Axions in alternative cosmological histories

Leszek Roszkowski

AstroCeNT, Nicolaus Copernicus Astronomical Center PAS

and

National Centre for Nuclear Research

- *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 → JCAP**
- *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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Outline

- Brief introduction:
  - Standard cosmology (SC) of the Big Bang
  - Nonstandard cosmology (NSC) alternatives
- Axion dark matter (DM) in SC and NSC with early matter domination (EMD) period
  - EMD with a period of increasing temperature
- Fermionic WIMP DM produced via freeze-in
  - Implications for DM searches
- Summary

➢ Standard Cosmology (SC) of the early Universe:

- **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**

- **Simplest assumption, but no observational evidence**
- **There are many possible alternatives to SC, called nonstandard cosmology (NSC)**

Examples:

- **early matter domination (EMD),**
- **kination**
- **…**
- **PBH evaporation**

How do results for DM change in NSCs?

Much work in the literature (see bibliography)

(Many slides from J. Osiński)

Nonstandard Cosmologies (NSCs)

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

$\boldsymbol{\omega = 0}$ **matter**	$\boldsymbol{\omega = 1/3}$ **radiation**	$\boldsymbol{\omega = 1}$ **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)

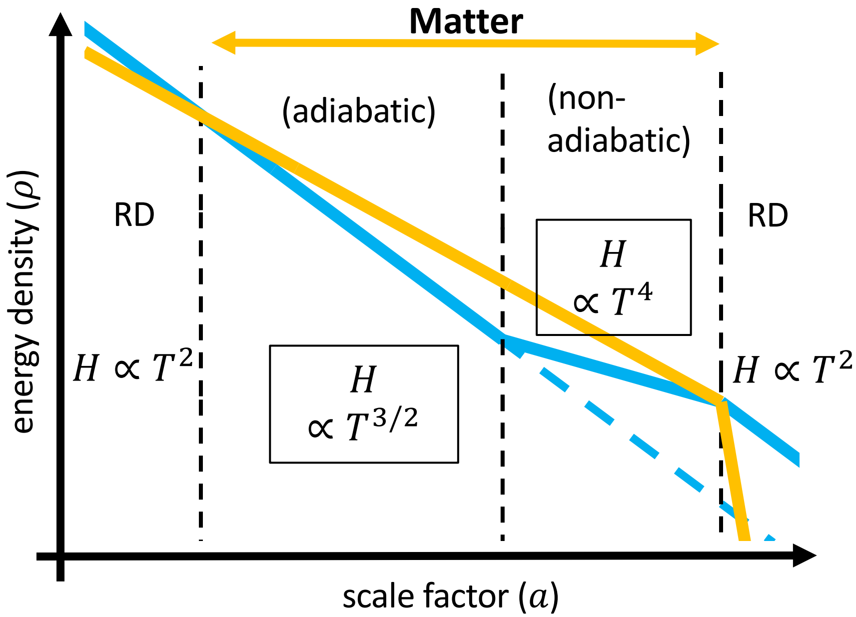
Kination-like: $\omega > 1/3$
- should begin dominant
- can be stable
- (fast-rolling scalar field)

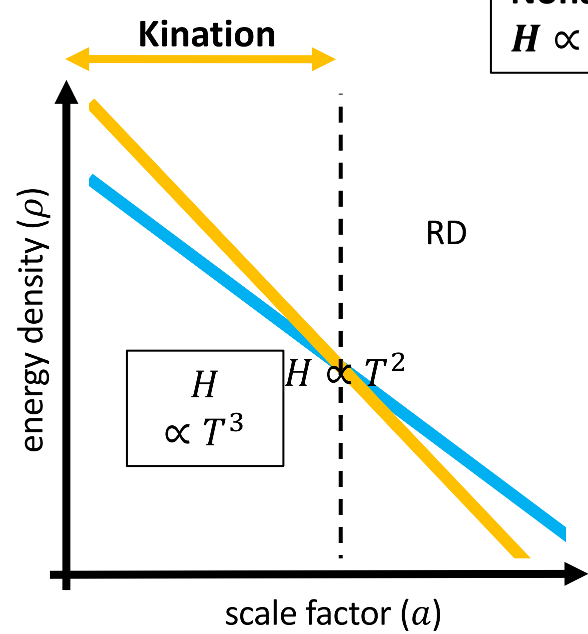
Examples of NSC

Standard RD:
$H \propto T^2$

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

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





NSC field
Radiation

Consequences of NSC

- **Two main effects:**

1. **Change evolution of expansion rate H and temperature T**

   → processes 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 or freeze-in)

Nonthermal

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

→ will focus on axions from misalignment

Axion misalignment mechanism

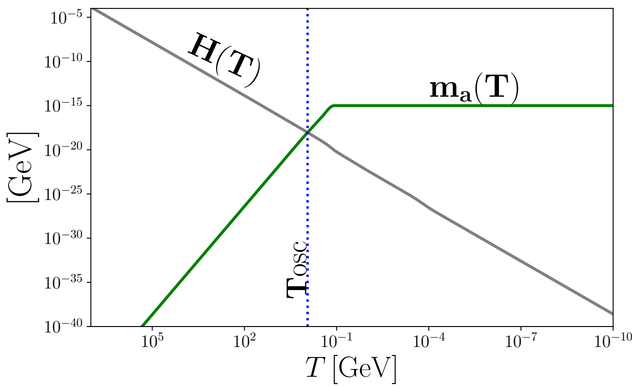
- **Initial value of angle θ fixed after Peccei-Quinn (PQ) breaking at a high scale f_a**
- **Axion field (a) frozen as long as Hubble rate > axion mass**

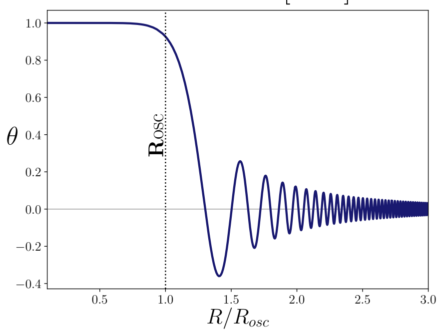
(zero-temp. axion mass)

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

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

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





Hubble rate:

$$H(T) \propto \frac{T^2}{M_P}$$

(radiation domination)

Axion mass:

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

Axion misalignment mechanism

- **As temperature of Universe cools,**
  axion mass increases while Hubble rate drops
- **Axion oscillation begins:**

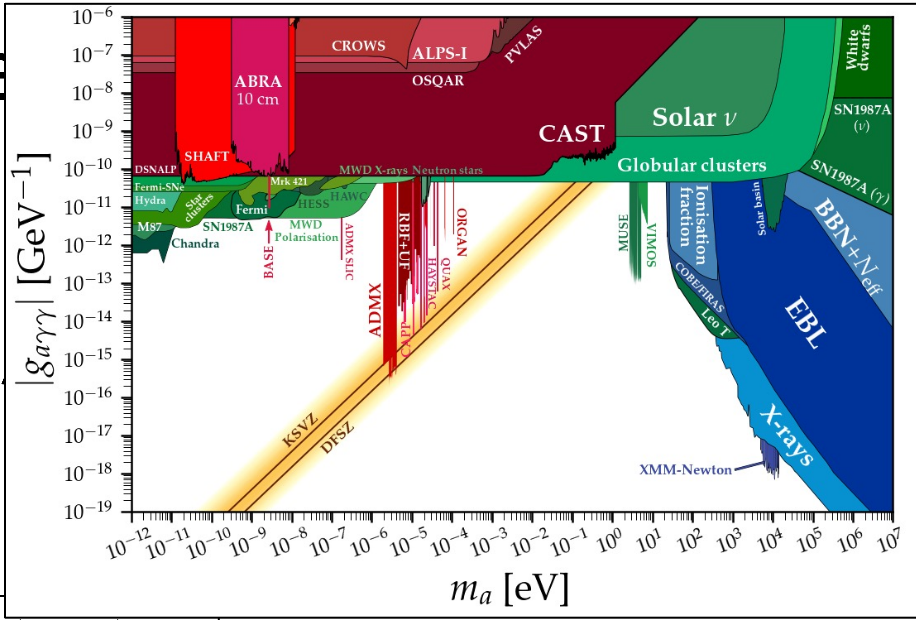
$$3\,H(T_{\mathrm{osc}}) \approx m(T_{\mathrm{osc}})$$

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

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

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

Axion misalignme



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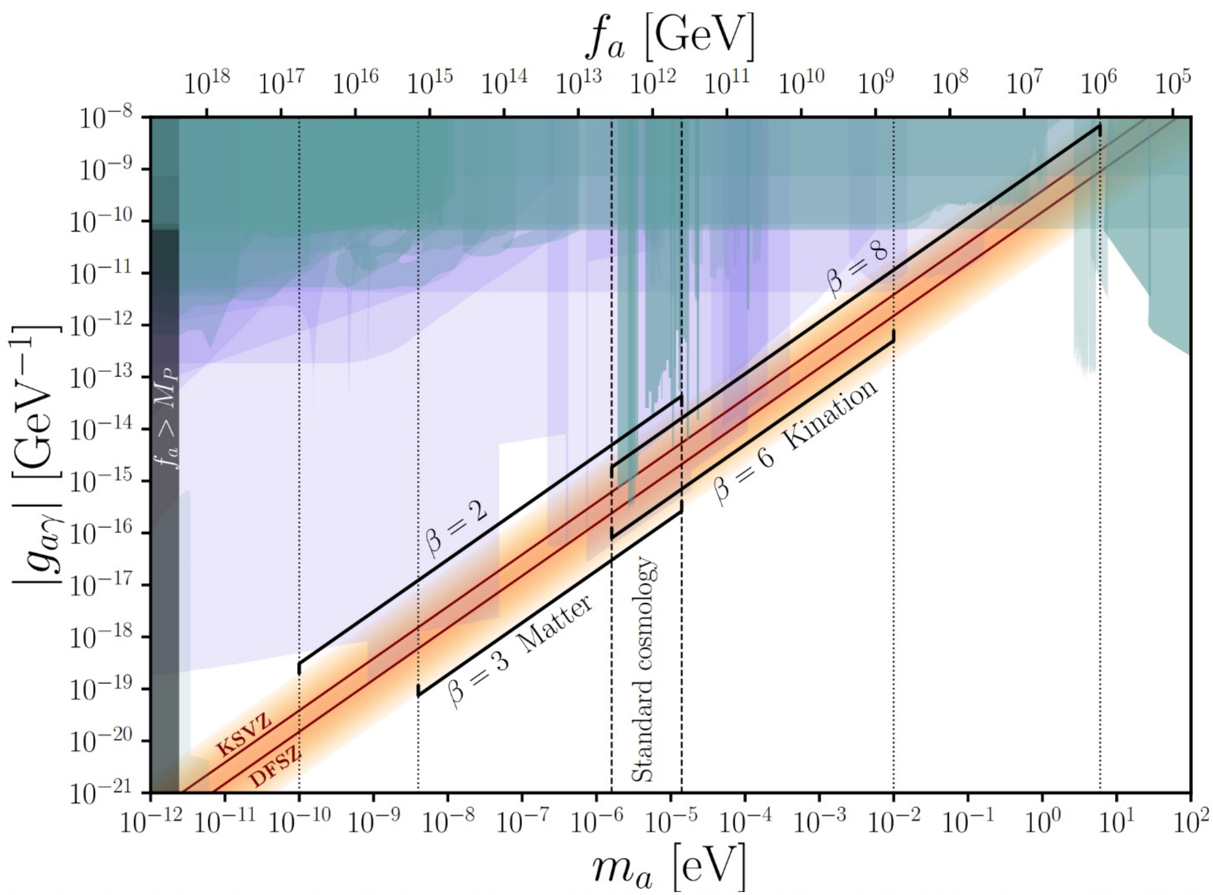
Axions in general NSC

- 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!)



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

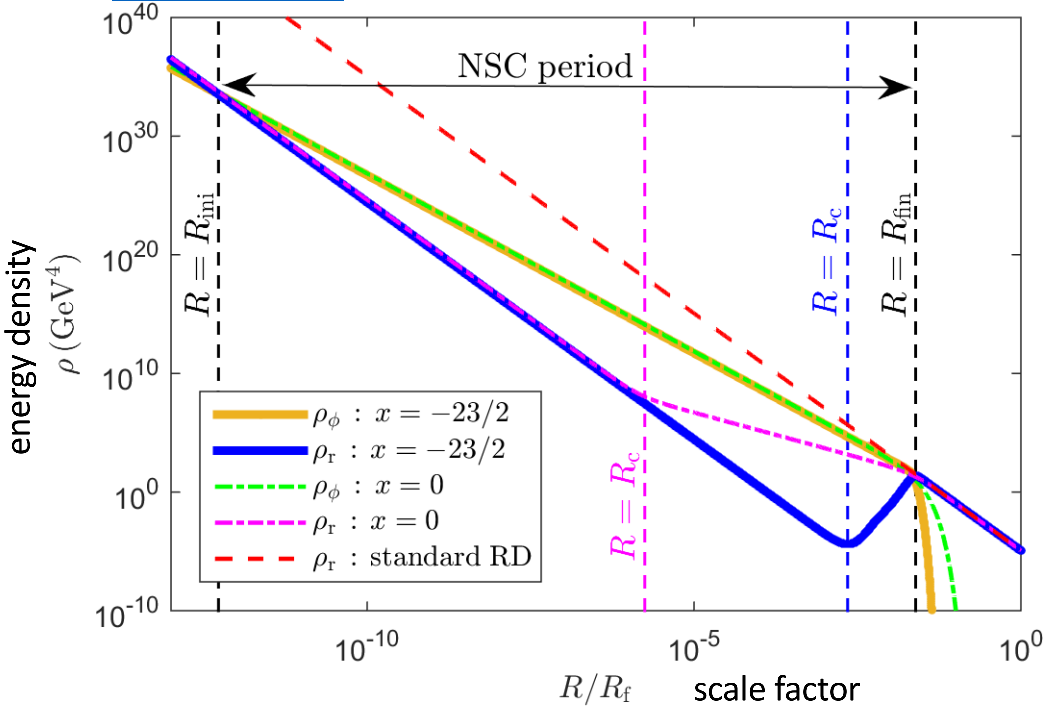
P. Arias, N. Bernal, D. Karamitros, C. Maldonado, L. Roszkowski, M. Venegas, 2107.13588 → JCAP

Axions with increasing-temperature EMD

P. Arias, N. Bernal, J.K. Osiński, L. Roszkowski, [2207.07677](2207.07677)

- **Consider early matter domination by scalar field**
- **Decay rate of dominating field <u>increases with time</u> (set by x, constant for $x = 0$)**
- **$\Gamma = \Gamma(T,R) \sim R^k T^n$**
- **Nonadiabatic phase is altered to $H \propto T^{12/(3+2x)}$**

$$x \equiv \frac{3\,n - 8\,k}{2\,(4 - n)}$$



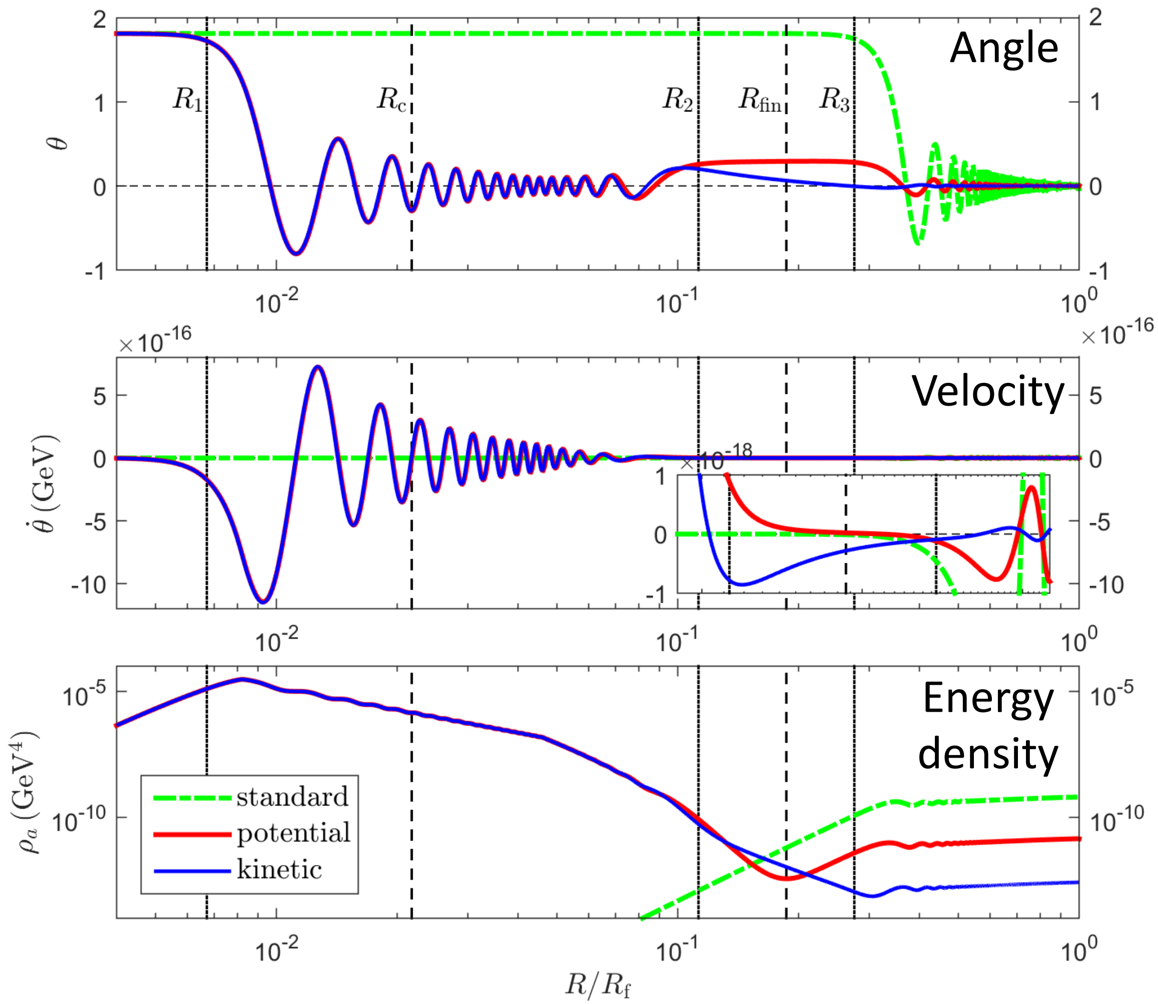
- **Same temperature can occur multiple times**

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

Axions with increasing-temperature EDM

- **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**

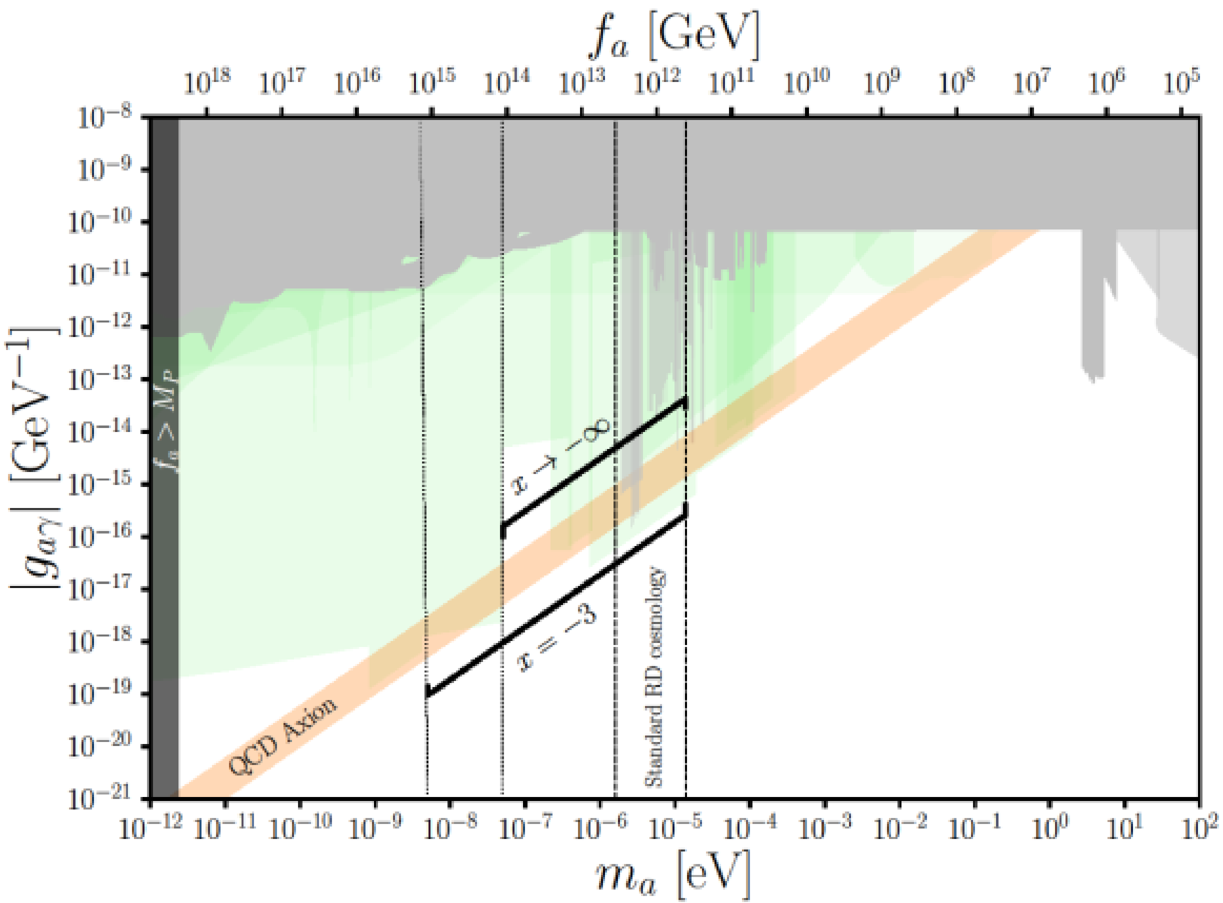
→ Smaller mass for axion DM



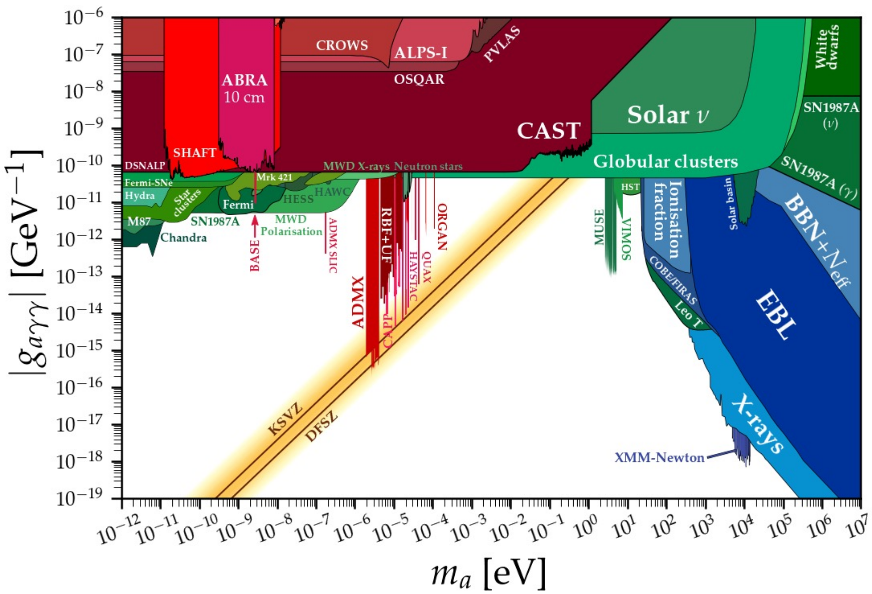
P. Arias, N. Bernal, J.K. Osiński, L. Roszkowski, 2207.07677 →JCAP

Axions with increasing-temperature EMD

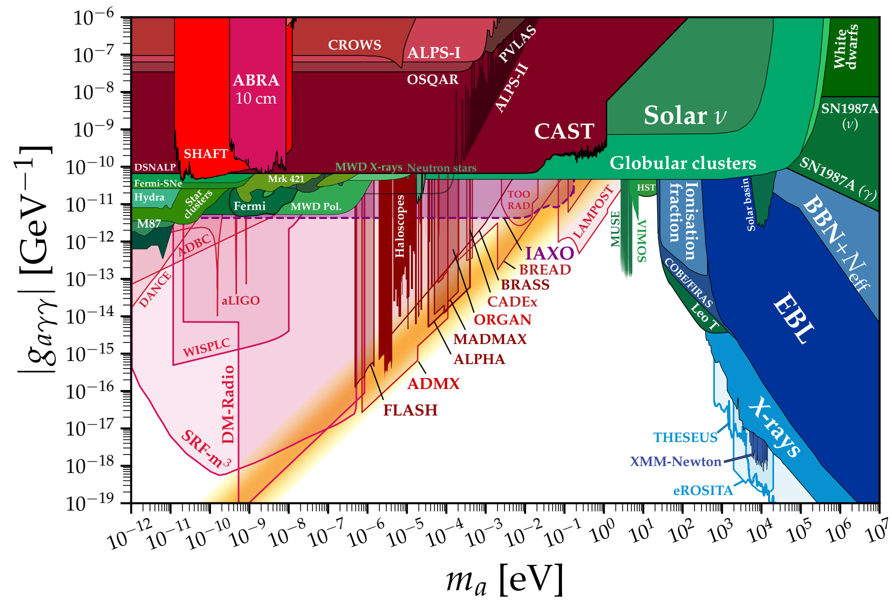
- Extended window toward smaller mass as before
- NSC histories add to motivation to look out of standard window
- Can probe NSC scenarios in coming years



P. Arias, N. Bernal, J.K. Osiński, L. Roszkowski, [2207.07677](2207.07677) current



future



https://github.com/cajohare/AxionLimits

To take home:

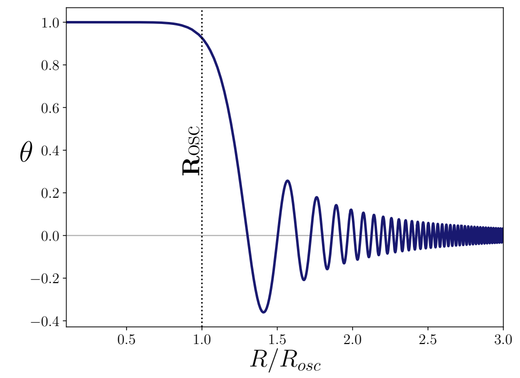
- **Standard cosmology is the simplest choice but not a unique one**
- **Many nonstandard cosmology scenarios exist**
- **NSC has significant effects on DM production:**
  - → **Shifts relevant times/temperatures, adds entropy dilution**
  - → **Can also fundamentally affect mechanisms themselves**
- **Axions in particular get extended mass window depending on history**
- **NSC scenarios will be probed in coming years**

- **Fermionic DM produced via freeze-in:**
  Significantly larger parameter space (larger Yukawa coupling)
  → **Implication for better prospects for direct detection**

Axion mass windows

❖ Initial value of theta is set after PQ symmetry breaking ~ f_a

$$\theta = a/f_a$$



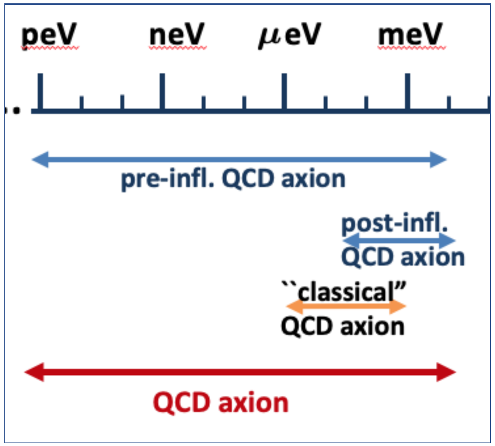
- Pre-inflationary case:
  the same value of θ_i in all observable Universe

  ($f_a < M_{pl}$ →) ~10^{-13} eV < m_a < ~10 meV ← $\theta_i \sim \pi$

- Post-inflationary case:
  different θ_i in many patches that were not in causal contact

  Need to average over all patches

  ~ 25 x 10^{-6} eV < m_a < ~15 meV



- Axion as DM:
  ``standard" QCD window:

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

APPEC DM Report 2104.07634

Accommodating both pre- and post-inflationary cases and assuming no fine tuning of the angle