Solar Neutrinos as a Probe of Dark Matter-Neutrino Interactions

based on arXiv:1702.08464, with I. Shoemaker and L. Vecchi

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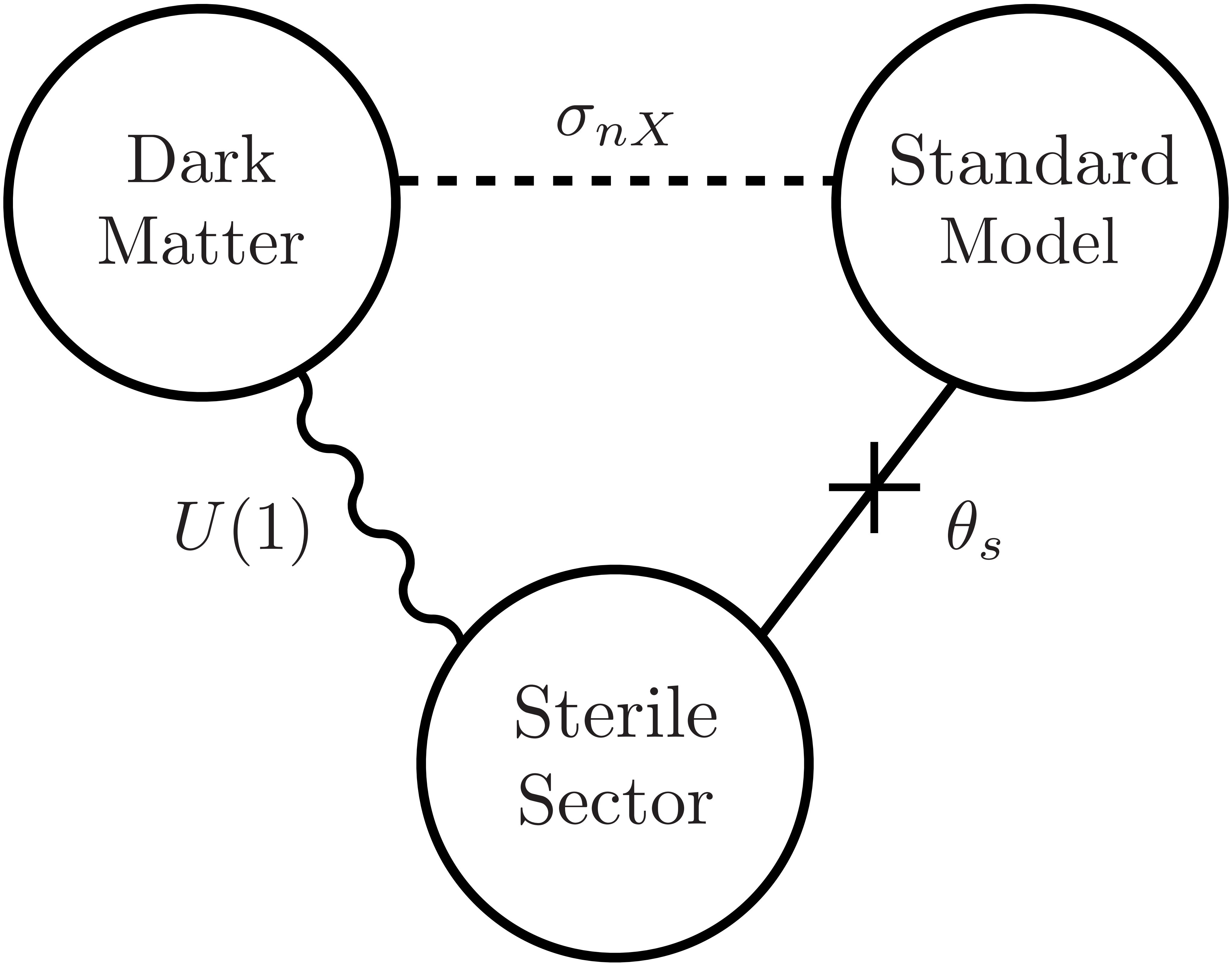
CCAPP

Model

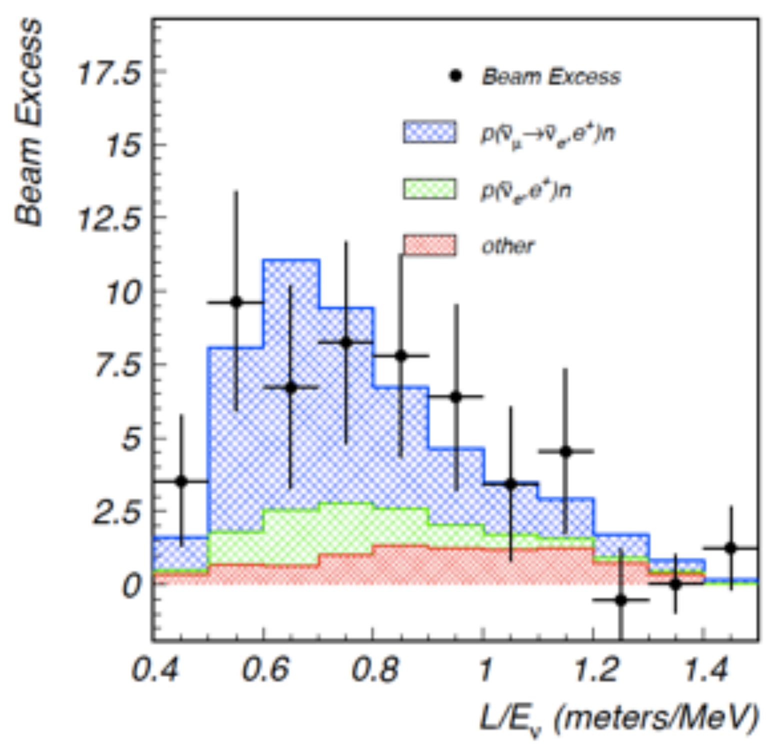


Dark
Matter
σ_{nX}
Standard
Model
$U(1)$
θ_s
Sterile
Sector

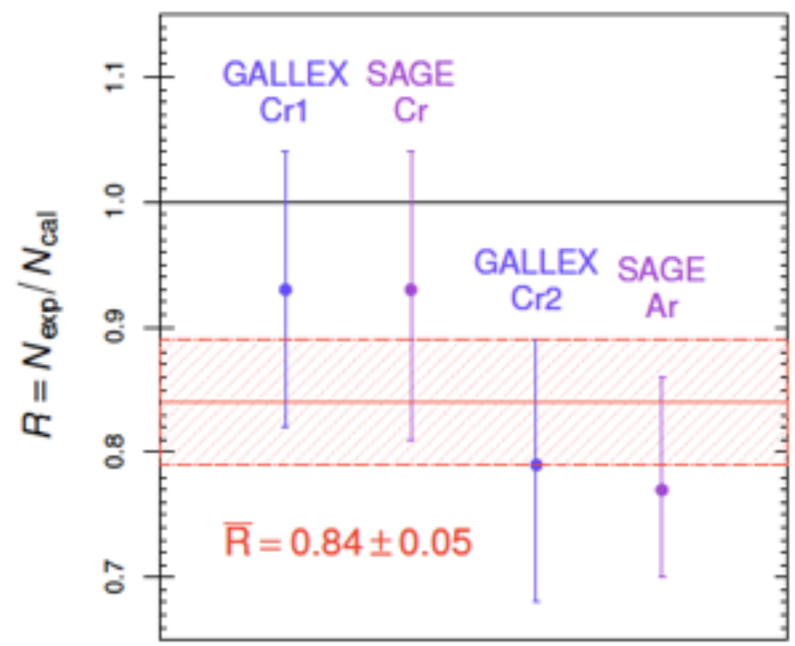
Motivation: SBL anomalies and ν_s

Almost all data from neutrino oscillation can be explained in a 3ν framework.
There are however a few **anomalies observed at very short baseline**:

LSND anomaly

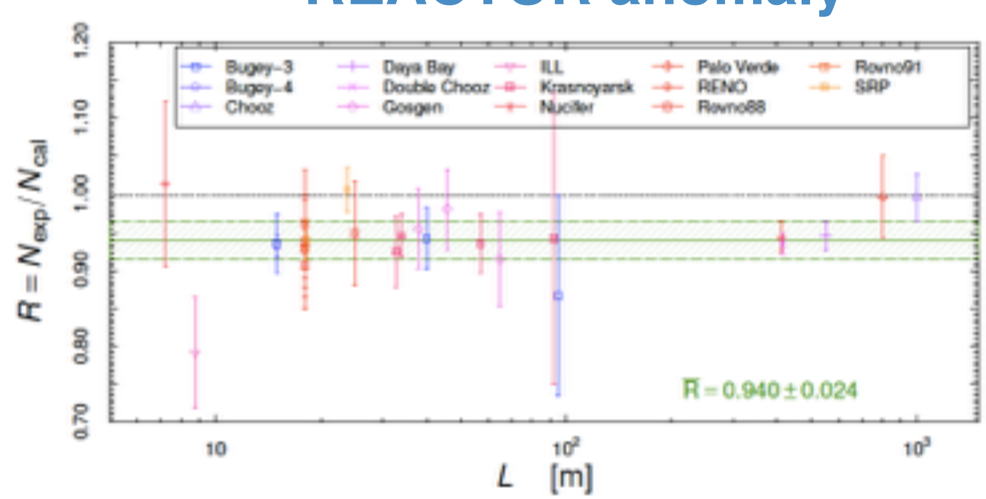


GALLIUM anomaly



$\Delta m^2_{SBL} \sim 1\ eV^2$

REACTOR anomaly



$\sin^2\theta \sim 0.01$

Motivation: ν_s secret interactions

ν_s secret interactions may reconcile SBL anomalies with Cosmology

- *K. S. Babu and I. Z. Rothstein, Phys.Lett. B275 (1992) 112–118.*
- *S. Hannestad, R. S. Hansen and T. Tram, Phys. Rev. Lett. 112 (2014) 031802*
- *B. Dasgupta and J. Kopp, Phys. Rev. Lett. 112 (2014) 031803.*
- *A. Mirizzi, G. Mangano, O. Pisanti and N. Saviano, Phys. Rev. D91 (2015) 025019*
- *J. F. Cherry, A. Friedland and I. M. Shoemaker, 1411.1071.*
- *X. Chu, B. Dasgupta and J. Kopp, JCAP 1510 (2015) 011.*
- *J. F. Cherry, A. Friedland and I. M. Shoemaker, 1605.06506.*
- *L. Vecchi, Phys. Rev. D94 (2016) 113015.*

ν - DM interaction may solve "missing satellite", "cusp-core" problems

- *D. Hooper, M. Kaplinghat, L. E. Strigari and K. M. Zurek, , Phys. Rev. D76 (2007) 103515.*
- *L. G. van den Aarssen, T. Bringmann and C. Pfrommer, Phys.Rev.Lett. 109 (2012) 231301.*
- *I. M. Shoemaker, Phys.Dark Univ. 2 (2013) 157–162.*
- *B. Bertoni, S. Ipek, D. McKeen and A. E. Nelson, JHEP 04 (2015) 170.*
- *T. Binder, L. Covi, A. Kamada, H. Murayama, T. Takahashi and N. Yoshida, 1602.07624.*

Constraints

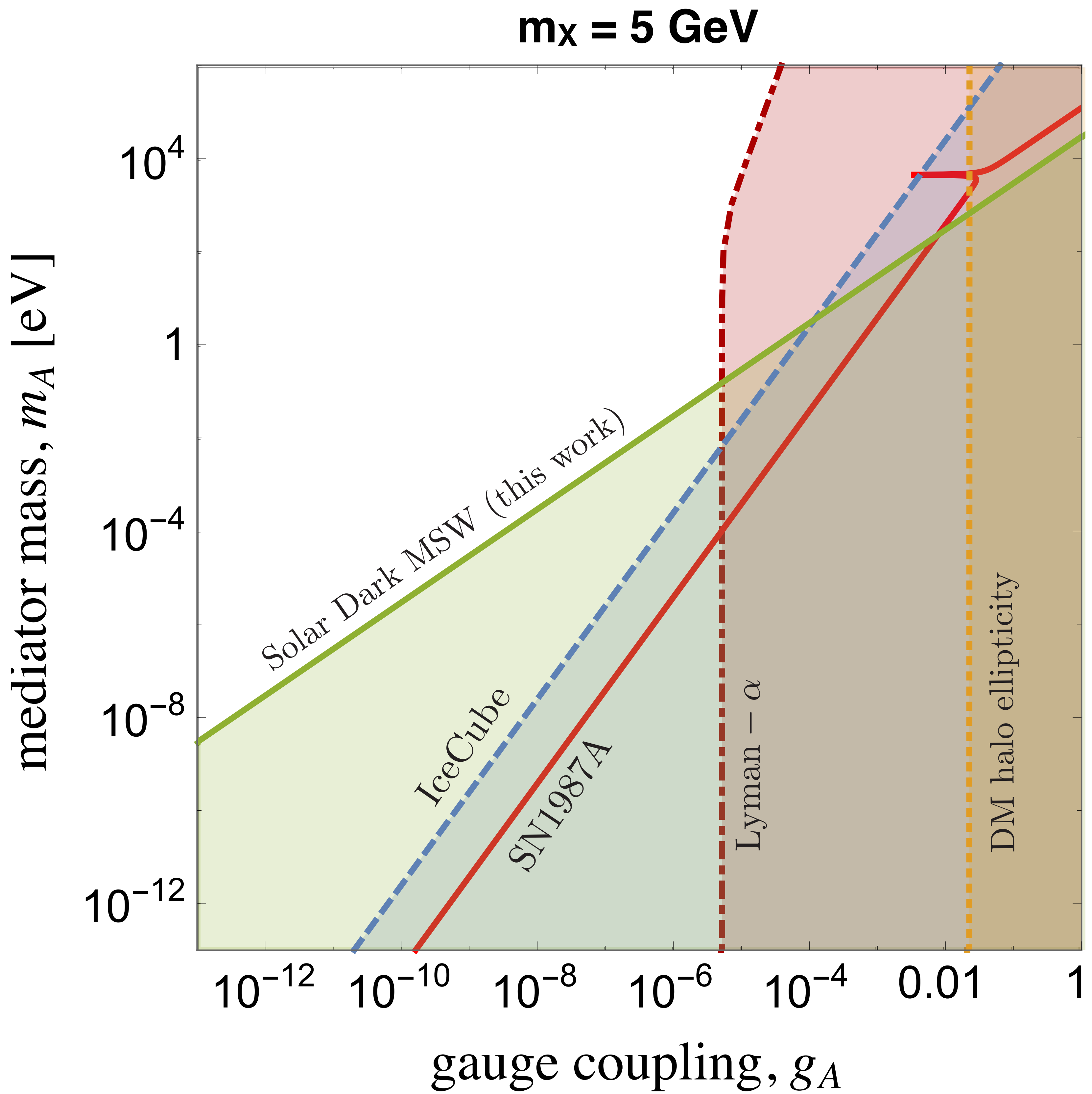
- Possibility that **active-sterile oscillations turned on after CMB**: no constraint from BBN or CMB.
  (L. Vecchi Phys. Rev. D 94 (2016) no.11, 113015)

- **UHEν interaction with CNB converts ν_a to ν_s, depleting ν_a from distant sources**: constraints from the isotropy observed by IceCube events.
  (J. F. Cherry, A. Friedland and I. Shoemaker, arXiv:1411.1071)

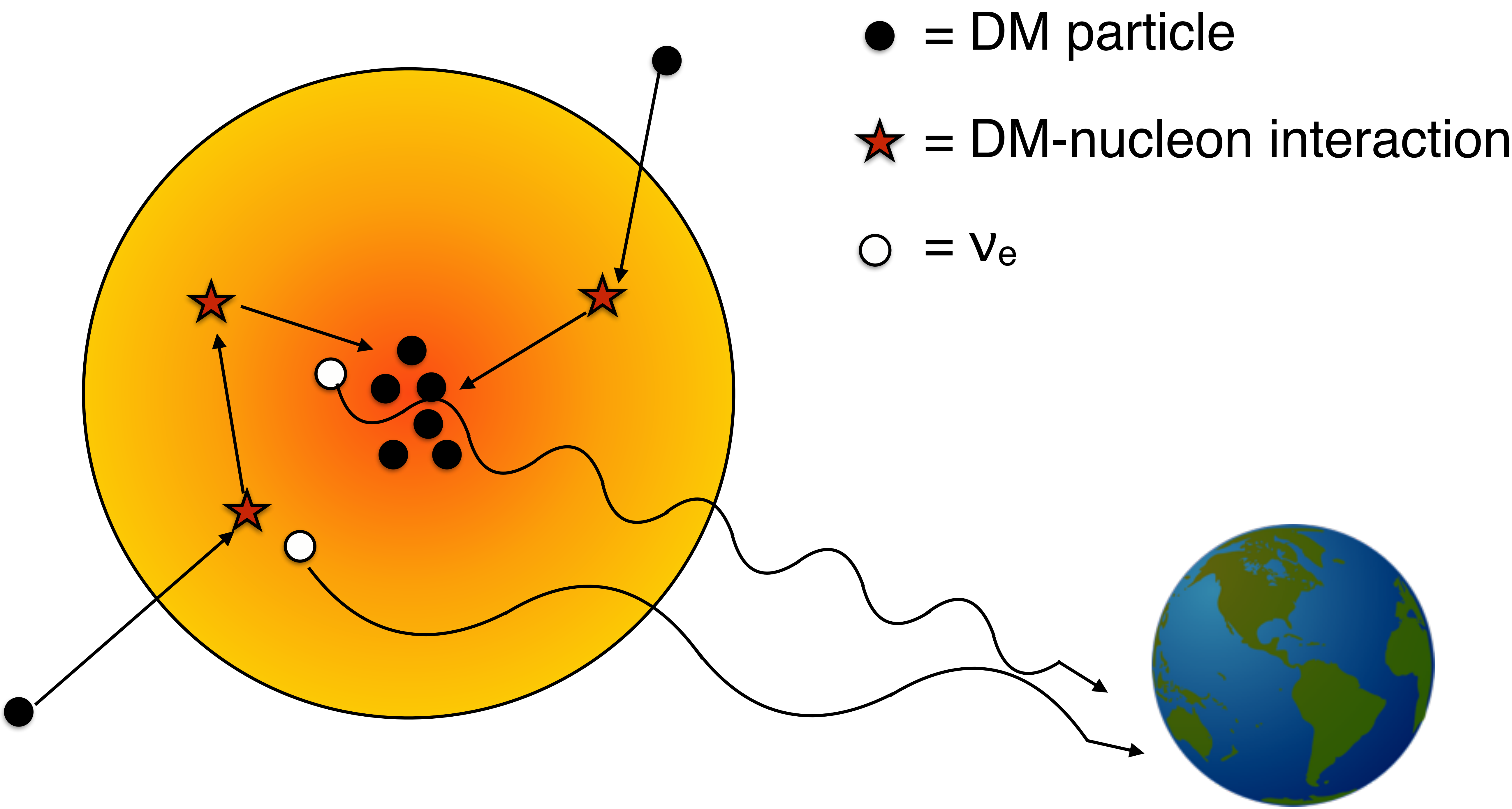
- **ν_s-DM or DM-DM interaction introduces a cutoff in the matter power spectrum**: contraints from Lyman-α ($M_{cut} < 5 \times 10^{10}\ M_\odot$).
  (L.G.van den Aarssen, T.Bringmann and C.Pfrommer, Phys. Rev. Lett. 109 (2012) 231301,
  D.Hooper, M.Kaplinghat, L.E.Strigari and K.M.Zurek, Phys. Rev. D 76 (2007) 103515)

- **DM-DM interaction modifies halo ellipticity, cluster mergers, as well as the mass profile of dwarf galaxies**.
  (P. Agrawal, F. Y. Cyr-Racine, L. Randall and J. Scholtz, arXiv:1610.04611)

Constraints



Possible signature: solar neutrinos



DM clusters in the core of the Sun. DM-ν_s interaction creates a **new matter potential which alters the expected number of ν_e observed on Earth**.

DM in the Sun

Neglecting DM annihilation (asymmetric DM), evaporation (M_X>4 GeV), and self-interactions, the equation describing DM clustering in the Sun is $N_X(t) = C\, t$:

(A. Gould, Astrophys.J. 321 (1987) 571)

$$N_X/N_e \sim 10^{-21}\left(\frac{\sigma_{nX}}{10^{-45}\mathrm{cm}^2}\right)$$

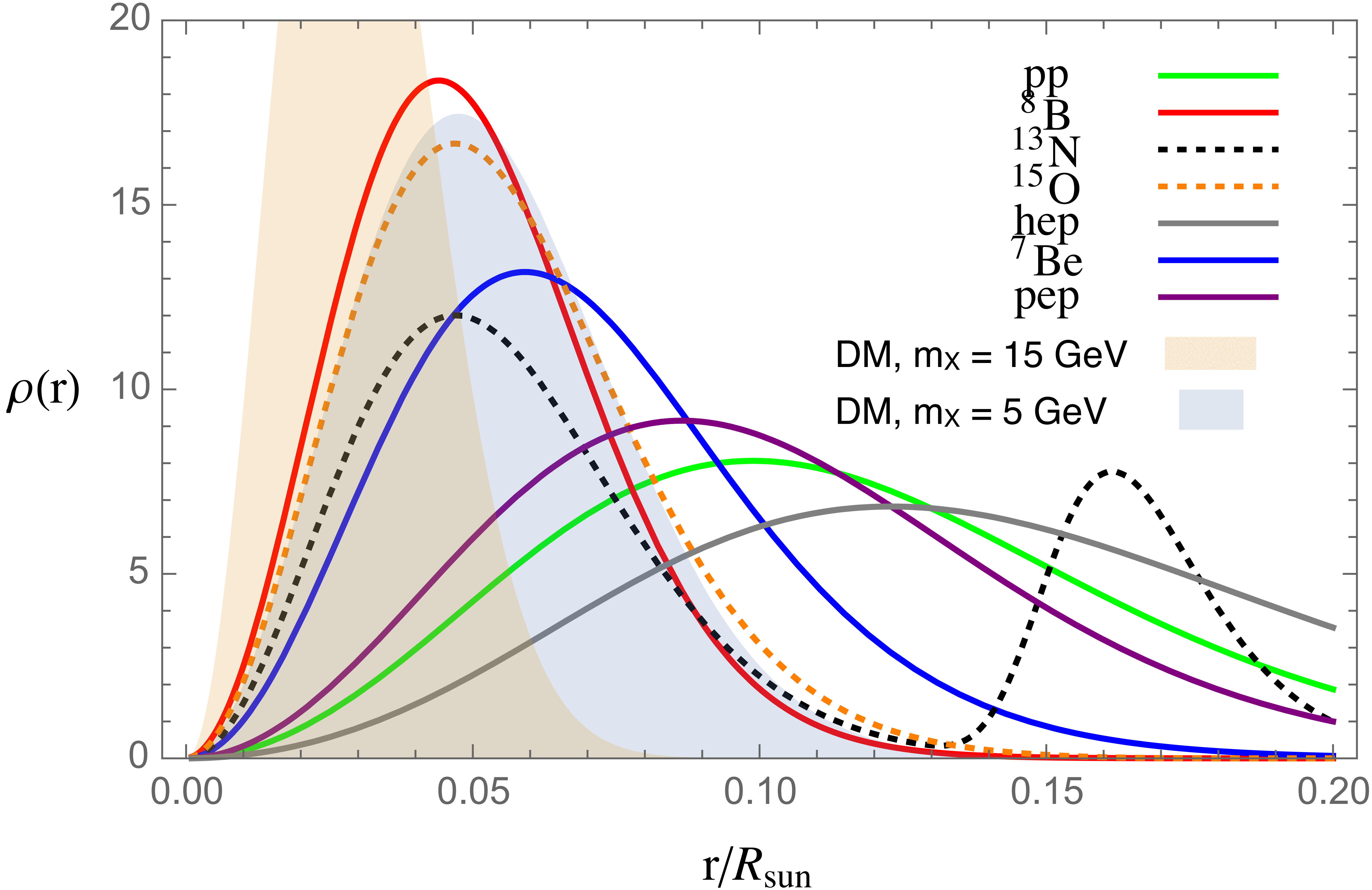
for spin-independent cross-section

After thermalization:

$$n_X(r) = \frac{N_X}{r_X^3\pi^{3/2}}e^{-r^2/r_X^2}$$

$$r_X(r) = \sqrt{\frac{3T_\odot}{2\pi G_N\rho_\odot m_X}} \sim 0.05\sqrt{\frac{5\mathrm{GeV}}{m_X}}R_\odot$$

DM in the Sun



20
15
10
5
0
$\rho(r)$
0.00
0.05
0.10
0.15
0.20
r/R_{sun}
pp
^8B
^{13}N
^{15}O
hep
^7Be
pep
DM, m_X = 15 GeV
DM, m_X = 5 GeV

New matter potential

The coherent scattering of active neutrinos, via oscillations into ν_s, is affected by DM. In the limit of zero average velocity of the DM: $\langle \overline{X} \gamma^\mu X \rangle = n_X \delta^{\mu 0}$ and

$$V_{\rm eff} = \epsilon_s \epsilon_X \frac{g_A^2}{\partial^2 + m_A^2} n_X .$$

If $m_A > 10^{-14}$ eV$\sqrt{m_X/5 \text{ GeV}}$ the **gradient of n_X can be neglected** (contact interaction)

$$V_{\rm eff} \simeq G_X n_X = \sqrt{2} \xi G_F n_e(0) e^{-r^2/r_X^2}$$

$$G_X = \epsilon_s \epsilon_X \frac{g_A^2}{m_A^2} \qquad \xi \equiv \frac{G_X n_X(0)}{\sqrt{2} G_F n_e(0)}$$

In this range of m_A, we can have **G_X >> G_F** in order to compensate small n_x ($\xi > 1$)

Neutrino oscillations: analytic approach

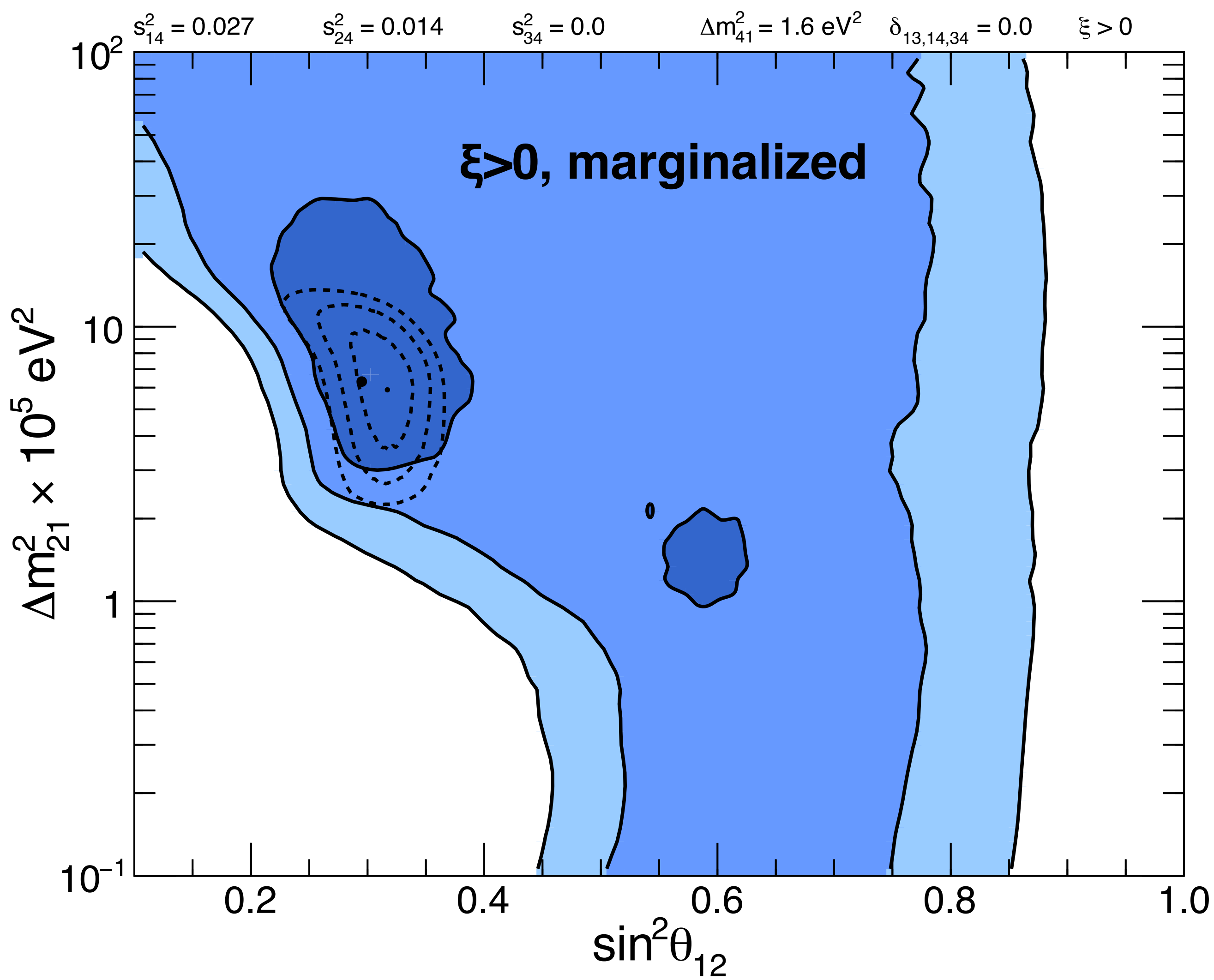
Assuming $\mathbf{\sin^2\theta_{i4}\, V_s < \Delta m^2_{31}}$, we have:

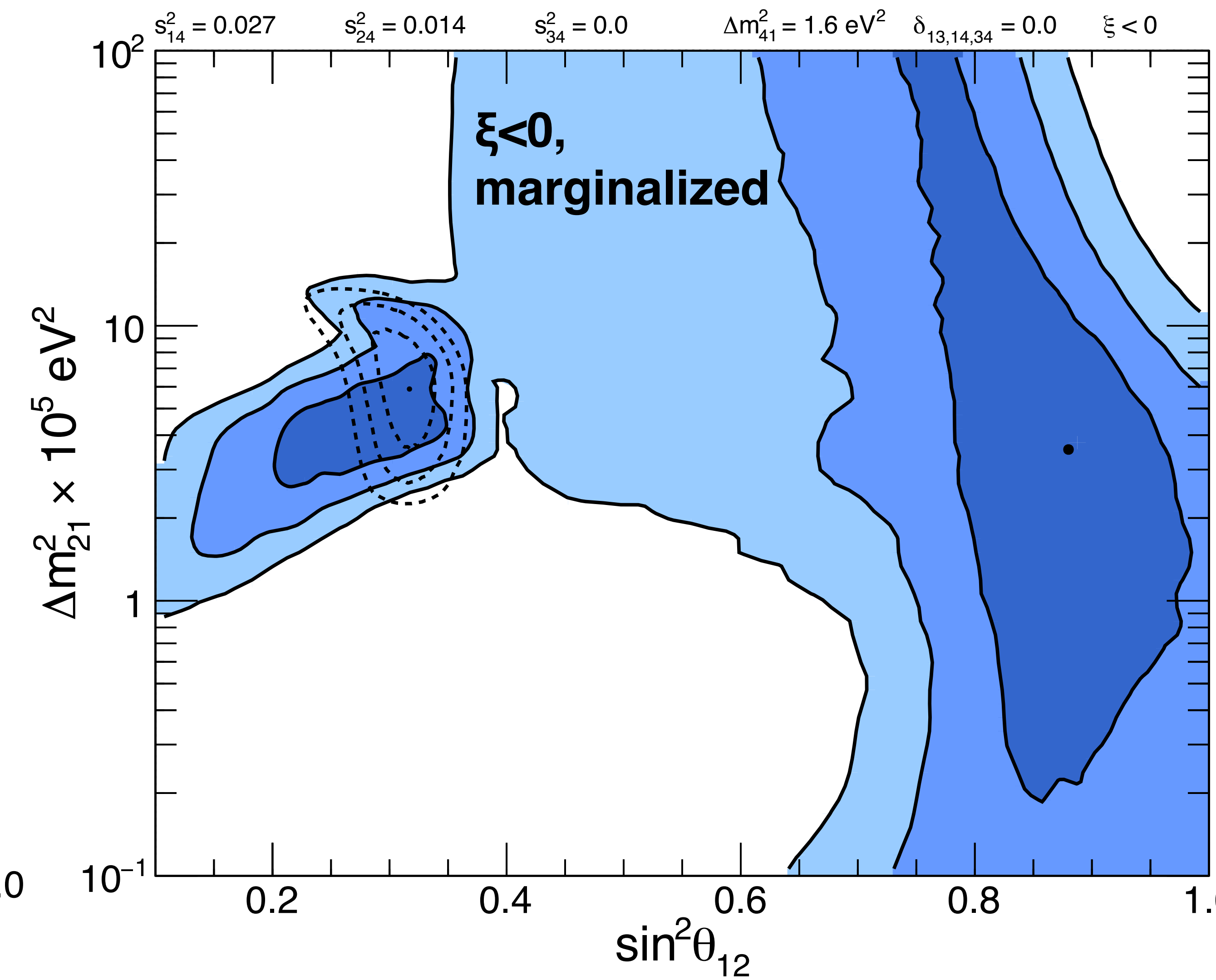
$$P_{ee,\mathrm{day}} = c_{13}^4 c_{14}^4 \frac{1}{2}\left(1+\cos 2\theta_{12}\cos 2\theta_m\right) + s_{13}^4 c_{14}^4 + s_{14}^4 + \mathcal{O}(s_{i4}^2 V_s E/\Delta m_{31}^2)$$

$$\cos 2\theta_m = \frac{\Delta \cos 2\theta_{12} - V_x}{\sqrt{|\Delta \sin 2\theta_{12} + V_y|^2 + (\Delta\cos 2\theta_{12} - V_x)^2}}$$

Constraints from solar neutrinos

We consider data on **^{8}B (SNO only), ^{7}Be and pep neutrinos**. pp neutrinos are almost unaffected by V_s. m_X is fixed to 5 GeV.





Presence of a Dark-LMA solution ($\theta_{12}>\pi/4$)

Comparison with NSI

$$H_{\rm NSI} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2} G_F \sum_{f=e,u,d} N_f(r) \begin{pmatrix} \epsilon^f_{ee} & \epsilon^f_{e\mu} & \epsilon^f_{e\tau} \\ \epsilon^{f*}_{e\mu} & \epsilon^f_{\mu\mu} & \epsilon^f_{\mu\tau} \\ \epsilon^{f*}_{e\tau} & \epsilon^{f*}_{\mu\tau} & \epsilon^f_{\tau\tau} \end{pmatrix}$$

In our model, in the limit sinθ—>0 and sinθ ξ held fixed, oscillations are described by the standard 3x3 Hamiltonian, plus:

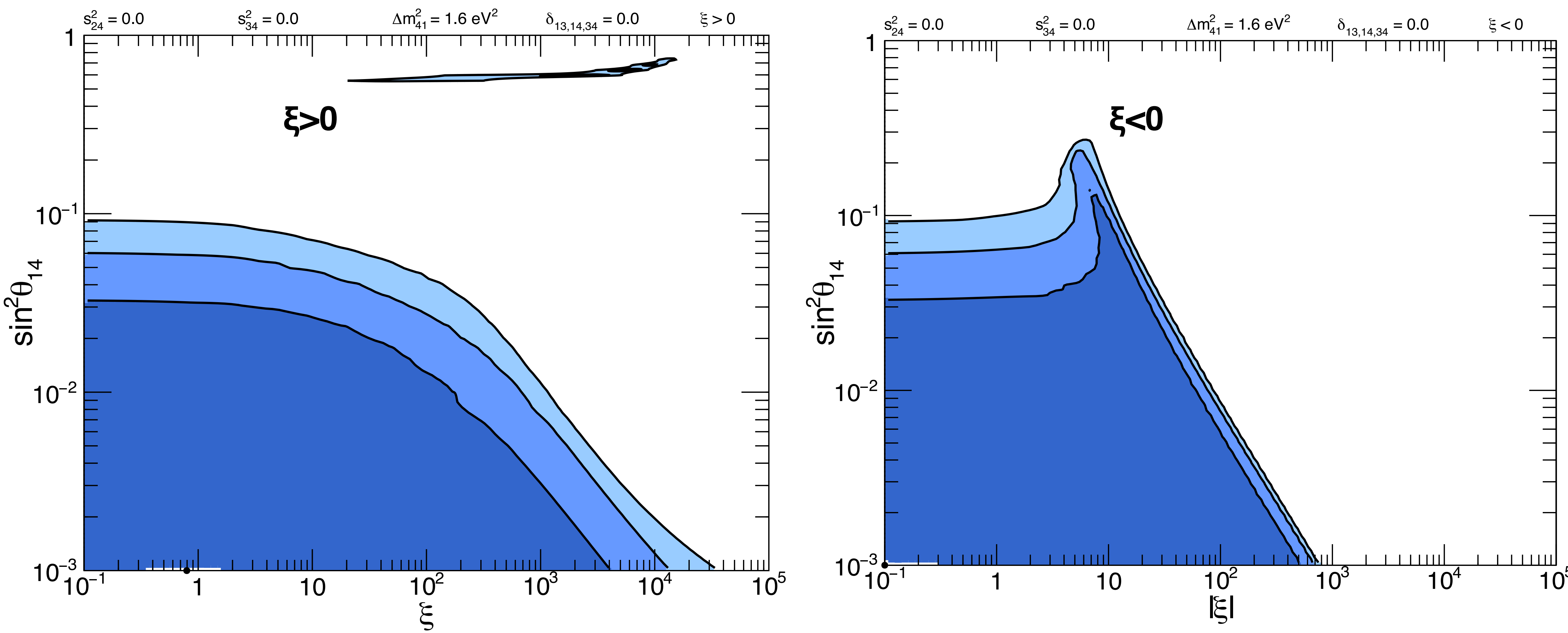
$$H^{\rm new}_{ij} = V_s (R_{34} R_{24} R_{14})^*_{4i} (R_{34} R_{24} R_{14})_{4j} \rightarrow \sqrt{2} \xi G_F n_e(0) e^{-r^2/r^2_X} \theta_{i4} \theta_{j4}$$

The potential **H_{new} has the same appearance of NSI**, provided we identify

$$\sqrt{2} \xi G_F n_e(0) e^{-r^2/r^2_X} \theta_{i4} \theta_{j4} = V_{\rm CC} \varepsilon_{ij}$$

Constraints from solar neutrinos

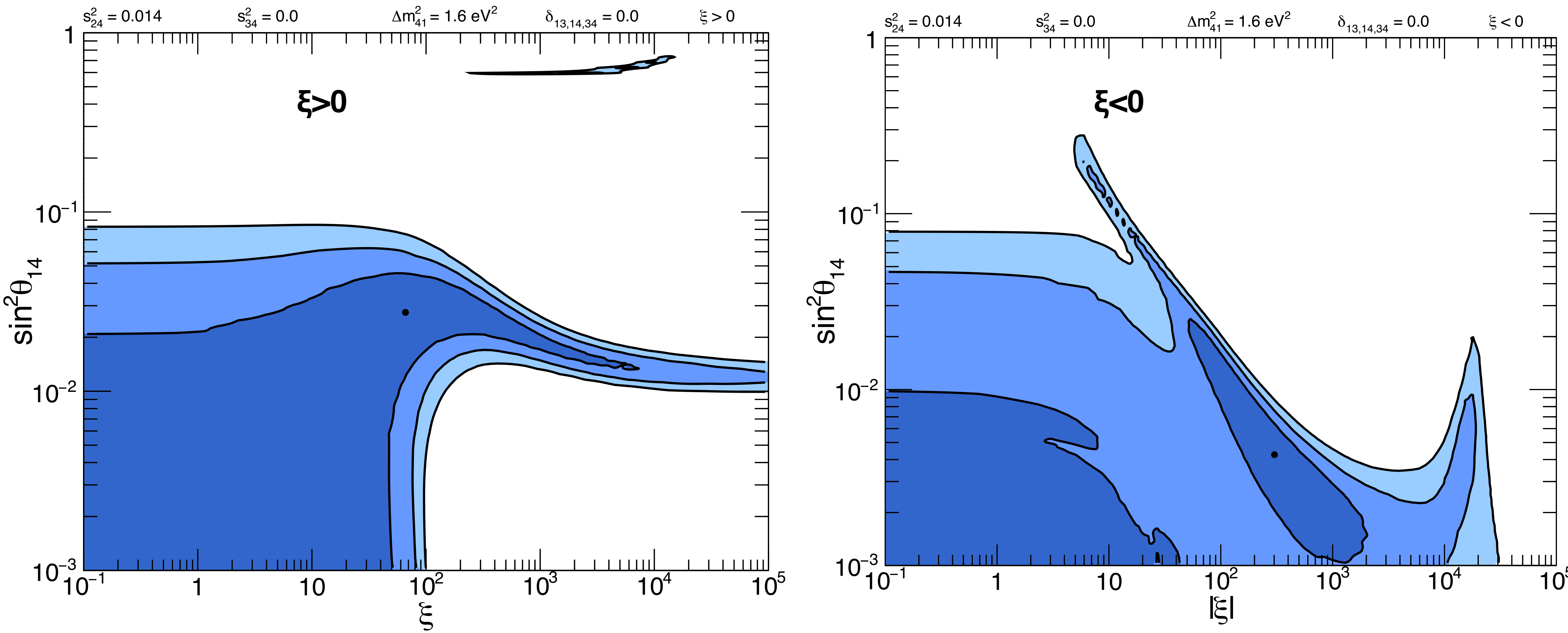
We **vary θ_{14} and ξ**, while $\theta_{24} = \theta_{34} = 0$. Solar parameters $(\Delta m^2_{21}, \theta_{12})$ held fixed to current global best fit.



Too large θ_{14} suppresses Pee.
$|\xi| \sin^2\theta_{14} < O(10)$

Constraints from solar neutrinos

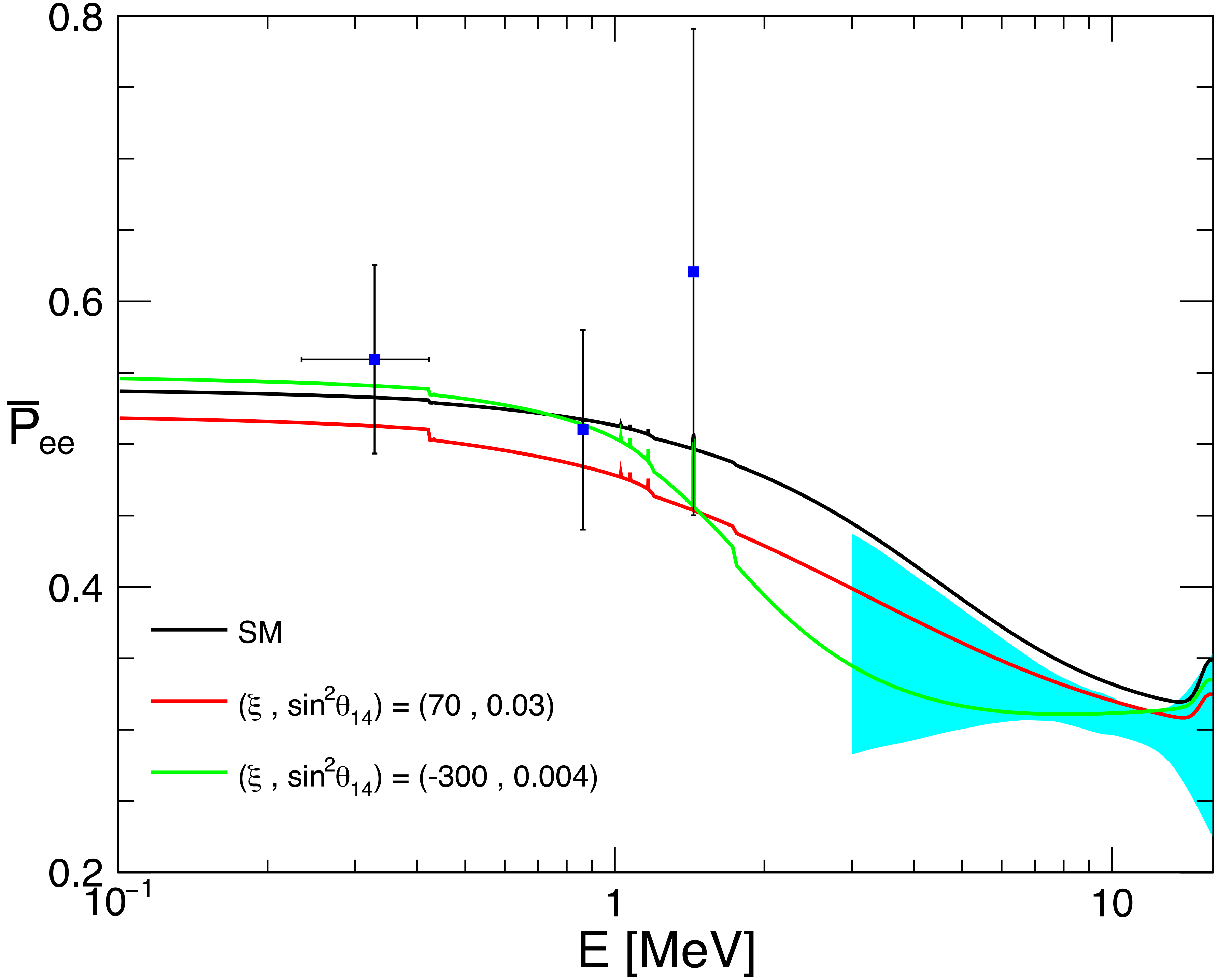
We **vary θ_{14} and ξ**, θ_{24} is fixed at SBL anomaly, while $\theta_{34} = 0$. Solar parameters ($\Delta m^2_{21}, \theta_{12}$) held fixed to current global best fit.



For large |ξ| there are regions of the parameter space where P_{ee} change abruptly

Constraints from solar neutrinos

$$\overline{P}_{ee}(E) = \int dr\, P_{ee,\text{day}}(r, E) \frac{\sum_i \phi_i(E)\rho_i(r)}{\sum_i \phi_i(E)}$$



Conclusions

- The **Sun might be a probe of neutrino-DM interactions**

- For sufficiently light exotic sectors, **G_X/G_F can be extremely large** and compensate the possibly small density of the DM

- It is mostly the physics of **^{8}B, ^{7}Be, and CNO neutrinos** that is modified

- $|\xi| \sin^2\theta_{14} < O(10)$

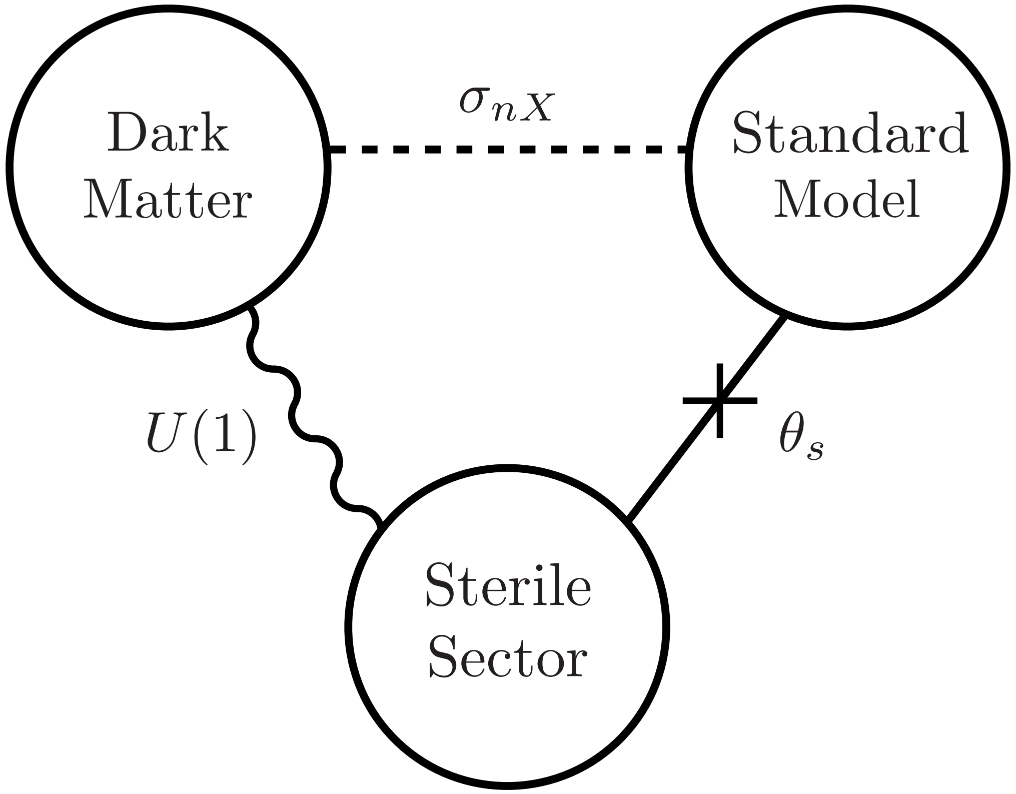
- Similarly to NSI, **a Dark-LMA solution** is mildly favored for $\xi < 0$

- Our framework **generalizes the more conventional neutrino-NSI**

Thank you

Backup

Model Lagrangian



N = SM singlet

ν_s = non sterile fermions coupling to U(1) gauge field A

ϕ = dark scalar with U(1) charge conjugate to ν_s

X = dark matter particle

$$\mathcal{L} \supset \overline{\nu_s} i\partial \nu_s + g_A A'_\mu J^\mu + y_s \overline{N} \phi \nu_s + y_a \overline{N} H L + \frac{m_N}{2} \overline{N} N^c + \mathrm{hc.}$$

$$J^\mu = \epsilon_s \overline{\nu_s} \gamma^\mu \nu_s + \epsilon_X \overline{X} \gamma^\mu X$$

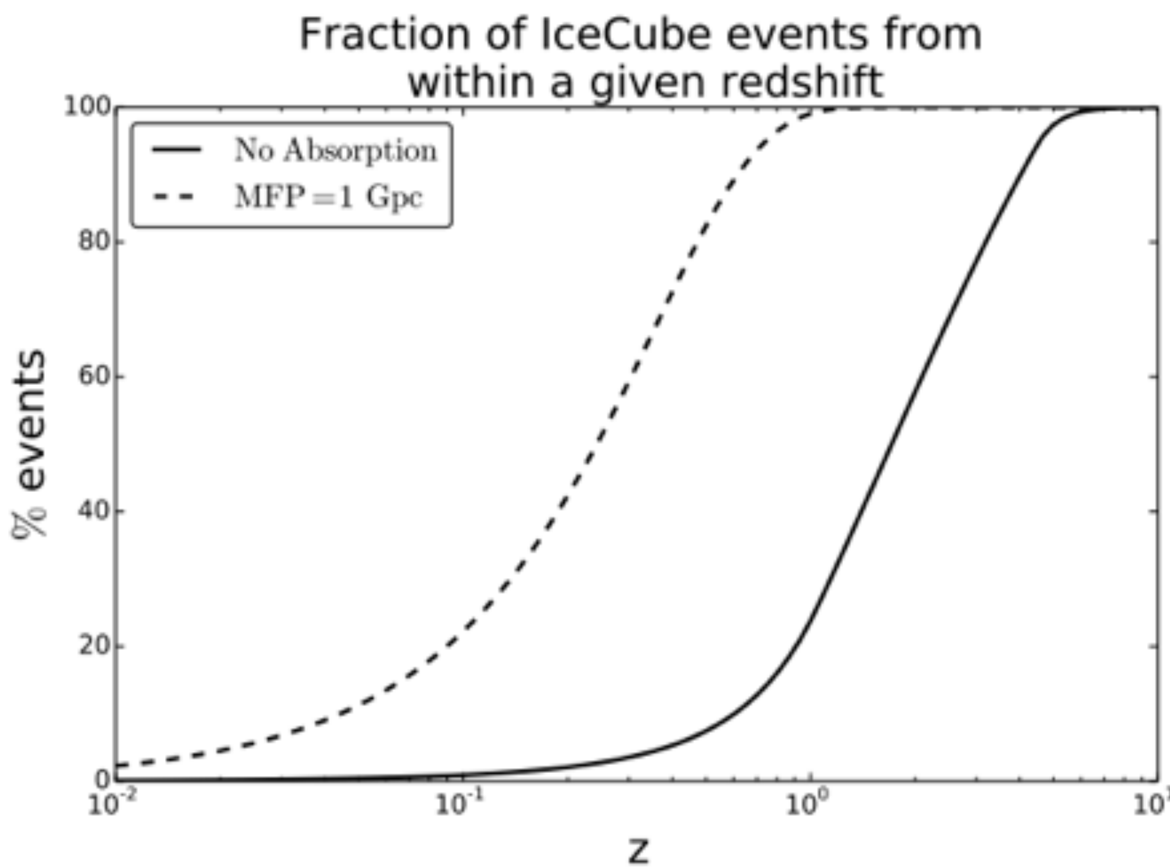
We assume ϕ acquires a vacuum expectation value which generates a mass m_A for A'_μ, as well as a N, ν_s mixing. Electroweak symmetry breaking the second line induces a mixing between active neutrinos and N.

$$\sin^2 \theta \sim \min(y_a \langle H \rangle / y_s \langle \phi \rangle, y_s \langle \phi \rangle / y_a \langle H \rangle)$$

Constraints

- **UHEν interaction with CNB converts ν_a to ν_s:** constraints from the isotropy observed by IceCube events.
  (J. F. Cherry, A. Friedland and I. Shoemaker, arXiv:1411.1071)

The MFP of high-energy neutrinos as they scatter on the CNB cannot be too short, as most of the flux originating at cosmological distances would not reach us.



J. F. Cherry, A. Friedland and I. M. Shoemaker, 1411.1071

Even if one boosts the flux emitted by the nearby sources by a large factor, the observed flux would look highly anisotropic

Constraints

- **ν_s-DM or DM-DM interaction introduces a cutoff in the matter power spectrum:** contraints from Lyman-α ($M_{cut} < 5 \times 10^{10}\ M_\odot$).
  (L.G.van den Aarssen, T.Bringmann and C.Pfrommer, Phys. Rev. Lett. 109 (2012) 231301, D.Hooper, M.Kaplinghat, L.E.Strigari and K.M.Zurek, Phys. Rev. D 76 (2007) 103515)

Structure cannot grow as long as the momentum-transfer rate exceeds the Hubble rate. We compute the momentum-transfer rate via

$$\gamma(T) = \sum_i \frac{g_i}{6 m_X T} \int_0^\infty \frac{d^3p}{(2\pi)^3} f_i(1 \pm f_i) \frac{p}{\sqrt{p^2 + m_i^2}} \int_{-4p^2}^0 dt(-t) \frac{d\sigma_{X+i \to X+i}}{dt}$$

T. Binder, L. Covi, A. Kamada, H. Murayama, T. Takahashi and N. Yoshida, 1602.07624.

The kinetic decoupling temperature is obtained by solving when the momentum transfer rate drops below the Hubble rate:

$$\gamma(T_{\mathrm{KD}}) = H(T_{\mathrm{KD}})$$

The mass of the largest gravitationally bound objects (i.e. the proto-halos) that can form causally is dictated by the mass enclosed in a Hubble volume at T_{KD}. We require $M < M(\text{Lyman-}\alpha) = 5 \times 10^{10}\ M_\odot$, which corresponds to $T_{KD} > 0.15$ KeV.

Neutrino oscillations

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & & & \\ & \Delta m^2_{21} & & \\ & & \Delta m^2_{31} & \\ & & & \Delta m^2_{41} \end{pmatrix} U^\dagger + \begin{pmatrix} V_{\mathrm{CC}} & & & \\ & 0 & & \\ & & 0 & \\ & & & V_s \end{pmatrix}, \qquad V_s = V_{\mathrm{eff}} - V_{\mathrm{NC}}$$

$$V_{\mathrm{eff}} = \sqrt{2}\xi G_F n_e(0) e^{-r^2/r_X^2}$$

$$\xi \equiv \frac{G_X n_X(0)}{\sqrt{2} G_F n_e(0)}$$

$$U = \tilde{R}_{34} R_{24} \tilde{R}_{14} R_{23} \tilde{R}_{13} R_{12}$$

Numerical analysis details

$$\chi^2(\mathbf{p}) = \chi^2_{\rm SNO}(\mathbf{p}) + \chi^2_{\rm Be7}(\mathbf{p}) + \chi^2_{\rm pep}(\mathbf{p})$$

$$\langle P^i_{ee}(\mathbf{p}, E)\rangle \equiv \int dr \rho_i(r) P_{ee}(\mathbf{p}, r, E)$$

$$\chi^2_{\rm Be7}(\mathbf{p}) = \left(\frac{\langle P^{^7{\rm Be}}_{ee}(\mathbf{p}, 862\ {\rm keV})\rangle - 0.51}{0.07}\right)^2$$

$$\chi^2_{\rm pep}(\mathbf{p}) = \left(\frac{\langle P^{\rm pep}_{ee}(\mathbf{p}, 1440\ {\rm keV})\rangle - 0.62}{0.17}\right)^2,$$

Numerical analysis details

$$\chi^2(\mathbf{p}) = \chi^2_{\rm SNO}(\mathbf{p}) + \chi^2_{\rm Be7}(\mathbf{p}) + \chi^2_{\rm pep}(\mathbf{p})$$

$$\langle P^i_{ee}(\mathbf{p},E)\rangle \equiv \int dr\,\rho_i(r) P_{ee}(\mathbf{p},r,E) \qquad \langle P^{\rm SNO}_{ee}(\mathbf{p},E)\rangle = \frac{\langle P^{^8\rm B}_{ee}(\mathbf{p},E)\rangle}{1-\langle P^{^8\rm B}_{es}(\mathbf{p},E)\rangle}$$

$$A(\mathbf{p},E) = 2\frac{\langle P^{^8\rm B}_{ee,\rm night}(\mathbf{p},E)\rangle - \langle P^{^8\rm B}_{ee,\rm day}(\mathbf{p},E)\rangle}{\langle P^{^8\rm B}_{ee,\rm night}(\mathbf{p},E)\rangle + \langle P^{^8\rm B}_{ee,\rm day}(\mathbf{p},E)\rangle}.$$

$$\chi^2_{\rm SNO}(\mathbf{p}) = \min_\Phi \left\{ \sum_{i,j=0}^{5} \left[a_i(\mathbf{p}) - a_i^{\rm SNO}\right] \Sigma^{-1}_{ij} \left[a_j(\mathbf{p}) - a_j^{\rm SNO}\right] + \chi^2_{\rm SSM}(\Phi) \right\}$$

a_1, a_2, a_3 derive from a quadratic fit of P_{ee}(day).

a_4, a_5, derive from a linear fit of A.

a_0 is the total ^{8}B flux Φ.

Σ is a correlation matrix given by the SNO collaboration

Neutrino oscillations: analytic approach

Assuming $\sin^2\theta_{i4}\, V_s < \Delta m^2_{31}$, we have:

$$P_{ee,\mathrm{day}} = c_{13}^4 c_{14}^4 \frac{1}{2}\left(1+\cos 2\theta_{12}\cos 2\theta_m\right) + s_{13}^4 c_{14}^4 + s_{14}^4 + \mathcal{O}(s_{i4}^2 V_s E/\Delta m_{31}^2)$$

$$\cos 2\theta_m = \frac{\Delta\cos 2\theta_{12} - V_x}{\sqrt{|\Delta \sin 2\theta_{12} + V_y|^2 + (\Delta\cos 2\theta_{12} - V_x)^2}}$$

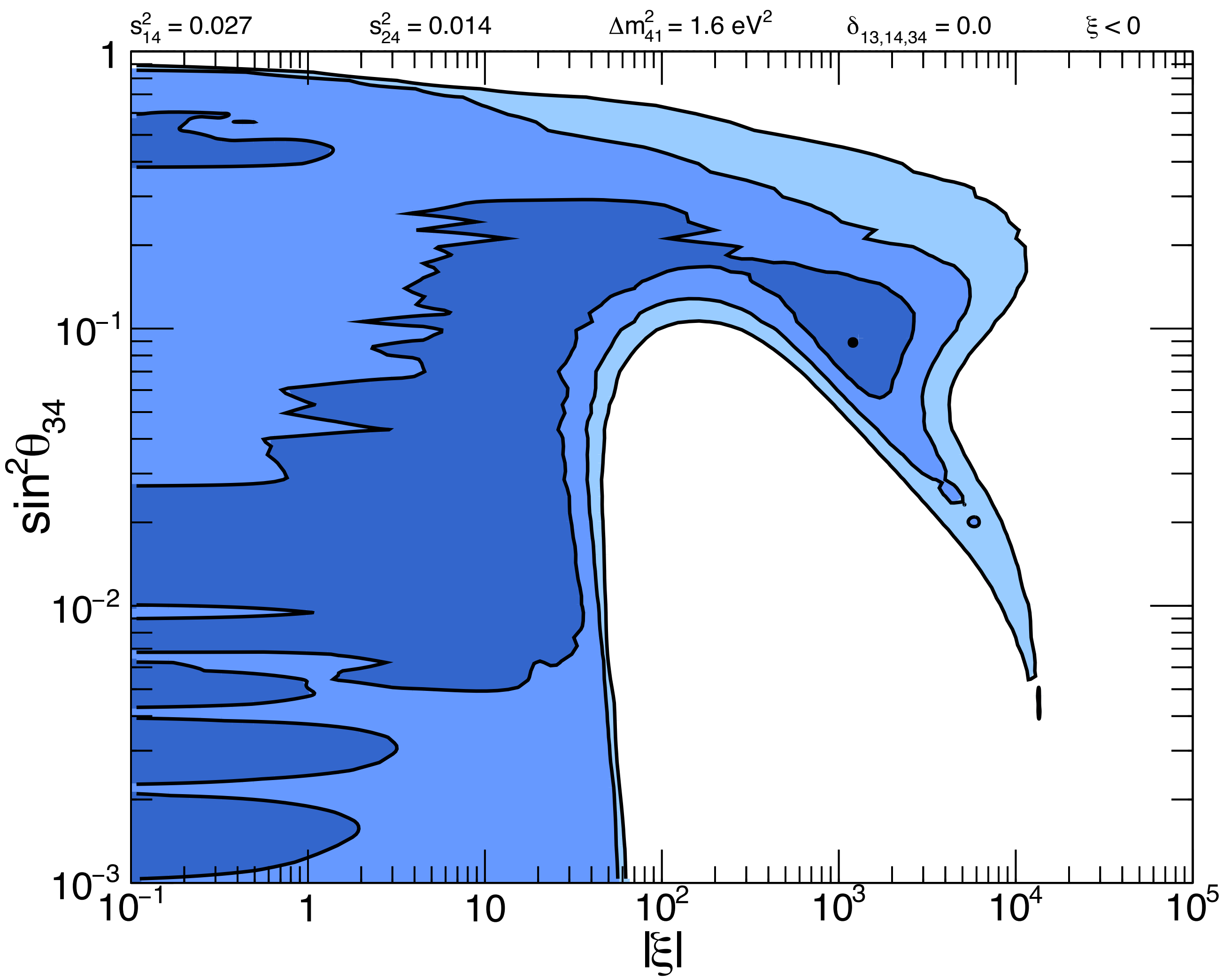
$$V_x = \frac{1}{2}\left[V_{\mathrm{CC}} c_{13}^2 c_{14}^2 + V_s\left(|A|^2 - |B|^2\right)\right]$$

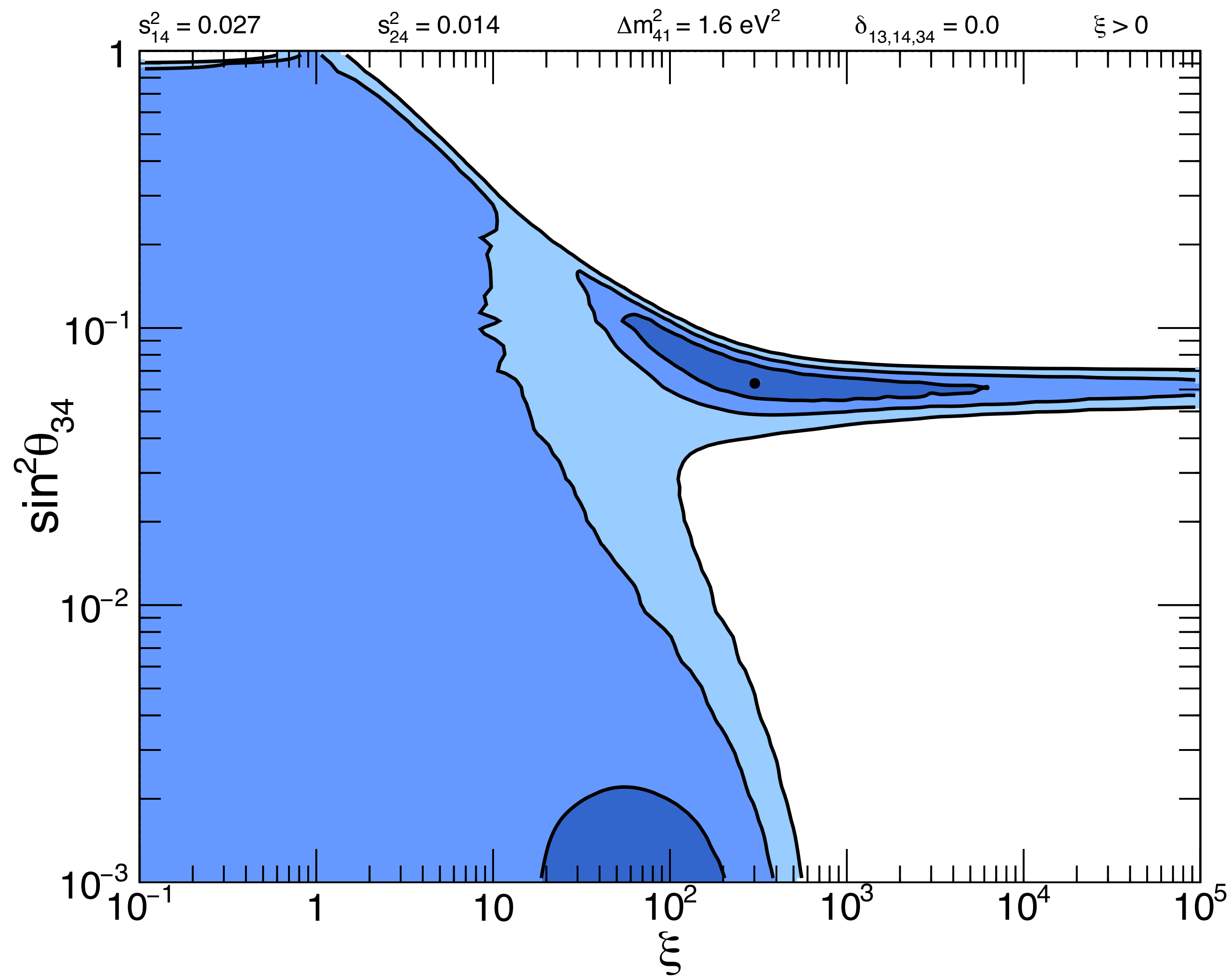
$$V_y = V_s A B$$

$$A = e^{-i\delta_{14}} c_{13} c_{24} c_{34} s_{14} - e^{-i\delta_{13}} s_{13}\left(c_{34} s_{23} s_{24} + e^{-i\delta_{34}} c_{23} s_{34}\right)$$

$$B = c_{23} c_{34} s_{24} - e^{i\delta_{34}} s_{23} s_{34}$$

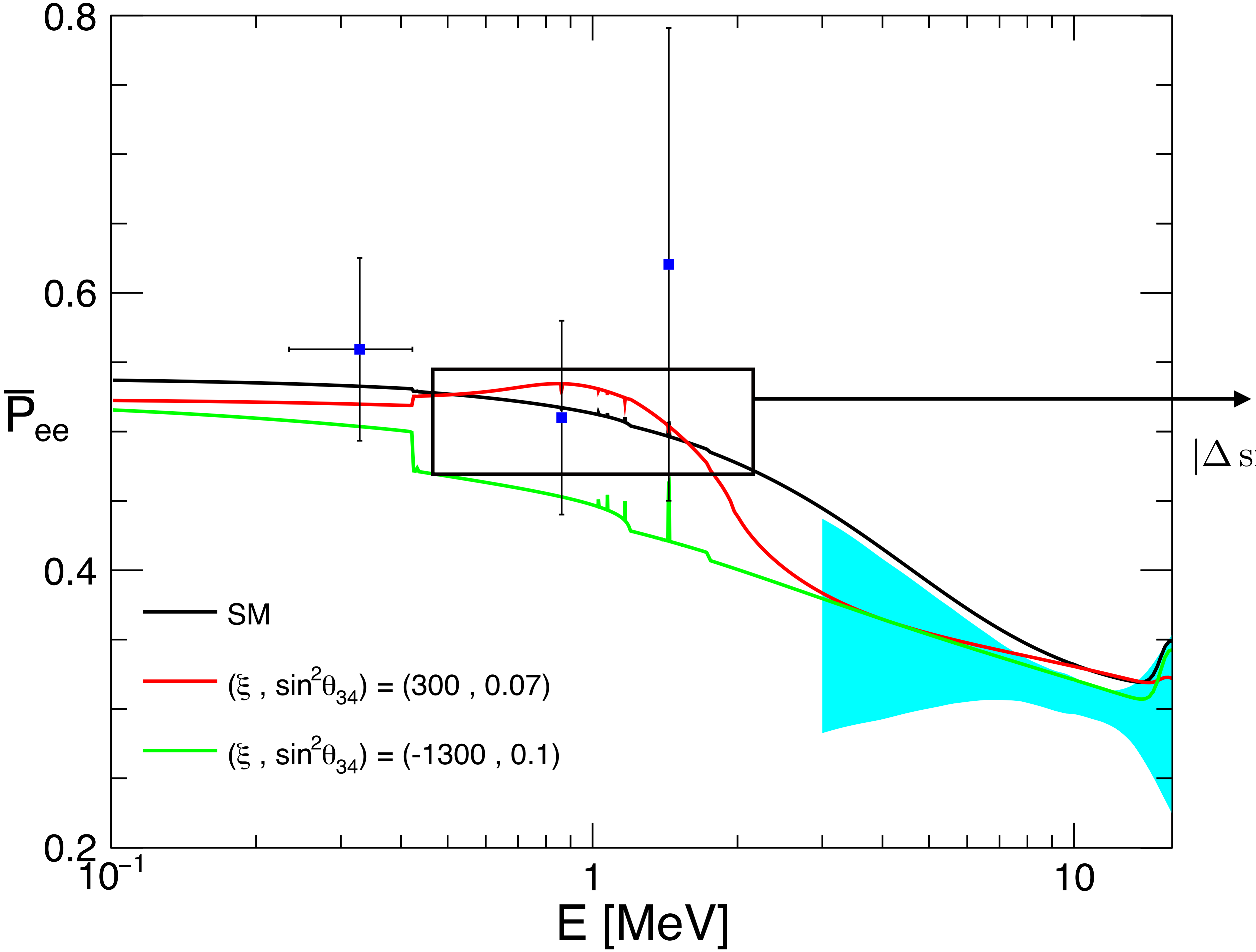
Constraints from solar neutrinos





Constraints from solar neutrinos

$$\overline{P}_{ee}(E) = \int dr\, P_{ee,\mathrm{day}}(r, E) \frac{\sum_i \phi_i(E)\rho_i(r)}{\sum_i \phi_i(E)}$$



$$P_{ee} \sim \cos^2\theta_{12}$$

$$|\Delta \sin 2\theta_{12} + V_y| \ll |\Delta \cos 2\theta_{12} - V_x|$$