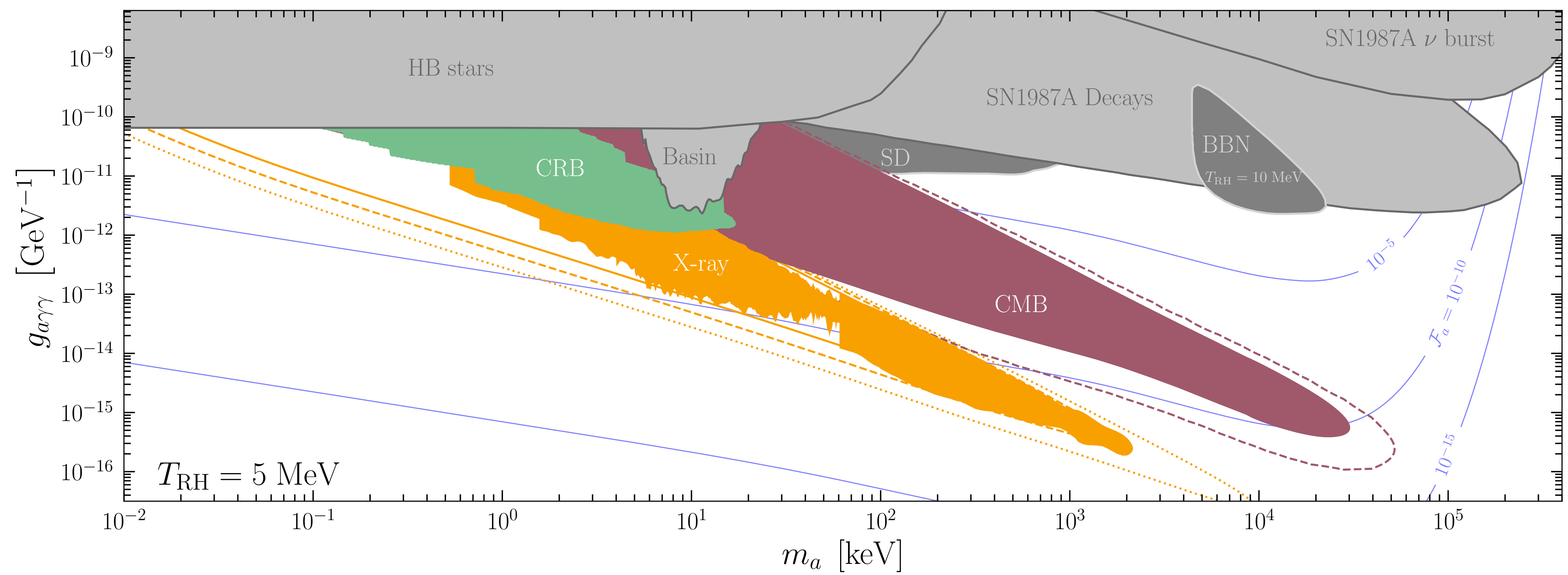
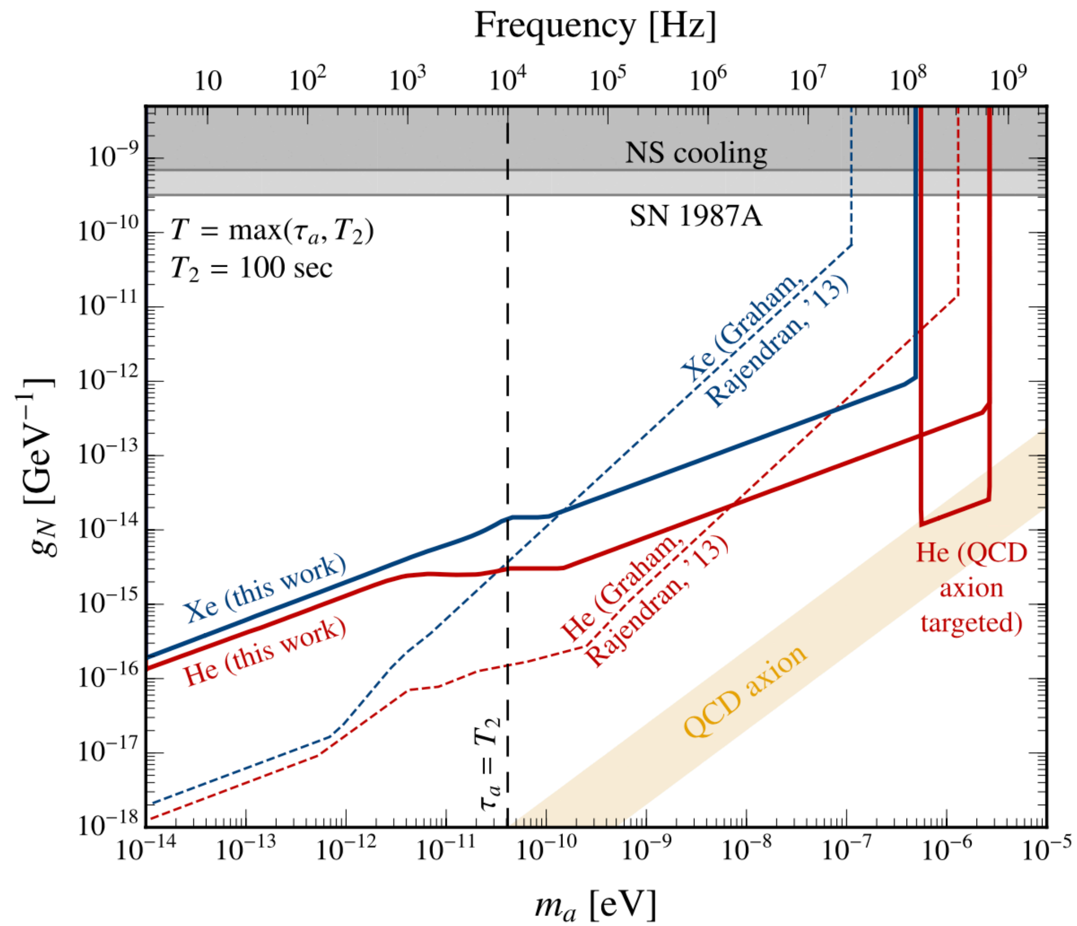


[PRL 2022] w/ Kevin Langhoff, Nadav Outmezguine

The Irreducible Axion

NICK RODD | GGI | 19 May 2023



[PRL 2023] w/ Jeff Dror, Stefania Gori, Jacob Leedom

Bonus: the SHO and axion haloscopes

Motivation

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a (F\tilde{F})$$

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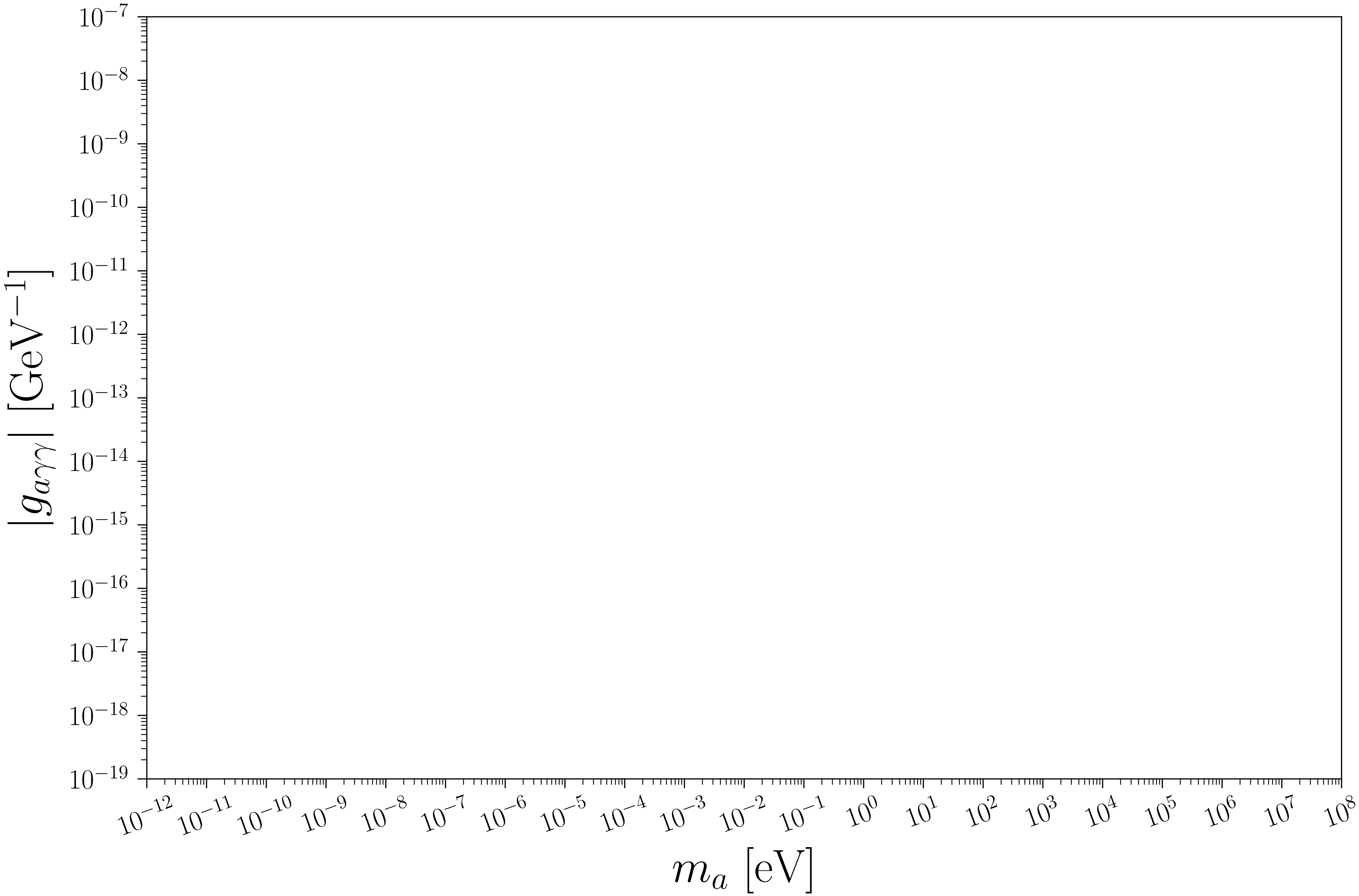
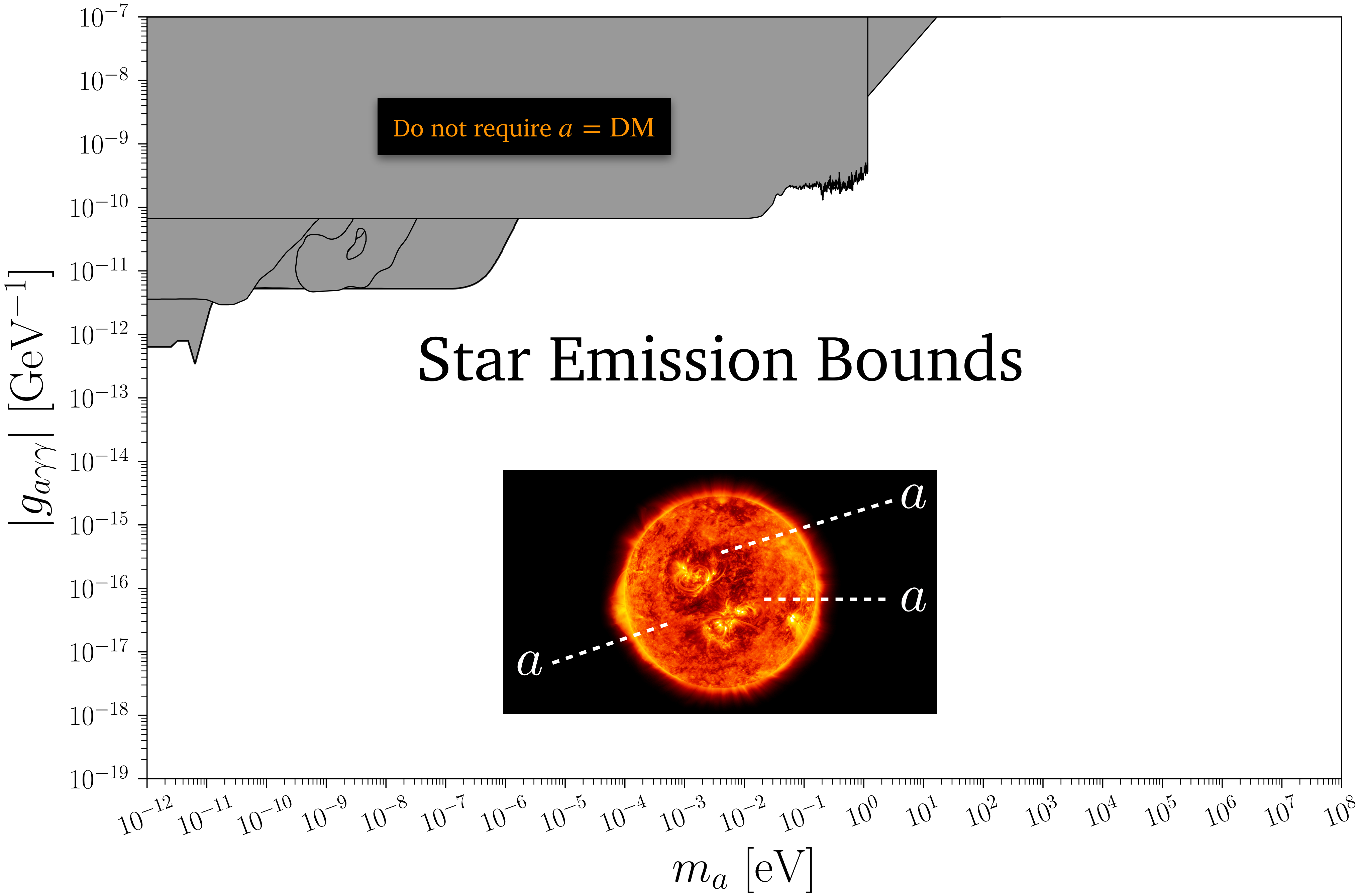


Partial summary
[O'Hare github]

Motivation

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a (F\tilde{F})$$



Partial summary [O'Hare github]

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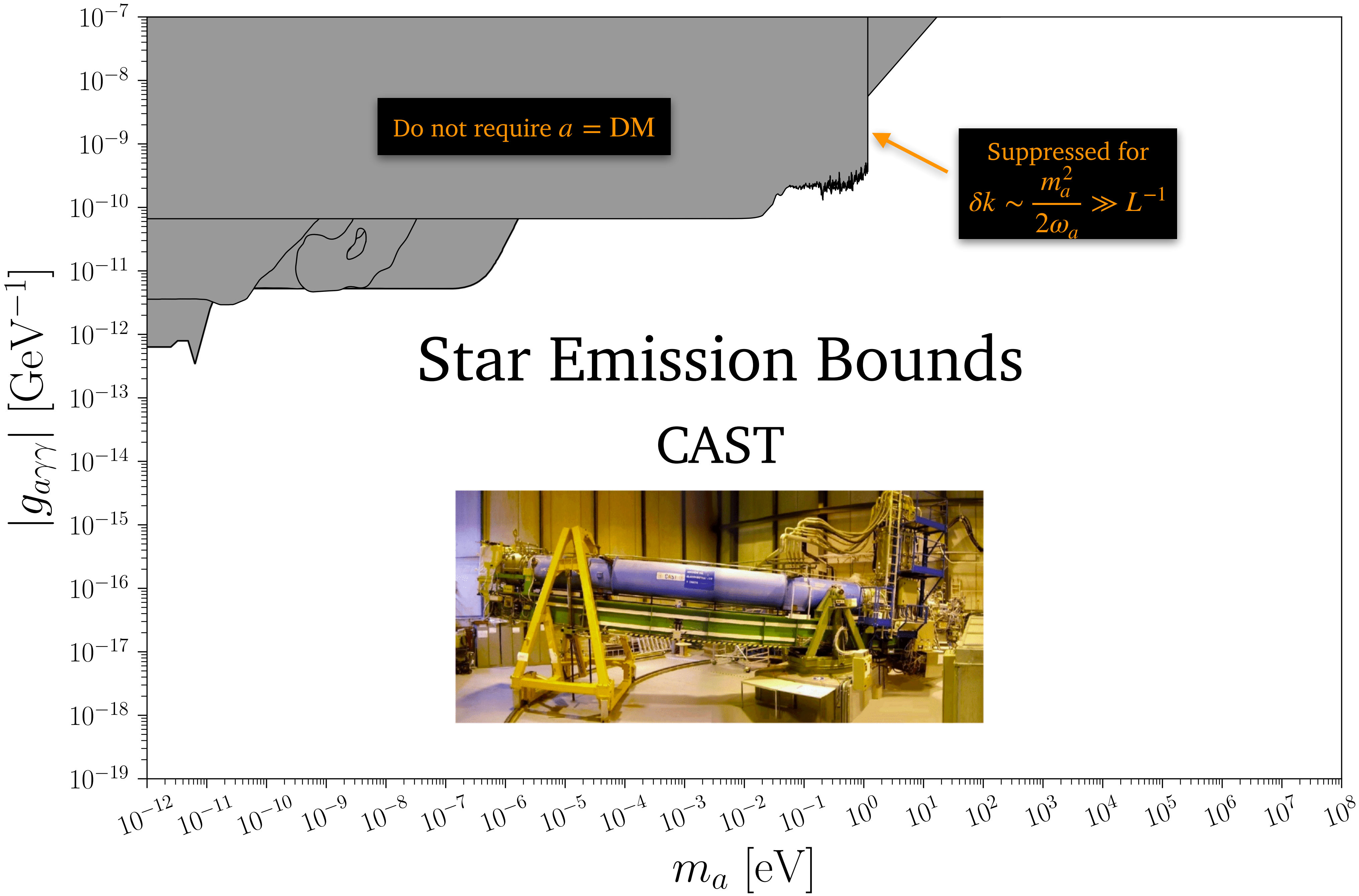

[CAST 2007, 2017]

Partial summary [O'Hare github]

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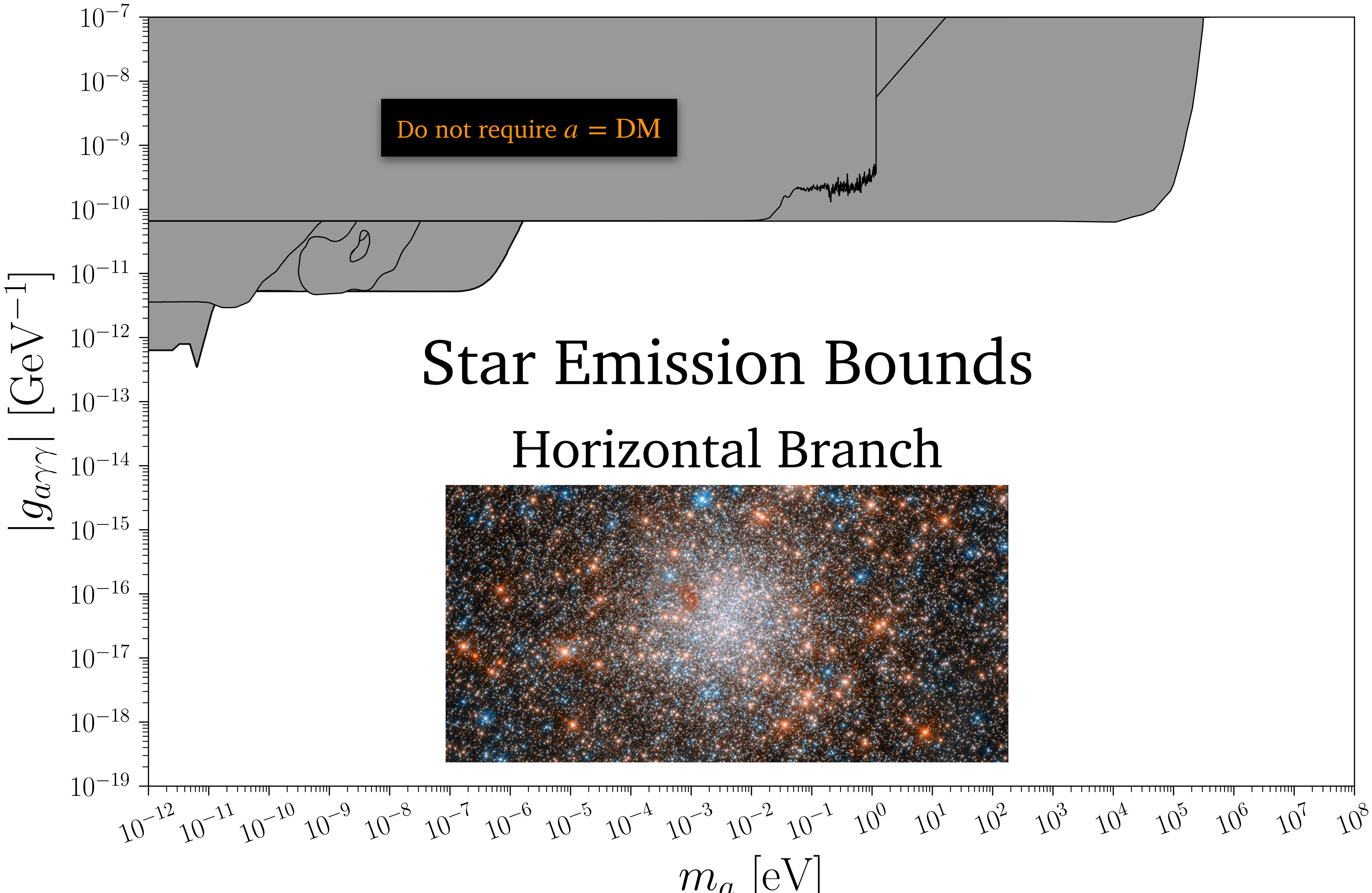

Partial summary
[O'Hare github]

[Ayala+ 2014], [Carenza+ 2020],
cf. [Dolan+ 2207.03102]

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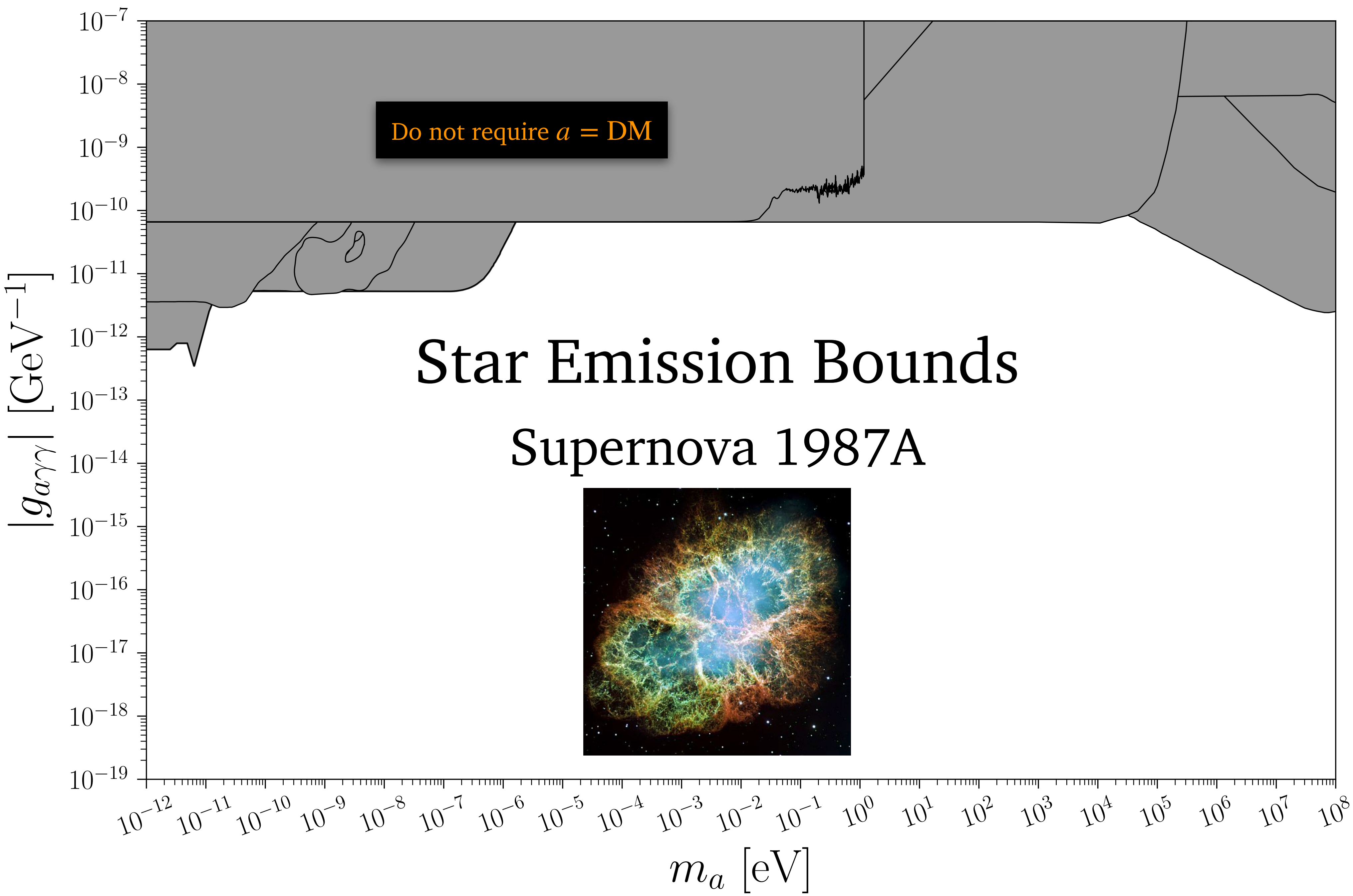

Partial summary [O'Hare github]

[Balázs+ 2205.13549], [Jaeckel+ 2018], [Massó+ 1995], [Lucente+ 2020], [Caputo+ 2022]

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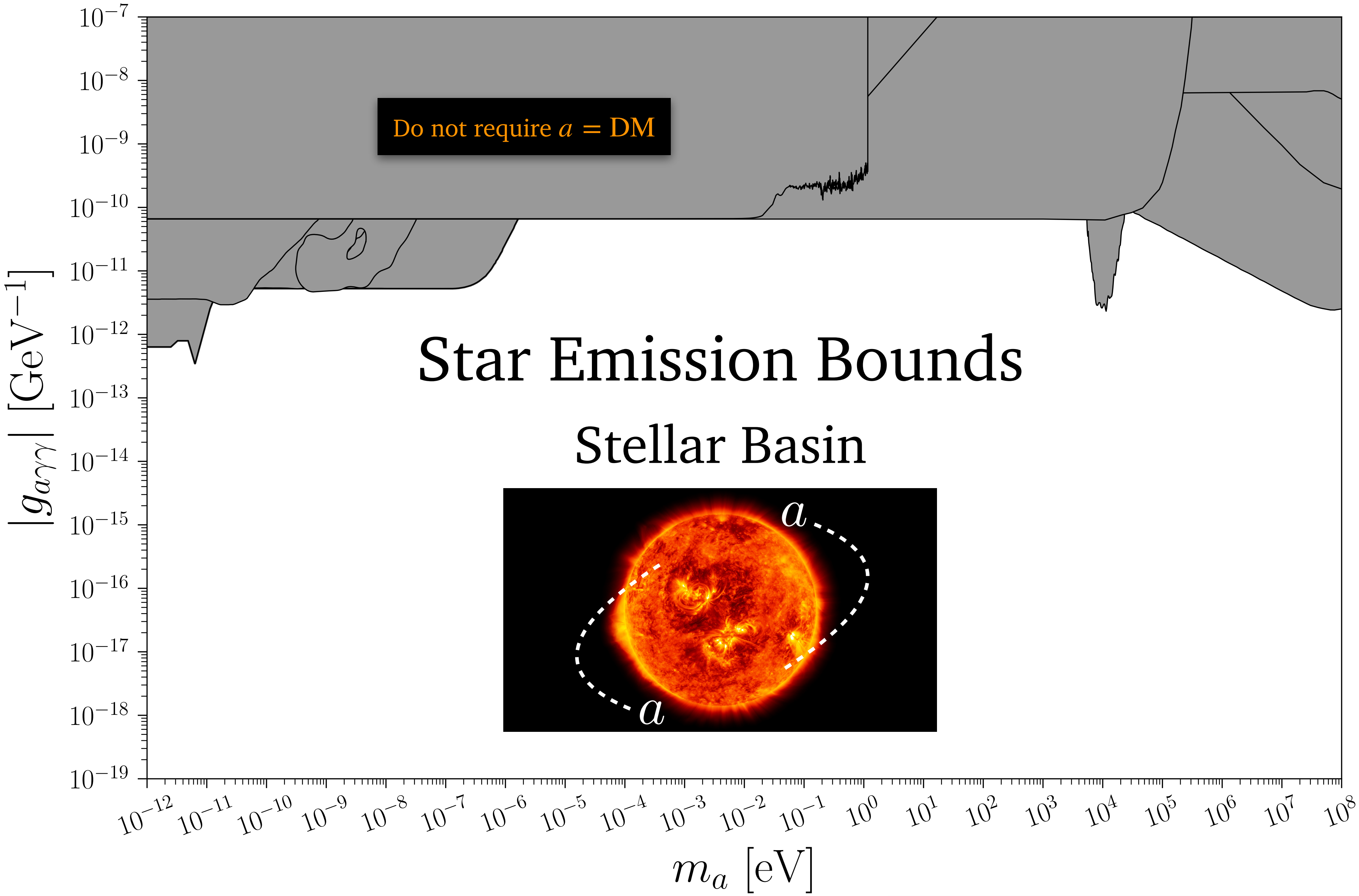

Partial summary [O'Hare github]

[Van Tilburg 2021], [DeRocco+ 2022]

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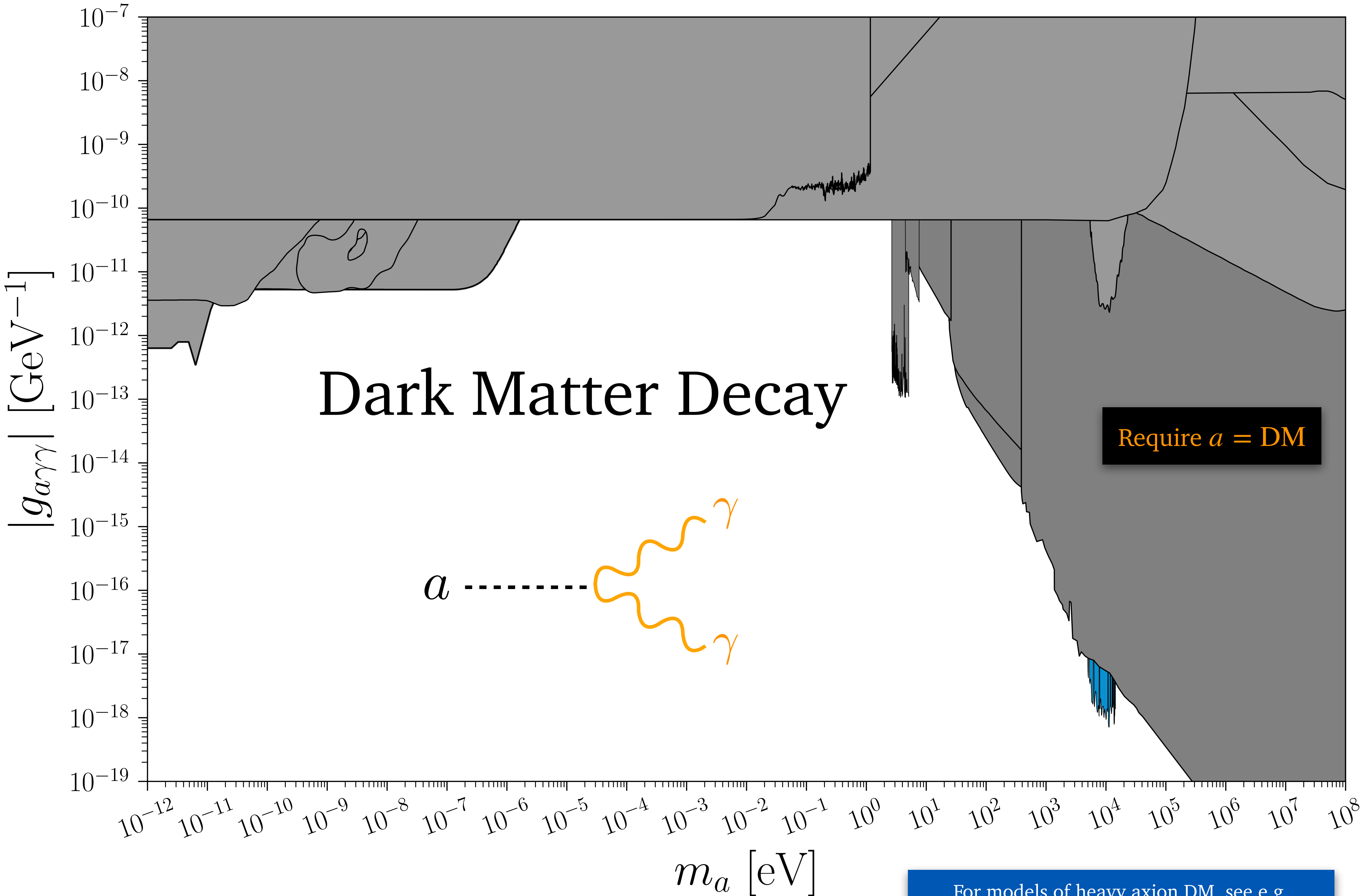

Partial summary [O'Hare github]

For models of heavy axion DM, see e.g. [Foster, Kumar, Safdi, Soreq 2208.10504], [Panci, Redigolo, Schwetz, Ziegler 2209.03371]

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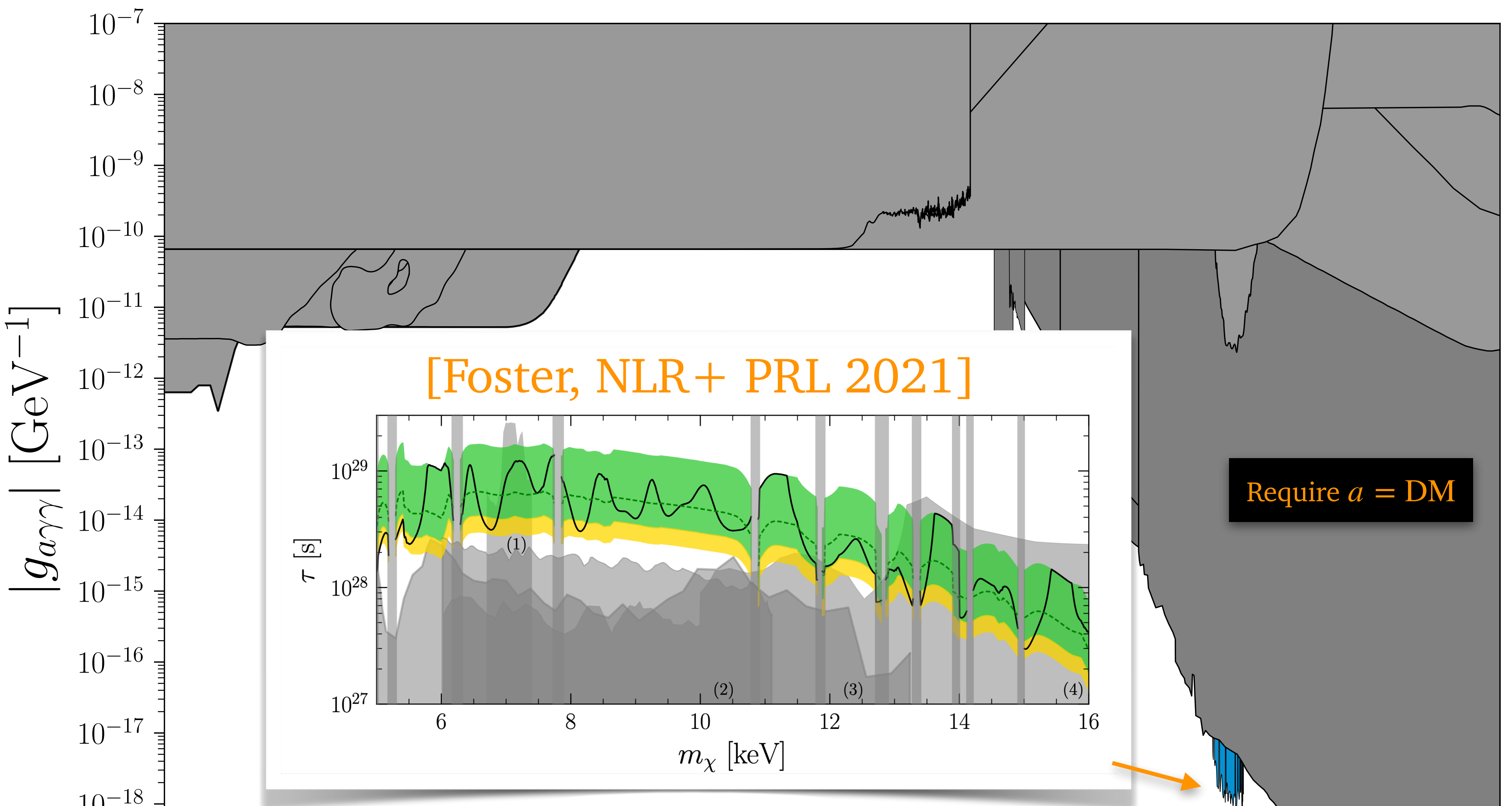

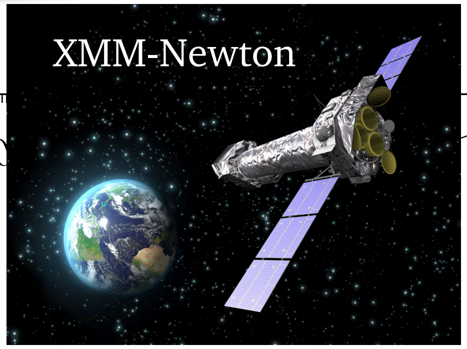

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Partial summary [O'Hare github]

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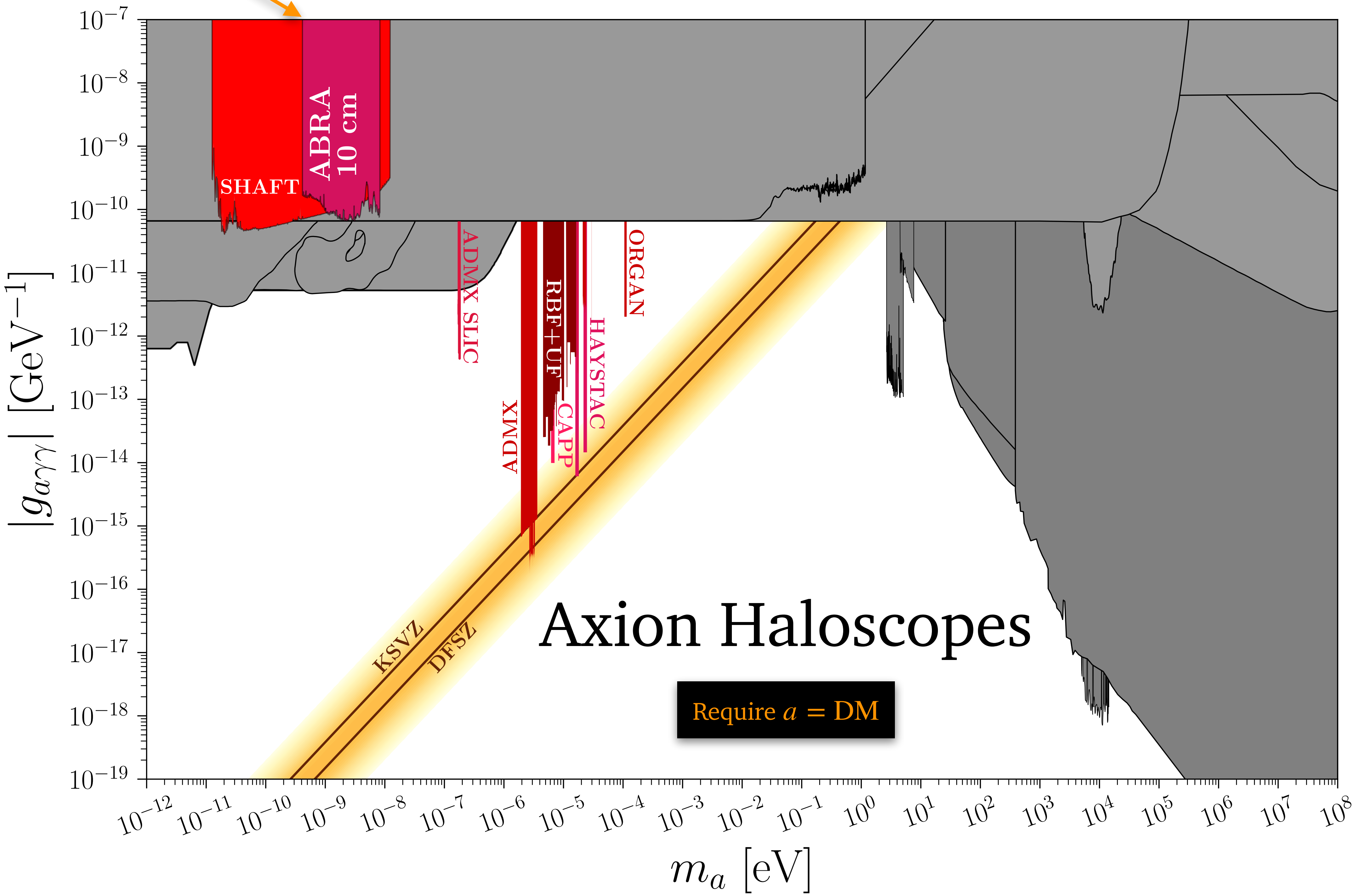
[Salemi, NLR+ PRL 2021]
[Gramolin+ Nature Physics 2021]



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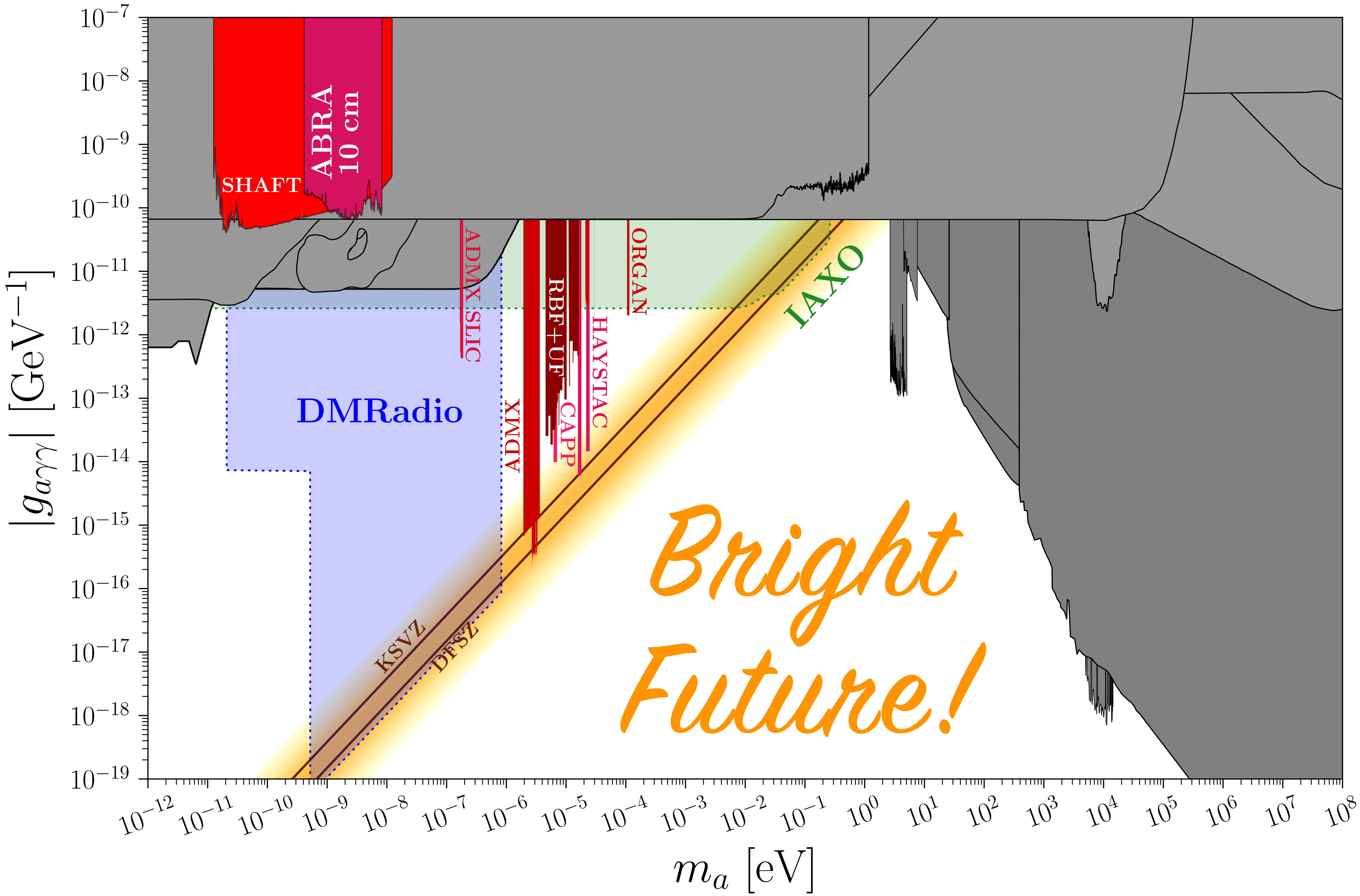

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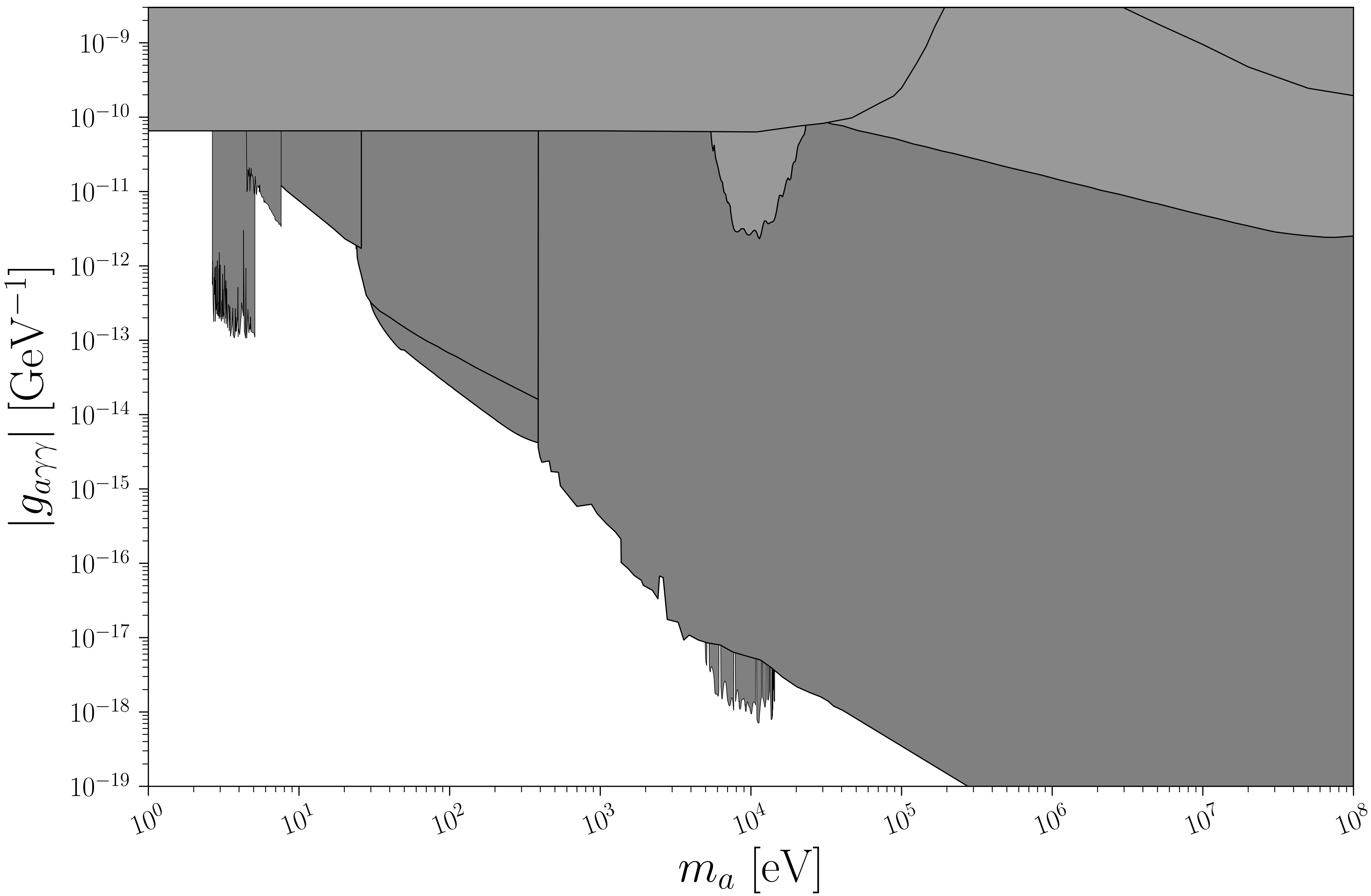

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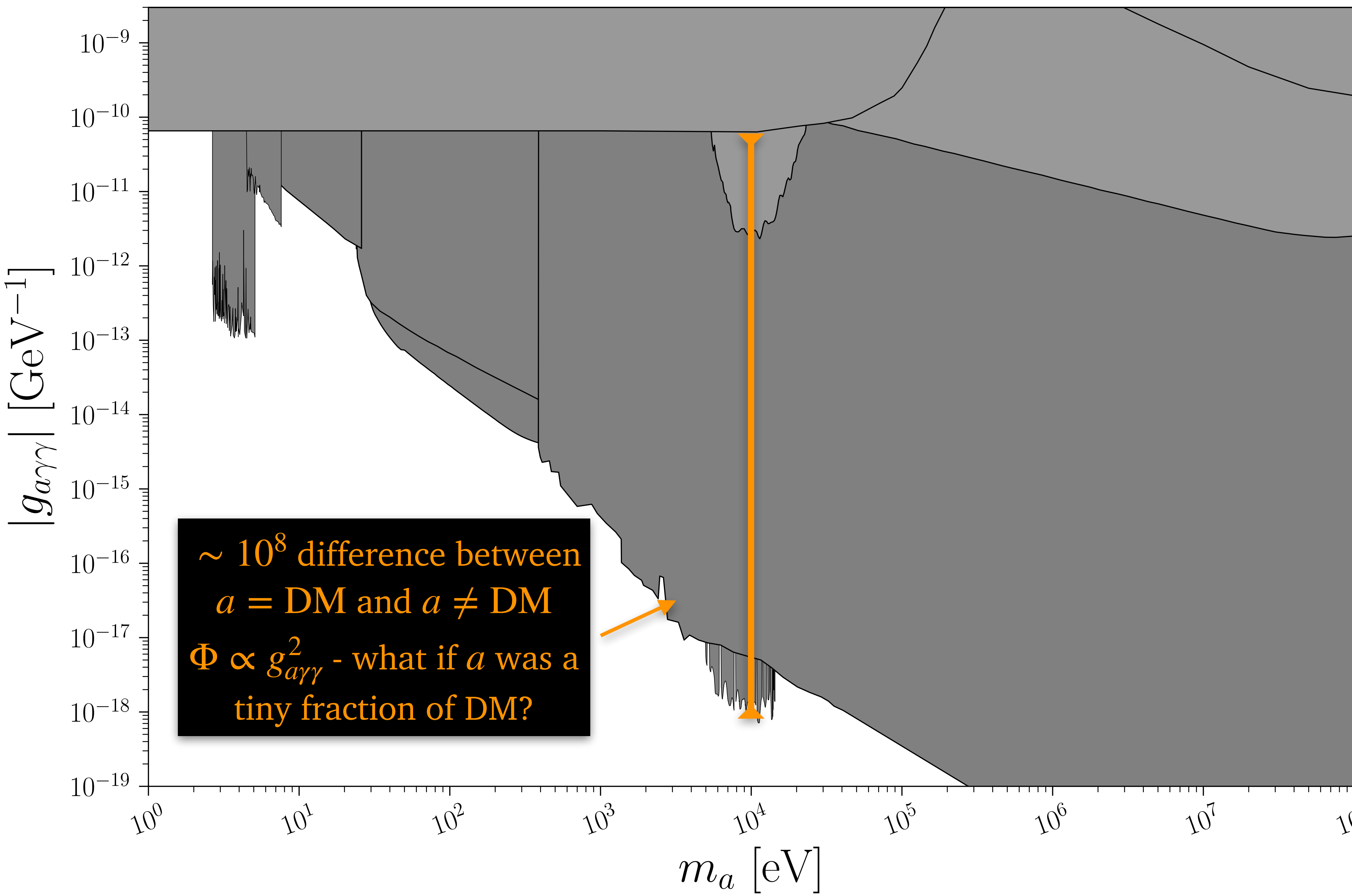

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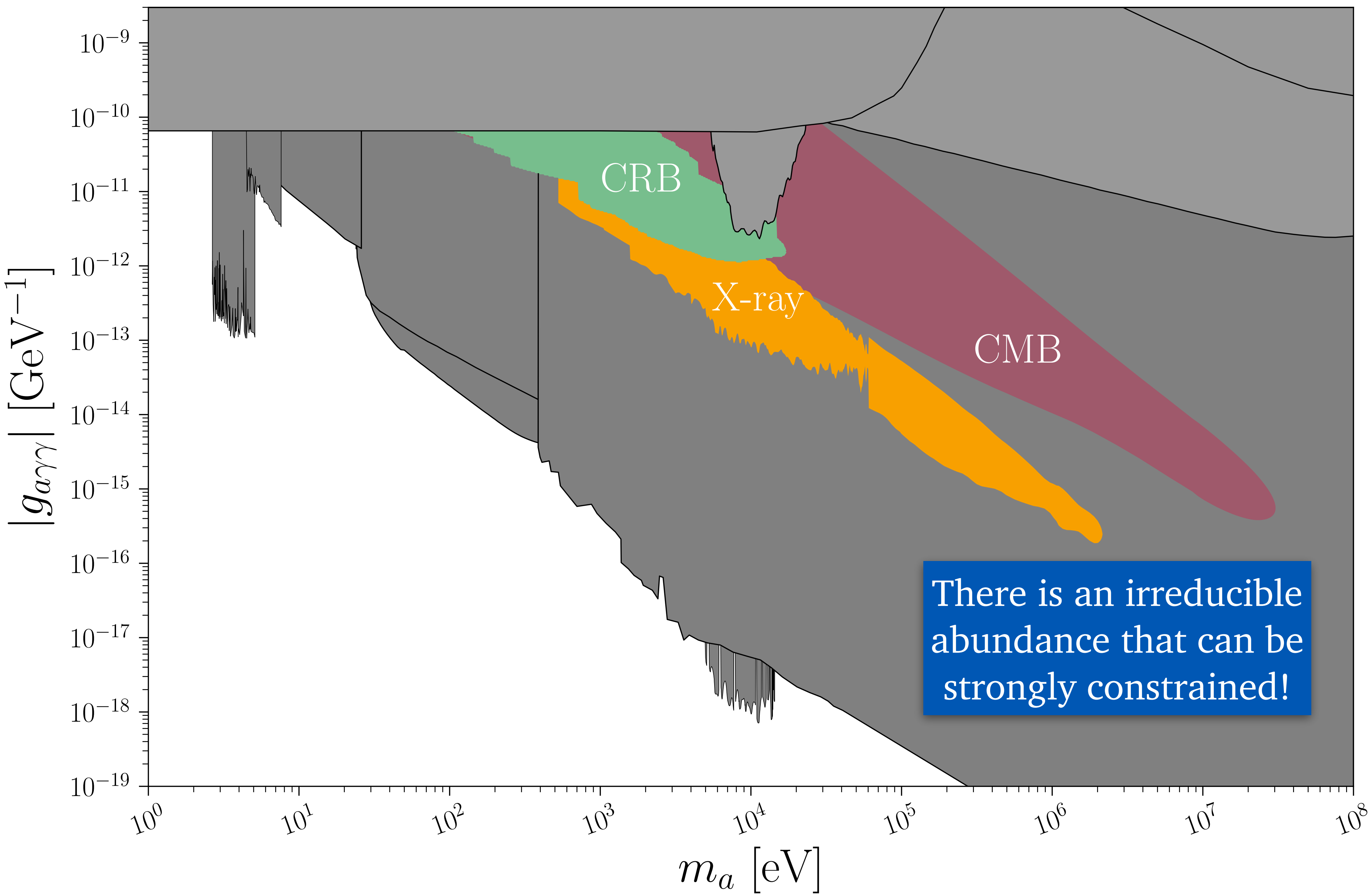


There is an irreducible abundance that can be strongly constrained!

Partial summary [O'Hare github]

Cf. [Balázs, Bloor, Gonzalo, Handley, Hoof, Kahloefer, Lecroq, Marsh, Renk, Scott, Stöcker 2205.13549]

Outline

1. Sensitivity Estimate

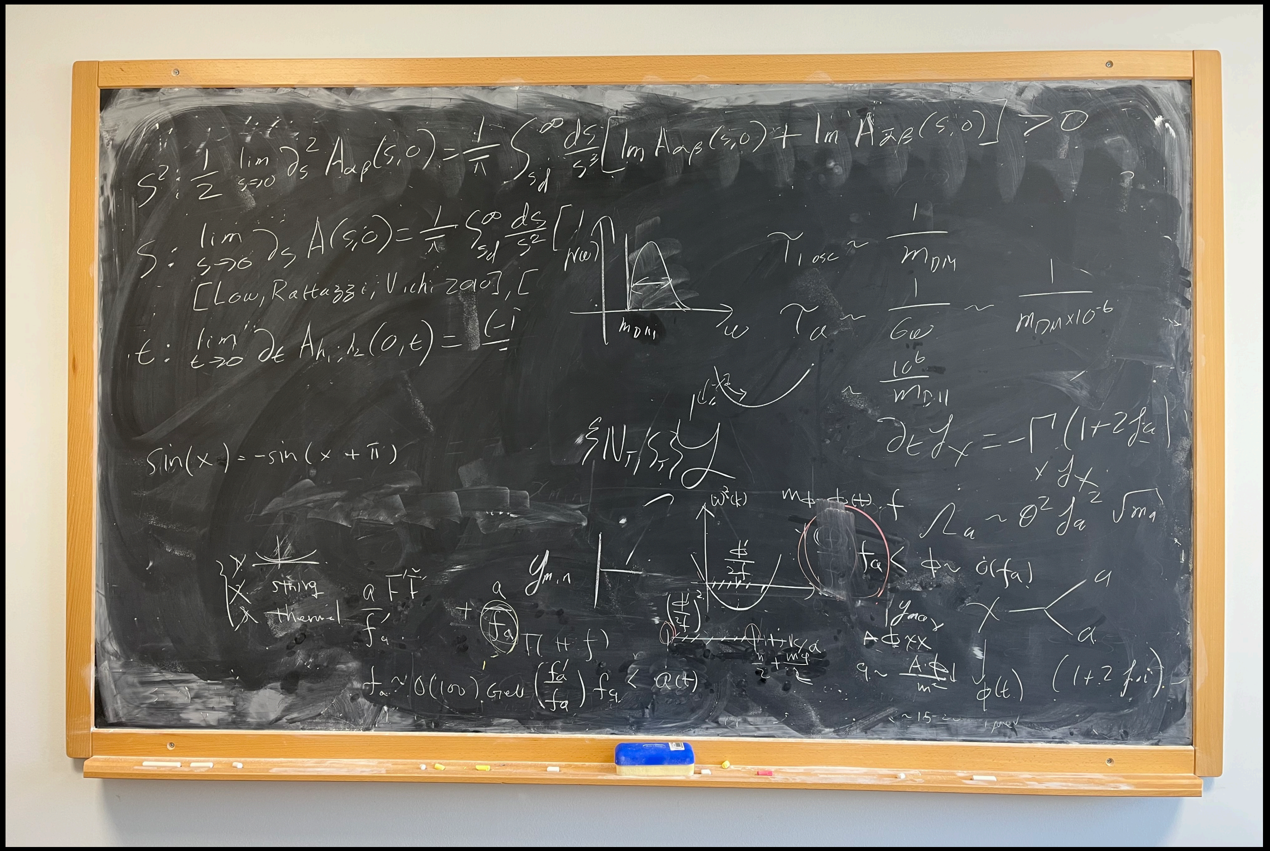
2. Abundance

3. Constraints

4. Extensions

(Bonus: a few words on Haloscope Sensitivity)

Sensitivity Estimate



Sensitivity Estimate

Take $m_a = 10$ keV

Early Universe: photon conversion ($\gamma e \to ae$) freezes-in axions

$$\mathcal{F}_a \simeq 10^{-4} \left(\frac{g_{a\gamma\gamma}}{g_{a\gamma\gamma}^{\mathrm{HB}}} \right)^2 \left(\frac{T_{\mathrm{RH}}}{5\ \mathrm{MeV}} \right) \quad (1)$$

$= \rho_a / \rho_{\mathrm{DM}}$

UV dominated

[Langhoff, Outmezguine, NLR PRL 2022]

Sensitivity Estimate

X-ray constraints at $\sim$10 keV require

$$\tau_{\rm DM} \gtrsim 10^{29}\ {\rm s} \Rightarrow g_{a\gamma\gamma}^{\rm DM} \lesssim 7 \times 10^{-19}\ {\rm GeV}^{-1} \simeq 10^{-8} g_{a\gamma\gamma}^{\rm HB}$$

[Langhoff, Outmezguine, NLR PRL 2022]

Sensitivity Estimate

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$$\tau_{\rm DM} \gtrsim 10^{29}\ {\rm s} \Rightarrow g_{a\gamma\gamma}^{\rm DM} \lesssim 7 \times 10^{-19}\ {\rm GeV}^{-1} \simeq 10^{-8} g_{a\gamma\gamma}^{\rm HB}$$

Must satisfy $\rho_a/\tau_a \lesssim \rho_{\rm DM}/\tau_{\rm DM}$ and $\tau^{-1} \propto g_{a\gamma\gamma}^2$, so

$$\mathscr{F}_a \lesssim \frac{\tau_a}{\tau_{\rm DM}} = \left(\frac{g_{a\gamma\gamma}^{\rm DM}}{g_{a\gamma\gamma}}\right)^2 \qquad (2)$$

[Langhoff, Outmezguine, NLR PRL 2022]

Sensitivity Estimate

$$\mathscr{F}_a \simeq 10^{-4} \left(\frac{g_{a\gamma\gamma}}{g_{a\gamma\gamma}^{\rm HB}} \right)^2 \left(\frac{T_{\rm RH}}{5~{\rm MeV}} \right) \quad (1)$$

$$\mathscr{F}_a \lesssim \frac{\tau_a}{\tau_{\rm DM}} = \left(\frac{g_{a\gamma\gamma}^{\rm DM}}{g_{a\gamma\gamma}} \right)^2 \quad (2)$$

Combine (1) and (2)

$$10^{-4} \left(\frac{g_{a\gamma\gamma}}{g_{a\gamma\gamma}^{\rm HB}} \right)^2 \lesssim \left(\frac{g_{a\gamma\gamma}^{\rm DM}}{g_{a\gamma\gamma}} \right)^2$$

[Langhoff, Outmezguine, NLR PRL 2022]

Sensitivity Estimate

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$$\Rightarrow \frac{g_{a\gamma\gamma}}{g_{a\gamma\gamma}^{\rm HB}} \lesssim \left[10^4 \left(\frac{g_{a\gamma\gamma}^{\rm DM}}{g_{a\gamma\gamma}^{\rm HB}} \right)^2 \right]^{1/4} \simeq (10^{-12})^{1/4} \simeq 10^{-3}$$

[Langhoff, Outmezguine, NLR PRL 2022]

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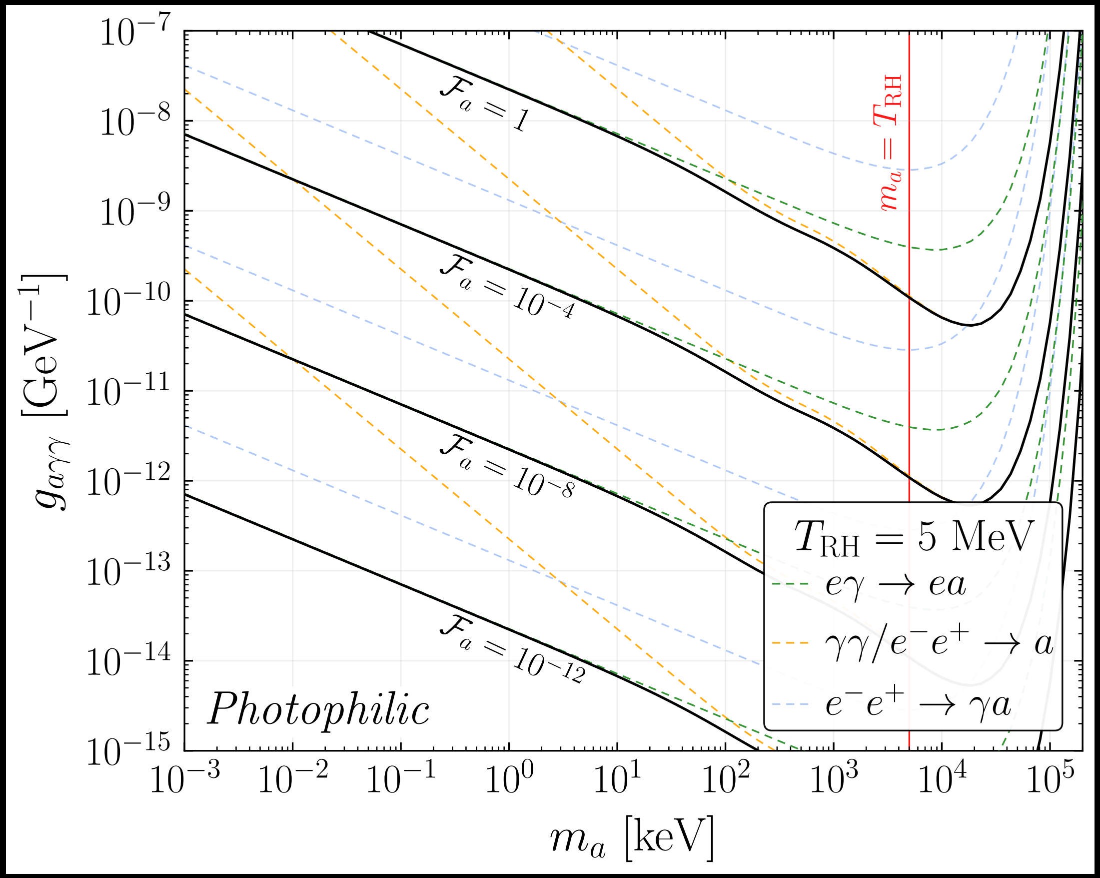
$$\Rightarrow \frac{g_{a\gamma\gamma}}{g_{a\gamma\gamma}^{\rm HB}} \lesssim \left[10^4\left(\frac{g_{a\gamma\gamma}^{\rm DM}}{g_{a\gamma\gamma}^{\rm HB}}\right)^2\right]^{1/4} \simeq (10^{-12})^{1/4} \simeq 10^{-3}$$

$$\Rightarrow g_{a\gamma\gamma} \lesssim 7\times 10^{-14}\ {\rm GeV}^{-1} \ll g_{a\gamma\gamma}^{\rm HB}$$

[Langhoff, Outmezguine, NLR PRL 2022]

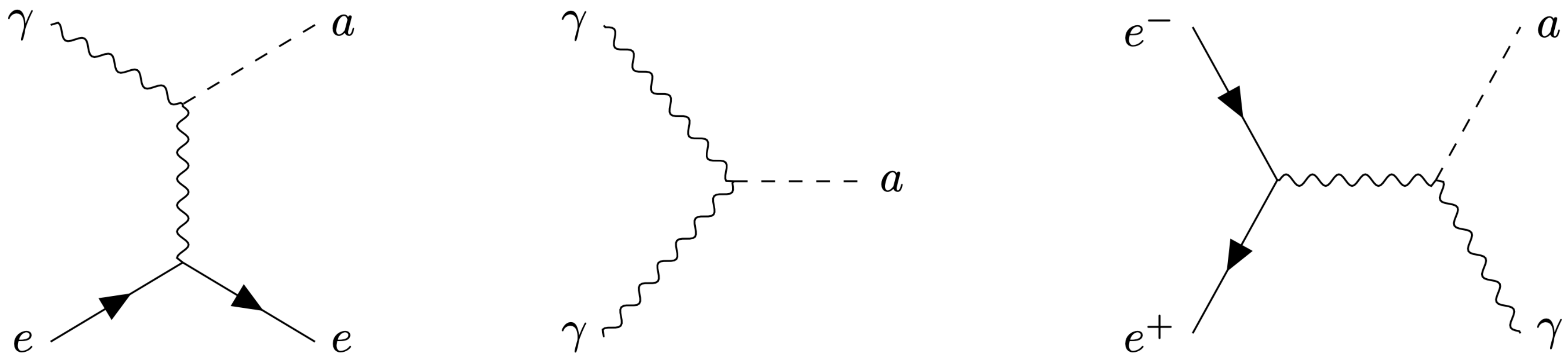
Abundance



$g_{a\gamma\gamma}$ [GeV^{-1}]
m_a [keV]
$\mathcal{F}_a = 1$
$\mathcal{F}_a = 10^{-4}$
$\mathcal{F}_a = 10^{-8}$
$\mathcal{F}_a = 10^{-12}$
$m_a = T_{\rm RH}$
$T_{\rm RH} = 5$ MeV
$e\gamma \to ea$
$\gamma\gamma/e^-e^+ \to a$
$e^-e^+ \to \gamma a$
Photophilic

Abundance

Axions produced by at least three interactions



Two are UV dominated - depend critically on $T_{\rm RH}$, but there is a minimal value consistent with BBN

$$T_{\rm RH} \gtrsim 5 \text{ MeV}$$

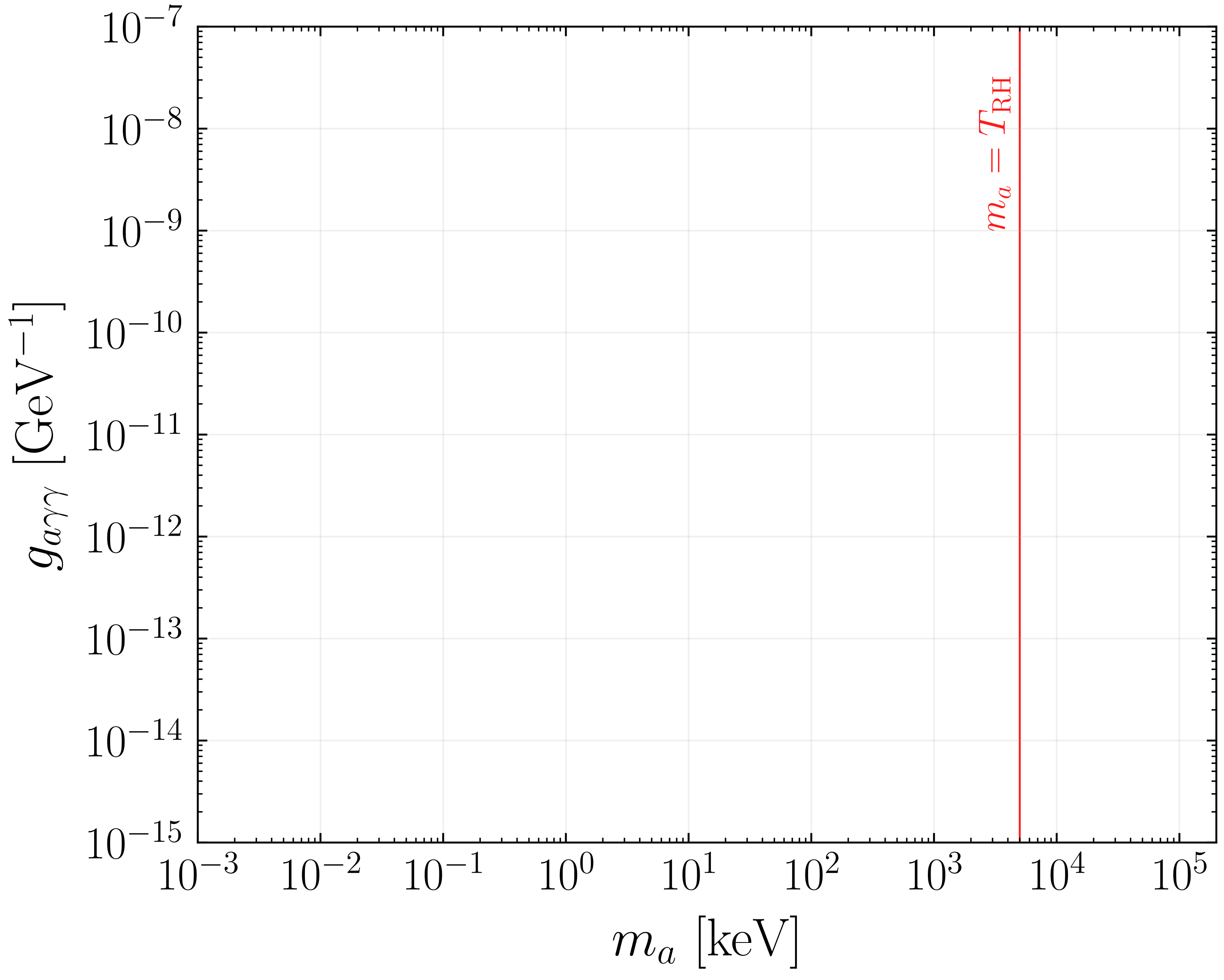
[Hannestad 2004], [Kawasaki+ 1999, 2000], [Ichikawa+ 2005, 2007], [Salas+ 2015], [Hasegawa+ 2019]

Cf. [Balázs+ 2205.13549]

[Langhoff, Outmezguine, NLR PRL 2022]

Abundance

Compute the freeze-in abundance* $\mathscr{F}_a = \rho_a/\rho_{\rm DM}$



*For $T_{\rm RH}^{\rm min}$ thermalizes for $g_{a\gamma\gamma} \gtrsim 10^{-7}$ GeV^{-1}

[Langhoff, Outmezguine, NLR PRL 2022]

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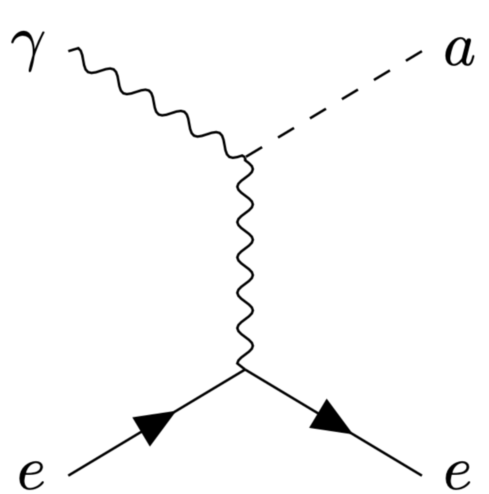
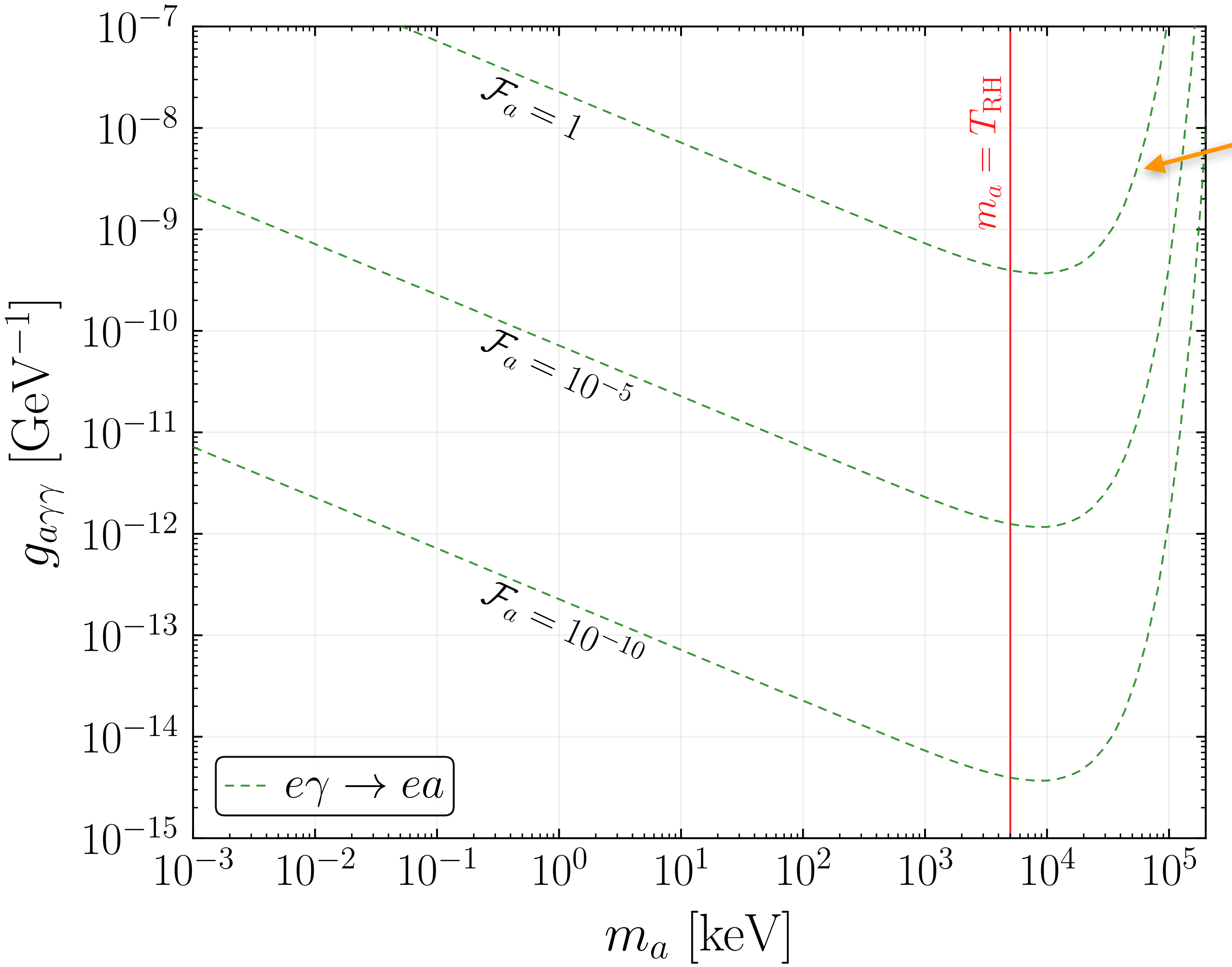


Photon Conversion



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

*For $T_{\rm RH}^{\rm min}$ thermalizes for $g_{a\gamma\gamma} \gtrsim 10^{-7}$ GeV^{-1}

[Langhoff, Outmezguine, NLR PRL 2022]

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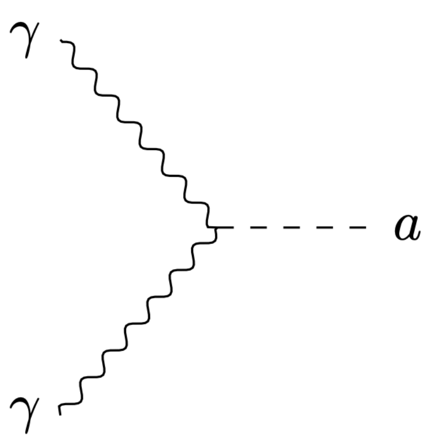
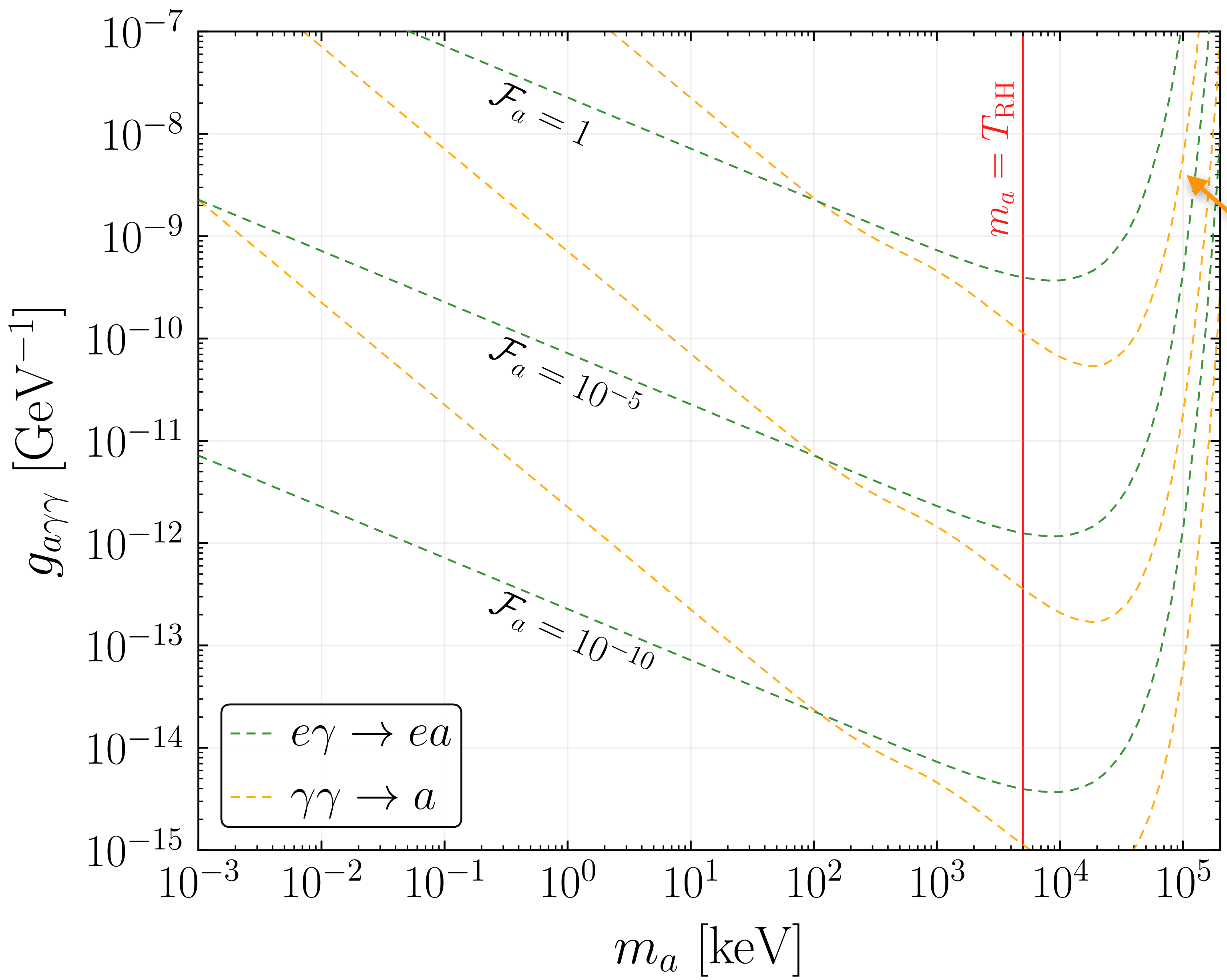


Inverse Decays



Dominant at large m_a

*For $T_{\rm RH}^{\rm min}$ thermalizes for $g_{a\gamma\gamma} \gtrsim 10^{-7}$ GeV^{-1}

[Langhoff, Outmezguine, NLR PRL 2022]

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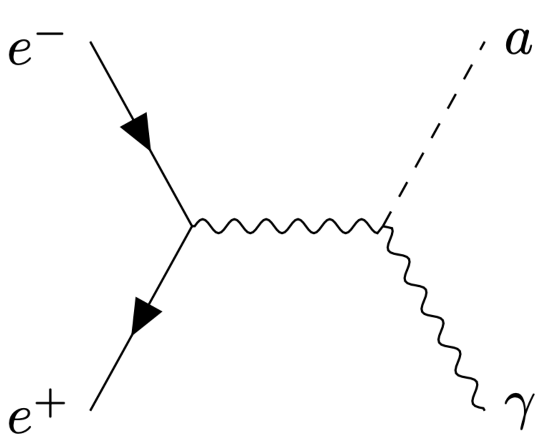
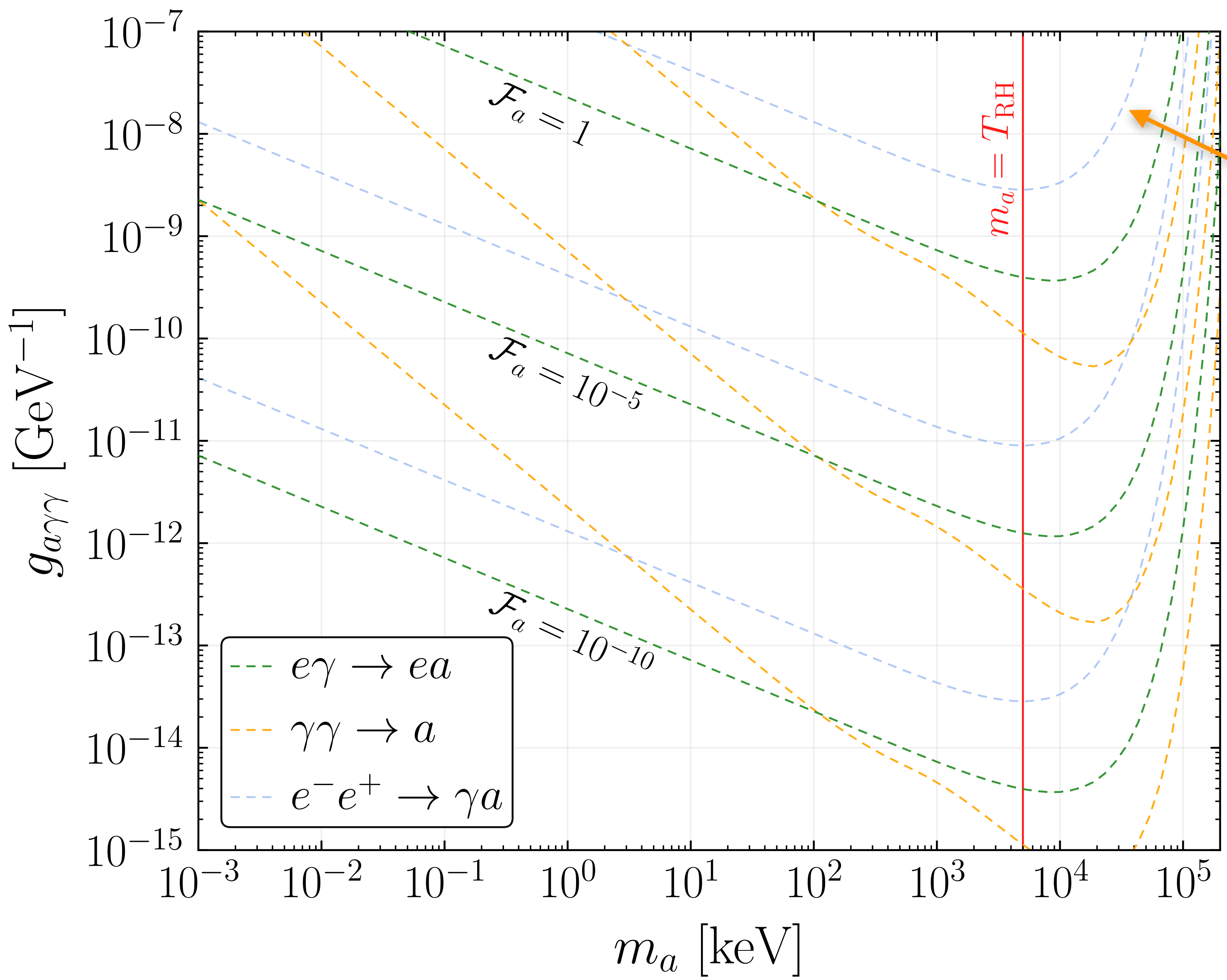
Compute the freeze-in abundance* $\mathscr{F}_a = \rho_a/\rho_{\rm DM}$



e^-e^+ annihilations



Strictly subdominant

*For $T_{\rm RH}^{\rm min}$ thermalizes for $g_{a\gamma\gamma} \gtrsim 10^{-7}$ GeV^{-1}

[Langhoff, Outmezguine, NLR PRL 2022]

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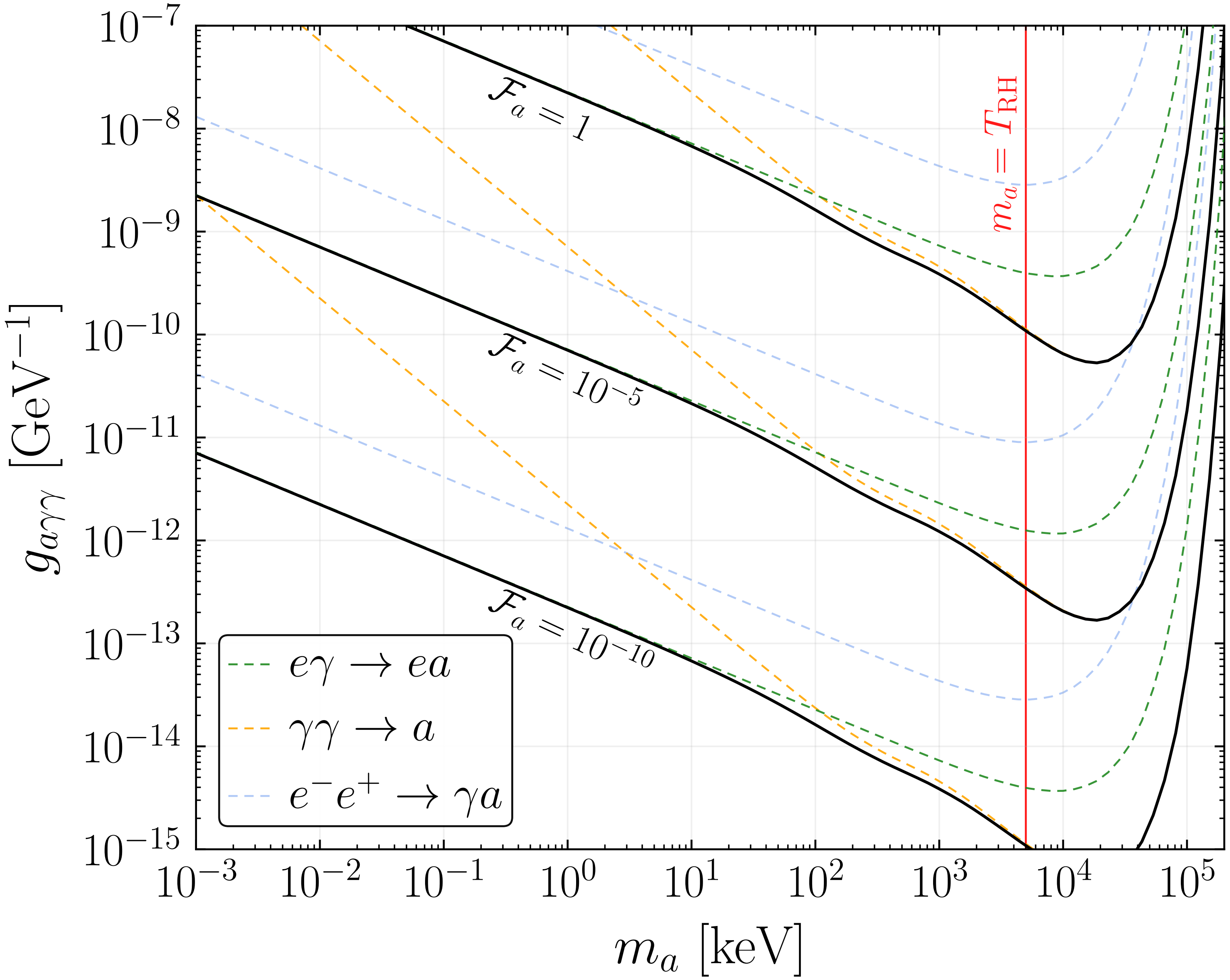

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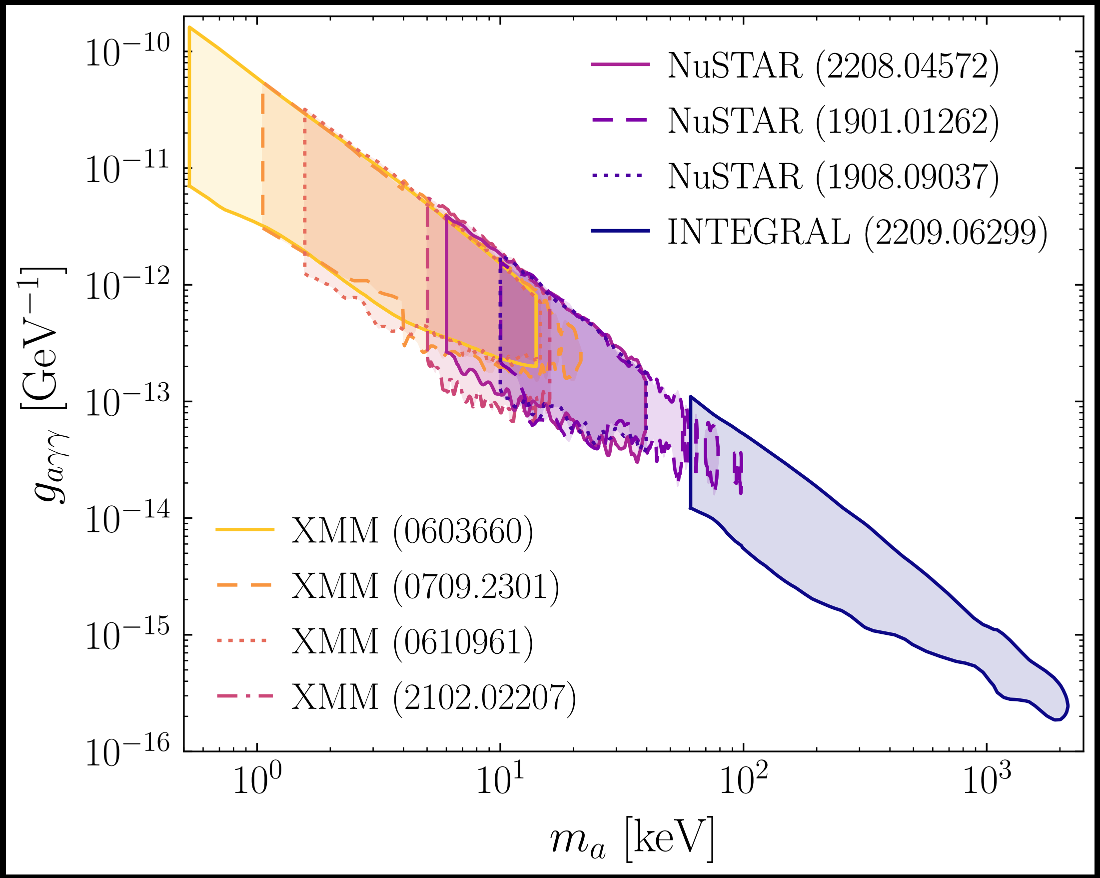
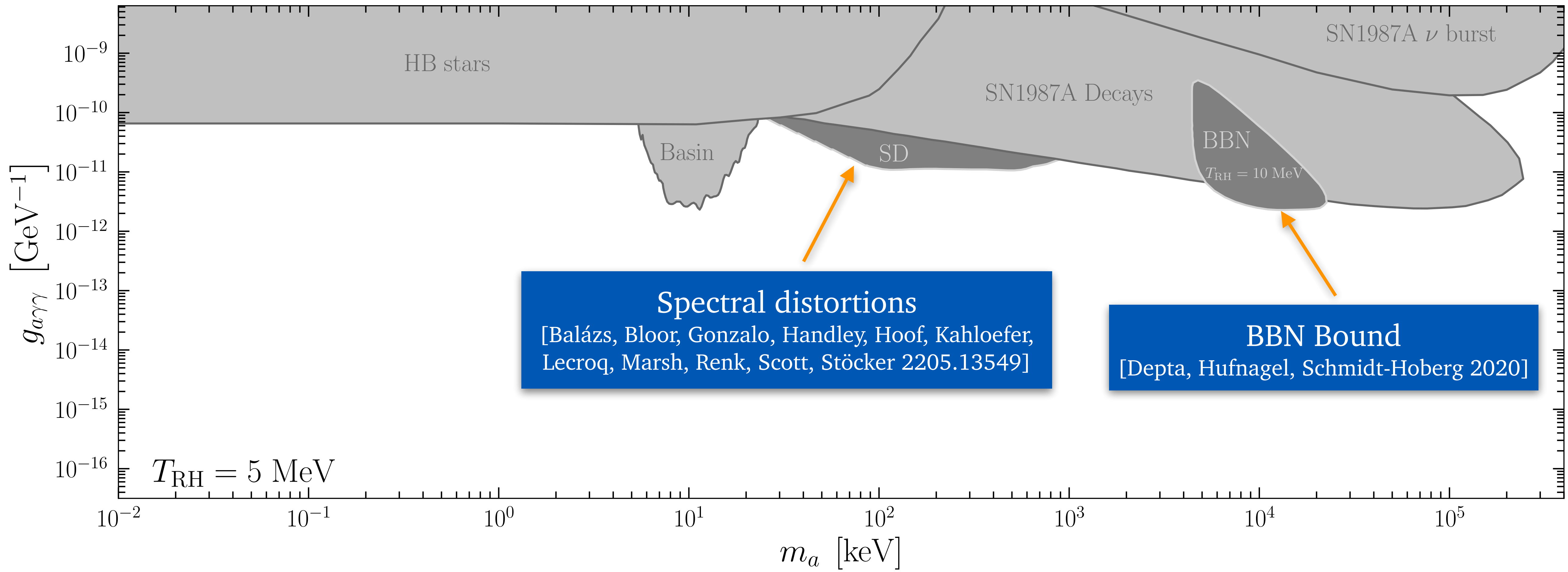
[Langhoff, Outmezguine, NLR PRL 2022]

Constraints



Constraints

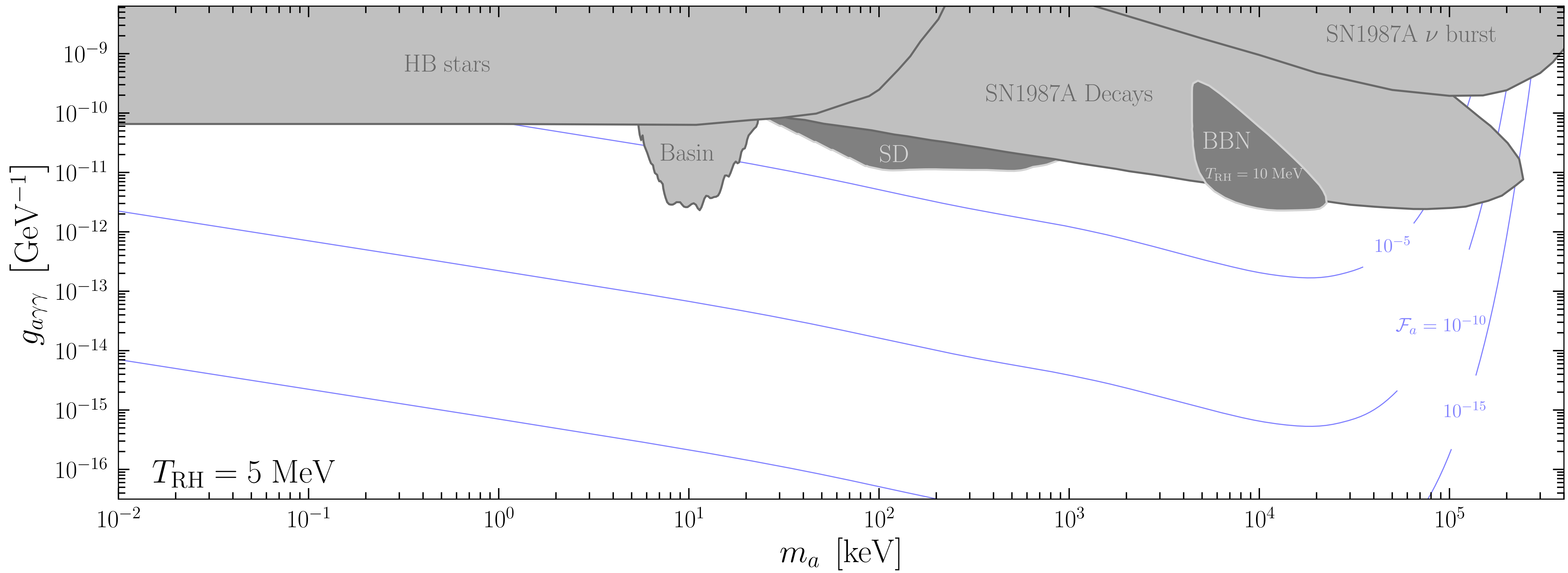
Start with $a \neq \text{DM}$ constraints



[Langhoff, Outmezguine, NLR PRL 2022]

Constraints

Irreducible abundance is small, but testable



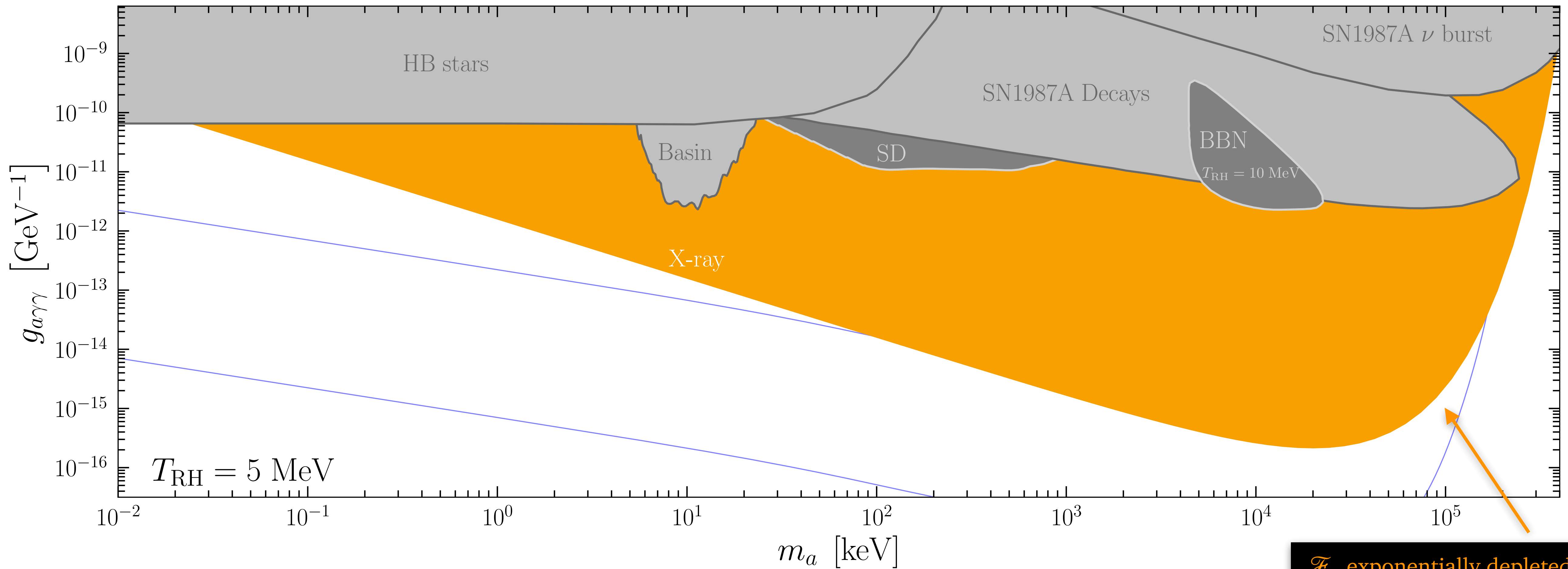
[Langhoff, Outmezguine, NLR PRL 2022]

Constraints

Starting point: X-ray Constraints

$$\Phi_a = \Phi_{\rm DM} \Rightarrow \mathscr{F}_a \simeq \tau_{a\to\gamma\gamma}/\tau_{\rm DM}$$

Assume mass independent $\tau_{\rm DM} = 10^{28}$ s



$\mathscr{F}_a$ exponentially depleted for $m_a \gg T_{\rm RH}$

For this simple example, ignore inverse decays

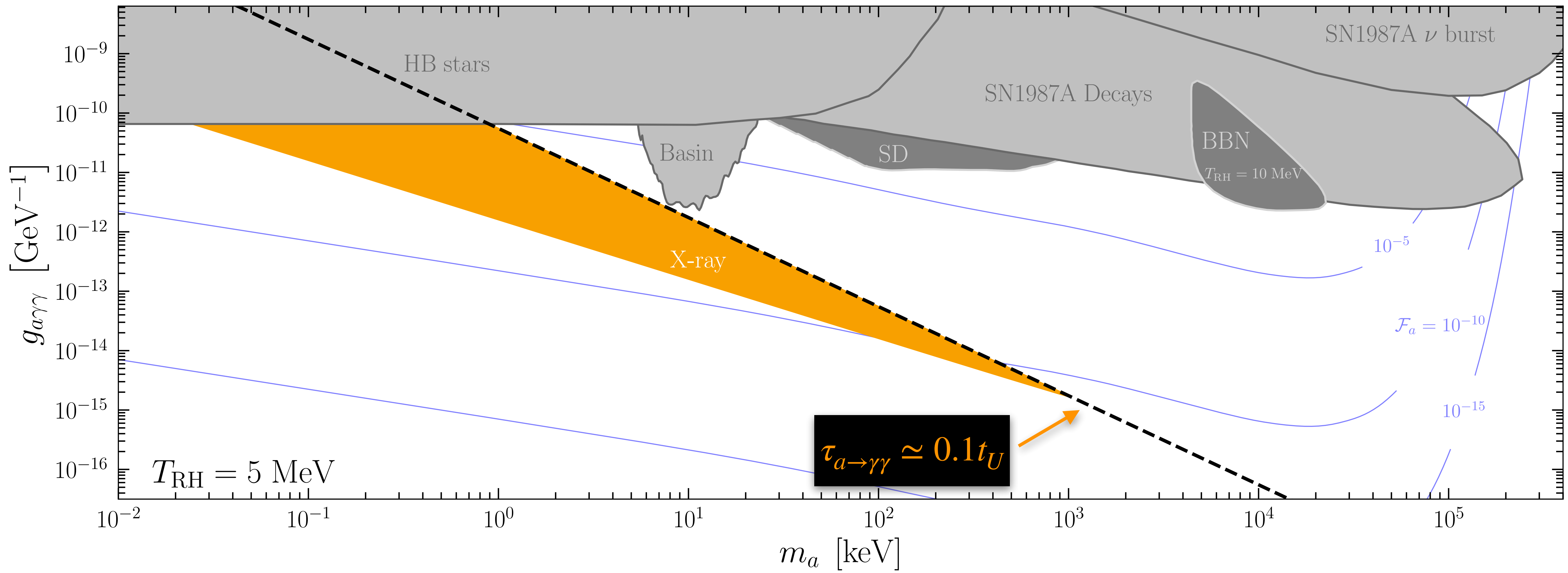
[Langhoff, Outmezguine, NLR PRL 2022]

Constraints

Starting point: X-ray Constraints

$$\Phi \propto \tau_{a\to\gamma\gamma}^{-1} \exp[-t_U/\tau_a]$$

Neglected previously - cuts constraints at large couplings



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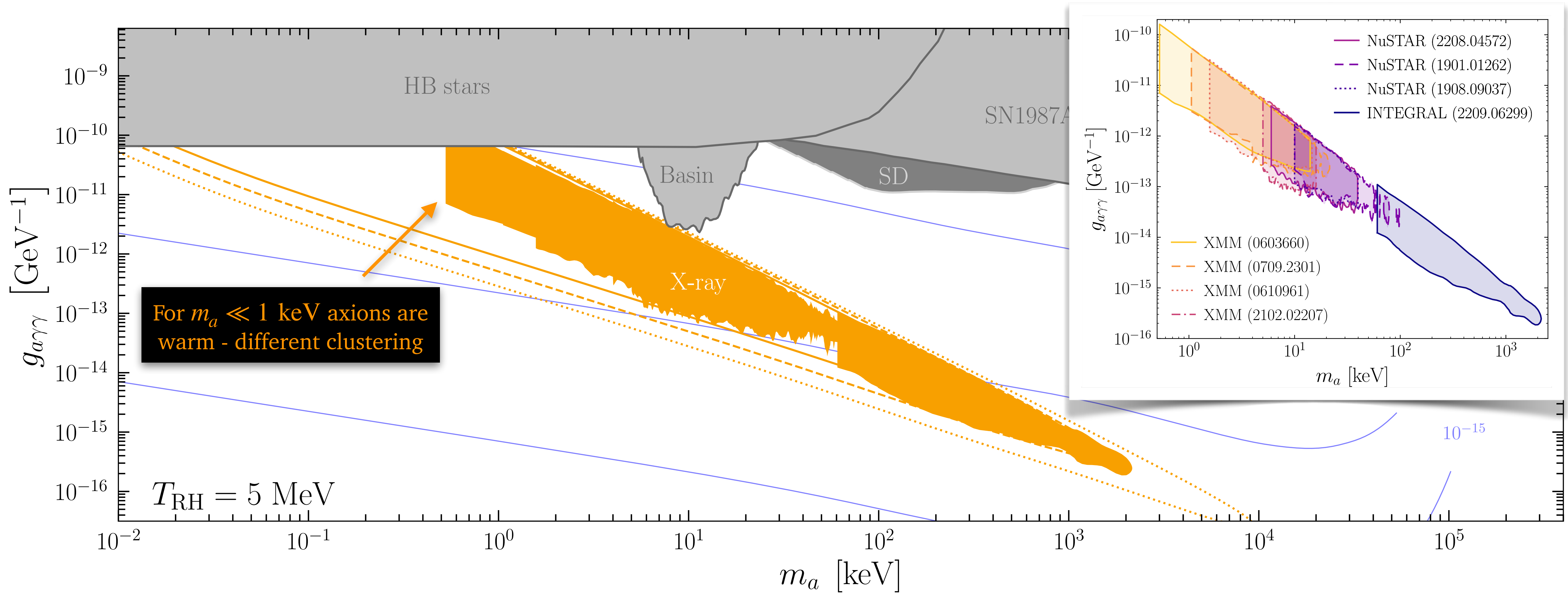


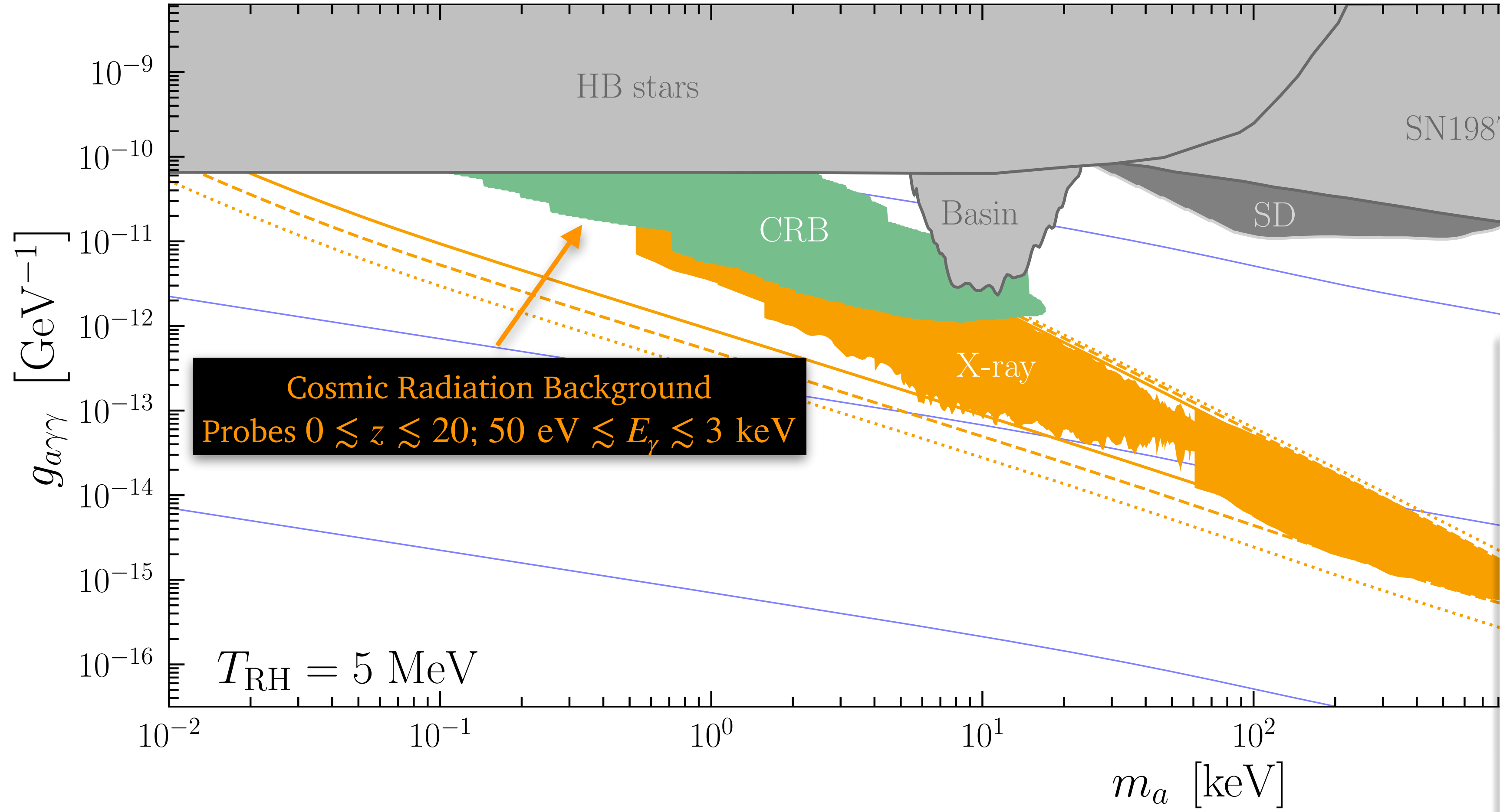
Solid/dashed/dotted curves: mass independent limits of $10^{29}/10^{30}/10^{31}$ s

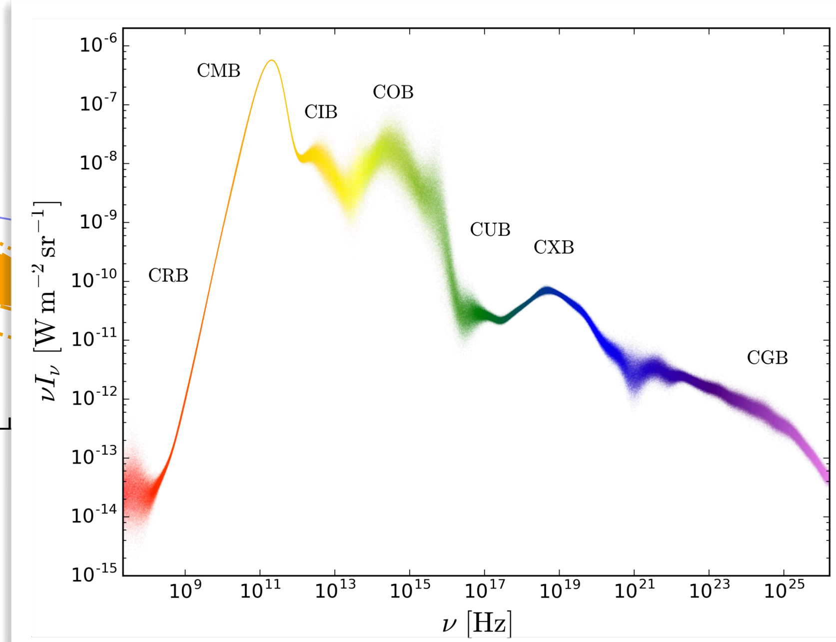
[Langhoff, Outmezguine, NLR PRL 2022]

Constraints

Need earlier probes, even if weaker for DM

Consider decays throughout the Universe



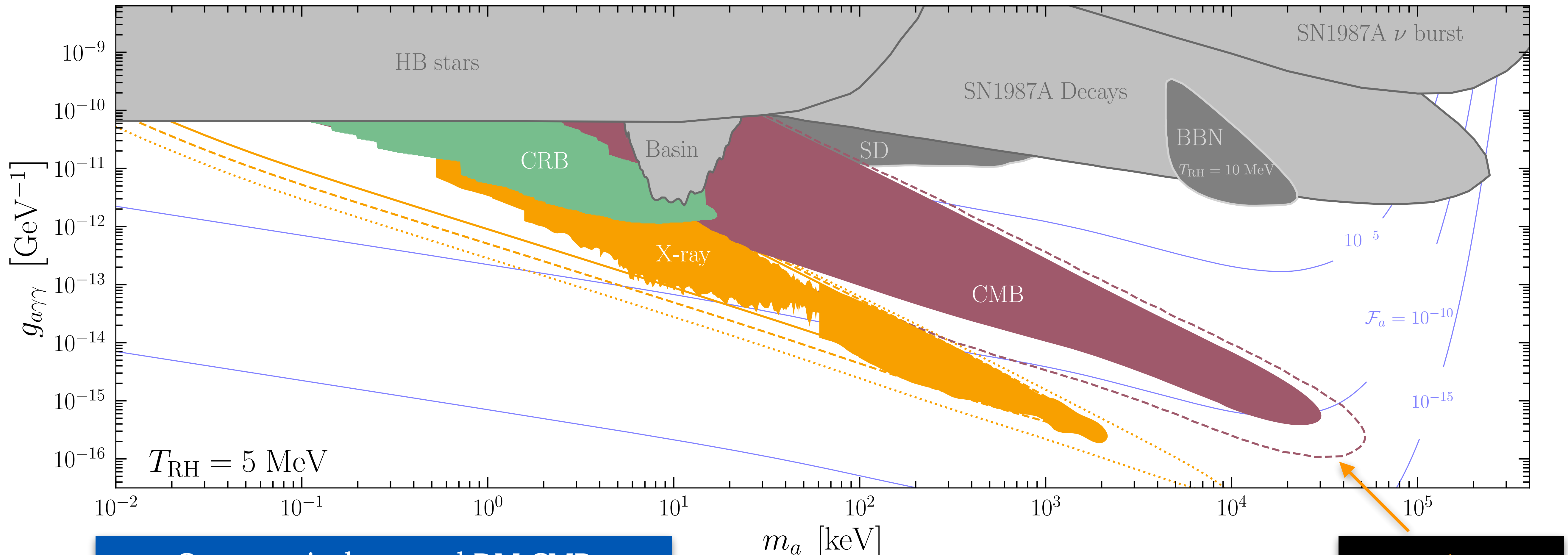


[“The Spectrum of the Universe” Hill, Masui, Scott 2018]

[Langhoff, Outmezguine, NLR PRL 2022]

Constraints

CMB allows for probes of earlier epochs still



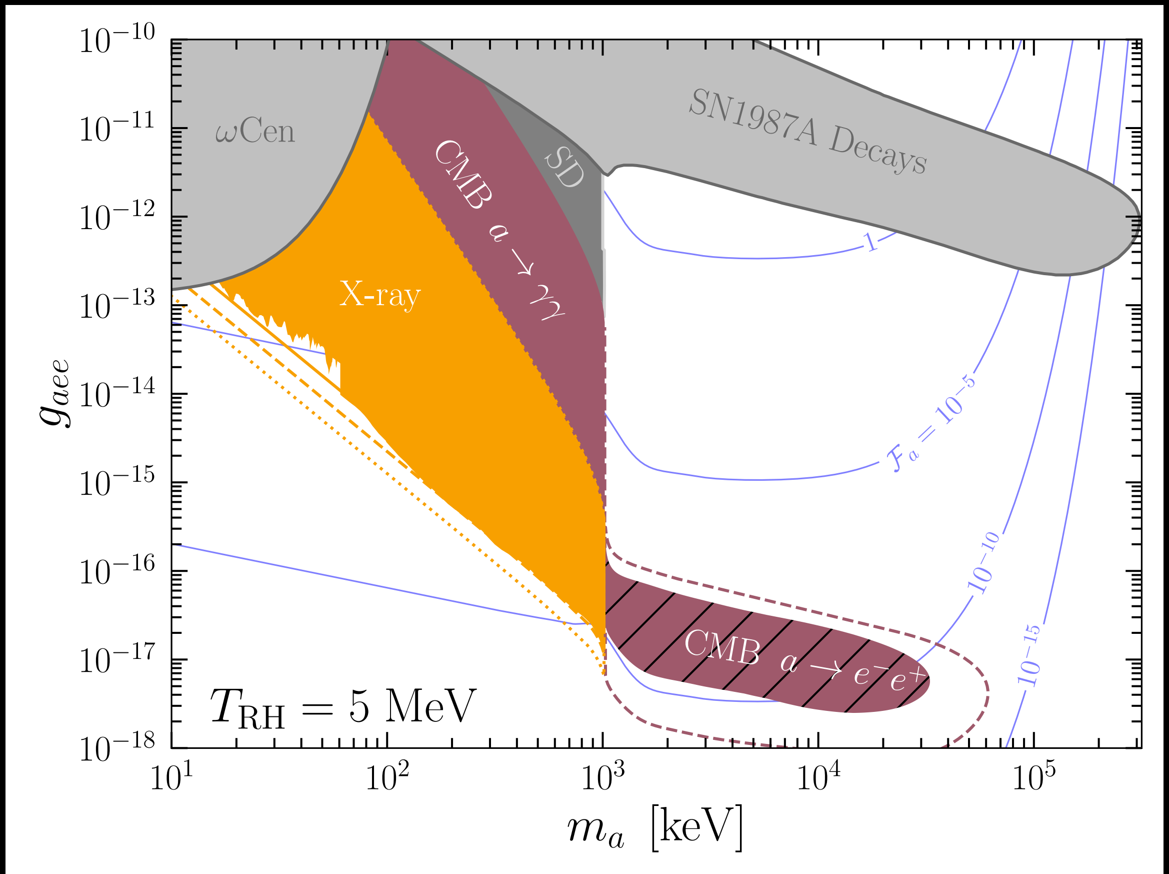
Conservatively extend DM CMB constraints to $\mathscr{F}_a \ll 1$

[Slatyer, Wu 2017], [Poulin, Lesgourgues, Serpico 2017], [Cang, Gao, Ma 2020], [Bolliet, Chluba, Battye 2021]

See [Balázs+ 2205.13549] for a full CMB analysis

[Langhoff, Outmezguine, NLR PRL 2022]

Extensions



10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
g_{aee}
ωCen
X-ray
CMB $a \to \gamma\gamma$
SD
SN1987A Decays
1
$\mathcal{F}_a = 10^{-5}$
10^{-10}
10^{-15}
CMB $a \to e^- e^+$
$T_{\rm RH} = 5$ MeV
10^1
10^2
10^3
10^4
10^5
m_a [keV]

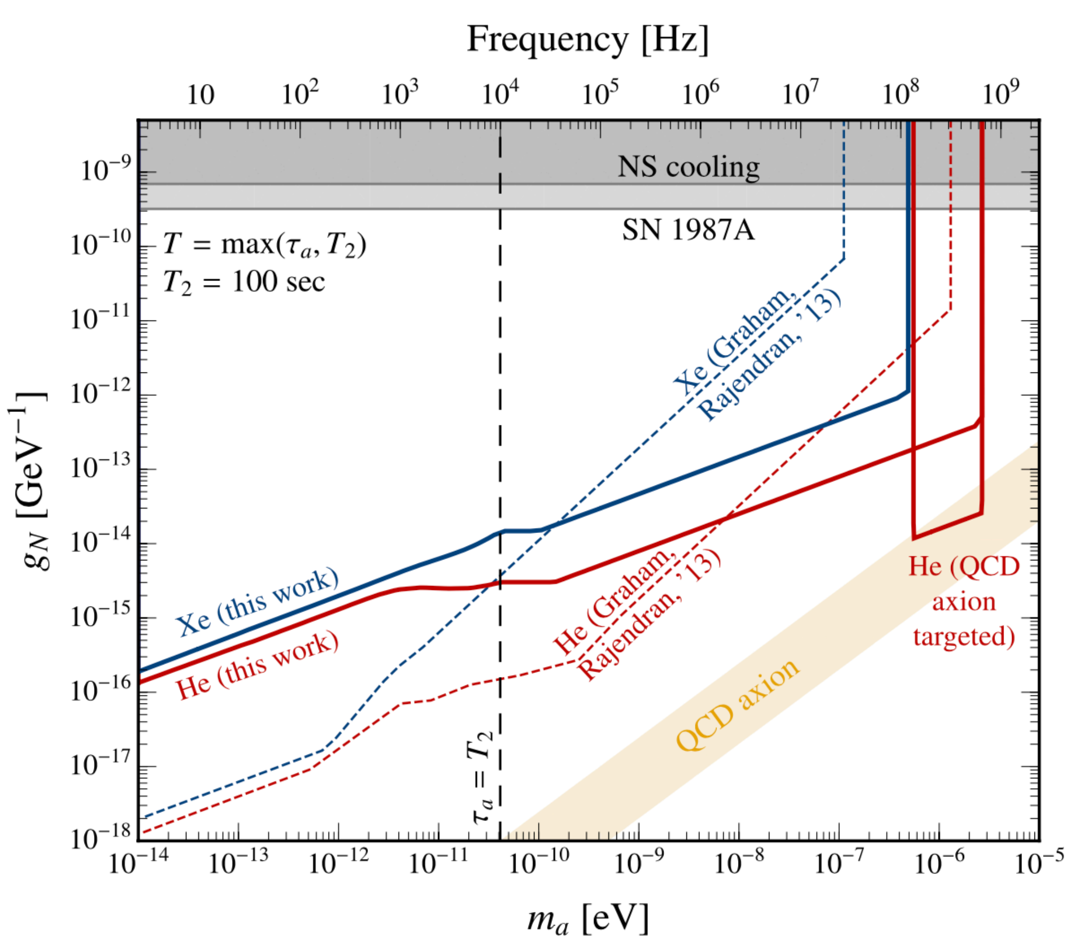
Extensions

Logic readily extends to the electron coupling and can also add a contribution from misalignment

Irreducible abundance can also be considered for the sterile neutrino, dark photon, gravitino, …

[Langhoff, Outmezguine, NLR PRL 2022]

Bonus: haloscope sensitivity



Haloscope Sensitivity

A result commonly used for haloscope sensitivity

$$g \propto \begin{cases} T^{-1/2} & T \ll \tau_a \\ T^{-1/4} & T \gg \tau_a \end{cases}$$

[Budker, Graham, Ledbetter, Rajendran, Sushkov 2013]

Haloscope Sensitivity

A result commonly used for haloscope sensitivity

$$g \propto \begin{cases} T^{-1/2} & T \ll \tau_a \\ T^{-1/4} & T \gg \tau_a \end{cases}$$

Axion coherence time
$\tau_a \sim 2\pi/m_a v^2$
~ 1 s $(1$ neV$/m_a)$

Dicke radiometer equation predicts: $T^{-1/4}$

[Budker, Graham, Ledbetter, Rajendran, Sushkov 2013]

Haloscope Sensitivity

That scaling does not hold in general

$$g \propto \begin{cases} T^{-3/2} & T \ll \tau_a,\, \tau_r \\ T^{-1} & \tau_a \ll T \ll \tau_r \\ T^{-1/2} & \tau_r \ll T \ll \tau_a \\ T^{-1/4} & T \gg \tau_a,\, \tau_r \end{cases}$$

Instrument coherence time, e.g. T_2 for NMR or $2\pi Q/\bar{\omega}$ for a cavity

Straightforward to derive: axion is a weak driving force for resonant systems, problem maps to the SHO, and can be solved analytically

[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

Example: axion NMR

$$\frac{d\mathbf{M}}{dt} = \mathbf{M} \times \gamma \mathbf{B} - \frac{M_x \hat{\mathbf{x}} + M_y \hat{\mathbf{y}}}{T_2} - \frac{(M_z - M_0)\hat{\mathbf{z}}}{T_1}$$

[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

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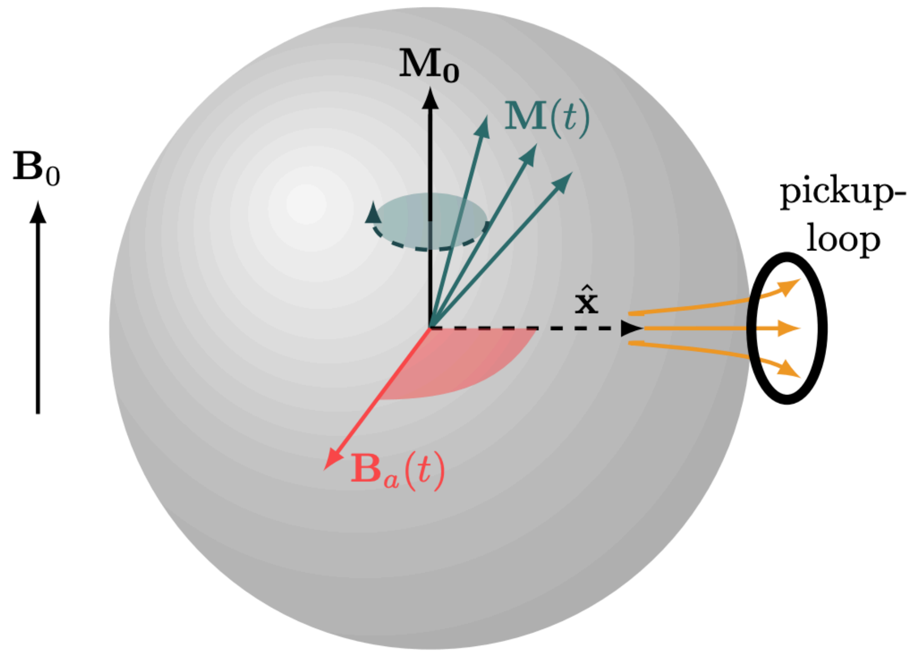
Axion-nucleon coupling generates a magnetic field $\mathbf{B} = (-2g_N/\gamma)\nabla a$



[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

Example: axion NMR

$$\frac{d\mathbf{M}}{dt} = \mathbf{M} \times \gamma \mathbf{B} - \frac{M_x \hat{\mathbf{x}} + M_y \hat{\mathbf{y}}}{T_2} - \frac{(M_z - M_0)\hat{\mathbf{z}}}{T_1}$$

Treat axion as a small perturbation

$$\ddot{M}_x + 2T_2^{-1}\dot{M}_x + \omega_0^2 = \gamma M_0[\omega_0 B_x - \dot{B}_y]$$

[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

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Treat axion as a small perturbation

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T_2 = coherence of the response

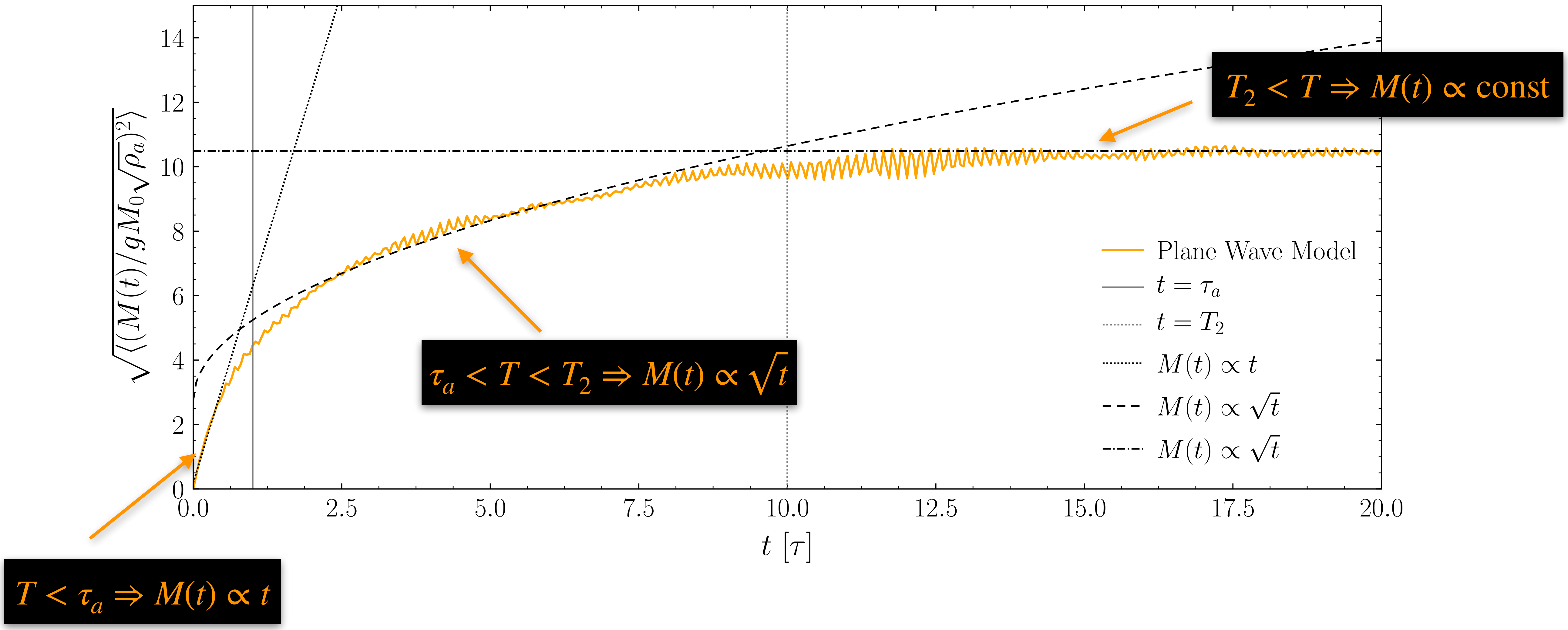
The simple harmonic oscillator - holds for general resonant axion halo scopes

τ_a = coherence of the driving force

[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

Solve for the growth of M_x analytically



[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

Sensitivity scaling: $\sigma = P_{\rm sig}/P_{\rm bkg}$ ($P_{\rm sig} \propto g^2$)

$$g \propto \begin{cases} T^{-3/2} & T \ll \tau_a,\, \tau_r \\ T^{-1} & \tau_a \ll T \ll \tau_r \\ T^{-1/2} & \tau_r \ll T \ll \tau_a \\ T^{-1/4} & T \gg \tau_a,\, \tau_r \end{cases}$$

[Dror, Gori, Leedom, NLR PRL 2023]

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$P_{\rm sig} \propto M^2 \propto T^2$ and $P_{\rm bkg} \propto 1/T$

White noise: larger T integrate over a smaller range

[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

Sensitivity scaling: $\sigma = P_{\text{sig}}/P_{\text{bkg}}$ ($P_{\text{sig}} \propto g^2$)

$$g \propto \begin{cases} T^{-3/2} & T \ll \tau_a, \tau_r \\ T^{-1} & \tau_a \ll T \ll \tau_r \\ T^{-1/2} & \tau_r \ll T \ll \tau_a \\ T^{-1/4} & T \gg \tau_a, \tau_r \end{cases}$$

$P_{\text{sig}} \propto M^2 \propto T$ and $P_{\text{bkg}} \propto 1/T$

[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

Sensitivity scaling: $\sigma = P_{\text{sig}}/P_{\text{bkg}}$ ($P_{\text{sig}} \propto g^2$)

$$g \propto \begin{cases} T^{-3/2} & T \ll \tau_a, \tau_r \\ T^{-1} & \tau_a \ll T \ll \tau_r \\ T^{-1/2} & \tau_r \ll T \ll \tau_a \\ T^{-1/4} & T \gg \tau_a, \tau_r \end{cases}$$

$P_{\text{sig}} \propto M^2 \propto \text{const}$ and $P_{\text{bkg}} \propto 1/T$

[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

Sensitivity scaling: $\sigma = P_{\rm sig}/P_{\rm bkg}$ $(P_{\rm sig} \propto g^2)$

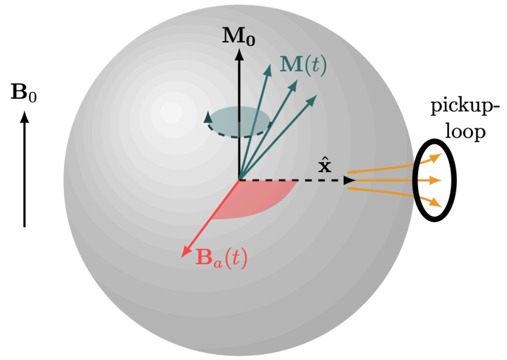
$$g \propto \begin{cases} T^{-3/2} & T \ll \tau_a\,,\, \tau_r \\ T^{-1} & \tau_a \ll T \ll \tau_r \\ T^{-1/2} & \tau_r \ll T \ll \tau_a \\ T^{-1/4} & T \gg \tau_a\,,\, \tau_r \end{cases}$$

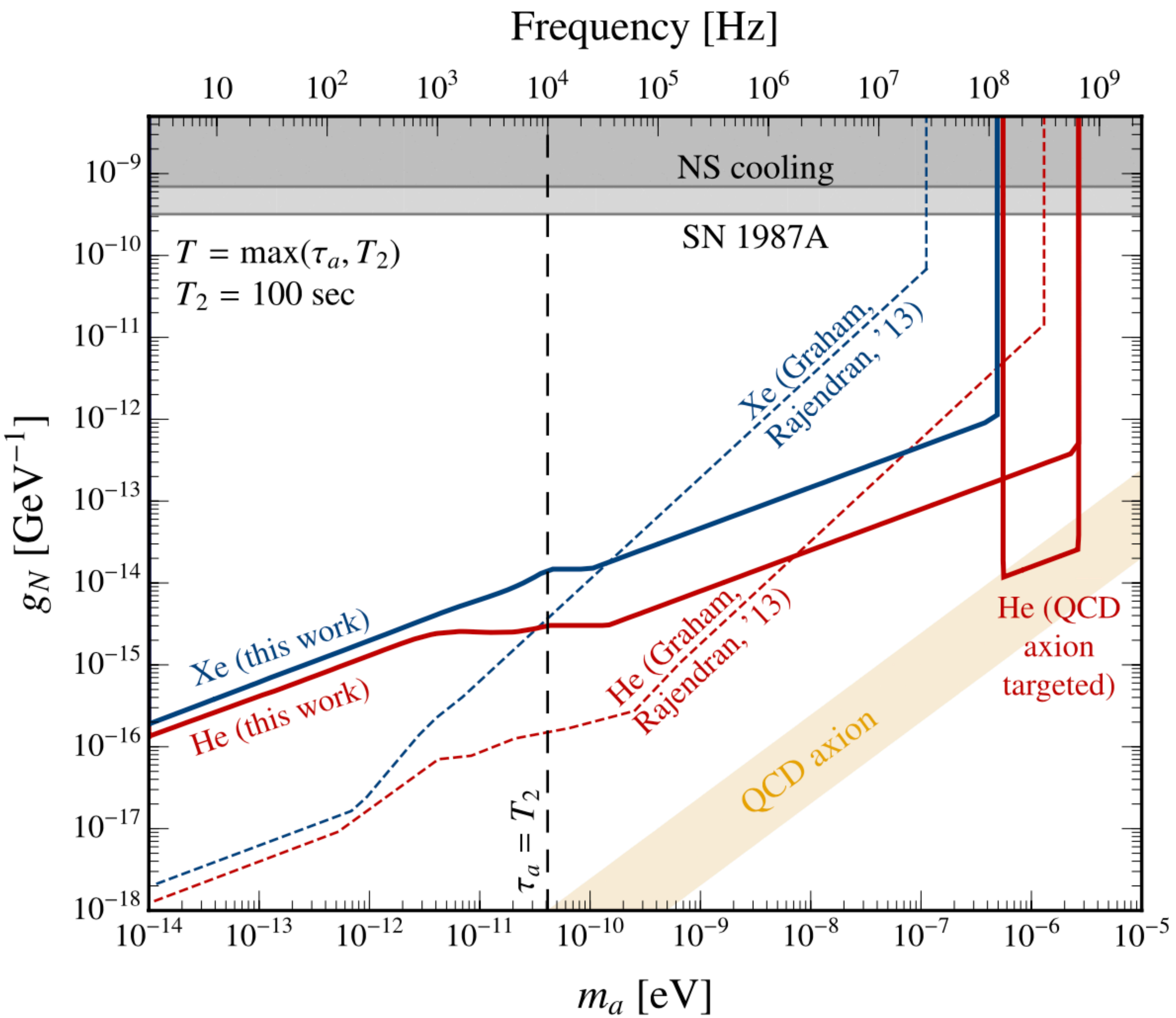
Resolve signal in $N \propto T$ bins, $P_{\rm sig}$ enhanced by $\sqrt{N}$

[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

Implications for CASPER-Wind

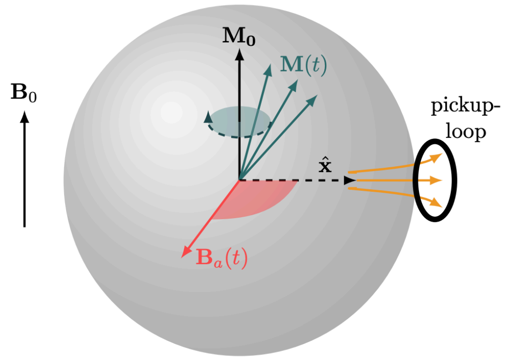


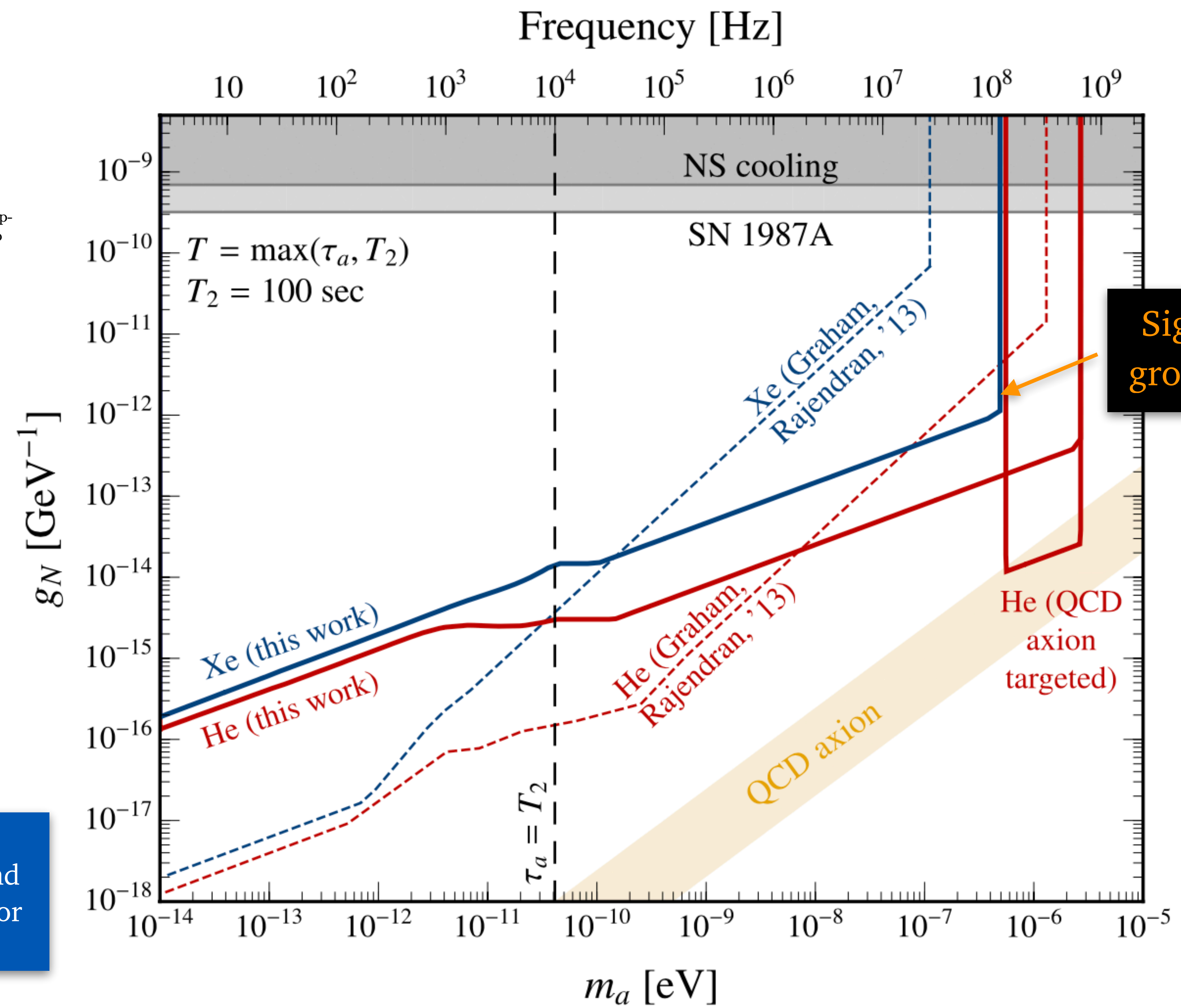


[Dror, Gori, Leedom, NLR PRL 2023]

Haloscope Sensitivity

Implications for CASPER-Wind





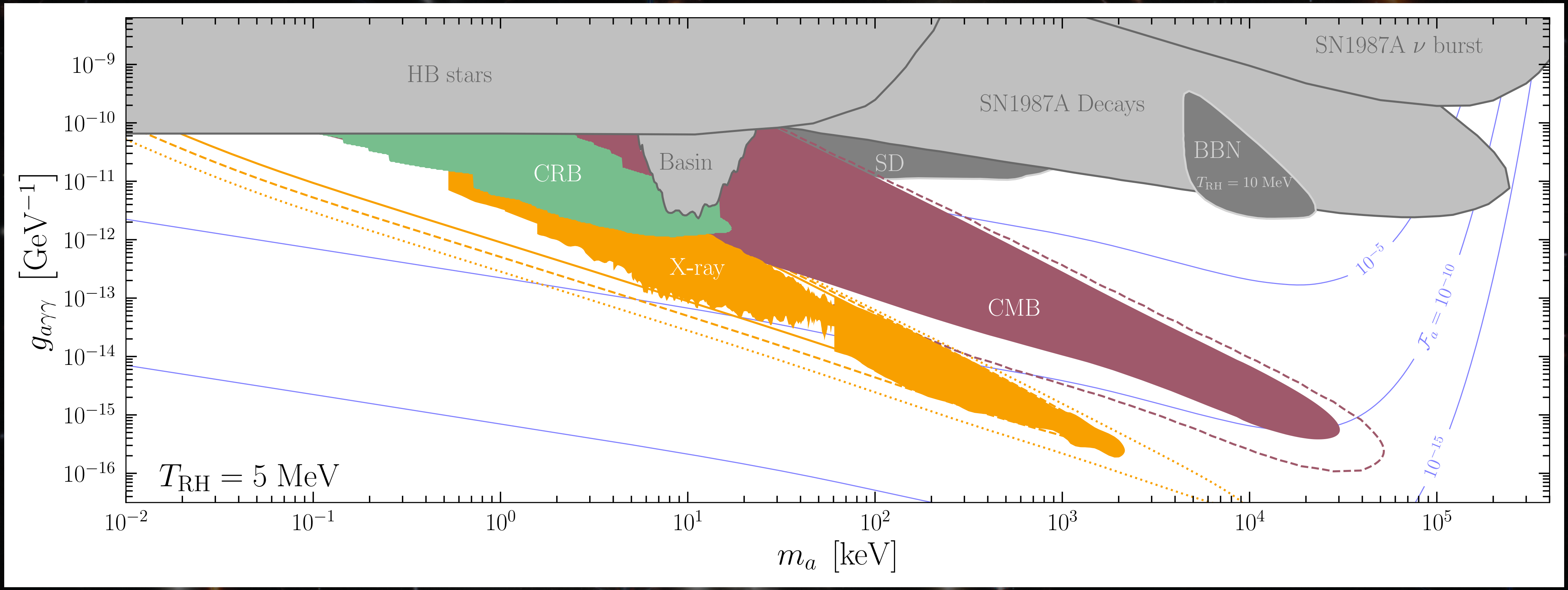
Signal continues to grow for $\tau_a < T < \tau_r$

Other corrections: treatment of background and factor of 2 in Larmor frequency

[Dror, Gori, Leedom, NLR PRL 2023]

Conclusion

DM searches can strongly constrain non-DM axions



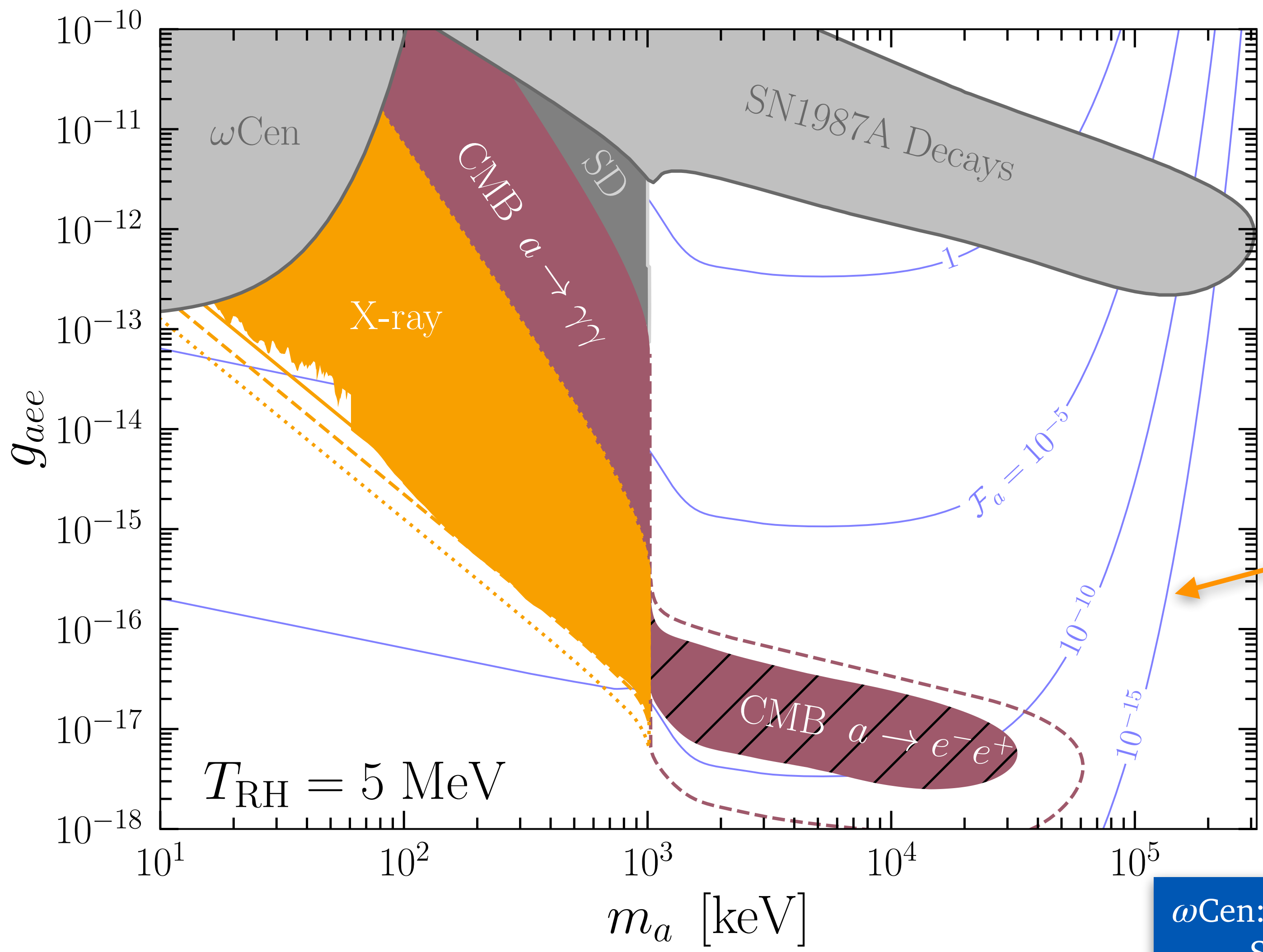
[Langhoff, Outmezguine, NLR PRL 2022]

Backup Slides

Extensions

Argument immediately extends to other couplings, e.g.

$$\frac{g_{aee}}{2m_e}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$$



Production IR dominated, mainly
$e^\pm\gamma \to e^\pm a$
$e^- e^+ \to a$

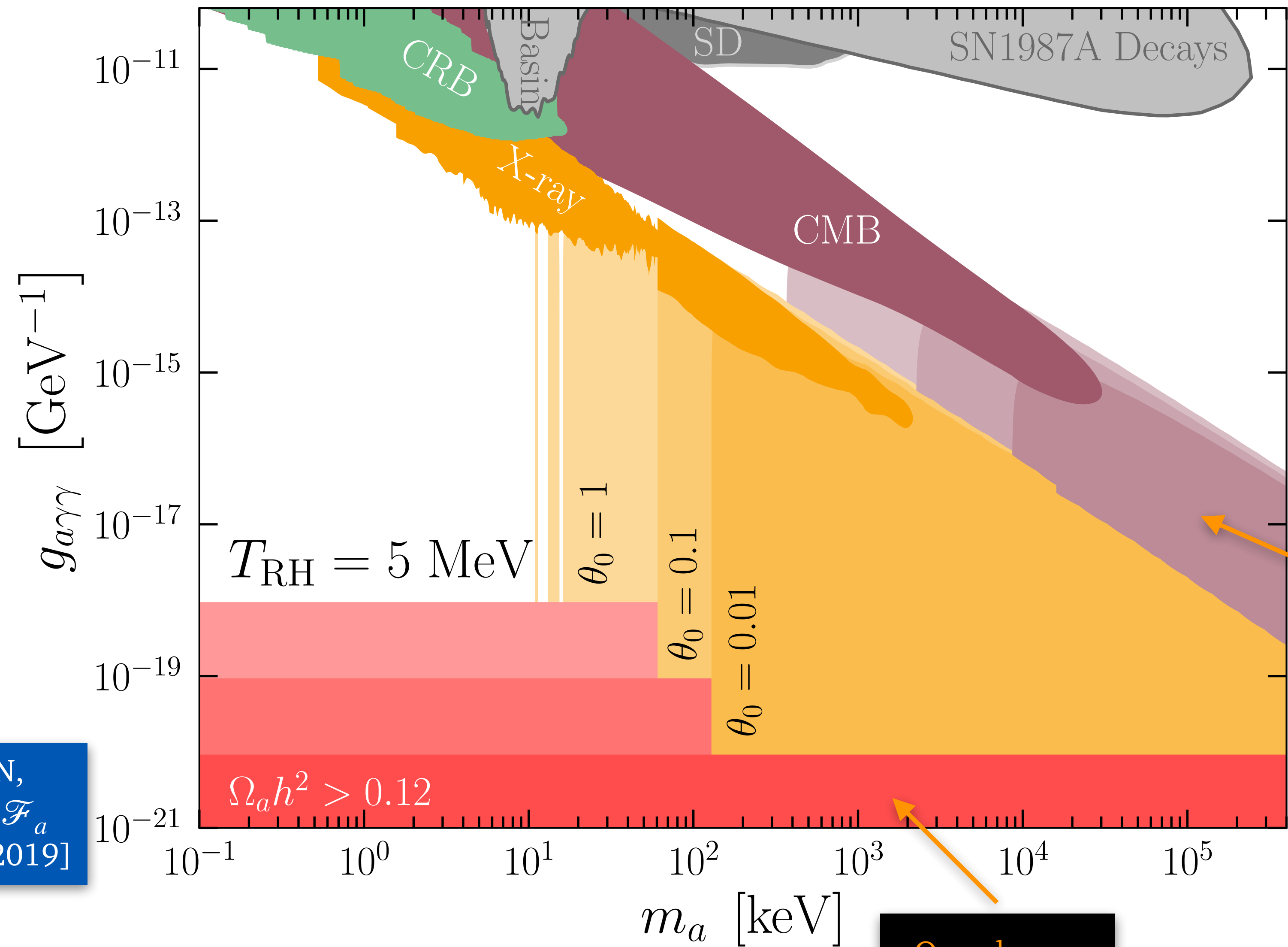
$a \to \gamma\gamma$ proceeds at 1-loop
τ_a dramatically shortens once $m_a > 2m_e$

ωCen: [Ferreira, Marsh, Müller 2205.07896]
SN1987A: [Capozzi, Raffelt 2020]

[Langhoff, Outmezguine, NLR PRL 2022]

Extensions

Misalignment contribution not irreducible, but can include conservatively*



Coupling only enters through e^{-t/τ_a}

$\Gamma \propto g_{a\gamma\gamma}^2 \propto f_a^{-2}$

$\mathscr{F}_a \propto f_a^2$

Overclosure

*Matter domination before BBN, radiation or kination give larger $\mathscr{F}_a$ [Blinov, Dolan, Draper, Kozaczuk 2019]

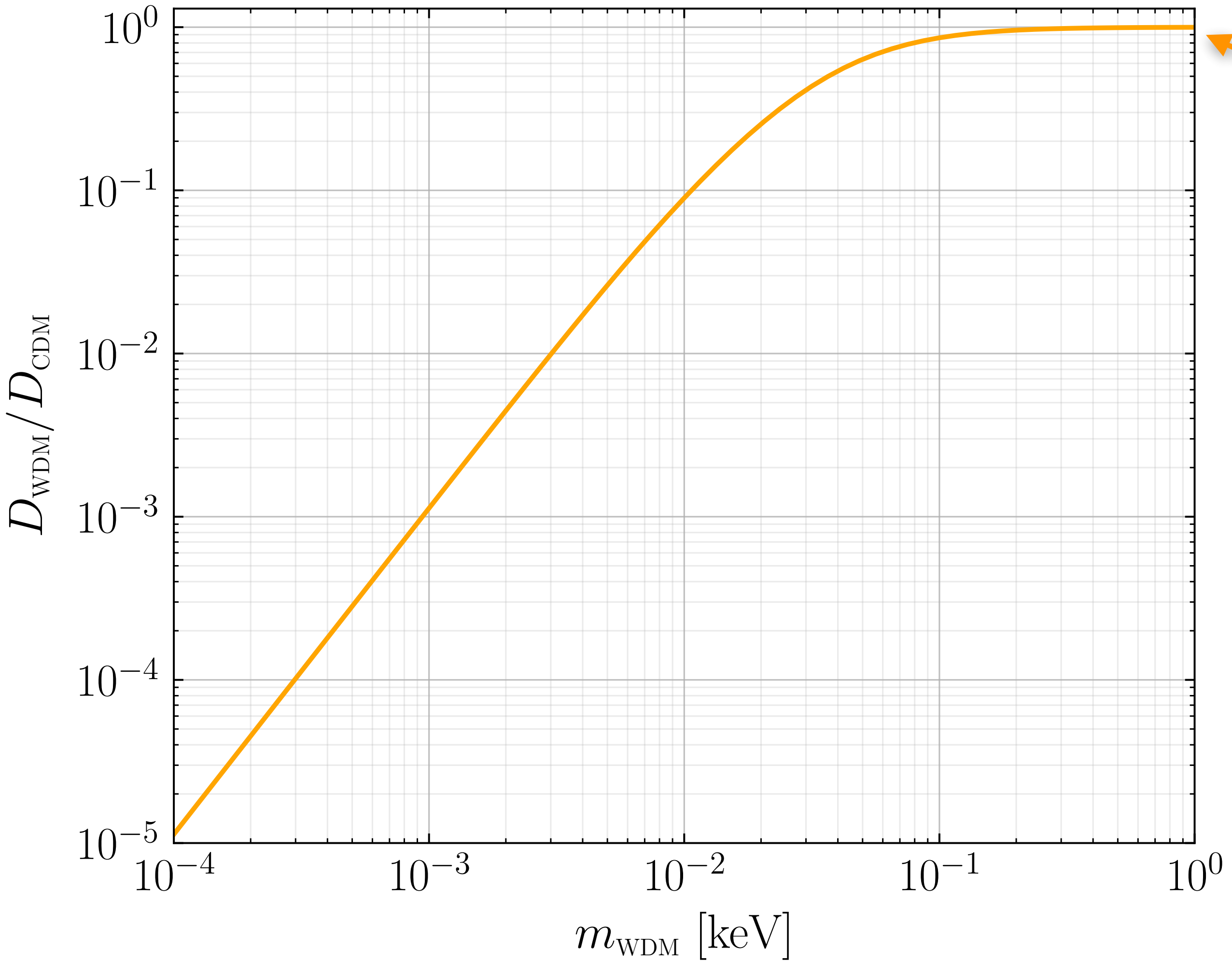
[Langhoff, Outmezguine, NLR PRL 2022]

Clustering at low mass

Impact on X-ray constraints due to warm DM not clustering

$$F_a^{\rm MW}(r) \simeq \mathscr{F}_a \times \left[1 + 0.008 \left(\frac{\rm keV}{m_a}\right)^2 \left(\frac{\rm kpc}{r}\right) \right]^{-1}$$

N-body Milky Way study [Anderhalden, Diemand, Bertone, Maccio, Schneider 2012]

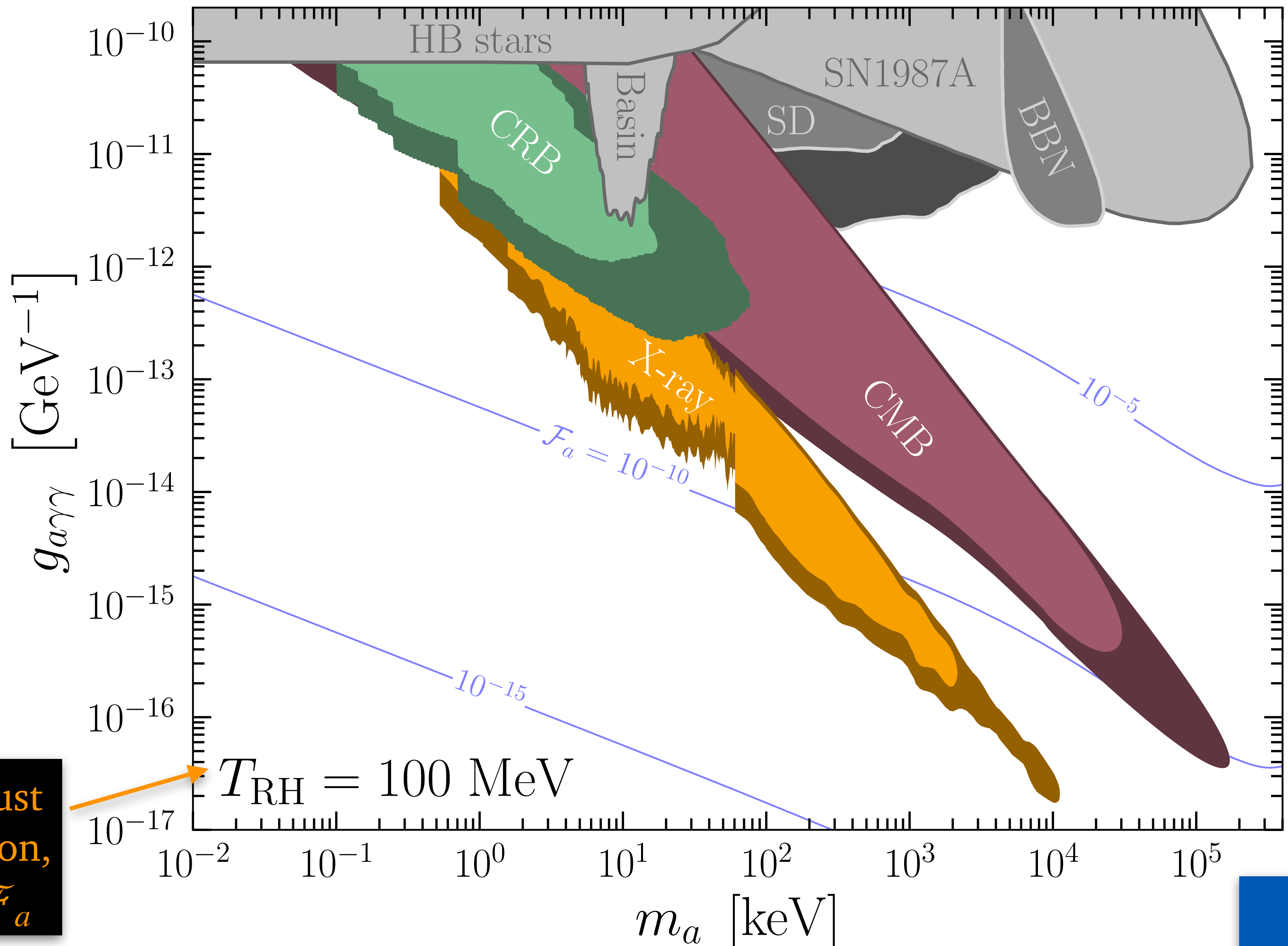


Safe for $m_a \gtrsim 1$ keV

[Langhoff, Outmezguine, NLR PRL 2022]

$T_{\rm RH}$ dependence

Production UV dominated: $\mathscr{F}_a \propto T_{\rm RH} \Rightarrow g_{a\gamma\gamma} \propto T_{\rm RH}^{1/4}$



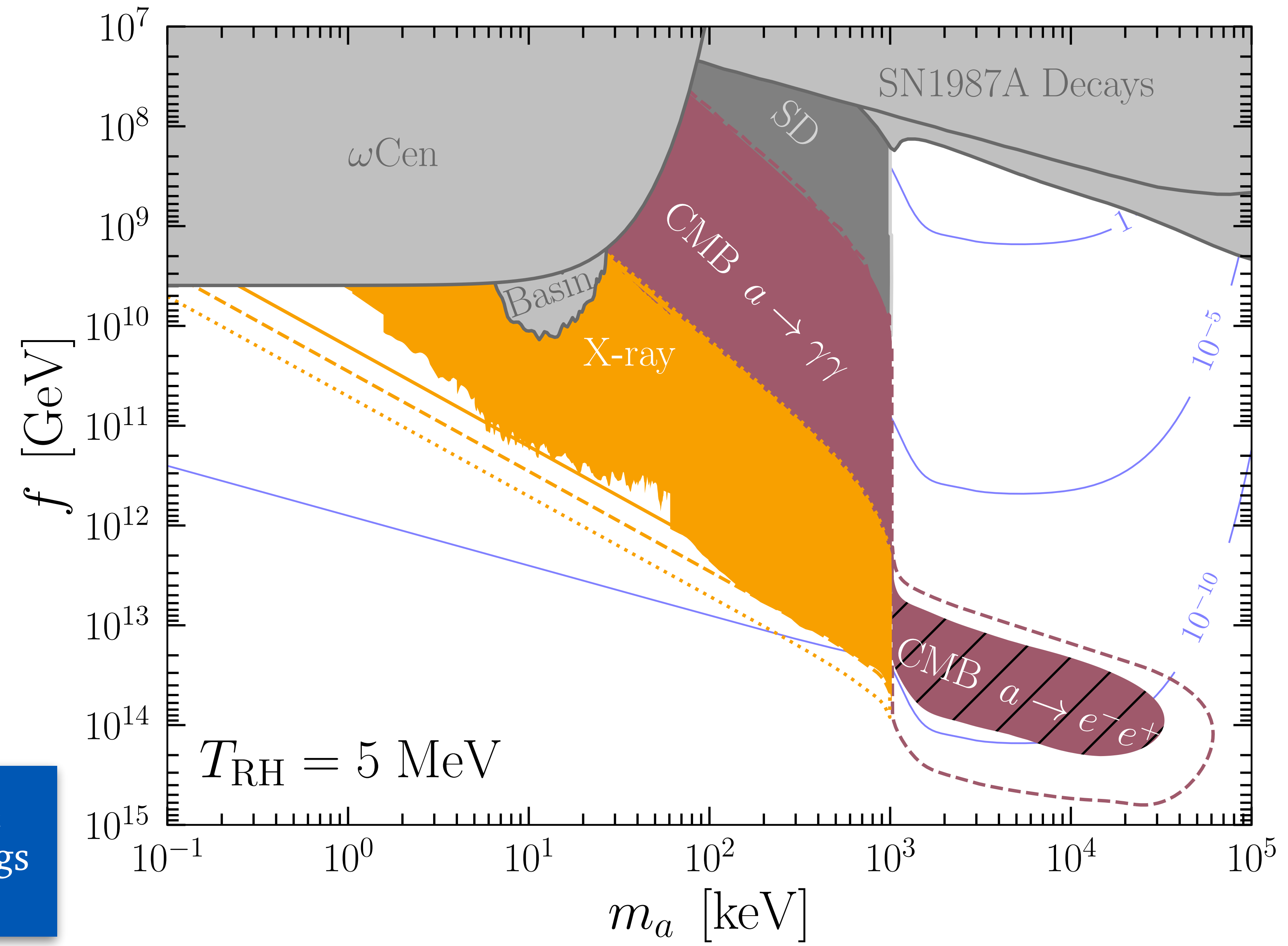
Beyond 100 MeV, must include pion and muon, will only increase $\mathscr{F}_a$

Impact for g_{aee} case weaker - IR dominated

[Langhoff, Outmezguine, NLR PRL 2022]

Universal Couplings

$$g_{a\gamma\gamma} = \alpha/2\pi f_a \text{ and } g_{aee} = m_e/f_a$$

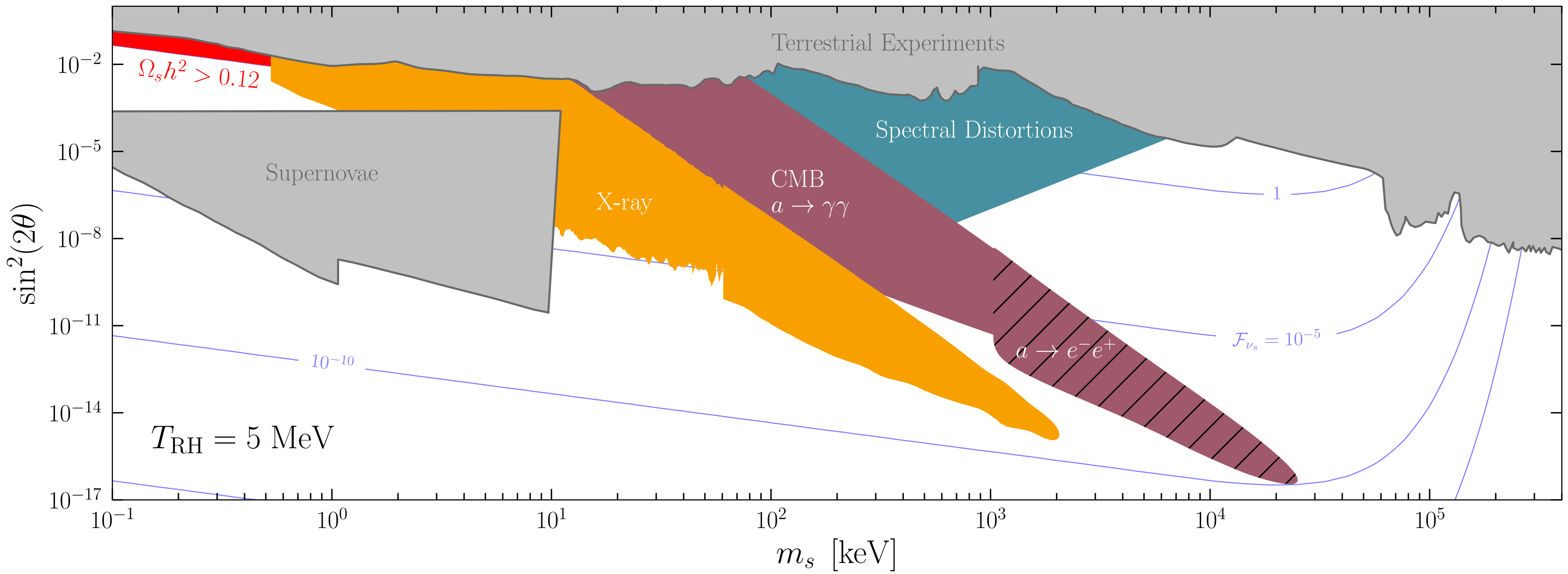


Results for fixed m_a varying both couplings in paper

[Langhoff, Outmezguine, NLR PRL 2022]

Sterile Neutrinos

Idea readily extend to other states (graviton, dark photon…)

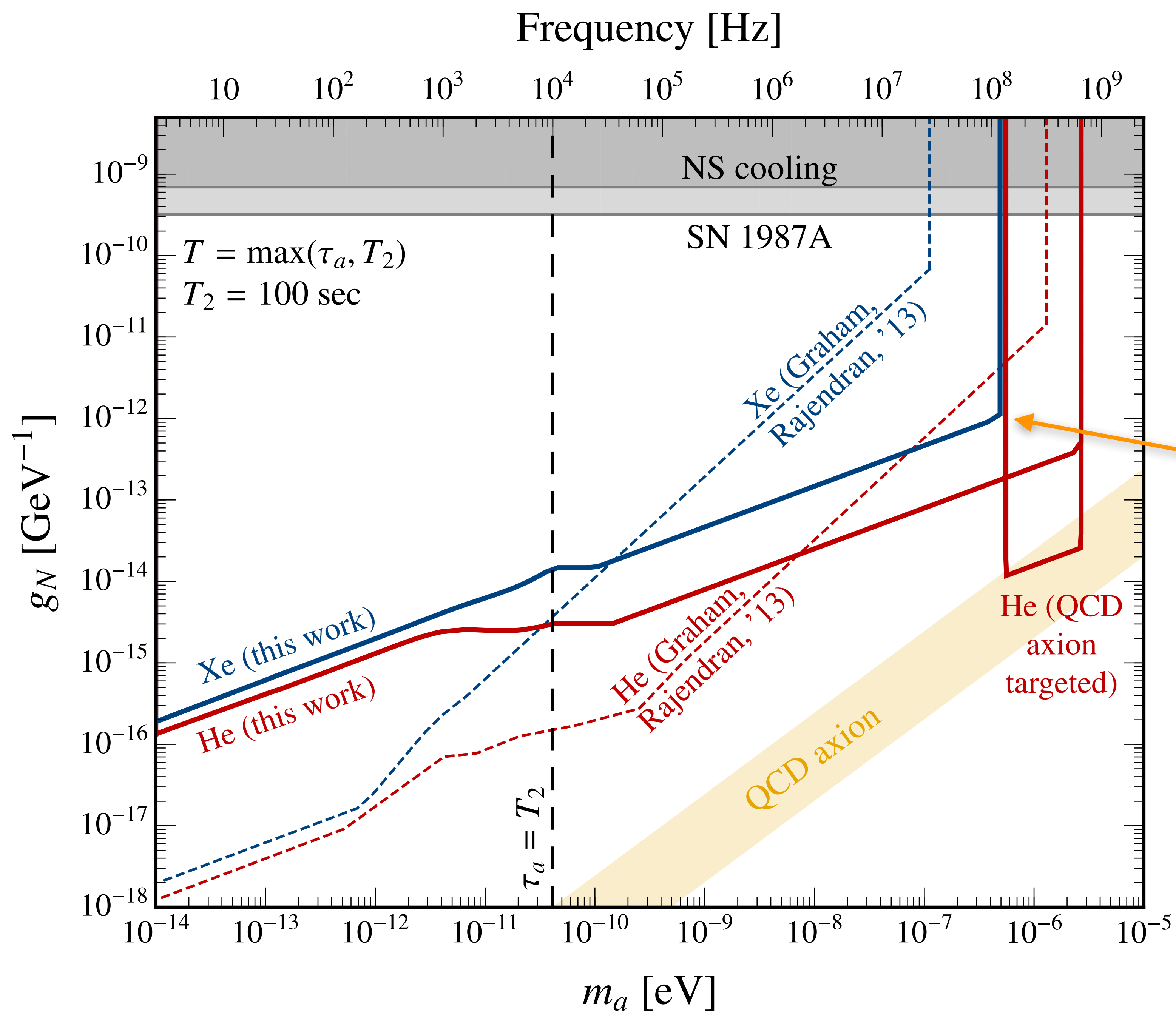


Cf. [Gelmini, Osoba, Palomares-Ruiz, Pascoli 2008], [Gelmini, Lu, Takhistov 2019]

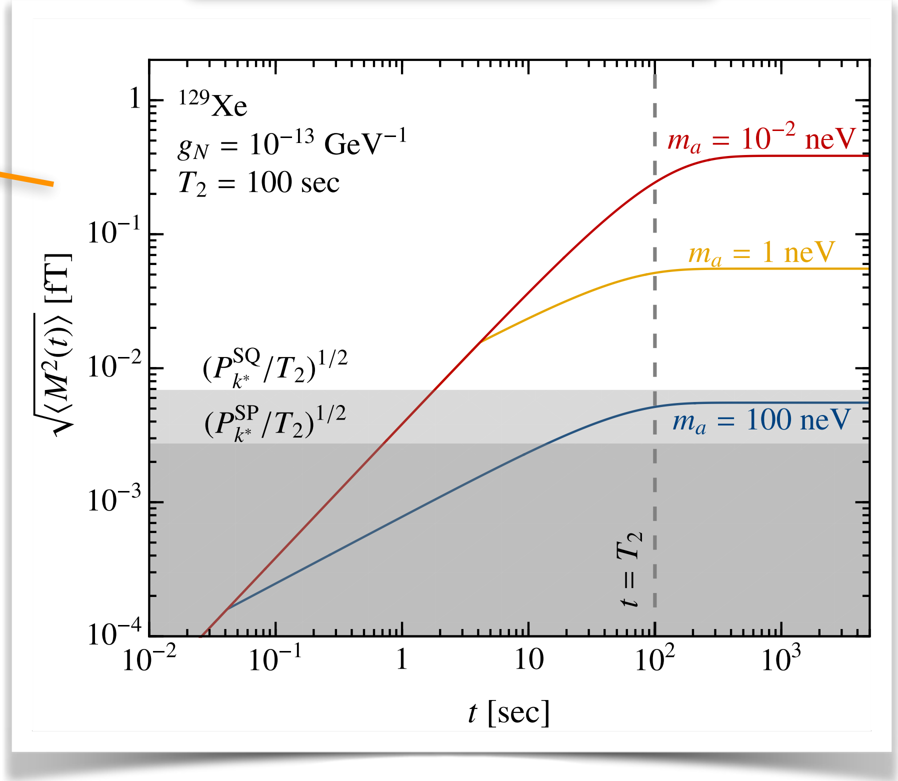
[Langhoff, Outmezguine, NLR PRL 2022]

Axion NMR

$$\mathcal{L} \supset g_N (\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N$$



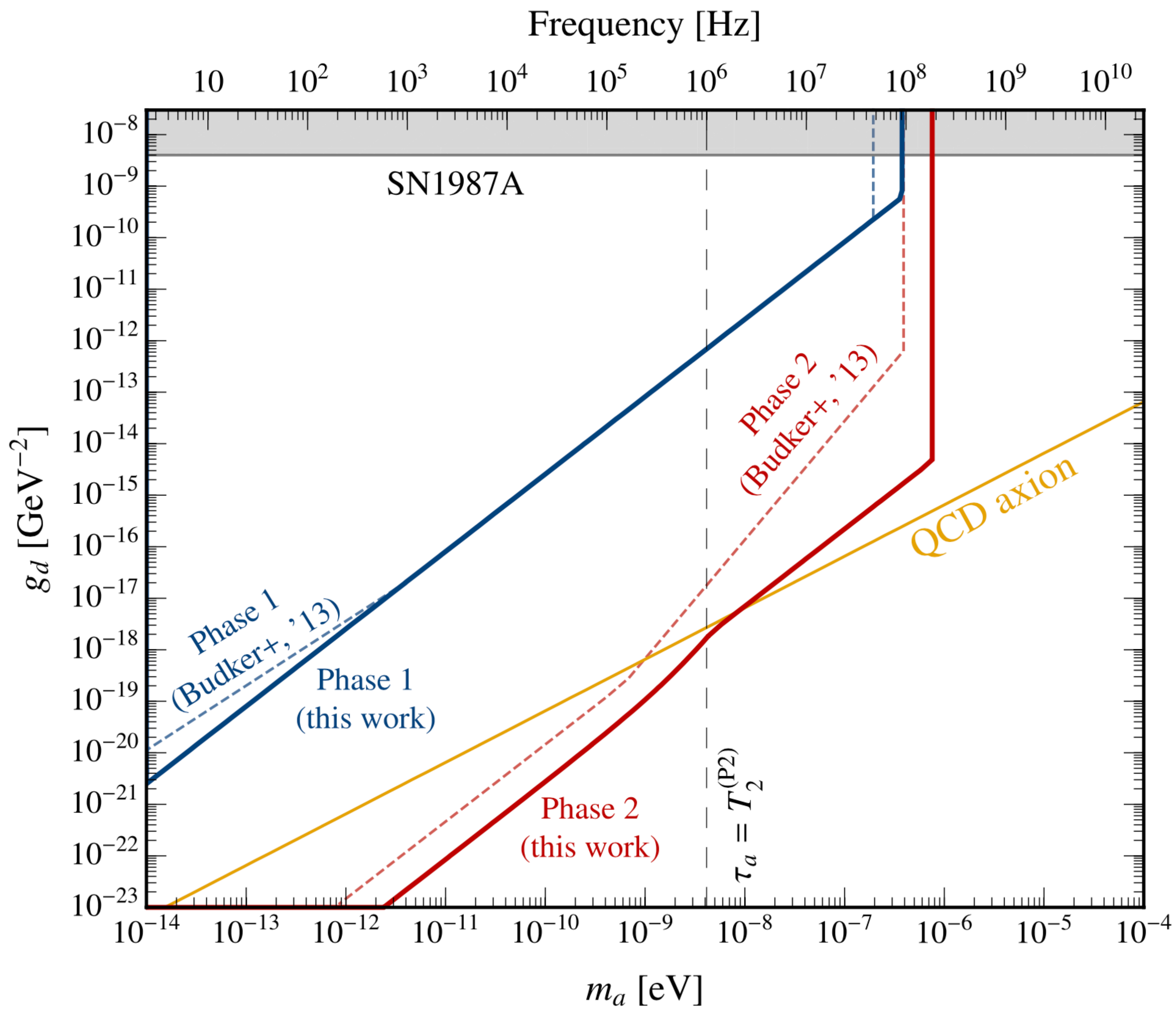
Axion signal continues to grow for $\tau_a < T < T_2$



[Dror, Gori, Leedom, NLR PRL 2023]

Axion NMR

Impact for CASPER-Electric



[Dror, Gori, Leedom, NLR PRL 2023]