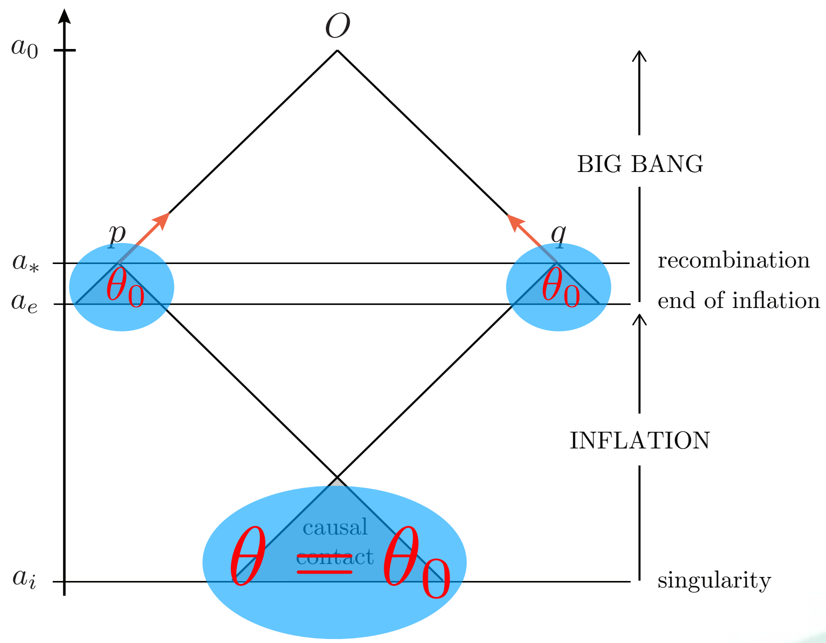
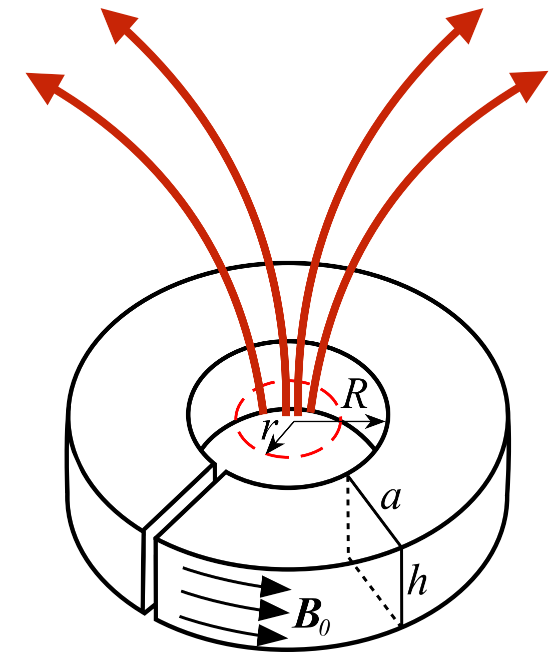
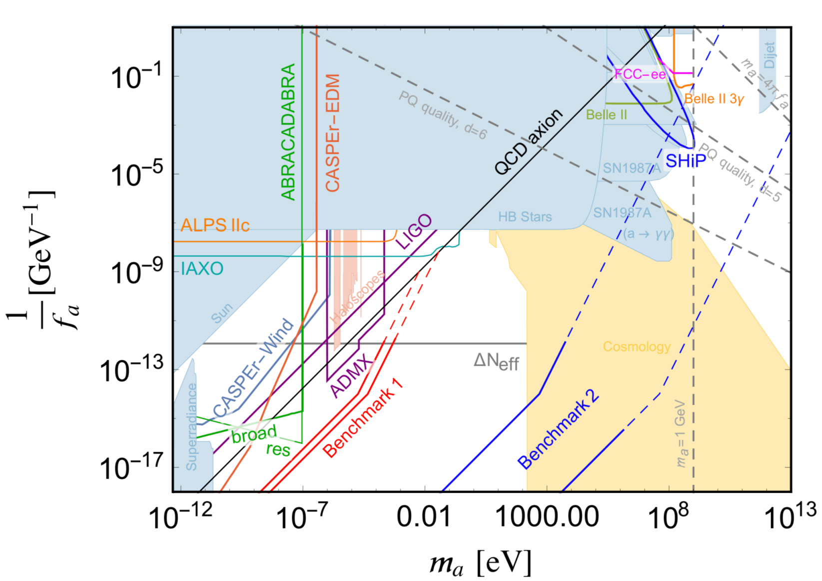
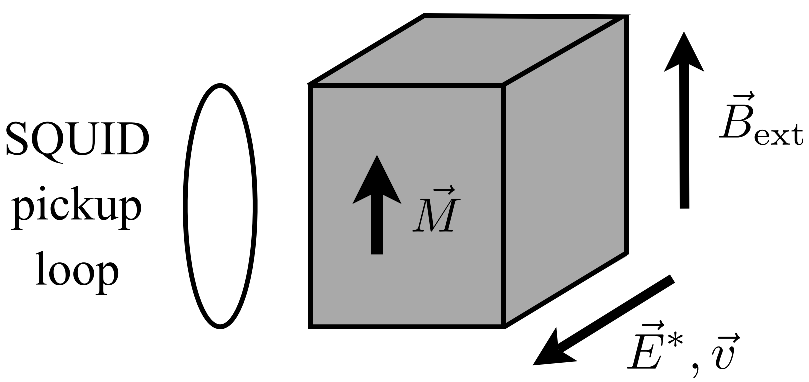




Perspectives on Axions

Yoni Kahn
UChicago/UIUC





Axion vitals

Mass: sub-eV
Spin: 0
Parity: odd
Charge: 0
Field value: angular

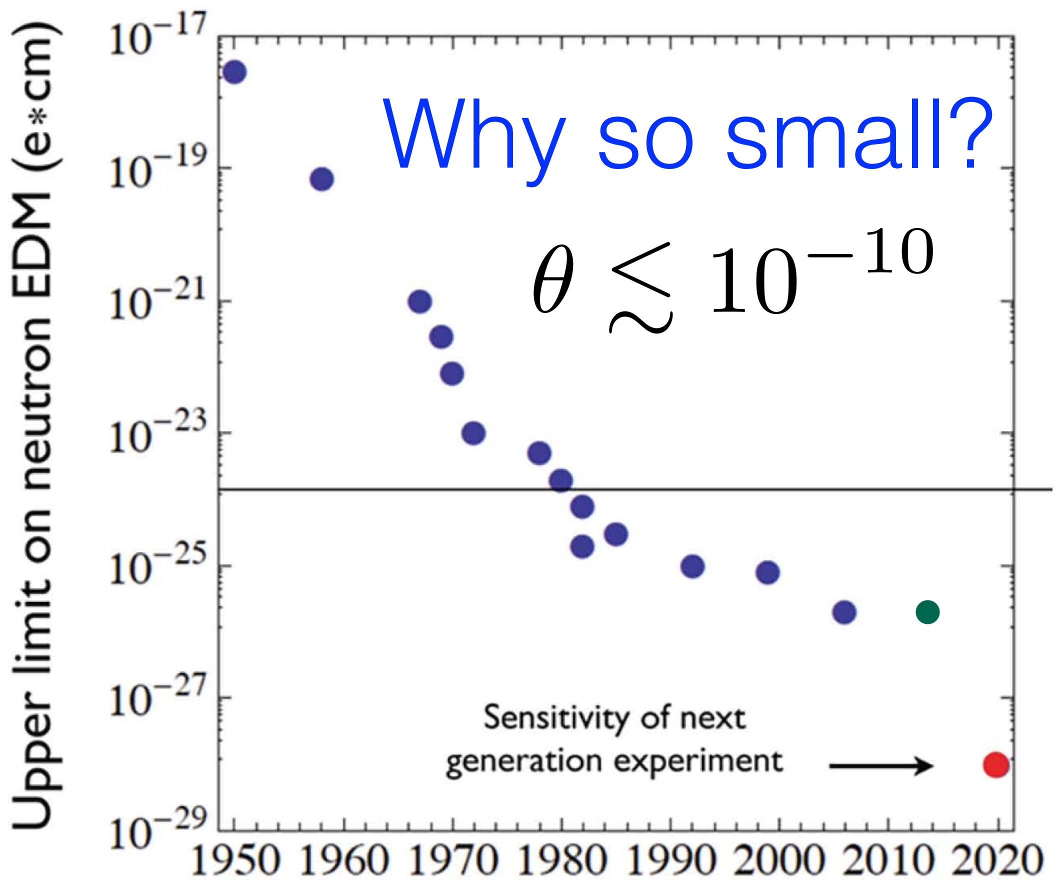
$$a(x^\mu) = f_a \theta(x^\mu)$$

"axion decay constant"
or
"Peccei-Quinn (PQ) scale"

$\theta \in [-\pi, \pi]$ (dimensionless)

Who ordered that?

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



Strong CP problem of QCD

Solution: axion dynamically cancels θ

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

[B. Filippone; Peccei & Quinn, Phys. Rev. Lett. 1977]

Axion DM: here and now

$$a(\mathbf{x}, t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \cos(m_a t + \mathcal{O}(v_{\rm DM})\mathbf{x})$$

amplitude set by local DM density

oscillates at frequency set by DM mass

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

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

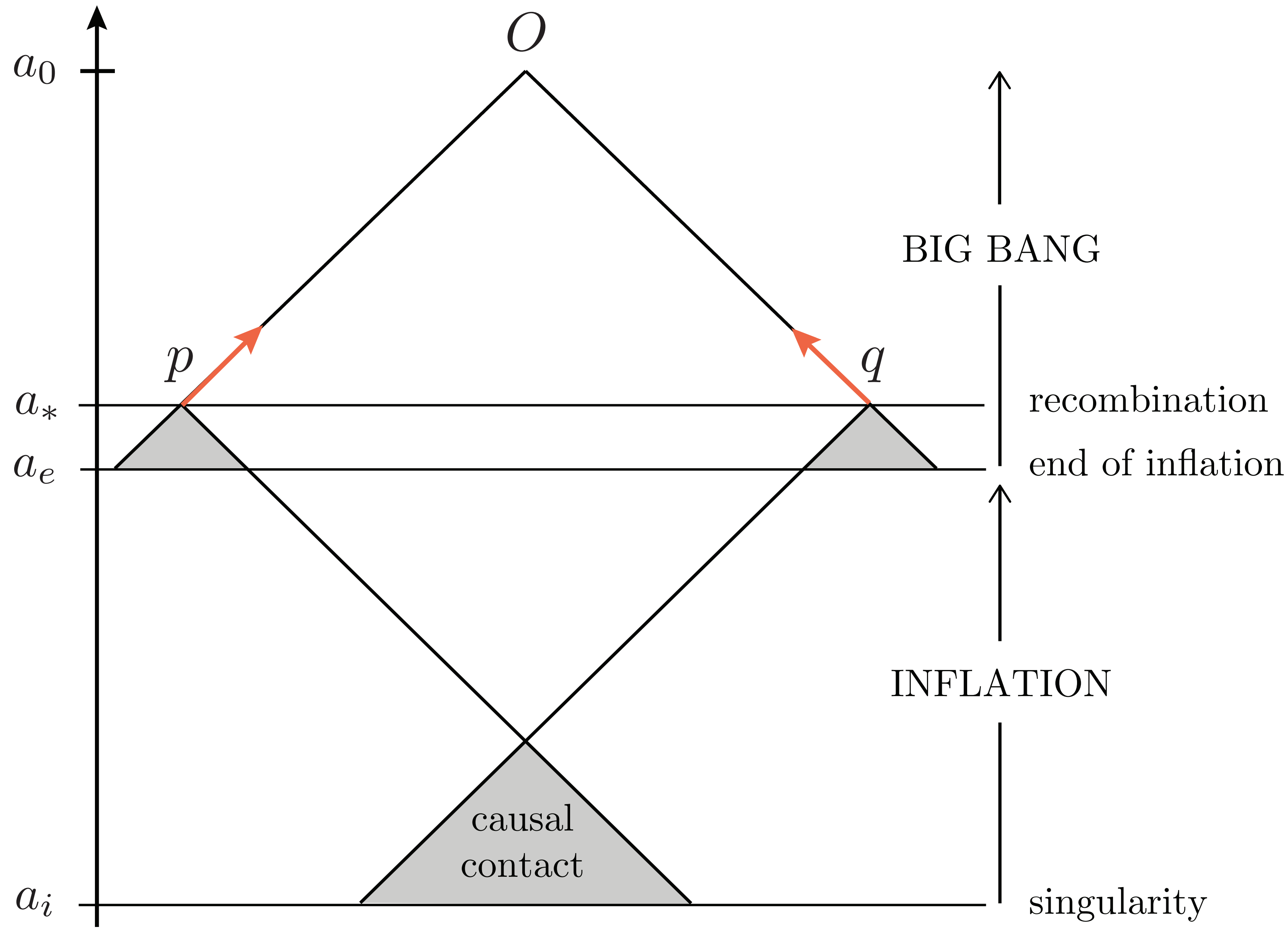
Experiments can exploit enhanced coherence time

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

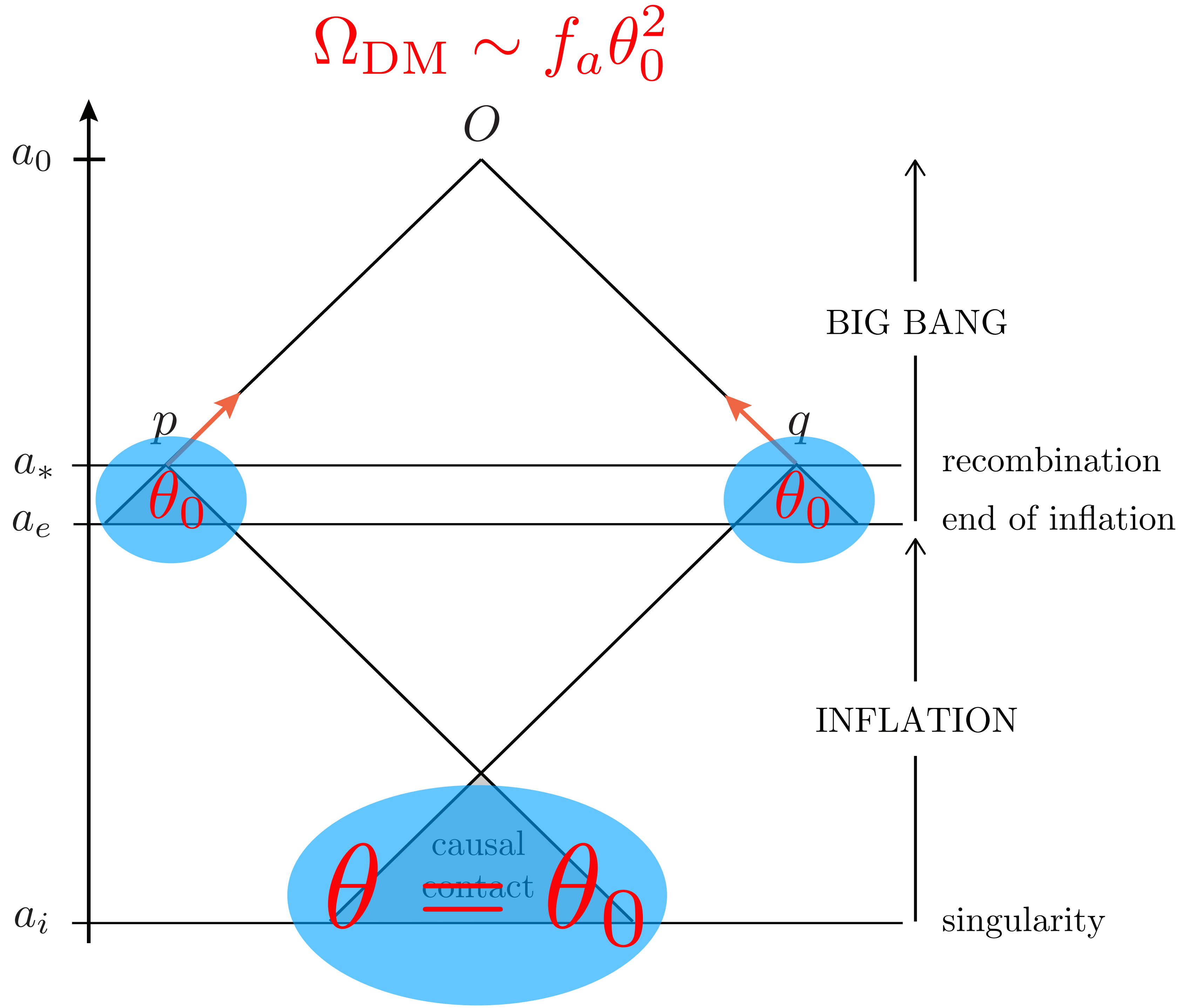
Perspective #0:
Everything I'm going to say has caveats.
(c.f. WIMP does not mean mSUGRA neutralino)

Perspective #1:
Axions can teach us a lot about cosmology and astrophysics

Two scenarios for PQ breaking



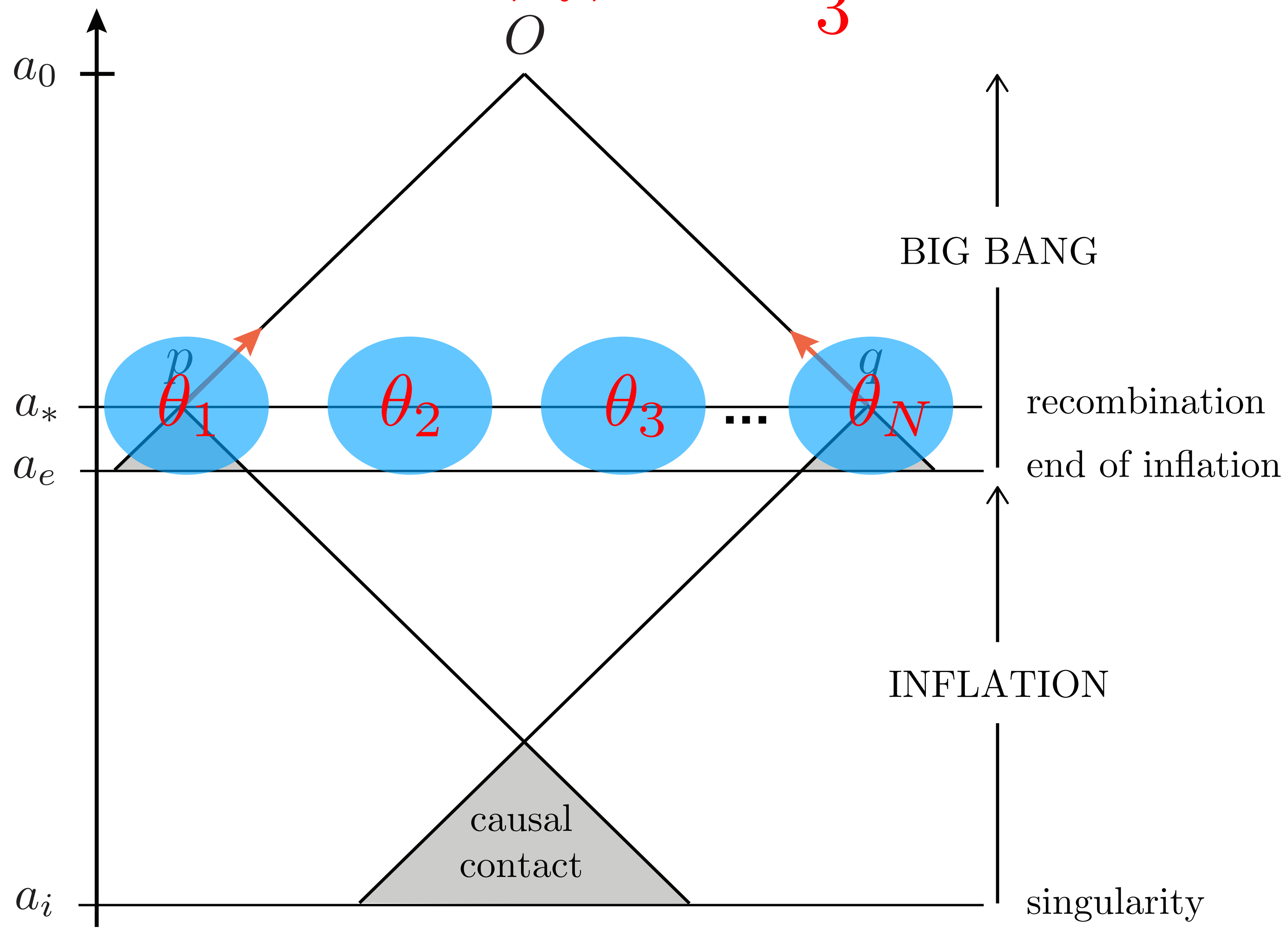
Two scenarios for PQ breaking



$f_a > H_I, T_R$: pre-inflation, two free params for relic density

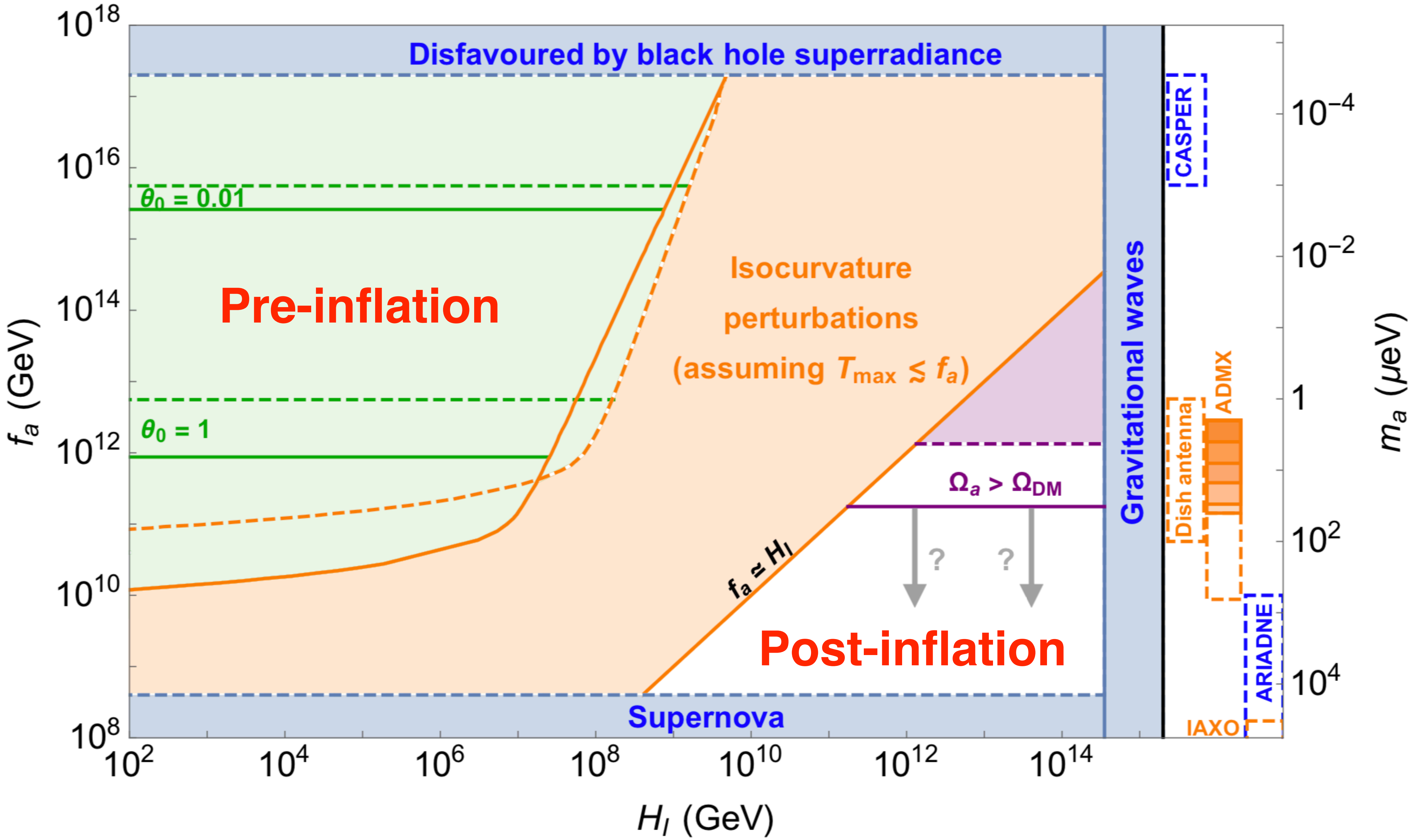
Two scenarios for PQ breaking

$$\Omega_{\rm DM} \sim f_a \langle \theta_i^2 \rangle \sim f_a \frac{\pi^2}{3}$$



$f_a < H_I$: post-inflation, one free param. for relic density

Axions and inflation

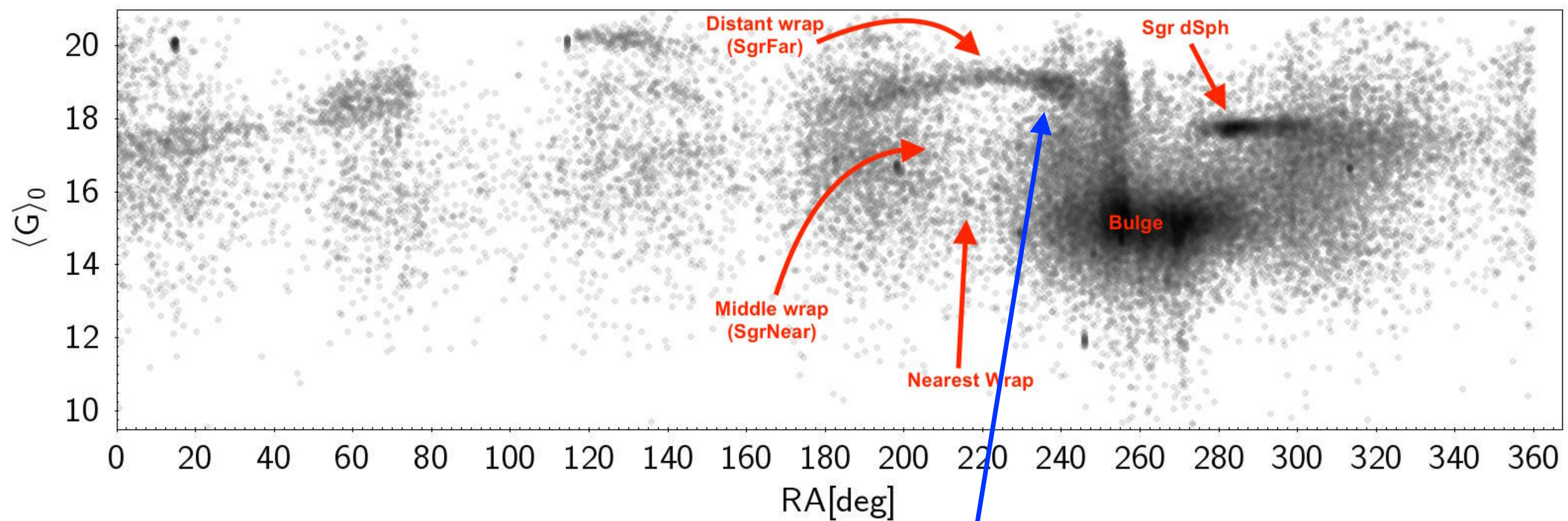


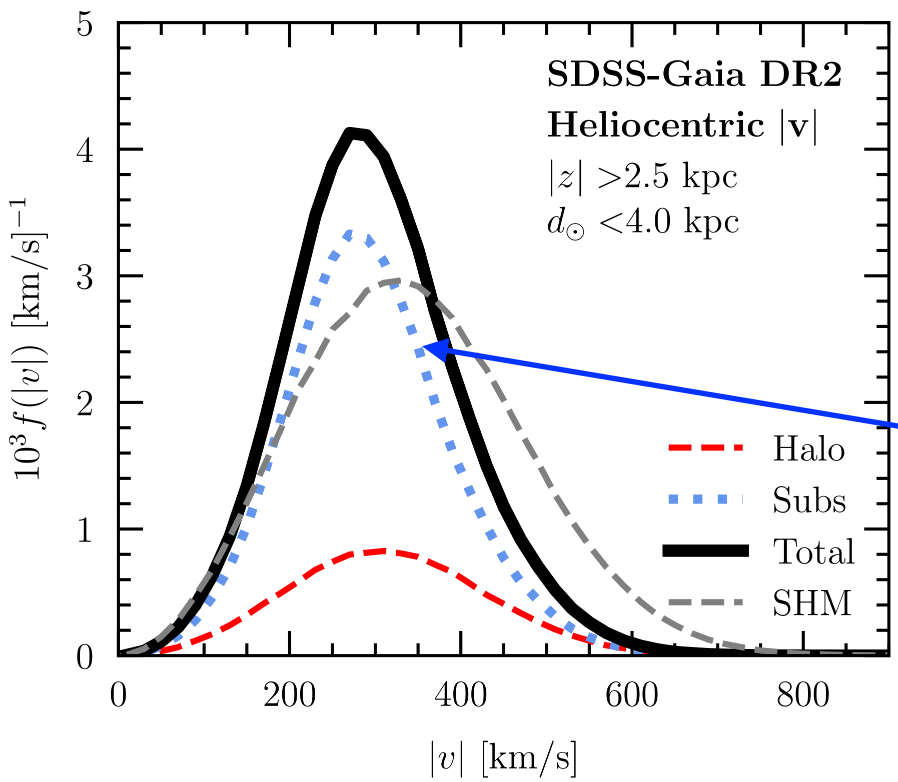
Axion DM discovery implies low/high inflation scale!

[Cortona et al., JHEP 1601 (2016)]

Dark matter substructure

Milky Way halo is not smooth!





If DM follows stream stars, could have **very** narrow dispersion

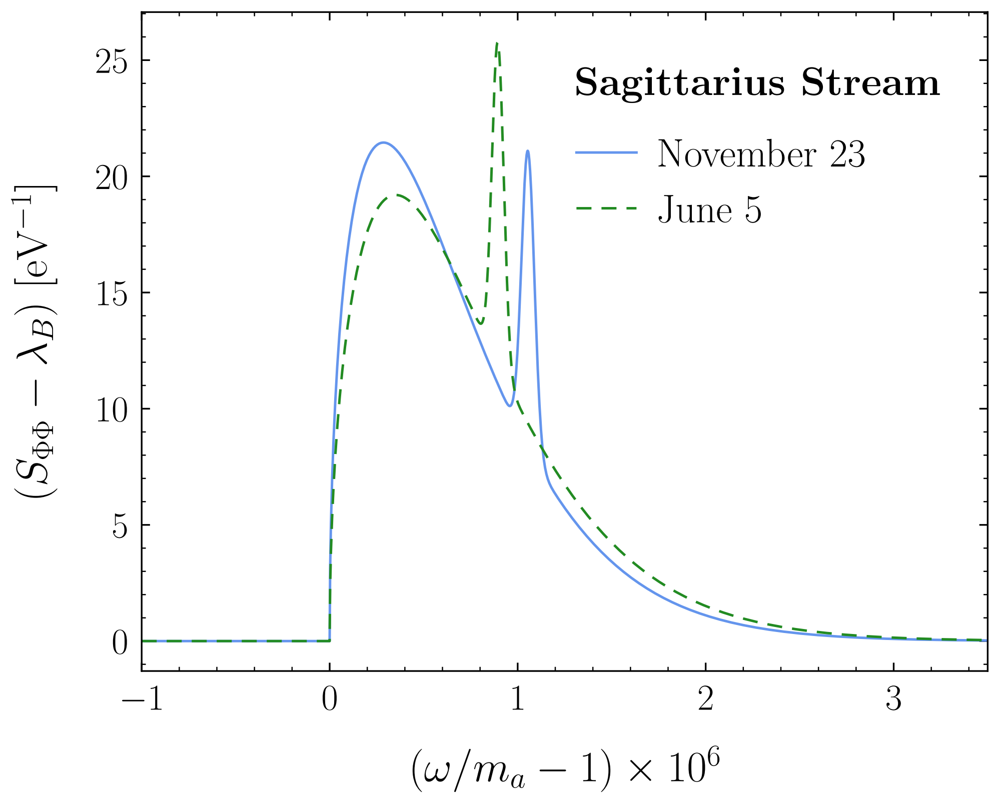
substructure has smaller dispersion

[Necib, Lisanti, Belokurov, arXiv:1807.02519; Bellazzini and Ibata, arXiv:1809.01102]

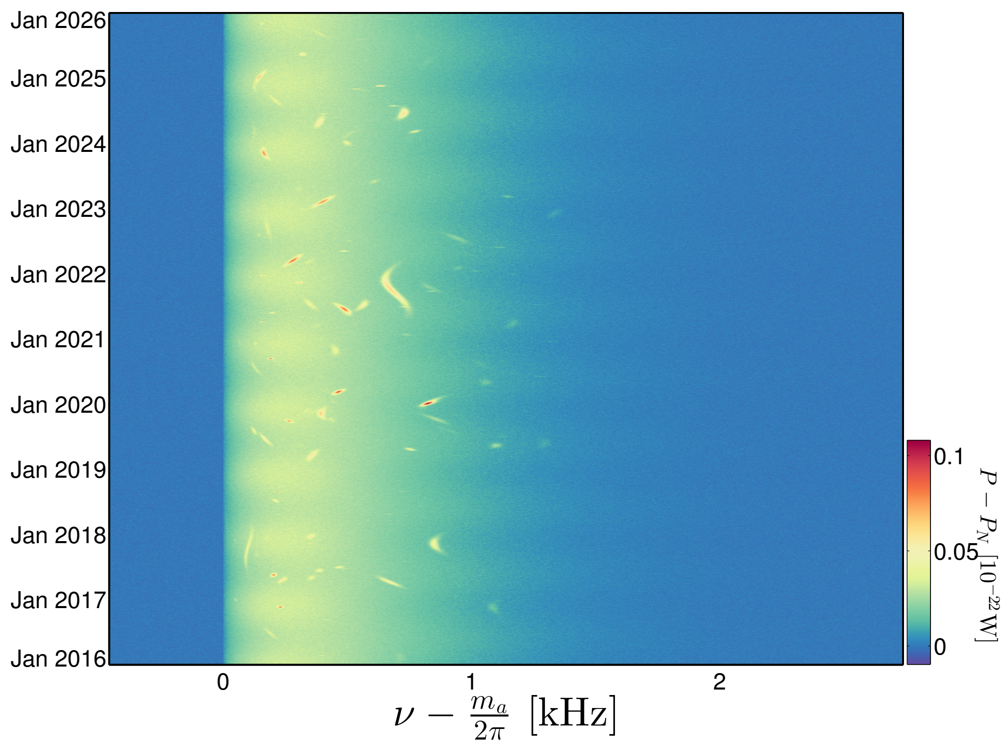
Axion "halometry"

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

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



Broadband-type (e.g. ABRACADABRA)



Resonant-type (e.g. ADMX)

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

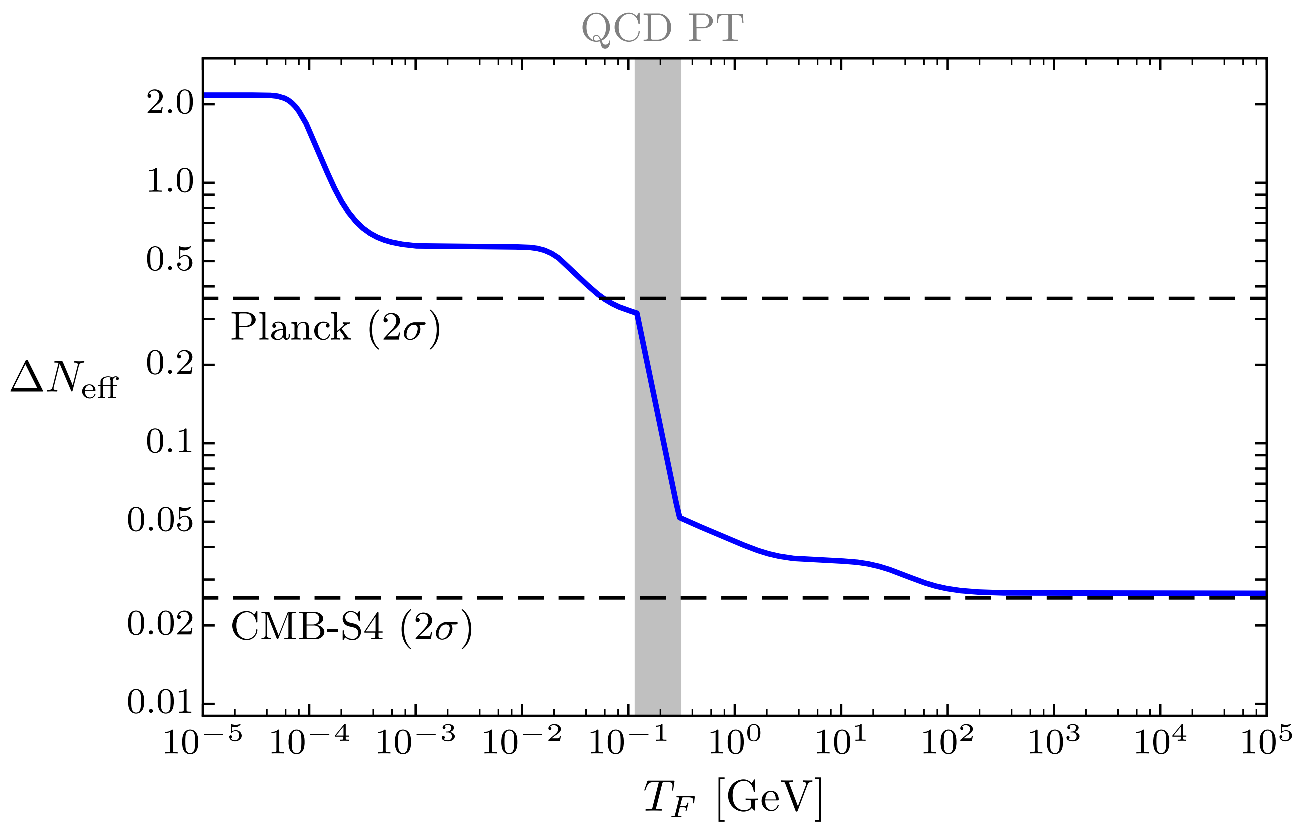
[O'Hare and Green, Phys. Rev. D95 (2017); Foster, Rodd, Safdi, Phys. Rev. D97 (2018)]

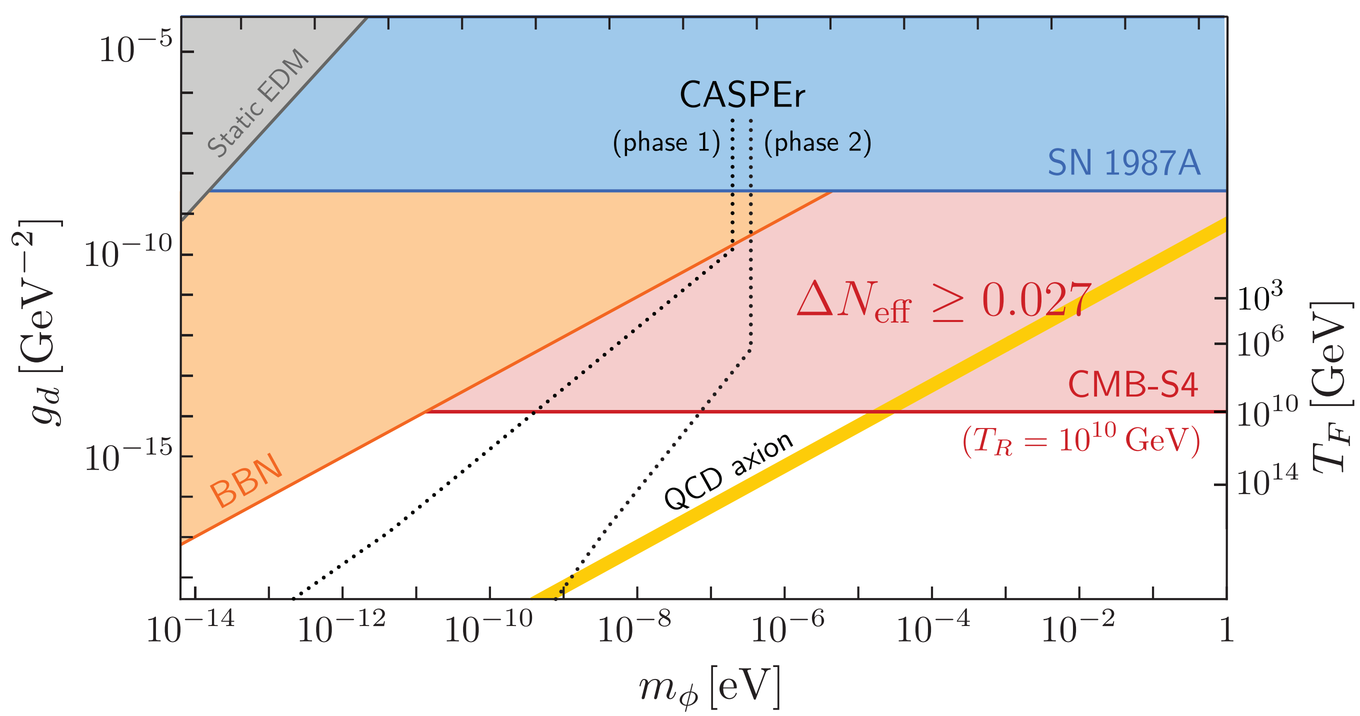
Axions and reheating

If reheat temperature is too high, axions thermalize and contribute to $N_{\rm eff}$:

decays to gluons

$$\frac{T_F^3}{f_a^2} \sim \frac{\pi}{\sqrt{90}} \sqrt{g_{*,R}} \frac{T_F^2}{M_{\rm pl}}$$





Axion discovery + null CMB-S4 implies upper bound on T_R!

[Baumann, Green, Wallisch, JCAP 1808 (2018)]

Perspective #2:
We will reach the QCD target for the axion-photon coupling in 20-30 years

Axion DM modifies Maxwell

Generic coupling to E+M:

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

In presence of static background EM fields,
induces oscillating response fields:

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

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

gradients suppressed by $v_{DM} \sim 10^{-3}$

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: $\lambda_{\rm Comp} \sim R_{\rm exp}$

ADMX

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

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

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: $\lambda_{\rm Comp} \ll R_{\rm exp}$

MADMAX

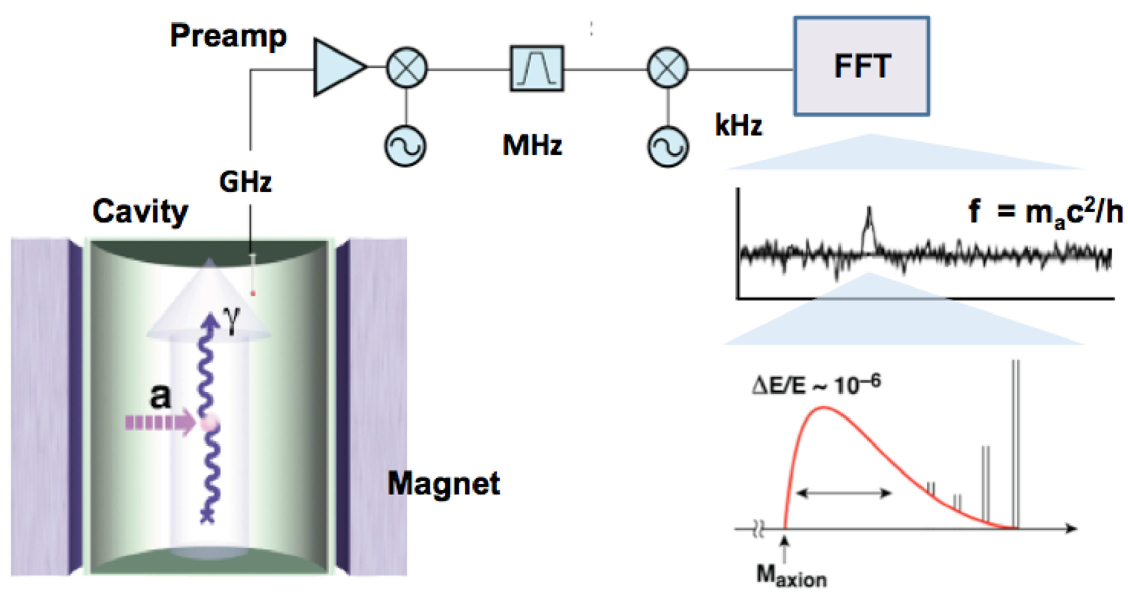
ADMX: resonant cavity detection

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

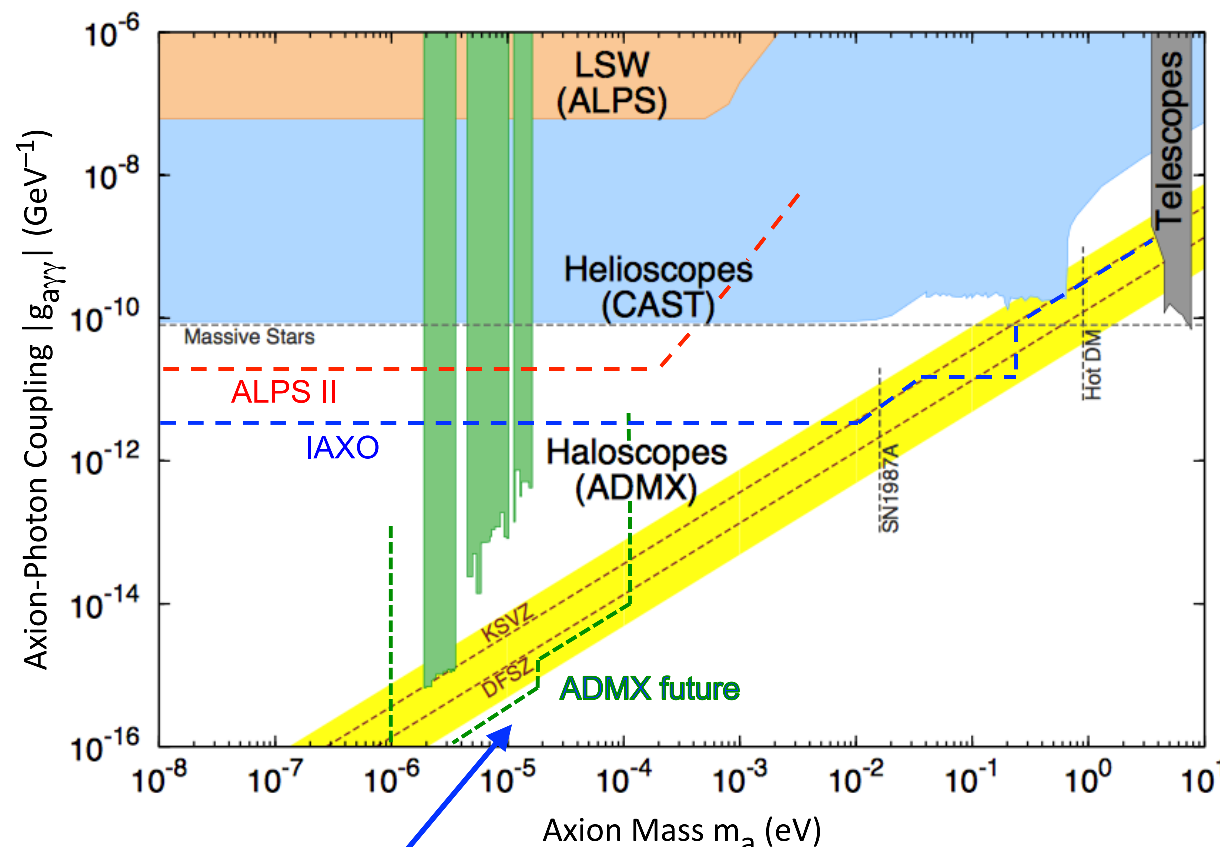
cavity response

axion source

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



Tune cavity modes to scan axion masses

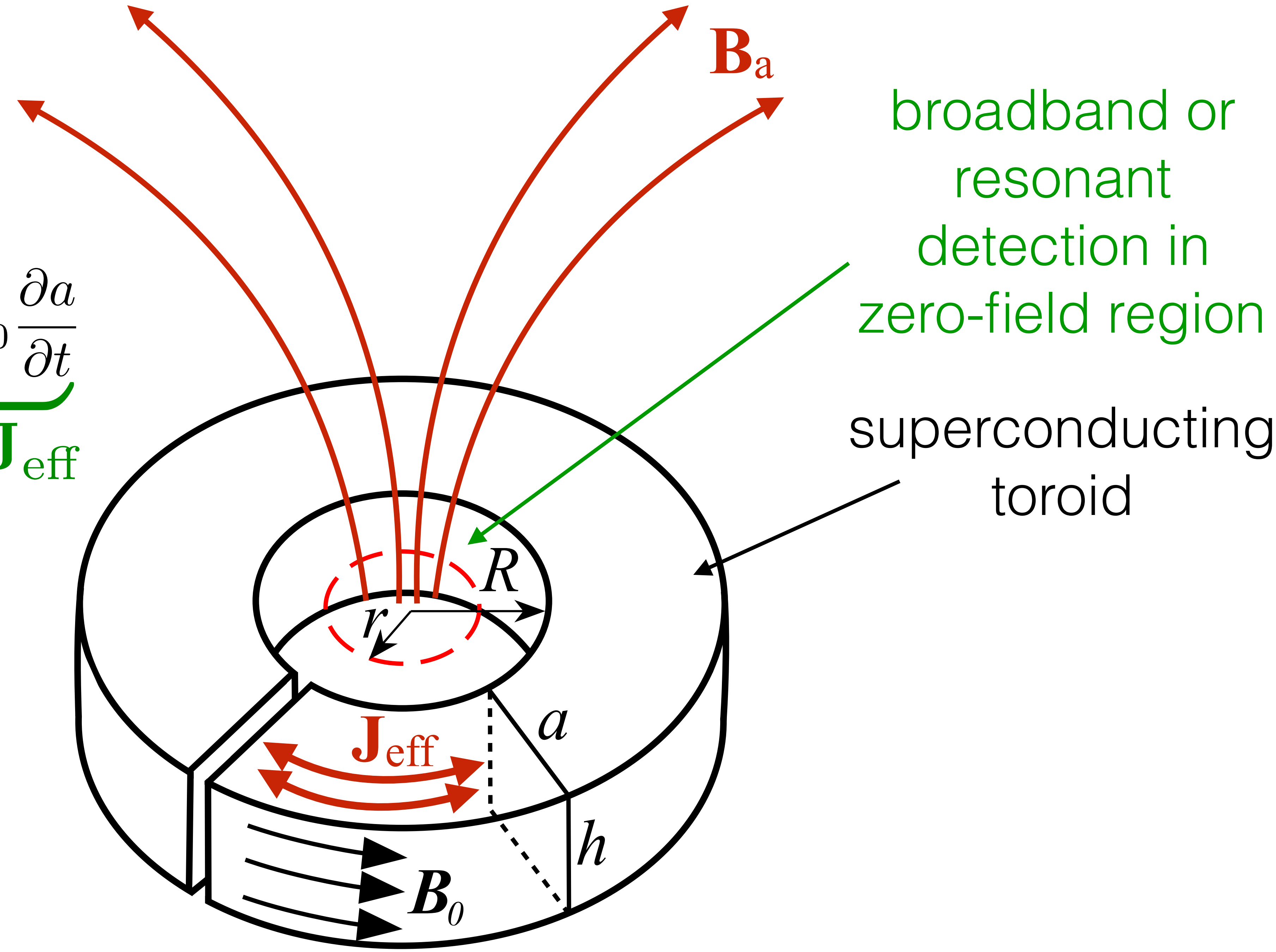


Cavity b.c. fix mass range to cavity size; larger masses -> smaller V

[Rosenberg et al., ADMX collab.; Graham et al., Ann. Rev. NPS 2015]

Quasistatic regime: ABRACADABRA

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



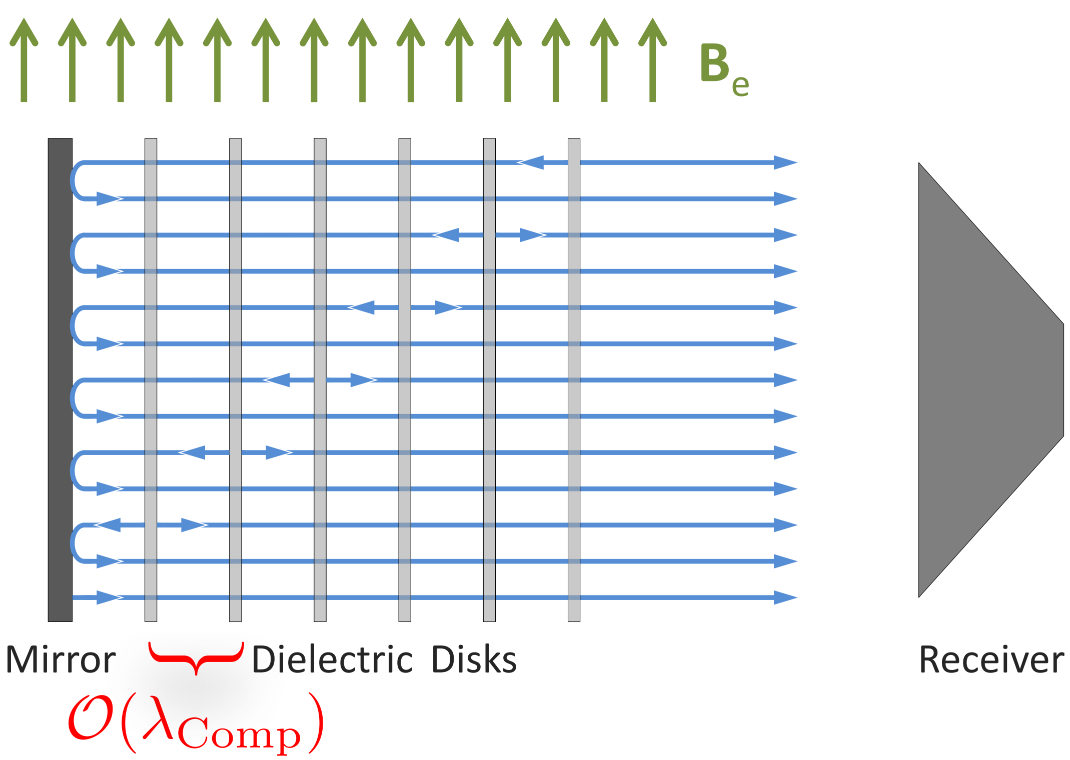
$$\Phi_a(t) = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\cos(m_a t) \times (B_{\rm max} V G_{\rm toroid})$$

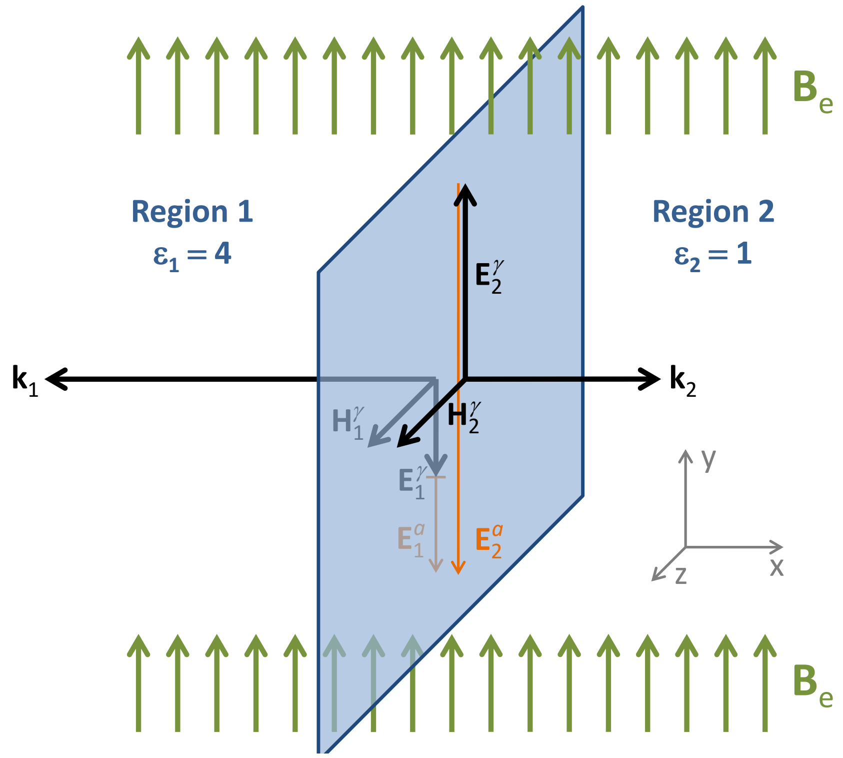
Volume enhancement: B-field energy scales as $B_0^2 V^2$

Radiation regime: MADMAX

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

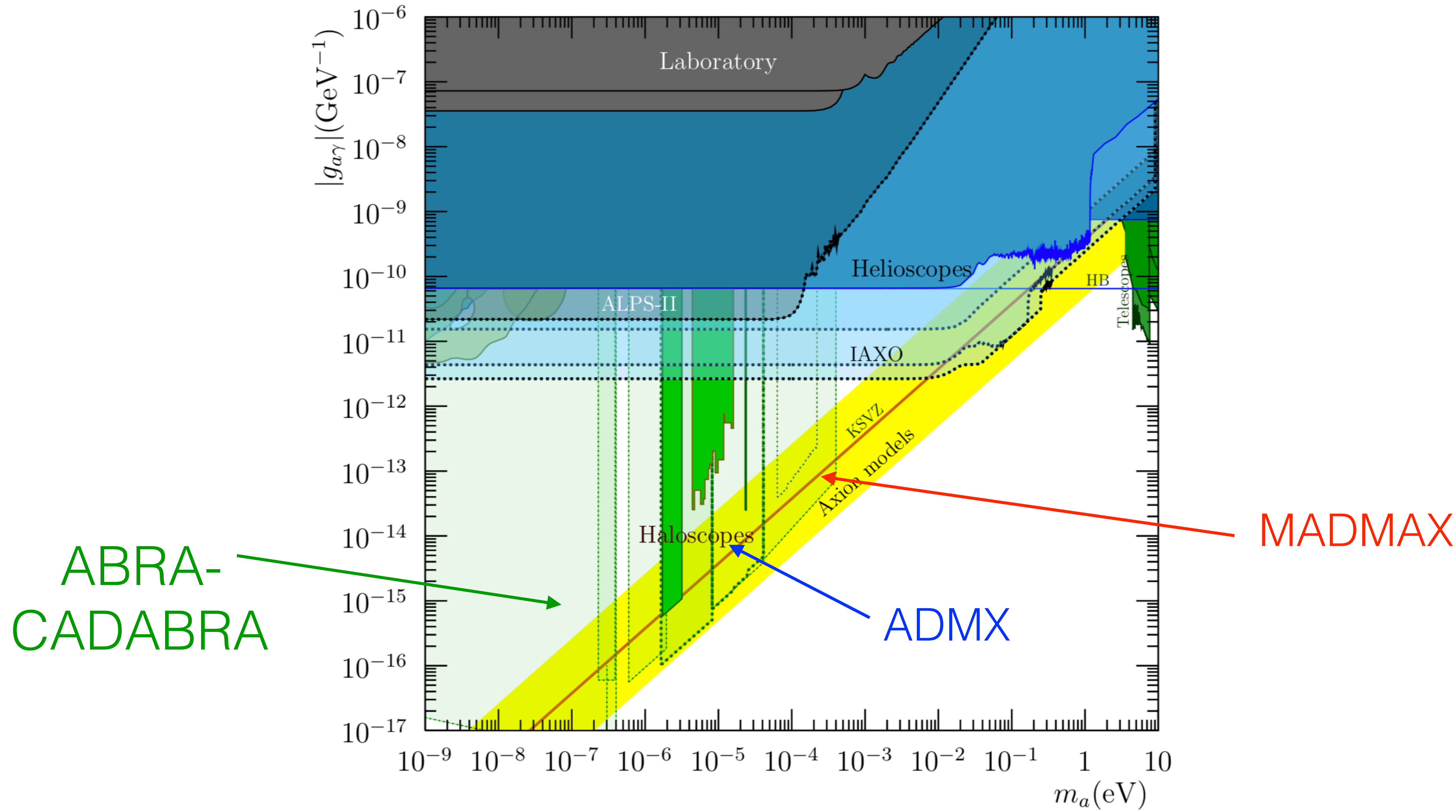
E+M boundary condition at interfaces forces radiation to cancel axion-induced **D**





Best of both worlds: large volume and high Q

Axion-photon coupling: the future



[Irastorza and Redondo, Prog. Part. Nucl. Phys. 2018]

Perspective #3:
The QCD target is
not the end of the game!

Line vs. band

For the "canonical" QCD axion:

$$\mathcal{L} \supset \frac{a}{f_a} G_{\mu\nu}\widetilde{G}^{\mu\nu} \implies d_n^{\mathrm{QCD}} \approx 2.4 \times 10^{-16} \frac{a}{f_a} e \cdot \mathrm{cm}$$

no wiggle room!

But photon coupling depends on UV completion

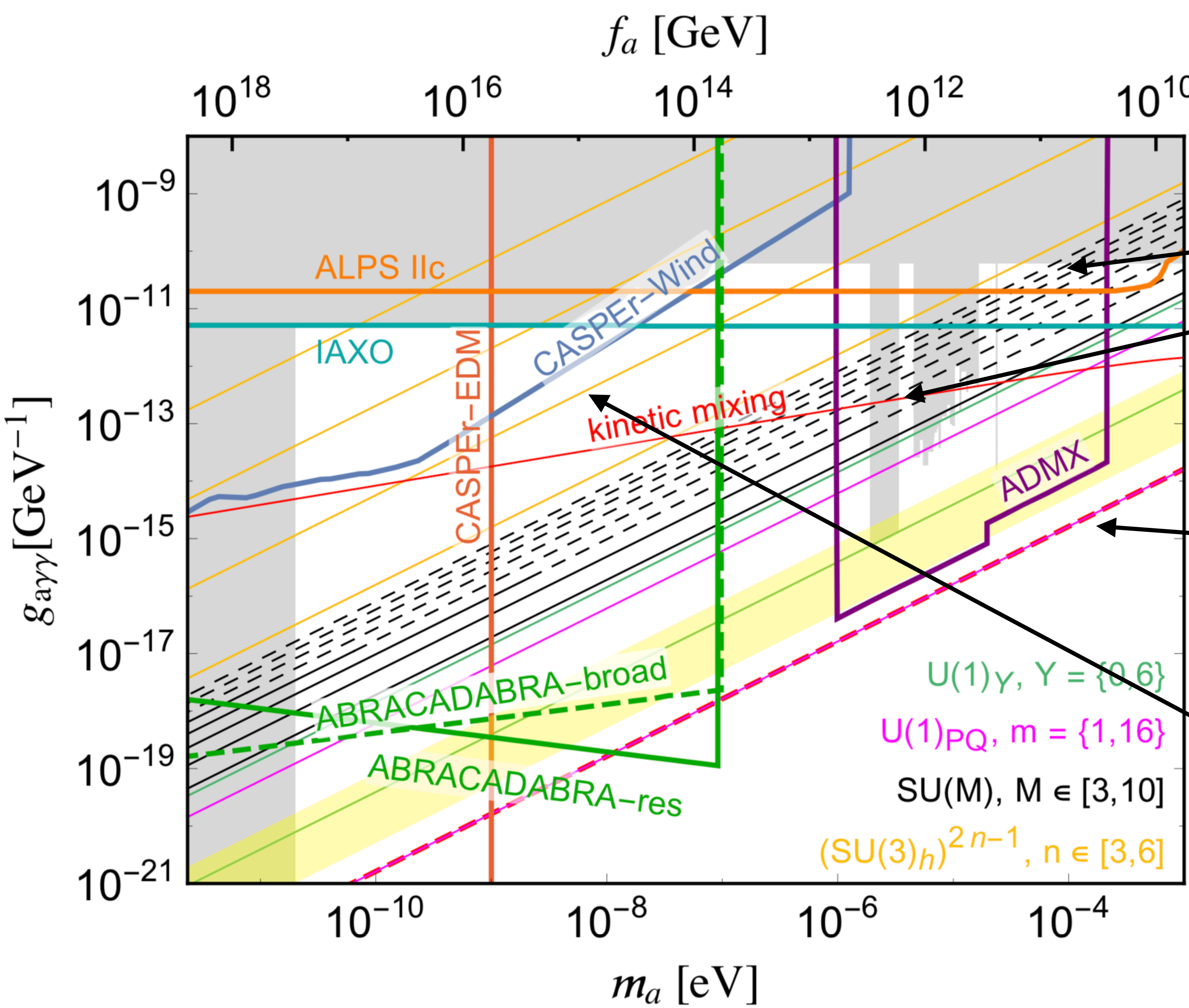
$$\varphi = \sigma e^{ia/f_a} \qquad \mathcal{L}_{\mathrm{KSVZ}} \supset \varphi \bar{Q}_L Q_R \qquad \mathcal{L}_{\mathrm{DFSZ}} \supset \varphi^2 H_u H_d$$

$$g_{a\gamma\gamma} = \frac{\alpha_{\mathrm{EM}}}{2\pi f_a} \times \left(\frac{\mathcal{E}}{\mathcal{C}} - 1.92(4) \right)$$

EM anomaly, color anomaly: integers

Range of possible values depending on PQ charges

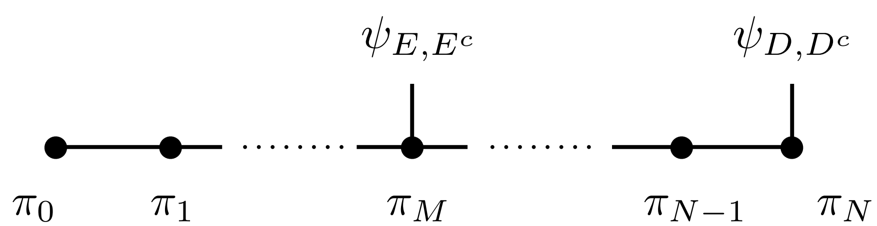
Living off the band (photons)



Two UV axions plus hidden confining gauge group

unlucky: $\mathcal{E}/\mathcal{C} = 2$

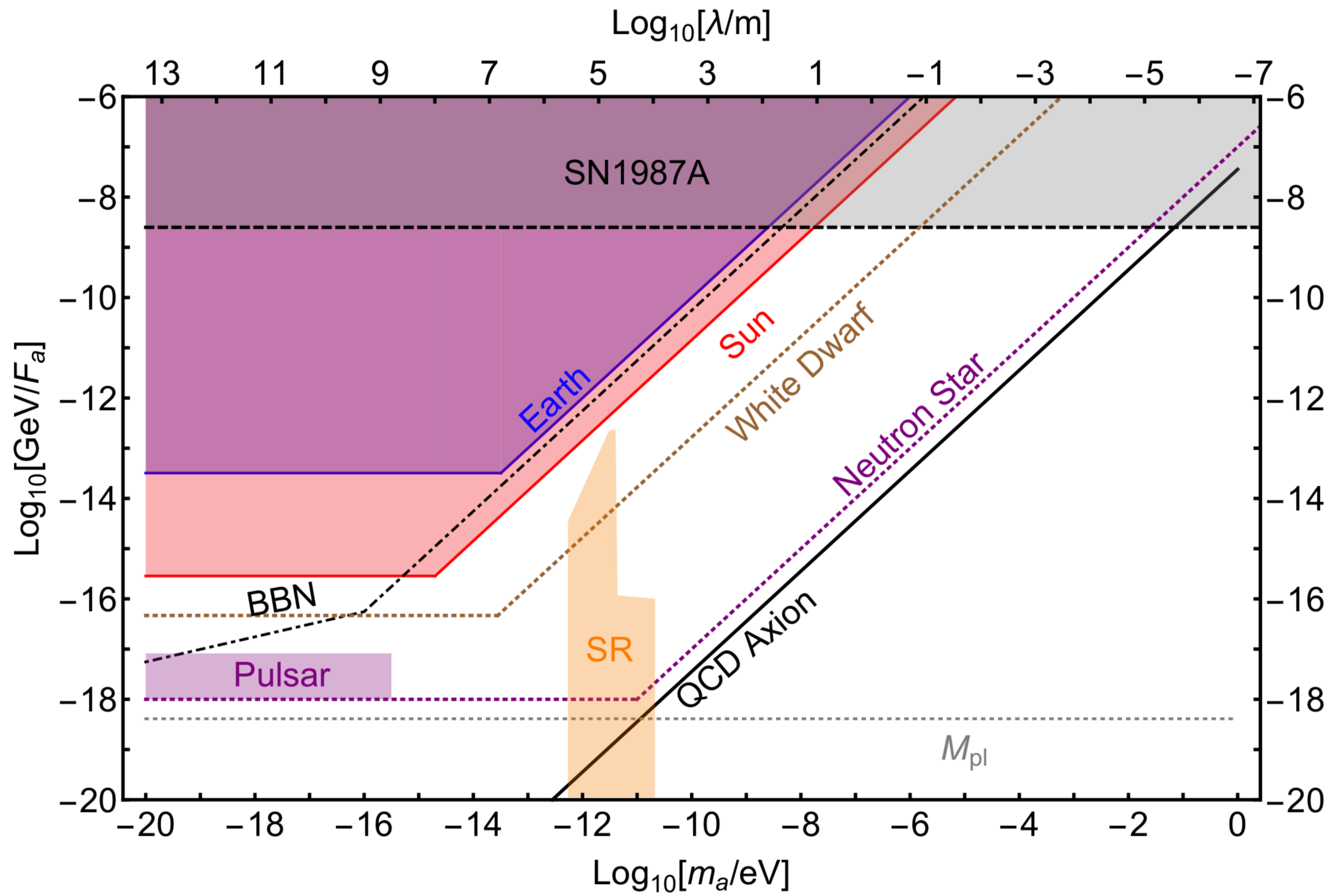
"Clockwork" axion



 [Agrawal et al., JHEP 1802 (2018); Farina, Pappadopulo, Rompineve, Tesi, JHEP 1701 (2017)]

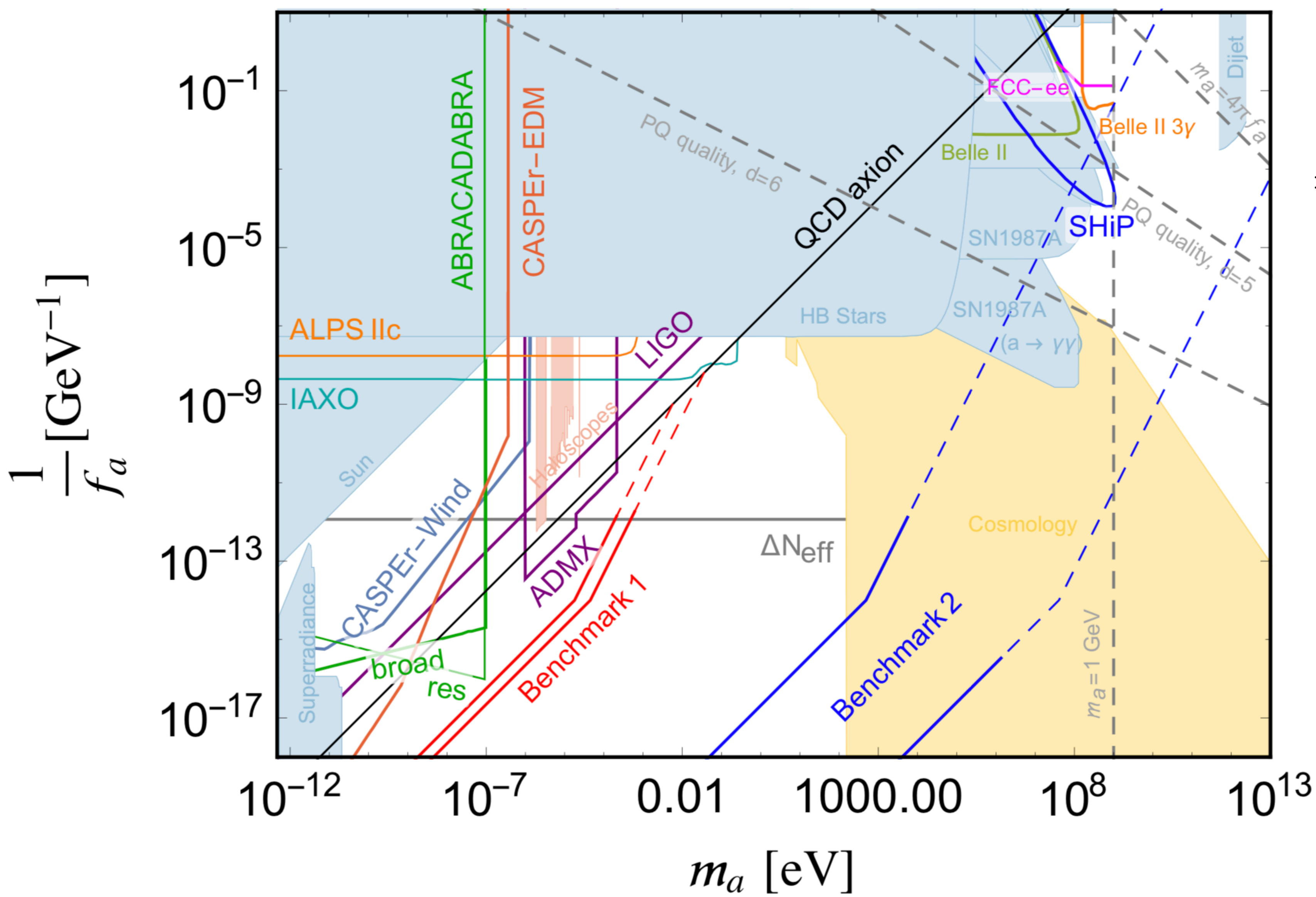
Living above the line (nEDM)…

N copies of QCD: $\mathcal{L} = \sum_k \left(\frac{a}{f_a} + \frac{2\pi k}{N} + \theta \right) G_k \widetilde{G}_k \Longrightarrow \frac{m_a(N)}{m_a(N=1)} \sim \frac{4}{2^{N/2}}$



[Hook, Phys. Rev. Lett (2018); Hook and Huang, JHEP 1806 (2018)]

…or below the line (nEDM)



$$SU(3)_1 \times SU(3)_2 \to SU(3)_c$$

$$\Longrightarrow \mathcal{L} \supset \Lambda_1^4 \cos(a_1/f_1 - \bar{\theta}_1) + \Lambda_2^4 \cos(a_2/f_2 - \bar{\theta}_2)$$

Instanton effects can make

$$\Lambda_1, \Lambda_2 \gg \Lambda_{\rm QCD}$$

$\Longrightarrow$ **heavy axion**

Perspective #4: Looking for the nEDM coupling for axion dark matter is really hard

Comparing EM response

$$\frac{a}{f_a} G_{\mu\nu}\widetilde{G}^{\mu\nu} \implies \underbrace{\frac{i}{2} g_d a \overline{N} \sigma_{\mu\nu}\gamma_5 N}_{\text{magnetization/polarization tensor}} F^{\mu\nu}$$

magnetization/polarization tensor

$$-\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} F^{\mu\nu}$$

NR limit in medium: $\mathbf{P} = n_n \kappa_p \epsilon_S d(t)$

$$\mathbf{D} \equiv \mathbf{E} + \mathbf{P}$$

$$\nabla \cdot \mathbf{D} \implies \mathbf{E}_{\rm EDM}$$

$$\partial \mathbf{D}/\partial t \implies \mathbf{B}_{\rm EDM}$$

$$\mathbf{J}_{\rm eff} = g_{a\gamma\gamma} \mathbf{B}_0 \partial a/\partial t$$

bounded by atomic physics

unrealistically large

$$\frac{\mathbf{B}_{\rm EDM}}{\mathbf{B}_{a\gamma\gamma}} = 10^{-4} \times \left(\frac{n_n}{10^{22}\ \mathrm{cm}^{-3}}\right)\left(\frac{B_0}{10\ \mathrm{T}}\right)\left(\frac{\epsilon_S \kappa_p}{1}\right)$$

The NMR loophole

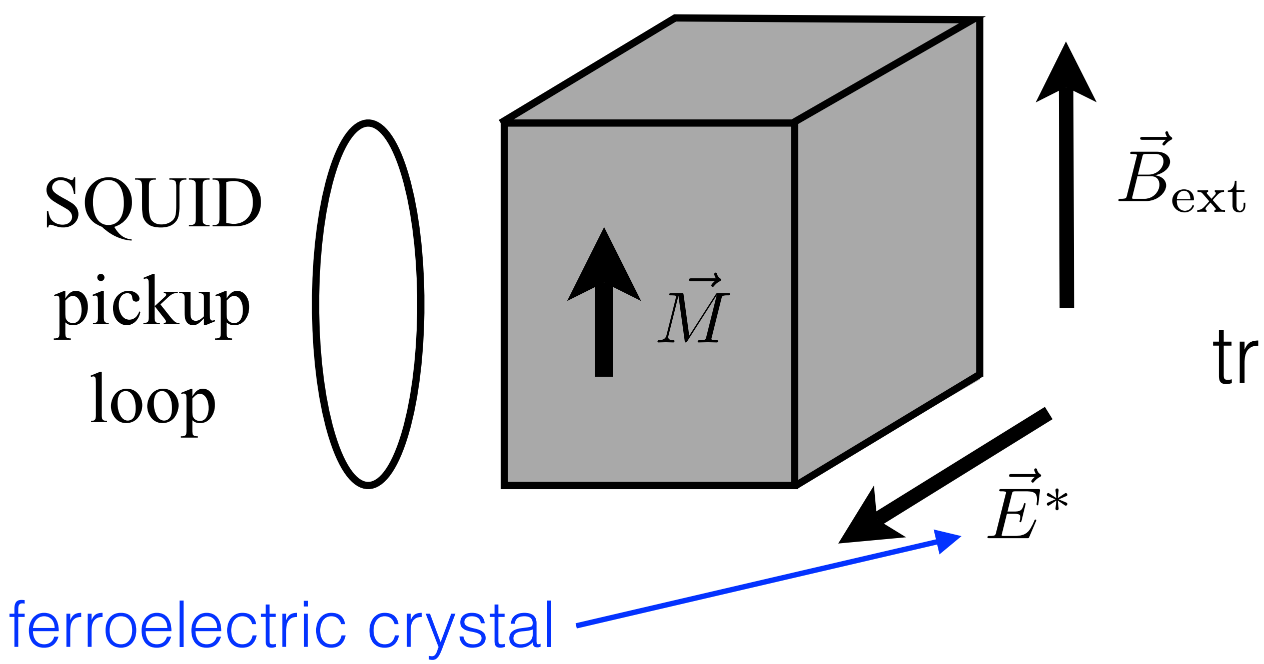
Previous argument based on Maxwell only…
but Dirac told us how spins couple to EM fields

$$H = \epsilon_S \mathbf{d}_n(t) \cdot \mathbf{E}^* \leftrightarrow \mu_N \cdot \mathbf{B}_\perp(t)$$

oscillates at $\omega = m_a$

Larmor oscillations:

$$\omega_L = 2\mu_N B_{\rm ext}$$

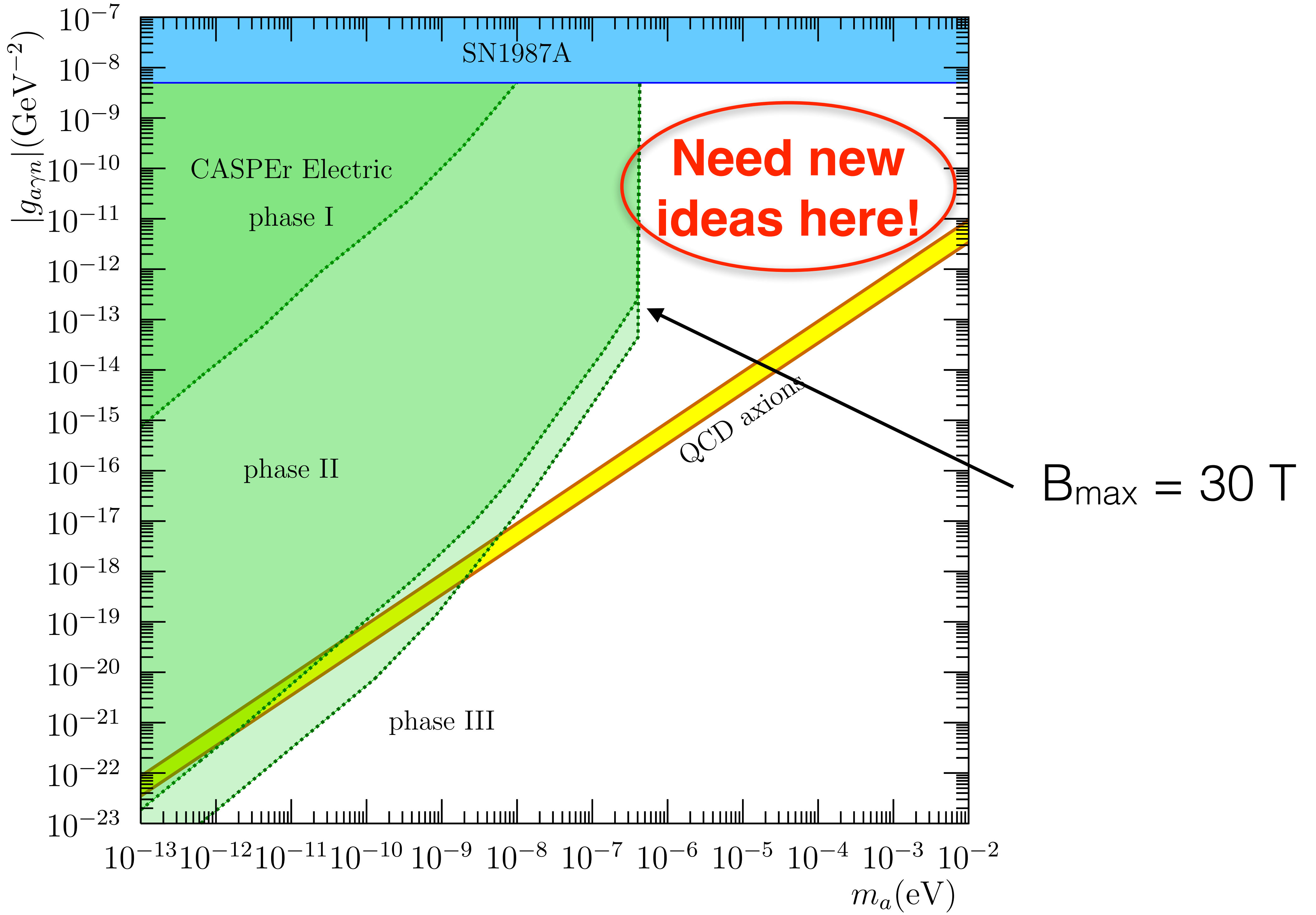


Spins precess around **B** and **E**, resonance in transverse magnetization when

$$2\mu_N B_{\rm ext} = m_a$$

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

nEDM parameter space



[Irastorza and Redondo, Prog. Part. Nucl. Phys. 2018]

Closing thoughts

- There is a clear parameter space target for the QCD axion, at least as well-motivated (in a Bayesian sense) as the canonical SUSY WIMP

- An exclusion of all or part of this parameter space would be great - but it wouldn't rule out axions!

- If we are lucky enough to discover axion DM, the prospects for learning more about inflation, DM halo, and the thermal history of our universe are even better than for the WIMP

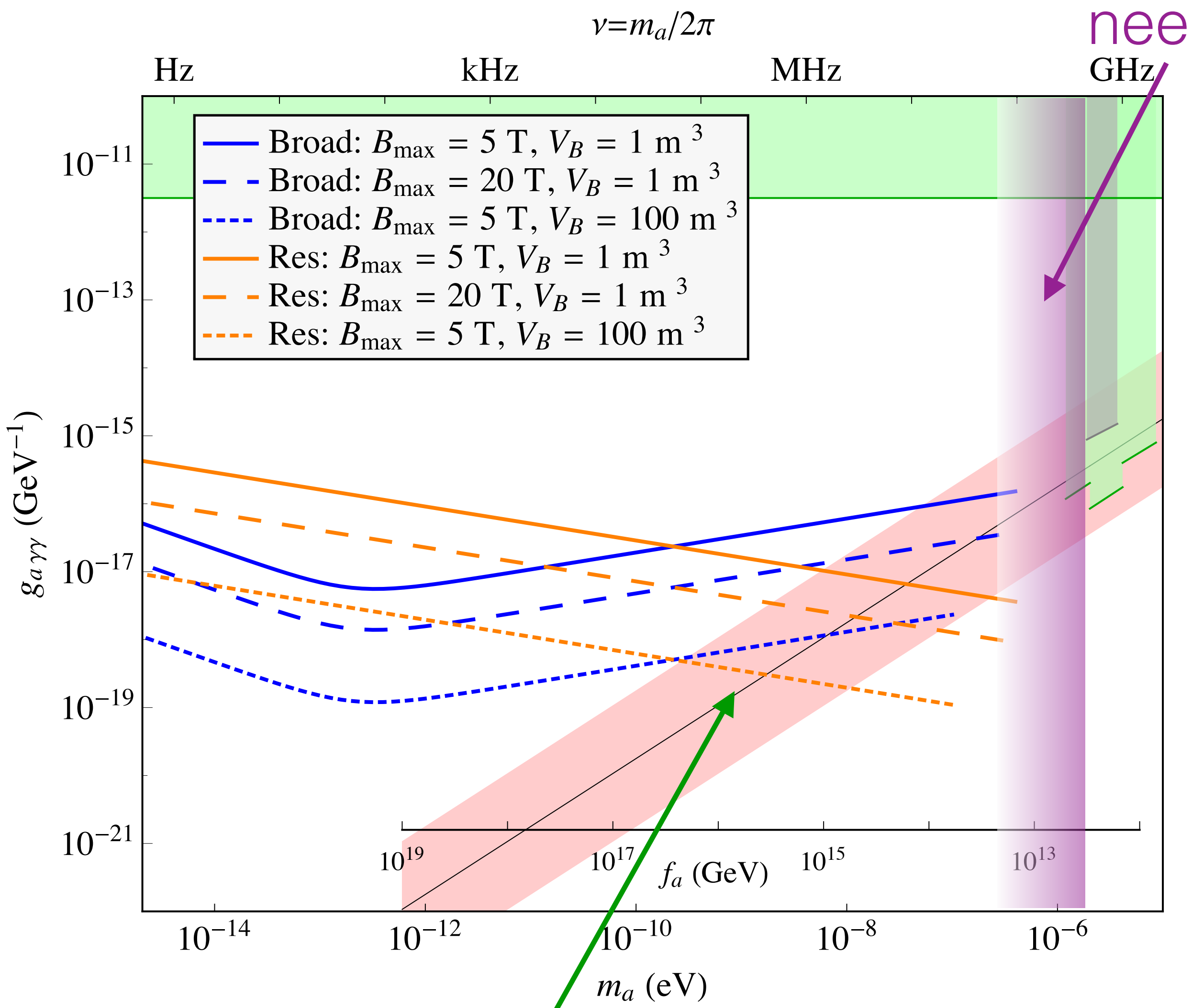
- Many more experiments in the coming years!

Backup Slides

ABRACADABRA reach

Full-scale reach:

QS breaks down (detailed sim. needed)



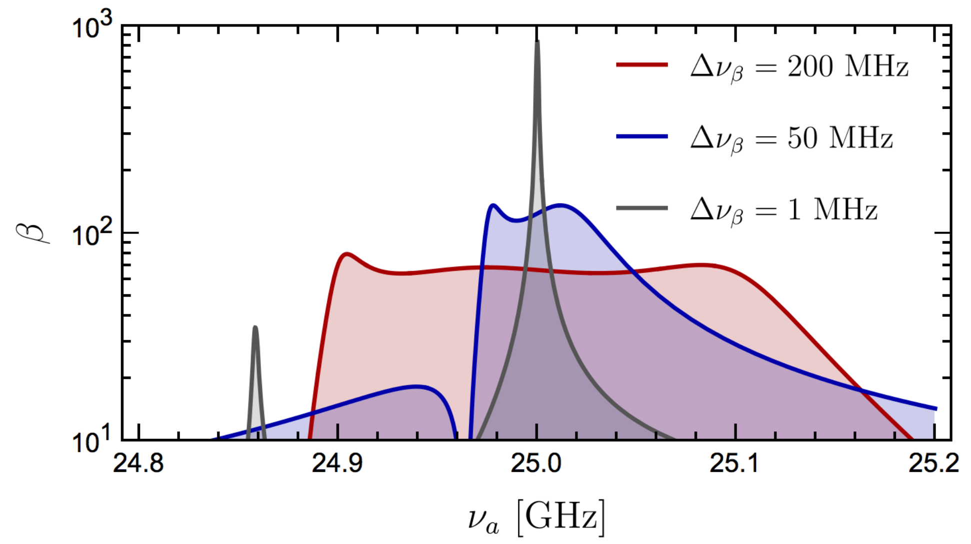
QCD axion

ABRA-10cm prototype:

Data being analyzed now - stay tuned!

MADMAX reach

Broadband and resonant modes possible:

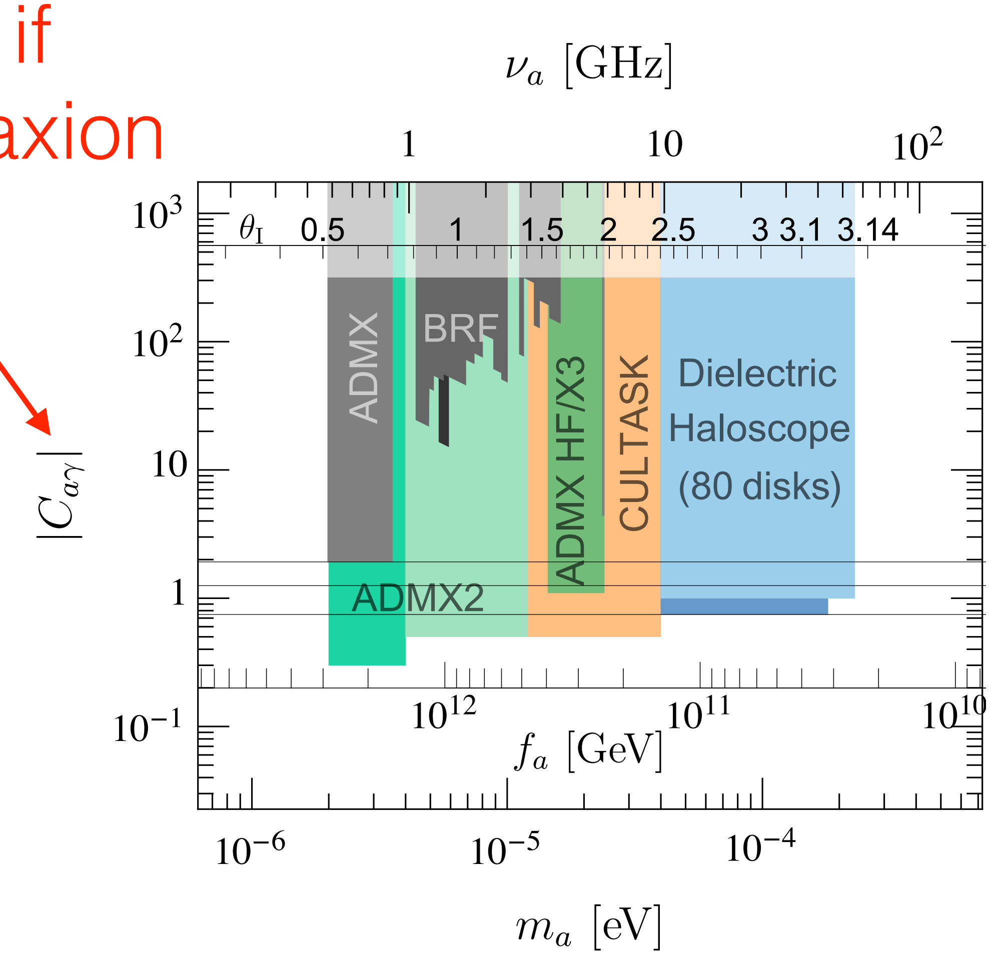


$$P \propto g_{a\gamma\gamma}^2 \rho_{\rm DM} B_0^2 A \beta^2$$

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

=1 if QCD axion

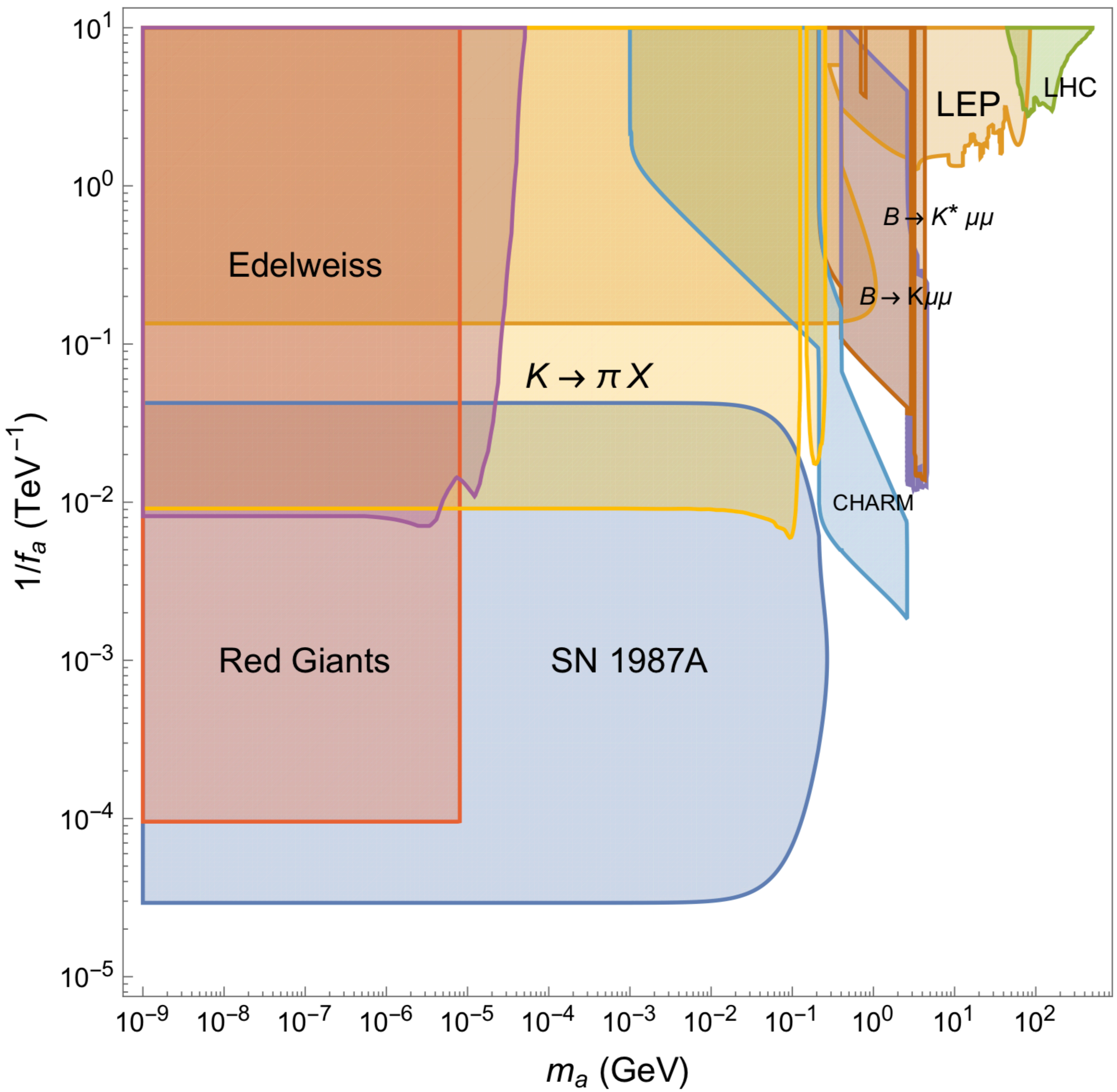
3-year runtime:



Excellent prospects in high-frequency regime

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

Photophobic ALP



Left-right symmetry:

$$\mathcal{L} \supset \frac{a}{f_a}(W_R\widetilde{W}_R - W_L\widetilde{W}_L)$$

IR coupling to photons only at two loops and/or suppressed by axion mass

Note: NOT the QCD axion! No coupling to gluons

[Craig, Hook, and Kasko, JHEP 1809 (2018)]