Title: Neutrino-Assisted Early Dark Energy: Theory and Cosmology

Speakers: Qiuyue Liang

Series: Cosmology & Gravitation

Date: December 13, 2022 - 11:00 AM

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Abstract: The tension between measurements of the Hubble constant obtained at different redshifts may provide a hint of new physics active in the relatively early universe, around the epoch of matter- radiation equality. A leading paradigm to resolve the tension is a period of early dark energy, in which a scalar field contributes a subdominant part of the energy budget of the universe at this time. This scenario faces significant fine-tuning problems which can be ameliorated by a non- trivial coupling of the scalar to the standard model neutrinos. These become non-relativistic close to the time of matter-radiation equality, resulting in an energy injection into the scalar that kick- starts the early dark energy phase, explaining its coincidence with this seemingly unrelated epoch. We present a minimal version of this neutrino-assisted early dark energy model, and perform a detailed analysis of its predictions and theoretical constraints. We consider both particle physics constraints -- that the model constitute a well-behaved effective field theory for which the quantum corrections are under control, so that the relevant predictions are within its regime of validity -- and the constraints provided by requiring a consistent cosmological evolution from early through to late times. Our work paves the way for testing this scenario using cosmological data sets.

Zoom link: https://pitp.zoom.us/j/95613703701?pwd=amlmNUdXdXFuQitFVk8xTnNwcDlMUT09

Neutrino-Assisted Early Dark Energy as a solution to Hubble tension

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2011.09895 M.C.González, **Q.Liang,** J.Sakstein, M.Trodden

Penn Arts & Sciences

—— Presentation for cosmology seminar at PI

Dec 13, 2022

Content

- Introduction to Hubble tension
  - Late time measurements (Supernovae; Quasars; Water Masers; Red Giants…)
  - Early time measurements (CMB; LSS…)
- Early Dark Energy (EDE) as an early time solution
- Neutrino-Assisted EDE
  - Model building; Cosmic evolution
  - Discussion

Hubble tension

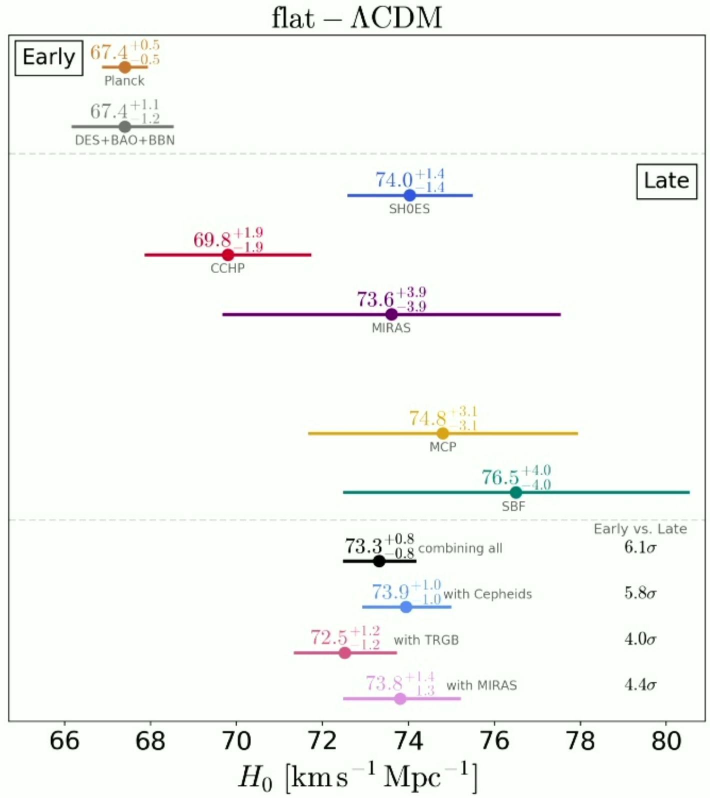
Local measurements

- Type Ia Supernovae & Cepheids; Standard Candle

  SH0ES, $H_0 = 74.0 \pm 1.4\ \mathrm{kms^{-1}Mpc^{-1}}$

- Quasars; Strong lensing time delay
- Gravitational waves; Standard Siren
- Local measurements combined to give

  $H_0 \approx 74.0\ \mathrm{kms^{-1}Mpc^{-1}}$



1907.10625, L. Verde, etc

Hubble tension

Early time measurements

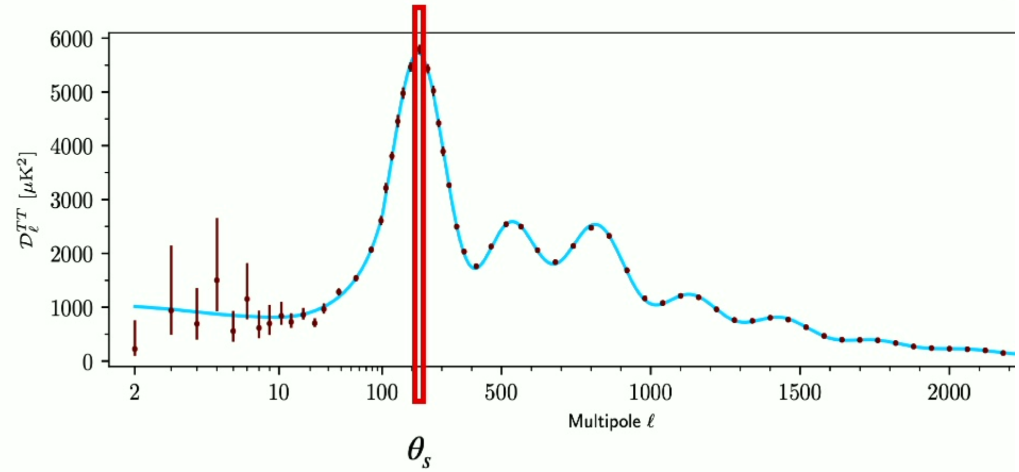
- Cosmic Microwave Background measurement

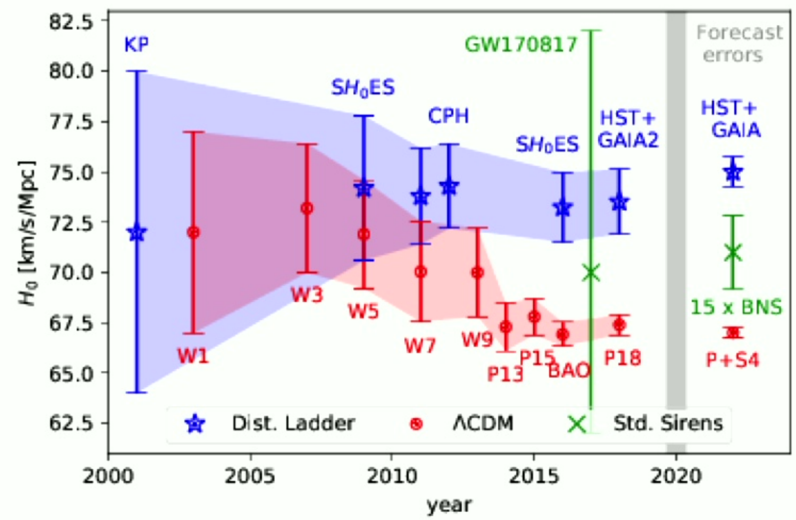
  Direct parameters:

  Sound horizon scale: θ_s

  Use ΛCDM model to fit H_0

- $H_0 \approx 67.0\ \mathrm{kms^{-1}Mpc^{-1}}$





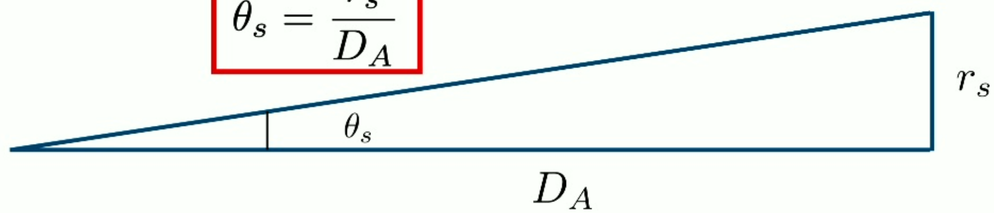
Solutions to the Hubble tension

- Observational issues: better resolution, new statistics for data analysis
- New physics!
- Late time solutions (post recombination): Modification of the Cepheid period-luminosity relation; Modify the distance ladder; H(z) wiggles ($z<3$)⋯
- Early time solutions (pre recombination): sound speed reduction; high temperature recombination; photon cooling; additional mass energy component⋯

Hubble tension

Early time measurements

$$\theta_s = \frac{r_s}{D_A}$$



- Sound horizon: $r_s(z_*) = \int_{z_*}^{z_{\rm re}} \frac{dz}{H(z)} c_s(z)$, where H is

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_{\rm rad}(1+z)^4 + \Omega_\Lambda + ...}$$

- Angular Distance to last scattering surface $D_A(z_*) = \int_0^{z_*} dz \frac{1}{H(z)} \propto H_0^{-1}$

Increasing energy density before recombination will decrease the sound horizon and lead to a larger H_0

$$H_0 \propto \frac{\theta_s}{r_s}$$

Model building

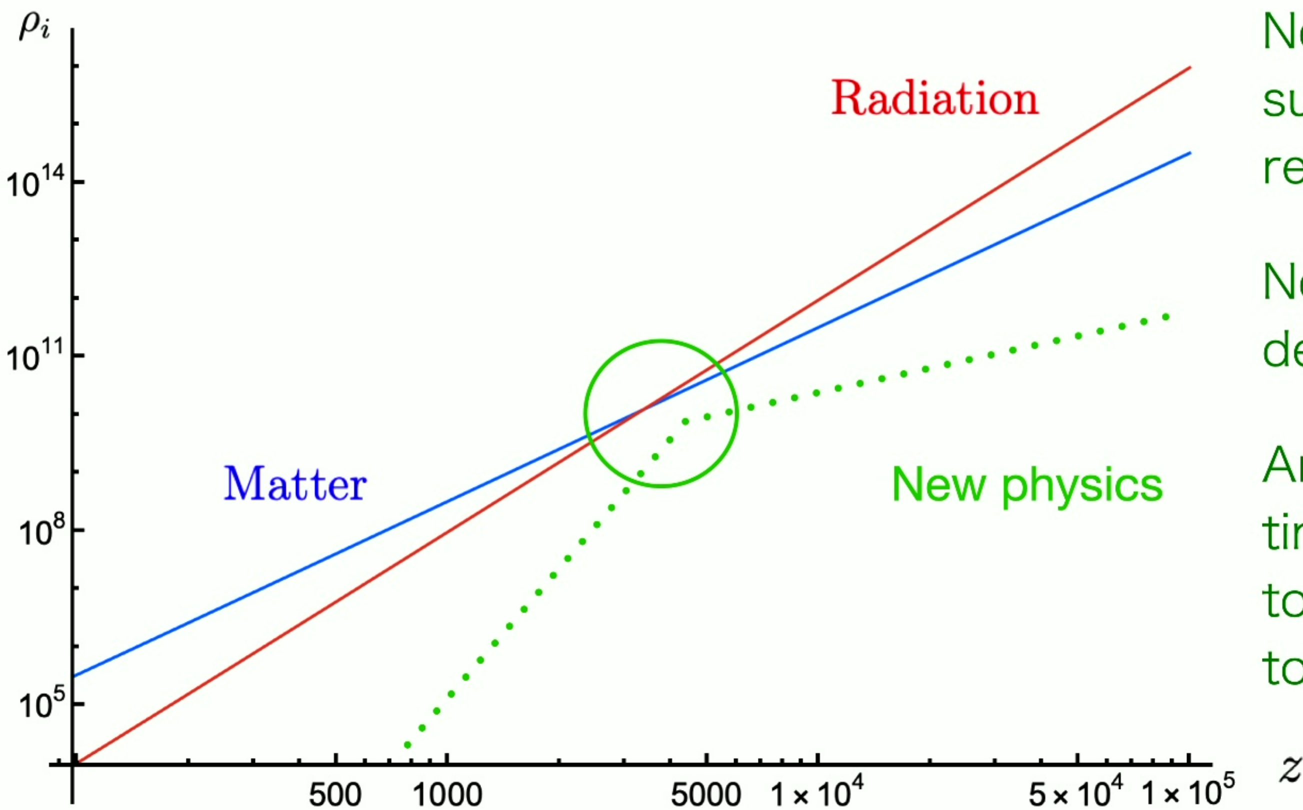
- Can we have extra radiation component?

  No, the relativistic species are tightly constrained

- Can we have extra matter component?

  No, the CMB constrained the energy density of matter

Model building



New physics should be subdominant before recombination;

New physics should also decay away quickly;

Around recombination time, it should contribute to around 10% of the total energy

Model building

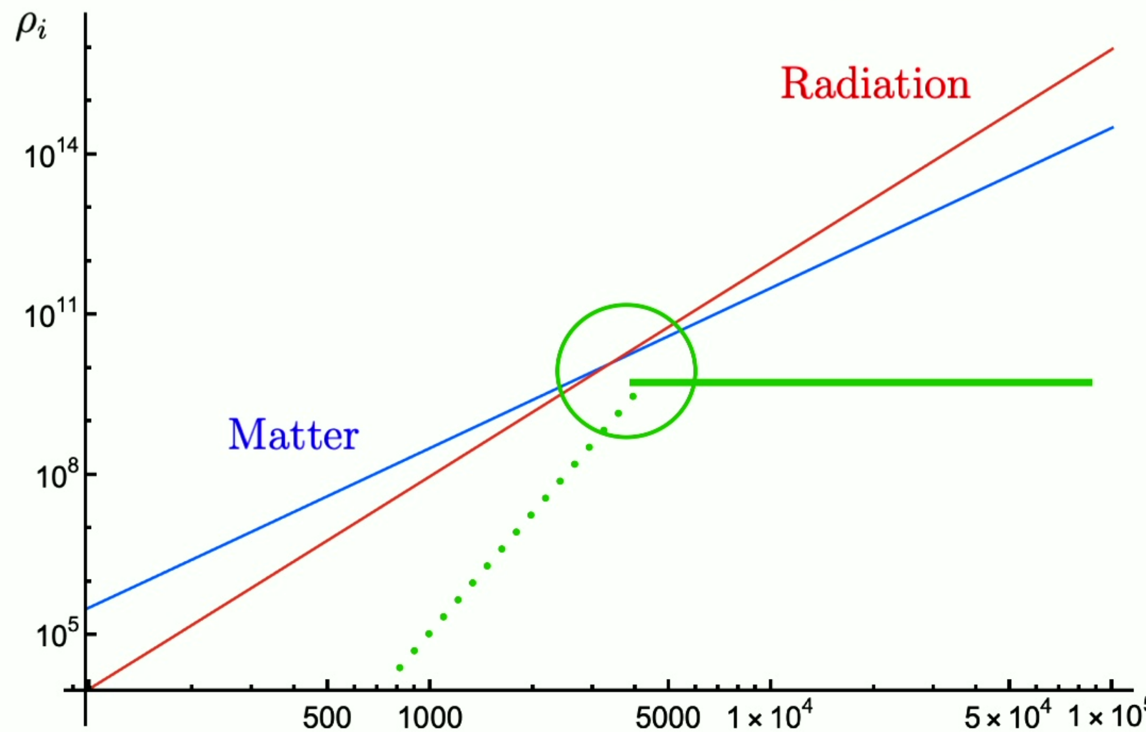
Try to write down a scalar field theory for the new physics:

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

The equation of motion:

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

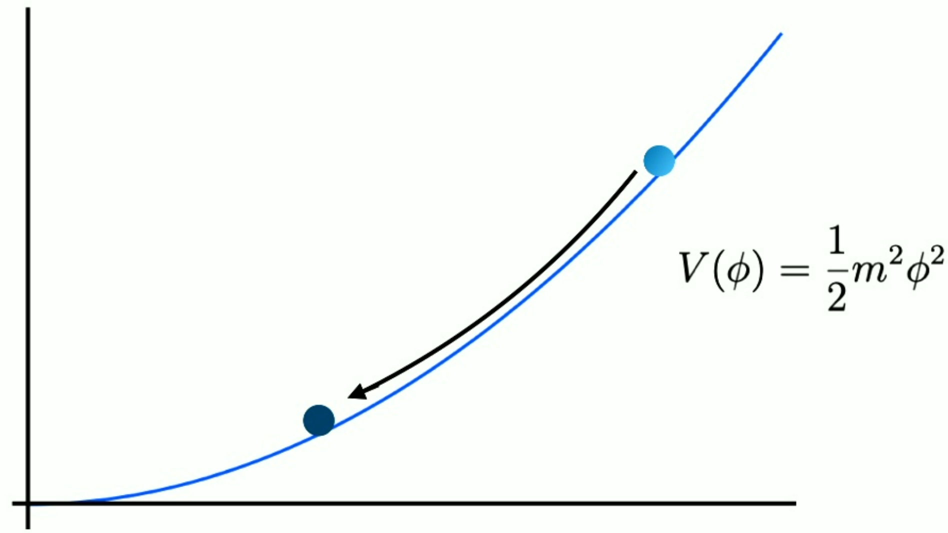
At early time, the Hubble friction will hold the field from rolling down



Model building

When Hubble rate decreases to the mass scale of the EDE, it starts to roll down the potential and gains kinetic energy

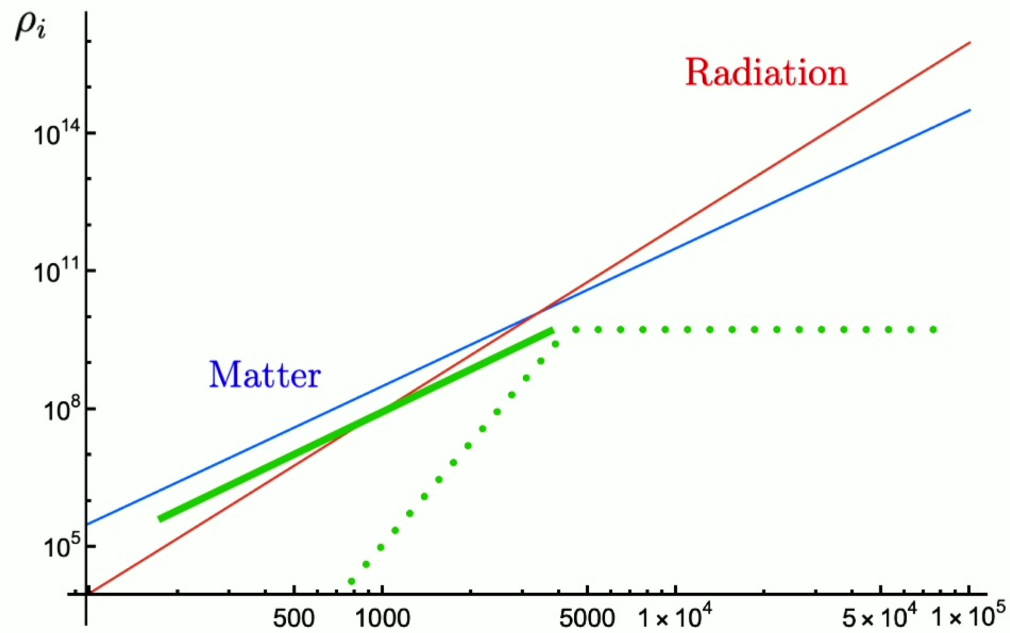
Around recombination, it can contribute to 10% of the total energy



Model building

However, it will behave like matter after the Matter-Radiation Equality!

We need something that decays faster! We need a flatter bottom for the potential.

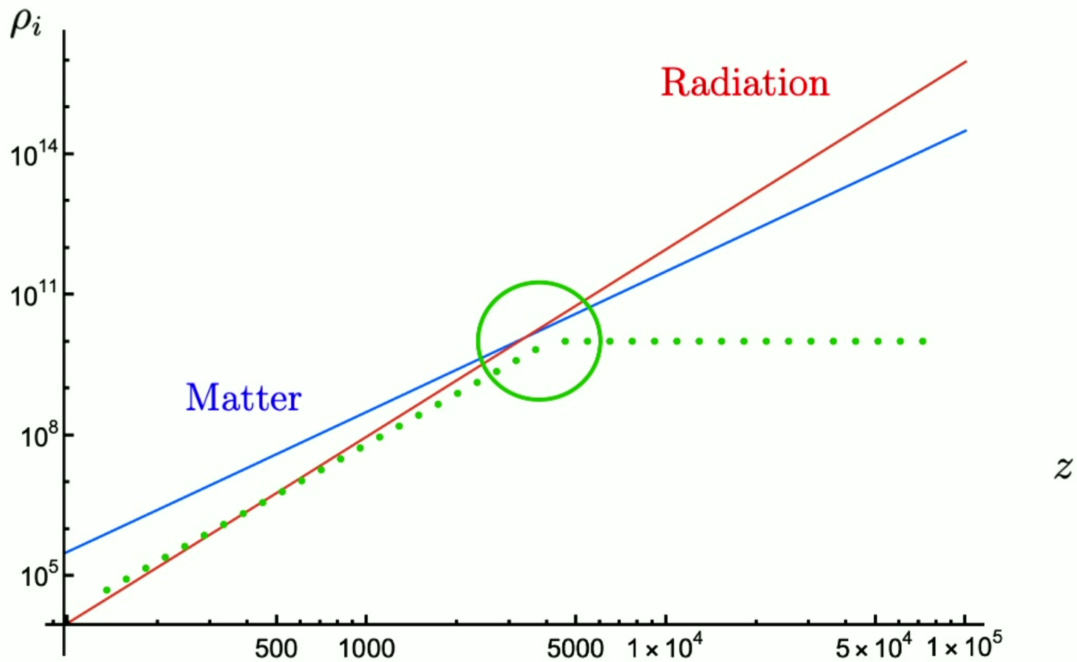


Model building

How about the self- interaction term?

$$V(\phi) = \frac{\lambda}{4}\phi^4$$

However, it's still not flat enough and does not fit the data very well



Early Dark Energy

Original EDE

Phys.Rev.Lett. 122 (2019) 22, 221301 • 1811.04083 V.Poulin, etc

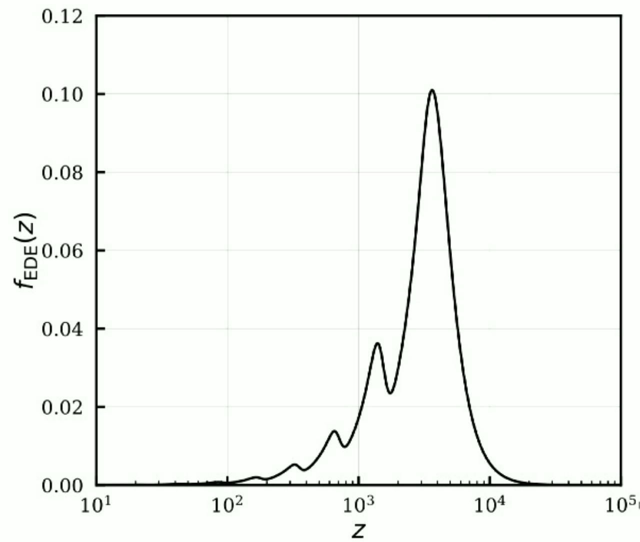
- One potential that fits data very well (n=3):

$$V_{\rm EDE} = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)^n$$

- At early time, the Hubble friction stops the field from rolling down the potential

- When Hubble rate decreases to the mass scale, the field starts to roll and gains kinetic energy

- After the recombination, it decays away faster than matter



Fractional energy, 2006.11235 M.M. Ivanov , etc

Early Dark Energy

Original EDE

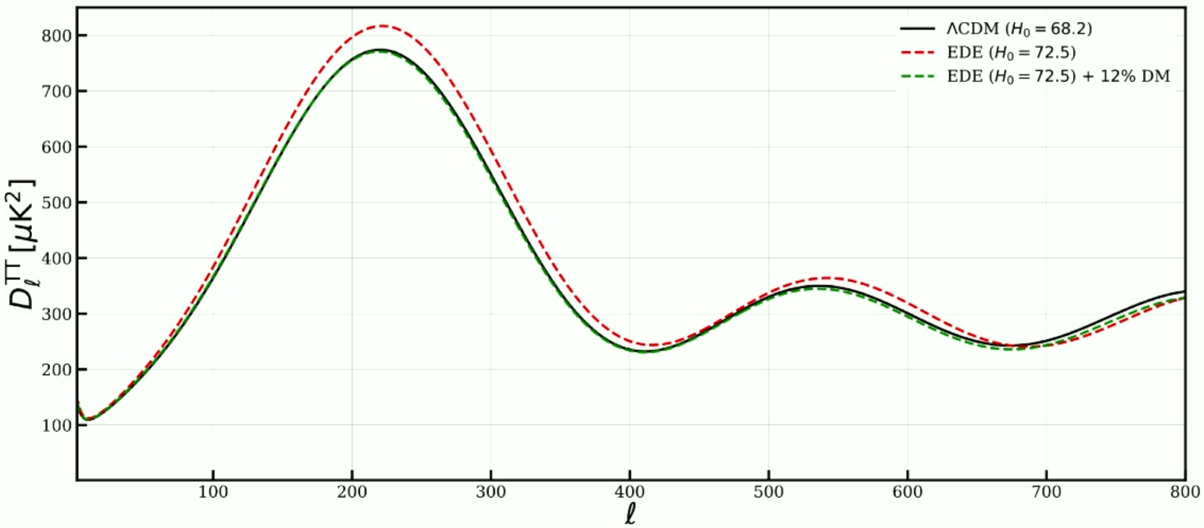
Phys.Rev.Lett. 122 (2019) 22, 221301 • e-Print: 1811.04083 V.Poulin, etc

- Advantages:
  when n = 3, it solves Hubble tension well;
  does not change the shape of damping tail in CMB;
  does not change $N_{\rm eff}$;
  it's a simple scalar field theory.

Early Dark Energy

Original EDE

- Disadvantage: need 12% more Dark Matter to fit Large Scale Structure data
- Drive the S8 tension in the wrong direction



e-Print: 2209.00011 E.McDonough[1], etc

Early Dark Energy

Original EDE

Phys.Rev.Lett. 122 (2019) 22, 221301 • e-Print: 1811.04083 V.Poulin, etc

- Two coincidence problems:
  - EDE has to have mass around $10^{-27}\mathrm{eV}$ to be active around recombination;
  - The initial conditions has to be fine tuned

Early Dark Energy

Original EDE

Phys.Rev.Lett. 122 (2019) 22, 221301 • e-Print: 1811.04083 V.Poulin, etc

- Two coincidence problems:
  - EDE has to have mass around $10^{-27}\mathrm{eV}$ to be active around recombination;
  - The initial conditions has to be fine tuned
- Can we relate it with physics that happened around recombination and make the model natural?

Neutrino-assisted Early Dark Energy

Model building

Phys.Rev.Lett. 124 (2020) 16, 161301 • e-Print: 1911.11760 [astro-ph.CO] J.Sakstein, M.Trodden

- Notice that the new physics become important around matter-radiation equality time, the trigger should also have characteristic behavior at energy scale around 0.3 eV

- The sum of the neutrino mass is order 0.1 eV.

- This suggests a coupling to neutrino might be a natural trigger. We call this neutrino-assisted early dark energy.

Neutrino-Assisted EDE

Model building

Phys.Rev.Lett. 124 (2020) 16, 161301 • e-Print: 1911.11760 [astro-ph.CO] J.Sakstein, M.Trodden

- The simplistic coupling one can write is a conformal coupling to neutrino sector: $S_{\tilde{\nu}}[\tilde{g}_{\mu\nu}]$ where $\tilde{g}_{\mu\nu} = e^{2\beta\frac{\phi}{M_{\rm pl}}} g_{\mu\nu}$

$$S = \int d^4x\sqrt{-g}\left[\frac{{M_{\rm pl}}^2}{2}R(g) - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi) + i\bar{\nu}\gamma^\mu\overleftrightarrow{\nabla}_\mu\nu - m_\nu\left(1 + \beta\frac{\phi}{M_{\rm pl}} + \cdots\right)\bar{\nu}\nu\right]$$

- The effective potential of EDE is: $V_{\rm eff}(\phi) \equiv V(\phi) - \beta\Theta(\nu)\frac{\phi}{M_{\rm pl}},$

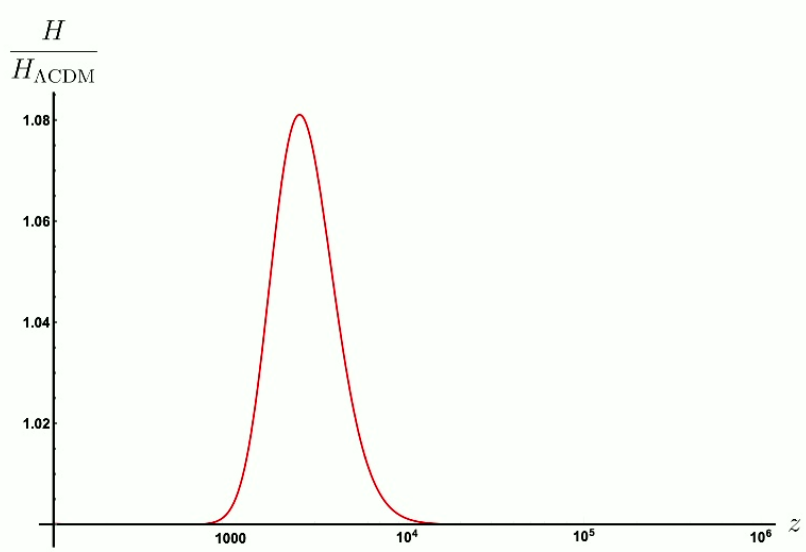
- $\Theta(\nu) = g_{\mu\nu}\Theta(\nu)^{\mu\nu} \equiv -\frac{2}{\sqrt{-g}}g_{\mu\nu}\frac{\delta S_\nu[g_{\mu\nu}]}{\delta g^{\mu\nu}} = -\rho_\nu + 3p_\nu$ is the trace of neutrino's energy momentum tensor computed by Fermi-Dirac distribution

Neutrino-Assisted EDE

Model building

Phys.Rev.Lett. 124 (2020) 16, 161301 • e-Print: 1911.11760 [astro-ph.CO] J.Sakstein, M.Trodden

- Then you could solve the EoM and find a peak in the scalar field and it induces a peak for Hubble constant



$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \frac{\beta}{M_{\mathrm{Pl}}}(\rho_\nu - 3P_\nu)$$

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_{\mathrm{rad}}(1+z)^4 + \Omega_\Lambda + \Omega_\phi(z)}$$

Neutrino-Assisted EDE

Model building

JCAP 04 (2021) 063 • e-Print: 2011.09895 [astro-ph.CO] M.C.González, **Q.Liang,** J.Sakstein, M.Trodden

- However, the simple coupling has some issues that I'm going to address.
- In the rest of the talk, I will discuss our paper and explore the details.
- I will show you how the simple coupling breaks the perturbation rules at high redshift and how we solve it by building a coupling within the effective filed theory.

Neutrino-Assisted EDE

Model building

JCAP 04 (2021) 063 • e-Print: 2011.09895 [astro-ph.CO] M.C.González, **Q.Liang,** J.Sakstein, M.Trodden

- For an effective potential $V_{\text{eff}}(\phi) \equiv \frac{\lambda}{4}\phi^4 - \beta\frac{\phi}{M_{\text{pl}}}(3p_\nu - \rho_\nu)$,

  the filed stays in the minimum

$$|\phi_{\text{min}}| = \left[\frac{\beta}{\lambda M_{\text{pl}}}(3P_\nu - \rho_\nu)\right]^{\frac{1}{3}} .$$

- The trace grows with redshift:

$$|3P_\nu - \rho_\nu| \sim m_\nu^2 T_\nu^2 \sim (1+z)^2$$

Neutrino-Assisted EDE

Model building

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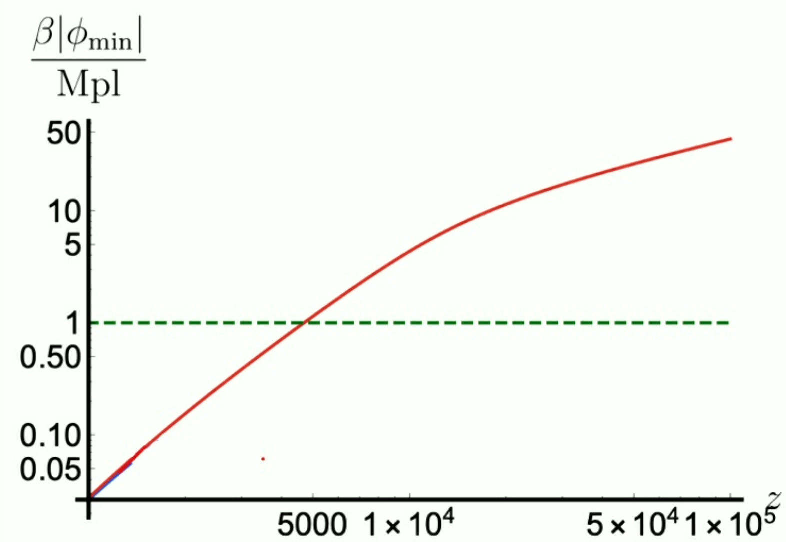

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Neutrino-Assisted EDE

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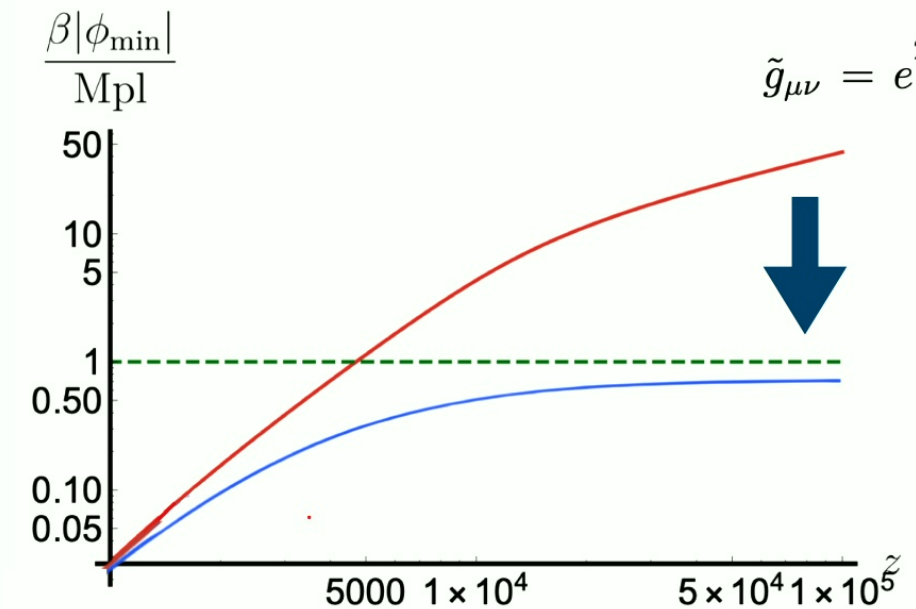

$$\tilde{g}_{\mu\nu} = e^{2\beta\frac{\phi}{M_{\rm pl}}} g_{\mu\nu} \qquad |\phi_{\min}| = \left[\frac{\beta}{\lambda M_{\rm pl}}\left(3P_\nu - \rho_\nu\right)\right]^{\frac{1}{3}}$$

Neutrino-Assisted EDE

Model building

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- We introducing the new coupling $\tilde{g}_{\mu\nu} = A(\phi)^2 g_{\mu\nu}$

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R(g) - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4}\phi^4 + i\bar{\nu}\gamma^\mu \overleftrightarrow{\nabla}_\mu \nu - m_\nu A(\phi)\bar{\nu}\nu\right]$$

- At late time, the coupling goes back to the simple linear one: $\ln[A(\phi)] \approx \dfrac{\beta\phi}{M_{\rm pl}}$

- At early time EDE has a minimum set by $A(\phi)$, where we can construct the coupling like $A(\phi) = 1 - \dfrac{A_2}{2}\bar{\phi}^2 + \dfrac{A_2}{2}\left(\phi + \bar{\phi}\right)^2 + \cdots$

Neutrino-Assisted EDE

Model building

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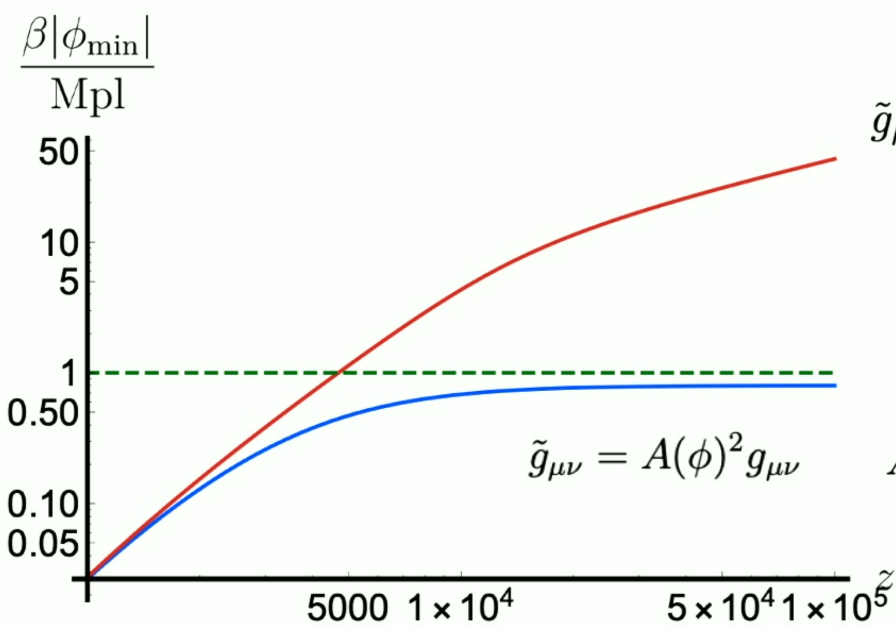
- 

$$\tilde{g}_{\mu\nu} = e^{2\beta\frac{\phi}{M_{\rm pl}}} g_{\mu\nu}$$

$$\tilde{g}_{\mu\nu} = A(\phi)^2 g_{\mu\nu}$$

$$A(\phi) = 1 - \frac{A_2}{2}\bar{\phi}^2 + \frac{A_2}{2}\left(\phi + \bar{\phi}\right)^2 + \cdots$$

Neutrino-Assisted EDE

Model building

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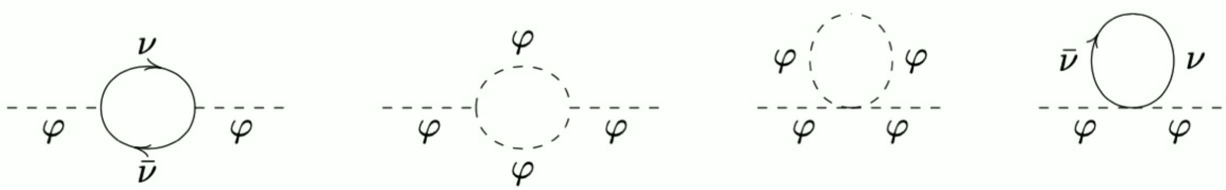
- We now try to find a minimal model for the potential, again we start with a mass term.

- The mass of EDE cannot be too light, otherwise it cannot protect the theory from the quantum corrections of neutrino loop



- The bare mass has to satisfy: $m_{\rm bare} \gtrsim \frac{\beta}{2\pi}\left(\frac{m_\nu}{M_{\rm pl}}\right) m_\nu \sim 1.5\times 10^{-27}\left(\frac{\beta}{100}\right)\left(\frac{m_\nu}{0.3{\rm eV}}\right)^2 {\rm eV}.$

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Model building

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- However, a simple mass term is not enough.
- A pure mass term leads to Ω_ϕ approaching a constant at early time.

Neutrino-Assisted EDE

Model building

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- However, a simple mass term is not enough.
- A pure mass term leads to Ω_ϕ approaching a constant at early time.
- We have to include EDE self-interaction term. Consider the $\mathbb{Z}_2$ symmetry, the simplest potential we can have is $V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4$

Neutrino-Assisted EDE

Model building

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- $$\phi_{\text{min}} = -\bar{\phi}$$

$$\downarrow$$

$$\phi_{\text{min}} = \left(\frac{\beta}{\lambda M_{pl}}(3P_\nu - \rho_\nu)\right)^{\frac{1}{3}}$$

$$\downarrow$$

$$\phi_{\text{min}} = -\left(\frac{\beta \rho_\nu}{M_{\text{pl}} m^2}\right)$$

- At early time EDE has a minimum set by $A(\phi)$
- The coupling goes to the linear approximation
- When the trace redshifts to the same scale as the self interaction term, both $\frac{\lambda}{4}\phi^4$ and neutrino coupling contribute to the minimum
- At late time, the mass term dominates and the pressure of neutrino is negligible

Neutrino-Assisted EDE

Model building

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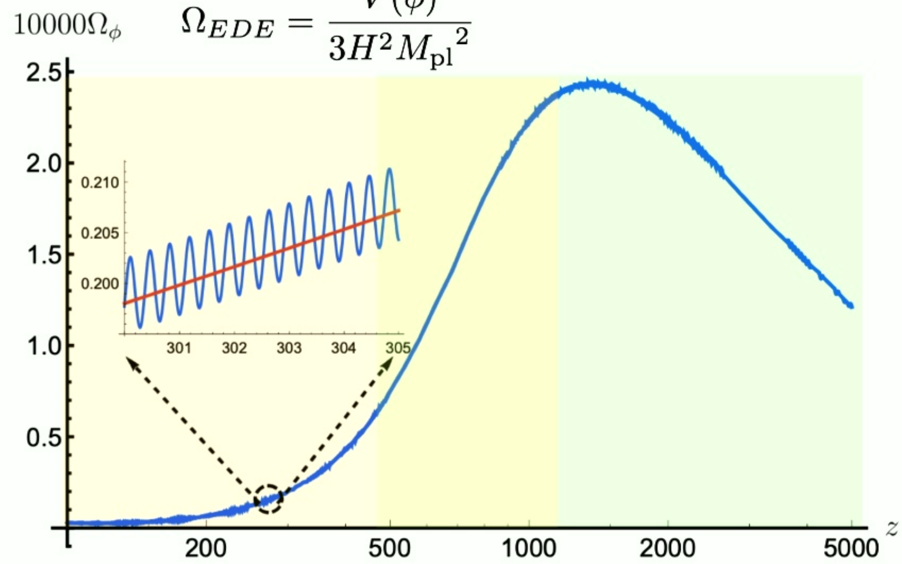
$$\Omega_{EDE} = \frac{V(\phi)}{3H^2 {M_{\rm pl}}^2}$$

- $$\phi_{\rm min} = \left(\frac{\beta}{\lambda M_{pl}}(3P_\nu - \rho_\nu)\right)^{\frac{1}{3}}$$

↓

$$\phi_{\rm min} = -\left(\frac{\beta \rho_\nu}{M_{\rm pl} m^2}\right)$$



$$m = 1.63 \times 10^{-26}\text{eV},\ \lambda = 10^{-98}, \beta = 500,\ \text{and}\ m_\nu = 0.3\text{eV}$$

Neutrino-Assisted EDE

Cosmic evolution

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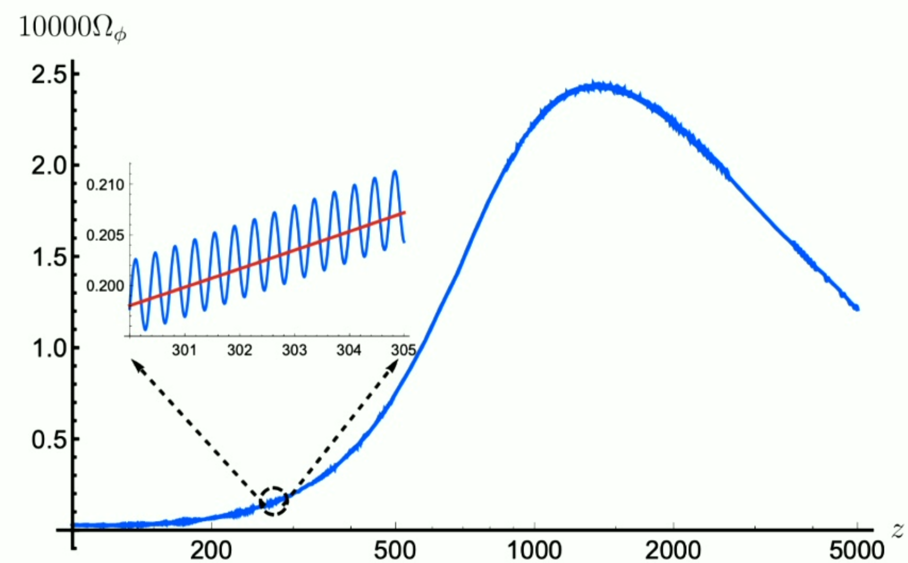
- Perturbation $\delta\phi = \phi - \phi_{min}$

  behaves like matter.

- Minimum would contribute as part of cosmological constant:

$$\rho_{\rm DE} \approx \Lambda {M_{\rm pl}}^2 + \frac{1}{2} m^2 \phi^2_{\rm min}(t).$$



$$m = 1.63 \times 10^{-26}{\rm eV},\ \lambda = 10^{-98}, \beta = 500,\ \text{and } m_\nu = 0.3{\rm eV}$$

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Numerical verification

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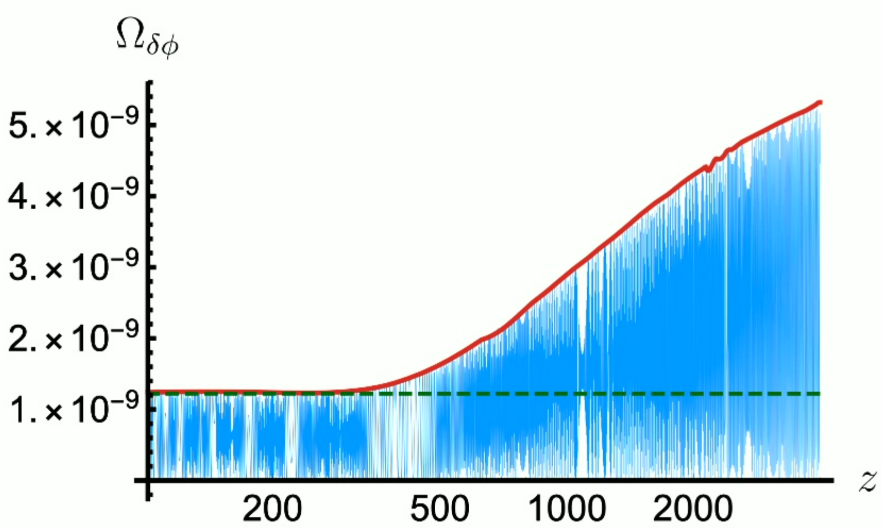
- Matter density approach a constant



$m = 1.63 \times 10^{-26}\text{eV}, \ \lambda = 10^{-98}, \beta = 500, \ \text{and} \ m_\nu = 0.3\text{eV}$

- The potential is,

$$V(\delta\phi) = \frac{\lambda}{4}\delta\phi^4 + \lambda\delta\phi^3\phi_{\rm min} + \frac{3\lambda}{2}\delta\phi^2\phi_{\rm min}^2 + \frac{m^2}{2}\delta\phi^2.$$

The equation of motion is

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

The energy density is

$$\Omega_{\delta\phi} \equiv \frac{\frac{1}{2}\dot{\delta\phi}^2 + V(\delta\phi)}{3H^2{M_{\rm pl}}^2}$$

Neutrino-Assisted EDE

Numerical verification

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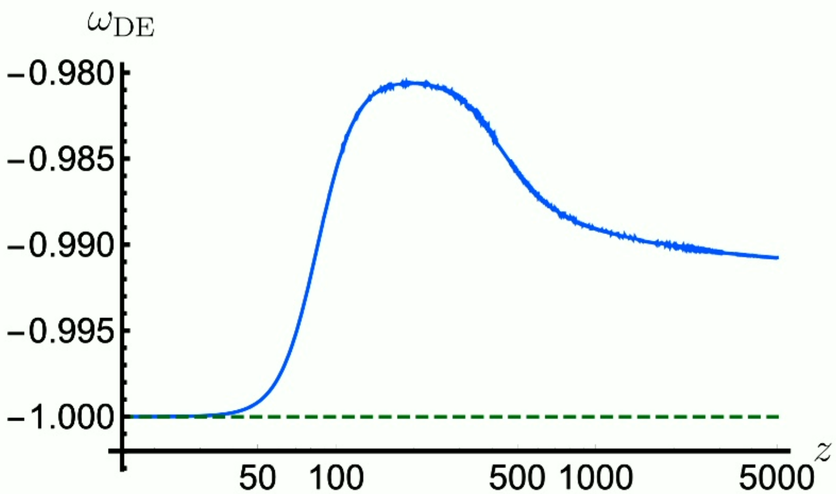
- Equation of state goes back to -1



$m = 1.63 \times 10^{-26}\text{eV},\ \lambda = 10^{-98}, \beta = 500,\ \text{and}\ m_\nu = 0.3\text{eV}$

- The total energy satisfy the continuity equation

$$\dot\rho_{\rm DE} + 3H(\rho_{\rm DE} + P_{\rm DE}) = 0$$

The equation of state is

$$\omega_{\rm DE} = \frac{P_{\rm DE}}{\rho_{\rm DE}} = -1 - \frac{m^2 \phi_{\rm min} \dot\phi_{\rm min}}{3H {M_{\rm pl}}^2 \Lambda}$$

$$= -1 + 3 \times 10^{-12} \beta^2 \frac{\Omega^2_{\nu,0}}{\Omega_{\Lambda,0}} \left(\frac{10^{-27}\ \text{eV}}{m}\right)^2$$

Neutrino-Assisted EDE

Parameter space

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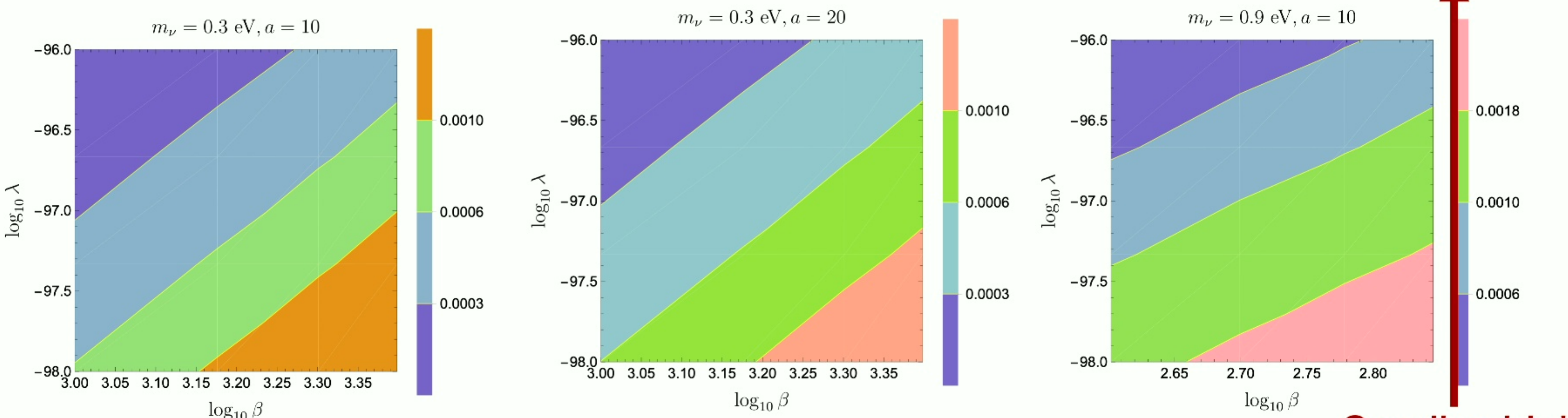
- Various parameters can give the similar kick behavior:



- Where $m^2 = a\delta m^2$ is the mass of EDE field.

- $\delta m^2 = \dfrac{\beta^2}{4\pi^2}\left(\dfrac{m_\nu}{M_{\rm pl}}\right)^2 m_\nu^2$ is the quantum correction to the mass term.

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Discussion

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- Bounds of neutrino scattering from CMB data $\beta \lesssim \left(\frac{10^{-2}\mathrm{eV}}{m_\nu}\right) 10^{23}$
- The fifth force between neutrino would give Yukawa-like potential

$$V_\phi^{\bar{\nu}\nu}(r) = -2\beta^2 \frac{Gm_\nu^2}{r} e^{-mr}$$

- This changes the Newton constant at late time like
- $\frac{\Delta G_\nu(k,\beta,m)}{G_\mathrm{N}} \approx 1 \left(\frac{\beta}{10^3}\right)^2 \left(\frac{k}{(6.4\ \mathrm{Mpc})^{-1}}\right)^2 \left(\frac{10^{-27}\ \mathrm{eV}}{m}\right)^2$

Neutrino-Assisted EDE

Discussion

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- Model extension:
  - Couple to other matter fields —— irrelevant for Hubble tension
  - Couple to different neutrino mass eigenstates with different coupling constants β_i , which can be constrained by neutrino oscillation experiments.
  - Bound from K2K: $\Delta\beta_{ij}^2 \leq 2 \times 10^{-16}$.

Neutrino-Assisted EDE

Discussion

JCAP 04 (2021) 063 • e-Print: 2011.09895 [astro-ph.CO] M.C.González, **Q.Liang,** J.Sakstein, M.Trodden

- Future work:
  - The coupling to neutrino changes both background cosmology and the structure formation, need full data analysis to test whether neutrino-assisted EDE can actually solve Hubble tension
  - Try to see if there is a solution to both Hubble tension and S8 tension
  - See if EDE can be related to the late time dark energy or early time inflation
  - Explore the UV completion of EDE

Conclusion

- I introduce the Hubble tension as a tension between the late time (local) measurements and the early time measurements;
- I discuss the early dark energy as a successful solution;
- I discuss the coincidence problems in EDE, and how the coupling to neutrino makes the model more natural;
- I discuss that the simple coupling to neutrino would break the perturbation, and we need to be more careful about the coupling;
- Evolution and other details in the neutrino-assisted EDE model.

Thanks for listening!