Dark Matter Axions in the Early Universe with a Period of Increasing Temperature

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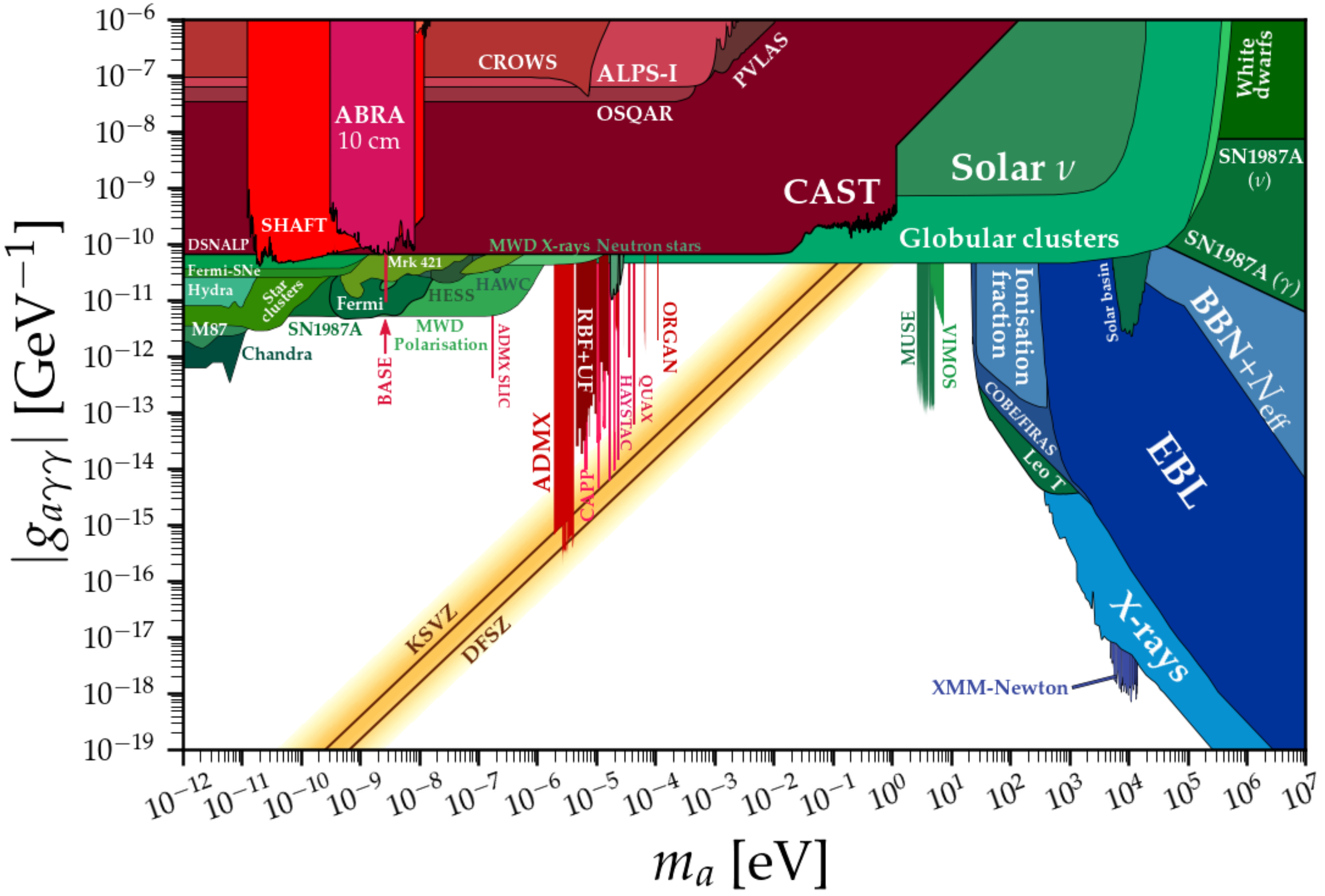
Introduction

- QCD axions are a promising dark matter (DM) candidate
- Many ongoing observational/experimental searches targeting a variety of couplings
- Part of their success as DM candidates is the misalignment mechanism



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

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:

"crossing" condition:
$$3\,H(T_{\rm osc}) \approx m(T_{\rm osc})$$

- Energy density averages to matter → "standard mass window" for correct DM relic abundance assuming standard RD history:

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

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

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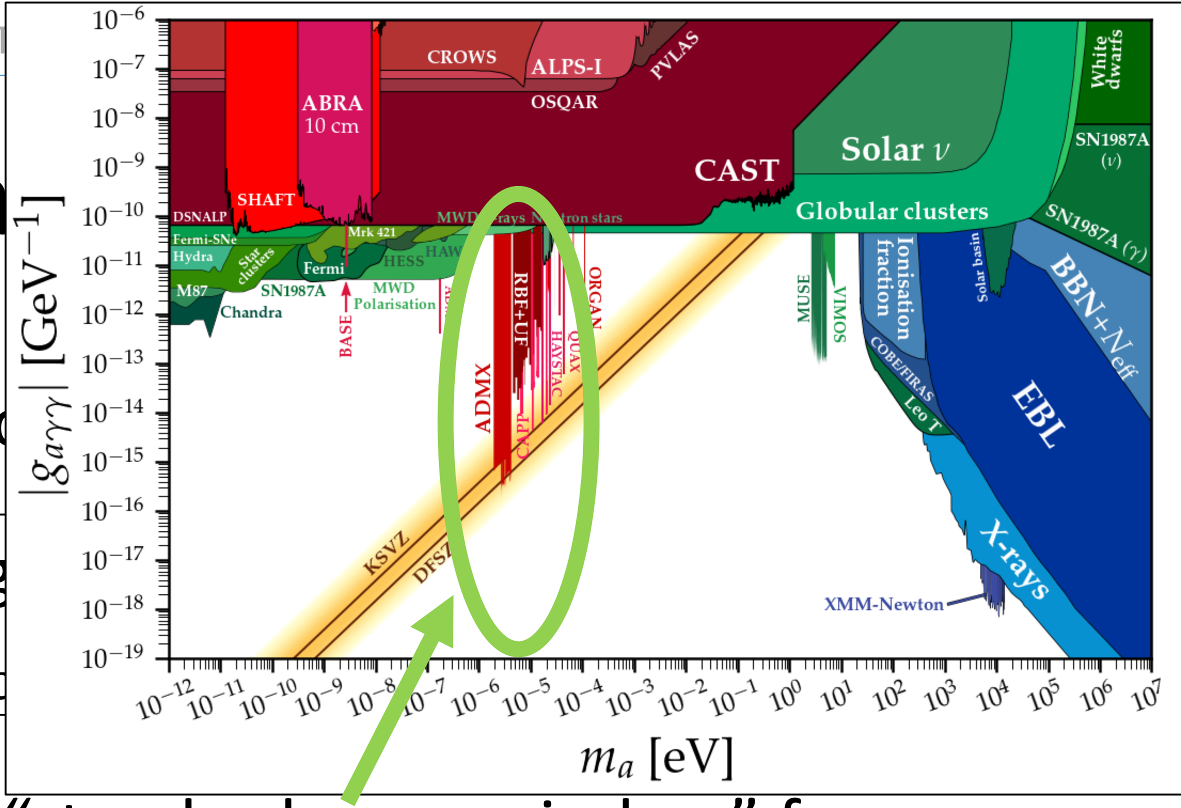
$3\,H(T_{\mathrm{osc}}$



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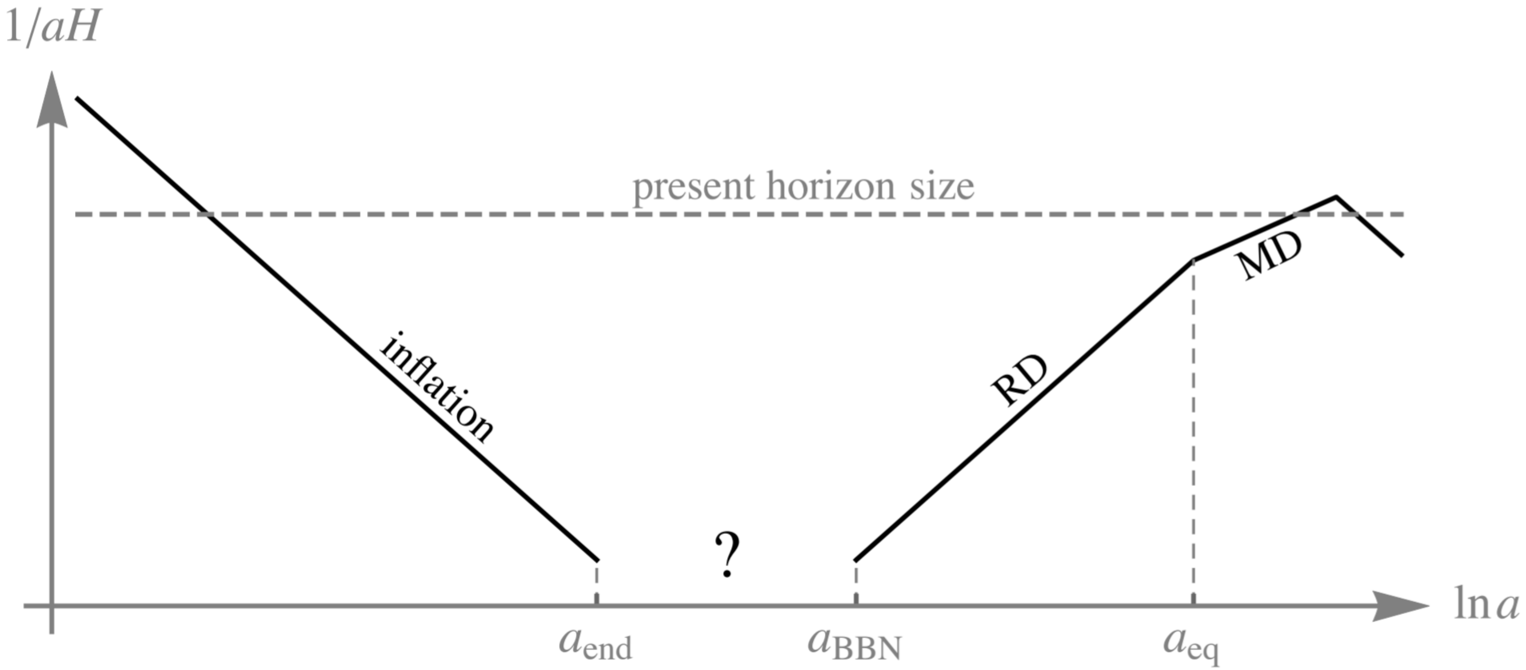
Nonstandard cosmologies (NSCs)

- Usual assumption is radiation domination (RD) between end of inflation and start of BBN
- Many well-motivated deviations: inflationary reheating, early matter domination (MD) from moduli, kination, etc. (for a review, see Allahverdi et al. 2006.16182)
- Must end before $T_{\text{BBN}} \sim \text{MeV}$
- Can significantly affect early processes



Allahverdi et al. 2006.16182

NSCs – increasing temperature

- Typically temperature decreases during NSC (though can be at a different rate)
- Particularly interesting class of alternate histories involves a period of increasing temperature
- Can be achieved in a variety of models where the decay rate of dominating component has explicit scale-factor (R) or temperature (T) dependence: $\Gamma(R, T)$
- Examples: higher-order operators, shapes of potentials, field-dependent mass, interaction with thermal background

Co et al. 2007.04328; Ahmed et al. 2111.06065;
Garcia et al. 2012.10756; Mukaida+Nakayama 1208.3399

Our scenario

- NSC history with intervening matter domination (MD) by scalar field ϕ: Inflation – RD – MD – RD (BBN)
- Period of increasing temperature from time-dependent decay rate Γ_ϕ
- Axion production from misalignment in this background

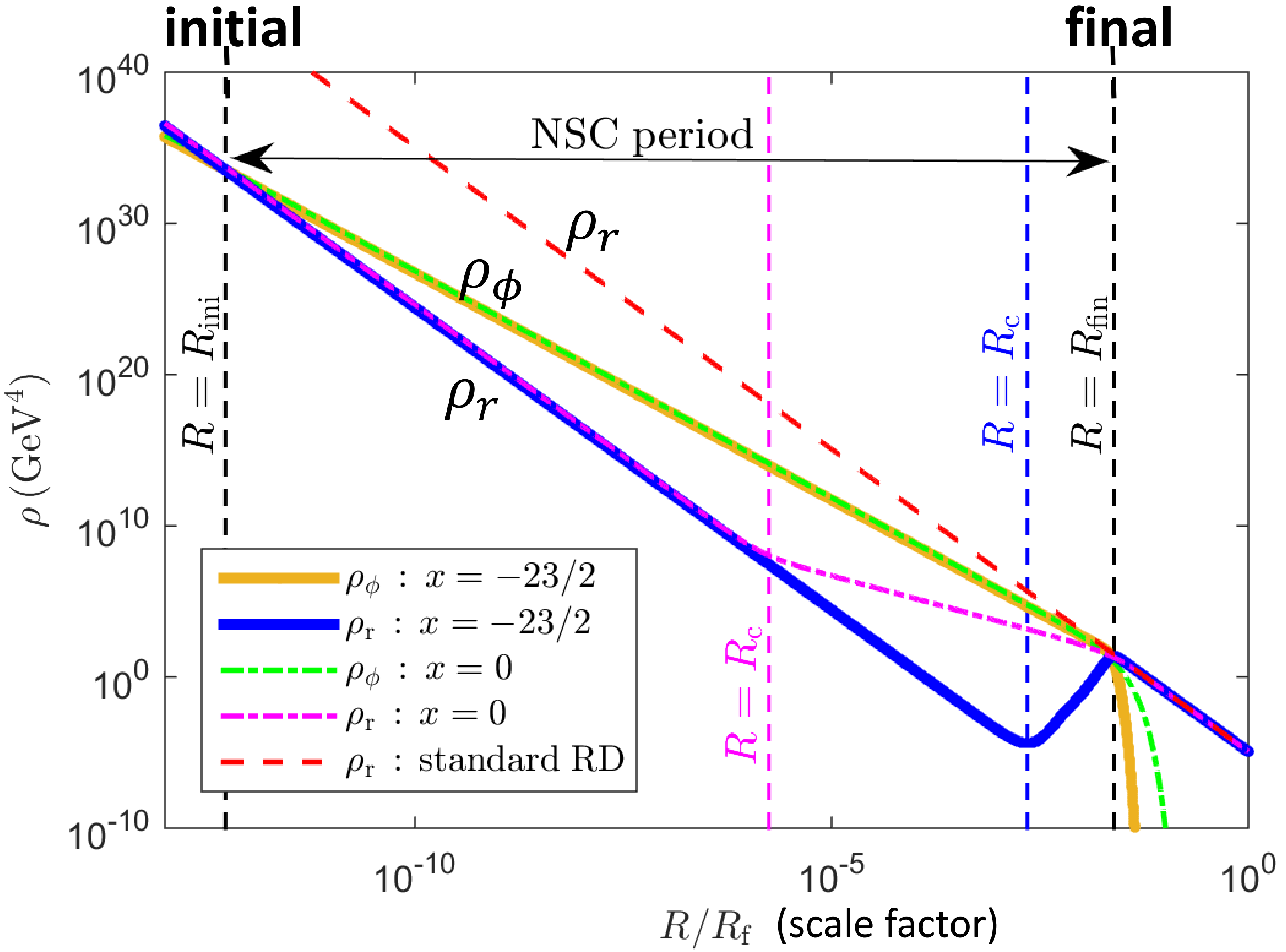
- Define parameter x during increasing-temperature period:

$$\Gamma_\phi \propto R^{-x} \qquad T \propto R^{\frac{-3-2x}{8}}$$

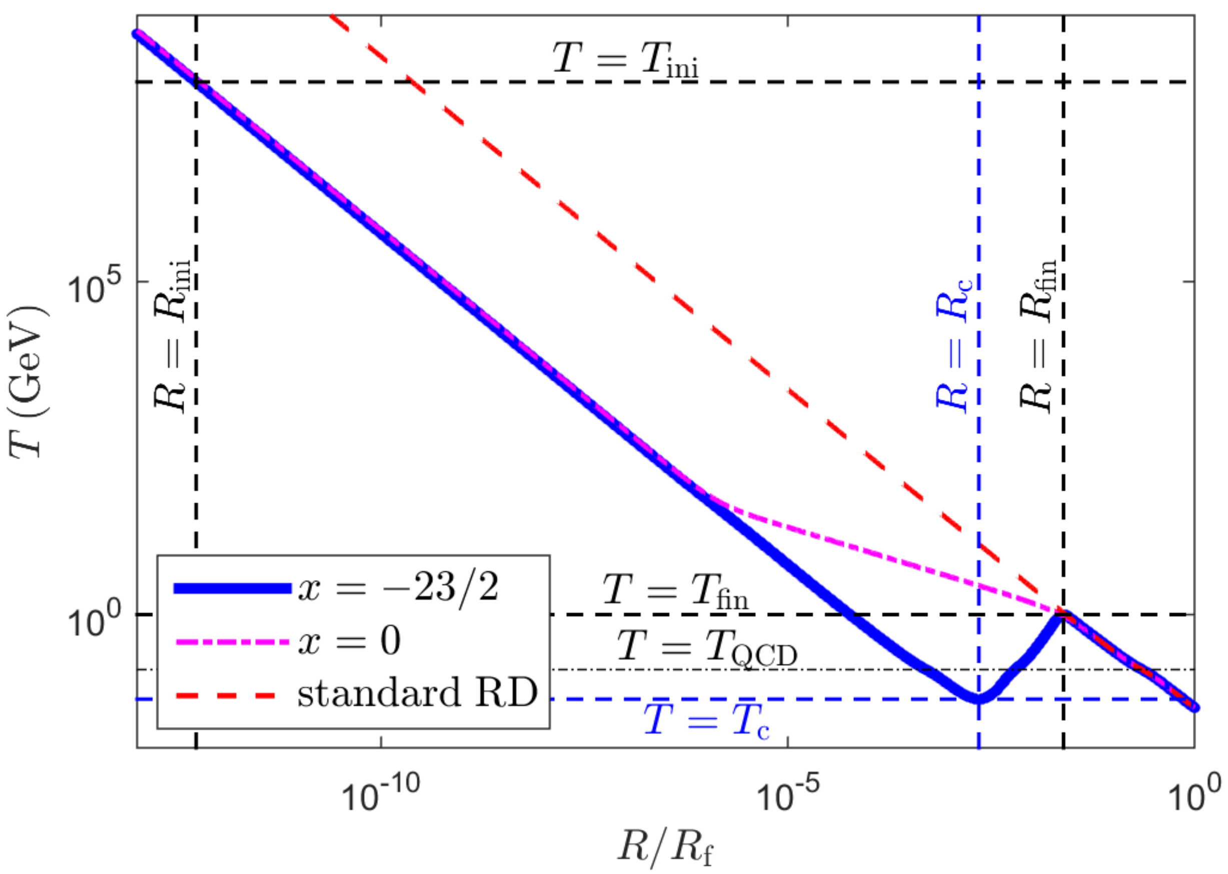
- Temperature increases for $x < -3/2$

Background energy density evolution

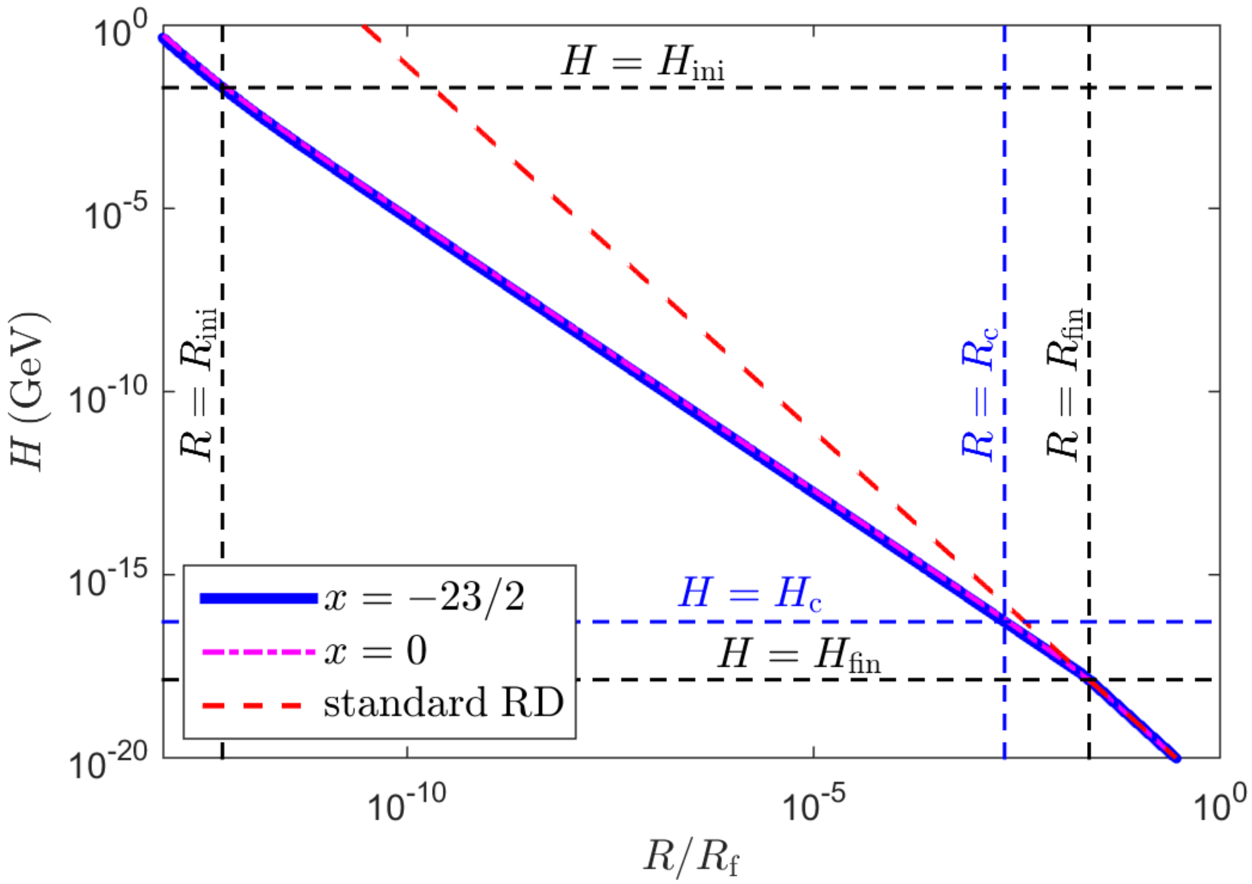
- Three example histories:
  - Standard RD (- - -)
  - NSC $x = 0$
  - NSC $x = -23/2$
- Adiabatic-nonadiabatic transition in NSC at $R = R_c$ as decay of ϕ affects radiation evolution



Temperature vs scale factor



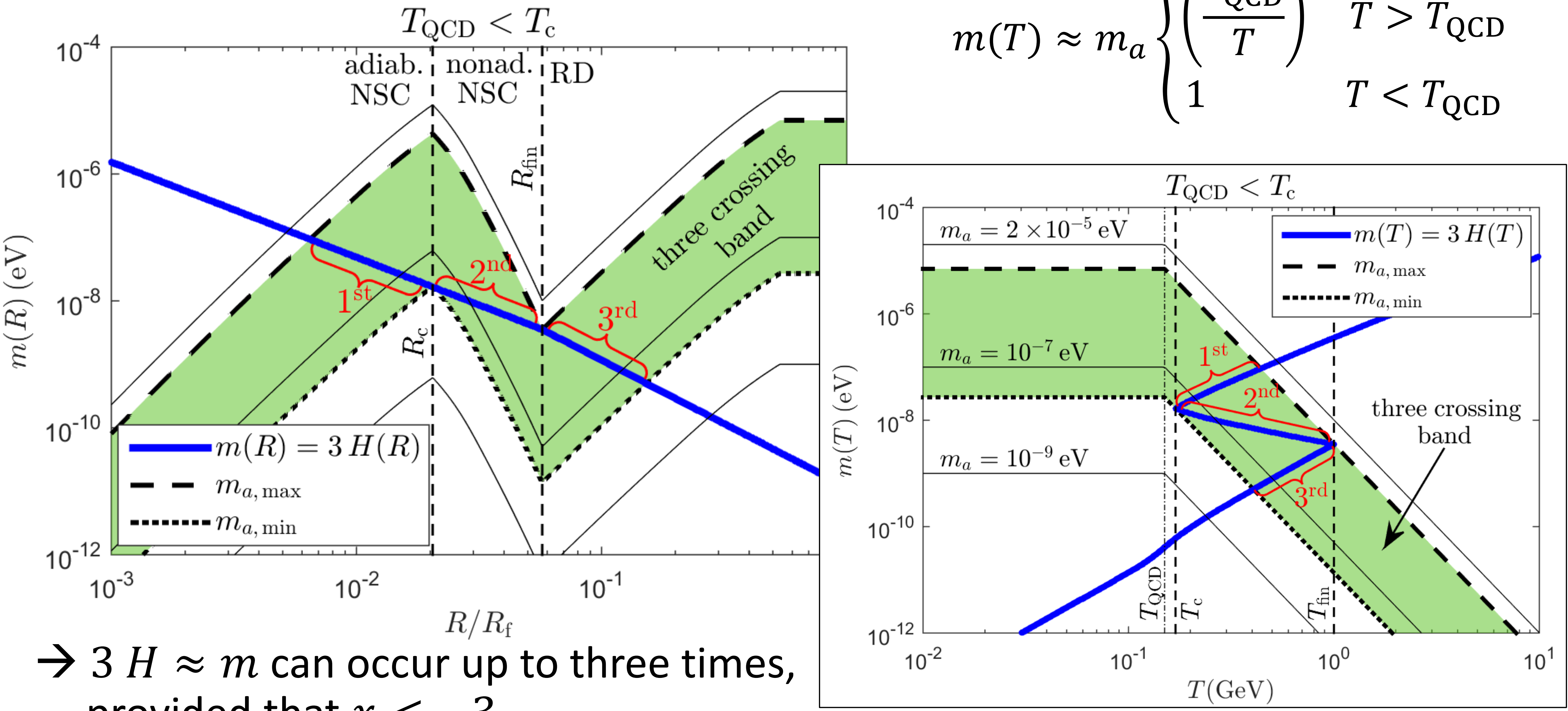
Hubble rate vs scale factor



- Lowest temperature reached during NSC is now T_{c} rather than reheat temperature T_{fin} → require $T_{\mathrm{c}} > T_{\mathrm{BBN}} \sim \mathrm{MeV}$
- Same temperature can occur multiple times

Axion mass and Hubble rate

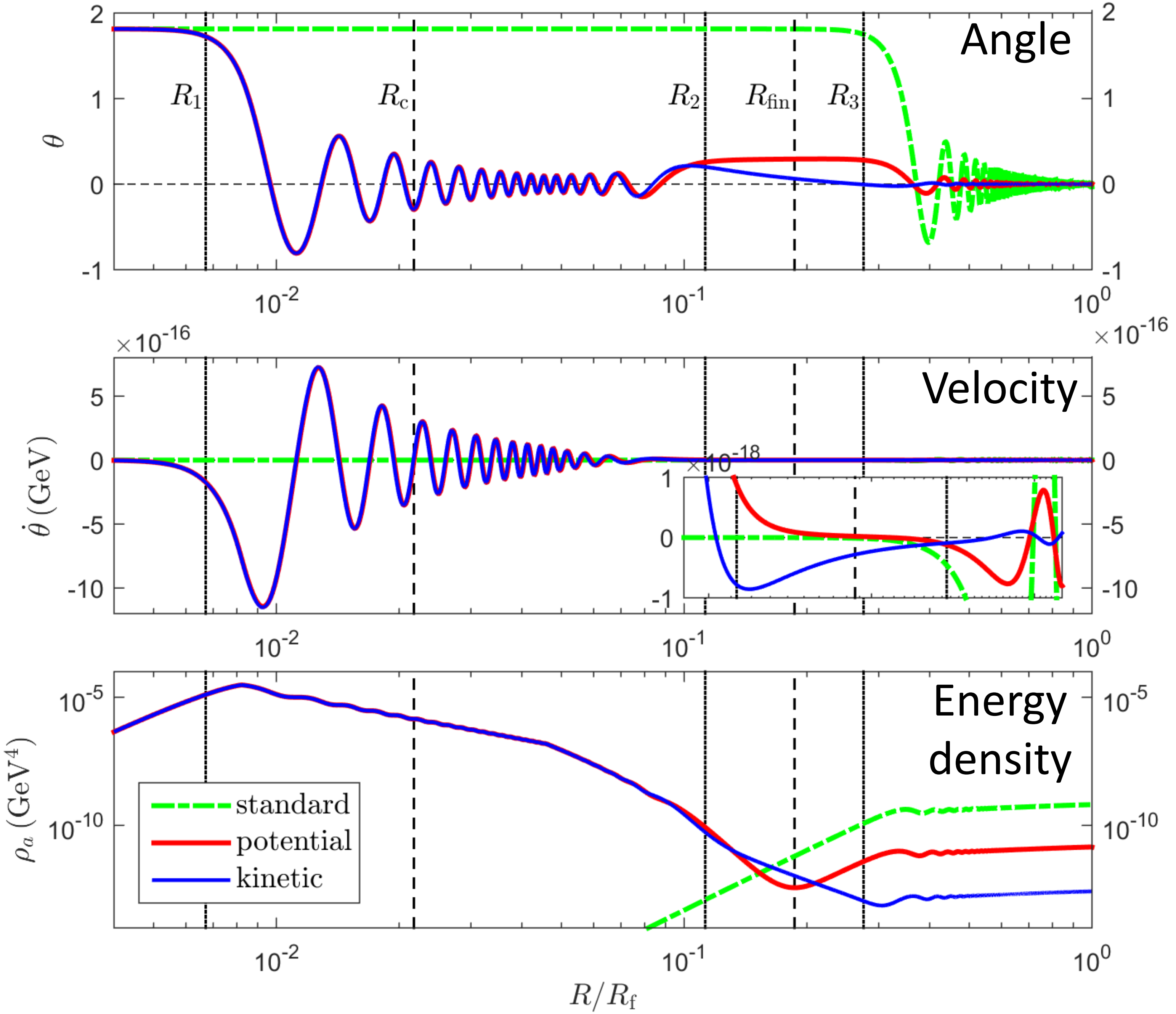
$$m(T) \approx m_a \begin{cases} \left(\frac{T_{\rm QCD}}{T}\right)^4 & T > T_{\rm QCD} \\ 1 & T < T_{\rm QCD} \end{cases}$$



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

Misalignment with three crossings

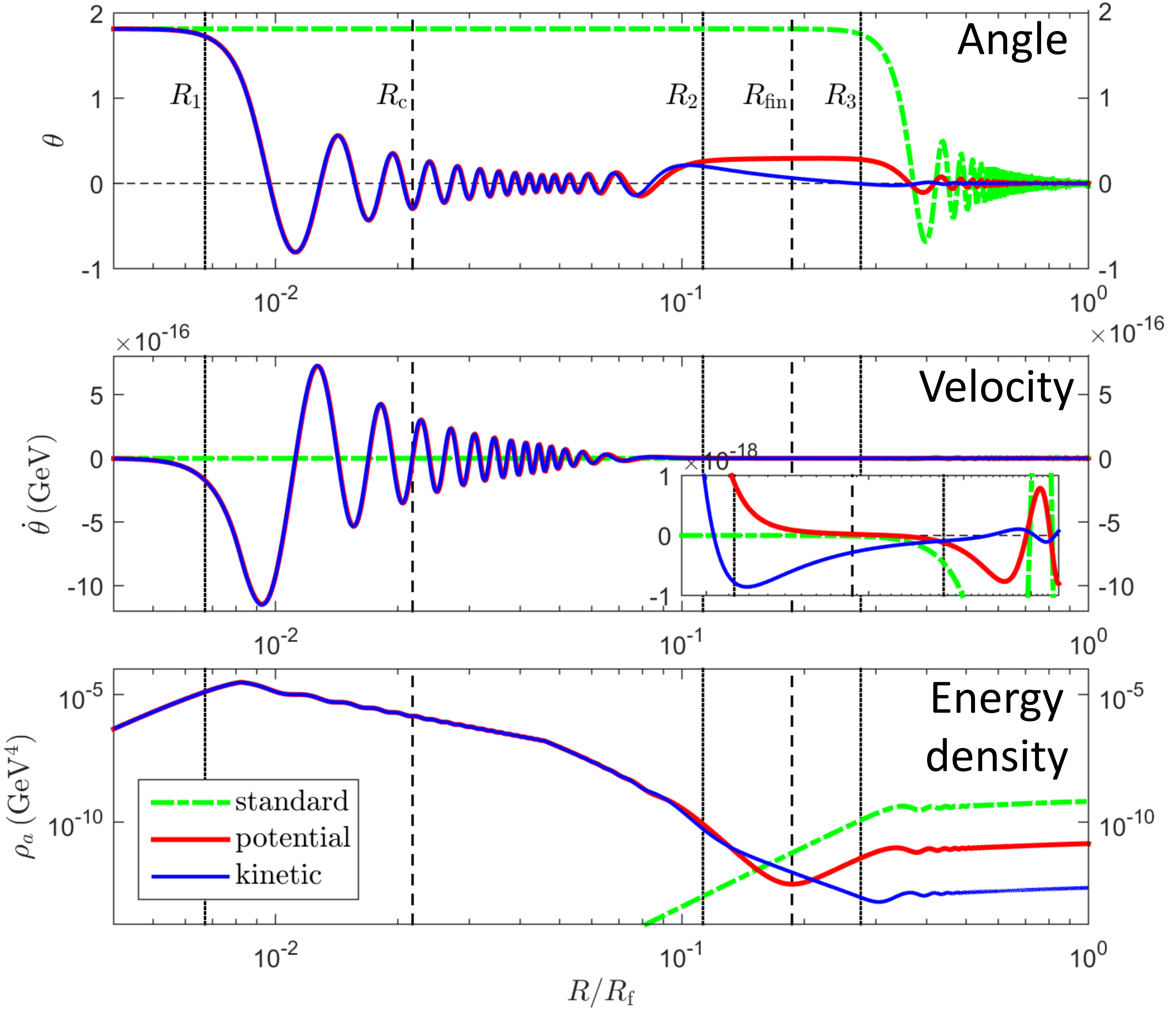
- First crossing (R_1): oscillations begin as normal
- Second crossing (R_2): Hubble friction restored, axion evolution dependent on kinetic/potential energy
- Third crossing (R_3): oscillations resume from a new configuration (smaller angle, velocity tending toward zero)



Misalignment with three crossings

- Misalignment is altered by restoration of Hubble friction
- Second period of oscillation with new "initial" condition
- Resultant axion energy density is smaller due to entropy injection and smaller amplitude

→ Smaller mass for axion DM



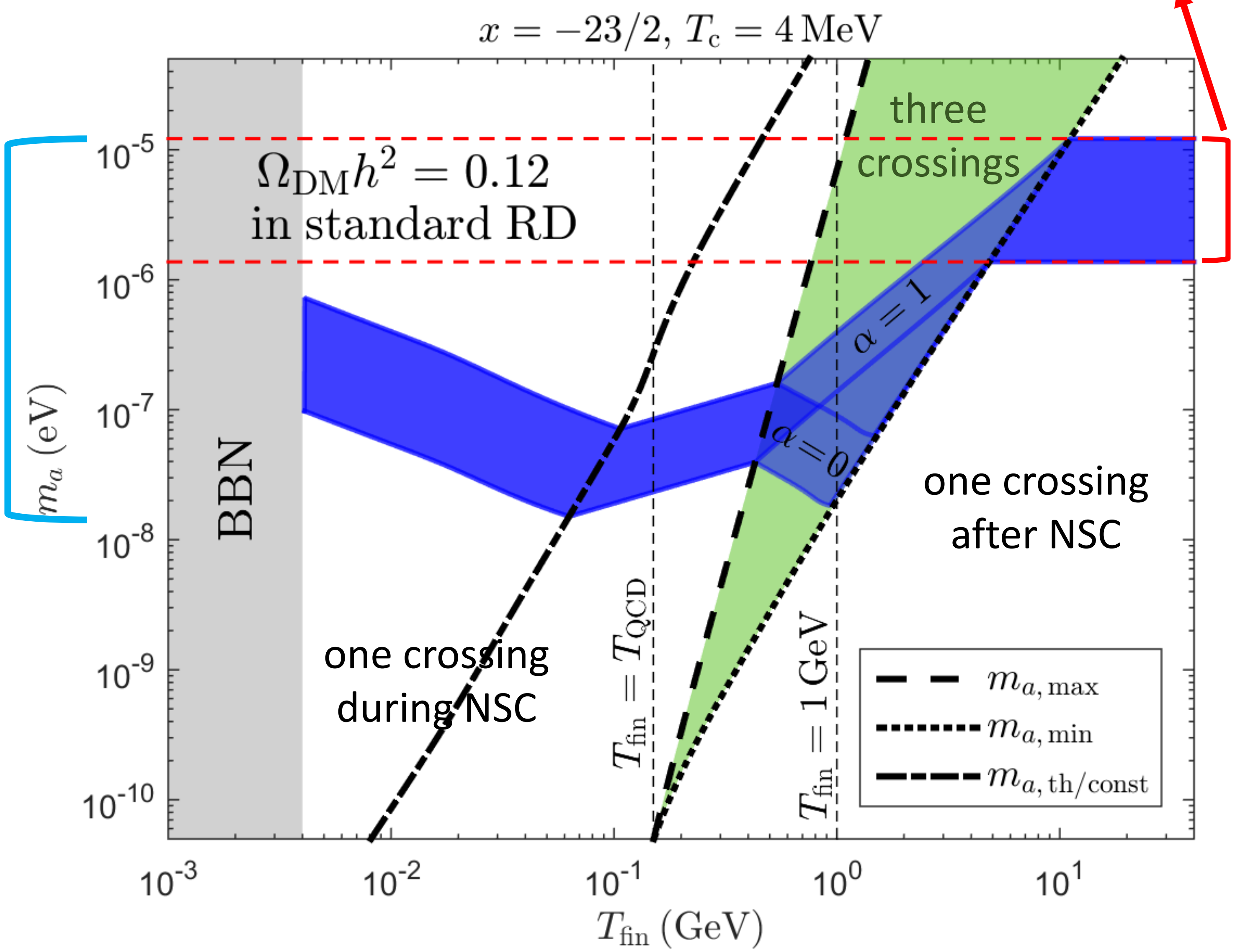
Extended DM axion mass window

$$\frac{1}{2} < \theta_\mathrm{i} < \frac{\pi}{\sqrt{3}}$$

- Mass window for observed DM abundance extended toward smaller values
- Lowest extent determined by θ_i and x

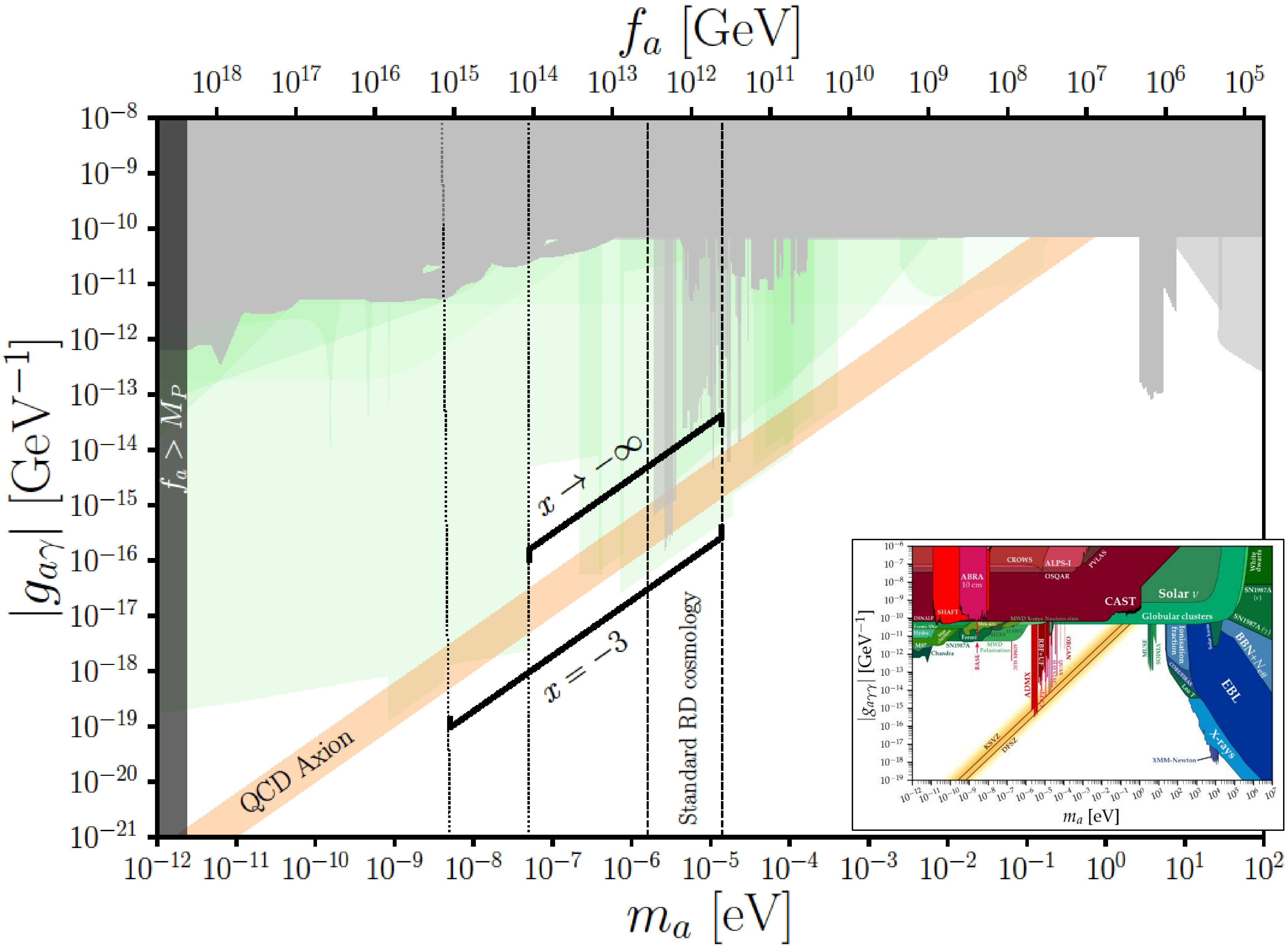
$\alpha \approx 0$: kinetic

$\alpha \approx 1$: potential



Axion photon coupling

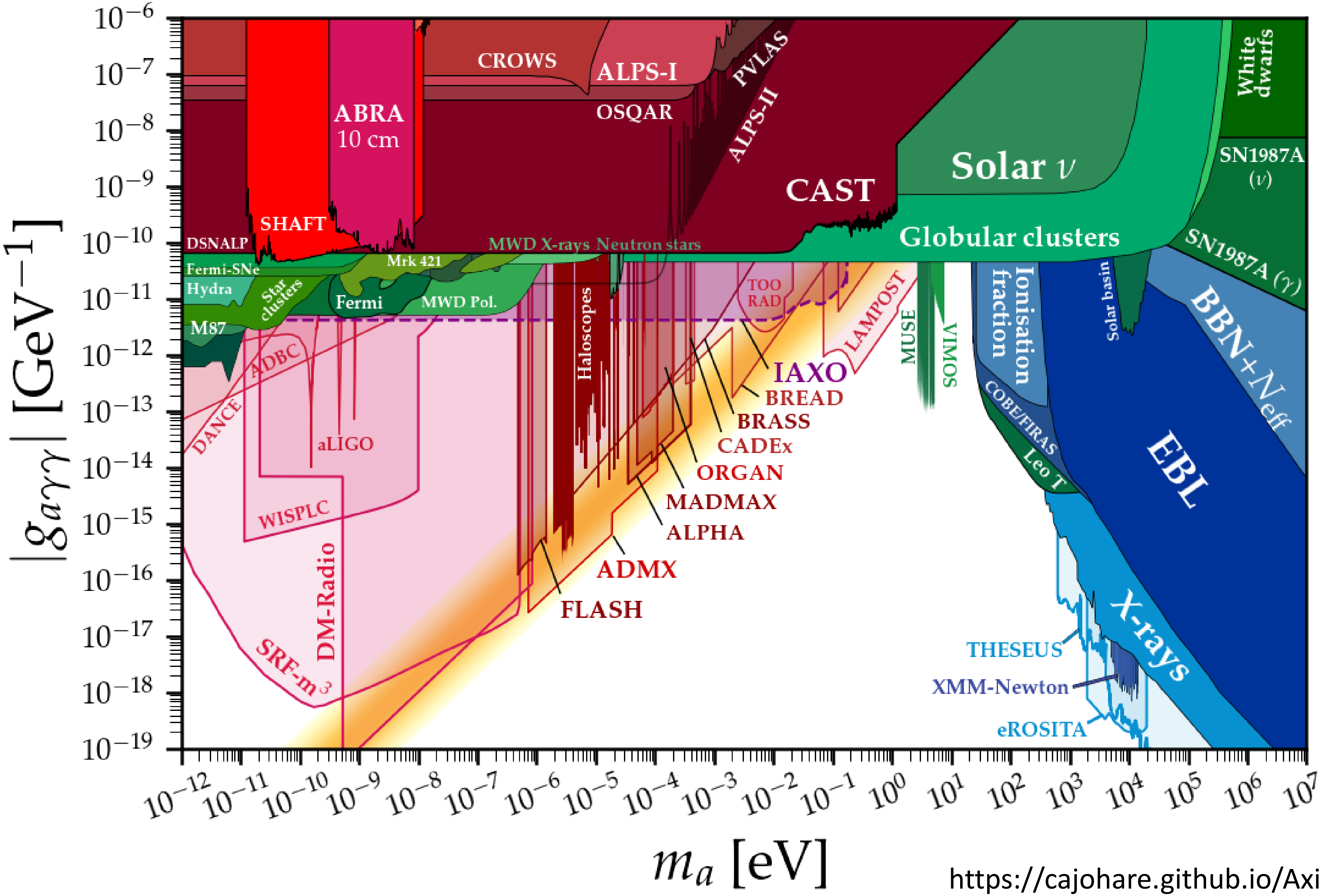
- Extended window overlaps with future projections outside of standard range
- Can probe NSC scenarios in coming years
- Adds to motivation to look out of standard window



Summary

- Axion misalignment mechanism depends on the cosmological history through m and H
- NSC period with increasing temperature can significantly alter axion production → $H(t) \approx m(t)$ up to three times
- Hubble friction can be temporarily restored → second period of oscillation with new initial condition
- Viable axion mass window for observed DM abundance extended to include smaller masses

Thank you!



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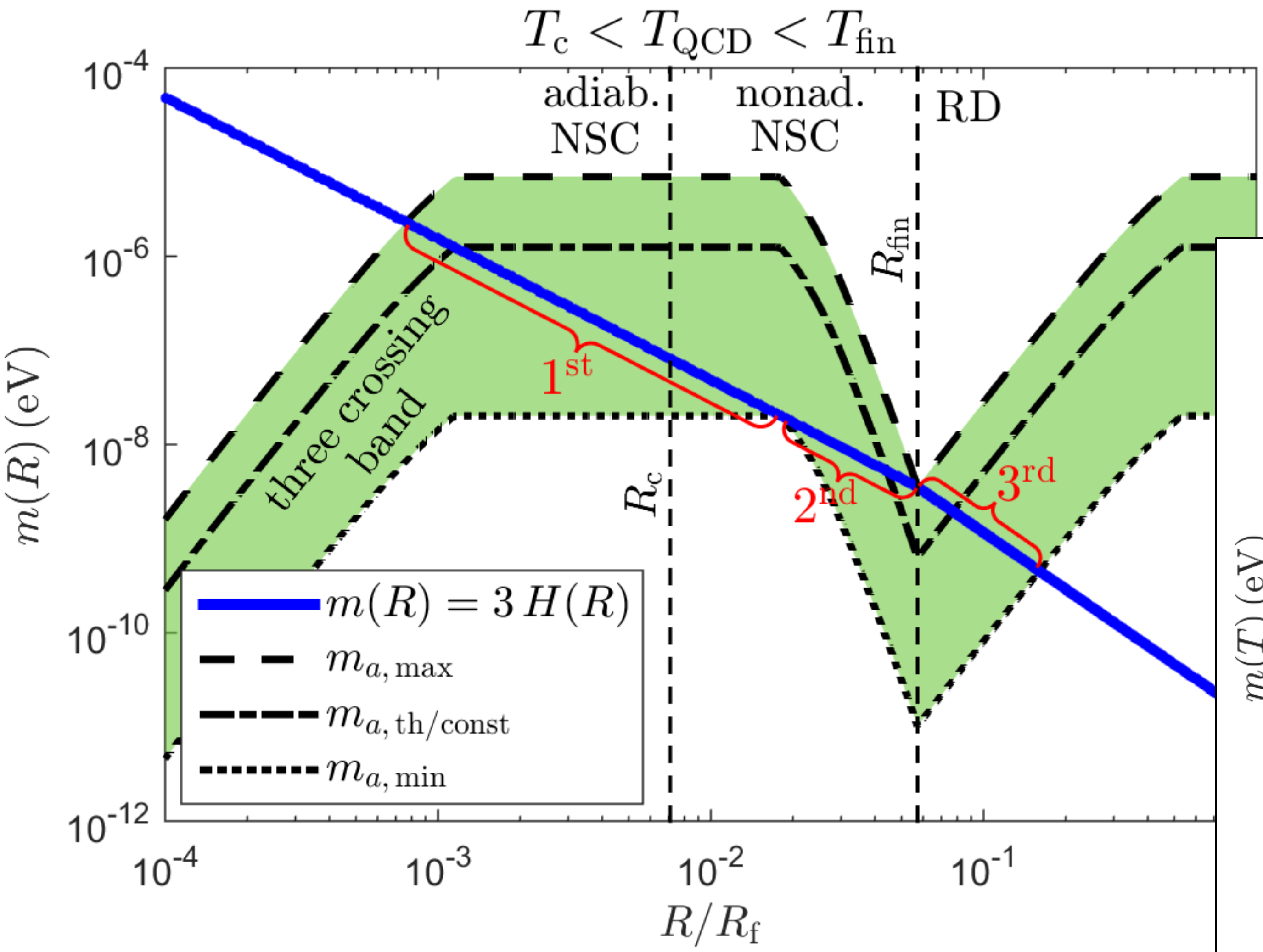

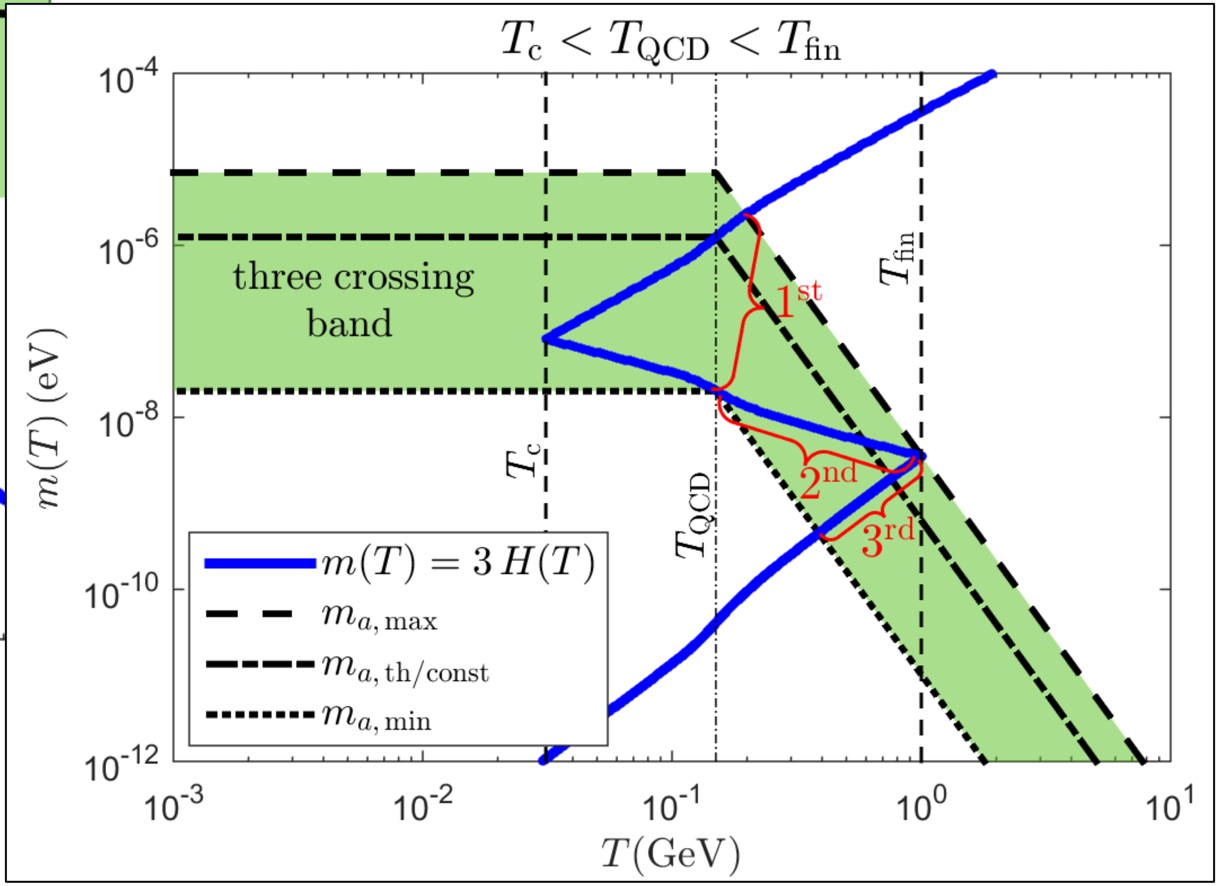

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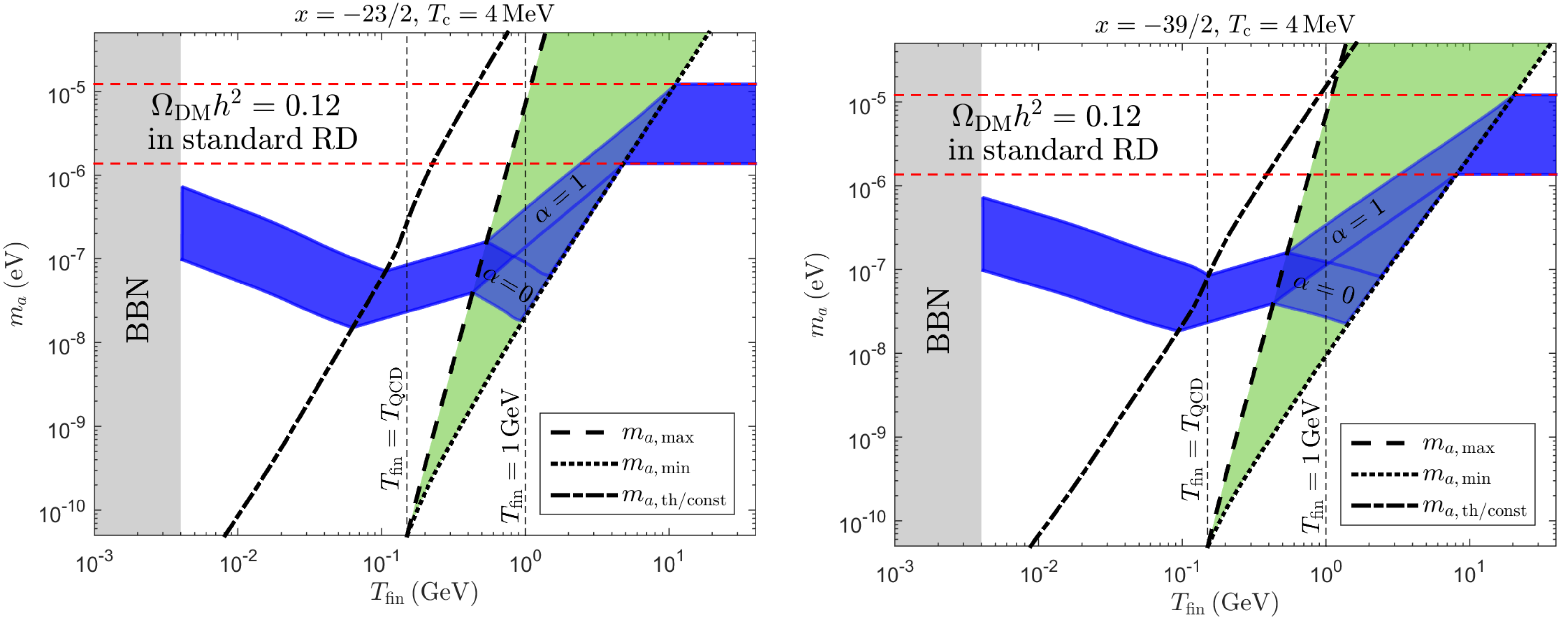
$x = -23/2,\ T_c = 4\,\mathrm{MeV}$
$\Omega_{\rm DM}h^2 = 0.12$
in standard RD
BBN
$T_{\rm fin} = T_{\rm QCD}$
$T_{\rm fin} = 1\,\mathrm{GeV}$
$\alpha = 1$
$\alpha = 0$
$m_{a,\,\rm max}$
$m_{a,\,\rm min}$
$m_{a,\,\rm th/const}$
m_a (eV)
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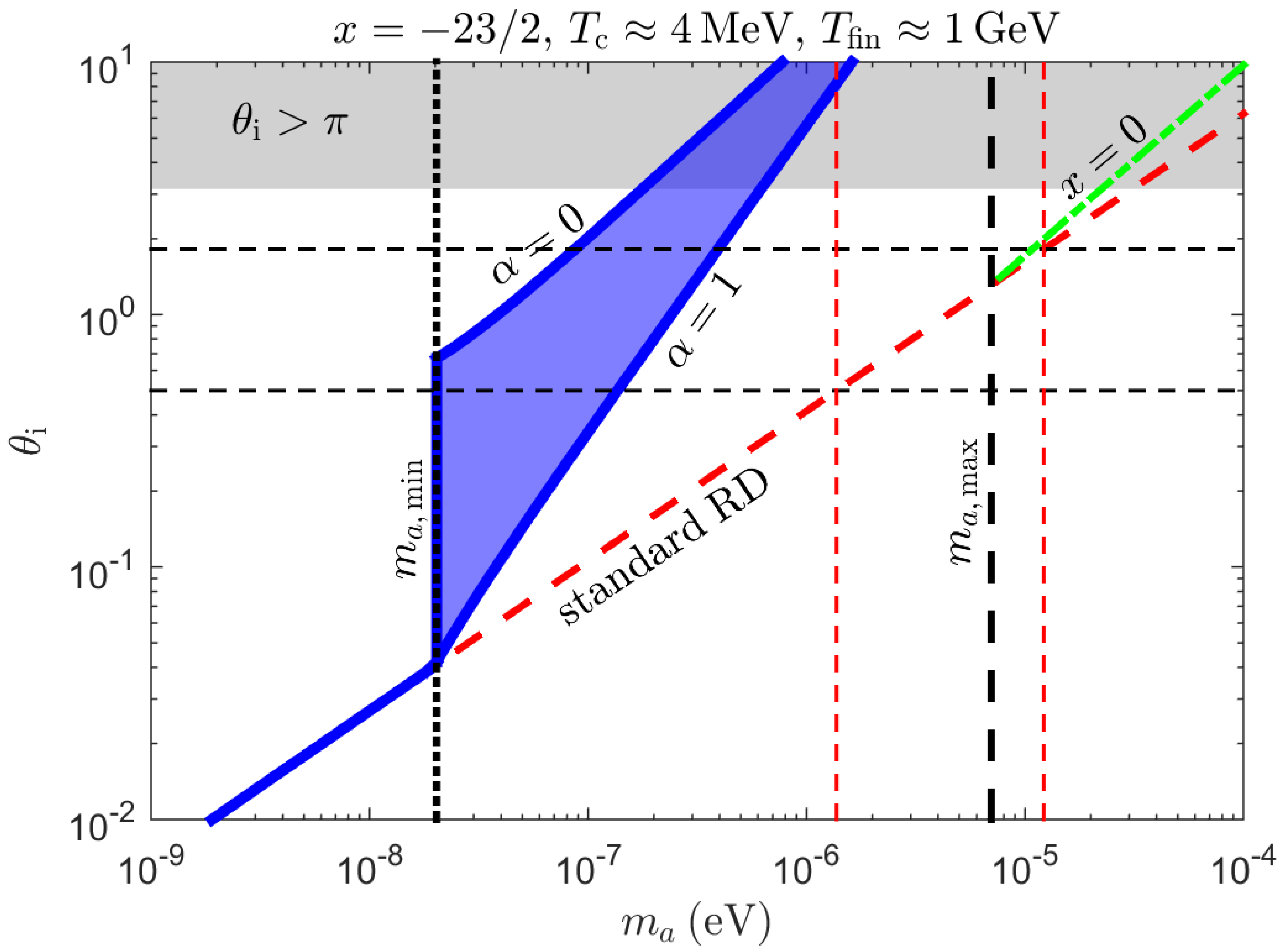
$x = -23/2,\ T_c \approx 4\,\mathrm{MeV},\ T_{\mathrm{fin}} \approx 1\,\mathrm{GeV}$
$\theta_i > \pi$
$\alpha = 0$
$\alpha = 1$
$x = 0$
standard RD
$m_{a,\,\mathrm{min}}$
$m_{a,\,\mathrm{max}}$
θ_i
m_a (eV)
10^1
10^0
10^{-1}
10^{-2}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}