Ultralight Dark Matter Coupled To Right Handed Neutrinos

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Work In Progress

PART 1

BACKGROUND

- Ultralight dark matter & right-handed neutrinos.
- Distorted neutrino oscillations.

PART 2

DYNAMICS

- Adabatic approximation.
- The relic potential.

PART 3

COSMOLOGY

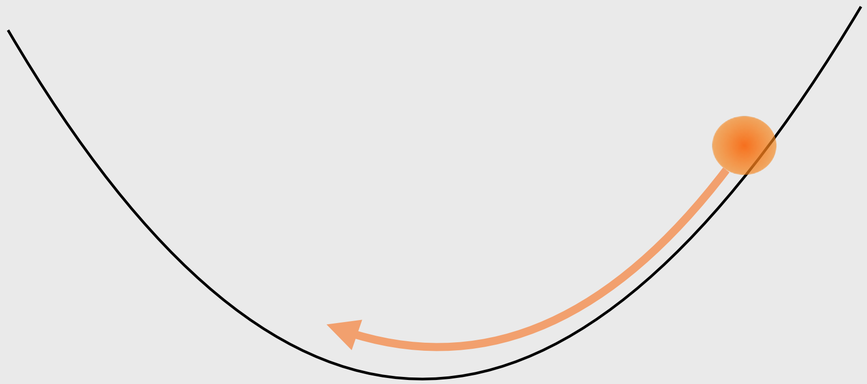
- Large negative initial conditions.
- Large positive initial conditions.

Ultralight Scalar Dark Matter

FRIEDMAN EQUATION

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

$$\rho = \frac{1}{2}m_\phi^2\phi^2$$



John Preskill, Mark B. Wise, Frank Wilczek (1983)

INITIAL CONDITIONS

$$\phi(t_0) = \phi_i \quad \dot{\phi}(t_0) = 0$$

$$\mathscr{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2$$

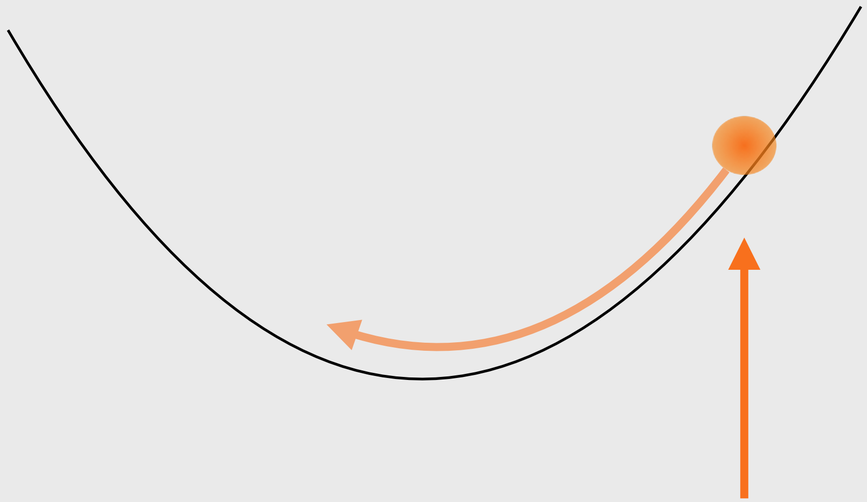
COMPLETELY SECLUDED

Misalignment & Relic Abundance

$$\rho = \rho_0 \times \left(\frac{T}{T_{\rm osc}}\right)^3 \frac{g_*(T)}{g_*(T_{\rm osc})}$$

SET BY INITIAL CONDITIONS

$$\rho = \frac{1}{2} m_\phi^2 \phi^2$$

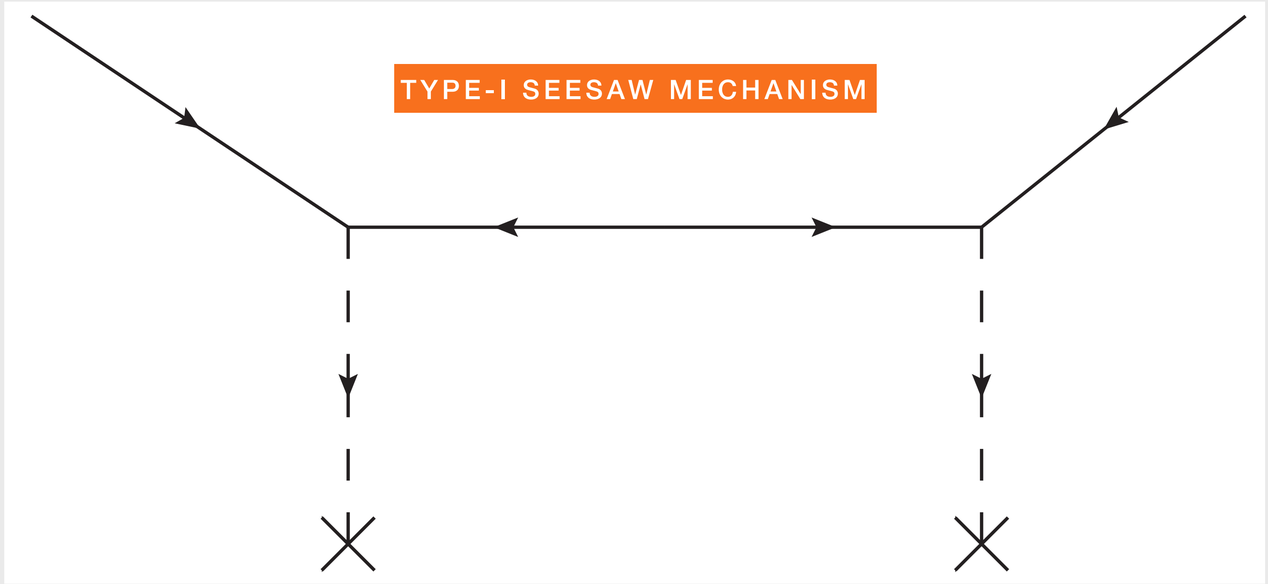


$$3H(T_{\rm osc}) = m_\phi$$

- Mechanism is simple, and entirely secluded.
- Can be generated by inflationary fluctuations.

Coupling To Right Handed Neutrinos

- Gauge singlets (e.g. RHNs) couple to scalar dark matter ϕ.
- We will study a quadratic potential for definiteness.



$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) + \overline{N}^c \sigma_\mu \partial^\mu N^c - \tfrac{1}{2} M_{ij} N_i^c N_j^c - \tfrac{1}{2} g_{ij} \phi N_i^c N_j^c$$

$$V(\phi) = \tfrac{1}{2} c_2 \phi^2$$

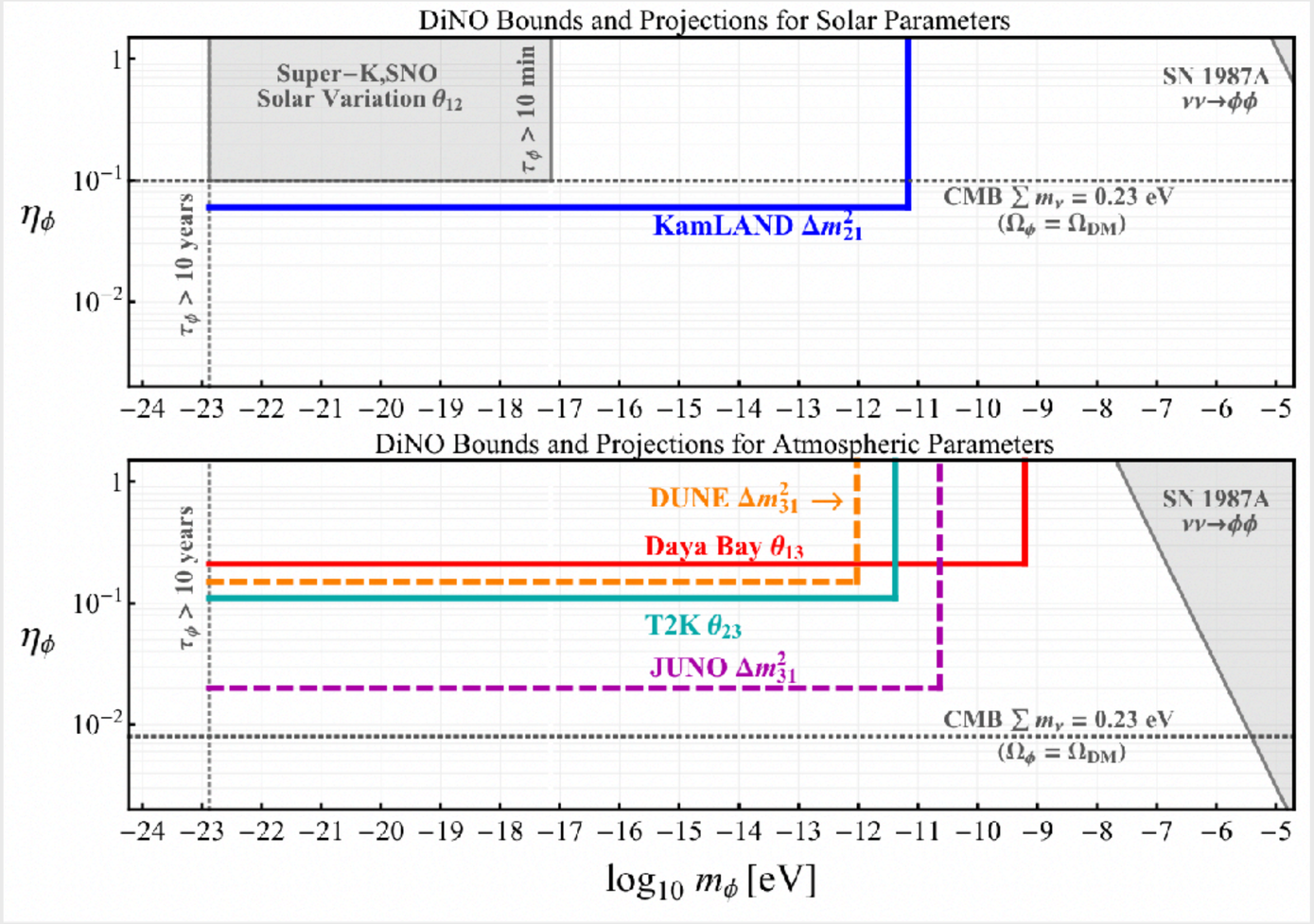
Distorted Neutrino Oscillations

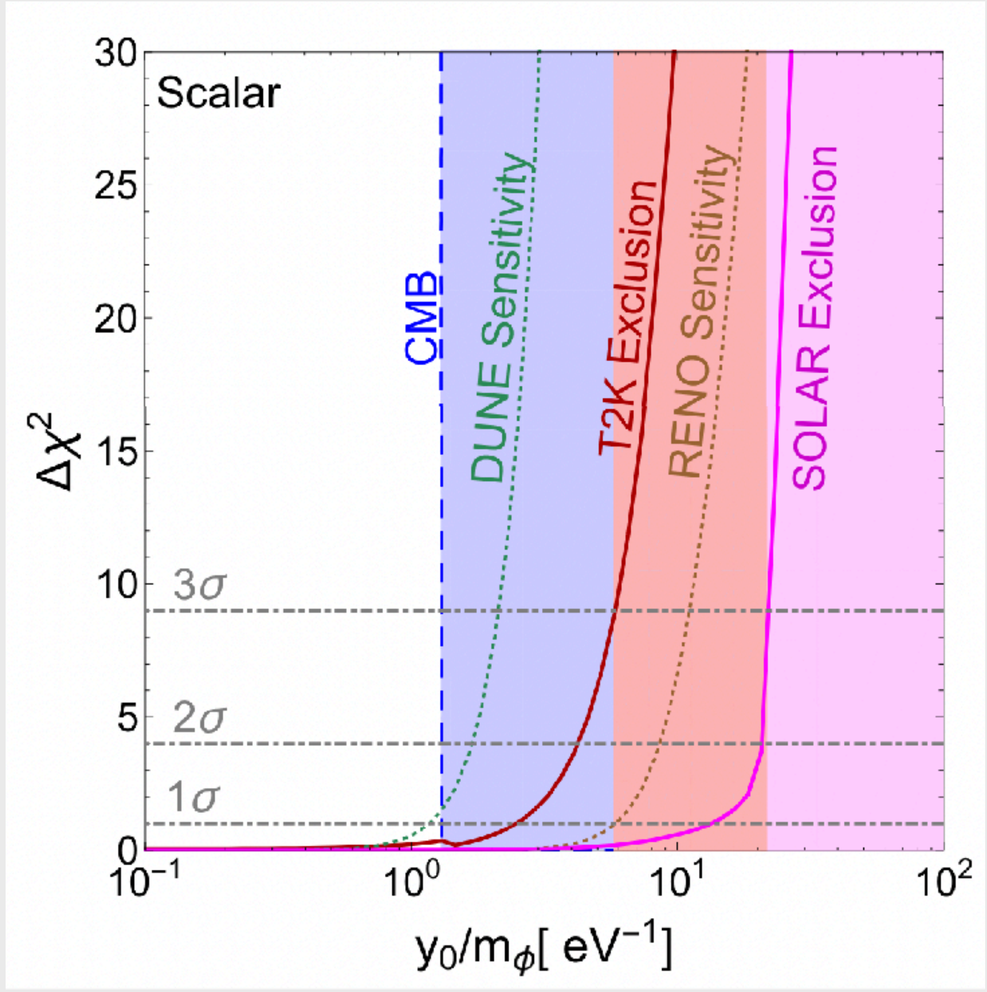
- An obvious probe of this kind of coupling is neutrino oscillations.

$$\frac{m_D^2}{m_N - gA_\phi \cos m_\phi t} \simeq \frac{m_D^2}{m_N}\left(1 + \frac{gA_\phi}{m_N}\cos m_\phi t + \ldots\right)$$

$$m_\nu \to m_\nu(1 + \delta \cos m_\phi t)$$

Distorted Neutrino Oscillations

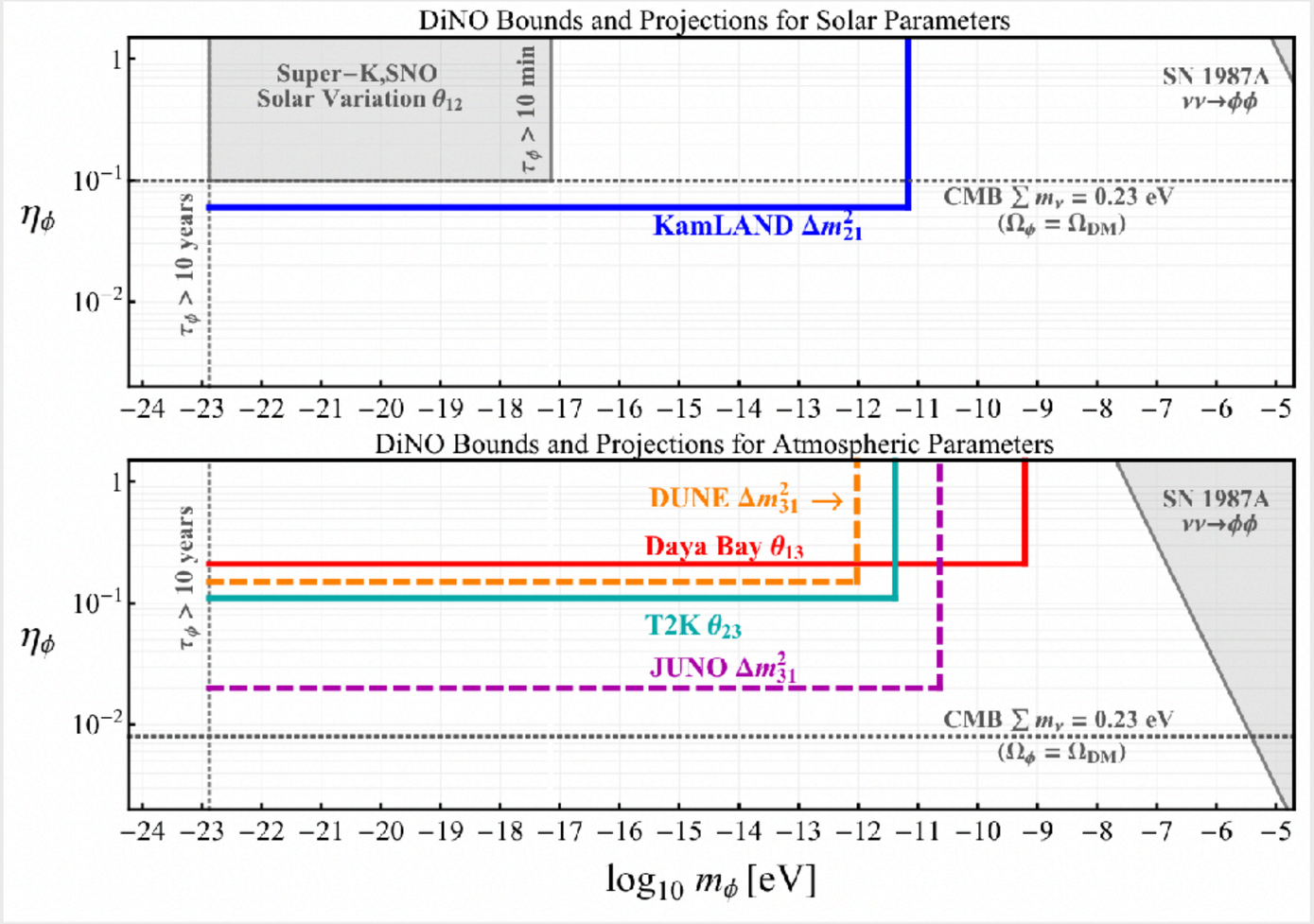




KRNJAIC, MACHADO, NECIB 1705.06740

BRDAR, KOPP, LIU, PRASS, WANG 1705.09455

Distorted Neutrino Oscillations



$$\int \frac{\mathrm{d}t}{\tau_\phi} P(\nu_\alpha \to \nu_\beta)$$

$$\sim \sin^2\theta_0 \left(1 - 4\frac{gA_\phi}{m_N}\right)$$

APPLIES EVEN AFTER TIME AVERAGING

KRNJAIC, MACHADO, NECIB 1705.06740

Cosmological Blue-Shift

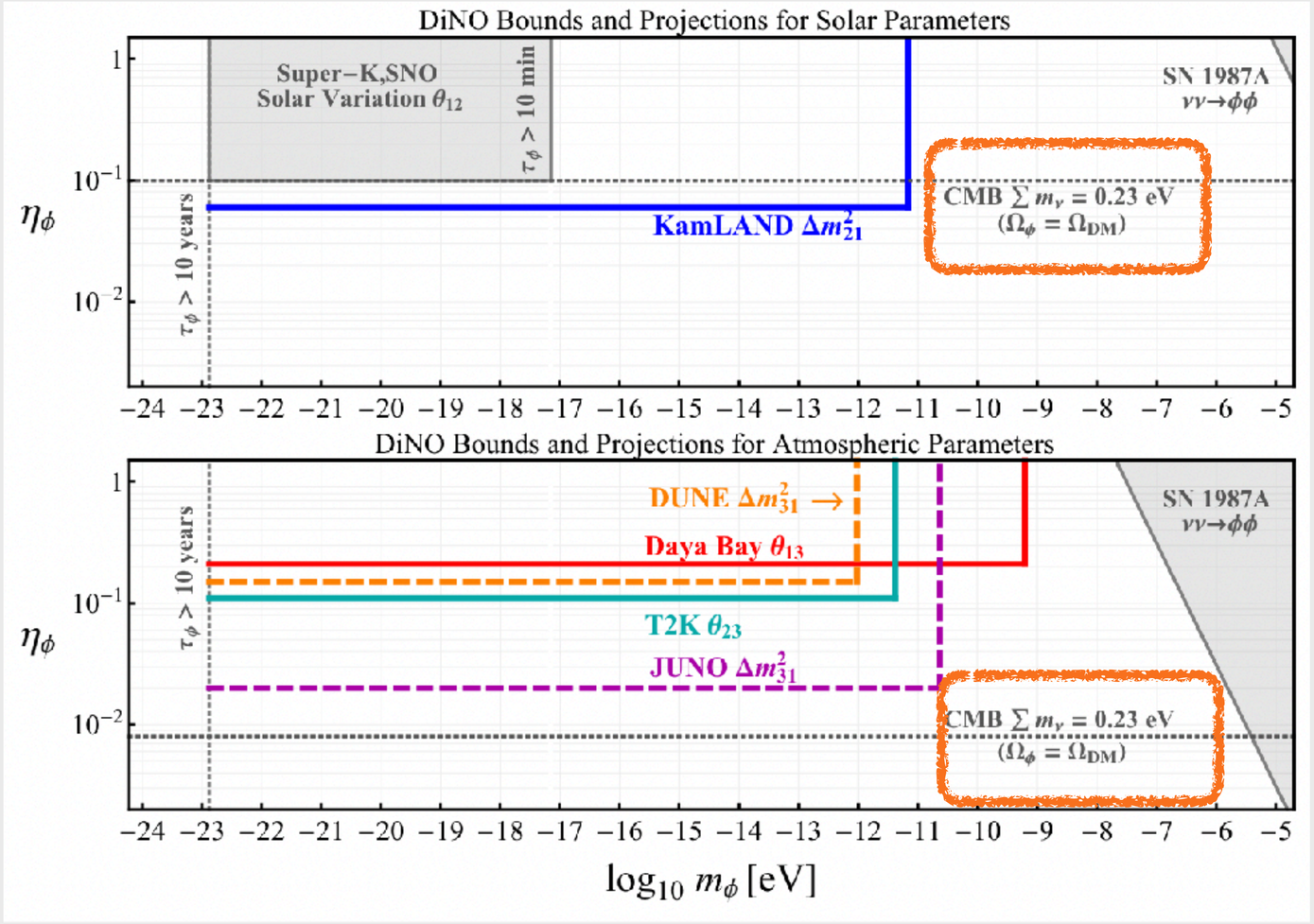
- There is a problem with this simple model.

$$\frac{m_D^2}{m_N - gA_\phi \cos m_\phi t} \simeq \frac{m_D^2}{m_N}\left(1 + \frac{gA_\phi}{m_N}\cos m_\phi t + \ldots\right)$$

$$A_\phi \sim (1+z)^{3/2}$$

LARGE AMPLITUDES AT HIGH REDSHIFT

Distorted Neutrino Oscillations



$$\langle \delta m_\nu \rangle_{z_{\rm CMB}} \sim O(1)$$

$$g A_\phi \sim m_N$$

MAJORANA MASS CROSSES ZERO!

KRNJAIC, MACHADO, NECIB 1705.06740

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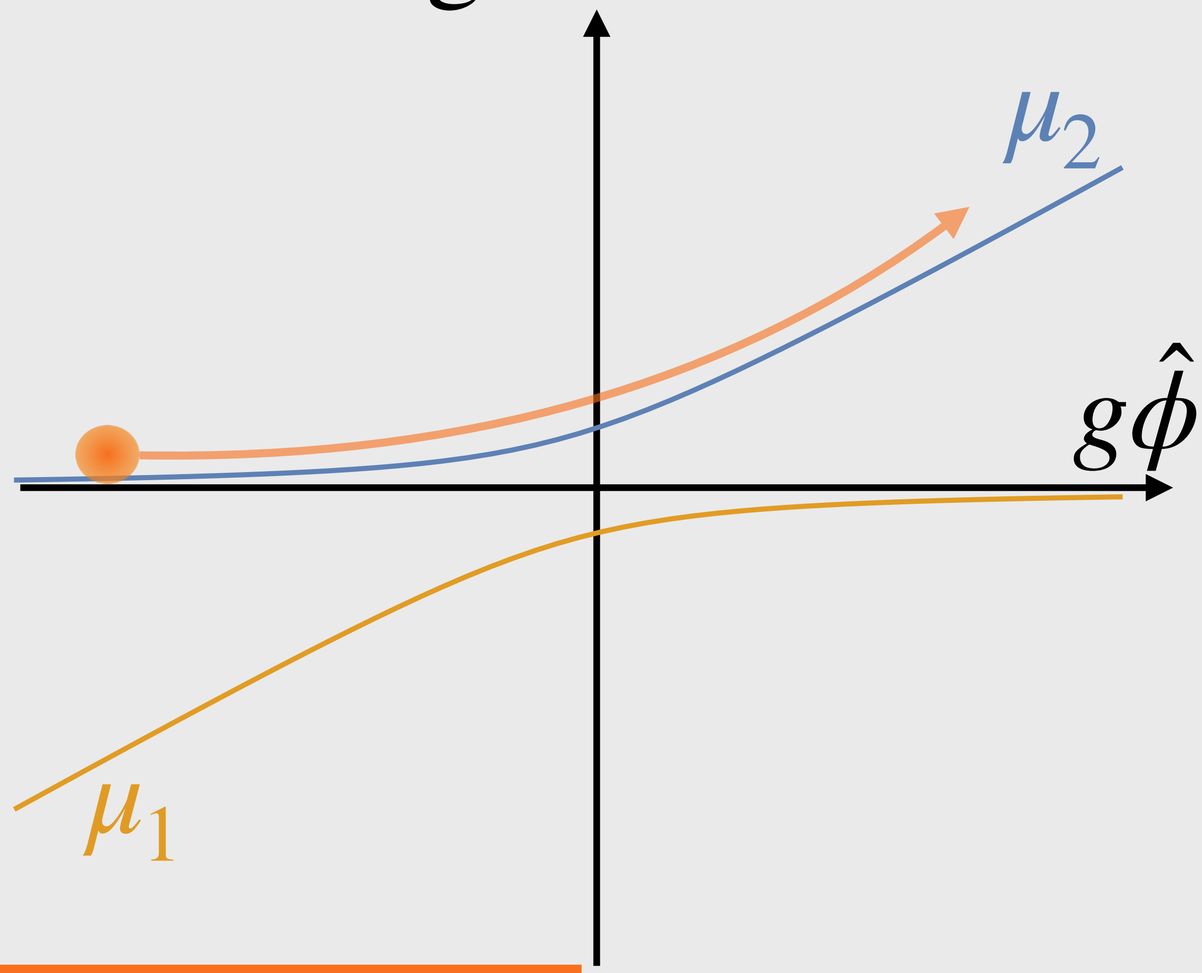
Adiabatic Dynamics

$$\begin{pmatrix} 0 & m_D \\ m_D & g\hat{\phi} \end{pmatrix}$$

Eigenvalues



AVOIDED CROSSING

PARTICLE LABELS (1,2) ARE CONSERVED

Relic Potential

IT COSTS ENERGY TO MAKE NEUTRINOS HEAVY

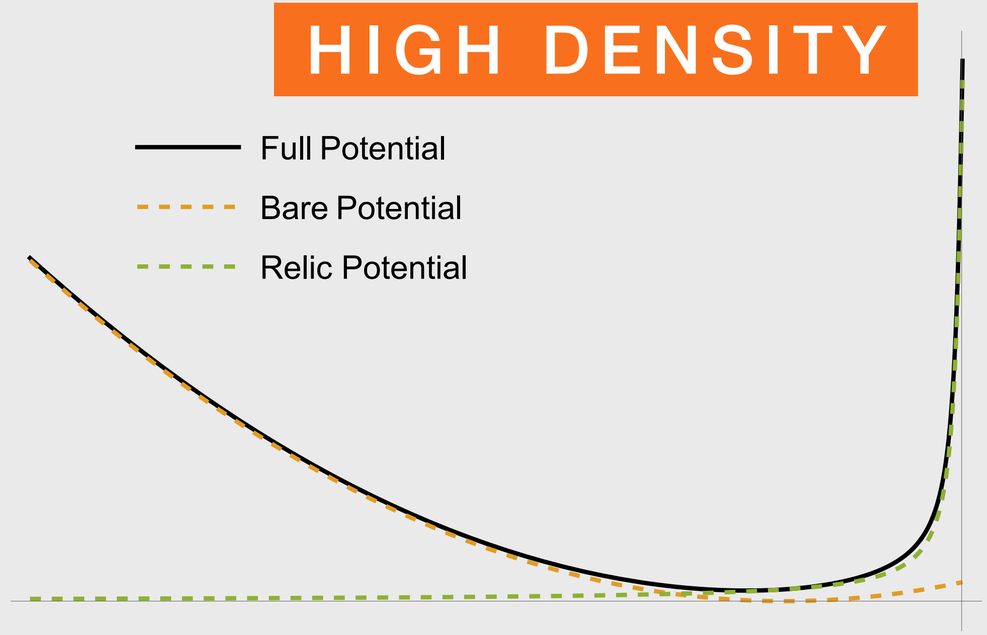
$$\frac{E}{V} \simeq V_0(\phi) + n_1 |\mu_1| + n_2 |\mu|_2$$

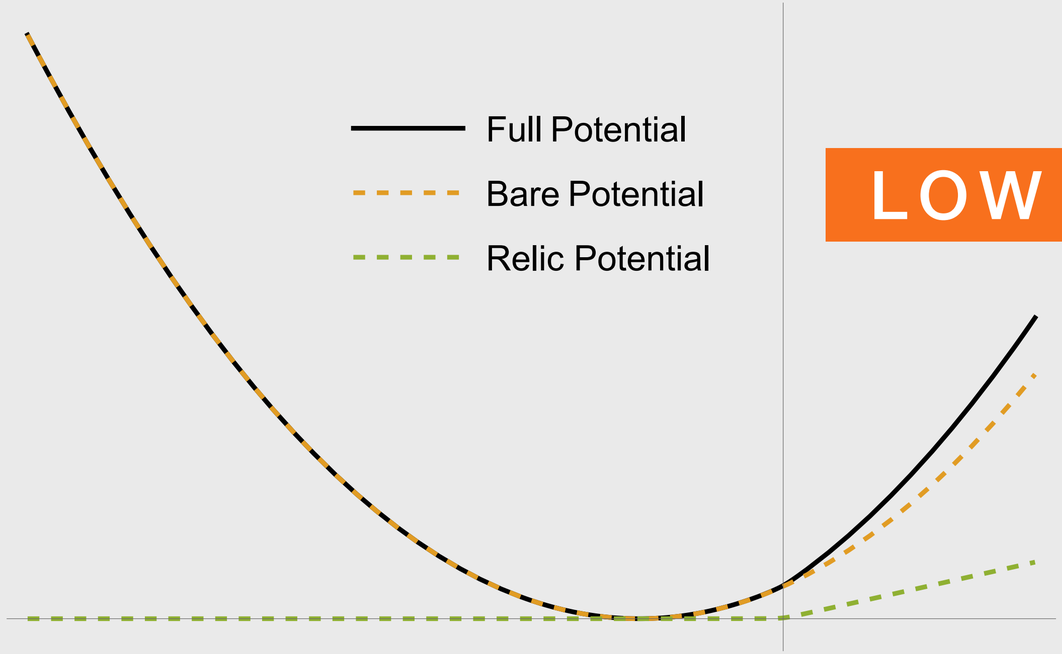
$$n_\nu \sim T^3$$

NEUTRINO DENSITY IS HIGH IN THE EARLY UNIVERSE

Relic Potential

- Shape of potential changes with temperature.
- Neutrino density can act as a ``wall''.
- Prevents zero crossing.





Interesting Consequences

- Neutrinos are chameleons (change mass in supernovae).
- Dark matter experiences temperature dependent potential.
- Neutrino mass oscillates wildly in the early universe (but can be prevented from crossing zero).
- Dark matter can get "stuck" at large field values.

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Aside: Red-Shifting A Scalar

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -3H\gamma\rho \qquad \rho \sim \rho_0 \times \left(\frac{a}{a_0}\right)^{-3\gamma}$$

$$\gamma = \frac{\langle \dot{\phi}^2 \rangle}{\rho}$$

VOLUME 28, NUMBER 6

Coherent scalar-field oscillations in an expanding universe

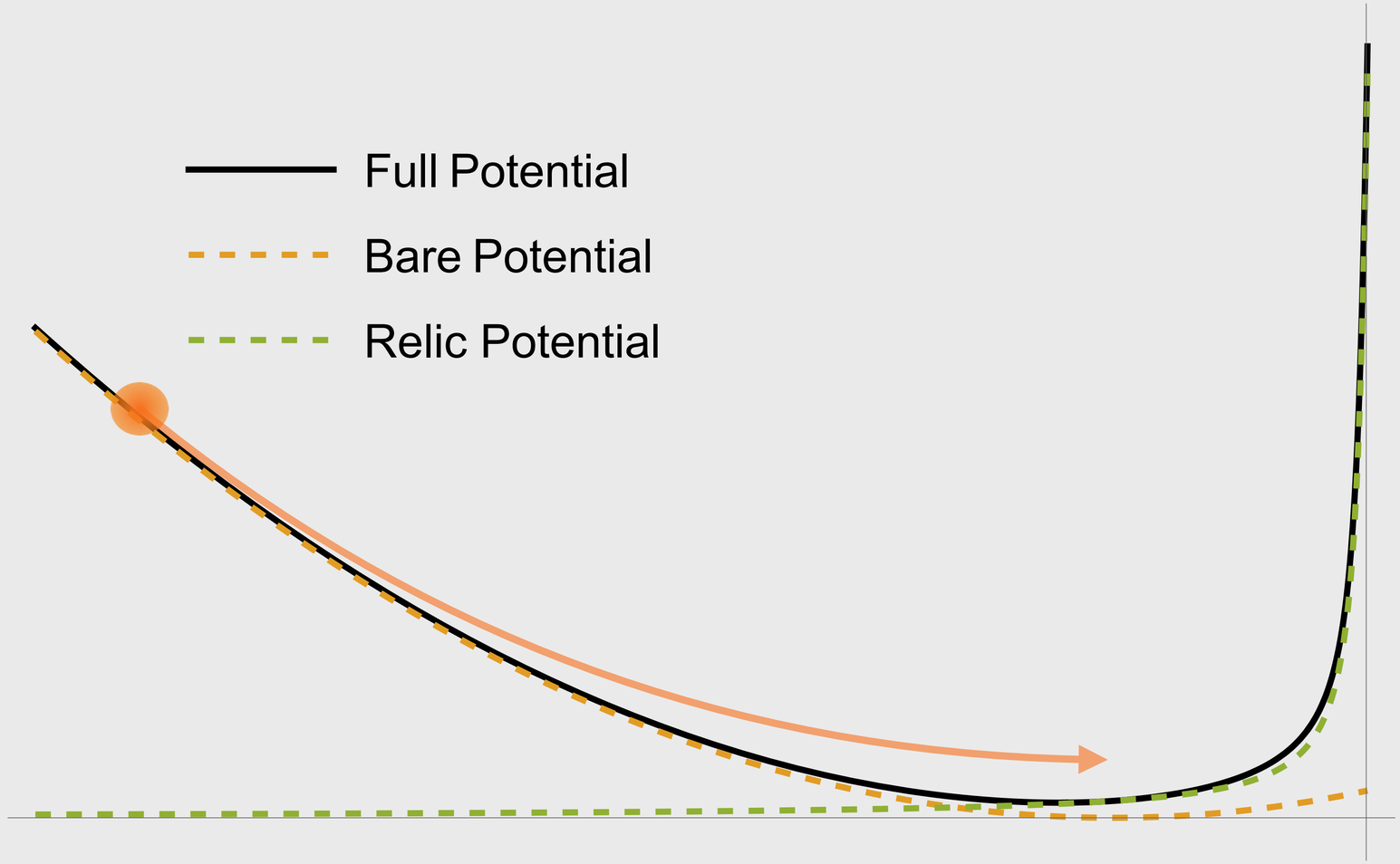
Michael S. Turner
Astronomy and Astrophysics Center, Enrico Fermi Institute,
The University of Chicago, Chicago, Illinois 60637
(Received 8 June 1983)

Large Negative Field Values

HIGH TEMPERATURE

$$\gamma \approx 1$$

$$\rho \sim \rho_0 \times \left(\frac{a}{a_0}\right)^{-3}$$



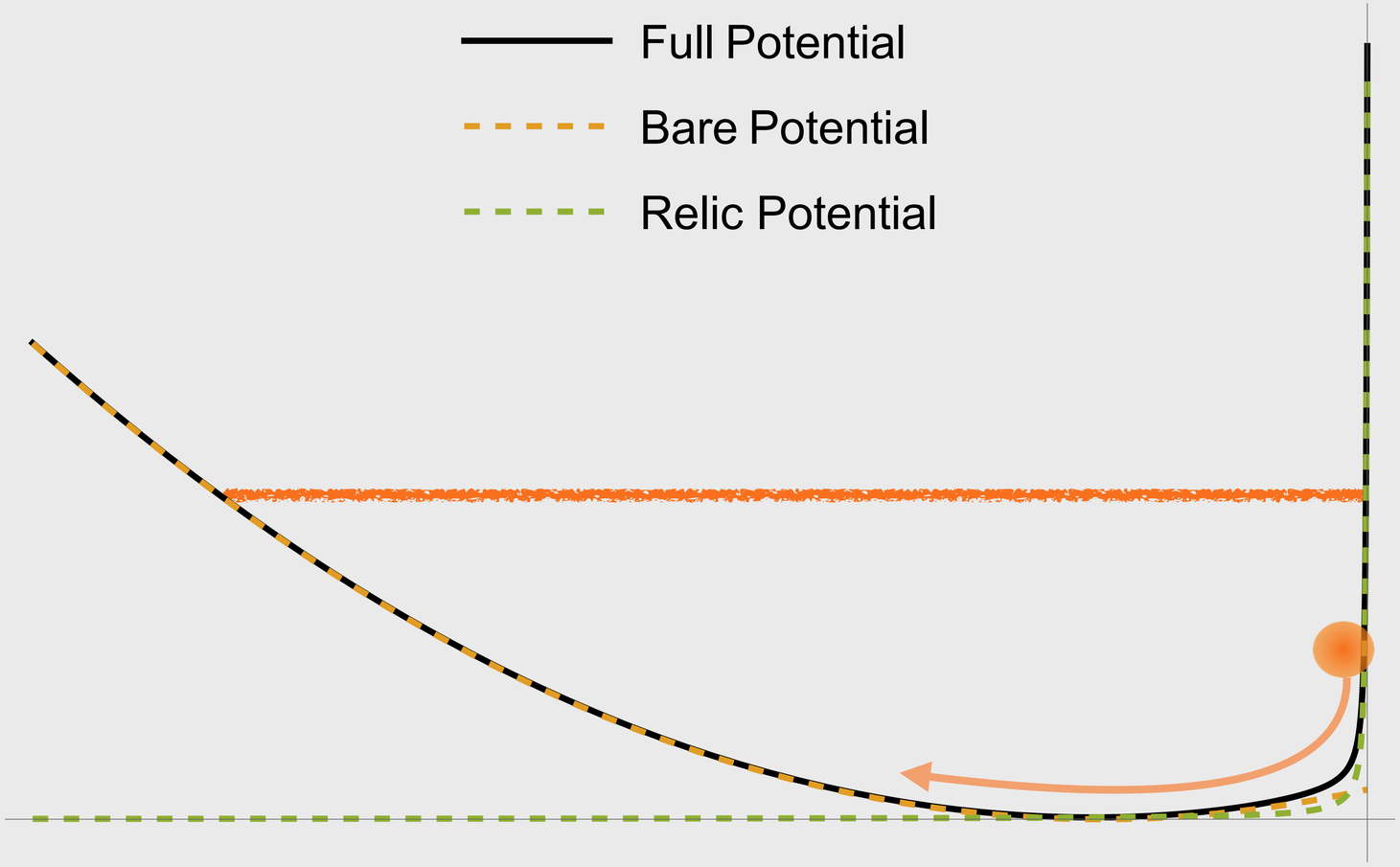
Large Negative Field Values

INTERMEDIATE TEMPERATURE

- Resembles a harmonic oscillator with a hard wall.

$$1 \lesssim \gamma(\rho) \lesssim 1.3$$

- Average kinetic energy is higher.



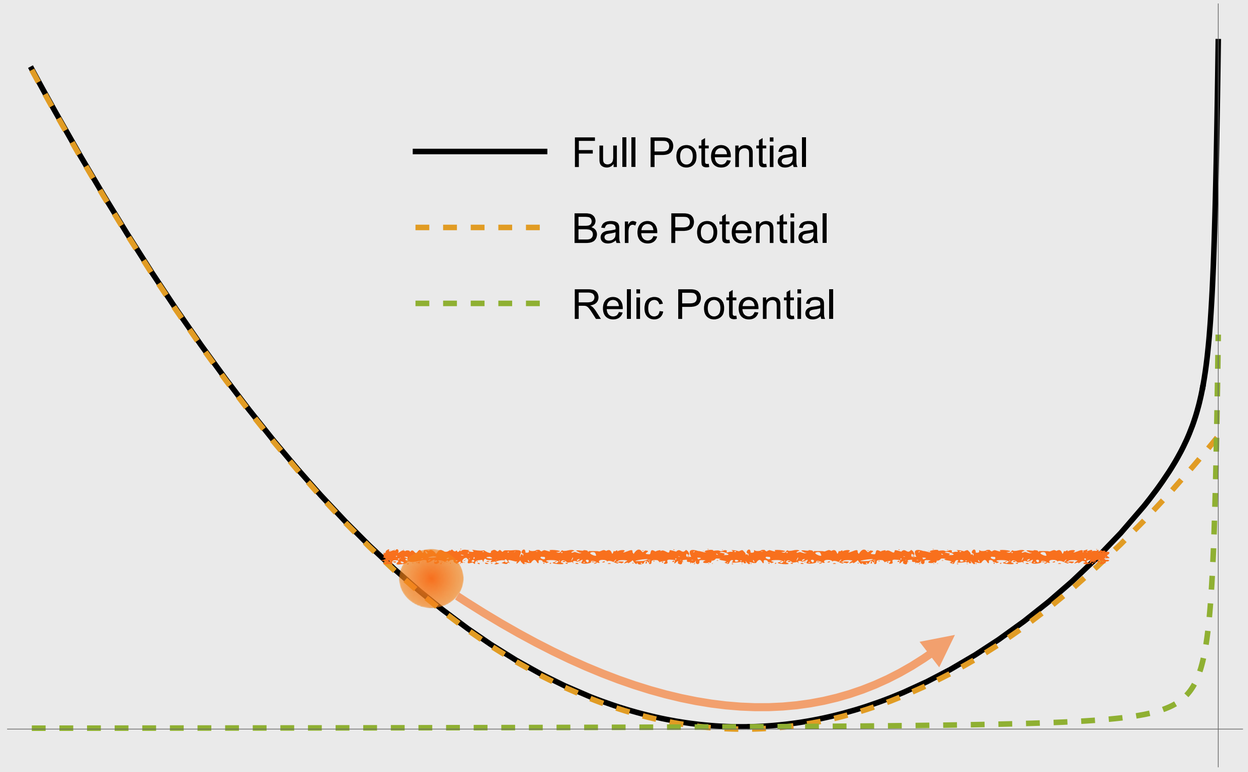
Large Negative Field Values

LOW TEMPERATURE

- Hard wall becomes inaccessible.

$$\gamma(\rho) \simeq 1$$

- Red-shift resembles a harmonic oscillator again.



Large Negative Field Values

$$\int \frac{1}{\gamma(\rho)} \mathrm{d}\log\rho = -3\int \mathrm{d}\log a$$

SUBTRACT NAIVE SOLUTION

$$\int_{\rho}^{\rho_0} \left[\frac{1}{\gamma(\rho')} - 1\right] \mathrm{d}\log\rho' = \Delta(\rho)$$

Large Negative Field Values

$$\left(\frac{\rho}{\rho_0}\right) e^{\Delta(\rho)} = \left(\frac{T}{T_0}\right)^3$$

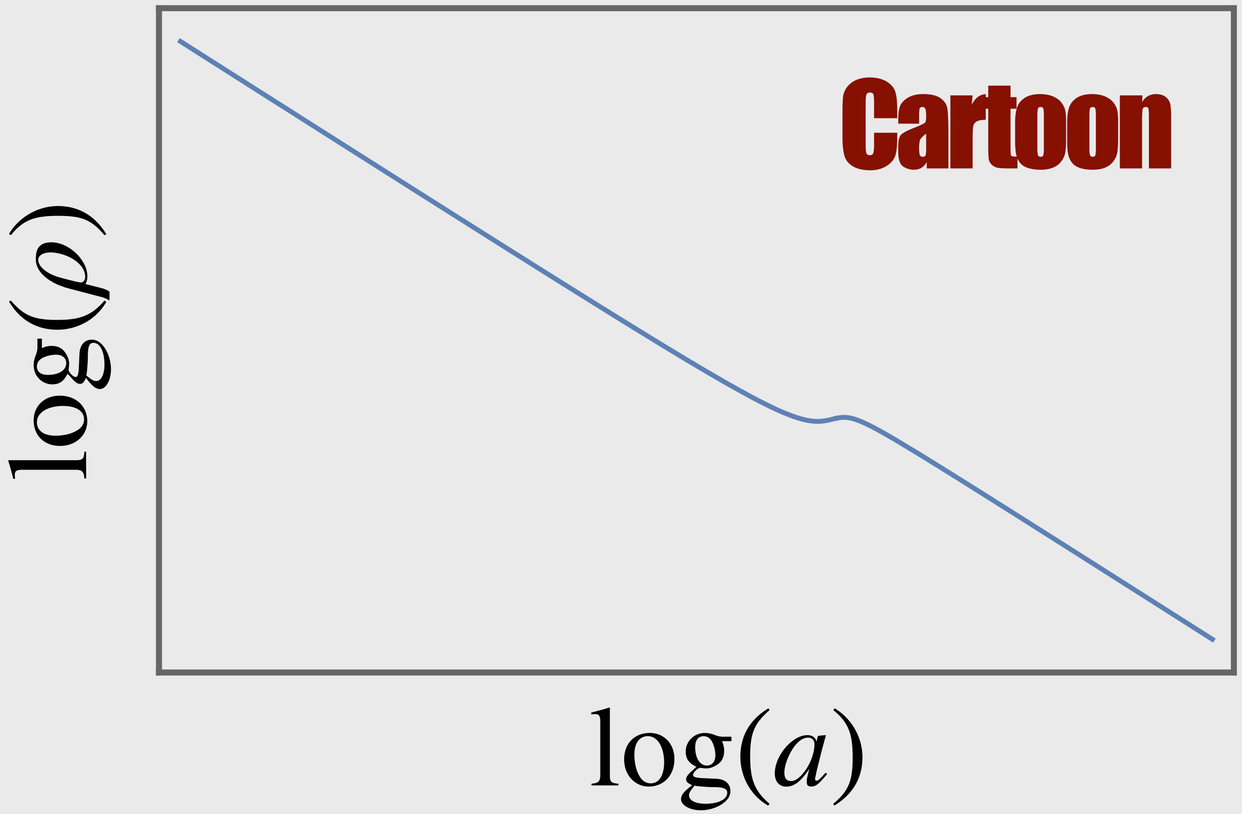
DARK MATTER DENSITY IS DECREASED

$$\left(\frac{\rho}{\rho_0}\right) < \left(\frac{T}{T_0}\right)^3$$

Dark Matter Evolution

$$\left(\frac{\rho_{\text{late}}}{\rho_0}\right) \approx 0.5 \times \left(\frac{T}{T_0}\right)^3$$

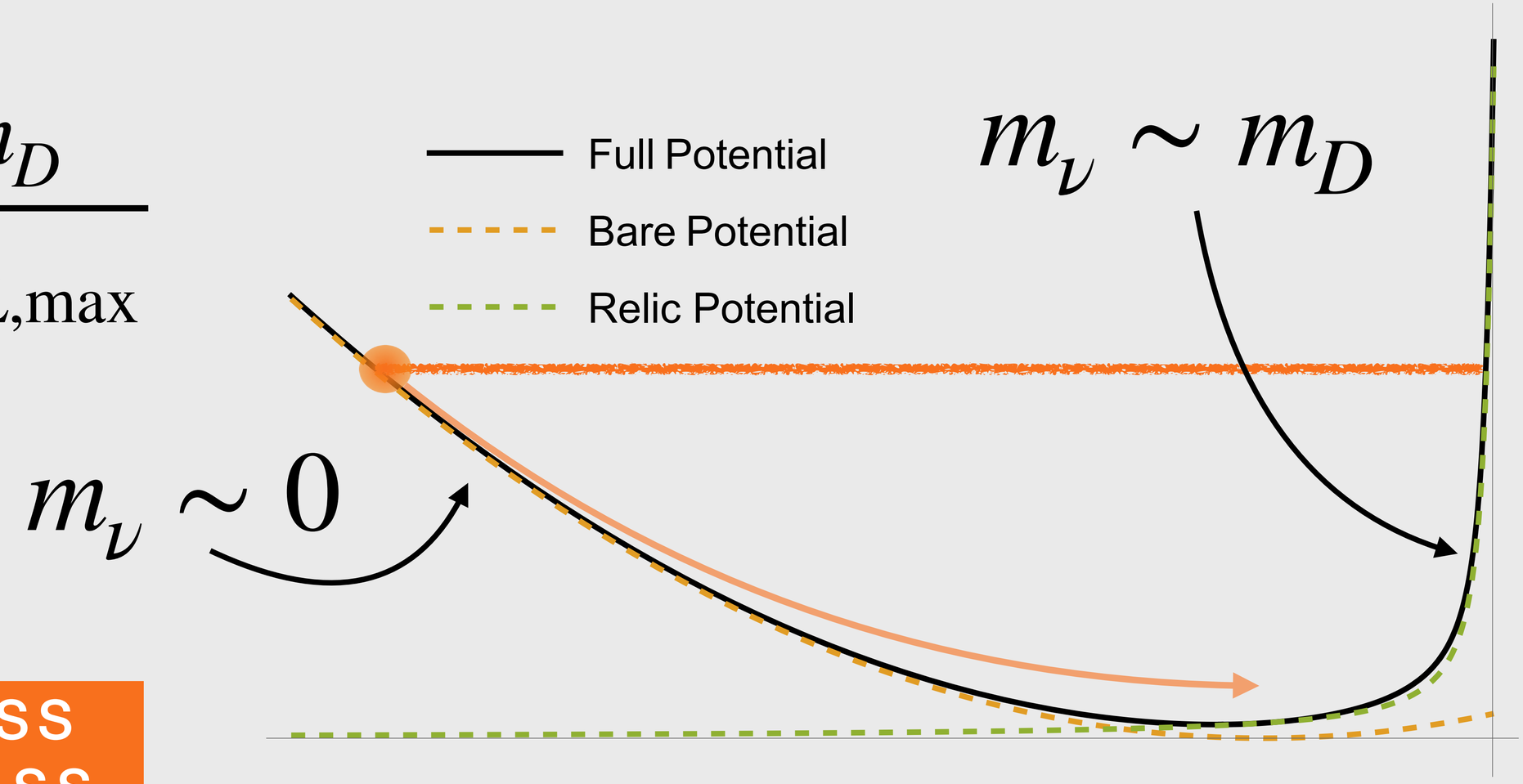
THIS CAN BE AVOIDED IF THE "DIP" HASN'T HAPPENED YET.



- Implies oscillations are ***not*** harmonic today.

Average Neutrino Mass

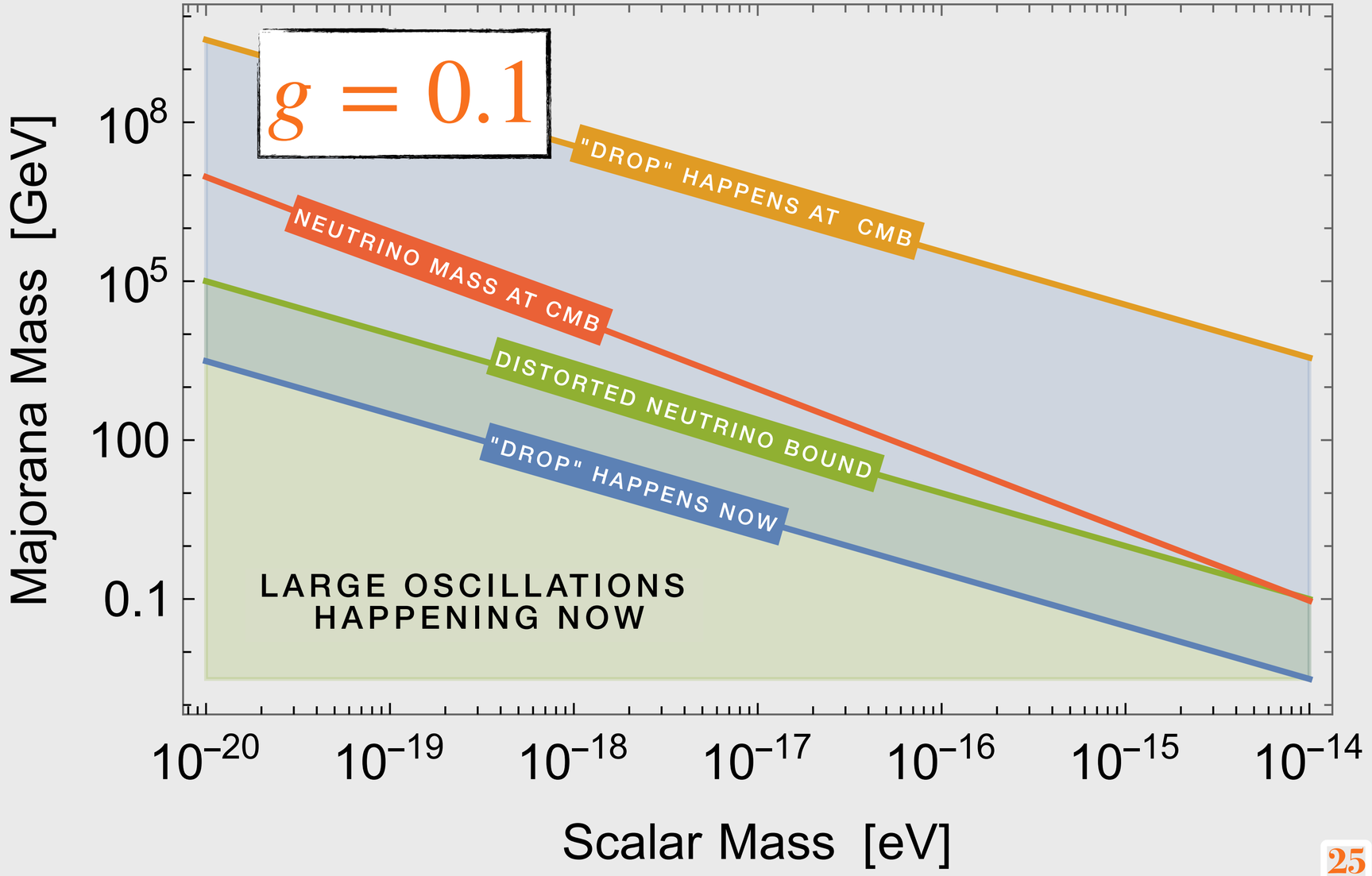
$$m_\nu \sim m_D \frac{m_D}{g\phi_{L,\max}}$$



CAN SUPPRESS NEUTRINO MASS

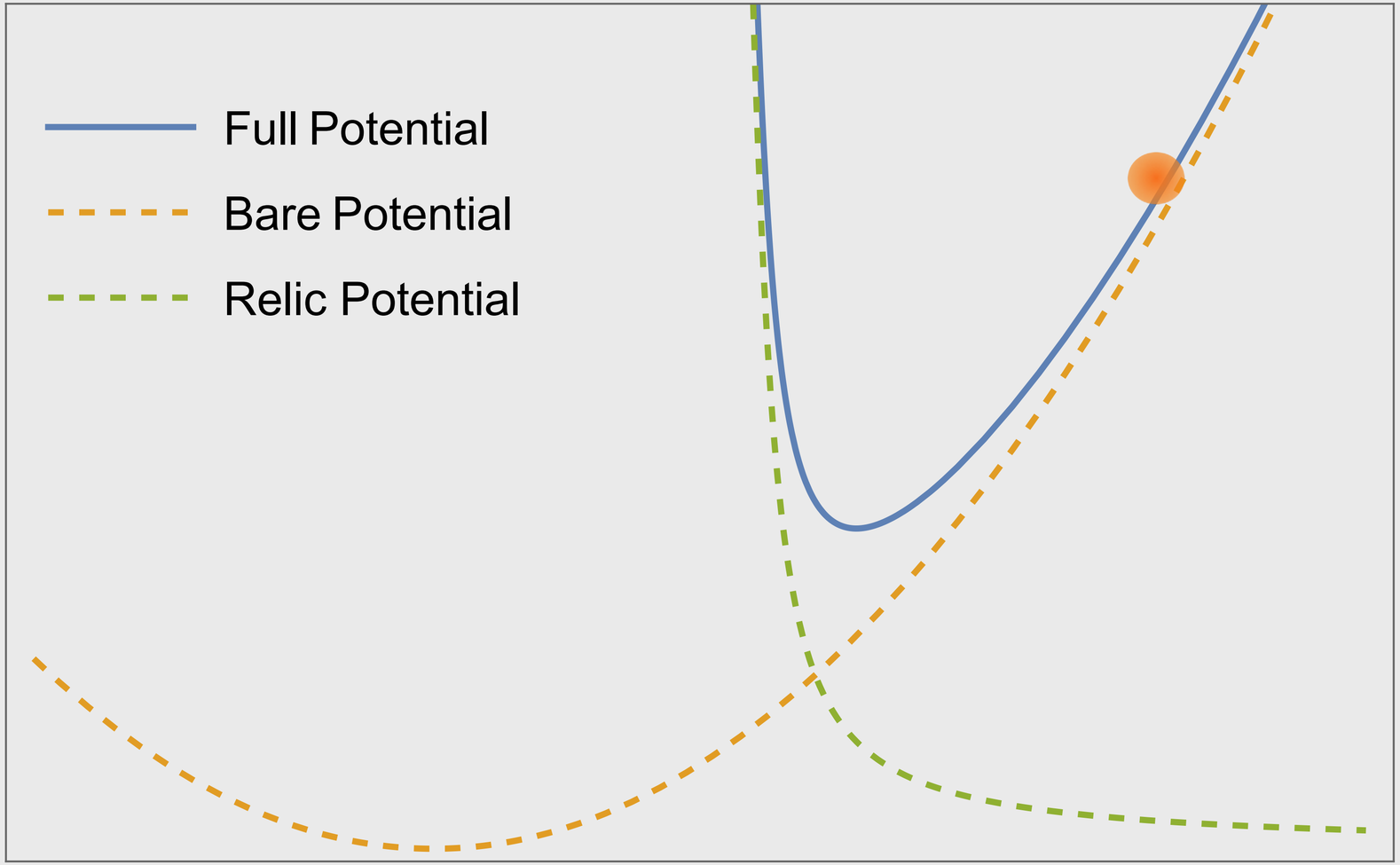
Qualitative Results

- DiNOs rule out large oscillations today.
- Constraint from DM concordance is strongest.
- Need large Majorana mass.



Large Positive Field Values

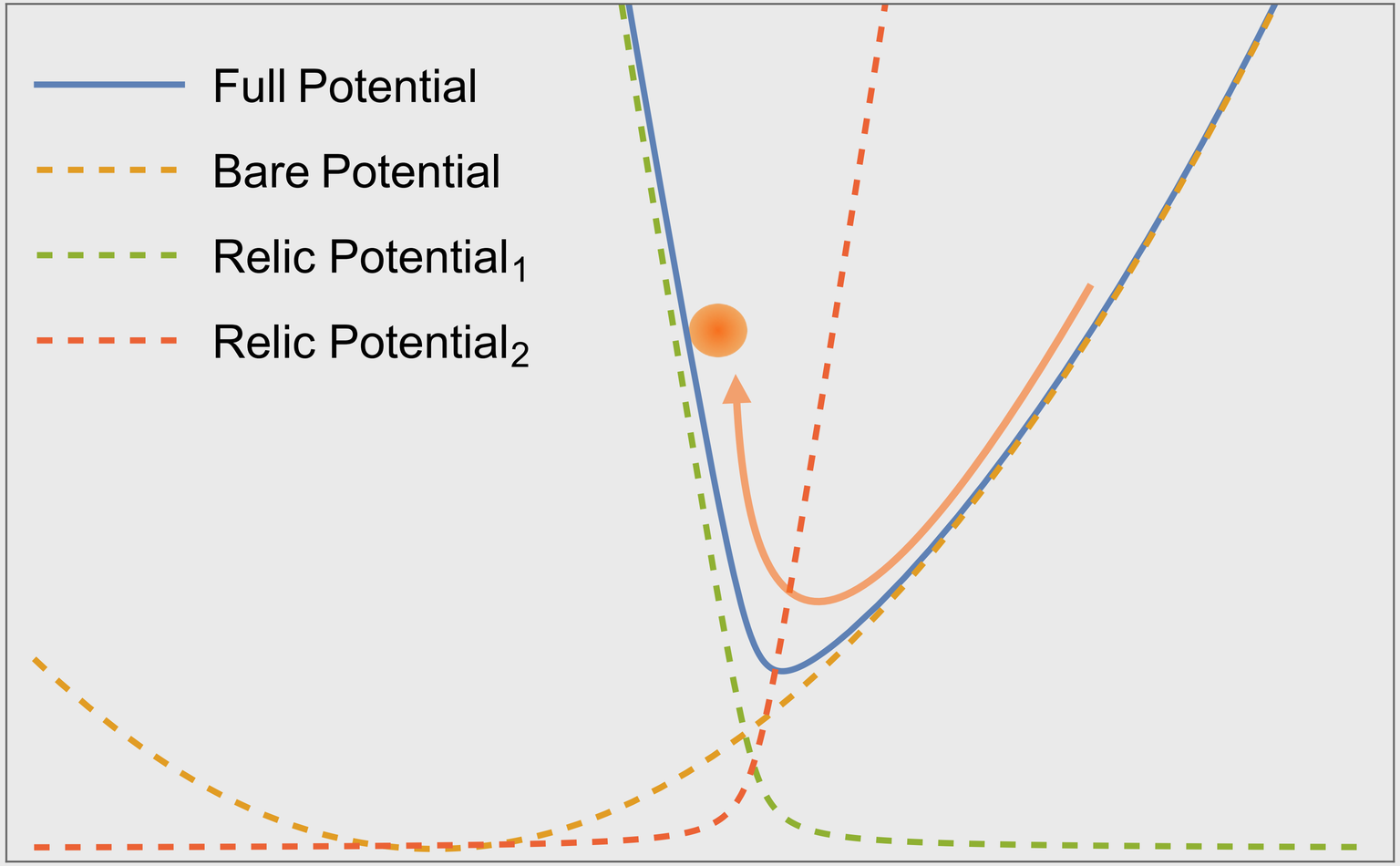
- Shape of potential is very different.



Dangerous Cosmologies

- Suppose you have enough energy to "crossover".
- Light and heavy-states switch roles

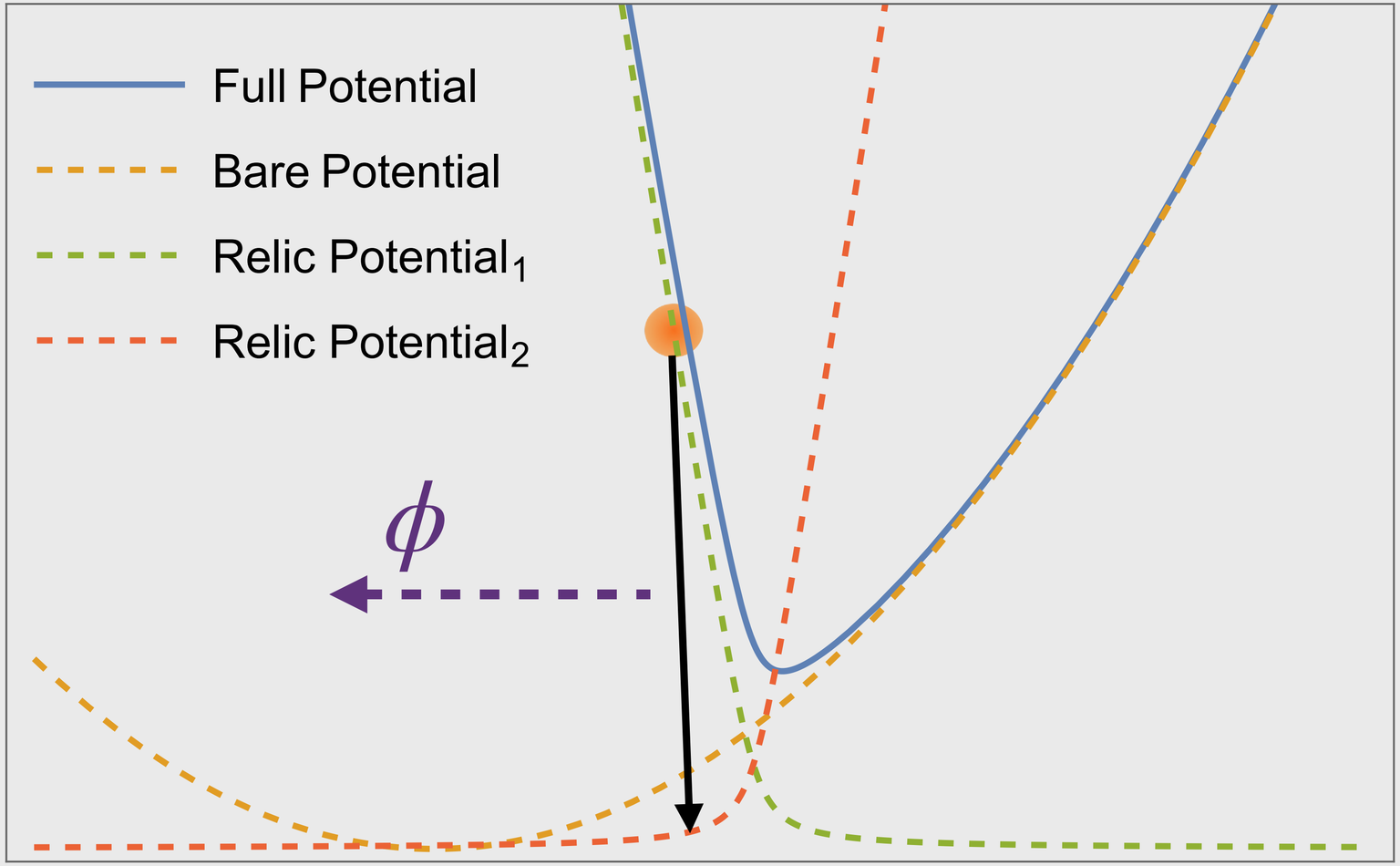
$$\nu_H \leftrightarrow \nu_L$$



Dangerous Cosmologies

- Heavy neutrino can now decay to light-neutrino.

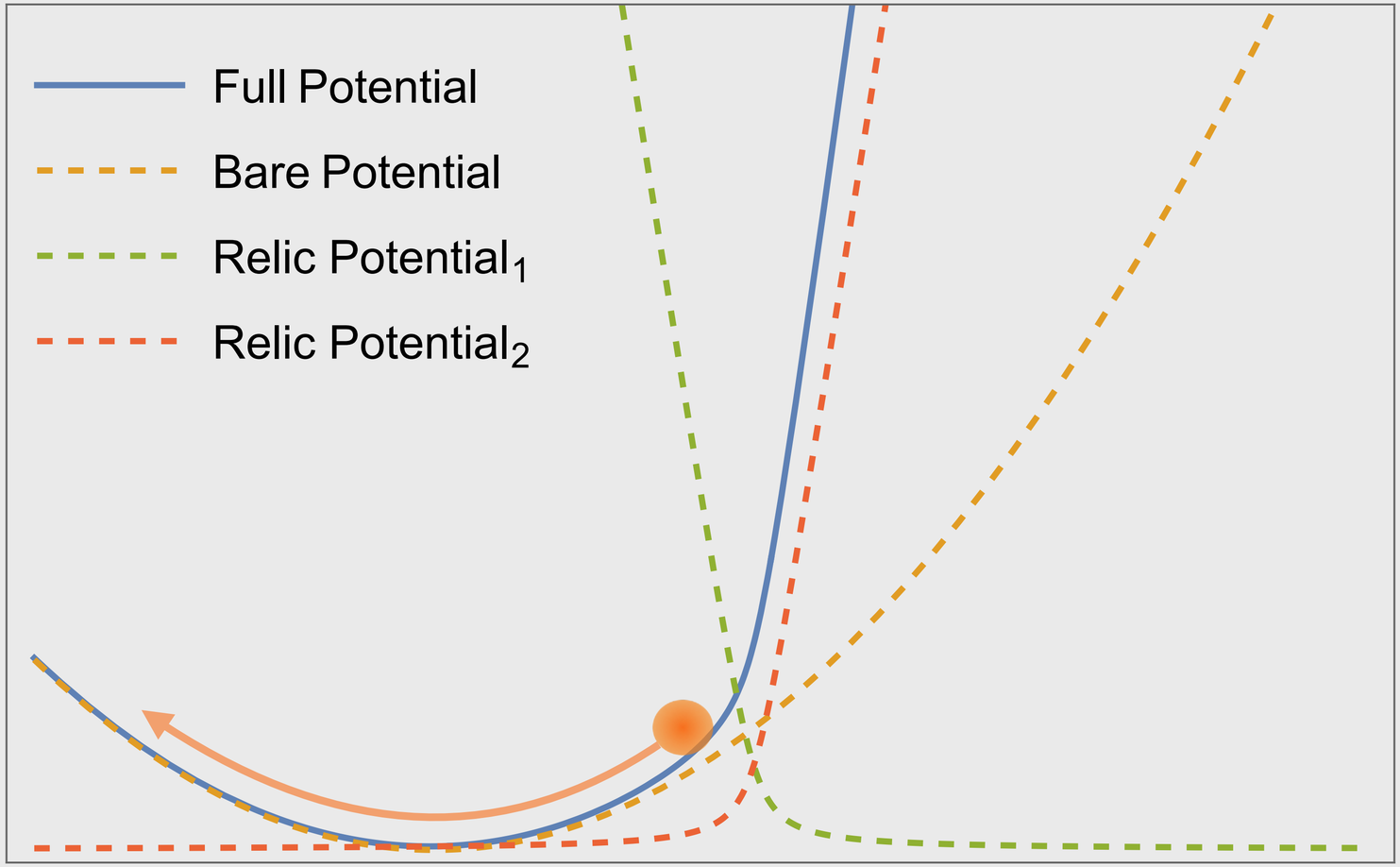
$$\nu_H \to \nu_L + \phi$$



Dangerous Cosmologies

- All heavy states become light states.
- Shape of potential "flips".

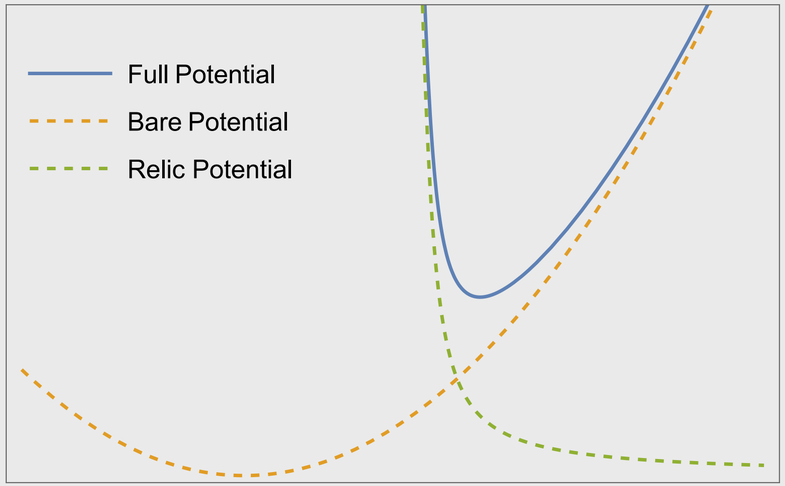
$$\nu_H \to \nu_L + \phi$$

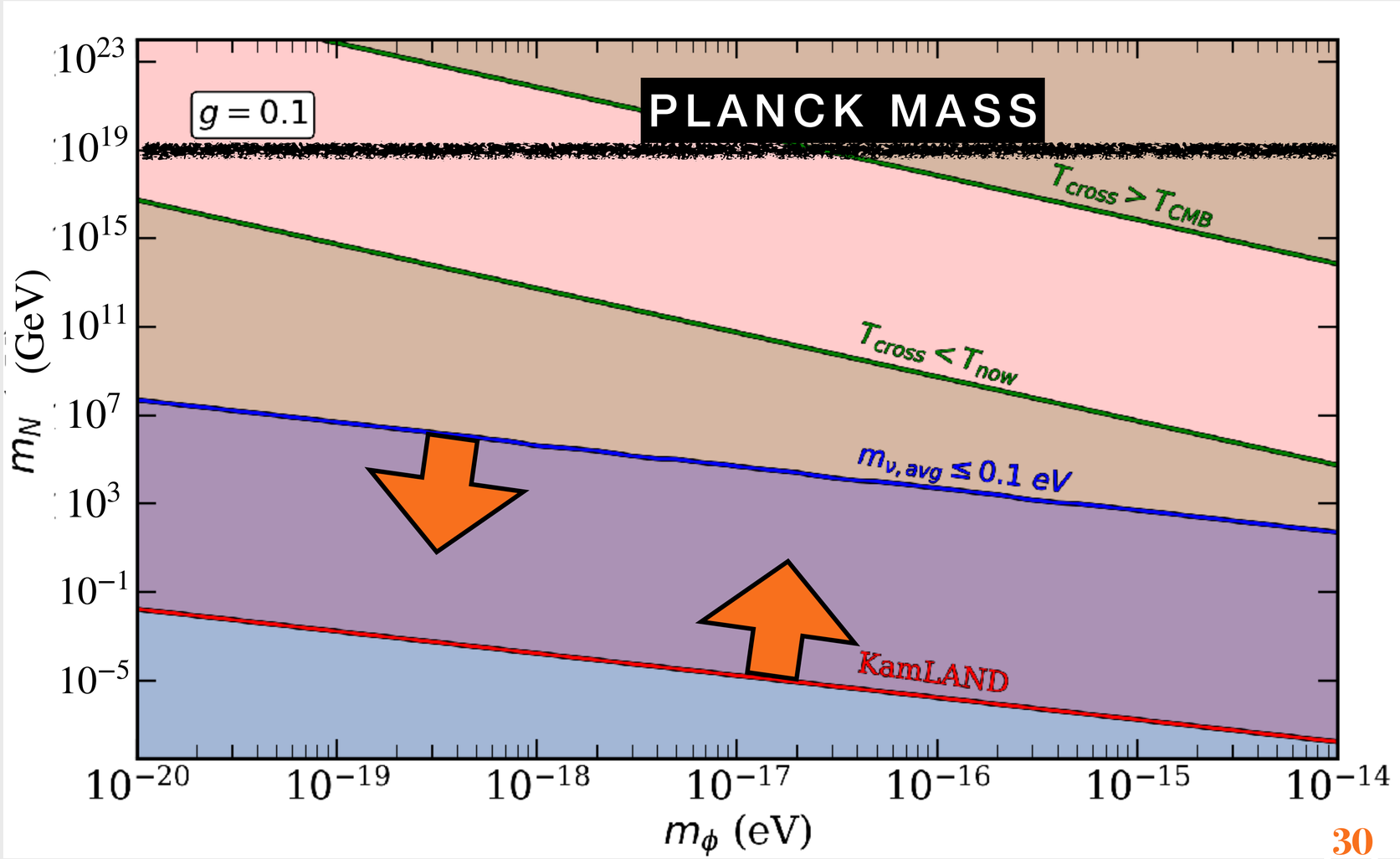


Large Positive Field Values

MAJORANA MASS IS NOT IT'S "BARE" VALUE TODAY

$$m_{N,\text{eff}} = \frac{g^2 n}{m_\phi^2} \frac{m_\nu^2}{m_D^2}$$





Summary

- Misaligned dark matter generically has very large amplitude oscillations in the early universe.
- If coupled to neutrinos this can cause Majorana mass to vanish.
- Relic potential from changing mass of background neutrino gas is very large. Dominates dynamics.
- Can alter cosmology of dark matter, neutrinos, and scalar radiation.