Indirect Searches for Dark Matter

Neutrinos as a probe

Deepak Tiwari

India-based Neutrino Observatory (INO)

Harish-Chandra Research Institute, Allahabad

Workshop on High Energy Physics Phenomenology XV
IISER Bhopal

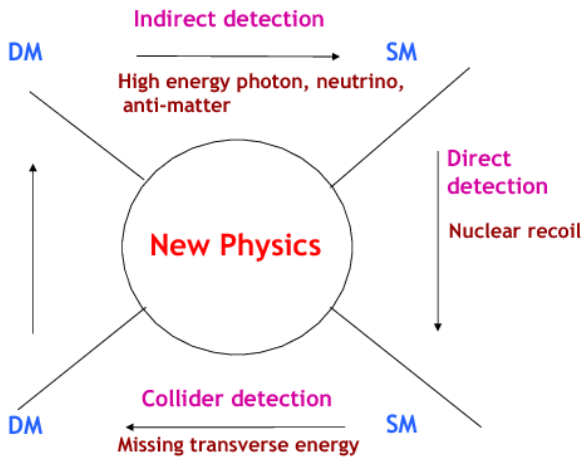
December 21, 2017

Dark Matter

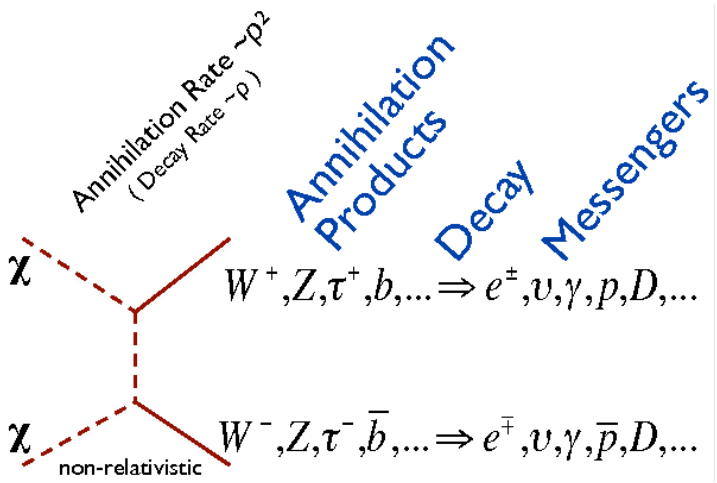
Indirect Searches

Introduction

- Various astrophysical and cosmological observations strongly indicate the existence of Dark Matter with an abundance $\sim$ 27%.
- Among the many candidates proposed, **Weakly Interactive Massive Particles (WIMPs)** are the most favored ones.



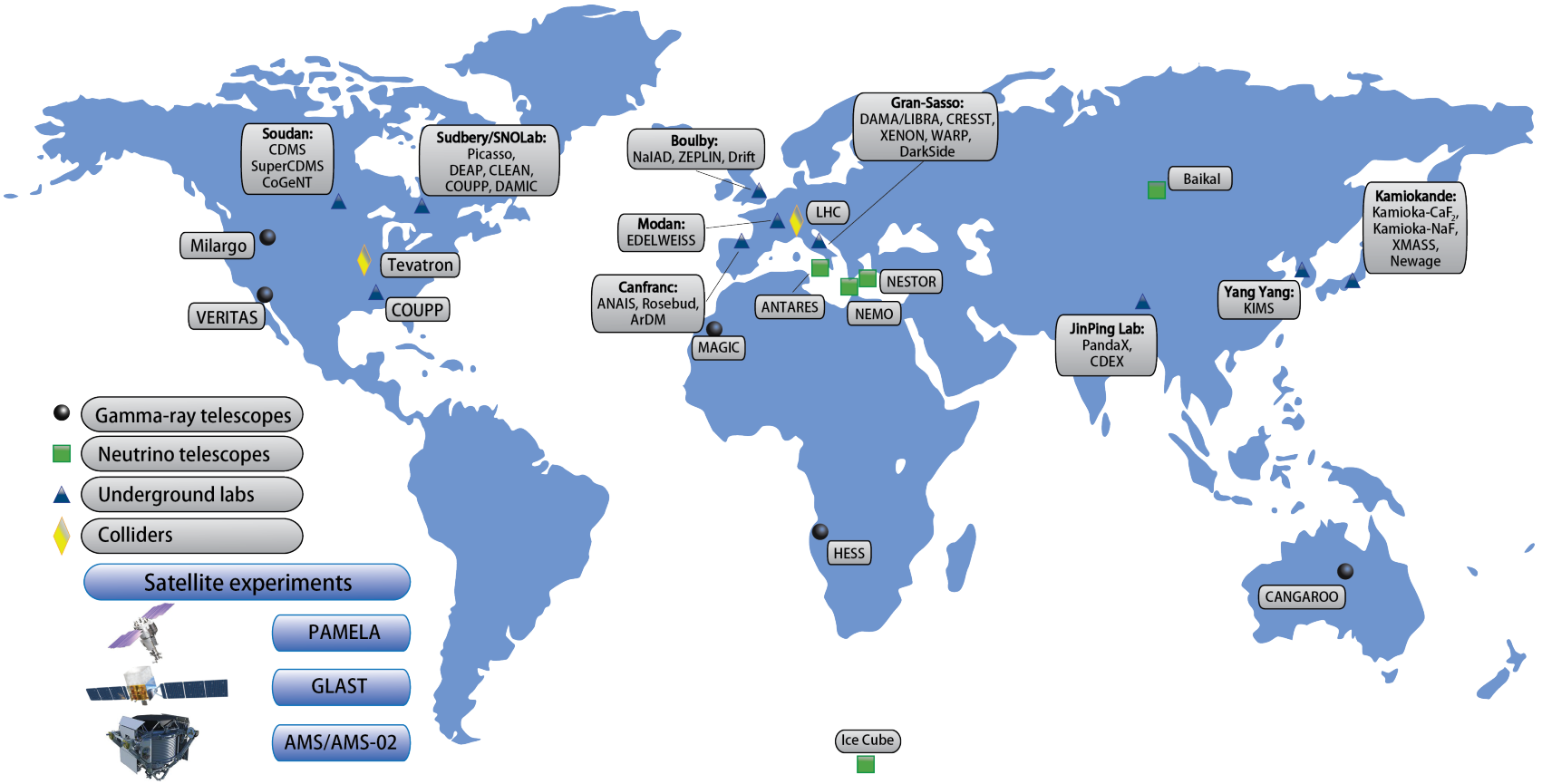
[arXiv:1409.4590]



Talks by Debanjan Bose, Debashish Borah

World experiments for Dark Matter detection

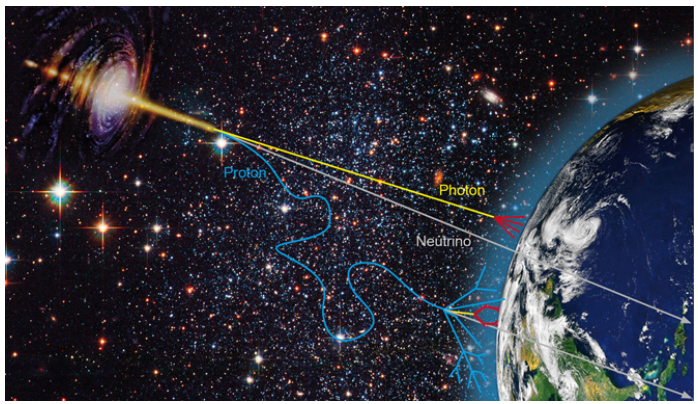
Direct and Indirect searches [arXiv:1510.06927]



Indirect Searches

Neutrinos as a probe to Dark Matter

- As the solar system moves through dark matter halo, the WIMPs get scattered on the nuclei in celestial bodies like the Sun/Earth and lose energy. If their final velocities are less than escape velocity of the celestial body, then they get gravitationally trapped by the gravitational potential of the body and sink to their respective cores. *Talk by Debashish Majumdar*
- The annihilation of WIMPs scales with ρ^2 and decay with ρ, where ρ the WIMP concentration. The centers of celestial bodies, galactic center etc are the centers of signal generation.
- Among the various messengers, neutrinos can escape the interiors of the celestial bodies and extreme conditions and hence are the most suitable probes of Dark matter searches. *Talk by Raj Gandhi*



source http://www.ung.si/en/research/cac/projects/cta

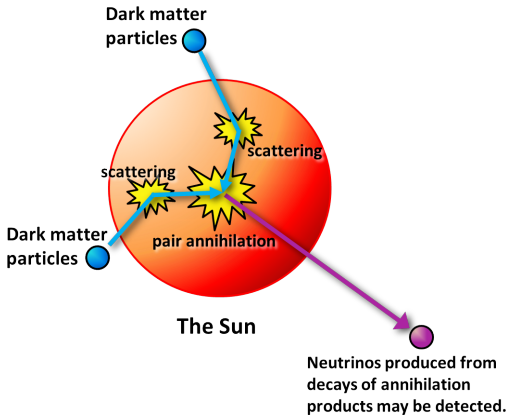
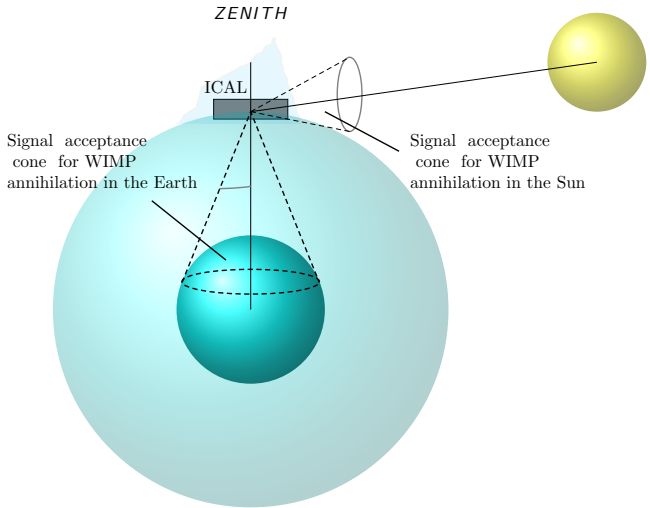
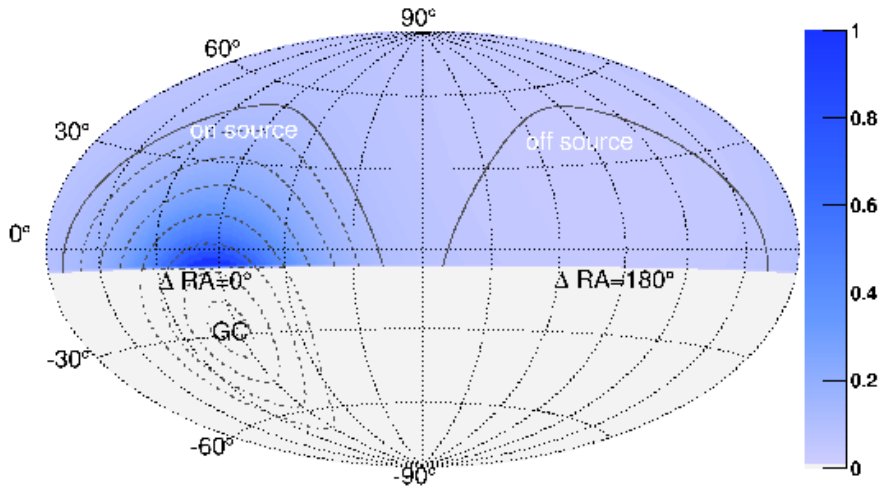


Image source:http://www-sk.icrr.u-tokyo.ac.jp/

Signal search cone

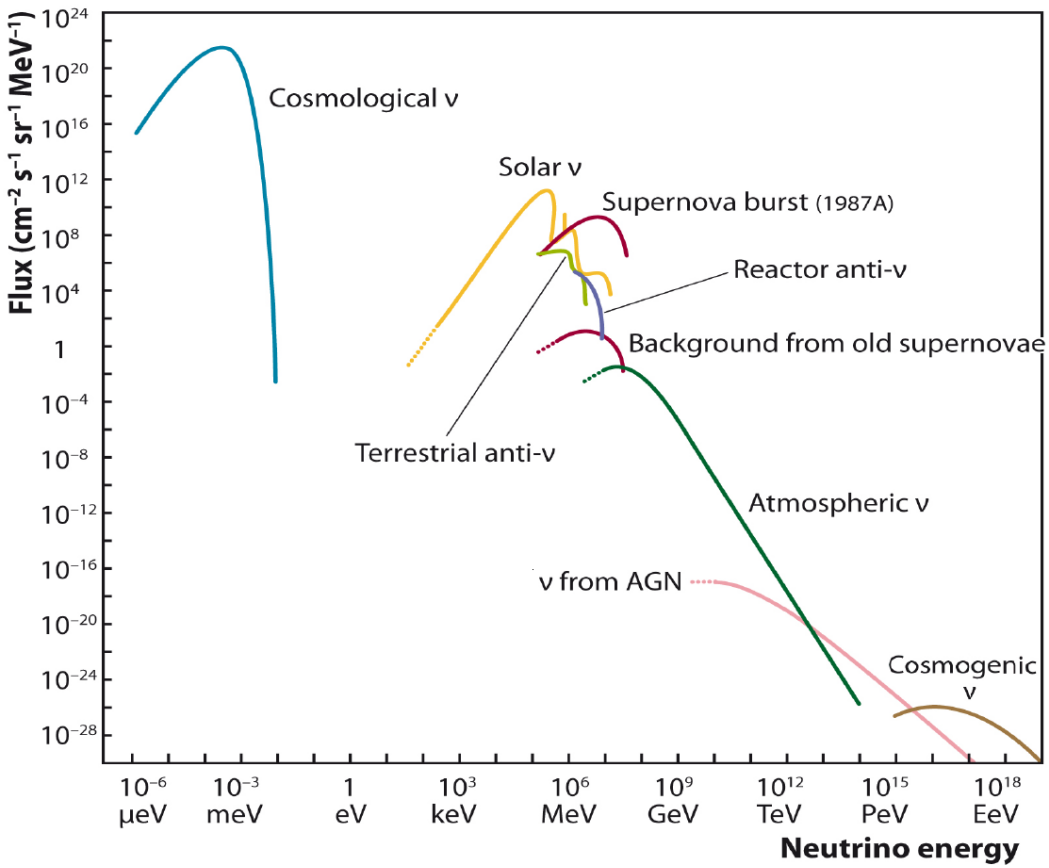
Neutrinos due to WIMP annihilation in the Sun, Earth and Galactic Center





Annihilations from Galactic Center,Phys.Rev. D84 (2011) 022004

Source of background neutrinos



Atmospheric neutrinos pose a severe background to the signal neutrinos arising out of WIMP annihilations/decay. Cosmic muons are also a major background. Figure source : arXiv:1111.0507

Signal rate calculations

Capture and Annihilation rate [**Choubey,Ghosh DT, arXiv:1711.02546**]

The number of WIMPs N(t) in the core of the Sun/ Earth :

$$\frac{\mathrm{d}}{\mathrm{d}t}(N) = C - C_A N^2 - EN$$

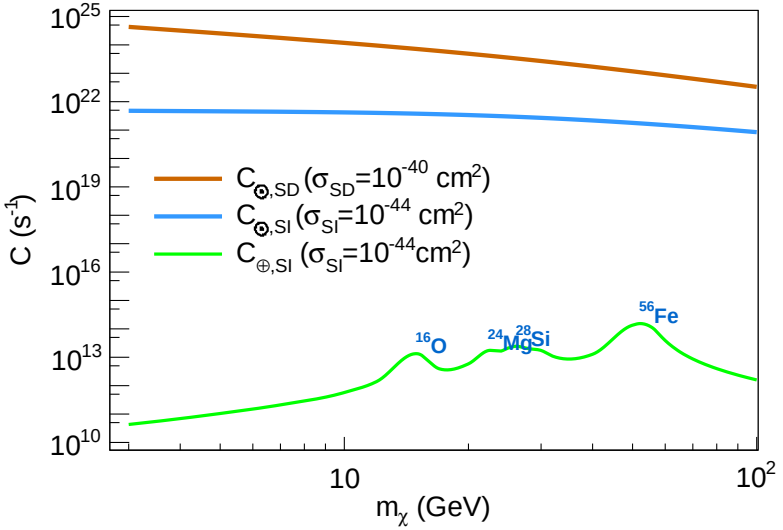
C = Capture Rate, C_A = Annihilation Rate term, E = Evaporation Rate and Annihilation rate : $\Gamma_A = C_A N^2/2$. Solving (1) and neglecting E :

$$\Gamma_A = \frac{1}{2} C \tanh^2(t/\tau)$$

$\tau = (CC_A)^{-1/2}$: time required for an equilibrium to be established between C and C_A. $t_\odot \simeq t_\oplus \simeq 4.5 \times 10^9$ years. Equilibrium has been established for the Sun but not for the Earth, hence :

$$\Gamma_\odot = \frac{1}{2} C_\odot$$

Capture may be due to Spin-Dependent (SD) or Spin-Independent (SI) scattering.



$$\Gamma_\oplus = \frac{1}{2} C_\oplus \tanh^2 \frac{t_\oplus}{\tau_\oplus}, \tau = (C_\oplus C_A)^{-1/2}$$

$\Gamma_A \propto C \propto \sigma_{WIMP-nucleon\ cross\ section}$

$\frac{t_\oplus}{\tau_\oplus} \propto < \sigma\ v >$

Signal rate calculations

Neutrino fluxes from WIMP annihilation in the Sun and the Earth [**Choubey,Ghosh DT, arXiv:1711.02546**]

The ν fluxes (in units of $\mathrm{GeV}^{-1} m^{-2} \Omega^{-1} s^{-1}$) at ICAL due to WIMP annihilation in the Sun/Earth are given by :

$$\frac{dN'_\nu}{d\Omega dt dE_\nu} = \frac{\Gamma_A}{4\pi R^2_{\odot/\oplus}} \sum_i BR_i \frac{dN_i}{dE_\nu}$$

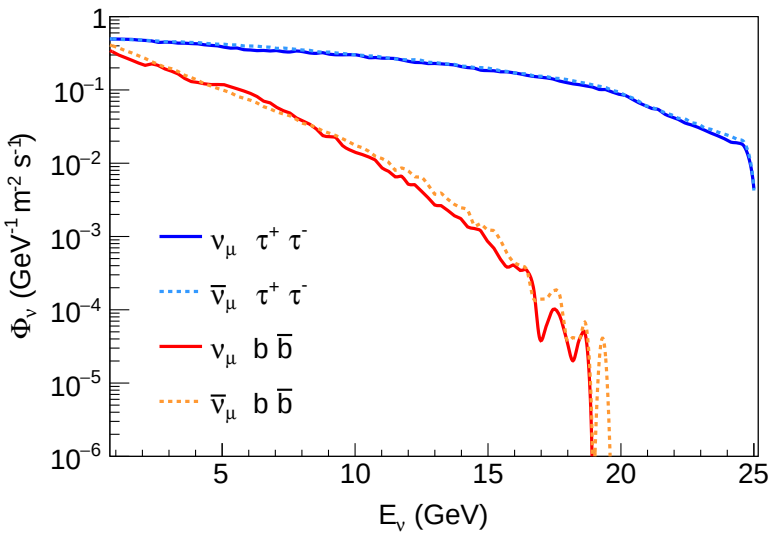


Figure : **SUN** ($\sigma_{SD} = 10^{-40} cm^2$)

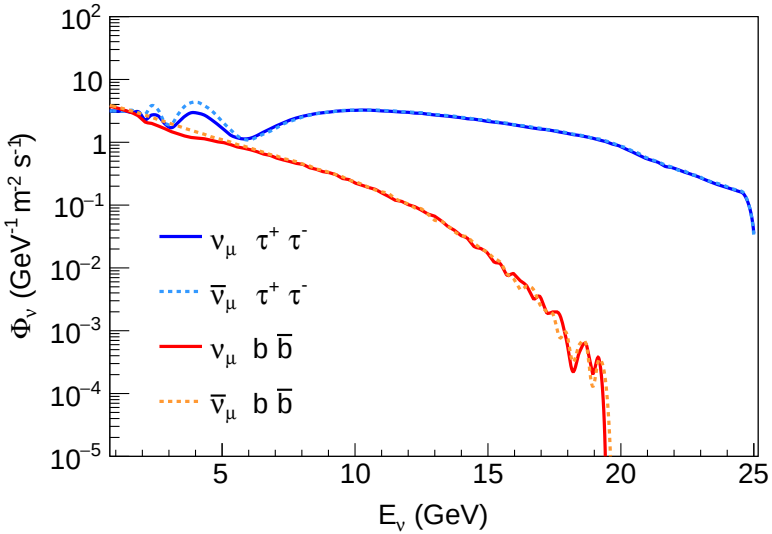


Figure : **EARTH** ($\sigma_{SI} = 10^{-40} cm^2$)

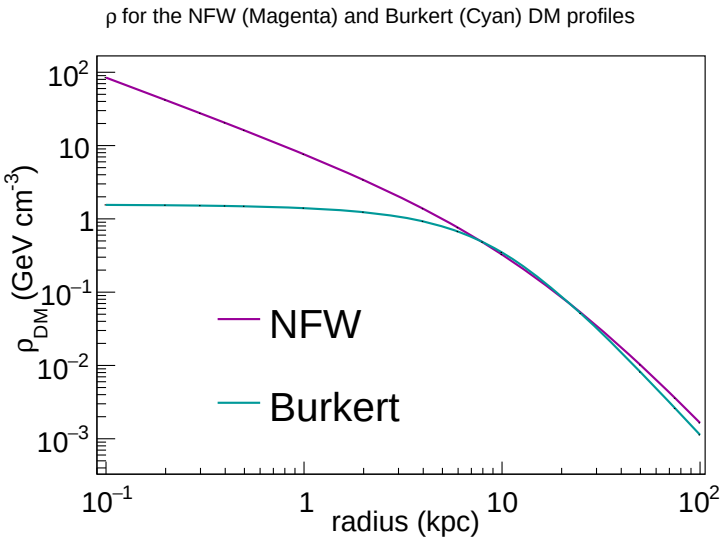
Neutrino fluxes from WIMP annihilation/decay in the Galactic Center

The ν flux $d\Phi/dE$ from dark matter annihilating/decaying particles is expressed as the product of a particle physics term by an astrophysical contribution J.

At energy E and in the direction (Ψ, θ) the flux integrated over the solid angle $\Delta\Omega = 2\pi(1 - cos\alpha)$ is given in which $d\Omega = d\beta sin\alpha d\alpha$ is the elementary solid angle around the line of sight direction (Ψ, θ).

$$\frac{d\Phi_\nu}{dE_\nu}(E, \Psi, \theta) = \frac{d\Phi_\nu}{dE_\nu}(E) \times J(\Psi, \theta, \Delta\Omega)$$

Due to core-cusp problem, results are quoted for various density profiles.



Talk by Amina Khatuun on diffused dark matter.

Annihilation

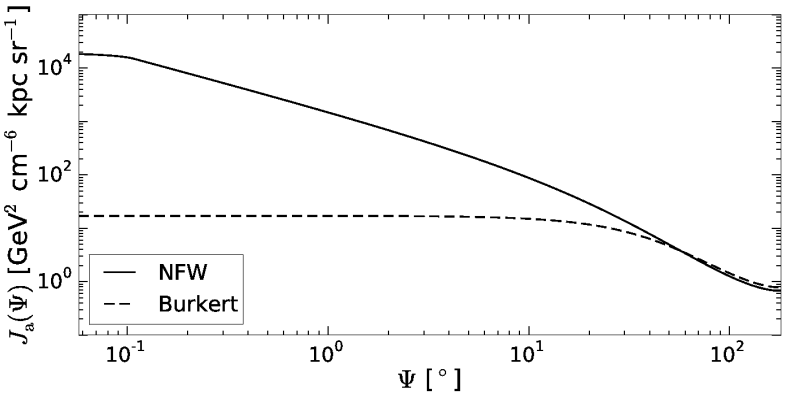
$$\frac{d\Phi_\nu}{dE_\nu}(E) = \frac{1}{4\pi} \frac{< \sigma_{ann}\, v >}{m_\chi^2 \delta} \sum_f BR_f \frac{dN_\nu}{dE_\nu}$$

$$J(\psi, \theta, \Delta\Omega) = \int_0^{\Delta\Omega} \int_{l.o.s} \rho^2 dl d\Omega$$

Decay

$$\frac{d\Phi_\nu}{dE_\nu}(E) = \frac{1}{4\pi} \frac{1}{\tau_\chi m_\chi} \sum_f BR_f \frac{dN_\nu}{dE_\nu}$$

$$J(\psi, \theta, \Delta\Omega) = \int_0^{\Delta\Omega} \int_{l.o.s} \rho dl d\Omega$$



IceCube, arXiv:1505.07259

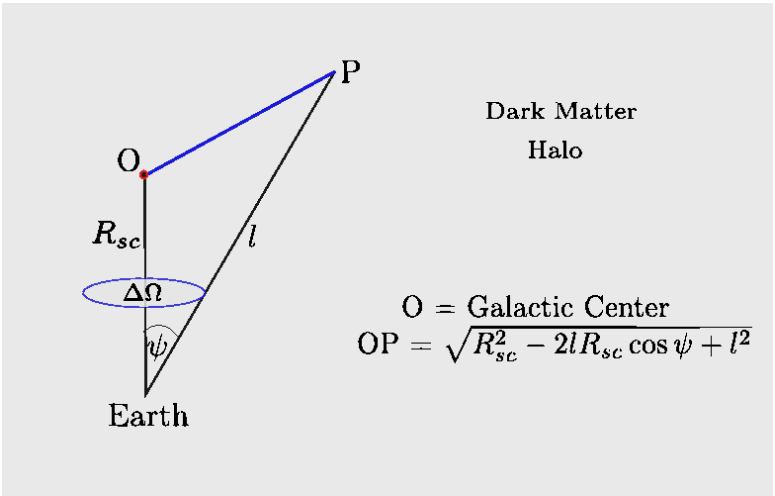


Fig Source : arXiv:1703.10221

Neutrino fluxes from Galactic center

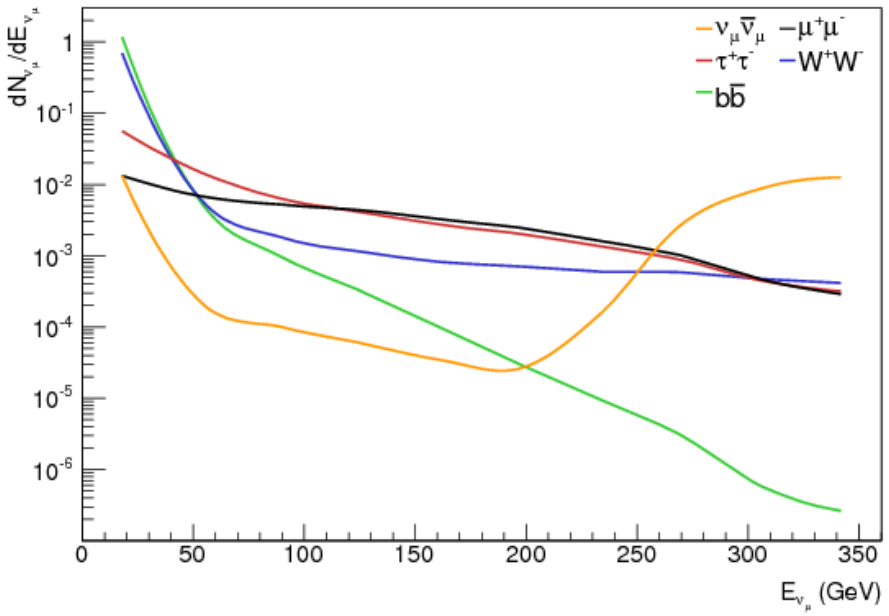


Figure : $dN_{\nu_\mu}/dE_{\nu_\mu}$ spectra at the earth due to annihilation of 360 GeV WIMP in the galactic center. ANTARES Collaboration (Adrian-Martinez, S. et al.) JCAP 1510 (2015)

Neutrino spectrum at Earth

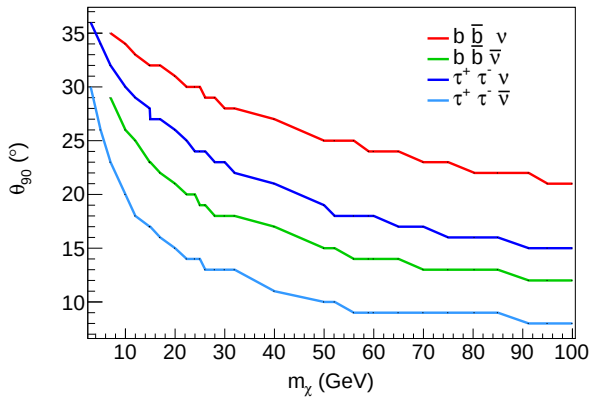
$$\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}}\Big|_{\oplus} = \sum_{\alpha} P(\nu_\alpha \to \nu_\mu)\frac{dN_{\nu_\alpha}}{dE_{\nu_\alpha}}\Big|_{\ominus}$$

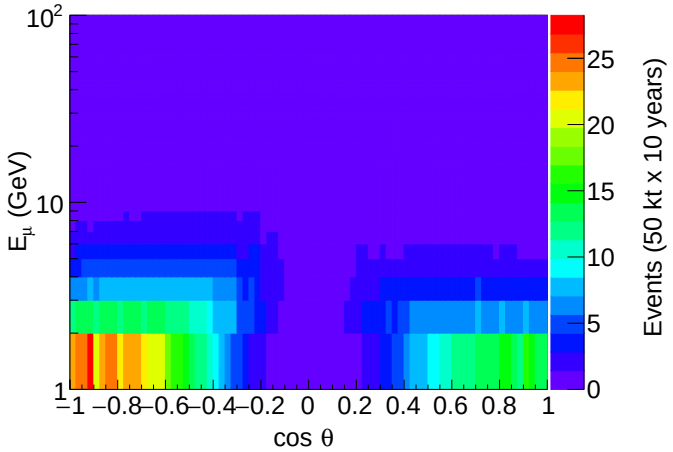
Atmospheric background suppression scheme

[Choubey,Ghosh DT, arXiv:1711.02546]

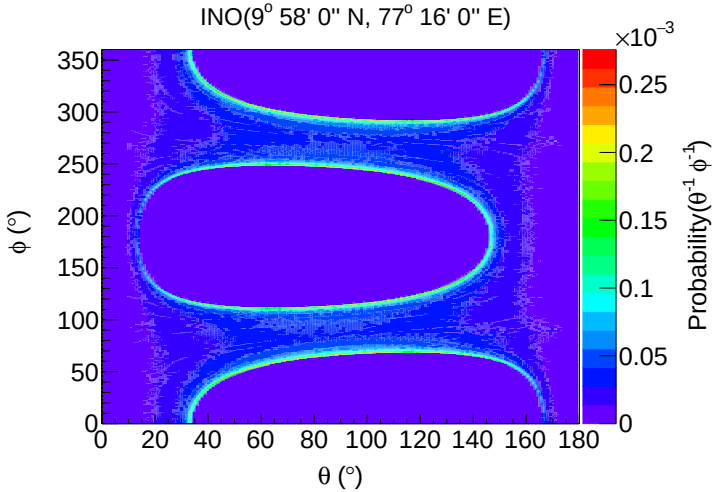
θ_{90} : Cone half angle containing 90% of the signal events.

For ICAL : Cosθ = 1 is upward going





- For each m_χ and annihilation channel : place θ_{90} cone around the signal ν direction and accept μ that fall within this cone!
- Atmospheric bkg. calculated with Honda fluxes at Theni.



Events due to WIMP annihilation in the Sun and the suppressed atmospheric Background

[Choubey,Ghosh DT, arXiv:1711.02546]

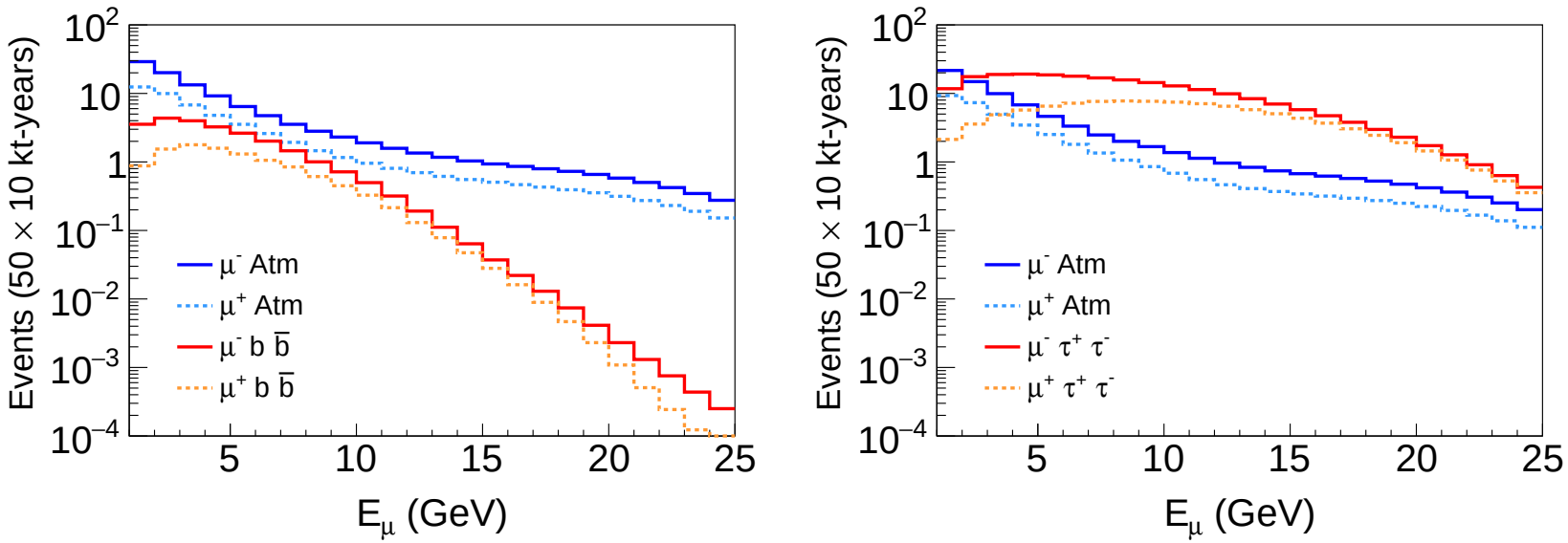


Figure : The μ^- (red solid lines) and μ^+ (orange dotted lines) event distribution at ICAL due to signal neutrinos arising out of WIMP annihilations in the sun. The signal events correspond to neutrino fluxes arising due to SD capture rate. A cross-section of $\sigma_{SD} = 10^{-39} cm^2$ has been assumed for the signal neutrinos and m_χ is taken as 25 GeV. The right-hand panel is for WIMP annihilating to the $\tau^+\tau^-$ channel while the left-hand panel is for the annihilation to $b\bar{b}$ channel. Also shown are μ^- (blue solid lines) and μ^+ (azure dotted lines) event distributions due the reduced atmospheric neutrino background after applying the cone-cut angular suppression and the solar exposure function suppression.

Neutrinos from annihilation WIMP in the Sun

Indirect searches with Super-Kamiokande

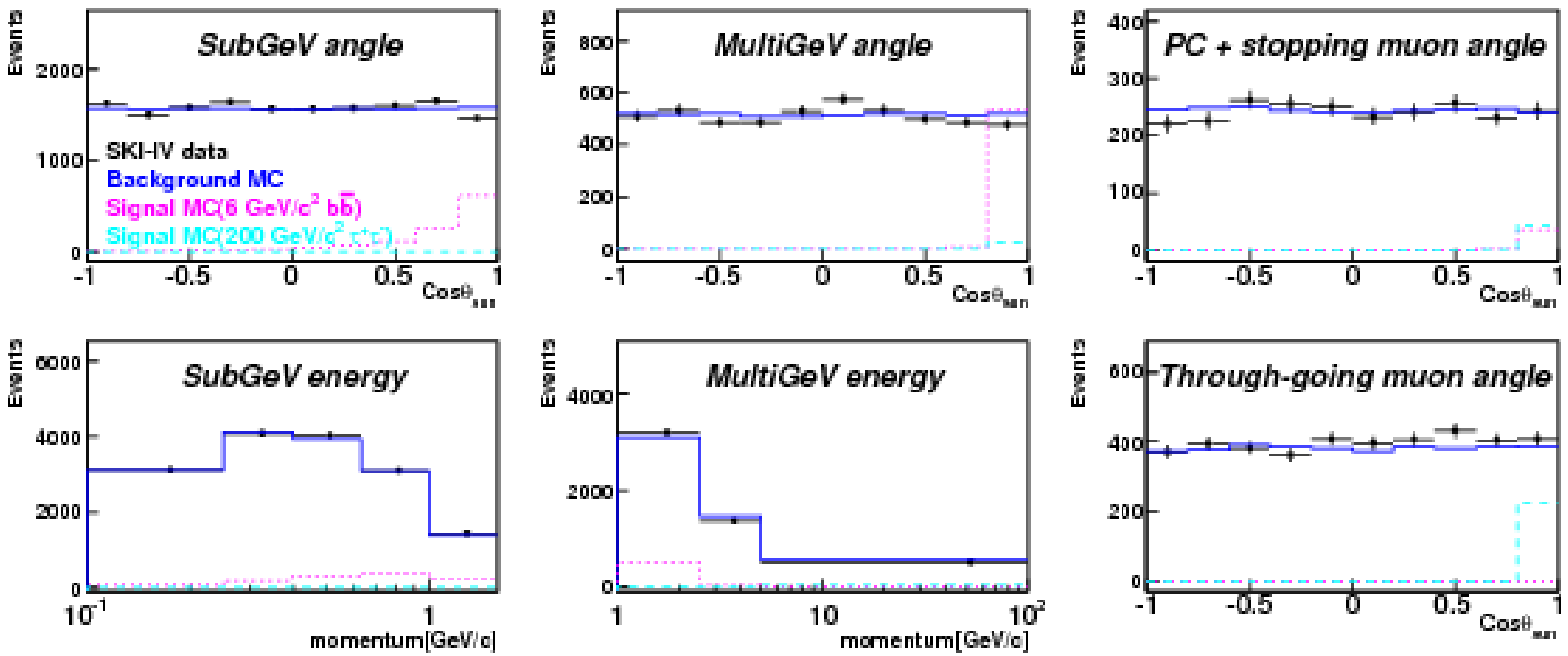
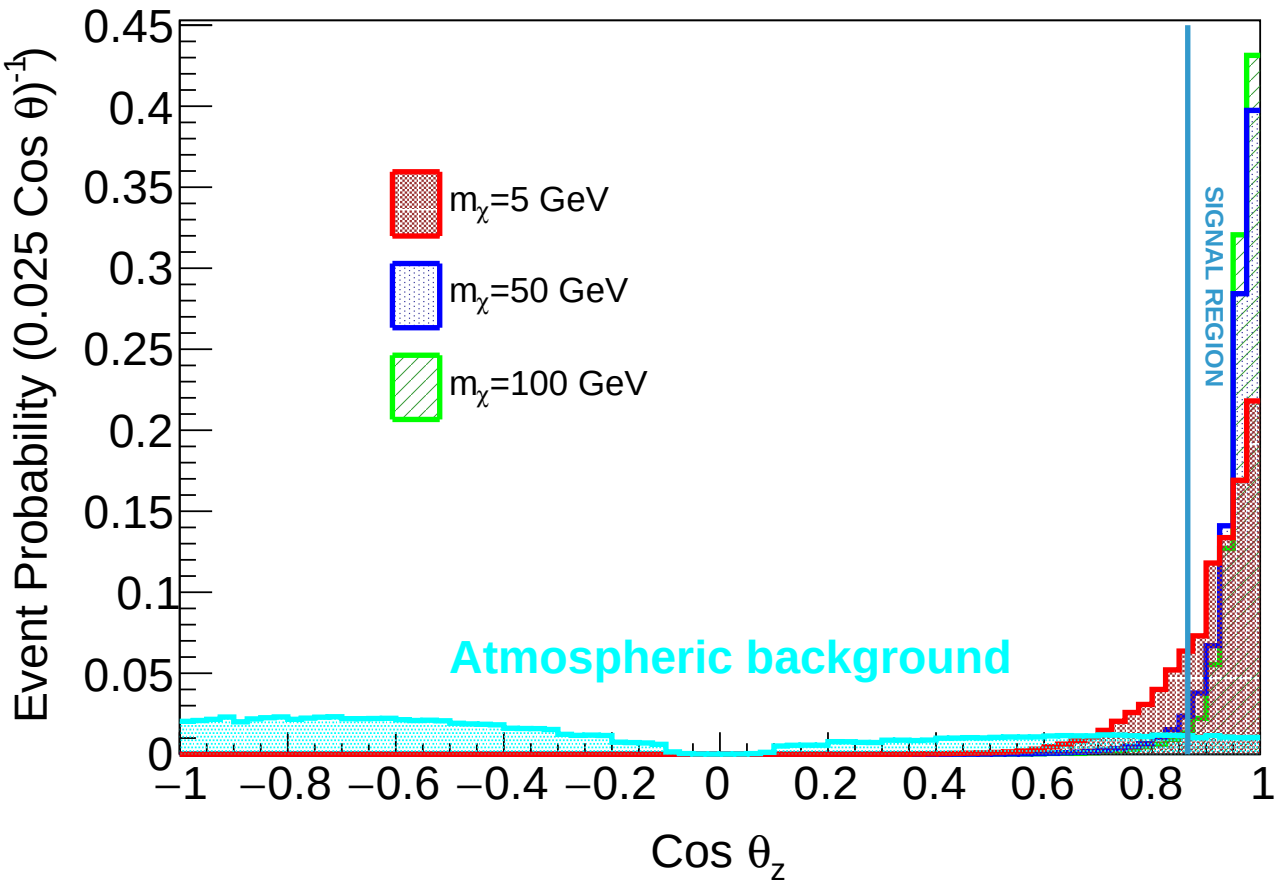


Figure : Angular and reconstructed momentum [GeV/c] distributions of SK I-IV data (black crosses); atmospheric-neutrino background MC (normalized to data live time, blue solid); WIMP neutrino signal MC at 90% upper limit, magnified 30 times for visibility.

(Choi, K. et al.) Phys.Rev.Lett. 114 (2015) no.14, 141301

Atmospheric Background Suppression

[**Choubey,Ghosh DT, in preparation**]



Angular probability distribution of reconstructed events at ICAL due to WIMP annihilations in the Earth.

Limits on WIMP-proton σ_{SD} from WIMP annihilation in the Sun

[Choubey,Ghosh DT, arXiv:1711.02546]

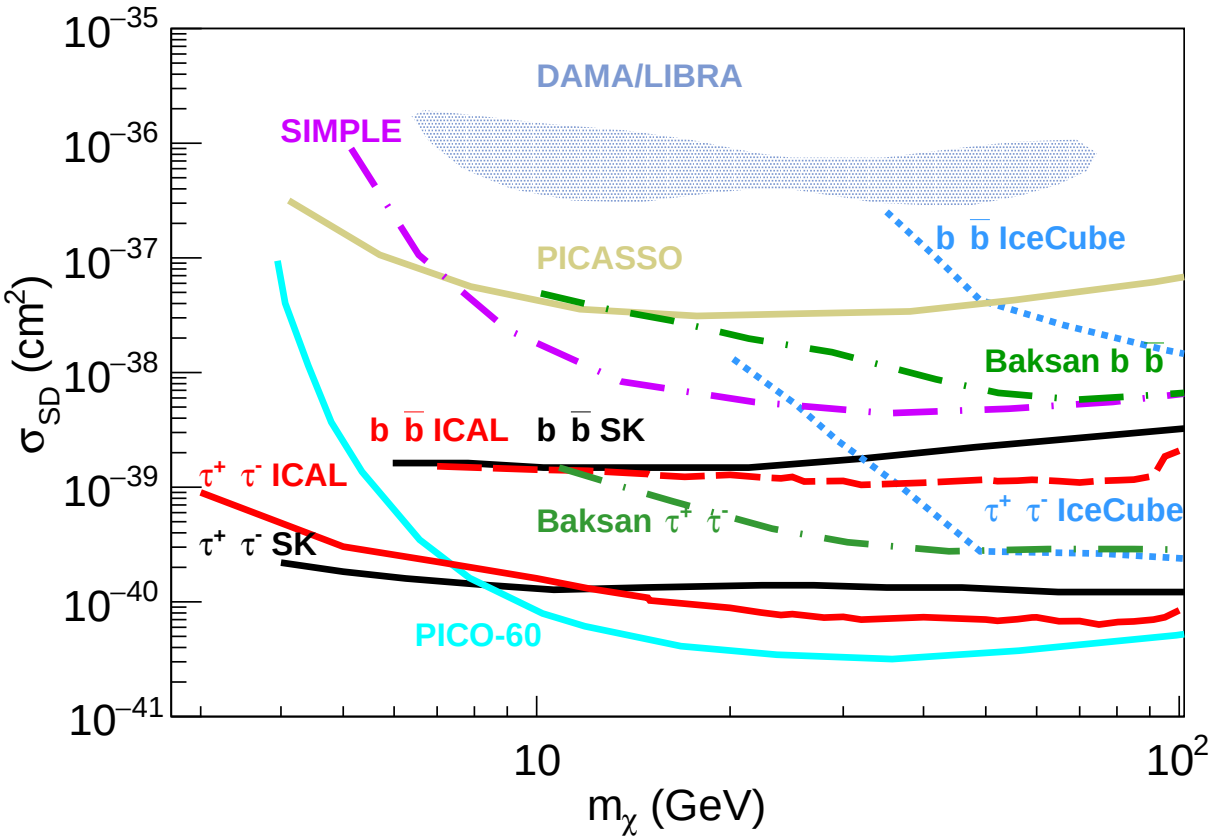


Figure : The expected 90 % C.L. sensitivity limit on the WIMP-nucleon spin-dependent cross-sections as a function of the WIMP mass. The ICAL expected sensitivity are for 10 years of running of ICAL. Current 90 % C.L. limits from other indirect detection and direct detection experiments have been shown.

Limits on WIMP-nucleon σ_{SI} from WIMP annihilation in the Sun

[Choubey,Ghosh DT, arXiv:1711.02546]

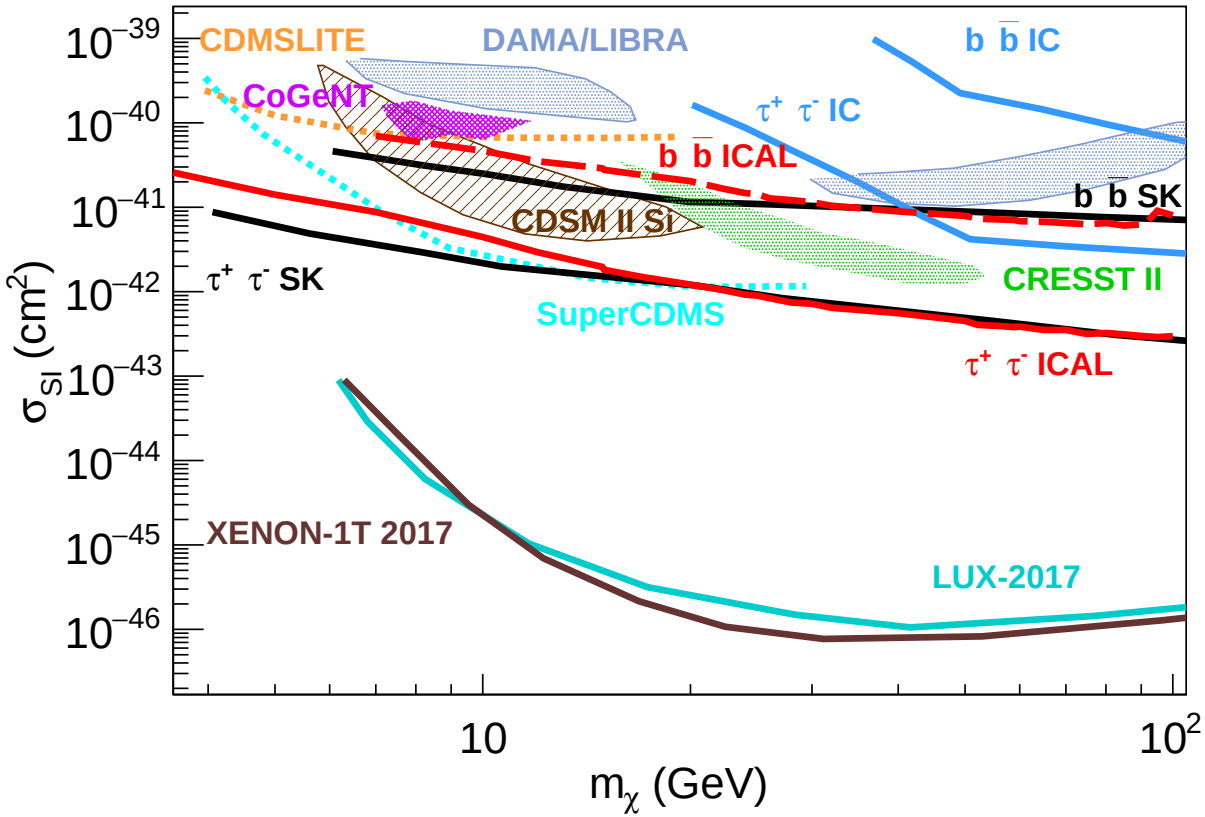


Figure : The expected 90 % C.L. sensitivity limit on the WIMP-nucleon spin-independent cross-sections as a function of WIMP mass. The expected ICAL sensitivity are for 10 years of running of ICAL. Current 90 % C.L. limits from other indirect detection and direct detection experiments have been shown.

Limits on WIMP-nucleon σ_{SI} from WIMP annihilation in the Earth

[Choubey,Ghosh DT, in preparation]

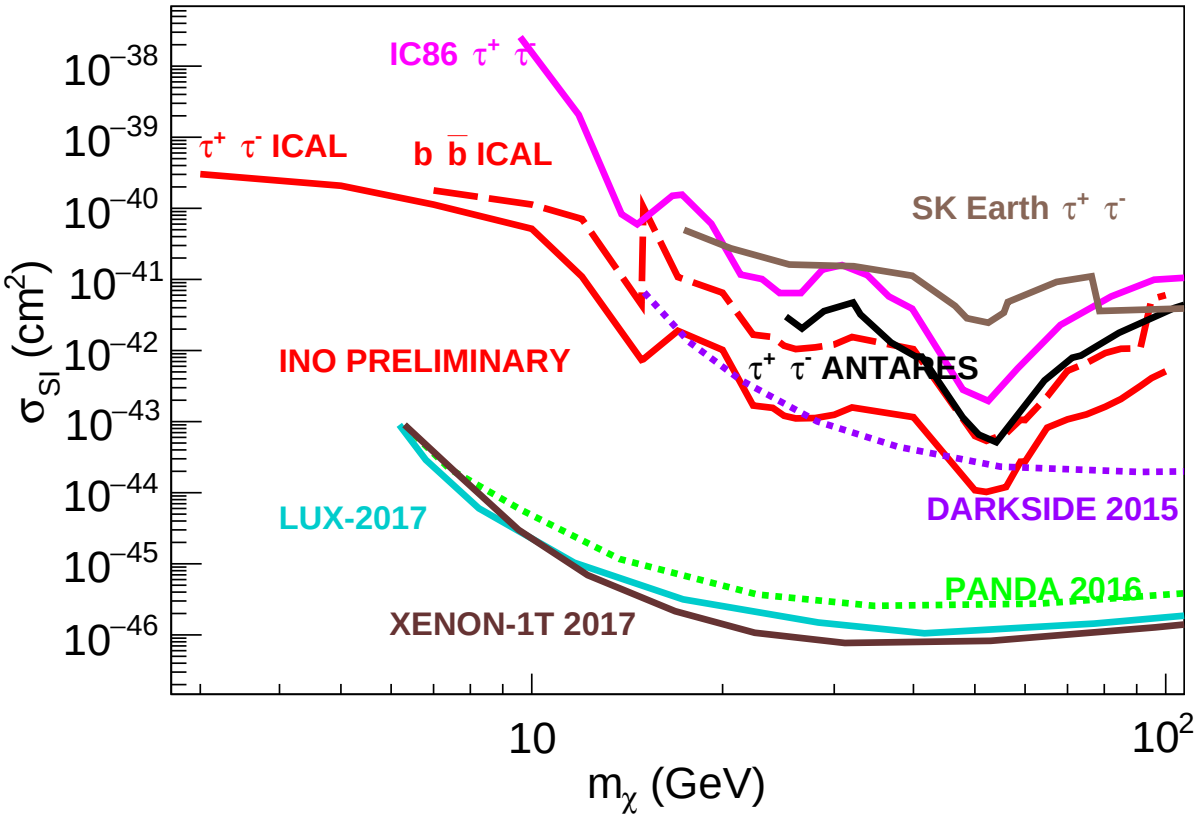


Figure : The expected 90% C.L. sensitivity limits on $\sigma^{SI}_{\chi-N}$ as a function of WIMP mass, assuming a WIMP annihilation cross section $< \sigma v >= 3 \times 10^{-26} cm^3 s^{-1}$. The displayed limits are for the local dark matter density $\rho = 0.3 GeV cm^{-3}$.The expected ICAL sensitivity are for 10 years of running of ICAL

Current Limits on $< \sigma\ v >$ from WIMP annihilation in the GC

Search with IceCube,M.G. Aartsen et al. EPJ C75 (2015) 492, arXiv:1505.07259

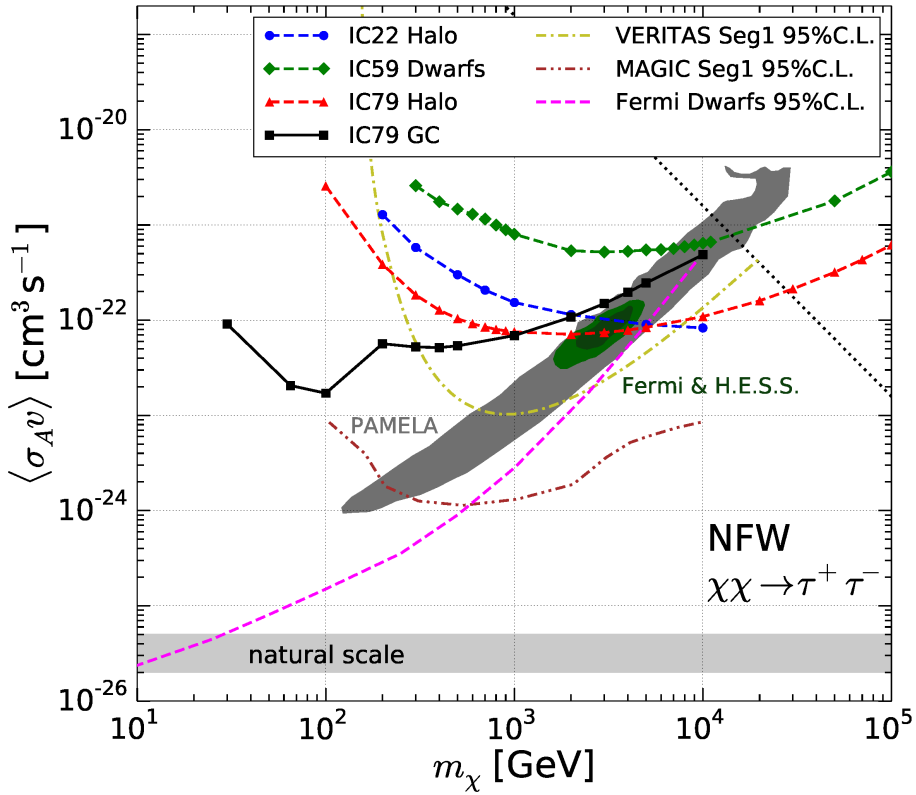


Figure : Comparison of limits from this work (IC79 GC) to other IceCube searches for dark matter annihilation in self-bound structures. Photon search limits from observation of dwarf spheroidals by VERITAS, MAGIC and Fermi are also shown. The grey-shaded region is a dark-matter interpretation of the positron excess reported by the PAMELA collaboration. The green-shaded regions are the 3-sigma and 5-sigma preferred regions from the electron-positron flux excess reported by Fermi and H.E.S.S.

Where are the WIMPs?

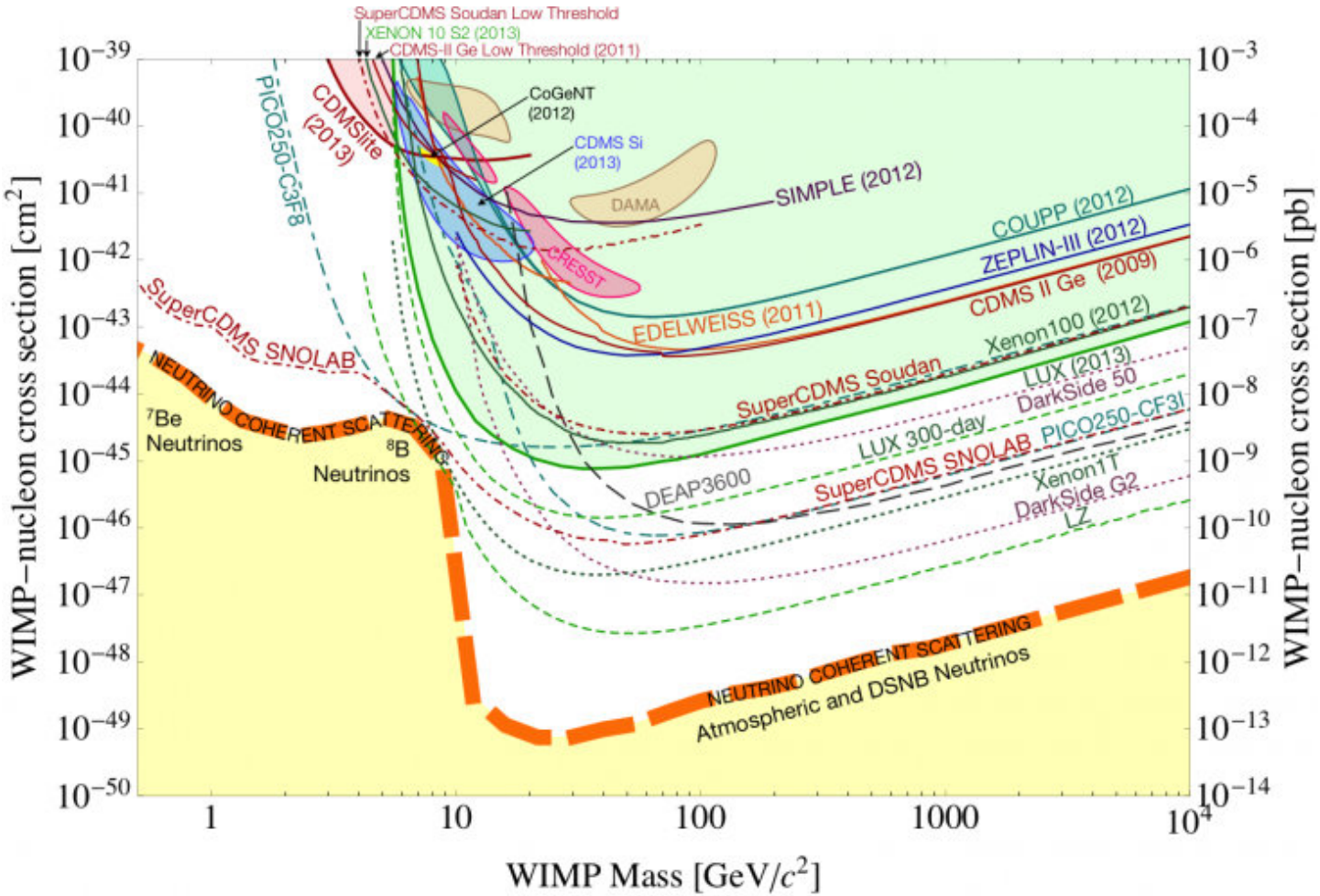
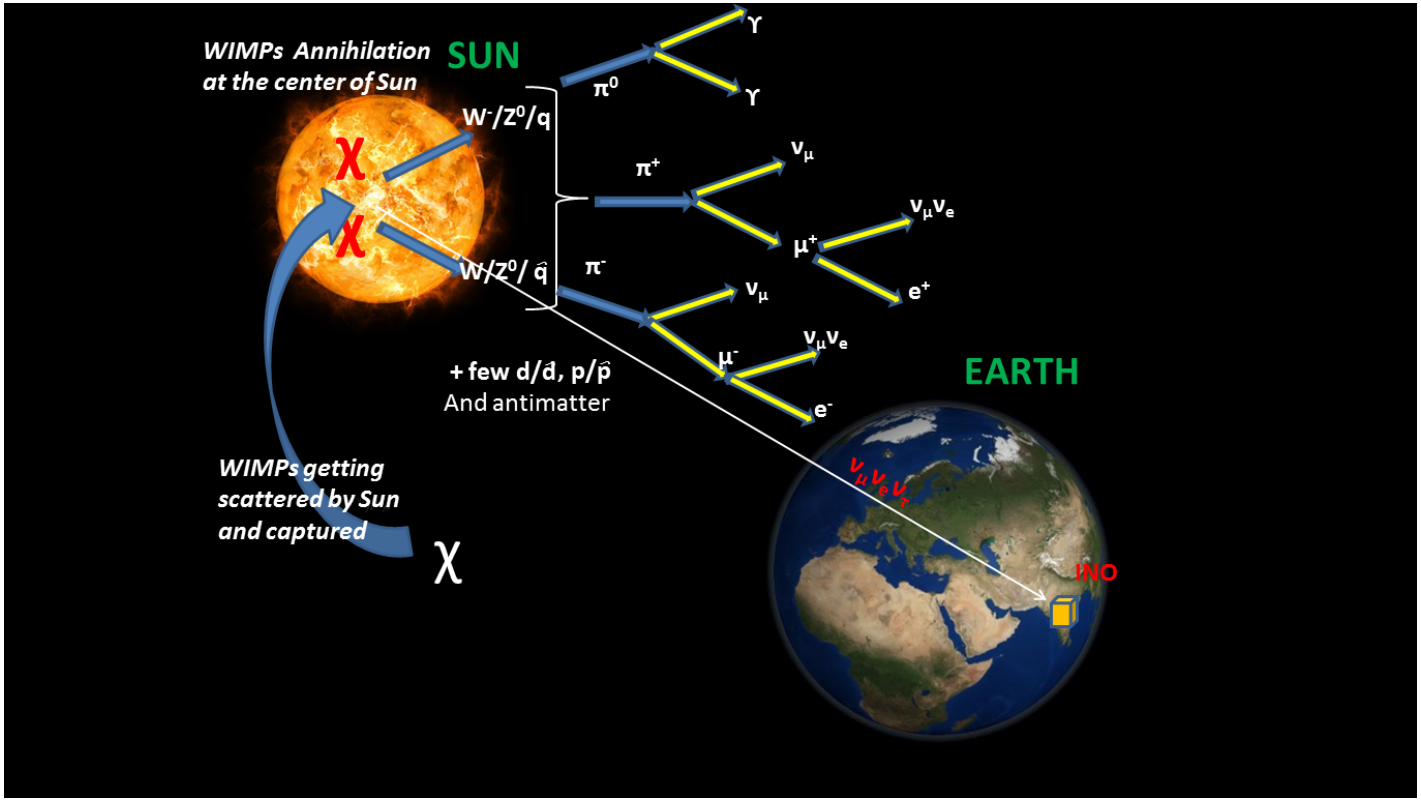


Figure : Credit: Snowmass report, 2013

THANK YOU


WIMPs Annihilation at the center of Sun
SUN
W⁻/Z⁰/q
W/Z⁰/ q̄
χ
χ
π⁰
γ
γ
π⁺
νμ
μ⁺
νμνe
e⁺
π⁻
νμ
μ⁻
νμνe
e⁻
+ few d/d̄, p/p̄
And antimatter
EARTH
INO
WIMPs getting scattered by Sun and captured
χ