Non-Sterile Neutrinos and the Dark MSW Effect

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(with F. Capozzi and I. Shoemaker)

Luca Vecchi

MPIK, Heidelberg

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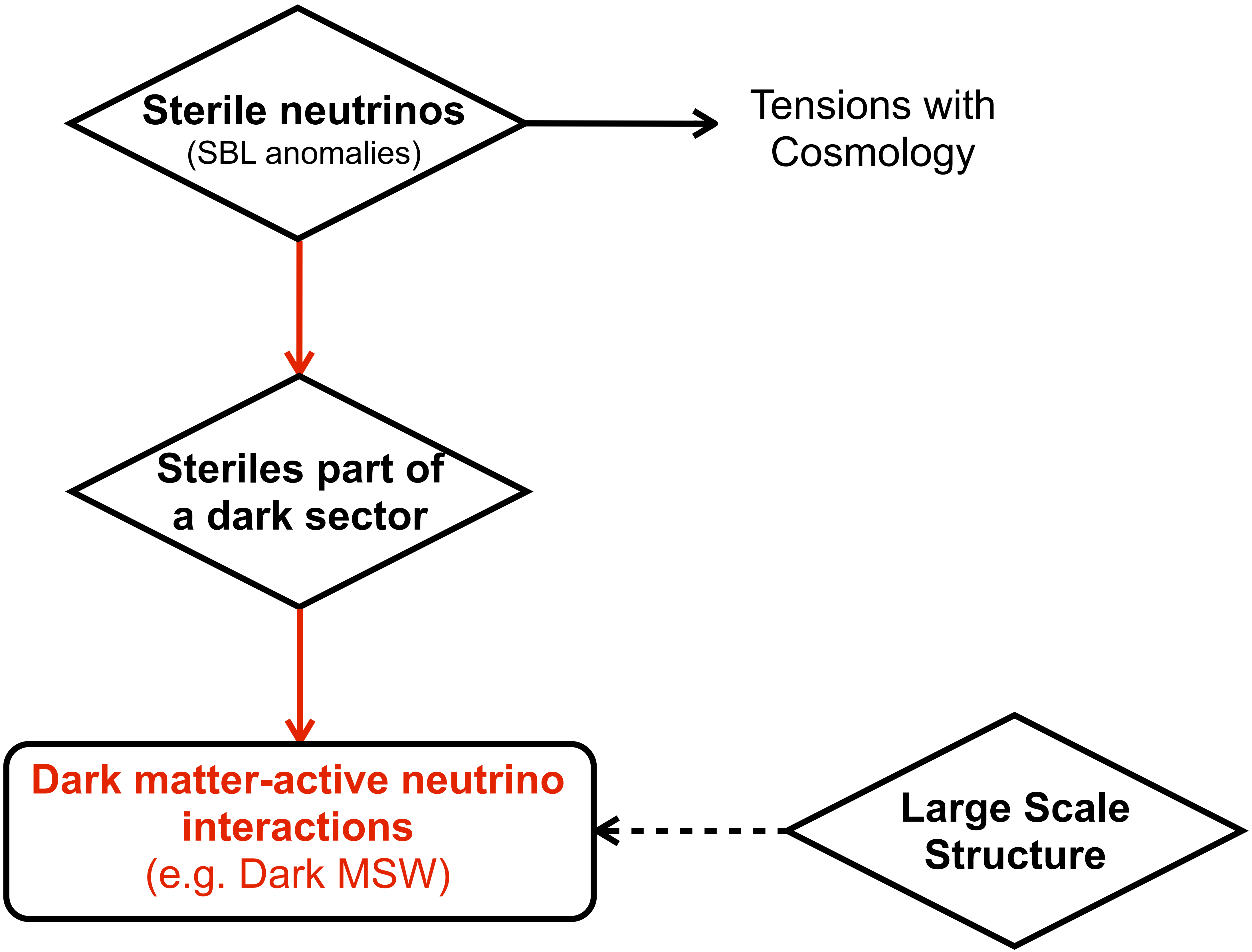
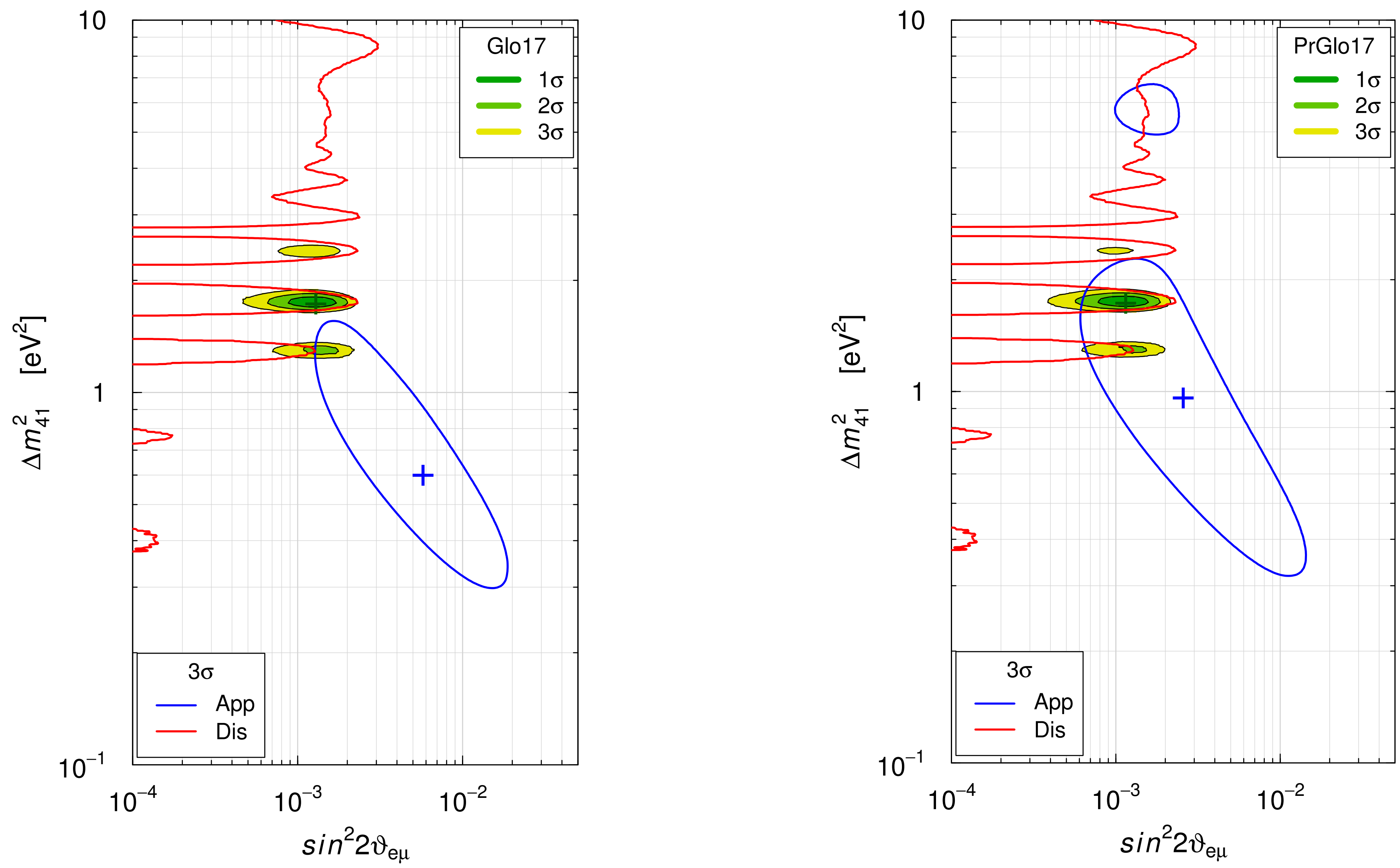
Flowchart


Sterile neutrinos
(SBL anomalies)
Tensions with
Cosmology
Steriles part of
a dark sector
Dark matter-active neutrino
interactions
(e.g. Dark MSW)
Large Scale
Structure

Light sterile neutrinos?

<u>Experimental reason</u>:
eV steriles behind SBL, reactor, Gallium anomalies?

3+1 model $\sin^2 2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$



Best fit:

$(\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu4}|^2)_{\rm bf} = (1.7\ {\rm eV}^2, 0.019, 0.015)$ Giunti et al. (2017)

Theoretical reason:

What new phenomena can be DISCOVERED in neutrino oscillations?

steriles can lead to sizable effects in oscillations and none elsewhere
(not a theorem, but hard to beat)

Why CMB & BBN data cannot robustly rule them out

The minimal model:
a gauge-singlet N

small

$$\delta\mathcal{L} = N^\dagger i\bar{\sigma}^\mu\partial_\mu N + \left(y_a NHL + \frac{m_N}{2}NN + \text{hc}\right)$$

Radiation at BBN & CMB and structure formation

$$\begin{cases} \Delta N_{\text{eff,BBN}} = 0.66 \pm 0.45 \\ \Delta N_{\text{eff,CMB}} = 0.10 \pm 0.23 \\ \sum_{\text{rel}} m_\nu < 0.3 \text{ eV} \end{cases}$$

Planck (2015)

Suppression of production via large lepton asymmetry:
Foot Volkas (95), Chu Cirelli (06), Krauss et al. (10), Hannestad et al. (12), Mirizzi et al. (12), ...
Dilution of the sterile population:
Gelmini Palomares-Ruiz Pascoli (04), Fuller et al. (11), Ho Scherrer (12), ...

LV (2016)

A chiral sterile
via the Dirac neutrino portal:

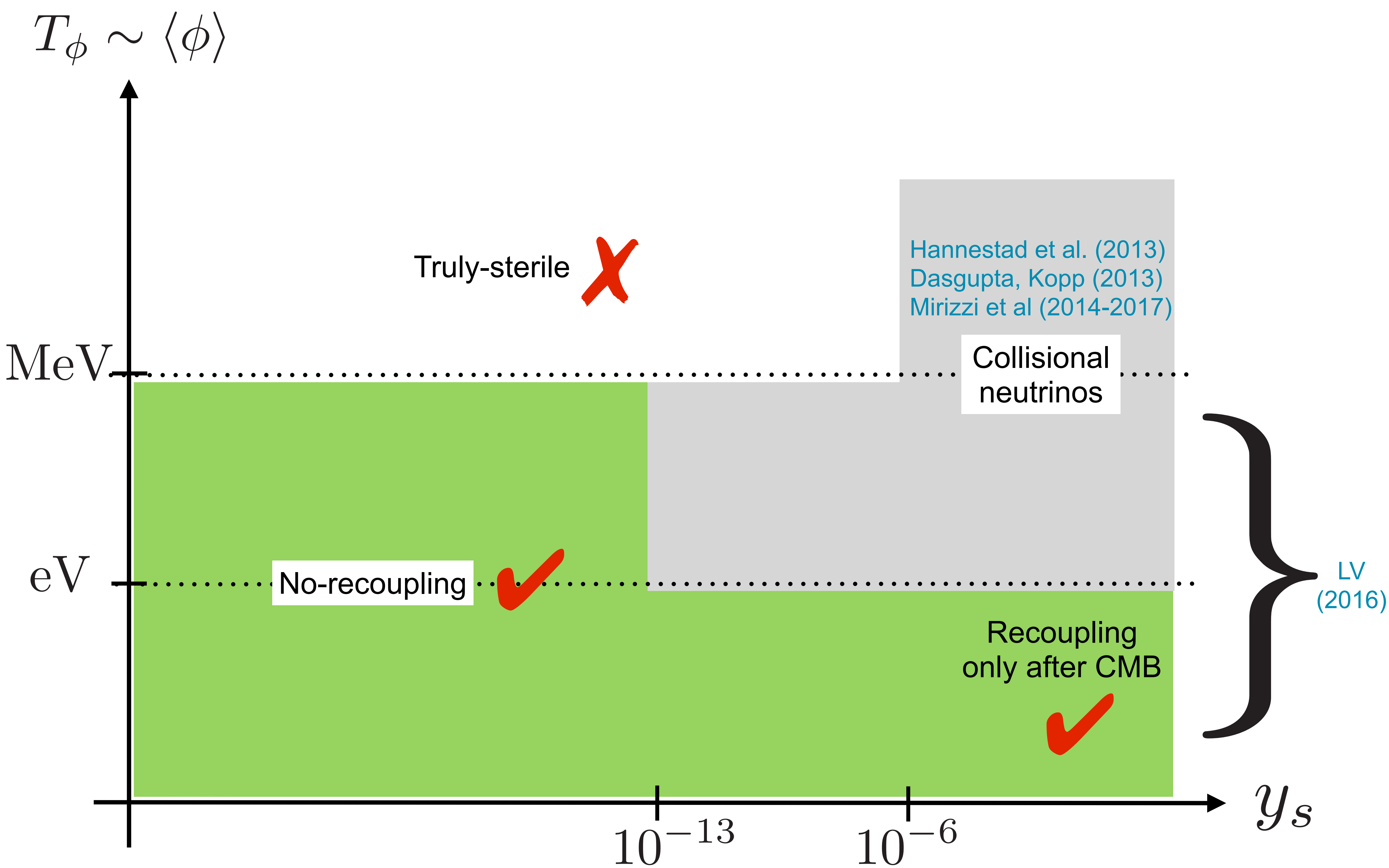
light sterile

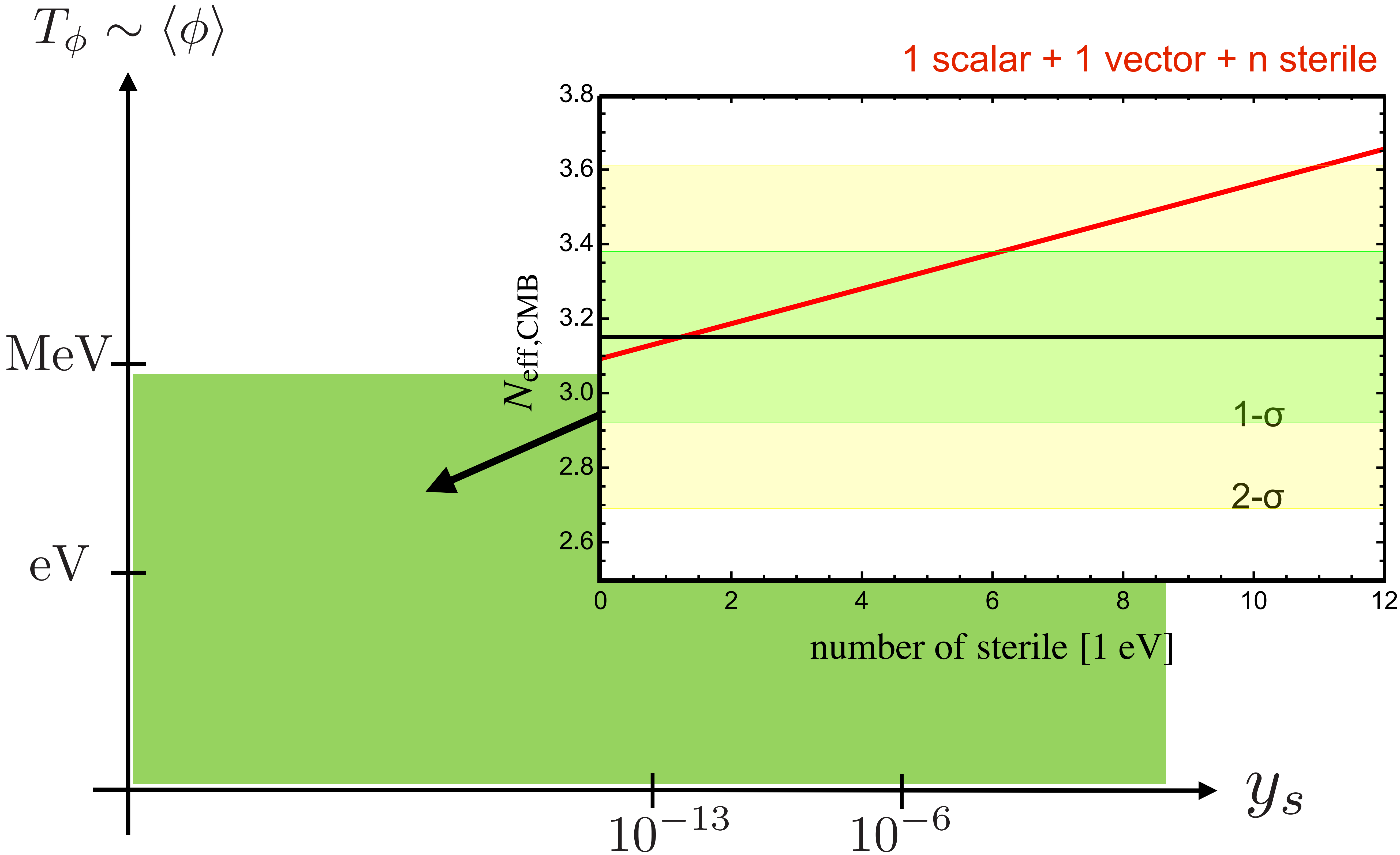
$$\mathcal{L} \supset y_a N H L + y_s N \phi \nu_s + \text{hc}$$

Dirac

1) N very weakly coupled to SM $\Longleftrightarrow$ the exotic sector is decoupled
2) Oscillations after symmetry breaking $\Longrightarrow$ **standard Cosmology for small <ϕ>**

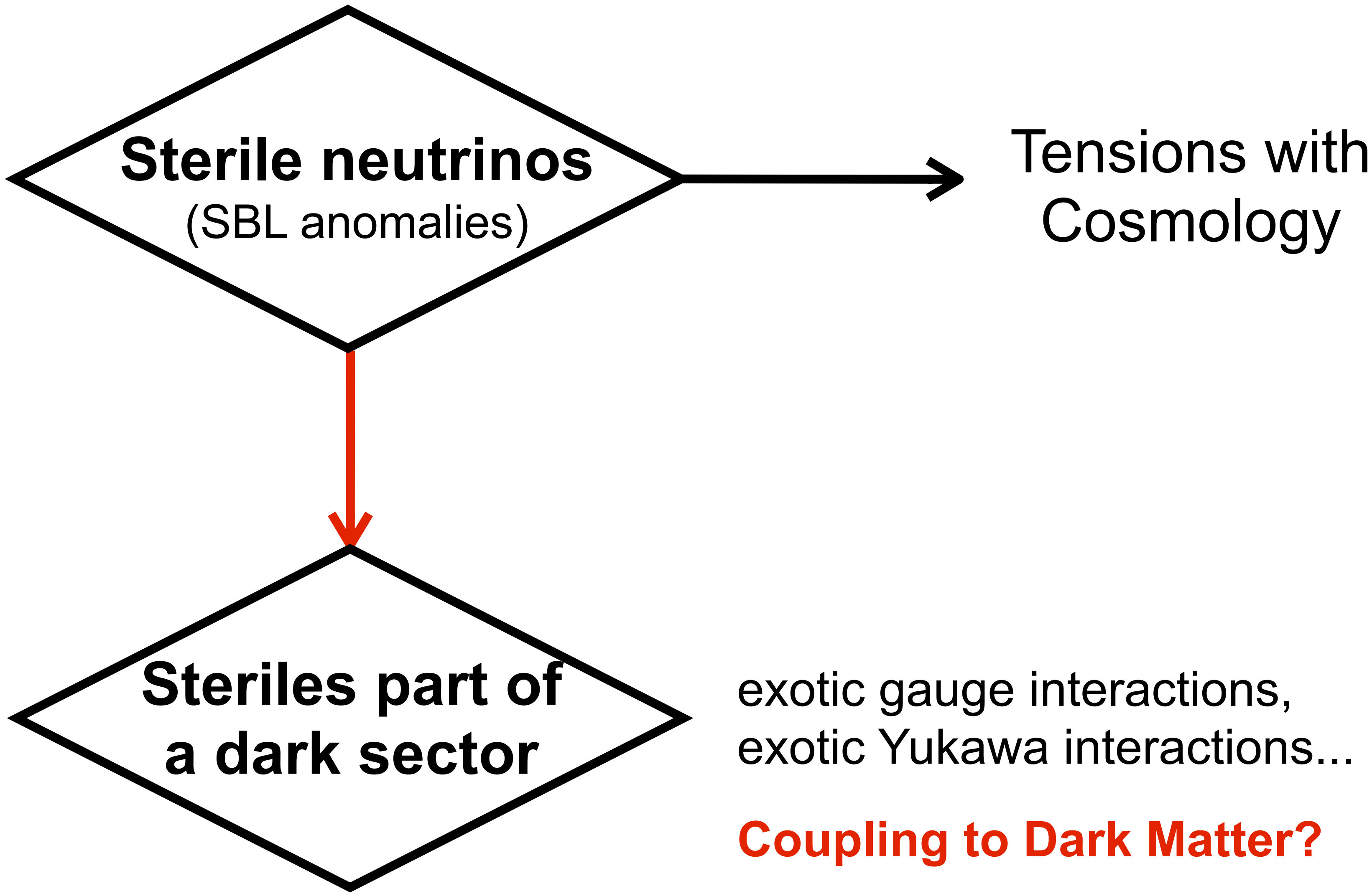
mixing: $\theta \sim \min\left(\frac{y\langle H\rangle}{y_s\langle\phi\rangle}, \frac{y_s\langle\phi\rangle}{y\langle H\rangle}\right)$ **KEY!**


$T_\phi \sim \langle \phi \rangle$
Truly-sterile
Hannestad et al. (2013)
Dasgupta, Kopp (2013)
Mirizzi et al (2014-2017)
MeV
Collisional neutrinos
eV
No-recoupling
LV (2016)
Recoupling only after CMB
10^{-13}
10^{-6}
y_s



$T_\phi \sim \langle\phi\rangle$
1 scalar + 1 vector + n sterile
3.8
3.6
3.4
3.2
3.0
2.8
2.6
$N_{\mathrm{eff,CMB}}$
1-σ
2-σ
0
2
4
6
8
10
12
number of sterile [1 eV]
MeV
eV
y_s
10^{-13}
10^{-6}

This motivates steriles with exotic interactions...



exotic gauge interactions,
exotic Yukawa interactions...

Coupling to Dark Matter?

Signatures of Sterile neutrinos-Dark Matter interactions

Benchmark model:

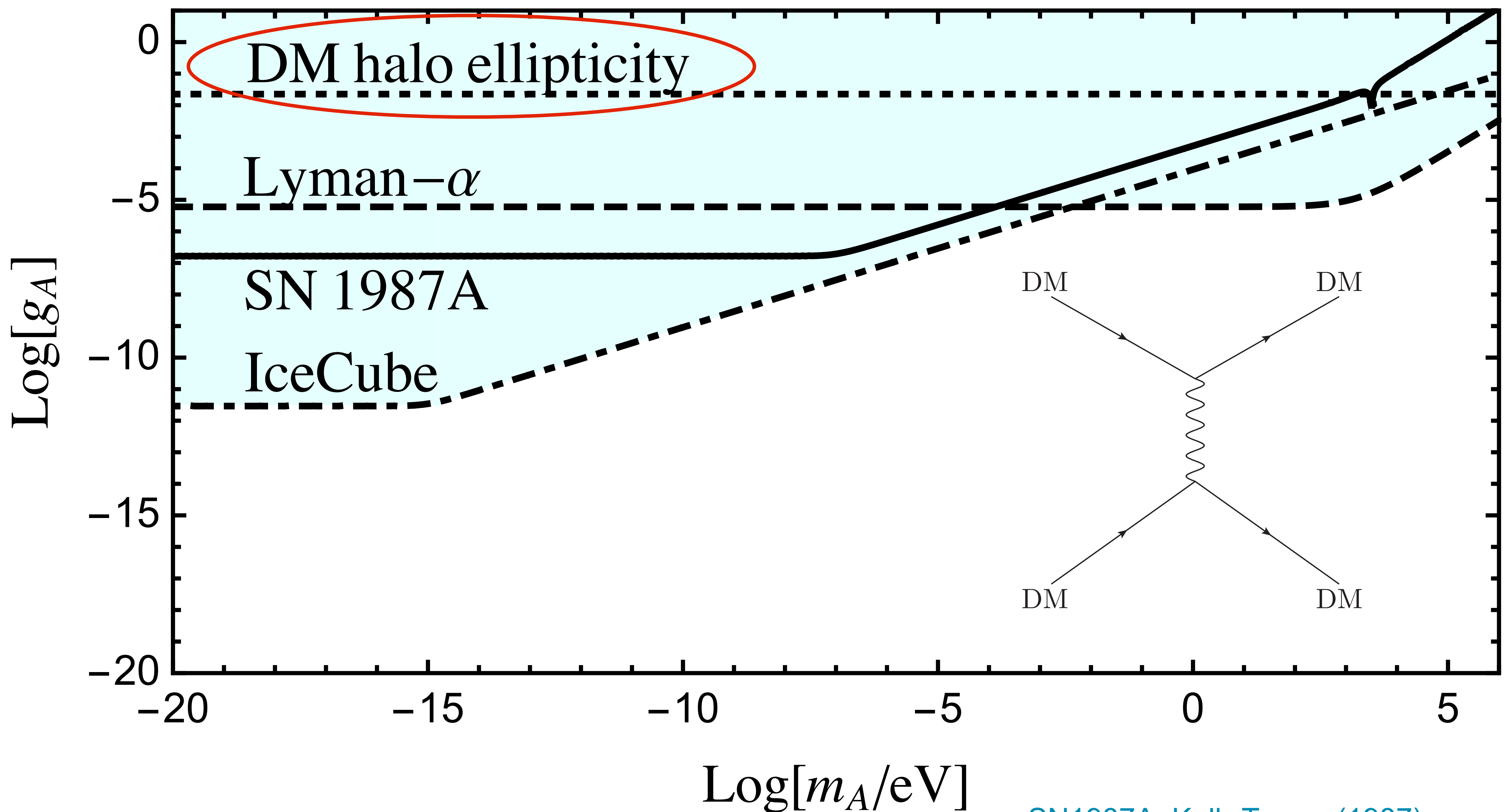
$$\mathcal{L} \supset \nu_s^\dagger \bar{\sigma}^\mu i(\partial_\mu + i q_s g_A A_\mu)\nu_s + y_a N H L + y_s N \phi \nu_s + \text{hc}$$
$$+ X^\dagger \bar{\sigma}^\mu i(\partial_\mu + i q_X g_A A_\mu) X + \cdots$$

Dark Matter

Steriles-Dark Matter interactions

Benchmark values

$m_{\rm DM} = 5 \text{ GeV} \quad m_4 = 1 \text{ eV} \quad s_{i4} = 0.1$



SN1987A: Kolb-Turner (1987)
Lyman-α: van der Aarssen et al (2012)
IceCube (PeV): Cherry et al. (2014), etc.
DM Halo: Agrawal et al. (2016) -- most recent

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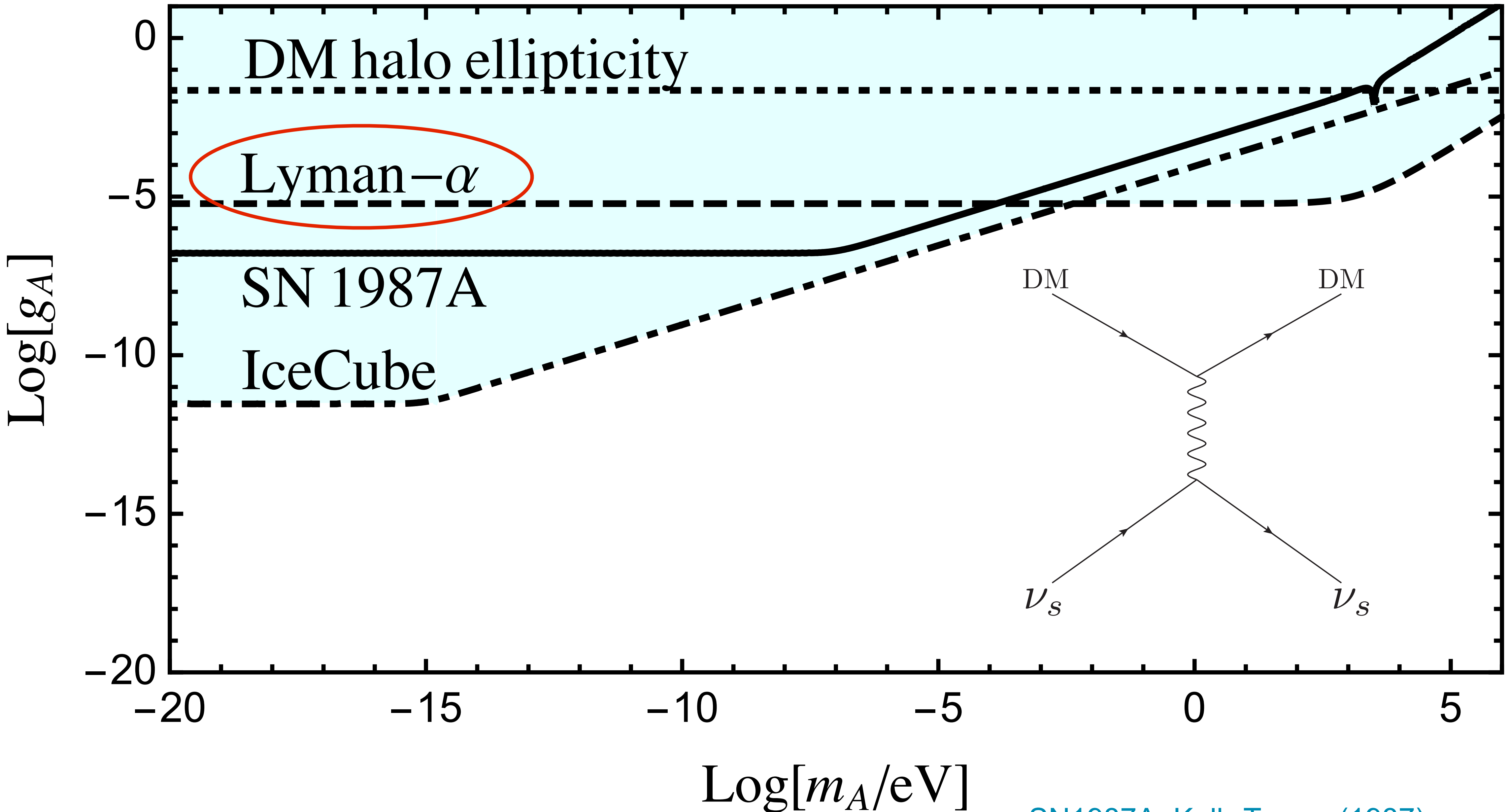

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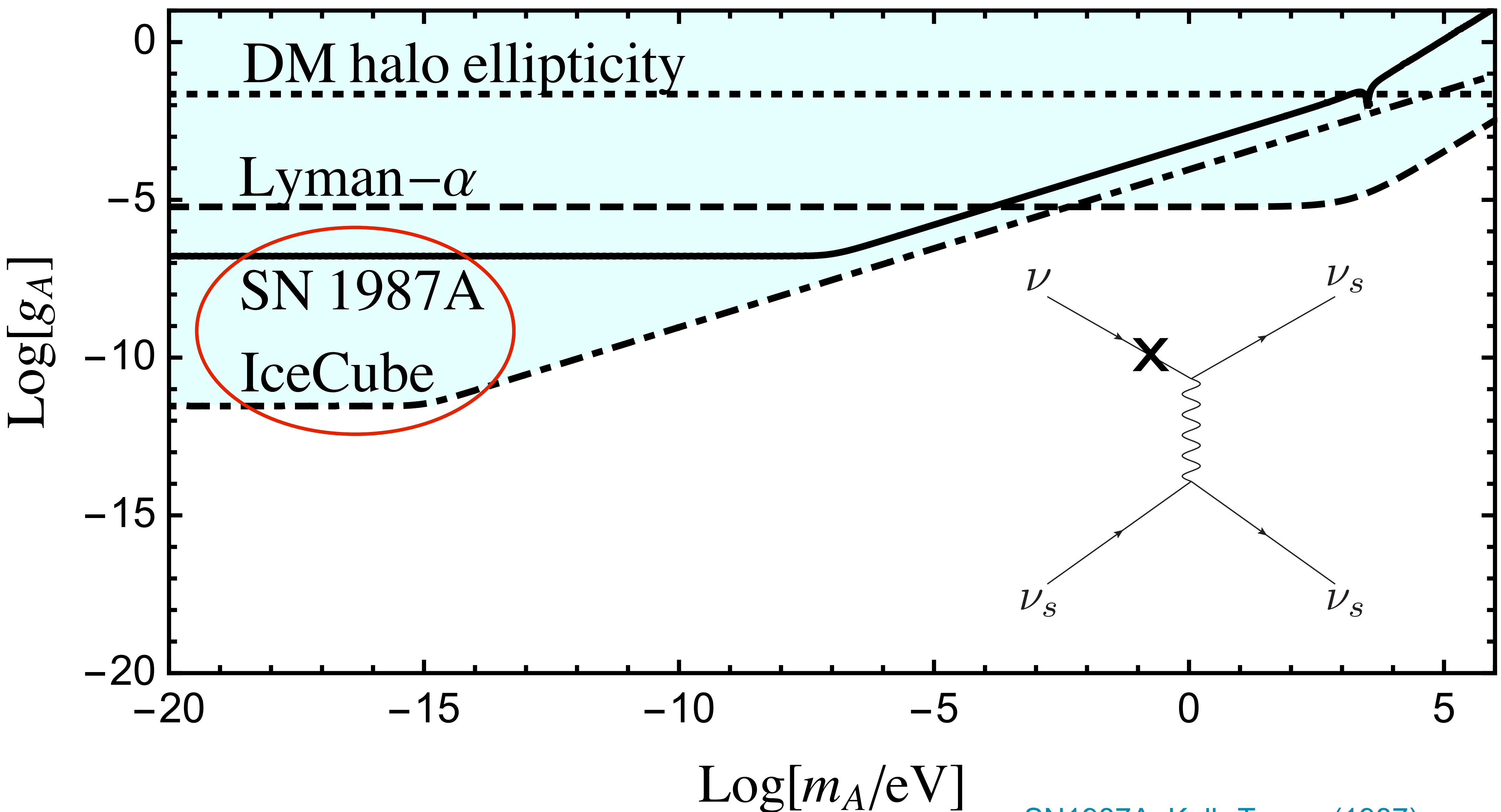

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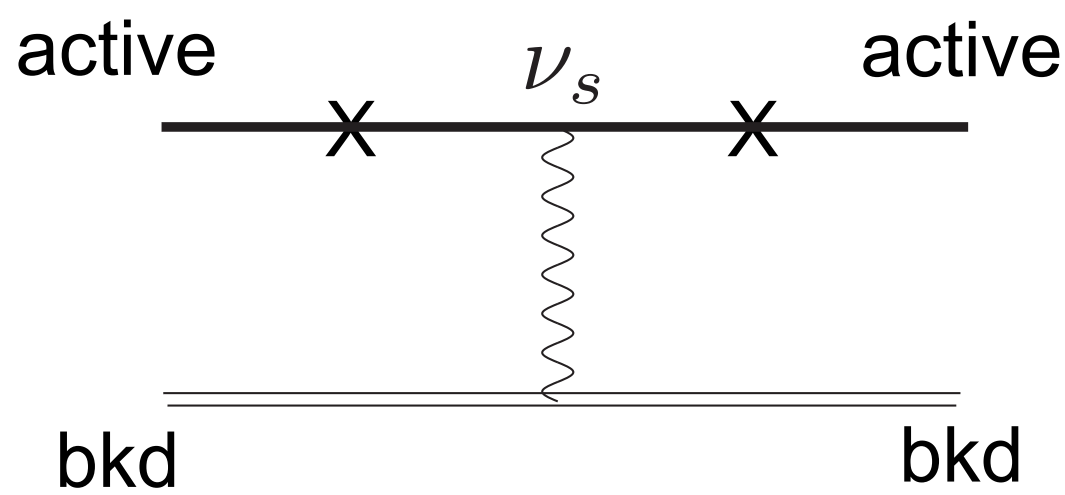
Dark MSW effect: Steriles-mediated potentials

with (asymmetric) cosmic neutrinos, Dark Matter, ordinary matter (not easy).

Ordinary matter:
Pospelov (2011)
Kopp et al. (2014)

Dark matter:
Capozzi et al. (2017)



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

$$V_s = \sqrt{2} G_F \frac{1}{2} n_n + V_{s,\rm new}$$

→ **Non-sterile effect**

$$V_{s,\mathrm{new}} = g_A A^0$$
$$\sim \frac{g_A^2}{\partial^2 + m_A^2} n_{\mathrm{bkd}}$$

Asymmetric Dark matter (net charge)

Nussinov (1985)
D.B. Kaplan (1992)
D.E. Kaplan et al. (2009), etc.
...

$$V_{s,\text{new}} = g_A A^0$$

$$\sim \frac{g_A^2}{\partial^2 + m_A^2} n_{\text{bkd}}$$

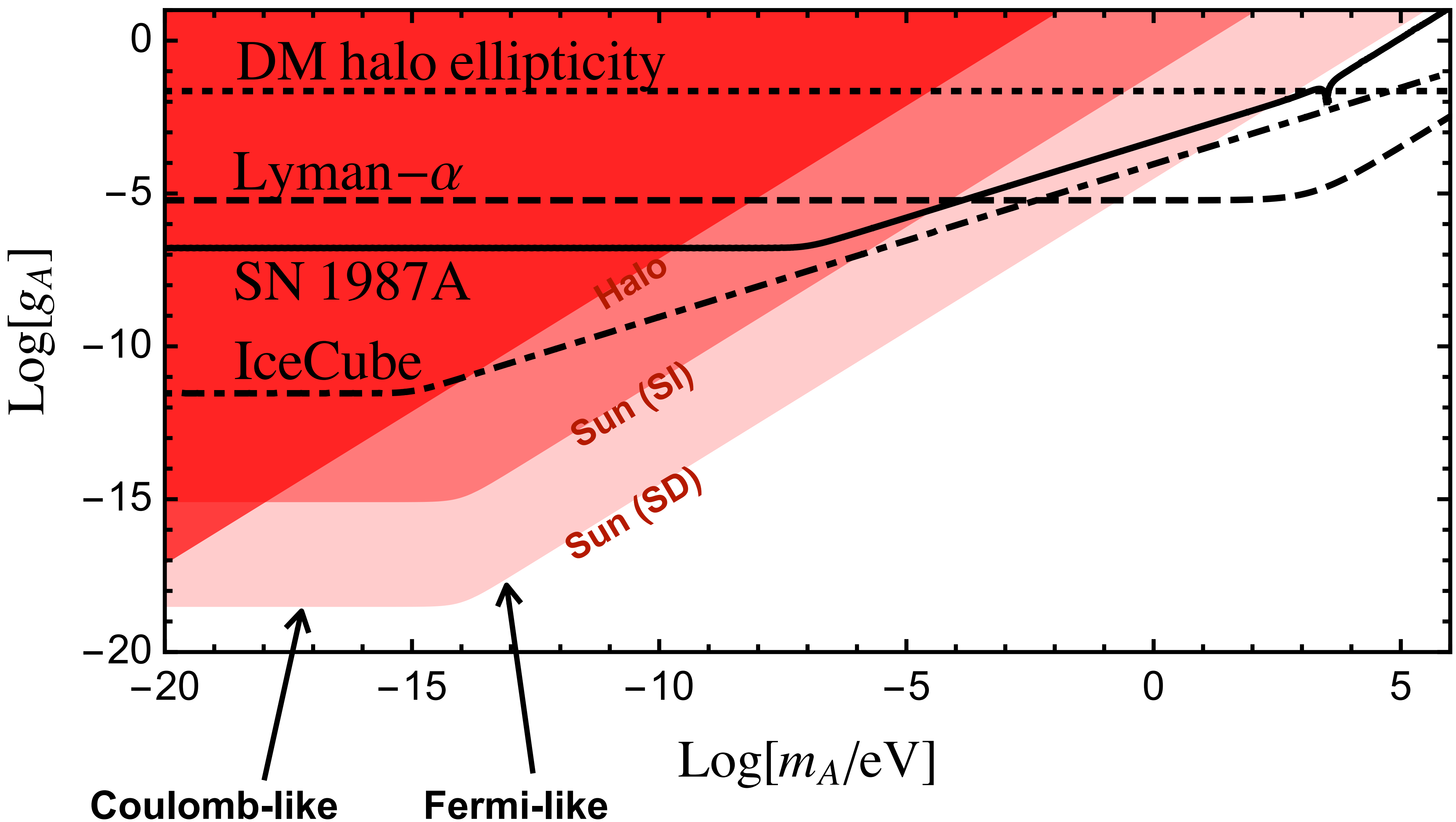
$$\sim \frac{g_A^2}{m_A^2} n_{\text{bkd}} \sim \frac{1}{\langle \phi \rangle^2} n_{\text{bkd}}$$

Oscillations are special!

strong sensitivity to low-scale exotic sectors

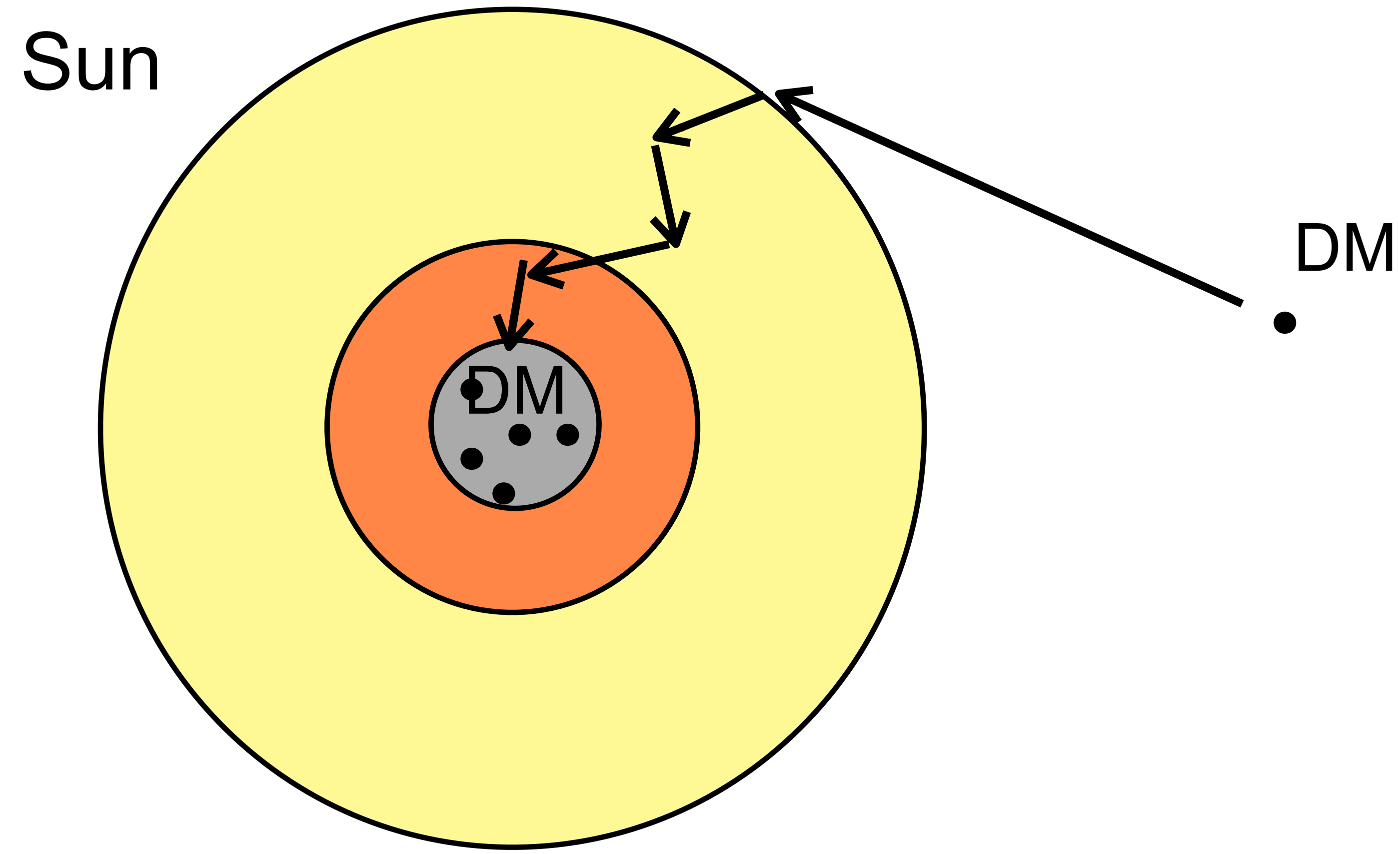
Benchmark values

$m_{\rm DM} = 5\ {\rm GeV}\quad m_4 = 1\ {\rm eV}\quad s_{i4} = 0.1$



Solar Dark MSW

Asymmetric Dark Matter in the sun
(generic consequence of asymmetry)



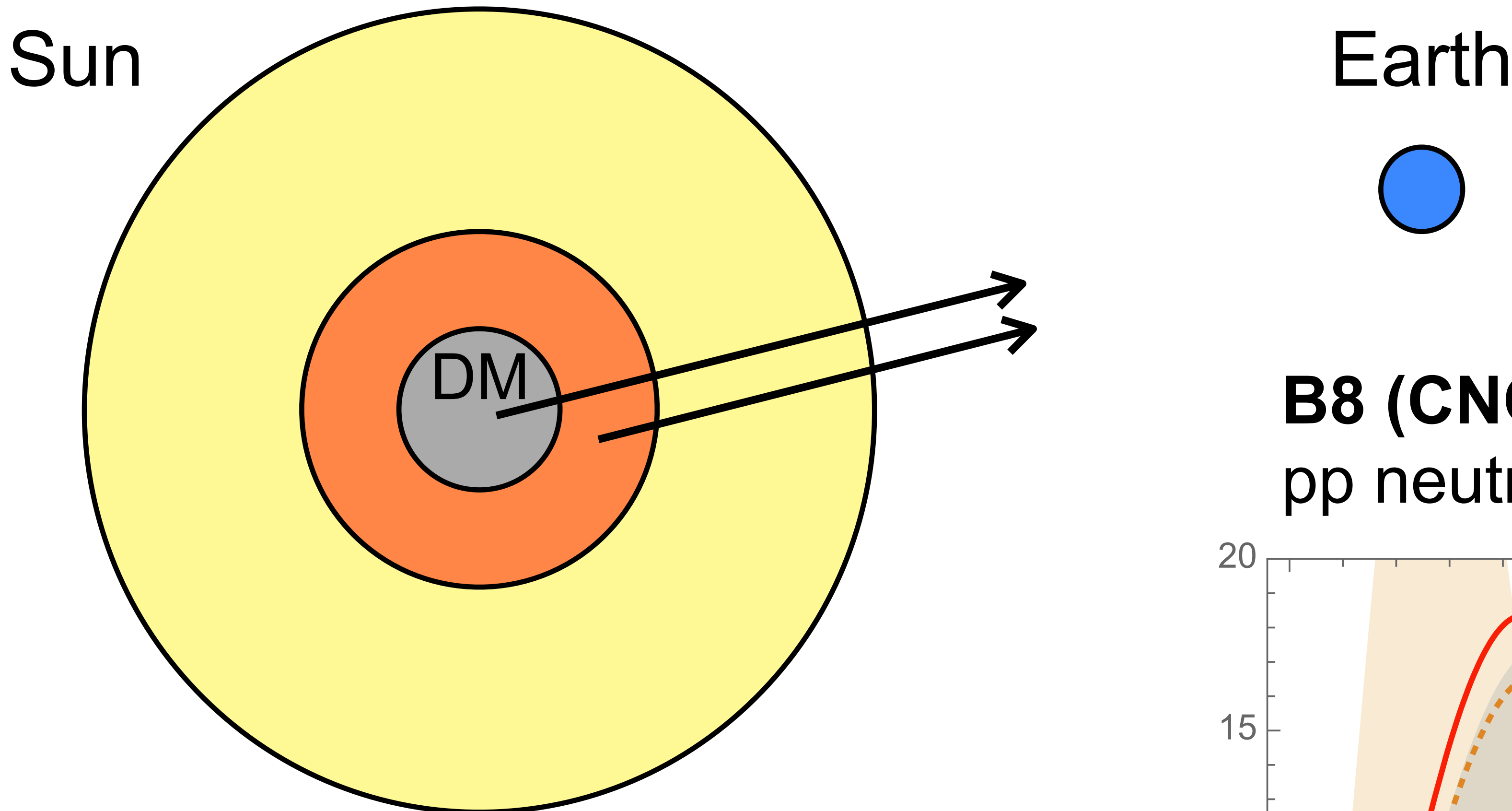
$$n_X(r) = \frac{N_X}{r_X^3 \pi^{3/2}} e^{-r^2/r_X^2}$$

$$r_X \simeq 0.05 \sqrt{\frac{5 \text{ GeV}}{m_X}} R_\odot$$

Also studied to address the Metallicity "problem":
Sarkar et al (2010)
Taoso et al (2010)
Silk et al. (2014)
Scott et al (2015)
Vagnozzi et al (2016)

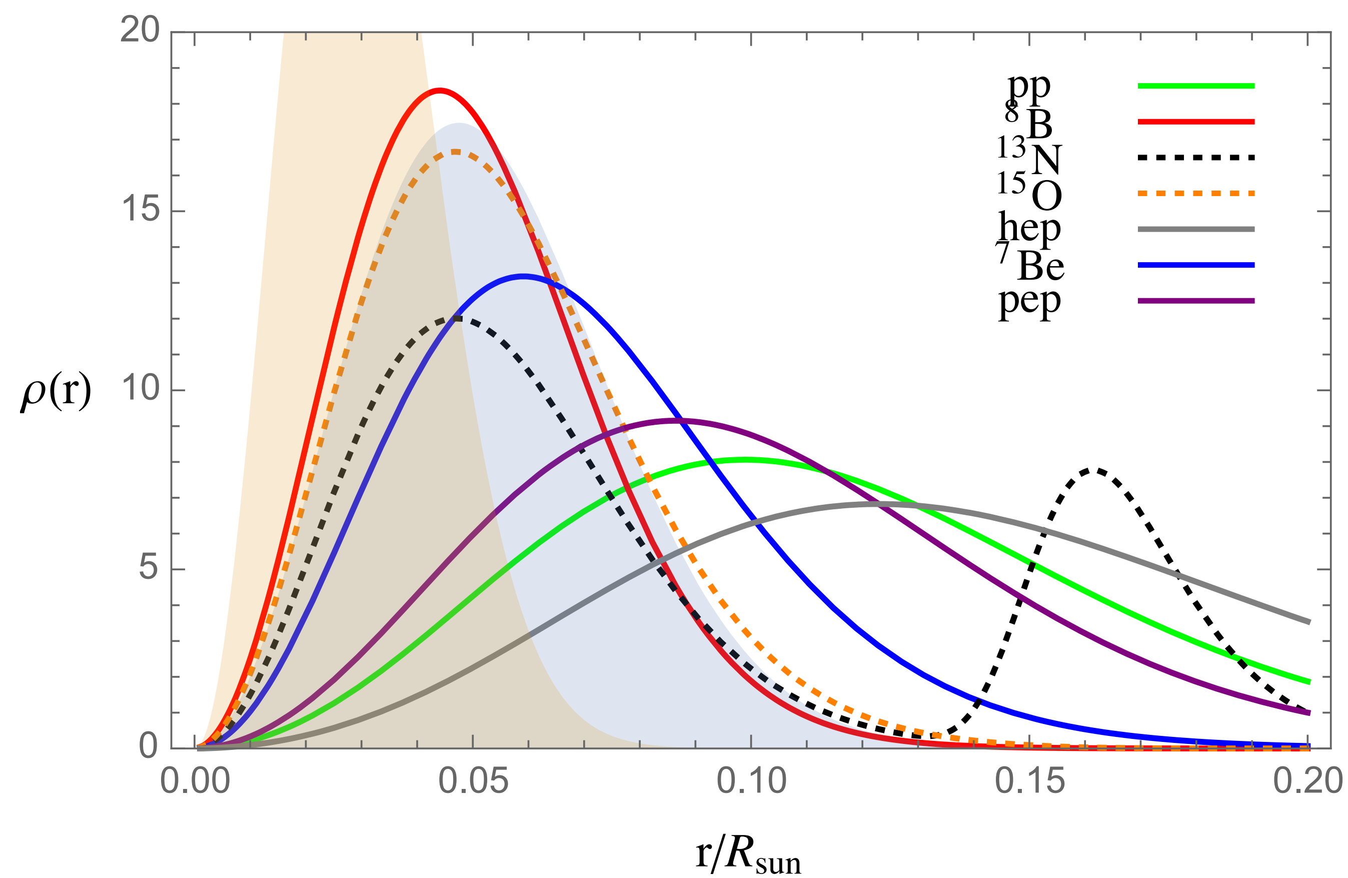
Solar Dark MSW

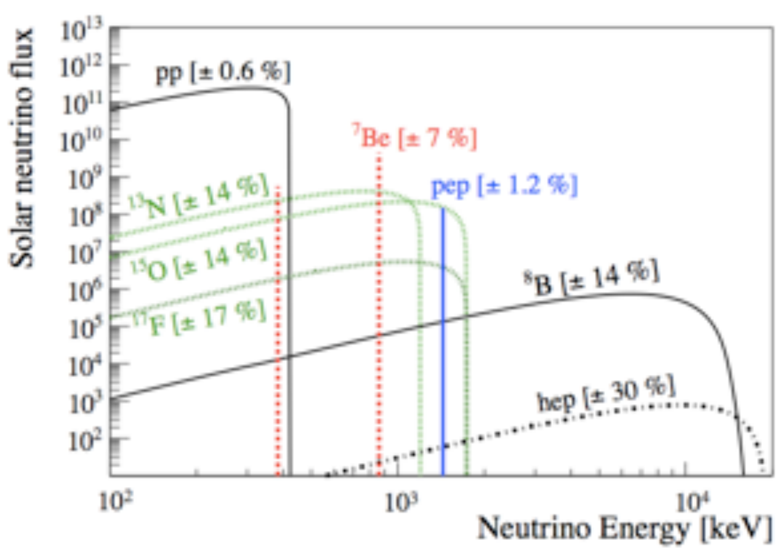
Capozzi, Shoemaker, LV (2017)



B8 (CNO) neutrinos are affected

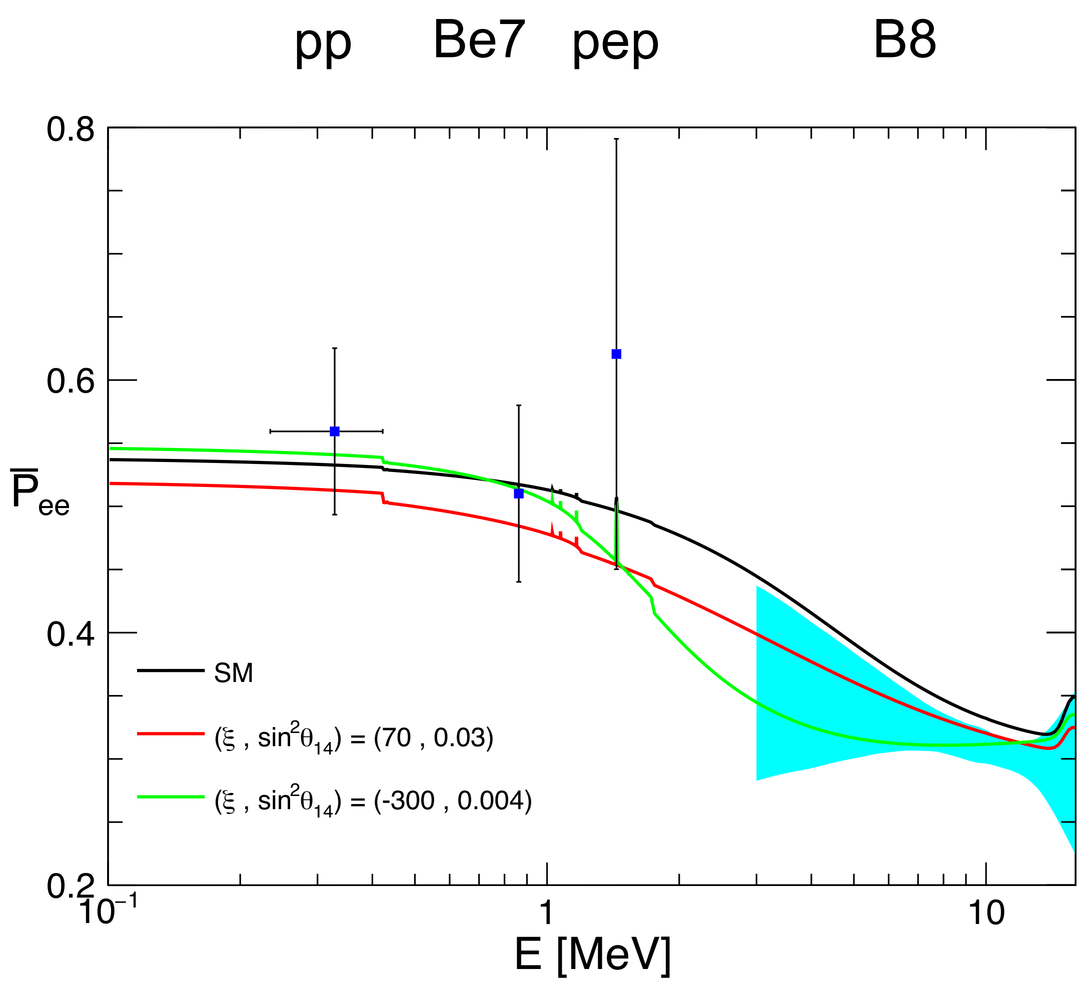
pp neutrinos only mildly

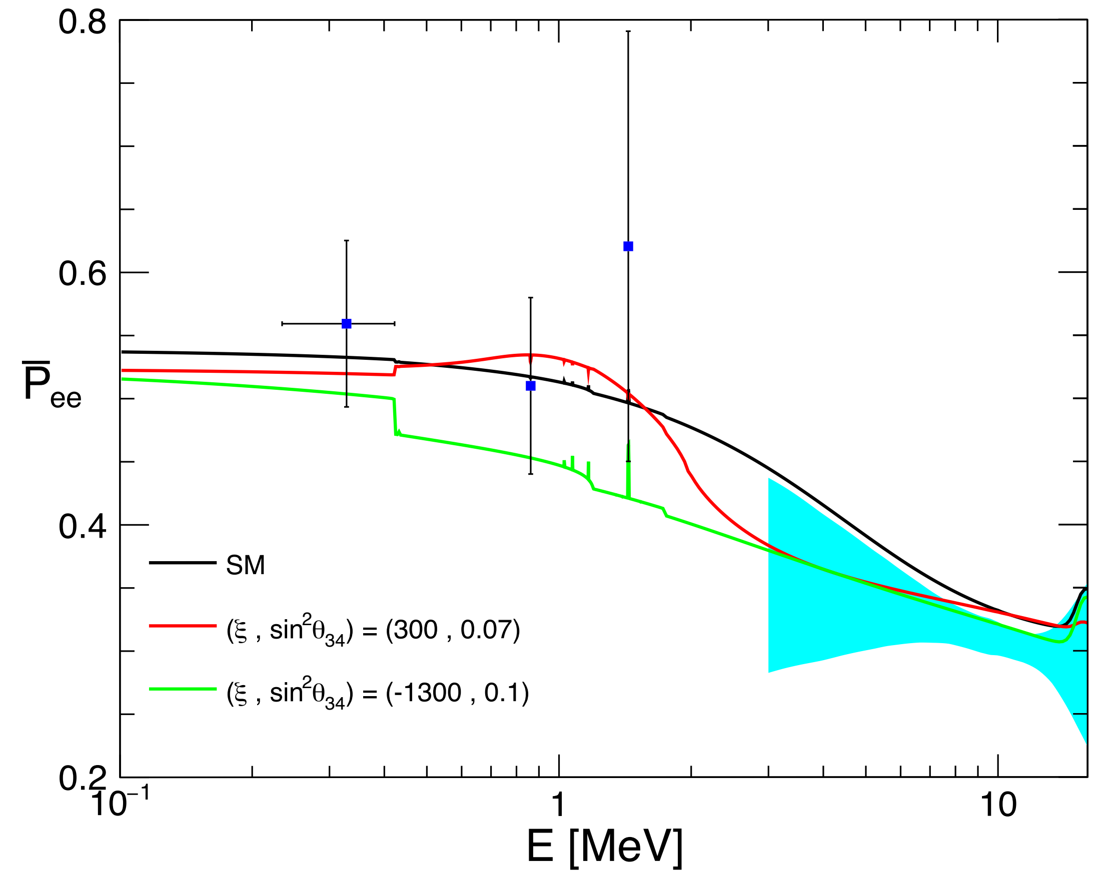




From John Bahcall et al. (BS2005)

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





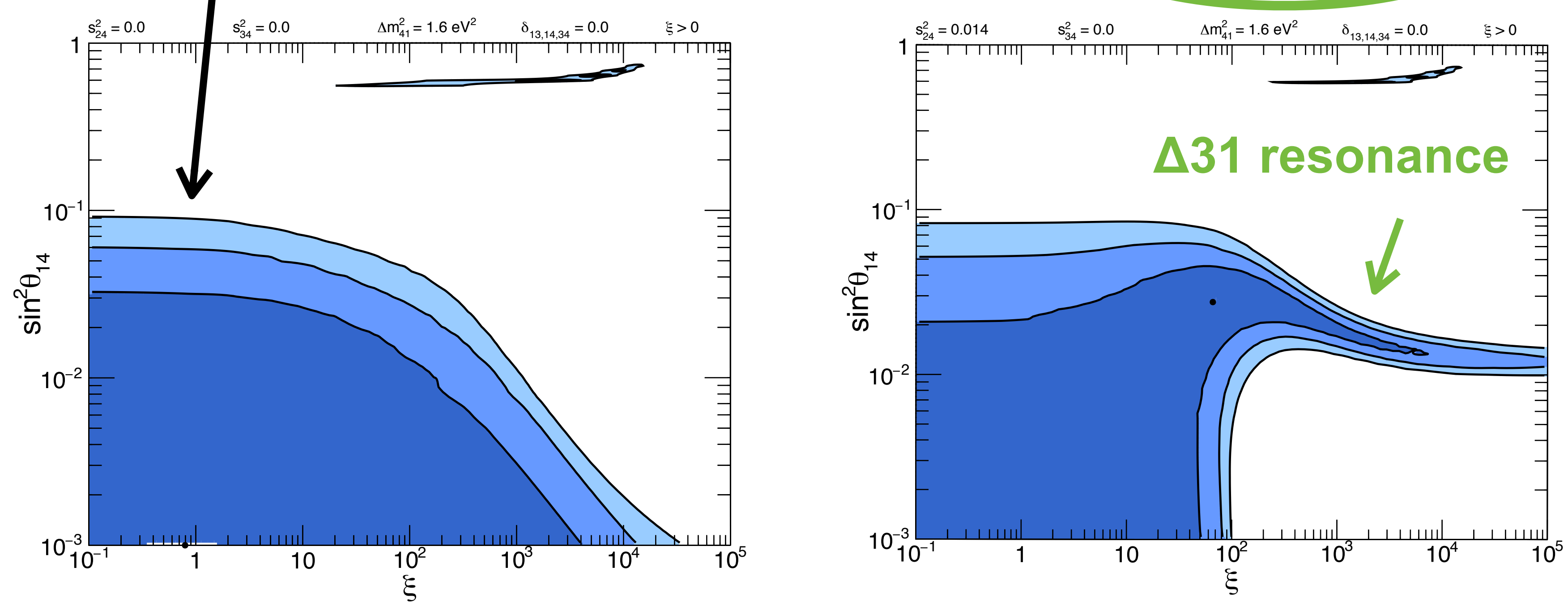
$$V_{s,\mathrm{new}} = \sqrt{2}\xi G_F n_e(0) e^{-r^2/r_{\mathrm{DM}}^2}$$

$$\xi \equiv \frac{G_{\mathrm{DM}} n_{\mathrm{DM}}(0)}{\sqrt{2} G_F n_e(0)}$$

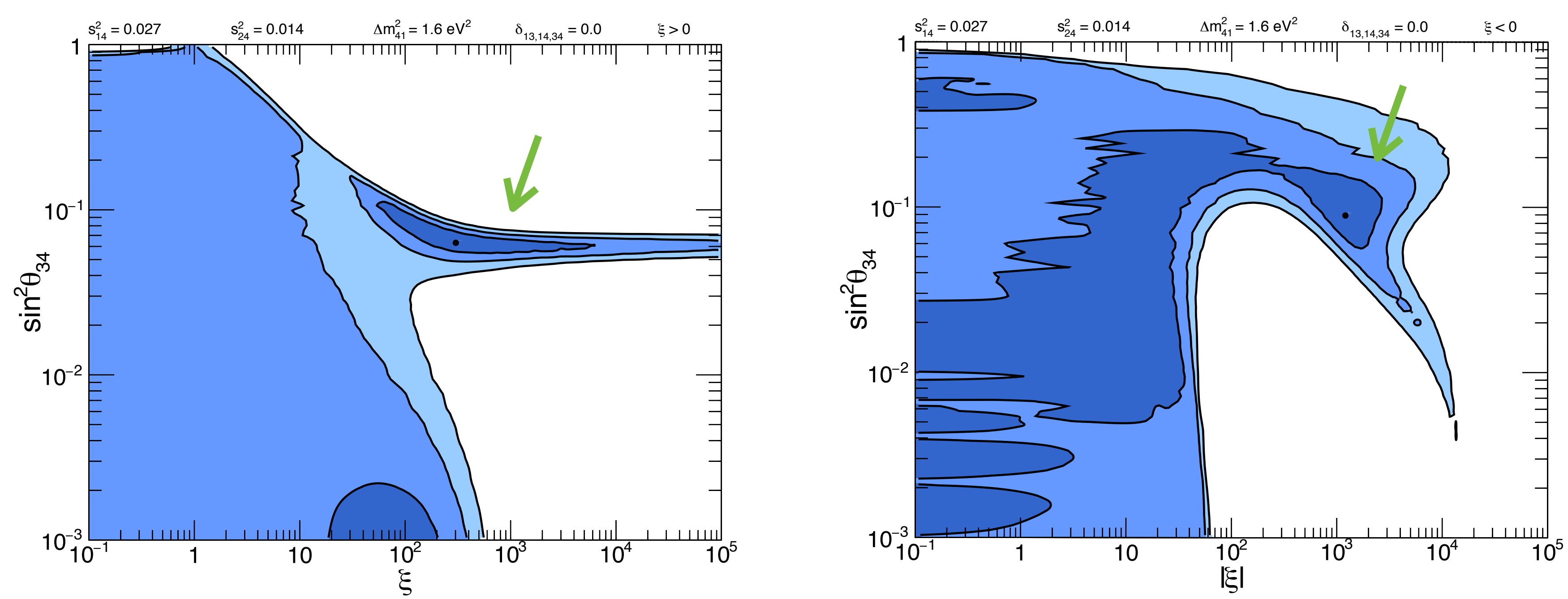
Scan of ξ, θ14 with θ34=0 and standard θ12, Δ21, Δ31

Away from 31-resonances:

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



Scan of ξ, θ34 with θ14,θ24 at SBL anom. and standard θ12, Δ21, Δ31



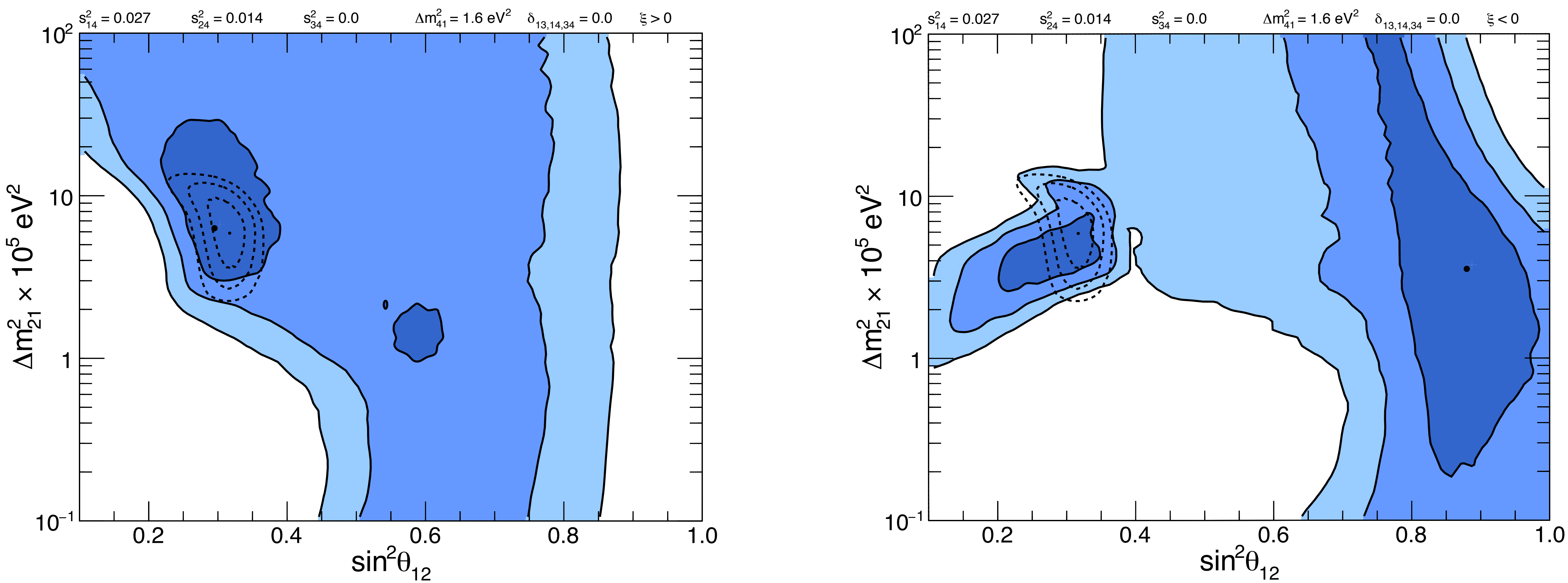
Off resonance:

$$\frac{\delta V_{\mathrm{SM}}}{V_{\mathrm{SM}}} \sim s_{i4}^2 \xi \leq \mathcal{O}(10)$$

Scan of ξ, θ12, Δ21 with θ14, θ24, Δ41 at SBL anomalies

$$10^{-2} \leq |\xi| \leq 10^5$$

$$\frac{\delta V_{\rm SM}}{V_{\rm SM}} \sim s_{i4}^2 \xi$$



-- V>0: generically relaxes solar-Kamland tension
-- V<0: "dark LMA" solution

Main messages

- **Sterile neutrinos:**
  - Most plausible extension of standard 3-neutrino paradigm (hide in all other channels)
  - CMB & BBN data cannot (and will not) robustly exclude steriles with exotic interactions

- **Sterile-mediated exotic interactions:**
  - Smoking gun of non-sterile neutrinos: exotic matter potentials (Dark MSW)
  - Oscillation experiments can probe very tiny couplings and mediator masses
  - Solar Dark MSW: mostly impact B8 and CNO, truly-steriles in all other neutrino experiments
  - Differences between sterile-mediated potentials & NSI:

    1) large $\delta V_{\rm SM}/V_{\rm SM}$ is in principle possible here

    2) potential involves exotic matter: only propagation, no production/detection

    3) sterile neutrinos are essential, but may decouple → NSI-like interactions $\frac{\delta V_{\rm SM}}{V_{\rm SM}} \sim s_{i4}^2 \xi$

Thank You

Away from resonance:

$$H'_{2\times 2} = \begin{pmatrix} -\Delta\cos 2\theta_{12} + V_x & \Delta\sin 2\theta_{12} + V_y \\ \Delta\sin 2\theta_{12} + V_y^* & \Delta\cos 2\theta_{12} - V_x \end{pmatrix}$$

$$P_{ee,\mathrm{day}} = c_{13}^4 c_{14}^4 \frac{1}{2}\left(1 + \cos 2\theta_{12}\cos 2\theta_m\right) + s_{13}^4 c_{14}^4 + s_{14}^4$$

In the decoupling limit $\Delta m_{41}^2 \gg EV_{\mathrm{CC}}, EV_s \qquad s_{i4}^2 \to 0 \qquad s_{i4}^2 V_s = \mathrm{finite}$

Standard 3x3 problem plus $(V_{\mathrm{eff}})_{ij} = V_s (U_{34}R_{24}U_{14})^*_{4i}(U_{34}R_{24}U_{14})_{4j}$

Formally like NSI (controlled by exotic matter! Off-diagonel IFF >1 exotic angles)
Potential = vacuum of a vector (looks like a class of CPT-violation!)