Title: Distorted Neutrino Oscillations (DiNOs) from ultra light, bosonic dark matter

Date: Jul 21, 2017 11:10 AM

URL: http://pirsa.org/17070019

Abstract:

DiNOs

Distorted Neutrino Oscillations from ultra light dark matter

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Fermilab

w/ Pedro Machado & Lina Necib

1705.06740

New Directions Dark Matter & Neutrino Physics
Perimeter Institute, July 21 2017


$\sim 100 M_\odot$
ge my mind.
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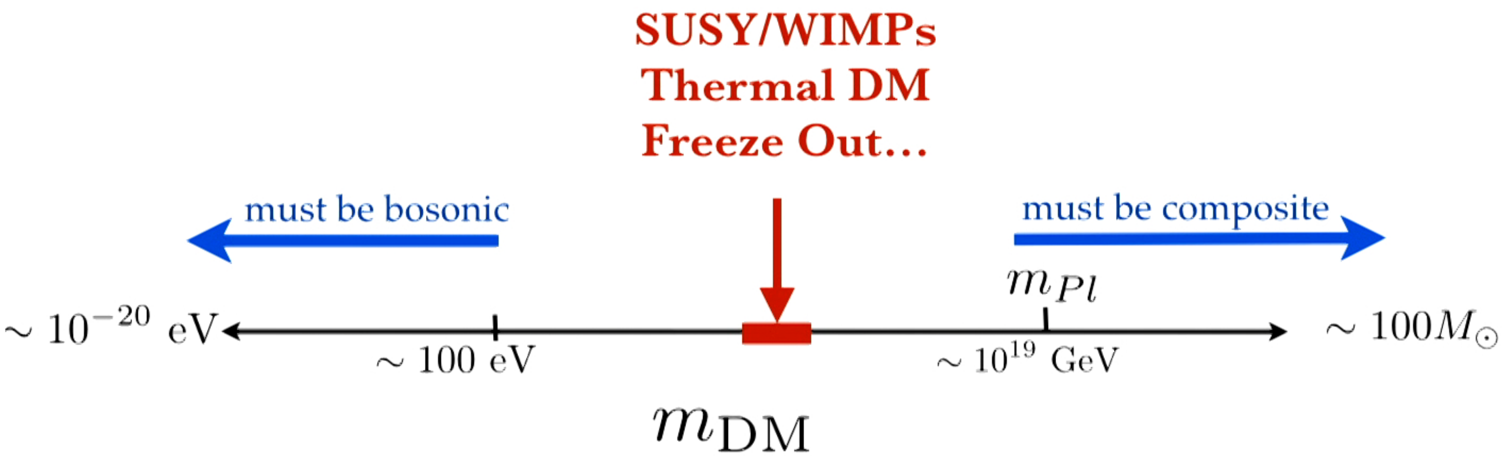
Dark Matter Status Report

Very Biased Dark Matter Status Report

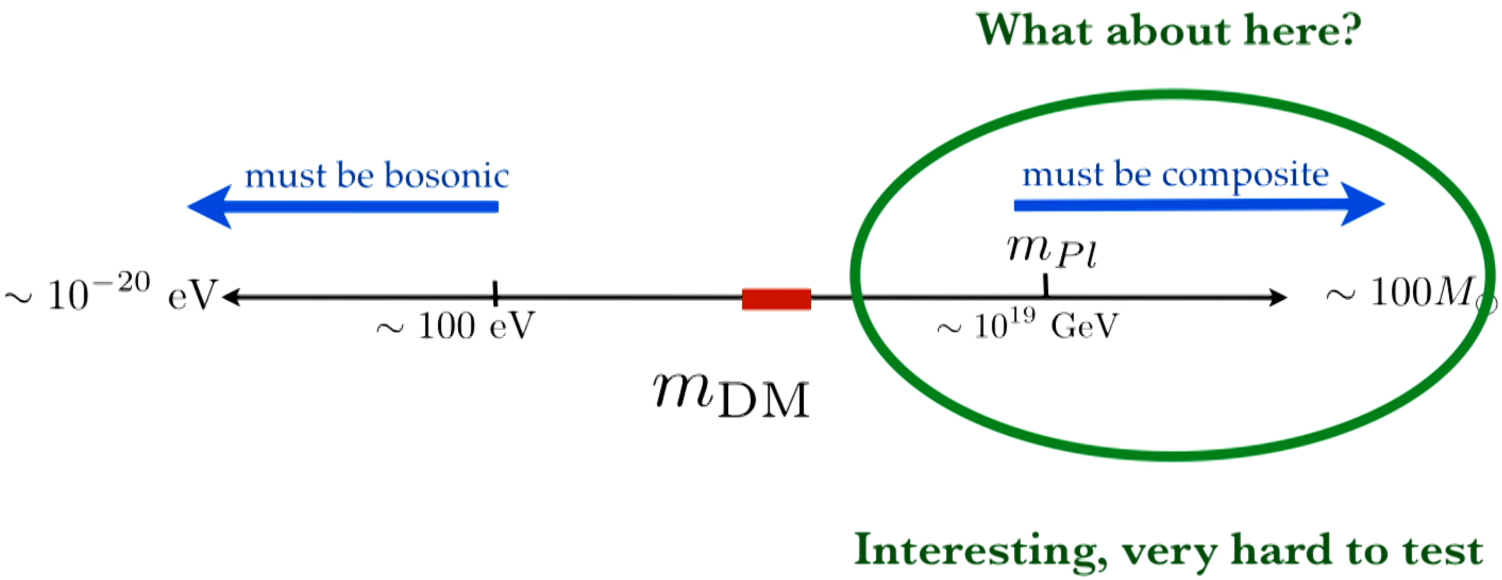


Extremely well motivated keV ~ 100 TeV range
but null results so far…

"When the facts change, I change my mind.
What do you do, sir?"

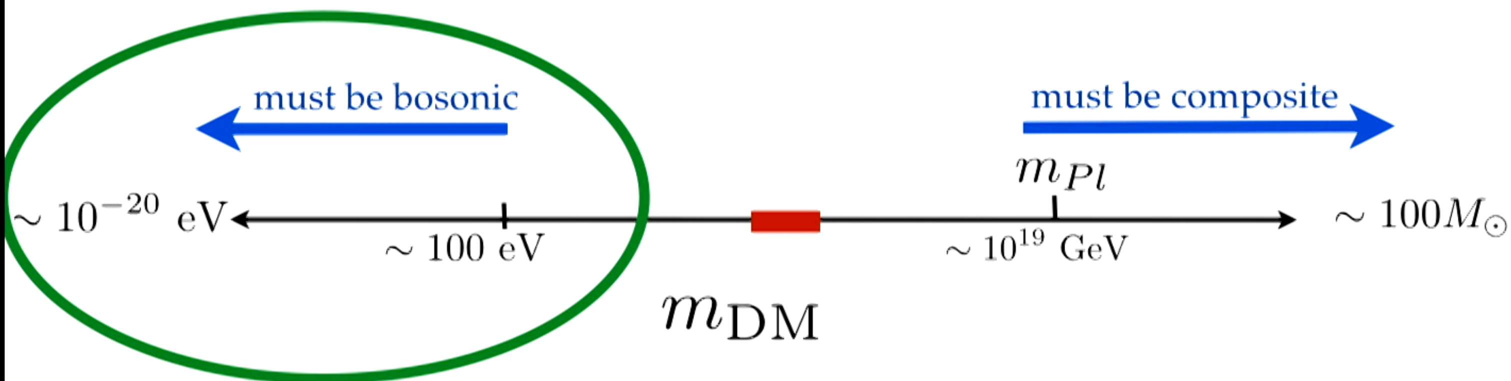
- John Maynard Keynes

Very Biased Dark Matter Status Report



Very Biased Dark Matter Status Report

What about here?

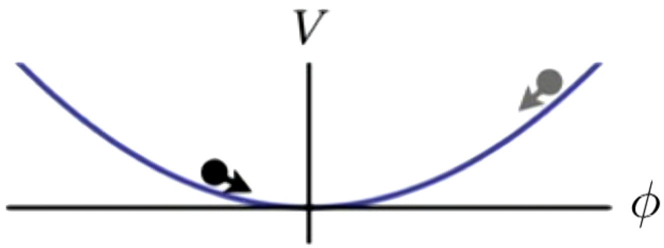


Behaves like classical field
Non thermal production
Gunn Tremaine bound

Lots of UV scenarios (axions, alps, dilatons…)

Misalignment Mechanism

(quasi) stable bosonic field displaced during early universe



$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

$$\phi \propto a^{-3/2} \cos(m_\phi t)$$

Begins oscillation @ horizon crossing $\quad m_\phi \sim H$

Redshifts like non relativistic matter $\quad \rho_\phi \sim m_\phi^2 \phi^2 \propto a^{-3}$

High occupation number (field like)

$$\rho_\phi = \rho_{\mathrm{DM}}^{\odot} \;\; \& \;\; m_\phi \lesssim \text{ few eV} \quad \Longrightarrow \lambda_\phi \gg n_\phi^{-1/3}$$

Cosmic Fields: Operators & Observables

Spin	Type	Operator	Interaction	Oscillating DM Effects	Searches
0	scalar	$\phi\, h^\dagger h,\ \phi\, \mathcal{O}_{\rm SM}$	Higgs portal / dilaton	m_e, m_p, α variation	Atomic clocks [56]
				acceleration	⋆
	pseudo-scalar	$a\, G^{\mu\nu} \tilde{G}_{\mu\nu}$	axion-QCD	nucleon EDM	CASPEr [18]
		$a\, F^{\mu\nu} \tilde{F}_{\mu\nu}$	axion-E&M	EMF along B field	ADMX [13]
		$(\partial_\mu a)\bar{\psi}\gamma^\mu \gamma_5 \psi$	axion-fermion	spin torque	CASPEr [18]
1	vector	$A'_\mu \bar{\psi}\gamma^\mu \psi$	minimally coupled	acceleration	⋆
		$F'_{\mu\nu} F^{\mu\nu}$	vector–photon mixing	EMF in vacuum	DM Radio [33], ADMX
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2 (?)	tensor	$h'_{\mu\nu} T^{\mu\nu}$ (?)	gravity-like	grav. wave-like	grav. wave detectors?

Rich variety of physical effects

Broad class of models

Graham, Mardon, Kaplan, Rajendran, Terrano 1512.06165

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Time variation in masses and couplings (e.g. Higgs portal)

Currently tested with atomic clocks & accelerometers

Q: How can we probe this effect in neutrinos?

Basic Setup

$$\mathscr{L}_{\text{eff}} = -m_\nu \left(1 + y\frac{\phi}{\Lambda}\right)\nu\nu + h.c.$$

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Local density and mass fix modulation amplitude

$$\phi(x,t) \simeq \frac{\sqrt{2\rho_\phi^\odot}}{m_\phi}\cos[m_\phi(t - \vec{v}\cdot\vec{x})] \qquad \eta_\phi \equiv \frac{\sqrt{2\rho_\phi^\odot}}{\Lambda m_\phi} \sim \frac{\delta m_\nu}{m_\nu}$$

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Introduces spacetime variation in oscillation parameters

$$\Delta m_{ij}^2(x,t) \equiv m_i^2 - m_j^2 \simeq \Delta m_{ij,0}^2\left(1 + 2\frac{\phi(x,t)}{\Lambda}\right)$$

$$\theta_{ij}(x,t) = \theta_{ij,0} + \frac{\phi(x,t)}{\Lambda}$$

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Limiting Regimes

$$\tau_\phi = \frac{2\pi}{m_\phi} \simeq 10\,\text{min}\left(\frac{7\times 10^{-18}\,\text{eV}}{m_\phi}\right);$$

1) DM field quasi-static $\tau_\phi \gg T_{\text{experiment}}$

Field just renormalizes neutrino oscillation parameters

Verdict: Boring

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3) Sweet Spot: $T_{\mathrm{exp}} < \tau_\phi < T_{\nu\ \mathrm{TOF}}$

Each neutrino samples nearly *static* field in flight
but, different neutrinos feel different phases

Verdict: Interesting

Neutrino Oscillation Observables

2 Flavour Example

Standard Calculation $$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Include Distortion $$\Delta m^2 = \Delta m^2[\phi(t)] \qquad \theta = \theta[\phi(t)]$$

Observed probability: period average

$$\langle P(\nu_\alpha \to \nu_\beta)\rangle = \int_0^{\tau_\phi} \frac{dt}{\tau_\phi} P(\nu_\alpha \to \nu_\beta)$$

Agnostic about flavor structure, consider effects in isolation

qualitatively similar for additional flavors

Neutrino Oscillation Observables

Mixing Angle Modulation

$$\int_0^{\tau_\phi} \frac{dt}{\tau_\phi} \sin^2 2\theta(t) = \frac{1}{2}\left[1 - J_0(4\eta_\phi)\cos 4\theta_0\right]$$
$$\simeq \sin^2 2\theta_0 \left(1 - 4\eta_\phi^2\right) + 2\eta_\phi^2 + \mathcal{O}(\eta_\phi^3)$$

Generic deviations away from extremal angles

Existing bounds from **nonzero** θ_{13} (Daya Bay)

& **near maximal** θ_{23} (T2K)

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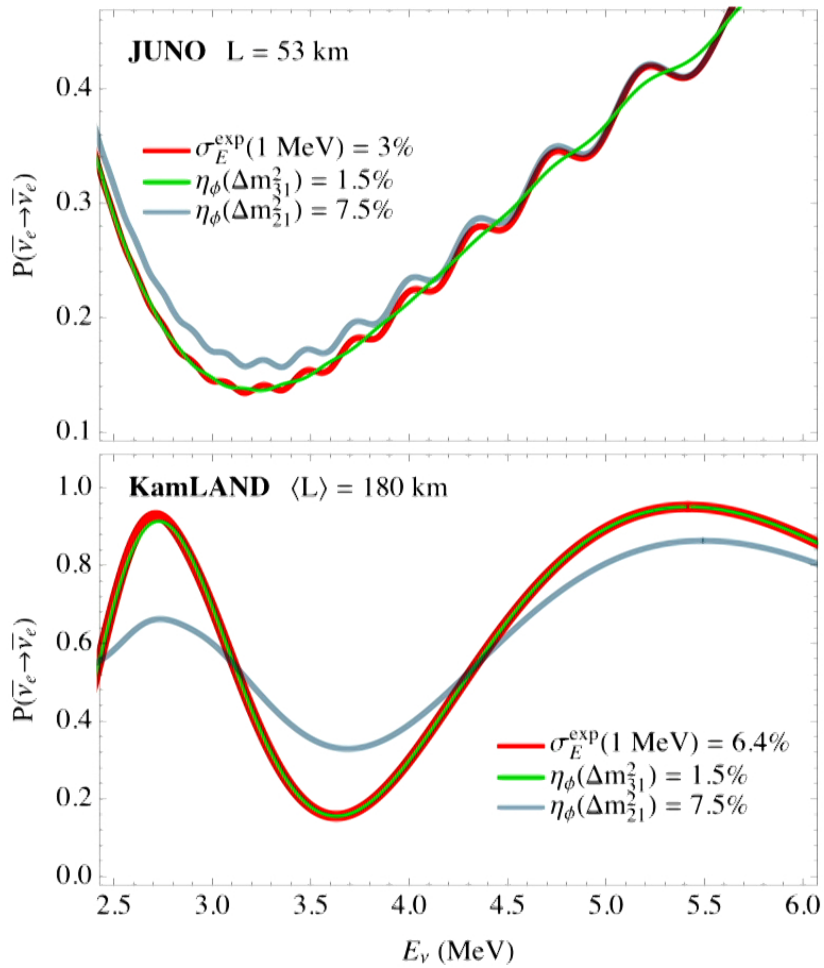
Mass Squared Modulation

$$\int_0^{\tau_\phi} \frac{dt}{\tau_\phi} \sin^2\left[\frac{\Delta m^2 L}{4E}\left(1 + 2\eta_\phi \cos m_\phi t\right)\right]$$

Existing bounds from Δm^2_{21} **(KamLAND)**

Neutrino Oscillation Observables



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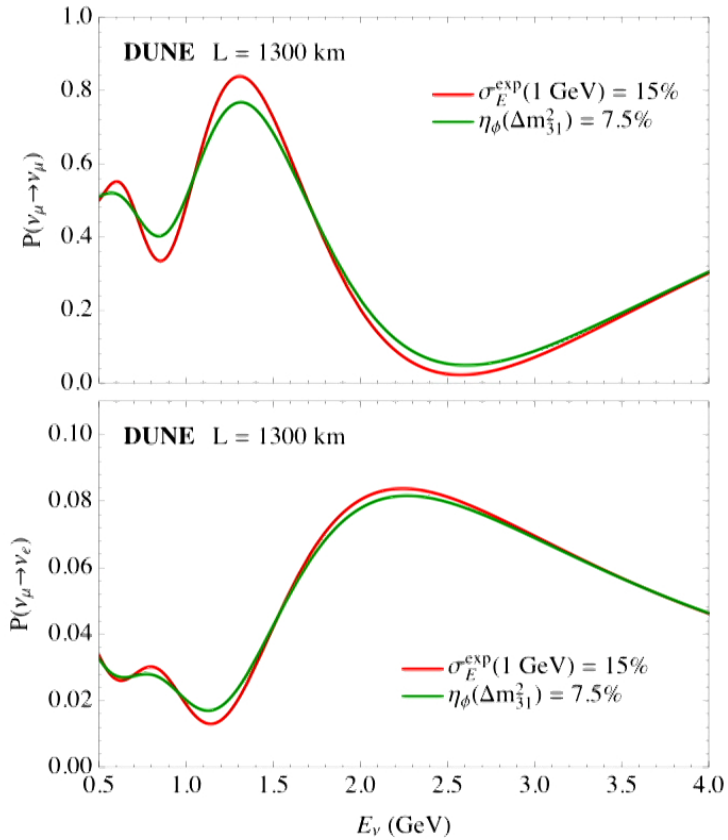

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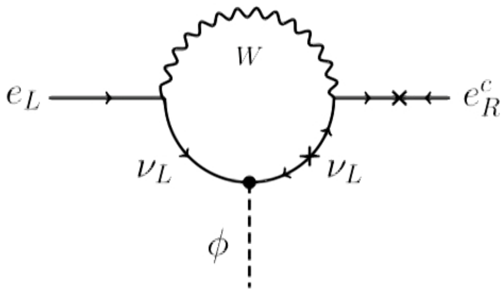
Constraint: Charged Lepton Variation?

Irreducible time dependence in charged sector



$$\frac{\delta m_e}{m_e} \sim \frac{G_F\, m_\nu^2}{16\pi^2}\, \eta_\phi \sim 10^{-28}\left(\frac{\eta_\phi}{0.1}\right);$$

Numerically negligible!

But, model dependent effect can arise from Higgs mixing

$$\phi H^\dagger H \qquad \phi^2 H^\dagger H$$

Constraint: CMB Neutrino Masses

DM density larger at earlier times

$$\eta_\phi(z) \sim \left(\frac{\delta m_\nu}{m_\nu}\right) \propto (1+z)^{3/2}$$

CMB (Planck)

$$\sum m_{\nu_i} \lesssim 0.23 \text{ eV}$$

If coupled to heaviest eigenstates

$$\eta_\phi(z=0) \equiv \frac{\sqrt{2\rho_\phi^\odot}}{\Lambda m_\phi} \lesssim 9 \times 10^{-3}$$

If coupled to lightest eigenstates

$$\eta_\phi(z=0) \equiv \frac{\sqrt{2\rho_\phi^\odot}}{\Lambda m_\phi} \lesssim 0.1$$

Irrelevant if field is not dynamical @ recombination

(but then it can't be all of the DM)

Constraint: SN 1987a

Can contribute to energy loss via neutrino annihilation

$$\sigma(\nu\nu \to \phi\phi) \sim \frac{1}{T^2}\left(\frac{m_\nu}{\Lambda}\right)^4$$

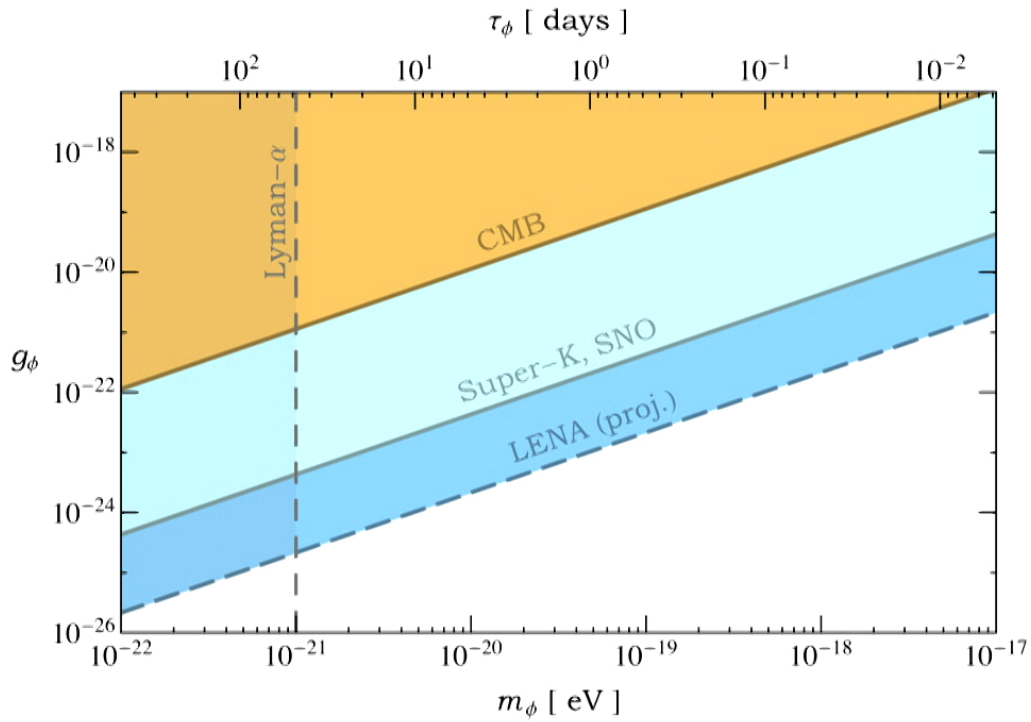
For T~ 30 MeV order one energy loss correction for

$$\Delta E_\phi \sim 4 \times 10^{50}\,\mathrm{erg}\left(\frac{50\,\mathrm{keV}}{\Lambda}\right)^4\left(\frac{\Delta t}{10\ \mathrm{sec}}\right)$$

Demands $\Lambda \lesssim 50\ \mathrm{keV}$ **if DM couples to heavy eigenstate**

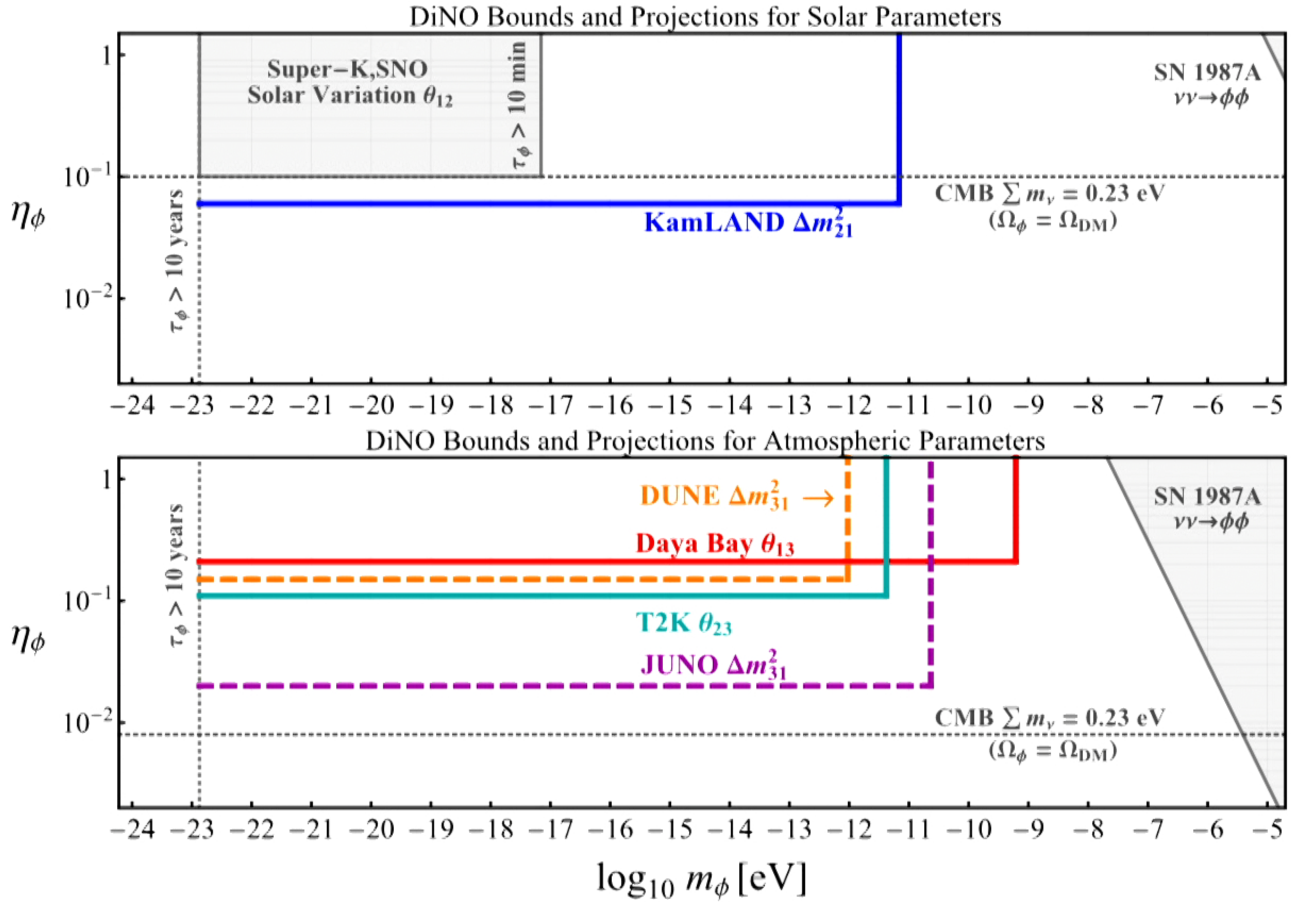
(weaker if coupled to lighter neutrinos)

Constraints: Solar Flux Periodicity



Berlin 1512.06165

$$g_\phi \to \frac{m_\nu}{\Lambda} \implies \eta_\phi \lesssim 10^{-1} \quad \text{for } m_\phi < 10^{-17}\ \text{eV}$$



dashed = projection
solid = excluded

$$\eta_\phi \equiv \frac{\sqrt{2\rho_\phi^\odot}}{\Lambda m_\phi} \sim \frac{\delta m_\nu}{m_\nu}$$

Conclusion

Long baseline experiments are DM detectors

Ultra light fields modulate masses/couplings/oscillations

Large neutrino modulation effect possible

Fractional effect ~ 10% allowed in neutrino sectors

Can be large even if subdominant DM fraction

Shifts extremal angles & distorts L/E dependence

Existing bounds from maximal/minimal measurements

Future experiments

Can greatly improve reach (JUNO, DUNE…)

Interesting **dedicated** analyses possible