INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Distinguishing neutrino mass hierarchy from DM annihilation

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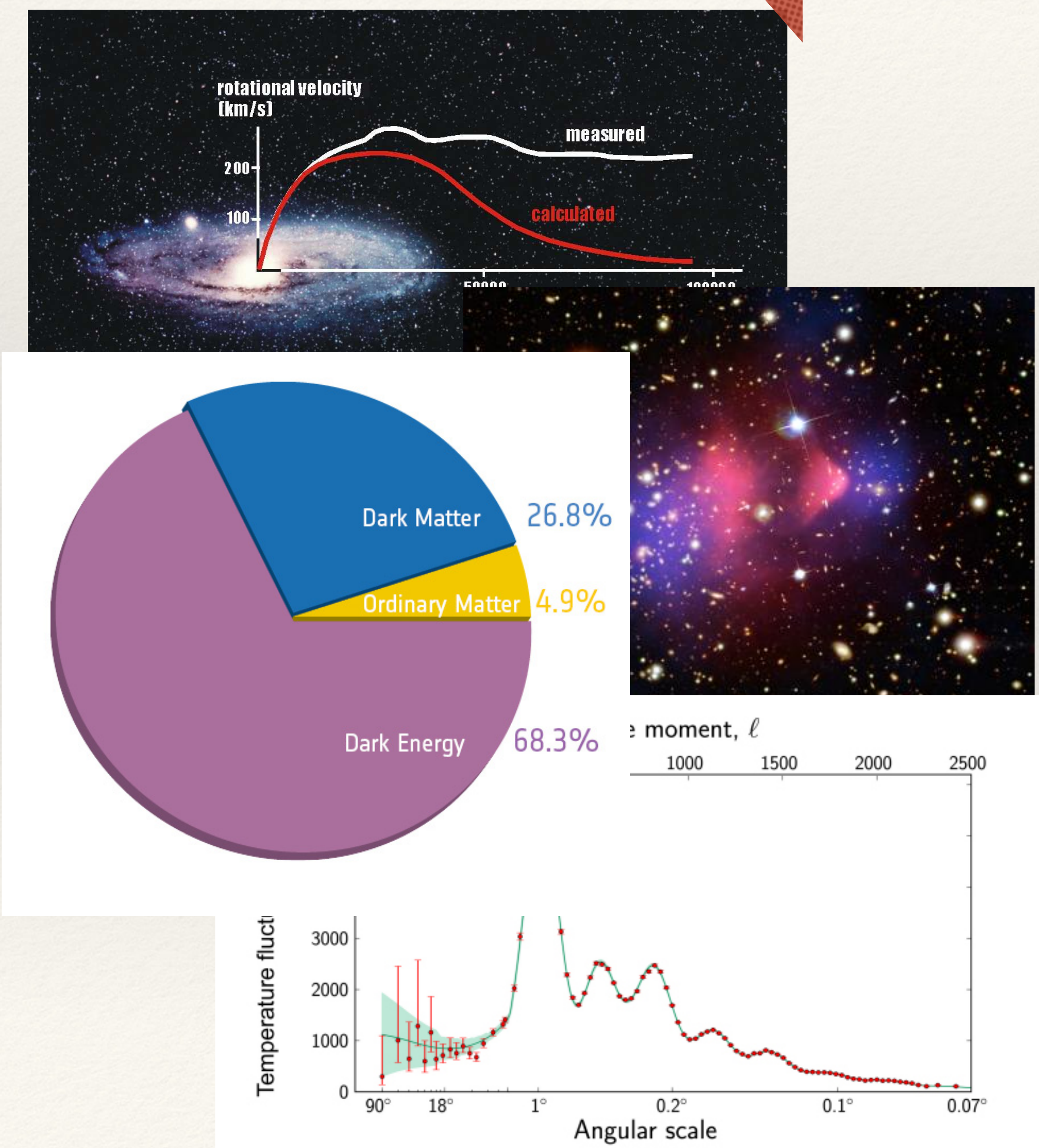
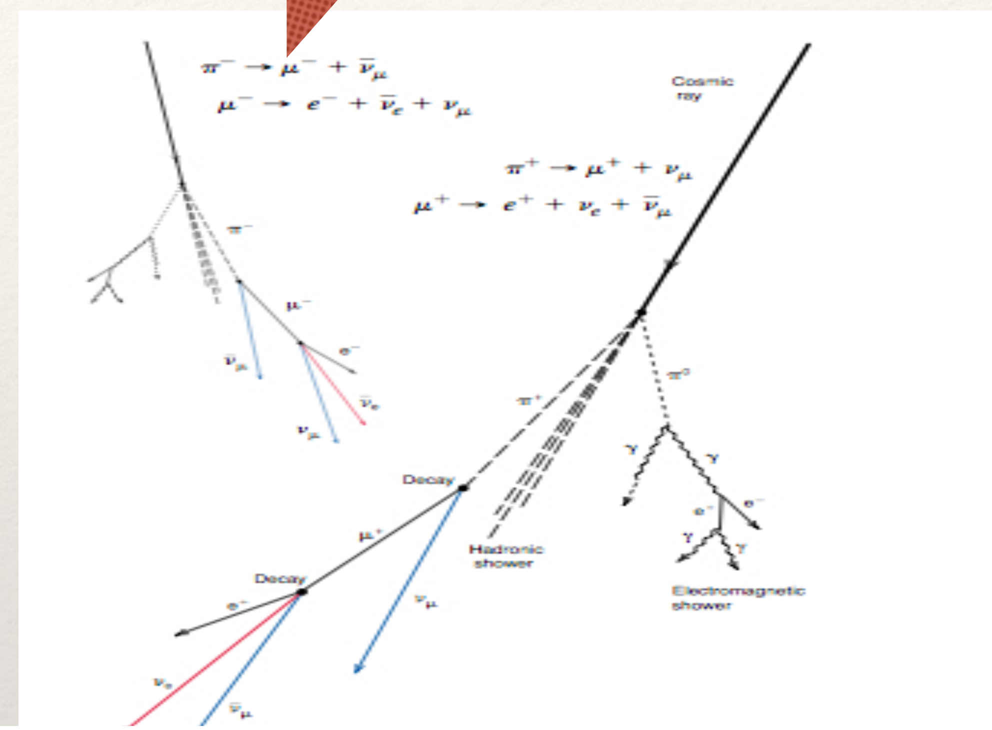
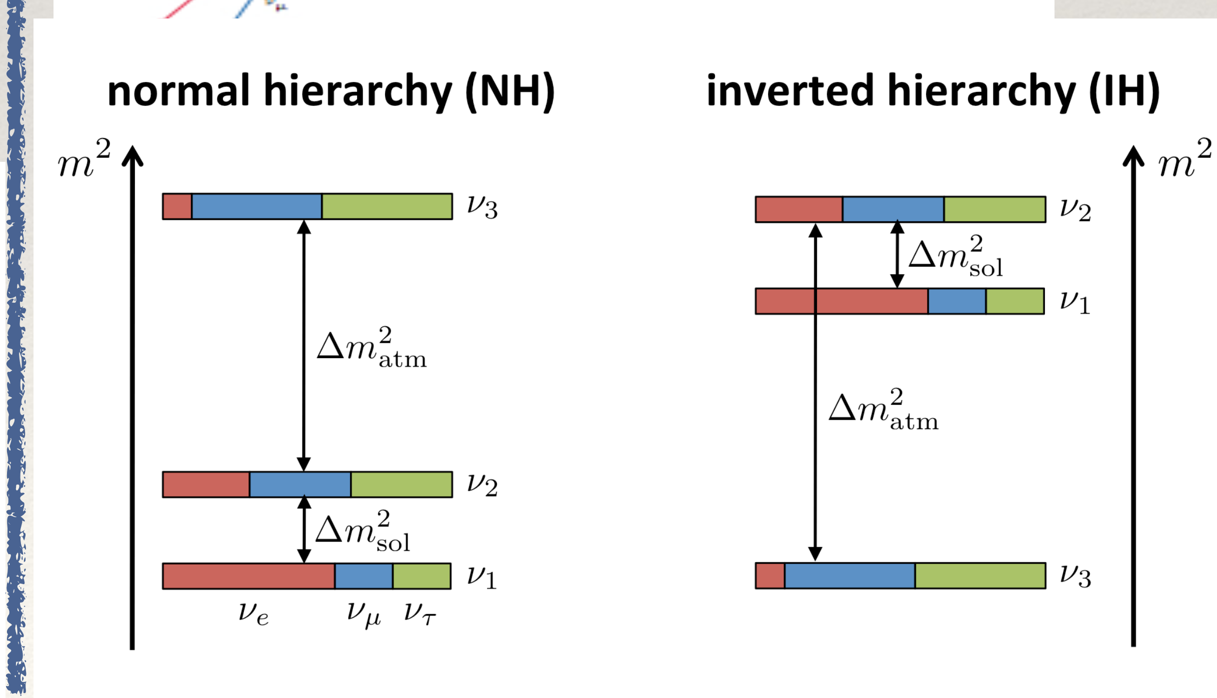
THE INVISIBLES

Dark Matter

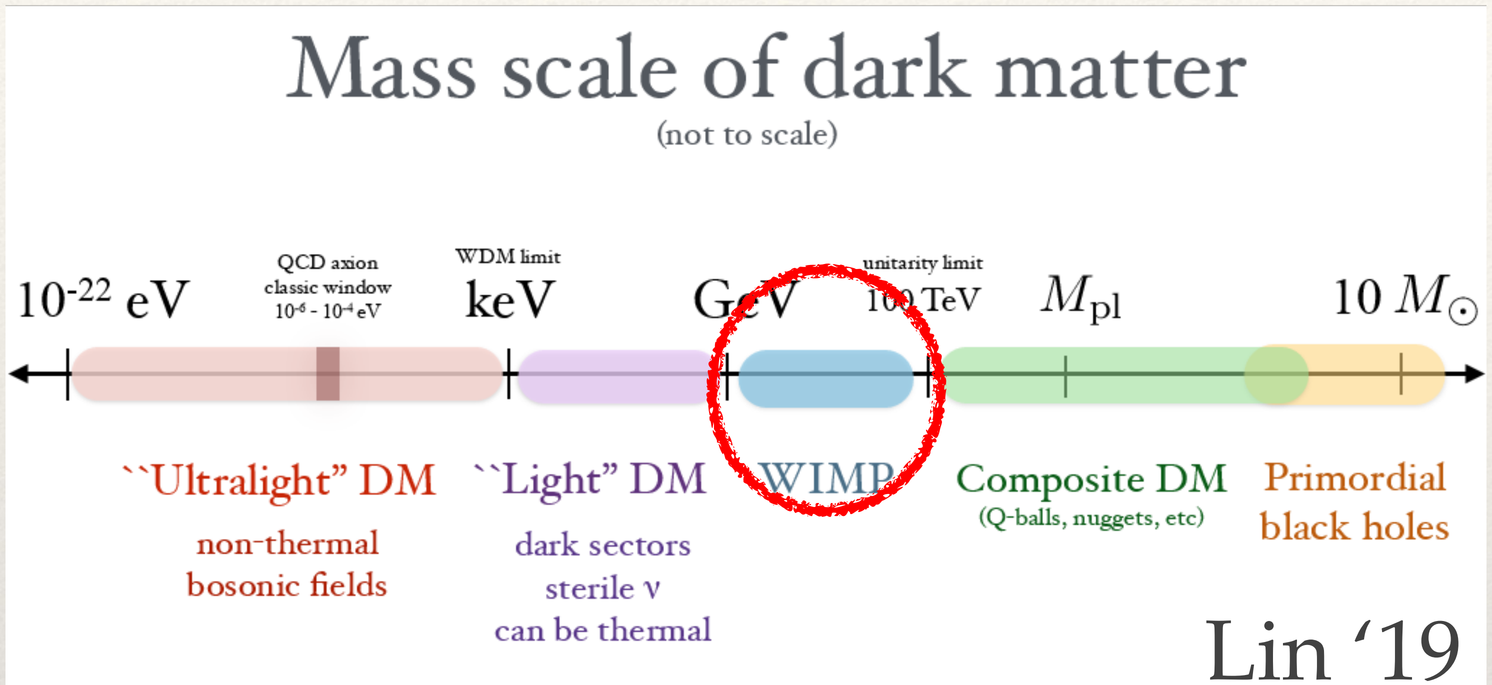


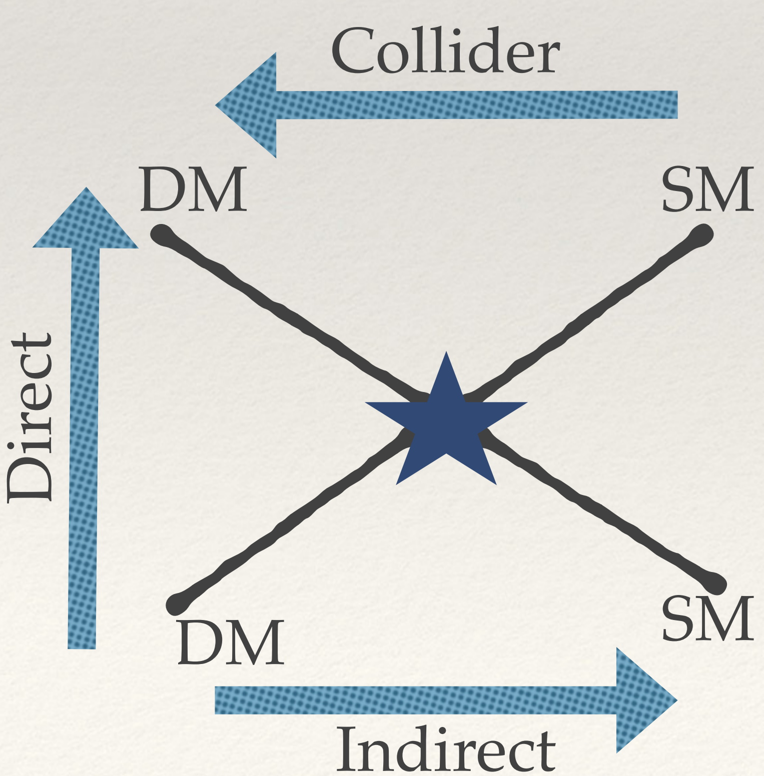
Neutrino





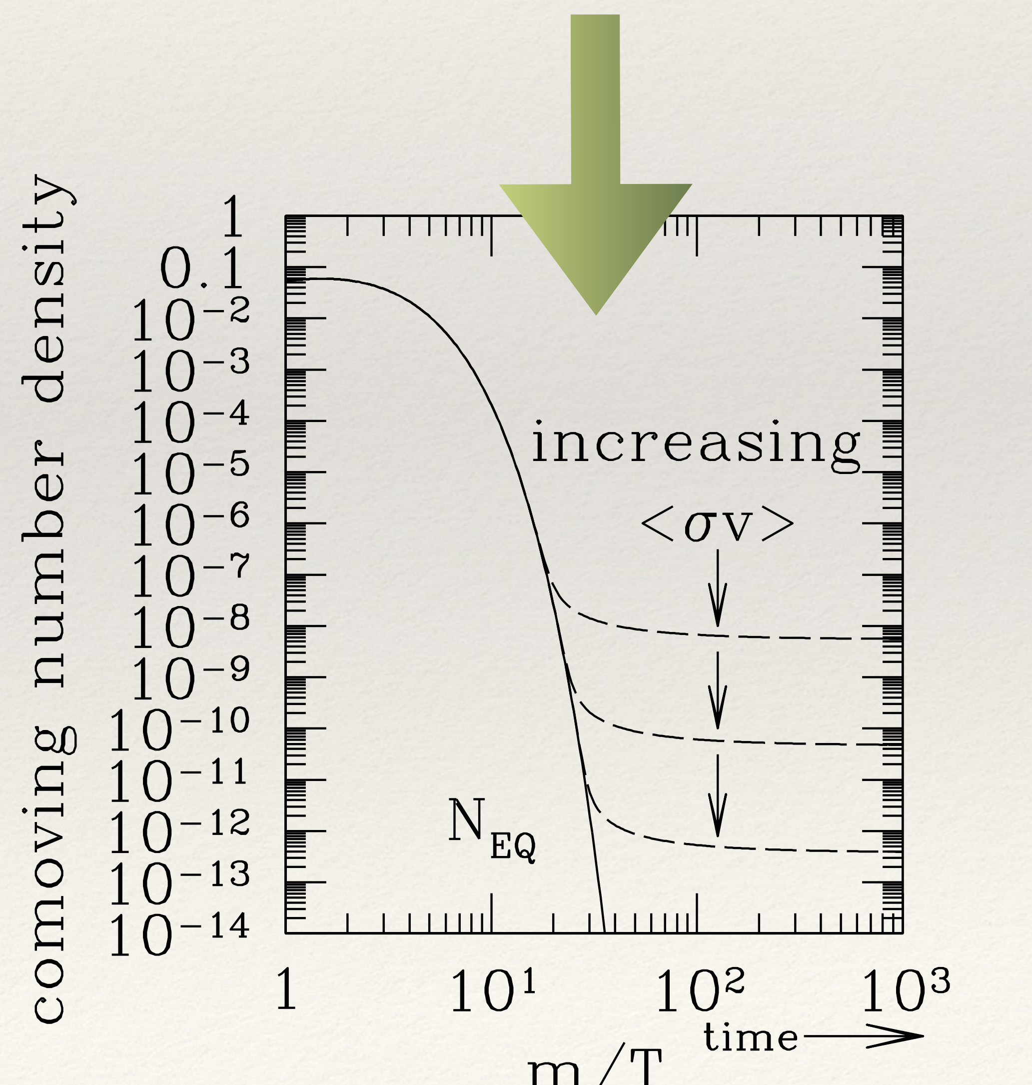
WIMP DM





Weak annihilation cross section is enough to get correct Ω_{DM}.

Chemical decoupling (freeze-out)



NEUTRINO MASS AND MIXING

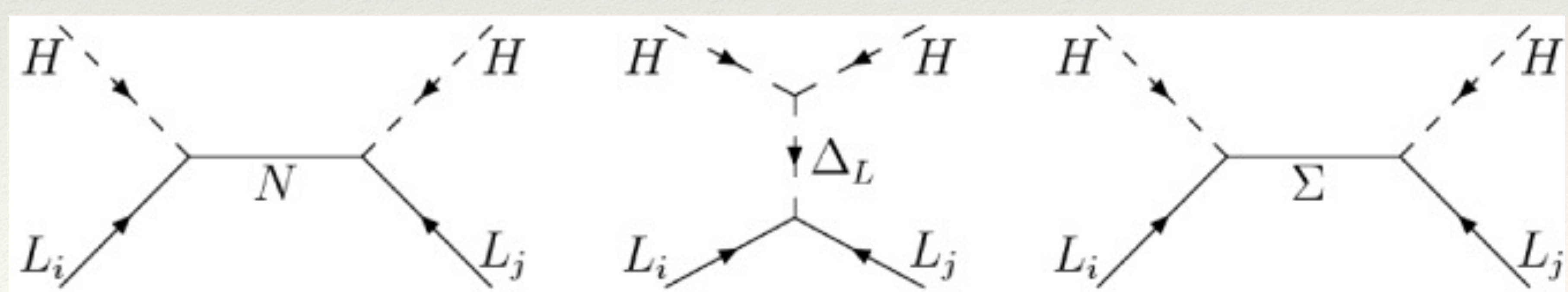
- Neutrino mixing : Gauge eigenstates would be a superposition of mass eigenstates.
- Dirac or Majorana fermion ??
- Majorana particles are their own antiparticles $\Rightarrow$ violates generational Lepton number (L_e, L_μ, L_τ).
- ν_R = right-handed gauge singlet. $-\mathcal{L}^{\text{mass}}_{\text{Dirac}} = \sum_{i,j} \bar{\nu}_{iL} (M_\nu)_{ij} \nu_{Rj} + h.c.\,,$

SEESAW MECHANISM

- Introduce Majorana mass term : $-\mathcal{L}_M = \frac{1}{2}\sum_{i,j}\overline{N_{iR}}(M_R)_{ij}N^c_{Rj} + h.c.$.
- Breaks the (B-L) symmetry of the SM.
- The neutrino mass term using the fields $\nu_L, N_R, (\nu^c_L), N^c_R$:

$$-\mathcal{L}_{\rm mass} = \frac{1}{2}\begin{pmatrix} \bar{\nu}_L & \overline{N^c_L} \end{pmatrix}\begin{pmatrix} M_L & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu^c_R \\ N_R \end{pmatrix}$$

- $M_\nu = {\rm diag}(m_1, m_2, m_3) \approx M_L - m_D M_R^{-1}(m_D)^T$.
- $\nu_L^T C^{-1}\nu_L$ breaks the gauge symmetry $\Rightarrow$ Requires $SU(2)_L$ **triplet**.
- Tiny neutrino mass from the heavy degrees of freedom and lepton number violation.
- Three tree-level realization of Effective dimension 5 Weinberg operators : $LL\phi\phi$.



CONNECTING NEUTRINO WITH DM

<u>Minimal extension of Seesaw</u>

- Majoron
- Sterile Neutrinos

Lattanzi et al '2014

<u>Non-minimal extension</u>

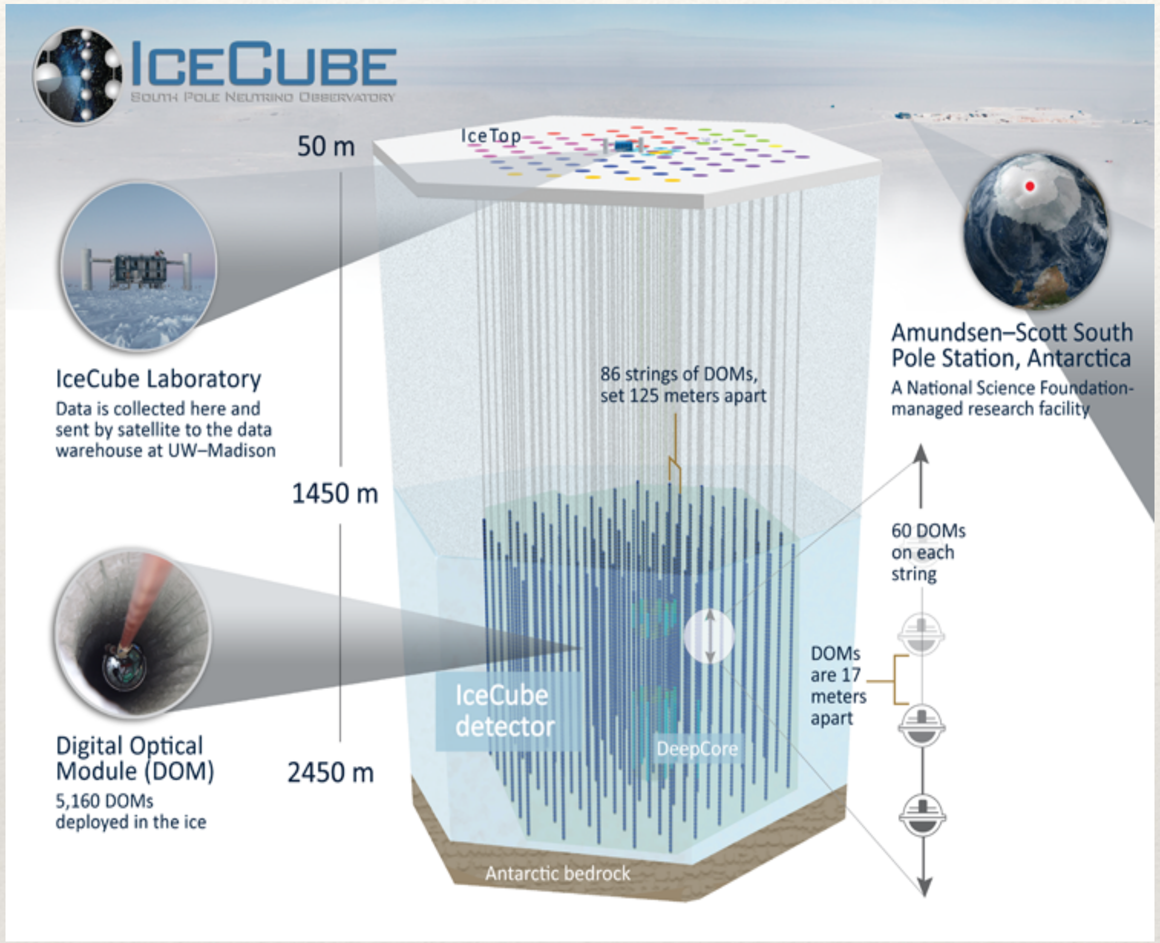
- Radiative neutrino mass and DM
  Ma'06, Gustafsson et al '2012, Hirsch et al. '2013, Restrepo et al '2013, Aoki & Toma '2014 etc..
- SUSY Extensions.
  Hirsch et al. '2005, Restrepo et al '2012, Diaz et al '2011 etc..
- Low-scale seesaw Extensions
  De Romeri & Hirsch '2012, Basso et al '2013, Arina et al'2014 etc..
- Extended gauge theories Perez et al'2019

LEPTOPHILIC

We consider Type-II Seesaw with a scalar singlet DM

Study DM annihilation into neutrino final state at the IceCube

IceCube Neutrino Observatory



- Atmospheric muon mimics high energy neutrino signal.
- Earth acts as shield but only in austral winter.
- Alternative : contained muons at DeepCore
- Atmospheric neutrino is dominant background.
- Energy threshold decreased from 100 GeV 10 GeV at the DeepCore

- 1 cubic Km Antarctic Ice. 5160 PMTs are part of Digital Optical Modules.
- 8 strings with 60 DOMs of high efficiency PMTs along with 7 regular strings consists the sub-detector DeepCore.
- Records the Cherenkov Radiation in the neutrino interaction with Ice. Both charged and neutral current interaction.
- Shower-like cascade events from Electron and tau neutrinos. Track from muon neutrinos.

The Example Model

TYPE II SEESAW

[Magg, Wetterich '80; Cheng, Li '80; Lazarides, Shafi, Wetterich '80; Schechter, Valle '80; Mohapatra, Senjanovic '81]

Features :

- Additional $SU(2)_L$ scalar triplet.
- Generates neutrino mass through seesaw mechanism.
- Seesaw scale can be $\mathcal{O}(100)$ GeV unlike Type I seesaw.
- Electroweak ρ-parameter puts an upper bound on triplet vev ($v_\Delta \leq 5$ GeV).
- Mixing between doublet and triplet is small.
- Five physical scalar : $(m_h, m_H, m_A, m_{H^\pm}, m_{H^{\pm\pm}})$.
- Doubly charged Higgs has phenomenological implications $\Rightarrow$ detectable at the LHC.

Theoretical Constraints and Phenomenological Implications:

- $m_h = 125$ GeV.
- Constraints from S, T, U parameters $\Rightarrow \Delta M \simeq \mid M_{H^{\pm\pm}} - M_{H^\pm} \mid \leq 40$ GeV.
  [Chun,Lee,Sharma '12]
- Loop induced Higgs decay mode ($h \to \gamma\gamma, h \to Z\gamma$) can be modified through charged scalars.

TYPE II SEESAW

- **Potential :** [M. A. Schmidt '07]

$$\begin{aligned}\mathcal{V}(\Phi,\Delta) &= -m_\Phi^2(\Phi^\dagger\Phi)+\frac{\lambda}{2}(\Phi^\dagger\Phi)^2+M_\Delta^2\mathrm{Tr}(\Delta^\dagger\Delta)+\frac{\lambda_1}{2}\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2\\ &+\frac{\lambda_2}{2}\left(\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2-\mathrm{Tr}\left[(\Delta^\dagger\Delta)^2\right]\right)+\lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta)\\ &+\lambda_5\Phi^\dagger[\Delta^\dagger,\Delta]\Phi+\left(\frac{\Lambda_6}{\sqrt{2}}\Phi^\mathsf{T} i\sigma_2\Delta^\dagger\Phi+\mathrm{H.c.}\right)\end{aligned}$$

- **Lagrangian :**

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\mathrm{kinetic}}^{\mathrm{SM}}+\mathcal{L}_Y^{\mathrm{SM}}-\mathcal{V}(\Phi,\Delta)+\mathrm{Tr}\left[(D_\mu\Delta)^\dagger(D^\mu\Delta)\right]\\ &-\left[\frac{1}{\sqrt{2}}(Y_\Delta)_{ij}L_i^\mathsf{T} C i\sigma_2\Delta L_j+\mathrm{H.c.}\right]\\ D_\mu\Delta &= \partial_\mu\Delta+i\frac{g}{2}[\sigma^a W_\mu^a,\Delta]+i\frac{g'}{2}B_\mu\Delta \qquad (a=1,2,3)\end{aligned}$$

- Majorana mass matrix for the neutrinos : $(M_\nu)_{ij}=v_\Delta(Y_\Delta)_{ij}$.

TYPE II SEESAW

- Fix the Yukawa structure from neutrino oscillation data:

$$Y_\Delta = \frac{M_\nu}{v_\Delta} = \frac{1}{v_\Delta} U^\mathsf{T} M_\nu^{\text{diag}} U$$

where $M_\nu^{\text{diag}} = \text{diag}(m_1, m_2, m_3)$ and U is the PMNS mixing matrix.

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \text{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1) ,$$

- For illustration purposes, take normal hierarchy with $m_1 = 0$.

$$Y_\Delta = \frac{10^{-2}\ \text{eV}}{v_\Delta} \times \begin{pmatrix} 1.08 - 0.29i & -1.55 + 0.09i & 1.23 - 0.31i \\ -1.55 + 0.09i & 2.07 + 0.26i & -1.59 - 0.21i \\ 1.23 - 0.31i & -1.59 - 0.21i & 2.59 - 0.00i \end{pmatrix} .$$

- v_Δ can not be arbitrarily small due to perturbativity.
- From EWPT constraints, $\frac{v_\Delta}{v} < 0.02$

DM in TYPE II SeeSaw

Addition of extra singlet(D) odd under Z_2 symmetry , provides a valid DM candidate. [I. Gogoladze, N. Okada and Q. Shafi '09] The Scalar Potential relevant for the DM physics:

$$\mathcal{V}_{\rm DM}(\Phi, \mathbf{\Delta}, D) = \frac{1}{2} m_D^2 D^2 + \lambda_D D^4 + \underbrace{\lambda_\Phi D^2 (\Phi^\dagger \Phi)} + \underbrace{\lambda_\Delta D^2 \mathrm{Tr}(\mathbf{\Delta}^\dagger \mathbf{\Delta})}$$

In terms of the physical scalar mass eigenstates,

$$\begin{aligned} \mathcal{V}_{\rm DM} &= \frac{1}{2} m_{\rm DM}^2 D^2 + \lambda_D D^4 + \lambda_\Phi v D^2 h + \frac{1}{2} \lambda_\Phi D^2 h^2 \\ &+ \lambda_\Delta D^2 \left(H^{++} H^{--} + H^+ H^- + \frac{1}{2} \left[(H^0)^2 + (A^0)^2 \right] + v_\Delta H^0 \right) \end{aligned}$$

In the non-relativistic limit (CDM),

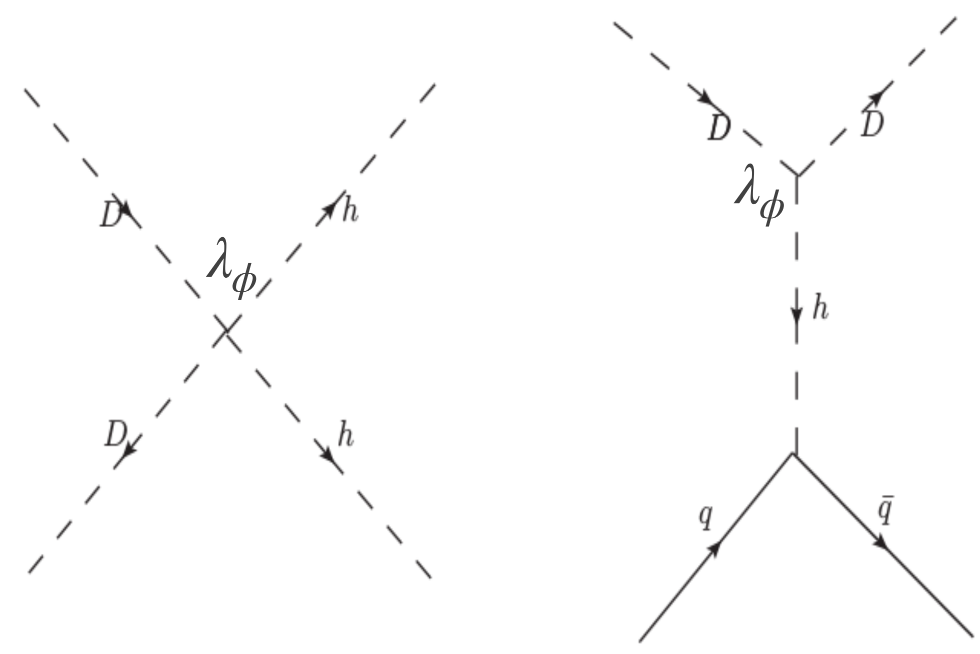
$$\langle \sigma v \rangle = \frac{1}{16\pi m_{\rm DM}^2} \left[\lambda_\Phi^2 \sqrt{1 - \frac{m_h^2}{m_{\rm DM}^2}} + 6\lambda_\Delta^2 \sqrt{1 - \frac{m_\Delta^2}{m_{\rm DM}^2}} \right]$$

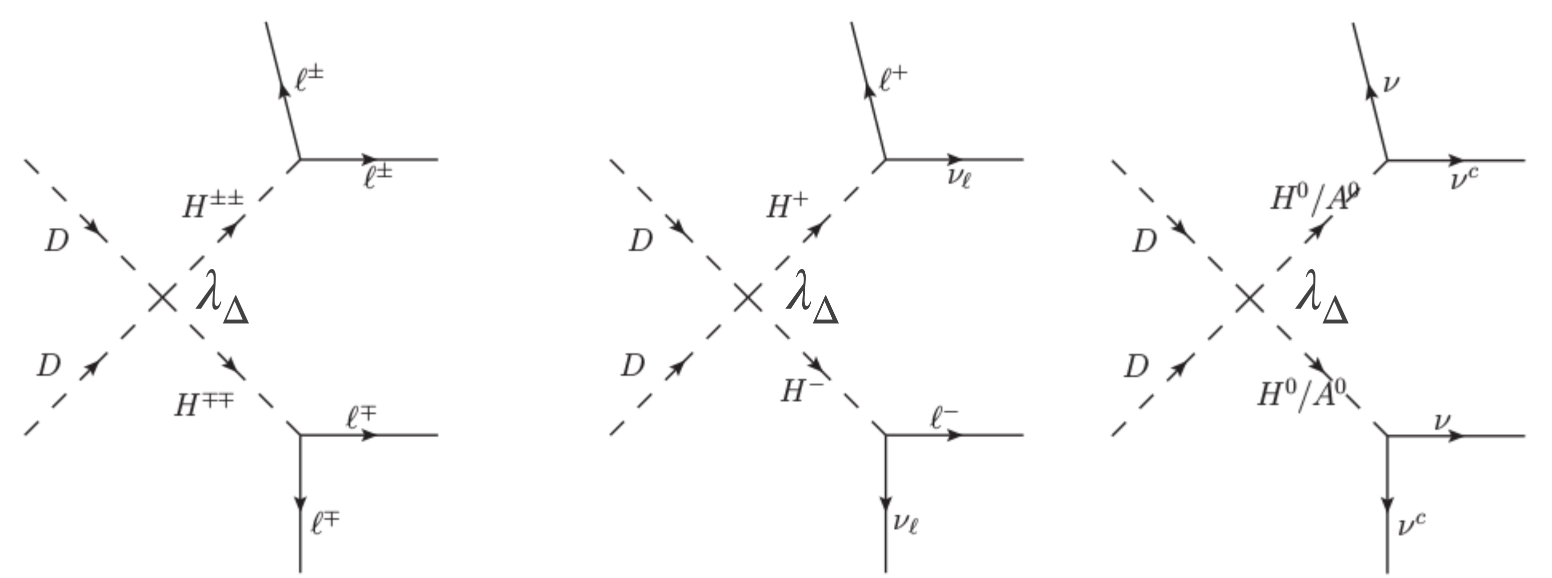
which should match the observed cold DM relic density of $\Omega_{\rm CDM} h^2 = 0.1199 \pm 0.0027$.

DM Scenario

Features :

- Only couple to triplet scalars or SM-like Higgs.
- For $v_\Delta \geq 0.1$ MeV, scalar triplets decay to **leptonic** final states with almost 100% branching ratio.
- Dominant annihilation to triplet scalars $\Rightarrow$ Leptophilic.
- The final state lepton flavor depends on the structure of the Yukawa coupling matrix. A correlation with Neutrino oscillation data.
- $H^0, A^0 \to \nu\nu \Rightarrow$ cosmic ray neutrino flux.





- The couplings are chosen to satisfy the correct relic abundance.
- λ_ϕ controls the SI direct detection cross section.
- On shell production of triplets.

We consider both the annihilation at the **Galactic Center** and inside the **Sun**.

Model Specification

$$\Gamma(H^{++} \to \ell_i^+ \ell_j^+) = \frac{m_{H^{++}}}{8\pi(1+\delta_{ij})} \left[\frac{U^T M_\nu^{\rm diag} U}{v_\Delta}\right]^2 ,$$

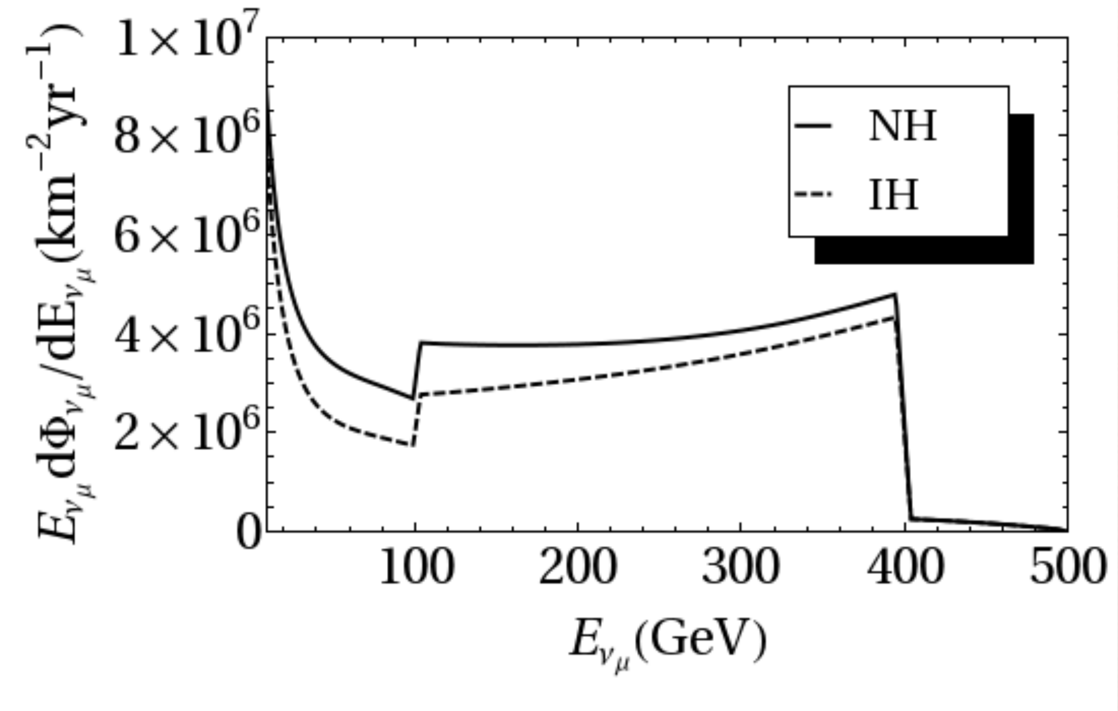
$$\Gamma(H^{++} \to W^+ W^+) = \frac{g^4 v_\Delta^2}{8\pi m_{H^{++}}} \sqrt{1 - \frac{4M_W^2}{m_{H^{++}}^2}} \left[2 + \left(\frac{m_{H^{++}}^2}{2M_W^2} - 1\right)^2\right] .$$

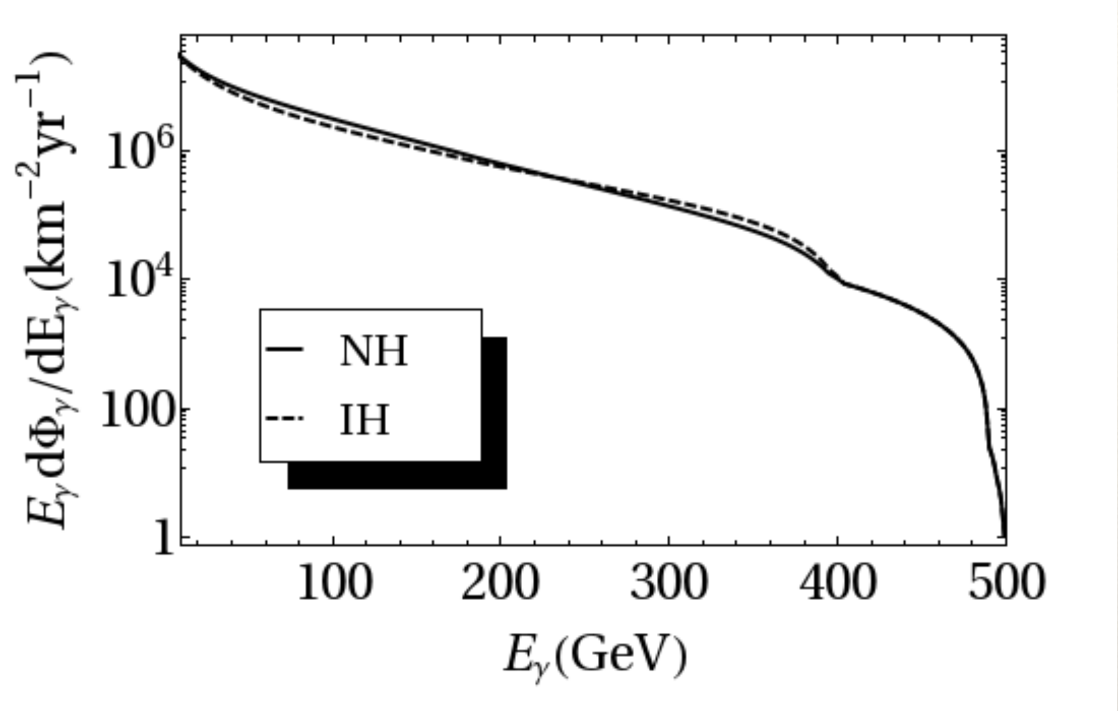
leptonic and gauge boson final states are respectively inversely and directly proportional to the square of the triplet vev. In particular, for $v_\Delta < 0.1$ MeV, the triplets decay to leptonic final state with almost 100% branching fraction.

- Constraint on doubly charged scalar from LHC same-sign dilepton searches.
- Degenerate triplet mass equals to 400 GeV.

- Two Choices of benchmarks depending on triplet vev.
- Limit from Fermi-LAT gamma ray flux is considered.
- For IceCube, both through-going and contained muons are considered.

DM Annihilation at the Galactic Center

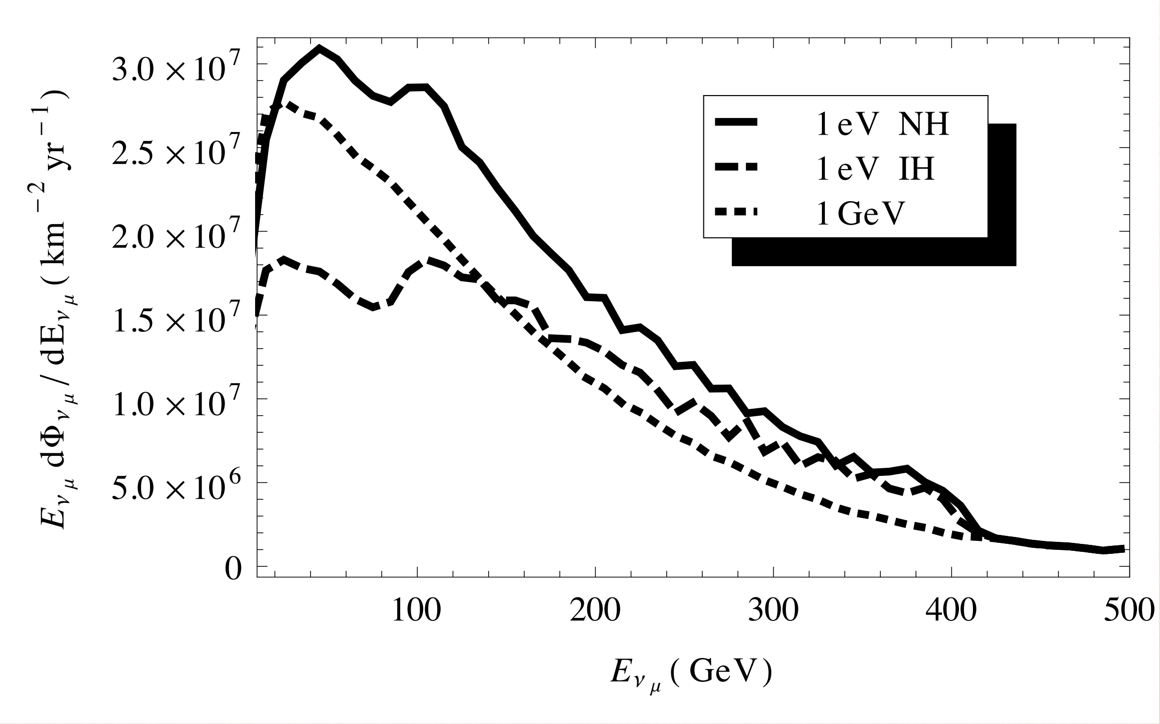




- Clear distinction in NH and IH case for neutrino flux, no difference in photon fluxes which is obvious.
- Neutrinos encounter oscillation during its travel.
- No significant change due to neutrino oscillation parameter uncertainties.
- On-shell triplets decay to neutrinos. Box like feature due to kinematics.
- NH produces more $\tau(\nu_\tau)$ which further give rise to ν_μ.

- In NH, triplets decay to third generation leptons are maximum Yukawa structure.
- More τs and ν_τs which subsequently give more muon neutrinos.
- For IH, the first generation lepton production is maximum.

DM Annihilation inside the Sun



- DM evolution equation inside the Sun,
$$\dot{N} = C_C - C_A N^2$$
- The annihilation rate inside the Sun
$$\frac{C_A}{2} N^2 = \Gamma_A = \frac{C_C}{2} \tanh^2\left(\frac{t}{\tau}\right)$$

C_C is the capture rate, and the equilibrium time Scale $\tau = 1/\sqrt{C_C C_A}$.
Equilibrium condition is achieved for the age of The Sun.

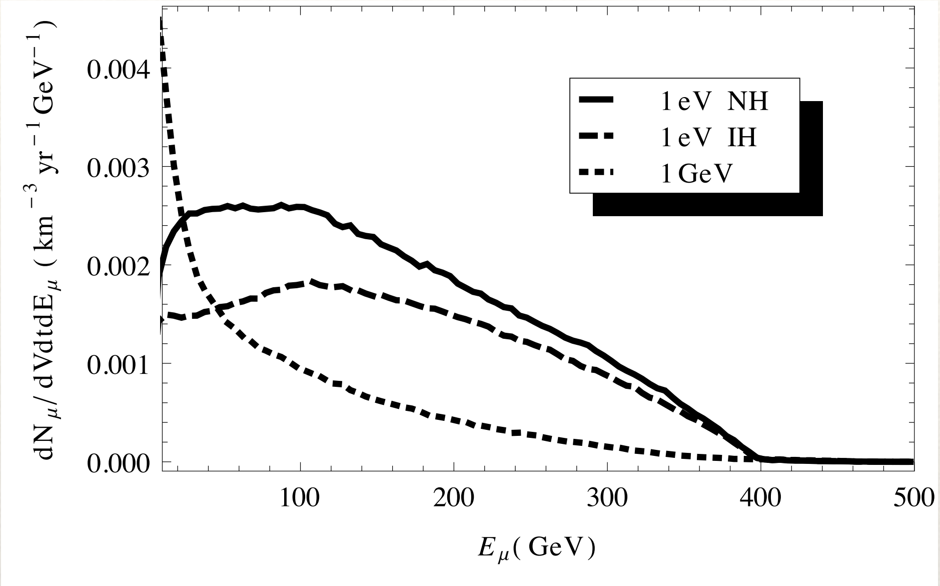
- Most relevant final states $H^0/A^0/H^+$ produces prompt neutrinos inside the Sun. Other final states (e, μ, lighter quarks) lose energy and produce neutrino with energy below threshold.
- τ and to a lesser extent ν_μ decays before losing a significant amount of energy and produces neutrinos.
- ν_e absorption is effective for neutrino energy > 300 GeV while ν_τ feels the regeneration effect.
- Sharp features like the Galactic Center spectrum are not prominent due to regeneration/absorption effect.

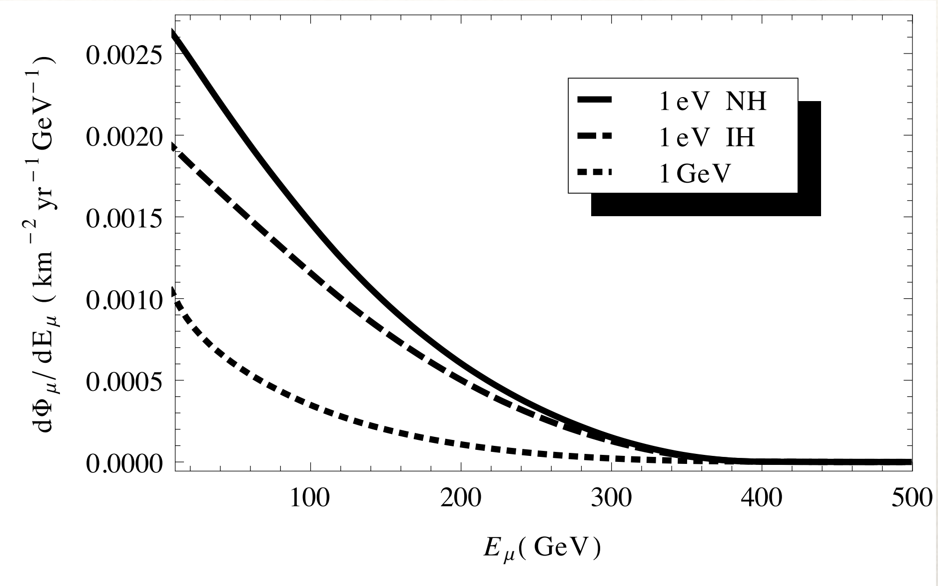
- DarkSUSY software to simulate neutrino production inside the Sun, propagation to the south pole and muon neutrino interaction with the ice.
- WimpSim for prompt neutrino channels.

Muon Spectra

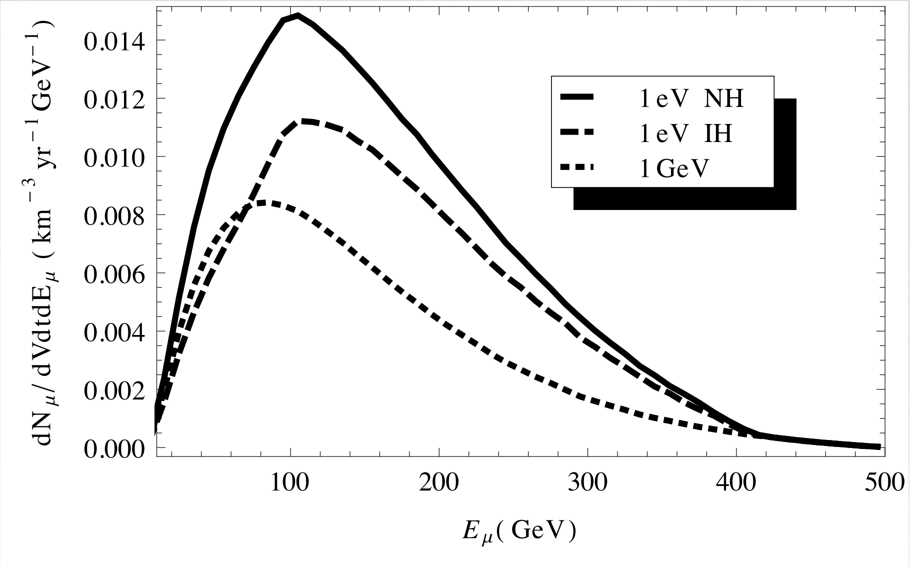
Contained muon

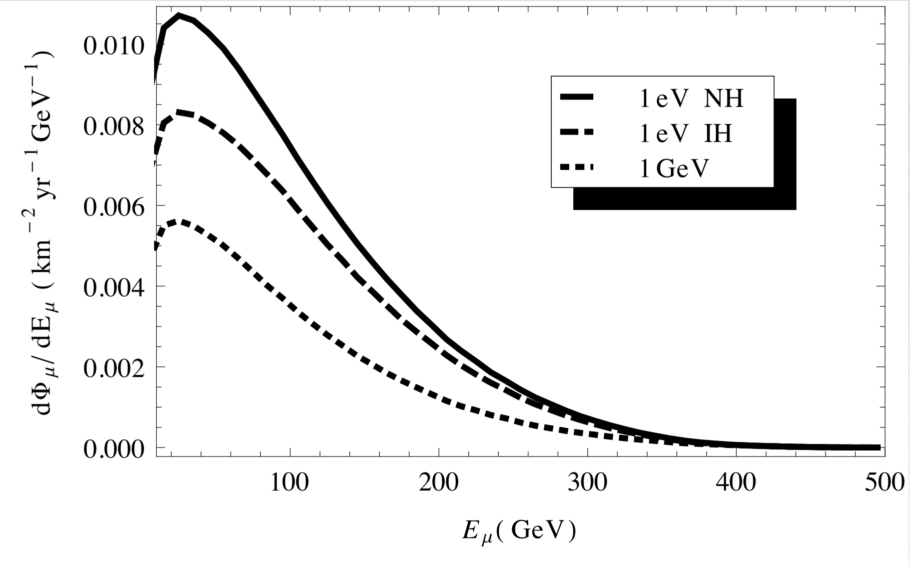
Through-going muon





Galactic Center

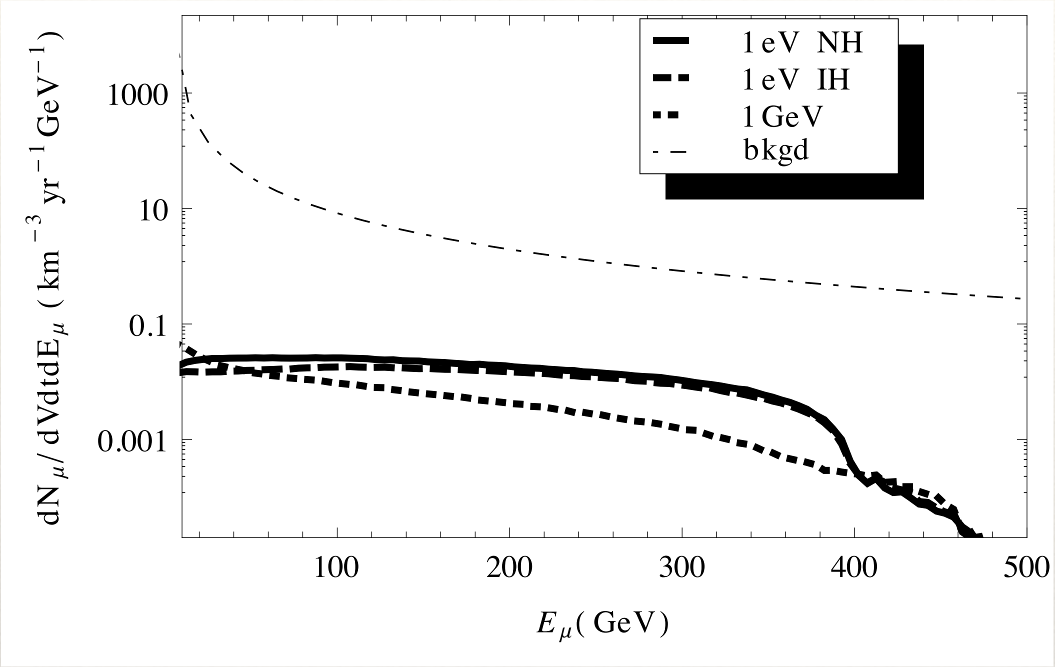




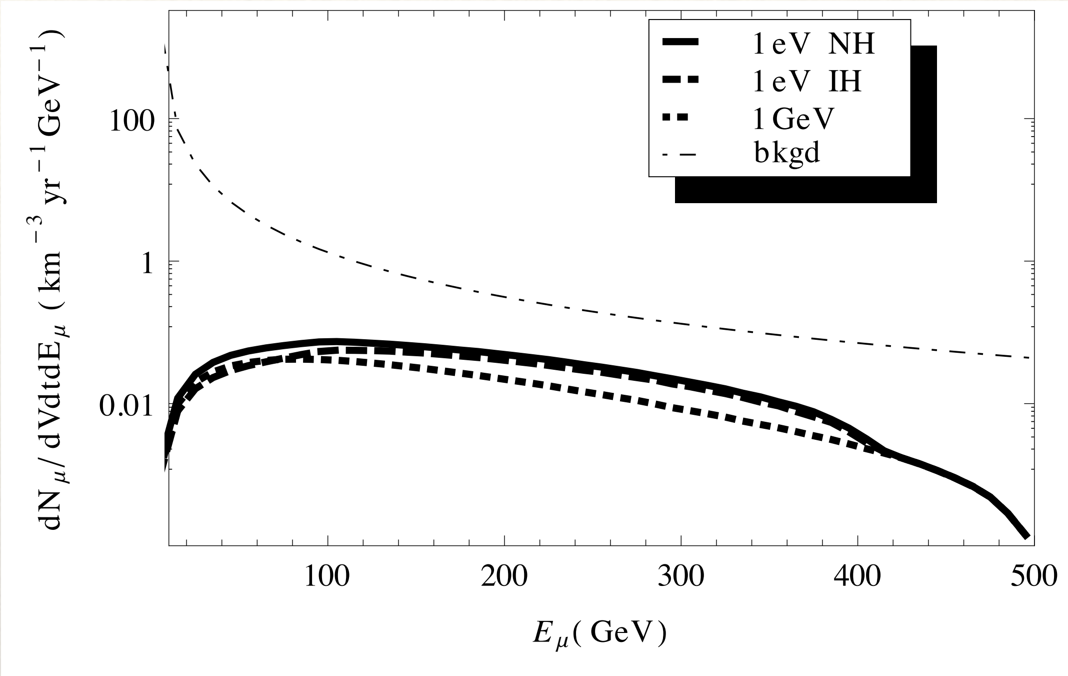
Sun

Theoretical Predictions

Contained muon predictions



Galactic Center



Sun

- Non-thermal production of DM can enhance the annihilation cross-section.
- Being consistent with Fermi-LAT limit from dwarf Spheroidal galaxy, $\langle \sigma_{\rm ann} v \rangle$ can be increased by a factor of 10.
- Contained muons from DM annihilation inside the Sun provide the best detection opportunity.
- For a neutrino telescope with same capability as IceCube DeepCore array may take 8 (12) years respectively to have a 3σ discovery of NH and IH scenarios.

Within energy interval of 100-400 GeV, the no. of contained muons from NH and IH are respectively 9 and 11 compared to 95 background events.

Summary

- We have discussed the possibilities of distinguishing neutrino mass hierarchy using DM annihilation signal at the IceCube.
- We have studied the possible neutrino signal from both the Galactic Center and inside the Sun.
- We have found that the neutrino flux from Galactic Center depends on the mass hierarchy (NH or IH) while the photon flux has no dependence.
- The NH produces larger flux and its the same for DM annihilation inside the Sun.
- Although the signal is more prominent if it arises at the Galactic Center since the neutrinos suffer from attenuation due to matter interaction inside the Sun.
- The same results hold for both contained and though-going muons at the detector.
- The prescription is general and can be applied to other models.

Thank You

Benchmarks	v_Δ	$m_{\rm DM}$(GeV)	m_Δ(GeV)	λ_Δ	λ_Φ	relic density	σ_{SI} (pb)
BP1	1 eV	500	400	0.055	0.04	0.117	2.25×10^{-10}
BP2	1 eV	700	400	0.075	0.05	0.122	1.79×10^{-10}
BP3	1 GeV	500	400	0.055	0.04	0.117	2.25×10^{-10}
BP4	1 GeV	700	400	0.075	0.05	0.122	1.79×10^{-10}

$$\sigma_{\nu N}(E_\nu) = 7.30\times 10^{-39}(E/{\rm GeV}){\rm cm}^2\,,$$

$$\sigma_{\bar\nu N}(E_\nu) = 3.77\times 10^{-39}(E/{\rm GeV}){\rm cm}^2\,,$$