Sensitivity of Spin Precession Experiments

Joint IQ Initiative
& PITT PACC Workshop

Jeff Dror

SUPERGALAX
BREAD
ADMX-HF
Tokyo
ALPHA
OSQAR
RBF
IAXO
ORGAN
DMRadio
LUXE
TASEH
CAPP-12TB
UF
HAYSTAC
SHAFT
ADMX

The Axion

CROWS
QUAX
ABRACADABRA
PVLAS
AMELIE
CULTASK
ALPS
JEDI
CASPEr
QSHS
ADMX-SLIC
FLASH
CADEx
WISPDMX
MADMAX
KLASH
CAST
TASTE
PASSAT
TOORAD
ADBC
BRASS
DANCE
SQuAD

Outline

The Axion Program

Spin Precession Experiments

Noise Sources and Sensitivity

Applications

Outline

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Spin Precession Experiments

Noise Sources and Sensitivity

Applications

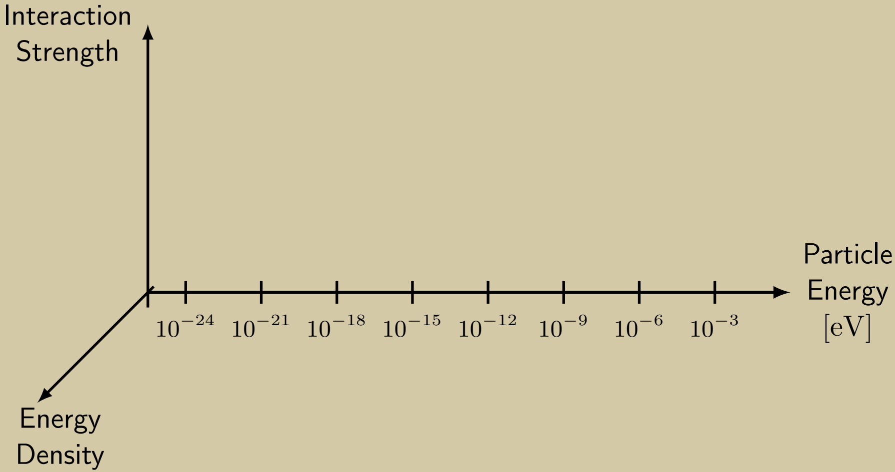
Outline

The Axion Program

Spin Precession Experiments

Noise Sources and Sensitivity → Applications

The Cosmic Axion Landscape



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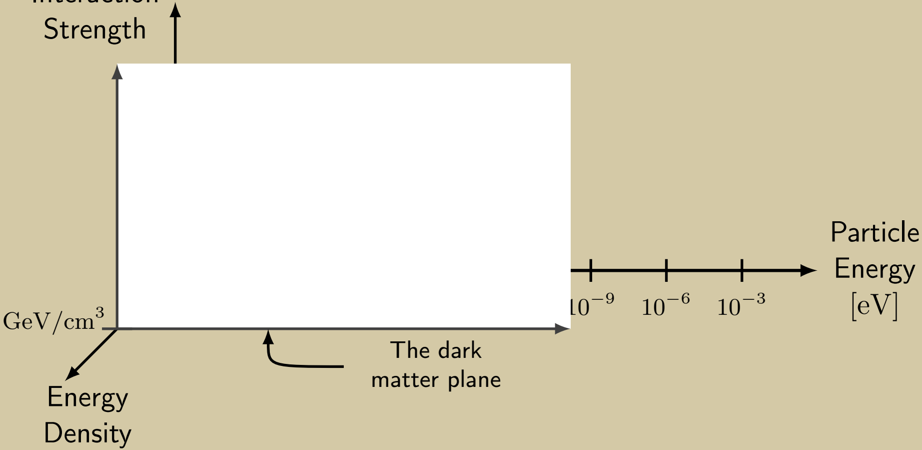


Interaction Strength

Particle Energy [eV]

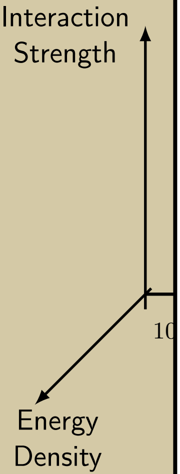
10^{-9} 10^{-6} 10^{-3}

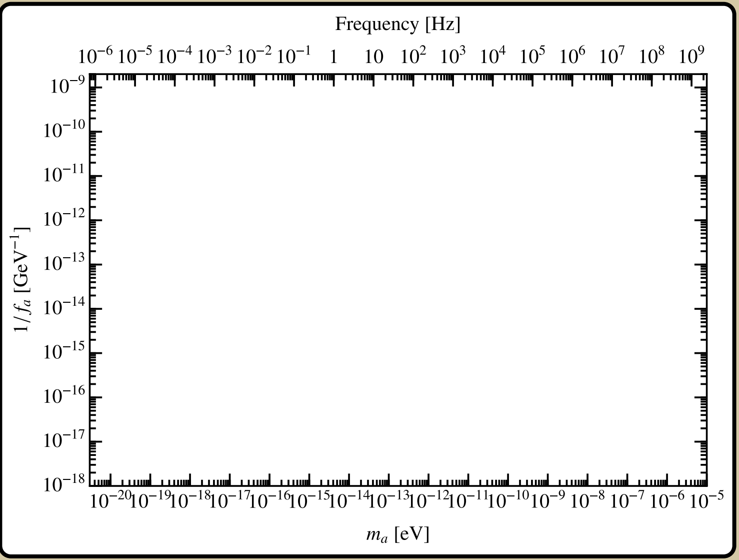
$\mathrm{GeV/cm^3}$

Energy Density

The dark matter plane

The Cosmic Axion Landscape





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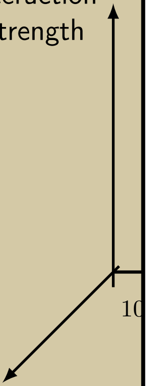
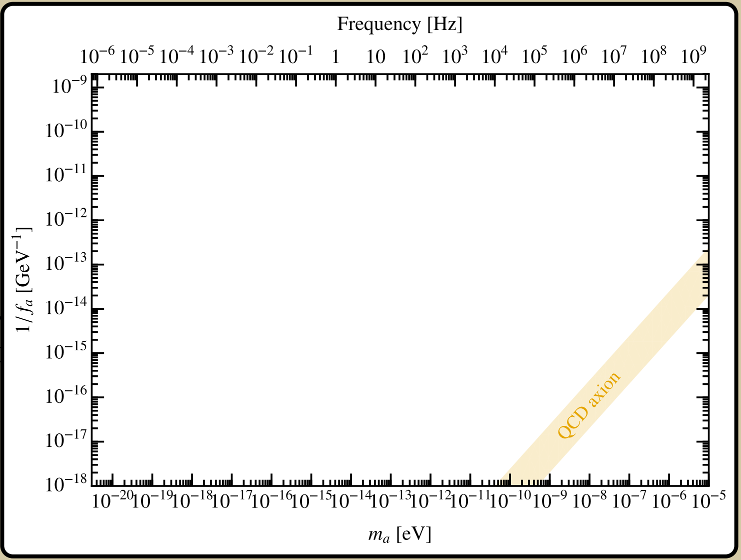


Interaction Strength

Energy Density



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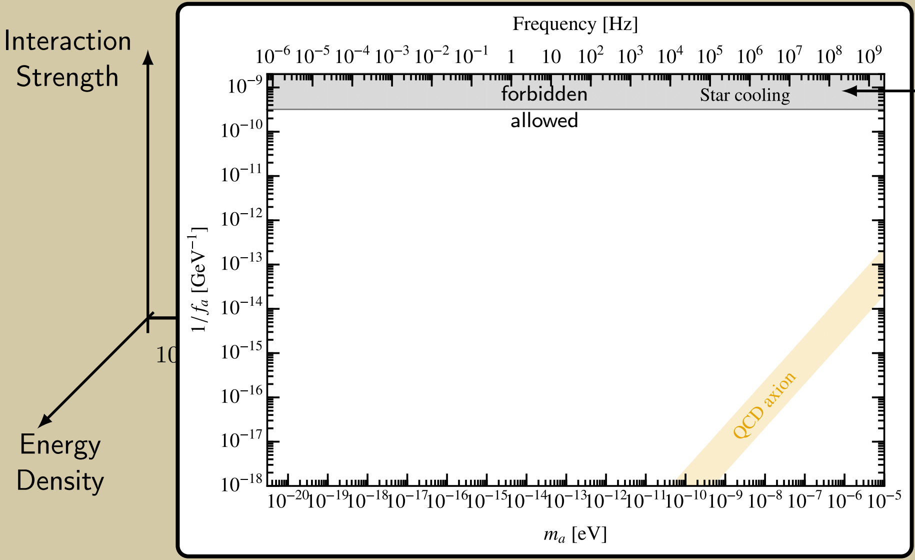
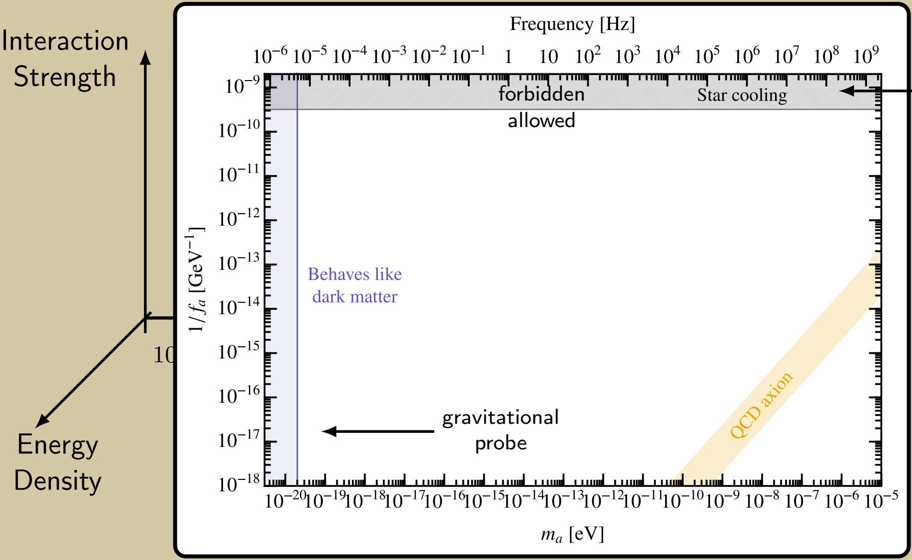


[Carenza et al - '19]

The Cosmic Axion Landscape



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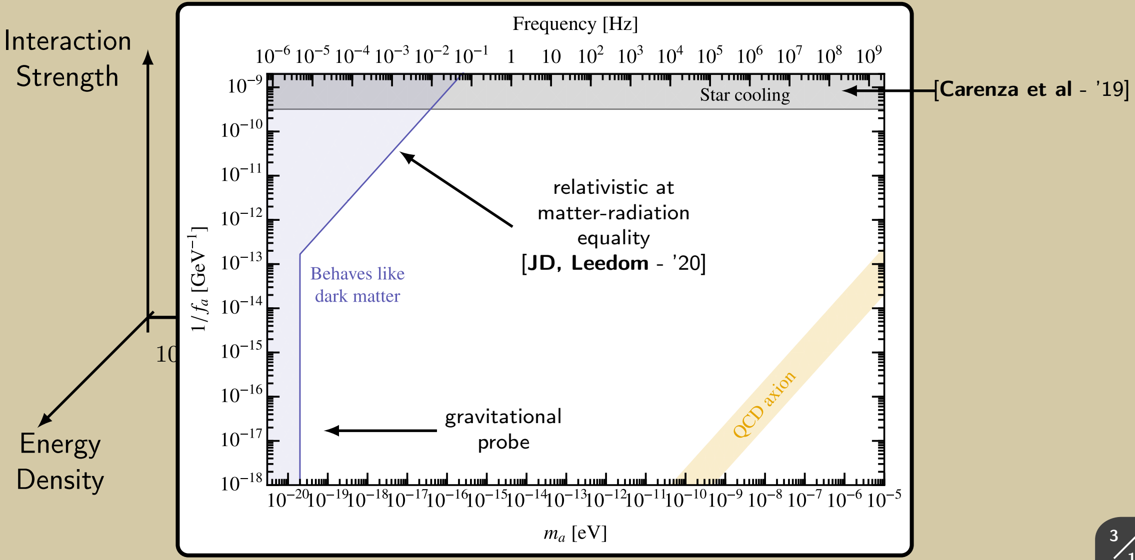
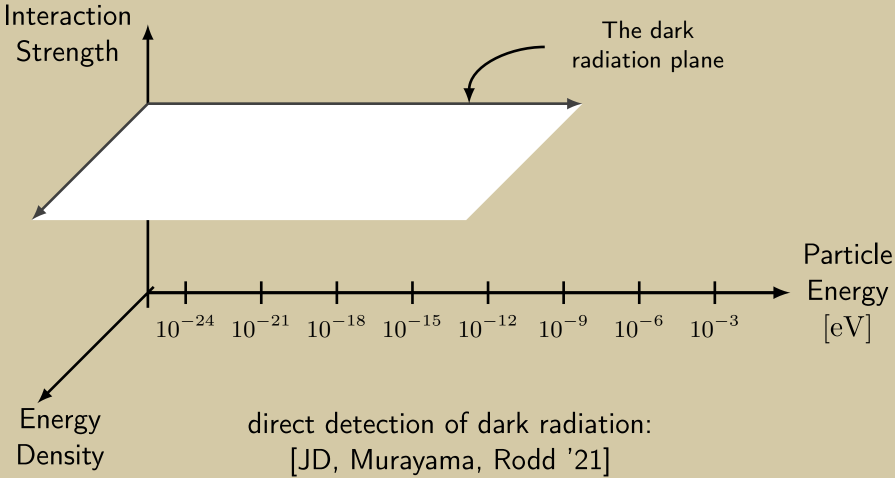


[Carenza et al - '19]

relativistic at
matter-radiation
equality
[JD, Leedom - '20]

gravitational
probe

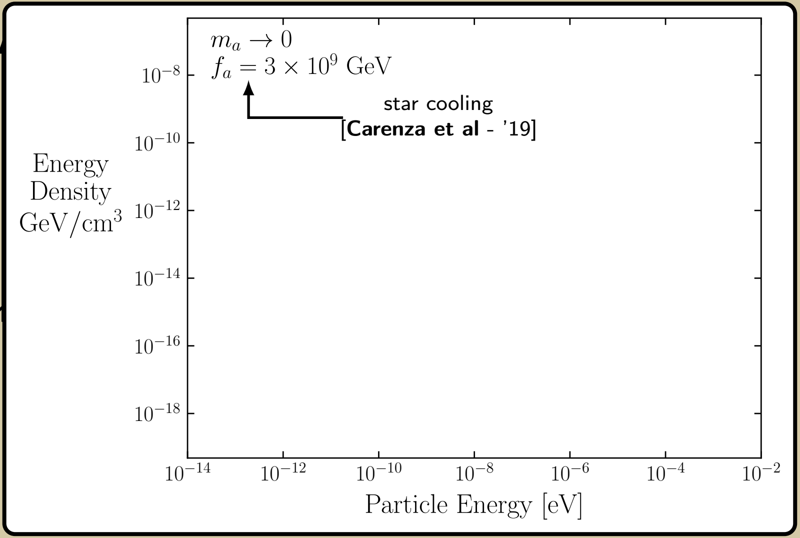
The Cosmic Axion Landscape



direct detection of dark radiation:
[JD, Murayama, Rodd '21]

The Cosmic Axion Landscape

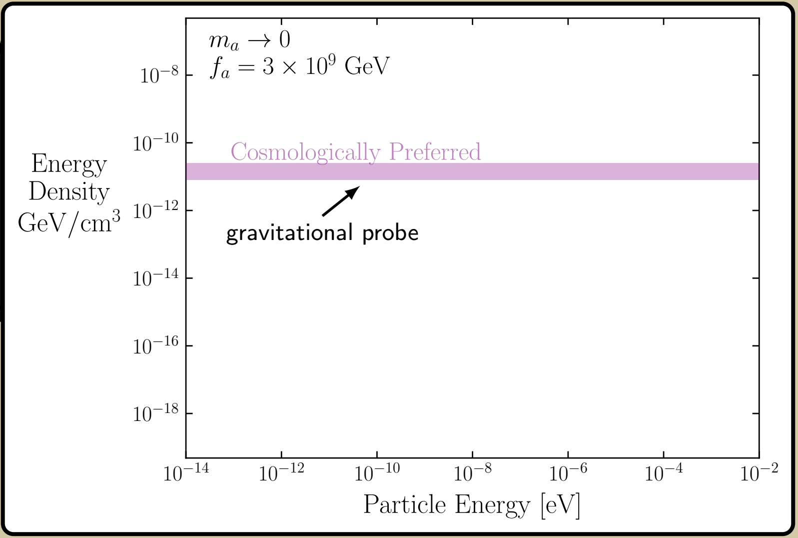
Interaction Strength



Energy Density

The Cosmic Axion Landscape

Interaction Strength



Energy Density

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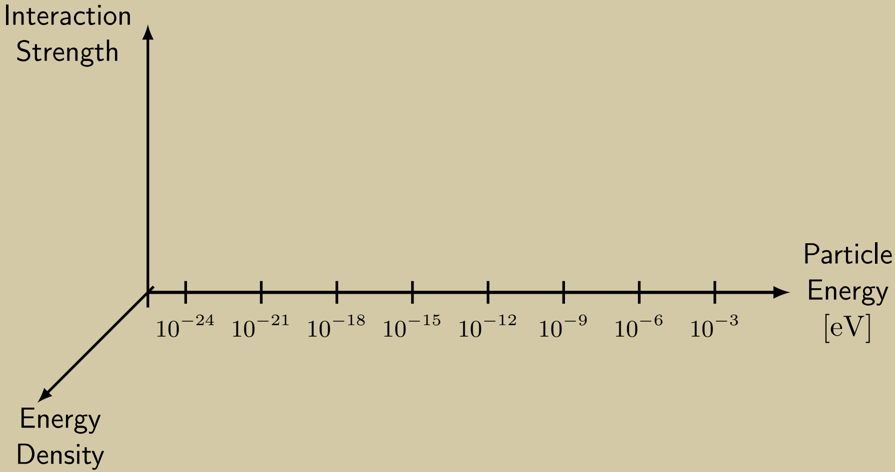

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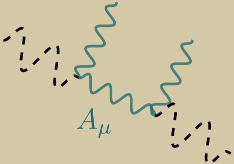
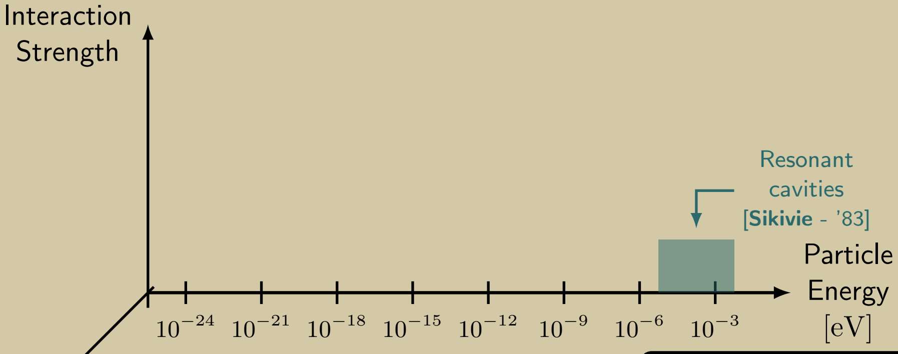
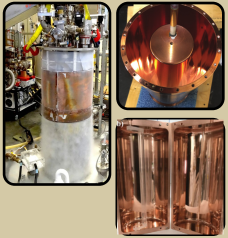
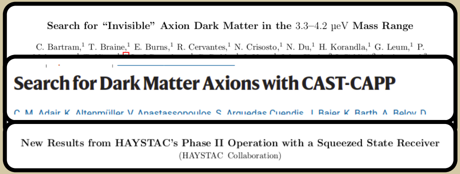




Resonant cavities **[Sikivie** - '83]





Search for "Invisible" Axion Dark Matter in the 3.3–4.2 μeV Mass Range

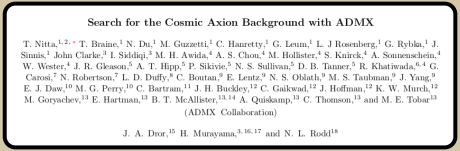
C. Bartram,[1] T. Braine,[1] E. Burns,[1] R. Cervantes,[1] N. Crisosto,[1] N. Du,[1] H. Korandla,[1] G. Leum,[1] P.

Search for Dark Matter Axions with CAST-CAPP

C. M. Adair, K. Altenmüller, V. Anastassopoulos, S. Arguedas Cuendis, J. Baier, K. Barth, A. Belov, D.

New Results from HAYSTAC's Phase II Operation with a Squeezed State Receiver

(HAYSTAC Collaboration)



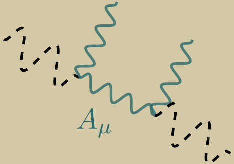
Search for the Cosmic Axion Background with ADMX

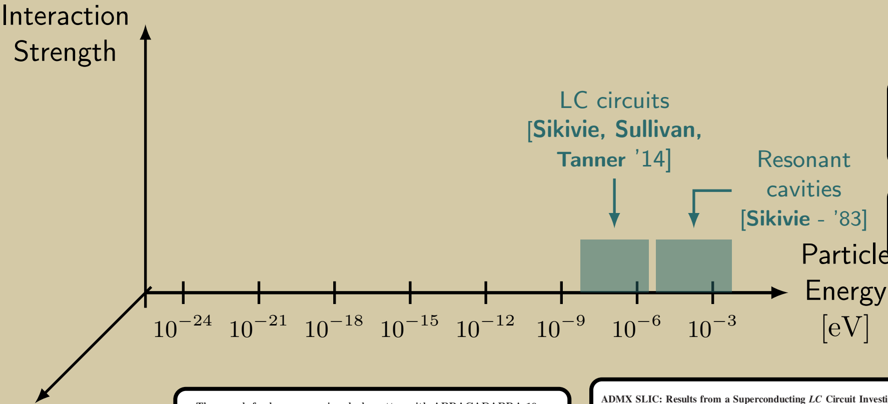
T. Nitta,[1, 2, *] T. Braine,[1] N. Du,[1] M. Guzzetti,[1] C. Hanretty,[1] G. Leum,[1] L. J Rosenberg,[1] G. Rybka,[1] J. Sinnis,[1] John Clarke,[3] I. Siddiqi,[3] M. H. Awida,[4] A. S. Chou,[4] M. Hollister,[4] S. Knirck,[4] A. Sonnenschein,[4] W. Wester,[4] J. R. Gleason,[5] A. T. Hipp,[5] P. Sikivie,[5] N. S. Sullivan,[5] D. B. Tanner,[5] R. Khatiwada,[6, 4] G. Carosi,[7] N. Robertson,[7] L. D. Duffy,[8] C. Boutan,[9] E. Lentz,[9] N. S. Oblath,[9] M. S. Taubman,[9] J. Yang,[9] E. J. Daw,[10] M. G. Perry,[10] C. Bartram,[11] J. H. Buckley,[12] C. Gaikwad,[12] J. Hoffman,[12] K. W. Murch,[12] M. Goryachev,[13] E. Hartman,[13] B. T. McAllister,[13, 14] A. Quiskamp,[13] C. Thomson,[13] and M. E. Tobar[13]

(ADMX Collaboration)

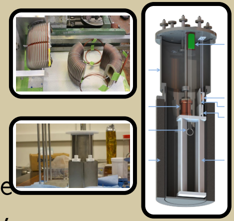
J. A. Dror,[15] H. Murayama,[3, 16, 17] and N. L. Rodd[18]

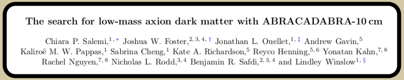
The Cosmic Axion Landscape





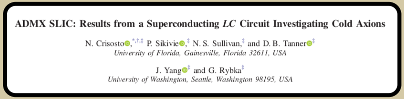
Energy Density





The search for low-mass axion dark matter with ABRACADABRA-10 cm

Chiara P. Salemi,[1,*] Joshua W. Foster,[2,3,4,†] Jonathan L. Ouellet,[1,‡] Andrew Gavin,[5] Kaliroë M. W. Pappas,[1] Sabrina Cheng,[1] Kate A. Richardson,[5] Reyco Henning,[5,6] Yonatan Kahn,[7,8] Rachel Nguyen,[7,8] Nicholas L. Rodd,[3,4] Benjamin R. Safdi,[2,3,4] and Lindley Winslow[1,§]

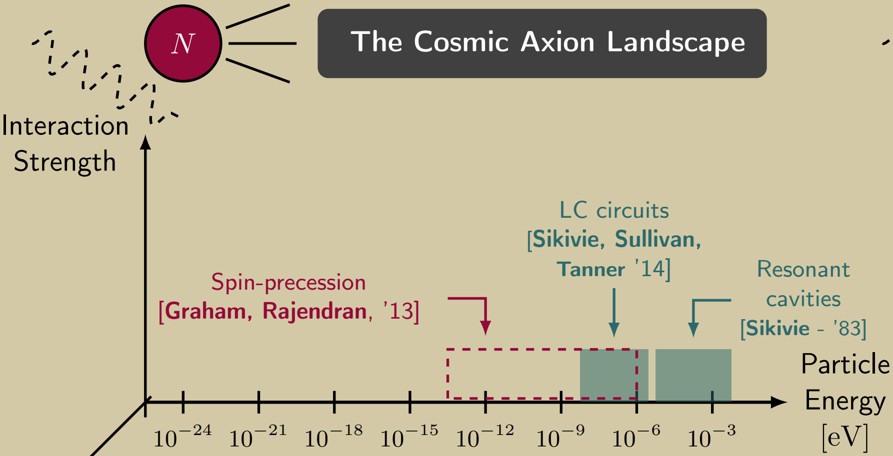


ADMX SLIC: Results from a Superconducting *LC* Circuit Investigating Cold Axions

N. Crisosto,[*,†,‡] P. Sikivie,[‡] N. S. Sullivan,[‡] and D. B. Tanner[‡]
University of Florida, Gainesville, Florida 32611, USA

J. Yang[‡] and G. Rybka[‡]
University of Washington, Seattle, Washington 98195, USA

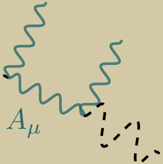
The Cosmic Axion Landscape



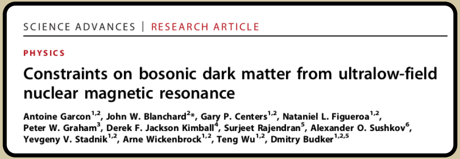
Spin-precession
[**Graham, Rajendran**, ’13]

LC circuits
[**Sikivie, Sullivan, Tanner** ’14]

Resonant cavities
[**Sikivie** - ’83]



Energy Density



SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Constraints on bosonic dark matter from ultralow-field nuclear magnetic resonance

Antoine Garcon[1,2], John W. Blanchard[2]*, Gary P. Centers[1,2], Nataniel L. Figueroa[1,2], Peter W. Graham[3], Derek F. Jackson Kimball[4], Surjeet Rajendran[5], Alexander O. Sushkov[6], Yevgeny V. Stadnik[1,2], Arne Wickenbrock[1,2], Teng Wu[1,2], Dmitry Budker[1,2,5]

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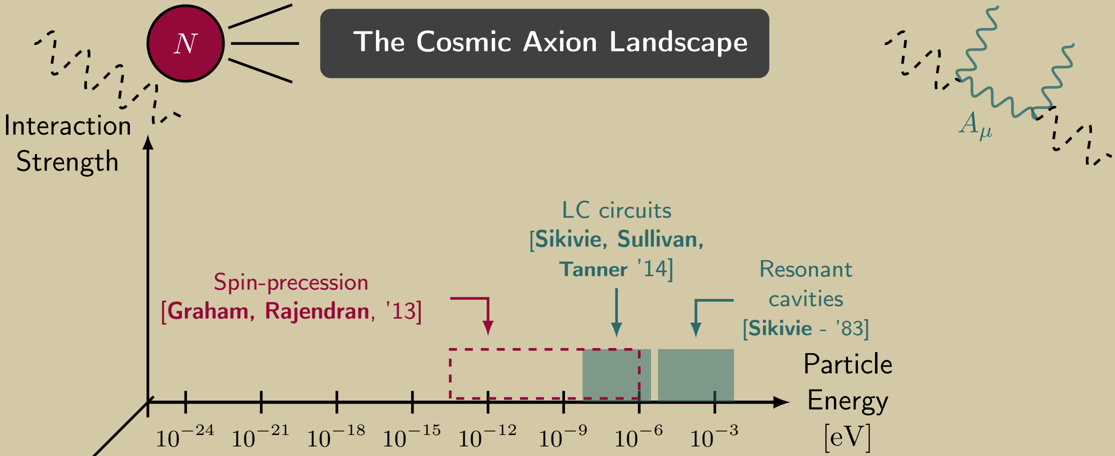


Interaction Strength

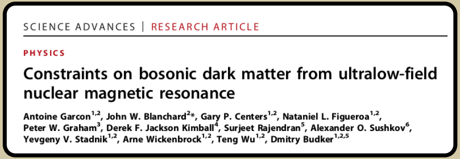
Spin-precession [**Graham, Rajendran**, '13]

LC circuits [**Sikivie, Sullivan, Tanner** '14]

Resonant cavities [**Sikivie** - '83]

Particle Energy [eV]

Energy Density



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[**Wang et al** - '17]
[**Abel et al** - '17]
[**Jackson Kimball et al** - '17]
[**Garcon et al** - '19]
[**Roussy et al** - '20]

[**Budker et al** - '21]
[**Aybas et al** - '21]
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. . .

Axions as Cosmic Relics

$$\mathcal{H} \simeq \frac{1}{2}m_a^2 a^2 + \frac{1}{2}\dot{a}^2 + \frac{1}{2}(\nabla a)^2$$

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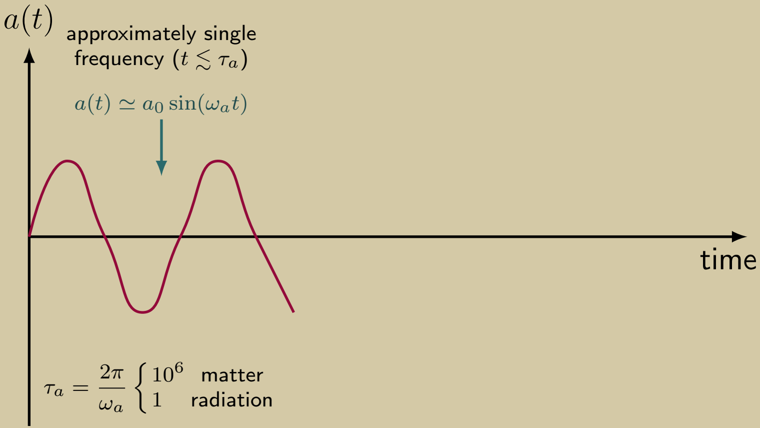

approximately single frequency ($t \lesssim \tau_a$)

$a(t) \simeq a_0 \sin(\omega_a t)$

$$\tau_a = \frac{2\pi}{\omega_a} \begin{cases} 10^6 & \text{matter} \\ 1 & \text{radiation} \end{cases}$$

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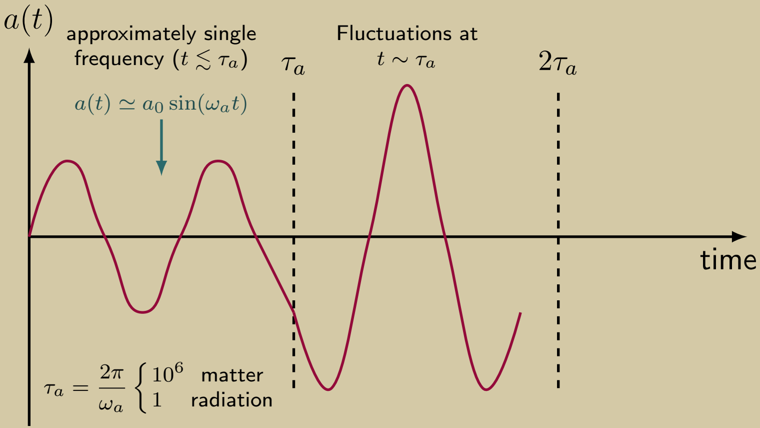

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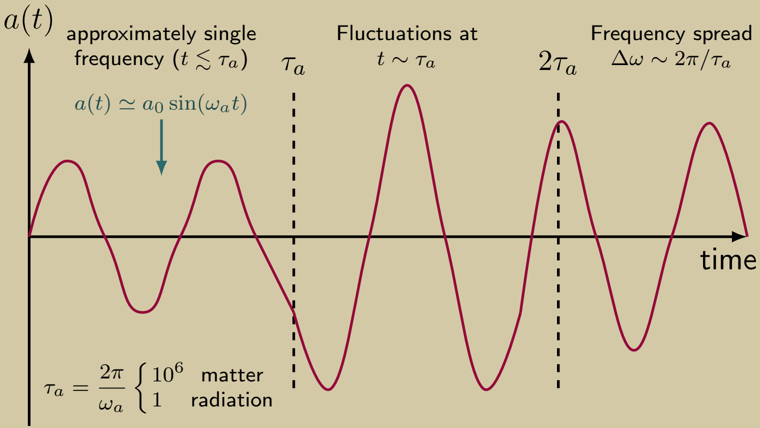

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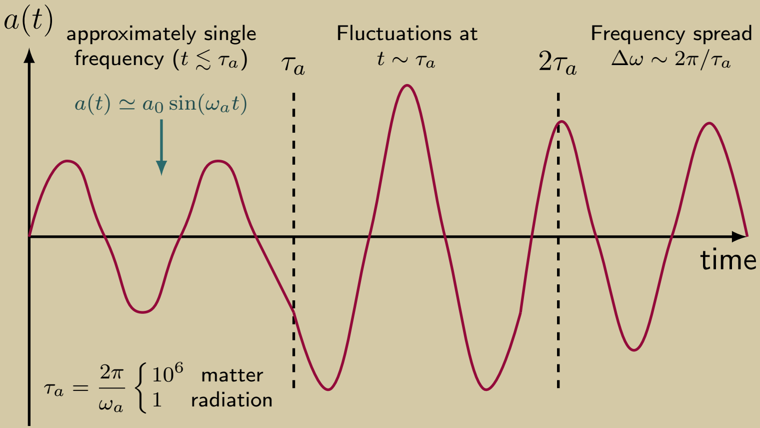
Models for $a(t)$:

(1) "Plane Wave"

$$\sum_i a_0^i \cos(m_a(1+\frac{v_i^2}{2})t+\varphi_i)$$

(2) "Jumping Phase"

$$a_0 \cos(m_a t + \varphi(t))$$



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Fluctuations at $t \sim \tau_a$

Frequency spread $\Delta\omega \sim 2\pi/\tau_a$

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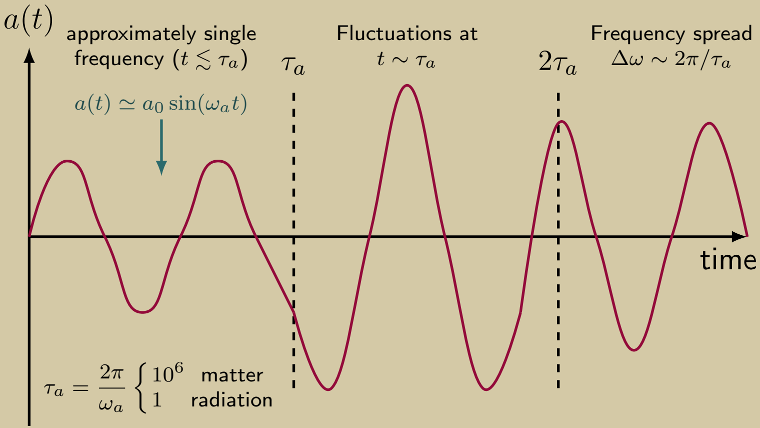

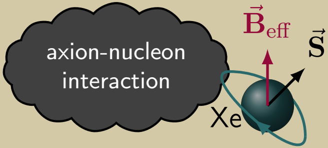

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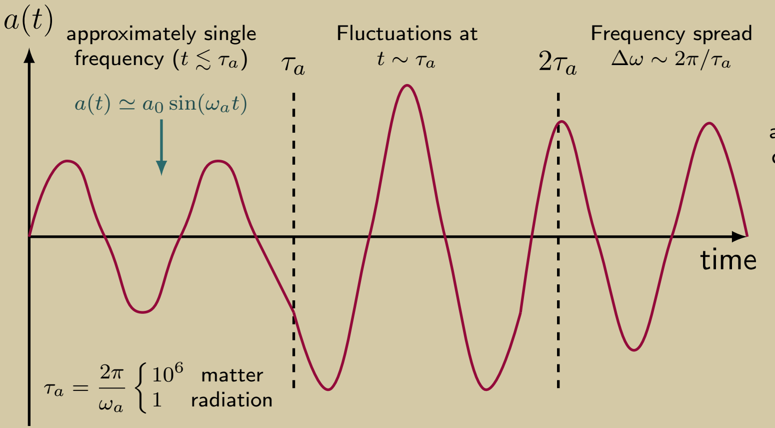

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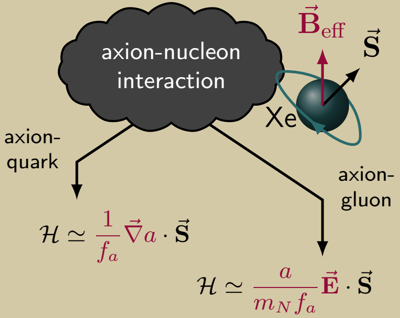

$$\mathcal{H} \simeq \frac{1}{f_a}\vec{\nabla}a \cdot \vec{\mathbf{S}}$$

$$\mathcal{H} \simeq \frac{a}{m_N f_a}\vec{\mathbf{E}} \cdot \vec{\mathbf{S}}$$

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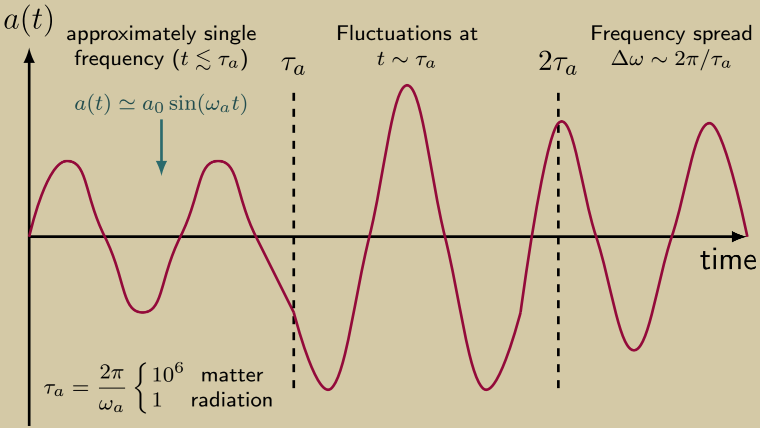

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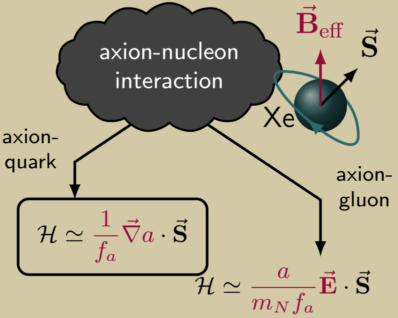

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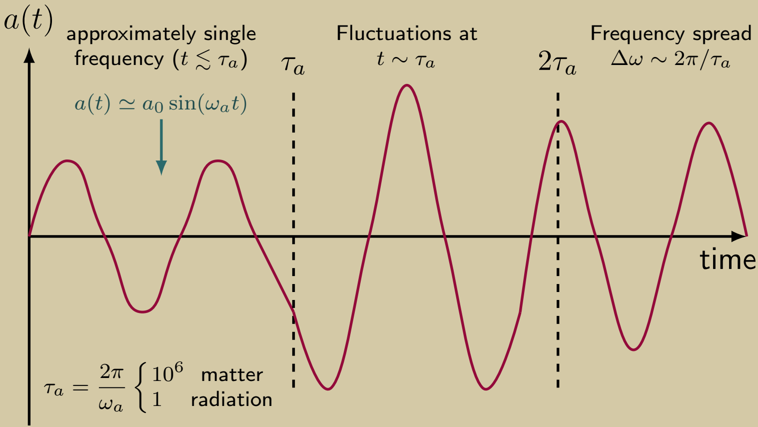

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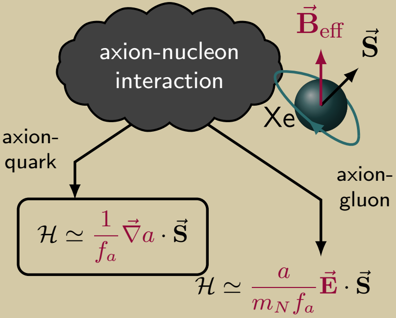

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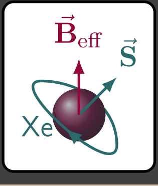
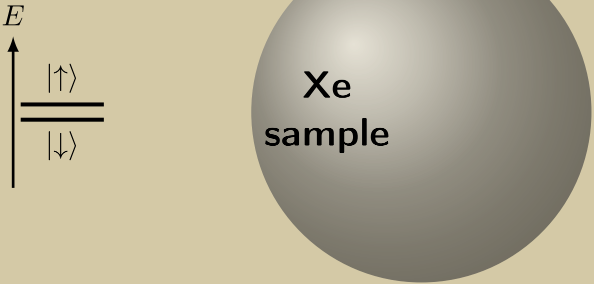
resonant frequency?

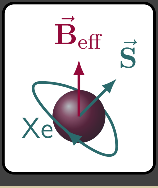
damping?

integration time?


$\vec{B}_{\text{eff}}$
$\vec{S}$
Xe

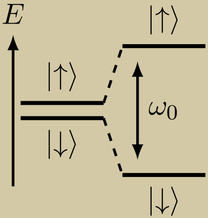


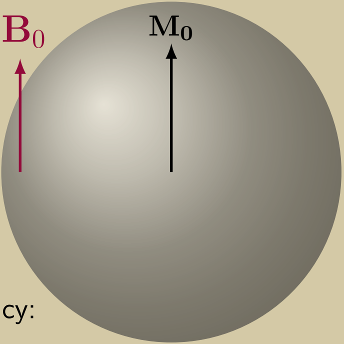
Xe sample



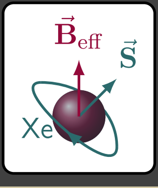
$$\mathcal{L} = -\gamma\,(\mathbf{B}_0 + \qquad\qquad) \cdot \mathbf{S}$$

applied (real) field





① resonant frequency:
$\omega_0 \equiv \gamma B_0$



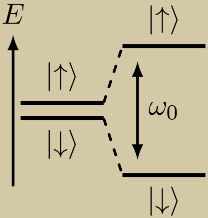
$$\mathcal{L} = -\gamma\left(\mathbf{B}_0 + \mathbf{B}_{\text{eff}}(t)\right)\cdot\mathbf{S}$$

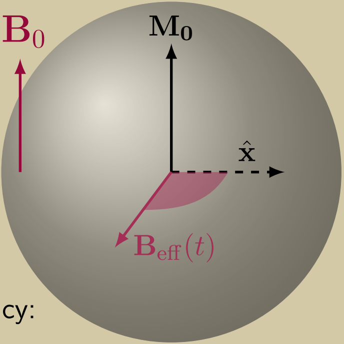
applied (real) field

(small) oscillatory perturbation

Spin-precession exp: effective field

NMR: applied field





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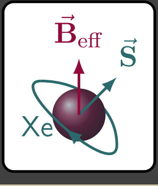

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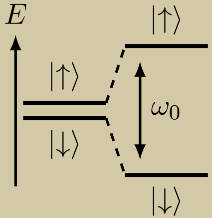
applied (real) field

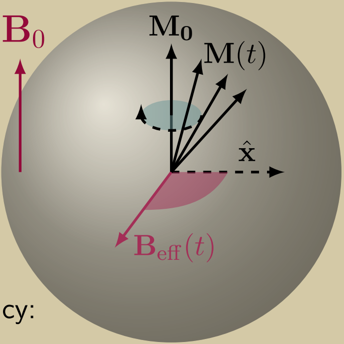
(small) oscillatory perturbation

Spin-precession exp: effective field

NMR: applied field

$$\mathbf{M}(t) = M_0\hat{\mathbf{z}} + \mathbf{M}_a(t)$$





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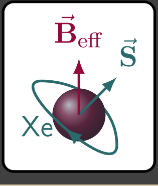

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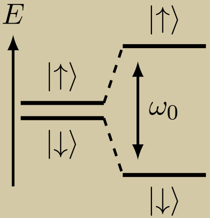

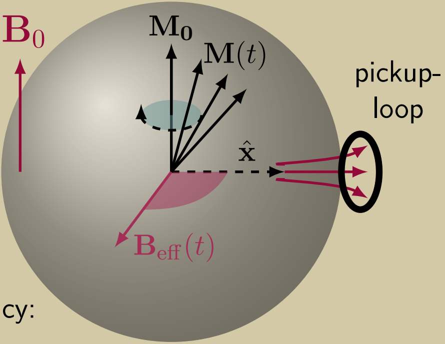

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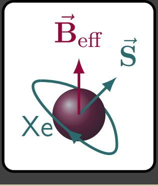


$$\mathcal{L} = -\gamma\left(\mathbf{B}_0 + \mathbf{B}_{\text{eff}}(t)\right) \cdot \mathbf{S}$$

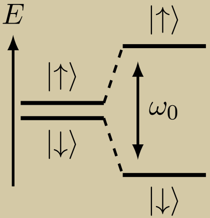
applied (real) field → $\mathbf{B}_0$

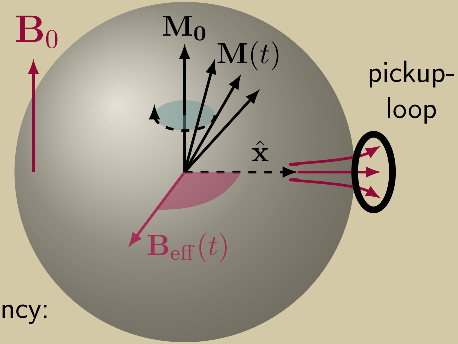
(small) oscillatory perturbation → $\mathbf{B}_{\text{eff}}(t)$

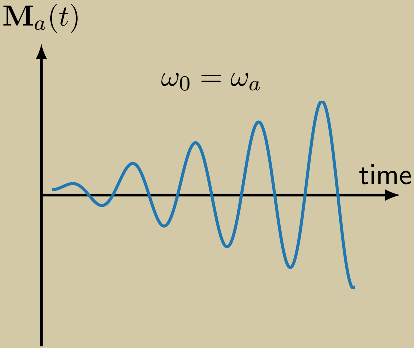
Spin-precession exp: effective field

NMR: applied field

$$\mathbf{M}(t) = M_0\hat{\mathbf{z}} + \mathbf{M}_a(t)$$







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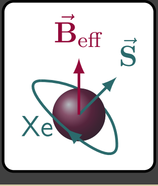

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applied (real) field

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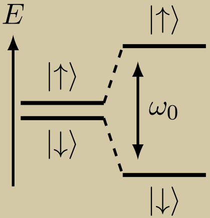
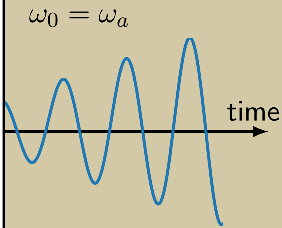
Nothing Grows Forever...





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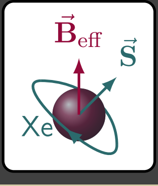

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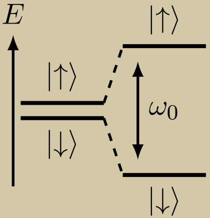
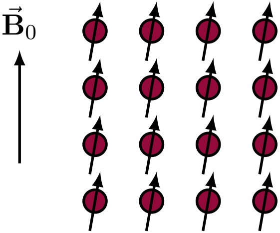
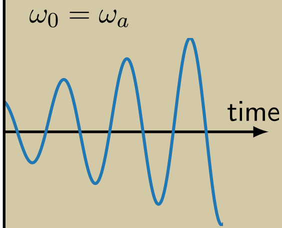


Nothing Grows Forever...





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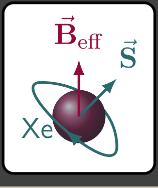

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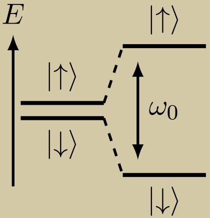

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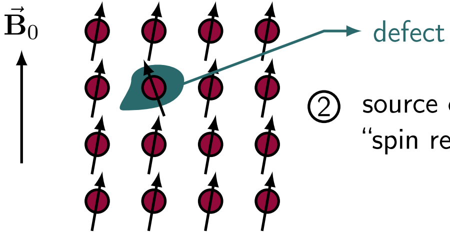
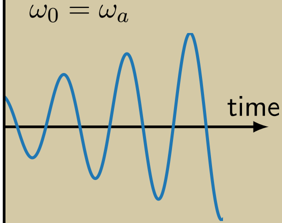
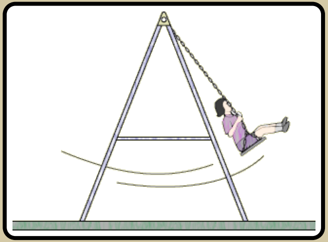


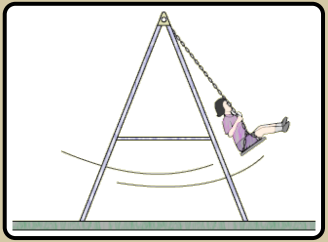
② source of friction: “spin relaxation”



Axion Experiment as a Harmonic Oscillator

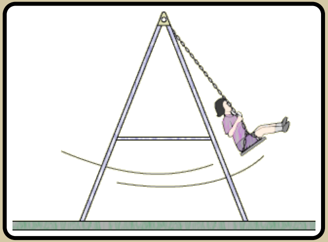


Axion Experiment as a Harmonic Oscillator



$$\underbrace{\ddot{M}_{a,x} + \omega_0^2 M_{a,x}}_{\substack{\uparrow \\ \text{harmonic} \\ \text{oscillator}}} + \underset{\substack{\uparrow \\ \text{damped}}}{\frac{2}{T_2}\dot{M}_{a,x}} \simeq \underset{\substack{\uparrow \\ \text{driving} \\ \text{force}}}{M_0 \omega_0 A \sin(\omega_a t + \varphi(t))}$$

Axion Experiment as a Harmonic Oscillator

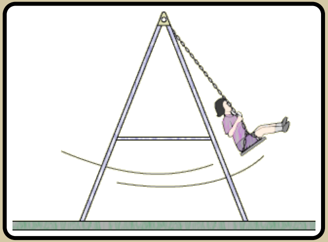


$$\ddot{M}_{a,x} + \omega_0^2 M_{a,x} + \frac{2}{T_2}\dot{M}_{a,x} \simeq M_0\omega_0 A\sin(\omega_a t + \varphi(t))$$

$$\downarrow$$

$$M_x(t) = M_0 \int_0^t dt'\ e^{(t'-t)/T_2} \sin\left[\omega_0(t-t')\right] A\sin(\omega_a t' + \varphi)$$

Axion Experiment as a Harmonic Oscillator



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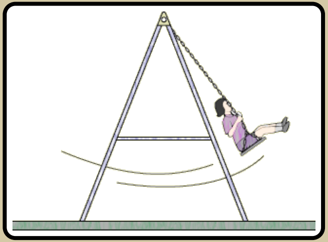

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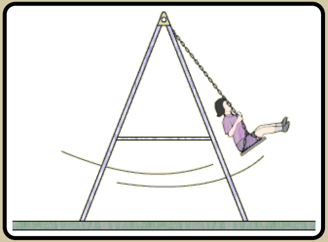
"deterministic",
rapidly growing

$$M_x(t) \simeq \frac{At}{2\omega_0} \sin(\omega_0 t + \varphi)$$

Axion Experiment as a Harmonic Oscillator



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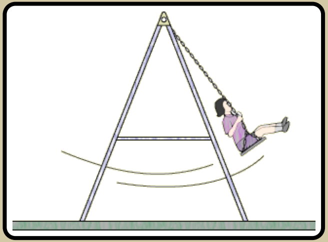
"deterministic",
rapidly growing

"stochastic",
slowly growing

$$M_x(t) \simeq \frac{At}{2\omega_0} \sin(\omega_0 t + \varphi)$$

$$\langle M_x(t) M_x(t') \rangle \simeq \frac{A^2 \tau_a t}{8\omega_0^2} \cos(\omega_0(t-t'))$$

Axion Experiment as a Harmonic Oscillator



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$$\downarrow$$

$$M_x(t) = M_0\int_0^t dt'\; e^{(t'-t)/T_2}\sin\left[\omega_0(t-t')\right] A\sin(\omega_a t' + \varphi)$$

"deterministic", rapidly growing

"stochastic", slowly growing

not growing

τ_a

T_2

time

$$M_x(t) \simeq \frac{At}{2\omega_0}\sin(\omega_0 t + \varphi)$$

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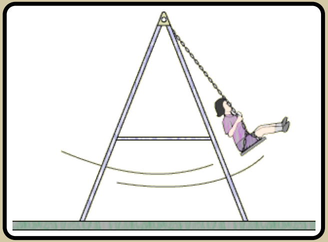

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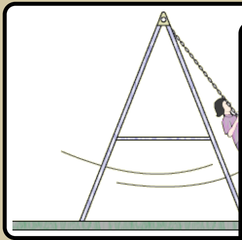
③ wait at least until τ_a or T_2

repeat at next ω_0 by varying B_0

Axion Experiment as a Harmonic Oscillator



n$(\omega_a t + \varphi(t))$

$t')]\, A\sin(\omega_a t' + \varphi)$

“d

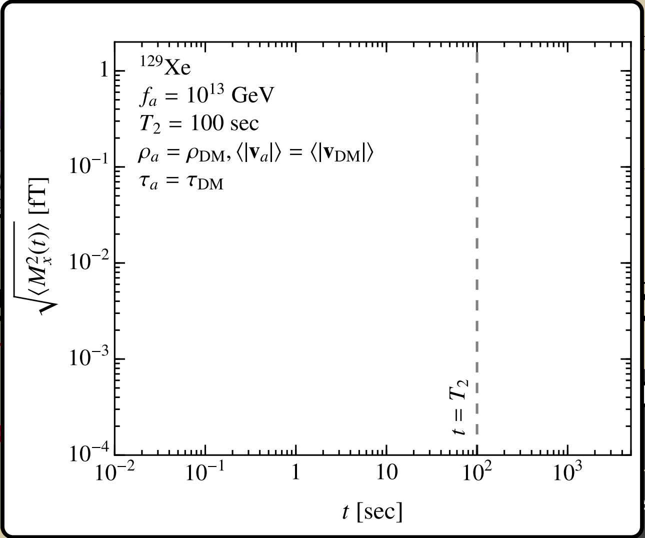
ra

rowing

time

$M_x(t) \simeq \frac{At}{2\omega_0}$ sin(

ω_0



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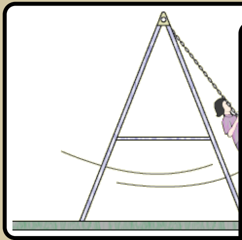
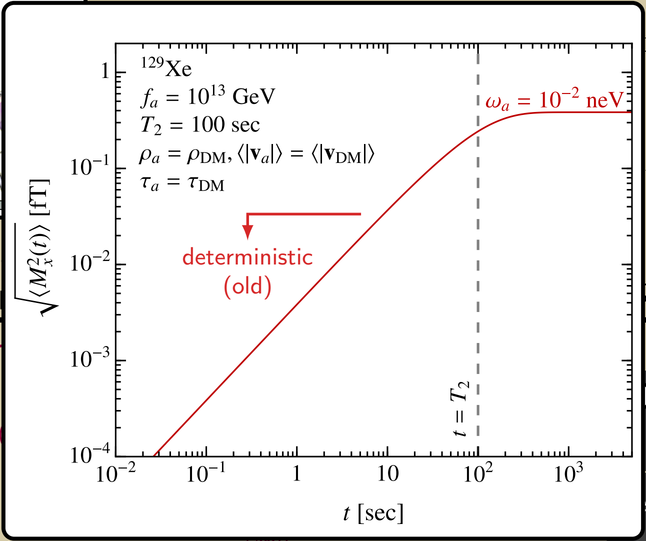
Axion Experiment as a Harmonic Oscillator





$\text{n}(\omega_a t + \varphi(t))$

$t')]\, A \sin(\omega_a t' + \varphi)$

“d

ra

rowing

time

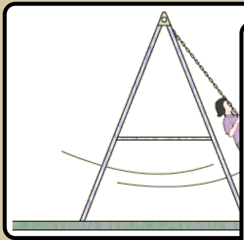
$M_x(t) \simeq \dfrac{At}{2\omega_0}\,\sin($

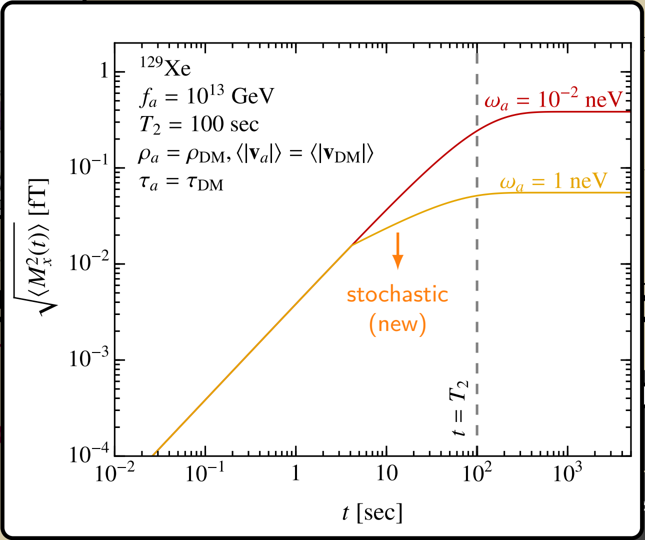
ω_0

wait at least until τ_a or T_2

peat at next ω_0 by varying B_0

Axion Experiment as a Harmonic Oscillator





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“d

ra

rowing

time

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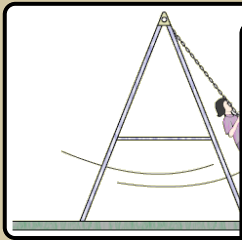
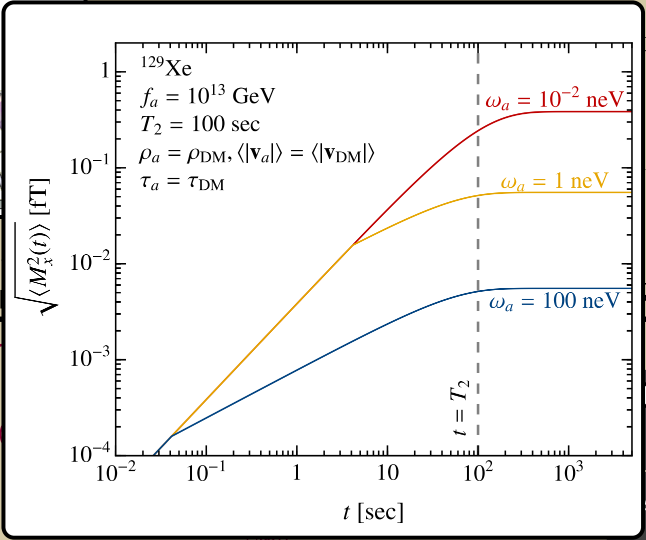
Axion Experiment as a Harmonic Oscillator





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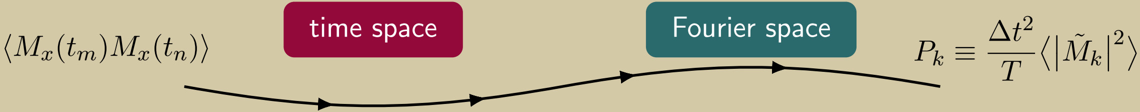
$$\langle M_x(t_m) M_x(t_n) \rangle$$

time space

Fourier space

$$P_k \equiv \frac{\Delta t^2}{T} \left\langle \left| \tilde{M}_k \right|^2 \right\rangle$$

$$\Delta\omega_k \equiv \frac{2\pi k}{T} - \omega_0$$



$\langle M_x(t_m) M_x(t_n) \rangle$

time space

Fourier space

$P_k \equiv \frac{\Delta t^2}{T} \langle |\tilde{M}_k|^2 \rangle$

$$\Delta\omega_k \equiv \frac{2\pi k}{T} - \omega_0$$

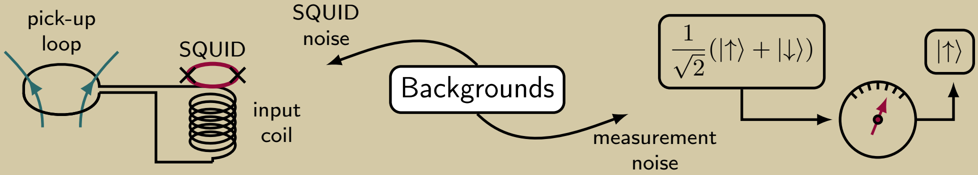
signal in
stationary limit
$(T \gg T_2)$

$$: \; P_k^a \simeq \frac{\langle A^2 \rangle T_2^2}{16\omega_0^2} \begin{cases} \frac{4}{\Delta\omega_k^2 T} \sin^2 \left[\frac{1}{2}\Delta\omega_k T\right] & T \ll \tau_a \\ \frac{\tau_a}{1 + \Delta\omega_k^2 T_2^2} & T \gg \tau_a \end{cases}$$

$\langle M_x(t_m) M_x(t_n) \rangle$ **time space** → **Fourier space** $P_k \equiv \frac{\Delta t^2}{T} \langle |\tilde{M}_k|^2 \rangle$

$$\Delta\omega_k \equiv \frac{2\pi k}{T} - \omega_0$$

signal in stationary limit ($T \gg T_2$) : $P_k^a \simeq \frac{\langle A^2 \rangle T_2^2}{16\omega_0^2} \begin{cases} \frac{4}{\Delta\omega_k^2 T} \sin^2\left[\frac{1}{2}\Delta\omega_k T\right] & T \ll \tau_a \\ \frac{\tau_a}{1 + \Delta\omega_k^2 T_2^2} & T \gg \tau_a \end{cases}$



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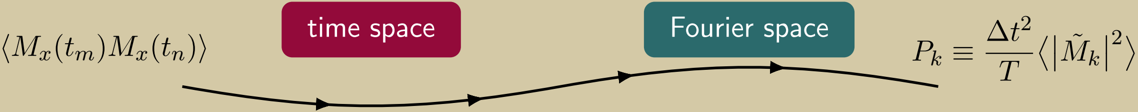
Fourier space

$$P_k \equiv \frac{\Delta t^2}{T} \langle |\tilde{M}_k|^2 \rangle$$

$$\Delta\omega_k \equiv \frac{2\pi k}{T} - \omega_0$$

signal in
stationary limit : $P_k^a \simeq \dfrac{\langle A^2 \rangle T_2^2}{16\omega_0^2} \begin{cases} \dfrac{4}{\Delta\omega_k^2 T} \sin^2\left[\frac{1}{2}\Delta\omega_k T\right] & T \ll \tau_a \\ \dfrac{\tau_a}{1 + \Delta\omega_k^2 T_2^2} & T \gg \tau_a \end{cases}$
$(T \gg T_2)$

background in
stationary limit : $P_k^{\mathrm{SQ}} \simeq \dfrac{1}{A_{\mathrm{eff}}^2} \dfrac{(\mu\Phi_0)^2}{\mathrm{Hz}} \qquad P_k^{\mathrm{SP}} = \dfrac{\gamma^2 n J}{2V} \dfrac{T_2}{1 + \Delta\omega_k^2 T_2^2}$
$(T \gg T_2)$



$\langle M_x(t_m) M_x(t_n) \rangle$

time space

Fourier space

$P_k \equiv \frac{\Delta t^2}{T} \langle |\tilde{M}_k|^2 \rangle$

$$\Delta\omega_k \equiv \frac{2\pi k}{T} - \omega_0$$

signal in stationary limit $(T \gg T_2)$: $P_k^a \simeq \frac{\langle A^2 \rangle T_2^2}{16\omega_0^2} \begin{cases} \frac{4}{\Delta\omega_k^2 T} \sin^2\left[\frac{1}{2}\Delta\omega_k T\right] & T \ll \tau_a \\ \frac{\tau_a}{1+\Delta\omega_k^2 T_2^2} & T \gg \tau_a \end{cases}$

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ⓐ $T < \max(T_2, \tau_a)$, signal in 1 k-bin $(k^* \equiv \omega_0 T/2\pi)$

ⓑ similar results for plane-wave model

$\langle M_x(t_m) M_x(t_n) \rangle$

time space

Fourier space

$$P_k \equiv \frac{\Delta t^2}{T} \langle |\tilde{M}_k|^2 \rangle$$

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$T \ll \tau_a, T_2$	$P_{k^*} \propto g^2 T^3$	$g \propto T^{-3/2}$
$\tau_a \ll T \ll T_2$	$P_{k^*} \propto g^2 T^2 \tau_a$	$g \propto T^{-1}$
$T_2 \ll T \ll \tau_a$	$P_{k^*} \propto g^2 T T_2^2$	$g \propto T^{-1/2}$
$\tau_a, T_2 \ll T$	$P_{k^*} \propto g^2 \tau_a T_2^2$	$g \propto T^{-1/4}$

sta

τ_a

τ_a

b

stationary limit : $P_k = \quad A_{\text{eff}}^2 \quad \text{Hz} \qquad P_k = \quad 2V \quad 1 + \Delta\omega_k^2 T_2^2$

$(T \gg T_2)$

ⓐ $T < \max(T_2, \tau_a)$, signal in 1 k-bin ($k^* \equiv \omega_0 T / 2\pi$)

ⓑ similar results for plane-wave model

Axion Dark Matter

Experimental Parameters

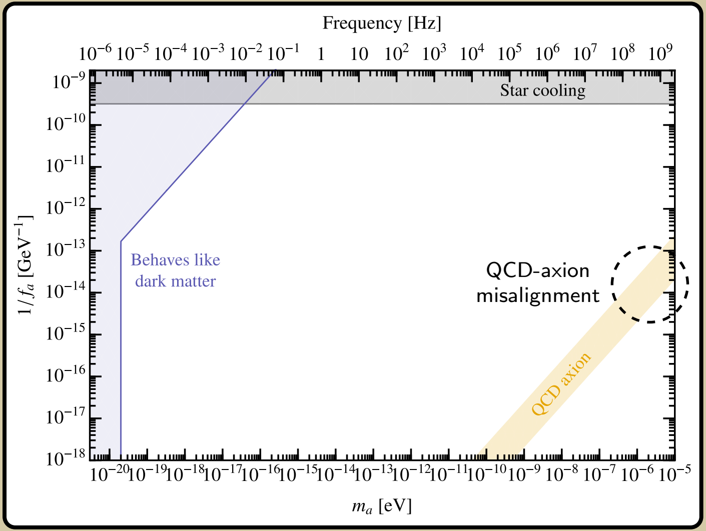
Element:

Density:

Polarization:

T_2:

$B_{\max}$:

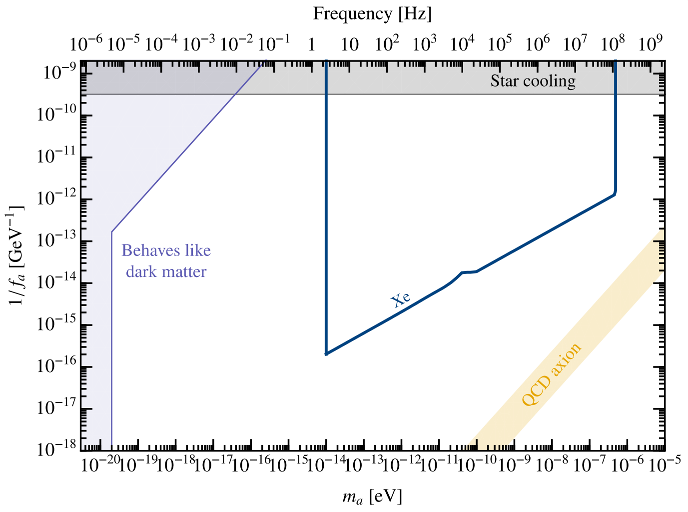


[JD, Gori, Leedom, Rodd - '22]

Axion Dark Matter

Experimental Parameters

Element:	Xe
Density:	$1.3 \cdot 10^{22}\mathrm{cm}^{-3}$
Polarization:	1
T_2:	100 s
$B_{\max}$:	10 T



[JD, Gori, Leedom, Rodd - ’22]

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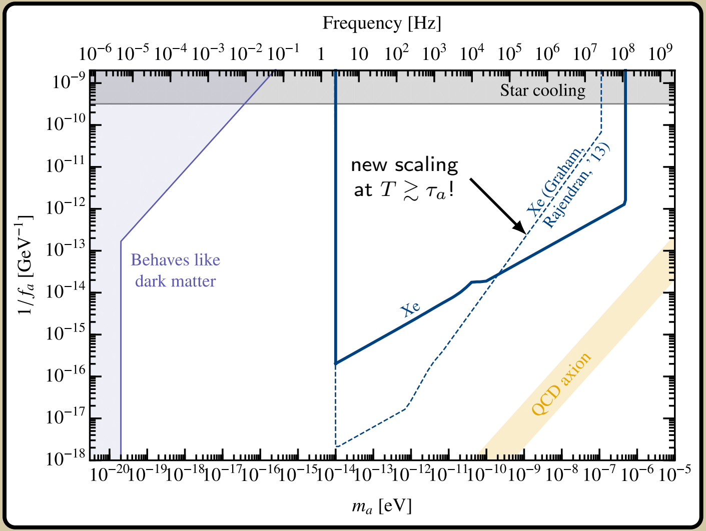


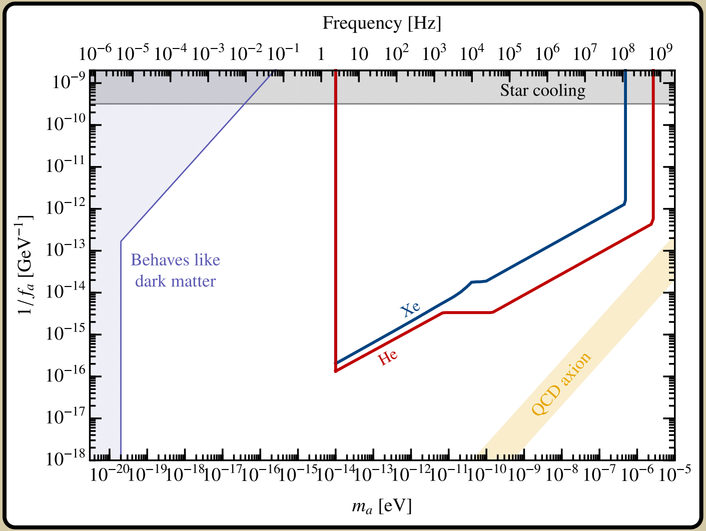
new scaling at $T \gtrsim \tau_a$!

[JD, Gori, Leedom, Rodd - '22]

Axion Dark Matter

Experimental Parameters

Element:	^{3}He
Density:	$2.8 \cdot 10^{22} \mathrm{cm}^{-3}$
Polarization:	1
T_2:	100 s
$B_{\max}$:	$20\ T$



[JD, Gori, Leedom, Rodd - '22]

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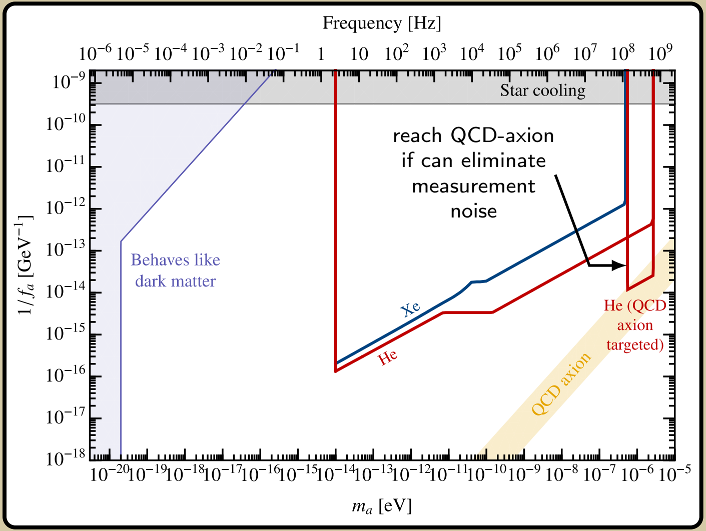
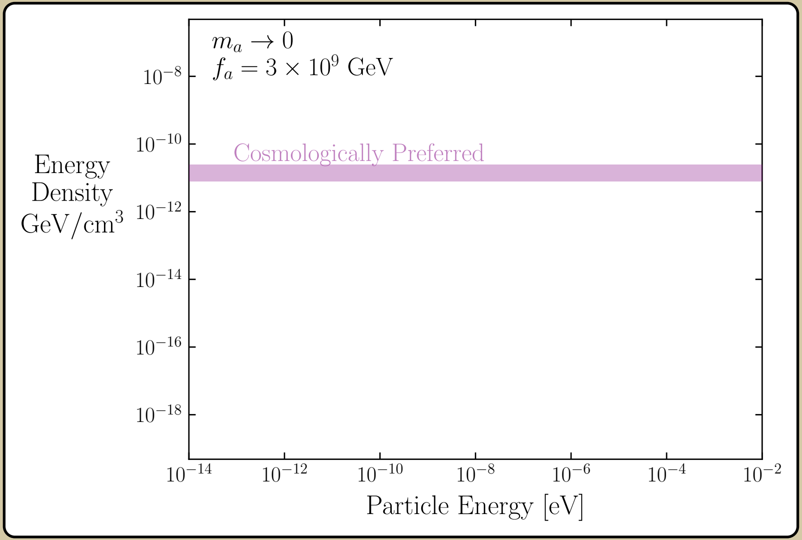


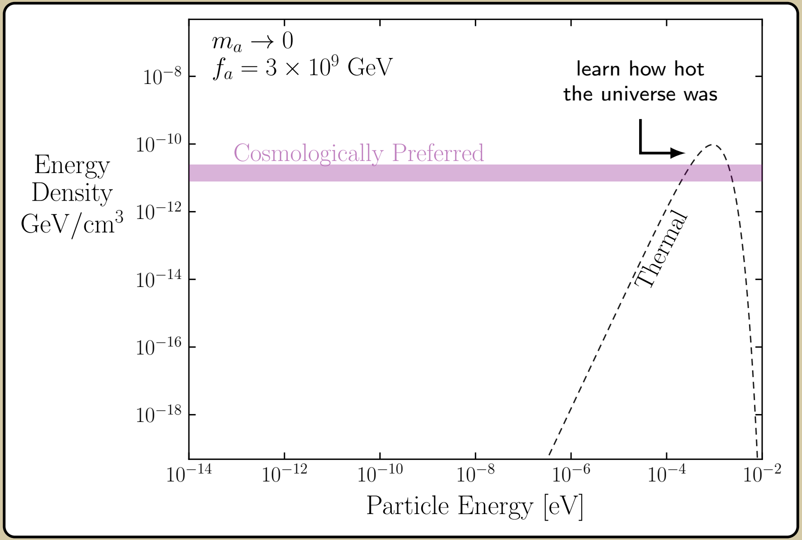
[JD, Gori, Leedom, Rodd - '22]

Axion Dark Radiation



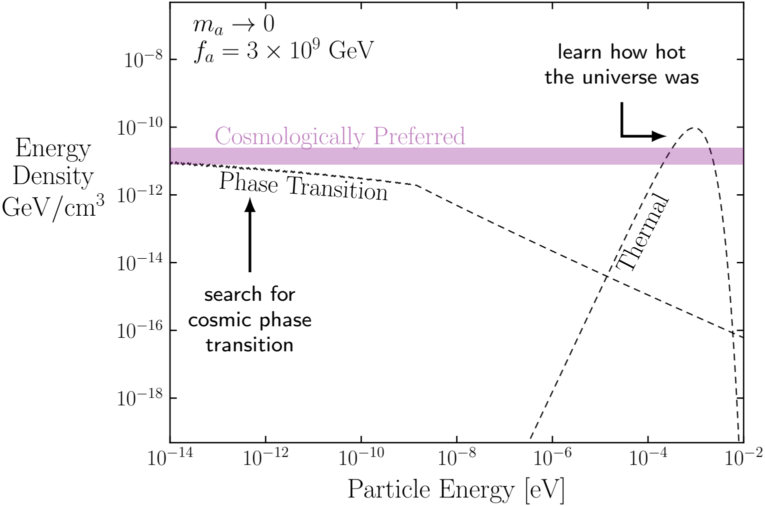
[JD, Murayama, Rodd '21]

Axion Dark Radiation



[JD, Murayama, Rodd '21]

Axion Dark Radiation

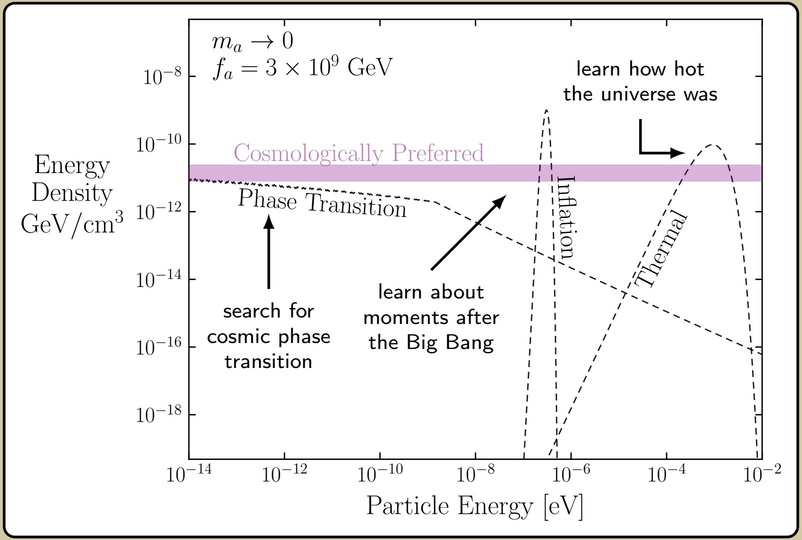


learn how hot the universe was

search for cosmic phase transition

[JD, Murayama, Rodd '21]

Axion Dark Radiation



[JD, Murayama, Rodd '21]

Axion Dark Radiation

Experimental Parameters

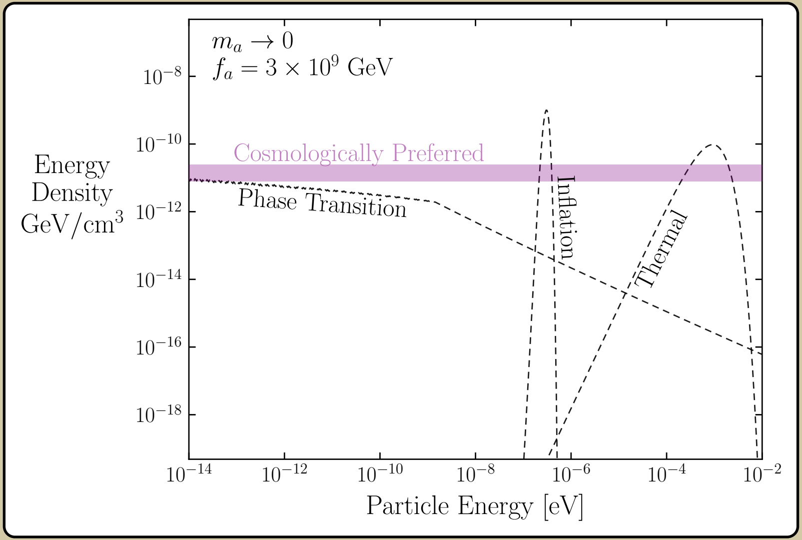
Element:

Density:

Polarization:

T_2:

$B_{\max}$:



[JD, Murayama, Rodd '21]

[JD, Gori, Leedom, Rodd - to appear]

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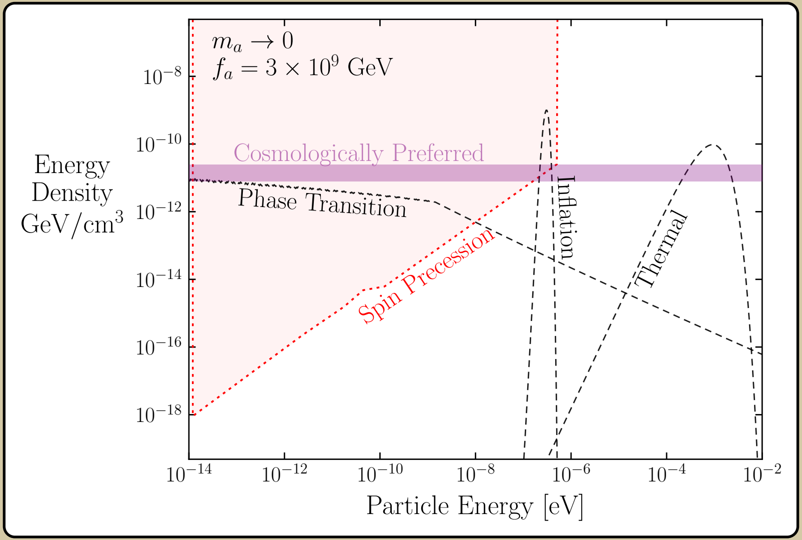

[JD, Murayama, Rodd '21]
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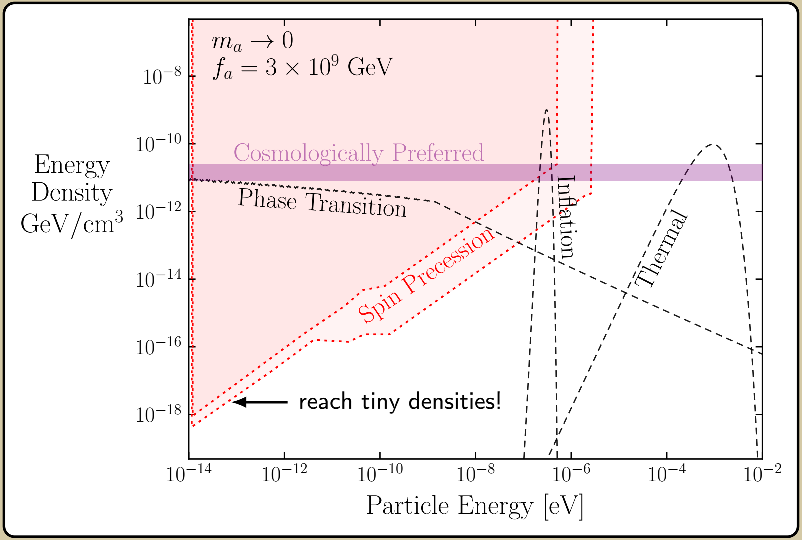
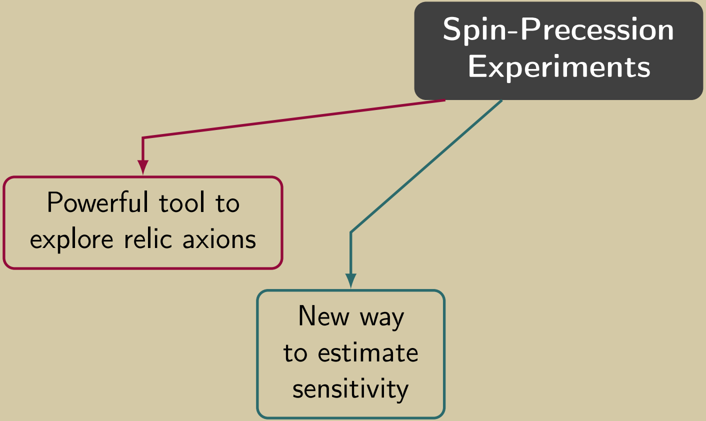


[JD, Murayama, Rodd '21]
[JD, Gori, Leedom, Rodd - to appear]

Spin-Precession Experiments

Powerful tool to explore relic axions



Spin-Precession Experiments

Powerful tool to explore relic axions

New way to estimate sensitivity

Spin-Precession Experiments

- Powerful tool to explore relic axions
- New way to estimate sensitivity
- Able to compute sensitivity for all T, τ_a, T_2

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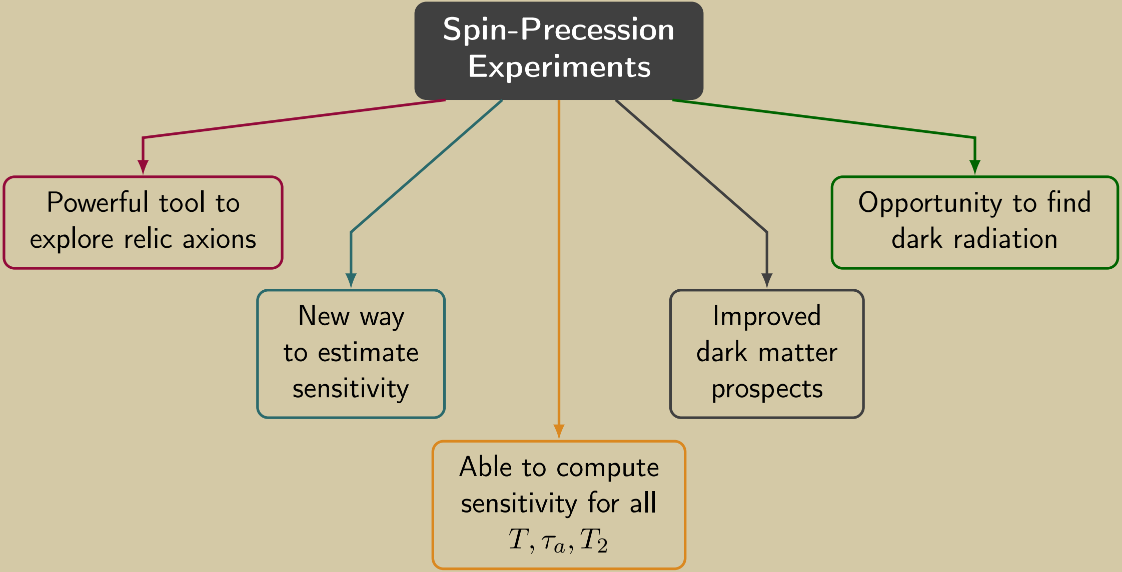
- Improved dark matter prospects



Spin-Precession Experiments

Powerful tool to explore relic axions

New way to estimate sensitivity

Able to compute sensitivity for all T, τ_a, T_2

Improved dark matter prospects

Opportunity to find dark radiation