower WIMP masses.