Early Dark Energy from Thermo-coupled Neutrinos

Anubhav Mathur

Dark Matter & Neutrinos
@ IHP Paris, May 2025

Based on arXiv/2411.09747 with Marc Kamionkowski

Overview

- Why bother?

  H_0 tension, early-time approaches, issues arising

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- How does it work?

  Background scalar, misaligned w/ quadratic coupling to SM ν

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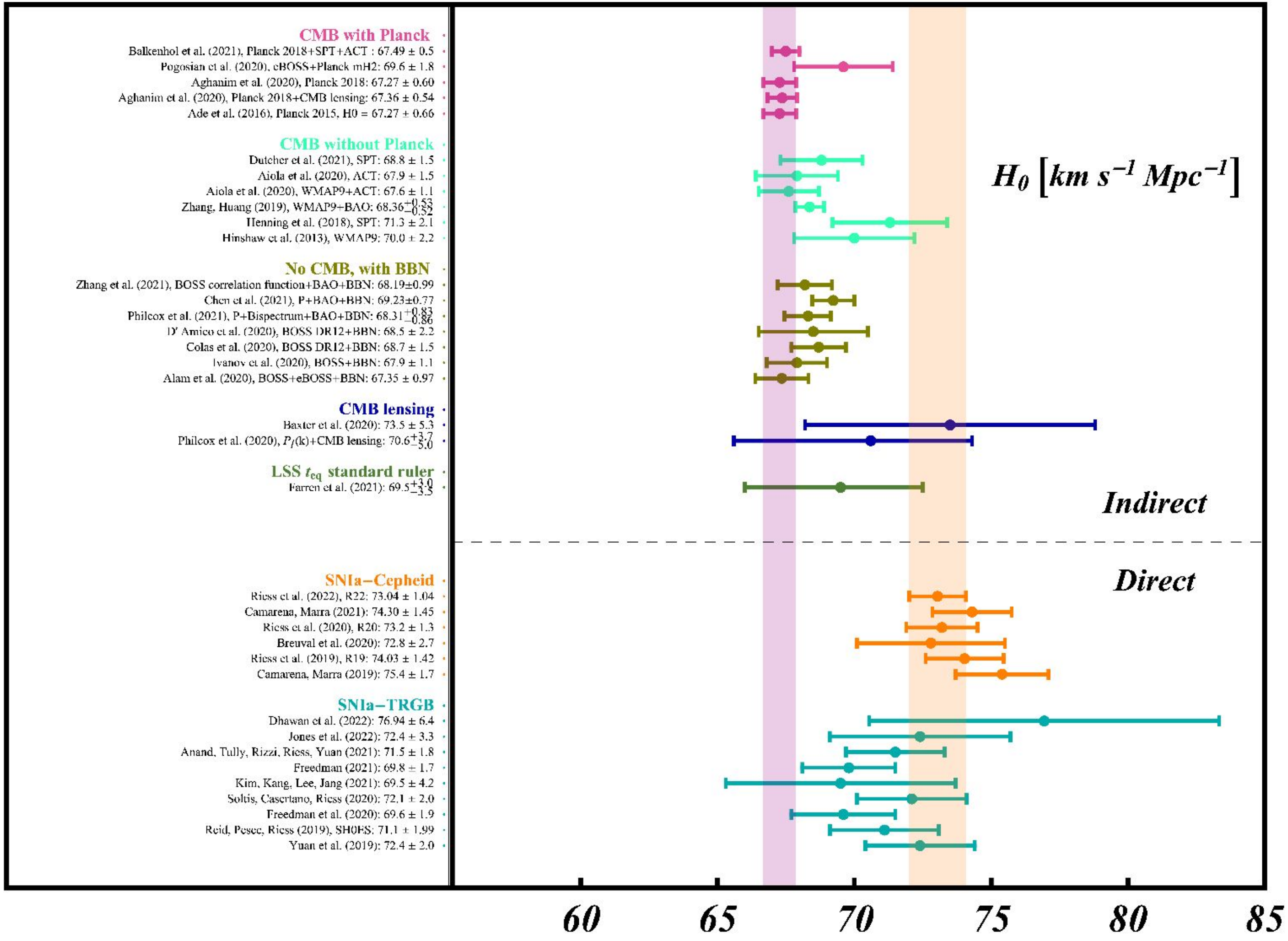
- Why bother?
  H_0 tension, early-time approaches, issues arising

- How does it work?
  Background scalar, misaligned w/ quadratic coupling to SM ν

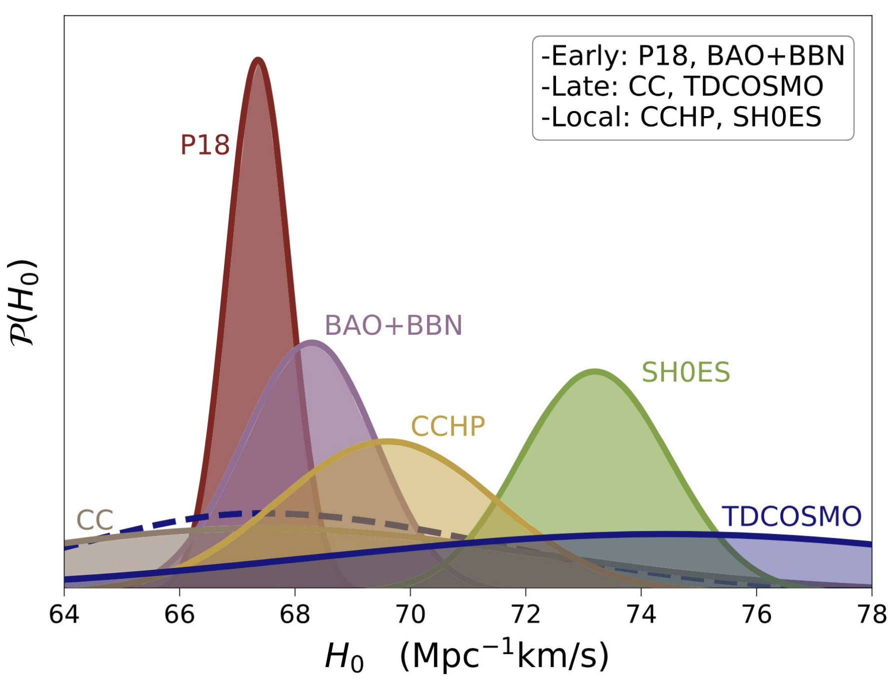
- Does it really work?
  Unique pheno, hints & prospects from new data


CMB with Planck
Balkenhol et al. (2021), Planck 2018+SPT+ACT : 67.49 ± 0.5
Pogosian et al. (2020), eBOSS+Planck mH2: 69.6 ± 1.8
Aghanim et al. (2020), Planck 2018: 67.27 ± 0.60
Aghanim et al. (2020), Planck 2018+CMB lensing: 67.36 ± 0.54
Ade et al. (2016), Planck 2015, H0 = 67.27 ± 0.66
CMB without Planck
Dutcher et al. (2021), SPT: 68.8 ± 1.5
Aiola et al. (2020), ACT: 67.9 ± 1.5
Aiola et al. (2020), WMAP9+ACT: 67.6 ± 1.1
Zhang, Huang (2019), WMAP9+BAO: $68.36^{+0.53}_{-0.52}$
Henning et al. (2018), SPT: 71.3 ± 2.1
Hinshaw et al. (2013), WMAP9: 70.0 ± 2.2
No CMB, with BBN
Zhang et al. (2021), BOSS correlation function+BAO+BBN: 68.19±0.99
Chen et al. (2021), P+BAO+BBN: 69.23±0.77
Philcox et al. (2021), P+Bispectrum+BAO+BBN: $68.31^{+0.83}_{-0.86}$
D' Amico et al. (2020), BOSS DR12+BBN: 68.5 ± 2.2
Colas et al. (2020), BOSS DR12+BBN: 68.7 ± 1.5
Ivanov et al. (2020), BOSS+BBN: 67.9 ± 1.1
Alam et al. (2020), BOSS+eBOSS+BBN: 67.35 ± 0.97
CMB lensing
Baxter et al. (2020): 73.5 ± 5.3
Philcox et al. (2020), P_l(k)+CMB lensing: $70.6^{+3.7}_{-5.0}$
LSS t_{eq} standard ruler
Farren et al. (2021): $69.5^{+3.0}_{-3.5}$
SNIa−Cepheid
Riess et al. (2022), R22: 73.04 ± 1.04
Camarena, Marra (2021): 74.30 ± 1.45
Riess et al. (2020), R20: 73.2 ± 1.3
Breuval et al. (2020): 72.8 ± 2.7
Riess et al. (2019), R19: 74.03 ± 1.42
Camarena, Marra (2019): 75.4 ± 1.7
SNIa−TRGB
Dhawan et al. (2022): 76.94 ± 6.4
Jones et al. (2022): 72.4 ± 3.3
Anand, Tully, Rizzi, Riess, Yuan (2021): 71.5 ± 1.8
Freedman (2021): 69.8 ± 1.7
Kim, Kang, Lee, Jang (2021): 69.5 ± 4.2
Soltis, Casertano, Riess (2020): 72.1 ± 2.0
Freedman et al. (2020): 69.6 ± 1.9
Reid, Pesce, Riess (2019), SH0ES: 71.1 ± 1.99
Yuan et al. (2019): 72.4 ± 2.0
$H_0\ [km\ s^{-1}\ Mpc^{-1}]$
Indirect
Direct
60
65
70
75
80
85

2203.06142

H_0 tension: status

- Mismatch across a range of experiments & observables (not just Planck, not just CMB!)



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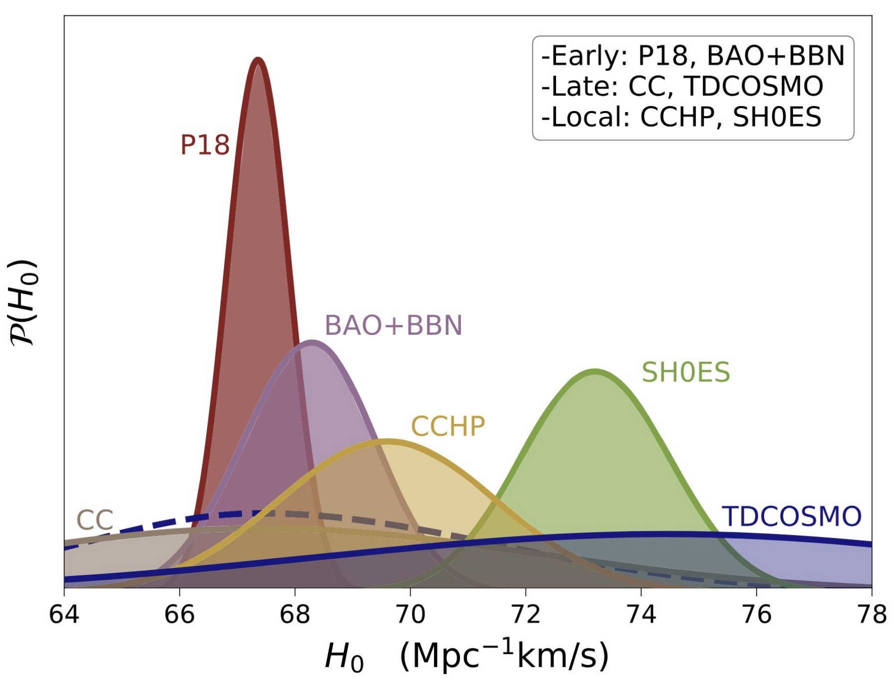
- Error bars continue to shrink yet tension persists—including ACT DR6 this year



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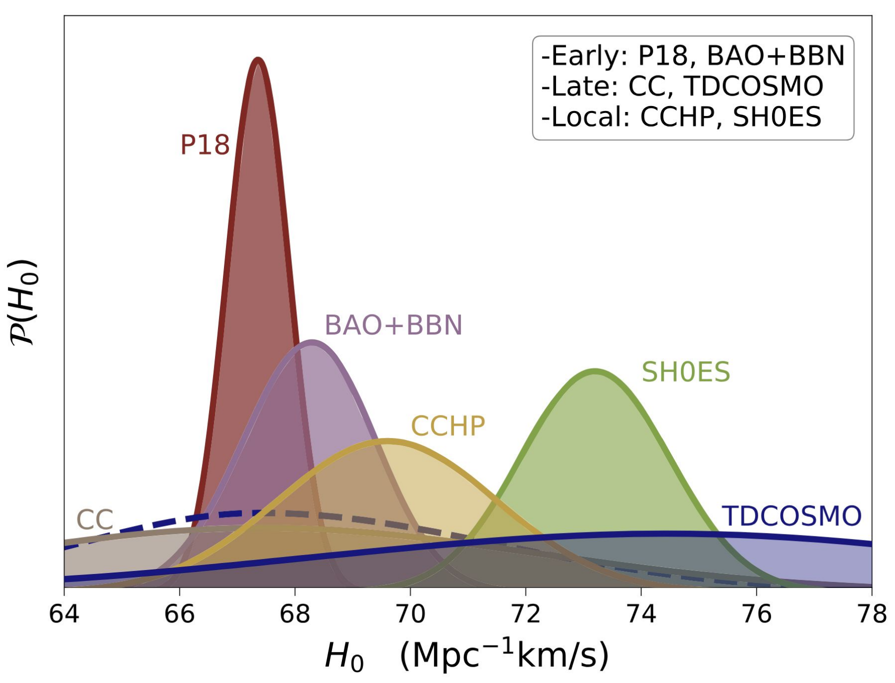
- Early-time inferences assume ΛCDM! Room for new physics



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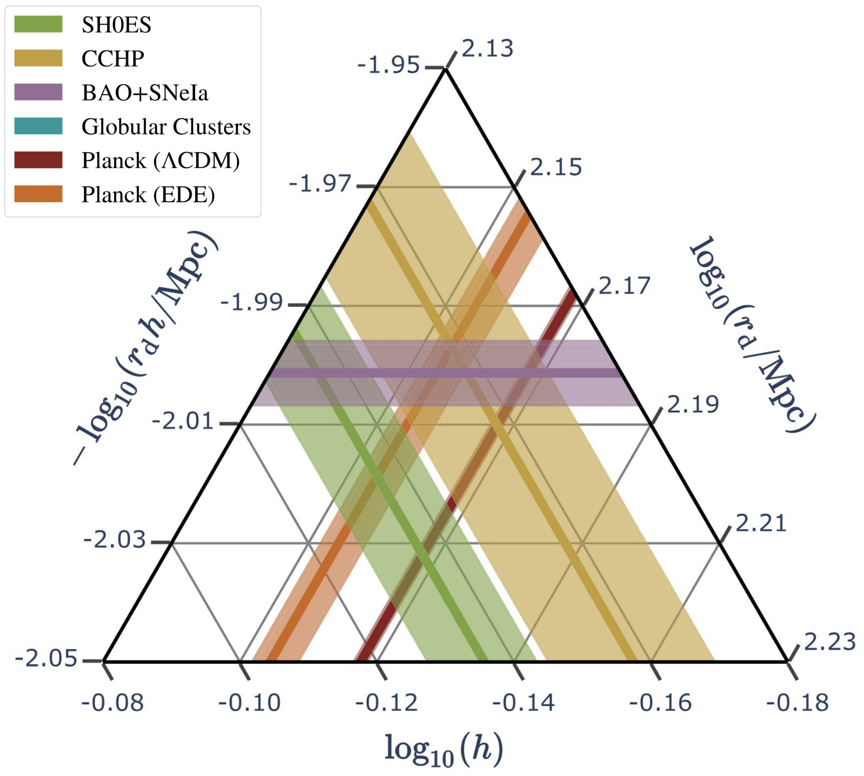
- Can add new physics at early/late times Latter often disfavoured as it worsens fit to BAOs and SN1a [2103.08723]



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- Can add new physics at early/late times
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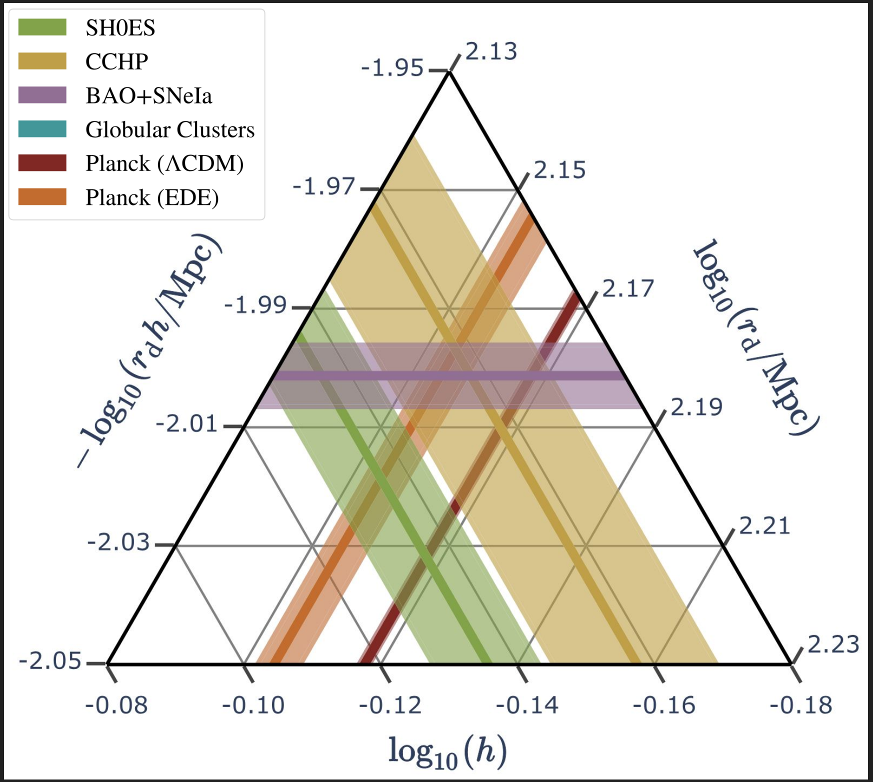
- But even early-time approaches may not be sufficient alone
  Very hard to attain SHoES' 73 km/s/Mpc



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Intervening at early times

$$r_d = \int_{z_{\rm CMB}}^{\infty} \frac{c_s(z)\,dz}{H(z)} = \frac{1}{\sqrt{3}H_{\rm CMB}} \int_{z_{\rm CMB}}^{\infty} \left(\frac{\rho(z)}{\rho(z_{\rm CMB})}\right)^{-1/2} \frac{dz}{\sqrt{1+R(z)}}$$

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Sound horizon: physical scale corresponding to peaks in angular power spectrum

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Concept: inject ~10% to the total energy density just before recombination, which subsequently disappears

$$H_0 = \sqrt{3}H_{\rm CMB}\theta_s \frac{\int_0^{z_{\rm CMB}} dz\,(\rho(z)/\rho_0)^{-1/2}}{\int_{z_{\rm CMB}}^{\infty} \frac{dz}{\sqrt{1+R(z)}}(\rho(z)/\rho(z_{\rm CMB}))^{-1/2}}$$

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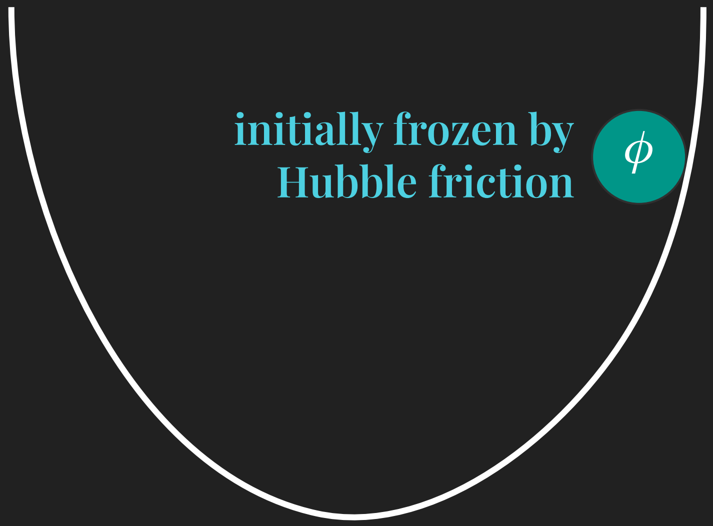
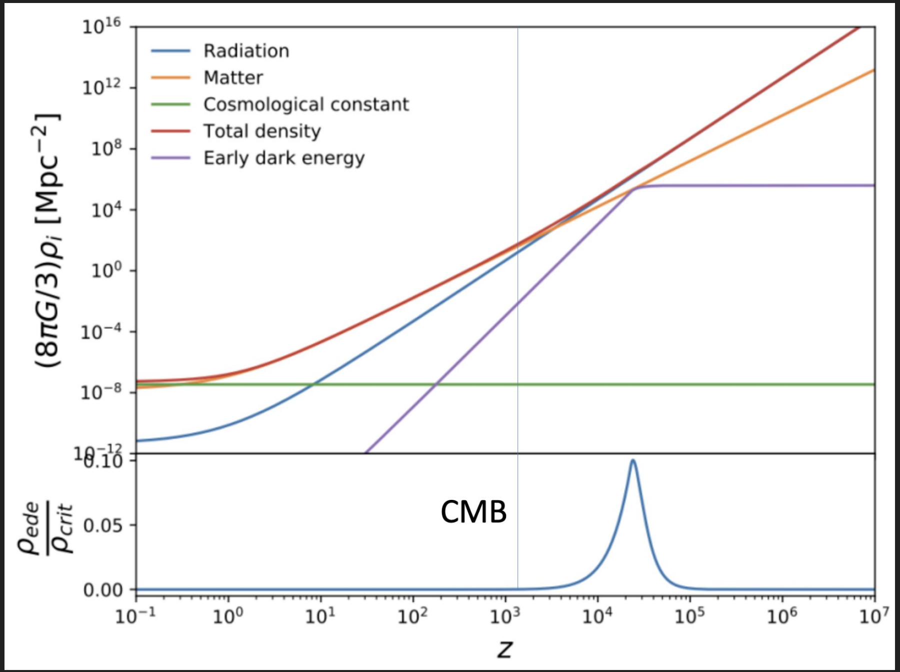
Alternatives: accelerated recombination, higher $N_{\rm eff}$ (with non-trivial dynamics), delay ν free-streaming with strong self-interactions

Enter EDE

New component: CC at early times



initially frozen by
Hubble friction



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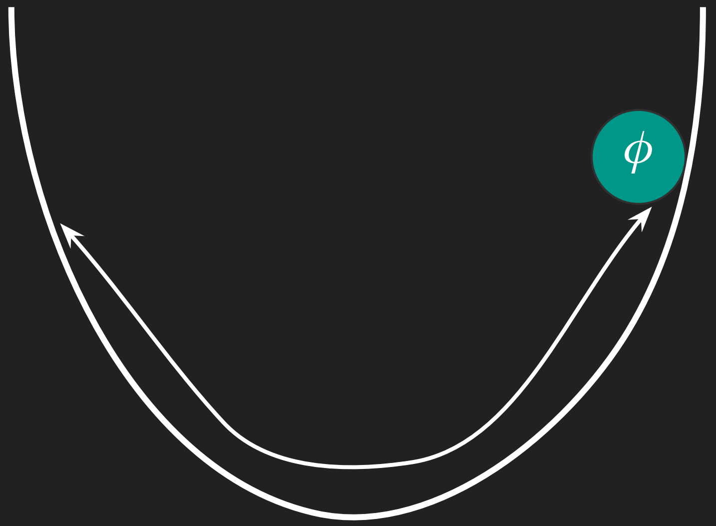
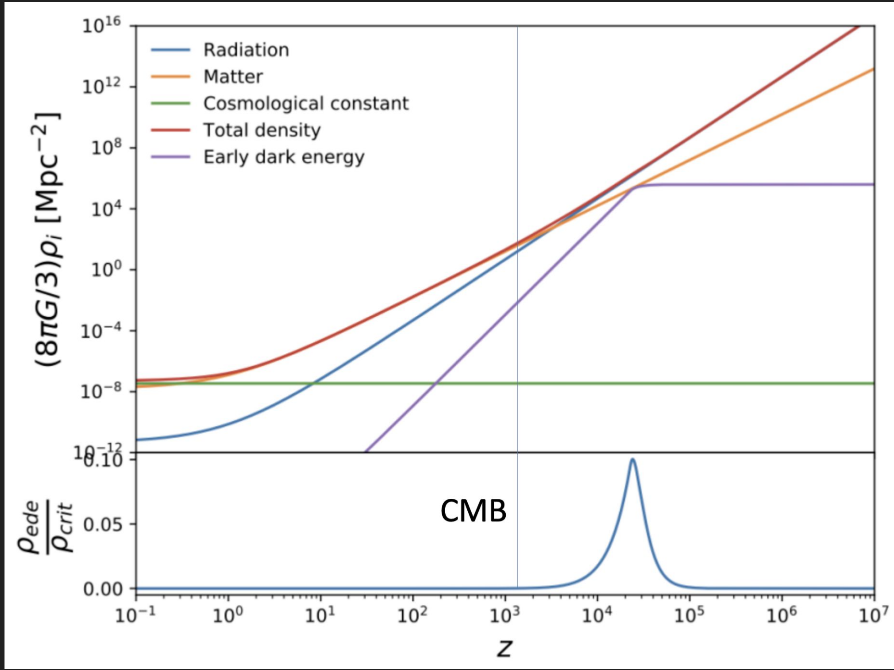
New component: CC at early times then redshifts faster than radiation





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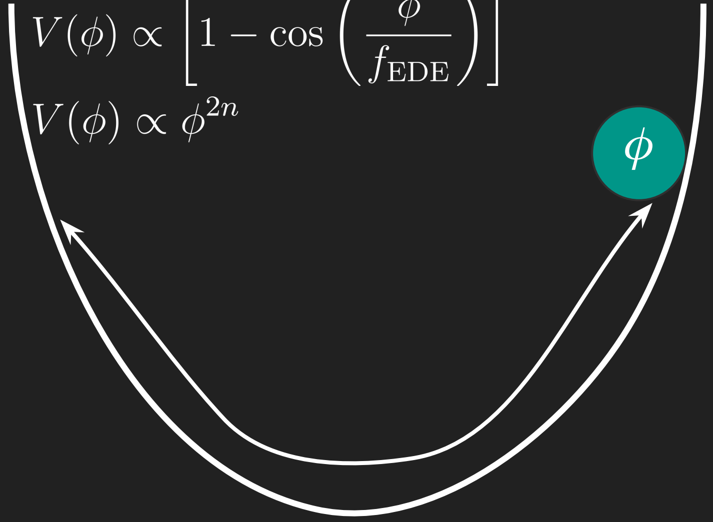
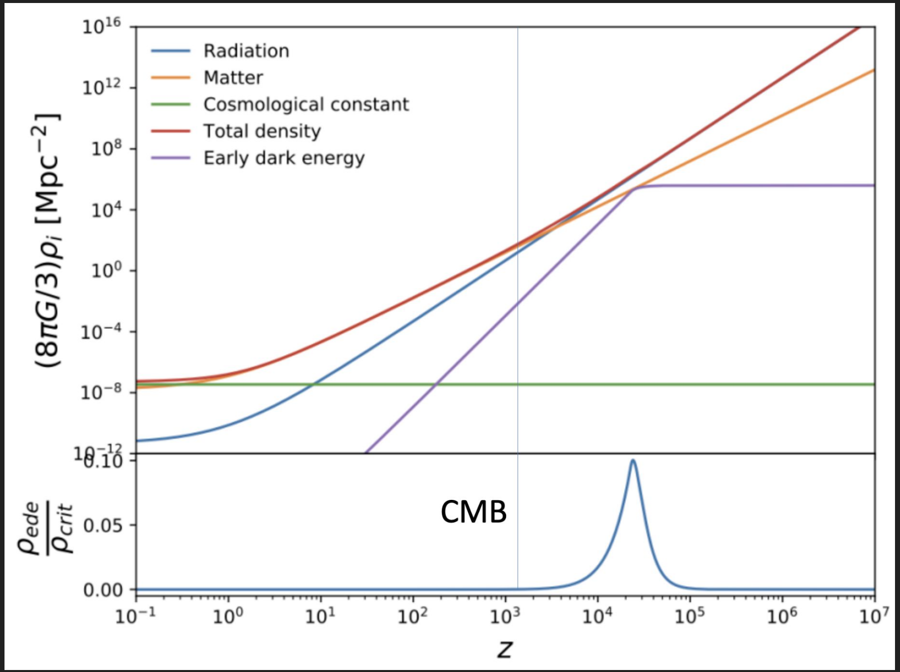
Enter EDE

New component: CC at early times then redshifts faster than radiation in steep potential (n = 2–3, depending on model)

$$V(\phi) \propto \left[1 - \cos\left(\frac{\phi}{f_{\rm EDE}}\right)\right]^n$$

$$V(\phi) \propto \phi^{2n}$$





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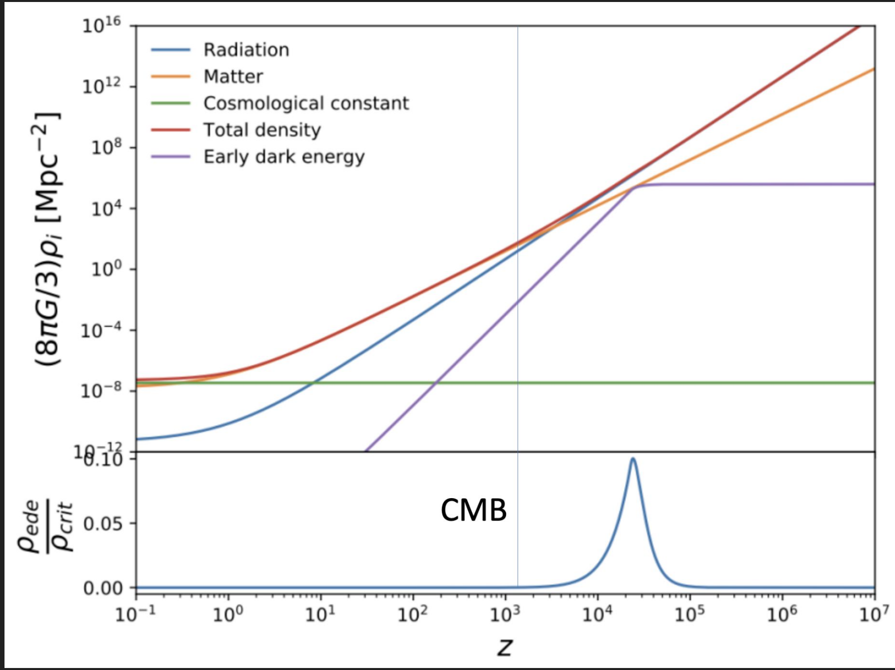
Fleshing out the physics

Unsatisfactory from a particle POV



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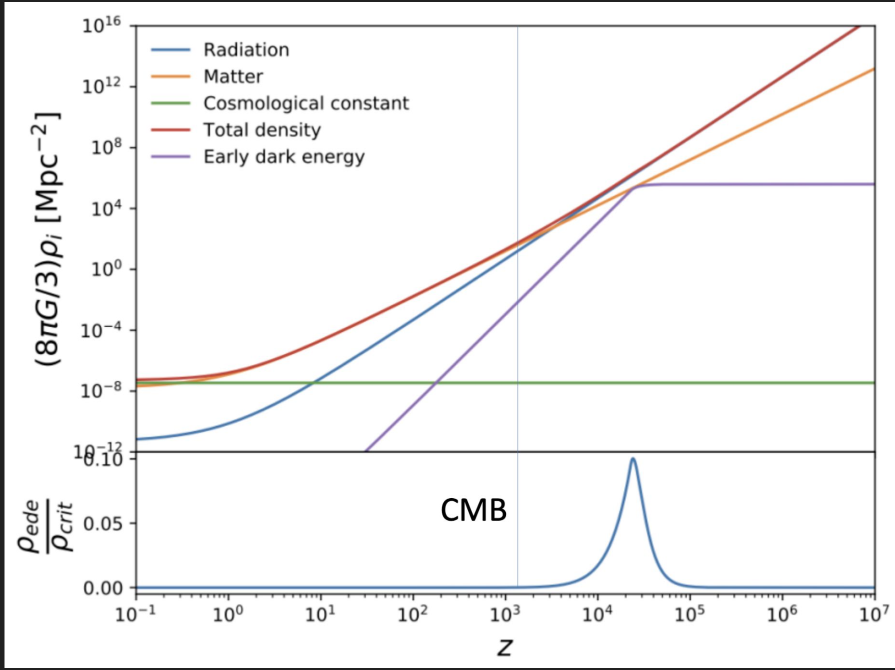
Unsatisfactory from a particle POV:

1. Steepness of the potential
   i.e. why redshift so rapidly?



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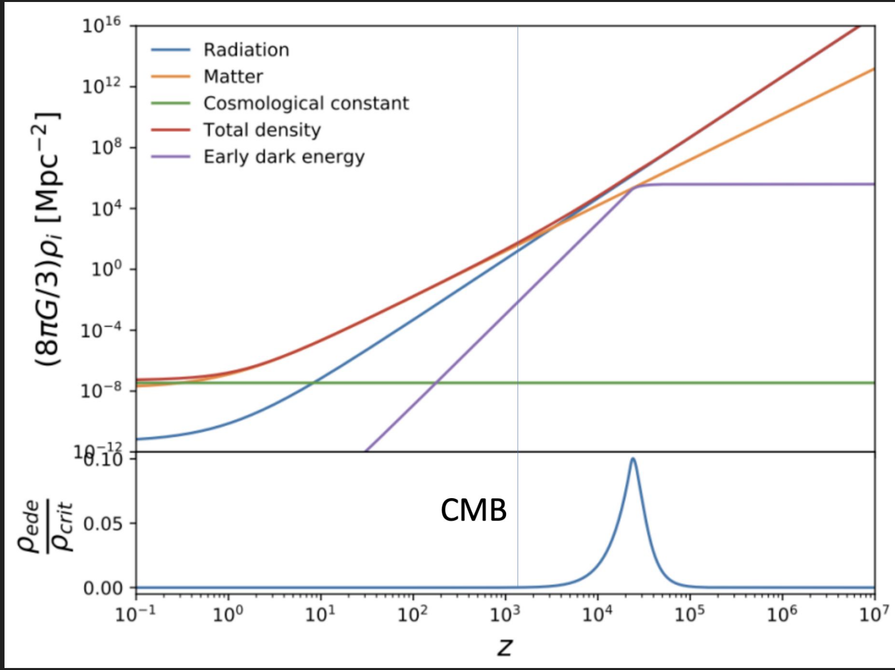

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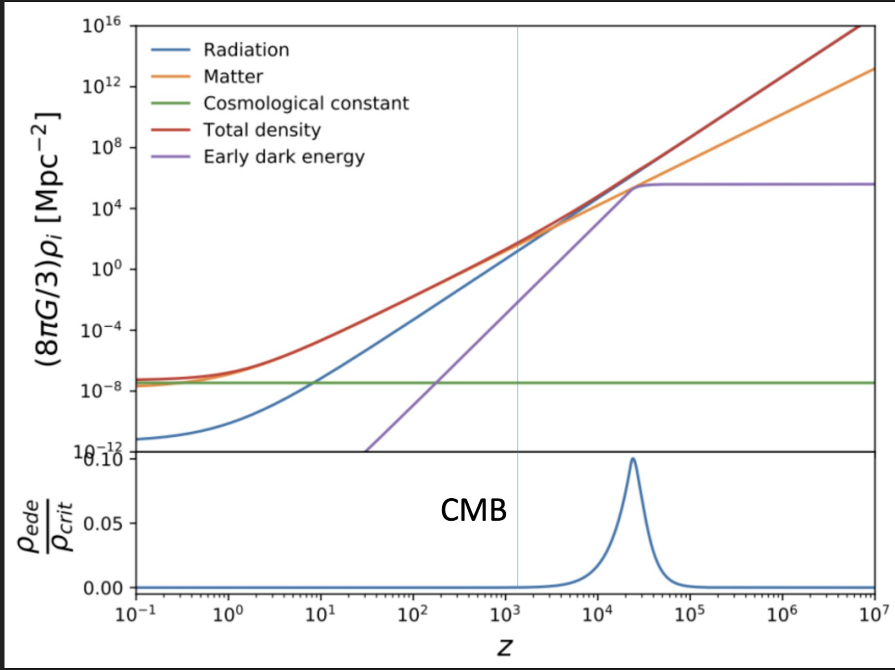
3. Source of the initial conditions
   i.e. why displaced from min?



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Model-building ideas

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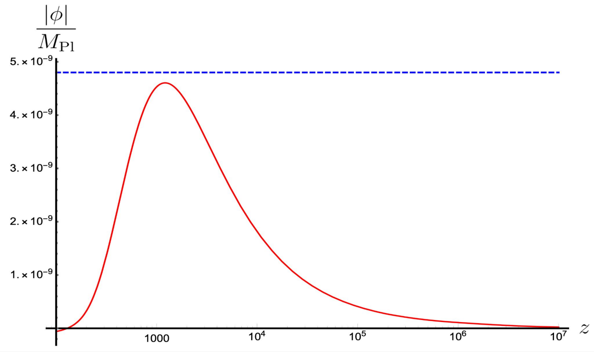
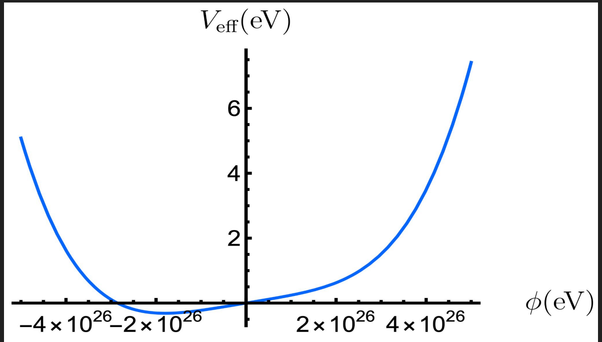
- Neutrino-assisted EDE
  Conformal coupling to neutrinos, leading to a *kick* when they become non-relativistic





1911.11760, 2302.09091

Model-building ideas

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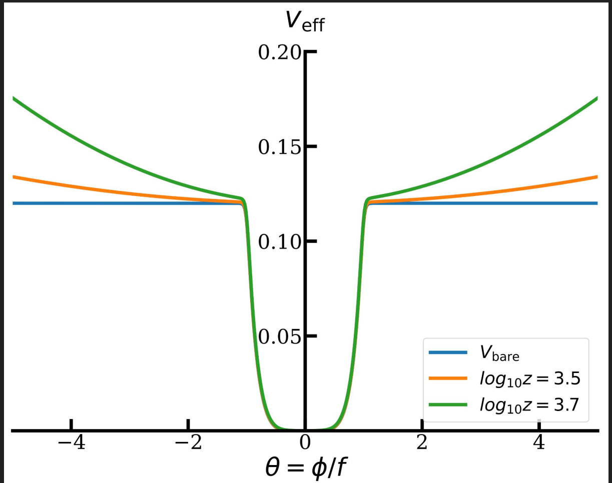
- Trigger early dark sectors
  Quadratic coupling to DM activates during matter domination, *pushes* scalar off a plateau independent of initial conditions



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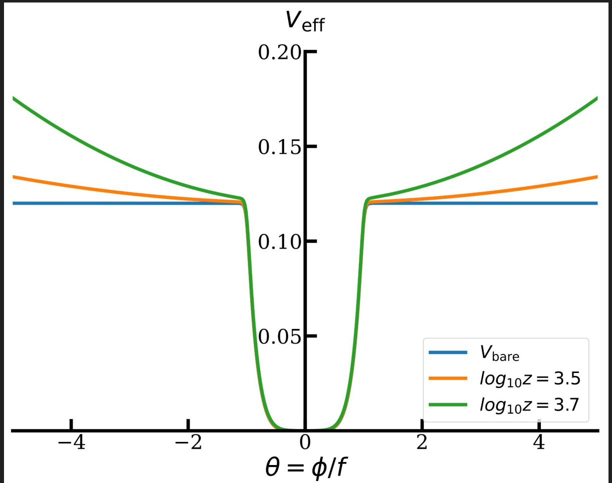

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All options imperfect: experimental constraints, naturalness, mysterious/unusual bare potential

Thermo-coupling

Thermo-coupling: model

$$\mathcal{L} \supset -\frac{\epsilon m_\psi}{M_{\mathrm{Pl}}^2}\phi^2\bar{\psi}\psi$$

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Background scalar $m_\phi < H(z_{\mathrm{CMB}}) \sim 10^{-29}$ eV,
Initial vev $\sim 0.1\, M_{\mathrm{Pl}}$

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Highly suppressed ~ 10^{45} GeV,
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Upshot: scalar and fermion co-evolve, each contributing to the effective potential for the other

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$$m_{\psi,\mathrm{eff}} = m_\psi\left(1+\epsilon\frac{\phi^2}{M_{\mathrm{Pl}}^2}\right)$$

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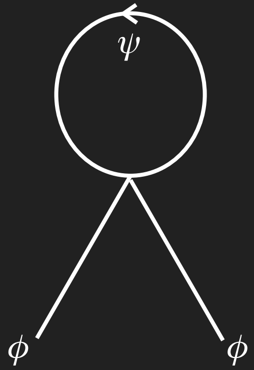

$$\frac{\epsilon m_\psi^2}{4\pi^2 M_{\rm Pl}^2}\Lambda_{\rm UV}^2$$

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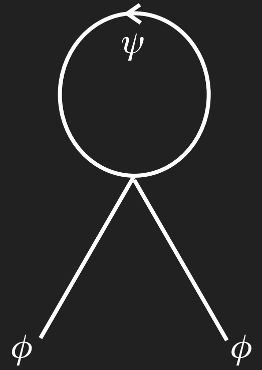

All scales light,
no other SM couplings
$\Rightarrow$ quantum corrections

$$\frac{\epsilon m_\psi^2}{4\pi^2 M_{\mathrm{Pl}}^2}\Lambda_{\mathrm{UV}}^2$$

are small

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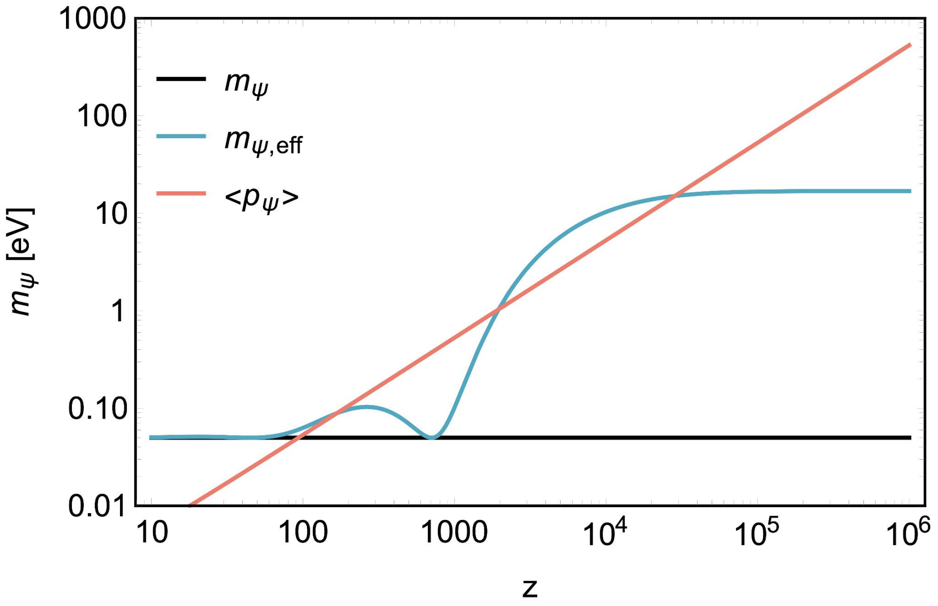

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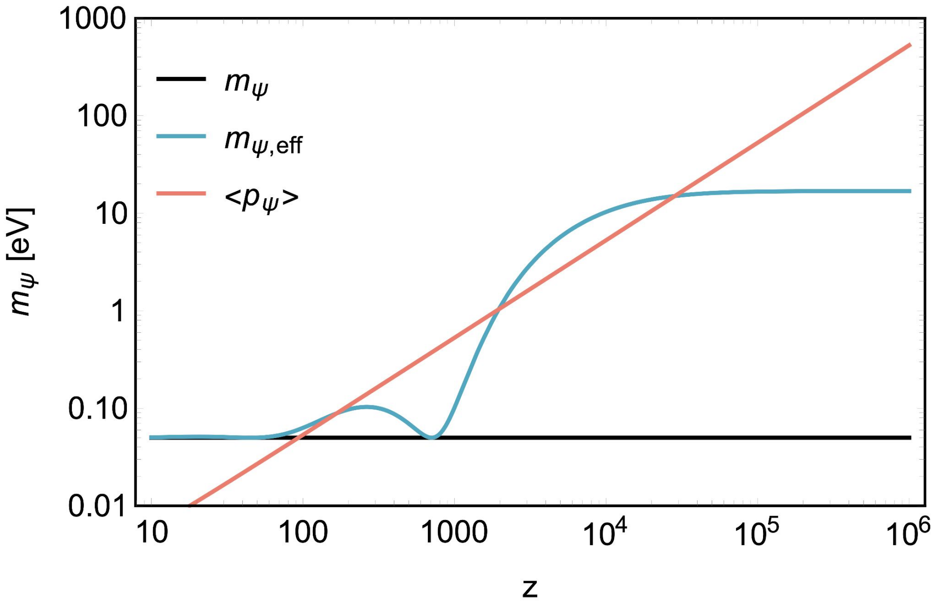

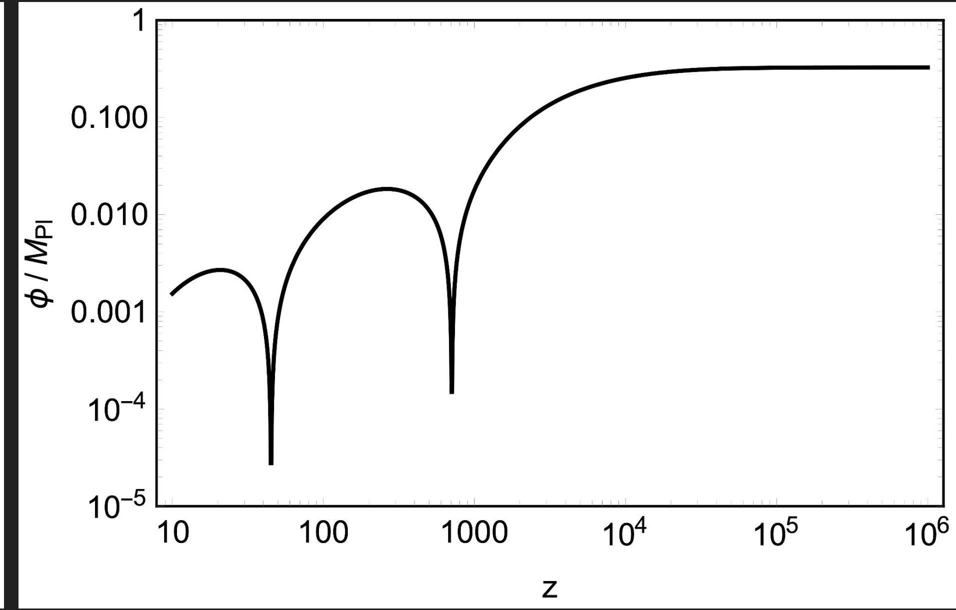

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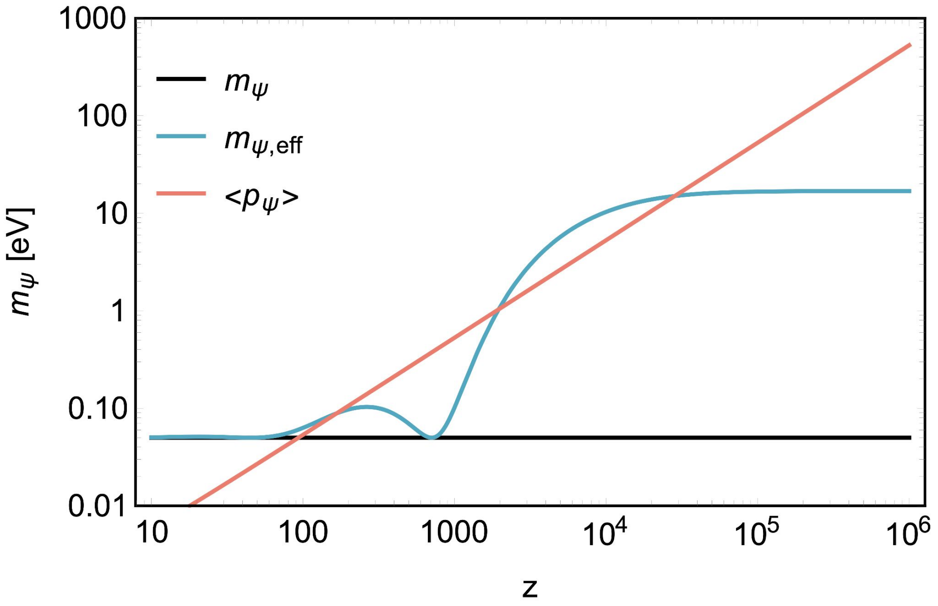

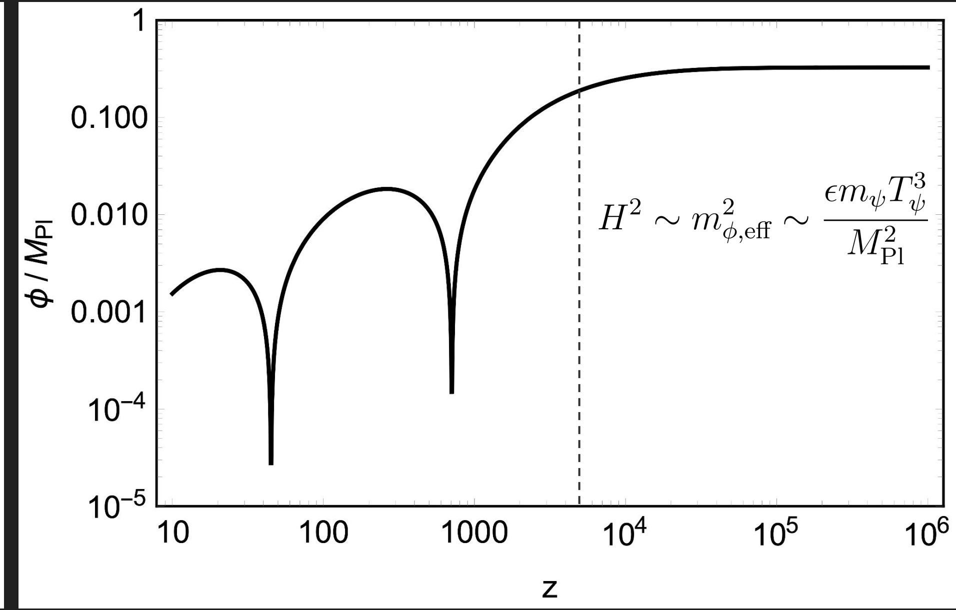

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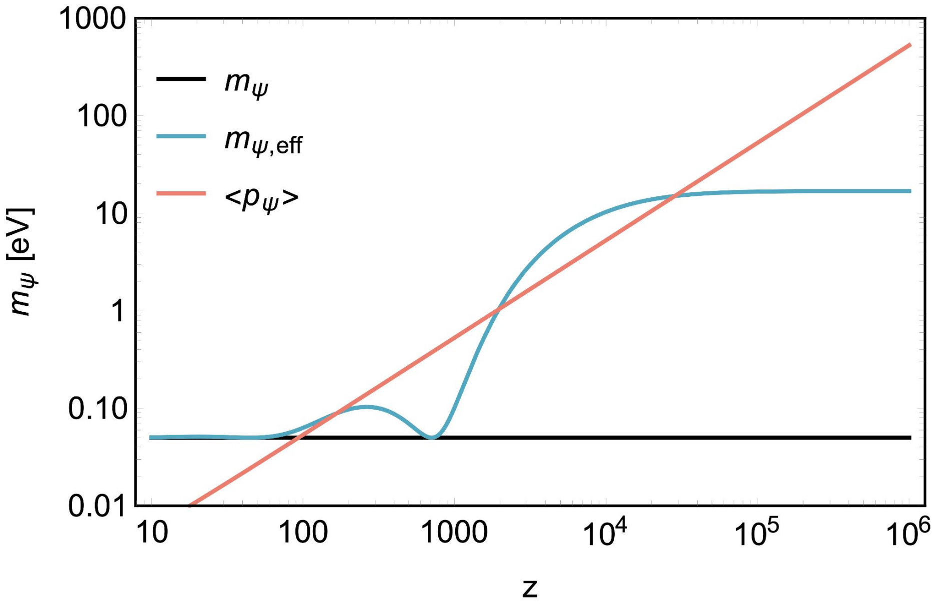

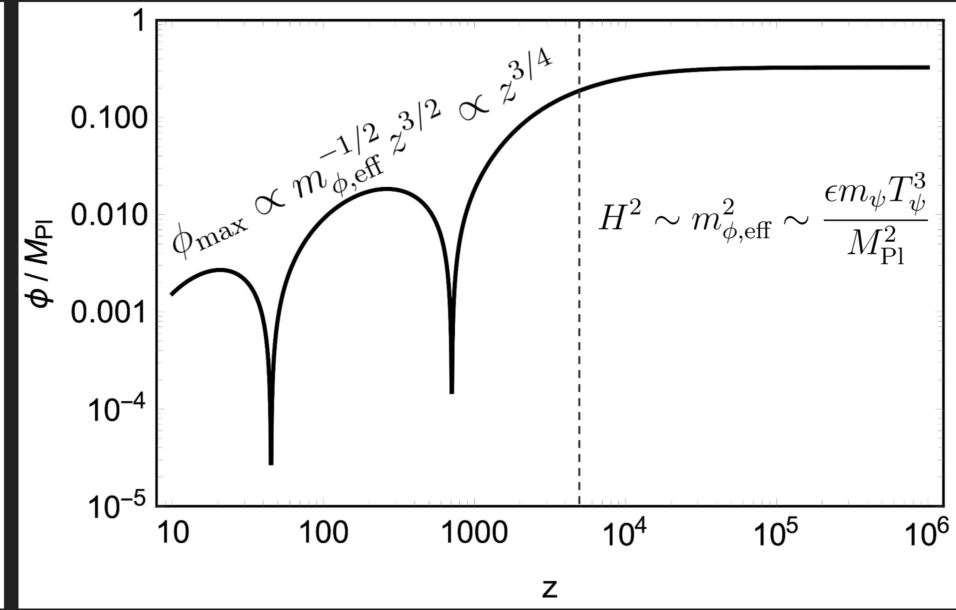

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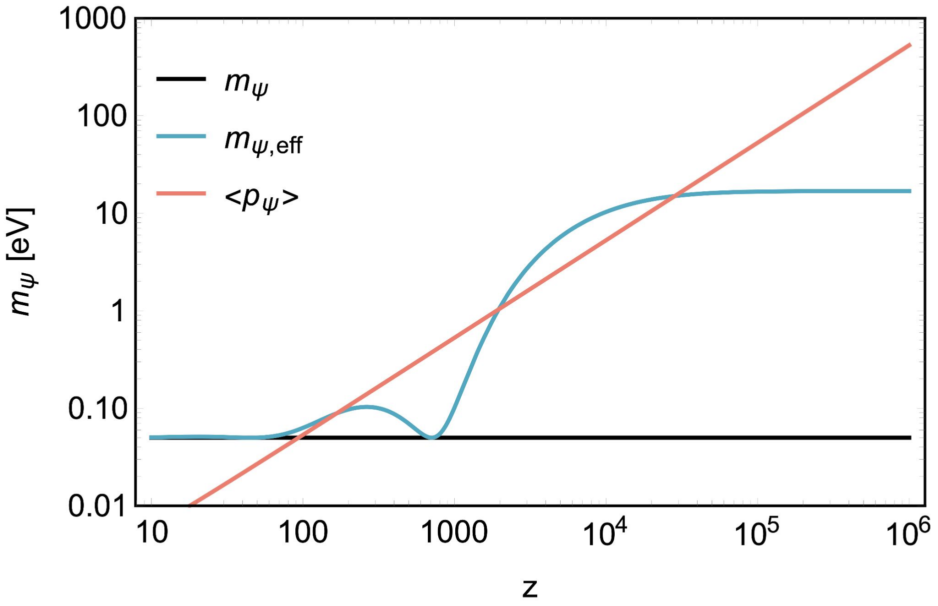

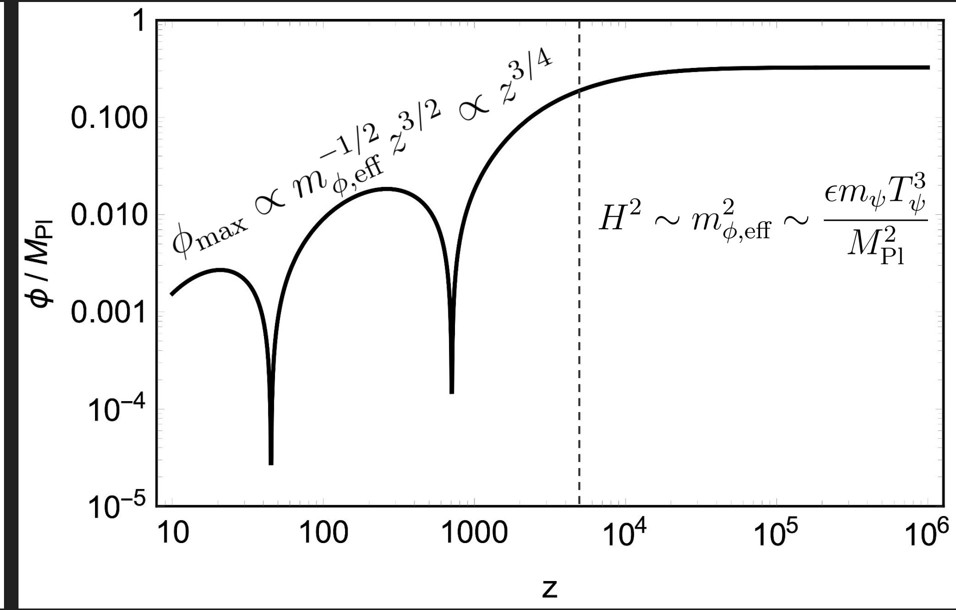

$$\rho_{\rm TCEDE} = \rho_\psi(m_{\psi,\rm eff}, T_\psi) - \rho_\psi(m_\psi, T_\psi)$$

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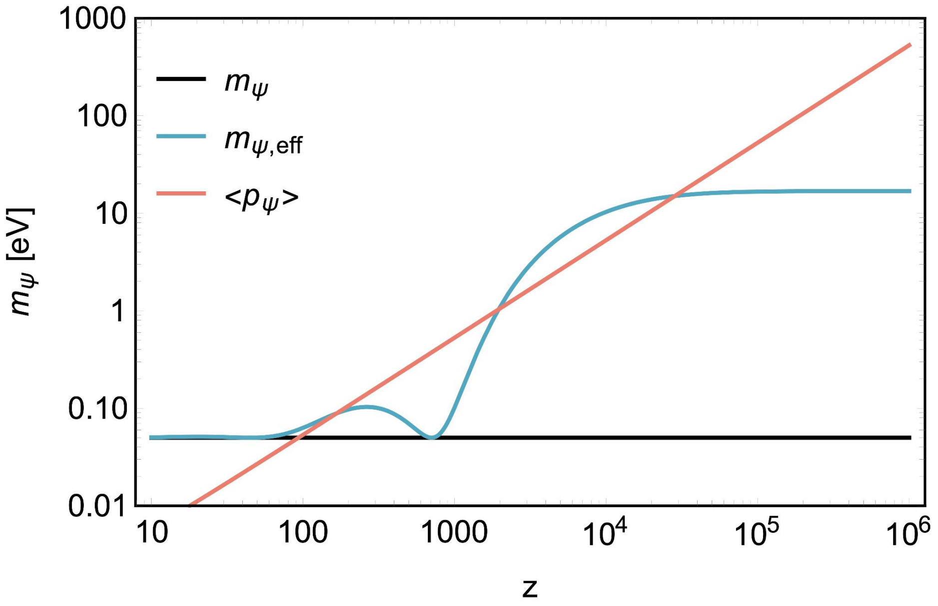

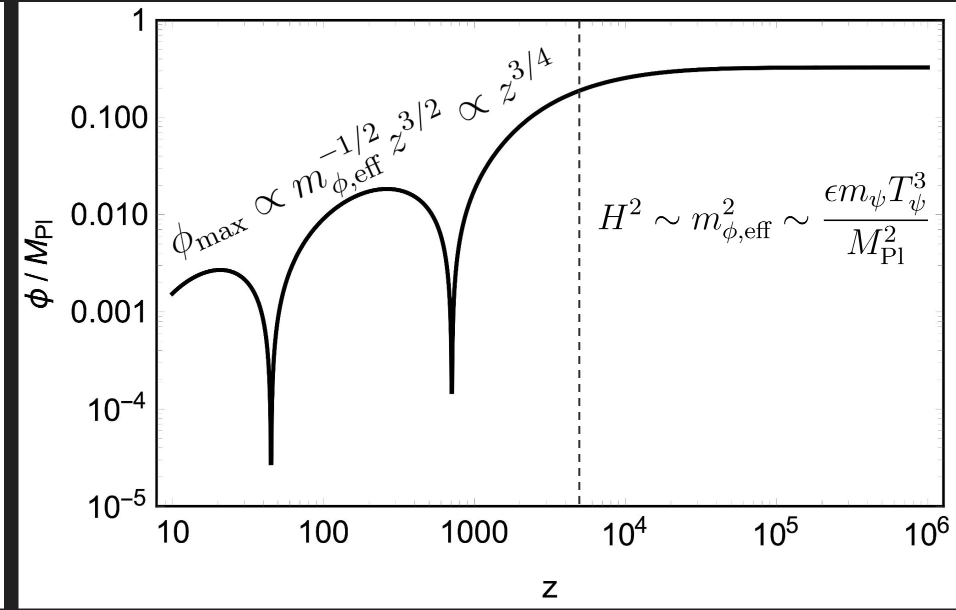

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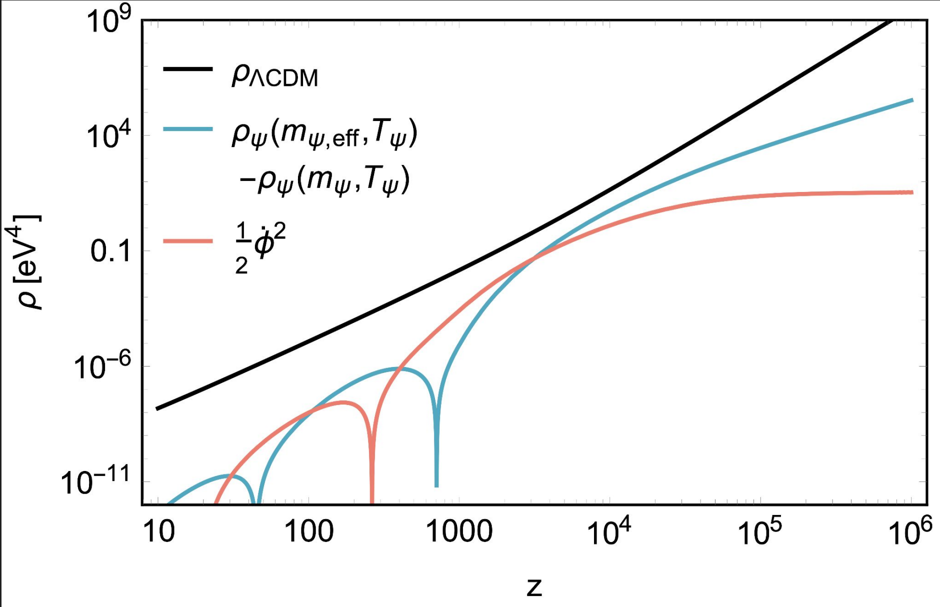

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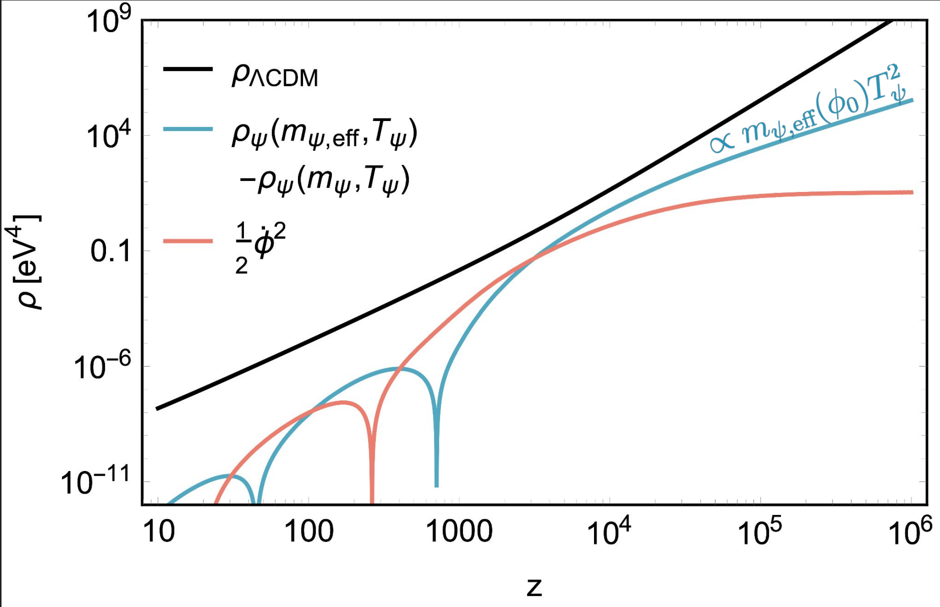

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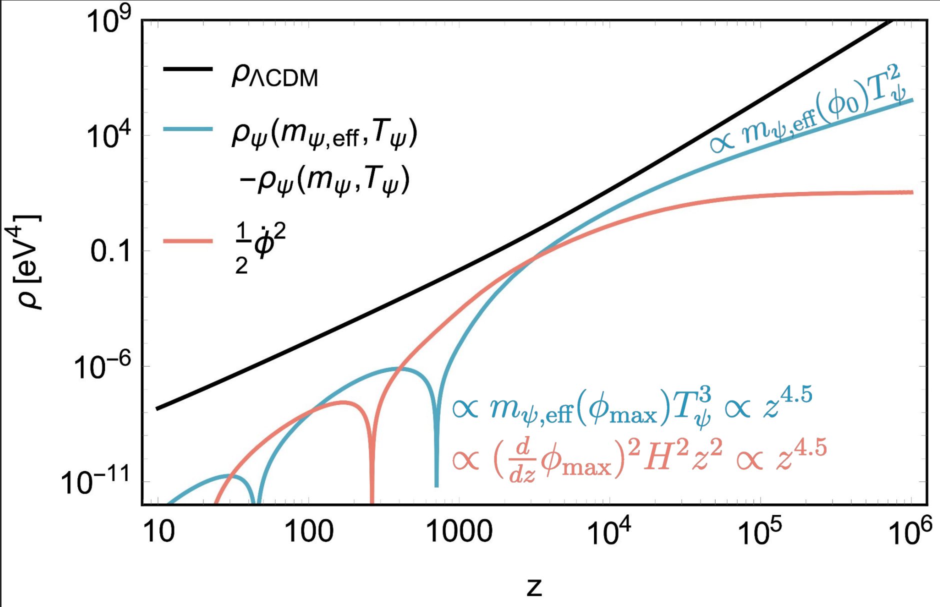

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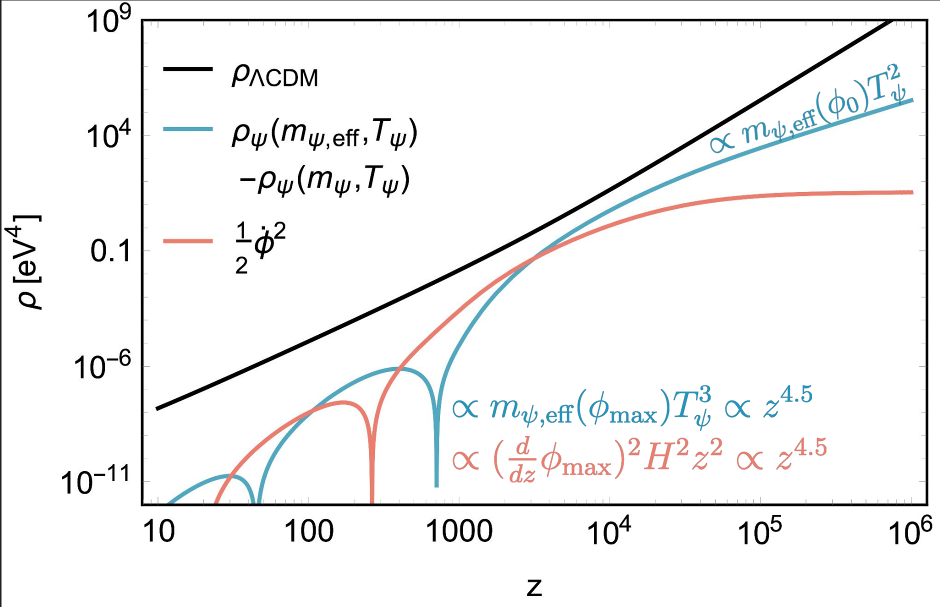

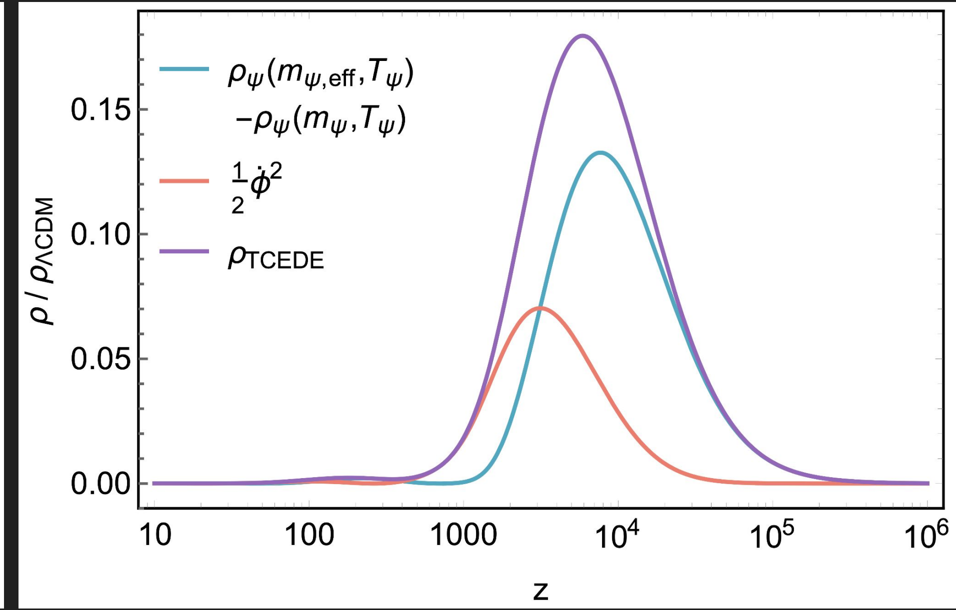

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$$\mathcal{L} \supset -\frac{\epsilon m_\psi}{M_{\rm Pl}^2}\phi^2\bar{\psi}\psi$$

$$1+\frac{\delta H_0}{H_0} \approx \frac{\int_{z_{\rm CMB}}^{\infty} \frac{dz}{\sqrt{1+R}}\rho_{\Lambda{\rm CDM}}^{-1/2}}{\int_{z_{\rm CMB}}^{\infty} \frac{dz}{\sqrt{1+R}}\left(\rho_{\Lambda{\rm CDM}}+\rho_{\rm TCEDE}\right)^{-1/2}} \times \frac{\int_0^{z_{\rm CMB}} dz\left(\rho_{\Lambda{\rm CDM}}+\rho_{\rm TCEDE}\right)^{-1/2}}{\int_0^{z_{\rm CMB}} dz\,\rho_{\Lambda{\rm CDM}}^{-1/2}}$$

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Provided ϕ ultralight & m_ν fixed, only 2 parameters

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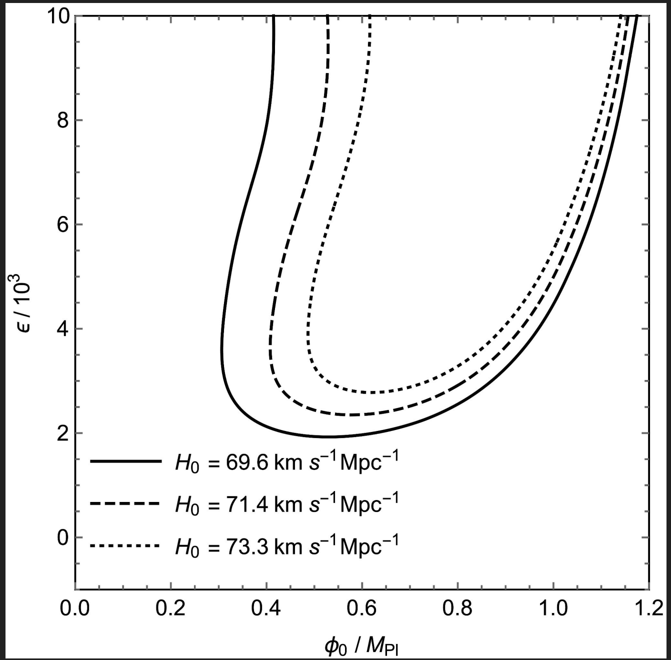

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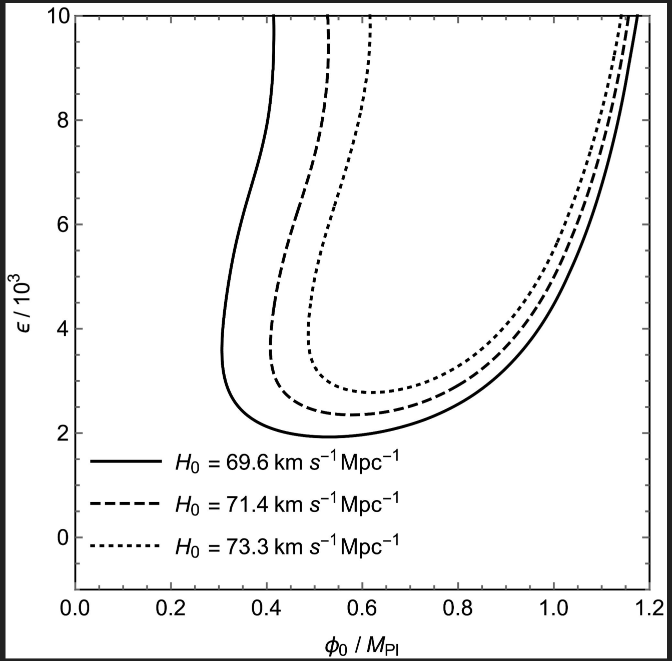
Set by:

1. $f_{\rm EDE} \sim 10\% \Rightarrow m_{\psi,\rm eff}(\phi_0) \approx 200\, m_\psi \sim 10$ eV

$$f_{\rm EDE}\frac{3M_{\rm Pl}^2 H^2(z_{\rm MRE})}{8\pi} = \rho_\psi(m_{\psi,\rm eff}(\phi_0), T_\psi) - \rho_\psi(m_\psi, T_\psi)$$



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2. Scalar dynamical at matter-radiation equality

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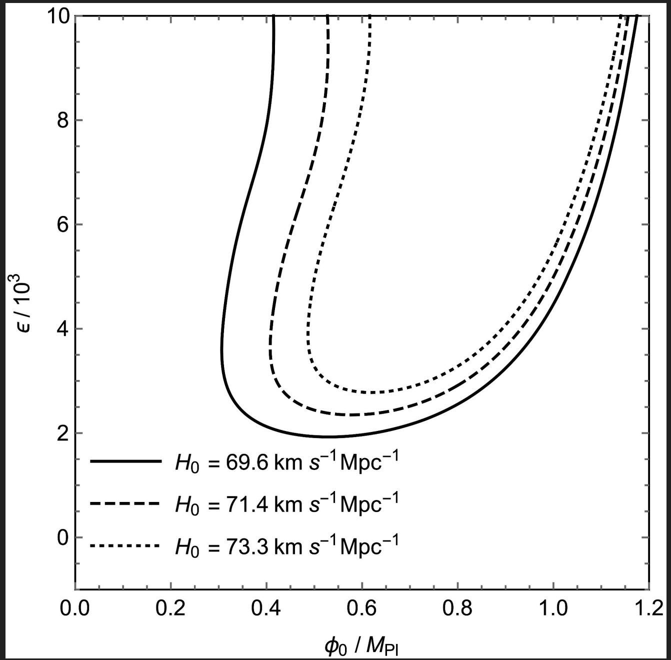
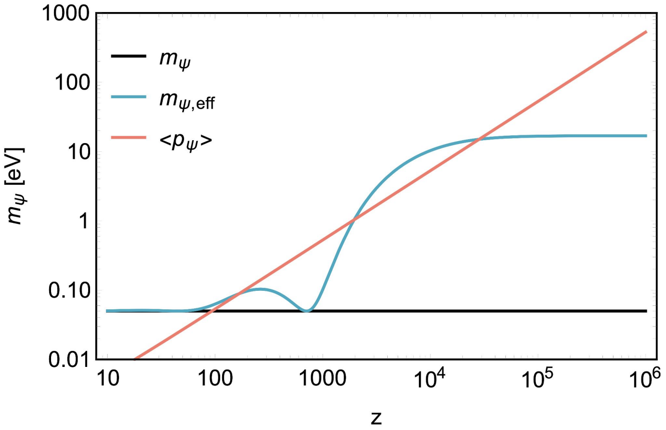
$$H^2(z_{\rm MRE}) \approx m_{\phi,\rm eff}^2(z_{\rm MRE}) \approx \frac{2.2\epsilon m_\psi}{6M_{\rm Pl}^2}T_\psi^3(z_{\rm MRE})$$



What's next?

- Full perturbation analysis with CLASS needed to quantify change in combined fit to data, esp. due to mass-varying neutrino



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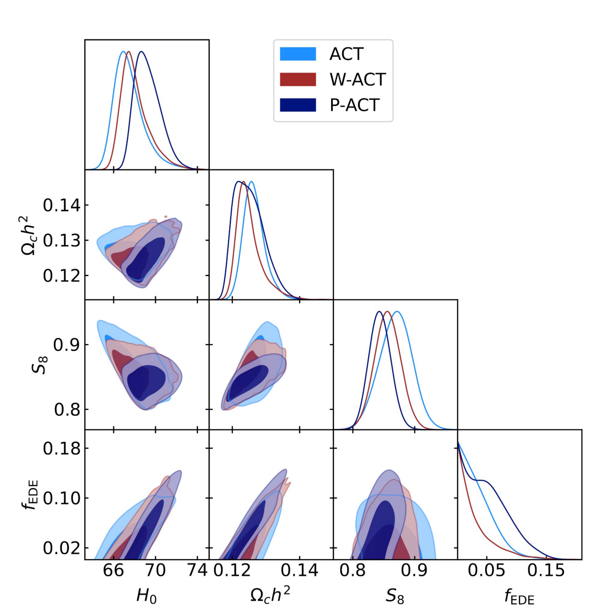

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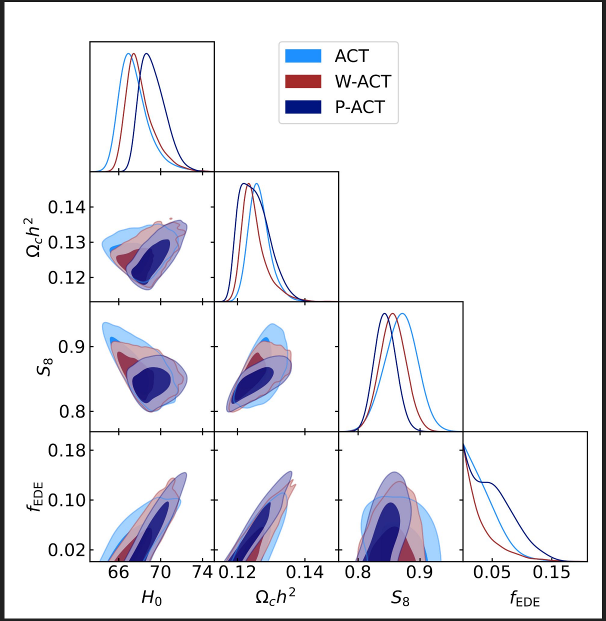

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Tony Zhou (NYU)

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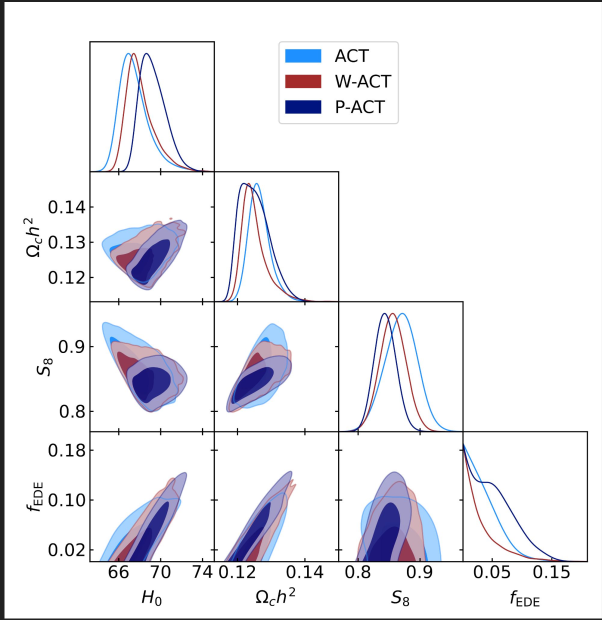

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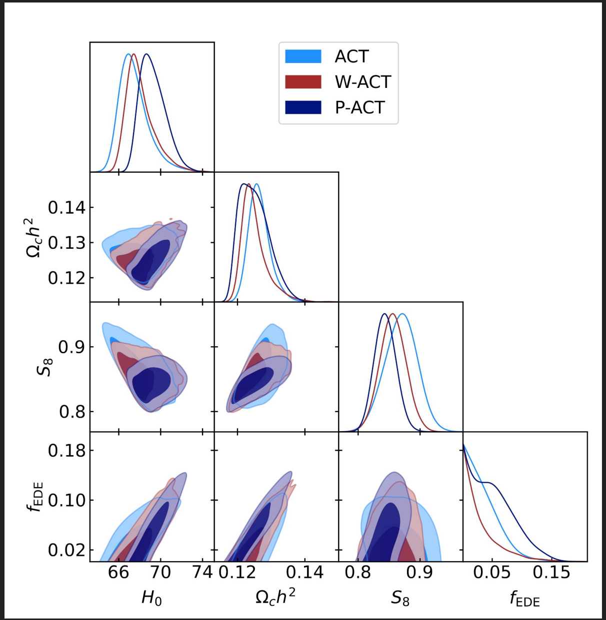
- Still useful as a (relatively) clean model with all the unusual features required to budge H_0



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