Dark Photon Dark Matter Produced by Axion Oscillations

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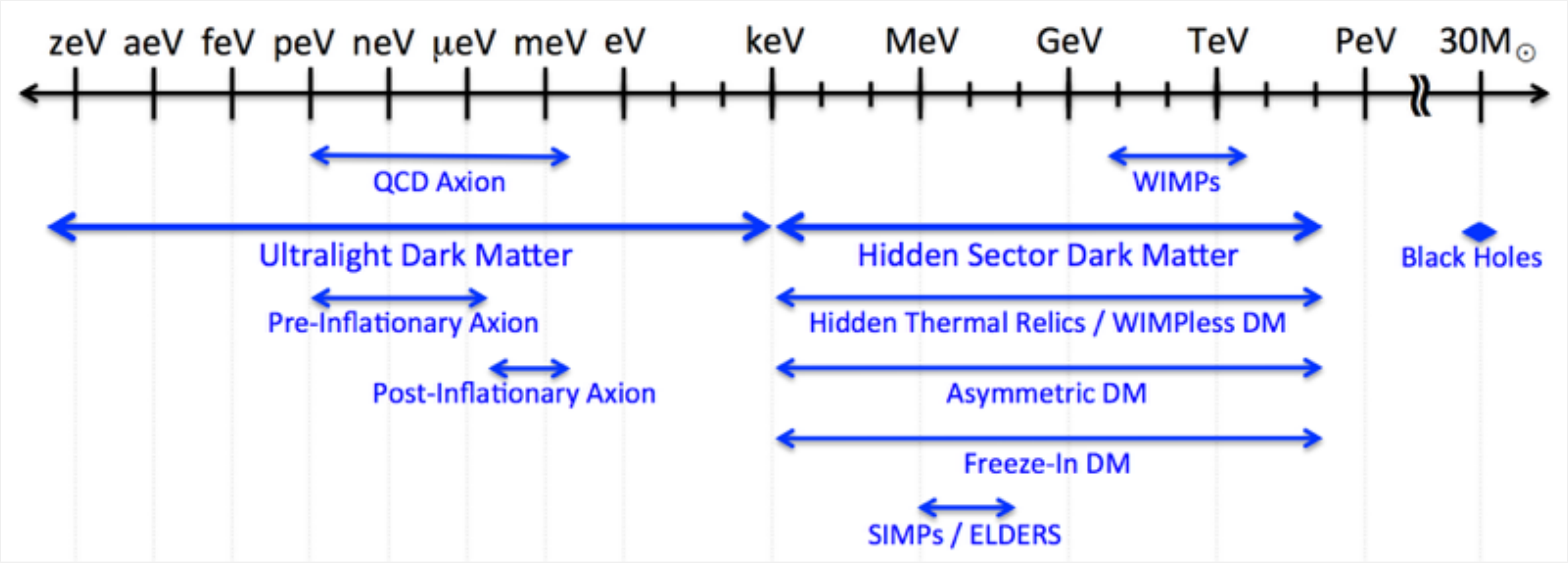
arXiv: 1810.07196.

Berkeley Week, IPMU, Jan. 2019

Intro: dark photon dark matter

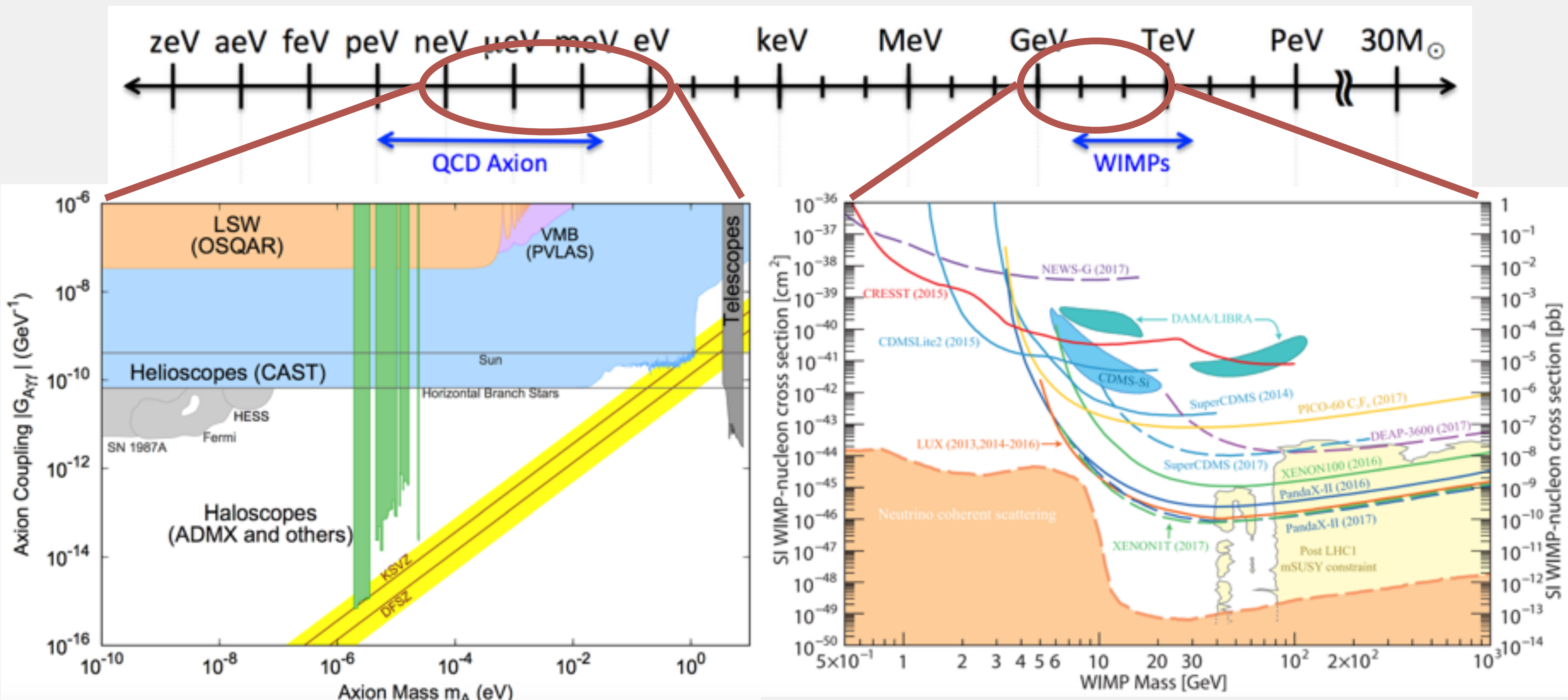
- Landscape of dark matter candidates:



US Cosmic Visions Community Report, 1707.04591

Intro: dark photon dark matter

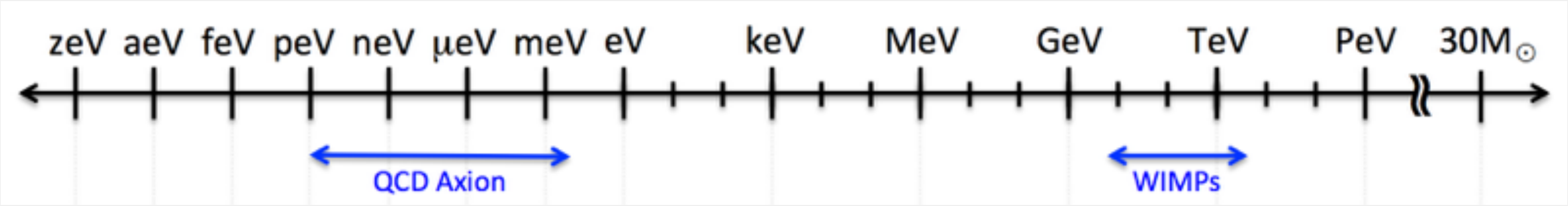
- Most studied candidates: WIMPs and axions (ALPs).
    - But lack of discovery urges us to broaden the scope.



PDG 2018

Intro: dark photon dark matter

- Most studied candidates: WIMPs and axions (ALPs).
  - But lack of discovery urges us to broaden the scope.



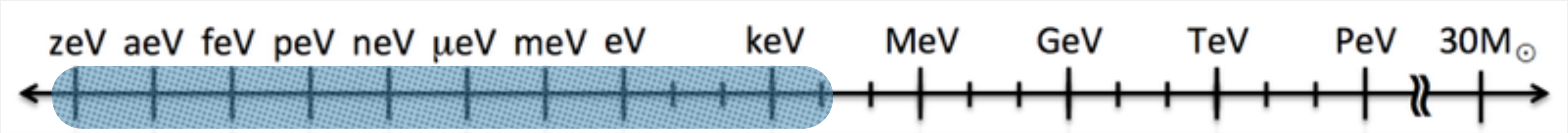
- Beyond WIMPs/axions: **dark photon** is an often discussed benchmark.

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + A'_\mu J^\mu_{\rm SM}$$

  - Dark photon mass may arise from the Higgs or Stueckelberg mechanism.
  - The SM current that A' couples to may be e.g. B or B-L current, or hypercharge current (from kinetic mixing).

Intro: dark photon dark matter

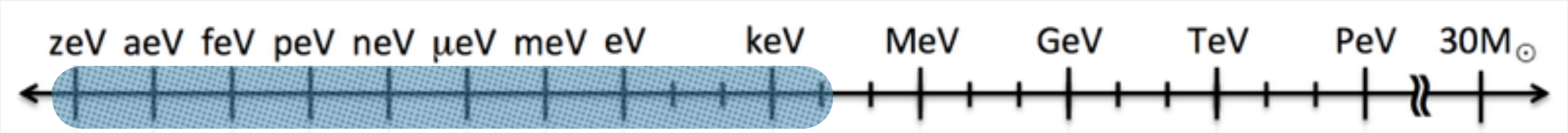
- Many detection concepts have been studied for **dark photon dark matter**, covering a broad mass range.



- ✓ Microwave cavity [Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald, 1201.5902]
- ✓ DM Radio [Chaudhuri, Graham, Irwin, Mardon, Rajendran, Zhao, 1411.7382] [Silva-Feaver et al, 1610.09344]
- ✓ Accelerometers [Graham, Kaplan, Mardon, Rajendran, Terrano, 1512.06165]
- ✓ Absorption in superconductors/semiconductors [Hochberg, Lin, Zurek, 1604.06800, 1608.01994]
- ✓ Absorption by bound electrons [Bloch, Essig, Tobioka, Volansky, Yu, 1608.02123]
- ✓ Magnetic bubble chambers [Bunting, Gratta, Melia, Rajendran, 1701.06566]
- ✓ Absorption in molecules [Arvanitaki, Dimopoulos, Van Tilburg, 1709.05354]
- ✓ Gravitational wave detectors [Pierce, Riles, Zhao, 1801.10161]
- ✓ Dielectric Haloscopes [Baryakhtar, Huang, Lasenby, 1803.11455]
- ✓ …

Intro: dark photon dark matter

- Many detection concepts have been studied for **dark photon dark matter**, covering a broad mass range.

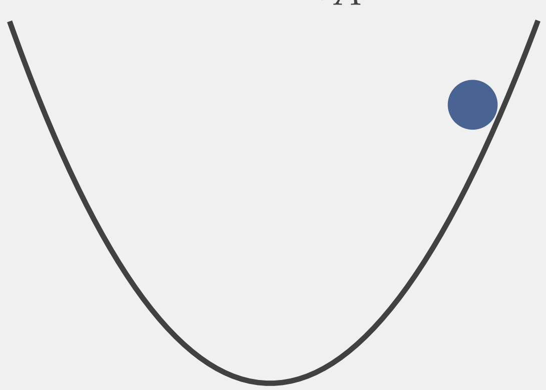


- But detectability ≠ plausibility.
- For any DM candidate: how does it fit into a consistent cosmology?
  - How is it produced? (Sub-keV DM requires non-thermal production.)
  - Is the cosmological history consistent with observational constraints?
  - Is there a preferred mass range so we can optimize experimental searches?

Intro: dark photon dark matter

- Ideas on non-thermal production of dark photon DM.
    - Misalignment (similar to axions)? [Nelson, Scholtz, 1105.2812]
        - If A' were a scalar… $\rho_{A'} \sim m_{A'}^2 A'^2$

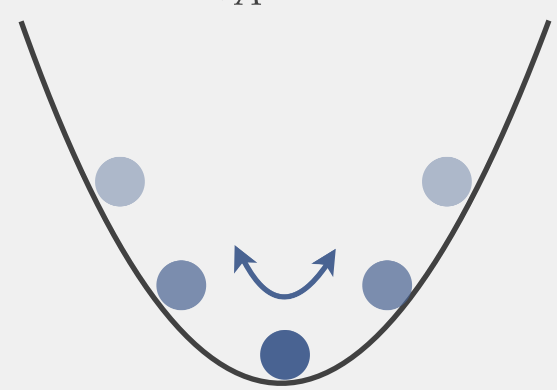
$H > m_{A'}$



$A' \sim \text{constant}$

$\rho_{A'} \sim \text{constant}$

$m_{A'} > H$



$A' \sim a^{-3/2}$

$\rho_{A'} \sim a^{-3}$

Intro: dark photon dark matter

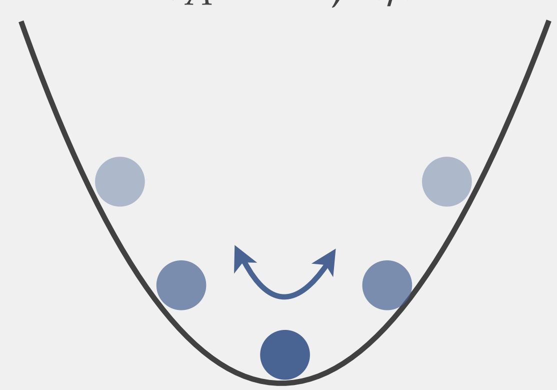
- Ideas on non-thermal production of dark photon DM.
  - Misalignment (similar to axions)? [Nelson, Scholtz, 1105.2812]
    - But a vector behaves differently… $\rho_{A'} \sim \boxed{g^{\mu\nu}} m_{A'}^2 A'_\mu A'_\nu$

$H > m_{A'} > k/a$

$A' \sim \text{constant}$

$\boxed{\rho_{A'} \sim a^{-2}}$

$m_{A'} > H, k/a$



$A' \sim a^{-1/2}$

$\rho_{A'} \sim a^{-3}$

    - Fix: (fine-tuned) non-minimal coupling to gravity to make A' behave like a scalar.
    - But that introduces a quadratic divergence for the A' mass.

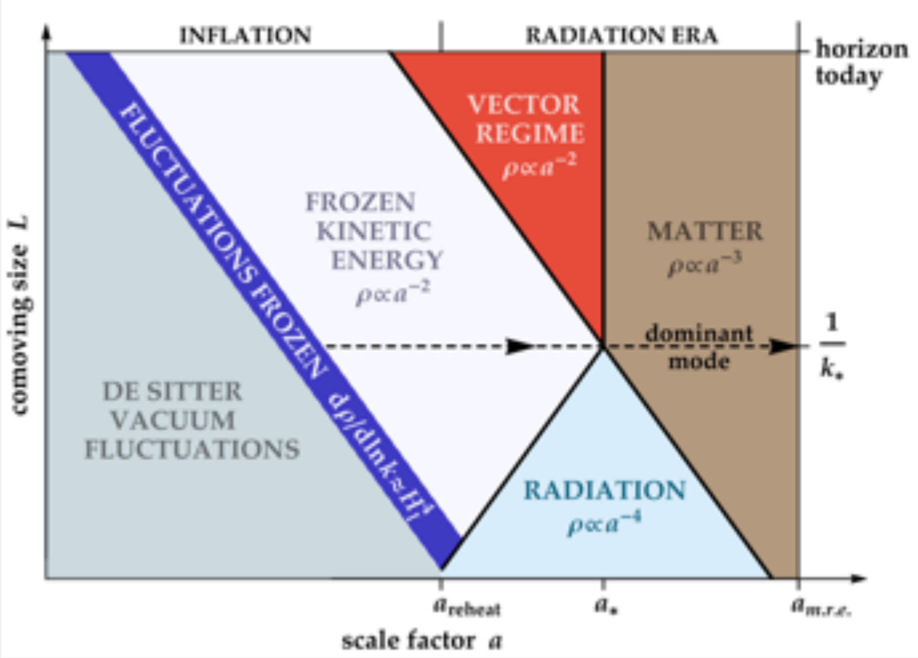
[Arias et al, 1201.5902] [Graham, Mardon, Rajendran, 1504.02102]

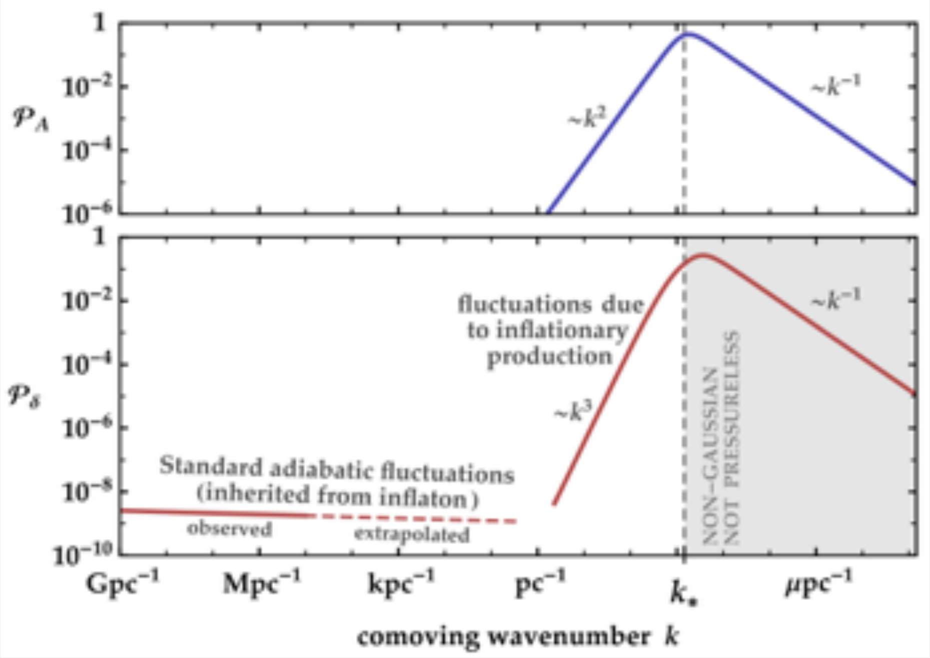
Intro: dark photon dark matter

- Ideas on non-thermal production of dark photon DM.
  - Misalignment (problematic/fine-tuned).
  - Inflationary fluctuations. [Graham, Mardon, Rajendran, 1504.02102]

$$\Omega_{A'} h^2 = 0.12 \sqrt{\frac{m_{A'}}{6 \times 10^{-6}\ \mathrm{eV}}} \left(\frac{H_I}{10^{14}\ \mathrm{GeV}} \right)^2$$

    - The spectrum is not flat because different modes redshift differently.
    - Long wavelength isocurvature perturbations are suppressed.





Intro: dark photon dark matter

- Ideas on non-thermal production of dark photon DM.
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$$\Omega_{A'} h^2 = 0.12 \sqrt{\frac{m_{A'}}{6 \times 10^{-6}\ \mathrm{eV}}} \left(\frac{H_I}{10^{14}\ \mathrm{GeV}} \right)^2$$

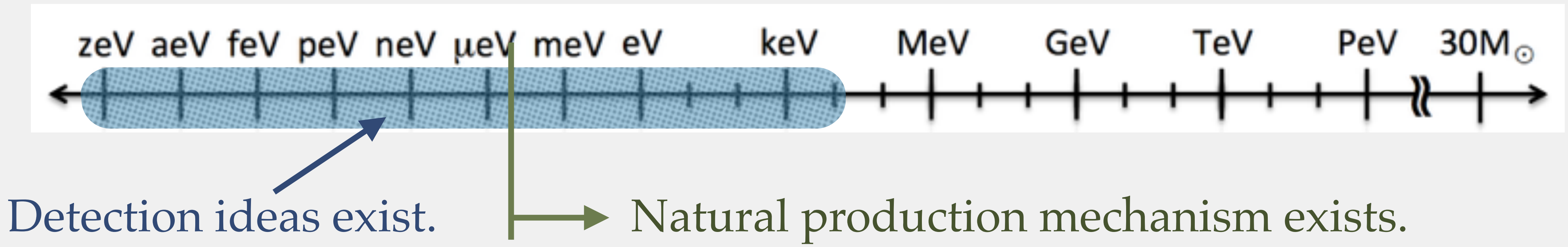
    - The spectrum is not flat because different modes redshift differently.
    - Long wavelength isocurvature perturbations are suppressed.
    - To the best of our knowledge, this is the only natural mechanism for non-thermal dark photon DM production in the previous literature.
    - However, the viable dark photon mass is limited by the scale of inflation.

$$H_I < 10^{14}\,\mathrm{GeV} \qquad \Rightarrow \qquad m_{A'} > 6 \times 10^{-6}\,\mathrm{eV}$$

(to account for all of DM)

Intro: dark photon dark matter

- Status of dark photon dark matter: many detection ideas exist, but its cosmological origin has been much less explored.



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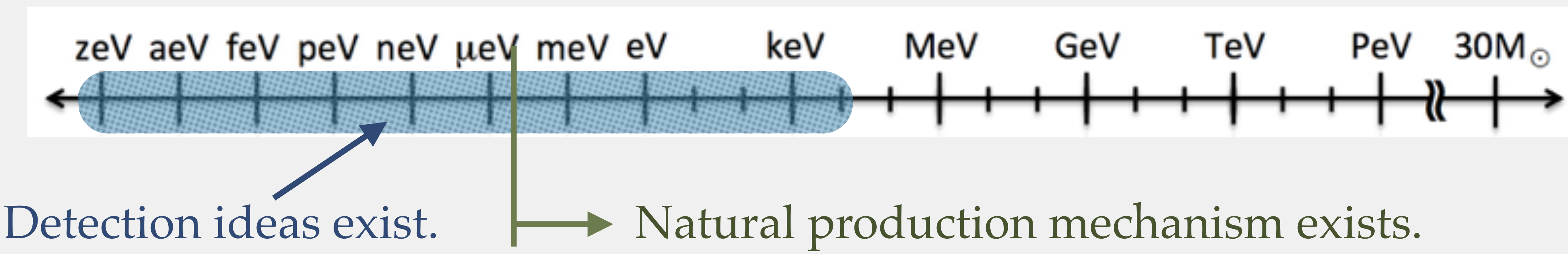
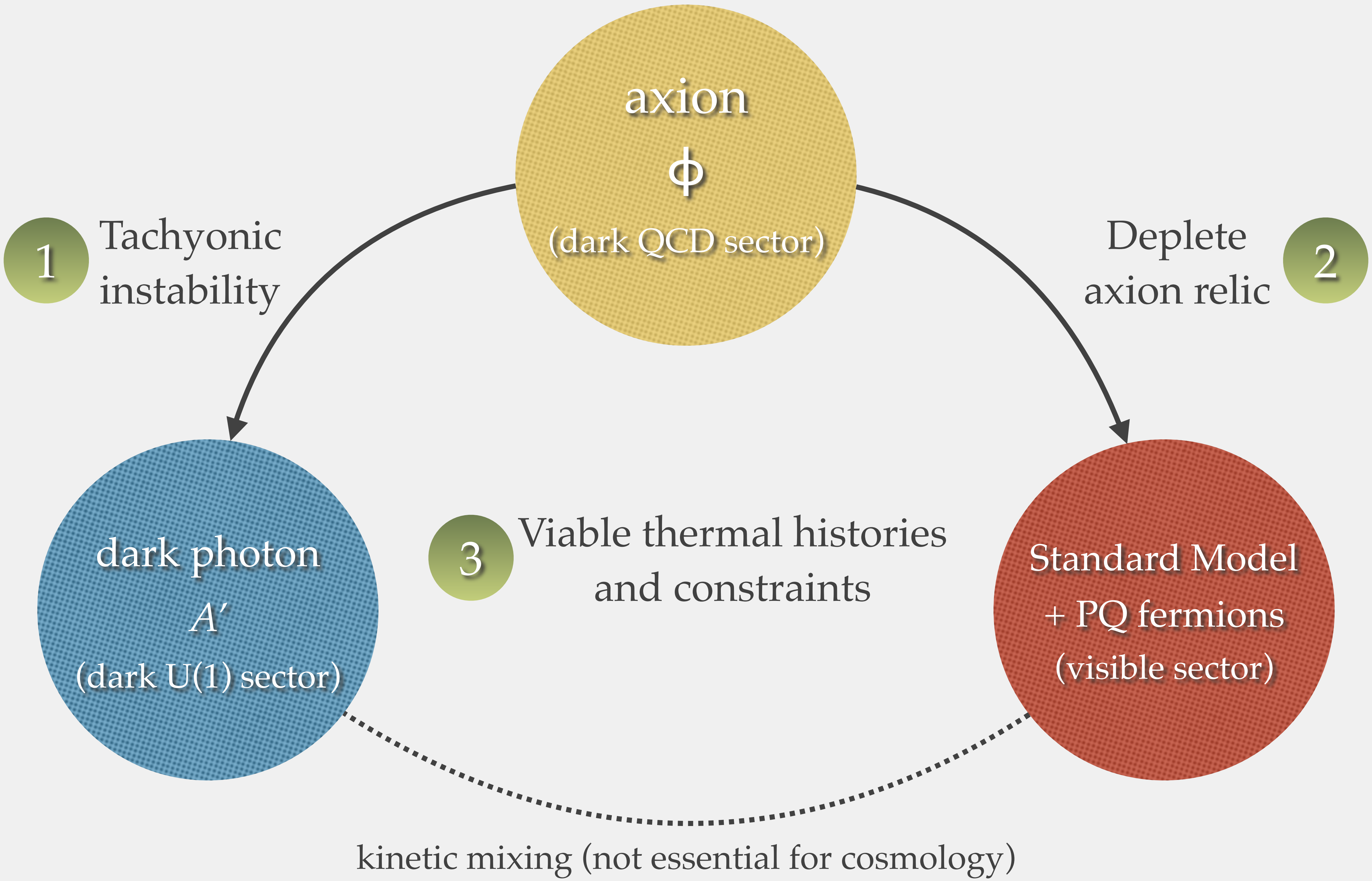


- Alternative ideas of how dark photon dark matter may be realized in a consistent cosmology?
  - Production from an axion via tachyonic instability (this talk). [Co, Pierce, ZZ, Zhao, 1810.07196]
  - Related ideas: [Agrawal, Kitajima, Reece, Sekiguchi, Takahashi, 1810.07188] [Dror, Harigaya, Narayan, 1810.07195] [Bastero-Gil, Santiago, Ubaldi, Vega-Morales, 1810.07208] (4 papers published on the same day!)

Outline of the idea (and the talk)



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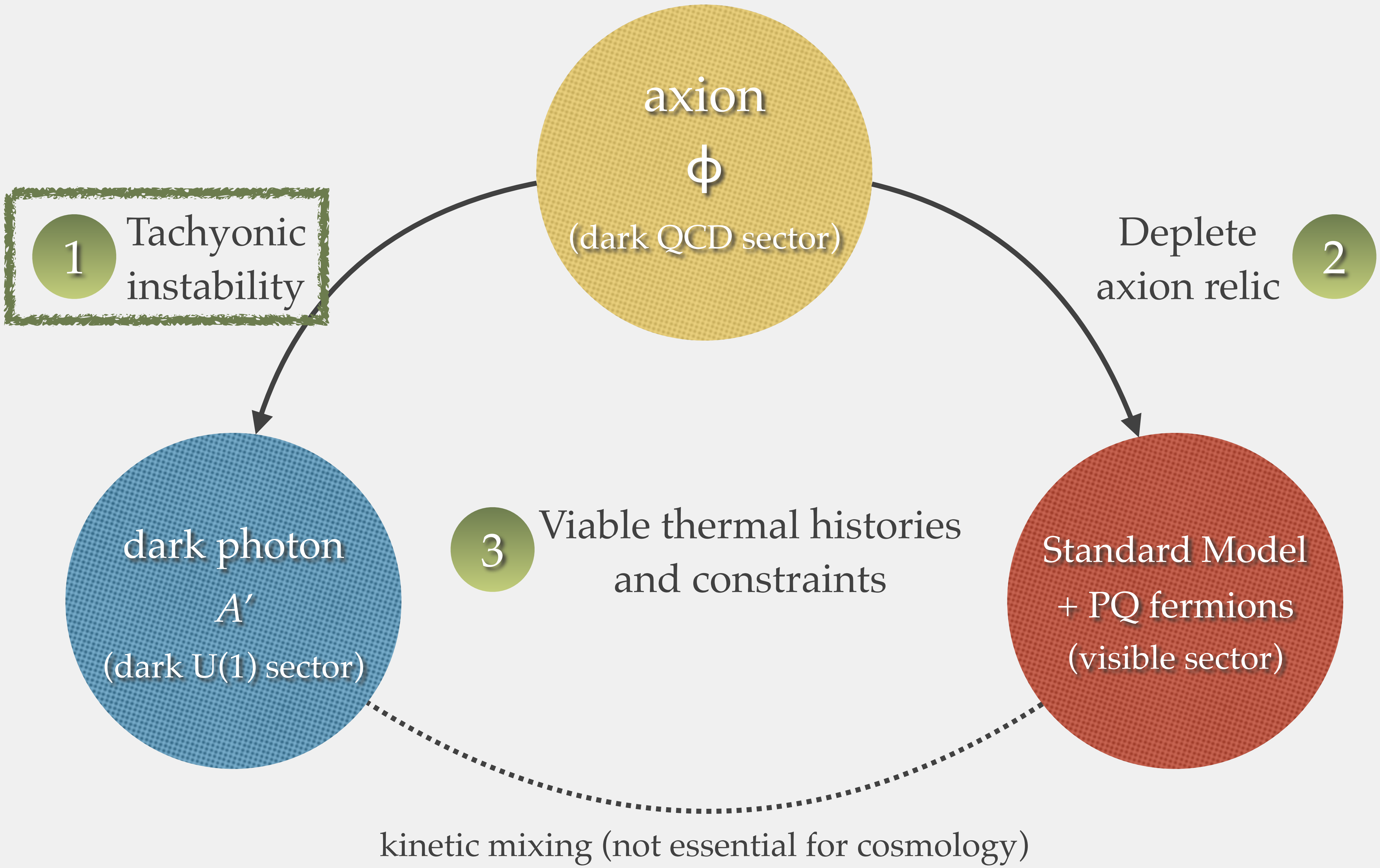
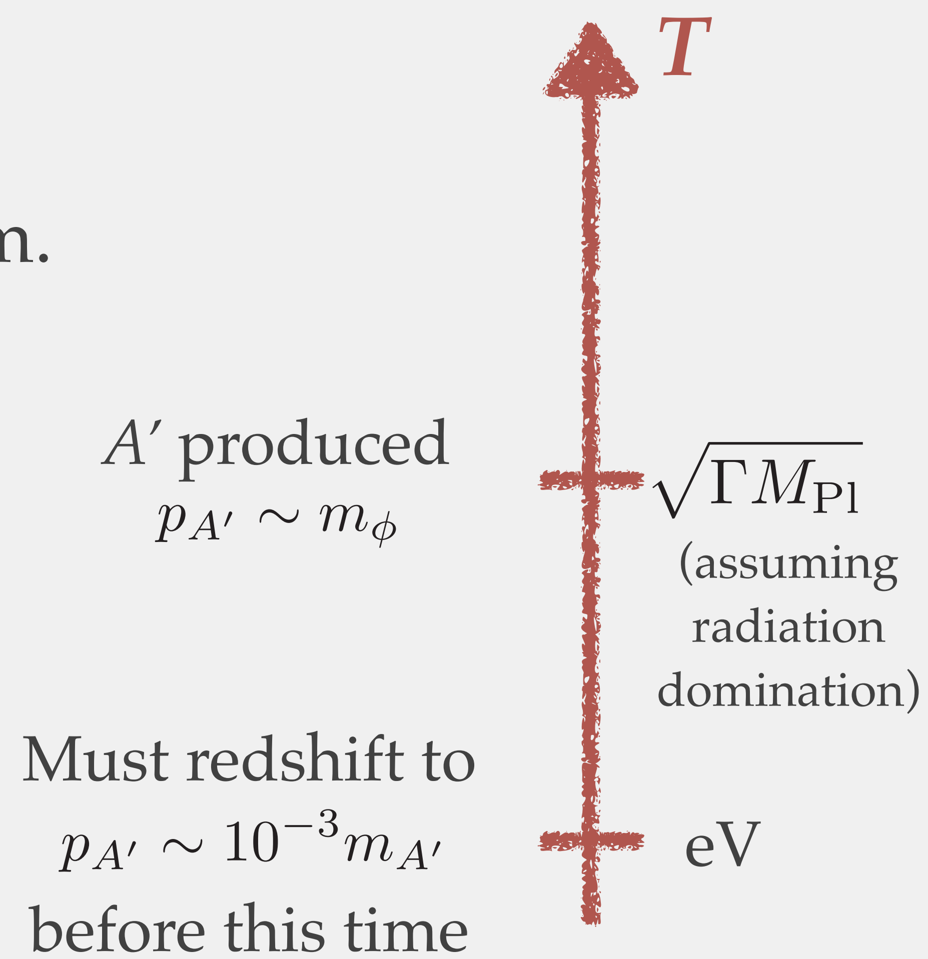


Dark photons from an axion

$$\mathcal{L}_{\phi A' A'} = \frac{\alpha_D}{8\pi f_D} \phi \, F'_{\mu\nu} \tilde{F}'^{\mu\nu}$$

- Simplest idea: perturbative decay $\phi \to A' A'$
- Difficulty: dark photons tend to be too warm.
  - Limited time to redshift after production.
- Can we produce A' much earlier?



Dark photons from an axion

$$\mathcal{L}_{\phi A' A'} = \frac{\alpha_D}{8\pi f_D} \phi \, F'_{\mu\nu} \tilde{F}'^{\mu\nu}$$

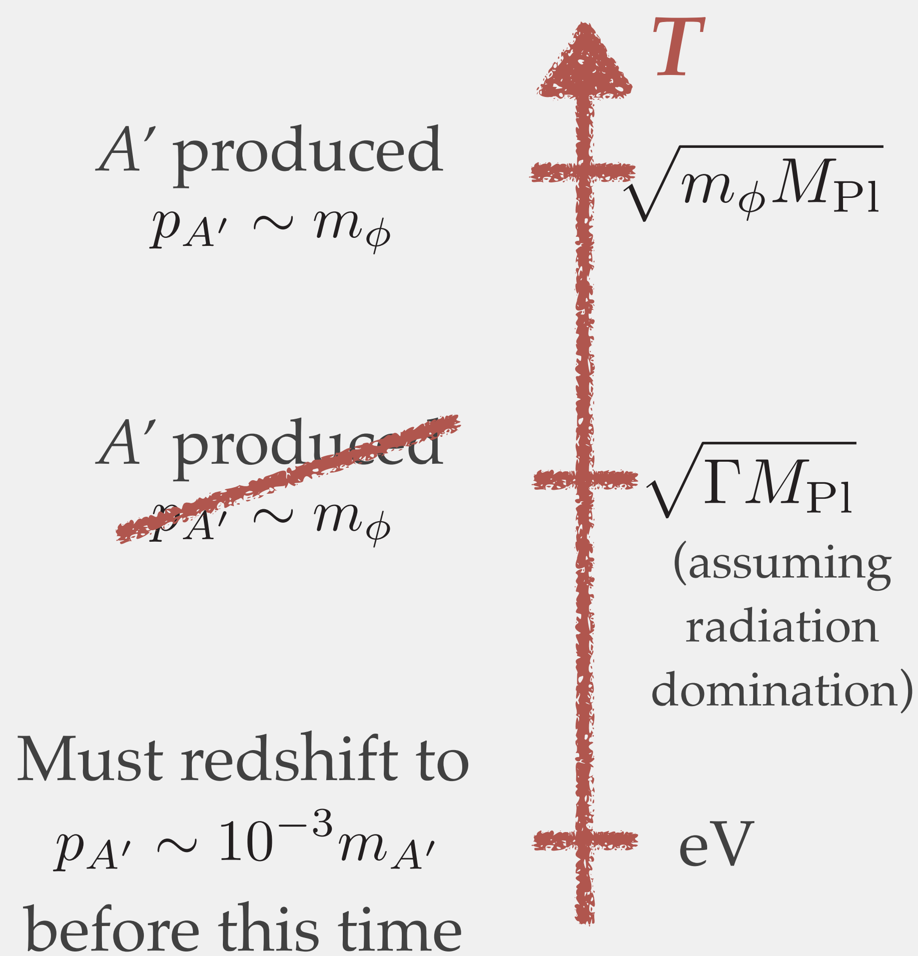
- We would like to use some process at

$$H \sim m_\phi \gg \Gamma$$

- If the axion field is initially displaced from the minimum of the potential, this is the time when coherent oscillations begin.

$$\boxed{T_{\rm osc} \simeq 0.3 \sqrt{m_\phi M_{\rm Pl}}}$$

- Dark photons are explosively produced via a **tachyonic instability**.

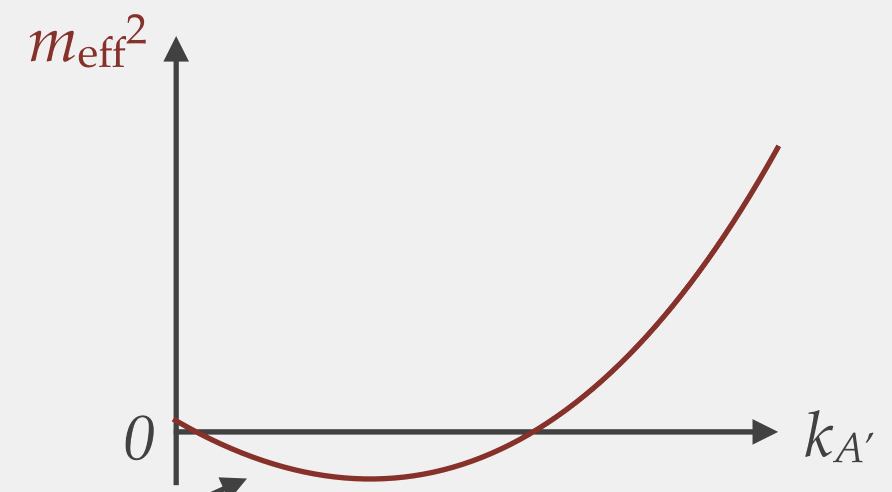


Tachyonic instability

- Dark photon equation of motion (in Fourier space):

$$\frac{\partial^2 A'_\pm}{\partial\eta^2} + \underbrace{\left(m_{A'}^2 + k_{A'}^2 \pm \frac{\alpha_D k_{A'}}{2\pi f_D}\frac{\partial\phi}{\partial\eta}\right)}_{m_{\text{eff}}^2} A'_\pm = 0$$

  - Assume negligible A' self interactions (justified post priori).
  - $A'_\pm$: helicity states.
  - η: conformal time.
  - $k_{A'}$: dark photon momentum.



These modes are tachyonic
=> exponentially produced.

Tachyonic instability

- The tachyonic growth stops when the produced A' back-reacts on the axion condensate to excite higher momentum modes.
- This non-perturbative process has to be calculated by lattice simulations.
  - Done previously in a different context. [Kitajima, Sekiguchi, Takahashi, 1711.06590]
    - Accommodating misalignment production of axion dark matter with higher f_a, without fine-tuning the initial misalignment angle. [Agrawal, Marques-Tavares, Xue, 1708.05008]
    - While misalignment overproduces axions, efficient conversion to dark photons via the tachyonic instability can reduce the axion abundance to observed value.
  - Here, instead, we are interested to know whether the **dark photon** produced this way can be **dark matter**. But the calculation is the same.

Tachyonic instability

- We take the following key results from previous lattice simulations:
  - Efficient tachyonic instability requires large initial axion field excursion:

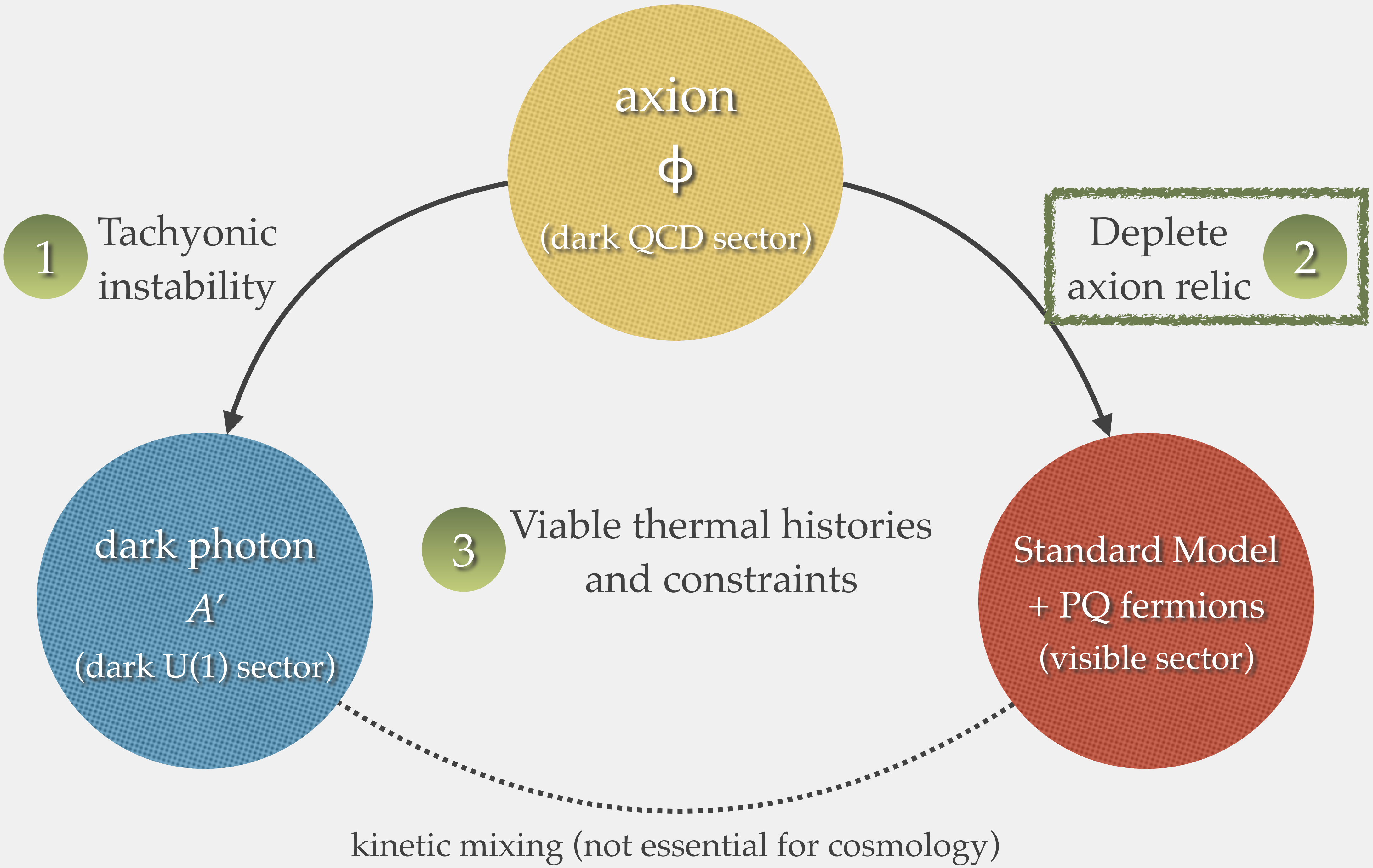
$$\frac{\alpha_D \phi_i}{2\pi f_D} \gtrsim \mathcal{O}(10)$$

    - Possible in several known setups [Agrawal, Fan, Reece, 1806.09621].
  - After back-reaction sets in,

$$p_{A'} \sim p_\phi \sim m_\phi \,, \qquad n_{A'} \sim n_\phi \sim m_\phi \phi_i^2$$

    - Axion -> dark photon conversion is not 100%.
    - Afterward, dark photons redshift as radiation, while the residual axions soon begin to redshift as matter and dominate over the dark photons.
    - Thus, the **residual axions** have to be **depleted later** for dark photon to be dark matter eventually (next part of the talk).

Outline of the idea (and the talk)



Minimal setup: axion-gauge boson coupling

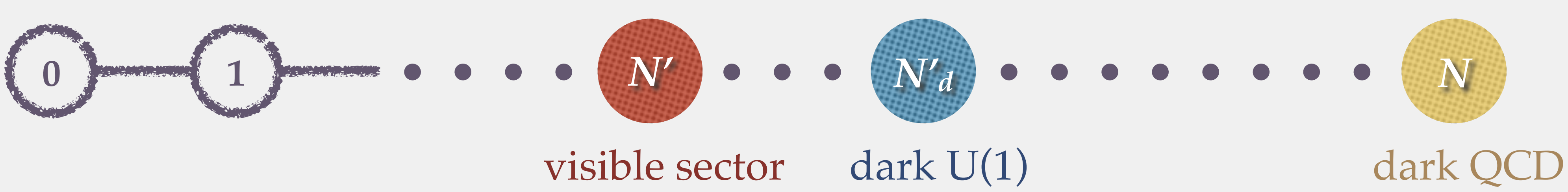
- Suppose the axion couples to hypercharge gauge boson:

$$\mathcal{L}_{\phi BB} = \frac{\alpha_Y}{8\pi f_B} \phi \, B^{\mu\nu} \tilde{B}_{\mu\nu}$$

  - Allow the decay constants to be different. Only make minimal assumption:

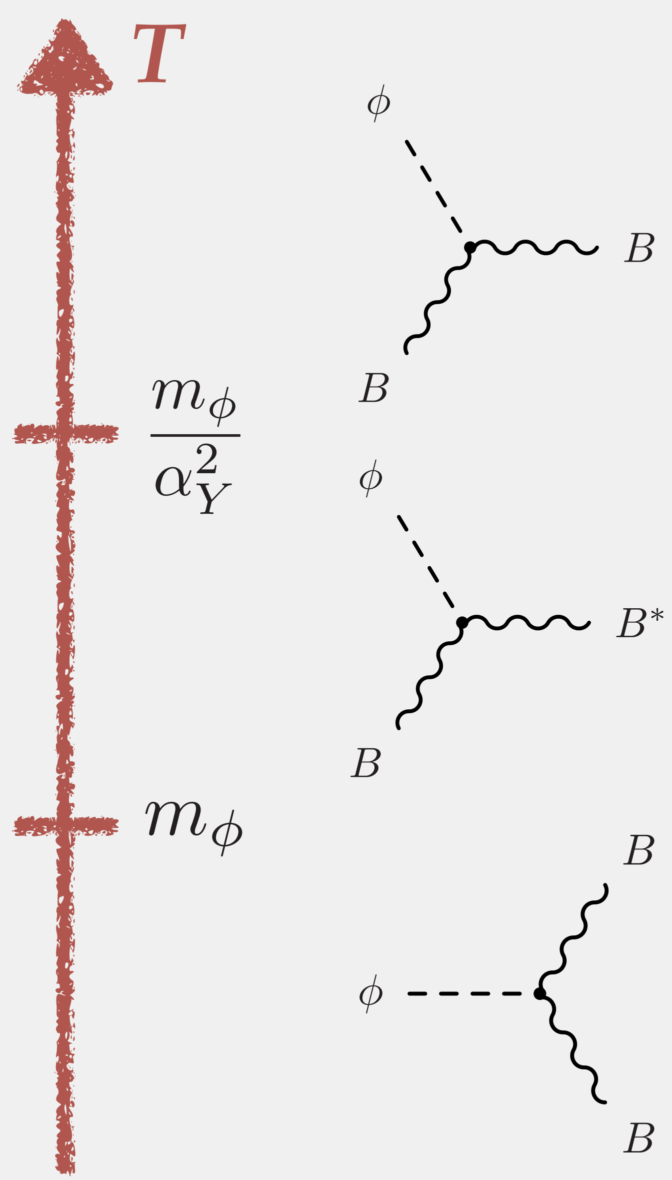
$$m_\phi < f_{\rm PQ} \lesssim f_{B,D} \ll f_a \sim \phi_i$$

  - Example realization (existence proof): clockwork theory [Choi, Kim, Yun, 1404.6209] [Choi, Im, 1511.00132] [Kaplan, Rattazzi, 1511.01827] [Farina, Pappadopulo, Rompineve, Tesi, 1611.09855] [Long, 1803.00786]



$f_B = q^{N'} f_{\rm PQ}$ $\quad f_D = q^{N'_d} f_{\rm PQ}$ $\quad f_a = q^N f_{\rm PQ}$

Thermalization channels



- Axion mass within gauge boson thermal width.
- Resonant absorption. [Rychkov, Strumia, hep-ph/0701104] [Salvio, Strumia, Xue, 1310.6982] [Moroi, Mukaida, Nakayama, Takimoto, 1407.7465]

$$\Gamma_{\phi B \to B} \simeq 10^{-3} \frac{m_\phi^2 T}{f_B^2}$$

- Resonance shuts off.
- Full 2->2 processes are UV dominated.
- => Axion thermalization cannot happen.

- Decay is no longer blocked by thermal mass.

$$\Gamma_{\phi \to BB} = \frac{\alpha_Y^2}{256\pi^3} \frac{m_\phi^3}{f_B^2}$$

Introducing PQ fermions

- The previous discussion assumed PQ fermions ψ_B are decoupled.
- But to have them decoupled at all times would require very high f_B.

$$f_B \gtrsim f_{\rm PQ} \gtrsim m_{\psi_B} > T_{\rm osc}$$

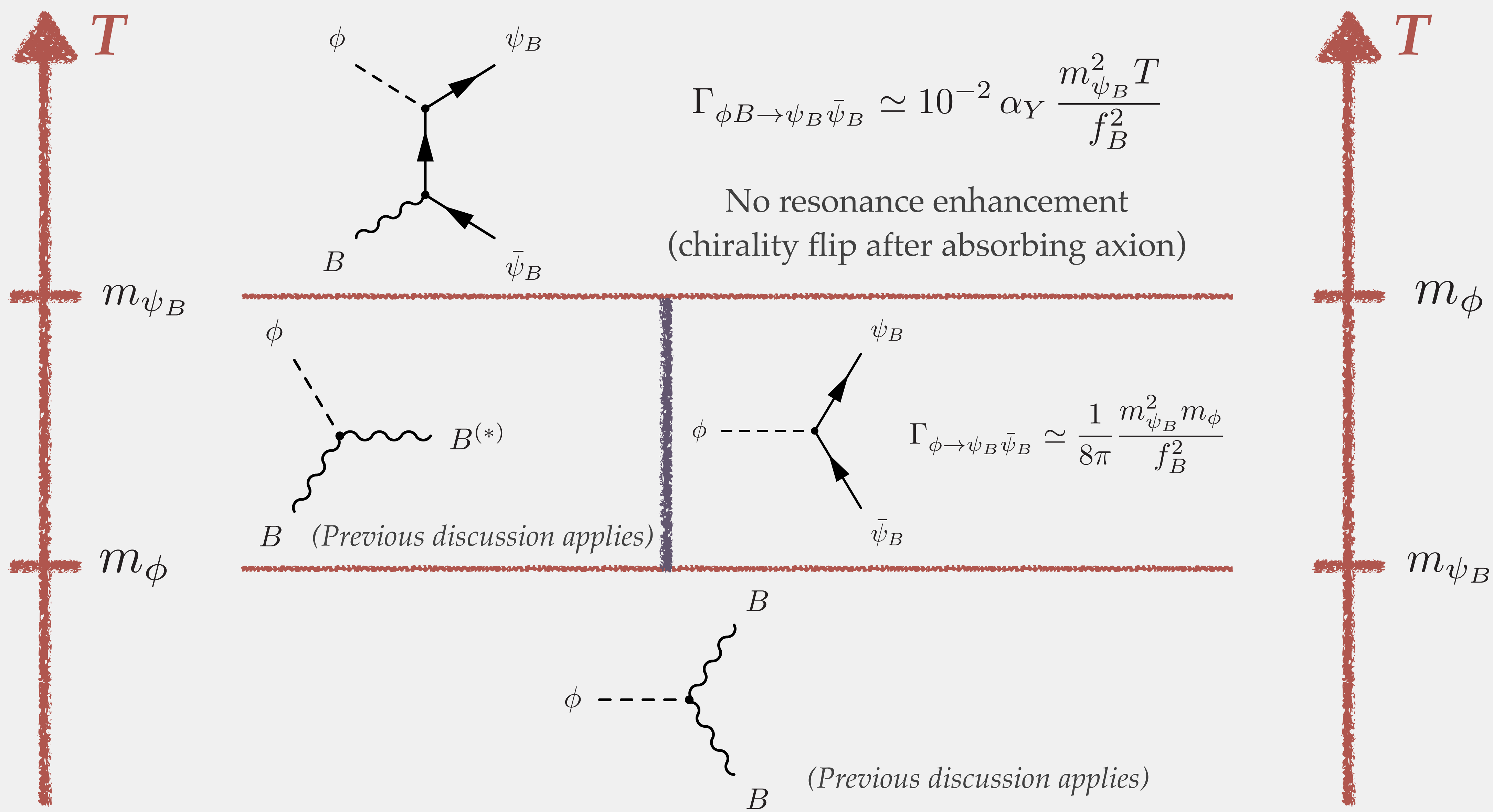
- This makes axion thermalization very inefficient.
- We thus consider non-decoupled ψ_B, to be integrated in above m_{ψ_B}.
- Minimal setup: just one species with unit hypercharge.

$$\mathcal{L}_{\phi\psi_B\bar{\psi}_B} = \frac{m_{\psi_B}}{f_B}\,\phi\,\bar{\psi}_B i\gamma^5\psi_B$$

- Bonus: additional thermalization channels.

Additional thermalization channels

- Two possible mass orderings between PQ fermion and axion:



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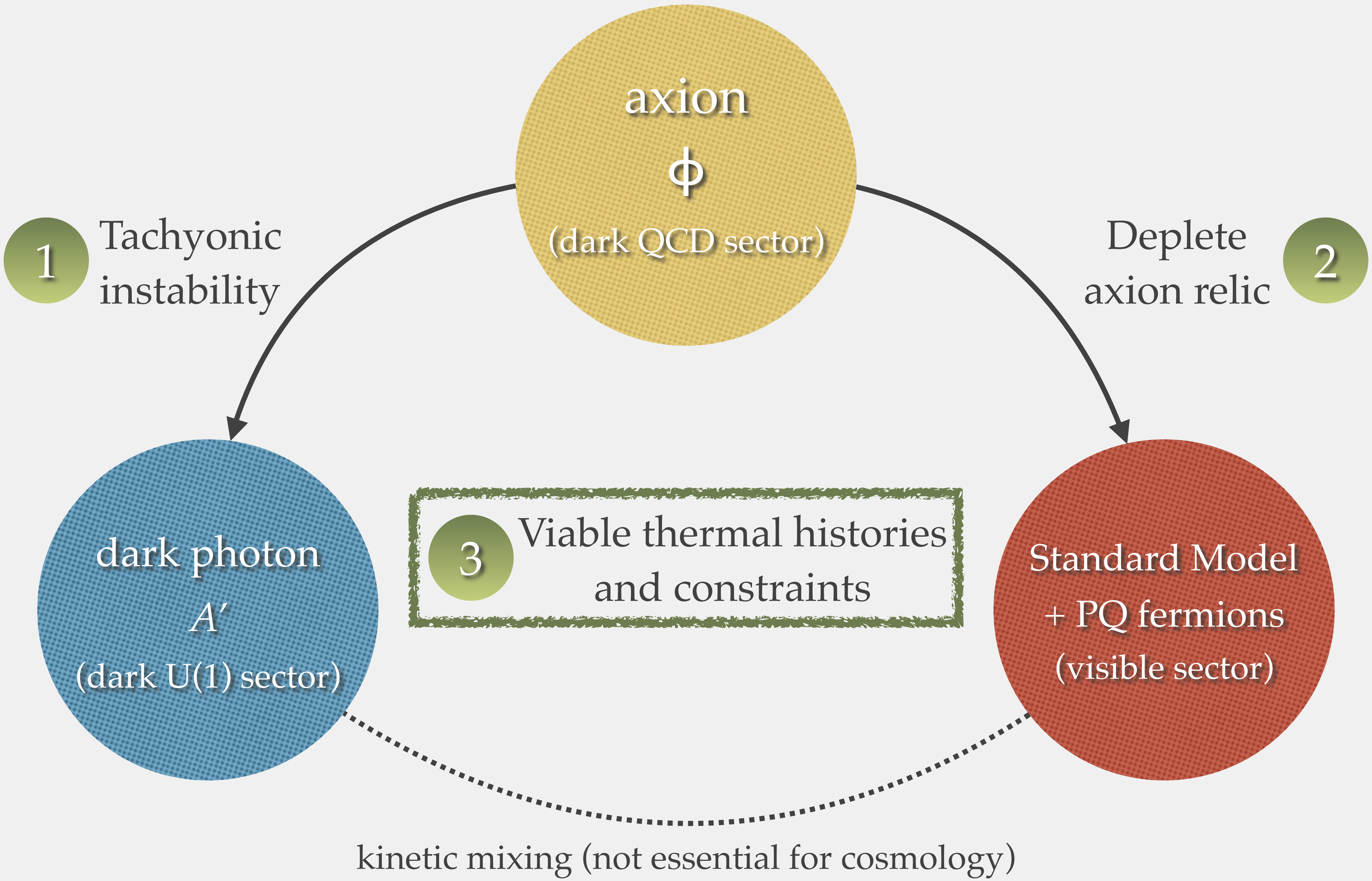
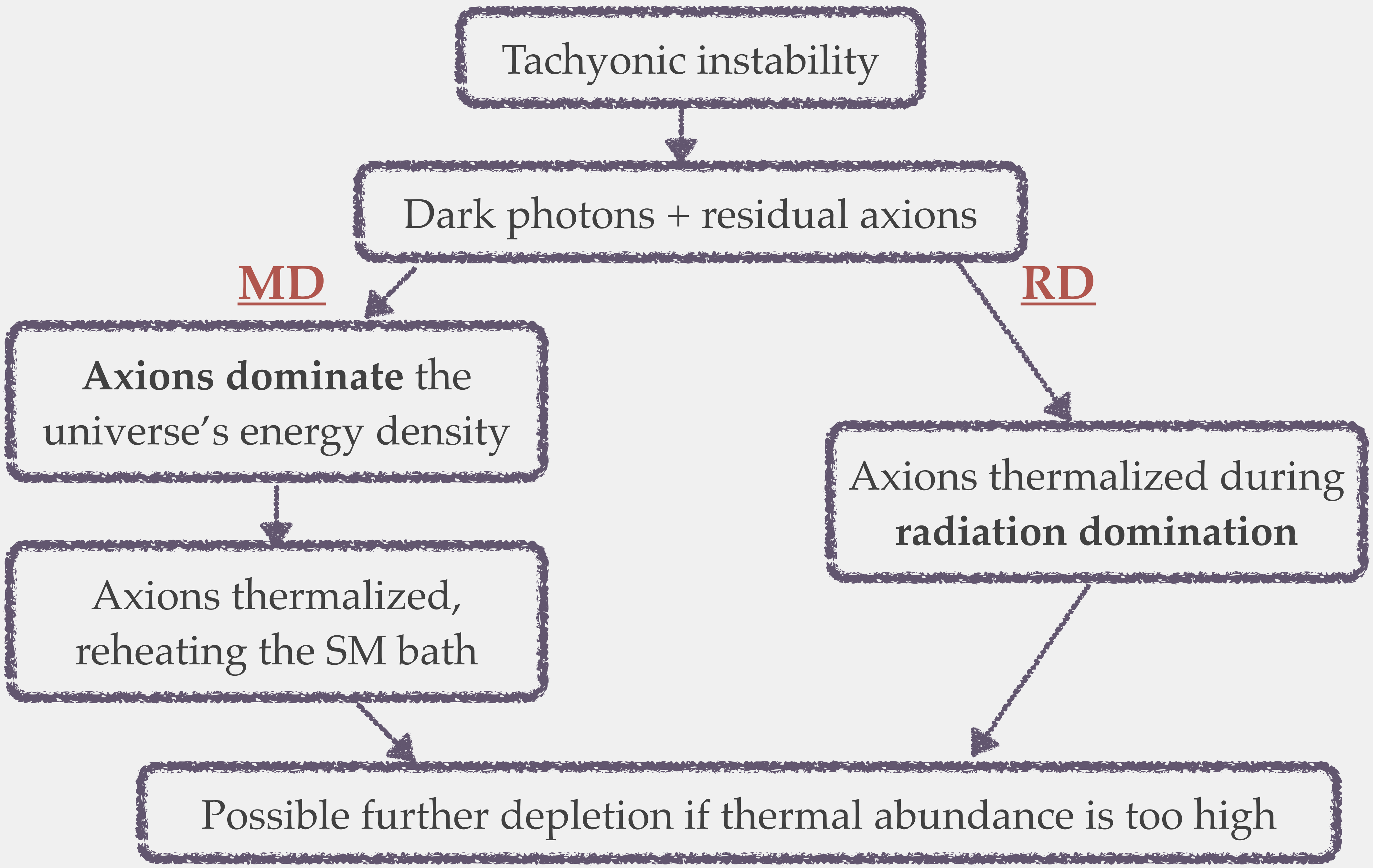
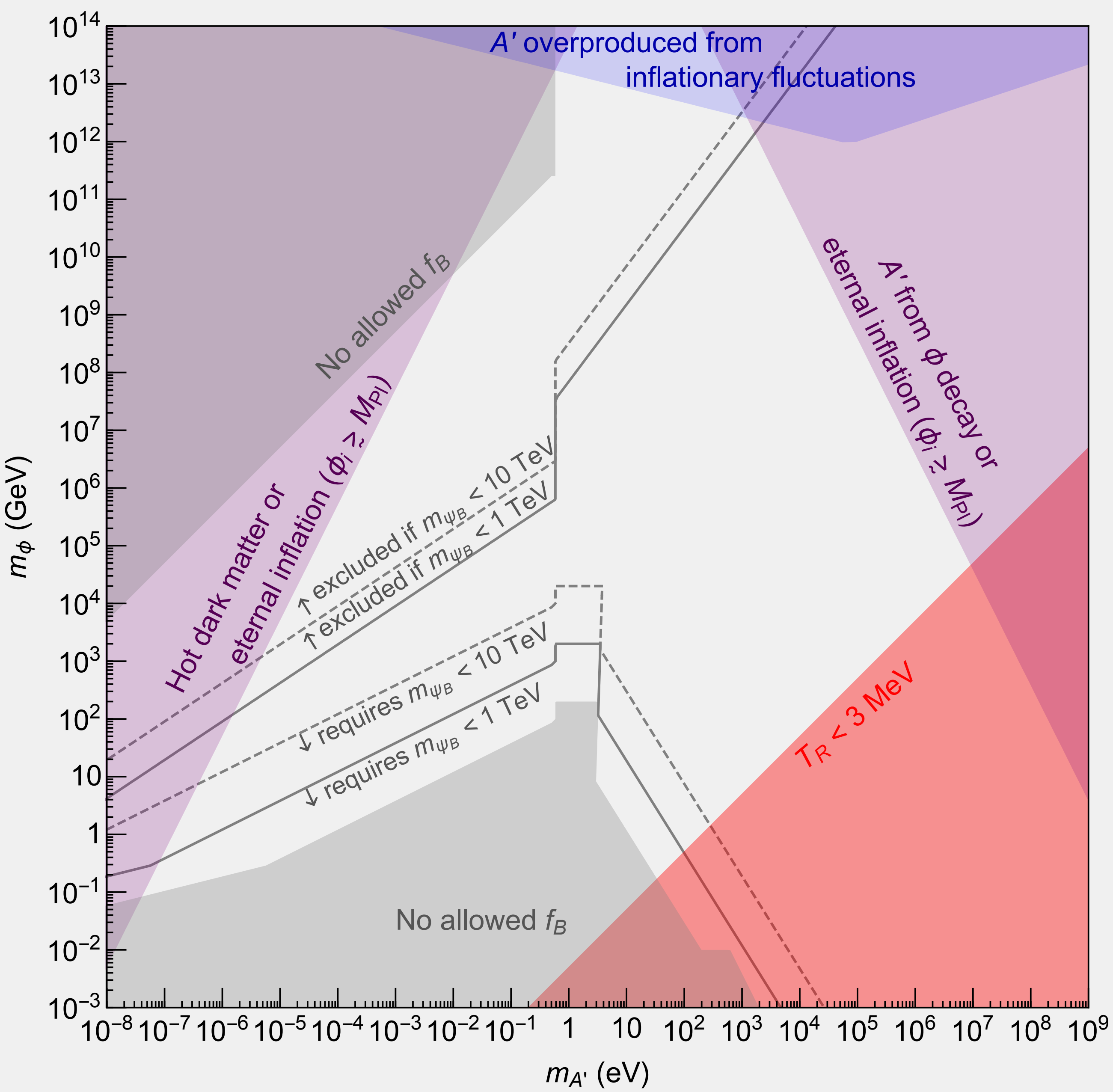


Two possible scenarios

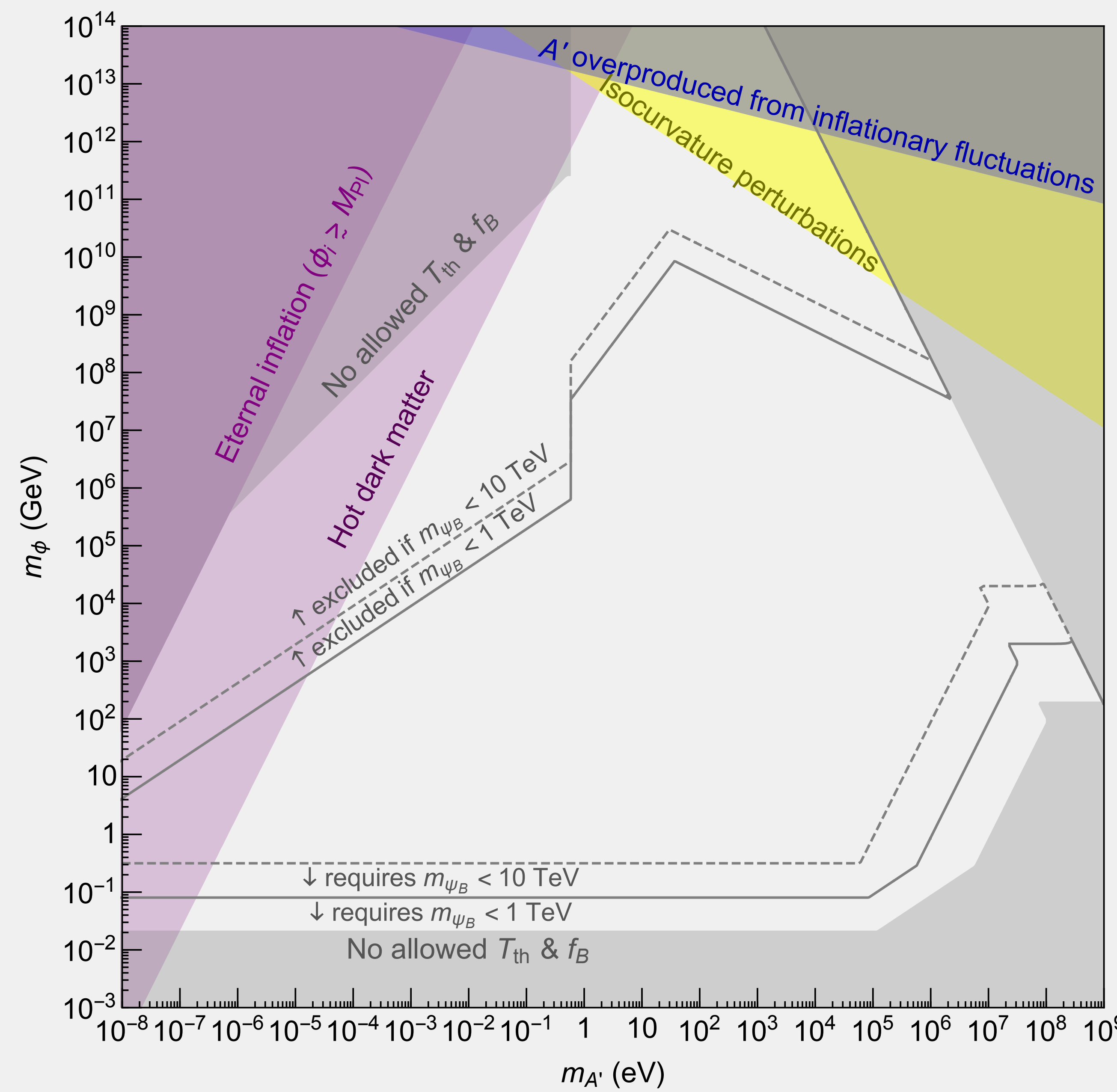


Results: viable parameter space in the $(m_{A'}, m_\phi)$ plane

Matter-dominated (MD) case



Radiation-dominated (RD) case



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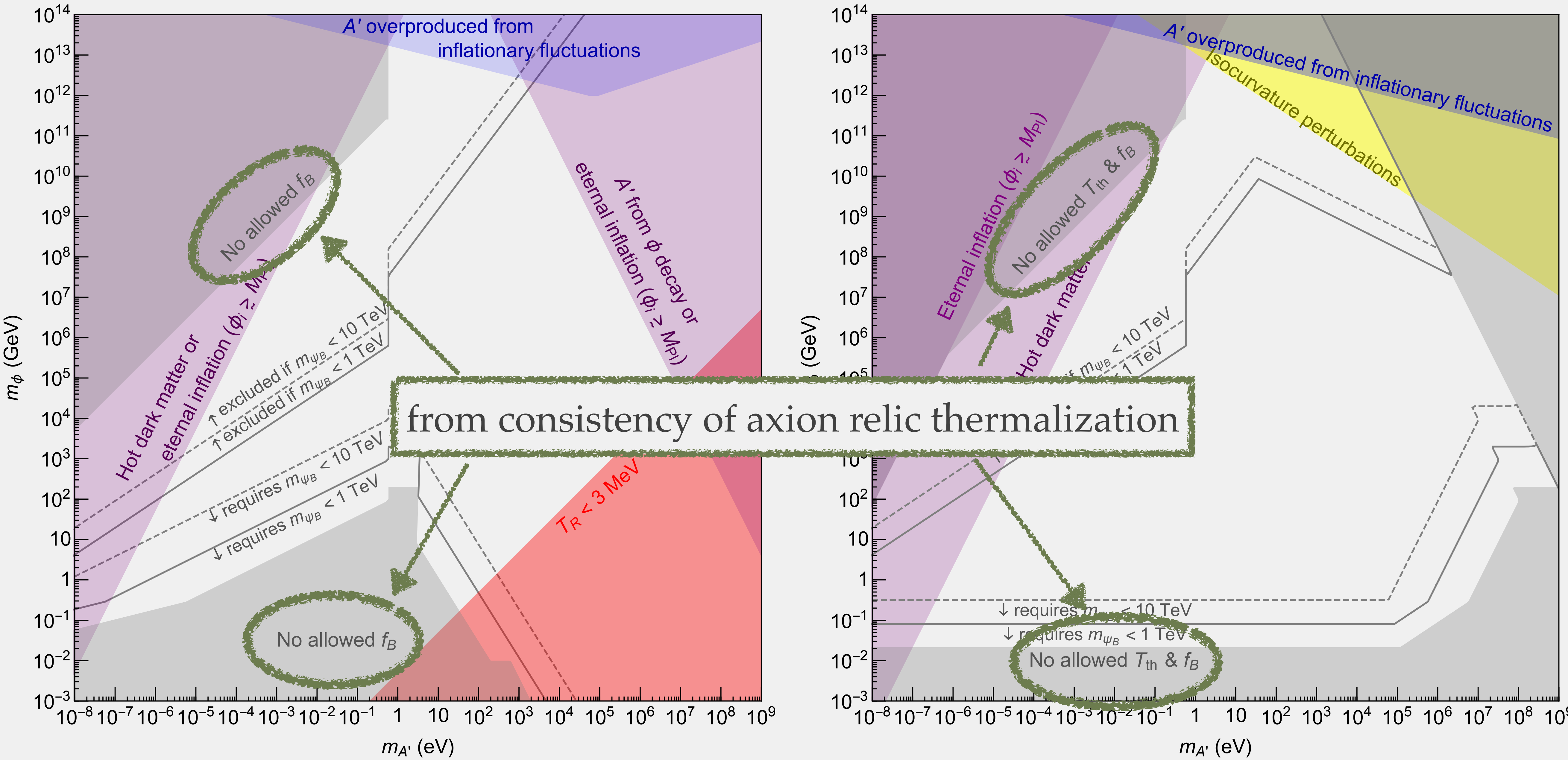


Consistent thermalization of the axion relic

- 3 additional parameters:

$$m_{\psi_B}\ ,\ f_B\ ,\ \phi_i$$

$$\Downarrow$$

Thermalization channels

$$\Downarrow \quad \Gamma(T) = H(T)$$

Thermalization temperature T_{th}

Consistent thermalization of the axion relic

- 3 additional parameters:

$$m_{\psi_B}\,,\ \overset{\boldsymbol{T_{th}}}{\cancel{f_B}}\,,\ \phi_i$$

$$\Downarrow$$

Thermalization channels

$$\Downarrow \quad \Gamma(T) = H(T)$$

~~Thermalization temperature T_{th}~~ ***f_B***

- In practice it is easier to solve for f_B.

Consistent thermalization of the axion relic

- 3 additional parameters: m_{ψ_B} , $\cancel{f_B}$ T_{th} , ϕ_i $\xrightarrow{\Gamma(T_{th}) = H(T_{th})}$ f_B
- One constraint: dark matter abundance $m_{A'} Y_{A'} \simeq 0.44\,\mathrm{eV}$

<u>Matter-dominated (MD) case</u>

$$Y_{A'} = \frac{n_{A'}}{s}\Big|_{T_{\rm th}} \sim \frac{n_\phi}{s}\Big|_{T_{\rm th}} = \frac{\rho_{\rm rad}}{m_\phi s}\Big|_{T_{\rm th}} = \frac{3}{4}\frac{T_{\rm th}}{m_\phi}$$

=> Fix $T_{\rm th} \simeq 0.6\,\mathrm{eV}\,\frac{m_\phi}{m_{A'}} \equiv T_R$

<u>Radiation-dominated (RD) case</u>

$$Y_{A'} = \frac{n_{A'}}{s}\Big|_{T_{\rm osc}} \sim \frac{n_\phi}{s}\Big|_{T_{\rm osc}} \sim \frac{m_\phi \phi_i^2}{s(T_{\rm osc})}$$

=> Fix $\phi_i \simeq 2 \times 10^{15}\,\mathrm{GeV}\left(\frac{m_\phi}{\mathrm{GeV}}\right)^{\frac{1}{4}}\left(\frac{\mathrm{meV}}{m_{A'}}\right)^{\frac{1}{2}} \equiv \phi_0$

<u>To see whether a point in the ($m_{A'}$, m_ϕ) plane is viable…</u>

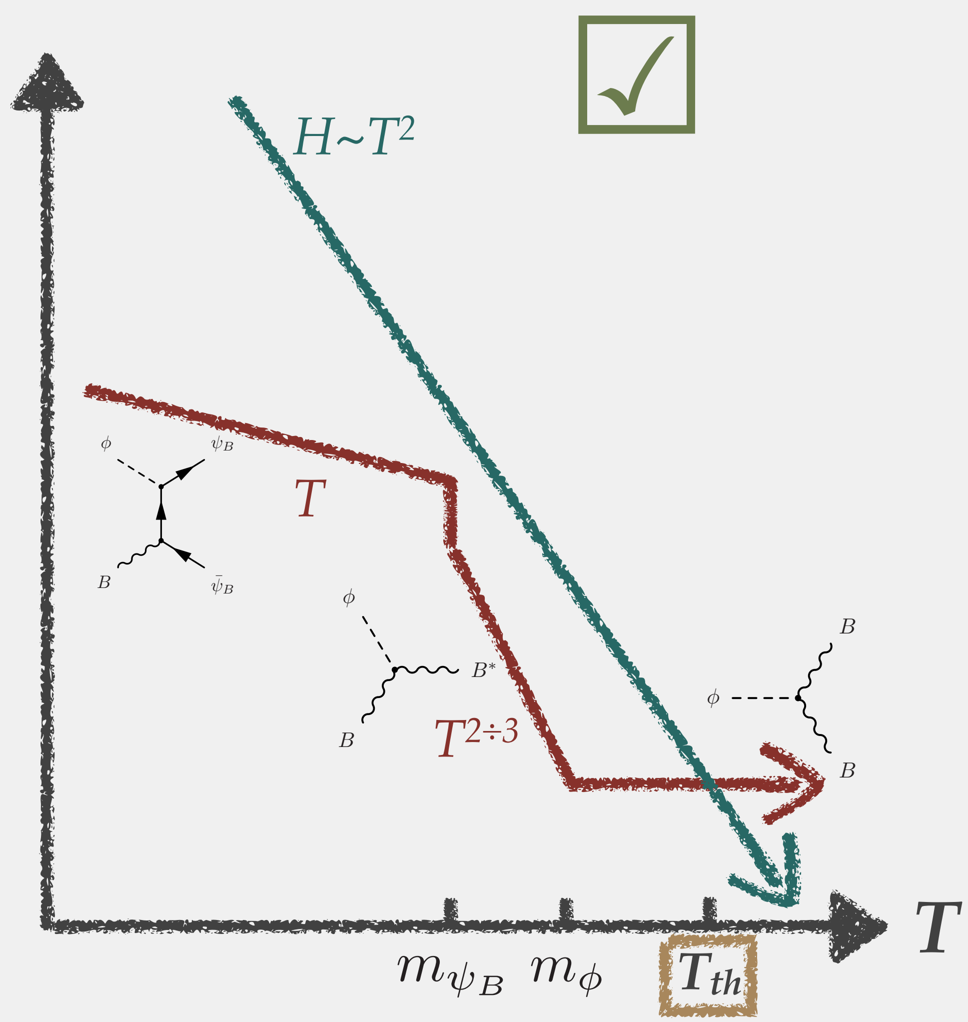
… we scan over $m_{\psi B}$ …

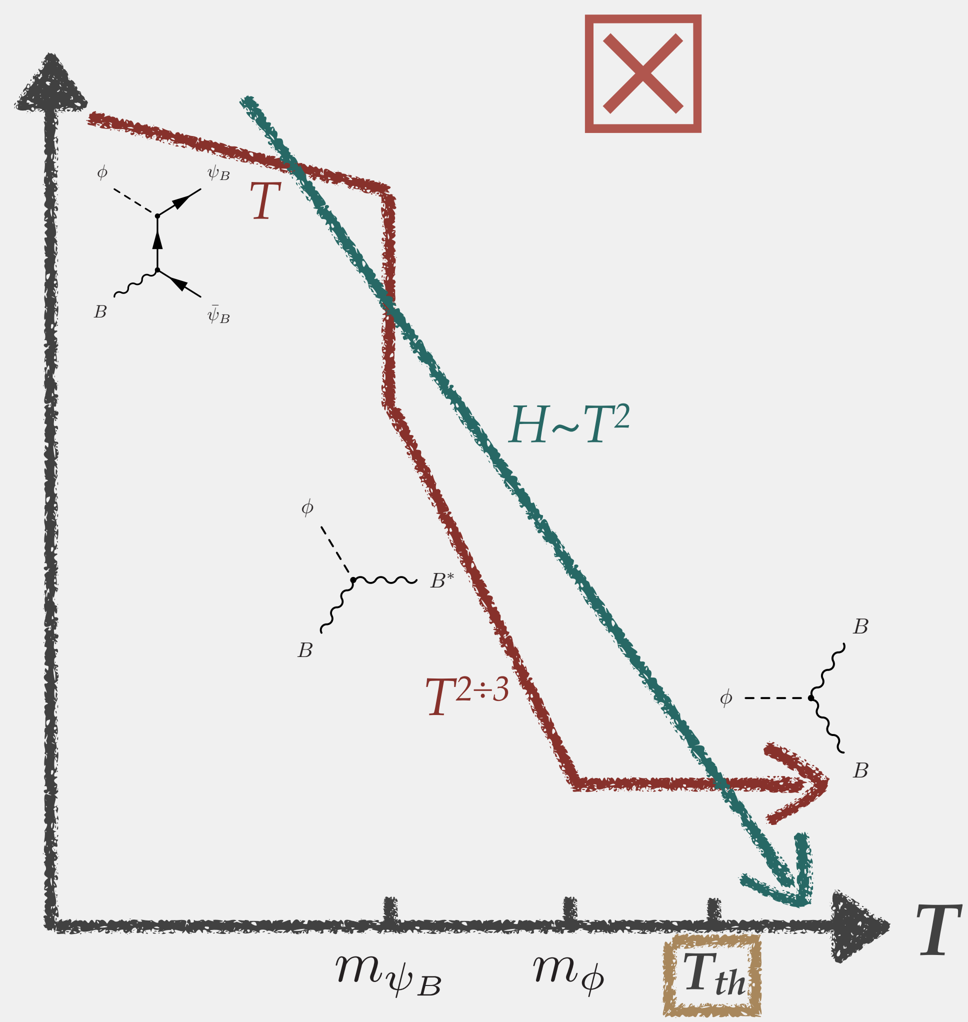
… we scan over $m_{\psi B}$ and T_{th} …

<u>… and see if there is a solution for f_B that satisfies a set of **consistency conditions** (next slide).</u>

Consistent thermalization of the axion relic

- No consistent solution for f_B if any of the following is violated:
  - $\Gamma(T) < H(T)$ at all higher temperatures (otherwise thermalized earlier).





Consistent thermalization of the axion relic

- No consistent solution for f_B if any of the following is violated:
  - $\Gamma(T) < H(T)$ at all higher temperatures (otherwise thermalized earlier).
  - Broken PQ symmetry (existence of axion field).
    - At the time of dark photon production, ψ_B should not induce a large thermal mass for the PQ breaking field to restore PQ symmetry.
    - Thermal mass $y_{\psi_B} T_{\rm osc} \sim \frac{m_{\psi_B}}{f_{\rm PQ}} T_{\rm osc}$ should not exceed f_{PQ} (for O(1) quartic).

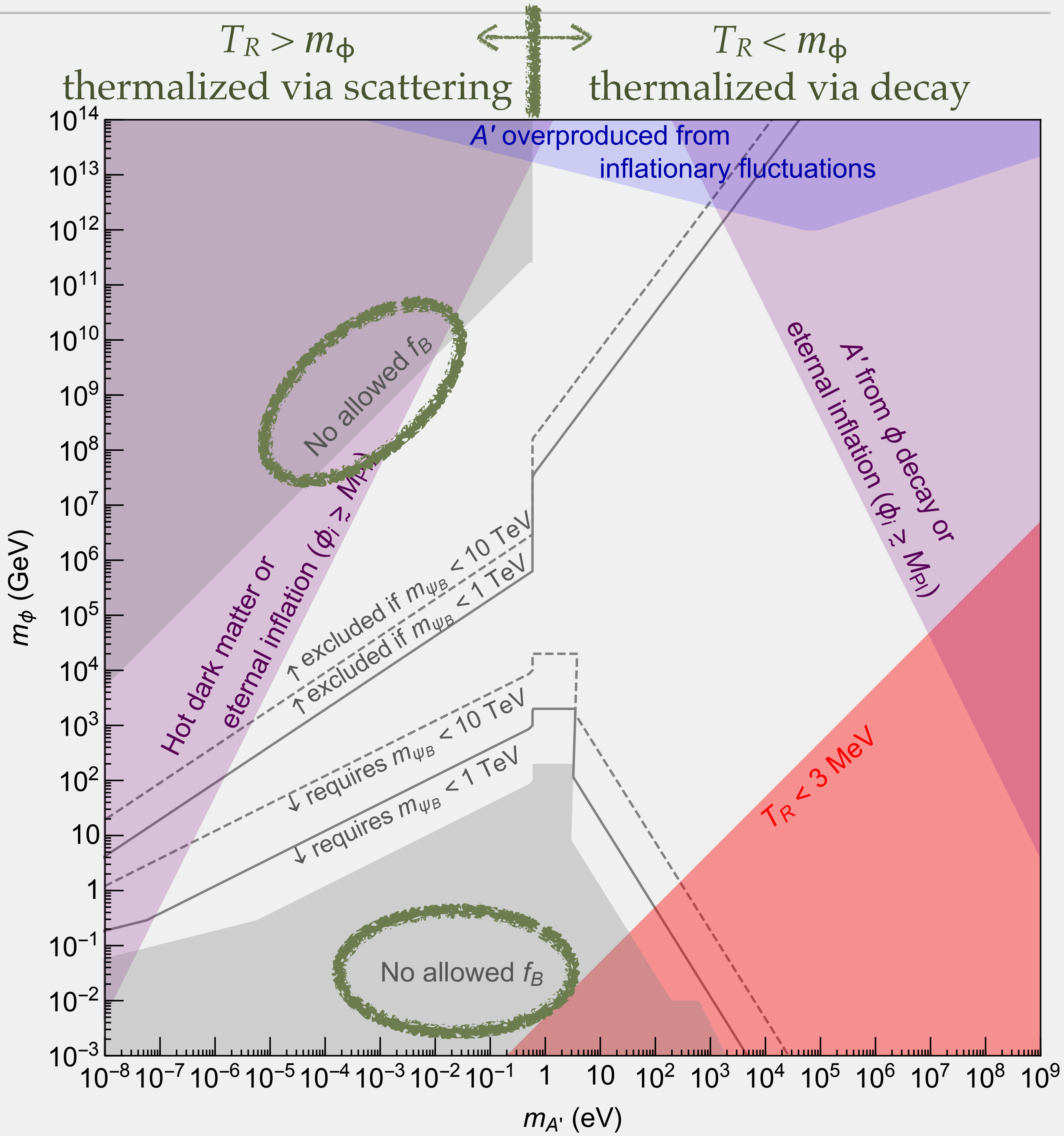
$$\Rightarrow \quad f_B \gtrsim f_{\rm PQ} \gtrsim 10^5\,\mathrm{GeV}\left(\frac{m_\phi}{\mathrm{GeV}}\right)^{\frac{1}{4}}\left(\frac{m_{\psi_B}}{100\,\mathrm{GeV}}\right)^{\frac{1}{2}}$$

Consistent thermalization of the axion relic

- No consistent solution for f_B if any of the following is violated:
  - $\Gamma(T) < H(T)$ at all higher temperatures (otherwise thermalized earlier).
  - Broken PQ symmetry (existence of axion field).
  - $f_B > m_\phi\,, \quad f_B > \frac{\sqrt{2}}{4\pi} m_{\psi_B}$ (assuming perturbative coupling).
  - Astrophysical constraints: $f_B > 10^7\,\mathrm{GeV} \quad \text{if} \ \ m_\phi < 10\,\mathrm{MeV}$
  - If $T_{\mathrm{th}} > m_\phi$, thermalization is not sufficient to deplete the axions. The thermal axion abundance has to decay away fast enough, setting an upper bound on f_B.

Consistent thermalization: MD scenario

- The aforementioned consistency conditions **exclude gray regions** (assuming $m_{\psi_B} > 100\,\mathrm{GeV}$).
  - Irregular shape is due to different thermalization channels.
  - Most constraining for light A' (high T_R).
    - Low m_ϕ => cannot decay in time after thermalization.
    - High m_ϕ => T_{osc} too high, easy to restore PQ symmetry.
  - Consistent thermalization requires (sub)TeV PQ fermion in some regions, potentially within collider reach.

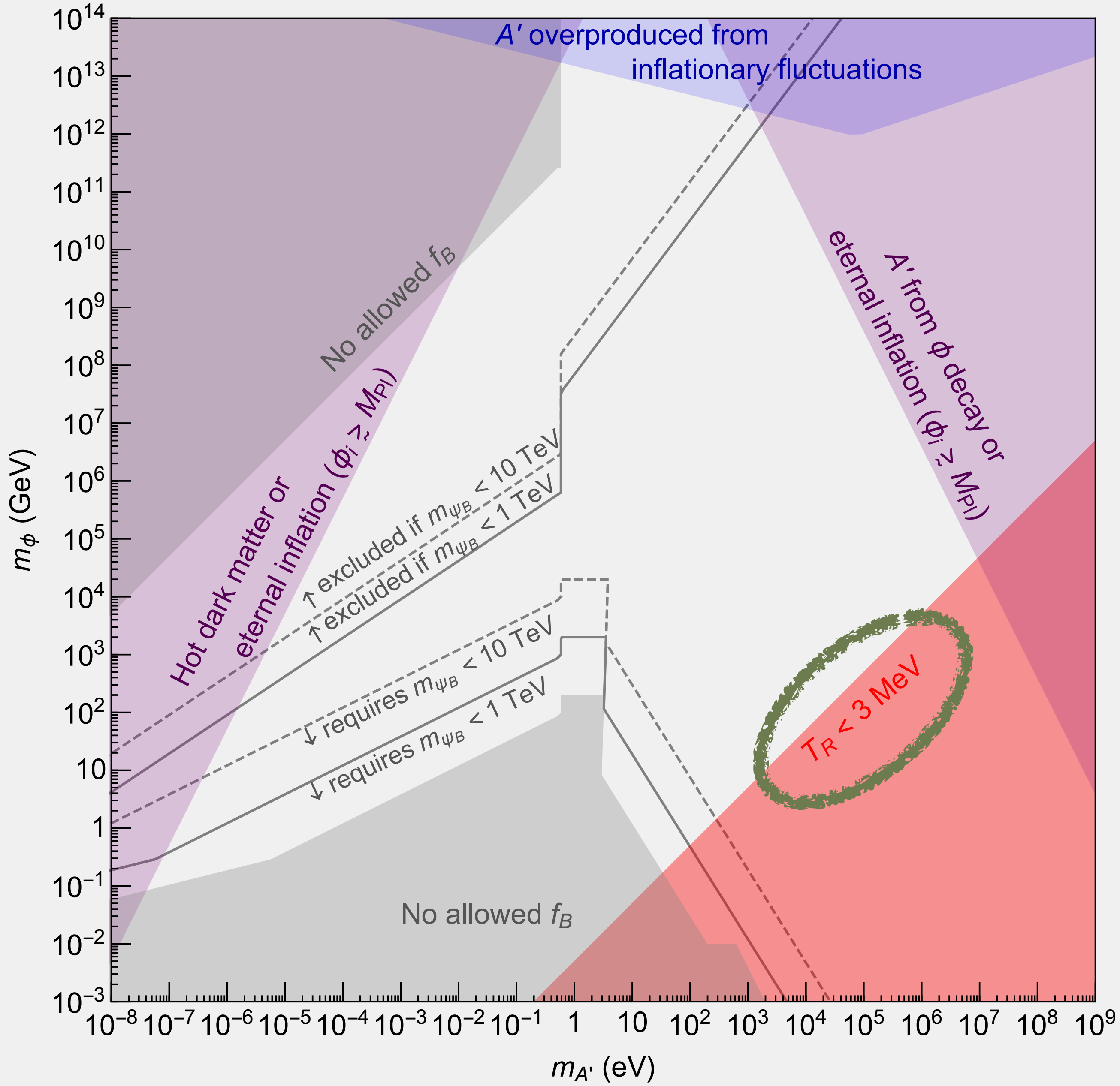


MD scenario: other constraints

- Successful BBN:

$$T_R \simeq 0.6\,\mathrm{eV}\frac{m_\phi}{m_{A'}} > 3\,\mathrm{MeV}$$

  - Mass ratio has to be large enough.
  - Exclude red region.



MD scenario: other constraints

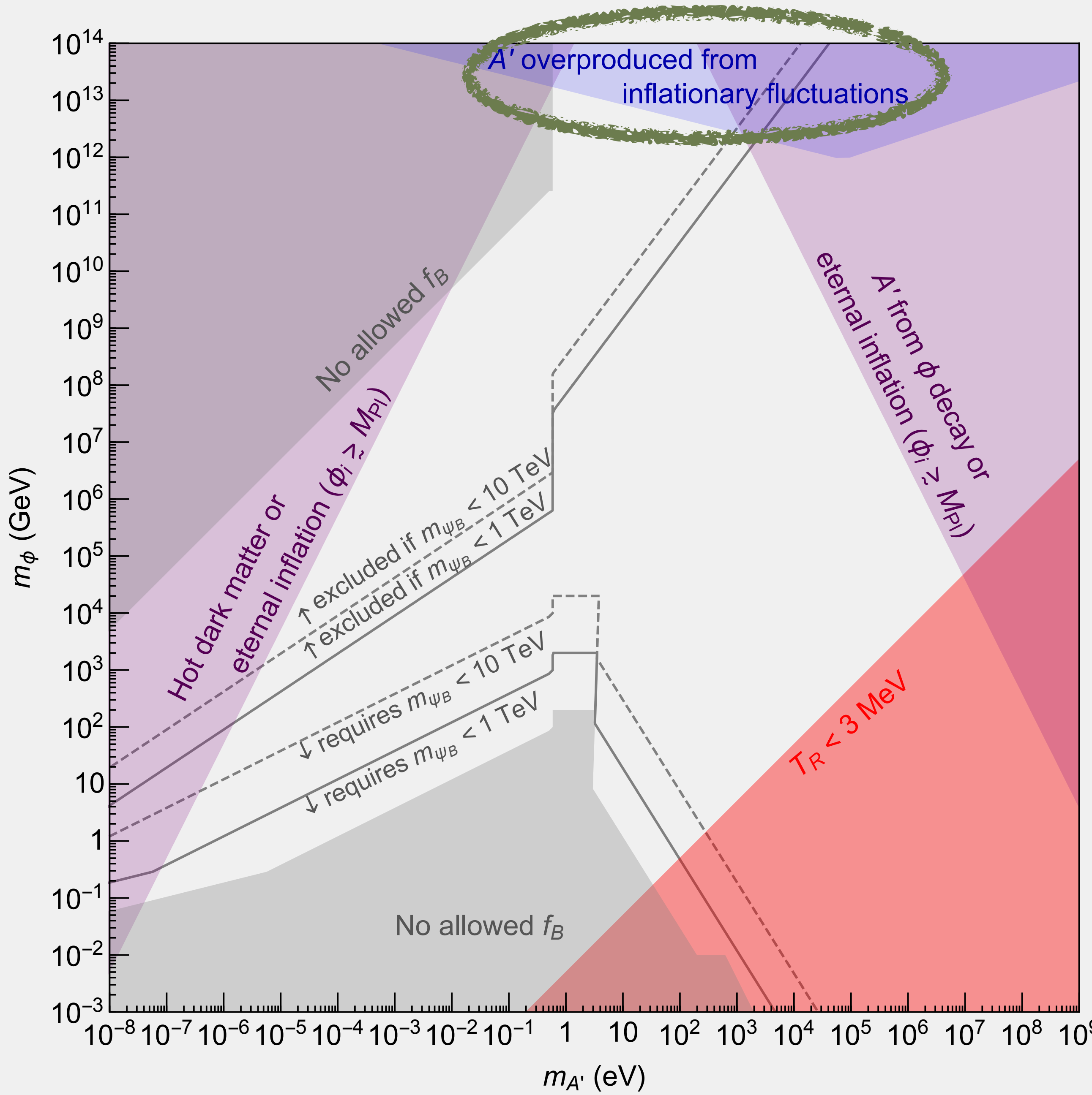
- Successful BBN:

$$T_R \simeq 0.6\,\mathrm{eV}\,\frac{m_\phi}{m_{A'}} > 3\,\mathrm{MeV}$$

  - Mass ratio has to be large enough.
  - Exclude red region.
- No excessive dark photon production from inflationary fluctuations [Graham, Mardon, Rajendran, 1504.02102]:

$$\frac{\Omega_{A'}^{\rm inf}}{\Omega_{\rm DM}} \simeq \min\left(1, \sqrt{H(T_R)/m_{A'}}\right)\left(\frac{m_{A'}}{6\times10^{-6}\,\mathrm{eV}}\right)^{\frac{1}{2}}\left(\frac{H_I}{10^{14}\,\mathrm{GeV}}\right)^2 < 1$$

  - Since m_ϕ cannot exceed H_I (otherwise oscillations begin during inflation), this sets an upper bound on m_ϕ.
  - Exclude blue region.



MD scenario: other constraints

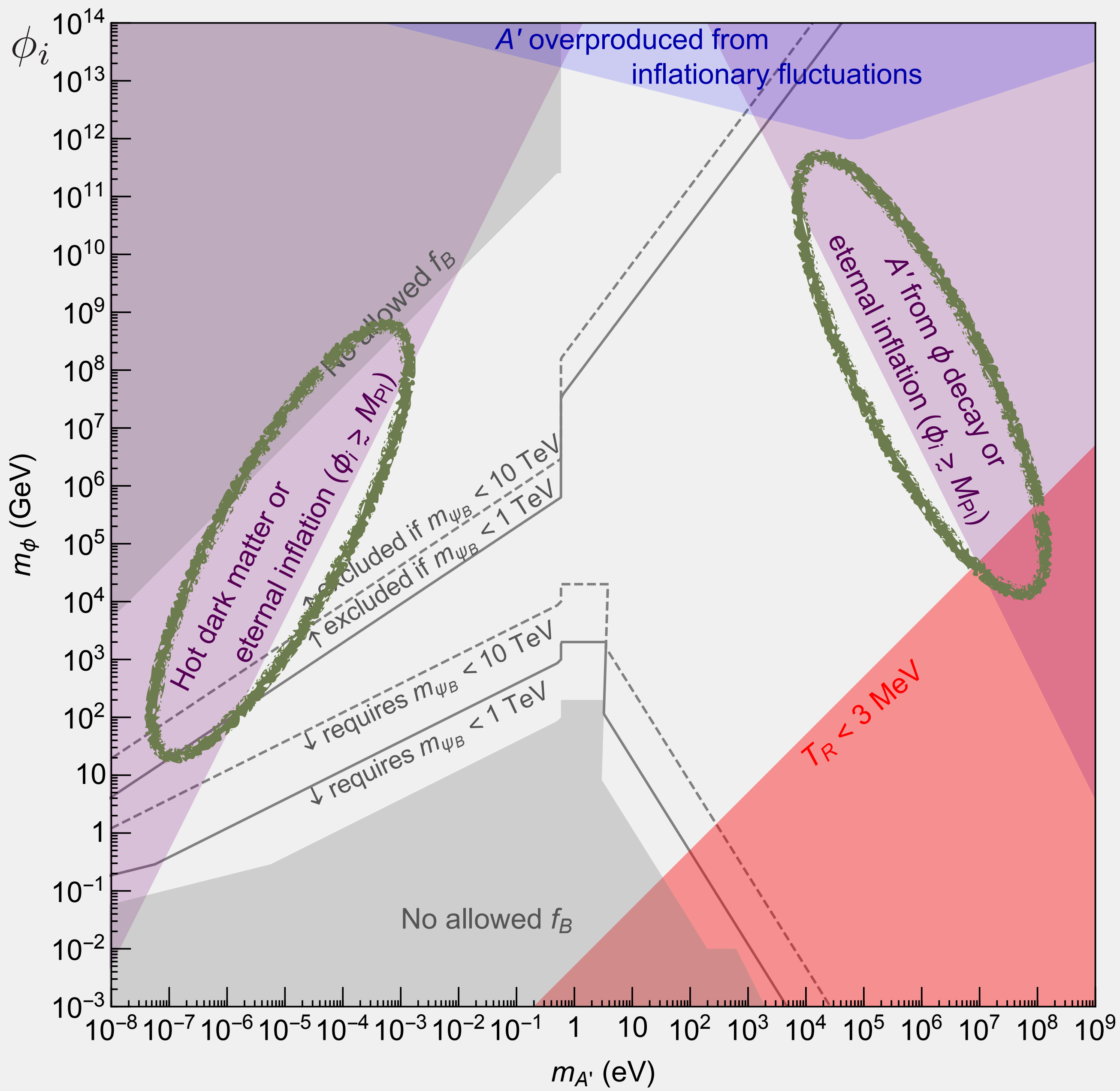
- Constraints on the other free parameter ϕ_i (irrelevant for thermalization).
  - It should be sub-Planckian because otherwise $H > \sqrt{m_\phi^2 \phi_i^2 / M_{\rm Pl}} > m_\phi$ => oscillations never begin.
- But this may be in tension with:
  - Coldness of dark matter =>

$$\phi_i \gtrsim 4 \times 10^{10}\,\text{GeV} \left(\frac{m_\phi}{\text{GeV}}\right) \left(\frac{\text{meV}}{m_{A'}}\right)^2$$

  - No perturbative decay into A' =>

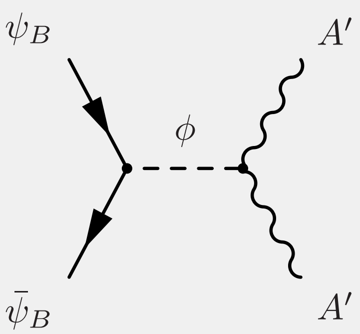
$$\phi_i \gtrsim 10 \cdot \frac{2\pi f_D}{\alpha_D} \gtrsim 10^6\,\text{GeV} \left(\frac{m_\phi}{\text{GeV}}\right)^{\frac{1}{2}} \left(\frac{m_{A'}}{\text{meV}}\right)$$

  - MD assumption (weaker).
  - Exclude purple regions.



RD scenario

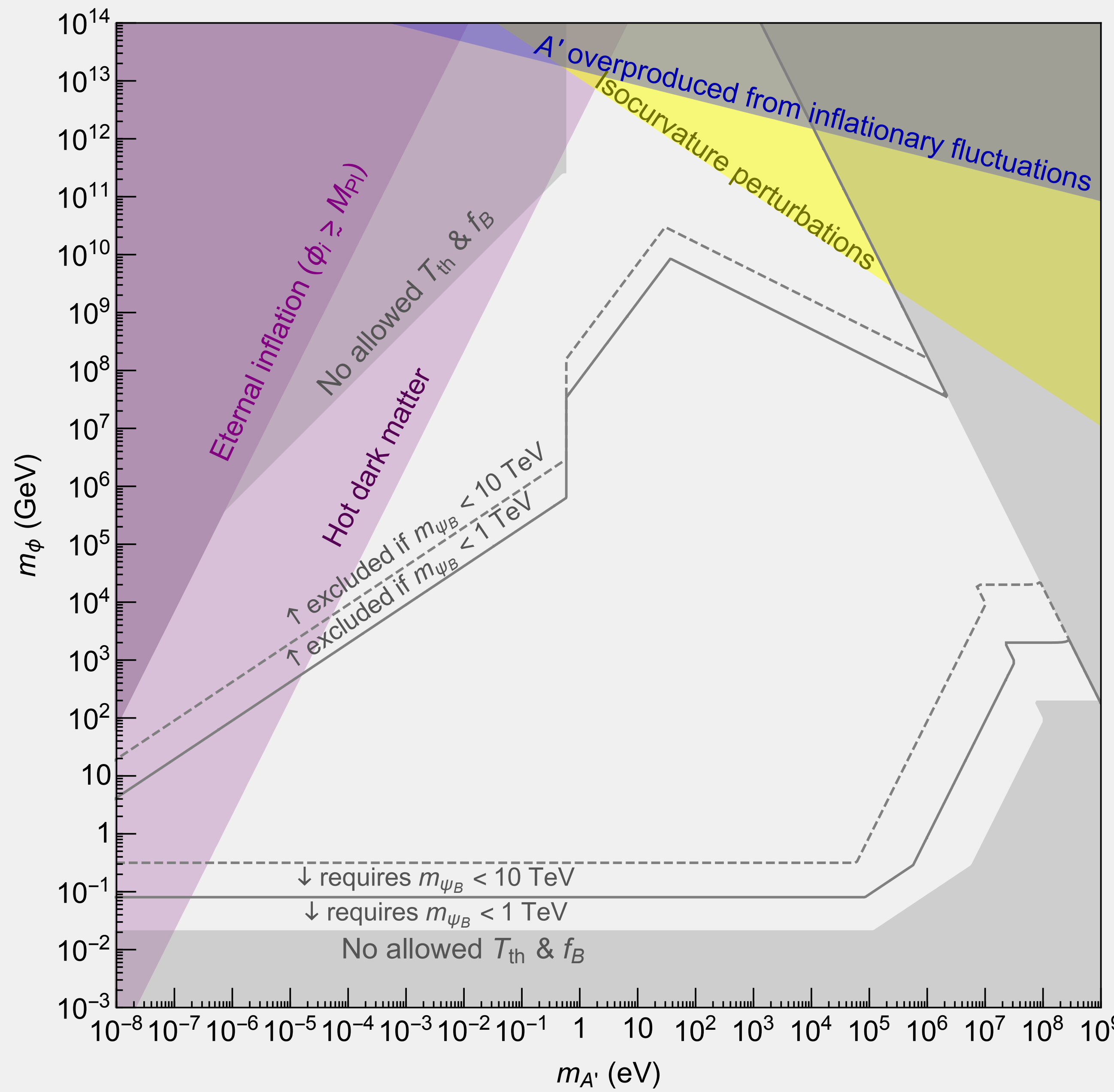
- One more parameter to scan => more parameter space allowed. Otherwise similar to the MD scenario.
- Additional constraints:
  - No excessive A' production via freeze-in (irrelevant for the MD case due to dilution): taken into account in the gray regions.



$$\frac{\Omega_{A'}^{\mathrm{FI}}}{\Omega_{\mathrm{DM}}} \simeq \left(\frac{m_{A'}}{0.1\,\mathrm{keV}}\right)^2 \left(\frac{m_{\psi_B}}{f_B}\right)^2 < 1$$

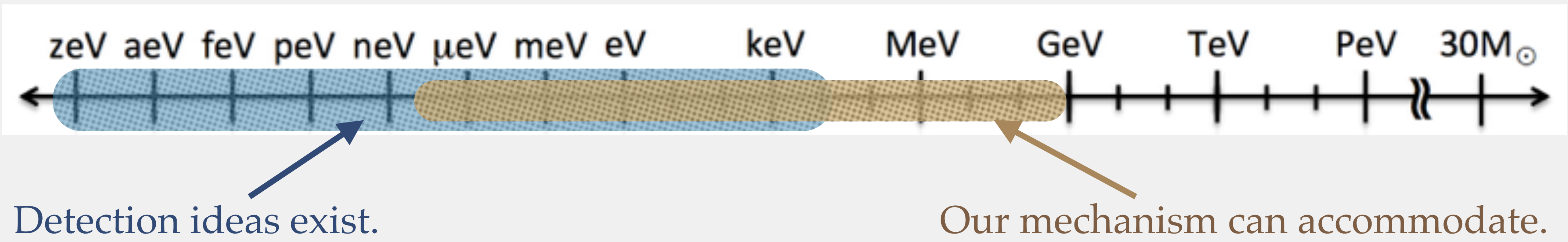
  - Isocurvature perturbation constraint from Planck [1807.06211] (weaker than other constraints in the MD case): yellow region.

$$\mathcal{P}_{\mathrm{iso}}^{A'} \simeq \mathcal{P}_{\mathrm{iso}}^{\phi} \simeq \left(\frac{H_I}{\pi\phi_i}\right)^2 \lesssim 8.7\times 10^{-11}$$

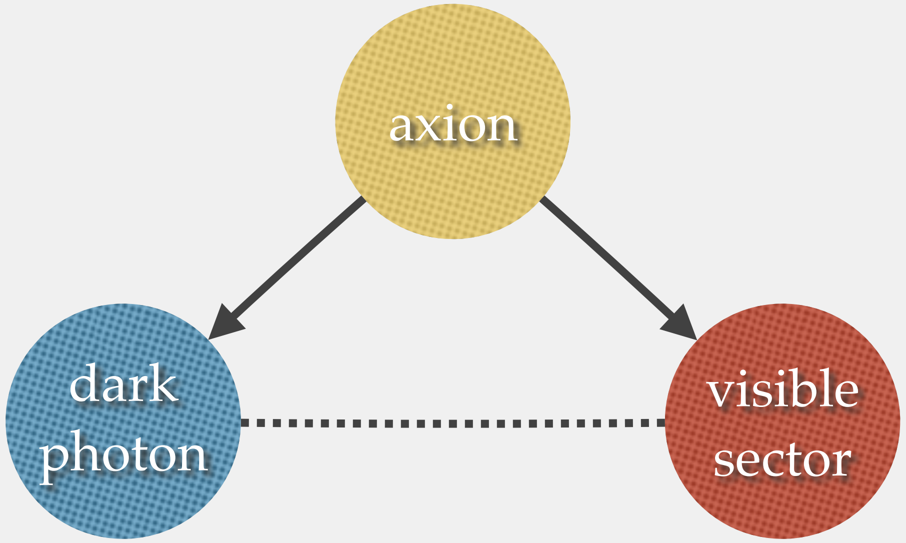


Summary

- We explored a novel mechanism for producing dark photon dark matter that works for a broad range of masses.



- Simple setup involving an axion. Dark photons produced from a tachyonic instability.
- Nontrivial constraints from requiring the residual axion relic be depleted.
- PQ fermions play an important role in axion thermalization, and may be probed at colliders.



The End

Thank you for your attention!