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Testing the dark origin of neutrino masses with oscillation experiments

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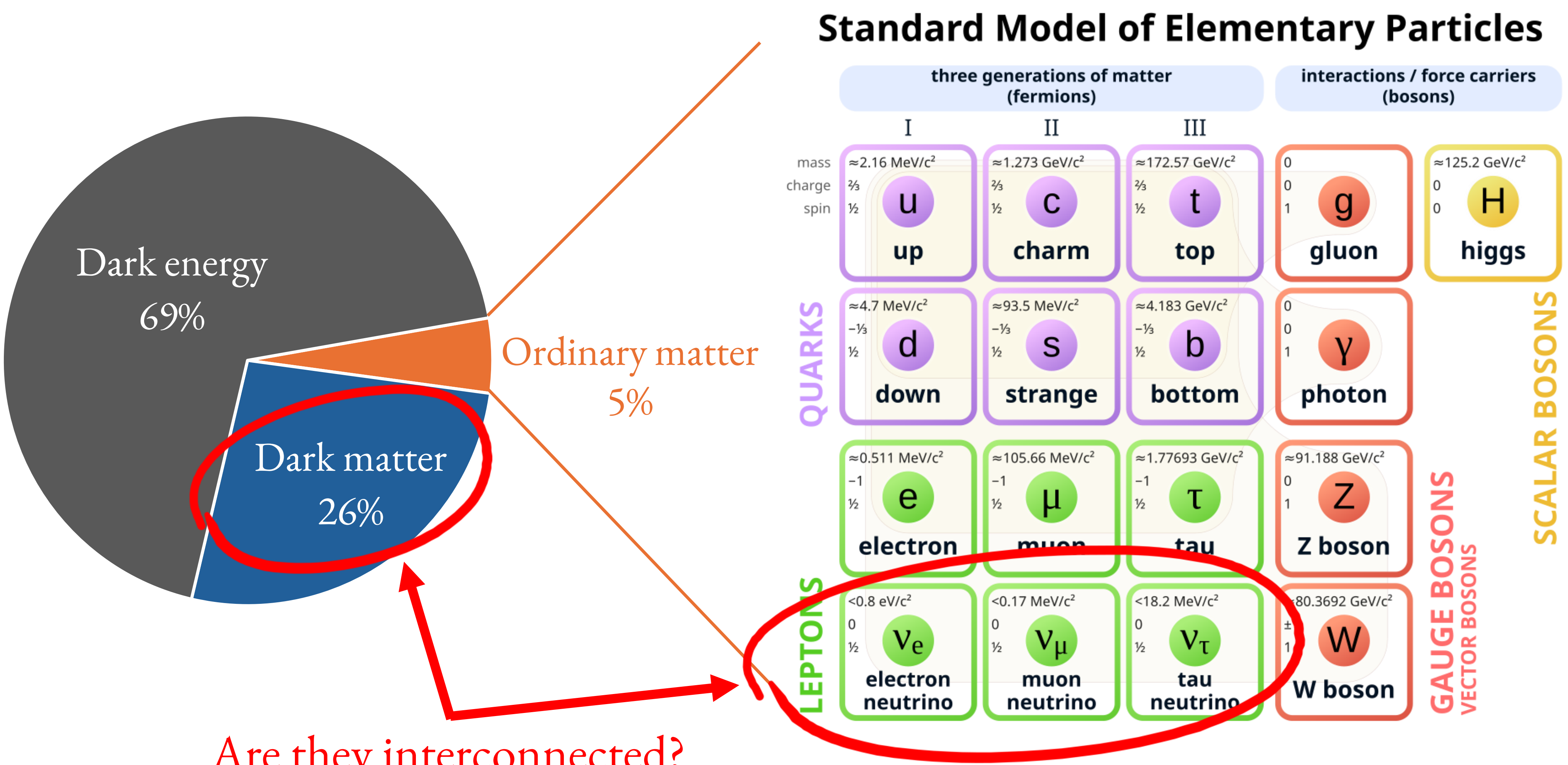
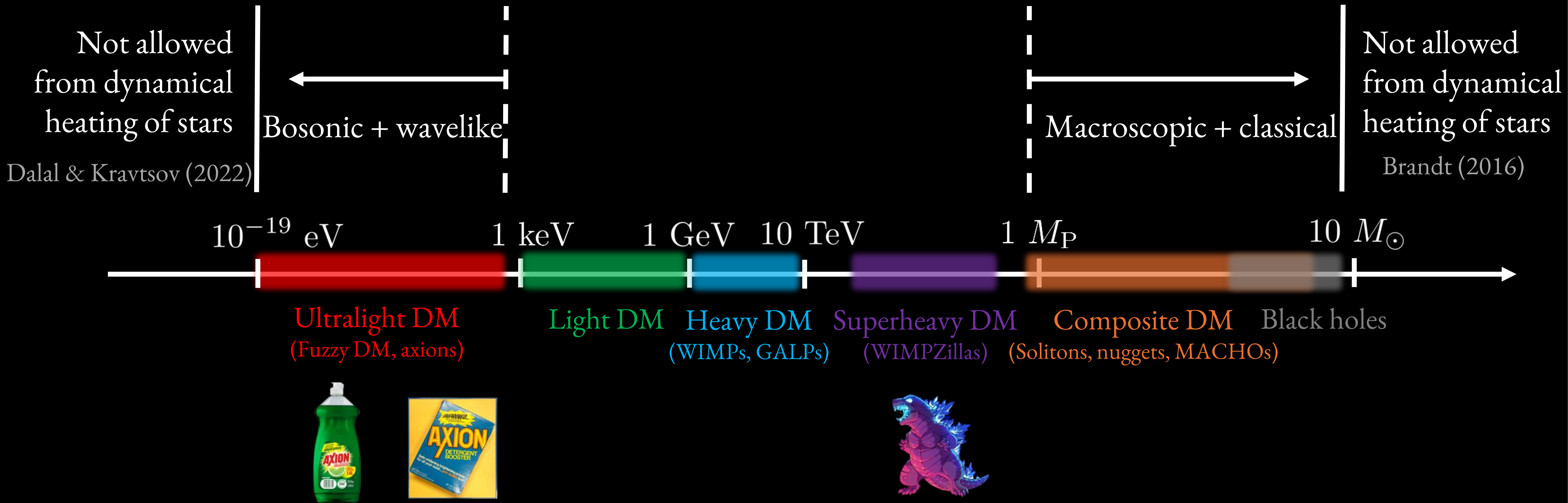
Standard model of cosmology and particle physics



Are they interconnected?

Dark matter mass landscape



Wavelike vs. particlelike

Ultralight dark matter

- Large occupation number ➞ Classical fields

$$n\lambda_{\rm dB}^3 \sim \left(\frac{40\ \rm eV}{m}\right)^4 \sim 3\times 10^{82}\left(\frac{10^{-19}\ \rm eV}{m}\right)^4$$

- Macroscopic/astrophysical scales

$$\lambda_{\rm dB} \sim 50\ \mu{\rm m}\left(\frac{40\ \rm eV}{m}\right) \sim 0.6\ {\rm pc}\left(\frac{10^{-19}\ \rm eV}{m}\right)$$

- Wave dynamics, rich phenomenology

Suppressed small-scale structure, interference, Bose-Einstein condensates, polarization, modulations of standard model "constants", etc.

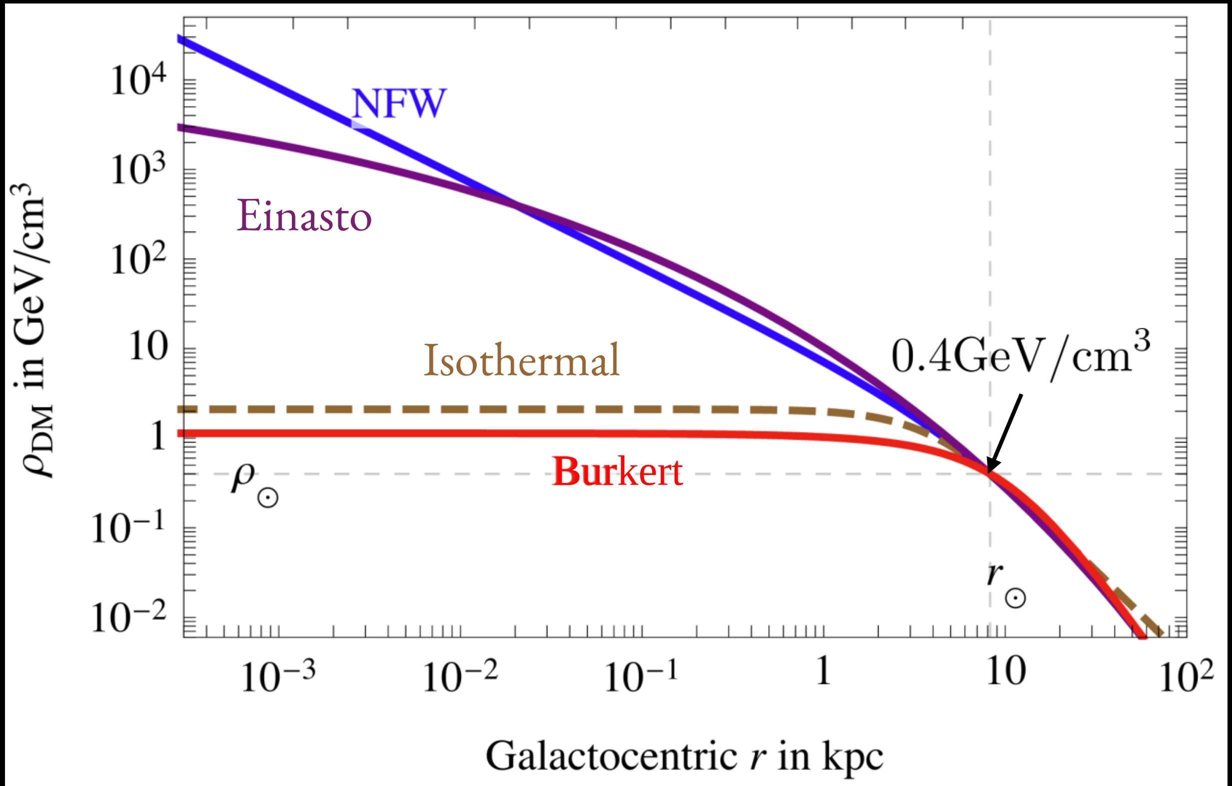
assuming $\rho \sim 0.4\ {\rm GeV/cm^{-3}}$, $v \sim 200\ {\rm km/s}$

Density profiles and fluctuations

Wave interference, causing $\gtrsim \mathcal{O}(1)$ fluctuations in local density.

$$\phi(t, \boldsymbol{x}) \simeq \phi_0(\boldsymbol{x}) \cos(m_\phi t)$$

$$\begin{cases} L \ll \lambda_{\rm dB} : \ \phi_0(\boldsymbol{x}) \approx \phi_0 \\ L \gg \lambda_{dB} : \ \text{stochastic } \phi_0(\boldsymbol{x}) \end{cases}$$



Cirelli et al. (2024)

Centers et al. (2021), Eggemeier et al. (2023), Nakatsuka et al. (2023)

Neutrino masses and the seesaw mechanism

$$\mathcal{L} \supset -m_D \bar{\nu}_D \nu_D - \frac{1}{2} m_R \overline{\nu_M^c} \nu_M + h.c.$$

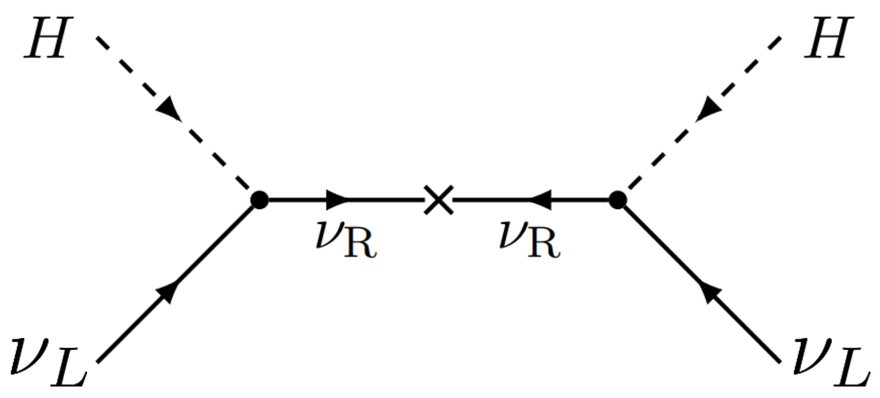
$$\nu_D = \nu_L + \nu_R \ , \quad \nu_M = \nu_R + \nu_R^c$$

Mass matrix for ν_L, ν_R

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}$$

$$\Big\downarrow \quad m_D \ll m_R$$

$$m_l \simeq \frac{m_D^2}{m_R} \ , \quad m_h \simeq m_R$$



ν_L : Left-handed neutrino
H : Higgs
ν_R : Right-handed neutrino

Vacuum neutrino masses as an explanation of oscillation data

$$H = \sqrt{p^2 + m_\nu^2} \approx p + \frac{m_\nu^2}{2E_\nu}$$

$$|\nu_i, t\rangle = e^{-iHt}|\nu_i\rangle$$

Oscillation phase $\propto \dfrac{\Delta m_{ij}^2 L}{E_\nu}$

What if $m_\nu = 0$ but with

$H = p + V \;, \quad V = \dfrac{m_\nu^{\text{eff}}}{2E_\nu}$?

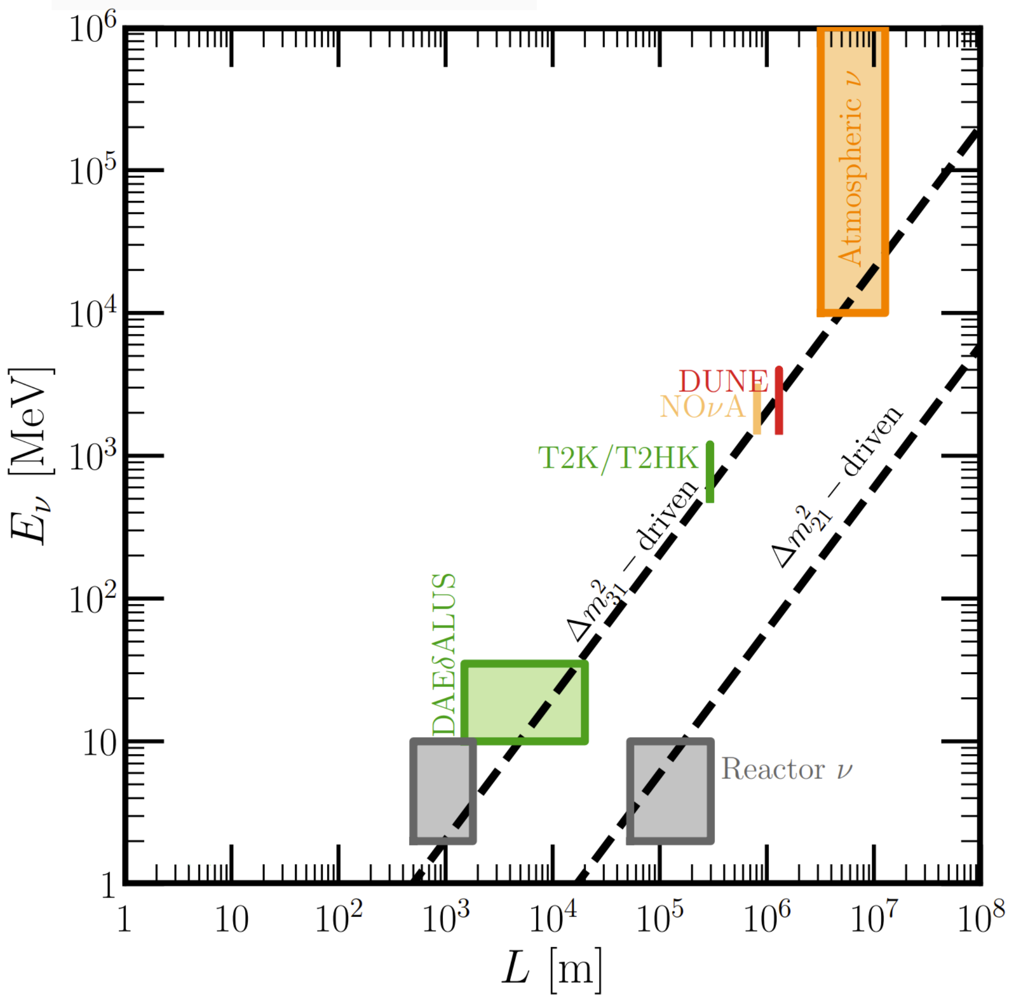


Figure adapted from Harnik, Kelly and Machado (2020)

For specific realization of "dark" neutrino mass, see:

- Capozzi, Shoemaker and Vecchi (2018)
- Choi, Chun and Kim (2020)
- Huang, Lindner, Martinez-Mirave and Sen (2022)
- ChoeJo, Kim and Lee (2023)
- Sen and Smirnov (2024)
- Lee (2024)
- Plestid and Tevosyan (2024)

Tests with oscillation experiments

Aiming for the entire ultralight (wavelike) mass range $10^{-19}\text{eV} \lesssim m_\phi \ll 10\text{eV}$

Several time and length scales

Parametrization for mass-squared difference: $\Delta m_{ij}^2 = \Delta m_{ijD}^2(\boldsymbol{x}) \cos^2(m_\phi t)$

Oscillation period: $T_\phi = \frac{\pi}{m_\phi} = 5.7\text{hr}\left(\frac{10^{-19}\text{eV}}{m_\phi}\right)$

Typical duration of oscillation experiments: $T_{\text{exp}} \gtrsim \mathcal{O}(10)\text{days}$

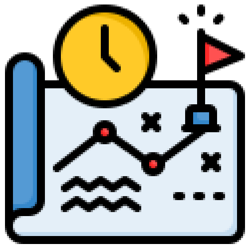
} Time-averaged probabilities

Dark matter coherence length: $\lambda_{\text{dB}} = 1.24\text{au}\left(\frac{10^{-14}\text{eV}}{m_\phi}\right)\left(\frac{200\text{km/s}}{v}\right)$

Crossing distance of Earth during an experiment: $l_\oplus = 1.16\text{au}\left(\frac{T_{\text{exp}}}{10\text{days}}\right)\left(\frac{v_\oplus}{200\text{km/s}}\right)$

} Space-averaged probabilities for $m_\phi \gg 10^{-14}\text{eV}$

Strategy



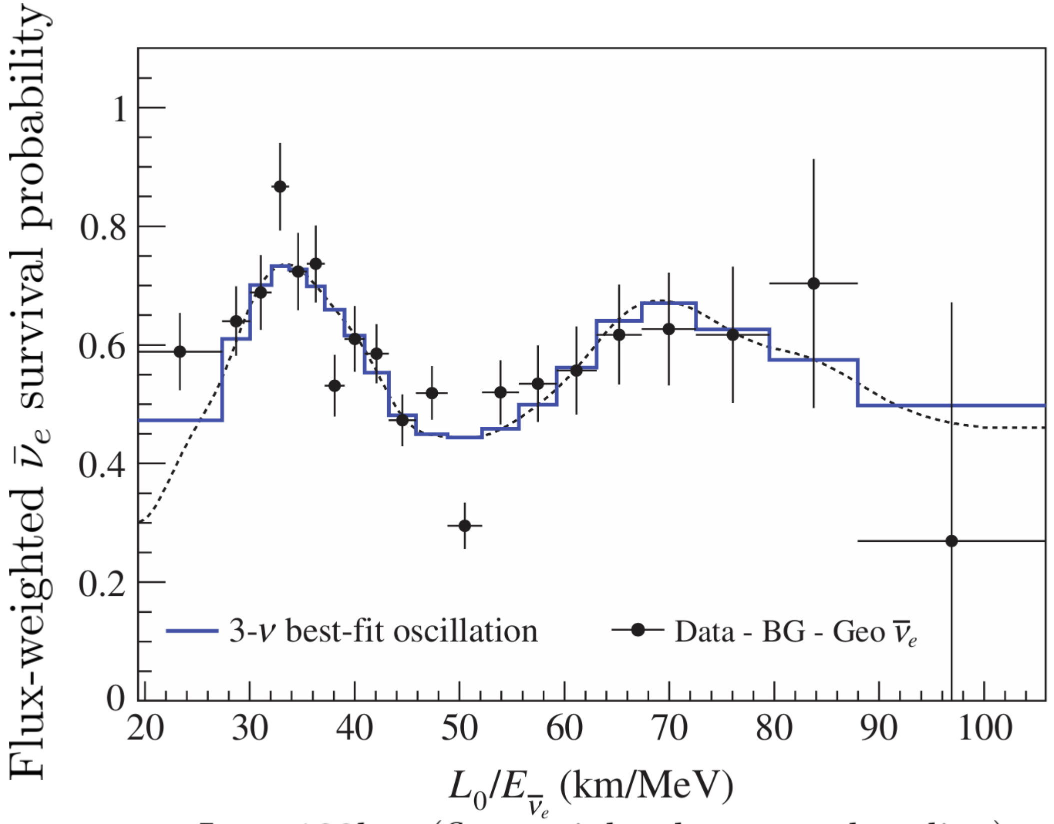
For $m_\phi \ll 10^{-14}\mathrm{eV}$, DM field has constant amplitude during an experiment:

1. Find time-averaged formulae for flavor oscillations
2. Fit the formula with oscillation data (e.g., KamLAND)

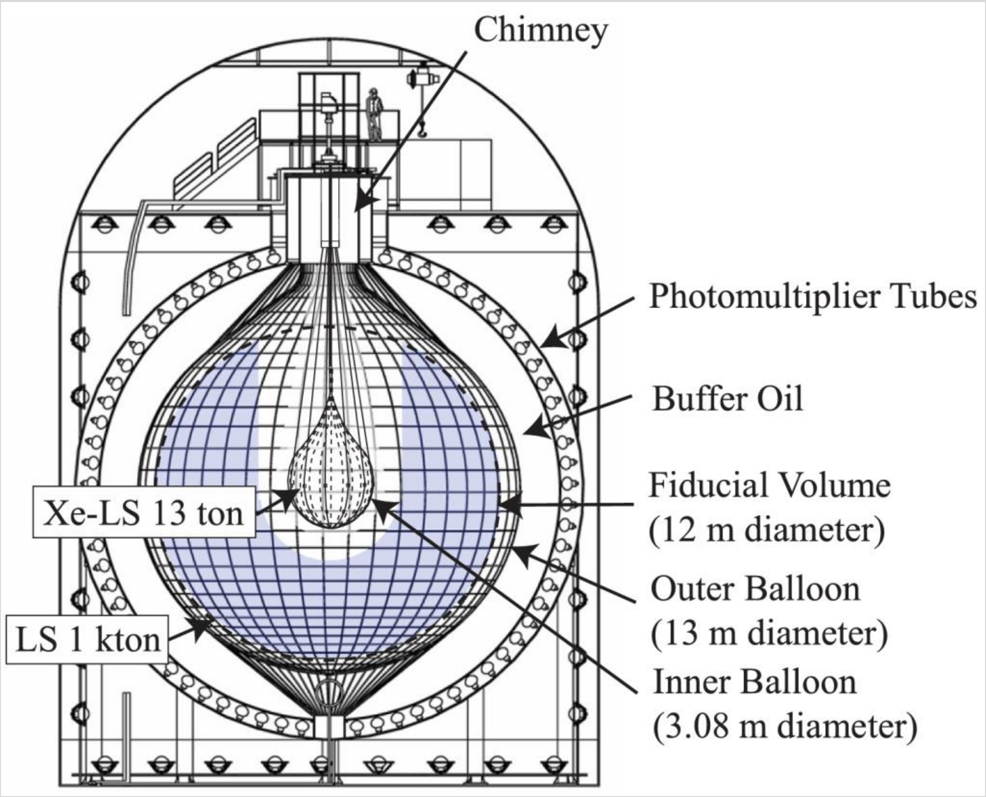
For $m_\phi \gg 10^{-14}\mathrm{eV}$, DM field has stochastic amplitudes in different de Broglie patches:

1. Model spatial fluctuations of ultralight dark matter
2. Take spatial average of the time-averaged formula
3. Compare the formula with oscillation data (if needed)

Long-baseline reactor experiment: KamLAND



$L_0 = 180$km (flux-weighted average baseline)



Located at 1km underground, Hida, Japan
Detected antineutrinos from >50 reactors (before 2013)
Sensitive to Δm^2_{21} , θ_{12} , θ_{13}

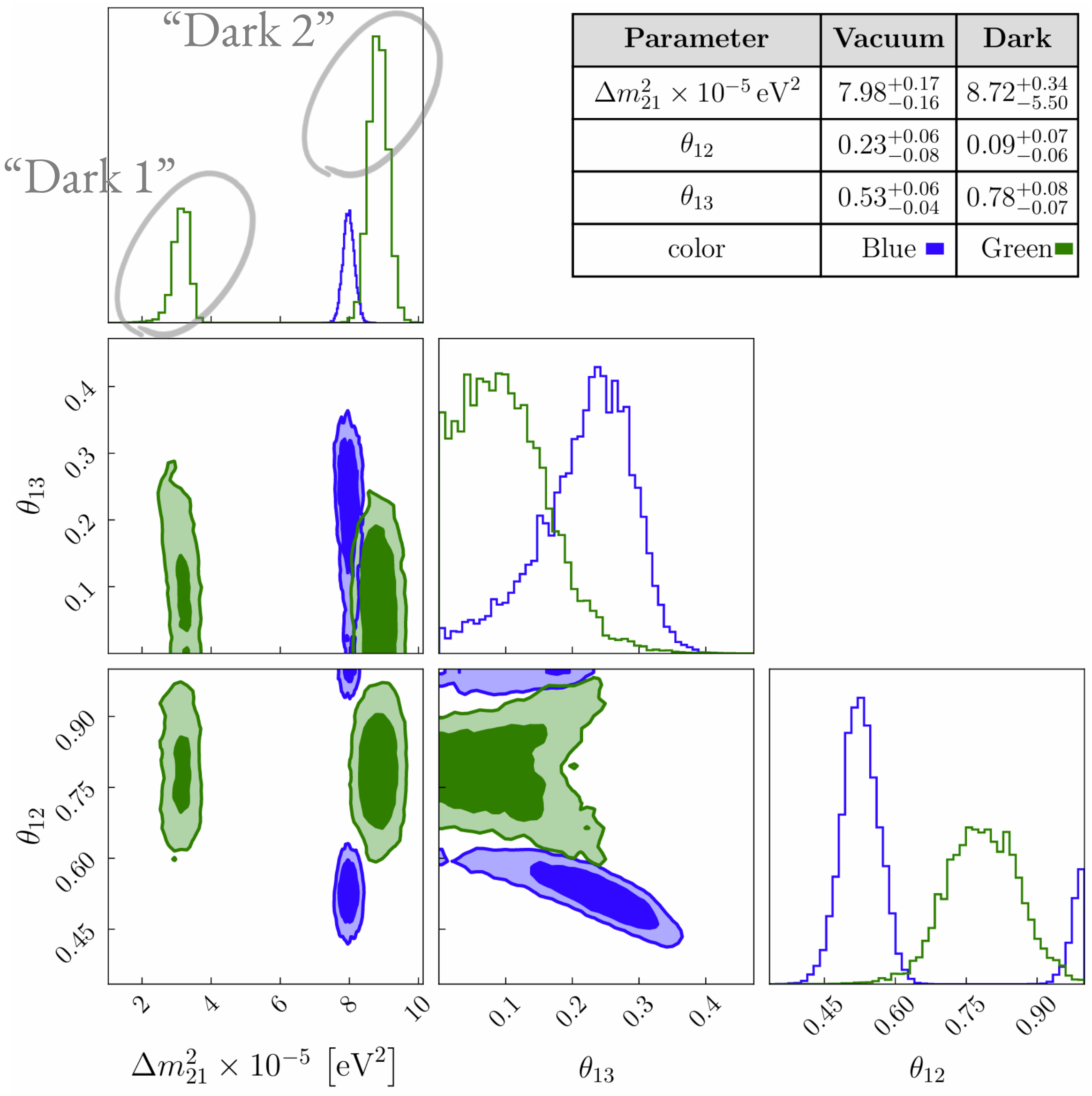
KamLAND Collaboration (2013)

Chi-square analysis

Time-averaged survival probability:

$$P_{ee} = 1 - \frac{1}{2}\cos^4\theta_{13}\sin^2(2\theta_{12})[1 - J_0(X_{21D})\cos X_{21D}] - \frac{1}{2}\sin^2(2\theta_{13})[1 - J_0(X_{32D})\cos X_{32D}]$$

$$X_{ijD} = \frac{\Delta m^2_{ij} L}{4E_\nu}\ , \quad J_0(x) \text{ is Bessel function}$$



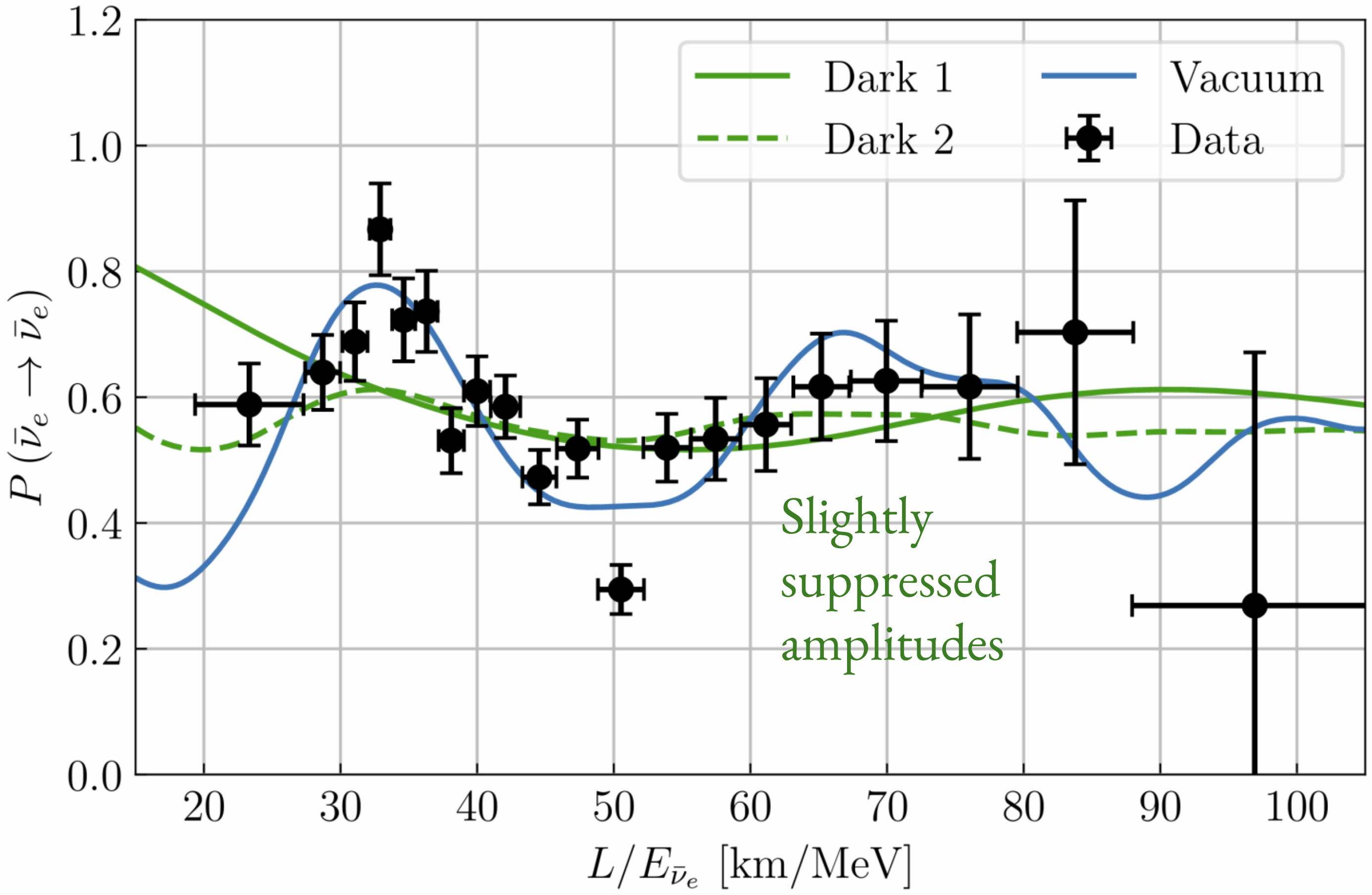
Parameter	Vacuum	Dark
$\Delta m^2_{21} \times 10^{-5}\,\mathrm{eV}^2$	$7.98^{+0.17}_{-0.16}$	$8.72^{+0.34}_{-5.50}$
θ_{12}	$0.23^{+0.06}_{-0.08}$	$0.09^{+0.07}_{-0.06}$
θ_{13}	$0.53^{+0.06}_{-0.04}$	$0.78^{+0.08}_{-0.07}$
color	Blue	Green

Survival probabilities with best-fit parameters

$\chi^2_{\text{min,vac}} = 35.5$

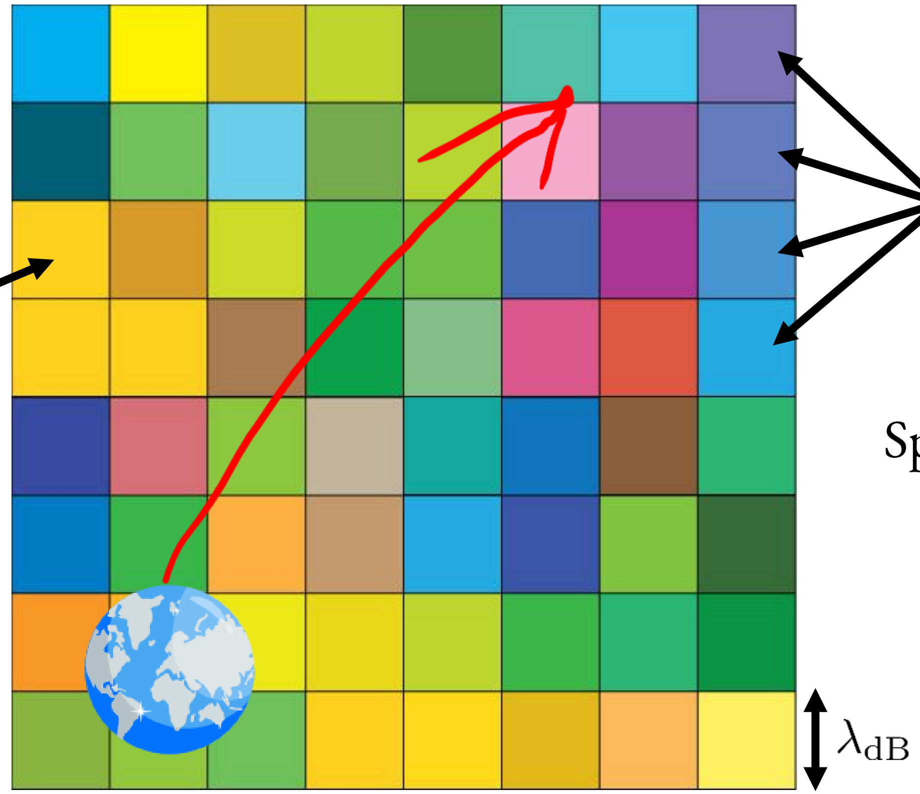
$\chi^2_{\text{min,dark}} = 61.7$

Vacuum (constant) mass is favored at 4.5σ



Earth crossing through different de Broglie patches

Constant density within a patch



Colors: Values of dark matter density

Density in different patches is uncorrelated and random

Spatial average ≈ Ensemble average

Suppressed oscillation behaviors

$$P_{\rm ee} = 1 - \cos^4\theta_{13}\sin^2(2\theta_{12})F_{21} - \sin^2(2\theta_{13})F_{32}$$

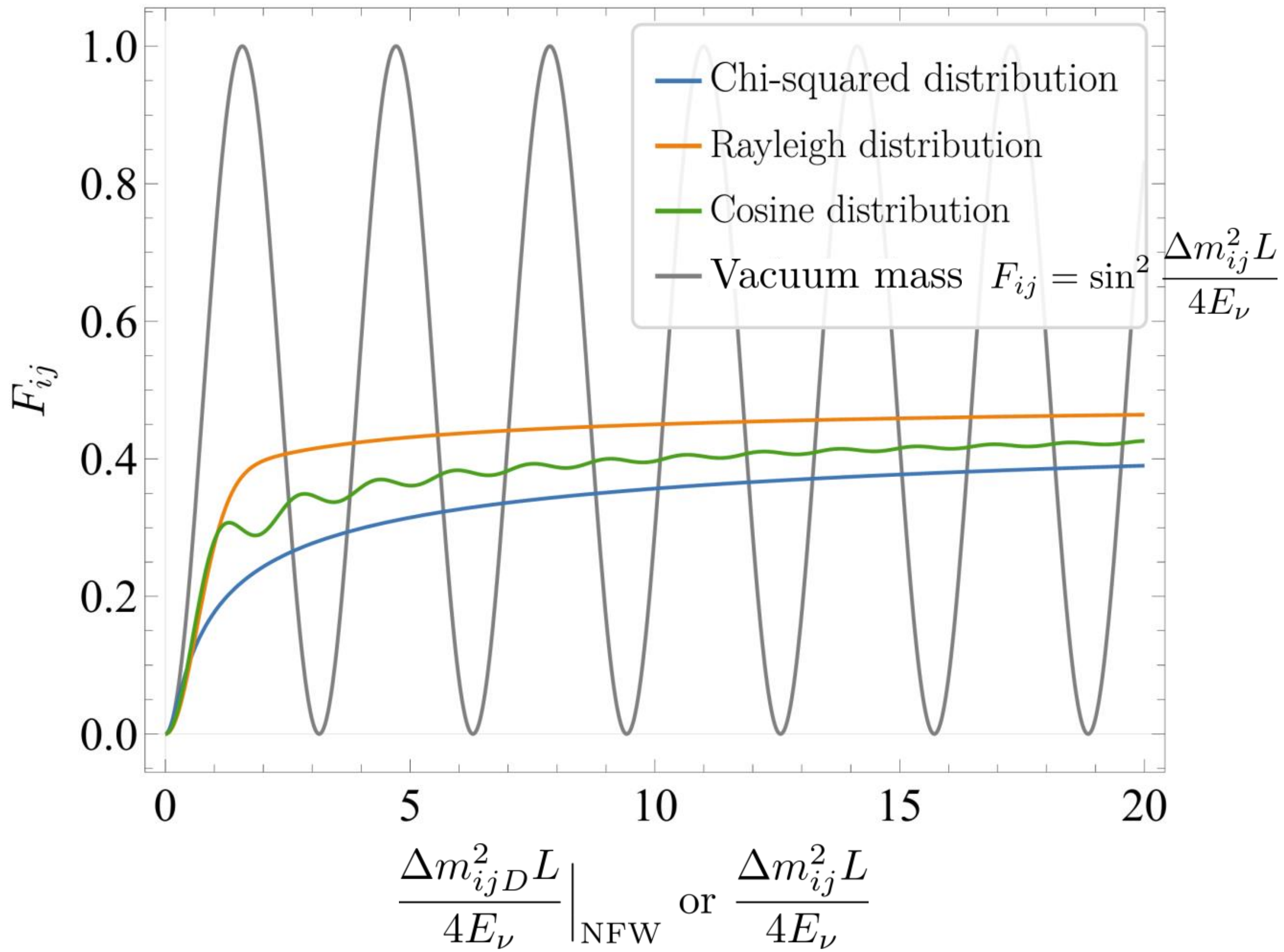
Time-averaged component:

$$F_{ij} = \frac{1}{2}\left[1 - J_0\left(\frac{\Delta m^2_{ijD}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{ijD}L}{4E_\nu}\right)\right]$$

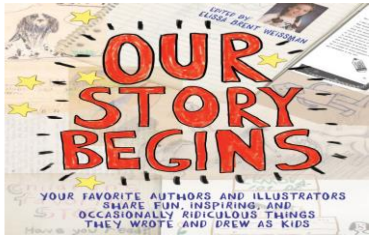
Distributions of mass-squared differences in different de Broglie patches:

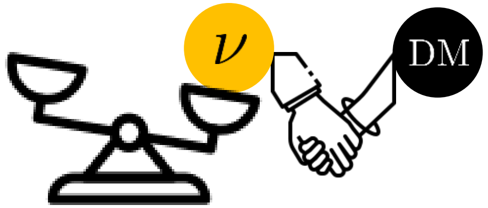
$$\frac{\Delta m^2_{ijD}}{\Delta m^2_{ijD}|_{\rm NFW}} \sim \chi^2(1),\ \text{Rayleigh},\ 1-\cos(k_\theta\theta)$$

Flavor oscillations in terms of distances are suppressed in a model-independent way!



Conclusions





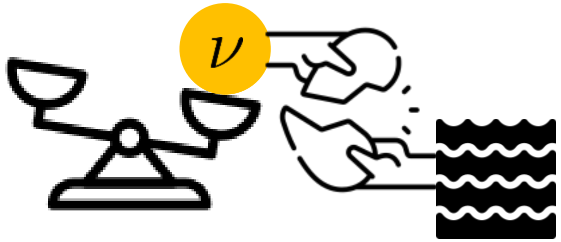
- For $10^{-19} \lesssim m_\phi \ll 10^{-14}\text{eV}$,

  KamLAND disfavors "dark" neutrino mass by more than 4σ.

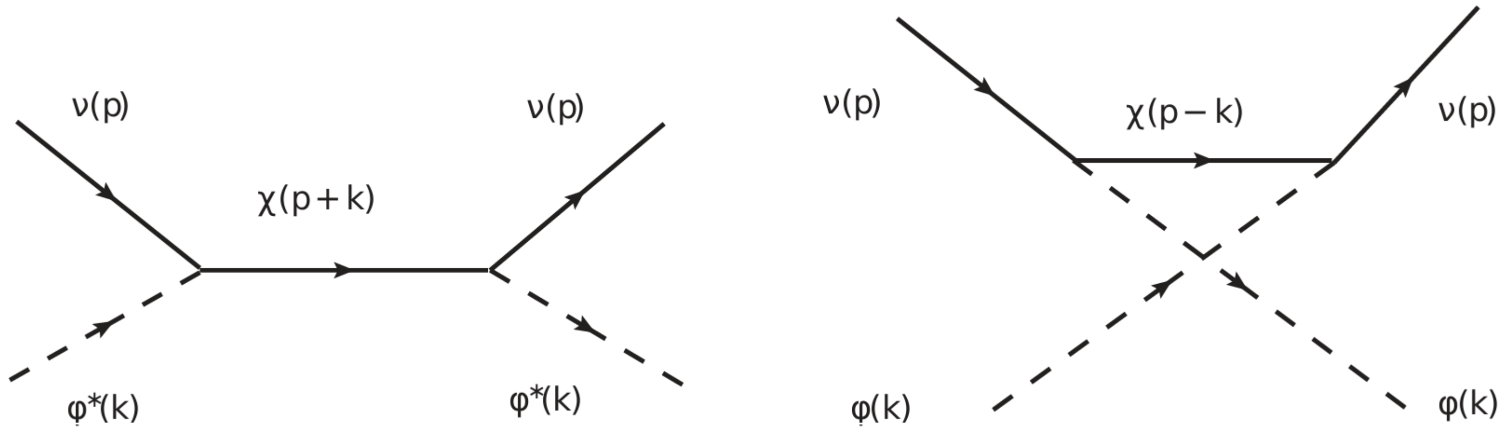
- For $10^{-14}\text{eV} \ll m_\phi \ll 10\text{eV}$,

  Stochastic DM fluctuations suppress neutrino oscillations.

- Ultralight/wavelike dark matter is unlikely to account for neutrino mass.



A specific realization of "dark" neutrino mass



ν : Neutrinos
χ : Fermionic mediators
φ : Scalar dark matter

ν, χ have zero bare mass

Cold gas of dark matter particles: (Forward scattering) $\quad m_\nu^2 \propto \frac{\rho_\phi}{m_\phi^2}\frac{y(y-\epsilon)}{y^2-1}\ , \quad y = \frac{2E_\nu m_\phi}{m_\chi^2}\ , \quad \epsilon = \frac{n_\phi - \bar{n}_\phi}{n_\phi + \bar{n}_\phi}$

Classical scalar field background: $\quad m_\nu^2 \propto \frac{\rho_\phi}{m_\phi^2}\cos^2(m_\phi t)$ (Relevant to ultralight dark matter)

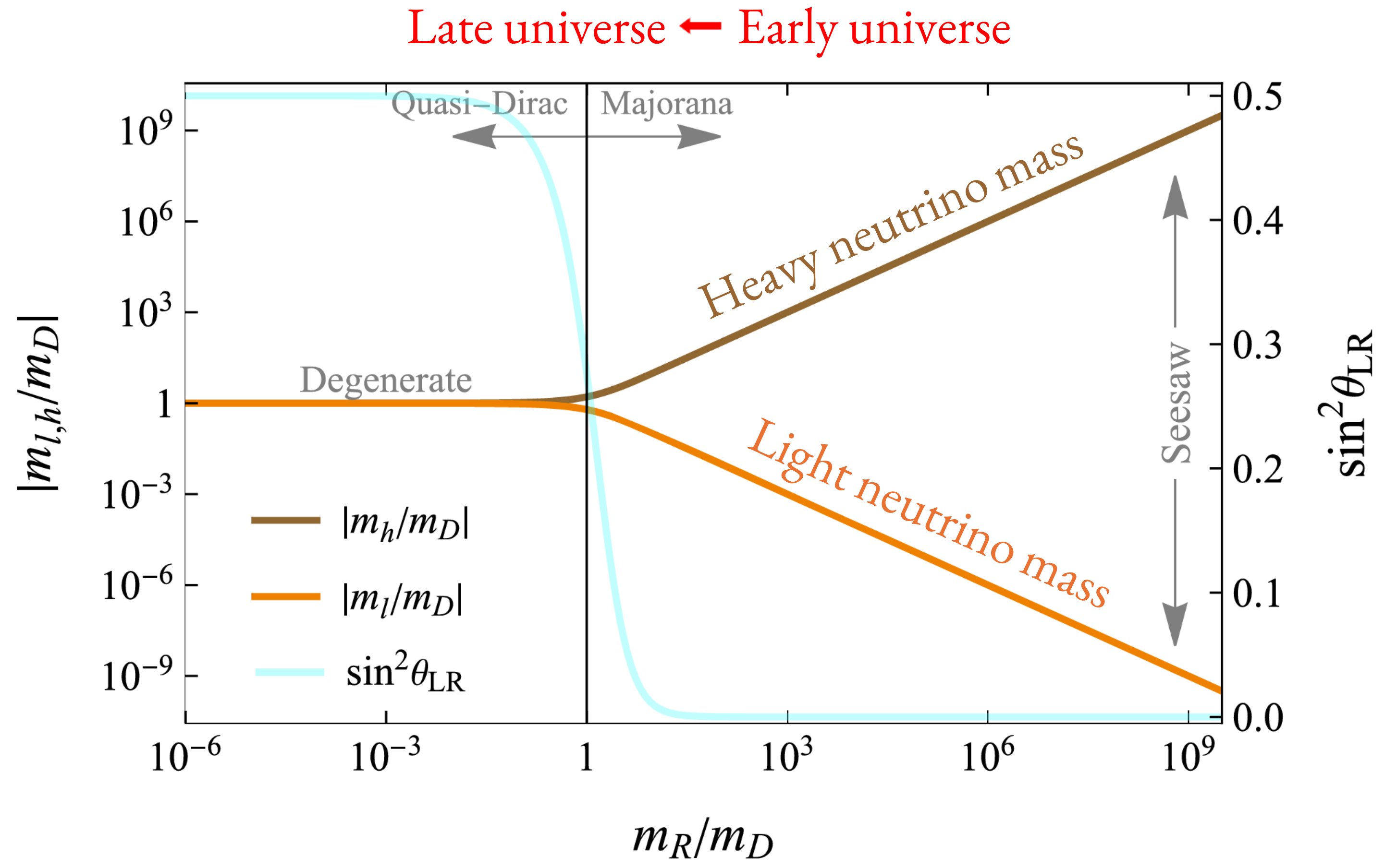
M. Sen and A. Y. Smirnov (2024)

Another realization of “dark” neutrino mass

$$\mathcal{L} \supset -m_D \bar{\nu}_D \nu_D - \frac{1}{2} m_R \overline{\nu^c_M} \nu_M + h.c.$$

If the Majorana mass is due to couplings to dark matter:

$$m_R = g\phi_0 \cos(m_\phi t)$$



$$\begin{pmatrix} \nu_l \\ \nu_h \end{pmatrix} = \begin{pmatrix} \cos\theta_{LR} & \sin\theta_{LR} \\ -\sin\theta_{LR} & \cos\theta_{LR} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{H.c.}$$

Y. ChoeJo, Y. Kim and H.-S. Lee (2024)

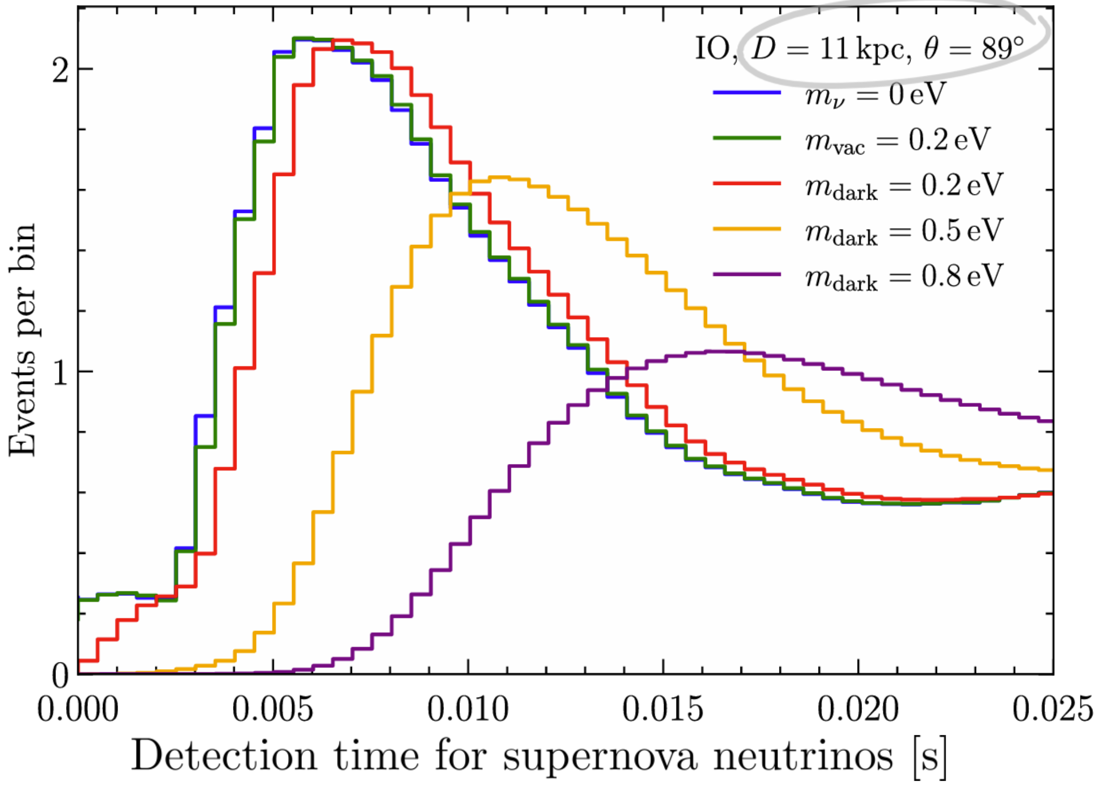
Testing the mass origin with supernova neutrinos

Rate for galactic core-collapse supernovae is low, ~O(1)/century Adams et al. (2013)

Arrival time delay effect is pronounced for:

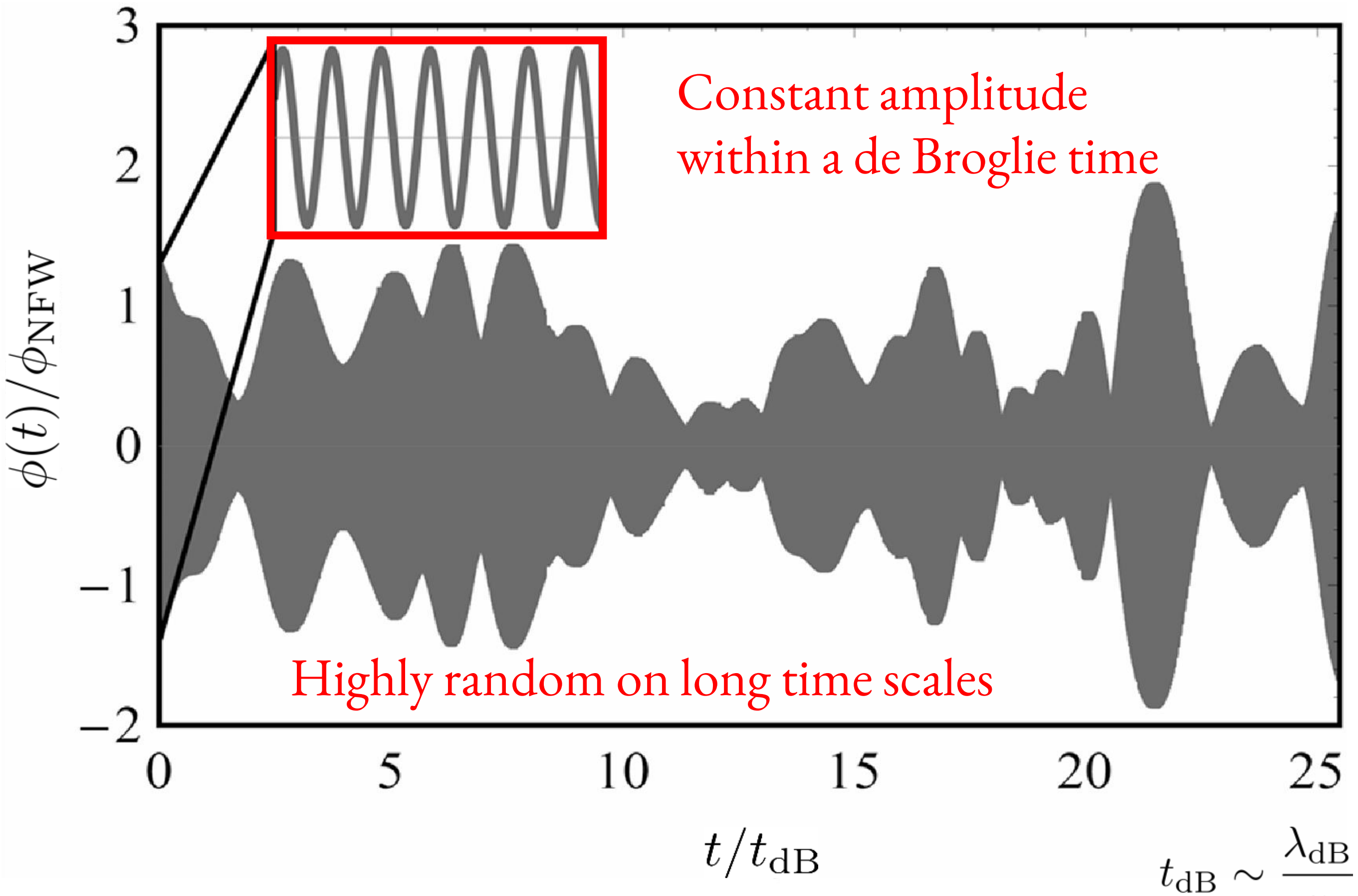
- Large “dark” mass
- Supernovae near galactic center (even lower rate)

Neutrinos crossing galactic center



S.-F. Ge, C.-F. Kong and A. Y. Smirnov (2024)
Assuming NFW profile for dark matter, neglecting time dependence and density fluctuations

Stochastic fluctuations for ultralight dark matter



$$t_{\rm dB} \sim \frac{\lambda_{\rm dB}}{v}$$

Centers et al. (2021)