Searches for Axion Dark Matter

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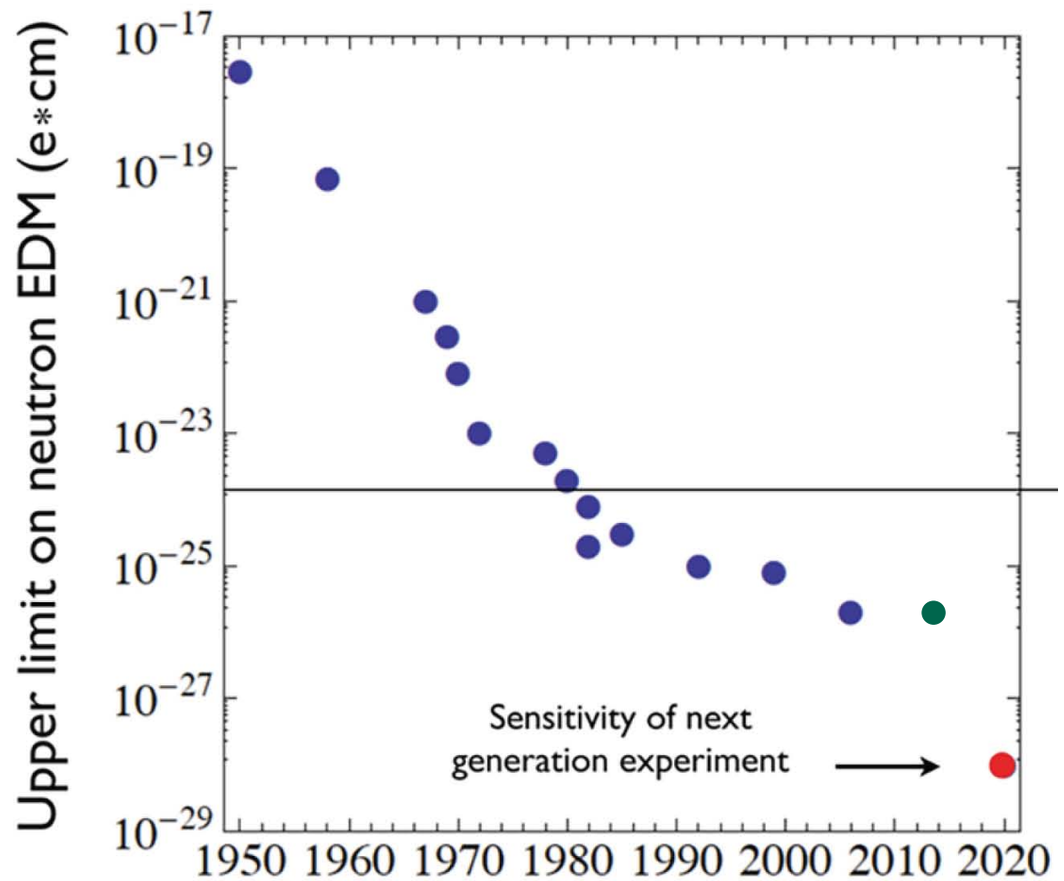
BLV 2017

Why axions?

$$\mathcal{L}_{\rm QCD} \supset \frac{\theta}{32\pi^2} {\rm Tr}\ G_{\mu\nu}\widetilde{G}^{\mu\nu} \quad \Rightarrow \quad d_n \approx 3.6 \times 10^{-16}\theta\ e\ {\rm cm}$$



[B. Fillipone]

Why so small?

$$\theta \lesssim 10^{-10}$$

Strong CP problem

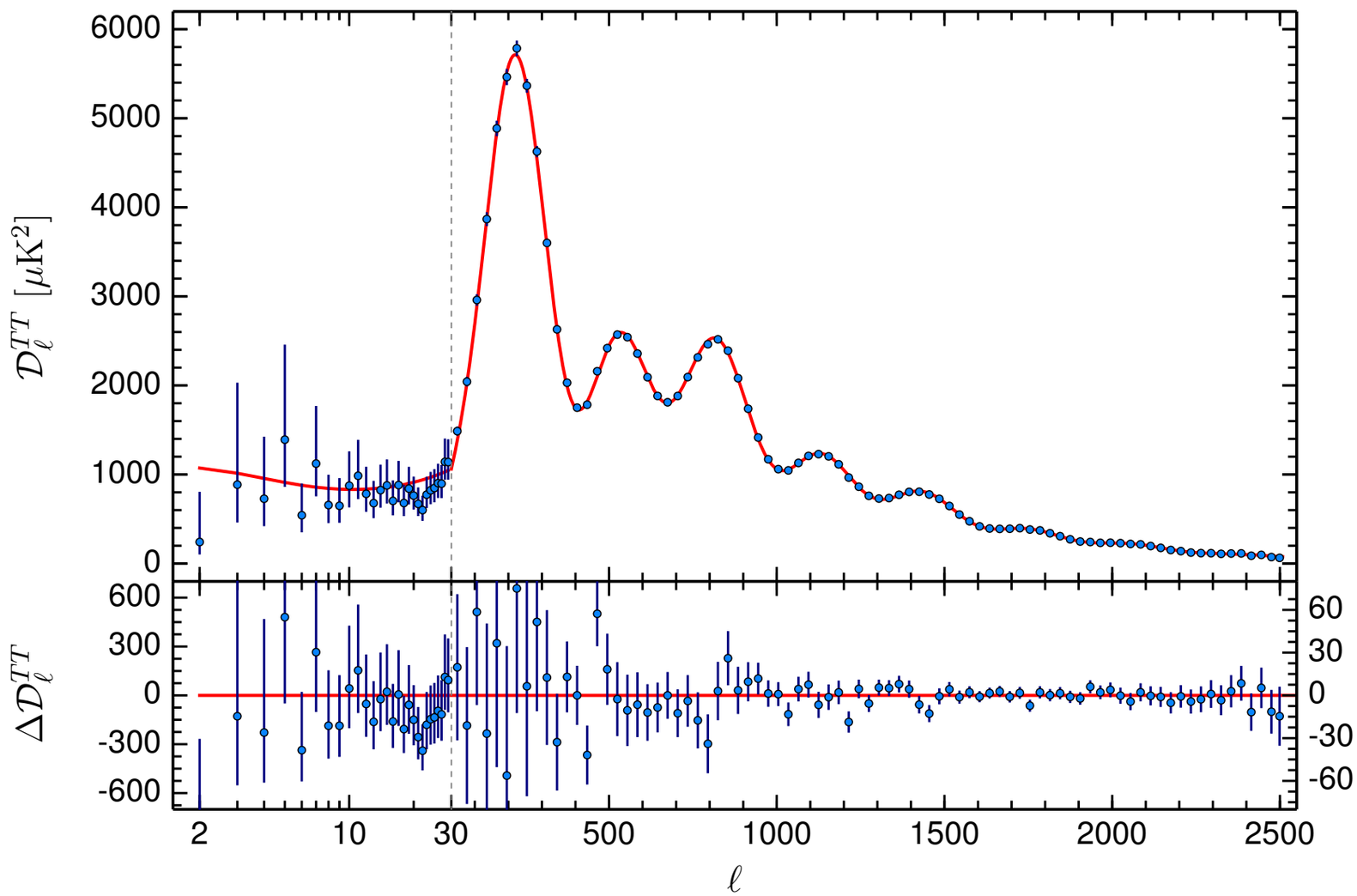
Axion can dynamically relax θ

[Peccei & Quinn, Phys. Rev. Lett. 1977]

$$\mathcal{L}_{\rm QCD} \supset \left(\theta - \frac{a}{f_a}\right) \frac{1}{32\pi^2} {\rm Tr}\ G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

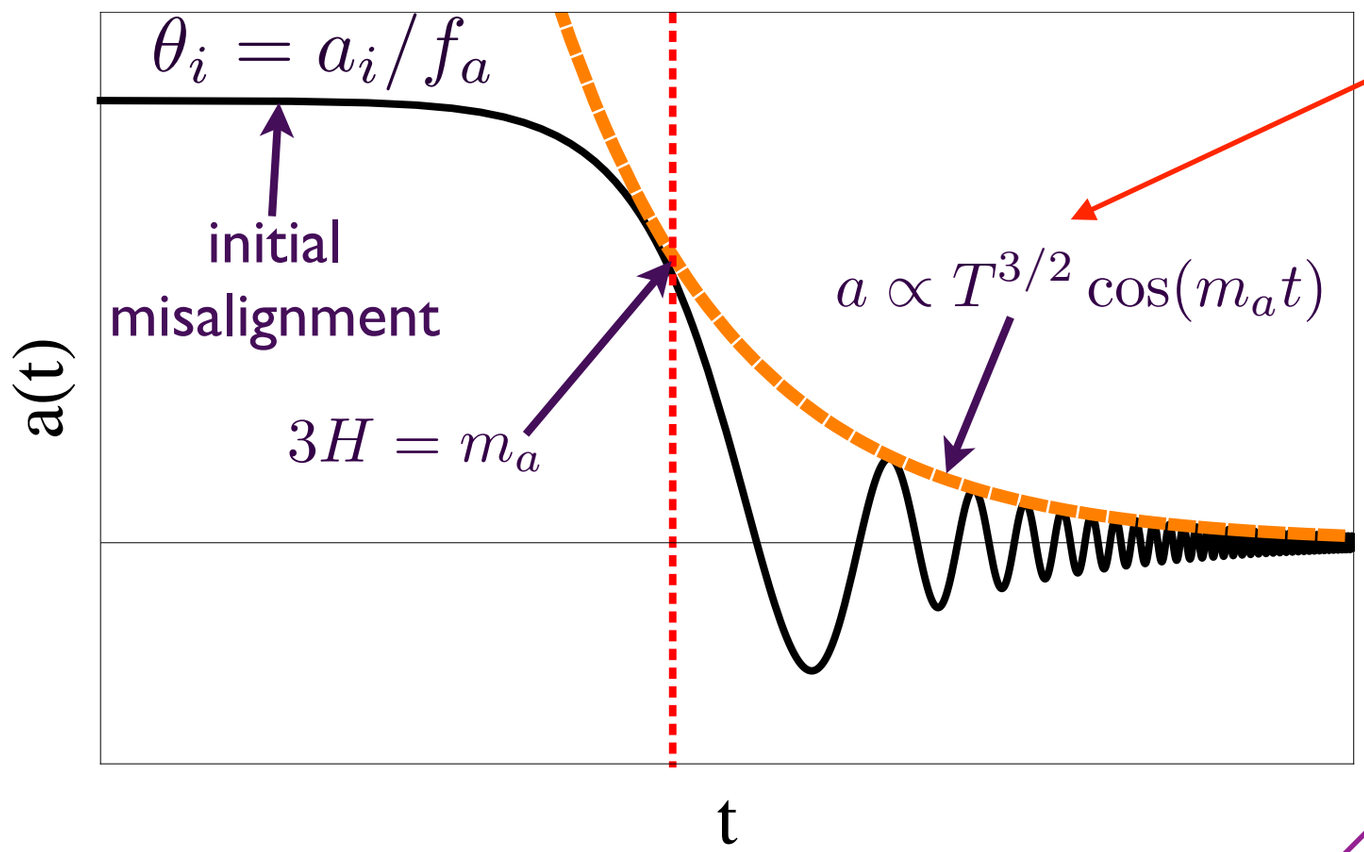
Why dark matter?

[Planck collab. A&A 2016]



Fit to CMB data is exquisitely good, and requires 26.8% of energy density in cold DM

Axion DM: one field solves two problems!



looks just like cold DM!

solve strong CP, DM with **at worst** ~1% tuning

$$\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{16}\ \mathrm{GeV}}\right)^{7/6} \left(\frac{\theta_i}{5\times 10^{-3}}\right)^2$$

$$m_a \sim 6\times 10^{-10}\ \mathrm{eV} \left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$$

Axion-SM interactions

[Graham and Rajendran, Phys. Rev. D88 (2013)]

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu} - \frac{i}{2} g_d a \overline{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu} + g_{aNN} (\partial_\mu a) \overline{N} \gamma^\mu \gamma_5 N + g_{aee} (\partial_\mu a) \overline{e} \gamma^\mu \gamma_5 e$$

Axion-photon conversion

Nucleon EDM

Nuclear axial moment

Electron axial moment

$$\underbrace{\qquad\qquad}_{\propto \nabla a}$$

Note: for QCD axion, $m_a \sim 6 \times 10^{-10}\ \mathrm{eV} \left(\frac{10^{16}\ \mathrm{GeV}}{f_a} \right)$

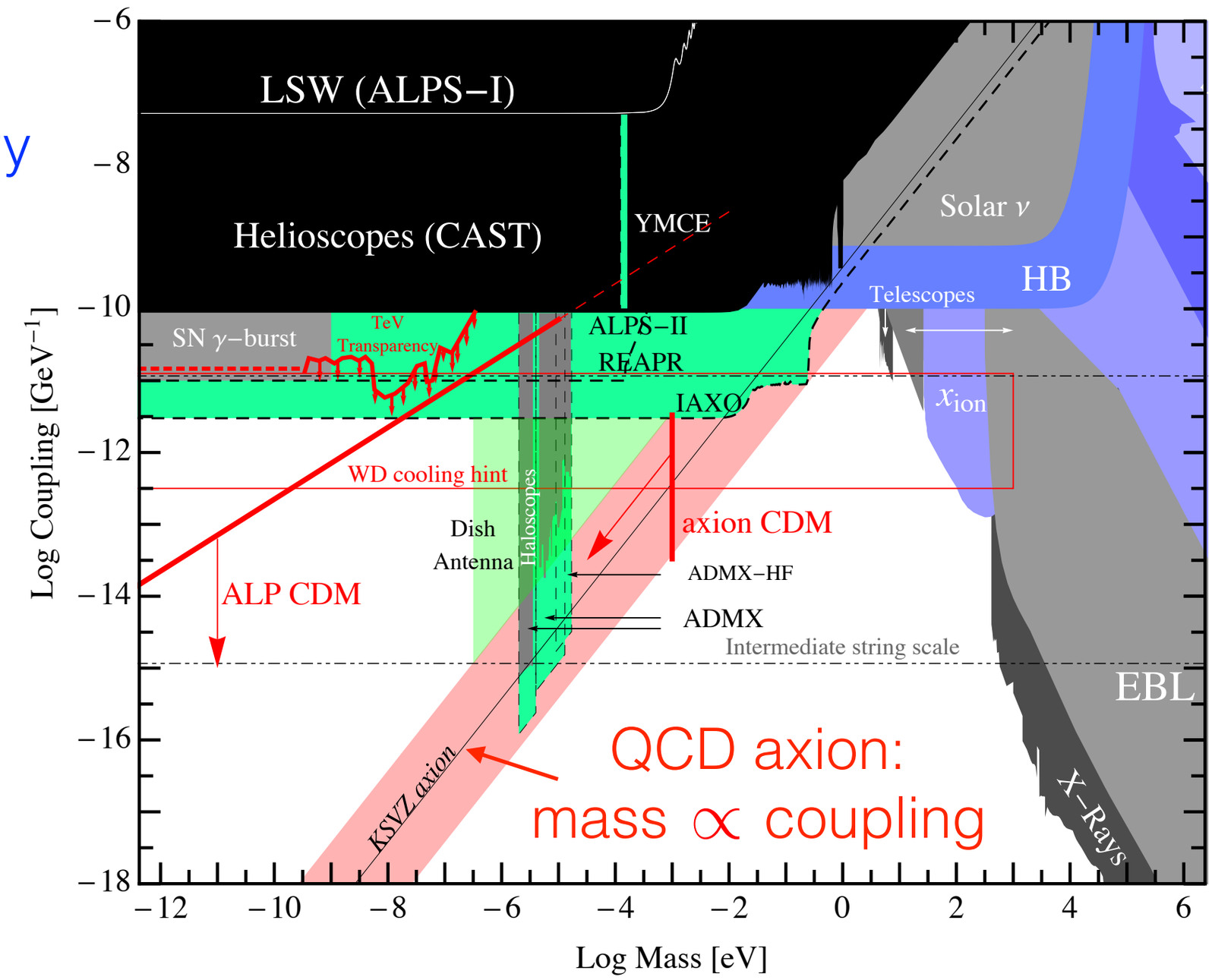
All couplings of order $1/f_a$

For "axion-like particles" (ALPs), couplings independent of m_a

ALP parameter space

[Essig et al., 1311.0029]

Couples very weakly to SM



QCD axion: mass ∝ coupling

Enormous mass range

ALP parameter space

[Essig et al., 1311.0029]

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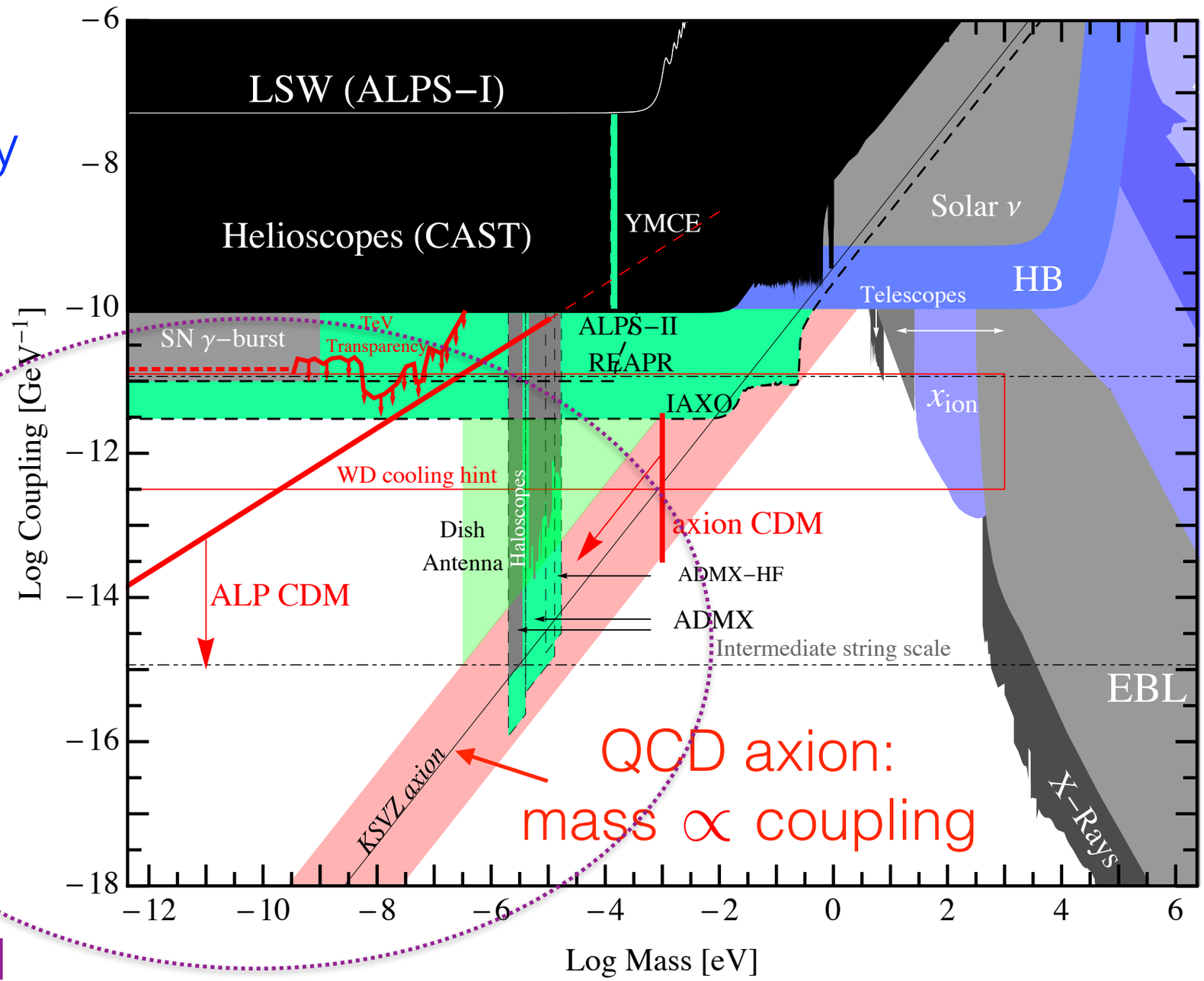


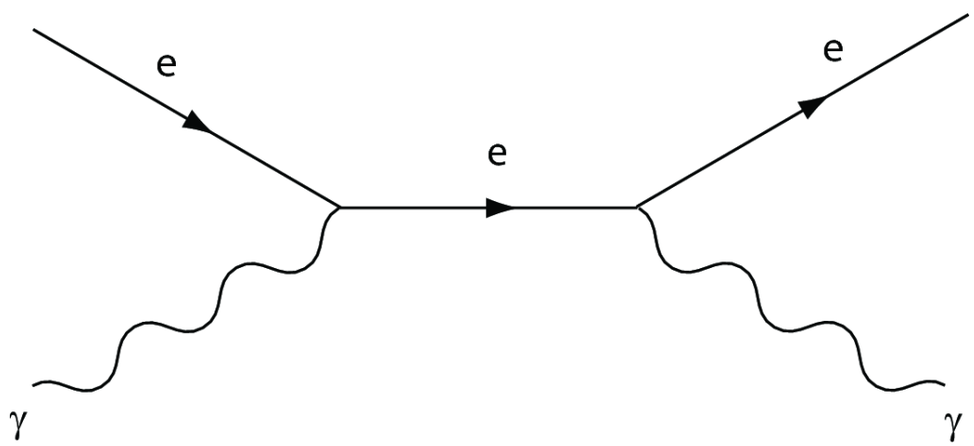
QCD axion: mass ∝ coupling

good DM candidates

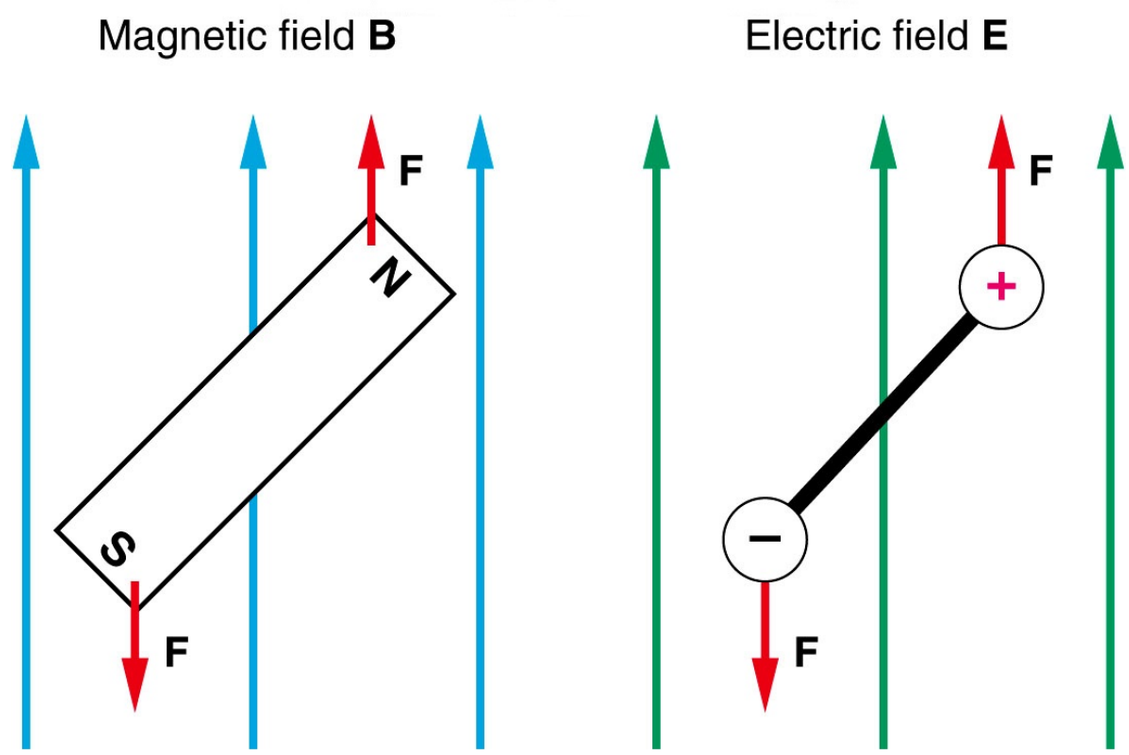
Enormous mass range

Axion DM today: field, not particle

Useful analogy:



vs.



Light bosonic DM behaves collectively:
think in terms of charges and currents,
not Feynman diagrams

Properties of axion DM

$$m_a \ll 1\text{eV}$$

Bosonic DM + macroscopic occupation # = classical field:

$$a(t) = a_0 \sin(m_a t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \sin(m_a t)$$

e.g. $m_a = 10^{-9}$ eV

$\lambda_{\rm Comp} \sim$ km

$\tau_{\rm Comp} \sim \mu$s

Local DM velocity → Spatial coherence → Temporal coherence

$$\Delta v_{\rm DM} \sim v_{\rm DM} \sim 10^{-3} \qquad \lambda_{\rm dB} = \frac{\lambda_{\rm Comp}}{v_{\rm DM}} \qquad \tau_{\rm dB} = \frac{\lambda_{\rm Comp}}{v_{\rm DM}^2}$$

Experiments can exploit enhanced coherence time

Properties of axion DM

$$m_a \ll 1\text{eV}$$

$$a(t) = a_0 \sin(m_a t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \sin(m_a t)$$

In axion DM background, get oscillating observables:

[Sikivie, Phys. Rev. Lett. (1983)]

$$\nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E}_0 \times \nabla a - \mathbf{B}_0 \frac{\partial a}{\partial t}\right)$$

$$\nabla \cdot \mathbf{E}_r = -g_{a\gamma\gamma}\mathbf{B}_0 \cdot \nabla a$$

Harmonic response from static fields

$$d_n = g_d a$$

Time-varying EDM

$$H_N \supset g_{aNN} \nabla a \cdot \vec{\sigma}_N$$

Spin-dependent force

Properties of axion DM

$$m_a \ll 1\mathrm{eV}$$

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Spin-dependent force

Note: $\nabla a \propto v_{\mathrm{DM}} \sim 10^{-3}$

Axion-photon searches

$$\underbrace{\nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t}} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Cavity regime: $\lambda_{\mathrm{Comp}} \sim R_{\mathrm{exp}}$

ADMX

$$\nabla \times \mathbf{B}_r = \cancel{\frac{\partial \mathbf{E}_r}{\partial t}} + \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\mathrm{eff}}}$$

Quasistatic regime: $\lambda_{\mathrm{Comp}} \gg R_{\mathrm{exp}}$

ABRACADBRA

$$\cancel{\nabla \times} \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Radiation regime: $\lambda_{\mathrm{Comp}} \ll R_{\mathrm{exp}}$

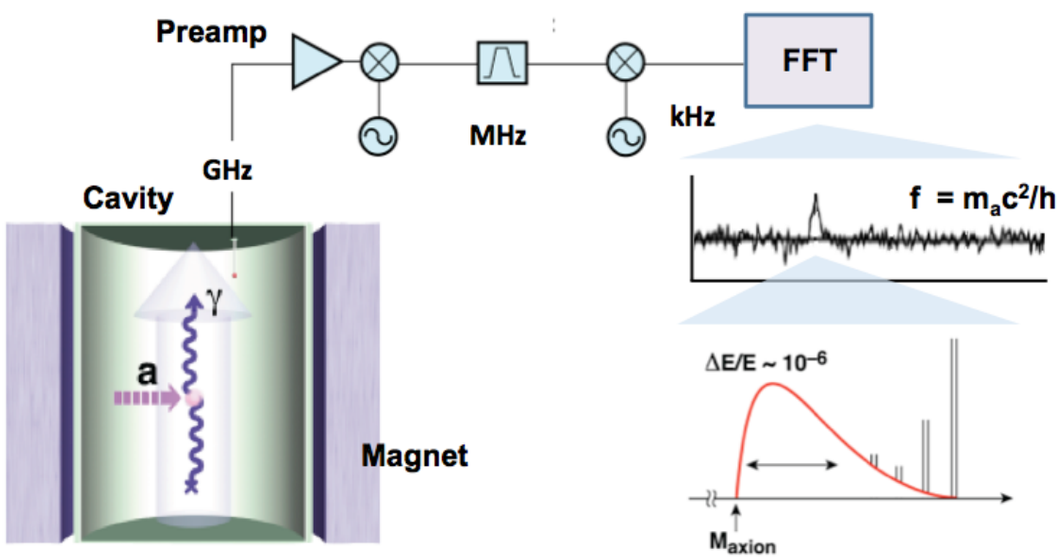
MADMAX

ADMX: resonant cavity detection

[Rosenberg et al., ADMX collab.]

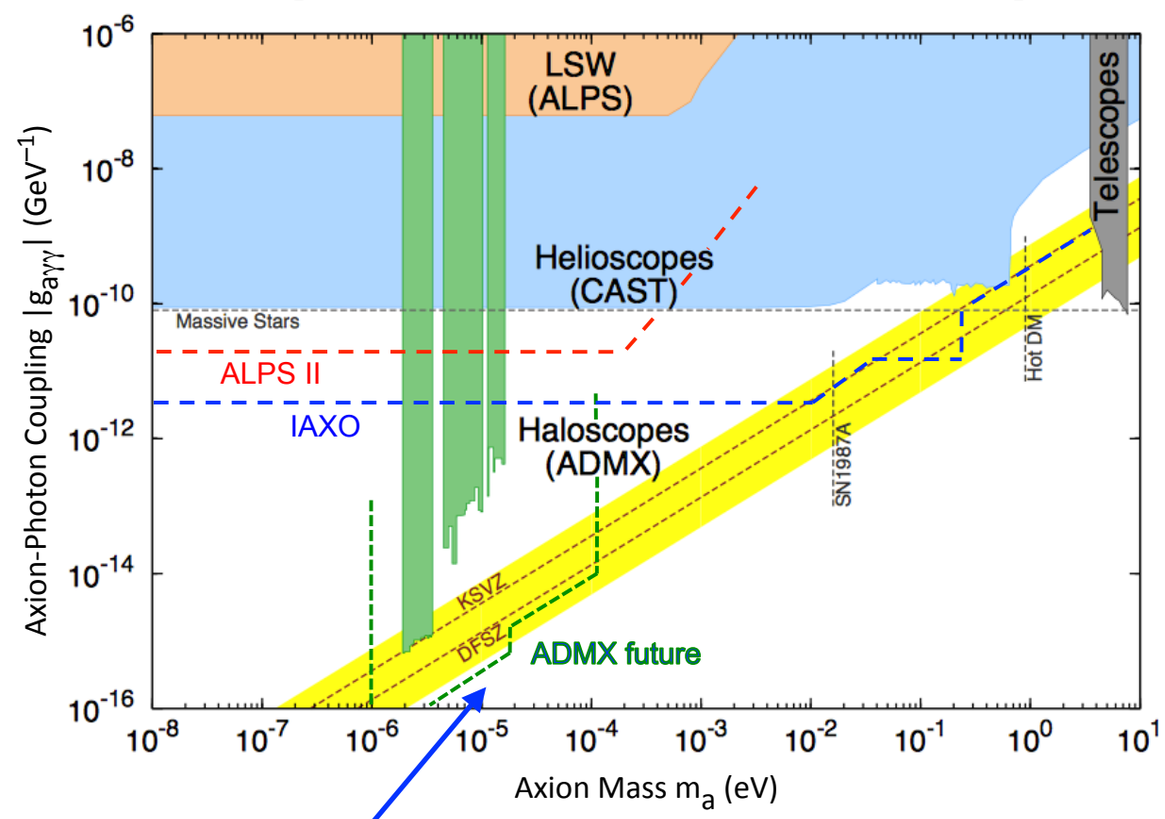
$$\underbrace{\nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t}}_{\text{cavity response}} + \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\text{axion source}}$$

$$P \sim g_{a\gamma\gamma}^2 \frac{\rho_{\rm DM}}{m_a} B_0^2 V Q$$



Tune cavity modes
to scan axion masses

[Graham et al., Ann. Rev. NPS 2015]



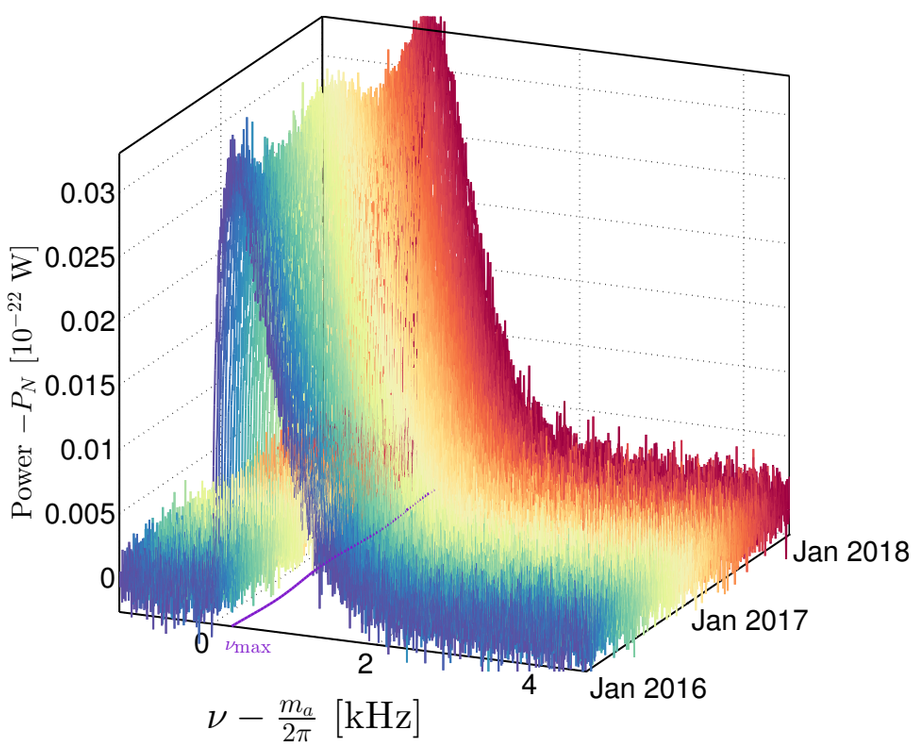
Cavity b.c. fix mass range to cavity size;
larger masses -> smaller V

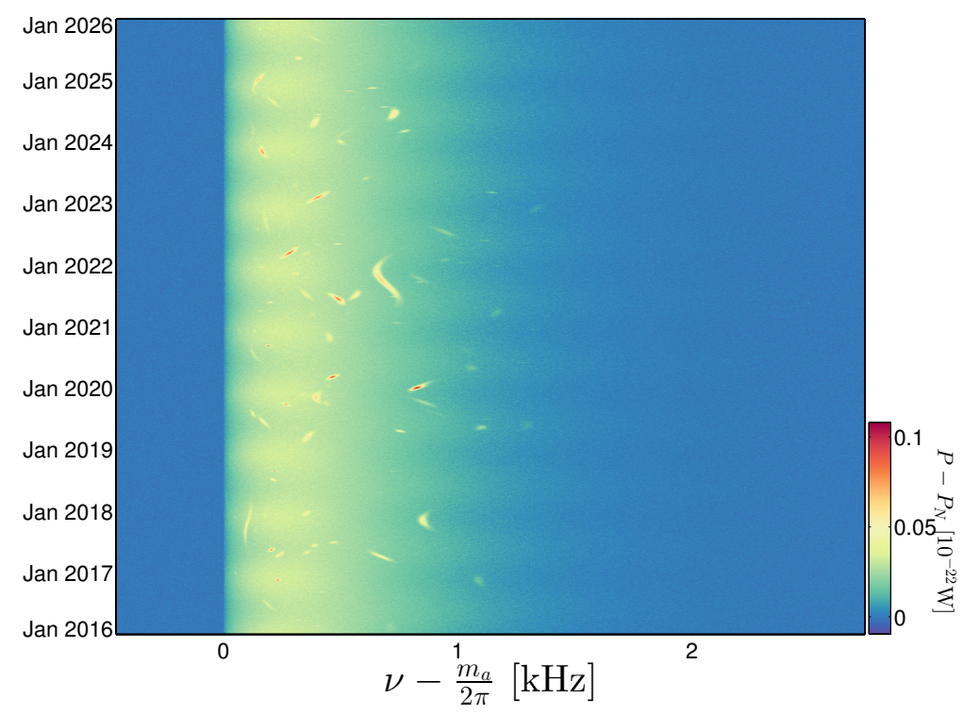
Axion astronomy with ADMX

[O'Hare and Green, Phys. Rev. D95 (2017)]

$$a(t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \int d^3\mathbf{v}\, g(\mathbf{v})\, \cos(\omega_{\mathbf{v}}(t - \mathbf{v}\cdot\mathbf{x}))$$

$$\omega_{\mathbf{v}} = m_a(1 + \frac{1}{2}v^2 + \mathcal{O}(v^4))$$



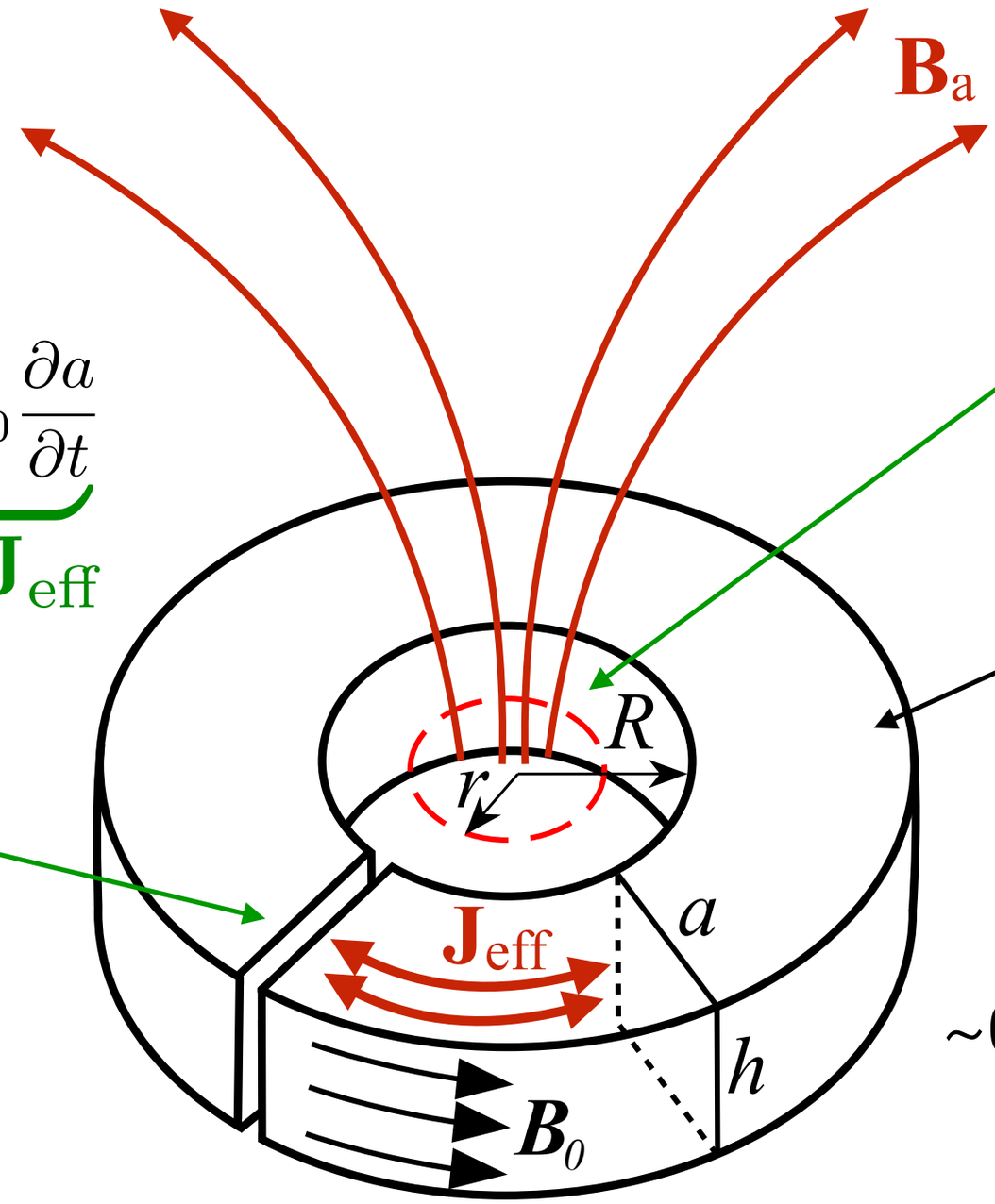


Much easier to identify structure in g(v) for axions than WIMPS!

Quasistatic regime: ABRACADABRA

[YK, Safdi, Thaler, Phys. Rev. Lett. 2016]

$$\nabla \times \mathbf{B}_r = \cancel{\frac{\partial \mathbf{E}_r}{\partial t}} + \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\rm eff}}$$



broadband or resonant detection in zero-field region

superconducting toroid

gap (or overlap) for return current in QS regime

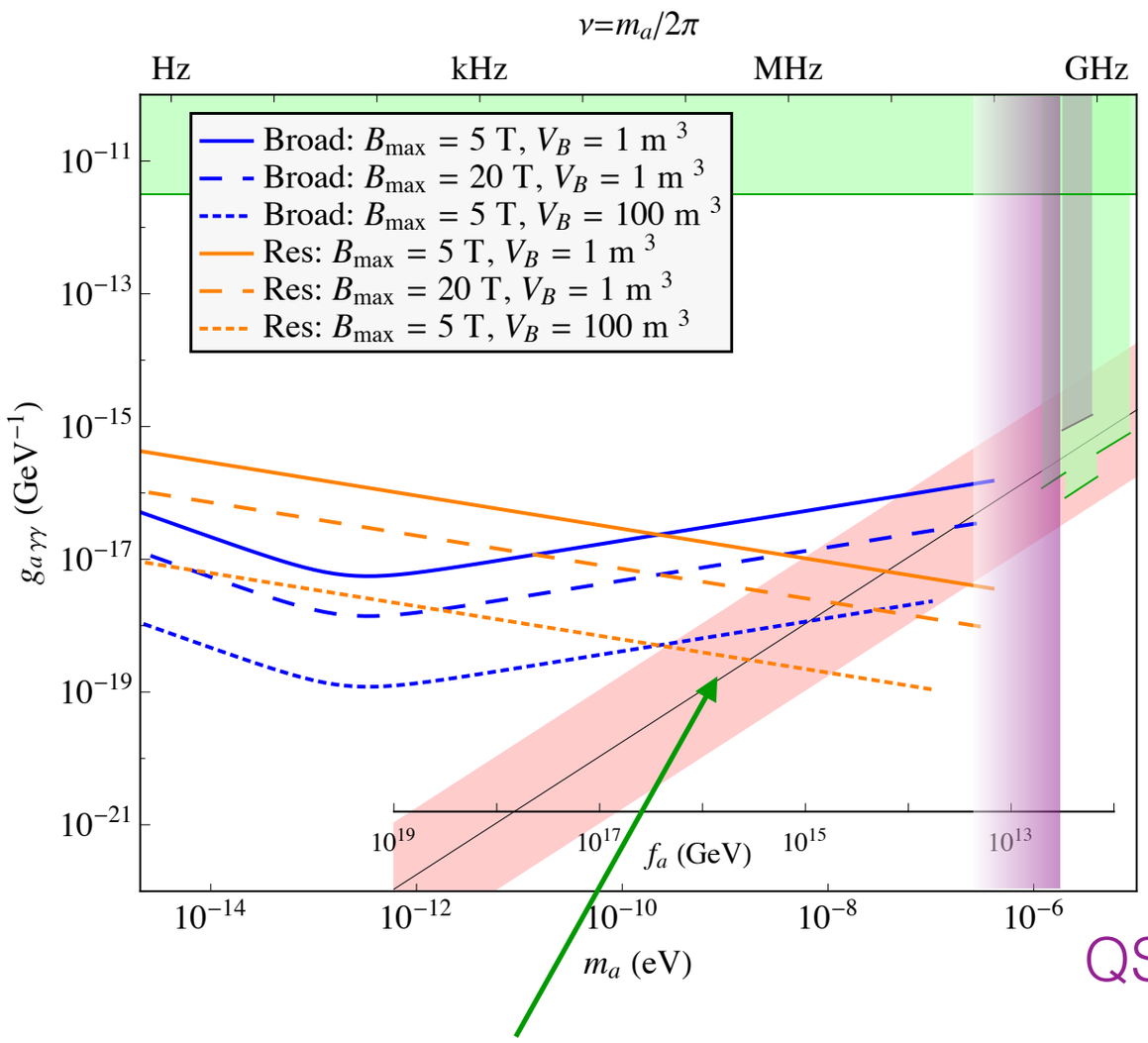
geometric factor, ~0.1 for r = R = a = h/3

$$\Phi_a(t) = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\cos(m_a t) \times (B_{\rm max} V G_{\rm toroid})$$

Volume enhancement: energy stored scales as $B_0^2 V^2$

ABRACADABRA reach

Full-scale reach:

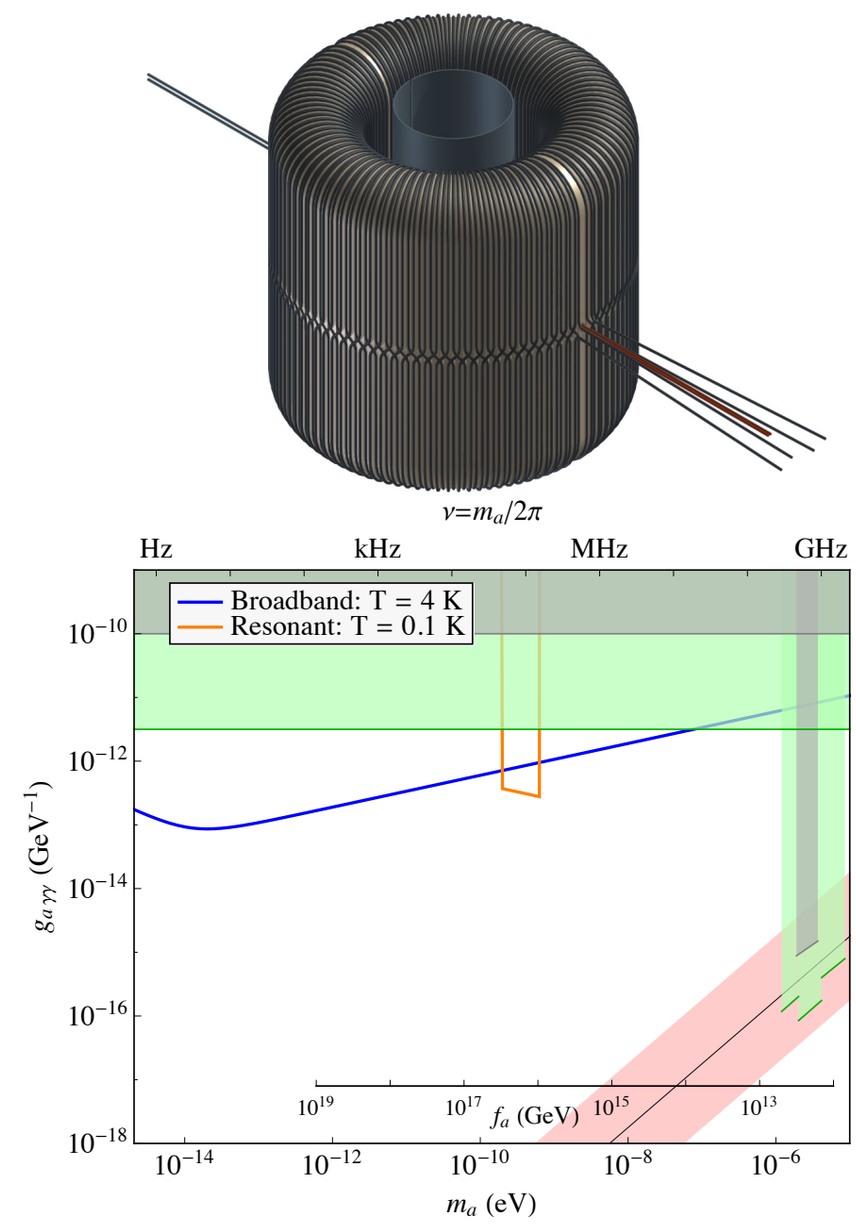


GUT-scale QCD axion

QS breaks down (detailed sim. needed)

ABRA-10cm prototype:

[Winslow et al., ABRACADABRA collab.]



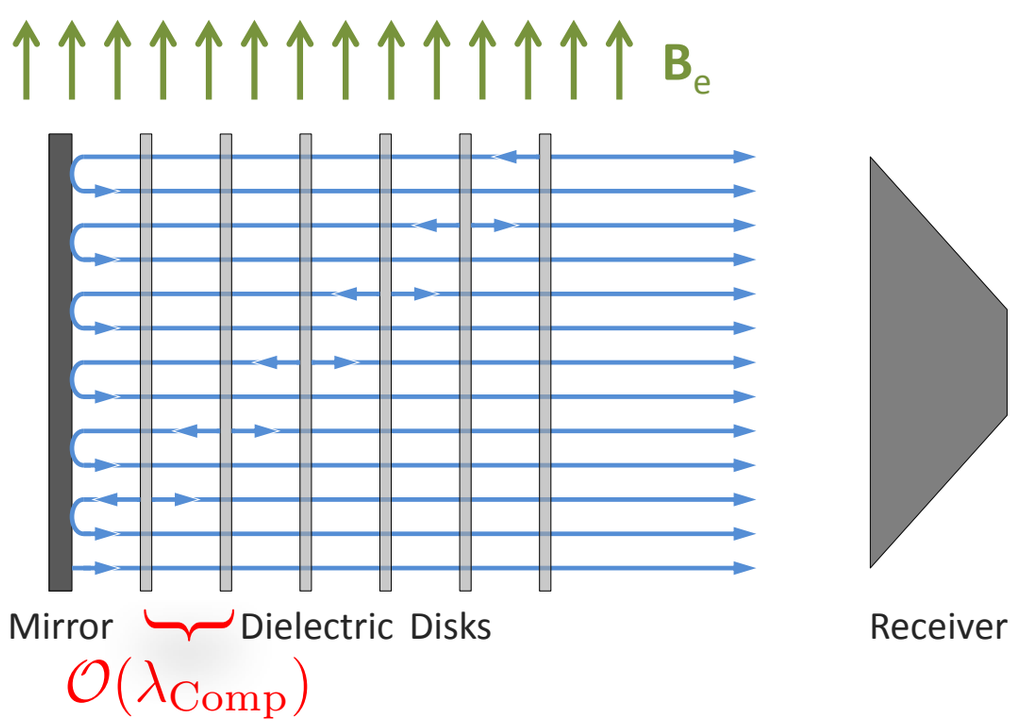
Data by end of 2017!

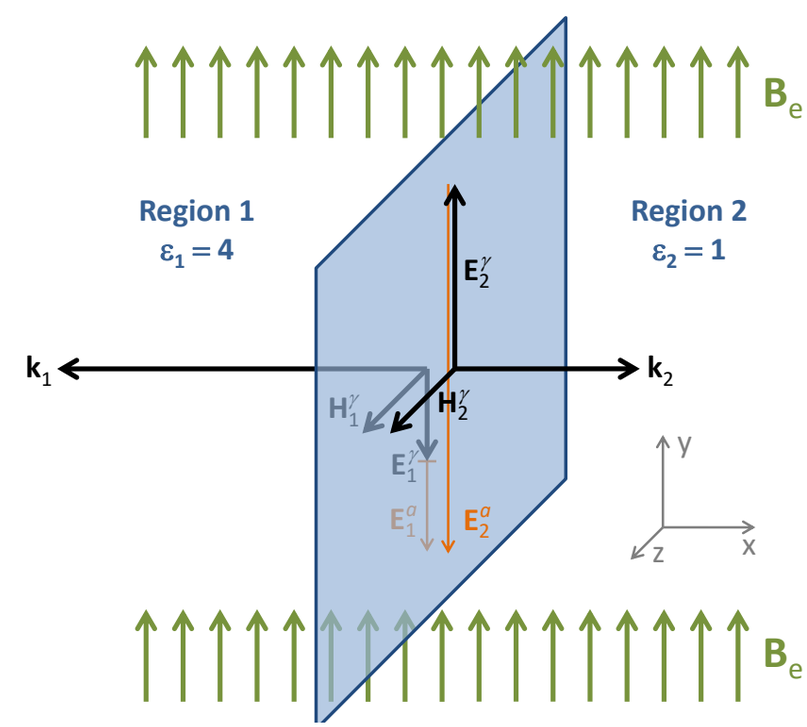
Radiation regime: MADMAX

[Millar et al. JCAP 1701 (2017), MADMAX working group Phys. Rev. Lett. 2017]

$$\nabla \times \mathbf{B}_r = \epsilon \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t} \implies \mathbf{D}_r(t) = \epsilon \mathbf{E}_r(t) = -g_{a\gamma\gamma} \mathbf{B}_0 \, a(t)$$

E+M boundary condition at interfaces forces radiation to cancel axion-induced **D**

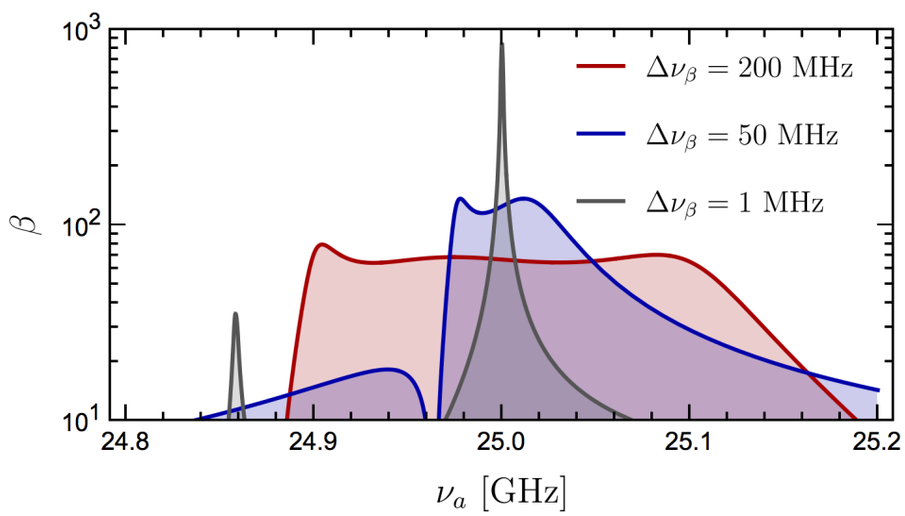




Best of both worlds: large volume and high Q

MADMAX reach

Broadband and resonant modes possible:

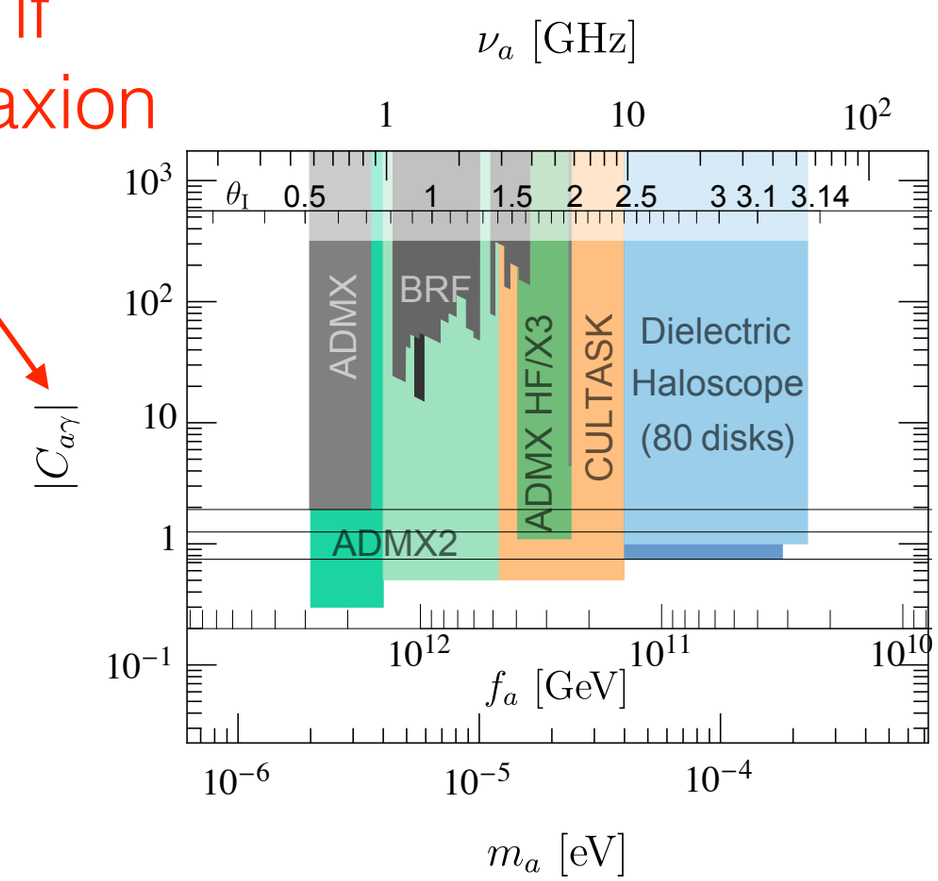


$$P \propto g_{a\gamma\gamma}^2 \rho_{\rm DM} B_0^2 A \beta^2$$

$$\int \beta(\nu_a)^2 \, d\nu_a = N_{\rm disks} \times {\rm const.}$$

=1 if QCD axion

3-year runtime:



Excellent prospects in high-frequency regime

CASPEr: NMR with axion DM

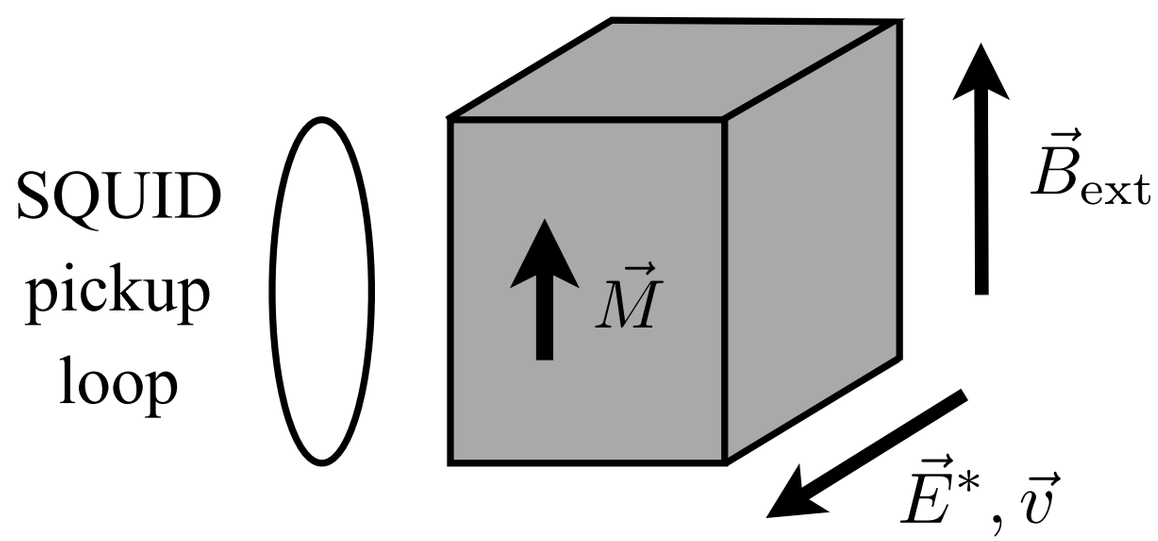
[Budker et al., Phys. Rev. X4 (2014); Graham and Rajendran, Phys. Rev. D88 (2013)]

Nuclei immersed in axion DM can have:

Oscillating EDM and/or Spin-dependent force

$$d_n = g_d \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \cos(m_a t)$$

$$H_N \supset g_{aNN} \sqrt{2\rho_{DM}} \cos(m_a t) \vec{v} \cdot \vec{\sigma}_N$$



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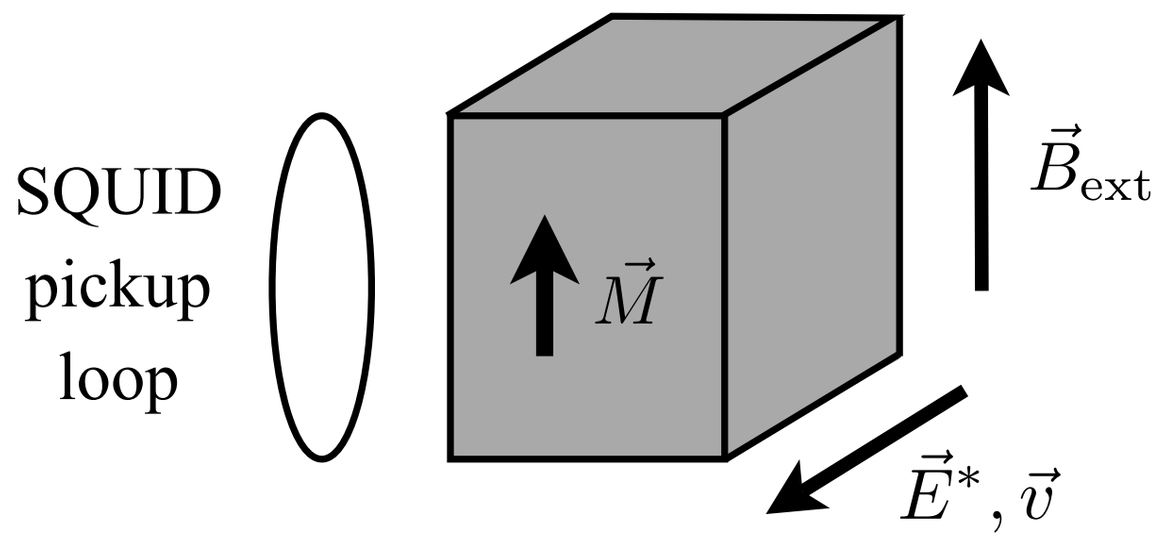
Polarize some spins, watch them precess around:

External E field and/or Axion field velocity



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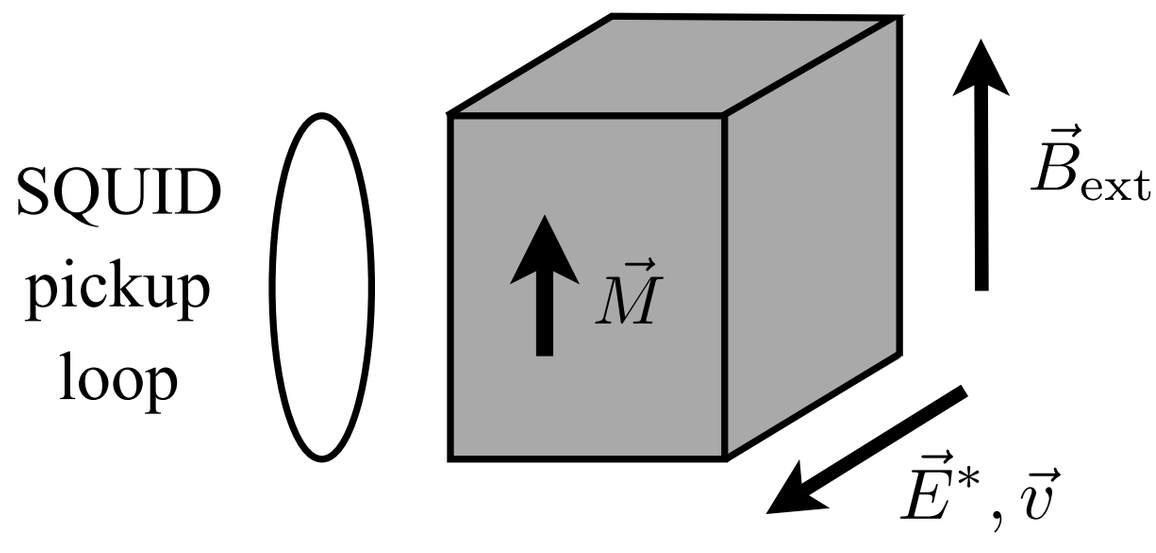


Axion DM is like NMR pulse

Resonance in transverse magnetization when $2\mu B_{\rm ext} = m_a$

CASPEr reach

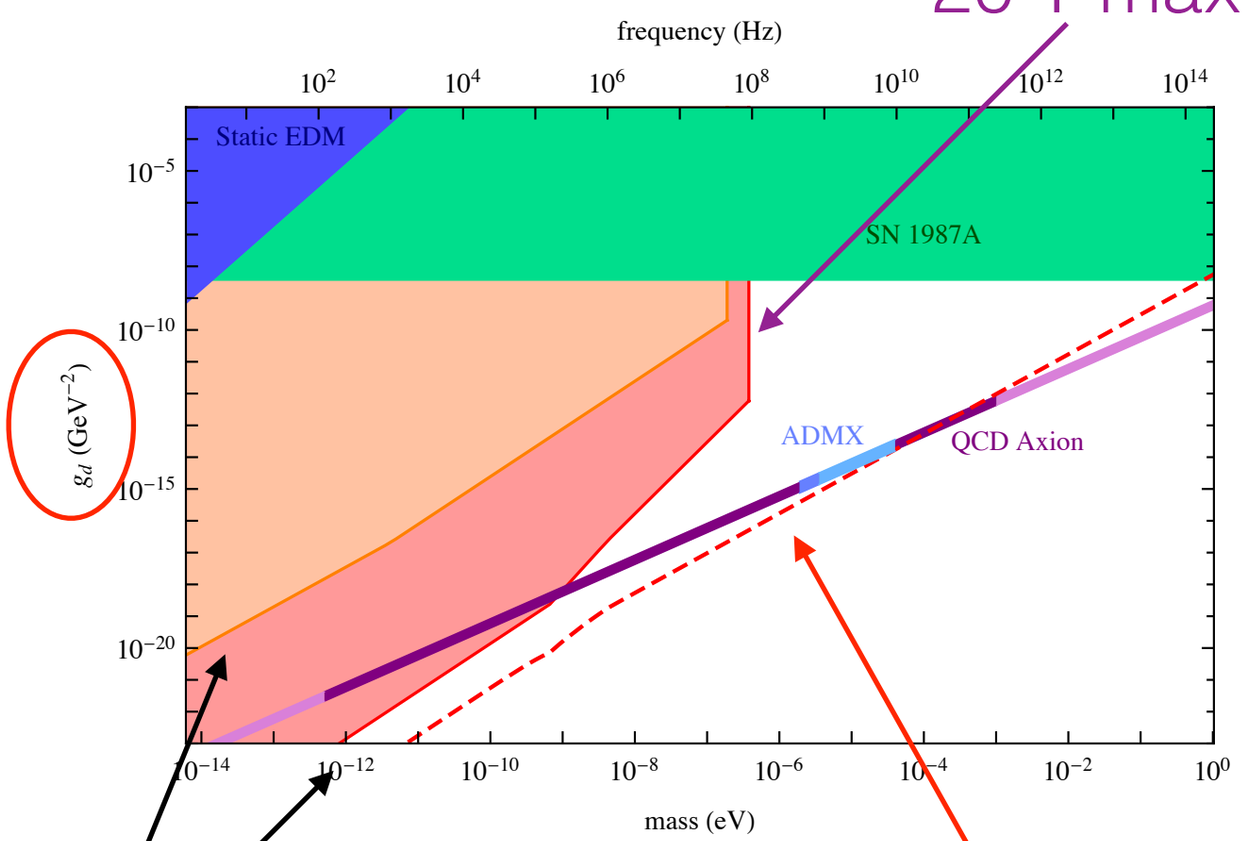
CASPEr-Electric

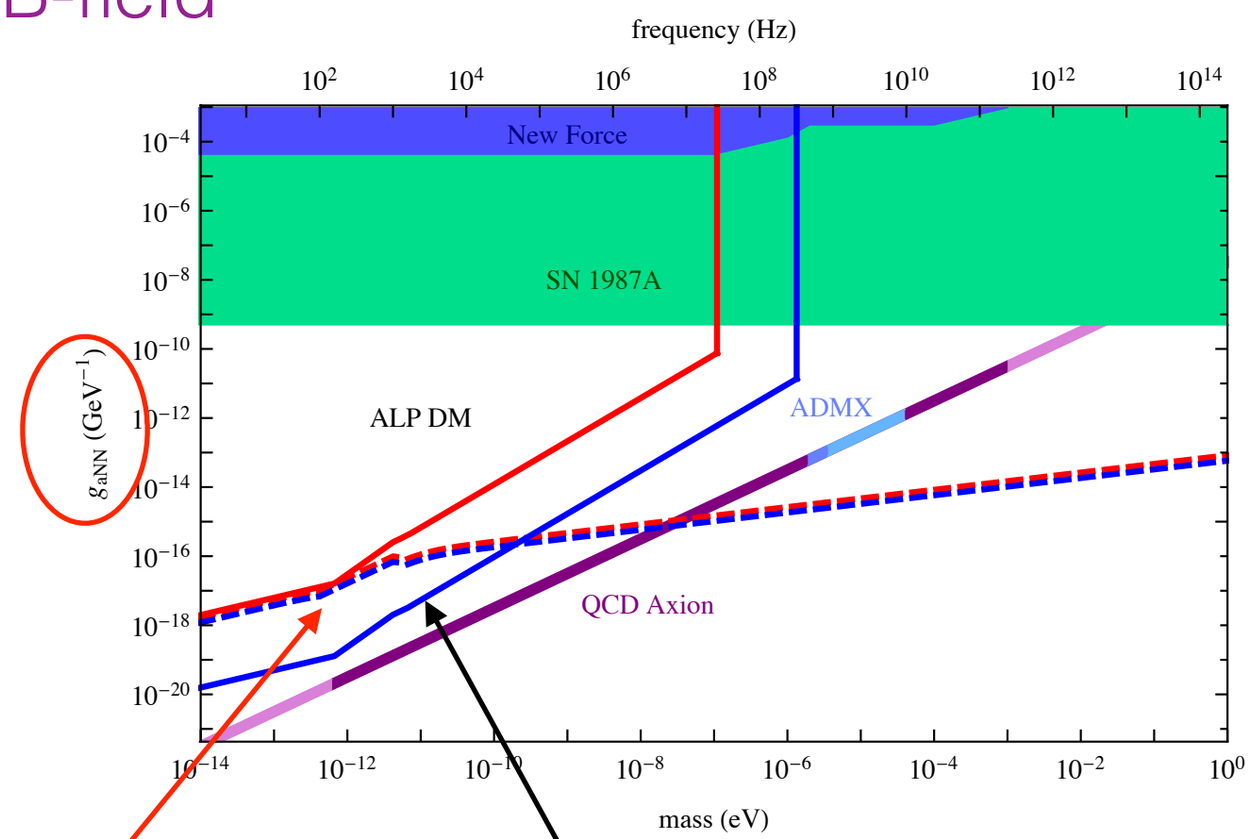
[Budker et al., Phys. Rev. Phys. Rev. X4 (2014)]

CASPEr-Wind

[Graham and Rajendran, Phys. Rev. D88 (2013)]

20 T max B-field





non-decoupling signal!

magnetization noise

velocity suppression:
can't quite reach QCD axion

(Also similar idea using electron spins: QUAX)

[Barbieri et al. Phys. Dark. Univ. 15 (2017)]

CASPEr reach

CASPEr-Electric

[Budker et al., Phys. Rev. Phys. Rev. X4 (2014)]

CASPEr-Wind

[Graham and Rajendran, Phys. Rev. D88 (2013)]

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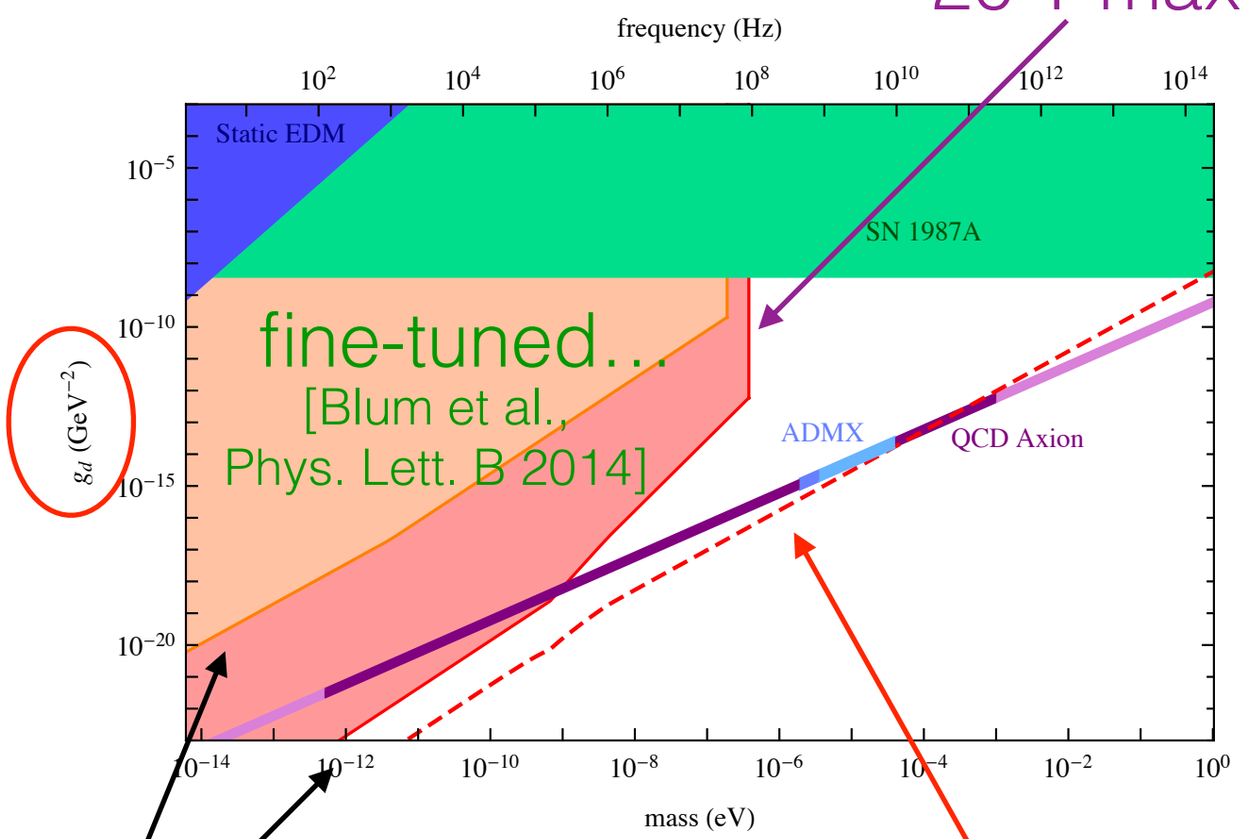
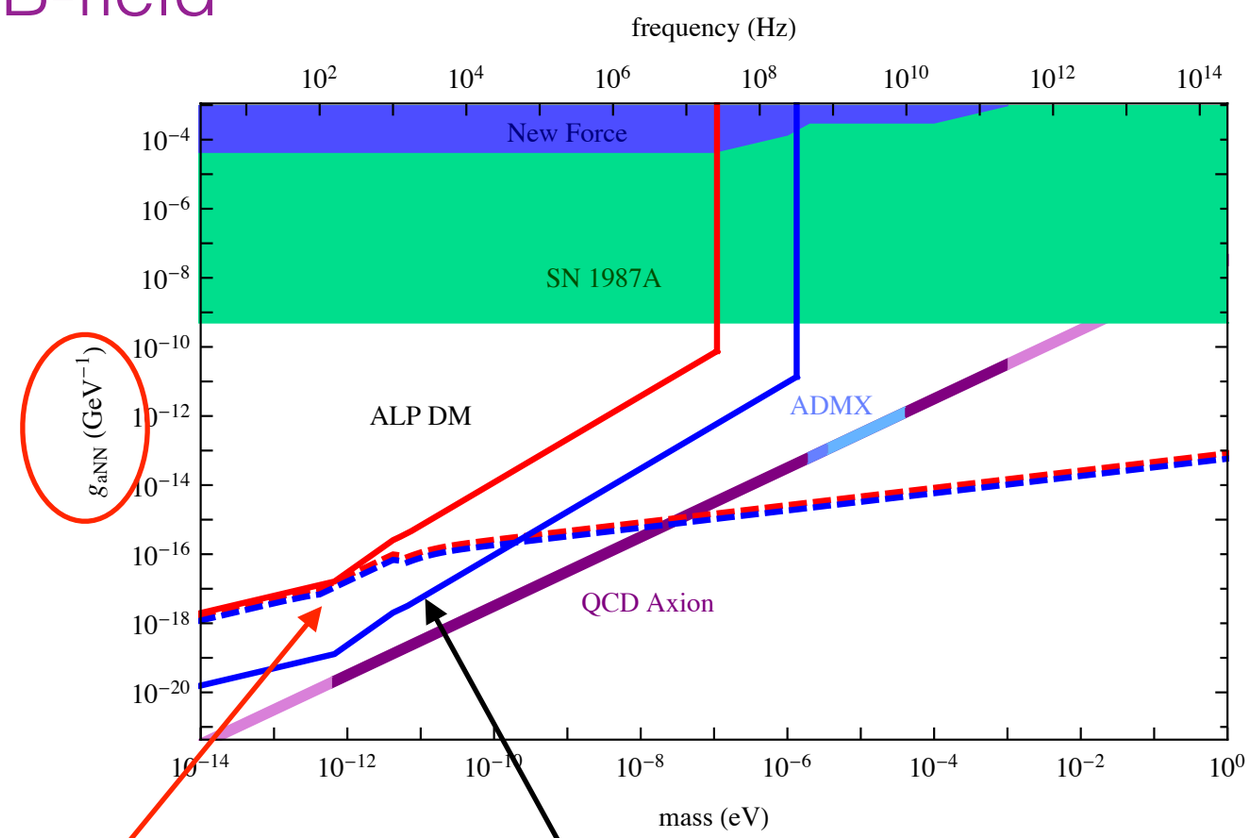


fine-tuned…
[Blum et al., Phys. Lett. B 2014]



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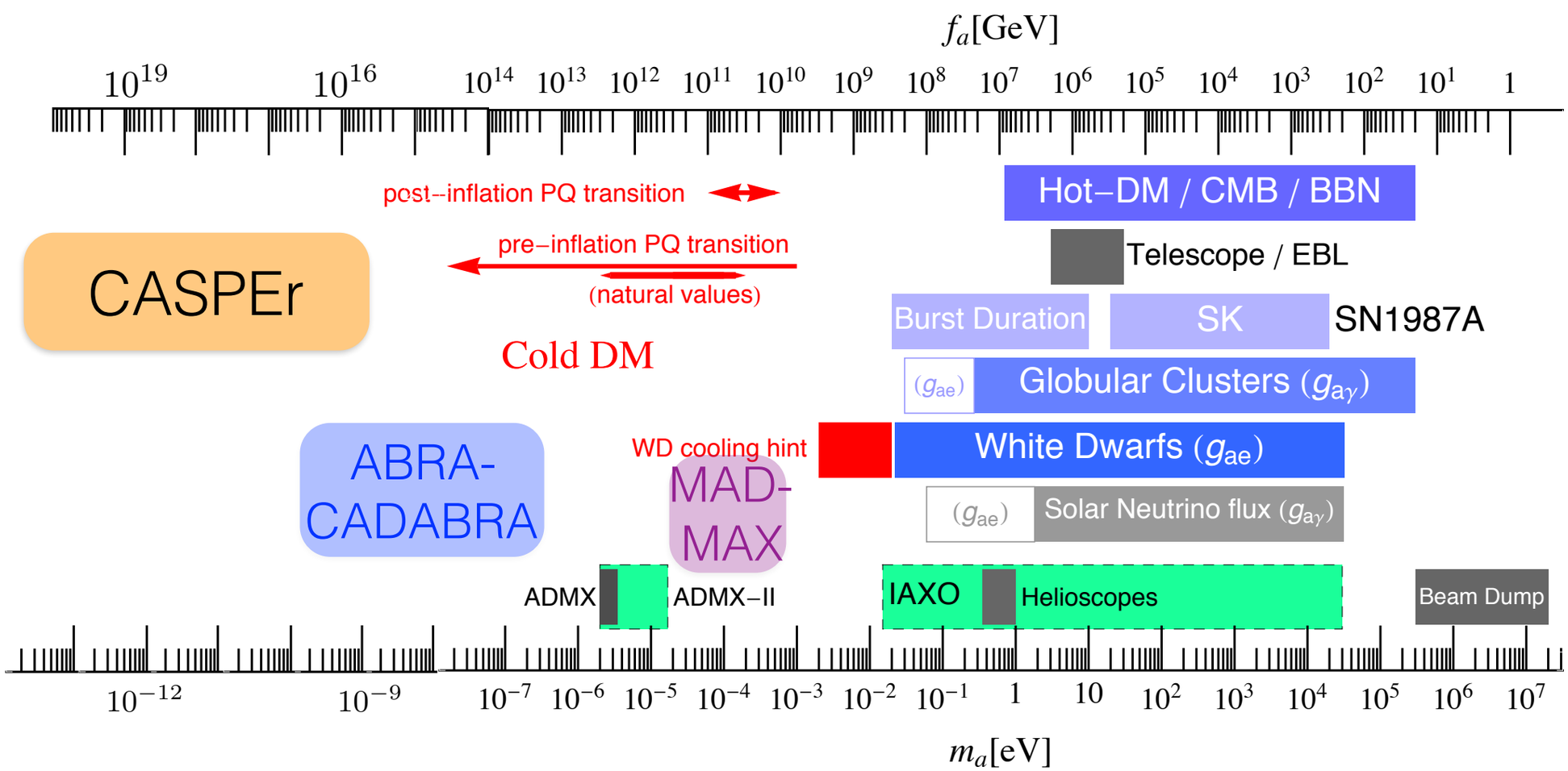
Outlook for QCD axion DM detection



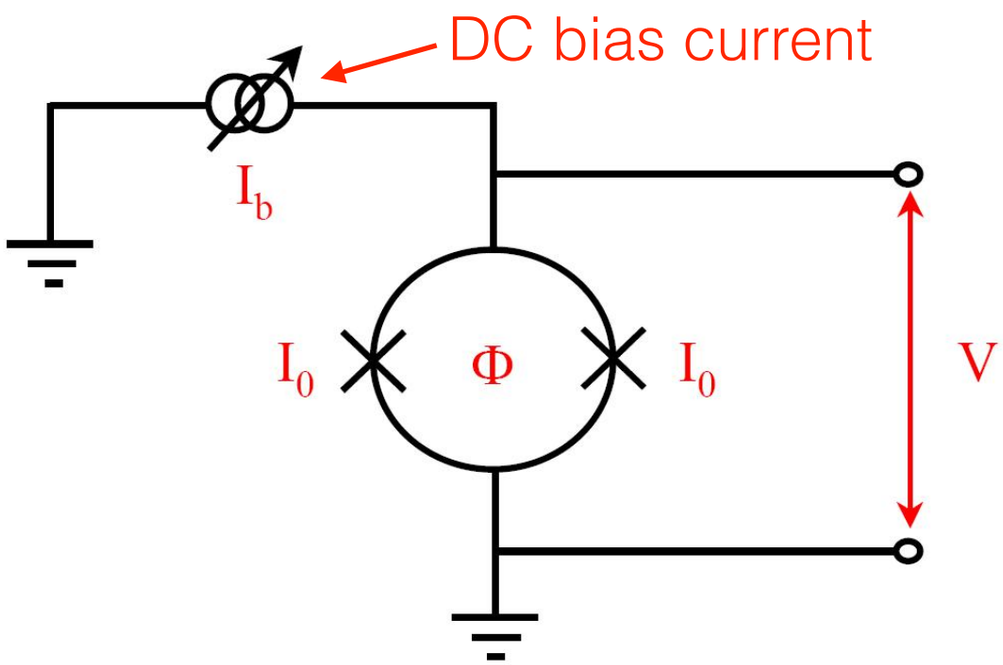
[adapted from Essig et al., 1311.0029]

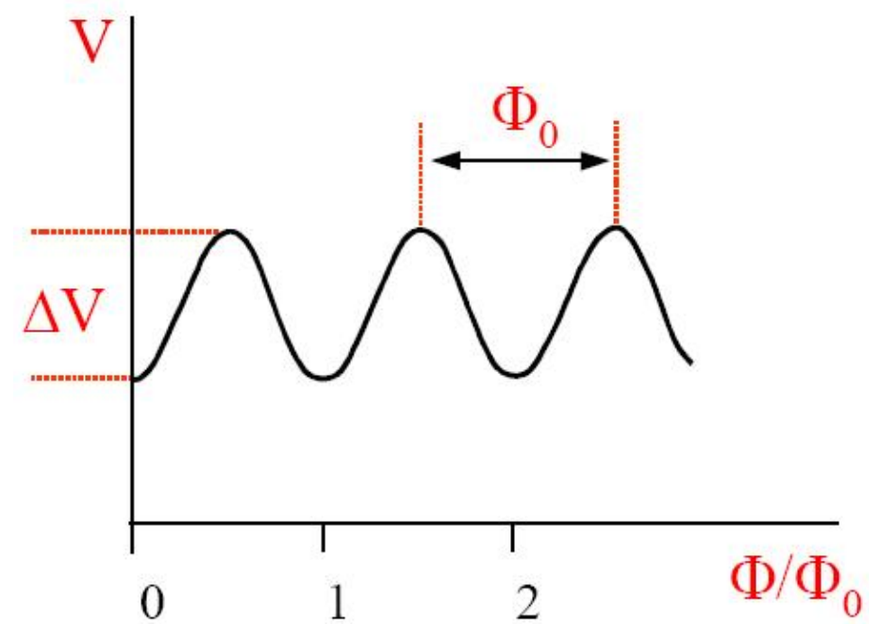
Next decades could definitively probe QCD axion as DM!

Backup slides

SQUID magnetometry basics

Cartoon picture: extremely sensitive flux-to-voltage amplifier



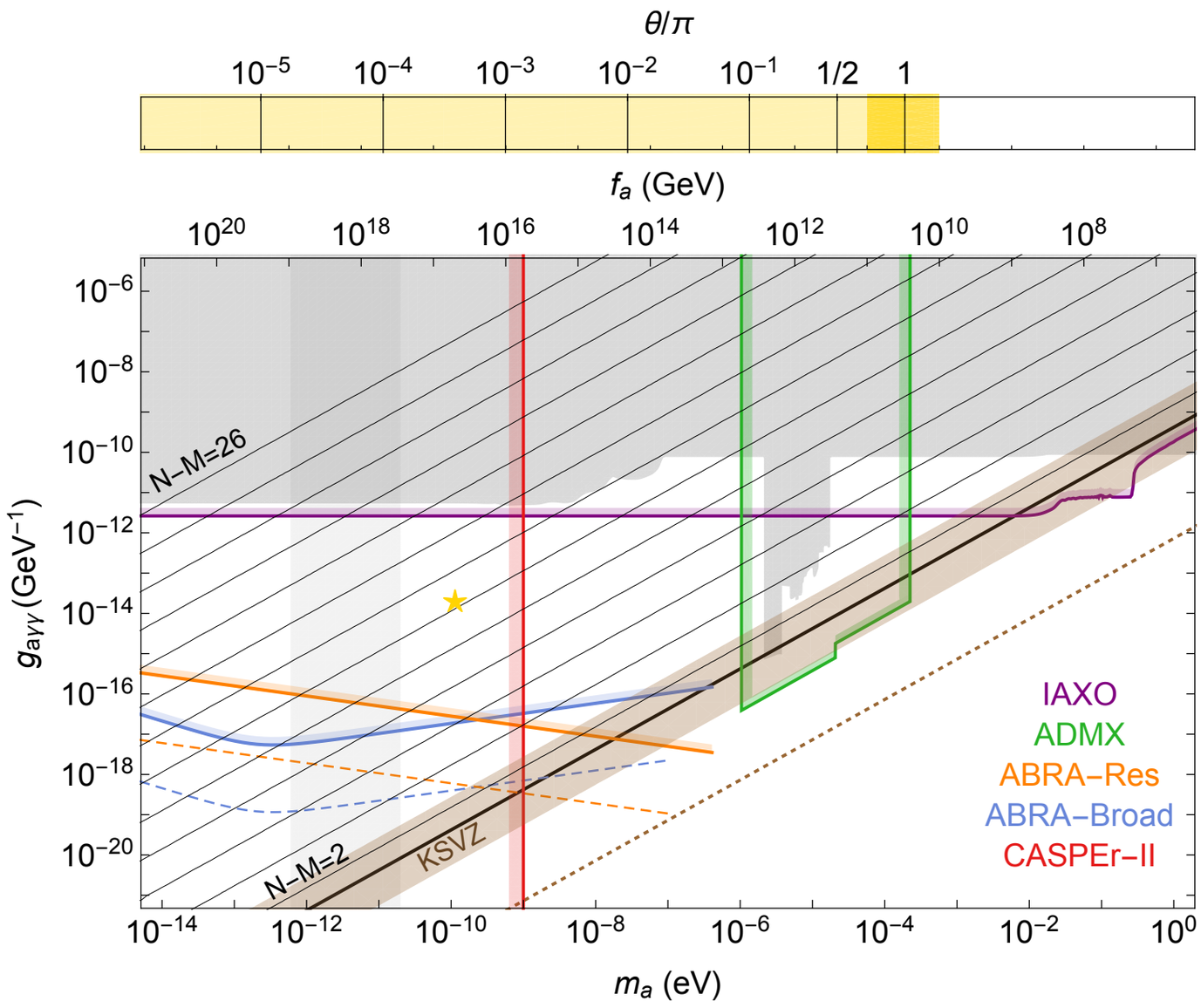


change in flux induces current across junction (DC Josephson effect)

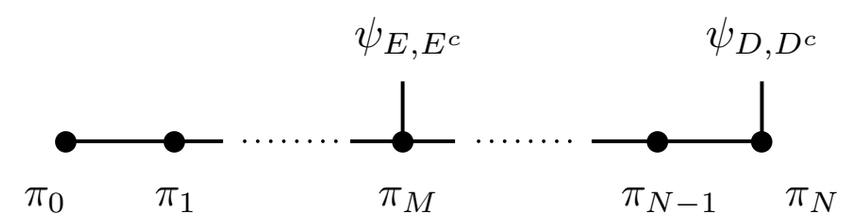
measure extremely small fractions of Φ_0 by fitting sine curve

$$\Phi_0 = \frac{h}{2e} = 2.1 \times 10^{-15}\ \mathrm{Wb} = 2.1 \times 10^{-15}\,\mathrm{T} \cdot \mathrm{m}^2$$

Beyond vanilla QCD axion…



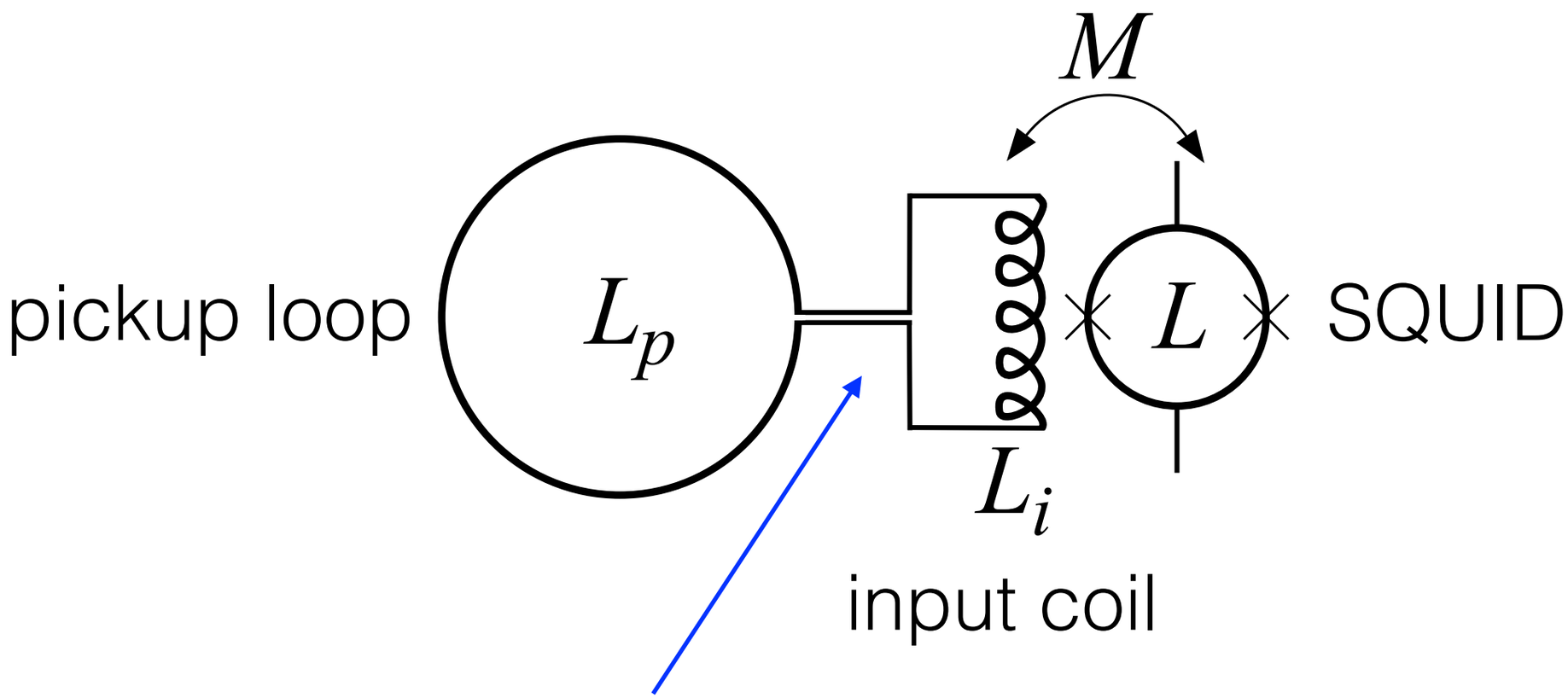
A "Clockwork" Axion: exponentially enhanced photon coupling



[Farina, Pappadopulo, Rompineve, Tesi, 1611.09855]
[based on Choi, Im, 1511.00132; Kaplan, Rattazzi, 1511.01827; Giudice, McCullough, 1610.07962]
[appears to evade misalignment bounds from Ariasa, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald, 1201.5902]

Further motivation to cover full axion parameter space!

Broadband: readout circuit



Cannot resolve thermal noise, SQUID noise dominates

Inductance matching: $L_i \approx L_p \implies \Phi_{\mathrm{SQUID}} \approx \underbrace{\frac{\alpha}{2}\sqrt{\frac{L}{L_p}}}\Phi_{\mathrm{pickup}}$

Optimal coupling*: $\frac{1}{2}\int \mathbf{B}^2\, dV = \frac{\Phi^2}{2L_p} \longrightarrow \approx 0.01$

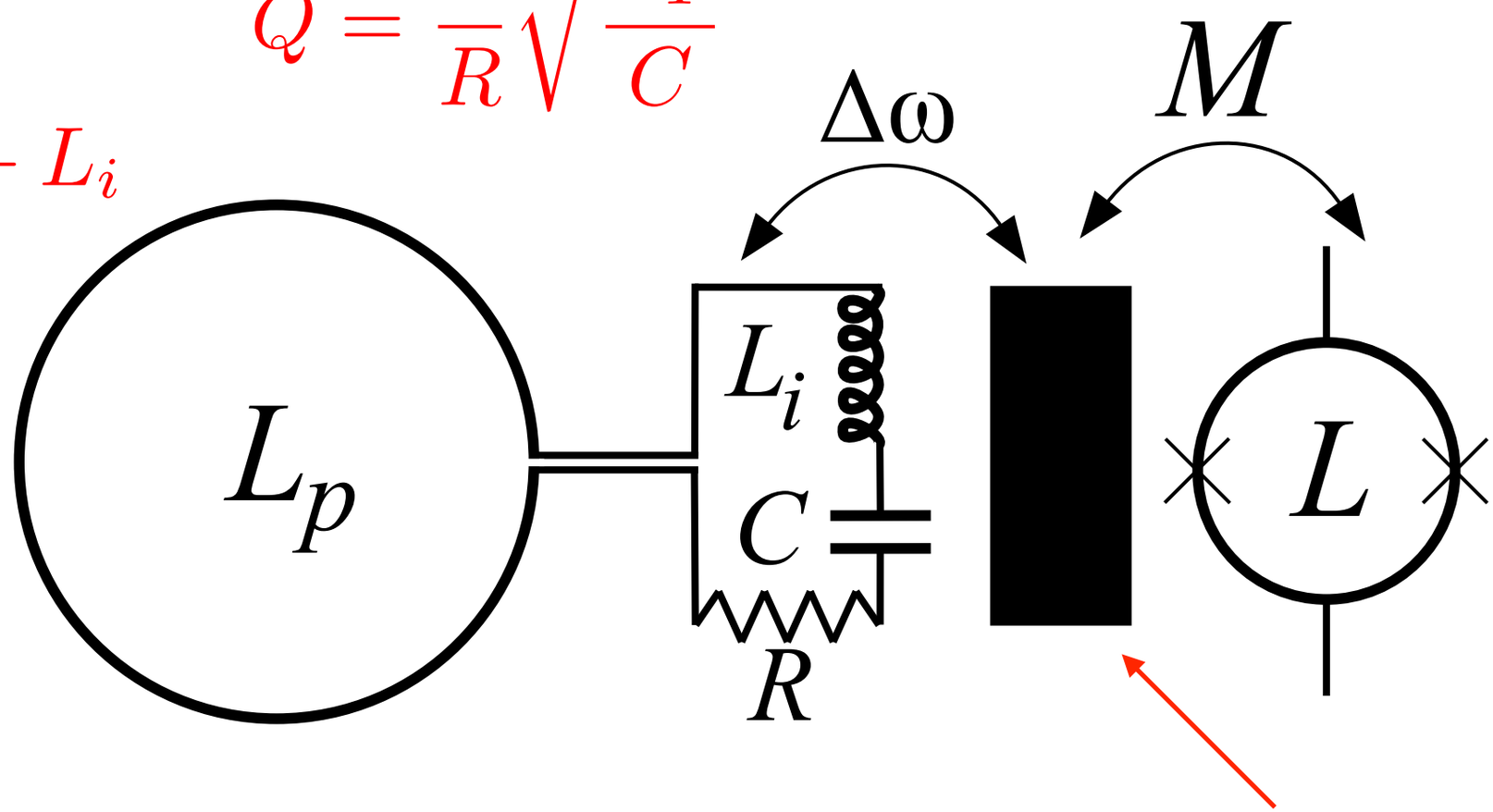
huge area = amplification

*thanks to K. Irwin for pointing this out

Resonant: readout circuit

$$Q = \frac{1}{R}\sqrt{\frac{L_T}{C}}$$

$$L_T = L_p + L_i$$



can use feedback
to match circuit
bandwidth to signal

Can resolve thermal noise, SQUID noise subdominant

Broadband: S/N and sensitivity

Take data for time t :

If $t < \tau$, S/N improves like $\sqrt{t}$ (random walk)

Our regime is $t \gg \tau$: $S/N \sim |\Phi_{\rm SQUID}|\,(t\tau)^{1/4}/S_{\Phi,0}^{1/2}$

$$S/N = 1$$

$\Longrightarrow$ sensitivity to

$$g_{a\gamma\gamma} > 6.3 \times 10^{-18}\ \mathrm{GeV}^{-1} \left(\frac{m_a}{10^{-12}\ \mathrm{eV}}\frac{1\ \mathrm{year}}{t}\right)^{1/4} \frac{5\ \mathrm{T}}{B_{\rm max}} \times \left(\frac{0.85\ \mathrm{m}}{R}\right)^{5/2} \sqrt{\frac{0.3\ \mathrm{GeV/cm^3}}{\rho_{\rm DM}}}\,\frac{S_{\Phi,0}^{1/2}}{10^{-6}\Phi_0/\sqrt{\mathrm{Hz}}}$$

improves at low masses
from coherence time

R = r = a = h/3:
tall toroid increases B-field energy

Resonant: S/N and sensitivity

$$P_S = Q_0 \frac{m_a \Phi^2_{\rm pickup}}{2L_T}, \quad P_N = k_B T \sqrt{\frac{m_a}{2\pi t_{\rm e-fold}}}$$

each e-fold of frequency scanned for equal time, only take data on resonance

(note: this is not optimal!)

$$P_S / P_N = 1$$

$\Longrightarrow$ sensitivity to

$$g_{a\gamma\gamma} > 9.0 \times 10^{-17}\ {\rm GeV}^{-1} \left(\frac{10^{-12}\ {\rm eV}}{m_a} \frac{20\ {\rm days}}{t_{\rm e-fold}} \right)^{1/4} \times \frac{5\ {\rm T}}{B_{\rm max}} \left(\frac{0.85\ {\rm m}}{R} \right)^{5/2} \sqrt{\frac{0.3\ {\rm GeV/cm^3}}{\rho_{\rm DM}} \frac{10^6}{Q_0} \frac{T}{0.1\ {\rm K}}}$$

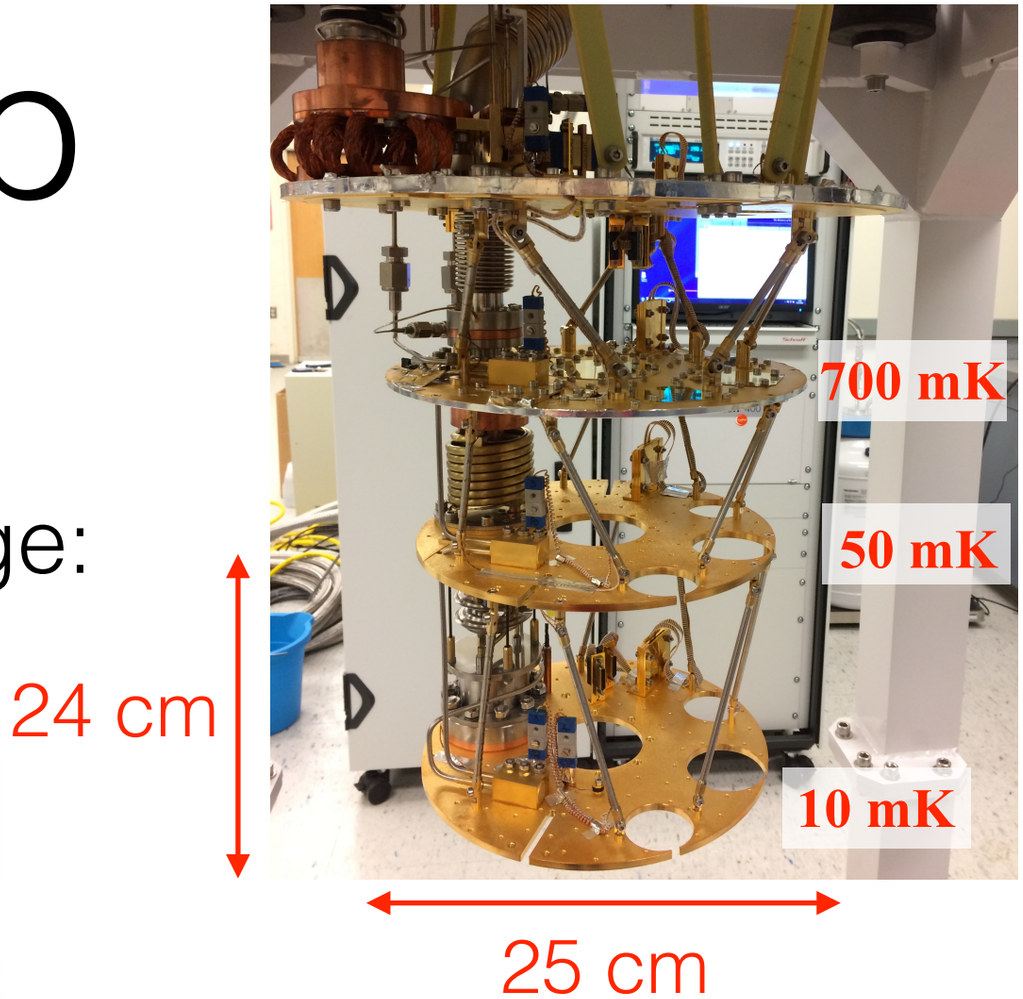
improves at high masses

improves at low temp

MIT lab

Oxford Instruments Triton 400 dil fridge:

12 L working volume

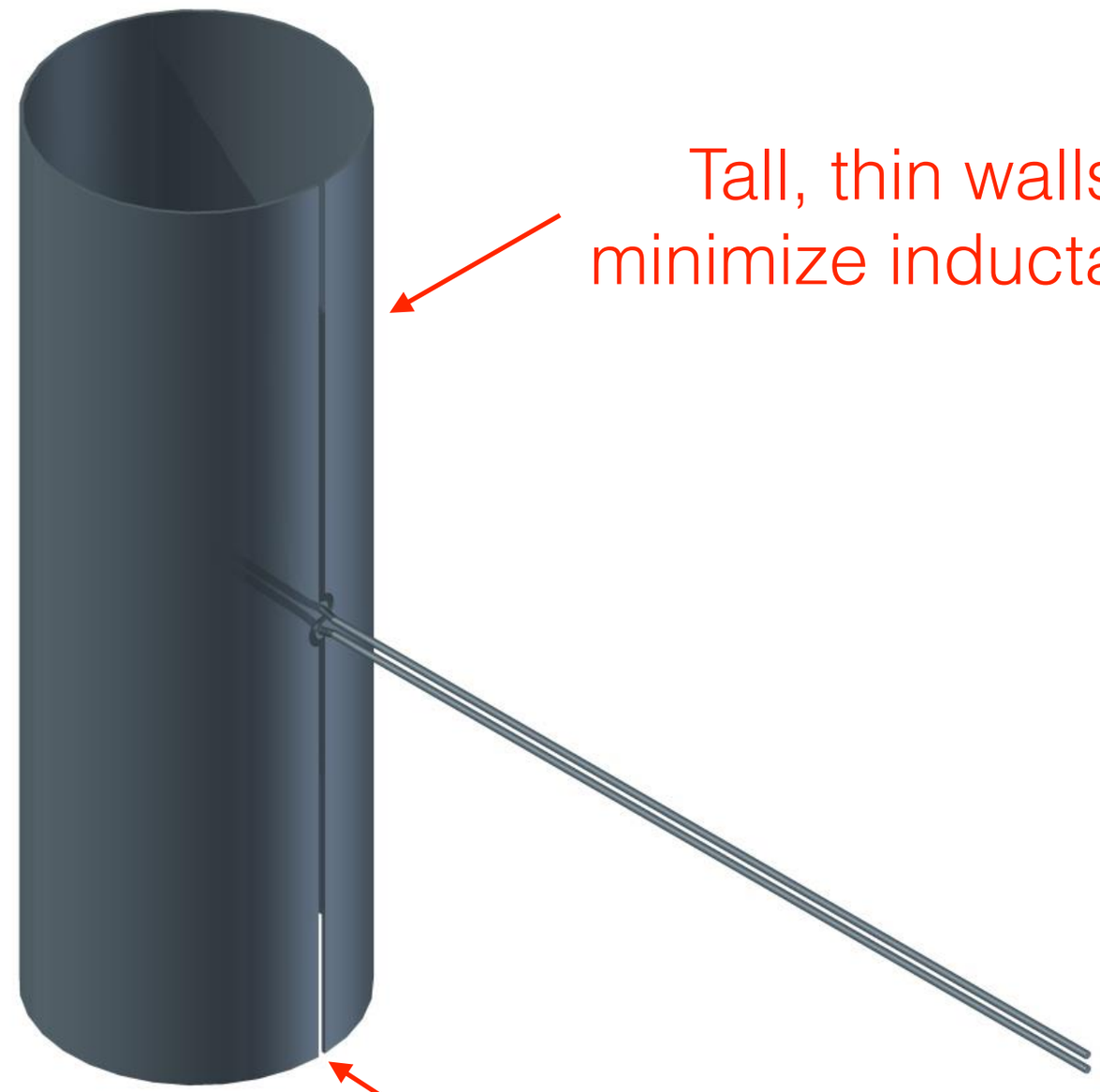


Normally used for 0νββ

Cryogen-free, can run weeks unattended

ABRACADABRA-10 cm

Superconducting pickup cylinder

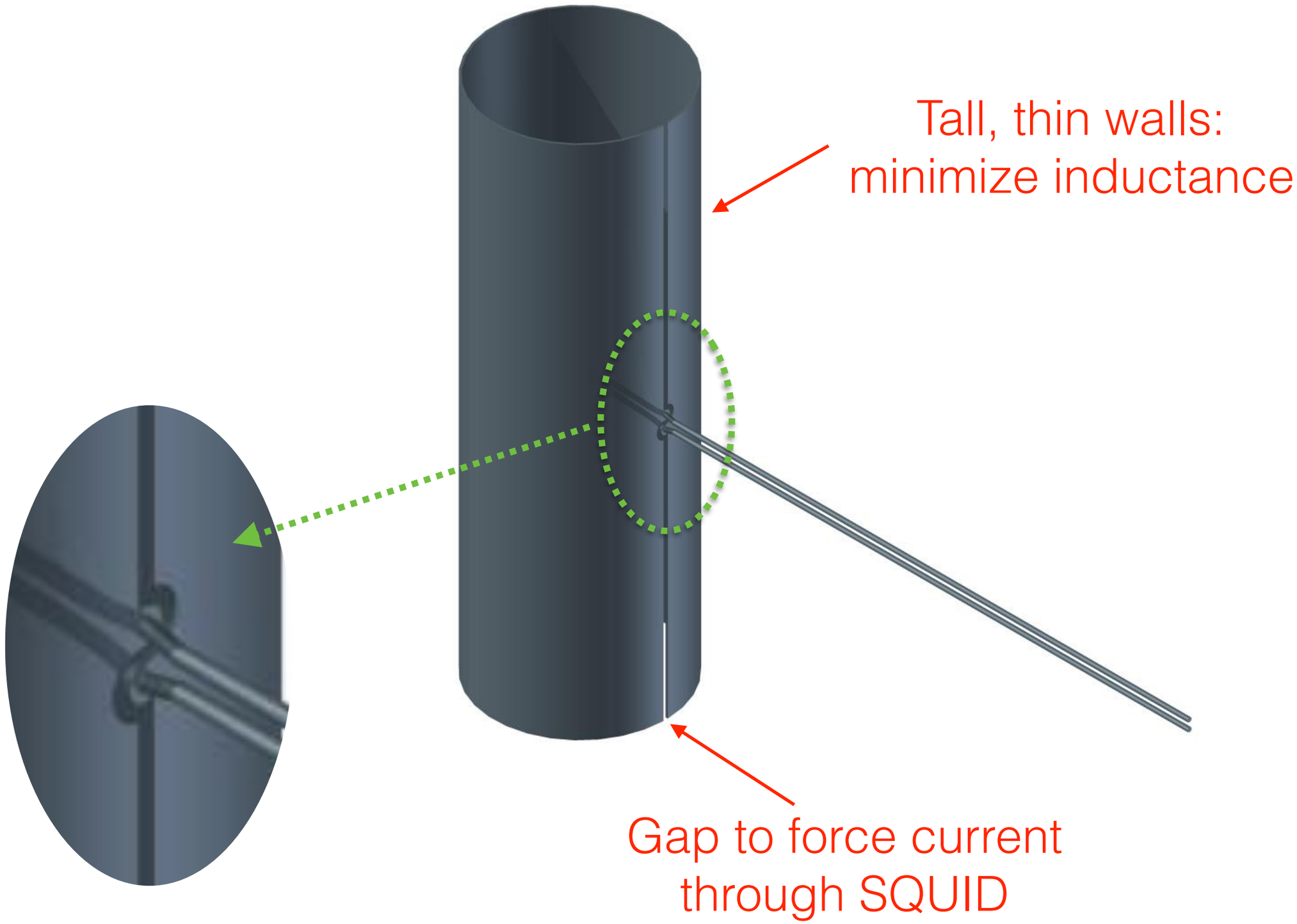


Tall, thin walls:
minimize inductance

Gap to force current
through SQUID

ABRACADABRA-10 cm

Superconducting pickup cylinder



SQUIDS

Pickup: looking to purchase a Magnicon SQUID current sensor

Typical noise: $1.2 \times 10^{-6}\ \Phi_0/(\mathrm{Hz})^{1/2}$ @ 4K, with 1/f corner at 3 Hz

Amplifier: currently have a set of Magnicon SQUID amplifier arrays