Lightish but clumpy:
Scalar dark matter from inflationary fluctuations

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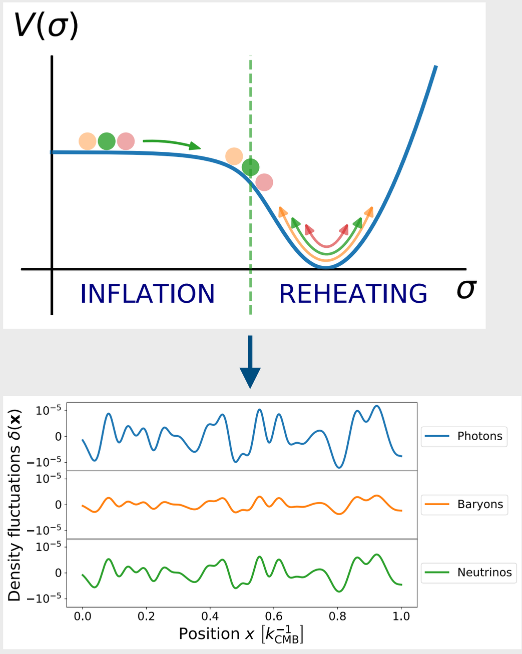
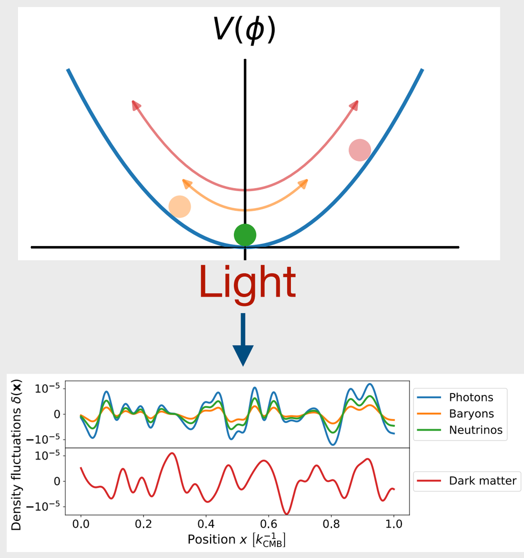
Motivation and idea

Ordinary matter in our Universe originates from quantum fluctuations of the inflation during inflation. Can dark matter be generated similarly?



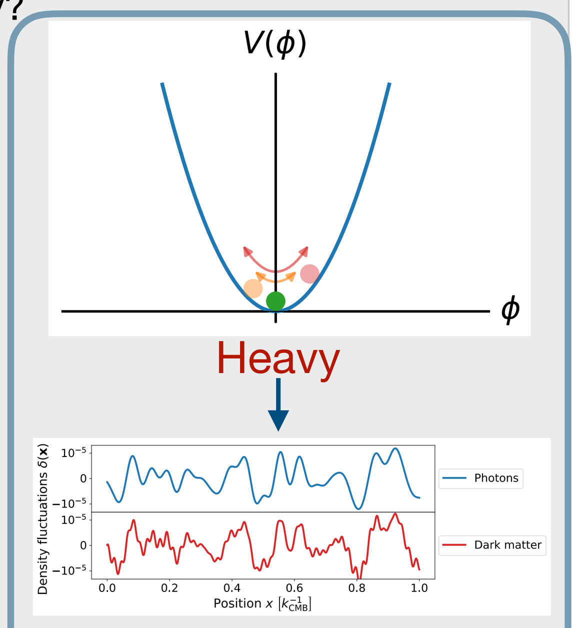
Adiabatic perturbations seen in the CMB



Isocurvature perturbations

$$\Rightarrow \frac{\delta\rho_{\rm iso}(k_\star)}{\delta\rho_{\rm ad}(k_\star)} \lesssim 0.03$$

at scales $k_{\rm CMB}^{-1} \simeq 20\ {\rm Mpc}$

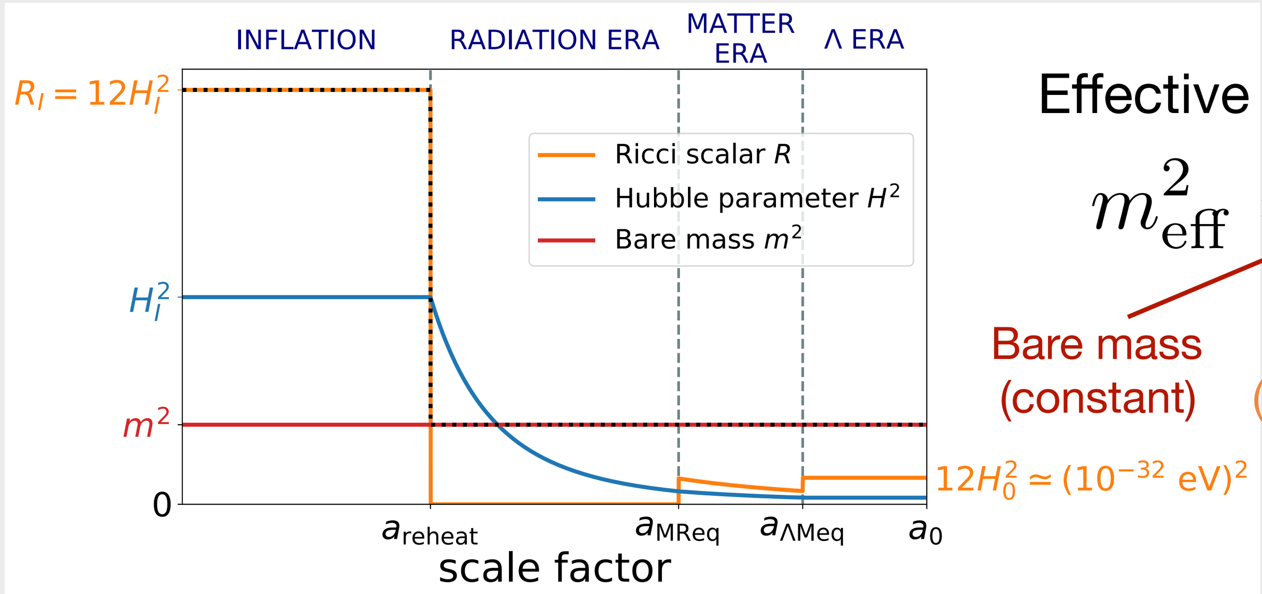


Isocurvature perturbations suppressed at large scales. But only if $m \sim \mathcal{O}(H_I)$! How may this happen?

Non-minimal coupling to gravity

Action in the Jordan frame:

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



Effective mass for ϕ:

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

Bare mass (constant)

Gravitational mass (space-time dependent)

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

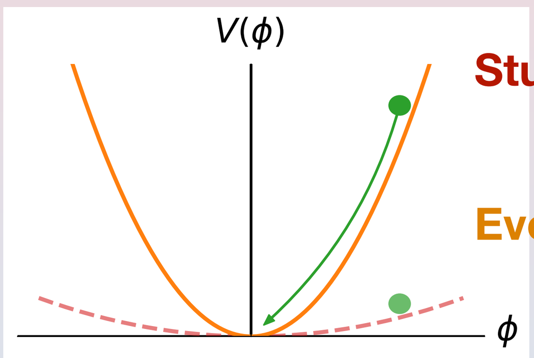
Excitation of momentum modes during inflation and posterior evolution

Evolution during inflation

Classically

The homogeneous field is damped away during inflation.

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



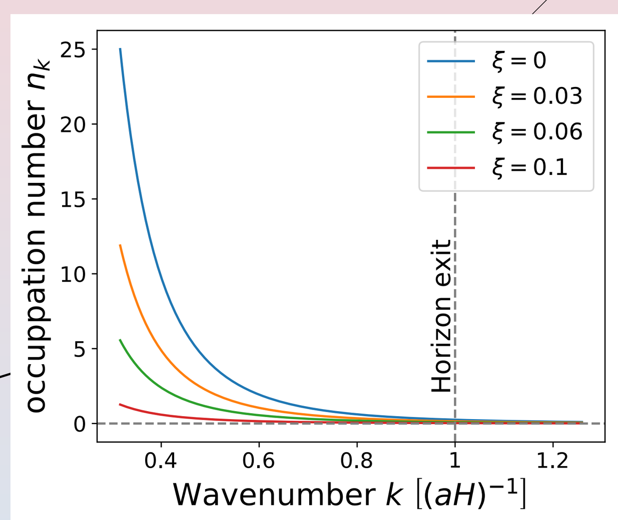
Stuck: $m \ll H_I$

Evolves to minimum: $R = 12H^2$

$$\Rightarrow \phi_{\rm E} \simeq \phi_0\, e^{-\frac{4}{3}\xi N}$$

Quantum mechanically

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

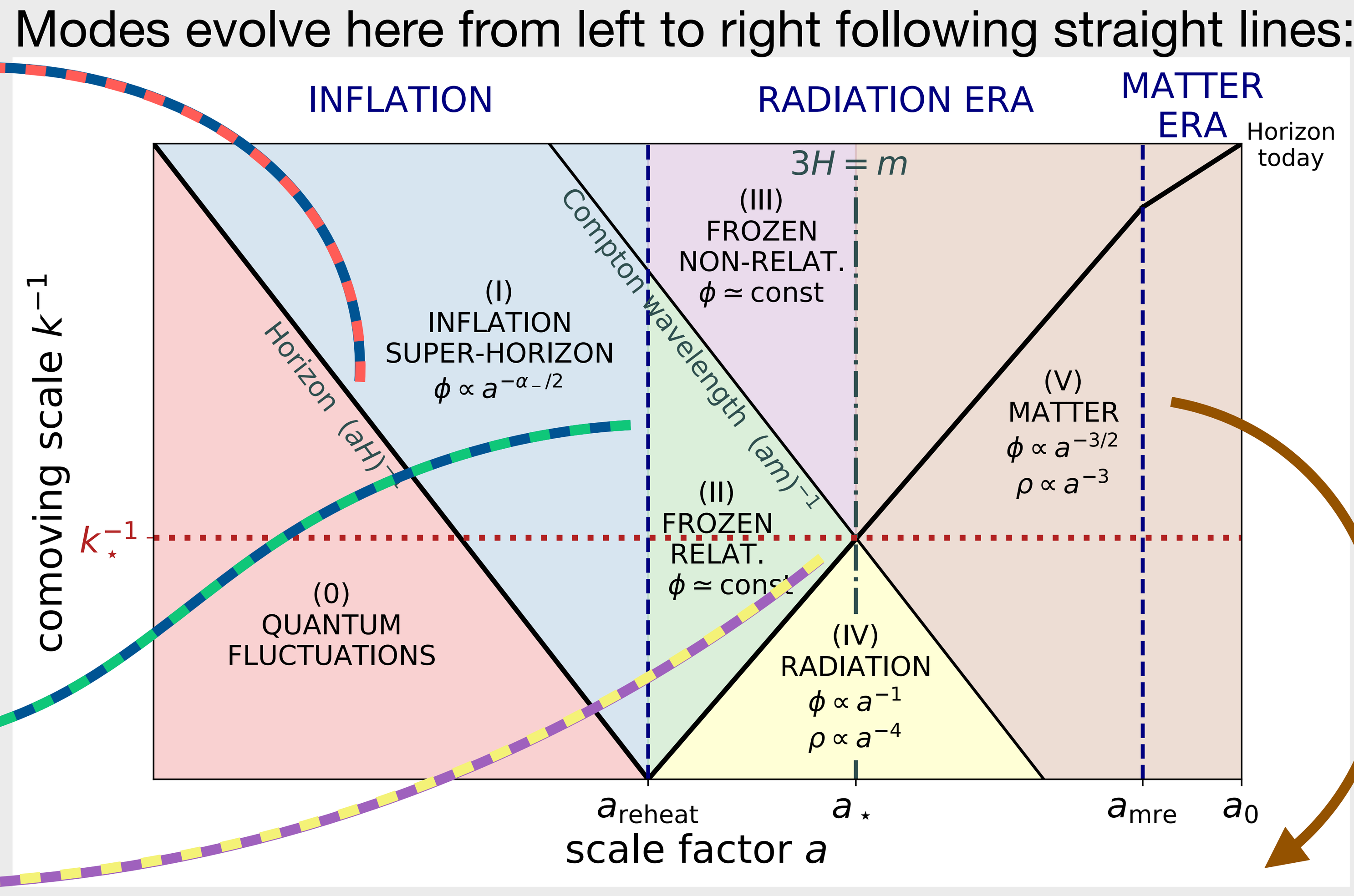


A larger ξ suppresses the occupation number.

After the modes become classical, solve their classical EOM:

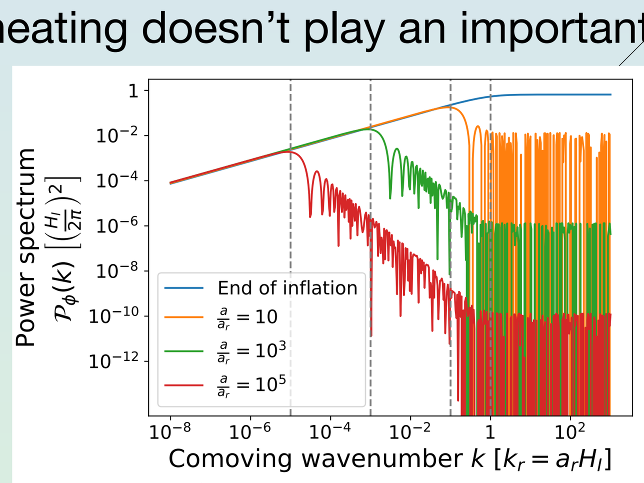
$$\ddot{\phi}_k + 3H\dot{\phi}_k + \left(\frac{k^2}{a^2(t)} + m^2 + \xi R\right)\phi_k = 0.$$

Modes evolve here from left to right following straight lines:



Reheating and early radiation era

Reheating doesn't play an important role.



Small scale modes reenter the horizon, start oscillating and are damped away.

Deep radiation era and the critical wavelength

Modes that spend longer in the blue or yellow regions are redshifted the most.

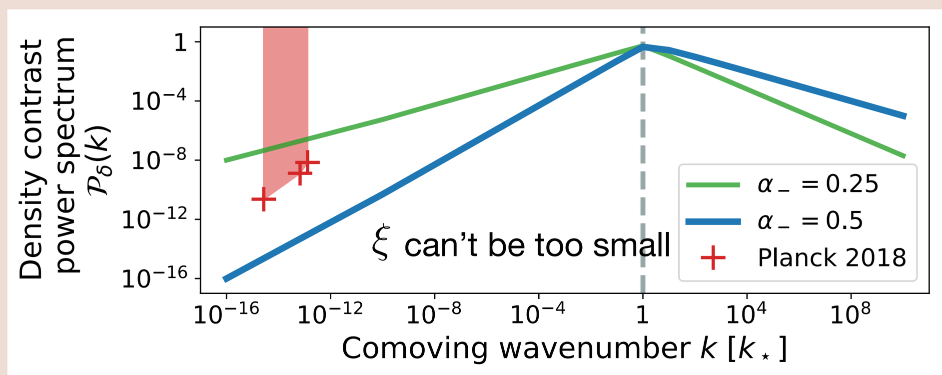
The mode $k_\star$, highlighted in red, is the one that has the largest amplitude at late times.

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

The energy density is stored in clumps of comoving size $k_\star^{-1}$.

Dark matter behaviour at late times

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

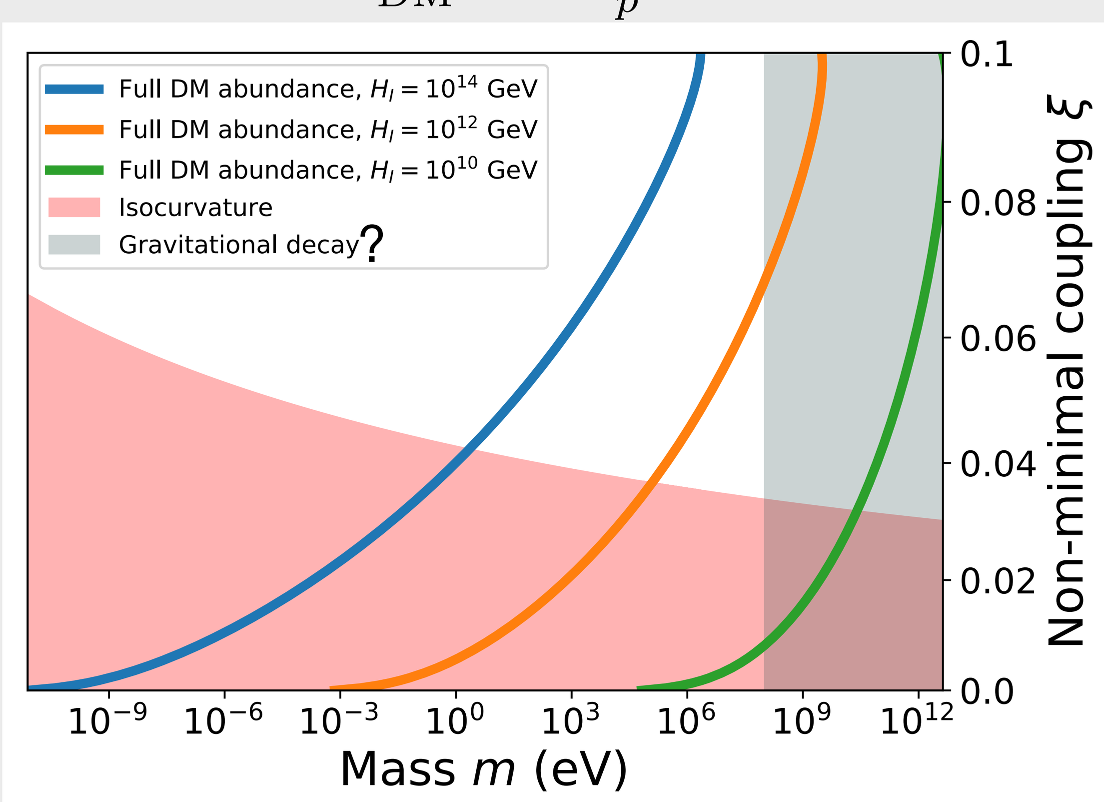


Isocurvature perturbations are small enough at the CMB scales.

Results

Relic abundance:
$$\frac{\Omega_\phi}{\Omega_{\rm DM}} \simeq \frac{f(\xi)}{M_p^2}\, H_{\rm eq}^{-\frac{1}{2}}\, H_I^{\,2-4\xi}\, m^{\frac{1}{2}+4\xi}$$

$$\frac{\Omega_\phi}{\Omega_{\rm DM}} = 1 \rightarrow$$



- For $m \sim 1\,{\rm eV}$, $\xi \lesssim 0.1$ and high-scale inflation, the right dark matter abundance is produced.
- The scenario is independent of any initial conditions.
- The production is purely gravitational, no other couplings are assumed.
- Large density fluctuations at intermediate scales are predicted.

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Discussion

Particle physics: Stability & Detection

- The mechanism only relies on gravitational processes.
- Direct couplings to SM fields could also be present.
- The action allows for a $\mathbb{Z}_2$ symmetry: $\phi \longleftrightarrow -\phi$
- But gravity might break global symmetries:

$\Rightarrow \frac{\phi}{M_{\rm Pl}}F^{\mu\nu}F_{\mu\nu}$, gravity mediated decay.

Cosmology: Substructure & clumpiness

- Two main features:

1. Potentially detectable component of isocurvature fluctuations.
   - "Axion II" scenario in Planck2018.
2. Enhancement of substructure at intermediate scales.
   - The bulk of the energy density is stored in clumps of size:

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

Conclusions

1. Dark matter can be generated from quantum fluctuations of a light scalar field during inflation.
2. A small non-minimal coupling to gravity suppresses isocurvature perturbations at large cosmological scales.