Coupled Early Dark Energy

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Copernicus Webinar

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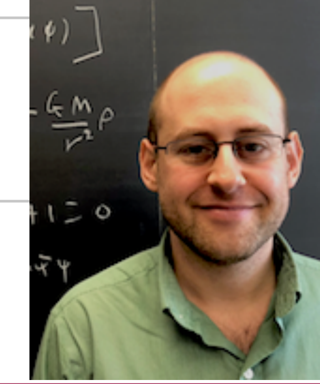
Overview

- The Hubble tension and possible solutions
- Early Dark energy and its coincidence problem
- Possible Solutions - coupling to matter species for which equality is an important epoch.
- Neutrino-Assisted Early Dark Energy
  - A simple implementation as an example
  - Constraints from Particle Physics and Cosmology
- Chameleon Early Dark Energy
  - Background Cosmology and basic mechanism.
  - Comments on detailed comparisons with data
- Future (ongoing) work.

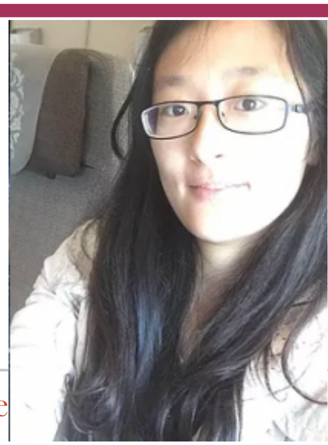
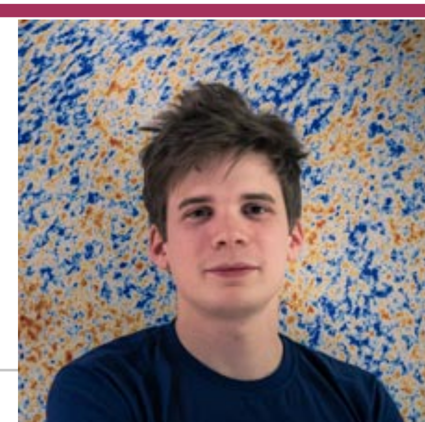
- M. Carrillo González and M.T., *"Field Theories and Fluids for an Interacting Dark Sector"*
  Phys.Rev. **D97** (2018) no.4, 043508 [arXiv:1705.04737]

- V. Miranda, M. Carrillo González, E. Krause and M.T., *"Finding structure in the dark: coupled dark energy, weak lensing, and the mildly nonlinear regime"*
  Phys.Rev. **D97** (2018) no.6, 063511 [arXiv:1707.05694]

- J. Sakstein and M.T., *"Early dark energy from massive neutrinos -- a natural resolution of the Hubble tension,"*
  Phys. Rev. Lett. **124** (2020) no.16, 161301, [arXiv:1911.11760].

- M. Carrillo Gonzalez, Q. Liang, J. Sakstein and M.T., *"Neutrino-Assisted Early Dark Energy: Theory and Cosmology,"*
  JCAP ***04****, 063 (2021),* [arXiv:2011.09895]

- T. Karwal, M. Raveri, B. Jain, J. Khoury and M.T., "*Chameleon Early Dark Energy and the Hubble Tension,*"
  [arXiv:2106.13290]

The H_0 Problem

- Standard cosmological model explains most observations.
- However, several anomalies and tensions have been found between cosmological and astrophysical data.
- May point to the presence of new physics.
- One much-discussed discrepancy is between measurements of the Hubble parameter at different redshifts.

- Local measurement obtained by observing Cepheid variables

$$H_0 = 74.0 \pm 1.4 \text{ km/s/Mpc}$$

[Riess et al. (2019)]

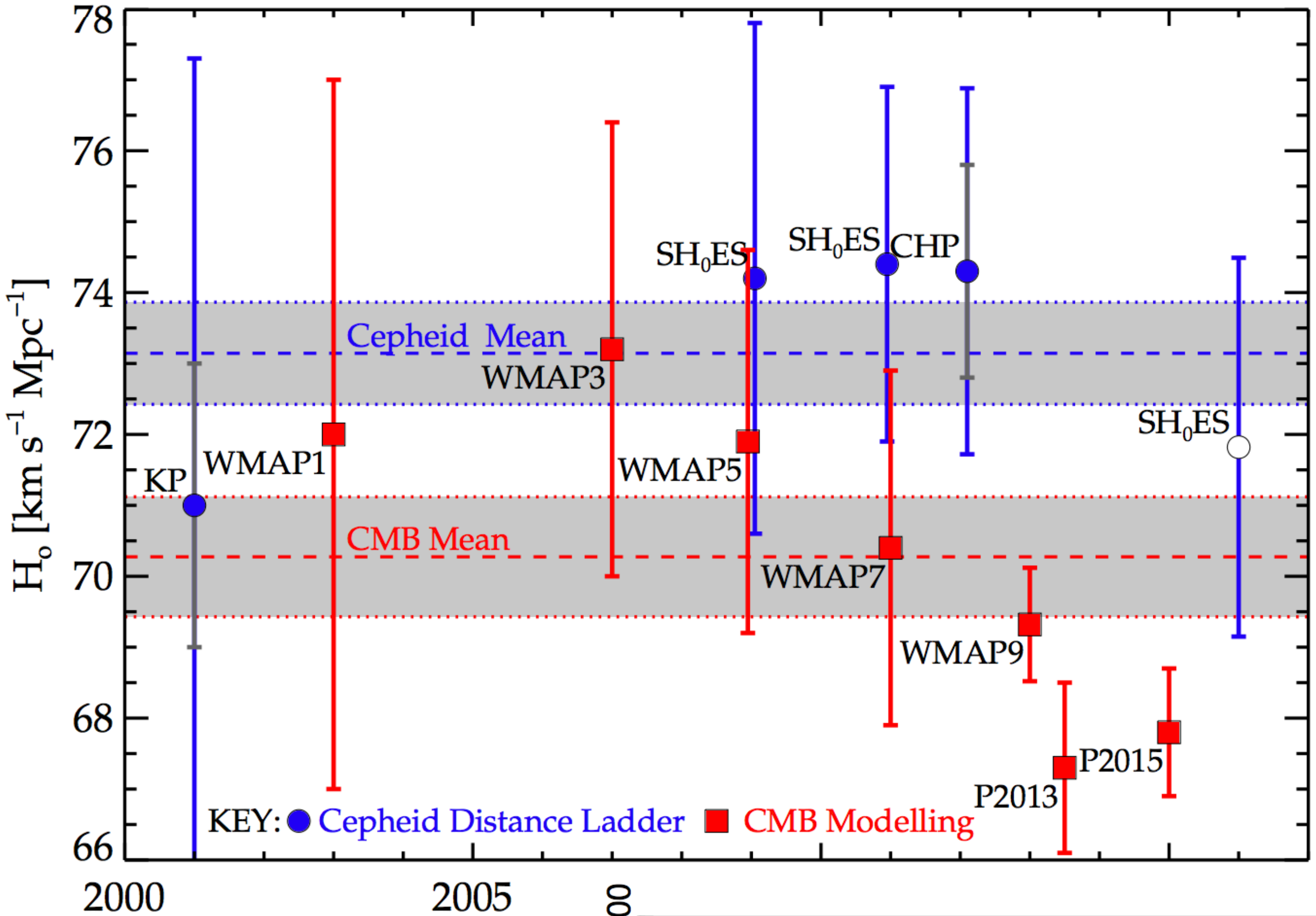
- Planck data estimate (LCDM, three 0.06eV neutrinos)

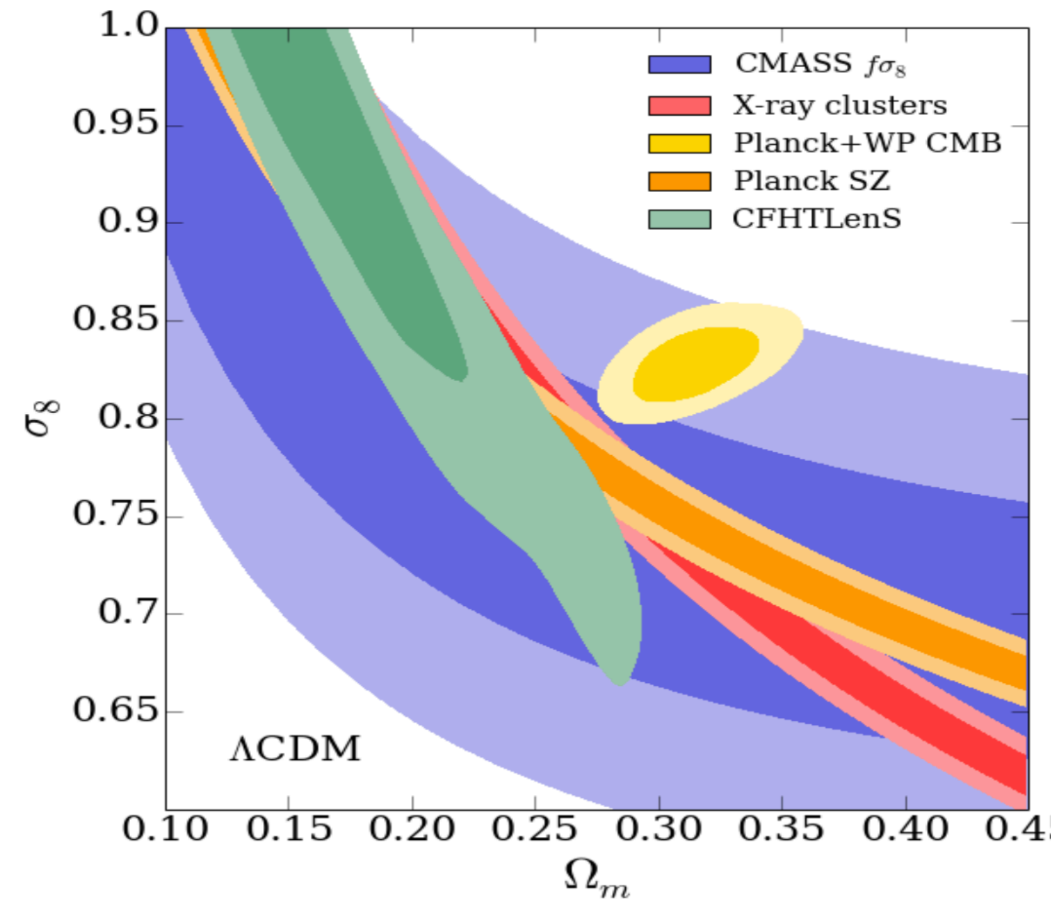
$$H_0 = 66.93 \pm 0.62 \text{ km/s/Mpc}$$

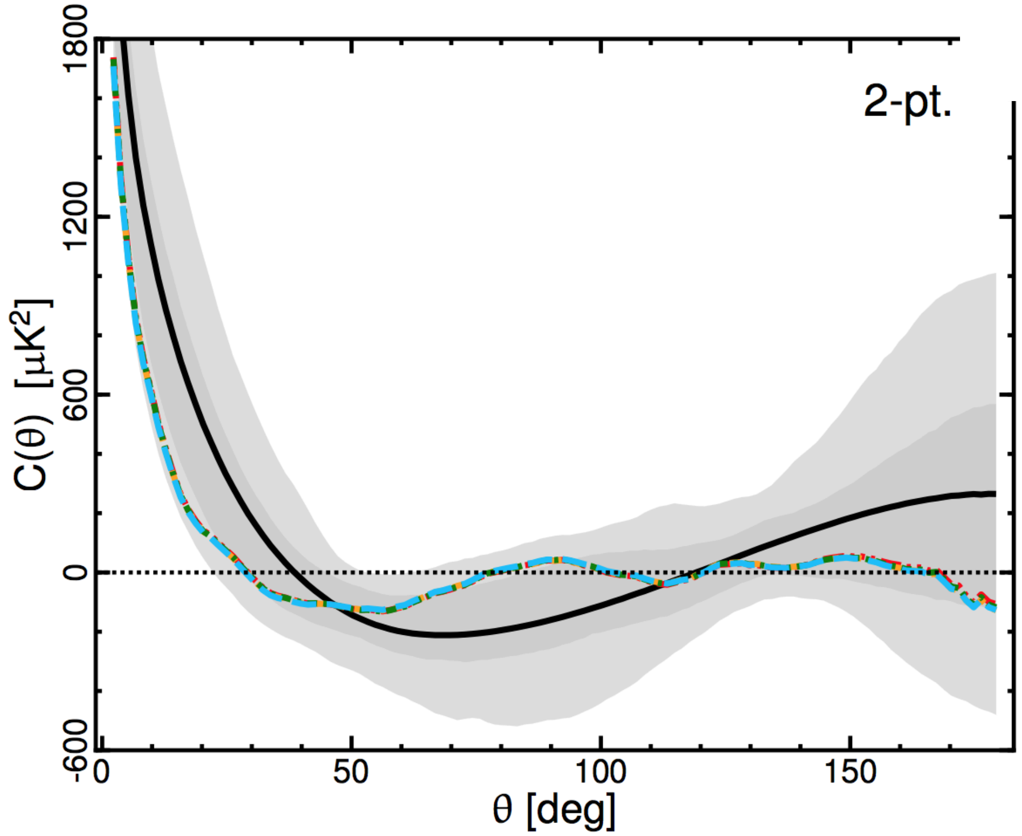
[Planck (2018)]

- This is a tension of $5.5\ \sigma$ and it doesn't seem to be going away!!!

One of a Number of Moderate Tensions

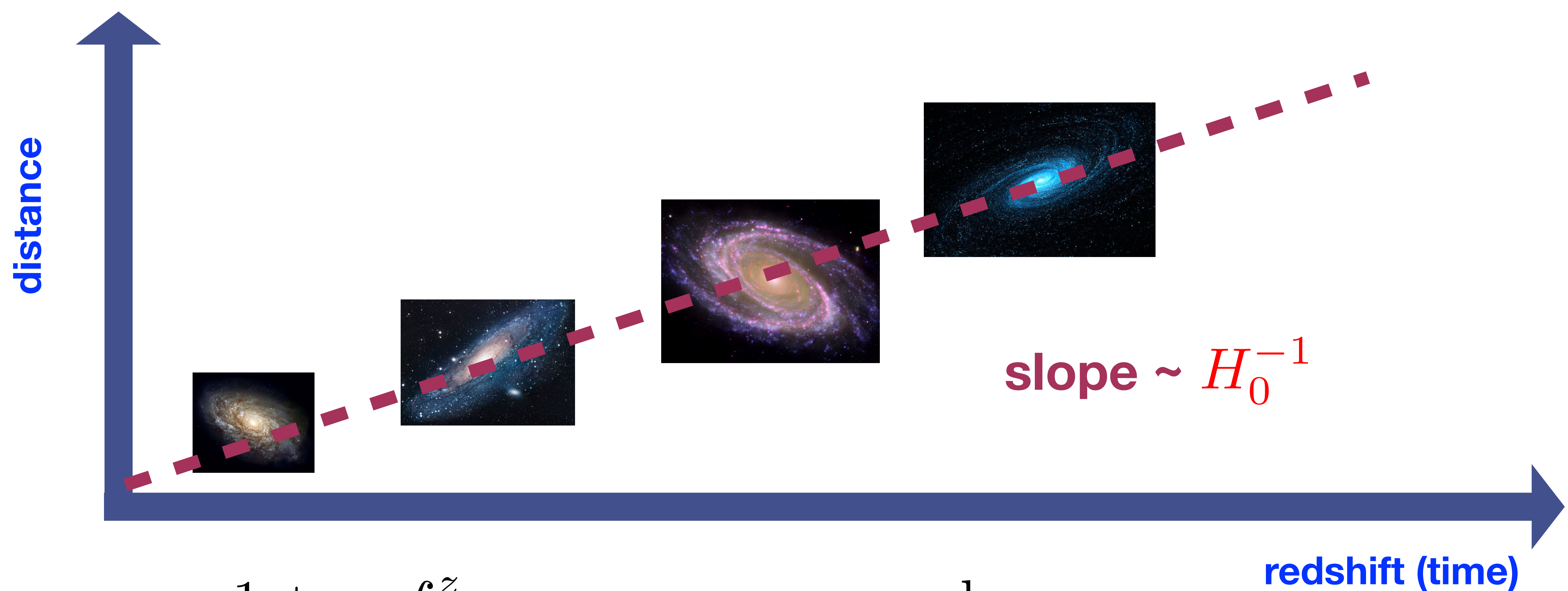






Ways to measure the Hubble constant - I

Locally — by measuring the distances to galaxies

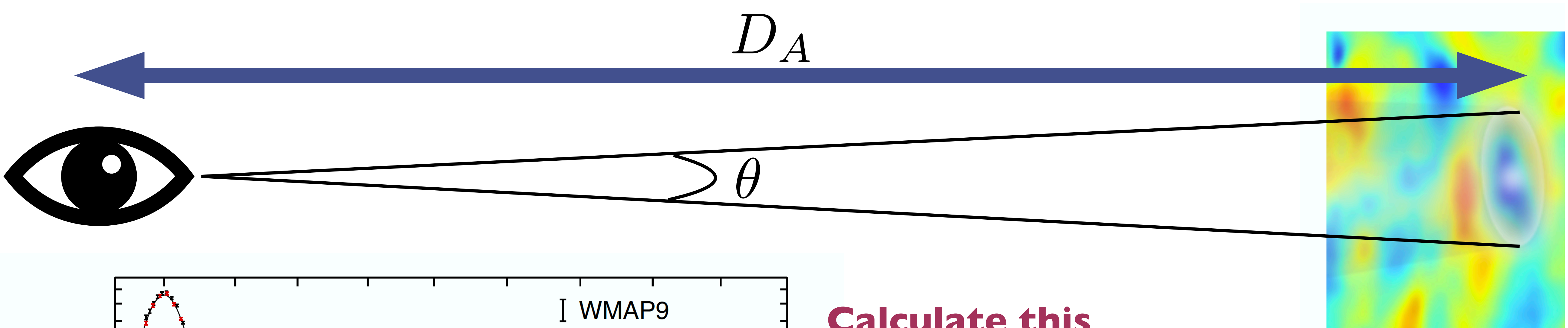


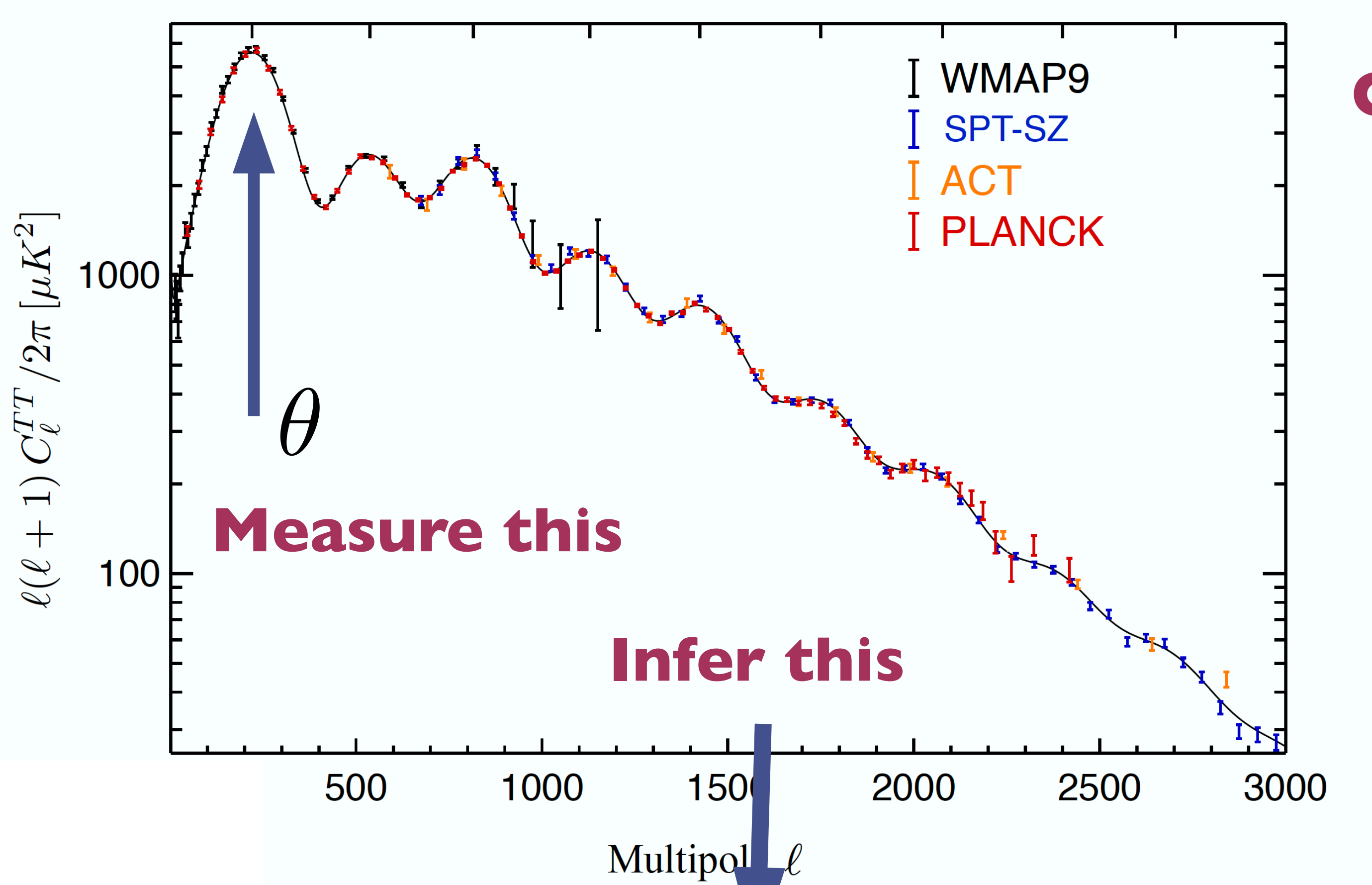
$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{\mathrm{d}z}{\sqrt{\Omega_{\text{Dark Mater}}(1+z)^3 + \Omega_{\text{Dark Energy}}(z)}}$$

$$\left(a = (1+z)^{-1}\right)$$

Ways to measure the Hubble constant - II

The CMB — by using the inherent distances in the CMB





Calculate this

$$r_s = \int_{z_{\rm CMB}}^{\infty} \frac{c_s dz}{H(z)}$$

$$D_A(z_{\rm CMB}) = \frac{r_s}{\theta}$$

$$D_A(z) = \frac{1}{(1+z)H_0} \int_0^{z_{\rm CMB}} \frac{\mathrm{d}z}{\Omega_{\rm dark\ matter}(1+z)^3 + \Omega_{\rm Dark\ Energy}(z)}$$

Possible Resolutions:

1) One or more measurements have unknown systematics

- Planck calibration issues
- Unknown distance ladder systematics

Riess et al.,
Freedman et al.,
.... many more

Efforts to improve this seem to make the tension worse!

2) Statistics need to be refined (tension not as bad as we think)

- Change statistical measure of the tension
- Different cuts, priors, etc.

Cardona et al.,
Spergel et al.,
.... many more

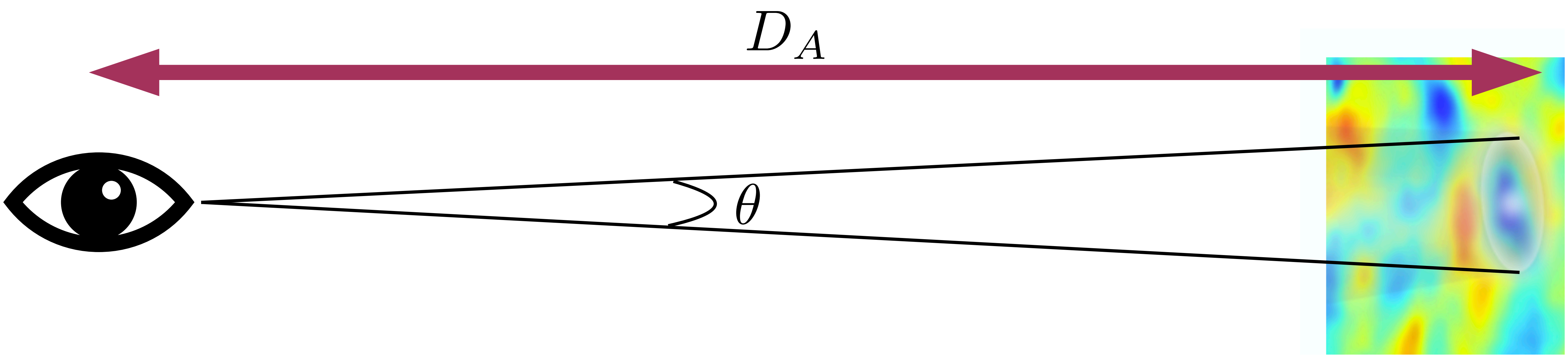
Different approaches agree, magnitude of discrepancy is getting larger!

3) New physics

An Early Time Resolution

One promising idea is Early dark energy (EDE) as a resolution to the Hubble tension!

(Poulin et al. 2018)



$$D_A = \frac{r_s}{\theta} \propto H_0^{-1}$$

$$r_s = \int_{z=1100}^{\infty} \frac{c_s \mathrm{d}z}{\sqrt{\Omega_m (1+z)^3 + \Omega_\gamma (1+z)^4 + \dots}}$$

Add new stuff here

You can't always get what you want!

EDE positives

- Resolves the Hubble tension
- Improves the fit to cosmological data relative to LCDM
- Can arise from numerous theoretical scenarios
- A simple scalar field (try to act shocked!) seems to do quite well

...and negatives

- Worsens the LSS tension
- Need to include local H_0 while fitting
- The potentials needed, e.g.

$$V(\phi) = (1 - \cos(\phi))^n$$

seem to be very contrived
- Solution is fine-tuned in theoretical parameters

Without dwelling on details in this talk, it is not that easy to make this idea work. Changing the sound horizon comes with other effects (such as on the damping scale of perturbations, which can conflict with observations in many models.

Early dark energy issues and questions

Nevertheless, EDE can help with the Hubble tension

- Pre-recombination energy injection close to matter-radiation equality.
- Reduces pre-rec expansion rate and therefore sound horizon
- Rapid dilution of energy thereafter, leaving late universe unchanged
- BUT: Higher $\omega_{\rm dm}$ preferred when fit to CMB so usually, worse LSS tension

There are also other issues, more relevant to this talk.

- What creates this phenomenological behavior?
- Why does EDE appear at MRE?
- Can we conceive of an EDE model that doesn't worsen LSS?

Will Mention two Recent Results Though. This …

J.C. Hill, E. Calabrese, S. Aiola, N. Battaglia, B. Bolliet, S.K. Choi, M.J. Devlin, A.J. Duivenvoorden, J. Dunkley and S. Ferraro, *et al.* "*The Atacama Cosmology Telescope: Constraints on Pre-Recombination Early Dark Energy*," [arXiv:2109.04451 [astro-ph.CO]].

Previous work has found that non-zero EDE is not preferred by Planck CMB power spectrum data alone, which yield a 95% confidence level (CL) upper limit fEDE<0.087 on the maximal fractional contribution of the EDE field to the cosmic energy budget. In this paper, we fit the EDE model to CMB data from the Atacama Cosmology Telescope (ACT) Data Release 4. We find that a combination of ACT, large-scale Planck TT (similar to WMAP), Planck CMB lensing, and BAO data prefers the existence of EDE at >99.7% CL: fEDE=0.091+0.020−0.036, with H0=70.9+1.0−2.0 km/s/Mpc (both 68% CL). From a model-selection standpoint, **we find that EDE is favored over ΛCDM by these data at roughly 3σ significance. In contrast, a joint analysis of the full Planck and ACT data yields no evidence for EDE, as previously found for Planck alone.** …

…

Understanding whether these differing constraints are physical in nature, due to systematics, or simply a rare statistical fluctuation is of high priority. The best-fit EDE models to ACT and Planck exhibit coherent differences across a wide range of multipoles in TE and EE, indicating that a powerful test of this scenario is anticipated with near-future data from ACT and other ground-based experiments.

… and this from the past week

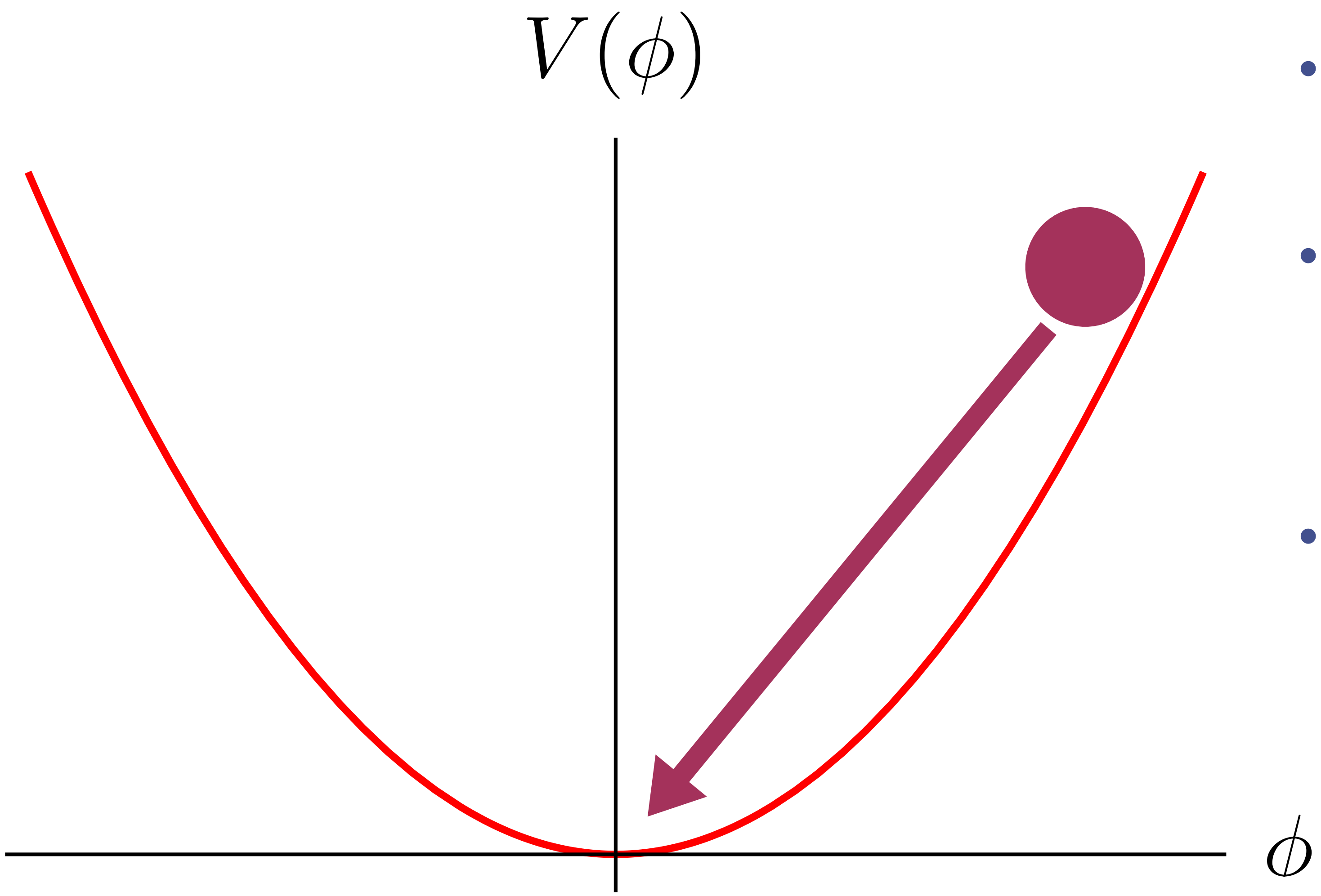
T.L. Smith, M. Lucca, V. Poulin, G.F. Abellan, L. Balkenhol, K. Benabed, S. Galli and R. Murgia. "*Hints of Early Dark Energy in Planck, SPT, and ACT data: new physics or systematics?*," [arXiv:2202.09379 [astro-ph.CO]].

We investigate constraints on early dark energy (EDE) using ACT DR4, SPT-3G 2018, Planck polarization, and restricted Planck temperature data (at l < 650), finding a 3.3σ preference for EDE over ΛCDM. The EDE contributes a maximum fractional energy density of fEDE(zc) = 0.163+0.047 at a redshift zc = 3357 ± 200 and −0.04 leads to a CMB inferred value of the Hubble constant H0 = 74.2+1.9 km/s/Mpc. … **<u>This is the first time that a moderate preference for EDE has been reported for these three combined CMB data sets.</u>** We find that including measurements of supernovae luminosity distances and the baryon acoustic oscillation standard ruler only minimally affects the preference (3.0σ), while measurements that probe the clustering of matter at late times – the lensing potential power spectrum from Planck and fσ8 from BOSS – decrease the significance of the preference to 2.6σ. Conversely, adding a prior on the H0 value as reported by the SH0ES collaboration increases the preference to the 4 − 5σ level.

Another Coincidence Problem

Why now?

Dark energy has a coincidence problem: field rolls when $H \sim m_\phi$



- Very finely-tuned. Hard to build models.
- Could be a pNGB, but don't want oscillations near minimum
- Need to suppress first and second instanton contributions - not natural.

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \qquad H(z_{\rm eq}) = 10^{-29}{\rm eV!}$$

An Idea

- Alternative mechanism to trigger onset of EDE, free of fine-tuning.
- Instead of balancing scalar mass against Hubble parameter, exploit the fact that EDE must become important at a time that other physics becomes active in the universe
- One example: coincidence between energy scale of matter-radiation equality and upper limit on the sum of neutrino masses suggests a coupling to neutrinos. We call this neutrino-assisted early dark energy
- Second example: since matter becomes dominant at matter-radiation equality, this suggests that a coupling to matter might be a natural trigger. We call this chameleon early dark energy.

Neutrino-Assisted Early Dark Energy

- Couple EDE scalar conformally to neutrinos
- Yields energy injection around time when neutrinos become non-relativistic.
- Happens when temperature is comparable to their mass; i.e. at matter-radiation equality.
- Field initially lies at minimum of potential - then displaced around matter-radiation equality by neutrinos
- Scalar then behaves as EDE as rolls back towards origin.
- Avoids fine-tuning issues

A (too) Simple Model

- Couple EDE field to neutrinos through a conformal coupling

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2 R(g)}{2} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi)\right] + S_\nu[\tilde{g}_{\mu\nu}],$$

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

- Can expand this action out to yield

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

- With resulting EOM

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \frac{\beta}{M_{\rm Pl}}\Theta(\nu)$$

Energy-momentum tensor of neutrinos

$$\Theta(\nu) = g_{\mu\nu}\Theta(\nu)^{\mu\nu}$$

Behavior of EDE Field

- Can treat as motion in an effective potential

$$V_{\rm eff}(\phi) = V(\phi) - \beta\Theta(\nu)\phi/M_{\rm Pl}$$

- Where, integrating over the Fermi-Dirac distribution, we have:

$$\Theta(\nu) = -\rho_\nu + 3P_\nu = -\frac{g_\nu T_\nu^4}{2\pi^2}\tau\left(\frac{m_\nu}{T_\nu}\right)$$

- with

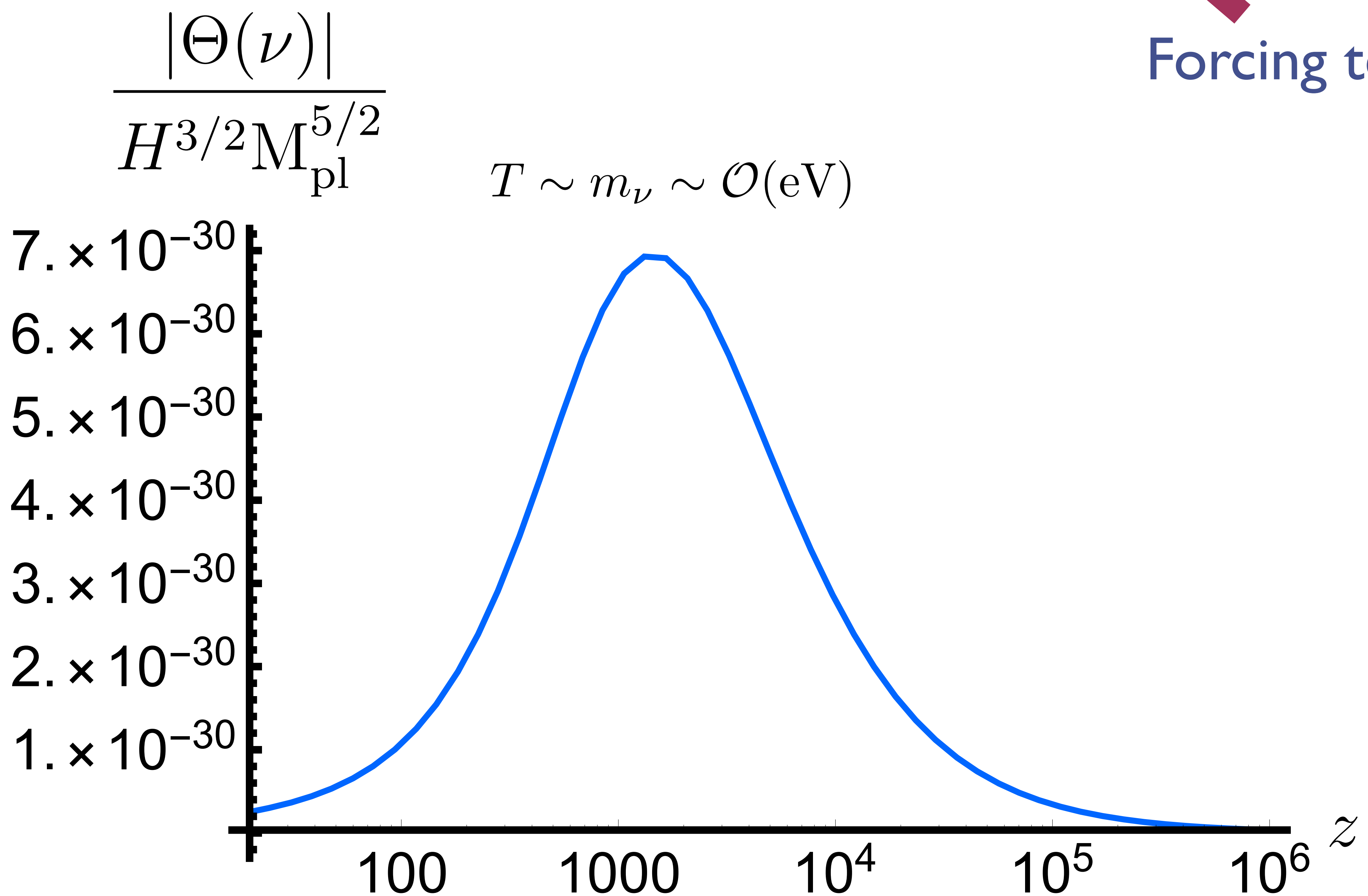
$$\tau(x) = x^2 \int_x^\infty \frac{\left(u^2 - x^2\right)^{\frac{1}{2}}}{e^u + 1}\, du$$

- At first order the details aren't too important. What matters is …

Main Property of this Integral

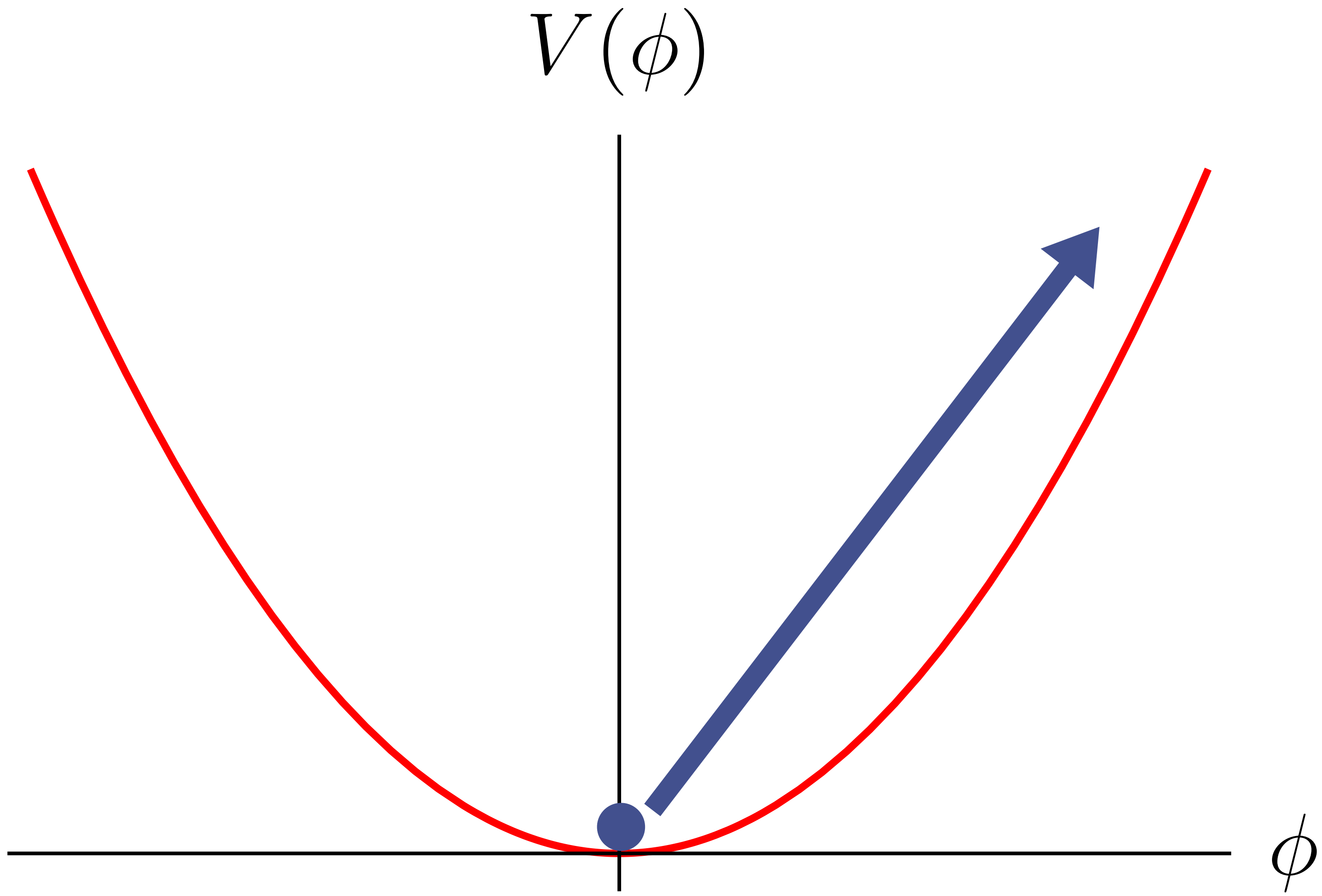
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \frac{\beta}{M_{\rm Pl}}(\rho_\nu - 3P_\nu)$$

Forcing term



Simplistic Argument

- Field is then displaced for a while by this forcing term, at temperatures around the neutrino mass.



- Quick check - can perform a simple analytic estimate of the displacement (kick), yielding

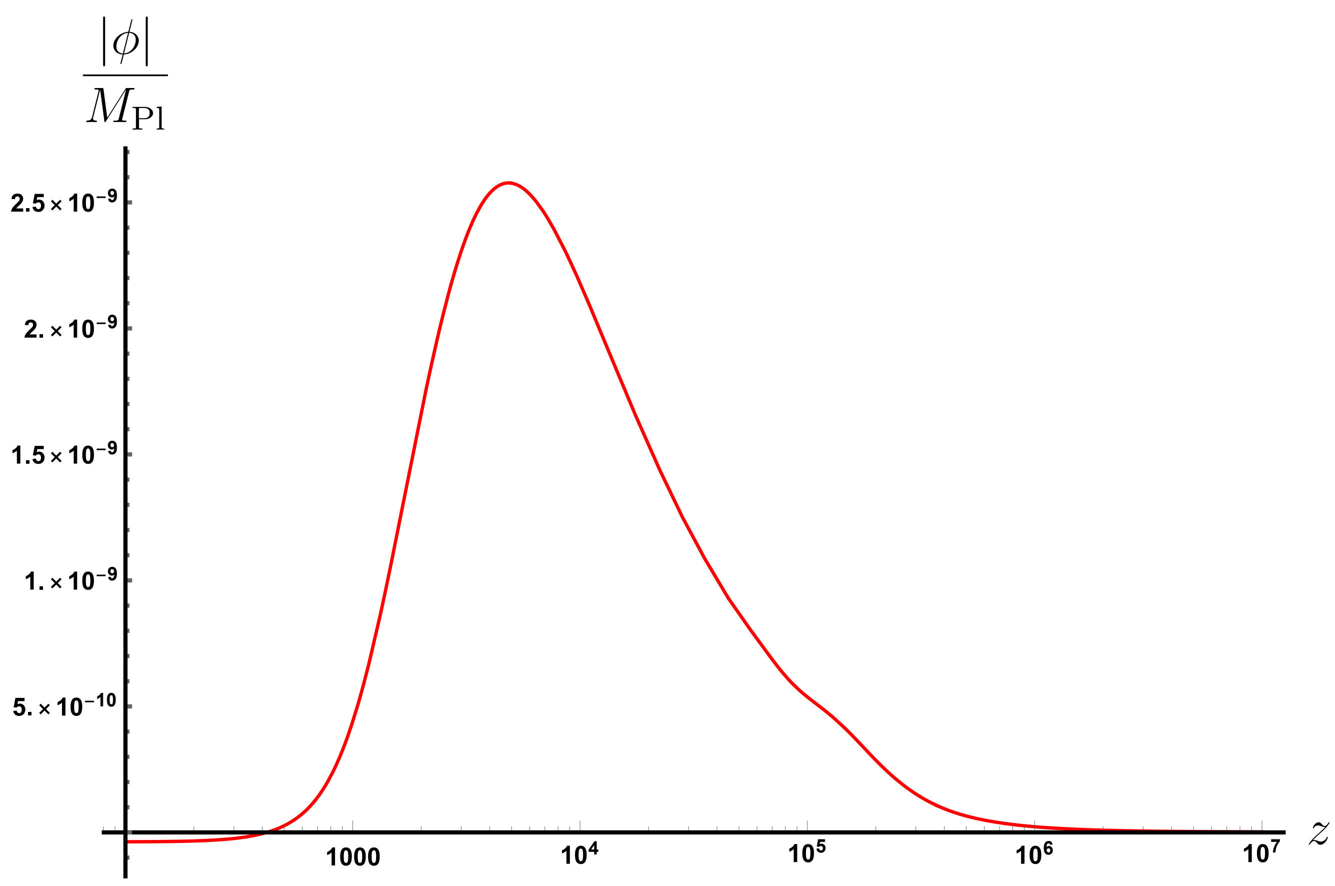
$$\phi_k \approx -0.03\beta M_{\rm Pl}$$

Full Numerical Solutions

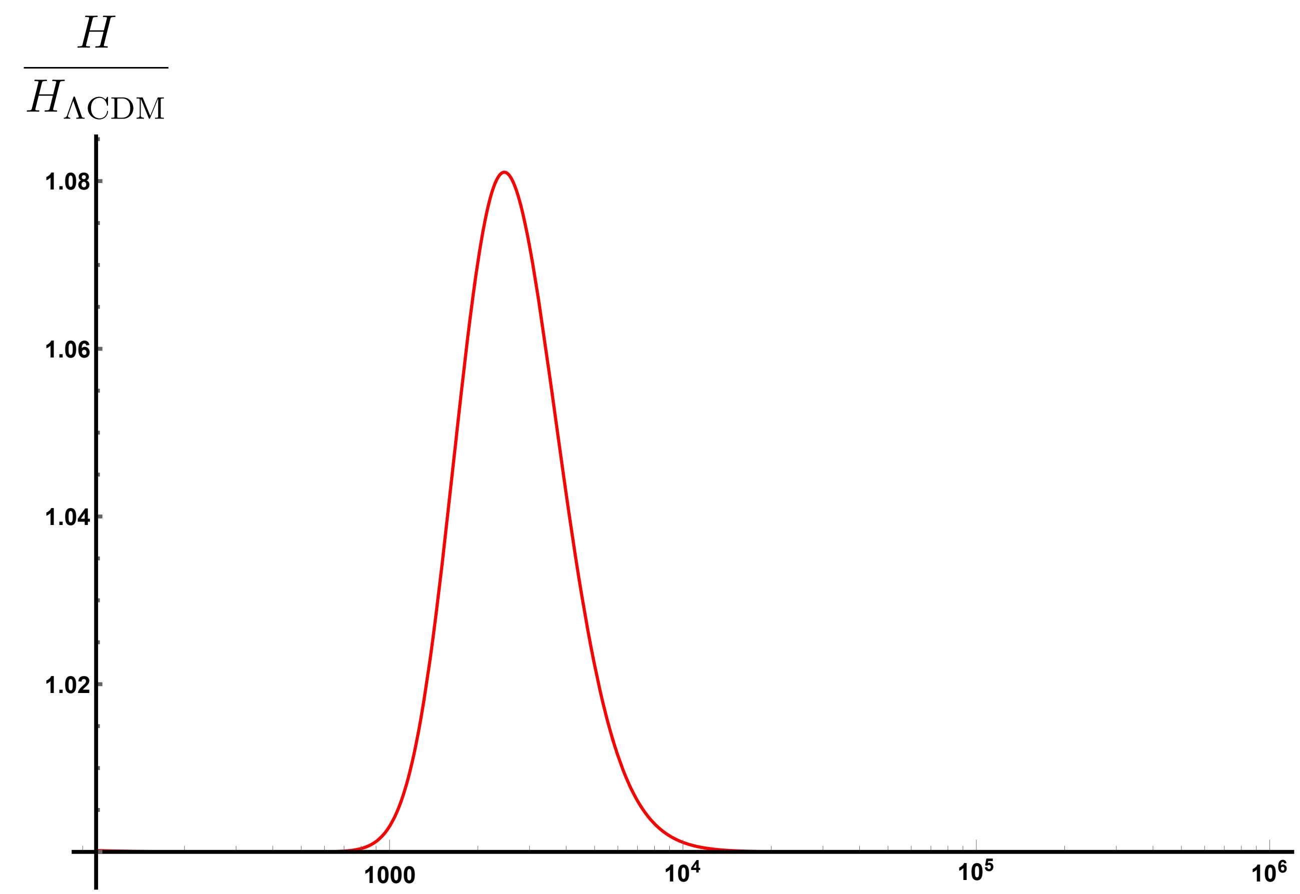
- Solve EDE EOM in conjunction with Einstein equations

$$3H^2M_{\rm Pl}^2 = \rho_m + \rho_\gamma + \frac{\dot\phi^2}{2} + \frac{\lambda}{4}\phi^4 + \Lambda M_{\rm Pl}^2 \qquad \frac{\dot H}{H^2} = -\frac{1}{2M_{\rm Pl}^2}\left(\sum_i(\rho_i+P_i)+\dot\phi^2\right)$$

Evolution of the EDE field



And the Hubble parameter



This is the key result

More Complete Model

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

Don't specify origin of neutrino mass or whether Dirac or Majorana

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

Have redefined $\nu = A^{3/2}(\phi)\tilde{\nu}$ and generalized conformal coupling

- Although quartic potential is excellent fit, EFT suggests including a mass also, even though this is tightly constrained by late time expansion.
- Have generalized the coupling function also, because of EFT considerations. If exponential, then effective potential minimized at

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

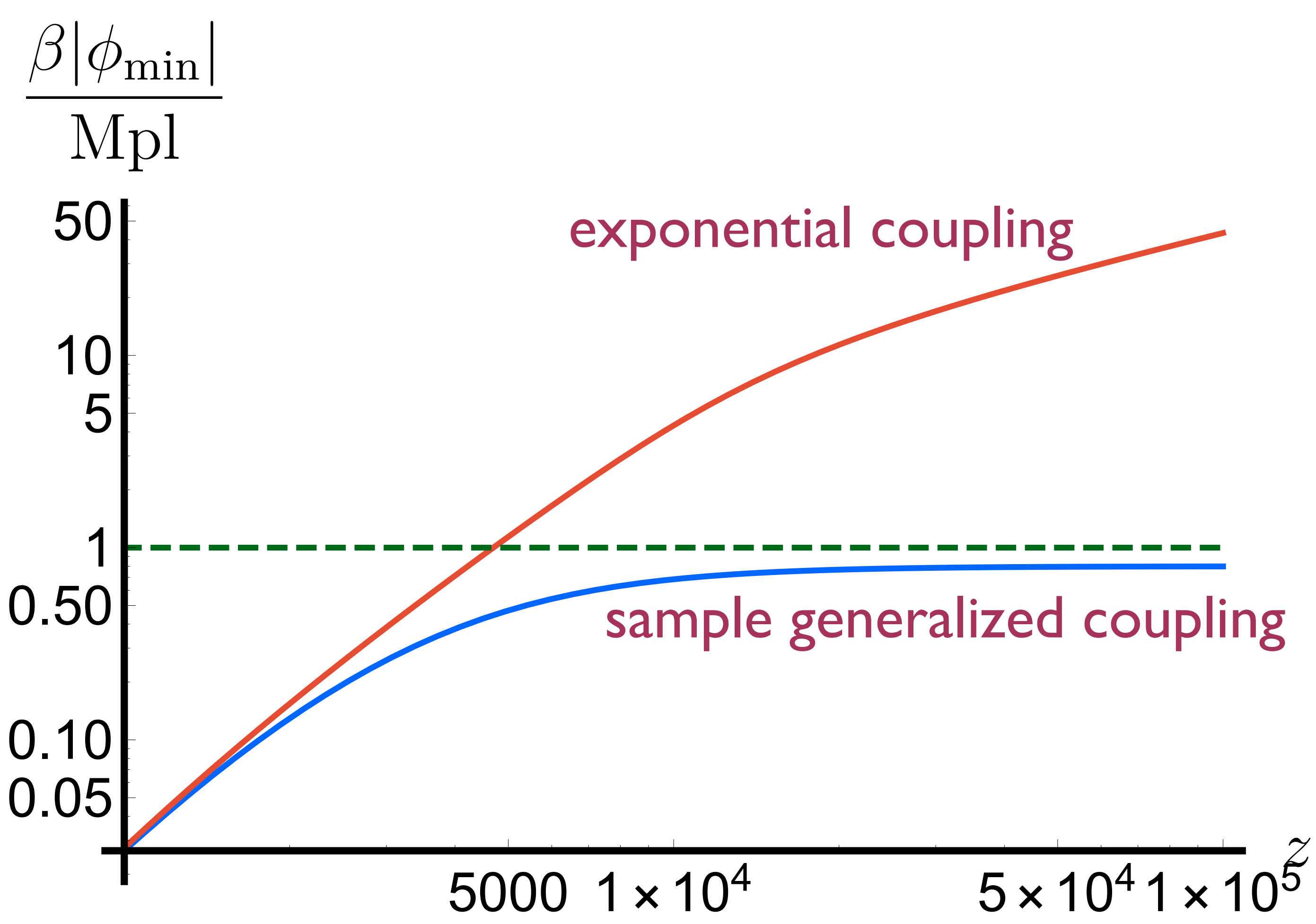
This **grows** with redshift, and eventually exits validity of the EFT

Making the EFT Well-Behaved

Can avoid if make one assumption about generalized coupling function:

When series is resumed, it has a minimum at some $\phi = -\bar{\phi}$
(as in some strongly-coupled string theory models)

Then: $$V_{\rm eff}(\phi) = V(\phi) + (\rho_\nu - 3P_\nu)\ln[A(\phi)]$$



e.g. could take

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

And remain ignorant about any UV completion.

Radiative Stability

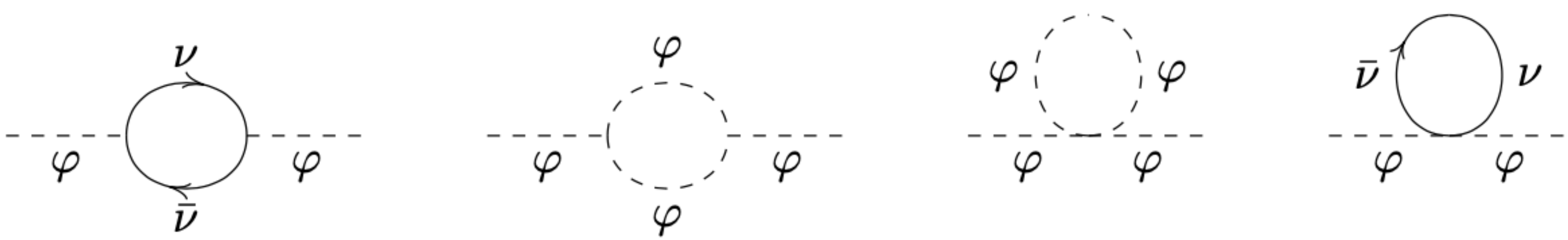
EFT forces a mass term. But can't be too large. Small value needs to be radiatively stable. Won't dwell on this, but there is a constraint.

Expand out interactions. Find coupling of EDE to neutrinos reads

$$\left[\frac{\beta}{M_{\rm pl}}\left(1+\frac{\phi_{\rm min}}{\bar{\phi}}\right)\varphi+\frac{\beta}{2M_{\rm pl}\bar{\phi}}\varphi^2\right]m_\nu\bar{\nu}\nu$$

Also have cubic and quartic EDE self-interactions

Compute 1-loop quantum corrections to EDE mass



Get

$$\delta m^2=\frac{\beta^2}{4\pi^2}\left(\frac{m_\nu}{M_{\rm pl}}\right)^2 m_\nu^2$$

So need

$$m^2+12\lambda\phi_{\rm min}^2\geq\frac{\beta^2}{4\pi^2}\left(\frac{m_\nu}{M_{\rm pl}}\right)^2 m_\nu^2$$

Cosmological Evolution (Qualitative)

At high redshifts, effective potential minimized at $\bar{\phi}$. Field is stuck there. Robust initial conditions for later evolution (improves fit)

Universe expands and $(3P_\nu - \rho_\nu)$ redshifts until contribution from quartic part of potential is non-negligible.

Then minimum adiabatically evolves away from $\bar{\phi}$ towards zero.

At this point, higher-order terms in the expansion of coupling function are not relevant, and evolution proceeds until $T_\nu \sim m_\nu$, neutrinos become non-relativistic and inject energy into scalar.

Leads to a kick feature in Ω_ϕ : onset of early dark energy phase, EDE causes Hubble constant to redshift at slower rate than in LCDM, lowering sound horizon, and increasing value of H_0 inferred from CMB. Transient effect as field reverts to tracking the minimum of the effective potential, which continues to decrease towards zero as neutrino density redshifts. Eventually, quartic term becomes negligible and mass term dominates

Cosmological Later-Time Behavior

During matter epoch, field can be decomposed into:

i) an adiabatic component that tracks $\phi_{\rm min}$ - acts as additional dark energy

ii) a rapidly-varying component $\delta\phi$ from oscillations about minimum - as an additional dark matter component

Total energy density of dark energy (including a cosmological constant) is

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

For the masses we need to choose, this is an irrelevant contribution.

Additional dark matter contribution at late times is

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

Potential tension with data - motivation behind neglecting mass term in EDE models. Important question: can EDE models can include mass large enough to be radiatively stable, but small enough not to be in tension with data.

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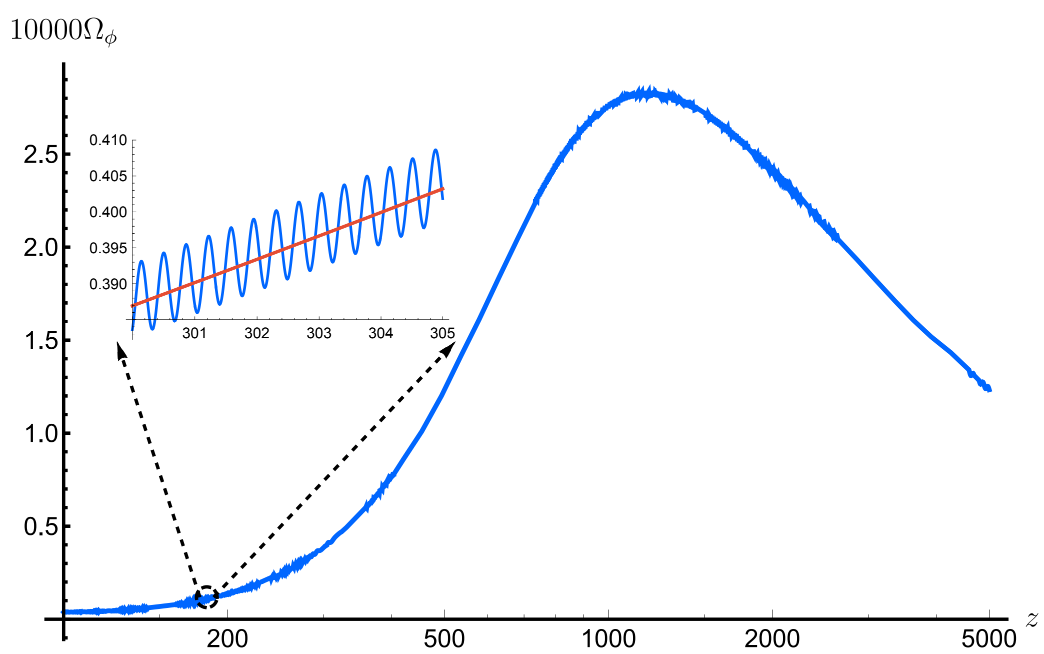
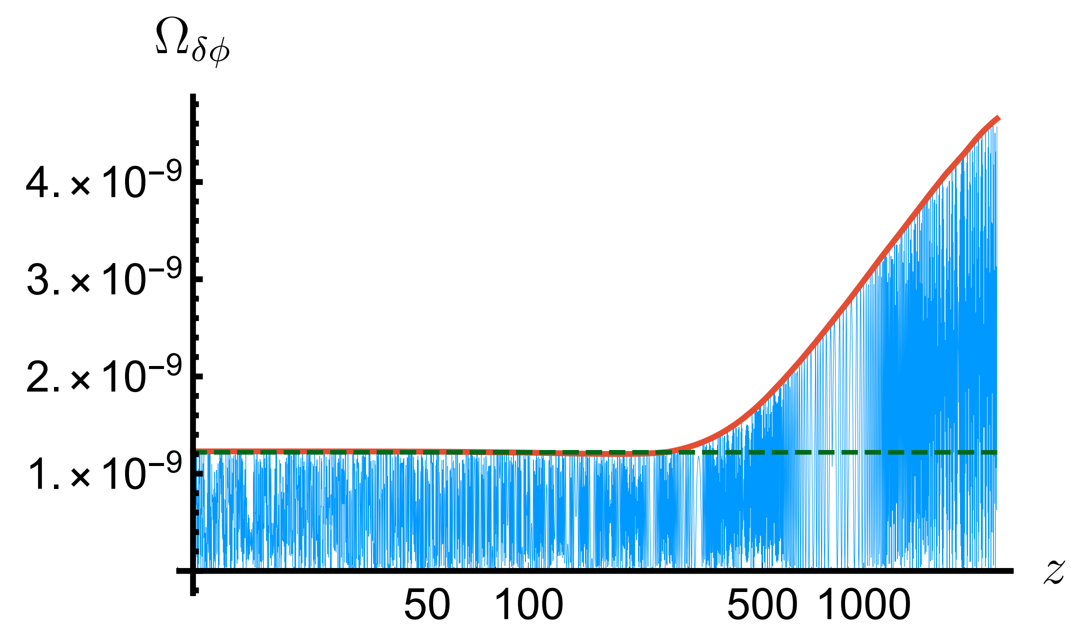
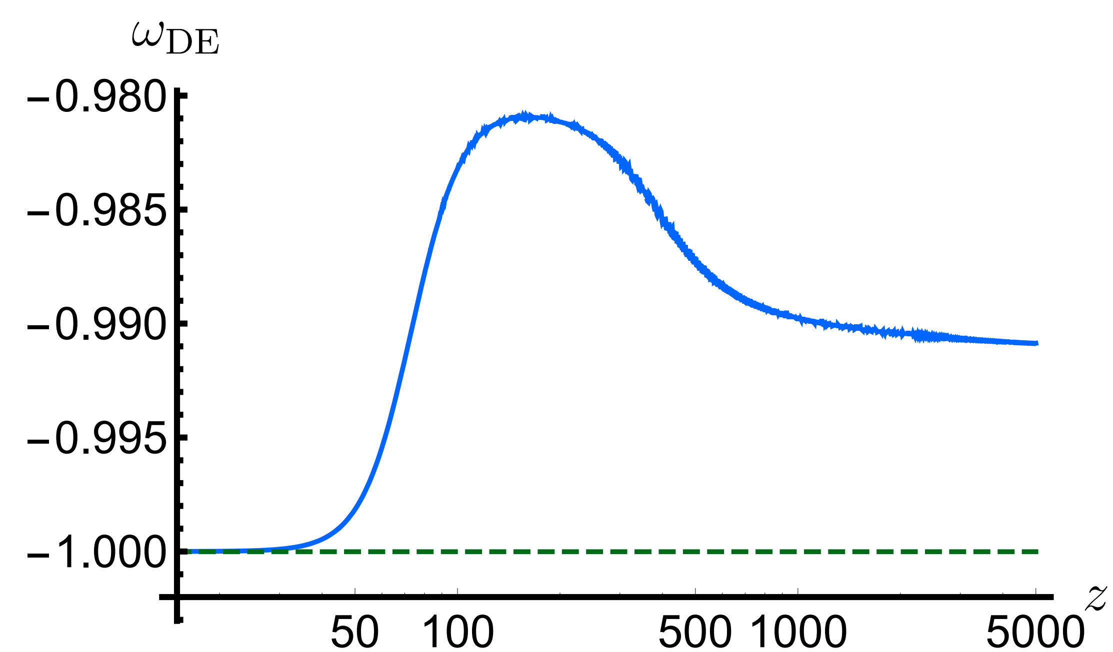
Cosmological Evolution (Numerical)

Have numerically solved coupled Friedman-neutrino-scalar system, including other energy components of universe. Generally, kick happens near z~1000, and at late times have a slowly varying component, and an oscillating one.





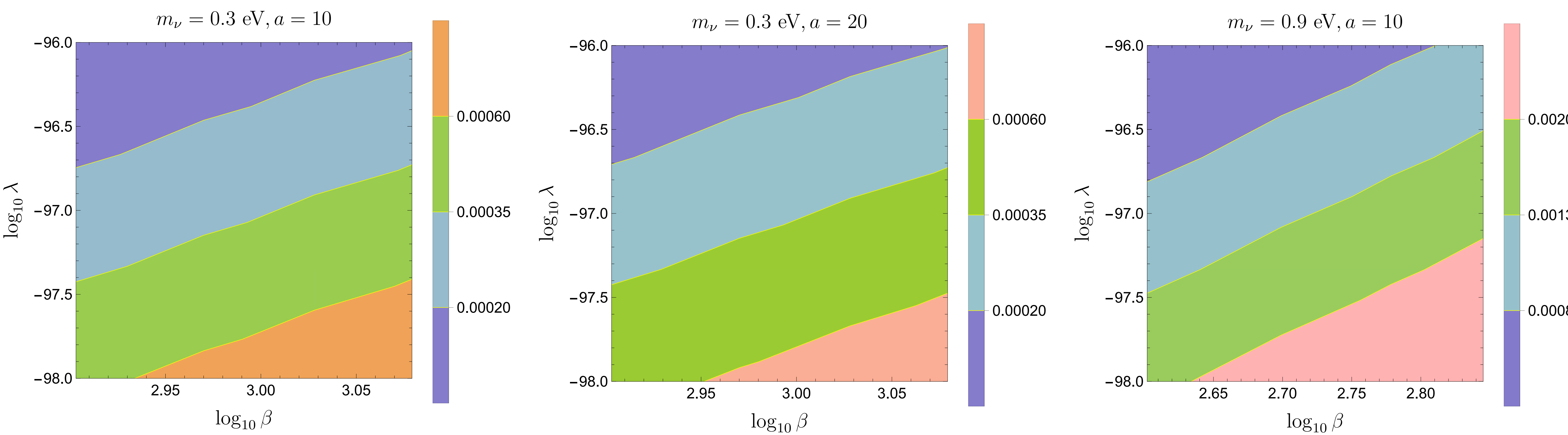
$$m = \sqrt{30}, \quad \delta m = 1.63 \times 10^{-26}\,\mathrm{eV},$$
$$\lambda = 10^{-98}\ \beta = 500\ m_\nu = 0.3\,\mathrm{eV}$$



$$m^2 = 5\delta m^2, \quad \beta = 800, \quad \lambda = 10^{-98}, \quad m_\nu = 0.3\mathrm{eV}$$

Indications of Viability

Have explored parameter space to understand correlation between size of kick and model parameters m, λ, β. (evolution after equality indep of $\bar{\phi}$)
Also allow m_ν to vary modestly from best-fit LCDM value (Planck)
Particularly interested in regions where kick magnitude is largest around epoch of equality. This is a prelude to a complete MCMC analysis, which would allow us to know if the model really works.
The regions of parameter space with largest kick magnitude are:



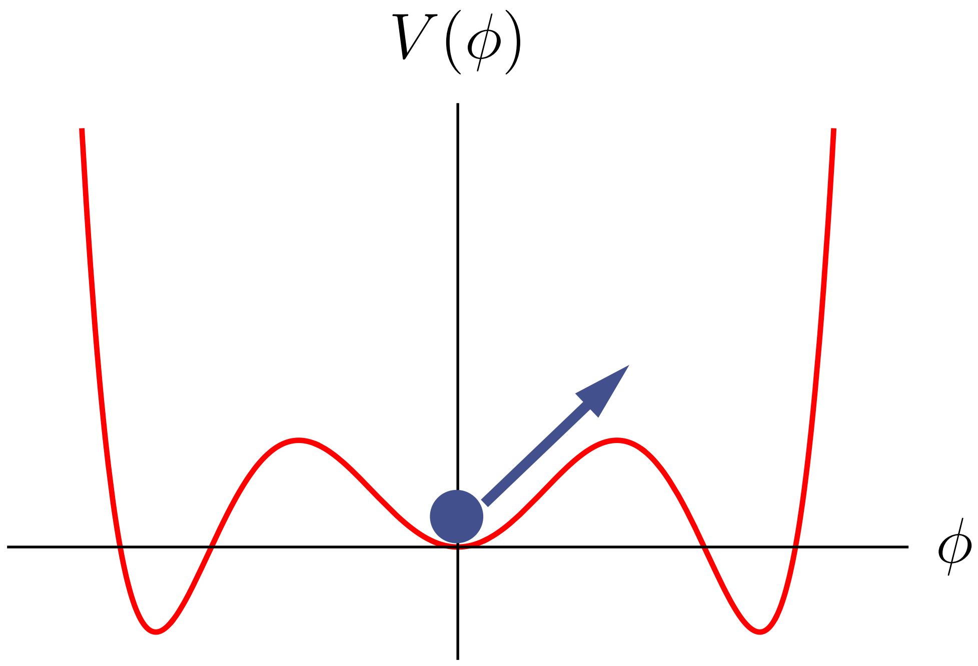
Contour plot of the kick's magnitude Note: $m^2 = a\delta m^2$
Magnitude of the kicks is slightly smaller for larger a

Many Open Questions and Directions

- Perform full MCMC analysis to find best fit models and to get correct parameter estimation (what neutrino masses are allowed?).

(w/ Tanvi Karwal and Marco Raveri)

- Construct explicit examples of field being pushed over a maximum to dissipate EDE energy sufficiently rapidly. (w/ Tanvi Karwal and Marco Raveri)



- Extensions, to help with the required small masses and parameters.
- . . .

(w/ Qiuyue Liang and Mariana Carrillo Gonzalez)

Comment on Constraints and Probes

Constraints on neutrino self-interactions

Can alter cosmological evolution & affect CMB (Planck) Bounds can't be directly applied, since cosmological evolution is different in our case. But, once we implemented model into cosmological solvers and MCMC codes, similar result could apply.

$$\beta \lesssim \left(\frac{10^{-2}\text{eV}}{m_\nu}\right) 10^{23}$$

Weak Equivalence Principle Violations

Neutrino-Scalar interaction leads to fifth force $2\beta^2$x strength gravity. Affects neutrino perturbations.

$$\ddot{\delta}_\nu + 2H\dot{\delta}_\nu - \frac{3}{2}\Omega_\nu(a)\left(1 + \frac{\Delta G_\nu(k,\beta,m)}{G_\mathrm{N}}\right)\delta_\nu = 0 \qquad \frac{\Delta G_\nu(k,\beta,m)}{G_\mathrm{N}} = \frac{2\beta^2}{1 + \frac{m^2 a^2}{k^2}}$$

Might be seen in the future in nonlinear matter power spectrum, or neutrino clustering within voids. Possibly constrained by next generation of lensing surveys.

Sketch of another New Idea

A different way to ameliorate the fine-tuning problems of early dark energy.

- Couple EDE scalar conformally to dark matter
- Yields energy injection around time when matter starts to dominate the universe
- Hope that dynamics are sufficiently different that more natural particle physics potentials are allowed

Recall, best-fit EDE model involves

$$V(\phi) = (1 - \cos(\phi))^n$$

Even if wanted to appeal to shift symmetries, would need to ignore many instant contributions,

Chameleon Early Dark Energy

Similar to the neutrino example, start with the action

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\rm pl}}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi)\right] + S_{\rm dm}[\phi_{\rm dm}, \tilde{g}_{\mu\nu}] + S_{\rm m}[\phi_{\rm m}, g_{\mu\nu}]$$

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

Background equations of motion

$$3H^2M_{\rm pl}^2 = \frac{1}{2}\dot{\phi}^2 + a^2V(\phi) + \tilde{\rho}_{\rm dm}A^4(\phi)a^2 + \rho_m a^2 + \rho_\Lambda a^2$$

$$\ddot{\phi} + 2\mathcal{H}\dot{\phi} = -a^2V_{,\phi} - a^2A_{,\phi}A^3(\phi)\tilde{\rho}_{\rm dm} \implies V_{\rm eff}(\phi) = V(\phi) + A(\phi)\rho_{\rm dm}$$

$$\dot{\tilde{\rho}}_{\rm dm} = -3\left(H + \frac{A_{,\phi}\dot{\phi}}{A}\right)\tilde{\rho}_{\rm dm}$$

Dilutes as $\tilde{\rho}_{\rm dm} = \tilde{\rho}^0_{\rm dm}a^{-3}\left(\frac{A_0}{A}\right)^3$

So sometimes convenient to use a quantity that does dilute in a standard way:

$$\rho_{\rm dm} \equiv \tilde{\rho}_{\rm dm}A^3$$

An Example Model

A very simple choice is

$$A(\phi) = e^{\beta\phi/M_{\rm pl}} \qquad V(\phi) = \lambda\phi^4$$

But EFT implies, without a symmetry, should include a mass term. We know scalar field must be ultra-light

$$m_\phi(\phi_{\rm i}) \sim \sqrt{\lambda}\phi_{\rm i} \sim 10^{-28}\ {\rm eV}$$

Whereas radiative corrections from DM loops would yield

$$\delta m_\phi \sim \beta\frac{\Lambda^2}{M_{\rm pl}}$$

Cutoff should be >> DM mass. Therefore radiatively stable if DM mass << eV
So could include a small mass without ruining predictions. Will ignore.

Initial Conditions

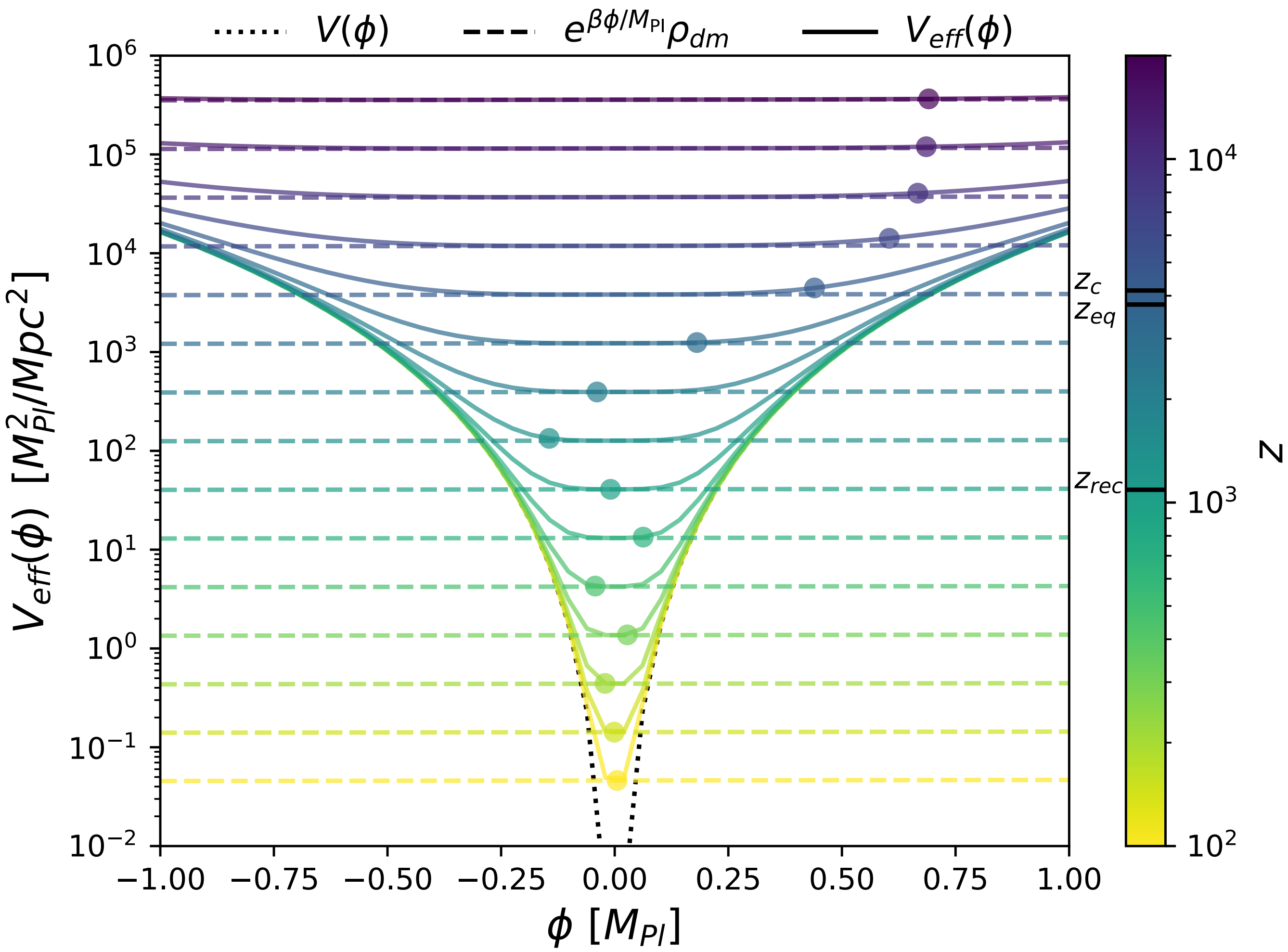
- Field initially rolls down effective potential with t-varying amplitude, since dark matter interaction term initially dominates (true for a very large range in beta, because DM density is huge at early times).
- Eventually, as DM dilutes away, native potential of scalar takes over.
- Depending on when this transition happens, scalar may be dominated by its native potential for a brief period.
- During this time it is Hubble frozen, before rolling down and oscillating in its effective potential.

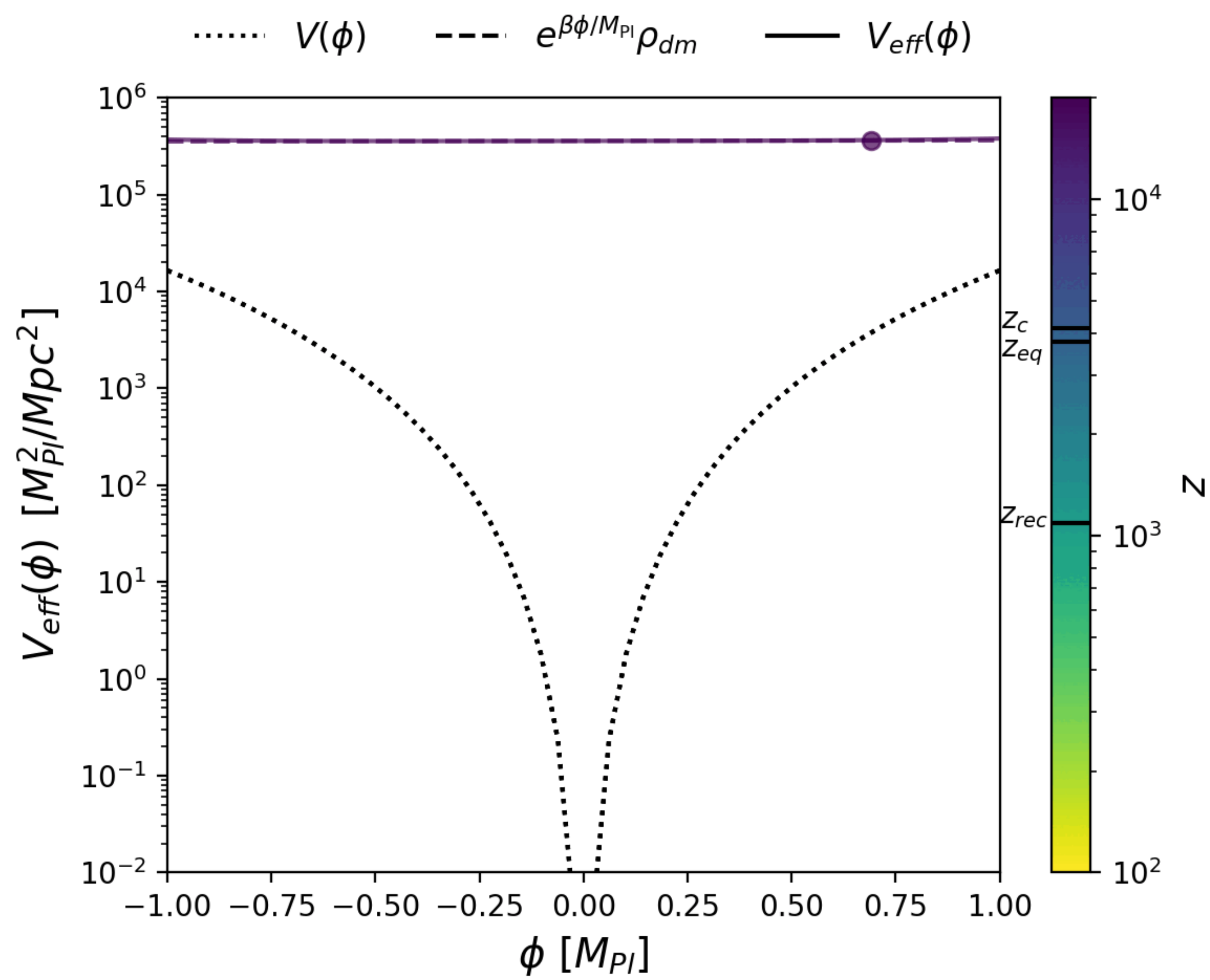
- The initial value ϕ_i is not set by an attractor solution.
- It is an input parameter that controls the maximal fractional energy density $f_{\rm ede}$ in CEDE.
- Note: there is a degeneracy between ϕ_i and $\Omega_{\rm dm,i}$ wherein changing ϕ_i simply rescales $\Omega_{\rm dm,i}$.

Cosmological Evolution

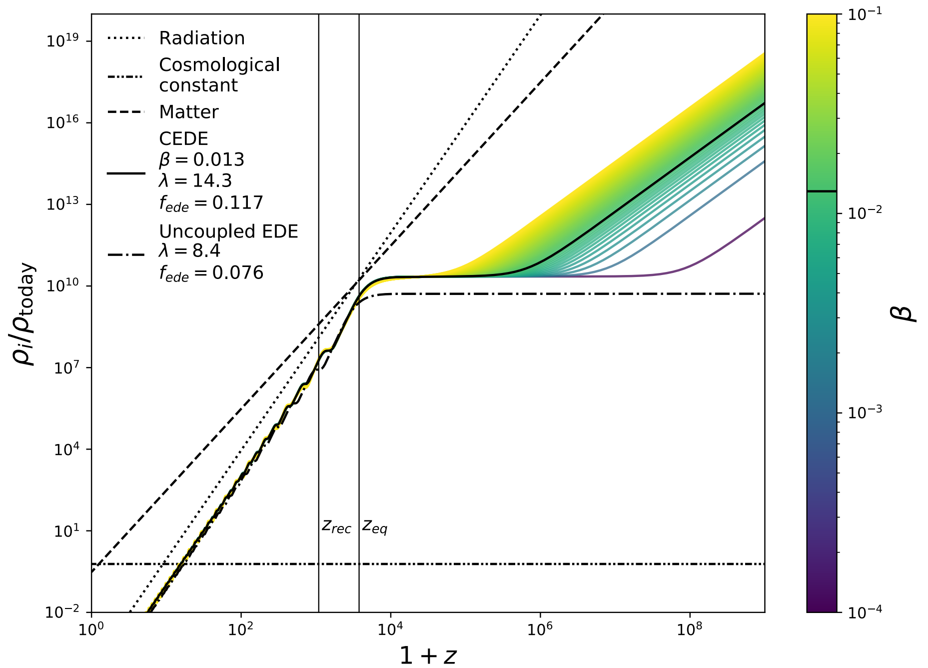
- At background level, coupling to DM modifies early behavior of scalar, when field is dominated by kinetic energy

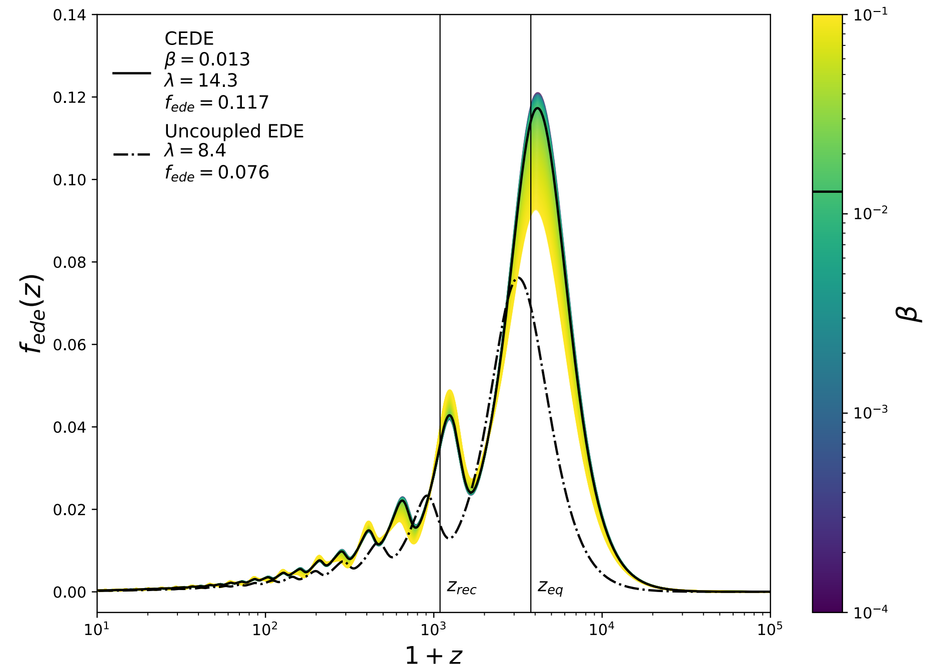
- This direct coupling to DM energy density offers possibility of EDE dynamics being triggered by DM becoming the dominant component of the Universe.

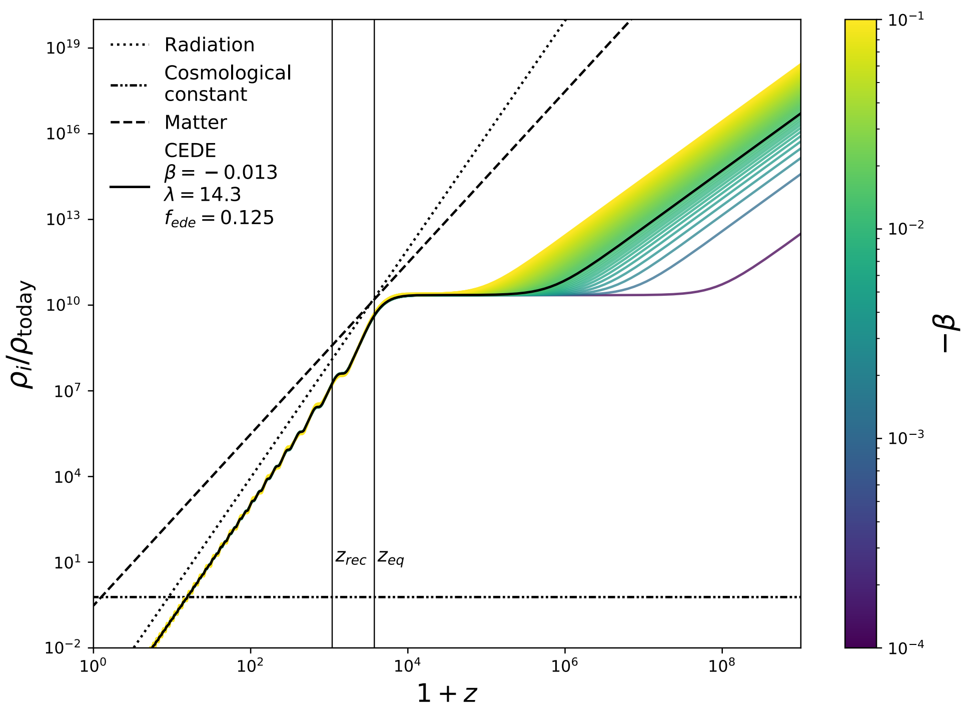


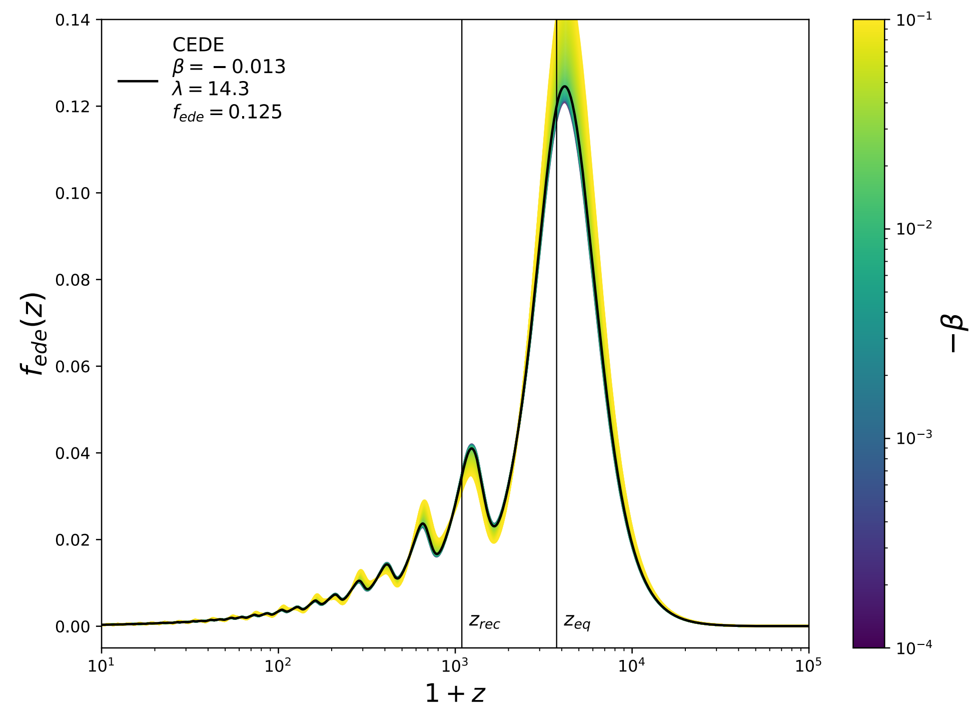


Background Numerical Solutions









Summary

- EDE promising resolution of Hubble tension, but suffers from a coincidence problem. Needs to contribute slightly before matter-radiation equality and end rapidly thereafter.
- Have proposed two new mechanisms to address this problem, both involving coupling to other components of the energy budget of the universe.
- If EDE scalar is coupled to neutrinos then it receives an energy injection when they become non-relativistic - around matter-radiation equality for an eV neutrino mass.
- Displaces scalar up its potential yielding onset of EDE without need to tune the scalar's mass.
- Proposal on verge of being excluded by neutrino mass bounds (Planck - $m<0.54$eV; Planck + lensing + BAO - $m<0.12$eV (for LCDM).
- Crucially we need to to make sure that energy injection does not occur at too low a redshift, otherwise models will be disfavored.

Summary

- If EDE scalar is coupled to dark matter, then the dominance of dark matter at matter-radiation equality triggers the onset of a brief non-negligible contribution of EDE to the cosmic energy budget, also addressing the coincidence challenge of EDE models.
- Furthermore, the coupling alleviates the rather unnatural potentials that have been some of the better fits to the data
- In both cases, a full MCMC analysis is needed to understand the kind of fit our models have to joint cosmological datasets.
- In the case of neutrino-assisted EDE, that analysis has begun, but is not close to completion yet. In the case of chameleon EDE, we are currently completing the analysis.
- As with other suggestions of new physics, we might expect that it does not exist in a vacuum. These are first attempts to understand the consequences of coupling to other matter.

Thank You!