Quintessence and equivalence principle violations in the dark sector

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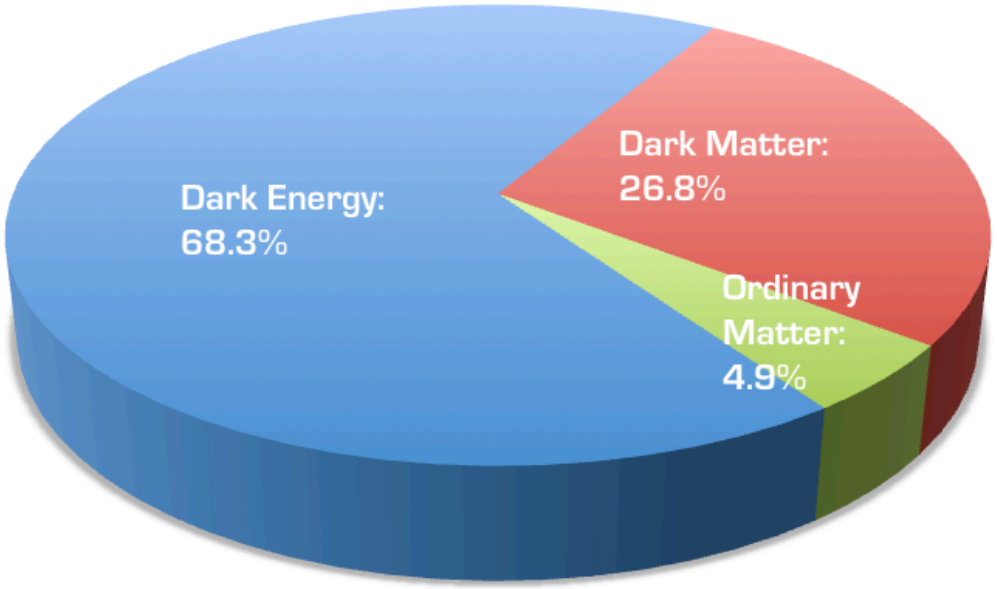

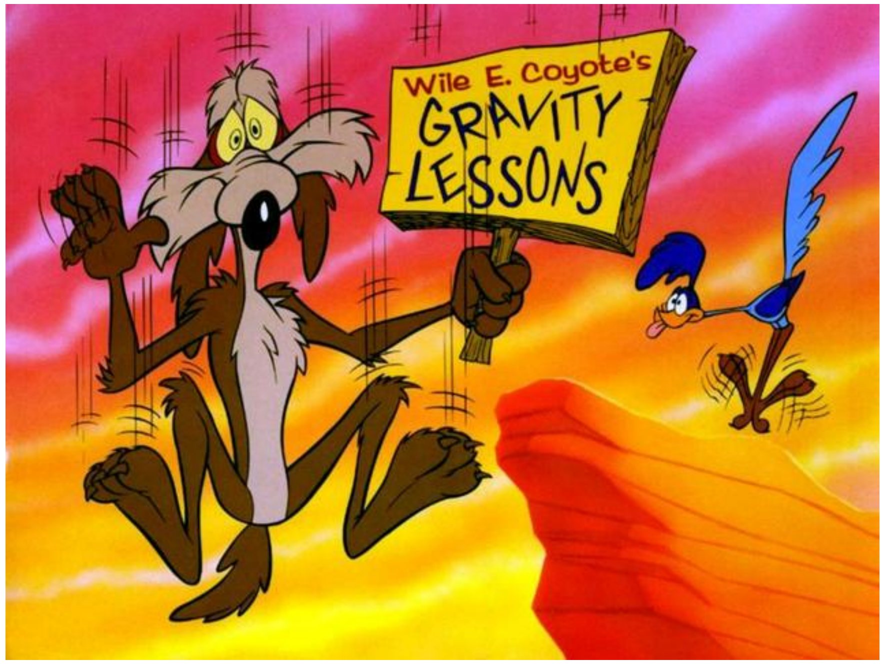

van de Bruck & Thomas (2019), arXiv: 1904.07082 (to appear in PRD)

Quintessence-interactions with the dark matter sector:

$$\mathcal{S} = \int d^4x \sqrt{-g} \left(\frac{M_{\rm Pl}^2}{2} \mathcal{R} - \frac{1}{2} (\nabla \phi)^2 - V(\phi) \right) + \mathcal{S}_{DM}(\chi_i, C(\phi) g_{\mu\nu}) + \mathcal{S}_{SM}(\Psi_i, g_{\mu\nu})$$

potential energy

dark matter metric

standard model (uncoupled)

Model specified by:

$$V(\phi)$$

$$C(\phi)$$

van de Bruck & Thomas (2019)

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Model specified by: $V(\phi)$ $C(\phi)$

Popular choices:

* $V(\phi) = V_0 \exp(-\lambda\phi/M_{\rm Pl})$
* $V(\phi) = M^{4+n}\phi^{-n}$
* ...

$$C(\phi) = \exp(\alpha\phi) \qquad (\alpha > 0 \quad \text{or} \quad \alpha < 0)$$

DM particle mass varies: $m_{\rm DM} \propto \sqrt{C(\phi)}$

van de Bruck & Thomas (2019)

Swampland criteria for EFT from string theory requires us to consider scalar fields for dark energy (de Sitter in string theory inconsistent/de Sitter conjecture).

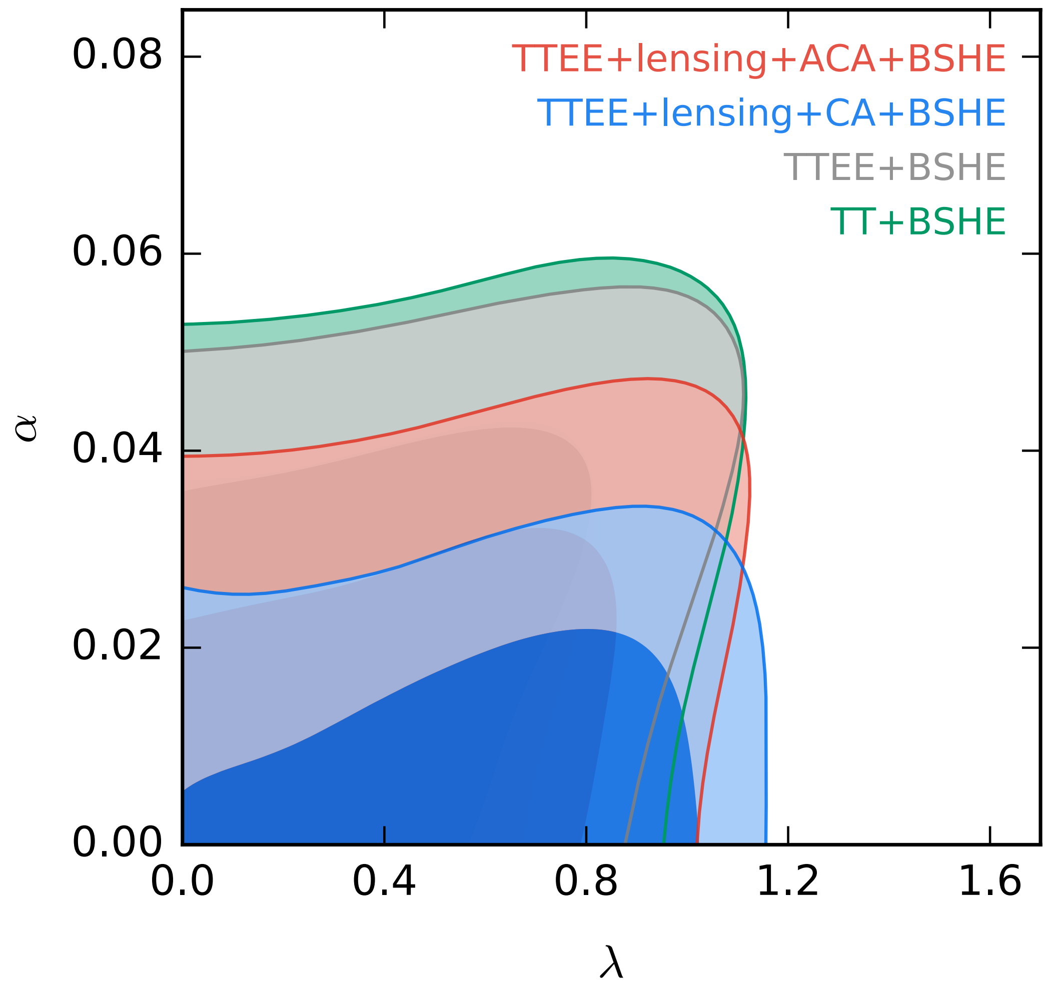
$$M_{\rm Pl}\frac{\partial V}{\partial \phi} \geq cV; \quad c \sim \mathcal{O}(1) \qquad\qquad \Delta\phi \lesssim d\, M_{\rm Pl}; \quad d \sim \mathcal{O}(1)$$

Matter couplings are expected (scalar fields in string theory typically determine coupling constants), i.e. they determine the mass of particles.

Couplings to SM strongly constrained (local + astrophysical + cosmological), dark matter only from cosmological observations.

Brennan et al (2017), Obied et al (2018), Ooguri et al (2018)

Modifications in the dark sector alone are strongly constrained too:



$$m_{DM} = m_0 e^{\alpha\phi/M_{\rm Pl}}; \quad V = V_0 e^{-\lambda\phi/M_{\rm Pl}}$$

Constraints for negative α similar.

Situation improves somewhat if disformal couplings are allowed.

Mifsud, vdB (2017)

If coupling operates/is important since the early universe, it is severely constrained. Effective gravitational constant between dark matter particles is

$$\boxed{G_{\rm eff} = G_N\left(1 + 2\beta^2\right), \quad \text{with} \quad \beta = \frac{M_{\rm Pl}}{2}\frac{d\ln C}{d\phi}}$$

Strength of fifth force less than 0.5% of gravity.

Coupling could "switch on" at late times (e.g. a tower of light states becomes important at late times; exact field description is unknown, but potentially has interesting phenomenology (Argawal et al 2019)).

Another possibility: coupling function has a minimum at finite field values, for example

$$C(\phi) \propto \exp(-\alpha(\phi - \phi_*)) + \exp(\alpha(\phi - \phi_*))$$

$$C(\phi) = 1 + (\exp(-\alpha(\phi - \phi_*)) - \exp(\alpha(\phi - \phi_*)))^2$$

Field is driven towards the minimum of coupling function at early times. Once the potential energy takes over, the field rolls down its potential and the dark matter particle masses evolve in time.

Thus, we consider:

$$C(\phi) \approx 1 + \frac{\alpha}{2}\frac{(\phi - \phi_*)^2}{M_{\rm Pl}^2}$$

Cosmological background equations:

Friedmann equation:

$$H^2 = \frac{1}{3M_{\rm Pl}^2}\left(\rho_b + \rho_c + \rho_\phi\right)$$

CDM energy conservation:

$$\dot{\rho}_c + 3H\rho_c = \frac{1}{2}\frac{\mathrm{d}\ln \mathrm{C}}{\mathrm{d}\phi}\dot{\phi}\rho_c = M_{\rm Pl}^{-1}\beta\dot{\phi}\rho_c$$

Klein-Gordon equation:

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = -M_{\rm Pl}^{-1}\beta\rho_c$$

The coupling is specified by:

$$\beta = \frac{M_{\rm Pl}}{2}\frac{d\ln C}{d\phi}$$

Define the effective equation of state for dark energy:

$$\boxed{\rho_{\mathrm{DE,eff}} = \rho_\phi + \rho_c - \rho_{c,0} a^{-3}}$$

$$\dot{\rho}_{\mathrm{DE,eff}} = -3H\left(1 + w_{\mathrm{DE}}\right) \qquad w_{\mathrm{DE}} = \frac{p_\phi}{\rho_{\mathrm{DE,eff}}}$$

$$\longrightarrow \quad H^2 = \frac{1}{3M_{\mathrm{Pl}}^2}\left(\rho_b + \frac{\rho_{c,0}}{a^3} + \rho_{\mathrm{DE,eff}}\right)$$

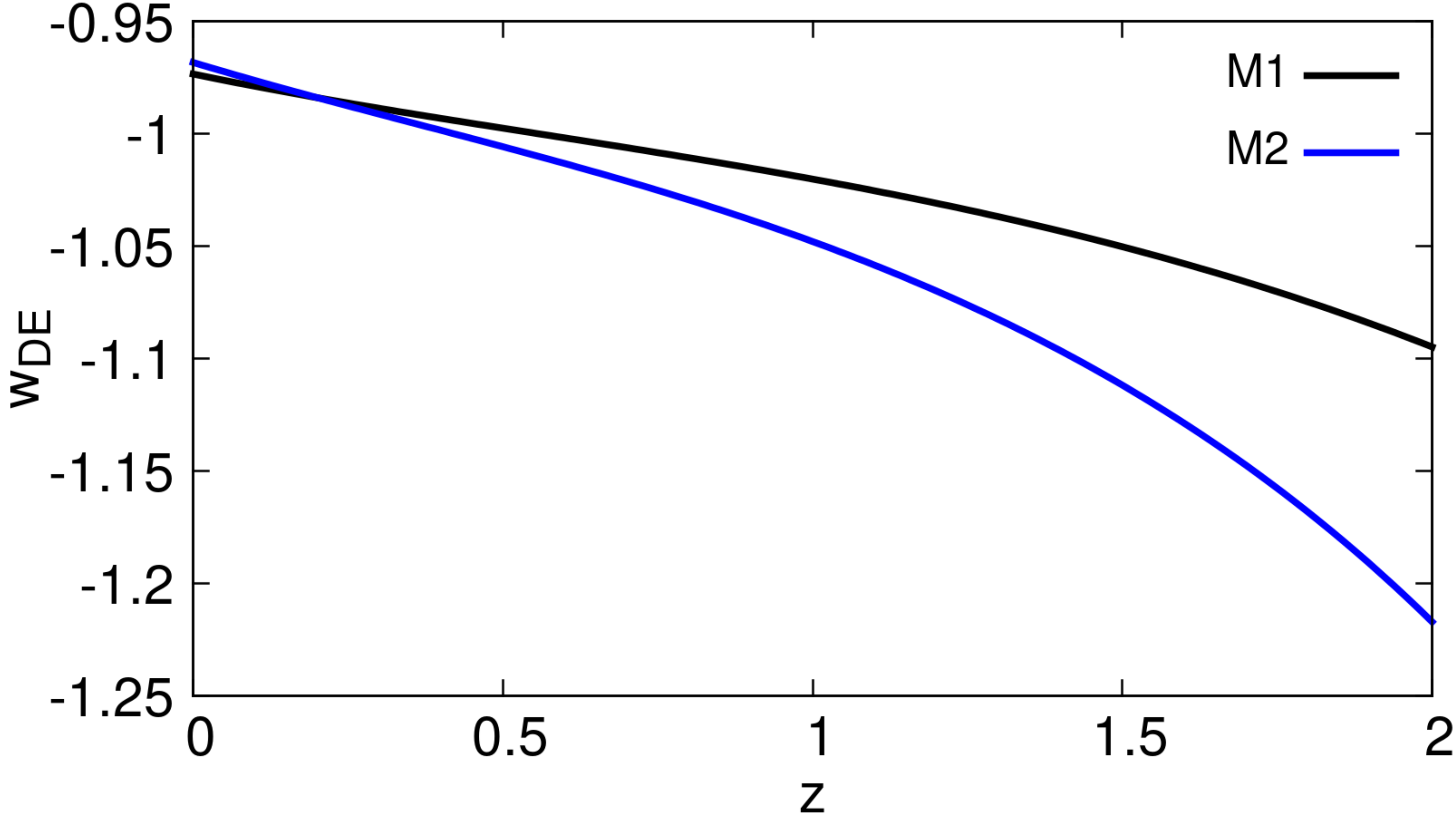
In the following plots I put the field in the minimum of the coupling function at the beginning of the integration (CLASS code):

$$C(\phi) \approx 1 + \frac{\alpha}{2}\frac{(\phi - \phi_*)^2}{M_{\rm Pl}^2} \qquad \phi_{\rm ini} = \phi_*$$

Good reasons to think this is the case (see later, but I will describe what happens if the field is displaced from its minimum as well).

van de Bruck & Thomas (2019)

Evolution of effective equation of state:

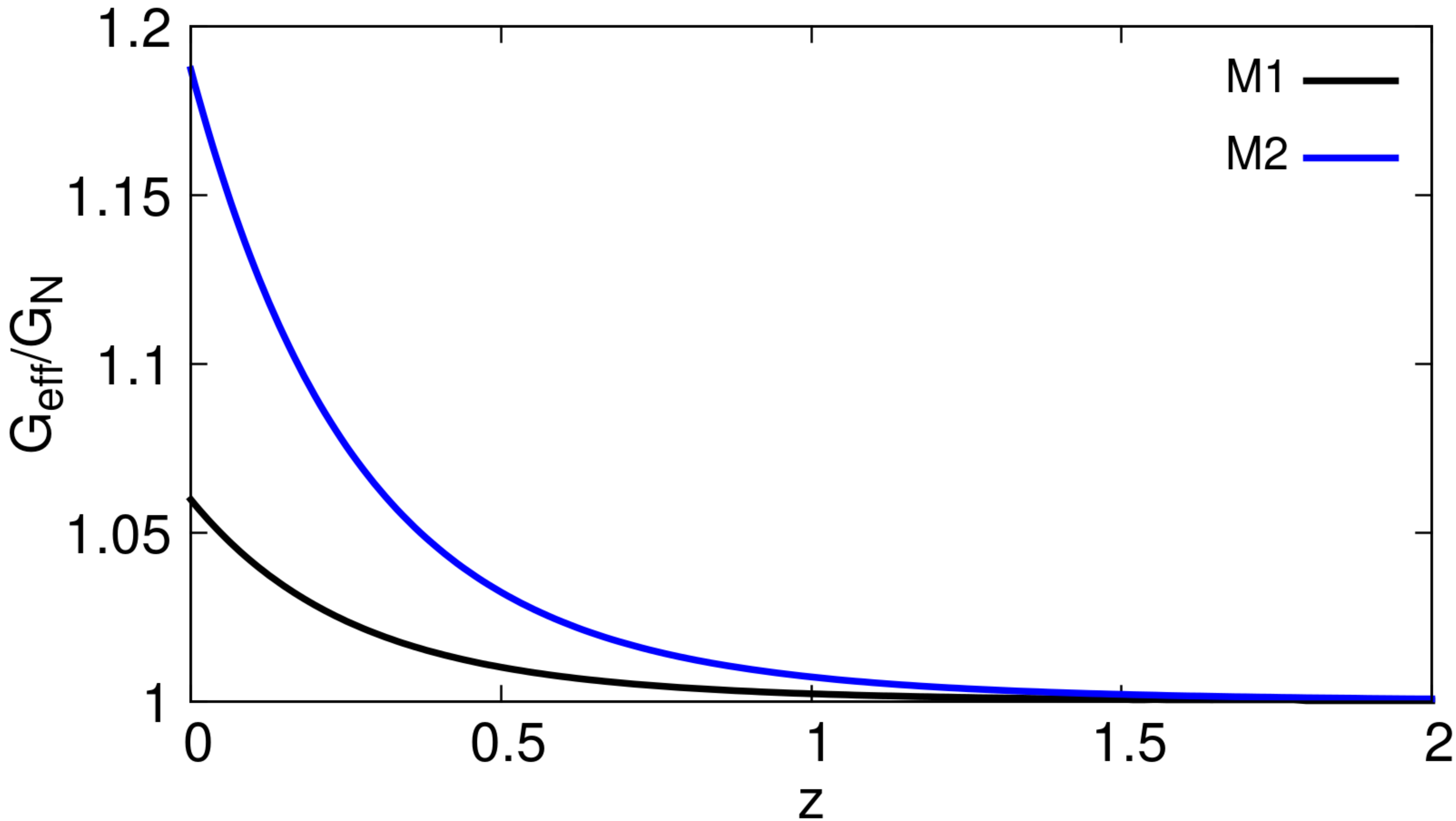


M1: $\alpha = 3, \ \ \lambda = 0.5$

M2: $\alpha = 5, \ \ \lambda = 0.6$

van de Bruck & Thomas (2019)

Evolution of effective gravitational constant between DM particles:



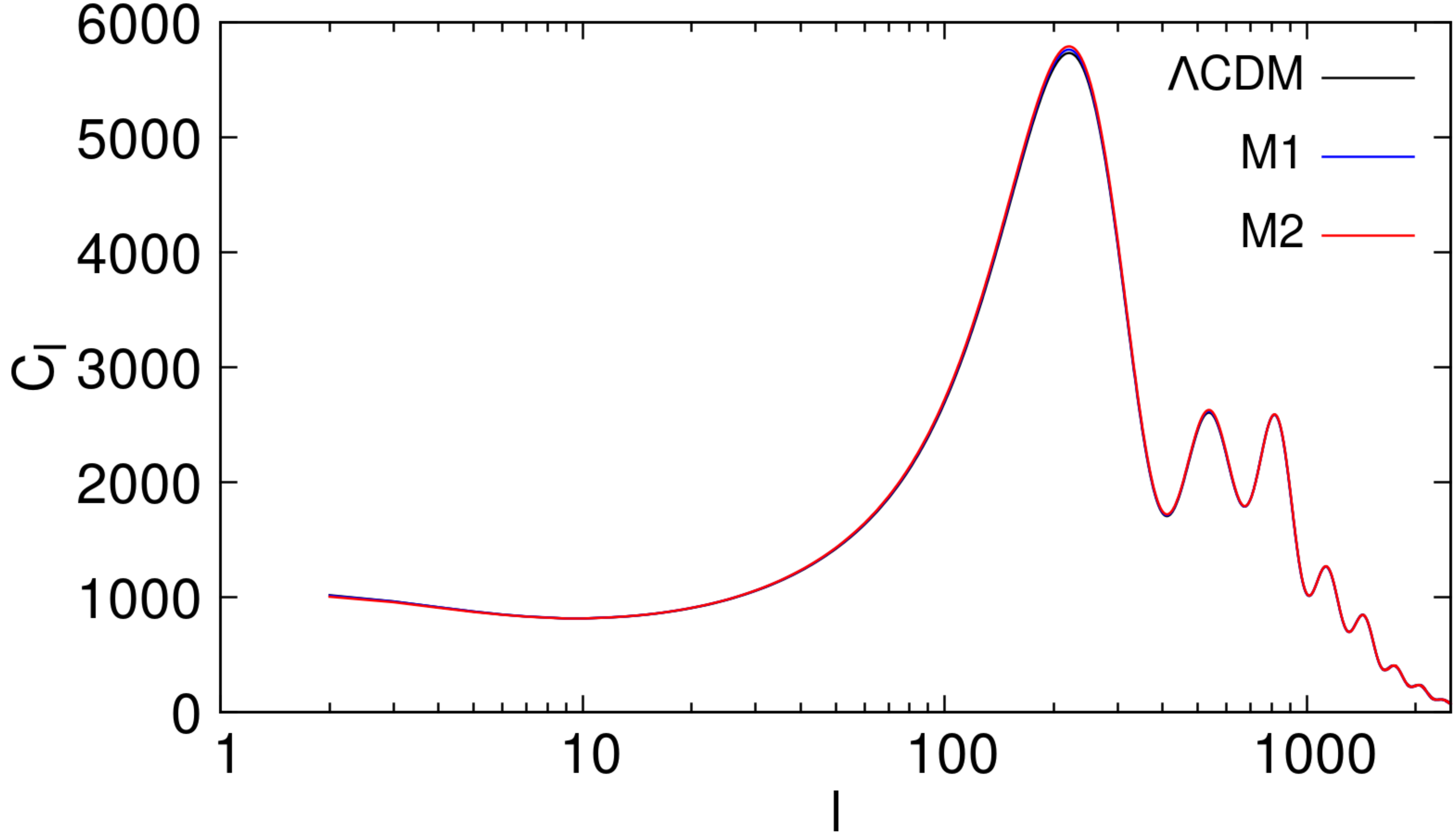
M1: $\alpha = 3, \;\; \lambda = 0.5$

M2: $\alpha = 5, \;\; \lambda = 0.6$

$$G_{\rm eff} = G_N\left(1 + 2\beta^2\right), \quad \text{with} \quad \beta = \frac{M_{\rm Pl}}{2}\frac{d\ln C}{d\phi}$$

van de Bruck & Thomas (2019)

CMB anisotropies:



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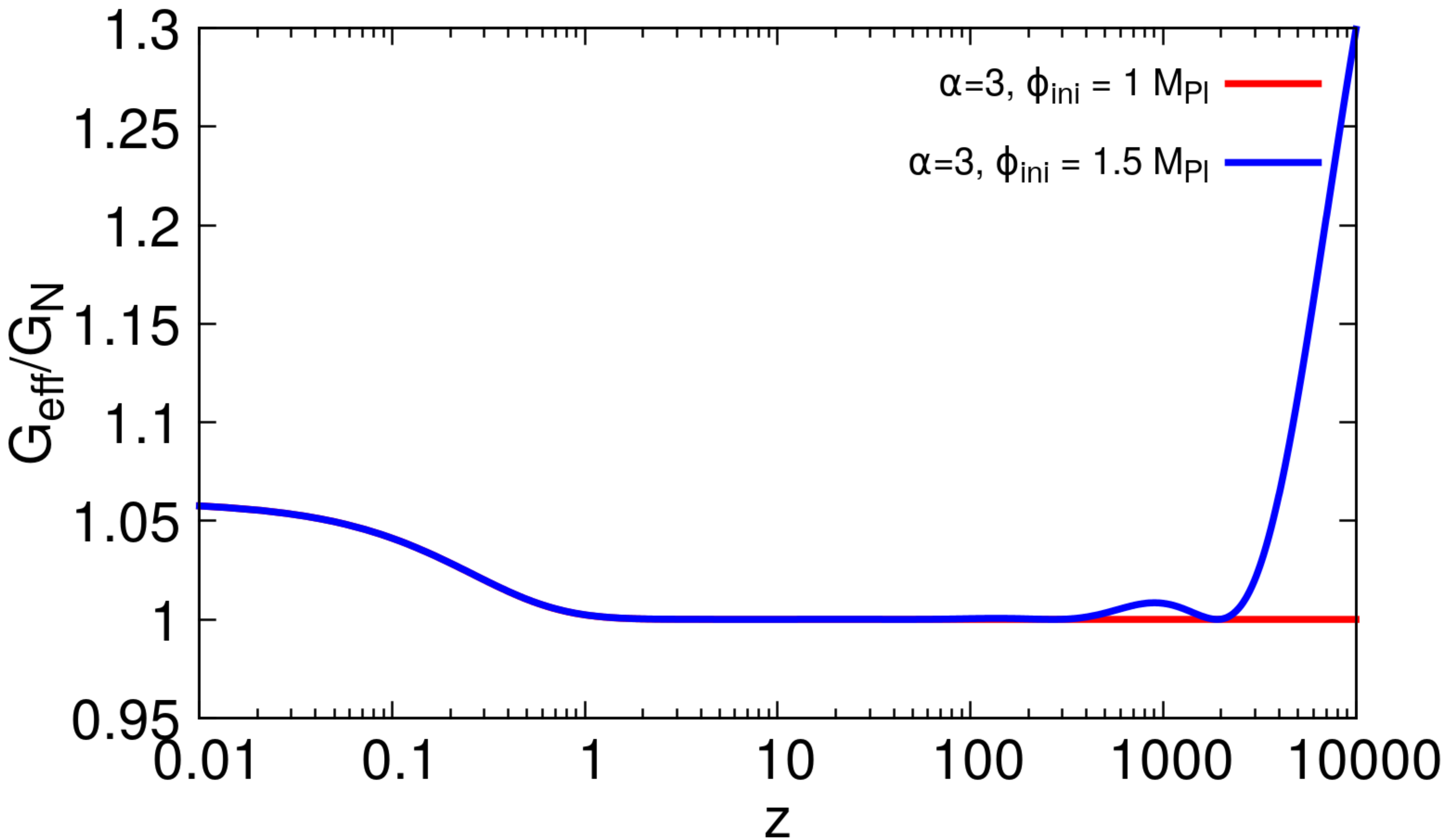
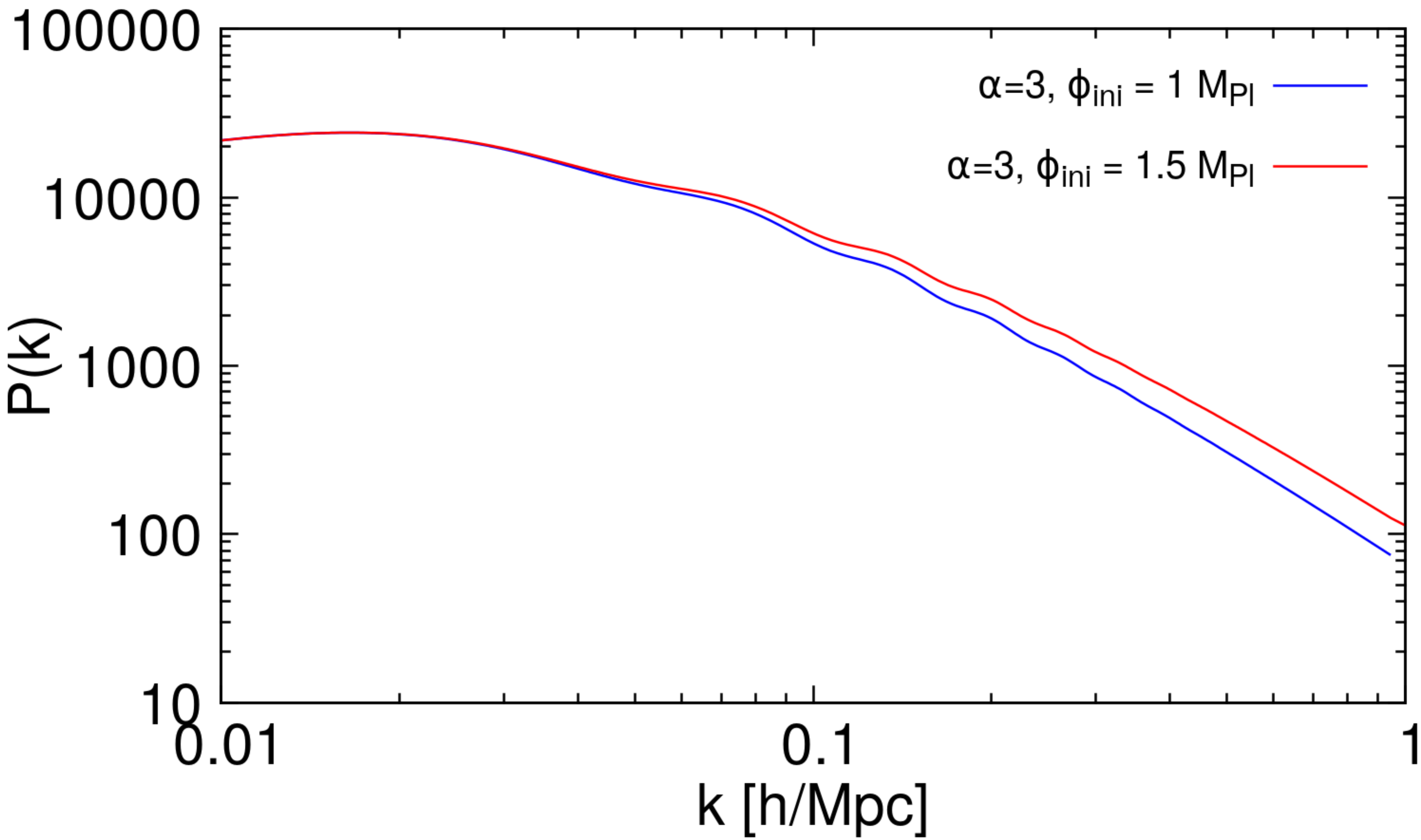
Displace the field from the minimum in the early universe:



van de Bruck & Thomas (2019)

Displace the field from the minimum in the early universe:



van de Bruck & Thomas (2019)

Relation to swampland de Sitter conjecture:

$$M_{\rm Pl}\frac{\partial V}{\partial \phi} \geq cV \quad c = \mathcal{O}(1)$$

$$\lambda = 0.6$$

α	$\omega_{\rm DE,0}$	σ_8	$G_{\rm eff,0}/G_N$
0	-0.947	0.805	1
3	-0.962	0.799	1.09
5	-0.969	0.799	1.19
10	-0.979	0.801	1.46
50	-0.995	0.821	2.91

Coupling seems to allow for larger values for the slope of the exponential potential. Comparison to data is ongoing...

van de Bruck & Thomas (2019)

Attractor mechanism in the very early universe:

- Inflation
- Dark matter becomes non-relativistic

van de Bruck & Thomas (2019)

Inflation

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + \sum_i \int d^4x\sqrt{-\tilde{g}}\left[-\frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\chi_i\partial_\nu\chi_i - U(\chi_i)\right].$$

Gravitational sector (including DE) | Inflation sector with several fields

Inflaton field potential obeys de Sitter-swampland conditions: inflaton possibly needs to be driven by several fields.

What is needed for the attractor mechanism is to have one field coupled to the DE field in the same way as DM is. In the action above, all fields are coupled.

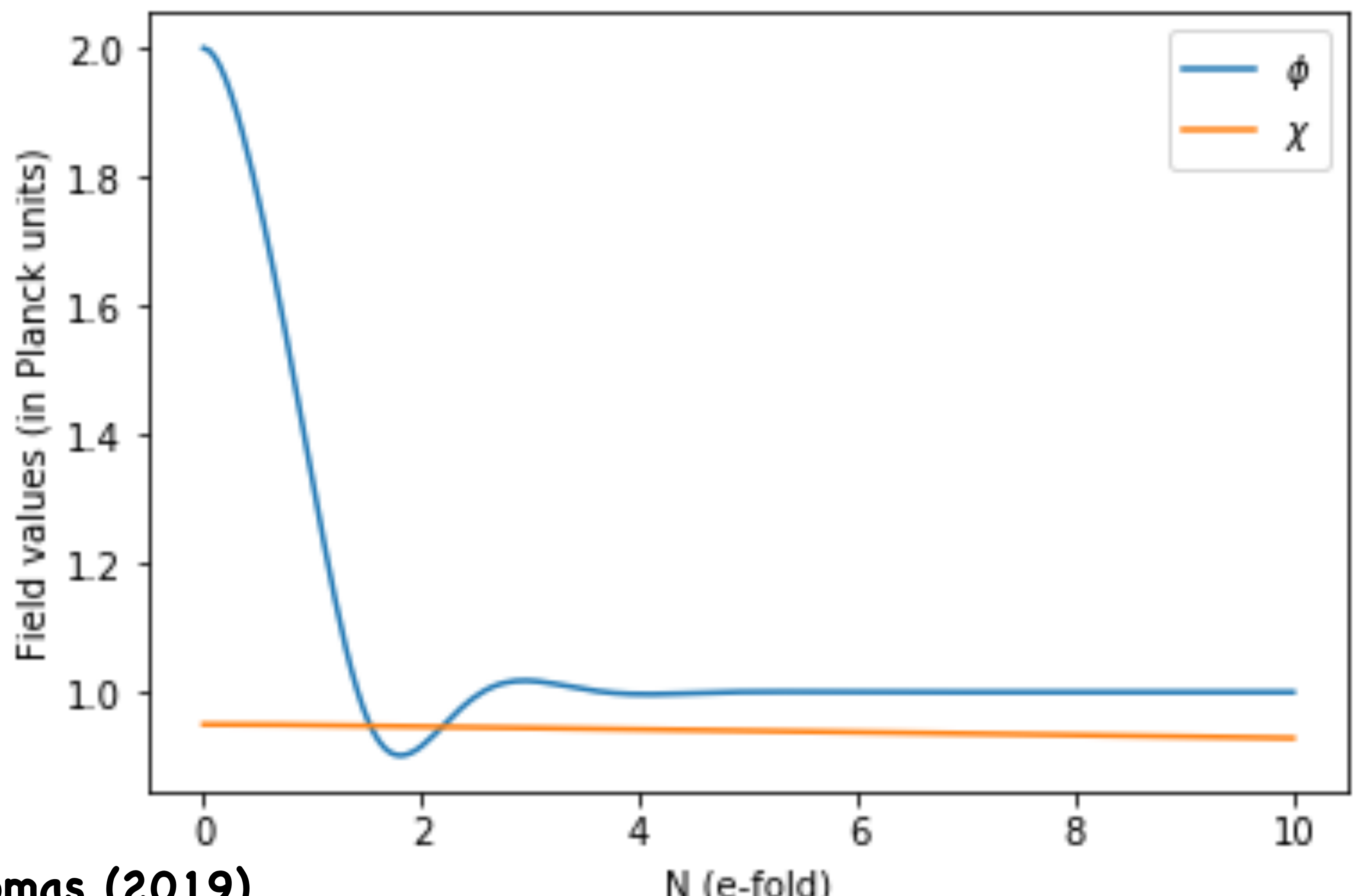
van de Bruck & Thomas (2019)

Inflation

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + \sum_i \int d^4x\sqrt{-\tilde{g}}\left[-\frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\chi_i\partial_\nu\chi_i - U(\chi_i)\right].$$

Gravitational sector (including DE) **Inflation sector with several fields**

Consider one inflaton field case (plateau potential):



van de Bruck & Thomas (2019)

Dark matter becomes non-relativistic

Full Klein-Gordon equation:

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = -M_{\rm Pl}^{-1}\beta\rho_c(1 - 3w_c)$$

vanishes when DM is relativistic, but becomes quickly non-zero afterwards.
Field gets a kick:

$$\frac{\Delta\phi}{M_{\rm Pl}} \approx -\frac{g_{\rm DM}}{g_*}\beta_{t_0}$$

coupling at time DM becomes NR.

van de Bruck & Thomas (2019)

Conclusions/summary:

- (Standard) Coupled DE is strongly constrained, but several options are still possible, such as field dependent couplings, e.g. coupling functions with maxima/minima.
- Equivalence principle (EP) can be violated in the dark sector, and this is much less constrained than previously thought.
- Attractor mechanism exists which can decoupled DE from DM but when DE takes over in the late universe, a fifth force emerges in dark sector.
- Need to find new tests to search for EP violations in the dark sector.