Unifying early and late dark energy

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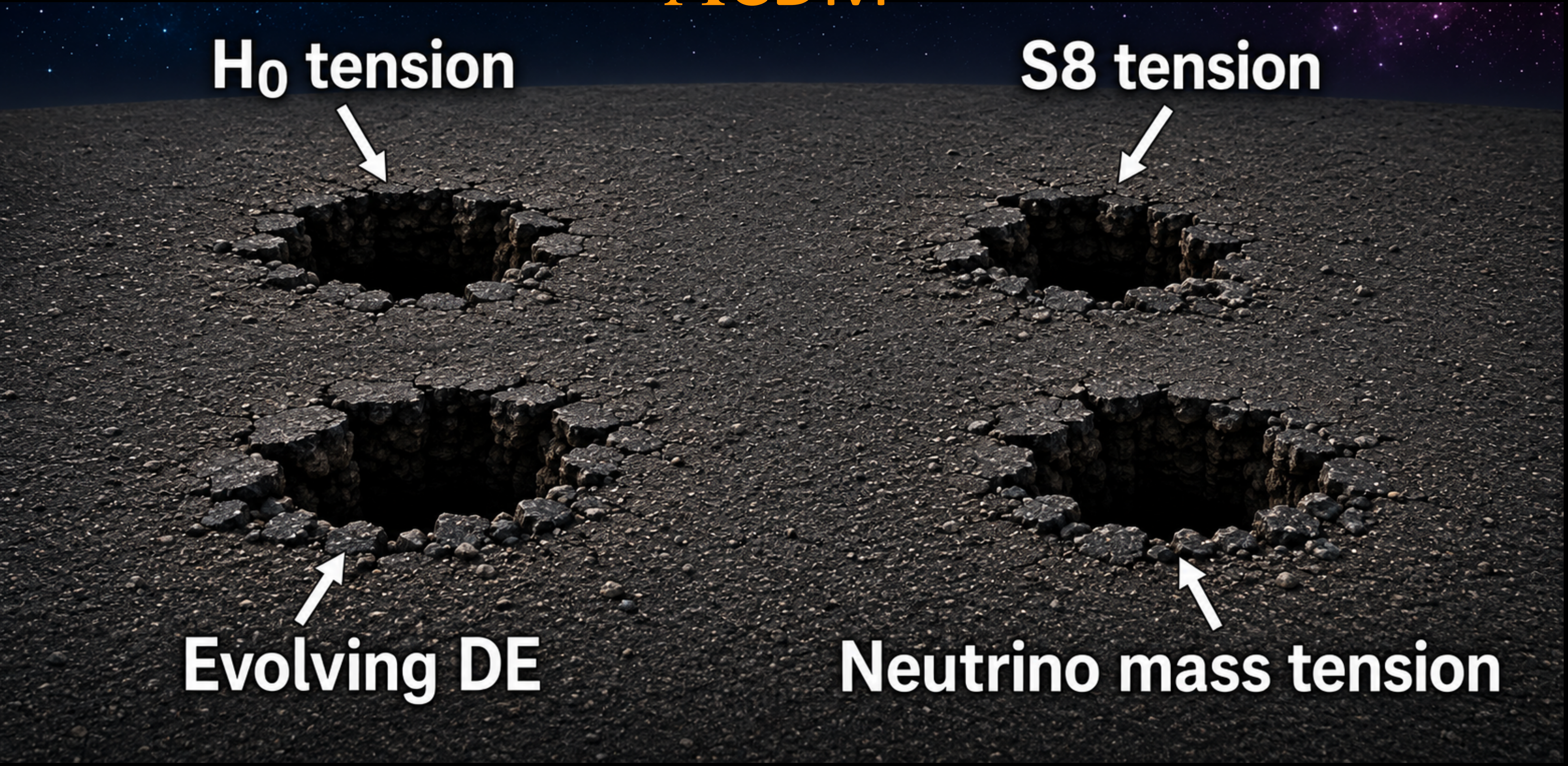
W/ Giare - 2605.26116
W/ Ramadan & Karwal - 2309.08082

ΛCDM



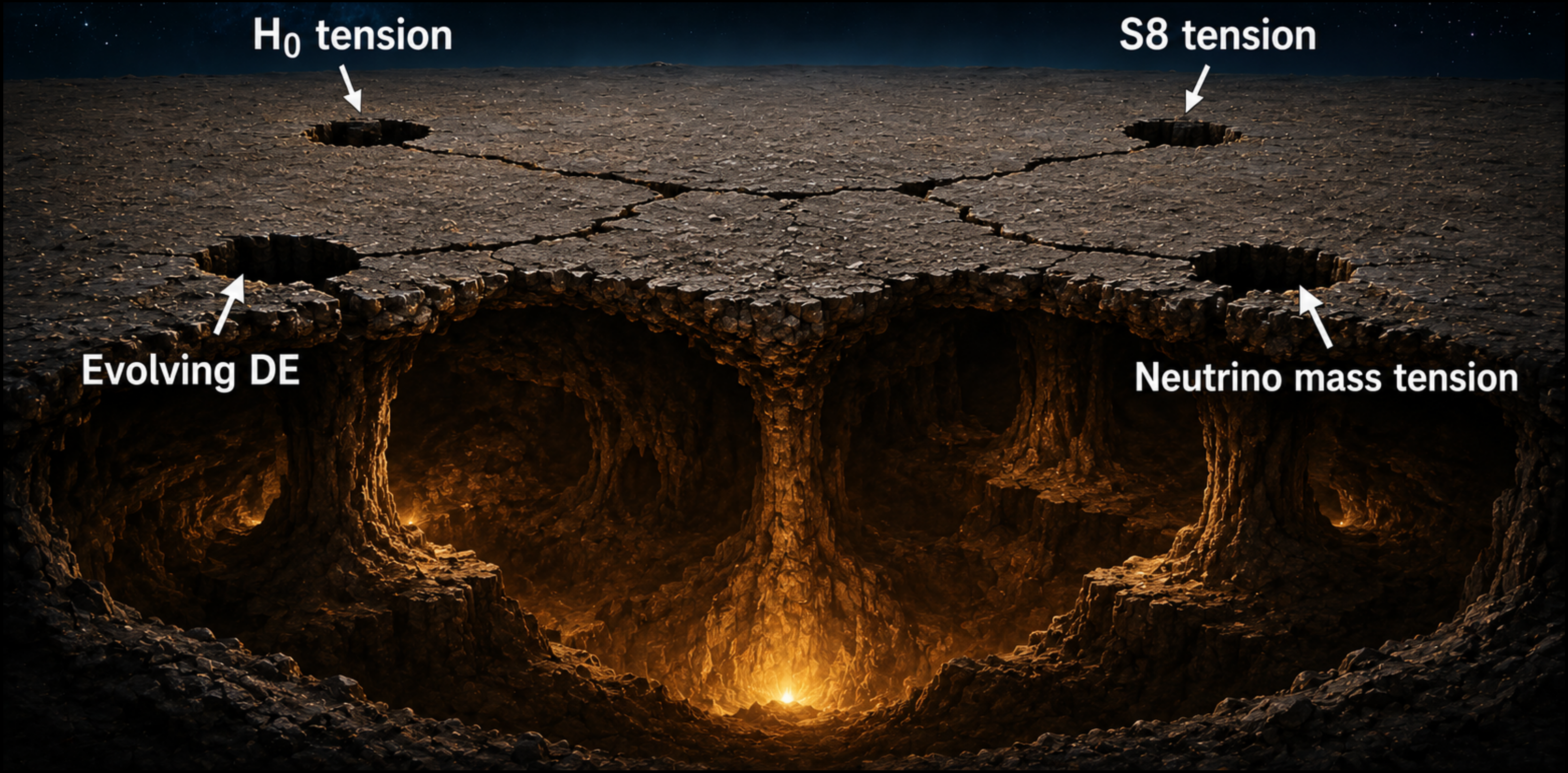
Cosmic anomalies

Discrepancies at the 1-7σ level:

- Hubble tension $\sim 5-7\sigma$
- DE appears to be evolving (DESI) $\sim 2.8\sigma - 4.2\sigma$
- S8 tension $\sim 3\sigma$
- Neutrino mass tension $\sim 2.5-5\sigma$
- Others at the 1-2σ level

What are these telling us?

ΛCDM



Are we seeing evidence for one coherent extension of ΛCDM,
or multiple unrelated cracks in different epochs?

Cosmic anomalies

Discrepancies/anomalies/tensions at the 1-7σ level:

- Hubble tension $\sim 5 - 7\sigma$
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Today: can we unify these phenomena?

Cosmic anomalies

Hubble tension:

Distance ladder: $$H_0 = 73.3 \pm 1.04\,\mathrm{km/s/Mpc}$$ **Riess et al. (2021)**

CMB: $$H_0 = 67.4 \pm 0.5\,\mathrm{km/s/Mpc}$$ **Planck (2018)**

Discrepant by $>5\sigma$

Evolving DE: DESI + SNIA preference for time-evolving DE **Karim et al. (2025)**

Can we find unified models of early and late DE?

Why early and late DE?

- Hubble tension motivates EDE
- Both phenomena can be described with scalar fields

Can a single scalar explain both?

$M_{\mathrm{Pl}} = 1$

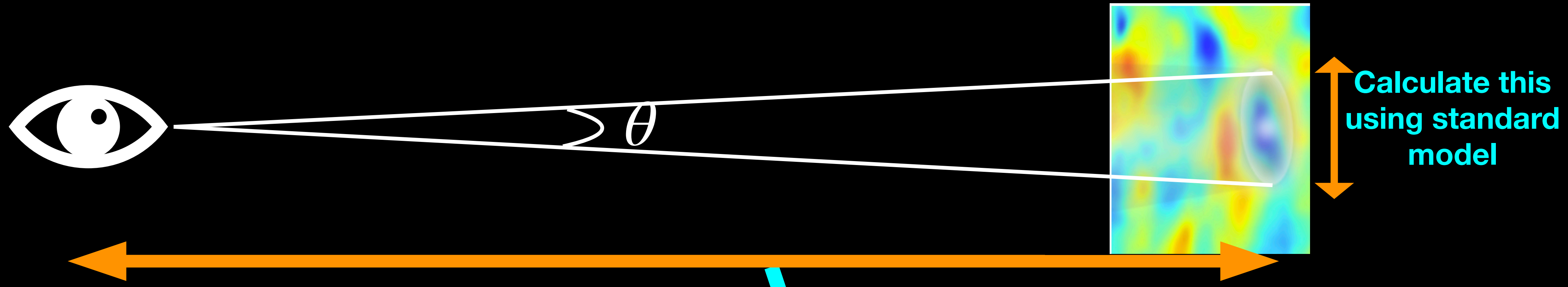
Formalism—quintessence

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{R}{2} - \frac{1}{2}(\nabla_\mu \phi)^2 - V(\phi) \right] + S_m[g_{\mu\nu}]$$

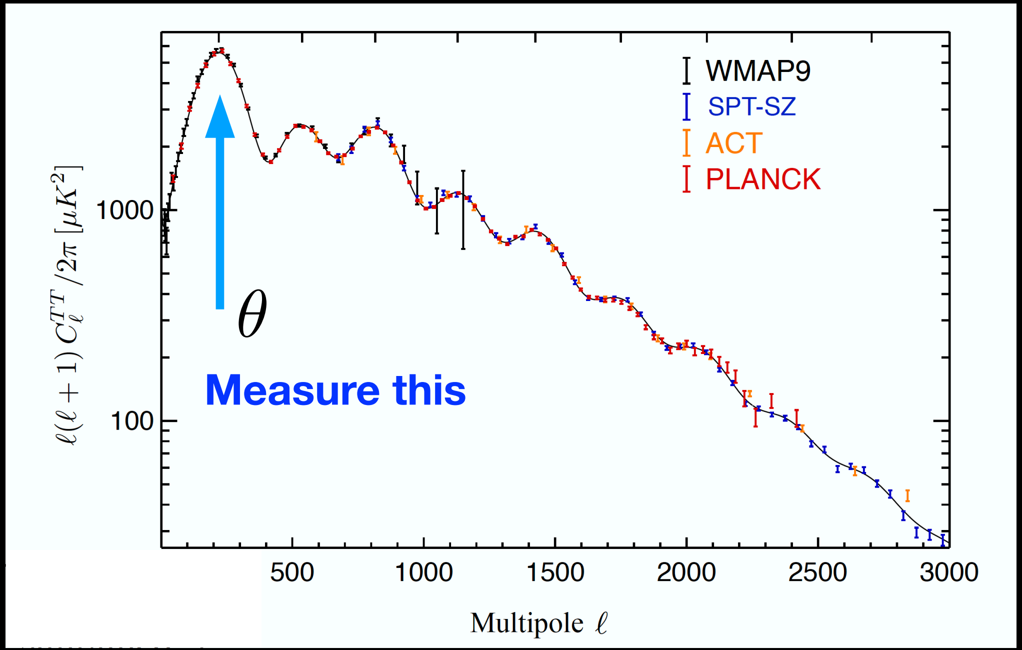
The data may not identify a unique Lagrangian
but they do constrain the behavior of new physics

Goal: Identify the features of $V(\phi)$ necessary to unify EDE and late DE

EDE alters the sound horizon r_s



Distance to CMB
(angular diameter distance D_A) $\propto H_0^{-1}$



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

Poulin, Smith, Karwal & Kamionkowski PRL 2018

Early dark energy

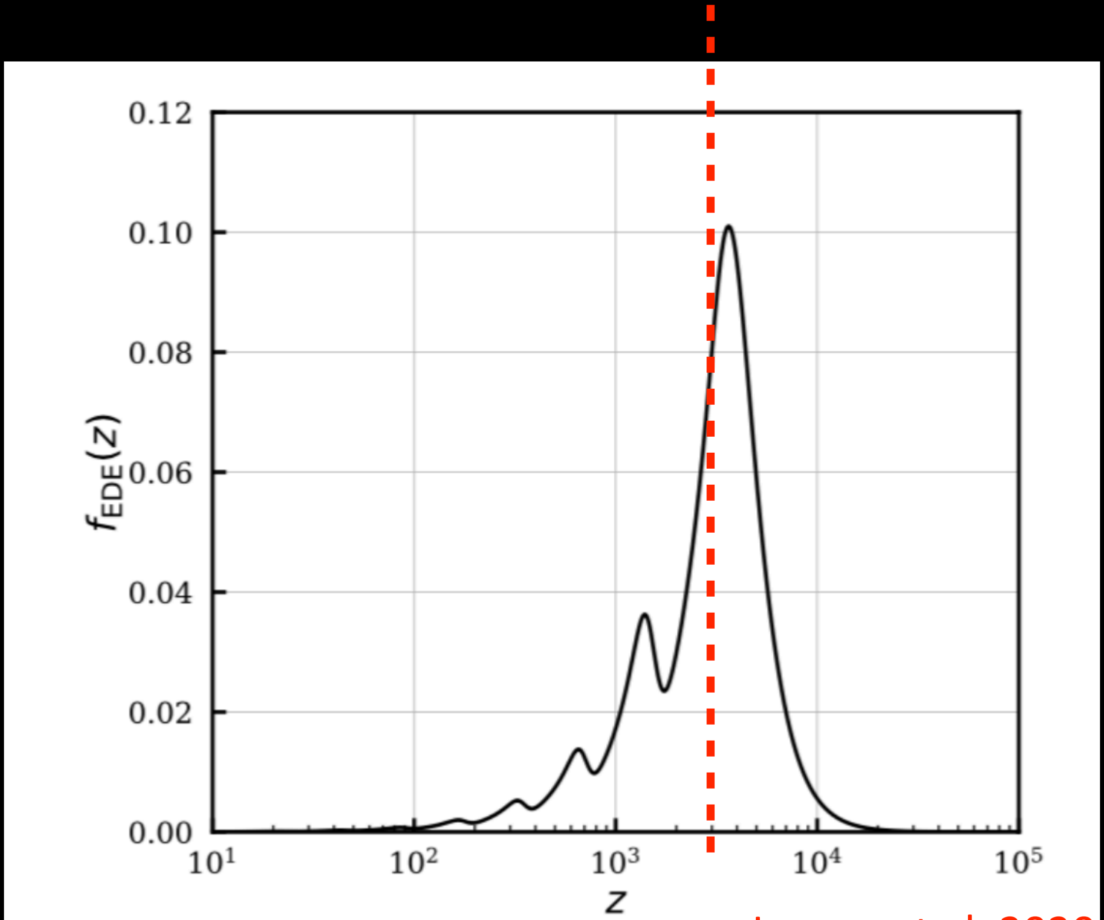
ΛCDM:

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

EDE:

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

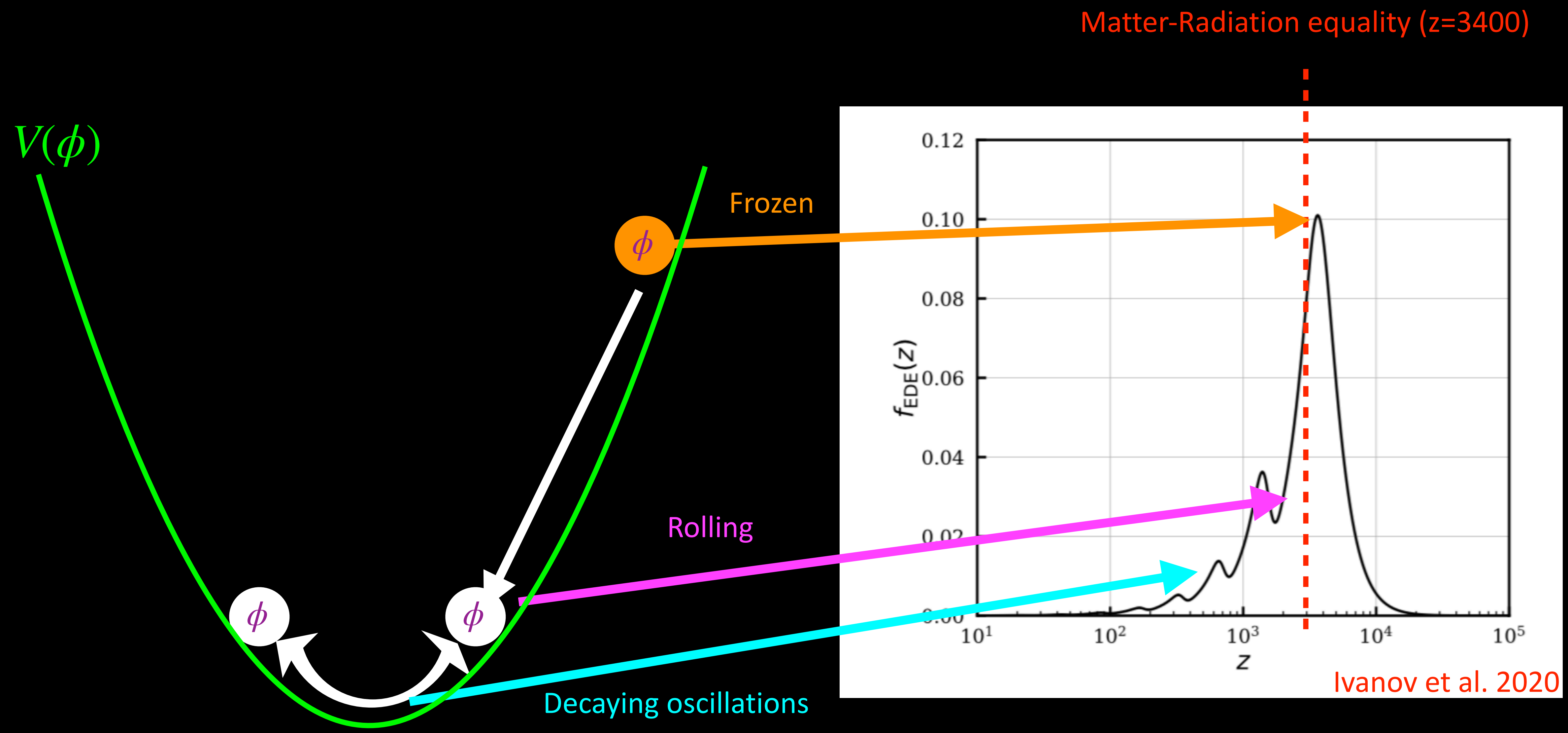
Matter-Radiation equality (z=3400)



Ivanov et al. 2020

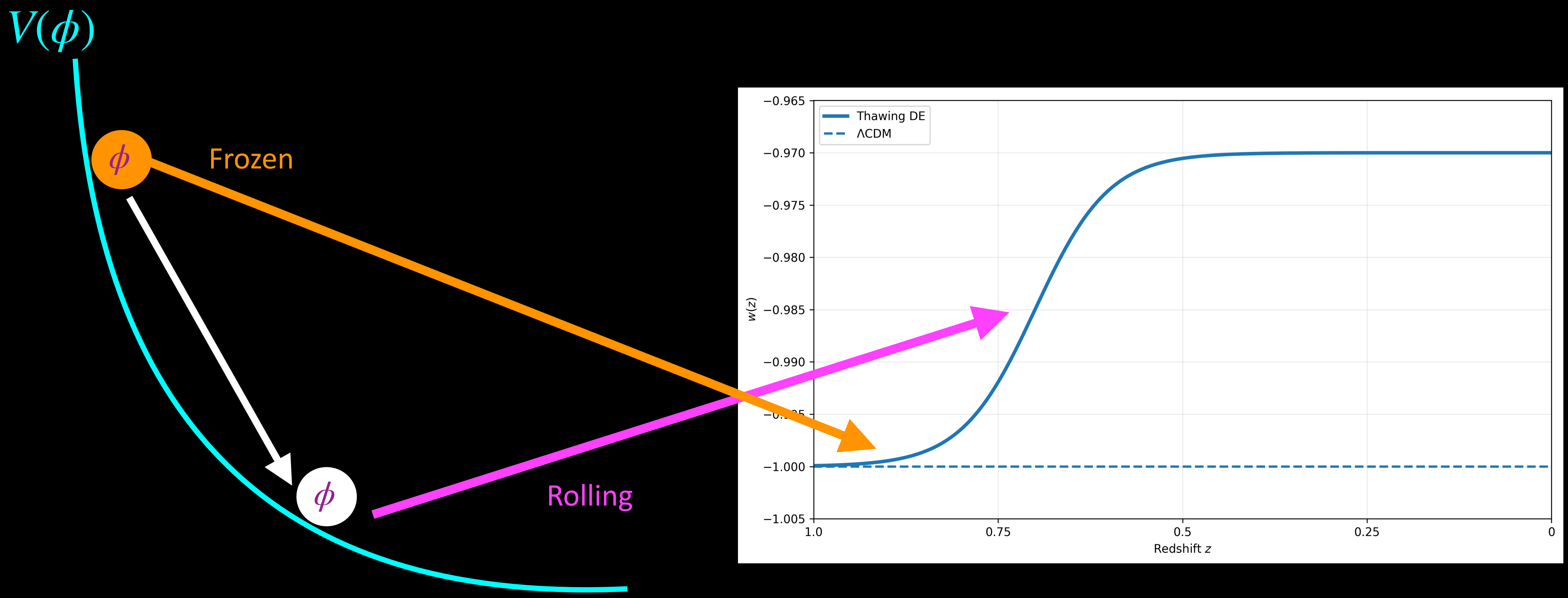
Poulin, Smith, Karwal & Kamionkowski PRL 2018

Early dark energy

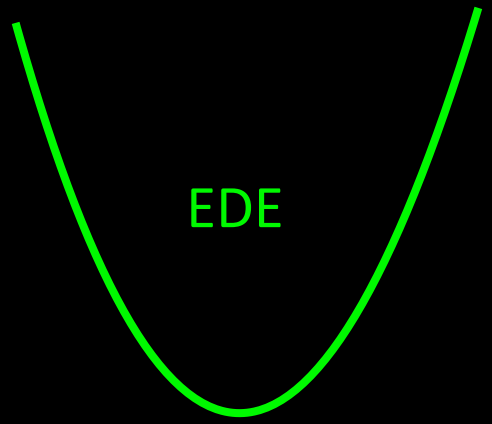


Late dark energy

Example: thawing quintessence



Unified early and late dark energy



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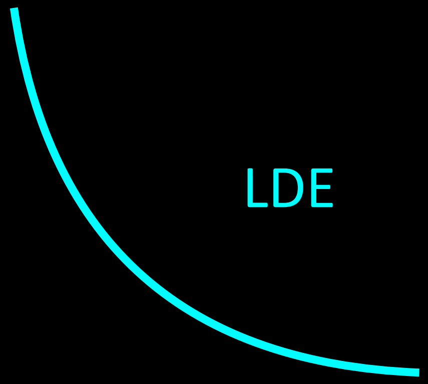

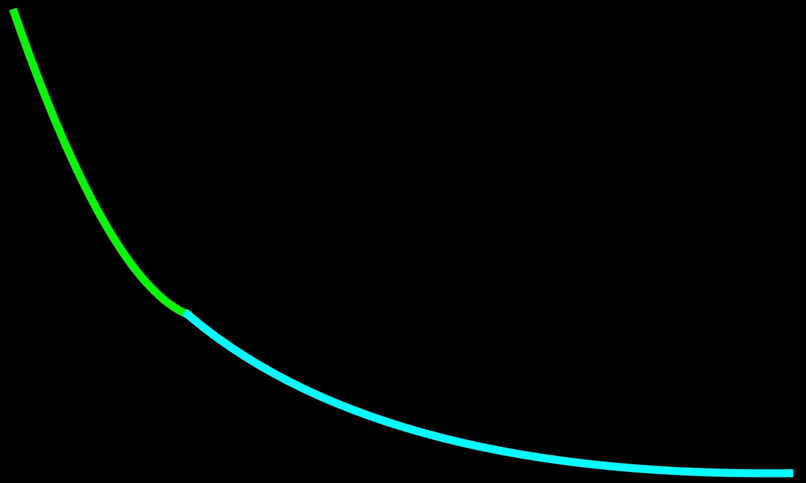

?

1) What must the scalar’s history look like?

2) What types of potentials can accomplish this?

What history must one field realize?

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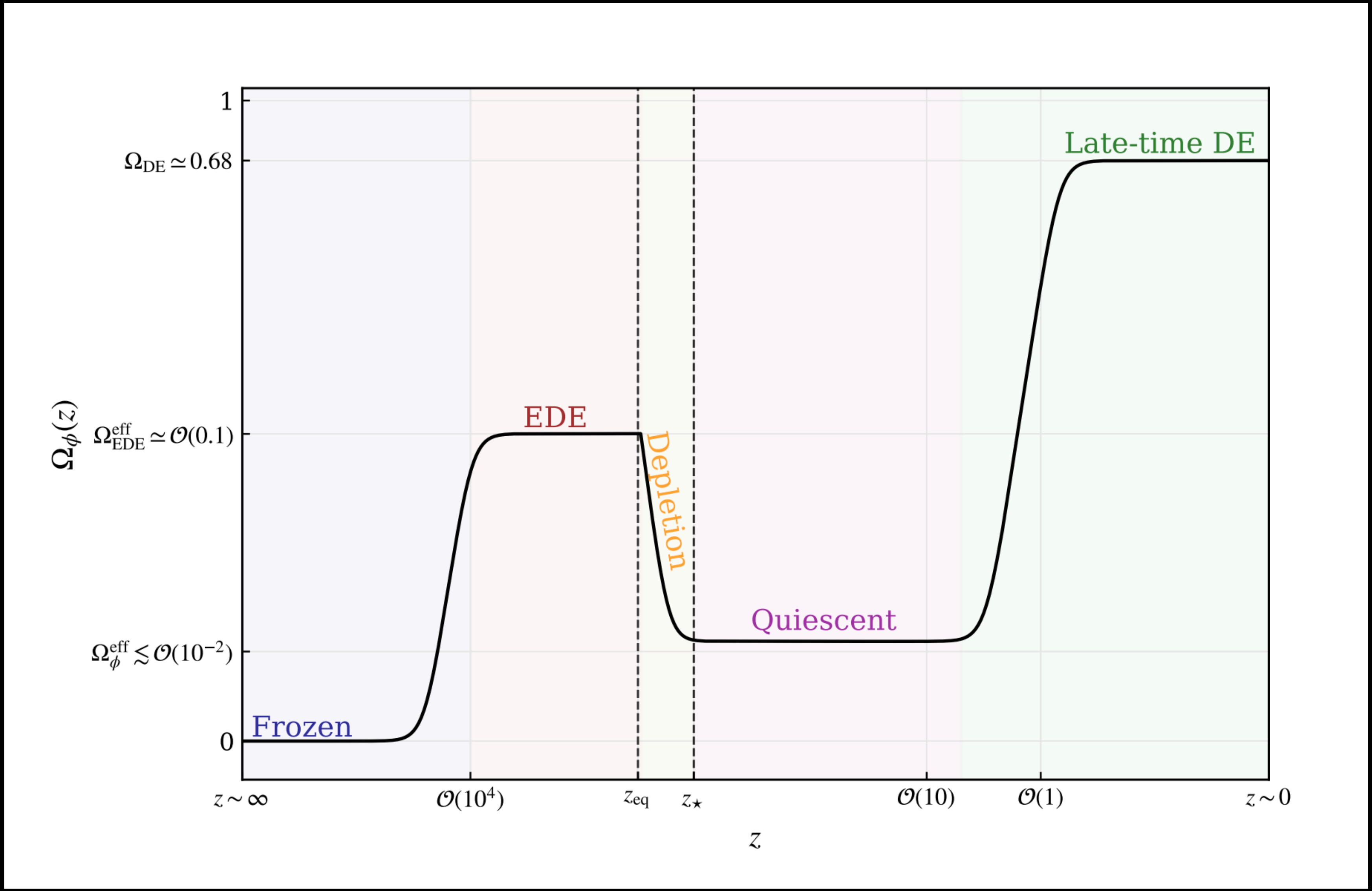
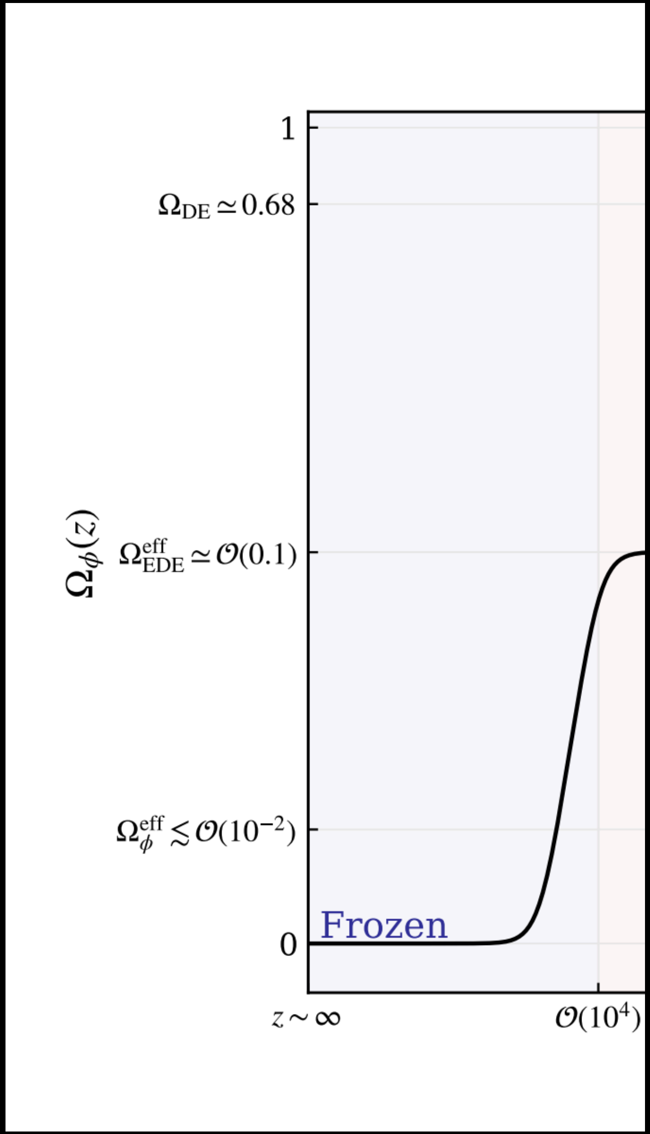


Frozen phase



Field needs to be frozen at ϕ_0 with $m_{\rm eff} \ll H$ $\quad \rho_\phi \ll \rho_\gamma$

Avoids messing up the early universe

Field must have mass $m_{\rm eff} = \sqrt{V''(\phi_0)} \sim H(z = 10^3) = 10^{-28}\,{\rm eV}$

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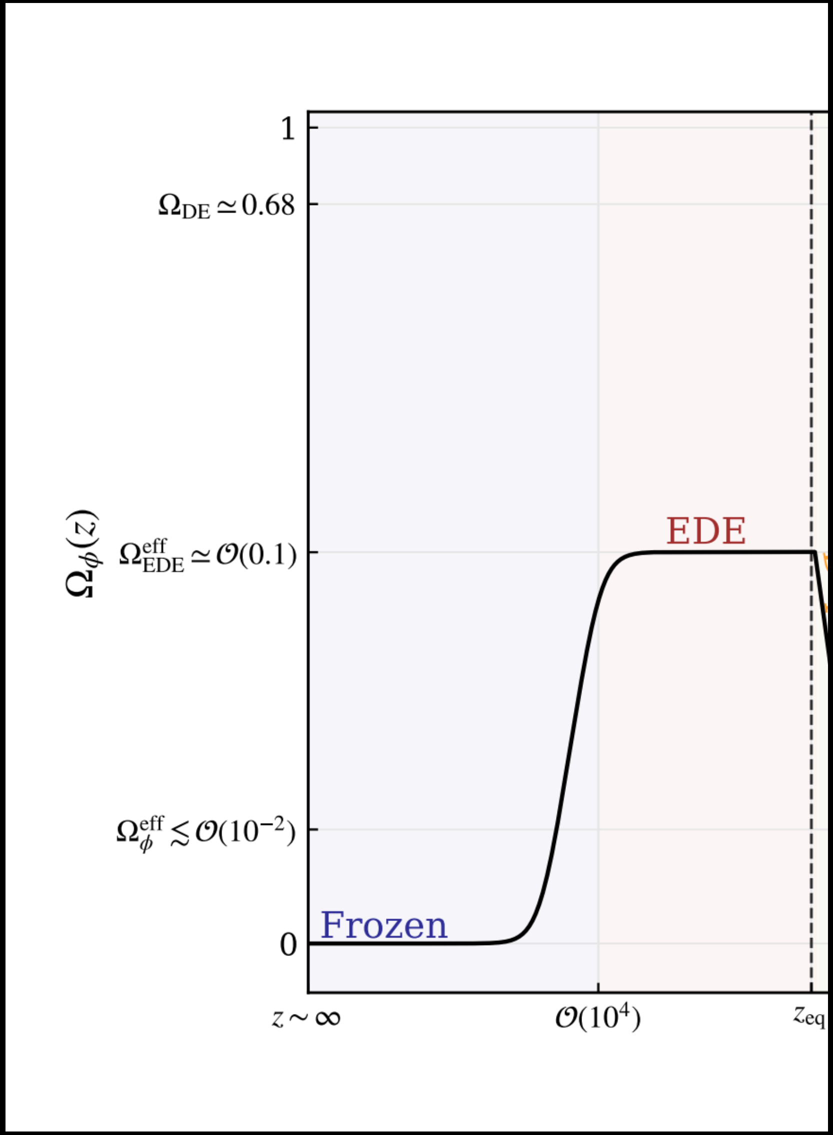
EDE phase



Field needs to become relevant around $z \sim 10^4$

Field must contribute $\Omega_{\rm EDE} \sim 0.1$

This can resolve the Hubble tension

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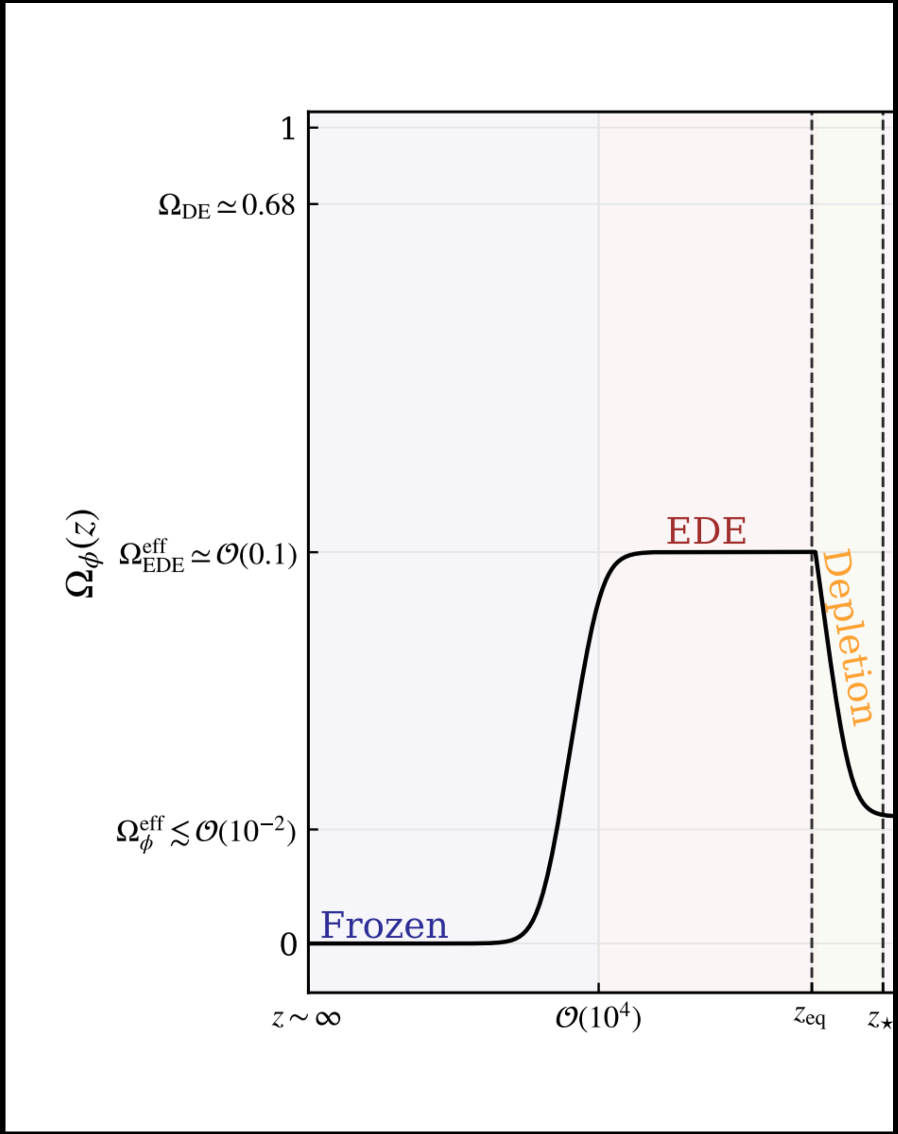
Depletion phase



Field needs to deplete between $z_{eq} \sim 3400$ and $z_* \sim 1100$

This preserves consistency with the CMB

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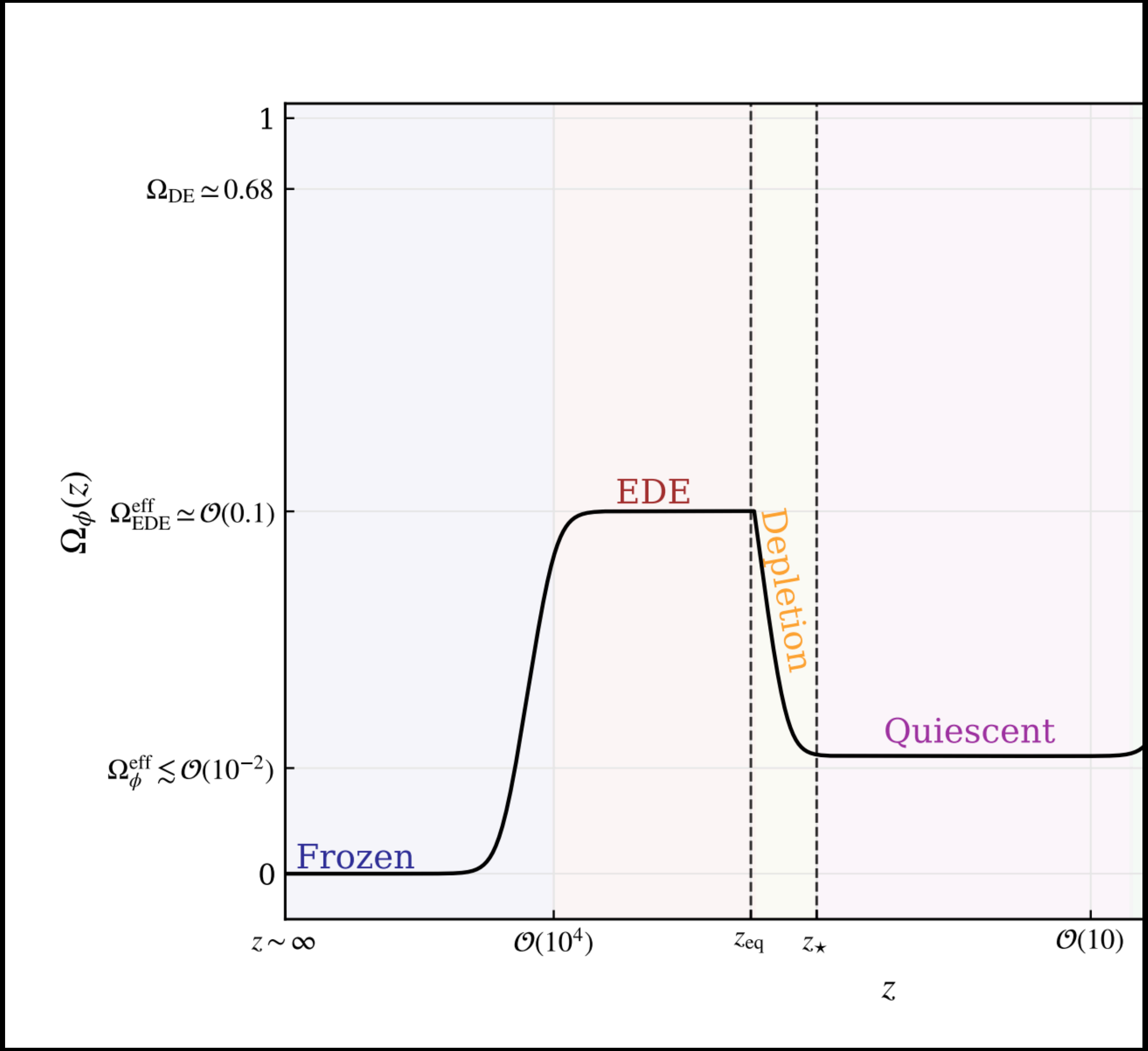
Quiescent phase



Need $\Omega_\phi < 10^{-2}$ during the matter era

This preserves consistency with late-time physics e.g., SNIa, BAO

Matter era looks like ΛCDM

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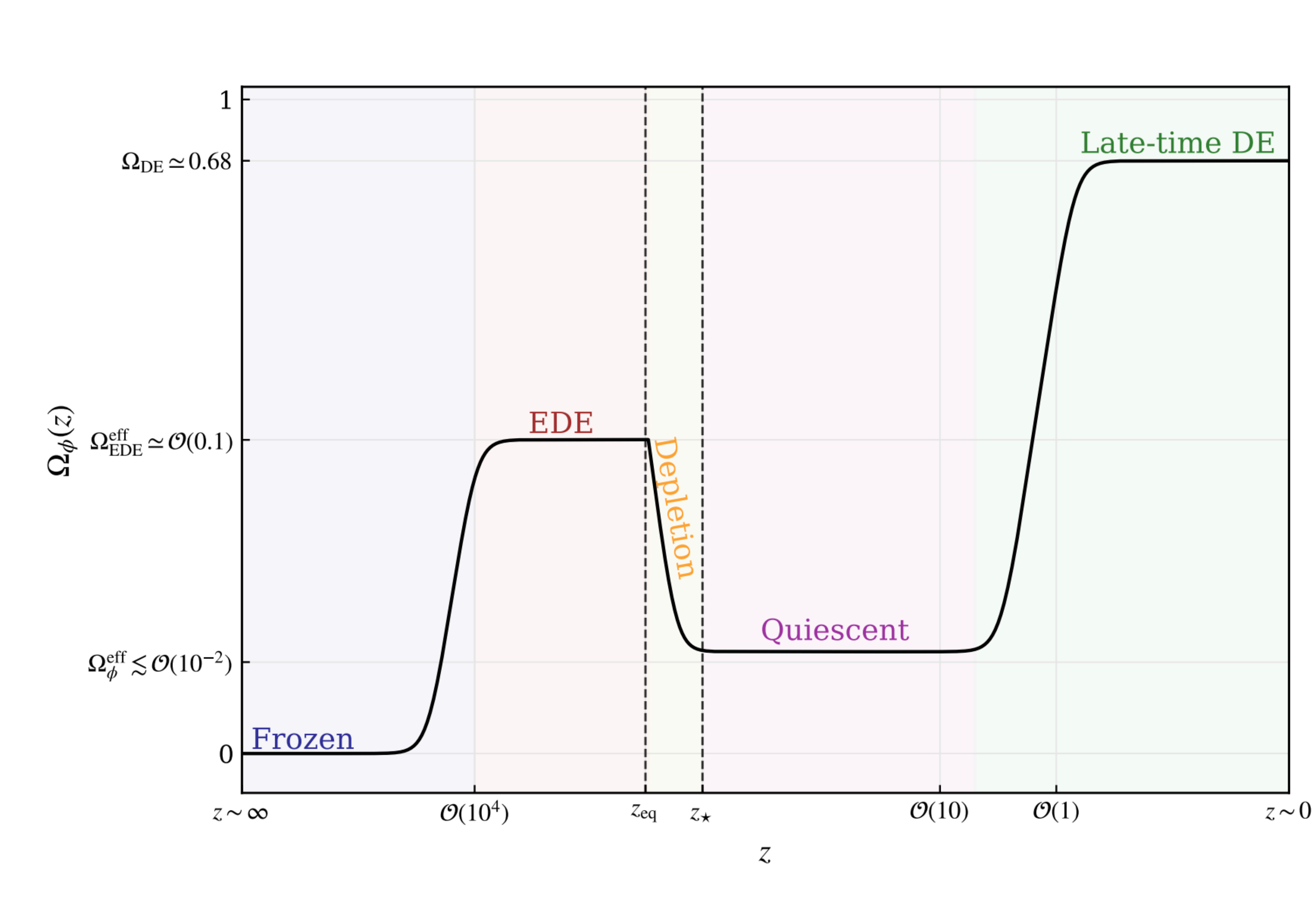
Dark energy phase

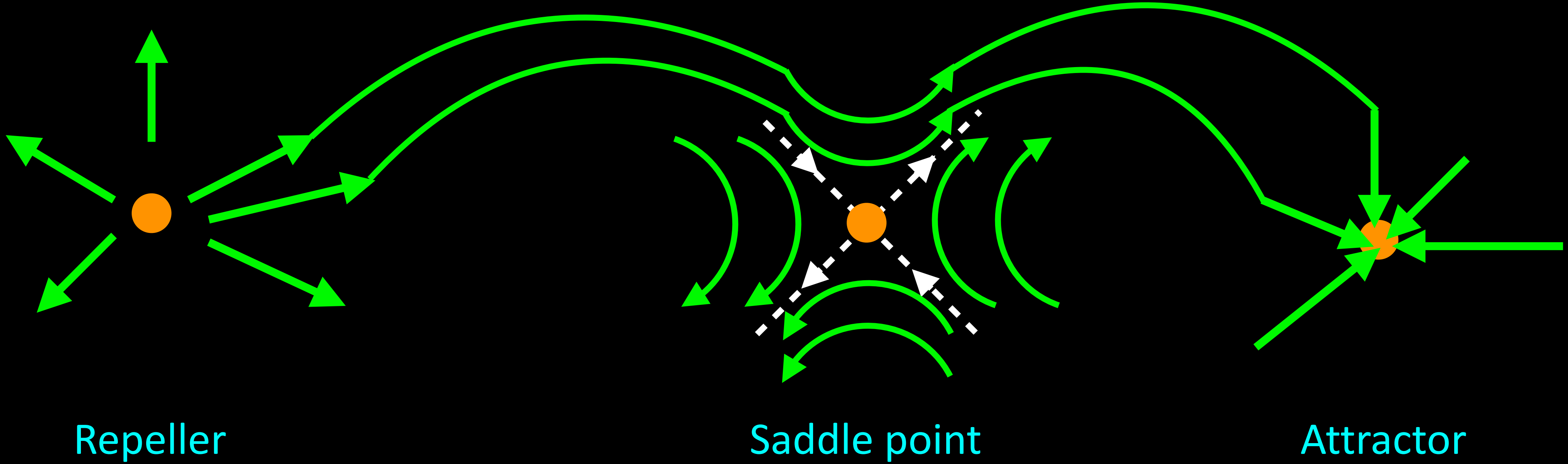


Need $\Omega_\phi \sim 0.7$ today

$w \sim -1$

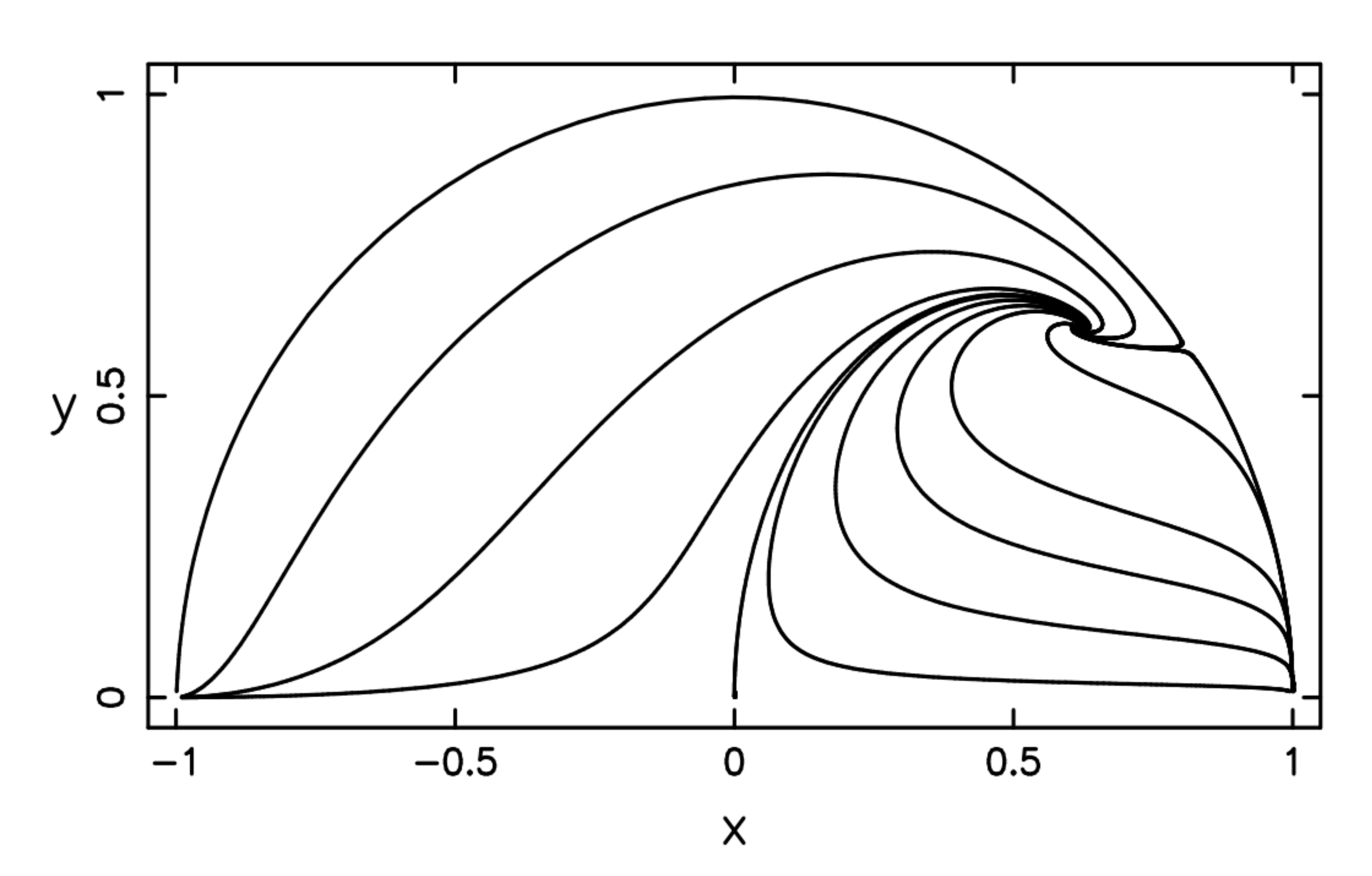
Time-evolving DE

Formalism— dynamical systems



- Avoids multiple fine-tunings
- Applicable to a wide range of models
- Model-independent framework

Dynamical systems - example



What we need?

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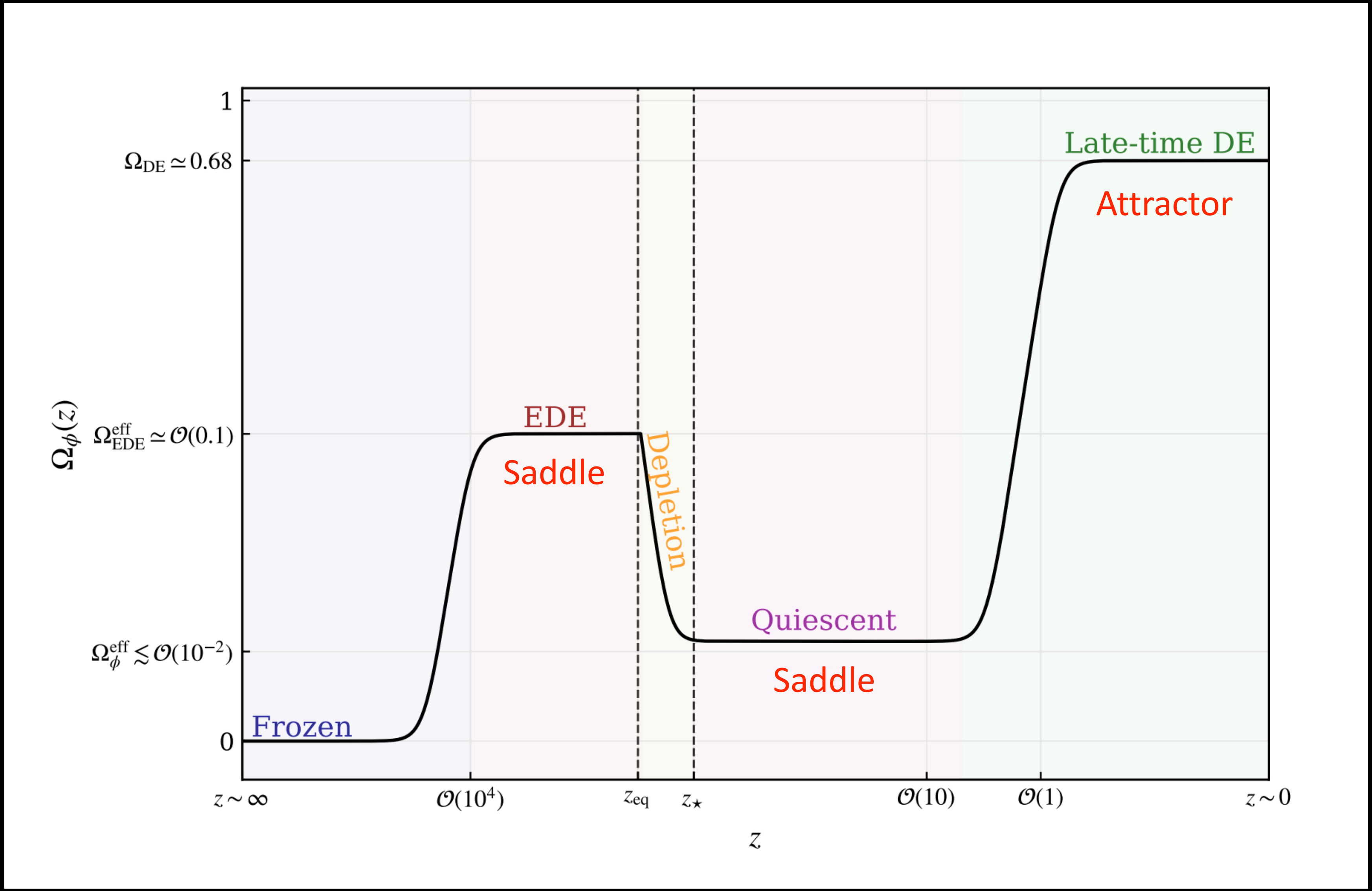


$M_{\mathrm{Pl}} = 1$

Example - exponential potential

$$V(\phi) = V_0 e^{-\lambda\phi}$$

Two attractors:

Existence

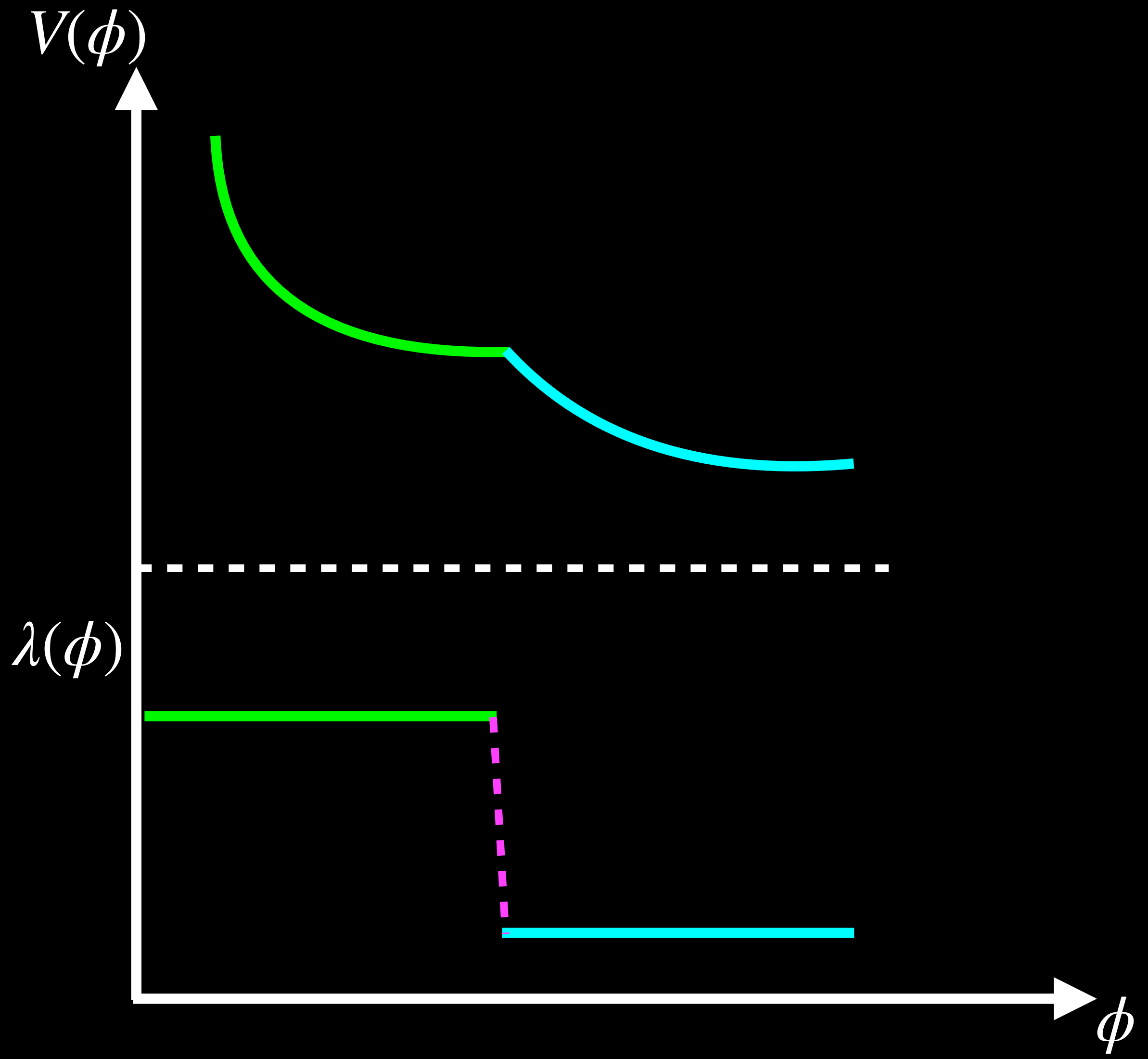
1) Scaling solution: $w_\phi = w_m \quad \Omega_\phi = \dfrac{3(1+w_m)}{\lambda^2}$ $\qquad \lambda^2 > 3(1+w_m)$

2) DE domination: $w_\phi = -1 + \dfrac{\lambda^2}{3} \quad \Omega_\phi = 1$ $\qquad \lambda^2 < 3(1+w_m)$

Generalization

$$V(\phi) = V_0 e^{-\lambda\phi}$$

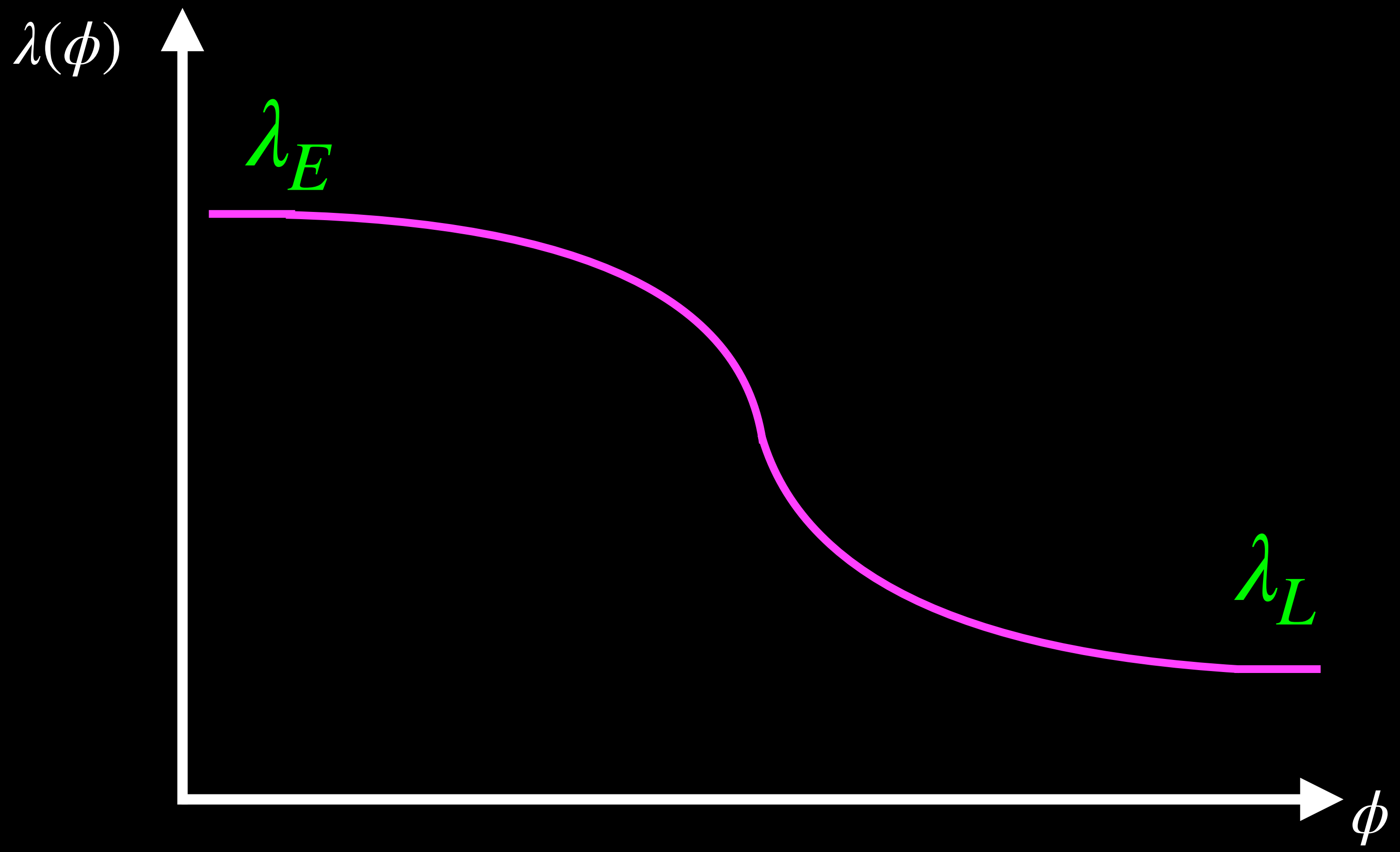
Generalize: $\lambda(\phi) = -\dfrac{\mathrm{d}\ln V}{\mathrm{d}\phi}$



$M_{\mathrm{Pl}} = 1$

Example - double exponential potential

$$V(\phi) = V_{\mathrm{early}} e^{-\lambda_E \phi} + V_{\mathrm{late}} e^{-\lambda_L \phi}$$



$M_{\rm Pl} = 1$

Example - double exponential potential

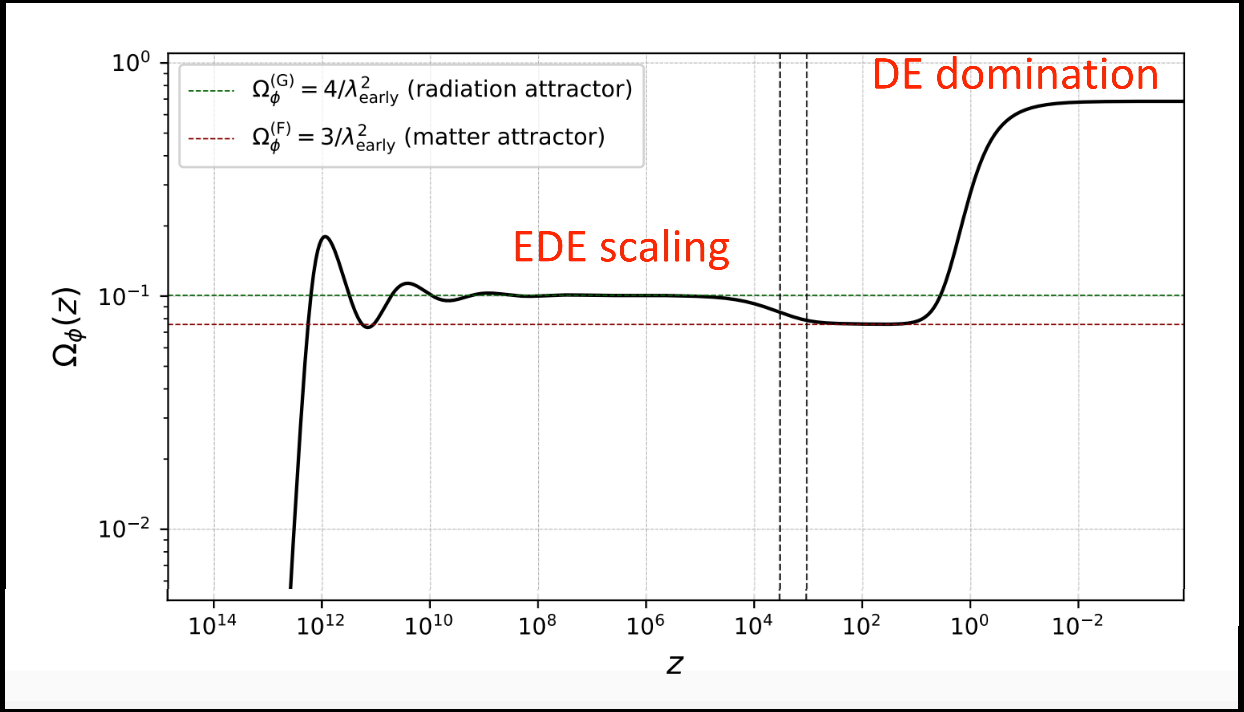
$$V(\phi) = V_{\rm early} e^{-\lambda_E \phi} + V_{\rm late} e^{-\lambda_L \phi}$$

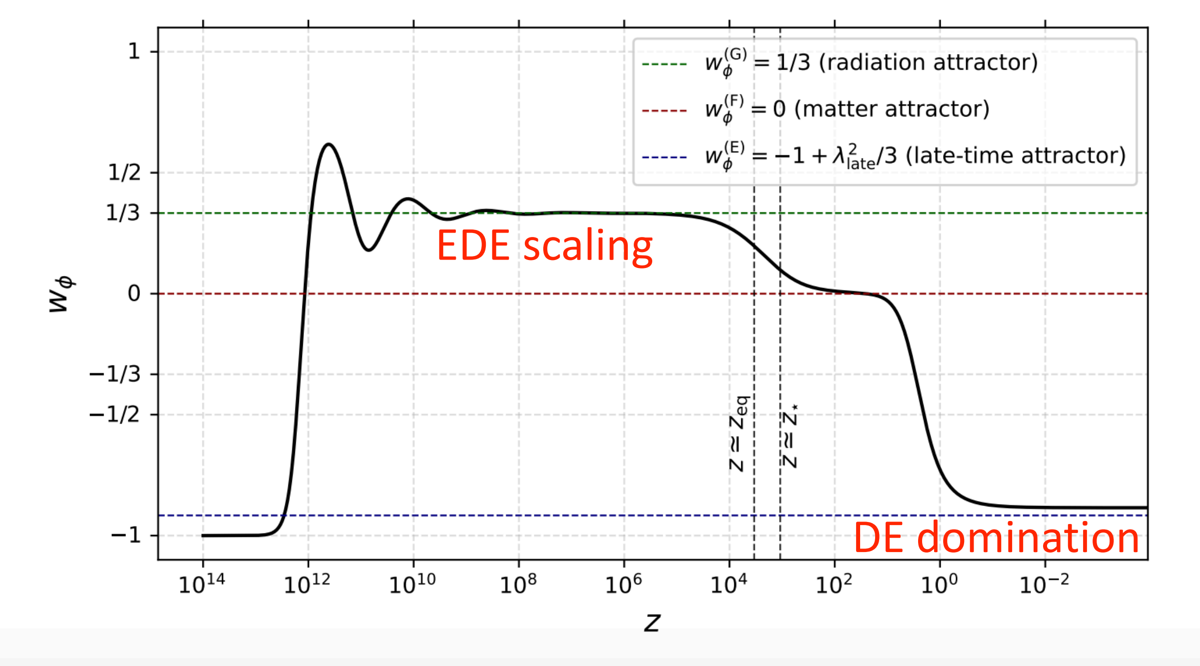
1) Early EDE scaling: $w_\phi = \frac{1}{3} \quad \Omega_\phi = \frac{4}{\lambda_E^2}$ $\lambda_E^2 = 40$ gives $\Omega_{\rm EDE} \sim 0.1$

2) Late DE domination: $w_\phi = -1 + \frac{\lambda_L^2}{3} \quad \Omega_\phi = 1$ $\lambda_L^2 \sim 0.01$ gives $w_{\rm DE} \sim -1$

Example - double exponential potential

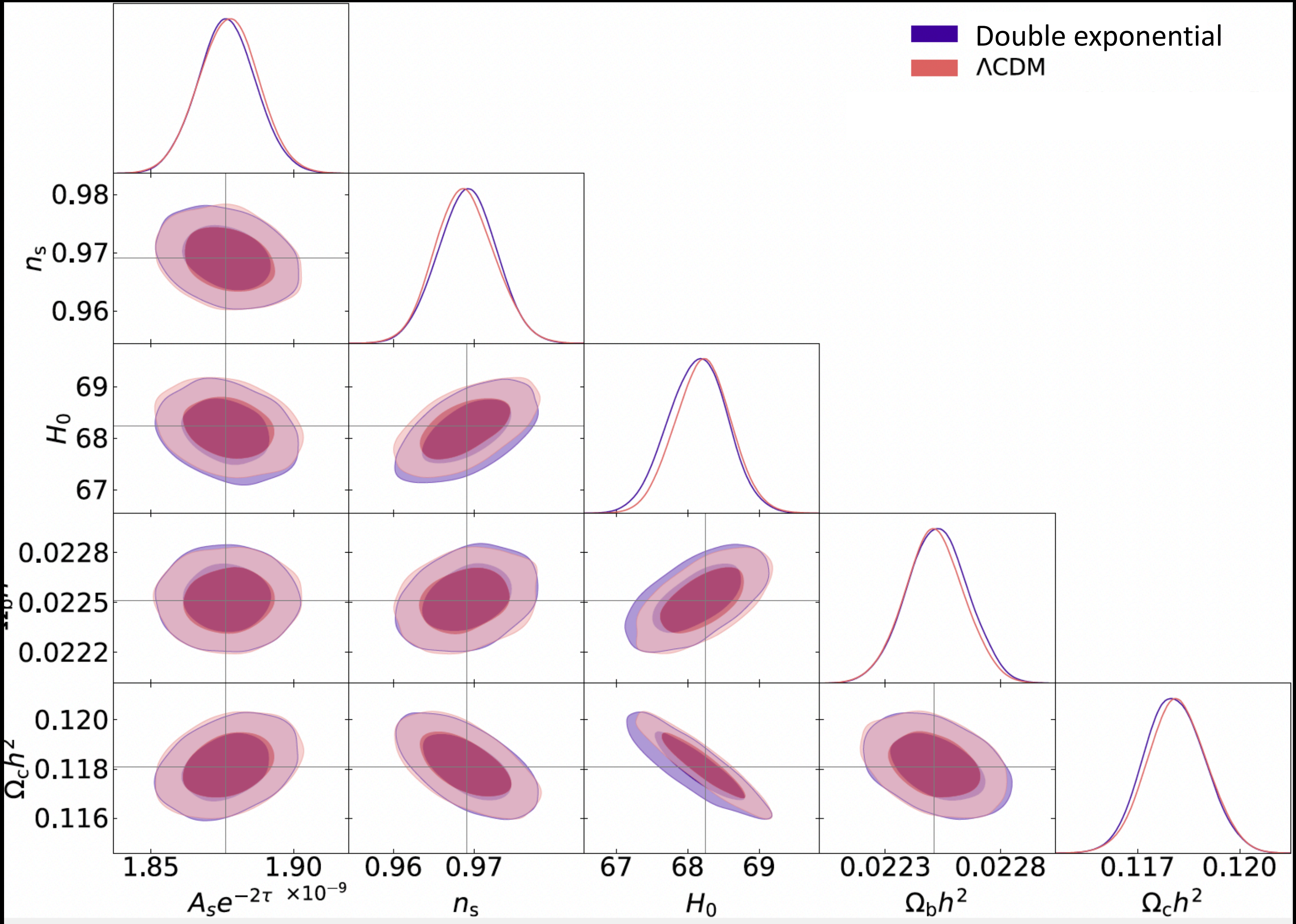
$$V(\phi) = V_{\rm early} e^{-\lambda_E \phi} + V_{\rm late} e^{-\lambda_L \phi}$$





Ramadan, Karwal & JS 2023 PRD

Example - double exponential potential



Parameter	ΛCDM	Double exponential
$\log(10^{10}A_s)$	$3.052(3.045) \pm 0.015$	$3.083(3.085) \pm 0.017$
n_s	$0.9689(0.9687)^{+0.0034}_{-0.0039}$	$0.9691(0.9700) \pm 0.0036$
ω_b	$0.02251(0.02249) \pm 0.00013$	$0.02262(0.02262) \pm 0.00013$
ω_c	$0.11816(0.11840) \pm 0.00088$	$0.12072(0.12043) \pm 0.00091$
τ_{reio}	$0.0599(0.0593) \pm 0.0076$	$0.0751(0.0769) \pm 0.0088$
D_A	(12.76)	(12.62)
r_{s*}	(144.85)	(143.12)
$100\theta_*$	(1.042009)	(1.040470)
H_0	$68.21(68.09) \pm 0.39$	$67.53(67.77) \pm 0.41$
σ_8	$0.8084(0.8084) \pm 0.0061$	$0.7729(0.7758) \pm 0.0069$
S_8	$0.813(0.815) \pm 0.010$	$793(0.792) \pm 0.010$
α	-	$> 14.8(15)$
β	-	$< 0.0883(1.69 \times 10^{-6})$
$\log_{10} V_\alpha$	-	(-15)
f_{ede}	-	$0.03480(0.03388)^{+0.00017}_{-0.00092}$
$\log_{10} z_c$	-	$7.20(6.56) \pm 0.46$
$\chi^2(\Delta)$	2069.49	2113.54(+44.05)

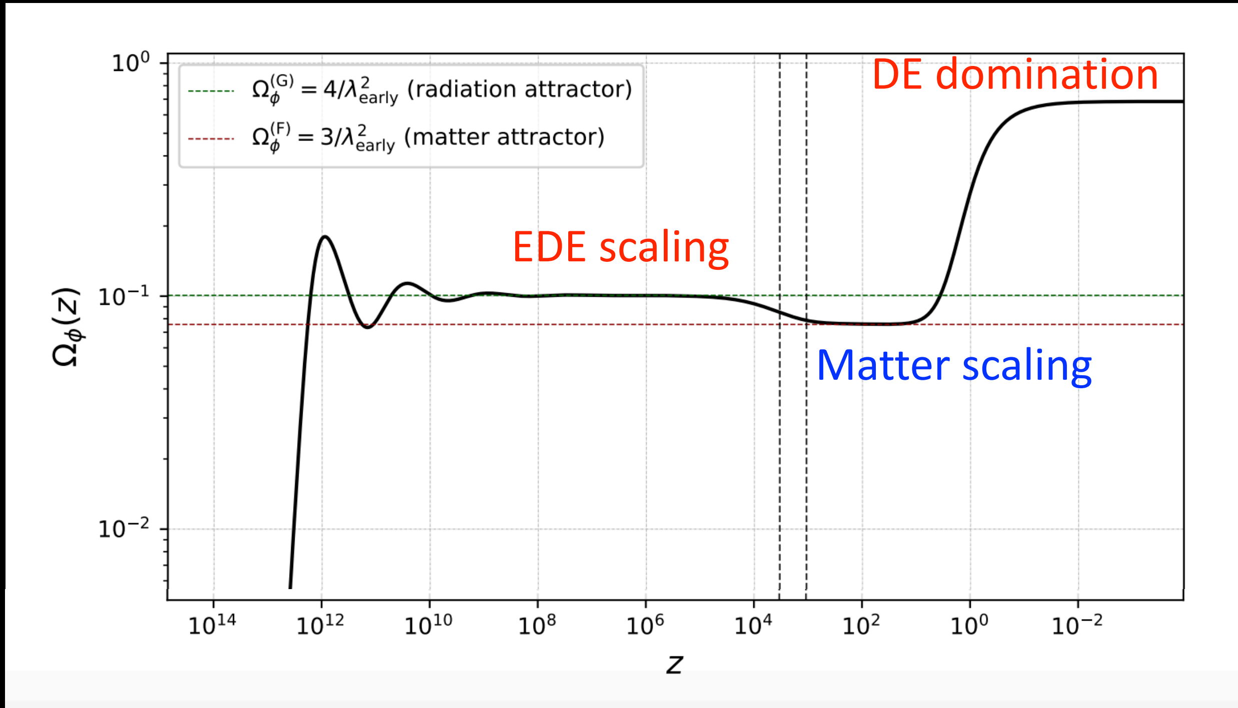
Parameter	ΛCDM	**@EDE: narrow priors**
$\chi^2_{CMB}(\Delta)$	1013.99	1052.70(+38.71)
$\chi^2_{BAO}(\Delta)$	5.23	7.98(+2.75)
$\chi^2_{H_0}(\Delta)$	15.45	17.45(+2.00)
$\chi^2_{Pantheon}(\Delta)$	1034.82	1035.41(+0.59)

$M_{\rm Pl} = 1$

Example - double exponential potential

$$V(\phi) = V_{\rm early} e^{-\lambda_E \phi} + V_{\rm late} e^{-\lambda_L \phi}$$

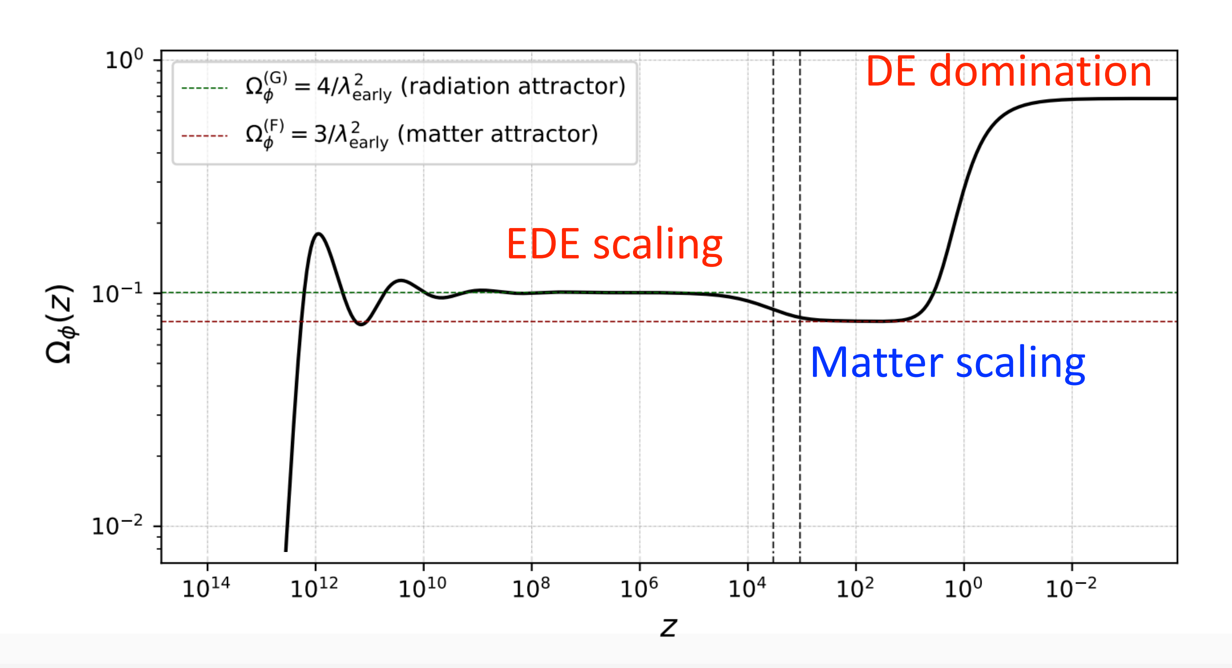
$$w_\phi = w_m \quad \Omega_\phi = \frac{3(1+w_m)}{\lambda^2}$$

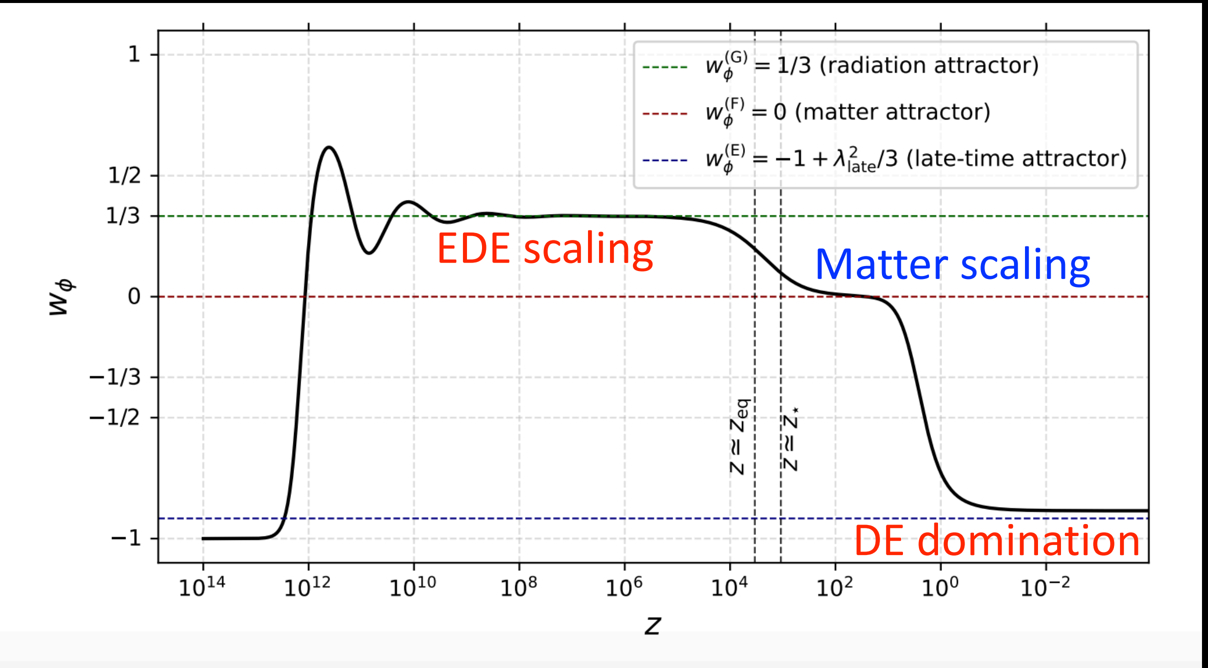


Example - double exponential potential

1) Early EDE scaling: $w_E = \frac{1}{3}$ $\Omega_\phi = \frac{4}{\lambda_E^2}$ $\lambda_E^2 = 40$ gives $\Omega_{\rm EDE} \sim 0.1$

2) Matter scaling: $w_E = 0$ $\Omega_\phi = \frac{3}{\lambda_E^2}$ $\lambda_E^2 = 40$ gives $\Omega_{\rm EDE} \sim 0.075$





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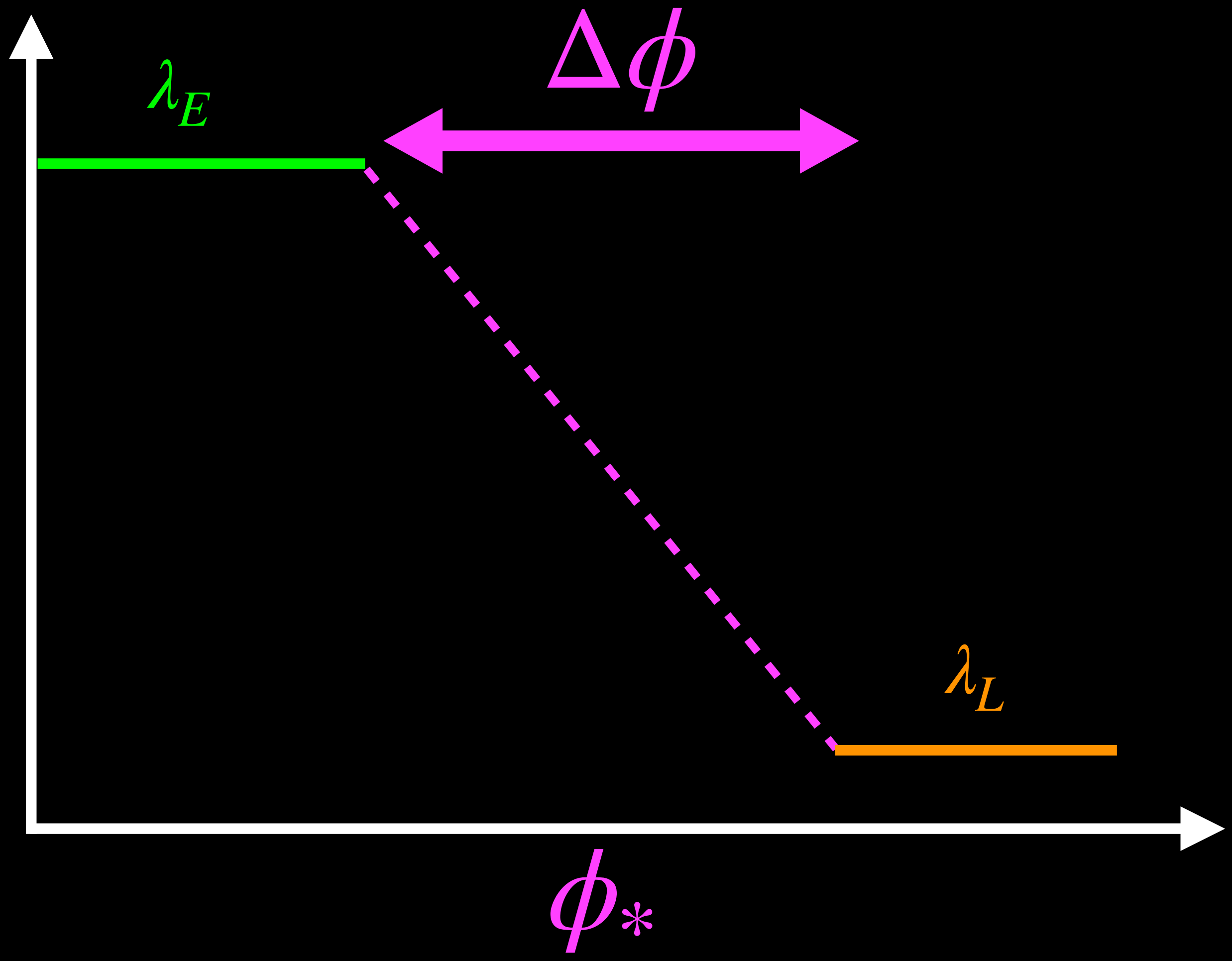
General two-slope potential



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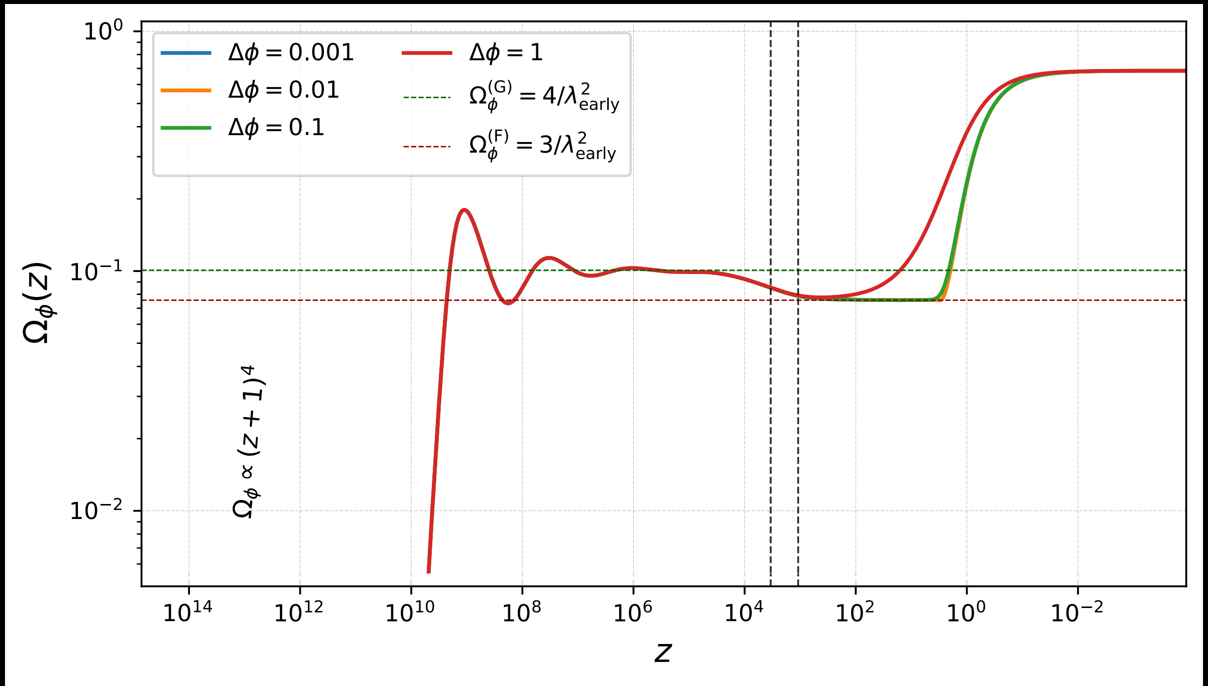

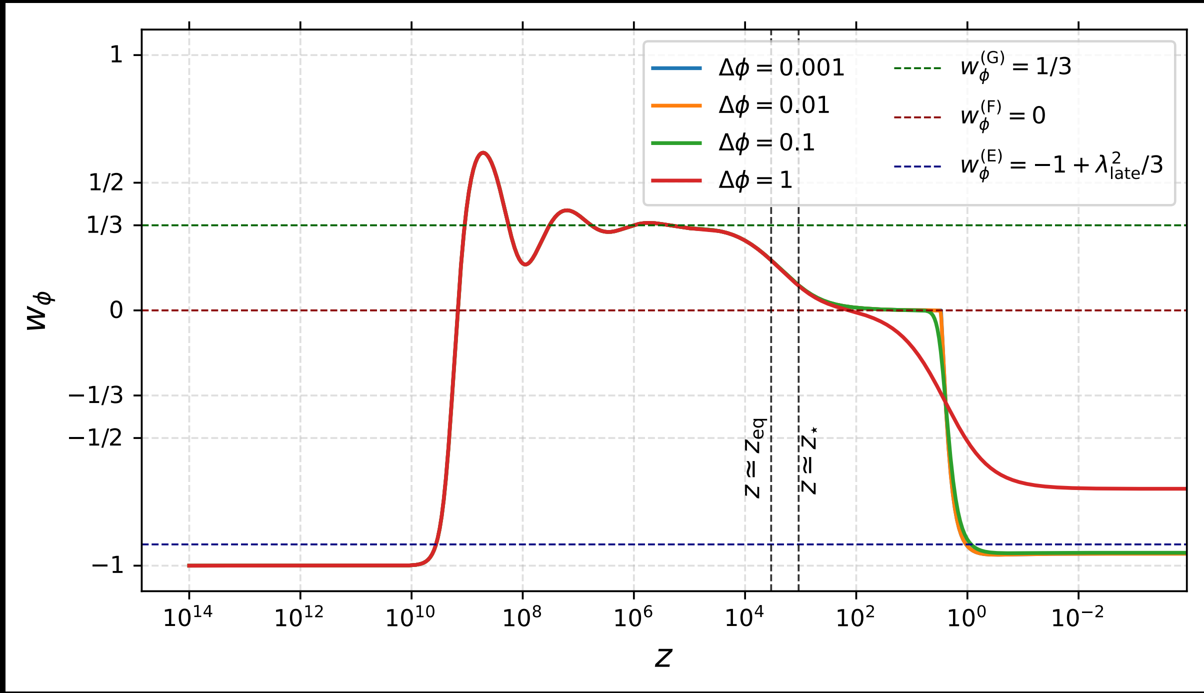

The quiescence phase needs its own fixed point

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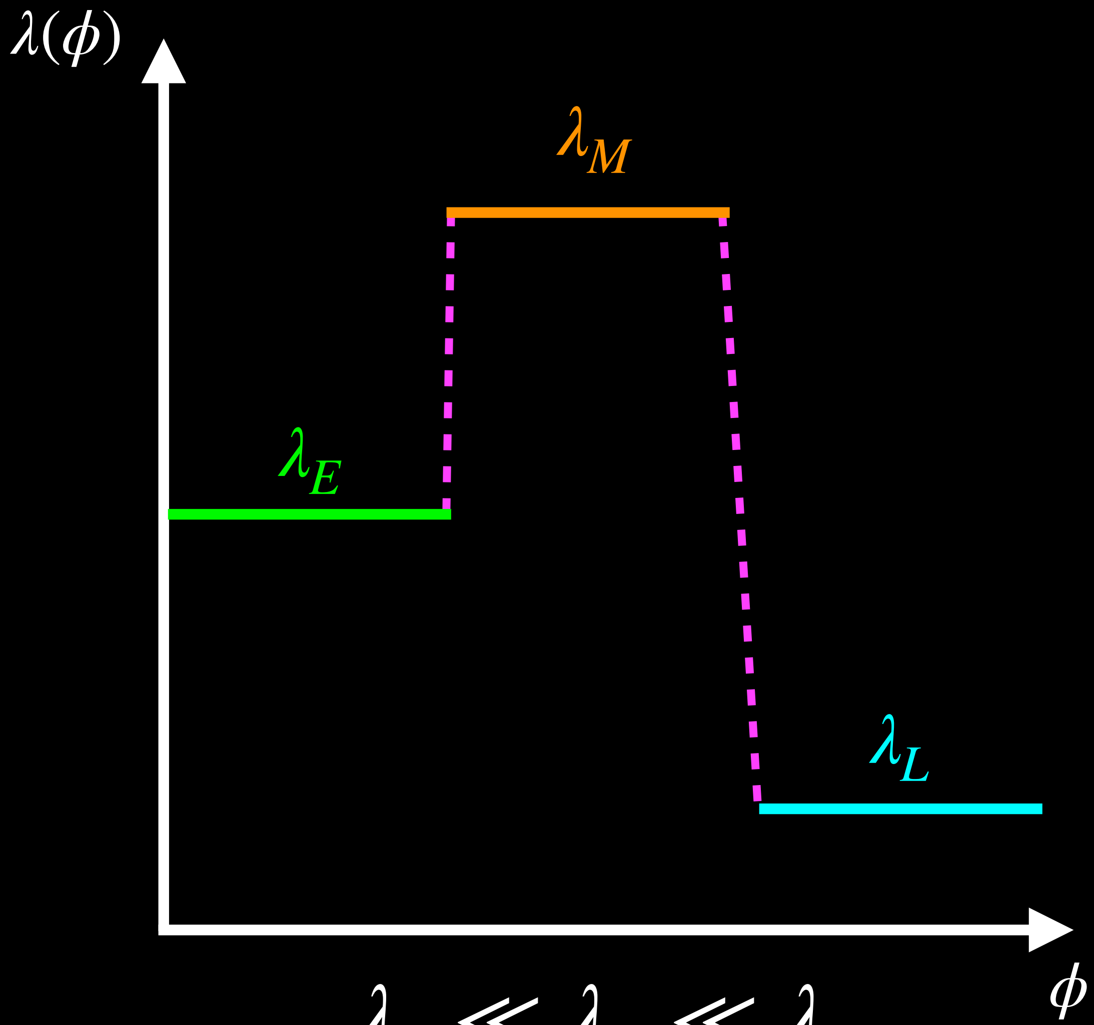
Three-slope potentials

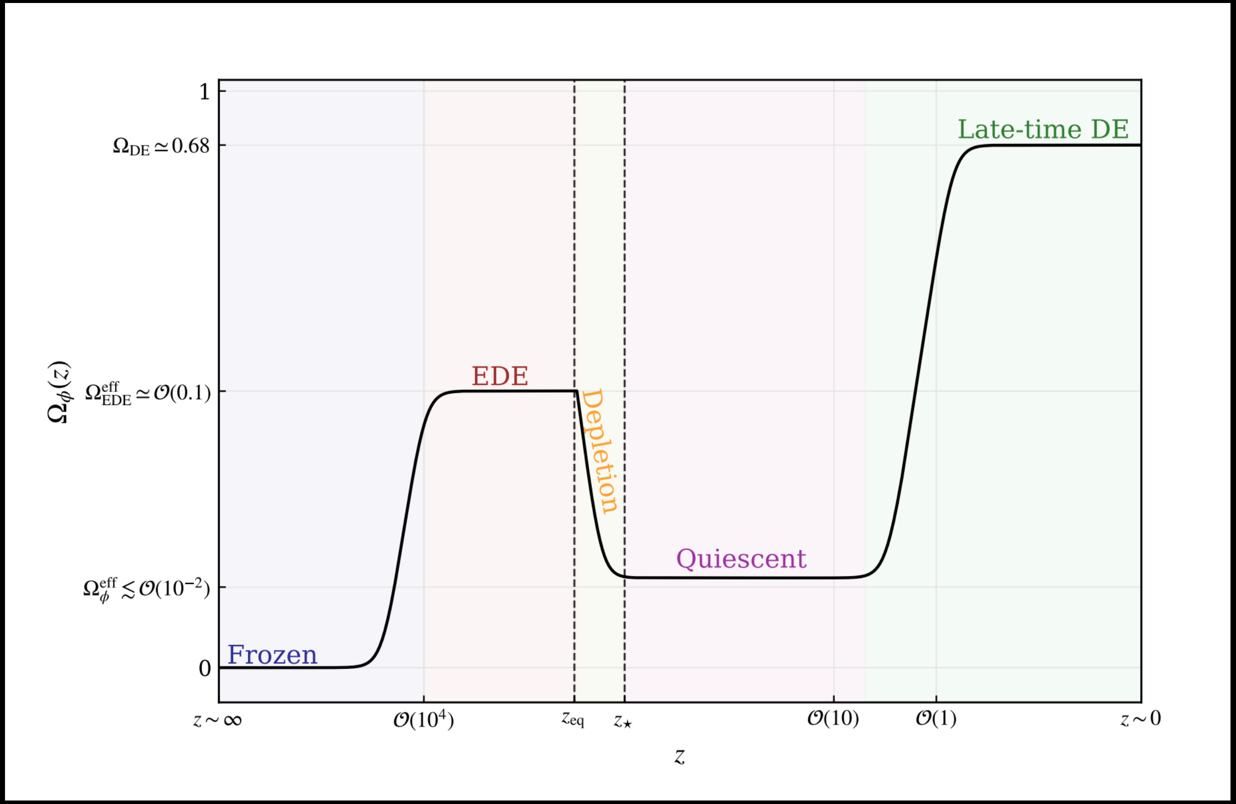
$\lambda_E^2 = 40$ gives $\Omega_{\rm EDE} \sim 0.1$

$\lambda_M^2 \gtrsim 300$ gives $\Omega_\phi \lesssim 10^{-2}$

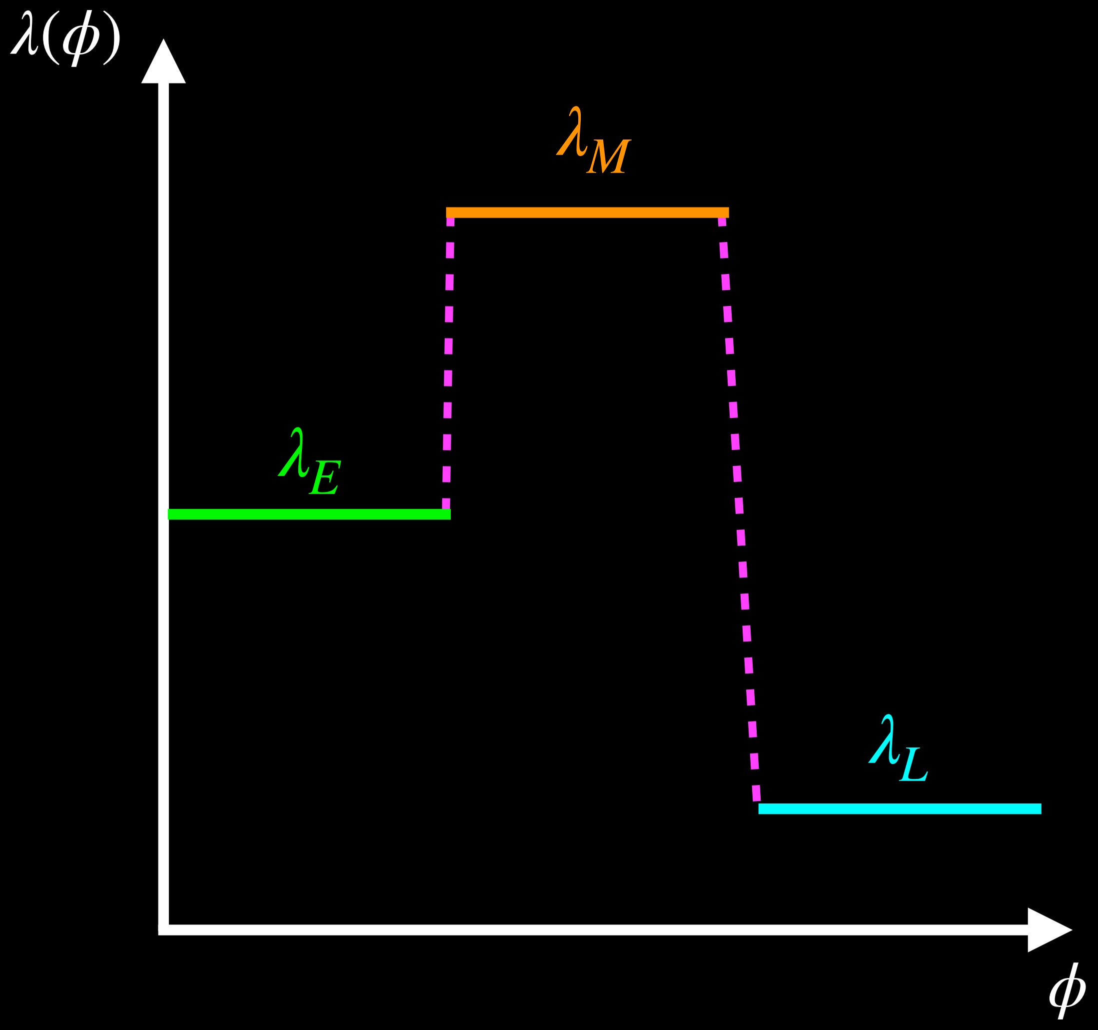
$\lambda_L^2 \sim 0.01$ gives $w_{\rm DE} \sim -1$

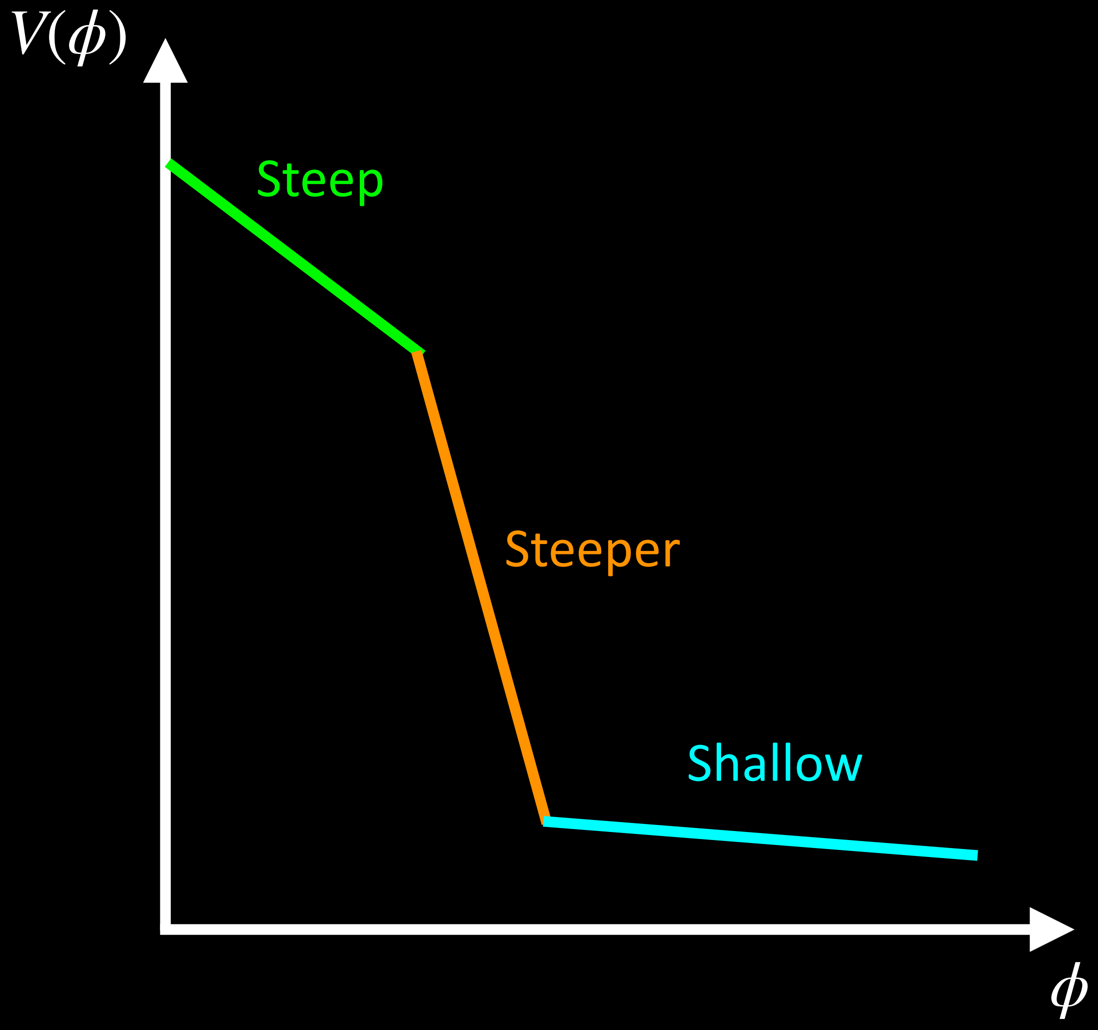


$$\lambda_L \ll \lambda_E \ll \lambda_M$$



Three-slope potentials

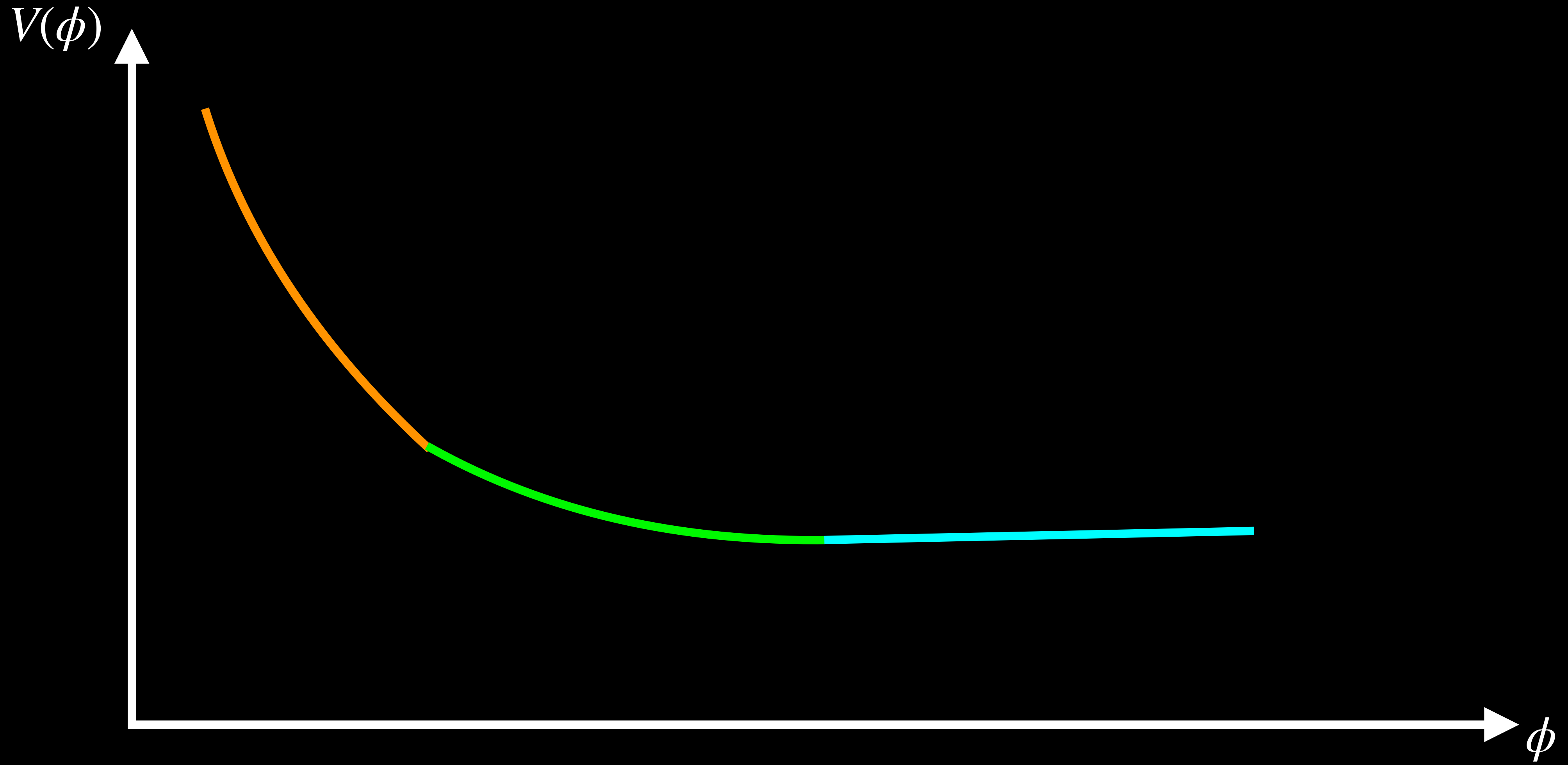




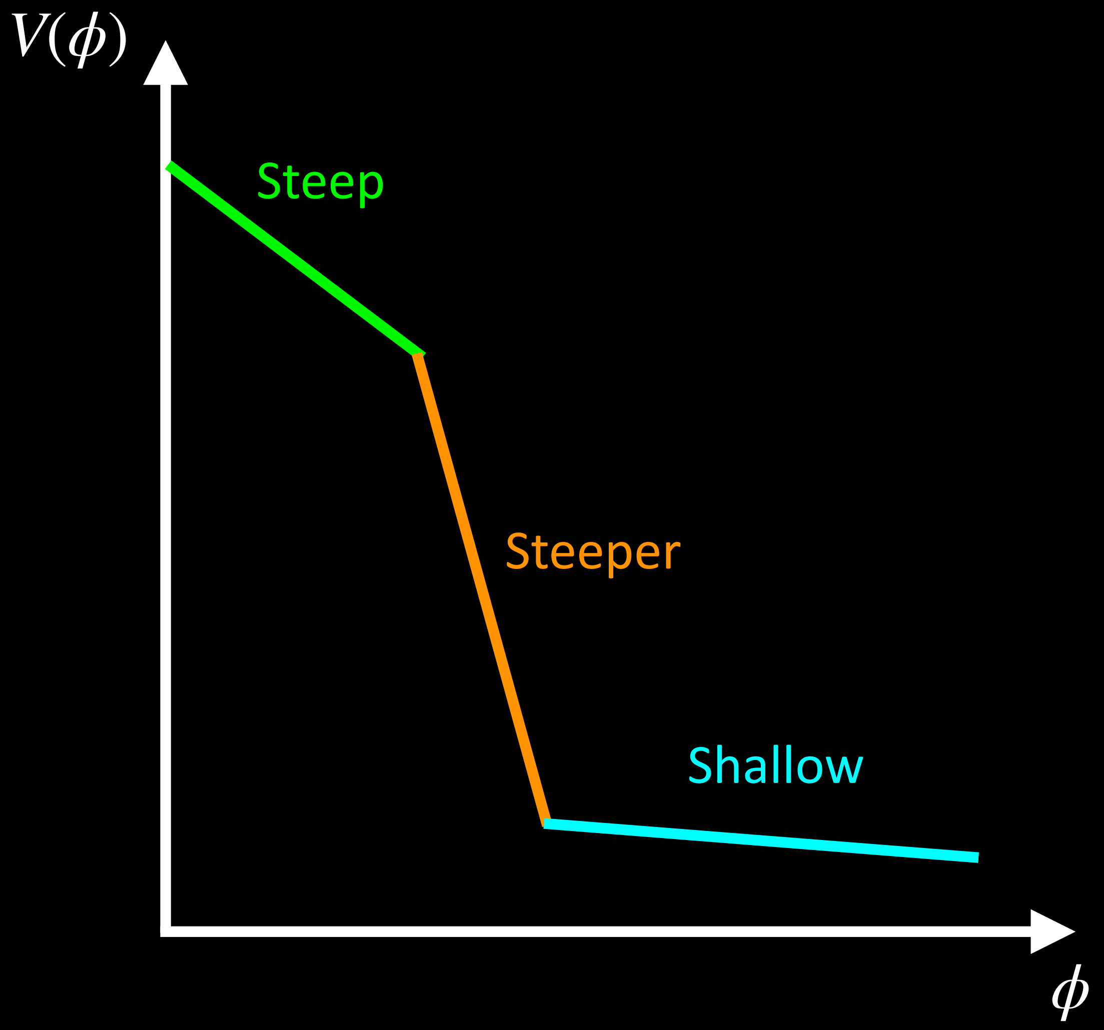
Three exponentials won't work

$$V(\phi) = V_E e^{-\lambda_E \phi} + V_M e^{-\lambda_M \phi} + V_L e^{-\lambda_L \phi}$$

$$\lambda_L \ll \lambda_E \ll \lambda_M$$



Can we find a potential that does this?



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Three-slope potential — example

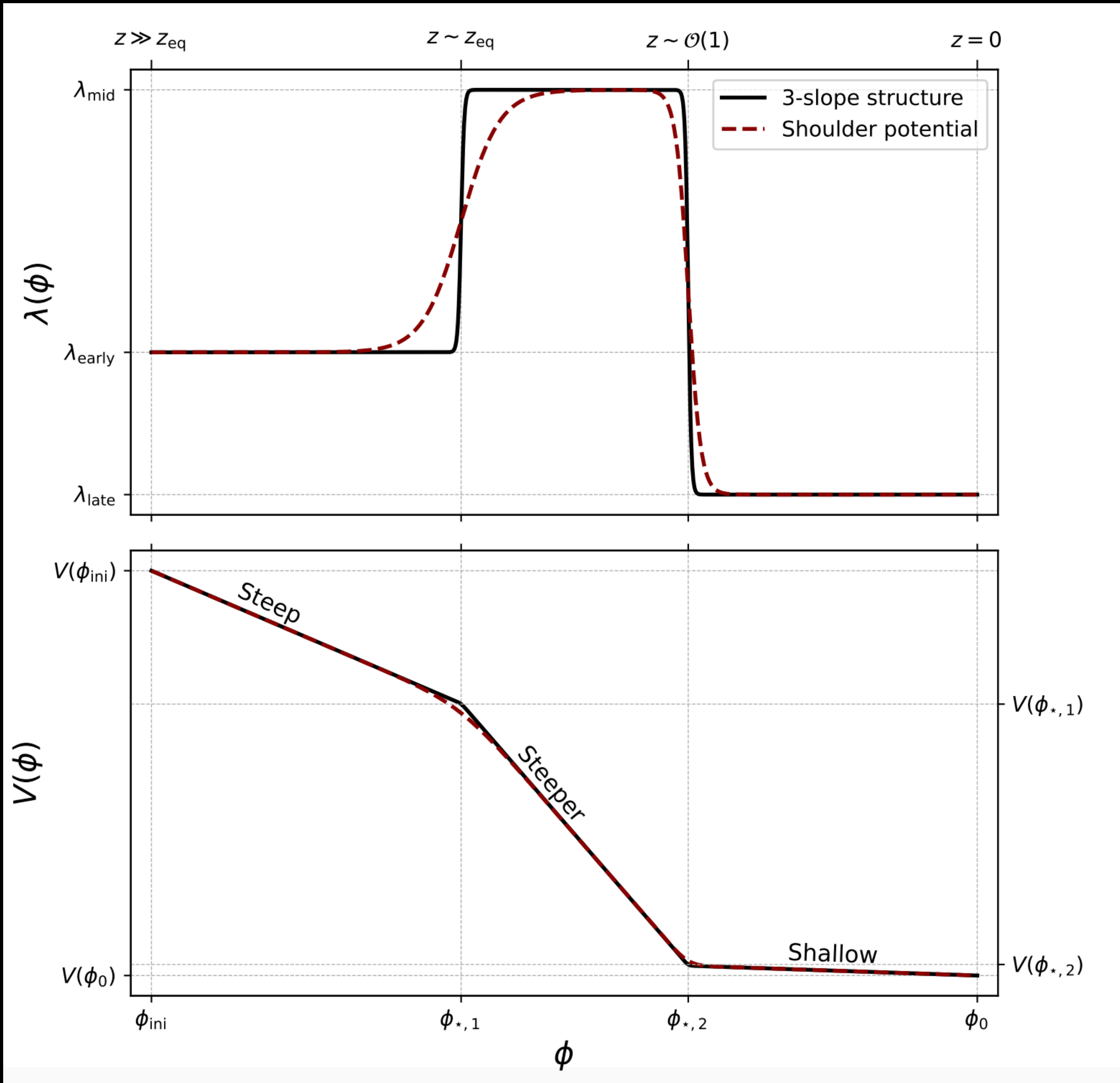
$$V(\phi) = V_L e^{-\lambda_L \phi} + V_E \frac{e^{-\lambda_E \phi}}{\left(1 + e^{\frac{\phi - \phi_*}{\Delta}}\right)^n}$$

$$\phi \gg \phi_* \Rightarrow V(\phi) = V_M e^{-\lambda_M \phi} + V_L e^{-\lambda_L \phi}$$

$$\phi \ll \phi_* \Rightarrow V(\phi) = V_E e^{-\lambda_E \phi}$$

$$\lambda_M = \lambda_E + \frac{n}{\Delta}$$

$\frac{n}{\Delta} \approx 11$ gives $\Omega_\phi \lesssim 10^{-2}$ during matter domination



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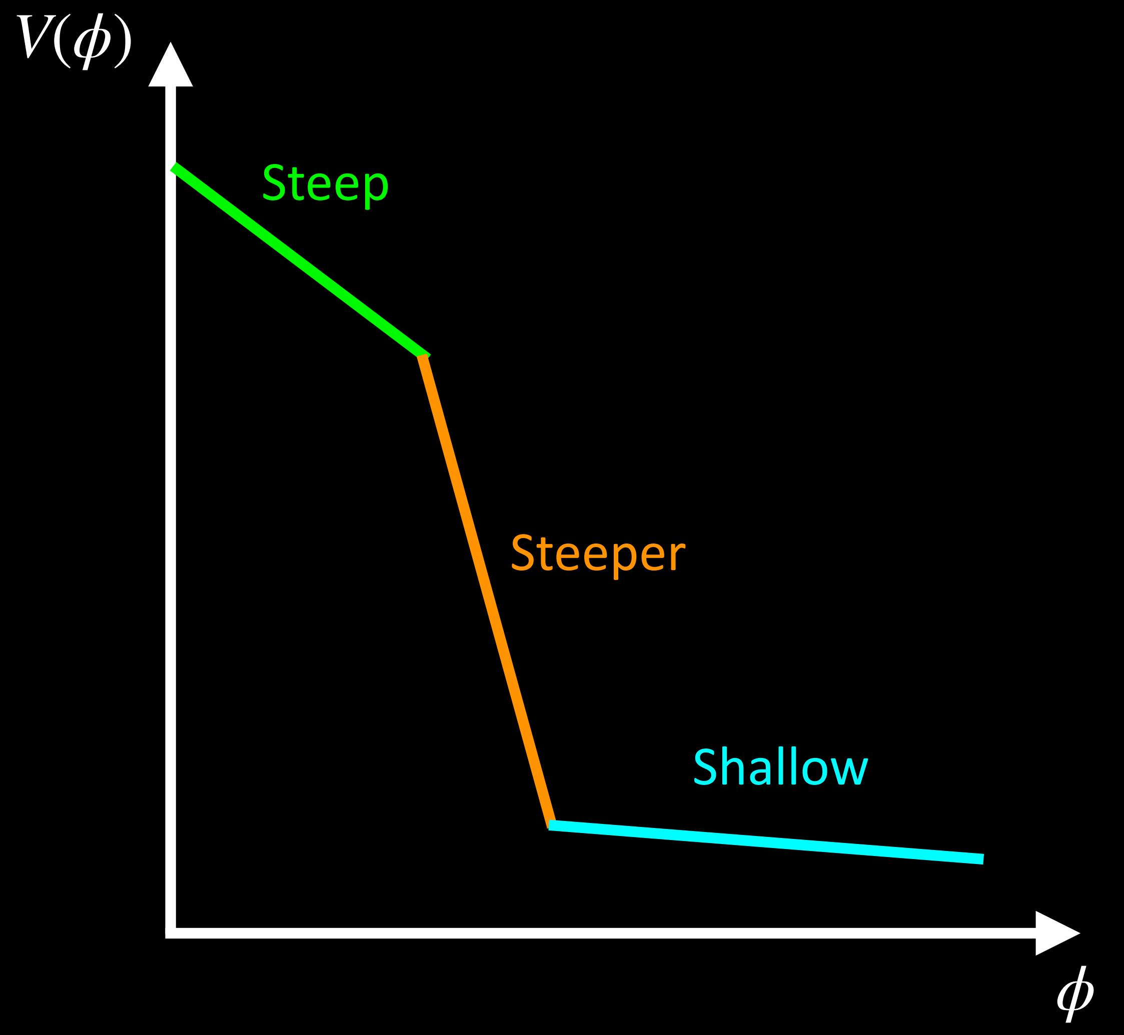
This is where we are

$$V(\phi) = V_L e^{-\lambda_L \phi} + V_E \frac{e^{-\lambda_E \phi}}{\left(1 + e^{\frac{\phi - \phi_*}{\Delta}}\right)^n}$$

We understand what is needed:

- Three slopes
- A specific hierarchy

We have a prototype potential



Next steps

- Perturbations
- Does this model fit the data?
- Natural/UV-motivated models?
- Extensions to (apparent) phantom DE
- More general theories
- Extensions to other tensions

$$V(\phi) = V_L e^{-\lambda_L \phi} + V_E \frac{e^{-\lambda_E \phi}}{\left(1 + e^{\frac{\phi - \phi_*}{\Delta}}\right)^n}$$

Are we seeing evidence for one coherent extension of ΛCDM,
or multiple unrelated cracks in different epochs?

It’s an exciting time to be a cosmologist!