Lightish but clumpy: scalar dark matter from inflationary fluctuations

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Based on: Gonzalo Alonso-Álvarez, J. Jaeckel, **arXiv:1807.09785 (Accepted JCAP)**

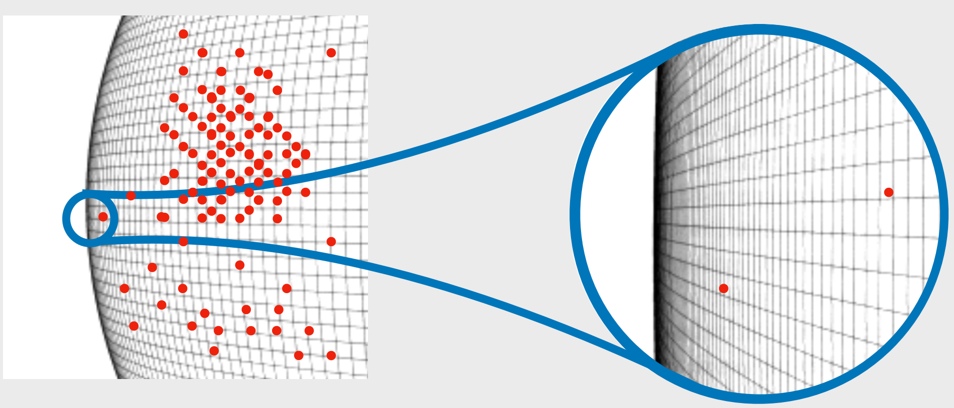
Dark Interactions 2018 Workshop
BNL, 2-5 October 2018

elusives
neutrinos, dark matter & dark energy physics
Horizon 2020
UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386
"la Caixa" Foundation

Goals & Motivation

Goal: Link high energy phenomena with low energy observables.

High Energy: Inflation ⟷ Low Energy: Dark matter



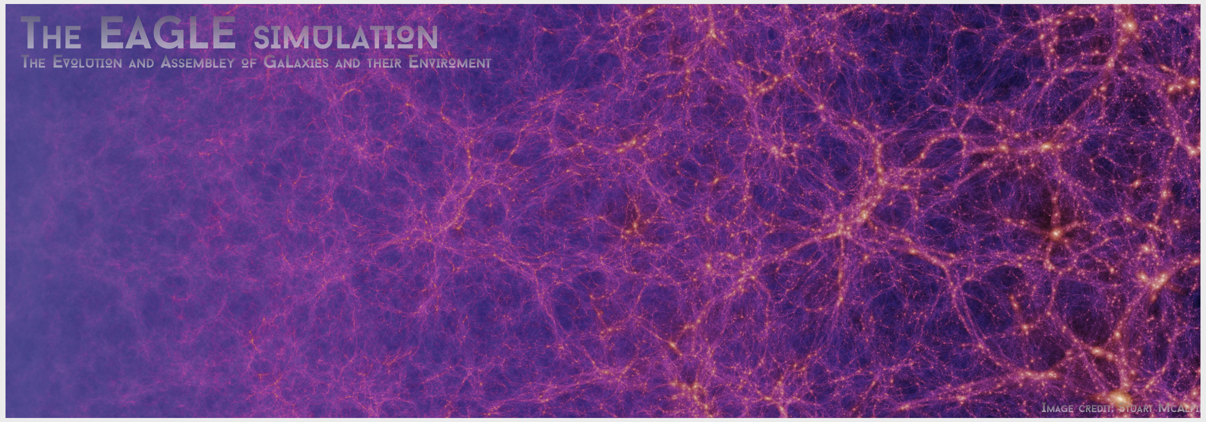


Image: http://icc.dur.ac.uk/Eagle

How: New mechanisms of non-thermal production of dark matter.

Main idea

Initial premise:

Dark matter can be generated **gravitationally** from quantum fluctuations of a scalar field during inflation.

Caveat:

Isocurvature perturbations are not observed.

Key observation:

A **non-minimal coupling to gravity** suppresses isocurvature and makes the scenario phenomenologically viable.

Different ideas in this direction

- Misalignement 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:

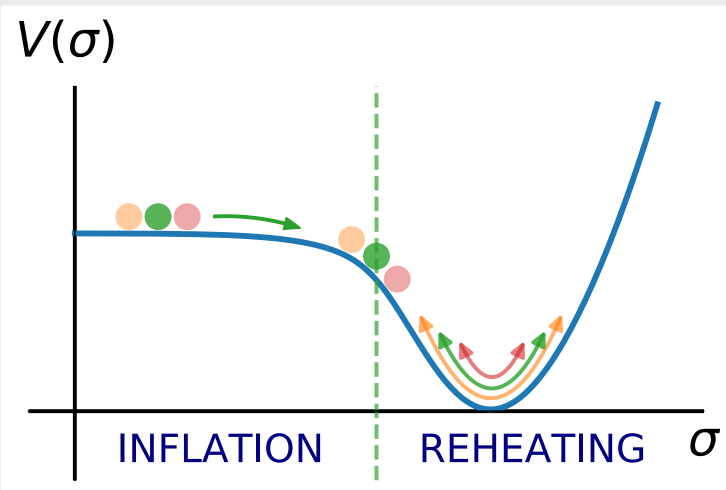
Gravitational generation of all the dark matter that we observe.

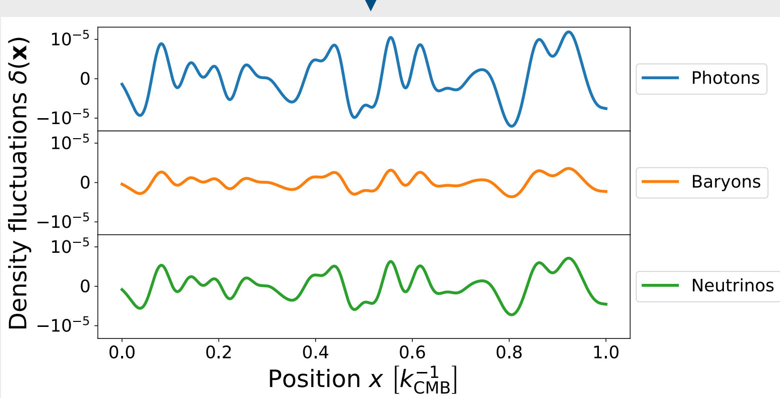
Other potentially interesting applications:

- 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]

(Dark) matter & inflation

Ordinary matter





Adiabatic perturbations

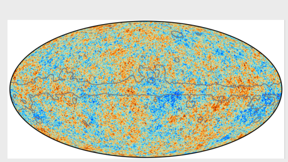
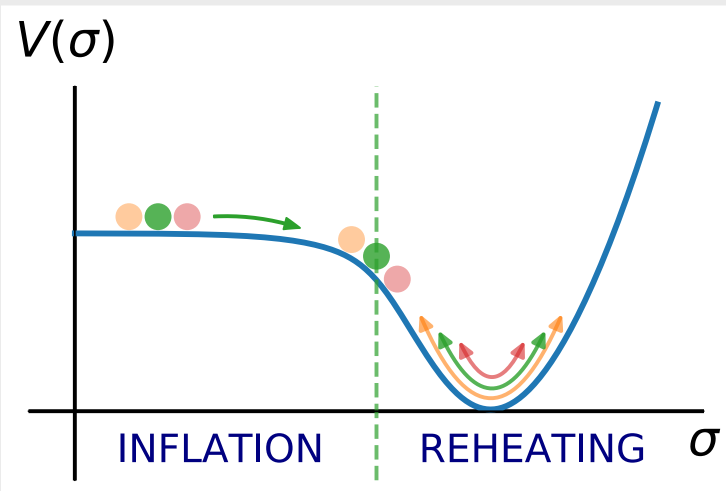
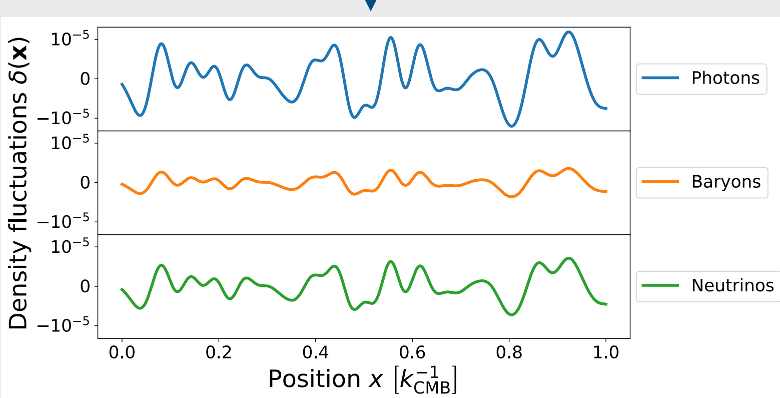
seen in the CMB 

Image: http://sci.esa.int/planck

(Dark) matter & inflation

Dark matter?





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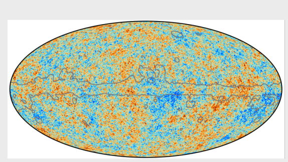
seen in the CMB 

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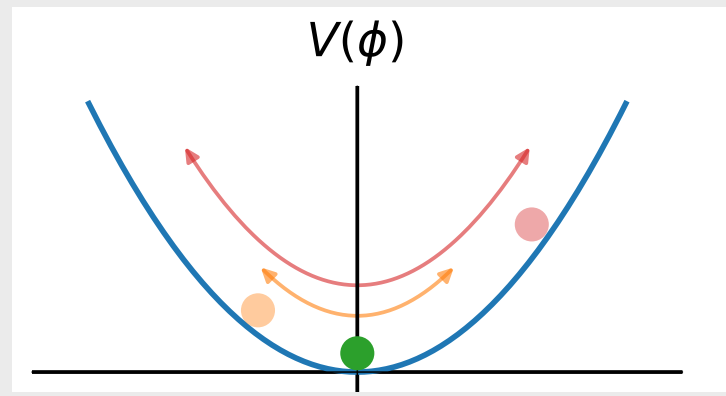
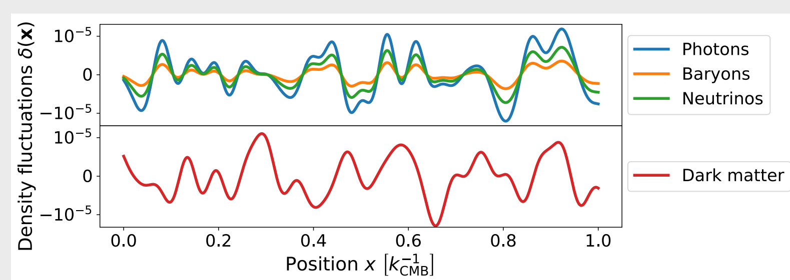


Light



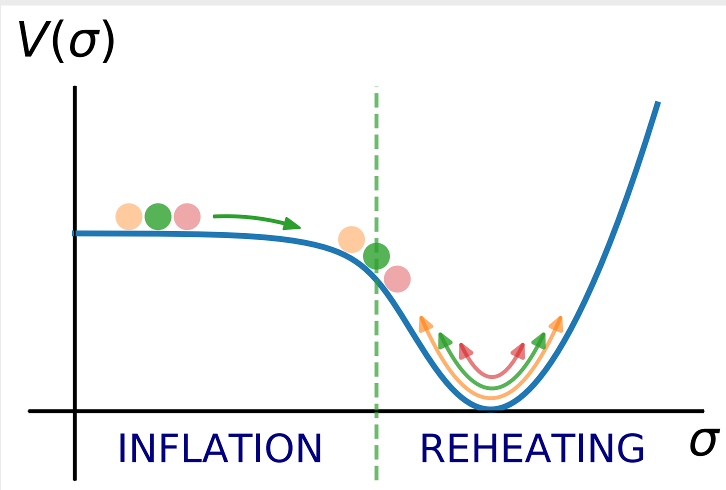
Isocurvature perturbations

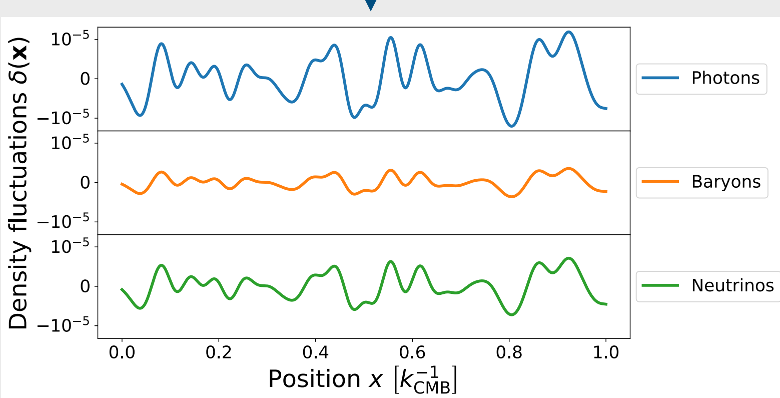
Planck 2018 [1807.06211]

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

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

(Dark) matter & inflation





Adiabatic perturbations

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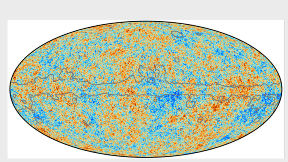

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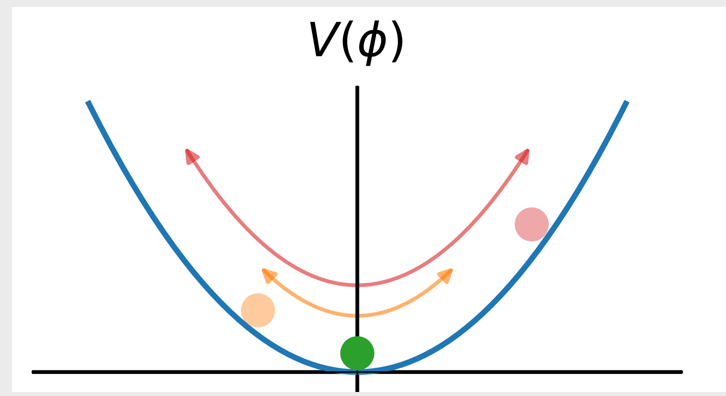
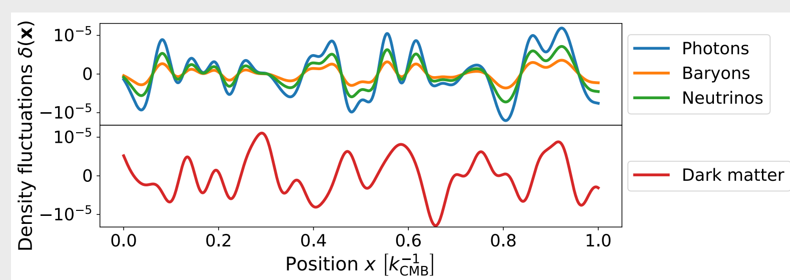


Light



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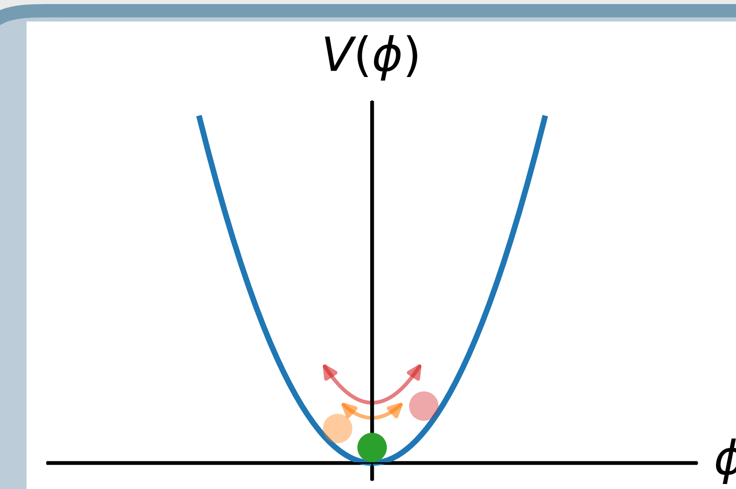
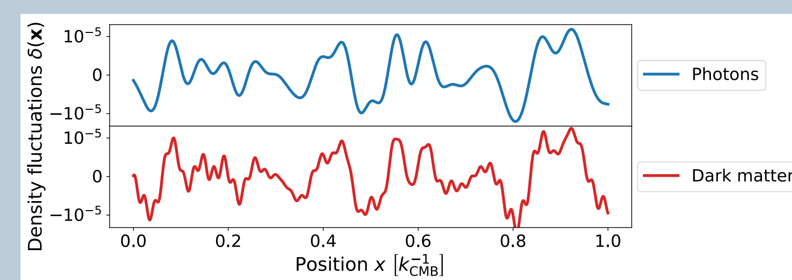
Dark matter!



Heavy



Isocurvature perturbations suppressed at large scales.

But only if $m \sim \mathcal{O}\left(H_I\right)$!

How may this happen?

Non-minimal coupling to gravity

Action in the Jordan frame:

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

Effective mass for ϕ :

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

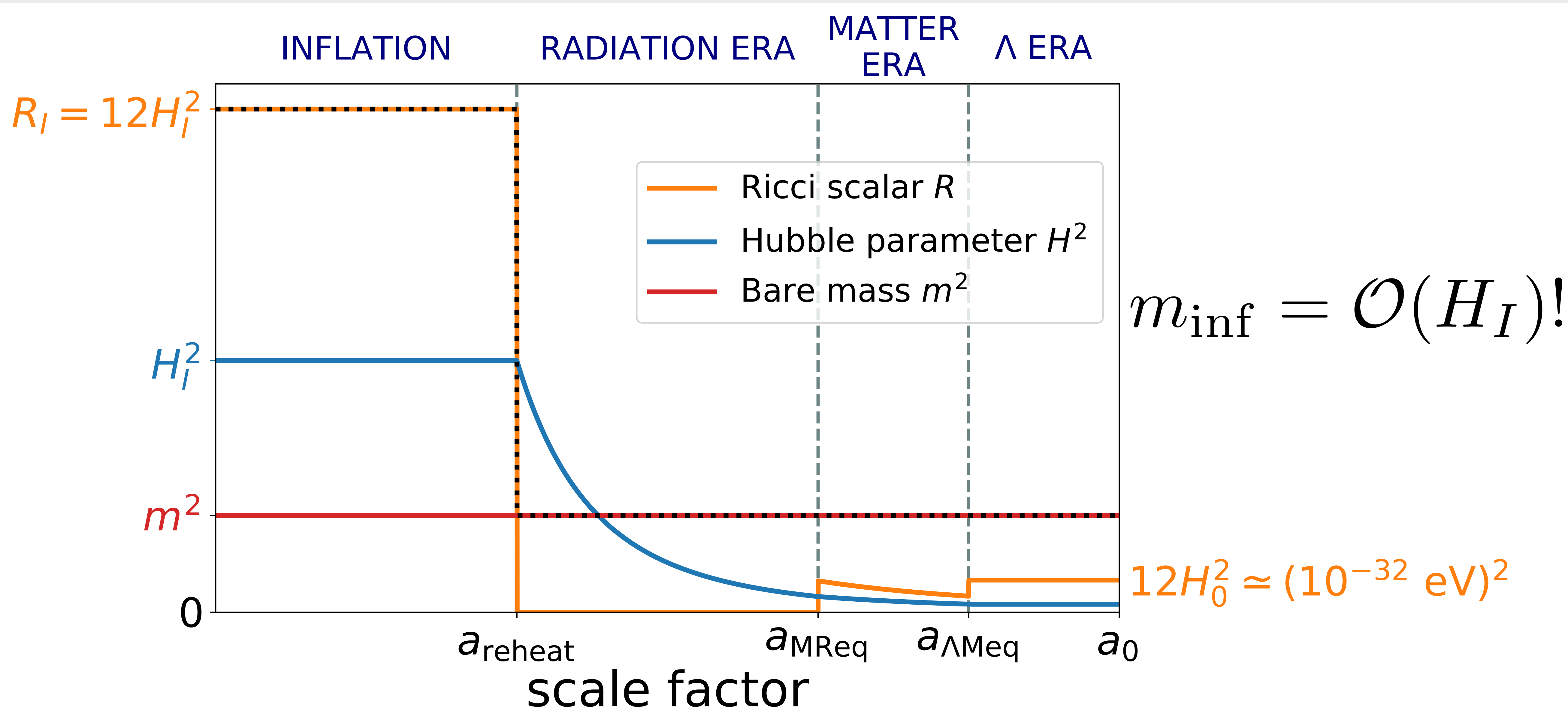
Bare mass (constant)

“Gravitational" mass (space-time dependent)

Negligible backreaction on the geometry.

Non-minimal coupling in cosmology

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



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

Cosmological evolution

I. Quantum evolution during inflation

   (i) Homogeneous field

   (ii) Non-zero momentum modes (fluctuations)

II. Classical evolution after inflation

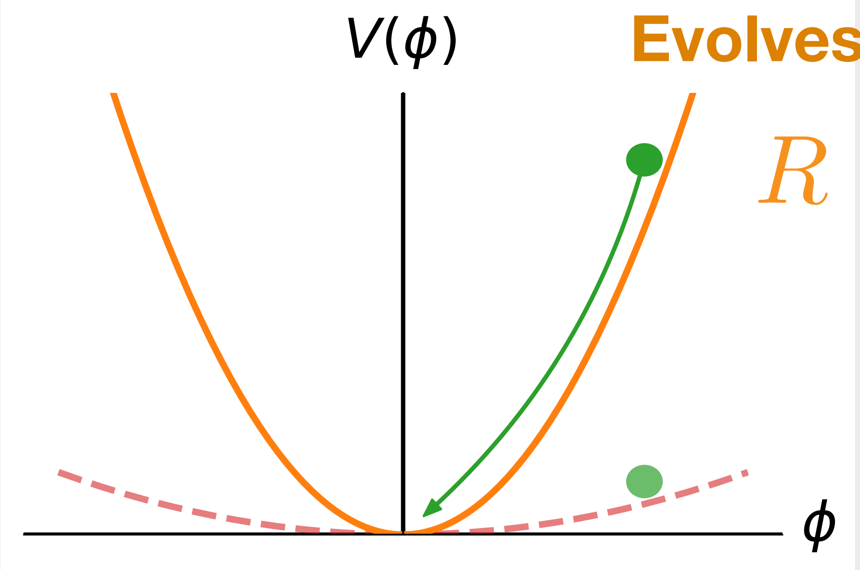
III. Late times power spectrum and relic abundance

I. Evolution during inflation

Classically

The homogeneous field is damped away during inflation.

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



Evolves to minimum:

$$R = 12H^2$$

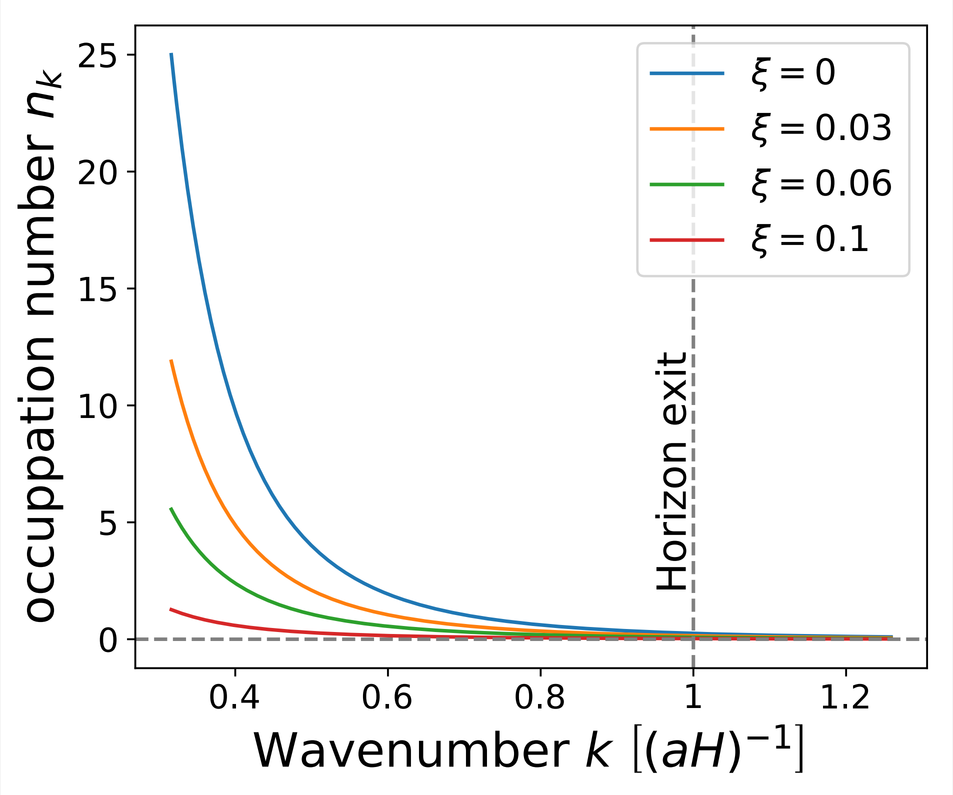
Stuck:

$$m \ll H_I$$

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

Quantum mechanically

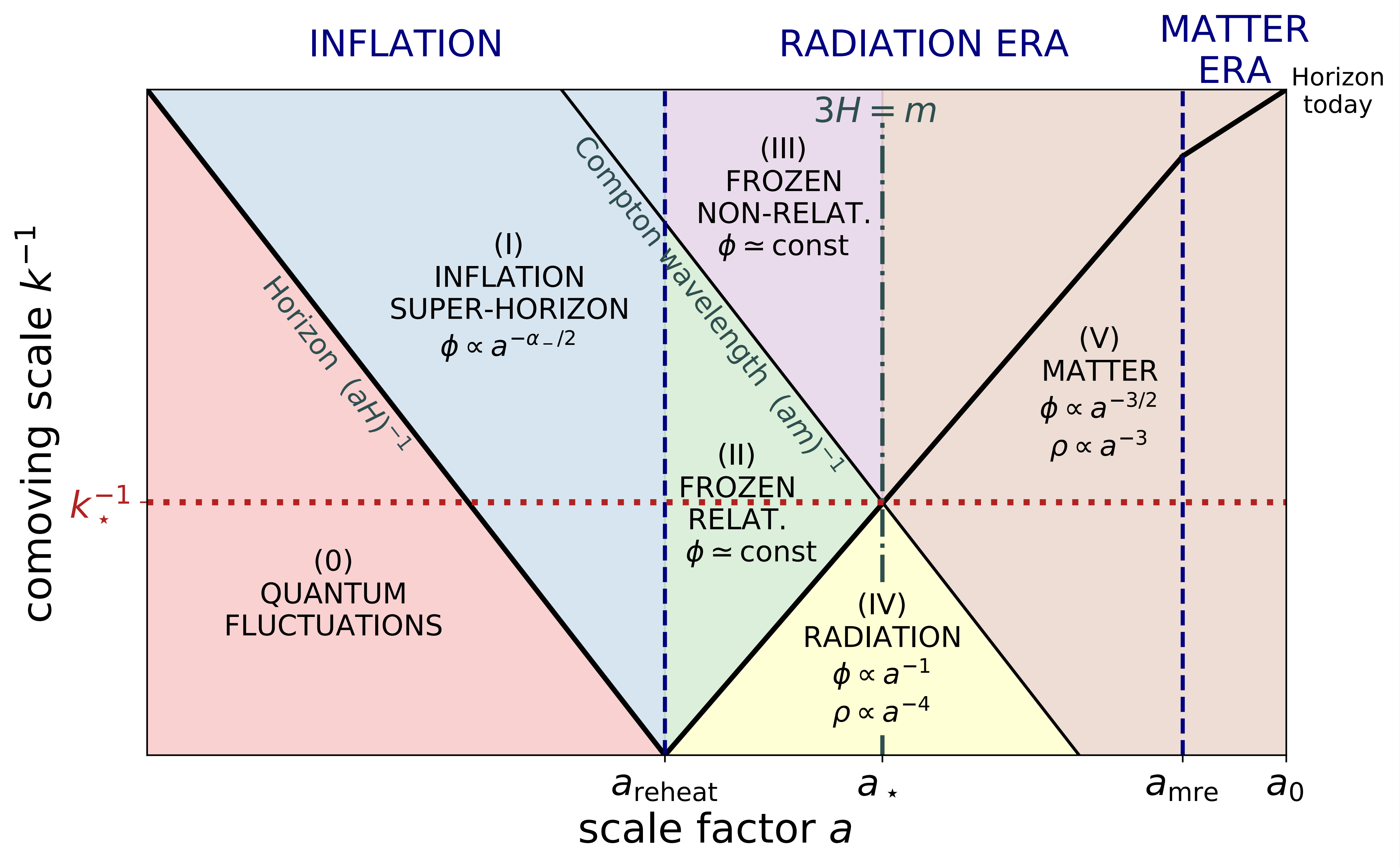
Higher momentum modes are excited due to the time-dependent gravitational background.



A larger ξ suppresses the occupation number.

II. Classical evolution after inflation

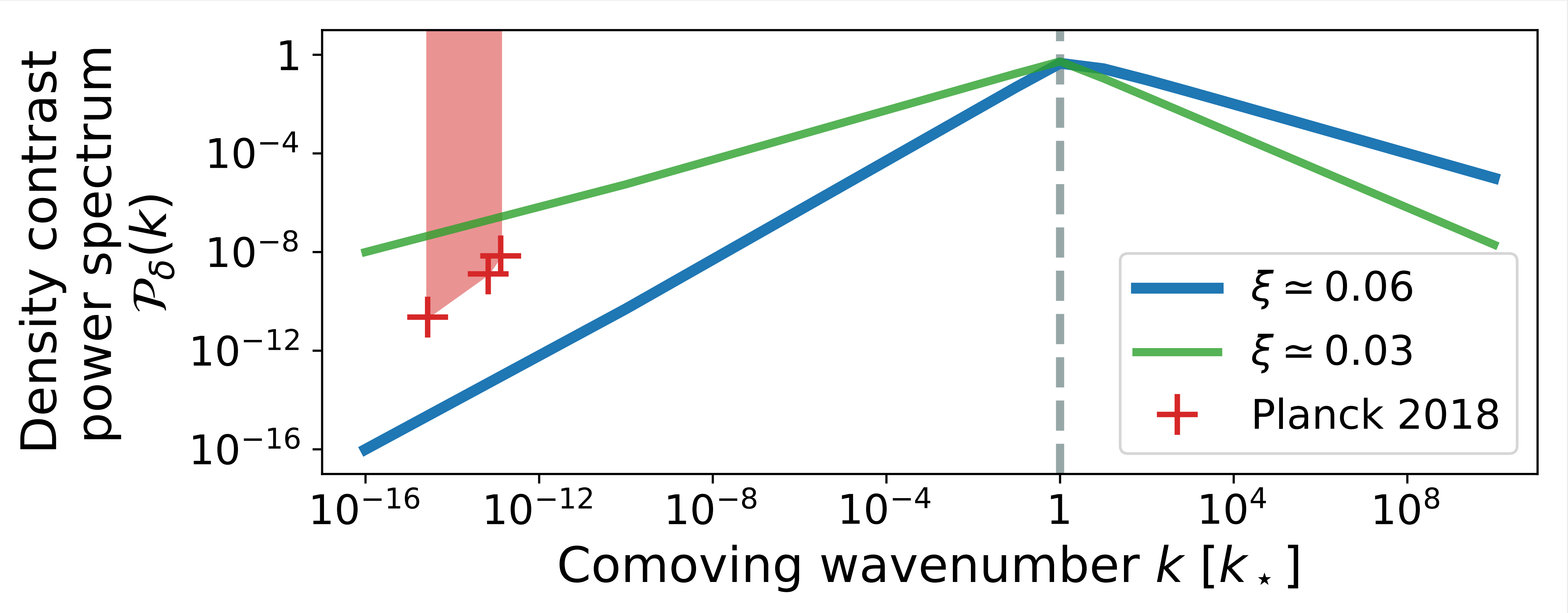
$$\ddot{\phi}_k + 3H\dot{\phi}_k + \left(\frac{k^2}{a^2(t)} + m^2 + \xi R\right)\phi_k = 0.$$



III. Isocurvature power spectrum

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

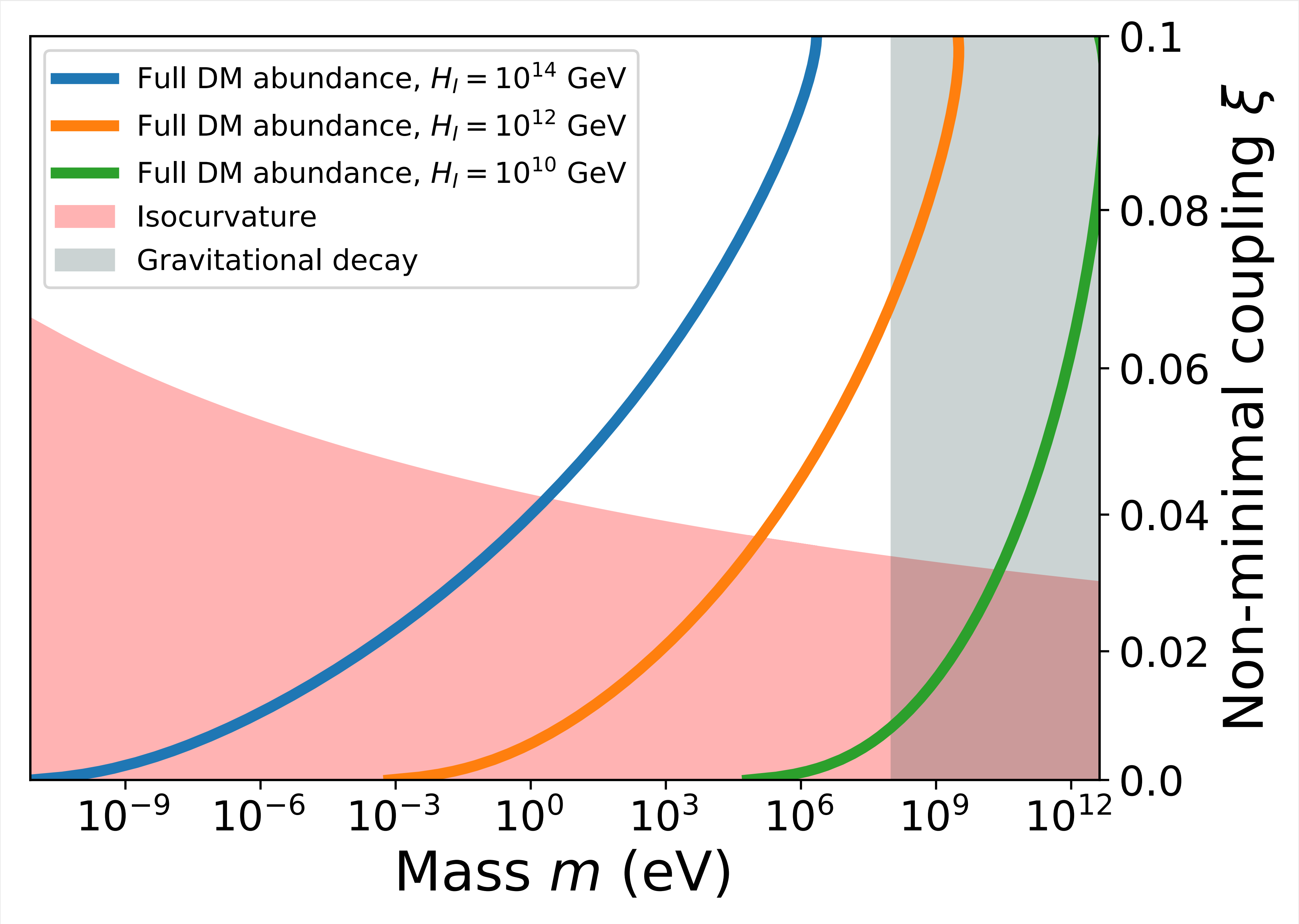
$$k_\star^{-1} \simeq \underset{(1\,\mu\mathrm{pc})}{4\cdot 10^7\,\mathrm{km}}\sqrt{\frac{\mathrm{eV}}{m}}$$



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.



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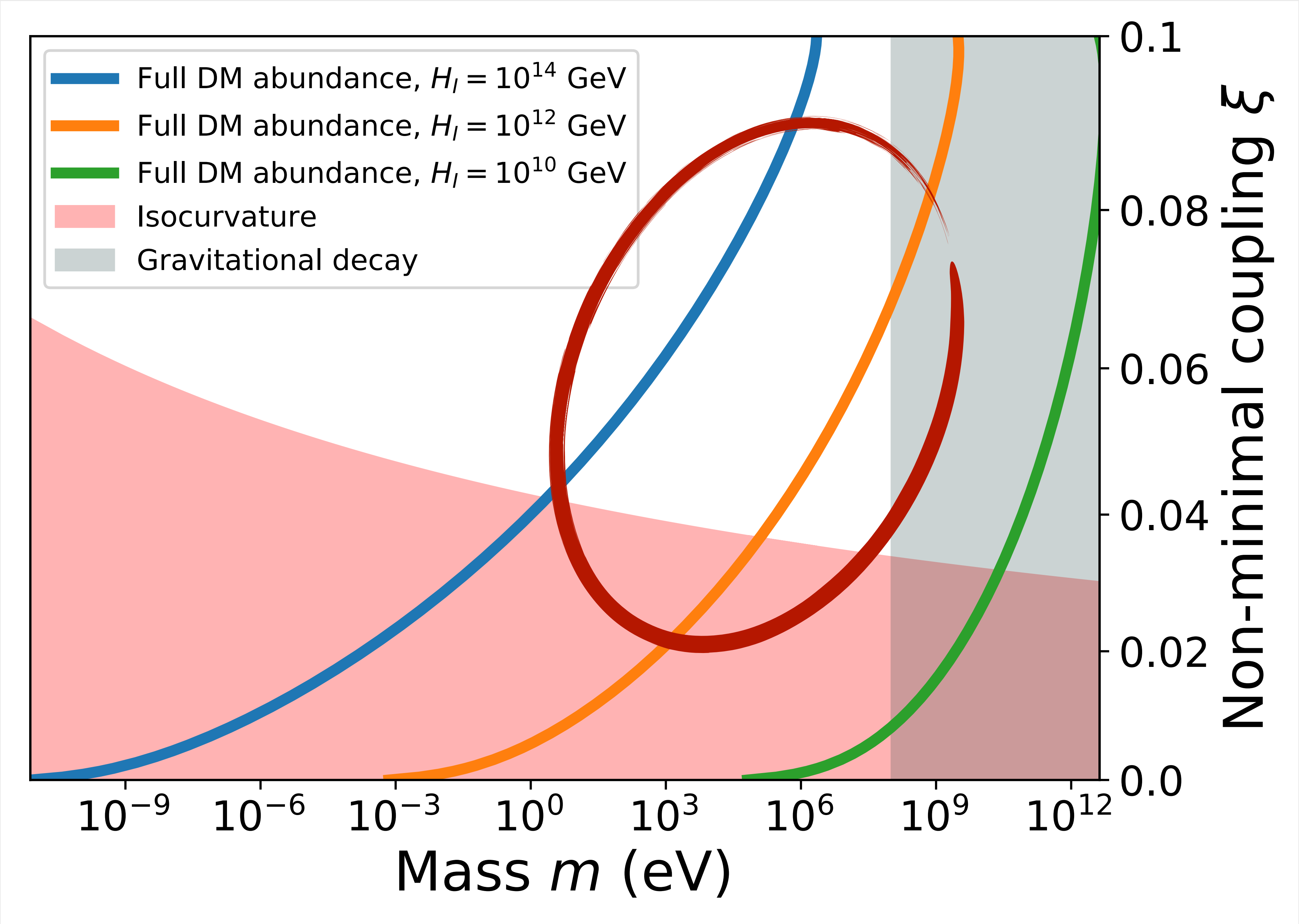

Observables: cosmology

Two main particular features of the mechanism:

1. Presence of a small component of isocurvature perturbations.
    - CDI "axion II" scenario in Planck 2018 analysis.
2. Very strong clumping at small scales.
    - Fluctuations at the peak are large and they collapse around matter-radiation equality.

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

    - 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.

$\Longrightarrow$ Gravitational-mediated decay, eg $\dfrac{\phi}{M_p}\mathcal{F}\mathcal{F}$

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

Other couplings are compatible with the production mechanism.

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 CMB scales.

- In the future: Study the phenomenology of the scenario
  - Cosmology: clumping at small scales.
  - Particle physics: coupling to other fields? Detection & stability.

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Thanks!

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This project has received funding/support from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 674896 "*ELUSIVES*".