A Win-Win Coupling: Alleviating the Hubble Tension in a Neutrino Early Dark Energy Model

Tina Kahniashvili, Sayan Mandal, Dylan McCauley, Abhinav Raghavan

Carnegie Mellon University

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Two Cosmological Puzzles

1. **The Hubble Tension (H_0)**
   - CMB measurements vs. local distance ladders disagree at $\sim 4\sigma$.
   - **Goal:** Inject Early Dark Energy (EDE) near matter-radiation equality to shrink the sound horizon.
2. **The Origin of Neutrino Mass**
   - Oscillations prove mass exists, but the origin of the scale ($\sum m_\nu \leq 0.12$ eV) is unknown.
   - **Goal:** Provide a dynamical mechanism that grows neutrino mass over cosmic time.

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[1] M. Kamionkowski and A. G. Riess, Ann. Rev. Nucl. Part. Sci. 73, 153 (2023).
[2] Y. Fukuda et al. (Super-Kamiokande), Phys. Rev. Lett. 81, 1562 (1998).

Neutrino-Assisted EDE (νEDE) & The Win-Win Scenario

We use a simple, **scale-free quartic potential**:

$$U(\phi) = \lambda\phi^4 \tag{1}$$

Coupling to the Cosmic Neutrino Background (CνB) dictates the effective mass:

$$m_\nu(\phi) = \mu\left(1 - \frac{\beta\phi^2}{\mu^2}\right) \tag{2}$$

The "Win-Win" Dynamic

While the field is frozen early on, neutrinos are forced to be **exactly massless** ($m_\nu = 0$). This protects the early universe from backreaction, allowing safe EDE injection.

[3] M. Carrillo González, Q. Liang, J. Sakstein, and M. Trodden, JCAP 04, 063 (2021).

System Dynamics & Equations of Motion

Thermal corrections to the potential ($\mathfrak{U}$):

$$\mathfrak{U} = \lambda\phi^4 + m_\nu(\phi)\langle\bar{\nu}\nu\rangle \tag{3}$$

Where the fermion bilinear $\langle\bar{\nu}\nu\rangle$ is defined as:

$$\langle\bar{\nu}\nu\rangle = \int \frac{d^3p}{(2\pi)^3} \frac{m_\nu(\phi)}{\sqrt{p^2 + m_\nu(\phi)^2}} \frac{1}{e^{p/T_\nu} + 1} = \frac{T_\nu^2 m_\nu(\phi)}{2\pi^2} \mathcal{F}\left(\frac{m_\nu(\phi)}{T_\nu}\right) \tag{4}$$

Exact, unapproximated equation of motion:

$$\ddot{\phi} + 3\tilde{H}\dot{\phi} = -4\lambda\phi^3 + \frac{2\beta\phi}{\mu} T_\nu^3 \mathcal{F}\left(\frac{m_\nu(\phi)}{T_\nu}\right) \tag{5}$$

Thermal Attractors in the High-Temperature Limit

For $T_\nu \gg m_\nu$, the effective potential simplifies:

$$\mathfrak{U} \approx \lambda\phi^4 + \frac{g\mu^2 T_\nu^2}{48}\left(1 - \beta\frac{\phi^2}{\mu^2}\right)^2 \tag{6}$$

This generates temperature-dependent **degenerate minima**:

$$\phi_\pm = \pm\sqrt{\frac{g\beta T_\nu^2\mu^2}{48\lambda\mu^2 + \beta^2 g T_\nu^2}} \tag{7}$$

Implication: The field is thermally trapped in these minima. Adiabatic tracking stabilizes the field, preventing premature rolling.

Constraining the Parameters

The bare parameters of the model are rigidly bounded by physical constraints, leaving only the initial field value to be phenomenologically determined:

- **Neutrino Coupling (β):** Fixed by requiring massless early neutrinos ($\beta = \mu^2/\phi_{init}^2$).
- **Self-Coupling (λ):** Fixed by the required $f_{EDE} \approx 10\%$ peak amplitude.
- **Initial Field (ϕ_{init}):** Phenomenologically tuned ($\sim 0.1 M_{Pl}$) to thaw exactly at $z_{eq} \approx 3400$.

Parameter	Symbol	Fiducial Value
Neutrino (bare) mass	μ	$0.10\,\mathrm{eV}$
Initial field value	ϕ_{init}	$\sim 3.5 \times 10^{26}\,\mathrm{eV}$
Neutrino coupling	β	$\sim 10^{-55}$
Scalar self-coupling	λ	$\sim 10^{-108}$

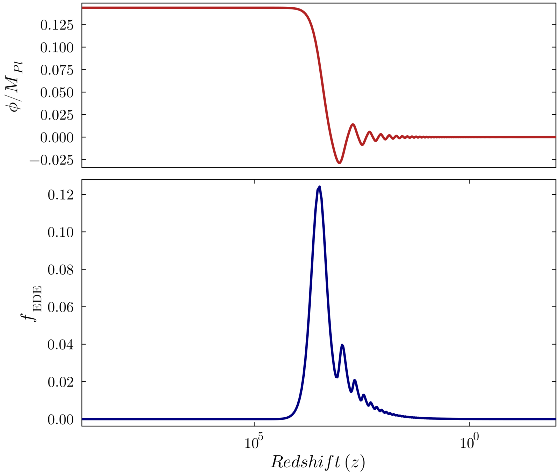
[4] M. Kamionkowski and A. Mathur, arXiv:2411.09747 (2024).

Results: Cosmological Evolution

Timeline of Injection:

- **Frozen Epoch:** Field trapped in thermal minima.
- **Trigger:** The threshold for field activation is reached
- **Peak:** The field starts rolling, and the EDE contribution actively dilutes.

Result: $\sim 10\%$ energy injection occurs naturally at $z \approx 3400$, easing the H_0 tension.

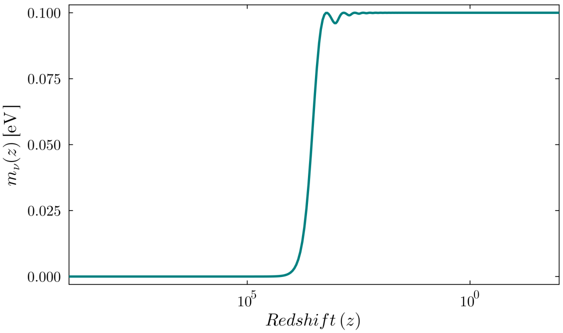


Results: Dynamical Origin of Neutrino Mass

Realizing the “Win-Win” synergy:

- $z > 3400$**:** Field sits at the mass root; $m_\nu = 0$.
- **Post-Trigger:** Field rolls to origin ($\phi \to 0$).
- **Late Universe:** $m_\nu(\phi)$ smoothly transitions to $\mu = 0.10$ eV.

Neutrino mass is a dynamical consequence of dark energy decay.



Results: The Stability Island

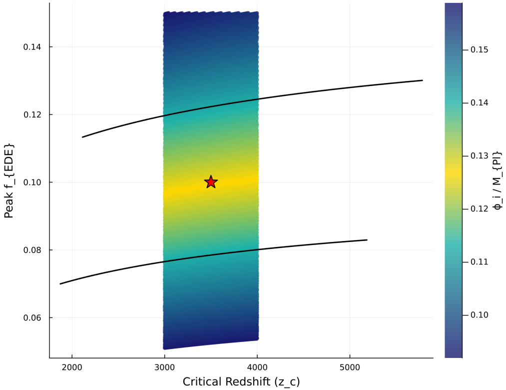
Addressing the "fine-tuning problem" of uncoupled EDE:

23% Parameter Window

Sub-Planckian conditions required to resolve the tension:

$$\phi_{init}/M_{pl} \in [0.112, 0.141]$$

Thermal corrections broaden the basin of attraction, mitigating the need for fine-tuning.



Concluding Remarks & Next Steps

Summary of Results:

- **Dual Resolution:** A single scalar field simultaneously eases the H_0 tension and provides a dynamical origin for neutrino masses.
- **Mitigated Fine-Tuning:** Thermal corrections from the CνB broaden the basin of attraction, creating a generous **23% stability window** for initial conditions.
- **Numerical Validation:** Field evolution confirmed via full integration of the equations of motion, avoiding standard analytical approximations.

Next Steps:

- **MCMC Sampling:** Performing full parameter space exploration to map νEDE constraints against the latest Planck and SH0ES data.
- **Large Scale Structure:** Investigating the impact of dynamical neutrino mass growth on the matter power spectrum (S_8 tension).

Acknowledgments

Thank You.

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Supplementary Slides

Supp 1: Computational Strategy

The Bottleneck: Standard ODE solvers require $\sim 10^5$ evaluations per timeline. A 400×400 parameter sweep demands 1.6×10^{10} expensive Fermi-Dirac integral solutions.

Algorithmic Optimization:

- **Cubic Spline Interpolation:** We pre-compute the dimensionless integrals $\mathcal{F}(y)$ and $\mathcal{D}(y)$ onto a high-resolution grid ($8,000$ nodes).
- $\mathcal{O}(1)$ **Complexity:** The solver performs 1D log-space lookups rather than active integration, reducing computation time by orders of magnitude.
- **High-Order Integration:** Implemented via the `Vern9` (Verner's 9th order) method for maximum stability during the field's "thawing" phase.

Result: Full cosmological histories simulate in milliseconds.

Supp 2: Computational Efficiency

Mapping the **23% stability window** required simulating over $160,000$ unique cosmic timelines.

Implementation Features (Julia):

- **Parallel Processing:** The 400×400 parameter grid is distributed across all CPU cores, allowing multiple universes to be simulated simultaneously.
- **GPU Integration:** `CUDA.jl` offloads the heavy Fermi-Dirac pre-computations to the graphics card, ensuring $\mathcal{O}(1)$ lookup times during ODE evolution.
- **High-Performance Libraries:** Leveraged the `DifferentialEquations.jl` ecosystem for fast, adaptive time-stepping without loss of precision.

Performance Impact:

- **Full Sweep Time:** ~ 1.9 minutes on a commercial laptop.
- **Throughput:** $> 1,400$ universes simulated per second.

Supp 3: Modified Hubble Dynamics

The field thaws when the potential curvature falls below the Hubble rate: $\left|\partial^2 \mathfrak{U}/\partial\phi^2\right| \approx 9\tilde{H}^2$.
We solve the augmented Hubble parameter exactly:

$$\tilde{H}^2 = H^2_{\Lambda\mathrm{CDM}} + \frac{8\pi}{3M^2_{\mathrm{Pl}}}\rho_{\mathrm{EDE}}$$

Total EDE Energy Density: We define ρ_{EDE} by subtracting the bare neutrino mass contribution (already in ΛCDM) from the coupled system:

$$\rho_{\mathrm{EDE}} = \underbrace{\frac{1}{2}\dot{\phi}^2 + \lambda\phi^4}_{\text{Scalar Field}} + \underbrace{T_\nu^4\left[\mathcal{D}\left(\frac{m_\nu(\phi)}{T_\nu}\right) - \mathcal{D}\left(\frac{\mu}{T_\nu}\right)\right]}_{\text{Neutrino Interaction Term}}$$

The $\mathcal{D}(y)$ Function: As discussed in Supp 1, we avoid slow numerical integration by pre-solving the energy density integral:

$$\mathcal{D}(y) = \frac{g}{2\pi^2}\int_0^\infty \mathrm{d}x\, \frac{x^2\sqrt{x^2+y^2}}{e^x+1}$$

Impact: This ensures $\rho_{EDE} \to 0$ at late times as the field settles, preserving agreement with late-time ΛCDM observations.