Dark Matter Production in Nonstandard Cosmologies: from WIMPs to Axions

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Standard Model and Beyond

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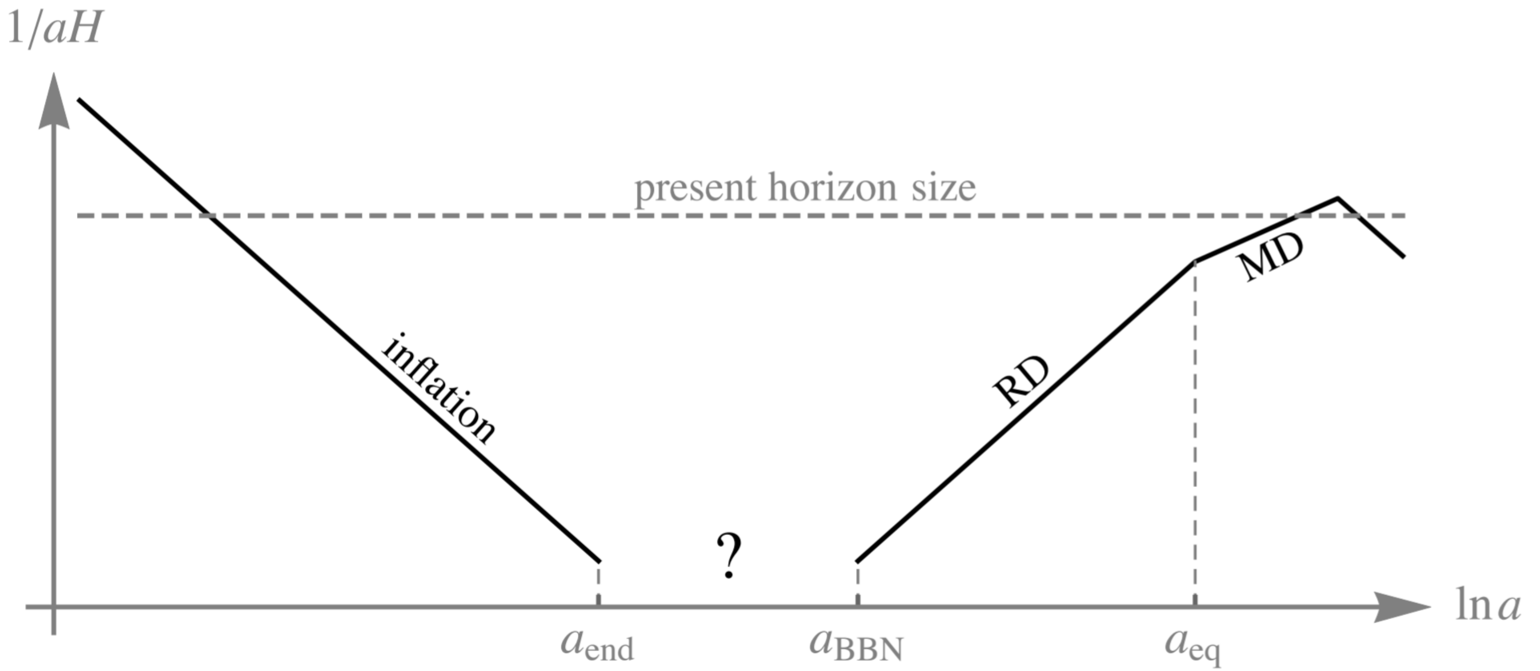
Introduction

- Standard cosmology assumes radiation domination (RD) before BBN
- Easiest assumption, but no observational evidence
- Many well-motivated deviations: inflationary reheating, early matter domination (EMD) from moduli, kination, etc.

→ Modification to expansion and thermal history affects early processes, such as dark matter (DM) production



Allahverdi et al., 2006.16182

Nonstandard Cosmologies (NSCs)

- Domination by energy density other than radiation before BBN
- General equation of state of dominating component: $p = \omega\rho$

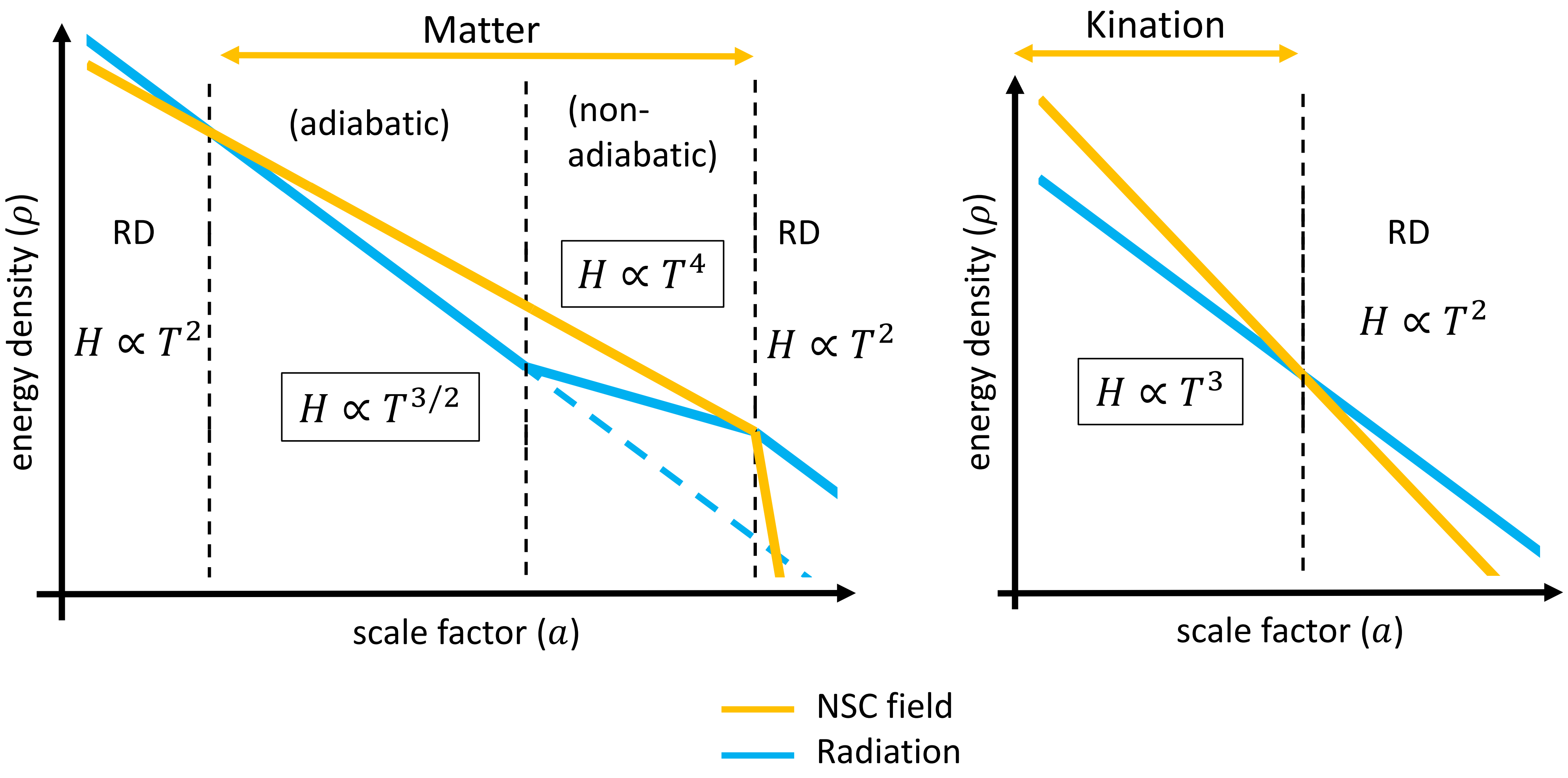
$\omega = 0$ matter	$\omega = 1/3$ radiation	$\omega = 1$ kination
$\rho \propto a^{-3}$	$\rho \propto a^{-4}$	$\rho \propto a^{-6}$
$a \propto t^{2/3}$	$a \propto t^{1/2}$	$a \propto t^{1/3}$

→ Faster redshift, slower expansion

Matter-like: $\omega < 1/3$
- can be initially subdominant
- should decay to end NSC
- (oscillating scalar field)

Kination-like: $\omega > 1/3$
- should begin dominant
- can be stable
- (fast-rolling scalar field)

Energy density evolution examples



Standard RD:
$H \propto T^2$

Adiab. NSC:
$H \propto T^{3(1+\omega)/2}$

Nonad. NSC:
$H \propto T^4$

Consequences of NSC

- Two main effects

1. Change evolution of expansion rate H and temperature T

   → Things happen at different times and temperatures

2. Entropy injection if dominant component decays to SM, mostly in matter-like cases

   → Dilution of other energy densities

→ NSC affects DM production (and other processes too)

DM production

Thermal

- DM can be produced directly from thermal bath (many possible interactions with either freeze-out/in)

→ brief look at WIMP-like DM

Nonthermal

- Does not originate from thermal bath (out-of-equilibrium decay, primordial black holes, scalar oscillations, topological sources)

→ will focus on axions from misalignment

Thermal example – WIMP-like DM

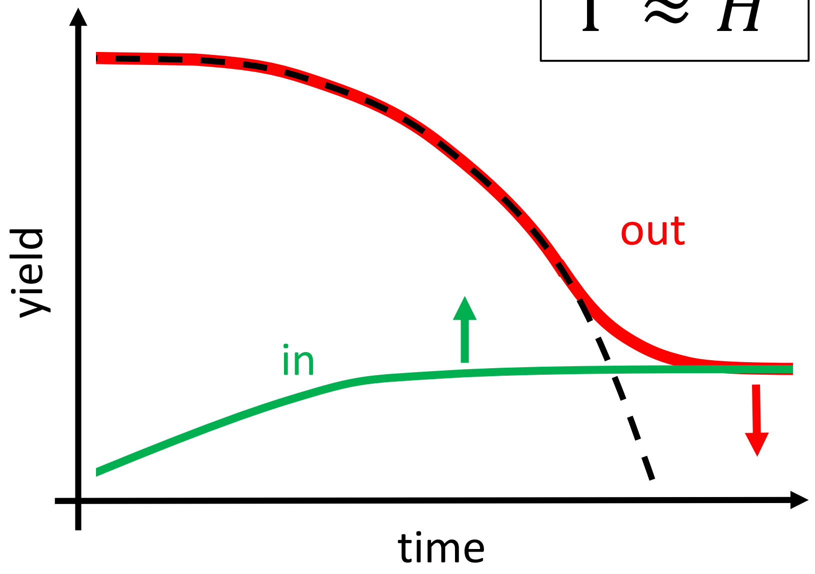
- DM particle χ produced by pair production from thermal bath
- Boltzmann equation:

$$\dot{n}_\chi + 3Hn_\chi = \langle \sigma_{\mathrm{ann}} v \rangle (n_{\mathrm{eq}}^2 - n_\chi^2)$$

- Freeze-out:
  stronger coupling → smaller abundance

- Freeze-in:
  stronger coupling → larger abundance

$\Gamma \approx H$



Thermal example – WIMP-like DM

- Final abundance in RD Universe ($H \propto T^2$)

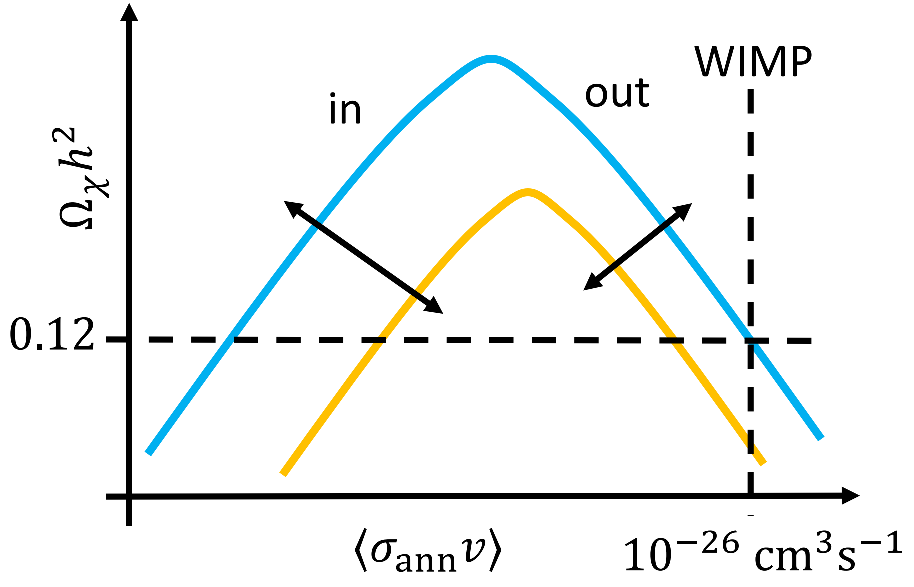
  Freeze-out: $\Omega_\chi h^2 \propto \langle \sigma_{\rm ann} v \rangle^{-1}$

  Freeze-in: $\Omega_\chi h^2 \propto \langle \sigma_{\rm ann} v \rangle$

- Example in nonadiabatic EMD ($H \propto T^4$)

  Freeze-out: $\Omega_\chi h^2 \propto \left(\frac{T_{\rm end}}{m_\chi}\right)^3 \langle \sigma_{\rm ann} v \rangle^{-1}$

  Freeze-in: $\Omega_\chi h^2 \propto \frac{T_{\rm end}^7}{m_\chi^5} \langle \sigma_{\rm ann} v \rangle$



Effect of NSC:
Moves with DM mass and NSC end temperature
→ Can bring FI values up closer to detectability

Nonthermal examples

- Evolution of H and T still important even if source is not the bath
- Decay of out-of-equilibrium source (can be NSC field)
- Primordial black holes (PBHs) – mass spectrum changed in EMD, can evaporate to DM or contribute themselves, also they can dominate
- Topological sources – defects from phase transitions
- Scalar field oscillations – Hubble rate compared to mass

  → Axions from misalignment

Axion misalignment mechanism

- Initial value of angle θ fixed after Peccei-Quinn (PQ) breaking at a high scale f_a
- Axion field (a) frozen as long as Hubble rate > axion mass

$$\theta(t) \equiv \frac{a(t)}{f_a}$$

(zero-temp. axion mass)

$$m_a \approx 5.7\ \mathrm{meV}\left(\frac{10^9\ \mathrm{GeV}}{f_a}\right)$$

$$T_{\mathrm{QCD}} \approx 150\ \mathrm{MeV}$$

Hubble rate:

$$H(T) \propto \frac{T^2}{M_{\mathrm{P}}}$$

(radiation domination)

Axion mass:

$$m(T) \approx m_a \begin{cases} \left(\frac{T_{\mathrm{QCD}}}{T}\right)^4 & T > T_{\mathrm{QCD}} \\ 1 & T < T_{\mathrm{QCD}} \end{cases}$$

Axion misalignment mechanism

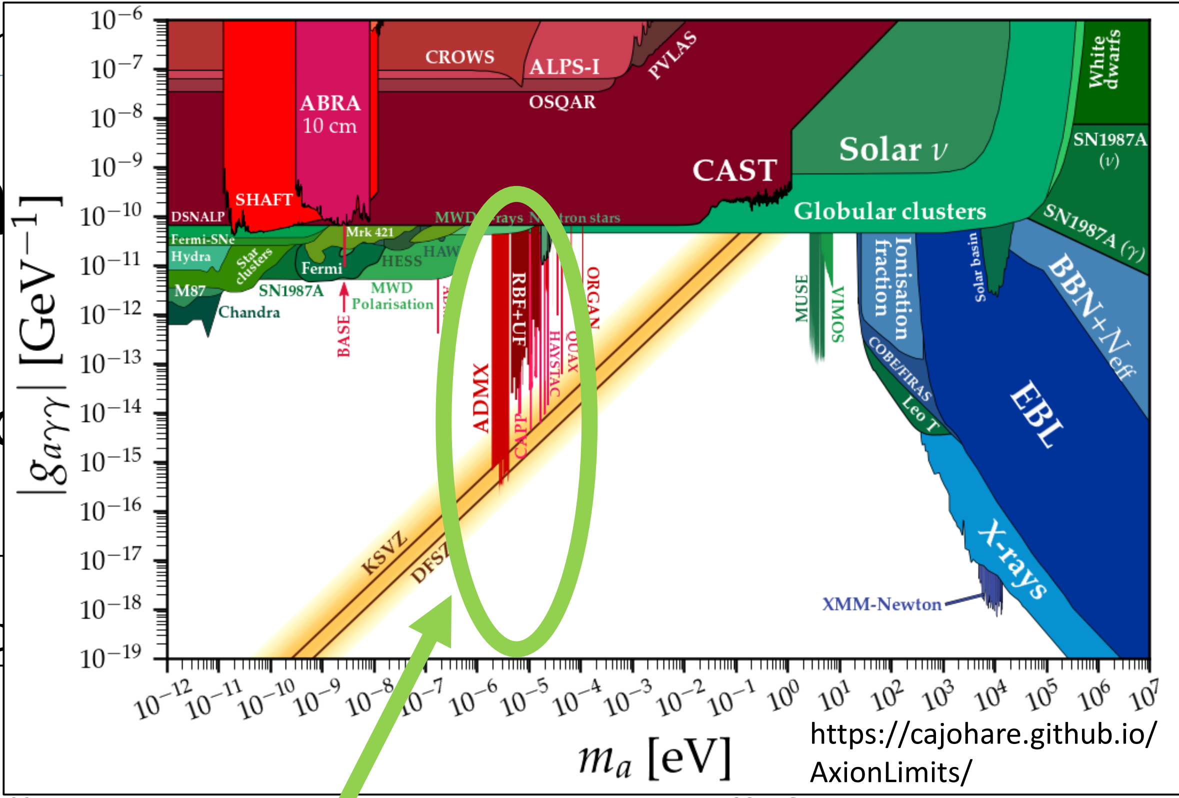
- As temperature of Universe cools, axion mass increases while Hubble rate drops
- Axion oscillation begins: $$3\, H(T_{\rm osc}) \approx m(T_{\rm osc})$$
- Energy density averages to matter → "standard mass window" for correct DM relic abundance assuming standard RD history:

$$10^{-6}\ \text{eV} \lesssim m_a \lesssim 10^{-5}\ \text{eV} \qquad \text{for} \qquad 0.5 \lesssim \theta_{\rm i} \lesssim \pi/\sqrt{3}$$

- Notice that this mechanism depends on thermal history → nonstandard cosmologies (NSCs) can alter axion production

Axion misalignment mecha

- As temperature of Universe cools, axio rate drops
- Axion oscillation begins: $3\,H(T_{osc}$



https://cajohare.github.io/AxionLimits/

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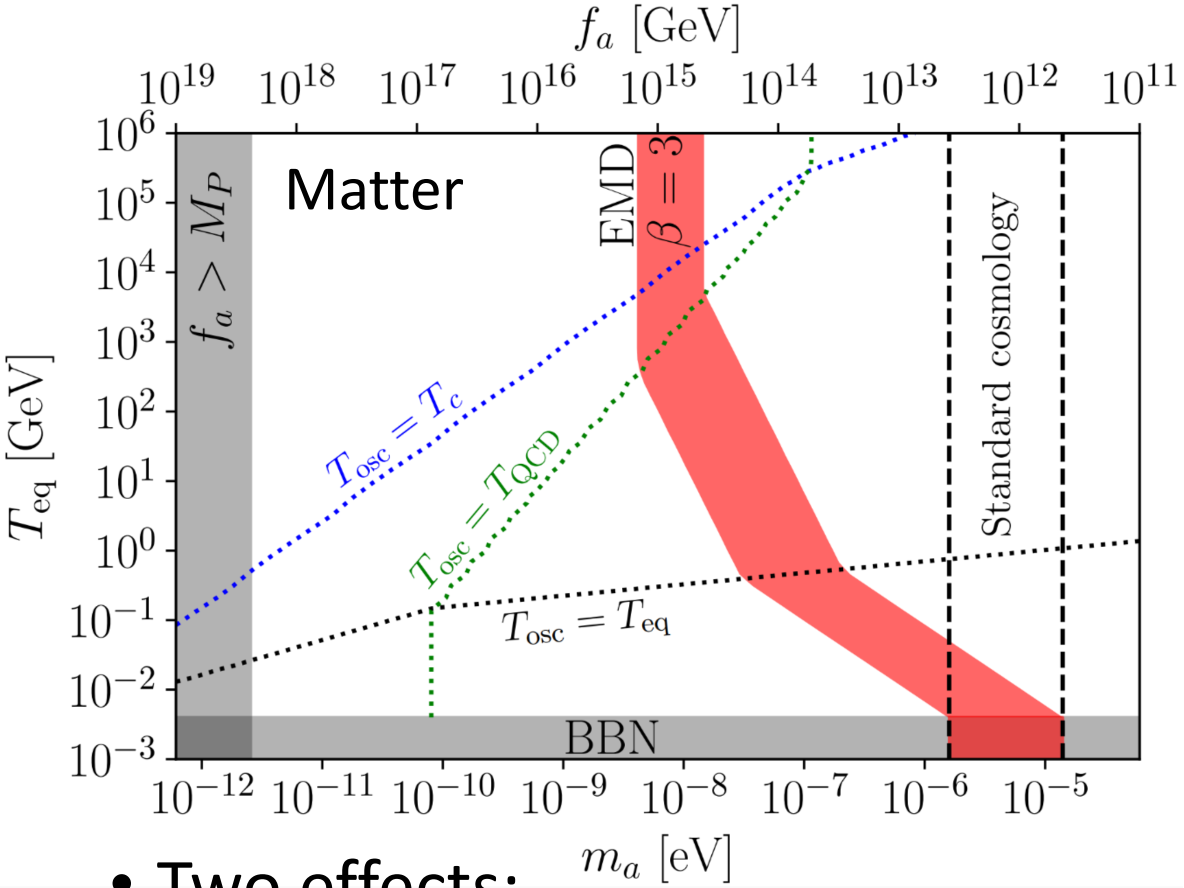
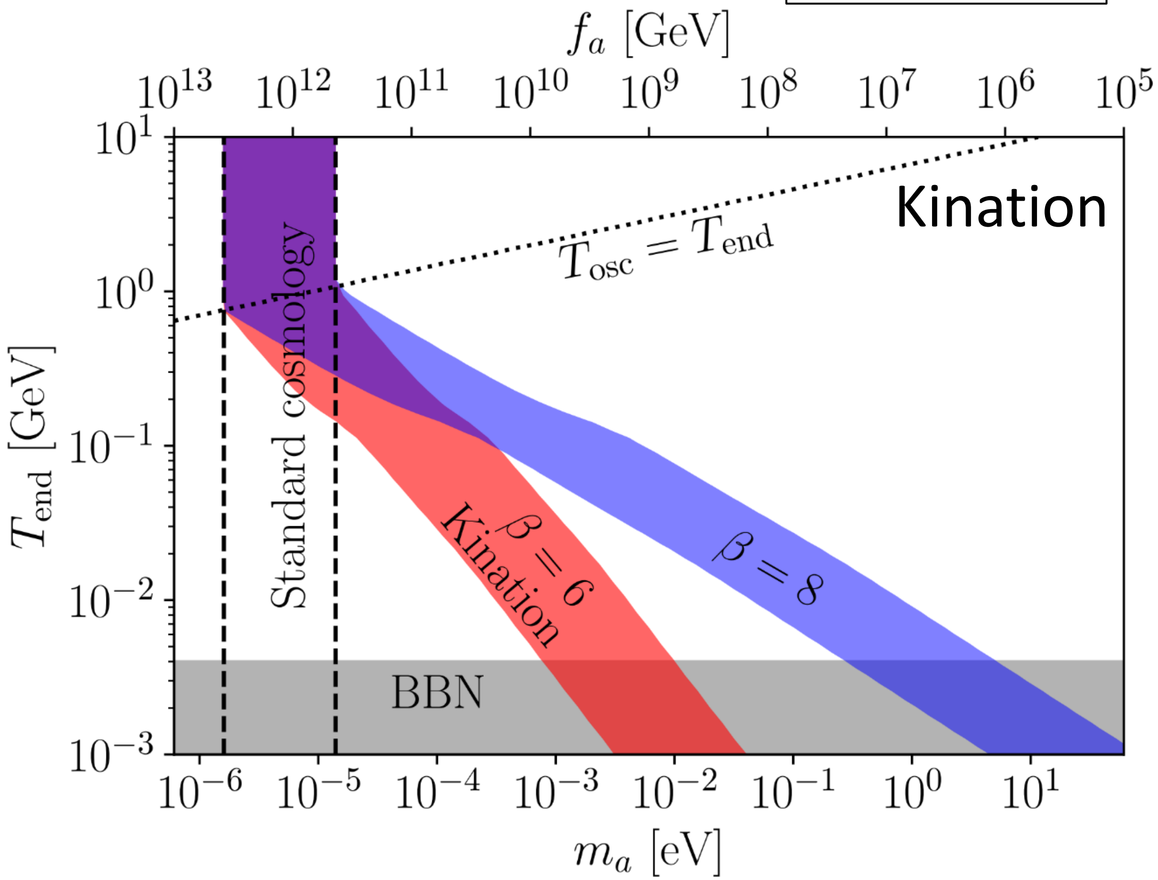
Axions in general NSC

$\beta = 3(1 + \omega)$





- Two effects:

→ Change in oscillation temperature favors larger masses

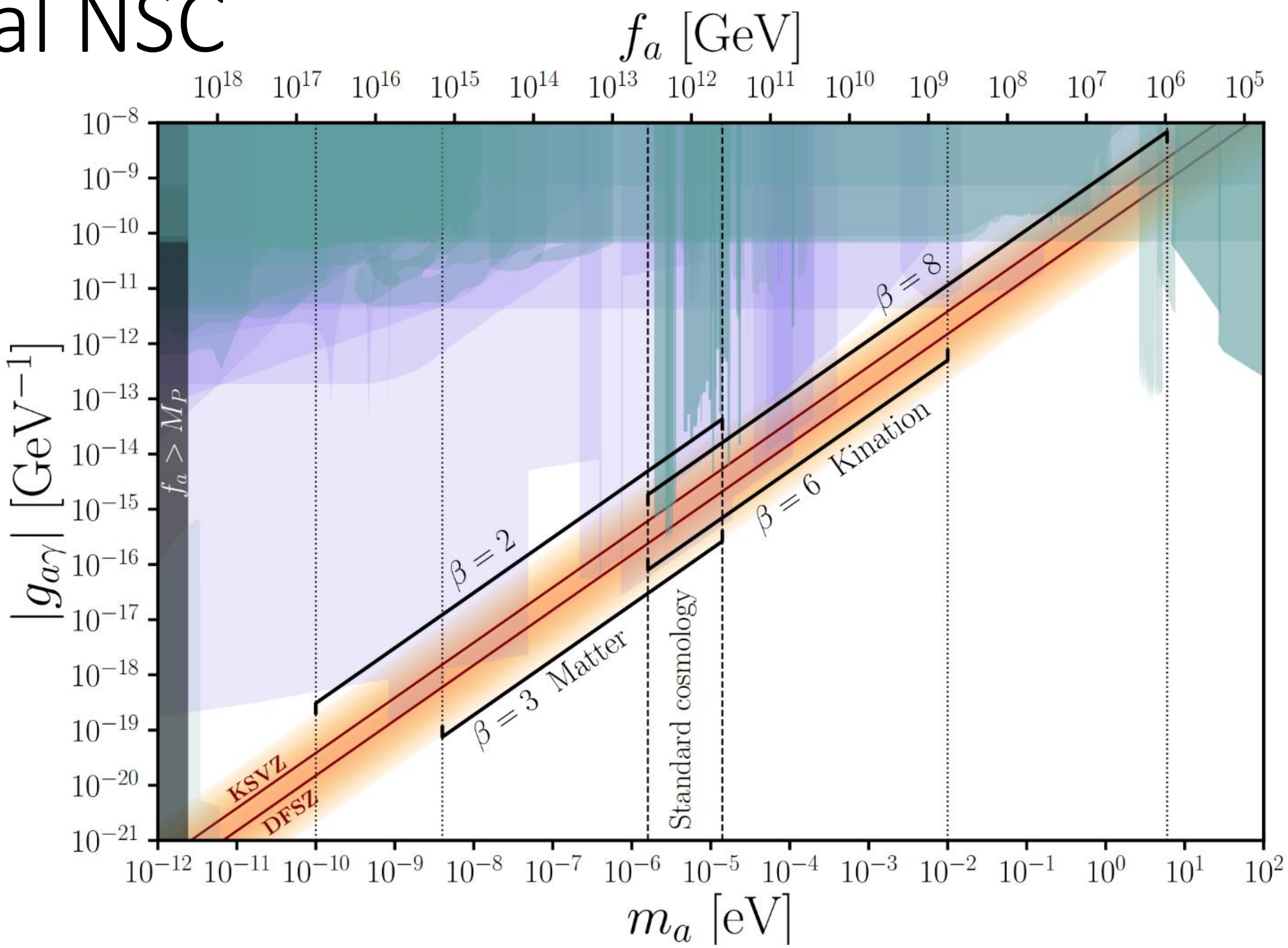
→ Dilution favors smaller masses

P. Arias, N. Bernal, D. Karamitros, C. Maldonado, L. Roszkowski, M. Venegas, 2107.13588

Axions in general NSC

- Extended mass window for axion DM
- Matter-like NSC: smaller mass
- Kination-like NSC: larger mass

(no dilution here for kination, but still large effect!)



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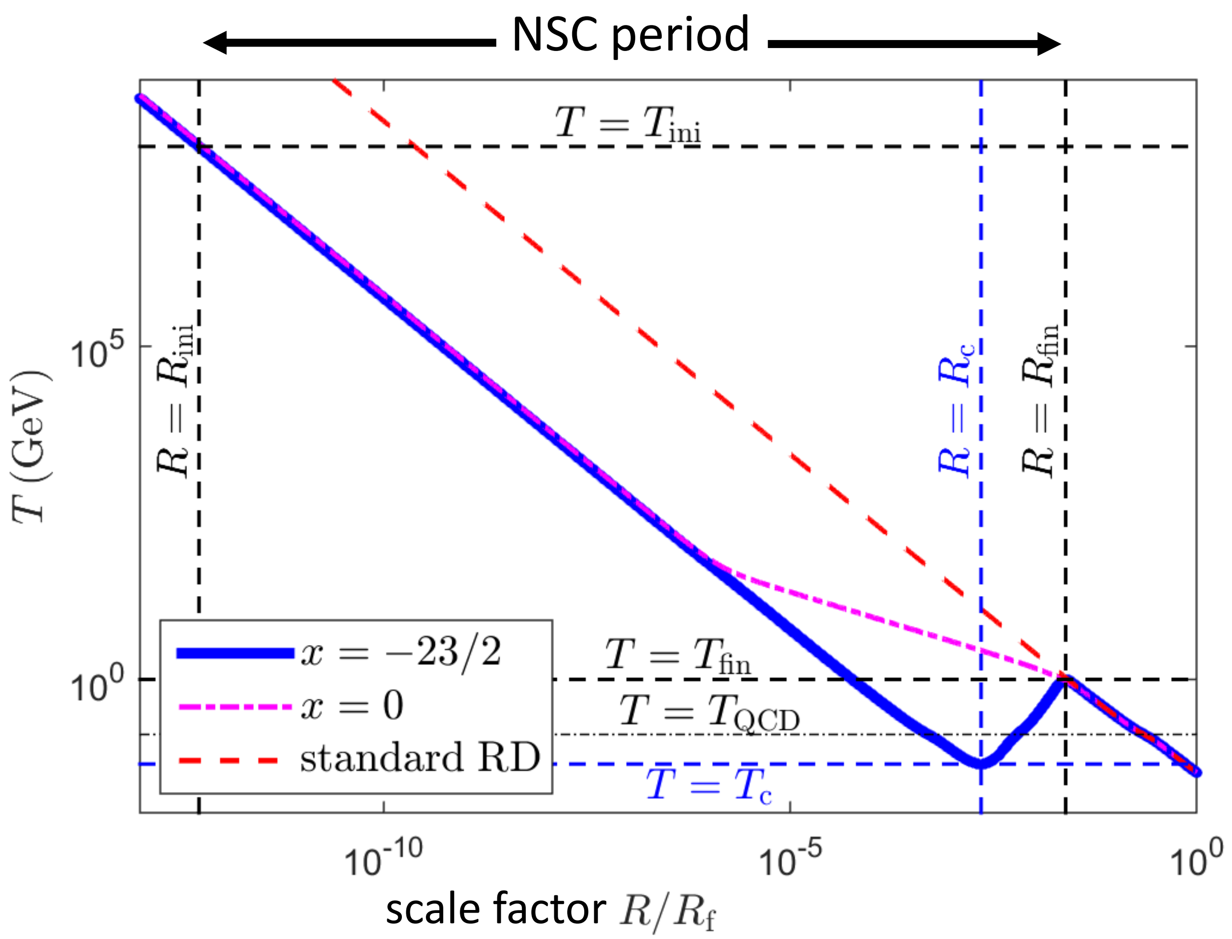
Axions with increasing-temperature EMD

- Time-dependent decay rate of dominating field (set by x, ordinary EMD for $x = 0$)
- Thermal axion mass inherits altered temperature evolution



- Same temperature can occur multiple times

→ $3\,H \approx m$ can occur up to three times (provided that $x < -3$)

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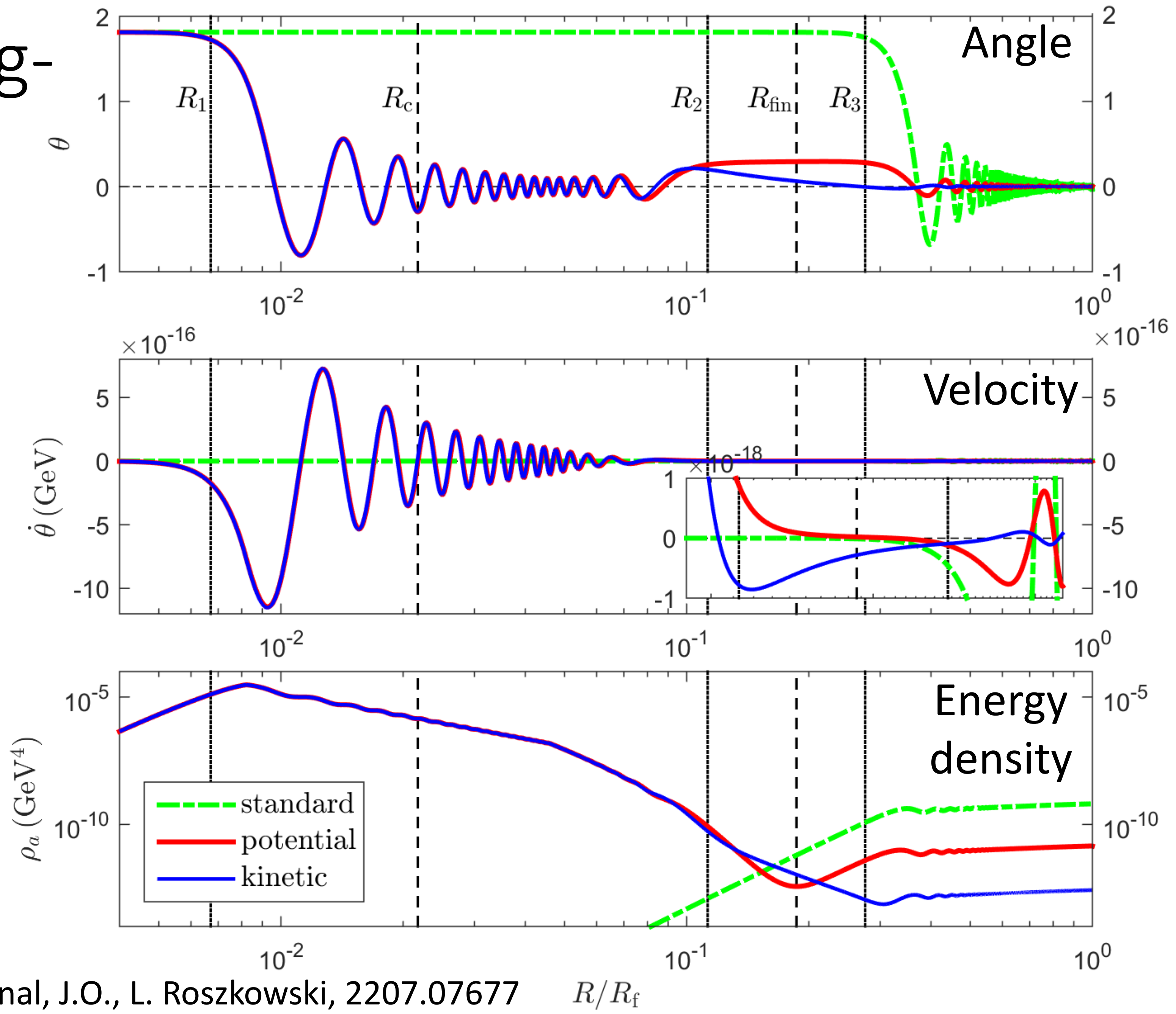
Axions with increasing-temperature EMD

- Axion misalignment altered by restoration of Hubble friction
- Second period of oscillation with new configuration
- Resultant axion energy density is smaller due to entropy injection and smaller amplitude

→ Smaller mass for axion DM



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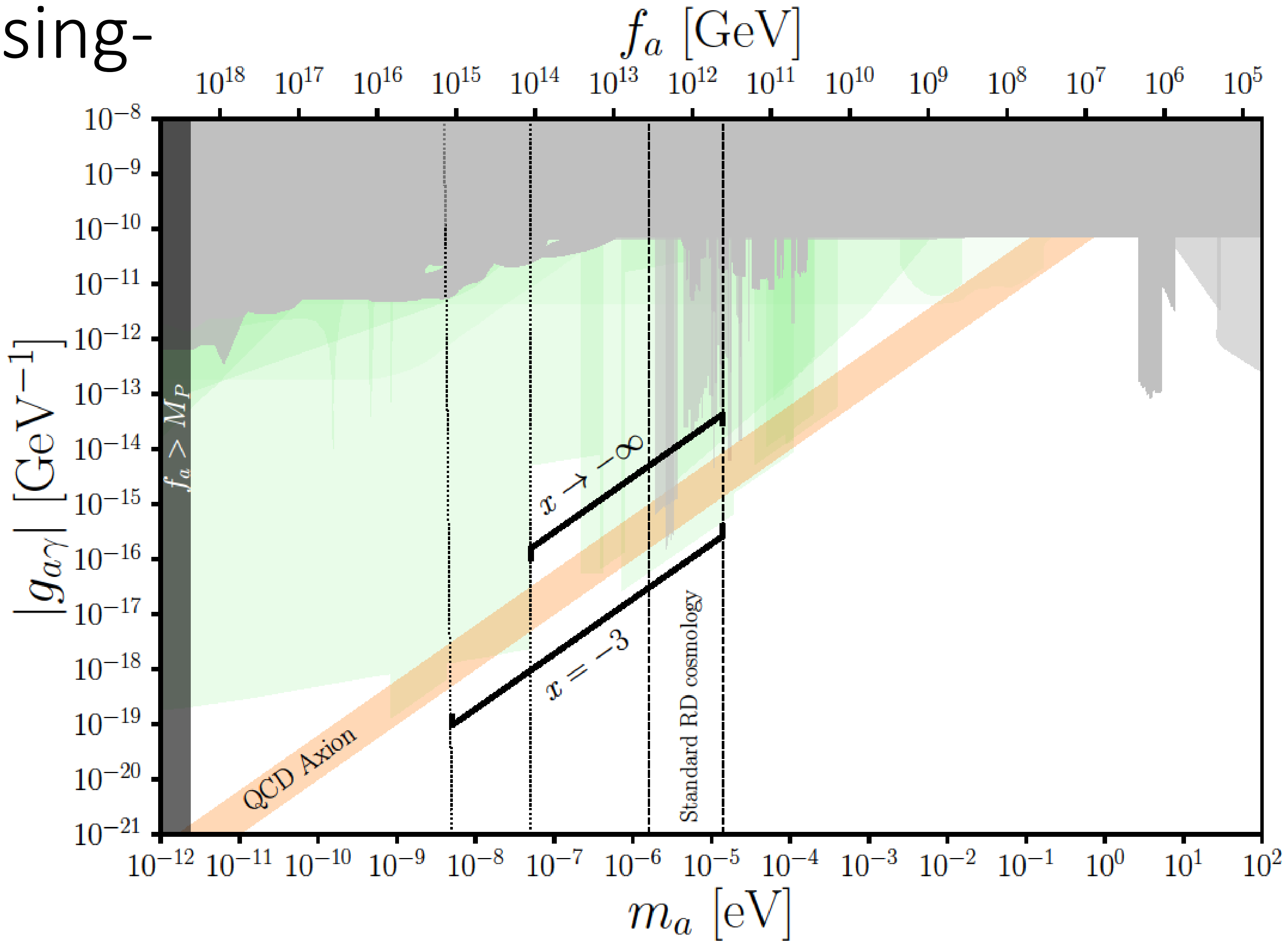
Axions with increasing-temperature EMD

- Extended window toward smaller mass as before
- NSC histories add to motivation to look out of standard window
- Can probe NSC scenarios in coming years



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Summary

- Standard RD history not necessarily the whole story
- NSC has significant effects on DM production:

  → Shifts relevant times/temperatures, and entropy dilution

  → Can also fundamentally affect mechanisms themselves (incr.-temperature misalignment)
- Axions in particular get extended mass window depending on history

  → Probe cosmological history with DM searches

Thank you!