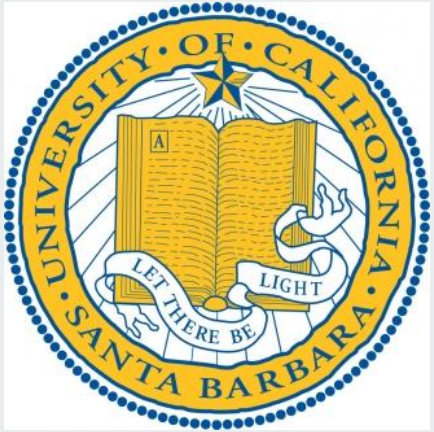
Dark Matter from Scalar Fleld Fluctuations

Hongyin Liu

09/25/2020



Some Intro?

- The requirements for DM isocurvature perturbations (perturbations in DM energy density) to be within the limits obtained from CMB (radiation from early universe).
- DM in hidden sector containing a scalar field.
- DM scalar field:
  - Provide initial conditions for nonthermal production of DM after inflation, or
  - Constitute all/part of observed DM abundance.
- Related: self-interacting DM, non-minimally coupled DM, DM coupled to inflation, axion DM.

This Paper

- Scalar field acting as/sourcing DM is a massive free field.
- Equilibrium between the classical drift and stochastic quantum fluctuation during inflation.
- Assume DM field was ight during inflation ($m/H_* < 1$)
- Show (matches CMB data):
  - Scalar field can constitute all DM (even in the simplest case).
  - Scalar field can start at minimum (or any value) and reach an equilibrium determining DM abundance.
  - Scalar field can also source only part of present DM density.
  - This class predicts enhanced structure formation: allow testing of DM only interacting gravitationally

In the Simplest Case

Simplest Possible DM lagrangian:

$$\mathcal{L}_{\rm DM} = \frac{1}{2}\partial^\mu\chi\partial_\mu\chi - \frac{1}{2}m^2\chi^2$$

Post-inflationary EQ of motion for DM field χ :

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

Solution:

$$\chi(t) = 2^{1/4}\Gamma\left(\frac{5}{4}\right)\chi_* \frac{J_{1/4}(mt)}{(mt)^{1/4}}$$

χ_* :expectation value of DM field χ

At later times:

- Solution oscillates with amplitude:

$$\chi_0(t) = \frac{2\Gamma\left(\frac{5}{4}\right)}{\sqrt{\pi}}\frac{\chi_*}{(mt)^{3/4}}, \qquad mt \gg 1$$

- χ 's associated energy density:

$$\rho_\chi = \frac{1}{2}m^2\chi_0^2 \simeq \frac{\Gamma^2\left(\frac{5}{4}\right)}{\pi}\frac{\sqrt{m}\chi_*^2 H_*^{3/2}}{a^3}$$

Field's contribution to present DM abundance:

$$\frac{\Omega_\chi h^2}{0.12} = 3.5\times 10^{17} g_*^{-1/4}(H_{\rm osc})\left(\frac{\chi_*}{M_P}\right)^2\sqrt{\frac{m}{\rm GeV}}$$

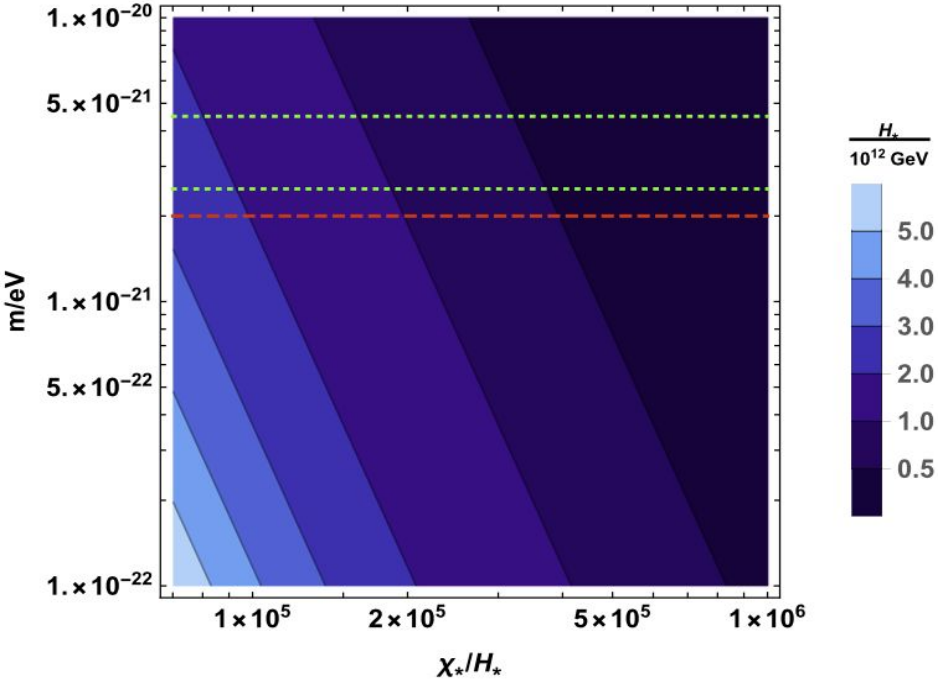
Hence, with suitable values of χ_* and m, field can constitute all of observed DM. ✔

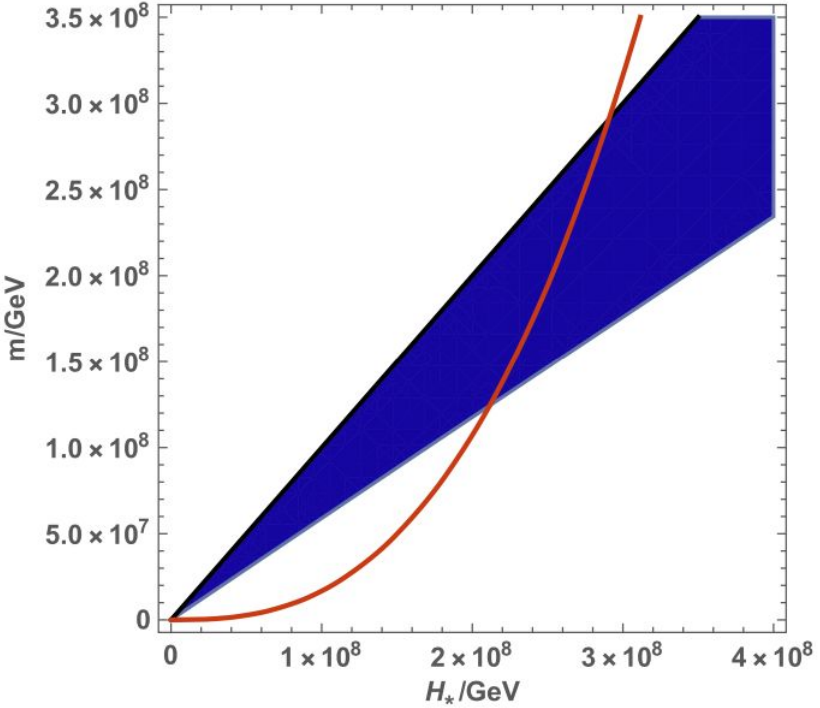
Two cases

Planck satellite mission: stringent constraints on DM isocurvature.

1. Misalignment mechanism:
   a. Field dynamics during inflation dominated by slow roll.
   b. For $m^2/H_*^2 << 1$, with field value $\frac{\chi_*}{H_*} \gtrsim \frac{1}{\sqrt{\pi^2 \beta \mathcal{P}_{\mathcal{R}}(k_*)}} \simeq 7 \times 10^4$, present model avoids curvature constraint.
2. For larger m/H_* , field reaches regime where classical drift (responsible for slow roll) and stochastic quantum fluctuations are in equilibrium.
   a. For quadratic potential, the distribution of field values at end of inflation is a Gaussian, with mean = 0, and variance = $\frac{3H_*^4}{8\pi^2 m^2}$
   b. Equilibrium naturally attained in $N \cong H_*^2/m^2$ e-folds, regardless of initial field value -- χ_* not free parameter and determined by the equilibrium distribution. ✔

Parameter Spaces





"Fuzzy DM" scenario

-when field simultaneously constitute all DM and evades isocurvature.

Along red curve: scalar constitute all DM.
Blue region: scalar avoids DM isocurvature constraints.

Generalizing

- If field decayed after inflation into relativistic hidden sector particles Ψ (never entered thermal equilibrium with radiation), the field's contribution to present DM abundance:

$$\frac{\Omega_\psi h^2}{0.12} = 1.2 \times 10^9 g_*^{-1/4} (H_{\rm osc}) \left(\frac{m}{\Gamma_\chi}\right)^{3/8} \left(\frac{\chi_*}{M_P}\right)^{3/2} \left(\frac{m_\psi}{\rm GeV}\right)$$

- DM field sourcing part of present DM density. ✔
- Freeze-in mechanism: provide additional contribution to the final DM abundance, which could be generalized to a sum of individual contributions from different mechanisms.
- After some math, conclude enhancement in small scales structure formation is generic prediction of models where DM resides in decoupled sector containing scalar fields. ✔

To Conclude ..

- The model cannot accommodate sizable DM self-interactions-- a detection would rule out the simplest scenario.
- Characteristic enhancement in small scale structure formation-- allow testing of models where DM interacts feebly or only gravitationally.

LDMX

- Freeze-out mechanism
- Thermal DM
- Light dark matter (lighter than traditional CDM)

This Paper's mentions

- Freeze-in mechanism
- Non-thermal DM (e.g. axions)
- Feebly interacting DM
- Cold dark matter (CDM)
- Fuzzy dark matter

Reference

[1] Tenkanen, T. (2019). Dark Matter from Scalar Field Fluctuations.

Physical Review Letters, 123(6). doi:10.1103/physrevlett.123.061302