Cosmological scalar fields and Big-Bang nucleosynthesis

J.-F. Coupechoux (PhD student)
A. Arbey (Supervisor)
Institut de Physique des 2 infinis de Lyon (IP2I)

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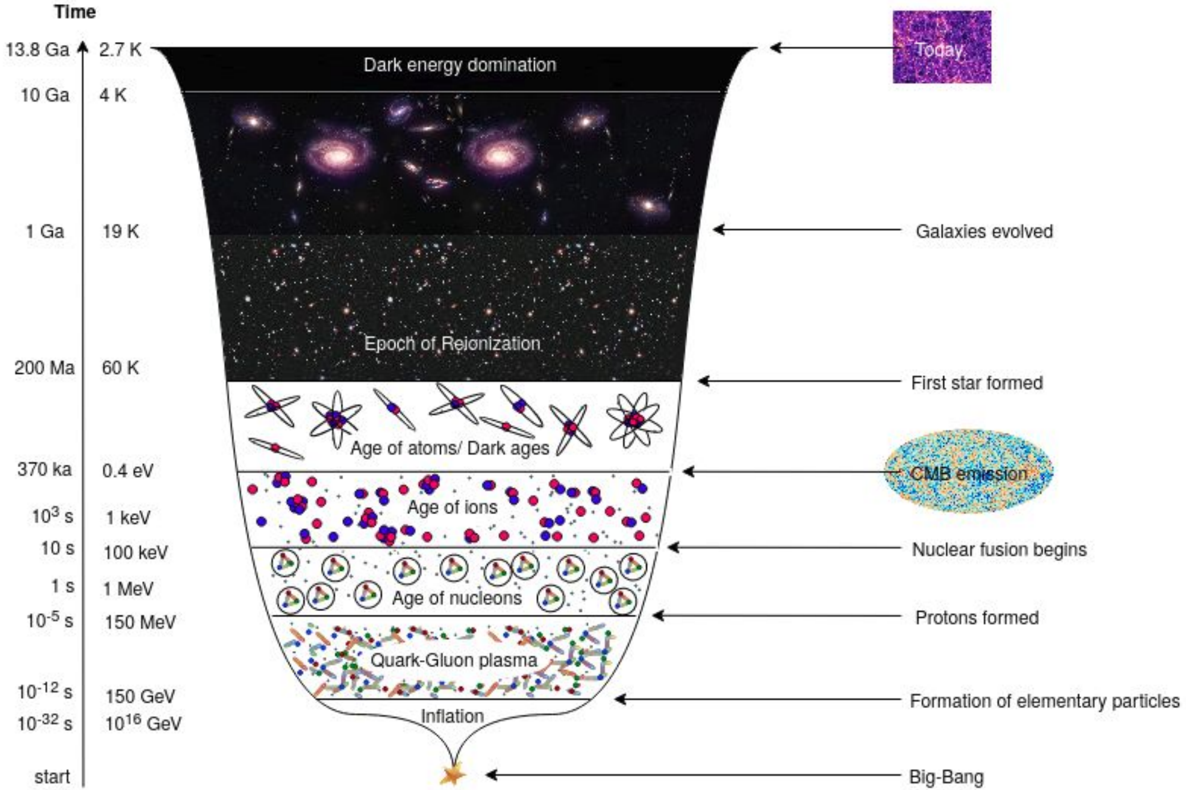
IP2I

Introduction

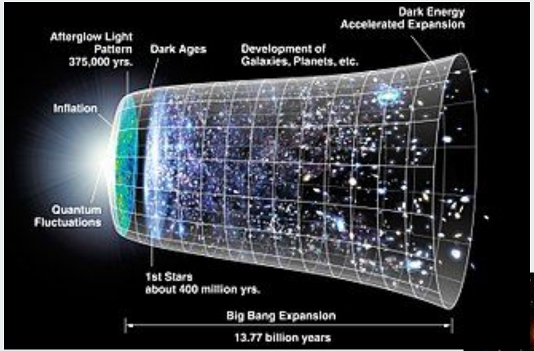
ΛCDM model

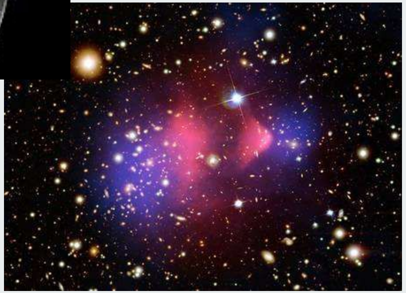
Solving dark matter problem:

- ❖ modified general relativity
  - ➢ MOND theory
- ❖ add some new ingredients
  - ➢ WIMPs
  - ➢ Primordial black holes
  - ➢ scalar fields



Plan





1. **Cosmological scalar fields**
   - Dark matter like scalar field
   - Dark energy like scalar field
   - Dark fluid model

2. **Triple unification**
   - Model
   - Spontaneous symmetry breaking
   - R^2 inflation
   - Dark fluid behavior

3. **Big-Bang nucleosynthesis**
   - BBN and Lithium problem
   - Constraints for stable scalar fields
   - Constraints for decaying scalar fields

Scalar field evolution

Equations in a homogeneous Universe:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\rho_\phi + \rho_{\text{other}}\right)$$

$$2\dot{H} + 3H^2 = -8\pi G\left(P_\phi + P_{\text{other}}\right)$$

Energy density evolution:

- ➔ Matter evolves like $\rho_m \propto a^{-3}$
- ➔ Radiation evolves like $\rho_r \propto a^{-4}$

For scalar field quickly oscillates:

- ➔ quadratic potential evolves like matter
- ➔ quartic potential evolves like radiation

Part I: Cosmological scalar fields

Fuzzy Dark Matter

Characteristics

- Ultralight particle: $m \sim 10^{-22} \text{eV}$
- Condensate through Bose-Einstein condensate:

$$L_{Compton} \sim \frac{h}{mc} \sim 10 \text{ kpc}$$

- Could replace the dark matter

Observational constraints

- Galaxy rotation curves *(arXiv:astro-ph/0301533)*:

  flat spiral galaxy rotation curves

- Bullet Cluster *(arXiv:astro-ph/0610682)*:

  solitonic behavior

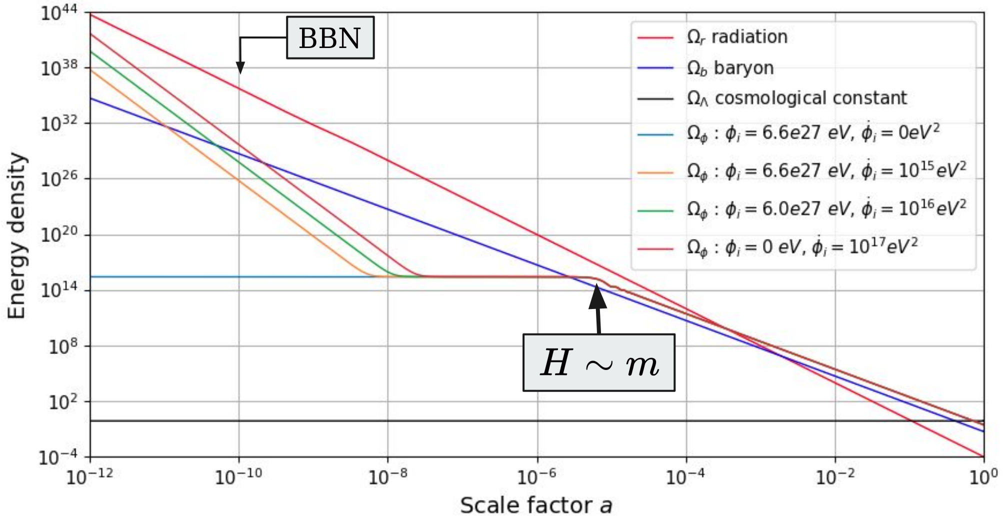
- Formation of galaxies *(arXiv:astro-ph/0003365)*:

  no cuspy halos and missing satellites problems

Quadratic potential:

$$\mathcal{L}_\phi = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + U(\phi)$$

$$U(\phi) = \frac{m^2}{2}\phi^2 \text{ with } m \sim 10^{-22}\text{eV}$$



Three-step evolution:

- domination of kinetic term decays as a^{-6}
- potential compensate the kinetic term: plateau
- matter behavior decays as a^{-3}

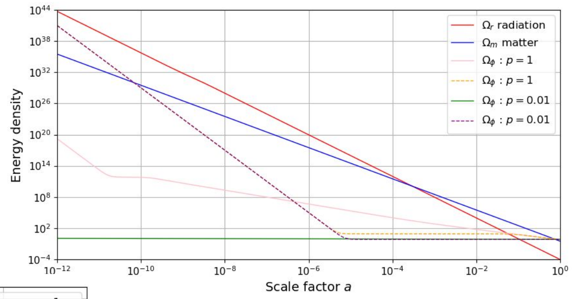
Quintessence models

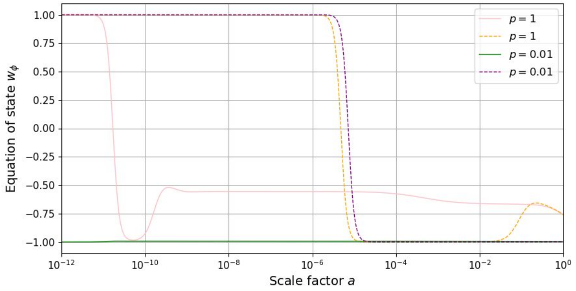
The cosmological constant Λ is replaced by a scalar field

- More naturals scenario to explain the recent acceleration of the expansion of the Universe

- The dark energy is expected to evolve and could have played a role at earlier stages

Tracking freezing models





$$\mathcal{L}_\phi = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + U(\phi)$$

$$U(\phi) = M^4 \left(\frac{M_P}{\phi} \right)^p$$

Dark Fluid Model

A unique scalar field for
the dark energy and dark matter

The simple dark fluid model

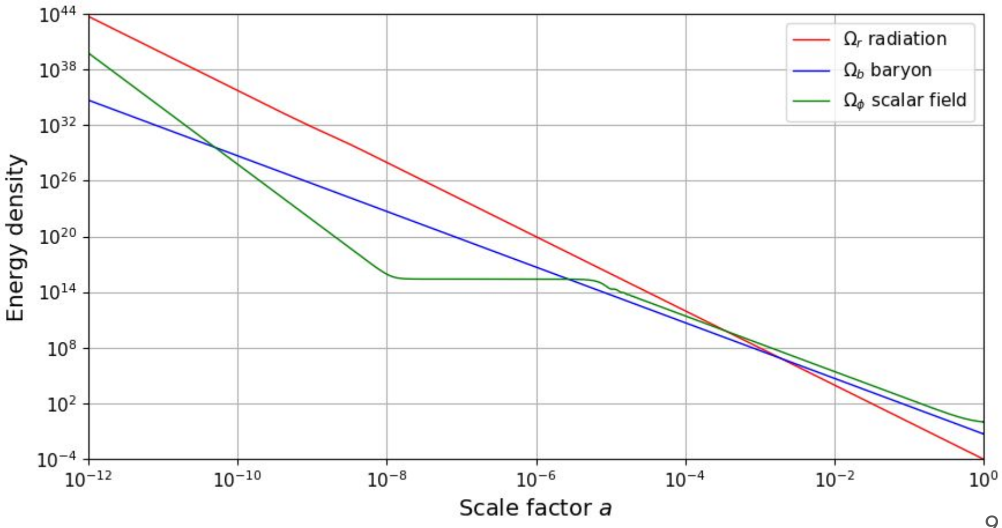
$$U(\phi) = V_0 + \frac{1}{2}m^2\phi^2$$

- Behaves as cold and fuzzy dark matter:

$$m \sim 10^{-22}\,\text{eV}$$

- Behaves as dark energy:

$$V_0 = \frac{\Lambda c^4}{8\pi G} = 2.5 \times 10^{-11}\,\text{eV}$$



Part II: Triple unification

ArXiv:2007.05376

Model:

Unifying dark matter, dark energy and inflation with a fuzzy dark matter

Inflation: another scalar field?

Inflaton dark matter from incomplete decay *(arXiv:1501.05539)*

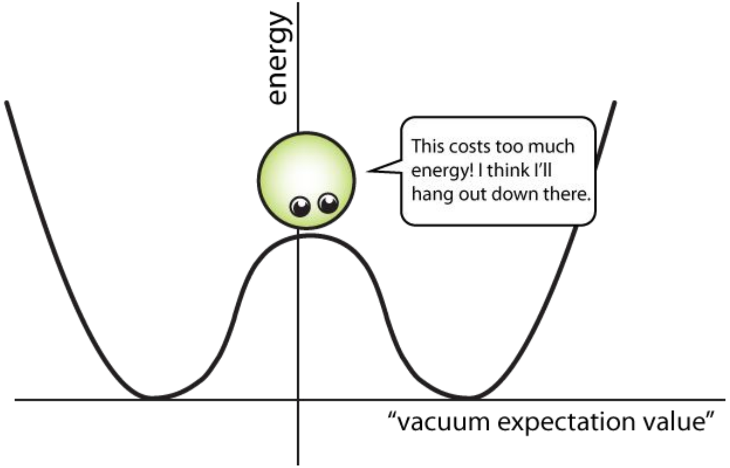
Non-minimal coupling: $\phi^2 R^2$

Action: $\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} \left(R + \alpha \phi^2 R^2 \right) - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right]$

Potential: $V(\phi) = V_0 + \frac{m^2}{8v^2} \left(\phi^2 - v^2 \right)^2$

Spontaneous symmetry breaking

- local maximum at $\phi = 0$
- the scalar field oscillate around one of the minima $\phi = \xi \pm v$
- after the symmetry breaking $|\xi| \ll v$



$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}\left(R + \alpha\phi^2 R^2\right) - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

$$V(\phi) = V_0 + \frac{m^2}{8v^2}\left(\phi^2 - v^2\right)^2$$

Symmetry breaking

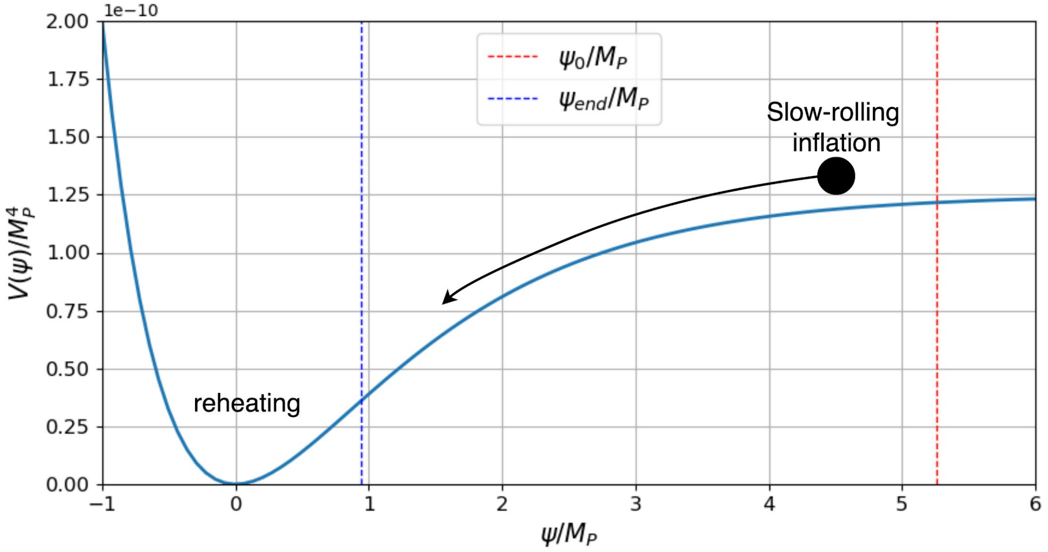
$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}\left(R + \alpha v^2\left(1 \pm \frac{2}{v}\xi + \frac{1}{v^2}\xi^2\right)R^2\right) - \frac{1}{2}g^{\mu\nu}\partial_\mu\xi\partial_\nu\xi - V(\xi)\right]$$

$$V(\xi) = V_0 + \frac{m^2}{2}\xi^2 \pm \frac{m^2}{2v}\xi^3 + \frac{m^2}{8v^2}\xi^4$$

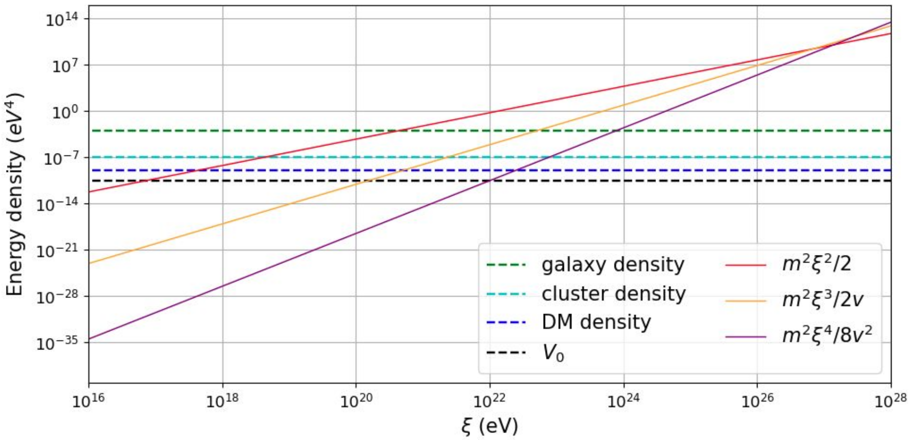
R^2 inflation

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}\underbrace{\left(R + \frac{\alpha v^2}{M_P^2}R^2\right)}_{f(R)}\right]$$

The scalar field ξ is negligible during inflation



Dark fluid behavior



The scalar field ξ comes from the symmetry breaking:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\xi\partial_\nu\xi - V(\xi)\right]$$

$$V(\xi) = V_0 + \frac{m^2}{2}\xi^2 \pm \frac{m^2}{2v}\xi^3 + \frac{m^2}{8v^2}\xi^4$$

The field evolves like the simple dark fluid model if:

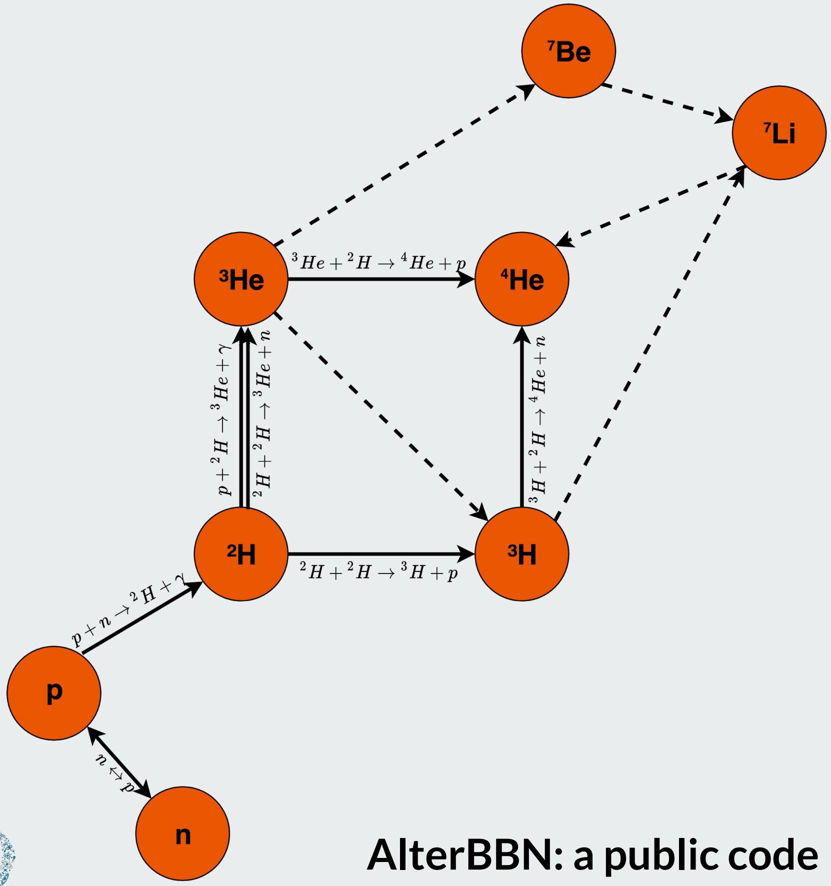
- $V_0 = \frac{\Lambda}{\kappa} = 2.5 \times 10^{-11}$ eV⁴
- $m \sim 10^{-22}$eV
- $v > 7 \times 10^{26}$ eV

The ξ^3 and ξ^4 terms are negligible

Part III: Big-Bang nucleosynthesis

ArXiv:1907.04367 Published in JCAP11(2019)038

Big Bang Nucleosynthesis



- High density, the dominating species are photons, electrons, positrons, baryons, neutrinos, antineutrinos and dark matter:
$$\rho_{tot} = \rho_\gamma + \rho_{\nu,\bar{\nu}} + \rho_b + \rho_{e^\pm} + \rho_\chi$$
- BBN occurs during radiation domination:
$$a_{\rm BBN} \sim 10^{-10} \text{ and } T_{\rm BBN} \sim 1\text{MeV}$$
- Temperature of 1MeV allows hydrogen nuclei to fuse into helium nuclei
- Freeze out by the Universe expansion

Observational measurements:

$Y_p = 0.245 \pm 0.003$

$^2H/H = (2.569 \pm 0.027) \times 10^{-5}$

$^3He/H = (1.1 \pm 0.2) \times 10^{-5}$

$^7Li/H = (1.6 \pm 0.3) \times 10^{-10}$

Theoretical predictions:

$Y_p = 0.2472 \pm 0.0006$

$^2H/H = (2.463 \pm 0.074) \times 10^{-5}$

$^3He/H = (1.03 \pm 0.03) \times 10^{-5}$

$^7Li/H = (5.4 \pm 0.7) \times 10^{-10}$

conflict

AlterBBN: a public code

J-F Coupechoux

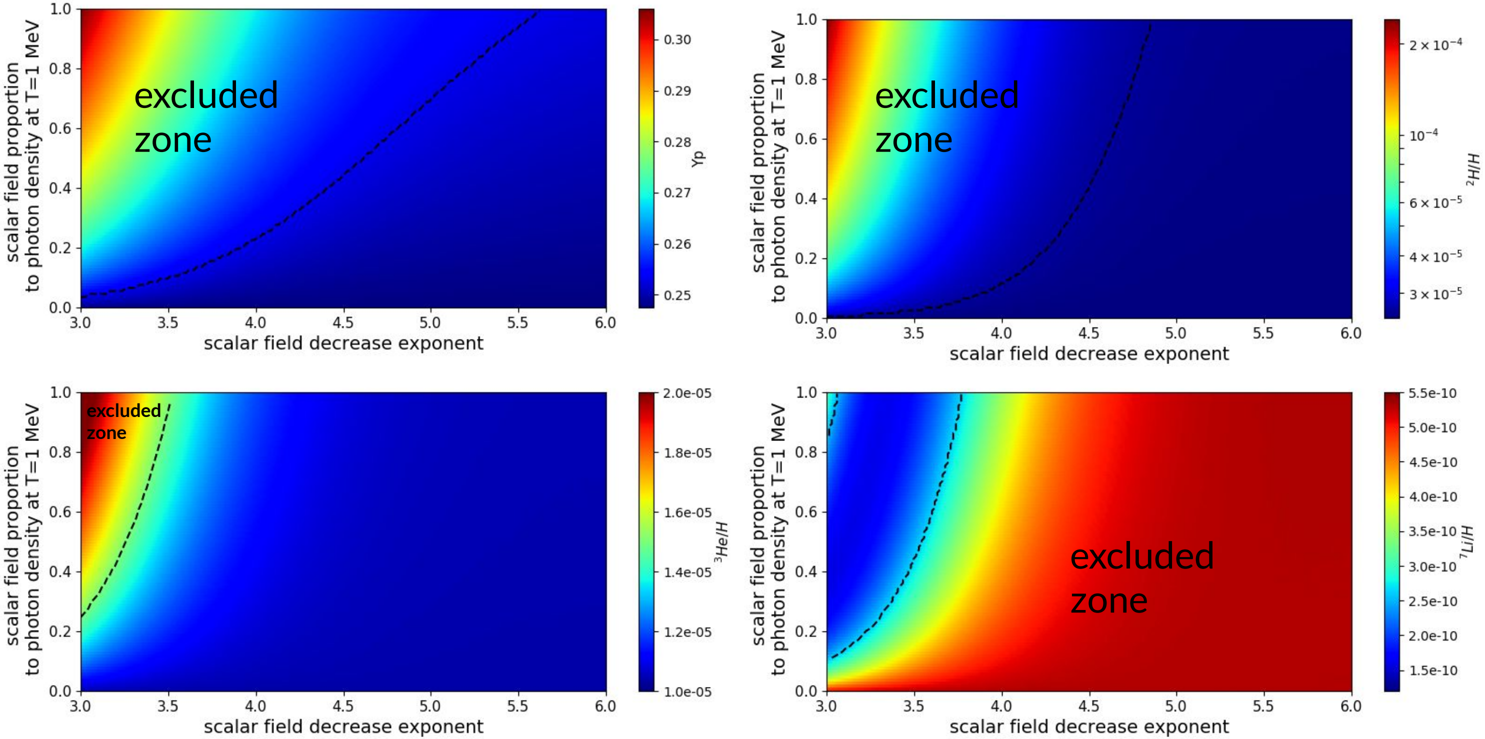
BBN constraints on stable cosmological scalar field

Scalar field density:

$$\rho_\phi = \rho_\phi^0(1\mathrm{MeV}).\,a^{-n}$$

Modification of the abundance of the elements via Hubble rate:

$$H^2 = \frac{8\pi G}{c^2}\rho_{tot}$$



BBN constraints for stable scalar fields at 95% C.L.

$$\text{for } n = 6: \quad \rho_\phi(1 \text{ MeV}) \leq 1.40\, \rho_\gamma(1 \text{ MeV})$$

$$\text{for } n = 4: \quad \rho_\phi(1 \text{ MeV}) \leq 0.11\, \rho_\gamma(1 \text{ MeV})$$

$$\text{for } n = 3: \quad \rho_\phi(1 \text{ MeV}) \leq 0.005\, \rho_\gamma(1 \text{ MeV})$$

$$\text{for } n = 0: \quad \rho_\phi(1 \text{ MeV}) \leq 2 \times 10^{-7} \rho_\gamma(1 \text{ MeV})$$

Decaying scalar fields

Klein-Gordon equation:

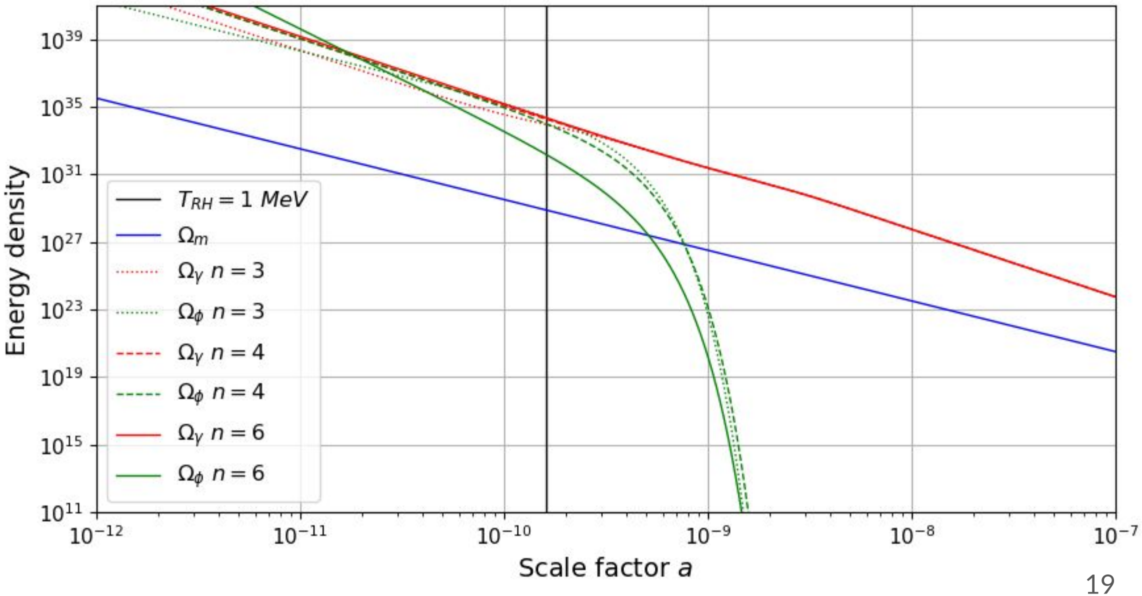
$$\frac{d\rho_\phi}{dt} = -nH\rho_\phi - \Gamma_\phi \rho_\phi$$

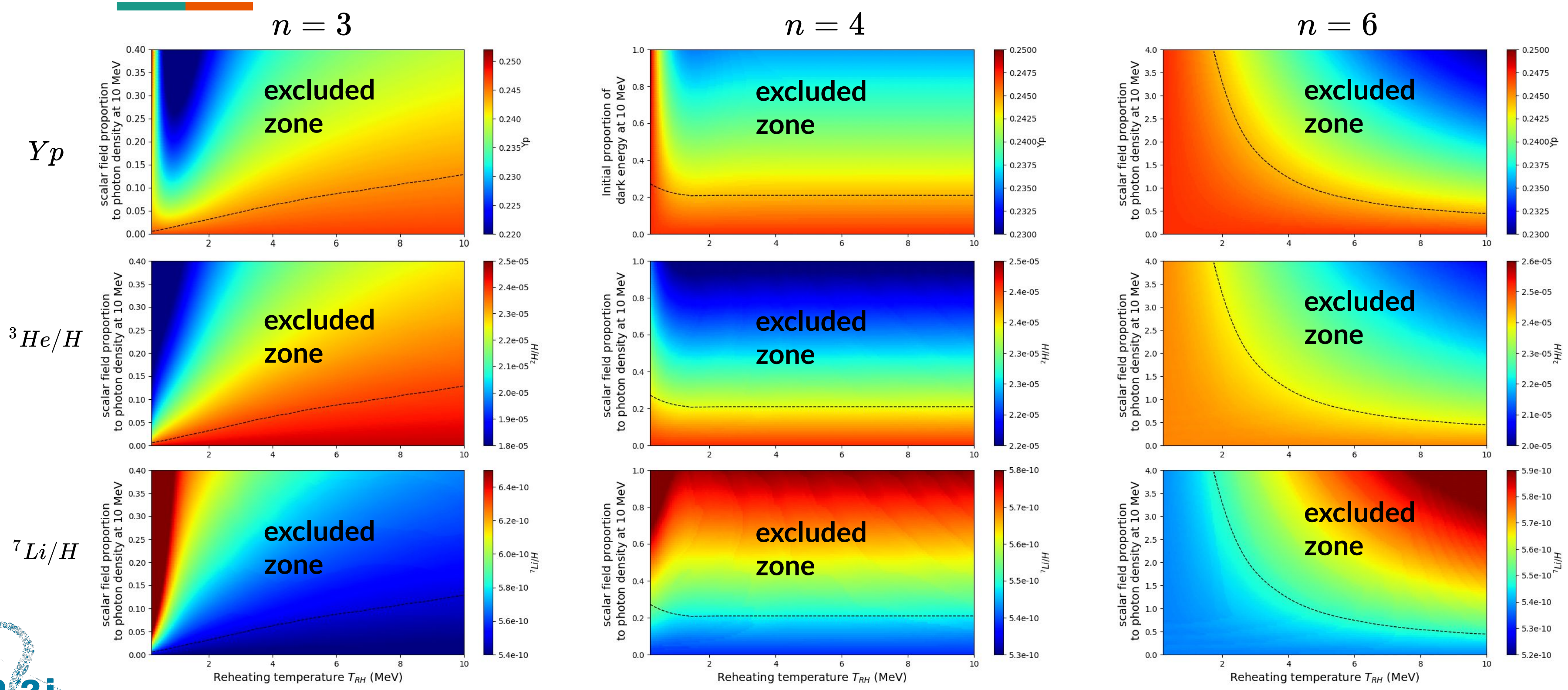
Definition of the reheating temperature:

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_{\text{eff}}(T_{RH})}{45}} \frac{T_{RH}^2}{M_P}$$

The scalar field decays into radiation, the total radiation entropy receives an injection:

$$\frac{\partial s_{rad}}{\partial t} = -3Hs_{rad} + \frac{\Gamma_\phi \rho_\phi}{T}$$





$n = 3$
$n = 4$
$n = 6$
Yp
$^3He/H$
$^7Li/H$
excluded zone
excluded zone
excluded zone
excluded zone
excluded zone
excluded zone
excluded zone
excluded zone
excluded zone
scalar field proportion to photon density at 10 MeV
Initial proportion of dark energy at 10 MeV
Reheating temperature T_{RH} (MeV)
Yp
$^2H/H$
$^7Li/H$

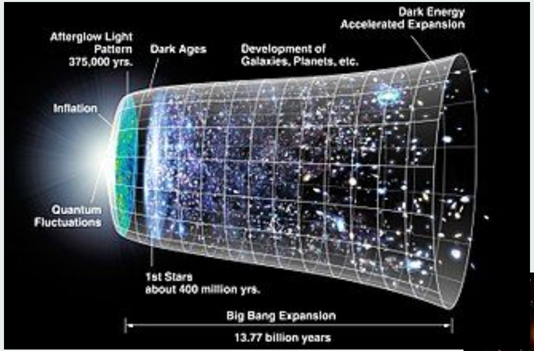
BBN constraints for decaying scalar field at 95% C.L.

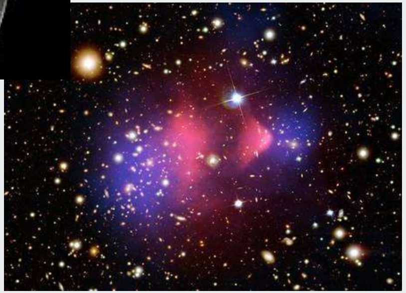
$$\text{for } n = 6: \quad \rho_\phi(10\text{ MeV}) \leq 0.5\,\rho_\gamma(10\text{ MeV})$$

$$\text{for } n = 4: \quad \rho_\phi(10\text{ MeV}) \leq 0.1\,\rho_\gamma(10\text{ MeV})$$

$$\text{for } n = 3: \quad \rho_\phi(10\text{ MeV}) \leq 0.01\left(\frac{T_{RH}}{1\text{ MeV}}\right)\rho_\gamma(10\text{ MeV})$$

Conclusion





- ❖ Fuzzy dark matter as dark matter
- ❖ Quintessence as dark energy
- ❖ One field to rule them all
- ❖ Big-Bang nucleosynthesis:
  - ➢ stable scalar field
  - ➢ decaying scalar field

Thank you for your attention