

The cosmological evolution of coupled neutrino-ultralight dark matter

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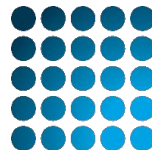
Pheno Symposium 2026, University of Pittsburgh

Based on work with J. López Sarrión and J. Salvadó

arXiv: 2509.22867



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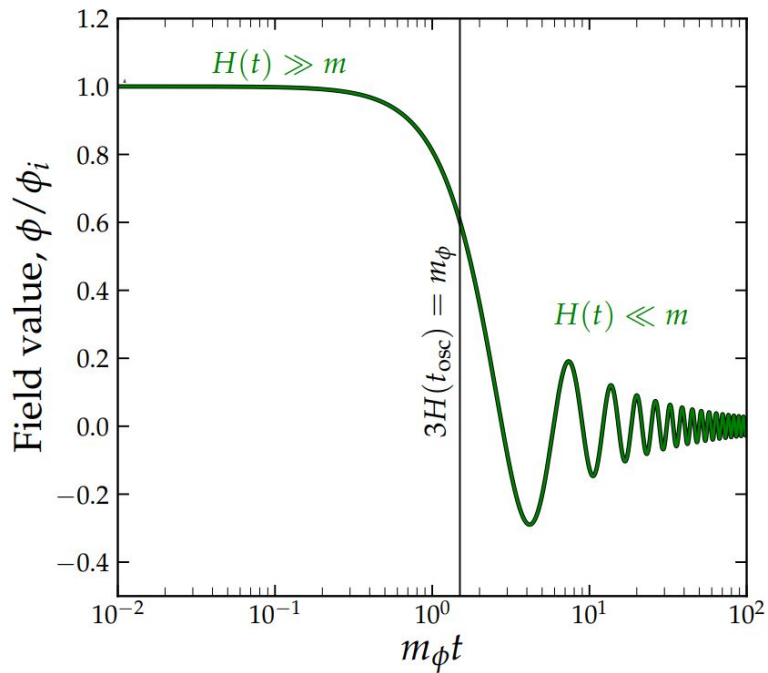
Our first ingredient is
Ultralight dark matter



$$m \ll 1 \text{ eV}$$

Non-thermal production: misalignment mechanism

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

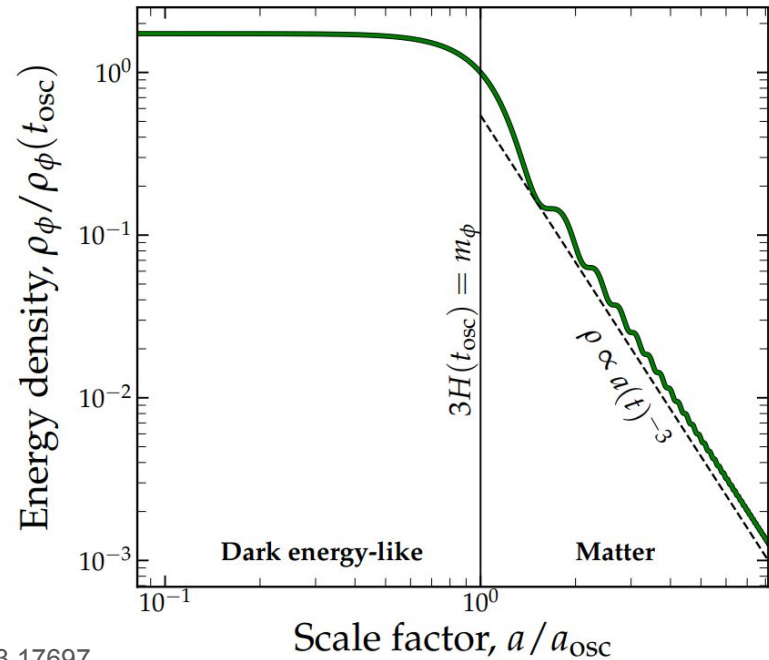
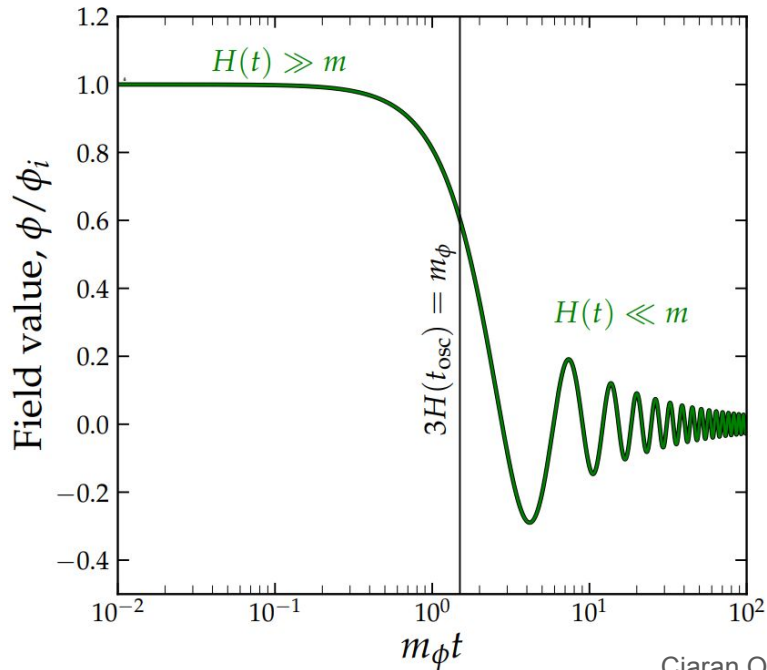


Non-thermal production: misalignment mechanism

Fast oscillations: vanishing pressure

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

$$p = \left\langle \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m_{\phi}^2\phi^2 \right\rangle = 0$$



Add **neutrinos**



coupled to ULDM



Neutrino mass from a background field

If we couple neutrinos to a *constant* pseudoscalar background field through

$$S = \int \sqrt{-\det g} d^4x \left(-\frac{1}{2} D_\mu \hat{\phi} D^\mu \hat{\phi} - \frac{1}{2} m_\phi^2 \hat{\phi}^2 + \bar{\psi} \left[iD - m_0 + ig\hat{\phi}\gamma^5 \right] \psi \right)$$

then neutrinos get an effective mass $m_\nu = \sqrt{m_0^2 + g^2 \phi^2}$

$$m_\nu = m_0$$



Neutrino masses
increase!



These couplings are hard to probe! There is a research interest looked for in time-dependent neutrino oscillations, but diagonal couplings cannot be observed there.

Sawyer [hep-ph/9809348]
Krnjaic et al. [1705.06740]
Choi et al. [2012.09474]
and many more!

Now add **an expanding universe**



and things go
wrong!

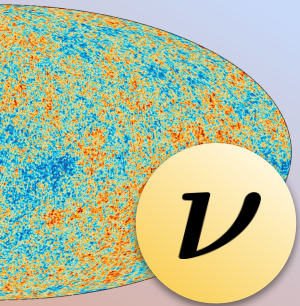
ULDM and mass-varying neutrinos

If the field is ULDM,
we could be able to explain
neutrino masses.

$$m_\nu \sim 0.06 \text{ eV}$$



ULDM and mass-varying neutrinos



$$m_\nu \sim 10 \text{ eV}$$

However, this predicts heavy neutrinos in early Universe observables, which would discard this explanation.

Berlin [1608.01307]
Sen, Smirnov [2306.15718]
Huang, Nath [2111.08732]

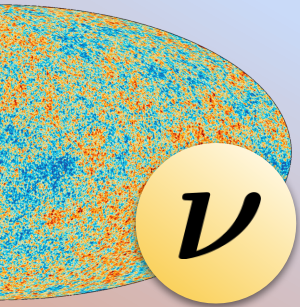
$$\rho_{\text{DM}} \sim a^{-3}$$
$$m_\nu \sim a^{-3/2}$$

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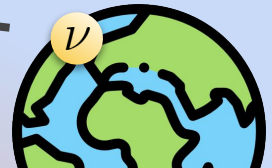
But this is naive!

Cosmo mass bounds are an *integrated* measurement, and there could be feedback from neutrinos to the scalar field.

$$\rho_{\text{DM}} \sim a^{-3}$$
$$m_\nu \sim a^{-3/2}$$

If the field is ULDM, we could be able to explain neutrino masses.

$$m_\nu \sim 0.06 \text{ eV}$$



The ULDM potential

In the standard case we only have

$$V(\phi) = \frac{1}{2}m_{\phi}^2\phi^2$$

The ULDM potential

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$$V(\phi) = \frac{1}{2}m_{\phi}^2\phi^2$$

but a coupling to neutrinos

$$\rho_{\nu} = \sqrt{p^2 + m^2 + g^2\phi^2}$$

is an energy expense for the system!

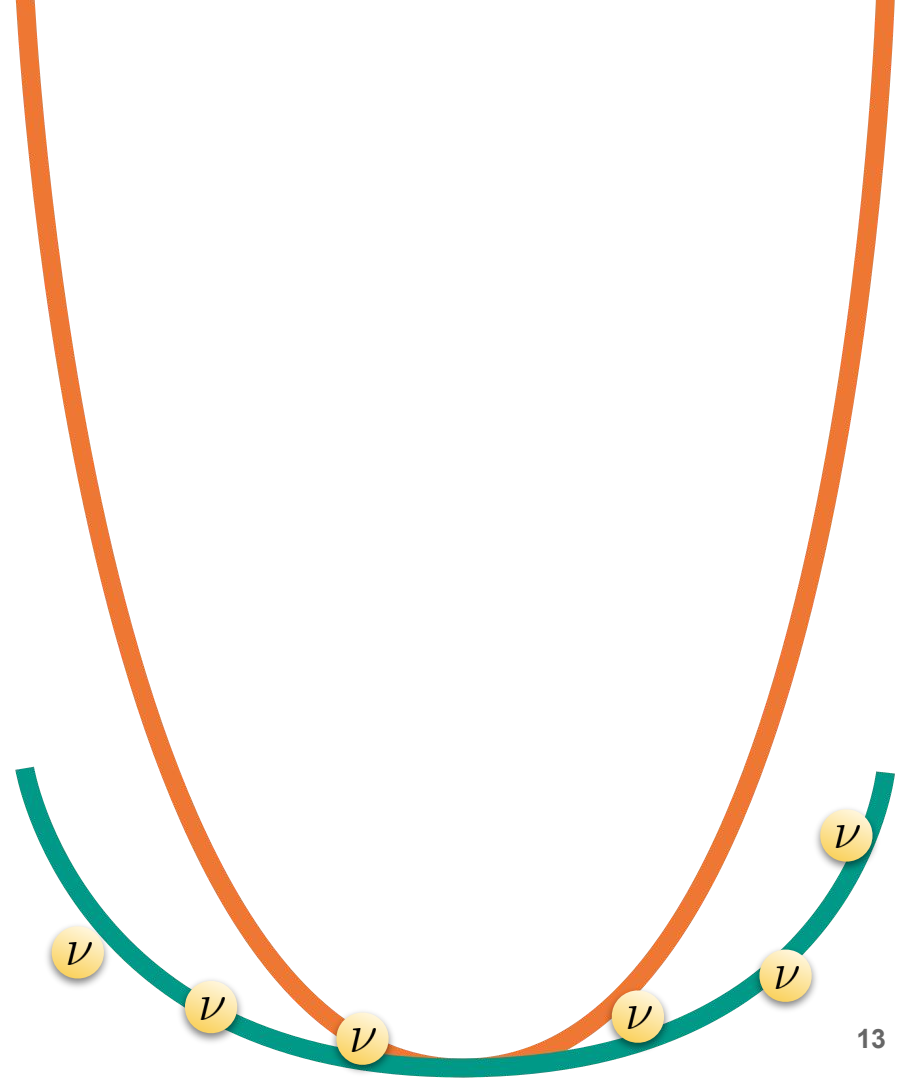


The ULDM potential

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2$$

$$\rho_\nu = \sqrt{p^2 + m^2 + g^2\phi^2}$$

The more neutrinos,
the narrower the potential.



The ULDM potential

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2$$

$$\rho_\nu = \sqrt{p^2 + m^2 + g^2\phi^2}$$

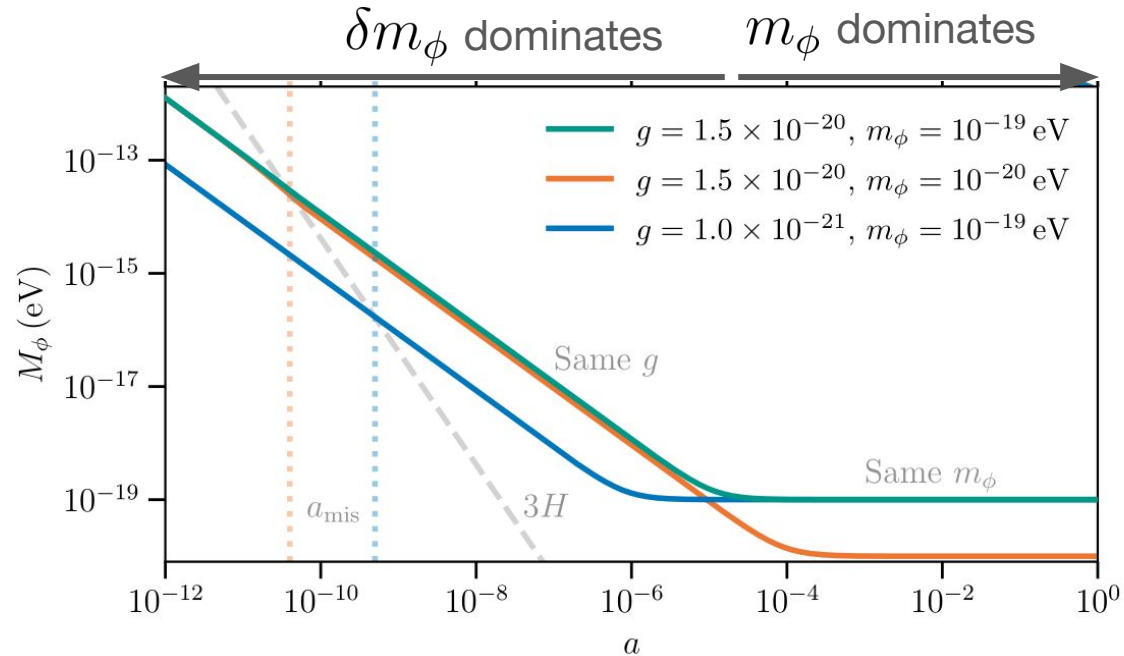
If the neutrino fluid is dense enough, ULDM dynamics are dominated by their interaction.



ULDM modified evolution

ULDM gets a time-dependent effective mass:

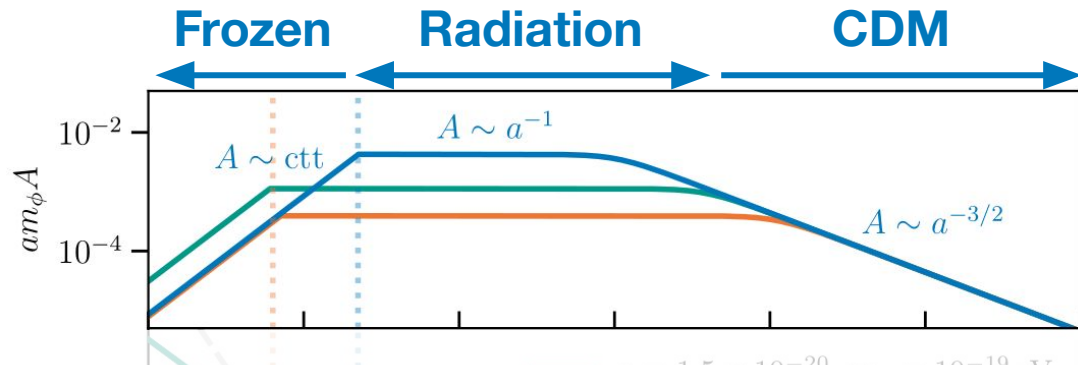
$$\delta m_\phi^2 = a^{-2} g^2 \mathfrak{g} \int 4\pi dq q^2 \frac{1}{\sqrt{q^2 + a^2 m_0^2}} f(q)$$



ULDM modified evolution

$$\delta m_\phi^2 = a^{-2}$$

$$g^2 \int 4\pi dq q^2 \frac{1}{\sqrt{q^2 + a^2 m_0^2}} f(q)$$



ULDM now behaves as **radiation**,

$$\rho_\phi = \delta m_\phi n_\phi \sim a^{-4}$$

Contributes to N_{eff} by BBN.

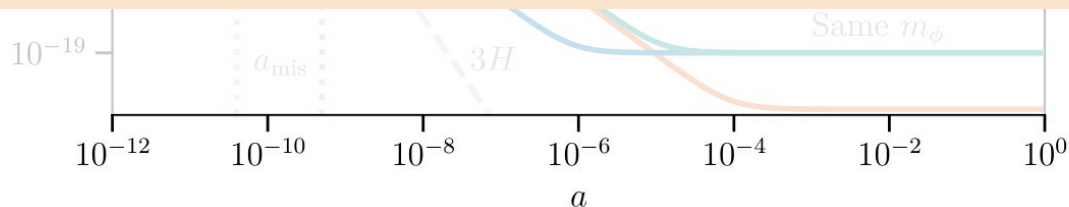
and scaling laws change!

$$m_\nu \propto A \sim a^{-1}$$

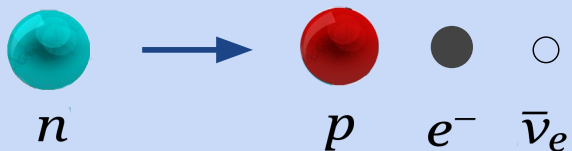
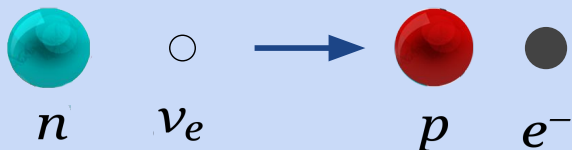
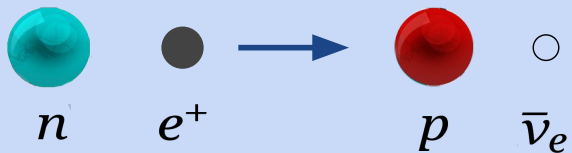
Cosmo bounds relax.

Pressure is modified too:

$$p(a) = \frac{1}{4} (\delta m_\phi^2 - \delta \mu_\phi^2) A^2 + p_\nu(a, 0).$$

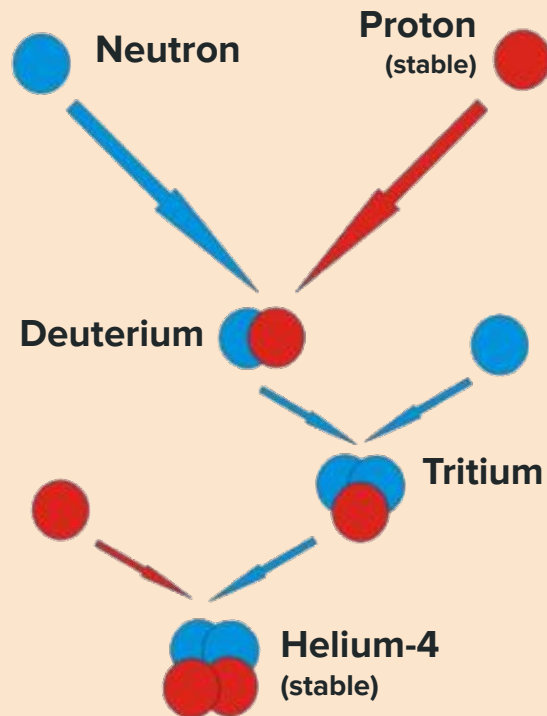


Neutrino masses reduce the available phase space of neutron-proton rates:



$$\Gamma_{n \rightarrow p} = \tilde{G}_F^2 \int_0^\infty dE_e E_e E_\nu^- \sqrt{E_e^2 - m_e^2} \sqrt{E_\nu^- - m_\nu^2} [f_\nu(E_\nu^-) f_e(-E_e) + f_\nu(-E_\nu^-) f_e(E_e)]$$

N_{eff} modifies the efficiency of nuclear rates at **Big Bang Nucleosynthesis**.

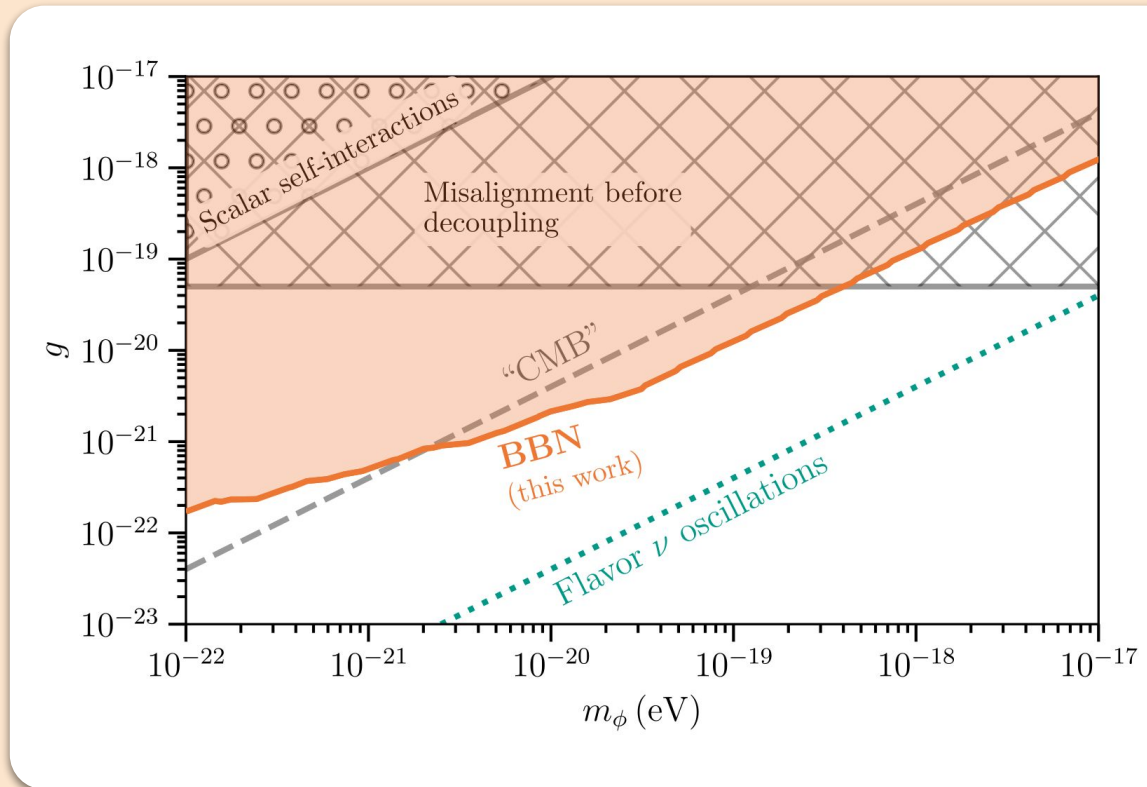


Competitive, consistent bounds

We improve over CMB bounds!

Even in regions where CMB bounds seem stronger, ours are results from a consistent and quantitative implementation: more robust!

This bound rules out neutrino masses coming from a direct coupling to ULDM.



Conclusion:
Cosmological coupled neutrino-ULDM is exciting!

We have developed a consistent formalism and placed competitive bounds.

There is room for improvement, since **BBN+CMB** might have more **constraining power**: it's necessary to understand ν -ULDM perturbations.

Further work also needed in understanding neutrino decoupling,
and applying the formalism to UV-complete models.



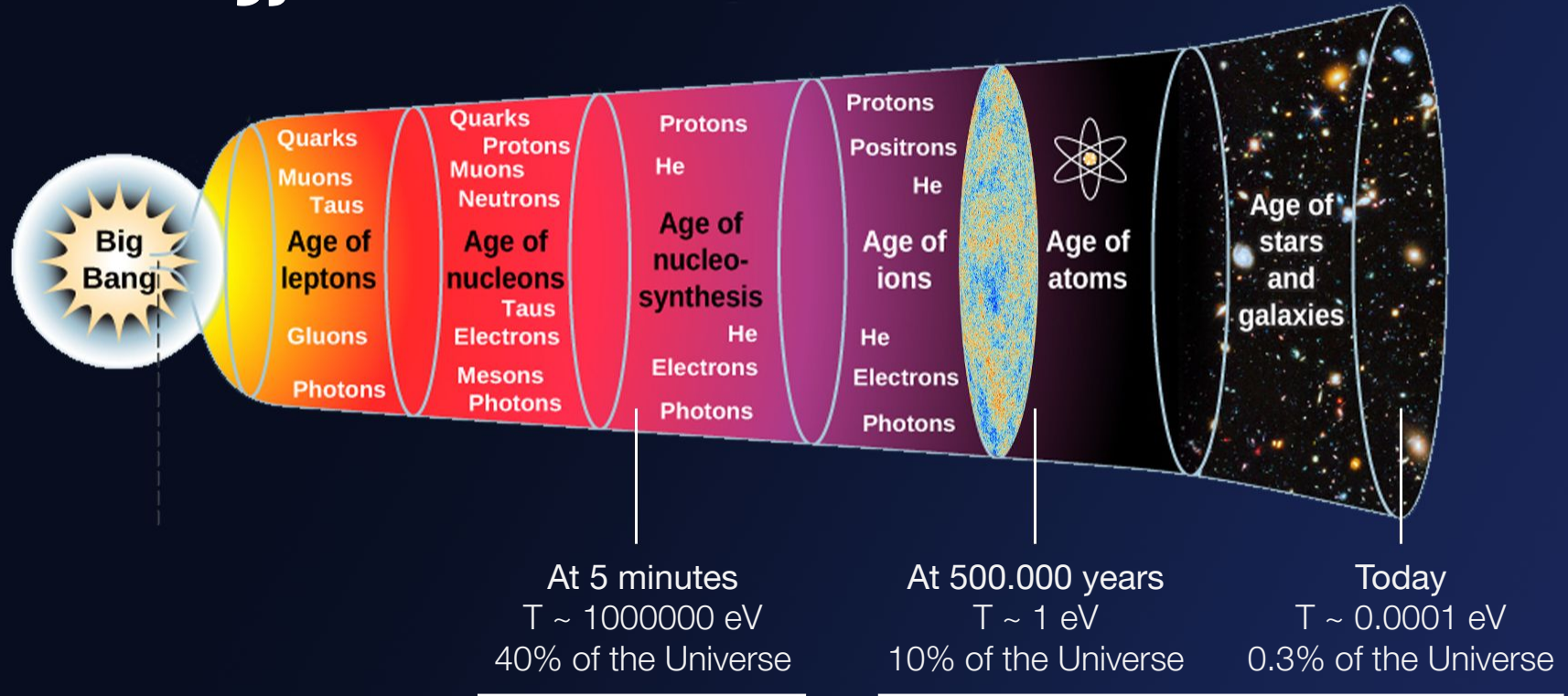
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Happy to be here, let's talk :)
Thank you!

Backup

Cosmology knows about neutrinos



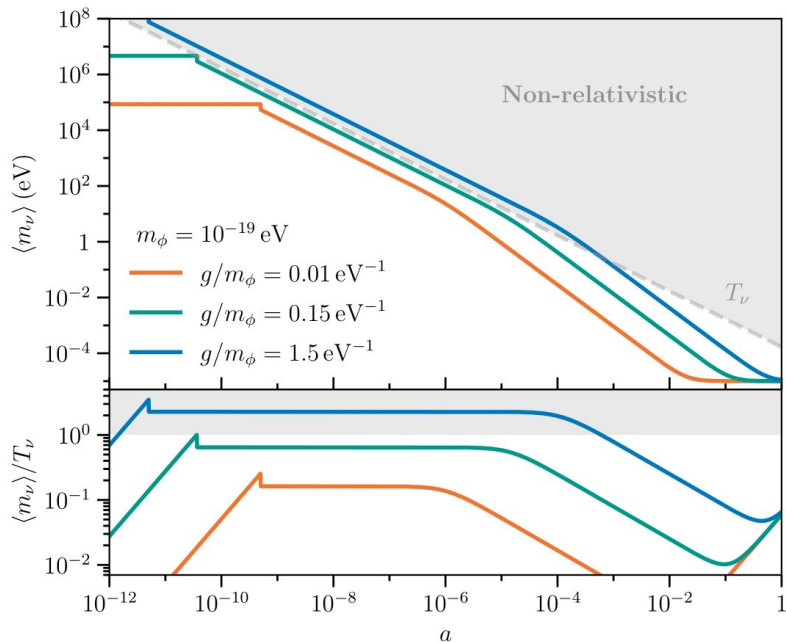
**The early Universe is
a powerful probe!**

$$\sum m_\nu \lesssim 0.12 \text{ eV}$$

Two pheno consequences

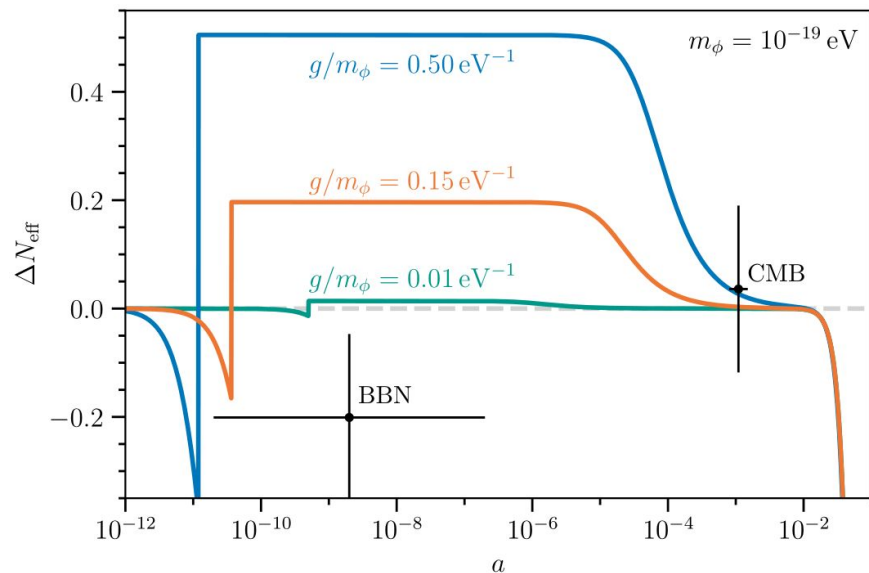
Neutrino mass scaling

The mass increase is relaxed. m_ν/T_ν is eventually constant and neutrino velocity saturates.



Relativistic dof

Converting CDM into radiation increases N_{eff} , specially at **Big Bang Nucleosynthesis (BBN)**.

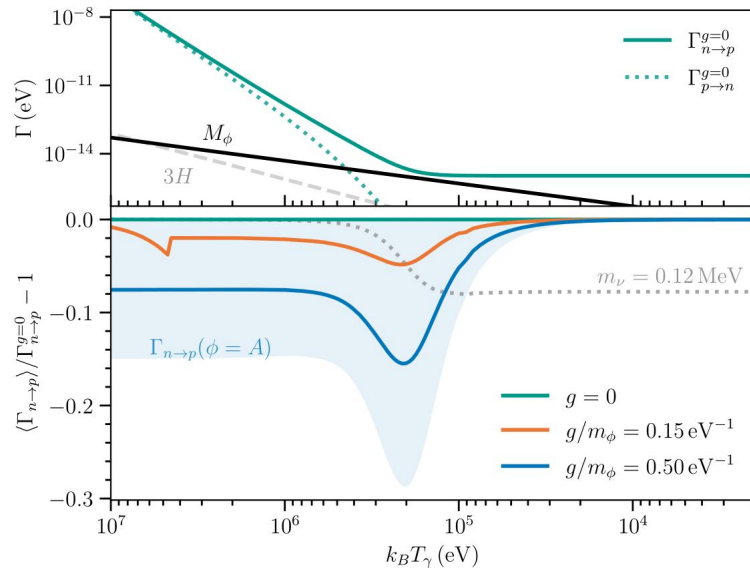


Consequences at Big Bang Nucleosynthesis

Interaction rates

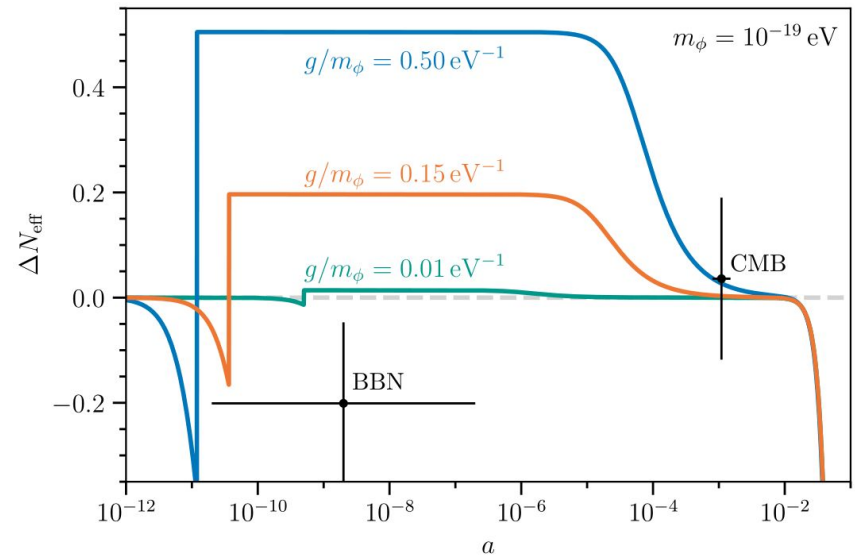
Neutrino masses reduce the available phase space of neutron-proton rates:

$$\Gamma_{n \rightarrow p} = \tilde{G}_F^2 \int_0^\infty dE_e E_e E_\nu^- \sqrt{E_e^2 - m_e^2} \sqrt{E_\nu^- - m_\nu^-} [f_\nu(E_\nu^-) f_e(-E_e) + f_\nu(-E_\nu^-) f_e(E_e)]$$



Relativistic dof

A larger N_{eff} increases $H(a)$ and the cooling of the Universe, shortening the production of heavier nuclei and making reactions less efficient.



Method

Boltzmann solver: modified CLASS

- Compute the amplitude of the ULDM field at every time: adiabatic approximation à la Landau.
- Average *all* cosmological quantities over oscillations of the field.
- Given $f_{\text{DM}} = 1$, compute $m_\nu(a)$ and $N_{\text{eff}}(a)$ at every scale factor.

BBN solver: modified PRyMordial

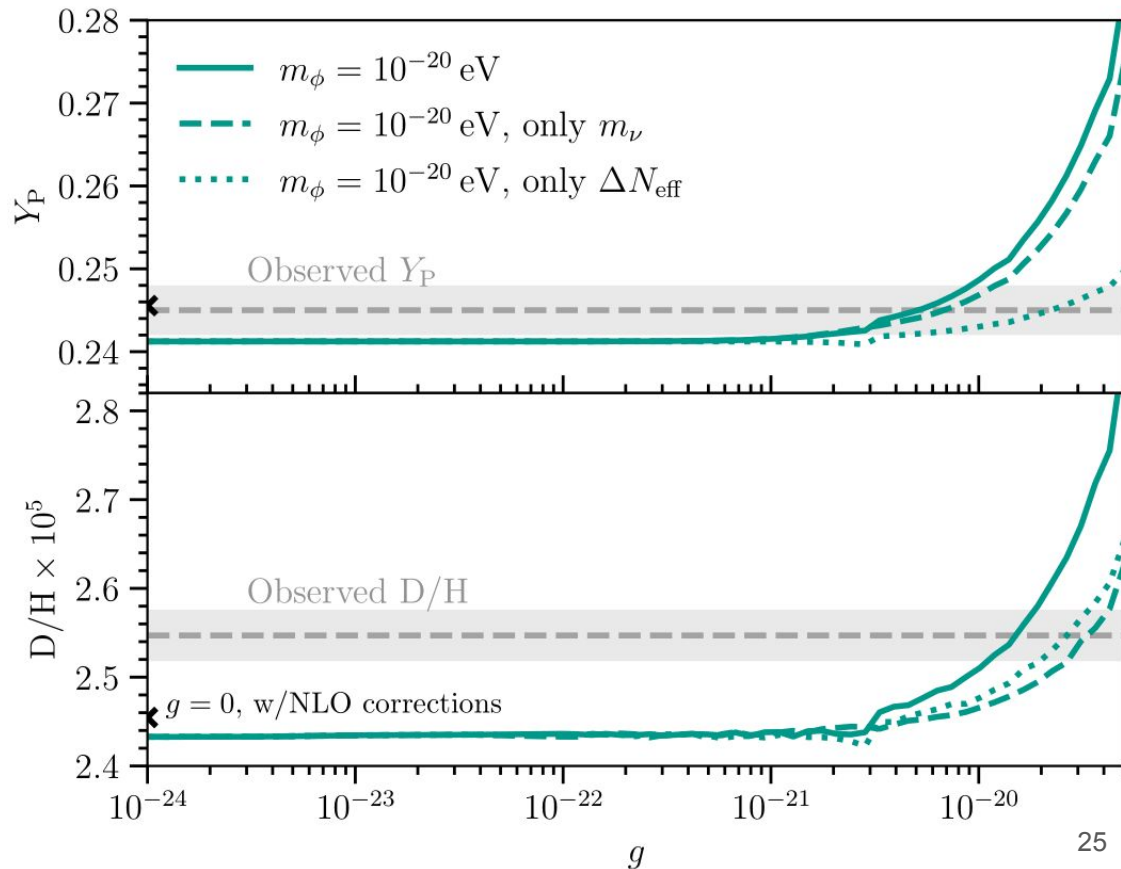
- **Assuming standard neutrino decoupling**, compute $T_\nu(a)$ to obtain $m_\nu(T_\nu)$ and $N_{\text{eff}}(T_\nu)$.
- Compute primordial element abundances for all parameters (g, m_ϕ) .
- Compare these abundances to helium-4 and deuterium observations using a simple χ^2 .

Modified predictions of elements

We introduce these modifications in BBN computations, and we can predict what are the primordial element abundances for the elements which we understand the better: helium-4 and deuterium.

We define a test statistic

$$\chi^2(g, m_\phi) = \left(\frac{Y_P(g, m_\phi) - Y_P^{\text{obs}}}{\sigma_{Y_P}} \right)^2 + \left(\frac{D/H(g, m_\phi) - (D/H)^{\text{obs}}}{\sigma_{D/H}} \right)^2,$$



Neutrino feedback and ULDM oscillations

To consistently analyze the cosmology of this model,

Take into account neutrino feedback.

If the field amplitude increases, neutrinos get mass.

This is **an additional potential** which modifies the dynamics of the ULDM field:

$$\ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{Bare potential}} + \underbrace{m_{\phi}^2\phi}_{\text{Interaction potential}} = -2g^2\phi \mathfrak{g} a^{-2} \int 4\pi dq q^2 \frac{1}{\sqrt{q^2 + a^2(m_0^2 + g^2\phi^2)}} f_0(q),$$

This evolution has a huge separation of scales:

- $E_{\nu} \gg m_{\phi}$: neutrino dynamics see the scalar field as constant at every time.
- $3H \ll m_{\phi}$: many oscillations happen within each cosmological time step!

To consistently analyze the cosmology of this model,

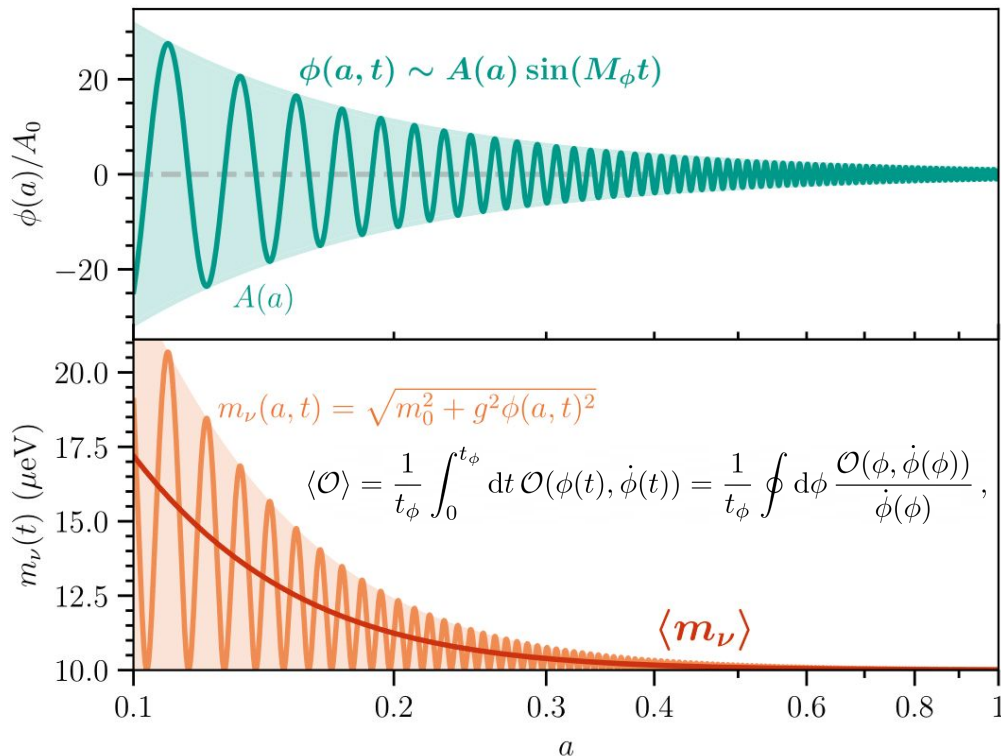
Take into account neutrino feedback.

If the field amplitude increases, this gives mass to neutrinos. This additional potential modifies the dynamics of the ULDM field.

Average over ULDM oscillations.

The instantaneous value of ULDM varies oscillates in timescales much shorter than cosmological time. We must average all cosmological observables over it.

(2509.22867) Neutrino feedback and ULDM oscillations



Ultralight Dark Matter

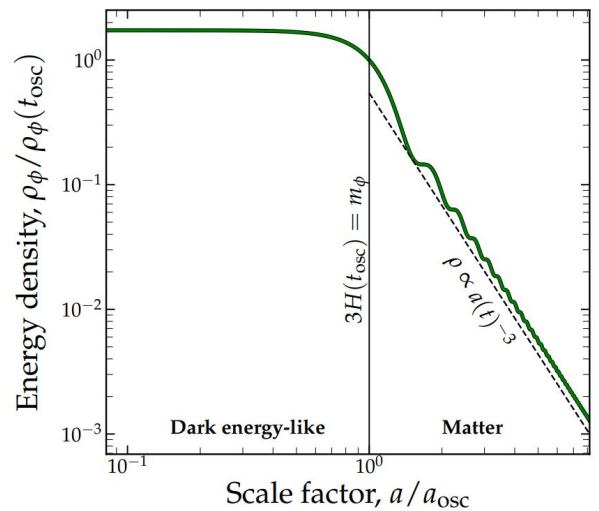
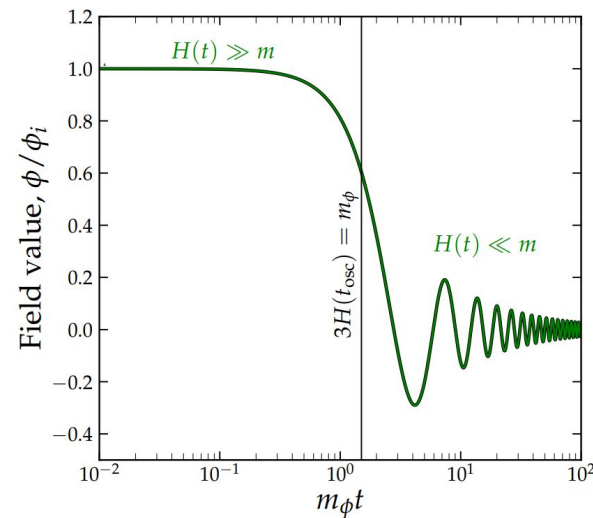
- Very light bosonic scalar field $m_\phi \lesssim \mu\text{eV}$, with
- huge occupation number $\mathcal{N} \gtrsim 10^{22}$, then
- can be understood as a classical field, with

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

This is a damped oscillator:

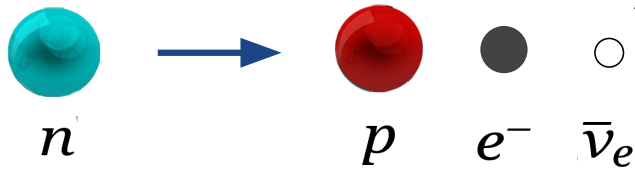
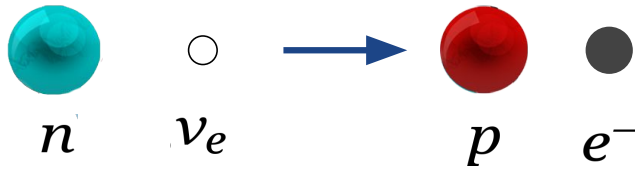
- For $3H \gg m_\phi$, the field is frozen (Dark Energy).
- For $3H \ll m_\phi$, the field begins to oscillate.

A rapidly oscillating field behaves as DM.



Big Bang Nucleosynthesis

It's the process by which protons and neutrons transform and interact in the early Universe to form the abundances of the lightest elements.



The amount of available neutrons affects the nucleons that we can form.

