Ultrafeeble Neutrino Interactions w/ Ultralight DM

Gordan Krnjaic
FNAL/UChicago

2205.06821 + Abhish Dev, Pedro Machado, Hari Ramani

Mitchell 2022, May 26, 2022

BSM Smoking Guns

Dark Matter Exists

CMB
LSS
BBN
Galaxies
Clusters

Neutrino Masses Exist

Solar
Atmospheric
Accelerator

Can we relate DM to origin of neutrino mass?

Overview

Model Description

Oscillations Regimes

Electron Neutrino Constraints

Mu/Tau Neutrino Variation

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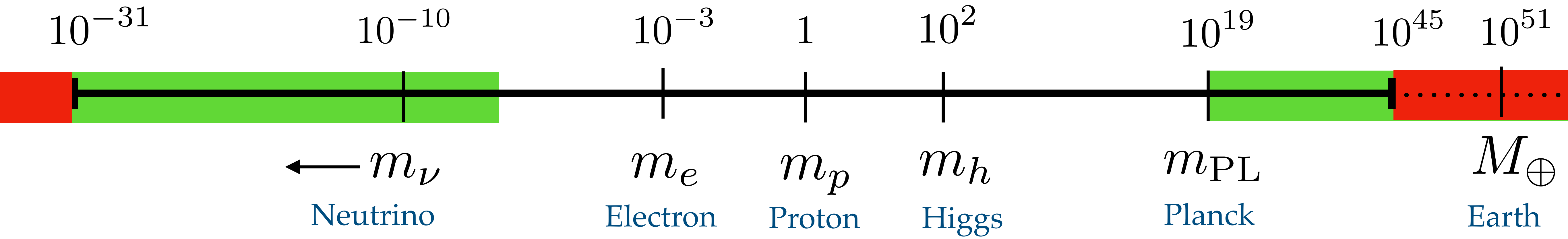
Huge Range of Possible DM masses



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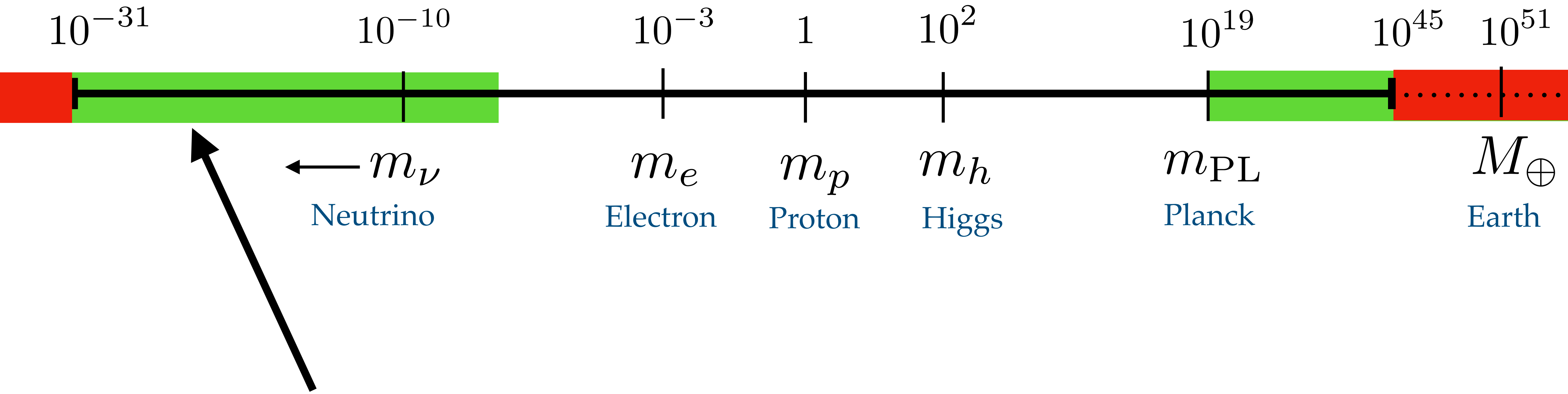

Must be bosonic, feebly coupled (can't thermalize w/ SM)

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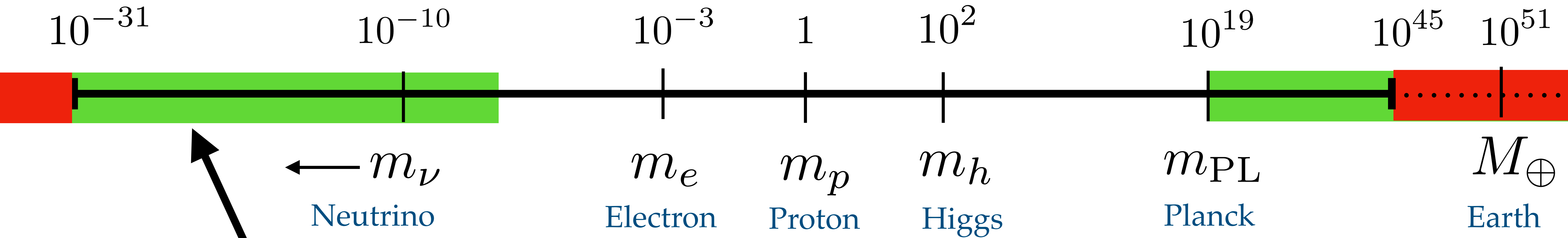


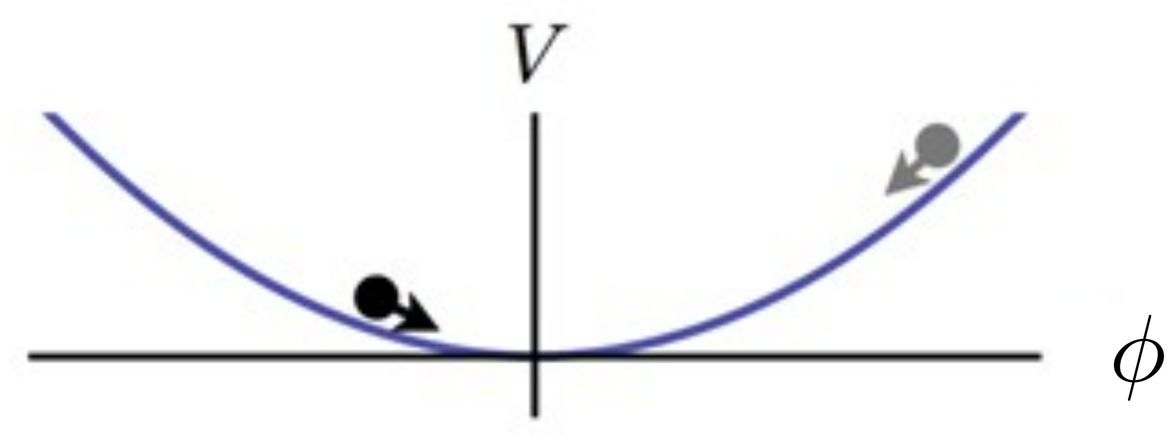
Must be bosonic, feebly coupled (can't thermalize w/ SM)

de-Broglie wavelength $\lambda_\phi = \frac{1}{m_\phi v_\phi} \approx 200\,\text{km} \left(\frac{\text{neV}}{m_\phi}\right)\left(\frac{10^{-3}}{v_\phi}\right)$

exceeds interparticle spacing $\longrightarrow$ classical field

Scalar Field Cosmological Evolution

Early universe misalignment — original field value set by initial conditions



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

Equation of motion

$$\phi(\vec{r}, t) = \frac{\sqrt{2\rho_\phi(t)}}{m_\phi} \cos[m_\phi(t + \vec{v}_\phi \cdot \vec{r}) + \varphi(\vec{r})]$$

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

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

Neutrino-DM Coupling

L = 2 scalar DM induces Majorana mass for right handed neutrinos

$$\mathcal{L} \supset y_\nu H \ell N + \frac{y_\phi}{2} \phi N N + h.c.$$

Post EWSB: static Dirac mass and dynamical Majorana mass

$$m_D = \frac{y_\nu v}{\sqrt{2}} \quad , \quad m_M = \frac{y_\phi}{2} \phi(t)$$

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Small Majorana mass = pseudo-Dirac fermion

$$m_{h,\ell}^2 = m_D^2 \pm m_D m_M \equiv m_\nu^2 \pm \tfrac{1}{2} \delta m^2$$

DM density dependent splitting between heavy/light eigenstates

Neutrino-DM Coupling

Active and sterile states (one pair per generation)

$$|\nu_e\rangle = \frac{1}{\sqrt{2}}\left(|\nu_h\rangle + |\nu_\ell\rangle\right)$$

$$|\nu_s\rangle = \frac{1}{\sqrt{2}}\left(|\nu_h\rangle - |\nu_\ell\rangle\right)$$

Near **maximal** mixing

$$\tan(2\theta) = \frac{2m_D}{m_M} \gg 1$$

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Neutrino oscillations between active/sterile $\nu_a \rightarrow \nu_s$

Survival prob $P_{ee}(t) = |\langle\nu(t)|\nu_e\rangle|^2 = \cos^2\left(\frac{1}{4E_\nu}\int_0^t dt'\,\delta m^2(t')\right)$

Neutrino-DM Coupling

Analogy with 2-flavor oscillation in more familiar constant-mass case

$$P(\nu_a \to \nu_s) = \sin^2(2\theta)\sin^2\left(\frac{\delta m^2 L}{4E_\nu}\right)$$

Density dependent active-sterile oscillation

$$1 - P_{ee} = \sin^2\left\{\frac{m_D}{2E_\nu}\frac{y_\phi\sqrt{2\rho_\phi}}{m_\phi^2}\left(\sin\left[m_\phi t + \varphi\right] - \sin\varphi\right)\right\}$$

Defines effective mass for comparison with reported limits

$$\delta m^2_{\text{eff}} \equiv \frac{2y_\phi m_D}{m_\phi}\sqrt{2\rho_\phi}$$

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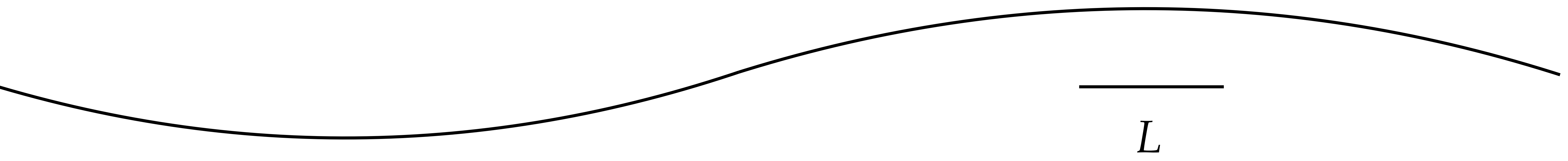
Oscillations Regimes

Constant ϕ: $m_\phi L \lesssim 1$

Neutrino encounters same offset phase across full trajectory



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Nontrivial effect when argument is order-one

$$\delta m^2_{\rm eff} \equiv \frac{2y_\phi m_D}{m_\phi}\sqrt{2\rho_\phi} \longrightarrow y_\phi < \frac{m_\phi}{2m_D}\frac{\delta m^2_{\rm lim}}{\sqrt{2\rho_\phi}};$$

Combination behaves like an effective mass-squared difference

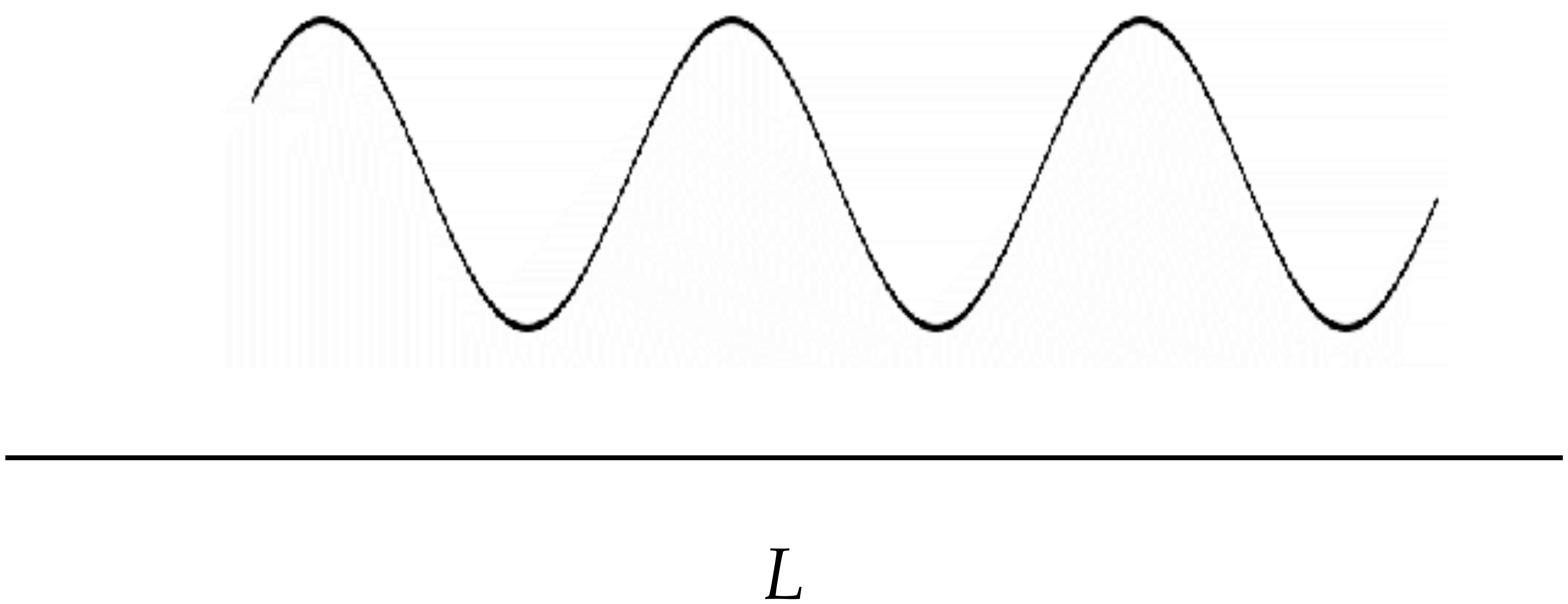
Can be matched with existing limits on pseudo-dirac neutrinos

Oscillations Regimes

Modulating ϕ: $(m_\phi v_\phi L < 1 \ll m_\phi L)$

Neutrino encounters many cycles of scalar modulation

… But all in the **same phase** domain



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$$\langle 1 - P_{ee} \rangle \approx \sin^2 \left(\frac{y_\phi m_D}{2 E_\nu m_\phi^2} \sqrt{2 \rho_\phi} \right)$$

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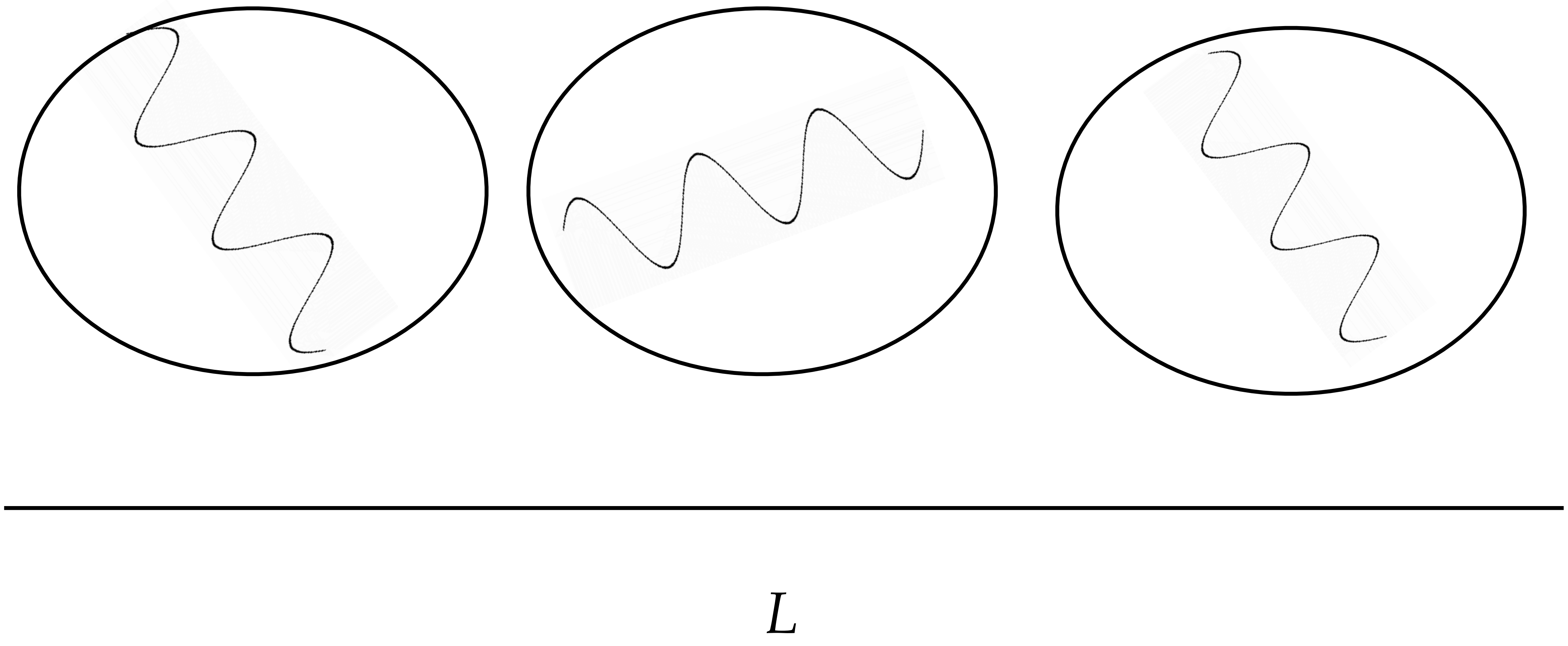
Demand order one argument for nontrivial active-sterile oscillation

$$y_\phi^{\mathrm{lim}} = \frac{\delta m_{\mathrm{lim}}^2 m_\phi^2 L}{2 m_D \sqrt{2\rho_\phi}}$$

Oscillations Regimes

Random walk: $1 \ll m_\phi v_\phi L$



Neutrino encounters many different scalar domains

→ random walk across phase variation

Oscillations Regimes

$$\textbf{Random walk:}\ 1 \ll m_\phi v_\phi L$$

Effective phase along trajectory $\varphi_{\rm eff} \sim \sqrt{m_\phi v_\phi L}$

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Path averaged survival probability

$$\langle 1 - P_{ee} \rangle \approx \sin^2 \left(\frac{y_\phi m_D \sqrt{2\rho_\phi v_\phi L}}{2 E_\nu m_\phi^{3/2}} \right)$$

Demand order one argument for nontrivial effect

$$y_\phi^{\text{lim}} = \frac{\delta m^2_{\text{lim}}}{m_D} \sqrt{\frac{m_\phi^3 L}{2\rho_\phi v_\phi}}$$

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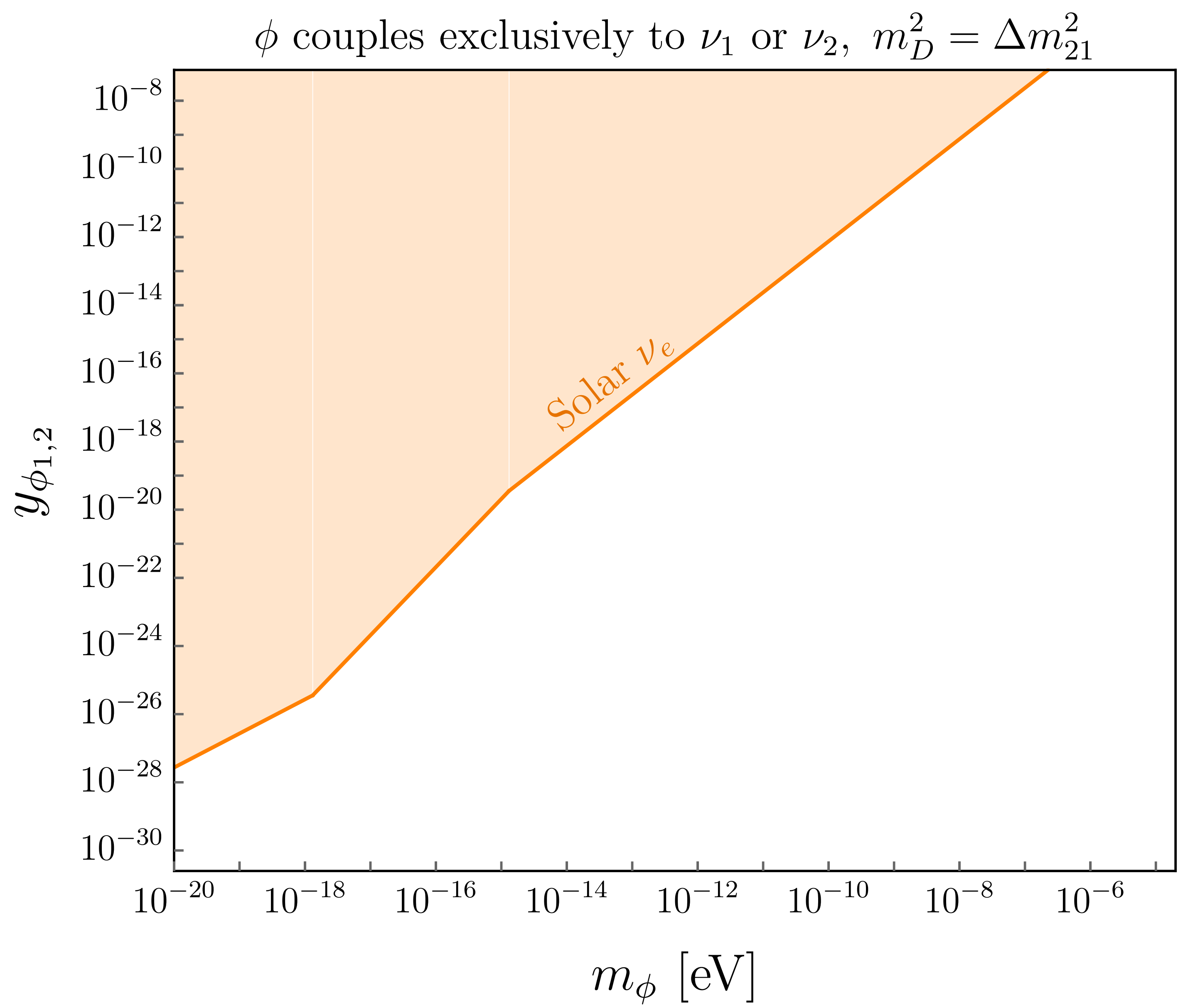
Solar Oscillations

$\nu_e \to \nu_s$ oscillations on baseline $L = 1.5 \times 10^8$ km



Impose limit based on $\delta m^2_{\rm lim} < 10^{-12}\,{\rm eV}^2$ de Gouvea, Huang, Jenkins 0906.1611

BBN / CMB Electron Neutrino Oscillations

$\nu_e \rightarrow \nu_s$ oscillations **before** neutrino decoupling add to Neff

Faster expansion rate $\longrightarrow$ less primordial helium

$\nu_e \rightarrow \nu_s$ oscillations **after** neutrino decoupling reduce ν_e

earlier n / p freeze out $\longrightarrow$ less primordial helium

BBN / CMB Electron Neutrino Oscillations

Dodelson Widrow sterile neutrino production

Solve for ratio of momentum moments $r_\beta \equiv \frac{\langle p^\beta \rangle_s}{\langle p^\beta \rangle_a}$

$$\frac{dr_\beta}{dT} = -\frac{1}{2HT\langle p^\beta \rangle_a} \int \frac{d^3p}{(2\pi)^3} \frac{p^\beta \Gamma \sin^2(2\theta_M)}{e^{p/T}+1}$$

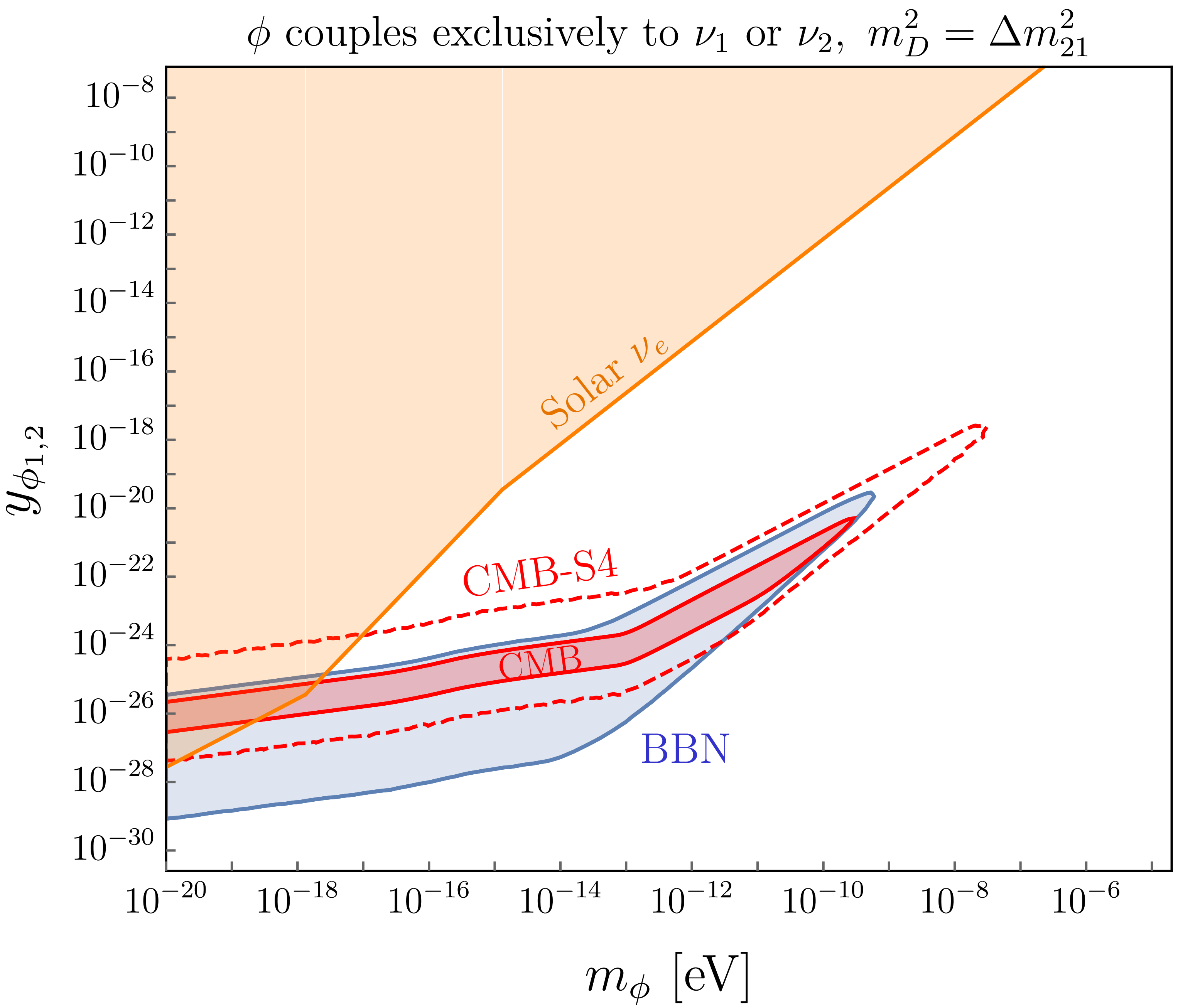
Vacuum mixing angle $\theta_0 = \tan^{-1}\left(\frac{y_\phi \sqrt{2\rho_\phi}}{m_D m_\phi}\right)$

Effective mixing angle in vacuum

$$\sin^2(2\theta_M) = \frac{\sin^2(2\theta_0)}{[\cos(2\theta_0) - 2pV_{\rm eff}/\Delta m^2]^2 + \sin^2(2\theta_0)}$$

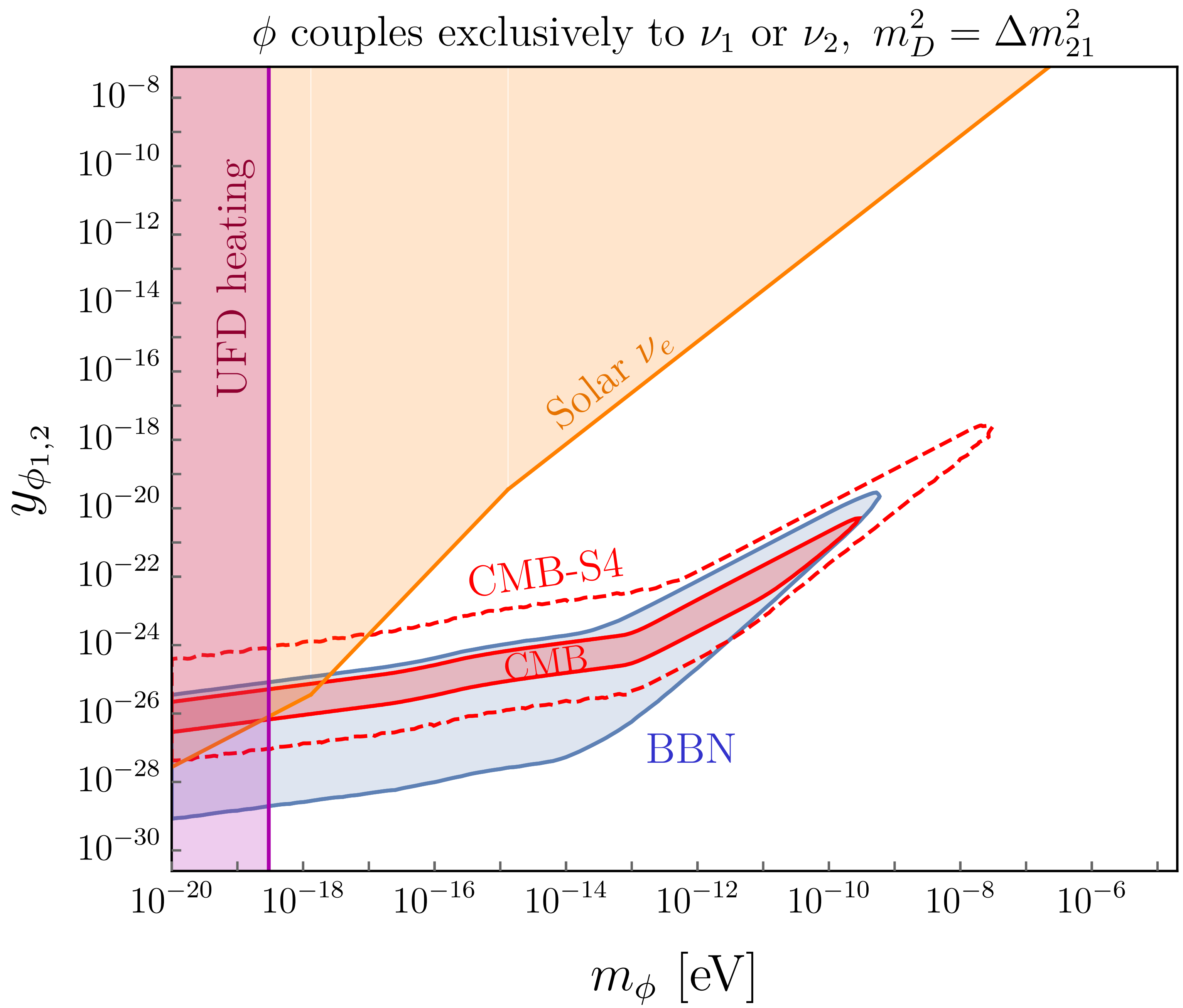
Dodelson, Widrow 9303287
Dolgov, Villante 0308083

BBN / CMB Electron Neutrino Oscillations



Effective mixing angle in vacuum

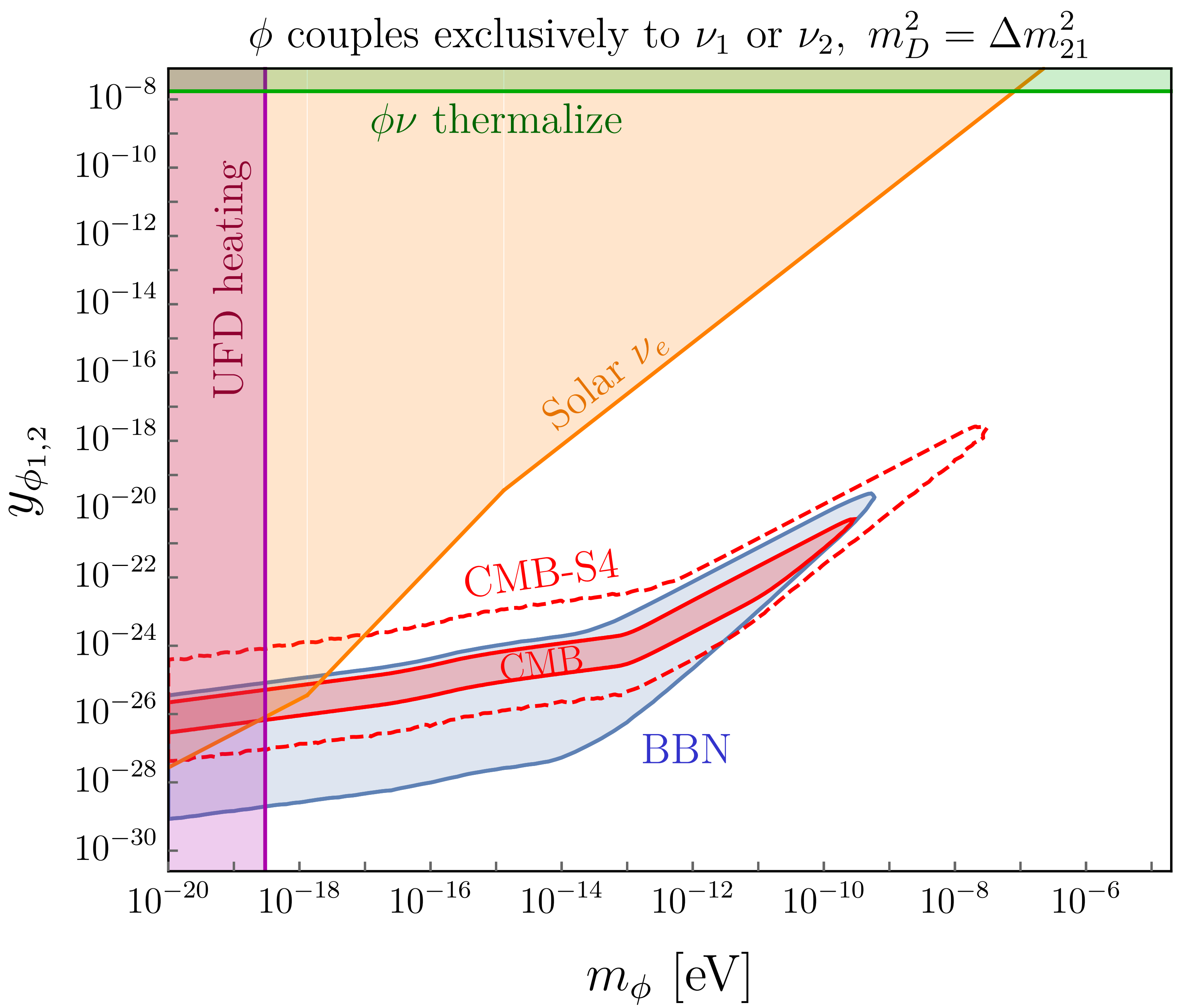
Fuzzy Dark Matter Bounds



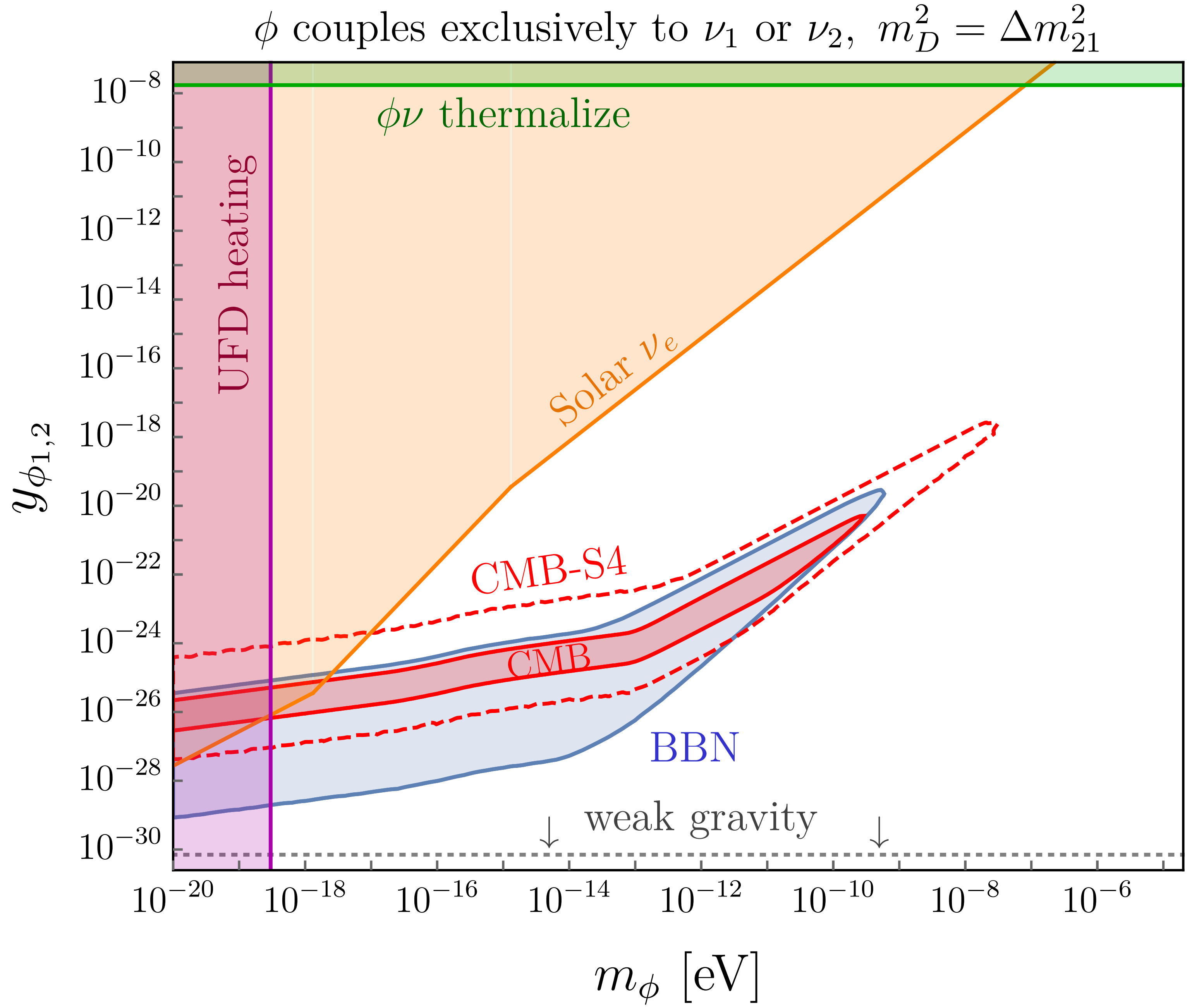
Potential fluctuations in ultra faint dwarfs affect velocity dispersion of visible stars

Hu, Barnana, Gruzinov 0003365
Dalal, Kravtsov, 2203.05750

Thermalization w/ SM Plasma



Compare to Gravity between Neutrinos



Low scalar mass bounds comparable to gravity between neutrinos

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Mu / Tau Oscillations: Key Differences

BBN/CMB simpler

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Dolgov, Villante 0308083

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Deficit of muon neutrinos

de Gouvea, Huang, Jenkins 0906.1611

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Dolgov, Villante 0308083

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de Gouvea, Huang, Jenkins 0906.1611

Structure formation

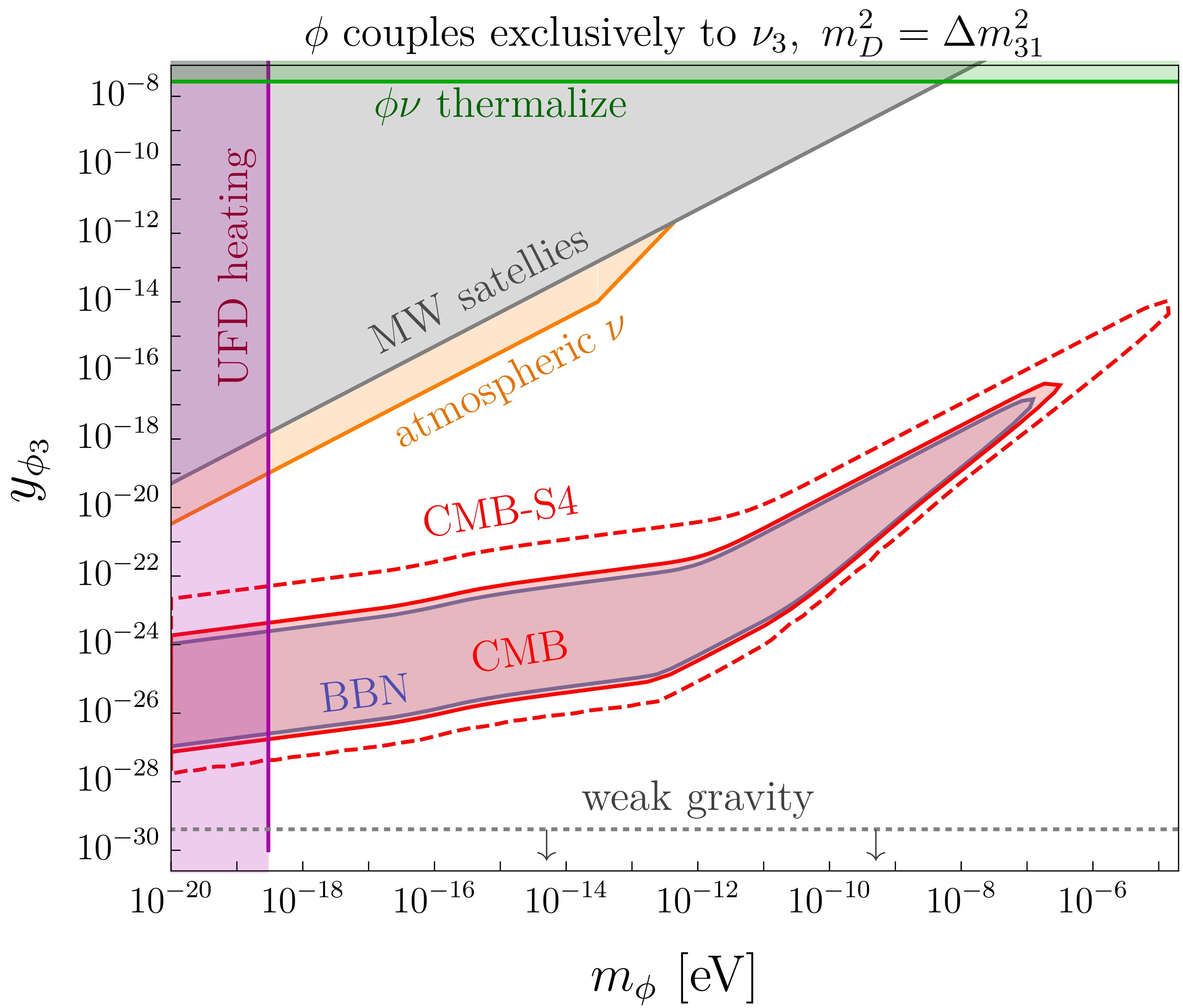
Scalar must redshift like matter after $z \sim 10^6$

Quadratic term must dominate in potential

Bound from Milky Way satellites

Das, Nadler 2010.01137

Mu / Tau Neutrino Oscillations



Summary / Conclusions

Ultralight DM induced Majorana mass —> pseudo-Dirac neutrinos

Active/sterile mass splitting time/density dependent

Strong bounds from lab/astro/cosmo

Solar / atmospheric oscillations
Milky Way satellites
BBN / CMB / Neff
Ultra Faint Dwarfs