Université de Montréal

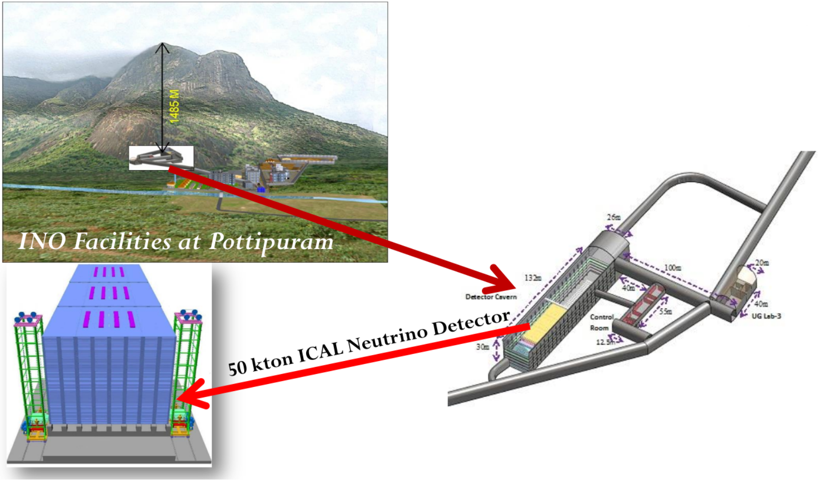
INO

Neutrinos as signal & background in the search for dark matter with INO

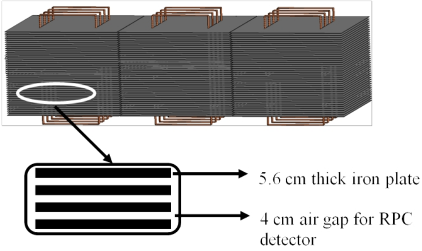
Deepak Tiwari for the INO Collaboration

XIX International Workshop on Neutrino Telescopes
18-26 February 2021

India-based Neutrino Observatory

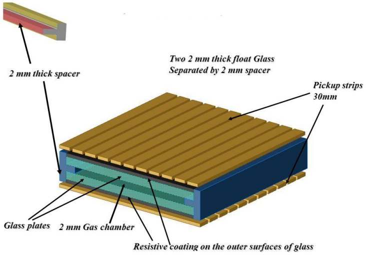


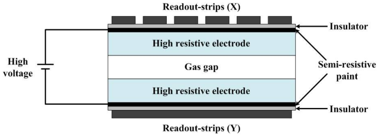
The ICAL@INO



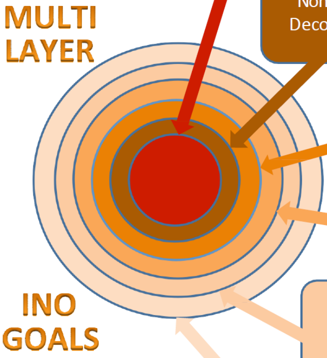
ICAL at a glance	
No. of modules	3
Module dimension	16 m × 16 m × 14.5 m
Detector dimension	48 m × 16 m × 14.5 m
No. of layers	151
Iron plate thickness	5.6 cm
Gap for RPC trays	4.0 cm
Magnetic field	1.5 Tesla
RPC	
RPC unit dimension	1.84 m × 1.84 m × 2.5 cm
Readout strip width	3 cm
No. of RPC units/layers/module	64
Total no. of RPC units	2 30,000
No. of electronic readout channels	3.9×10^6

ICAL (Iron CALorimeter) is a proposed 50kt magnetized iron detector with glass Resistive Plate Chambers (RPCs) as the active detectors.





INO Goals



Determining neutrino mass ordering / Independent verification in neutrinos and antineutrinos / Detection of Earth matter effects

Measuring neutrino properties: Mixing parameters, Non–Standard Interactions, CPT violation, Decay, Decoherence, Sterile neutrinos, Long–range forces
*Earth Tomography

Searching for physics beyond the Standard Model (beyond neutrinos): Magnetic monopoles, long–lived particles, dark matter annihilation

Act as a long–term detector looking for atmospheric and astrophysical phenomena: Searching for unknown,
*Multi–messenger astronomy

ICAL @ INO

Underground, radiation–free lab infrastructure useful for other experiments: High energy physics, Biology, Material Science, Geology.
*Readiness for future opportunities

A large scale international experiment running in India for development of Experimental physics manpower, Detector development expertise.
*Education and training hub for students all over India

INO

INO: A long journey

- **Circa 2000**: An idea for a large underground neutrino detector conceived.
- **2002**: An MoU between 6 Department of Atomic Energy (DAE) Institutions signed.
- **2006**: INO Report submitted to the Chairman DAE.
- **2010** : Detailed Project Report (DPR) on INO Site by Tamil Nadu (TN) Electricity Board, environmental clearance for Pottipuram Site.
- **2015** : Financial approval for the full project came in January.
- Present: Awaiting clearances from National Board of Wildlife, Madurai Town Planning, authority for Civil construction at the Site, and finally TN Pollution Control Board.

Major hurdles:

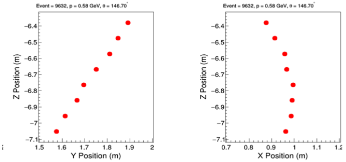
- An unfortunate beginnings of misinformed campaign since September 2012.
- Legal hurdles since 2015, delays due to various other, non-scientific, considerations.

INO: Present status

- Forest & Environment clearance obtained and Civil DPR report completed. Geotechnical studies completed.
- Land for surface facilities and for the Inter-Institutional Centre for HEP (IICHEP), Madurai procured.
- IICHEP will be the nodal centre for all activities, and will operate and maintain the INO laboratory and as a center for detector R&D for HEP, NP, Astrophysics in general.

- Strong outreach efforts are underway to counter misinformation spread by NGOs, politicians, some sections of media and press.
- Overwhelming support for INO from the International Neutrino Community.

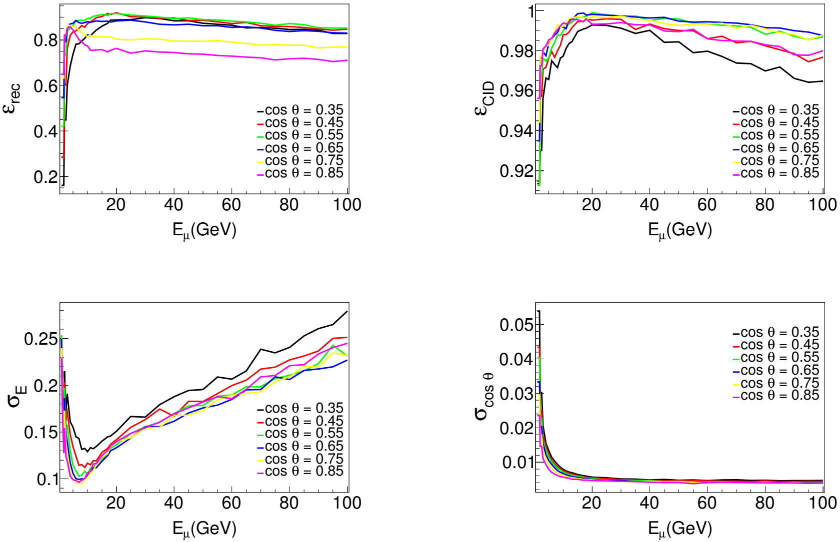
INO: status & way ahead



85 ton magnetized mini-ICAL (4m × 4m × 11 layers) commissioned in May 2018 at the transit campus of IICHEP, Madurai

- ICAL detector R&D complete – DPR for detector, DAQ systems ready, gas system design finalized.
- Ready for Industrial production of all components of the detector.
- Plan to have Cosmic Muon Veto Detector (CMVD) for mini-ICAL using extruded Plastic Scintillator.
- Construction of Engineering module (eICAL) (700 ton) at the IICHEP in Madurai to test all aspects of ICAL and logistics of operation. to be built in next 2.5 years, all the requisite clearances obtained from the state government.
- R&D going on to explore the possibilities of a shallow depth (30-100 m) detector.

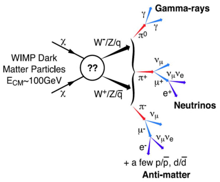
ICAL response to muons

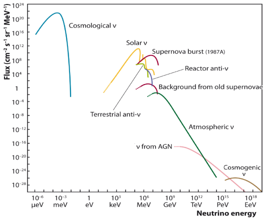


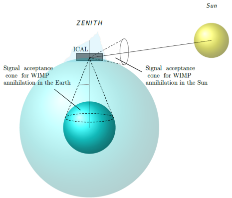
Tiwari et al, JCAP 1805 (2018) no.05, 006

Indirect searches with neutrinos as a probe

- At regions of high WIMP concentration, annihilation can give rise to neutrino-anti neutrino fluxes as their final product.
- The atmospheric neutrinos pose a severe background to the signal neutrinos due to WIMP annihilation.



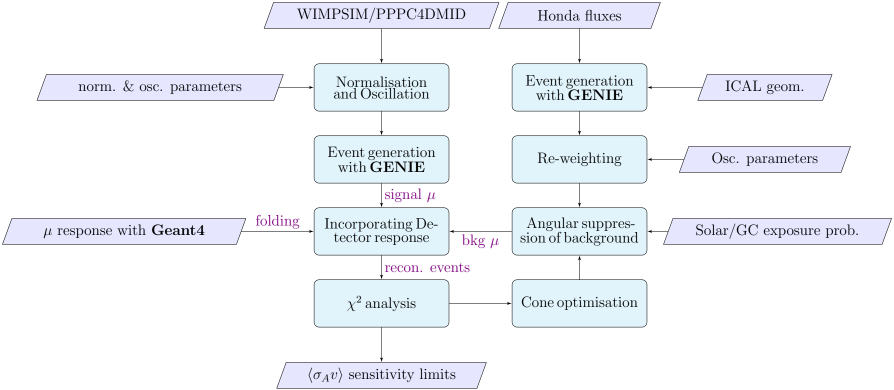




- The fact that signal and background neutrinos differ in their energy and angular distribution can be used for background suppression.

Image source : https://fermi.gsfc.nasa.gov/science/eteu/dm/
Image source : arXiv:1111.0507

The simulation & analysis framework



THEORY = Atmospheric + DM ; DATA = Atmospheric

ν from WIMP annihilation in the Sun

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

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

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

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

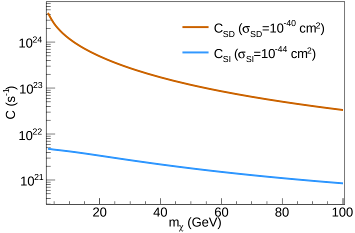
$\tau = (CC_A)^{-1/2}$ equilibration time. $t_\odot \simeq 4.5 \times 10^9$ years.

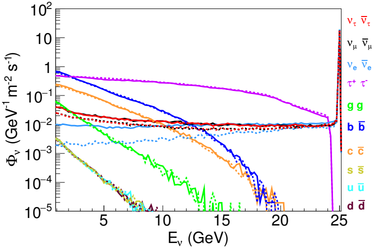
Equilibrium is assumed for the sun, hence :

$$\Gamma_A = \frac{1}{2} C$$

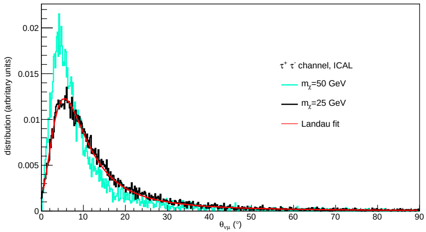
$\Gamma_A \propto C \propto \sigma_{WIMP-nucleon\ cross\ section}$

$$\frac{d\Phi_\nu}{d\Omega dt dE_\nu} = \frac{\Gamma_A}{4\pi R^2} \sum_{i=1} BR_i \frac{dN_i}{dE_\nu}$$

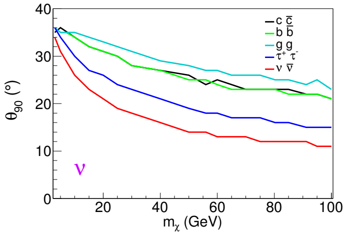


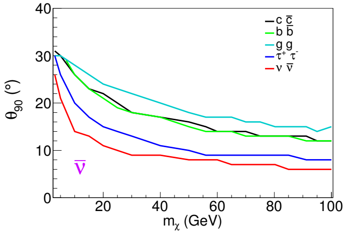


Background suppression scheme



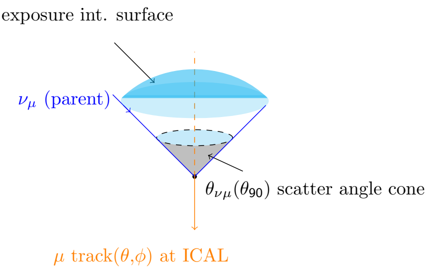
θ_{90} : Cone half angle containing 90% of the signal events.

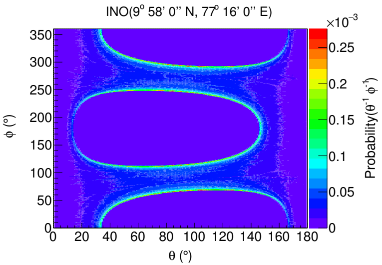


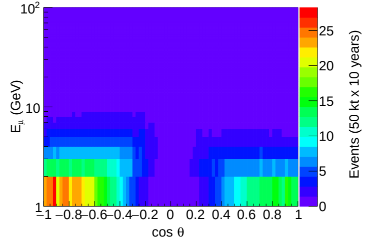


- The value of $\theta_{\nu\mu}$ corresponding to 90% of integral of the distribution of $\nu - \mu$ scatter angle, gives θ_{90}.

Background suppression scheme

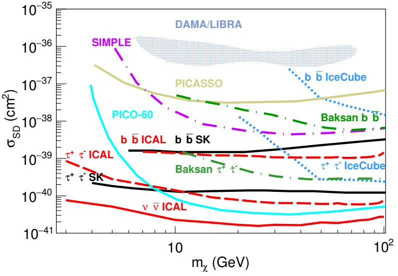


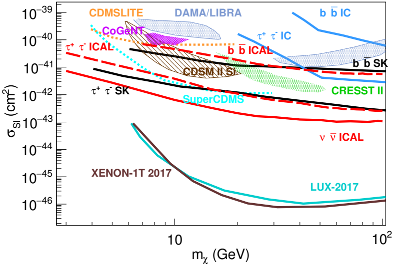




- Take a bkg muon track, put a θ_{90} cone around it, compute the intergrate the solar exposure on the cone surface, and assign the intergral as a weight to the muon event.

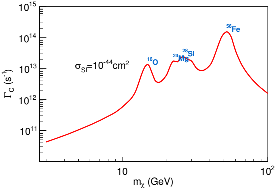
Searches for WIMP annihilation in the sun





Sandhya Choubey, DT, Anushree Ghosh, JCAP 1805 (2018) no.05, 006

Searches for WIMP annihilation in the earth

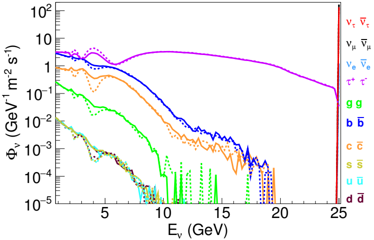


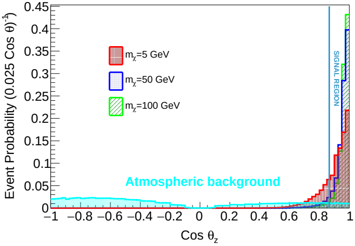
$$\Gamma_\oplus = \frac{1}{2} C_\oplus \tanh^2 \frac{t_\oplus}{\tau_\oplus}, \tau = (C_\oplus C_A)^{-1/2}$$

$$\Gamma_A \propto C \propto \sigma_{WIMP-nucleon\ cross\ section} \frac{t_\oplus}{\tau_\oplus} \propto \langle \sigma\ v \rangle >$$

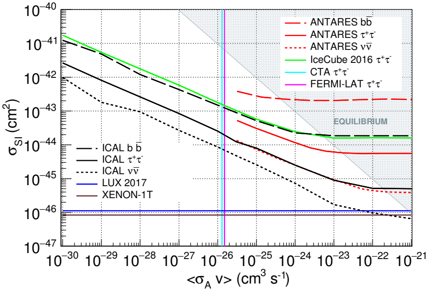
$$\frac{d\Phi_\nu}{d\Omega dt dE_\nu} = \frac{\Gamma_A}{4\pi R_\oplus^2} \sum_{i=1} BR_i \frac{dN_i}{dE_\nu}$$

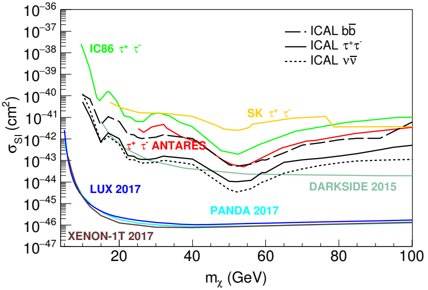
Angular probability distribution of reconstructed events at ICAL due to WIMP annihilations in the Earth. For $\langle \sigma v \rangle = 3 \times 10^{-26} cm^3 s^{-1}$, $\rho = 0.3$ GeV cm^{-3} and $\sigma_{SI} = 10^{-38} cm^2$.





Searches for WIMP annihilation in the earth



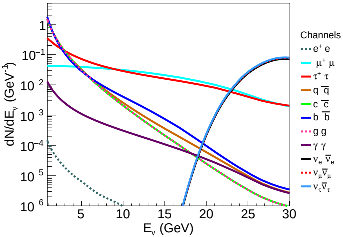


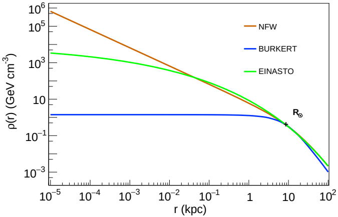
DT,Sandhya Choubey, Anushree Ghosh [JHEP 1905 (2019)039]

ν due to WIMP annihilation in the galactic center

At energy E and in the direction of G.C. the flux $d\Phi/dE$ integrated over the solid angle $\Delta\Omega = 2\pi(1 - cos\Psi)$ is given by:

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





$$\frac{d\Phi_\nu}{dE_\nu}(E) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{m_\chi^2\,\delta}\sum_f BR_f\frac{dN_\nu}{dE_\nu}$$

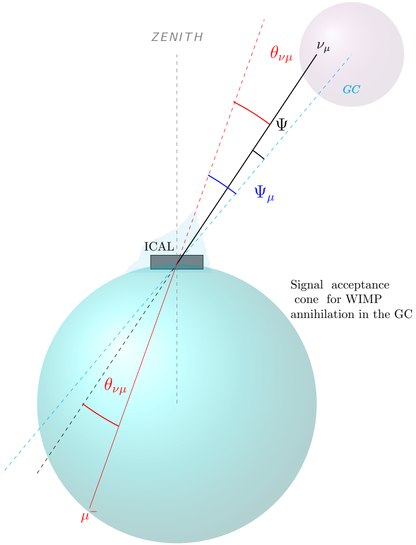
$\langle\sigma_A v\rangle$ velocity-averaged WIMP annihilation cross section
ν spectra for a 30 GeV WIMP taken from PPPC4DMID [Cirell et al.]

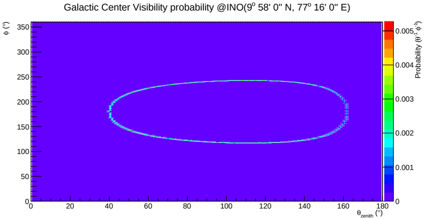
The J-Factor is given by:

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

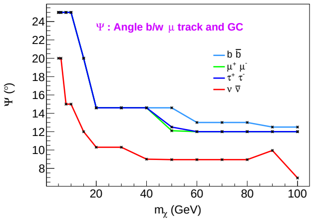
Due to core-cusp problem, results are quoted for various density profiles.

Background suppresion scheme

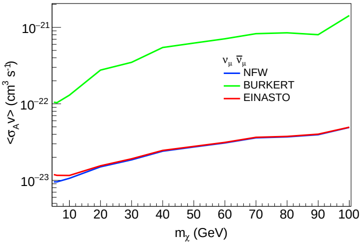


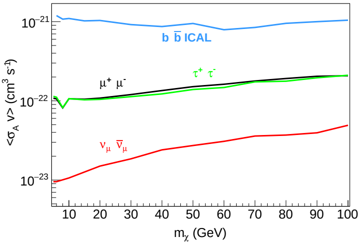


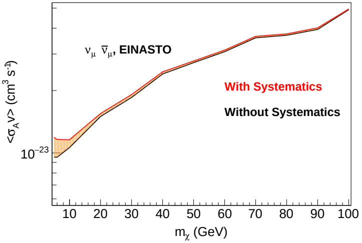
Ψ used for calculating signal rate and acceptance cone for background suprression.

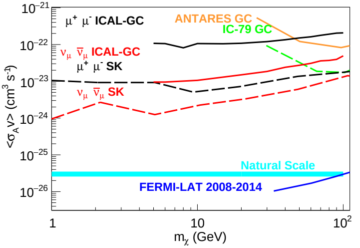


Searches for WIMP annihilation in the galactic centre









PhD thesis, DT

Summary & Outlook

- Understanding the nature of dark matter is one of the major goals of the contemporary physics and astrophysics.
- In that pursuit, we perform a study of muon events arising at ICAL due to neutrinos from WIMP annihilation in the sun, earth and galactic centre for several annihilation channels and WIMP masses upto 100 GeV.
- With an effective atmospheric background suppression scheme, the expected sensitivity limits for ICAL are quite competitive to other neutrino experiments.
- With a more rigorous analysis, better sensitivity could be achieved.
- Plans to extend this analysis to probe other dark matter models such as inelastic DM.
- This analysis offer a complementary approach to other dark matter searches.


Chair of Galileo, from which, according to tradition, he gave lectures - Credits: Univ. of Padova - M. Pistore

Thank you!

Back-up slides

Statistical analysis

With THEORY = Atmospheric + DM ; DATA = Atmospheric,
we calculate:

$\chi^2 = \chi^2(\mu^-) + \chi^2(\mu^+)$ where

$$\chi^2(\mu^\pm) = \min_{\xi_k^\pm} \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} \left[2\left(N_{ij}^{\text{th}}(\mu^\pm) - N_{ij}^{\text{ex}}(\mu^\pm) \right) + 2N_{ij}^{\text{ex}}(\mu^\pm) \ln \left(\frac{N_{ij}^{\text{ex}}(\mu^\pm)}{N_{ij}^{\text{th}}(\mu^\pm)} \right) \right] + \sum_{k=1}^{l} {\xi_k^\pm}^2 ,$$

$$N_{ij}^{\text{th}}(\mu^\pm) = {N'}_{ij}^{\text{th}}(\mu^\pm) \left(1 + \sum_{k=1}^{l} \pi_{ij}^k \xi_k^\pm \right) + \mathcal{O}({\xi_k^\pm}^2) ,$$

${N'}_{ij}^{\text{th}}(\mu^\pm)$: predicated no. of events.
$N_{ij}^{\text{ex}}(\mu^\pm)$: ‘observed’ number of $\mu^\pm$ events.
π_{ij}^k : correction factors due to the k^{th} systematic uncertainty.
$\xi_k^\pm$: pull parameters.

- 20 % error on flux normalisation,
- 10 % error on cross-section
- 5 % uncorrelated error on the zenith angle distribution of atmospheric neutrino fluxes
- 5 % tilt error
- 5 % overall error to account for detector systematics

ν due to WIMP annihilation in the galactic center

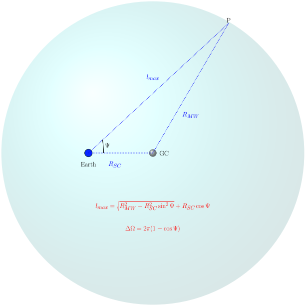
The ν fluxes due to WIMP annihilation at GC is expressed as the product of a particle physics term by an astrophysical contribution J.

At energy E and in the direction of G.C. the flux $d\Phi/dE$ integrated over the solid angle $\Delta\Omega = 2\pi(1 - cos\Psi)$ is given by:

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

$$\frac{d\Phi_\nu}{dE_\nu}(E) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{m_\chi^2 \delta}\sum_f BR_f \frac{dN_\nu}{dE_\nu}$$

$\langle\sigma_A v\rangle$ velocity-averaged WIMP annihilation cross section BR : Branching Ratio



l : distance between a point P and the earth ρ_{sc} : local dark matter density, R_{sc}: solar radius.