Lessons for dark matter from nonstandard cosmologies

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- New opportunities for axion dark matter searches in nonstandard cosmological models,
  P. Arias, N. Bernal, A. Narino, D. Karamitros, C. Maldonado, LR, M. Venegas,
  JCAP 11 No 11 (2021) 003
- (Dark Matter Axions in the Early Universe with a Period of Increasing Temperature,
  P. Arias, N. Bernal, J.K. Osiński, LR, e-Print: 2207.07677 🡐 talk by J. Osiński)
- Frozen-in fermionic singlet dark matter in non-standard cosmology with a decaying fluid,
  P. Arias, D. Karamitros, LR, JCAP 05 (2021) 041

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Standard Cosmology (SC):

- Period of inflation, reheating
- Radiation domination (RD) follows until BBN (and later, until radiation-matter EQ)
- Dark matter (DM) production takes place between inflation and BBN
  - Axion: misalignment mechanism
  - WIMP: freeze-out or freeze-in

Most studies of DM production, properties and prospects for discovery assume SC

There are many possible alternatives to SC
Called nonstandard cosmology (NSC) models/scenarios

Examples:

- early matter domination (EMD),
- kination
- …

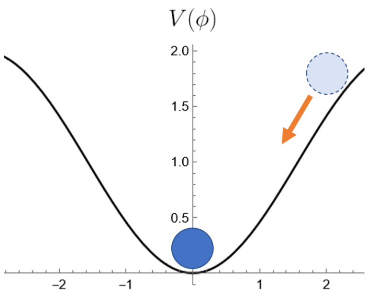
Much work in the literature
(see bibliography)

How do results for DM change in NSCs?

Axion production

- Peccei-Quinn solution to the strong CP problem
- Axion a: pseudoscalar
- Equation of motion: $\ddot{\theta} + 3H(T)\dot{\theta} + m_a(T)^2 \sin\theta = 0$ $\theta = a/f_a$
- picks up mass at T_{QCD}

$$m_a(T) = \begin{cases} m_a, & T \lesssim T_{QCD} \\ m_a \left(\frac{T_{QCD}}{T}\right)^4, & T \gtrsim T_{QCD} \end{cases} \qquad m_a(T) = \frac{\chi(T)^{\frac{1}{2}}}{f_a}$$

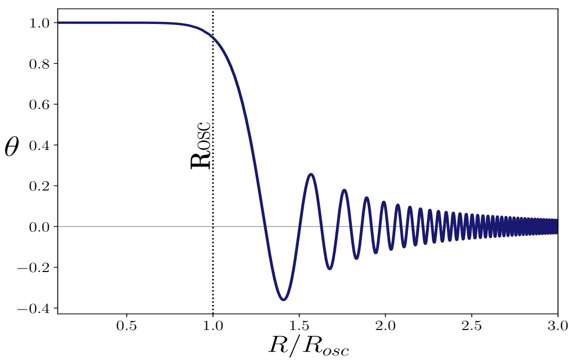


- Misalignment mechanism

$H > m_a$: $\theta \approx \theta_i$= const. - initial misalignment angle

$H \sim m_a$ - Coherent axion oscillations start at T_{osc}

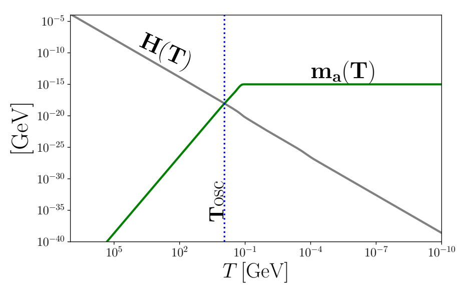
$$H(T_{osc}) \approx m_a(T_{osc})$$



(M. Venegas)

- Standard Cosmology (SC):

$H \propto T^2$



- Axion as DM:
  standard QCD window:
  $\sim 10^{-6}$eV < m_a < $\sim 10^{-5}$eV

Simple NSC scenario

New opportunities for axion dark matter searches in nonstandard cosmological models, P. Arias, et al, JCAP 11 No 11 (2021) 003

Consider:

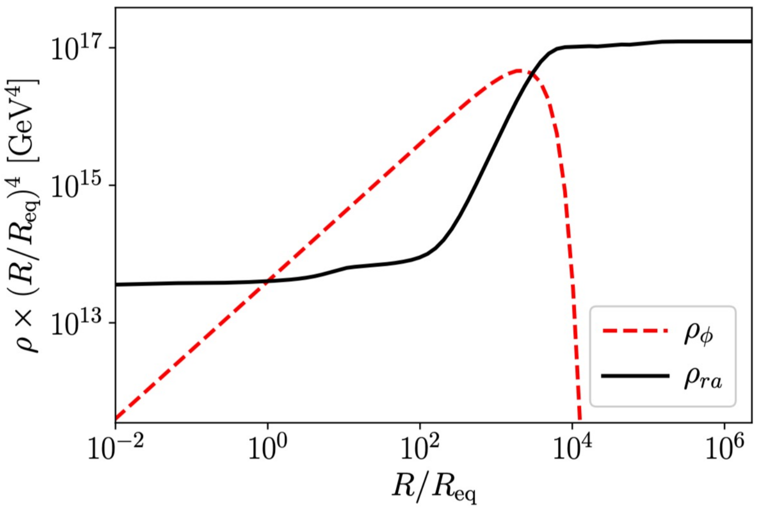
- Some new scalar field ϕ
- It dominates the energy density over some period between inflation and BBN (EMD)
- It decays into Standard Model (SM) degrees of freedom prior to BBN

Equation of state $\omega_\phi = P_\phi/\rho_\phi$

$$\rho_\phi \propto R^{-\overbrace{3(1+\omega_\phi)}^{\beta}}$$

radiation

$\beta = 4$



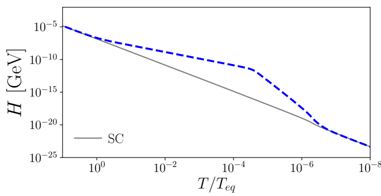
Boltzmann equations

$$\frac{d\rho_\phi}{dR} + \beta\,\frac{\rho_\phi}{R} = -\frac{\Gamma_\phi \rho_\phi}{R, H}$$

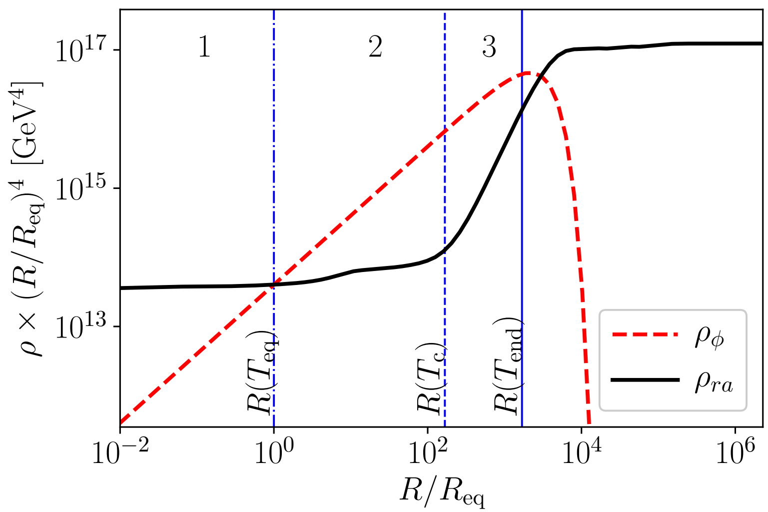
$$\frac{d\rho_{ra}}{dR} + 4\,\frac{\rho_{ra}}{R} = \frac{\Gamma_\phi\, \rho_\phi}{R\, H}$$

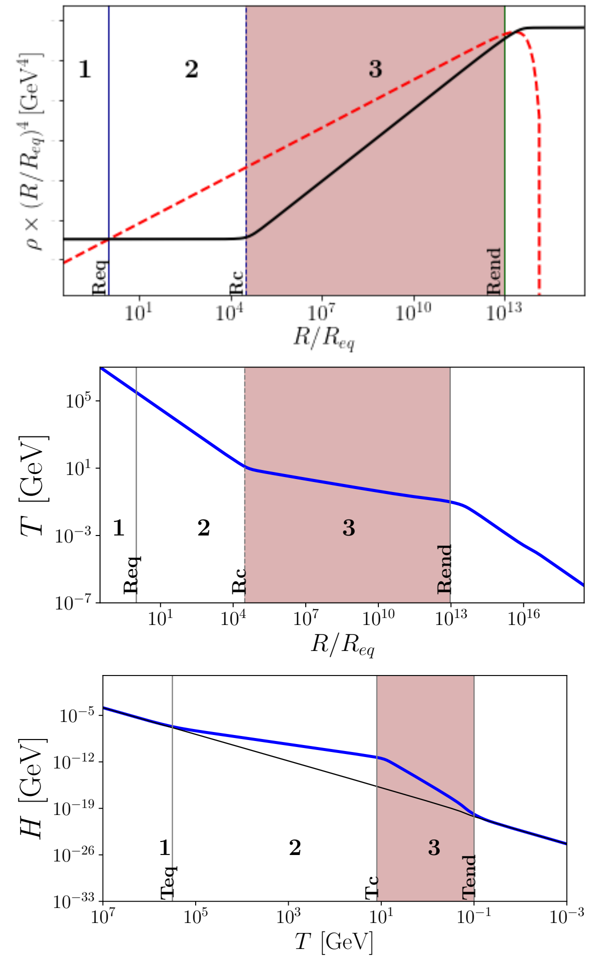
Hubble parameter

$$H = \sqrt{\frac{\rho_\phi + \rho_{ra}}{3M_p^2}}$$



Here and below: M. Venegas)





Initial condition: T_{eq}

NSC parameters: β, T_{eq}, T_{end}

(M. Venegas)

Region 1
$R<R_{eq}$

· Fields evolution: $\rho_{ra} \propto R^{-4}$, $\rho_{\phi} \propto R^{-\beta}$

· Domination: radiation $H \propto R^{-2}$

the universe expands as standard cosmology.

· Entropy: conserved $H \propto T^2$

Region 2
$R_{eq}<R<R_c$

· Domination: ϕ $H \propto R^{-\frac{\beta}{2}}$

faster expansion

· Entropy: conserved $H \propto T^{\frac{\beta}{2}}$

mild dependency

Region 3
$R_c<R<R_{end}$

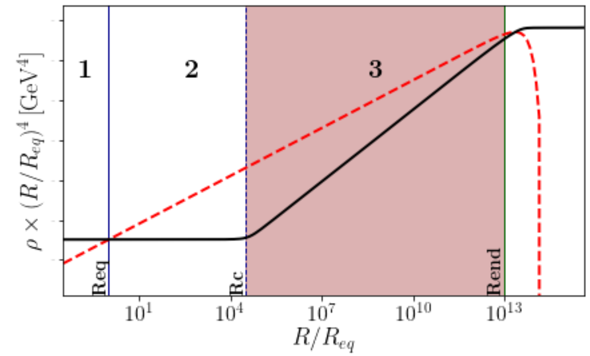
· Domination: ϕ

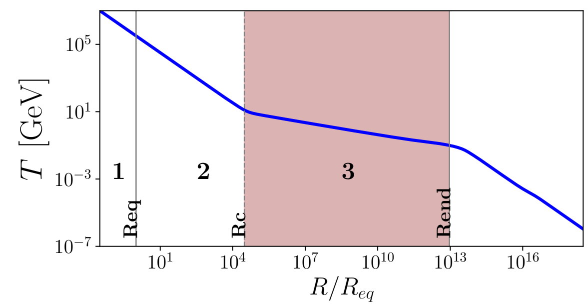
but ϕ decays start to affect radiation: $\rho_{ra} \propto R^{-\beta/2}$

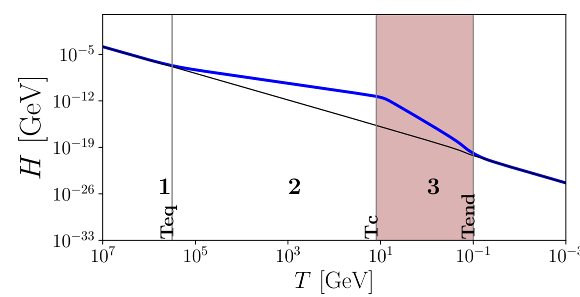
· Entropy: not conserved $H \propto T^4$

stronger dependency

H does not depend on β





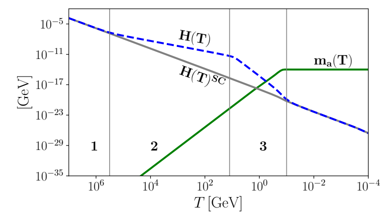


(M. Venegas)

Initial condition: T_{eq}

NSC parameters: β, T_{eq}, T_{end}

Effects of NSC on axion production via misalignment mechanism

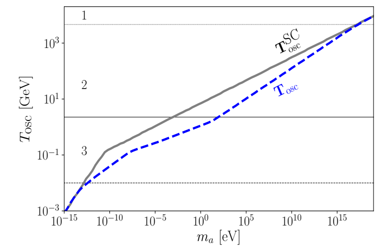


1. From H(T)> H(T)^{SC}

$$H(T_{\rm osc}) = m_a(T_{\rm osc})$$

T_{osc} lower than in SC

→ **increase in axion energy density**



2. From entropy injection to SM plasma (for $\beta < 4$)

- **dilution of axion density**

$$\rho_a(T_0) = \rho_a(T_{osc}) \frac{m_a}{m_a(T_{osc})} \frac{s(T_0)}{s(T_{osc})} \gamma \qquad \gamma \equiv \frac{S(T_{osc})}{S(T_{end})}, \qquad \gamma \leq 1$$

The dilution factor is a function of NSC parameters, depending which region the axion starts to oscillate

(M. Venegas)

- For $\beta < 4$
  - Competition between both effects
    - Dilution factor is stronger

$$\Omega_a^{NSC}(m_a) < \Omega_a^{SC}(m_a)$$

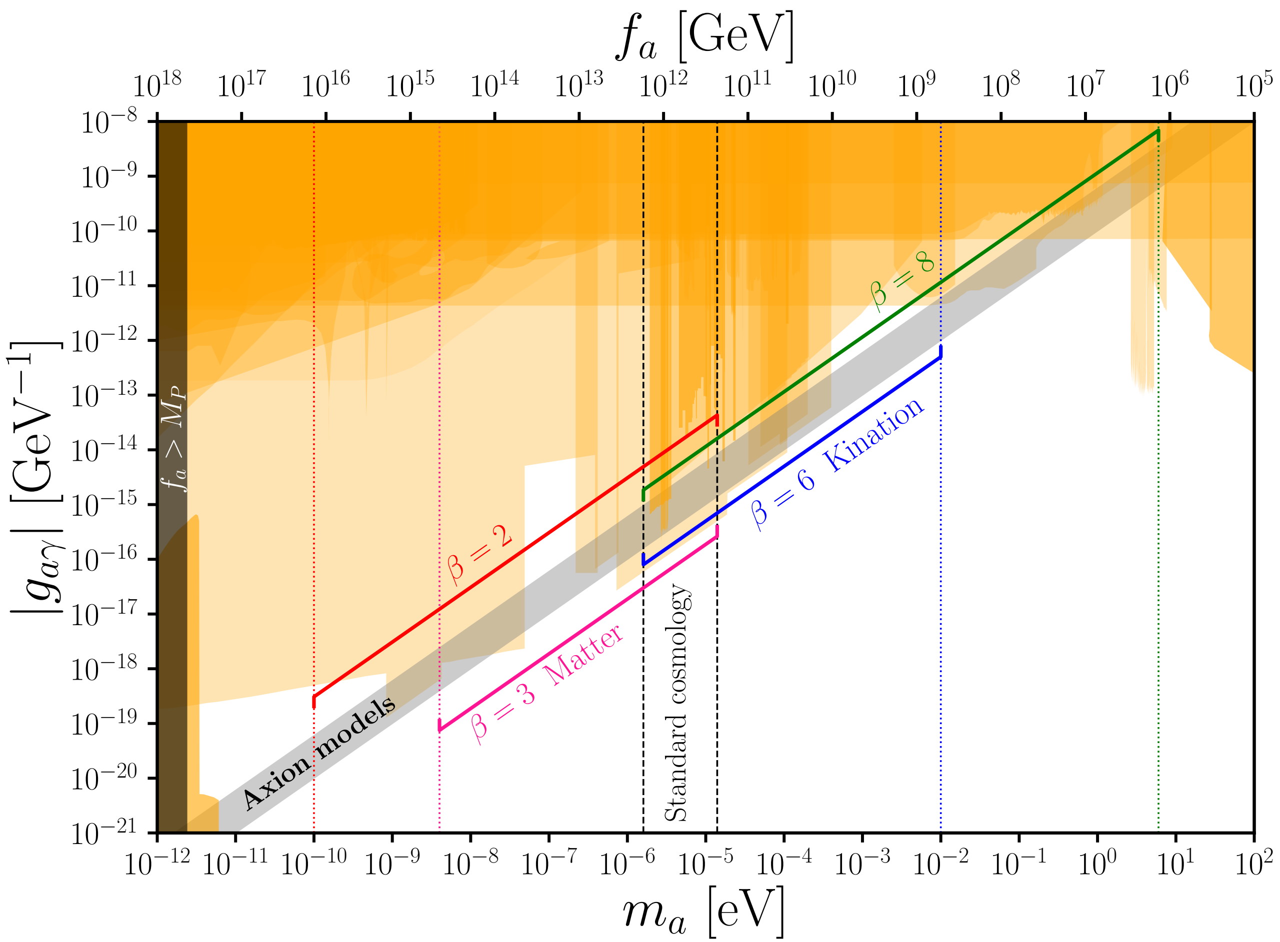
➡ **Lower mass values open up, below the standard QCD window**

- For $\beta > 4$
  - No entropy injection
  - Only lower T_{OSC}

$$\Omega_a^{NSC}(m_a) > \Omega_a^{SC}(m_a)$$

➡ **Larger mass values open up, above the standard QCD window**

M. Venegas



SC: 10^{-6} eV $\lesssim m_a \lesssim 10^{-5}$ eV.

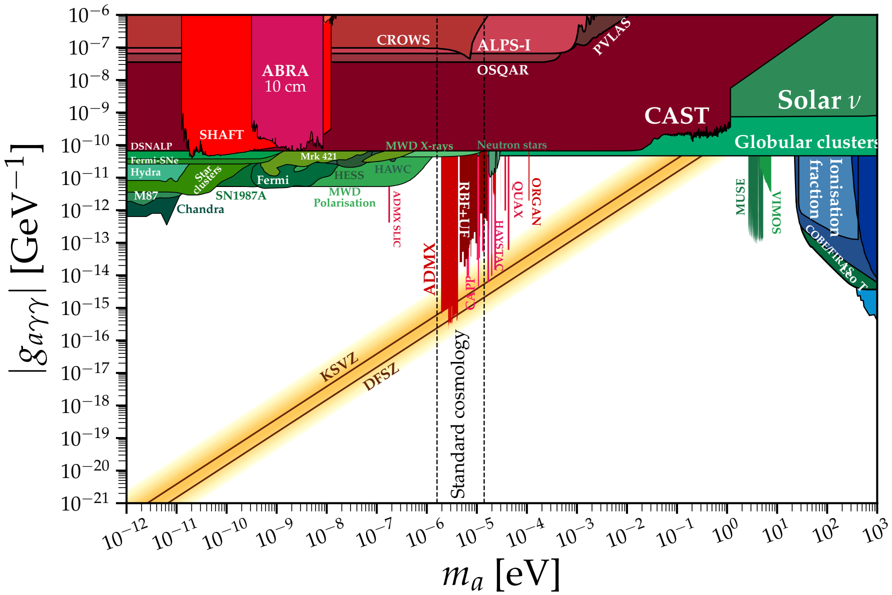
$\beta = 3$: 10^{-8} eV $\lesssim m_a \lesssim 10^{-5}$ eV

$\beta = 2$: 10^{-10} eV $\lesssim m_a \lesssim 10^{-5}$ eV

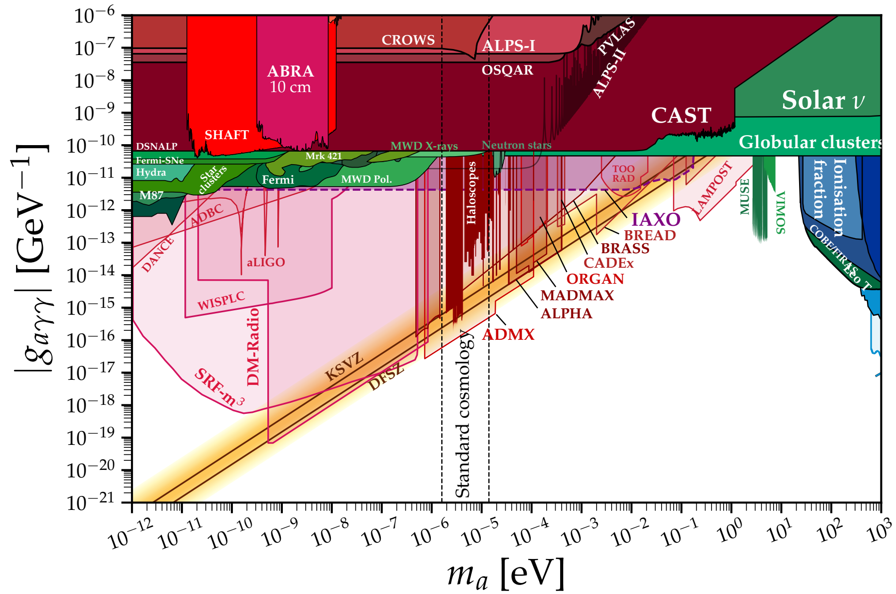
$\beta = 6$: 10^{-6} eV $\lesssim m_a \lesssim 10^{-2}$ eV

$\beta = 8$: 10^{-6} eV $\lesssim m_a \lesssim 6$ eV.

current



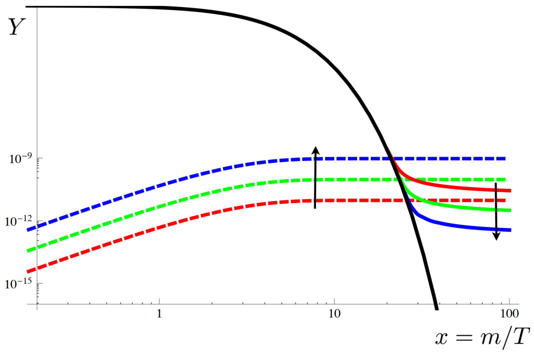
future



https://github.com/cajohare/AxionLimits

WIMP DM Production in NSCs

- **Thermal: freeze-out**
- **Non-thermal: freeze-in, ….**



Both are sensitive to thermal history of the Universe
And not only WIMP mass and interactions

Focus on freeze-in:

Number density of DM depends on:
- Process that produces them
- The evolution of the plasma temperature
- The expansion rate of the Universe H

The DM abundance depends on:
- The DM number density, AND
- The photon number density

Effect: significantly altered, often strongly relaxed parameter space

Freeze-in of fermionic DM in NSC

Frozen-in fermionic singlet dark matter in non-standard cosmology with a decaying fluid, P. Arias, D. Karamitros, LR, JCAP 05 (2021) 041

- DM is produced from some scalar field S
  - S decays $S \to \chi\chi$
  - S scattering $SS \to \chi\chi$

$$\mathcal{L}_{\rm int} = -\frac{y_\chi}{2}\, S\, \left(\chi\chi + \chi^\dagger\chi^\dagger\right)$$

- S remains in thermal equilibrium via interactions with Higgs boson

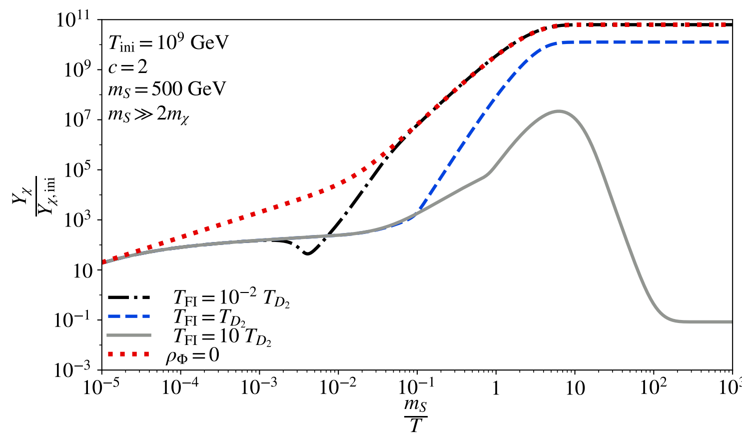
$$\mathcal{L}_{HS} = -\frac{\lambda_{HS}}{2}\, S^2\, H^\dagger H$$

- Boltzmann equations $Y_\chi \equiv n_\chi / s$

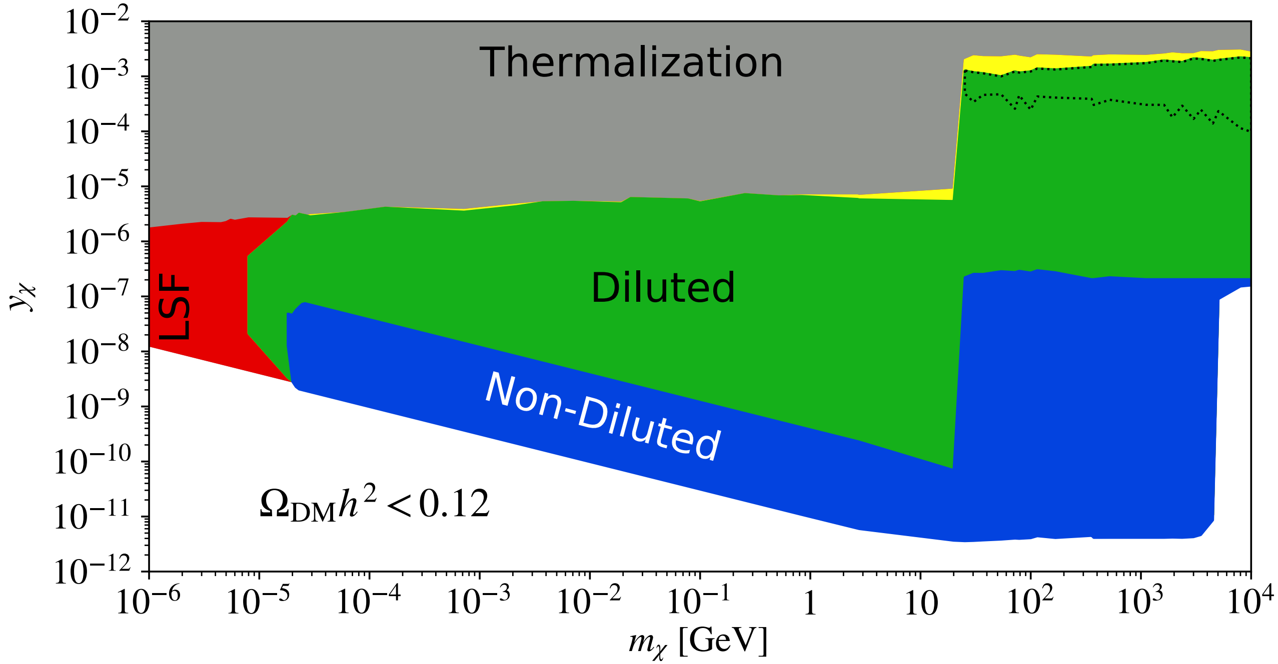
$$\frac{d\log Y_\chi}{d\log \frac{T_{\rm ini}}{T}} = \delta_h \frac{\{S\to\chi\chi\} + \{SS \to \chi\chi\}}{H_{\rm R} n_\chi} \times$$

$$\underbrace{\frac{H_{\rm R}}{H}}_{0<\mathcal{F}_1\leq 1} \underbrace{\left(1 - \frac{\Gamma_\Phi}{H}\frac{\rho_\Phi}{3s\,T}\right)^{-1}}_{1\leq\mathcal{F}_2\lesssim 8/c} \underbrace{\left[1 - \frac{d\log S}{d\log\frac{T_{\rm ini}}{T}}\left(\frac{d\log N_\chi}{d\log\frac{T_{\rm ini}}{T}}\right)^{-1}\right]}_{\mathcal{F}_3\leq 1}$$

$$p_\Phi = 1/3\,(c-3)\,\rho_\Phi$$



- EMD significantly alters DM production
- The relic density is lower than in SC (dilution)



Allowed:

- Blue: SC
- Green: NSC

Forbidden:

- Gray: no FI
- Red: LSF

- NSC: dilution of relic density opens up much larger values of y_χ
- Also relaxes large scale formation (LSF) bound

To take home:

- Standard cosmology is the simplest choice but by no means a unique one
- Many nonstandard cosmology scenarios exist
- In NSC implications for observable quantities can be large
- Simple NSC cases of early matter domination by some scalar field was presented here:
  - Axion DM produced via misalignment mechanism: mass can be much less, or much more than standard QCD window
  - Fermionic DM produced via freeze-in: Significantly larger parameter space (larger Yukawa coupling) → Implication for better prospects for direct detection