On the Oscillation of Neutrinos
Produced by the Annihilation of Dark Matter inside the Sun

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A. E. and Yasaman Farzan; Phys. Rev. D 81 (2010) 113010 [arXiv:0912.4033 [hep-ph]],

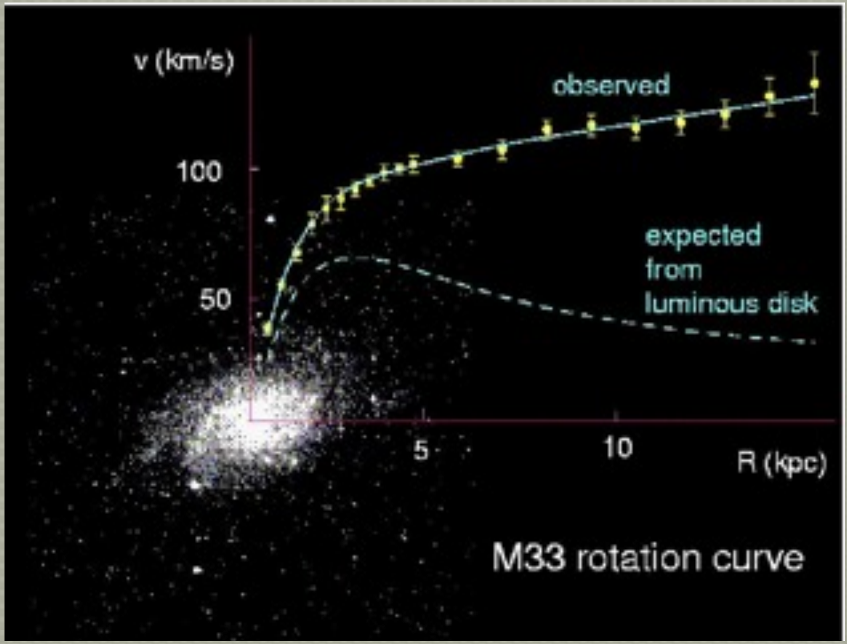
A. E. and Yasaman Farzan; JCAP 1104 (2011) 007 [arXiv:1011.0500 [hep-ph]].

OUTLINE:

- A brief introduction to DM
- DM capture inside the Sun
- Coherence of neutrinos
- Seasonal effect
- Summary

Dark Matter Evidences

Bullet Galaxies



Rotation Curves

Dark Matter evidences

Other Evidences from a wide range of astrophysical observations

Lensing Clusters BBN SN1a LSS

- Each observes dark matter through its gravitational influence
- Still no (reliable) indications of dark matter's particle nature

The Dark Matter Candidate Zoo

- **Axions, Neutralinos, Gravitinos, Axinos, Kaluza-Klein Photons, Kaluza-Klein Neutrinos, Heavy Fourth Generation Neutrinos, Mirror Photons, Mirror Nuclei, Stable States in Little Higgs Theories, WIMPzillas, Cryptons, Sterile Neutrinos, Sneutrinos, Light Scalars, Q-Balls, D-Matter, Brane World Dark Matter, Primordial Black Holes, …**

?

WIMPs
(Weakly Interacting Massive Particles)

- Thermal production---freeze out

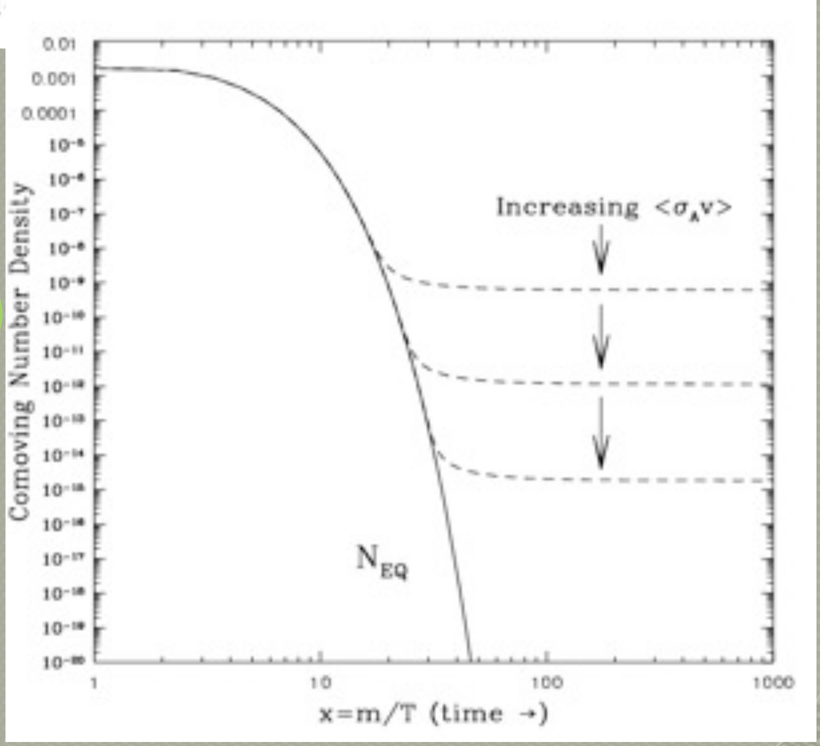
Jungman, Kamionkowski and Griest, Phys. Rep. 267 (1996) 195.

$$\frac{dn_X}{dt} + 3Hn_X = - \langle \sigma_{X\bar{X}} |v| \rangle (n_X^2 - n_{X,\mathrm{eq}}^2),$$

$$n_{X,\mathrm{eq}} = g_X \left(\frac{m_X T}{2\pi} \right)^{3/2} e^{-m_X/T}$$

$$\Omega_X h^2 \approx 0.1 \left(\frac{x_{\mathrm{FO}}}{20} \right) \left(\frac{g_\star}{80} \right)^{-1/2} \left(\frac{a + 3b/x_{\mathrm{FO}}}{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}} \right)^{-1}$$

$\langle\sigma\rangle \sim$ pb

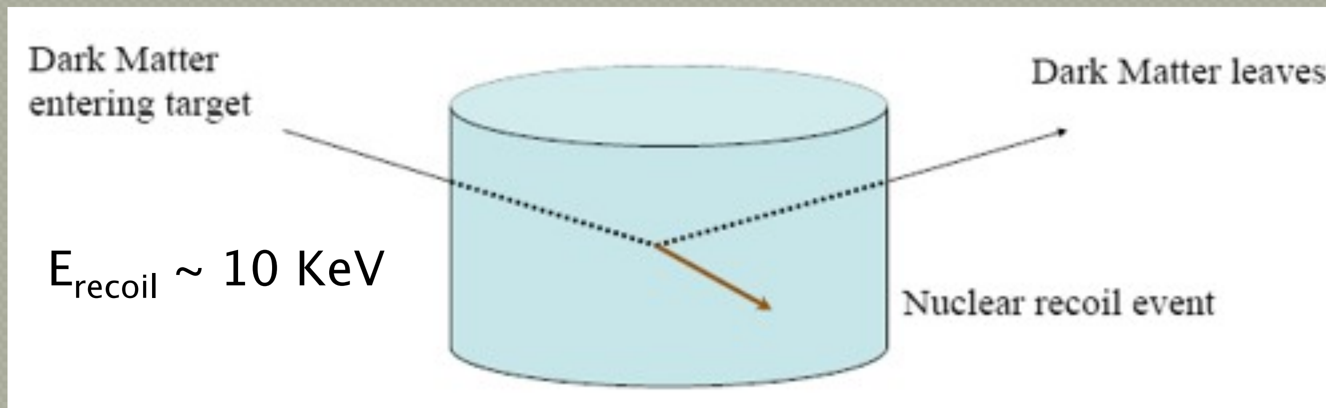


- Generic weak interaction yields:

$\langle\sigma\rangle \sim \alpha^2$ (100 GeV)$^{-2}$ $\sim$ pb

Detection of WIMPs

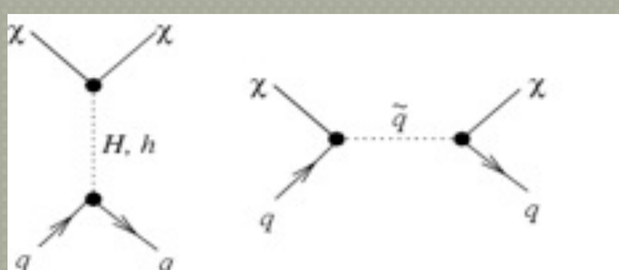
- Direct Detection:

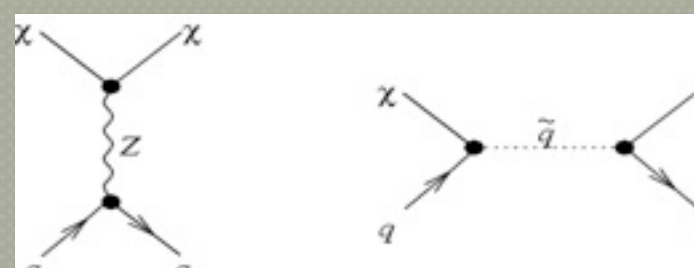


Effective Lagrangian

$$L = f_q(\bar{\chi}\chi)\cdot(\bar{q}q) + d_q(\bar{\chi}\gamma^{\mu}\gamma^{5}\chi)\cdot(\bar{q}\gamma_{\mu}\gamma^{5}q) + \ldots$$

scalar interaction — *spin-dep. interaction*

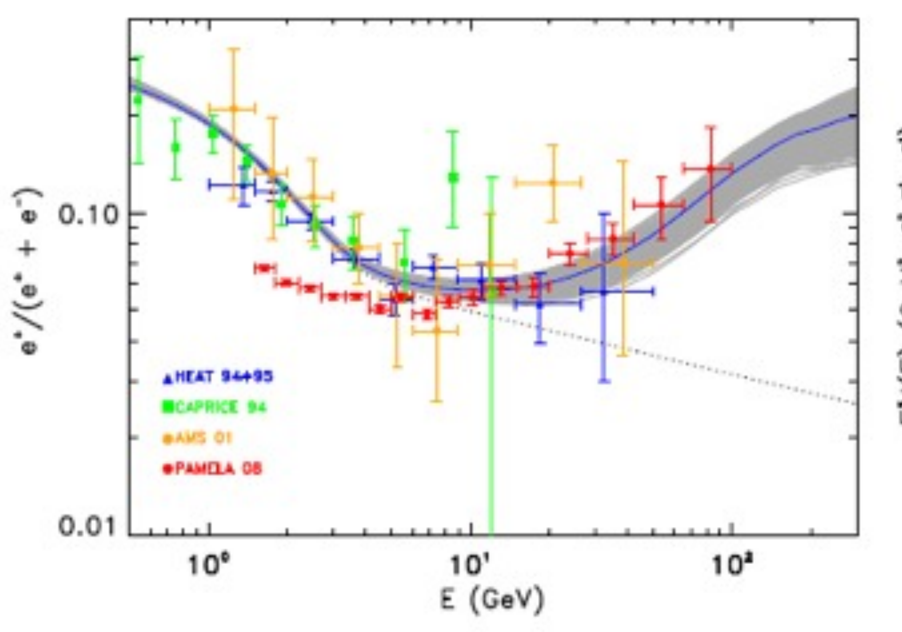




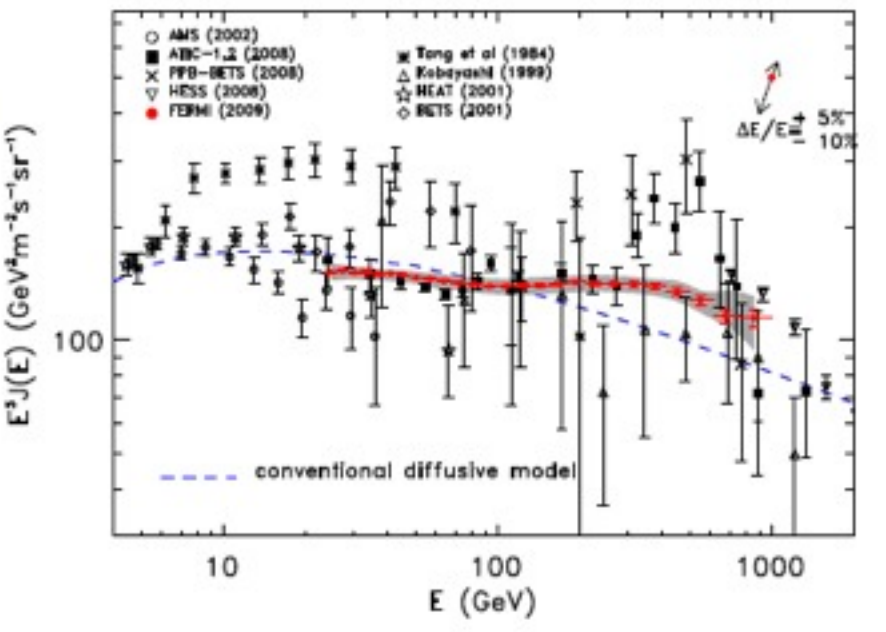
➢ Indirect Detection:

- With Anti-Matter

PAMELA

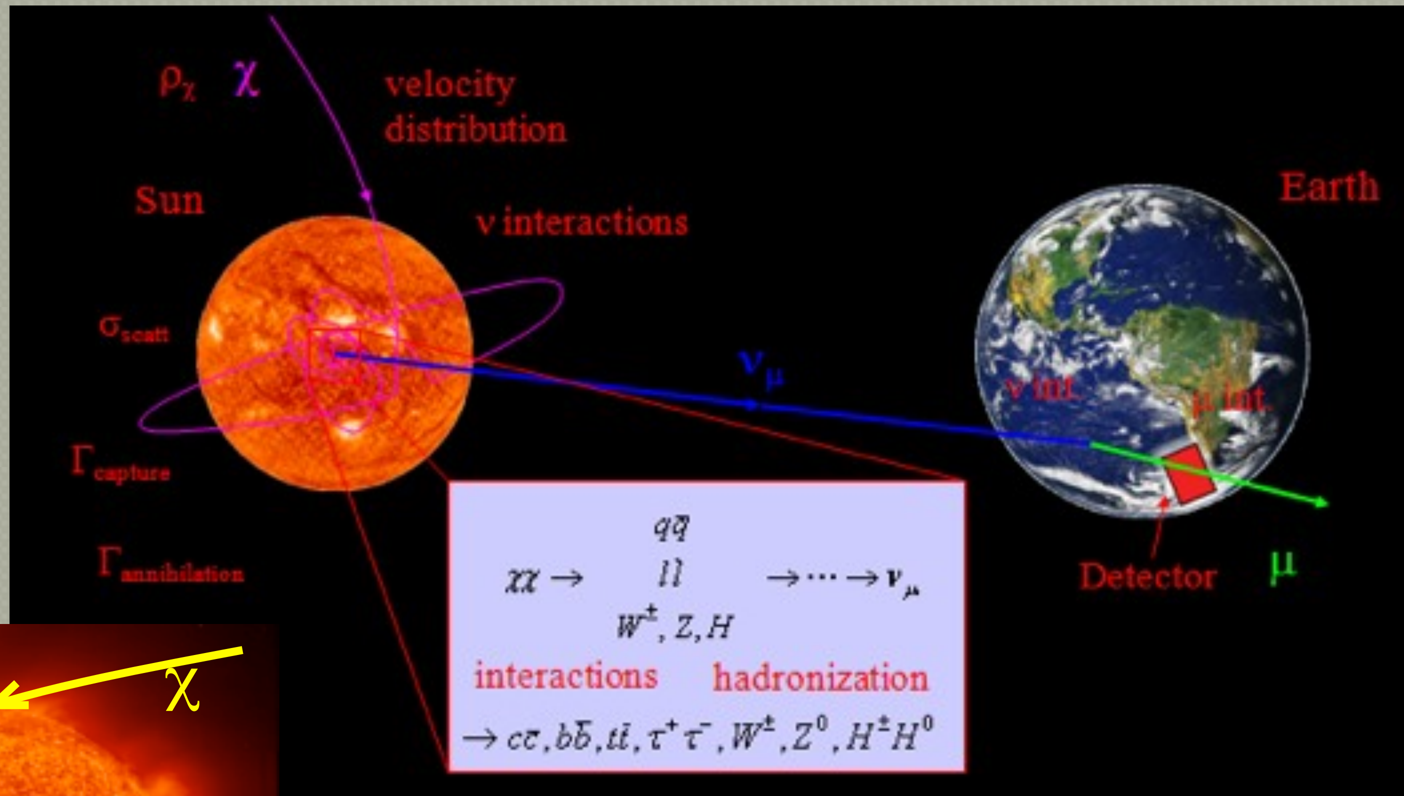


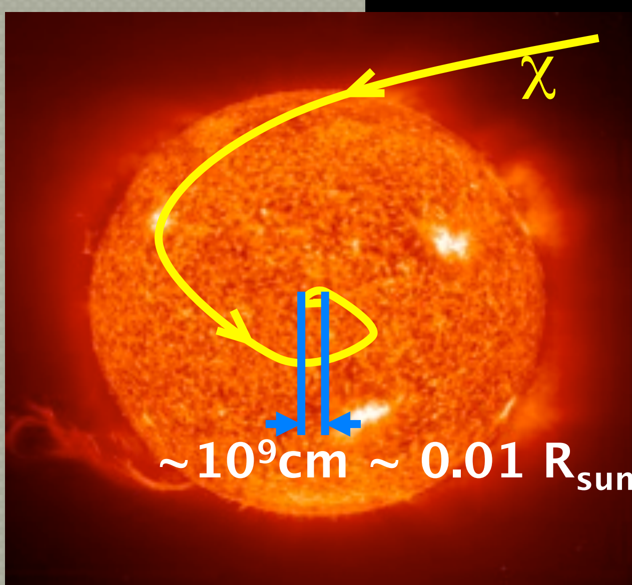
ATIC/Fermi LAT



- With gamma rays (Fermi)

- With Neutrinos





Capture of Neutrinos at the Sun

The evolution of the WIMP population is governed by the equation

$$\dot{N} = C - C_A N^2$$

C: capture rate

C_A: annihilation rate per WIMP^2

$$\frac{1}{2} C_A N^2$$

$$\Gamma_A = \frac{1}{2} C \tanh^2(t/\tau_{eq}) \xrightarrow{\text{Long time}} \Gamma_A = \frac{1}{2} C$$

$$\tau_{eq} = (C C_A)^{-1/2}$$

$$\frac{t_\odot}{\tau_{\rm eq}} = 10^3 \left(\frac{C}{10^{25}\ \mathrm{sec}^{-1}}\right)^{1/2} \left(\frac{\langle \sigma_A v \rangle}{3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{sec}^{-1}}\right)^{1/2} \left(\frac{7 \times 10^8\ \mathrm{cm}}{r_{th}}\right)^{3/2}$$

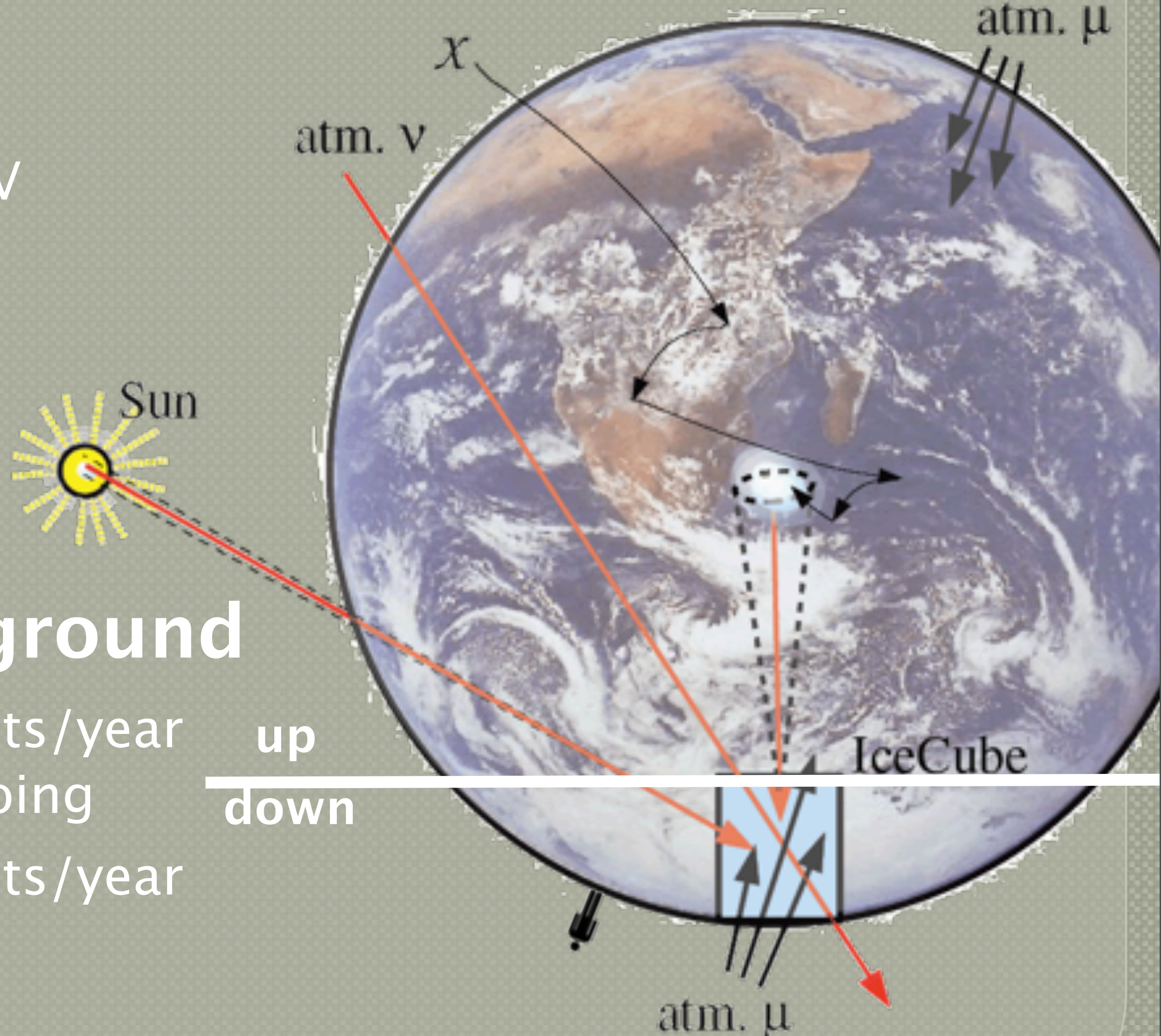
Detection of Neutrinos at the Earth

neutralino signal

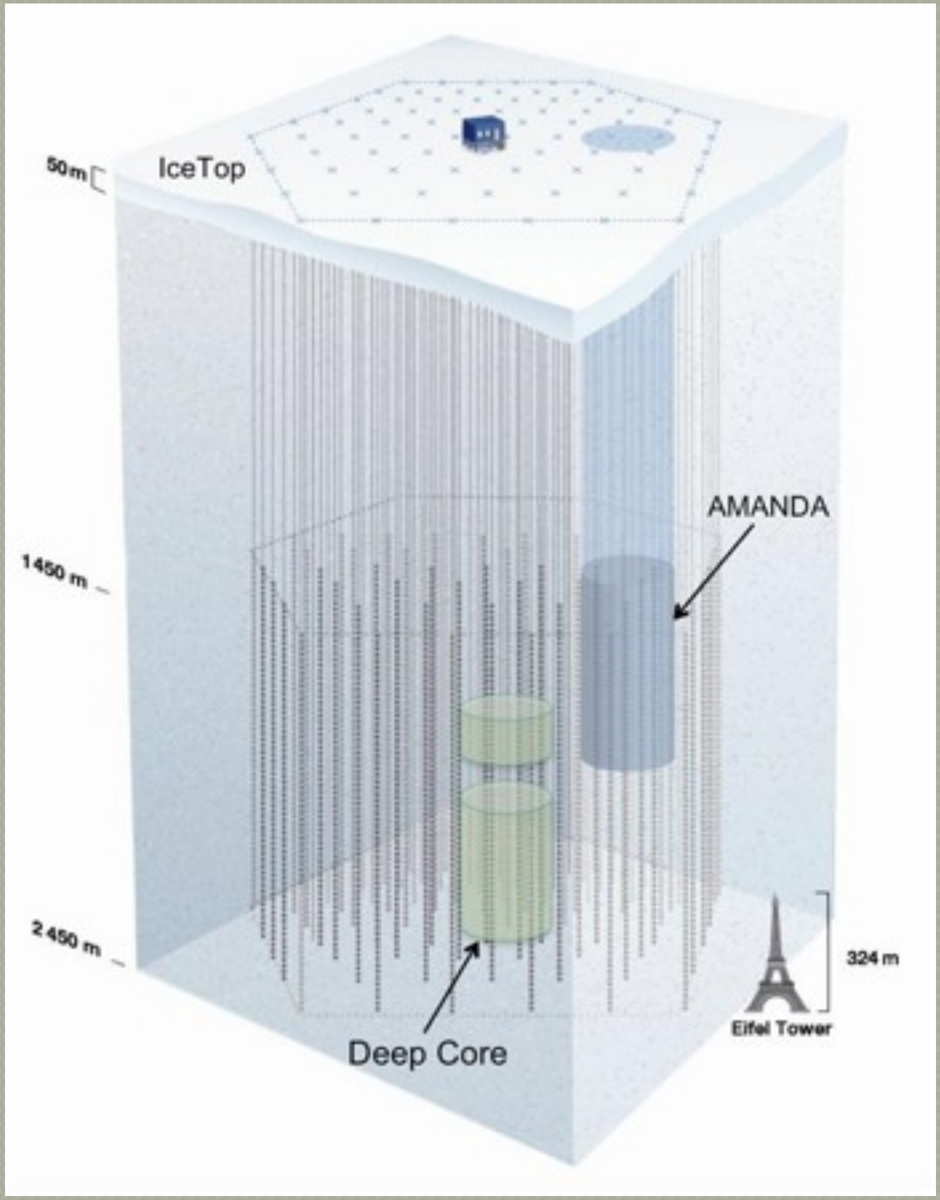
- 30 GeV < M_χ < 5000 GeV
- vertically upward (Earth) horizontal (Sun)

atmospheric background

- muons ~O(10^9) events/year downward going
- neutrinos ~O(10^3) events/year all directions



IceCube Detector



- Here we consider the case that DM+DM → $\nu\,\nu$

Thus the neutrinos are monochromatic.

Average velocity of the DM particles in the Sun

$$(3T_{\odot}/m_{DM})^{1/2} \simeq 60\ \mathrm{km/sec}.$$

↓

We expect the spectrum on neutrinos remain monochromatic

$$L_{osc} = \frac{4\pi E_\nu}{\Delta m_{12}^2} \sim 3 \times 10^{11}\ \mathrm{cm}\ \left(\frac{E_\nu}{100\ \mathrm{GeV}}\right)\left(\frac{8 \times 10^{-5}\ \mathrm{eV}^2}{\Delta m_{12}^2}\right)$$

L_{osc} is of the order of the variation of Earth-Sun distance over a year

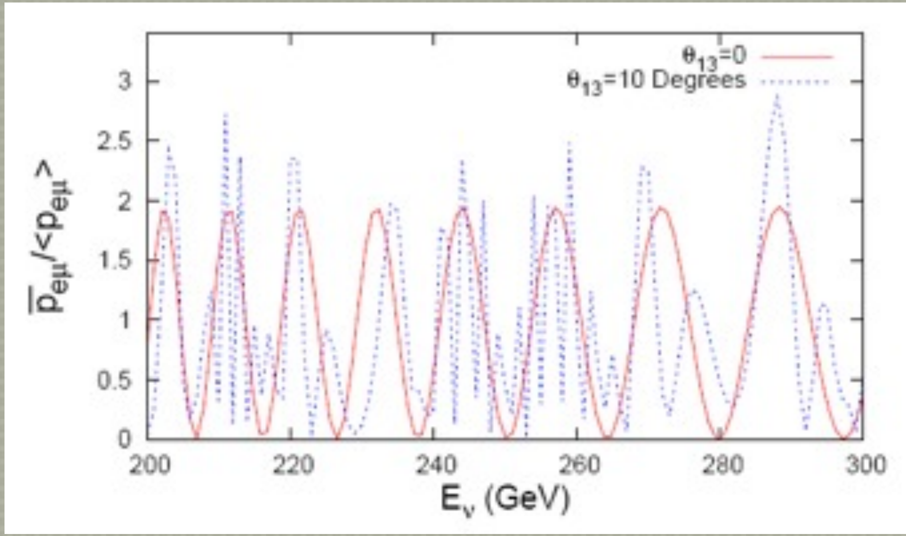
⇓

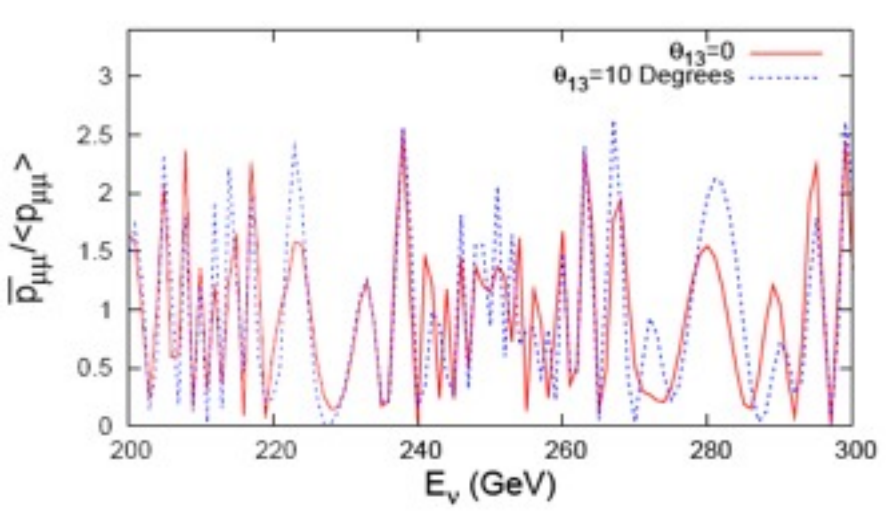
Observable seasonal effects should be seen

Average over the production point

$$r_{DM} \approx \left(\frac{9T}{8\pi G_N \rho m_{DM}} \right)^{1/2}$$

$r_{DM} \sim 0.01 \, R_{sun}$





Widening of the wave packet

- Thermal widening $\frac{\Delta E}{E} \sim \frac{\bar{v}}{c} \sim 10^{-4} \left(\frac{T}{1.3\text{ keV}}\right)^{1/2} \left(\frac{100\text{ GeV}}{m_{DM}}\right)^{1/2}$

- Gravitational widening $\frac{\Delta p}{p} = \left(\frac{4\pi G \rho r_{DM}}{3 m_{DM}}\right)^{1/2} \sim 5 \times 10^{-17} \left(\frac{100\text{ GeV}}{m_{DM}}\right)^{1/2}$

- Natural width of the neutrino wave packet

$\frac{\Delta p}{p} > \frac{n_{DM}\langle\sigma_{ann} v\rangle}{m_{DM}}$ And $\frac{n_{DM}\langle v \sigma_{ann}\rangle}{m_{DM}} \sim 10^{-38}$

- Widening due to scattering

NC inter. $$\ell_{NC} = \frac{1}{n_0 \sigma_{NC}} = 1.5 \times 10^6 \text{ km} \left(\frac{5 \times 10^{25} \text{ cm}^{-3}}{n_0} \right) \left(\frac{1.3 \times 10^{-37} \text{ cm}^2}{\sigma_{NC}} \right)$$

Matter density in the Sun falls as: $e^{-r/(0.1 R_\odot)}$

ratio of neutrinos undergoing neutral current interactions should be of the order of $0.1 R_\odot / \ell_{NC} \simeq 5\%$

For $E_\nu = 500$ GeV

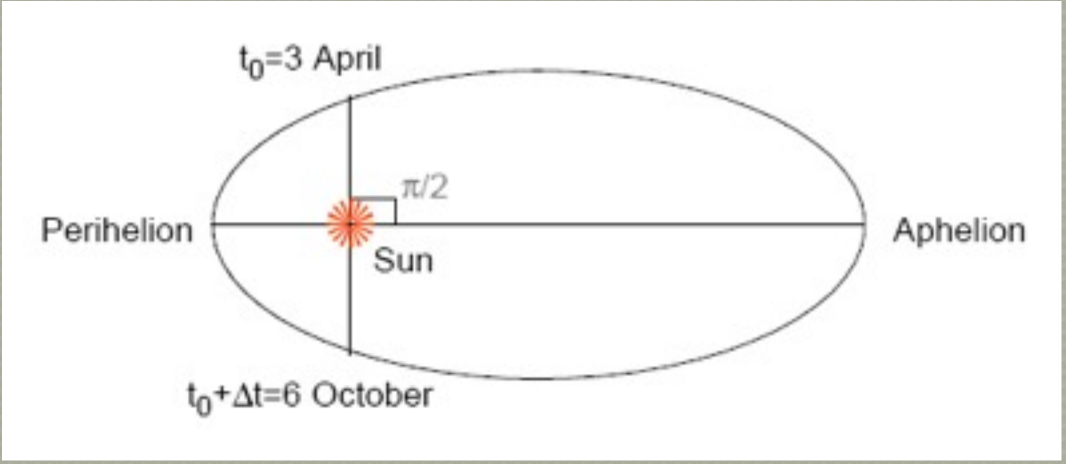
The ratio will be 35 %

Seasonal Variation

We define:

$$\tilde{N}(t_0, \Delta t) \equiv \frac{\int_{t_0}^{t_0+\Delta t} (dN_\mu/dt)\ dt}{\int_{t_0}^{t_0+\Delta t} A_{eff}(\theta[t])/[L(t)]^2\ dt}.$$

$$\Delta(t_1, \Delta t_1; t_2, \Delta t_2) \equiv \frac{\tilde{N}(t_1, \Delta t_1) - \tilde{N}(t_2, \Delta t_2)}{\tilde{N}(t_1, \Delta t_1) + \tilde{N}(t_2, \Delta t_2)}$$



Electron neutrinos at the Sun

E_ν (GeV)	Δ(20March, 186days)				Δ(3April, 186days)			
	$\theta_{13} = 0°$		$\theta_{13} = 10°$		$\theta_{13} = 0°$		$\theta_{13} = 10°$	
	NH	IH	NH	IH	NH	IH	NH	IH
100	18 %	18 %	9 %	11 %	12 %	12 %	6 %	7 %
300	57 %	57 %	37 %	42 %	60 %	60 %	39 %	43 %

Muon neutrinos at the Sun

E_ν (GeV)	Δ(20March, 186days)				Δ(3April, 186days)			
	$\theta_{13} = 0°$		$\theta_{13} = 10°$		$\theta_{13} = 0°$		$\theta_{13} = 10°$	
	NH	IH	NH	IH	NH	IH	NH	IH
100	9 %	6 %	4 %	1 %	7 %	4 %	3 %	0.3 %
300	12 %	7 %	6 %	19 %	13 %	7 %	6 %	20 %

We consider the flavor oscillation, matter effect inside the Sun, absorption and tau neutrino regeneration

$$\frac{dN_\mu^{\rm IC}}{dt} = \int_{E_{\rm thr}}^{m_{\rm DM}} \int_{E_{\rm thr}}^{E_{\nu_\mu}} \frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} \left[\frac{d\sigma_{\nu p}^{\rm CC}}{dE_\mu}(E_{\nu_\mu})\rho_p + \frac{d\sigma_{\nu n}^{\rm CC}}{dE_\mu}(E_{\nu_\mu})\rho_n \right]$$

$$\times A_{\rm eff}(E_\mu, \theta[t]) \left(R_\mu(E_\mu, E_{\rm thr}) + d\right) dE_\mu dE_{\nu_\mu} + (\nu_\mu \to \bar{\nu}_\mu)$$

$$\frac{dN_\mu^{\rm DC}}{dt} = \int_{E_{\rm thr}}^{m_{\rm DM}} \int_{E_{\rm thr}}^{E_{\nu_\mu}} \frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} \left[\frac{d\sigma_{\nu p}^{\rm CC}}{dE_\mu}(E_{\nu_\mu})\rho_p + \frac{d\sigma_{\nu n}^{\rm CC}}{dE_\mu}(E_{\nu_\mu})\rho_n \right] \times V_{\rm eff}^{\rm DC}(E_\mu)\, dE_\mu\, dE_{\nu_\mu} + (\nu_\mu \to \bar{\nu}_\mu)\,,$$

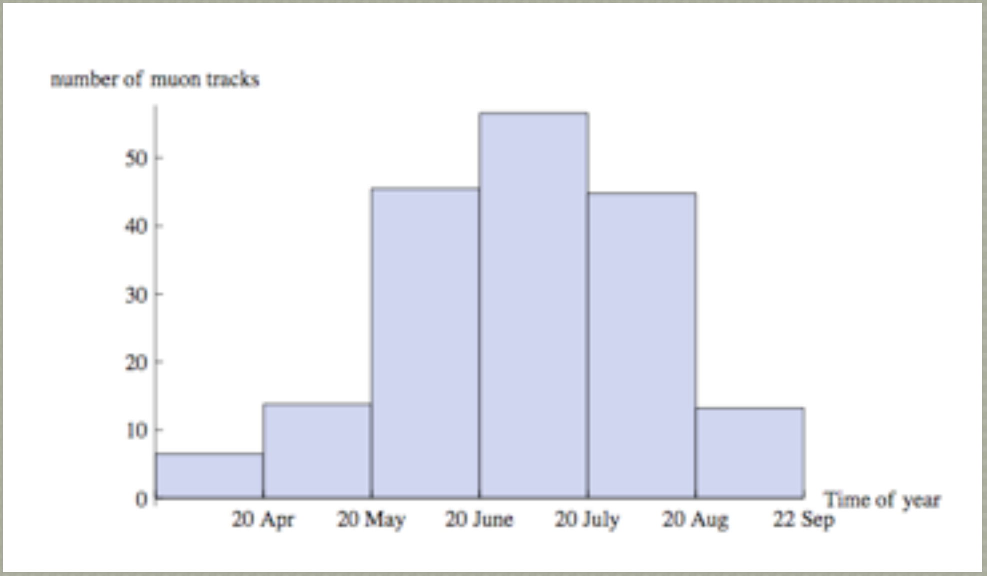
Backgrounds:

- Through-going events: ~ 6/year
- DeepCore events: ~ 3/year

$DM+DM \rightarrow \nu_e \bar{\nu}_e$

$\theta_{13} = 0$

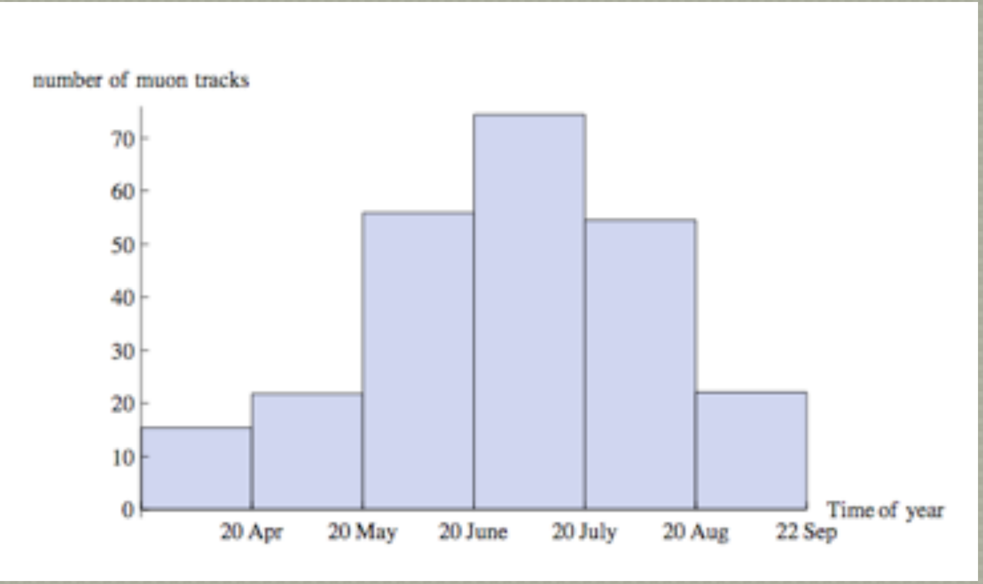
$m_{DM} = 270$ GeV



$DM+DM \rightarrow \nu_e \bar{\nu}_e$

$\theta_{13} = 7^\circ$

$m_{DM} = 270$ GeV



One more observable in the IceCube

$$R \equiv \frac{\text{Number of } \mu\text{-track events}}{\text{Number of shower-like events}}$$

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- Muon-track events

  - CC interaction of ν_μ

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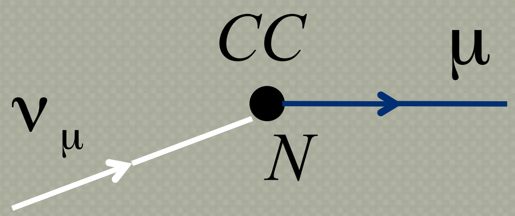
Muon-track events

- CC interaction of ν_μ

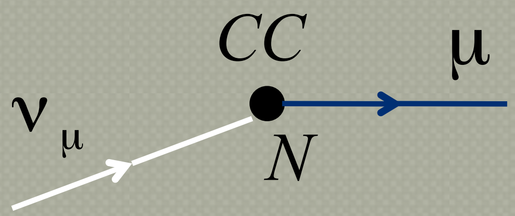


- CC interaction of ν_τ

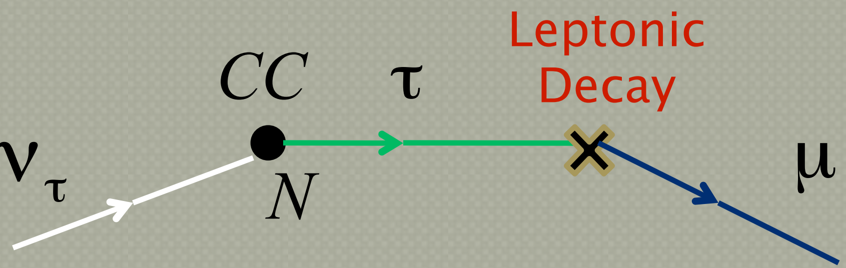
One more observable in the IceCube

$$R \equiv \frac{\text{Number of } \mu\text{-track events}}{\text{Number of shower-like events}}$$

- Muon-track events
  - CC interaction of ν_μ



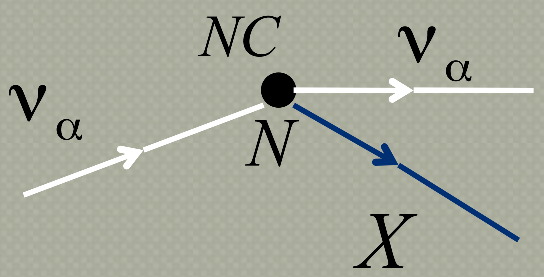
  - CC interaction of ν_τ



- Shower-like events

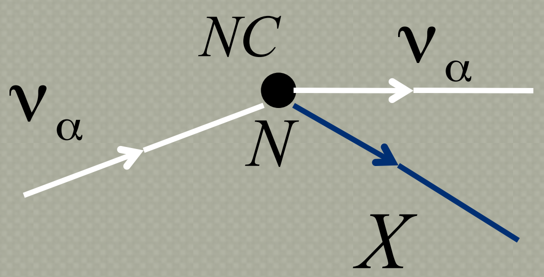
Shower-like events

- NC interaction of ν_α

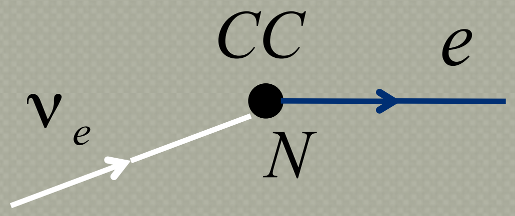


Shower-like events

- NC interaction of ν_α

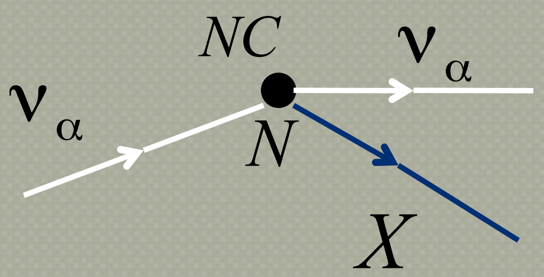


- CC interaction of ν_e

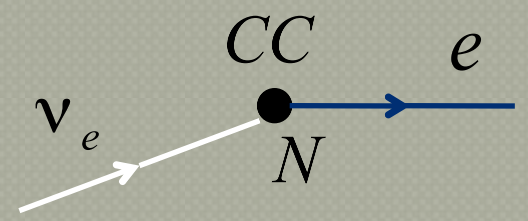


Shower-like events

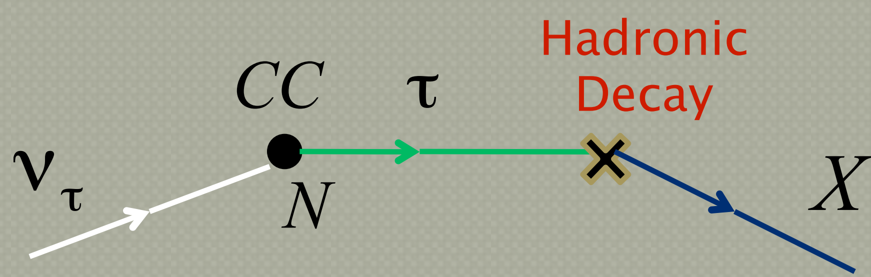
- NC interaction of ν_α



- CC interaction of ν_e



- CC interaction of ν_τ



$$\Delta_{20\mathrm{Mar}} \equiv \Delta(20\ \mathrm{Mar}, 186\ \mathrm{days}, 23\ \mathrm{Sep}, 179\ \mathrm{days})$$

$$\Delta_{3\mathrm{Apr}} \equiv \Delta(3\ \mathrm{Apr}, 186\ \mathrm{days}, 6\ \mathrm{Oct}, 179\ \mathrm{days})$$

DM + DM → $\nu_e \nu_e$

m_{DM}	N/I	θ_{13}	δ	R^{IC}	R^{DC}	$\Delta^{\mathrm{IC}}_{20\mathrm{Mar}}$	$\Delta^{\mathrm{IC}}_{3\mathrm{Apr}}$	$\Delta^{\mathrm{DC}}_{20\mathrm{Mar}}$	$\Delta^{\mathrm{DC}}_{3\mathrm{Apr}}$
197	N	0	0	0.4	14	0.7	0.7	0.7	0.7
197	I	0	0	0.4	14	0.7	0.7	0.7	0.7
197	N	7°	0	0.5	18	0.5	0.6	0.6	0.6
197	I	7°	0	0.6	20	0.6	0.6	0.6	0.6
197	N	7°	$\pi/2$	0.5	18	0.5	0.5	0.5	0.5
197	I	7°	$\pi/2$	0.6	19	0.5	0.5	0.5	0.5
197	N	7°	π	0.4	14	0.6	0.6	0.6	0.6
197	I	7°	π	0.5	16	0.4	0.5	0.4	0.5
200	N	0	0	0.5	15	0.5	0.5	0.5	0.5
200	I	0	0	0.5	15	0.5	0.5	0.5	0.5
200	N	7°	0	0.6	19	0.4	0.5	0.4	0.4
200	I	7°	0	0.7	22	0.4	0.4	0.3	0.4
200	N	7°	$\pi/2$	0.6	17	0.4	0.5	0.4	0.4
200	I	7°	$\pi/2$	0.7	19	0.4	0.4	0.4	0.4
200	N	7°	π	0.5	14	0.4	0.4	0.4	0.4
200	I	7°	π	0.5	15	0.4	0.4	0.4	0.4
203	N	0	0	0.5	15	0.1	0.2	0.2	0.2
203	I	0	0	0.5	15	0.1	0.2	0.1	0.2
203	N	7°	0	0.6	19	0.1	0.1	0.2	0.2
203	I	7°	0	0.7	20	0.1	0.1	0.1	0.1
203	N	7°	$\pi/2$	0.6	19	0.0	0.0	0.1	0.1
203	I	7°	$\pi/2$	0.6	19	0.0	0.1	0.1	0.1
203	N	7°	π	0.5	15	0.1	0.1	0.2	0.2
203	I	7°	π	0.6	17	0.1	0.1	0.2	0.2

DM+DM$\rightarrow \nu_\mu \nu_\mu$

m_{DM}	N/I	θ_{13}	δ	R^{IC}	R^{DC}	Δ^{IC}_{20Mar}	Δ^{IC}_{3Apr}	Δ^{DC}_{20Mar}	Δ^{DC}_{3Apr}
197	N	0	0	1.0	47	0.1	0.1	0.0	0.1
197	I	0	0	1.0	48	0.1	0.1	0.0	0.1
197	N	7°	0	0.9	42	0.1	0.1	0.1	0.1
197	I	7°	0	0.9	42	0.1	0.1	0.1	0.1
197	N	7°	$\pi/2$	0.9	44	0.1	0.1	0.1	0.1
197	I	7°	$\pi/2$	1.0	48	0.0	0.0	0.0	0.0
197	N	7°	π	1.0	51	0.0	0.0	0.0	0.0
197	I	7°	π	1.0	50	0.0	0.0	0.0	0.0
200	N	0	0	1.0	49	0.1	0.1	0.1	0.1
200	I	0	0	1.0	47	0.1	0.1	0.0	0.0
200	N	7°	0	0.9	43	0.1	0.1	0.05	0.05
200	I	7°	0	0.8	41	0.1	0.2	0.1	0.1
200	N	7°	$\pi/2$	0.9	46	0.1	0.1	0.1	0.1
200	I	7°	$\pi/2$	1.0	48	0.1	0.1	0.0	0.0
200	N	7°	π	1.0	52	0.1	0.1	0.1	0.1
200	I	7°	π	1.0	50	0.0	0.0	0.0	0.0
203	N	0	0	1.0	50	0.0	0.0	0.0	0.0
203	I	0	0	1.1	52	0.0	0.0	0.0	0.0
203	N	7°	0	0.9	45	0.1	0.1	0.0	0.1
203	I	7°	0	1.0	46	0.1	0.1	0.1	0.1
203	N	7°	$\pi/2$	1.0	47	0.0	0.0	0.0	0.0
203	I	7°	$\pi/2$	1.1	52	0.0	0.0	0.0	0.0
203	N	7°	π	1.1	54	0.0	0.0	0.0	0.0
203	I	7°	π	1.0	52	0.1	0.1	0.0	0.0

Summary

- In neutrino telescopes such as ICECUBE, the direction of muon-track can be reconstructed by amazing precision of 1 degree which means neutrinos from the Sun can be singled out.

- Measurement of the spectrum of neutrinos is going to be challenging

- Thus, two situations can be considered
  - ❖ Spectrum can be reconstructed
  - ❖ Spectrum cannot be reconstructed

❖ If spectrum cannot be reconstructed

$\Delta \neq 0$ → A sharp feature should be present in the spectrum of neutrinos

❖ If spectrum can be reconstructed

If the spectrum contains a sharp line, generally we expect Δ to be nonzero

If a sharp line is observed in the spectrum but $\Delta = 0$ → $F^0_{\nu_e} = F^0_{\nu_\mu} = F^0_{\nu_\tau}$

Seasonal Variation

$$\frac{dN_\mu(t)}{dt} = \int \frac{F^0_{\nu_\alpha} w P_{\alpha\mu}(t)(\sigma^{CC}_{\nu_\mu p}\rho_p + \sigma^{CC}_{\nu_\mu n}\rho_n) R_\mu A_{eff}(\theta[t])}{[L(t)]^2}\, dV + \int \frac{F^0_{\bar\nu_\alpha} \bar w P_{\bar\alpha\bar\mu}(t)(\sigma^{CC}_{\bar\nu_\mu p}\rho_p + \sigma^{CC}_{\bar\nu_\mu n}\rho_n) R_\mu A_{eff}(\theta[t])}{[L(t)]^2}\, dV$$

$$i\frac{d|\nu_\gamma\rangle}{dt} = [\frac{m_\nu^\dagger \cdot m_\nu}{2p} + \mathrm{diag}(V_e, 0, 0)]_{\gamma\sigma}|\nu_\sigma\rangle$$

$$i\frac{d|\bar\nu_\gamma\rangle}{dt} = [\frac{m_\nu^T \cdot m_\nu^*}{2p} - \mathrm{diag}(V_e, 0, 0)]_{\gamma\sigma}|\bar\nu_\sigma\rangle$$

$$V_e = \sqrt{2} G_F N_e.$$