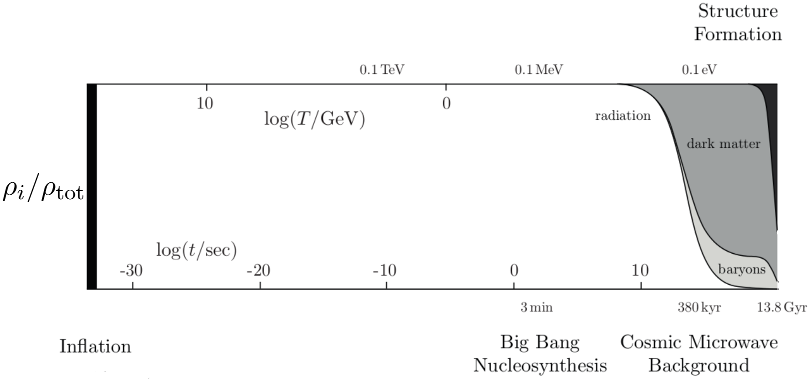
The Cosmic Axion Background

Jeff Dror

JD w/ Rodd & Murayama
2101.09287
...



[Bkg photo: Baumann - 2013]

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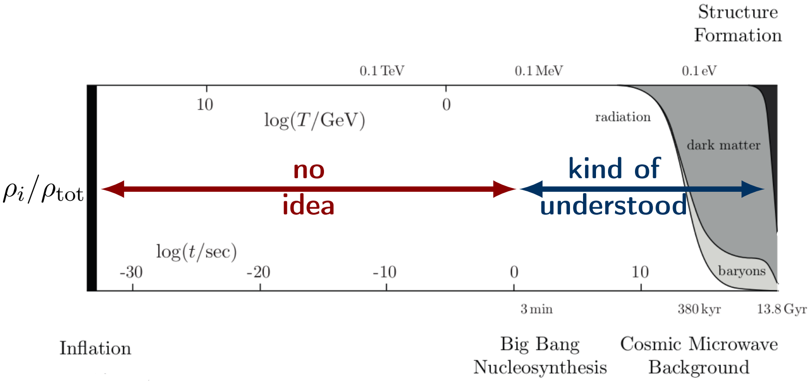

no idea

kind of understood

[Bkg photo: Baumann - 2013]

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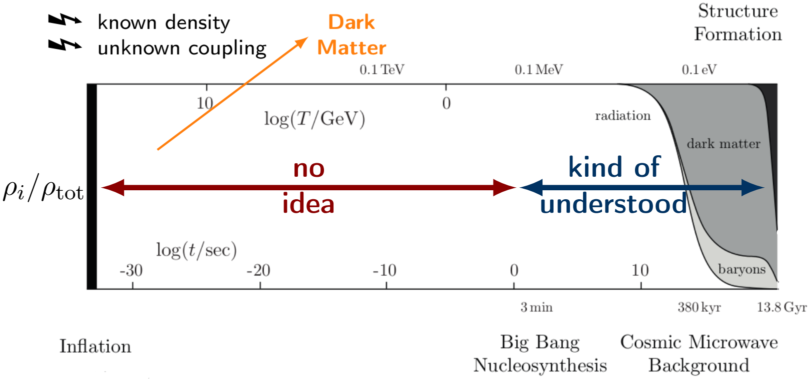

- known density
- unknown coupling

Dark Matter

no idea

kind of understood

[Bkg photo: Baumann - 2013]

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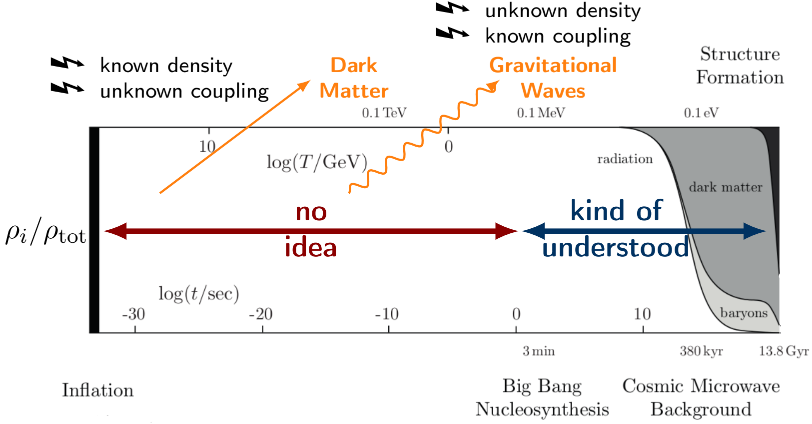

↯ known density
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Gravitational Waves

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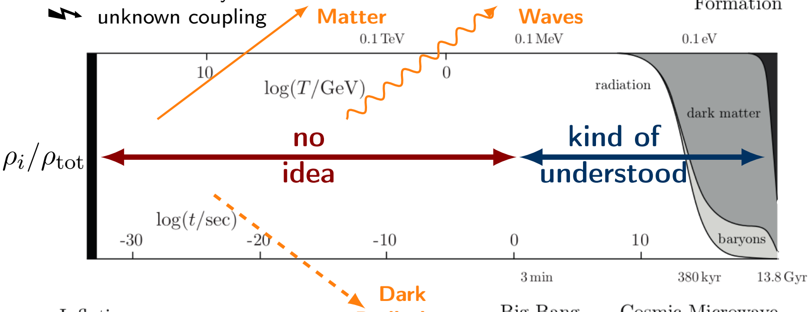

no idea

kind of understood

- known density
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Dark Matter

- unknown density
- known coupling

Gravitational Waves

Structure Formation

Dark Radiation

- unknown density
- unknown coupling

Inflation

Big Bang Nucleosynthesis

Cosmic Microwave Background

[Bkg photo: Baumann - 2013]

Outline

What

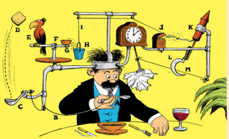
Why

How

C*a*B?

Detection

Production

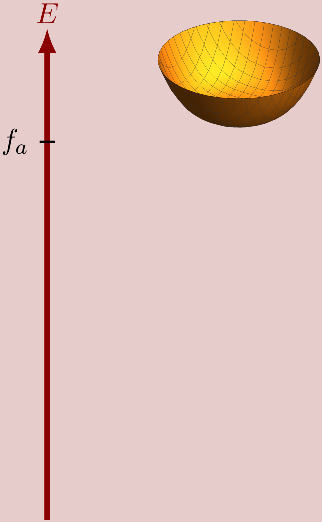


Axions and dark radiation

Why axions?

Energy scales

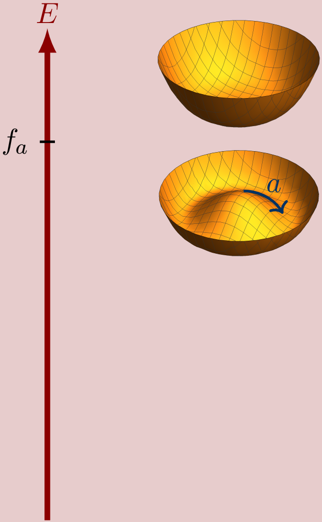
Global
symmetry



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

Why axions?

Energy scales



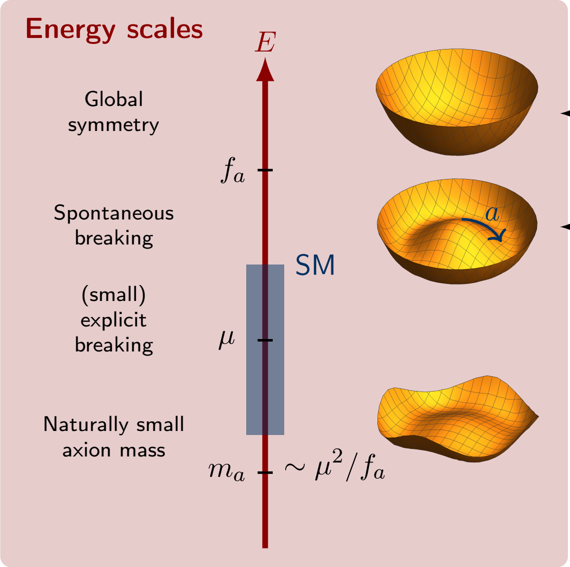
Global symmetry

Spontaneous breaking

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

$$\Phi = (\chi + f_a)e^{ia/f_a}$$

Why axions?



Energy scales

E

Global symmetry

f_a

Spontaneous breaking

SM

(small) explicit breaking

μ

Naturally small axion mass

$m_a \sim \mu^2/f_a$

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

$$\Phi = (\chi + f_a)e^{ia/f_a}$$

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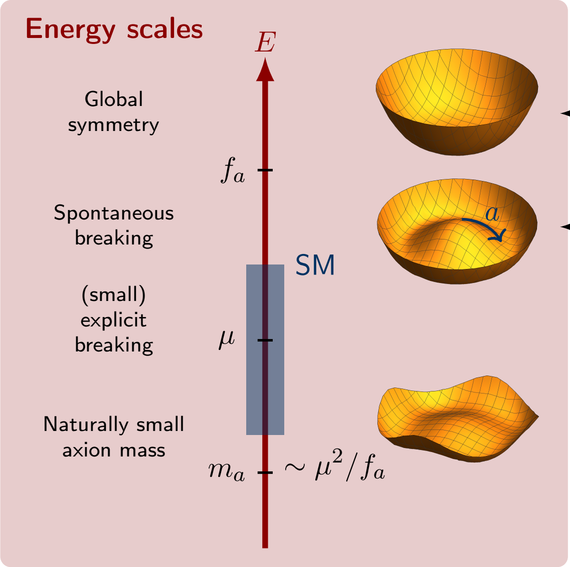

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$$\Phi = (\chi + f_a)e^{ia/f_a}$$

One axion or an entire axi-verse?

[Svrcek, Witten - hep-th/0605206]
[Arvanitaki et al - 0905.4720]
[Halverson et al - 1903.04495]
[Halverson et al - 1909.05257]
...

Axion detection

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

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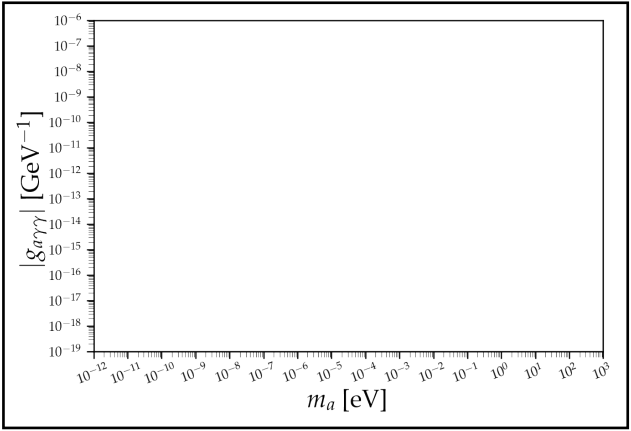

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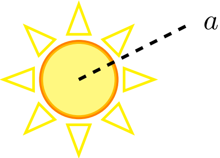
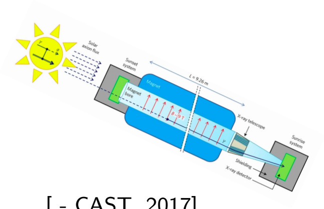
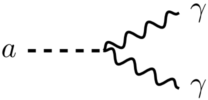
direct production





[- CAST, 2017]



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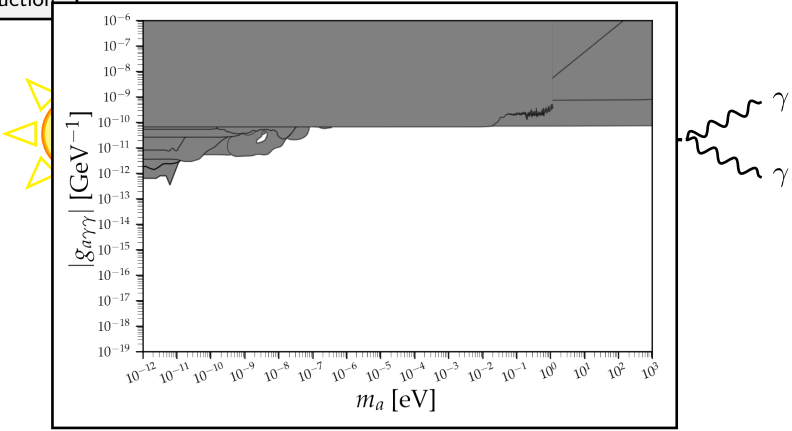

[compiled at - https://github.com/cajohare/AxionLimits]

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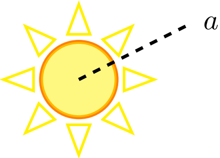

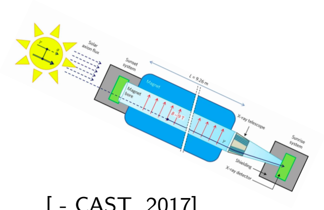

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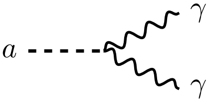
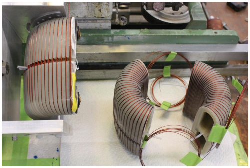


axion dark matter

e.g., ADMX

[- Scientific American]

e.g., ABRACADBRA



[- abracadabra.mit.edu/]

Axion detection

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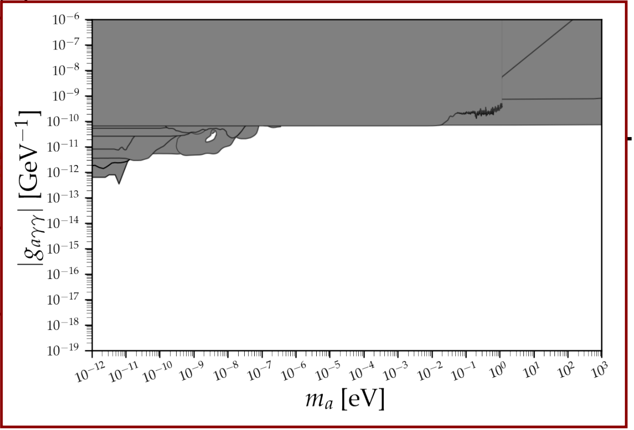
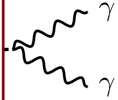
direct production

axion dark matter





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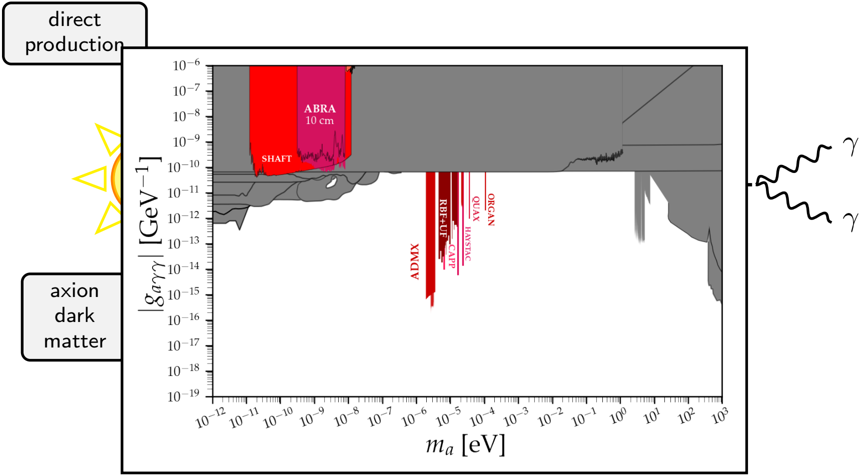

direct production

axion dark matter

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

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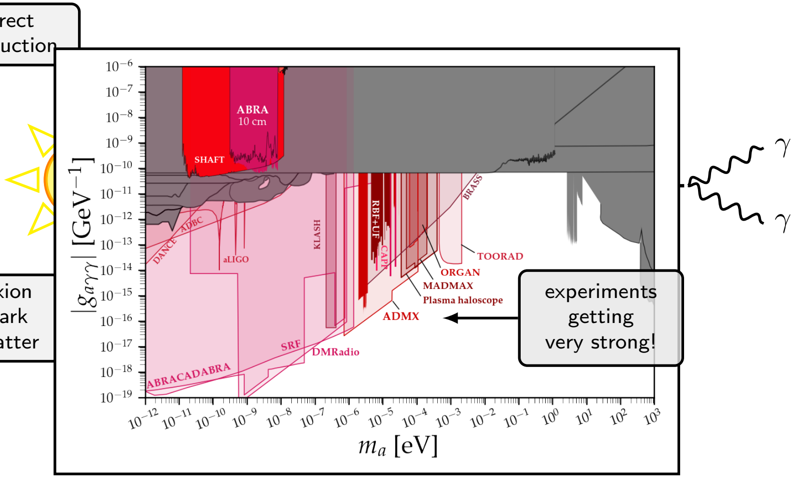

direct production

axion dark matter

experiments getting very strong!

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

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Population of relativistic axions?

Copiously produced in early universe

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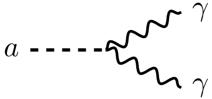
Population of relativistic axions?

Copiously produced in early universe

Light axions are stable



$$\frac{\Gamma}{H_0} \sim \left(\frac{m_a}{100\ \mathrm{eV}}\right)^3 \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^2$$

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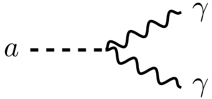

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Could be responsible for H_0-tension ("universe-age" mystery)

$$\tau_{\text{universe}} = \begin{cases} 12.7 \pm 0.1\ \text{byr} & \text{(late)} \\ 13.7 \pm 0.1\ \text{byr} & \text{(early)} \end{cases}$$

[`Verde, Treu, Riess` - 1907.10625]
[`Planck` - 1807.06209]

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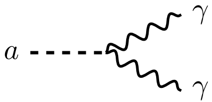

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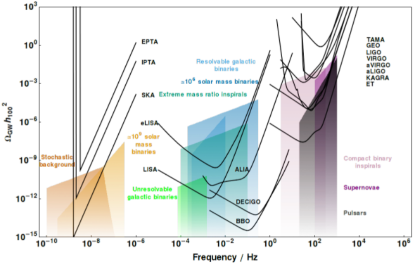
[`Verde, Treu, Riess` - 1907.10625]
[`Planck` - 1807.06209]

$\rho_a \sim \rho_\gamma$

Seeing the axi-verse through $g_{a\gamma\gamma}$

[`Moore,Cole,Berry` - 1408.0740]



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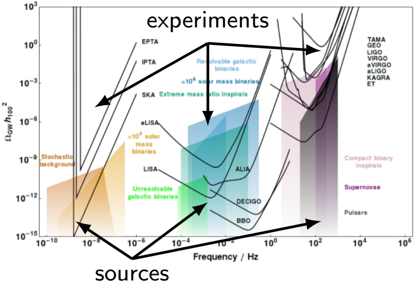

experiments

sources

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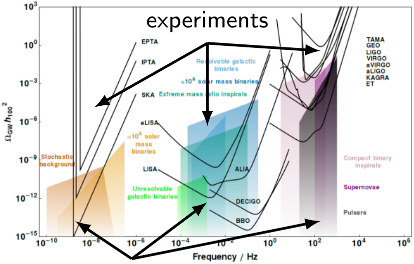
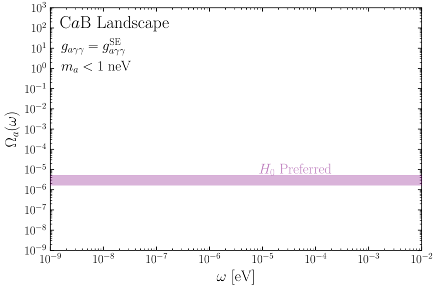


experiments

sources

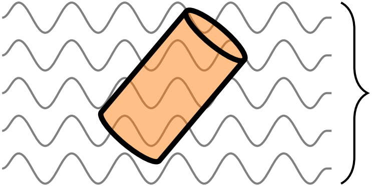
[JD, Murayama, Rodd - '21]



dark radiation analog

Calculating experimental sensitivities

Experimental power



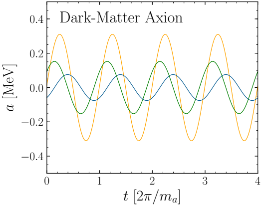
$$\xrightarrow{\text{sampled from}} \quad p(\vec{\mathbf{v}}) \sim e^{-|\vec{\mathbf{v}}|^2/v_0^2}$$

mostly same freq

$$a(t) \propto \sum_i \cos(m_a(1 + v_i^2/2)t + \varphi_i)$$

Experimental power

Axion dark matter $\xrightarrow{\text{sampled from}}$ $p(\vec{\mathbf{v}}) \sim e^{-|\vec{\mathbf{v}}|^2/v_0^2}$



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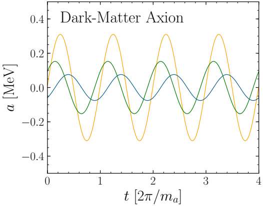

$$a(t) \propto \sum_i \cos(m_a(1 + v_i^2/2)t + \varphi_i)$$

$$\boxed{\rho_a(m_a) = Q_a\ m_a\ n_a}$$

$\frac{d\rho_a}{d\log\omega}$

$\mathcal{O}(10^6)$

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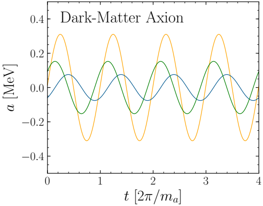

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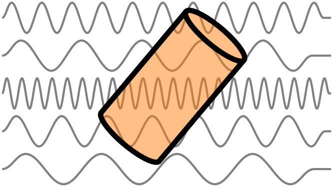
CaB $\xrightarrow{\text{sampled from}}$ $p(\omega) = ?$

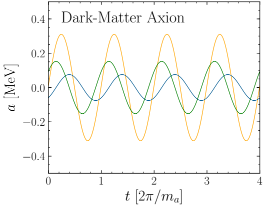


large
freq
spread

$$a(t) \propto \sum_i \cos(\omega_i t + \mathbf{k}_i \cdot \mathbf{x} + \varphi_i)$$

Experimental power

Axion dark matter $\xrightarrow{\text{sampled from}}$ $p(\vec{\mathbf{v}}) \sim e^{-|\vec{\mathbf{v}}|^2/v_0^2}$



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$\frac{d\rho_a}{d\log\omega}$ $\mathcal{O}(10^6)$

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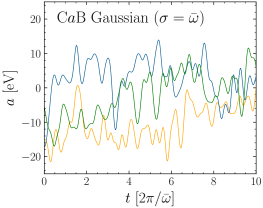

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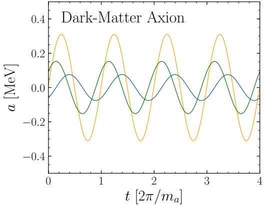

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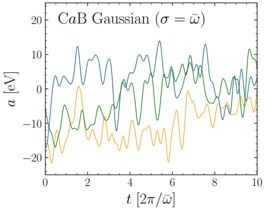
$\frac{d\rho_a}{d\log\omega}$ → $\rho_a(m_a)$

Q_a ← $\mathcal{O}(10^6)$

CaB $\xrightarrow{\text{sampled from}}$ $p(\omega) = ?$



$$a(t) \propto \sum_i \cos(\omega_i t + \mathbf{k}_i \cdot \mathbf{x} + \varphi_i)$$

$$\rho_a(\bar{\omega}) = Q_a \; \bar{\omega} \; n_a$$

Q_a ← often $\mathcal{O}(1)$

Axion electrodynamics

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

Axion electrodynamics

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

$$\boxed{\begin{aligned}
&\nabla\cdot\mathbf{E} = \rho - g_{a\gamma\gamma}(\nabla a)\cdot\mathbf{B}\\
&\nabla\times\mathbf{E} = -\dot{\mathbf{B}}\\
&\nabla\cdot\mathbf{B} = 0\\
&\nabla\times\mathbf{B} = \dot{\mathbf{E}} + \mathbf{J} + g_{a\gamma\gamma}(\dot{a}\mathbf{B} + \nabla a\times\mathbf{E})
\end{aligned}}$$

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\end{aligned}} \longleftarrow \text{effective charge}$$

Axion electrodynamics

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\end{aligned}}$$

← effective charge

← effective current

Axion electrodynamics

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$$\boxed{\begin{aligned}
&\nabla\cdot\mathbf{E} = \rho - g_{a\gamma\gamma}\cancel{(\nabla a)}\cdot\mathbf{B}\\
&\nabla\times\mathbf{E} = -\dot{\mathbf{B}}\\
&\nabla\cdot\mathbf{B} = 0\\
&\nabla\times\mathbf{B} = \dot{\mathbf{E}} + \mathbf{J} + g_{a\gamma\gamma}(\dot{a}\mathbf{B} + \cancel{\nabla a\times\mathbf{E}})
\end{aligned}}$$

effective charge

effective current

Dark Matter

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

Axion electrodynamics

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

$$\begin{aligned}
&\nabla\cdot\mathbf{E} = \rho - g_{a\gamma\gamma}(\nabla a)\cdot\mathbf{B} \\
&\nabla\times\mathbf{E} = -\dot{\mathbf{B}} \\
&\nabla\cdot\mathbf{B} = 0 \\
&\nabla\times\mathbf{B} = \dot{\mathbf{E}} + \mathbf{J} + g_{a\gamma\gamma}(\dot{a}\mathbf{B} + \nabla a\times\mathbf{E})
\end{aligned}$$

effective charge

effective current

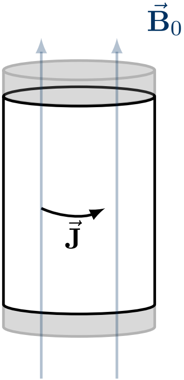
Dark Matter

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

CaB

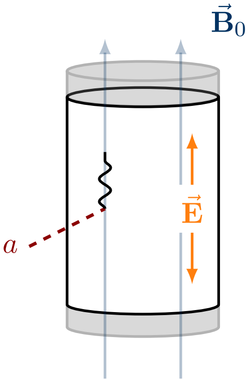
- current + charge
- dependence on direction

Resonant cavities



e.g., ADMX,
HAYSTAC

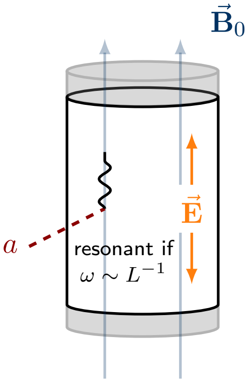
Resonant cavities



e.g., ADMX, HAYSTAC

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

Resonant cavities

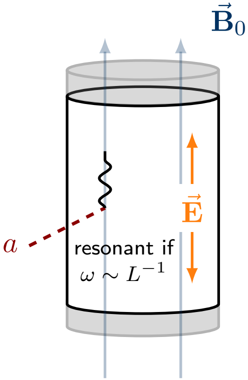


resonant if
$\omega \sim L^{-1}$

e.g., ADMX,
HAYSTAC

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

Resonant cavities



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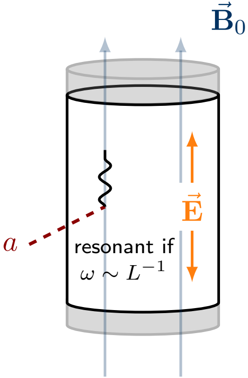
$$(\nabla^2 - \partial_t^2)\vec{\mathbf{E}} = g_{a\gamma\gamma}\left(\vec{\mathbf{B}}_0 \partial_t^2 a - (\vec{\mathbf{B}}_0 \cdot \vec{\nabla})\vec{\nabla} a\right)$$

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

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

3) Insert and solve for A_n

Resonant cavities



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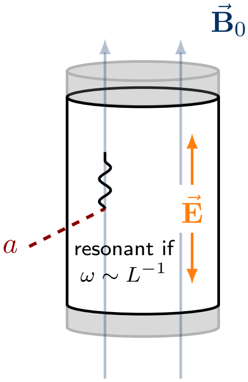
new term

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

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

Resonant cavities



e.g., ADMX, HAYSTAC

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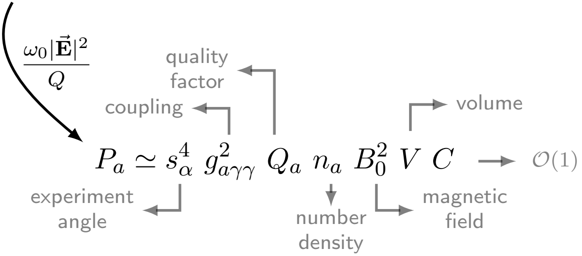
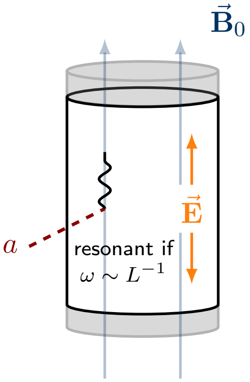


$$P_a \simeq s_\alpha^4 \; g_{a\gamma\gamma}^2 \; Q_a \; n_a \; B_0^2 \; V \; C \longrightarrow \mathcal{O}(1)$$

Resonant cavities



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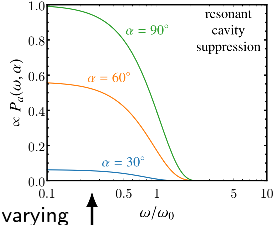


$\cos\alpha$

varying angles

daily/ yearly modulation

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

quality factor

coupling

volume

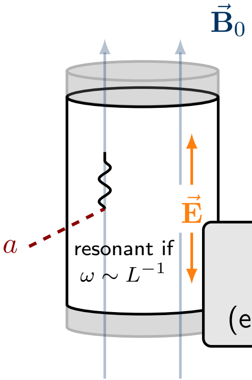
$$P_a \simeq s_\alpha^4 \; g_{a\gamma\gamma}^2 \; Q_a \; n_a \; B_0^2 \; V \; C \rightarrow \mathcal{O}(1)$$

experiment angle

number density

magnetic field

Resonant cavities



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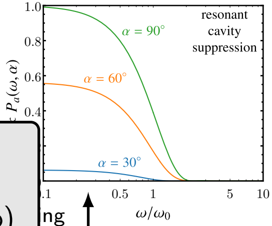
3) Insert and solve for A

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

ng
es



daily/ yearly modulation

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Simplified projections

simplified limits

$$P_a^{\mathrm{DM}}(\omega) = P_a^{\mathsf{C}a\mathsf{B}}(\omega)$$

caution: DM may be easier to see

Simplified projections

simplified limits

$$P_a^{\mathrm{DM}}(\omega) \ = \ P_a^{\mathsf{C}a\mathsf{B}}(\omega)$$

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$$g_{a\gamma\gamma}^2(\omega)\ \Omega_{\mathrm{DM}} Q_{\mathrm{DM}} \ = \ \Omega_a(\omega)\ (g_{a\gamma\gamma}^{\mathrm{SE}})^2 Q_a$$

Simplified projections

simplified limits

$$P_a^{\mathrm{DM}}(\omega) \;=\; P_a^{\mathsf{C}a\mathsf{B}}(\omega)$$

caution: DM may be easier to see

$$g_{a\gamma\gamma}^2(\omega)\;\underset{\substack{\downarrow\\ \sim 10^6}}{\Omega_{\mathrm{DM}}Q_{\mathrm{DM}}} \;=\; \Omega_a(\omega)\;(\underset{\substack{\downarrow\\ \sim 10^{-10}\ \mathrm{GeV}^{-1}}}{g_{a\gamma\gamma}^{\mathrm{SE}}})^2\underset{\substack{\downarrow\\ \sim 1}}{Q_a}$$

Simplified projections

simplified limits

$$P_a^{\mathrm{DM}}(\omega) = P_a^{\mathsf{C}a\mathsf{B}}(\omega)$$

caution: DM may be easier to see

$$g_{a\gamma\gamma}^2(\omega)\;\Omega_{\mathrm{DM}} Q_{\mathrm{DM}} = \Omega_a(\omega)\;(g_{a\gamma\gamma}^{\mathrm{SE}})^2 Q_a$$

1 bin

$\Omega_{\mathrm{DM}} Q_{\mathrm{DM}} \downarrow\ \sim 10^6$

$g_{a\gamma\gamma}^{\mathrm{SE}} \downarrow\ \sim 10^{-10}\ \mathrm{GeV}^{-1}$

$Q_a \rightarrow\ \sim 1$

$$\Omega_a \simeq \Omega_{\mathrm{DM}} \left(\frac{g_{a\gamma\gamma}}{g_{a\gamma\gamma}^{\mathrm{SE}}}\right)^2 \sqrt{\frac{Q_{\mathrm{DM}}}{Q_a}}$$

all bins

Simplified projections

simplified limits

$$P_a^{\rm DM}(\omega) = P_a^{\mathsf{C}a\mathsf{B}}(\omega)$$

caution: DM may be easier to see

$$g^2_{a\gamma\gamma}(\omega)\ \underbrace{\Omega_{\rm DM} Q_{\rm DM}}_{\sim 10^6} = \Omega_a(\omega)\ \underbrace{(g^{\rm SE}_{a\gamma\gamma})^2}_{\sim 10^{-10}\ \mathrm{GeV}^{-1}} \underbrace{Q_a}_{\sim 1}$$

1 bin

$$\Omega_a \simeq \underbrace{\Omega_{\rm DM}}_{\text{lose}} \underbrace{\left(\frac{g_{a\gamma\gamma}}{g^{\rm SE}_{a\gamma\gamma}}\right)^2}_{\text{win}} \sqrt{\frac{Q_{\rm DM}}{Q_a}}$$

all bins

Simplified projections

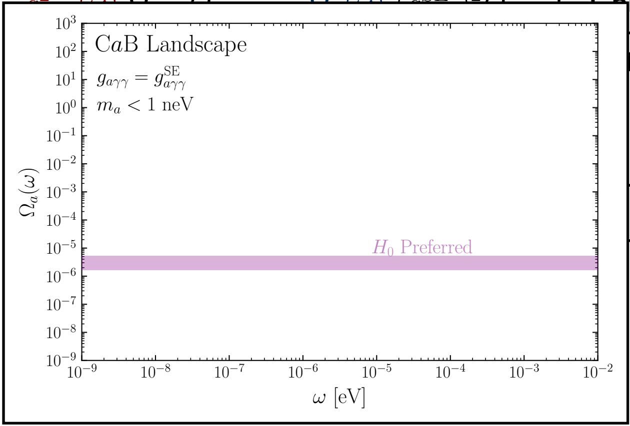
simplified limits

$$P_a^{\mathrm{DM}}(\omega) \;=\; P_a^{\mathsf{C}a\mathsf{B}}(\omega)$$

caution: DM may be easier to see

1 bin

ins



Simplified projections

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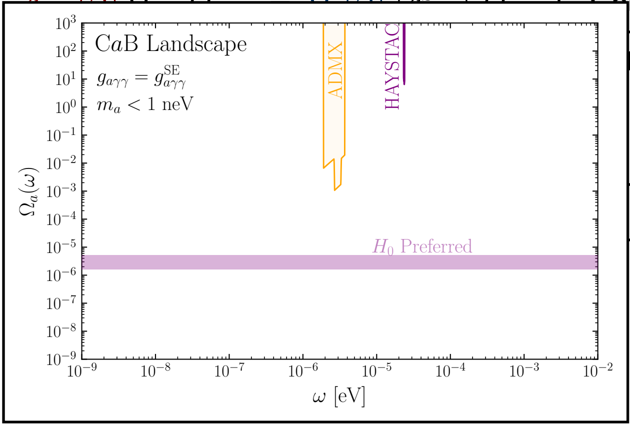

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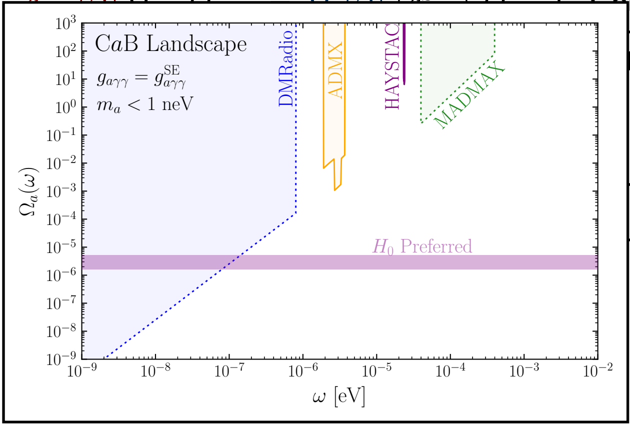


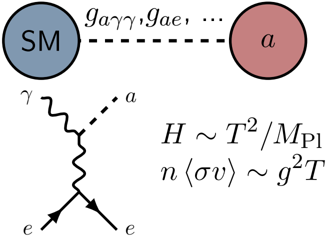
Producing a cosmic axion background

Thermal axions

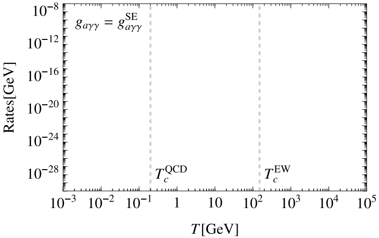
Thermalization with Standard Model

Thermal axions

Thermalization with Standard Model

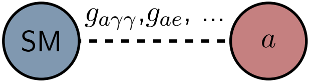


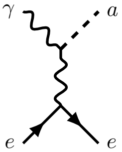
$$H \sim T^2/M_{\rm Pl}$$
$$n\,\langle \sigma v \rangle \sim g^2 T^3$$



Thermal axions

Thermalization with Standard Model





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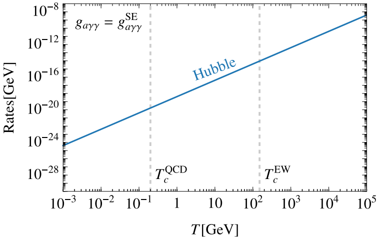
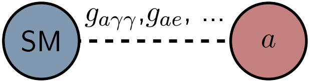
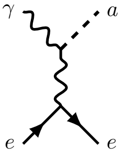


Thermalization with Standard Model





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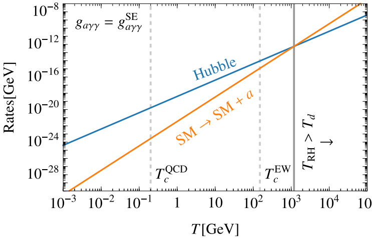

Thermal axions

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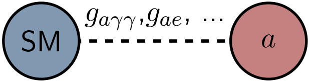

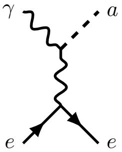

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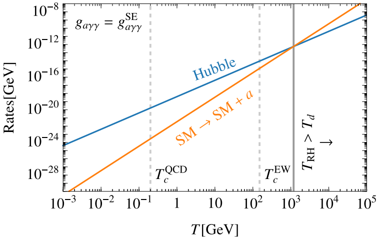

abundance dilutes with
Standard Model evolution

$$\frac{\rho_a}{\rho_\gamma} = \frac{1}{g_*(T_0)}\left(\frac{g_{*,S}(T_0)}{g_{*,S}(T_d)}\right)^{4/3}$$

Decoupling temperature

other interactions drive equilibrium?

Thermal production - spectrum

spectrum (almost) fixed

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

T_d is free-ish

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

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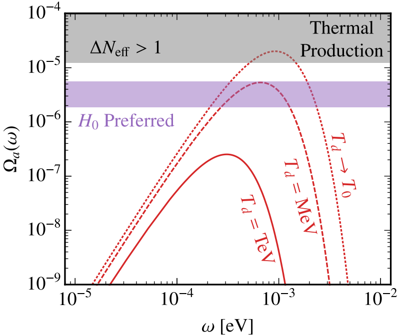

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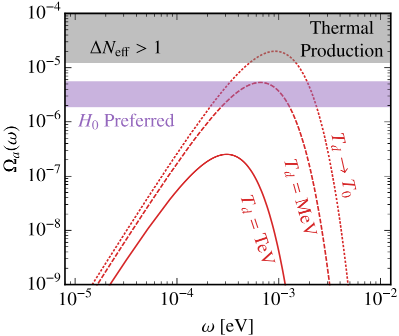

Detection prospects

small numbers - $\mathcal{O}(10^3/\mathrm{cm}^3)$

small energy deposits

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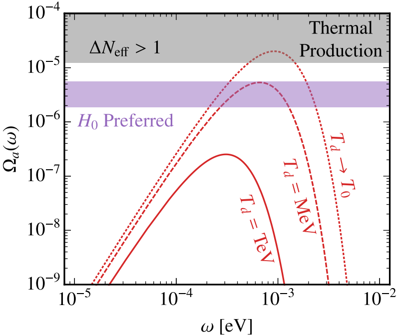


Detection prospects

small numbers - $\mathcal{O}(10^3/\mathrm{cm}^3)$

small energy deposits

dedicated experiment?

$$N_{a\to\gamma} \simeq 10^9\left(\frac{n_a}{100/\mathrm{cm}^3}\right)\left(\frac{g_{a\gamma\gamma}}{g_{a\gamma\gamma}^{\rm SE}}\right)^2\left(\frac{B_0}{10\ \mathrm{T}}\right)^2\left(\frac{L}{10\ \mathrm{m}}\right)^4\left(\frac{t_{\rm exp}}{\mathrm{year}}\right)$$

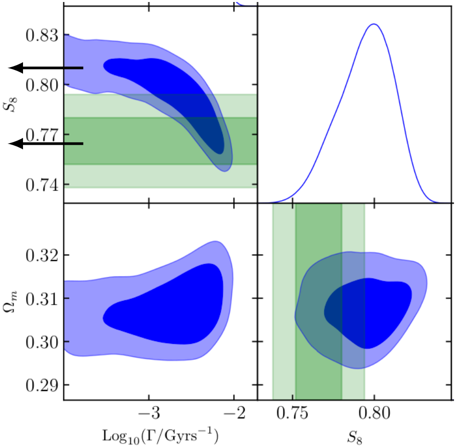
Indirect detection

Dark matter decaying into axions?

Dark matter decaying into axions?

Planck+ measurements

Local (lensing) measurements



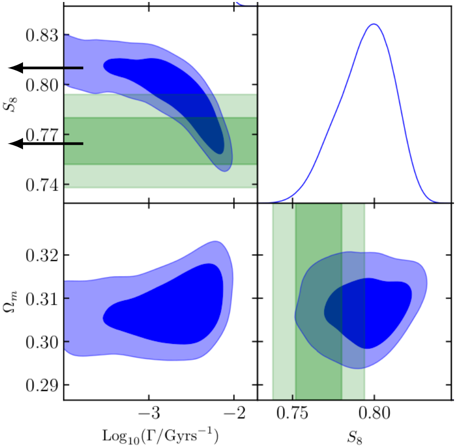
Suggests
$\Gamma \sim 100$ Gyr

[2102.12498
Abellan, Murgia, Poulin]

Dark matter decaying into axions?

Planck+ measurements

Local (lensing) measurements



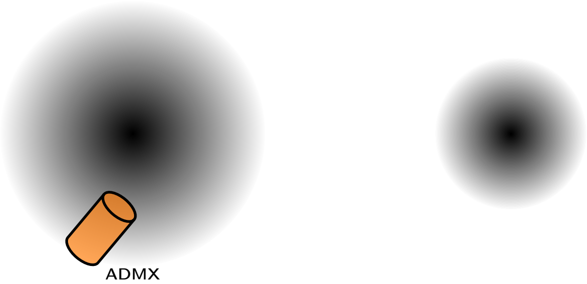
[2102.12498 Abellan, Murgia, Poulin]

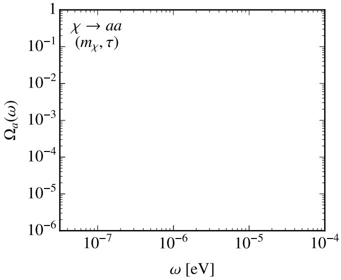
Suggests $\Gamma \sim 100$ Gyr

example model

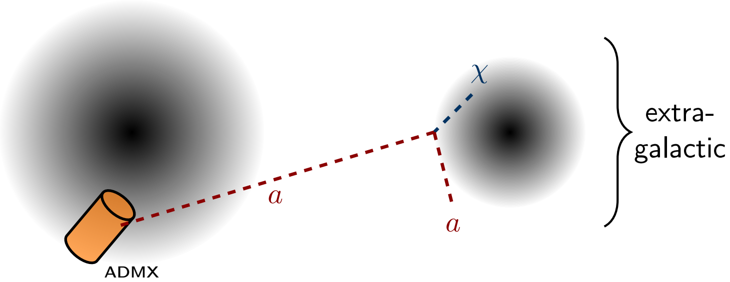
$$V(\Phi) = \lambda^2 \left(|\Phi|^2 - f_a^2 \right)^2 \qquad \Phi = (\chi + f_a)\, e^{ia/f_a}$$

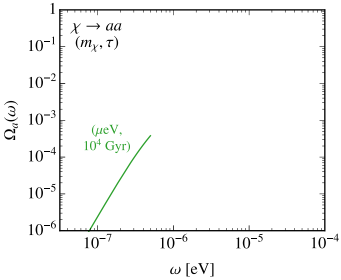
Dark matter decay



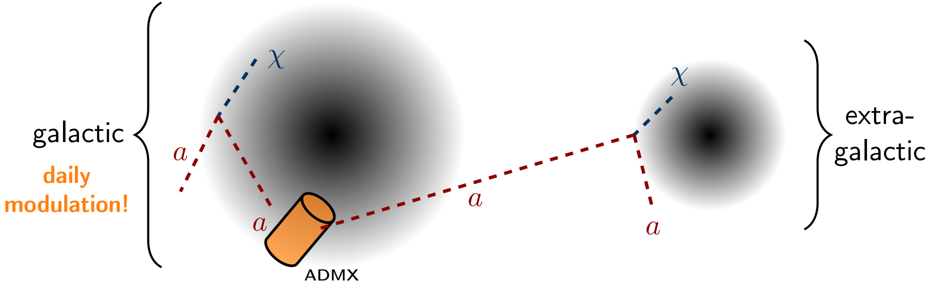


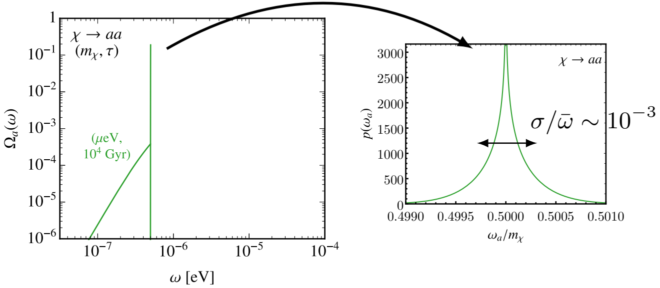
Dark matter decay





Dark matter decay

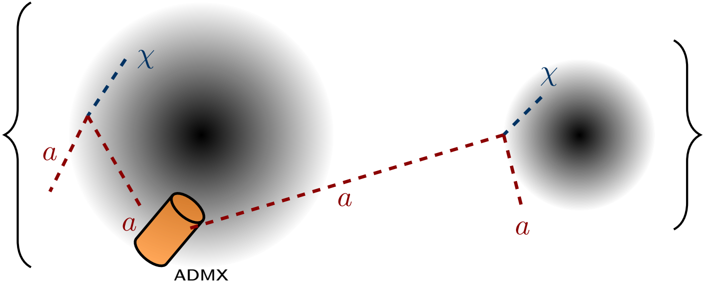




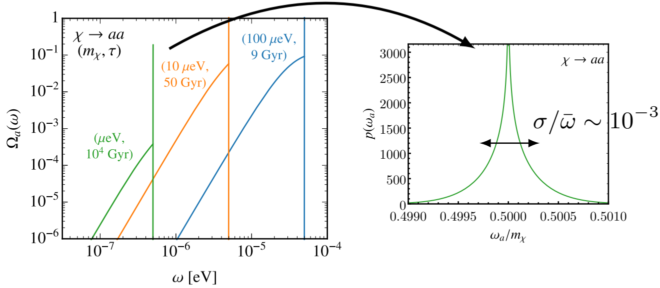
Dark matter decay

galactic

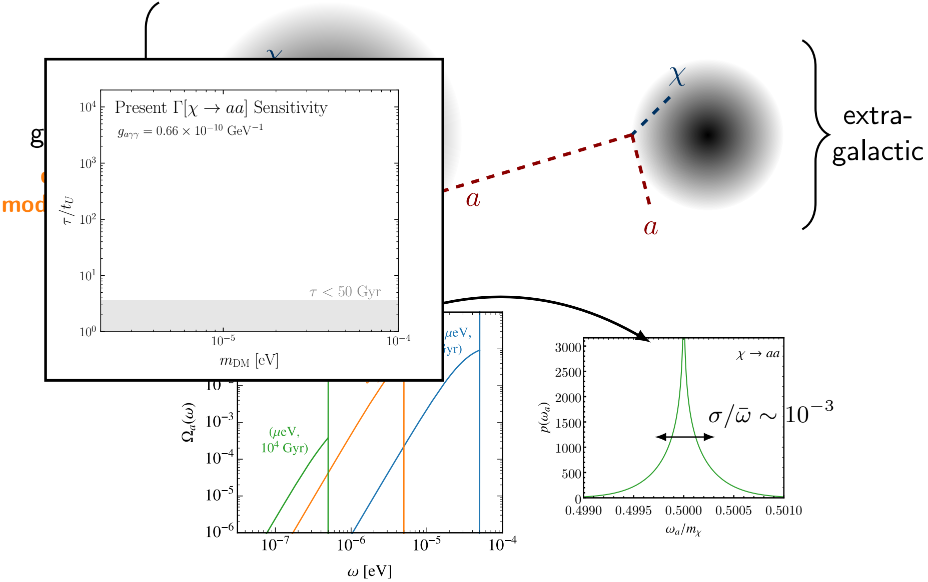
daily modulation!



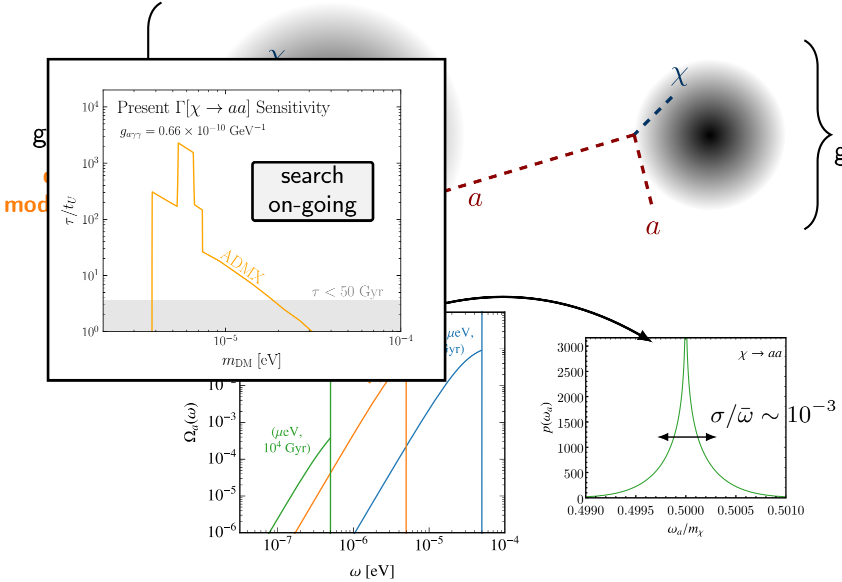
extra-galactic



Dark matter decay



Dark matter decay

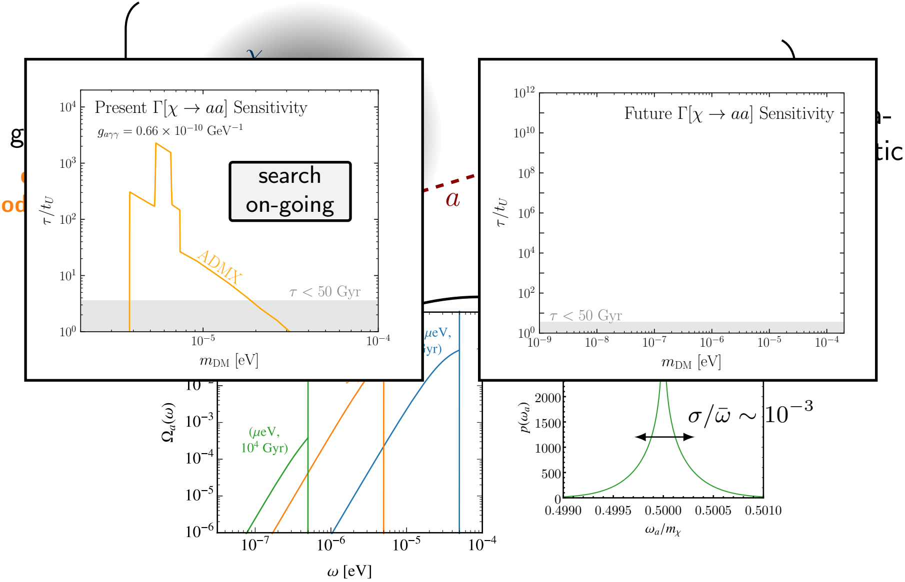


search on-going

extra-galactic

$\sigma/\bar{\omega} \sim 10^{-3}$

Dark matter decay



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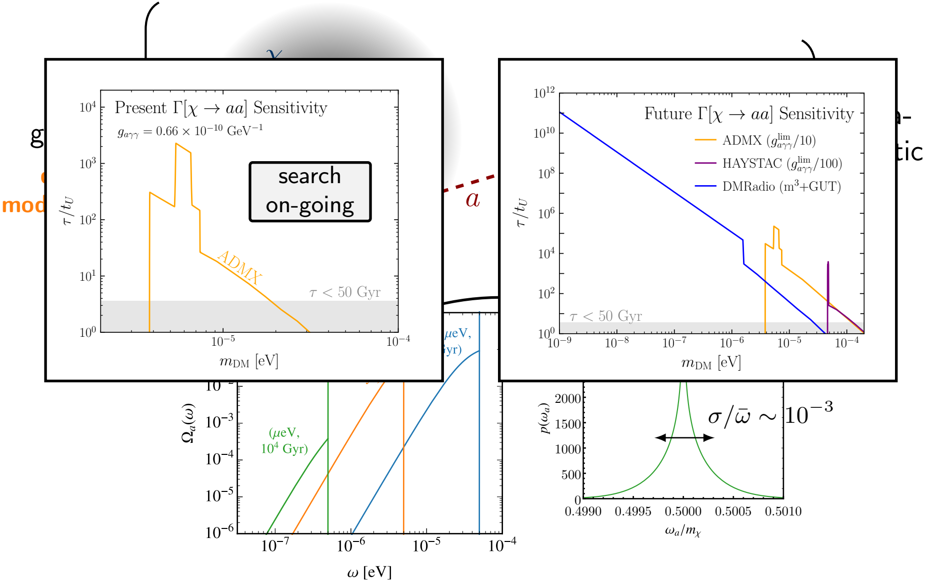
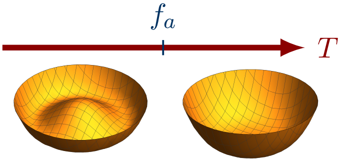
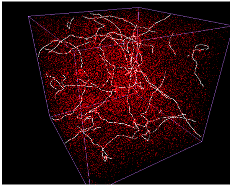


Cosmic strings

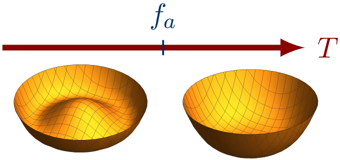


strings form upon symmetry breaking



[- Ringeval, Bouchet]

Cosmic strings



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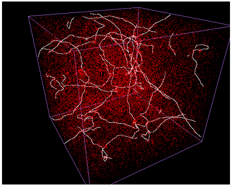
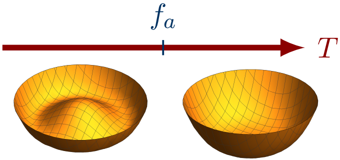


[- Ringeval, Bouchet]

string evolution

Cosmic strings



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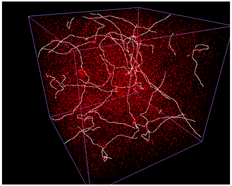


[- Ringeval, Bouchet]

string evolution

most of energy
radiated in axions

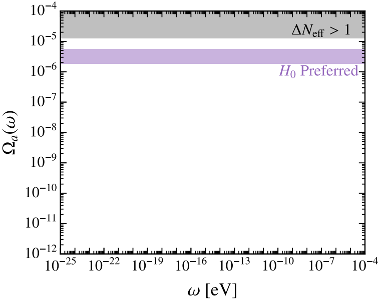
large loop
emission dominates?

calculate axions
semi-analytically

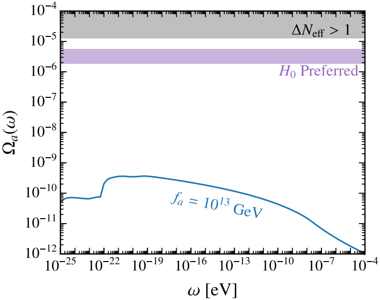
[`Gorghetto, Hardy, Villadoro` - 1806.04677,2007.04990]

Cosmic strings

The string spectrum



The string spectrum



Cosmic strings

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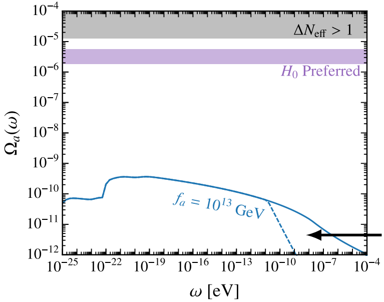
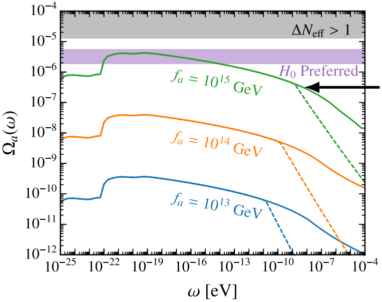


uncertainty in start of scaling

see, e.g., `[Hindmarsh, Lizarraga, Lopez-Eiguren, Urrestilla 2102.07723]`

Cosmic strings

The string spectrum

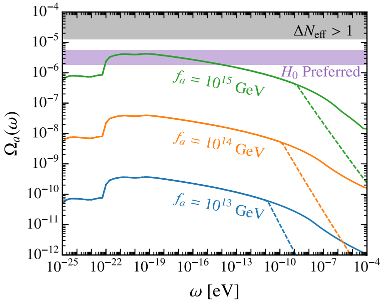


large f_a
needed
for $\rho_a \sim \rho_\gamma$

see, e.g., `[Hindmarsh, Lizarraga, Lopez-Eiguren, Urrestilla 2102.07723]`

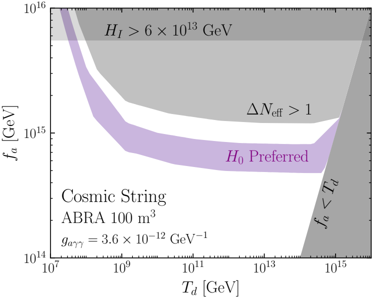
Cosmic strings

The string spectrum



[Hindmarsh, Lizarraga,
see, e.g., Lopez-Eiguren, Urrestilla
2102.07723]

Experimental sensitivity

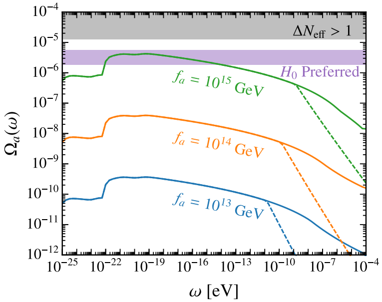


$f_a \lesssim 10^{14}$ GeV if $m_a \lesssim 10^{-28}$

[Lopez-Eiguren, Lizarraga,
Hindmarsh, Urrestilla
1705.04154]

Cosmic strings

The string spectrum



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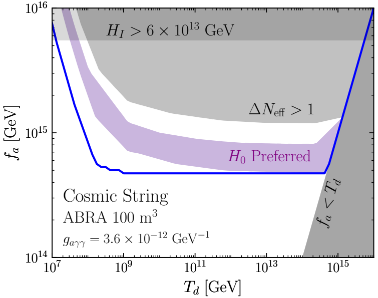

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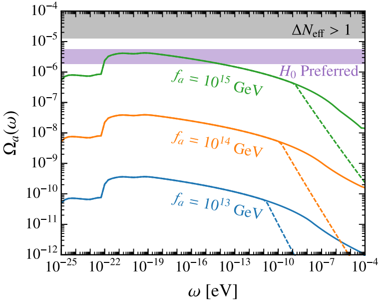

see, e.g., `[Hindmarsh, Lizarraga, Lopez-Eiguren, Urrestilla 2102.07723]`

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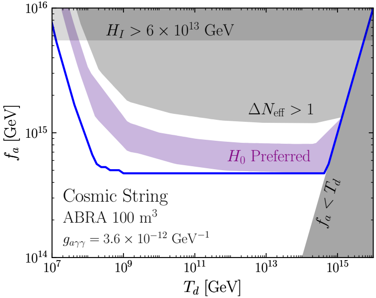

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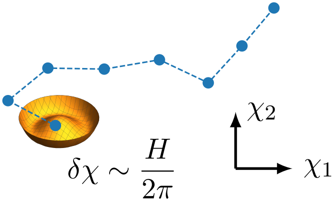
`[Lopez-Eiguren, Lizarraga, Hindmarsh, Urrestilla 1705.04154]`

Upcoming experiments probe $g_{a\gamma\gamma} \gg \dfrac{\alpha}{4\pi f_a}$

Requires clockwork or related mechanisms

Parametric resonance

Scalar pushed
from minimum
during inflation



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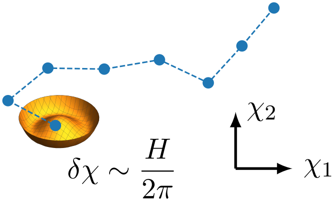

$\chi_i \gg f_a$ at end of inflation

Parametric resonance

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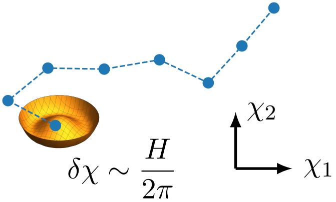
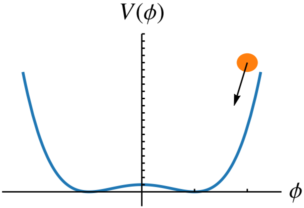


$\chi_i \gg f_a$ at end of inflation

Scalar oscillations
produce axions
when $H \sim m_{\rm eff}(\chi)$



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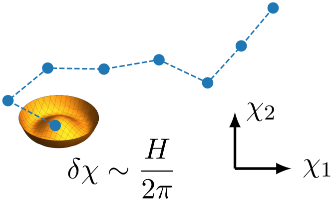

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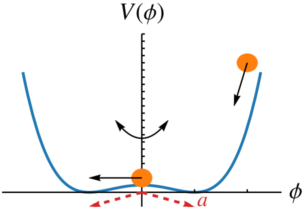

Parametric resonance

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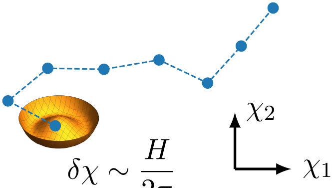
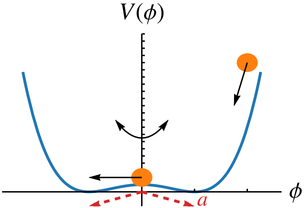


$$\delta\chi \sim \frac{H}{2\pi}$$

$$\boxed{\chi_i \gg f_a \text{ at end of inflation}}$$

Scalar oscillations
produce axions
when $H \sim m_{\rm eff}(\chi)$



$$\Omega_a \sim \text{Gaussian}$$

Parametric resonance

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

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

Typical energy:

Energy density:

Parametric resonance

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

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detectable?

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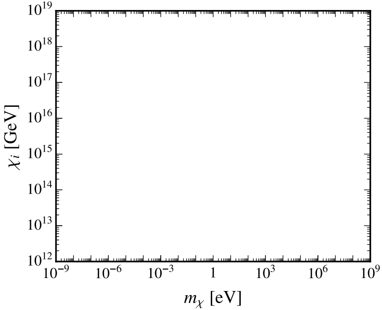
Assume χ dark matter



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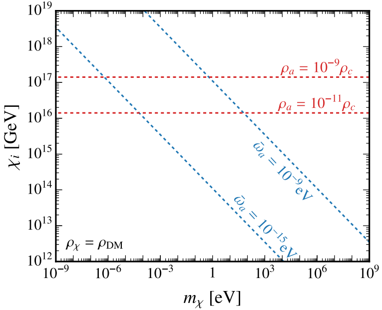

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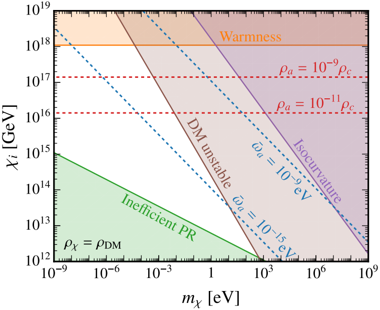

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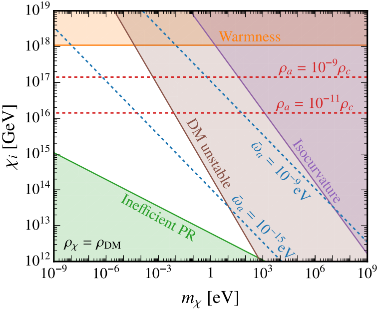

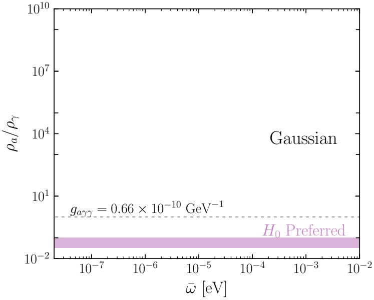

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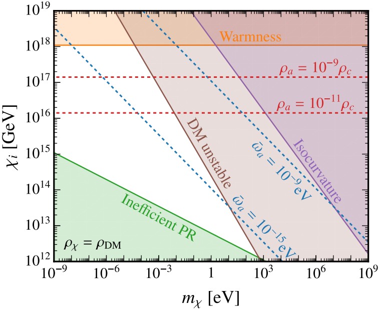

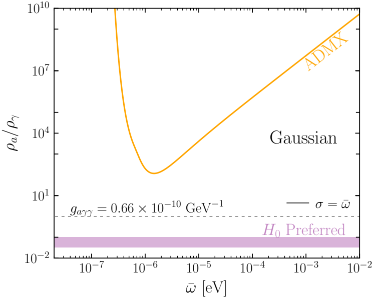

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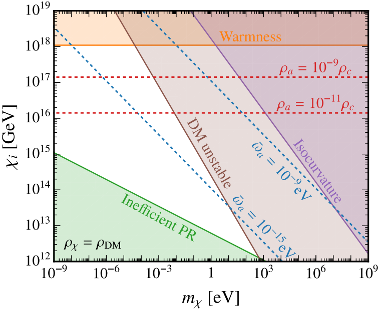

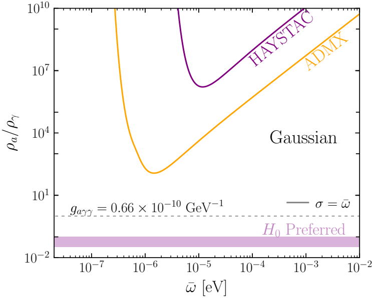

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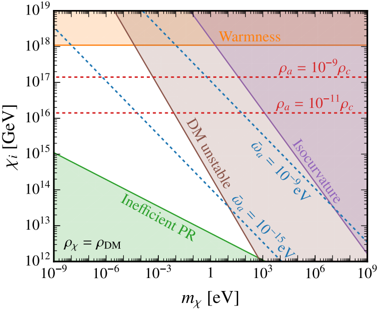
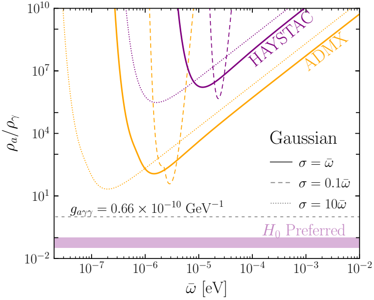
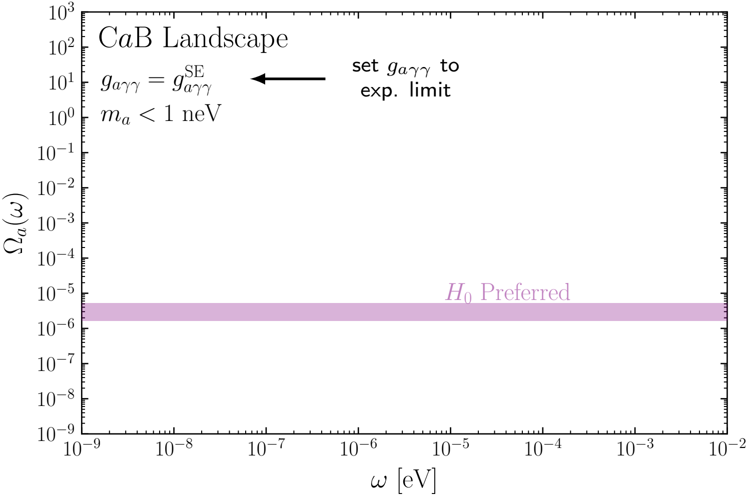




Conclusions: axi-verse through $g_{a\gamma\gamma}$

[JD, Murayama, Rodd - '21]



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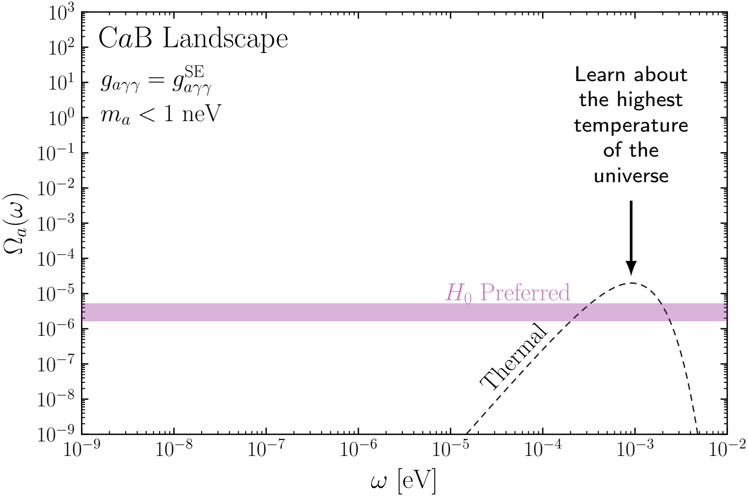
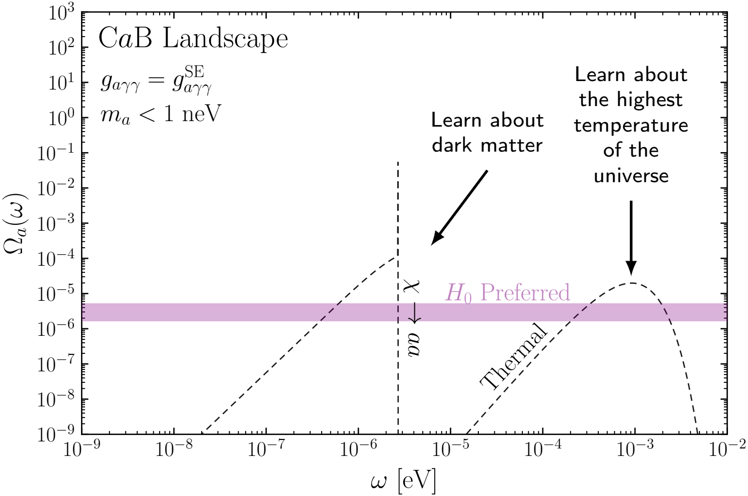


Learn about the highest temperature of the universe

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

[JD, Murayama, Rodd - '21]



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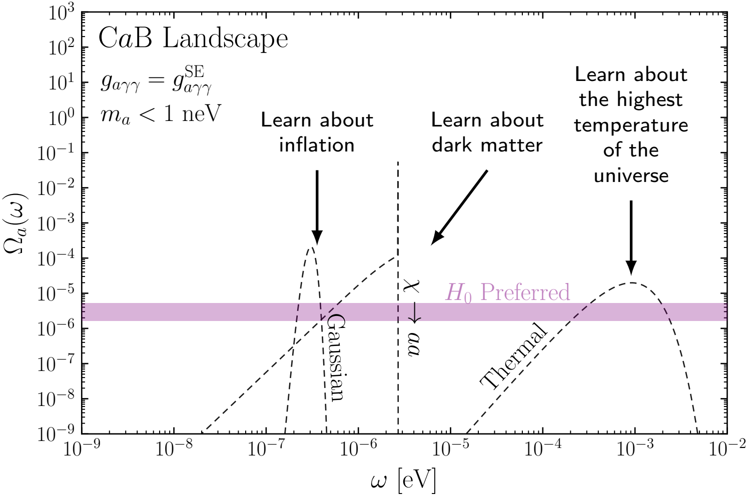

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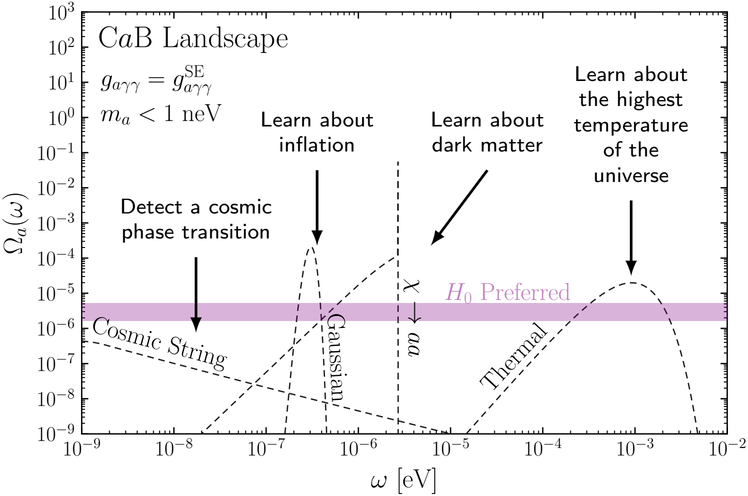


Detect a cosmic phase transition

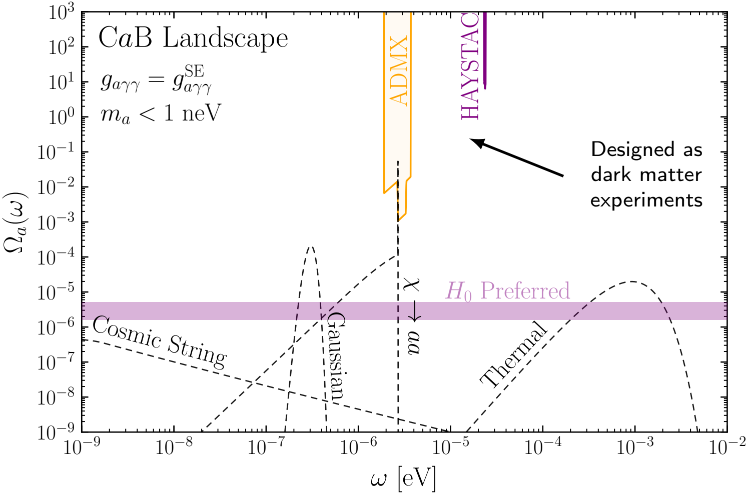
Learn about inflation

Learn about dark matter

Learn about the highest temperature of the universe

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

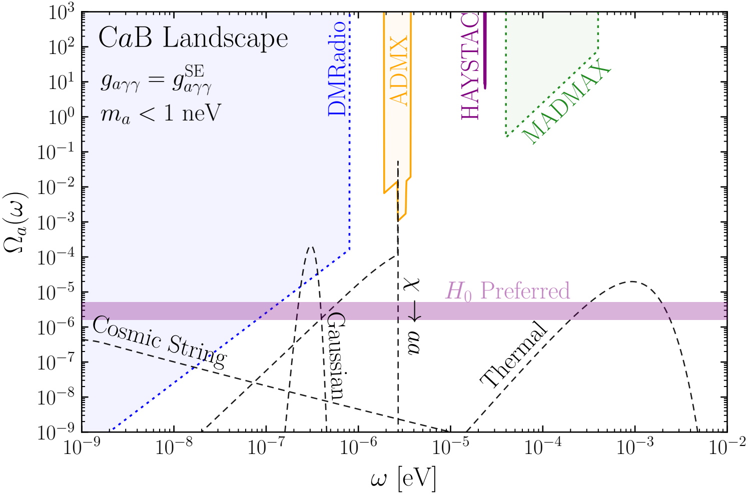
[JD, Murayama, Rodd - '21]



Designed as dark matter experiments

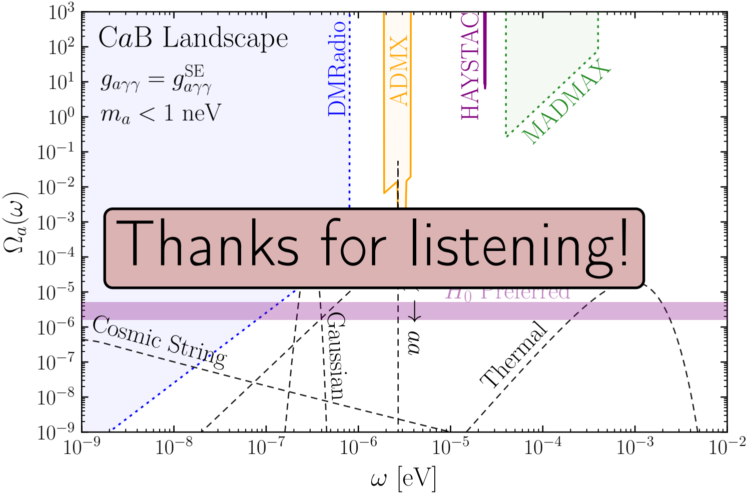
Conclusions: axi-verse through $g_{a\gamma\gamma}$

[JD, Murayama, Rodd - '21]



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

[JD, Murayama, Rodd - '21]



Thanks for listening!

Lumped-element resonators

How to probe $\omega \ll \mathrm{meter}^{-1}$?

$$\vec{\mathbf{J}}_{\mathrm{eff}} = g_{a\gamma\gamma}\vec{\mathbf{B}}_0 \partial_t a - g_{a\gamma\gamma}\vec{\mathbf{E}}_0 \times \nabla a$$

LC circuit for readout

[1310.8545 - Sikivie, Sullivan, Tanner]

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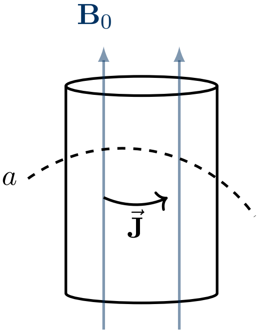

"ABRACADABRA"
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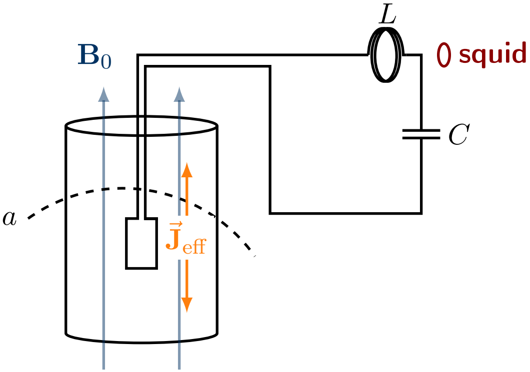

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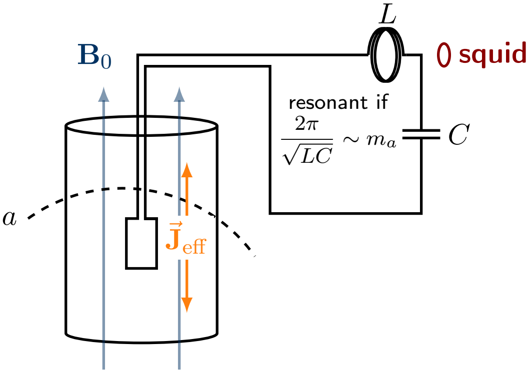

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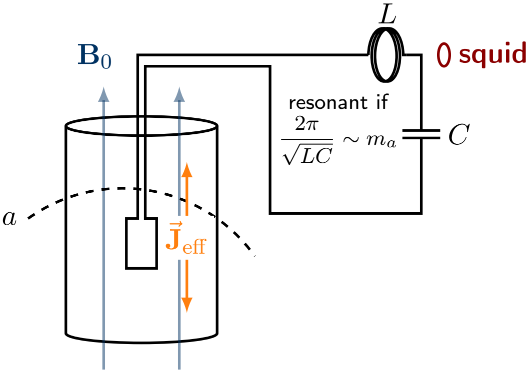

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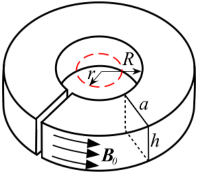
Toroid is better?



[Kahn, Safdi, Thaler 1602.01086]

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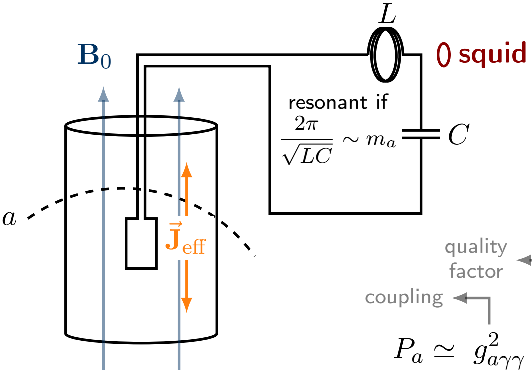

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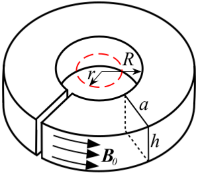

[Kahn, Safdi, Thaler 1602.01086]

$$P_a \simeq \overbrace{g^2_{a\gamma\gamma}}^{\text{coupling}}\ \overbrace{Q_a}^{\text{quality factor}}\ \underbrace{n_a}_{\text{number density}}\ \underbrace{B_0^2}_{\text{magnetic field}}\ \overbrace{V_B}^{\text{volume}}\ C \rightarrow \mathcal{O}(10^{-2})$$