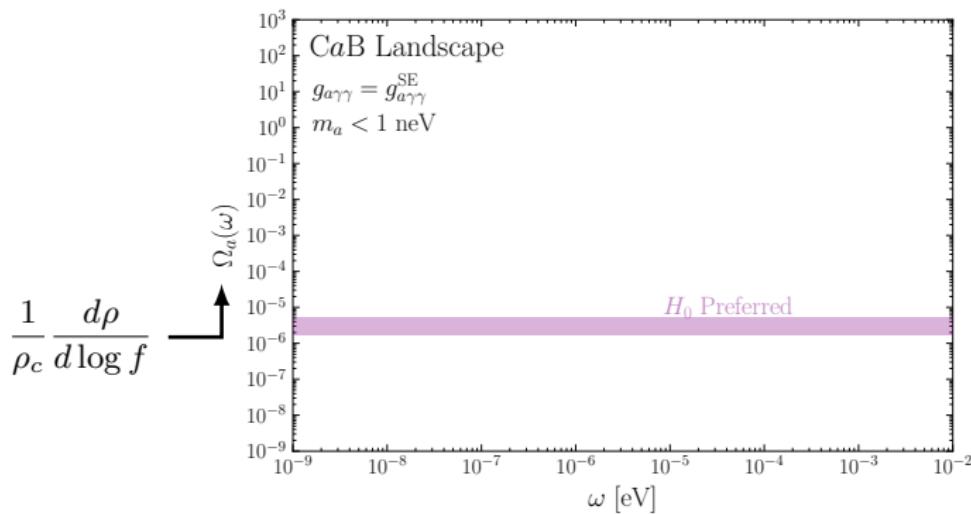


# The Cosmic Axion Background

Jeff Dror

JD w/ Rodd & Murayama  
2101.09287

...

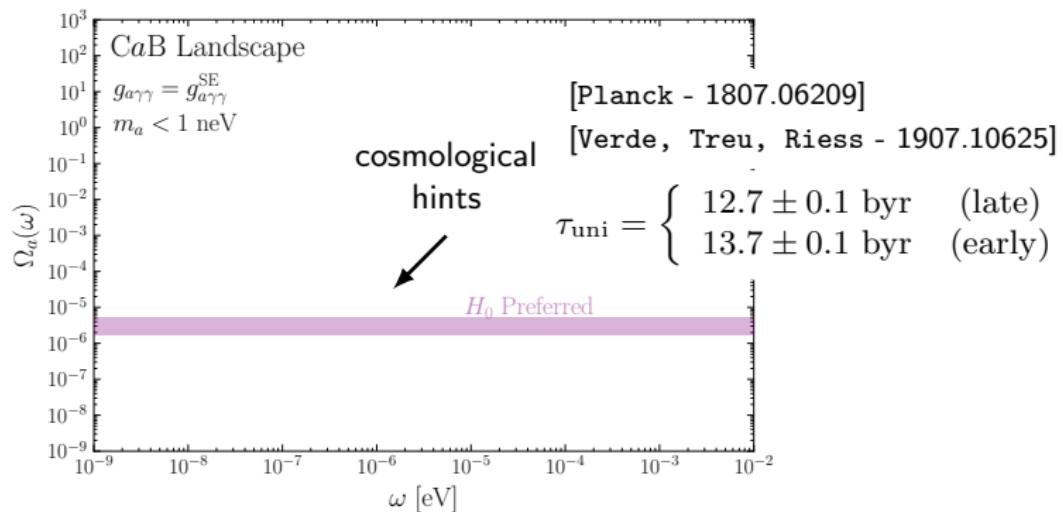


# The Cosmic Axion Background

Jeff Dror

JD w/ Rodd & Murayama  
2101.09287

...

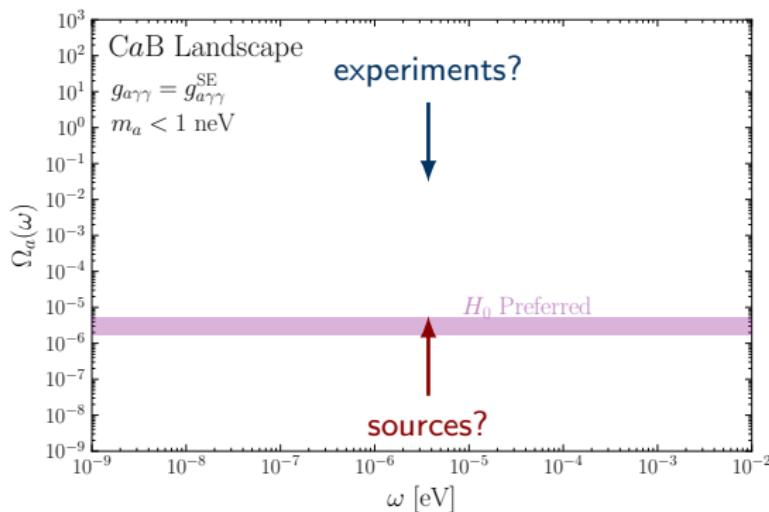


# The Cosmic Axion Background

Jeff Dror

JD w/ Rodd & Murayama  
2101.09287

...



# Axion detection

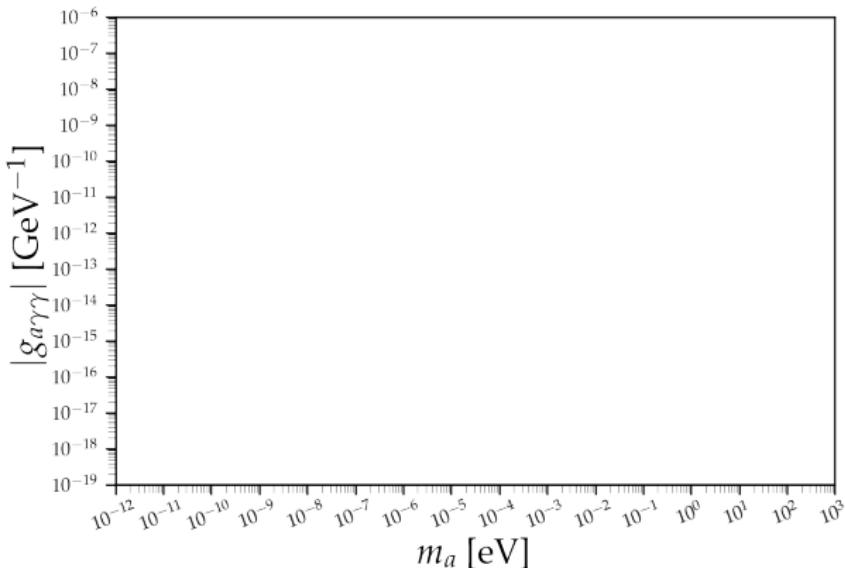


$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \supset g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

# Axion detection



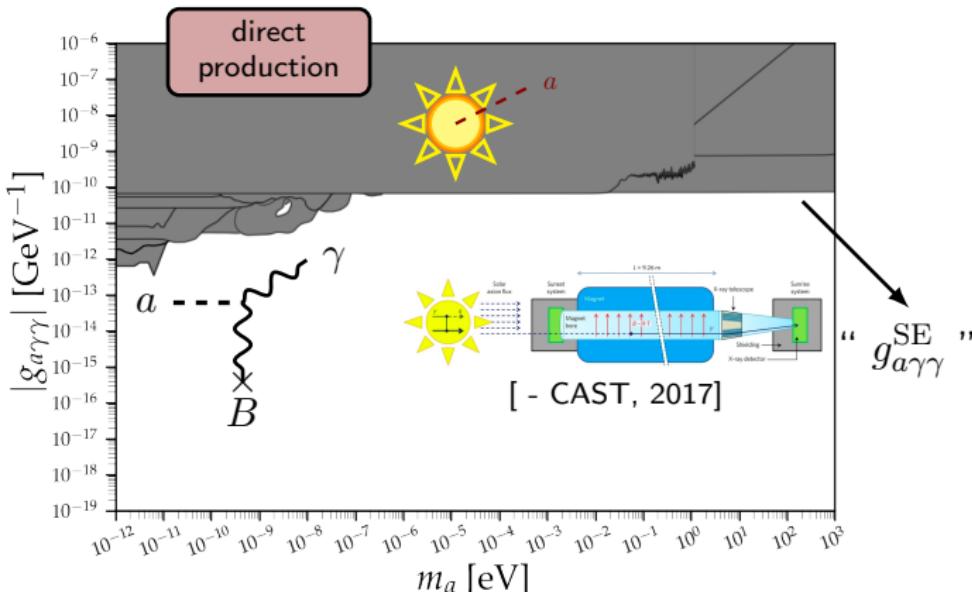
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \supset g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



# Axion detection



$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \supset g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

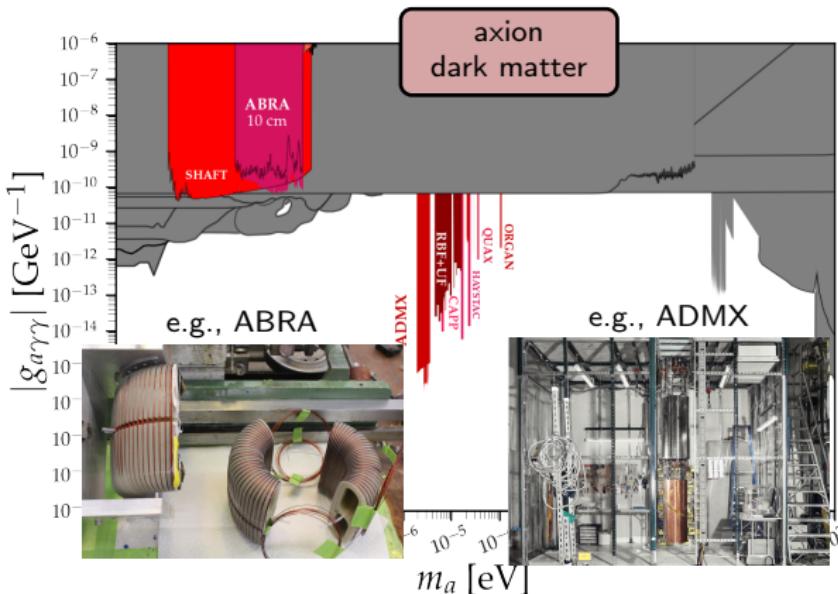


[compiled at - <https://github.com/cajohare/AxionLimits>]

# Axion detection



$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \supset g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

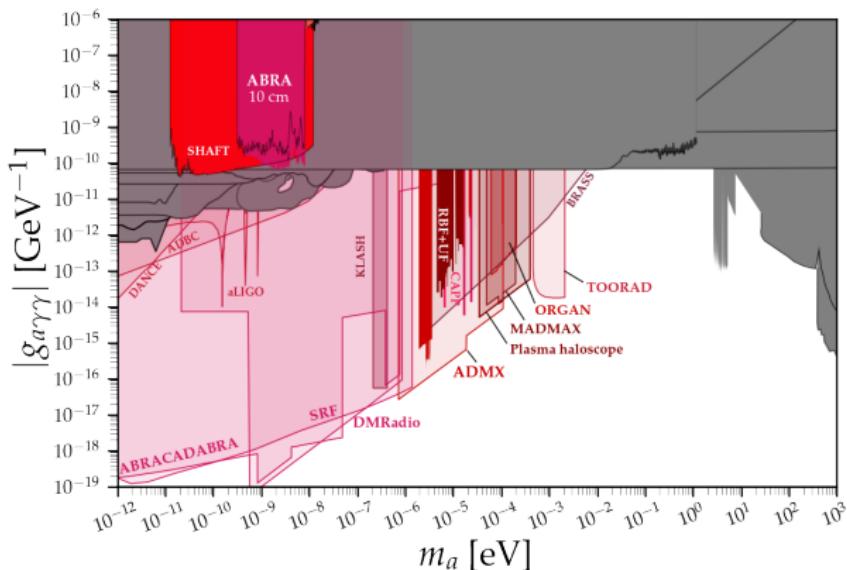


[compiled at - <https://github.com/cajohare/AxionLimits>]

# Axion detection



$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \supset g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

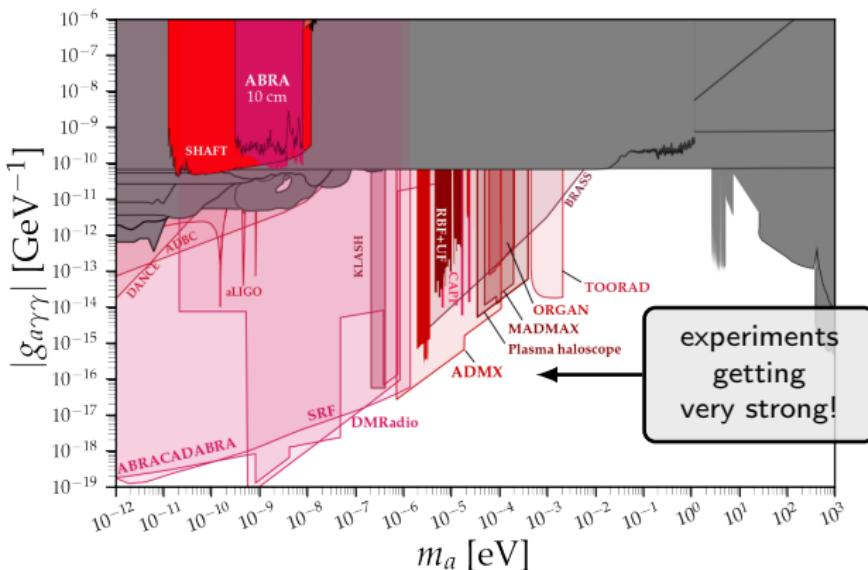


[compiled at - <https://github.com/cajohare/AxionLimits>]

# Axion detection

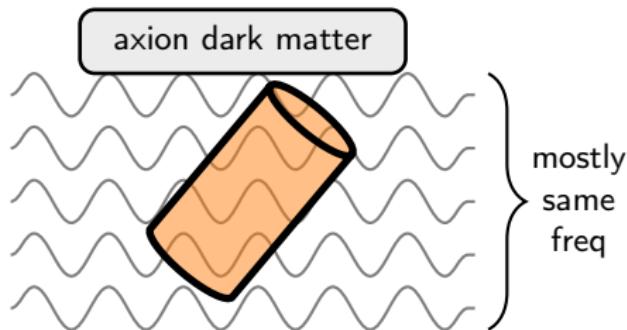


$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \supset g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

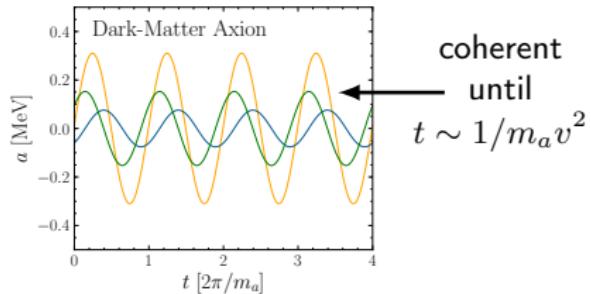


[compiled at - <https://github.com/cajohare/AxionLimits>]

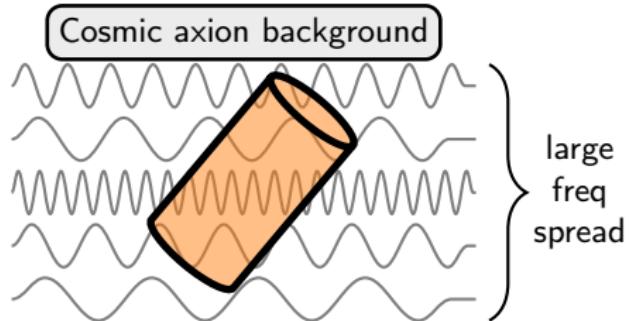
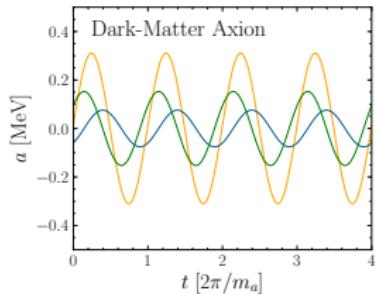
# Experimental power



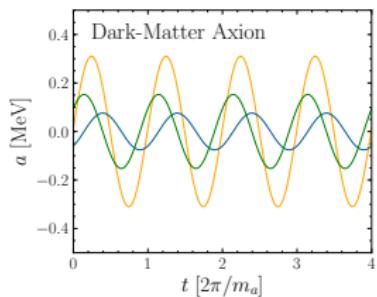
# Experimental power



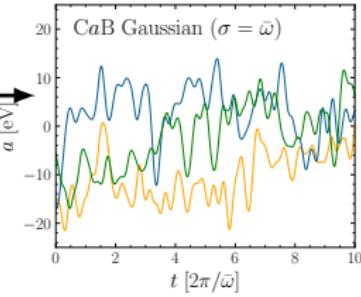
# Experimental power



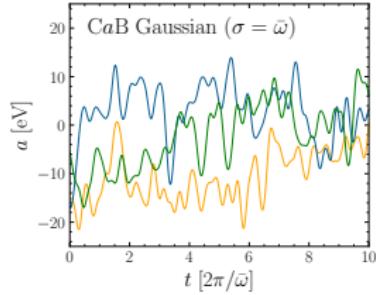
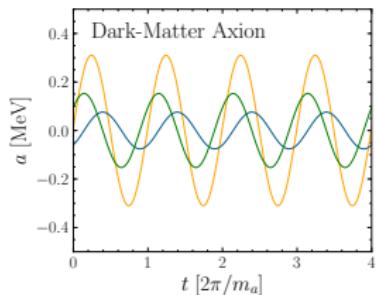
# Experimental power



coherent  
until →  
 $t \sim 1/\omega$

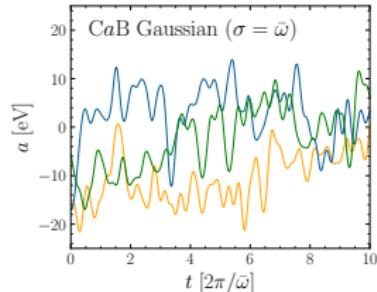
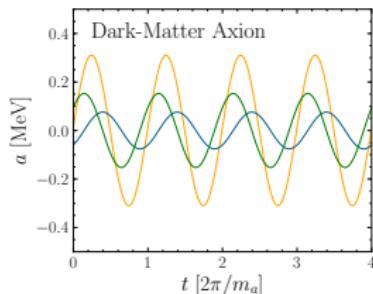


# Experimental power



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J_\mu A^\mu + g_{a\gamma\gamma}a\mathbf{E} \cdot \mathbf{B}$$

# Experimental power



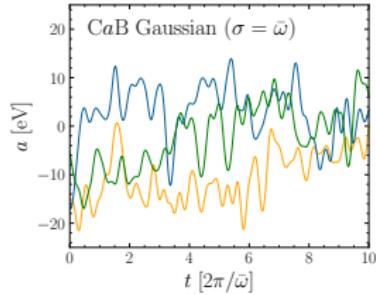
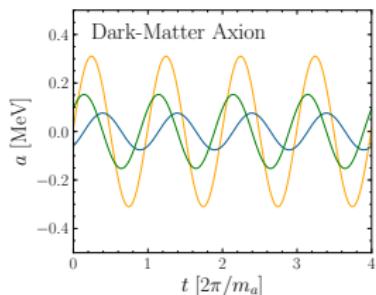
$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} (\nabla a) \cdot \mathbf{B}$$

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

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

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

# Experimental power



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

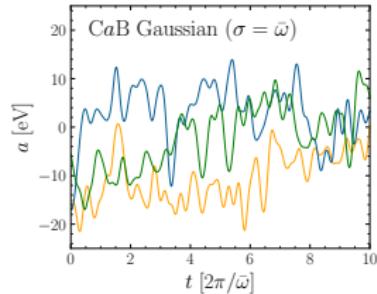
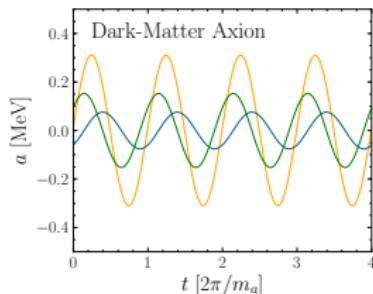
← effective charge

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

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

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

# Experimental power



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

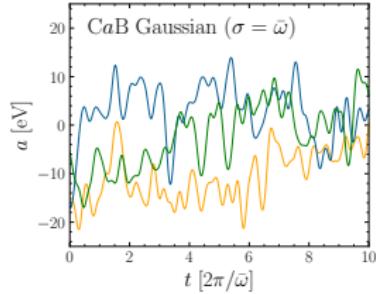
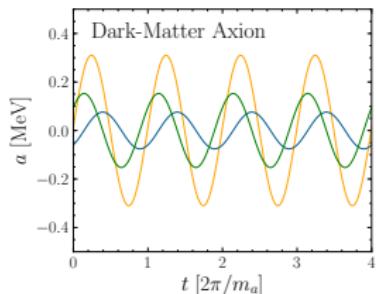
$$\nabla \times \mathbf{E} = -\dot{\mathbf{B}}$$

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

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

← effective current

# Experimental power



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

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

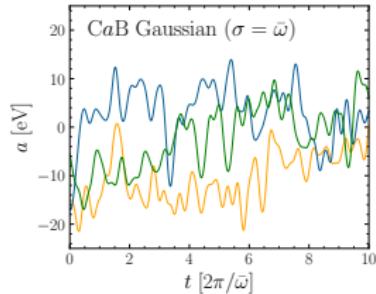
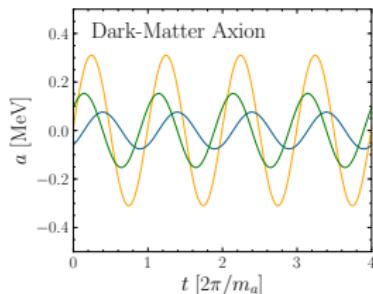
$$\nabla \cdot \mathbf{B} = 0$$

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

## Dark Matter

- ↳  $\nabla a \propto |\vec{v}_a| \sim 10^{-3}$
- ↳ only effective current

# Experimental power



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

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

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

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

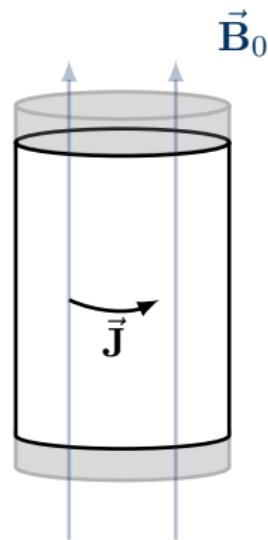
## Dark Matter

- ⚡  $\nabla a \propto |\vec{v}_a| \sim 10^{-3}$
- ⚡ only effective current

## CaB

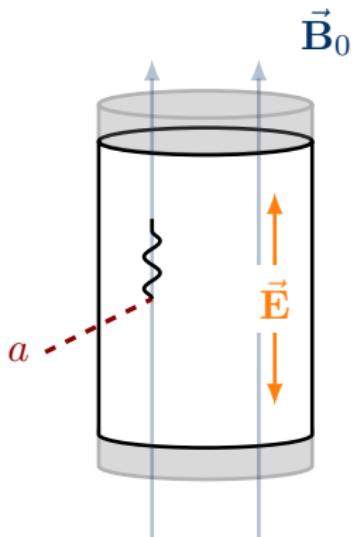
- ⚡ current + charge
- ⚡ dependence on direction

# Resonant cavities



e.g., ADMX,  
HAYSTAC

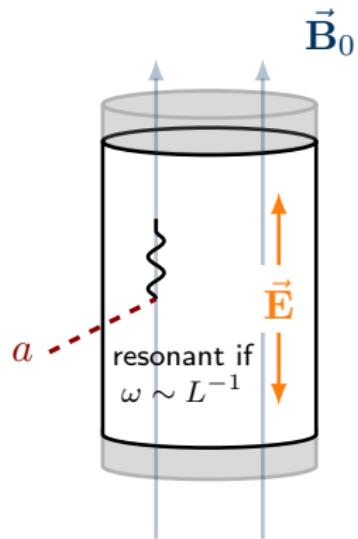
# Resonant cavities



$$(\nabla^2 - \partial_t^2) \vec{E} = g_{a\gamma\gamma} (\vec{B}_0 \partial_t^2 \vec{a} - (\vec{B}_0 \cdot \vec{\nabla}) \vec{\nabla} \vec{a})$$

e.g., ADMX,  
HAYSTAC

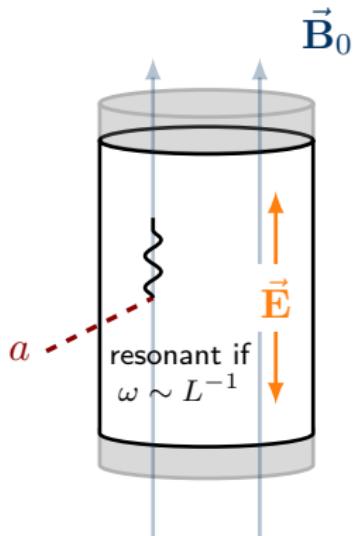
# Resonant cavities



$$(\nabla^2 - \partial_t^2) \vec{E} = g_{a\gamma\gamma} (\vec{B}_0 \partial_t^2 \vec{a} - (\vec{B}_0 \cdot \vec{\nabla}) \vec{\nabla} \vec{a})$$

e.g., ADMX,  
HAYSTAC

# Resonant cavities

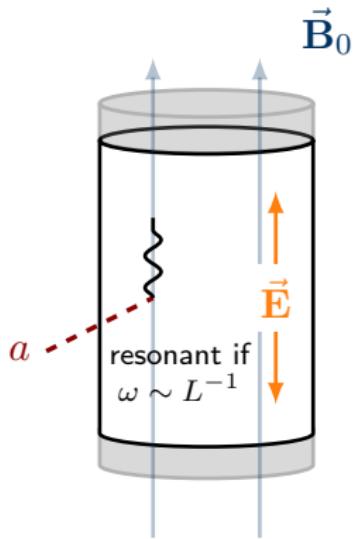


$$(\nabla^2 - \partial_t^2) \vec{E} = g_{a\gamma\gamma} (\vec{B}_0 \partial_t^2 \vec{a} - (\vec{B}_0 \cdot \vec{\nabla}) \vec{\nabla} \vec{a})$$

- 1) Solve  $\vec{B}_0 = 0$  modes,  $\vec{e}_n$
- 2) Expand  $\vec{E} = \sum_n A_n \vec{e}_n$
- 3) Insert and solve for  $A_n$

e.g., ADMX,  
HAYSTAC

# Resonant cavities



e.g., ADMX,  
HAYSTAC

$$(\nabla^2 - \partial_t^2) \vec{E} = g_{a\gamma\gamma} (\vec{B}_0 \partial_t^2 \vec{a} - (\vec{B}_0 \cdot \vec{\nabla}) \vec{\nabla} \vec{a})$$

1) Solve  $\vec{B}_0 = 0$  modes,  $\vec{e}_n$

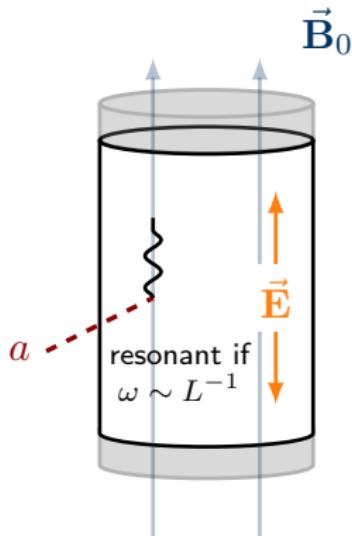
2) Expand  $\vec{E} = \sum_n A_n \vec{e}_n$

3) Insert and solve for  $A_n$

$$A_n \propto \int_{\mathbf{x}} \cos(\hat{\mathbf{k}} \cdot \vec{\mathbf{x}}) \left[ (\hat{\mathbf{k}} \cdot \hat{\mathbf{B}}_0) \hat{\mathbf{k}} - \hat{\mathbf{B}}_0 \right] \cdot \vec{e}_n^*$$

new  
term  
 $\hat{\mathbf{k}}$ -axion  
direction

# Resonant cavities



e.g., ADMX,  
HAYSTAC

$$(\nabla^2 - \partial_t^2) \vec{E} = g_{a\gamma\gamma} (\vec{B}_0 \partial_t^2 \vec{a} - (\vec{B}_0 \cdot \vec{\nabla}) \vec{\nabla} \vec{a})$$

1) Solve  $\vec{B}_0 = 0$  modes,  $\vec{e}_n$

2) Expand  $\vec{E} = \sum_n A_n \vec{e}_n$

3) Insert and solve for  $A_n$

$$A_n \propto \int_x \cos(\vec{k} \cdot \vec{x}) \left[ (\hat{k} \cdot \hat{B}_0) \hat{k} - \hat{B}_0 \right] \cdot \vec{e}_n^*$$

$$\frac{\omega_0 |\vec{E}|^2}{Q}$$

quality factor  
coupling

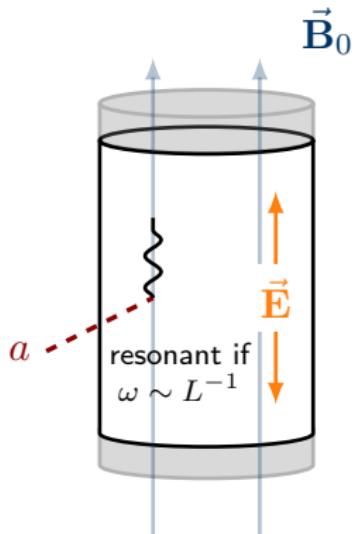
$$P_a \simeq s_\alpha^4 g_{a\gamma\gamma}^2 Q_a n_a B_0^2 V C \rightarrow \mathcal{O}(1)$$

experiment angle

volume

magnetic field  
number density

# Resonant cavities



e.g., ADMX,  
HAYSTAC

$$(\nabla^2 - \partial_t^2) \vec{E} = g_{a\gamma\gamma} (\vec{B}_0 \partial_t^2 \vec{a} - (\vec{B}_0 \cdot \vec{\nabla}) \vec{\nabla} \vec{a})$$

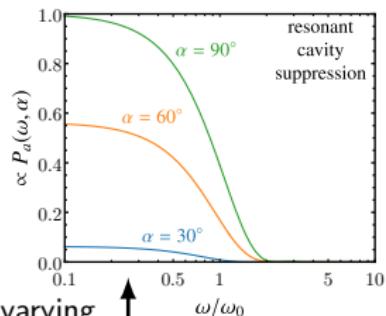
1) Solve  $\vec{B}_0 = 0$  modes,  $\vec{e}_n$

2) Expand  $\vec{E} = \sum_n A_n \vec{e}_n$

3) Insert and solve for  $A_n$

$$A_n \propto \int_x \cos(\vec{k} \cdot \vec{x}) [(\hat{k} \cdot \hat{B}_0) \hat{k} - \hat{B}_0] \cdot \vec{e}_n^*$$

$\cos \alpha$   
varying angles



$$\frac{\omega_0 |\vec{E}|^2}{Q}$$

quality factor  
coupling

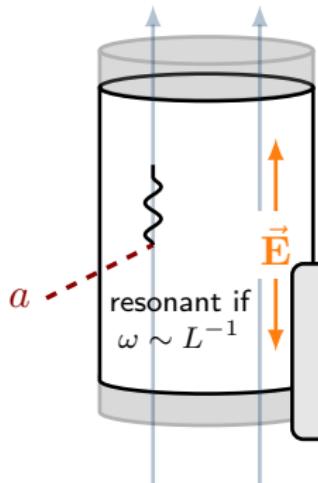
$$P_a \simeq s_\alpha^4 g_{a\gamma\gamma}^2 Q_a n_a B_0^2 V C$$

experiment angle      number density      volume      magnetic field

# Resonant cavities



$$\vec{B}_0$$



$$(\nabla^2 - \partial_t^2) \vec{E} = g_{a\gamma\gamma} (\vec{B}_0 \partial_t^2 \vec{a} - (\vec{B}_0 \cdot \vec{\nabla}) \vec{\nabla} \vec{a})$$

1) Solve  $\vec{B}_0 = 0$  modes,  $\vec{e}_n$

$$2) \text{Expand } \vec{E} = \sum_n A_n \vec{e}_n$$

LC circuit readout  
allows low frequency detection  
(e.g., ABRACADBARA, DM-Radio)

e.g., ADMX,  
HAYSTAC

$$\frac{\omega_0 |\vec{E}|^2}{Q}$$

quality factor  
coupling

$$P_a \simeq s_\alpha^4 g_{a\gamma\gamma}^2 Q_a n_a B_0^2 V C \rightarrow \mathcal{O}(1)$$

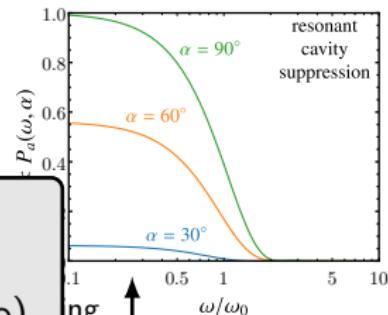
experiment angle

number density

magnetic field

volume

daily/ yearly  
modulation



# Simplified projections



boot-strap  
dark matter  
searches

$$P_a^{\text{DM}}(\omega) = P_a^{\text{CaB}}(\omega)$$

$$P_a \propto Q_a \Omega_a g_{a\gamma\gamma}^2$$

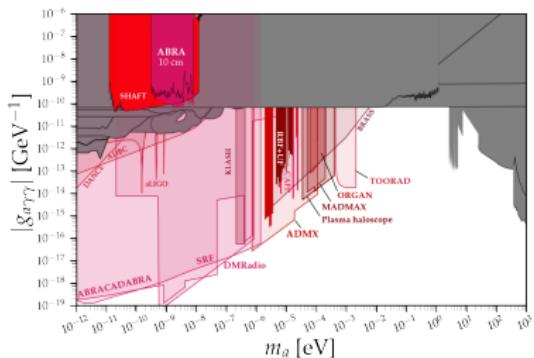
# Simplified projections



boot-strap  
dark matter  
searches

$$P_a^{\text{DM}}(\omega) = P_a^{\text{CaB}}(\omega)$$

$$P_a \propto Q_a \Omega_a g_{a\gamma\gamma}^2$$



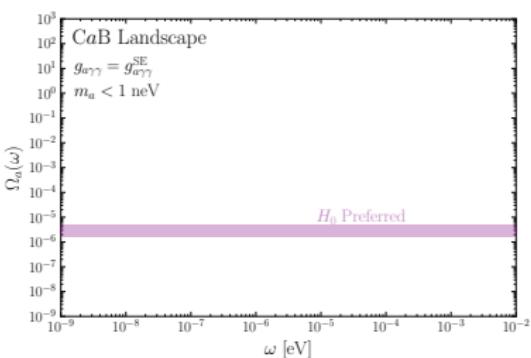
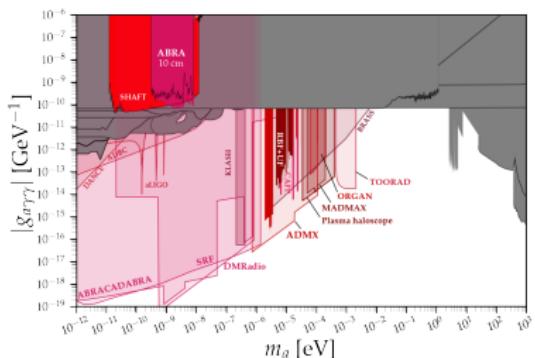
hold  $\Omega_a$   
fixed

# Simplified projections

boot-strap  
dark matter  
searches

$$P_a^{\text{DM}}(\omega) = P_a^{\text{CaB}}(\omega)$$

$$P_a \propto Q_a \Omega_a g_{a\gamma\gamma}^2$$



hold  $\Omega_a$   
fixed

sum frequency bins

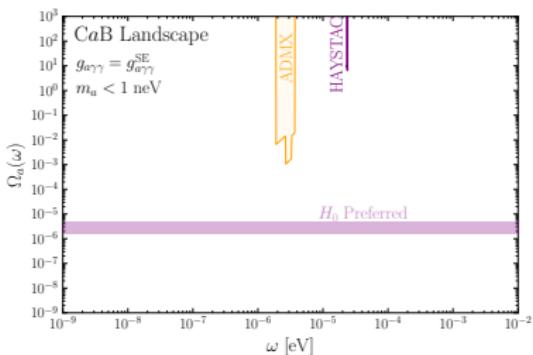
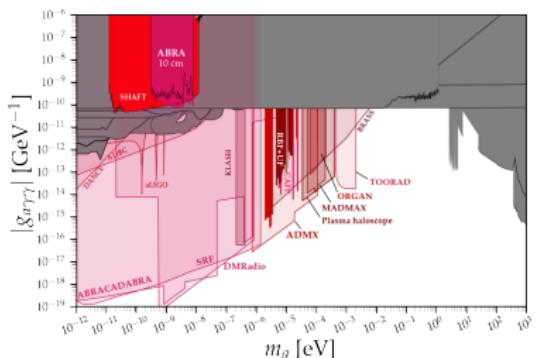
hold  $g_{a\gamma\gamma}$   
fixed

# Simplified projections

boot-strap  
dark matter  
searches

$$P_a^{\text{DM}}(\omega) = P_a^{\text{CaB}}(\omega)$$

$$P_a \propto Q_a \Omega_a g_{a\gamma\gamma}^2$$



hold  $\Omega_a$   
fixed

sum frequency bins

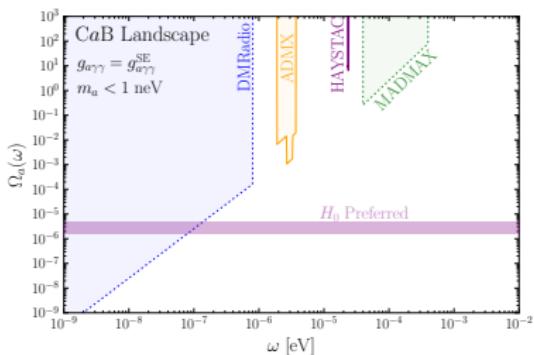
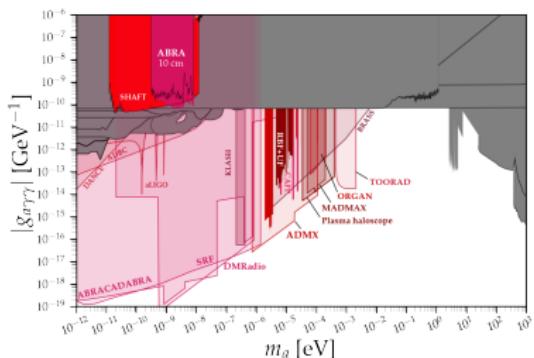
hold  $g_{a\gamma\gamma}$   
fixed

# Simplified projections

boot-strap  
dark matter  
searches

$$P_a^{\text{DM}}(\omega) = P_a^{\text{CaB}}(\omega)$$

$$P_a \propto Q_a \Omega_a g_{a\gamma\gamma}^2$$

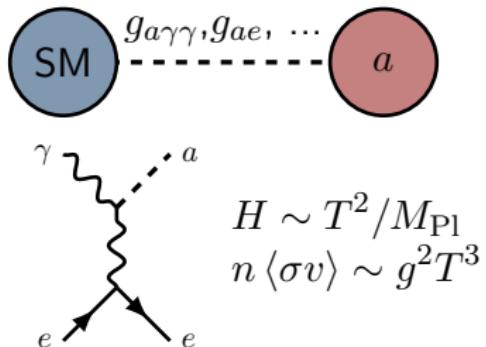


hold  $\Omega_a$   
fixed

sum frequency bins

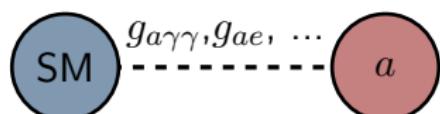
hold  $g_{a\gamma\gamma}$   
fixed

## Thermalization with Standard Model

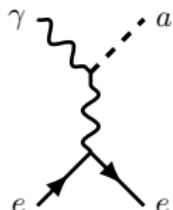


$$H \sim T^2/M_{\text{Pl}}$$
$$n \langle \sigma v \rangle \sim g^2 T^3$$

## Thermalization with Standard Model

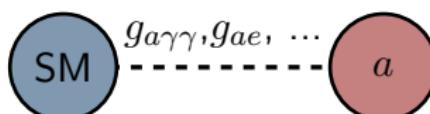


$$T_{\text{therm}} \sim 10 \text{ TeV} \left( \frac{g_{a\gamma\gamma}^{\text{SE}}}{g_{a\gamma\gamma}} \right)^2$$

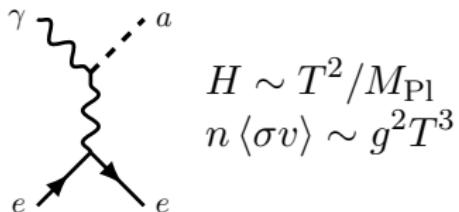


$$H \sim T^2/M_{\text{Pl}}$$
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## Thermalization with Standard Model



$$T_{\text{therm}} \sim 10 \text{ TeV} \left( \frac{g_{a\gamma\gamma}^{\text{SE}}}{g_{a\gamma\gamma}} \right)^2$$



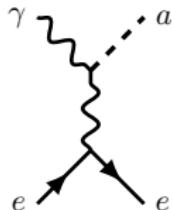
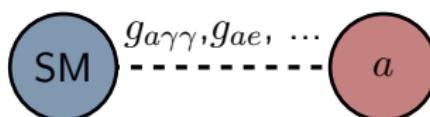
spectrum (almost) fixed

$$\rho_a = \frac{1}{2\pi^2} \frac{\omega^4}{e^{\omega/T_a} - 1}$$

$T_a$  is free-ish

$$T_a \sim T_\gamma \sim 10^{-4} \text{ eV}$$

## Thermalization with Standard Model



$$H \sim T^2/M_{\text{Pl}}$$

$$n \langle \sigma v \rangle \sim g^2 T^3$$

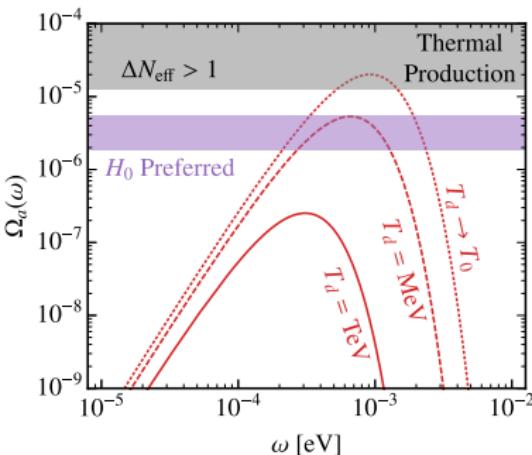
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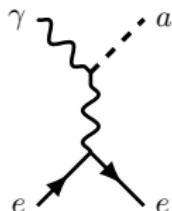
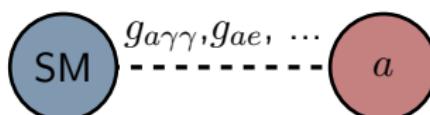
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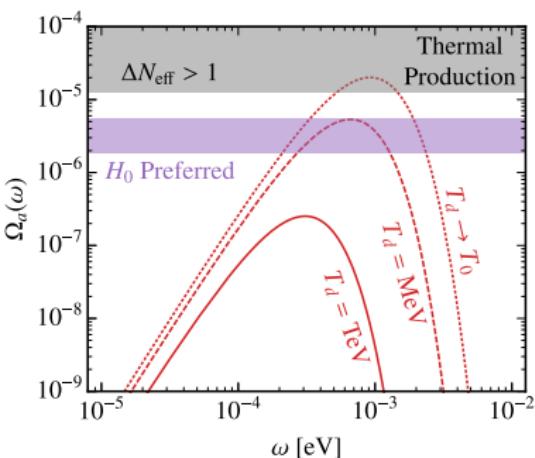
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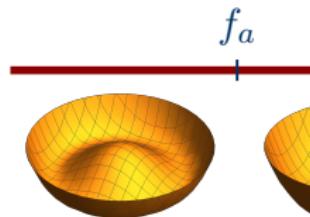
$$T_{\text{therm}} \sim 10 \text{ TeV} \left( \frac{g_{a\gamma\gamma}^{\text{SE}}}{g_{a\gamma\gamma}} \right)^2$$



Detection  
prospects

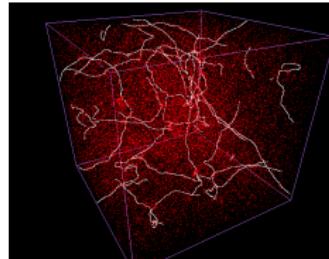
small numbers -  $\mathcal{O}(100/\text{cm}^3)$   
small energy deposits

# Cosmic strings



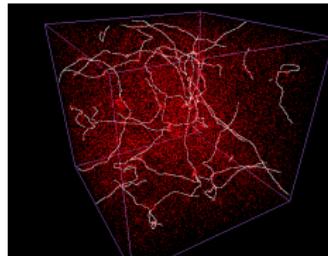
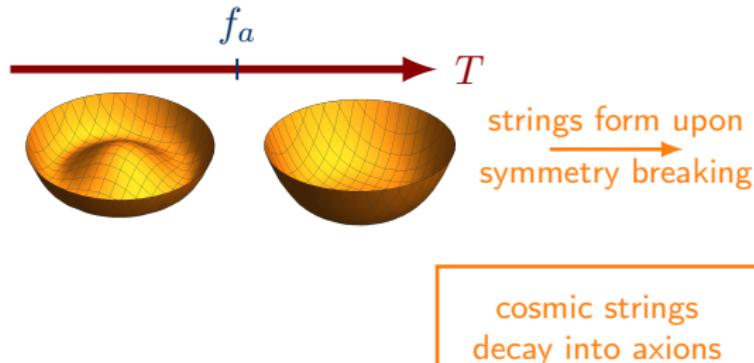
$T$

strings form upon  
symmetry breaking

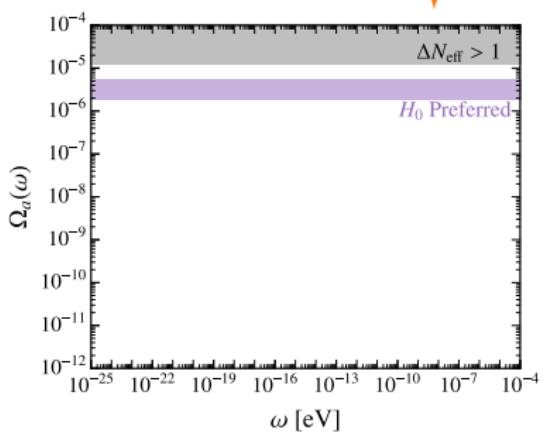


[ - Ringeval, Bouchet]

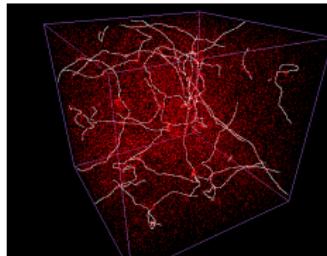
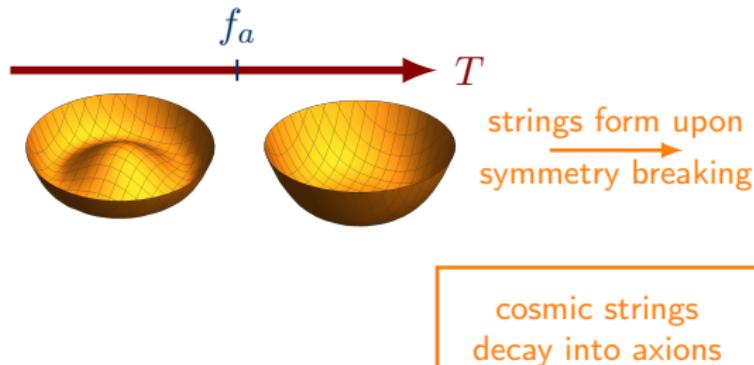
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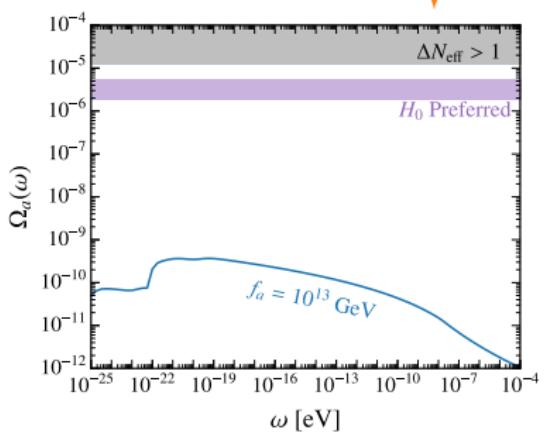
[ - Ringeval, Bouchet]



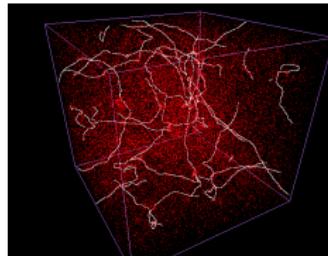
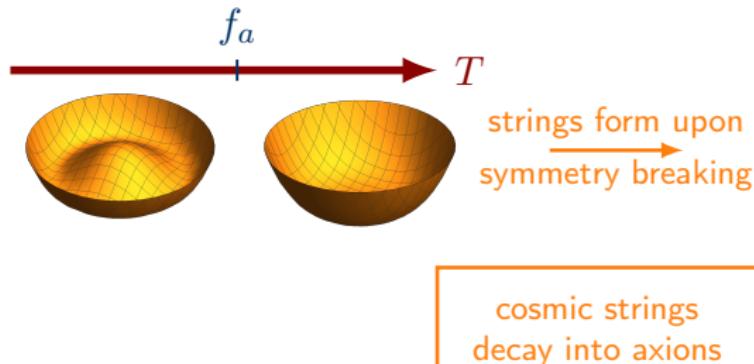
# Cosmic strings



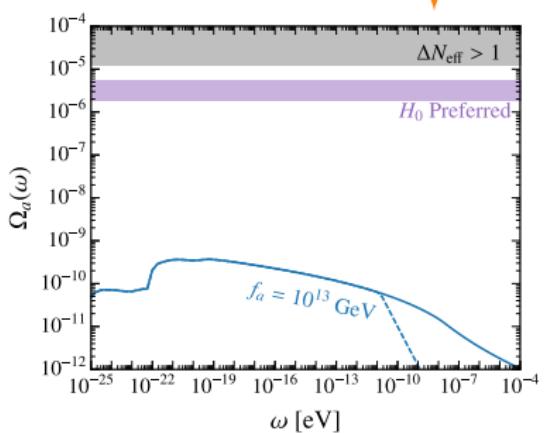
[ - Ringeval, Bouchet]



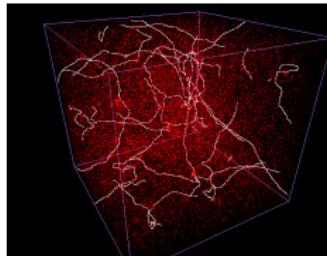
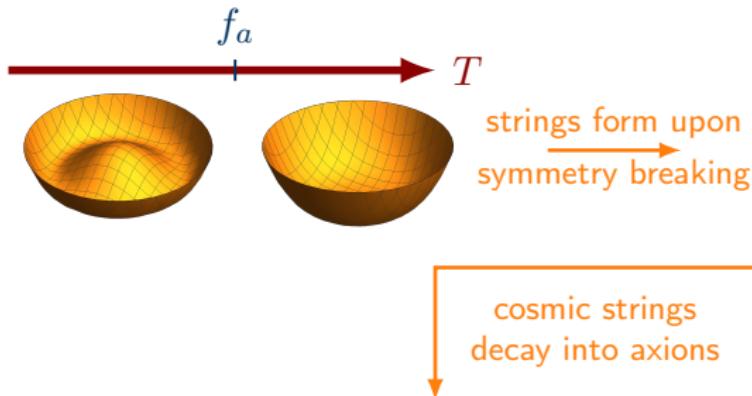
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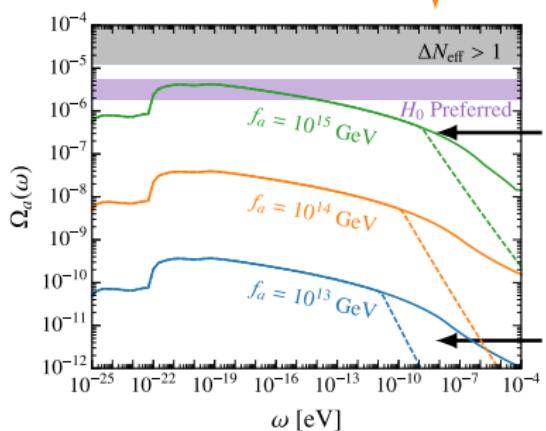
[ - Ringeval, Bouchet]



# Cosmic strings



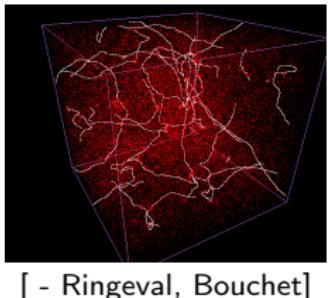
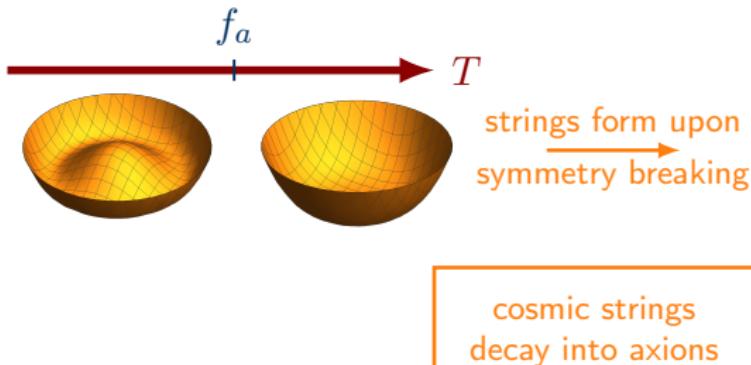
[ - Ringeval, Bouchet]



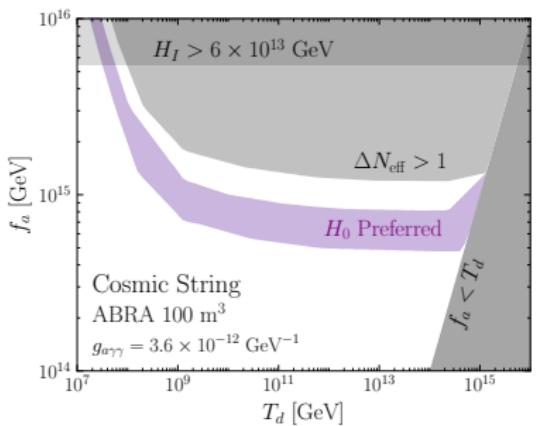
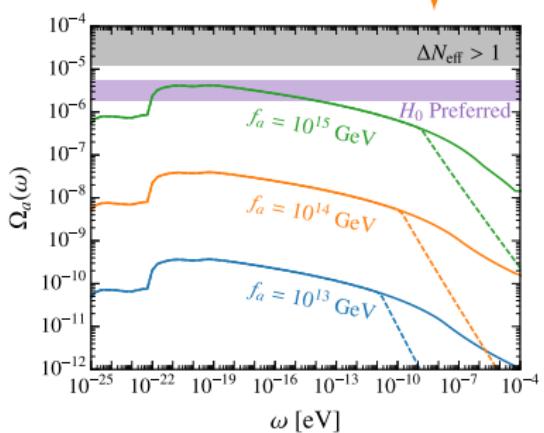
large  $f_a$   
needed  
for  $\rho_a \sim \rho_\gamma$

uncertainty  
in start of  
scaling

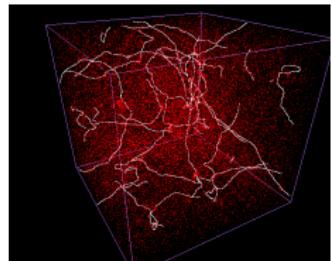
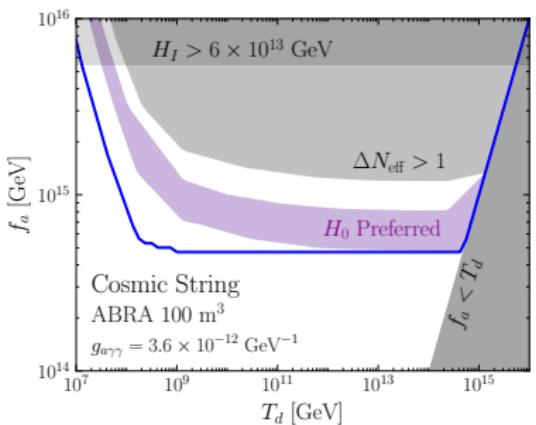
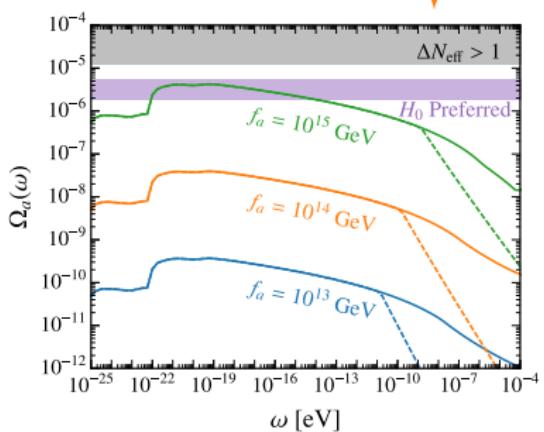
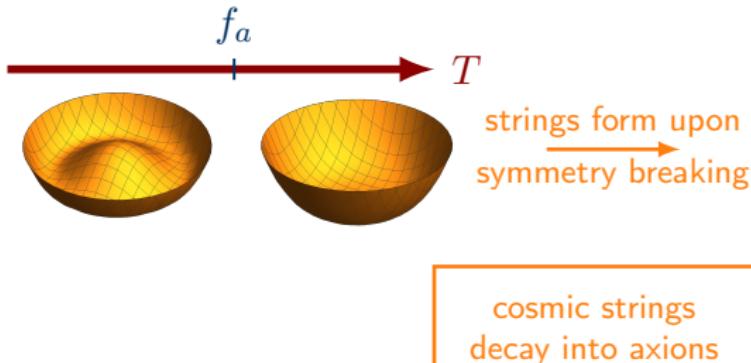
# Cosmic strings



[ - Ringeval, Bouchet]



# Cosmic strings

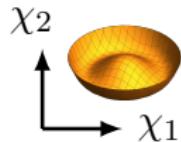


[ - Ringeval, Bouchet]

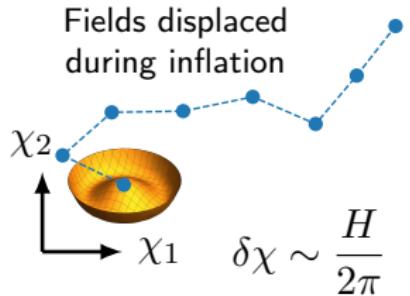
# Parametric resonance



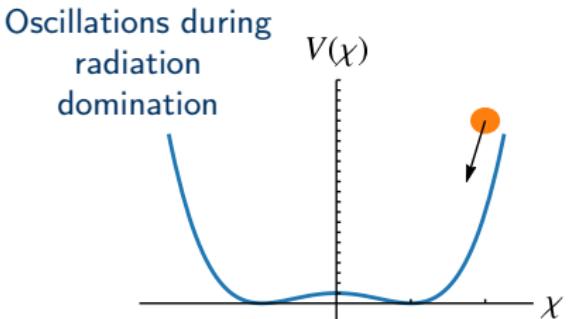
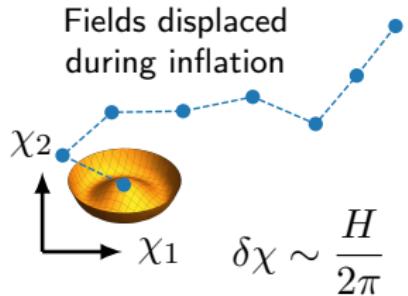
Fields displaced  
during inflation



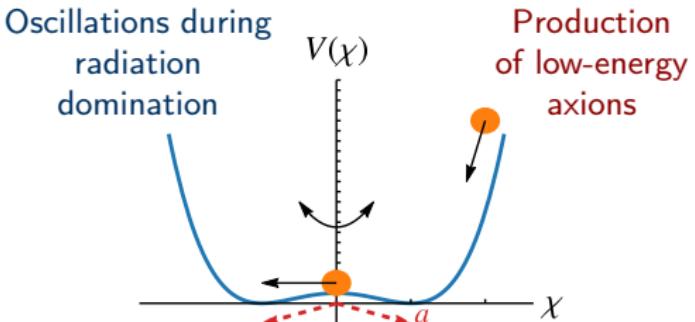
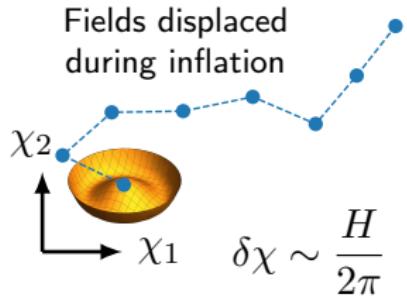
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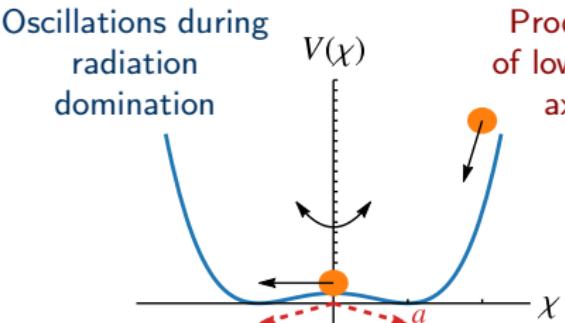
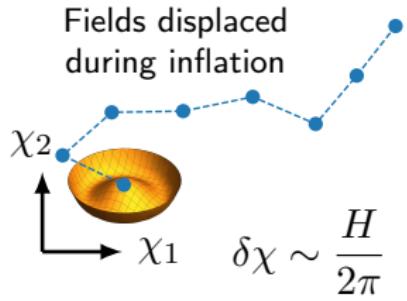
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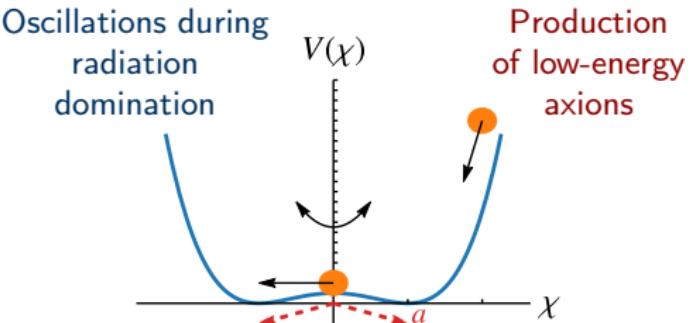
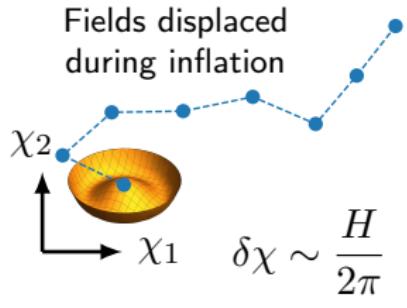


Production of low-energy axions

Typical energy:

Energy density:

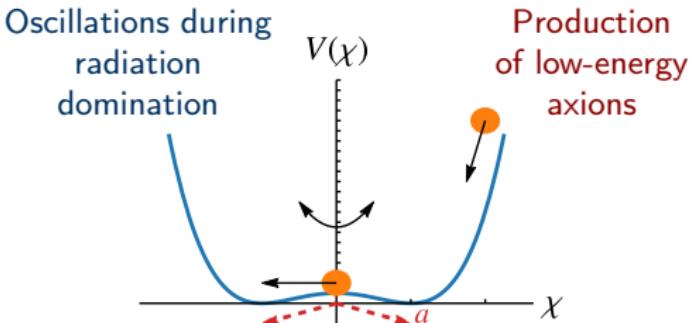
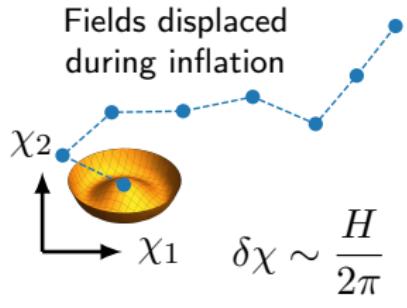
# Parametric resonance



Typical energy:  $\bar{\omega}_a \sim 10^{-15} \text{ eV} \left( \frac{\lambda \chi_i}{\text{MeV}} \right)^{1/2}$

Energy density:

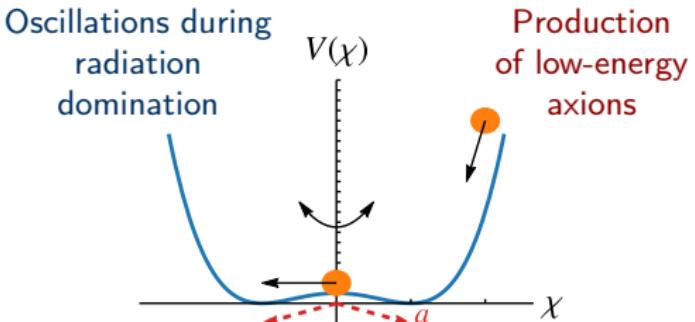
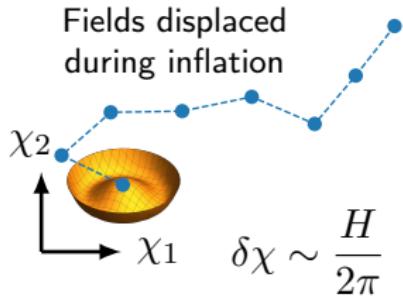
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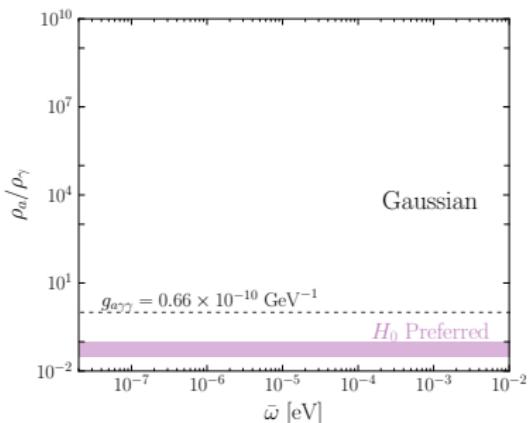
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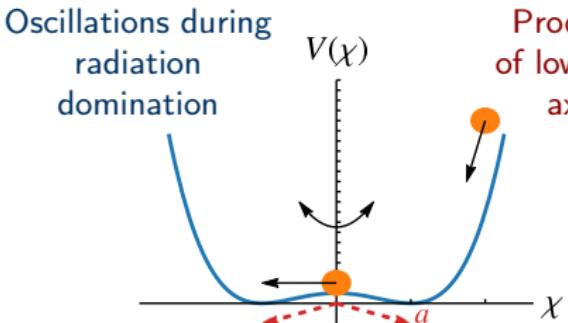
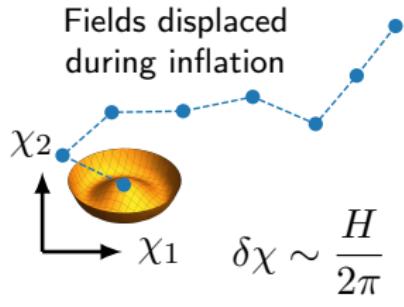
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detectable?



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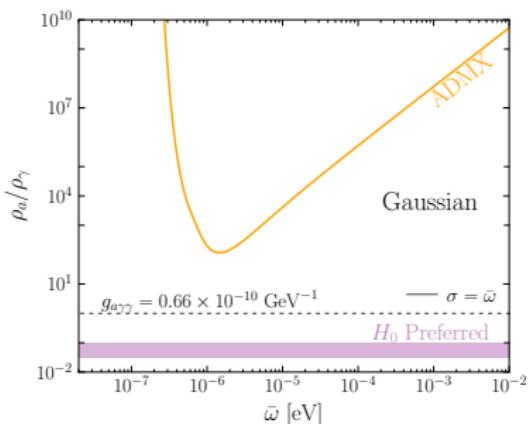


Production of low-energy axions

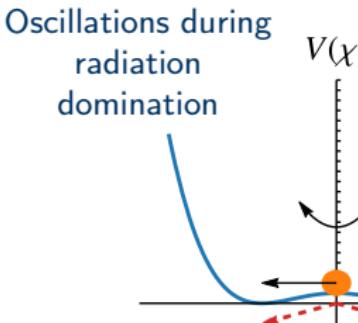
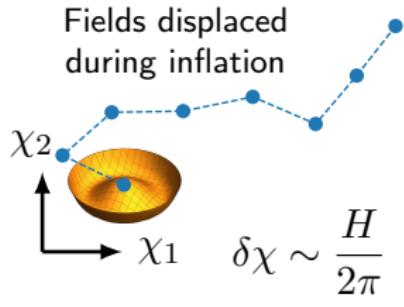
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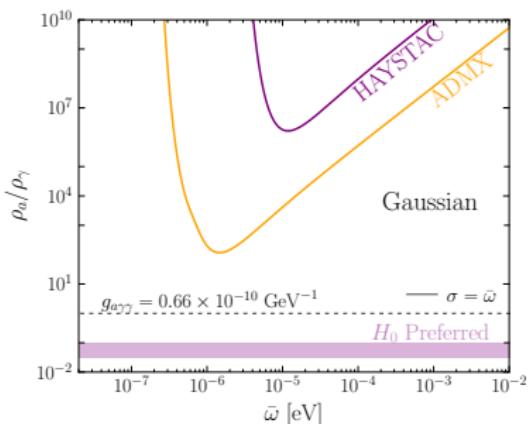


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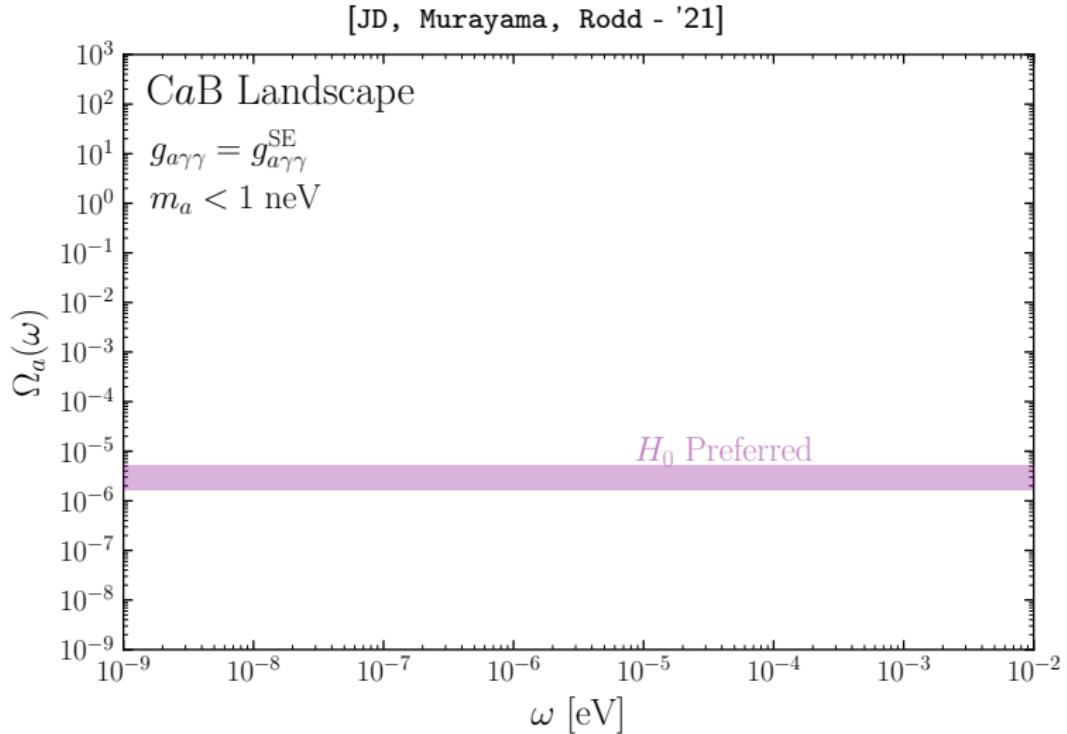
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detectable?



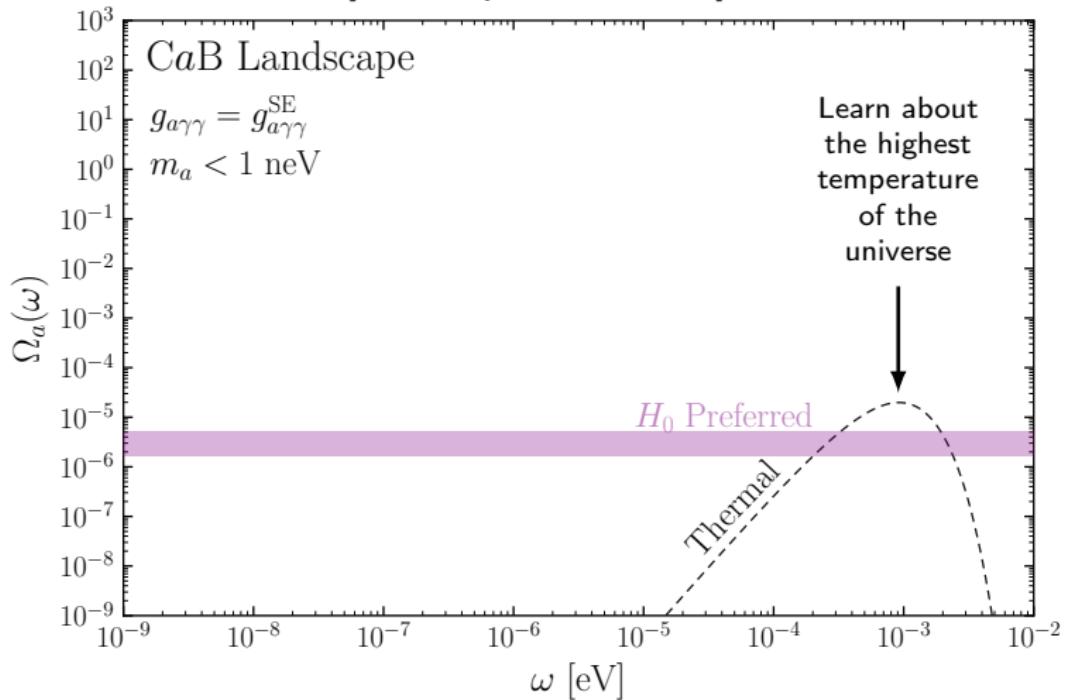
# Conclusions: axi-verse through $g_{a\gamma\gamma}$



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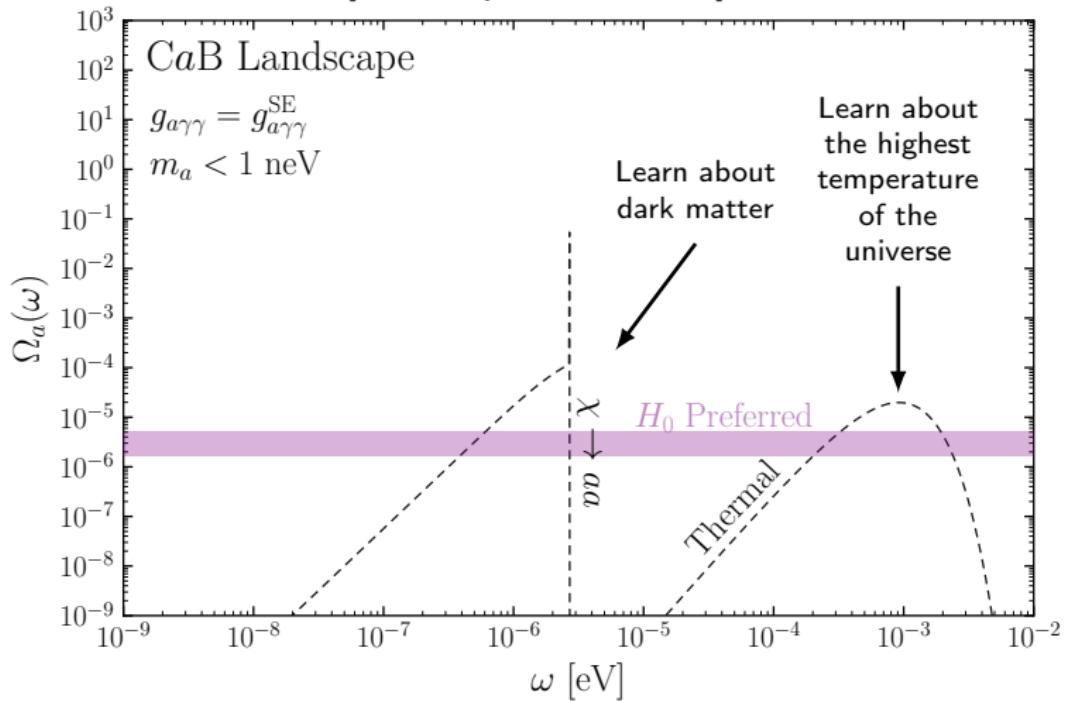
[JD, Murayama, Rodd - '21]



# Conclusions: axi-verse through $g_{a\gamma\gamma}$



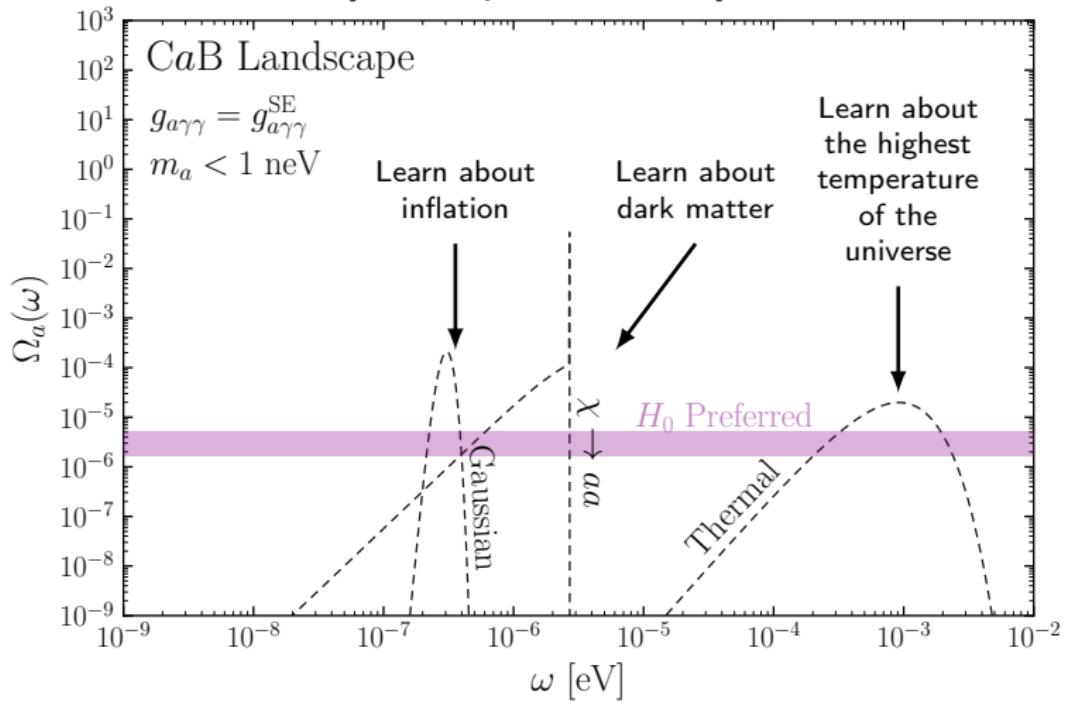
[JD, Murayama, Rodd - '21]



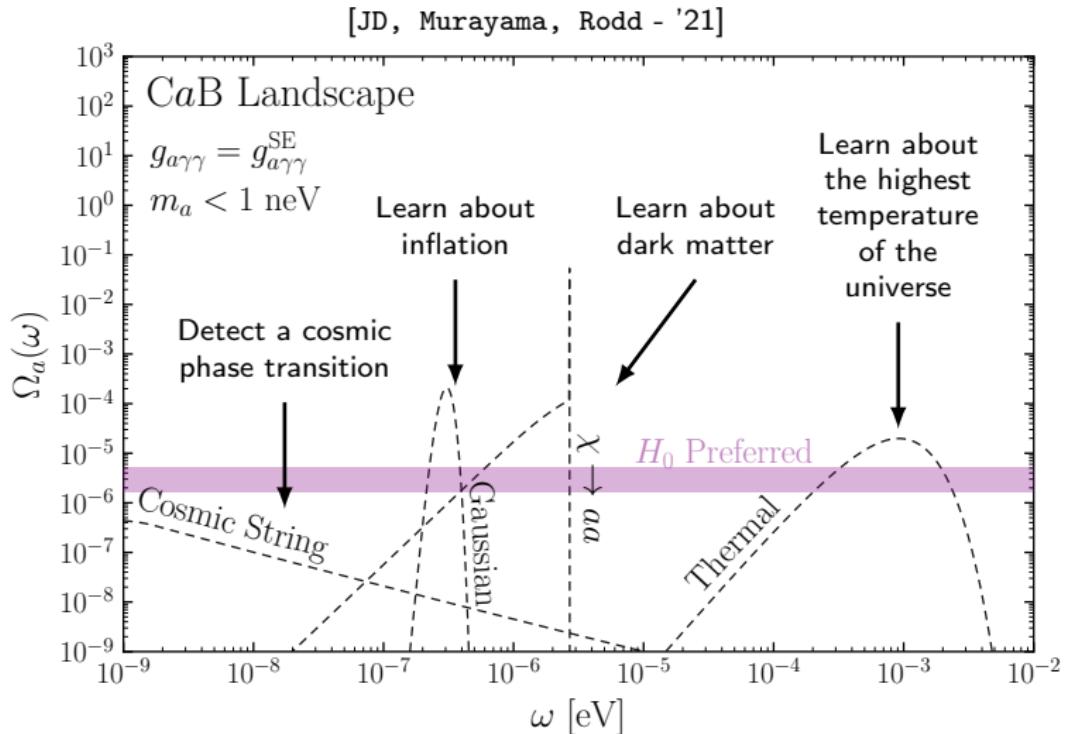
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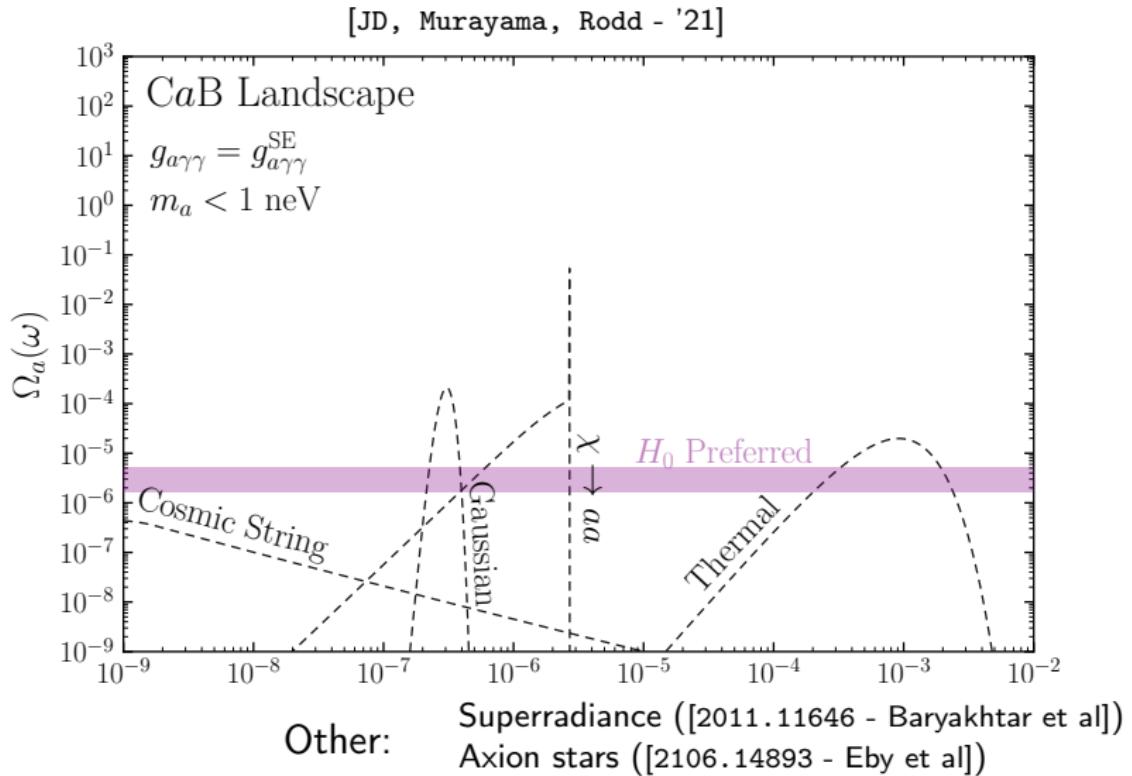
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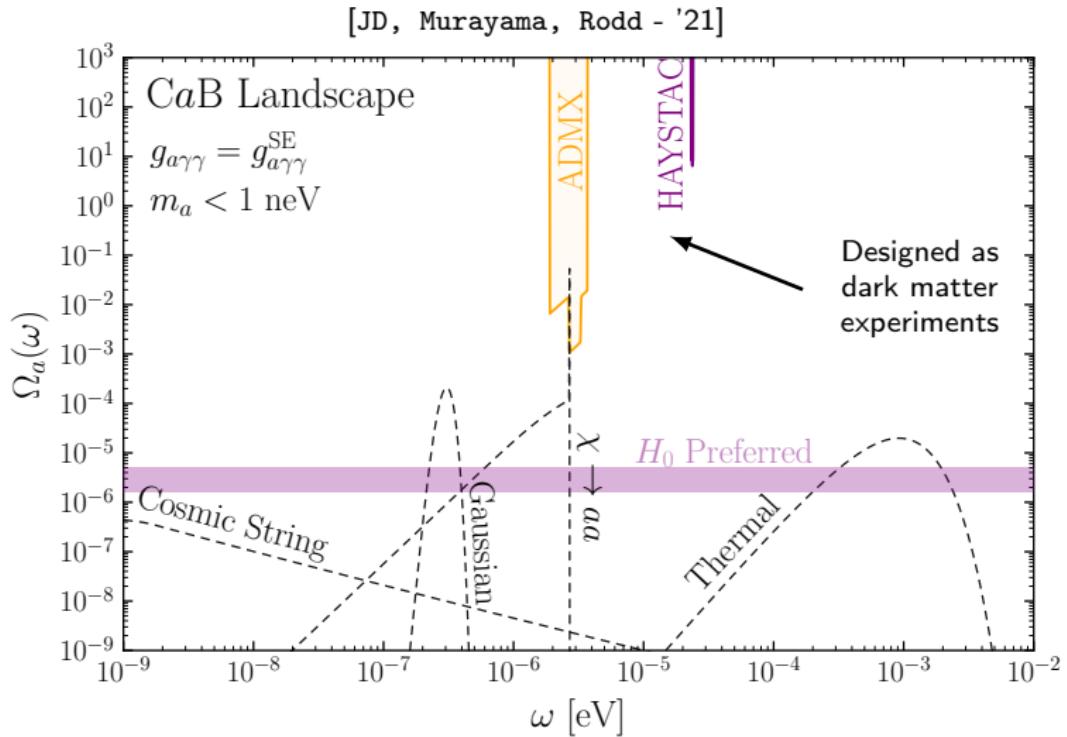
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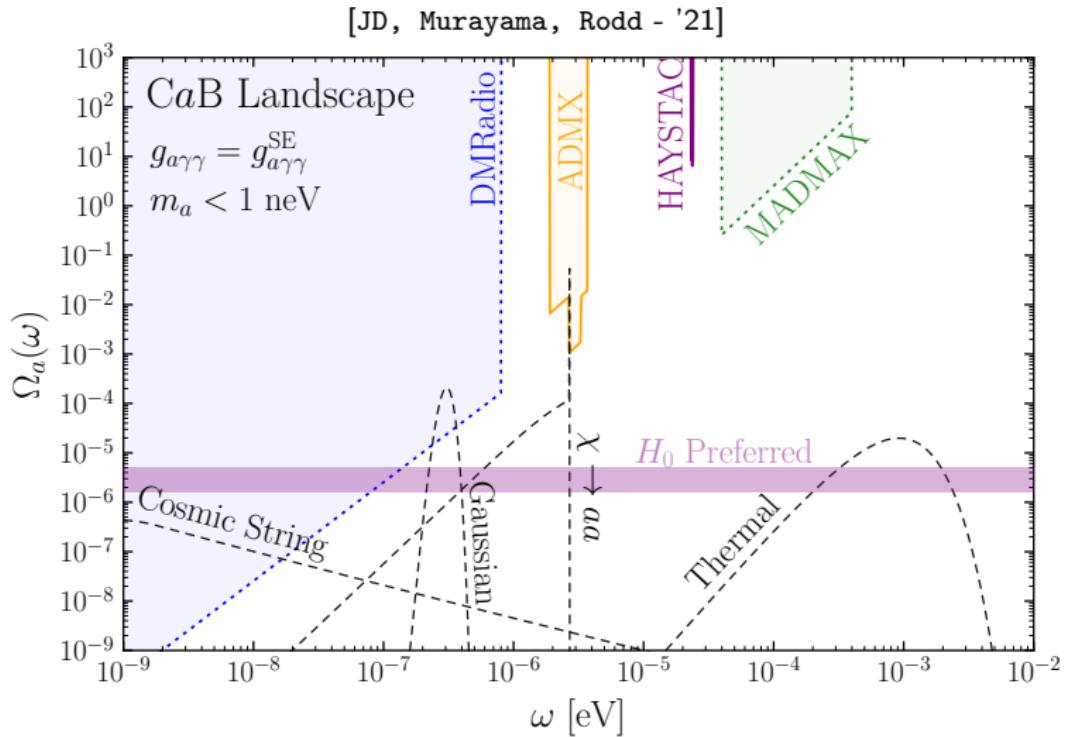
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