Indirect Dark Matter Detection in the Light of Sterile Neutrinos

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In collaboration with O. L. G. Peres

Outline:

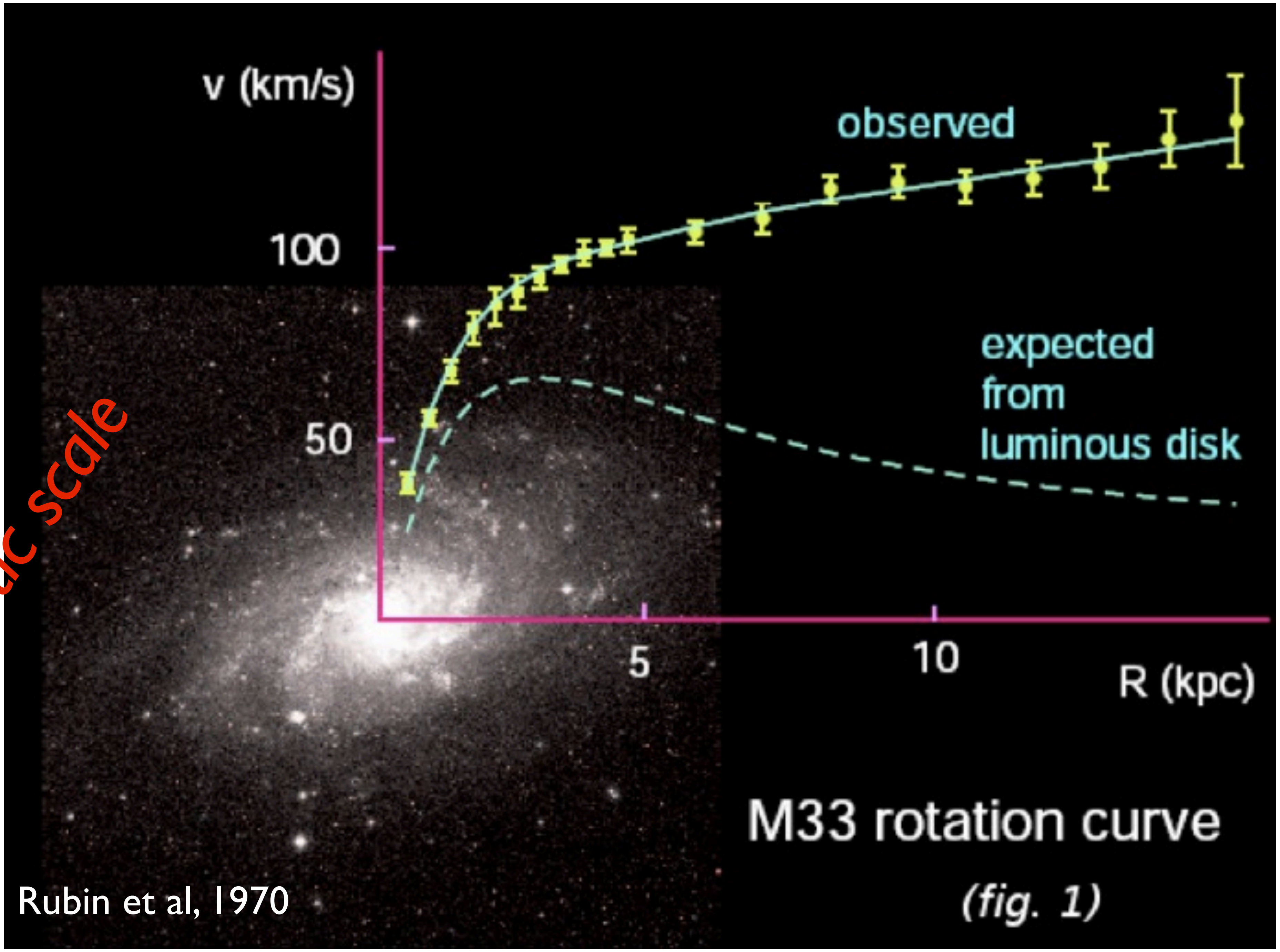
- ✓ A brief introduction to DM
- ✓ Strategies to detect DM
- ✓ Capturing inside the Sun
- ✓ Indirect Detection in the presence of sterile neutrino
- ✓ The case of monochromatic neutrinos

A brief introduction to DM

DM exist!

Evidences of existence are at different scales

Galactic scale



Rubin et al, 1970

A brief introduction to DM

DM exist!

Evidences of existence are at different scales

Cluster of Galaxies

first evidence for the existence of dark matter (postulated by Zwicky in the 1930's)

F. Zwicky, Astrophysical Journal, vol. 86, p.217 (1937)

A brief introduction to DM

DM exist!

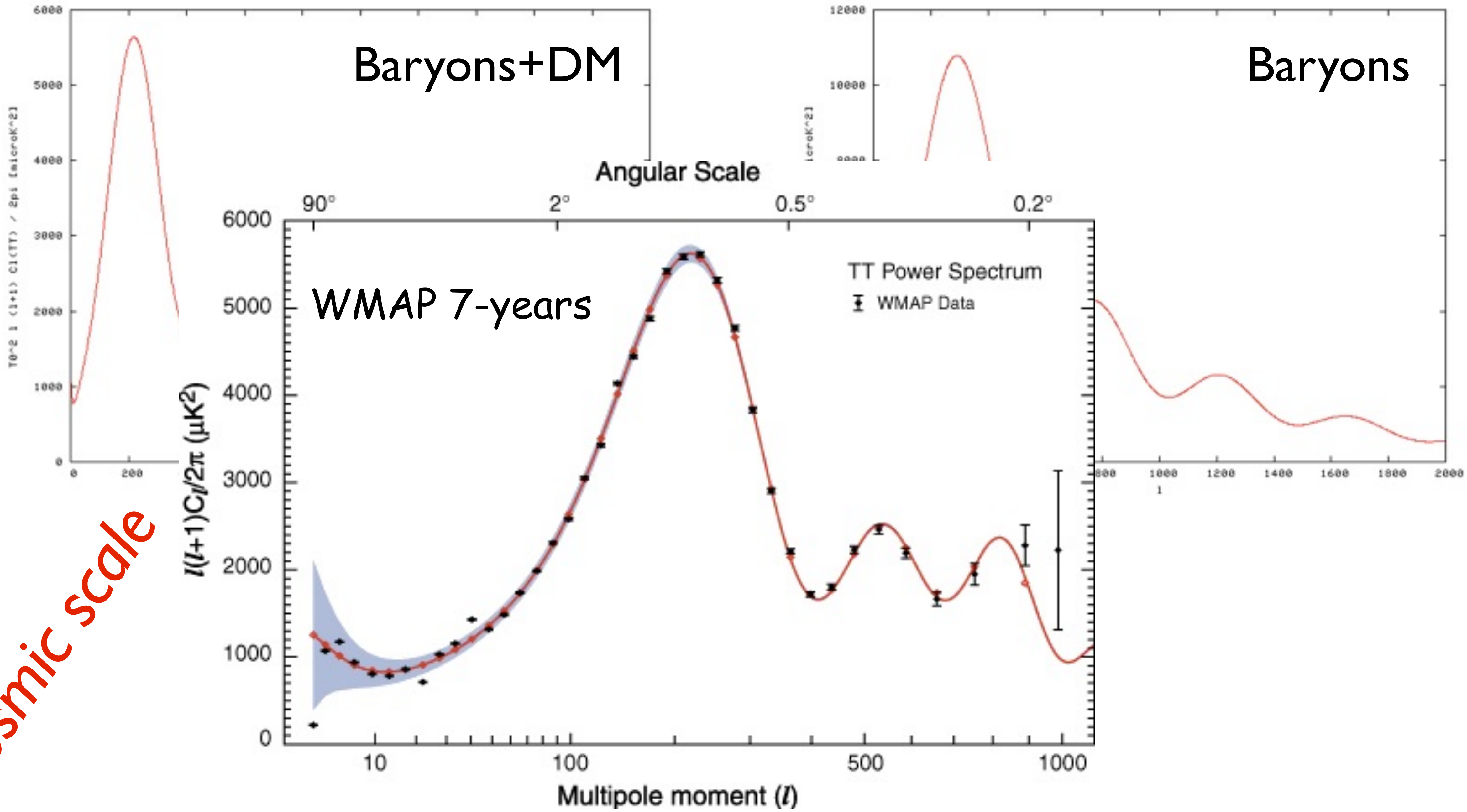
Evidences of existence are at different scales

Bradac et al (2006)

A brief introduction to DM

DM exist!

Evidences of existence are at different scales



Cosmic scale

A brief introduction to DM

DM exist!

Evidences of existence are at different scales

Various Scales

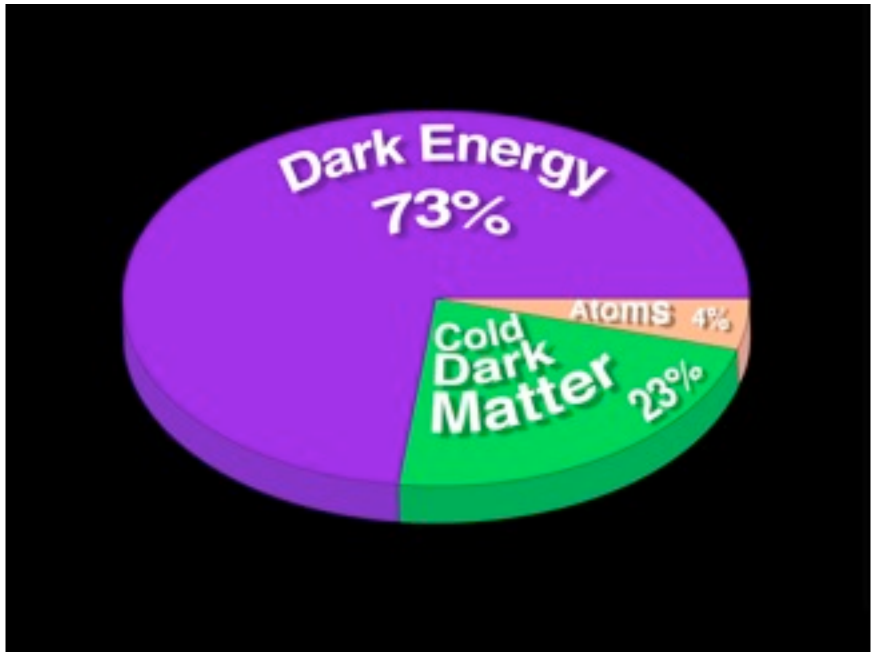
BBN

LSS

SN1a

Lensing

Present day Cosmic Pie



A brief introduction to DM

DM exist!

What We Know?

- ✓ Non Baryonic
- ✓ No Charge
- ✓ Cold (or perhaps warm)
- ✓ Long lived (not necessarily stable)

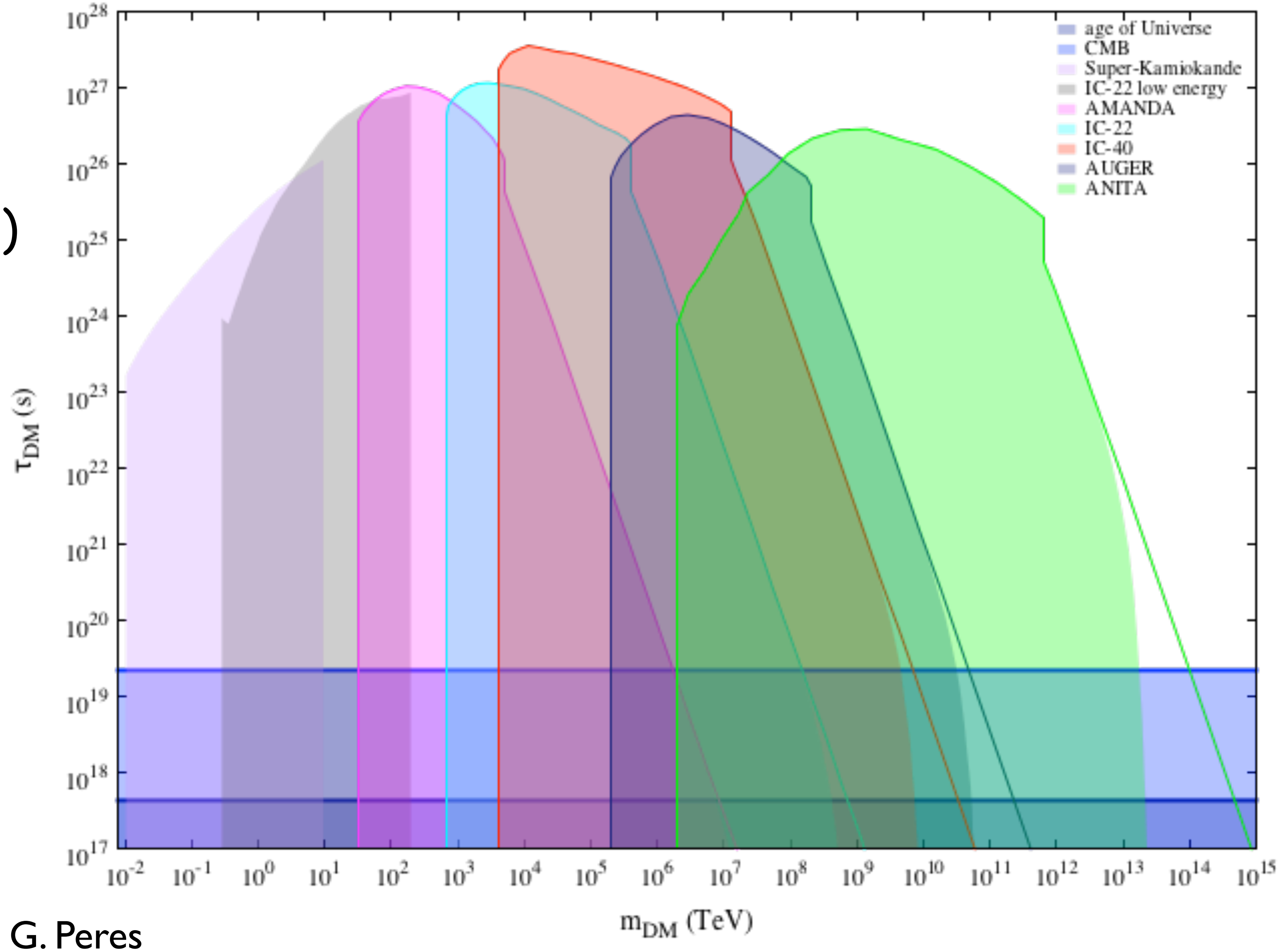
Lower limit on DM lifetime

$$\mathrm{DM} \rightarrow \nu\bar{\nu}$$

(galactic and extra-galactic)

Using AMANDA, IceCube, Auger and ANITA data

90 % C. L.



A.E., Alejandro Ibarra and Orlando L. G. Peres
arXiv: 1205.5281

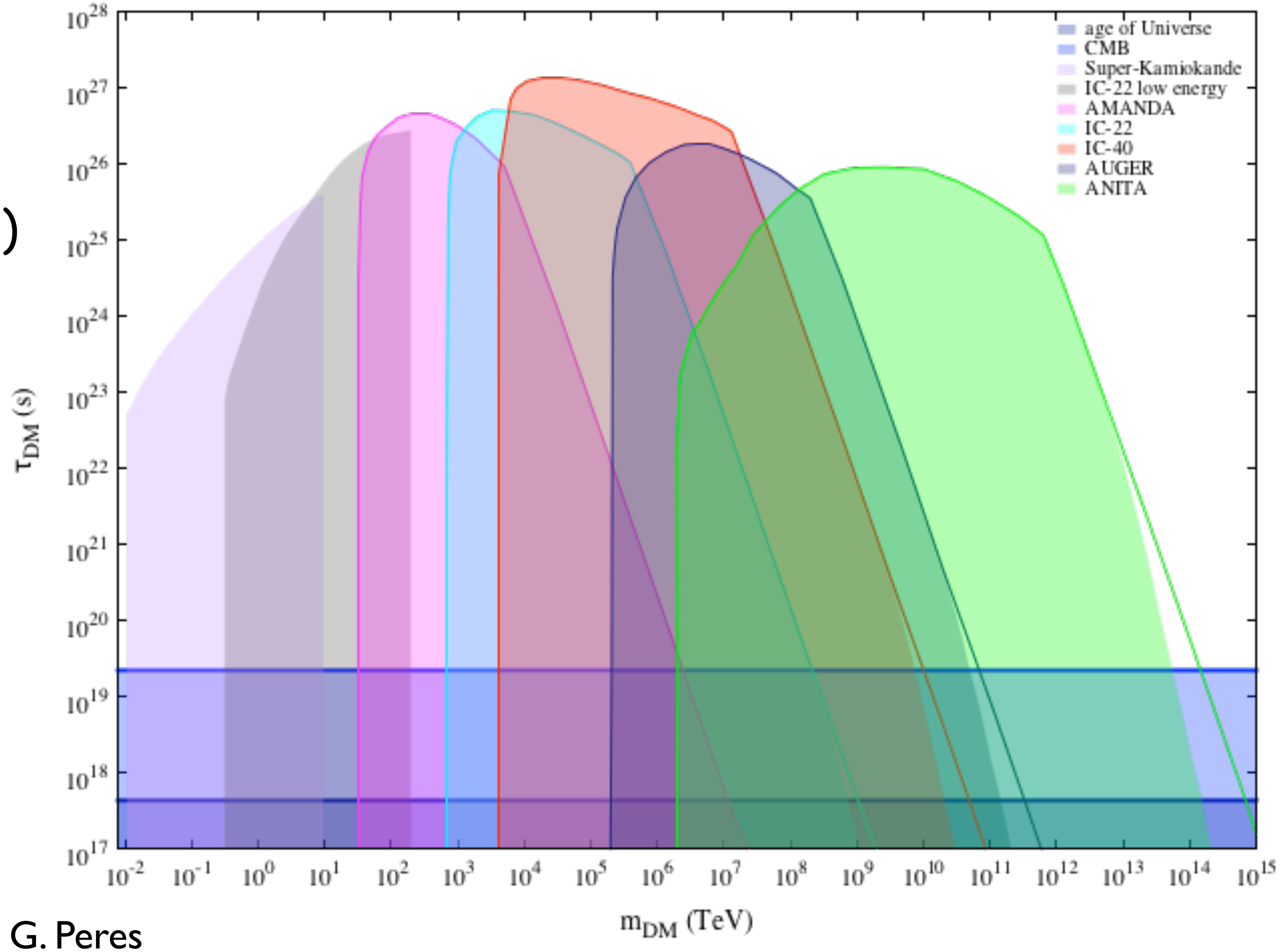
Lower limit on DM lifetime

90 % C. L.

$$\mathrm{DM} \to e^- e^+ \nu(\bar{\nu})$$

(galactic and extra-galactic)

Using AMANDA, IceCube, Auger and ANITA data



A.E., Alejandro Ibarra and Orlando L. G. Peres
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A brief introduction to DM

DM exist!

What We Know?

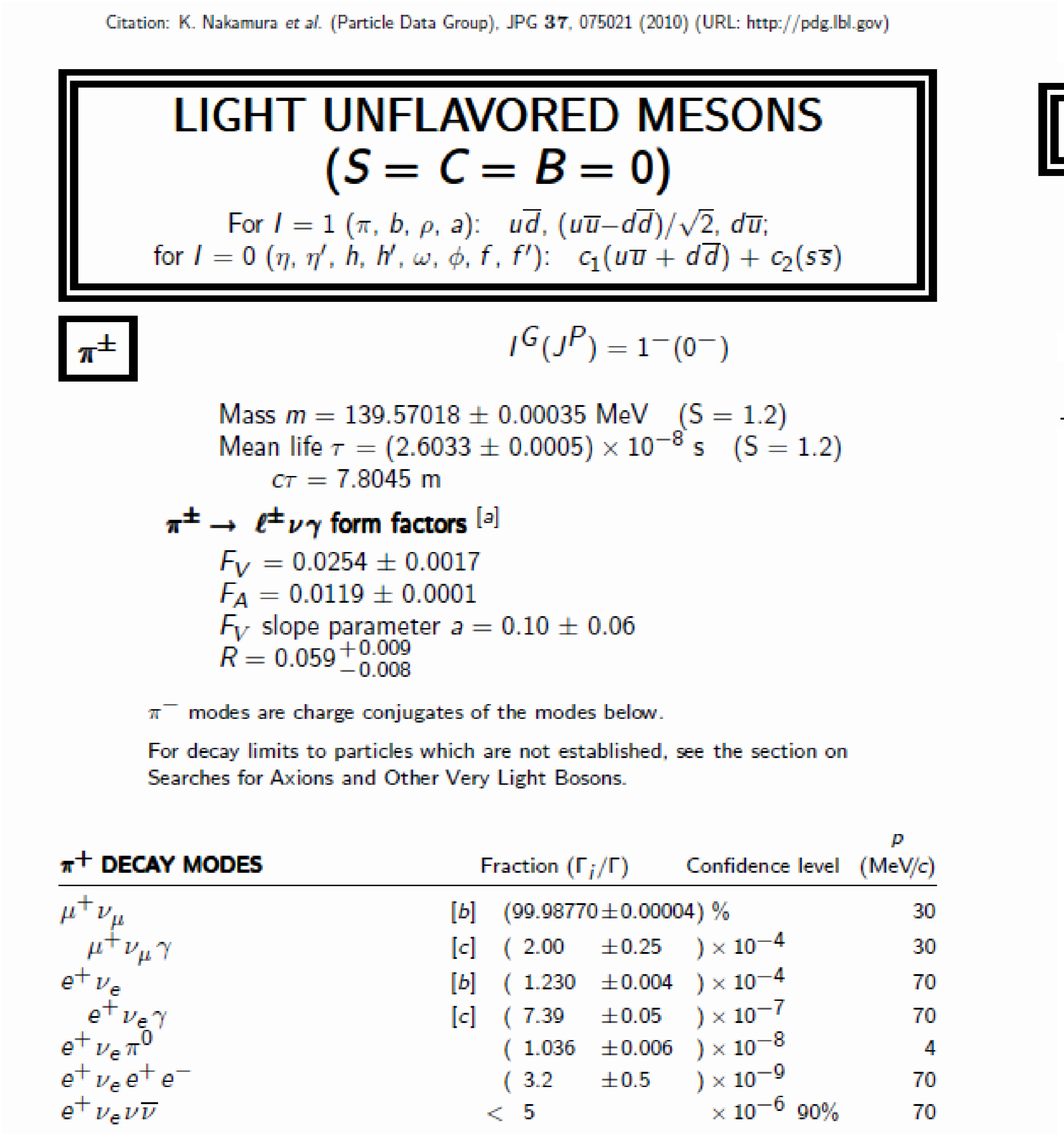
- ✓ Non Baryonic
- ✓ No Charge
- ✓ Cold (or perhaps warm)
- ✓ Long lived (not necessarily stable)

All of these come from gravitational effects

A brief introduction to DM

DM exist!

What We Know?



Citation: K. Nakamura *et al.* (Particle Data Group), JPG **37**, 075021 (2010) (URL: http://pdg.lbl.gov)

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u} - d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ $(\eta, \eta', h, h', \omega, \phi, f, f')$: $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

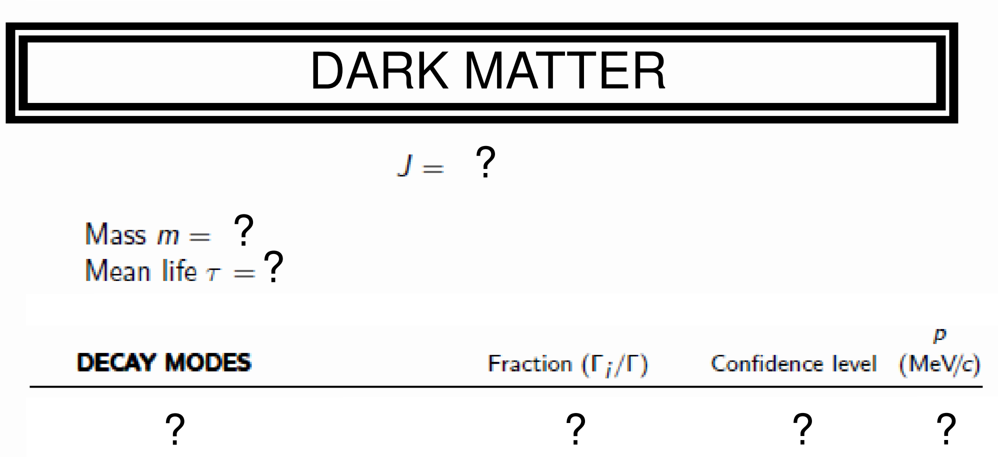
$\pi^{\pm} \rightarrow \ell^{\pm} \nu \gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+ \nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+ \nu_\mu \gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+ \nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+ \nu_e \gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+ \nu_e \pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+ \nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+ \nu_e \nu \overline{\nu}$		$< 5 \times 10^{-6}$	90%	70



DARK MATTER

$J =$?

Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
?	?	?	?

Still no (reliable) indications of dark matter particle nature

Slide from A. Ibarra

A brief introduction to DM

No SM candidate!

The Dark Matter Candidates 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

?

WIMPs (Weakly Interacting Massive Particles)

$$T > m_\chi \qquad \chi\bar{\chi} \rightleftarrows f\bar{f}$$

$$T < m_\chi \qquad \chi\bar{\chi} \to f\bar{f}$$

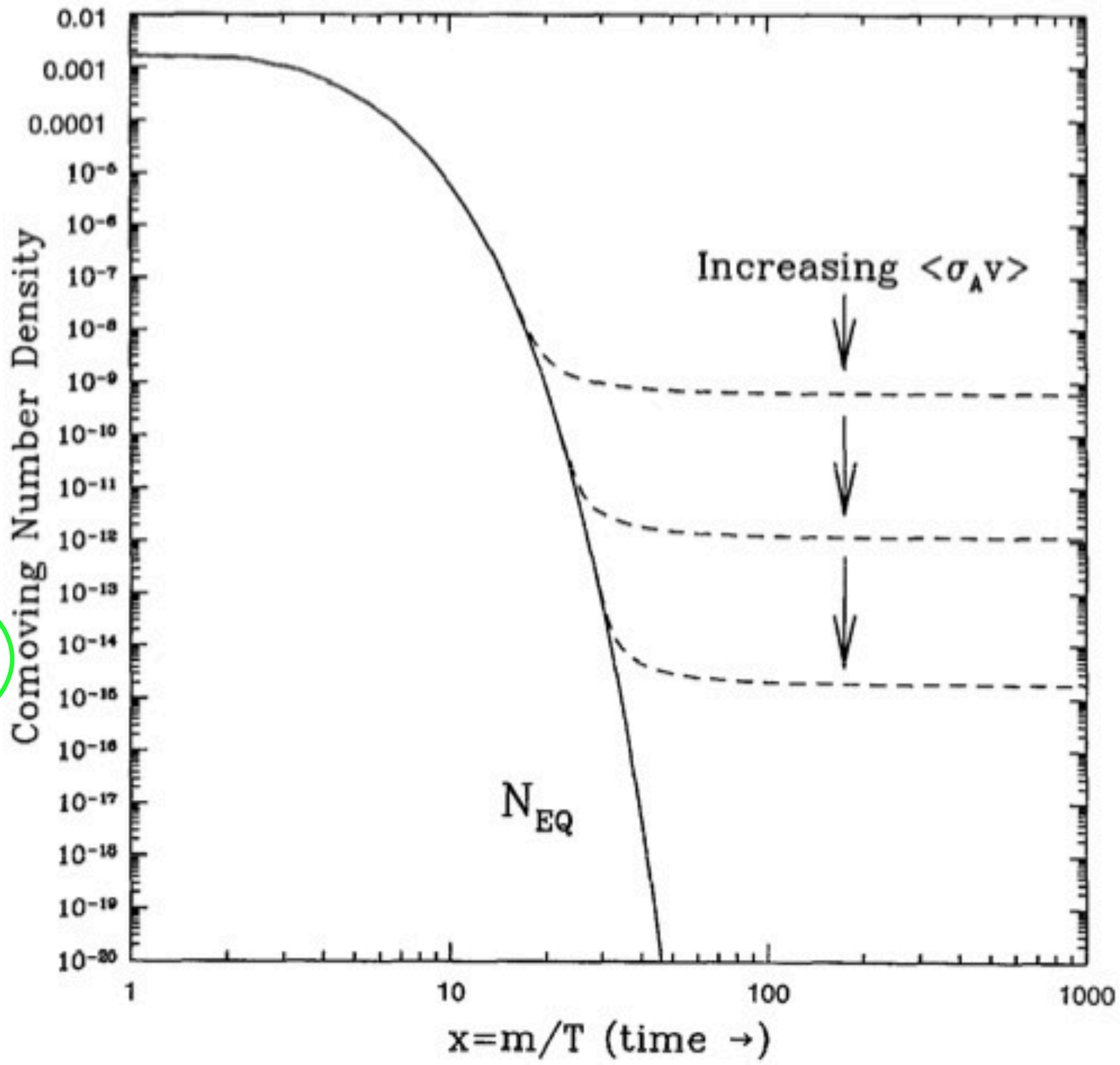
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\chi\bar{\chi}|v|}\rangle(n_\chi^2 - n_{\chi,\mathrm{eq}}^2)$$

$$\Omega_\chi h^2 \approx 0.1\left(\frac{x_{FO}}{20}\right)\left(\frac{g_*}{80}\right)^{-1/2}\left(\frac{a+3b/x_{FO}}{3\times10^{-26}\mathrm{cm}^3/\mathrm{s}}\right)^{-1}$$

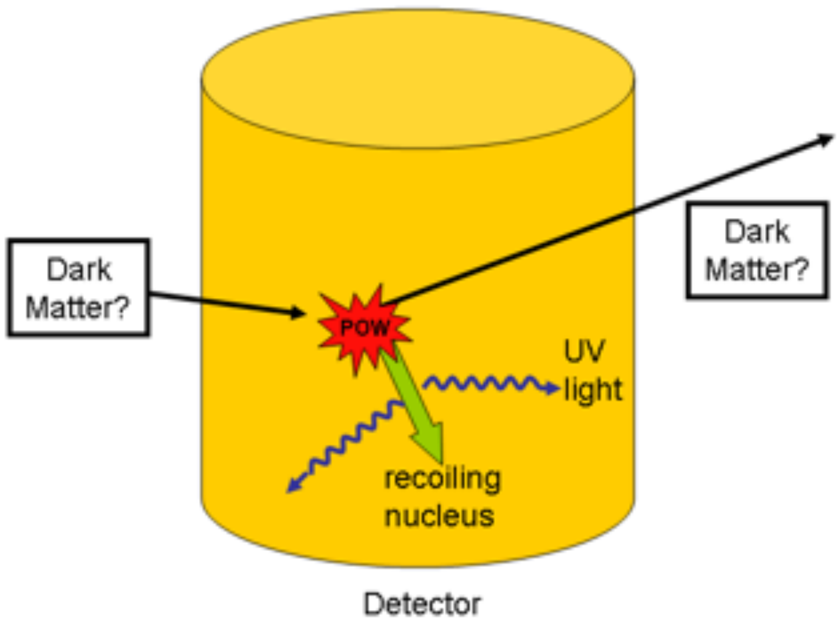
WIMP Miracle

$$\sigma \sim \frac{\alpha^2}{(100\,\mathrm{GeV})^2} \sim \sigma \sim \mathrm{pb}$$

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

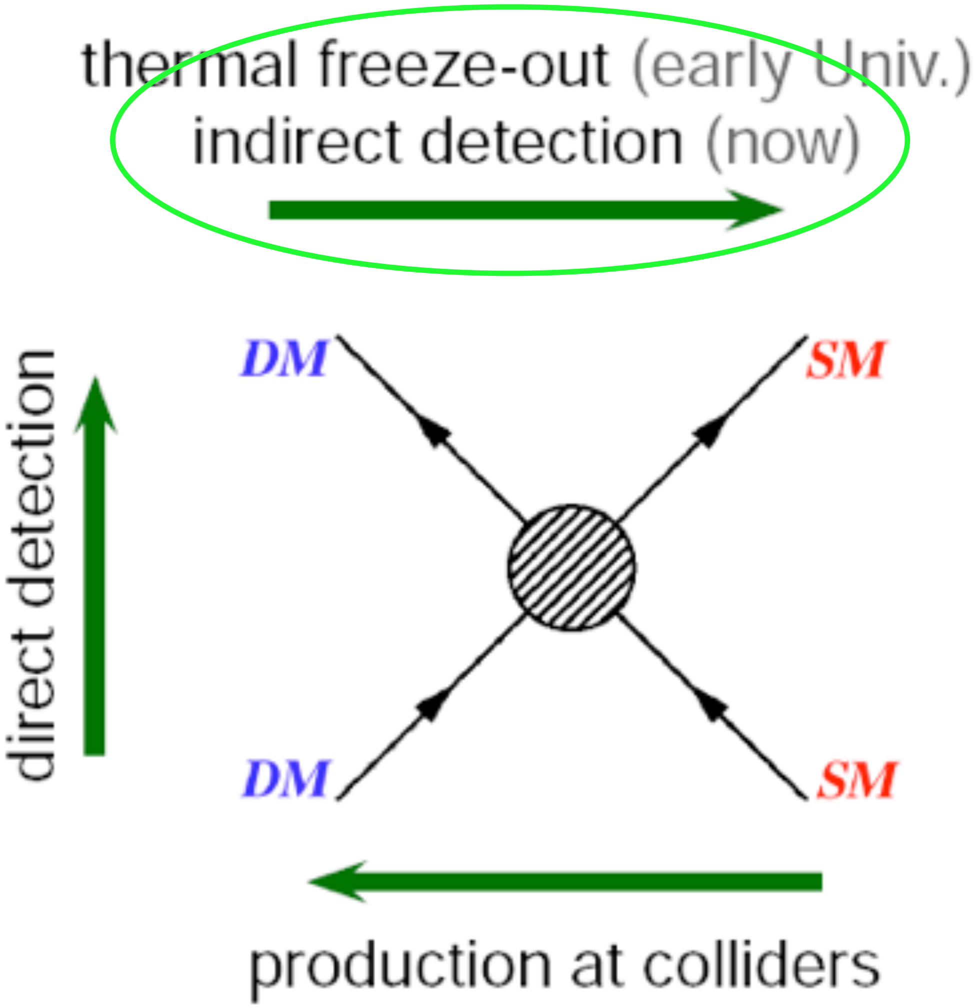


Strategies to detect DM



$$E_{\mathrm{recoil}} \sim 10\,\mathrm{keV}$$

XENON100, DAMA/LIBRA, CRESST,
EDELWEISS, CDMS, CoGeNT, ...

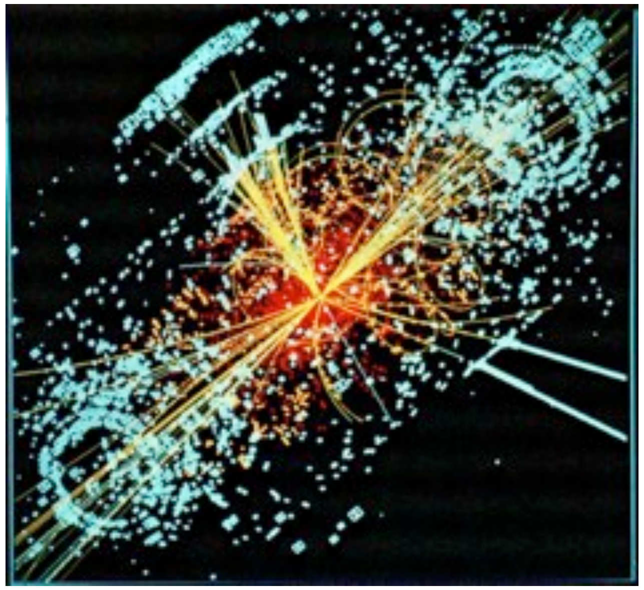


thermal freeze-out (early Univ.)
indirect detection (now)

direct detection

production at colliders

Missing Energy



LHC,
Tevatron, ...

Strategies to detect DM

DM-nuclei scattering effective Lagrangian

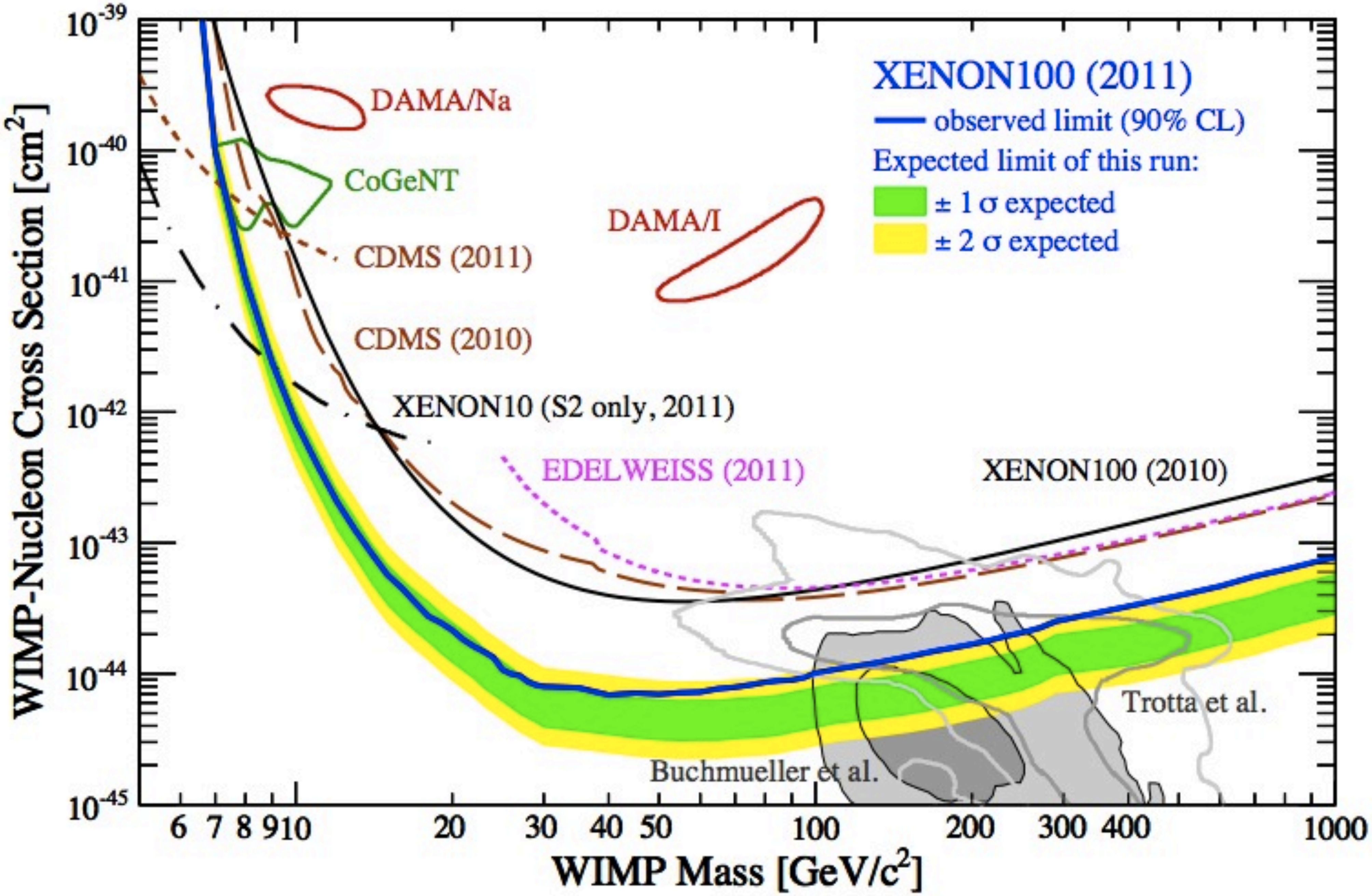
$$\mathcal{L} = \underbrace{\lambda_{\rm SI}\,(\bar{\chi}\chi)(\bar{q}q)} + \underbrace{\lambda_{\rm SD}\,(\bar{\chi}\gamma^5\gamma^\mu\chi)(\bar{q}\gamma^5\gamma_\mu q)}$$

Spin
Independent

Spin
Dependent

Strategies to detect DM

Spin Independent



Phys.Rev.Lett. 107 (2011)

Strategies to detect DM

Indirect Detection

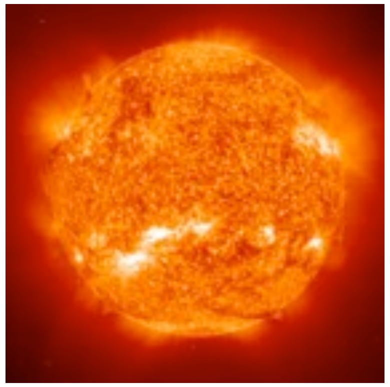
Annihilation $\chi\bar{\chi} \to q\bar{q}\,, W^+W^-\,, ZZ\,, \gamma\gamma\,, \ell\bar{\ell}\,, \nu\bar{\nu}, \ldots$

Decay $\chi \to \gamma X\,, \ell X\,, \nu X, \ell\bar{\ell}\nu\,, \ldots$

Where to look?

$\Gamma_{\rm ann} \propto n_\chi^2$

$\Gamma_{\rm dec} \propto n_\chi$



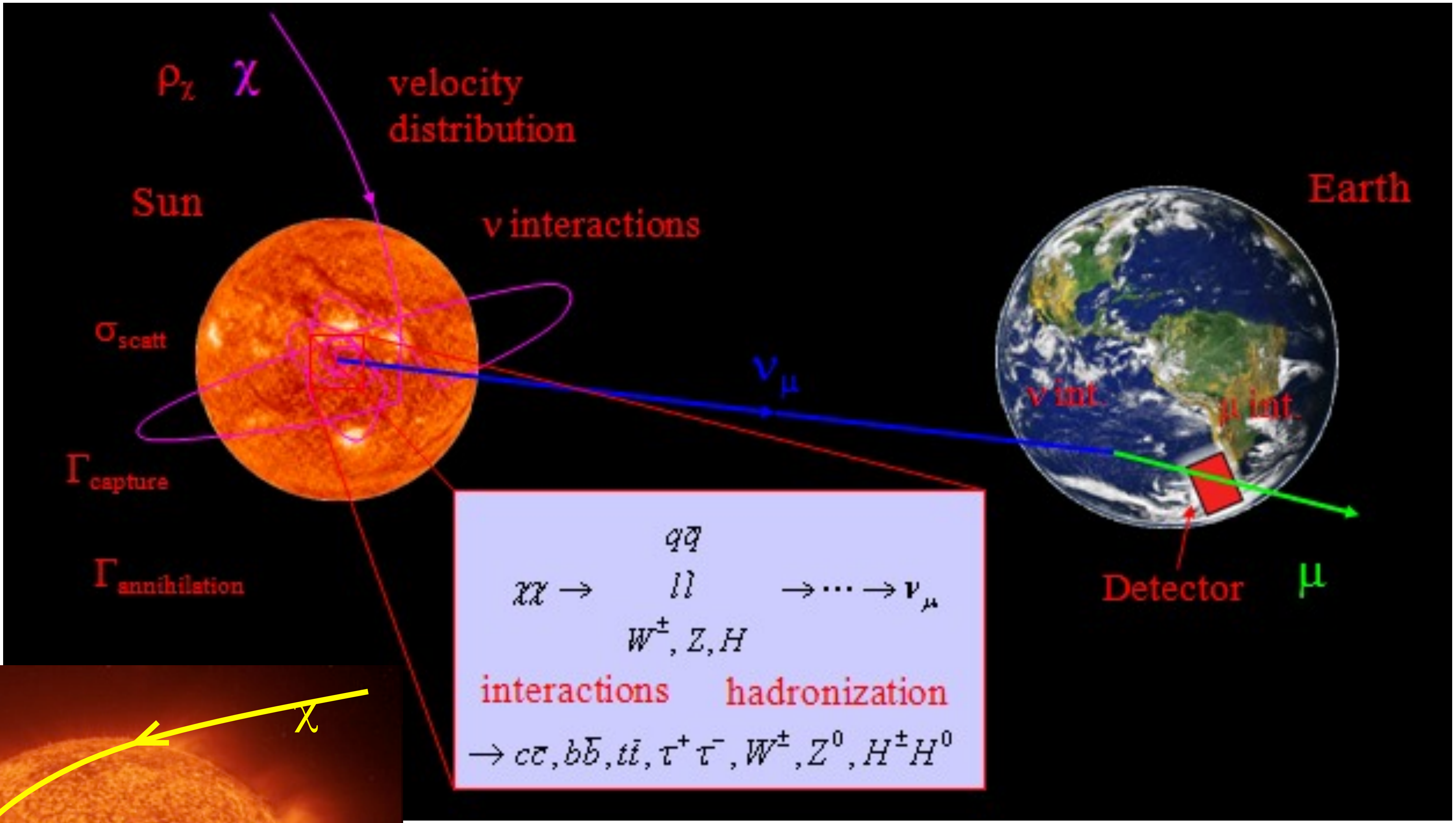
center of galaxy
astrophysical objects

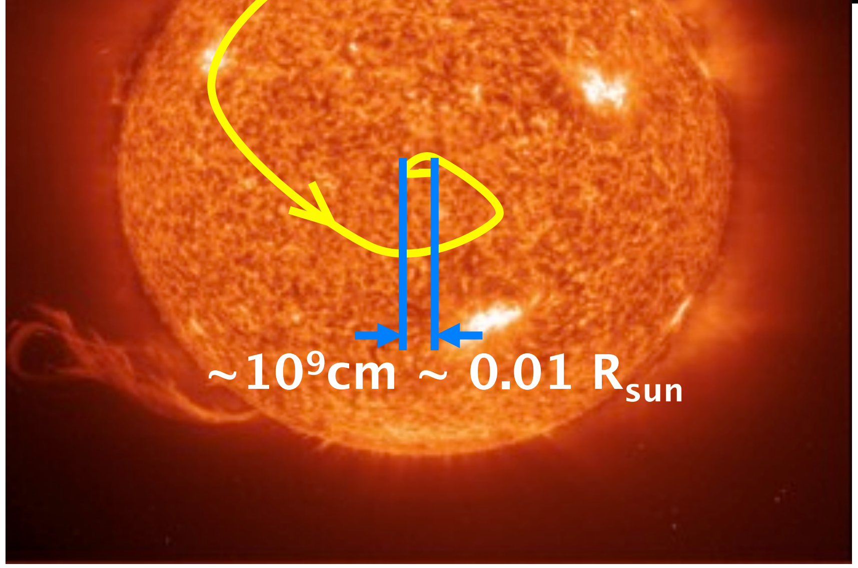
halo, diffuse flux

Which experiment?

EGRET, HESS, PAMELA, ATIC, FERMI-LAT, IceCube, HEAT, CAPRICE, ...

Capturing inside the Sun





DM elastically scatter from a nucleus inside the Sun. If the velocity drops below the escape velocity, DM will be captured.

Capturing inside the Sun

K. Griest and D. Seckel, Nucl. Phys. B 283 (1987)

A. Gould, Astrophys. J. 321 (1987)

W.H. Press and D.N. Spergel, Astrophys. J. 296 (1985)

A. Gould, Astrophys. J. 388 (1991)

Evolution eq.

$$\frac{dN}{dt} = C^{\odot} - C_A N^2$$

capture rate

2 × annihilation rate Γ_A

$$\boxed{C_A = \frac{\langle \sigma_{\rm ann} v \rangle V_2}{V_1^2}}$$

Solution:

$$\Gamma_A = \frac{1}{2} C_A N^2 = \frac{1}{2} C^{\odot} \tanh^2 \left(\frac{t}{\tau_{\rm eq}} \right)$$

time sale of equilibrium

$$\tau_{\rm eq} = \frac{1}{\sqrt{C^{\odot} C_A}}$$

$$t \gg \tau_{\rm eq} \quad \longrightarrow \quad \Gamma_A = \frac{1}{2} C^{\odot}$$

satisfied for the Sun

$$C^{\odot} \approx 3.35 \times 10^{20}\,{\rm s}^{-1} \left(\frac{\rho_{\rm local}}{0.3\,{\rm GeV/cm^3}} \right) \left(\frac{270\,{\rm km/s}}{\bar{v}_{\rm local}} \right)^3 \left(\frac{100\,{\rm GeV}}{m_\chi} \right)^2$$

$$\times \left(\frac{\sigma_{\chi {\rm H,SD}} + \sigma_{\chi {\rm H,SI}} + 0.07 \sigma_{\chi {\rm He,SI}} + 0.0005\, S(\frac{m_\chi}{m_{\rm O}}) \sigma_{\chi {\rm O,SI}}}{10^{-6}\,{\rm pb}} \right)$$

Capturing inside the Sun

Signal

horizontal direction at South Pole

(θ_z =90° ± tilt (23.5°))

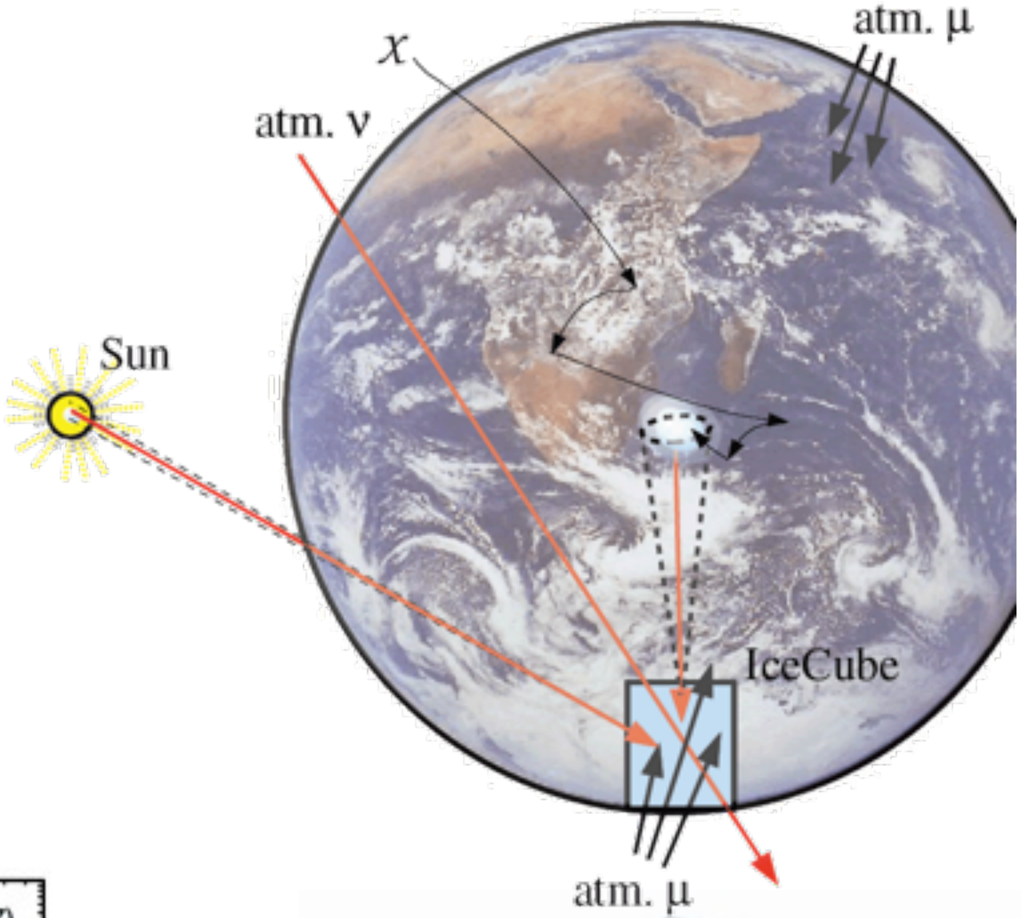
Background

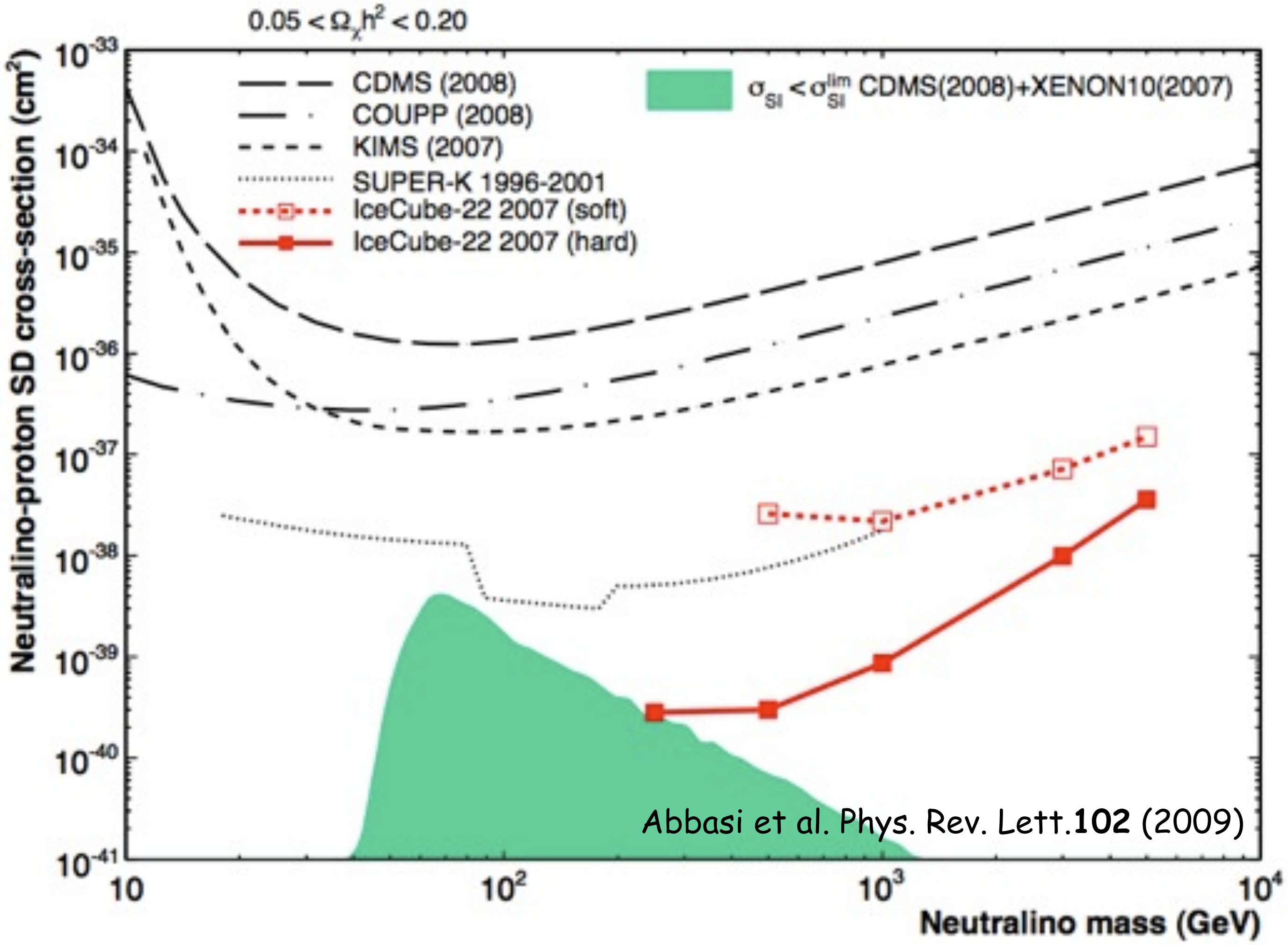
atmospheric muons

~$O(10^9)$ events/year (downward going)

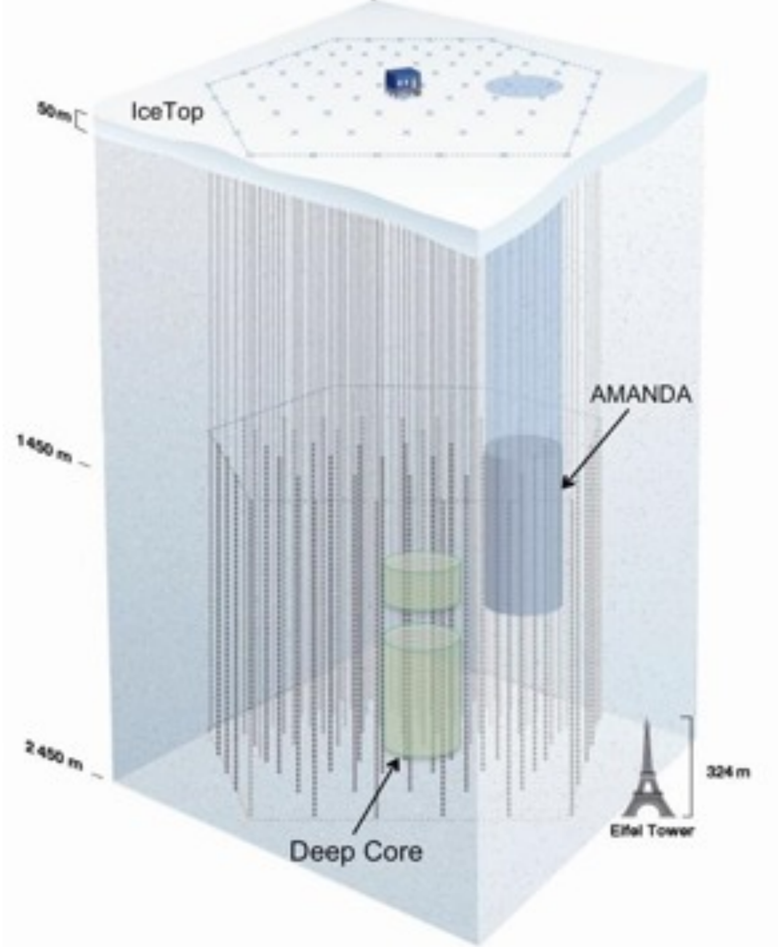
atmospheric neutrinos

~$O(10^3)$ events/year (all directions)



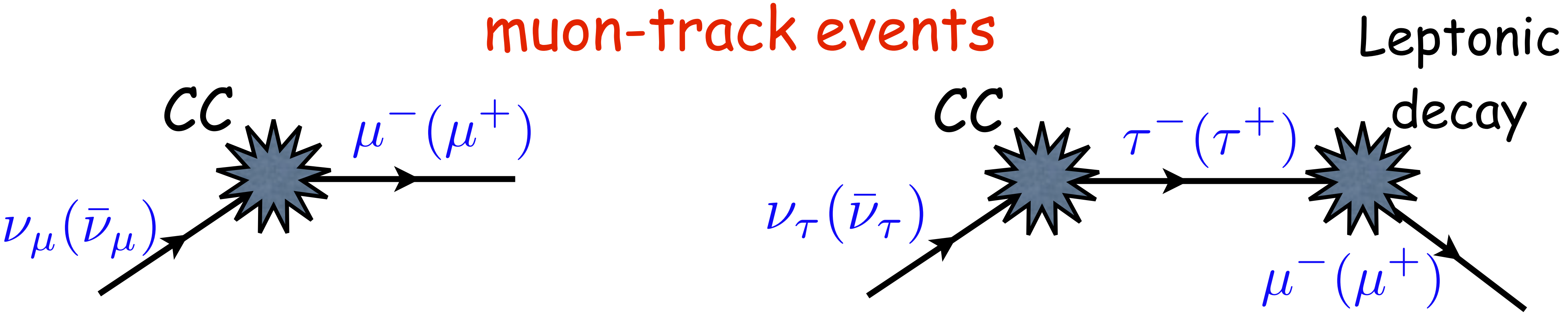


Abbasi et al. Phys. Rev. Lett.**102** (2009)

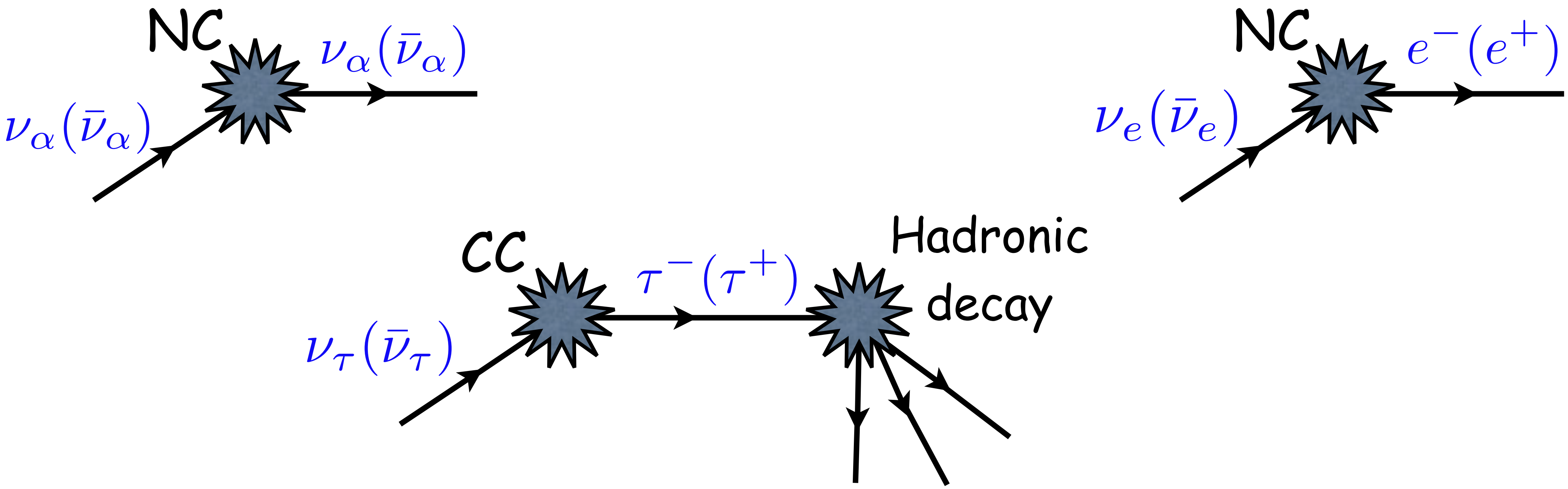


Flavoring at IceCube

muon-track events



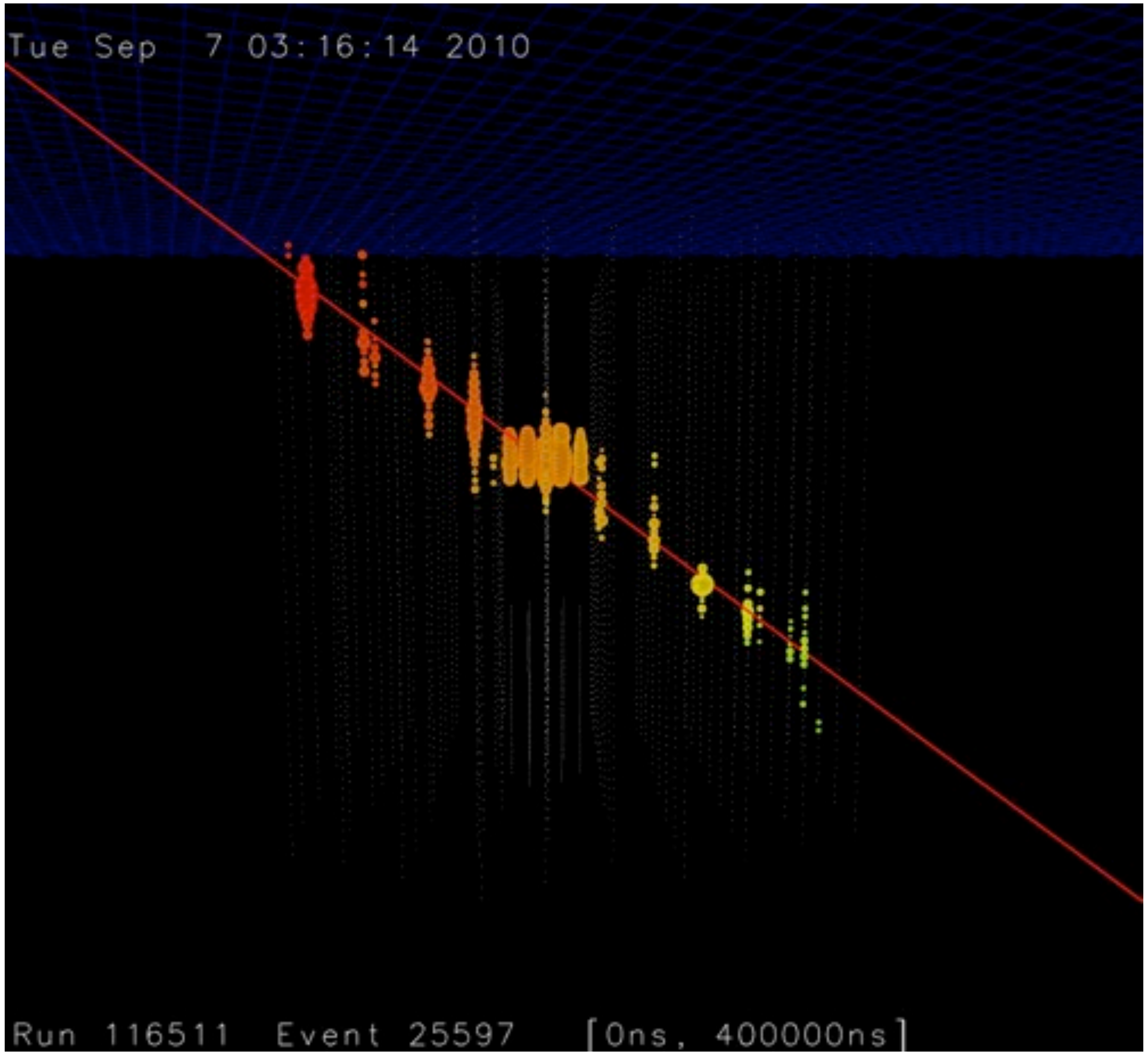
cascade events



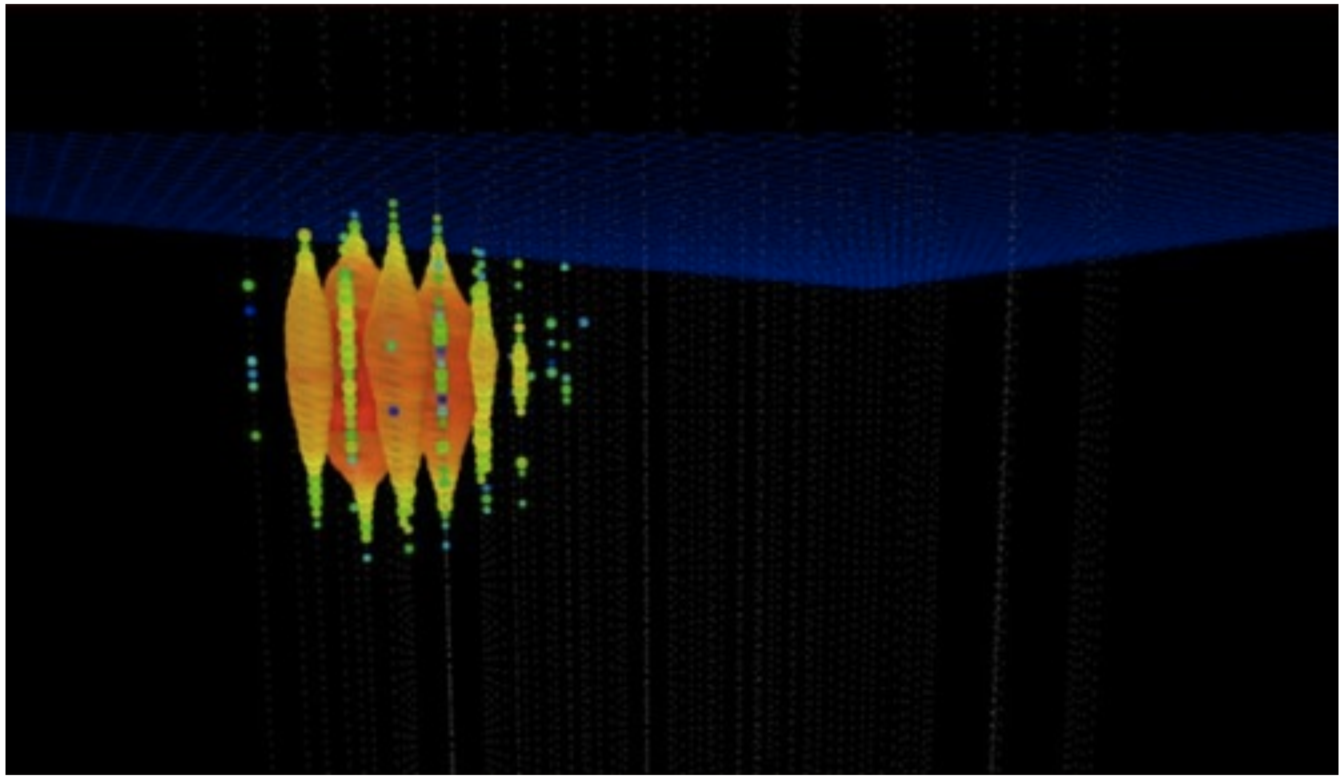
Capturing inside the Sun

Flavoring at IceCube

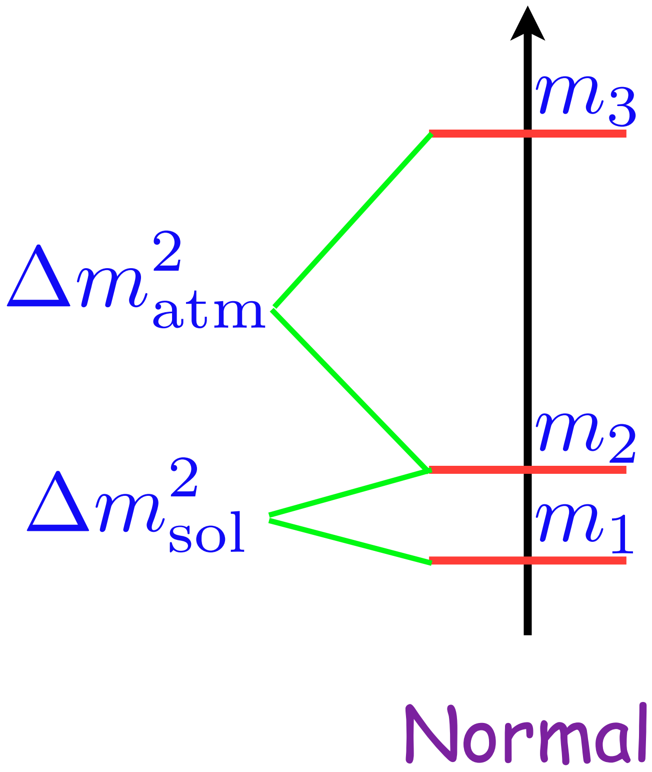
muon-track events



cascade events



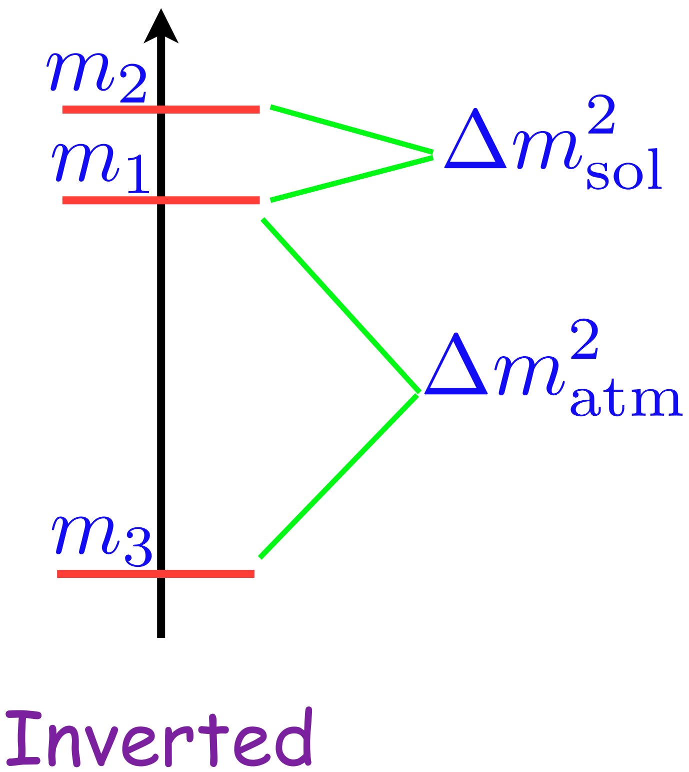
Standard picture of neutrino sector



$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i$$

$$\alpha = e, \mu, \tau$$

$$U_{\rm PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



$$\Delta m^2_{\rm atm} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{31}| \simeq 2 \times 10^{-3}\,{\rm eV}^2$$

$$\Delta m^2_{\rm sol} = \Delta m^2_{21} \simeq 8 \times 10^{-5}\,{\rm eV}^2$$

$$\delta = ?$$

$$\sin^2\theta_{12} = 0.3$$

$$m_1(m_3) = ?$$

$$\sin^2\theta_{23} = 0.5$$

$$\sin^2\theta_{13} = 0.03$$

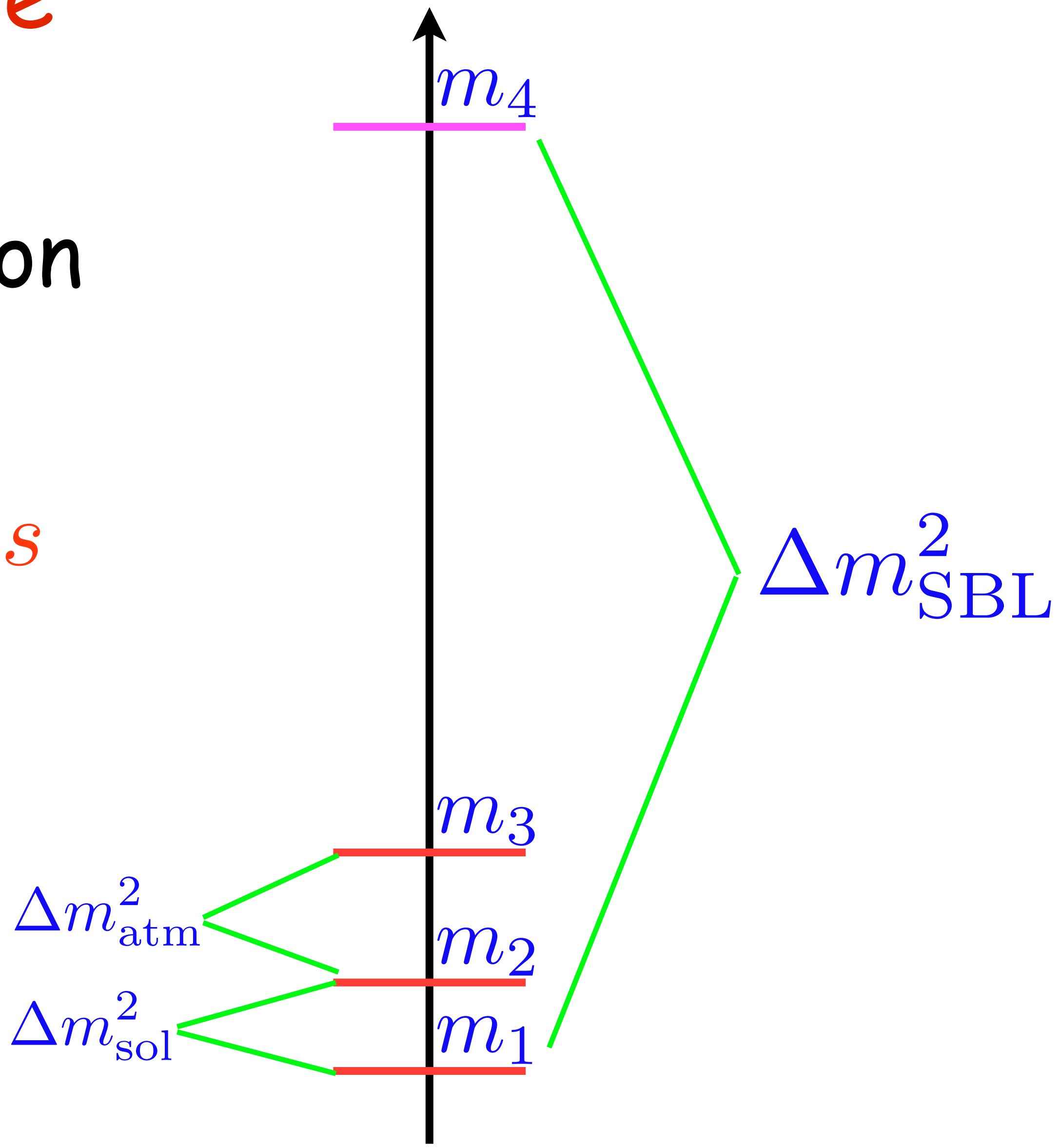
RENO, Daya-Bay, Double CHOOZ

3+1 scheme

Sterile ↔ No SM Interaction

$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\nu_i \qquad \alpha = e, \mu, \tau, s$$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



3+1 scheme

three new mixing angles θ_{14}, θ_{24}, θ_{34} and effectively one new mass-squared difference Δm^2_{14}

Fogli, Lisi and A. Marrone, Phys. Rev. D 63 (2001); O. L. G. Peres and A. Y. Smirnov, Nucl. Phys. B 599 (2001); Grimus and Schwetz, Eur. Phys. J. C 20 (2001); M. C. Gonzalez-Garcia, M. Maltoni and C. Pena-Garay, Phys. Rev. D 64 (2001); M. Maltoni, T. Schwetz and J. W. F. Valle, Phys. Lett. B 518 (2001); A. Strumia, Phys. Lett. B 539 (2002); G. Karagiorgi, Z. Djurcic, J. M. Conrad, M. H. Shaevitz and M. Sorel, Phys. Rev. D 80 (2009); A. Palazzo, Phys. Rev. D 83 (2011); C. Giunti and M. Laveder, Phys. Rev. D 84 (2011)

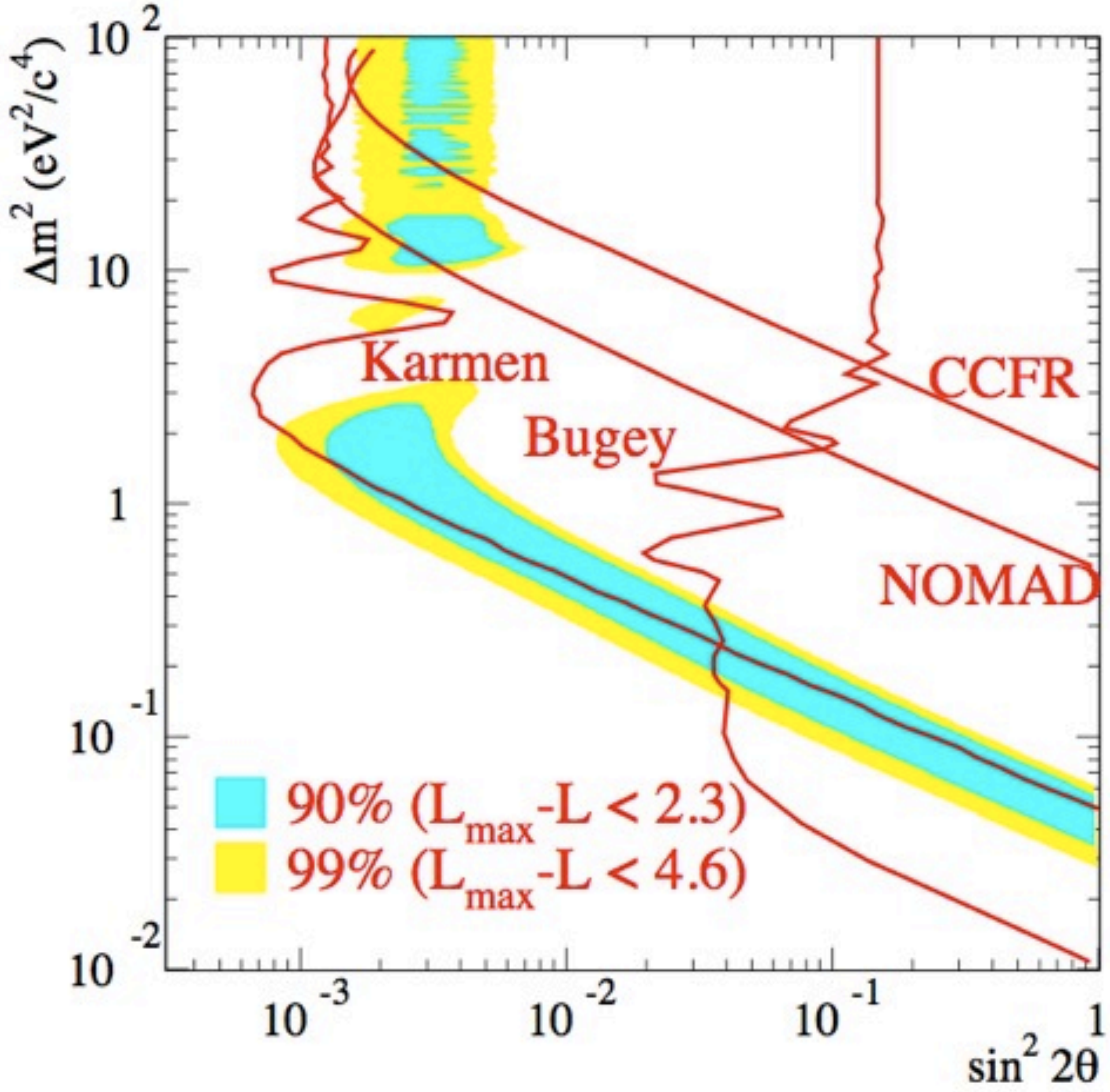
Hints on the presence of sterile neutrino

LSND

PRD 64 (2001) 112007

$$\bar{\nu}_\mu \to \bar{\nu}_e$$

$$L \simeq 30\,\mathrm{m}\,,\ 20\,\mathrm{MeV} \leq E_\nu \leq 200\,\mathrm{MeV}$$

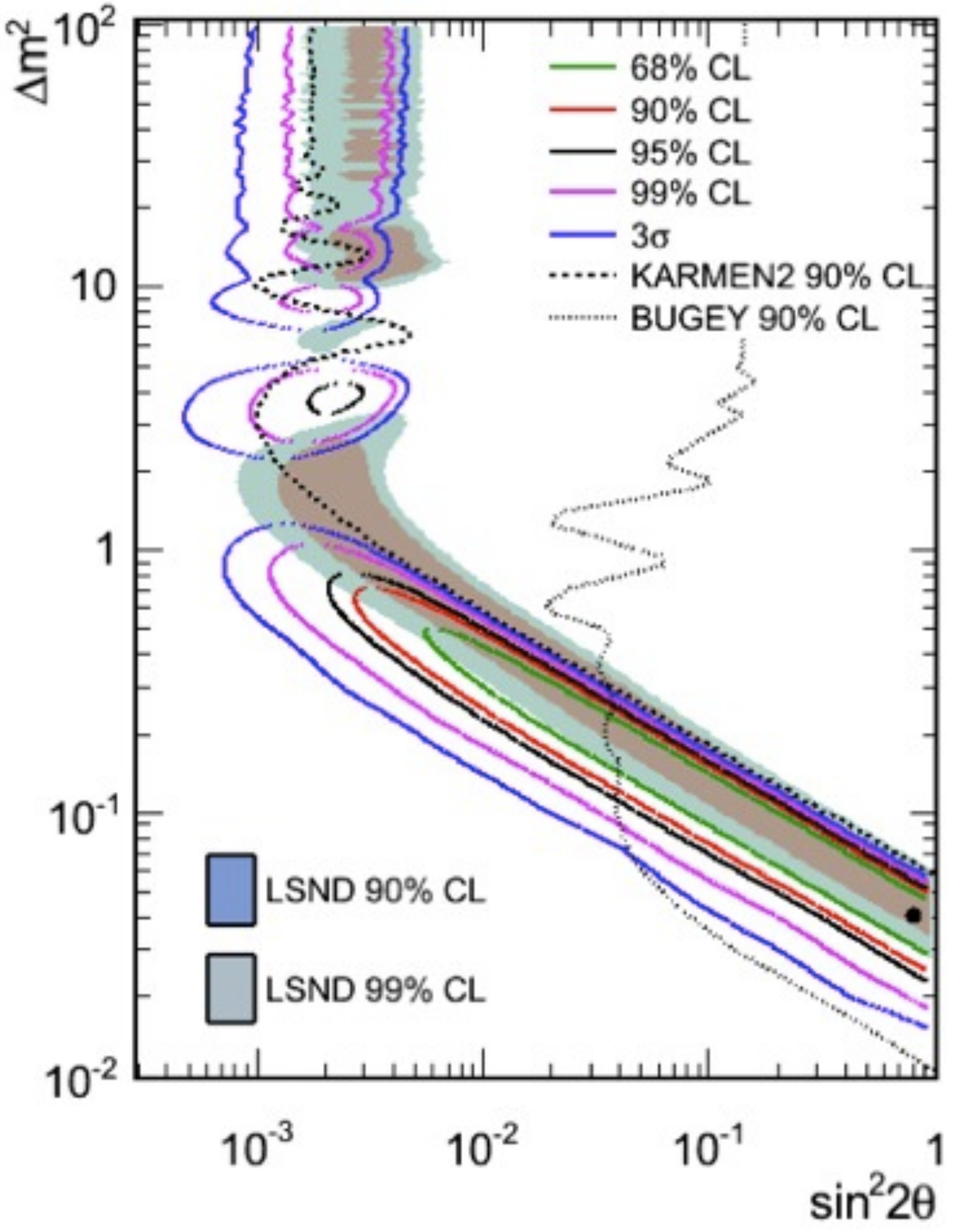


MiniBooNE

from C. Polly talk at Neutrino 2012

$$\bar{\nu}_\mu \to \bar{\nu}_e \quad \text{and} \quad \nu_\mu \to \nu_e$$

$$L \simeq 541\,\mathrm{m}\,,\ 200\,\mathrm{MeV} \leq E_\nu \leq 3\,\mathrm{GeV}$$

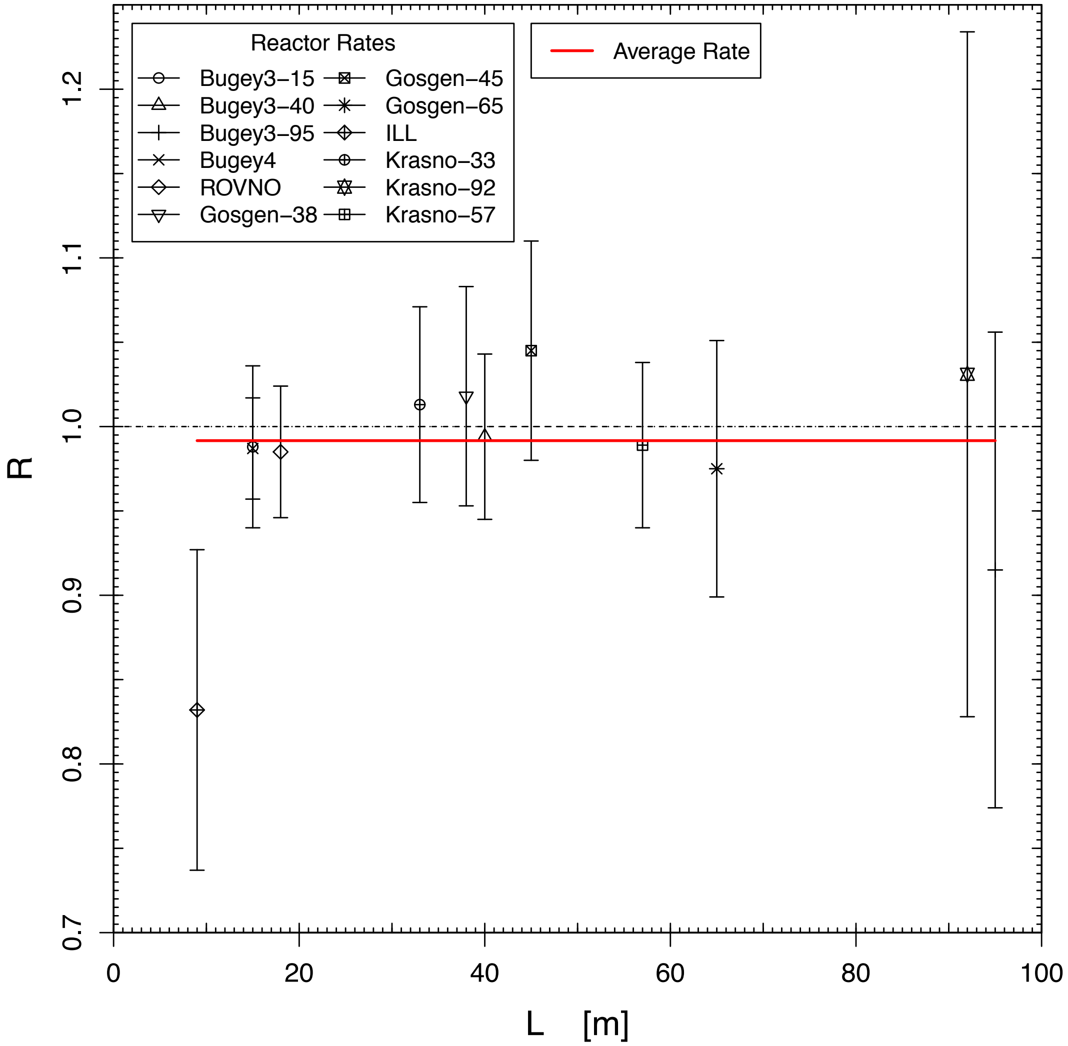


Hints on the presence of sterile neutrino

Reactor Antineutrino Anomaly

[Mention et al, arXiv:1101.2755]

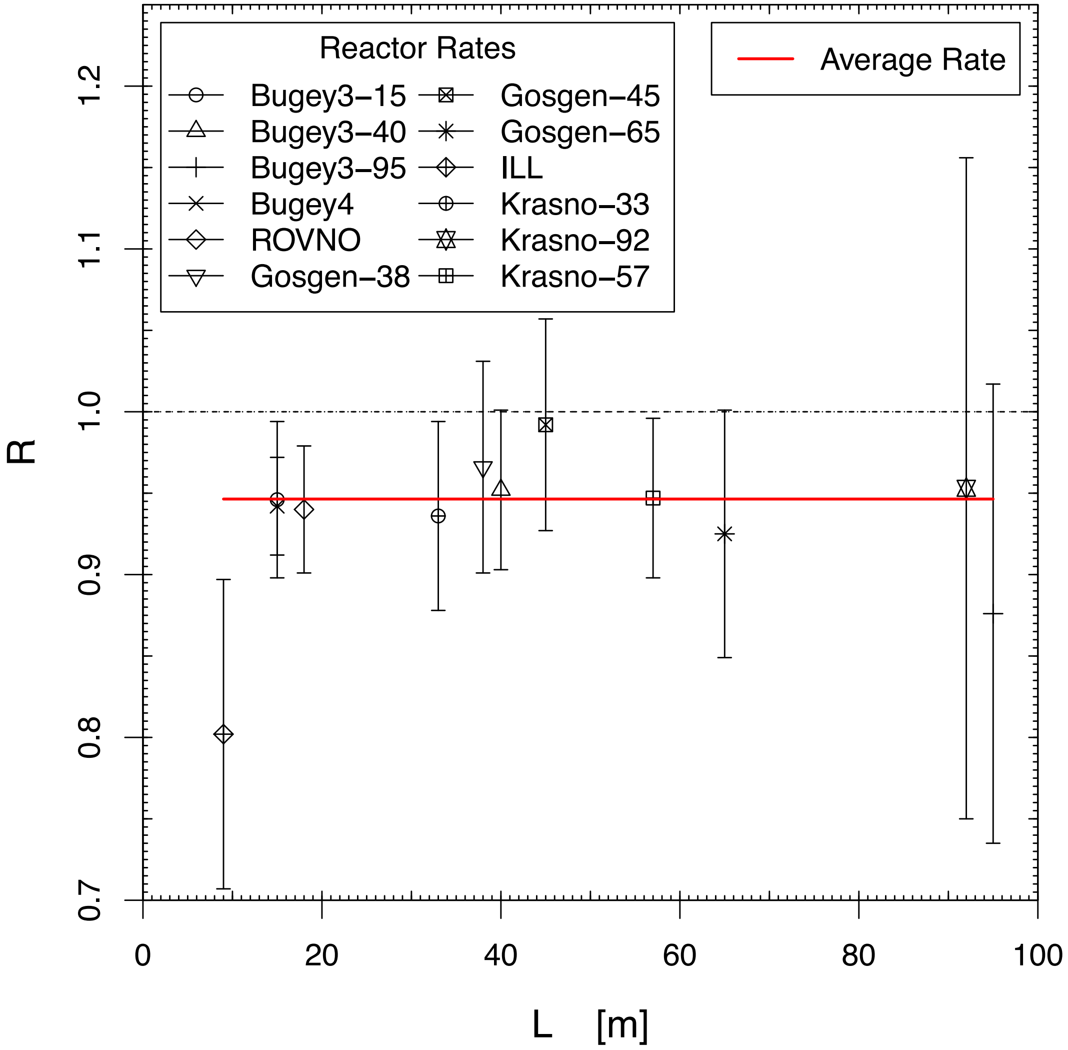
Old Reactor $\bar{\nu}_e$ Fluxes



$$\overline{R} = 0.992 \pm 0.024$$

New Reactor $\bar{\nu}_e$ Fluxes

[Mueller et al, arXiv:1101.2663]

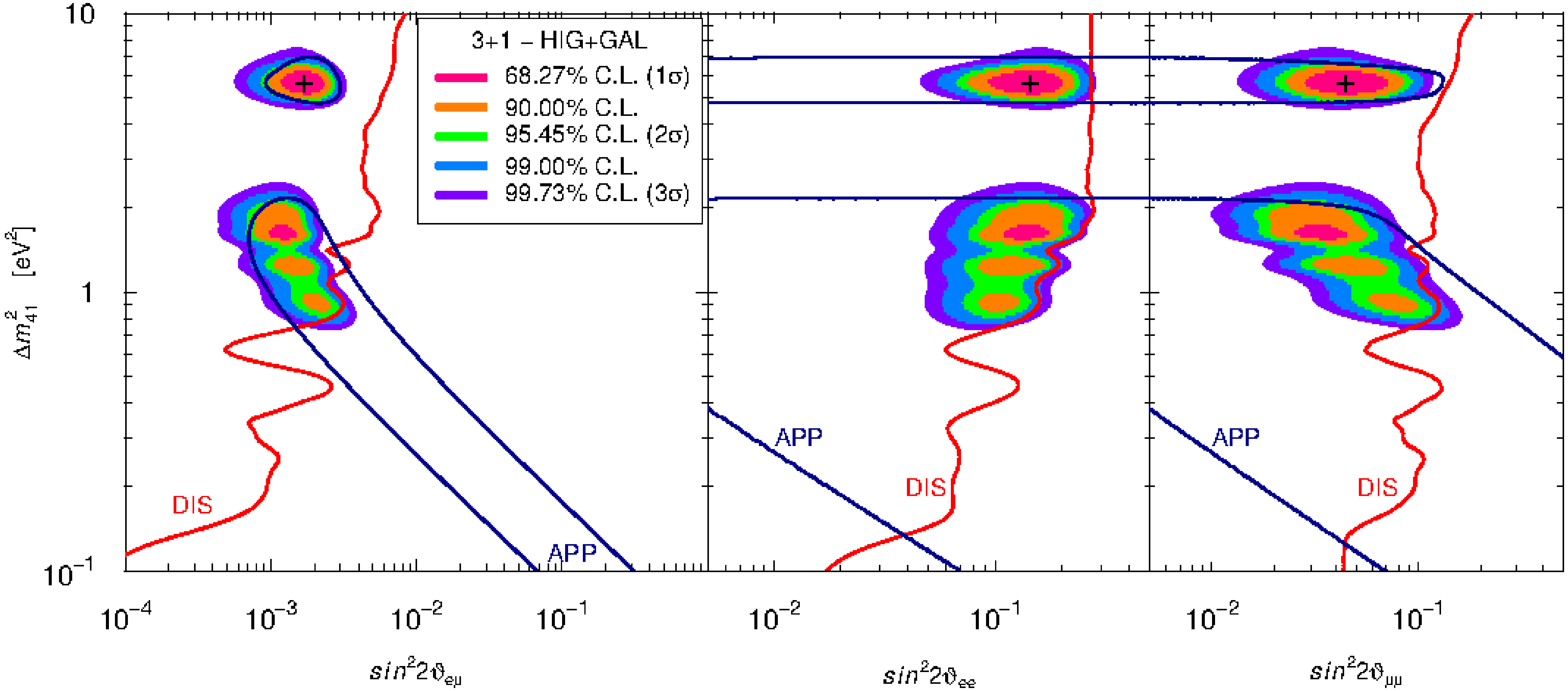


$$\overline{R} = 0.946 \pm 0.024$$

Hints on the presence of sterile neutrino

Gallium Anomaly, ...

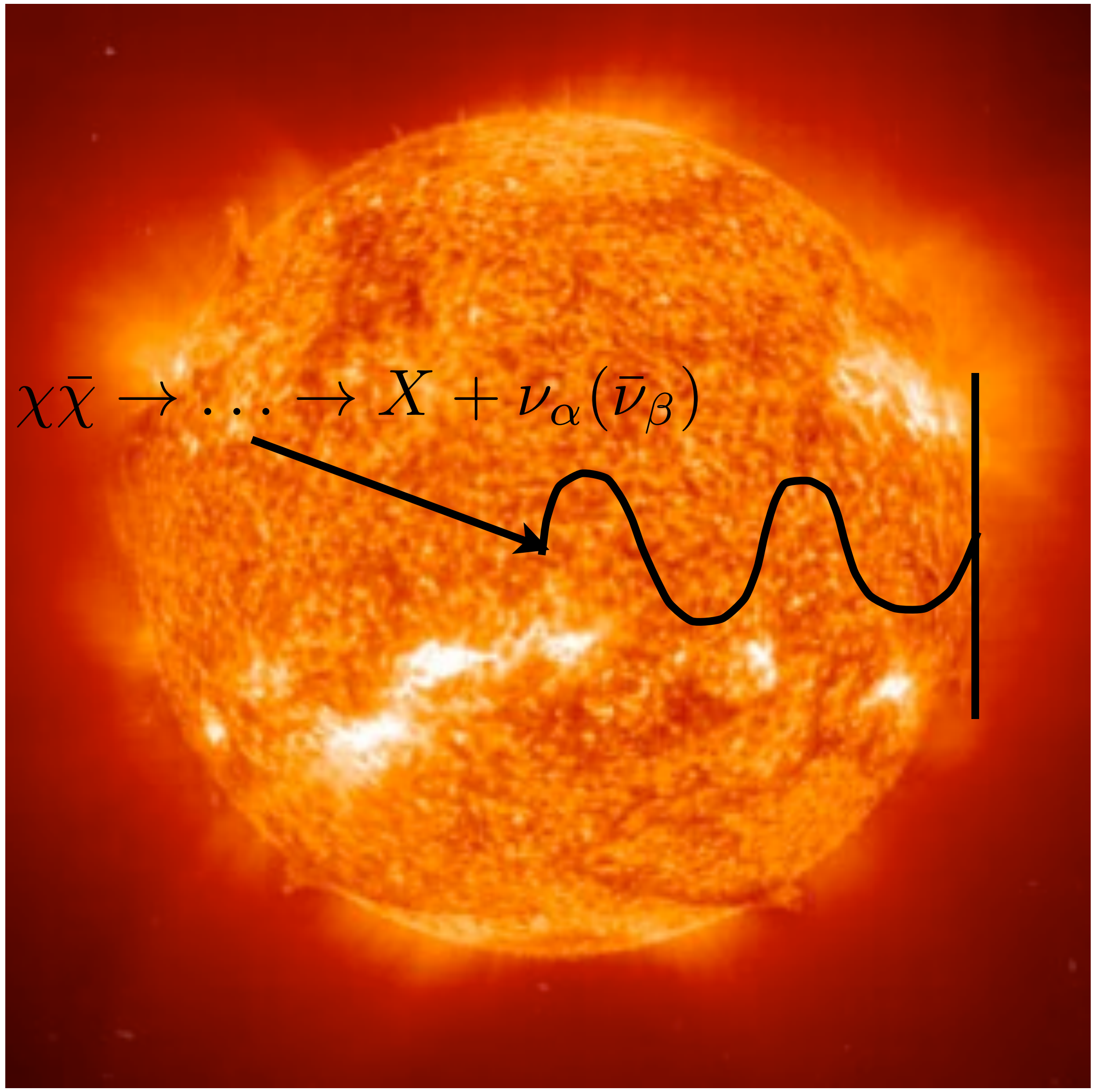
C. Giunti and M. Laveder, Phys. Rev. D 84 (2011); C. Giunti and M. Laveder, Phys. Lett. B706 (2011); J. Fan and P. Langacker, JHEP1204 (2012); A. Palazzo, Phys. Rev. D 85 (2012); ....



C. Giunti and M. Laveder, Phys. Rev. D 84 (2011)

Indirect Detection in the presence of sterile neutrino

We assume a sterile state with $\Delta m^2 \sim 1\ \mathrm{eV}^2$ and mixing angles in the allowed region



$$i\frac{d\nu_\alpha}{dr} = \left[\frac{1}{2E_\nu}\left(UM^2U^\dagger\right) + V(r)\right]_{\alpha\beta} \nu_\beta$$

$$M^2 = \begin{pmatrix} 0 & & & \\ & \Delta m^2_{21} & & \\ & & \Delta m^2_{31} & \\ & & & \Delta m^2_{41} \end{pmatrix}$$

$$V(r) = \sqrt{2}G_F \begin{pmatrix} N_e(r) & & & \\ & 0 & & \\ & & 0 & \\ & & & \frac{N_n(r)}{2} \end{pmatrix}$$

Mikheev-Smirnov-Wolfenstein (MSW) Effect

$$\sigma \sim \frac{G_F^2 E_\nu^2}{\pi} \sim 10^{-43}\,\mathrm{cm}^2 \left(\frac{E_\nu}{1\,\mathrm{MeV}} \right)$$

Too small to have any effect!

But forward elastic coherent scattering can be very important!

$$V_{CC} = \pm\sqrt{2} G_F N_e$$

for $\nu_e (\bar{\nu}_e)$

effective
potential
in matter

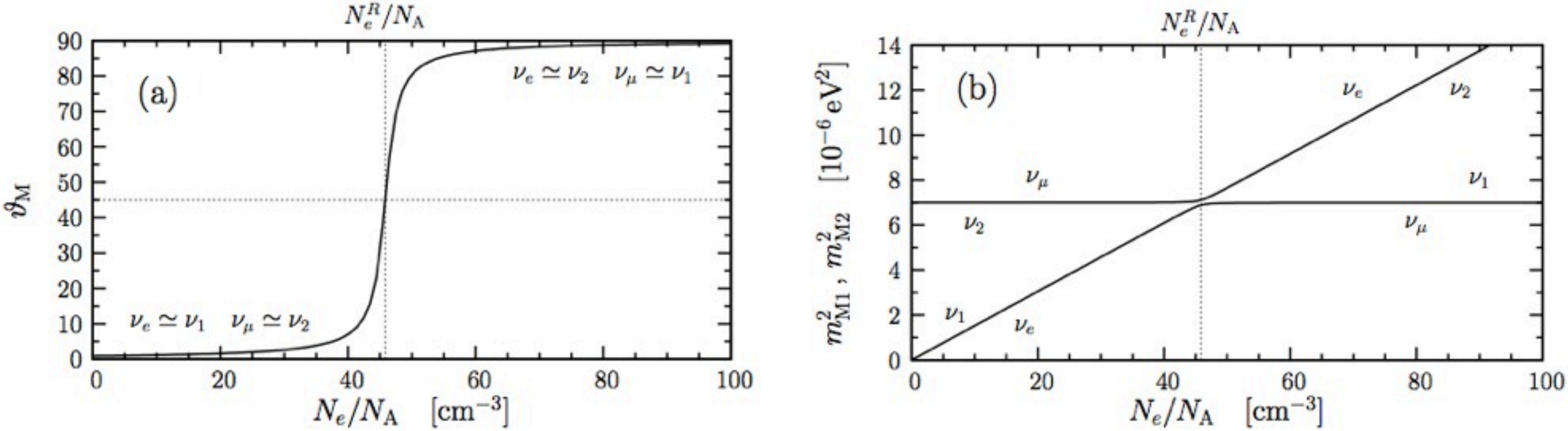
$$V_{NC} = \mp \frac{G_F}{\sqrt{2}} N_n$$

for $\nu_\alpha (\bar{\nu}_\alpha)$

$$\left(\Delta m_{ij}^2\right)_M = \sqrt{\left(\Delta m_{ij}^2 \cos 2\theta - 2\sqrt{2} G_F E_\nu N_e(r)\right)^2 + \left(\Delta m_{ij}^2 \sin 2\theta\right)^2}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{2\sqrt{2} G_F E_\nu N_e(r)}{\Delta m^2 \cos 2\theta}}$$

Mikheev-Smirnov-Wolfenstein (MSW) Effect



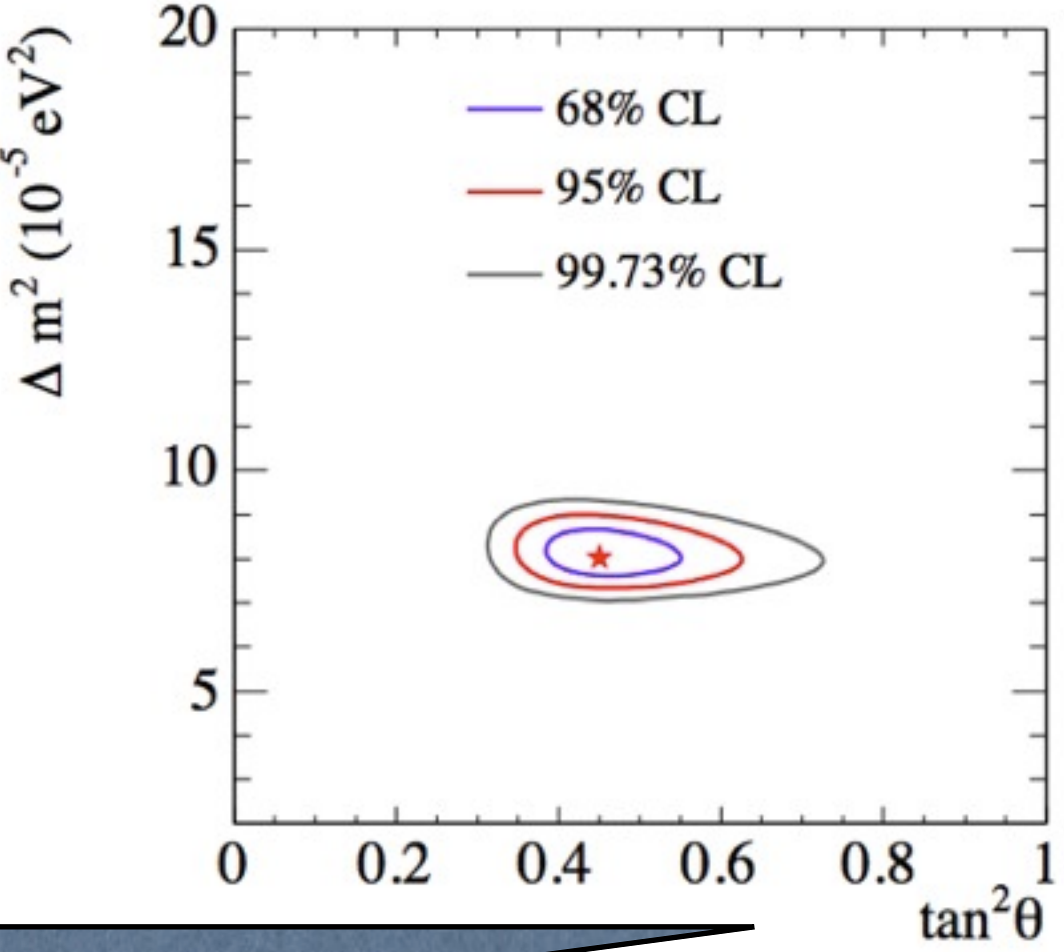
S. P. Mikheev and A. Y. Smirnov, Sov. J. Nucl. Phys. 42 (1985)
S. P. Mikheev and A. Y. Smirnov, Nuovo Cim. C 9 (1986)

$$\left(\Delta m^2\right)_M\Big|_{\text{resonance}} = \Delta m^2 \sin 2\theta$$

$$E_{\text{resonance}} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F N_e}$$

Mikheev-Smirnov-Wolfenstein (MSW) Effect

the Solar Neutrino Problem
solved by MSW effect
(LMA solution)



$$\Delta m^2_{\rm sol} = \Delta m^2_{21} \simeq 8 \times 10^{-5}\,{\rm eV}^2$$

$$\sin^2\theta_{12} = 0.3$$

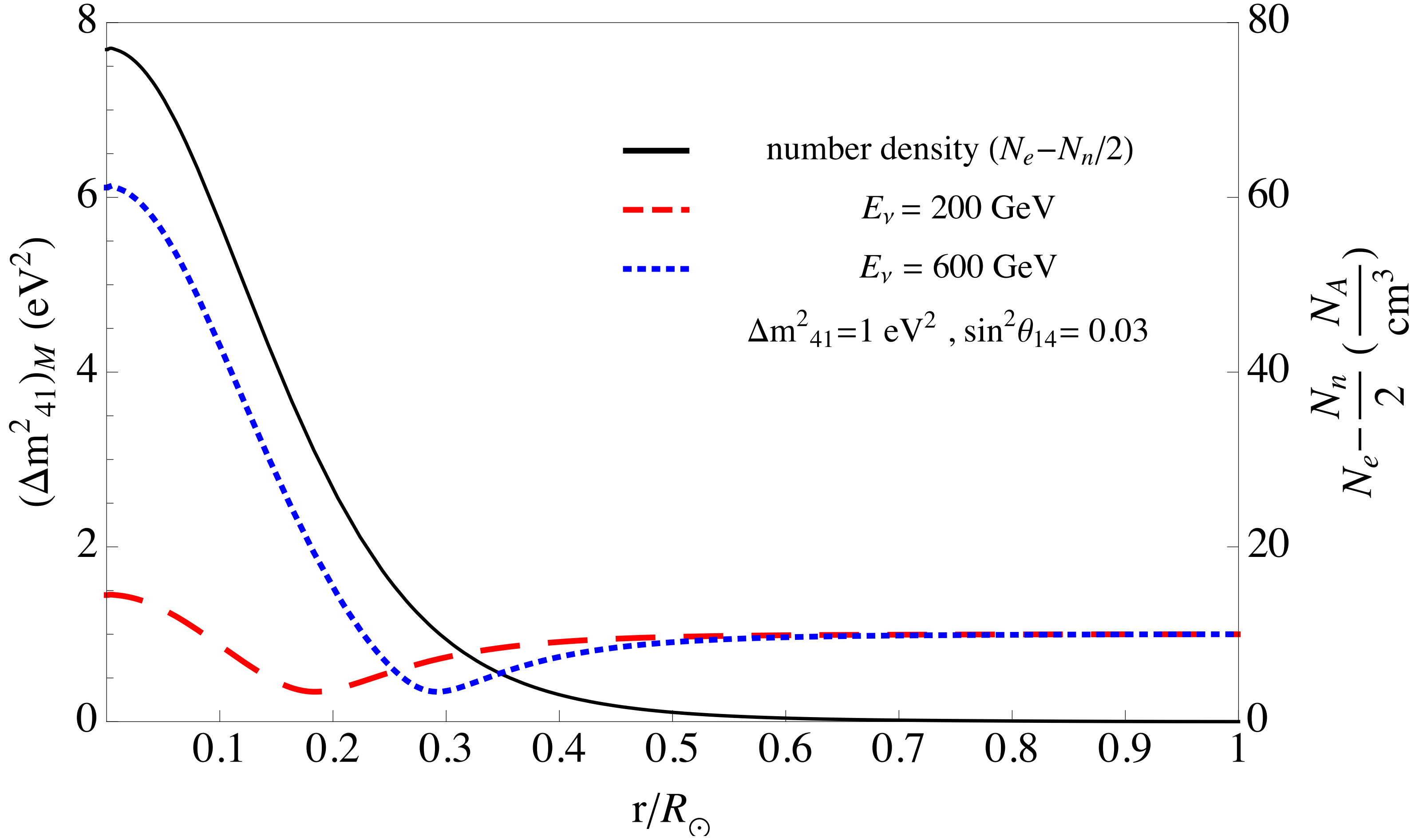
$$E_\nu \sim \ {\rm MeV}$$

same mechanism would change the flavor of neutrinos produced from the annihilation of DM particles at the center of Sun

For $\Delta m^2 \sim 1\,{\rm eV}^2$ → $E_\nu \sim 100\ \ {\rm GeV}$

Indirect Detection in the presence of sterile neutrino

A. E. and O. L. G. Peres,
JCAP 05, (2012)



$$E_{\rm res} \sim 6.55 \times 10^3 \ {\rm GeV} \left(\frac{\Delta m^2_{41}}{1\,{\rm eV}^2}\right)\left(\frac{\cos 2\theta}{1}\right)\left(\frac{N_A {\rm cm}^{-3}}{N_{eff}}\right)$$

$$\text{Max}\left[(N_{eff})^{e-s}\right] = \left(N_e - \frac{N_n}{2}\right)\Bigg|_{\rm center} = 76.9 \quad \frac{N_A}{{\rm cm}^3}$$

$$\text{Max}\left[(N_{eff})^{\mu/\tau-s}\right] = \left(\frac{N_n}{2}\right)\Bigg|_{\rm center} = 26.9 \quad \frac{N_A}{{\rm cm}^3}$$

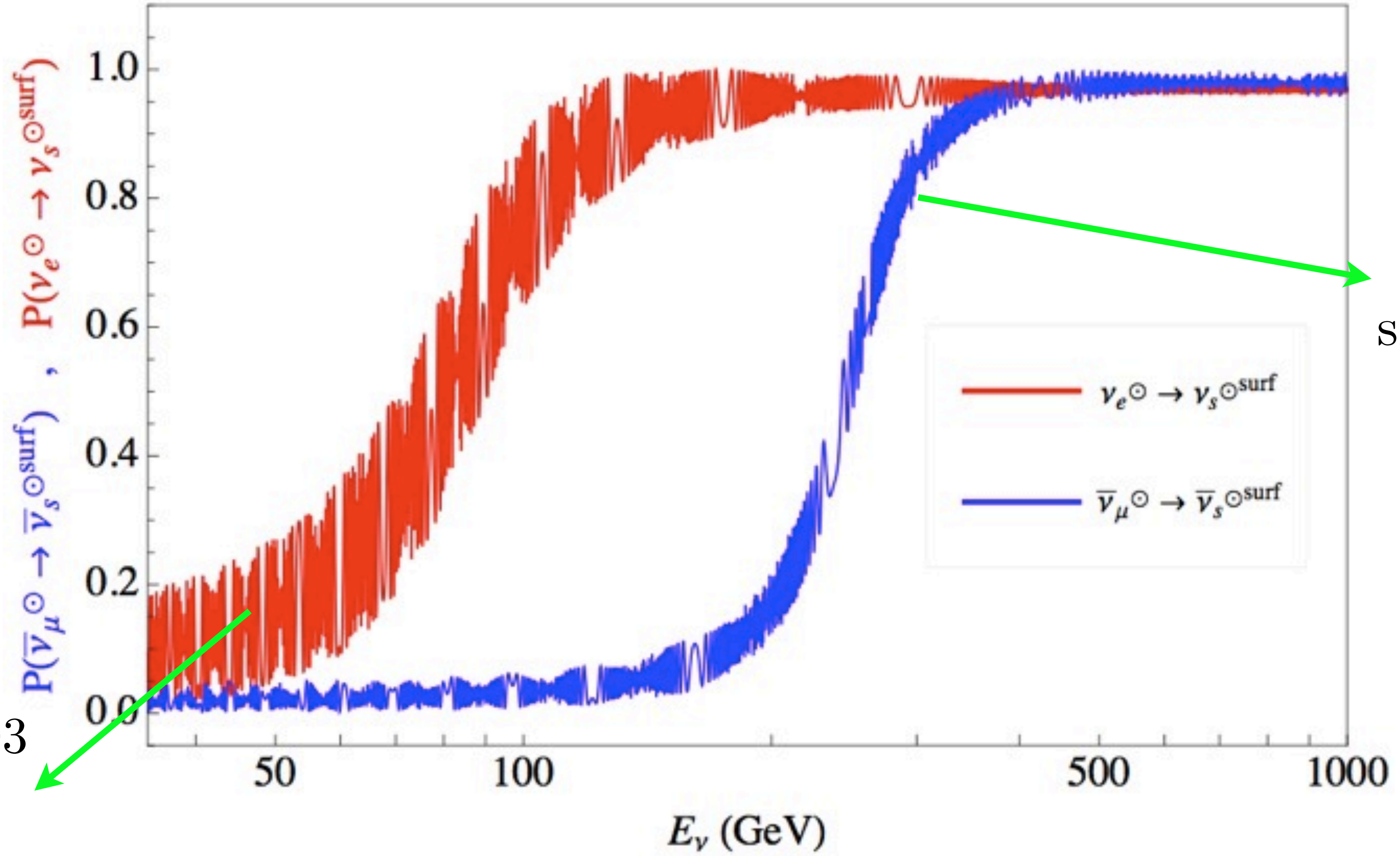
$\nu_e - \nu_s$ resonance $\Delta m^2_{41} > 0$ $\bar{\nu}_{\mu/\tau} - \bar{\nu}_s$ resonance

Indirect Detection in the presence of sterile neutrino

A. E. and O. L. G. Peres,
JCAP 05, (2012)

$\Delta m^2_{41} = 1\,\mathrm{eV}^2$

$\sin^2\theta_{34} = 0$



$\sin^2\theta_{14} = 0$

$\sin^2\theta_{24} = 0.01$

$\sin^2\theta_{14} = 0.03$

$\sin^2\theta_{24} = 0$

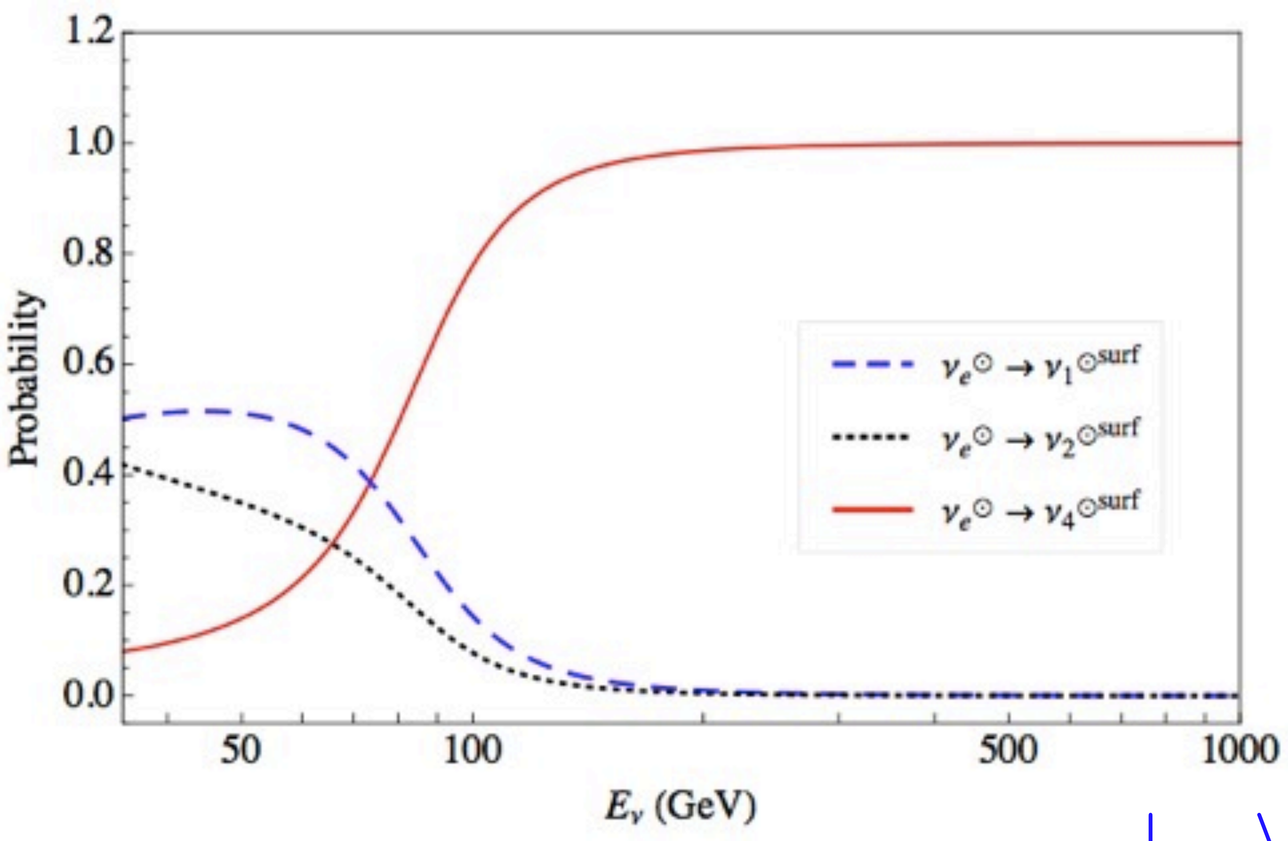
complete conversion to sterile neutrino

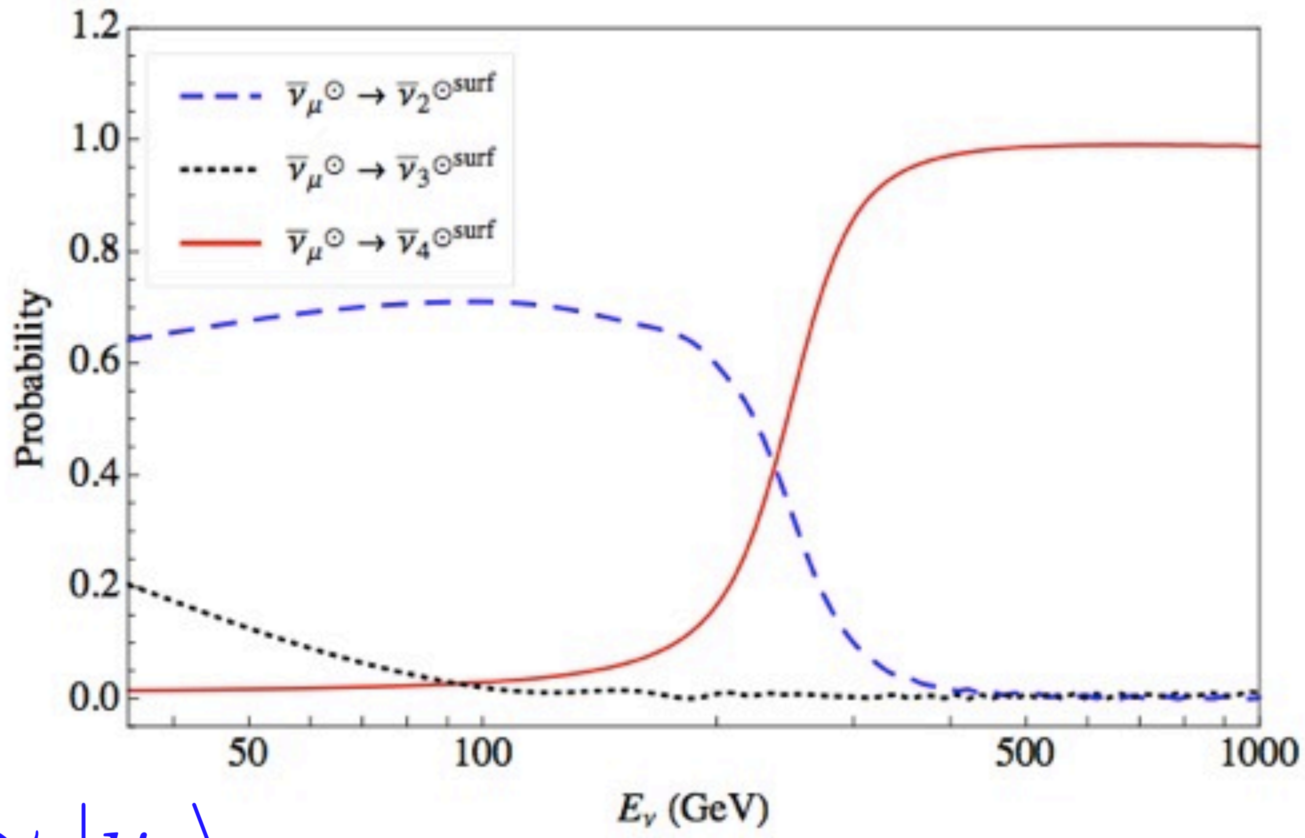
$E_{\mathrm{res}}^{e-s} \sim 85$ GeV

$E_{\mathrm{res}}^{\mu/\tau-s} \sim 240$ GeV

Indirect Detection in the presence of sterile neutrino

A. E. and O. L. G. Peres,
JCAP 05, (2012)





$$|\nu_s\rangle \simeq |\nu_4\rangle$$

$\Delta m_{41}^2 = 1\,\text{eV}^2$ $\sin^2\theta_{14} = 0.03$

$\sin^2\theta_{34} = 0$ $\sin^2\theta_{24} = 0$

$\Delta m_{41}^2 = 1\,\text{eV}^2$ $\sin^2\theta_{14} = 0$

$\sin^2\theta_{34} = 0$ $\sin^2\theta_{24} = 0.01$

Flux of Neutrinos at the Earth

$$\mathcal{A}(\nu_\alpha^{\odot} \to \nu_\beta^{\rm Det}) = \sum_i \mathcal{A}(\nu_\alpha^{\odot} \to \nu_i^{\odot\rm surf}) \exp\left[-i\frac{\Delta m_{i1}^2 L_{\rm ES}}{2E_\nu}\right] \mathcal{A}(\nu_i^{\oplus\rm surf} \to \nu_\beta^{\rm Det})$$

flavor oscillation amplitude

we assume the IceCube detector at South Pole

Earth-Sun distance ~ 1.5 × 10^8 km

flavor oscillation probability

$$P\left(\nu_\alpha^{\odot} \to \nu_\beta^{\rm Det}\right) = \left|\mathcal{A}\left(\nu_\alpha^{\odot} \to \nu_\beta^{\rm Det}\right)\right|^2$$

But when the spectrum of neutrinos at the center of Sun is continuous

$$\chi\bar{\chi} \to q\bar{q}, ZZ, W^+W^-, \ldots$$

$$\left\langle \exp\left[-i\frac{\Delta m_{i1}^2 L_{\rm ES}}{2E_\nu}\right]\right\rangle = 0$$

$$P\left(\nu_\alpha^{\odot} \to \nu_\beta^{\rm Det}\right) = \sum_i \left|\mathcal{A}\left(\nu_\alpha^{\odot} \to \nu_i^{\odot\rm surf}\right)\mathcal{A}\left(\nu_i^{\oplus\rm surf} \to \nu_\beta^{\rm Det}\right)\right|^2$$

Flux of Neutrinos at the Earth

For the case of
monochromatic
neutrinos

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

$$E_\nu = m_\chi$$

$$\left\langle \exp\left[-i\frac{\Delta m_{i1}^2 L_{\rm ES}}{2E_\nu}\right]\right\rangle \neq 0$$

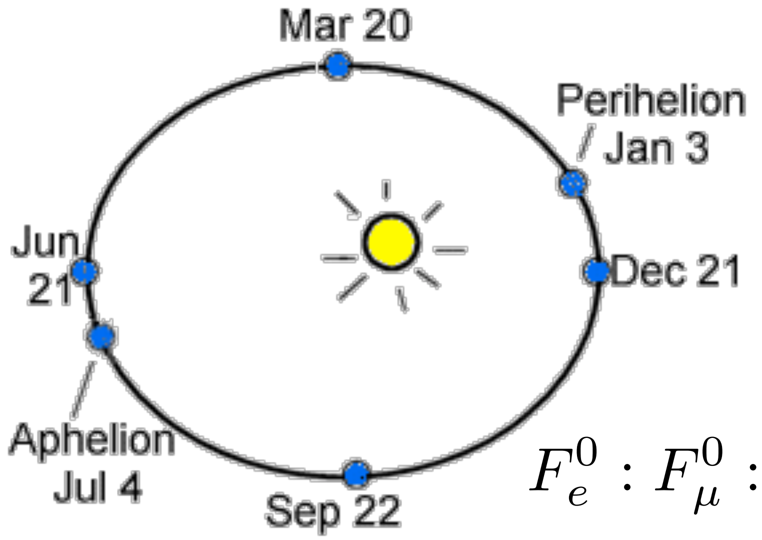
Are the interference terms observable?

$$L_{\rm osc}^{21} = \frac{4\pi E_\nu}{\Delta m_{12}^2} \sim 3\times 10^{11}\ {\rm cm}\ \left(\frac{E_\nu}{100\ {\rm GeV}}\right)\left(\frac{8\times 10^{-5}\ {\rm eV}^2}{\Delta m_{21}^2}\right)$$

A. E. and Y. Farzan, Phys. Rev. D 81 (2010)

$$L_{\rm osc}^{31} = \frac{4\pi E_\nu}{\Delta m_{13}^2} \sim 10^{10}\ {\rm cm}\ \left(\frac{E_\nu}{100\ {\rm GeV}}\right)\left(\frac{2.4\times 10^{-3}\ {\rm eV}^2}{\Delta m_{31}^2}\right)$$

A. E. and Y. Farzan, JCAP 1104 (2011)



$$F_e^0 : F_\mu^0 : F_\tau^0 \neq 1:1:1$$

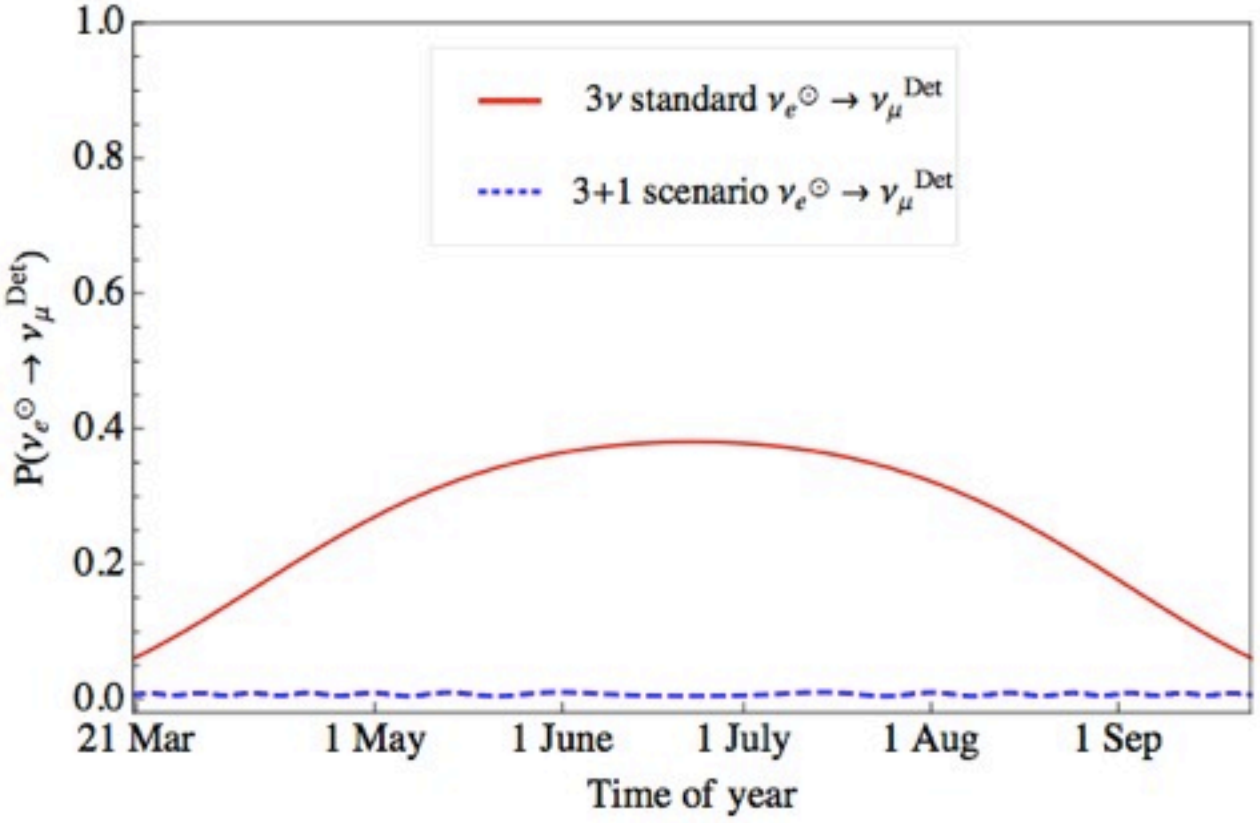
Aphelion – Perihelion ~ 5 × 10^{11} cm

Southern hemisphere fall and winter:

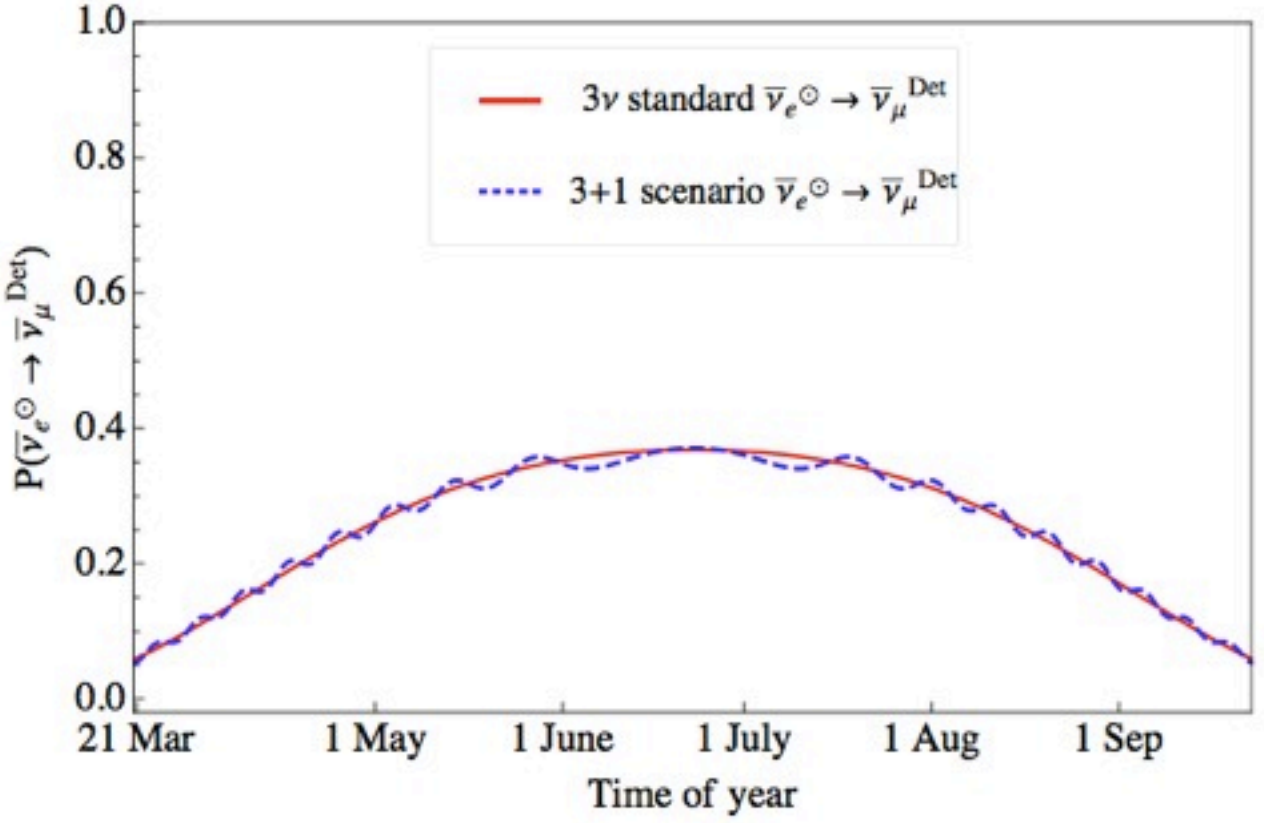
ΔL_{ES} ~ 3 × 10^{11} cm

Flux of Neutrinos at the Earth

$\nu_e^{\odot}$, $E_\nu = 300$ GeV



$\bar{\nu}_e^{\odot}$, $E_\nu = 300$ GeV



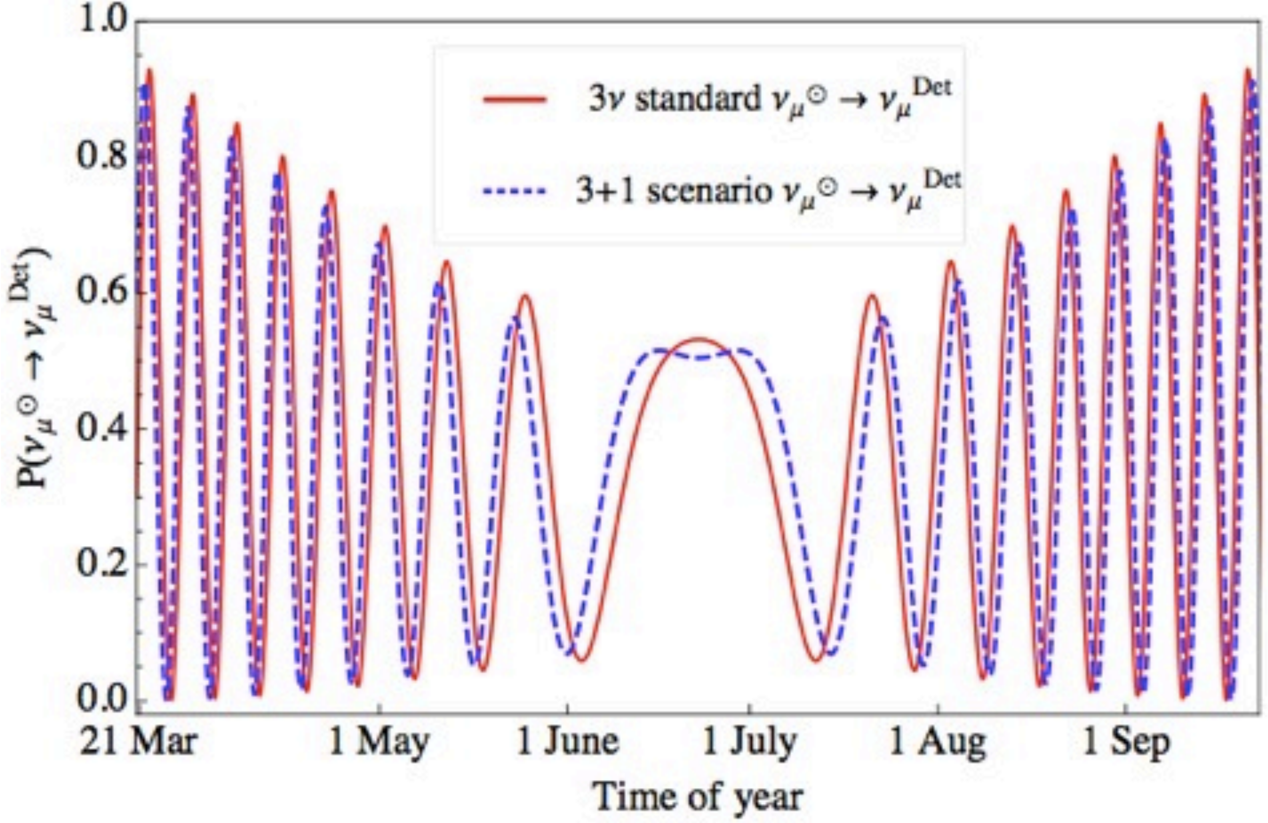
$$\Delta m_{41}^2 = 1\,\mathrm{eV}^2$$

$$\sin^2\theta_{14} = \sin^2\theta_{24} = \sin^2\theta_{34} = 8 \times 10^{-3}$$

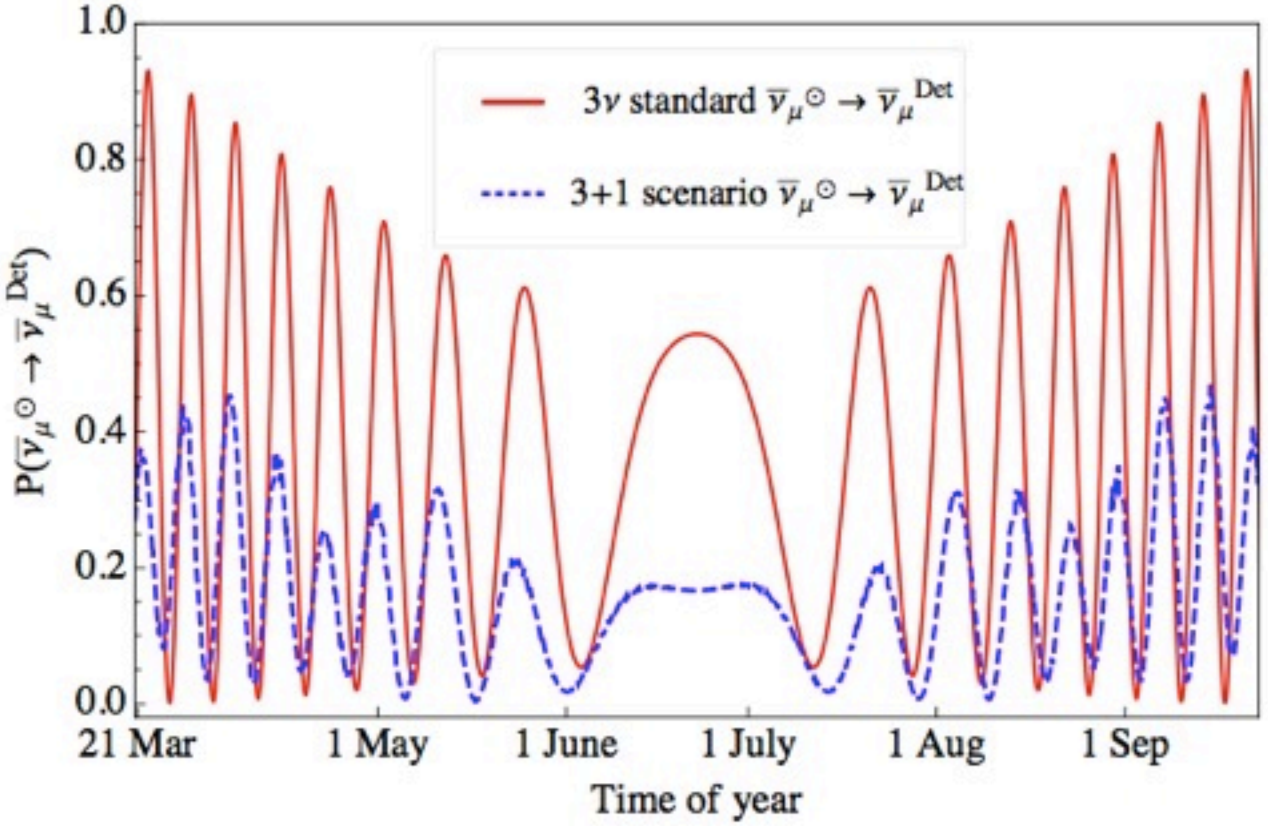
Mixing angles are well below the current upper limit values by short base-line experiments

Flux of Neutrinos at the Earth

$\nu_\mu^{\odot}$, $E_\nu = 300\ \mathrm{GeV}$



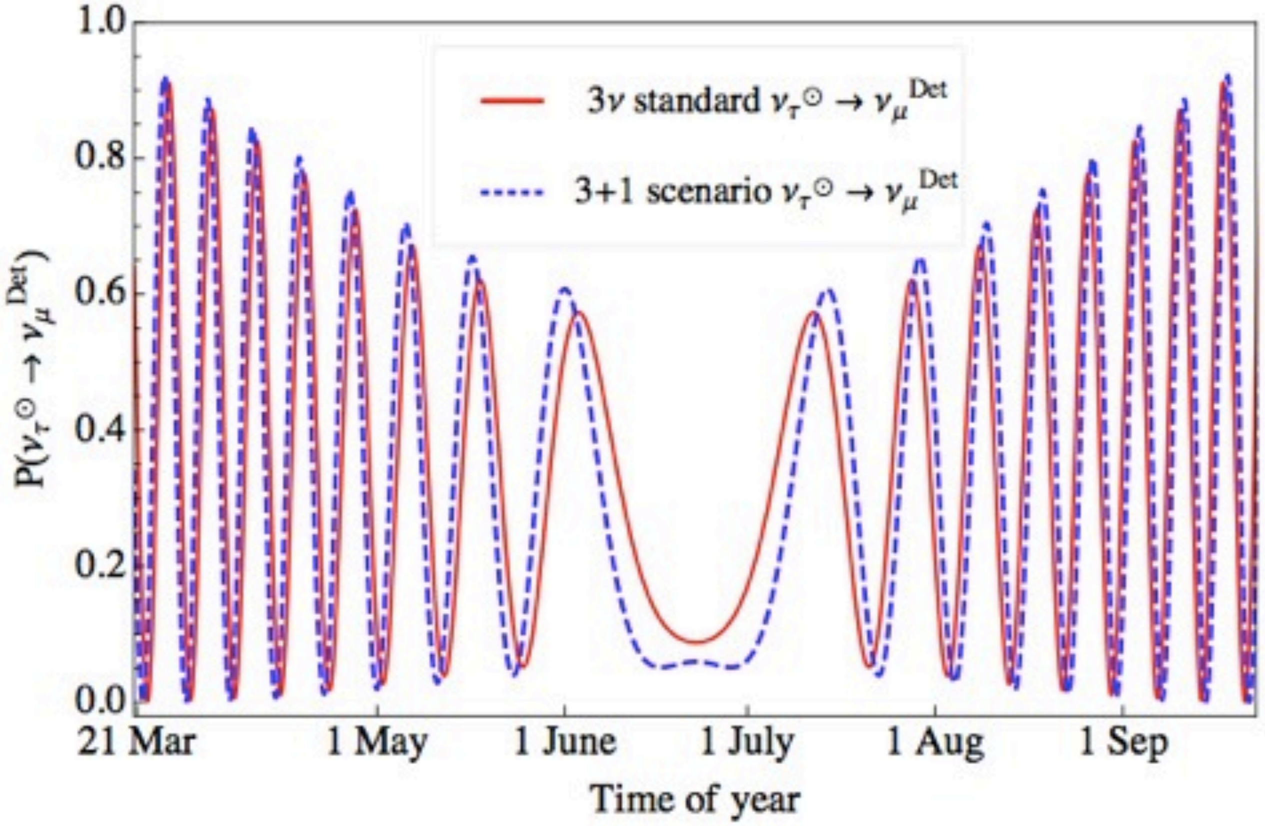
$\bar{\nu}_\mu^{\odot}$, $E_\nu = 300\ \mathrm{GeV}$



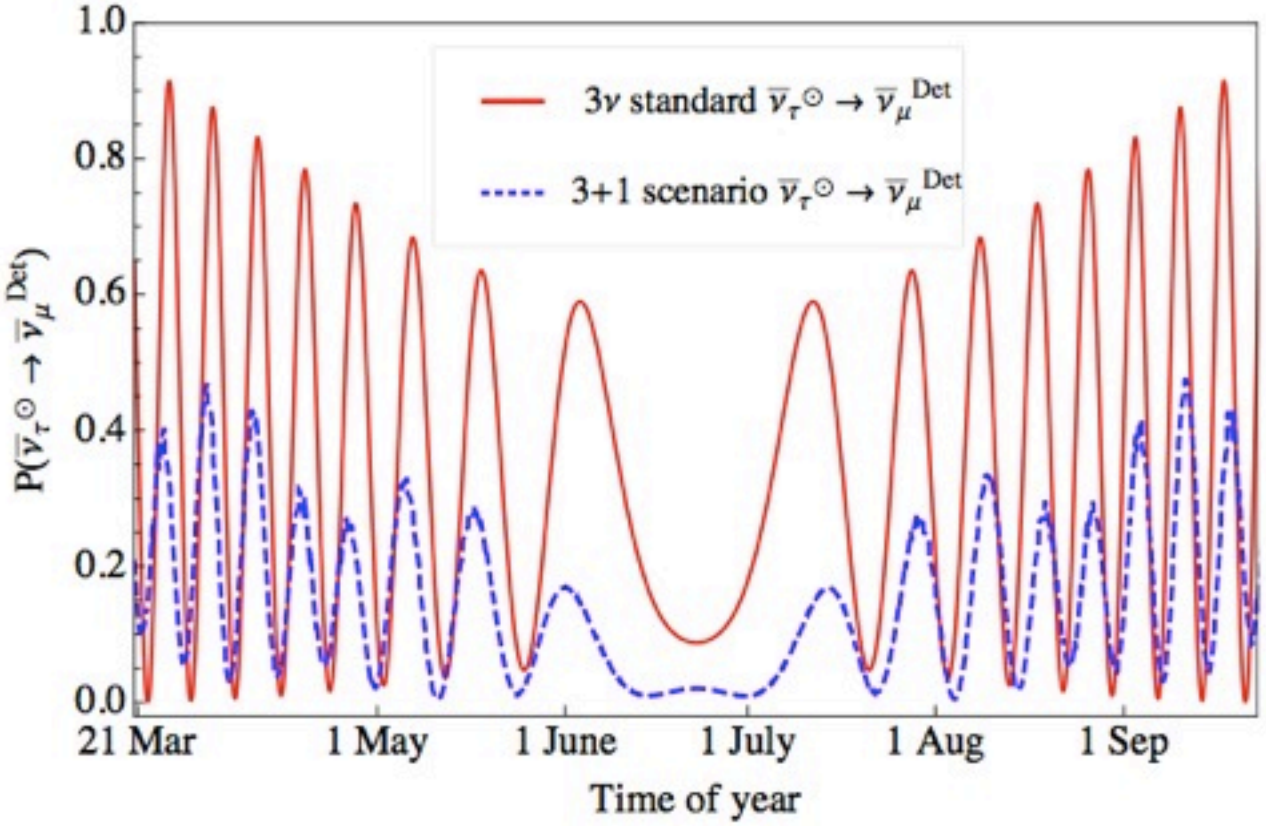
$$\Delta m_{41}^2 = 1\,\mathrm{eV}^2, \sin^2\theta_{14} = \sin^2\theta_{24} = \sin^2\theta_{34} = 8 \times 10^{-3}$$

Modulation of two oscillatory terms
induced by $\Delta m^2{}_{12}$ and $\Delta m^2{}_{13}$

Flux of Neutrinos at the Earth



$\nu_\tau^\odot$, $E_\nu = 300$ GeV



$\bar{\nu}_\tau^\odot$, $E_\nu = 300$ GeV

$$\Delta m^2_{41} = 1\,\mathrm{eV}^2, \sin^2\theta_{14} = \sin^2\theta_{24} = \sin^2\theta_{34} = 8\times 10^{-3}$$

Modulation of two oscillatory terms
induced by Δm^2_{12} and Δm^2_{13}

Flux of Neutrinos at the Earth

A new interesting annihilation channel

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

Y. Farzan, JHEP 1202 (2012)

From model building
point of view

$$\mathcal{L} = g' \left(\bar{\nu}_s \gamma^\mu \left(\frac{1-\gamma^5}{2} \right) \nu_s - \bar{\psi} \gamma^\mu \left(\frac{1-\gamma^5}{2} \right) \psi \right) Z'_\mu$$

sterile neutrino
with a mass of the
order of active
neutrinos

a new Dirac
fermion field
playing the role of
DM

gauge boson of
a new U(1)'
symmetry

$$\langle \sigma(\bar{\psi}\psi \to \bar{\nu}_s \nu_s) \rangle = \frac{g'^4}{8\pi} \frac{m_{\rm DM}^2}{[(2m_{\rm DM})^2 - m_{Z'}^2]^2}$$

Flux of Neutrinos at the Earth

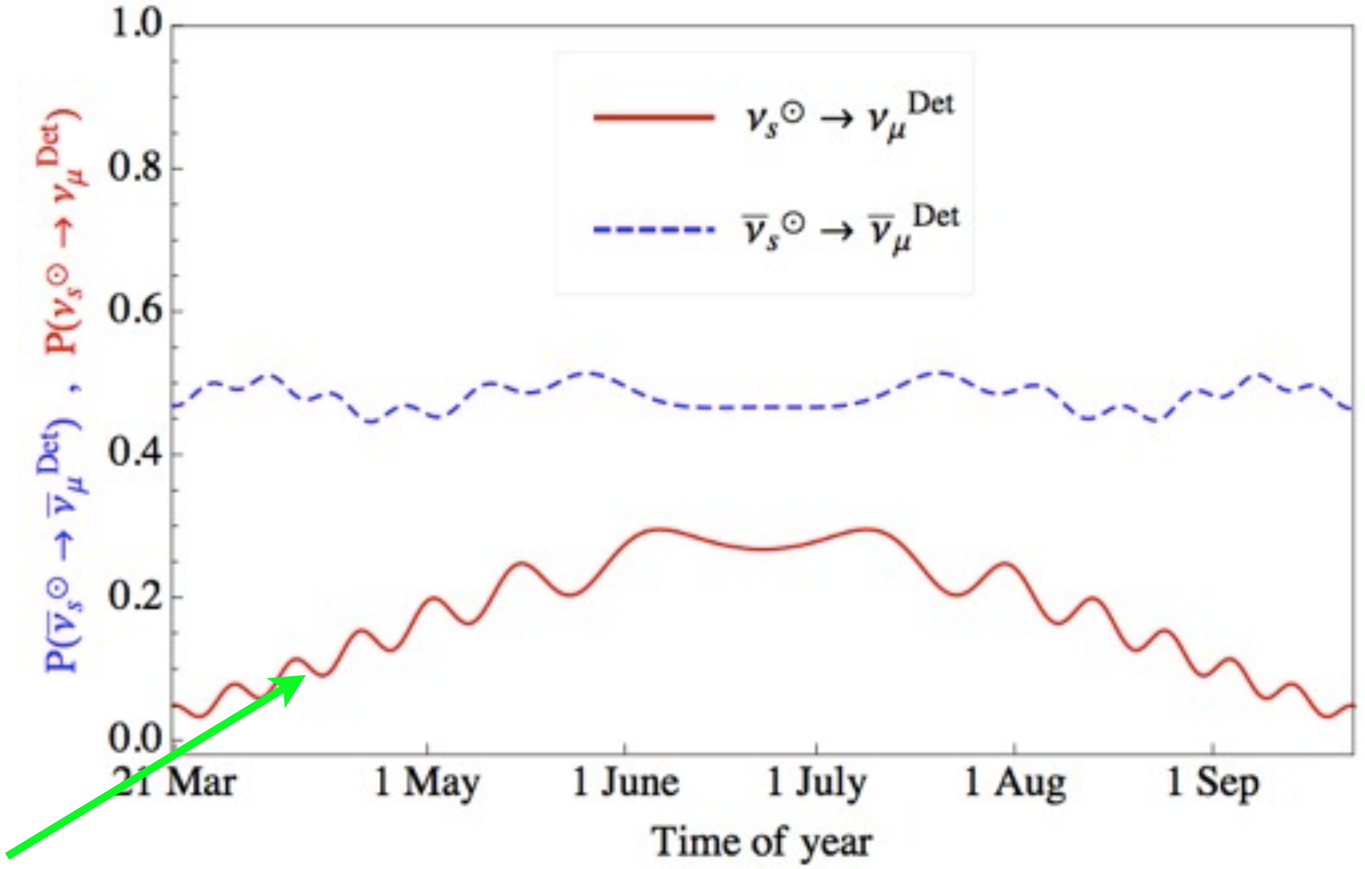
$$\Delta m^2_{41} = 1\,\mathrm{eV}^2$$

$$\sin^2\theta_{14} = 8\times 10^{-3}$$

$$\sin^2\theta_{24} = 8\times 10^{-3}$$

$$\sin^2\theta_{34} = 8\times 10^{-3}$$

$$\nu_s^\odot\ ,\ \bar\nu_s^\odot\ ,\ E_\nu = 400\ \mathrm{GeV}$$



small amplitude oscillations ?

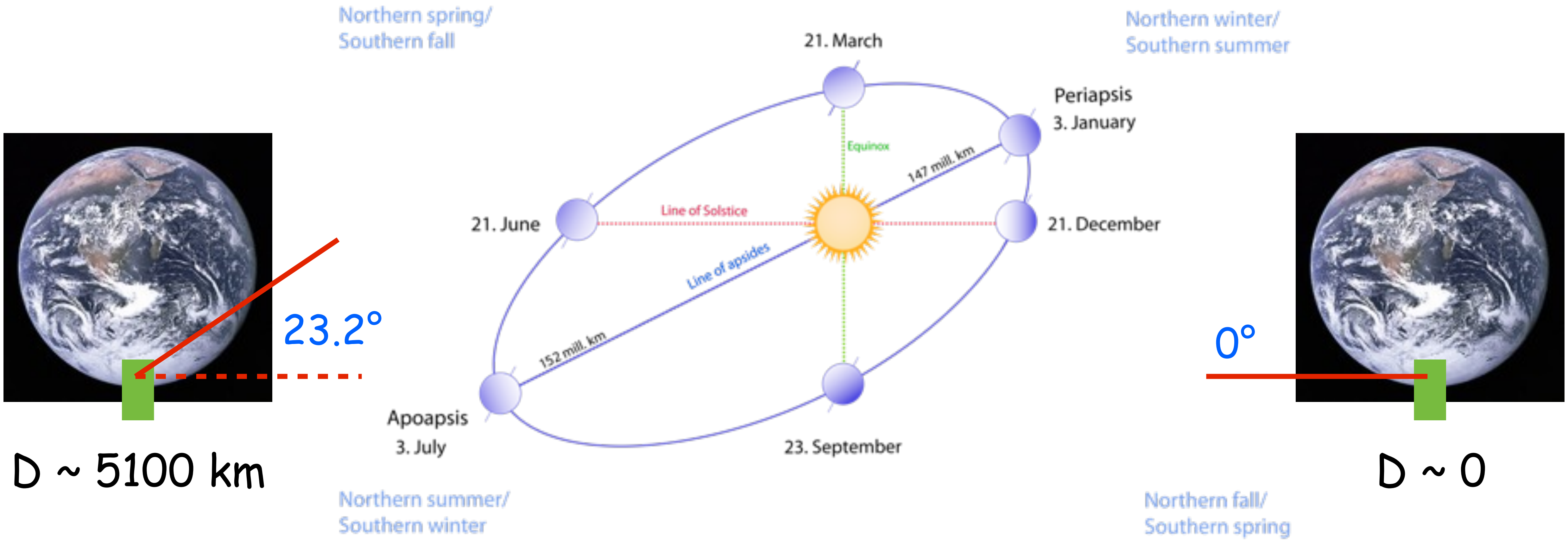
$$|\nu_s^\odot\rangle \longrightarrow c_{12}|\nu_1^{\odot\mathrm{surf}}\rangle + s_{12}|\nu_2^{\odot\mathrm{surf}}\rangle \xrightarrow[|\nu_\mu^{\oplus\mathrm{surf}}\rangle]{\text{decomposing to}}$$

Max: $4c^2_{24}c^2_{23}c^2_{12}s^2_{12} \sim 0.28$

Min: $s^2_{14}s^2_{24} \sim 0$

$$|\bar\nu_s^\odot\rangle \longrightarrow |\bar\nu_3^{\odot\mathrm{surf}}\rangle \xrightarrow[|\nu_\mu^{\oplus\mathrm{surf}}\rangle]{\text{decomposing to}} c^2_{24}s^2_{23} \sim 0.5$$

Flux of Neutrinos at the Earth



$$L_{\rm osc}^{41} = \frac{4\pi E_\nu}{\Delta m^2_{14}} \sim 246\ {\rm km}\ \left(\frac{E_\nu}{100\ {\rm GeV}}\right)\left(\frac{1\ {\rm eV}^2}{\Delta m^2_{41}}\right)$$

active-sterile oscillation with small oscillation amplitude is expected

conclusions

✓ DM exists! and one of the promising non-gravitational methods to detect it is through the neutrinos produces in its annihilation.

✓ recent global fit of the short base-line neutrino oscillation experiments (in the light of reactor anomaly, ...) favors the existence of one or more sterile state with $\Delta m^2 \sim 1$ eV^2.

✓ we considered the effect of these new sterile states on the evolution of neutrino flux from the annihilation of DM inside the Sun.

✓ we have shown that the presence of sterile neutrino would depletes the electron neutrino and muon/tau anti-neutrinos through the MSW active-sterile resonance conversion. The depletion occur even for very small active-sterile mixing angles ($\sin^2\theta_{i4} > 10^{-3}$).

✓ as an example, we presented the oscillation probabilities for monochromatic neutrino from direct annihilation of DM to neutrinos

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✓ a detailed analysis using the published IC-40 data is going on ....

Thank you !

IPMU
13/June/2012