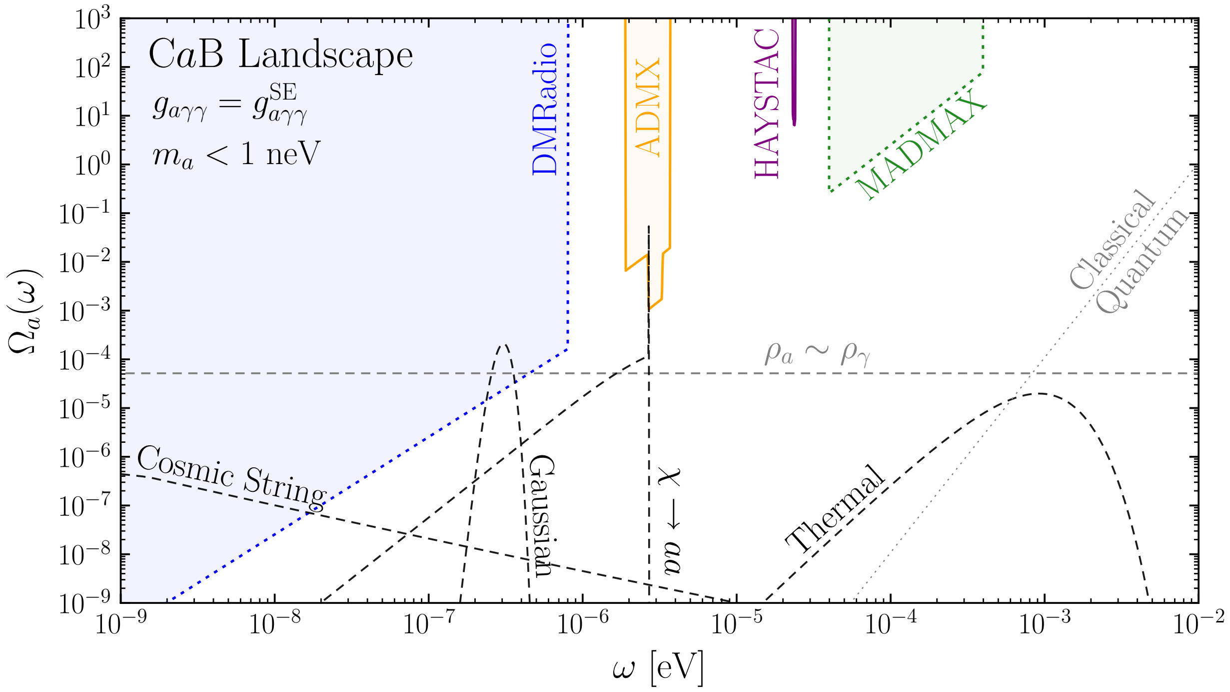
Echos of the Early Universe in Axion Haloscopes

NICK RODD | Max Planck Institute for Physics, Munich | 21 November 2023

The Cosmic Axion Background

PRD 2021

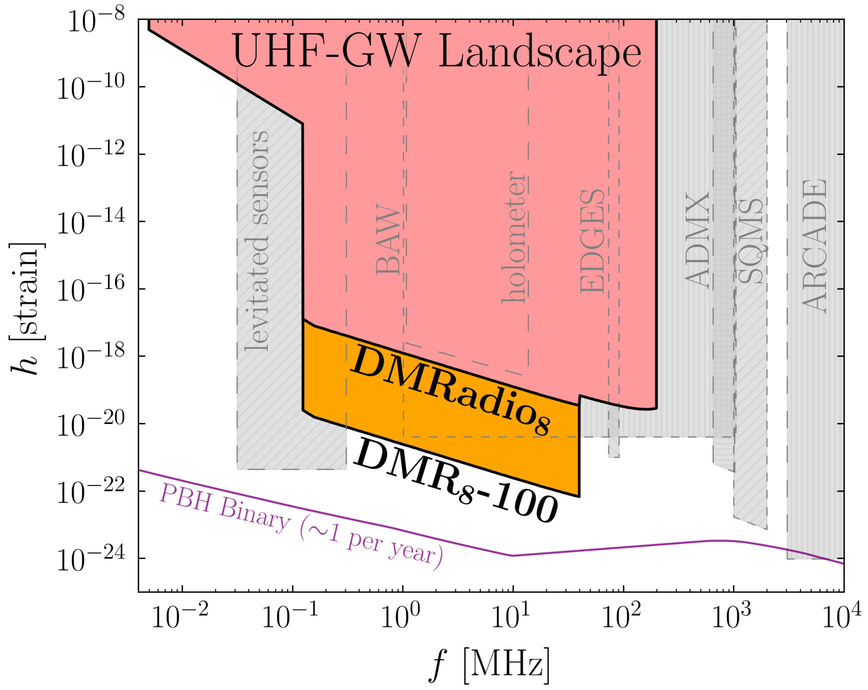
w/ Jeff Dror, Hitoshi Murayama



High-Frequency Gravitational Waves

PRL 2022

w/ Valerie Domcke, Camilo Garcia-Cely



Echos of the Early Universe in Axion Haloscopes

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Motivation

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

The axion

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Introduces a new source for E&M fields

$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J} + g_{a\gamma\gamma} \mathbf{B} \partial_t a$$

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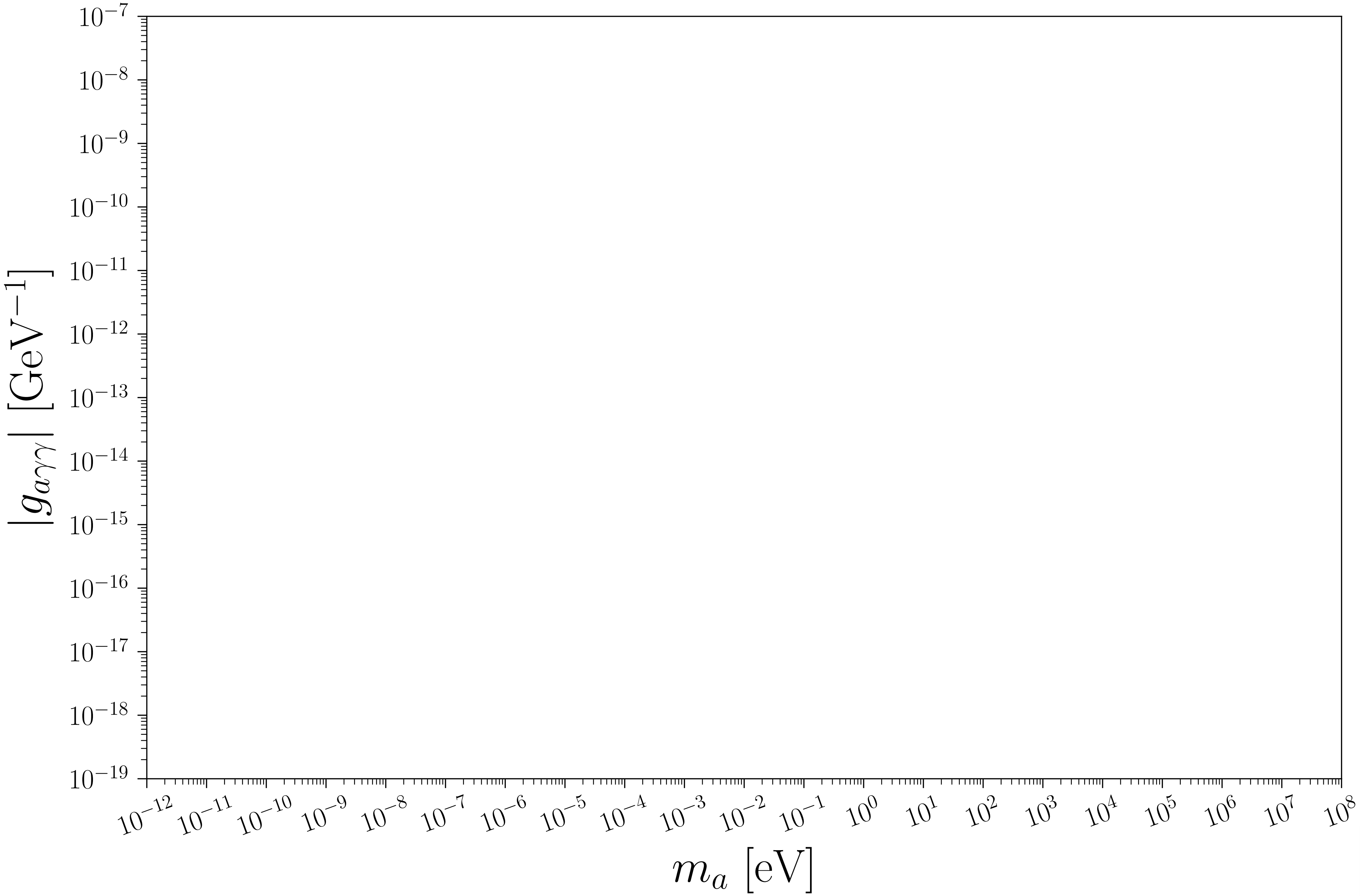

Partial summary
[O'Hare github]

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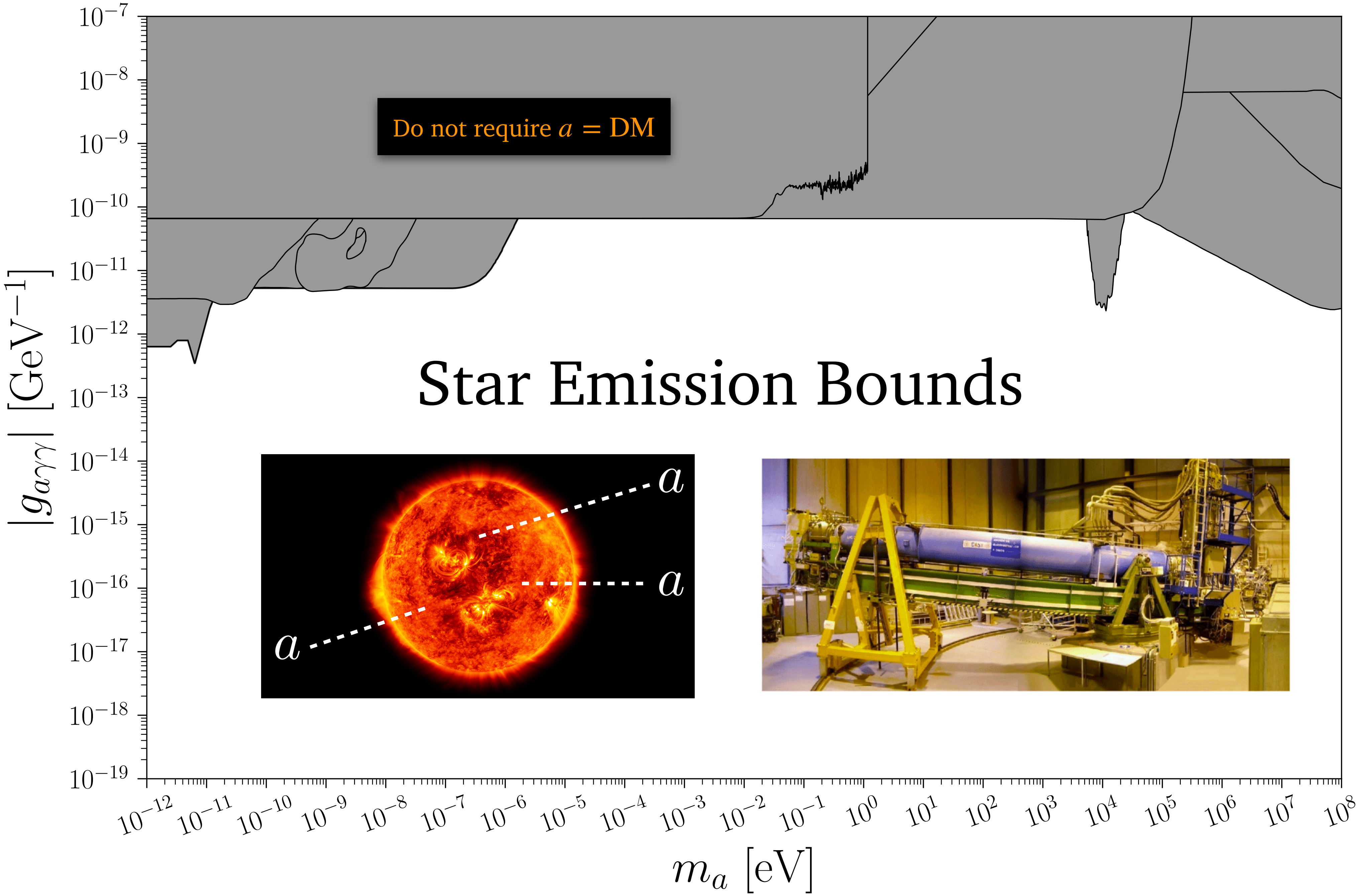

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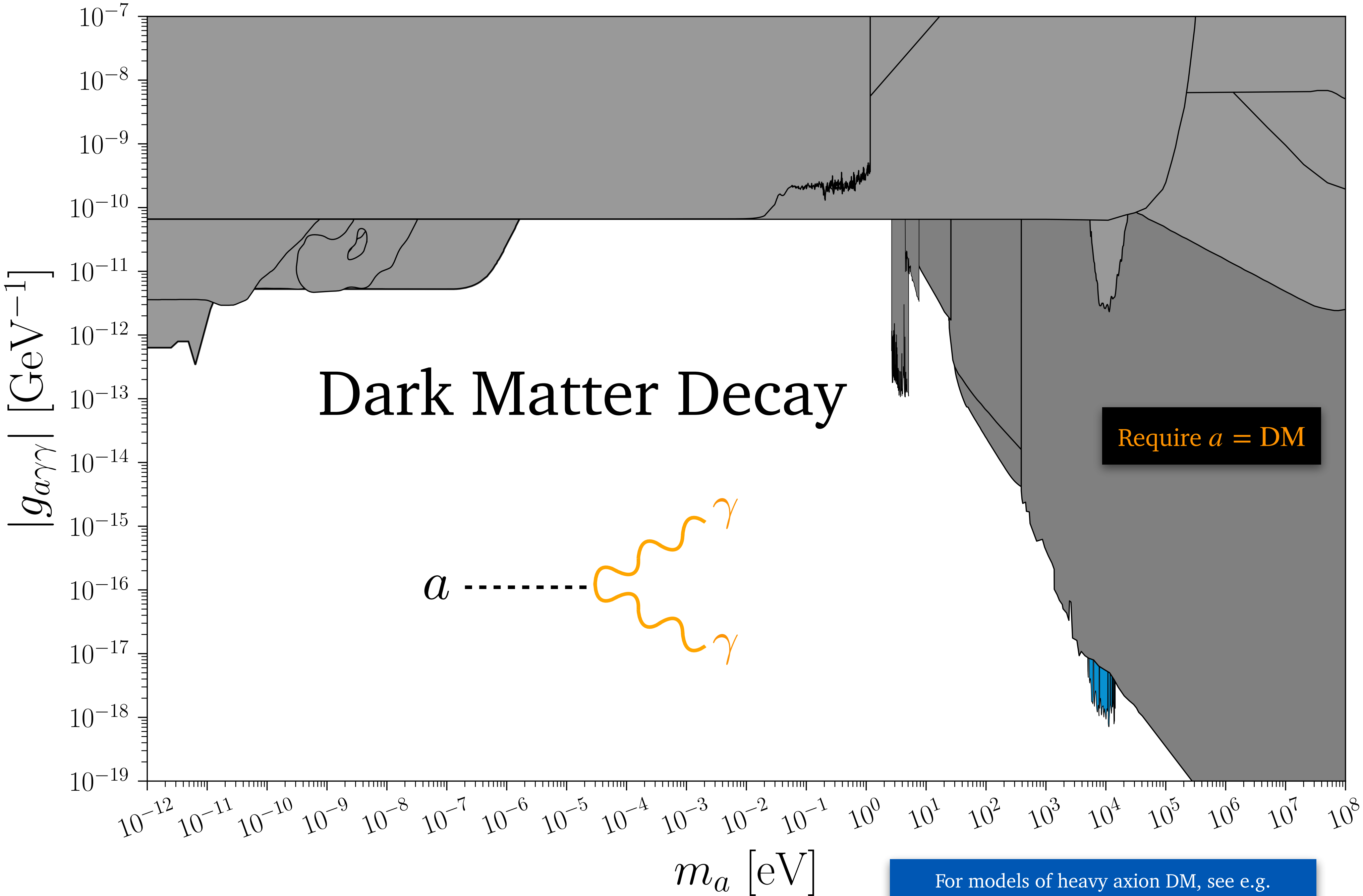

For models of heavy axion DM, see e.g. [Foster, Kumar, Safdi, Soreq 2208.10504], [Panci, Redigolo, Schwetz, Ziegler 2209.03371]

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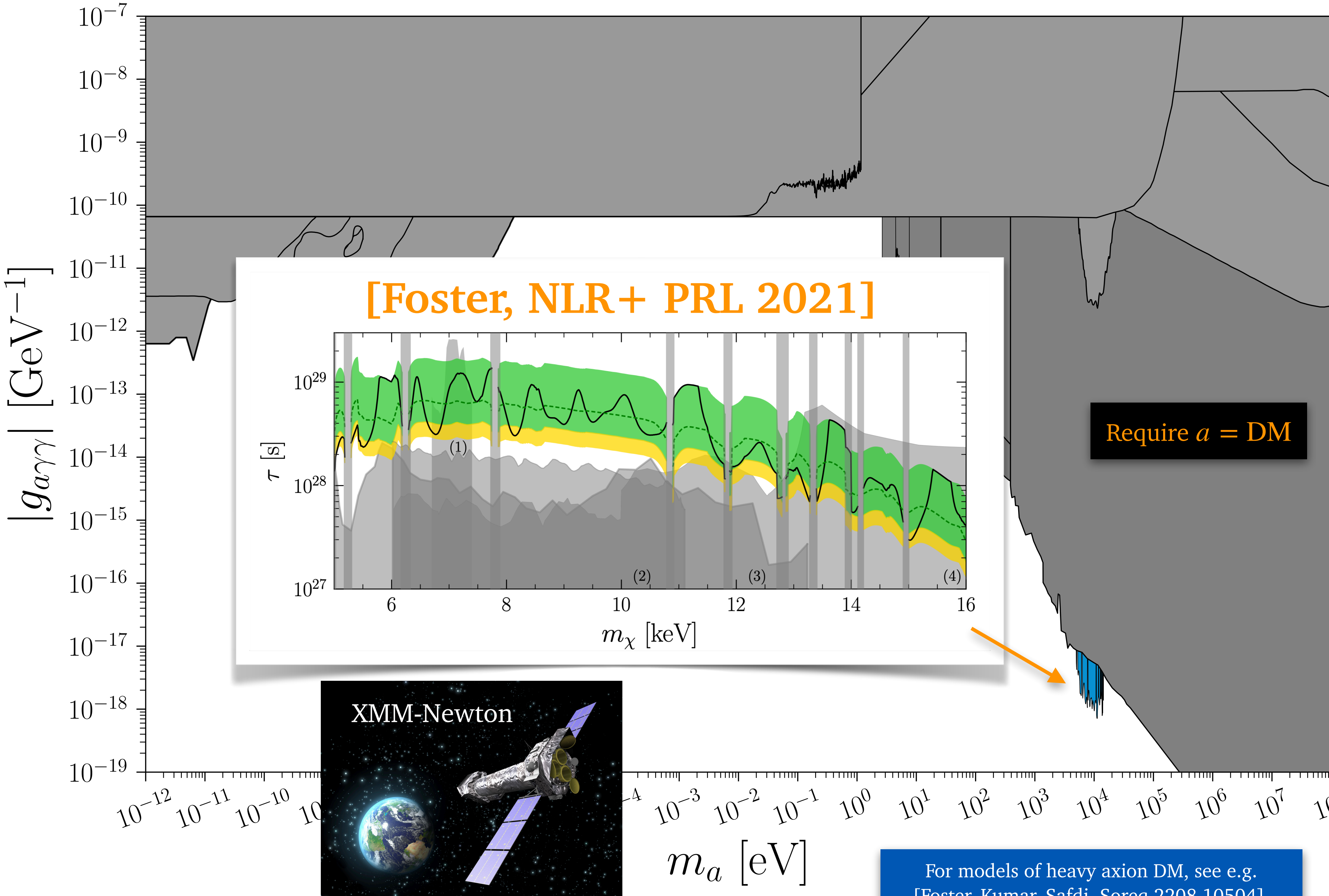

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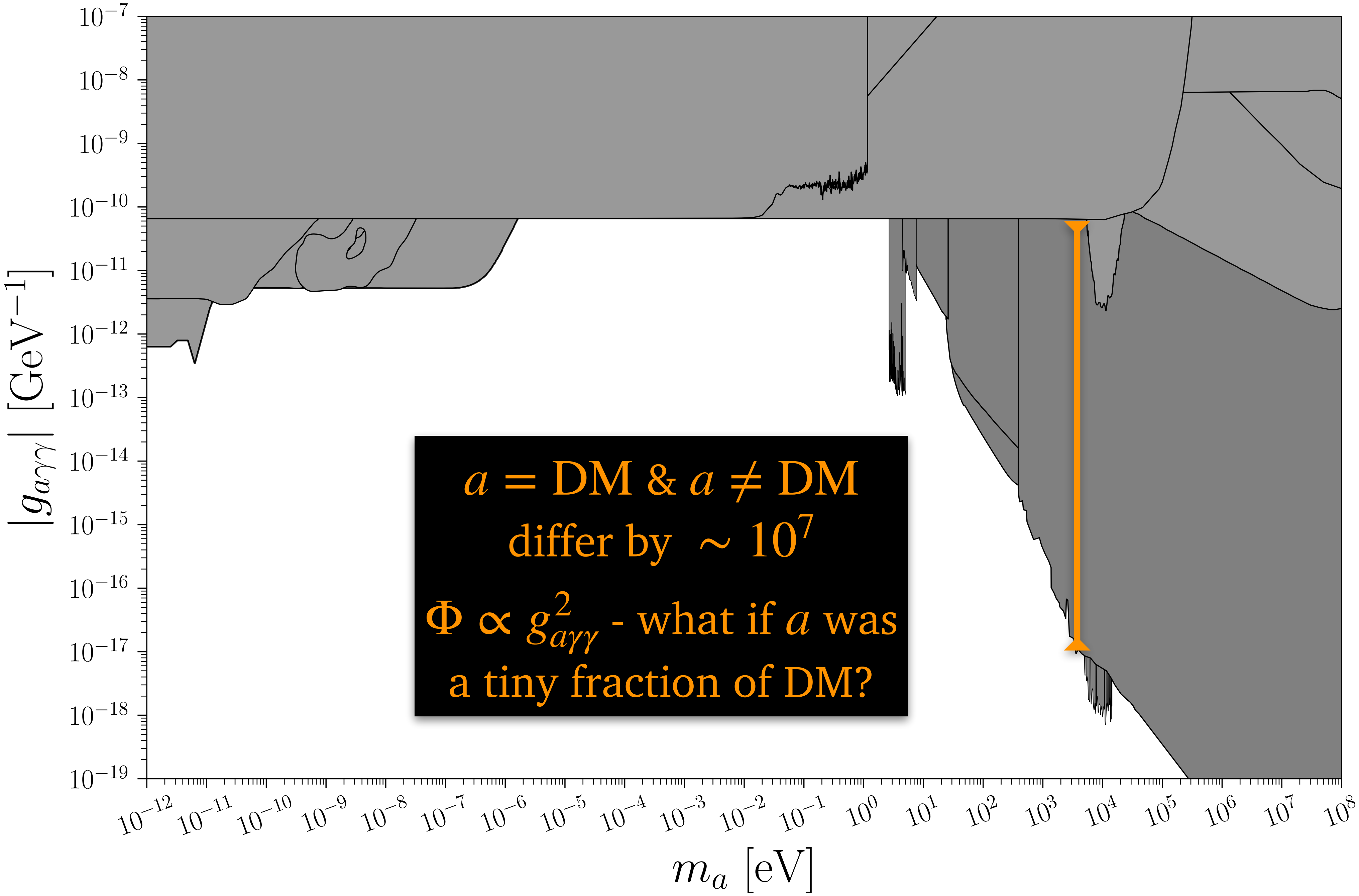

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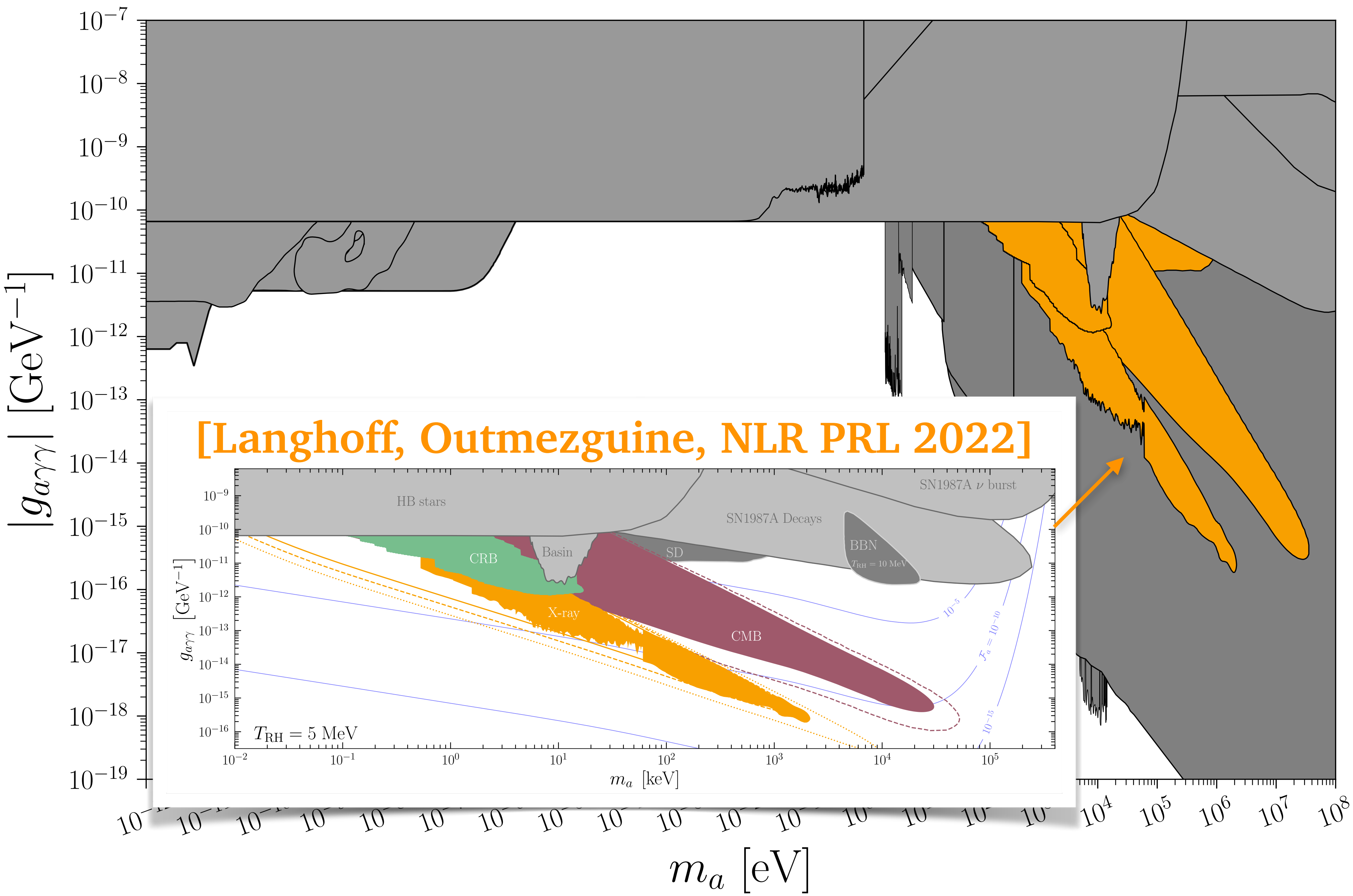

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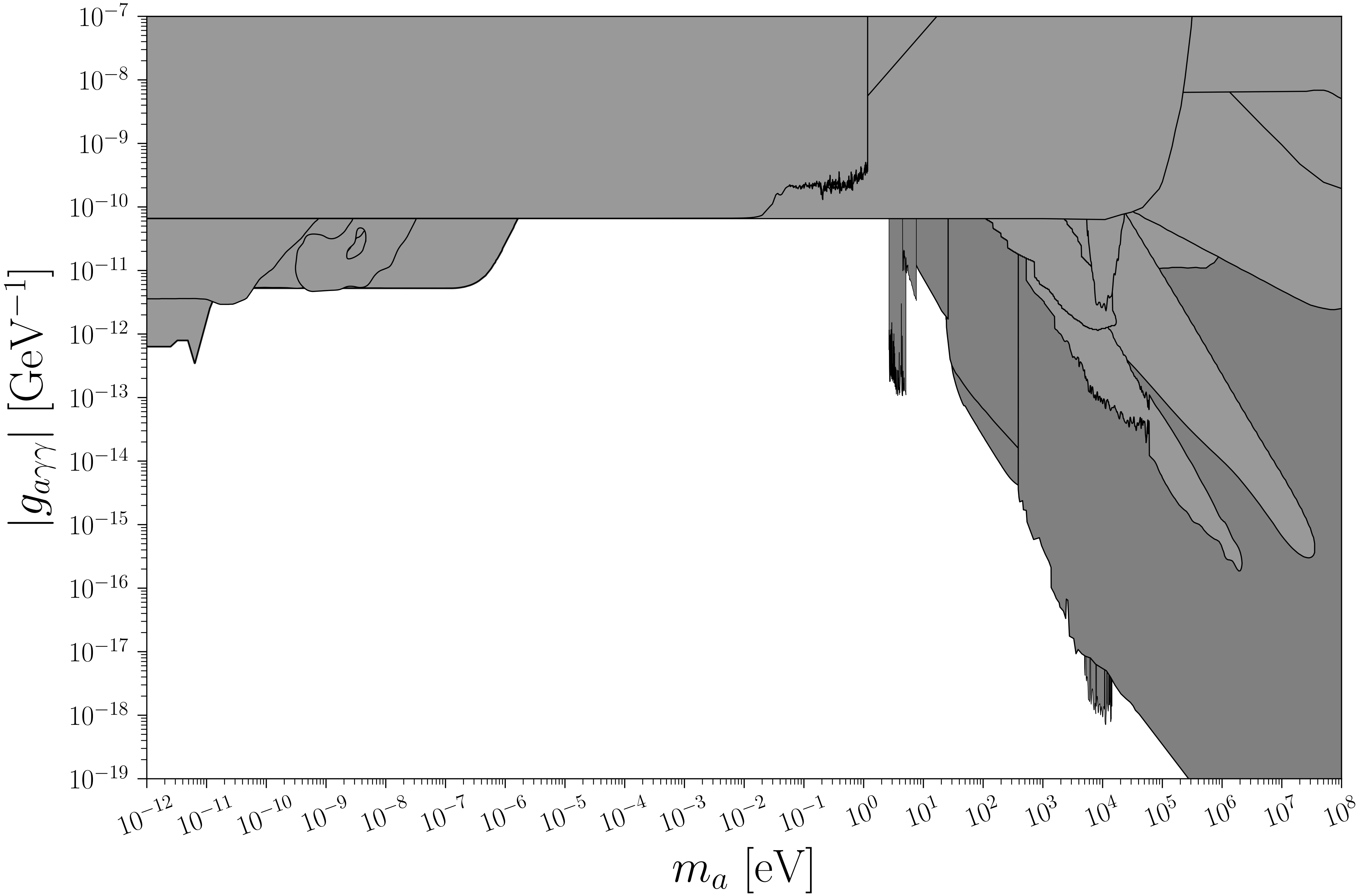

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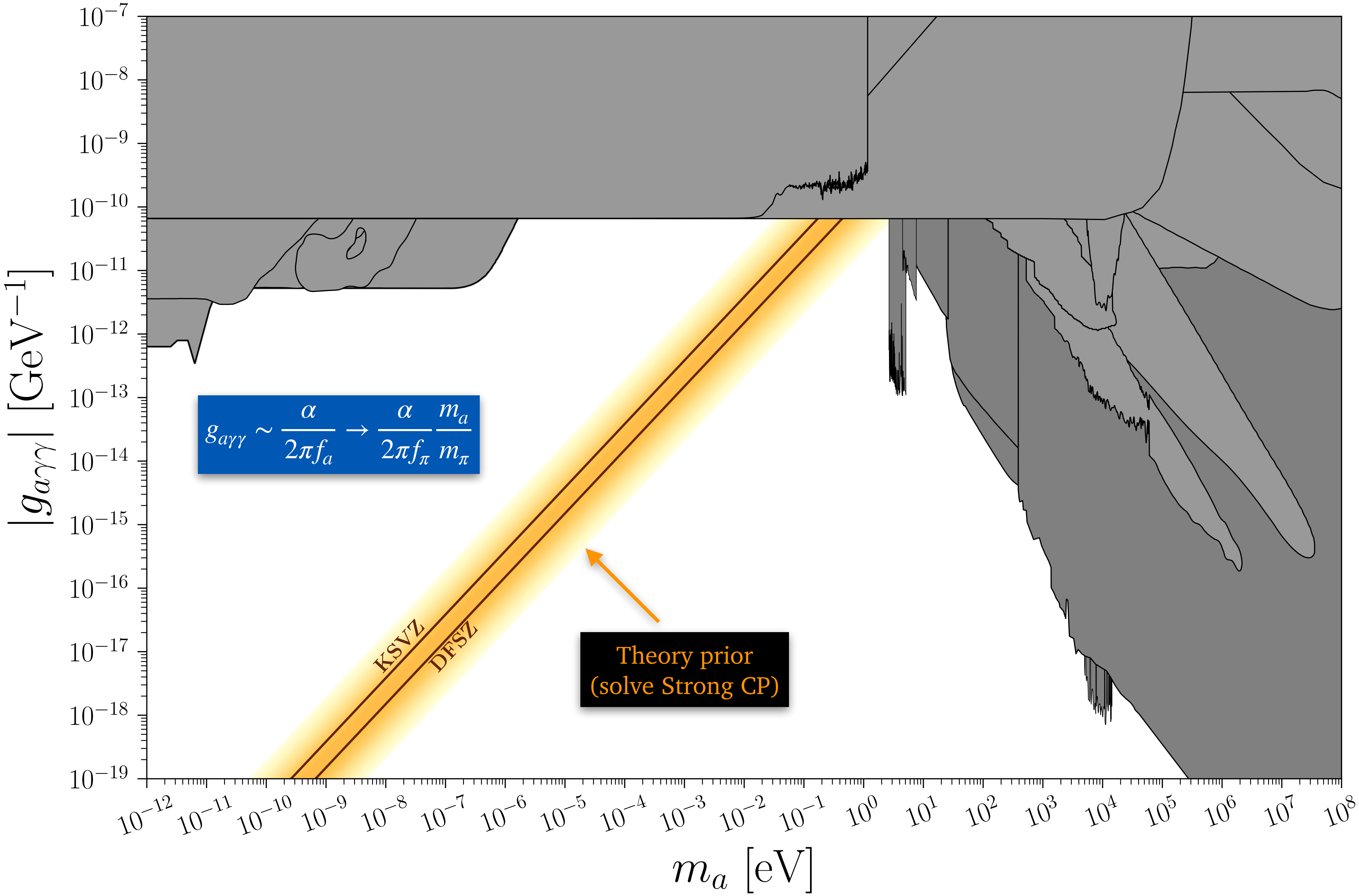

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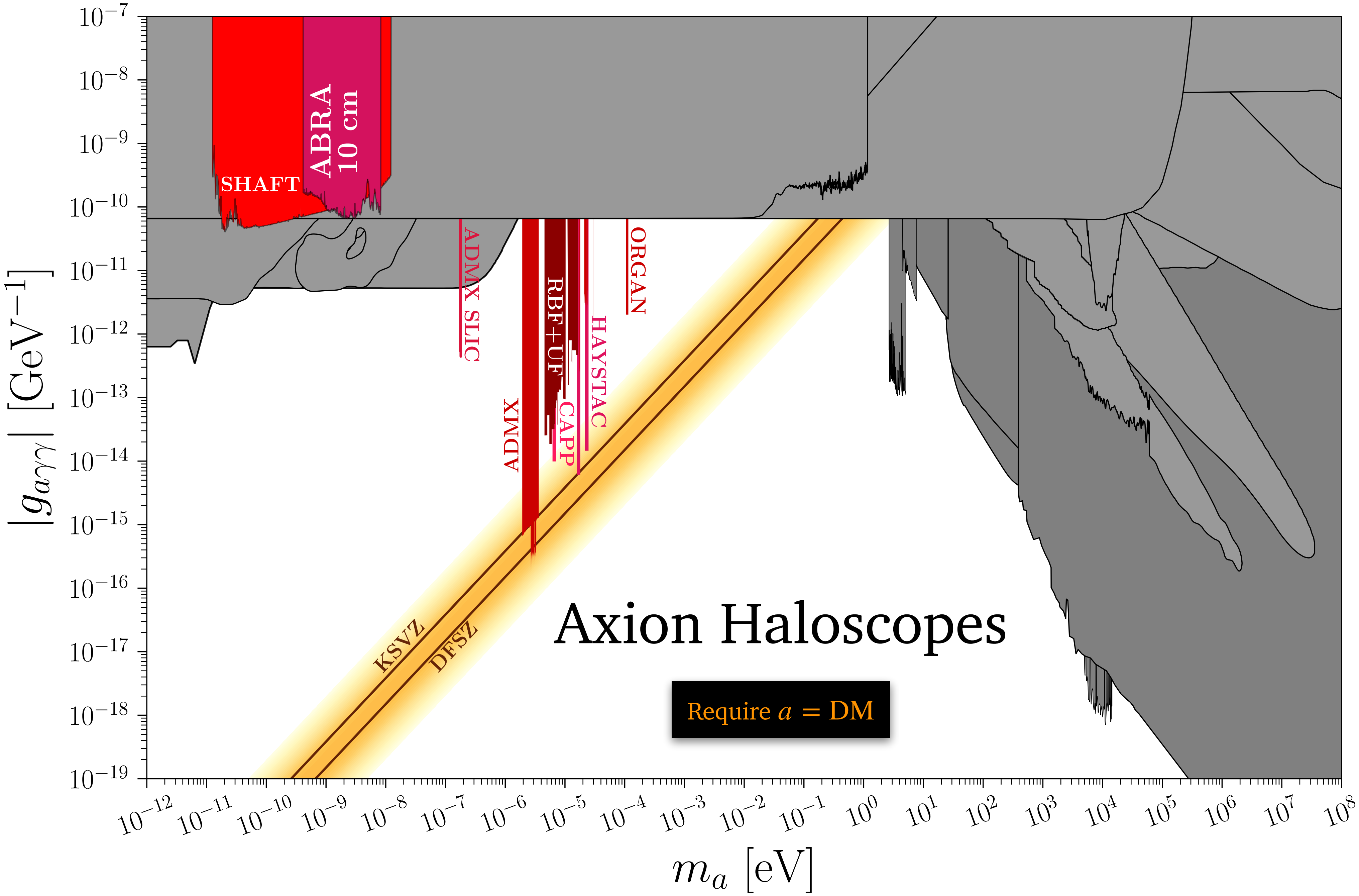

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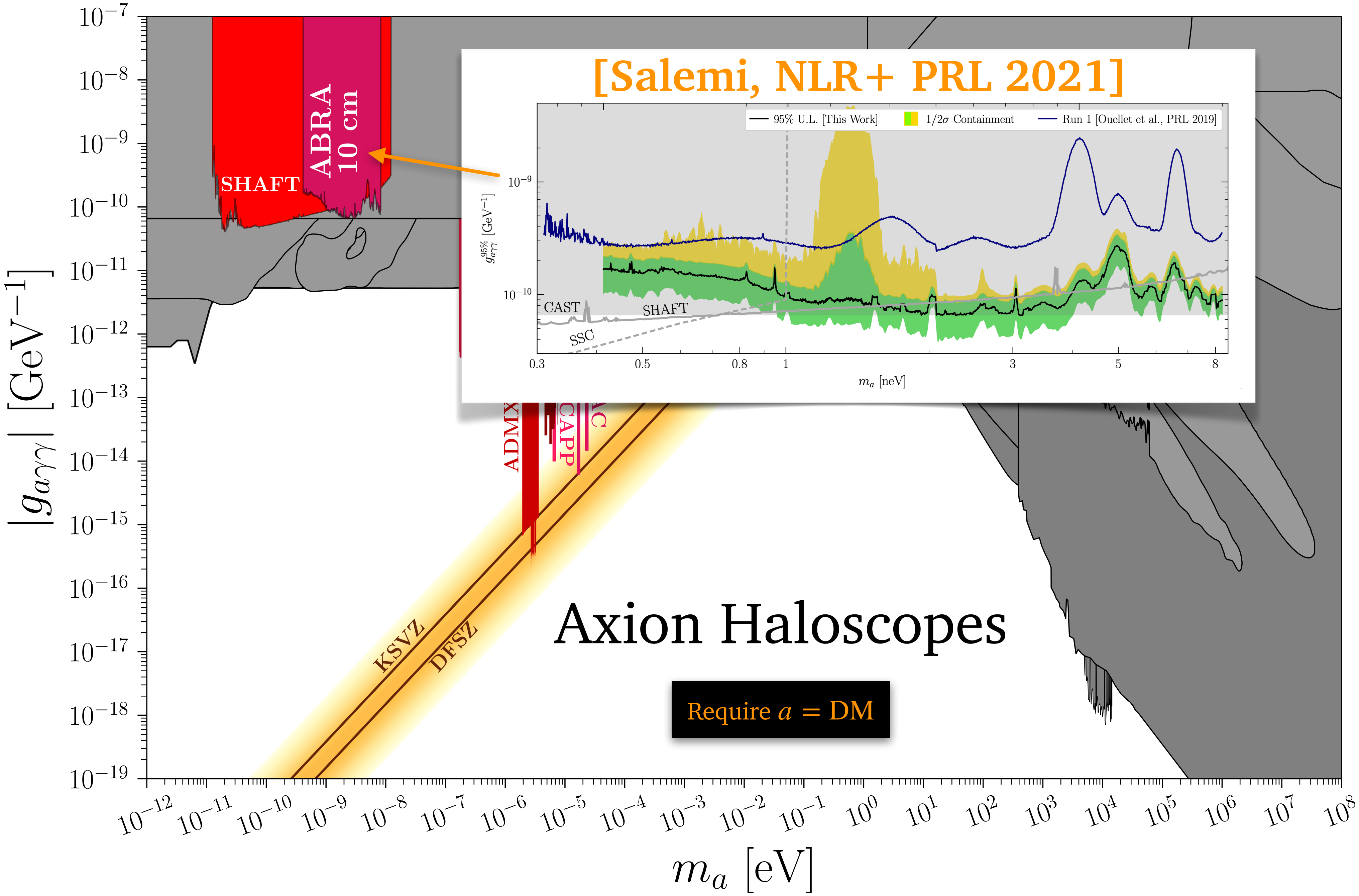

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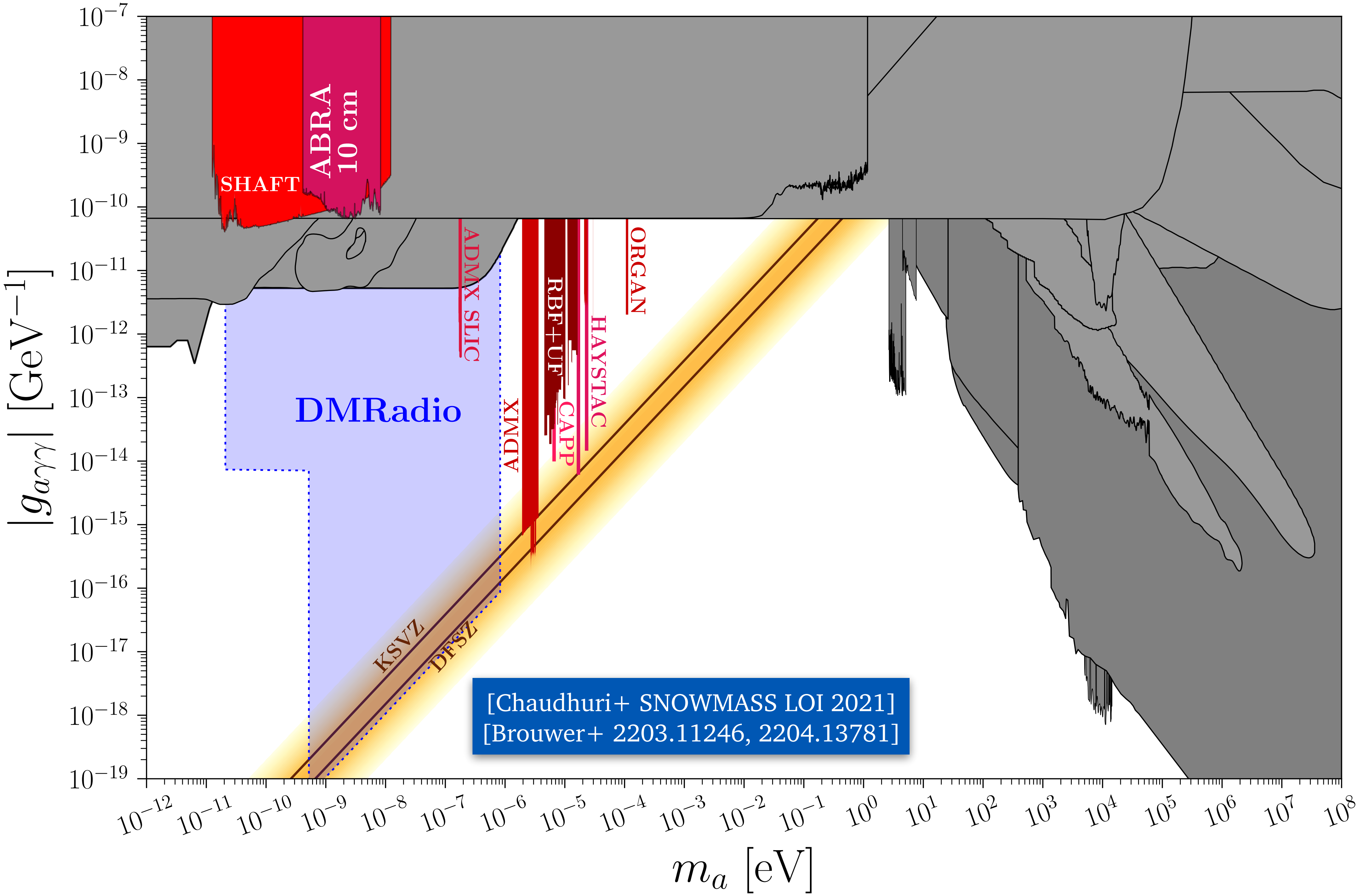

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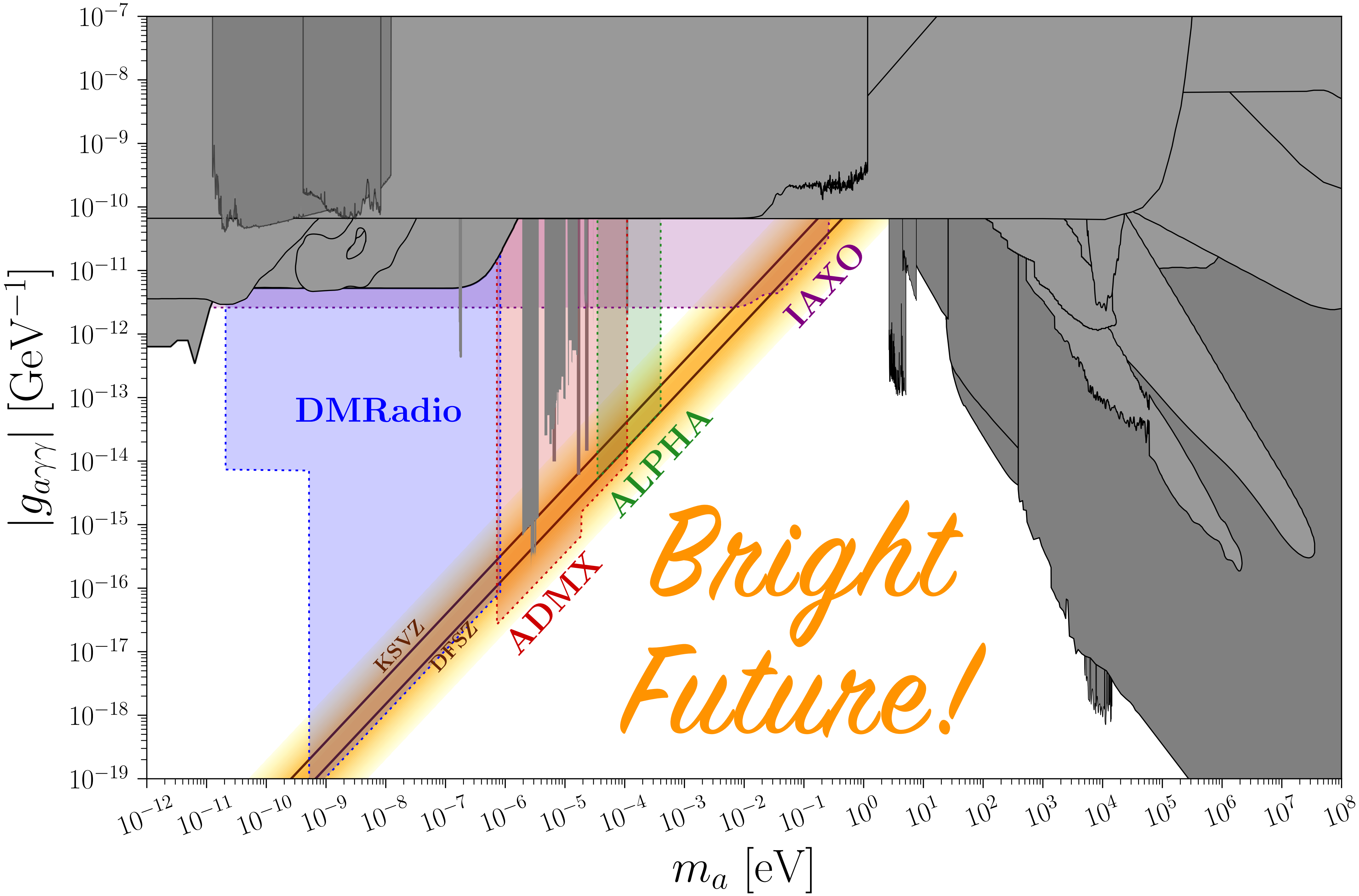


Partial summary
[O'Hare github]

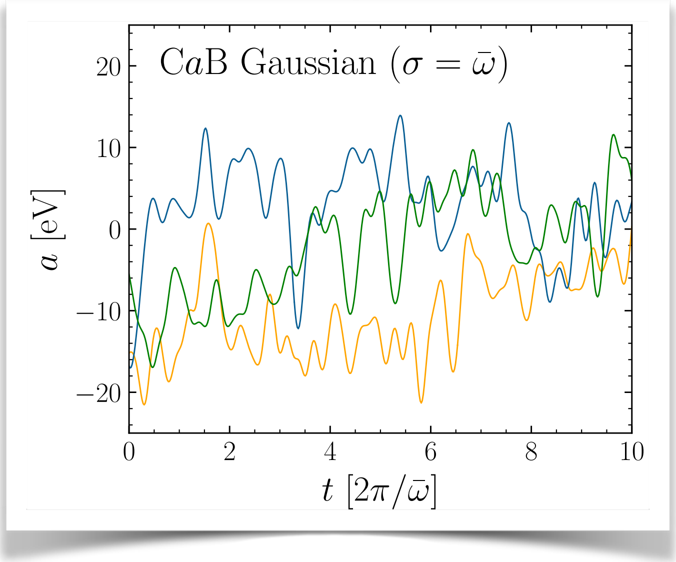
Outline

What else might we see with these instruments?

Outline

1. Could non-dark matter axions leave a signal?

The Cosmic Axion Background



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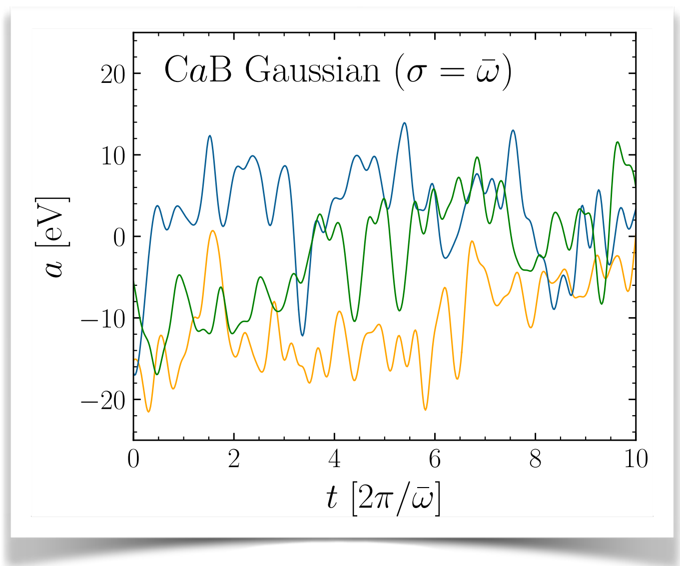
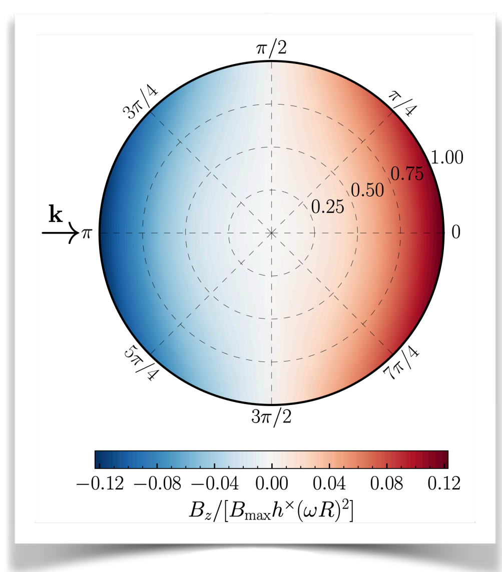


2. What other passing waves could a haloscope detect?

High-Frequency Gravitational Waves



WARMUP

How to Discover Dark Matter

Axion Dark Matter

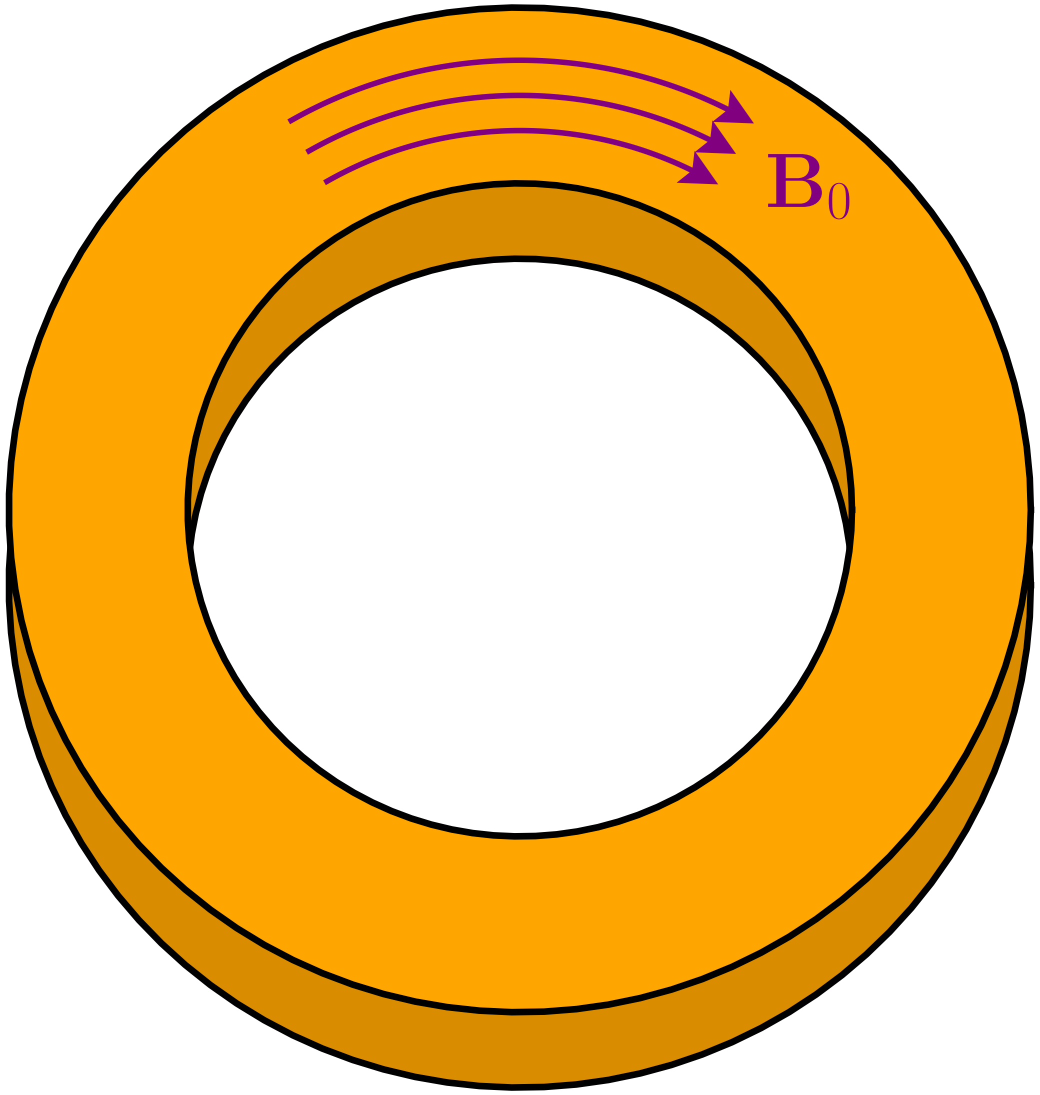
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a (F\tilde{F})$$

Introduces a new source for E&M fields

$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J} + g_{a\gamma\gamma} \mathbf{B} \partial_t a$$

Not shown: $\rho_{\text{eff}} = -\, g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$ and $\mathbf{J}_{\text{eff}} = -\, g_{a\gamma\gamma} \mathbf{E} \times \nabla a$

Detection with a Toroidal Magnet



DMRadio-50L: toroidal geometry [Kahn, Safdi, Thaler 2016]
DMRadio-m3: solenoidal geometry [Sikivie, Sullivan, Tanner 2014]

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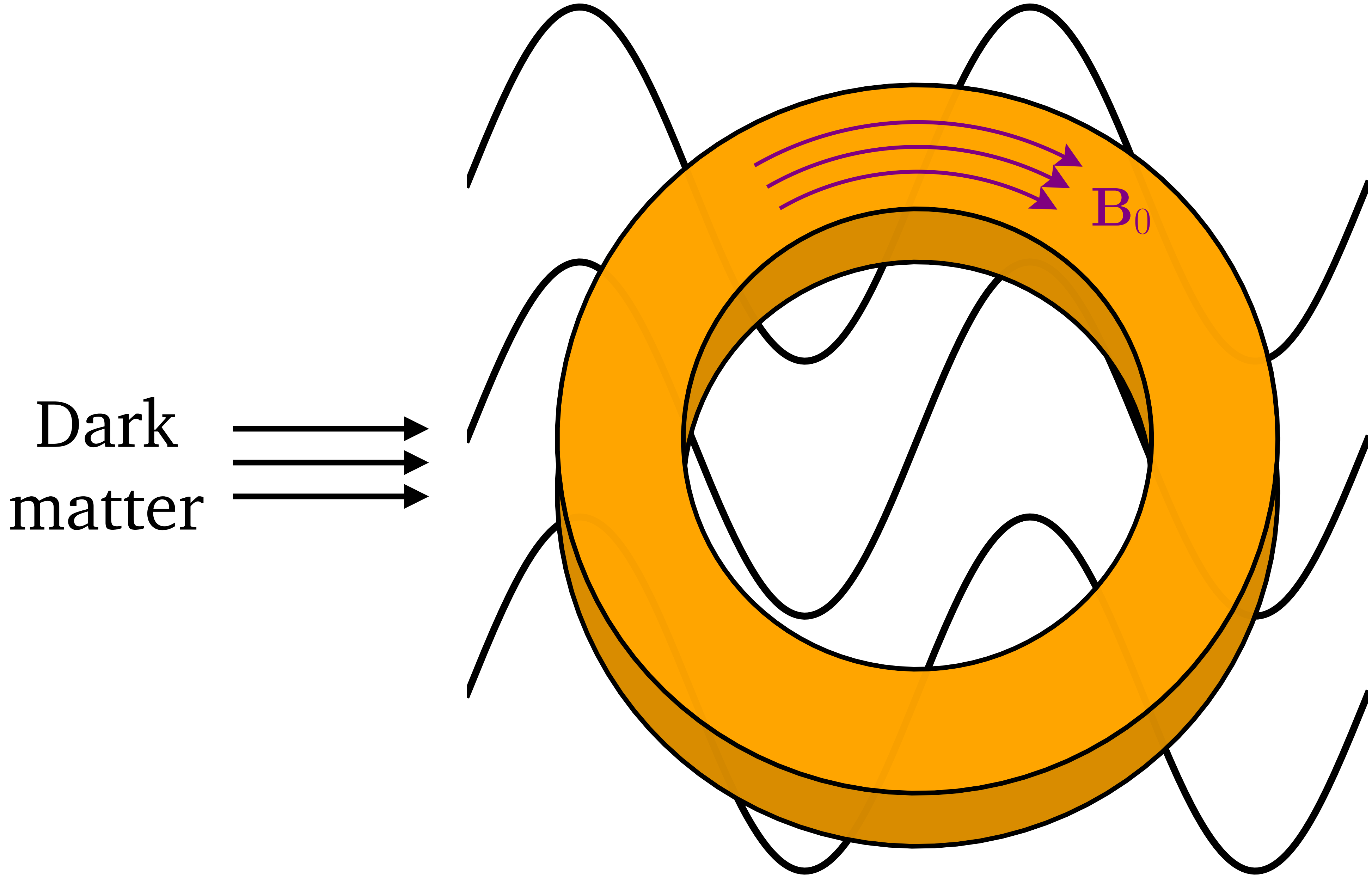

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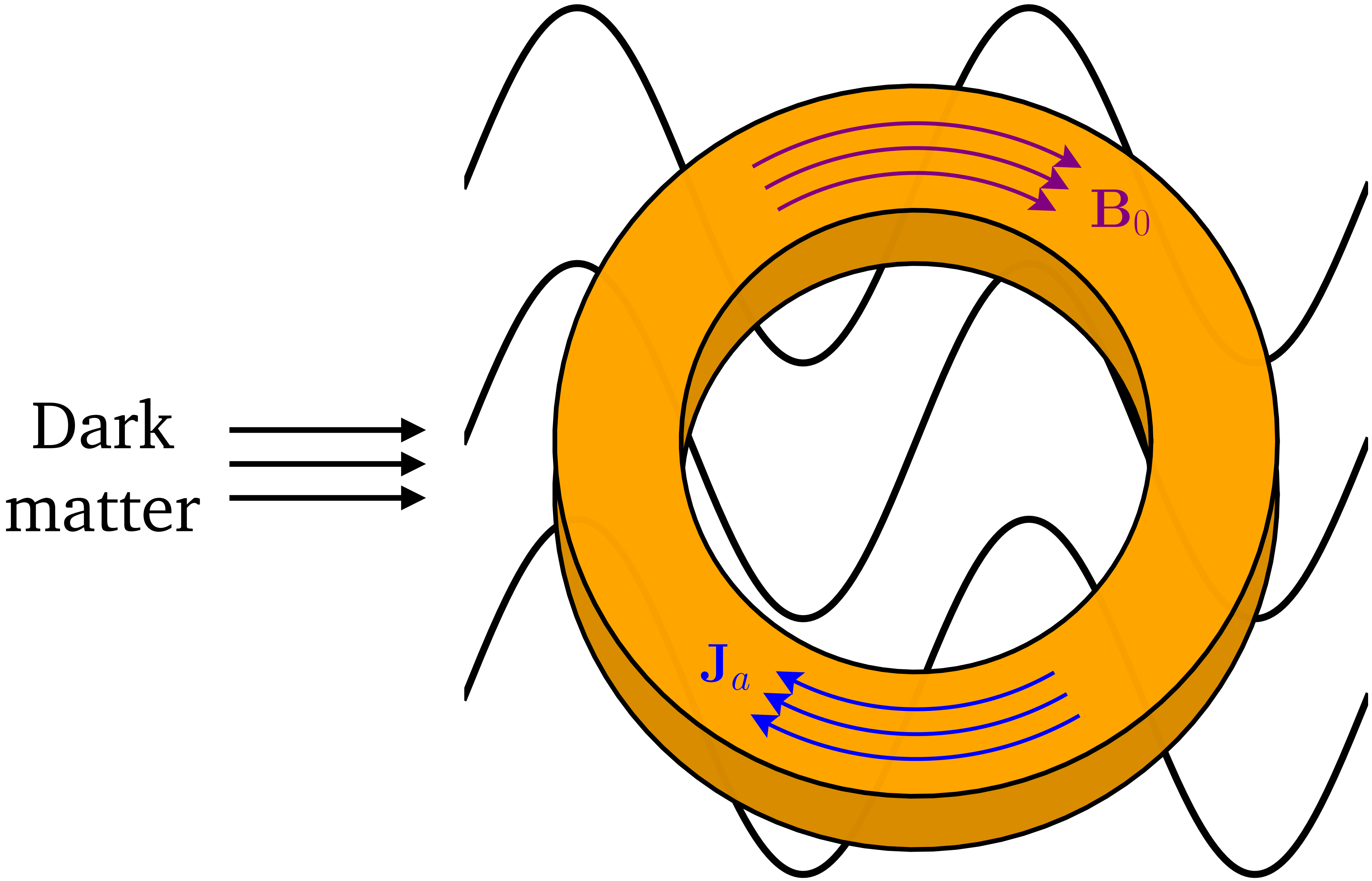

$$\mathbf{J}_a = g_{a\gamma\gamma}(\partial_t a)\mathbf{B}_0$$

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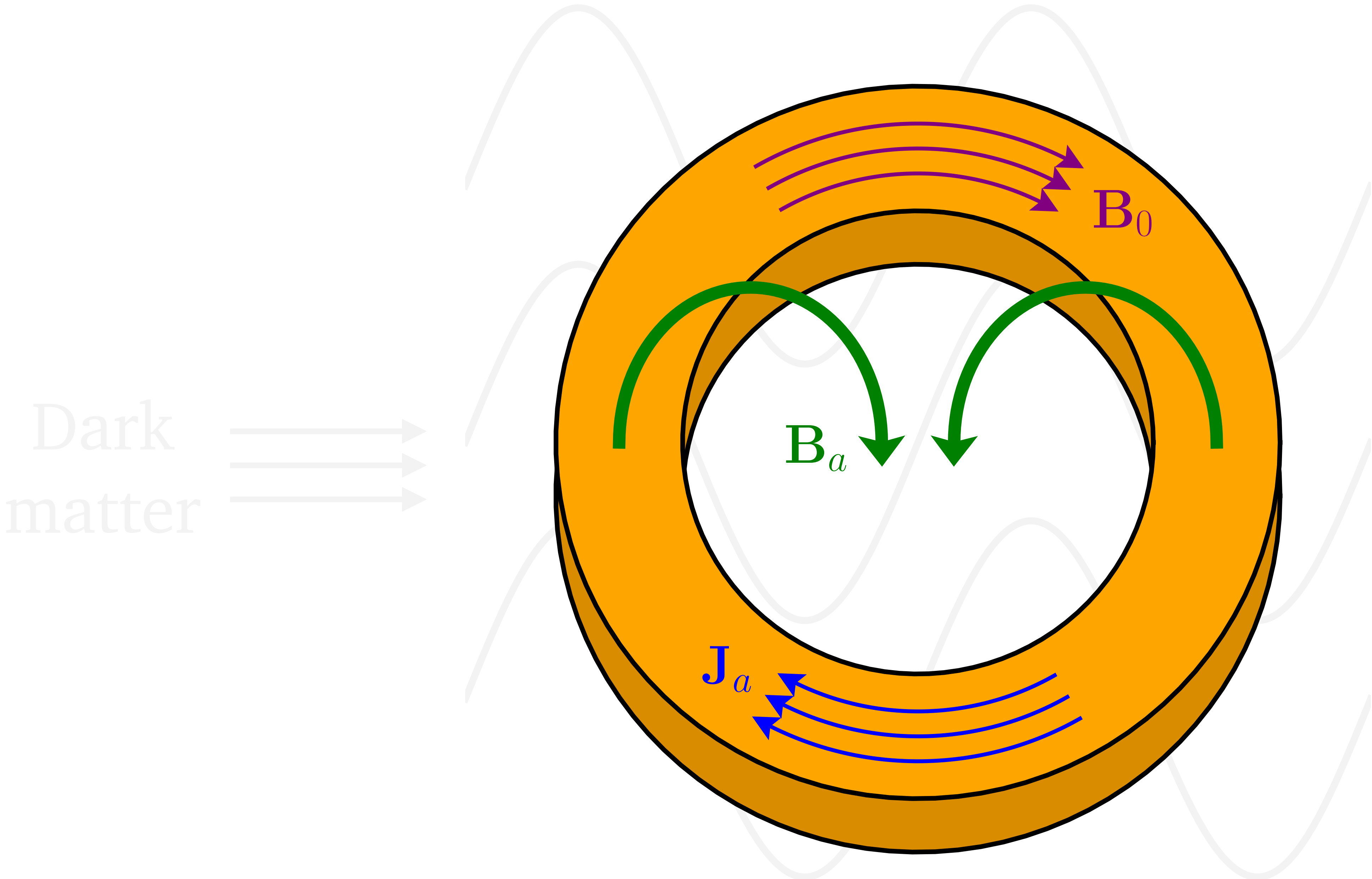

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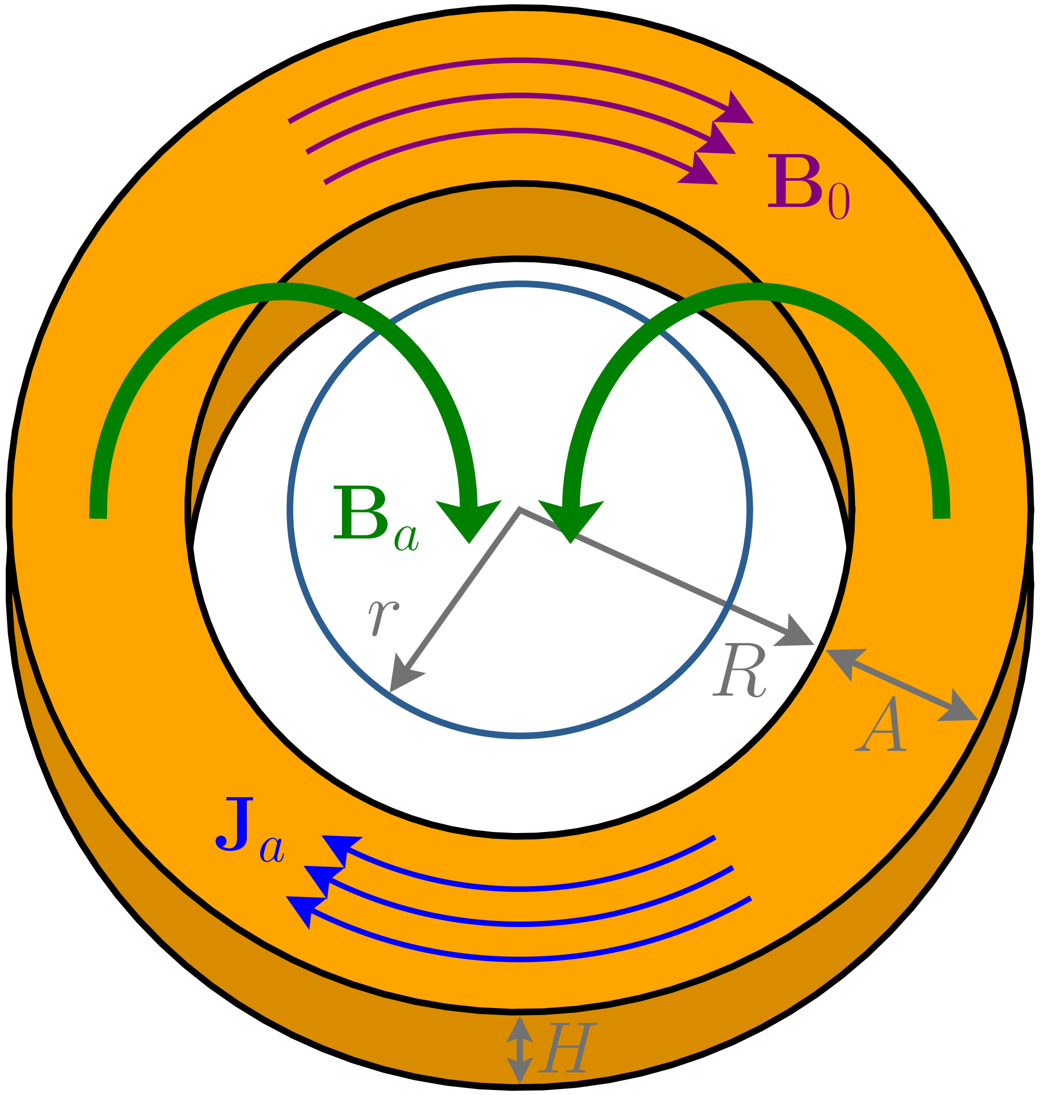

$$\Phi_a(t) \simeq g_{a\gamma\gamma}(\partial_t a) B_0 \pi r^2 R \ln(1 + A/R) \sim g_{a\gamma\gamma}(\partial_t a) B_0 V$$

$H \gg R + A$

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Cosmic Axion Background

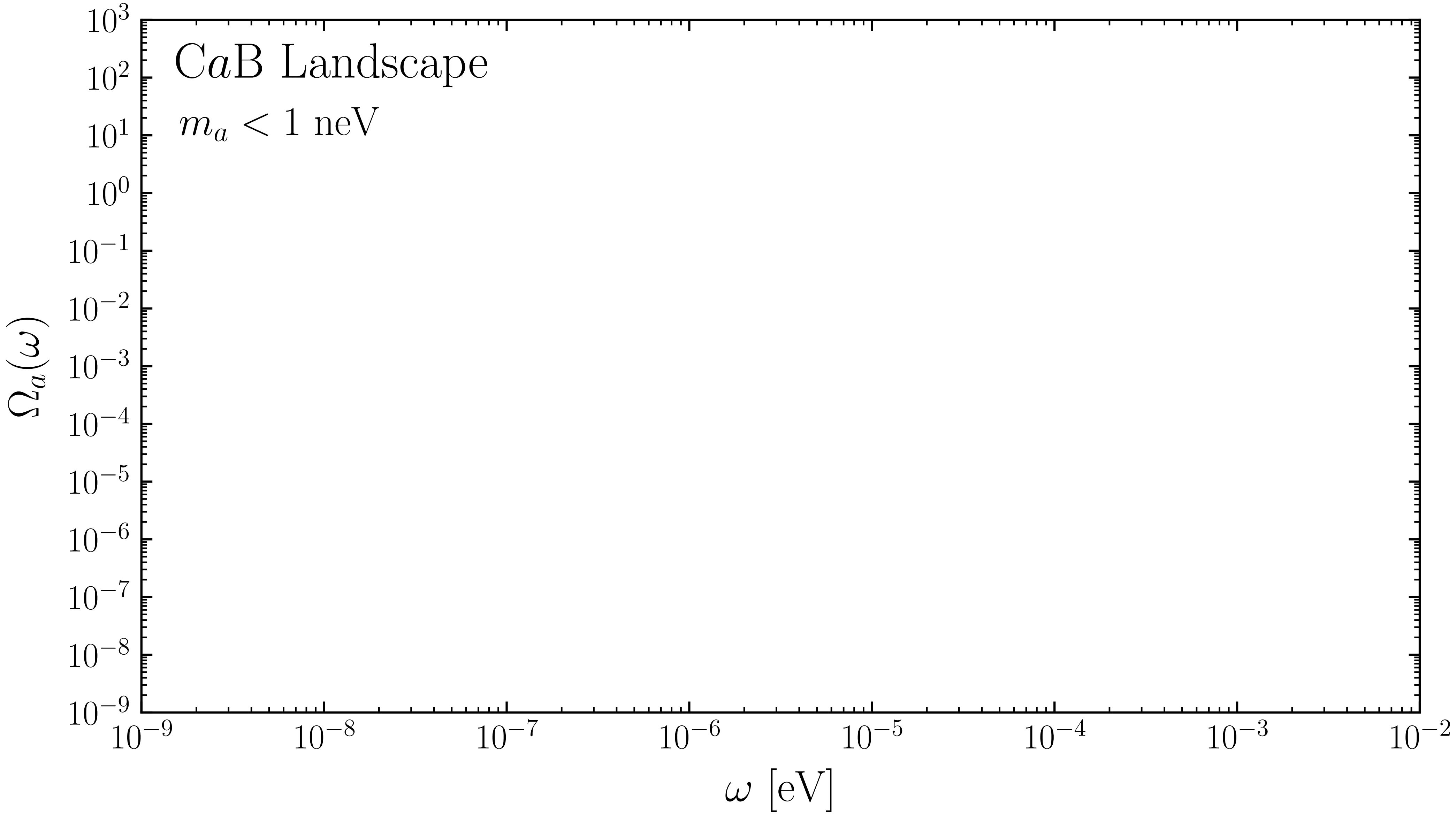
[Dror, Murayama, NLR PRD 2021]

The Cosmic Axion Background

Can we detect relativistic axions that are a relic of the early Universe?

[Dror, Murayama, NLR 2021]

Landscape



[Dror, Murayama, NLR 2021]

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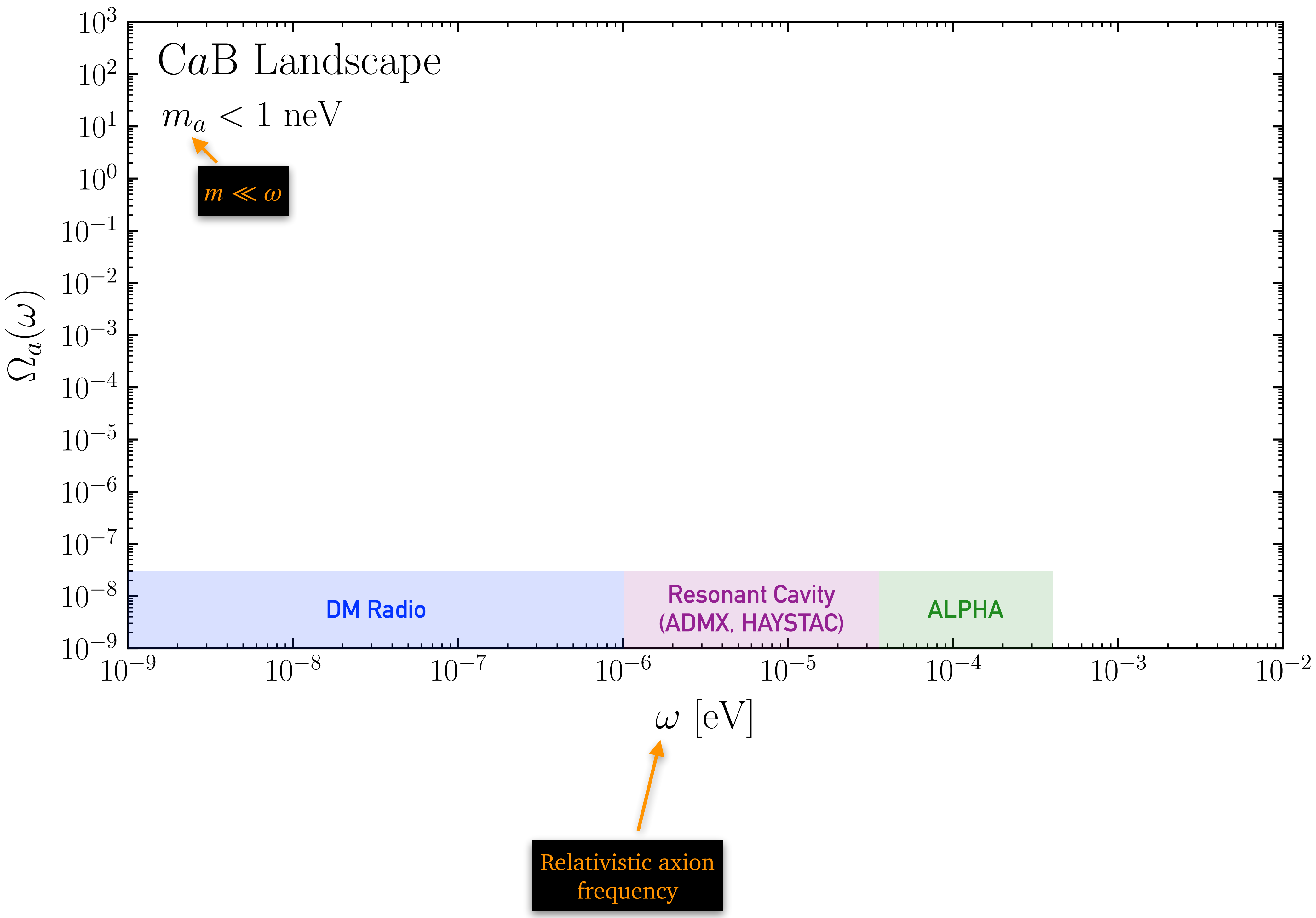

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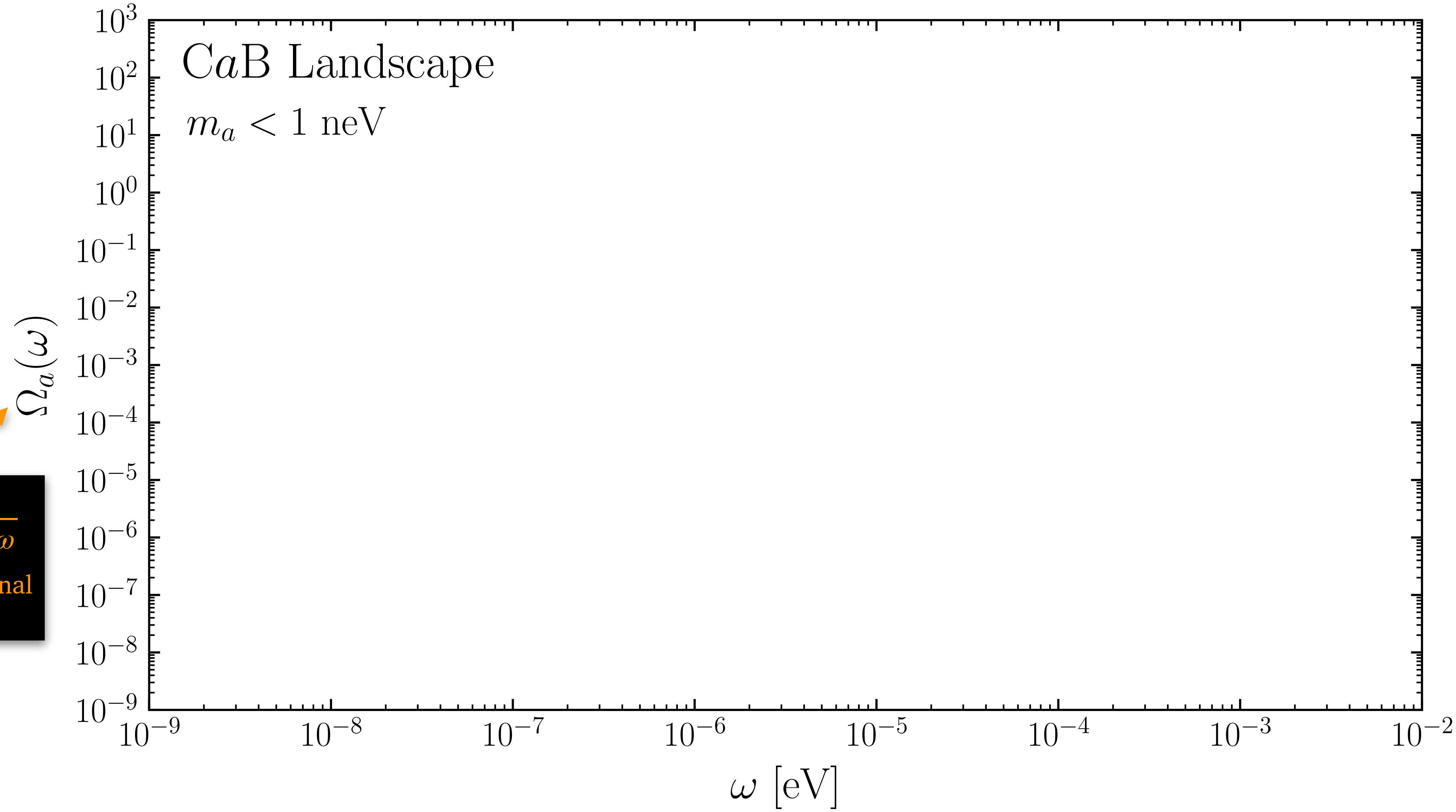

$$= \frac{1}{\rho_c} \frac{d\rho_a}{d \ln \omega}$$

cf. gravitational waves

Where is $g_{a\gamma\gamma}$?
Coming in a few slides

[Dror, Murayama, NLR 2021]

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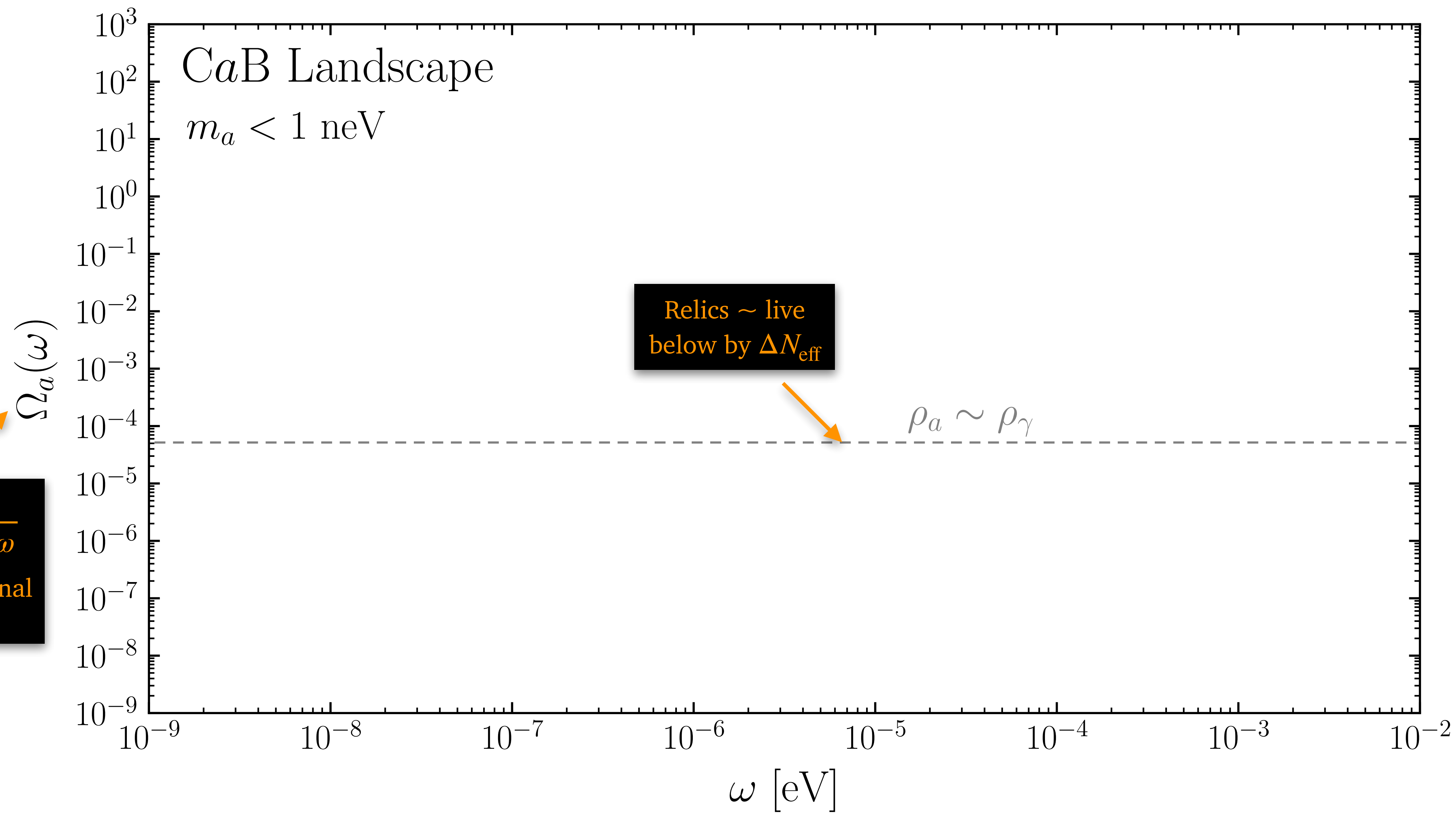

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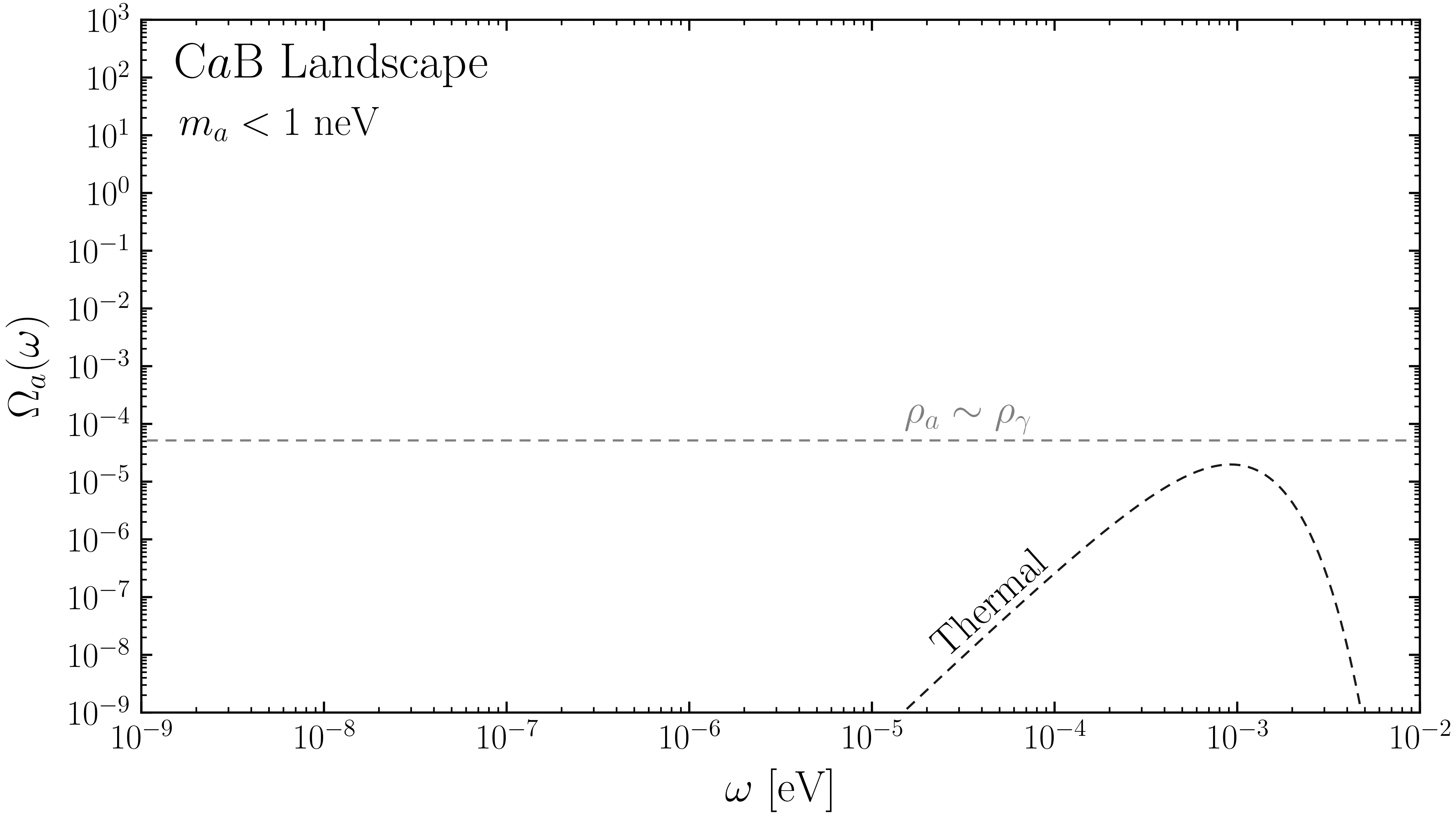

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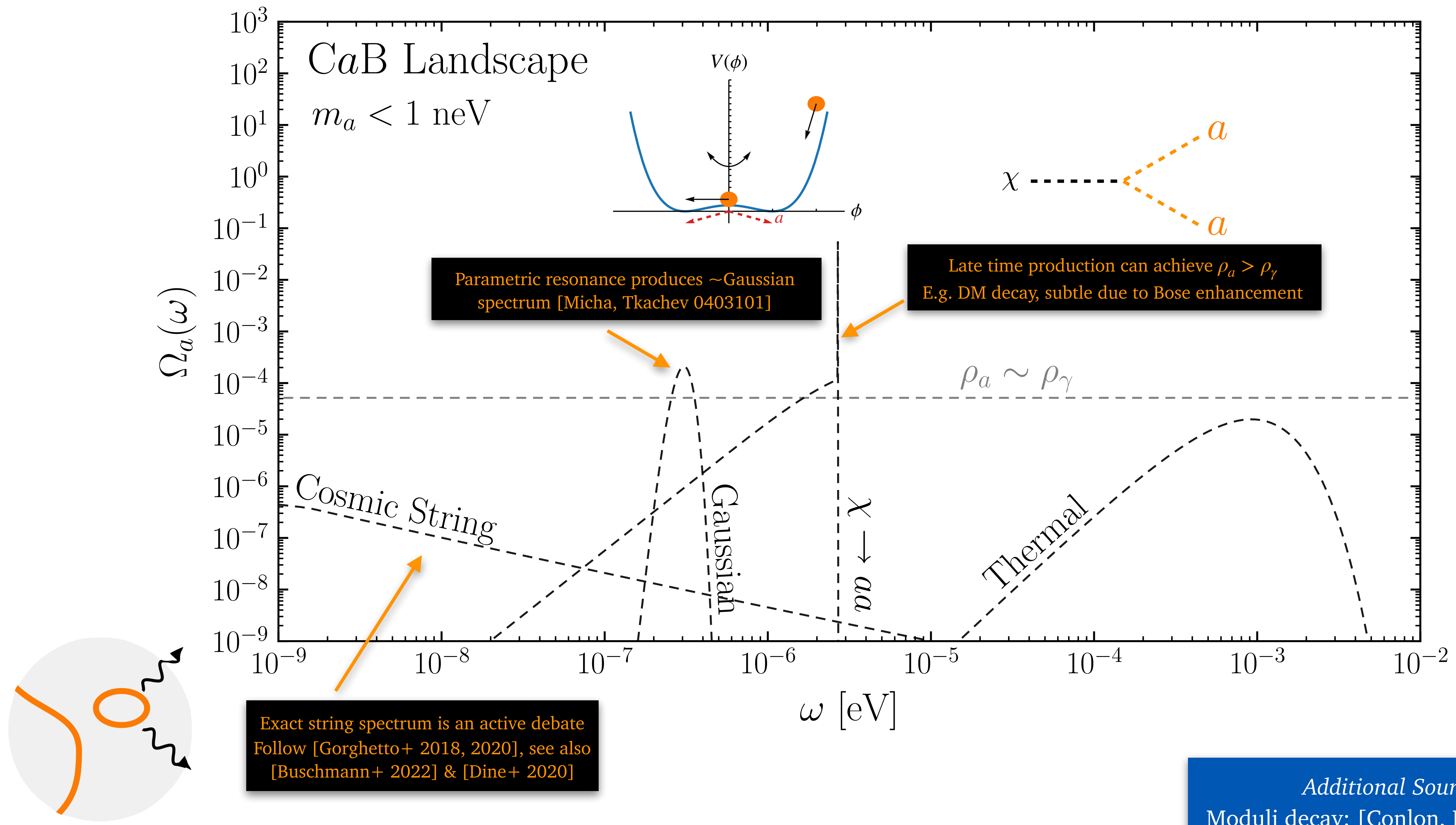
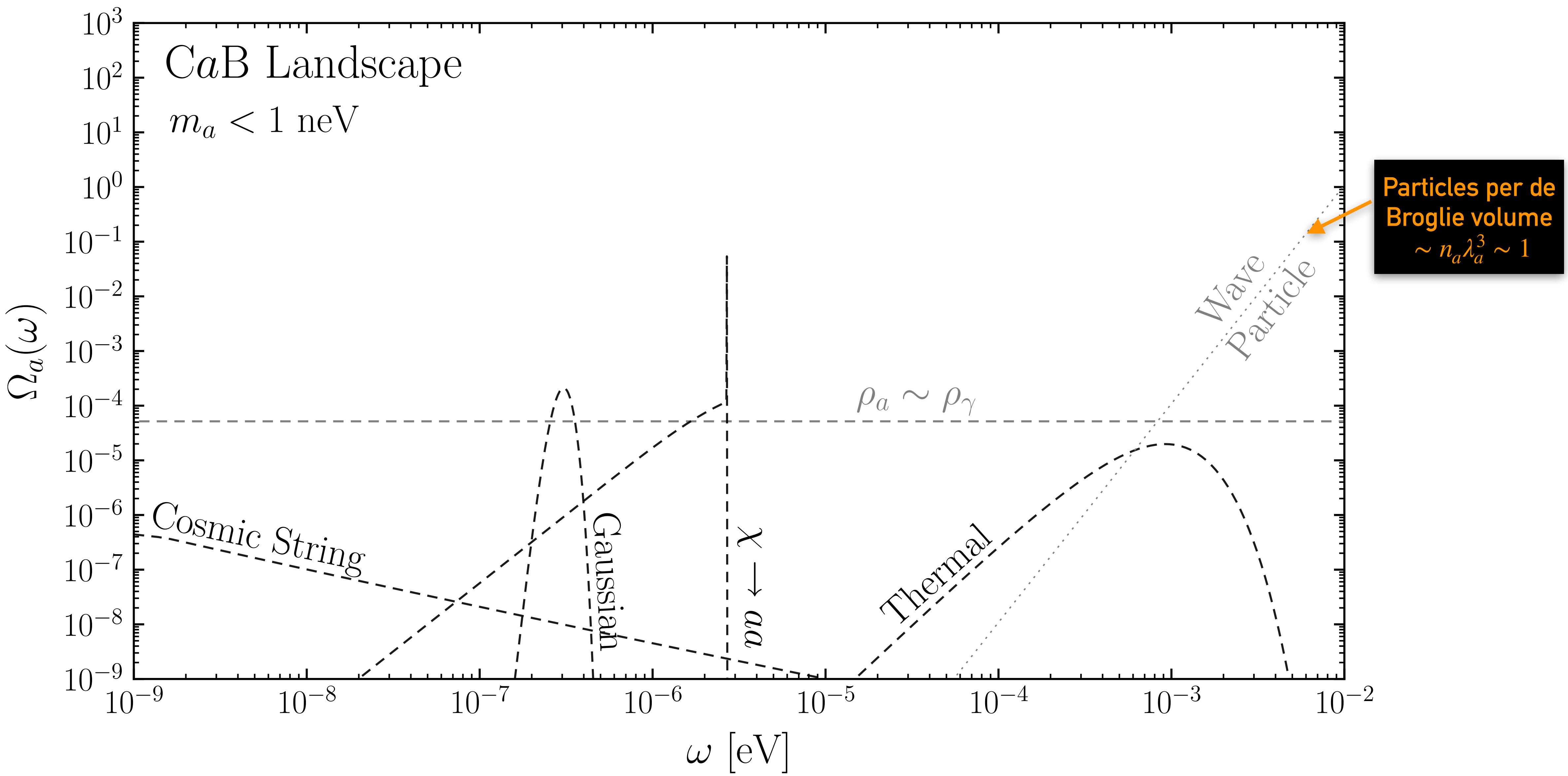


Additional Sources
Moduli decay: [Conlon, Marsh 2013]
Bosenova: [Eby+ 2022]

[Dror, Murayama, NLR 2021]

Landscape



[Dror, Murayama, NLR 2021]

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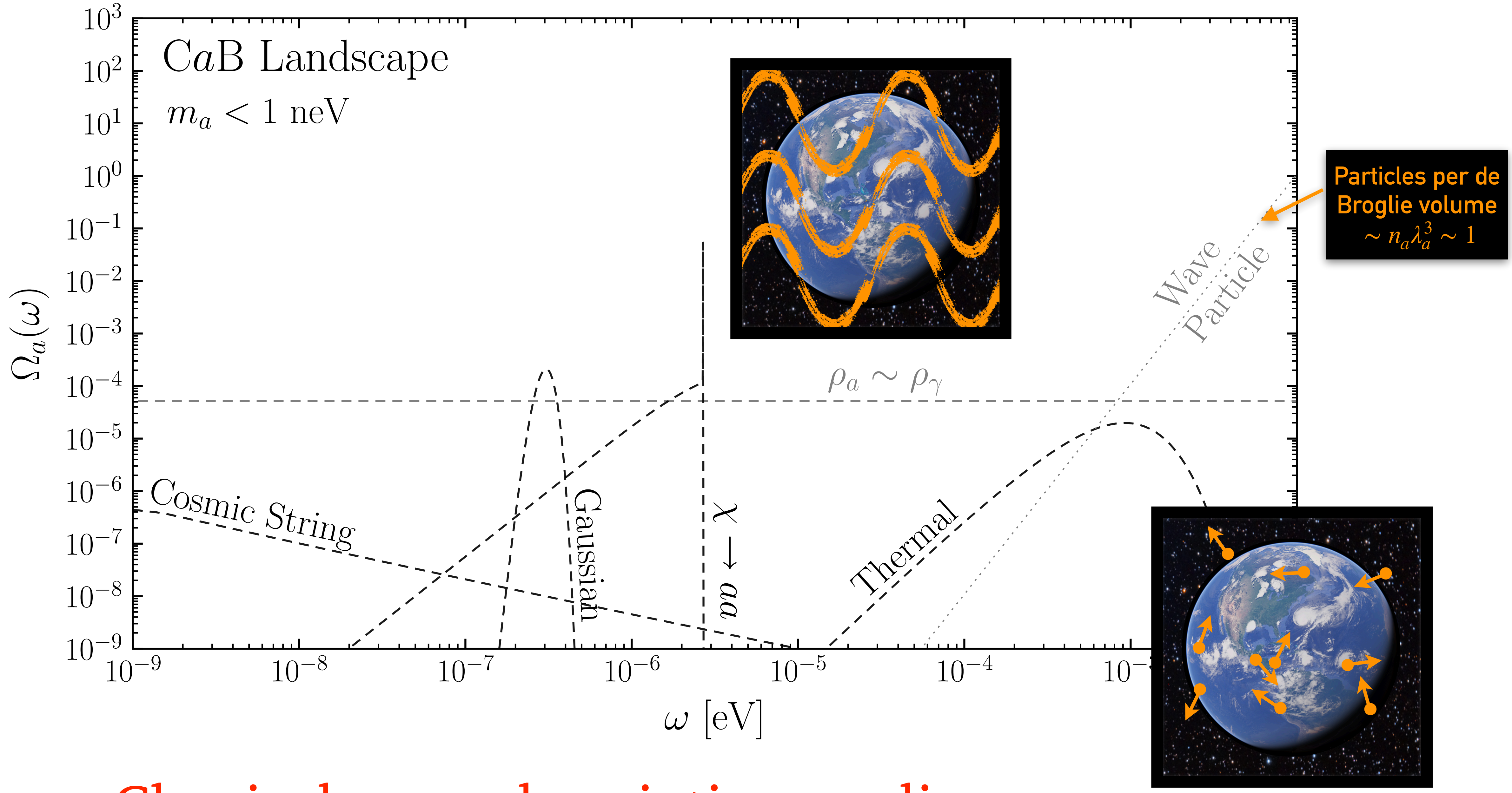

Classical wave description applies

[Dror, Murayama, NLR 2021]

Rough Sensitivity

$$a(t) \sim \sum_i \cos(\omega_i t + \phi_i)$$

Sampled from $p(\omega)$, the pdf of frequency/energy

Random phase

[Dror, Murayama, NLR 2021]

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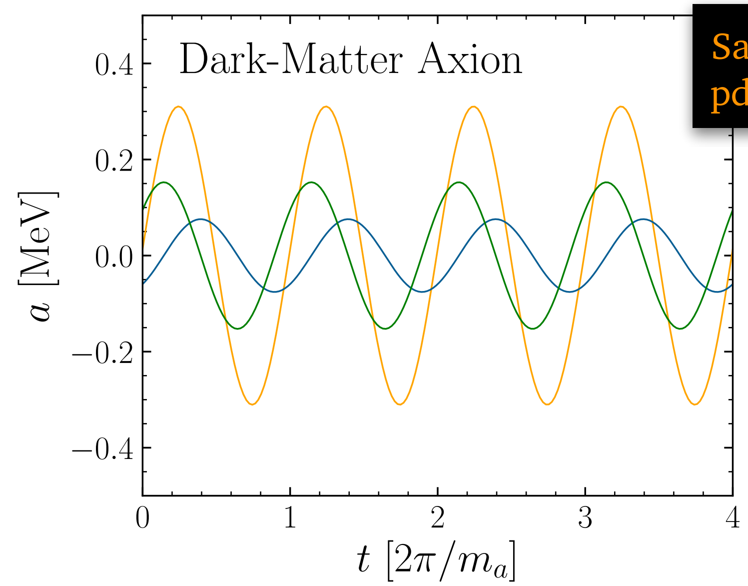
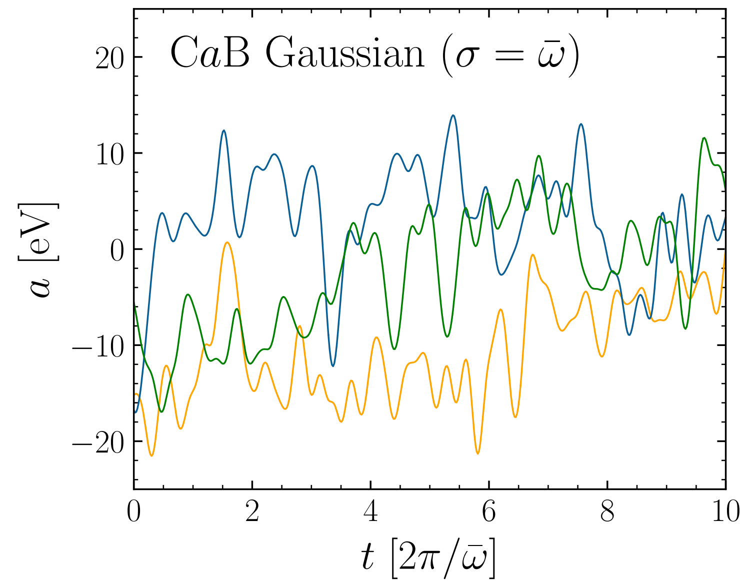
Dark Matter



CaB



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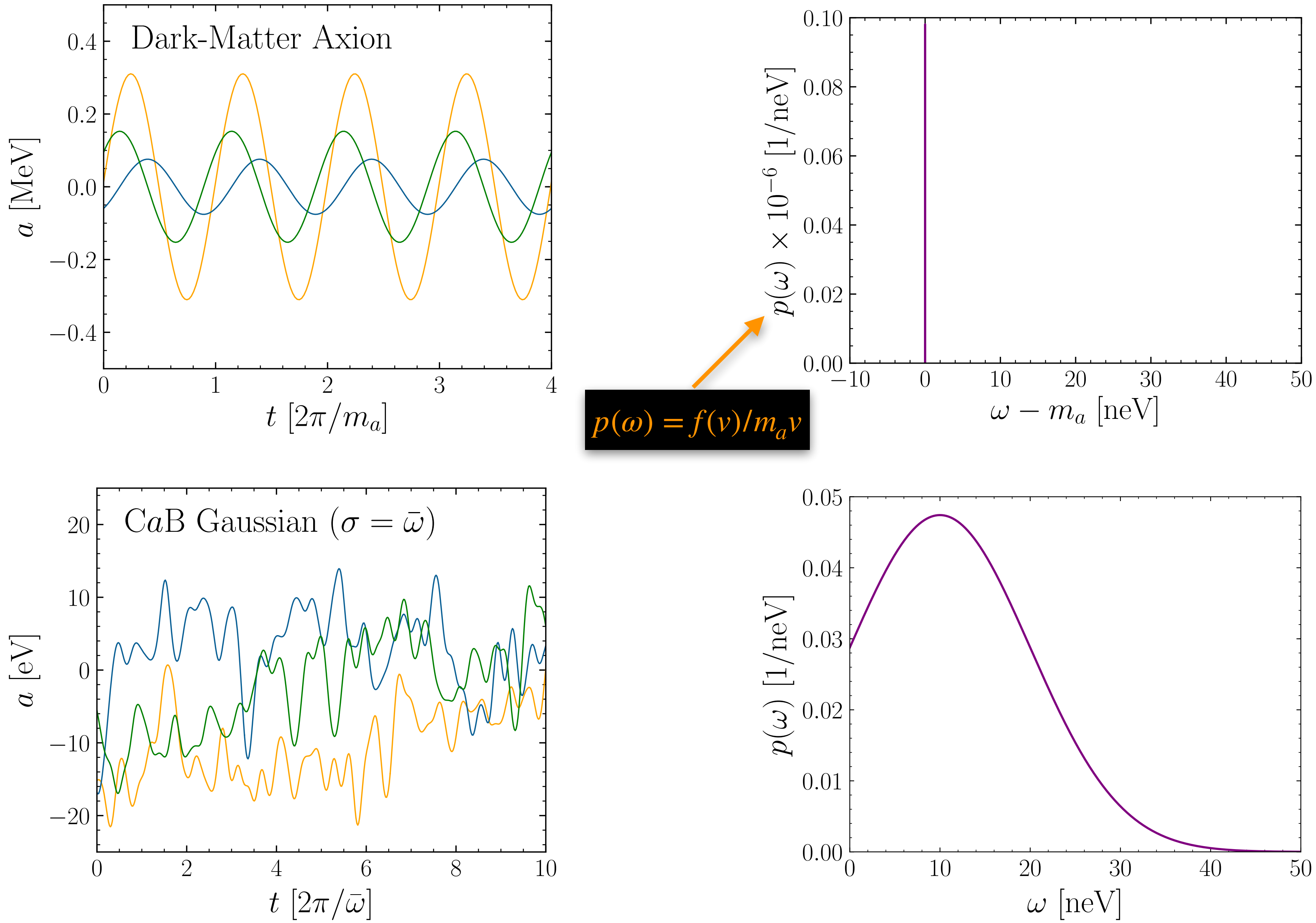

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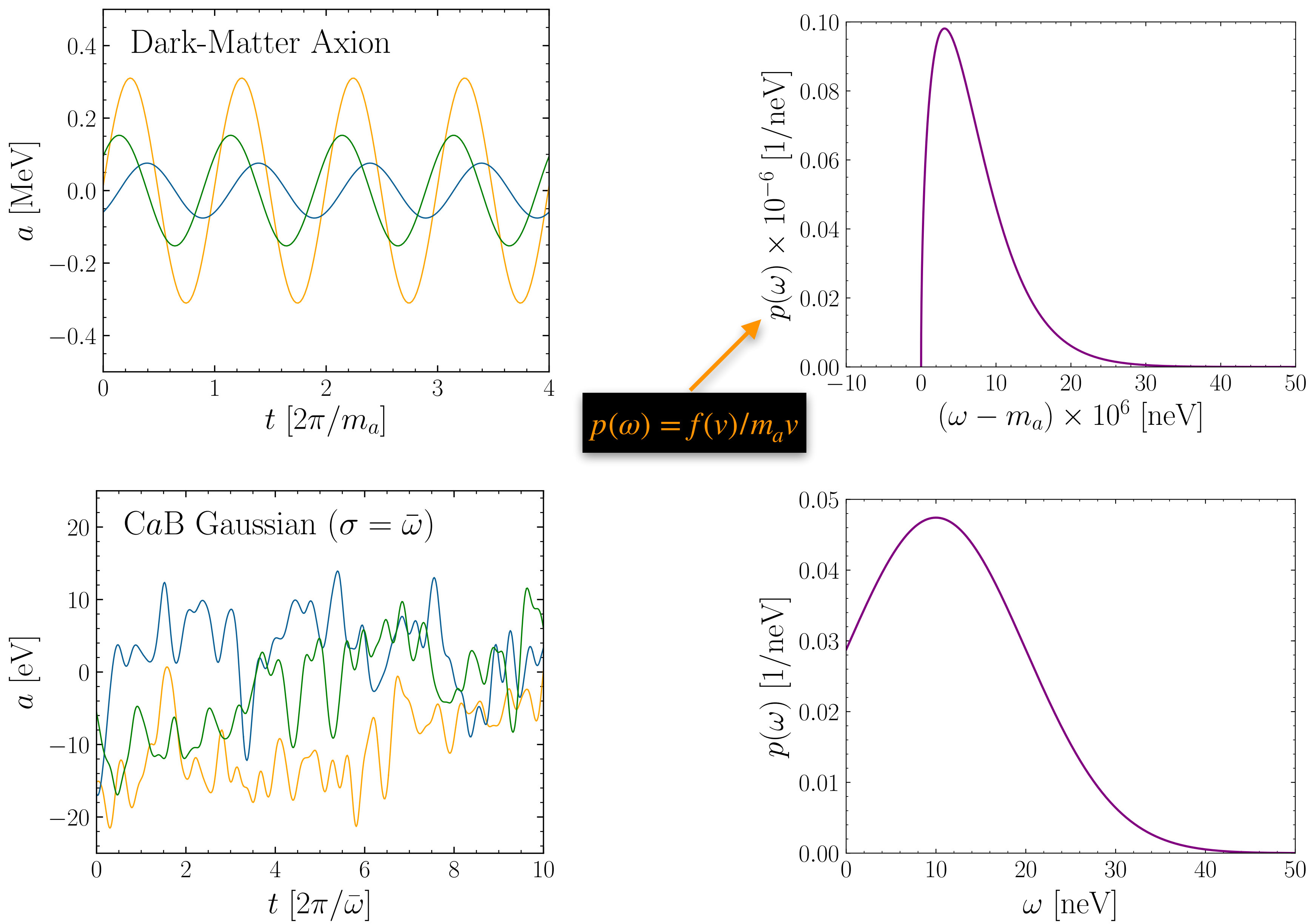

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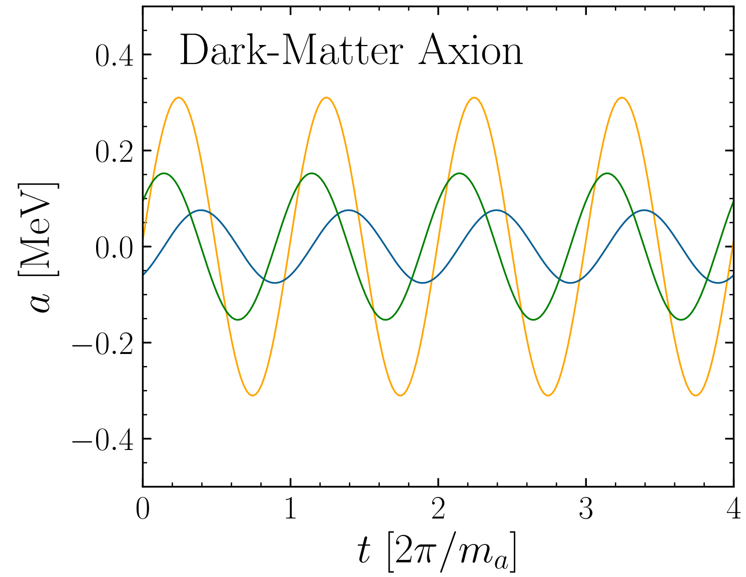

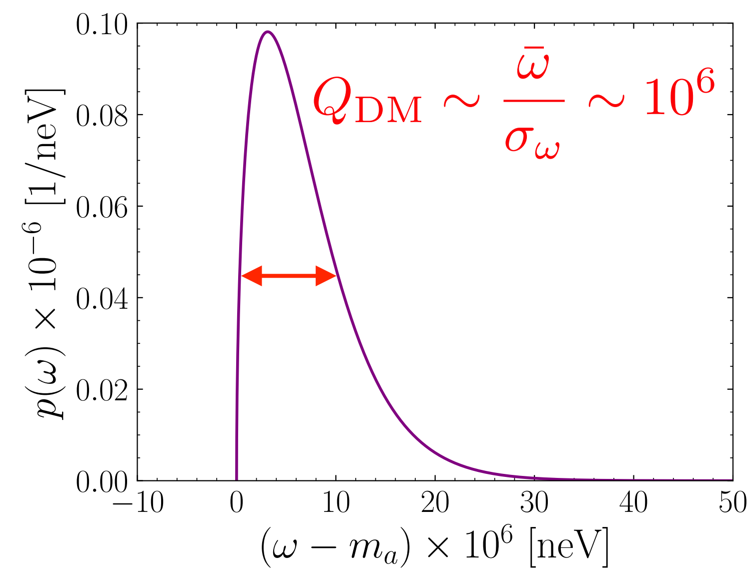

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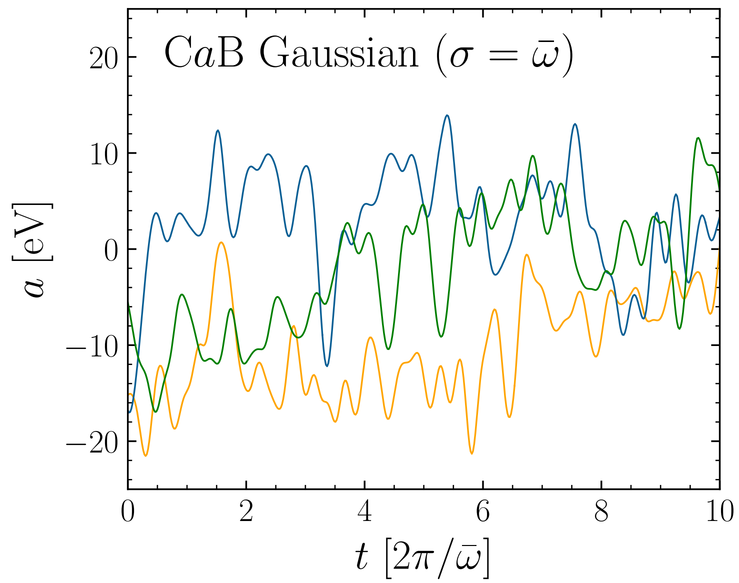

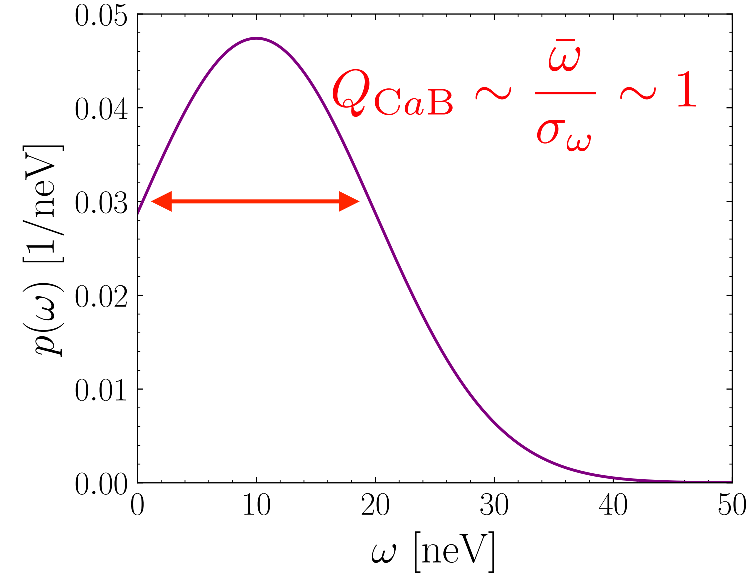

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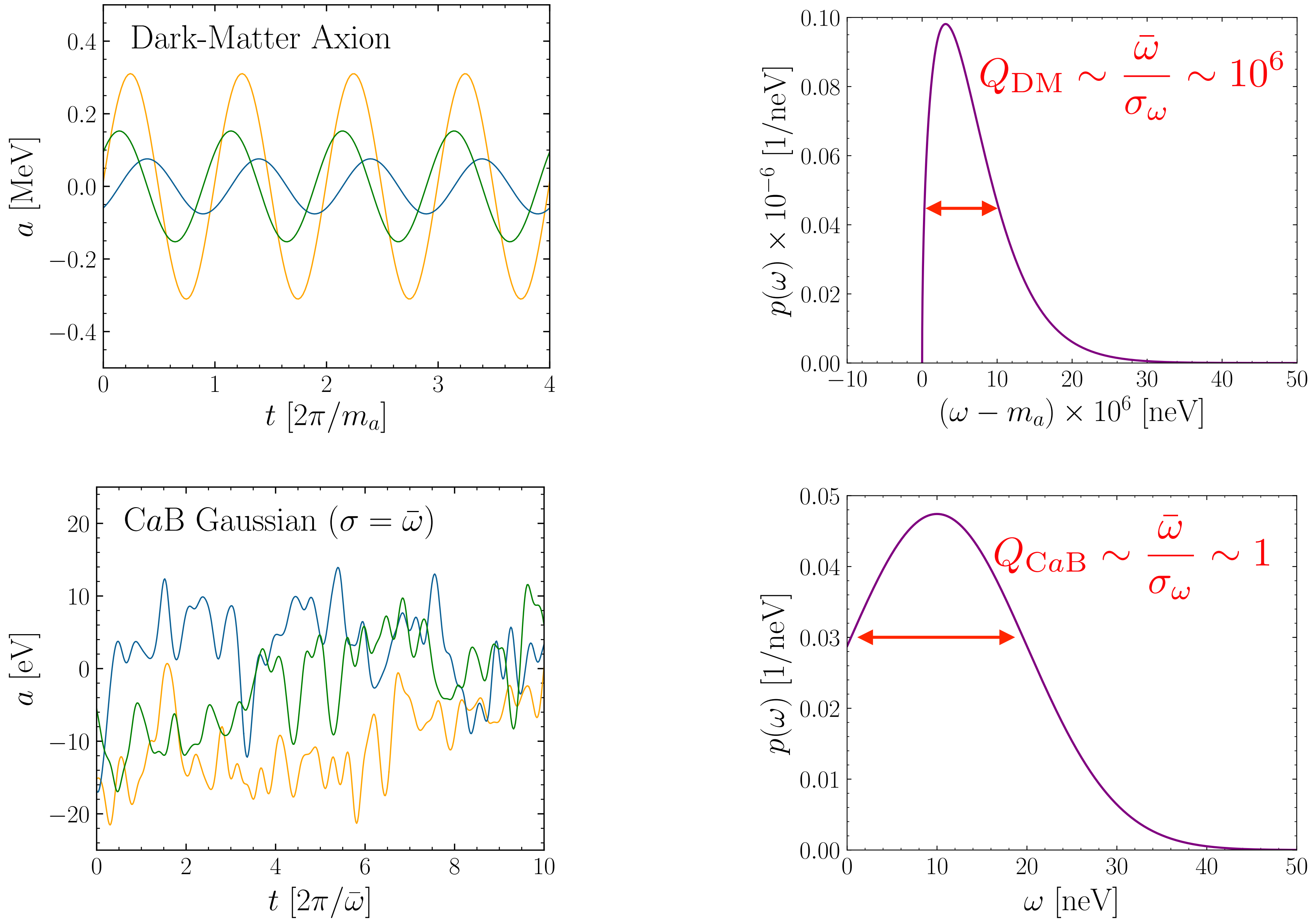

Broad signal - existing searches remove as background

Resolved with ADMX

[Dror, Murayama, NLR 2021]

Rough Sensitivity

$$a(t) \sim \sum_i \cos(\omega_i t + \phi_i)$$

Accessible power in the axion field

Power spectral density - measures power at a given frequency

$$\langle S_{g\partial a}(\omega) \rangle = \pi g_{a\gamma\gamma}^2 \rho_a \frac{\omega}{\bar{\omega}} p(\omega)$$

[Dror, Murayama, NLR 2021]

Rough Sensitivity

$$a(t) \sim \sum_i \cos(\omega_i t + \phi_i)$$

Accessible power in the axion field

$$\langle S_{g\partial a}(\bar{\omega}) \rangle = \frac{\pi g_{a\gamma\gamma}^2 \rho_a Q_a}{\bar{\omega}}$$

Power spectral density - measures power at a given frequency

Approximate $p(\omega) \sim Q_a/\bar{\omega}$

Recall $Q_a \sim \bar{\omega}/\sigma_\omega$

[Dror, Murayama, NLR 2021]

Rough Sensitivity

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Approximate $p(\omega) \sim Q_a/\bar{\omega}$

Recall $Q_a \sim \bar{\omega}/\sigma_\omega$

Estimate sensitivity by matching power $P_{\rm DM} = P_{{\rm C}a{\rm B}}$

[Dror, Murayama, NLR 2021]

Rough Sensitivity

$$\rho_a = \rho_{\rm DM} \left(\frac{g_{a\gamma\gamma}^{\rm DM}}{g_{a\gamma\gamma}^{\rm SE}} \right)^2 \sqrt{\frac{Q_{\rm DM}}{Q_{\rm C\it a\rm B}}}$$

Lose: $\rho_a \ll \rho_{\rm DM}$

Win: $g_{a\gamma\gamma}^{\rm DM} \ll g_{a\gamma\gamma}^{\rm SE}$

Lose: $Q_{\rm C\it a\rm B} \ll Q_{\rm DM}$

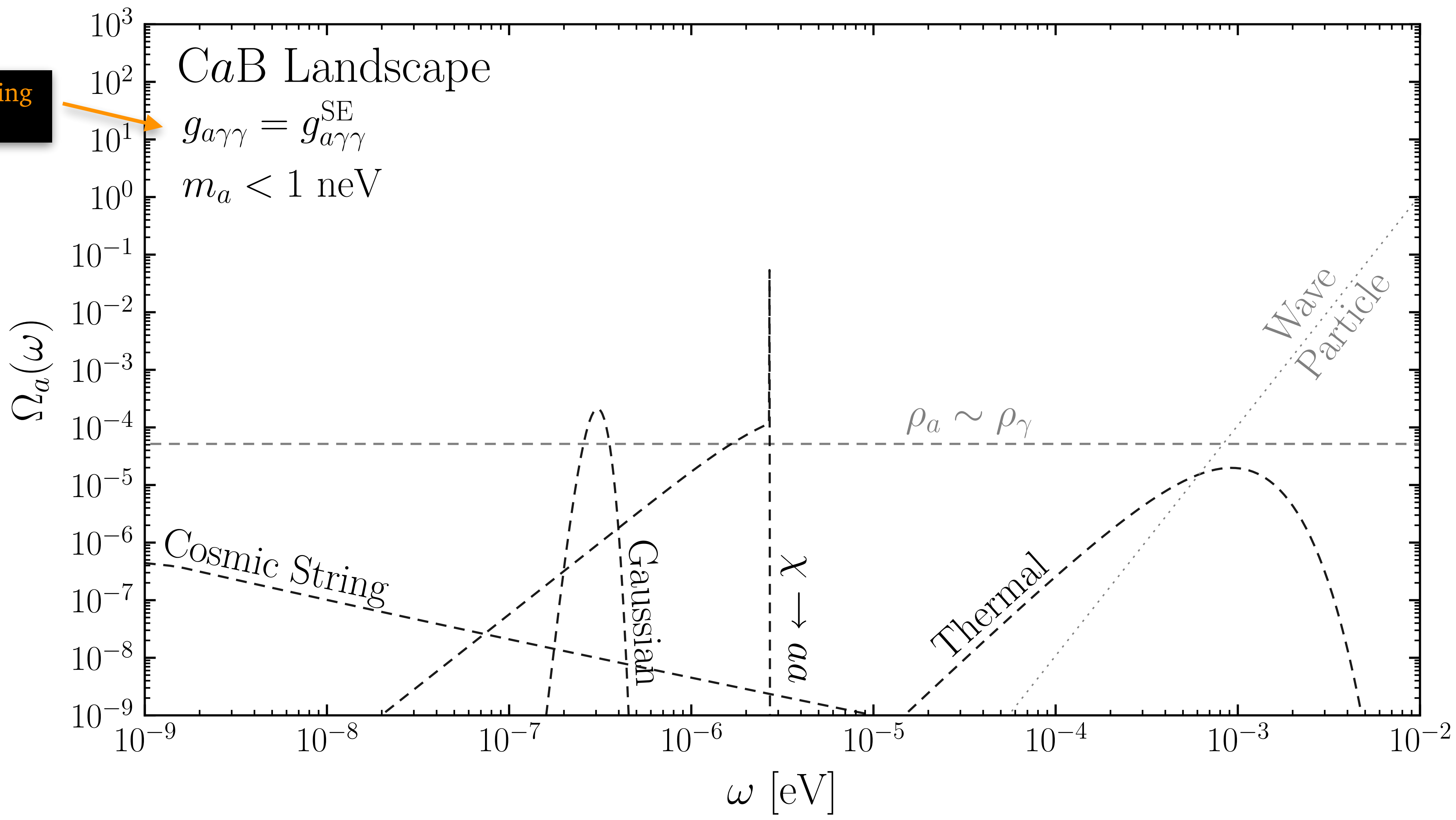
Parametric scaling confirmed by detailed calculations for both resonant and broadband instruments

Detection requires enhanced $g_{a\gamma\gamma}$, e.g. [Choi, Im 2015], [Farina+ 2016], [Agrawal+ 2017], [Dror, Leedom 2020]

[Dror, Murayama, NLR 2021]

Experimental Landscape

Saturate existing bounds



[Dror, Murayama, NLR 2021]

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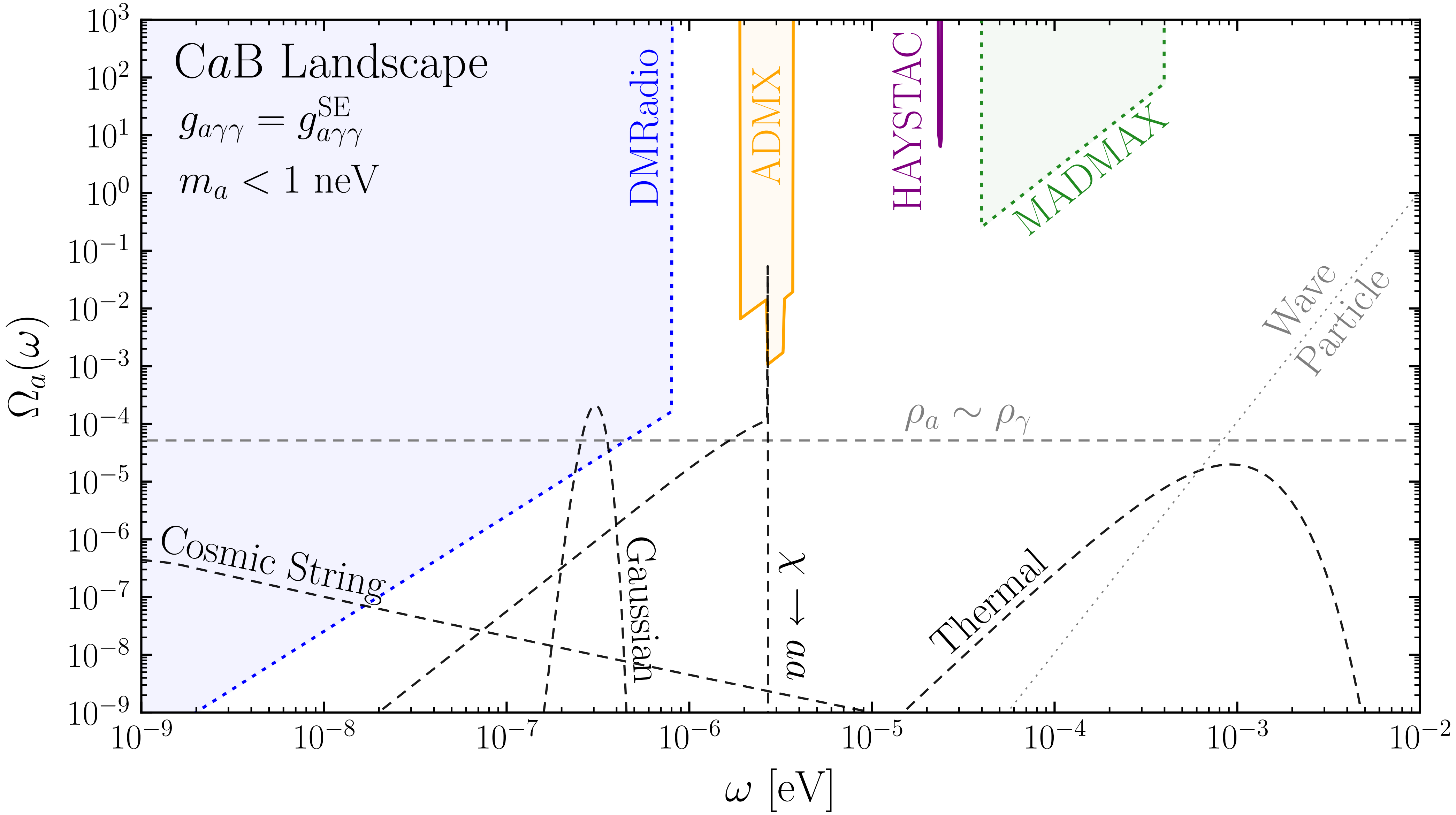

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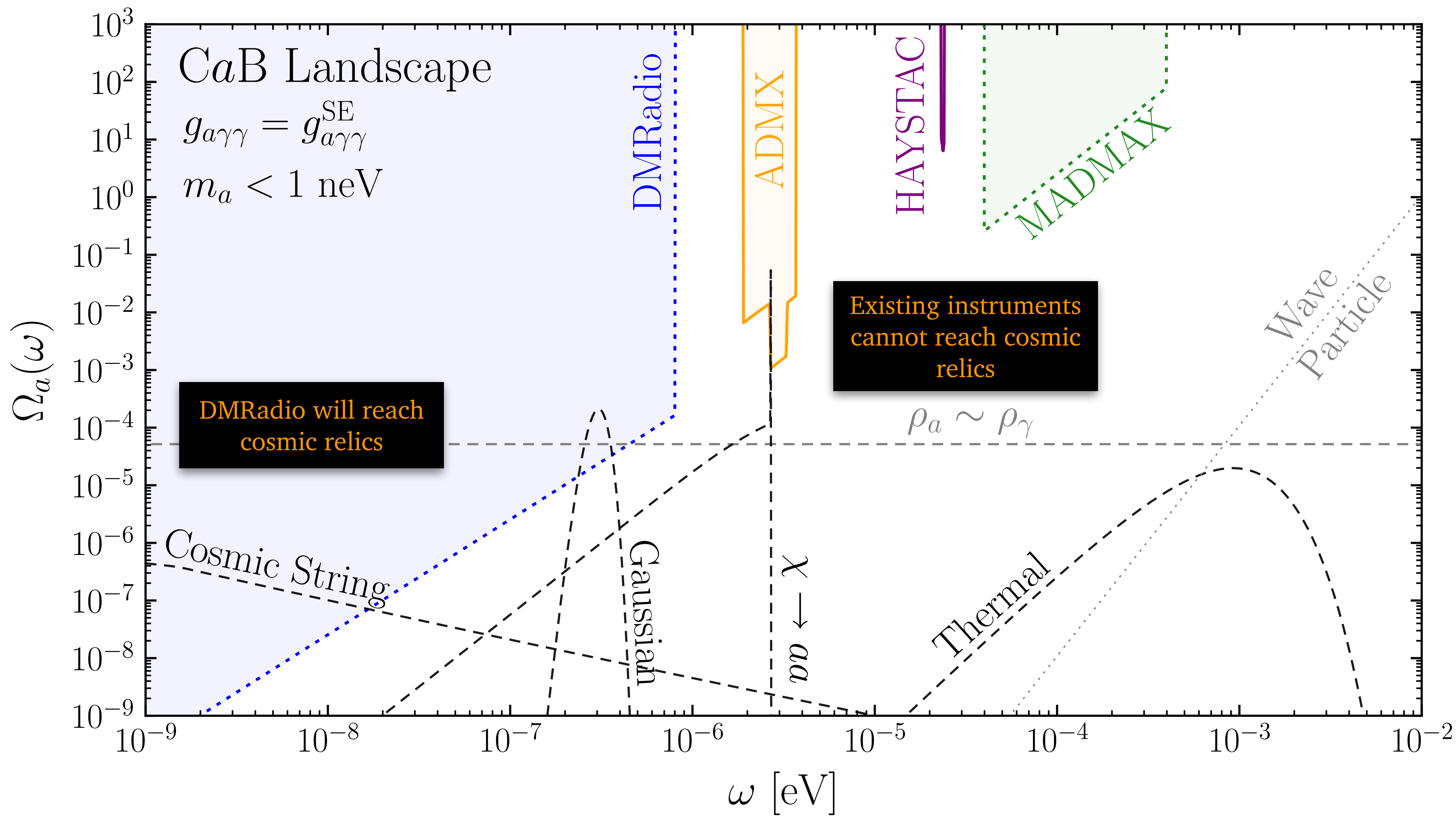
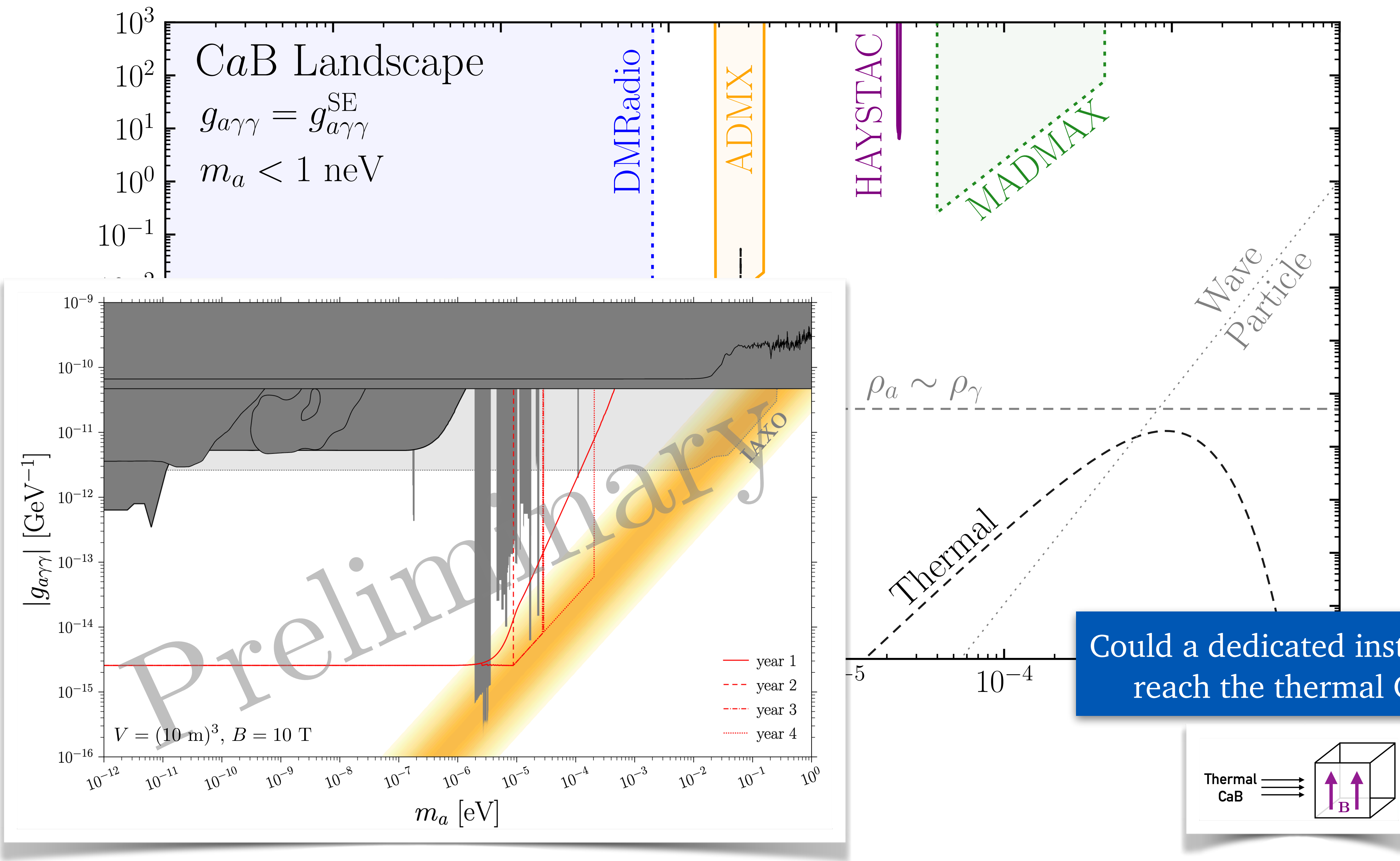


[Dror, Murayama, NLR 2021]

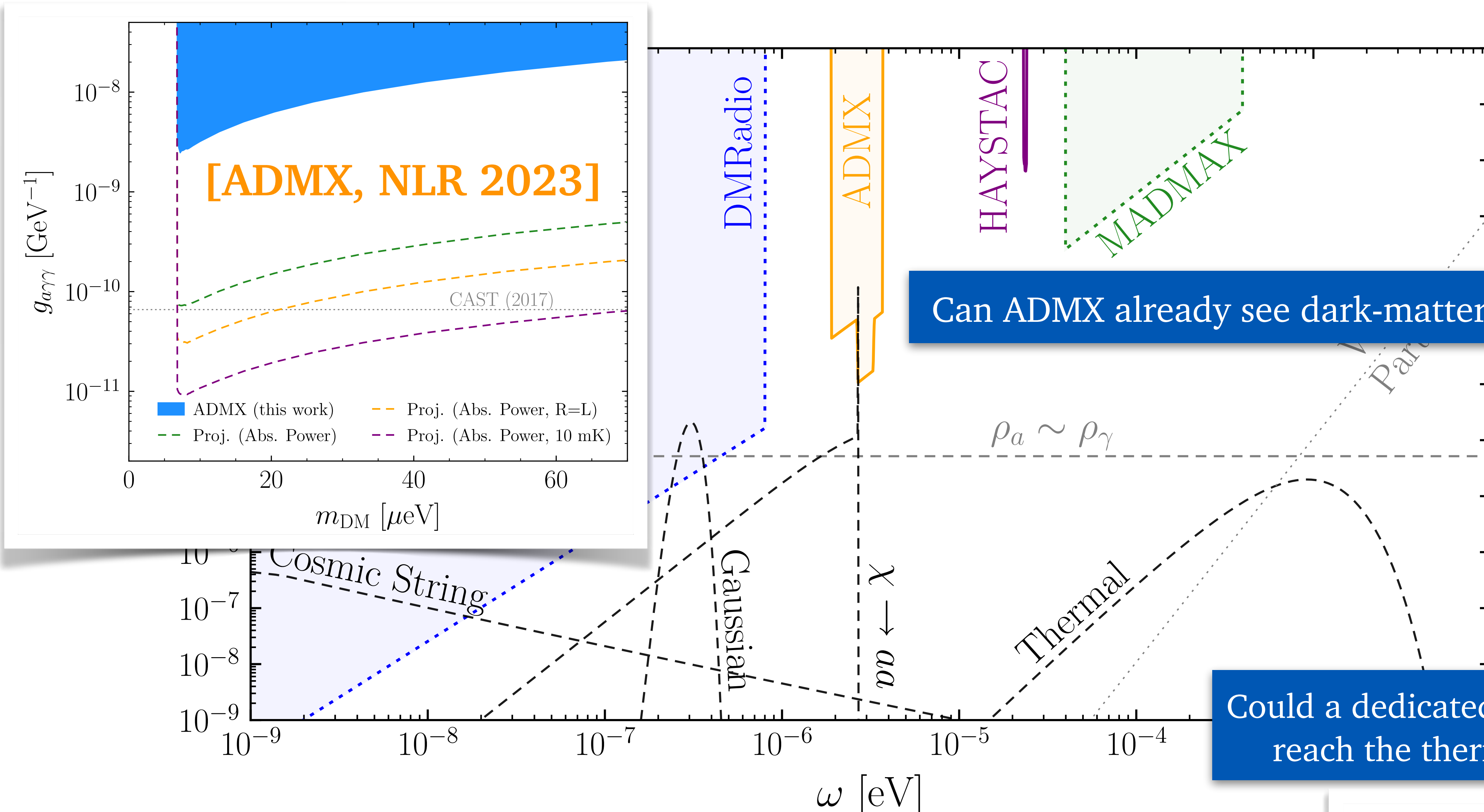
Future Directions



Could a dedicated instrument reach the thermal CaB?

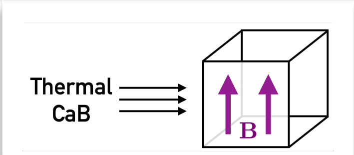
[Dror, Murayama, NLR 2021]

Future Directions



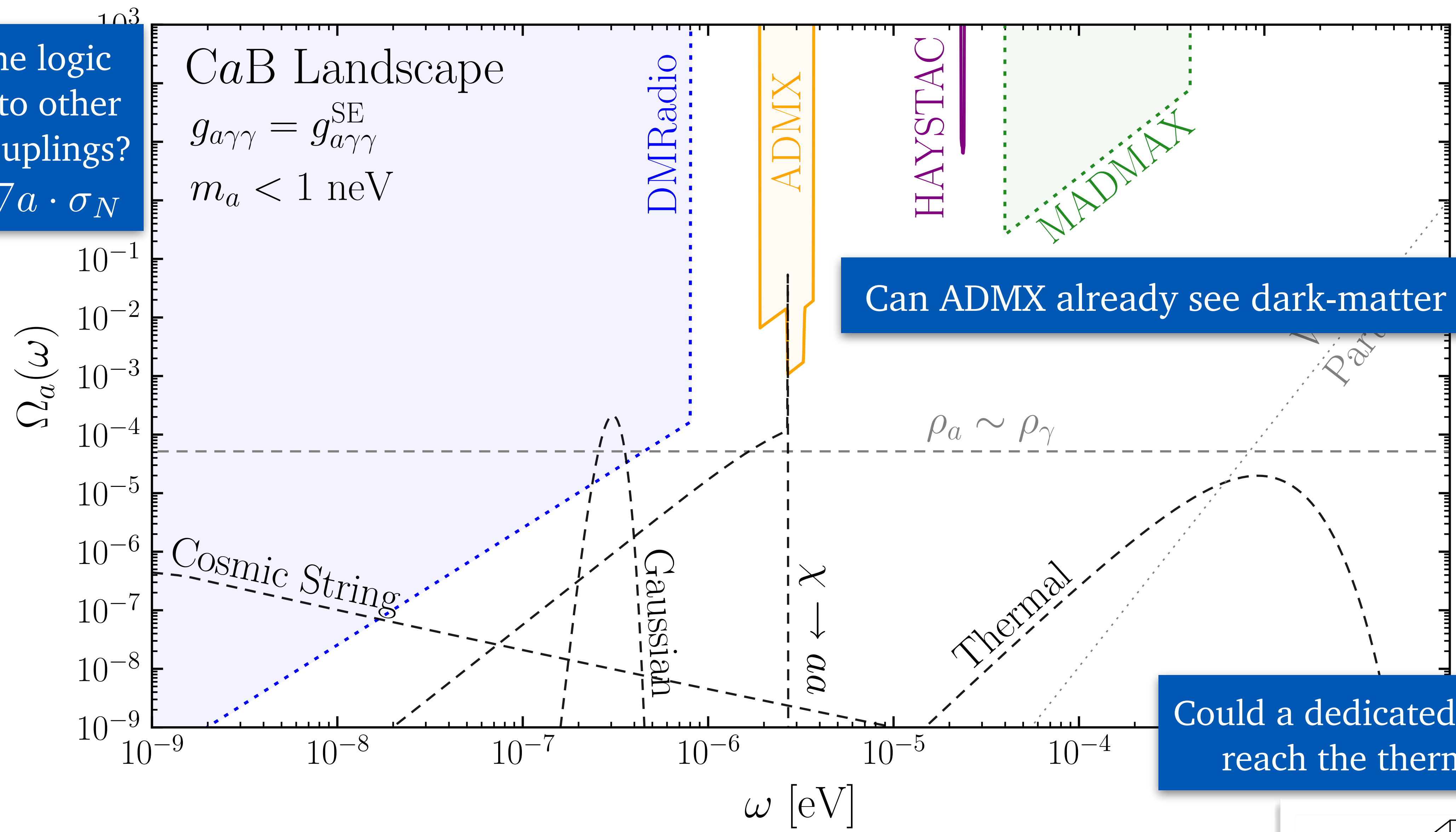
Can ADMX already see dark-matter decay?

Could a dedicated instrument reach the thermal CaB?



Future Directions

Does the logic extend to other axion couplings? $g_{aNN}\nabla a \cdot \sigma_N$



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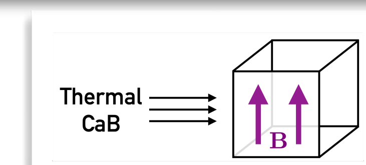
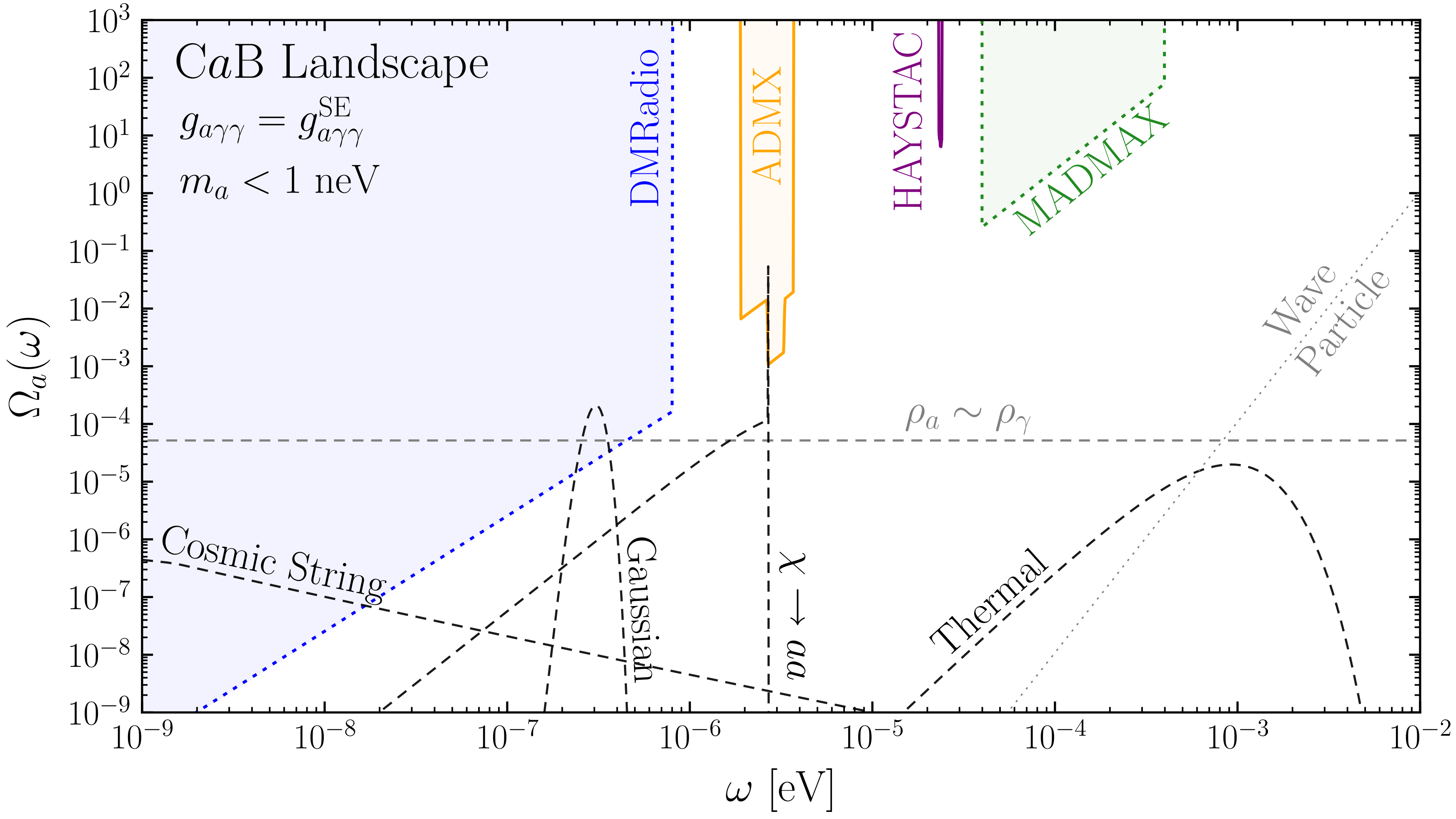


Summary

The Cosmic Axion Background could emerge as we drive towards dark matter



[Dror, Murayama, NLR 2021]

High-Frequency Gravitational Waves

[Domcke, Garcia-Cely, NLR PRL 2022]

High-Frequency Gravitational Waves

Is an axion haloscope also a
gravitational-wave telescope?

[Domcke, Garcia-Cely, NLR 2022]

Gravitational Wave Electrodynamics

$$S \supset \int d^4x \sqrt{-g} \left(-\frac{1}{4} F^2 \right)$$

Work with a linearized metric

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad |h_{\mu\nu}| \ll 1$$

Induces terms of the schematic form

$$hF^2$$

[Gertsenshtein 1962]
[Boccaletti+ 1970]
[Raffelt, Stodolsky 1988]

[Domcke, Garcia-Cely, NLR 2022]

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$$hF^2 \quad \leftrightarrow \quad g_{a\gamma\gamma} a F \tilde{F}$$

[Gertsenshtein 1962]
[Boccaletti+ 1970]
[Raffelt, Stodolsky 1988]

Clear analogy with axion electrodynamics

[Domcke, Garcia-Cely, NLR 2022]

Gravitational Wave Electrodynamics

$$hF^2 \quad \leftrightarrow \quad g_{a\gamma\gamma} a F \tilde{F}$$

0th order estimate by pushing this analogy

See also [Berlin, Blas, Tito D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel 2021]

[Domcke, Garcia-Cely, NLR 2022]

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[Domcke, Garcia-Cely, NLR 2022]

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QCD Axion

See also [Berlin, Blas, Tito D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel 2021]

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Far from bound on cosmological sources

$$h \lesssim 10^{-27} \left(\frac{1\ \mathrm{MHz}}{f}\right) \Delta N_{\rm eff}^{1/2}$$

Only sensitive to late time sources
e.g. PBH Binary signal within reach

See also [Berlin, Blas, Tito D'Agnolo, Ellis, Harnik, Kahn, Schutte-Engel 2021]

[Domcke, Garcia-Cely, NLR 2022]

Gravitational Wave Electrodynamics

As for the axion, induce new E&M sources

$$\nabla \cdot \mathbf{E} = -\nabla \cdot \mathbf{P}$$
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \nabla \times \mathbf{M} + \partial_t \mathbf{P}$$

although with a more complicated from

$$P_i = -h_{ij} E_j + \tfrac{1}{2} h E_i + h_{00} E_i - \epsilon_{ijk} h_{0j} B_k$$
$$M_i = -h_{ij} B_j - \tfrac{1}{2} h B_i + h_{jj} B_i + \epsilon_{ijk} h_{0j} E_k$$

Axion equivalent
$\mathbf{P} = g_{a\gamma\gamma} a \mathbf{B},\ \mathbf{M} = g_{a\gamma\gamma} a \mathbf{E}$

[Domcke, Garcia-Cely, NLR 2022]

Gravitational Wave Electrodynamics

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Following [Berlin+ 2021] work in proper detector frame, where

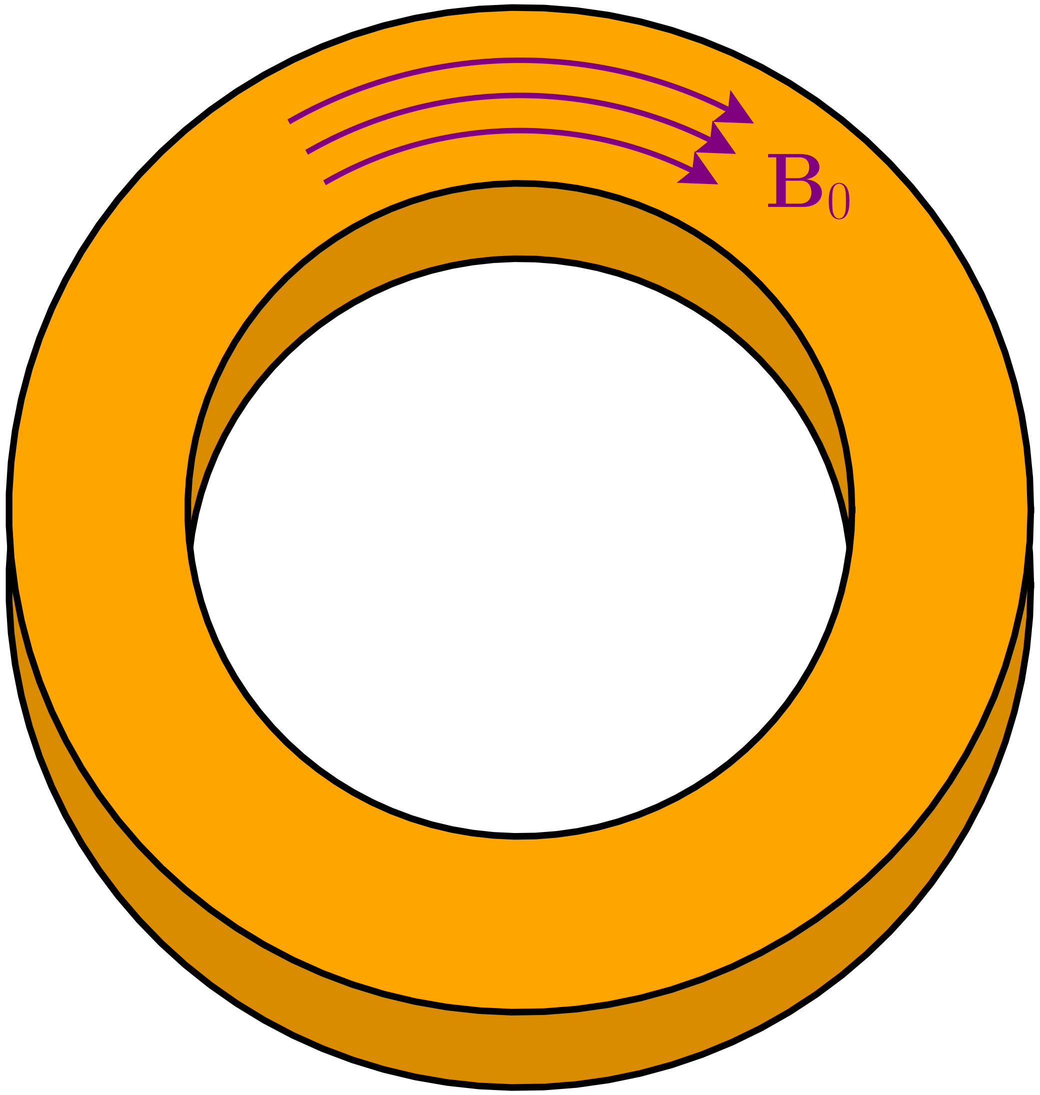
Axion equivalent
$\mathbf{P} = g_{a\gamma\gamma} a \mathbf{B}, \ \mathbf{M} = g_{a\gamma\gamma} a \mathbf{E}$

$$h \sim \omega^2 + \mathcal{O}(\omega^3)$$

See also [Fortini and Gualdi 1982], [Marzlin 1994], [Rakhmanov 2014]

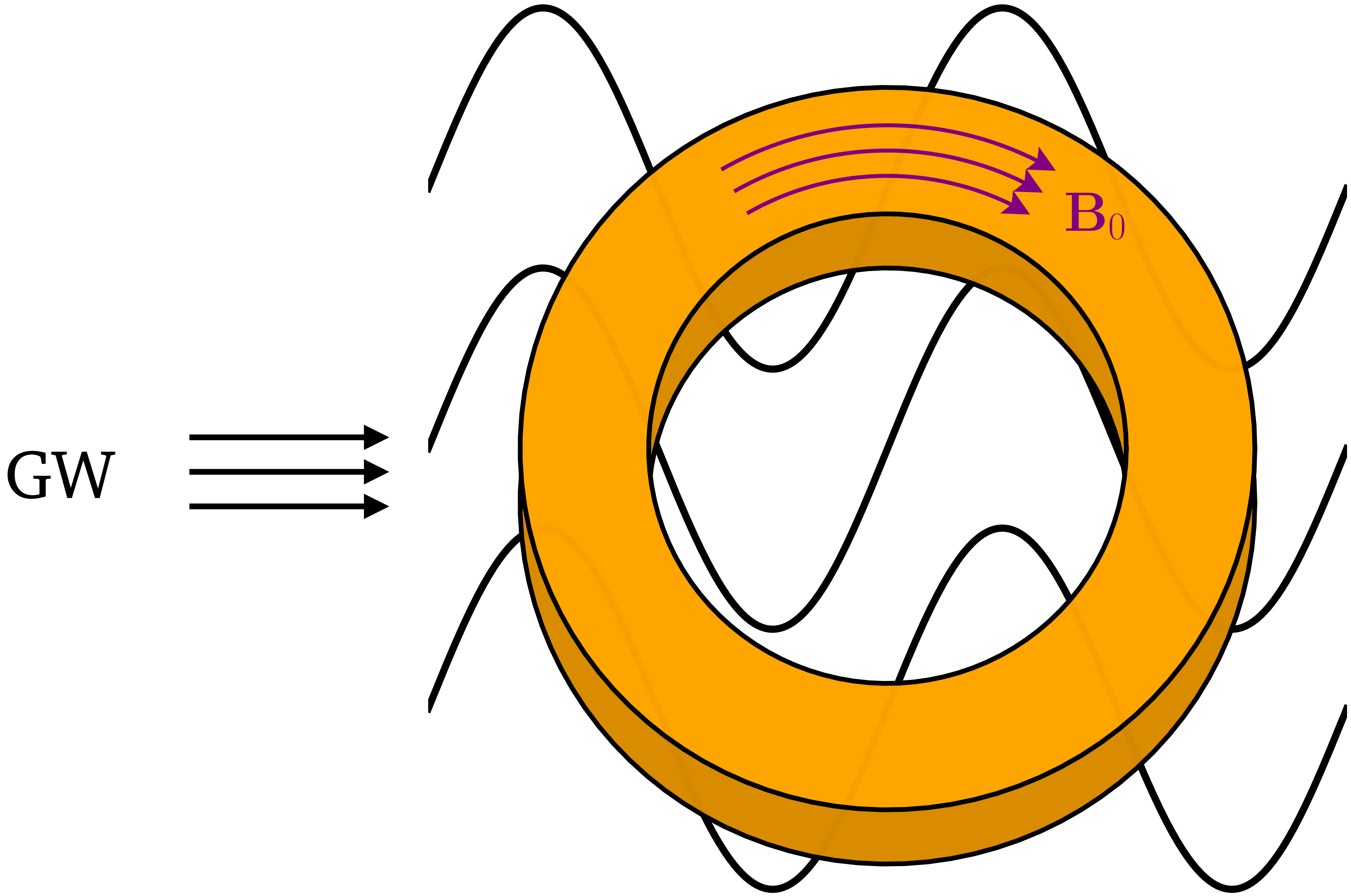
[Domcke, Garcia-Cely, NLR 2022]

Detection Strategy



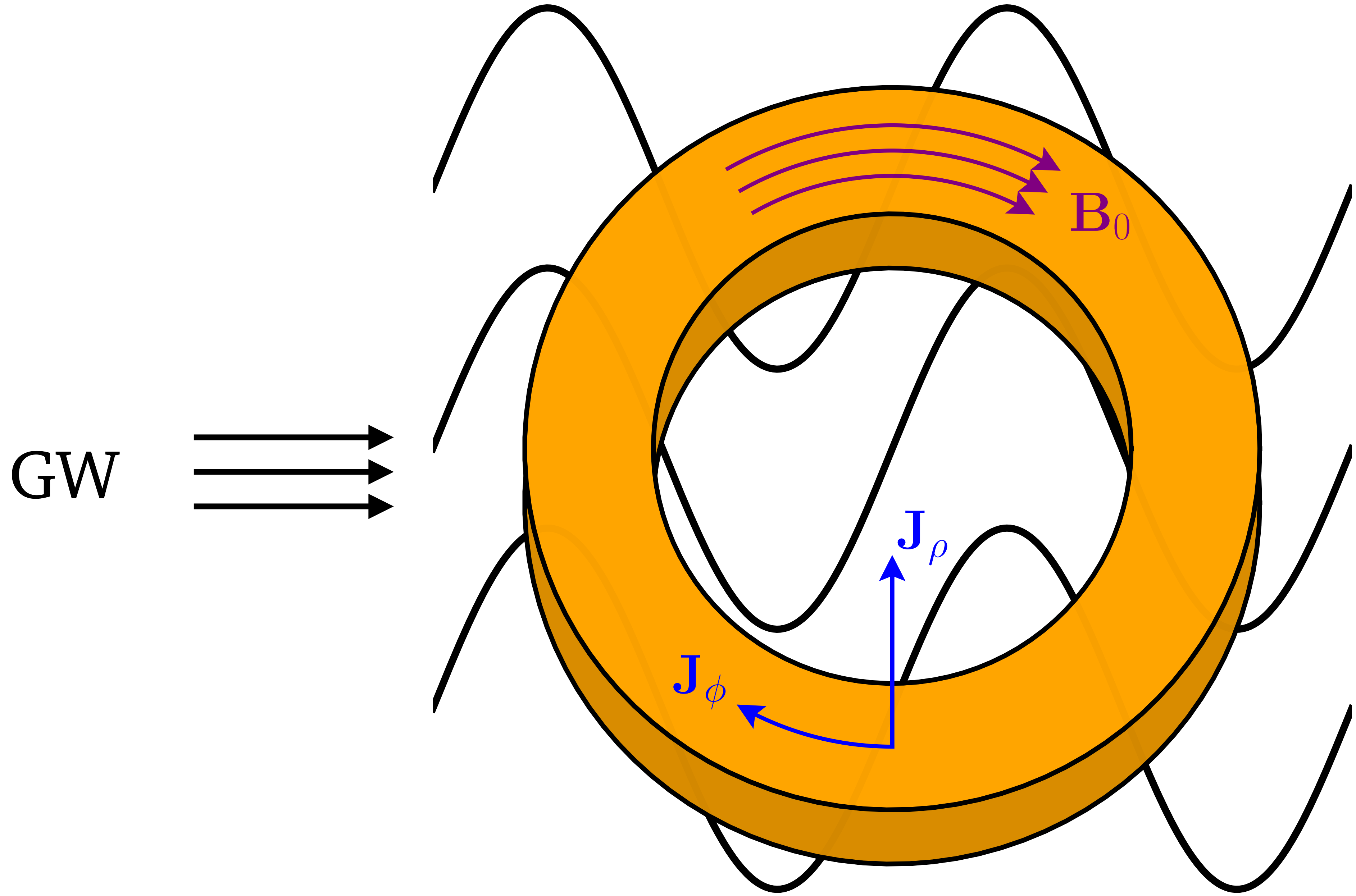
[Domcke, Garcia-Cely, NLR 2022]

Detection Strategy



[Domcke, Garcia-Cely, NLR 2022]

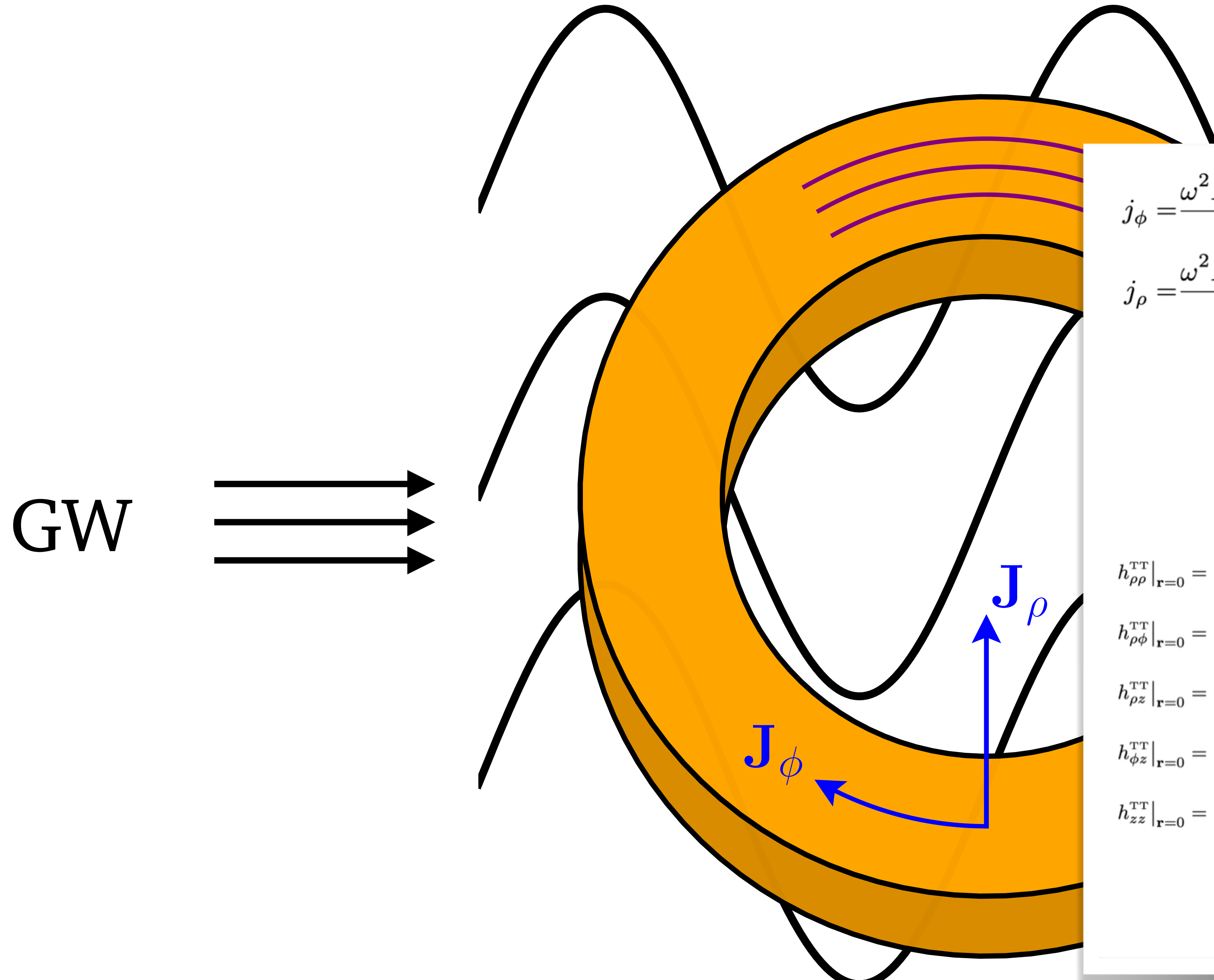
Detection Strategy



$\mathbf{J}_z$ also non-zero

[Domcke, Garcia-Cely, NLR 2022]

Detection Strategy



$$j_\phi = \frac{\omega^2 B_{\rm max} R}{\rho}\left[\frac{e^\kappa}{\kappa} - \frac{2e^\kappa}{\kappa^2} + \frac{2(e^\kappa - 1)}{\kappa^3}\right]\left(z\, h^{\rm TT}_{\rho\phi}\big|_{\mathbf{r}=0} - \rho\, h^{\rm TT}_{\phi z}\big|_{\mathbf{r}=0}\right),$$

$$\begin{aligned} j_\rho = \frac{\omega^2 B_{\rm max} R}{\rho}\Bigg(&\left[-\frac{1}{2} - \frac{1}{\kappa} + \frac{2e^\kappa}{\kappa^2} + \frac{2(1-e^\kappa)}{\kappa^3}\right]\left(\rho\, h^{\rm TT}_{\rho z}\big|_{\mathbf{r}=0} + z\, h^{\rm TT}_{zz}\big|_{\mathbf{r}=0}\right) \\ &+ \left[\frac{e^\kappa}{\kappa} + \frac{2}{\kappa^2} + \frac{2(1-e^\kappa)}{\kappa^3}\right]\left(z\, h^{\rm TT}_{\rho\rho}\big|_{\mathbf{r}=0} + z\, h^{\rm TT}_{zz}\big|_{\mathbf{r}=0}\right) \\ &+ \mathrm{i}k_z\left[\frac{1}{2\kappa} + \frac{1}{2\kappa^2} - \frac{1+2e^\kappa}{\kappa^3} + \frac{3(e^\kappa - 1)}{\kappa^4}\right] r_i r_j h^{\rm TT}_{ij}\big|_{\mathbf{r}=0}\Bigg), \end{aligned}$$

$\kappa = i\mathbf{k}\cdot\mathbf{r}$

$$h^{\rm TT}_{\rho\rho}\big|_{\mathbf{r}=0} = \frac{e^{-\mathrm{i}\omega t}}{\sqrt{2}}\left(-h^+(\sin^2(\phi-\phi_h) - \cos^2(\phi-\phi_h)\cos^2\theta_h) + 2\,h^\times\cos\theta_h\cos(\phi-\phi_h)\sin(\phi-\phi_h)\right),$$

$$h^{\rm TT}_{\rho\phi}\big|_{\mathbf{r}=0} = \frac{e^{-\mathrm{i}\omega t}}{\sqrt{2}}\left(-h^+(1+\cos^2\theta_h)\sin(\phi-\phi_h)\cos(\phi-\phi_h) + h^\times\cos(2(\phi-\phi_h))\cos\theta_h\right),$$

$$h^{\rm TT}_{\rho z}\big|_{\mathbf{r}=0} = -\frac{e^{-\mathrm{i}\omega t}}{\sqrt{2}}\left(h^+\cos\theta_h\sin\theta_h\cos(\phi-\phi_h) + h^\times\sin\theta_h\sin(\phi-\phi_h)\right),$$

$$h^{\rm TT}_{\phi z}\big|_{\mathbf{r}=0} = \frac{e^{-\mathrm{i}\omega t}}{\sqrt{2}}\left(h^+\cos\theta_h\sin\theta_h\sin(\phi-\phi_h) - h^\times\sin\theta_h\cos(\phi-\phi_h)\right),$$

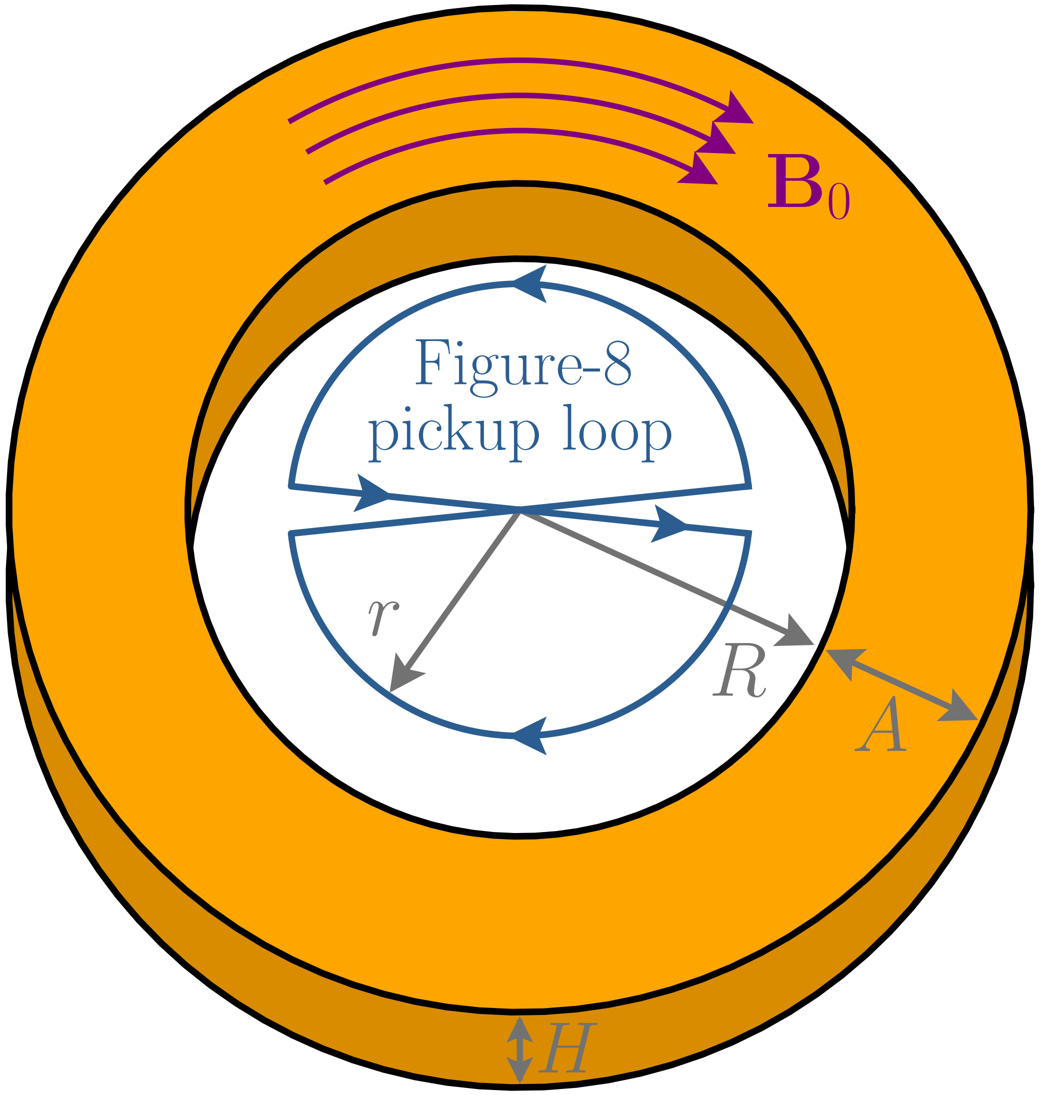
$$h^{\rm TT}_{zz}\big|_{\mathbf{r}=0} = \frac{e^{-\mathrm{i}\omega t}}{\sqrt{2}} h^+\sin^2\theta_h.$$

Cf. axion: $\mathbf{J}_a = g_{a\gamma\gamma}(\partial_t a)\mathbf{B}_0$

$\mathbf{J}_z$ also non-zero

[Domcke, Garcia-Cely, NLR 2022]

Optimized Reach

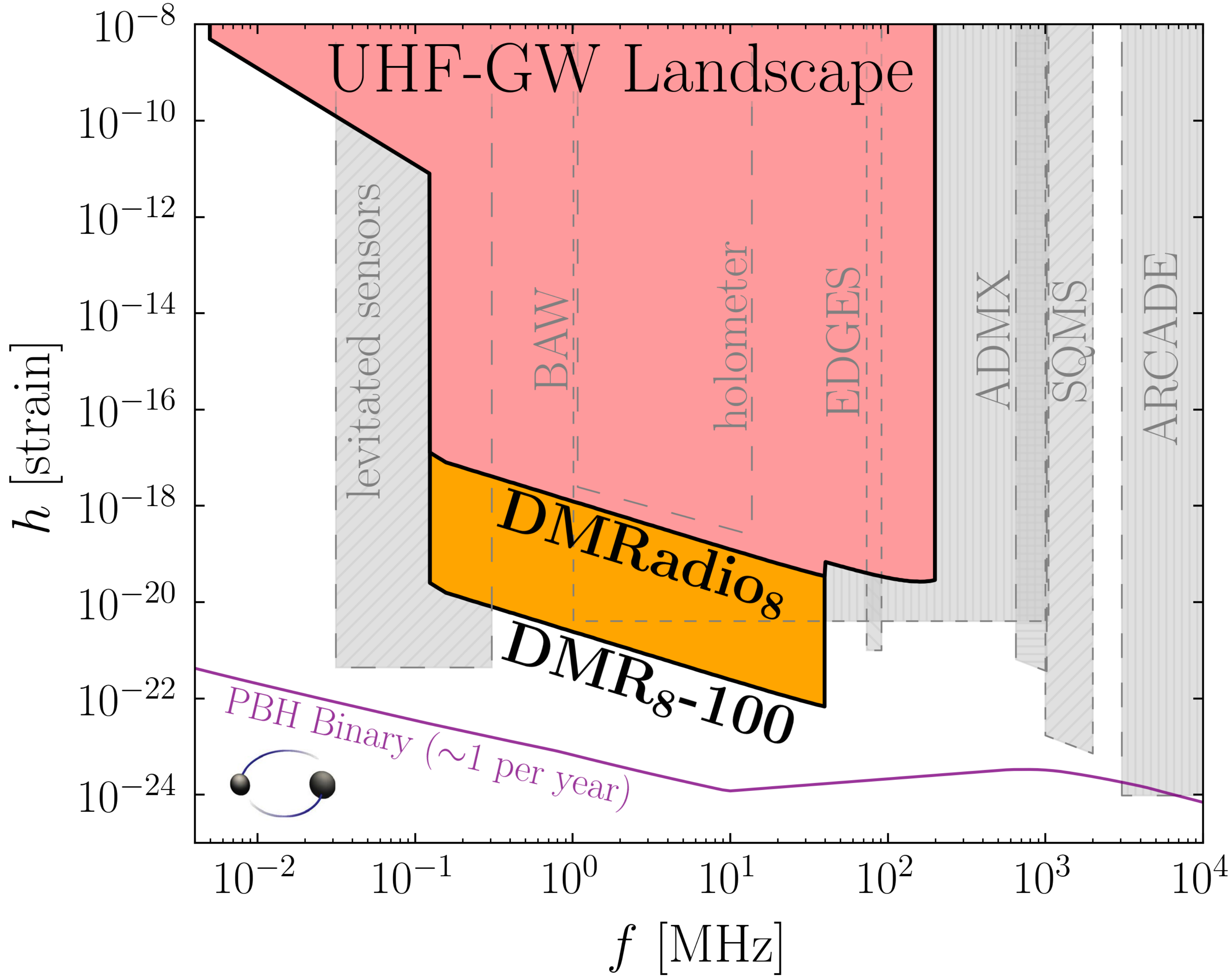


Circular loop is not optimal
Why? Symmetry implies **selection rules** for GW
[Domcke, Garcia-Cely, Lee, NLR 2306.03125]

$$\Phi_h(t) \simeq \frac{e^{-i\omega t}}{3\sqrt{2}} \omega^2 B_0 r^3 R \ln(1 + A/R) s_{\theta_h} (h^\times s_{\phi_h} - h^+ c_{\theta_h} c_{\phi_h}) \sim \omega^2 h B_0 V^{4/3}$$

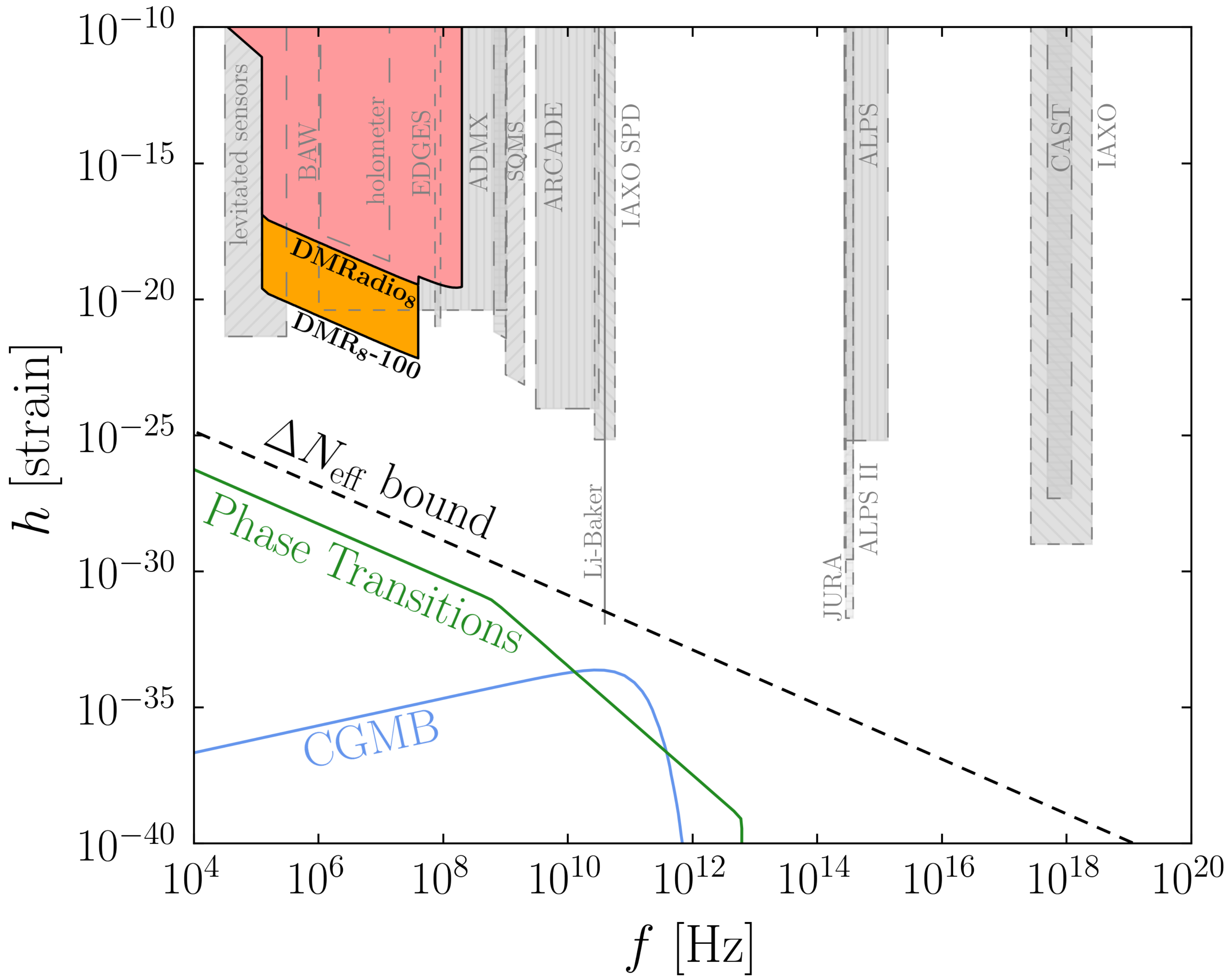
[Domcke, Garcia-Cely, NLR 2022]

Optimized Reach



[Domcke, Garcia-Cely, NLR 2022]

Future Directions



[Domcke, Garcia-Cely, NLR 2022]

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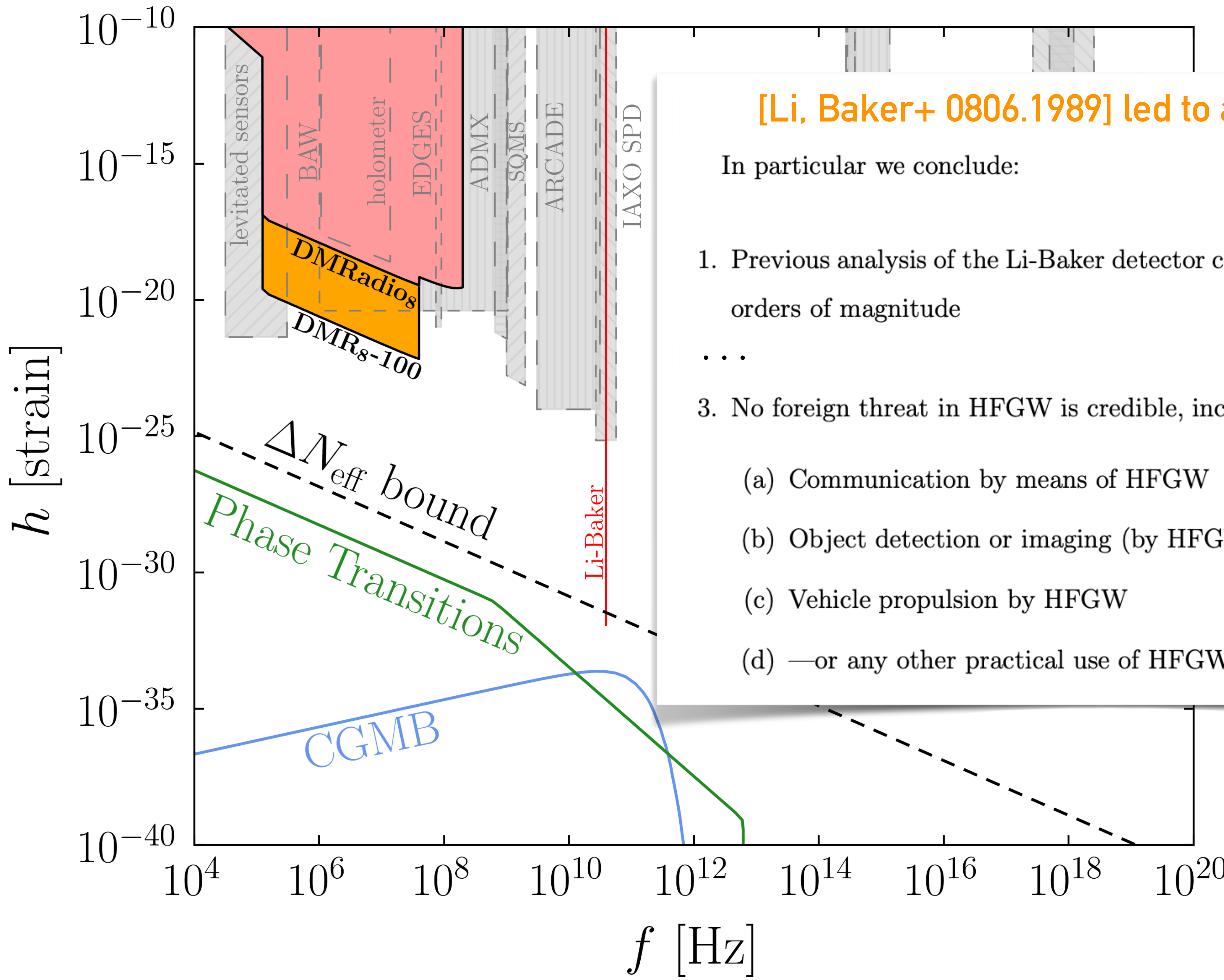


[Li, Baker+ 0806.1989] led to a JASON report

In particular we conclude:

1. Previous analysis of the Li-Baker detector concept is incorrect by many orders of magnitude

. . .

3. No foreign threat in HFGW is credible, including:

   (a) Communication by means of HFGW

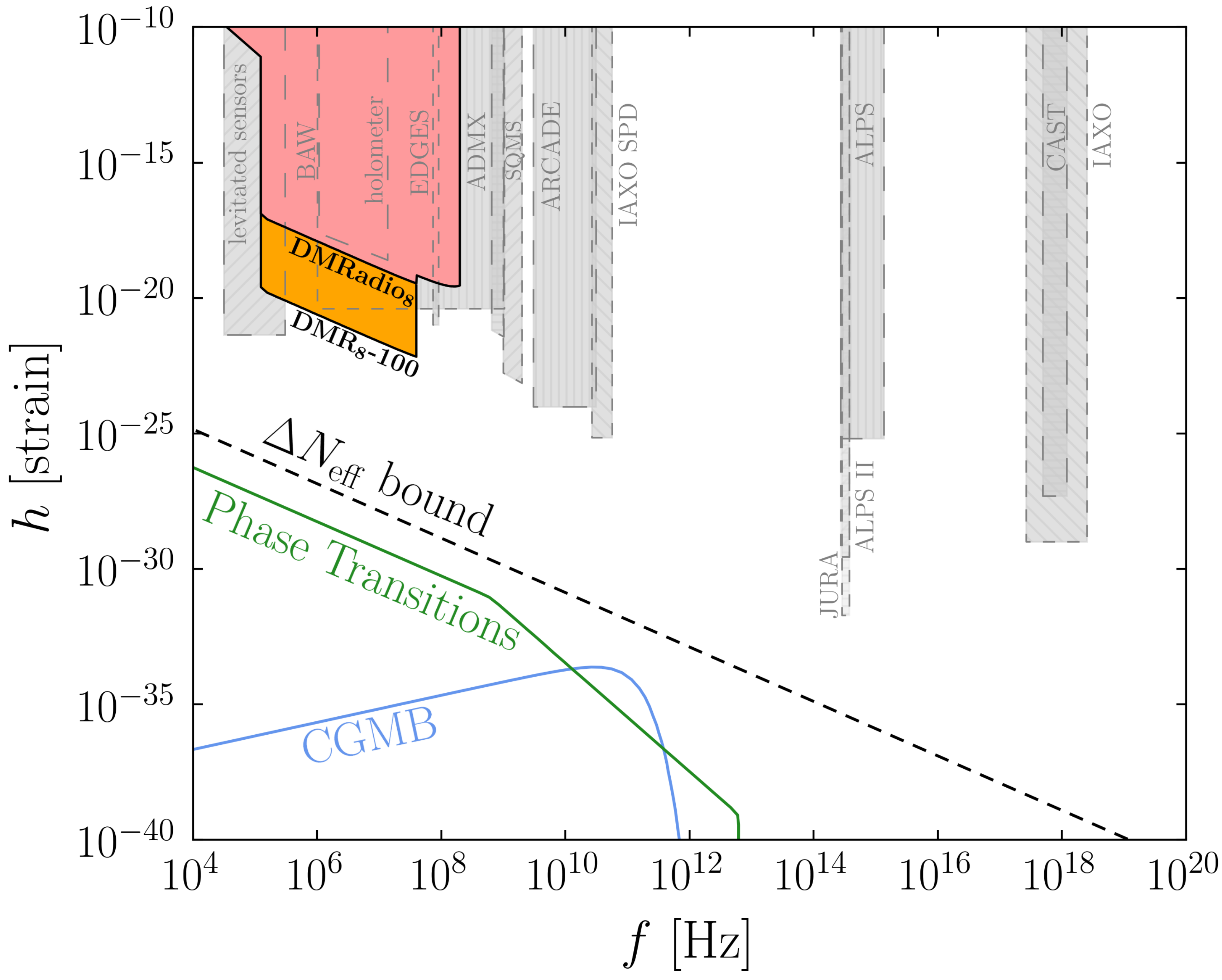
   (b) Object detection or imaging (by HFGW radar or tomography)

   (c) Vehicle propulsion by HFGW

   (d) —or any other practical use of HFGW.

[Domcke, Garcia-Cely, NLR 2022]

Future Directions



[Domcke, Garcia-Cely, NLR 2022]

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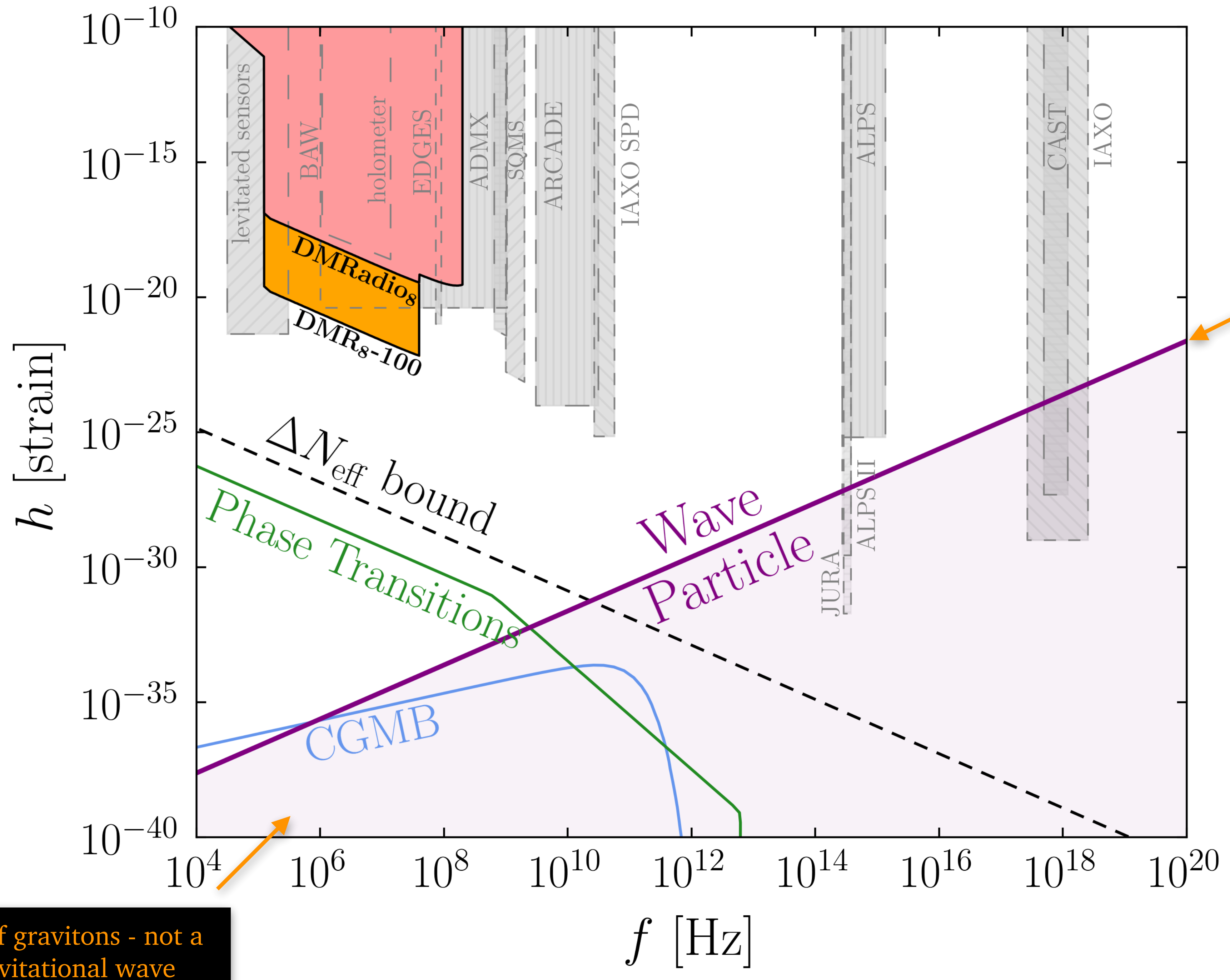
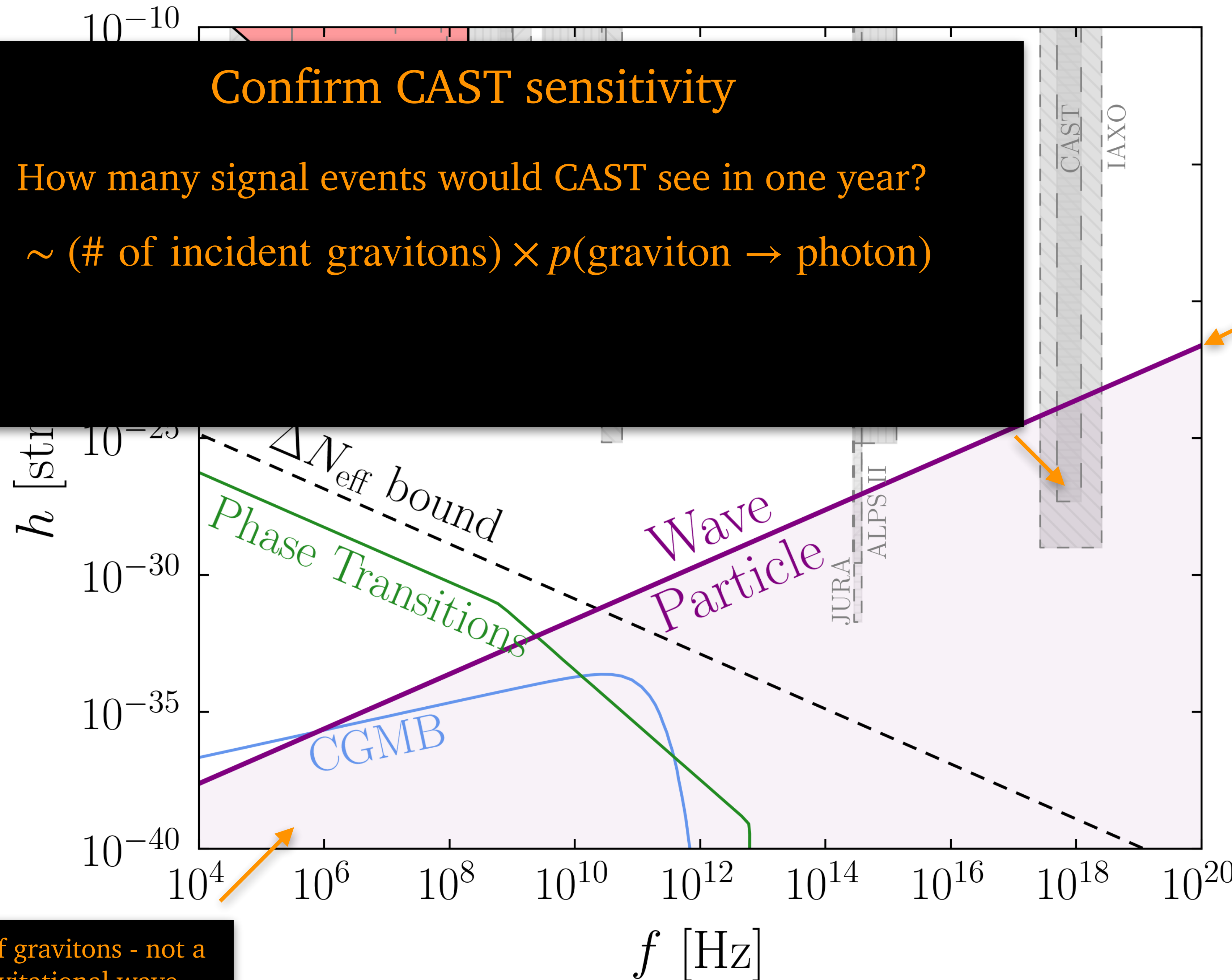


$$n_h \lambda_h^3 \sim \frac{\rho}{\omega^4} \sim \frac{h^2 M_{\rm Pl}^2}{\omega^2} \sim 1$$

Gas of gravitons - not a gravitational wave

[Domcke, Garcia-Cely, NLR 2022]

Future Directions



Confirm CAST sensitivity

How many signal events would CAST see in one year?

$\sim$ (# of incident gravitons) $\times\, p$(graviton $\to$ photon)

$$n_h \lambda_h^3 \sim \frac{\rho}{\omega^4} \sim \frac{h^2 M_{\text{Pl}}^2}{\omega^2} \sim 1$$

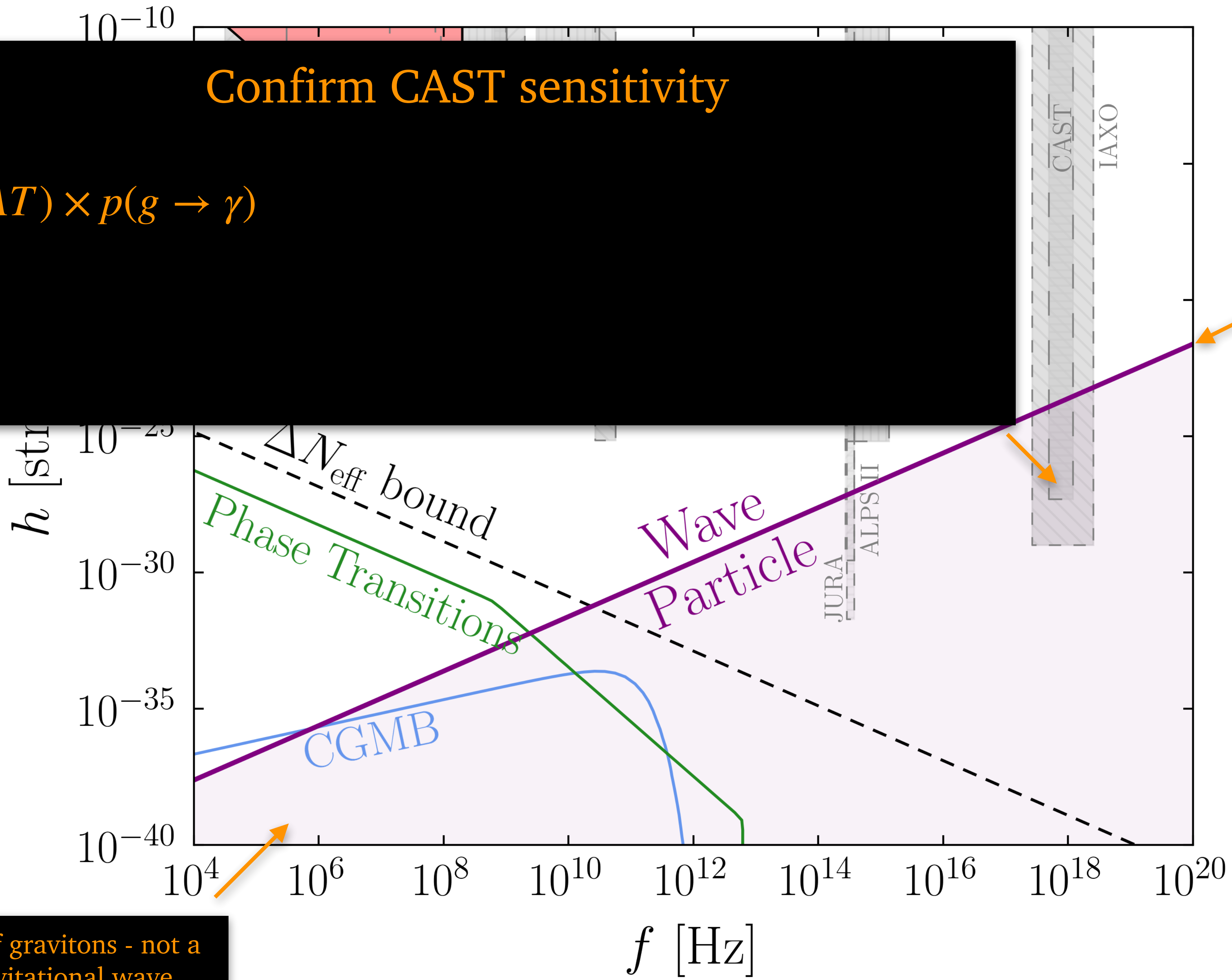
Gas of gravitons - not a gravitational wave

[Domcke, Garcia-Cely, NLR 2022]

Future Directions

Confirm CAST sensitivity

$(n_h AT) \times p(g \to \gamma)$



$n_h \lambda_h^3 \sim \frac{\rho}{\omega^4} \sim \frac{h^2 M_{\rm Pl}^2}{\omega^2} \sim 1$

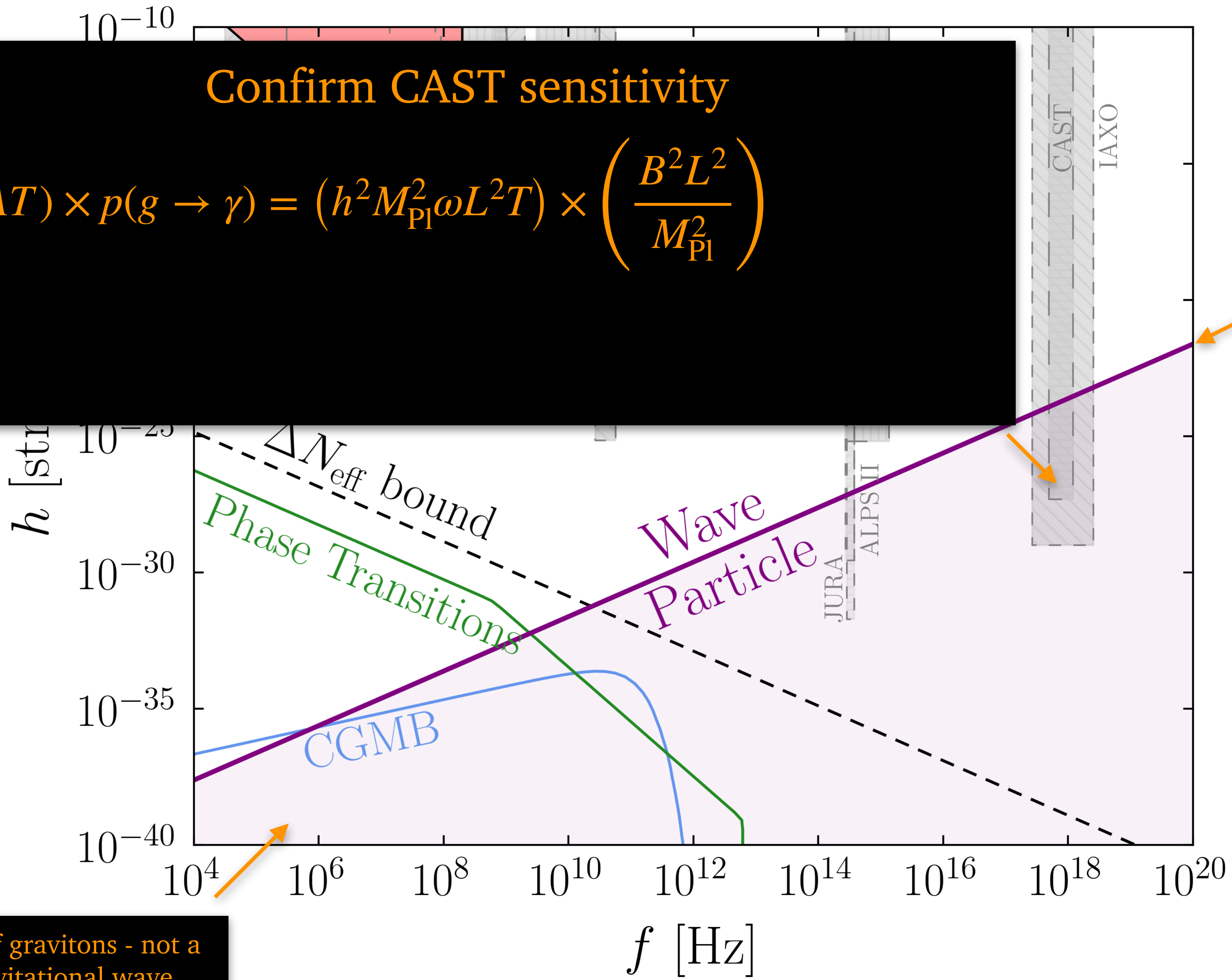
Gas of gravitons - not a gravitational wave

Future Directions

Confirm CAST sensitivity

$$(n_h A T) \times p(g \to \gamma) = \left(h^2 M_{\rm Pl}^2 \omega L^2 T\right) \times \left(\frac{B^2 L^2}{M_{\rm Pl}^2}\right)$$

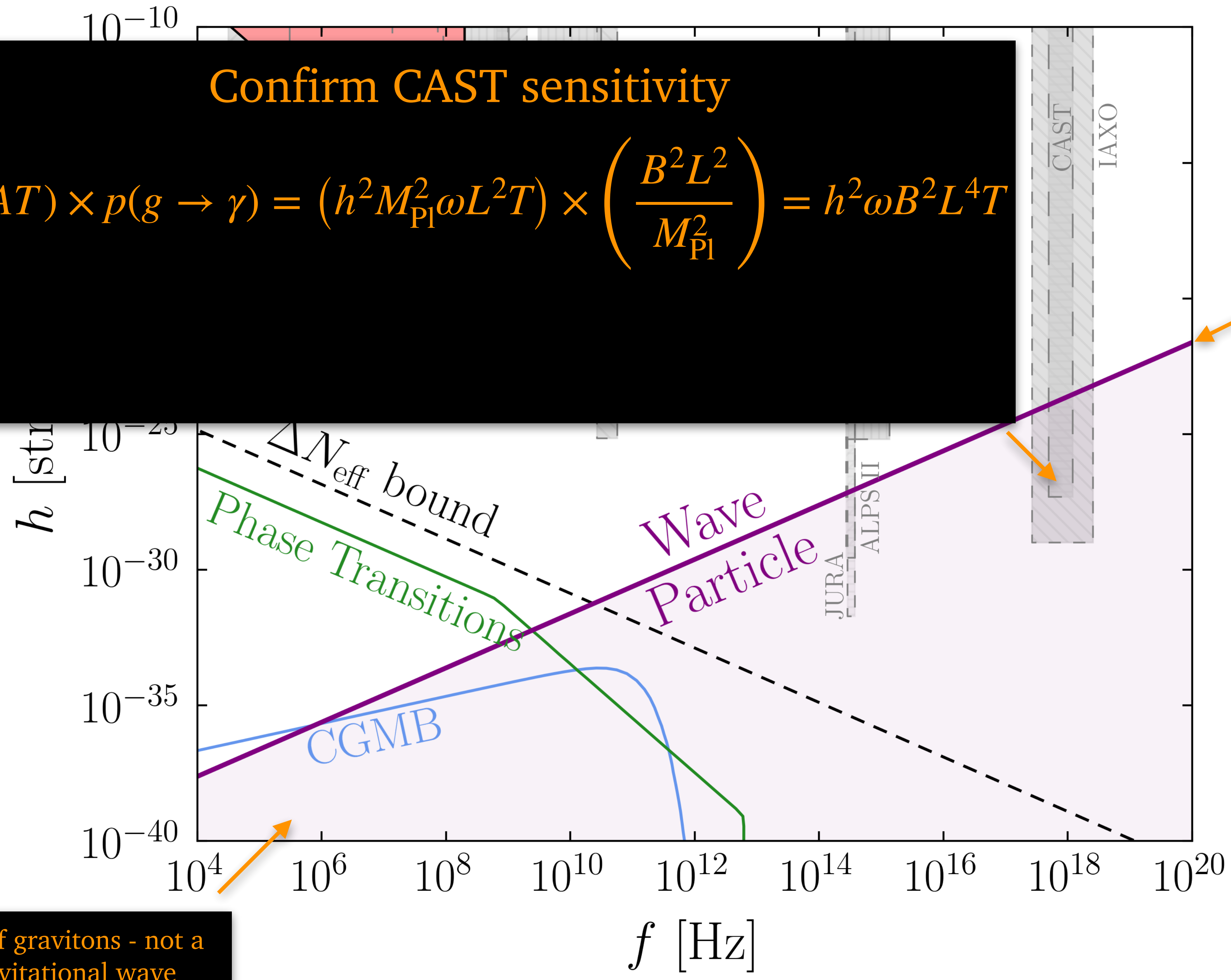
$$n_h \lambda_h^3 \sim \frac{\rho}{\omega^4} \sim \frac{h^2 M_{\rm Pl}^2}{\omega^2} \sim 1$$



Gas of gravitons - not a gravitational wave

[Domcke, Garcia-Cely, NLR 2022]

Future Directions



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$$(n_h A T) \times p(g \to \gamma) = \left(h^2 M_{\rm Pl}^2 \omega L^2 T\right) \times \left(\frac{B^2 L^2}{M_{\rm Pl}^2}\right) = h^2 \omega B^2 L^4 T$$

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Gas of gravitons - not a gravitational wave

[Domcke, Garcia-Cely, NLR 2022]

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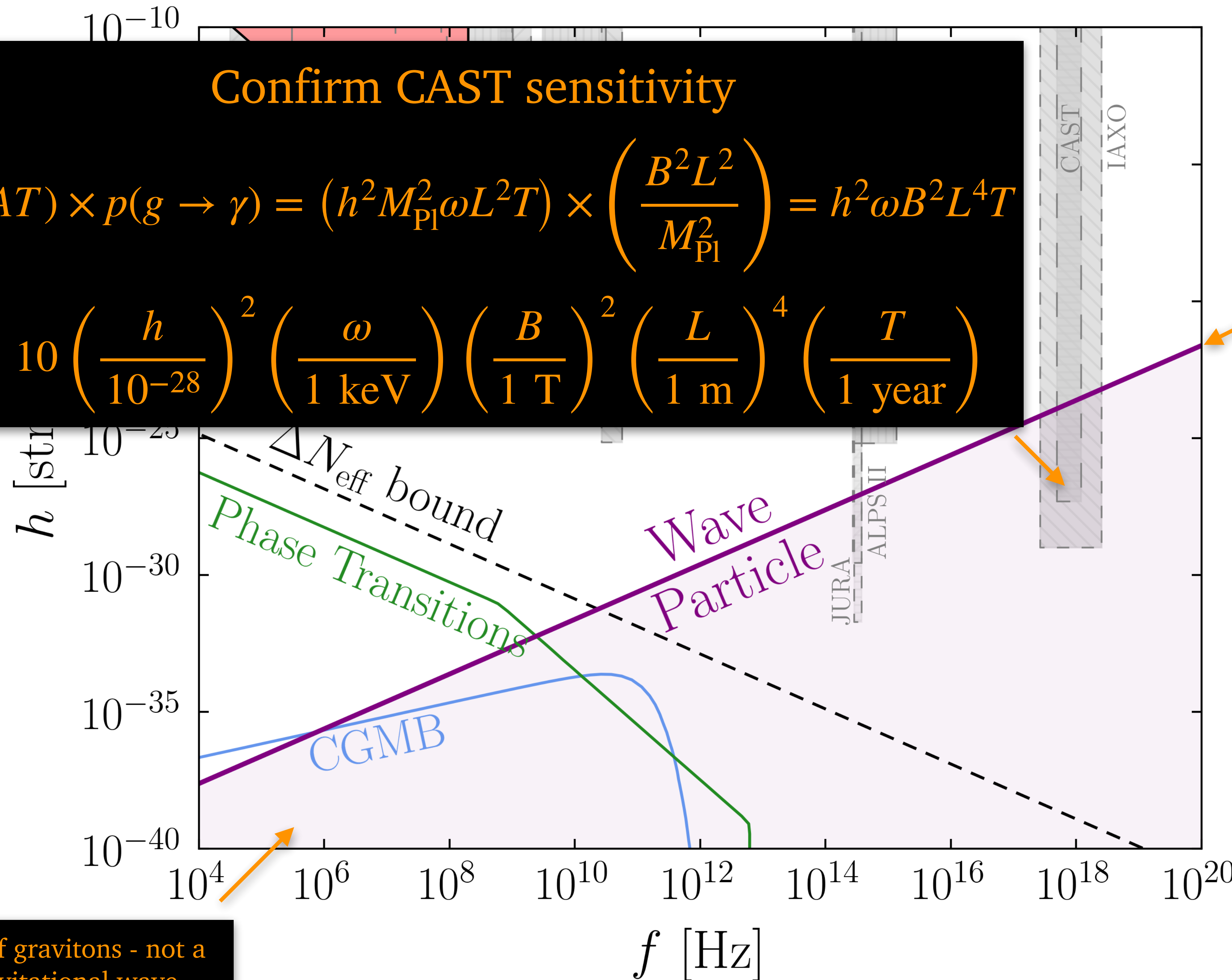


Confirm CAST sensitivity

$$(n_h A T) \times p(g \to \gamma) = \left(h^2 M_{\rm Pl}^2 \omega L^2 T\right) \times \left(\frac{B^2 L^2}{M_{\rm Pl}^2}\right) = h^2 \omega B^2 L^4 T$$

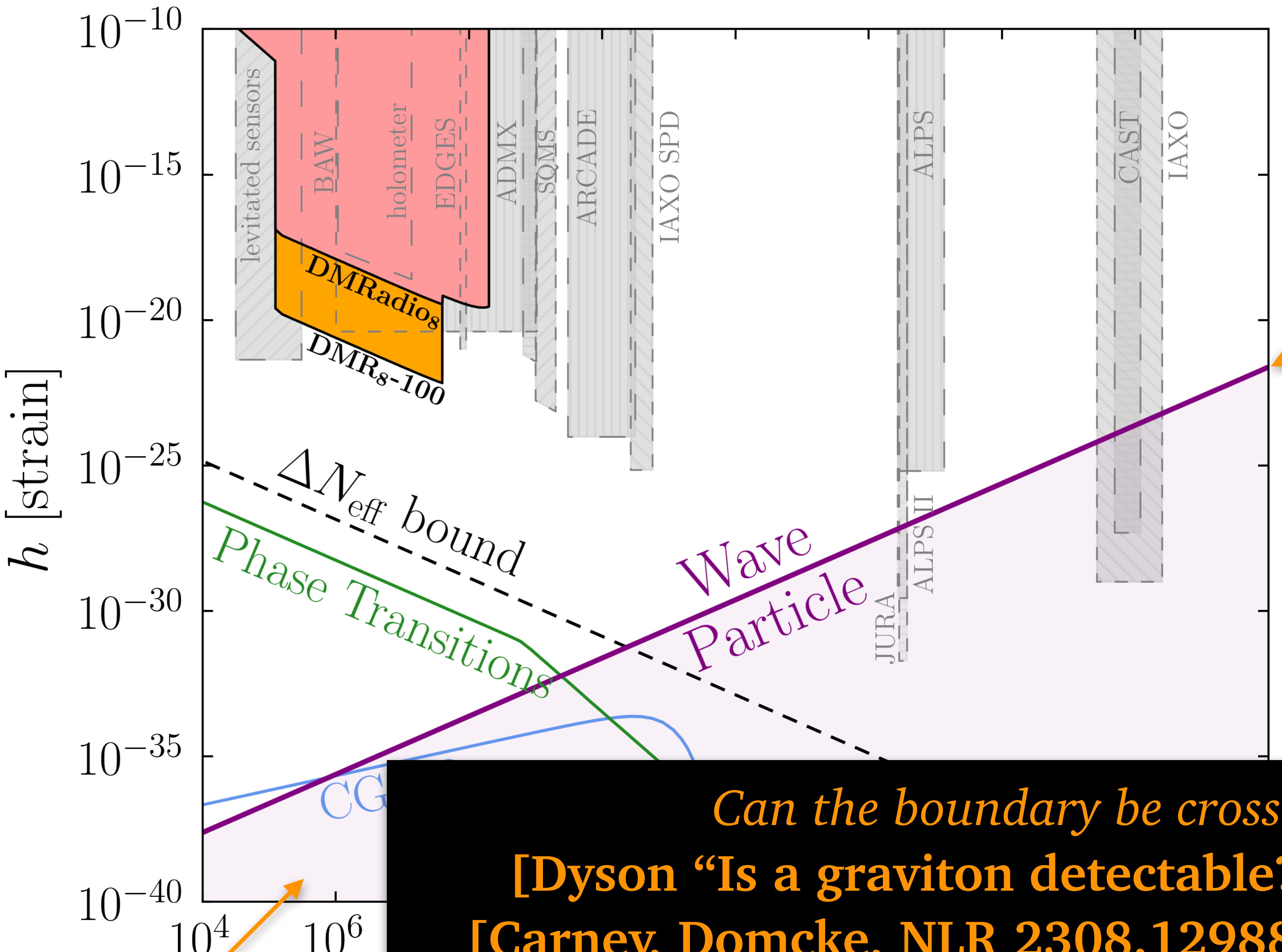
$$\sim 10 \left(\frac{h}{10^{-28}}\right)^2 \left(\frac{\omega}{1\ \text{keV}}\right) \left(\frac{B}{1\ \text{T}}\right)^2 \left(\frac{L}{1\ \text{m}}\right)^4 \left(\frac{T}{1\ \text{year}}\right)$$

$$n_h \lambda_h^3 \sim \frac{\rho}{\omega^4} \sim \frac{h^2 M_{\rm Pl}^2}{\omega^2} \sim 1$$

Gas of gravitons - not a gravitational wave

[Domcke, Garcia-Cely, NLR 2022]

Future Directions



$$n_h \lambda_h^3 \sim \frac{\rho}{\omega^4} \sim \frac{h^2 M_{\rm Pl}^2}{\omega^2} \sim 1$$

Gas of gravitons - not a gravitational wave

Can the boundary be crossed?

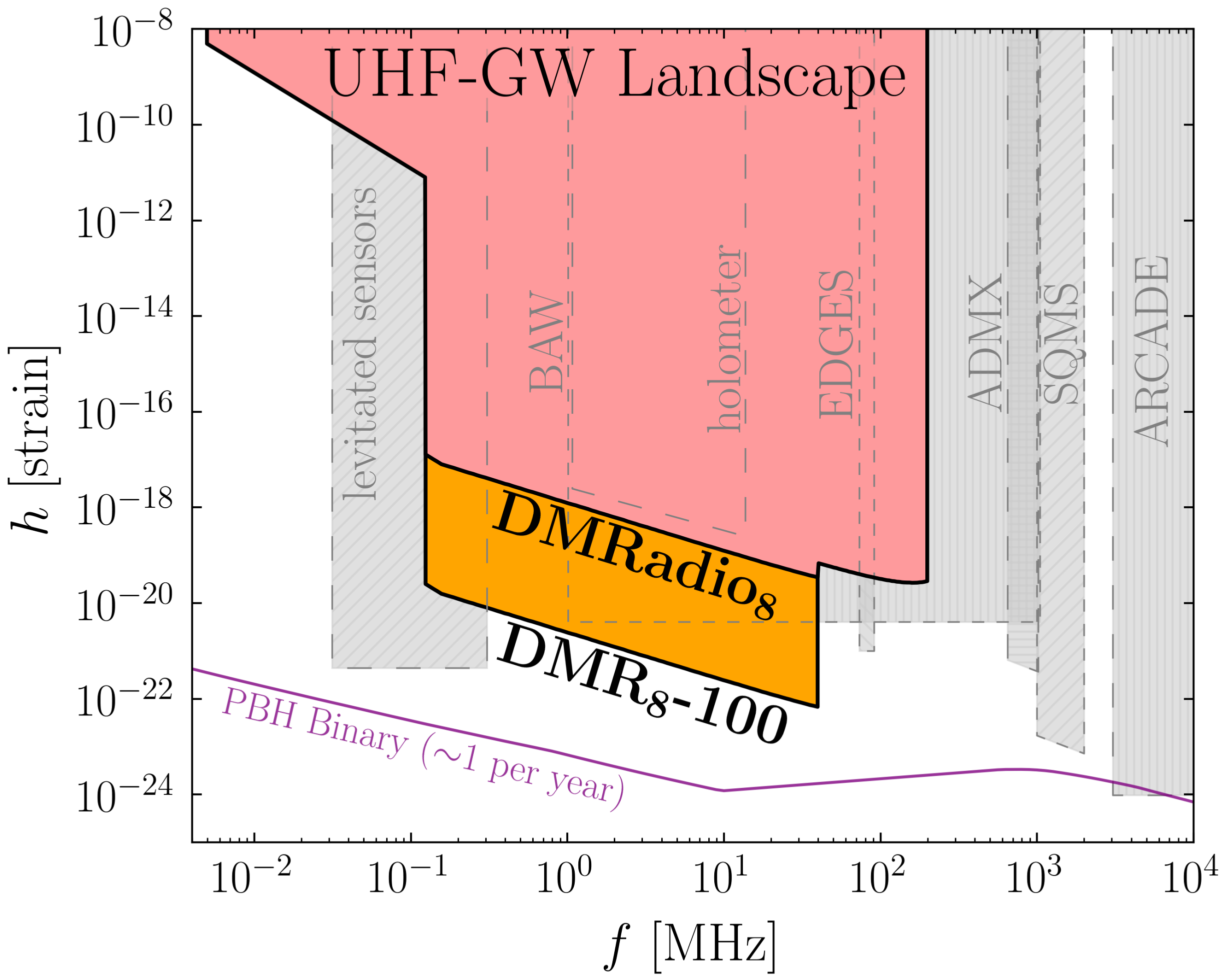
[Dyson "Is a graviton detectable?" 2013] No

[Carney, Domcke, NLR 2308.12988] Yes, but this wouldn't prove gravity was quantised

[Domcke, Garcia-Cely, NLR 2022]

Summary

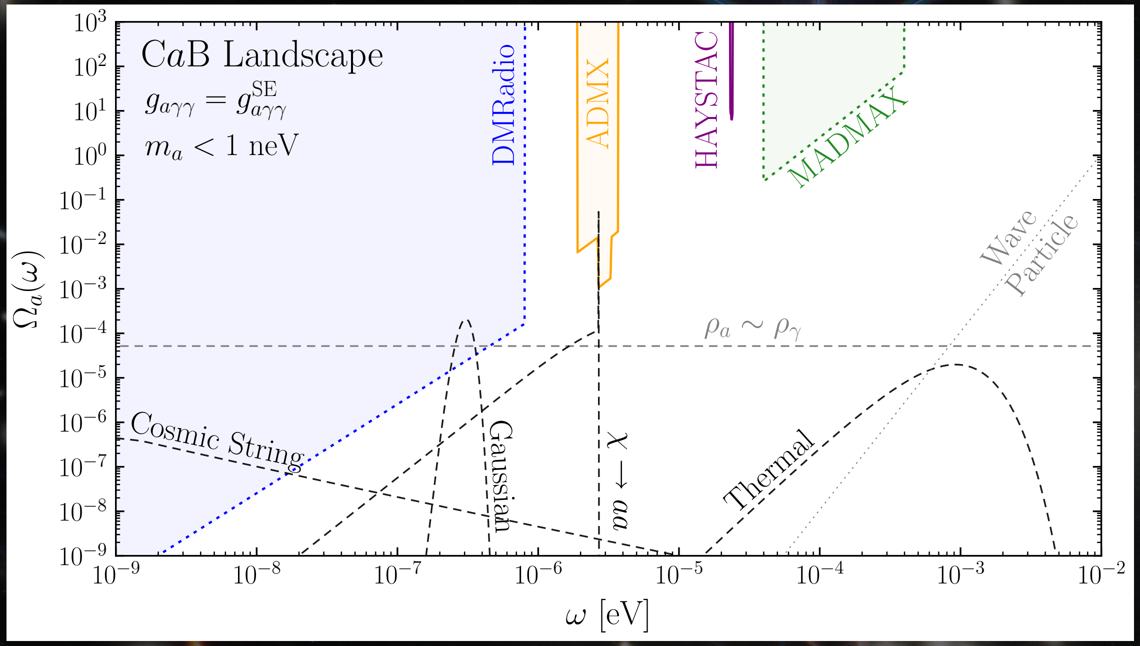
Axion haloscopes are gravitational wave telescopes



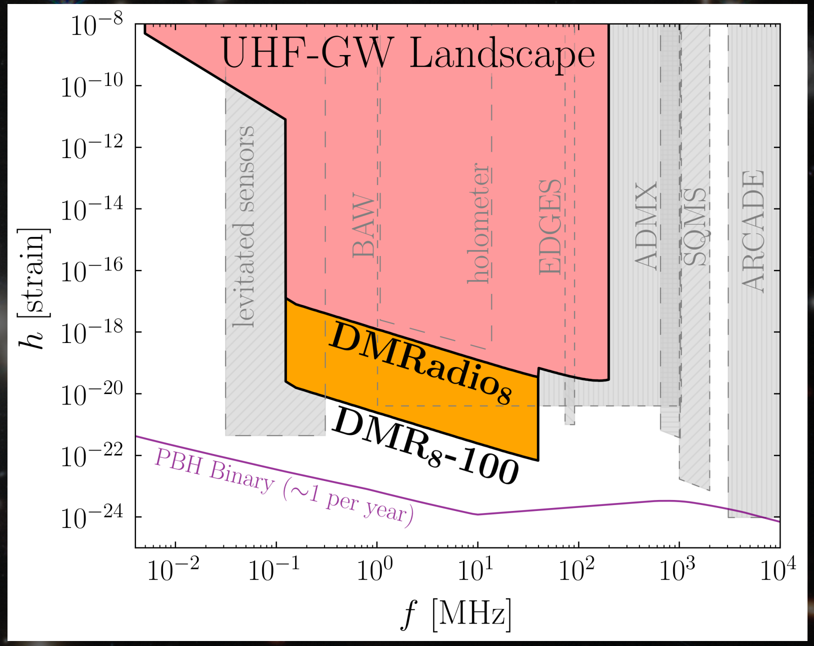
[Domcke, Garcia-Cely, NLR 2022]

Conclusion

Our deepening search for dark matter opens a path to many new discoveries



[Dror, Murayama, NLR PRD 2021]

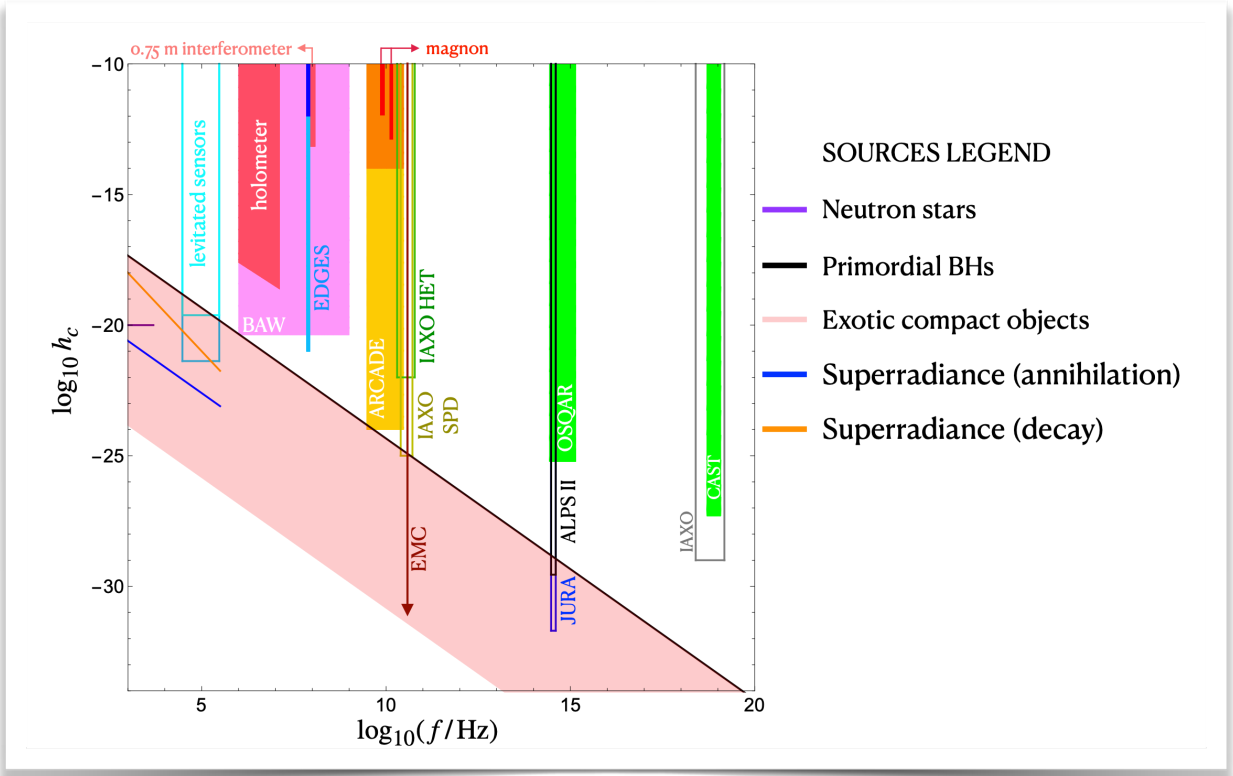


[Domcke, Garcia-Cely, NLR PRL 2022]

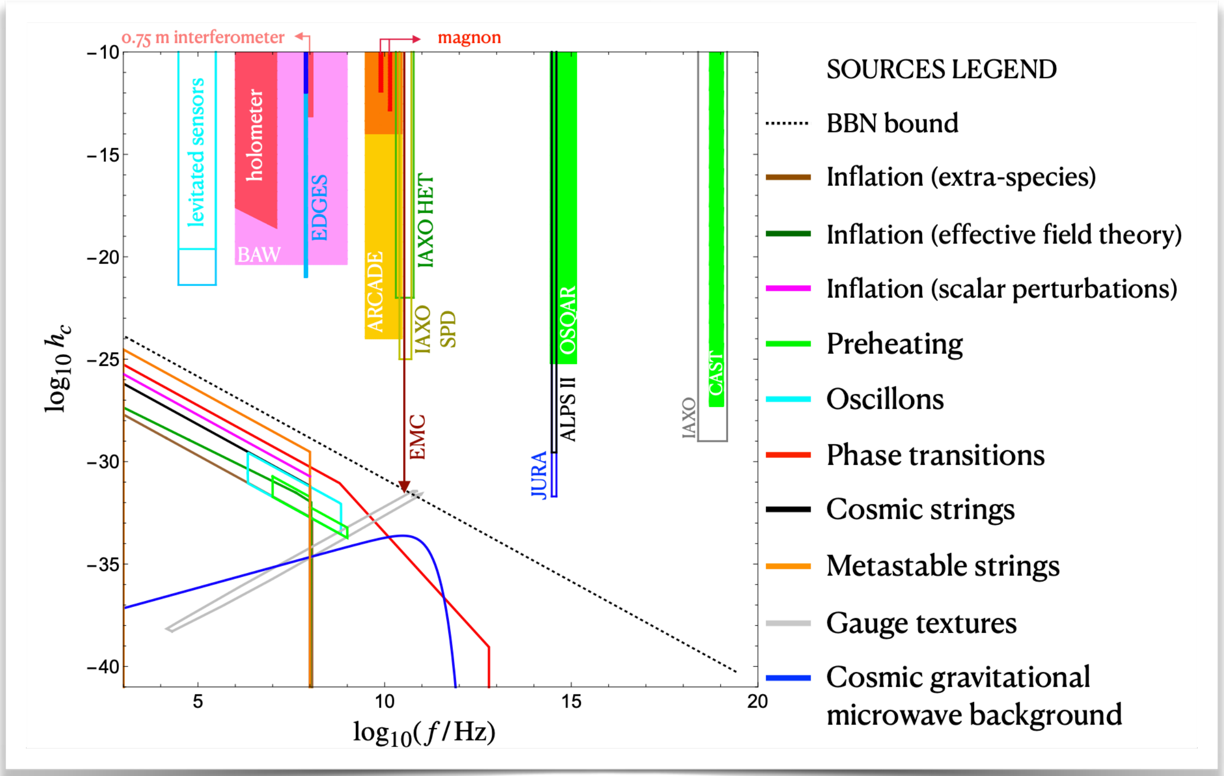
Backup Slides

Sources

Late Universe



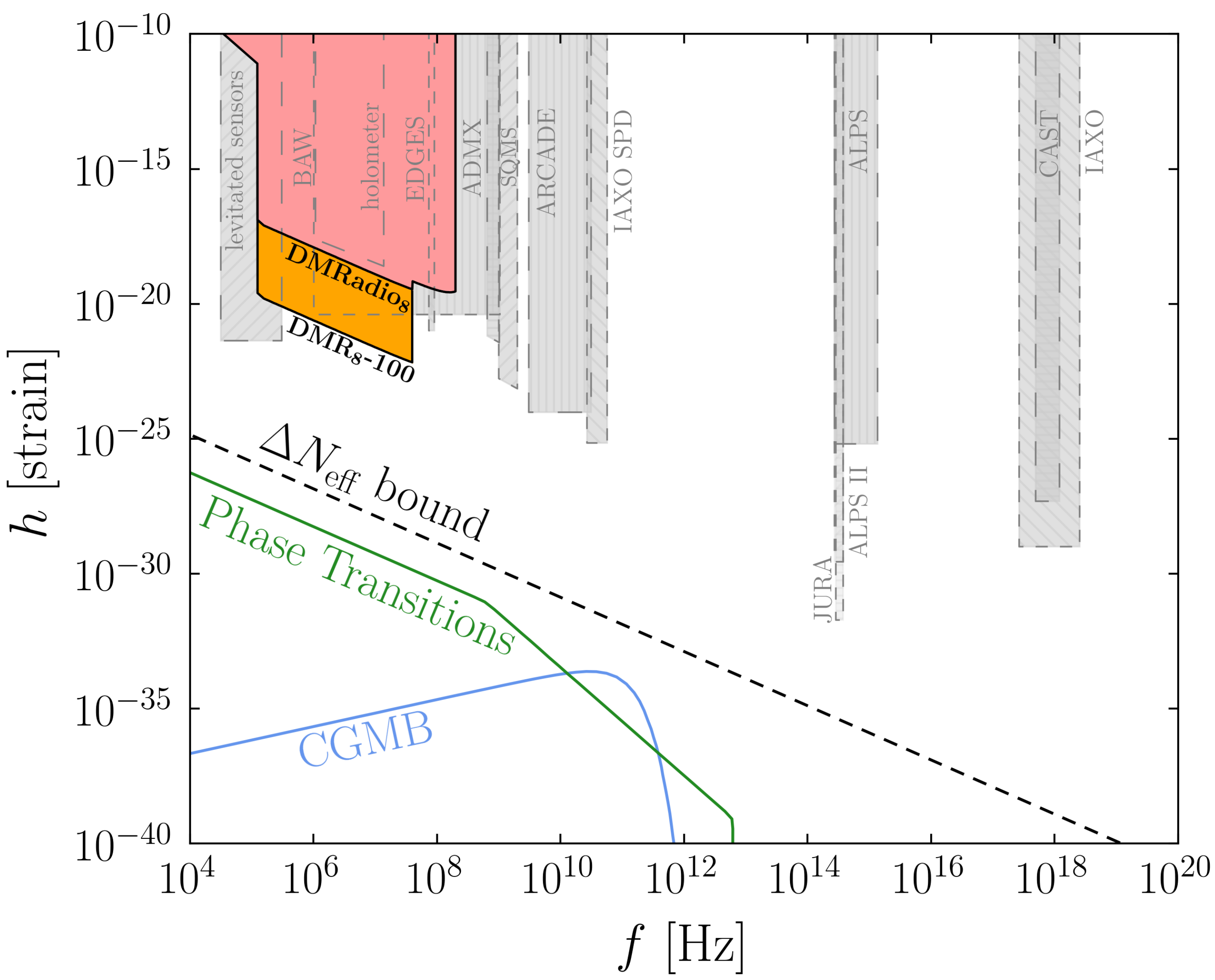
Early Universe



[Aggarwal+ 2020]

[Domcke, Garcia-Cely, NLR 2022]

Sources: Phase Transitions



Temperature of PT

$$f \simeq 3\ \text{GHz} \left(\frac{1}{\epsilon_\star}\right)\left(\frac{T_\star}{10^{16}\ \text{GeV}}\right)$$

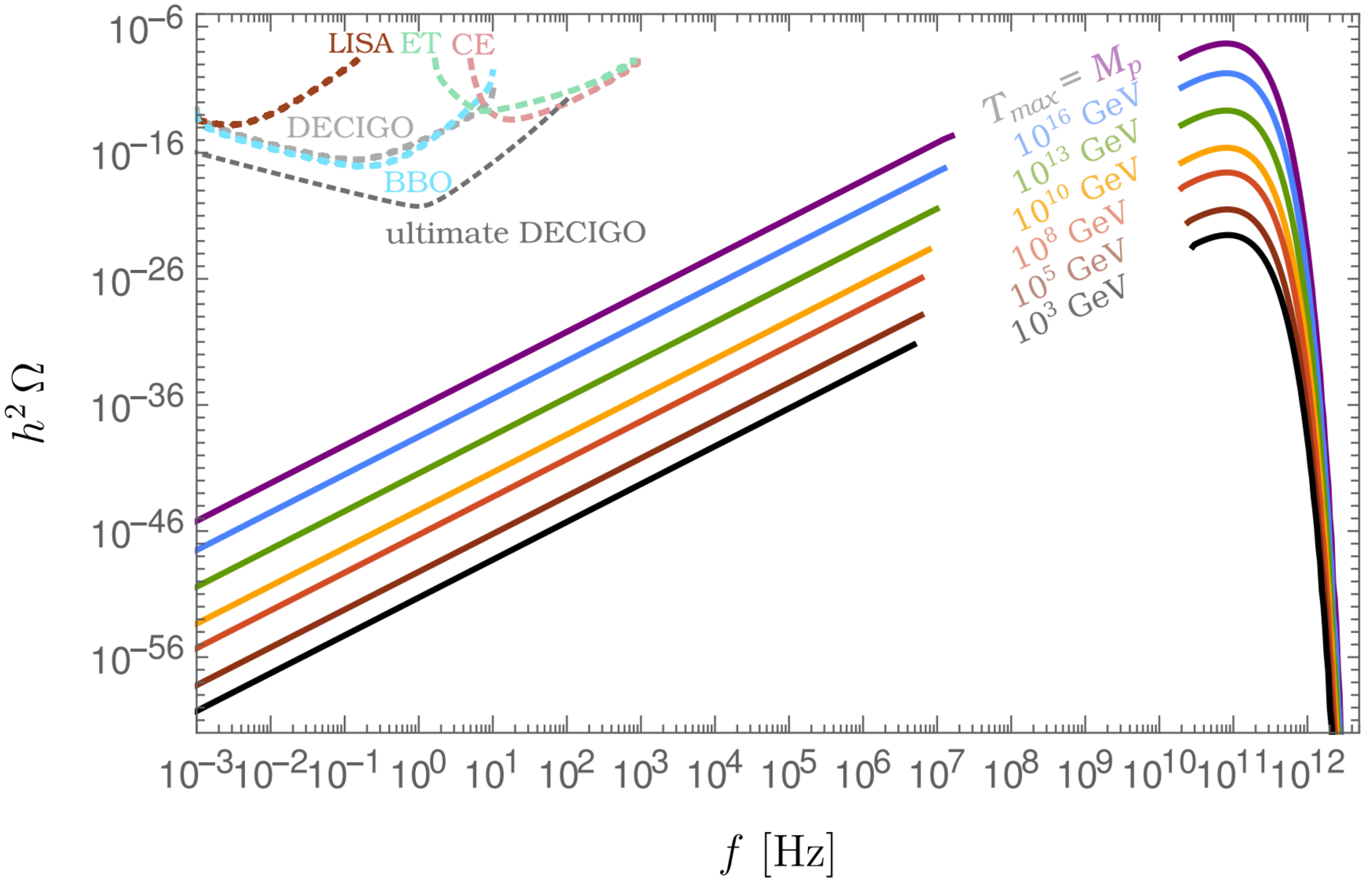
$\epsilon_\star = \lambda_\star H_\star$

$\lambda_\star$ = GW wavelength at PT

[Domcke, Garcia-Cely, NLR 2022]

Sources: CGMB

Blackbody only if $T_{\mathrm{RH}} > M_{\mathrm{Pl}}$ - arises from non-thermal emission



[Ringwald, Schütte-Engel, Tamarit 2020]

[Domcke, Garcia-Cely, NLR 2022]

Proper Detector Frame

TT gauge: GW is a plane wave $\sim e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}$

Proper Detector Frame: more involved

$$h_{00} = \omega^2 F(\mathbf{k}\cdot\mathbf{r})\,\mathbf{b}\cdot\mathbf{r}, \qquad b_j \equiv r_i h_{ij}^{\mathrm{TT}}\big|_{\mathbf{r}=0},$$

$$h_{0i} = \frac{1}{2}\omega^2\left[F(\mathbf{k}\cdot\mathbf{r}) - iF'(\mathbf{k}\cdot\mathbf{r})\right]\left(\hat{\mathbf{k}}\cdot\mathbf{r}\;b_i - \mathbf{b}\cdot\mathbf{r}\;\hat{k}_i\right),$$

$$h_{ij} = -i\omega^2 F'(\mathbf{k}\cdot\mathbf{r})\left(|\mathbf{r}|^2\, h_{ij}^{\mathrm{TT}}\big|_{\mathbf{r}=0} + \mathbf{b}\cdot\mathbf{r}\,\delta_{ij} - b_i r_j - b_j r_i\right),$$

$$F(\xi) = (e^{i\xi} - 1 - i\xi)/\xi^2 = -1/2 + \mathcal{O}(\xi)$$

See also [Domcke, Garcia-Cely, Lee, NLR 2306.03125]

[Domcke, Garcia-Cely, NLR 2022]

Proper Detector Frame

TT gauge: GW is a plane wave $\sim e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}$

Proper Detector Frame: more involved

$$h_{00} = \omega^2 F(\mathbf{k}\cdot\mathbf{r})\,\mathbf{b}\cdot\mathbf{r} \qquad b_i = x_j h^{\rm TT}_{ij}$$

$$h_{0i} = \frac{1}{2}\omega^2 [F(\ldots$$

$$h_{ij} = -i\omega^2 F'(\ldots x_i),$$

$$F(\xi) = (e^{i\xi} - 1 - i\xi)/\xi^2 = -1/2 + \mathcal{O}(\xi)$$

$$g_{\mu\nu}(x) = \underbrace{g_{\mu\nu}(x_0)}_{=\eta_{\mu\nu}} + \underbrace{(x-x_0)^\alpha \partial_\alpha g_{\mu\nu}(x_0)}_{=0 \;\; (\because\; \Gamma^\mu_{\nu\rho}(x_0)=0)} + \underbrace{(x-x_0)^\alpha (x-x_0)^\beta \partial_\alpha \partial_\beta g_{\mu\nu}(x_0)}_{\mathcal{O}(\omega^2 R^2)} + \ldots$$

See also [Domcke, Garcia-Cely, Lee, NLR 2306.03125]

[Domcke, Garcia-Cely, NLR 2022]

Proper Detector Frame

In the TT gauge GW satisfies

$$h_{0\mu} = 0, \quad h^{\mu}{}_{\mu} = 0, \quad \partial^{\mu} h_{\mu\nu} = 0$$

Treating the GW as a plane wave, takes the form

$$h_{ij}^{\rm TT} = \left[\left({\rm U}_i {\rm U}_j - {\rm V}_i {\rm V}_j \right) h^{+} + \left({\rm U}_i {\rm V}_j + {\rm V}_i {\rm U}_j \right) h^{\times} \right] \frac{e^{i(\mathbf{k}\cdot\mathbf{r} - \omega t)}}{\sqrt{2}},$$

$$\hat{\mathbf{k}} = s_{\theta_h} \hat{\mathbf{e}}_{\rho}^{\phi_h} + c_{\theta_h} \hat{\mathbf{e}}_z, \;\; \mathbf{V} = \hat{\mathbf{e}}_{\phi}^{\phi_h}, \;\; \mathbf{U} = \mathbf{V} \times \hat{\mathbf{k}}$$

Incident angle (θ_h, ϕ_h)

Convention

TT frame is not a locally inertial coordinate system: description of experimental apparatus complex

[Domcke, Garcia-Cely, NLR 2022]

Proper Detector Frame

Use Fermi normal coordinates

Locally inertial coordinates along a geodesic **[Fermi 1922]**

$$h_{ij} = -2\sum_{n=0}^{\infty} \frac{n+1}{(n+3)!} \hat{R}_{ikjl,m_1\ldots m_n} r_k r_l r_{m_1} \ldots r_{m_n} \,,$$

$$h_{0i} = -2\sum_{n=0}^{\infty} \frac{n+2}{(n+3)!} \hat{R}_{0kil,m_1\ldots m_n} r_k r_l r_{m_1} \ldots r_{m_n} \,,$$

$\hat{R}$ is evaluated at the coordinate origin

$$h_{00} = -2\sum_{n=0}^{\infty} \frac{n+3}{(n+3)!} \hat{R}_{0k0l,m_1\ldots m_n} r_k r_l r_{m_1} \ldots r_{m_n}$$

[Fortini and Gualdi 1982], [Marzlin 1994], [Rakhmanov 2014]

Proper Detector Frame

Proper detector frame:
Fermi normal coordinates transformed to the non-inertial reference frame of the detector

[Ni, Zimmermann 1978]

Non-inertial corrections (Earth's gravity, Coriolis effect, etc) are irrelevant at higher frequencies - effectively can just use Fermi normal coordinates

[Domcke, Garcia-Cely, NLR 2022]

Proper Detector Frame

All orders currents for a toroidal magnetic field

$$j_\phi = \frac{\omega^2 B_{\max} R}{\rho}\left[\frac{e^\kappa}{\kappa} - \frac{2e^\kappa}{\kappa^2} + \frac{2(e^\kappa - 1)}{\kappa^3}\right]\left(z\, h^{\rm TT}_{\rho\phi}\big|_{\mathbf{r}=0} - \rho\, h^{\rm TT}_{\phi z}\big|_{\mathbf{r}=0}\right),$$

$$\begin{aligned} j_\rho = \frac{\omega^2 B_{\max} R}{\rho}\Bigg(&\left[-\frac{1}{2} - \frac{1}{\kappa} + \frac{2e^\kappa}{\kappa^2} + \frac{2(1-e^\kappa)}{\kappa^3}\right]\left(\rho\, h^{\rm TT}_{\rho z}\big|_{\mathbf{r}=0} + z\, h^{\rm TT}_{zz}\big|_{\mathbf{r}=0}\right) \\ &+ \left[\frac{e^\kappa}{\kappa} + \frac{2}{\kappa^2} + \frac{2(1-e^\kappa)}{\kappa^3}\right]\left(z\, h^{\rm TT}_{\rho\rho}\big|_{\mathbf{r}=0} + z\, h^{\rm TT}_{zz}\big|_{\mathbf{r}=0}\right) \\ &+ i k_z\left[\frac{1}{2\kappa} + \frac{1}{2\kappa^2} - \frac{1+2e^\kappa}{\kappa^3} + \frac{3(e^\kappa - 1)}{\kappa^4}\right] r_i r_j h^{\rm TT}_{ij}\big|_{\mathbf{r}=0}\Bigg), \end{aligned}$$

$\kappa = i\mathbf{k}\cdot\mathbf{r}$

$$h^{\rm TT}_{\rho\rho}\big|_{\mathbf{r}=0} = \frac{e^{-i\omega t}}{\sqrt{2}}\left(-h^+(\sin^2(\phi-\phi_h) - \cos^2(\phi-\phi_h)\cos^2\theta_h) + 2\,h^\times \cos\theta_h\cos(\phi-\phi_h)\sin(\phi-\phi_h)\right),$$

$$h^{\rm TT}_{\rho\phi}\big|_{\mathbf{r}=0} = \frac{e^{-i\omega t}}{\sqrt{2}}\left(-h^+(1+\cos^2\theta_h)\sin(\phi-\phi_h)\cos(\phi-\phi_h) + h^\times\cos(2(\phi-\phi_h))\cos\theta_h\right),$$

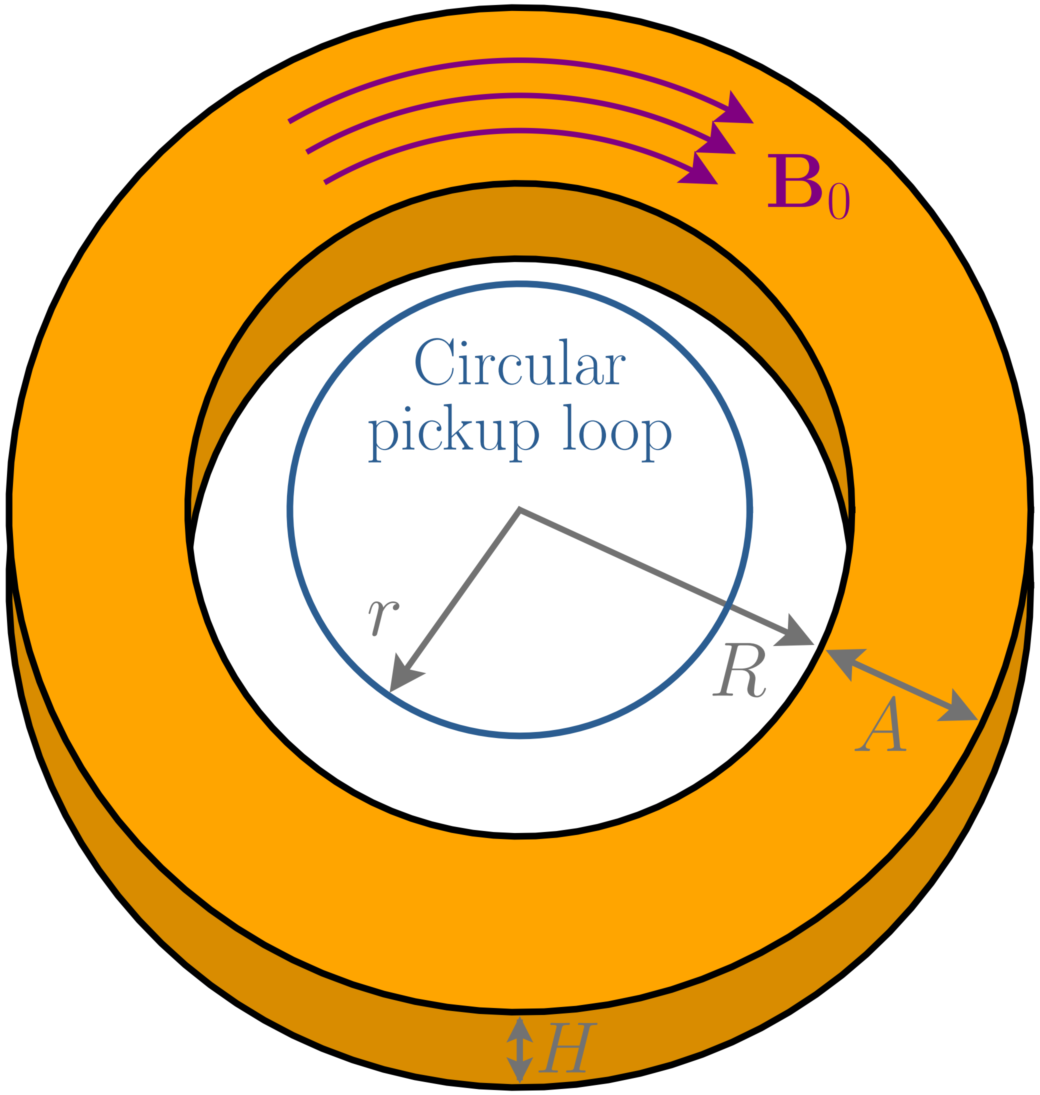
$$h^{\rm TT}_{\rho z}\big|_{\mathbf{r}=0} = -\frac{e^{-i\omega t}}{\sqrt{2}}\left(h^+\cos\theta_h\sin\theta_h\cos(\phi-\phi_h) + h^\times\sin\theta_h\sin(\phi-\phi_h)\right),$$

$$h^{\rm TT}_{\phi z}\big|_{\mathbf{r}=0} = \frac{e^{-i\omega t}}{\sqrt{2}}\left(h^+\cos\theta_h\sin\theta_h\sin(\phi-\phi_h) - h^\times\sin\theta_h\cos(\phi-\phi_h)\right),$$

$$h^{\rm TT}_{zz}\big|_{\mathbf{r}=0} = \frac{e^{-i\omega t}}{\sqrt{2}} h^+\sin^2\theta_h.$$

[Domcke, Garcia-Cely, NLR 2022]

Detection Strategy

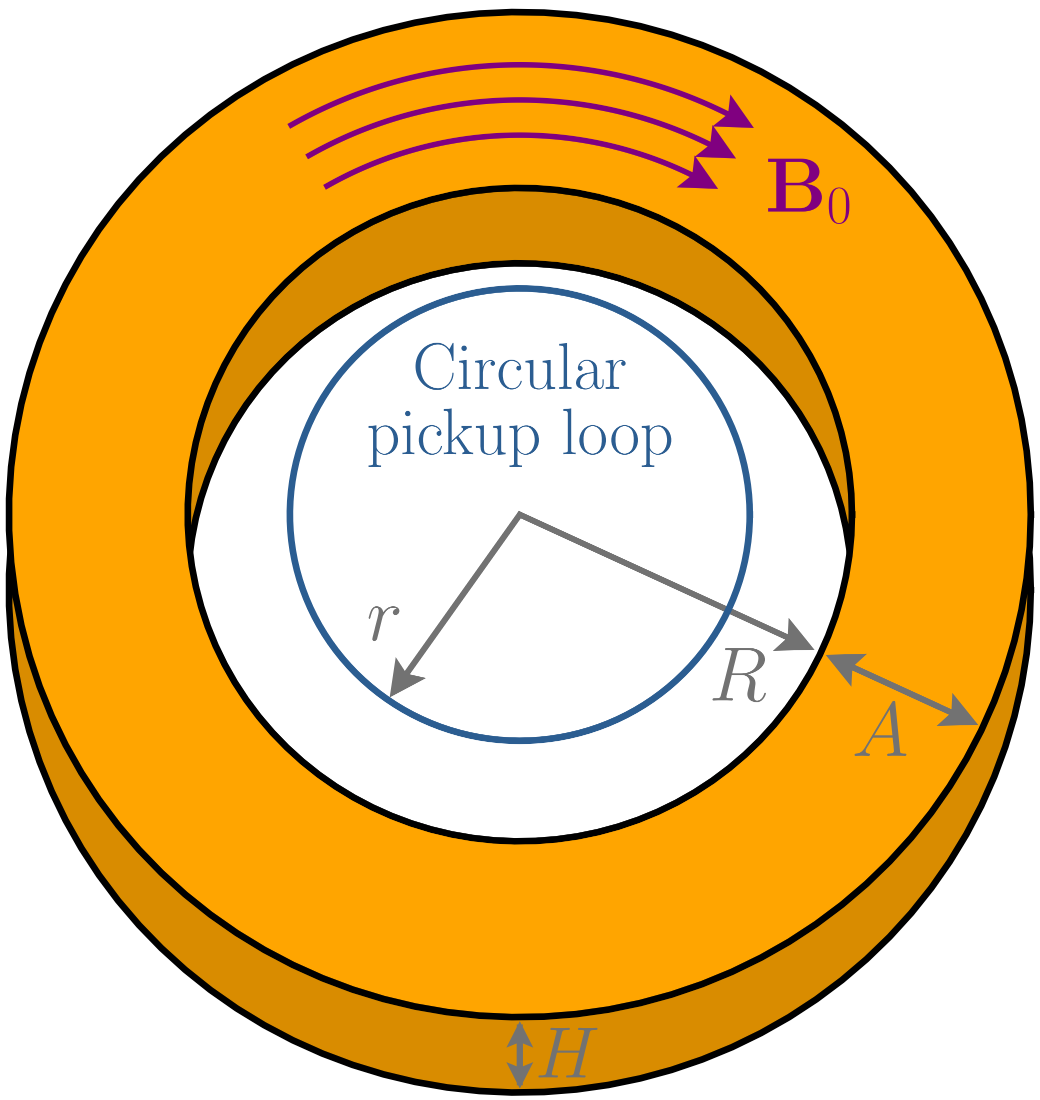


cf. axion
$\Phi_a(t) \sim g_{a\gamma\gamma}(\partial_t a) B_0 V$

$$\Phi_h(t) \simeq \frac{ie^{-i\omega t}}{16\sqrt{2}} \omega^3 h^\times B_0 \pi r^2 RA(A+2R) \sin^2\theta_h \sim \omega^3 h B_0 V^{5/3}$$

[Domcke, Garcia-Cely, NLR 2022]

Detection Strategy



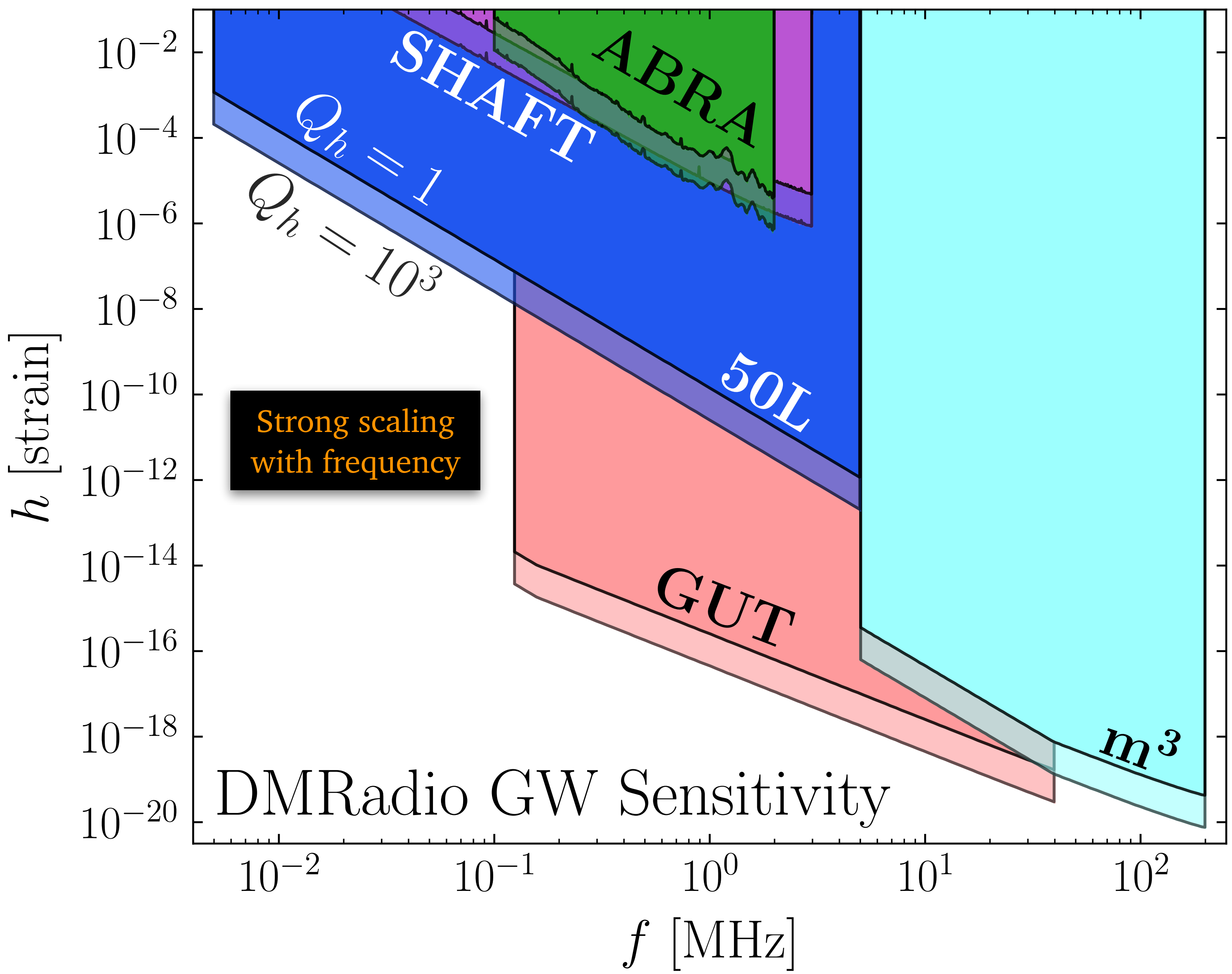
$\mathcal{O}(\omega^2)$ contribution has vanished!

$$\Phi_h(t) \simeq \frac{ie^{-i\omega t}}{16\sqrt{2}}\omega^3 h^\times B_0 \pi r^2 RA(A+2R)\sin^2\theta_h \sim \omega^3 h B_0 V^{5/3}$$

[Domcke, Garcia-Cely, NLR 2022]

Circular pickup loop reach

Sensitivity set by $\Phi_h = \Phi_a (Q_a/Q_h)^{1/4}$



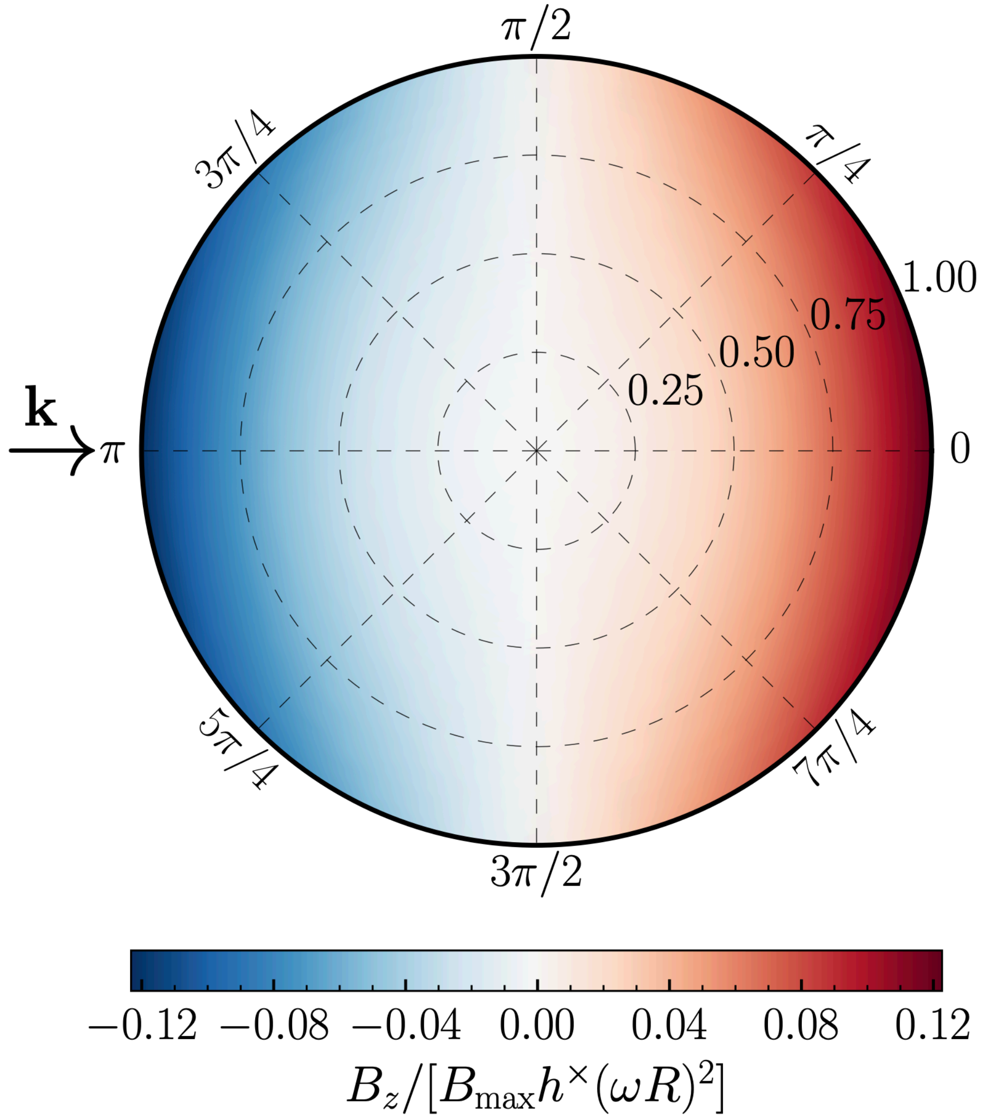
Strong scaling with frequency

Comparable to $h \sim 10^{-22}$

[Domcke, Garcia-Cely, NLR 2022]

Optimized Reach

What happened to the leading contribution?



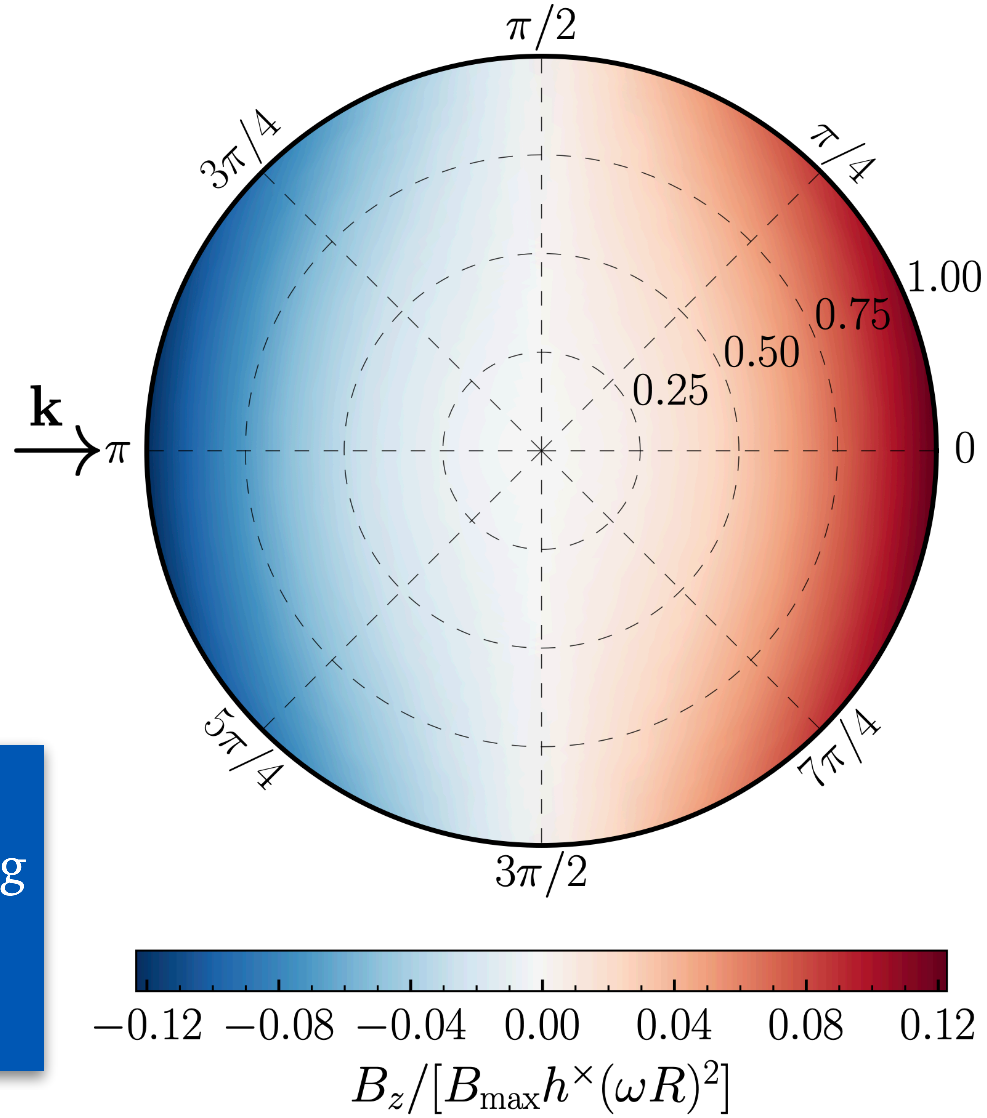
Leading contribution vanishes when integrated over a circular pickup loop

But why? Symmetry imposes selection rules GW must satisfy

[Domcke, Garcia-Cely, Lee, NLR 2023]

Optimized Reach

What happened to the leading contribution?



Leading contribution vanishes when integrated over a circular pickup loop

Selection rules: determine leading terms without calculating
Apply also to scalar (ϕF^2) vs axion ($aF\tilde{F}$)

But why? Symmetry imposes selection rules GW must satisfy

[Domcke, Garcia-Cely, Lee, NLR 2023]

What could CAST see?

Detecting gravitons requires an extremely large flux

$$p(g \to \gamma) \simeq 4.6 \times 10^{-35} \left(\frac{B}{9\ \mathrm{T}}\right)^2 \left(\frac{L}{9.26\ \mathrm{m}}\right)^2$$

Could be produced by a nearby PBH inspiral, naively require

$$m \simeq 2 \times 10^{-15}\ M_\odot, \qquad d \simeq 1.4 \times 10^6\ \mathrm{m} \simeq 0.2\ R_\oplus$$

At this mass, PBHs can be 100% of DM **[Carr, Kühnel 2021]**

Final merger generate $f \sim$ keV gravitons

Distance incorporates the extremely short duration of such a merger

But in principle possible, unlike examples Dyson gave

[Carney, Domcke, NLR 2023]

What could CAST see?

Would such a detection prove a GW is made of quanta? **No**

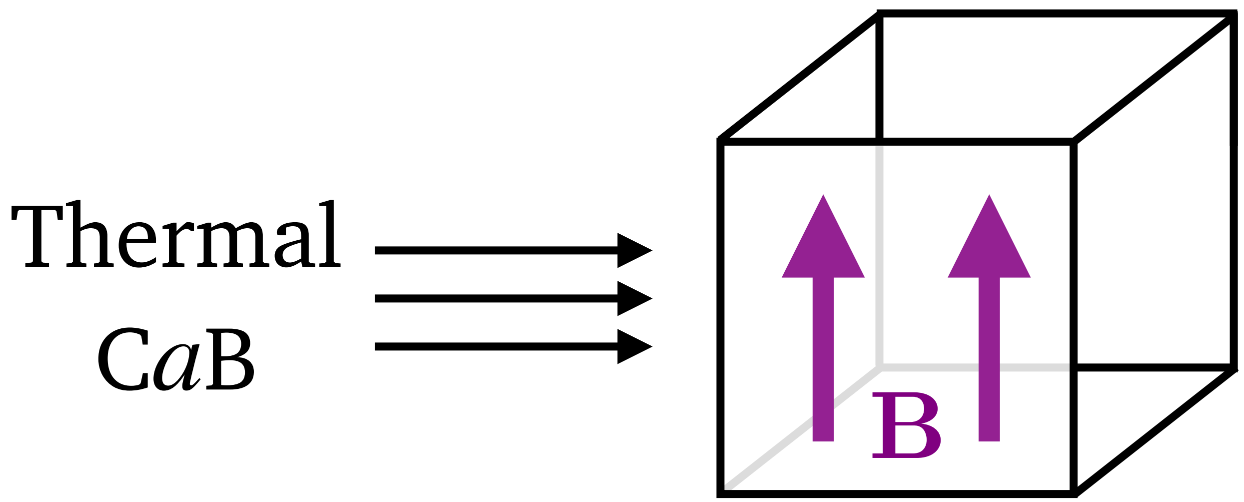
Even if the GW was perfectly antibunched, 1σ evidence for a quantised signal would require the following number of events

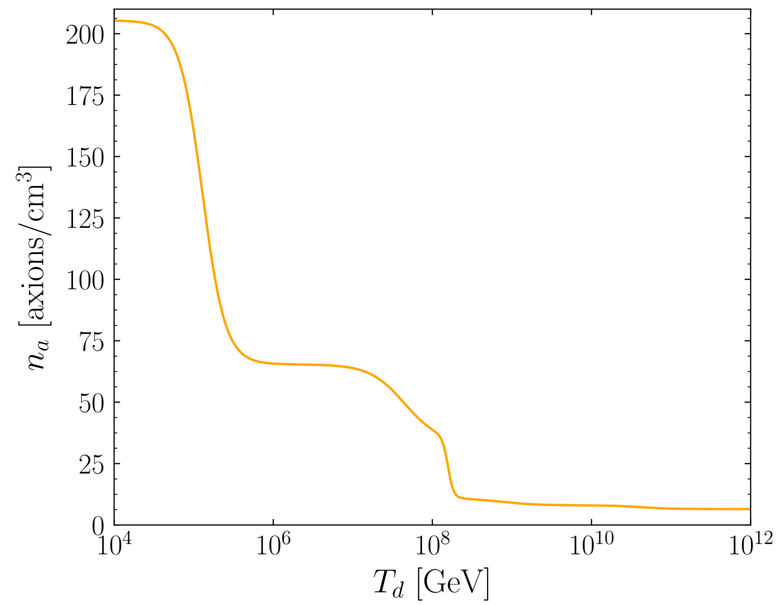
$$N \gtrsim p(g \to \gamma)^{-2} \simeq 10^{70}$$

Cf. the proposal on the last slide: $N = 1$

[Carney, Domcke, NLR 2023]

Detecting the Thermal CaB

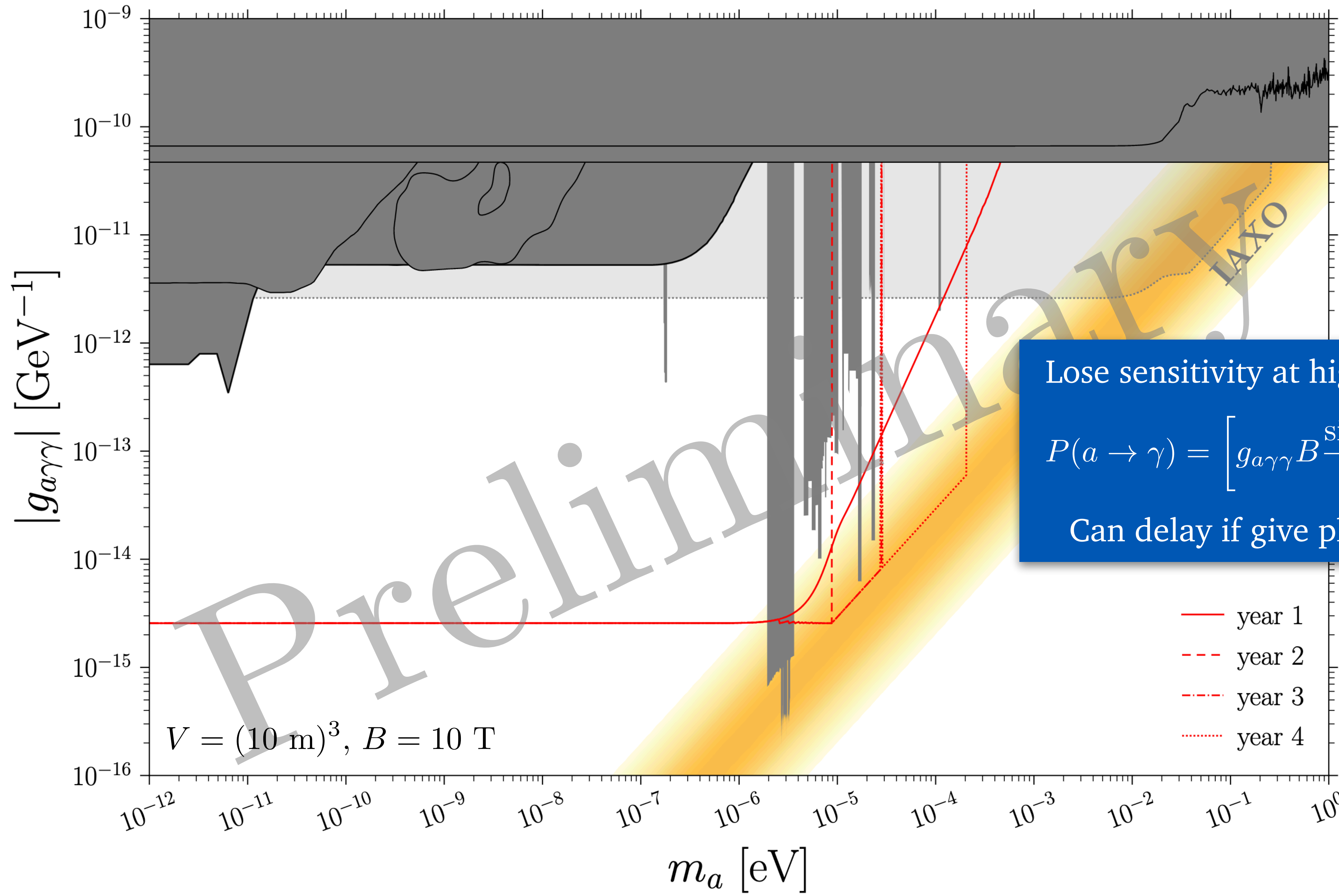




$$N(a \to \gamma) \simeq 2.5 \times 10^9 \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}} \right)^2 \left(\frac{B}{10\ \mathrm{T}} \right)^2 \left(\frac{L}{10\ \mathrm{m}} \right)^4 \left(\frac{t_{\mathrm{exp}}}{1\ \mathrm{year}} \right)$$

Potentially detectable!

Detecting the Thermal CaB



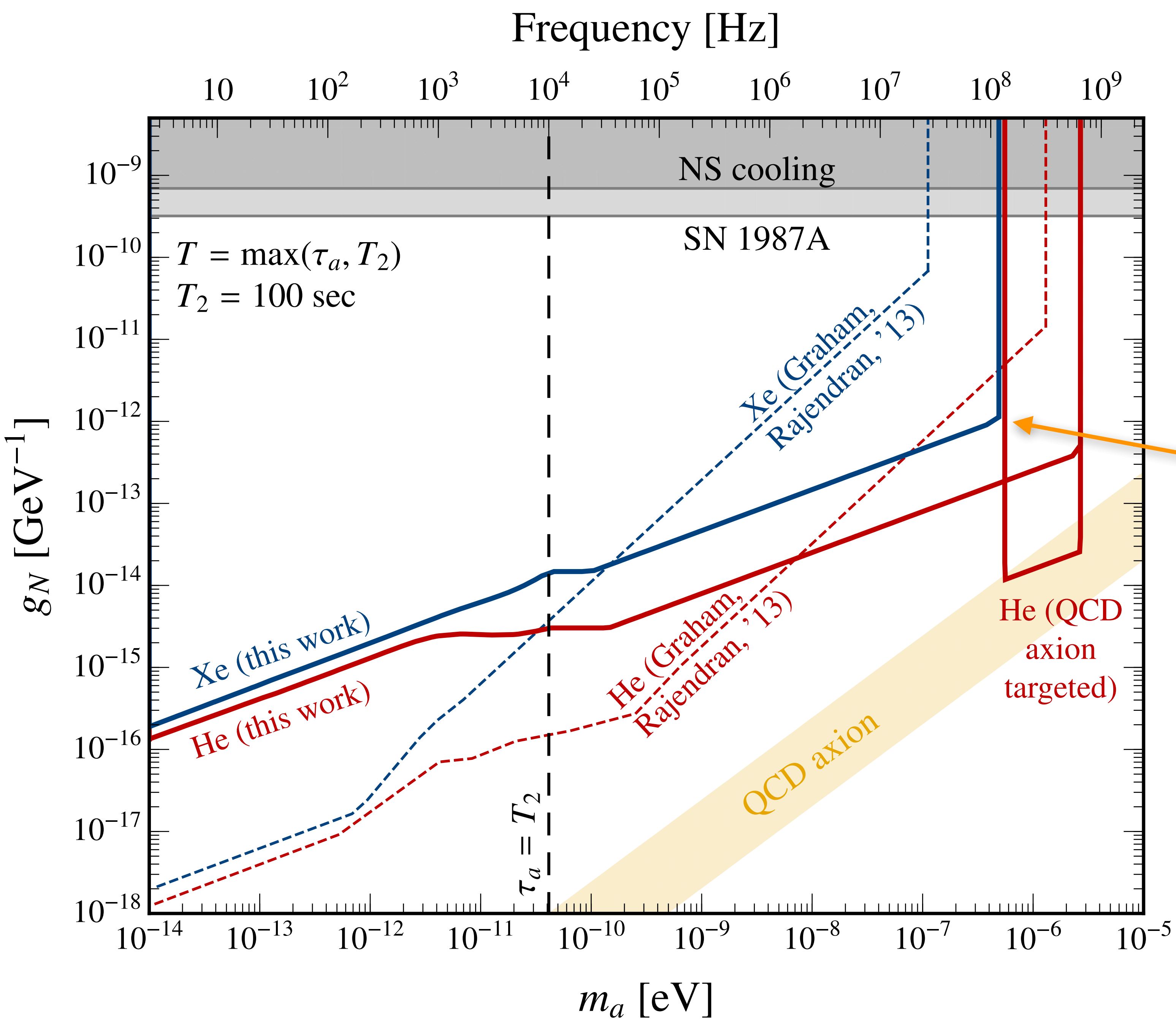
Lose sensitivity at higher masses as

$$P(a \to \gamma) = \left[g_{a\gamma\gamma} B \frac{\sin(m_a^2 L/2\omega_a)}{m_a^2/\omega_a} \right]^2$$

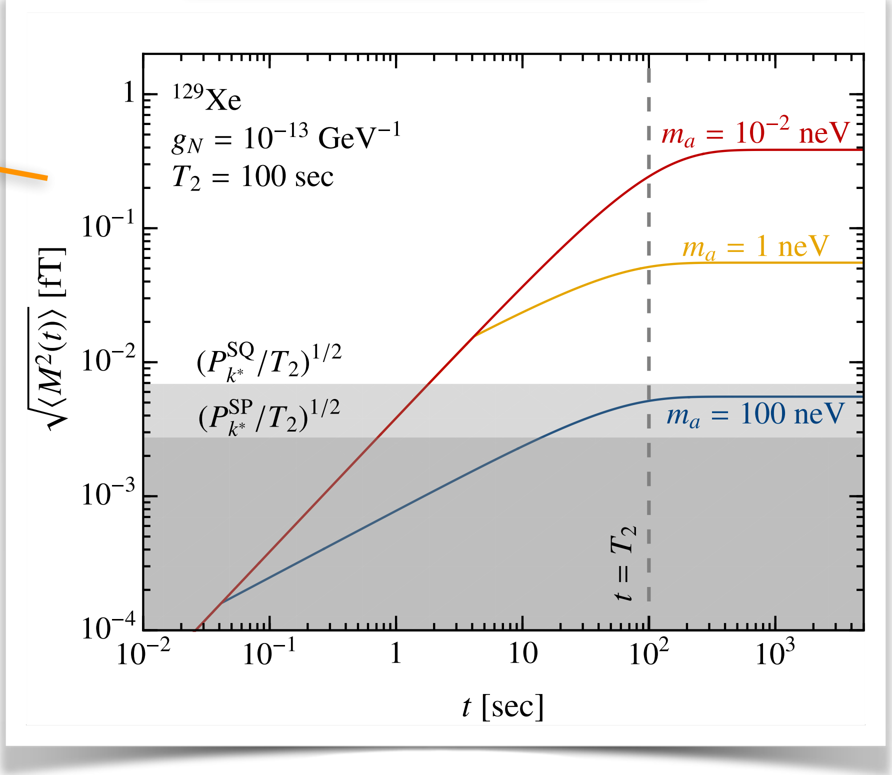
Can delay if give photon a mass

Axion NMR

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

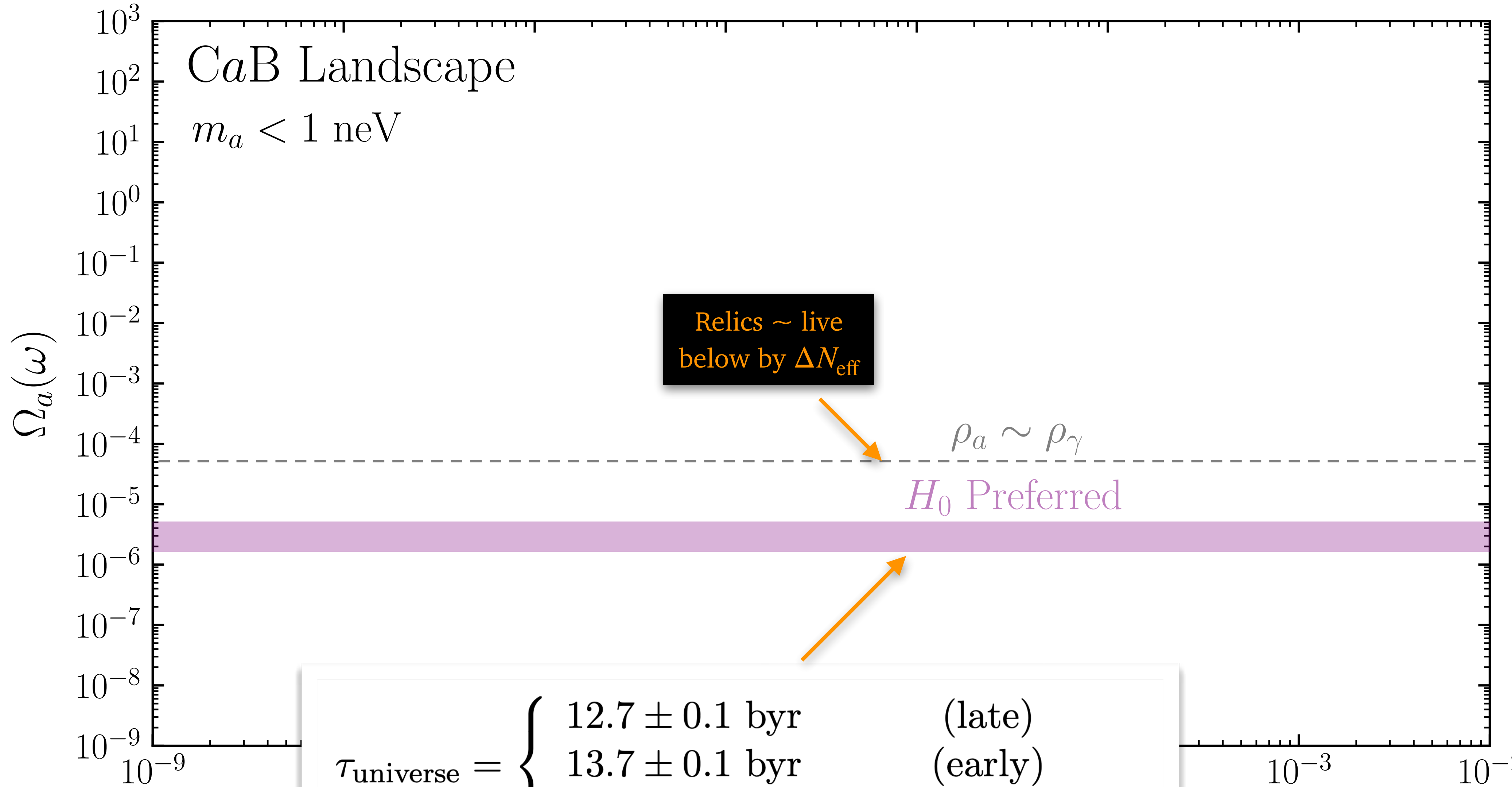


Axion signal continues to grow for $\tau_a < T < T_2$



[Dror, Gori, Leedom, NLR 2022]

Hubble Tension



$$\tau_{\rm universe} = \begin{cases} 12.7 \pm 0.1 \text{ byr} & \text{(late)} \\ 13.7 \pm 0.1 \text{ byr} & \text{(early)} \\ 14.0 \pm 0.3 \text{ byr} & (\text{early}, \Delta N_{\rm eff} \neq 0) \end{cases}$$

See e.g. **[Valentino+ "In the Realm of the Hubble tension – a Review of Solutions" 2021]**
Not a finalist in the H_0 Olympics
[Schoneberg+ 2021]

[Dror, Murayama, NLR 2021]

Bose Enhancement

Relevant when $f_a \gg 1$

$$f_a = \frac{2\pi^2}{\omega^3}\frac{d\rho_a}{d\omega} \simeq 4 \times 10^{10} \left(\frac{Q_a}{1}\right)\left(\frac{\rho_a}{\rho_\gamma}\right)\left(\frac{\bar{\omega}}{1\ \mu\text{eV}}\right)^{-4}$$

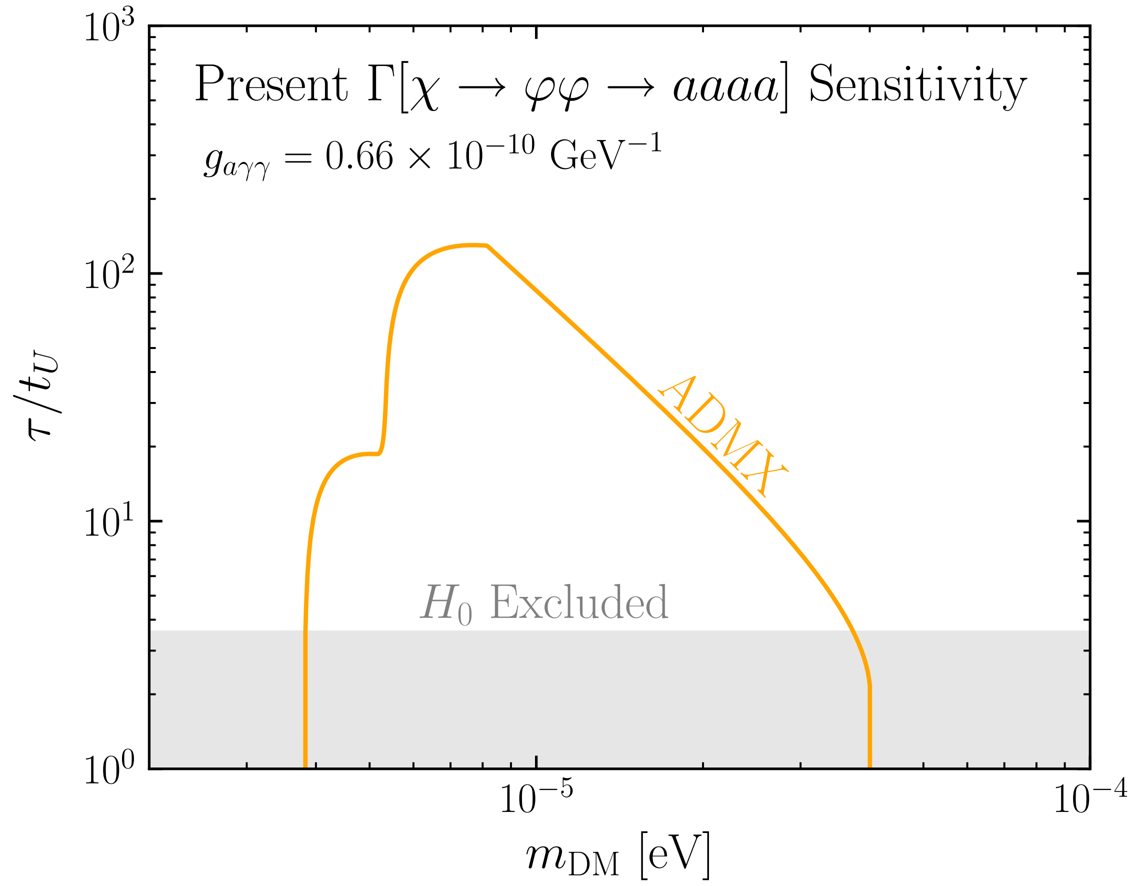
Large over the entire range we consider

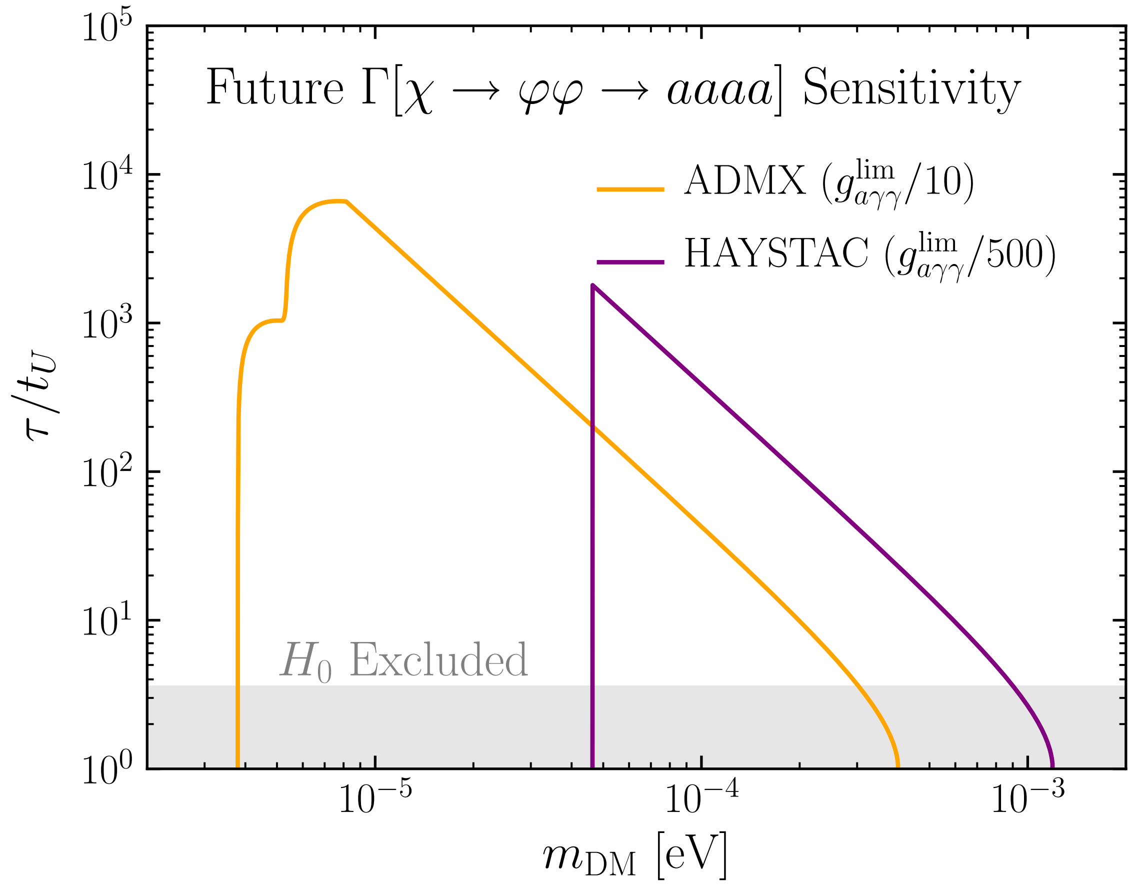
[Dror, Murayama, NLR 2021]

Bose Enhancement

Exploit daily modulation of the signal

Can lift with cascade decays

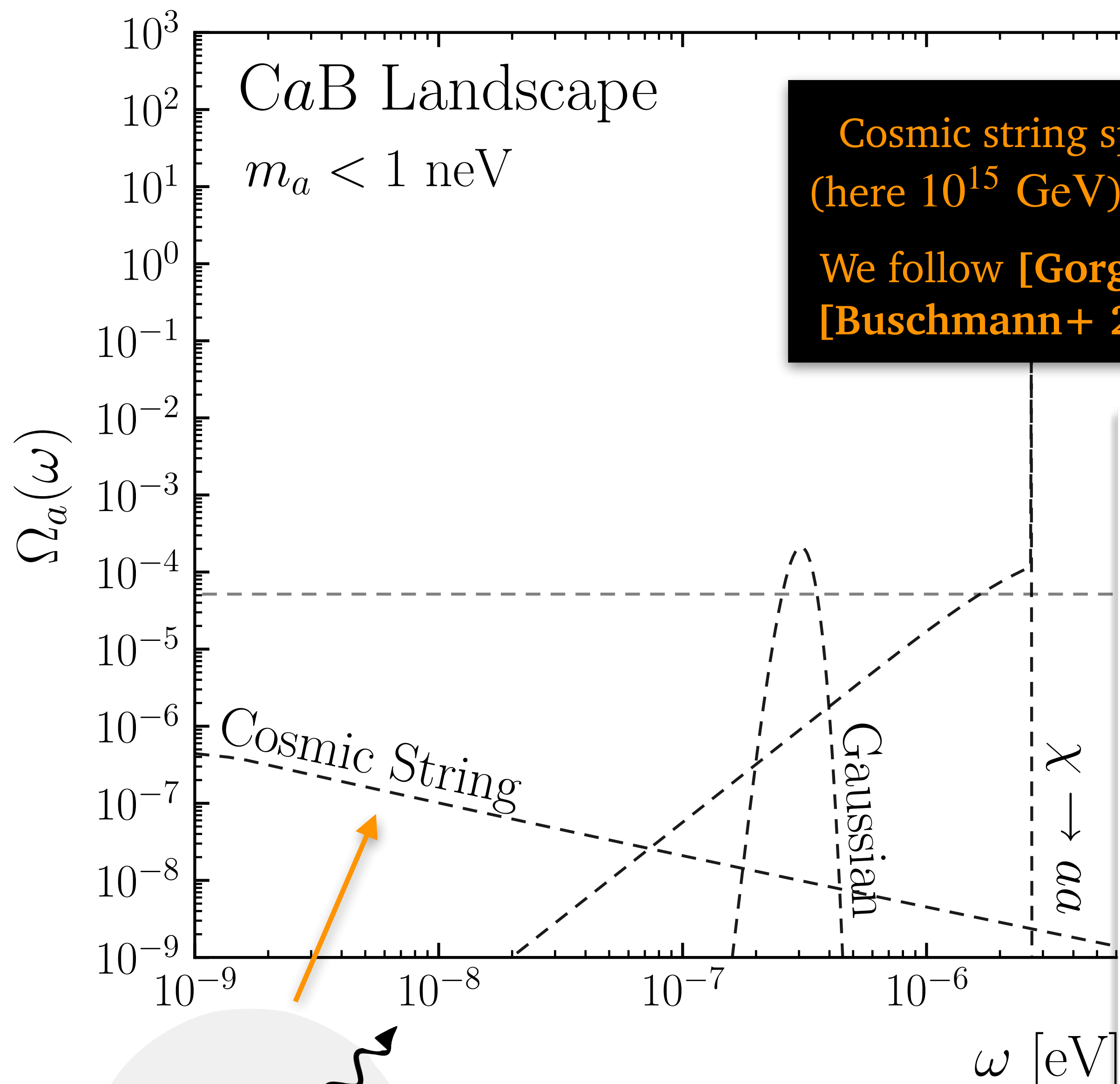




Finalizing this analysis with ADMX

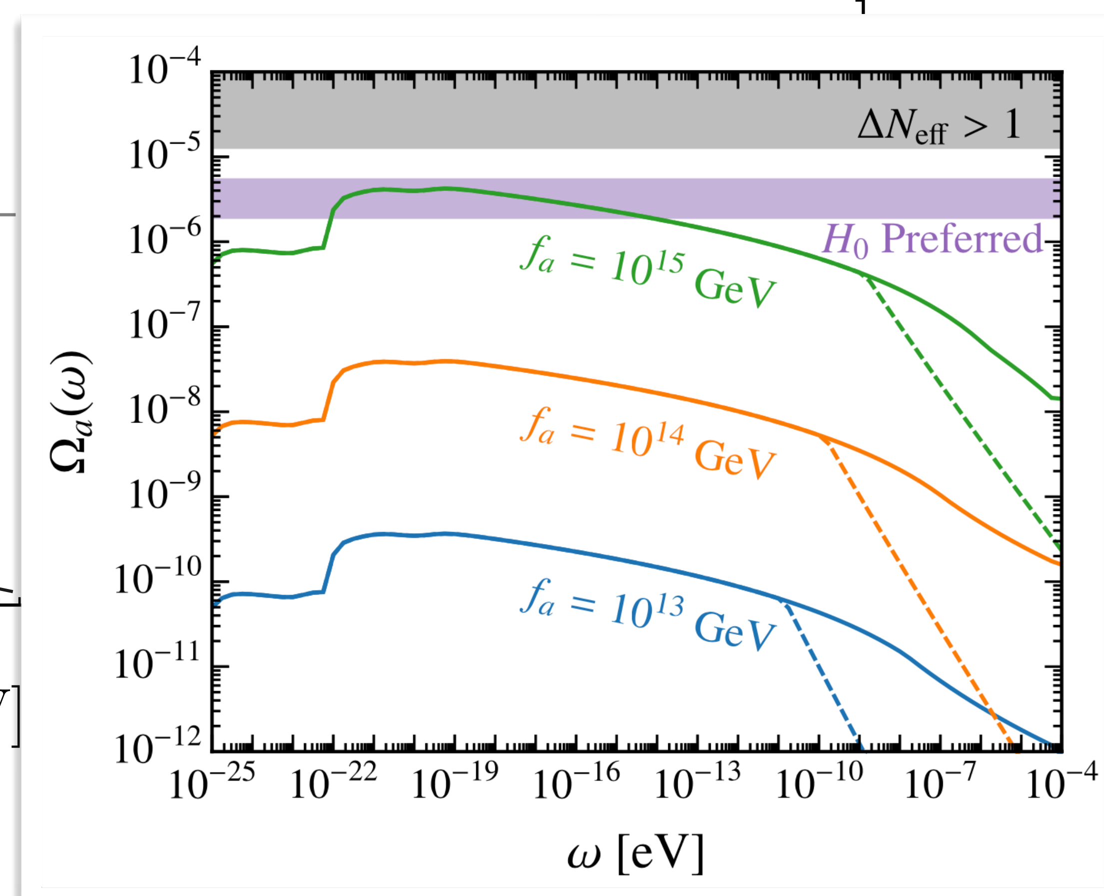
[Dror, Murayama, NLR 2021]

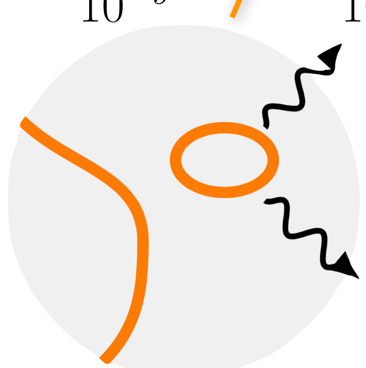
Cosmic Strings



Cosmic string spectrum depends on the symmetry breaking scale f_a (here 10^{15} GeV) and the exact distribution is an area of active debate

We follow **[Gorghetto, Hardy, Villadoro 2018, 2020]**, but see also **[Buschmann+ 2021]** & **[Dine, Fernandez, Ghalsasi, Patel 2020]**





[Dror, Murayama, NLR 2021]

Parametric Resonance

$$V(\Phi) = \lambda^2 \left(|\Phi|^2 - f_a^2/2\right)^2$$

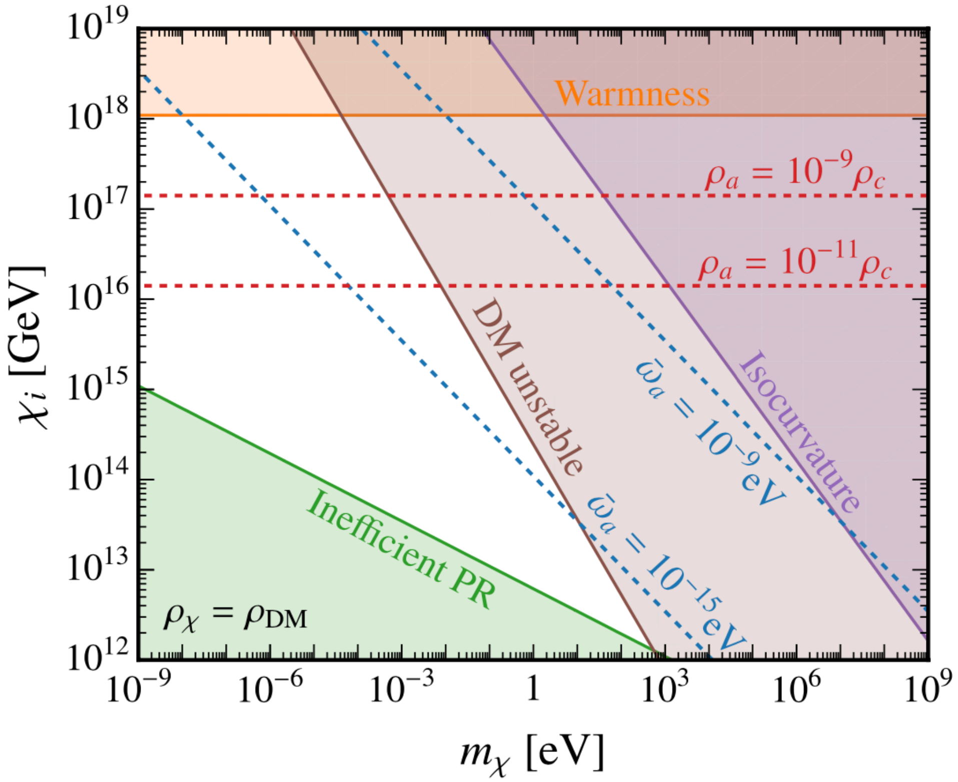
Oscillations when
$m_\chi^{\rm eff}(\chi_i) \simeq \lambda\chi_i \sim H$

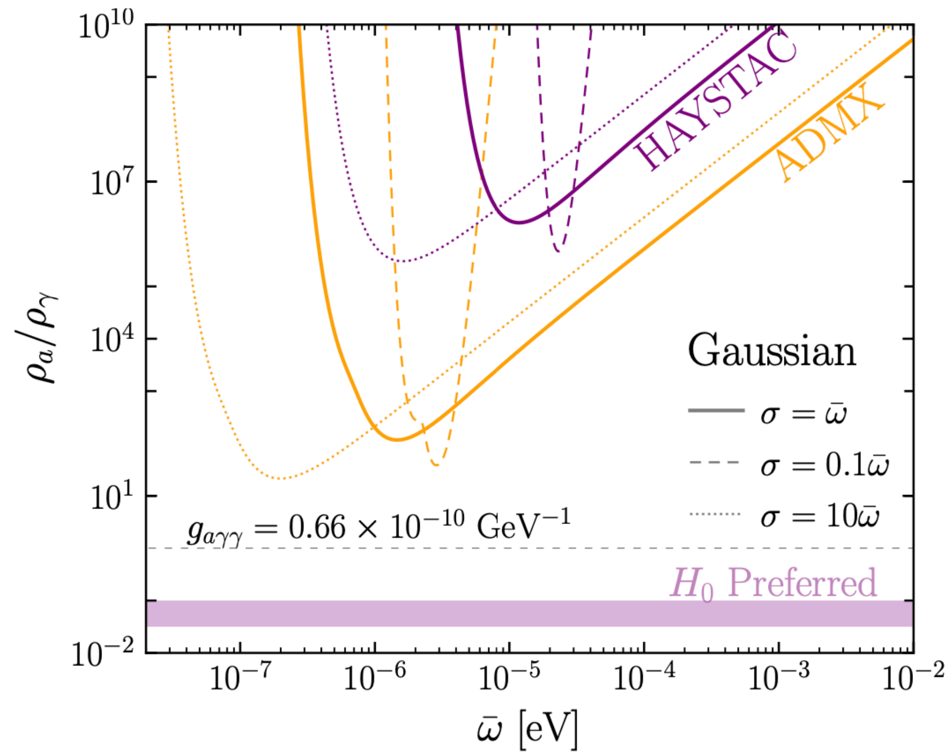
Typical energy: $\bar{\omega}_a \sim m_\chi^{\rm eff}(\chi_i)\left(\frac{s(T_0)}{s(T_{\rm osc})}\right)^{1/3} \sim 10^{-15}\ {\rm eV}\left(\frac{m_\chi^{\rm eff}(\chi_i)}{\rm MeV}\right)^{1/2}$

Energy density: $\Omega_a \sim 3\times 10^{-7}\left(\frac{\chi_i}{M_{\rm Pl}}\right)^2$

detectable?

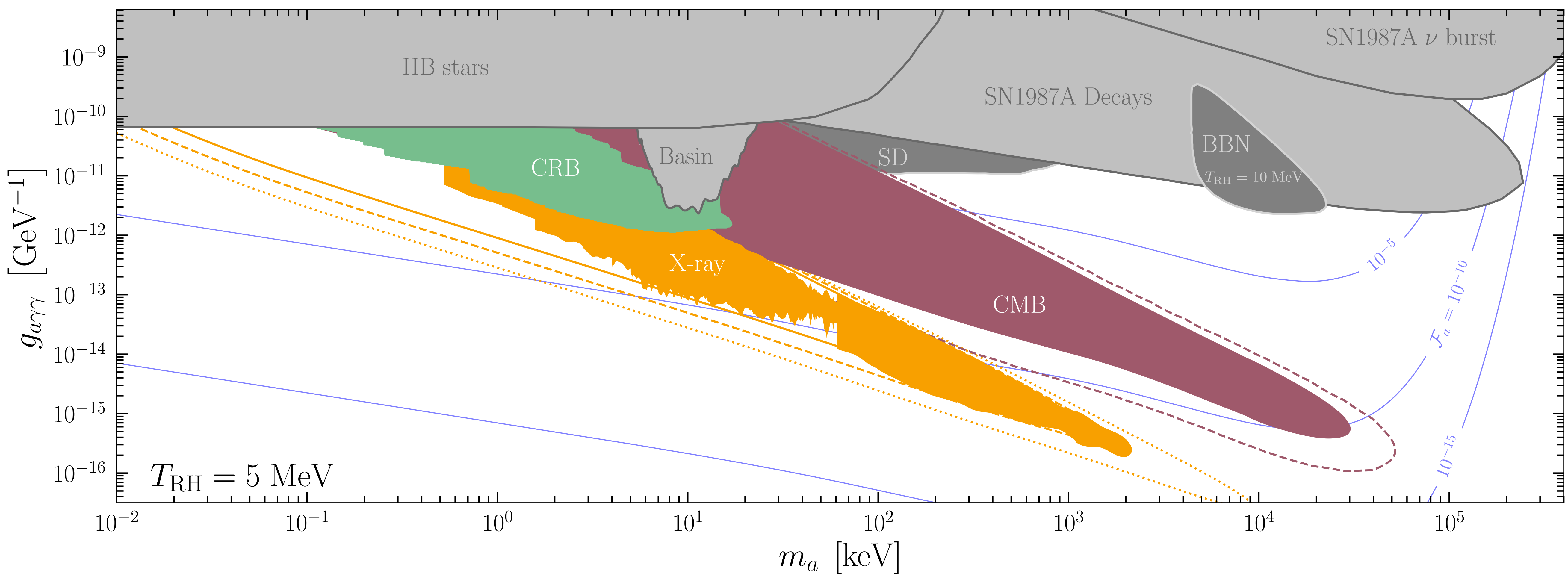
Assume χ dark matter





[Dror, Murayama, NLR 2021]

The Irreducible Axion



[Langhoff, Outmezguine, NLR 2022]

The Irreducible Axion

Take $m_a = 10$ keV

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

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

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

UV dominated

[Langhoff, Outmezguine, NLR 2022]

The Irreducible Axion

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

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

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

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

[Langhoff, Outmezguine, NLR 2022]

The Irreducible Axion

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

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

Combine (1) and (2)

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

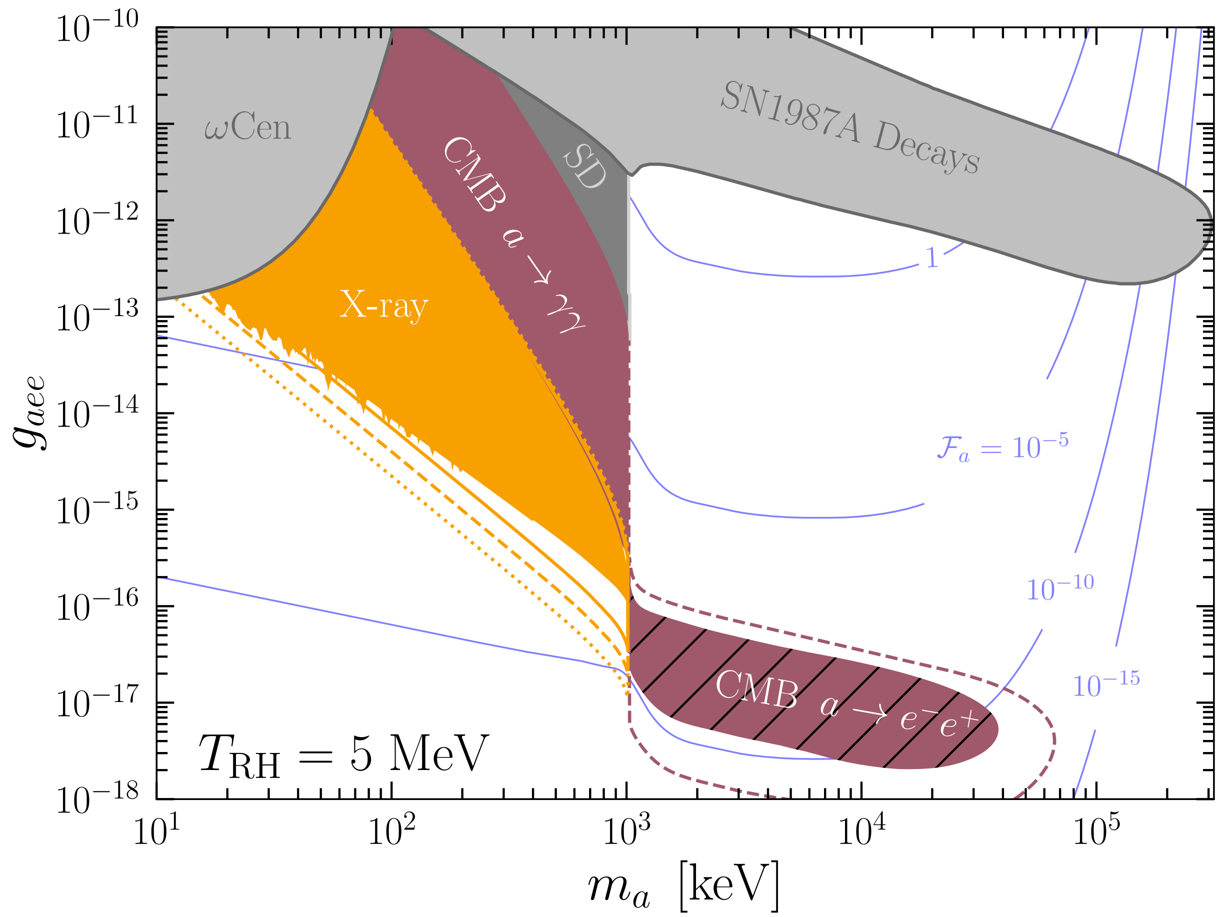
$$\Rightarrow \frac{g_{a\gamma\gamma}}{g_{a\gamma\gamma}^{\rm HB}} \lesssim \left[10^4 \left(\frac{g_{a\gamma\gamma}^{\rm DM}}{g_{a\gamma\gamma}^{\rm HB}} \right)^2 \right]^{1/4} \simeq (10^{-12})^{1/4} \simeq 10^{-3}$$

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

[Langhoff, Outmezguine, NLR 2022]

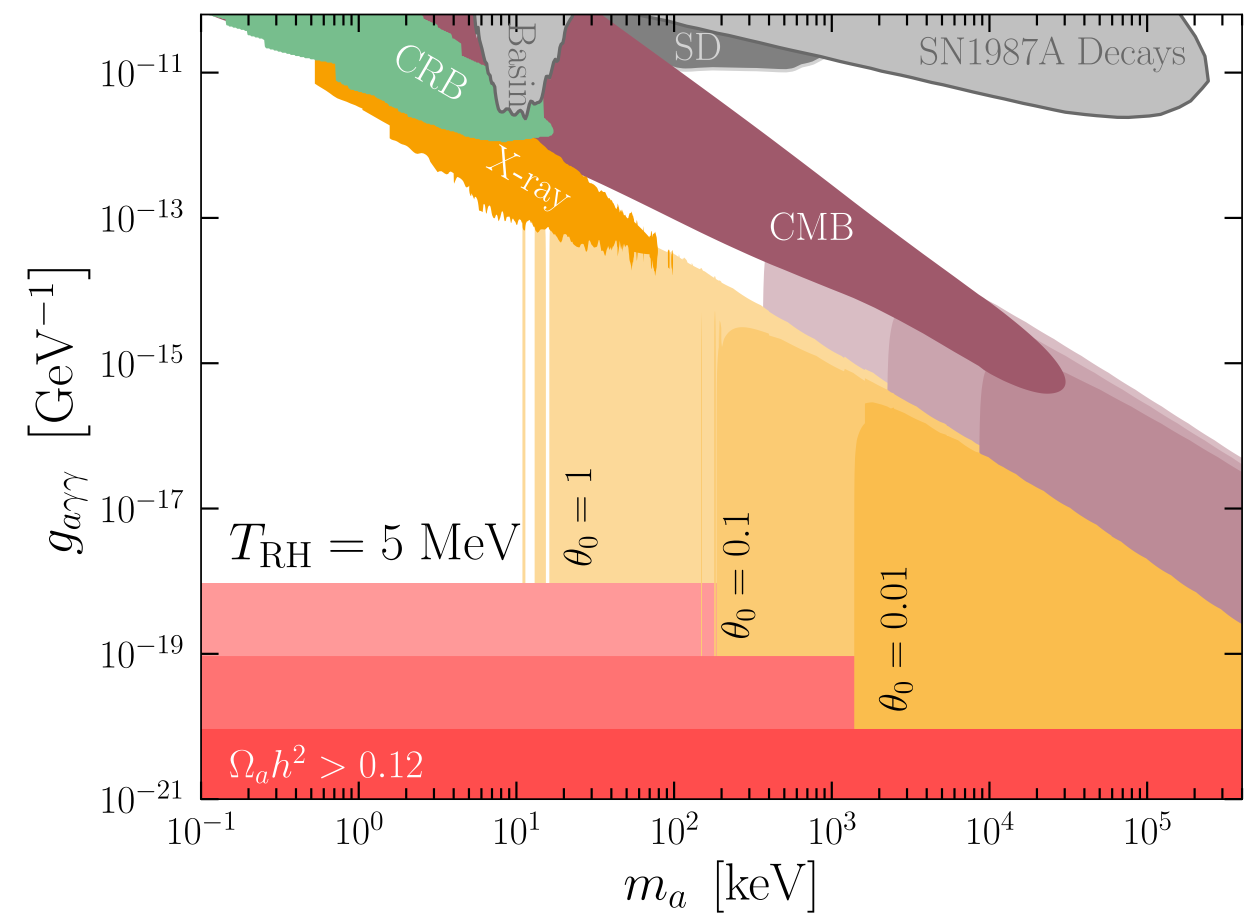
The Irreducible Axion

Electron Couplings



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

With misalignment



[Langhoff, Outmezguine, NLR 2022]

QCD Axion Mass

At $T = 0$ one can compute the axion effective potential

$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a}\right)}$$

Expanding out, we find

$$m_a = \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 0.5 \frac{m_\pi f_\pi}{f_a}$$

[Cortona, Hardy, Vega, Villadoro 2015]

Axion Dark Matter

In an FRW universe, the axion evolves according to

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

For early times, $H \gg m_a$, $a(t) = a_0$

At late times, $H \ll m_a$

$$a = \left[\frac{R(H = m_a)}{R(t)}\right]^{3/2} a_0 \cos(m_a t)$$

The energy density, $\rho \propto a^2$, behaves like CDM

$$\rho(t) = \rho(H = m_a)\left[\frac{R(H = m_a)}{R(t)}\right]^3$$

See, e.g. **[Hook 2018]**

Axion Dark Matter

Signal Power of the QCD Axion

$$P_a \simeq 5\,\mathrm{yW} \;\; \text{at} \;\; 5\,\mathrm{GHz}$$

10^{-24}

For a detailed discussion see **[Brubaker 2018]**