Neutrino Oscillations and Light Dark Sectors

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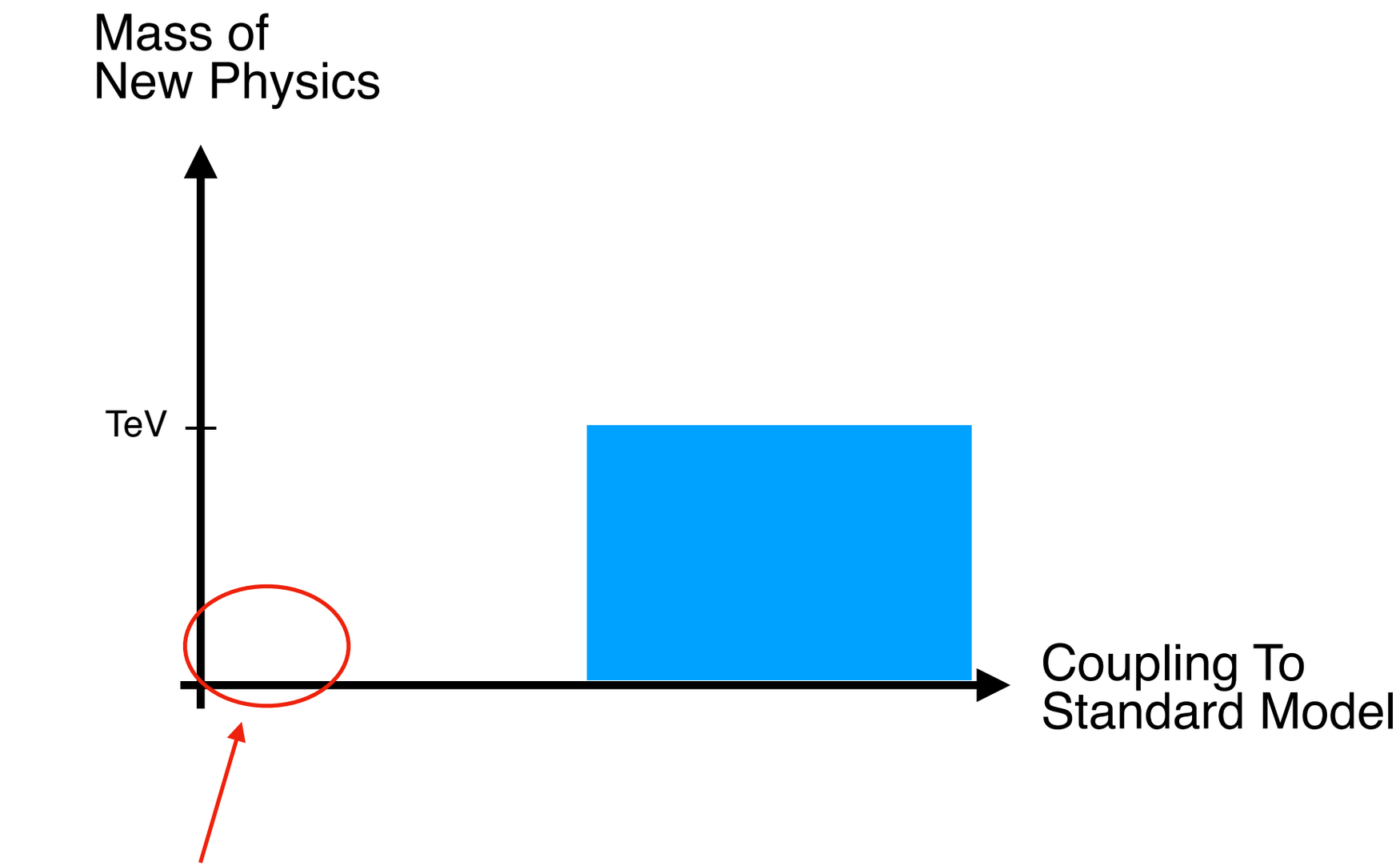
NOW 10/09/2018

Main message:



(1) Neutrino oscillations are special!
(2) Only for a class of new physics models!

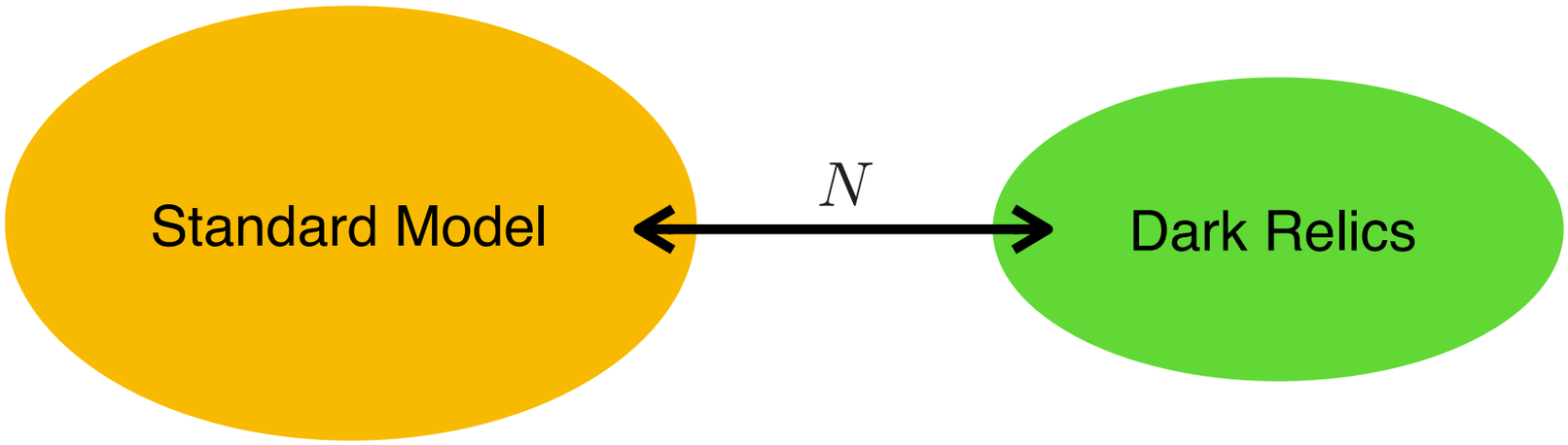
Outline

- **Introduction**
  - What new physics models?
  - Why are neutrino oscillations special?
- **Oscillations signature**
  - Atmospheric and solar neutrinos
  - Dark energy or neutrino masses?
- **Conclusions**

What are the assumptions?

Why oscillations are special?

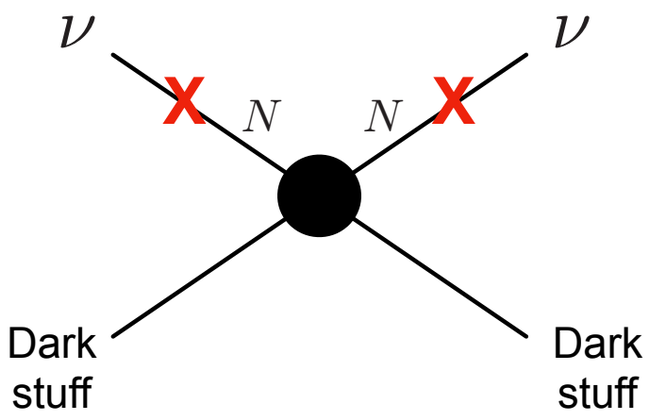
Setup:
Sterile neutrinos as mediators of exotic interactions

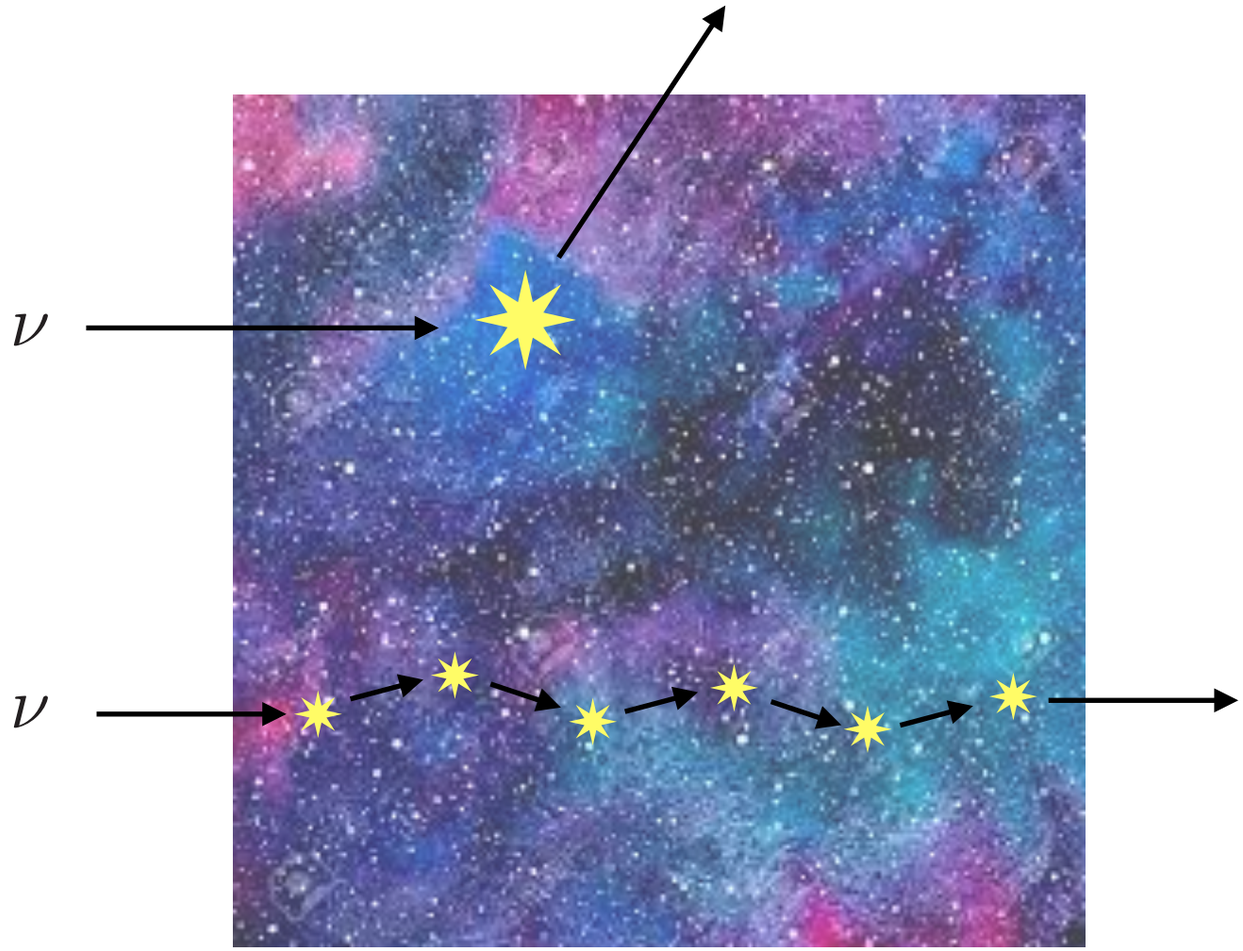


$$\delta\mathcal{L} = yHLN + \cdots$$

Couplings to the dark sector
have implications in:
—Cosmology
—Astrophysics
—**Oscillations!**

Why oscillations:
Dark MSW





Unknown

Radiation or Matter

$$V \sim \frac{g_D^2}{m_D^2}\theta^2 n_D \begin{cases} 10^{-23}\ \mathrm{GeV}\left(\frac{\theta}{10^{-3}}\right)^2\left(\frac{\mathrm{eV}}{m_D/g_D}\right)^2 \frac{\rho_{\mathrm{DM}}}{0.4\ \mathrm{GeV/cm^3}}\frac{1\ \mathrm{keV}}{m_{\mathrm{DM}}} & \text{Dark Matter} \\ 10^{-23}\ \mathrm{GeV}\left(\frac{\theta}{10^{-3}}\right)^2\left(\frac{\mathrm{meV}}{m_D/g_D}\right)^2 \frac{n_D}{1/\mathrm{cm^3}} & \text{Dark Radiation} \end{cases}$$

Unknown mediator scale

Unique sensitivity to light & weakly-coupled dark sectors

Signatures in Oscillation Experiments

Neutrino oscillations in (nearly homogeneous) **dark backgrounds…**

F. Capozzi, I. M. Shoemaker, LV (JCAP 2018)

$$\mathcal{L} = N^\dagger_\alpha \bar{\sigma}^\mu [i\partial_\mu \delta_{\alpha\beta} + (V_\mu)_{\alpha\beta}] N_\beta + \left\{ \frac{1}{2} N^\dagger_\alpha \left[m_{\alpha\beta} + (F_{\mu\nu})_{\alpha\beta} \bar{\sigma}^{\mu\nu} \right] i\sigma_2 N^*_\beta + \mathrm{hc} \right\}$$

neutrino/neutrino (anti-neutrino/anti-neutrino)

Indistinguishable from a mass…

neutrino/anti-neutrino

Effective “Hamiltonian” for constant backgrounds

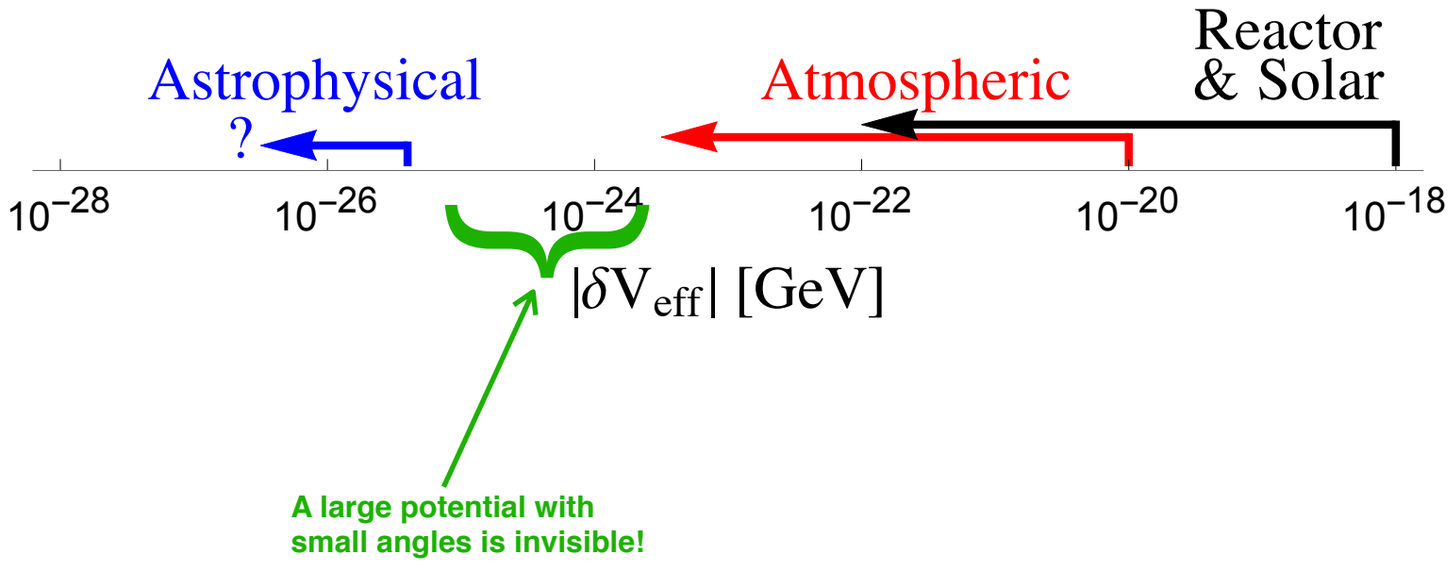
$$H_{\mathrm{eff}} = \begin{pmatrix} |\mathbf{p}| + \frac{m m^*}{2|\mathbf{p}|} - \frac{p^\mu V_\mu}{|\mathbf{p}|} & \frac{4\sqrt{2}}{|\mathbf{p}|} p^\mu (F_{\mu\nu}) \epsilon^\nu \\ \frac{4\sqrt{2}}{|\mathbf{p}|} p^\mu (F_{\mu\nu})^\dagger (\epsilon^\nu)^* & |\mathbf{p}| + \frac{m^* m}{2|\mathbf{p}|} + \frac{p^\mu V^*_\mu}{|\mathbf{p}|} \end{pmatrix} \Bigg|_{p_0 = |\mathbf{p}|}$$

- Large E is good → V,F become more important than the standard mass effect
- But not “too large” → If V,F dominate we lose info on the the dark energy scale

$$H_{\rm eff} = \begin{pmatrix} |\mathbf{p}| + \frac{mm^*}{2|\mathbf{p}|} & \\ & |\mathbf{p}| + \frac{m^*m}{2|\mathbf{p}|} \end{pmatrix} + \begin{pmatrix} -a & b \\ b^\dagger & a^* \end{pmatrix}$$

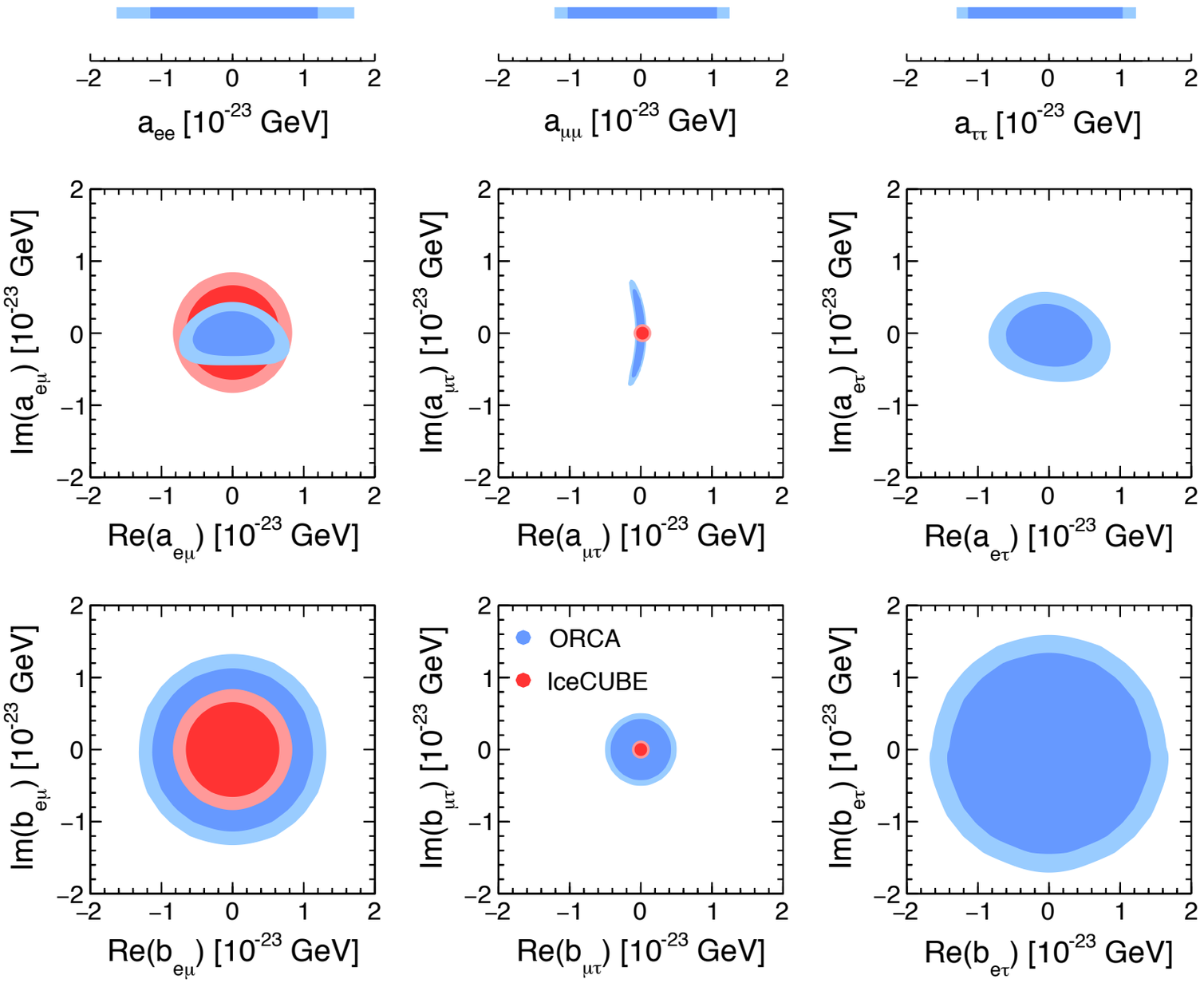
$$a(\hat{\mathbf{p}}) = -V_0 + \hat{\mathbf{p}} \cdot \mathbf{V}$$
$$b(\hat{\mathbf{p}}) = -4\sqrt{2}(\mathbf{E} + i\mathbf{B}) \cdot \vec{\epsilon}(\hat{\mathbf{p}})$$

neutrino/anti-neutrino



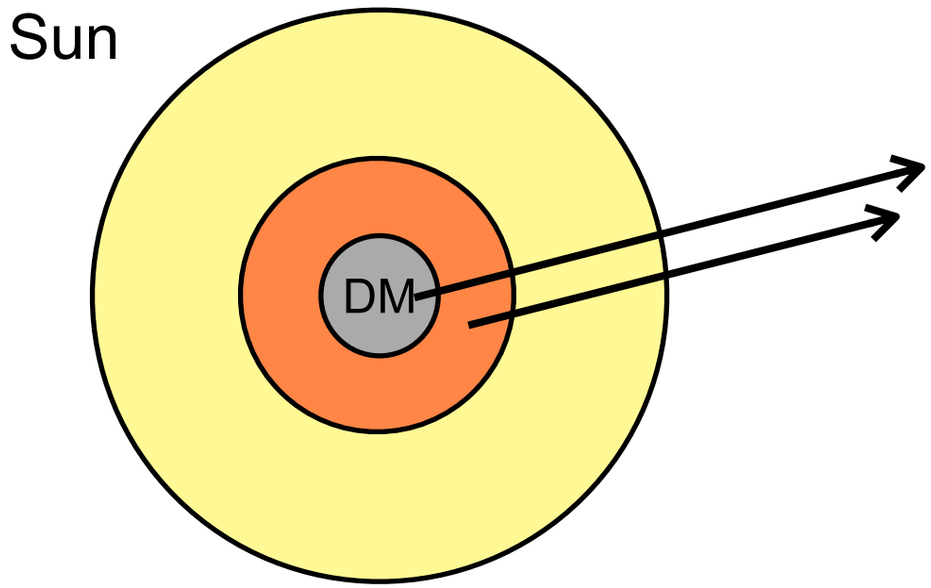
Atmospheric neutrinos

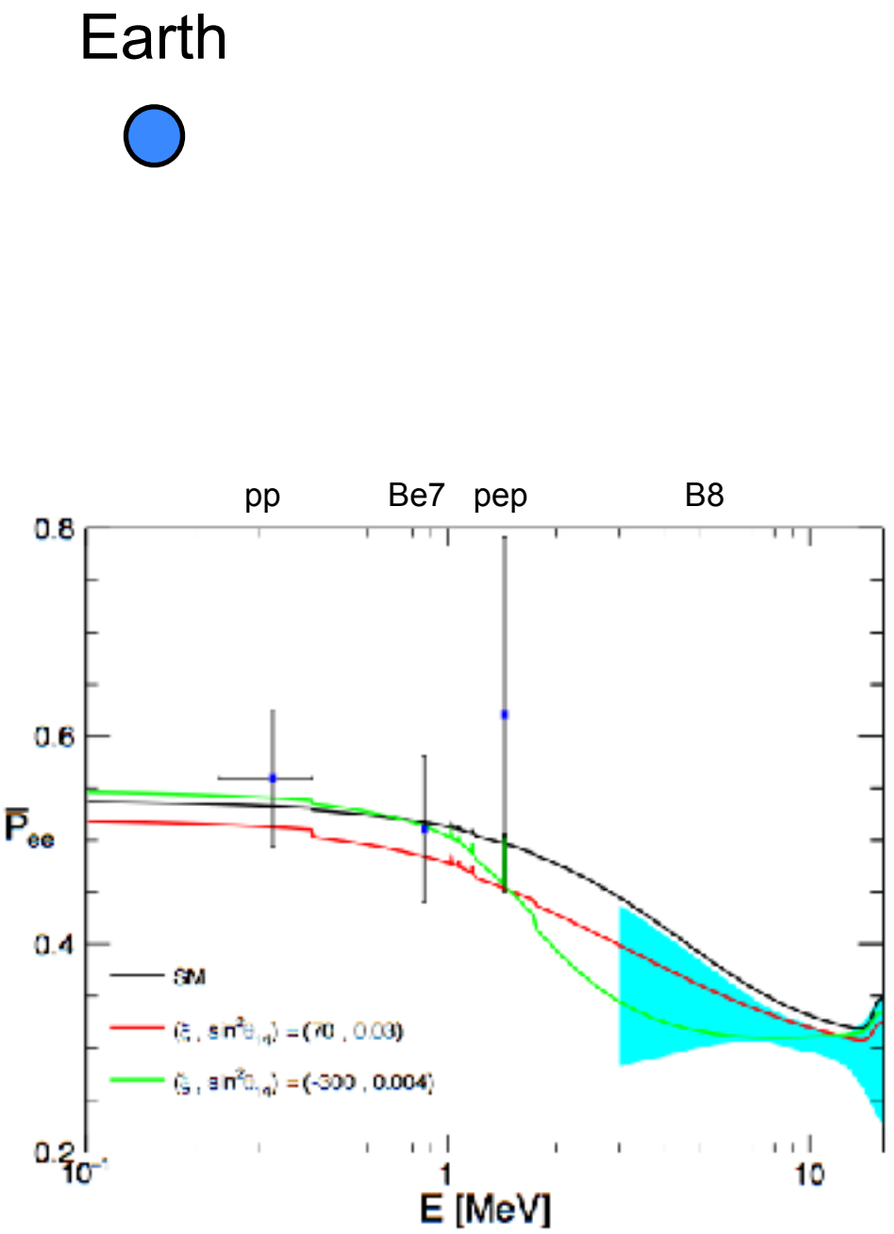
ORCA (KM3NeT project)+IceCube



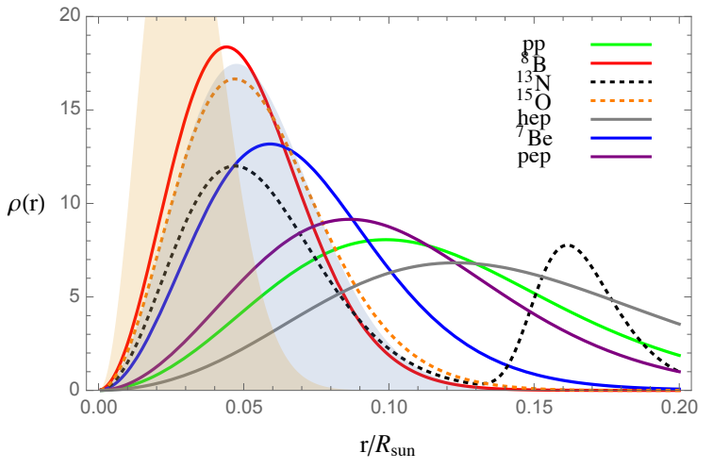
F. Capozzi, I. M. Shoemaker, LV
(JCAP 2017)

Solar neutrinos (ONLY if some dark matter is captured…)





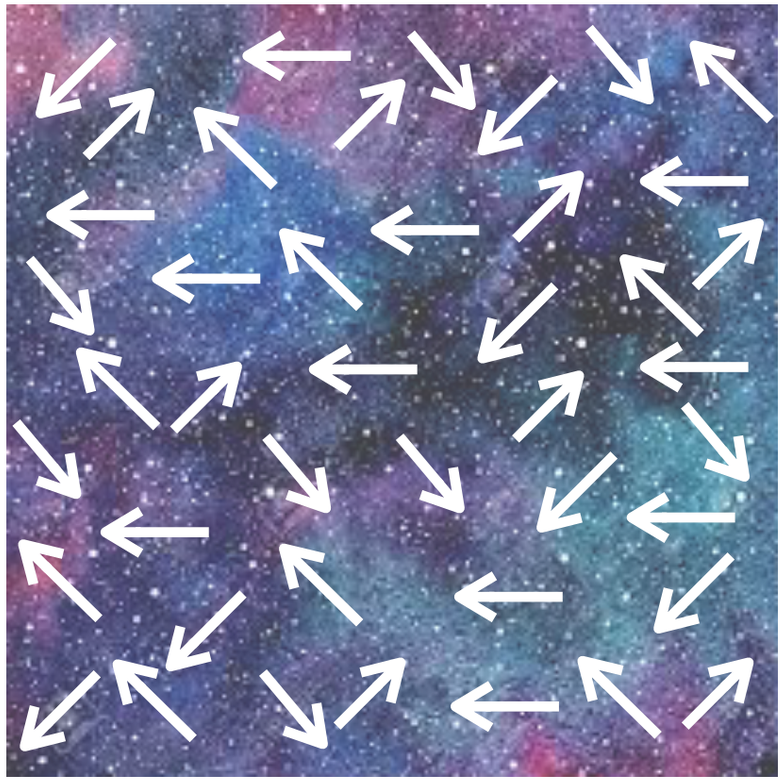
B8 & CNO neutrinos are affected
pp neutrinos only mildly



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

Dark Energy or Neutrino Masses?

$$L^\dagger \bar{\sigma}^\mu L V_\mu$$



Random orientation in small domains:
Rotation invariance preserved on intermediate scales (magnets).

$$\begin{cases} \langle \mathbf{V} \rangle = 0 \\ \langle \mathbf{V^2} \rangle \neq 0 \end{cases}$$

$$\langle E(\mathbf{p}) \rangle = \begin{cases} |\mathbf{p}| + \frac{1}{3|\mathbf{p}|}\langle \mathbf{V}^2 \rangle + \cdots & |\mathbf{p}| \gg |\mathbf{V}| \\ |\mathbf{V}| + \frac{1}{3|\mathbf{V}|}\mathbf{p}^2 + \cdots & |\mathbf{p}| \ll |\mathbf{V}|, \end{cases}$$

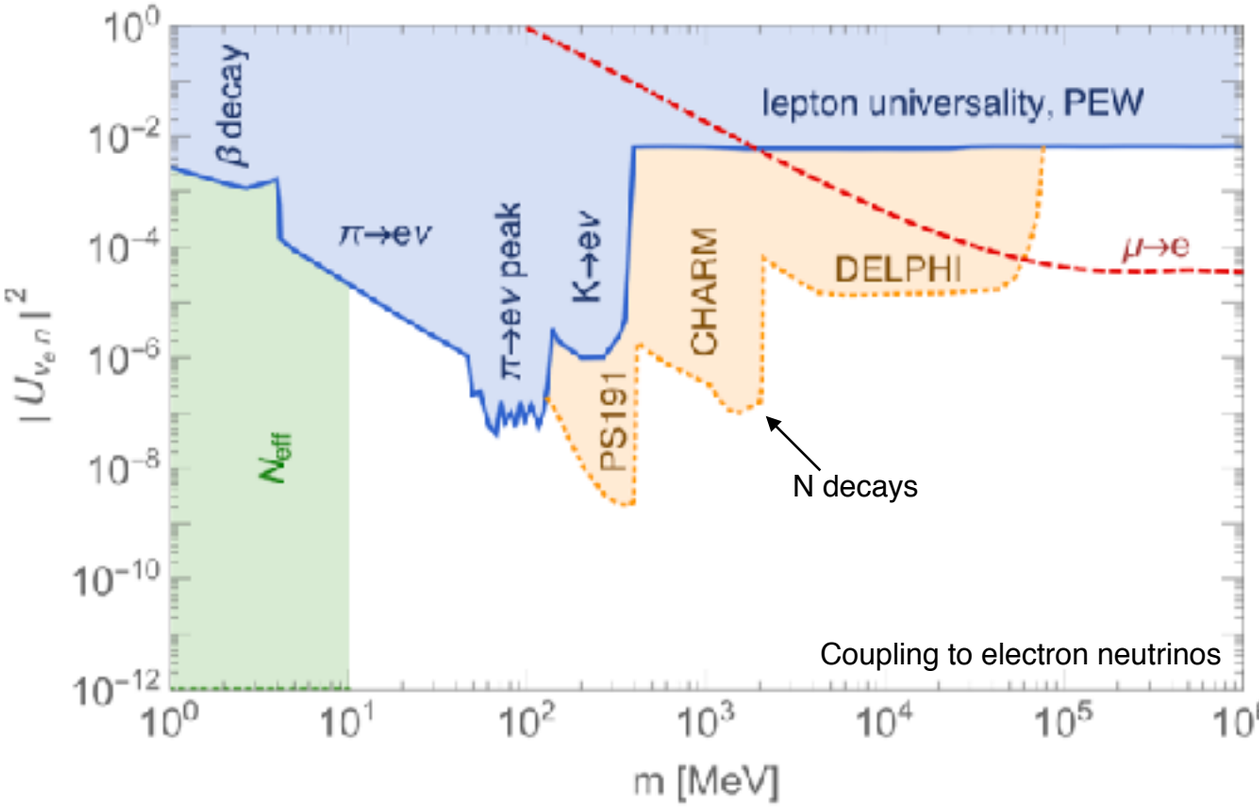
No EW symmetry breaking needed to explain oscillations…

$$\rho_{\rm DE} \sim \langle \mathbf{V}^4 \rangle \sim m_\nu^4$$ **Dark energy?**

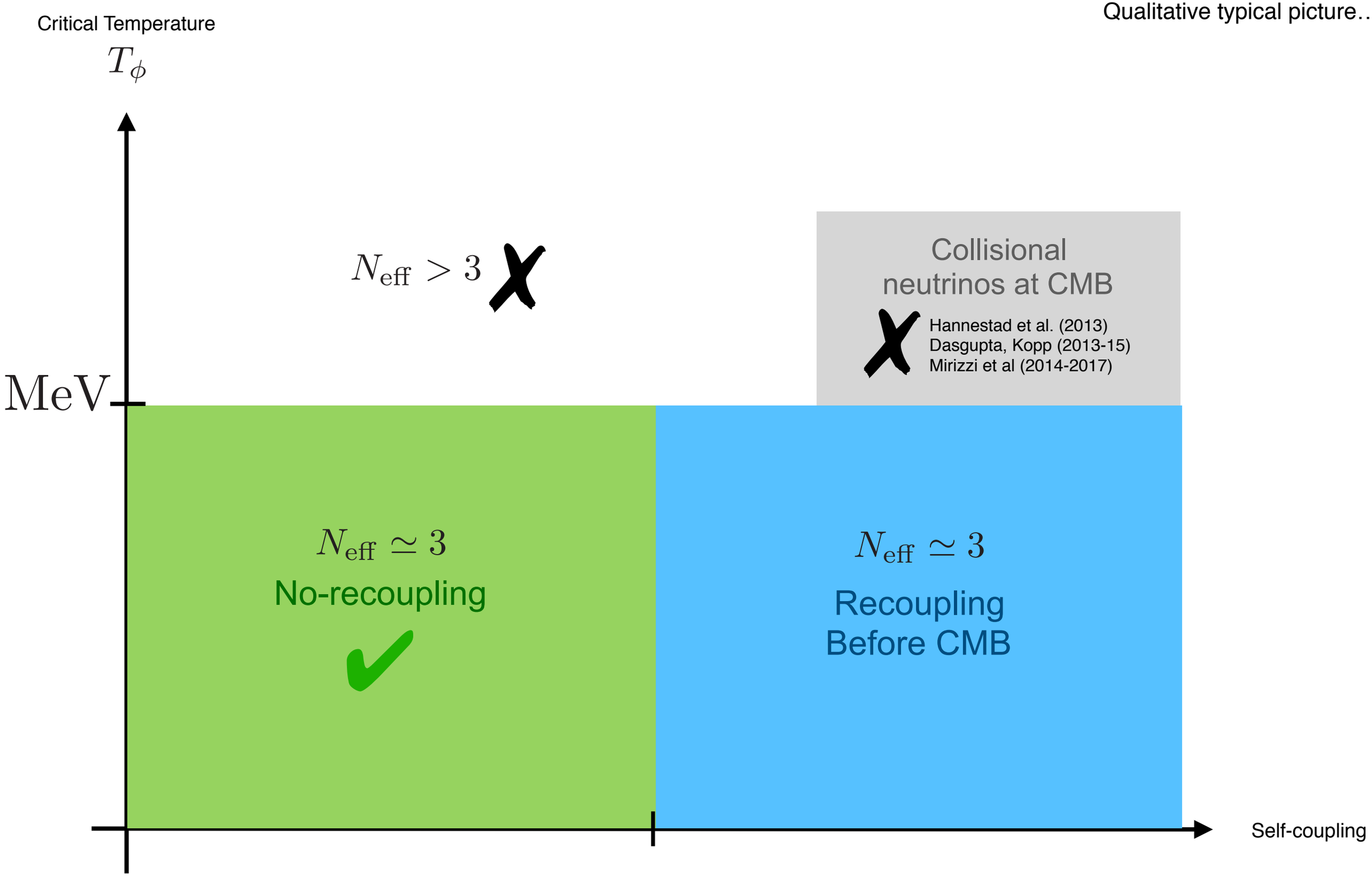
Conclusions

- Light dark sectors are plausible (what is the mass of dark matter?!) and might couple to neutrinos.
- IF TRUE: oscillation experiments have a **UNIQUE ABILITY** to discover them.
- Steriles (above or below MeV) as mediators of exotic potentials (in the cosmo, in the sun, etc).
- Atmospheric data are key to test the dark mass scale.
- Can couplings to dark sectors explain the proximity of dark energy and neutrino masses?

Thank You



From Schmaltz-Weiner (2017)


Critical Temperature
T_ϕ
MeV
$N_{\rm eff} > 3$
Collisional neutrinos at CMB
Hannestad et al. (2013)
Dasgupta, Kopp (2013-15)
Mirizzi et al (2014-2017)
$N_{\rm eff} \simeq 3$
No-recoupling
$N_{\rm eff} \simeq 3$
Recoupling Before CMB
Self-coupling

Atmospheric neutrinos

ORCA (KM3NeT project)+IceCube