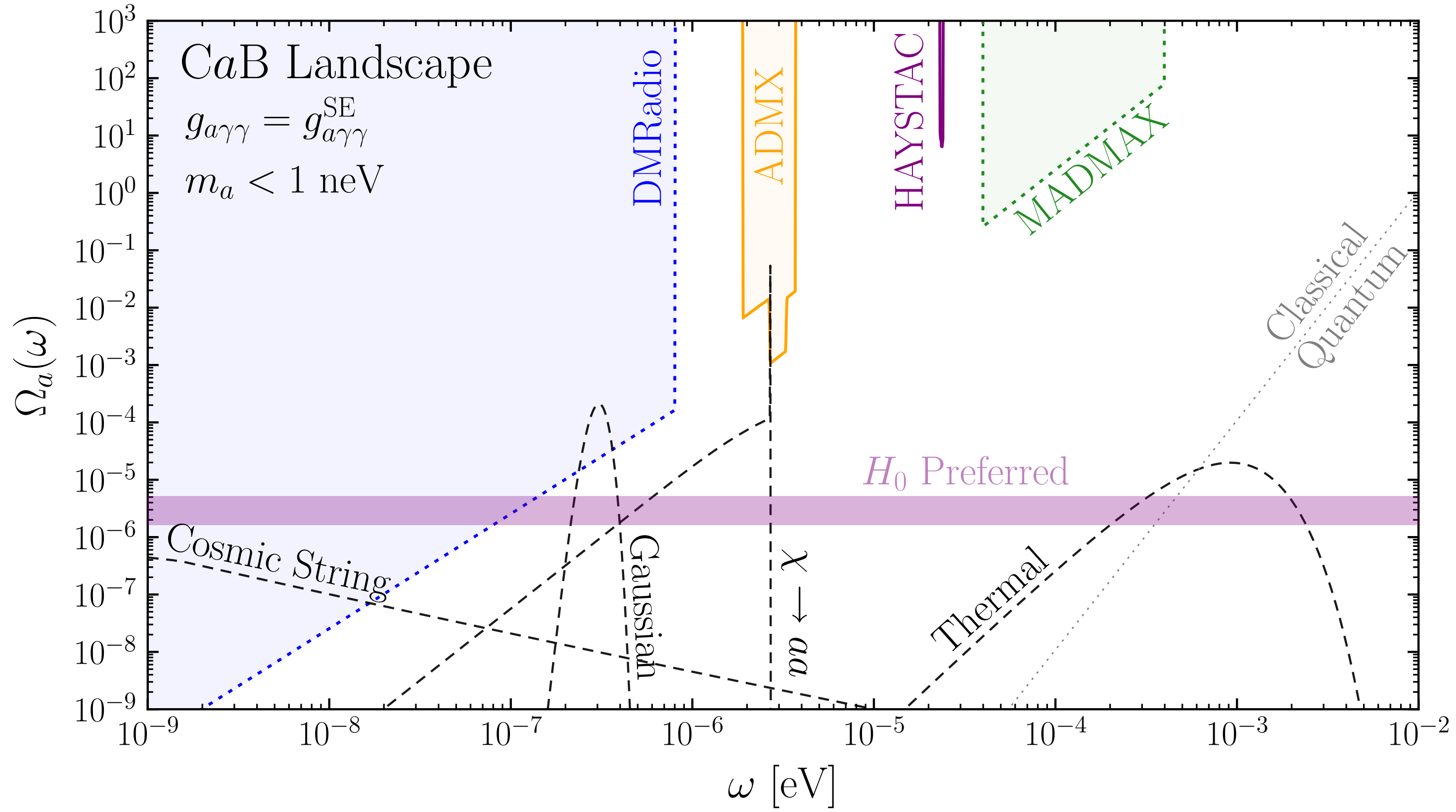
The Cosmic Axion Background

NICK RODD | CMB-S4 COLLABORATION MEETING | 10 AUGUST 2021



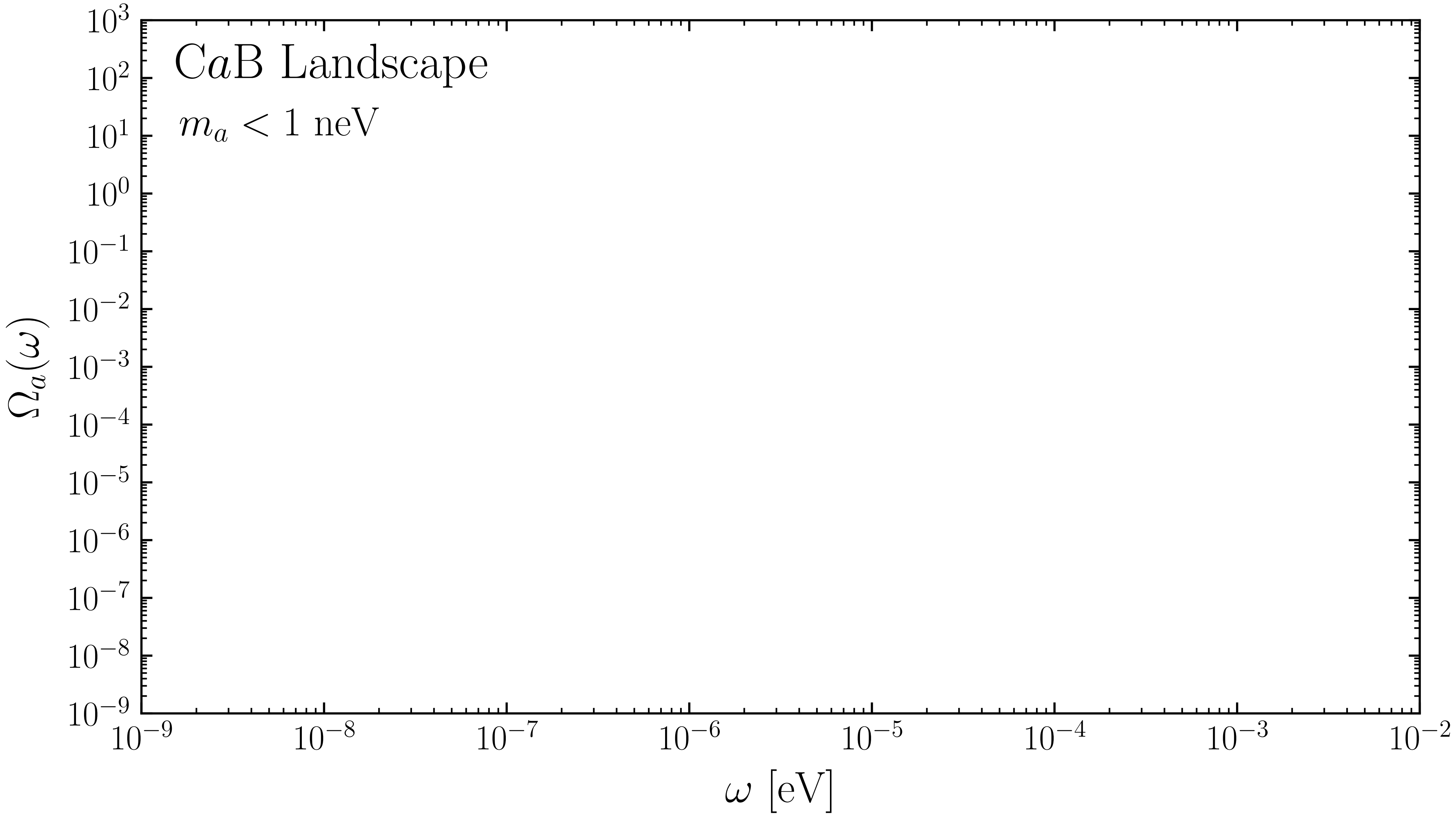
PRD 2021 (Editors' Suggestion) 2101.09287
w/ Jeff Dror & Hitoshi Murayama

The Cosmic Axion Background

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

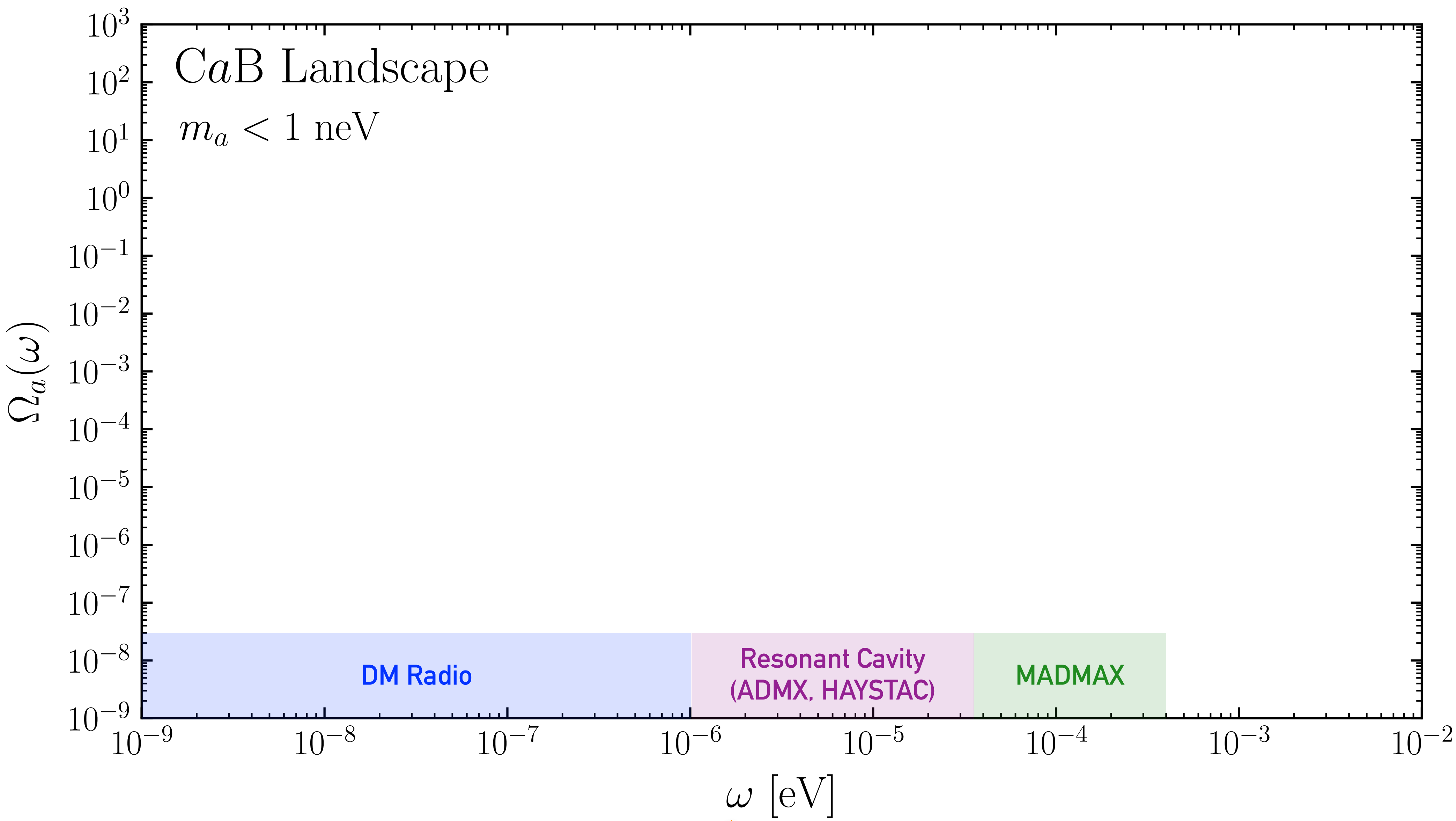
[Dror, NLR, Murayama 2021]

Landscape



[Dror, NLR, Murayama 2021]

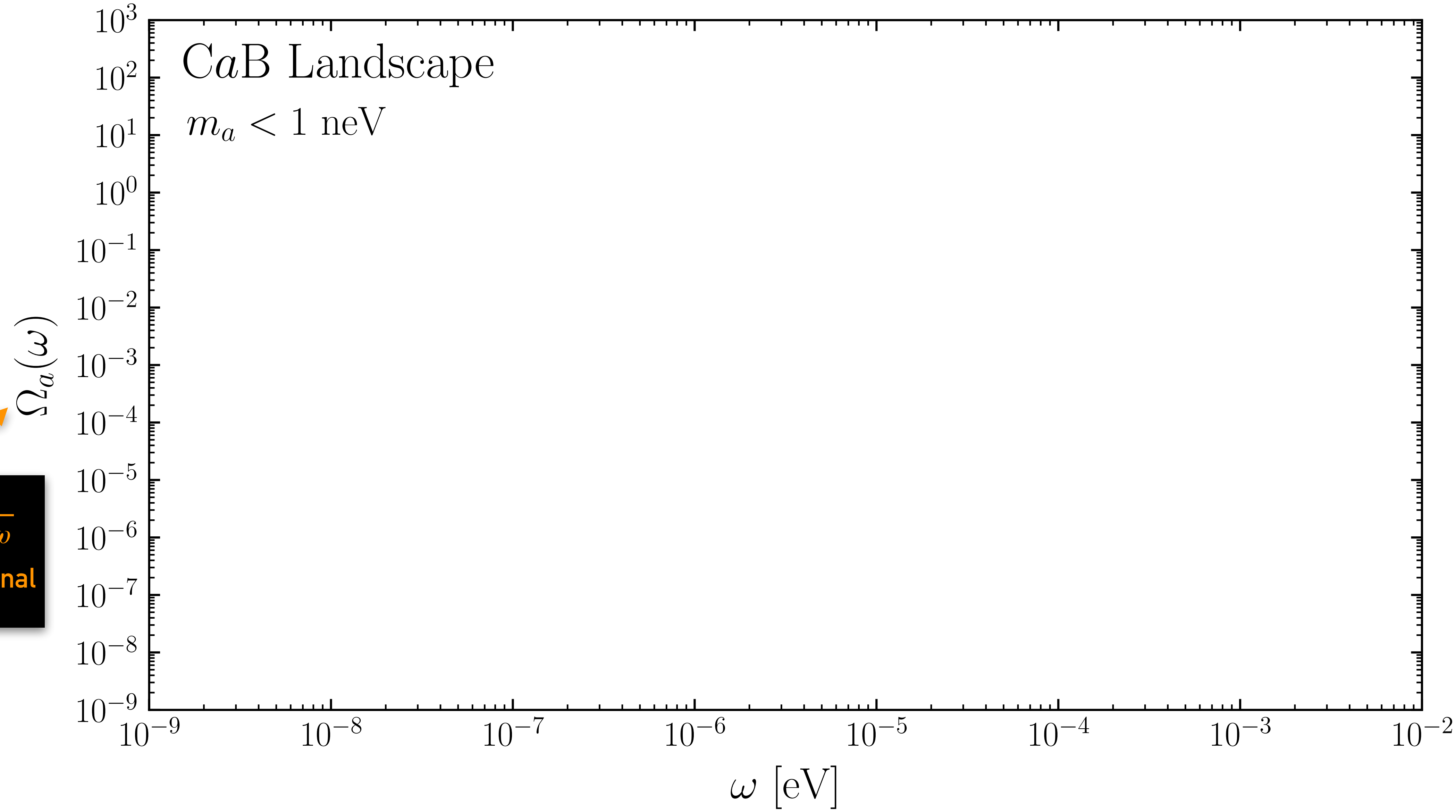
Landscape



Relativistic axion frequency

[Dror, NLR, Murayama 2021]

Landscape

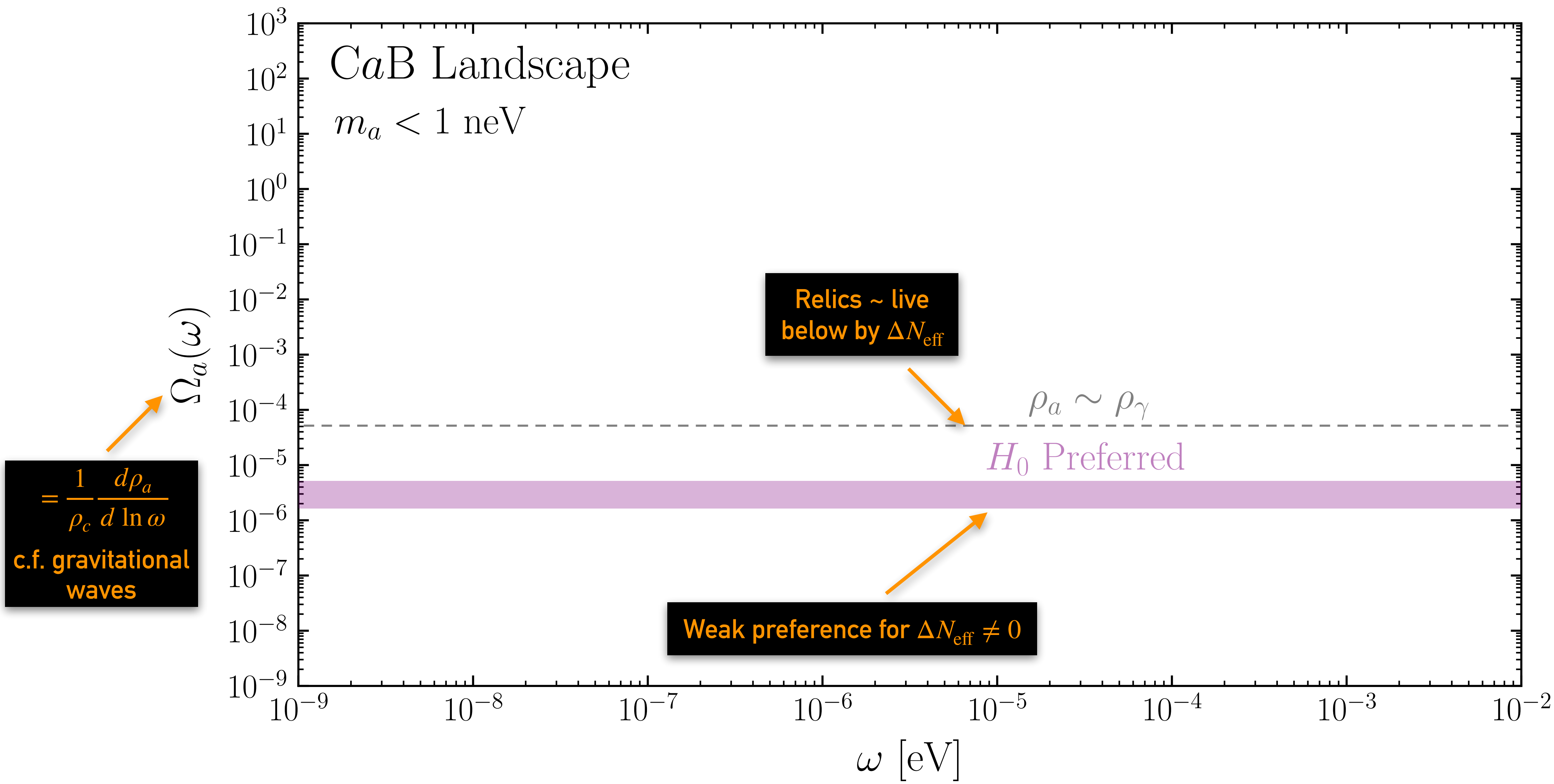


$= \frac{1}{\rho_c} \frac{d\rho_a}{d \ln \omega}$

c.f. gravitational waves

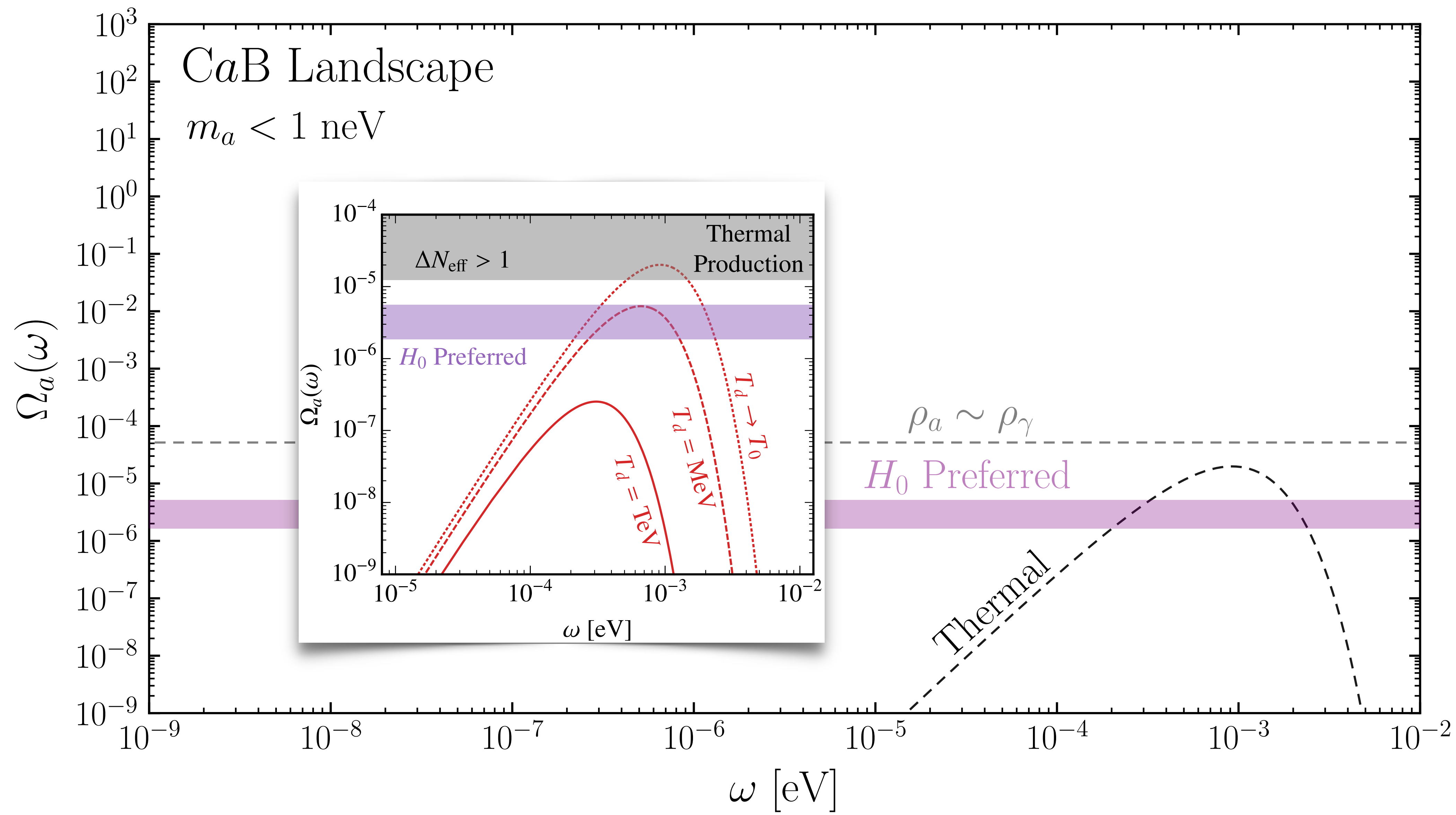
[Dror, NLR, Murayama 2021]

Landscape



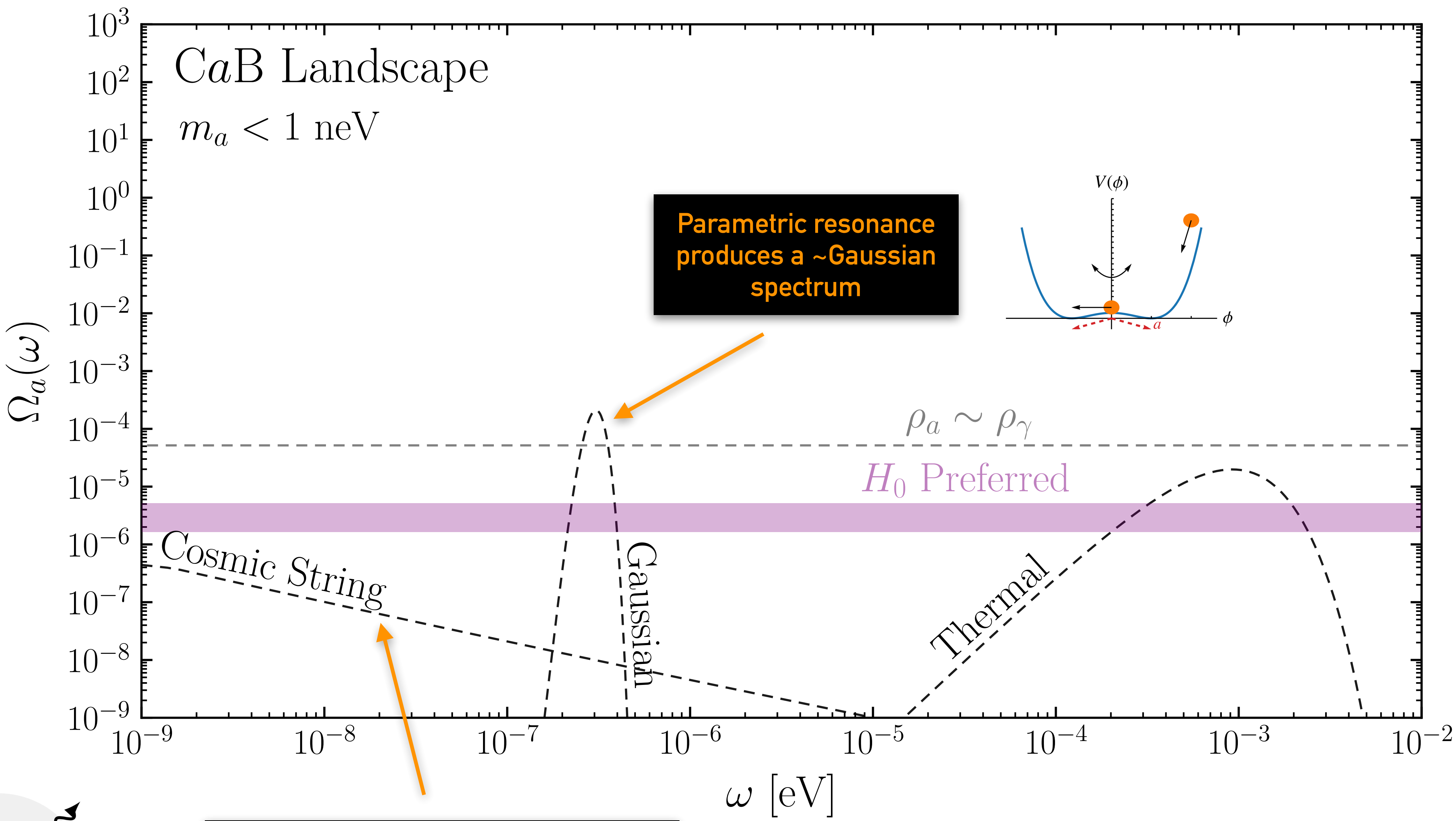
[Dror, NLR, Murayama 2021]

Landscape

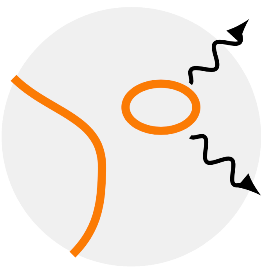


[Dror, NLR, Murayama 2021]

Landscape



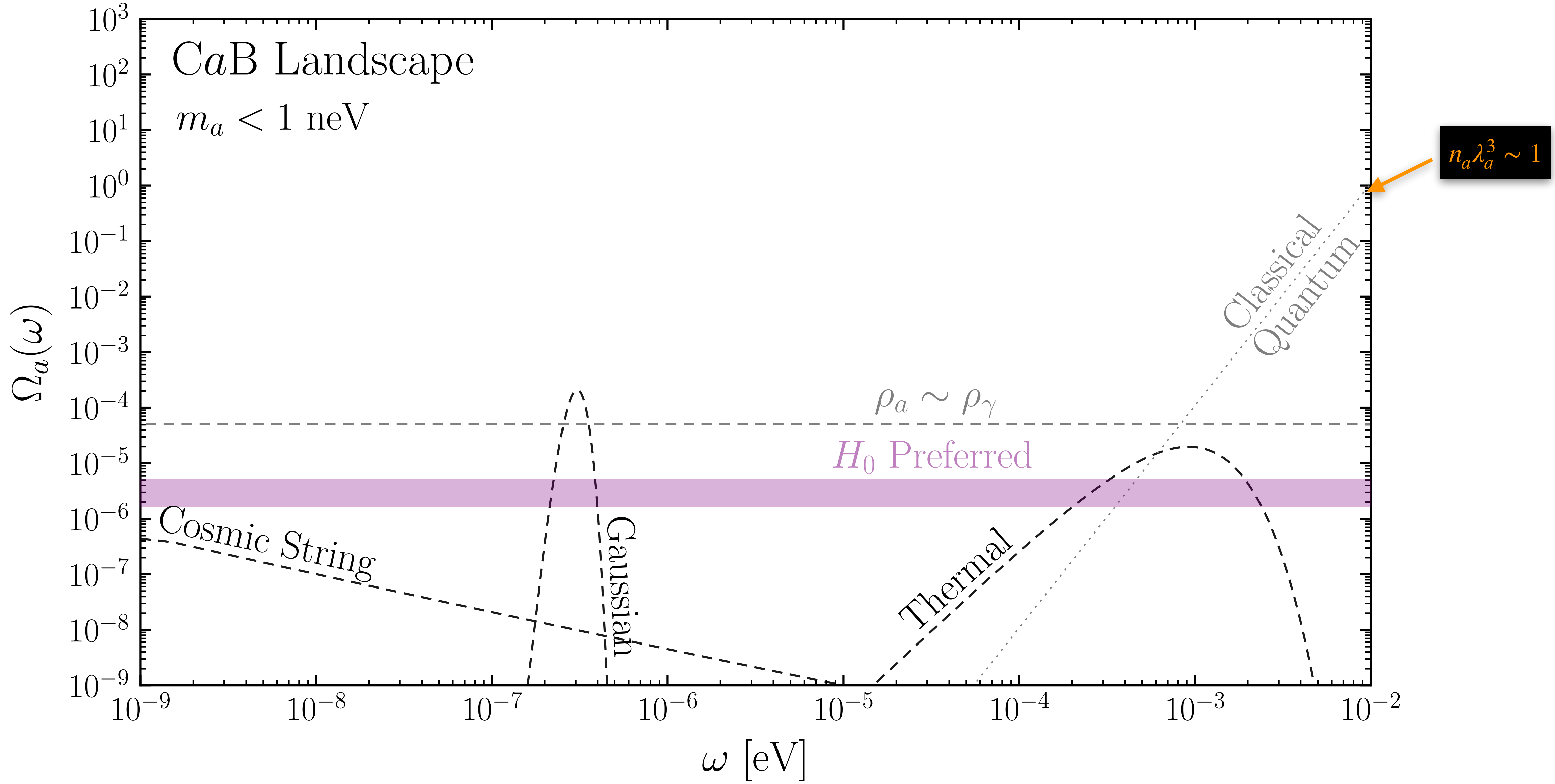
Parametric resonance produces a ~Gaussian spectrum



Cosmic string network will emit axions (exact spectrum an active debate, we follow [Gorghetto+ 2020])

[Dror, NLR, Murayama 2021]

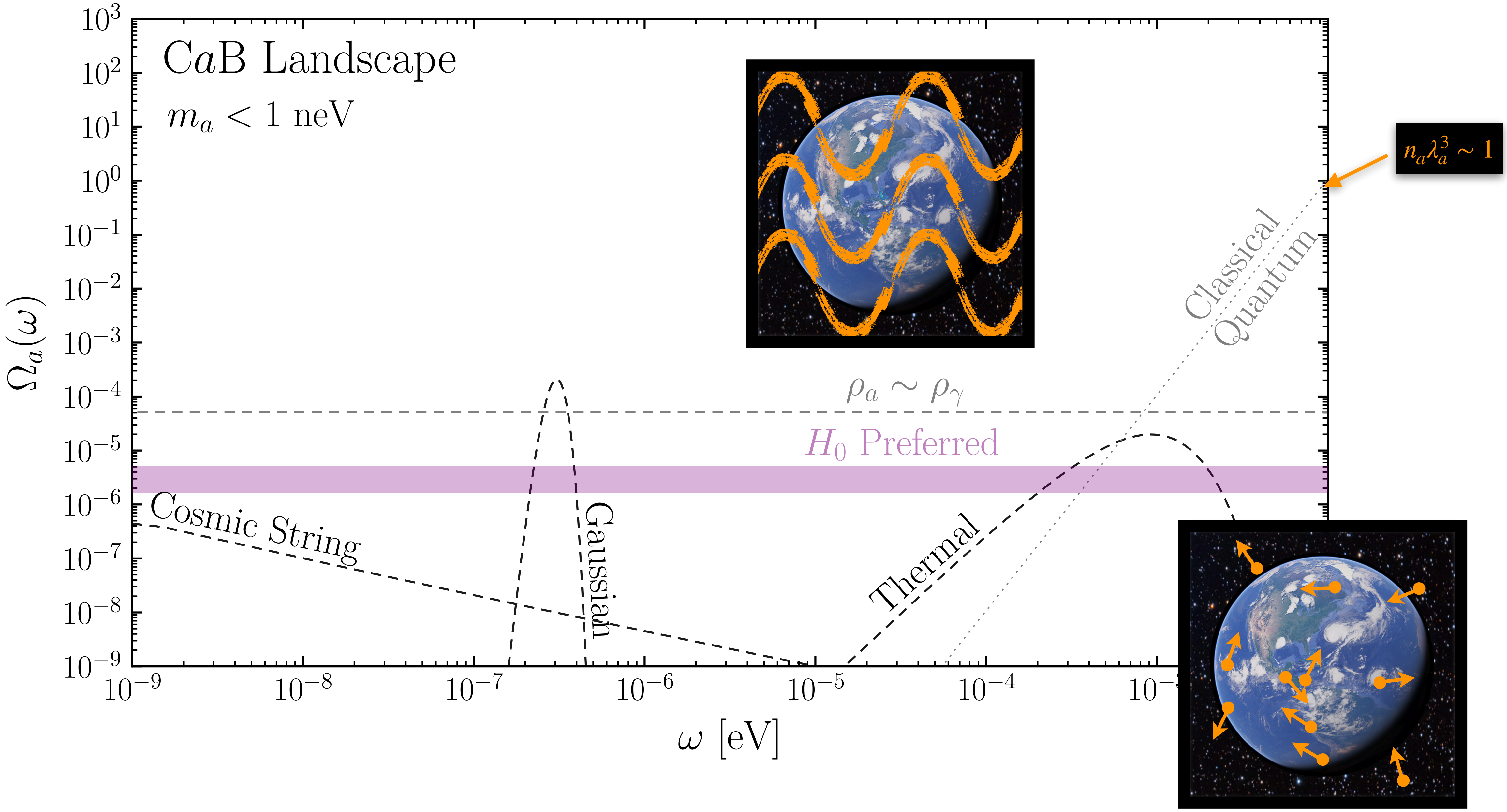
Landscape



[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 frequency distribution $p(\omega)$

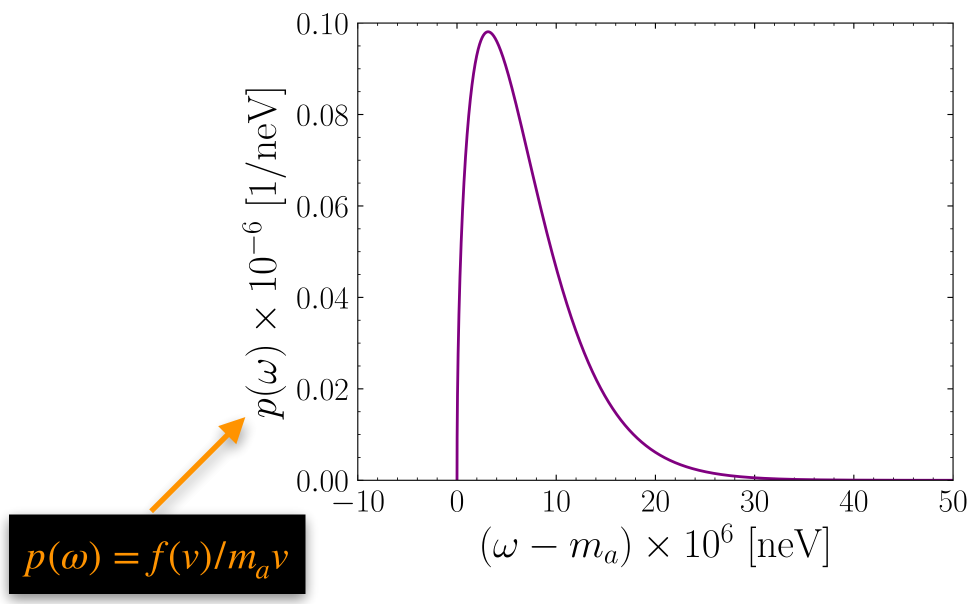
Random phase

[Dror, NLR, Murayama 2021]

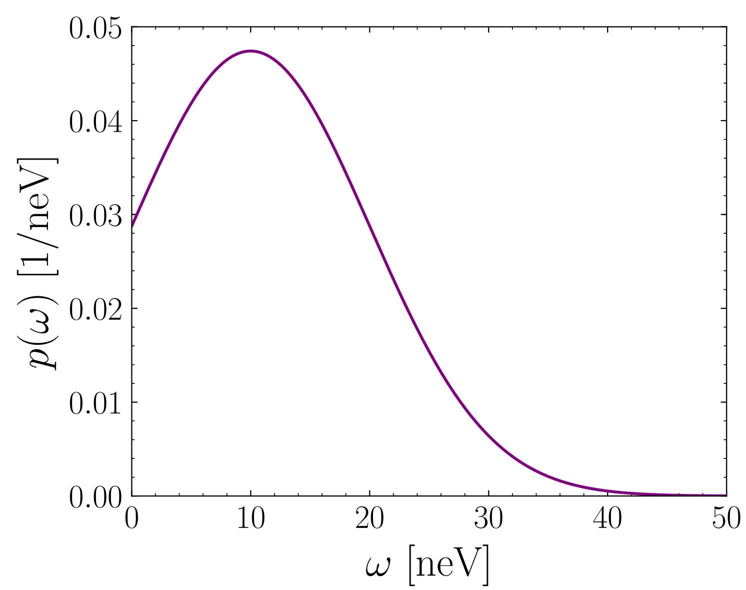
Rough Sensitivity

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

Dark Matter



CaB



[Dror, NLR, Murayama 2021]

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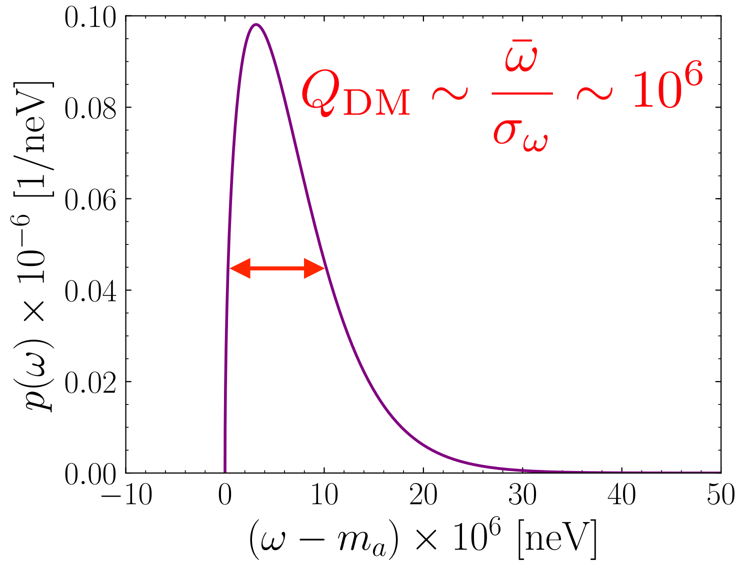
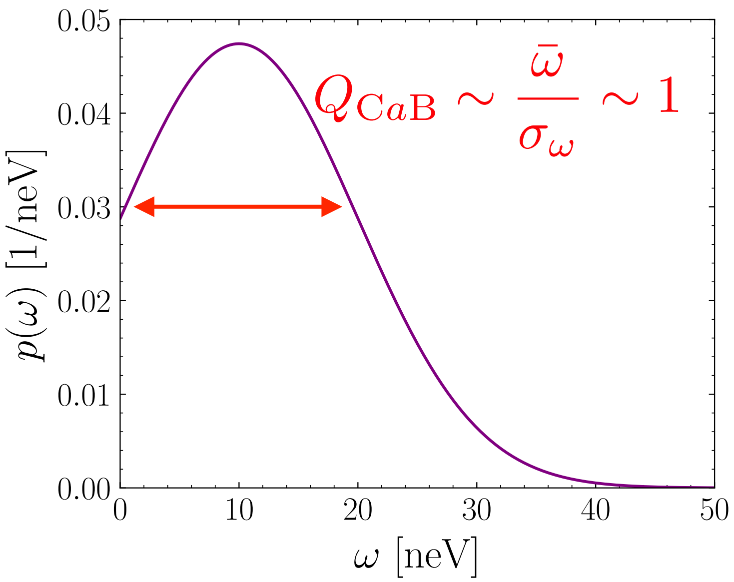
Dark Matter



CaB



[Dror, NLR, Murayama 2021]

Rough Sensitivity

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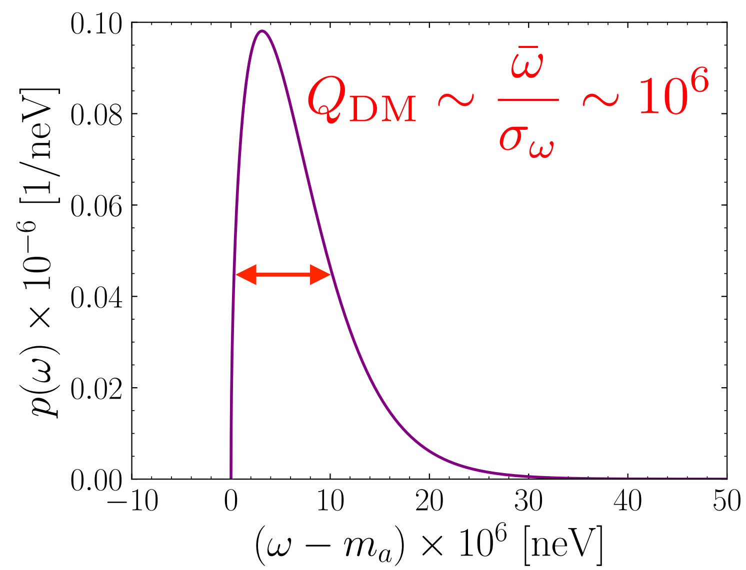
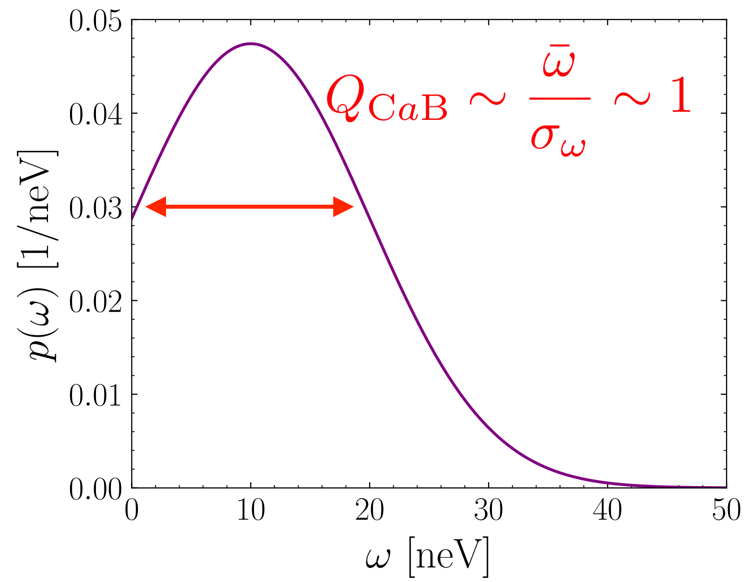


C*a*B



Much broader signal - existing searches would throw out as background

[Dror, NLR, Murayama 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

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

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 (e.g. CAST)

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

[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]

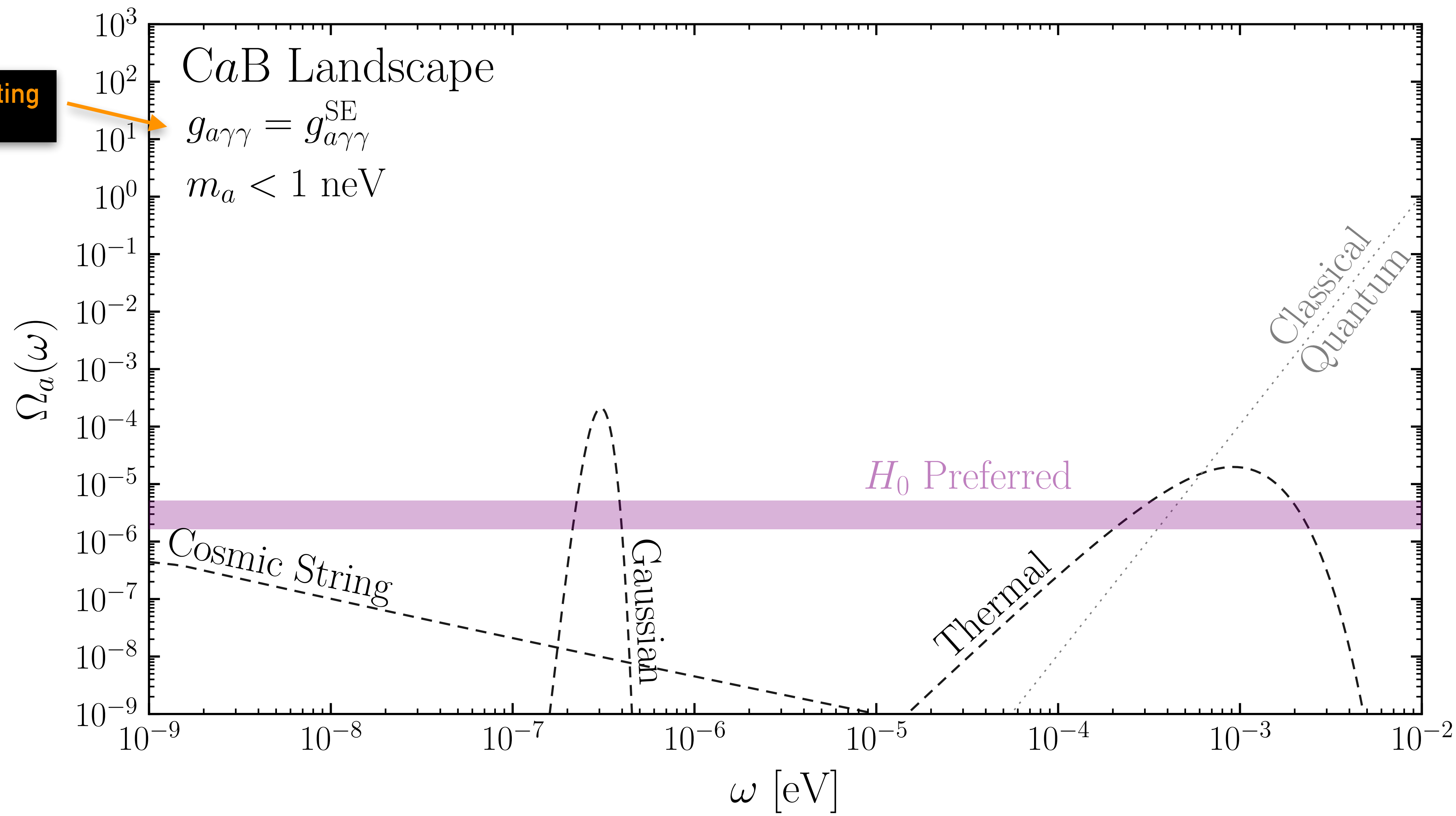
Rough Sensitivity

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

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

[Dror, NLR, Murayama 2021]

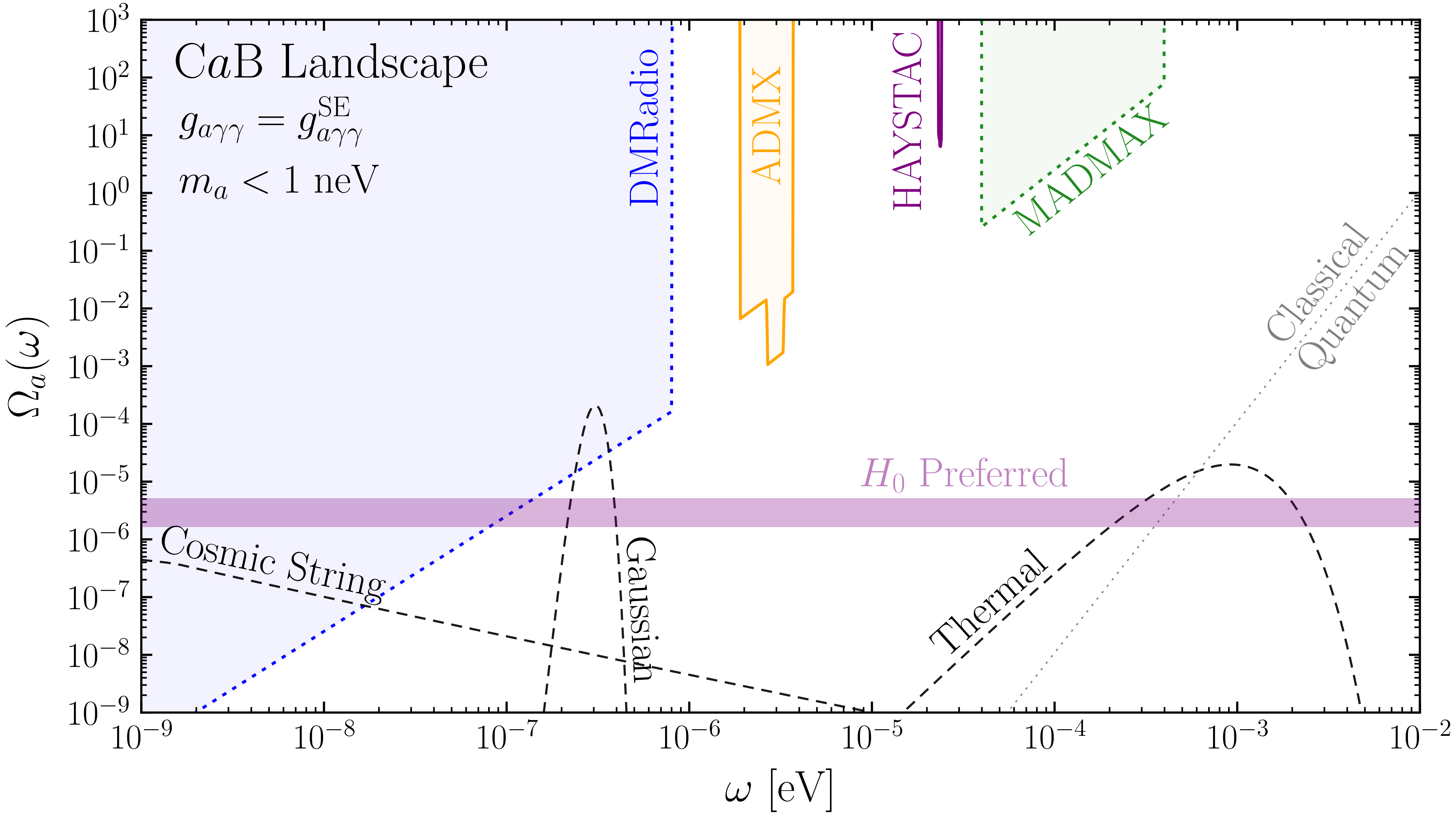
Experimental Landscape



Saturate existing bounds

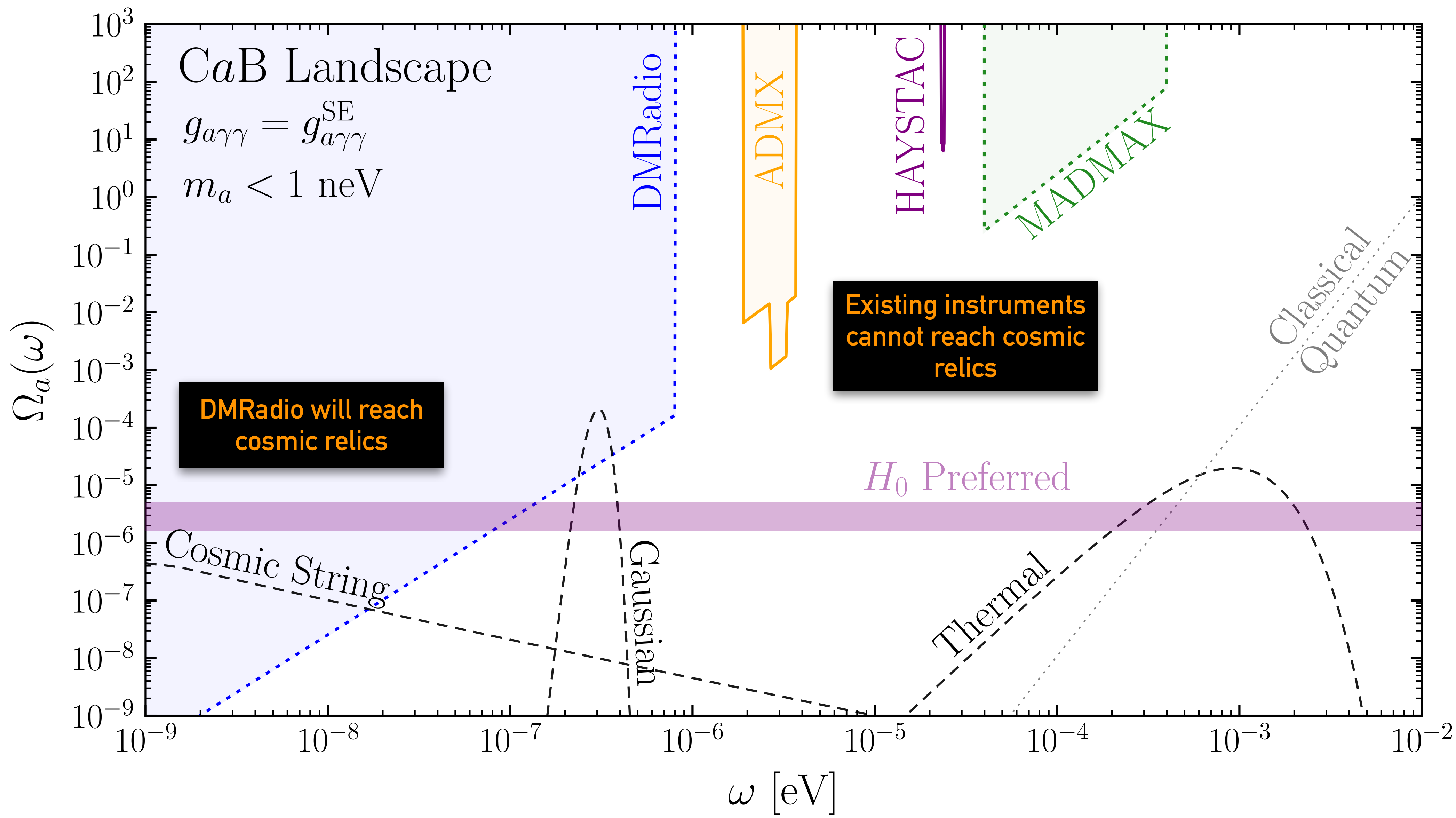
[Dror, NLR, Murayama 2021]

Experimental Landscape



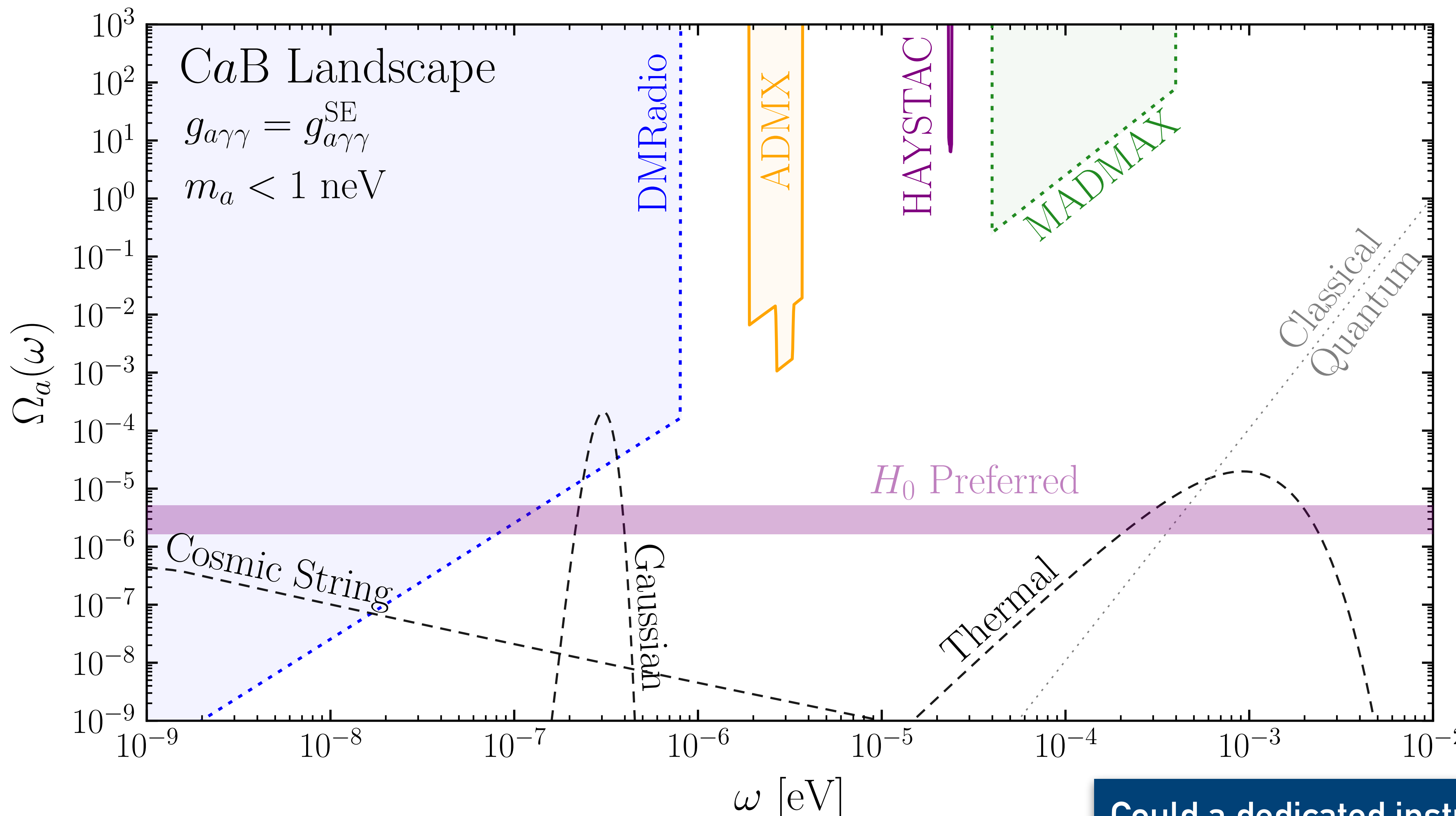
[Dror, NLR, Murayama 2021]

Experimental Landscape



[Dror, NLR, Murayama 2021]

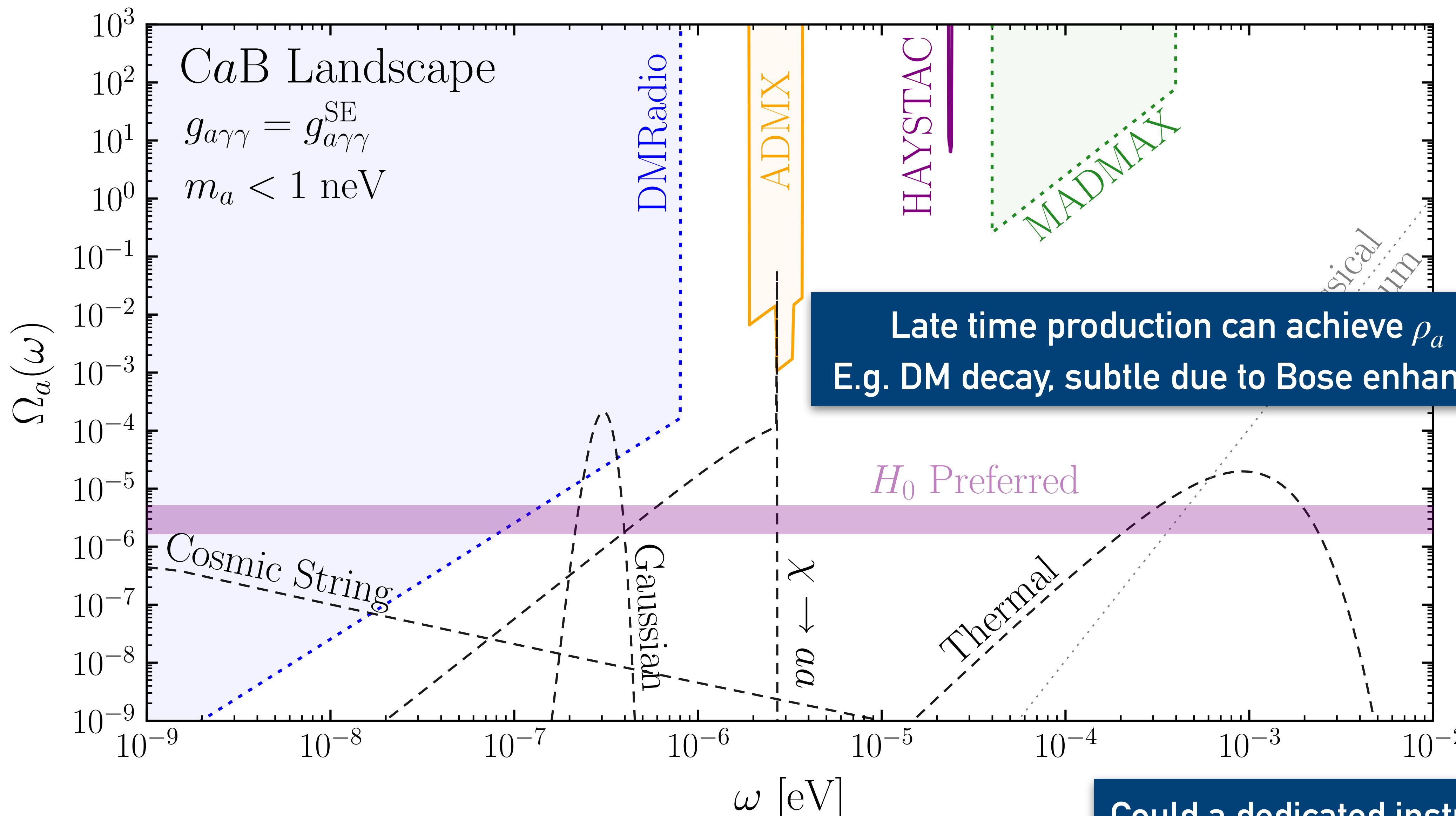
Future Directions



Could a dedicated instrument reach the thermal CaB?

[Dror, NLR, Murayama 2021]

Future Directions



Late time production can achieve $\rho_a > \rho_\gamma$
E.g. DM decay, subtle due to Bose enhancement

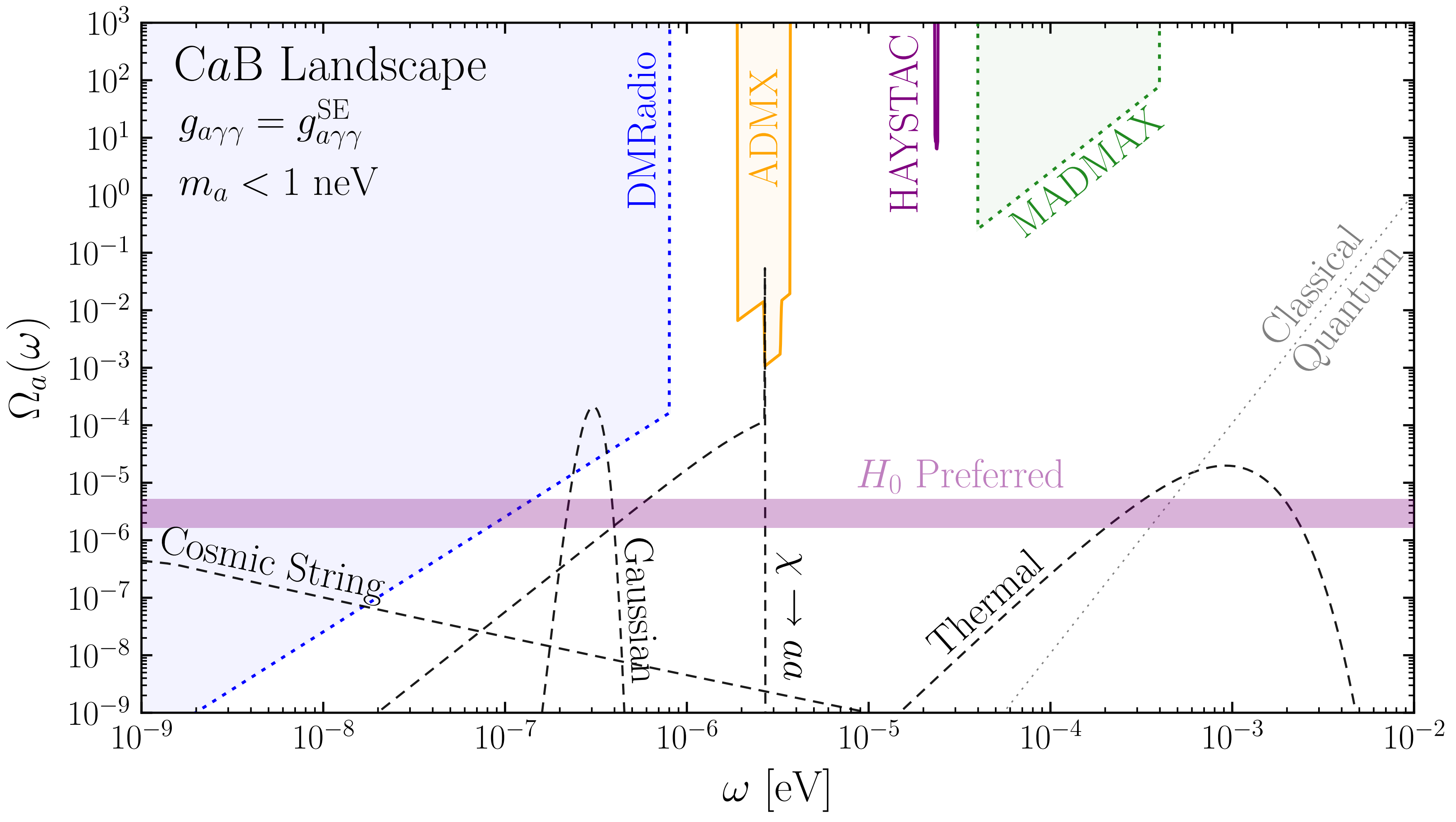
Could a dedicated instrument reach the thermal CaB?

For another late time production mechanism see [Eby+ 2106.14893]

[Dror, NLR, Murayama 2021]

Conclusion

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



Backup Slides

Motivation

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

Introduces corrections to Maxwell's equations

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

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

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

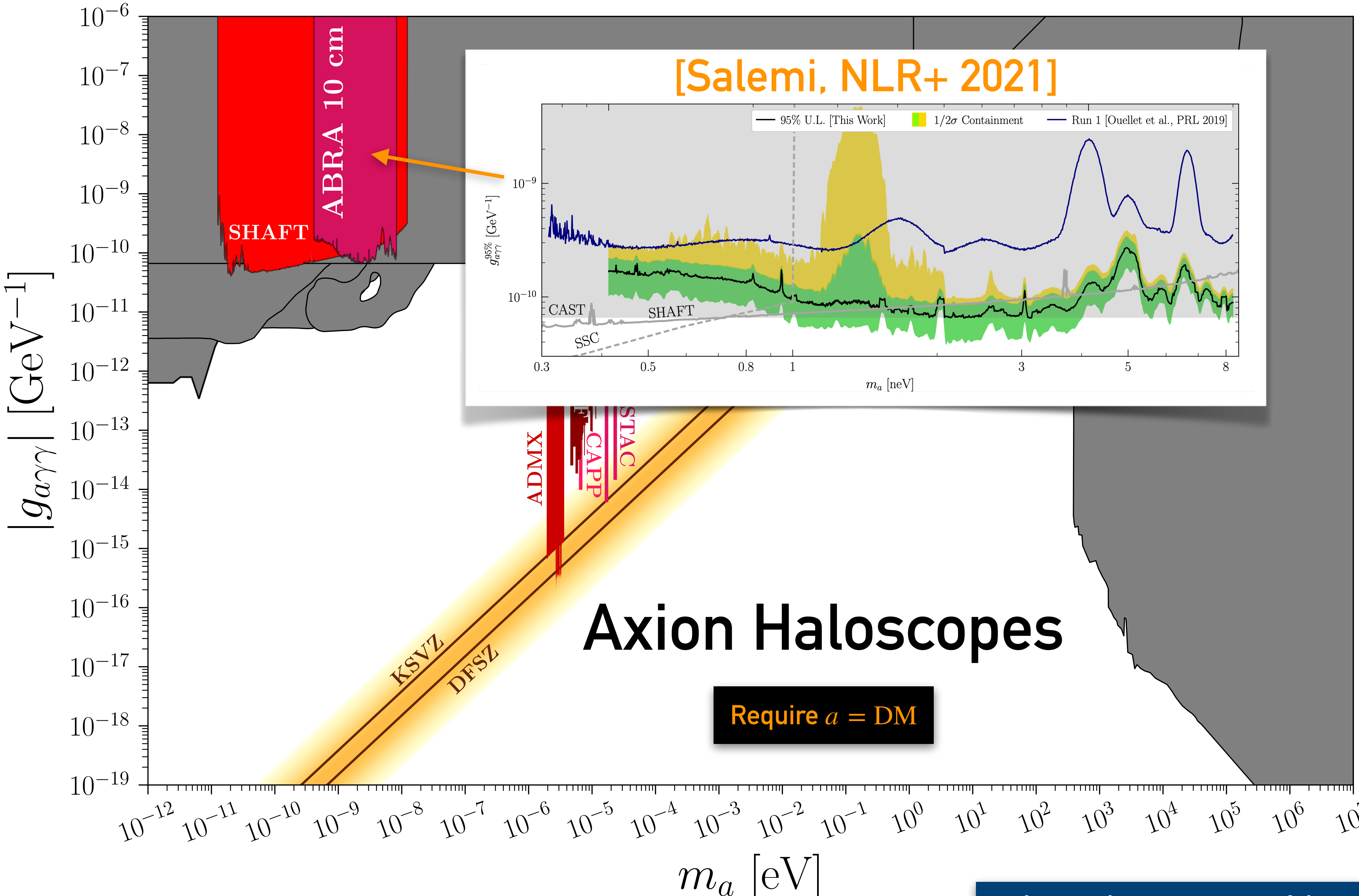
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J} - g_{a\gamma\gamma} (\mathbf{E} \times \nabla a - \mathbf{B} \partial_t a)$$

Suppressed for non-relativistic DM axions

Focus of axion DM searches

Motivation

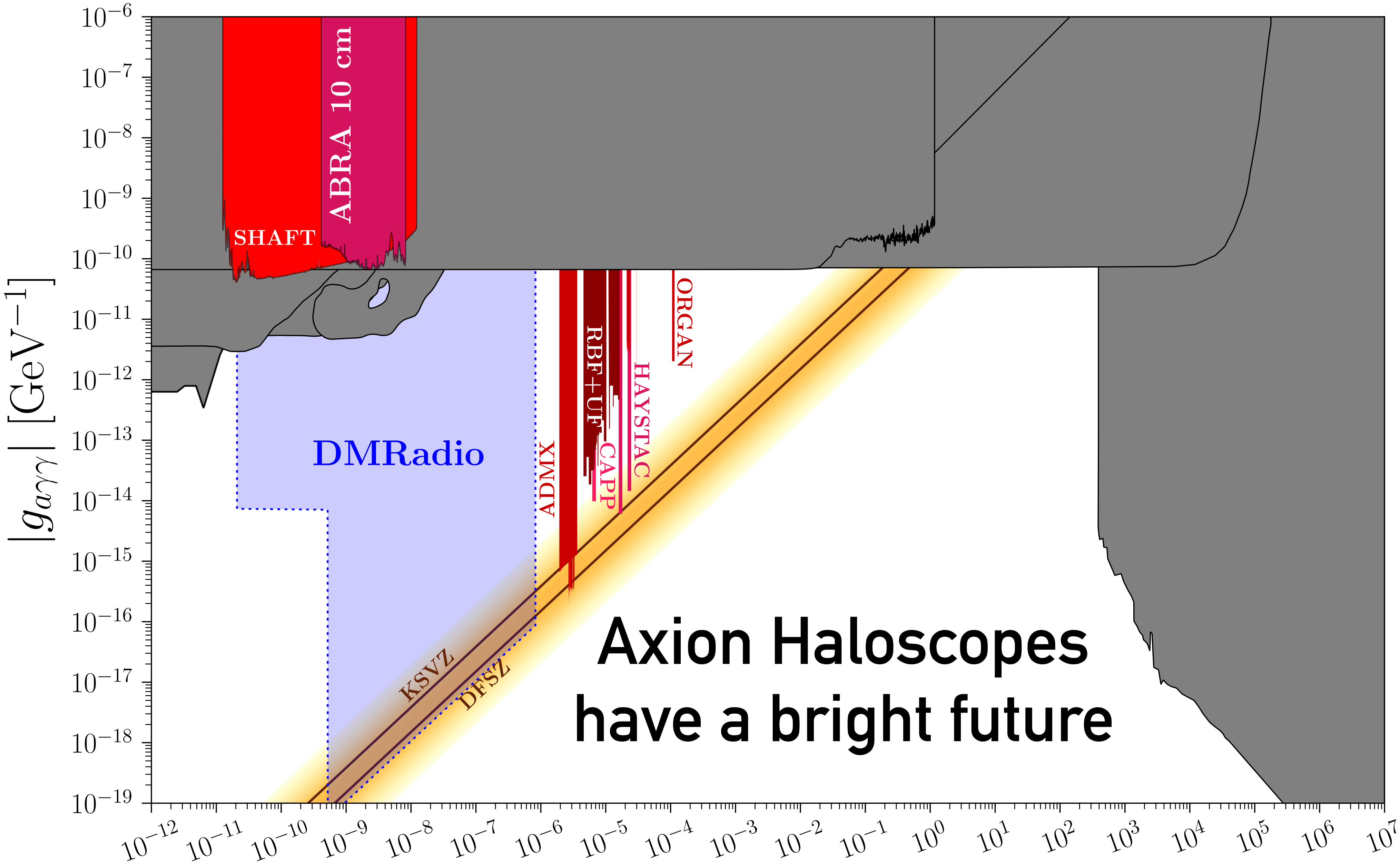
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a (F\tilde{F})$$



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

Motivation

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



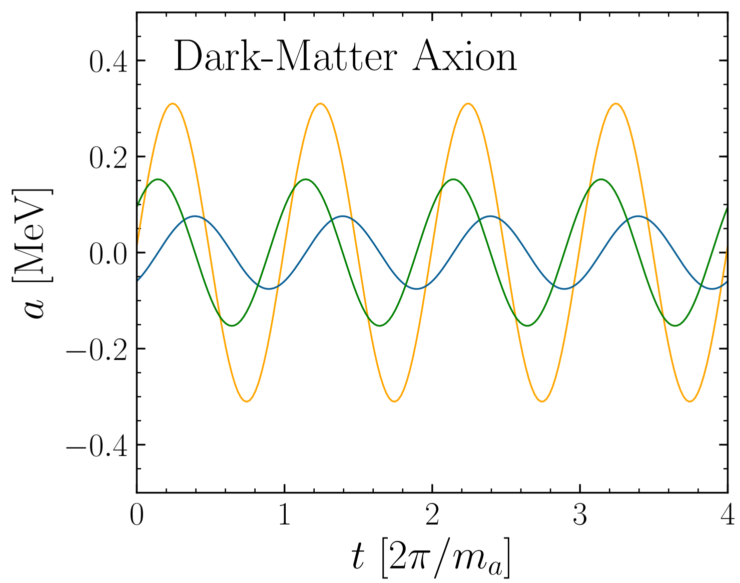
[Chaudhuri+ SNOWMASS LOI 2021]

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

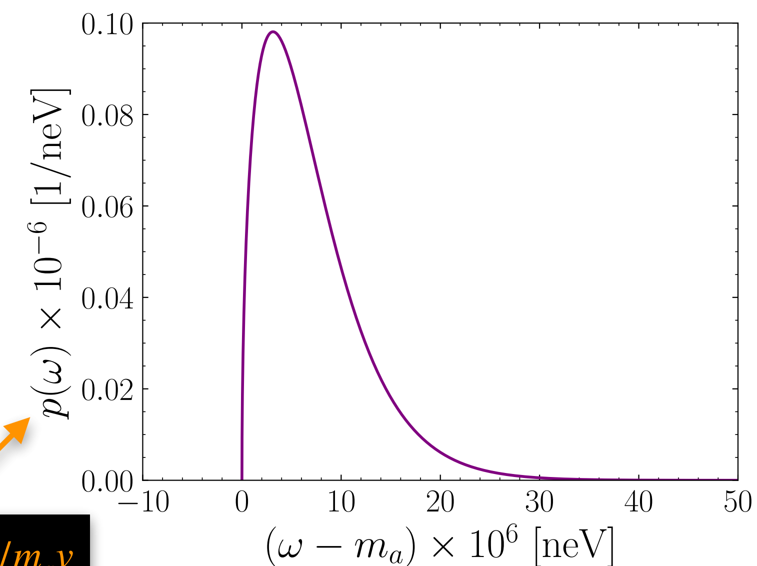
Rough Sensitivity

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

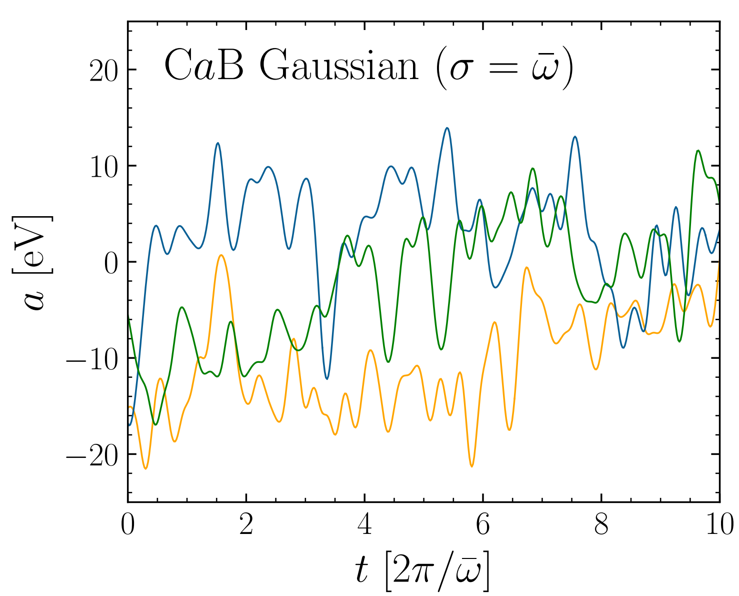
Dark Matter

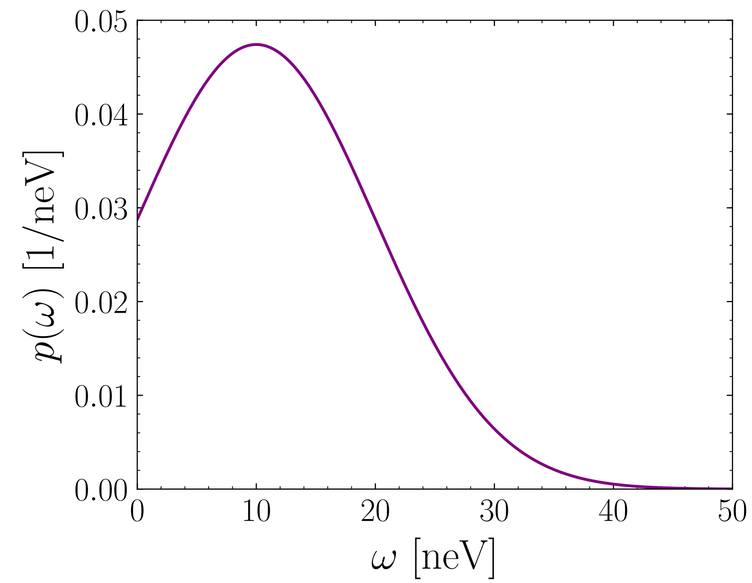


$p(\omega) = f(v)/m_a v$



CaB





[Dror, NLR, Murayama 2021]

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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[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

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

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

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

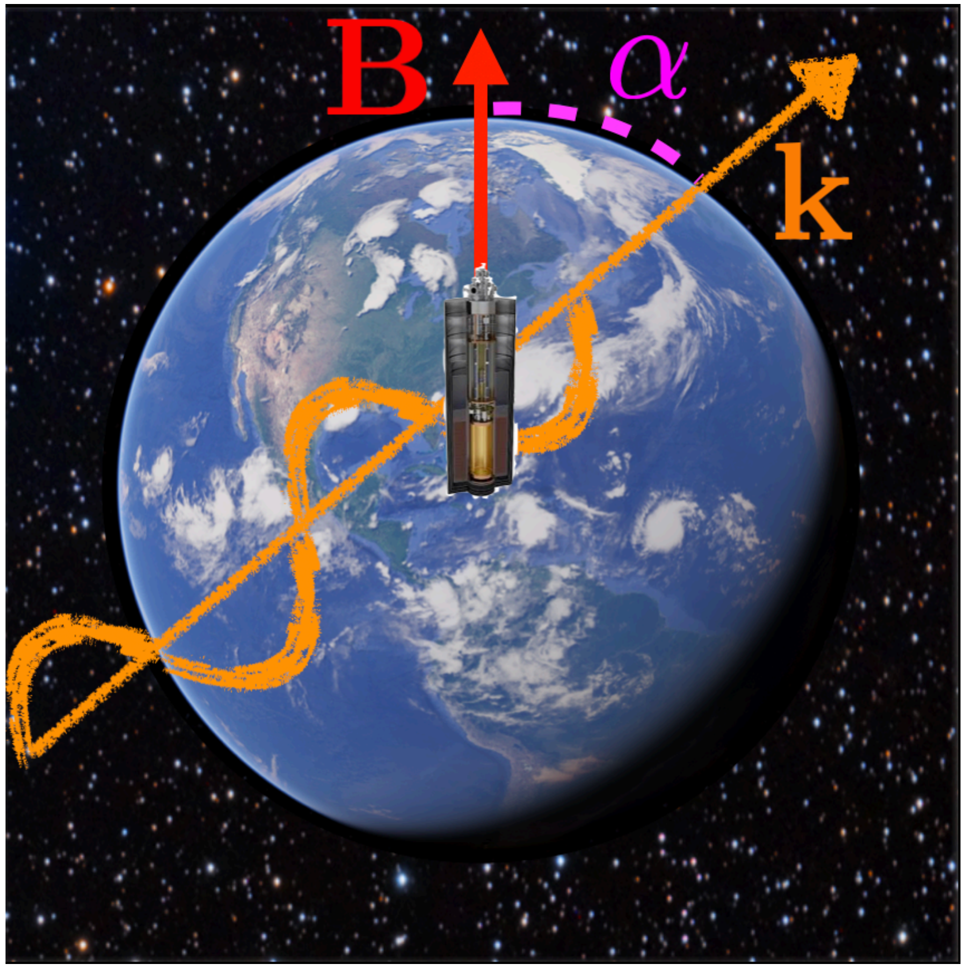
Effective Current

[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

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

Daily modulation
in the signal!

[Dror, NLR, Murayama 2021]

Bose Enhancement

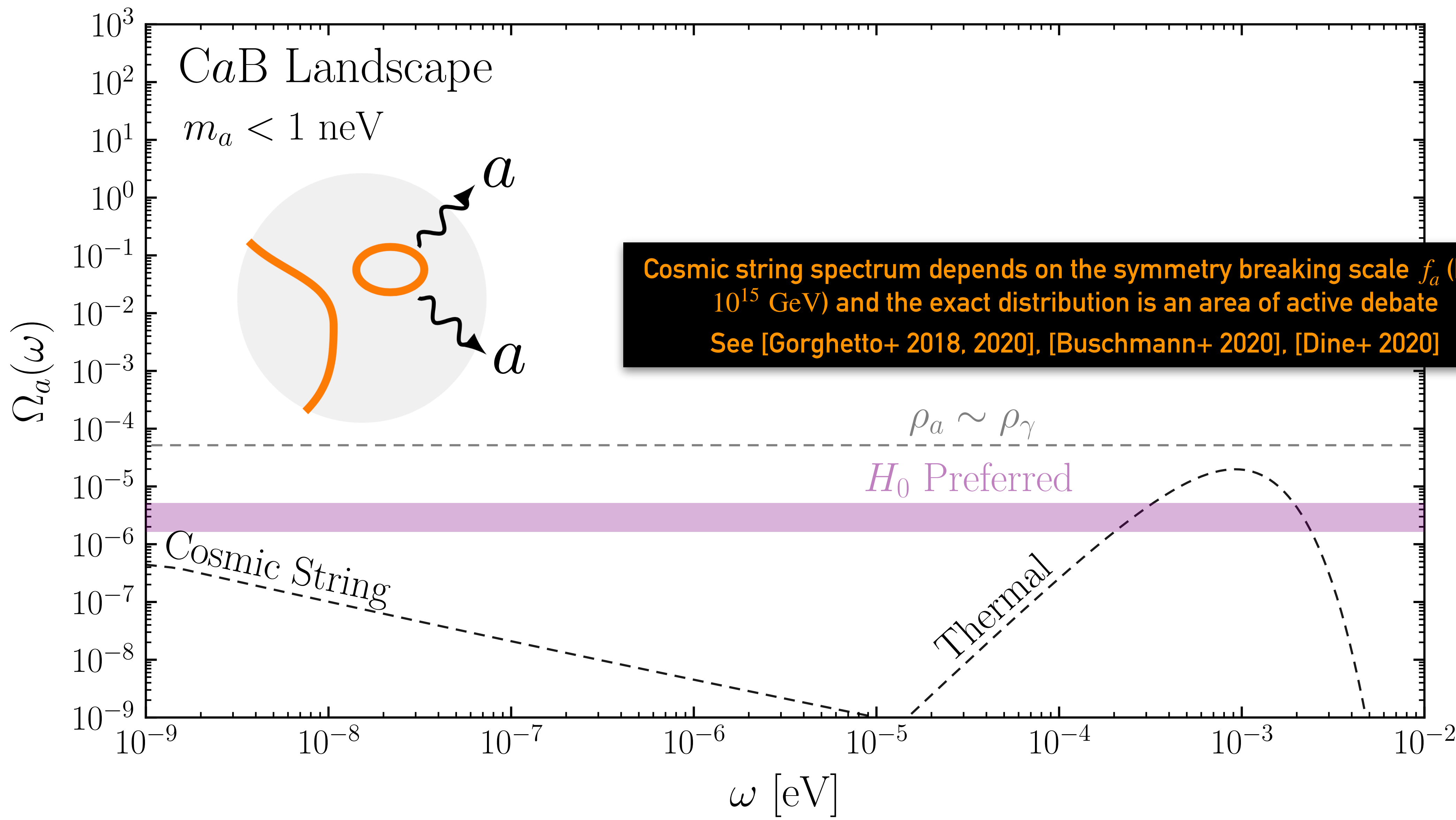
Relevant when $f_a \gg 1$

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

Large over the entire range we consider

[Dror, NLR, Murayama 2021]

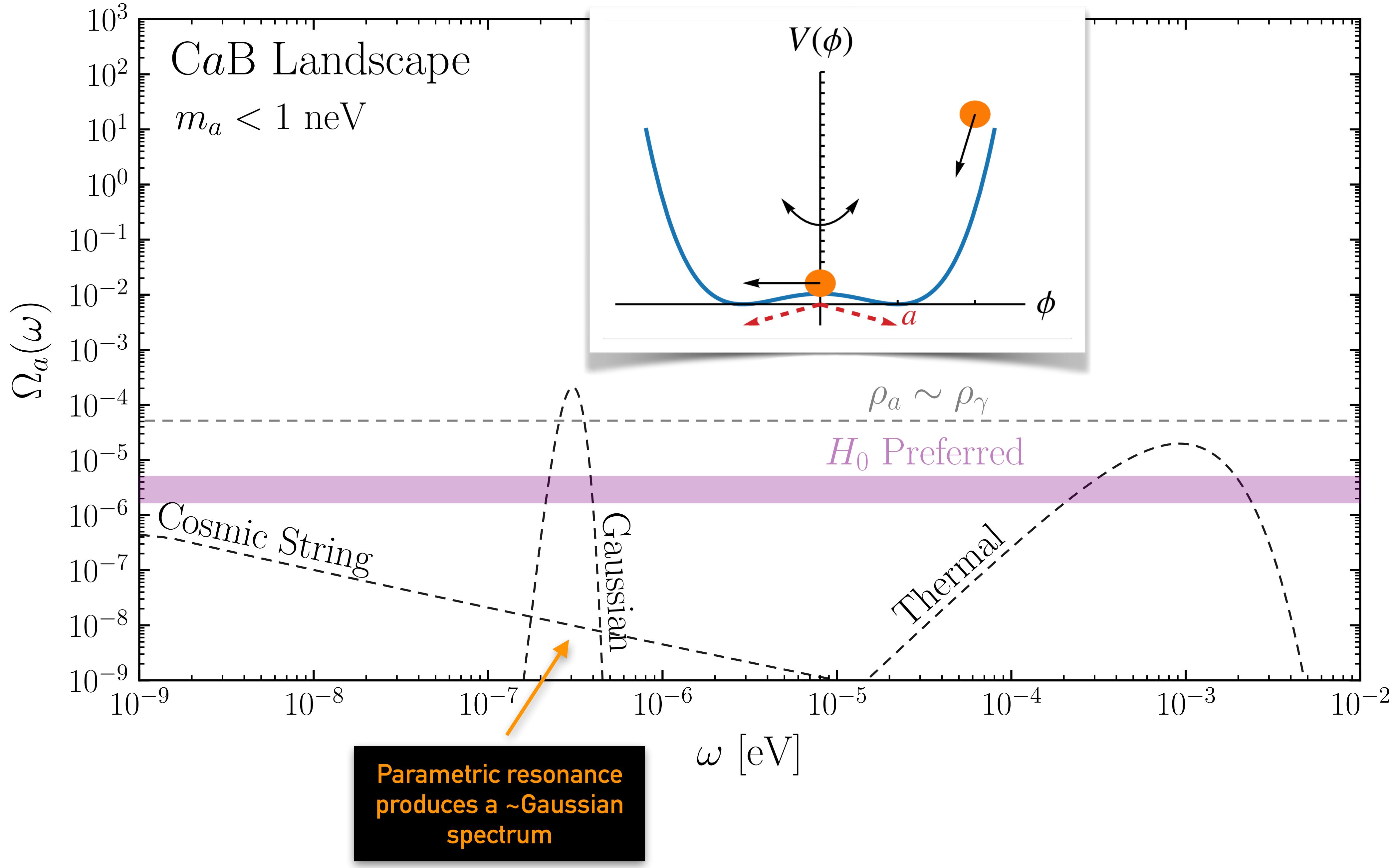
Landscape



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
See [Gorghetto+ 2018, 2020], [Buschmann+ 2020], [Dine+ 2020]

[Dror, NLR, Murayama 2021]

Landscape



[Dror, NLR, Murayama 2021]

Parametric Resonance

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

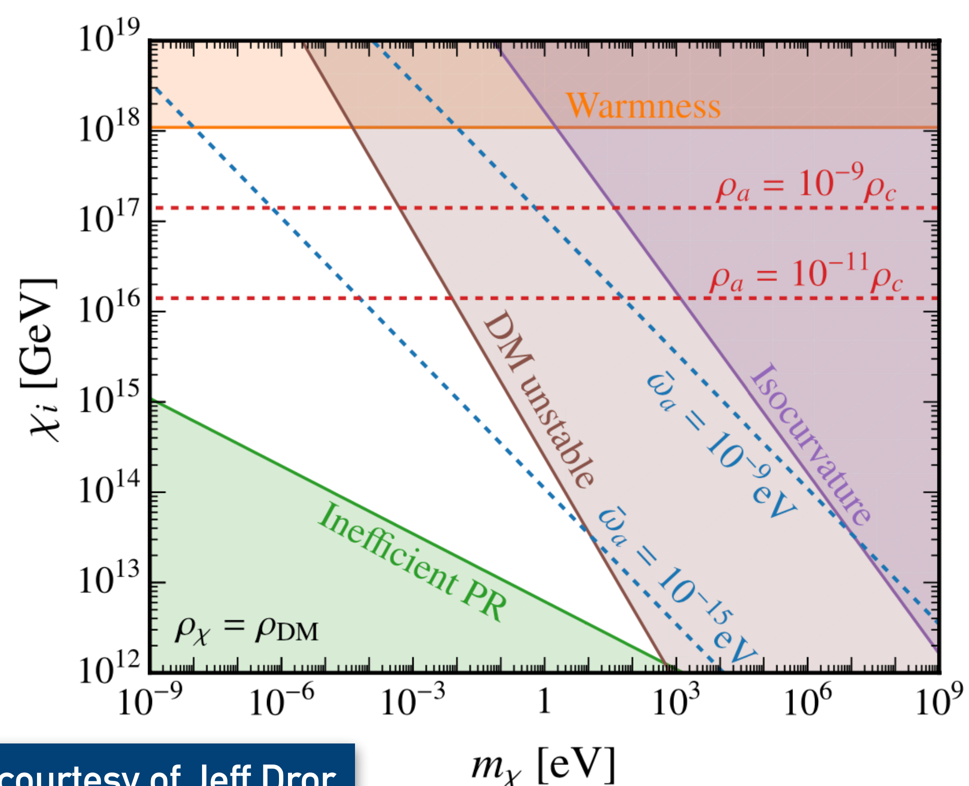
Oscillations when
$m_\chi^{\rm eff}(\chi_i) \simeq \lambda \chi_i \sim H$

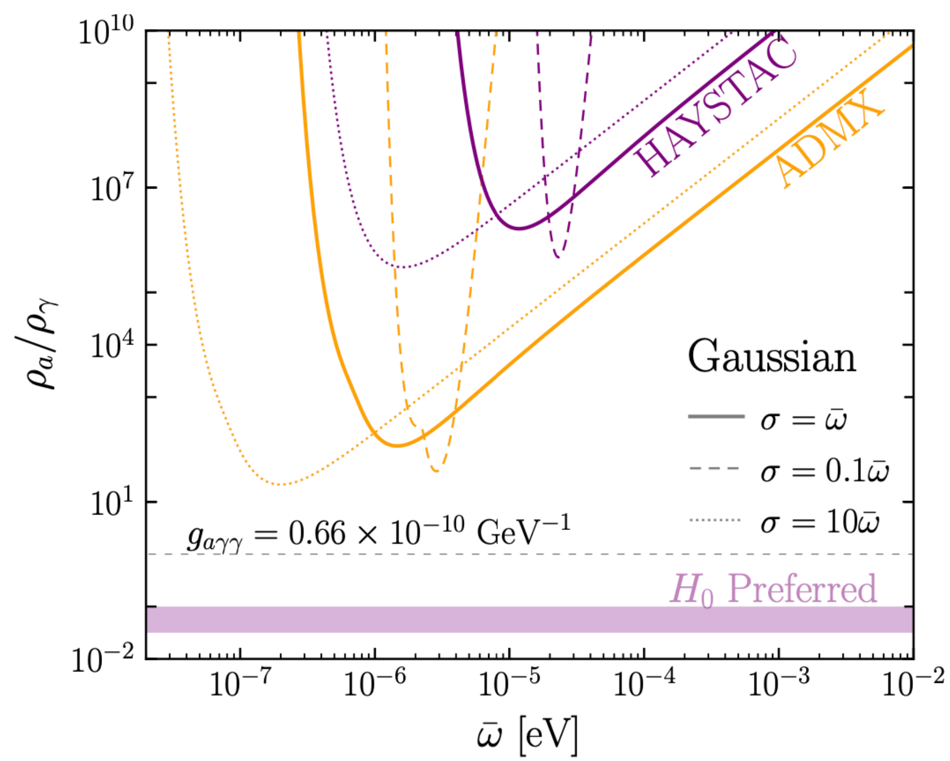
Typical energy: $\bar{\omega}_a \sim m_\chi^{\rm eff}(\chi_i) \left(\frac{s(T_0)}{s(T_{\rm osc})} \right)^{1/3} \sim 10^{-15}\ {\rm eV} \left(\frac{m_\chi^{\rm eff}(\chi_i)}{\rm MeV} \right)^{1/2}$

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

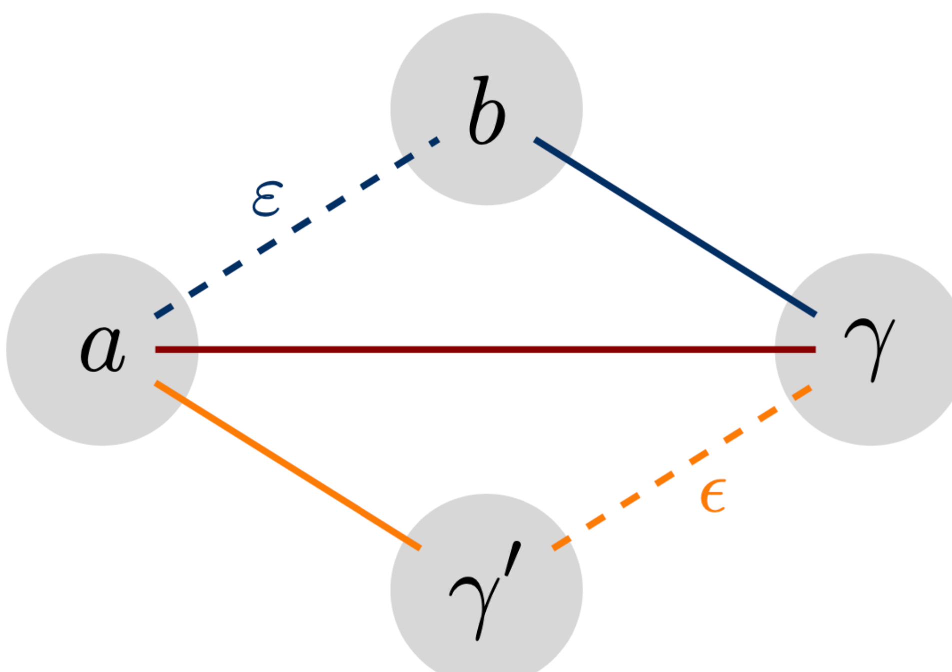
[Dror, NLR, Murayama 2021]

Dark Matter Decaying to Axions

example model

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

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



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

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

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

Slide courtesy of Jeff Dror

[Dror, NLR, Murayama 2021]