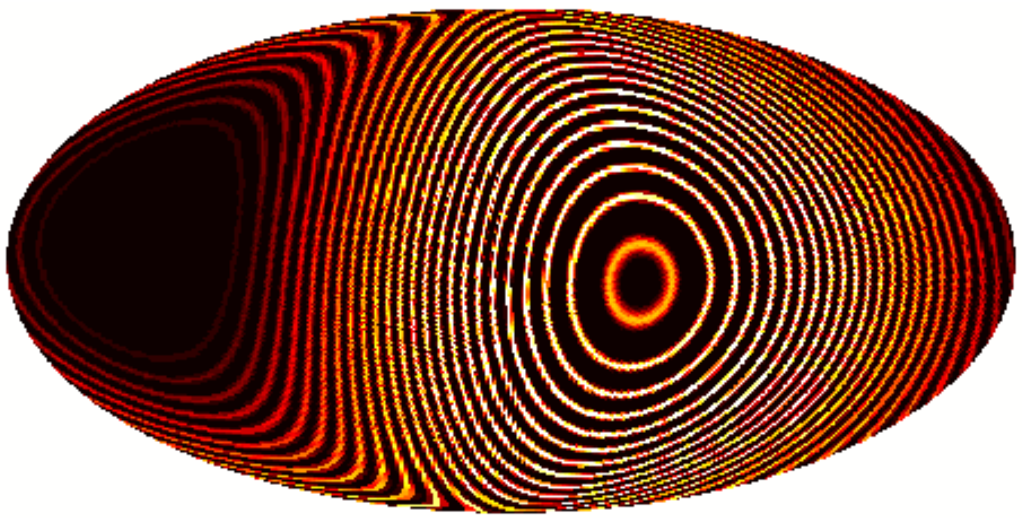
New Ideas for the Axion Dark Matter Program

NICK RODD | KAVLI IPMU | 12 MAY 2021

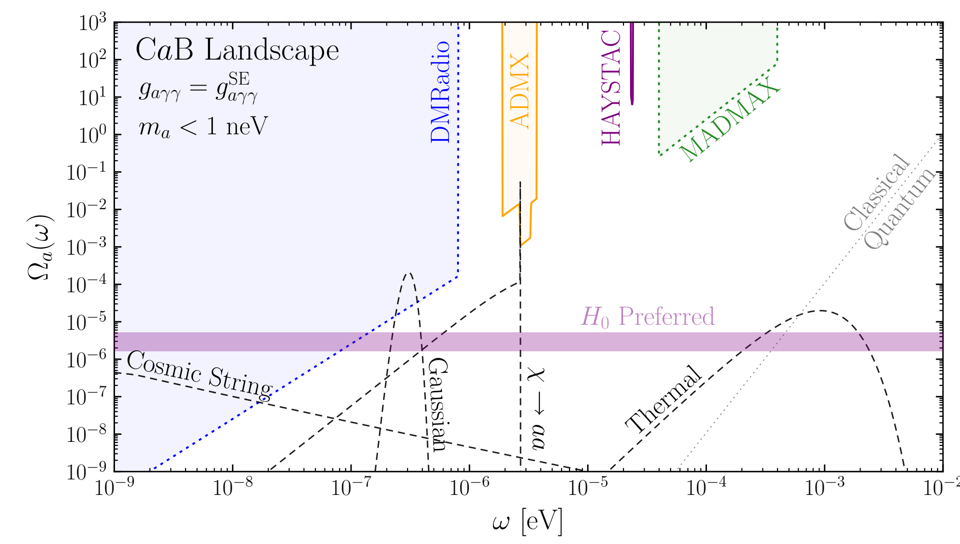
Dark Matter Interferometry

2009.14201 w/ Foster, Kahn, Nguyen, Safdi



The Cosmic Axion Background

2101.09287 w/ Dror, Murayama



Motivation

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

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Introduces corrections to Maxwell's equations

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

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

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Suppressed for non-relativistic DM axions

Focus of axion DM searches

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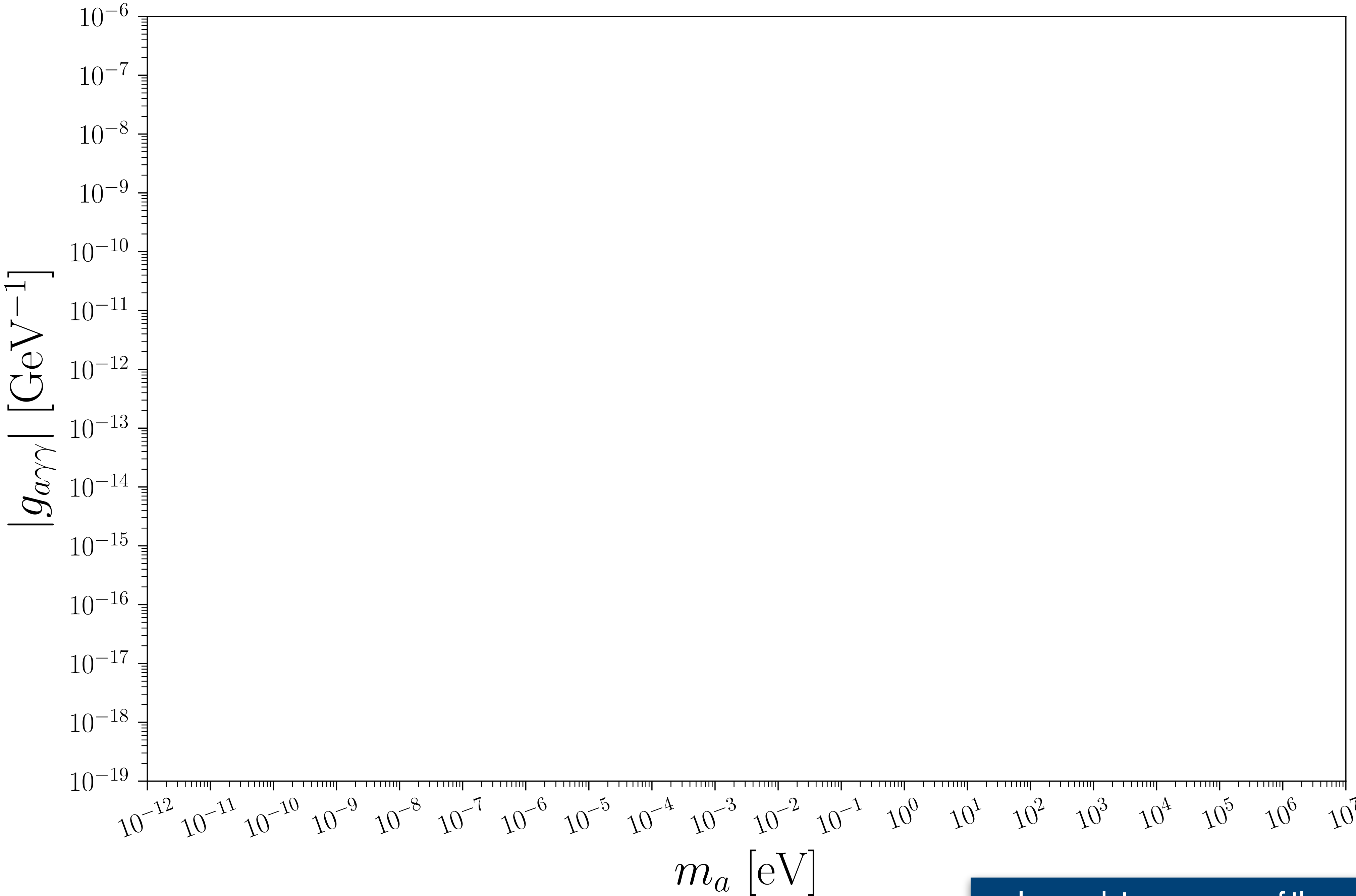

Incomplete summary of the landscape, partially based on github.com/cajohare/AxionLimits

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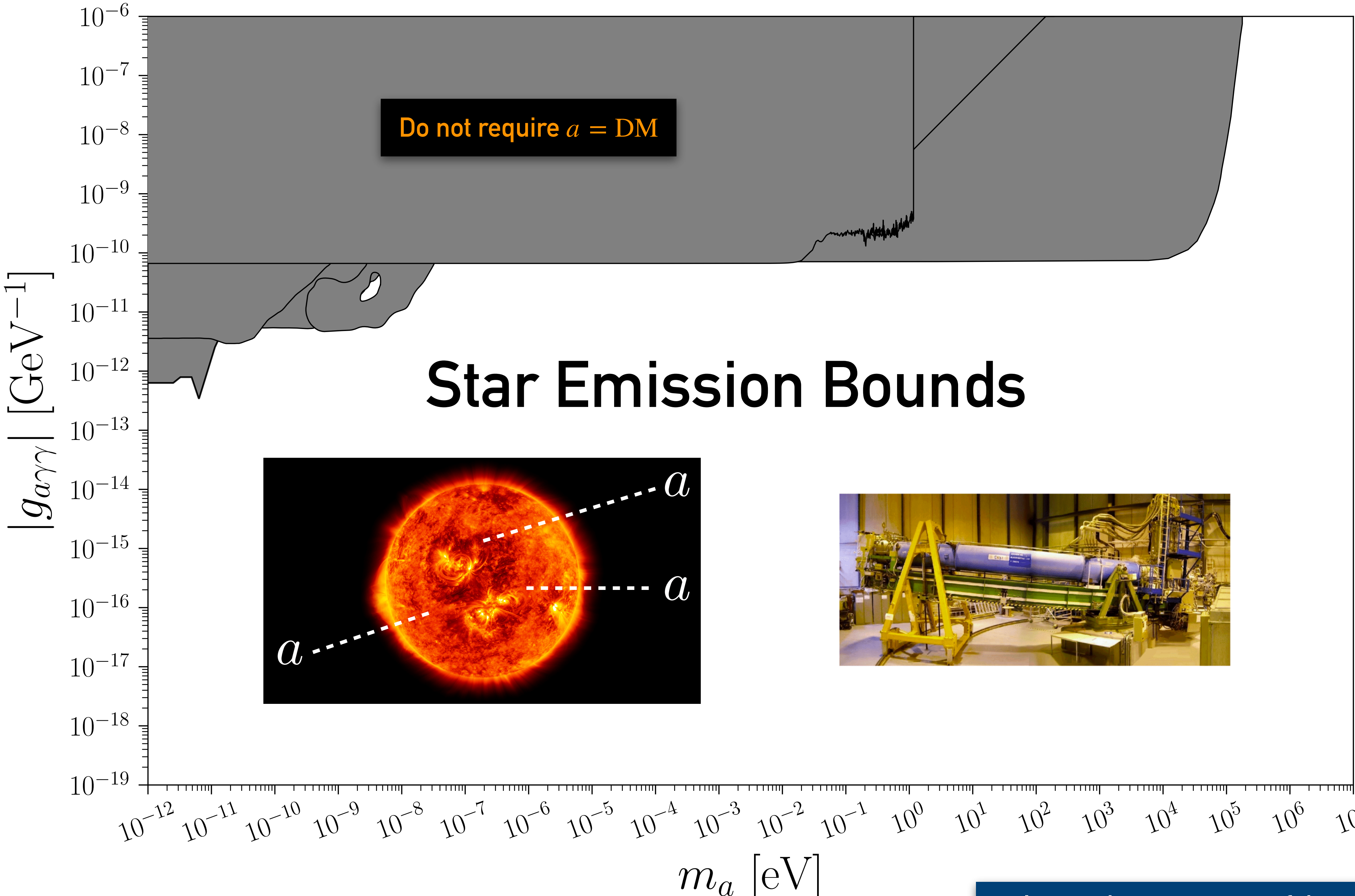

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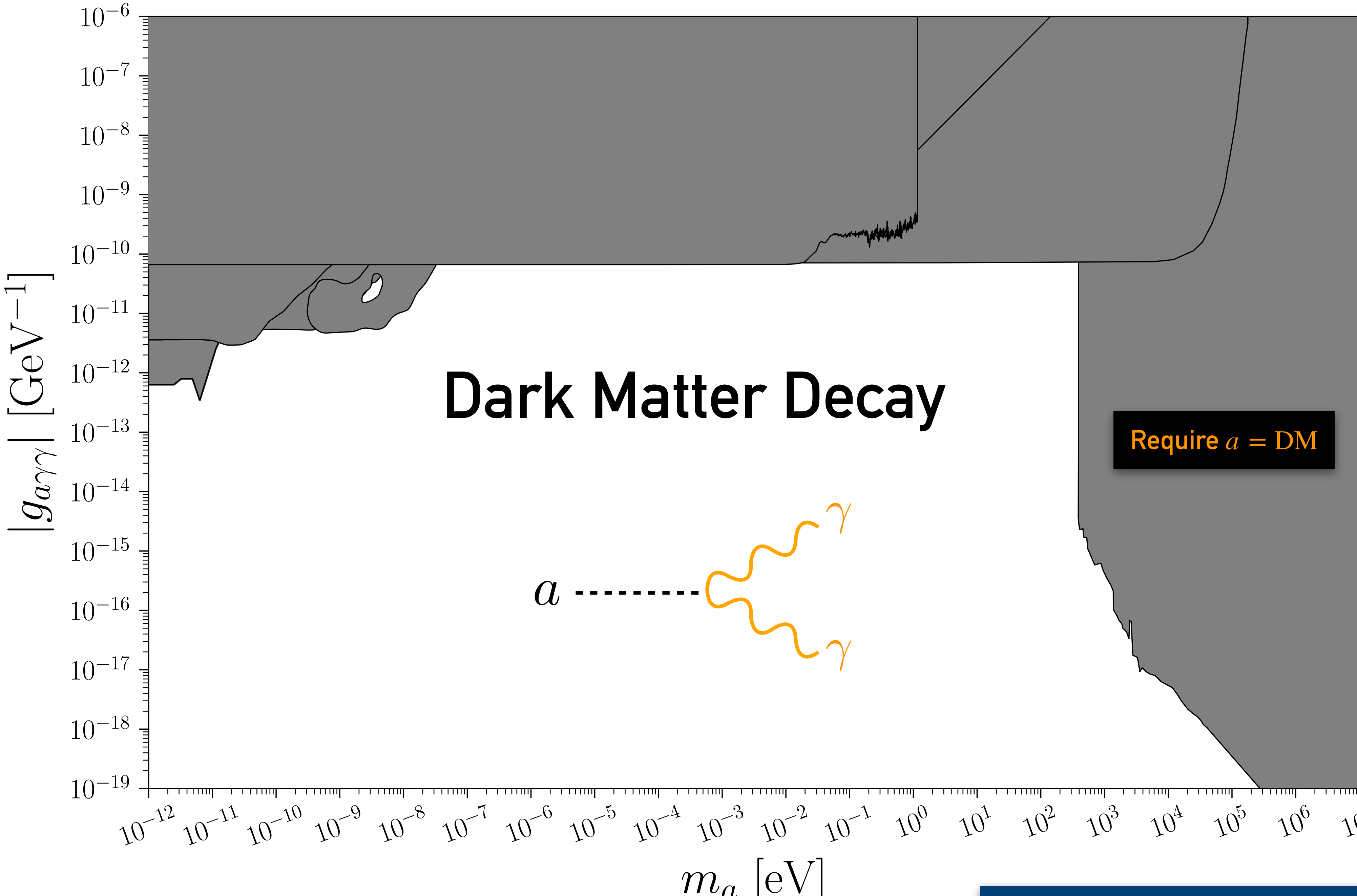

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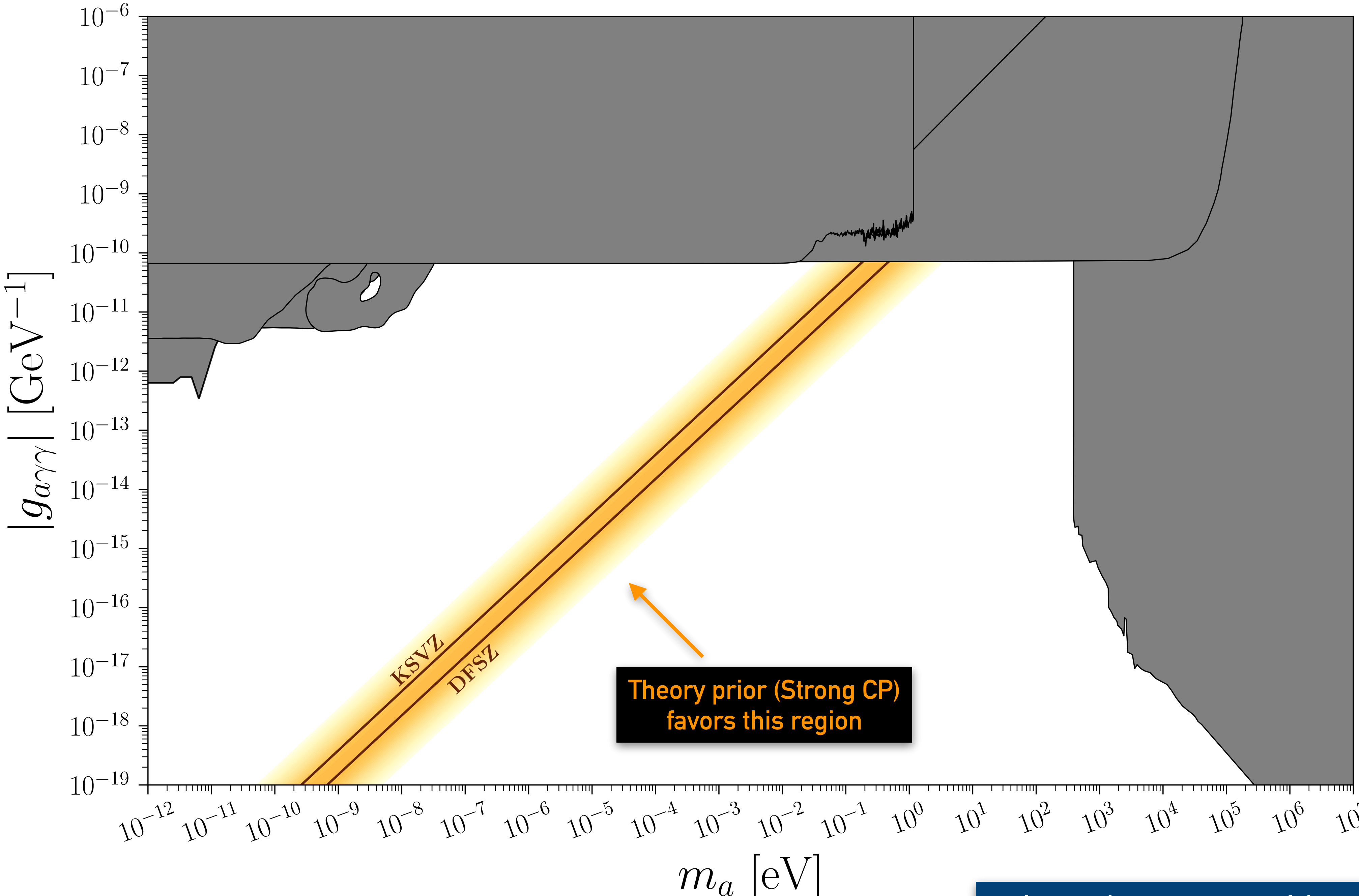

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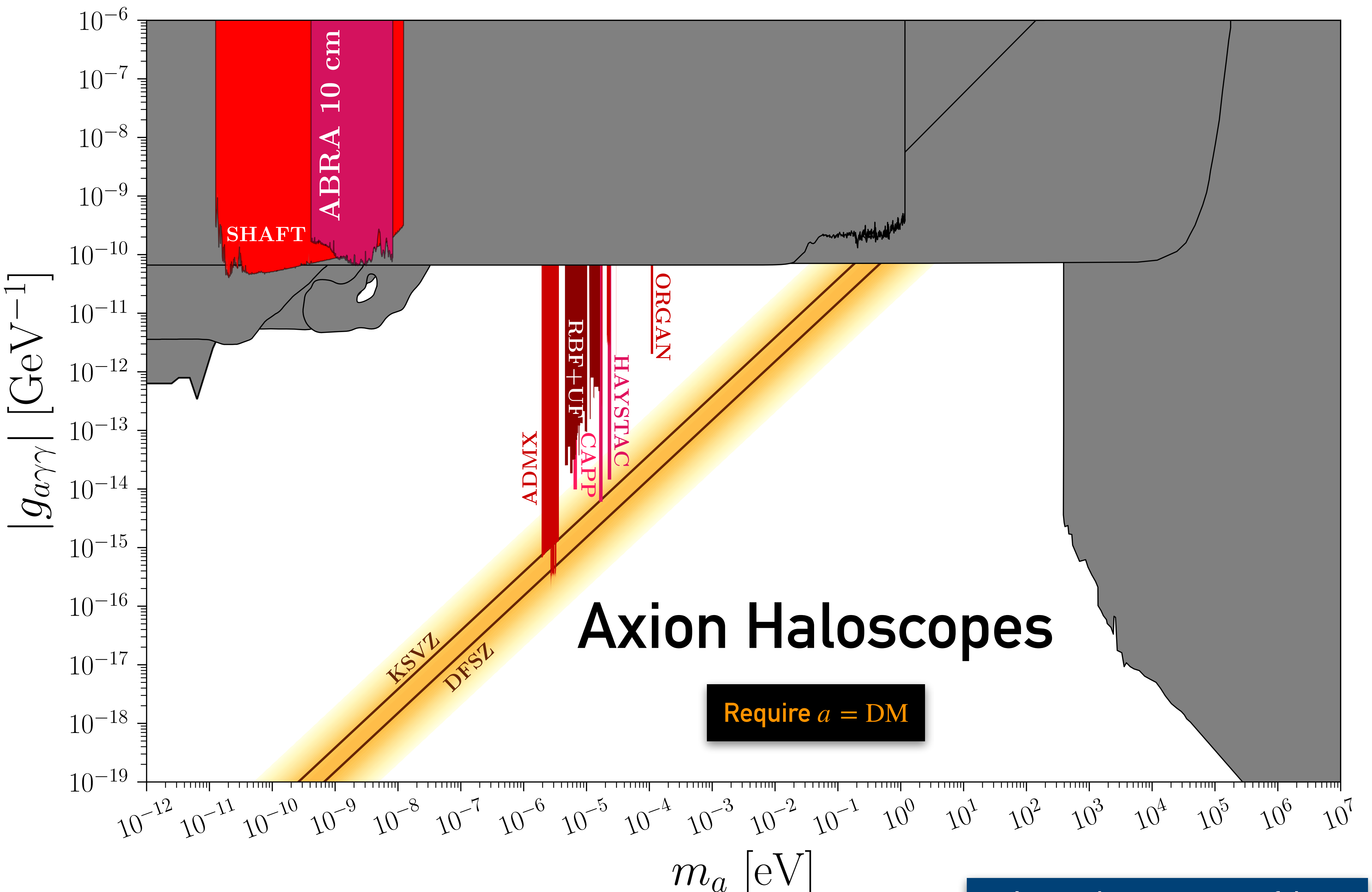

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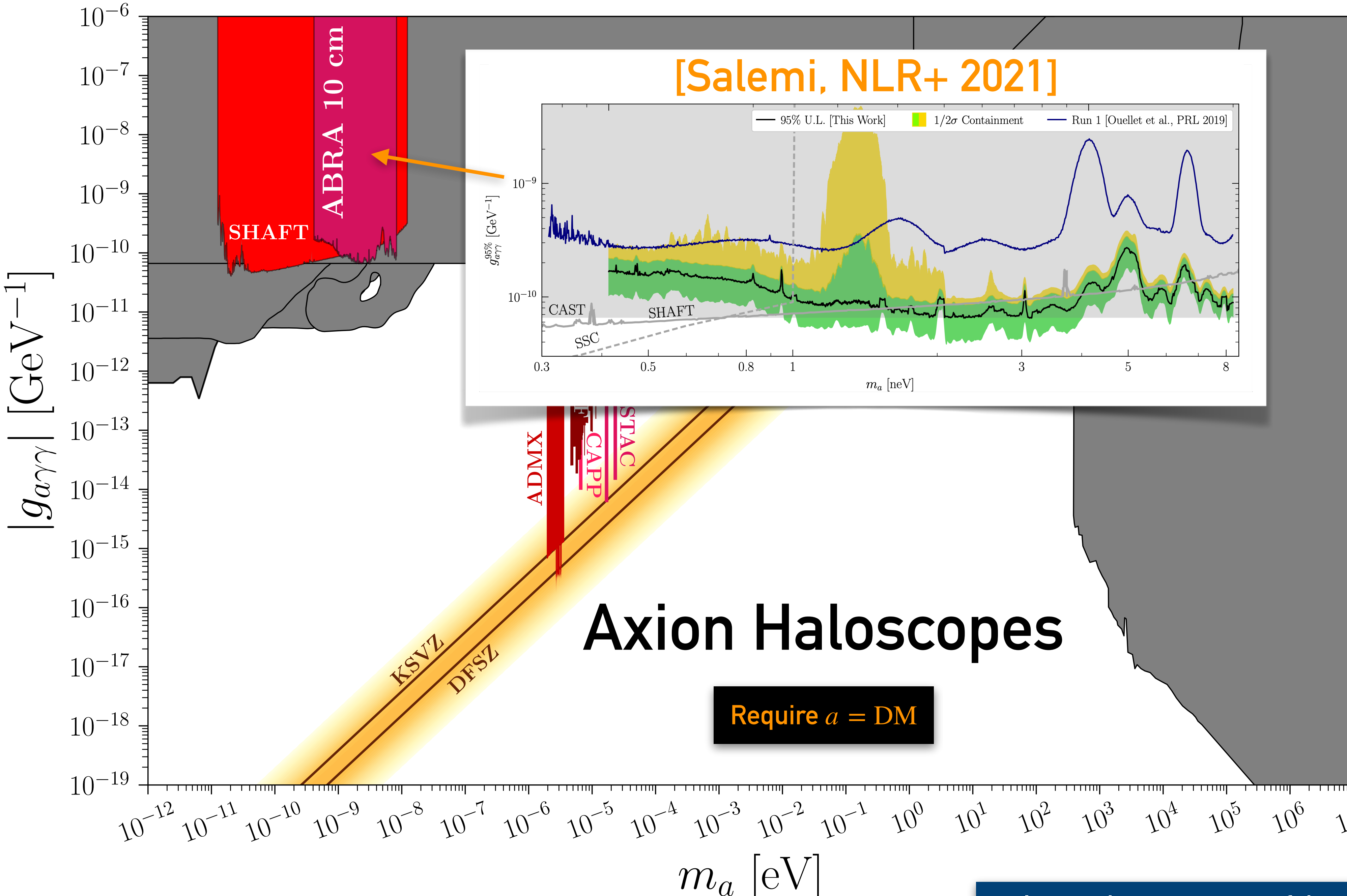

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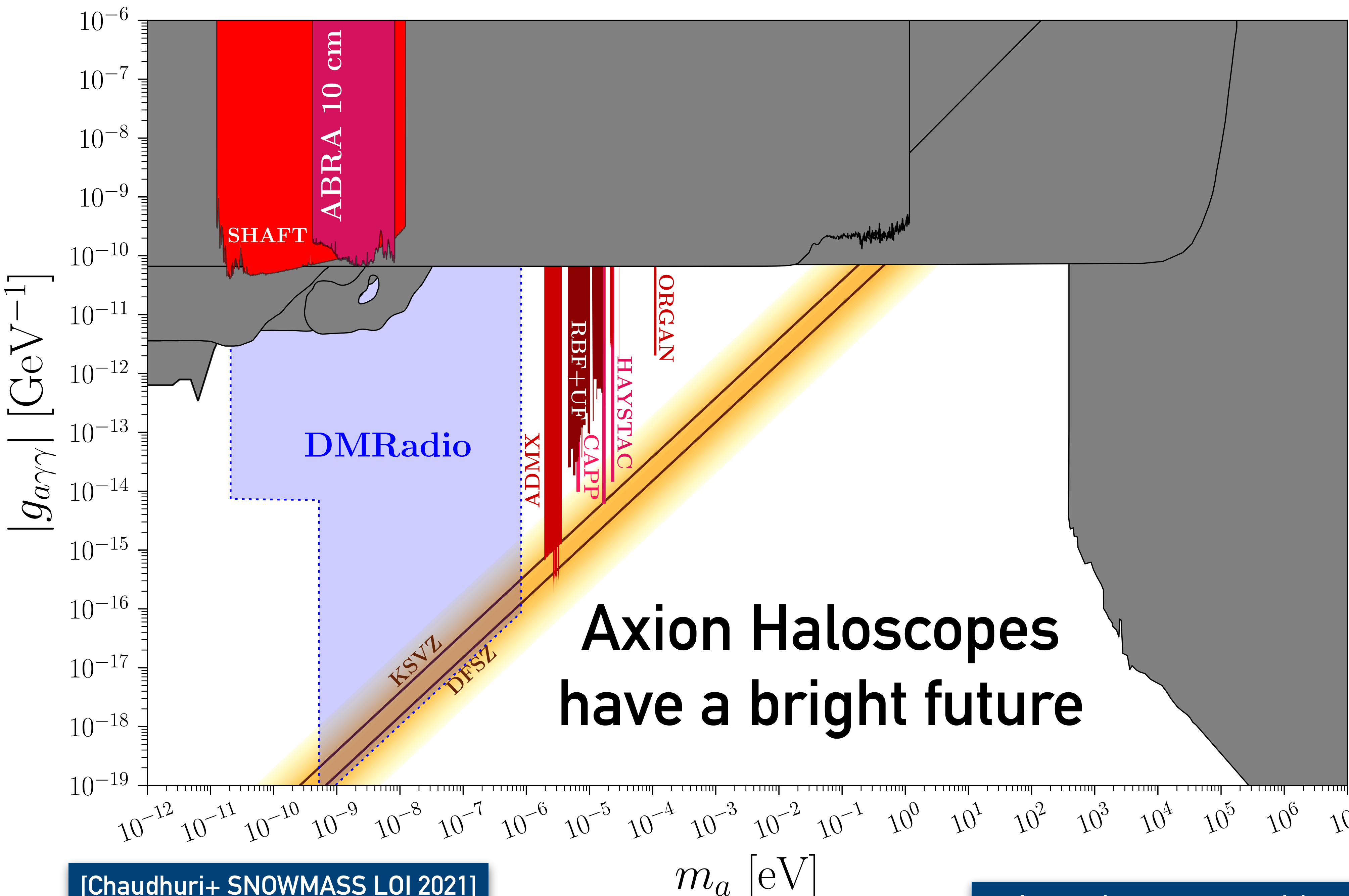

[Chaudhuri+ SNOWMASS LOI 2021]

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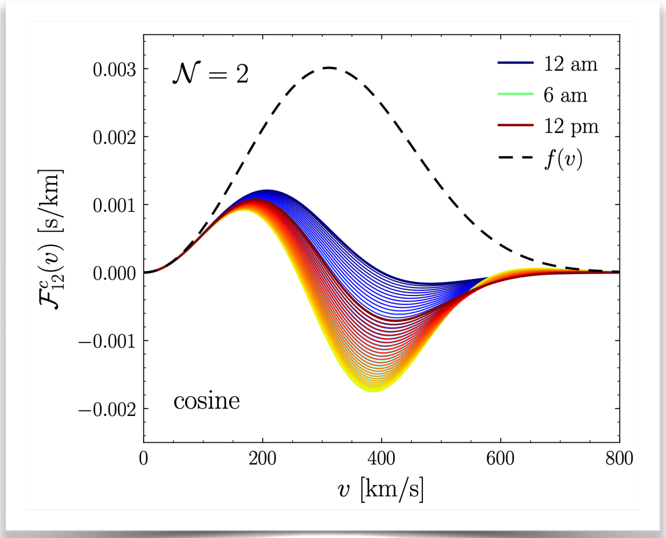
Outline

Two new ideas for exploiting this progress

Outline

1. More information for DM searches?

Dark Matter Interferometry



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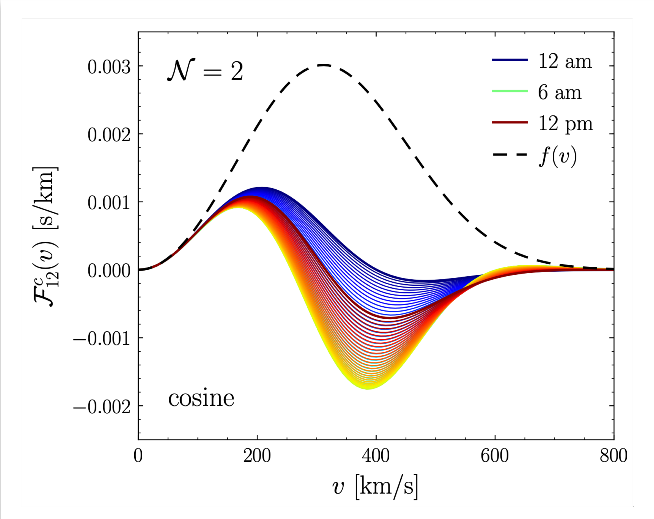
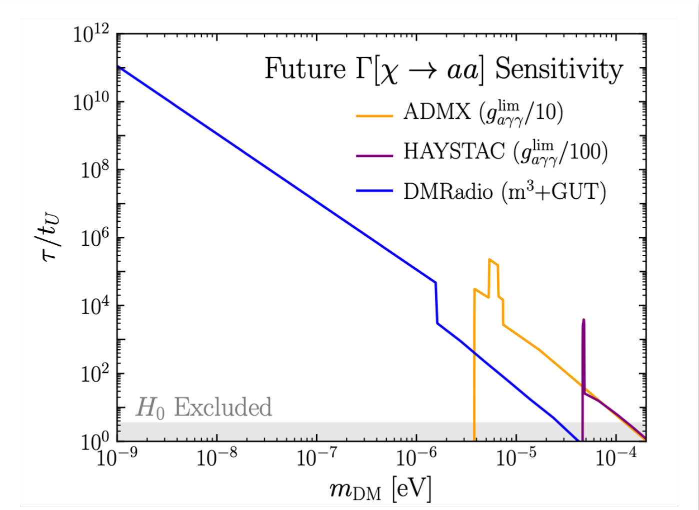


2. What else could these instruments see?

The Cosmic Axion Background



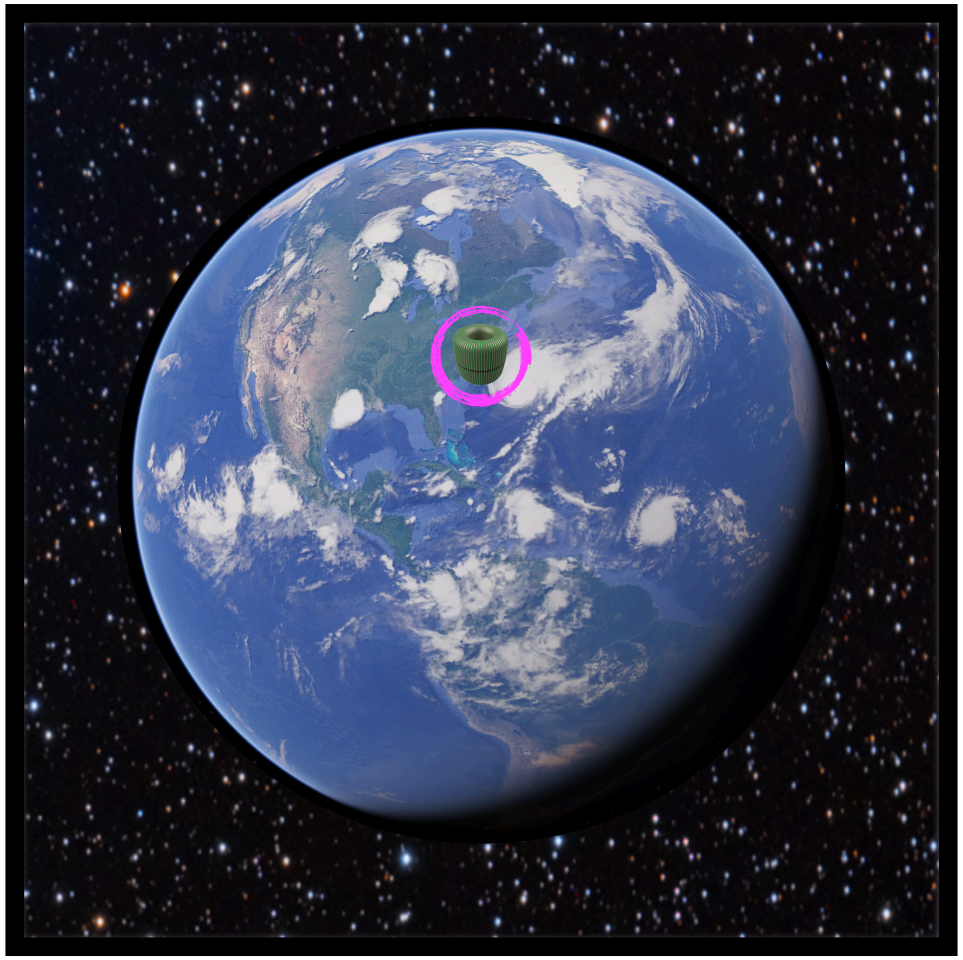
Dark Matter Interferometry

2009.14201

w/ Josh Foster, Yoni Kahn,
Rachel Nguyen, Ben Safdi

Basic Idea

Wave-like Dark Matter

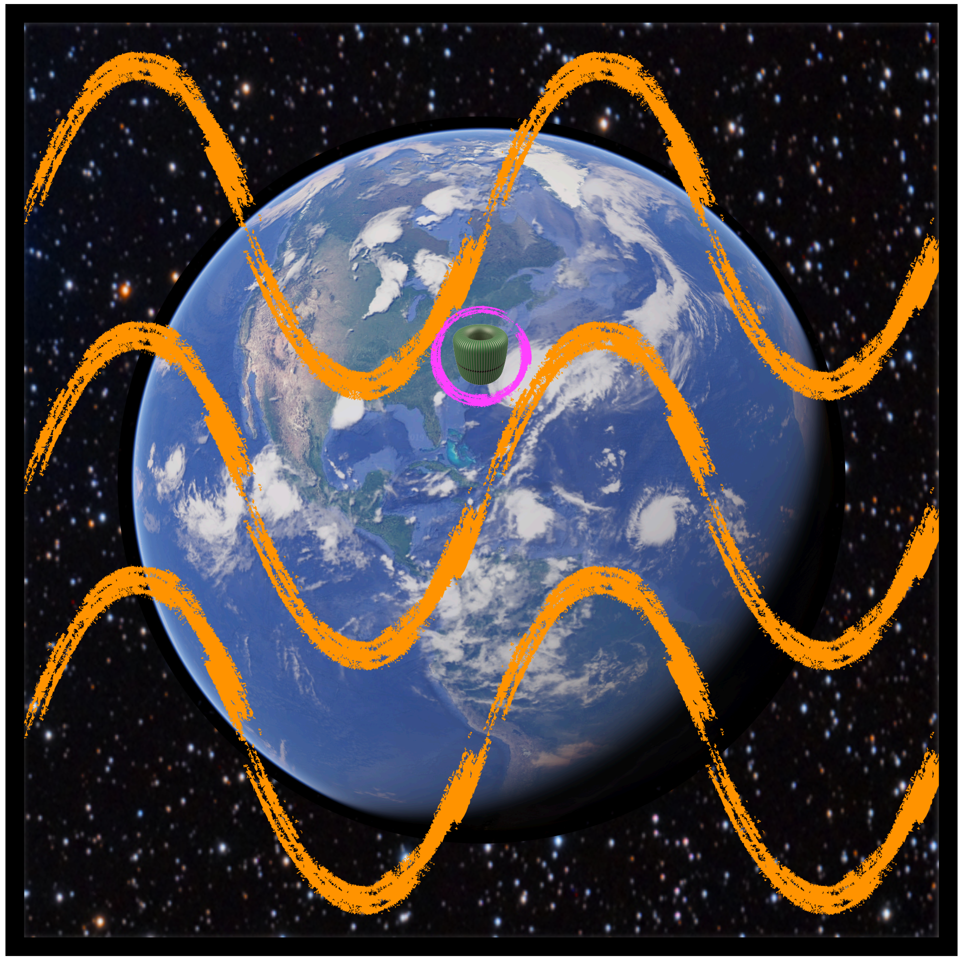


[Foster, NLR+ 2020]

Basic Idea

Wave-like Dark Matter

$$a \sim \cos(m_a t)$$



[Foster, NLR+ 2020]

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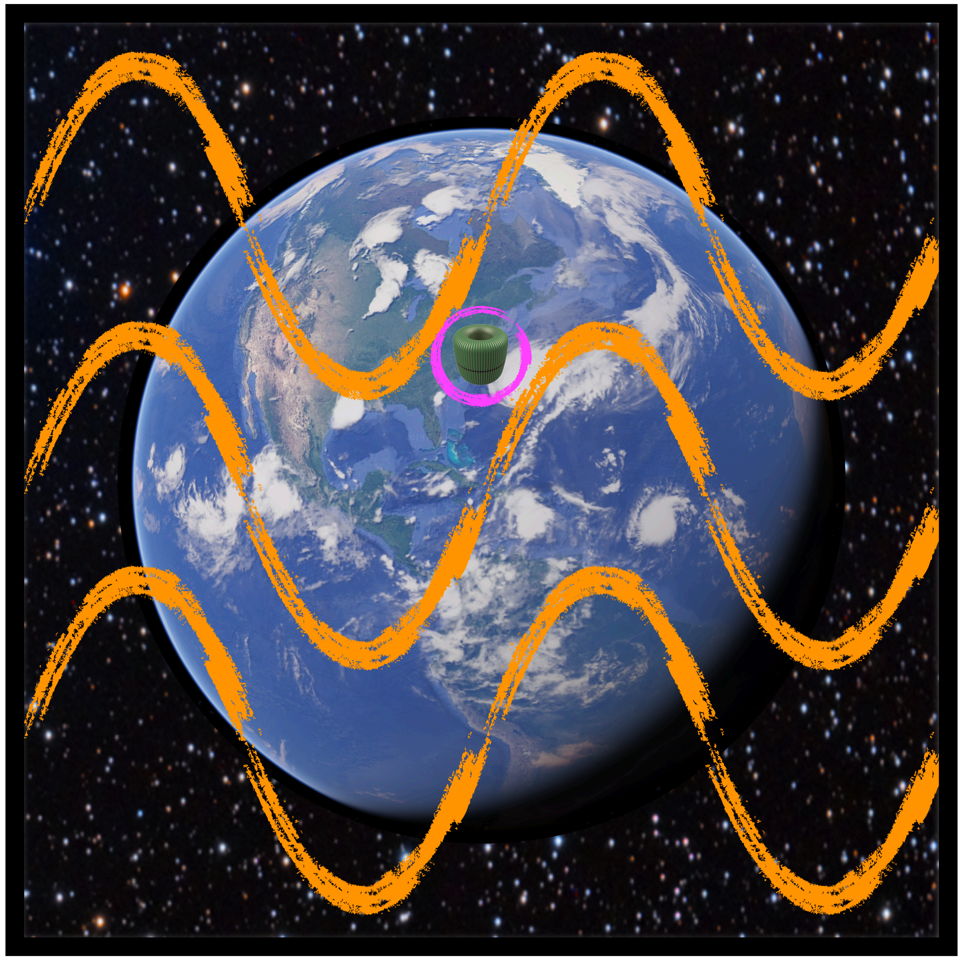
Wave-like Dark Matter

$$a \sim \cos(\omega t - \mathbf{k} \cdot \mathbf{x})$$



[Foster, NLR+ 2020]

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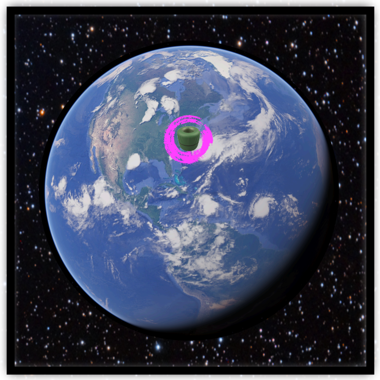
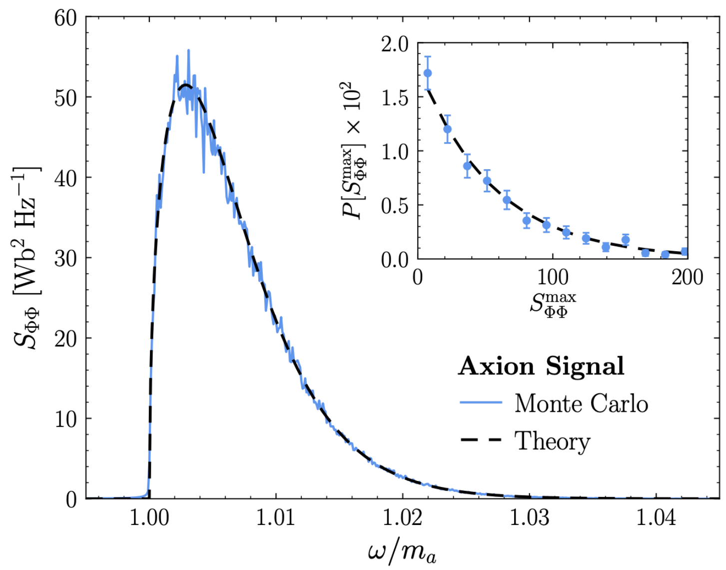


Wave-like Dark Matter

$$a \sim \cos(\omega t - \mathbf{k} \cdot \mathbf{x})$$

Speed $\omega \approx m_a(1 + |\mathbf{v}|^2/2)$

Determined by $f(v)$



[Foster, NLR, Safdi 17]

[Foster, NLR+ 2020]

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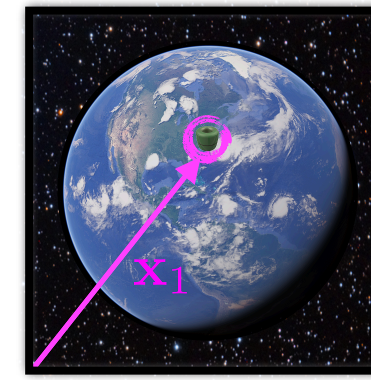

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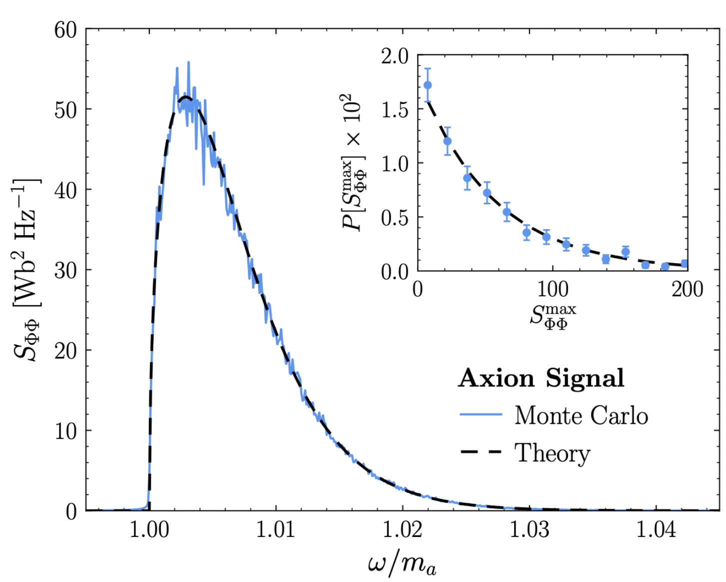


[Foster, NLR, Safdi 17]

Velocity $\mathbf{k} = m_a \mathbf{v}$

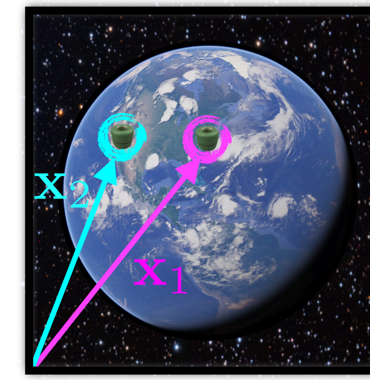
Determined by $f(\mathbf{v})$

Invisible to a single detector

1. $\nabla a \sim \mathbf{k} \ll \omega \sim \partial_t a$
2. For 1 experiment, can choose $\mathbf{x} = 0$

[Foster, NLR+ 2020]

Basic Idea



Wave-like Dark Matter

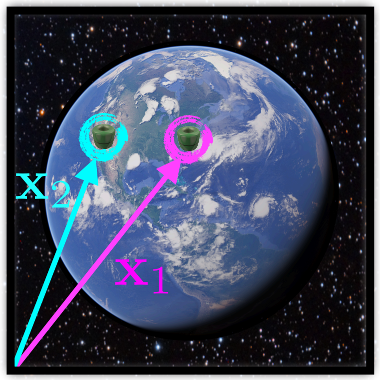
$$a \sim \cos(\omega t - \mathbf{k} \cdot \mathbf{x})$$

Key insight: two detectors will reveal the dependence on $\mathbf{k}$

[Foster, NLR+ 2020]

Interferometry

$$f(v) \to \mathcal{F}^c_{12}(v) = \int d^3\mathbf{v} f(\mathbf{v}) \cos(m_a \mathbf{v} \cdot \mathbf{x}_{12}) \delta[|\mathbf{v}| - v]$$



$\mathbf{x}_{12} = \mathbf{x}_1 - \mathbf{x}_2$

Derived in the context of a full likelihood description in our paper

[Foster, NLR+ 2020]

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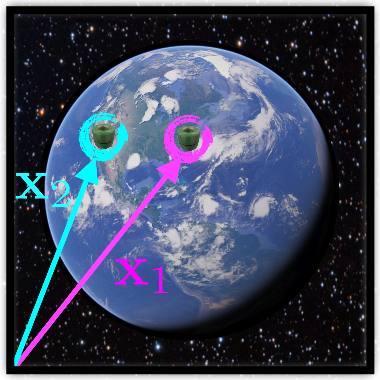

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Nearby detectors $\mathbf{x}_{12} \to 0$

$$\mathcal{F}^c_{12}(v) \to \int d^3\mathbf{v}\, f(\mathbf{v}) \delta[|\mathbf{v}| - v] = f(v)$$

[Foster, NLR+ 2020]

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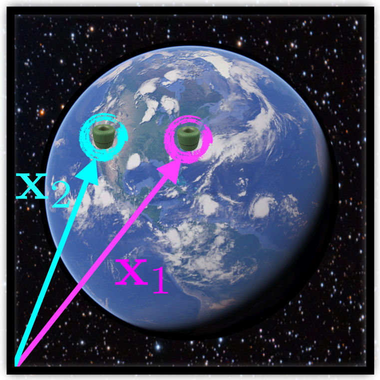

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Nearby detectors $\mathbf{x}_{12} \to 0$

$$\mathcal{F}^c_{12}(v) \to \int d^3\mathbf{v}\, f(\mathbf{v})\delta[|\mathbf{v}| - v] = f(v)$$

Far apart detectors $\mathbf{x}_{12} \to \infty$

$$\langle \mathcal{F}^c_{12}(v) \rangle \to 0$$

[Foster, NLR+ 2020]

Interferometry

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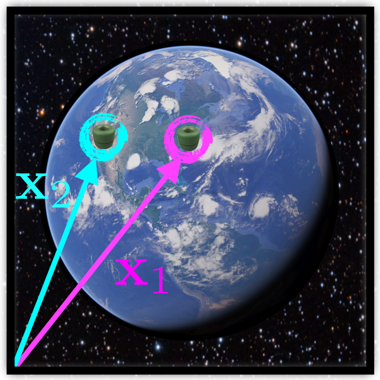

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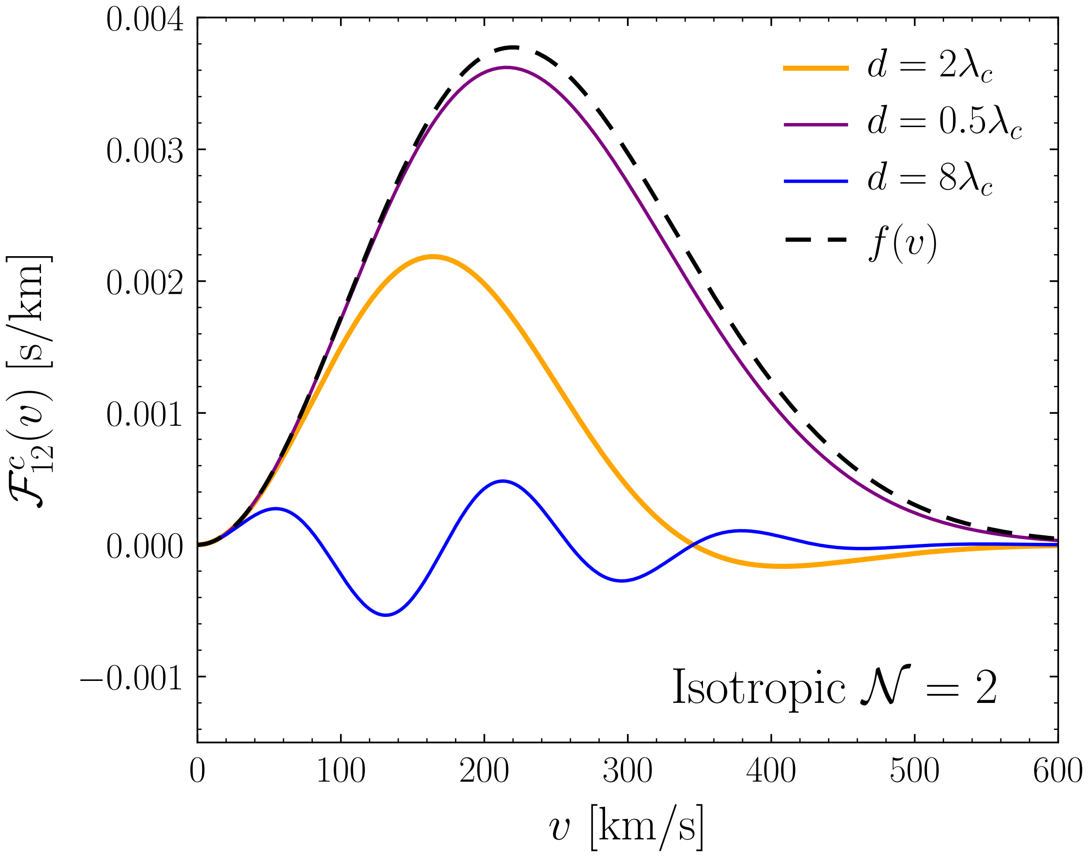
Depends on Coherence Length

$$d = |\mathbf{x}_{12}| \qquad \lambda_c \sim \frac{1}{m_a v_0}$$

- $m_a = 25\ \mu\text{eV} \Rightarrow \lambda_c \approx 10$ m
- $m_a = 1$ neV $\Rightarrow \lambda_c \approx 300$ km



[Foster, NLR+ 2020]

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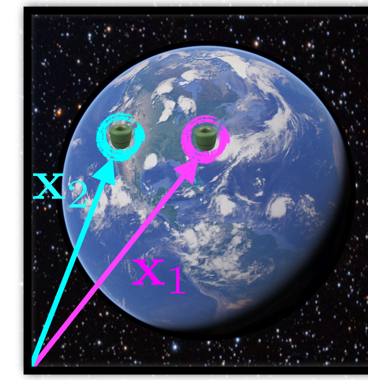
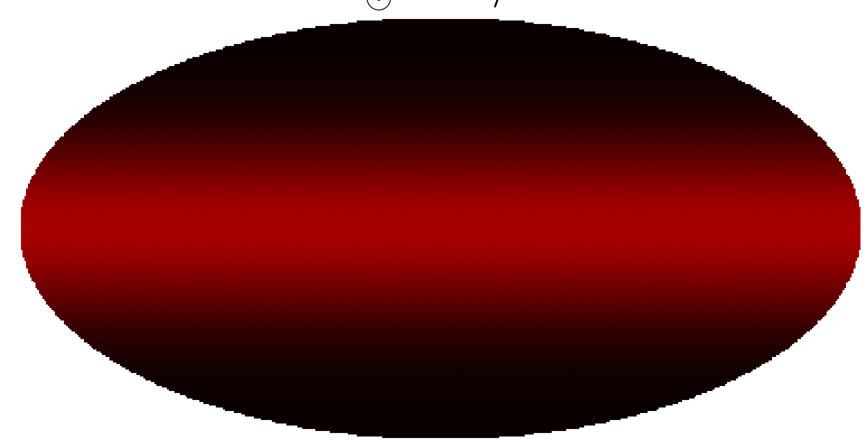


$\mathbf{x}_{12} = \mathbf{x}_1 - \mathbf{x}_2$

$\theta^t_\odot = \pi/2$

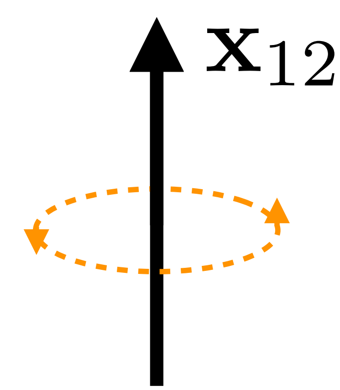


True location: image center

Inherent Degeneracy in Problem

- Rotations around $\mathbf{x}_{12}$ leave $\mathbf{v} \cdot \mathbf{x}_{12}$ unchanged
- Need multiple $\mathbf{x}_{12}$ to break
- Obstructs localization

Symmetry axis



[Foster, NLR+ 2020]

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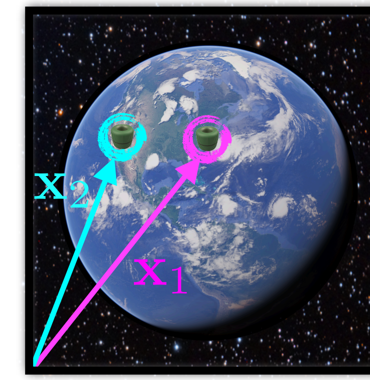
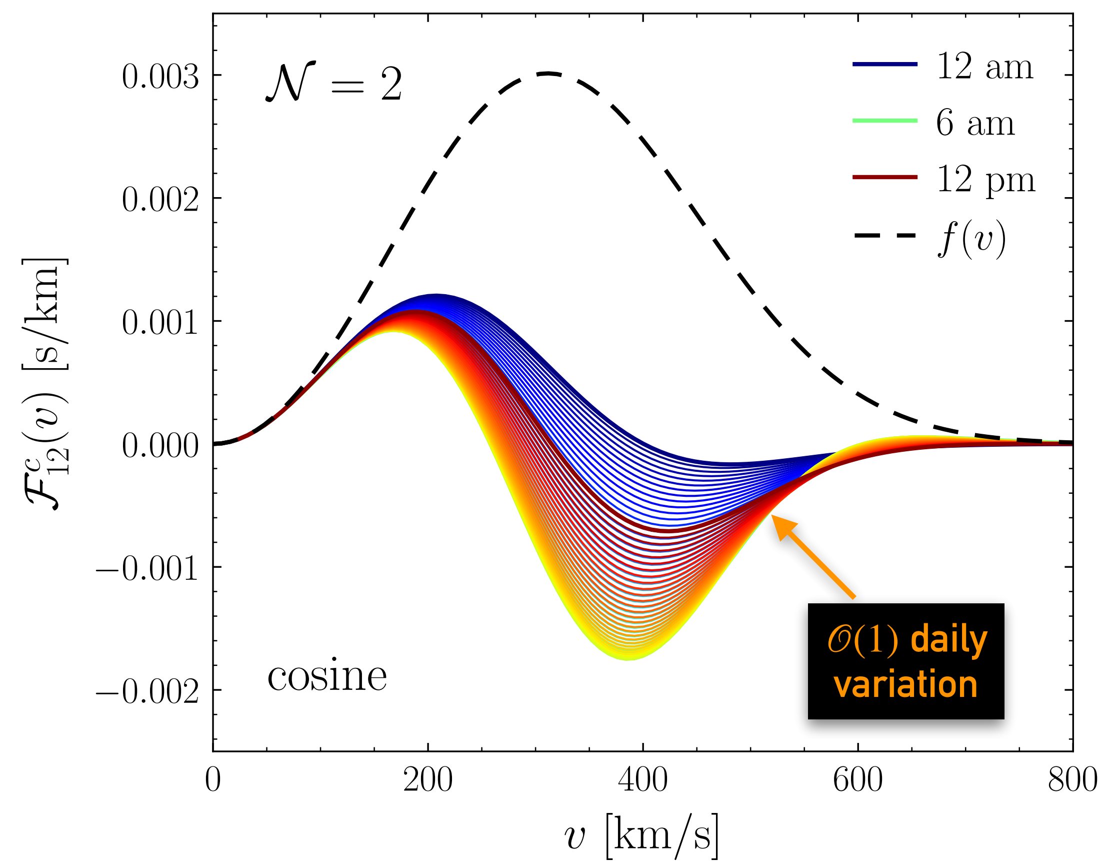


$\mathbf{x}_{12} = \mathbf{x}_1 - \mathbf{x}_2$

Broken by Daily Modulation!



[Foster, NLR+ 2020]

Standard Halo Model

Can we determine the direction of the DM wind?

SHM: $f(\mathbf{v}) = \frac{1}{\pi^{3/2} v_0^3} e^{-\mathbf{v}^2/v_0^2}$

[Foster, NLR+ 2020]

Standard Halo Model

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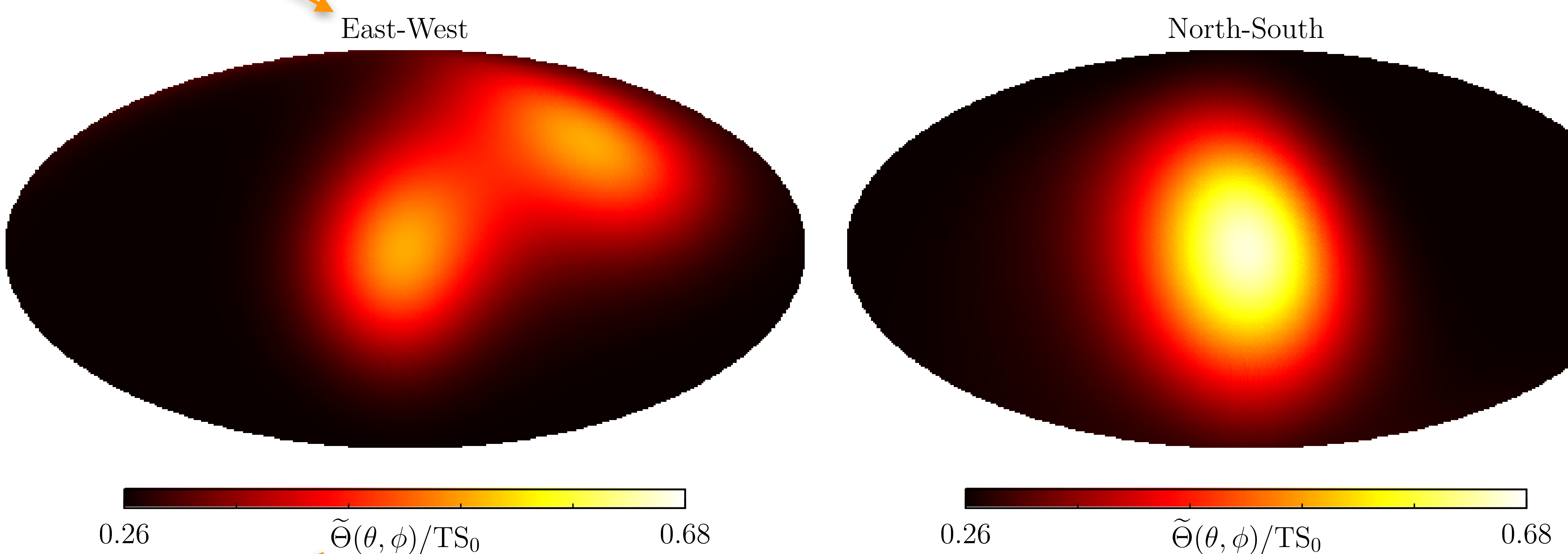
Detector Configuration



Asimov TS $\sim \sigma^2$

Axion detection TS for $d = 0$

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[Foster, NLR+ 2020]

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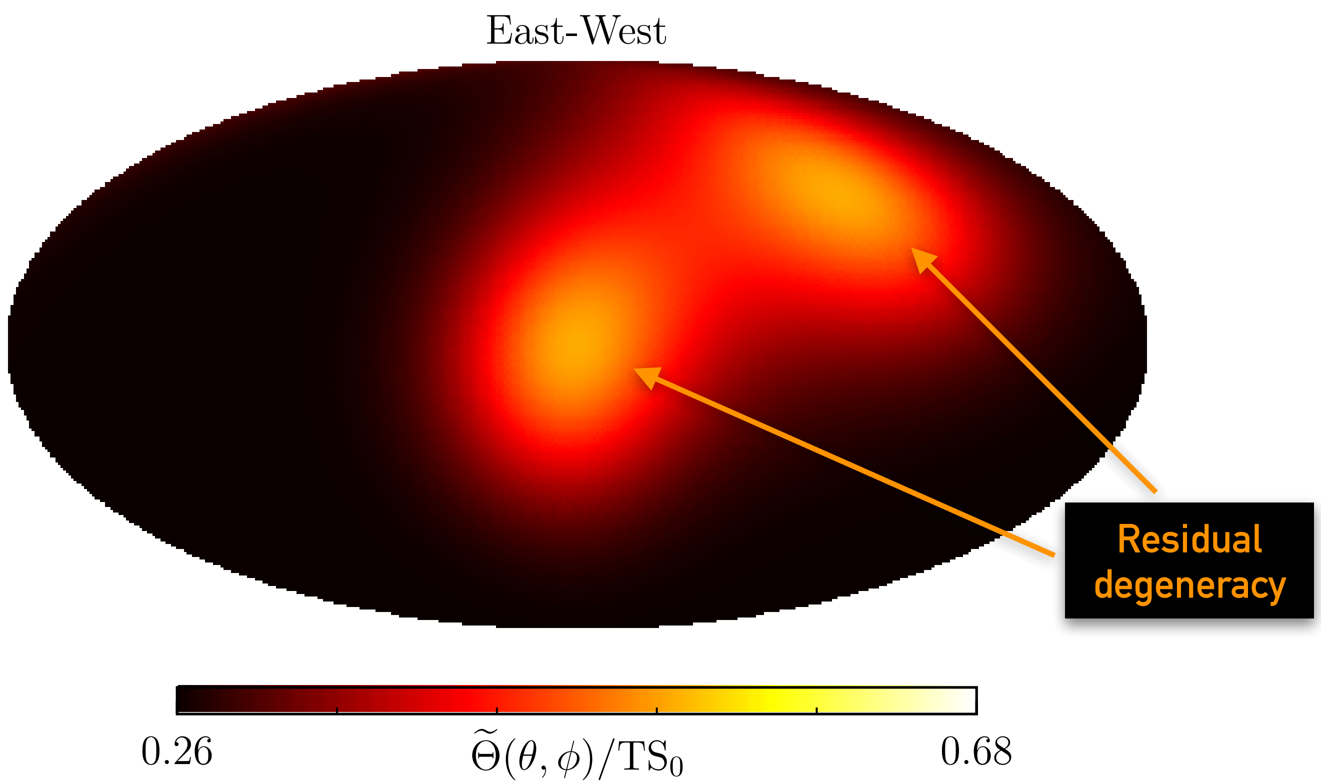

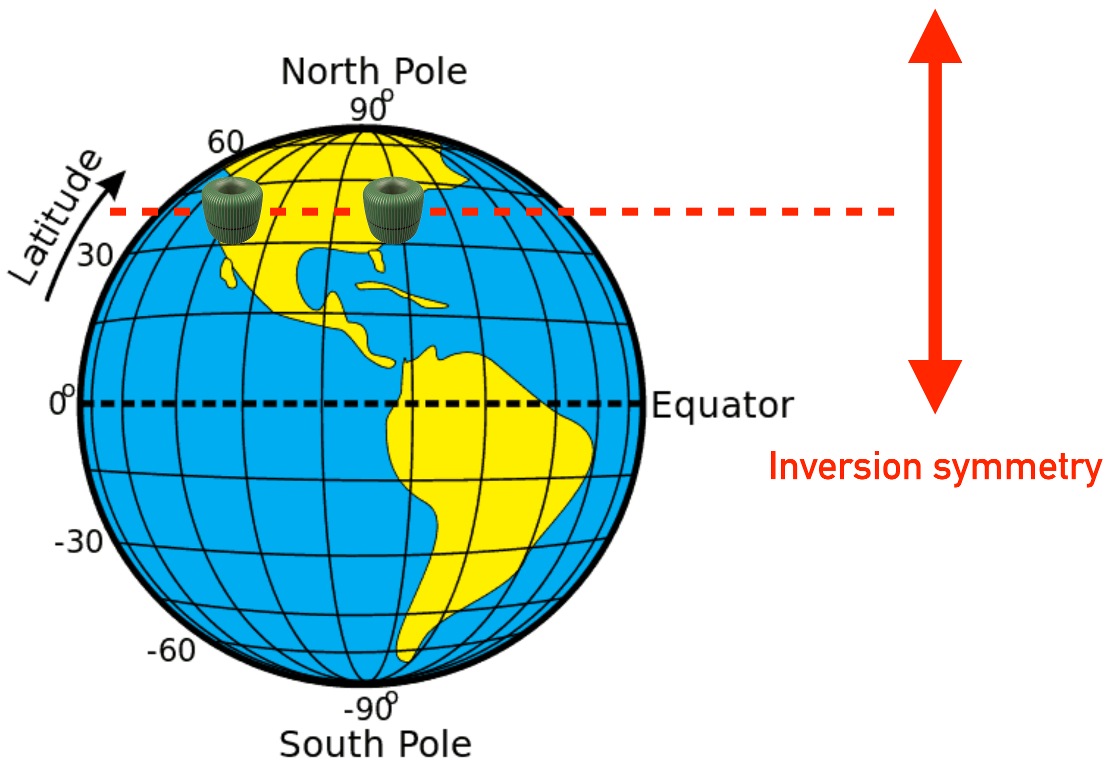

[Foster, NLR+ 2020]

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If HAYSTAC discovers DM, how well can they infer $\mathbf{v}_{\odot}$ with 2 detectors and 1 day of data?

[Foster, NLR+ 2020]

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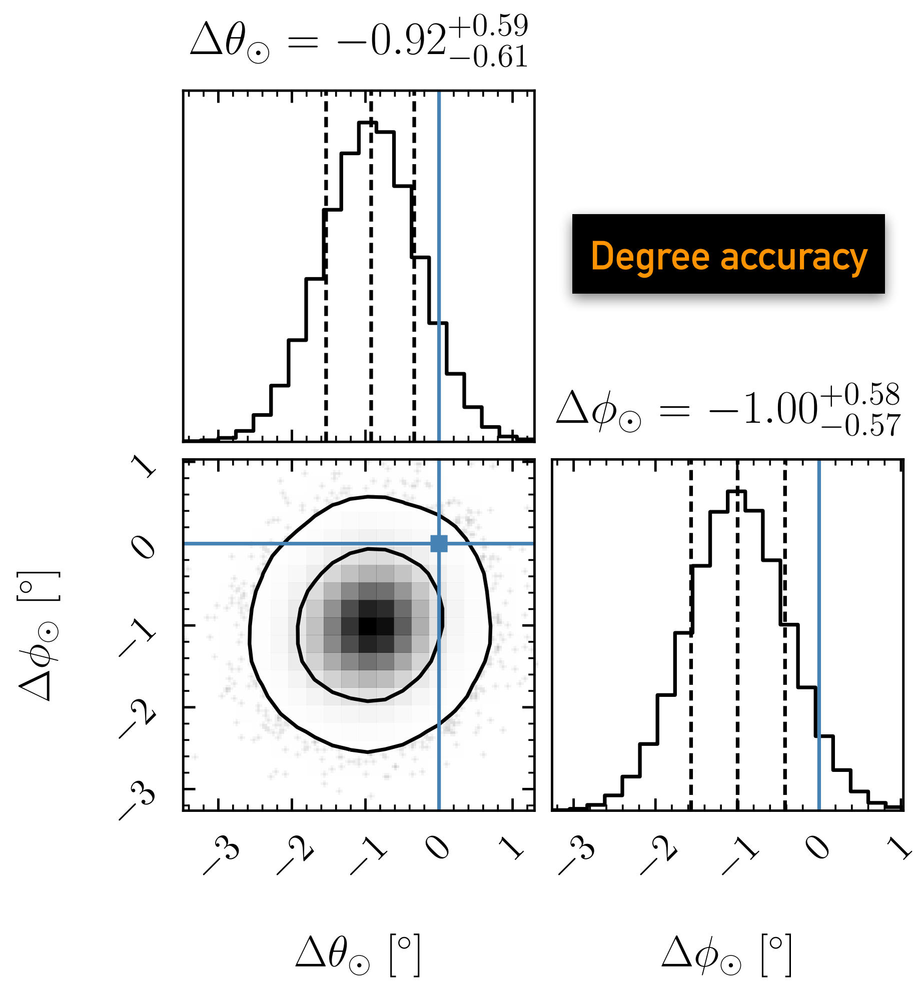


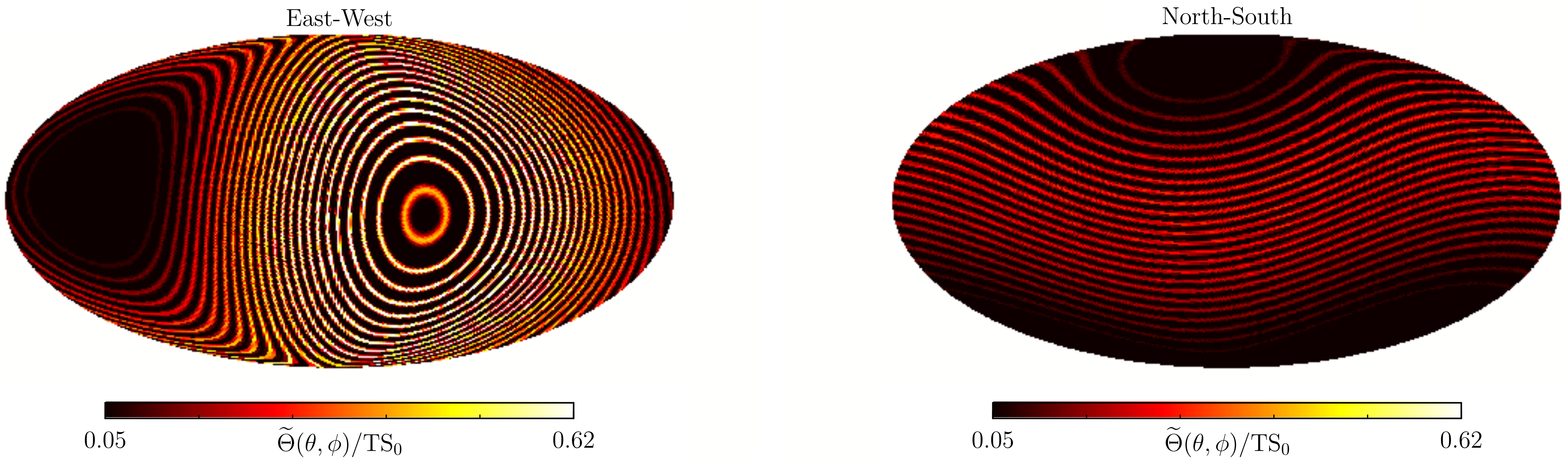
Degree accuracy

Results use the full likelihood formalism

[Foster, NLR+ 2020]

Stream Localization

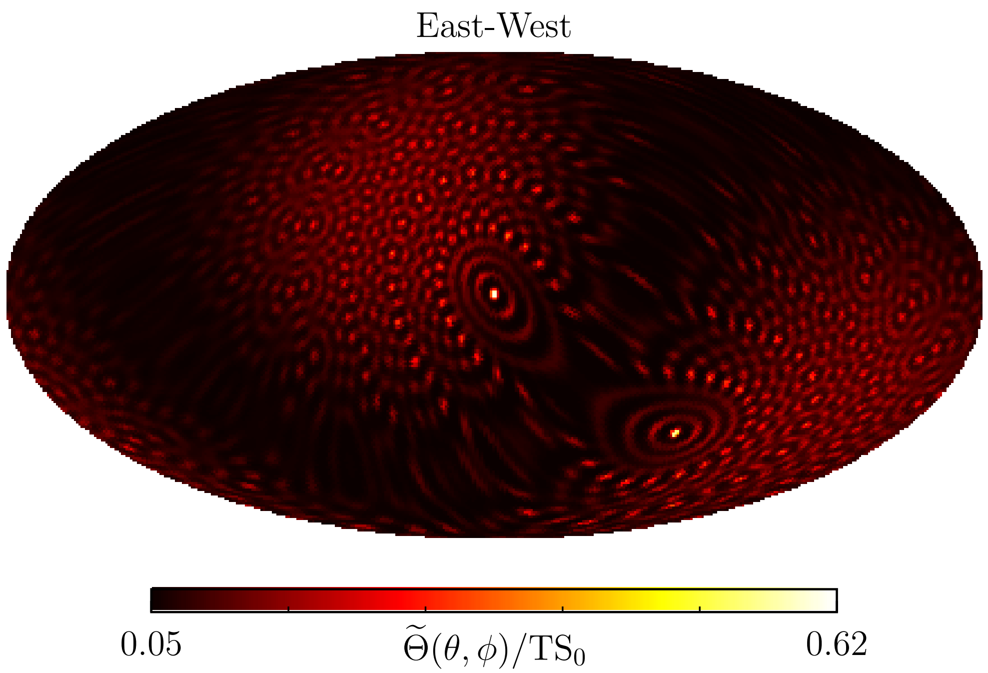
Can we determine the direction of an incident DM stream?

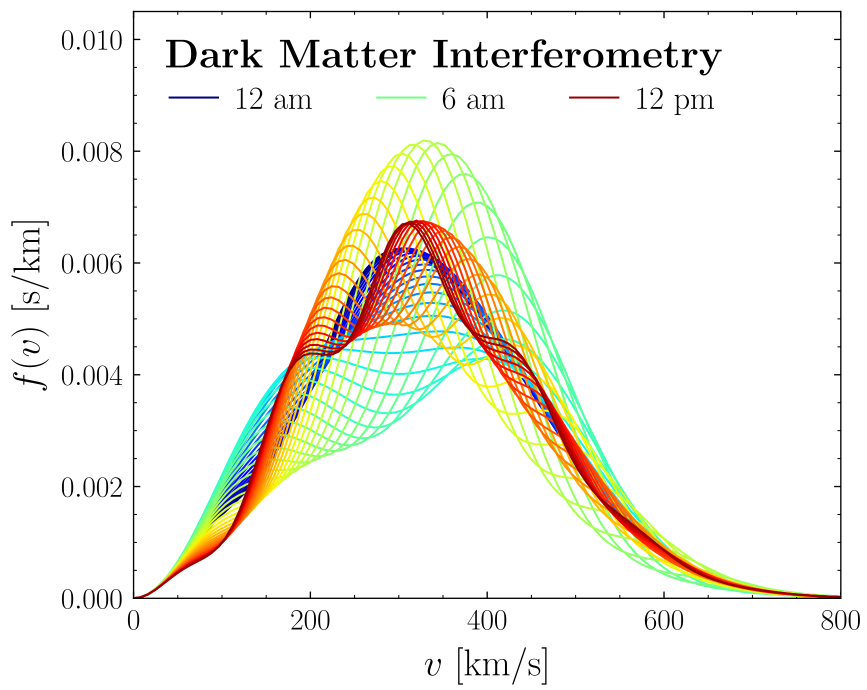


[Foster, NLR+ 2020]

Summary

Interferometry performed directly on the axion wave reveals hidden DM structure





[Foster, NLR+ 2020]

Cosmic Axion Background

2101.09287

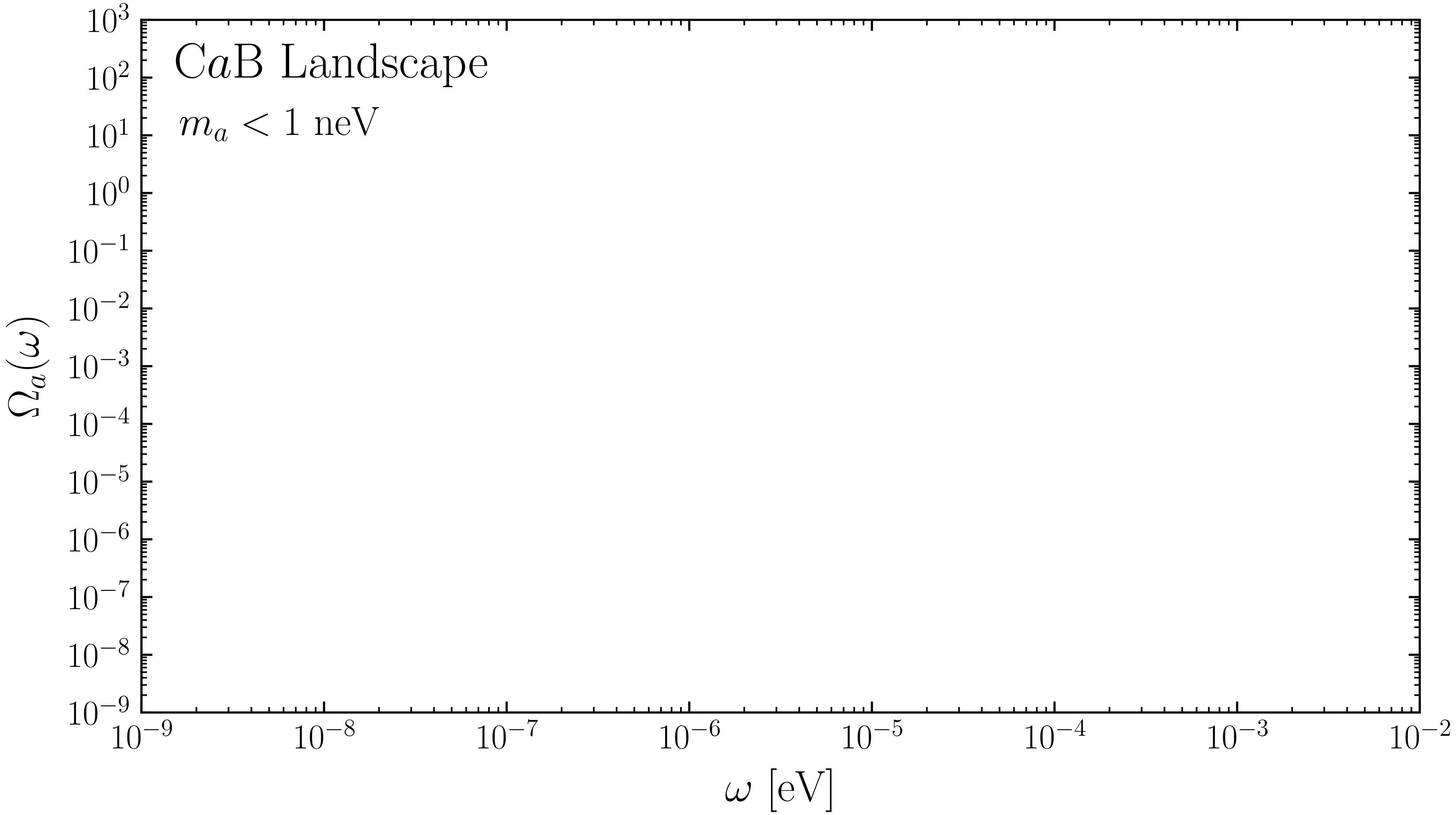
w/ Jeff Dror, Hitoshi Murayama

The Cosmic Axion Background

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

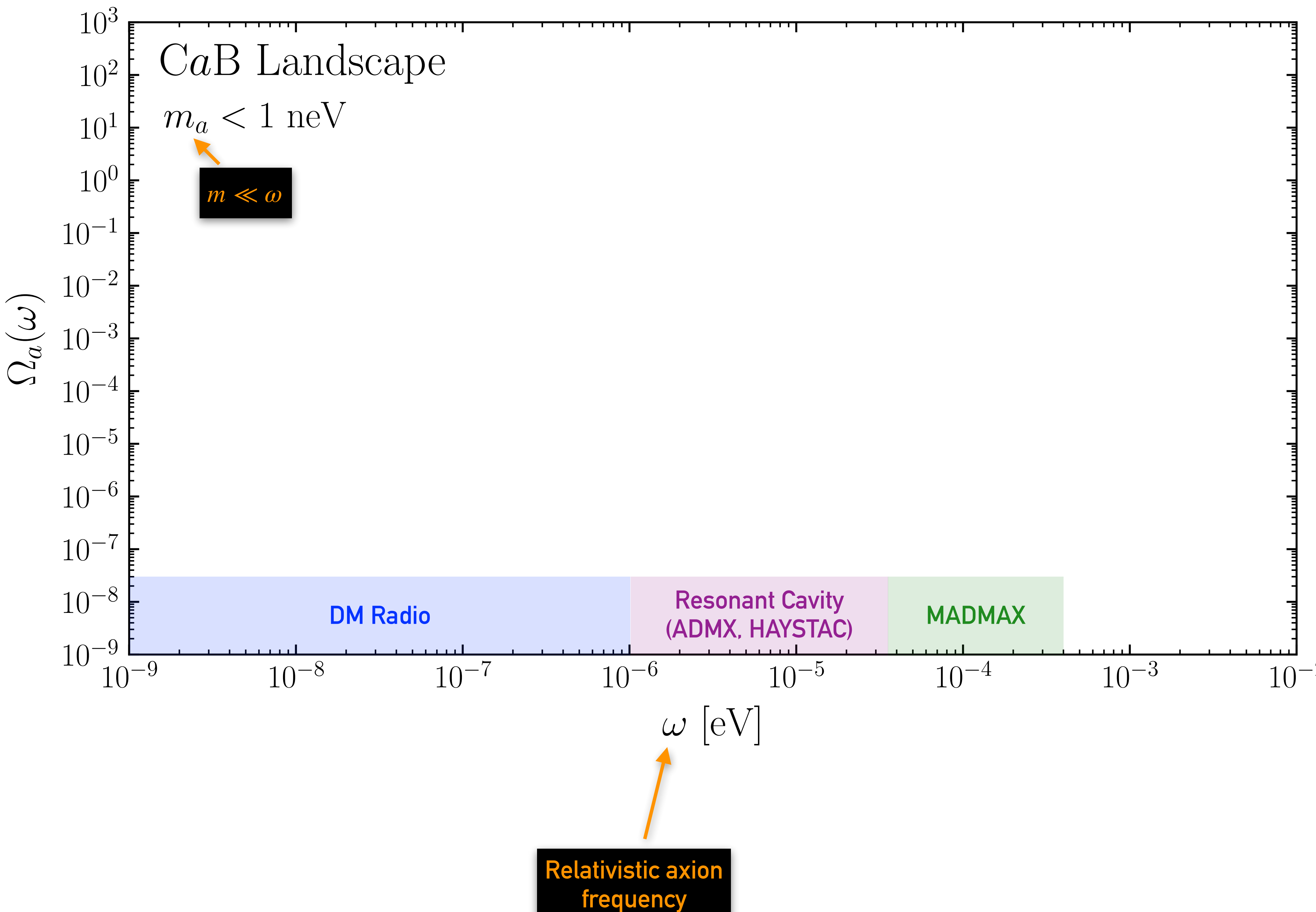
[Dror, NLR, Murayama 2021]

Landscape



[Dror, NLR, Murayama 2021]

Landscape



[Dror, NLR, Murayama 2021]

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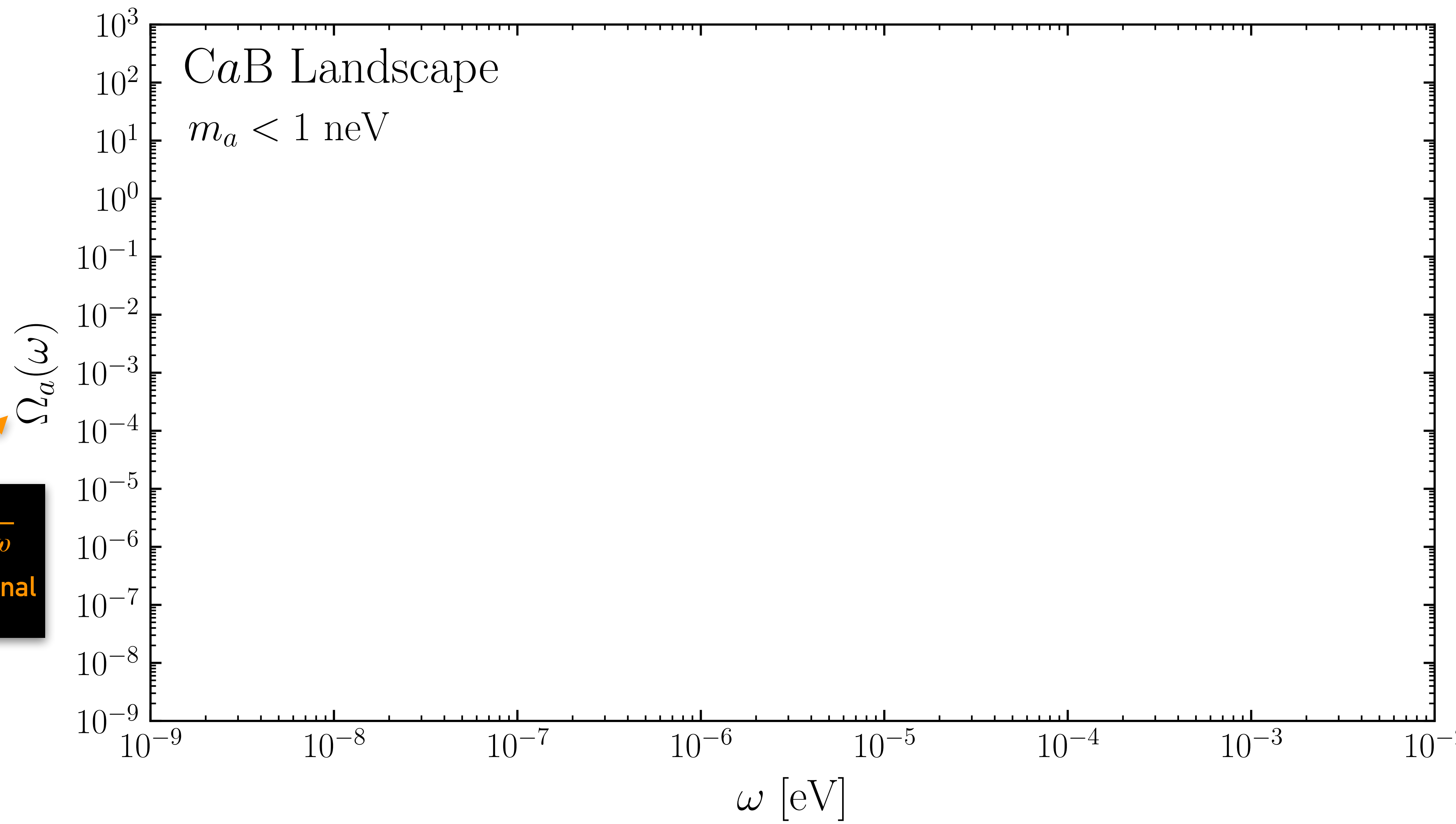
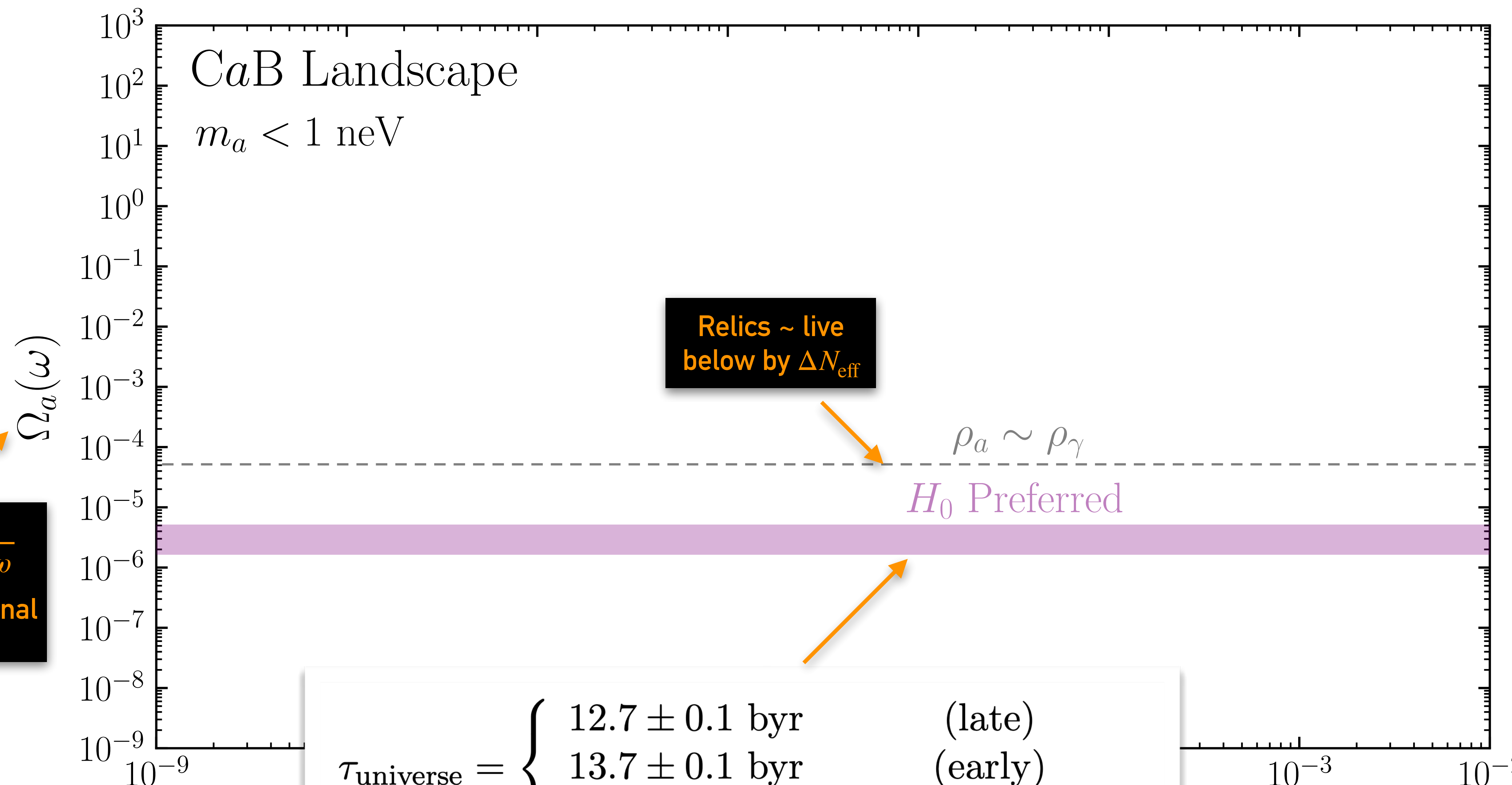


$= \frac{1}{\rho_c} \frac{\rho_a}{d \ln \omega}$

c.f. gravitational waves

[Dror, NLR, Murayama 2021]

Landscape



Relics ~ live below by $\Delta N_{\rm eff}$

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

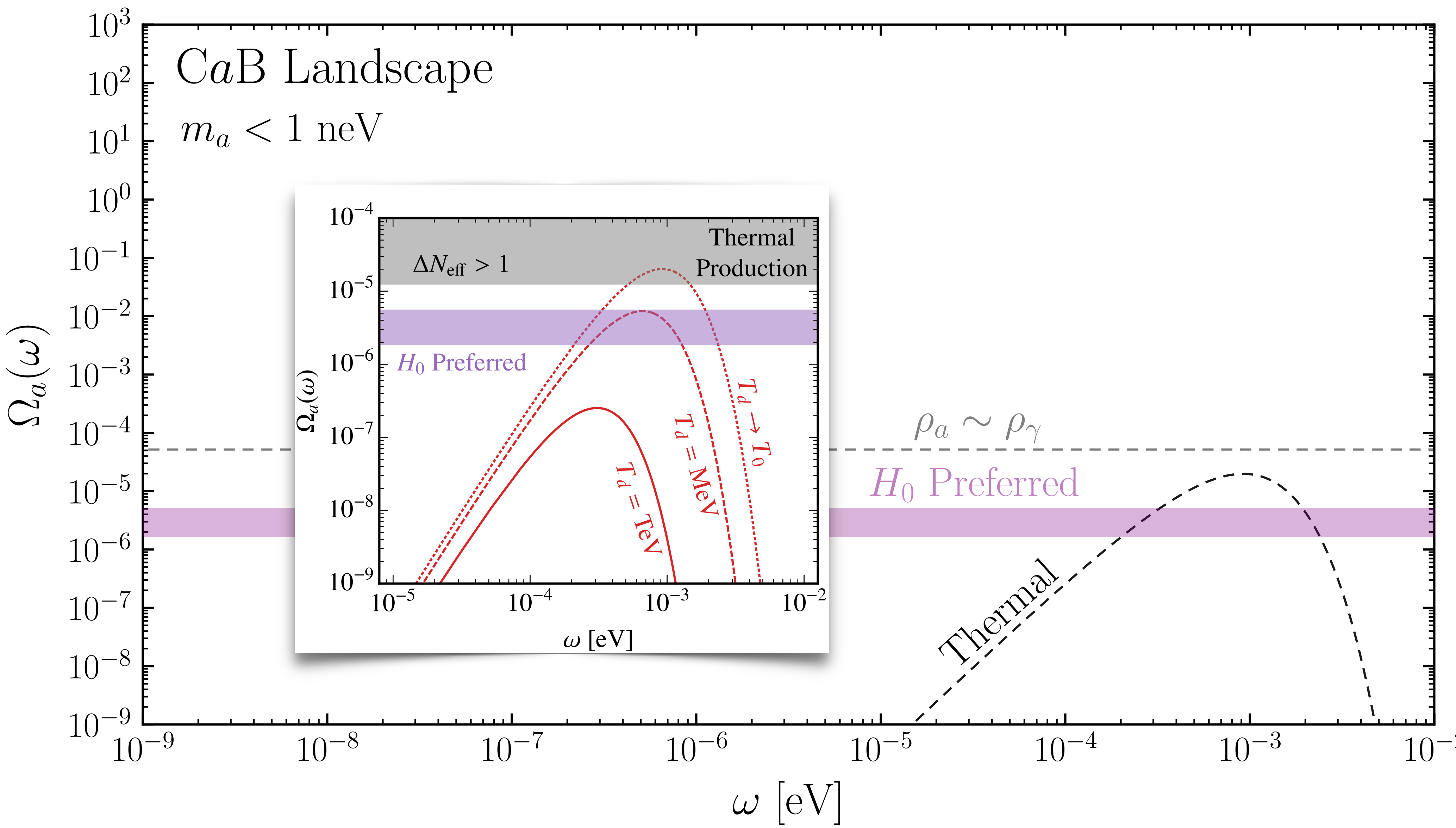
c.f. gravitational waves

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

See e.g. [Valentino+ "In the Realm of the Hubble tension – a Review of Solutions" 2103.01183]

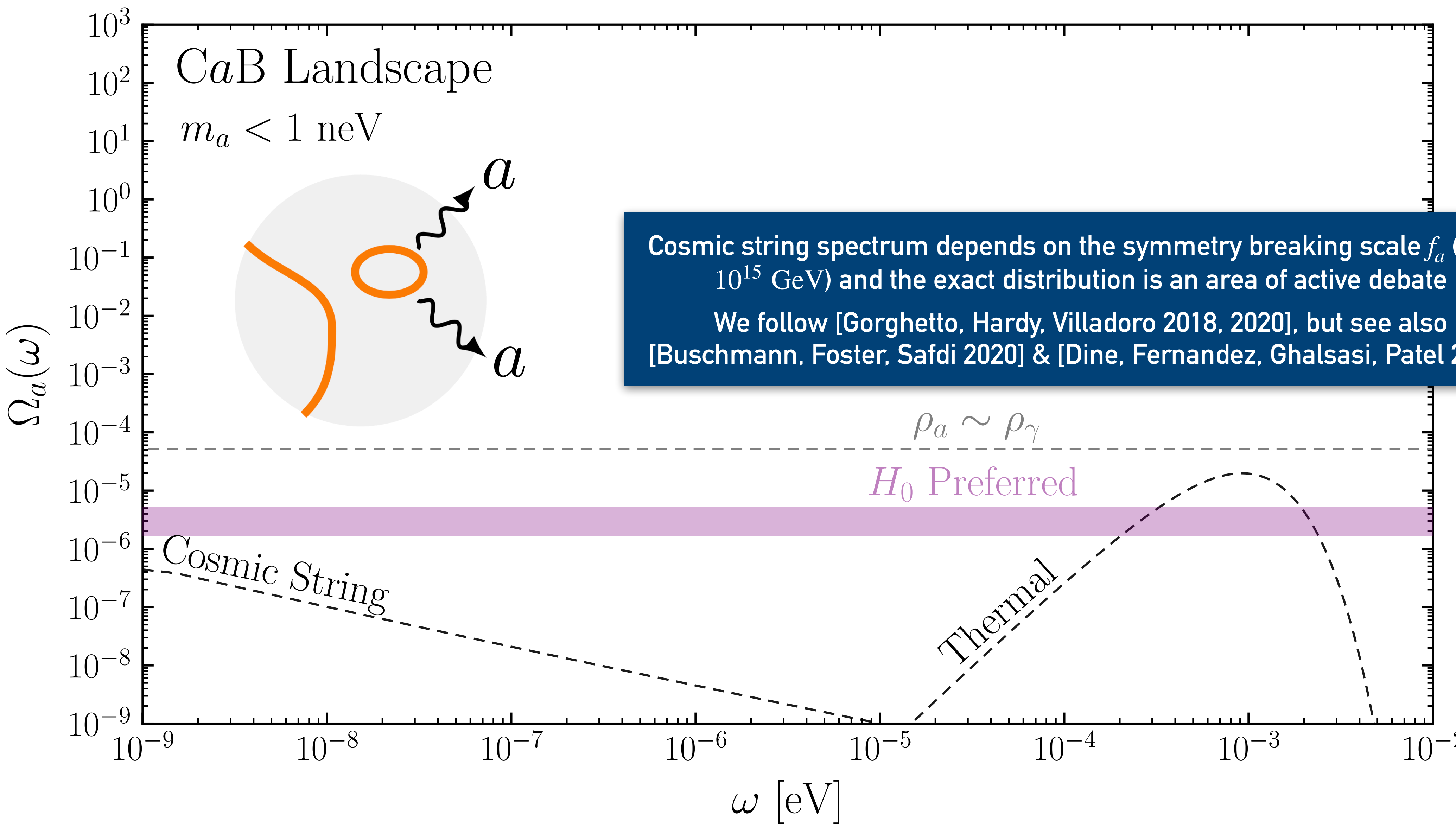
[Dror, NLR, Murayama 2021]

Landscape



[Dror, NLR, Murayama 2021]

Landscape

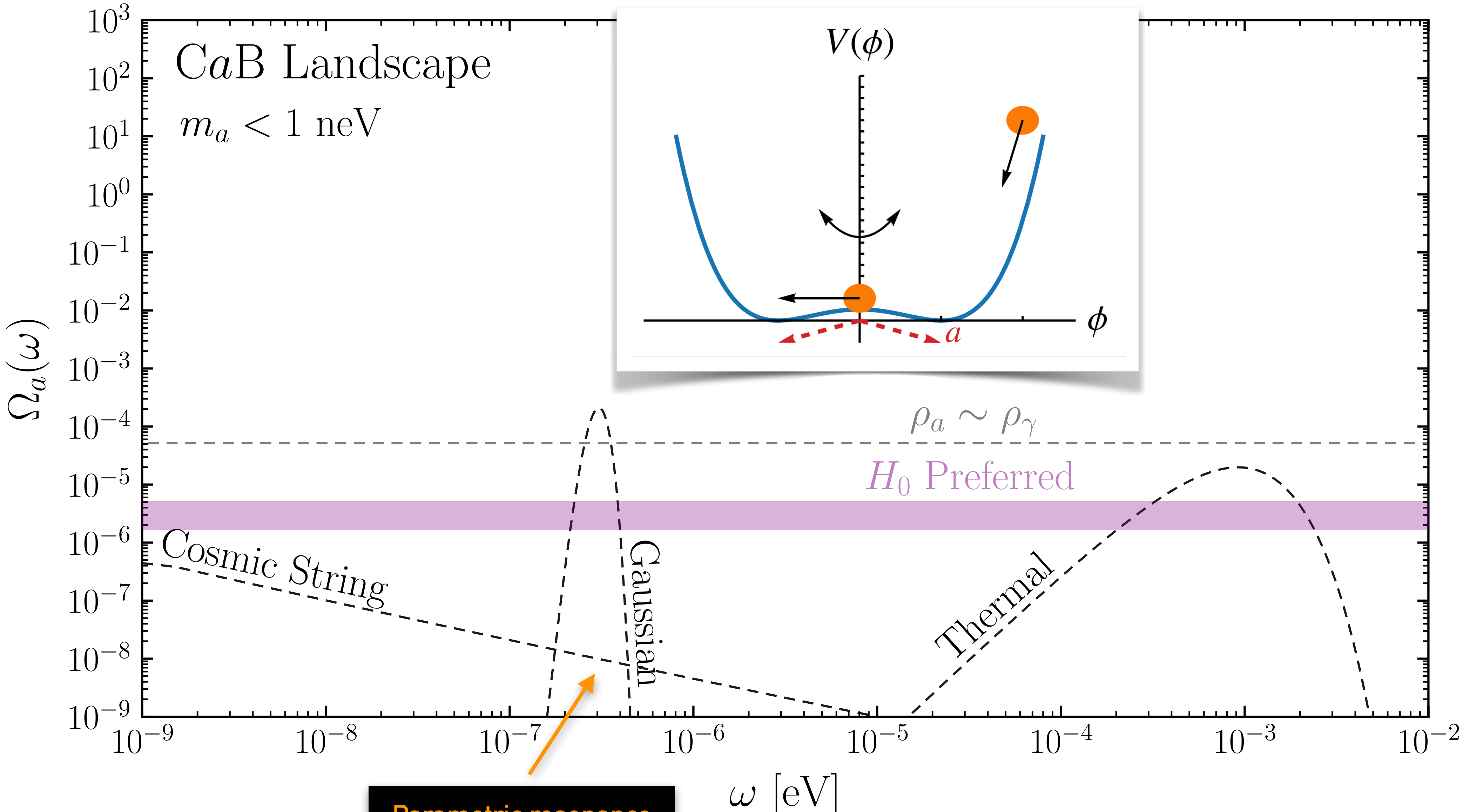


Cosmic string spectrum depends on the symmetry breaking scale f_a (here 10^{15} GeV) and the exact distribution is an area of active debate

We follow [Gorghetto, Hardy, Villadoro 2018, 2020], but see also [Buschmann, Foster, Safdi 2020] & [Dine, Fernandez, Ghalsasi, Patel 2020]

[Dror, NLR, Murayama 2021]

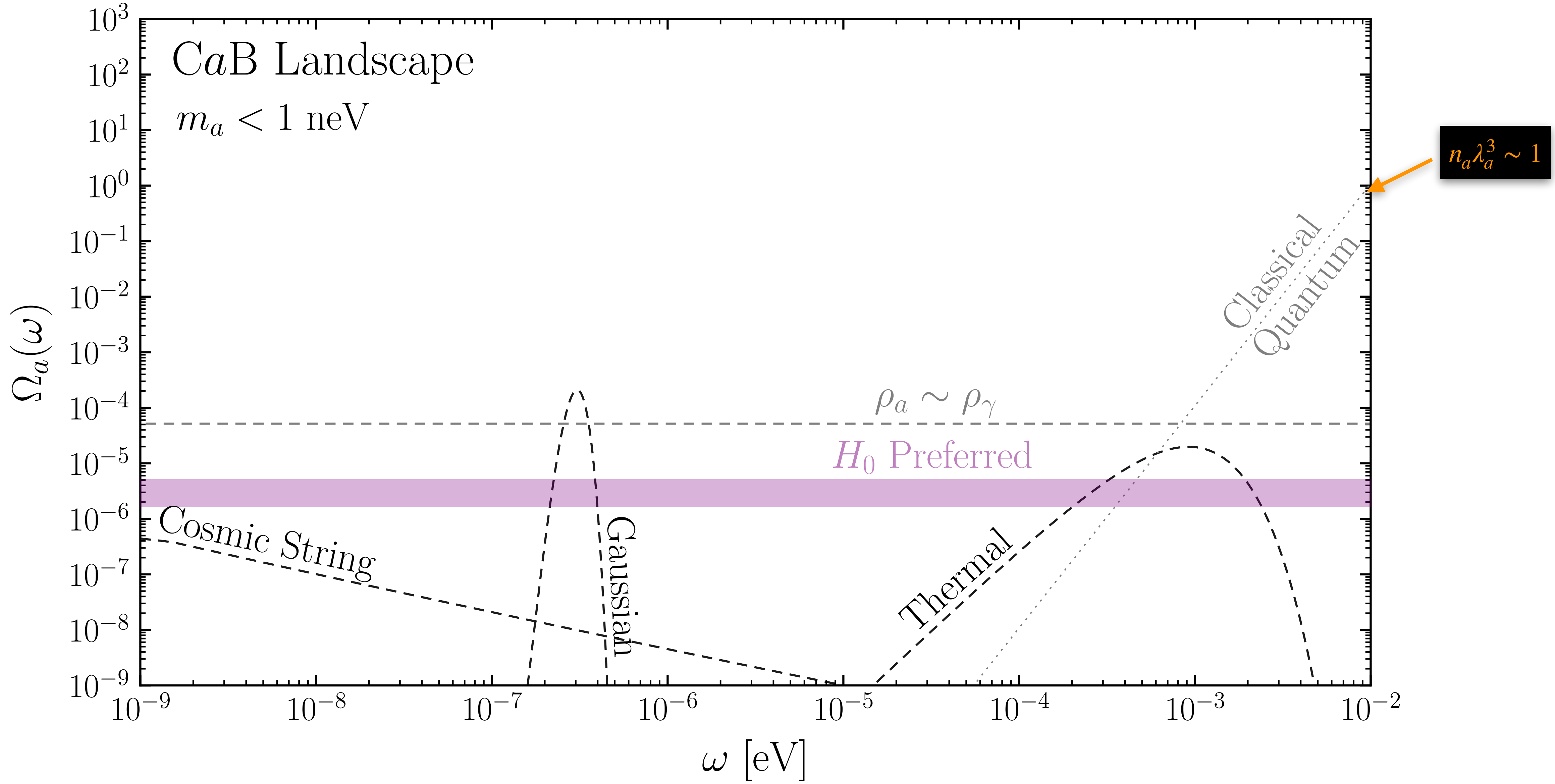
Landscape



Parametric resonance produces a ~Gaussian spectrum

[Dror, NLR, Murayama 2021]

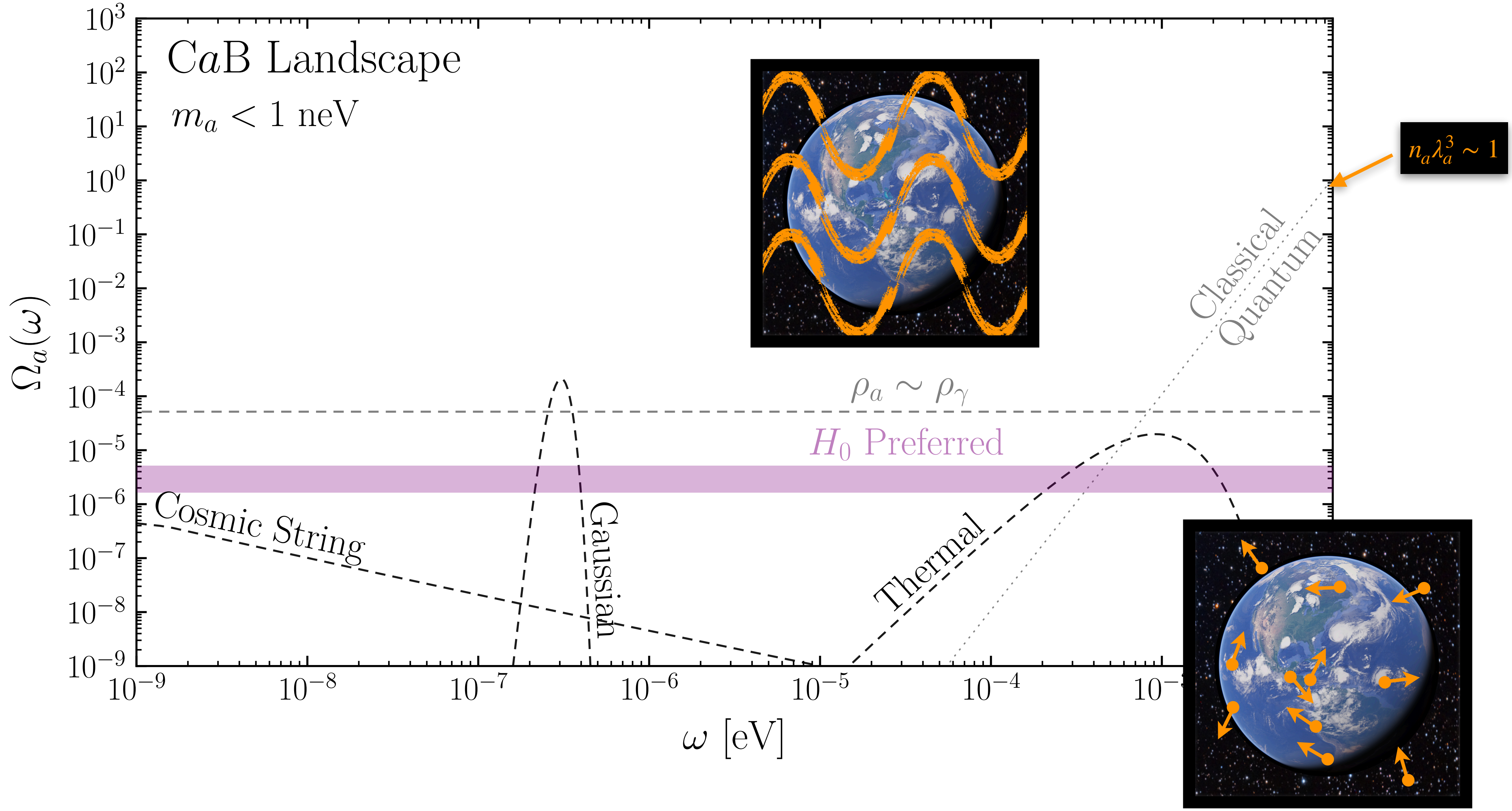
Landscape



[Dror, NLR, Murayama 2021]

Landscape

Classical wave description applies



[Dror, NLR, Murayama 2021]

Rough Sensitivity

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

Sampled from $p(\omega)$

Random phase

[Dror, NLR, Murayama 2021]

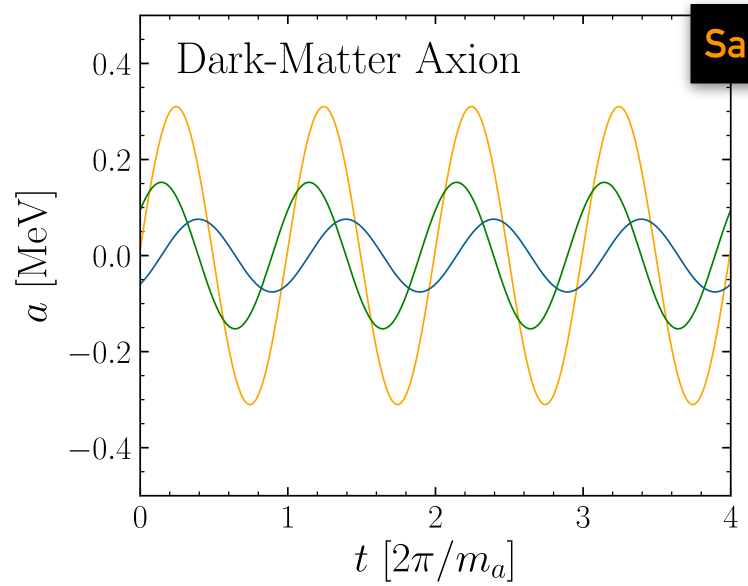
Rough Sensitivity

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

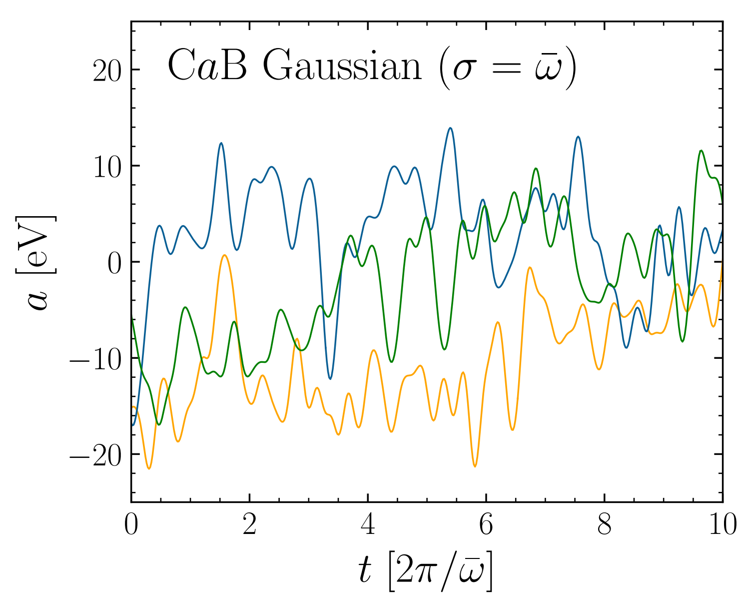
Sampled from $p(\omega)$

Random phase

Dark Matter



CaB

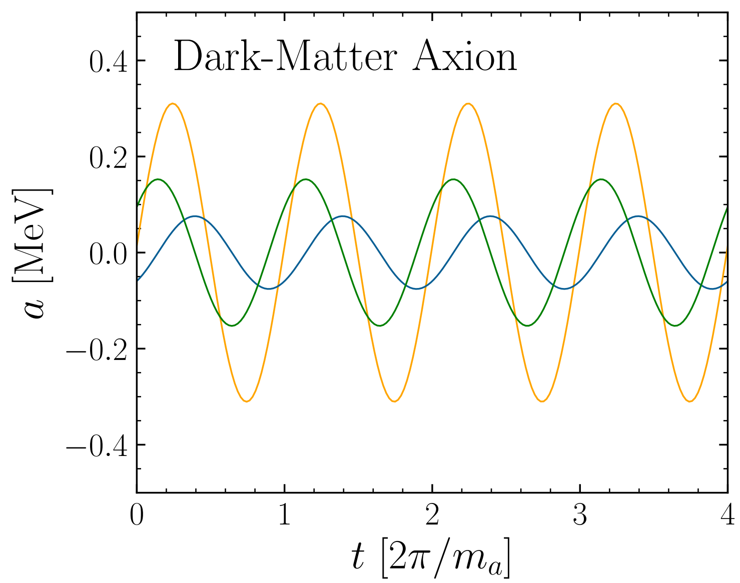


[Dror, NLR, Murayama 2021]

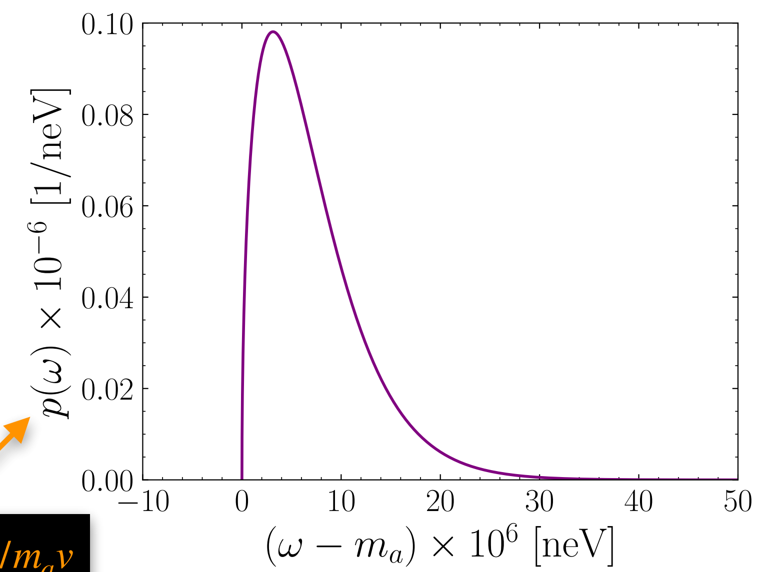
Rough Sensitivity

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

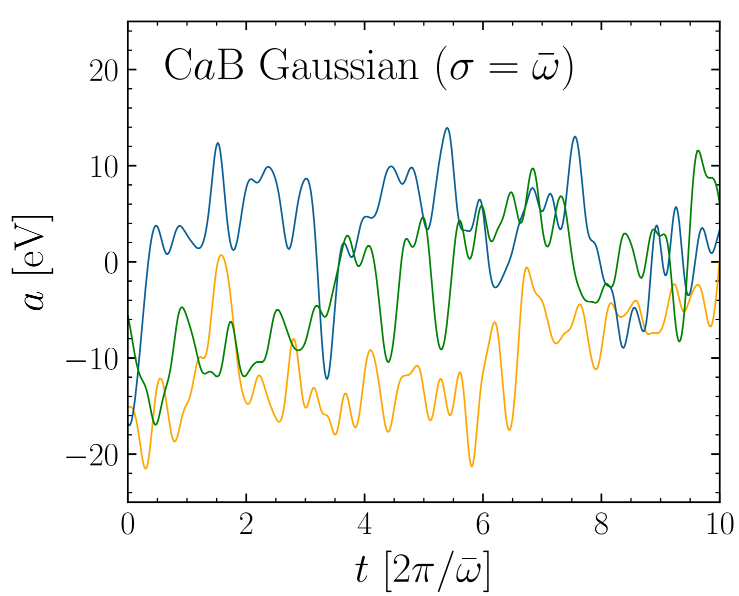
Dark Matter

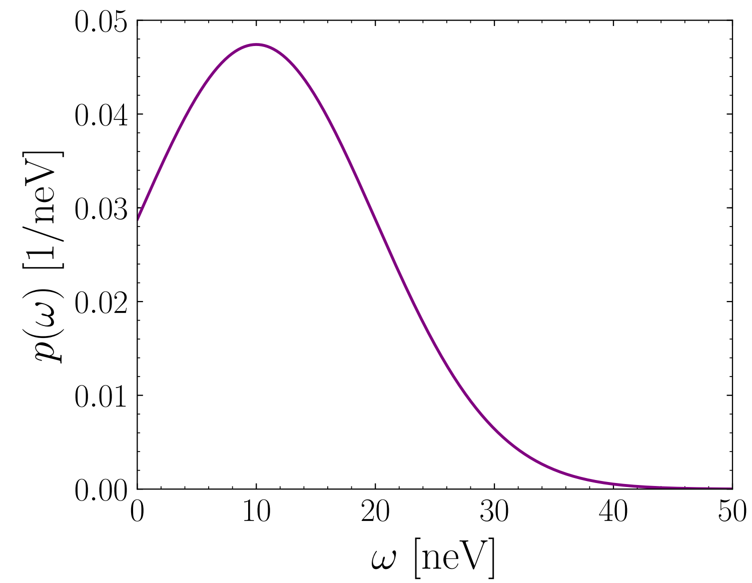


$p(\omega) = f(v)/m_a v$



CaB



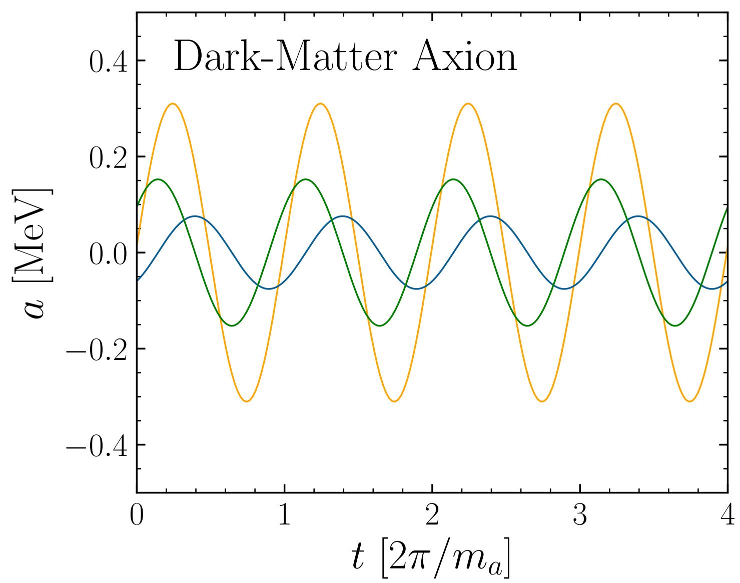


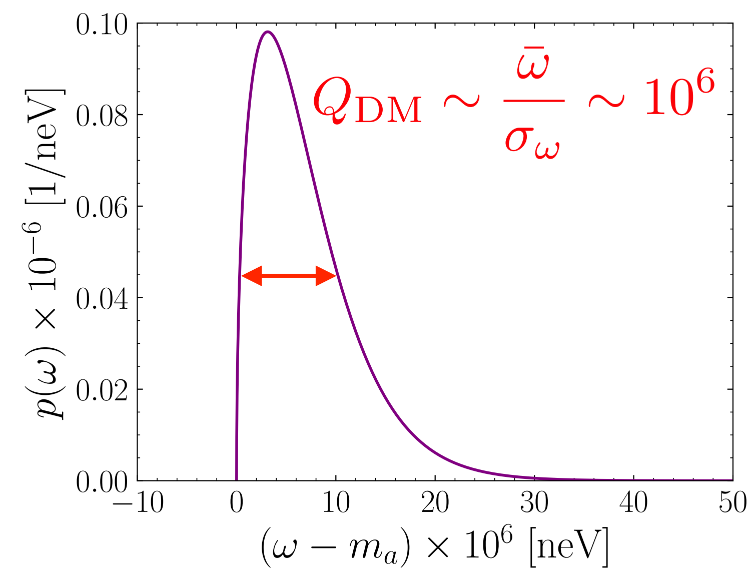
[Dror, NLR, Murayama 2021]

Rough Sensitivity

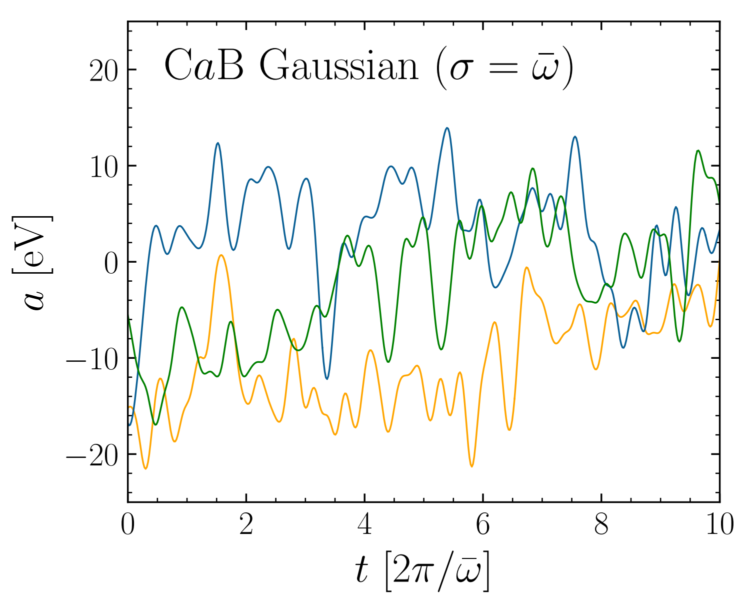
$$a(t) \sim \sum_i \cos(\omega_i t + \phi_i)$$

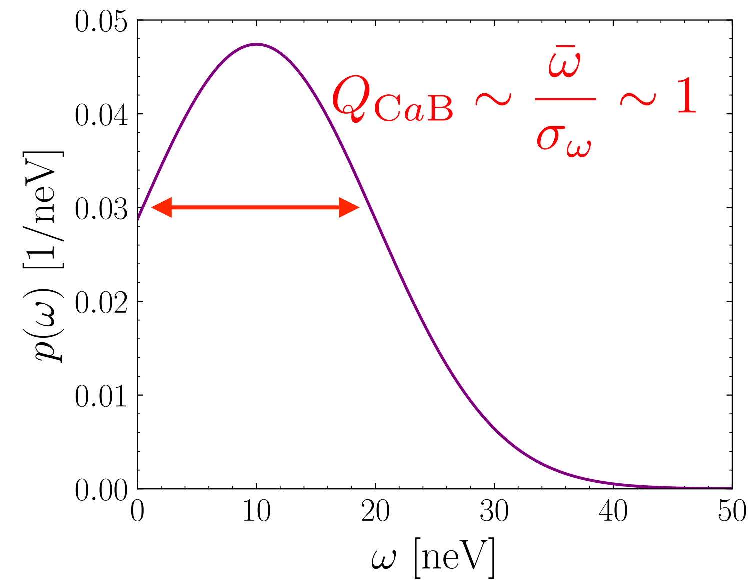
Dark Matter





CaB



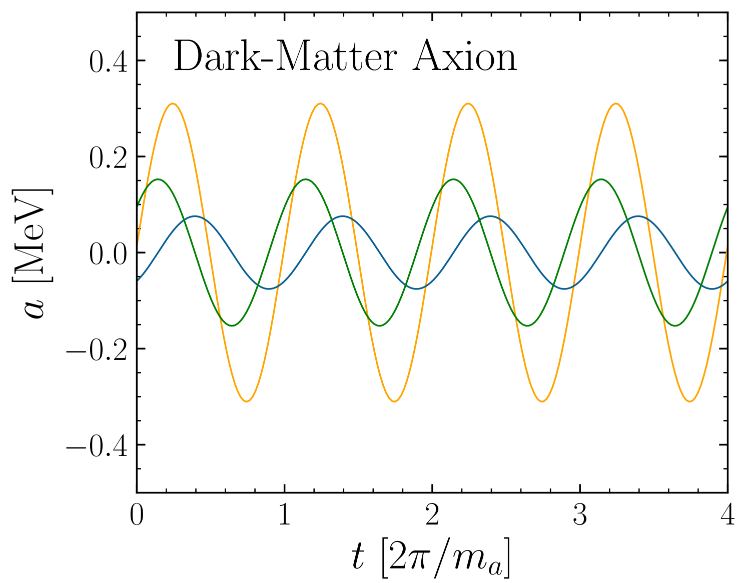


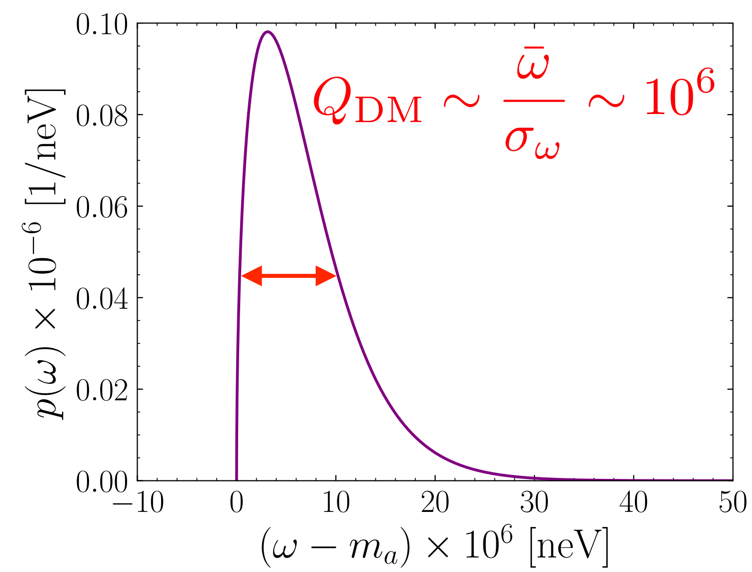
[Dror, NLR, Murayama 2021]

Rough Sensitivity

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

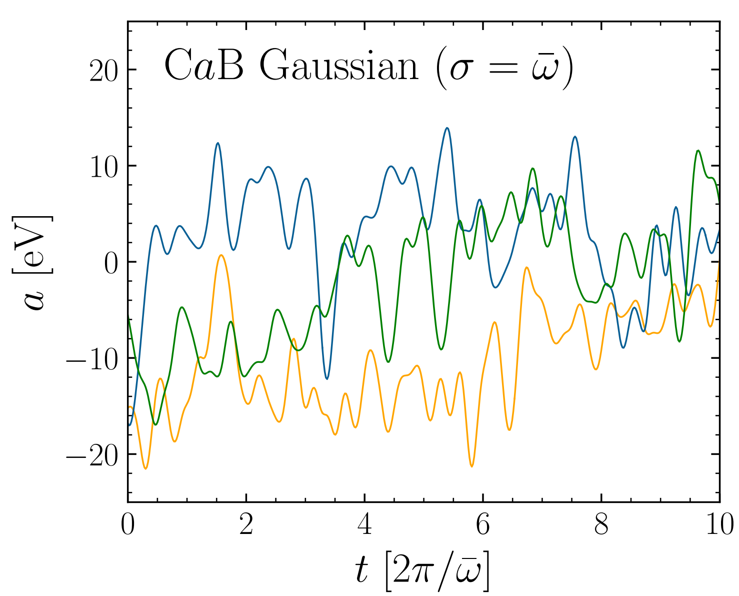
Dark Matter

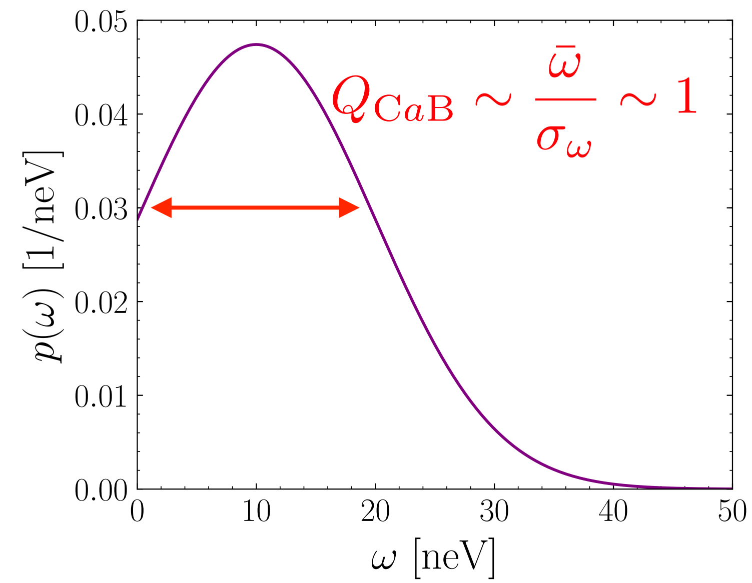




Much broader signal - existing searches would throw out as background

C*a*B





[Dror, NLR, Murayama 2021]

Rough Sensitivity

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

Power in the axion field

Power spectral density - measures power at a given frequency

$$\langle S_a(\omega) \rangle = \frac{\pi \rho_a}{\bar{\omega}} \frac{p(\omega)}{\omega}$$

[Dror, NLR, Murayama 2021]

Rough Sensitivity

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

Power in the axion field

$$\langle S_a(\omega) \rangle = \frac{\pi \rho_a}{\bar{\omega}} \frac{p(\omega)}{\omega}$$

Experimentally accessible power

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

[Dror, NLR, Murayama 2021]

Rough Sensitivity

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

Power in the axion field

$$\langle S_a(\omega) \rangle = \frac{\pi \rho_a}{\bar{\omega}} \frac{p(\omega)}{\omega}$$

Experimentally accessible power

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

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

[Dror, NLR, Murayama 2021]

Rough Sensitivity

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

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

[Dror, NLR, Murayama 2021]

Rough Sensitivity

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

Single bin: $(g_{a\gamma\gamma}^{\rm lim})^2 \rho_{\rm DM} Q_{\rm DM} = (g_{a\gamma\gamma}^{\rm SE})^2 \rho_a Q_{{\rm C}a{\rm B}}$

Dark Matter sensitivity

Star Emission sensitivity

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

[Dror, NLR, Murayama 2021]

Rough Sensitivity

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

Single bin: $$(g_{a\gamma\gamma}^{\rm lim})^2 \rho_{\rm DM} Q_{\rm DM} = (g_{a\gamma\gamma}^{\rm SE})^2 \rho_a Q_{{\rm C}a{\rm B}}$$

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

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

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

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

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

[Dror, NLR, Murayama 2021]

Rough Sensitivity

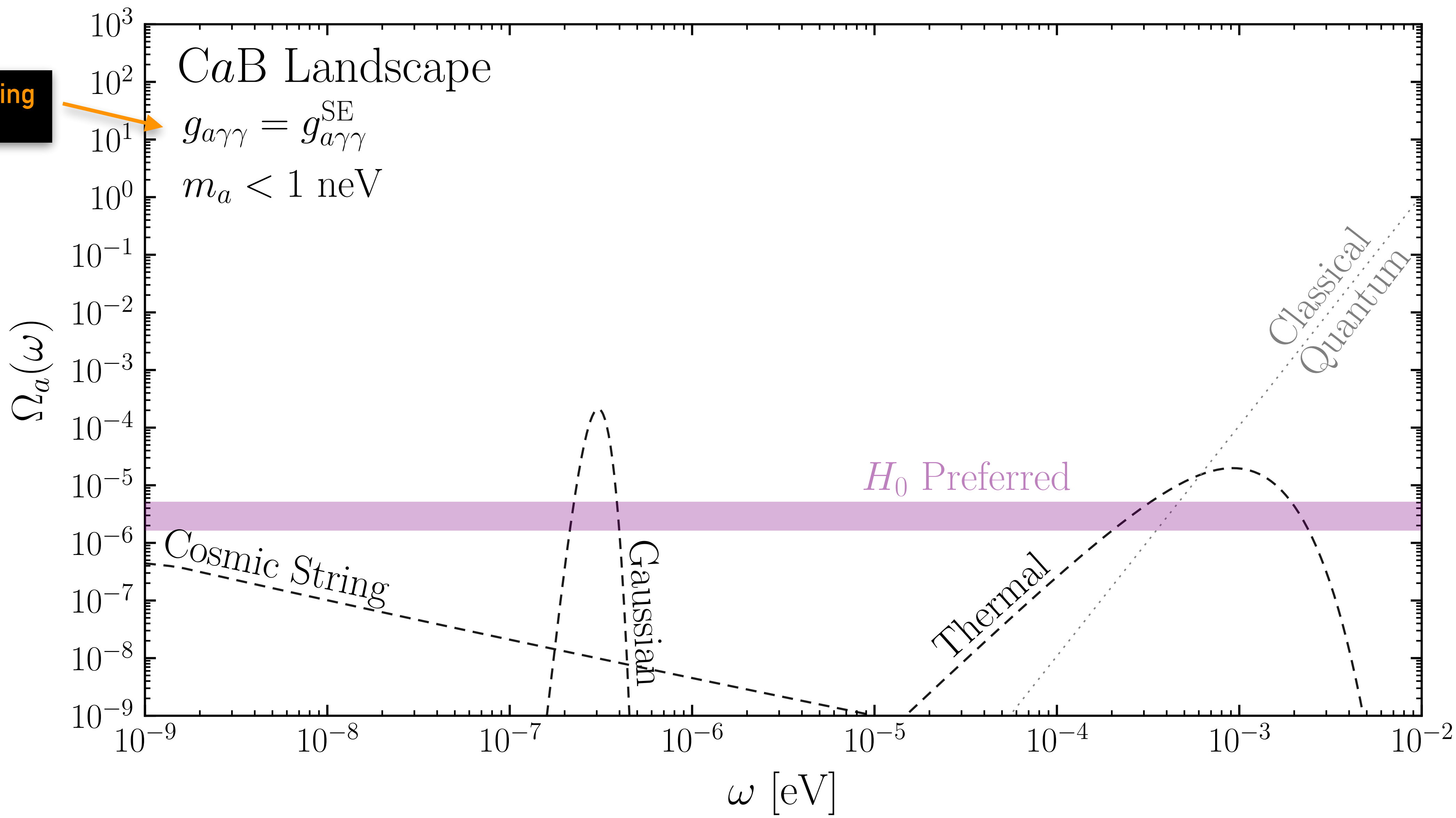
$$\rho_a = \rho_{\mathrm{DM}} \left(\frac{g_{a\gamma\gamma}^{\mathrm{lim}}}{g_{a\gamma\gamma}^{\mathrm{SE}}} \right)^2 \sqrt{\frac{Q_{\mathrm{DM}}}{Q_{\mathrm{C}a\mathrm{B}}}}$$

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

[Dror, NLR, Murayama 2021]

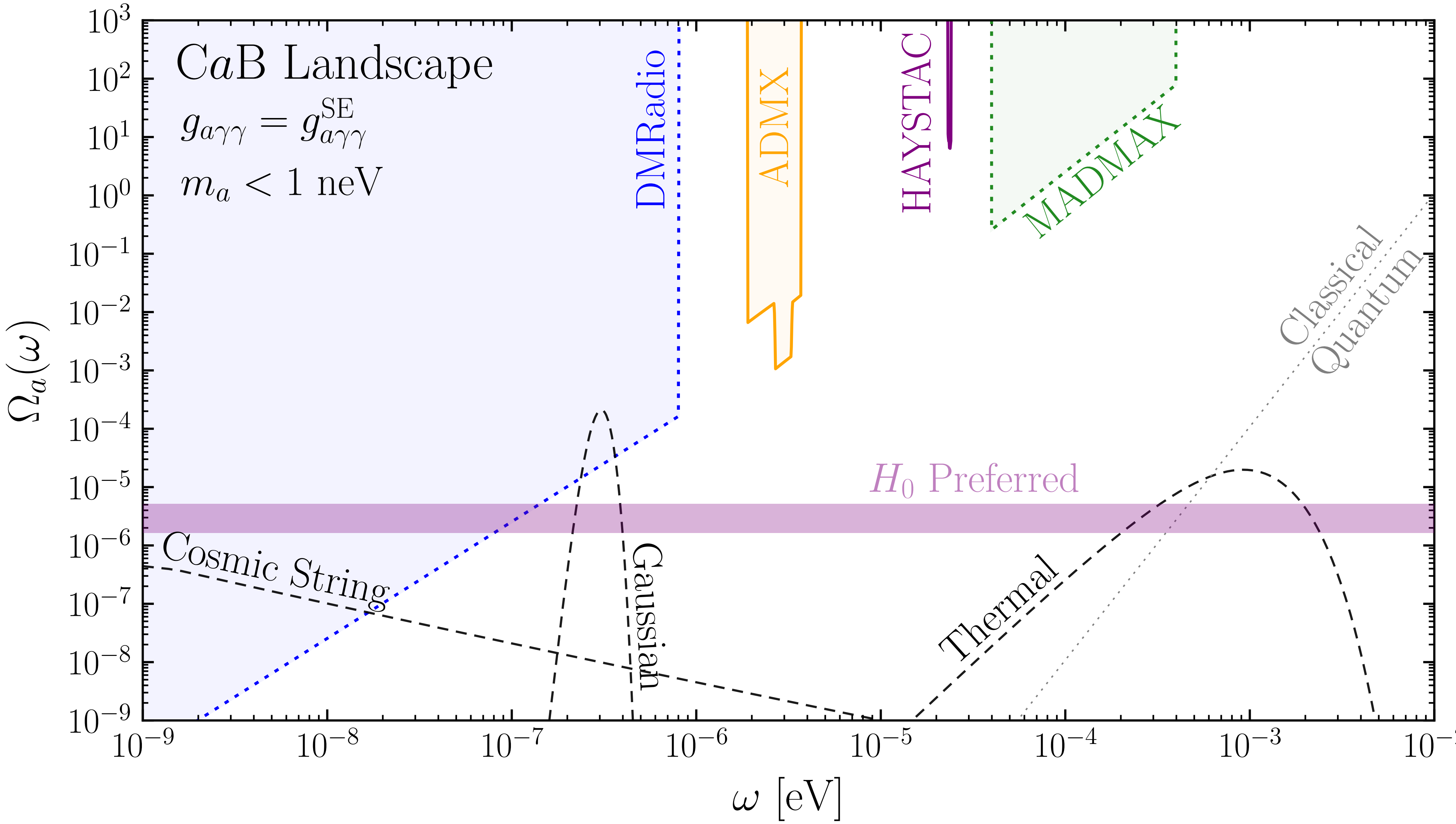
Experimental Landscape

Saturate existing bounds



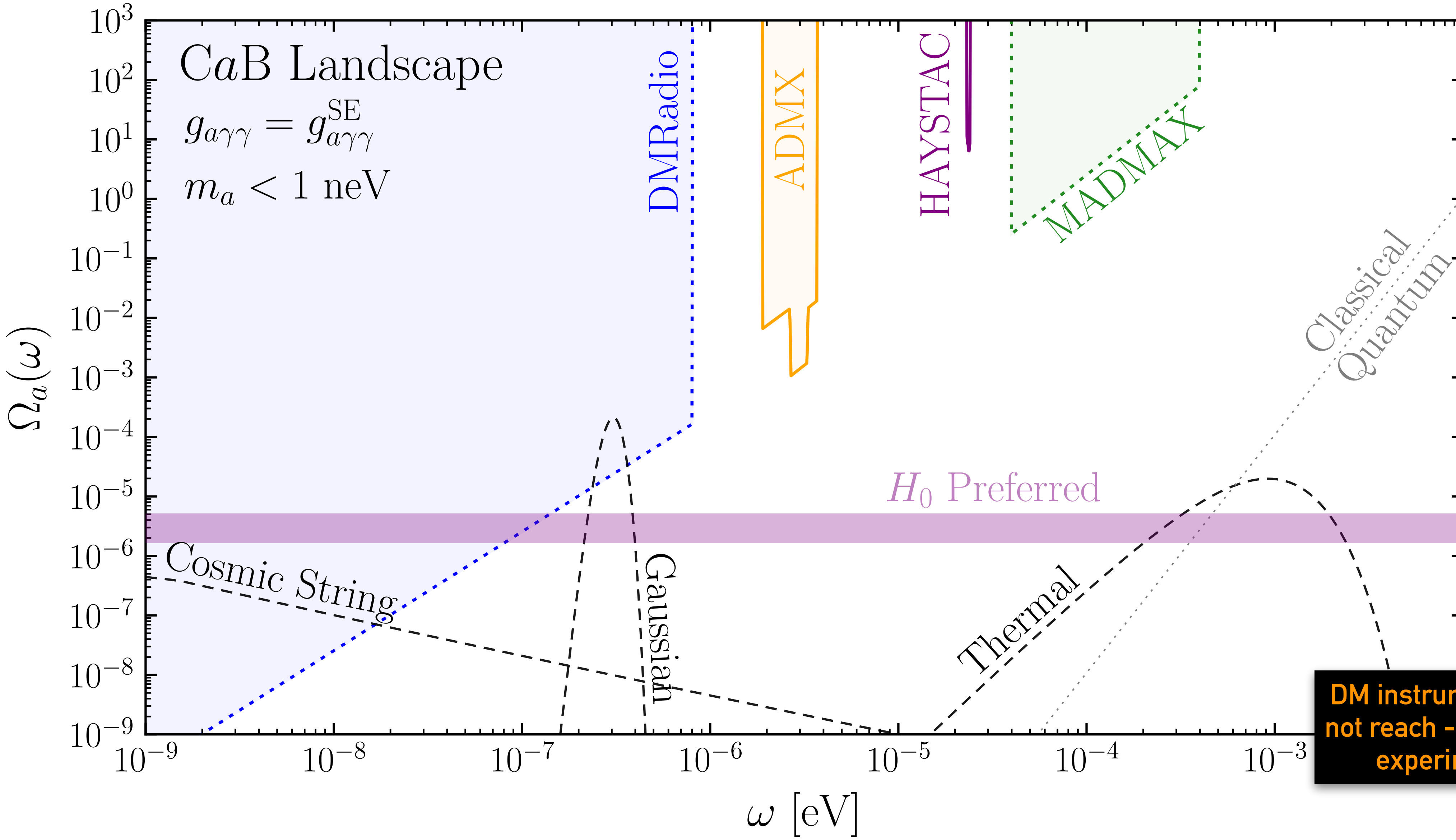
[Dror, NLR, Murayama 2021]

Experimental Landscape



[Dror, NLR, Murayama 2021]

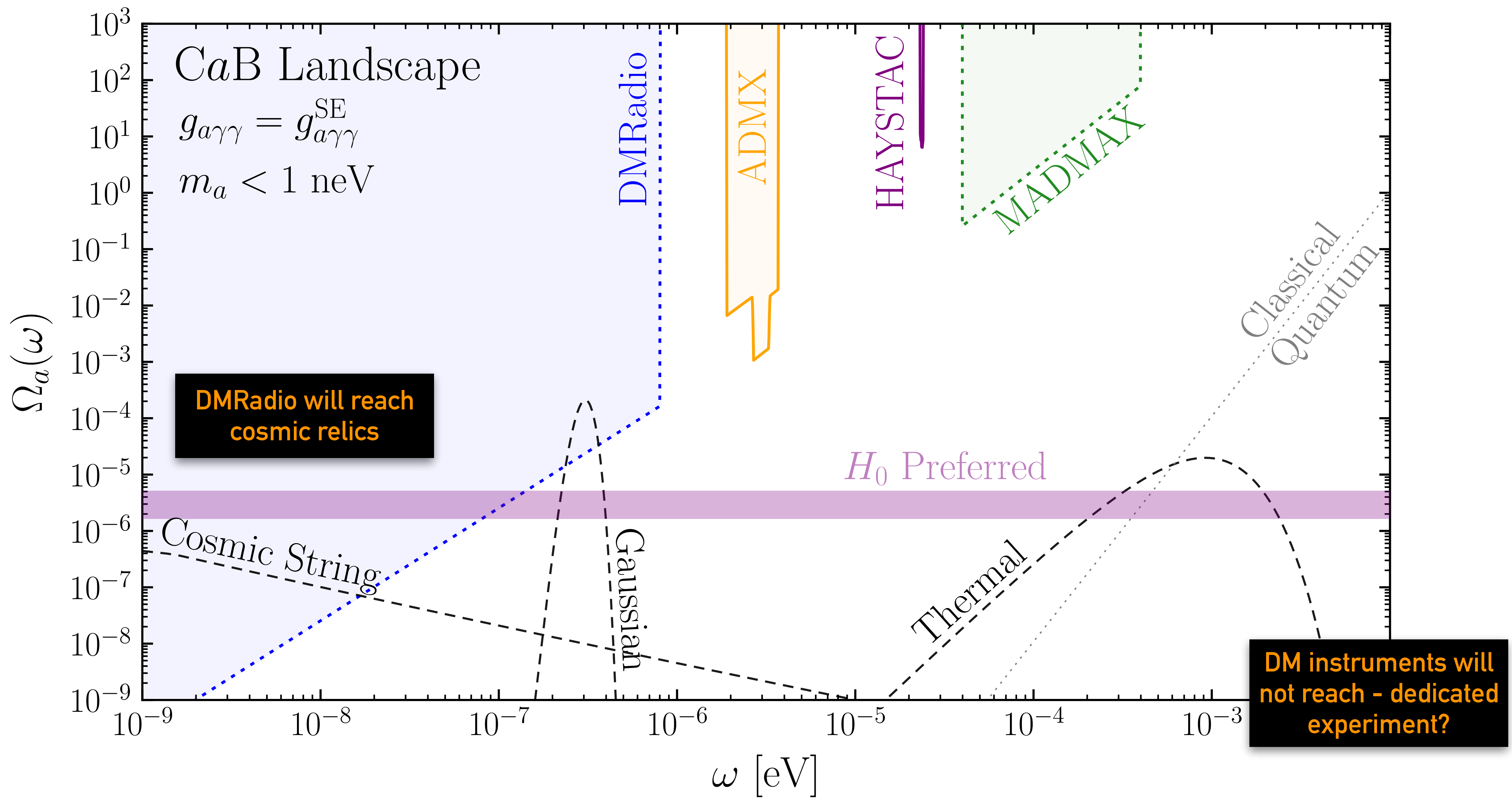
Experimental Landscape



DM instruments will not reach - dedicated experiment?

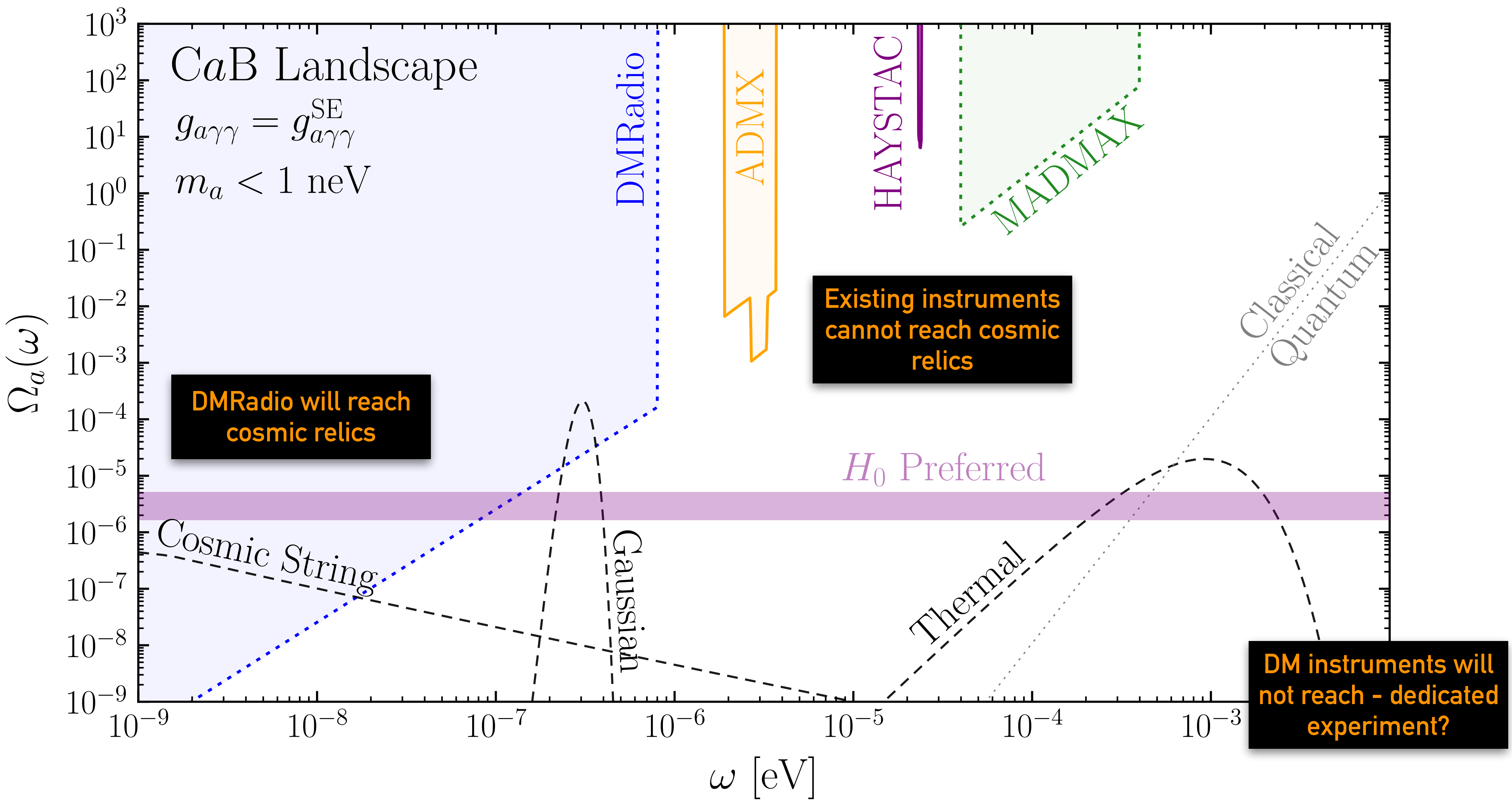
[Dror, NLR, Murayama 2021]

Experimental Landscape



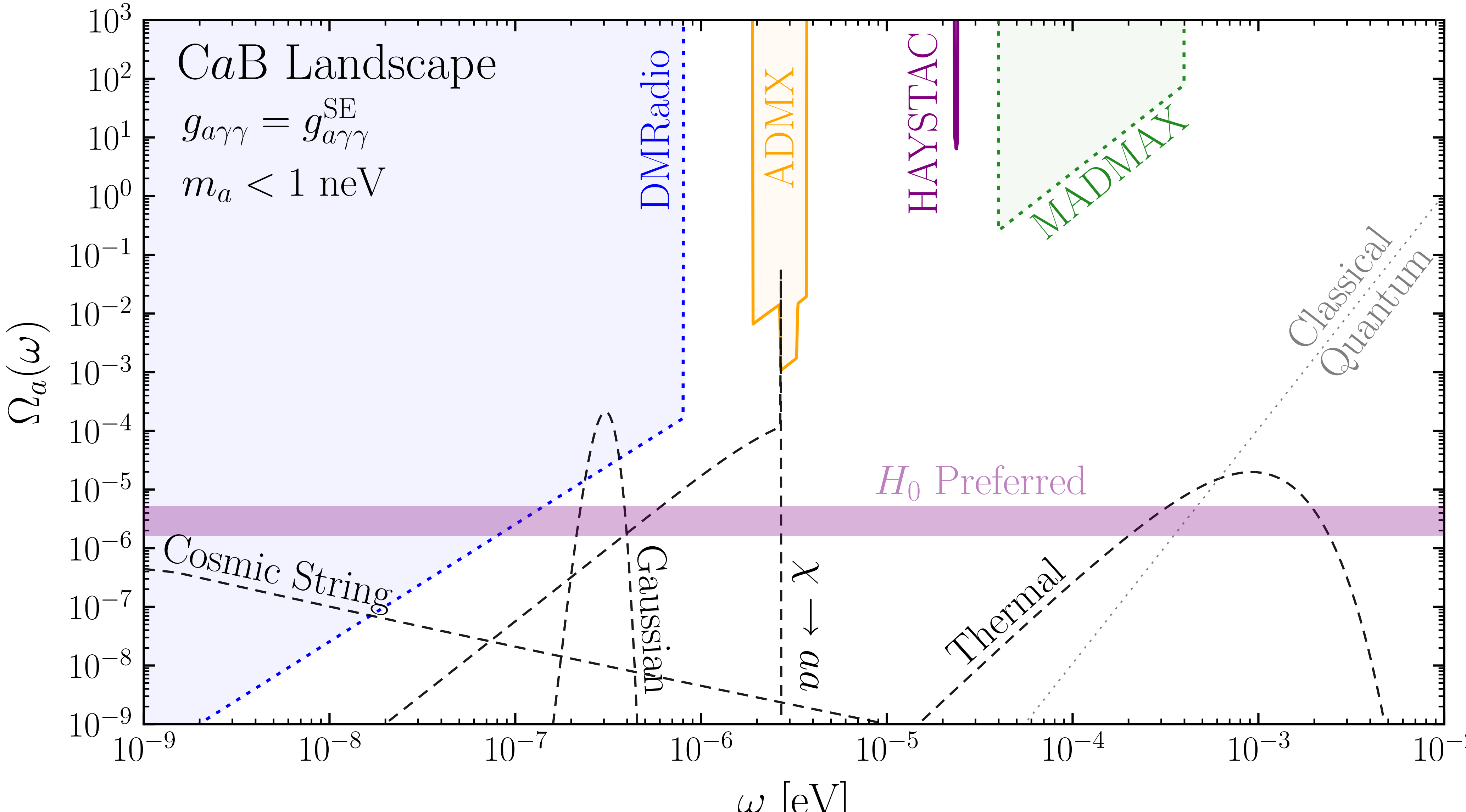
[Dror, NLR, Murayama 2021]

Experimental Landscape



[Dror, NLR, Murayama 2021]

Experimental Landscape

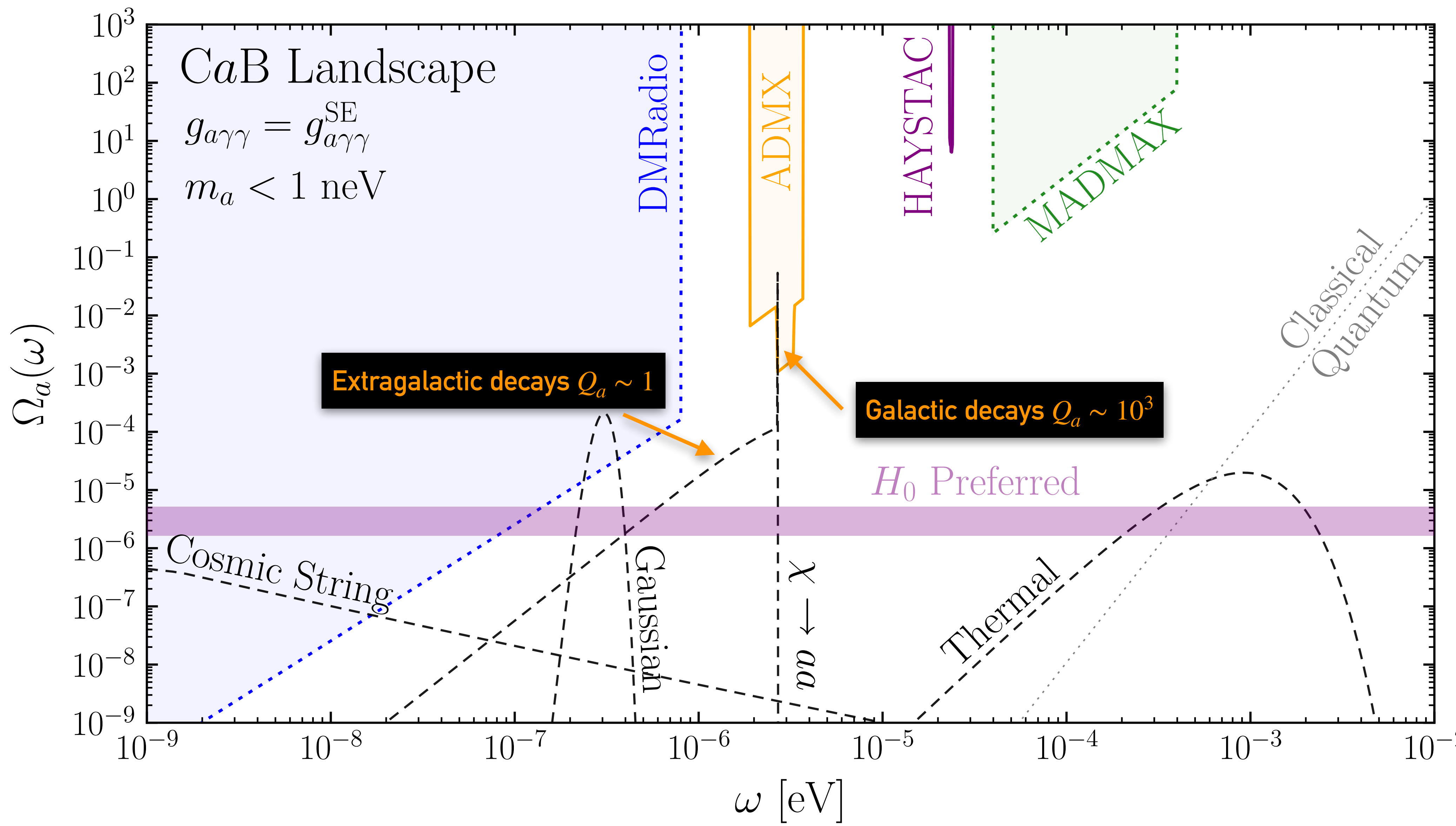


Late time production can generate $\rho_a > \rho_\gamma$

Dark matter decay is one example

[Dror, NLR, Murayama 2021]

Experimental Landscape

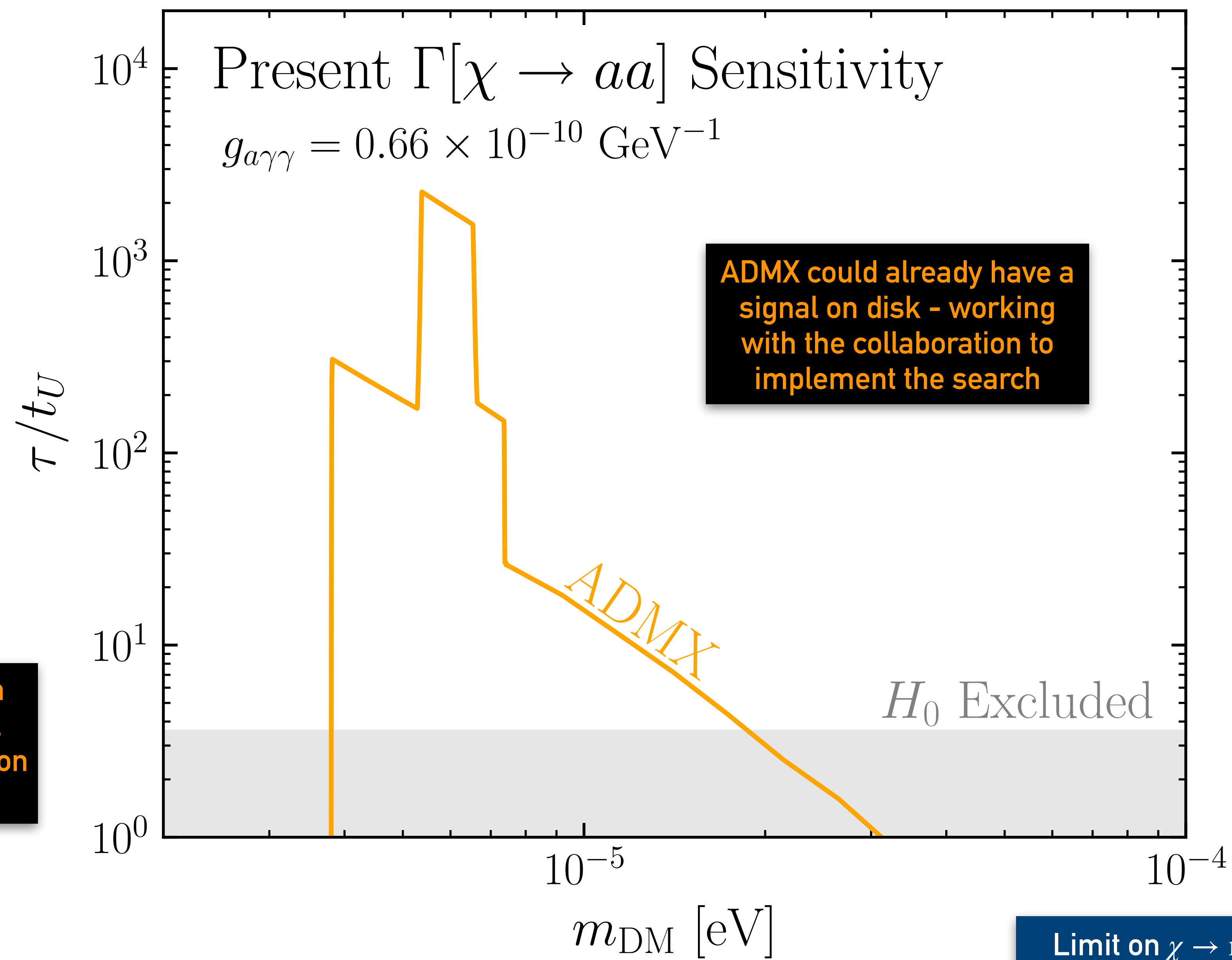


Late time production can generate $\rho_a > \rho_\gamma$

Dark matter decay is one example

[Dror, NLR, Murayama 2021]

Dark Matter Decay Sensitivity



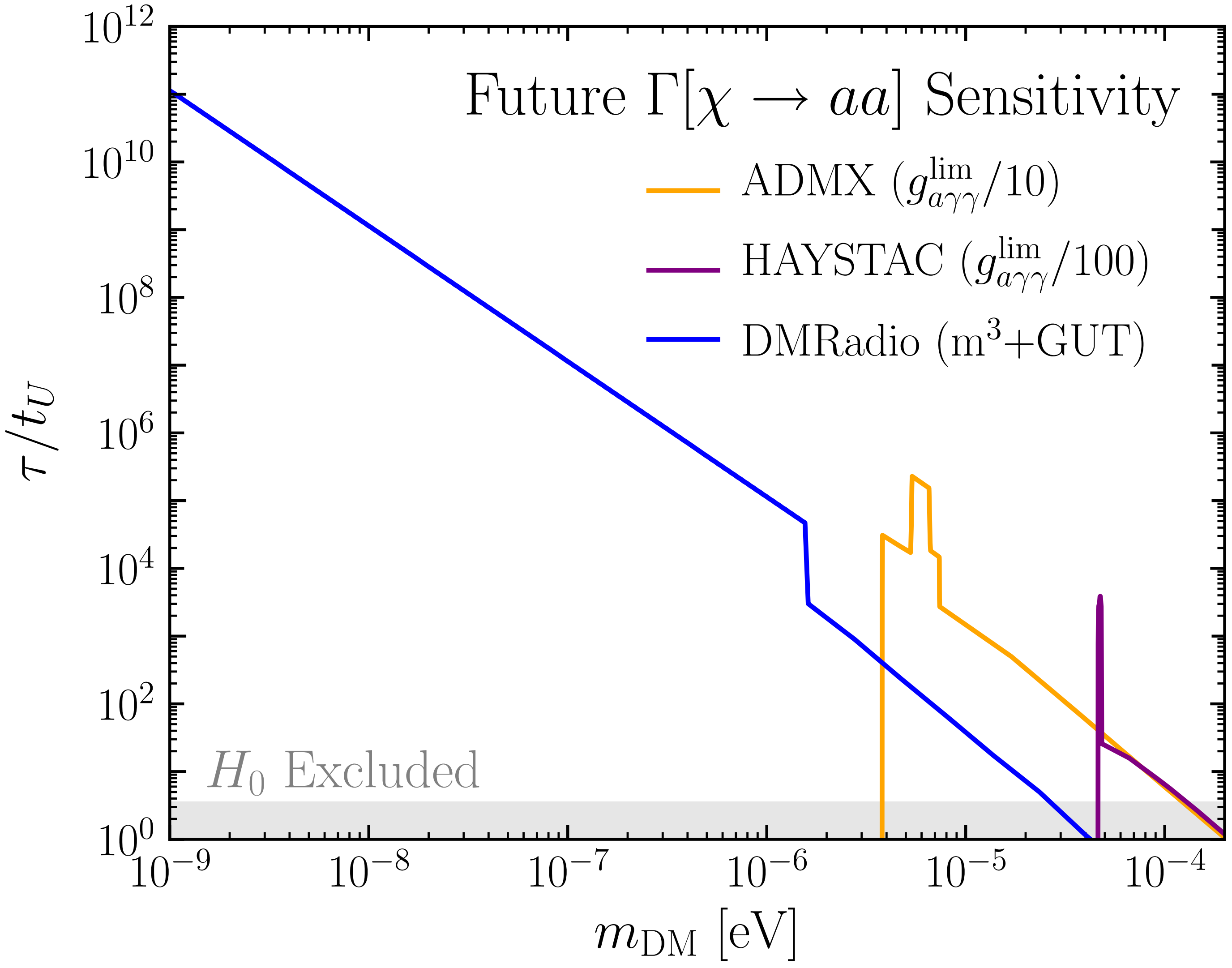
ADMX could already have a signal on disk - working with the collaboration to implement the search

ADMX is converted to an axion telescope - signal undergoes daily modulation due to $(\nabla a) \cdot \mathbf{B}$

Limit on $\chi \to$ relativistic of $\tau \gtrsim 50$ Gyr from [DES Collaboration 2020]

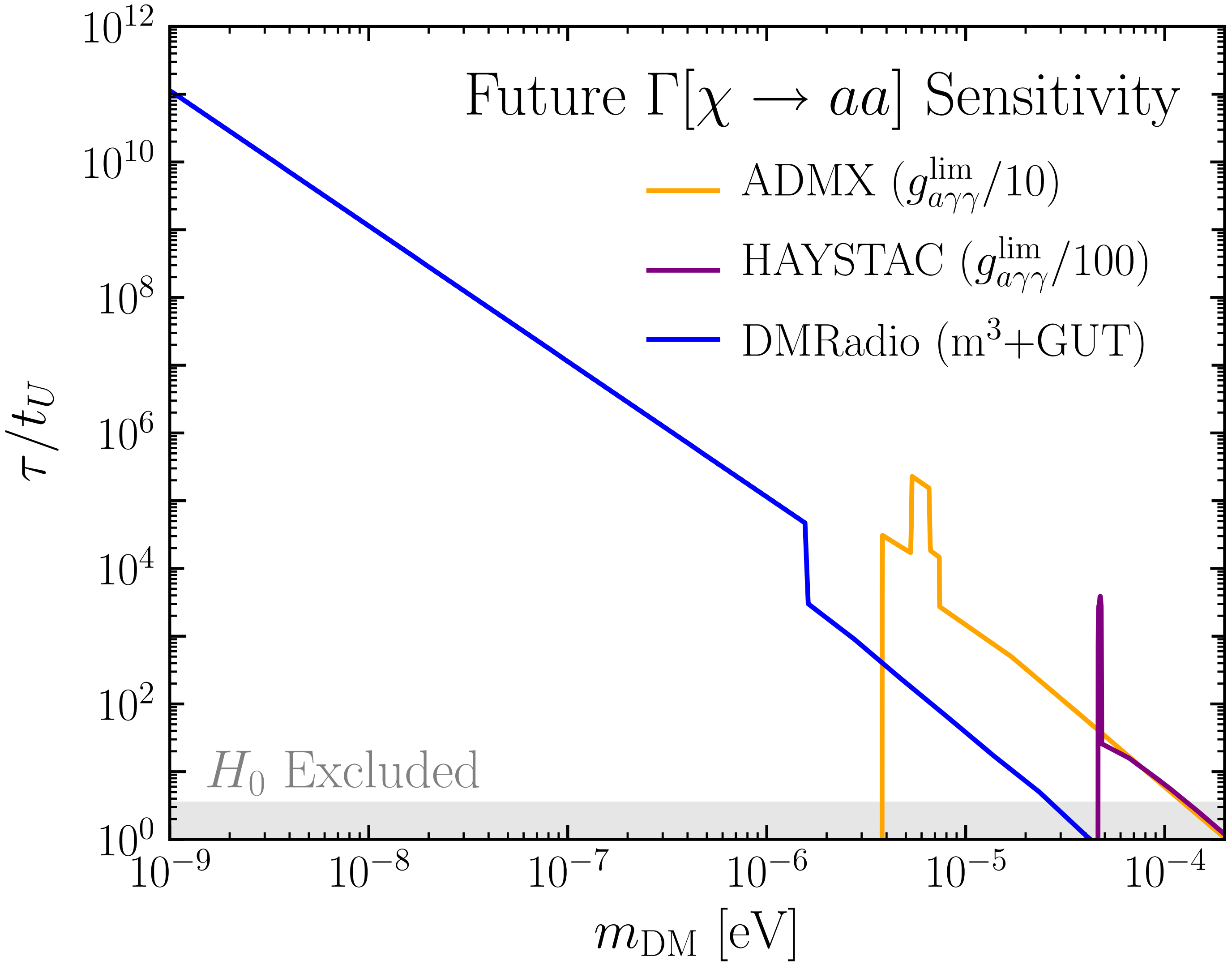
[Dror, NLR, Murayama 2021]

Dark Matter Decay Sensitivity



[Dror, NLR, Murayama 2021]

Dark Matter Decay Sensitivity

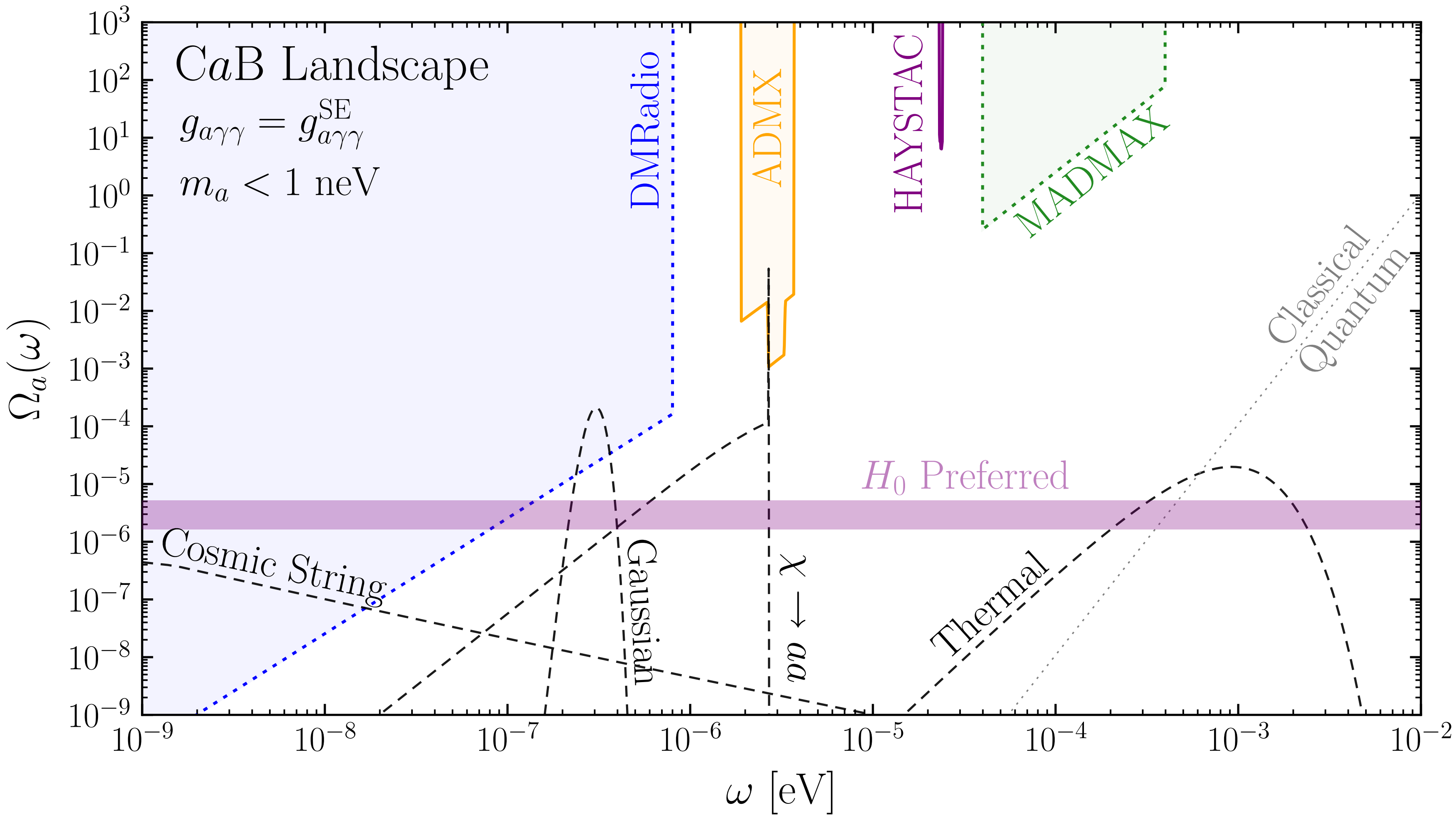


Above neglects Bose enhancement - will be a huge effect
Working to include

[Dror, NLR, Murayama 2021]

Summary

Data collected by axion DM instruments is sensitive to a cosmic axion background

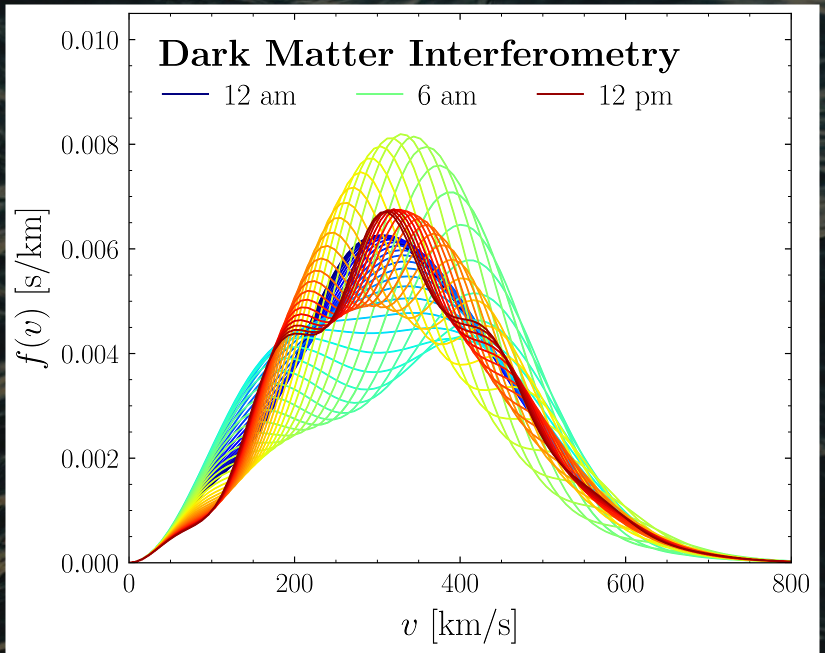


[Dror, NLR, Murayama 2021]

Conclusion

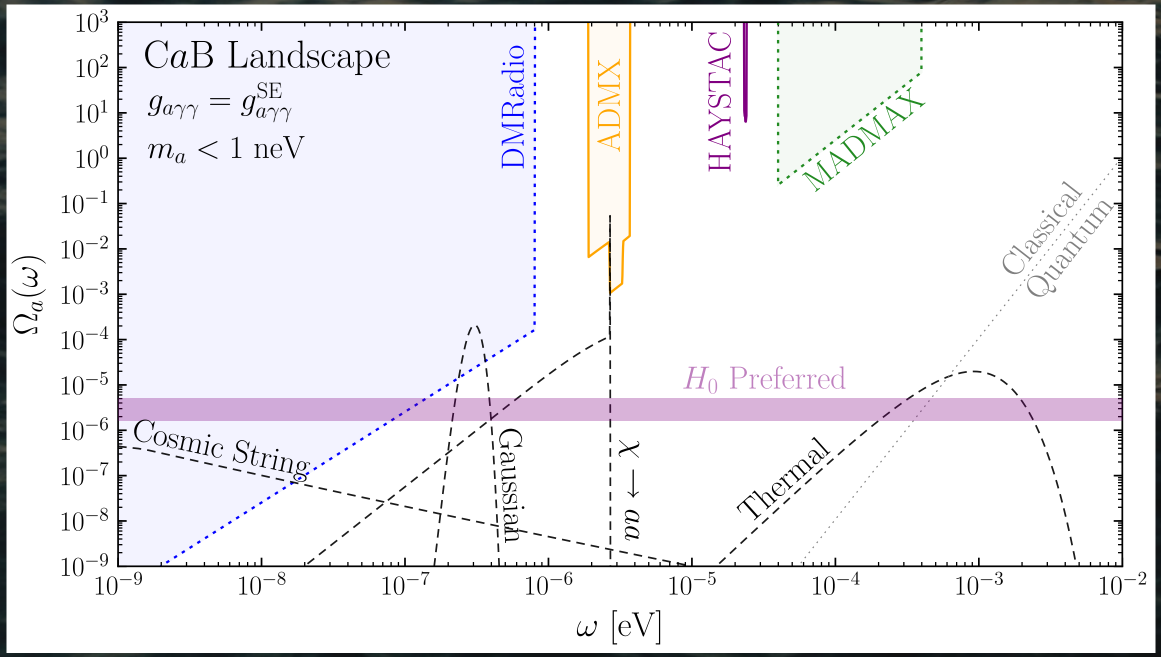
Dark Matter Interferometry

2009.14201 w/ Foster, Kahn, Nguyen, Safdi



The Cosmic Axion Background

2101.09287 w/ Dror, Murayama



Backup Slides

Stream Localization

$$\mathcal{F}^c_{12}(v) = \int d^3\mathbf{v}\, f(\mathbf{v}) \cos(m_a \mathbf{v} \cdot \mathbf{x}_{12}) \delta[|\mathbf{v}| - v]$$

- Velocity distribution support sets $|\mathbf{v}| \sim \bar{v}$

$$m_a \mathbf{v} \cdot \mathbf{x}_{12} \sim (m_a \bar{v} d) \hat{\mathbf{v}} \cdot \hat{\mathbf{x}}_{12}$$

- Recall, for maximum sensitivity we want $d \sim \lambda_c$

$$(m_a \bar{v} d) \hat{\mathbf{v}} \cdot \hat{\mathbf{x}}_{12} \to (m_a \bar{v} \lambda_c) \hat{\mathbf{v}} \cdot \hat{\mathbf{x}}_{12} \sim \frac{\bar{v}}{v_0} \hat{\mathbf{v}} \cdot \hat{\mathbf{x}}_{12}$$

- For bulk halo, expect $\bar{v} \sim v_0$, whereas for stream $\bar{v} \gg v_0$
- Small differences in $\hat{\mathbf{v}} \cdot \hat{\mathbf{x}}_{12}$ results in a large change in cos argument

[Foster, NLR+ 2020]

Daily Modulation

Full Equations

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J} - g_{a\gamma\gamma} \left(\mathbf{E} \times \nabla a - \partial_t a \mathbf{B} \right)$$

[Dror, NLR, Murayama 2021]

Daily Modulation

Assume only large static $\mathbf{B}$ field

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma}\mathbf{B} \cdot \nabla a$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

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

[Dror, NLR, Murayama 2021]

Daily Modulation

Assume only large static $\mathbf{B}$ field

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

Effective Charge

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

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

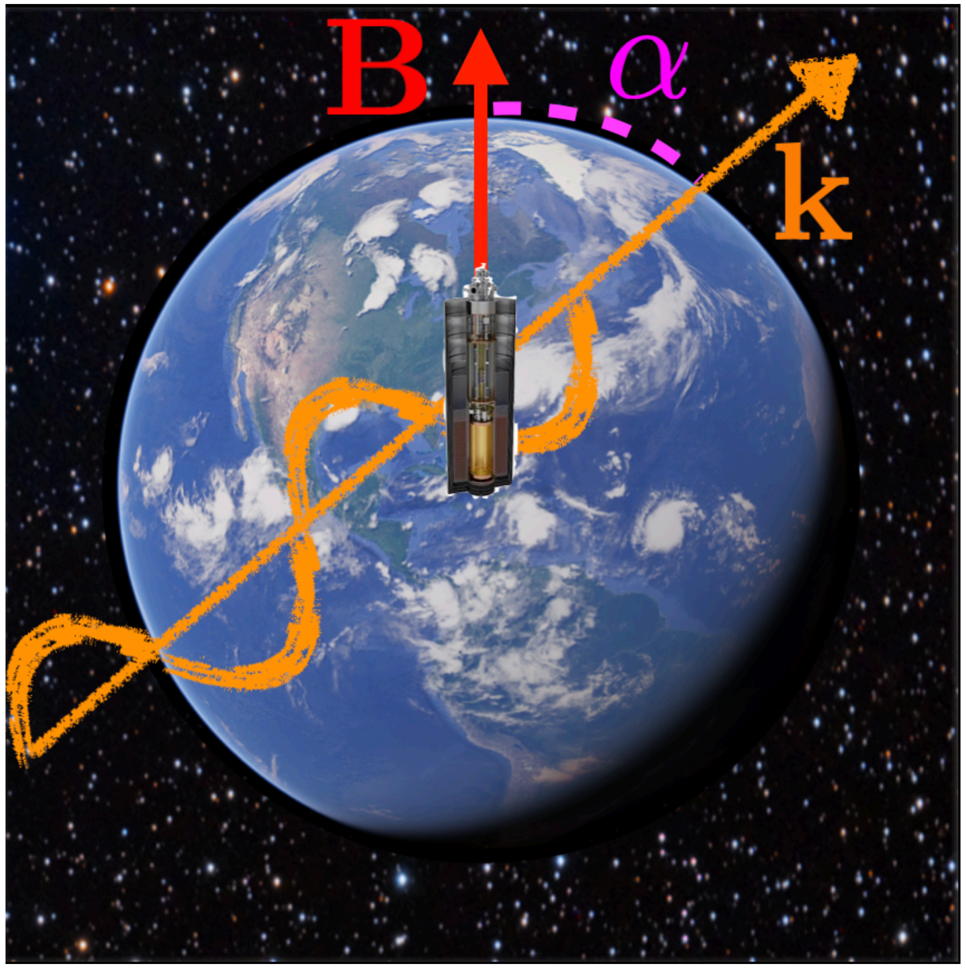
Effective Current

[Dror, NLR, Murayama 2021]

Daily Modulation

Sensitive to the incident direction

$$\mathbf{B} \cdot \nabla a = a(t)\mathbf{k} \cdot \mathbf{B}$$



[Dror, NLR, Murayama 2021]

Daily Modulation

Power deposited sensitive to α

$$P_a^{\mathrm{CaB}} = \frac{\pi}{8} \sin^4 \alpha \, g_{a\gamma\gamma}^2 Q_a B_0^2 V C \frac{\rho_a}{\bar{\omega}}$$

Daily modulation in the signal!

[Dror, NLR, Murayama 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

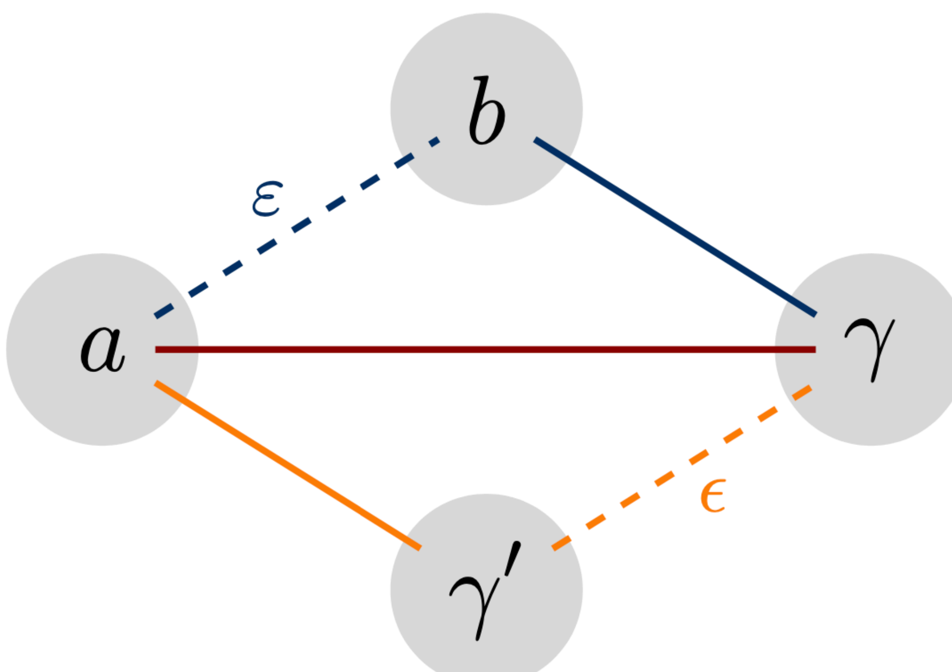
[Dror, NLR, Murayama 2021]

Dark Matter Decaying to Axions

example model

$$V(\Phi) = \lambda^2 \left(|\Phi|^2 - f_a^2/2 \right)^2 \qquad \Phi = (\chi + f_a)\, e^{ia/f_a}$$

$$\frac{\Gamma_{\varphi \to aa}}{H_0} \simeq \left(\frac{m_\varphi}{10\ \mu\text{eV}} \right)^3 \left(\frac{100\ \text{MeV}}{f_a} \right)^2 \rightarrow$$



$$\frac{\varepsilon \alpha}{4\pi f_b}$$

$$\frac{\alpha}{4\pi f_a}$$

$$\frac{\epsilon^2 \alpha'}{4\pi f_a}$$

Slide courtesy of Jeff Dror

[Dror, NLR, Murayama 2021]

Parametric Resonance

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

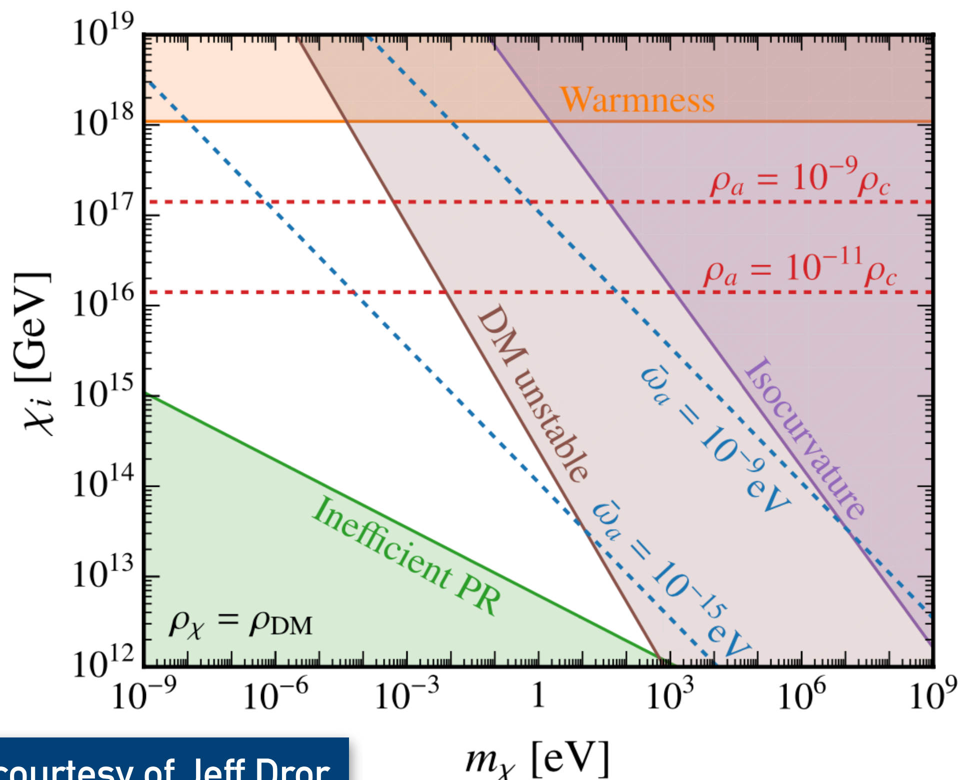
Oscillations when
$m_\chi^{\text{eff}}(\chi_i) \simeq \lambda \chi_i \sim H$

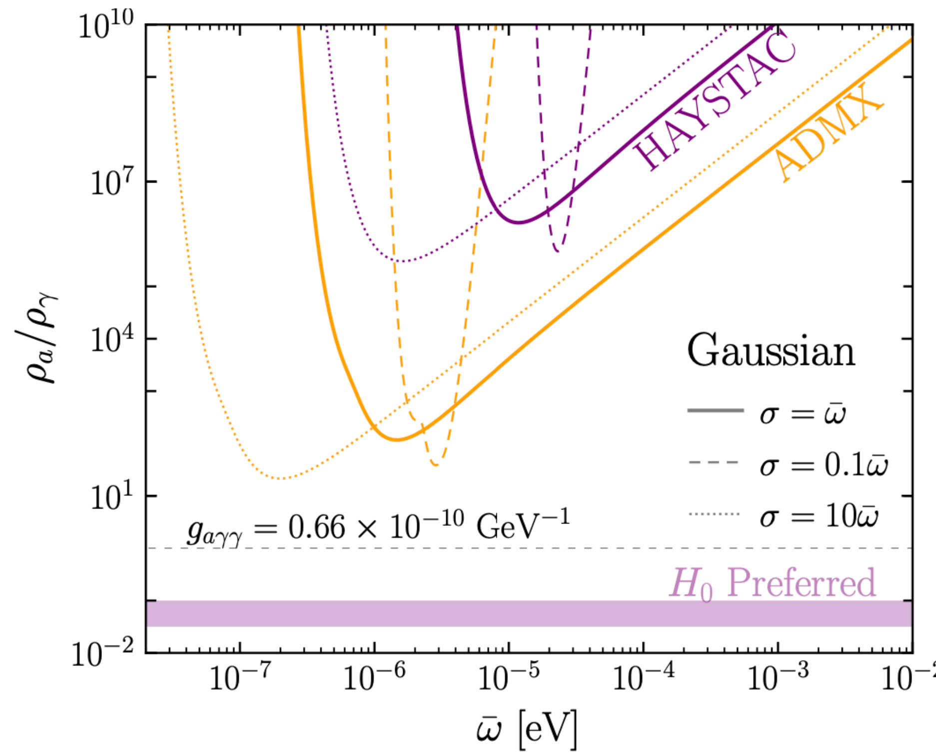
Typical energy: $\bar{\omega}_a \sim m_\chi^{\text{eff}}(\chi_i) \left(\frac{s(T_0)}{s(T_{\text{osc}})}\right)^{1/3} \sim 10^{-15}\ \text{eV} \left(\frac{m_\chi^{\text{eff}}(\chi_i)}{\text{MeV}}\right)^{1/2}$

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

detectable?

Assume χ dark matter





Slide courtesy of Jeff Dror

[Dror, NLR, Murayama 2021]