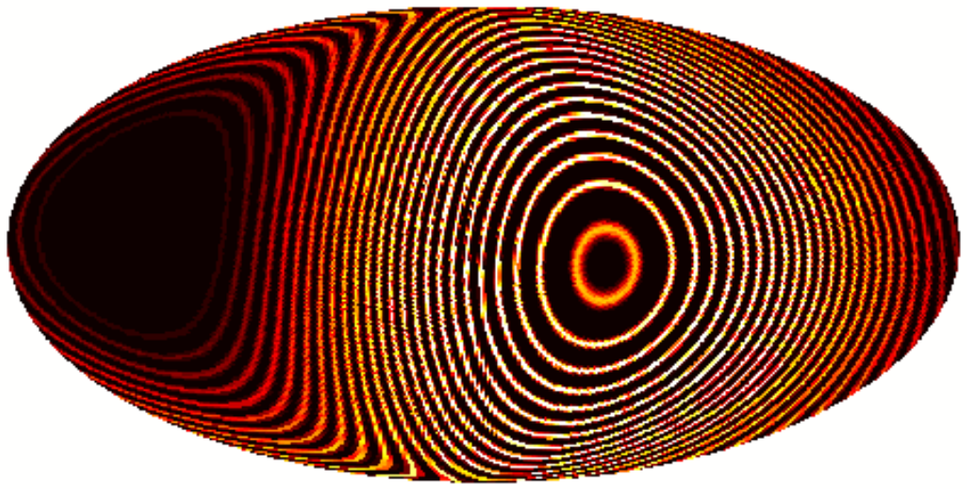
New Ideas for the Axion Dark Matter Program

NICK RODD | RUTGERS UNIVERSITY | 9 MARCH 2021

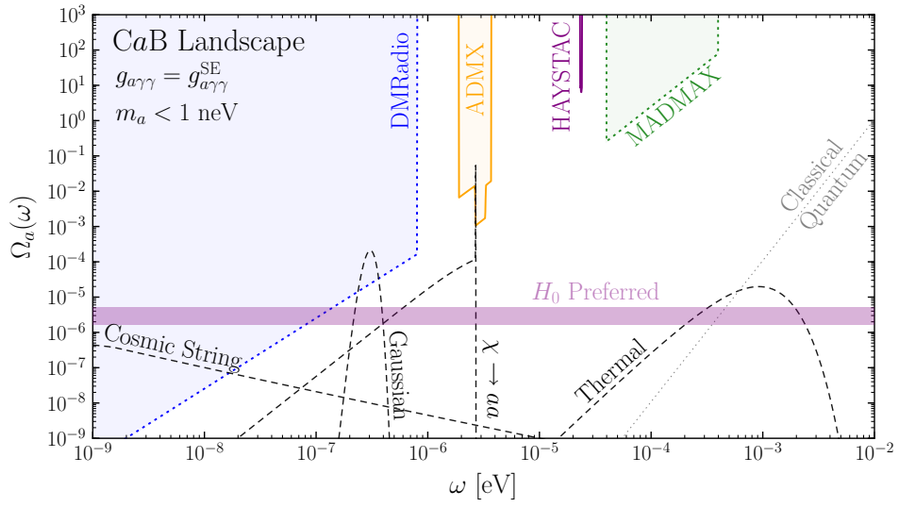
Dark Matter Interferometry

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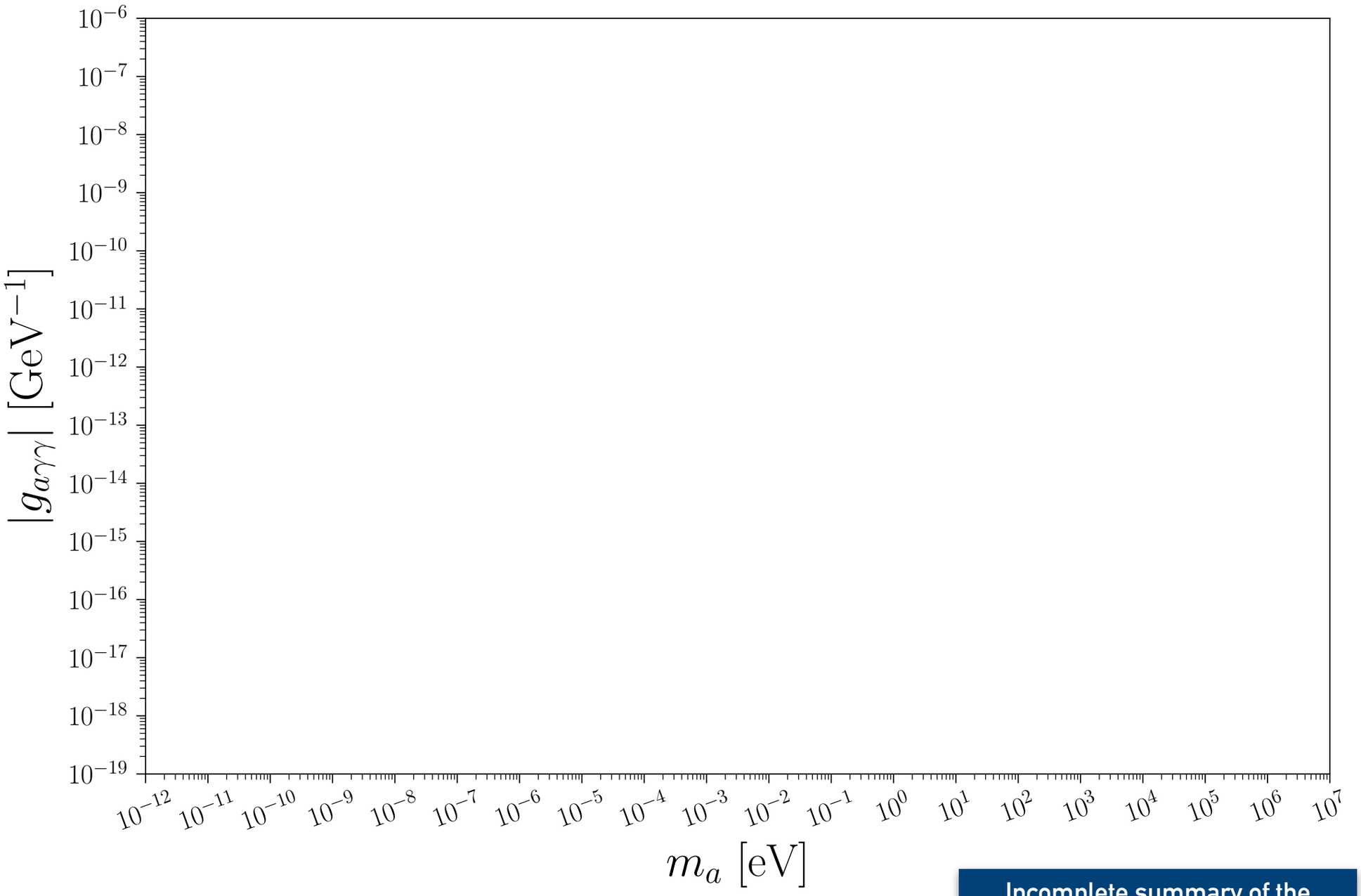
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J} - g_{a\gamma\gamma} (\mathbf{E} \times \nabla a - \mathbf{B} \partial_t a)$$

Suppressed for non-relativistic DM axions

Focus of axion DM searches

Motivation

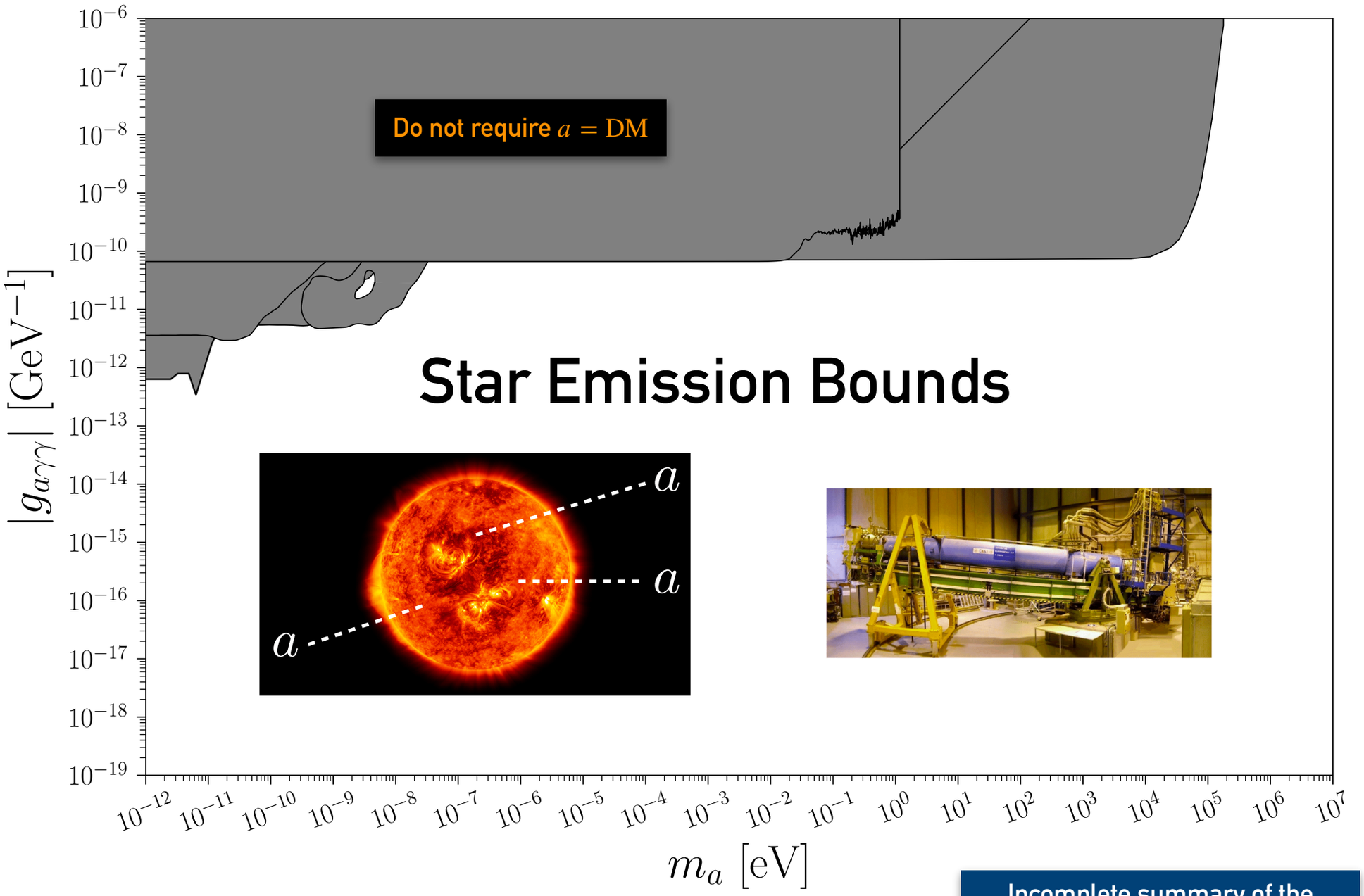
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a (F\tilde{F})$$



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

Motivation

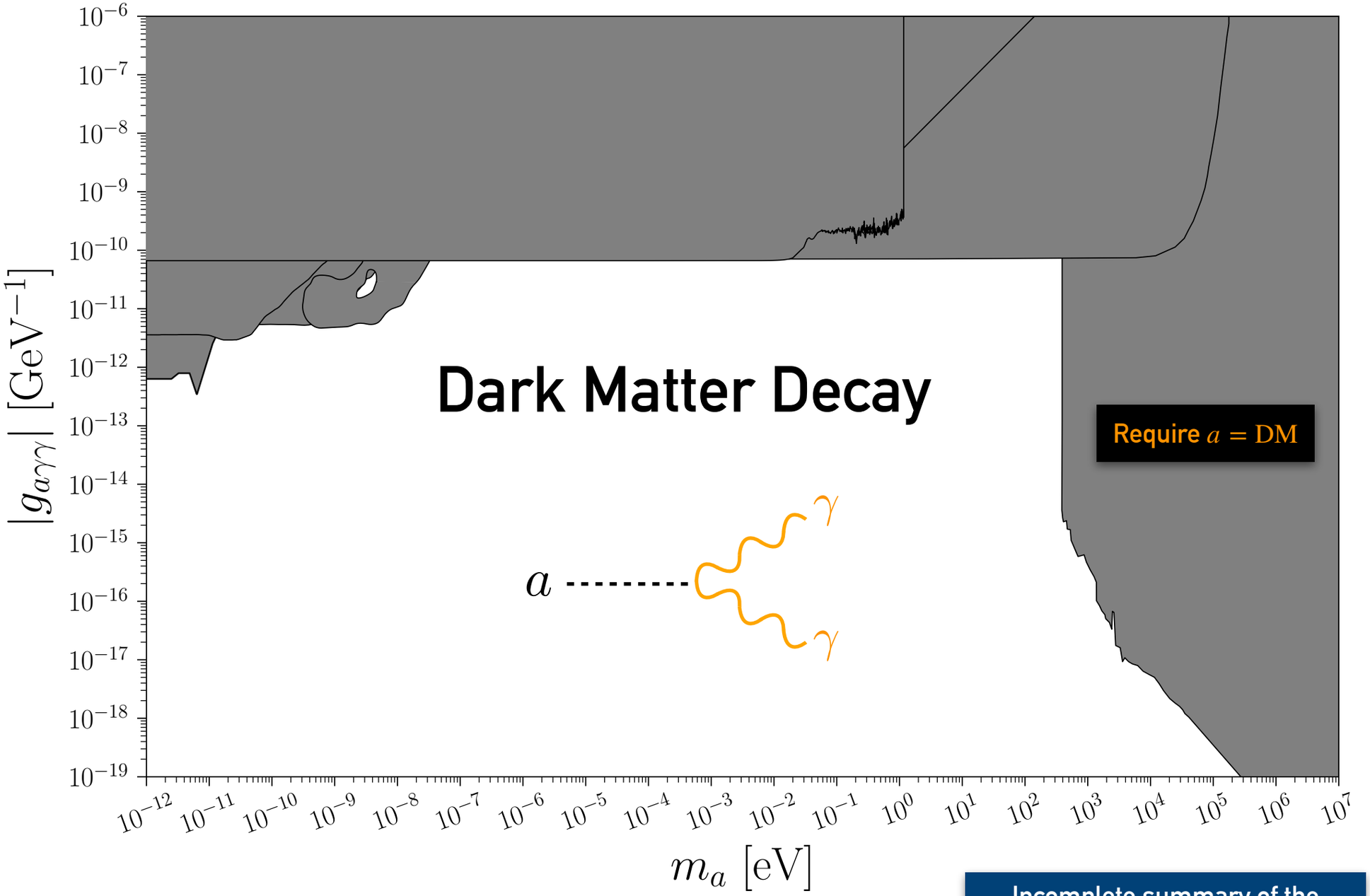
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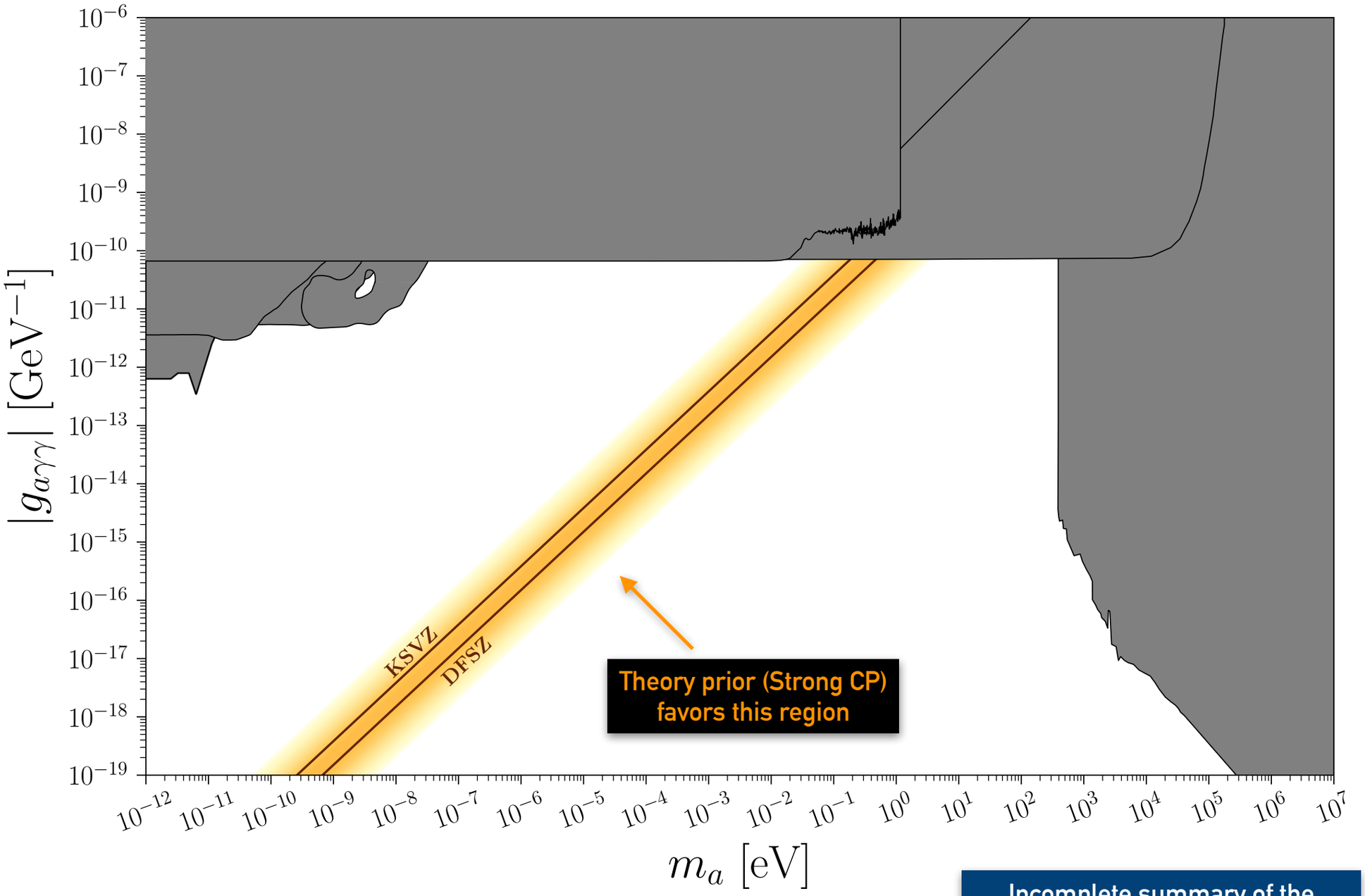
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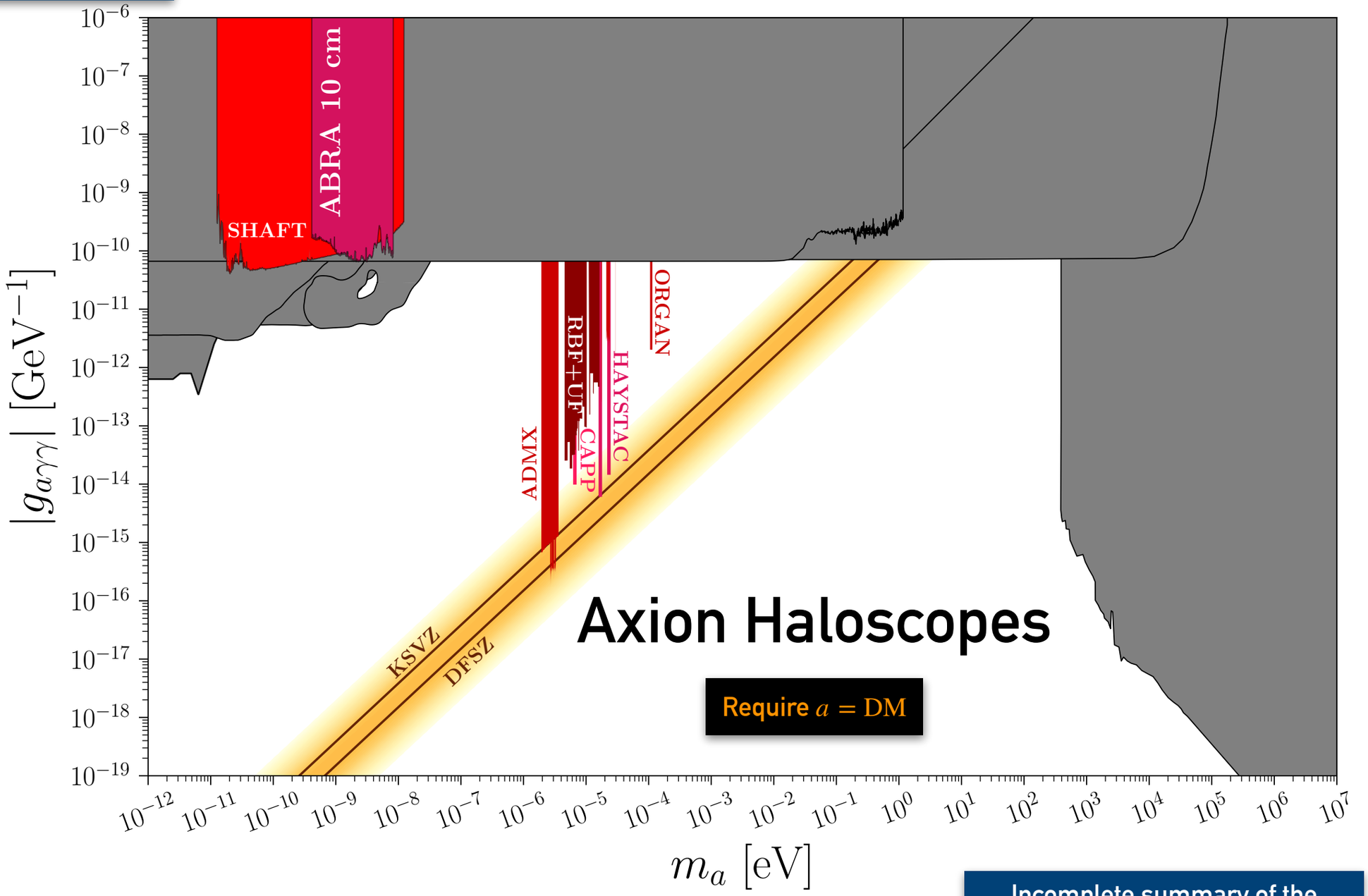


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Low masses exploit LC circuit ideas originally noted by S. Thomas, see [Svrcek, Witten 2006]

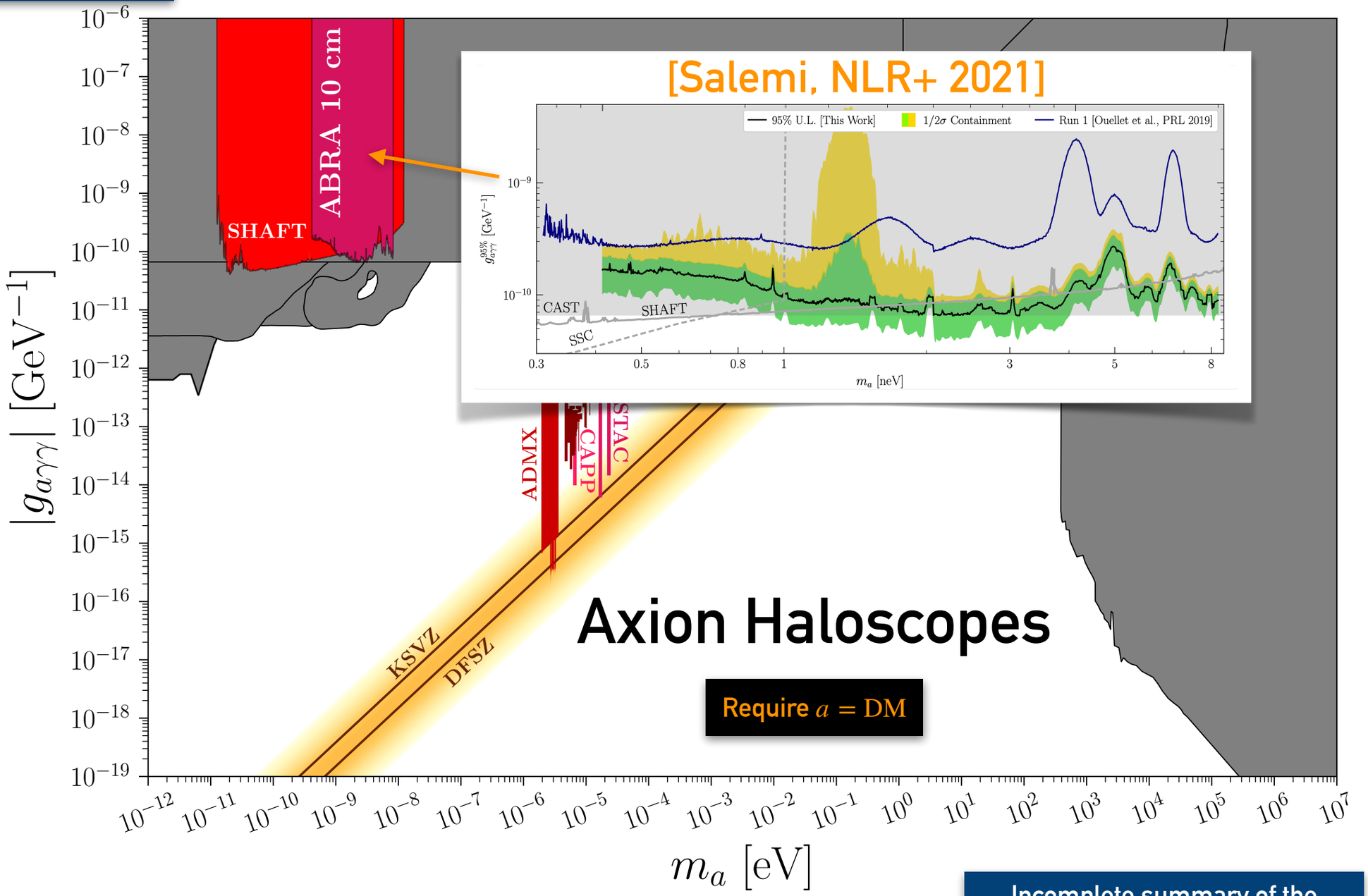


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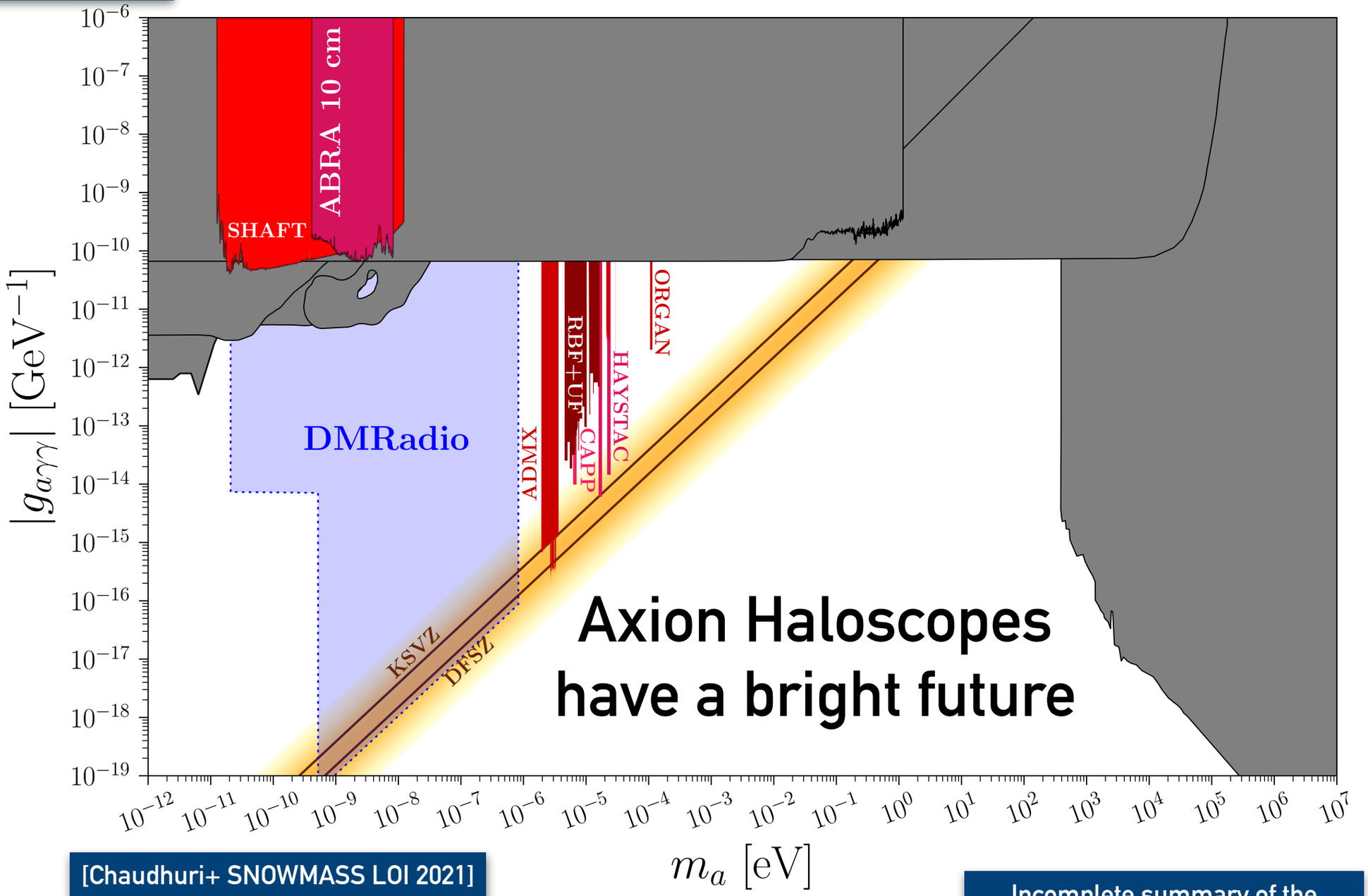


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[Chaudhuri+ SNOWMASS LOI 2021]

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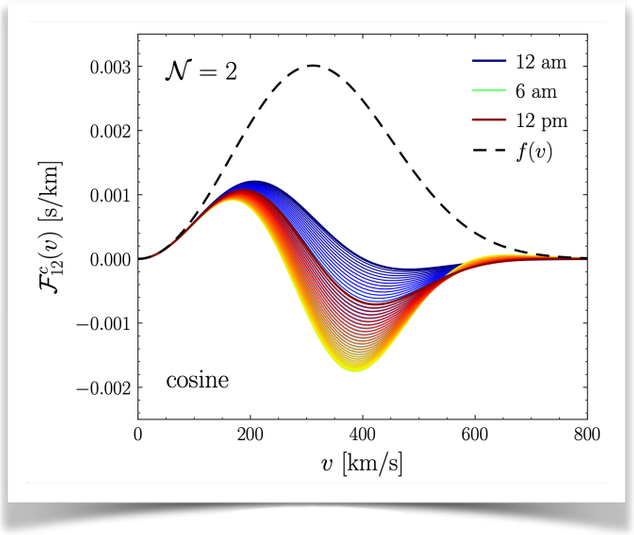
Outline

Two new ideas for exploiting this progress

Outline

1. More information for DM searches?

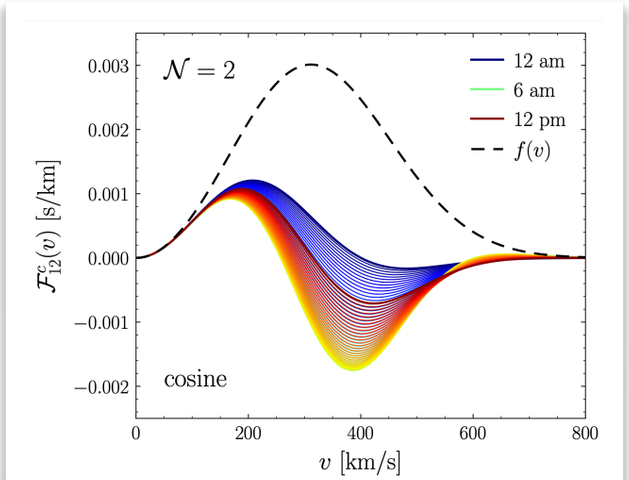
Dark Matter Interferometry



Outline

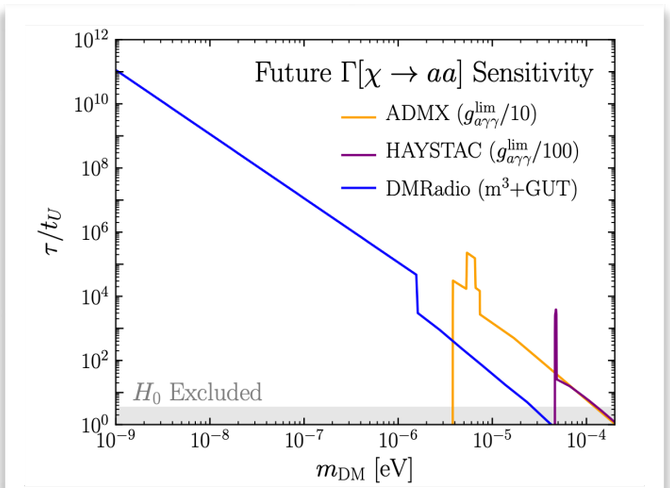
1. More information for DM searches?

Dark Matter Interferometry



2. What else could these instruments see?

The Cosmic Axion Background



Dark Matter Interferometry

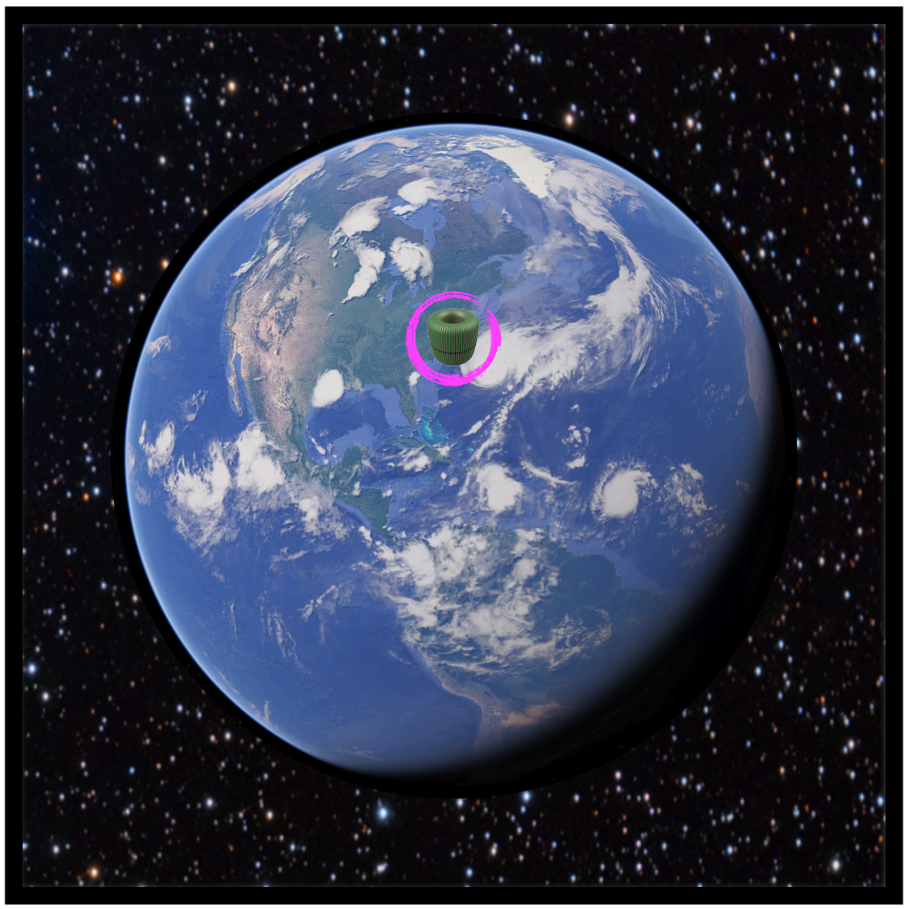
2009.14201

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

DARK MATTER INTERFEROMETRY

Basic Idea

Wave-like Dark Matter



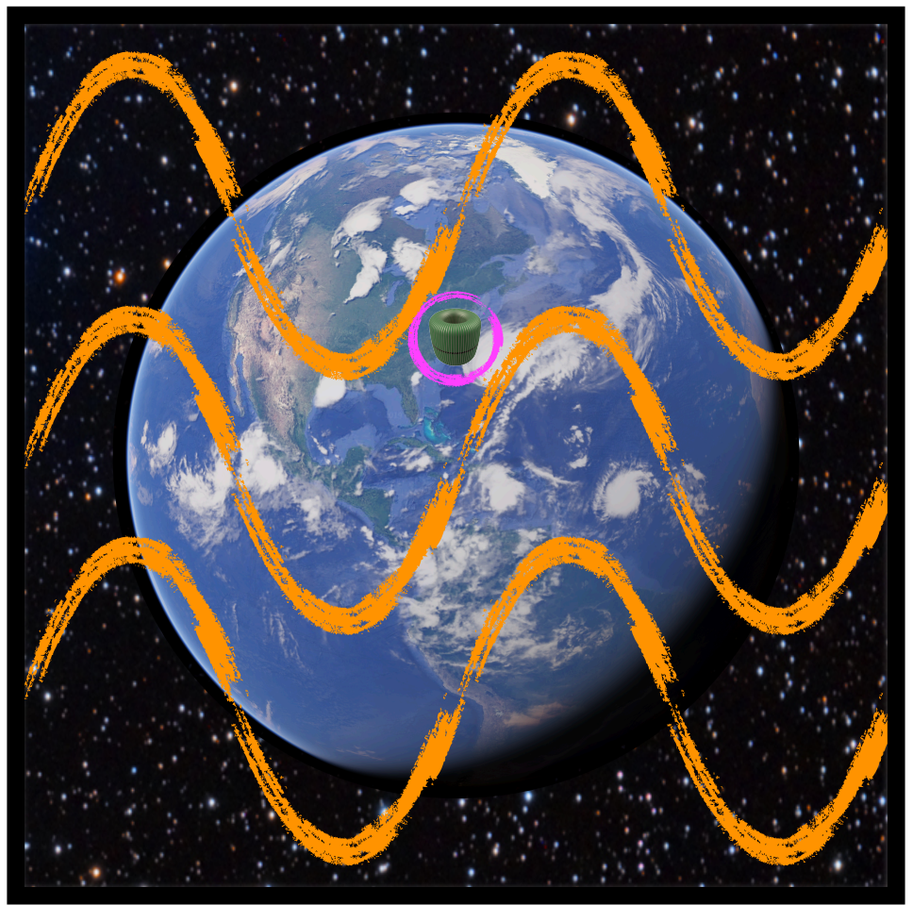
[Foster, NLR+ 2020]

DARK MATTER INTERFEROMETRY

Basic Idea

Wave-like Dark Matter

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

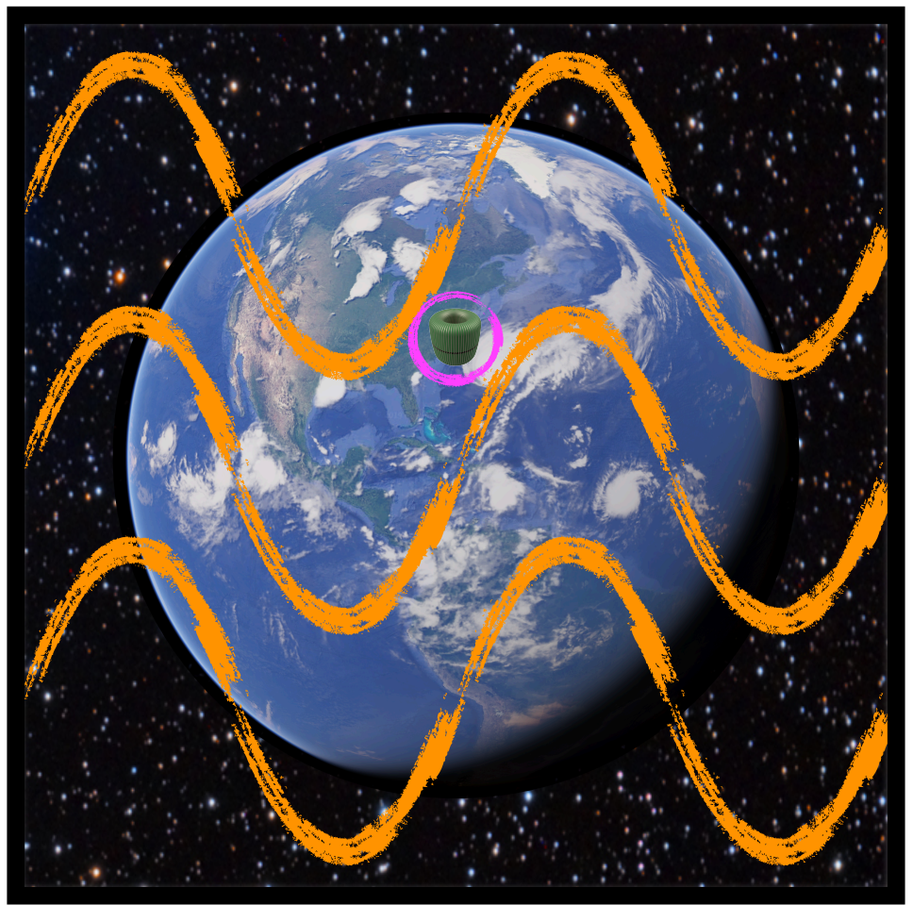


[Foster, NLR+ 2020]

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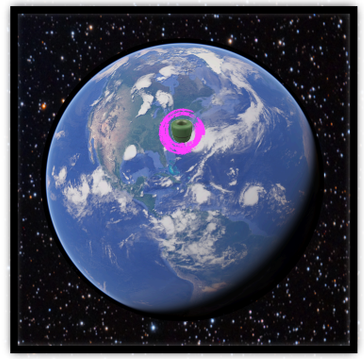
Wave-like Dark Matter

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



[Foster, NLR+ 2020]

Basic Idea

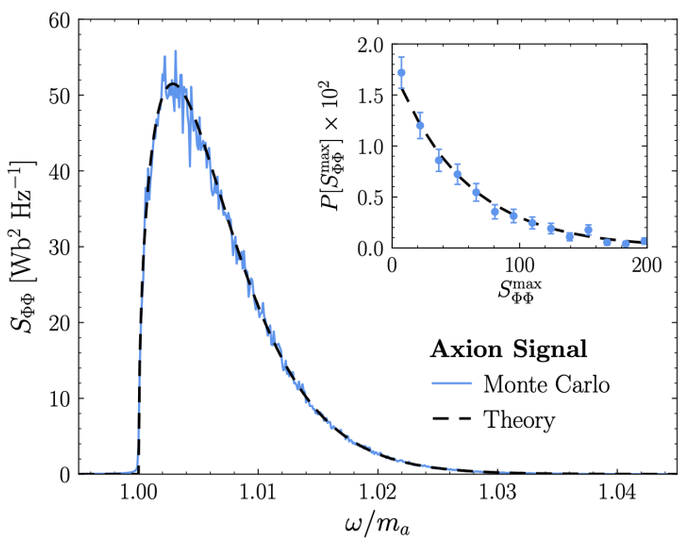


Wave-like Dark Matter

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

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

Determined by $f(v)$



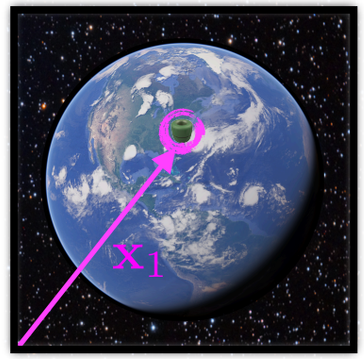
[Foster, NLR, Safdi 17]

[Foster, NLR+ 2020]

Basic Idea

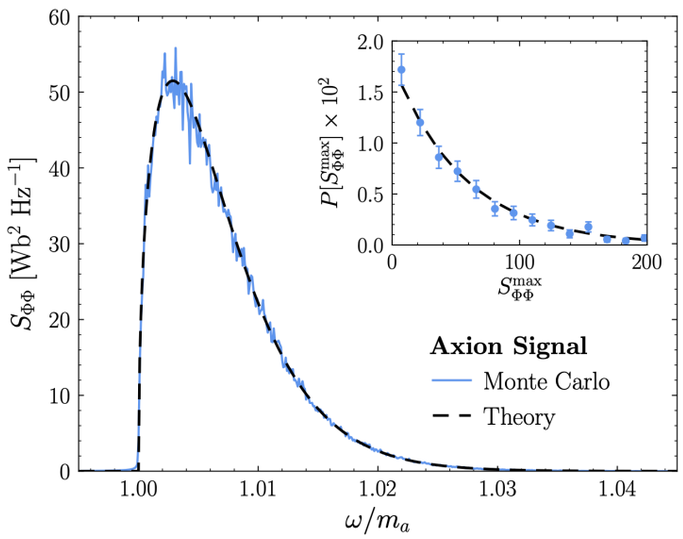
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[Foster, NLR, Safdi 17]

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

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

Invisible to a single detector

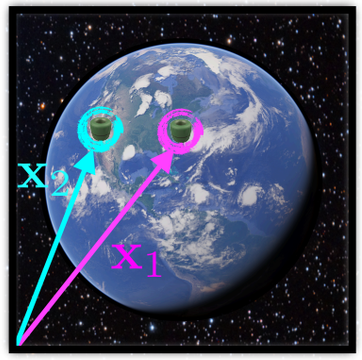
1. $\nabla a \sim \mathbf{k} \ll \omega \sim \partial_t a$
2. For 1 experiment, can choose $\mathbf{x} = 0$

[Foster, NLR+ 2020]

Basic Idea

Wave-like Dark Matter

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



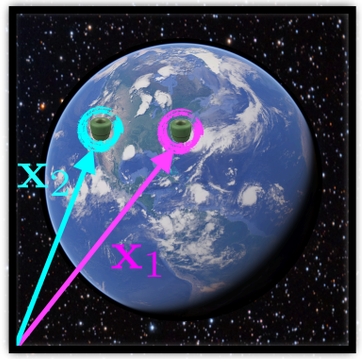
Key insight: two detectors will reveal the dependence on $\mathbf{k}$

[Foster, NLR+ 2020]

Interferometry

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

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

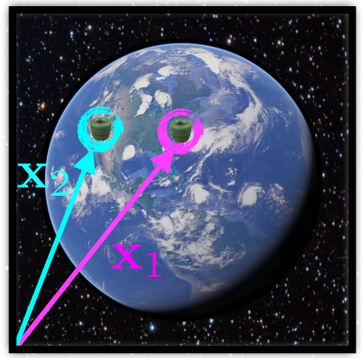


$\mathbf{x}_{12} = \mathbf{x}_1 - \mathbf{x}_2$

[Foster, NLR+ 2020]

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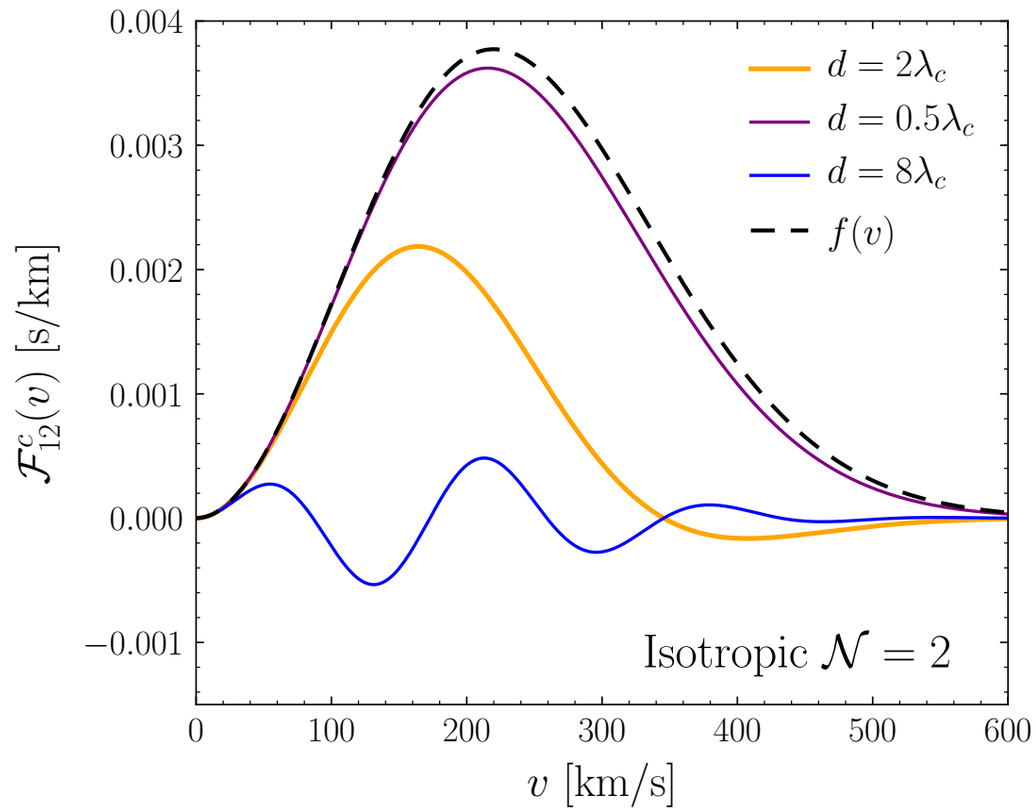


$\mathbf{x}_{12} = \mathbf{x}_1 - \mathbf{x}_2$

Depends on Coherence Length

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

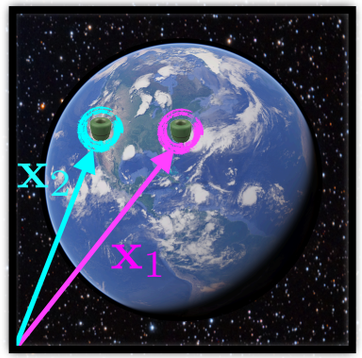
- $m_a = 25\ \mu\text{eV} \Rightarrow \lambda_c \approx 10\ \text{m}$
- $m_a = 1\ \text{neV} \Rightarrow \lambda_c \approx 300\ \text{km}$



[Foster, NLR+ 2020]

Interferometry

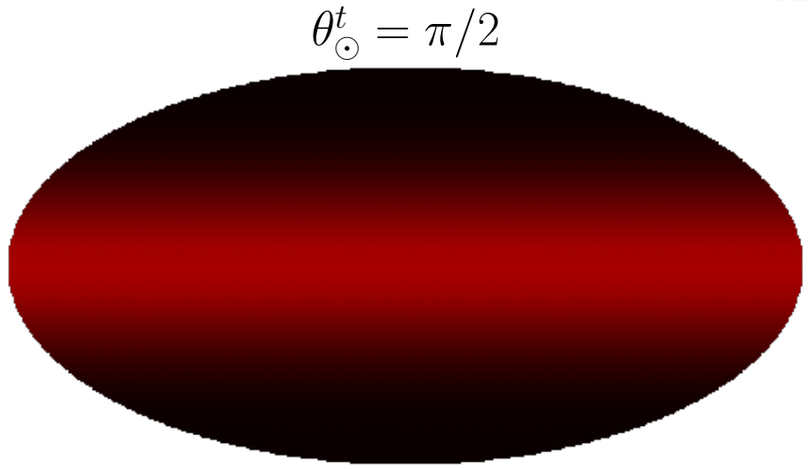
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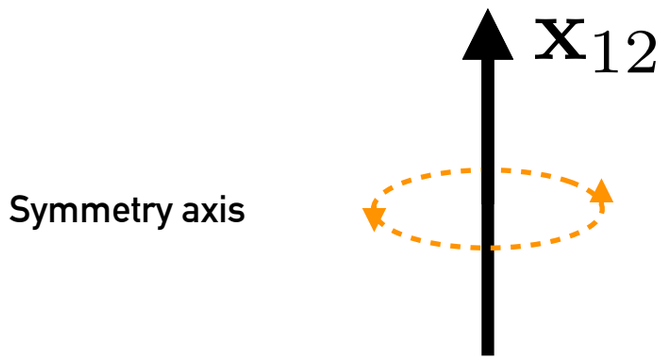
$\mathbf{x}_{12} = \mathbf{x}_1 - \mathbf{x}_2$

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



True location: image center

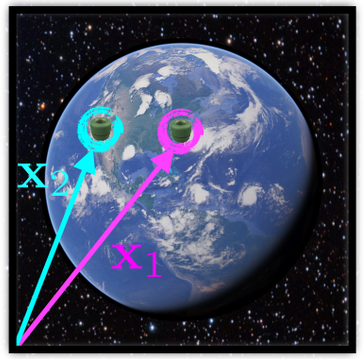


[Foster, NLR+ 2020]

DARK MATTER INTERFEROMETRY

Interferometry

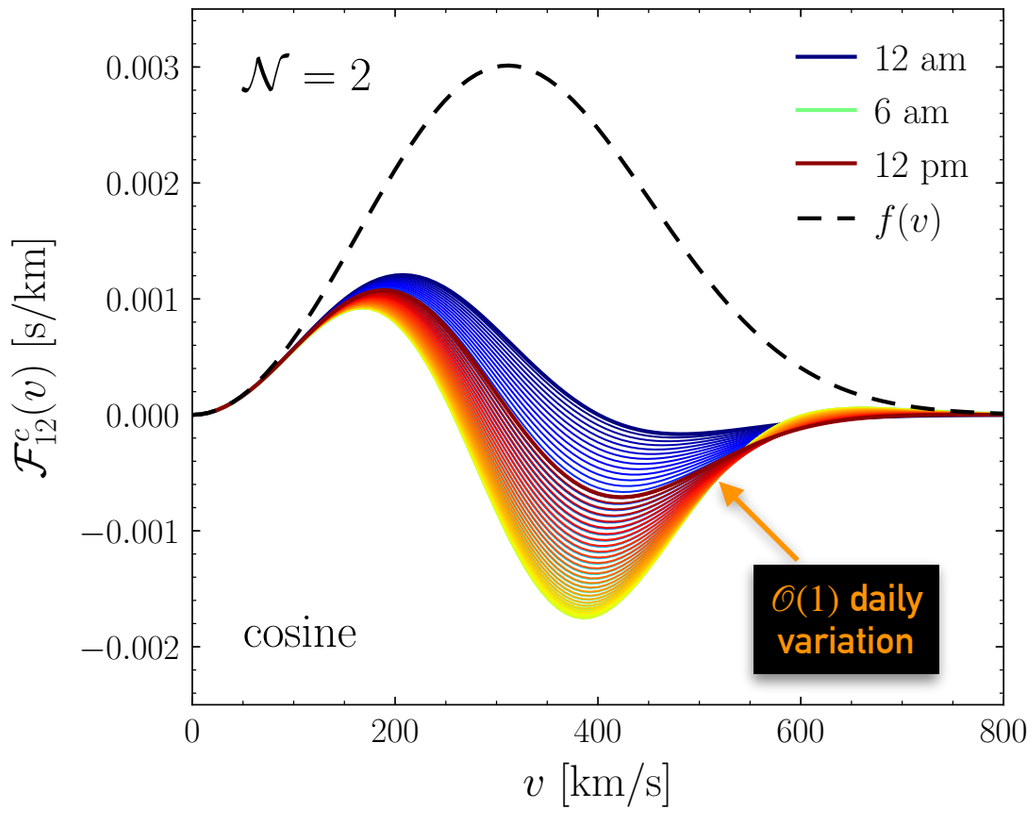
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$\mathbf{x}_{12} = \mathbf{x}_1 - \mathbf{x}_2$

Broken by Daily Modulation!





[Foster, NLR+ 2020]

DARK MATTER INTERFEROMETRY

Standard Halo Model

Can we determine the direction of the DM wind?

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

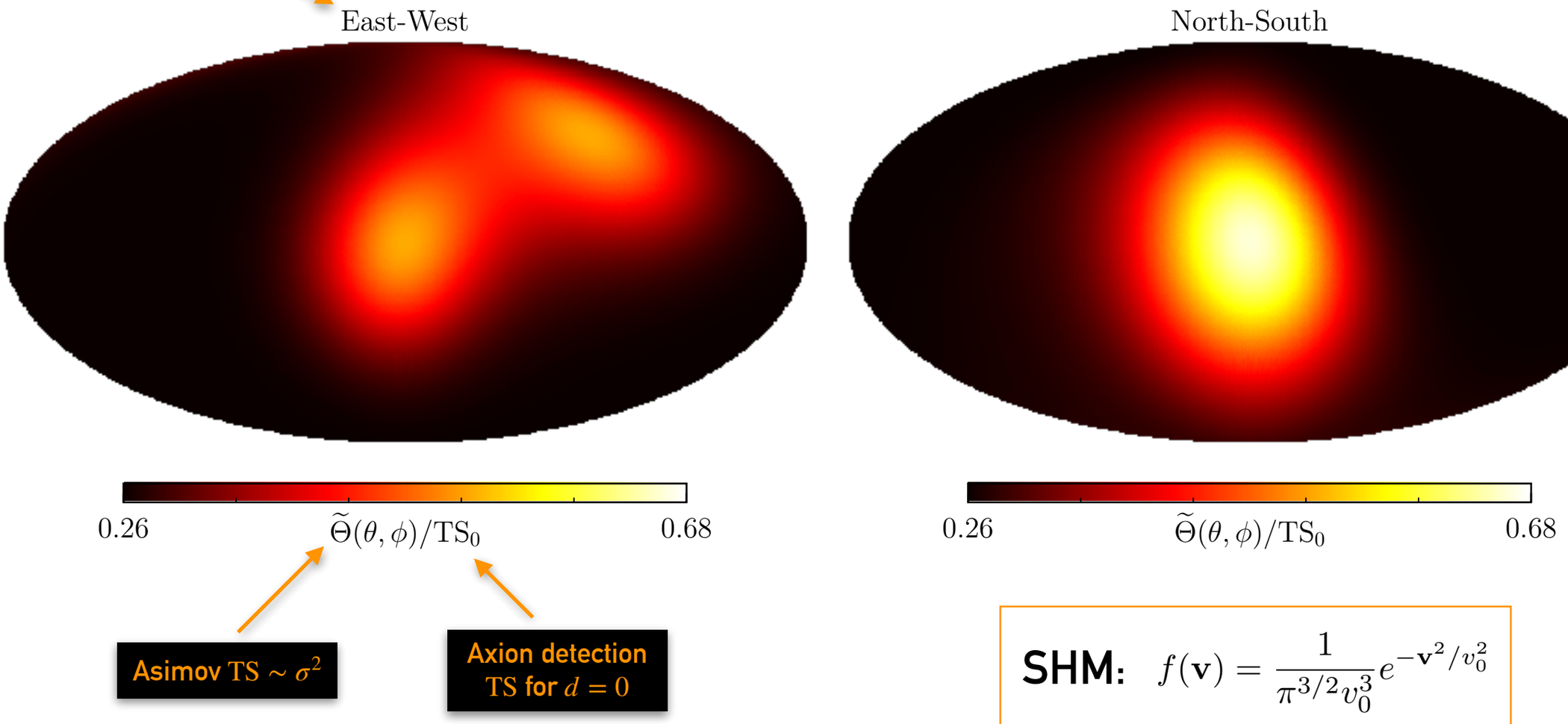
[Foster, NLR+ 2020]

DARK MATTER INTERFEROMETRY

Standard Halo Model

Can we determine the direction of the DM wind?

Detector Configuration



Asimov TS $\sim \sigma^2$

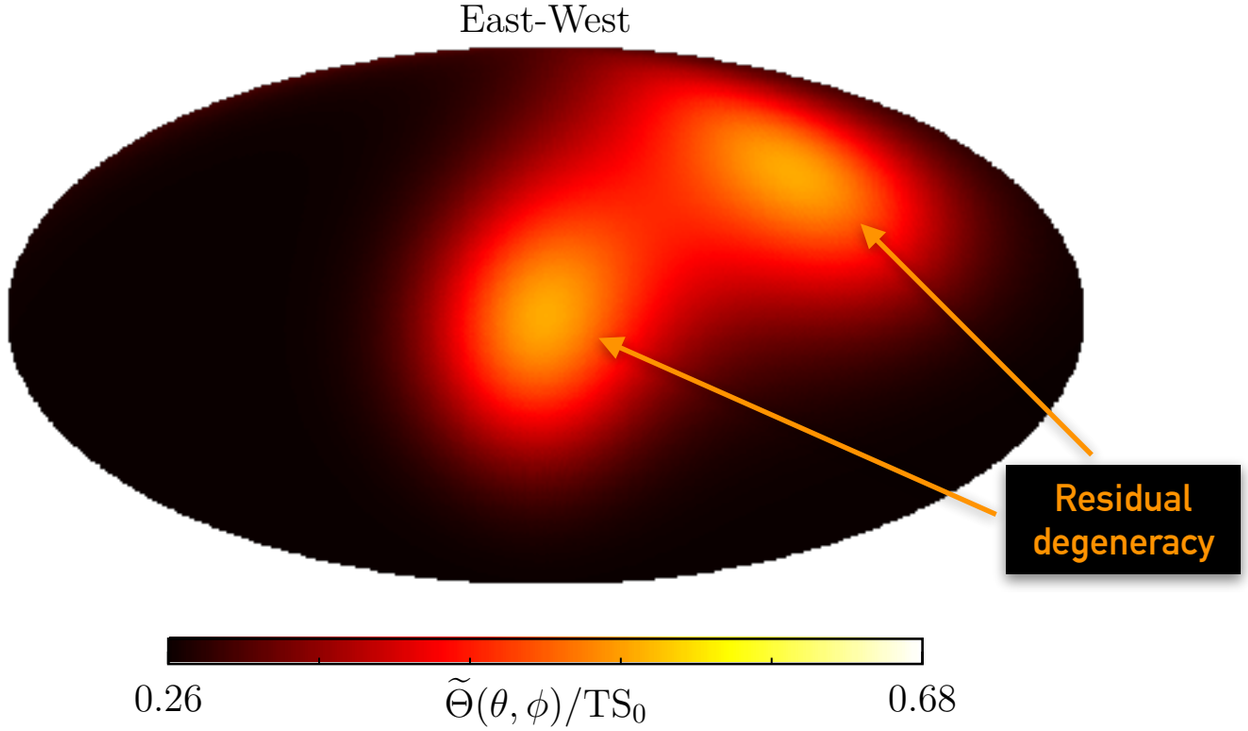
Axion detection TS for $d = 0$

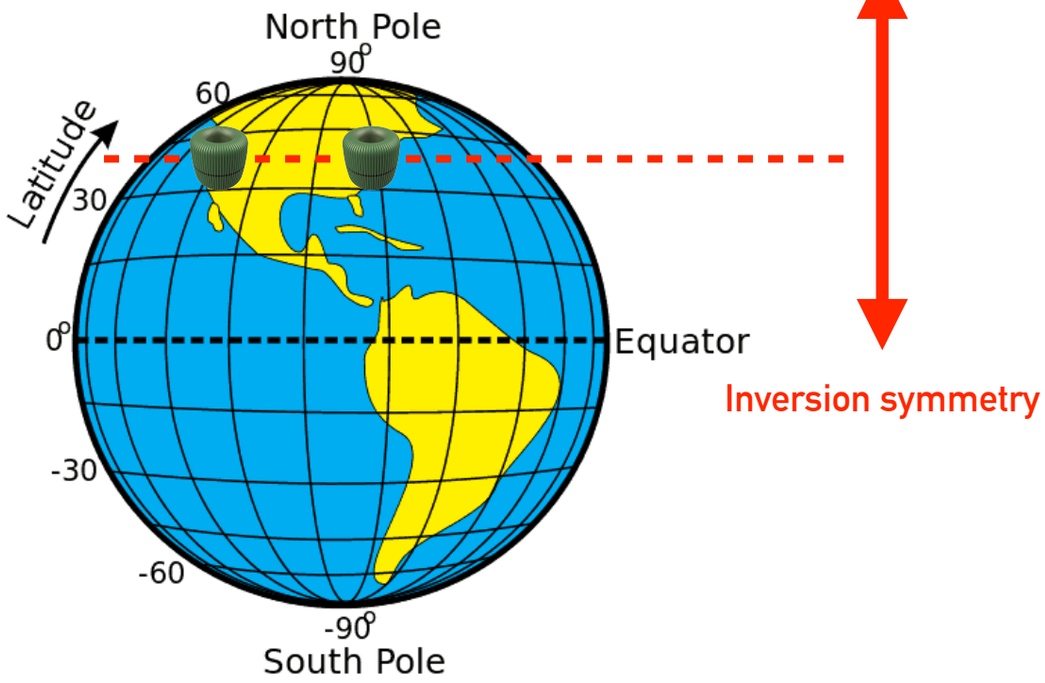
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[Foster, NLR+ 2020]

Standard Halo Model

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[Foster, NLR+ 2020]

Standard Halo Model

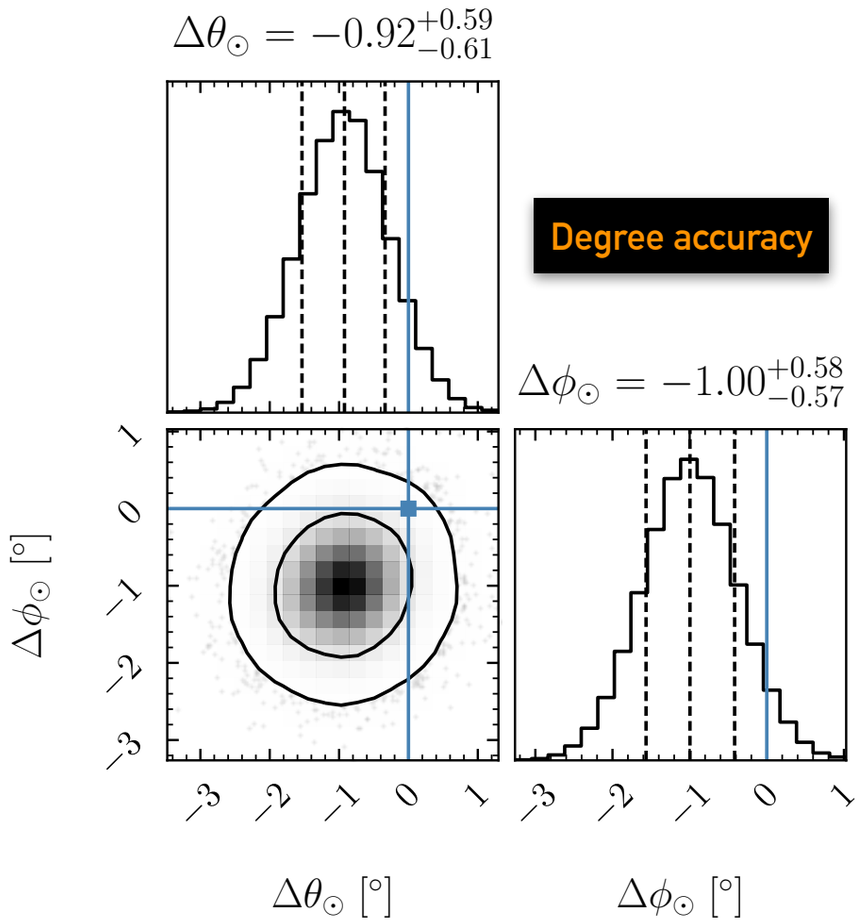
If HAYSTAC discovers DM, how well can they infer $\mathbf{v}_\odot$ with 2 detectors and 1 day of data?

[Foster, NLR+ 2020]

Standard Halo Model

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

Results use the full likelihood formalism



Degree accuracy

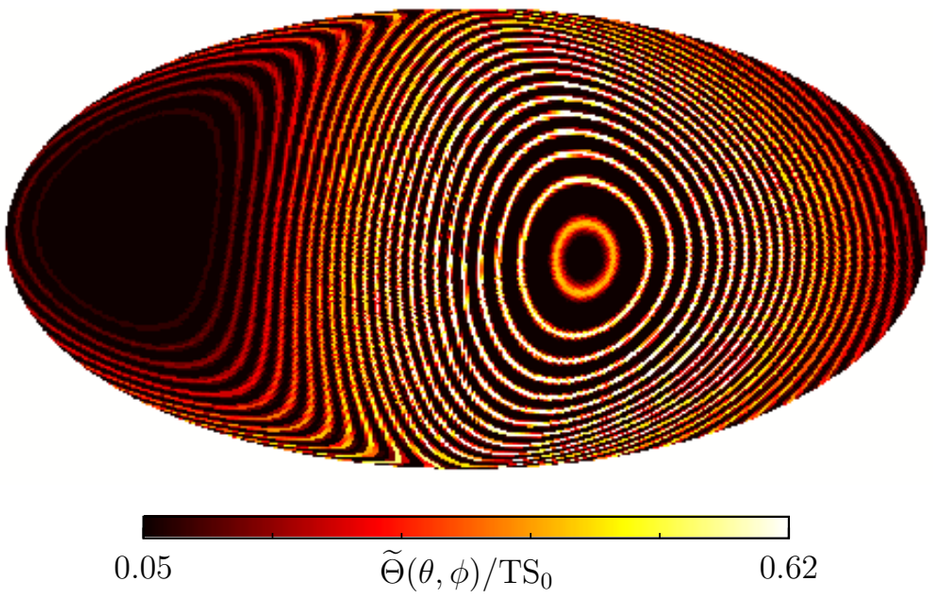
[Foster, NLR+ 2020]

DARK MATTER INTERFEROMETRY

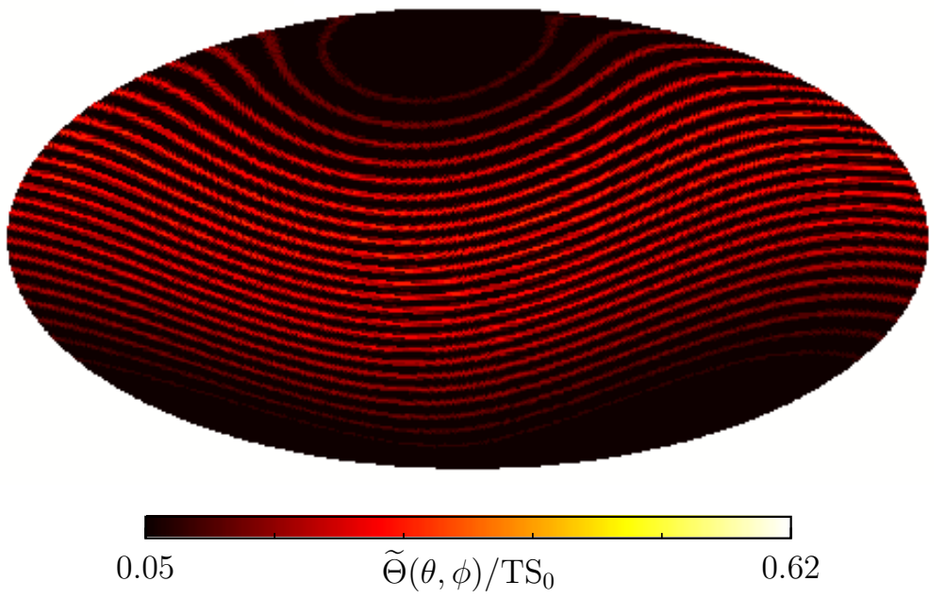
Stream Localization

Can we determine the direction of an incident DM stream?

East-West



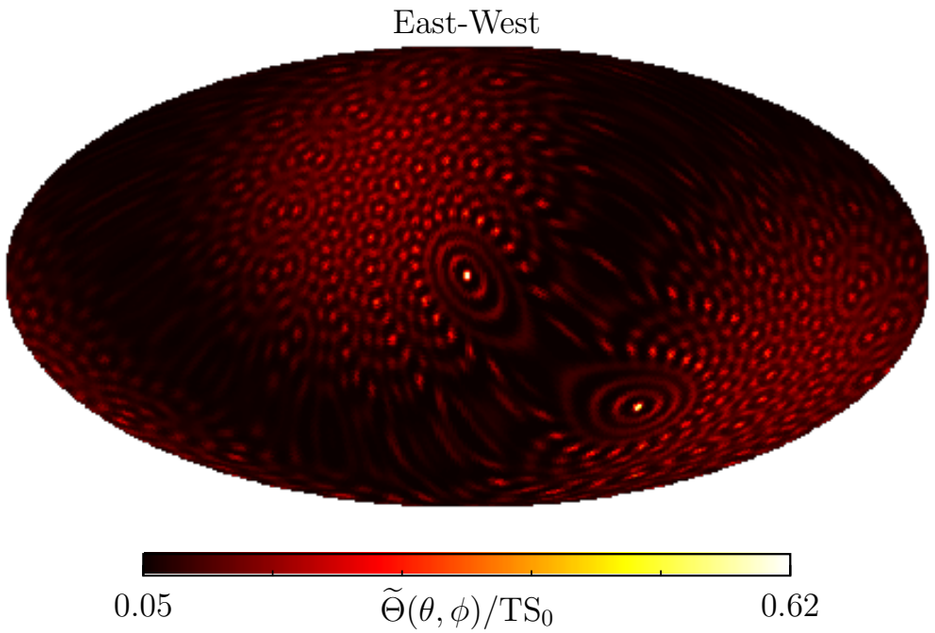
North-South

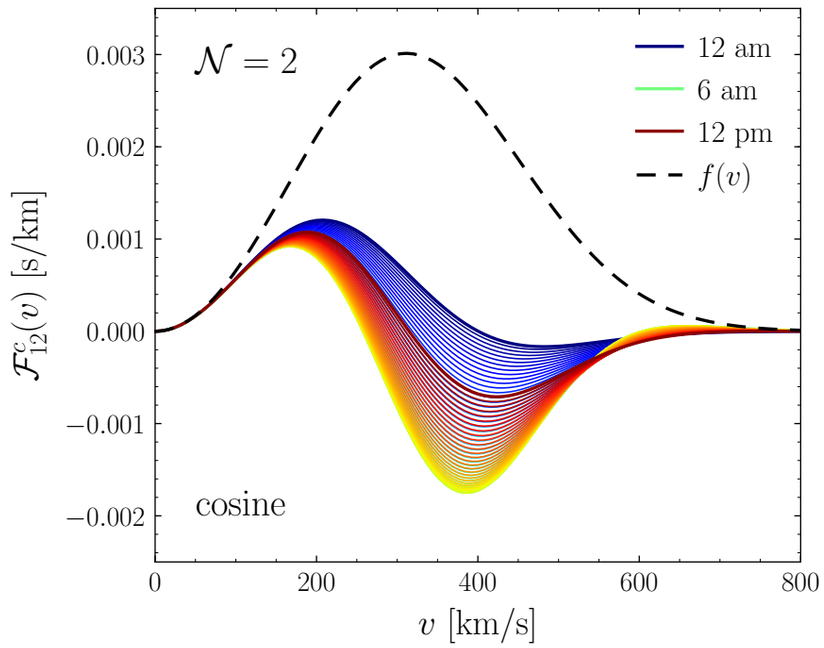


[Foster, NLR+ 2020]

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

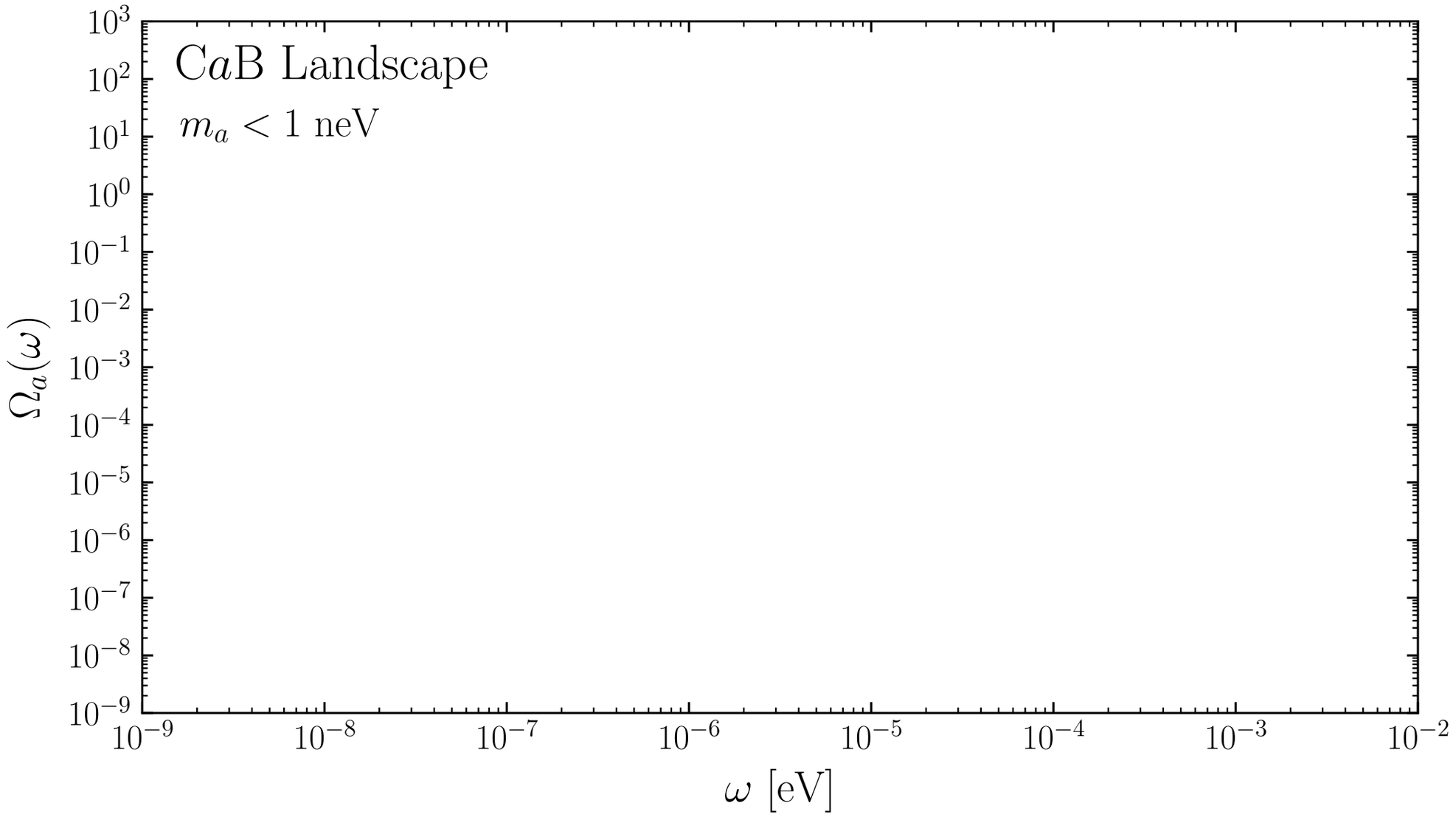
The Cosmic Axion Background

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

[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

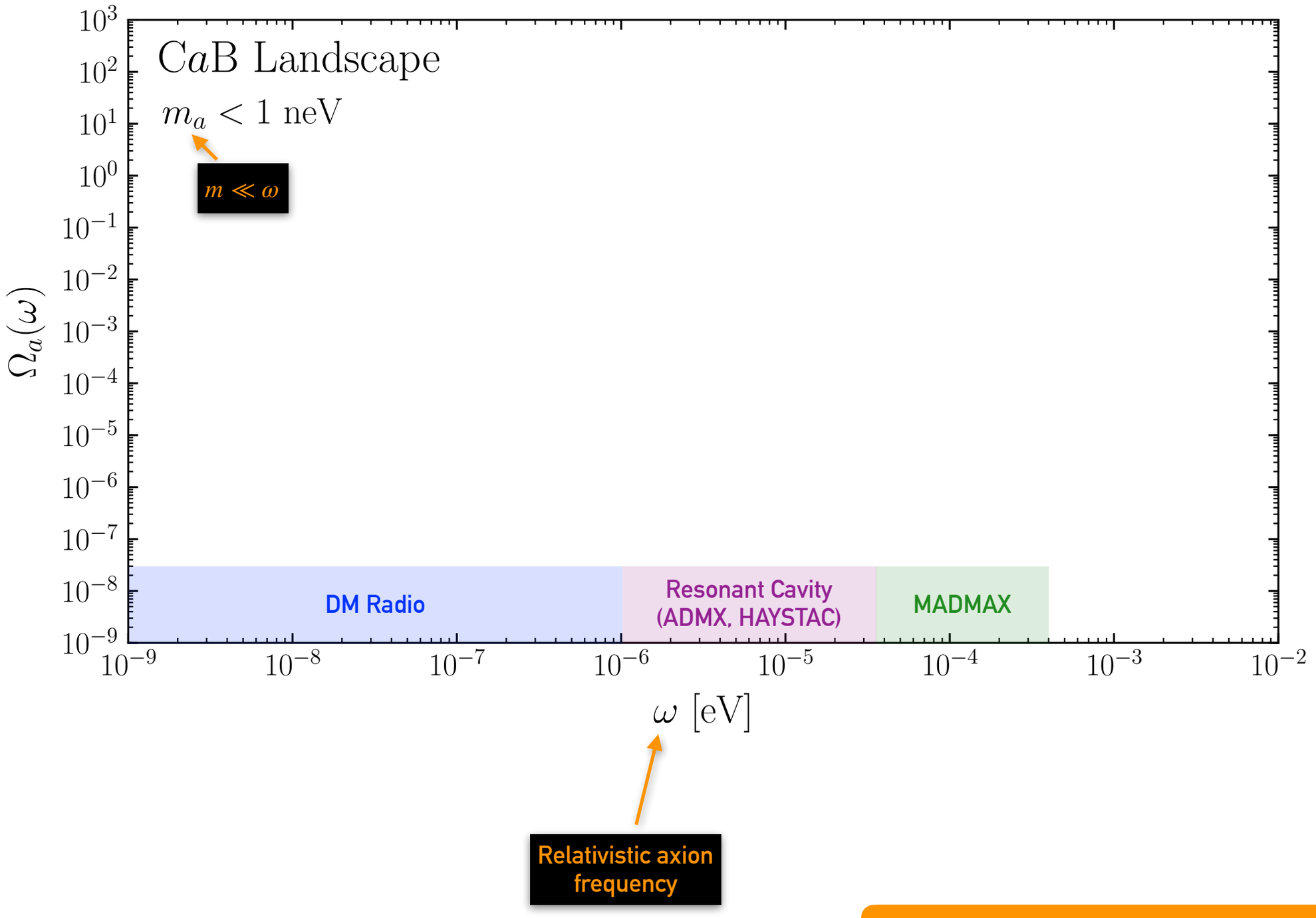
Landscape



[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

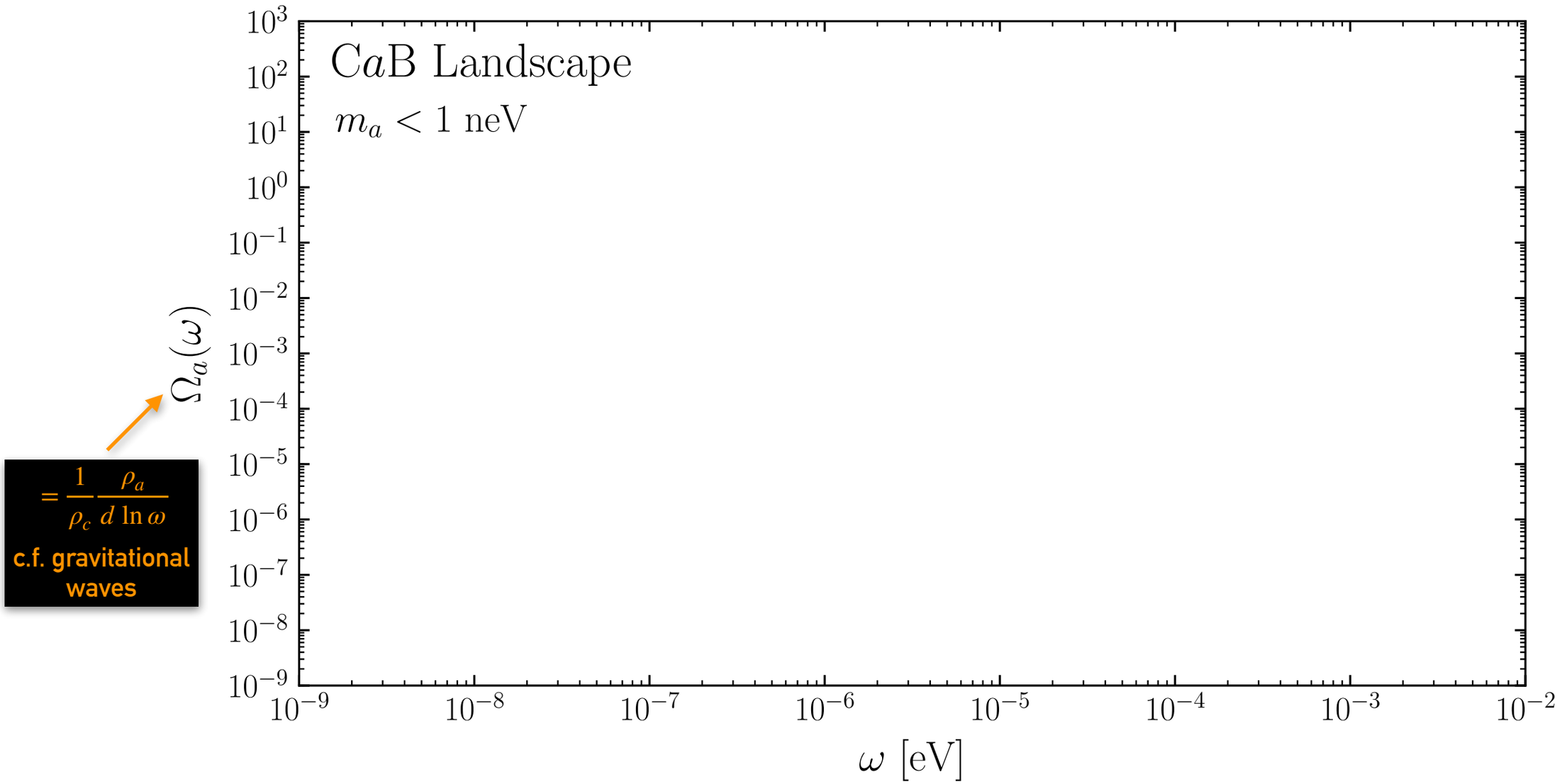
Landscape



[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

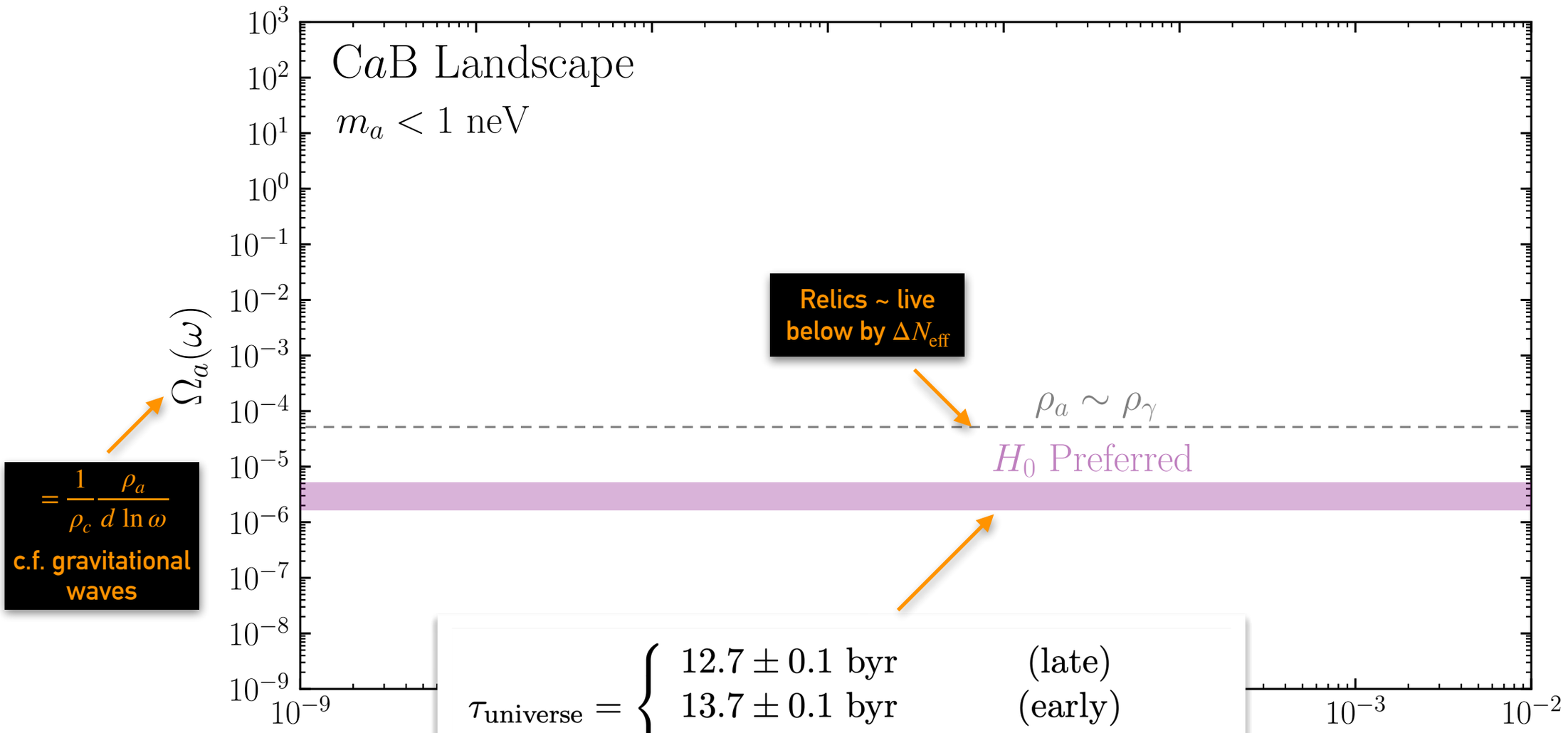
Landscape



[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

Landscape



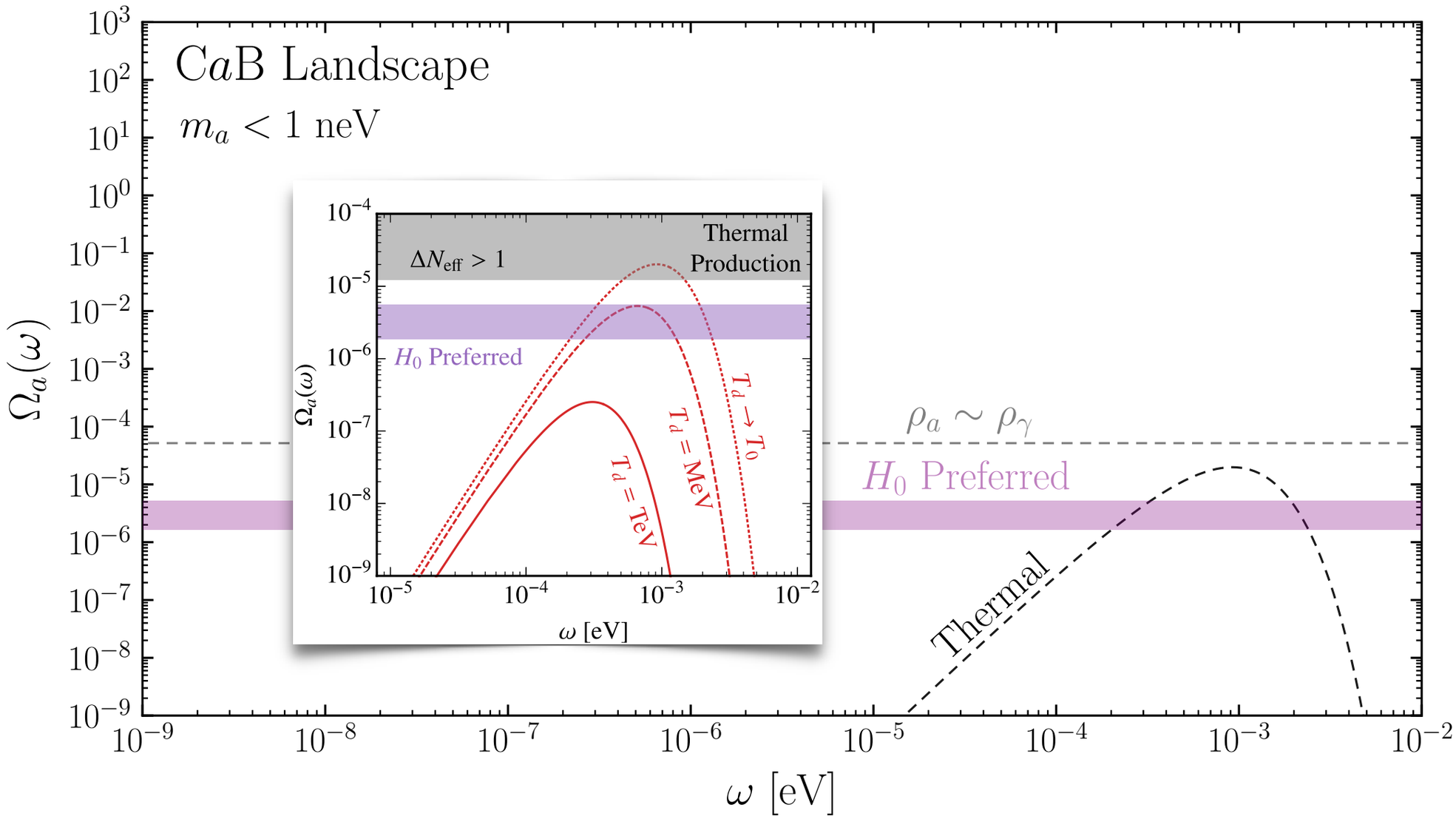
$$\tau_{\rm universe} = \begin{cases} 12.7 \pm 0.1 \text{ byr} & \text{(late)} \\ 13.7 \pm 0.1 \text{ byr} & \text{(early)} \\ 14.0 \pm 0.3 \text{ byr} & \text{(early, } \Delta N_{\rm eff} \neq 0\text{)} \end{cases}$$

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

[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

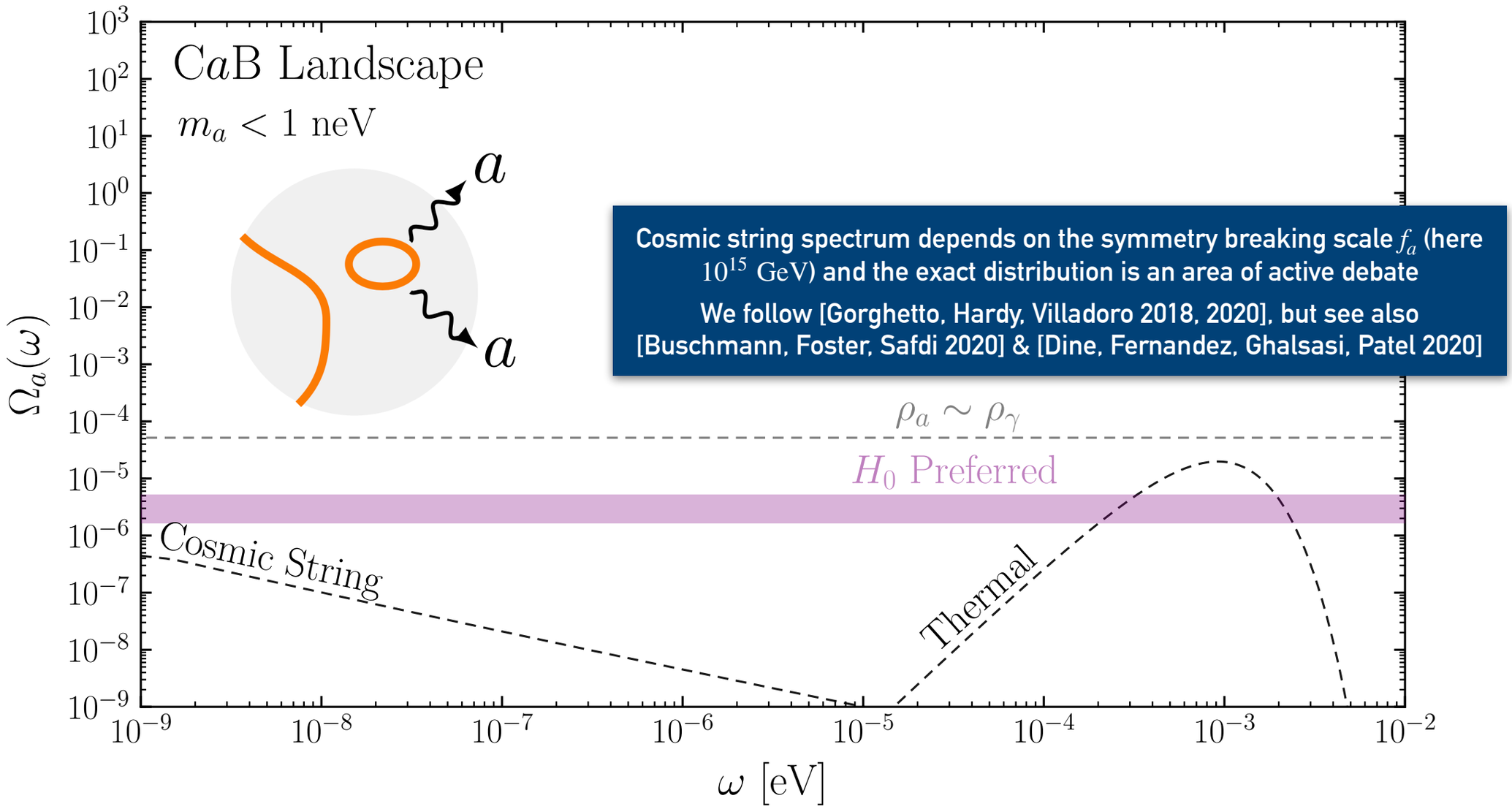
Landscape



[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

Landscape



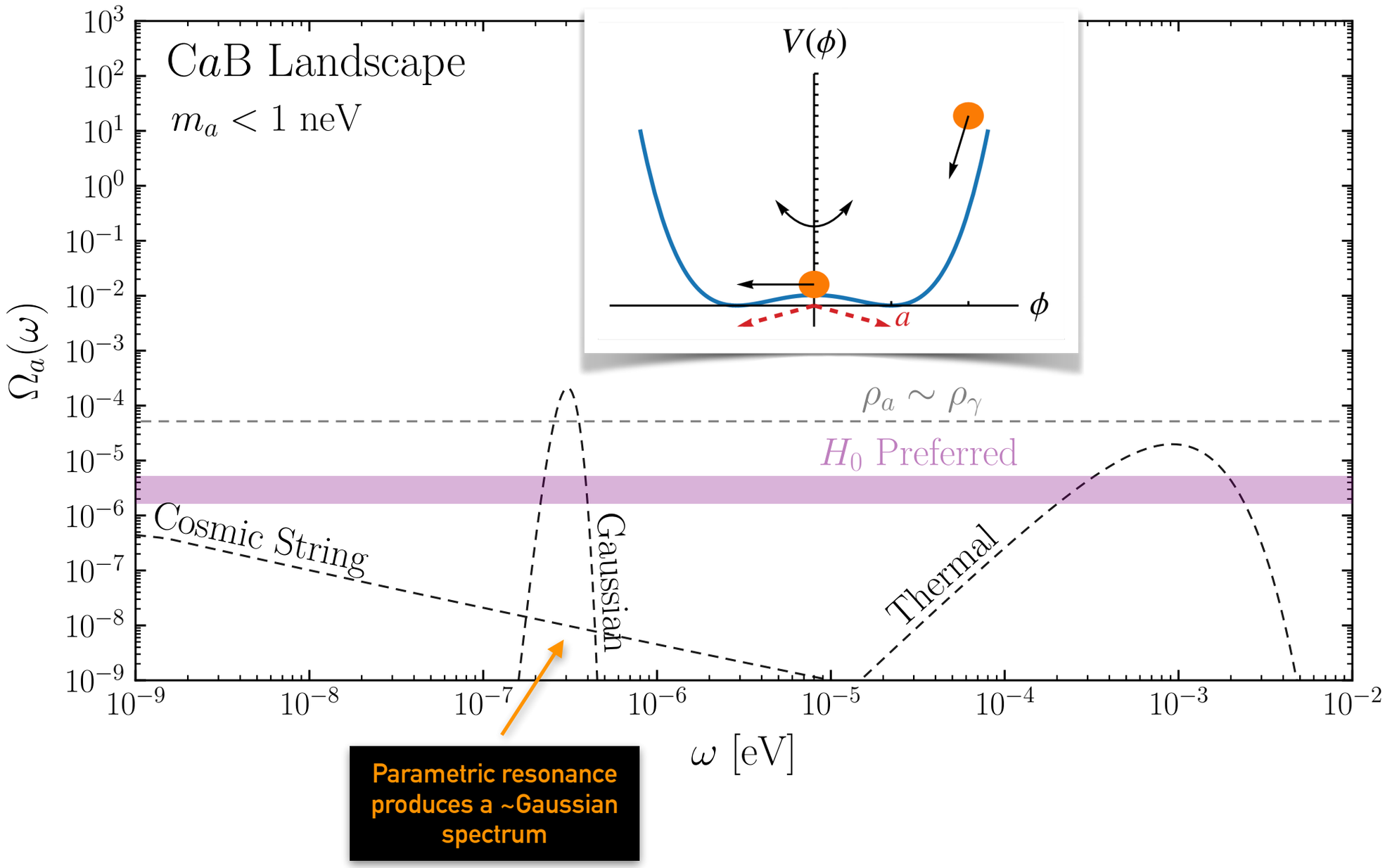
Cosmic string spectrum depends on the symmetry breaking scale f_a (here 10^{15} GeV) and the exact distribution is an area of active debate

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

[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

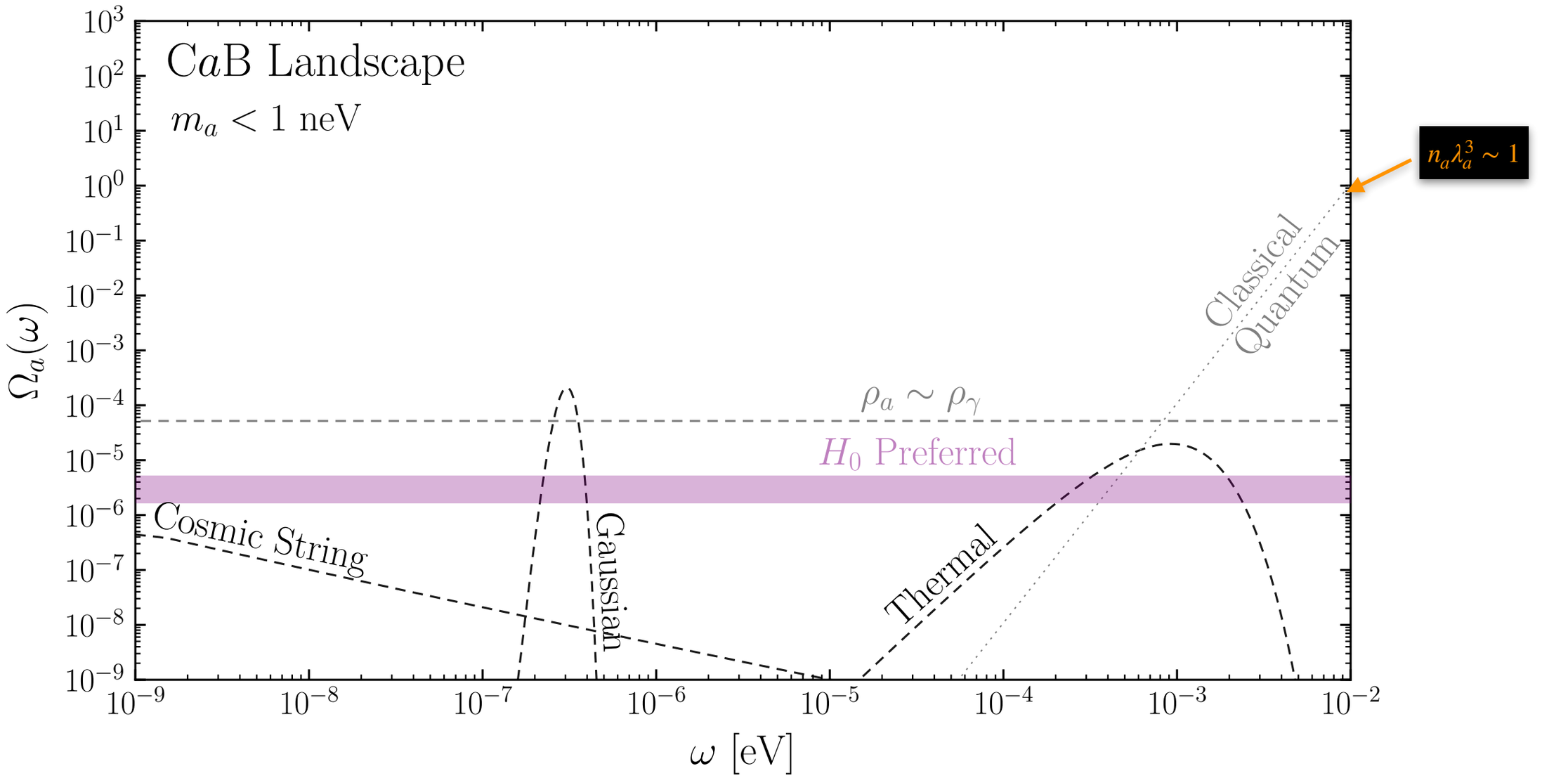
Landscape



[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

Landscape

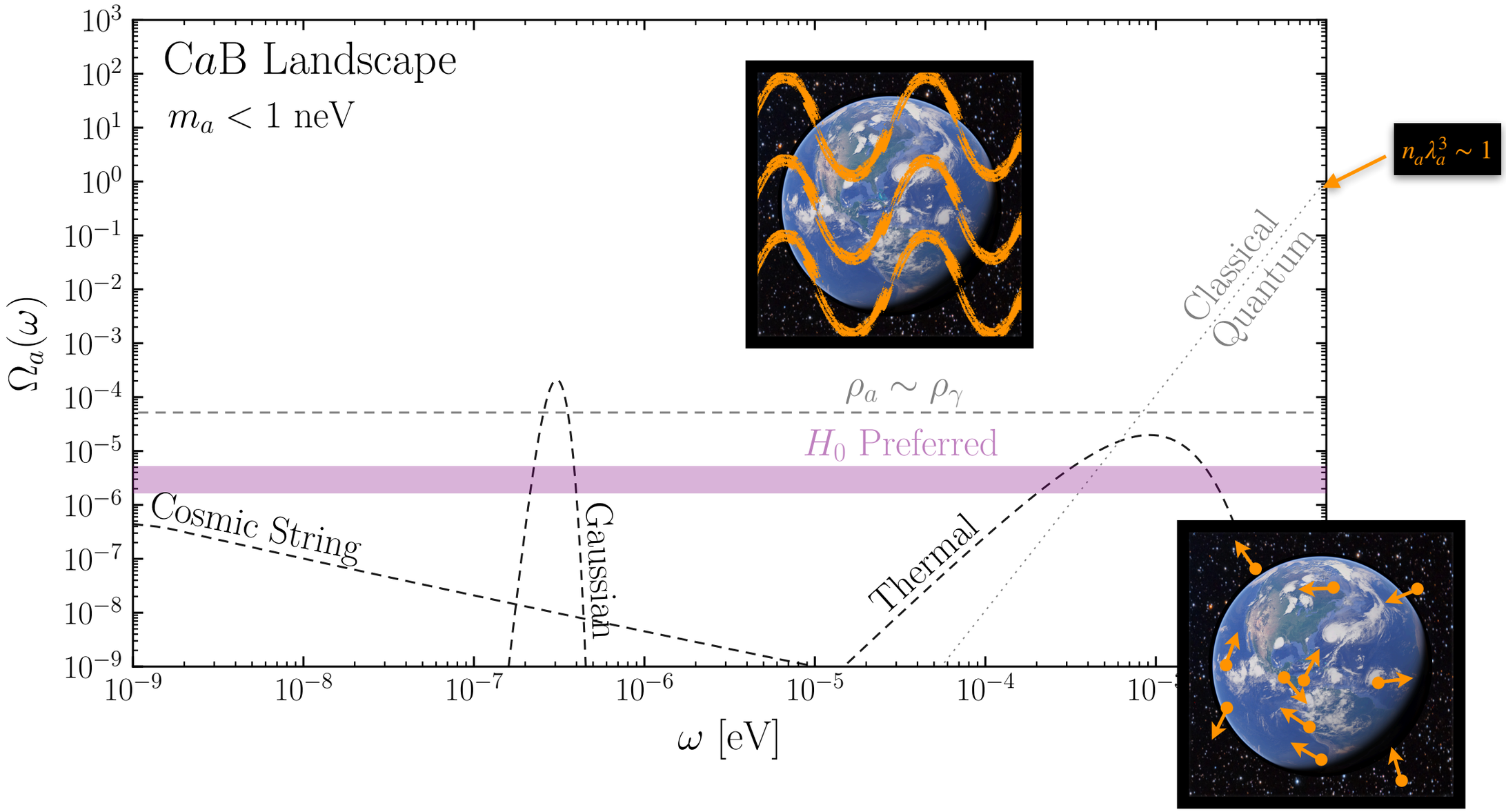


[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

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]

THE COSMIC AXION BACKGROUND

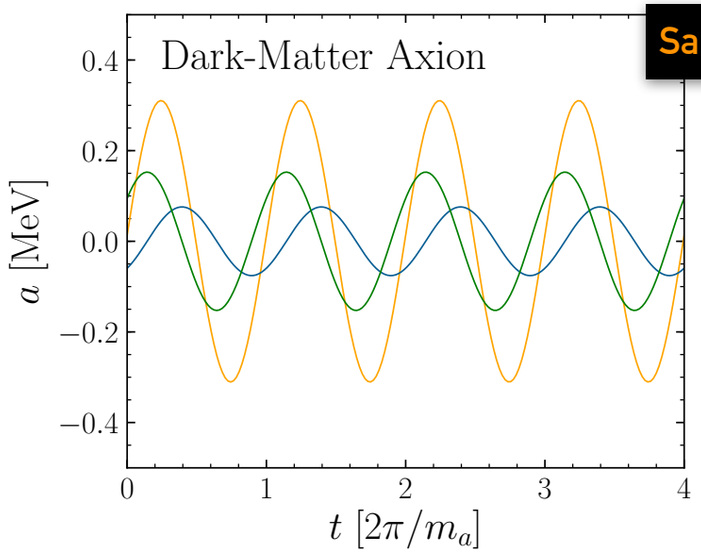
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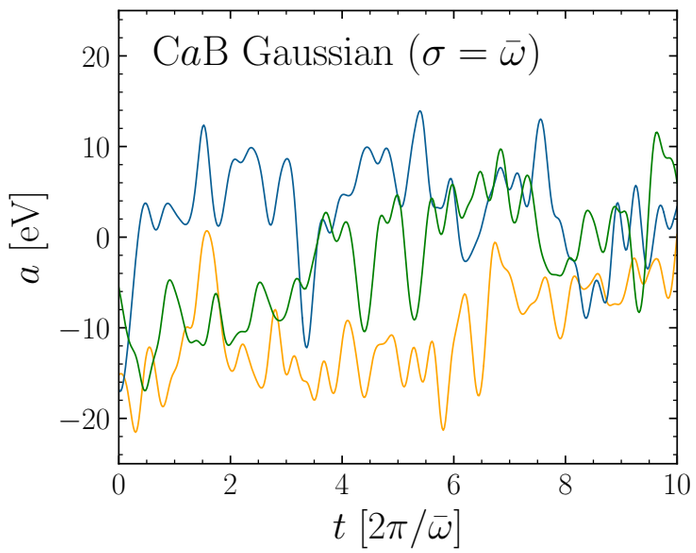
Sampled from $p(\omega)$

Random phase

Dark Matter



CaB



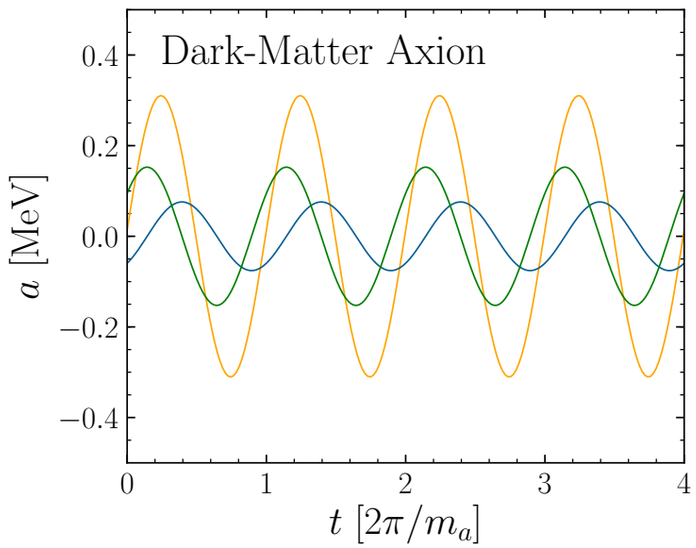
[Dror, NLR, Murayama 2021]

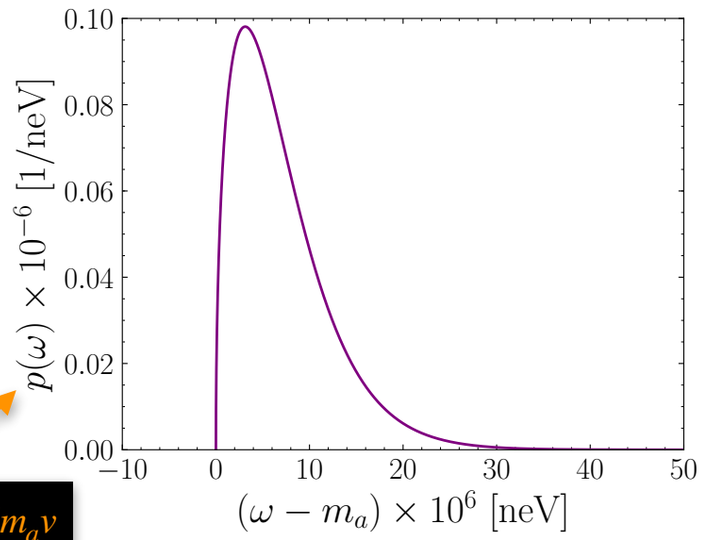
THE COSMIC AXION BACKGROUND

Rough Sensitivity

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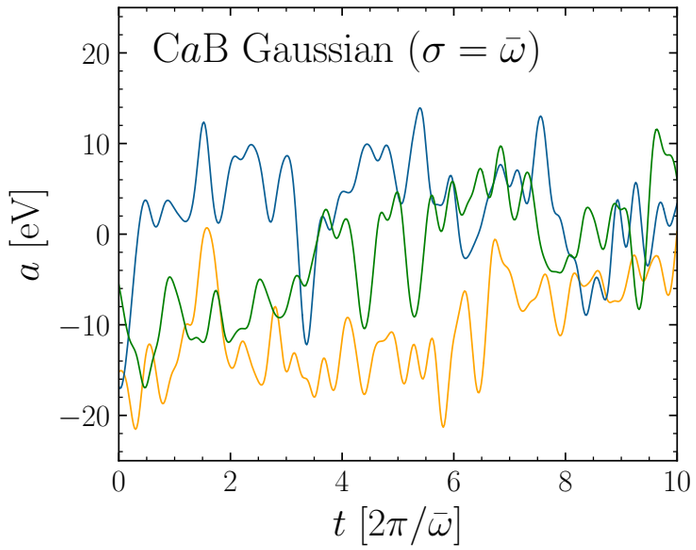
Dark Matter

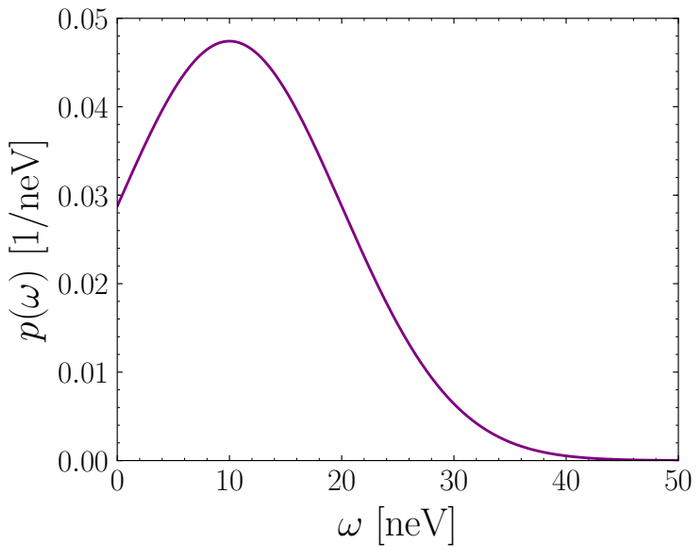




$p(\omega) = f(v)/m_a v$

CaB





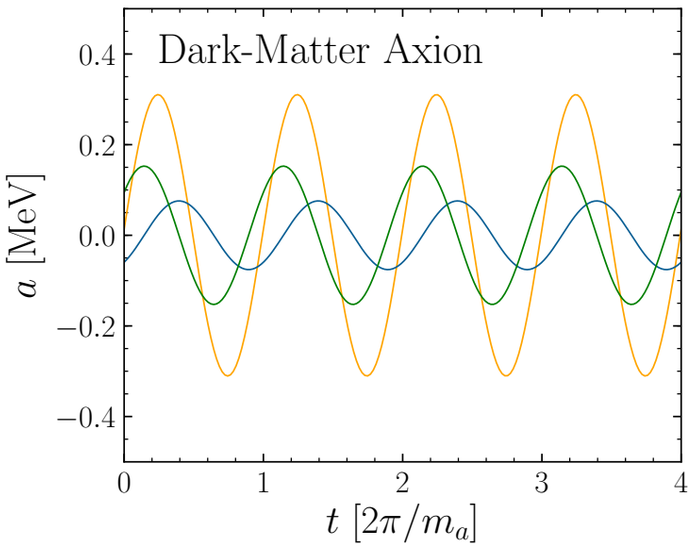
[Dror, NLR, Murayama 2021]

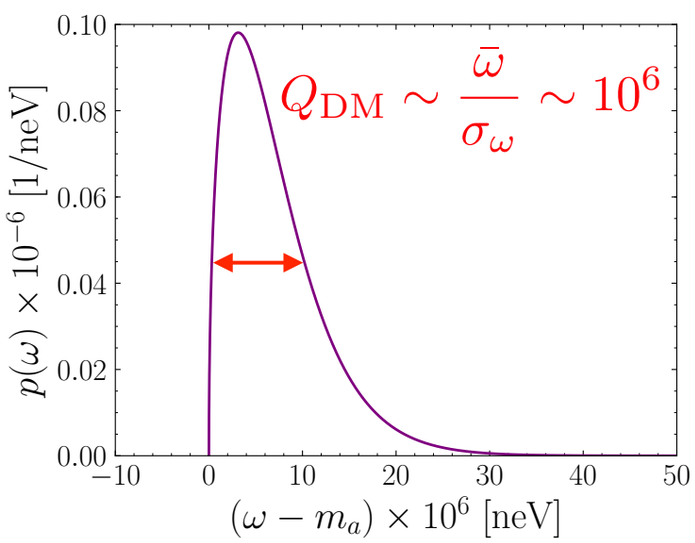
THE COSMIC AXION BACKGROUND

Rough Sensitivity

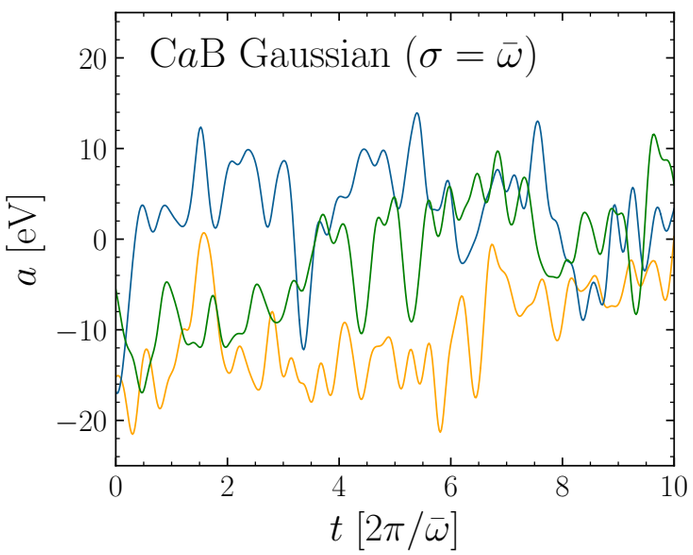
$$a(t) \sim \sum_i \cos(\omega_i t + \phi_i)$$

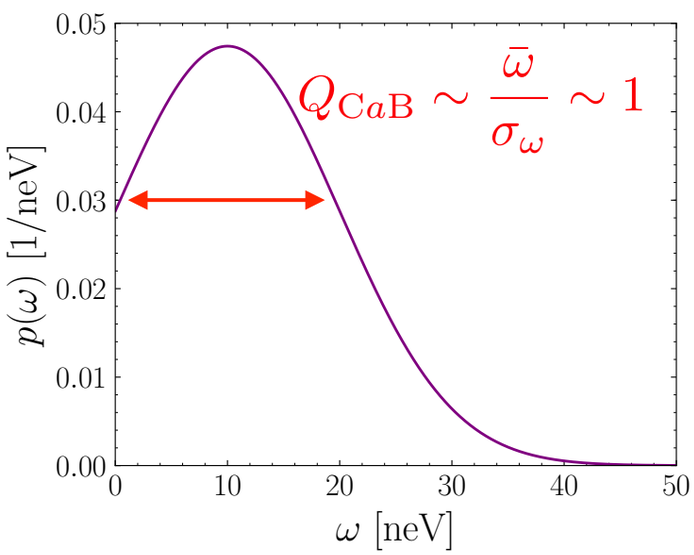
Dark Matter





CaB





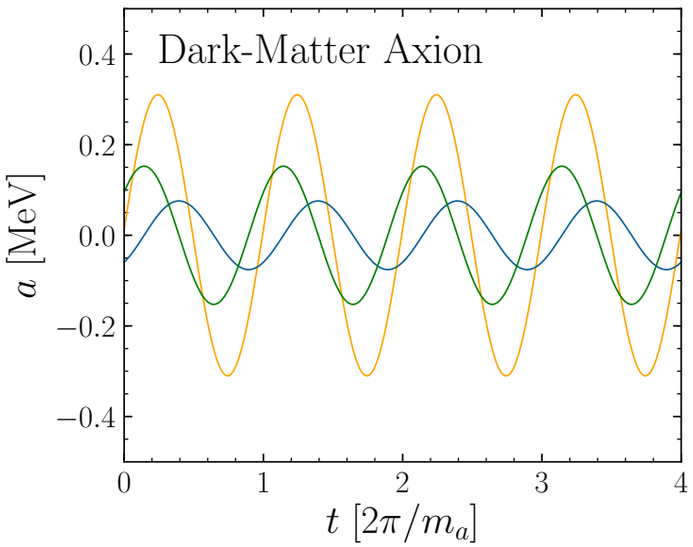
[Dror, NLR, Murayama 2021]

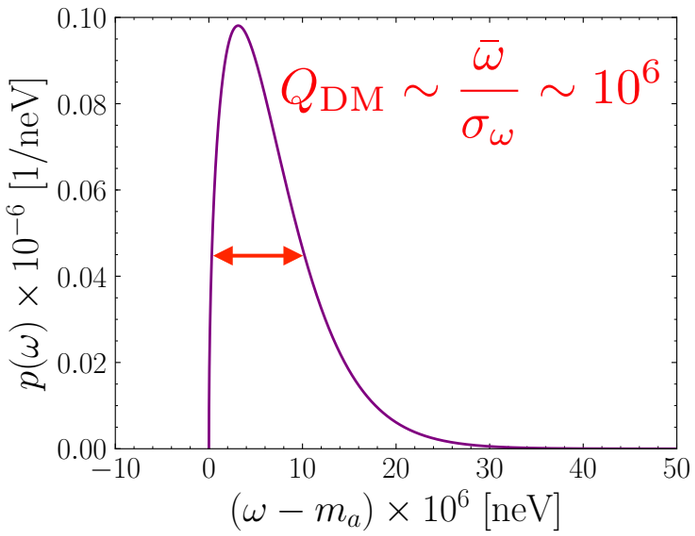
THE COSMIC AXION BACKGROUND

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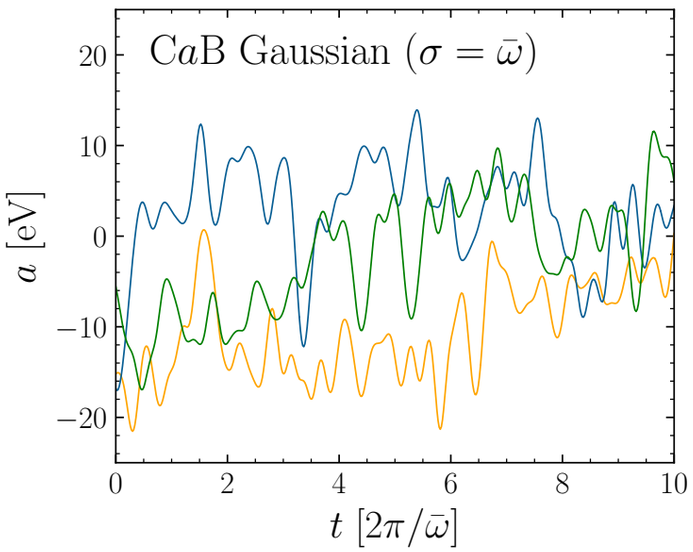
Dark Matter

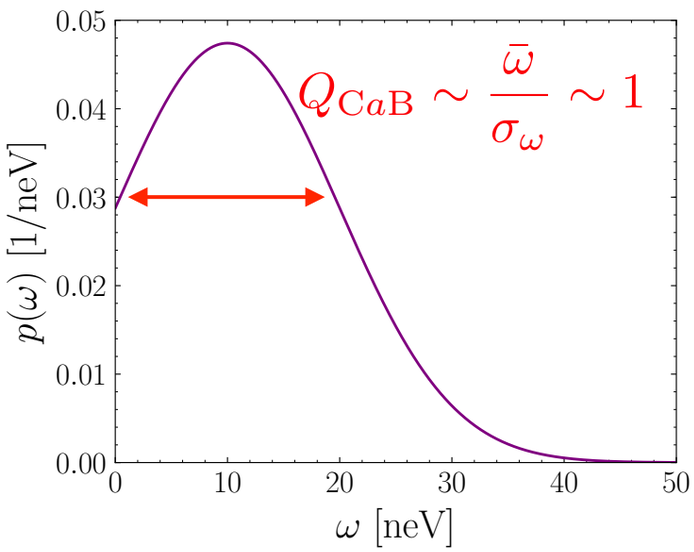




Much broader signal - existing searches would throw out as background

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

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

Power spectral density - measures power at a given frequency

[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 $P_{\rm DM} = P_{\rm C\mathit{a}B}$

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

[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

Rough Sensitivity

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

Single bin: $(g^{\rm lim}_{a\gamma\gamma})^2 \rho_{\rm DM} Q_{\rm DM} = (g^{\rm SE}_{a\gamma\gamma})^2 \rho_a Q_{\rm CaB}$

Dark Matter sensitivity

Star Emission sensitivity

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

[Dror, NLR, Murayama 2021]

Rough Sensitivity

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

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

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

- Lose: $\rho_a \ll \rho_{\rm DM}$
- Win: $g^{\rm lim}_{a\gamma\gamma} \ll g^{\rm SE}_{a\gamma\gamma}$
- Lose: $Q_{\rm C\mathit{a}B} \ll Q_{\rm DM}$

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

[Dror, NLR, Murayama 2021]

Rough Sensitivity

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

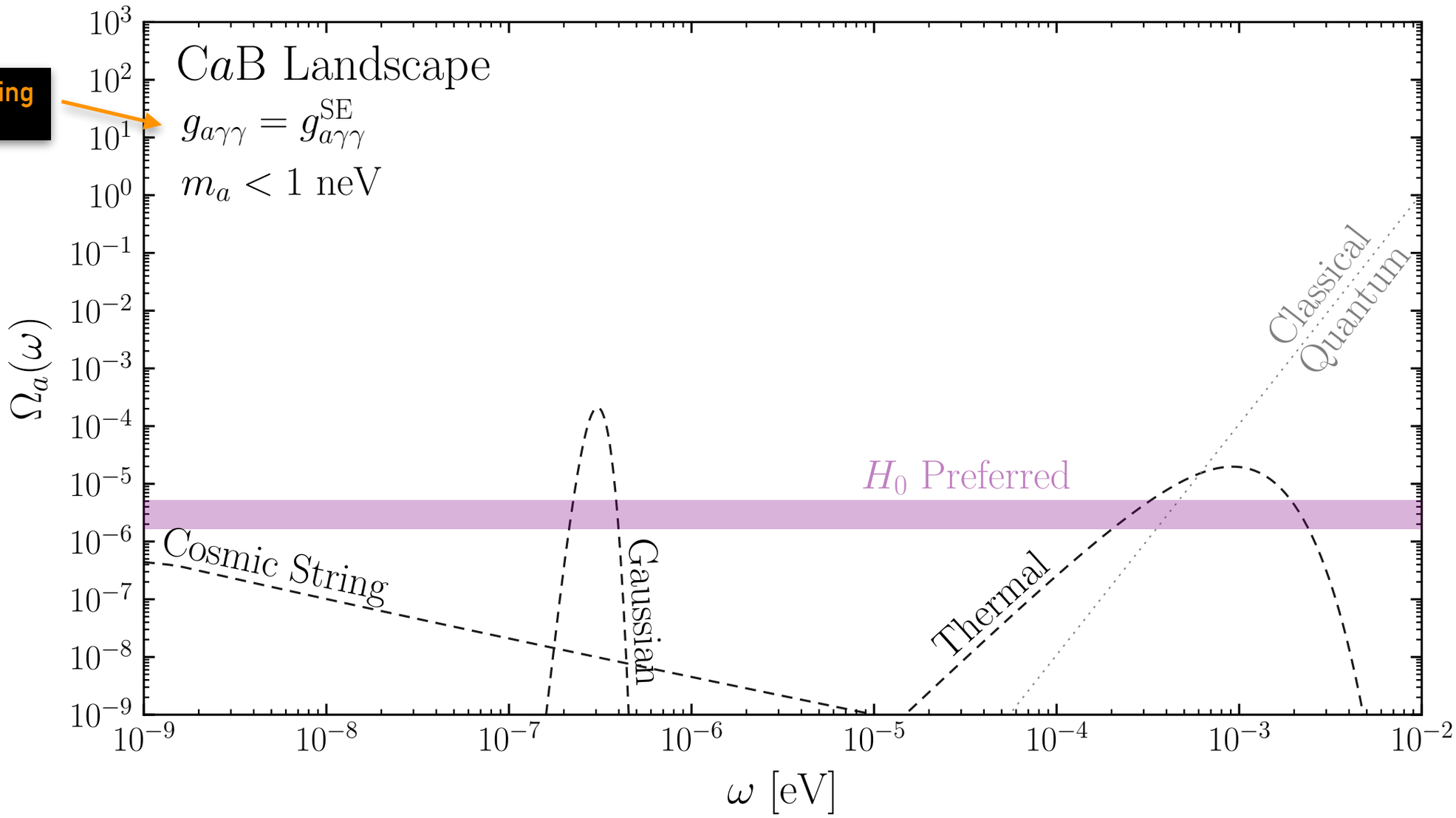
Parametric scaling confirmed by detailed calculations for both resonant and broadband instruments

[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

Experimental Landscape

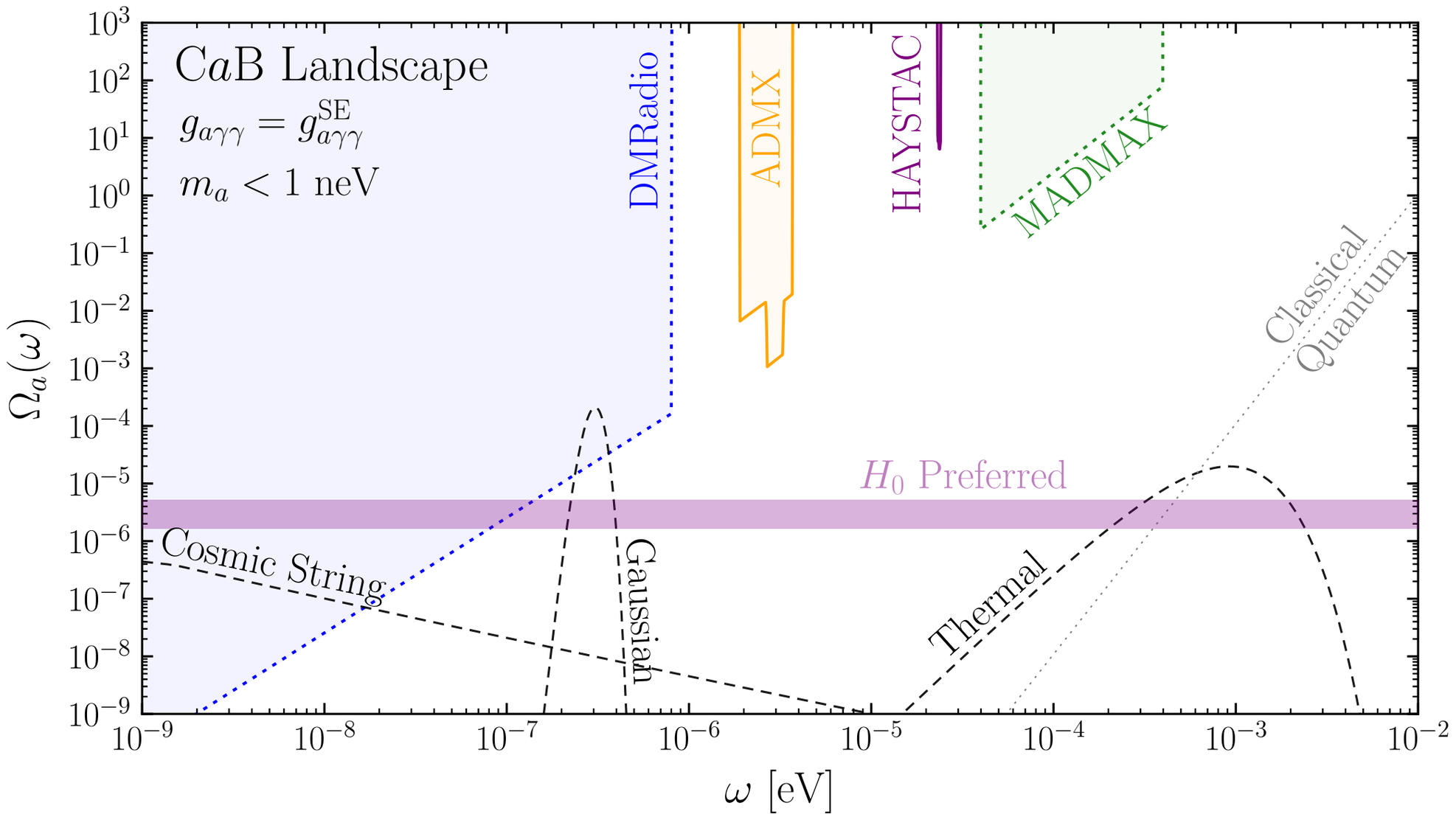
Saturate existing bounds



[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

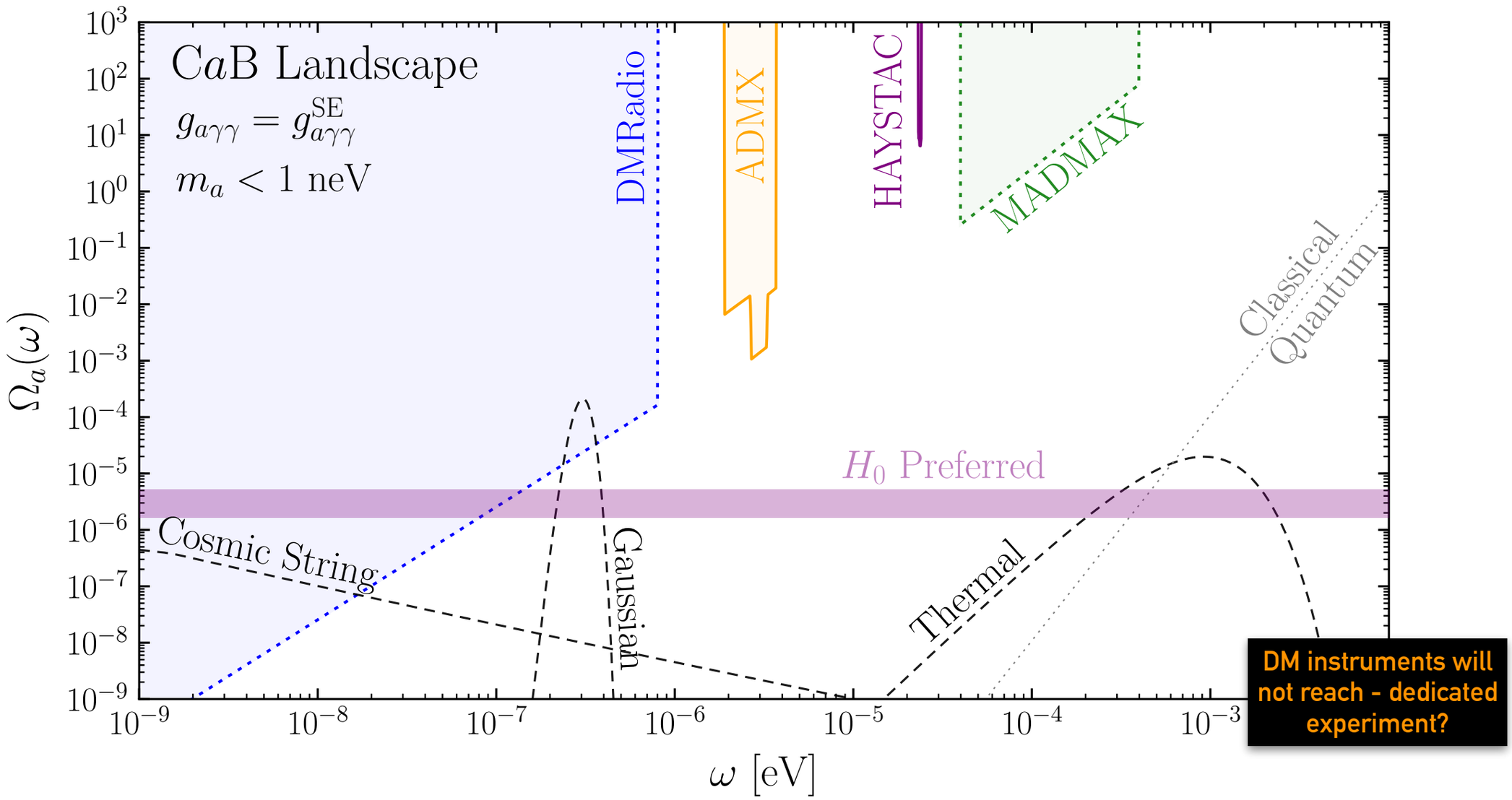
Experimental Landscape



[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

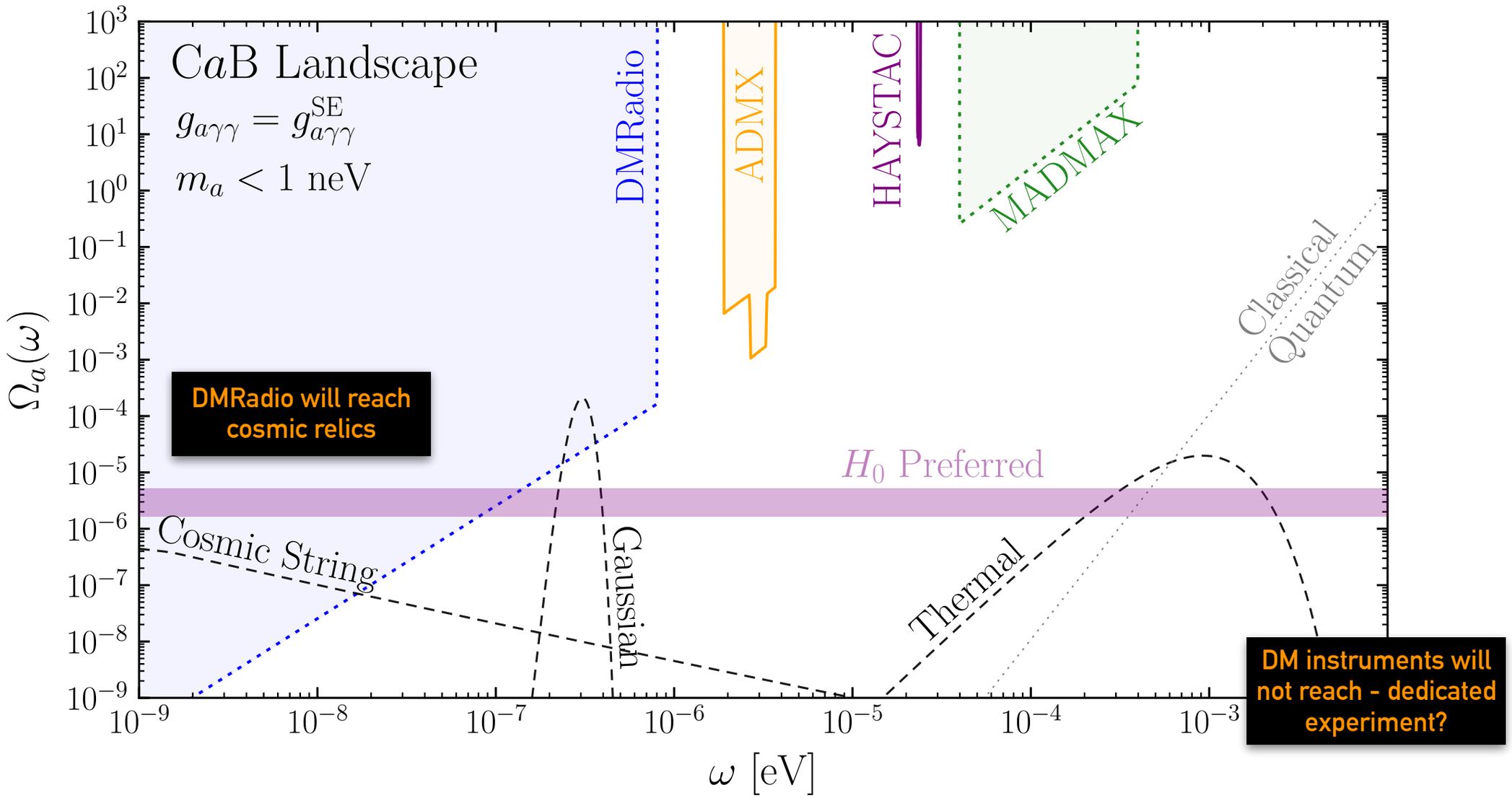
Experimental Landscape



[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

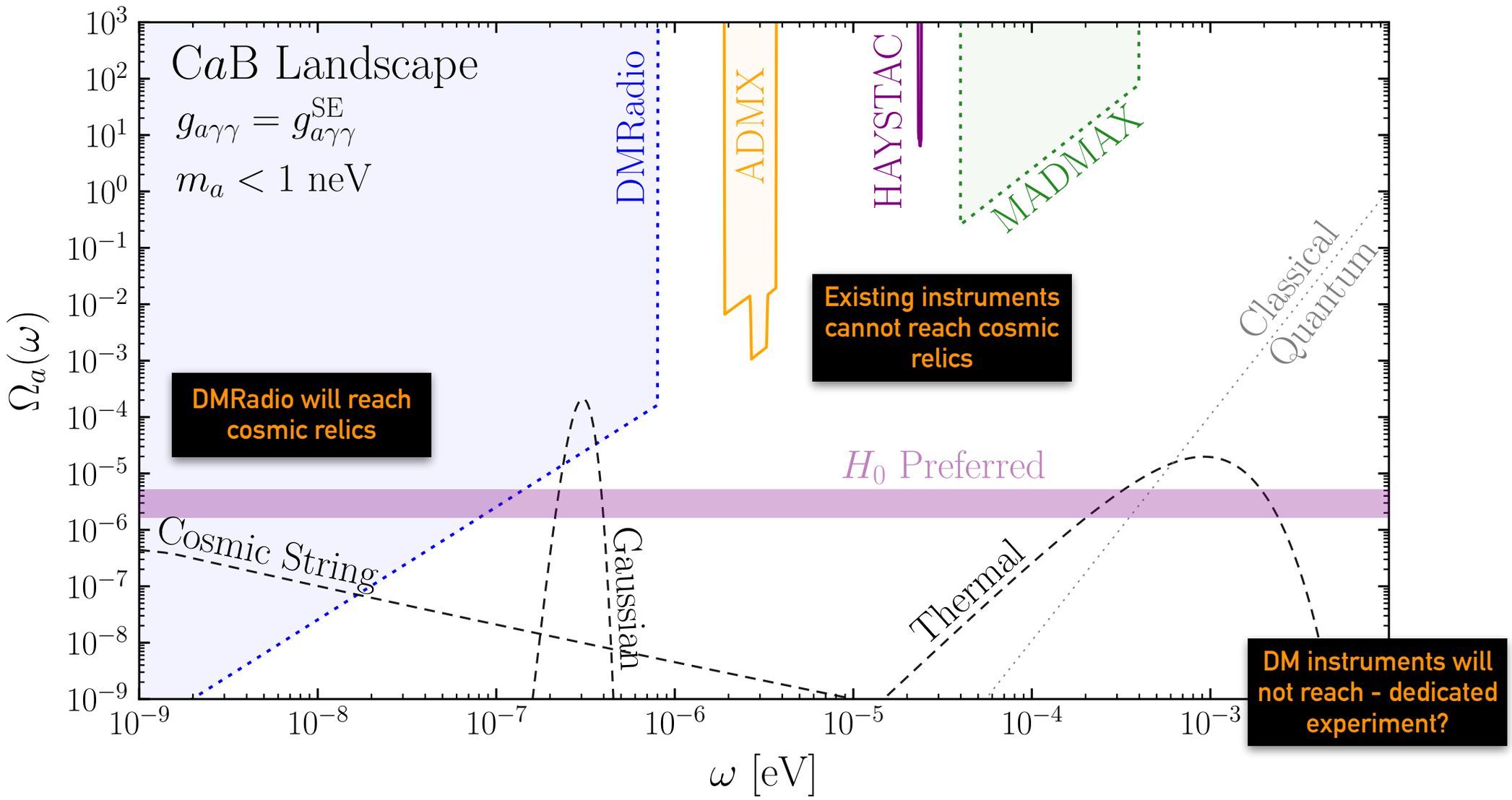
Experimental Landscape



[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

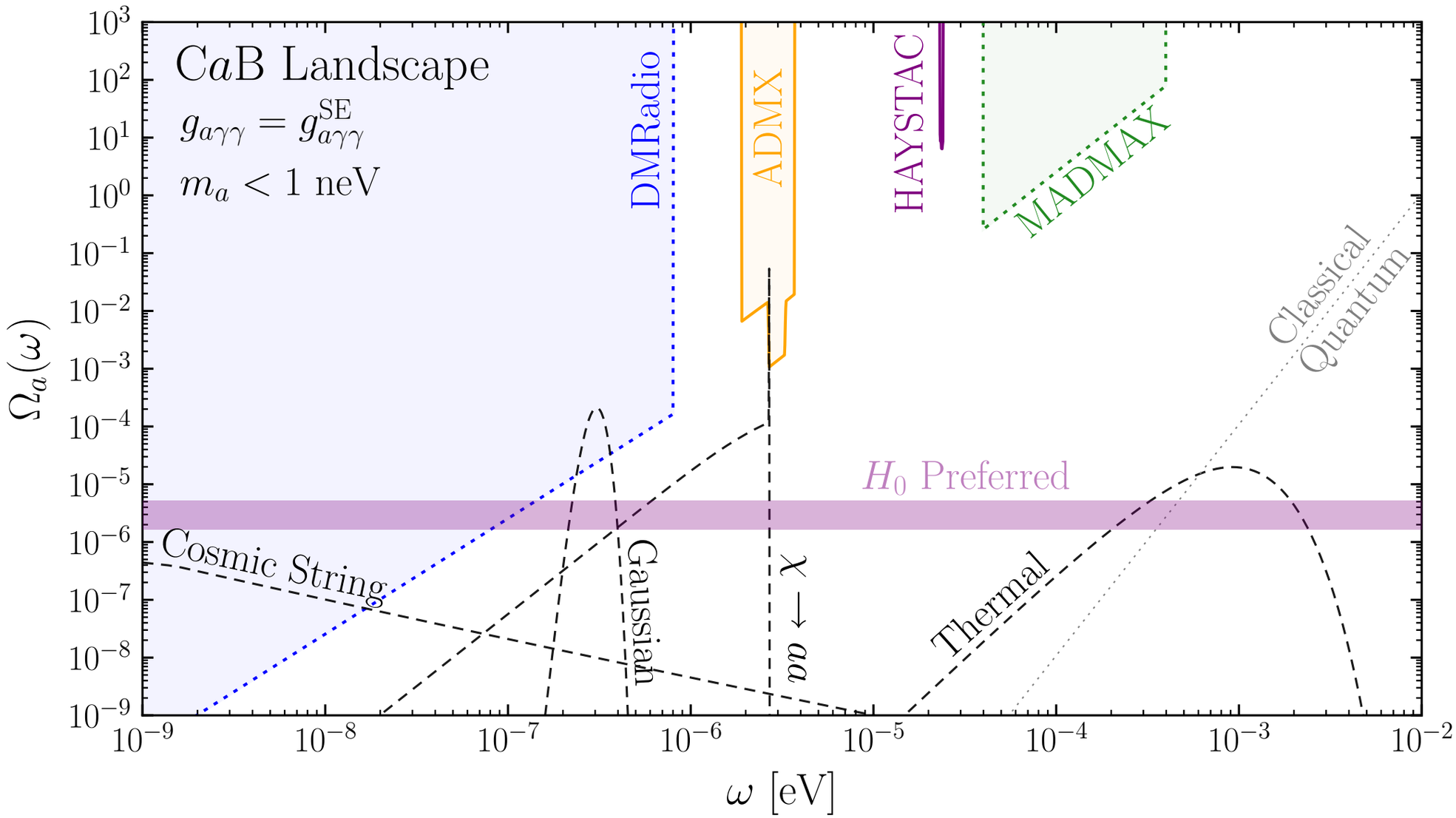
Experimental Landscape



[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

Experimental Landscape



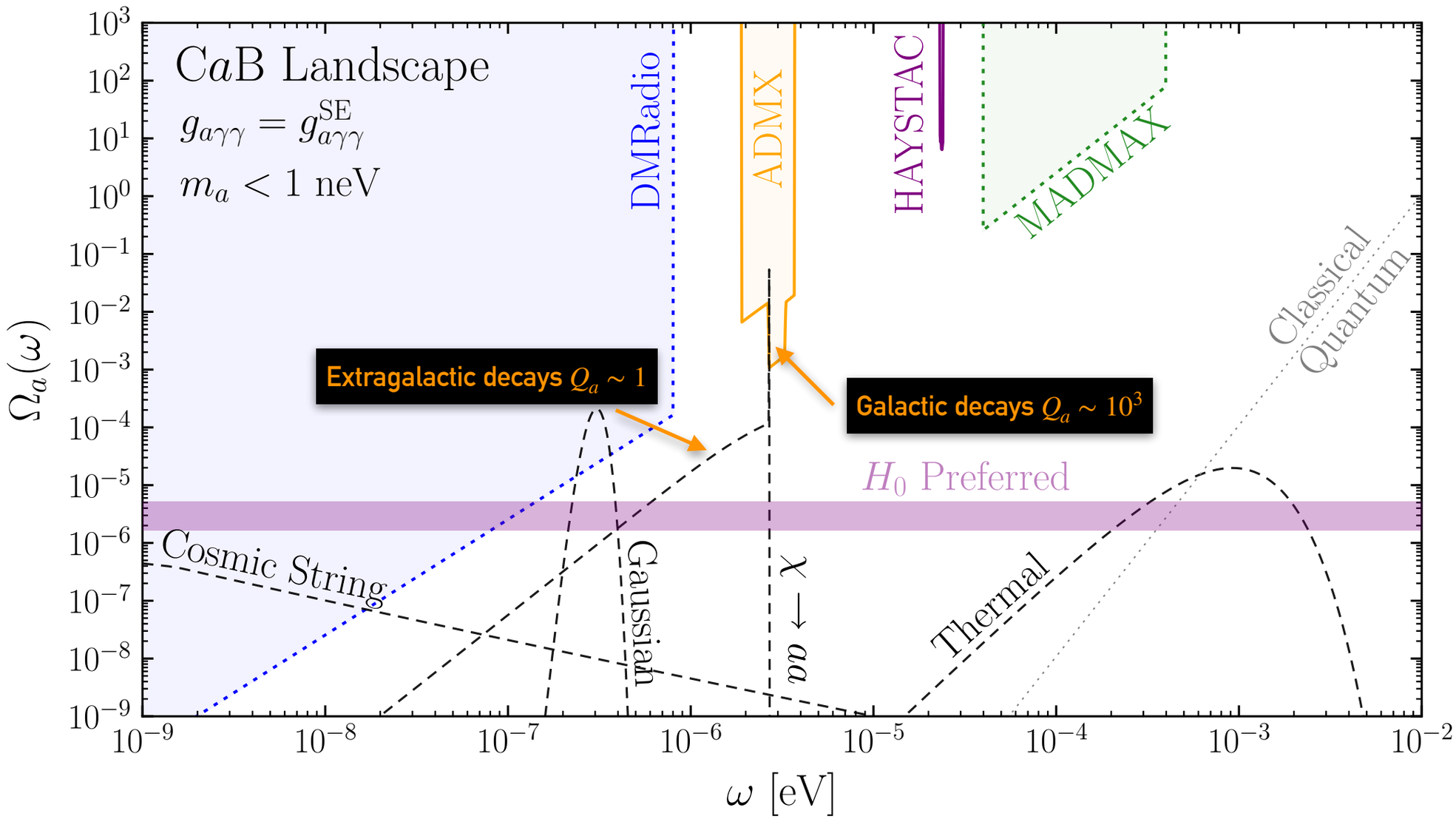
Late time production can generate $\rho_a > \rho_\gamma$

Dark matter decay is one example

[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

Experimental Landscape



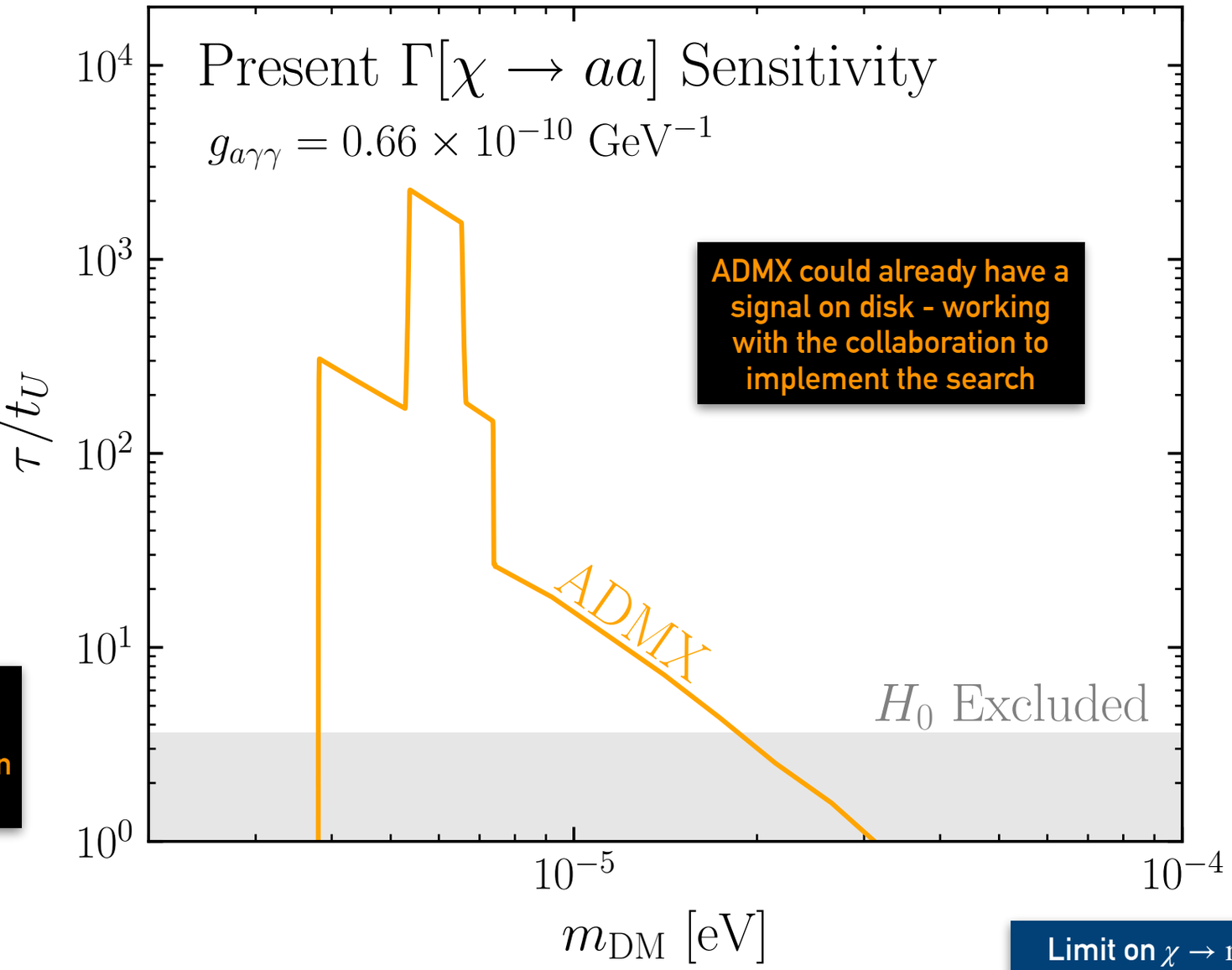
Late time production can generate $\rho_a > \rho_\gamma$

Dark matter decay is one example

[Dror, NLR, Murayama 2021]

THE COSMIC AXION BACKGROUND

Dark Matter Decay Sensitivity



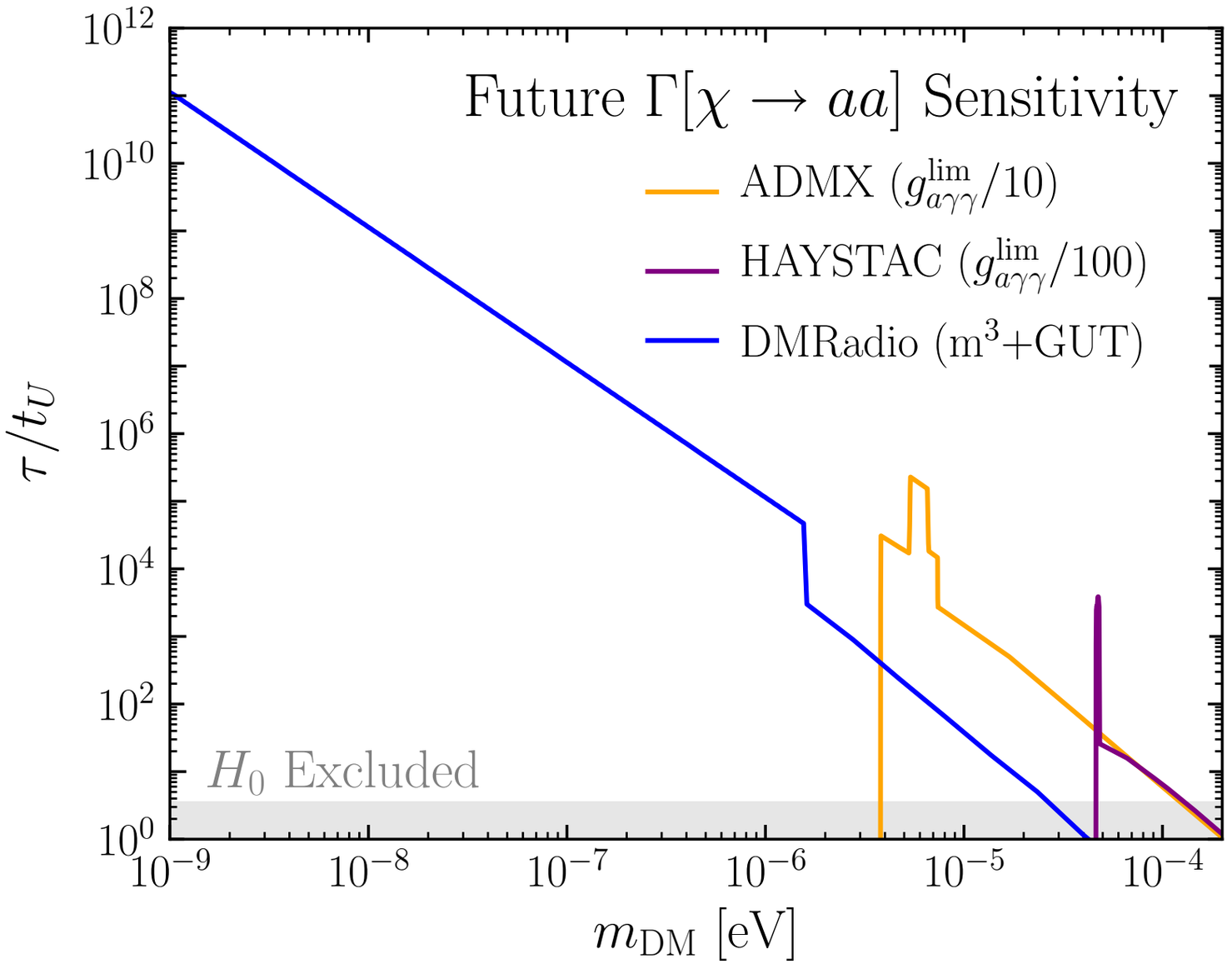
ADMX could already have a signal on disk - working with the collaboration to implement the search

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]

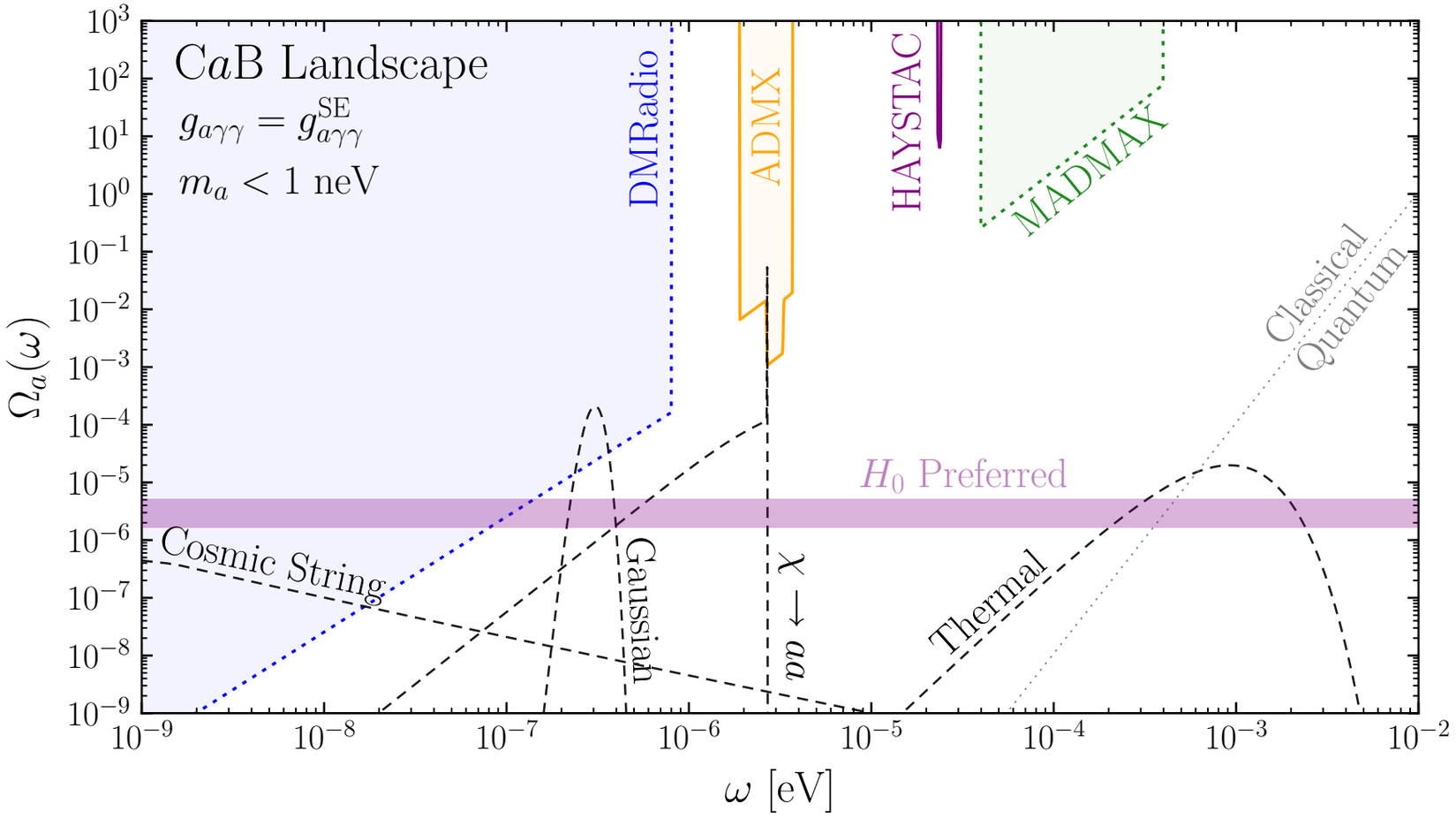
Dark Matter Decay Sensitivity



[Dror, NLR, Murayama 2021]

Summary

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

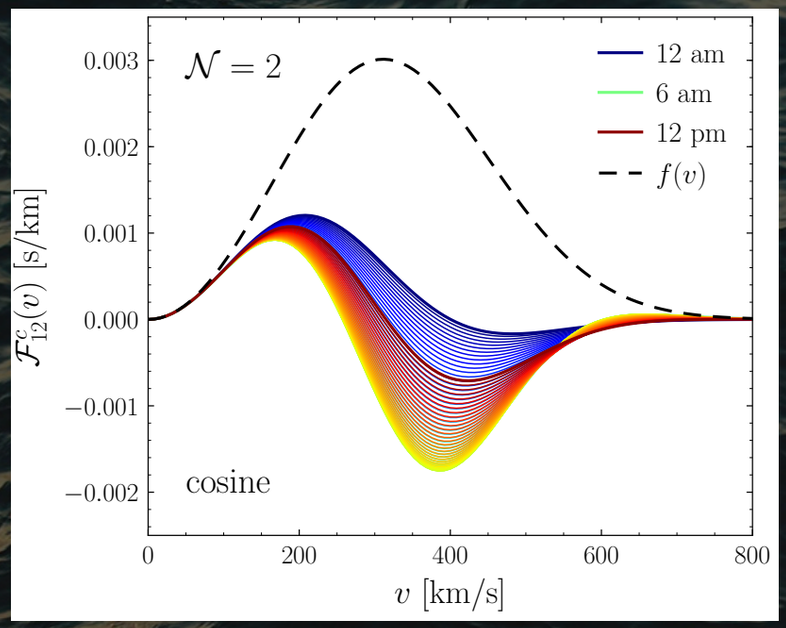


[Dror, NLR, Murayama 2021]

Conclusion

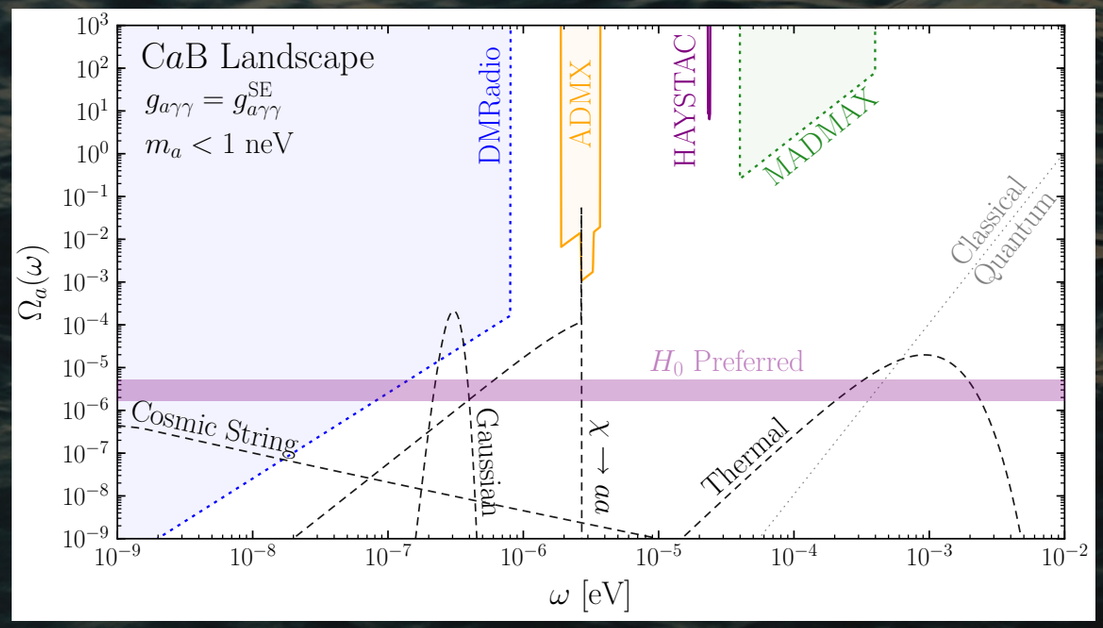
Dark Matter Interferometry

2009.14201 w/ Foster, Kahn, Nguyen, Safdi



The Cosmic Axion Background

2101.09287 w/ Dror, Murayama



Backup Slides

Stream Localization

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

- 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

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

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

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

[Dror, NLR, Murayama 2021]

Daily Modulation

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

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

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

Effective Charge

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

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

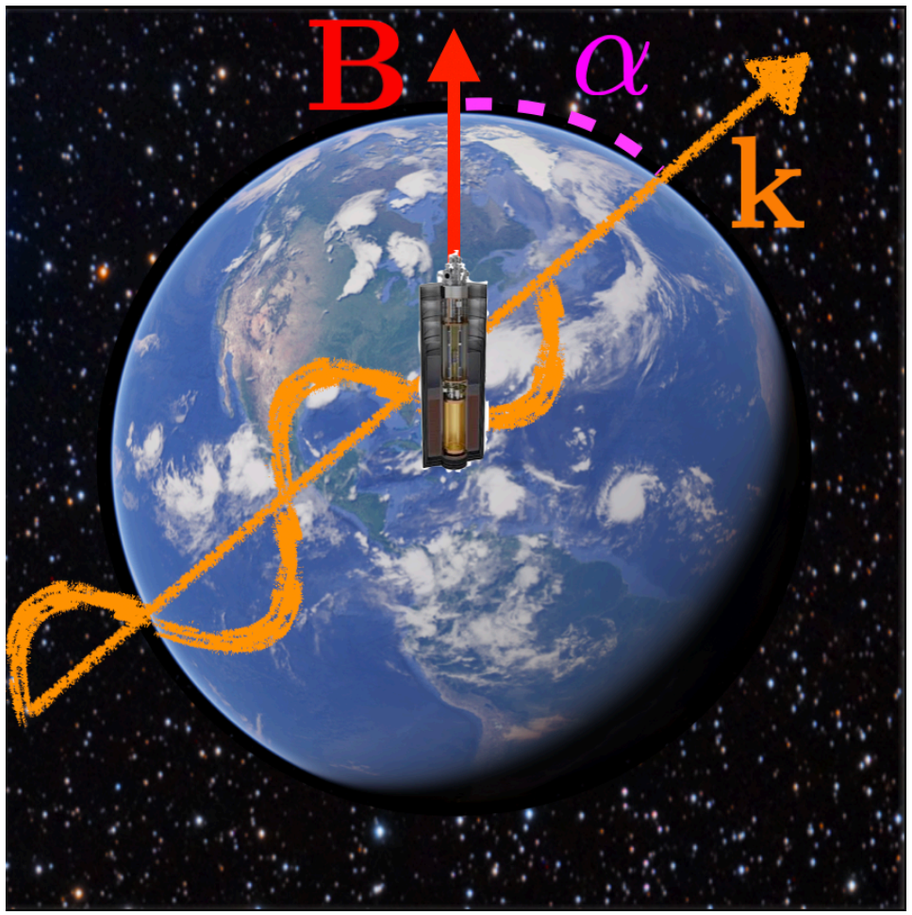
Effective Current

[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]

THE COSMIC AXION BACKGROUND

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]

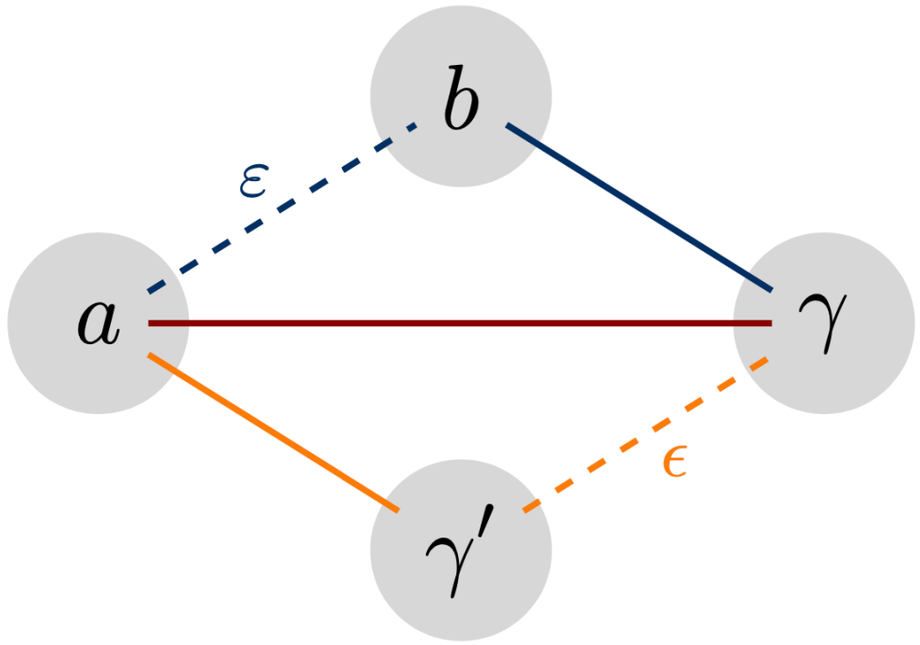
Dark Matter Decaying to Axions

example model

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

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





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

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

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

Slide courtesy of Jeff Dror

[Dror, NLR, Murayama 2021]

Parametric Resonance

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

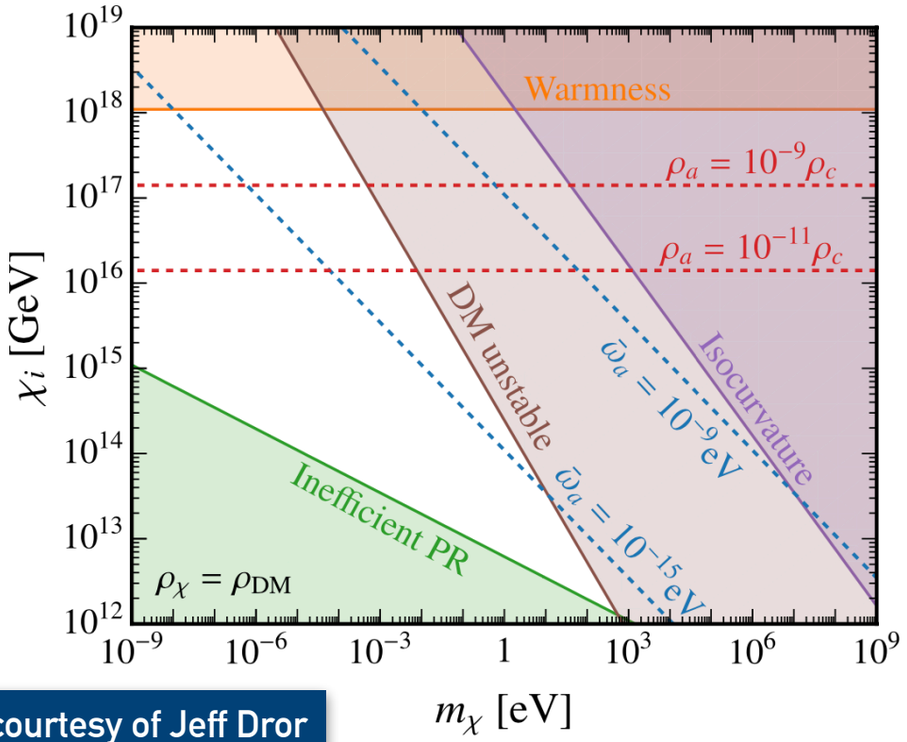
Oscillations when
$m_\chi^{\rm eff}(\chi_i) \simeq \lambda \chi_i \sim H$

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

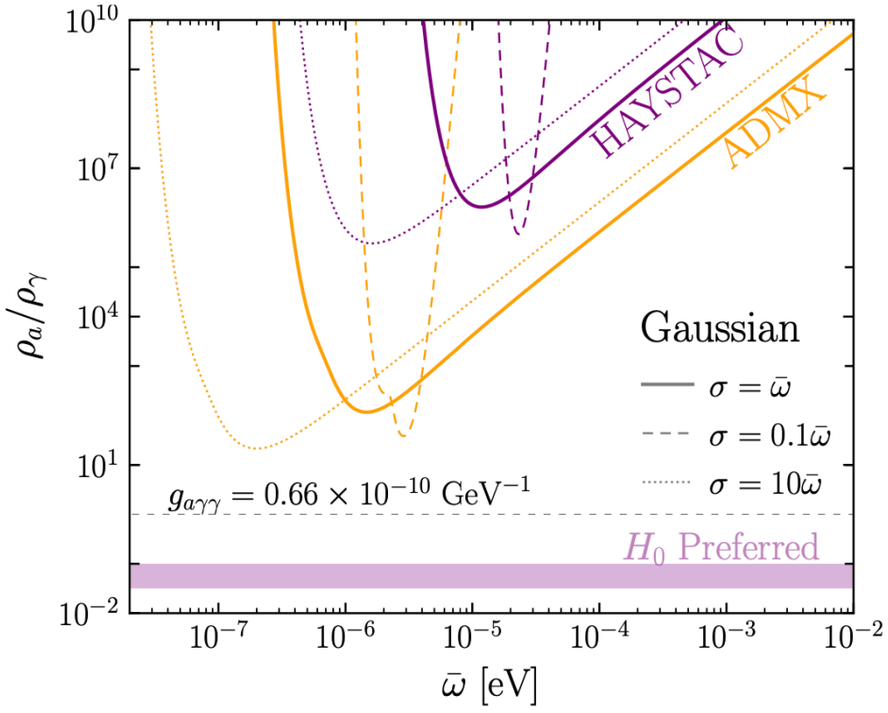
Energy density:
$$\Omega_a \sim 3 \times 10^{-7} \left(\frac{\chi_i}{M_{\rm Pl}} \right)^2$$

detectable?

Assume χ dark matter



Slide courtesy of Jeff Dror



[Dror, NLR, Murayama 2021]