

Scalar dark matter: a non-minimal perspective

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Based on work with T. Hugle and J. Jaeckel
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neutrinos, dark matter & dark energy physics



Horizon 2020



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Motivation

As we have seen during this week, scalar particles can play an important role in cosmology:

- Inflation, dark energy, ..., **dark matter.**

We know dark matter feels gravity. What about other couplings?

- Non-minimal coupling to gravity: $\mathcal{L}_J \supset (M_p^2 - \xi \phi^2) R$
 - Allowed by symmetries.
 - Dimension 4.
 - Motivated in perturbative approaches to quantum gravity.

Main ideas & goal of the talk

- Explore the cosmological relevance of the non-minimal coupling.
- Important for non-thermal dark matter production:
 - Misalignment mechanism *revisited*.
 - Production from inflationary fluctuations.

Other ideas in this direction

- Misalignment mechanism for scalars and vectors
Arias et al [1201.5902], *Nelson & Scholtz* [1105.2812], ...
- Resonant production at (p)reheating
 - WIMPZILLAs: *Chung et al* [hep-ph/9802238], ...
 - Non-minimally coupled scalars: *Fairbairn et al* [1808.08236], ...
- Vector dark matter from inflationary fluctuations
Graham et al [1504.02102]
- Thermal production via graviton exchange
Garny et al [1511.03278], *Ema et al* [1804.07471], ...

Relevance & applications

Most immediate and minimal scenario:

Gravitational generation of all the dark matter that we observe.

Other potentially interesting applications:

- Freeze-in dark matter: Hall *et al* [0911.1120] (Bernal *et al* [1706.07442])
- Affleck-Dine baryogenesis: Bettoni & Rubio [1805.02669]
- Asymmetric dark matter: Kaplan *et al* [0901.4117] (Zurek [1308.0338])
- Higgs portal DM: Cosme et al [1802.09434]

Non-minimally coupled scalar

$$S = \int d^4x \sqrt{-g} \left(\left(\tilde{M}_p^2 - \xi \phi^2 \right) R - \frac{1}{2} g^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi - m^2 \phi^2 \right)$$

Jordan frame

vs

Einstein frame

- Non-minimal coupling

$$\mathcal{L}_J \supset (M_p^2 - \xi \phi^2) R$$

- Effective mass for ϕ

$$m_{\text{eff}}^2 = m^2 + \xi R$$

Conformal trafo

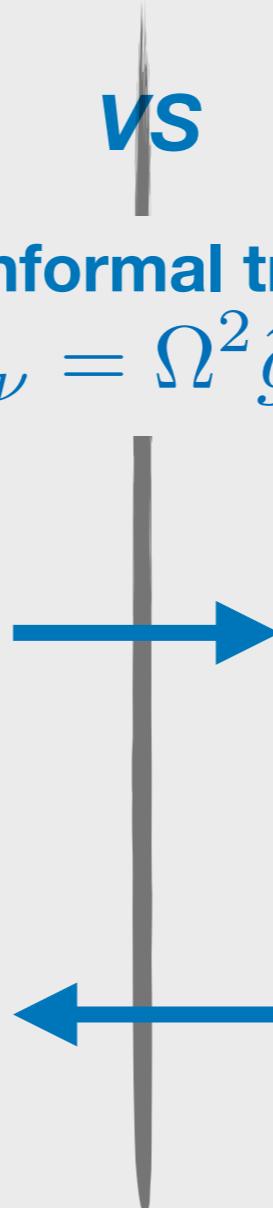
$$g_{\mu\nu} = \Omega^2 \tilde{g}_{\mu\nu}$$

- Minimal coupling

$$\mathcal{L}_E \supset M_p^2 R - m_\sigma^2 \sigma^2 \frac{\xi \phi^2}{M_p^2}$$

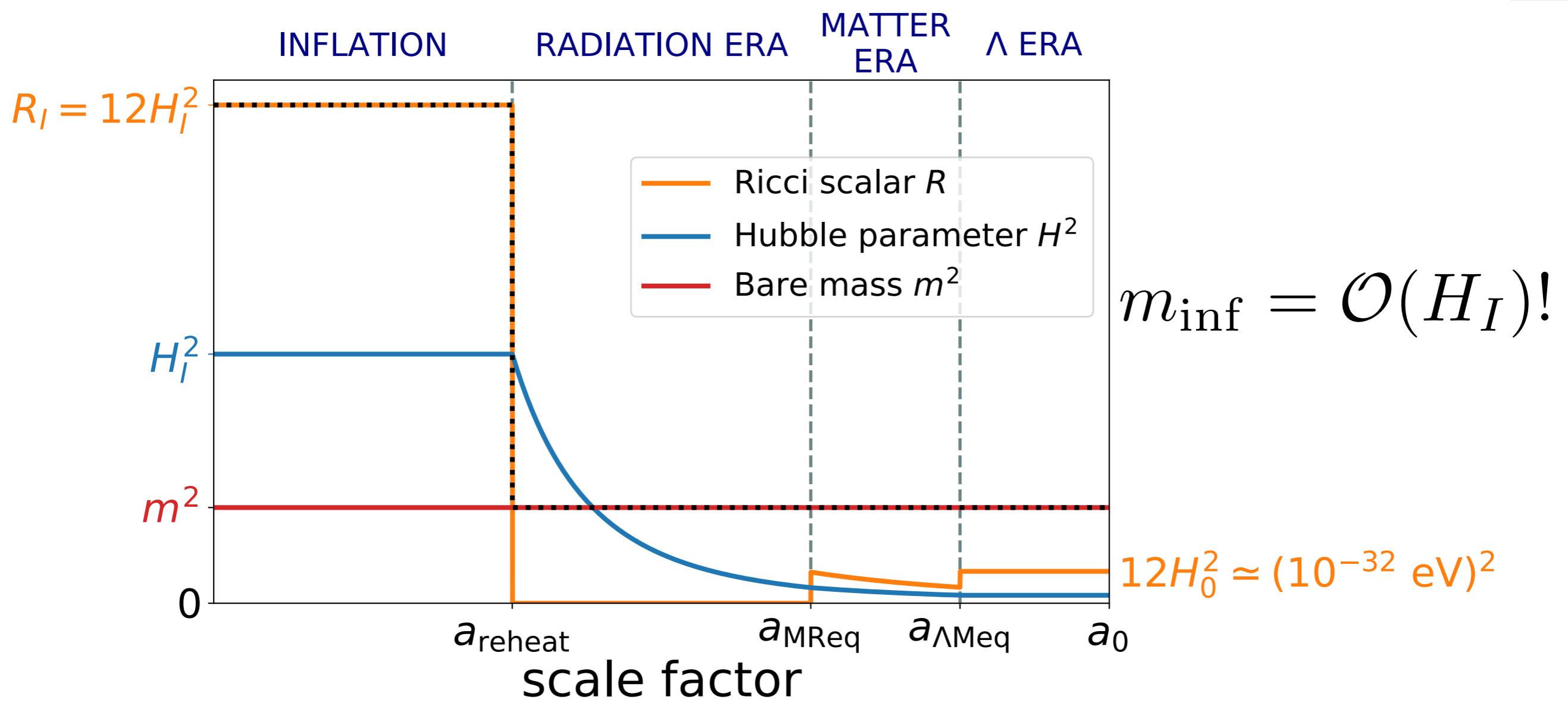
- If $\xi \phi^2 \ll M_p^2$

Backreaction is negligible



Non-minimal coupling in cosmology

Effective mass for ϕ : $m_{\text{eff}}^2 = m^2 + \xi R$, $R \propto H^2$



The field is heavy during inflation, but it can be light from then on.

Misalignment mechanism *revisited*

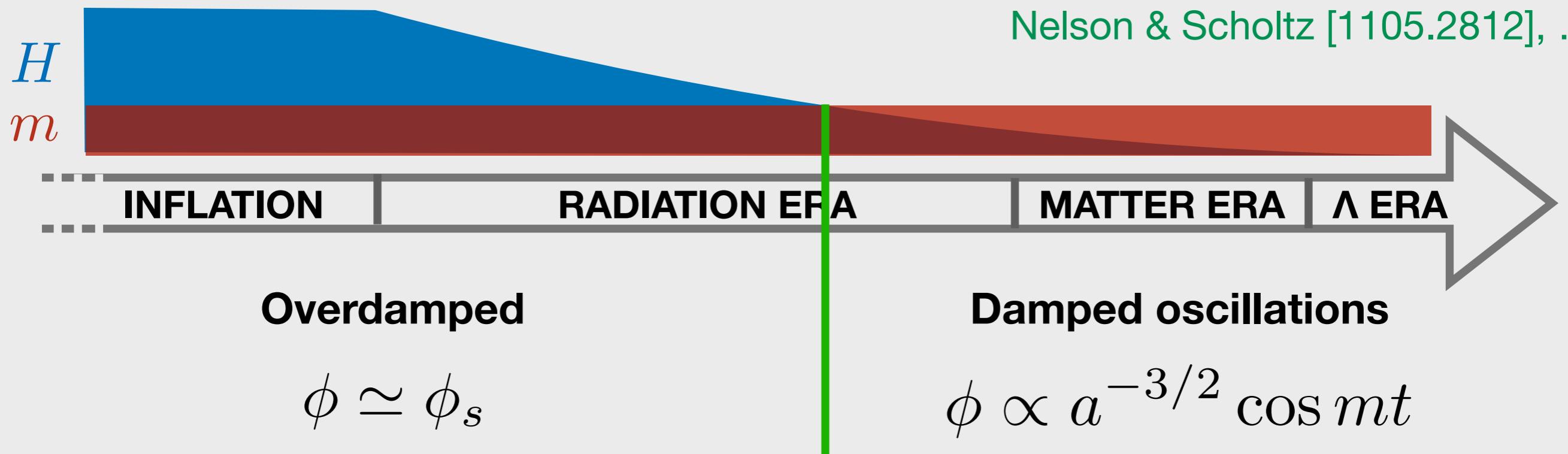
Misalignment mechanism

EOM of a minimally coupled homogeneous scalar field:

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

Harmonic oscillator!

Arias *et al* [1201.5902],
Nelson & Scholtz [1105.2812], ...



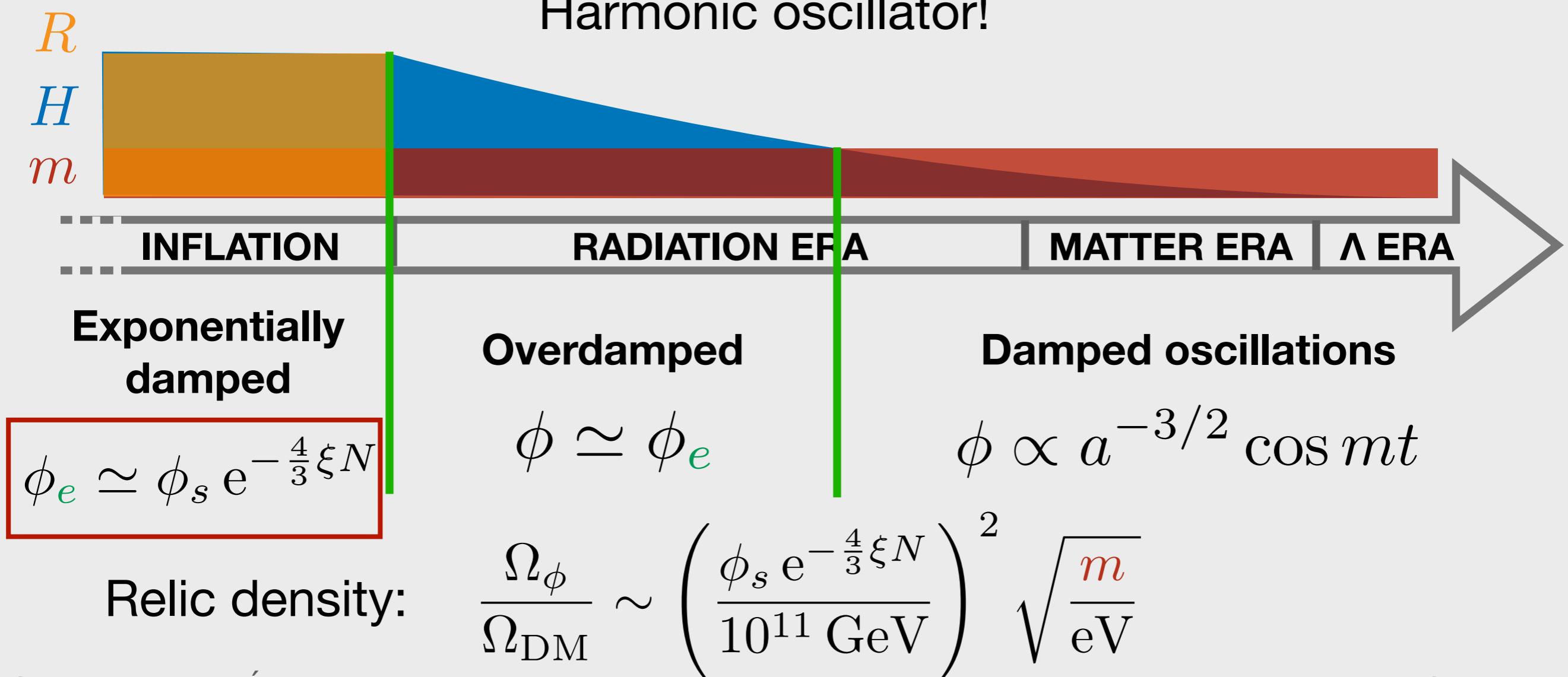
Relic density: $\frac{\Omega_\phi}{\Omega_{\text{DM}}} \sim \left(\frac{\phi_s}{10^{11} \text{ GeV}} \right)^2 \sqrt{\frac{m}{\text{eV}}}$

Misalignment mechanism *revisited*

EOM of a non-minimally coupled homogeneous scalar field:

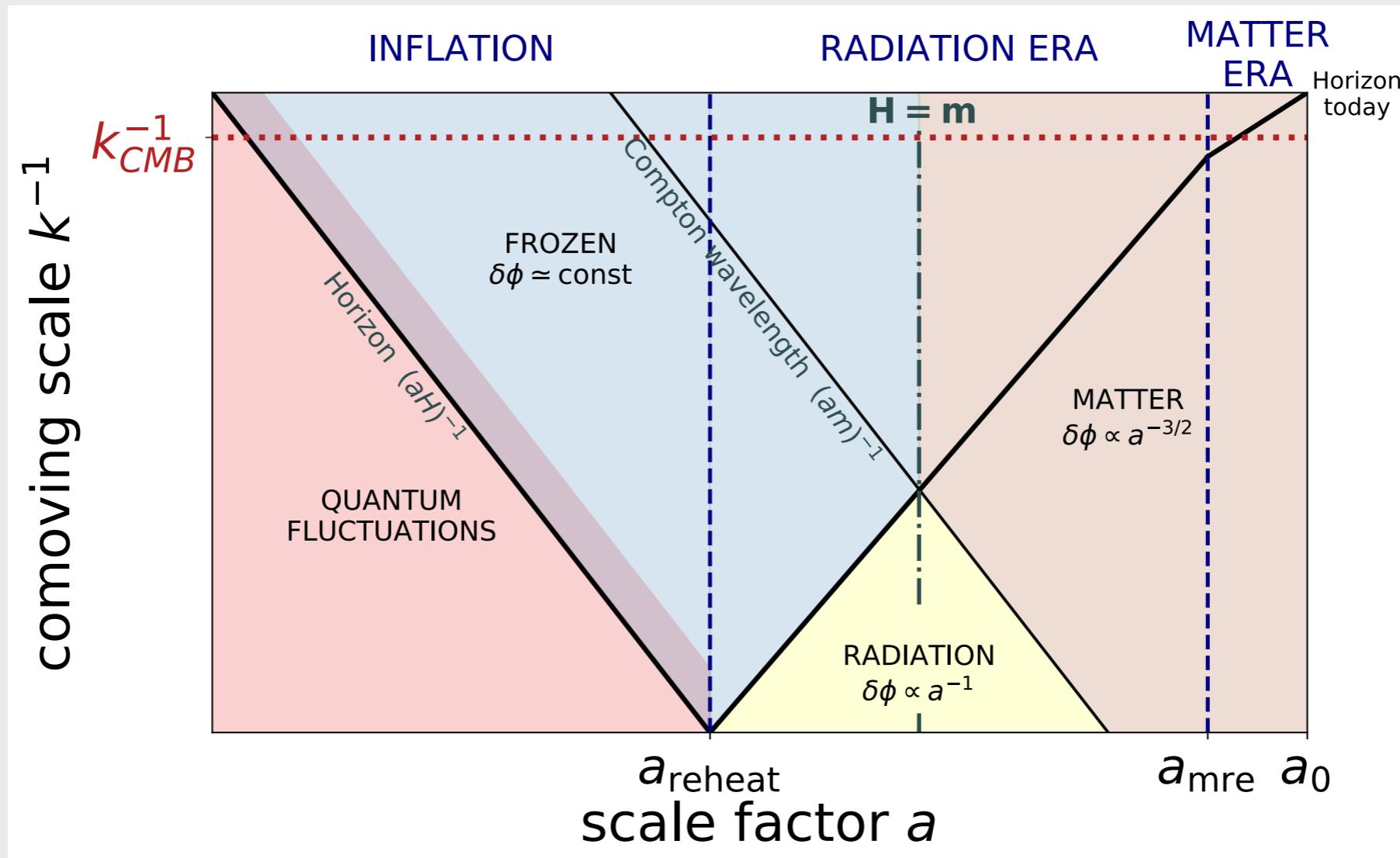
$$\ddot{\phi} + 3H\dot{\phi} + (m^2 + \xi R)\phi = 0$$

Harmonic oscillator!



Isocurvature fluctuations

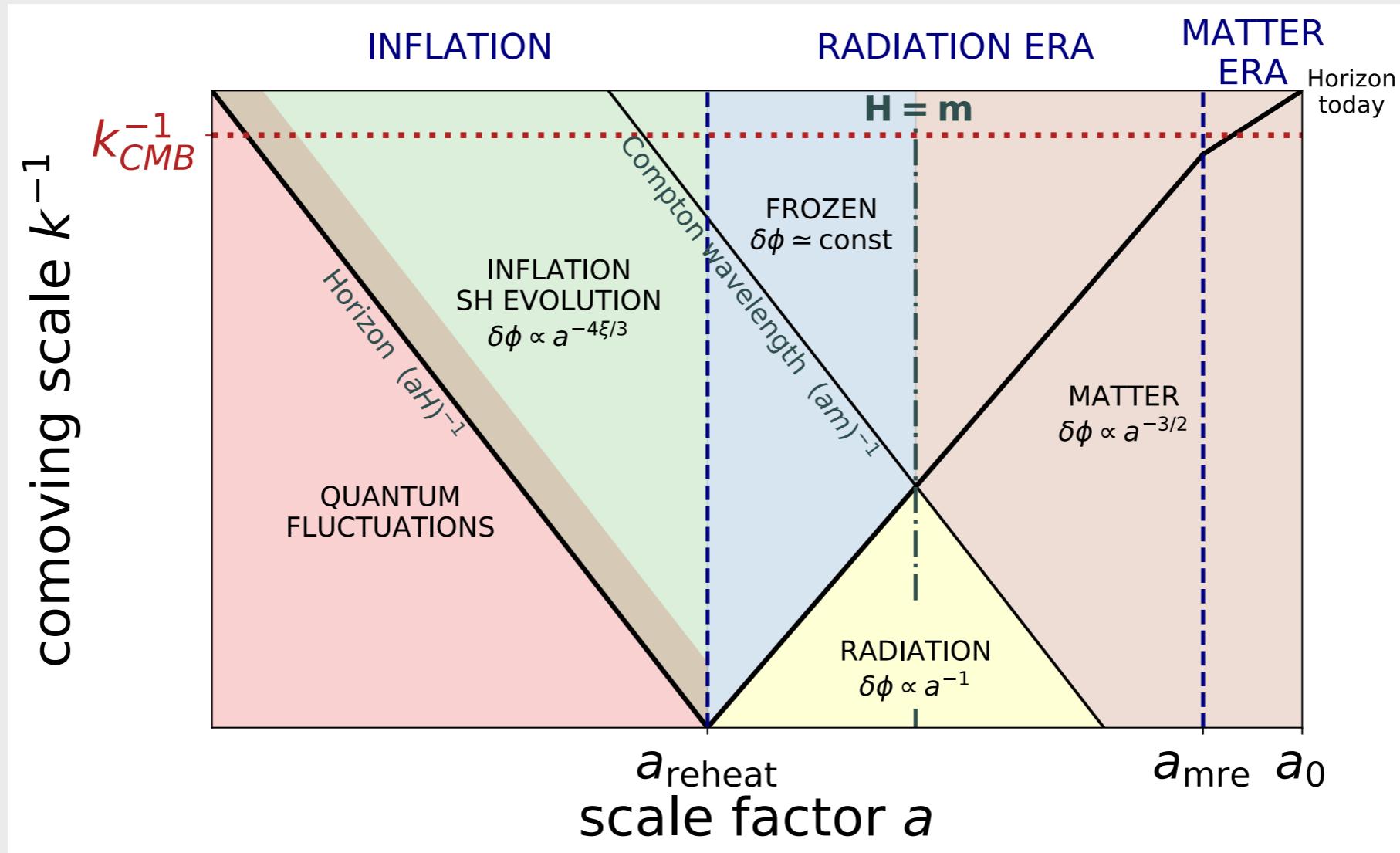
Fluctuations freeze as the modes exit the horizon during inflation.



$$\mathcal{P}_\delta(k_{\text{CMB}}) \simeq \frac{4}{\phi_e^2} \left(\frac{H_I}{2\pi} \right)^2$$

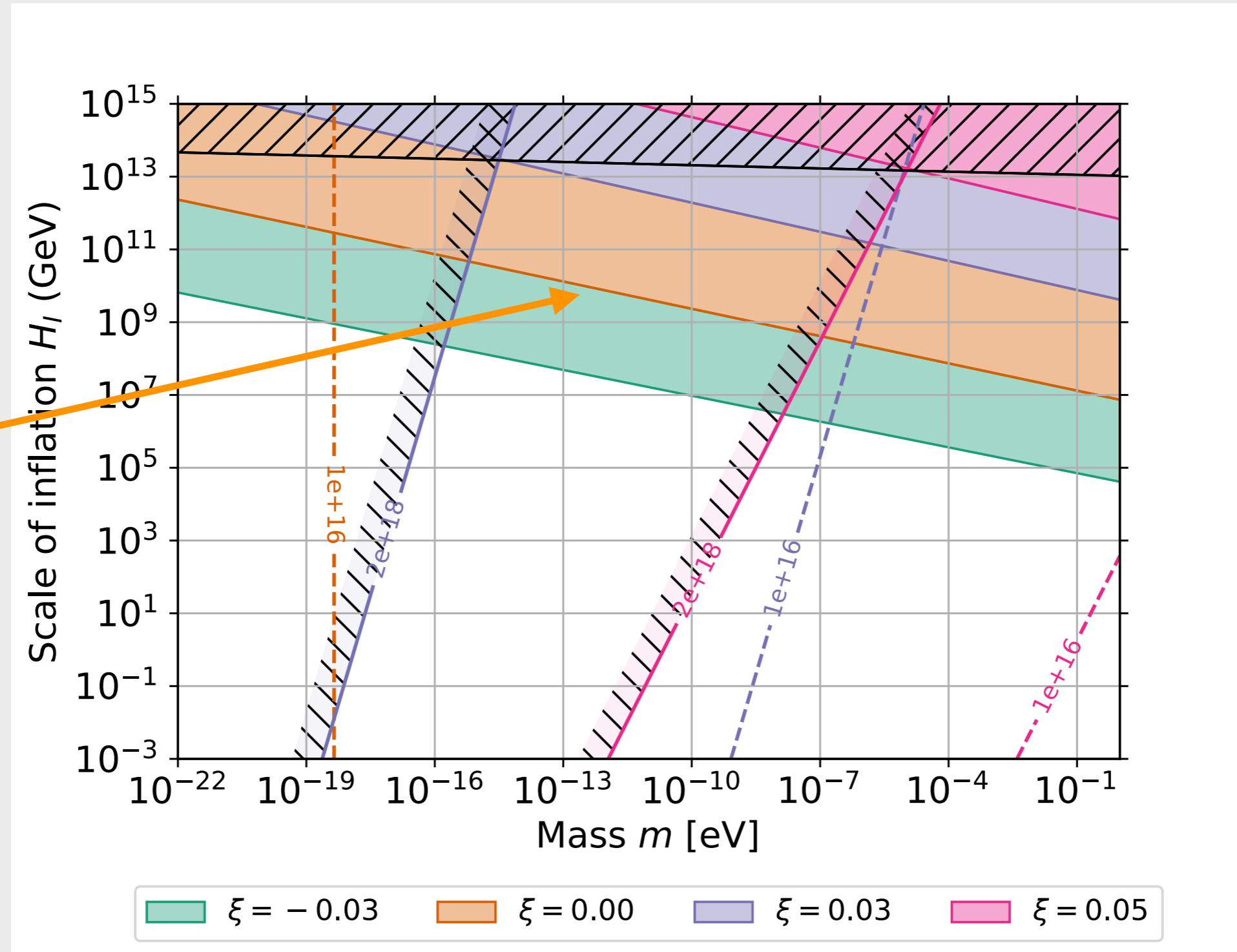
Isocurvature fluctuations *revisited*

Superhorizon modes are not frozen during inflation.



$$\mathcal{P}_\delta(k_{CMB}) \simeq \frac{4}{\phi_e^2 e^{-\frac{8}{3}\xi N(k_{CMB})}} \left(\frac{H_I}{2\pi} \right)^2$$

Misalignment parameter space *revisited*



Isocurvature constraints are weakened for $\xi > 0$.

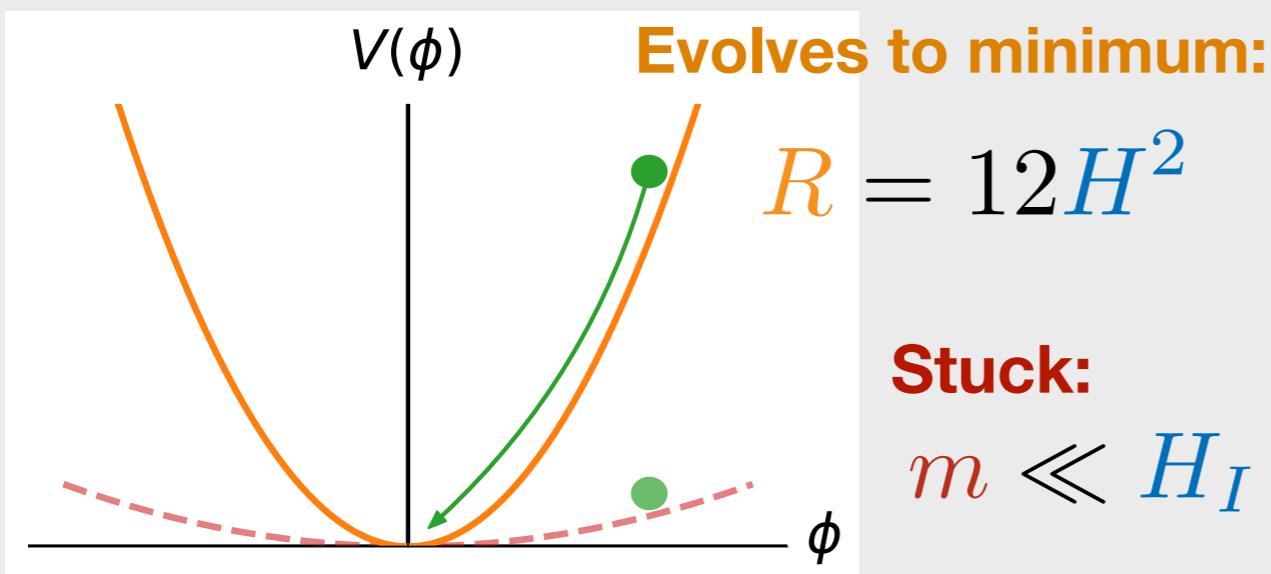
Dark matter from fluctuations

Dark matter from fluctuations

Classically

The homogeneous field is damped away during inflation.

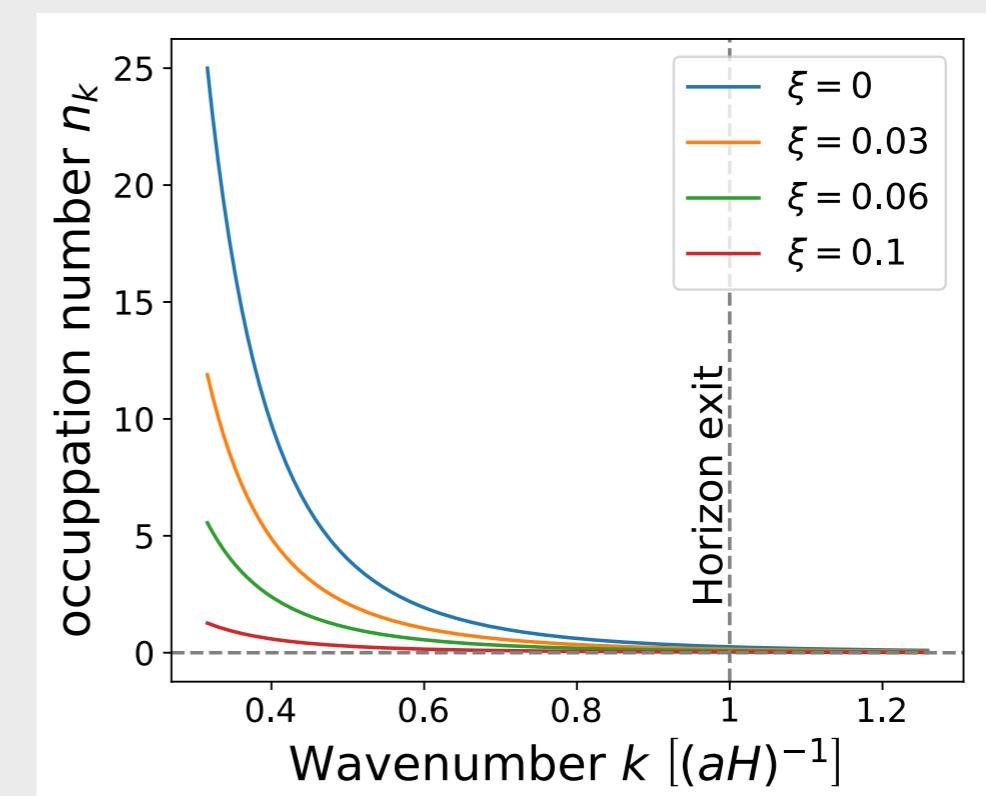
$$\ddot{\phi} + 3H\dot{\phi} + (m^2 + \xi R) \phi = 0.$$



$$\phi_e \simeq \phi_s e^{-\frac{4}{3}\xi N}$$

Quantum mechanically

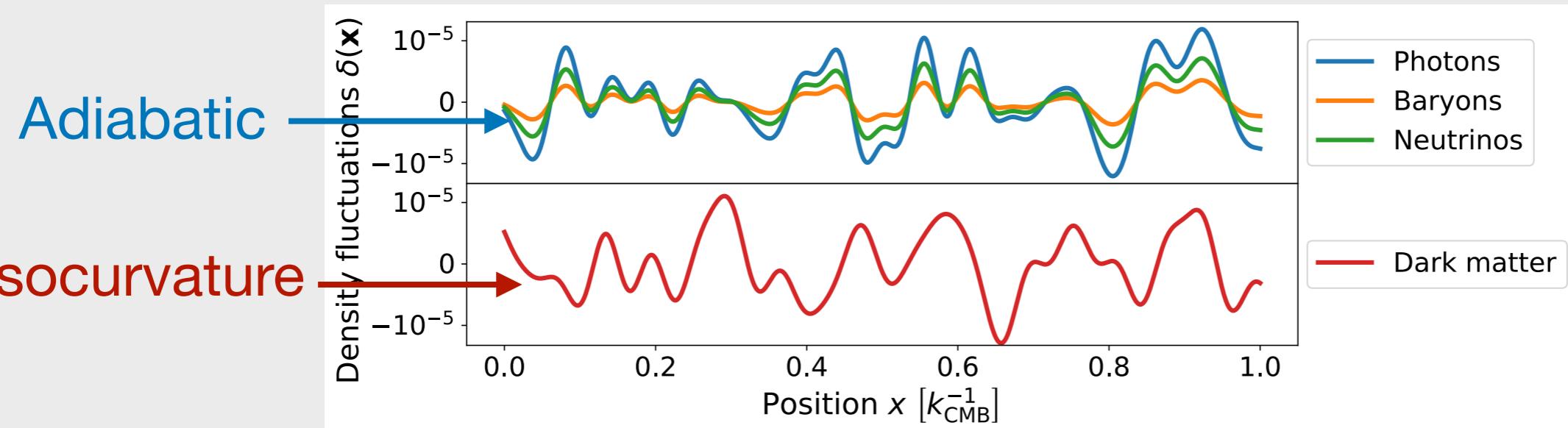
Higher momentum modes are excited due to the time-dependent gravitational background.



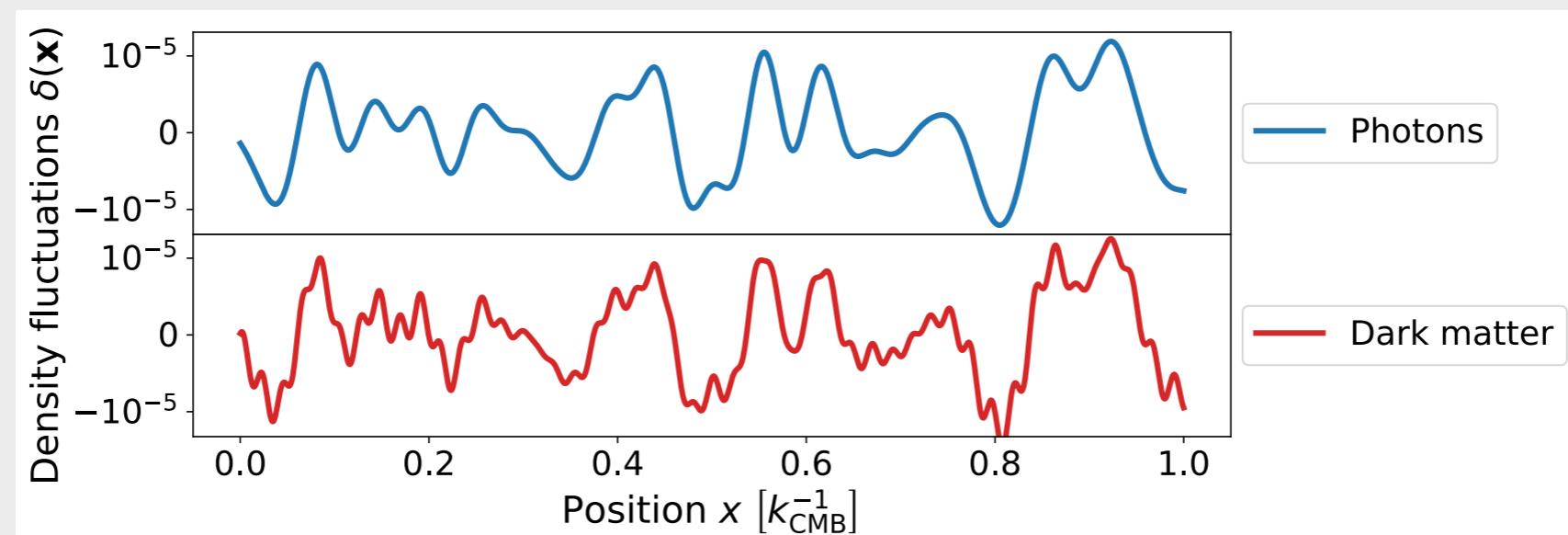
A larger ξ suppresses the occupation number.

But aren't the fluctuations isocurvature?

Spectrum of fluctuations of a minimally coupled scalar.



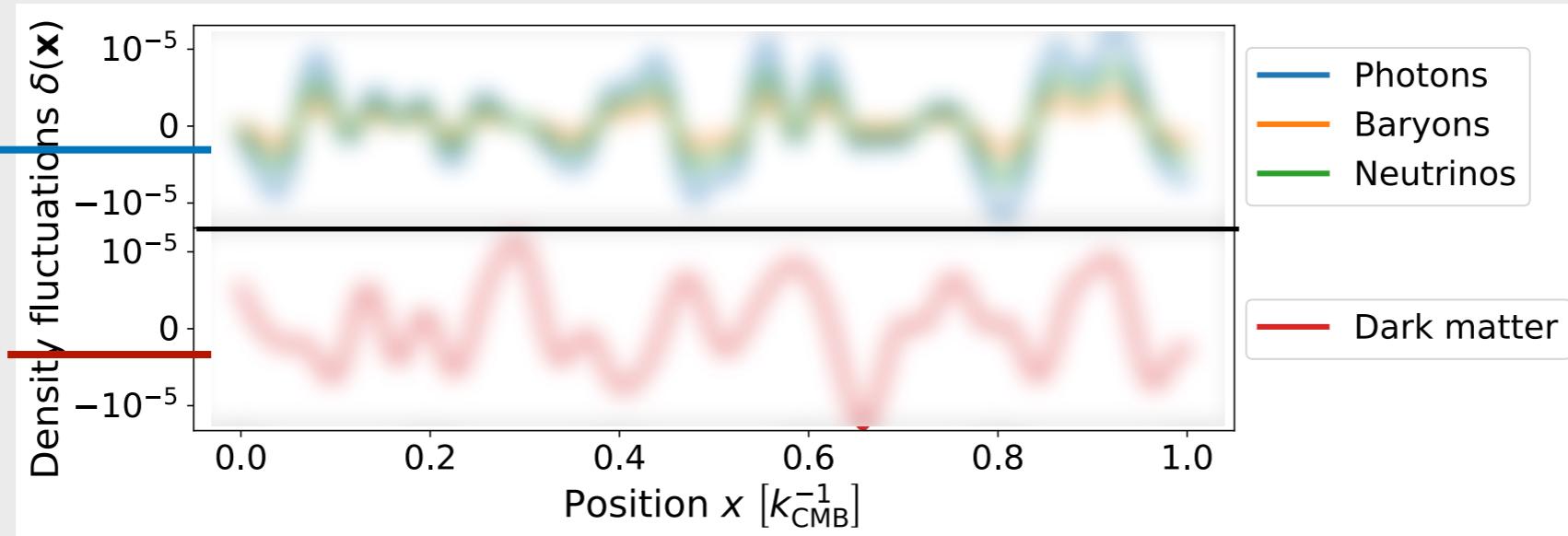
Spectrum of fluctuations of a non-minimally coupled scalar.



Looking with an observationalist's googles

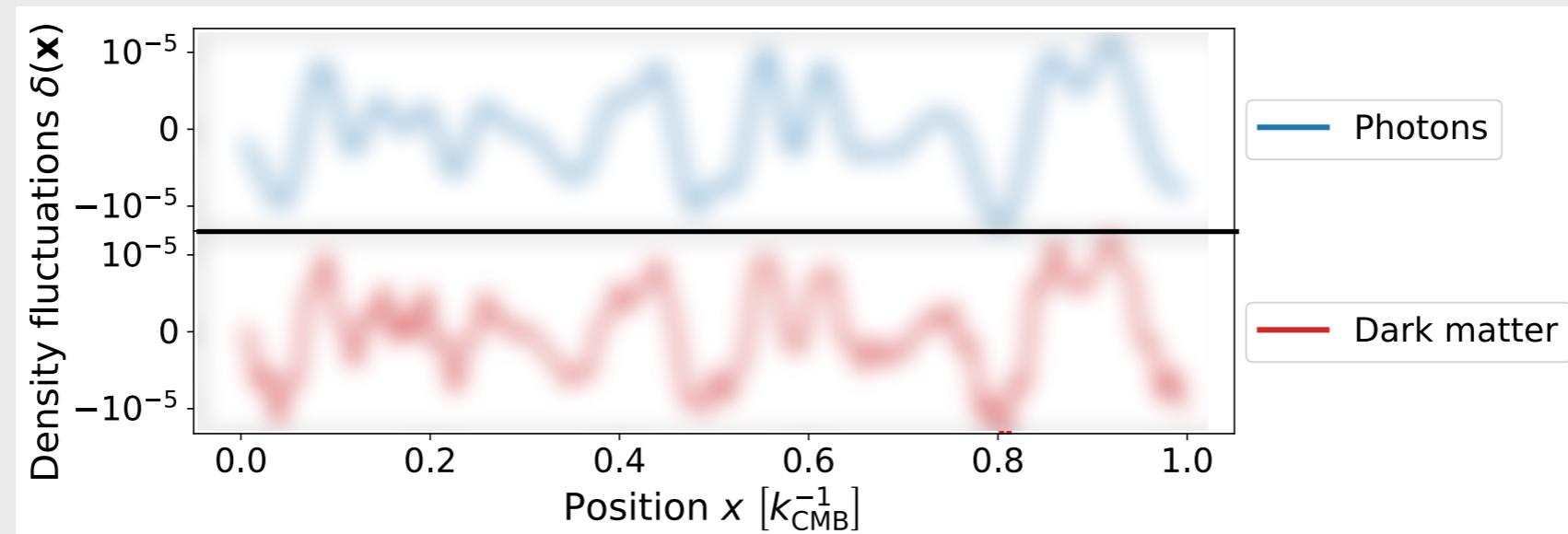
Spectrum of fluctuations of a minimally coupled scalar.

Adiabatic



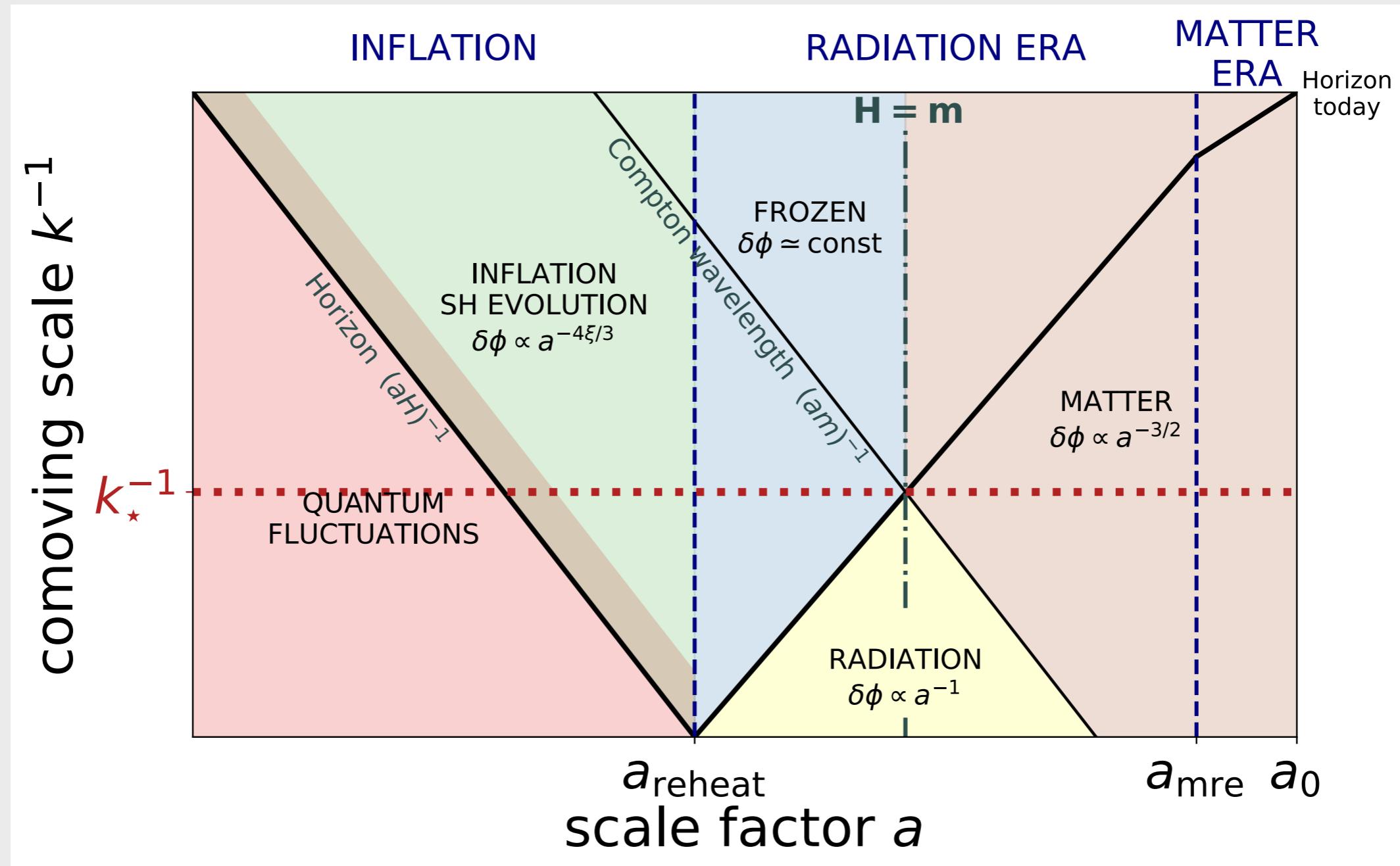
Isocurvature

Spectrum of fluctuations of a non-minimally coupled scalar.



Evolution of the fluctuations

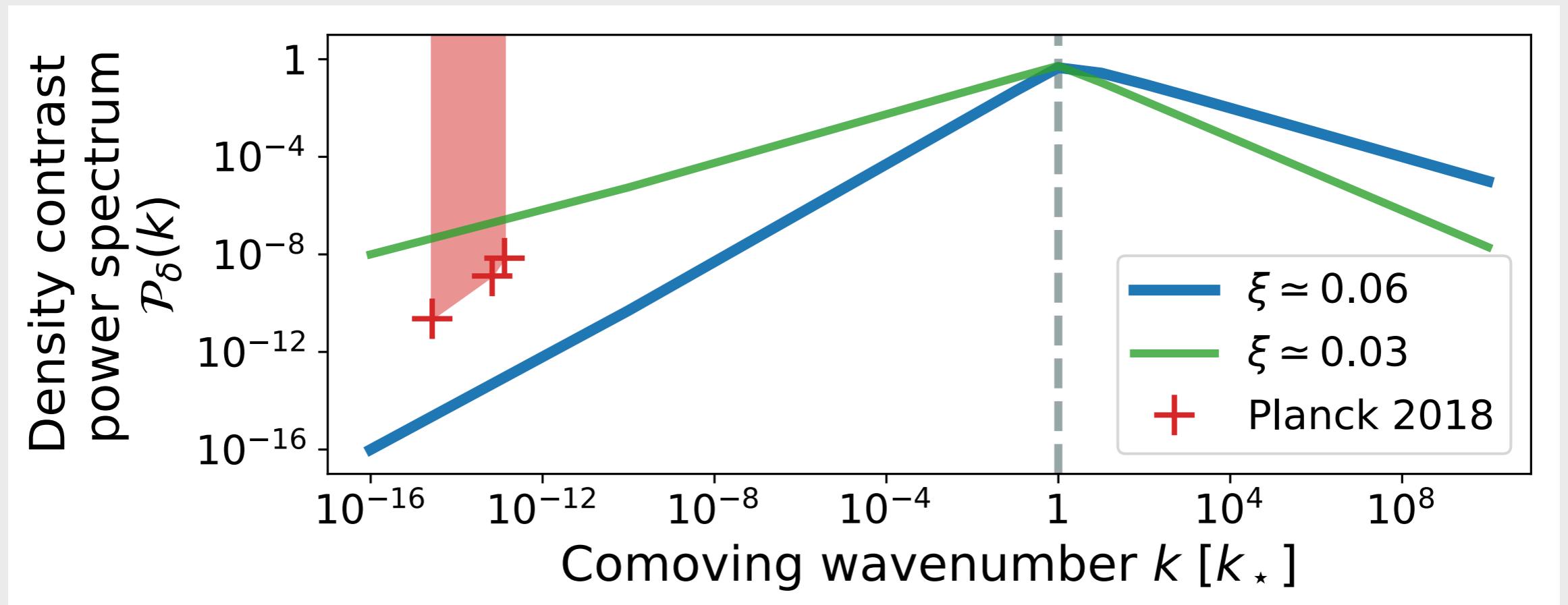
$$\ddot{\phi}_{\textcolor{teal}{k}} + 3H\dot{\phi}_{\textcolor{teal}{k}} + \left(\frac{k^2}{a^2(t)} + m^2 + \xi R \right) \phi_{\textcolor{teal}{k}} = 0.$$



Isocurvature power spectrum

The density power spectrum is peaked at the comoving scale k_\star^{-1} .

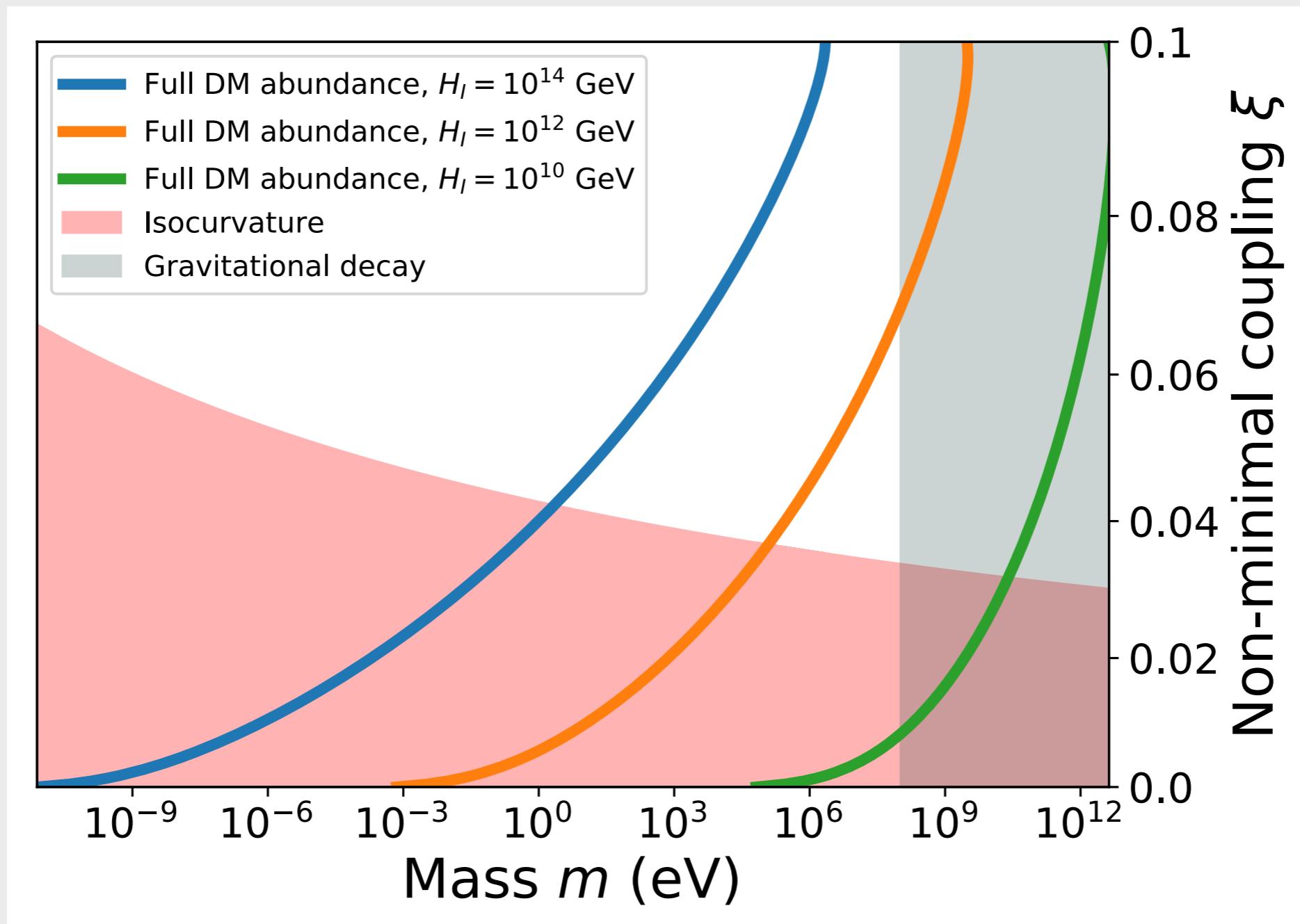
$$k_\star^{-1} \simeq 4 \cdot 10^7 \text{ km} \sqrt{\frac{\text{eV}}{(1 \mu\text{pc}) m}}$$



Isocurvature fluctuations are small enough at the CMB scales.

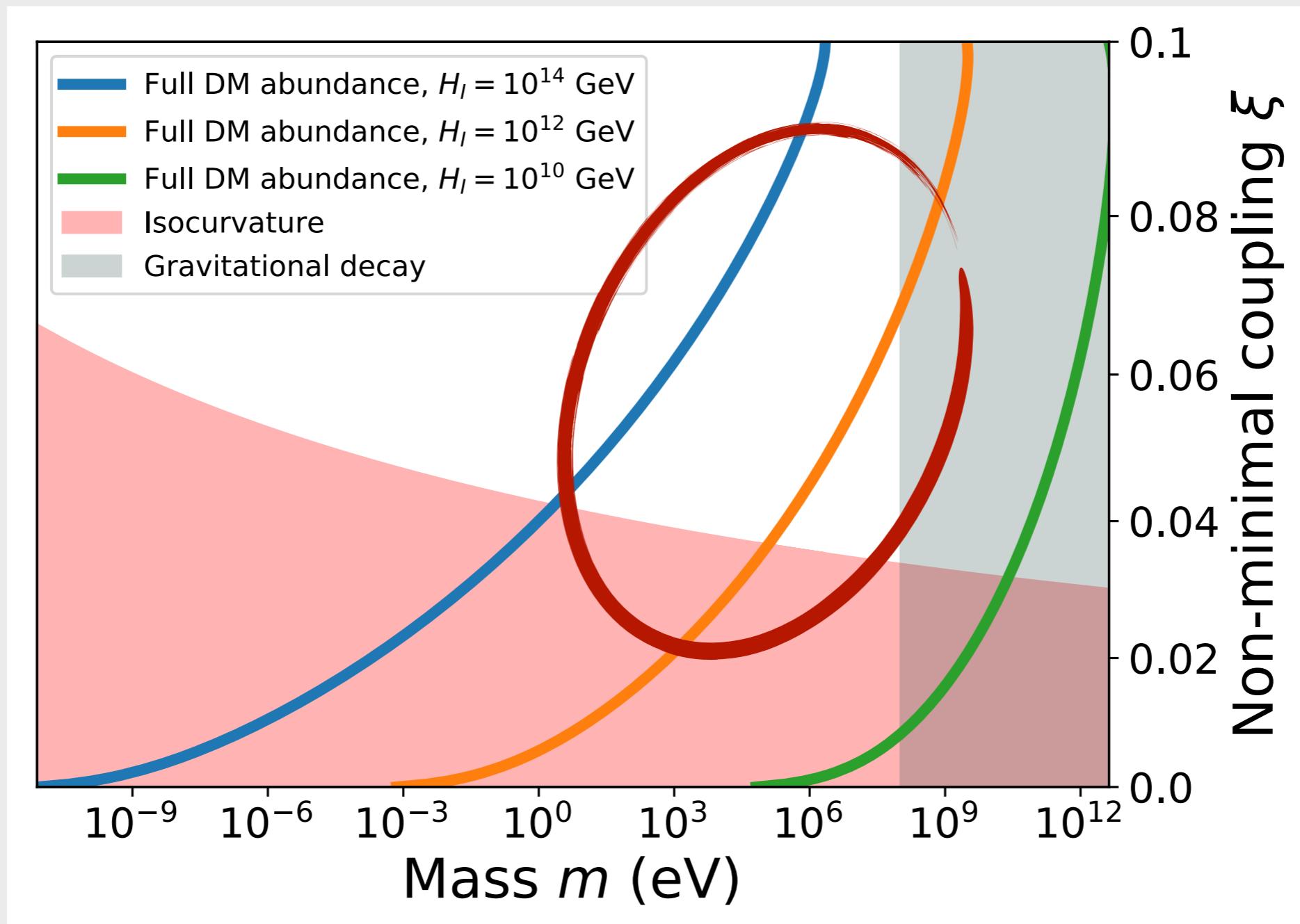
Relic density

For a given m and ξ , fixing the abundance to the dark matter one selects a scale of inflation.



Relic density

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Observables: cosmology

Two main particular features of the mechanism:

1. Presence of a small component of isocurvature perturbations.
 - The spectral tilt depends on ξ .
2. Very strong clumping at small scales.
 - Fluctuations at the peak are large and they collapse around matter-radiation equality.

$$\ell_{\text{today}} \simeq \frac{1}{z_{\text{eq}}} k_{\star}^{-1} \simeq 10^4 \text{ km} \sqrt{\frac{\text{eV}}{m}}$$

- Potential signals in gravitational lensing, astrophysical processes and direct & indirect detection.

Observables: particle physics

So far, we haven't considered any non-gravitational interactions with other fields.

The field has a \mathbb{Z}_2 symmetry that impedes the decay.

$$\phi \longleftrightarrow -\phi$$

We can assume that at least gravity breaks this global symmetry.

\Rightarrow Gravitational-mediated decay, eg $\frac{\phi}{M_p} \mathcal{F}\mathcal{F}$

Stability: $\tau = \Gamma^{-1} \sim \frac{64\pi M_p^2}{m^3} \lesssim \tau_{\text{univ}} \sim 10^{-33} \text{ eV}$

Other couplings are compatible with the production mechanism.

Conclusions

1. Non-minimal couplings to gravity can have an impact on the cosmological evolution of scalar fields.
2. Relevant for non-thermal dark matter production:
 - Misalignment mechanism is modified.
 - Production from inflationary fluctuations becomes possible.
- In the future: Study the phenomenology
 - Cosmology: clumping at small scales.
 - Particle physics: coupling to other fields? Detection & stability.

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Thanks!



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