Indirect Searches of Galactic Diffuse Dark Matter in INO-MagICAL Detector

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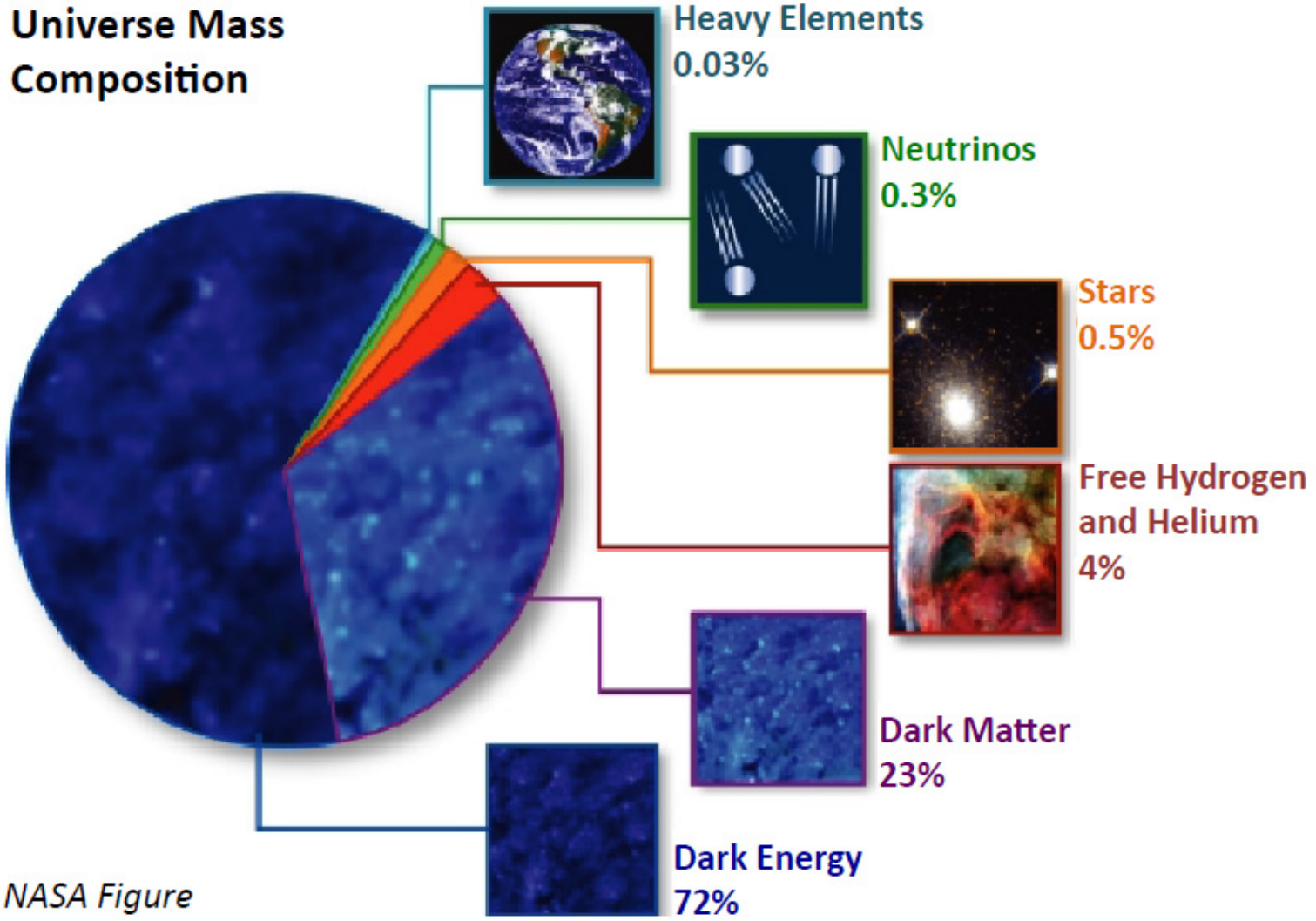
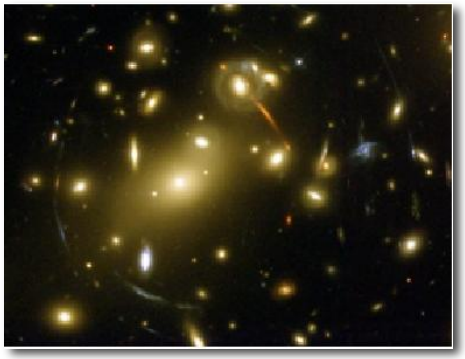
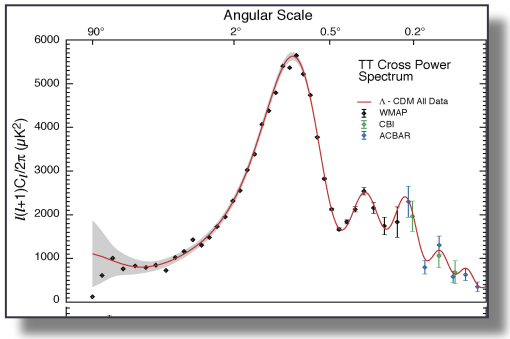
The Cosmic Budget

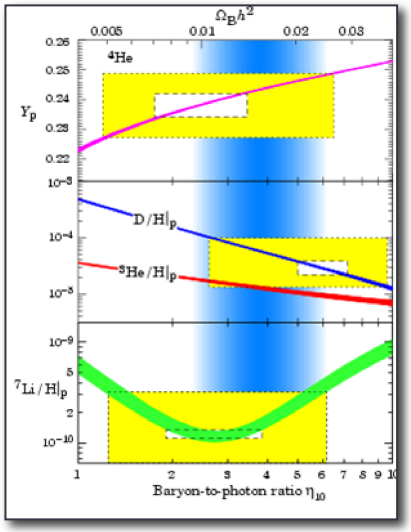


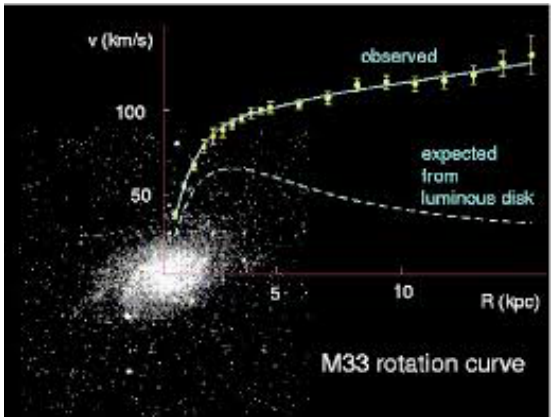
Evidence for Dark Matter

- Galactic Rotation Curves
- Gravitational Lensing
- Light Element Abundances
- Large scale structure (LSS)
- CMB Anisotropies
- Other reasons…



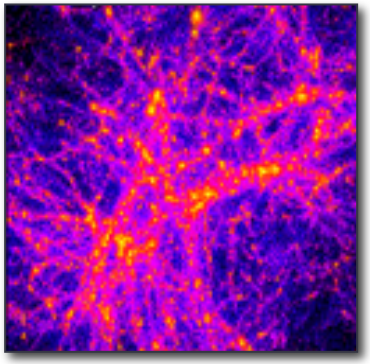






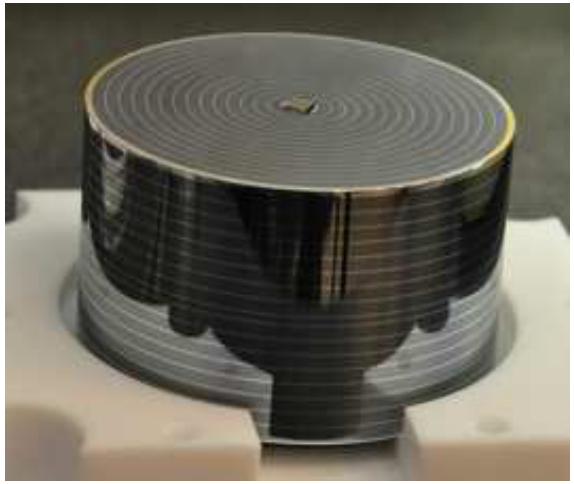
Properties:

- non-radiating
- approximately collisionless
- non-relativistic



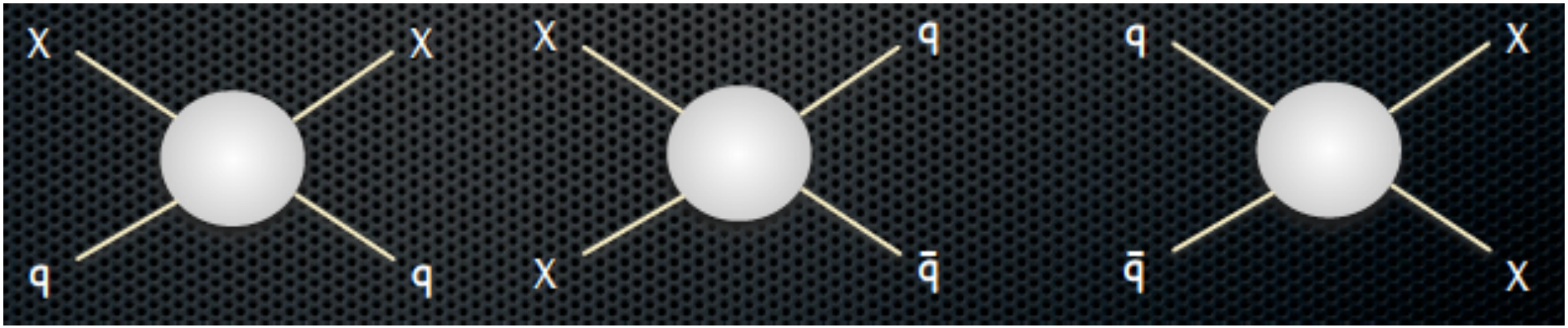
The WIMP Hunting

Direct Detection



Indirect Detection

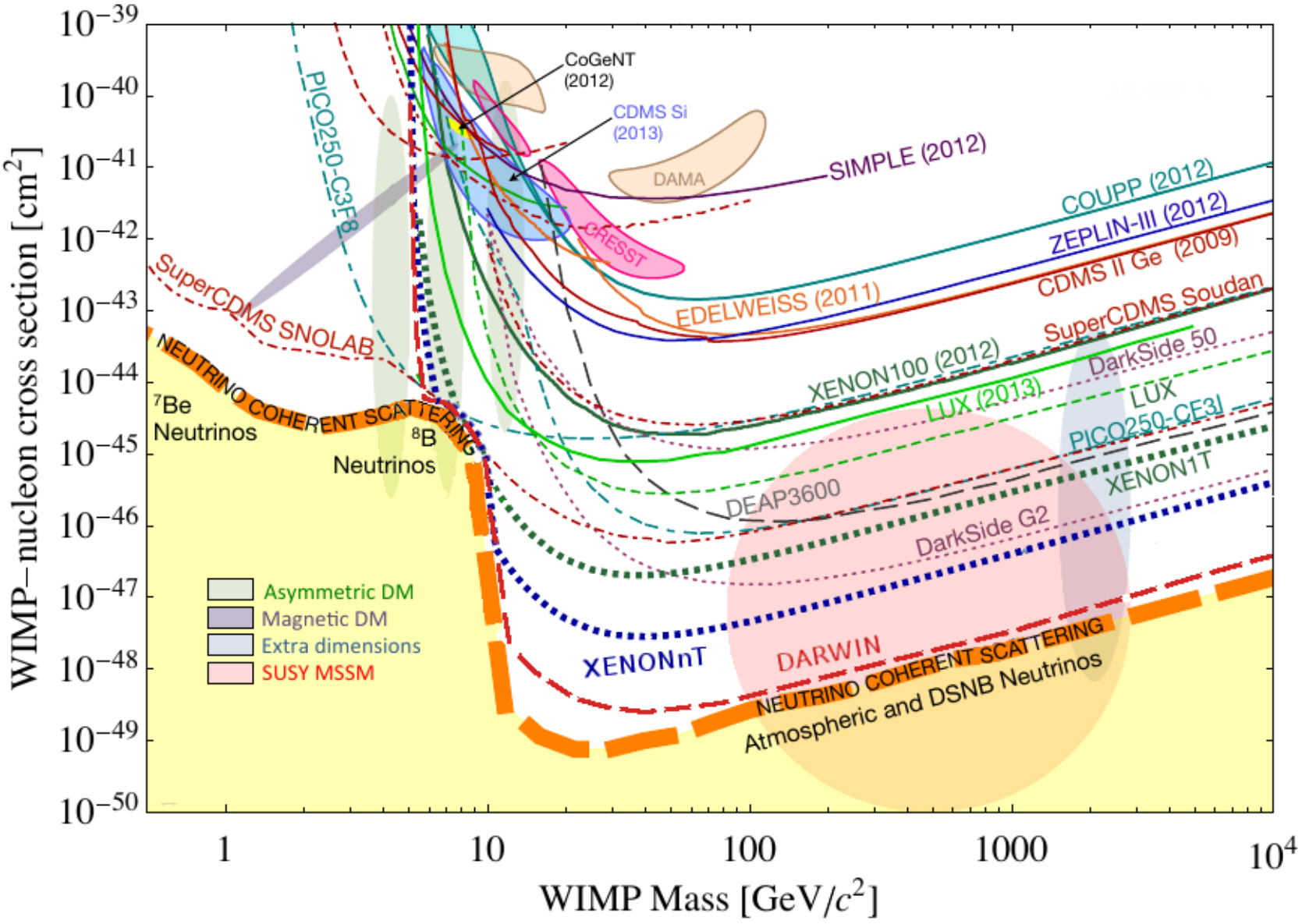
Collider Searches



Scattering **Annihilation** **Production**

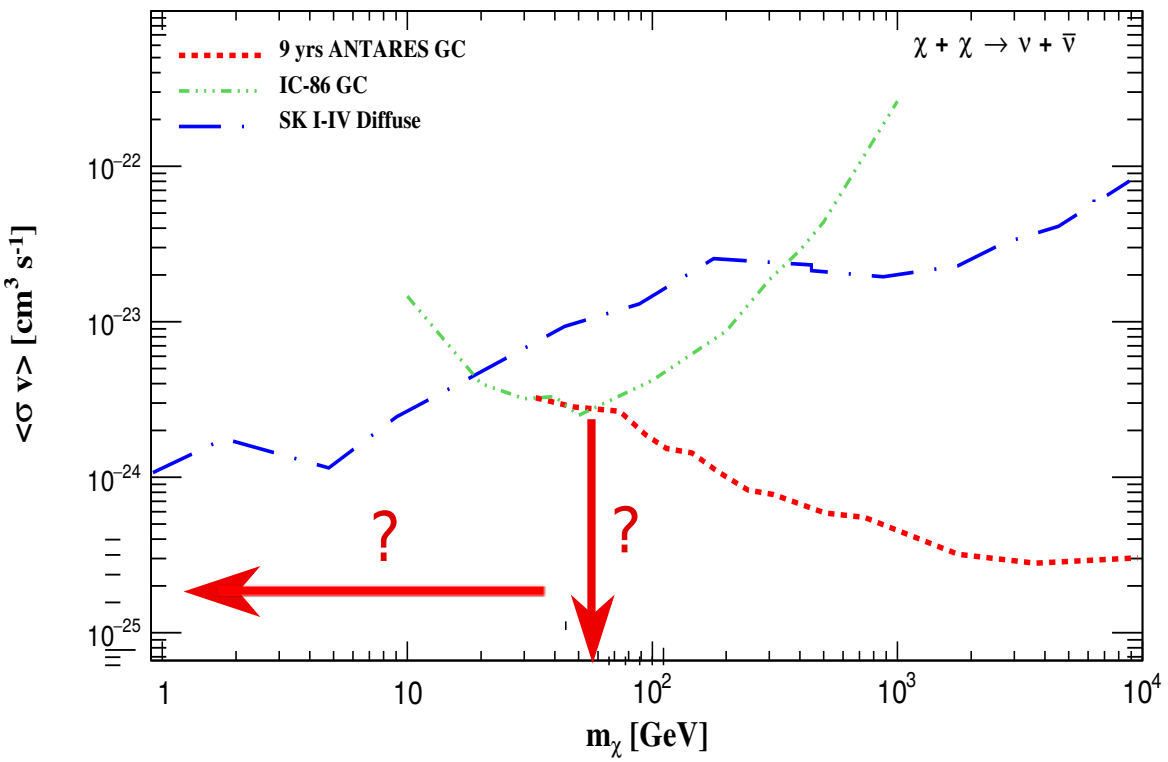
time →

A Snapshot of Results from Direct Detection Experiments



Sensitivities are improving rapidly

Limits from Indirect Detection Experiments



Being neutral and weakly interacting, $\nu\bar{\nu}$ channel is an interesting option

Other channels like $b\bar{b}$, $t\bar{t}$, $f\bar{f}$ are also possible at tree level

Can we improve the limits for low m_χ?

$\langle\sigma v\rangle$ = velocity averaged self-annihilation cross-section

ANTARES: arXiv:1612.04595, IceCube: arXiv:1705.08103
SK I-IV: J.Phys.Conf.Ser. 718(2016)042040

JHEP

Published for SISSA by Springer

Received: April 7, 2017
Accepted: June 4, 2017
Published: June 12, 2017

Indirect searches of Galactic diffuse dark matter in INO-MagICAL detector

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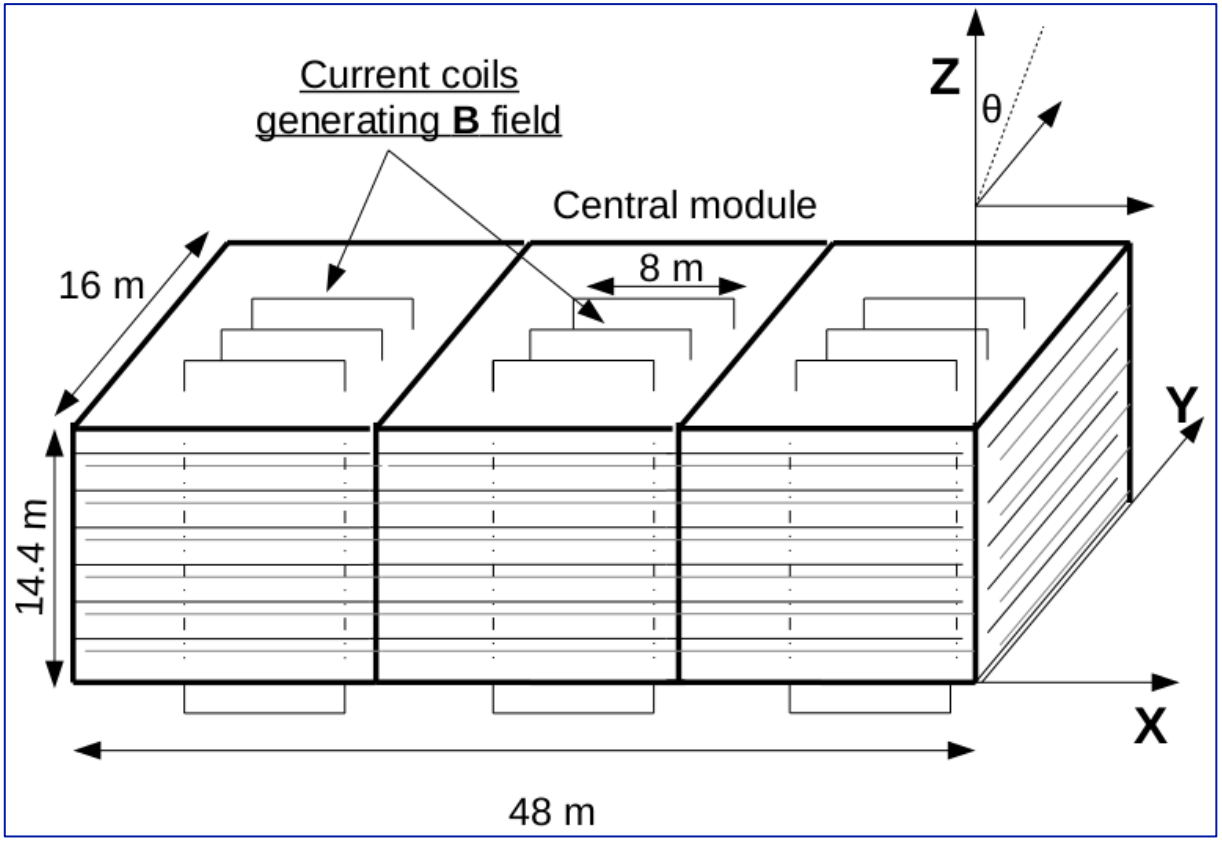
Abstract: The signatures for the existence of dark matter are revealed only through its gravitational interaction. Theoretical arguments support that the Weakly Interacting Massive Particle (WIMP) can be a class of dark matter and it can annihilate and/or decay to Standard Model particles, among which neutrino is a favorable candidate. We show that the proposed 50 kt Magnetized Iron CALorimeter (MagICAL) detector under the

JHEP06(2017)057

Magnetized Iron CALorimeter (MagICAL) @ INO



3 modules each of size 16m × 16m × 14.4m, sampling detector with 151 layers

Each layer: Resistive Plate Chamber (RPC) as active detector& a 5.6 cm thick Iron Slab as target

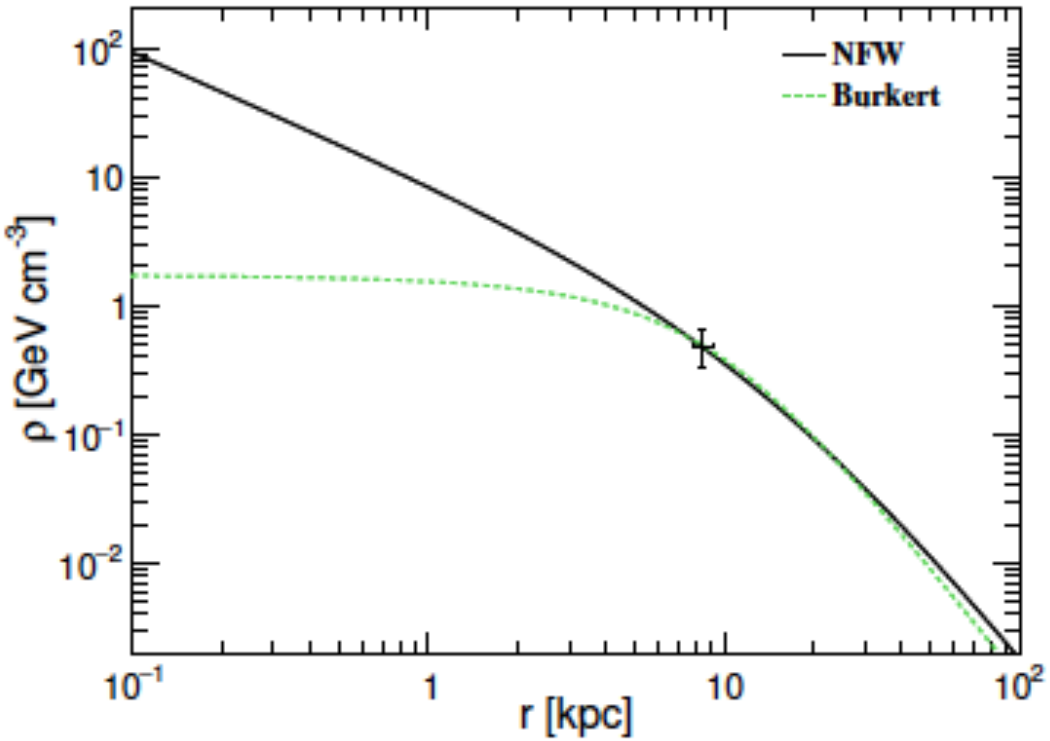
1.5 T Mag. field: Excellent Charge-Id, can probe the DM properties in ν and $\bar{\nu}$ modes separately

Timing information will be used to distinguish between upward and downward going events

DM Density Profile

Spherically Symmetric Dark Matter Density Profile

$$\rho(r) = \frac{\rho_0}{\left[\delta + r/r_s\right]^{\gamma} . \left[1 + (r/r_s)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$



r → distance from the center of the Milky Way Galaxy

Uncertainty in the DM density profile

Study both NFW & Burkert profiles

NFW: Cuspy Halos (astro-ph/9508025)

Burkert: Cored Halos (astro-ph/9904159)

	$(\alpha, \beta, \gamma, \delta)$	ρ_{sc} [GeV cm^{-3}]	r_s [kpc]
NFW	(1, 3, 1, 0)	0.471	16.1
Burkert	(2, 3, 1, 1)	0.487	9.26

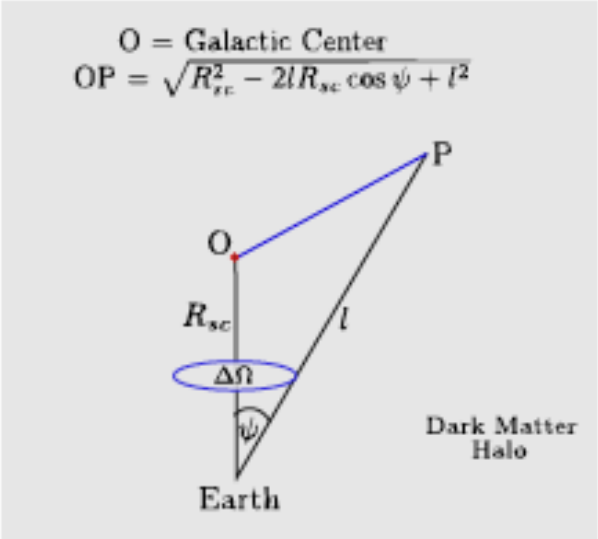
IceCube Collaboration: arXiv:1505.07259

$$\chi\chi \to \nu\bar{\nu}$$

- Neutrino can be ν_e, ν_μ type and ν_τ type.

Flux of neutrinos from dark matter Phys. Rev. D76 (2007)

$$\frac{d^2\Phi^{ann}}{dE\,d\Omega} = \frac{\langle\sigma v\rangle}{2}\mathcal{J}^{ann}_{\Delta\Omega}\,\frac{R_{sc}\rho_{sc}^2}{4\pi\, m_\chi^2}\,\frac{1}{3}\frac{dN^{ann}}{dE}\,.$$



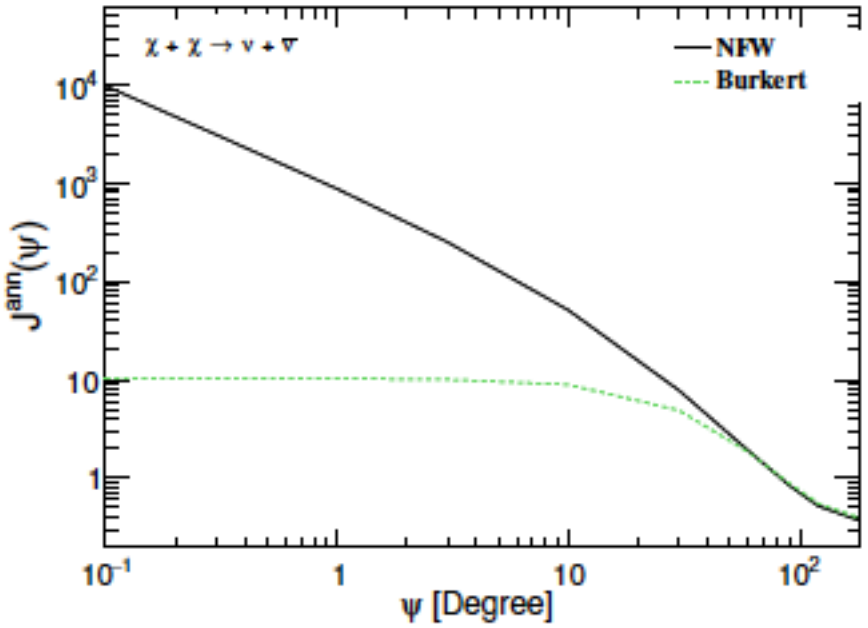
$$\mathcal{J}^{ann}(\psi) = \frac{1}{R_{sc}\rho_{sc}^2}\int_0^{l_{max}} dl\;\rho^2\left(\sqrt{R_{sc}^2 - 2l\,R_{sc}\cos\psi + l^2}\right),$$

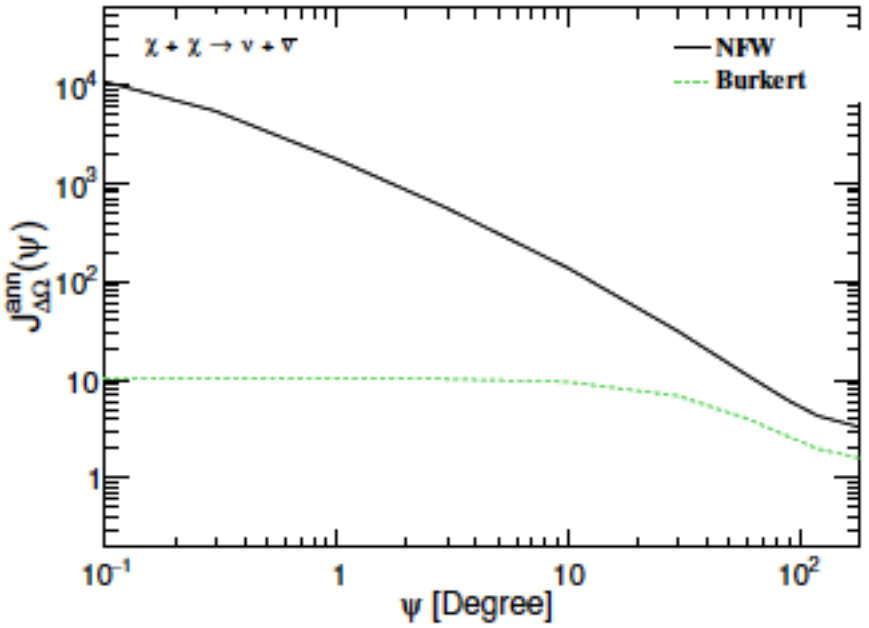
$$l_{max} = \sqrt{\left(R_{MW}^2 - R_{sc}^2\sin^2\psi\right)} + R_{sc}\cos\psi\,,$$

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

$$\frac{dN^{ann}}{dE} = \delta(E_{\nu\bar{\nu}} - m_\chi)\,.$$

DM Annihilation





- Large $\mathcal{J}^{ann}(\psi)$ and $\mathcal{J}^{ann}_{\Delta\Omega}(\psi)$ at small ψ improves statistics : analysis with DM at galactic center.
- But, large uncertainty in the $\mathcal{J}^{ann}(\psi)$ and $\mathcal{J}^{ann}_{\Delta\Omega}(\psi)$ at small ψ.
- At large ψ less uncertainty, analysis is more robust.
- $\mathcal{J}^{ann}_{\Delta\Omega}(\psi = 180^o)$: Diffuse dark matter, independent of direction.

$$N_{ij}^{atm}(\mu^-) = 2\pi\, N_t\, \mathcal{T} \int_{E^i_{min}}^{E^i_{max}} dE' \int_{\cos\theta^j_{min}}^{\cos\theta^j_{max}} d(\cos\theta') \int_{-1}^{1} d(\cos\theta) \int_0^{\infty} dE\, R(E,E')$$
$$R(\theta,\theta') \Big[\sigma^{CC}_{\nu_\mu}(E)\, \mathcal{E}\, \mathcal{C} \left\{ \frac{d^2\Phi_{\nu_\mu}}{d\cos\theta\, dE} P_{\mu\mu} + \frac{d^2\Phi_{\nu_e}}{d\cos\theta\, dE} P_{e\mu} \right\} +$$
$$\bar{\sigma}^{CC}_{\nu_\mu}(E)\, \bar{\mathcal{E}}\, (1-\bar{\mathcal{C}}) \left\{ \frac{d^2\bar{\Phi}_{\nu_\mu}}{d\cos\theta\, dE} \bar{P}_{\mu\mu} + \frac{d^2\bar{\Phi}_{\nu_e}}{d\cos\theta\, dE} \bar{P}_{e\mu} \right\} \Big]. \qquad (2)$$

$$N_{ij}^{dm}(\mu^-) = 2\pi\, N_t\, \mathcal{T} \int_{E^i_{min}}^{E^i_{max}} dE' \int_{\cos\theta^j_{min}}^{\cos\theta^j_{max}} d(\cos\theta') \int_{-1}^{1} d(\cos\theta) \int_0^{\infty} dE\, R(E,E')\, R(\theta,\theta')$$
$$\frac{d^2\Phi^{dm}}{d\cos\theta\, dE} \Big[\sigma^{CC}_{\nu_\mu}(E)\, \mathcal{E}\, \mathcal{C} \Big\{ P_{e\mu} + P_{\mu\mu} + P_{\tau\mu} \Big\} + \bar{\sigma}^{CC}_{\nu_\mu}(E)\, \bar{\mathcal{E}}\, (1-\bar{\mathcal{C}}) \Big\{ \bar{P}_{e\mu} + \bar{P}_{\mu\mu} + \bar{P}_{\tau\mu} \Big\} \Big]. \qquad (3)$$

Necessary Ingredients for Calculation

Binning Scheme

Observables	Range	Width	Total bins	
E_ν (GeV)	$1, 15$	1	14	29
	$15, 25$	2	5	
	$25, 50$	5	5	
	$50, 100$	10	5	
$\cos\theta_\nu$	$-1, 1$	0.5	4	

Oscillation Parameters

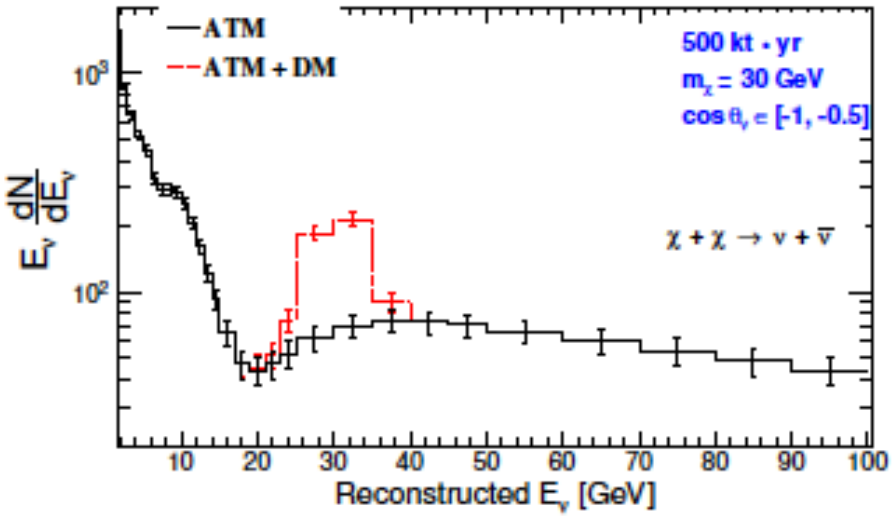
Parameter	Benchmark value
$\sin^2\theta_{23}$	0.5
$\sin^2 2\theta_{13}$	0.1
Δm^2_{eff} [eV^2]	$\pm 2.4 \times 10^{-3}$
$\sin^2 2\theta_{12}$	0.84
Δm^2_{21} [eV^2]	7.5×10^{-5}
δ_{CP} [Degree]	0

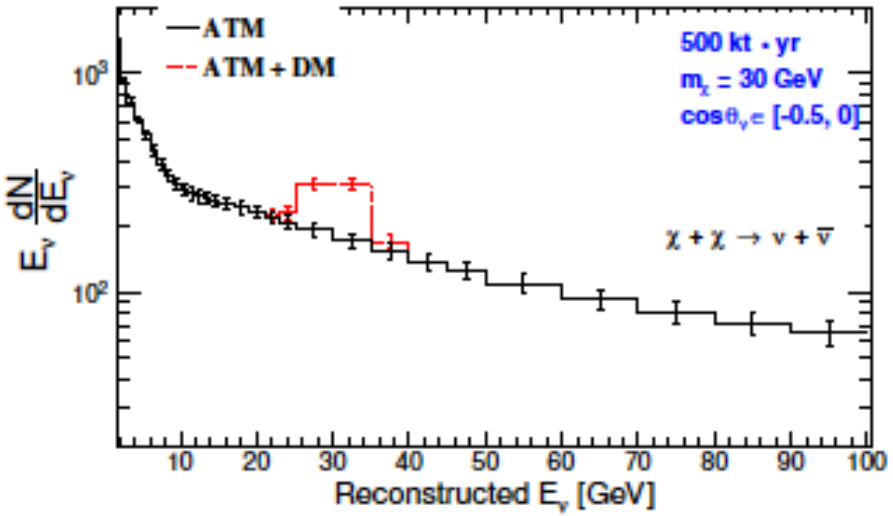
Detector Properties

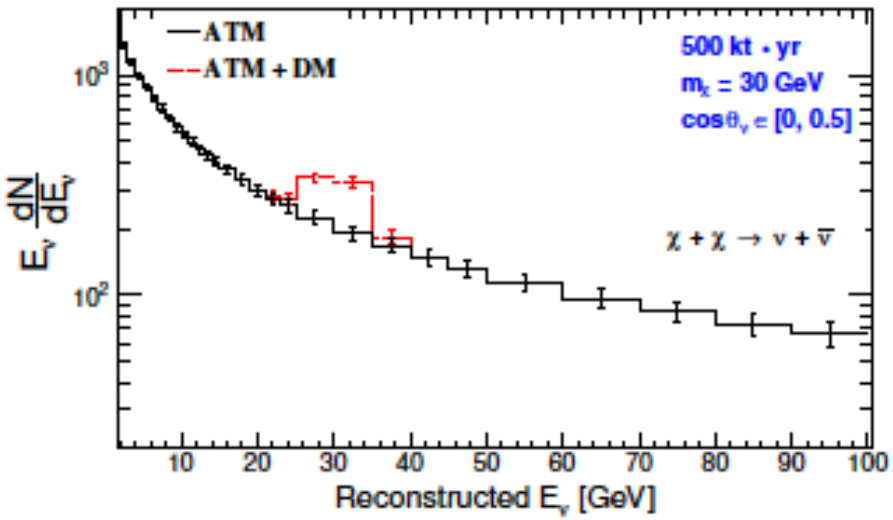
Energy resolution (σ_E) (GeV)	$0.1 \times (E/\text{GeV})$
Angular resolution ($\Delta\theta$)	10°
Detection efficiency ($\mathcal{E}$)	80%
CID efficiency ($\mathcal{C}$)	90%

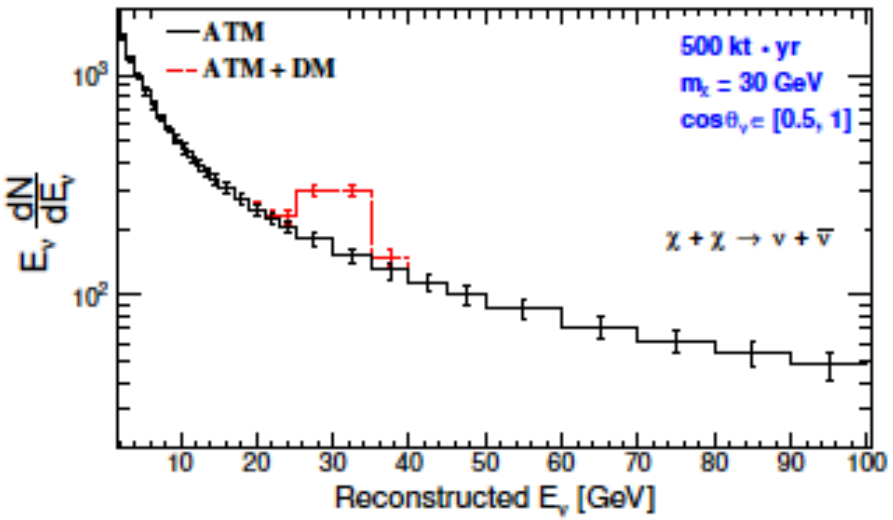
Event Spectrum

$$< \sigma v >= 3.5 \times 10^{-23}\ \mathrm{cm^3\,s^{-1}}$$



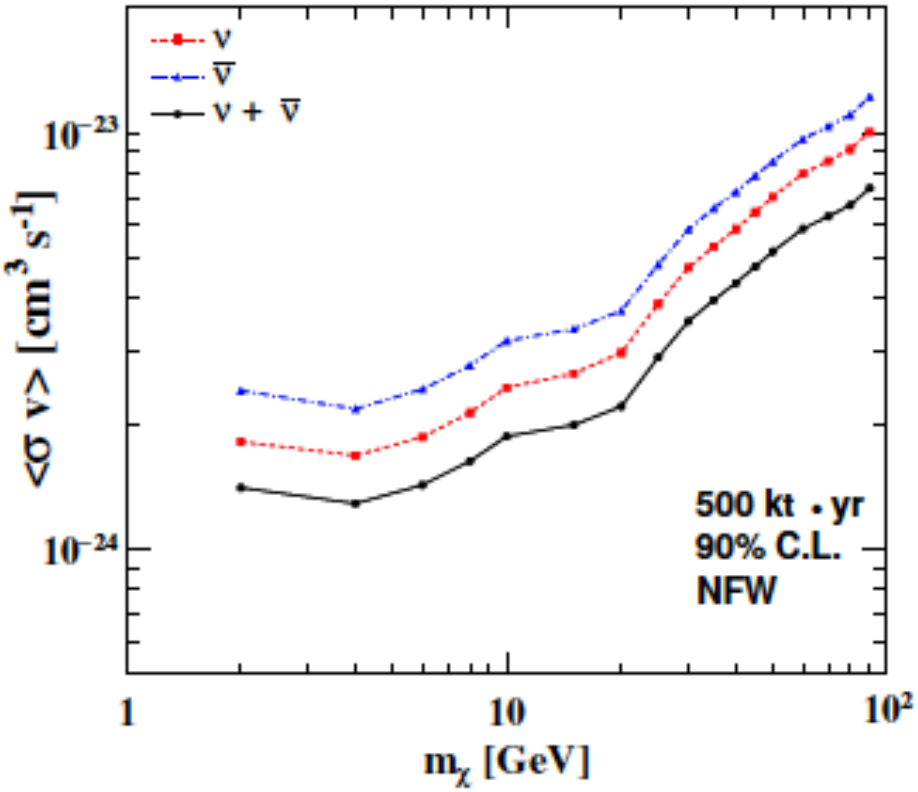


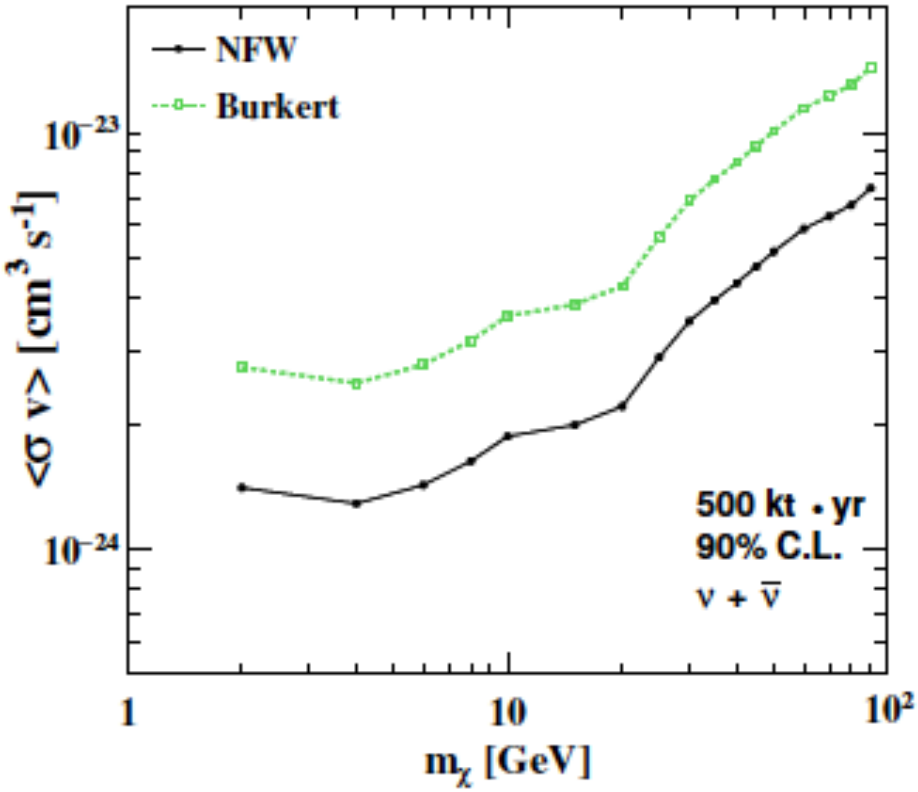




Data: Predicted atmospheric neutrino event in MagICAL (ATM), Theory: ATM + DM

Model Independent Upper Bound on <σv>



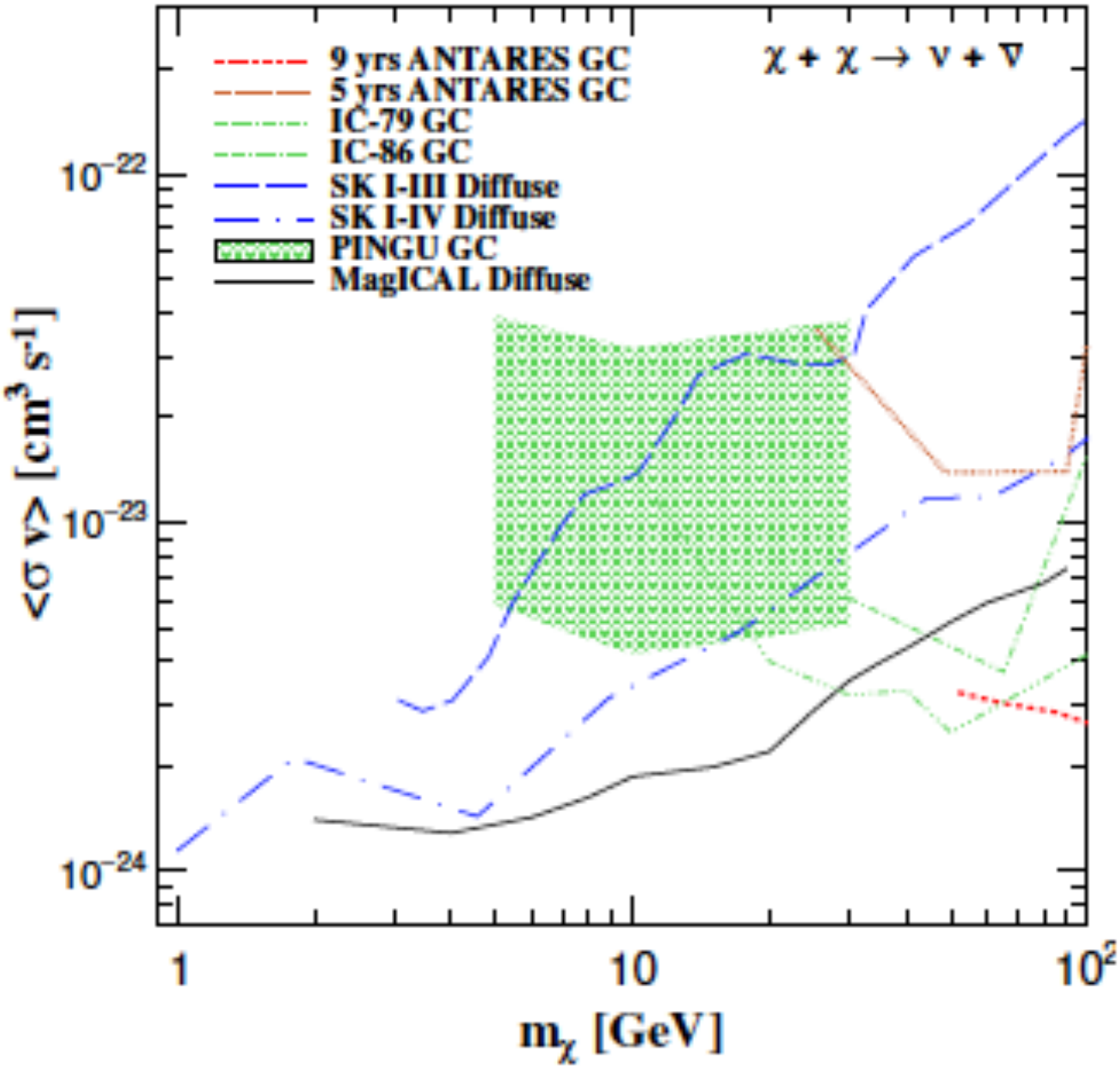


500 kt·yr MagICAL

Poissonian $\Delta\chi^2$

20% normalization uncertainties in both atmospheric neutrino event and dark matter induced events

A Comparison



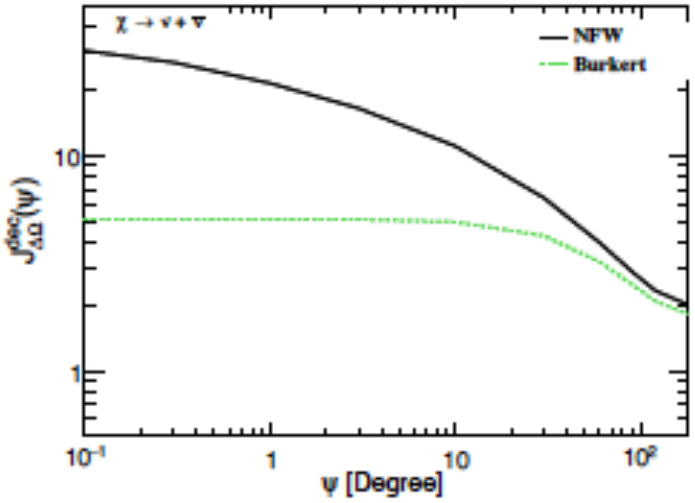
$$\chi \to \nu\bar{\nu}$$

$$\mathcal{J}^{dec} = \frac{1}{R_{sc}\rho_{sc}} \int_0^{l_{max}} dl\ \rho(\sqrt{R_{sc}^2 - 2lR_{sc}\cos\psi + l^2}),$$

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

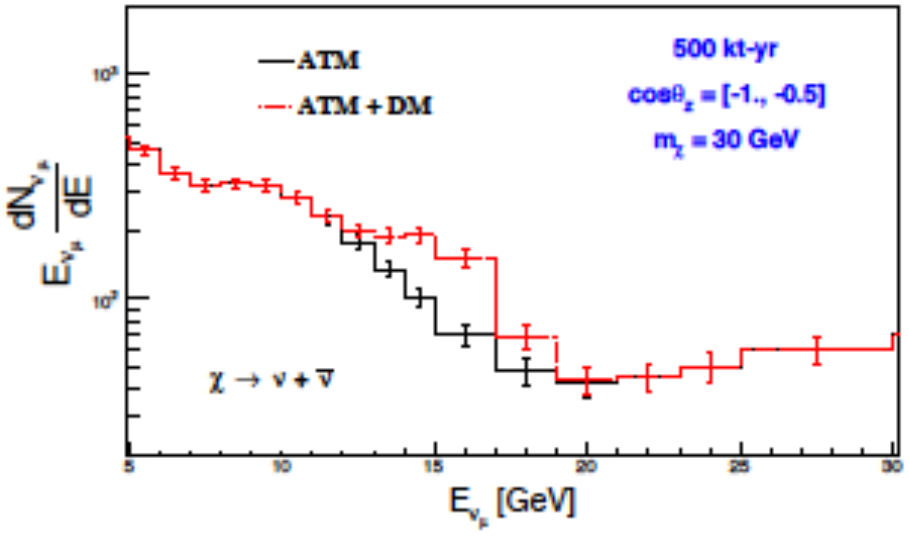
$$\frac{d^2\Phi^{dec}_{\nu,\bar{\nu}}}{dE\, d\Omega} = \mathcal{J}^{dec}_{\Delta\Omega} \frac{R_{sc}\rho_{sc}}{4\pi\, m_\chi\, \tau_\chi} \frac{1}{3} \frac{dN^{dec}}{dE},$$

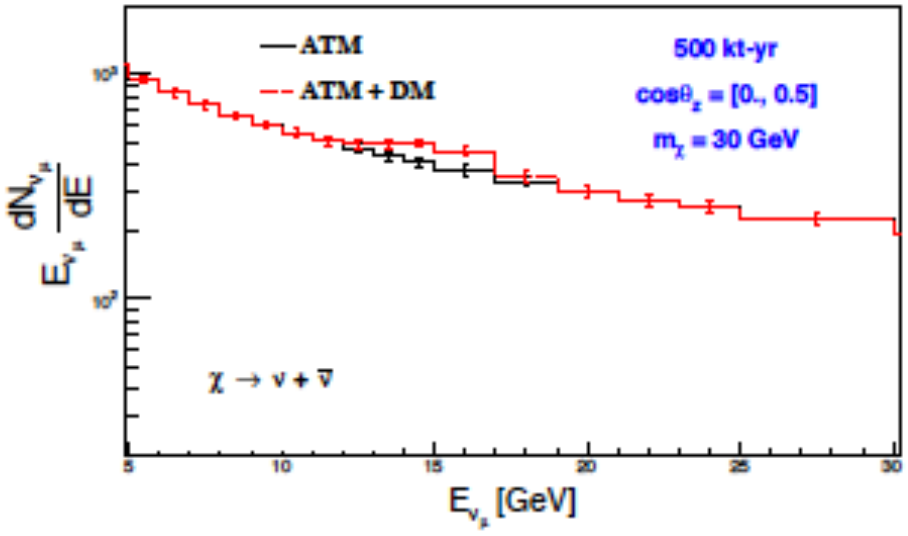
$$\frac{dN^{ann}}{dE} = \delta(E_{\nu\bar{\nu}} - \frac{m_\chi}{2}).$$



Event Spectrum

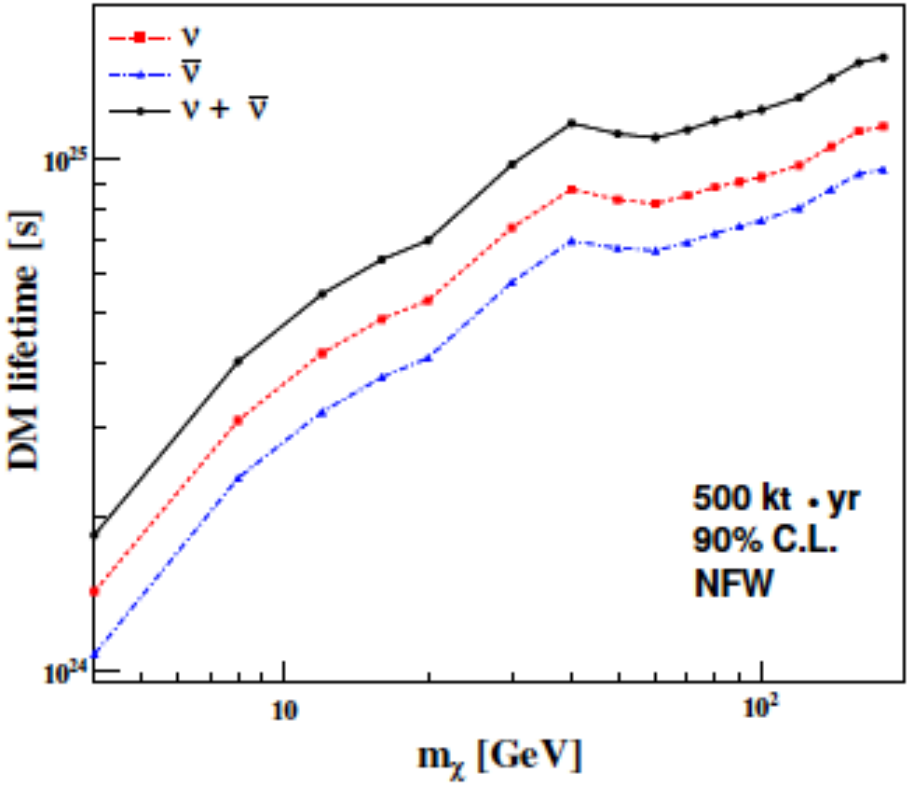
$(4.7 \times 10^{24}\ \mathrm{s})$

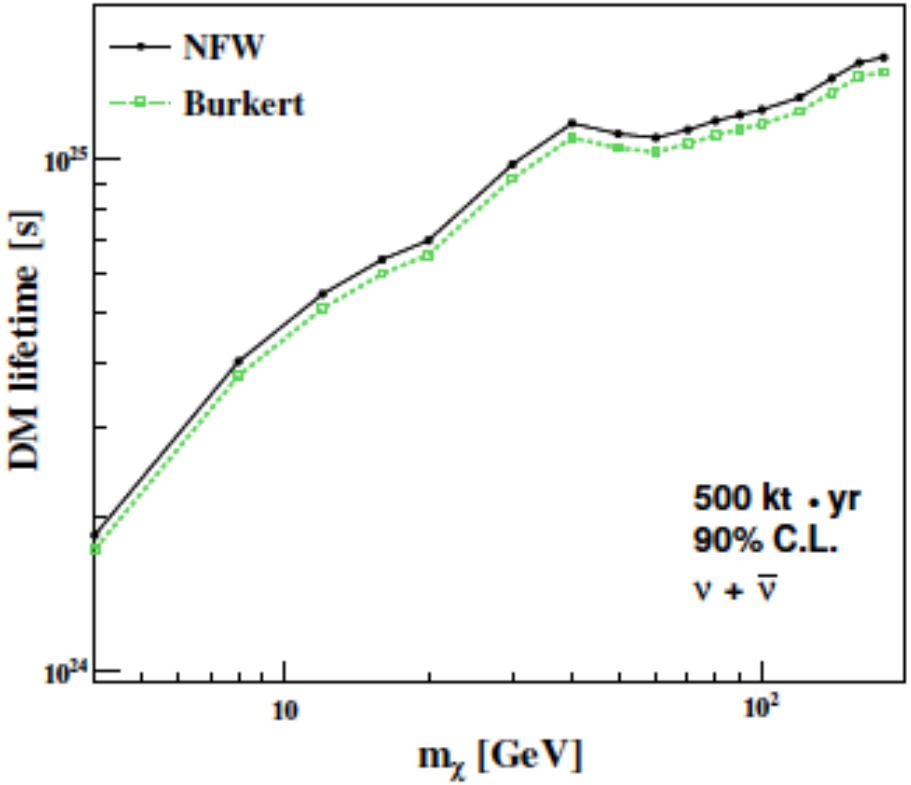




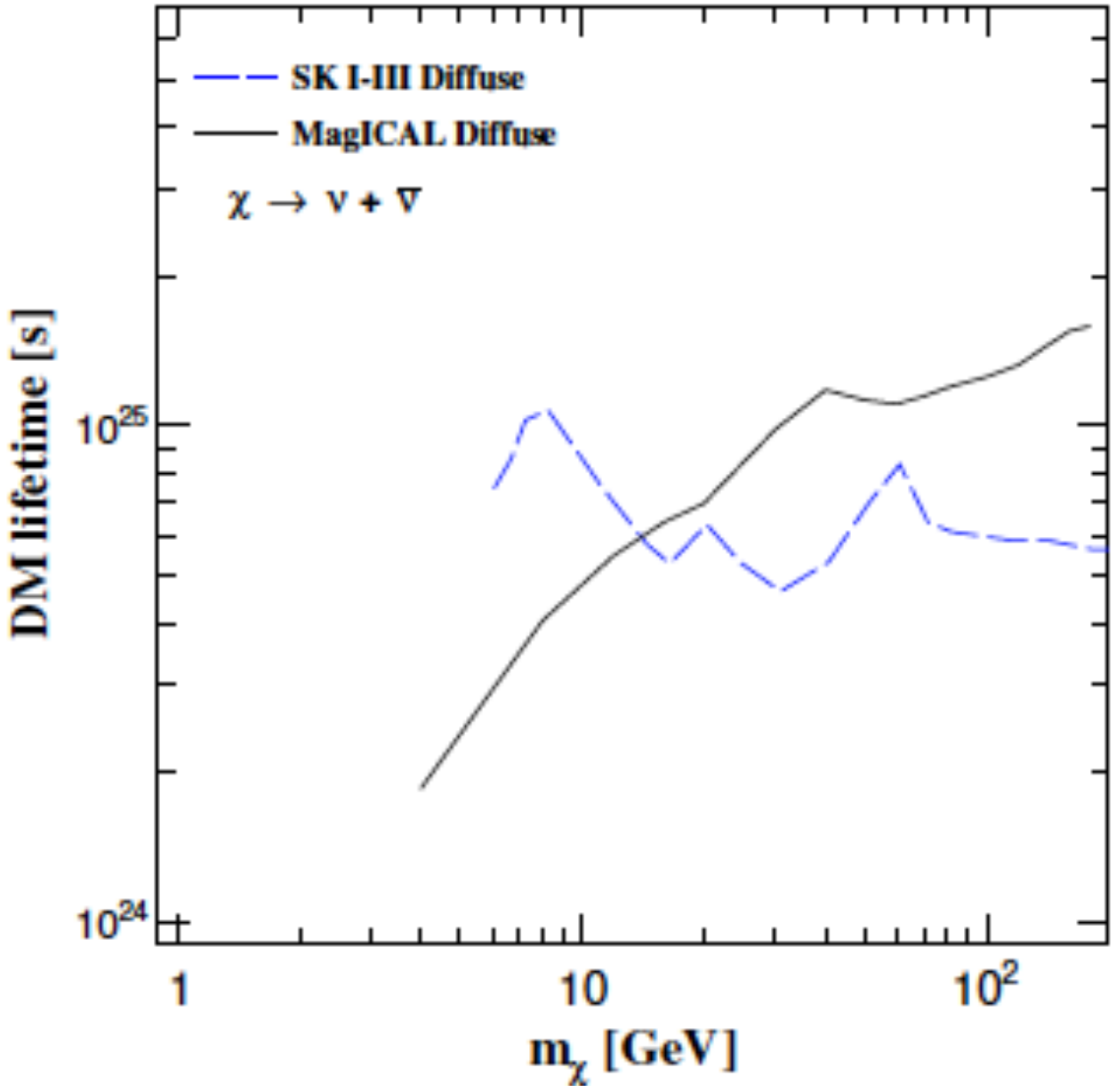
- 30 GeV dark matter decay to neutrino having energy 15 GeV.

Lower Bound on the Decay Lifetime of Dark Matter





A Comparison



Conclusions

- **We have done the analysis for the diffuse DM component of the Milky Way Galaxy**

- **Therefore, our constraints on velocity-averaged self-annihilation cross-section and decay lifetime are robust and conservative, having very mild dependence on the DM density profile**

- **INO-MagICAL can play an important role in the DM mass range of 2 to 50 GeV, complementary to the searches performed by Super-K & IceCube**

Charge-ID helps INO-Magical to probe the properties of DM in neutrino & antineutrino modes separately

Thank you