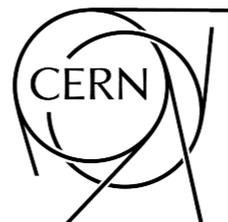


Theories Beyond the SM and Neutrinos

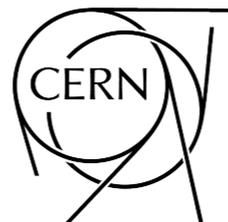
Joachim Kopp | CERN & JGU Mainz | Lectures at INSS 2019, Fermilab



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Sterile Neutrinos



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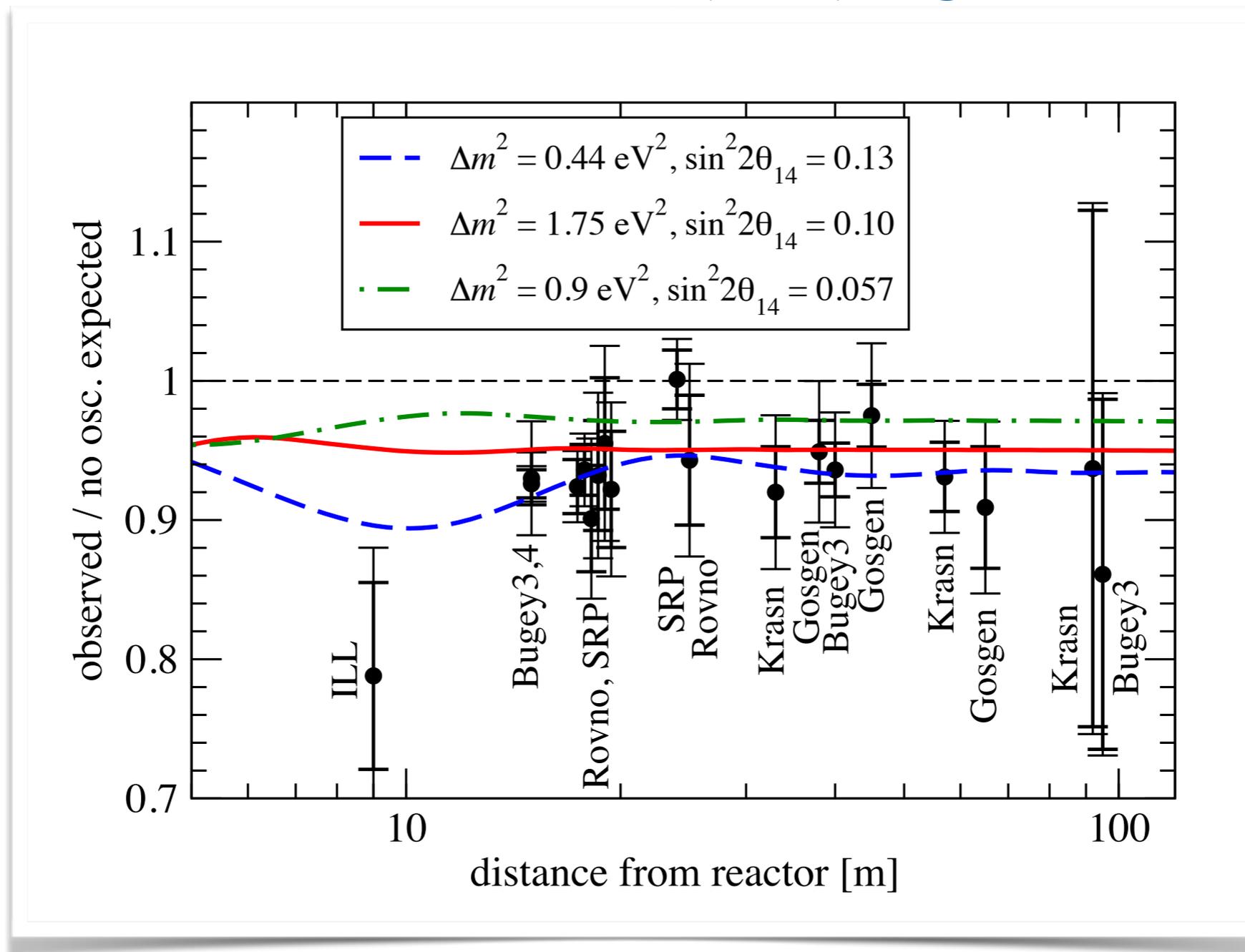
The Reactor Neutrino Anomaly

From yesterday's lecture:
predicted reactor ν flux is $\sim 3.5\%$ ($\sim 3\sigma$) higher than observed

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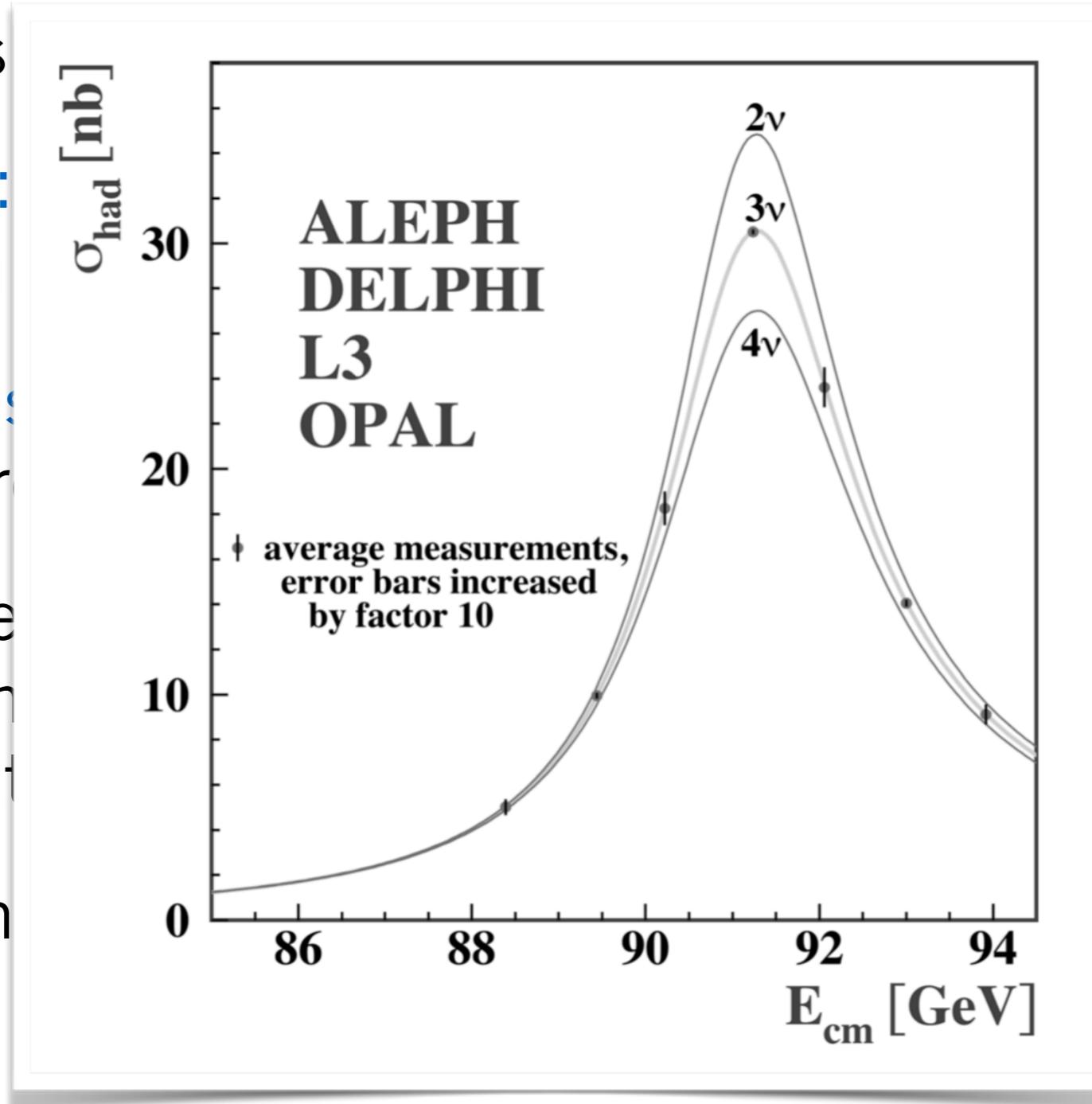


The Reactor Neutrino Anomaly

- ☑ Could this be due to neutrino oscillations?
- ☑ In the SM: **NO!**
oscillation lengths $4\pi E_\nu/\Delta m_{31}^2$ and $4\pi E_\nu/\Delta m_{21}^2$ too long.
- ☑ Hypothesis:
could there be a **fourth neutrino flavor** with mass $\sim eV$
- ☑ Would need to be “sterile”, i.e. not couple to the weak interaction to avoid LEP constraints on the invisible Z decay width
- ☑ Oscillations $\bar{\nu}_e \rightarrow \bar{\nu}_s$ could explain reactor anomaly

The Reactor Neutrino Anomaly

- ☑ Could this
- ☑ In the SM: oscillation
- ☑ Hypothesis could there
- ☑ Would need interaction decay width
- ☑ Oscillation



θ_{21}^2 too long.

mass $\sim eV$

the weak
visible Z

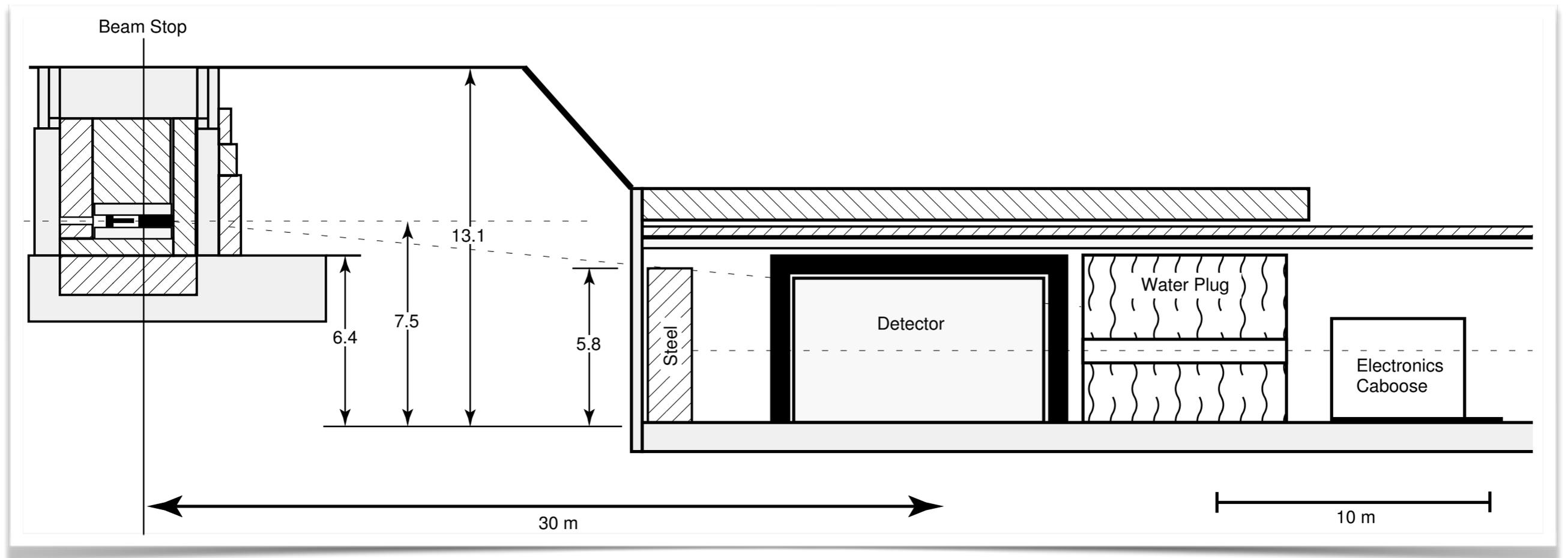
omaly

Definition: sterile neutrino = SM singlet fermion

- ☑ Very generic extension of SM
 - can be leftover of extended gauge multiplet
 - ☑ Useful phenomenological tool
 - can explain ν masses (seesaw mechanism, $m \sim \text{TeV} \dots M_{\text{Pl}}$)
 - can explain cosmic baryon asymmetry (leptogenesis, $m \gg 100 \text{ GeV}$)
 - can explain dark matter ($m \sim \text{keV}$)
 - can explain oscillation anomalies ($m \sim \text{eV}$)
- Promote mixing matrix to 4×4 , oscillation formula unchanged:

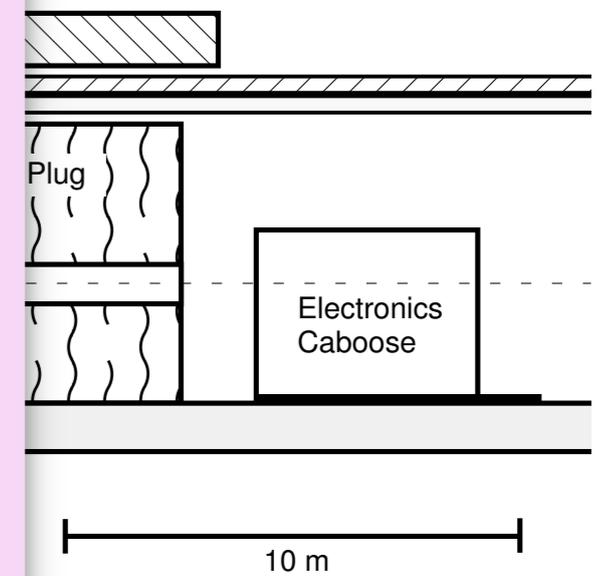
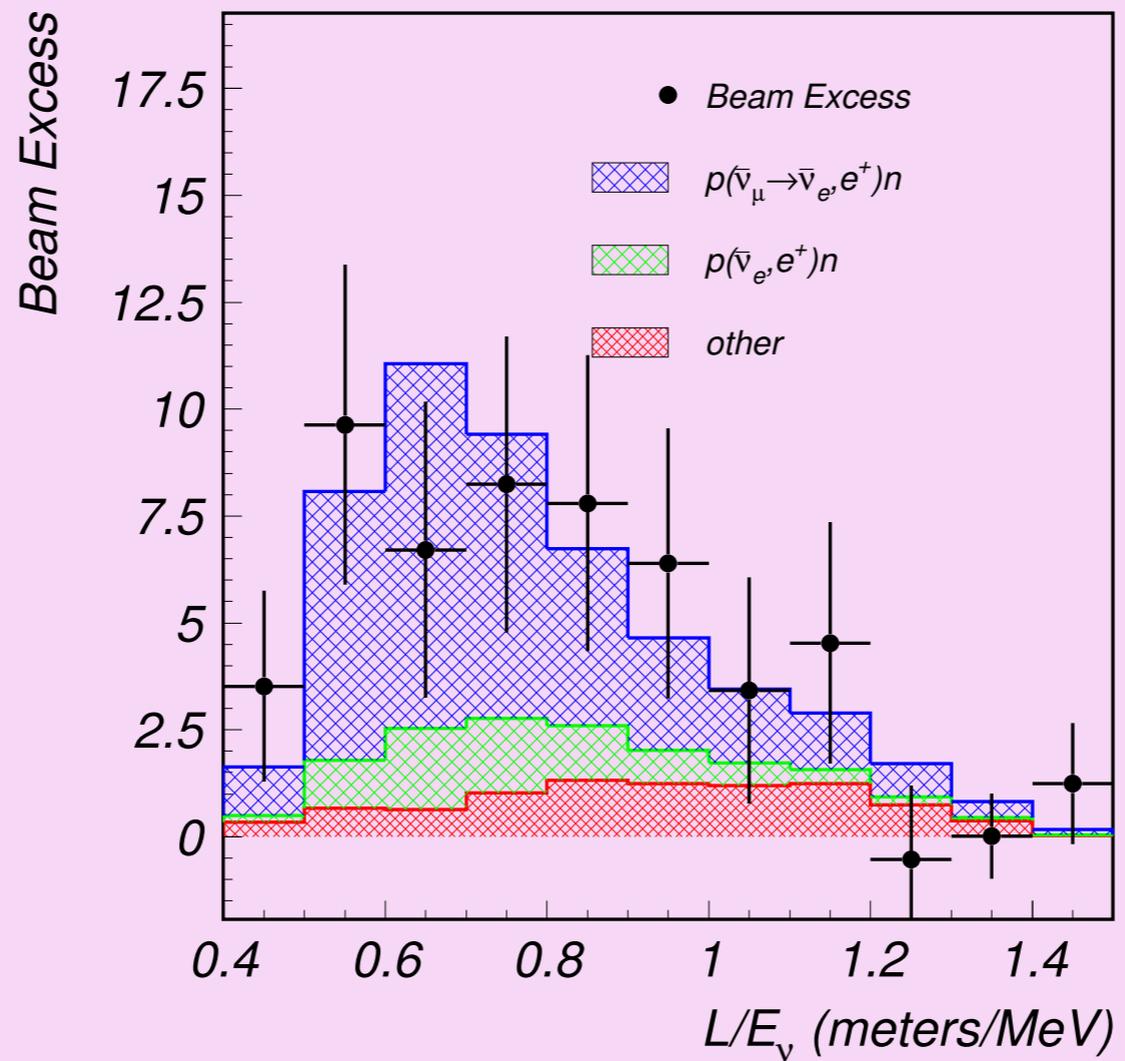
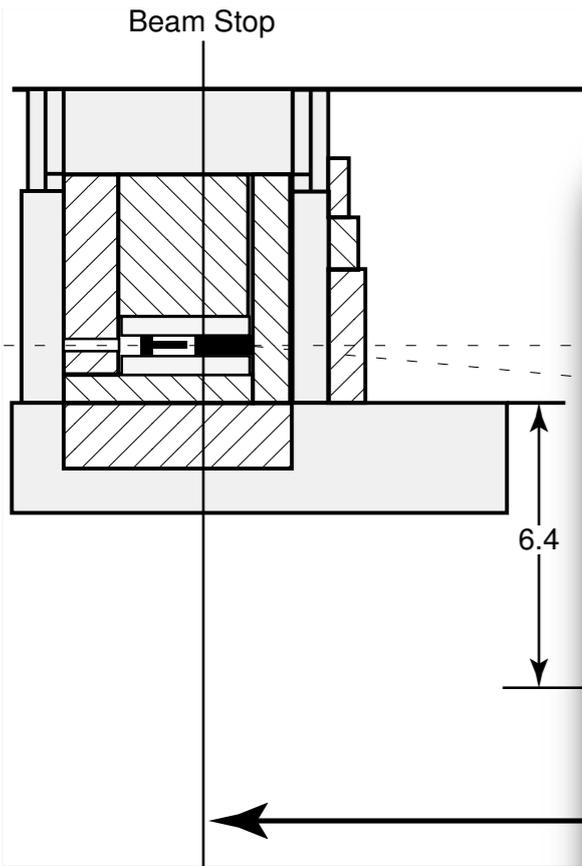
$$P_{\alpha \rightarrow \beta} = \sum_{j,k} U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \exp \left[-i(E_j - E_k)T \right]$$





☑ $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam

☑ Source—detector distance (“baseline”) ~ 30 m



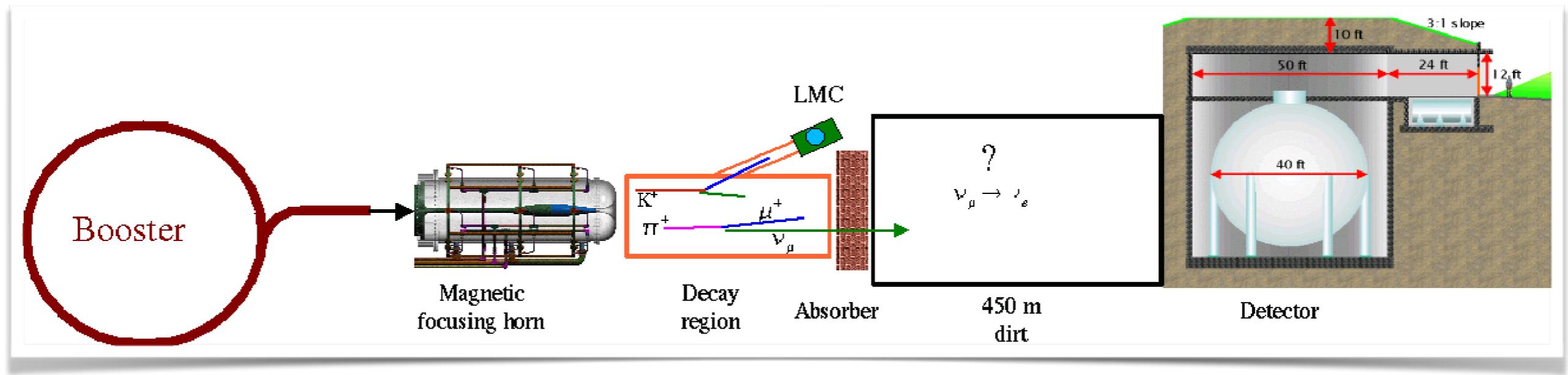
$\bar{\nu}_e$ appearance

Source—d

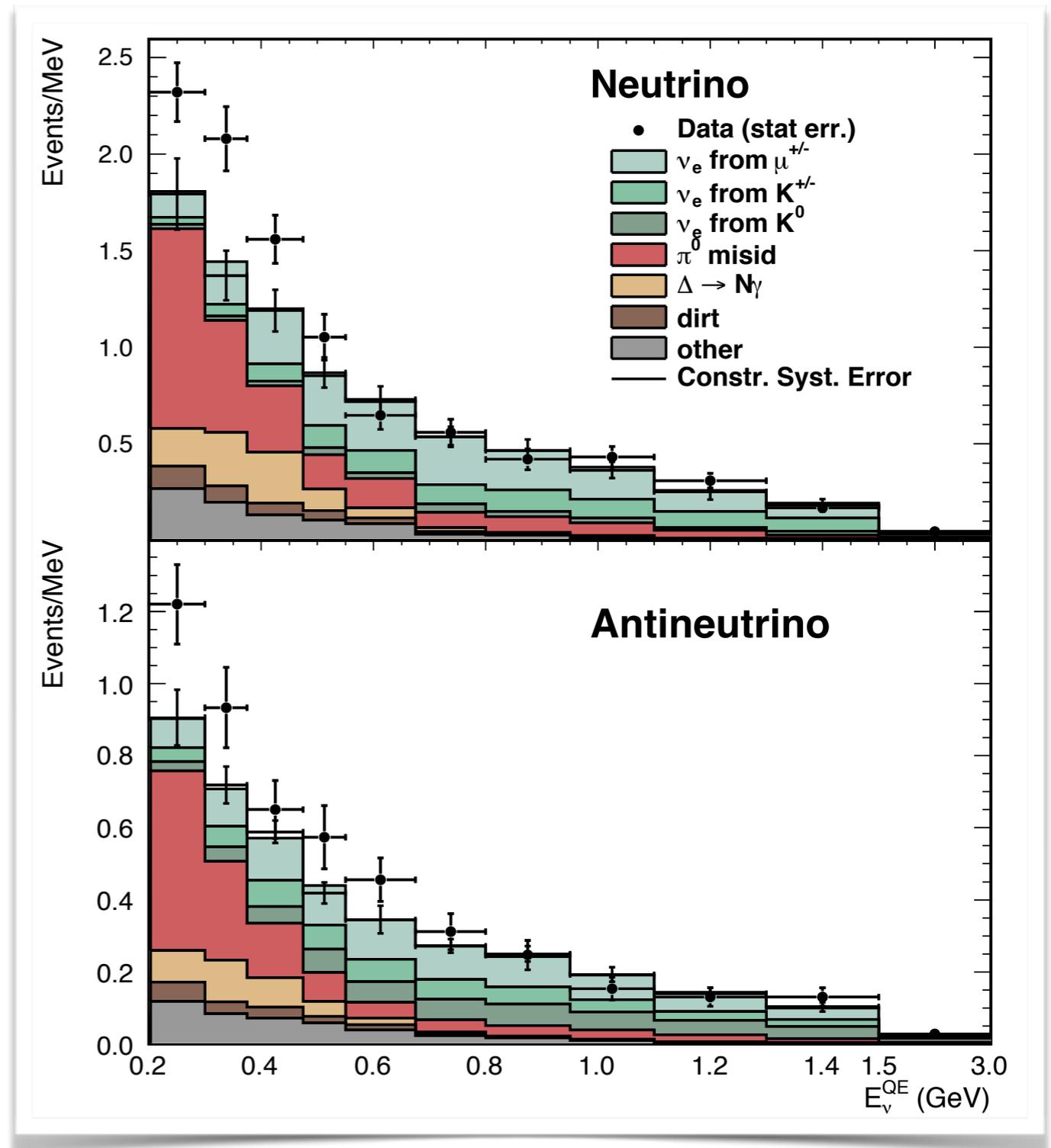
m

LSND Collaboration, [hep-ex/0104049](https://arxiv.org/abs/hep-ex/0104049)

MiniBooNE



- ✓ No significant ν_e or $\bar{\nu}_e$ excess in the LSND-preferred L/E region
- ✓ But consistent with LSND
- ✓ Low-energy excess not understood
- ✓ L/E too small to be explained in 3-flavor framework (wrong Δm^2)



Relation Between Oscillation Channels

☑ Reactor anomaly: $\bar{\nu}_e \rightarrow \bar{\nu}_s$

☑ LSND / MiniBooNE: $\nu_\mu \rightarrow \nu_e$

☑ Oscillation channels are related:

$$P_{\nu_e \rightarrow \nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

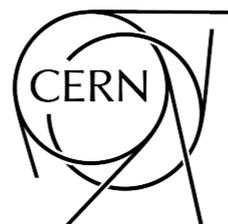
$$P_{\nu_\mu \rightarrow \nu_\mu} \simeq 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2)$$

$$P_{\nu_\mu \rightarrow \nu_e} \simeq 2|U_{e4}|^2|U_{\mu4}|^2$$

(for $4\pi E / \Delta m_{41}^2 \ll L \ll 4\pi E / \Delta m_{31}^2$)

☑ Models can be **over-constrained**. See lectures by G. Karagiorgi

Sterile Neutrinos in Cosmology



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Sterile Neutrinos in Cosmology

Standard picture: ν_s production via oscillation at $T \gtrsim \text{MeV}$

- ☑ $\nu_{e,\mu,\tau}$ evolve into superposition with ν_s
- ☑ Hard interaction collapses ν wave function
 - $\frac{1}{2} \sin^2 2\theta$ of ν converted to ν_s
- ☑ Remaining $\nu_{e,\mu,\tau}$ start to oscillate again
- ☑ Constrained by **CMB, LSS, BBN**:

$$\Sigma m_\nu \approx 0.12 \text{ eV} \text{ ⚡}$$

$$N_{\text{eff}} \approx 3.16 \text{ ⚡}$$

Testing Neutrinos in Cosmology

N_{eff}

- ☑ “Effective number of neutrino species”
- ☑ Really just a measure of the **energy density** of **relativistic particles**
- ☑ affects **expansion rate** of the Universe

Σm_ν

- ☑ “sum of neutrino masses”
- ☑ affects structure formation:
 - neutrinos do not form small structures
 - shallower gravitational wells for DM and baryons to fall into

$z = 48.4$

$T = 0.05 \text{ Gyr}$

500 kpc

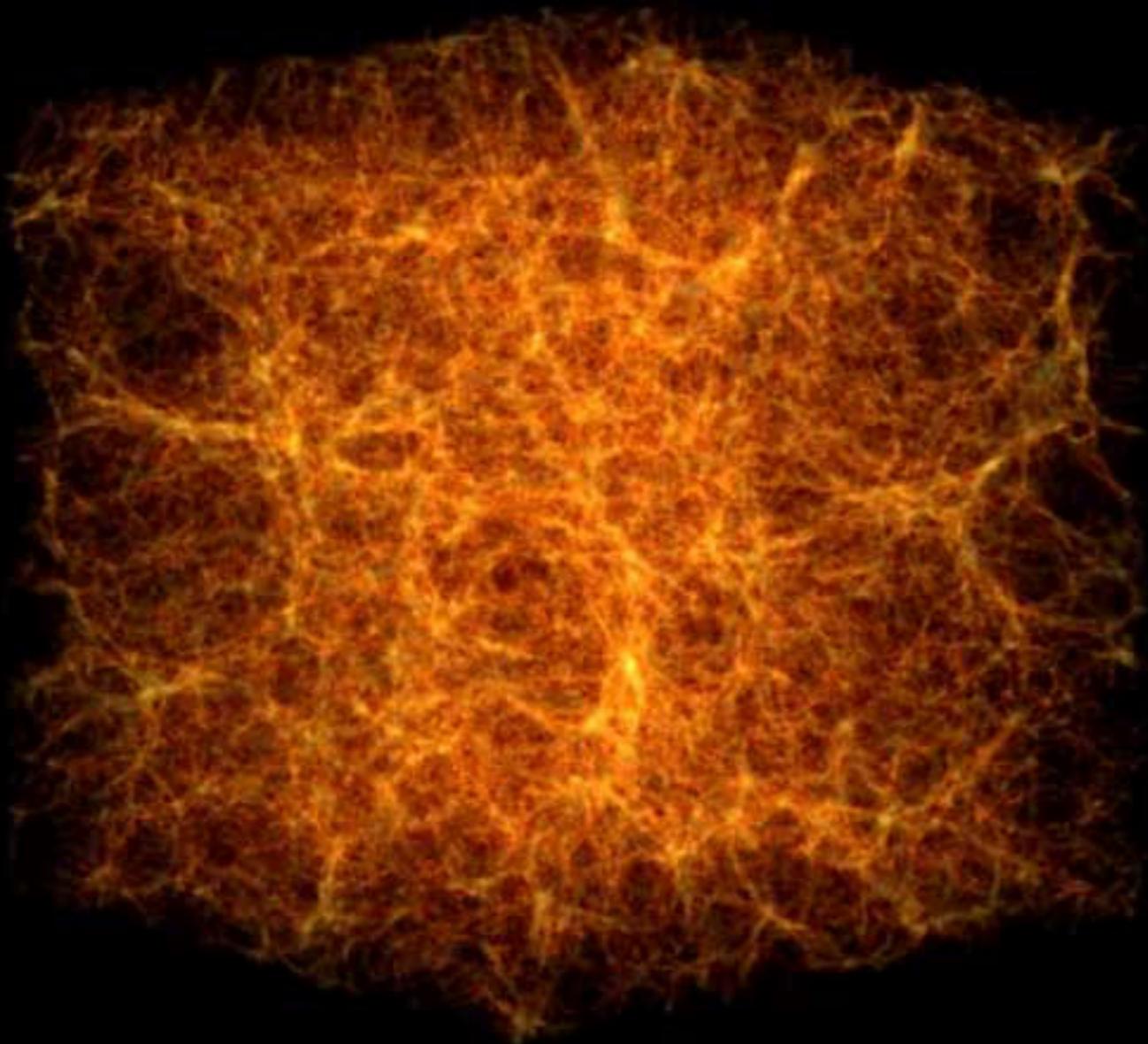


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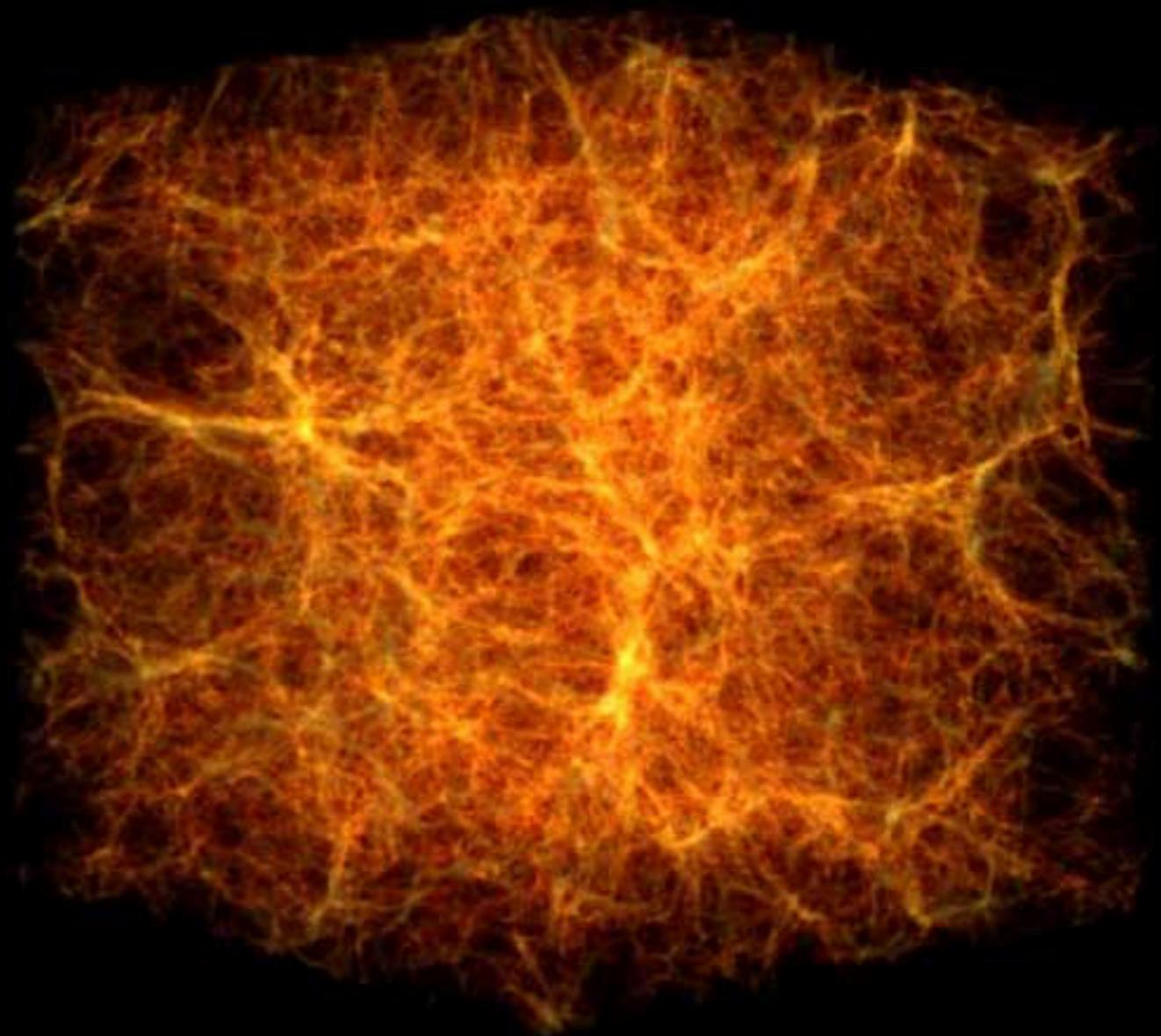
$T = 0.05 \text{ Gyr}$

500 kpc





small neutrino mass



large neutrino mass

Reconciling Sterile Neutrinos with Cosmology

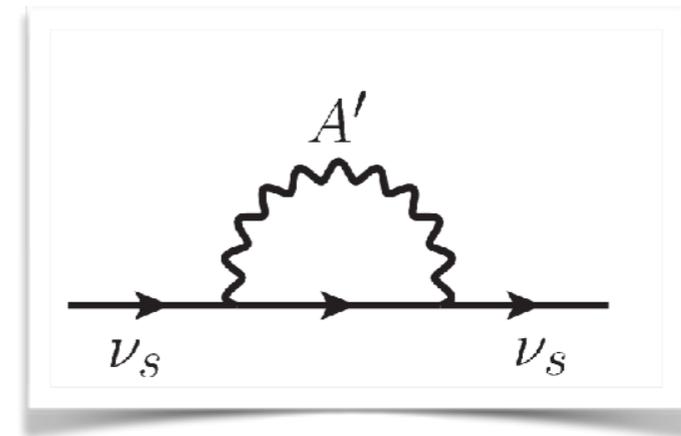
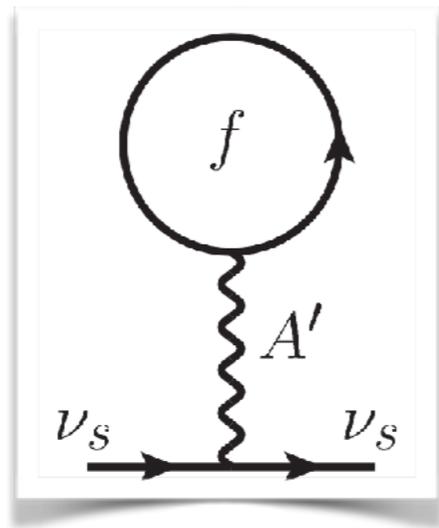
- ☑ New interactions in the ν_s sector
 - production suppressed by thermal potential
 - avoids N_{eff} constraint, weakens or avoids Σm_ν constraint
- ☑ ν_s properties change in late phase transition
- ☑ Coupling to slow-rolling scalar field
- ☑ ...

Reconciling Sterile Neutrinos with Cosmology

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Dasgupta JK, [1310.6337](#)
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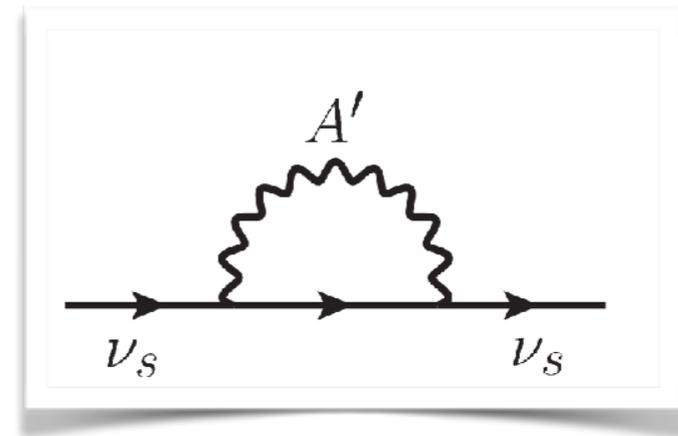
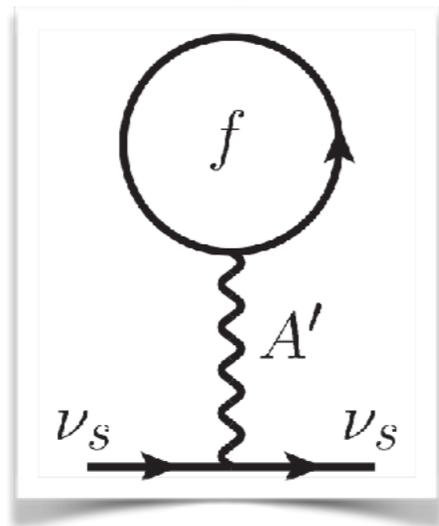
New Interaction in the Sterile Sector

- ☑ Assume ν_s charged under a new $U(1)'$ gauge group
- ☑ Neutrino self-energy contributes to effective potential V^{eff}



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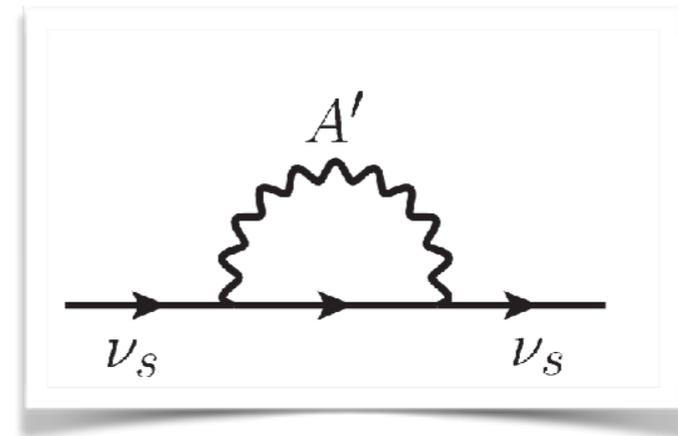
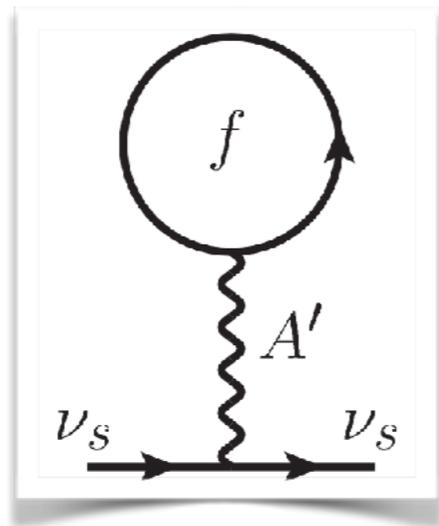


- ✓ Thermal propagators

$$S(p) = (\not{p} + m) \left[\frac{1}{p^2 - m^2} + i\Gamma_f(p) \right]$$
$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2) \left[\frac{1}{p^2 - M^2} + i\Gamma_b(p) \right]$$

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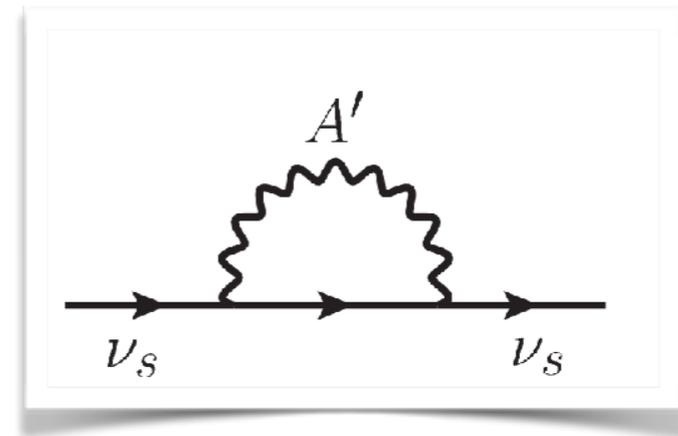
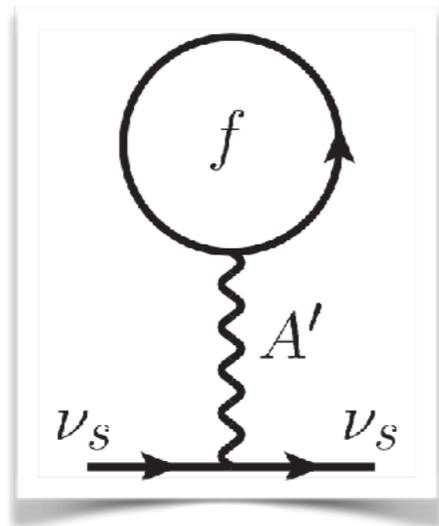
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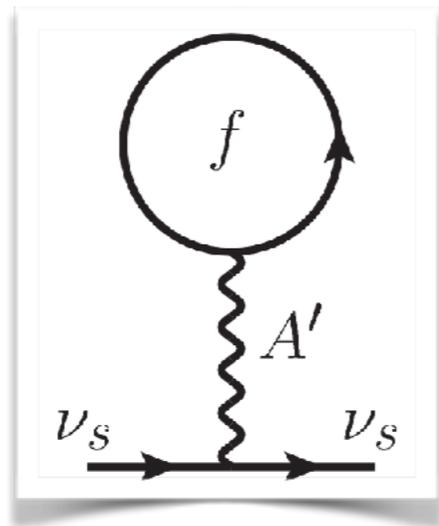
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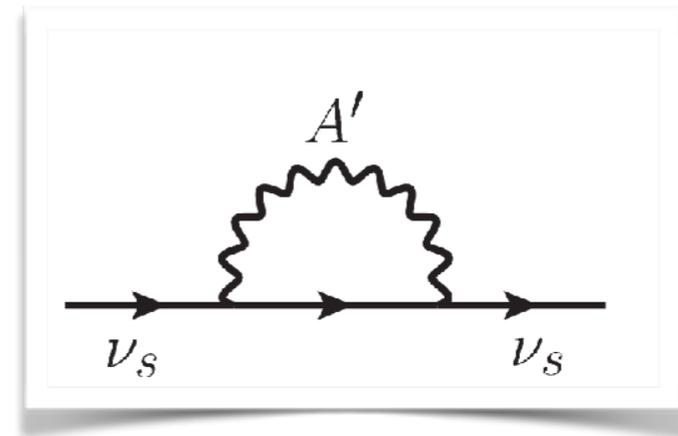
$$n_{f,b}(p) = [e^{|p \cdot u|/T_s} \pm 1]^{-1}$$

New Interaction in the Sterile Sector

- ✓ Assume ν_s charged under a new $U(1)'$ gauge group
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MSW potential $V \sim n_f - n_{\bar{f}}$



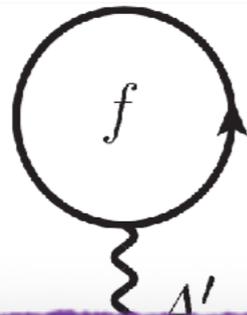
thermal correction $V \sim T^a$

- ✓ Effective mixing angle:

$$\sin^2 2\theta_{\text{eff}} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta - \frac{2EV^{\text{eff}}}{\Delta m^2} \right)^2}$$

New Interaction in the Sterile Sector

- ✓ Assume ν_s charged under a new $U(1)'$ gauge group
- ✓ Neutrino self-energy contributes to effective potential V^{eff}



- ★ ν_s production strongly suppressed at high T
- ★ cosmological constraints avoided

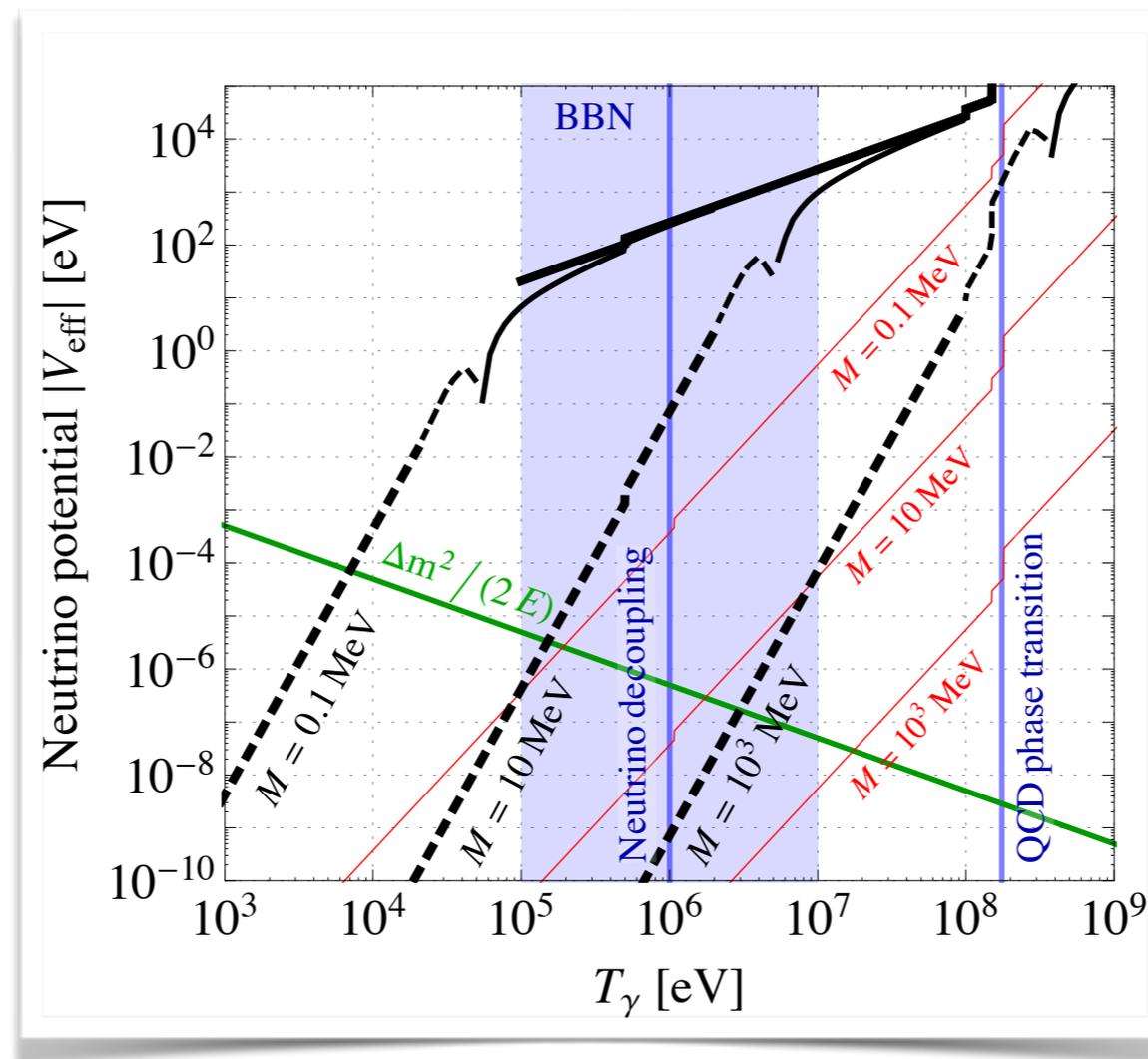
new potential $V^{\text{eff}} = \dots$

thermal correction $V^{\text{eff}} = \dots$

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New Interaction in the Sterile Sector



☑ While $V_{eff} \gg \Delta m^2 / (2T)$: ν_s production suppressed

Hannestad *et al.* [1310.5926](#), Dasgupta JK [1310.6337](#)

☑ Later: equilibration between $\nu_{e,\mu,\tau}$ and ν_s

(N_{eff} is fixed by then, but Σm_ν still worrisome)

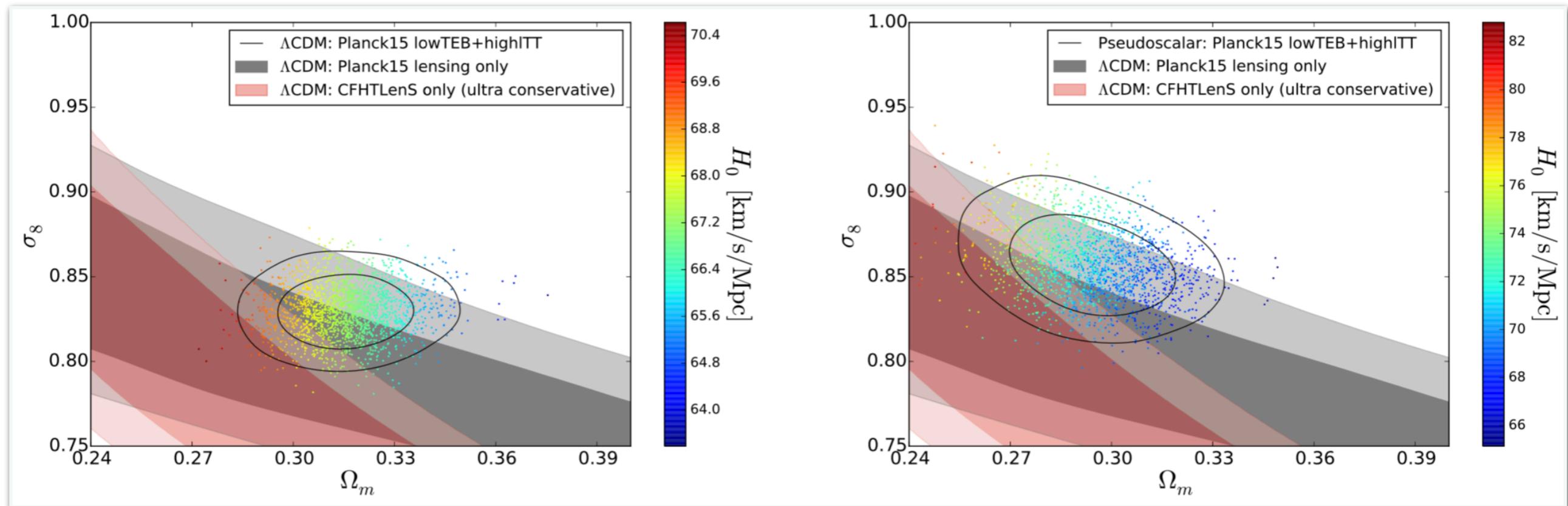
Chu Dasgupta JK [1505.02795](#), Cherry Friedland Shoemaker [1605.06506](#)

Forastieri *et al.* [1704.00626](#), Chu Dasgupta Dentler JK Saviano [1806.10629](#)

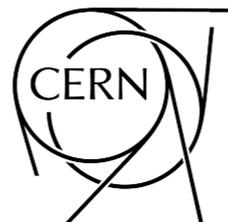
New Interaction in the Sterile Sector

- ☑ While $V^{\text{eff}} \gg \Delta m^2 / (2T)$: ν_s production suppressed
- ☑ Later: equilibration between $\nu_{e,\mu,\tau}$ and ν_s
(N_{eff} is fixed by then, but Σm_ν still worrisome)
- ☑ Can be solved by $\nu_s \nu_s \rightarrow \varphi \varphi$ annihilation
if mediator φ is a light pseudoscalar
- ☑ Could solve H_0 tension

Archidiacono *et al.* [1606.07673](https://arxiv.org/abs/1606.07673)



Non-Standard Neutrino Interactions

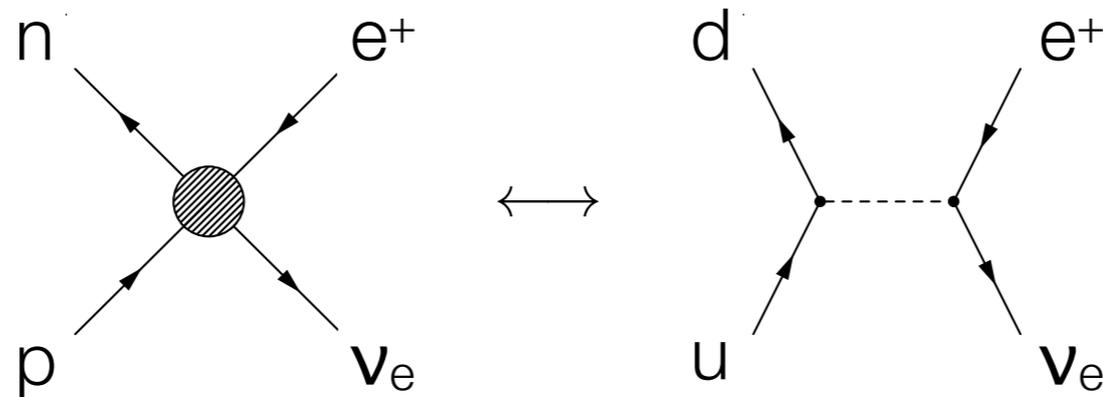


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Effective Field Theory

- ☑ The effect of new, heavy particles on low-energy experiments often admits a simplified description.
- ☑ Example: Fermi theory of weak interactions



- full theory: $\mathcal{L} \supset \frac{g}{2\sqrt{2}} \bar{d} \gamma^\mu (1 - \gamma^5) u W_\mu + \frac{g}{2\sqrt{2}} \nu_e \gamma^\mu (1 - \gamma^5) e W_\mu$
- effective theory: $\mathcal{L} \supset G_F [\bar{d} \gamma^\mu (1 - \gamma^5) u] [\nu_e \gamma^\mu (1 - \gamma^5) e]$

- ☑ Effective theory
 - is simpler (fewer particles)
 - is more generic (multiple high-energy theories reduce to the same EFT)

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{f, f'} \tilde{\epsilon}_{\alpha\beta}^{s, f, f'} [\bar{\nu}_\beta \gamma^\rho (1 - \gamma^5) \ell_\alpha] [\bar{f}' \gamma_\rho (1 - \gamma^5) f]$$
$$+ \frac{G_F}{\sqrt{2}} \sum_f \tilde{\epsilon}_{\alpha\beta}^{m, f} [\bar{\nu}_\alpha \gamma^\rho (1 - \gamma^5) \nu_\beta] [\bar{f} \gamma_\rho (1 - \gamma^5) f] + h.c.,$$

- ☑ Lorentz structures different from V–A are possible as well

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{f, f'} \tilde{\epsilon}_{\alpha\beta}^{s, f, f'} [\bar{\nu}_\beta \gamma^\rho (1 - \gamma^5) \ell_\alpha] [\bar{f}' \gamma_\rho (1 - \gamma^5) f] \\ + \frac{G_F}{\sqrt{2}} \sum_f \tilde{\epsilon}_{\alpha\beta}^{m, f} [\bar{\nu}_\alpha \gamma^\rho (1 - \gamma^5) \nu_\beta] [\bar{f} \gamma_\rho (1 - \gamma^5) f] + h.c.,$$

New **CC** interactions
(affect neutrino production
and detection)

- ☑ Lorentz structures different from V–A are possible as well

EFT in the Neutrino Sector

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{f, f'} \tilde{\epsilon}_{\alpha\beta}^{s, f, f'} [\bar{\nu}_\beta \gamma^\rho (1 - \gamma^5) \ell_\alpha] [\bar{f}' \gamma_\rho (1 - \gamma^5) f] \\ + \frac{G_F}{\sqrt{2}} \sum_f \tilde{\epsilon}_{\alpha\beta}^{m, f} [\bar{\nu}_\alpha \gamma^\rho (1 - \gamma^5) \nu_\beta] [\bar{f} \gamma_\rho (1 - \gamma^5) f] + h.c.$$

New **CC** interactions
(affect neutrino production
and detection)

New **NC** interactions
(affect neutrino propagation:
non-standard matter effects)

☑ Lorentz structures different from V–A are possible as well

EFT in the Neutrino Sector

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{f, f'} \tilde{\epsilon}_{\alpha\beta}^{s, f, f'} [\bar{l}_\alpha \gamma^\rho (1 - \gamma^5) l_\beta] [\bar{f}' \gamma_\rho (1 - \gamma^5) f]$$
$$+ \frac{G_F}{\sqrt{2}} \sum_f \tilde{\epsilon}_{\alpha\beta}^{m, f} [\bar{\nu}_\alpha \gamma^\rho (1 - \gamma^5) \nu_\beta] [\bar{f} \gamma_\rho (1 - \gamma^5) f] + h.c.,$$

coupling strength
(relative to G_F)

- ☑ Lorentz structures different from V–A are possible as well

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{f, f'} \tilde{\epsilon}_{\alpha\beta}^{s, f, f'} [\bar{\nu}_\beta \gamma^\rho (1 - \gamma^5) \ell_\alpha] [\bar{f}' \gamma_\rho (1 - \gamma^5) f]$$
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- Lorentz structures different from V–A are possible as well

Neutrino Oscillation with NSI

☑ Standard oscillations:

$$P_{\nu_\alpha \rightarrow \nu_\beta} = |\langle \nu_\beta | e^{-iHL} | \nu_\alpha \rangle|^2$$

☑ with NSI:

$$P_{\nu_\alpha^s \rightarrow \nu_\beta^d} = |\langle \nu_\beta^d | e^{-i(H+V_{\text{NSI}})L} | \nu_\alpha^s \rangle|^2$$

where

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}^s |\nu_\beta\rangle$$

$$\text{e.g. } \pi^+ \xrightarrow{\varepsilon_{\mu e}^s} \mu^+ \nu_e$$

$$\langle \nu_\beta^d | = \langle \nu_\beta | + \sum_{\alpha=e,\mu,\tau} \varepsilon_{\alpha\beta}^d \langle \nu_\alpha |$$

$$\text{e.g. } \nu_\tau N \xrightarrow{\varepsilon_{\tau e}^d} e^- X$$

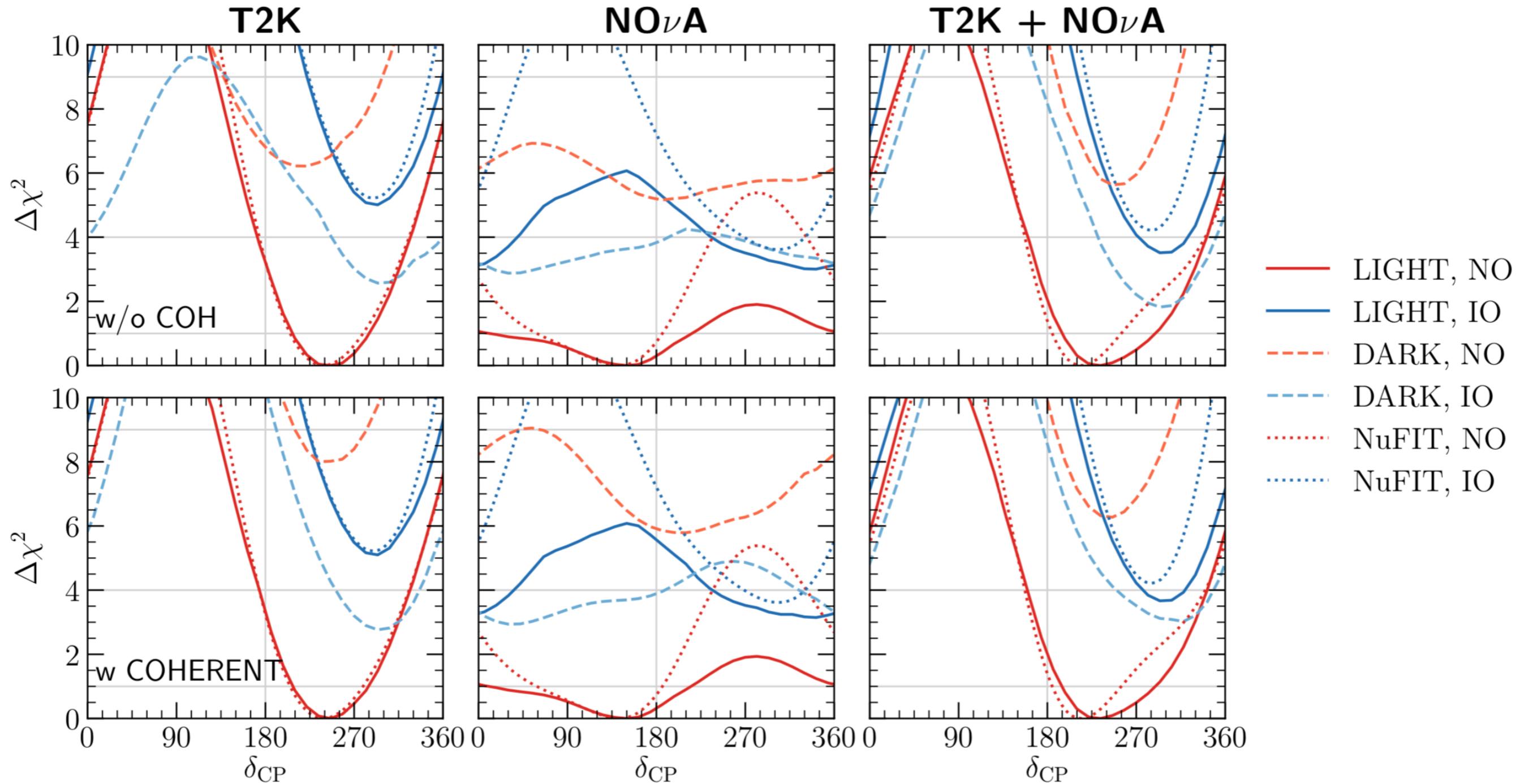
and the matter potential now receives an extra contribution

$$(V_{\text{NSI}})_{\alpha\beta} = \sqrt{2}G_F N_e \varepsilon_{\alpha\beta}^m$$

NSI in Oscillation Experiments

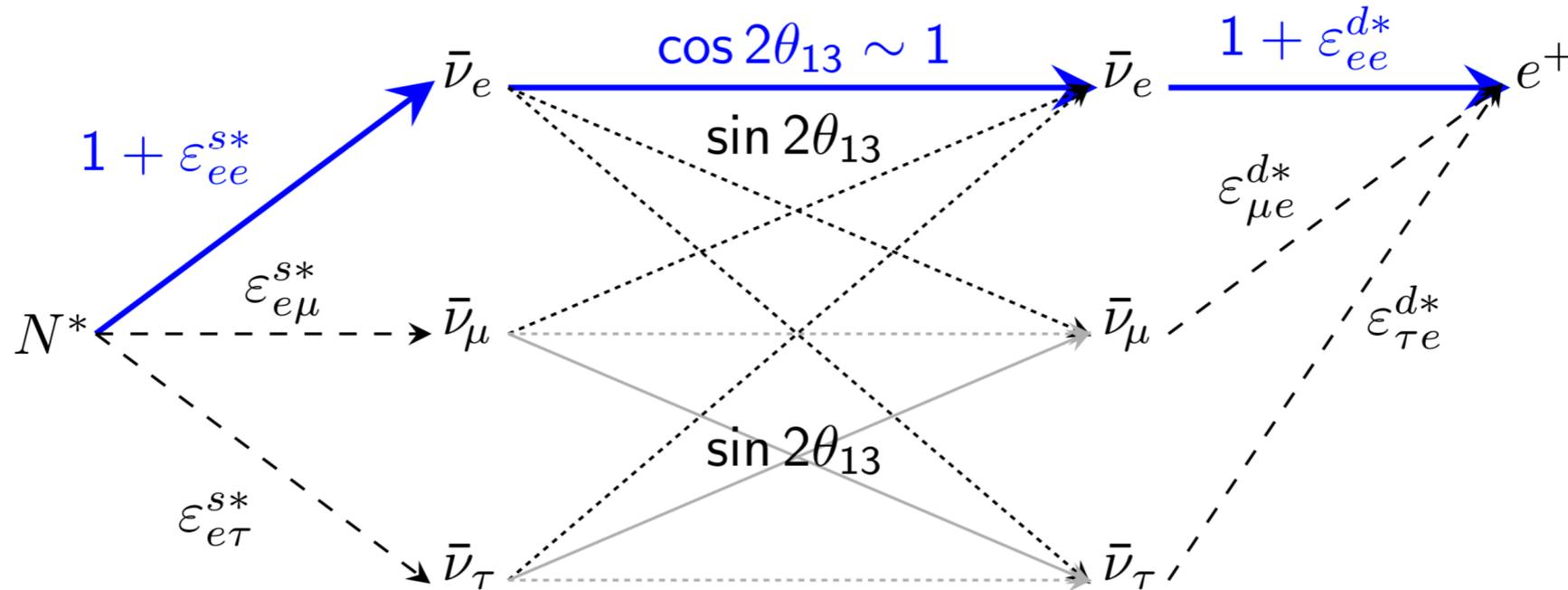
- ☑ **Interference** between standard and NSI-induced flavor transition amplitudes
 - effects linear in ϵ
 - most constraints based on processes suppressed by ϵ^2 (e.g. charged lepton flavour violation)
- ☑ Possible consequences in oscillation experiments
 - **poor quality** of standard oscillation fit
 - enables detection of NSI
 - **mismatch** between standard osc. fits in different experiments
 - enables detection of NSI
 - consistent, but **wrong reconstruction** of standard osc. parameters
 - dangerous!

NSI in Oscillation Experiments



Esteban Gonzalez-Garcia Maltoni 1905.05203

Qualitative Arguments



Example: reactor neutrinos

○ standard path: $N^* \rightarrow \bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+$

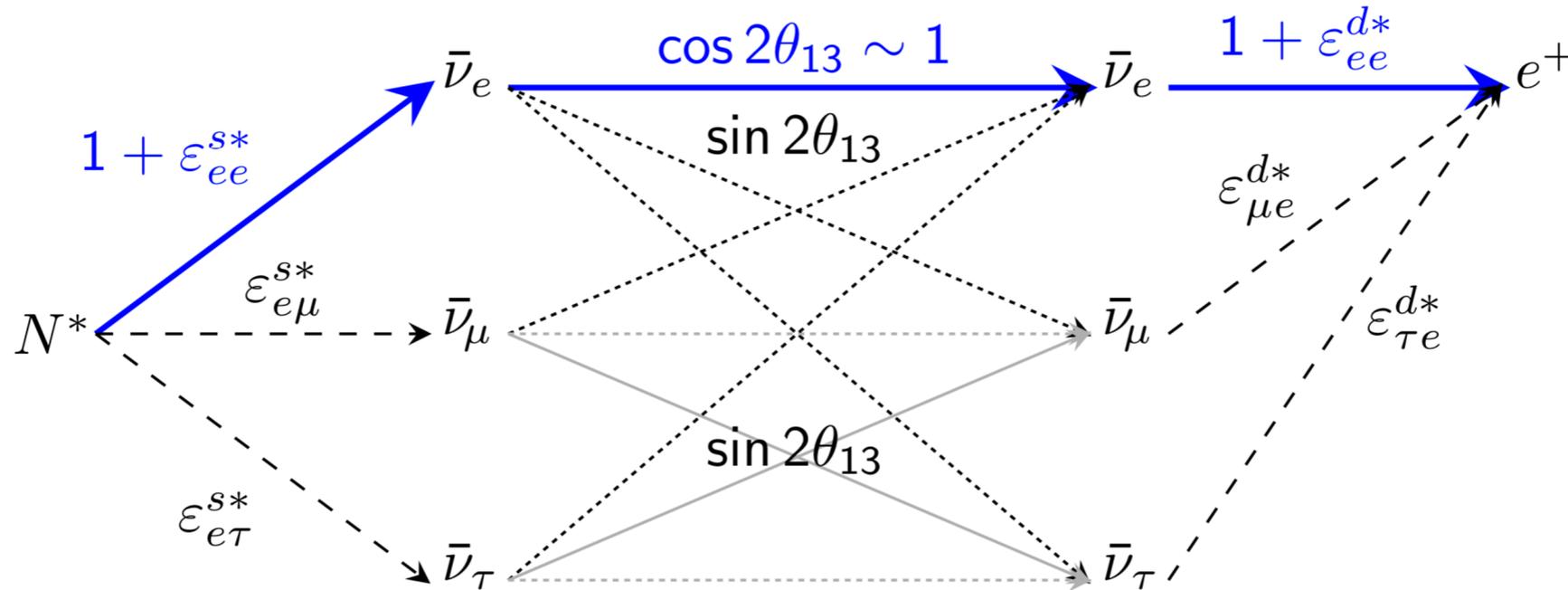
○ NSI in production: $N^* \xrightarrow{\epsilon_{ee}^{s*}} \bar{\nu}_e$ $N^* \xrightarrow{\epsilon_{e\mu}^{s*}} \bar{\nu}_\mu$ $N^* \xrightarrow{\epsilon_{e\tau}^{s*}} \bar{\nu}_\tau$

○ NSI in detection: $\bar{\nu}_e \xrightarrow{\epsilon_{ee}^{d*}} e^+$ $\bar{\nu}_\mu \xrightarrow{\epsilon_{\mu e}^{d*}} e^+$ $\bar{\nu}_\tau \xrightarrow{\epsilon_{\tau e}^{d*}} e^+$

○ $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_\tau$ oscillations suppressed by θ_{13}

○ Assume only one ϵ parameter sizeable

Qualitative Arguments



- $N^* \xrightarrow{\epsilon_{ee}^{s*}} \bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+ \quad \mathcal{O}(\epsilon) \quad \text{but: absorbed in flux uncertainty}$
- $N^* \rightarrow \bar{\nu}_e \rightarrow \bar{\nu}_e \xrightarrow{\epsilon_{ee}^{d*}} e^+ \quad \mathcal{O}(\epsilon) \quad \text{but: absorbed in flux uncertainty}$
- $N^* \xrightarrow{\epsilon_{e\mu}^{s*}} \bar{\nu}_\mu \xrightarrow{\sin \theta_{13}} \bar{\nu}_e \rightarrow e^+ \quad \mathcal{O}(\epsilon \sin \theta_{13})$
- $N^* \xrightarrow{\epsilon_{e\tau}^{s*}} \bar{\nu}_\tau \xrightarrow{\sin \theta_{13}} \bar{\nu}_e \rightarrow e^+ \quad \mathcal{O}(\epsilon \sin \theta_{13})$
- $N^* \rightarrow \bar{\nu}_e \xrightarrow{\sin \theta_{13}} \bar{\nu}_\mu \xrightarrow{\epsilon_{\mu e}^{d*}} e^+ \quad \mathcal{O}(\epsilon \sin \theta_{13})$
- $N^* \rightarrow \bar{\nu}_e \xrightarrow{\sin \theta_{13}} \bar{\nu}_\tau \xrightarrow{\epsilon_{\tau e}^{d*}} e^+ \quad \mathcal{O}(\epsilon \sin \theta_{13})$

Constraints on NSI

- NSI typically imply **similar interactions in the charged lepton sector** thanks to the $SU(2)_L$ symmetry of the SM
 - strong constraints from charged lepton flavour violation
- Loopholes:
 - full theory could involve **lepton—Higgs interactions**
 - extra suppression by v^2/Λ^2 (Λ = mass scale of new particles)
 - $\nu_{e,\mu,\tau}$ could mix with sterile ν_s , interactions only among ν_s
 - extra suppression by active—sterile mixing angles
- Maximum size of NSI in specific models: [Bischer Rodejohann Xu 1807.08102](#)

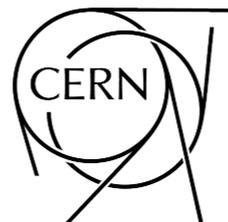
	ϵ_e^F	$\epsilon_e^\triangleright$	$\epsilon_n^\triangleright$	$\epsilon_p^\triangleright$	ϵ_e^\square	ϵ_n^\square	ϵ_p^\square
model A	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-3})$	0	0
model B	0	$\mathcal{O}(10^{-1})$	$\mathcal{O}(1)$	$\mathcal{O}(10^{-1})$	0	0	0
model C	0	0	0	0	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$

Constraints on NSI



Large NSI in the neutrino sector
are not a generic prediction of BSM scenarios,
but can occur in some models

Neutrino–Dark Matter Interactions



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- ☑ Lots of recent interest in ultralight (“fuzzy”) dark matter
 - Very low DM mass ($\approx 10^{-20}$ eV)
 - Compton wave length \sim pc
 - quantum effects on galaxy scales
 - might resolve small-scale structure anomalies (e.g. cusp vs. core problem in dwarf galaxies)

24. Cold and fuzzy dark matter

Wayne Hu, Rennan Barkana, Andrei Gruzinov (Princeton, Inst. Advanced Study). Mar 2000. 4 pp.

Published in **Phys.Rev.Lett.** 85 (2000) 1158-1161

DOI: [10.1103/PhysRevLett.85.1158](https://doi.org/10.1103/PhysRevLett.85.1158)

e-Print: [astro-ph/0003365](https://arxiv.org/abs/astro-ph/0003365) | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#)

[Detailed record](#) - [Cited by 635 records](#) 500+

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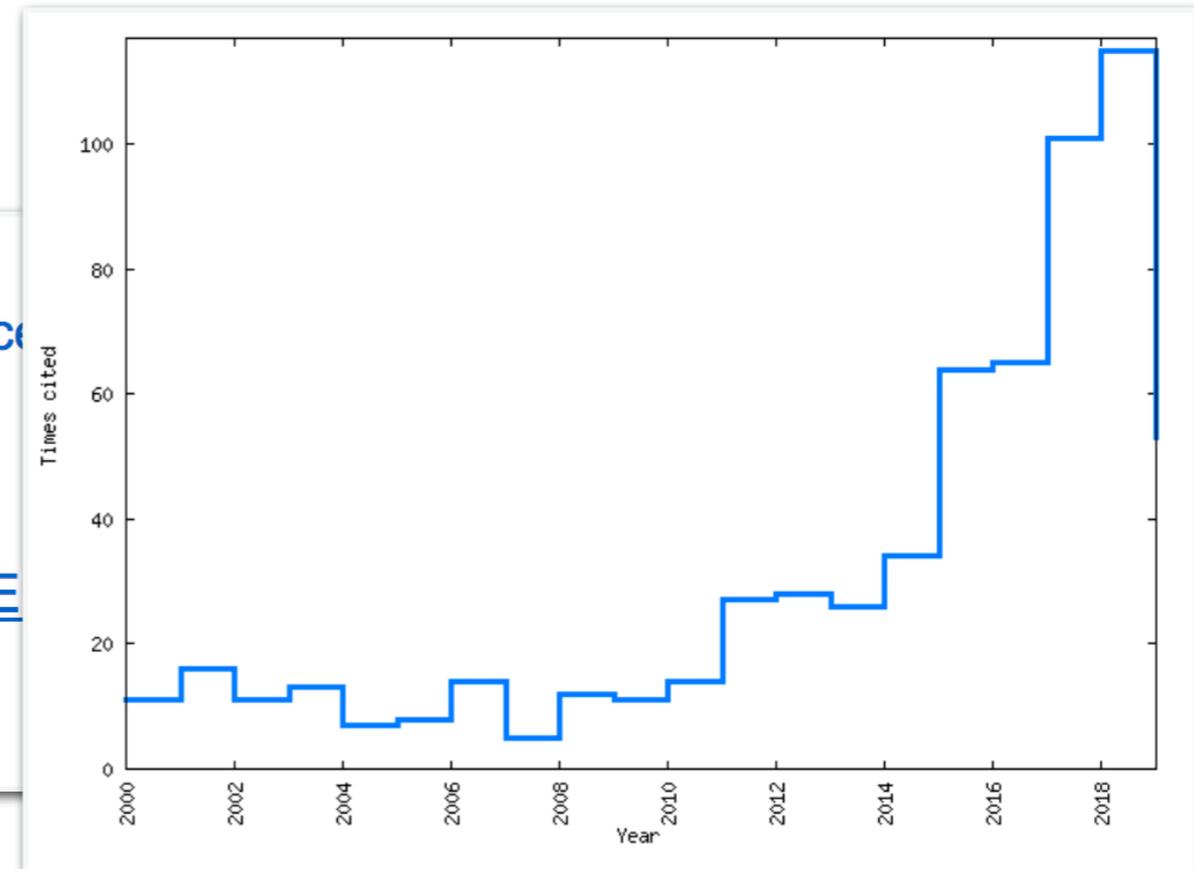
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[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(E\)](#)
[ADS Abstract Service](#)

[Detailed record](#) - [Cited by 635 records](#) **500+**



(Dark) Matter Effects in Neutrino Oscillations

☑ Phenomenological consequences

- Scalar DM ϕ : $\mathcal{L} \supset \frac{1}{2} g \phi \bar{\nu}^c \nu$ \Rightarrow modified ν masses/mixings:

$$m_\nu \rightarrow m_\nu + g \langle \phi \rangle$$

- Vector DM A_μ : $\mathcal{L} \supset \frac{1}{2} g A^\mu \bar{\nu} \gamma_\mu \nu$ \Rightarrow modified dispersion relation:

$$p^\mu p_\mu = m_\nu^2 \rightarrow (p^\mu + g \langle A^\mu \rangle)(p_\mu + g \langle A_\mu \rangle) = m_\nu^2$$

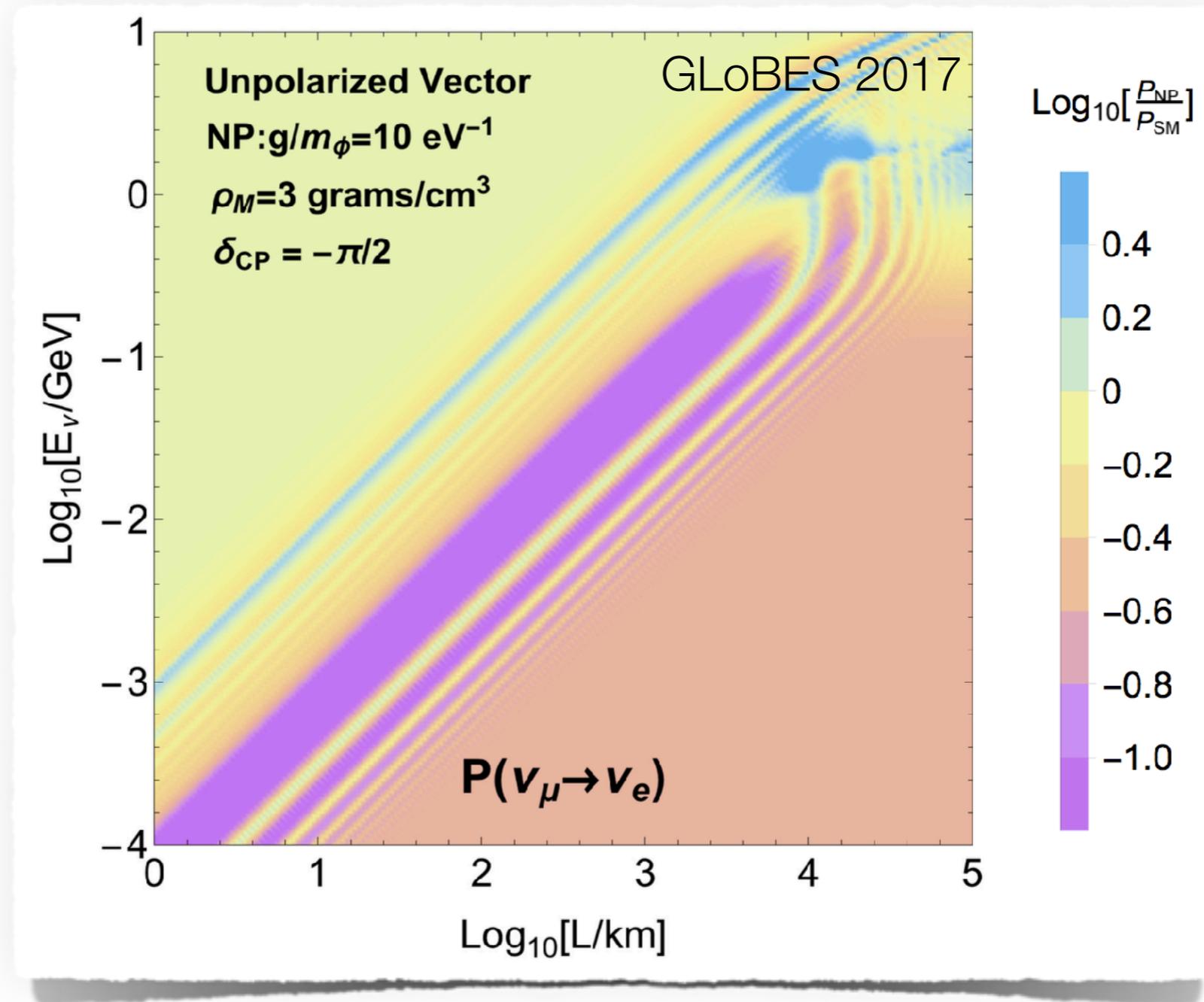
- ☑ Can be interpreted as **dynamical Lorentz violation**

- ☑ Can be rewritten as **modified MSW potential**

$$V_{\text{eff}} = \frac{1}{2E_\nu} \left(\langle \phi \rangle (g m_\nu + m_\nu y) + \langle \phi \rangle^2 y^2 \right) \quad (\text{scalar DM})$$

$$V_{\text{eff}} = -\frac{1}{2E_\nu} \left(2g p \cdot \langle A_\mu \rangle + g^2 \langle A_\mu \rangle \langle A^\mu \rangle \right) \quad (\text{vector DM})$$

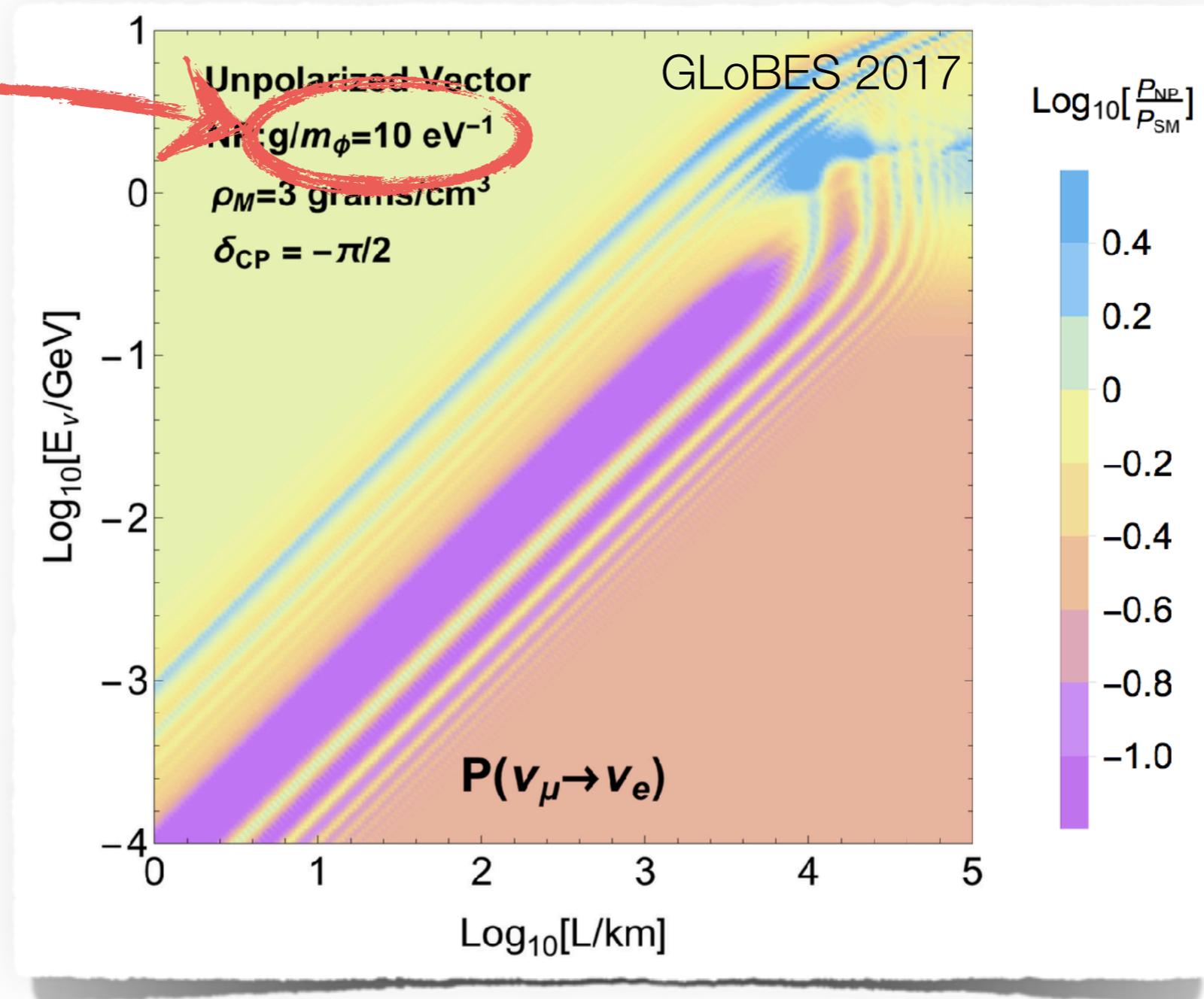
Modified Oscillation Probabilities



$O(1)$ modifications possible

Modified Oscillation Probabilities

Figure of Merit:
Coupling strength
divided by DM mass



$O(1)$ modifications possible

Current and Future Constraints

GLOBES 2017

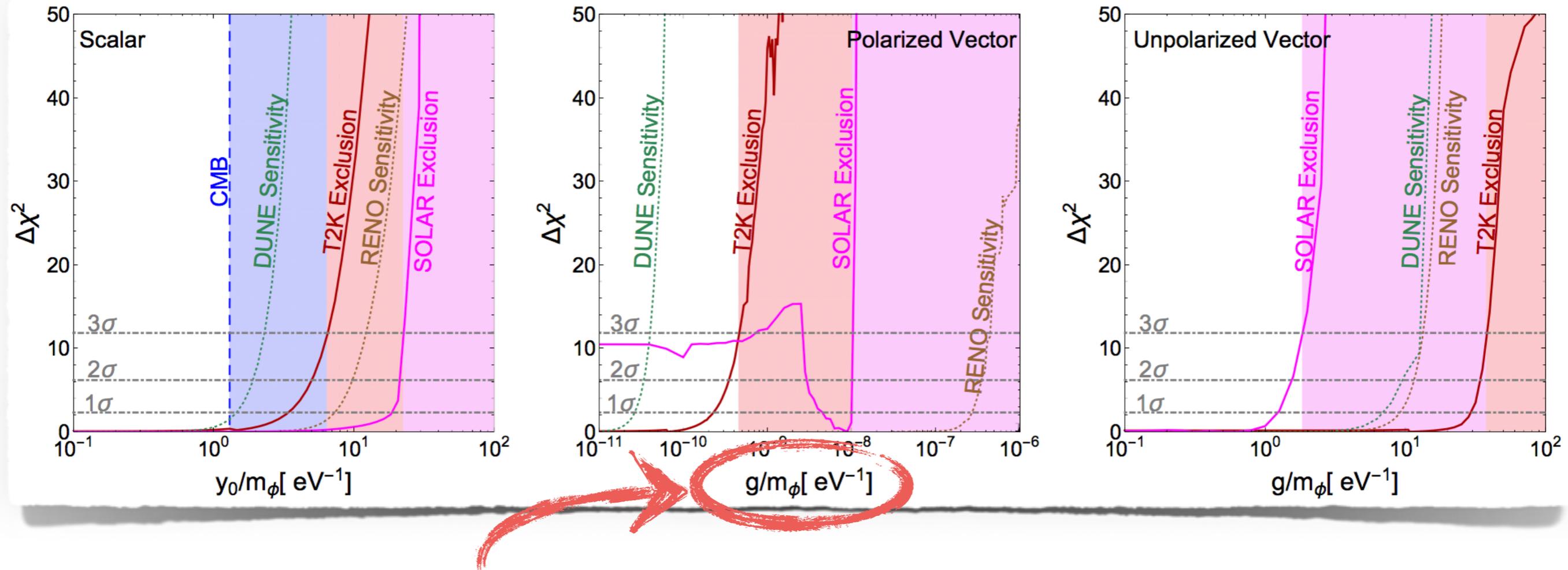


Figure of Merit:
Coupling strength
divided by DM mass

Plot Twist: Time Dependence

- ☑ Signal changes over time
 - Intrinsic oscillations of DM field ϕ , $A_\mu \sim e^{imt}$
 - Moreover, for vector DM:
orientation of Earth w.r.t. DM polarization modulates
- ☑ Particularly relevant for flavor-blind interactions

References on neutrino–DM interactions:

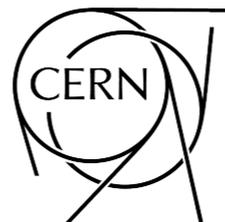
Berlin [1608.01307](#)

Krnjaic Machado Necib, [1705.06740](#)

Brdar JK Liu Prass Wang, [1705.09455](#)

Capozzi Shoemaker Vecchi [1804.05117](#)

Summary



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Sterile Neutrinos

- experimental hints?
- would have exciting consequences for cosmology

Non-Standard Neutrino Interactions:

- exciting signals (but strongly constrained in many models)

Neutrino–Dark Matter Interactions

- for ultralight (“Fuzzy”) Dark Matter

Not discussed here

- extra dimensions
- neutrino decay
- decoherence
- ...