The Irreducible Axion Background

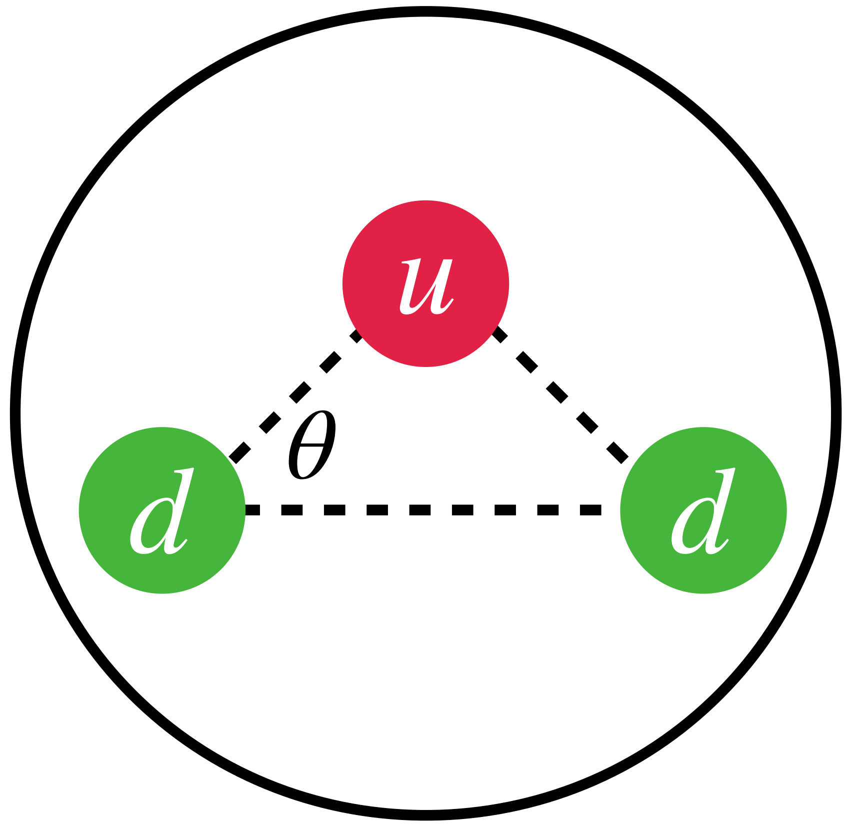
Kevin Langhoff - UC Berkeley

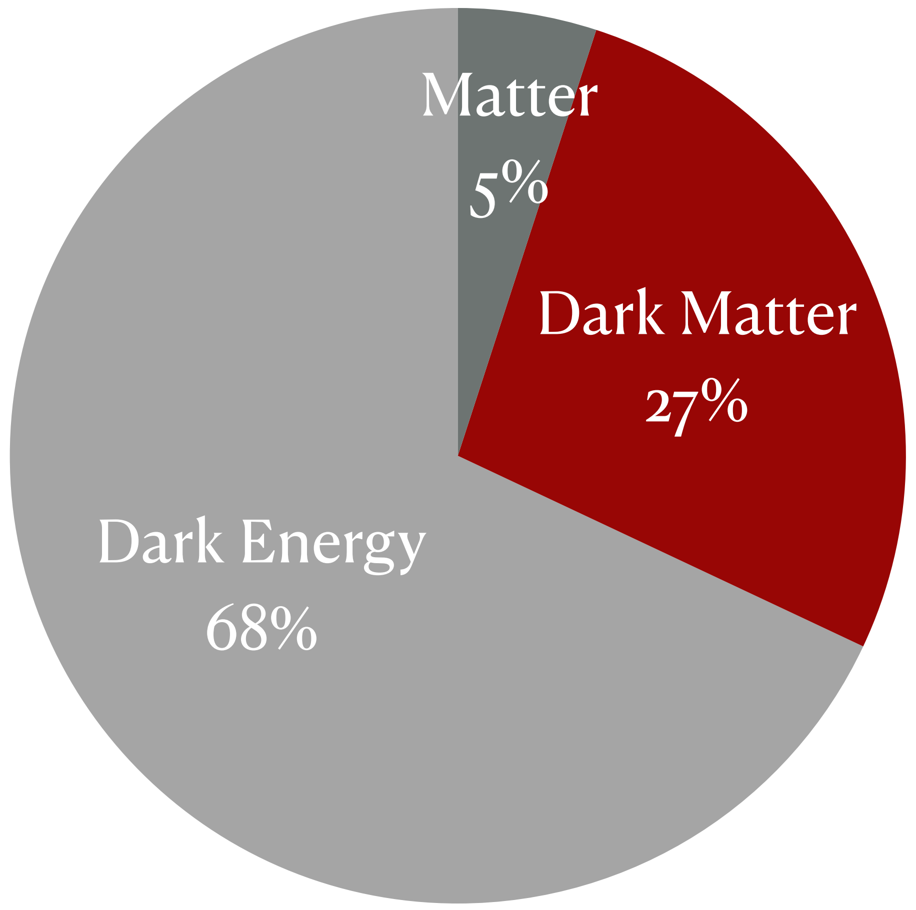
Nadav Outmezguine (UCB) and Nick Rodd (CERN)

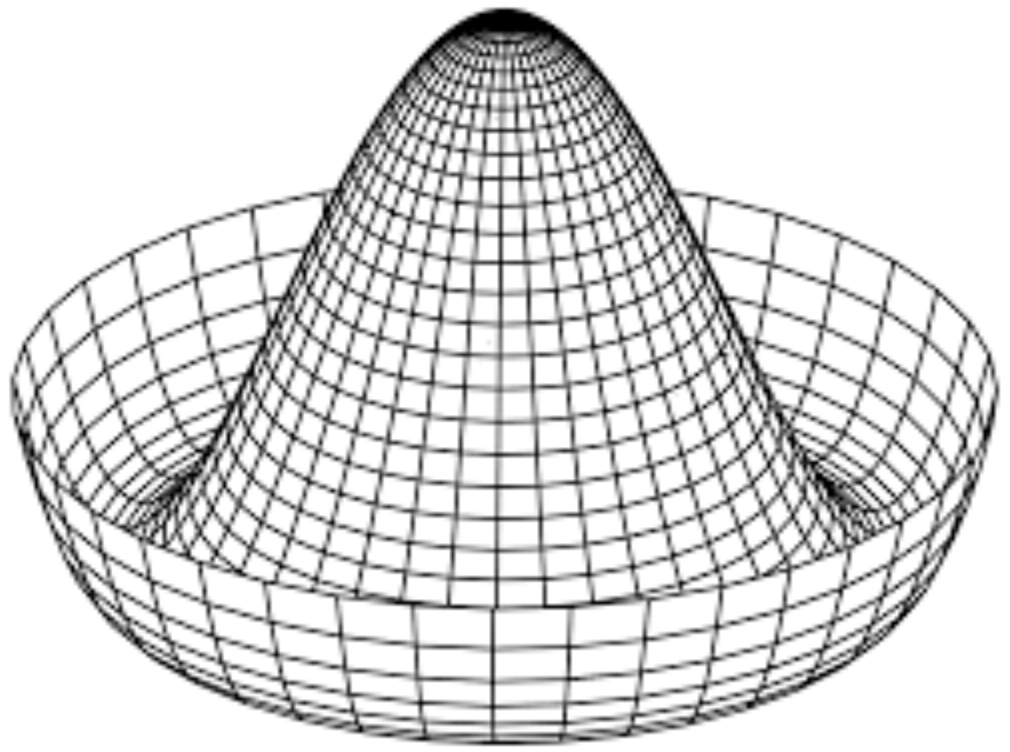
[2208.07882]

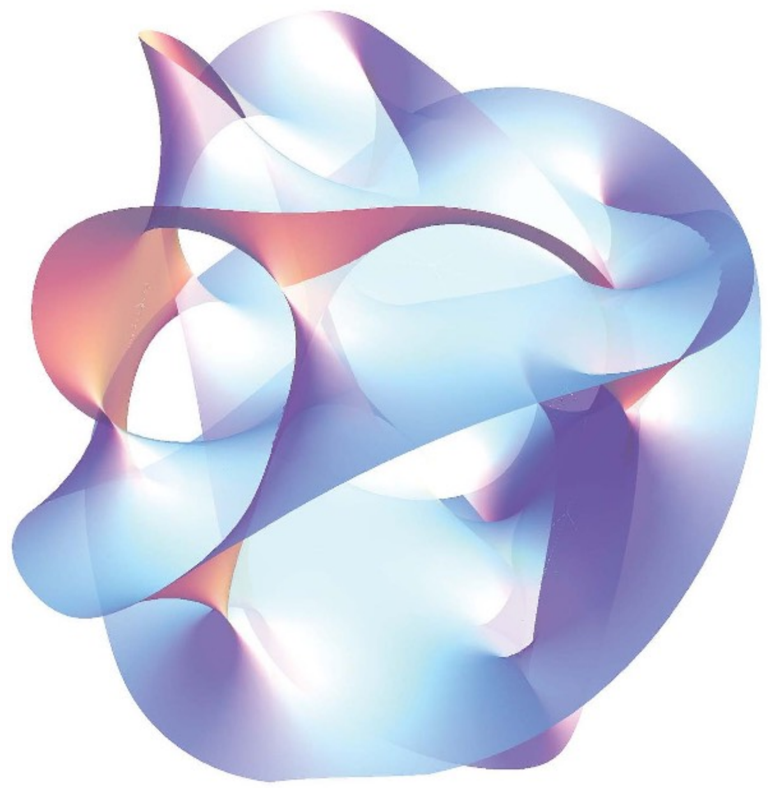
Why Axions?

- Strong CP
- Dark matter candidate
- Potential mediator to dark sector
- Prevalent in string theories.
- Goldstone bosons of global symmetries



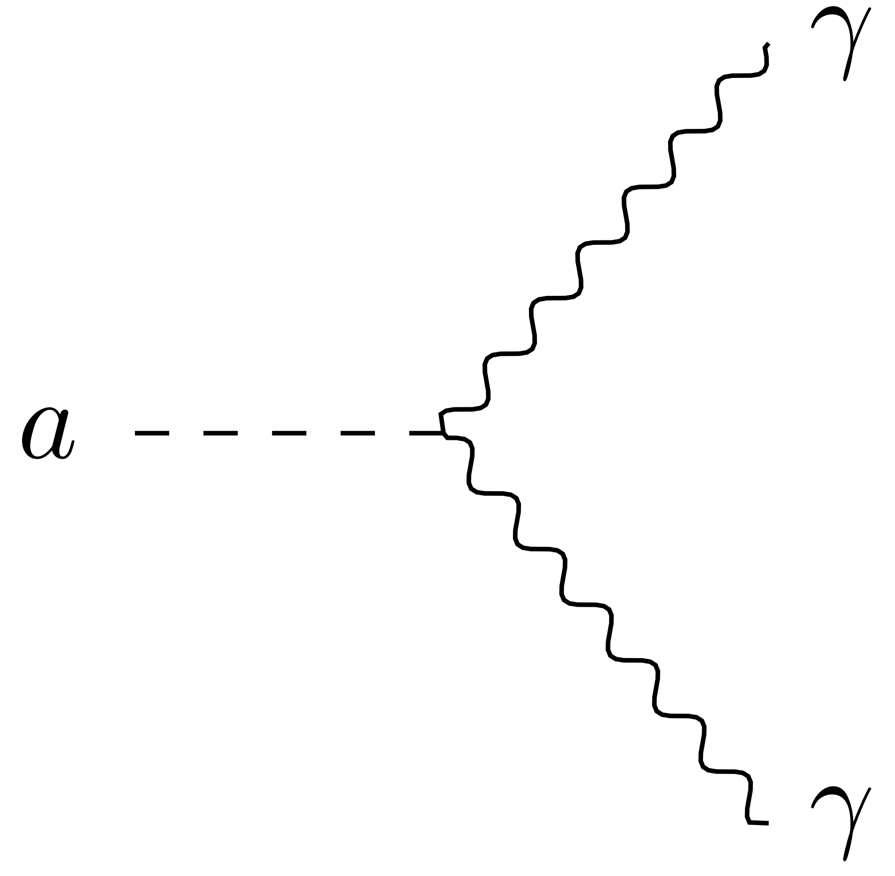


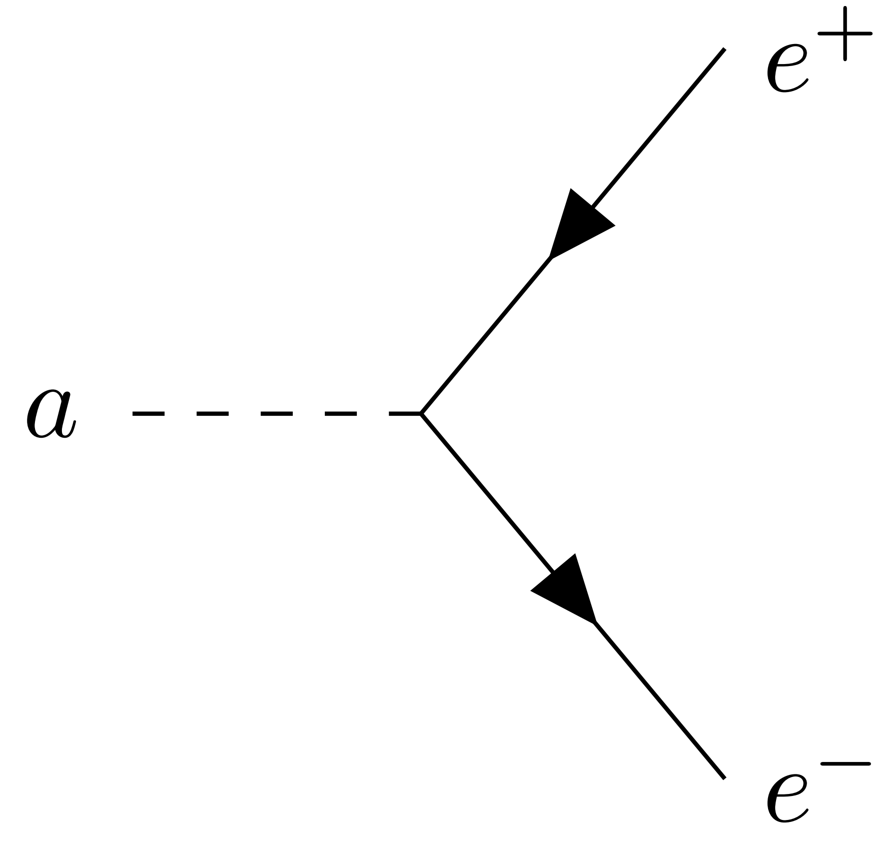




Today's Definition of Axions

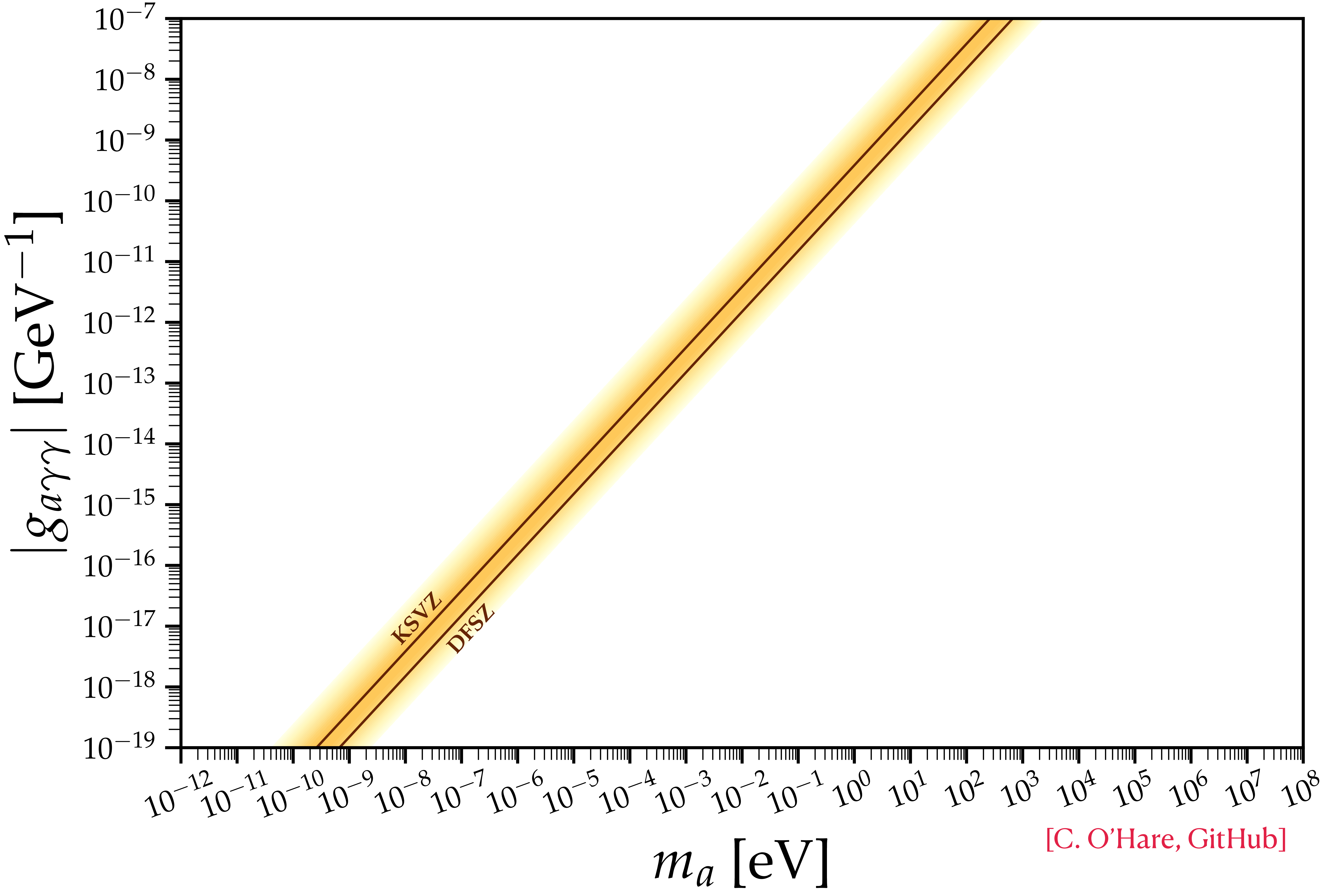
$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{g_{aee}}{2m_e}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$





Axion Parameter Space

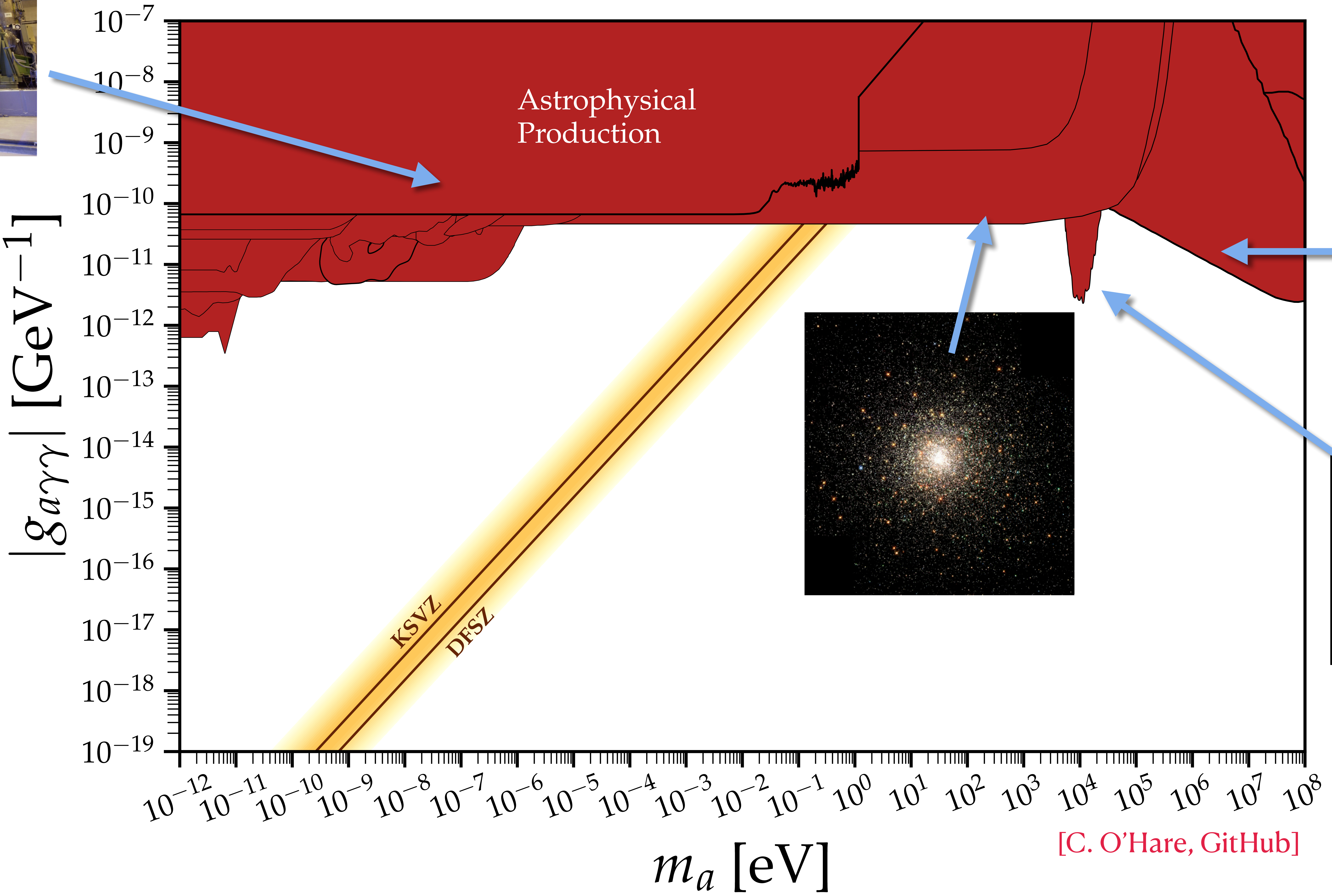
If it solves strong CP (Canonically)

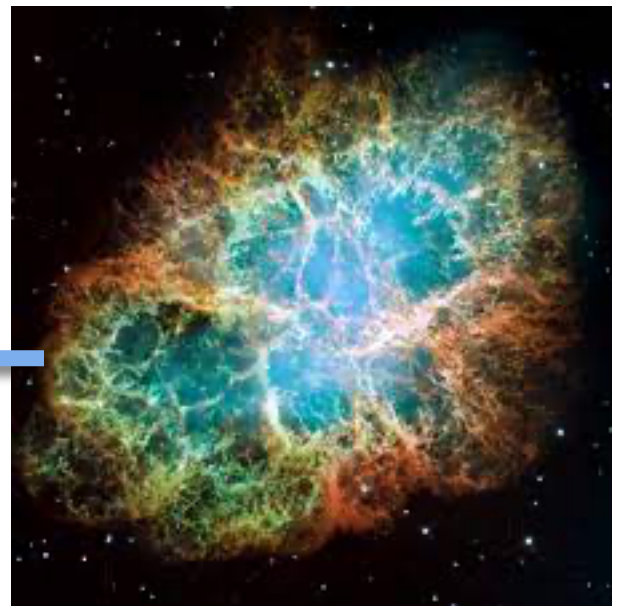


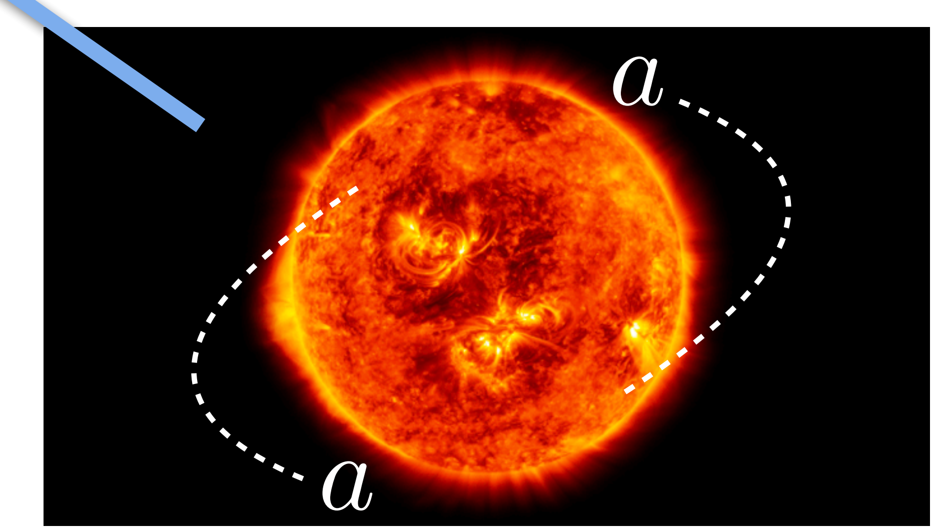
[C. O'Hare, GitHub]

Axion Parameter Space

If it exists



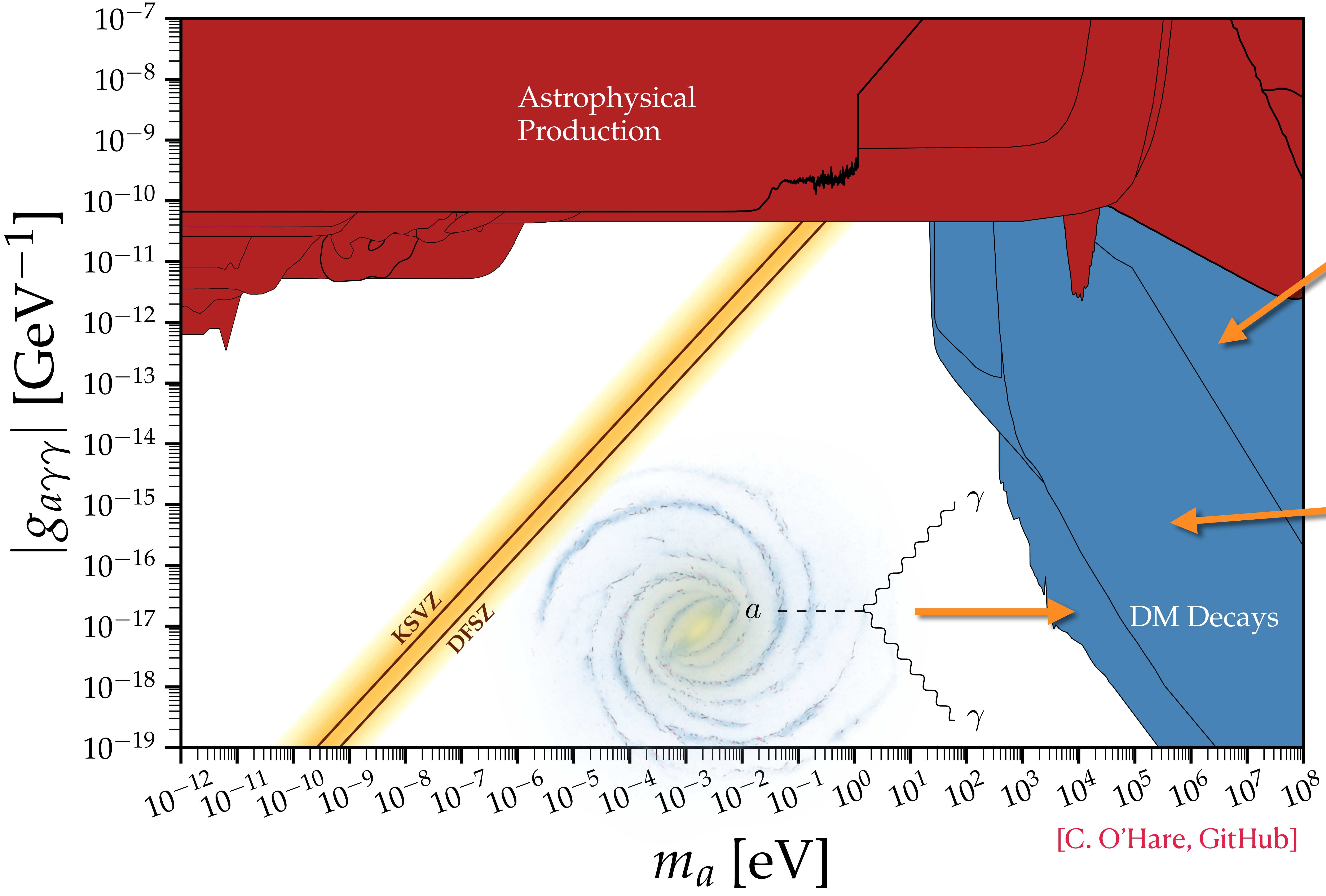




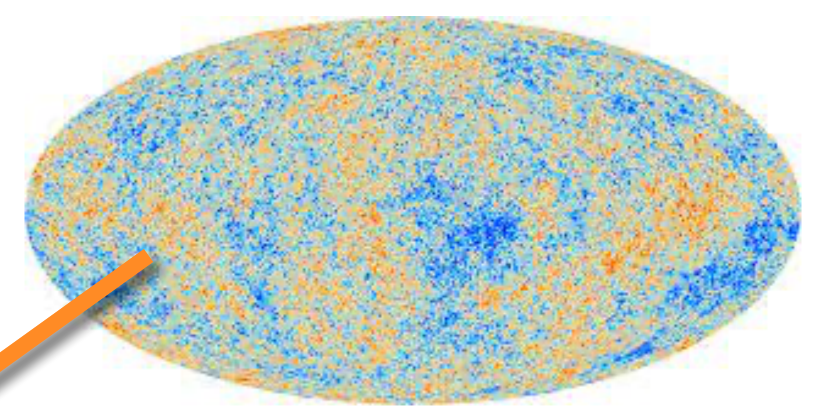
[C. O'Hare, GitHub]

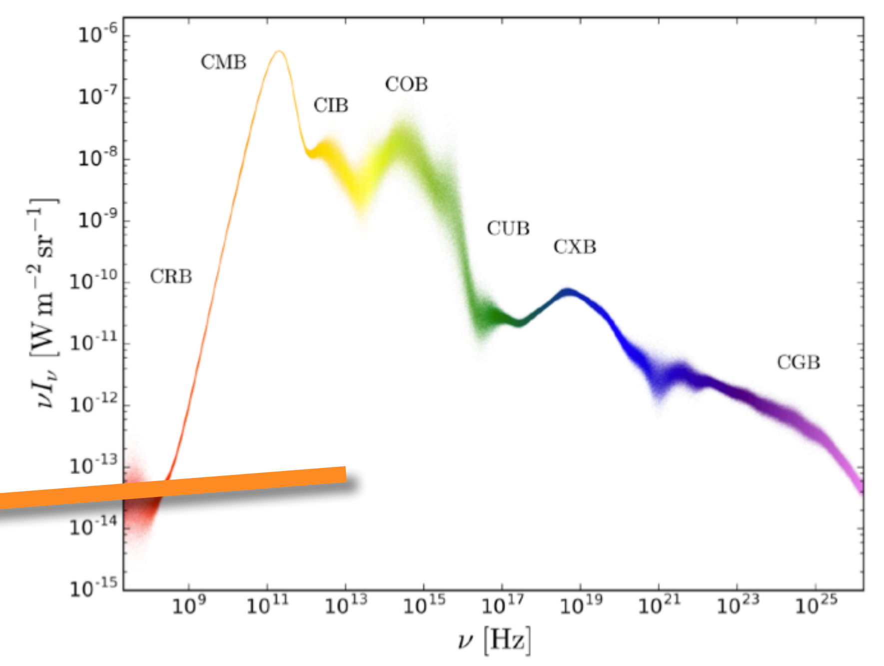
Axion Parameter Space

If it is all of DM



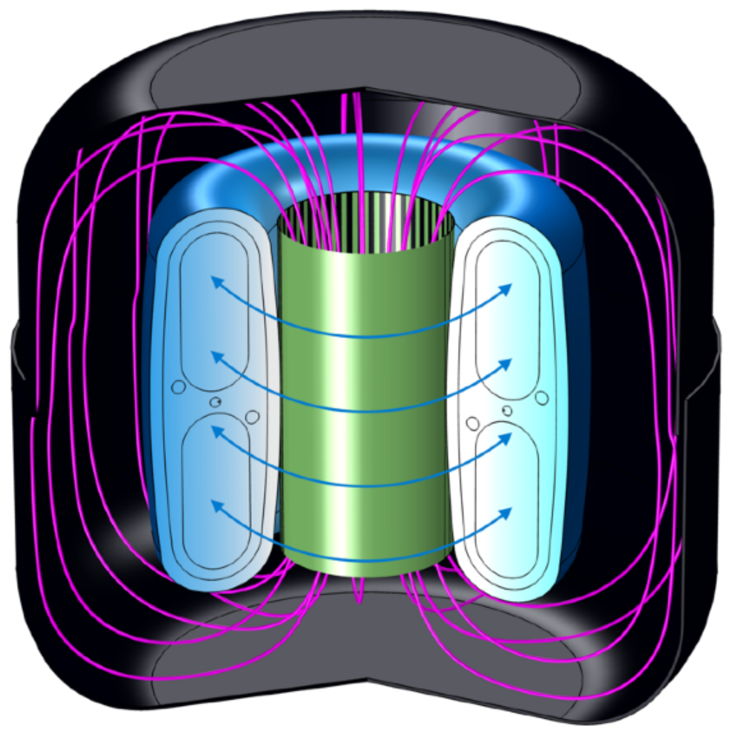
[C. O'Hare, GitHub]



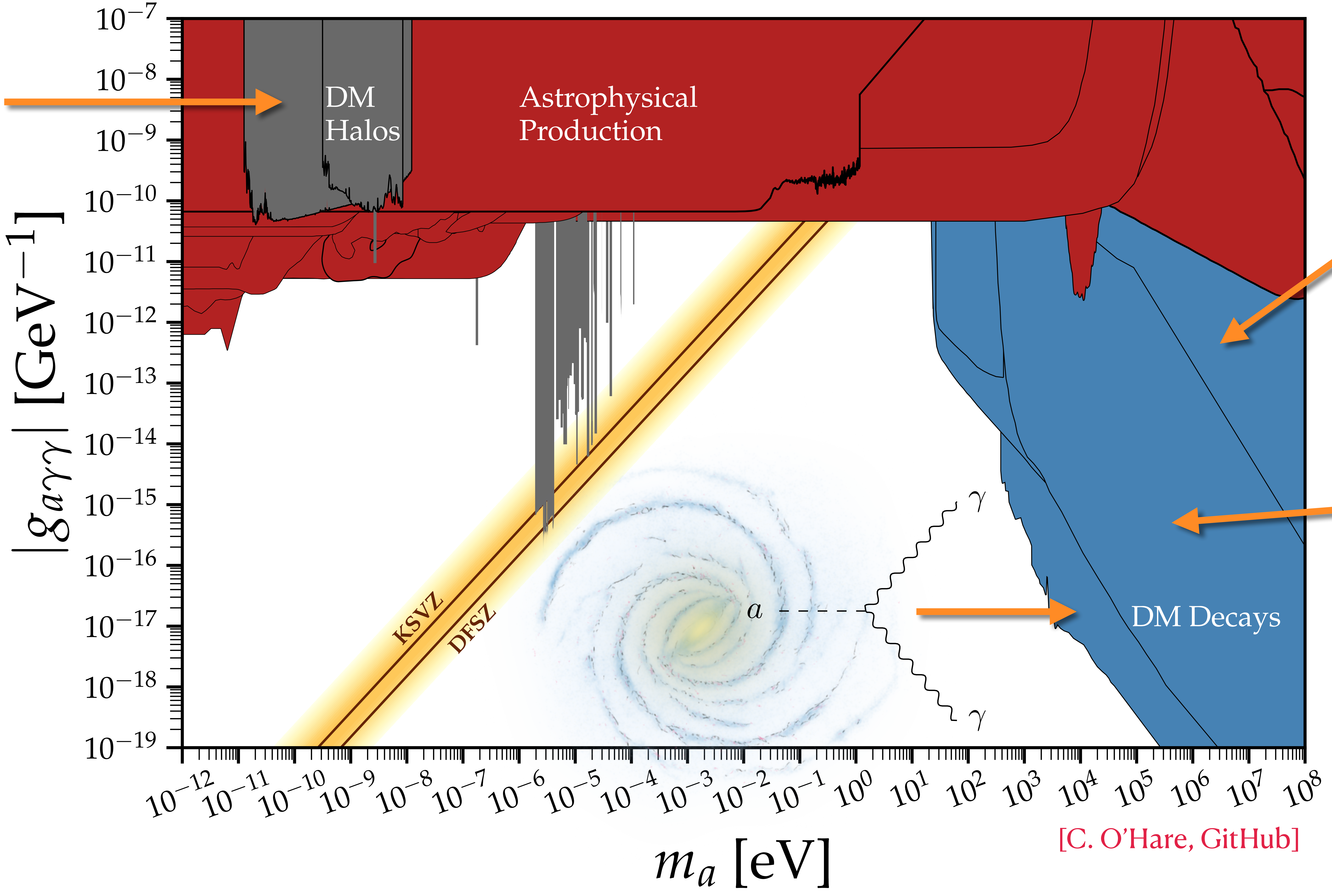


[Cadamuro & Redondo, 2012]

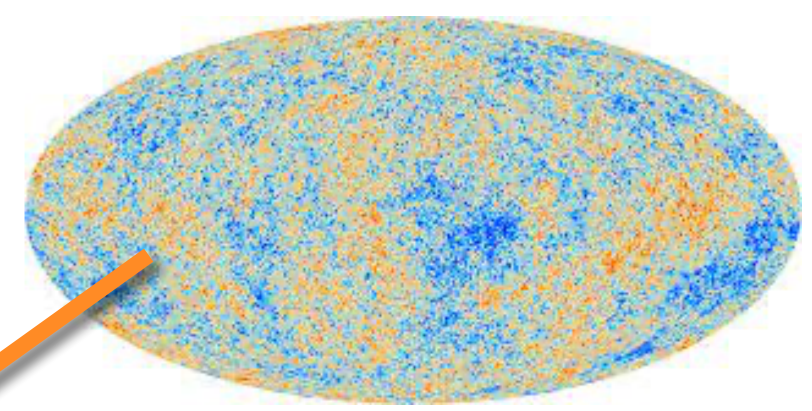
Axion Parameter Space

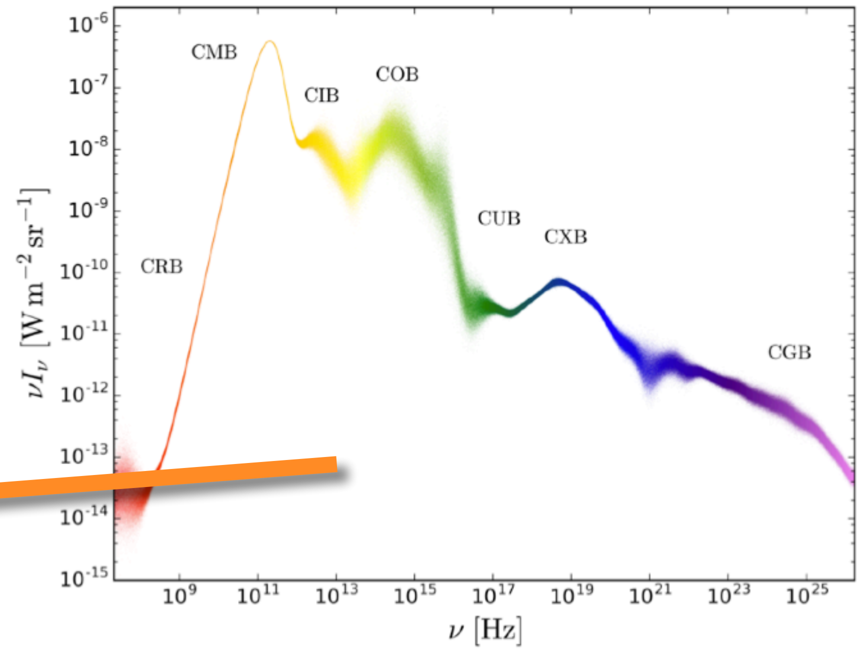


If it is all of DM



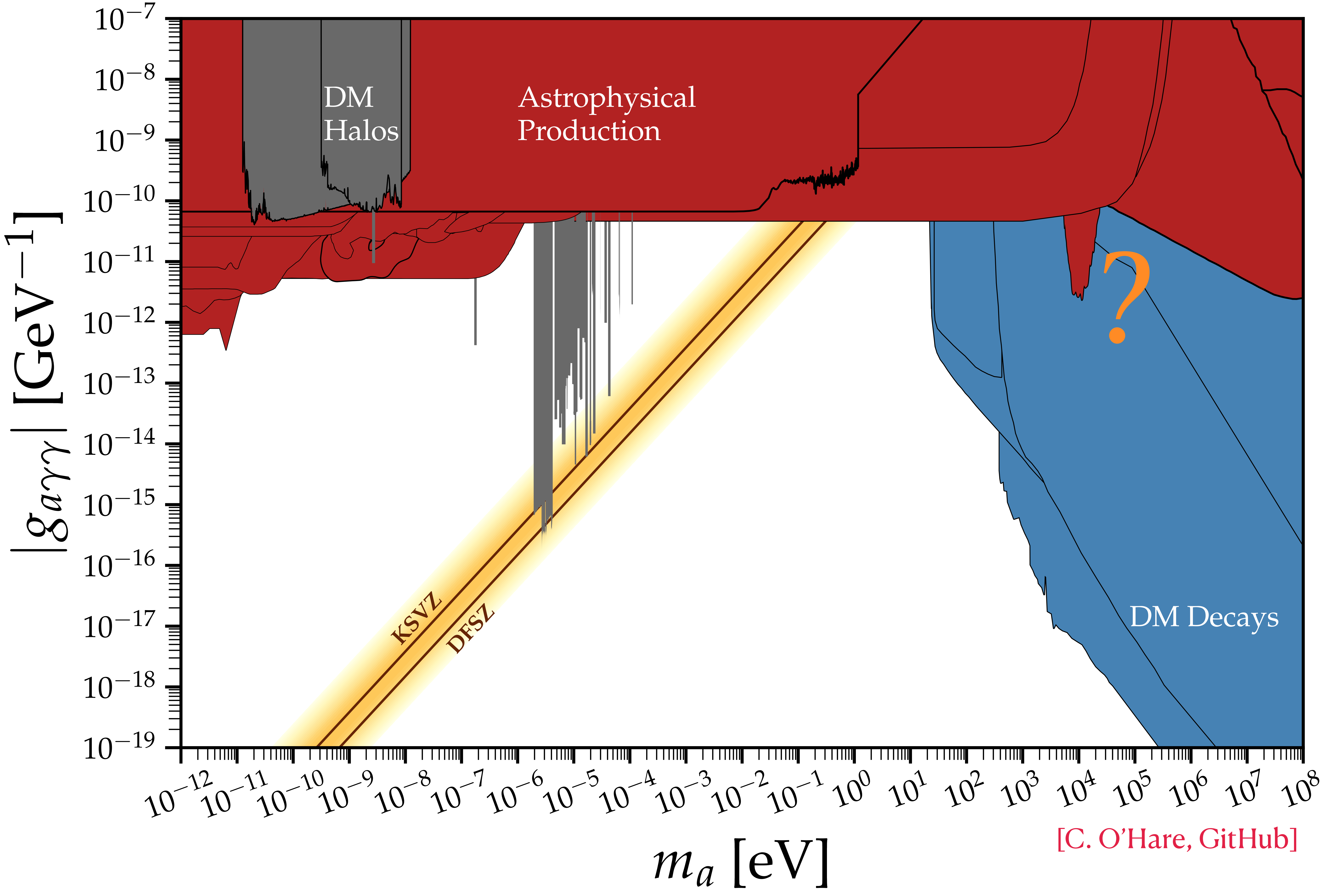
[C. O'Hare, GitHub]





Axion Parameter Space

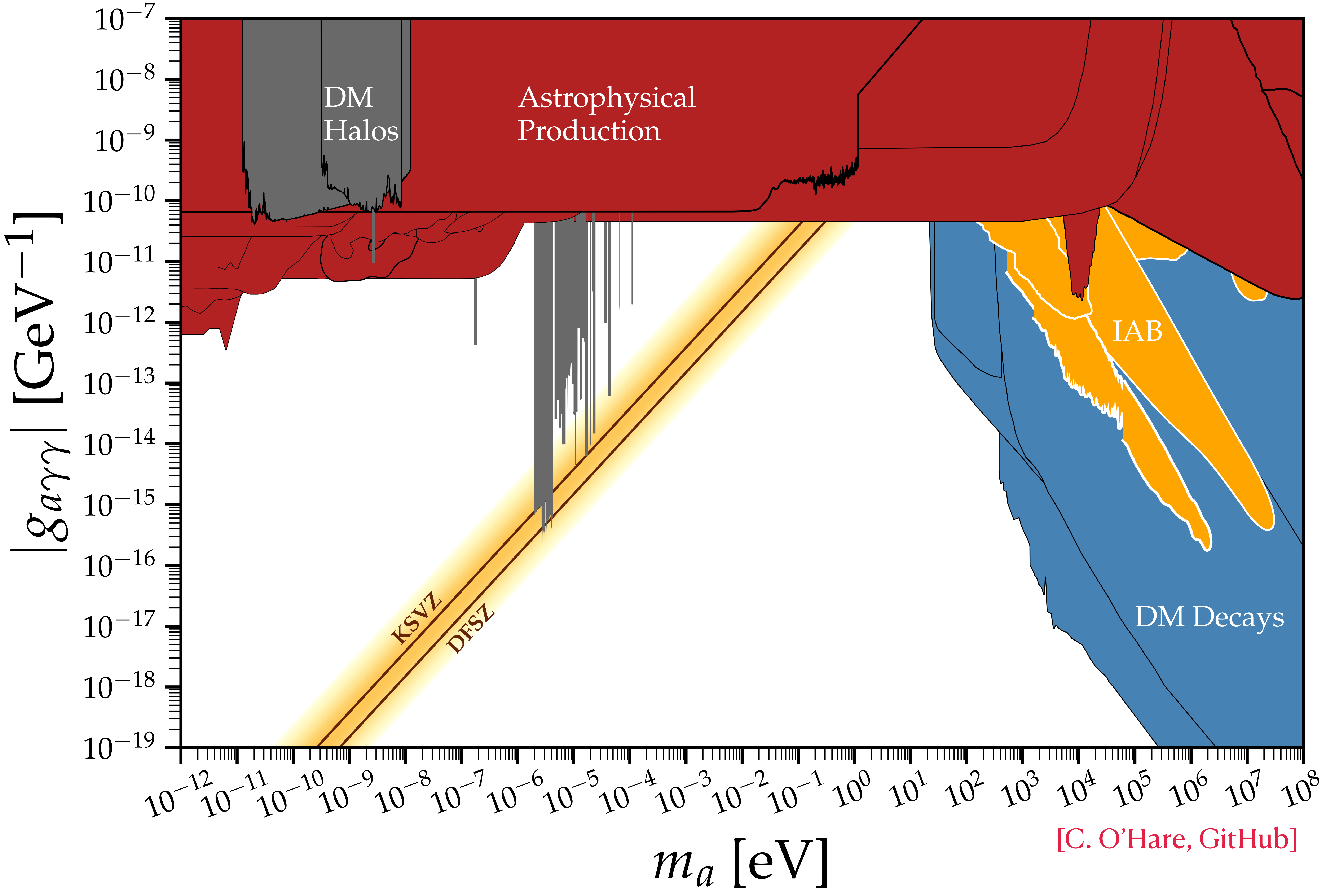
What if it is not ALL of DM?



[C. O'Hare, GitHub]

Axion Parameter Space

What if it is not ALL of DM?



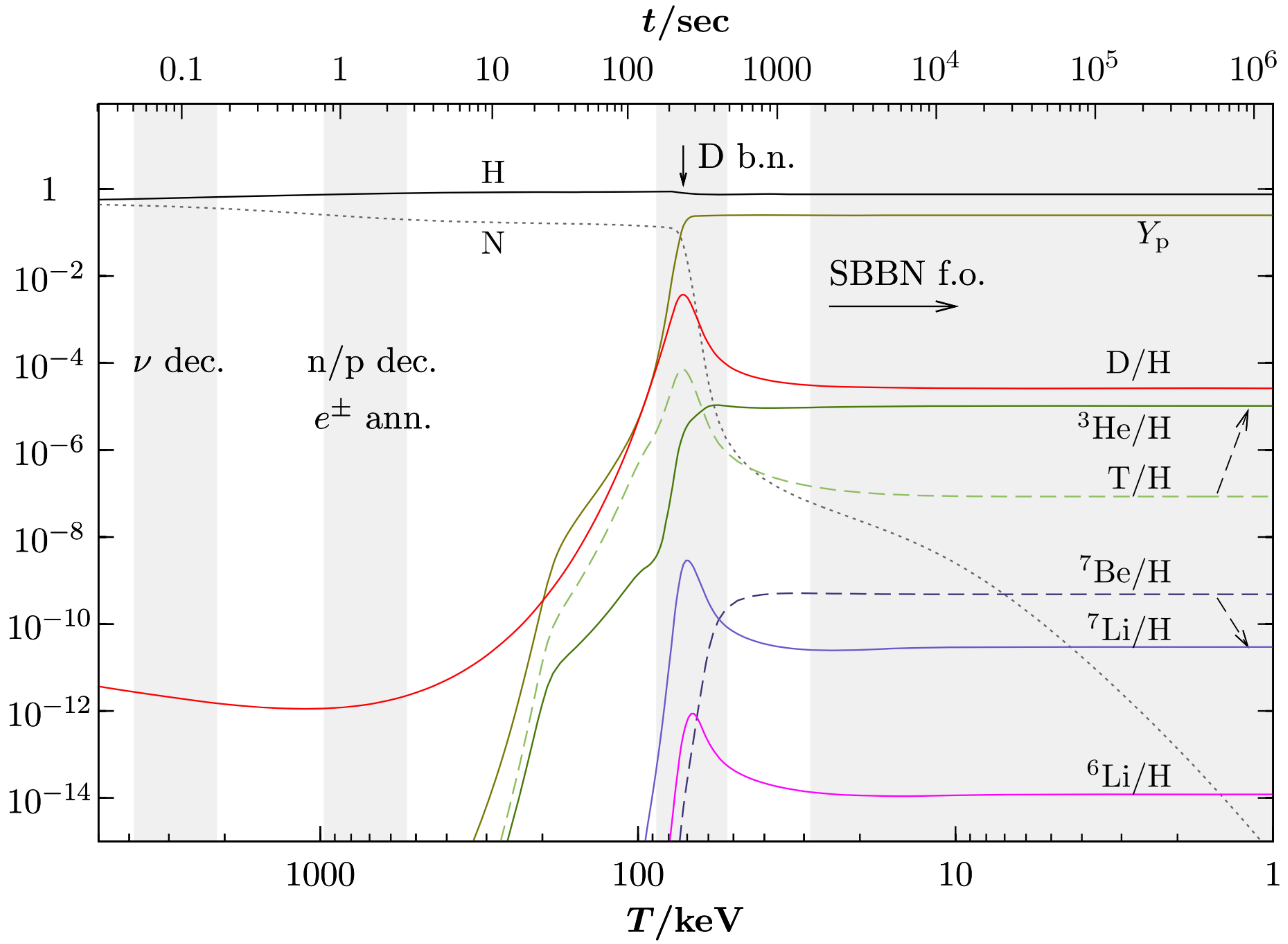
[C. O'Hare, GitHub]

Irreducible Axion Background (Freeze-in relics)

Irreducible Cosmic Abundance & Constraints

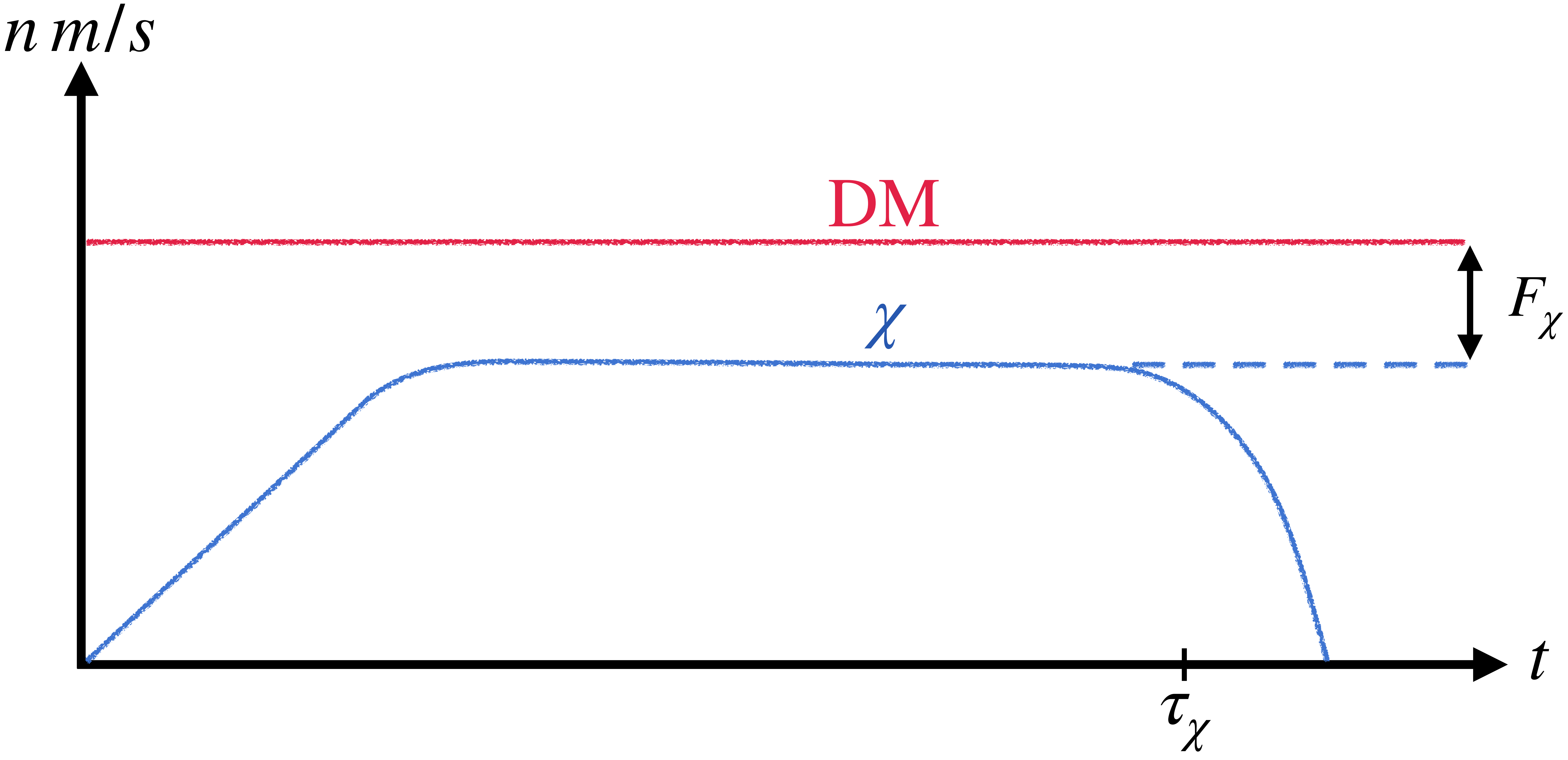
The General Picture

Dark matter may consist of **more than one species.**



[“Modern Cosmology” by Dodelson]

Definition of F_χ



$\rho_\chi \approx F_\chi \rho_{\rm DM} e^{-t/\tau_\chi}$ (For non-relativistic χ after freeze-in)

Constraints on Sub-component DM

- Many constraints on *DM* can immediately be modified to constraints on χ.

  For example (for $\tau_\chi \gg t_\mathrm{U}$):

  - $\sigma_{DM-N} \to F_\chi \times \sigma_{\chi-N}$
  - $\Gamma_{DM\to\gamma\gamma} \to F_\chi \times \Gamma_{\chi\to\gamma\gamma}$
  - $\langle\sigma_{DM+DM\to SM}v\rangle \to F_\chi^2 \times \langle\sigma_{\chi+\chi\to SM}v\rangle$

- Current indirect detection experiments for decay can probe down to $F_\chi \sim 10^{-12}$!

Constraints on Sub-component DM

Broadly speaking searches for a dark particle χ constrain the parameters (m_χ, g_χ, F_χ).

- DM Approach : $F_\chi = 1$ and $\tau_\chi \gg t_{\rm U}$.
- Agnostic Approach : F_χ is an additional free parameter.
- Calculational Approach : $F_\chi = F_\chi(m_\chi, g_\chi, C)$, where C is some cosmology.

Constraints depending on C are not **robust**.

Irreducible Cosmic Abundance Constraints

Instead we calculate the **irreducible** abundance $F_{\chi,\mathrm{irr}}(m_\chi, g_\chi)$.

This is determined by considering only production after the beginning of BBN ($T < 5$ MeV).

Constraints obtained using $F_{\chi,\mathrm{irr}}(m_\chi, g_\chi)$ are **robust** under two mild assumptions:

1. χ does not decay/annihilate to a dark sector.
2. Standard cosmology holds from BBN on.

Summary

- Sub-componets are well motivated and interesting in their own right.
- DM searches can also constrain subcomponents.
- There exists an irreducible abundance which can be used to obtain robust constraints.

Application to Axions

Irreducible Axion Background Constraints

1. Calculate $F_{a,\mathrm{irr}}$
2. Apply astrophysical and cosmological constraints.

Production of Axions

- The irreducible axion background is obtained by freezing-in axions beginning at $T = 5\ \mathrm{MeV}$.
- What does freezing-in mean?
- Definition: Freeze-in is the process where particles are created from the primordial plasma of the universe without ever being in a state of thermal equilibrium with it.

✗

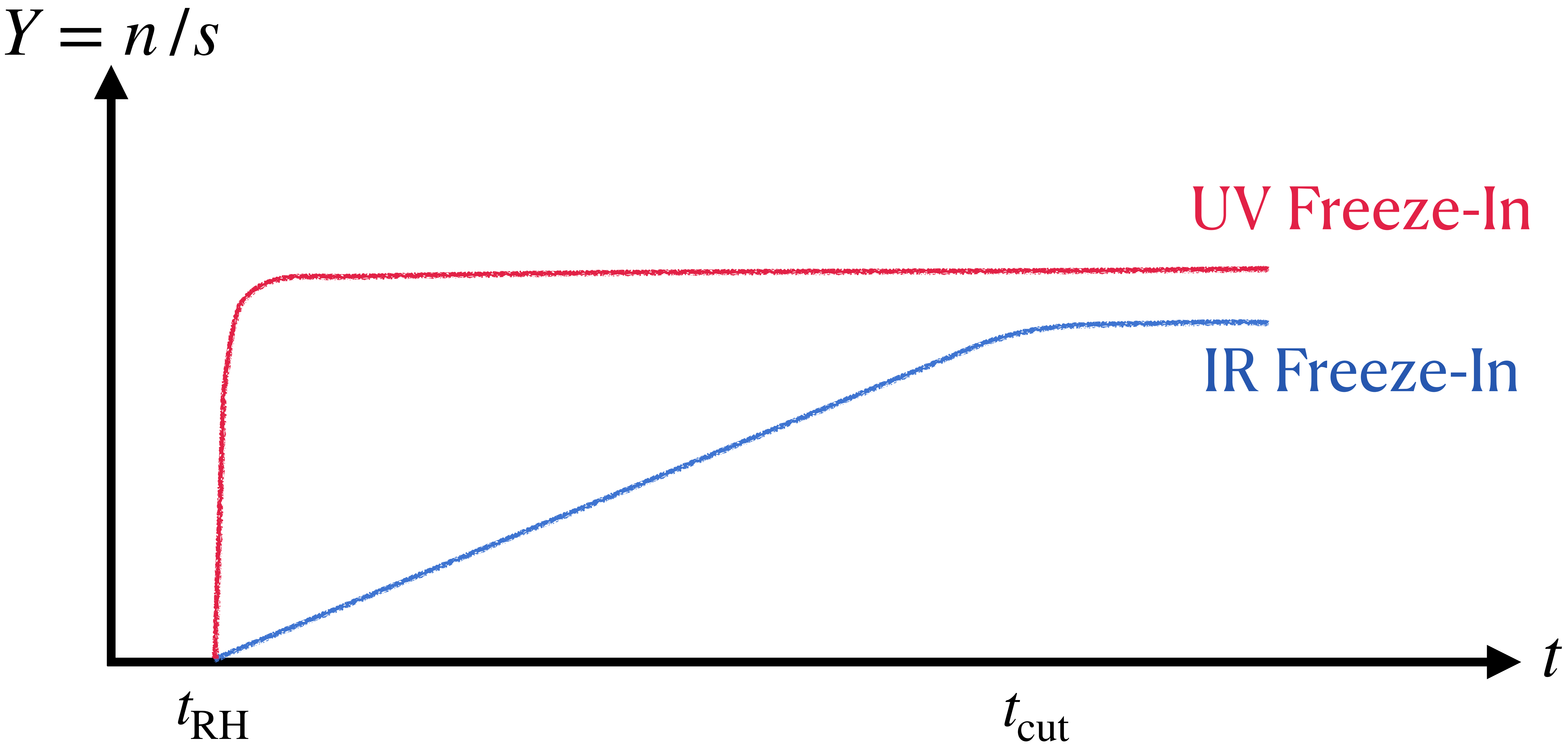
$$\mathrm{SM} \leftrightharpoons \chi$$

✓

$$\mathrm{SM} \rightarrow \chi$$

Types of Freeze-In (Rough Idea)

There exist many types of freeze-in, but can generally be classified into two groups.



Logic of Freeze-In (Simplified)

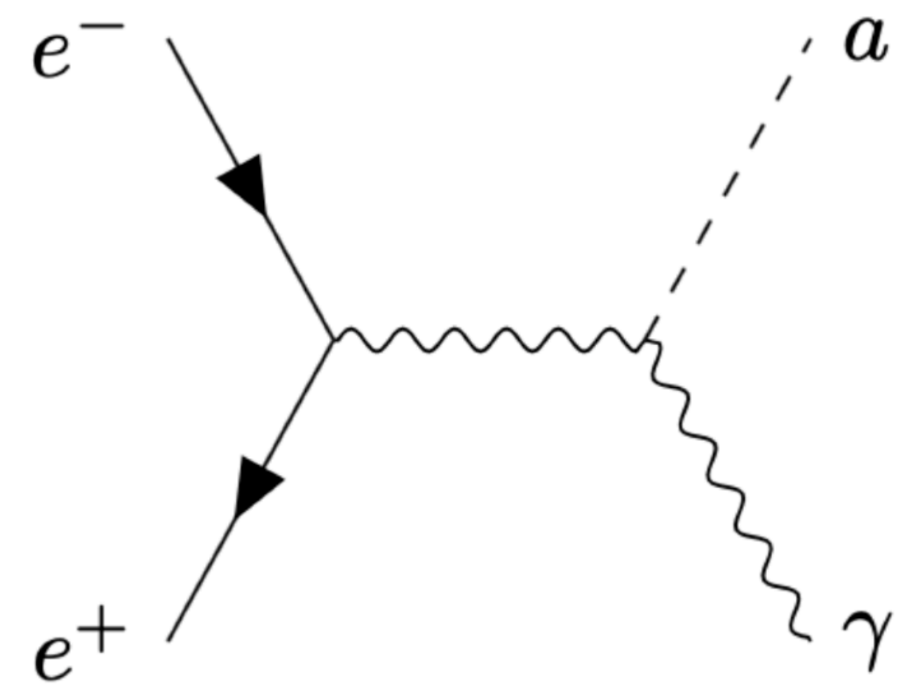
$$\frac{dn_a}{dt} + 3Hn_a = \underbrace{n_{\rm SM}\Gamma_{{\rm SM}\to a}}_{\text{Axion Production}} - \underbrace{n_a\Gamma_{a\to{\rm SM}}}_{\text{Axion Destruction}}$$

≈ 0

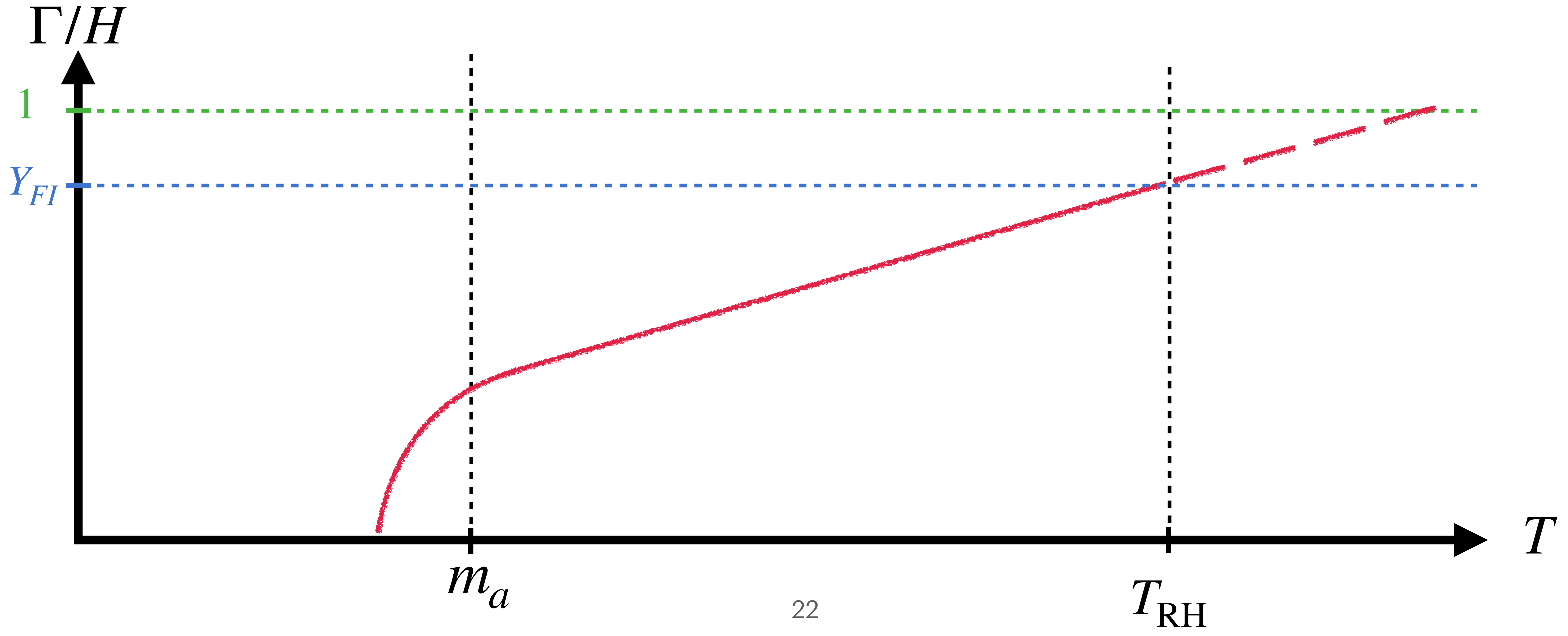
Define: $Y_a = n_a/s \sim n_a R^{-3}$

$$\frac{dY_a}{d\log T} \sim -\frac{\Gamma_{{\rm SM}\to a}}{H} \implies \boxed{Y_{a,{\rm FI}} \sim \left.\frac{\Gamma_{{\rm SM}\to a}}{H}\right|_{T_*}}$$

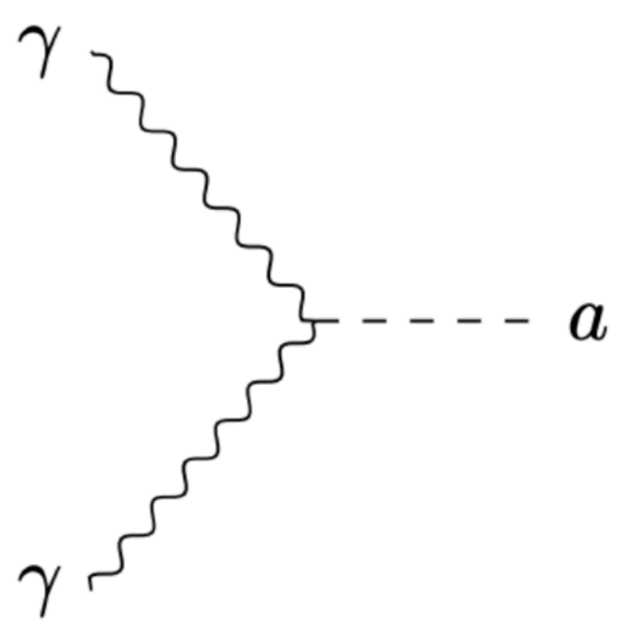
UV Freeze-In Example



$$\Gamma \sim g_{a\gamma\gamma}^2 T^3 \implies \frac{\Gamma}{H} \sim g_{a\gamma\gamma}^2 M_{\mathrm{Pl}} T$$

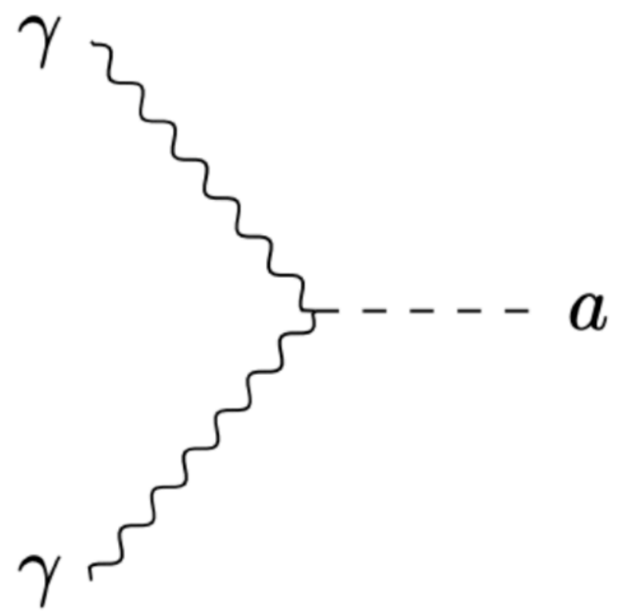


IR Freeze-In Example



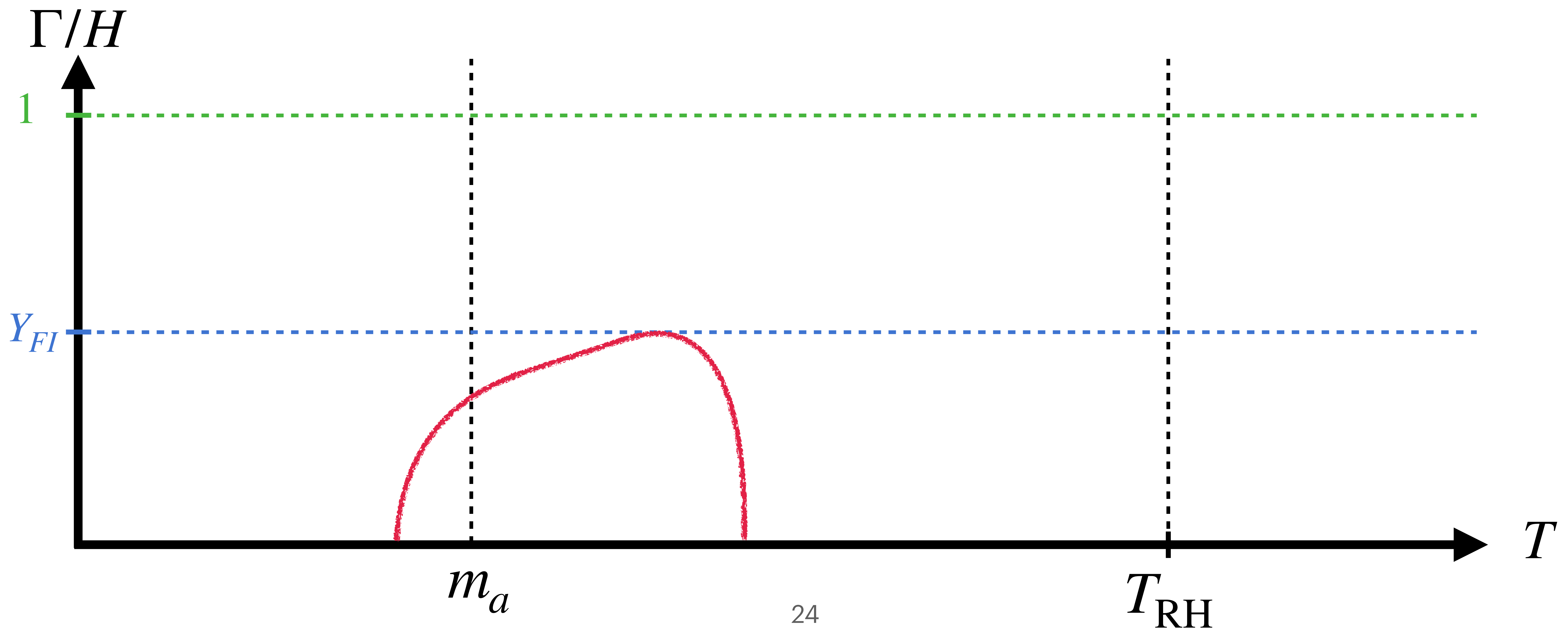
$\Gamma \sim g_{a\gamma\gamma}^2 T^3$ (Naively)

IR Freeze-In Example

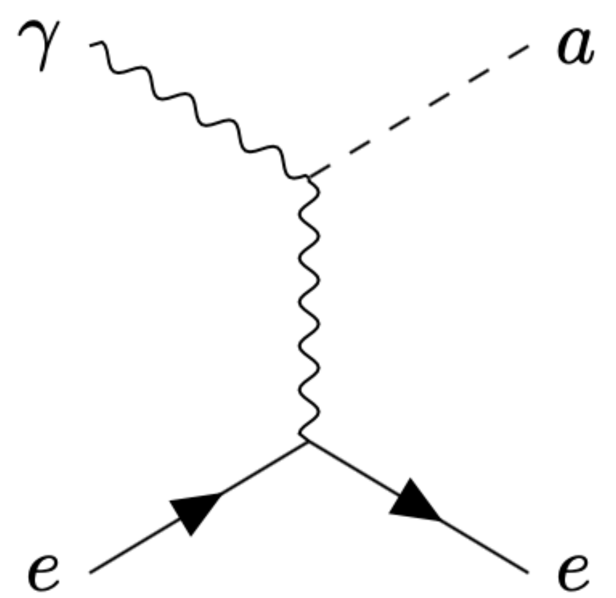
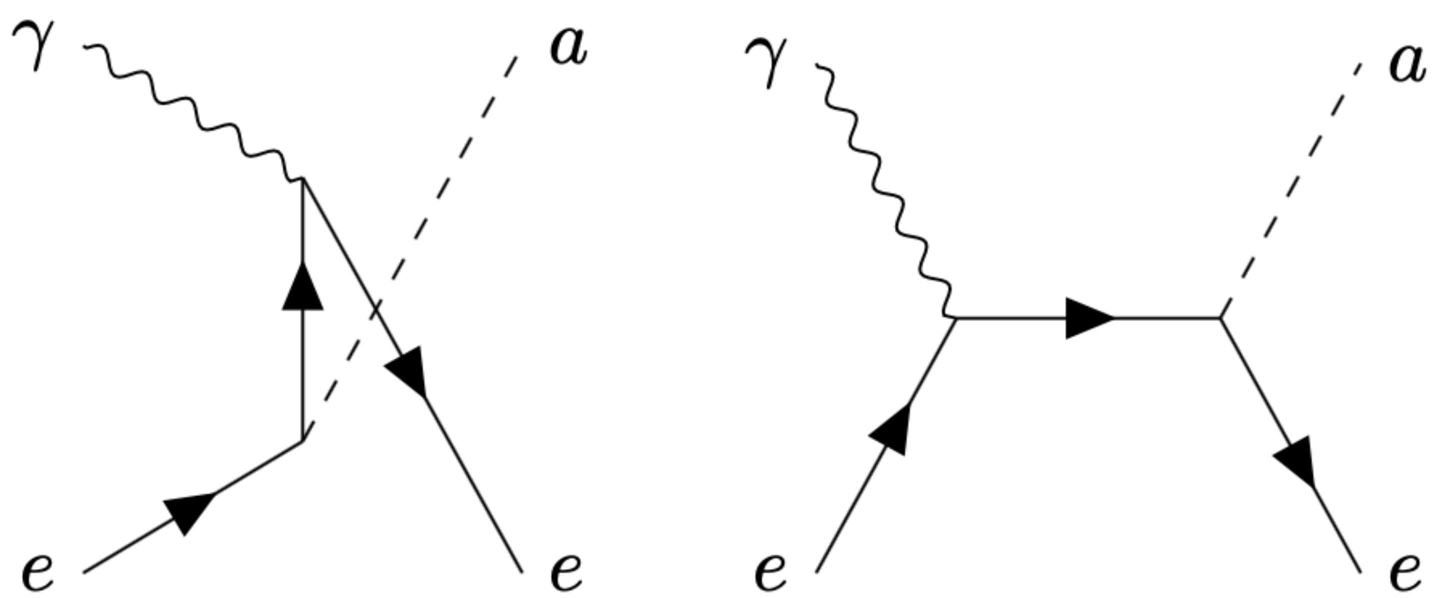
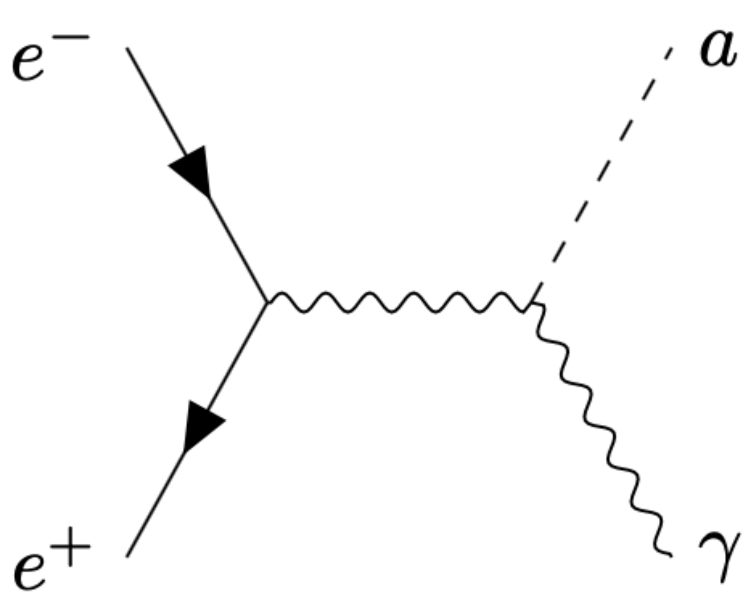
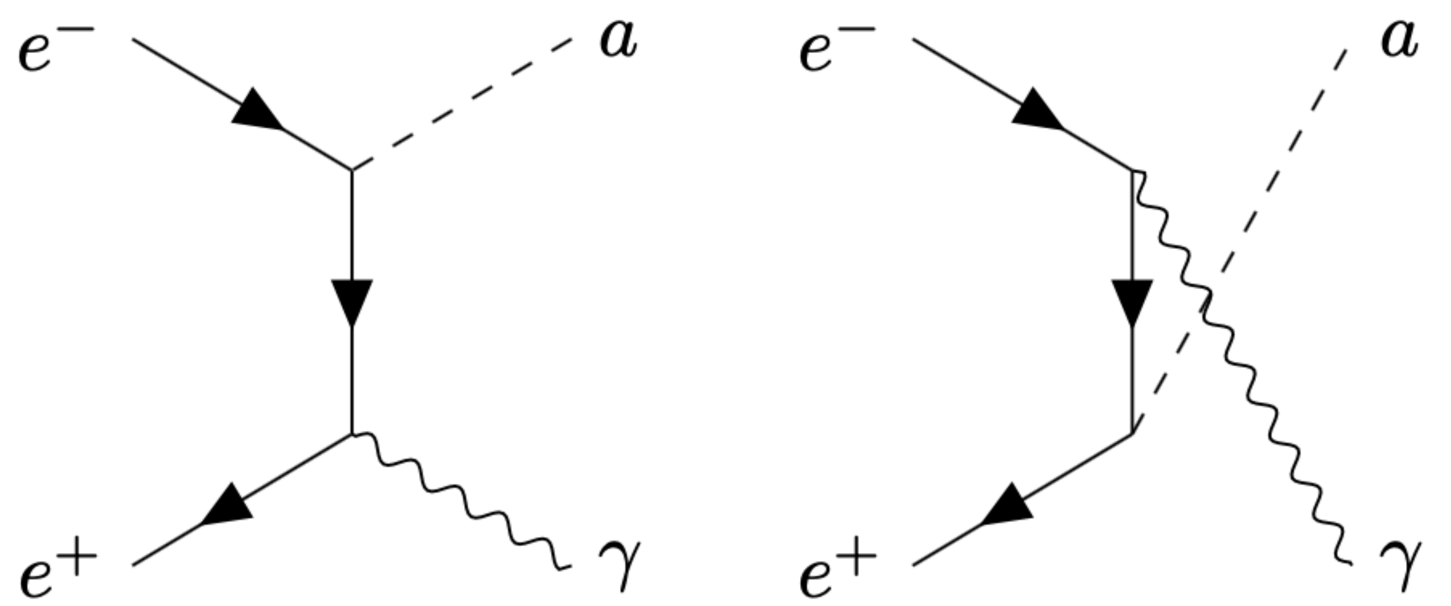
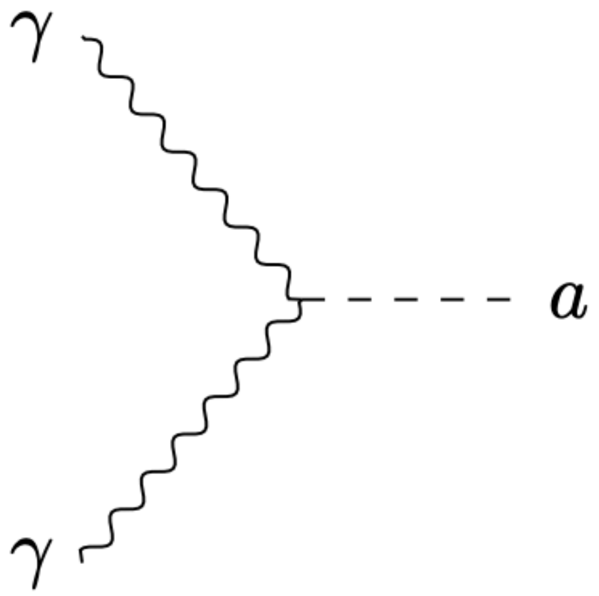
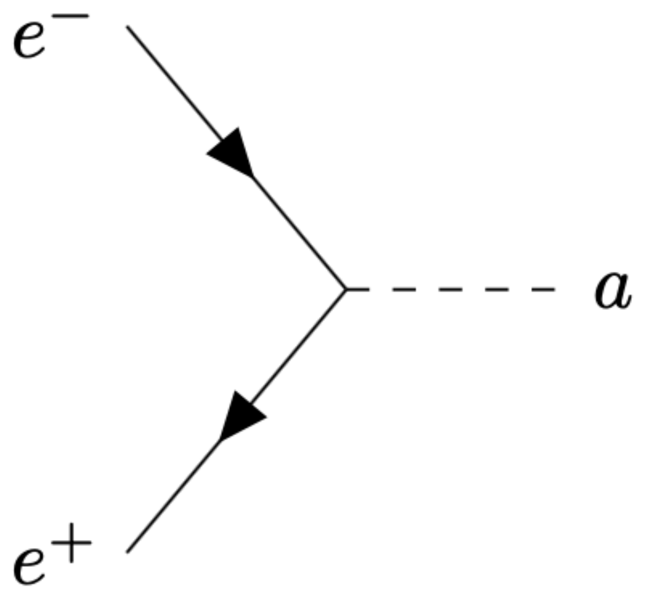


$$\Gamma \sim \begin{cases} 0, & m_\gamma(T) > m_a/2 \\ g_{a\gamma\gamma}^2 m_a T^2, & m_\gamma(T) < m_a/2 \end{cases}$$

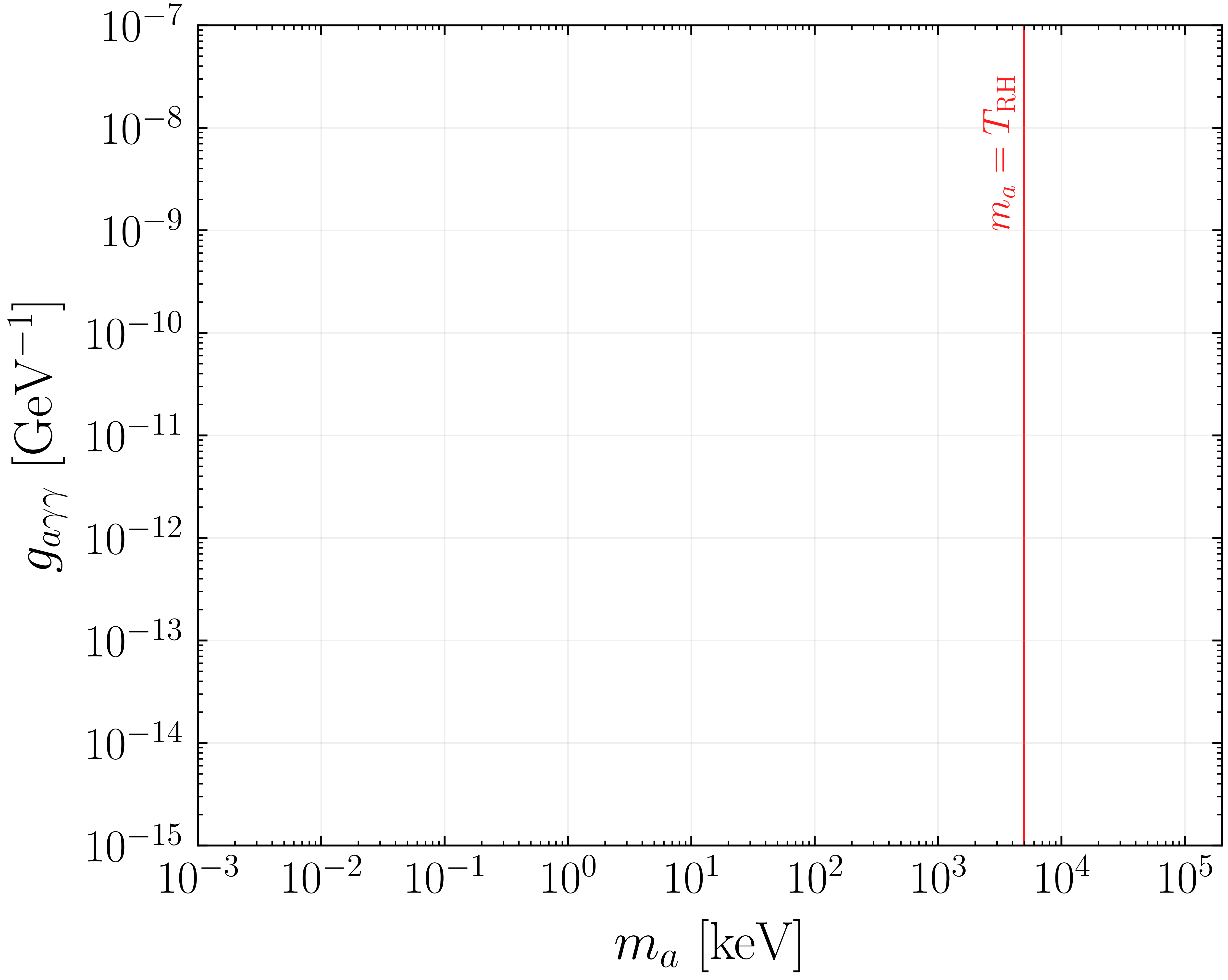
where $m_\gamma(T) \approx eT/3$



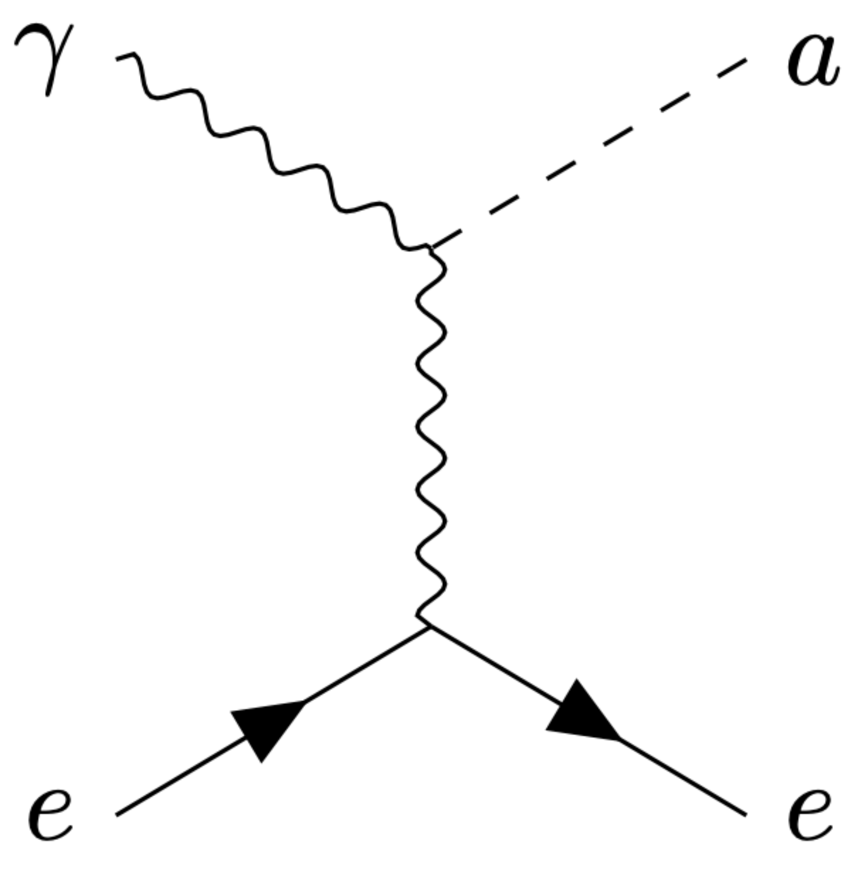
General Production of Axions

	$g_{a\gamma\gamma}$	g_{aee}
Photon Conversion $\gamma e \to a e$		
Fermion Annihilation $e^- e^+ \to a\gamma$		
Inverse Decay $\gamma\gamma \to a$ or $e^- e^+ \to a$		

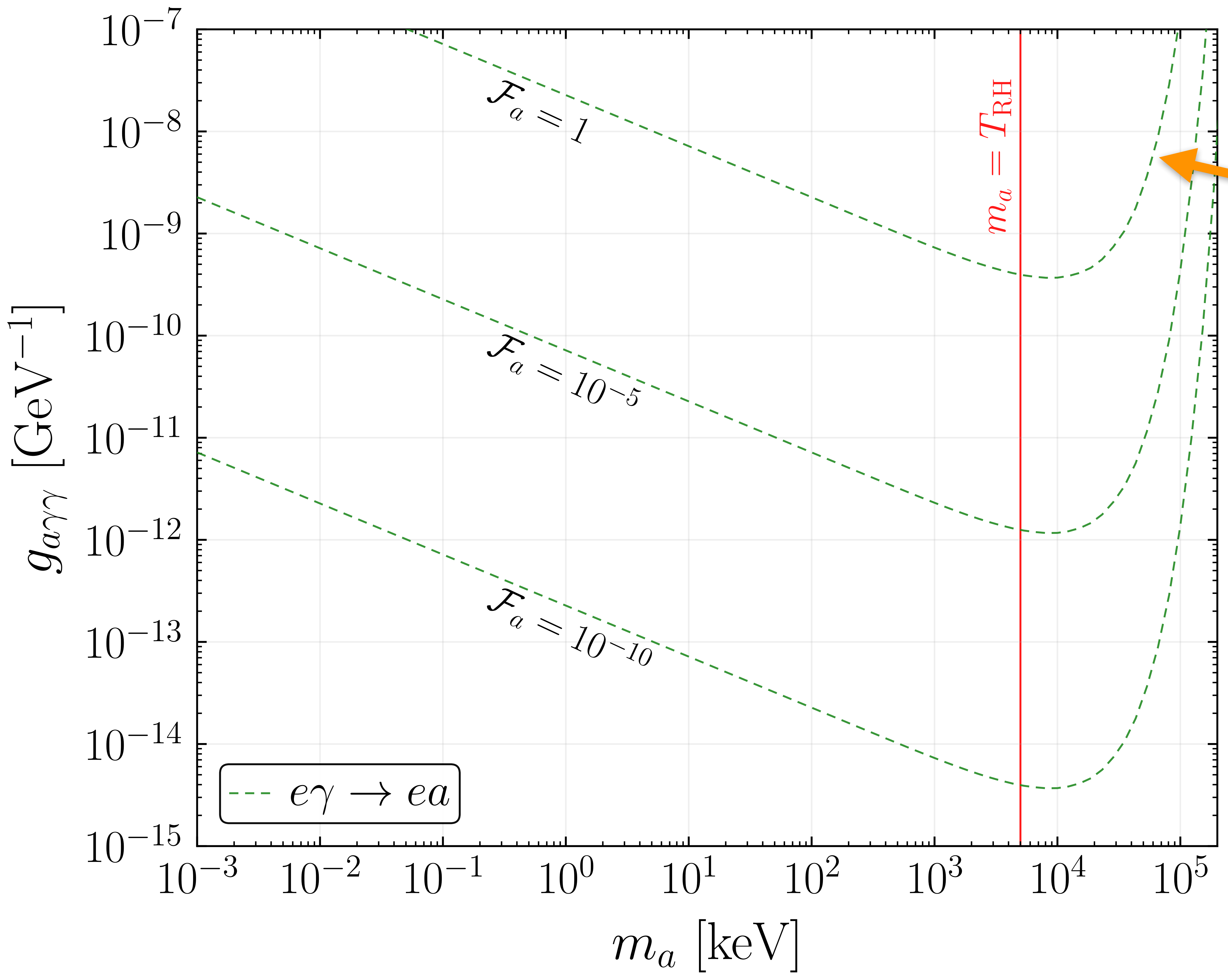
Irreducible Freeze-In Background



Irreducible Freeze-In Background

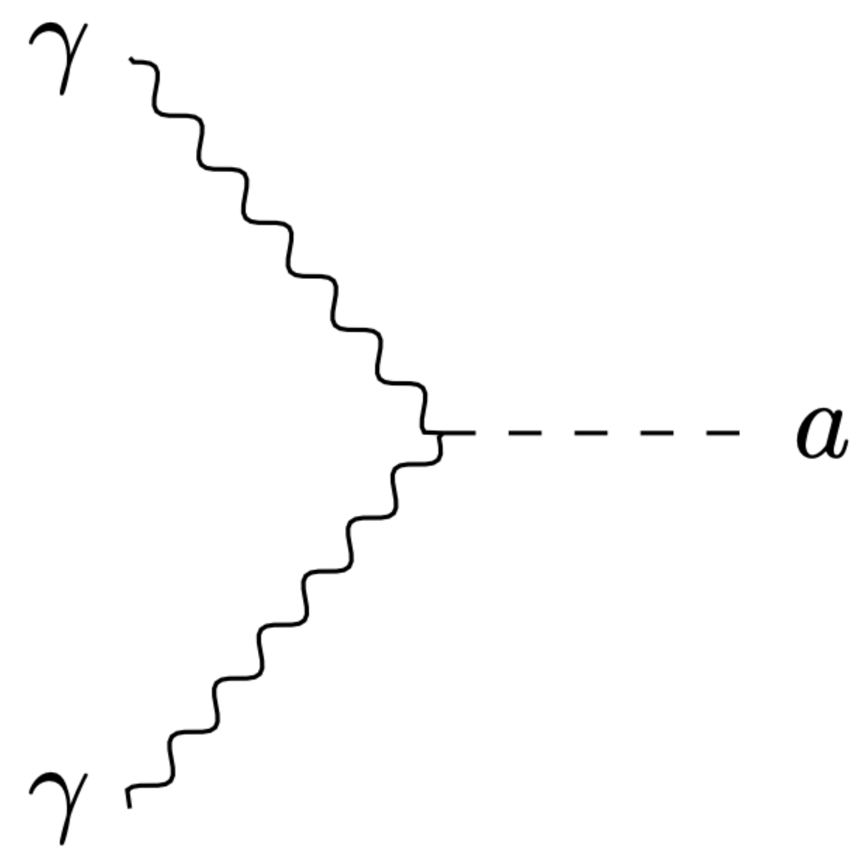


Photon Conversion

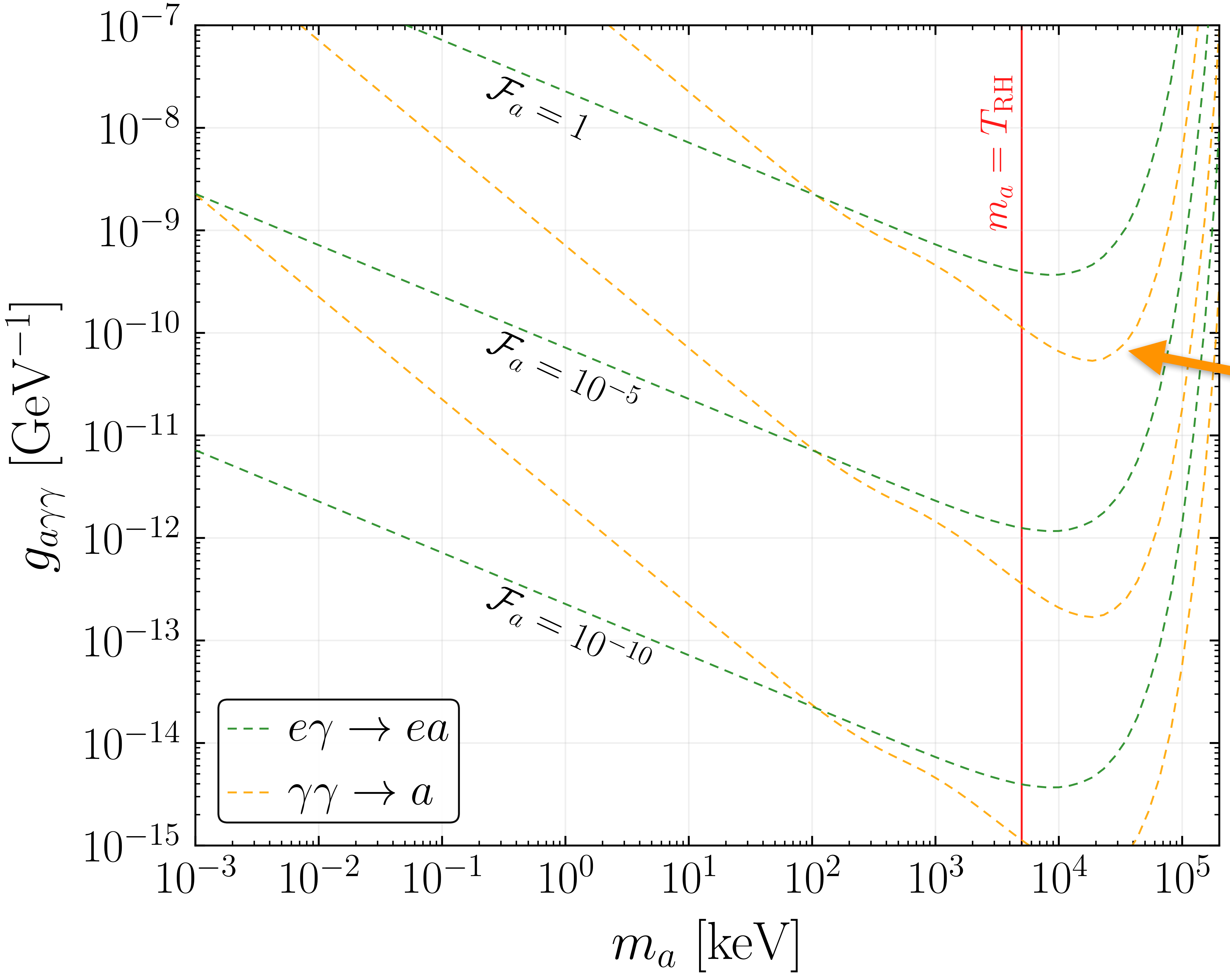


Exponentially suppressed for $m_a \gg T_{\rm RH}$

Irreducible Freeze-In Background

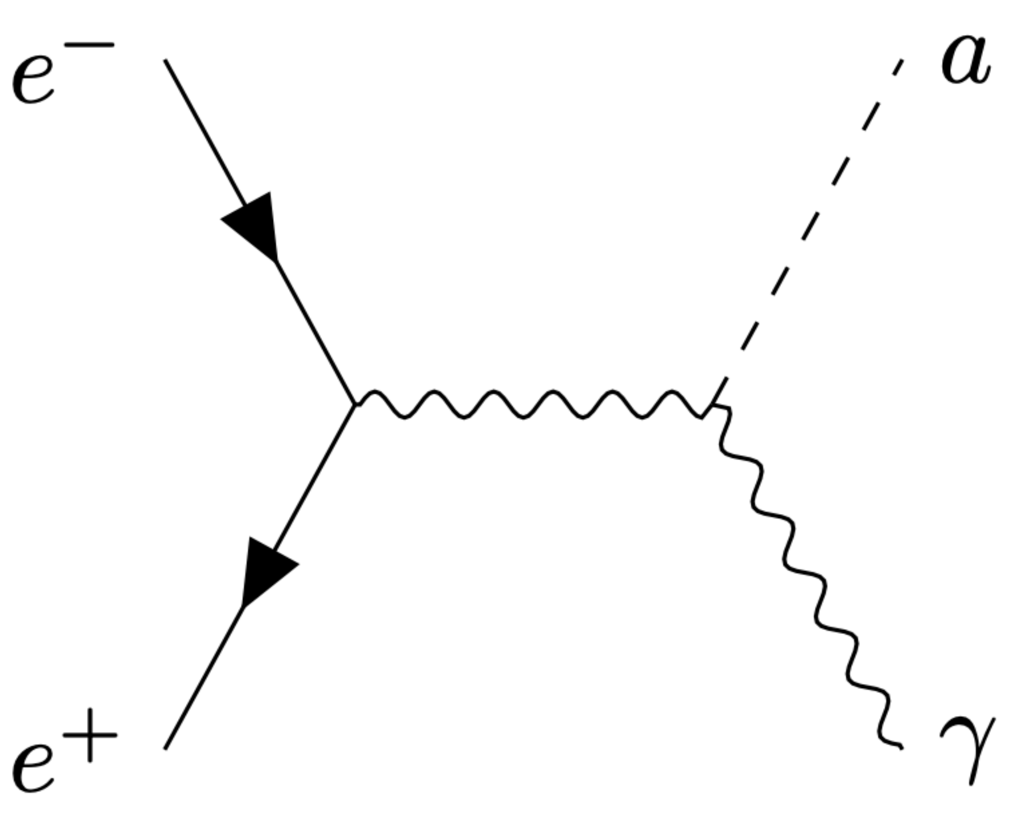


Inverse Decay

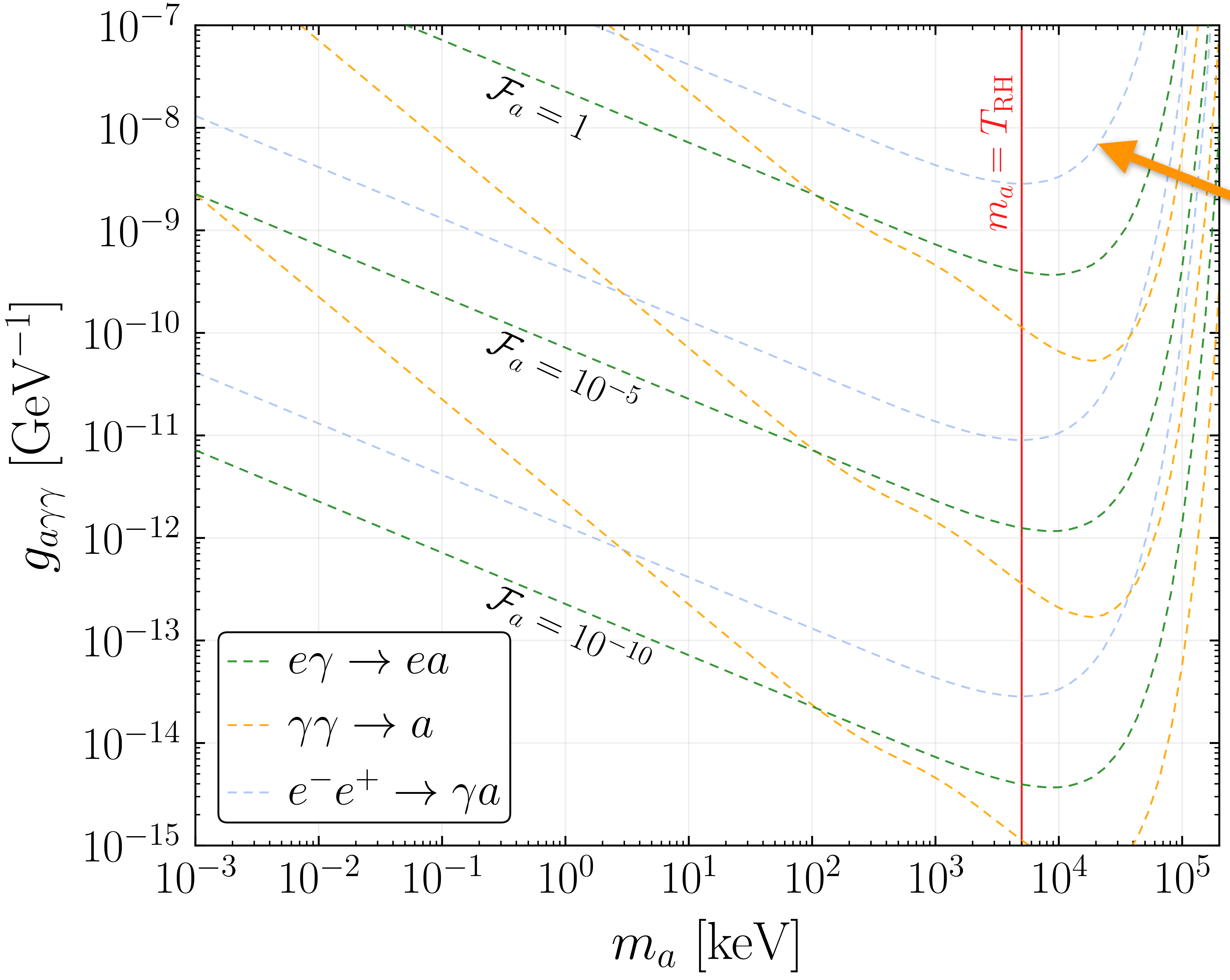


Dominant at large m_a

Irreducible Freeze-In Background

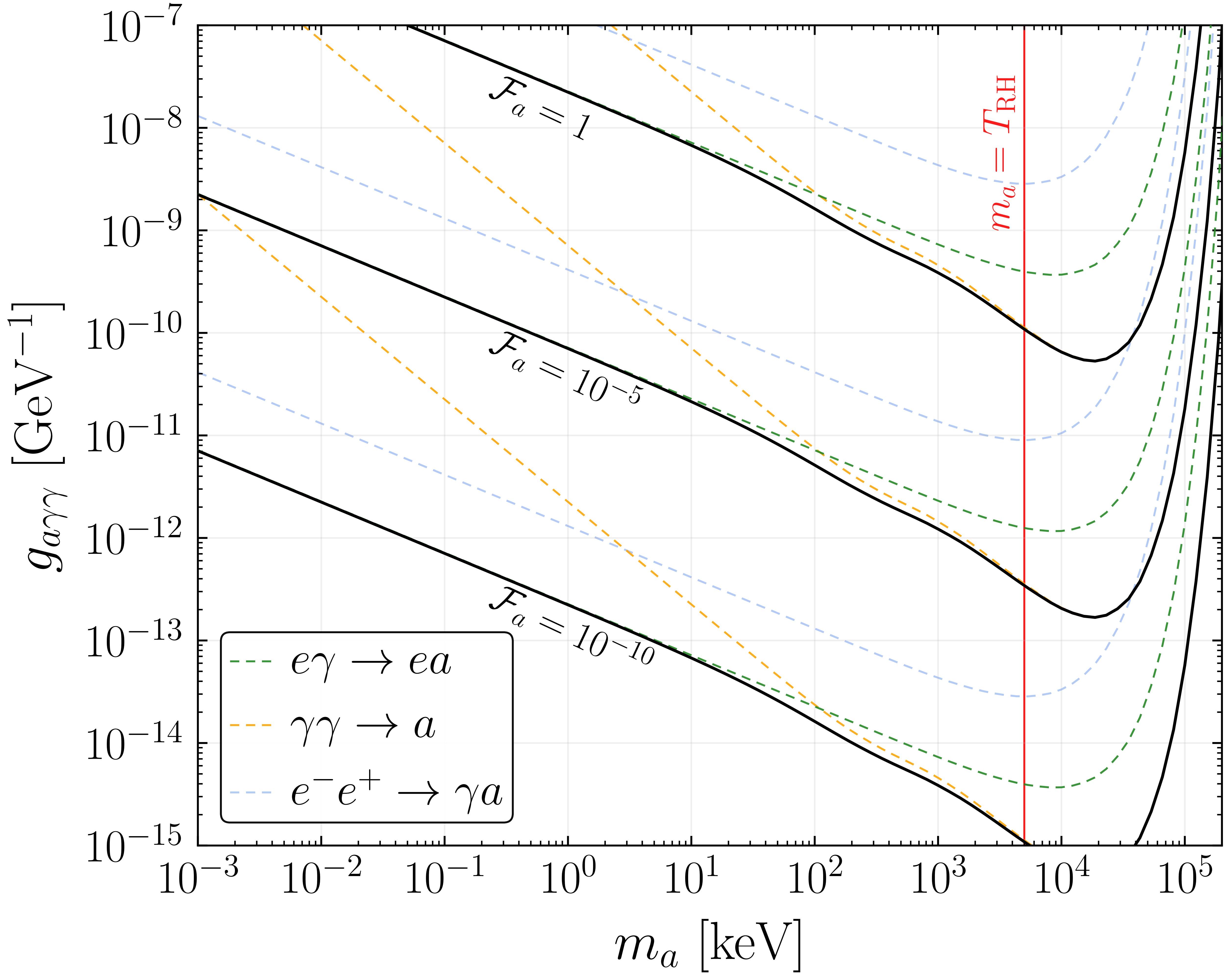


Fermion Annihilation



Strictly sub-dominant

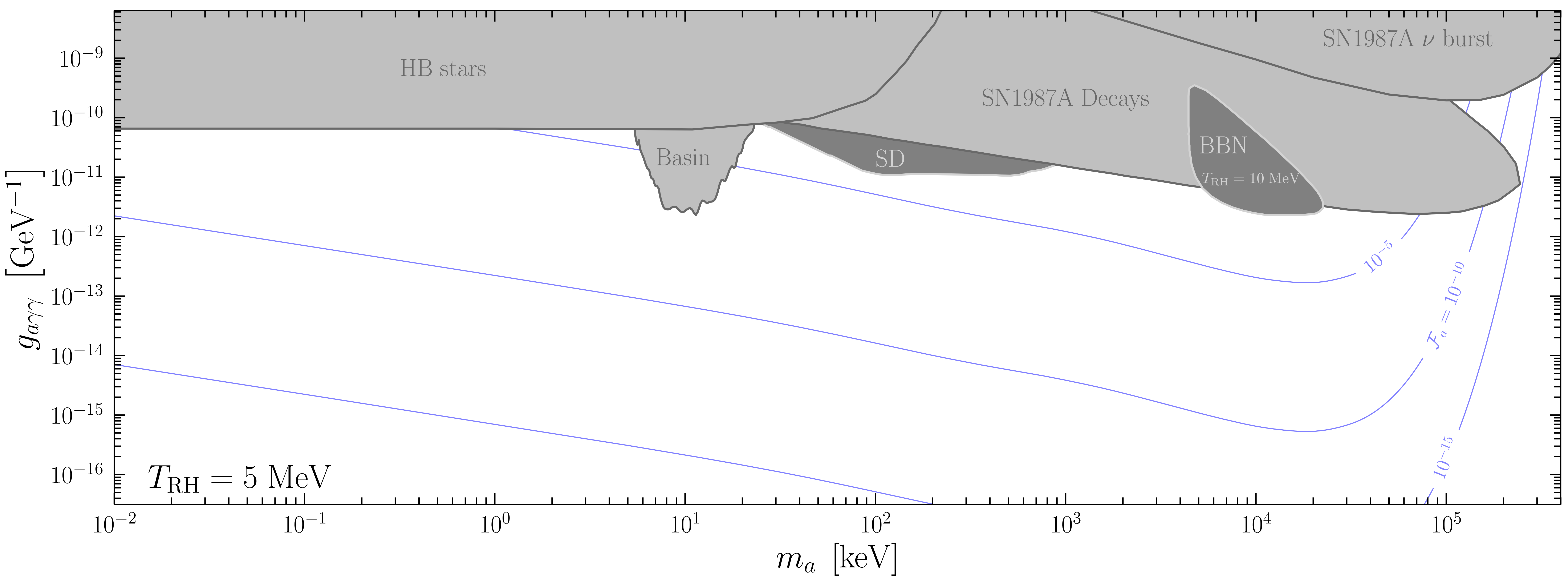
Irreducible Freeze-In Background



Astrophysical and Cosmological Constraints

Intuition: X-rays

- Consider the benchmark constraint $\tau_{\rm DM} > 10^{28}{\rm s} \implies \tau_a > F_a \tau_{\rm DM}$.



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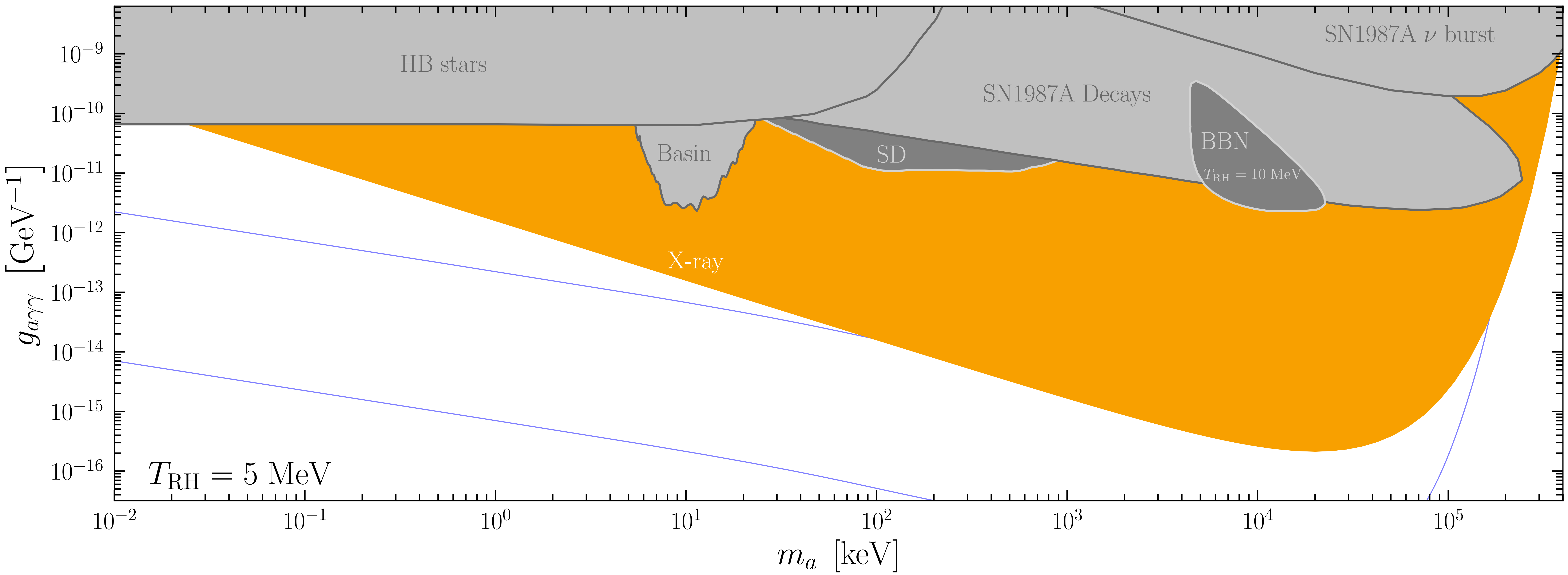
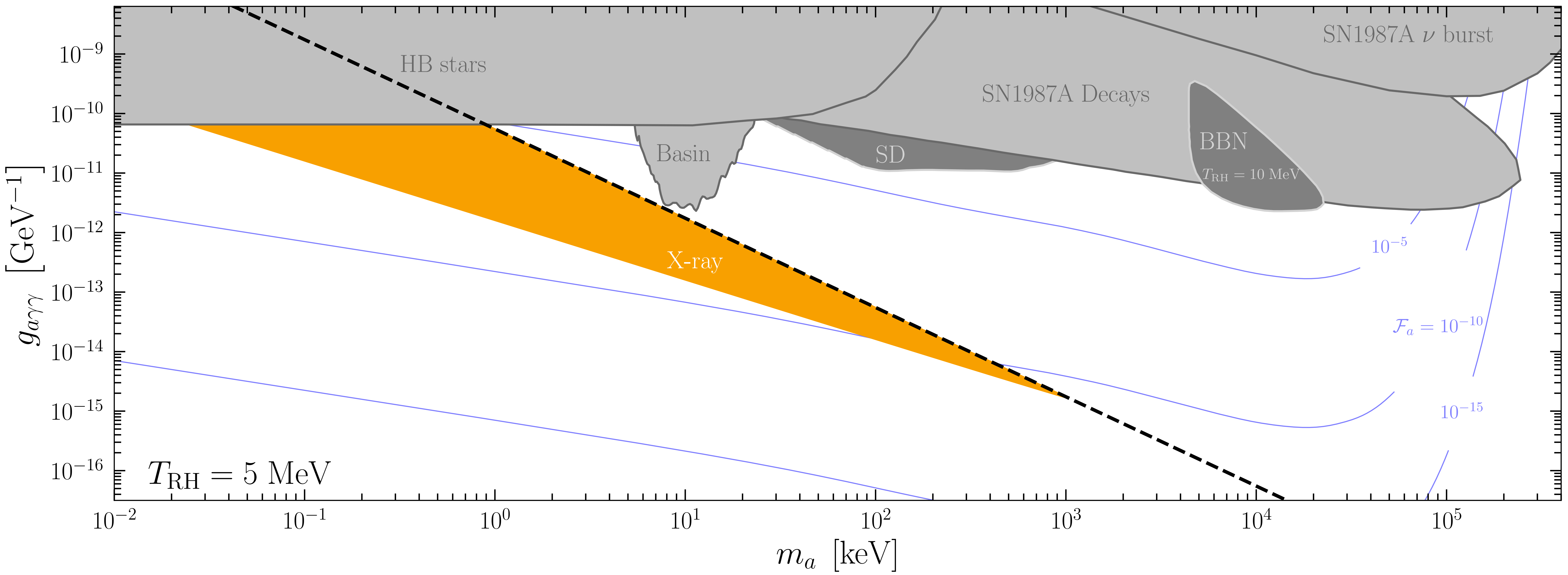


Intuition: X-rays

- Consider the benchmark constraint $\tau_{\mathrm{DM}} > 10^{28}\mathrm{s} \implies \tau_a > F_a \tau_{\mathrm{DM}}$.
- To observe decays today we require $\tau_a \gtrsim 0.1 \times t_{\mathrm{U}}$.



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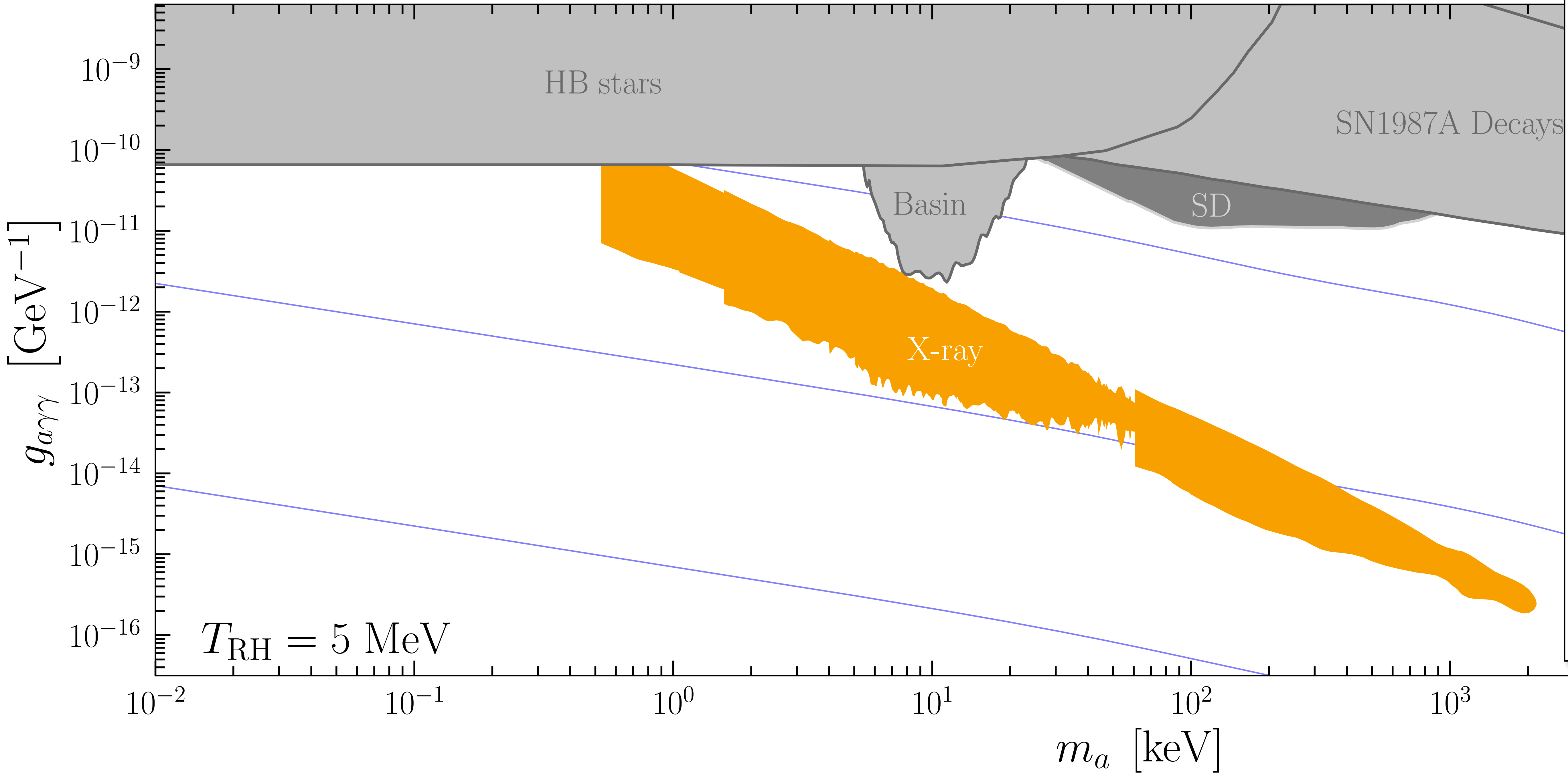
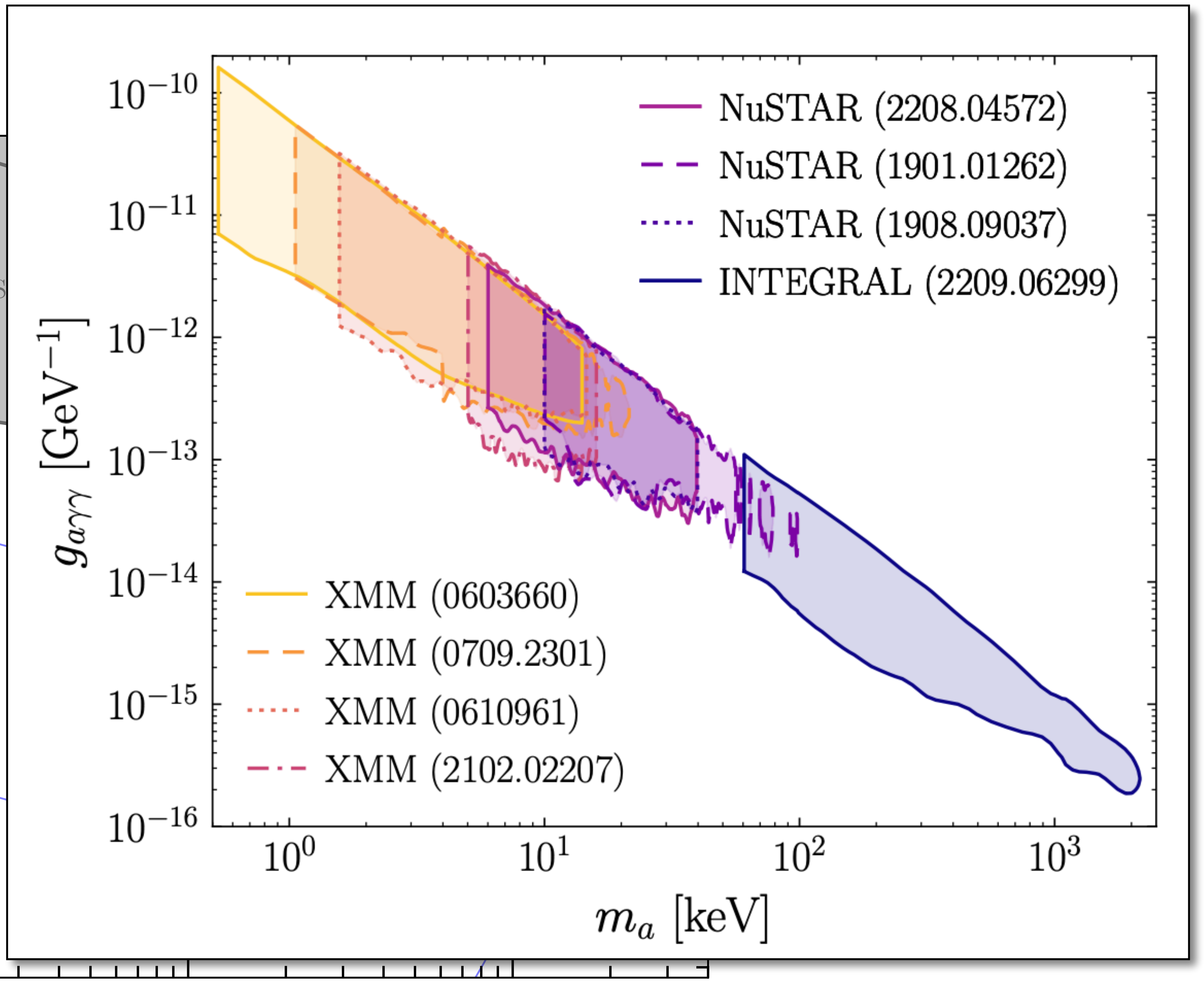




Cosmological and Astrophysical Constraints

How we observe the decay of axions depends on when they decay.

Cosmological and Astrophysical Constraints

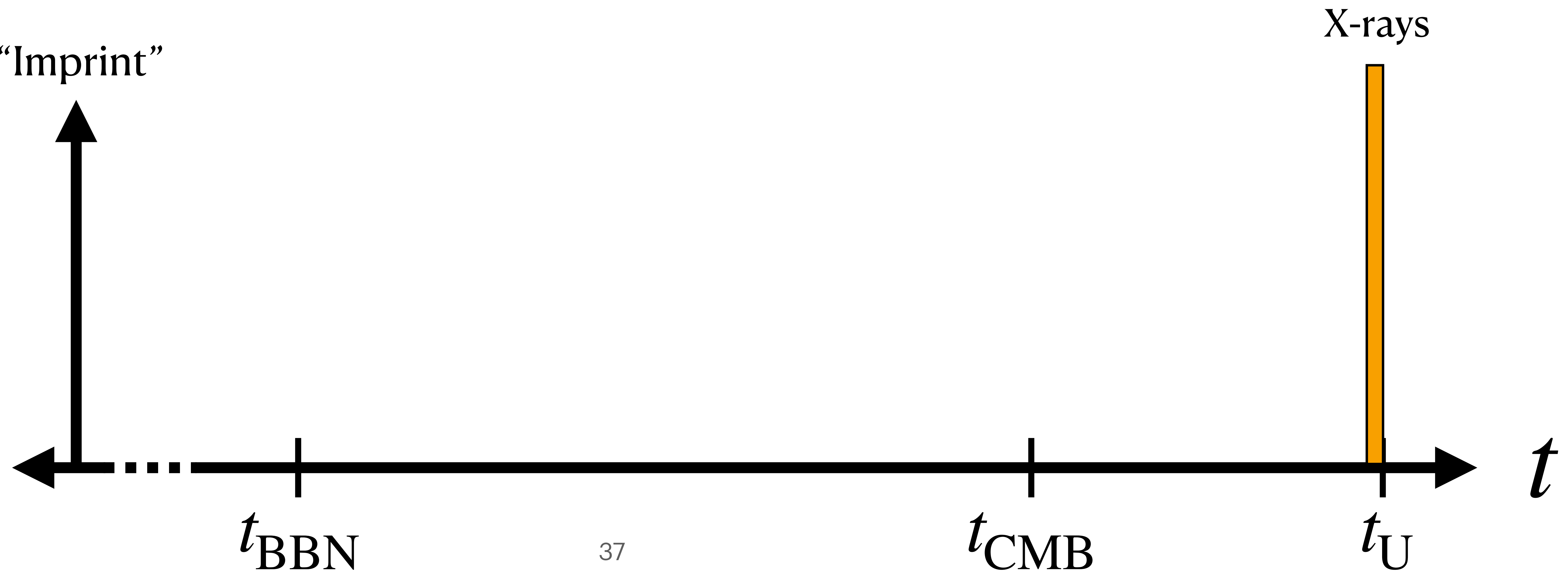
How we observe the decay of axions depends on when they decay.

For $\tau_a \gtrsim t_{\rm U}$, we can look for decays in local sources of axions:

- Galactic Center
- Dwarf Spheroidal Galaxies

$$\frac{d\Phi}{dE} = \frac{D}{2\pi\, m_a \tau_a} \delta(E - m_a/2)$$

Very schematic!

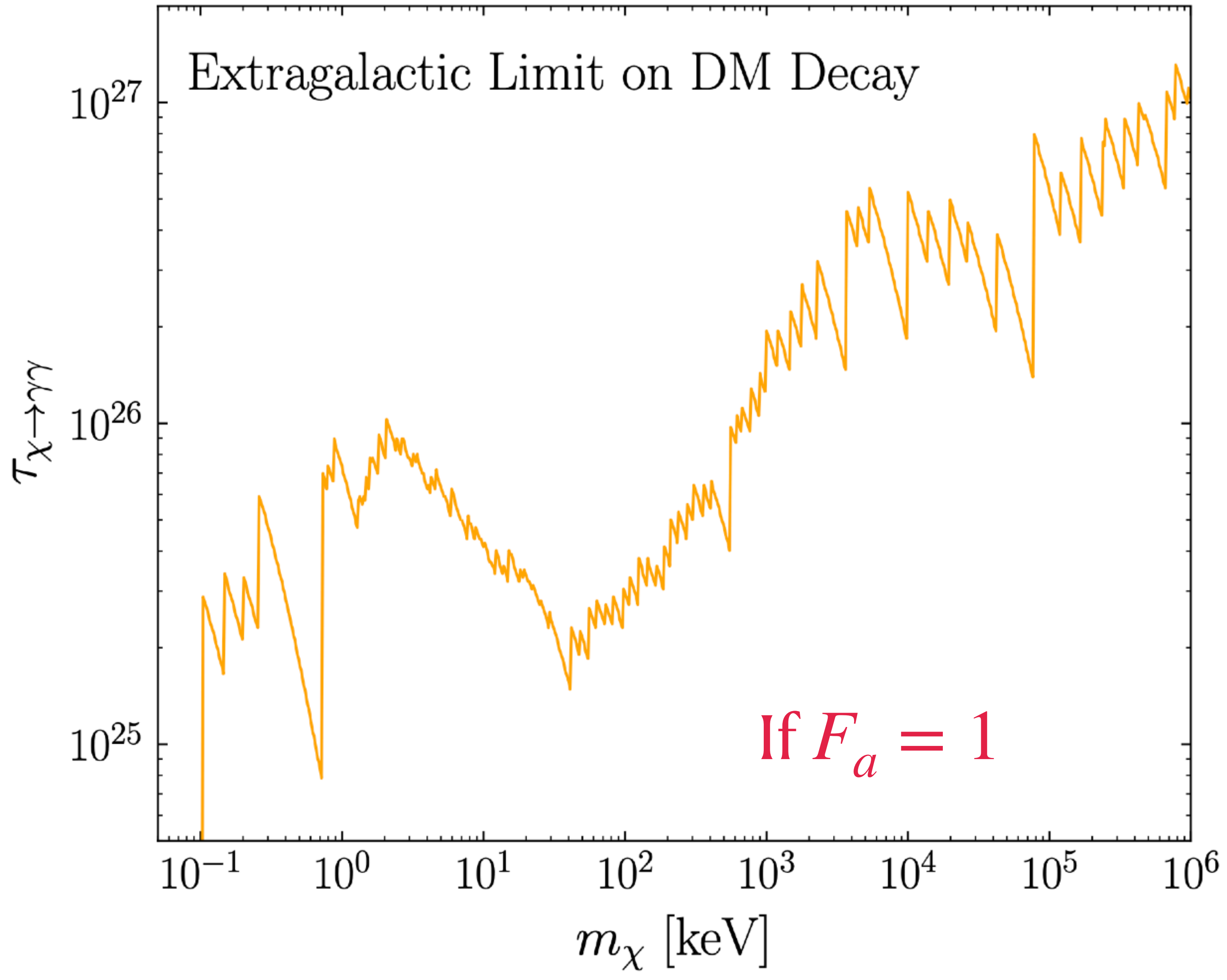


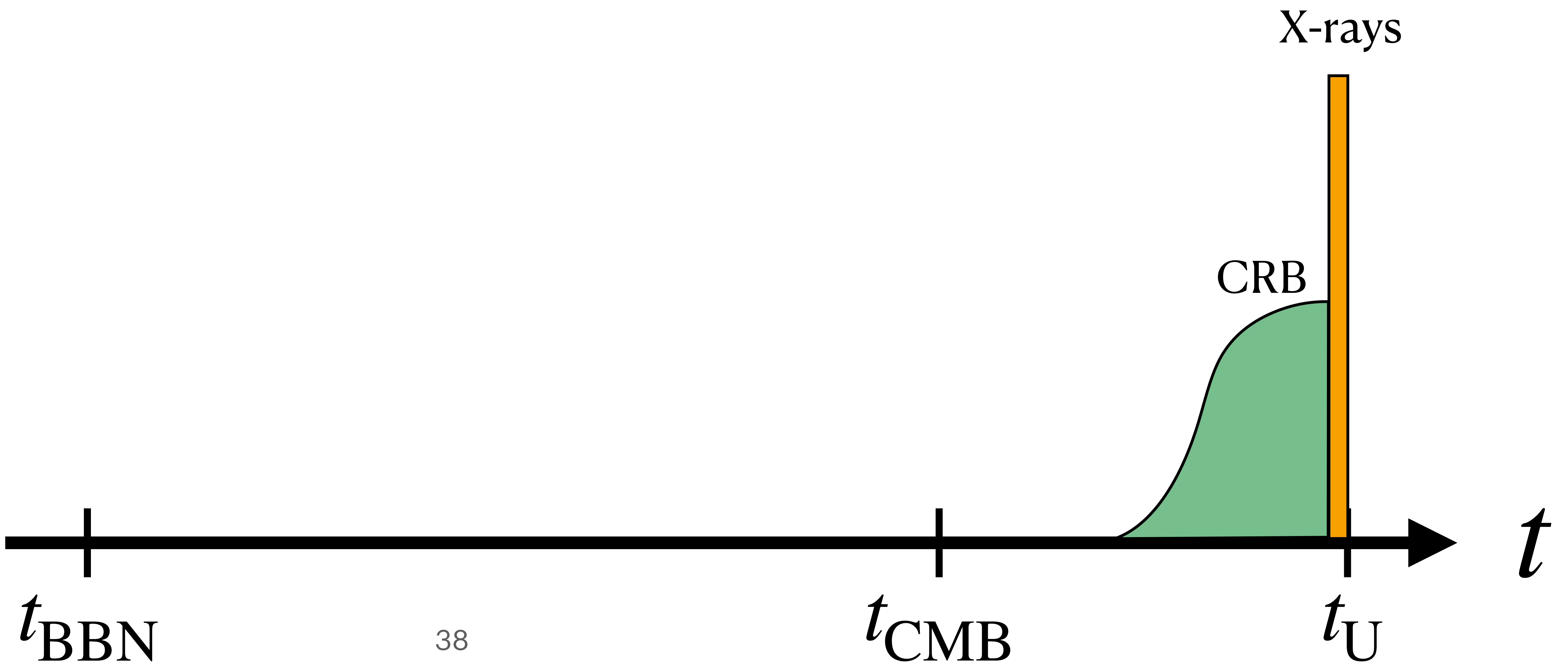
Cosmological and Astrophysical Constraints

How we observe the decay of axions depends on when they decay.

For $t_{\mathrm{CMB}} \ll \tau_a \lesssim t_{\mathrm{U}}$, we can look for decays in the diffuse axion background. [Zurek et al, 2013]

$$\frac{d\Phi}{dE} = \frac{2\rho_a}{m_a\, E\, H_0} \frac{e^{-t(E)/\tau_a}}{\tau_{a\to\gamma\gamma}} \frac{e^{-\kappa(z,\,E)}}{\sqrt{\Omega_m (m_a/2E)^3 + \Omega_\Lambda}} \Theta(m_a - 2E)$$

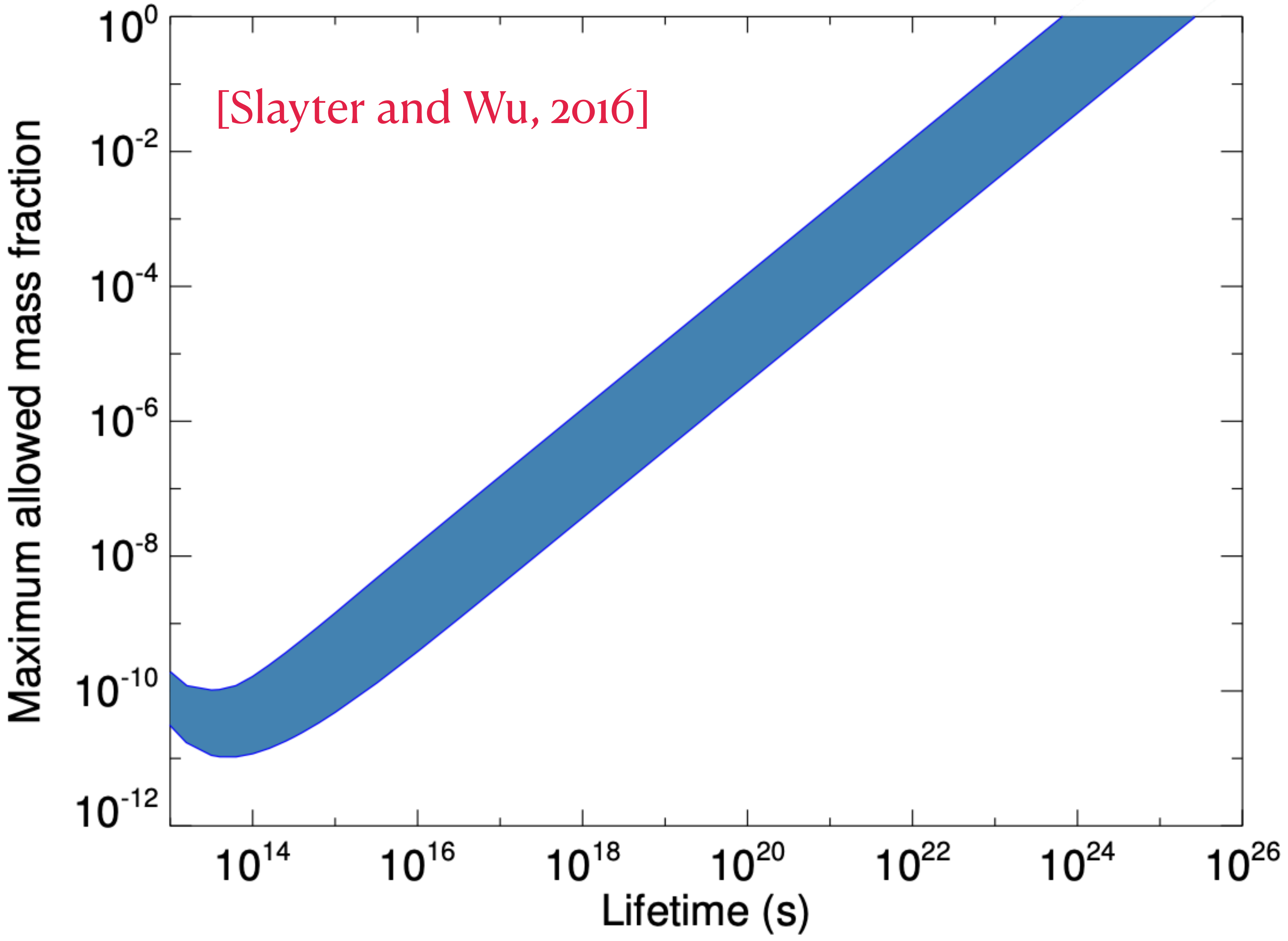


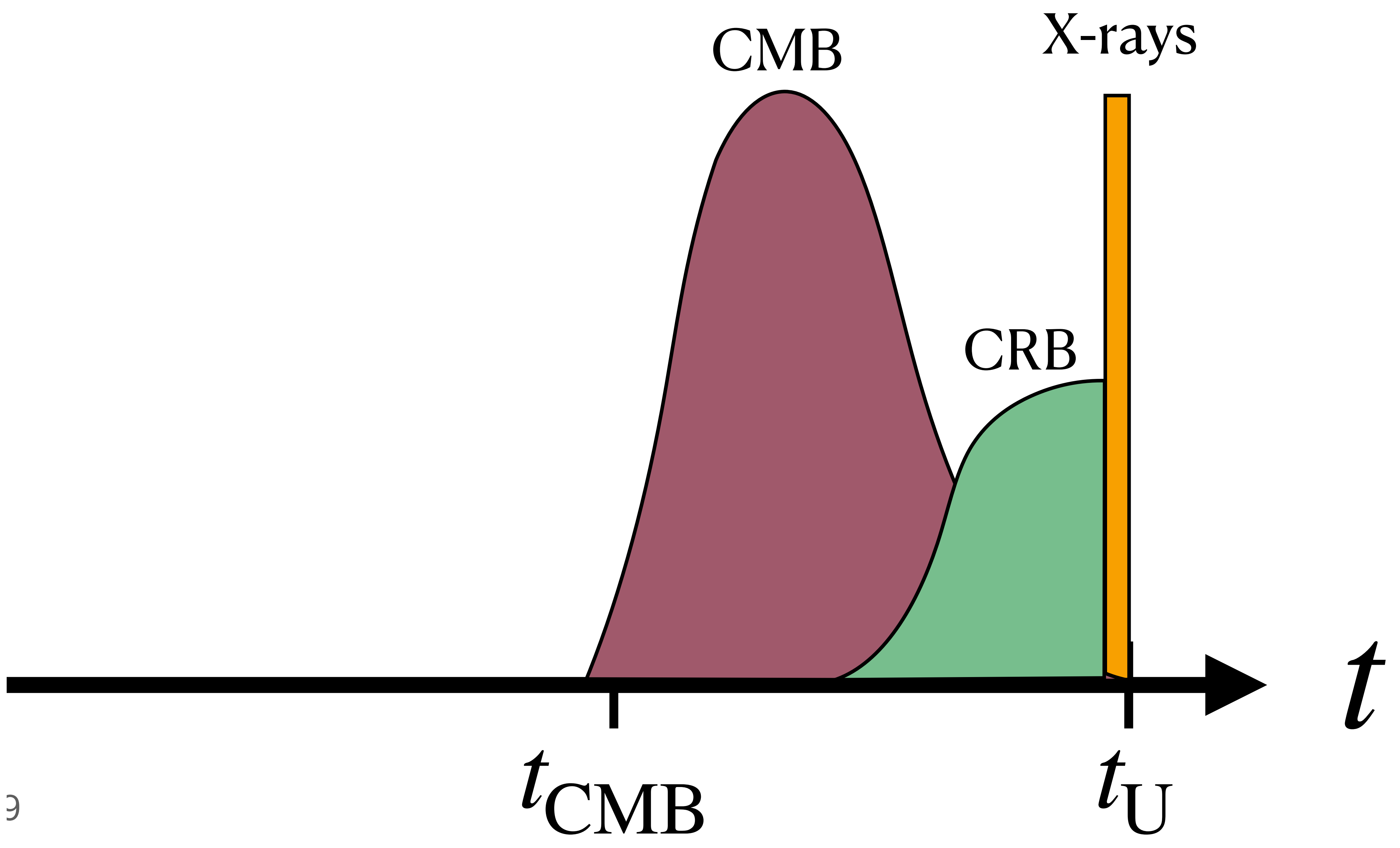


Cosmological and Astrophysical Constraints

How we observe the decay of axions depends on when they decay.

For $t_{\mathrm{CMB}} \lesssim \tau_a$, we can look for the effect of decays on CMB anisotropies ($z \lesssim 1100$)

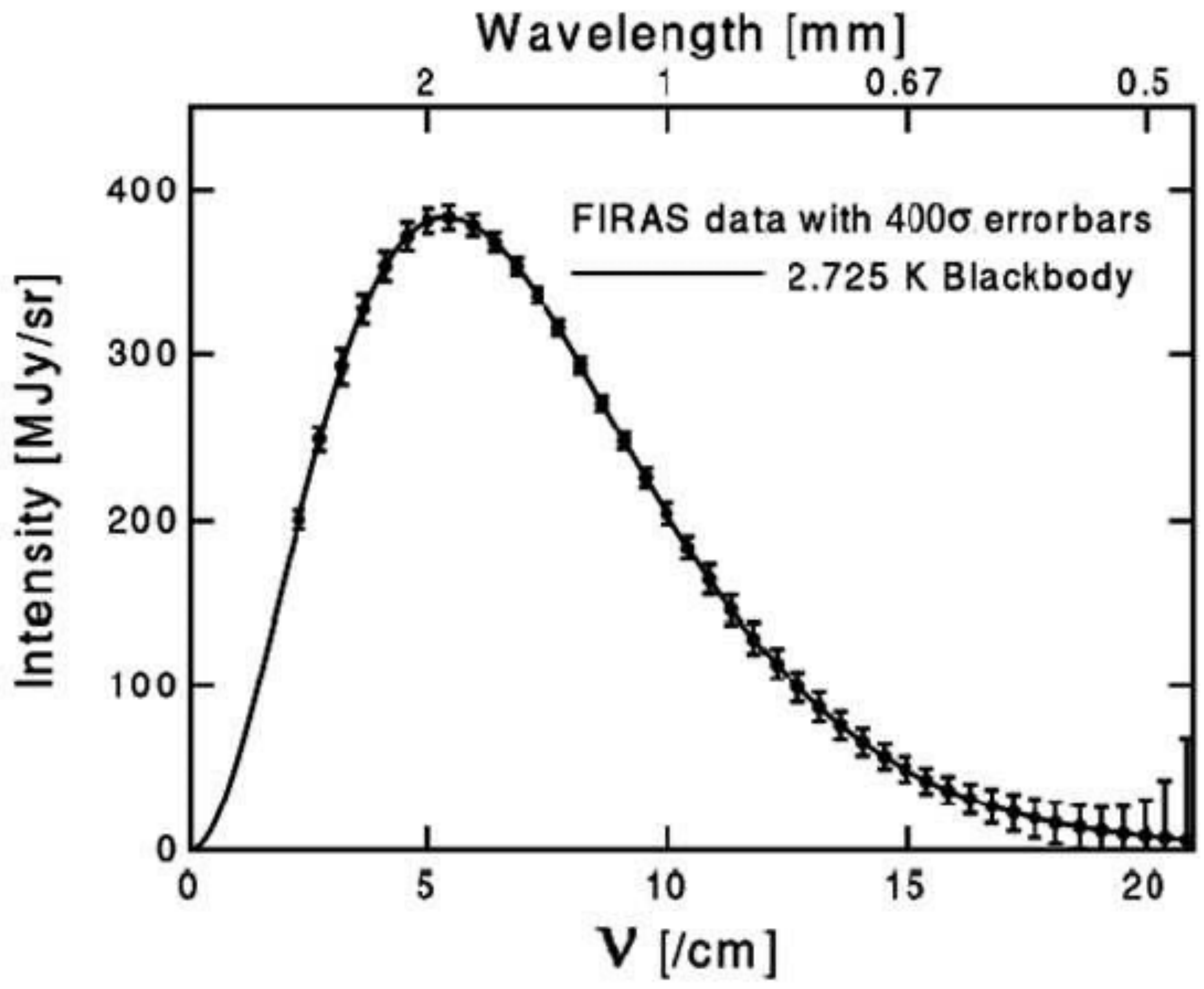


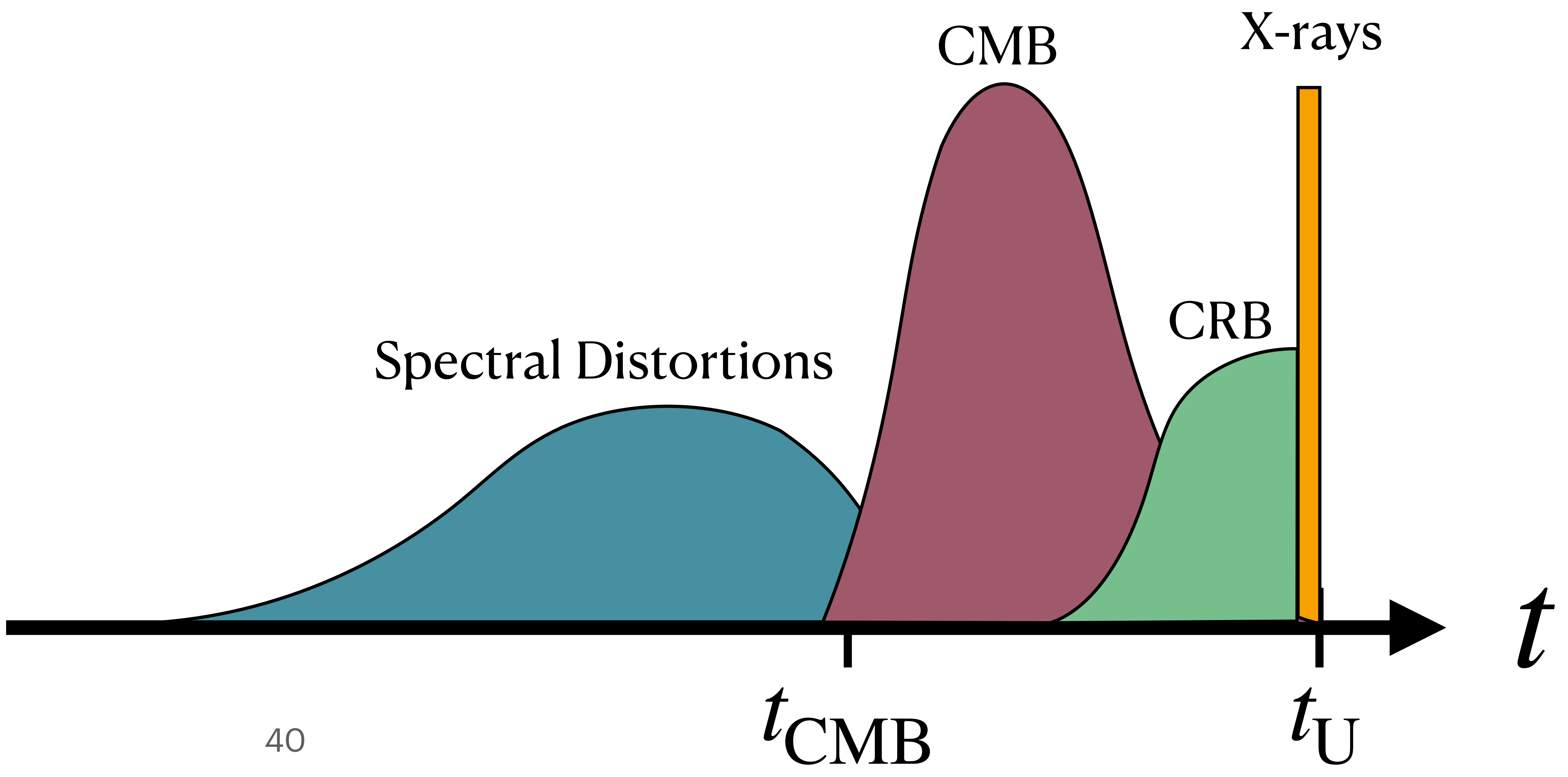


Cosmological and Astrophysical Constraints

How we observe the decay of axions depends on when they decay.

For $\tau_a \lesssim t_{\rm CMB}$, we can look for the effect of decays on CMB spectral distortions ($1100 \lesssim z \lesssim 2 \times 10^6$) [Balzas et al, 2022]

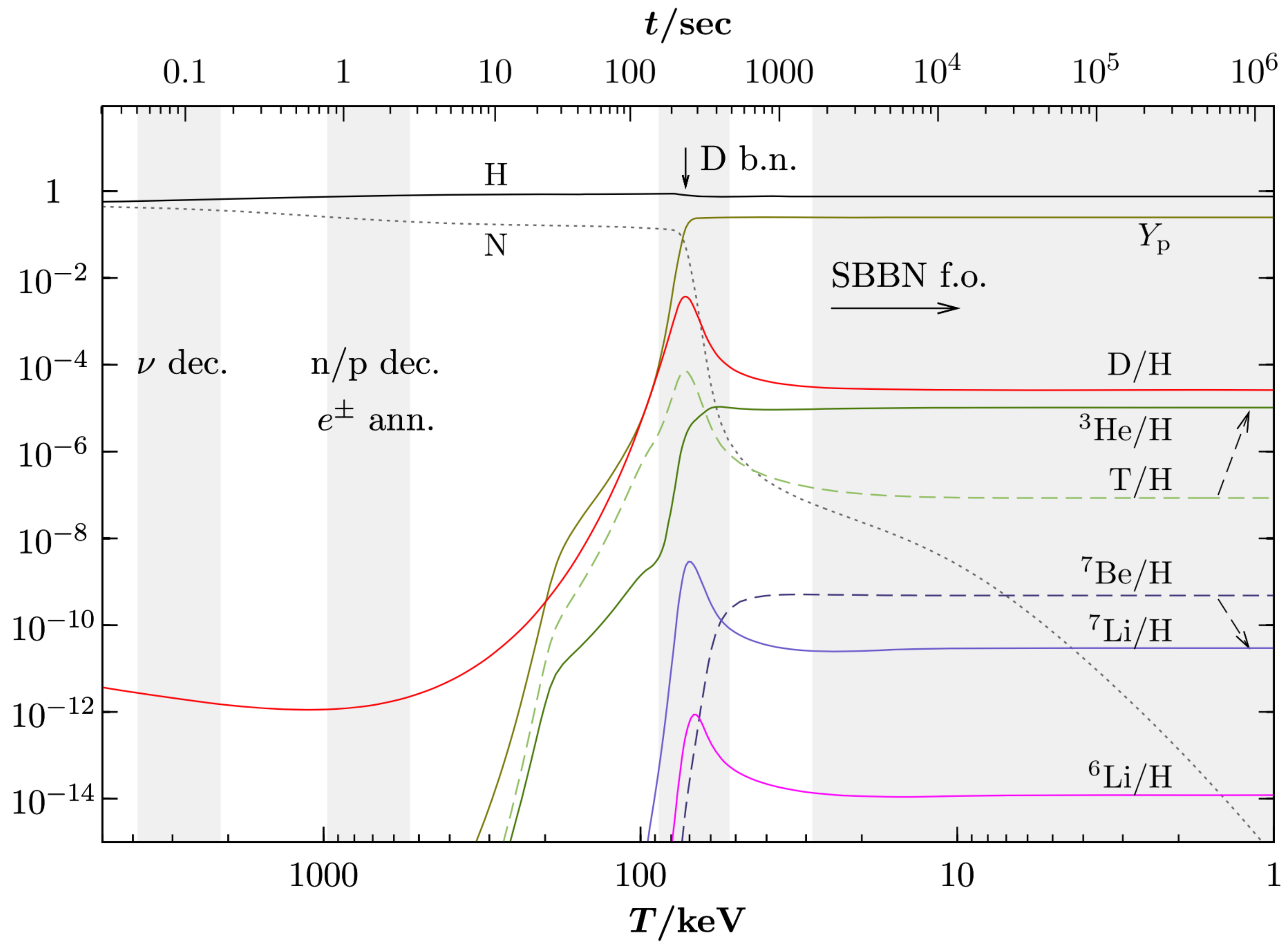


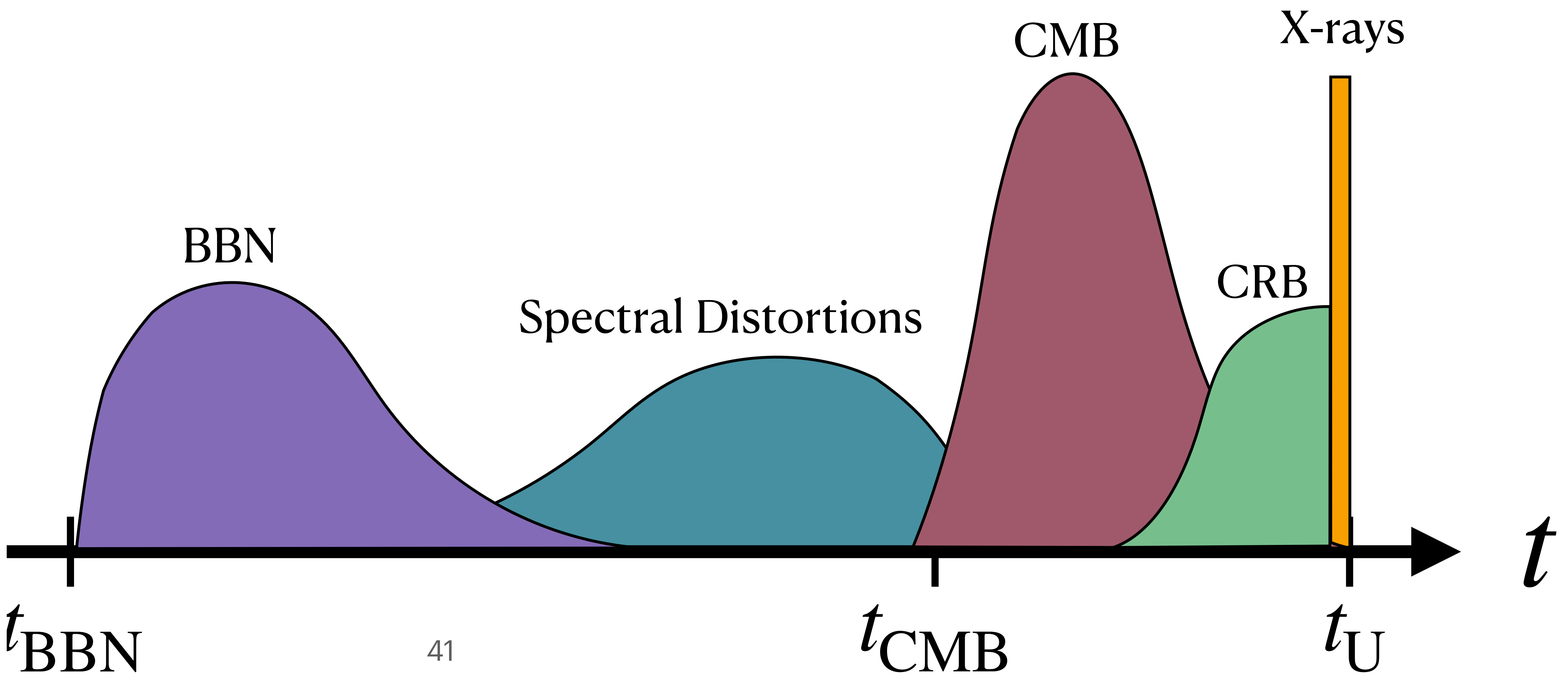


Cosmological and Astrophysical Constraints

How we observe the decay of axions depends on when they decay.

For $t_{\mathrm{BBN}} \lesssim \tau_a$, we can look for the effect of decays light element abundance



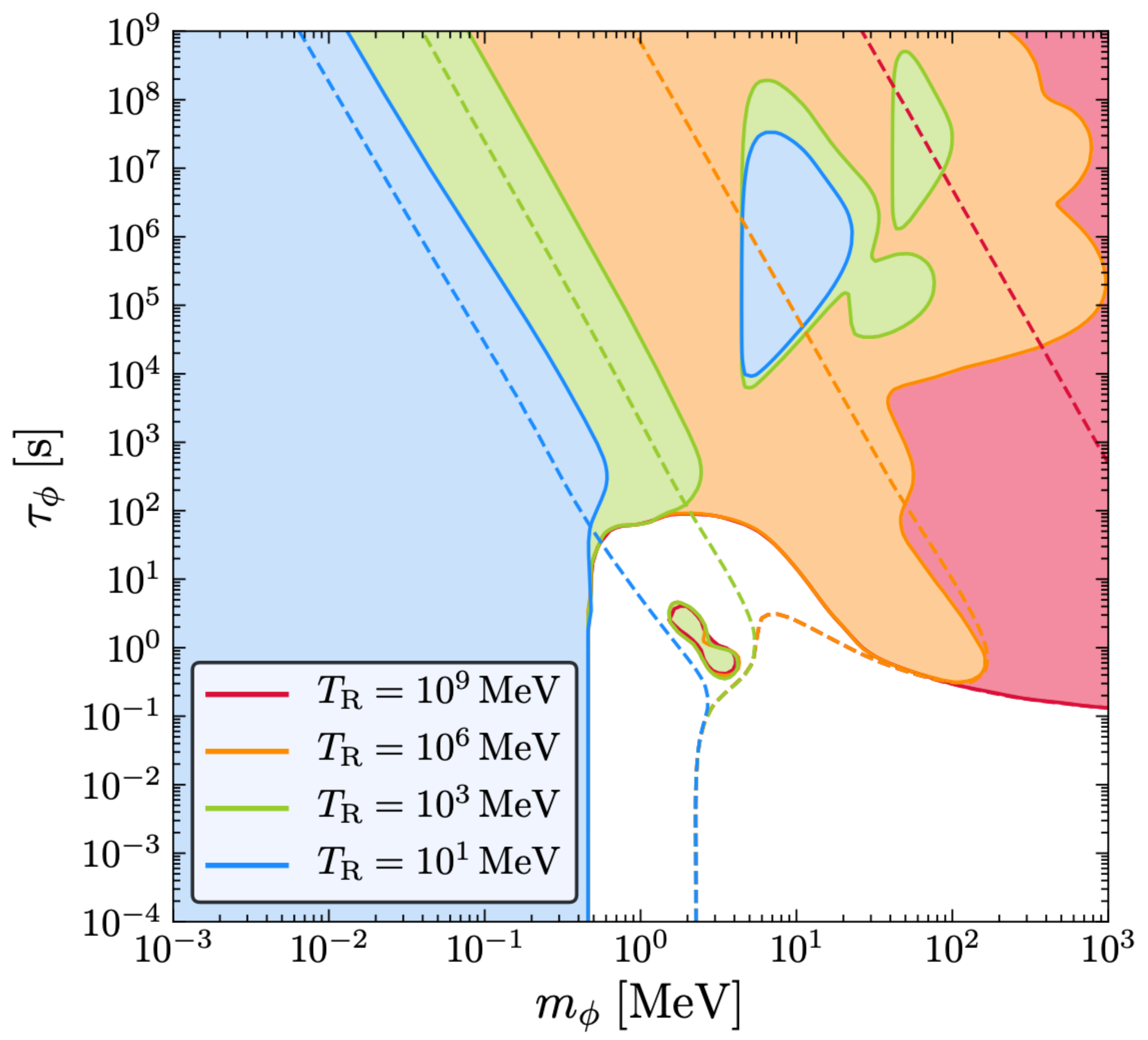


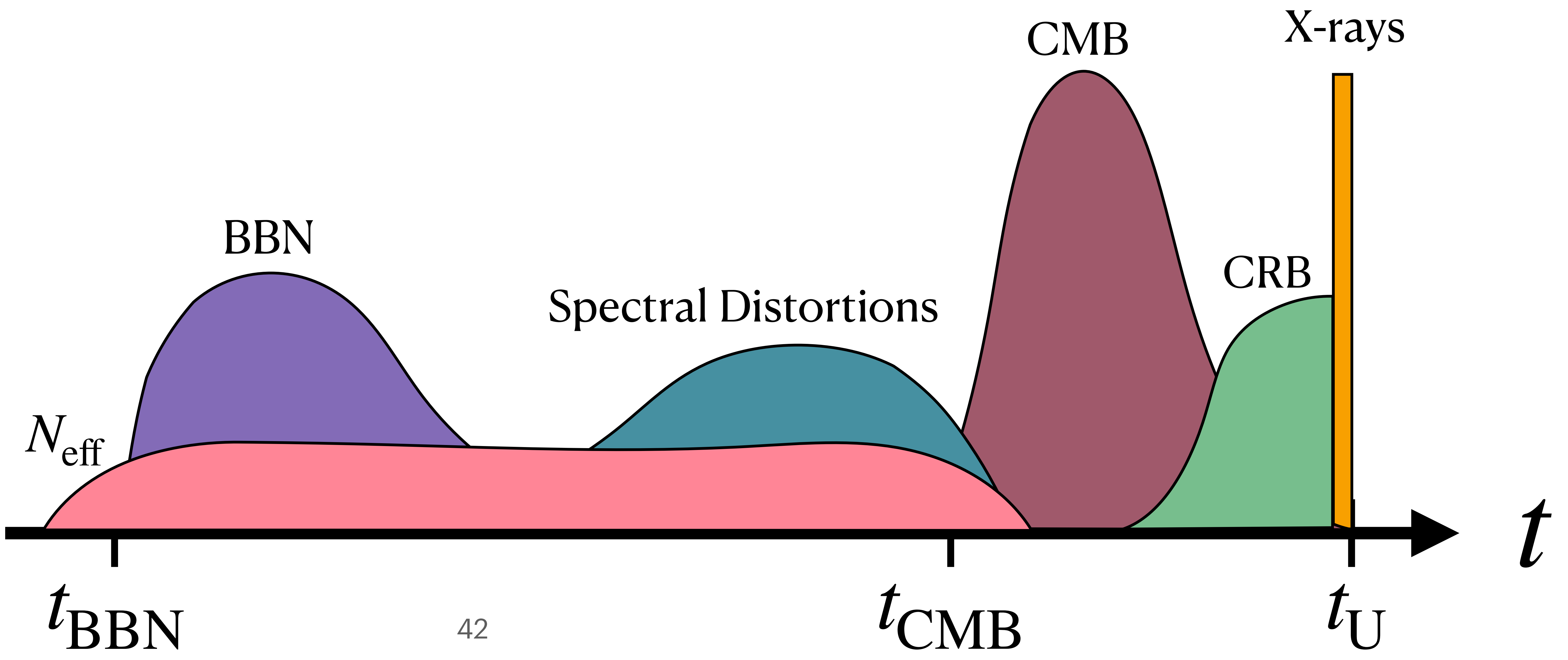
Cosmological and Astrophysical Constraints

How we observe the decay of axions depends on when they decay.

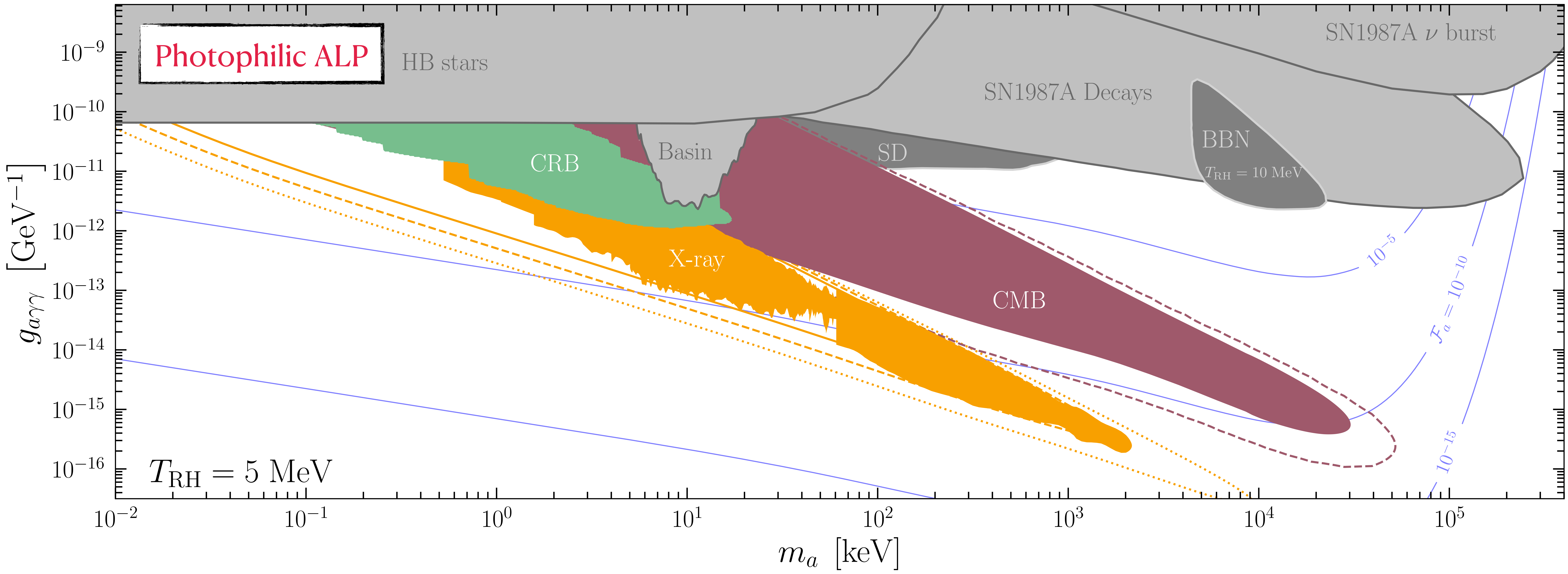
$t_{\rm BBN} \lesssim \tau_a \lesssim t_{\rm CMB}$, we can look for the effect of decays in $\Delta N_{\rm eff}$.

[Depta, Hufnagel, and Schmidt-Hoberg , 2020]

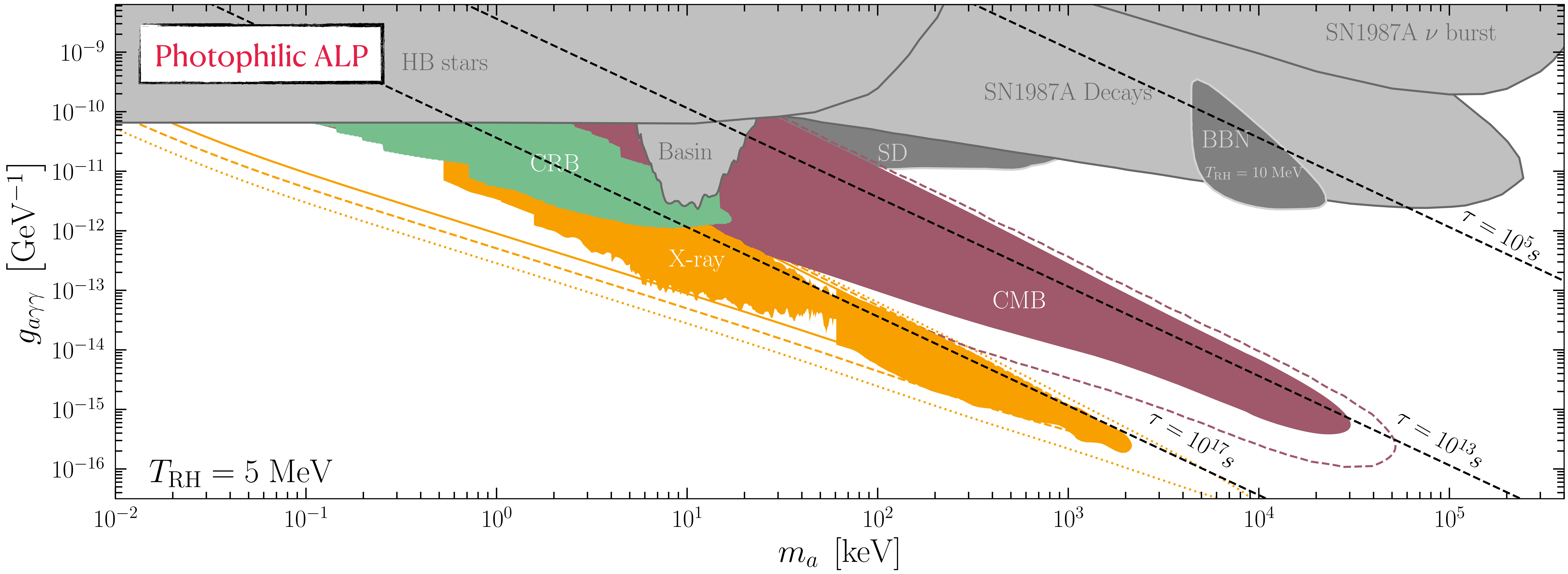




Photophilic Axion Bounds

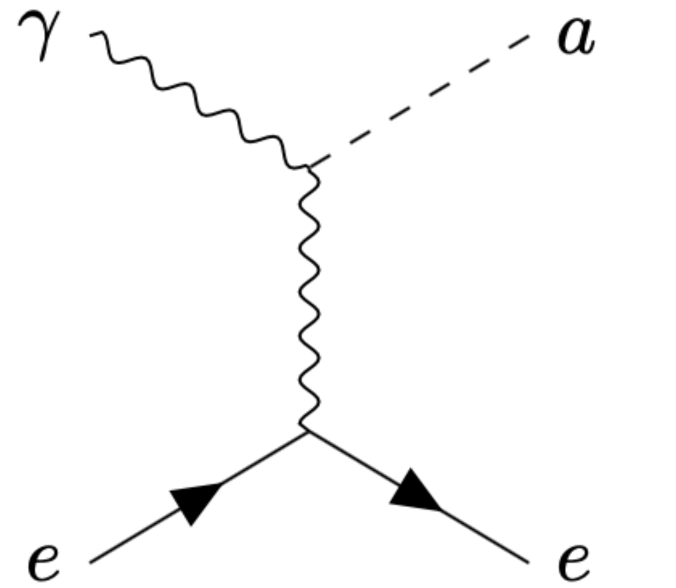
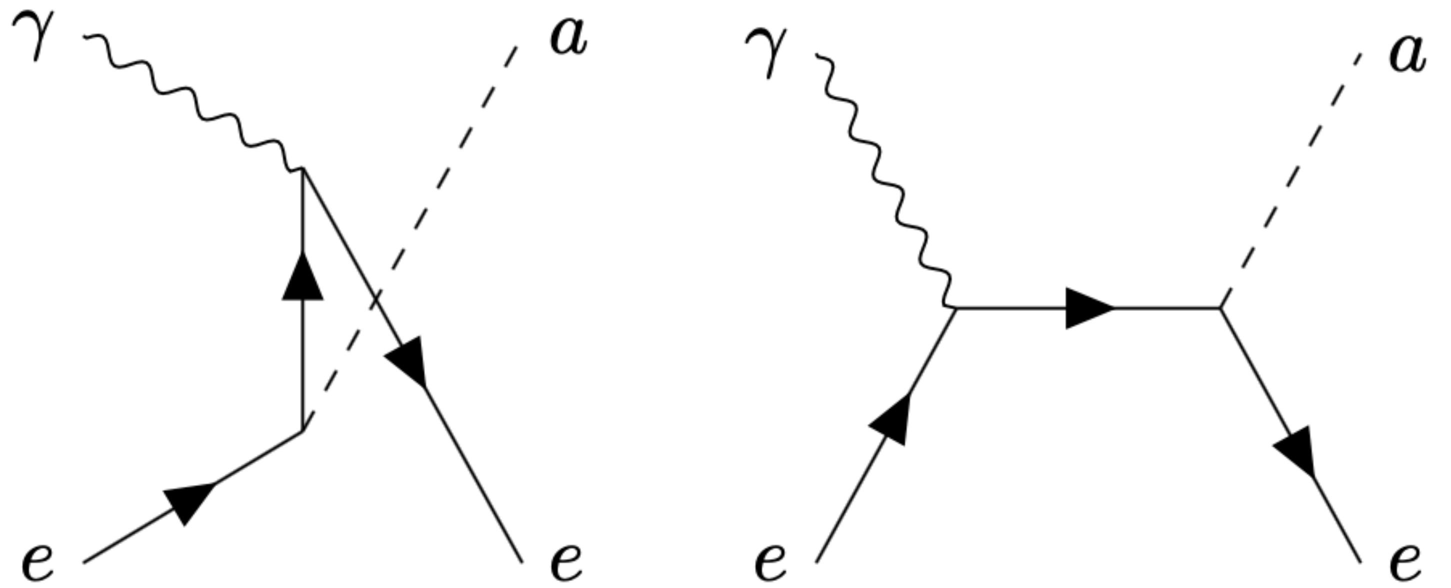
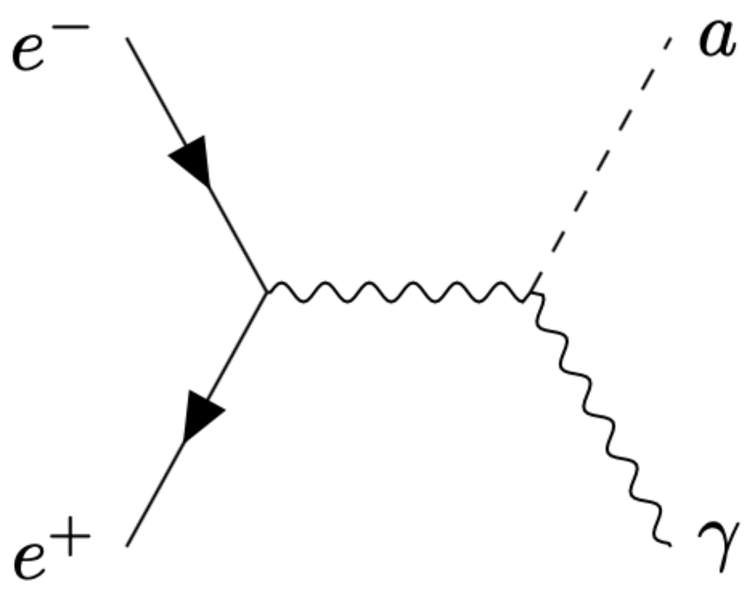
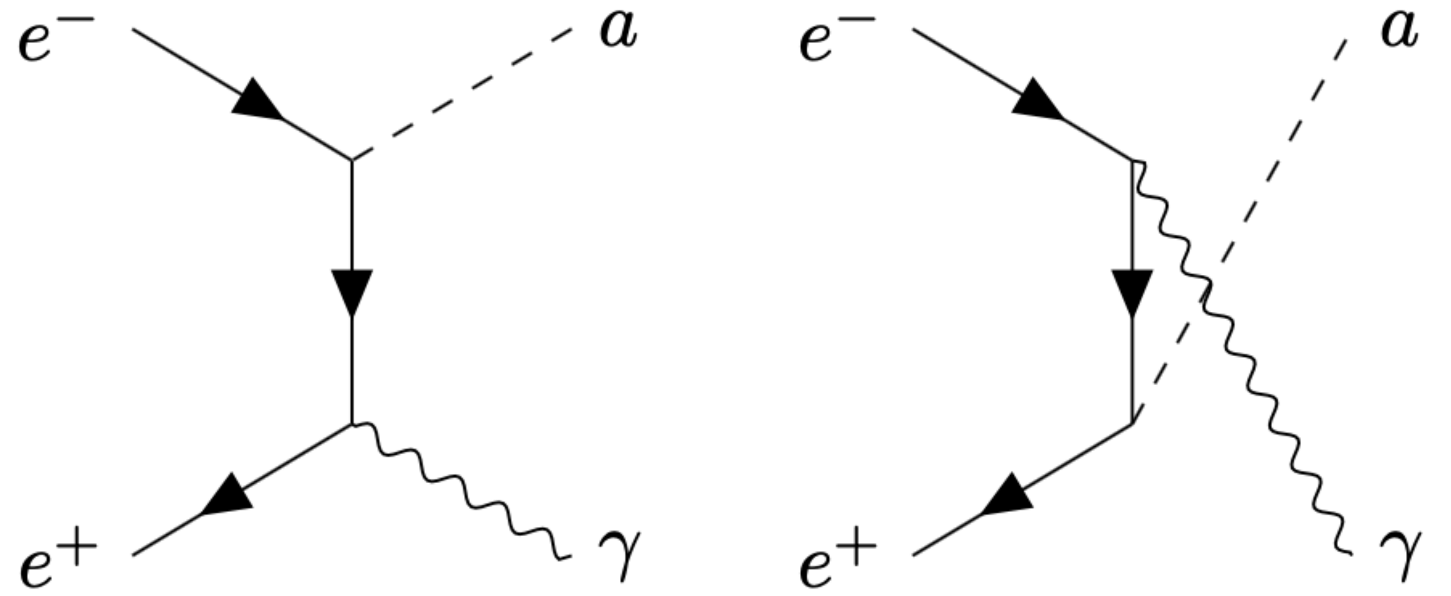
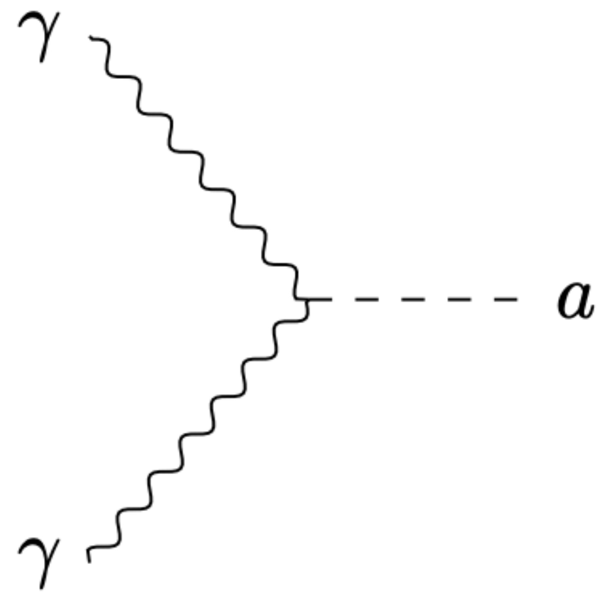
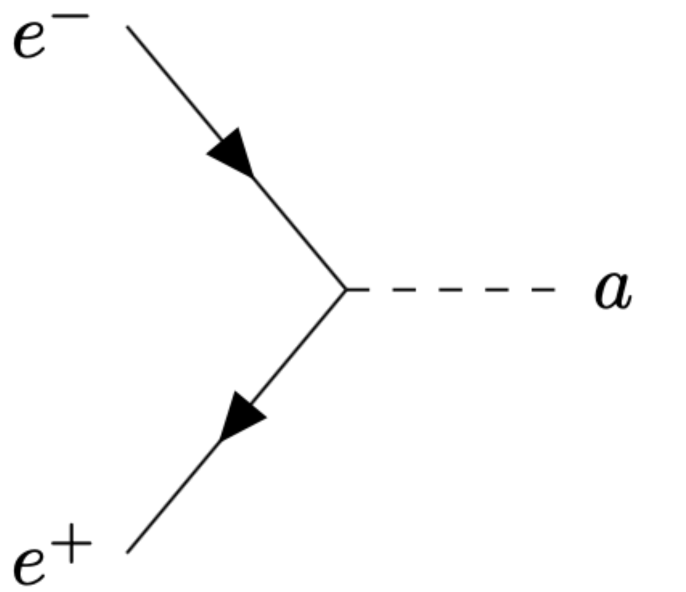


Photophilic Axion Bounds

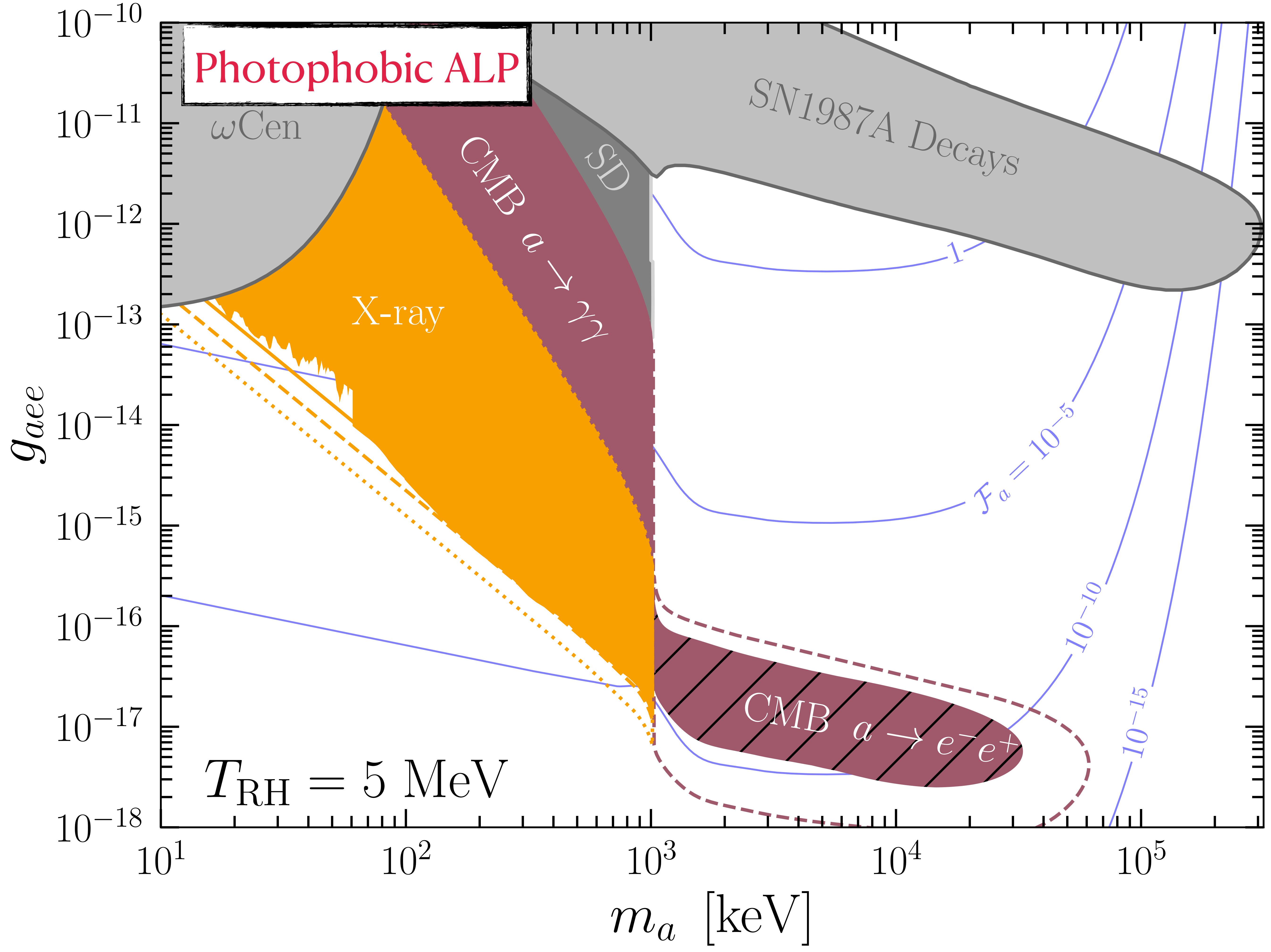


Generalizations

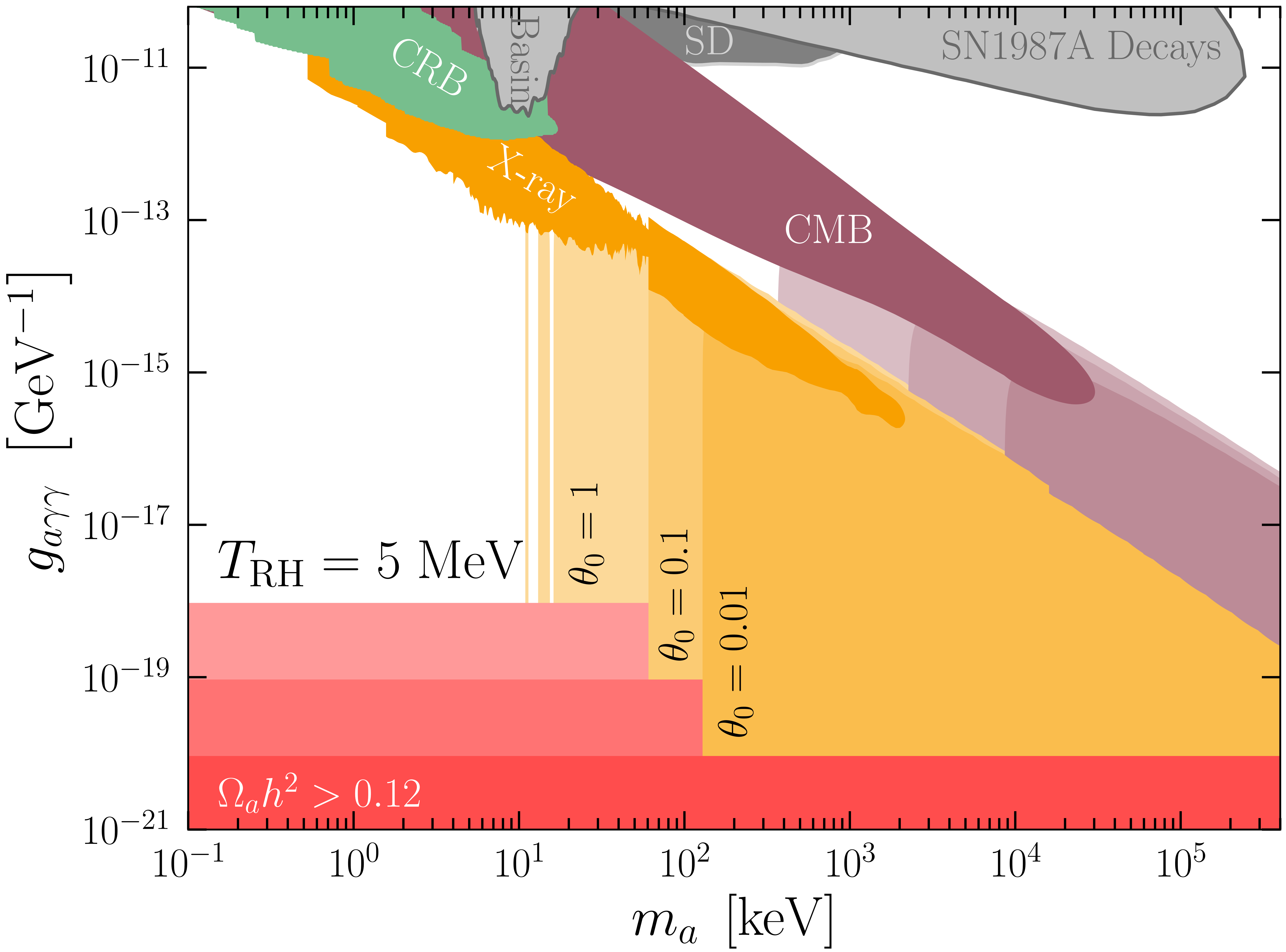
Photophobic Axion Constraints

	$g_{a\gamma\gamma}$	g_{aee}
Photon Conversion $\gamma e \to ae$		
Fermion Annihilation $e^- e^+ \to a\gamma$		
Inverse Decay $\gamma\gamma \to a$ or $e^- e^+ \to a$		

Photophobic Axion Constraints



Photophilic Axions with Misalignment



Production of Sterile Neutrinos

- For simplicity, assume sterile neutrino mixes only with ν_e .

$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- The Boltzmann equation will have the following form:

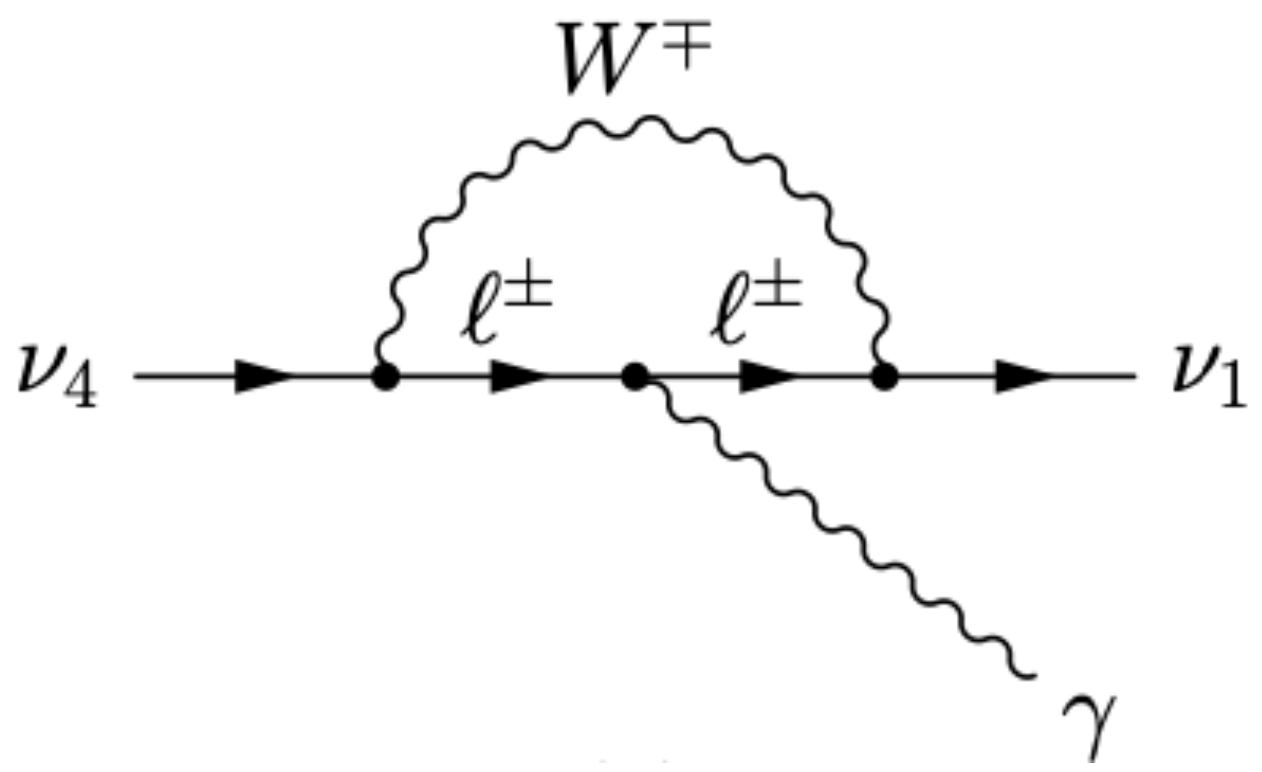
$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_s(T,p) = (f_s^{\text{eq}} - f_s)\Gamma_s(T,p)$$

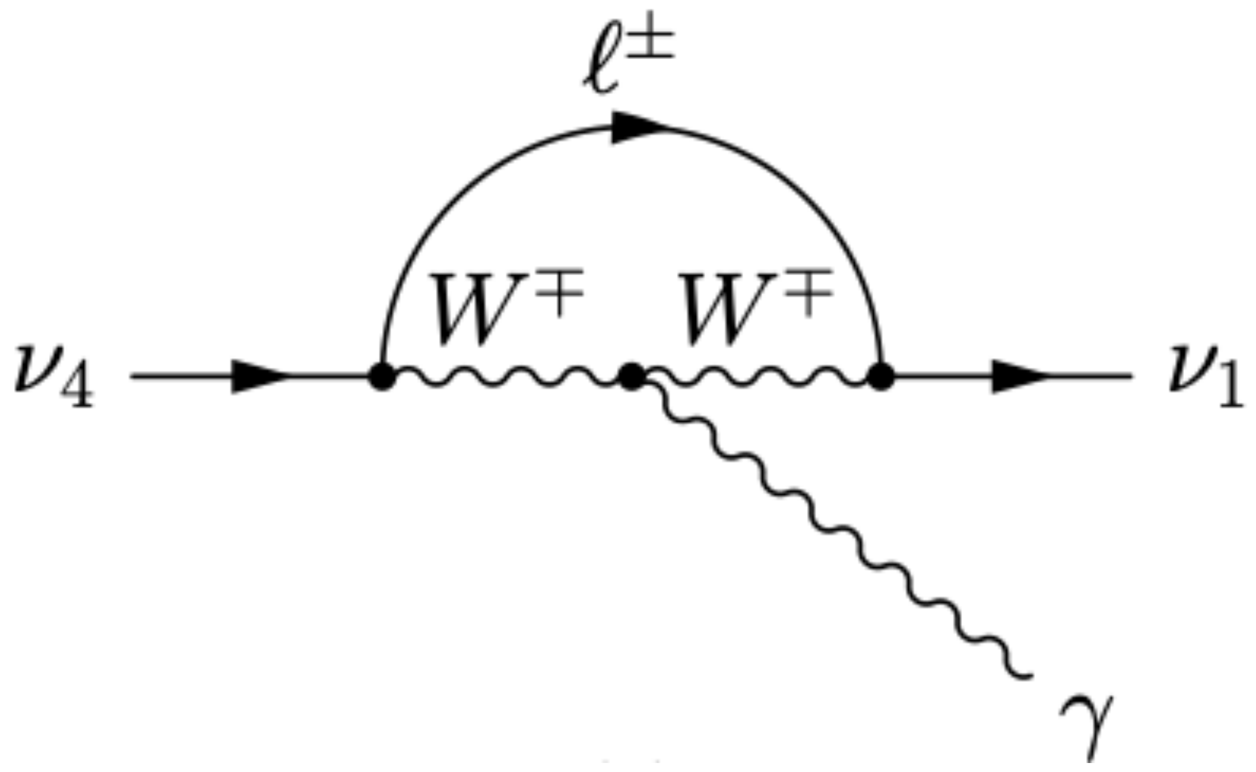
$$\Gamma_s(T,p) \approx \begin{cases} \frac{1}{4}\sin^2(2\theta) d_e G_F^2 E T^4, & m_s \ll T_{\text{RH}} \\ \frac{1}{\tau_s}\left[\frac{m_s}{E} + \frac{288\zeta(3)T^3}{m_s^3} + \frac{112\pi^4 T^3}{3m_s^5}\left(ET + \frac{p^2 T}{3E}\right)\right], & m_s \gg T_{\text{RH}} \end{cases}$$

[G. Gelmini, E. Osoba, S. Palomares-Ruiz, S. Pascoli, 2008]

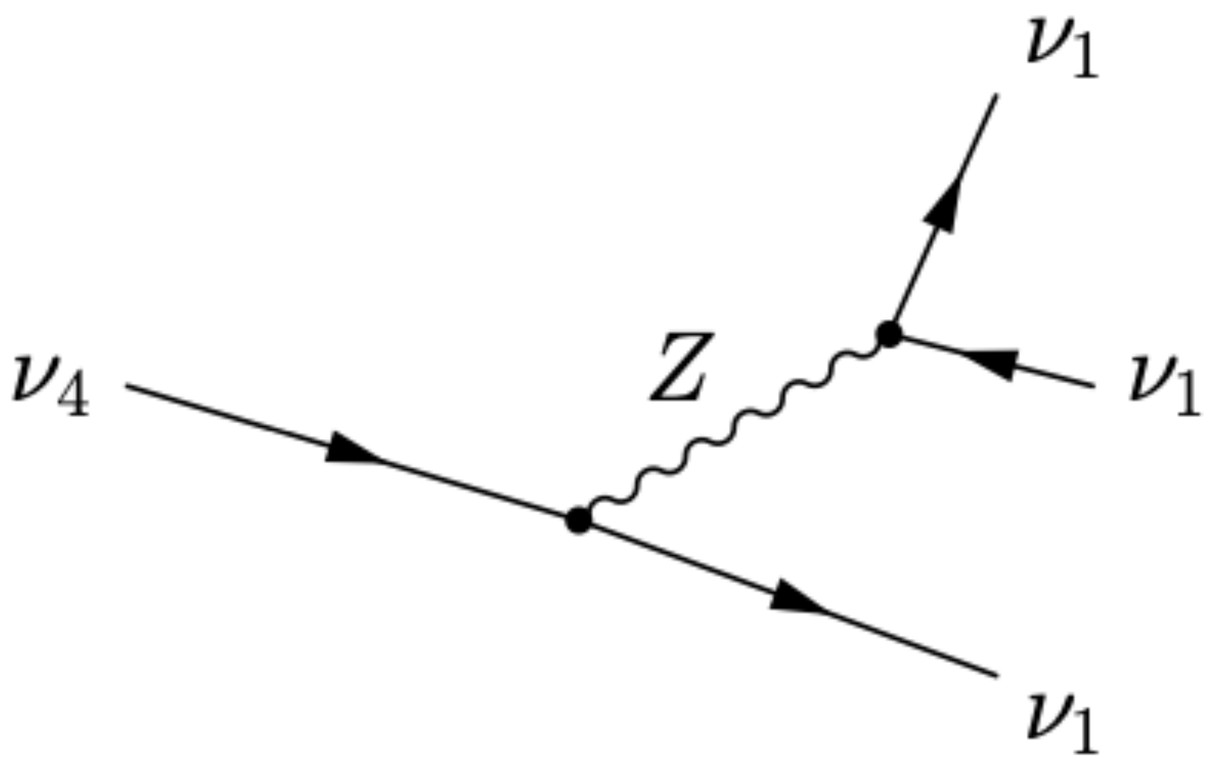
Cosmological and Astrophysical Constraints

The easiest way to observe sterile neutrinos is through their radiative decay.





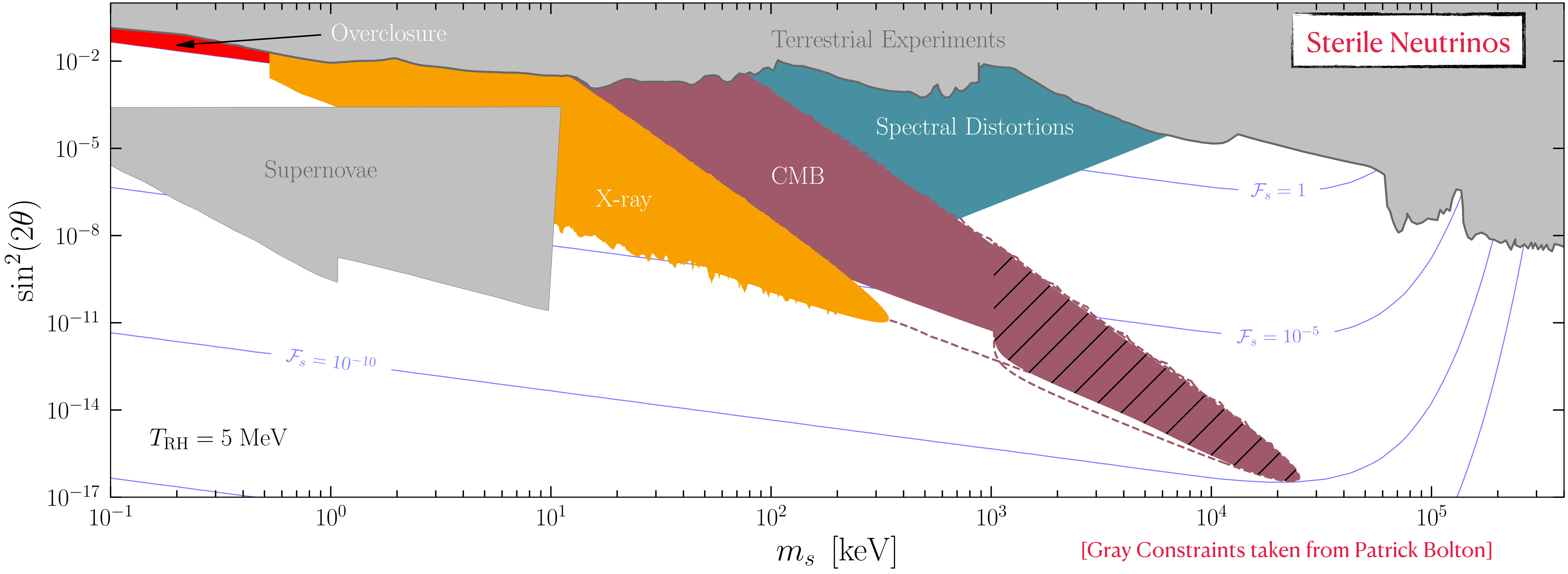
However, their lifetime is determined by a different process



(Also to e^+e^- when $m_s > 2m_e$)

[Diagrams from Kopp and Dasgupta, 2021]

Sterile Neutrino Constraints

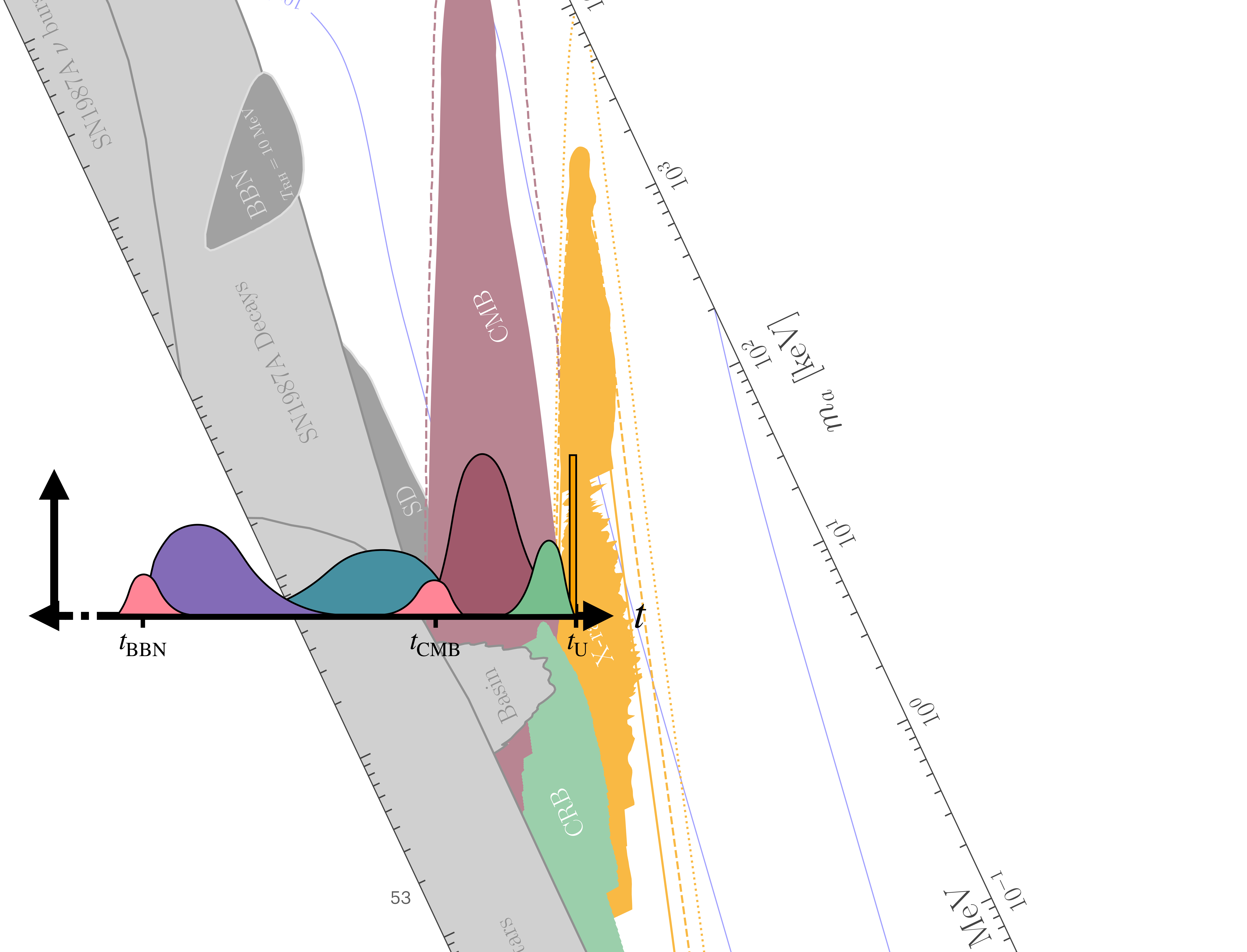


[Gray Constraints taken from Patrick Bolton]

Thank You

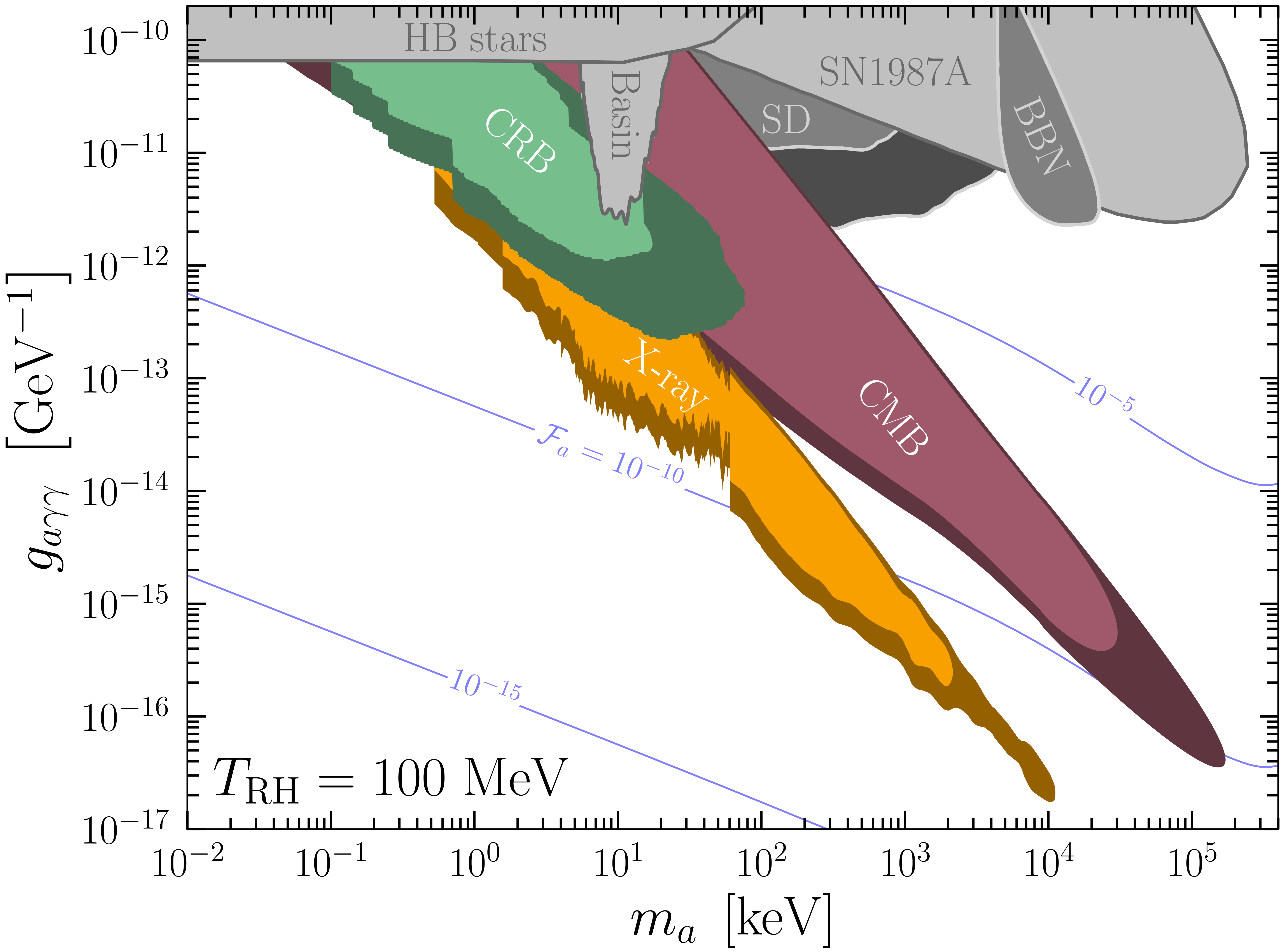
Upcoming work:

- Axiverse with SU(N) SYM Domain Walls
- PBH Production with SUSY Axions
- Observing Light BSM Particles with Muon Decay
- Axion Dark Matter in the Mirror World

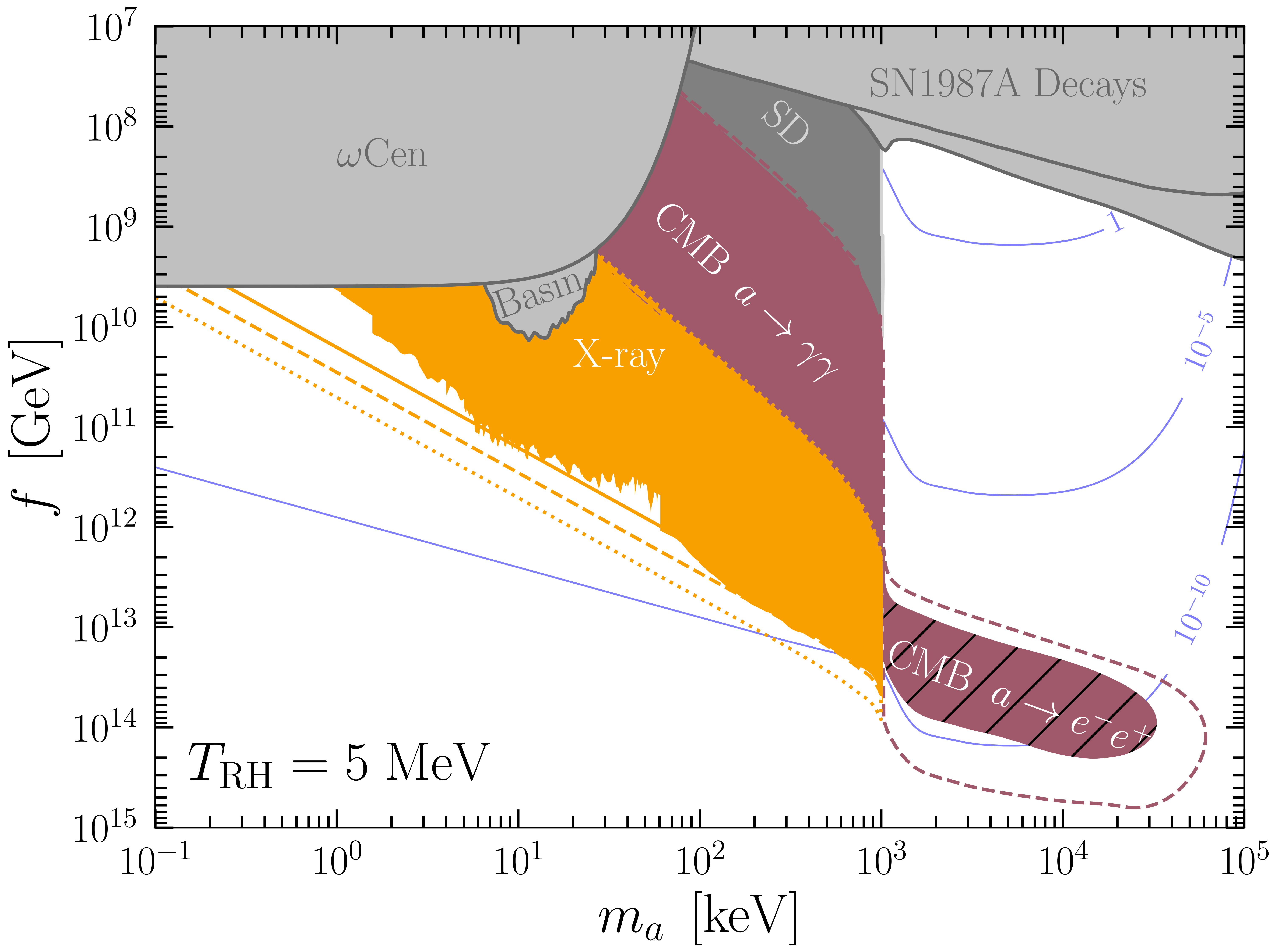


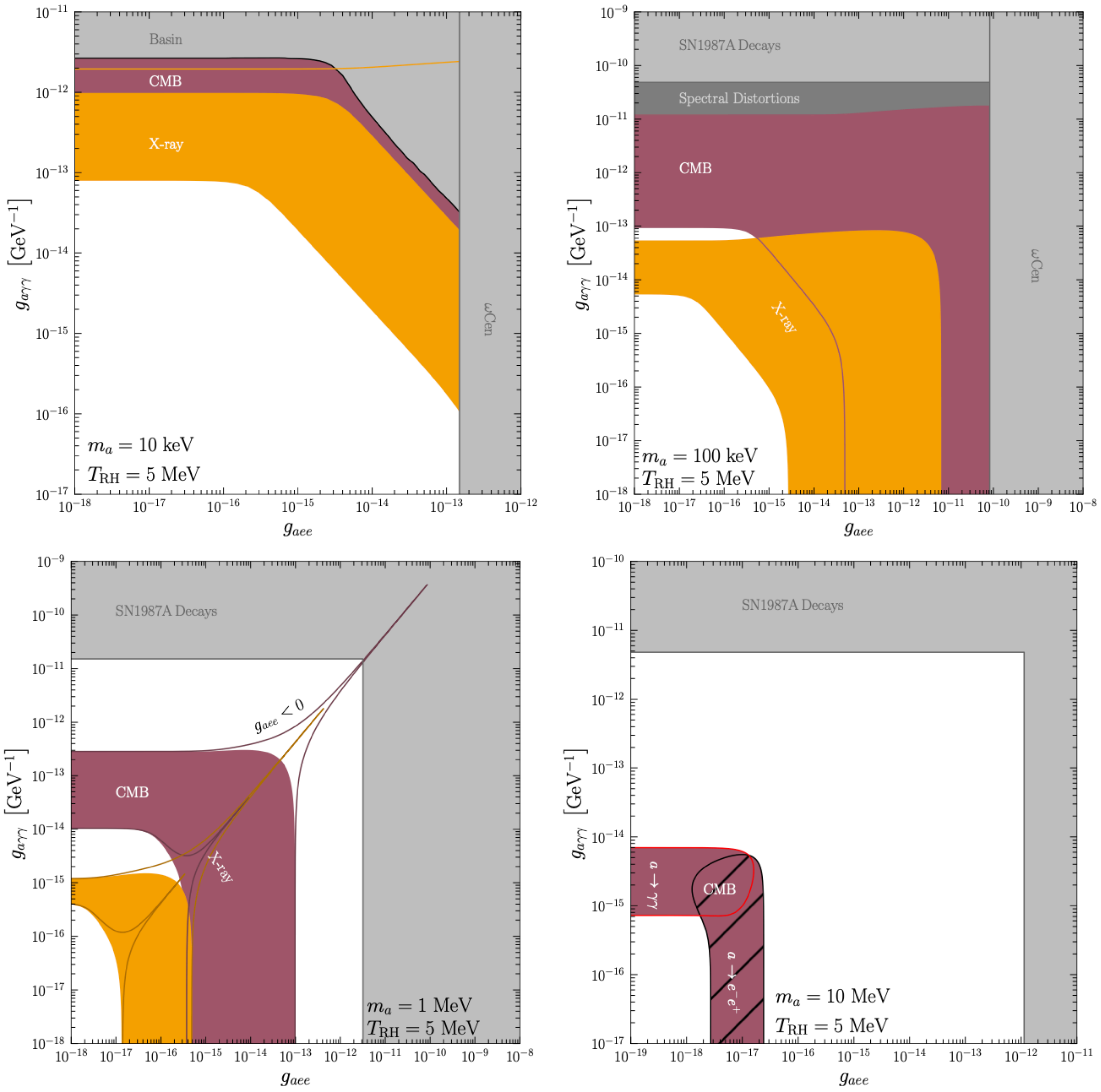
SN1987A Decays
BBN
$T_{RH} = 10$ MeV
SD
CMB
Basin
CRB
t_{BBN}
t_{CMB}
t_U
t
m_a [keV]
10^3
10^2
10^1
10^0
10^{-1}
MeV

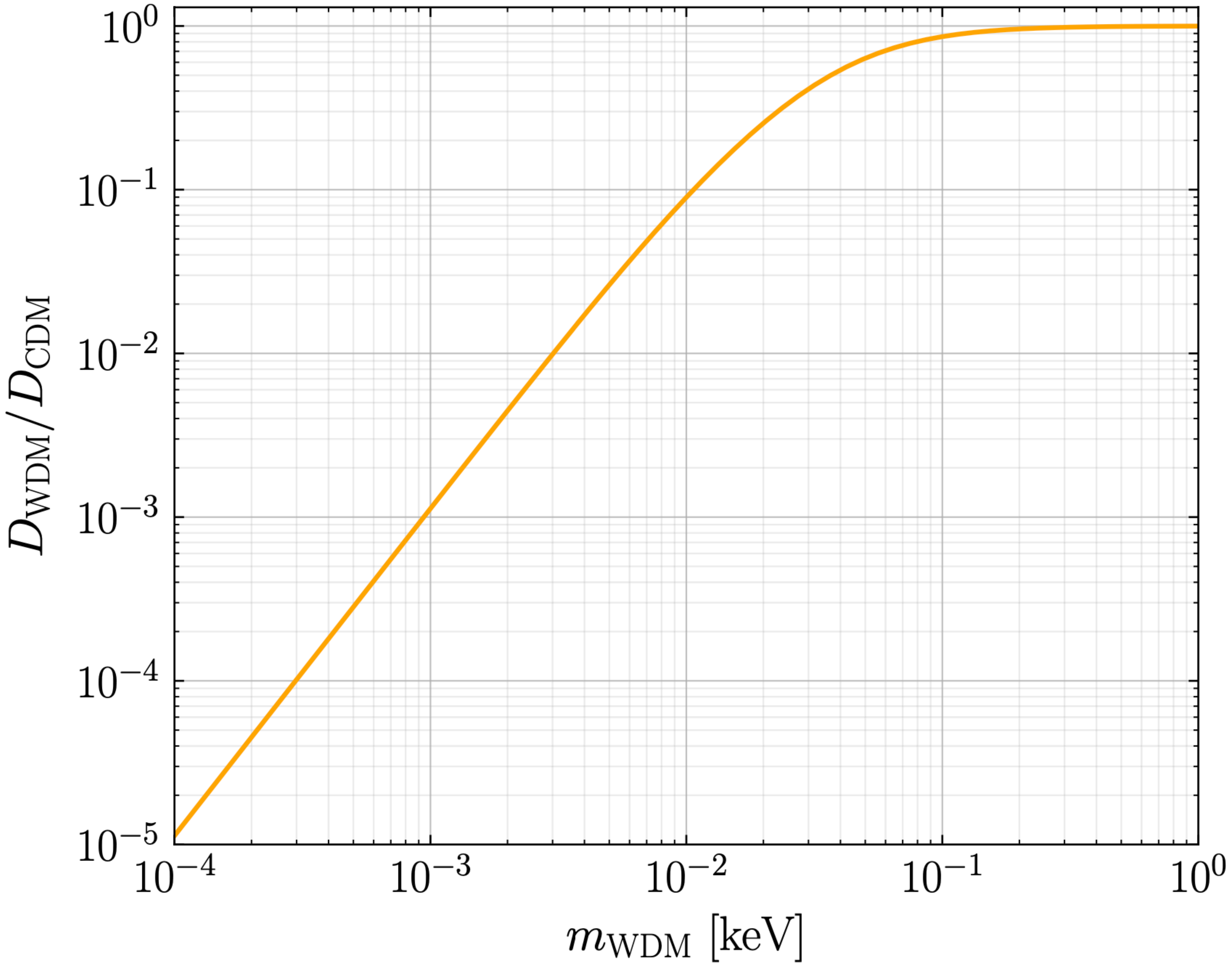
Photophilic Axions with $T_{RH} = 100$ MeV



Axions with "Universal" Couplings




Basin
CMB
X-ray
ωCen
$m_a = 10$ keV
$T_{RH} = 5$ MeV
$g_{a\gamma\gamma}$ [GeV^{-1}]
g_{aee}
SN1987A Decays
Spectral Distortions
CMB
X-ray
ωCen
$m_a = 100$ keV
$T_{RH} = 5$ MeV
SN1987A Decays
$g_{aee} < 0$
CMB
X-ray
$m_a = 1$ MeV
$T_{RH} = 5$ MeV
SN1987A Decays
$a \to \gamma\gamma$
CMB
$a \to e^- e^+$
$m_a = 10$ MeV
$T_{RH} = 5$ MeV



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$D_{\rm WDM}/D_{\rm CDM}$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
$m_{\rm WDM}$ [keV]

Production of Axions

- Abundance obtained from solving the Boltzmann equation.

$$\dot{n}_a + 3Hn_a = R(t)$$

$$R(t) = \sum_{\text{process}} \int \left(\prod_i d\Pi_i\right)\left(\prod_f d\Pi_f\right)(2\pi)^4\delta^4\left(\sum_i p_i - \sum_f p_f\right)|\mathcal{M}_{i\to f}|^2 \times \Phi$$

$$\Phi = (f_a^{\rm eq} - f_a) \times \left[\prod_i \left(1 \pm f_i^{\rm eq}\right)\prod_{f\neq a} f_f^{\rm eq} - \prod_{f\neq a}\left(1 \pm f_f^{\rm eq}\right)\prod_i f_i^{\rm eq}\right]$$

$\ll f_a^{\rm eq}$

Note dropping f_a decouples the Boltzmann equation!
(Production by different processes are independent)

Production of Axions

Make the following definitions:

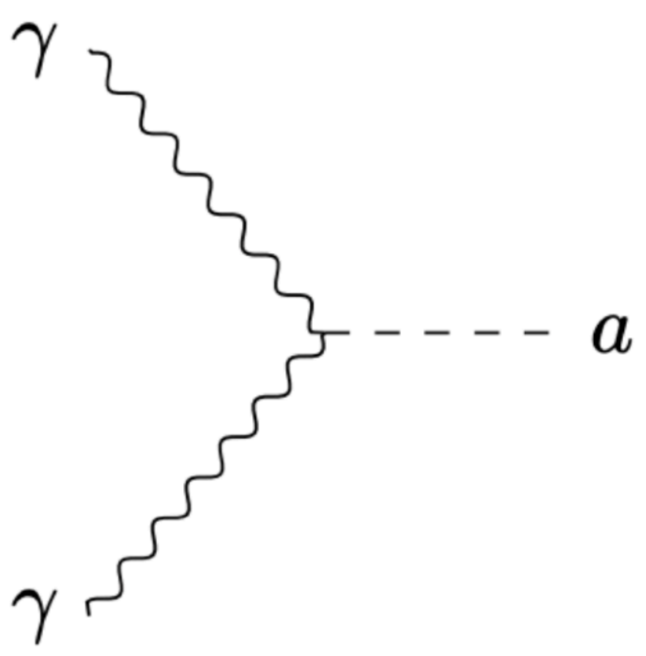
1. $x = m_a / T$
2. $Y_a = n_a / s$
3. $\tilde{g}(x) = 1 - \frac{1}{3}\frac{d \log g_{\star,s}}{d \log x}$

The Boltzmann equation simplifies to

$$\frac{dY_a}{dx} = \frac{\tilde{g}(x)}{xH(x)s(x)} R(x) \implies \mathcal{F}_a \simeq \frac{m_a s_0}{\rho_{\mathrm{DM},0}} Y_a(\infty)$$

(Ignoring Axion Decay)

Production of Axions (Inverse Decay)



$$\sum |\mathcal{M}_{\gamma\gamma\to a}|^2 = \frac{1}{2} g_{a\gamma\gamma}^2 m_a^2 (m_a^2 - 4m_\gamma^2)$$

$$R_{\rm ID}(T) = \sum |\mathcal{M}_{\gamma\gamma\to a}|^2 \int d\Pi_1 d\Pi_2 d\Pi_a (2\pi)^4 \delta^4 (p_1 + p_2 - p_a) \times f_a^{\rm eq}[1 + (f_1^{\rm eq} + f_2^{\rm eq})]$$

$$= \frac{\sum |\mathcal{M}_{\gamma\gamma\to a}|^2}{32\pi^3} \int_{m_a}^{\infty} dE_a\, f_a^{\rm eq} \left(\beta\, p_a + 2T \ln \left[\frac{1 - e^{-E_+/T}}{1 - e^{-E_-/T}} \right] \right)$$

$$\beta = \sqrt{1 - 4m_\gamma(T)^2/m_a^2} \qquad E_\pm = (E_a \pm \beta p_a)/2$$

- $R_{\rm ID}(T) = 0$ for $2m_\gamma(T) > m_a$ where $m_\gamma(T) \approx eT/3 \sim T/10$
- Similar calculation for electrons.

Production of Axions (2→2)

$$R_{2\to 2}(T) \approx \frac{g_1 g_2 T}{32\pi^4}\int_{s_{\min}}^{\infty} ds\,\lambda(s, m_1^2, m_2^2)\frac{K_1(\sqrt{s}/T)}{\sqrt{s}}\sigma_{12\to 3a}(s)$$ [D'Eramo et al, 2017]

$$\sigma_{\rm FA}(s) = \frac{\alpha g_{a\gamma\gamma}^2}{24\beta}\left(1-\frac{m_a^2}{s}\right)^3\left(1+\frac{2m_e^2}{s}\right) + \frac{\alpha g_{aee}^2}{2s^2\,(s-m_a^2)\,\beta^2}\left[(s^2-4m_e^2m_a^2+m_a^4)\ln\left(\frac{1+\beta}{1-\beta}\right)-2\beta m_a^2 s\right] - \frac{\alpha g_{a\gamma\gamma}g_{aee}m_e}{2s\beta^2}\left(1-\frac{m_a^2}{s}\right)^2\ln\left(\frac{1+\beta}{1-\beta}\right)$$

$$\sigma_{\rm PC}(s) = \frac{\alpha g_{a\gamma\gamma}^2}{32s^2}\left[2(2s^2-2m_a^2 s+m_a^4)\ln\left(\frac{s-m_a^2}{m_\gamma^2}\right)-7s^2+10m_a^2 s-5m_a^4\right] + \frac{\alpha g_{aee}^2}{8s^3}\left[2\left(2s^2-2m_a^2 s+m_a^4\right)\ln\left(\frac{s}{m_e^2}\right)-3s^2+10m_a^2 s-7m_a^4\right] - \frac{\alpha g_{a\gamma\gamma}g_{aee}m_e}{8s^3(s-m_a^2+m_e^2)}\left[2(s^3+m_a^6)\ln\left(\frac{(s-m_a^2)^2}{(s+m_a^2)m_e^2}\right)-3(s+m_a^2)(s-m_a^2)^2\right]$$

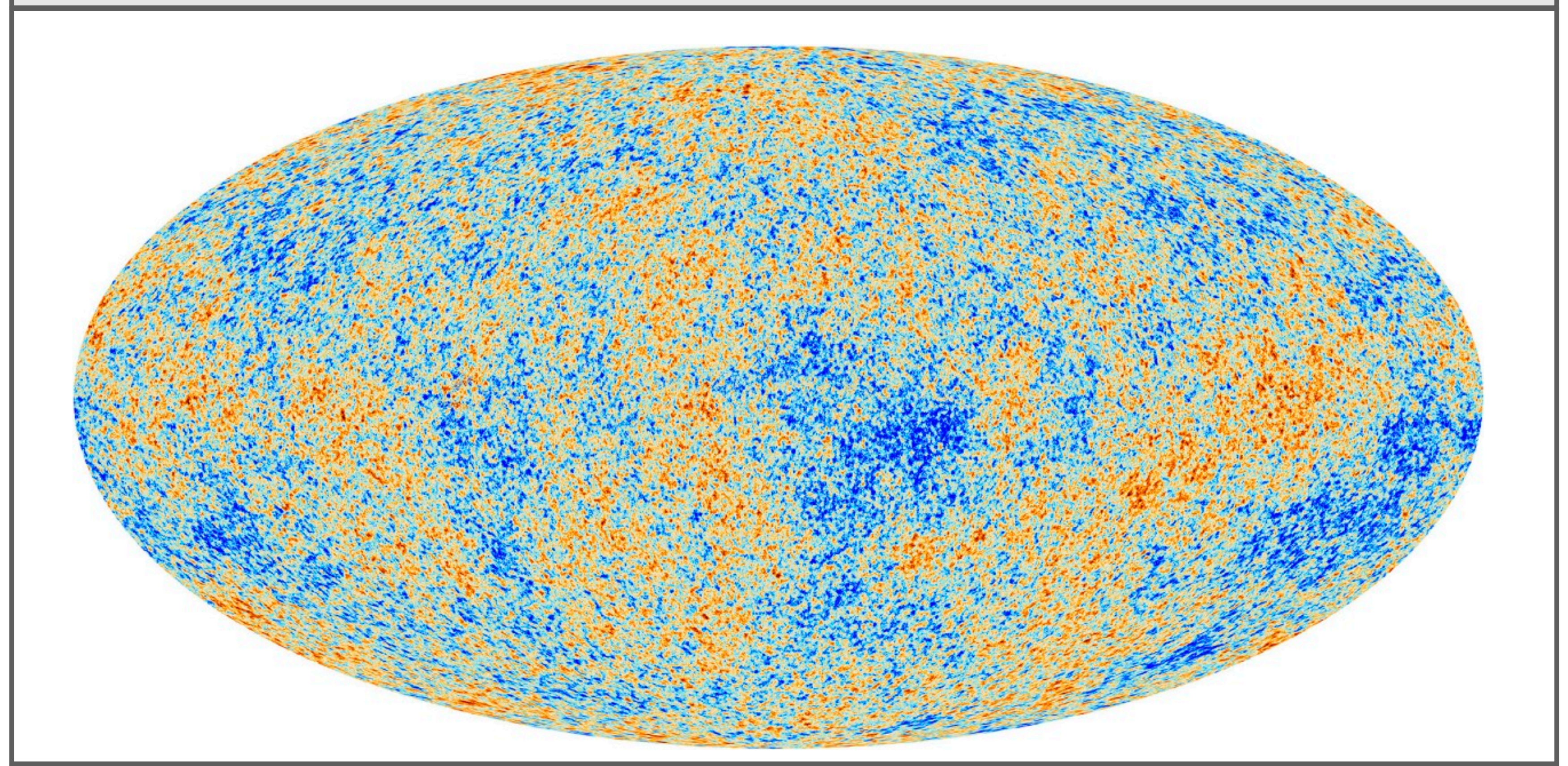
Irreducible Cosmic Abundance Constraints

How do you calculate $F_{\chi,\mathrm{irr}}(m_\chi, g_\chi)$?

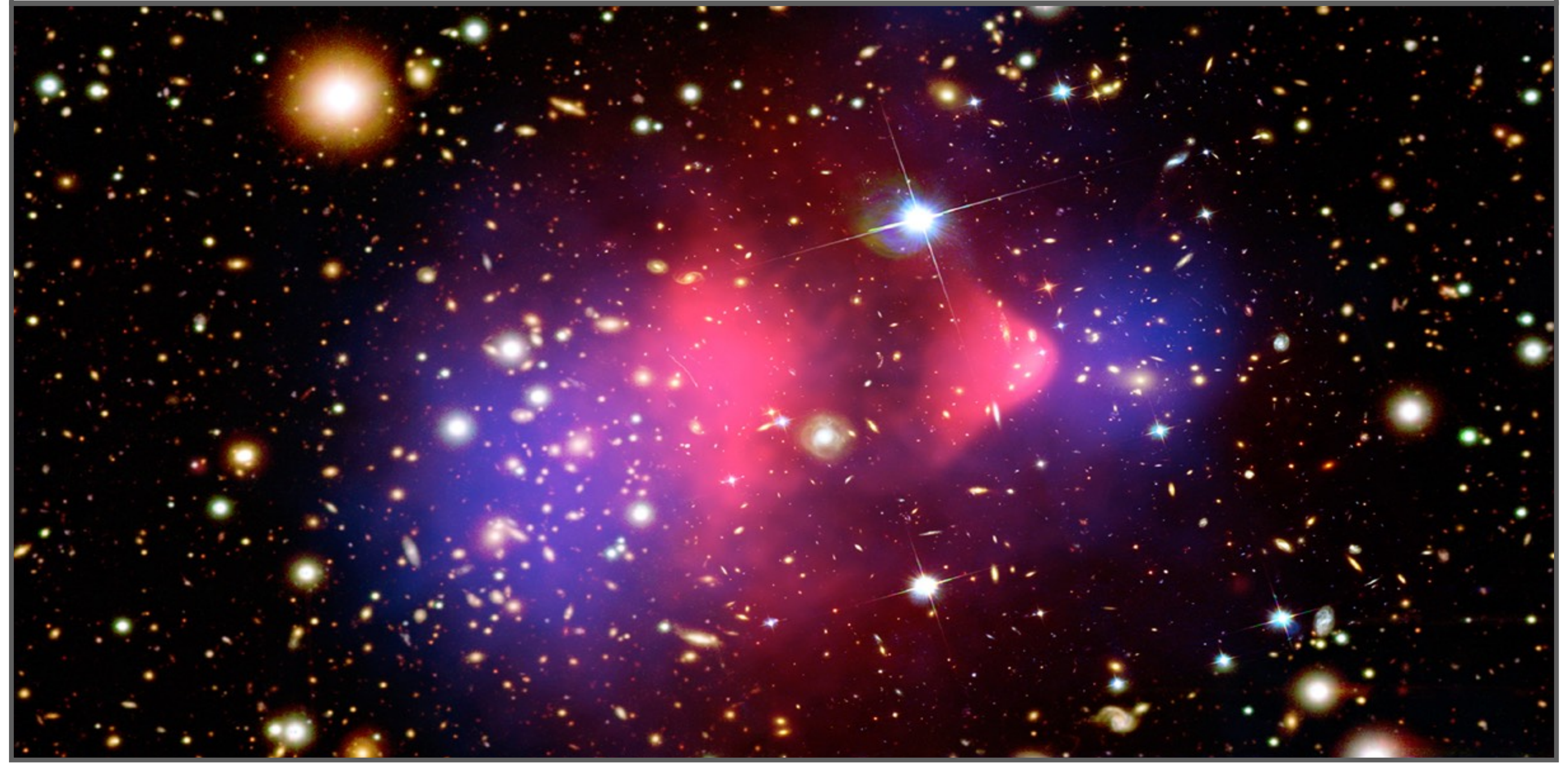
- Generally found by setting $n_\chi(T = 5\ \mathrm{MeV}) = 0$ and having χ freeze-in.
- Roughly equivalent to having reheating occur at $T_{\mathrm{RH}} = 5\ \mathrm{MeV}$.
- Generally $F_{\chi,\mathrm{irr}}(m_\chi, g_\chi) \approx 0$ for $m_\chi \gg 100\ \mathrm{MeV}$ because of Boltzmann suppression.

Evidence of dark matter

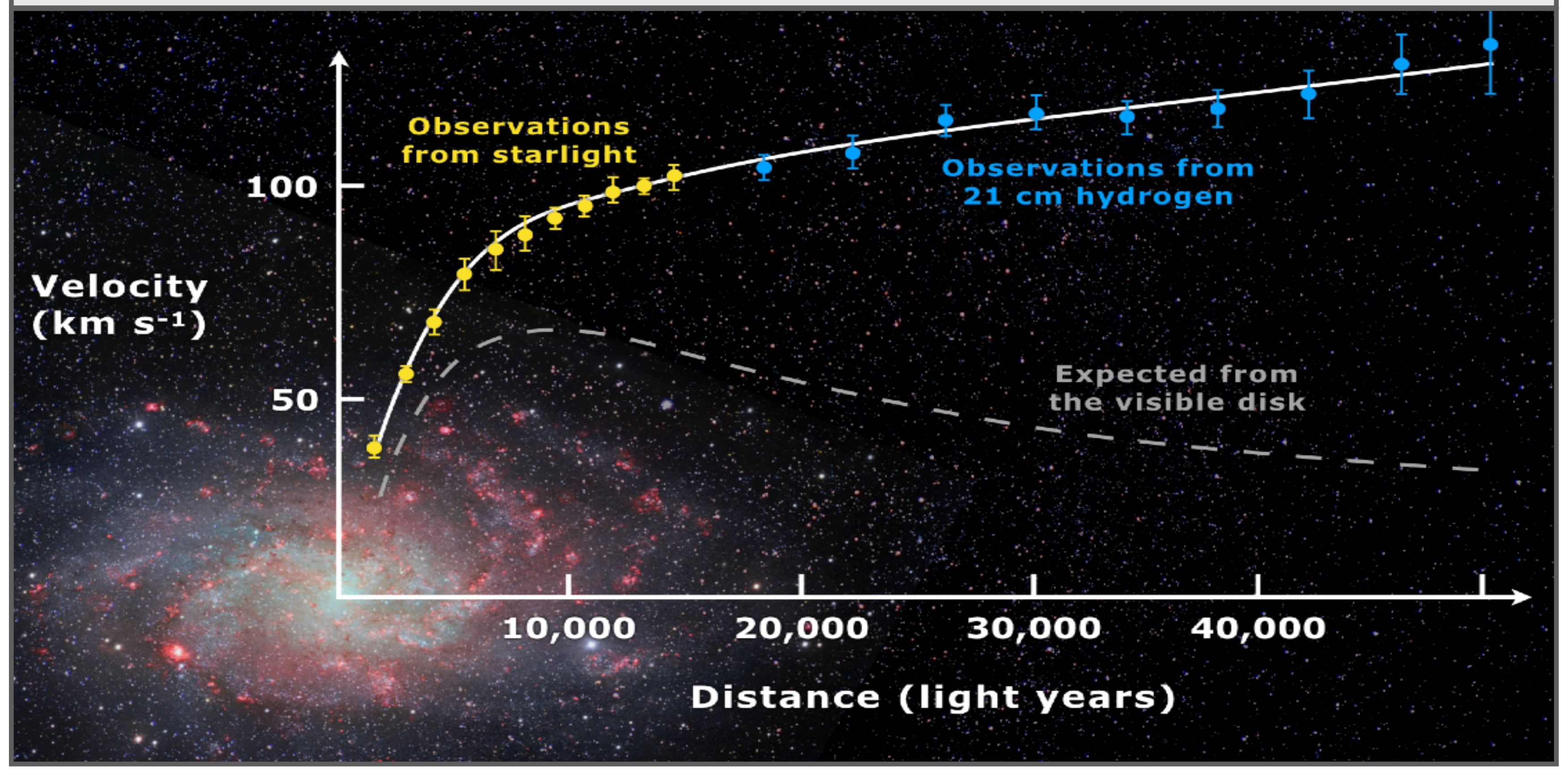
CMB



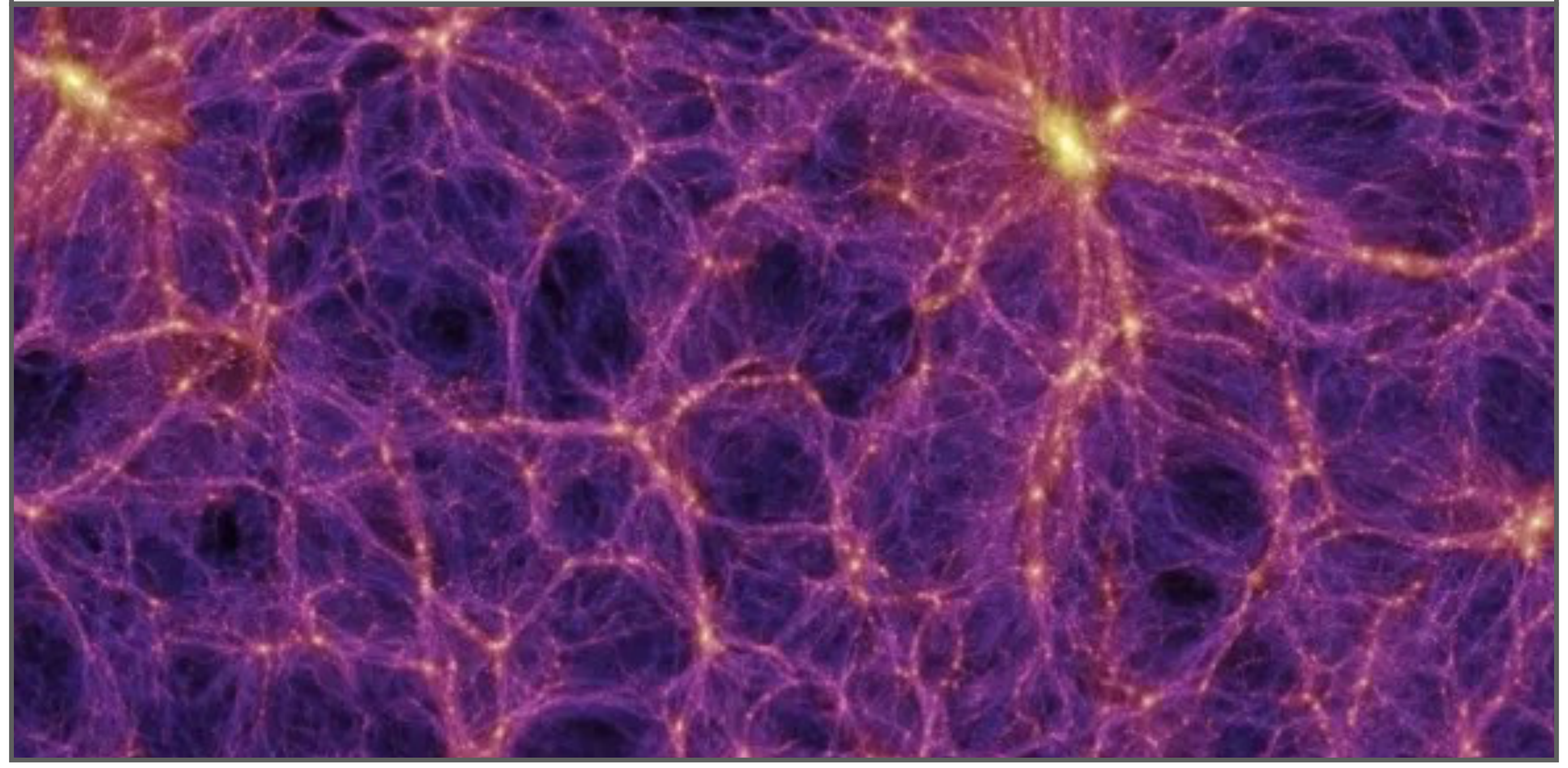
Bullet Cluster



Rotation Curves



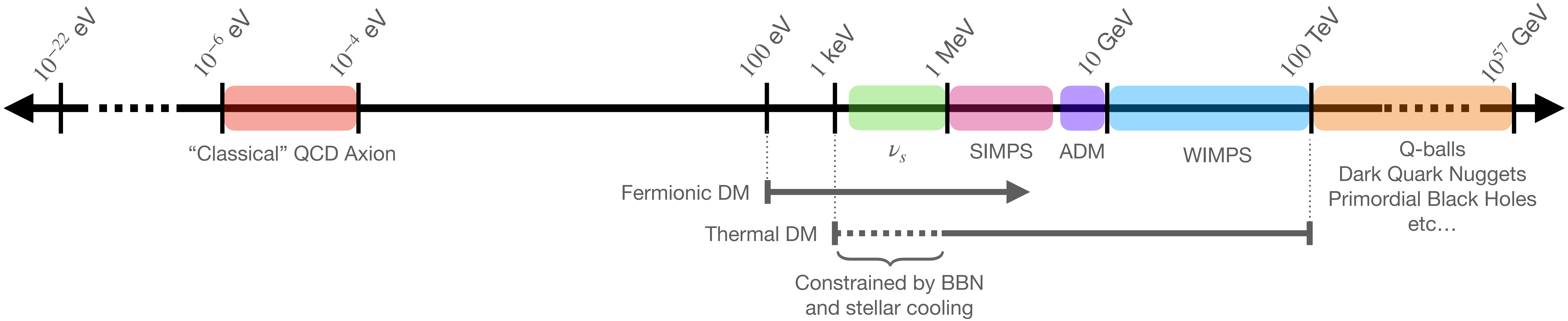
Structure Formation



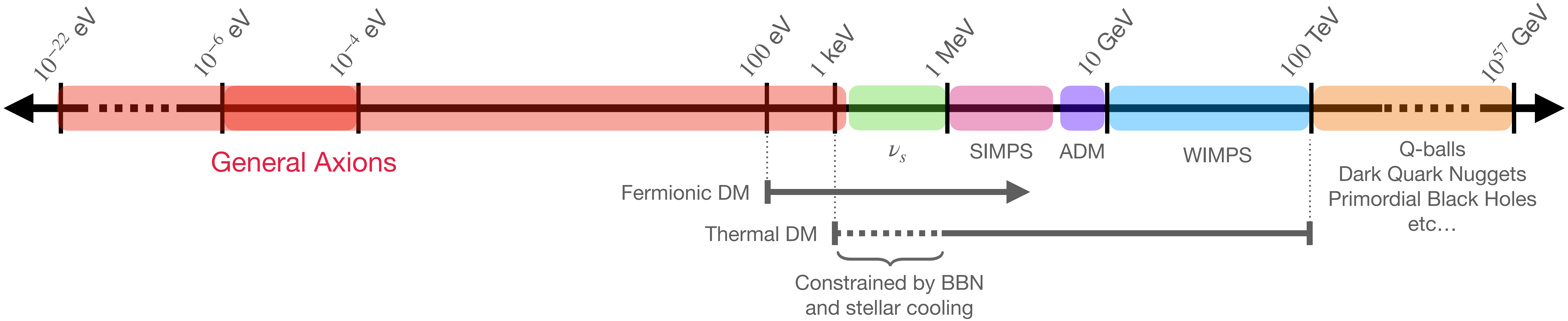
Model independent facts about dark matter

- It exists.
- It is not hot.
- Rough idea of DM halo density.
- Mass dependent constraints on self interactions.
- No known consistent explanation within SM.
- Thats about it...

Dark Matter Mass Range



Dark Matter Mass Range



My talk will focus on <u>sub-components</u> of DM, not DM itself.

More flexible mass ranges.