AXIONS

Axions

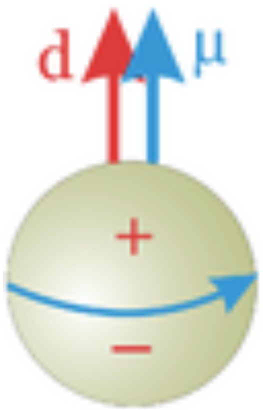
in cosmology

in astrophysics

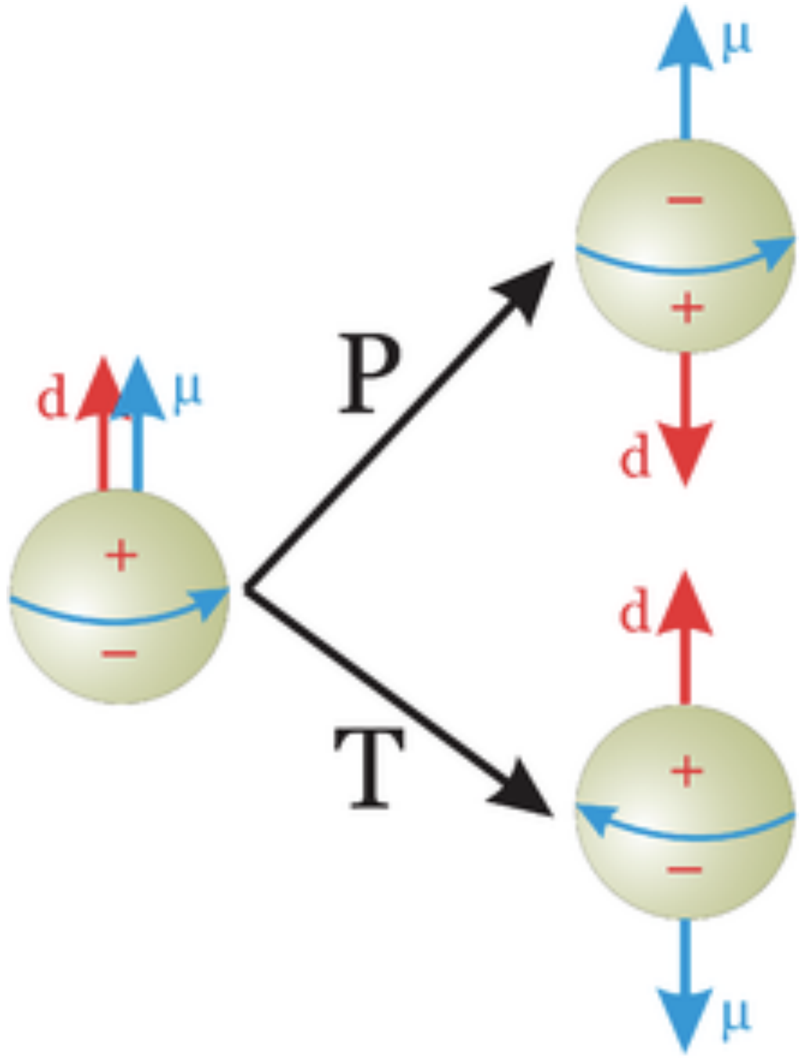
in the lab

The neutron

The neutron has a magnetic moment, and in principle could have an electric (dipole) moment as well.

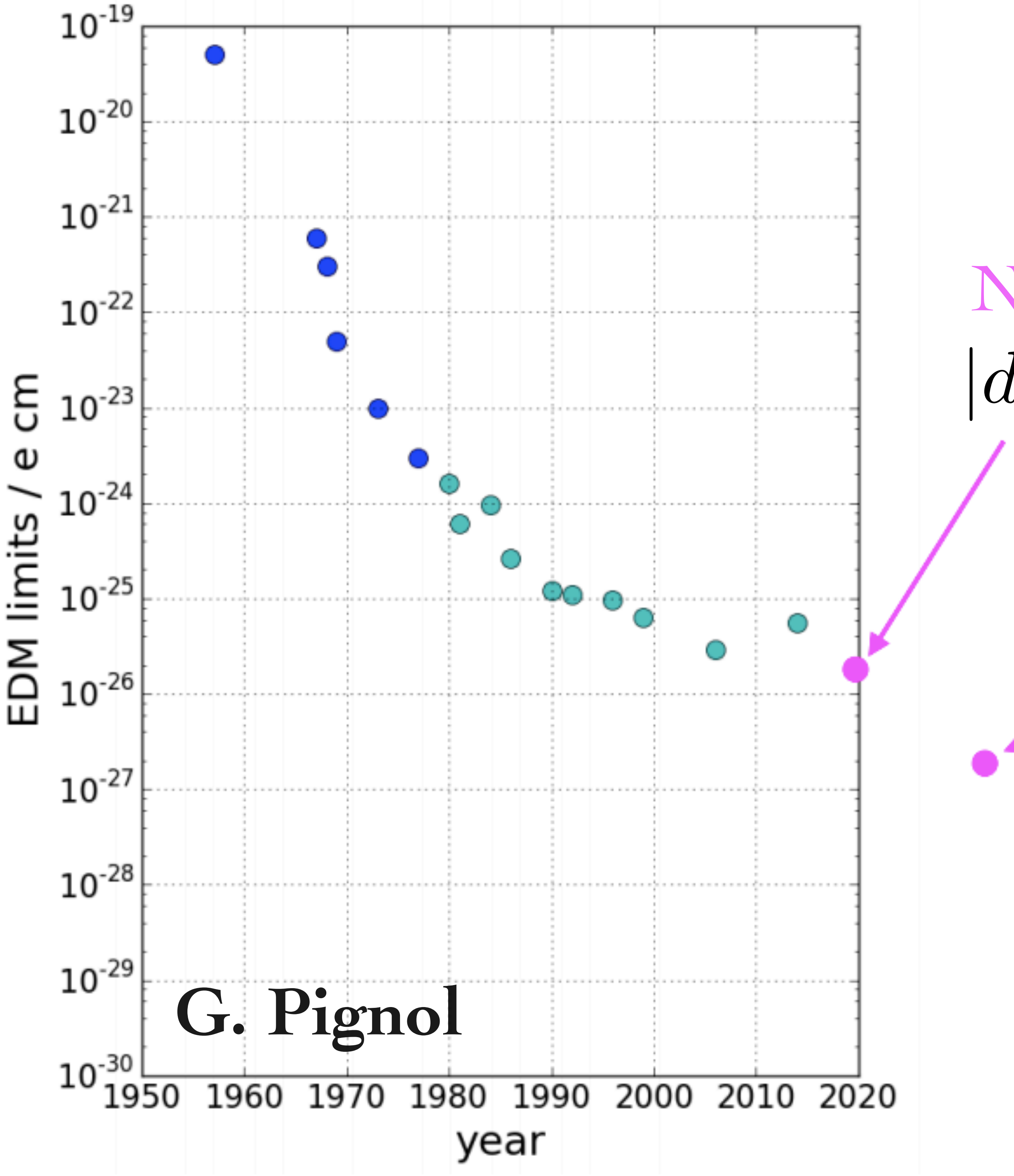


If the neutron has a permanent dipole then it will violate both parity (P) and time reversal (T) transformations



Since CPT is a fundamental symmetry of nature, we say that a neutron EDM would **violate CP**

Measurement of neutron's EDM (from last month)



G. Pignol

Newest measurement [2001.11966]

$$|d_n| < 1.8 \times 10^{-26}\, e\, \mathrm{cm} \;\; (90\%\ \mathrm{CL})$$

Future (with systematics under control)

Conclusion: the strong interaction seems to conserve CP

Should the strong interaction violate CP or not?

QCD Lagrangian

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4}G_{\mu\nu a}G^{\mu\nu}_{a} + \sum_{q} i\bar{q}\gamma^{\mu}D_{\mu}q - \bar{q}mq$$

gluons

quarks

Should the strong interaction violate CP or not?

QCD Lagrangian

$$\mathcal{L}_{\mathrm{QCD}} = \underset{\text{gluons}}{-\frac{1}{4}G_{\mu\nu a}G_a^{\mu\nu}} + \sum_q \underset{\text{quarks}}{i\bar{q}\gamma^\mu D_\mu q - \bar{q}mq} + \frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}$$

Vacuum structure of QCD will give rise to a CP violating term, given by a phase θ

But any observable CP-violation, could contain an *O(1)* contribution from electroweak sector via the **quark mass matrices**:

$$\theta = \bar{\theta}_{\rm QCD} + \arg\det M_u M_d \sim 1$$

Neutron EDM depends on this θ:

$$d_n = (2.4 \pm 1.0)\theta \times 10^{-3} e\,{\rm fm}$$

So, $\underline{|\theta| < 7.5 \times 10^{-11}}$

This is the **strong-CP problem**: why do these two phases seem to be cancelling each other so precisely?

The axion

Peccei & Quinn: the phase is zero because it is driven there dynamically

→ New global U(1) symmetry added to SM, broken below f_a

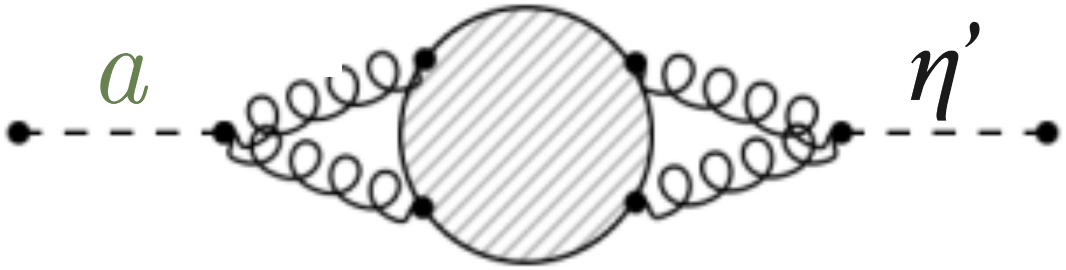
CP-violating phase now written as:

$$\theta = \frac{a}{f_a}$$

← Axion field

← PQ scale

a mixes with pion, eta' and other mesons, generating a mass:

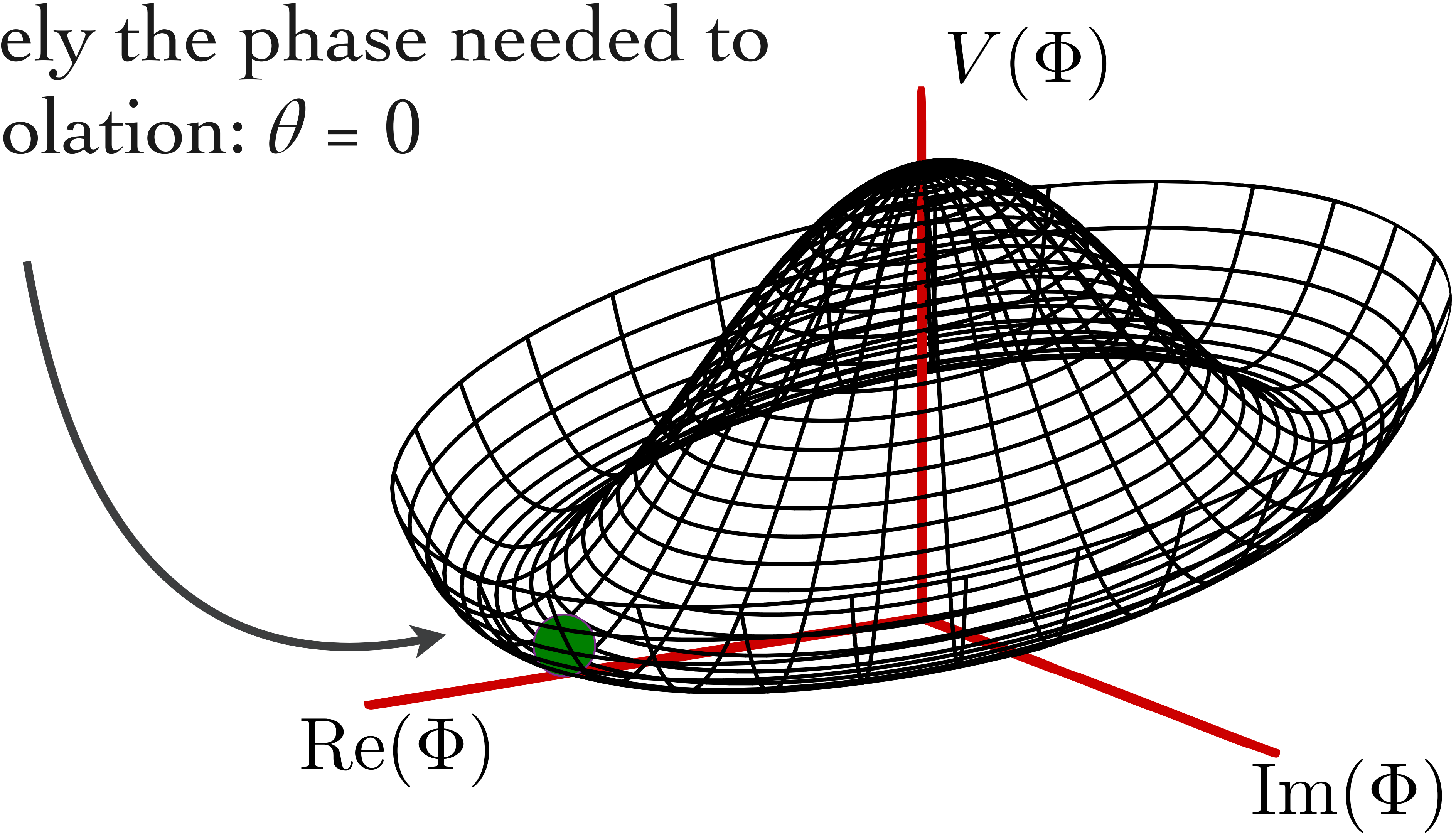


$$m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6\,\mathrm{meV}\left(\frac{10^9\mathrm{GeV}}{f_a}\right)$$

e.g. axion as angular d.o.f of complex scalar

$$\Phi(\mathbf{x}) \sim \rho(\mathbf{x}) e^{ia(\mathbf{x})/f_a}$$

Theory is constructed so that below $\Lambda_{\rm QCD}$, the potential of complex scalar tilts to precisely the phase needed to nullify CP-violation: $\theta = 0$



Axion is a new, massive particle with all interactions with SM suppressed by high scale f_a

…sounds like it could be dark matter?

Axion-DM is very nice aesthetically:

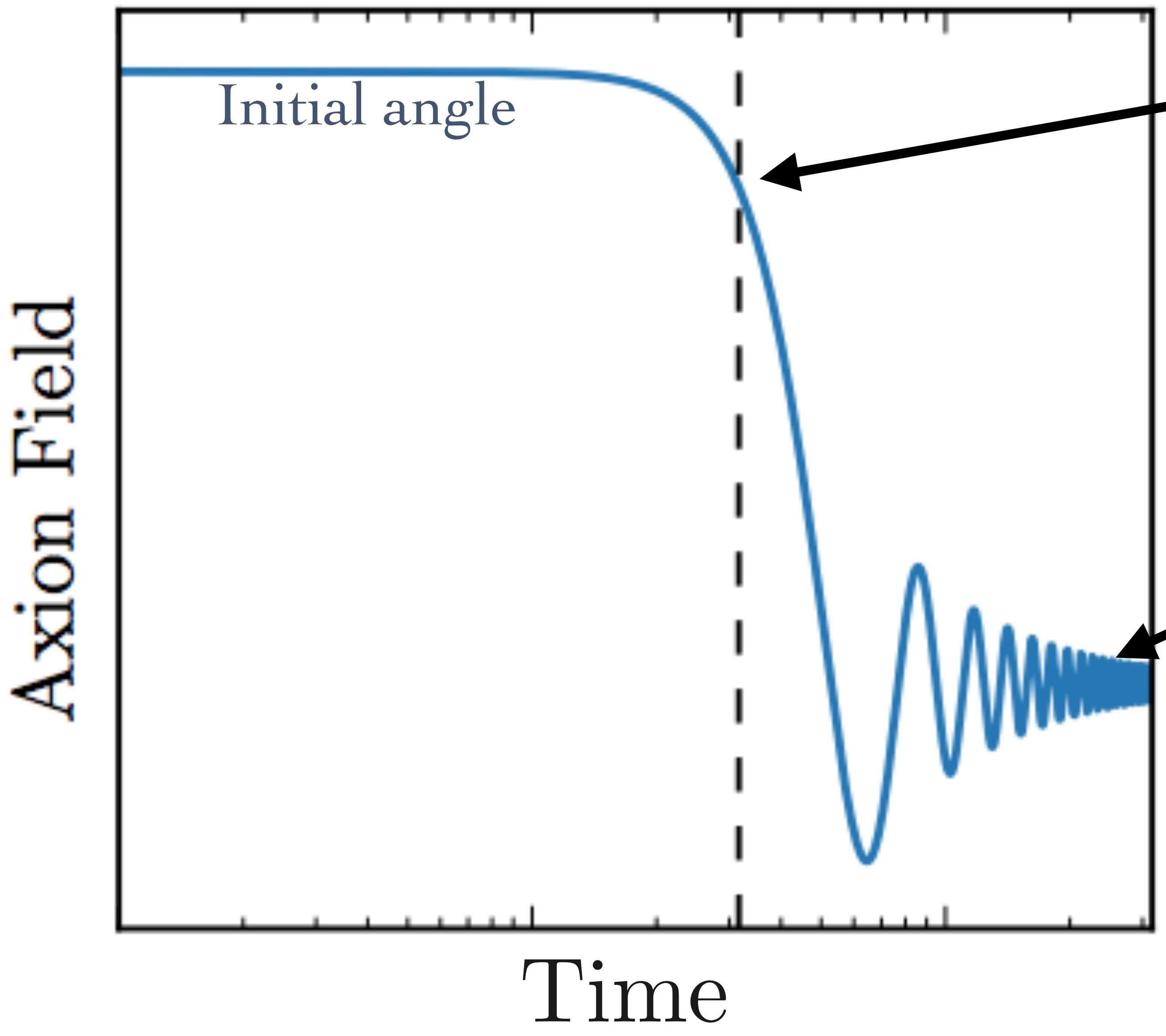
- Axion is a one parameter theory
- We get to solve strong-CP problem simultaneously

But we need to check a few things:

- Can we recover the observed DM relic density?
- Do axions form galaxies like CDM?
- Can we test for it?

Cosmological evolution of the axion field: misalignment mechanism

$$\ddot{a} + 3H\dot{a} + \frac{\partial \mathcal{V}(a)}{\partial a} = 0 \quad \text{where,} \quad \mathcal{V}(a) \approx \frac{1}{2} m_a^2 a^2$$



$H \sim m_a$
Axion field rolls down to minimum

$H < m_a$
Axion field starts damped oscillations with frequency $\sim m_a$
→ **axions produced**

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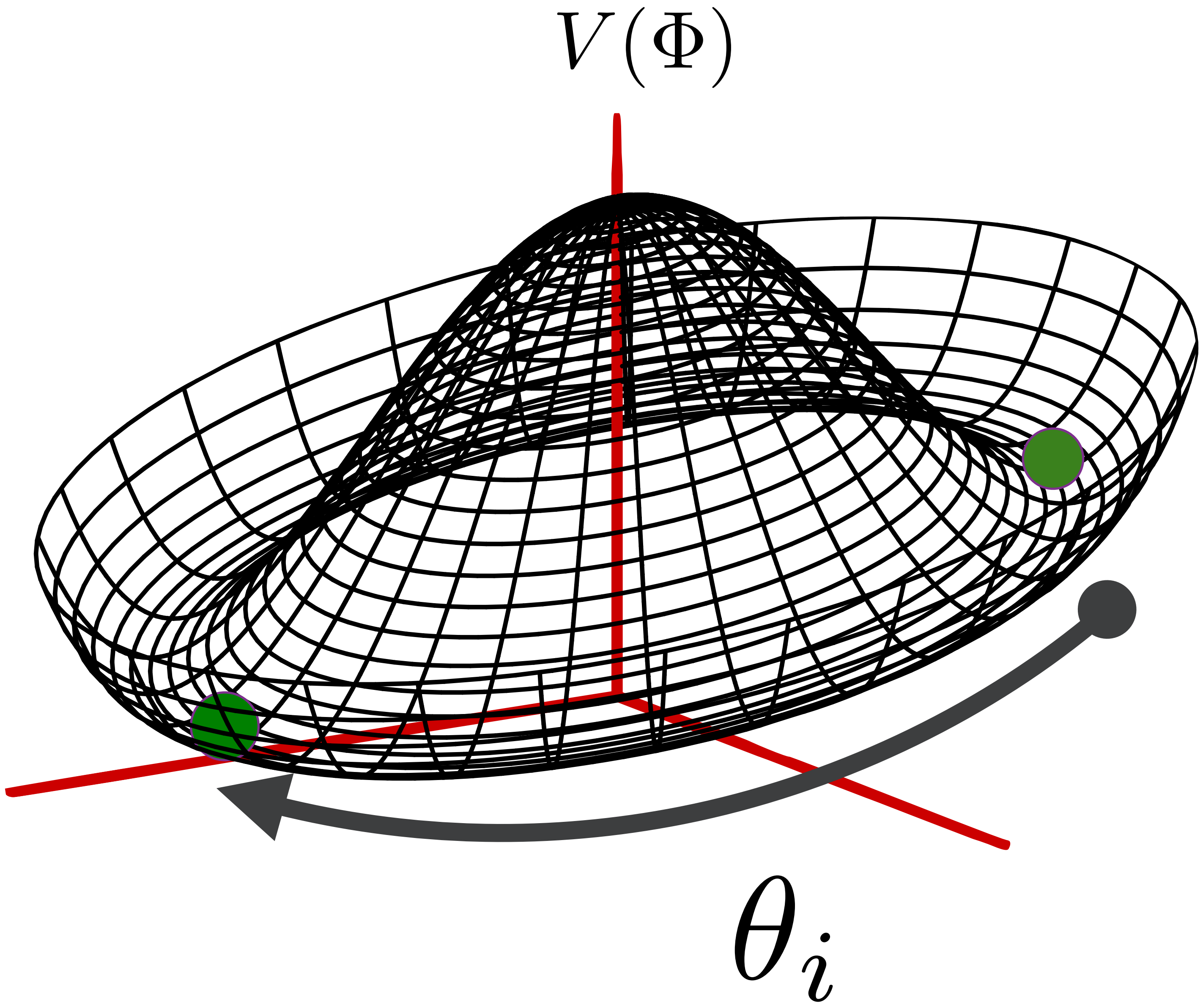
Quantity of axions produced depends on the initial value of the field before it rolled down



Axion production

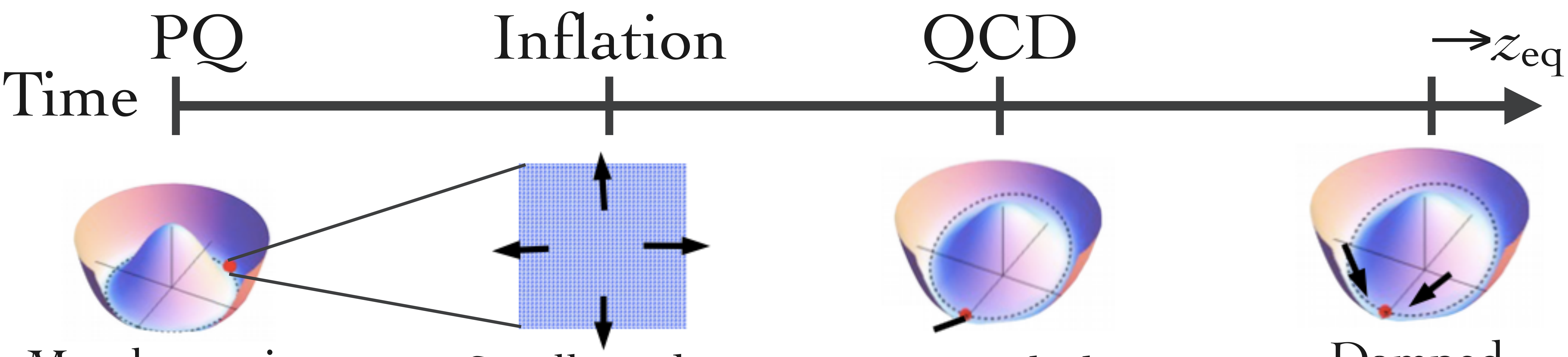
- Axion field appears after PQ phase transition at scale f_a
- Axion density depends on initial field value
- At some point inflation happens…

Distribution of initial field values will be radically different if the phase transition happens **before or after inflation**

Scenario 1: Pre-inflationary axions

Scenario 2: Post-inflationary axions

Scenario 1: PQ broken before inflation



Time

PQ

Inflation

QCD

$\rightarrow z_{\mathrm{eq}}$

Massless axion field born with random phases everywhere

Small random patch inflated → single field value fills horizon

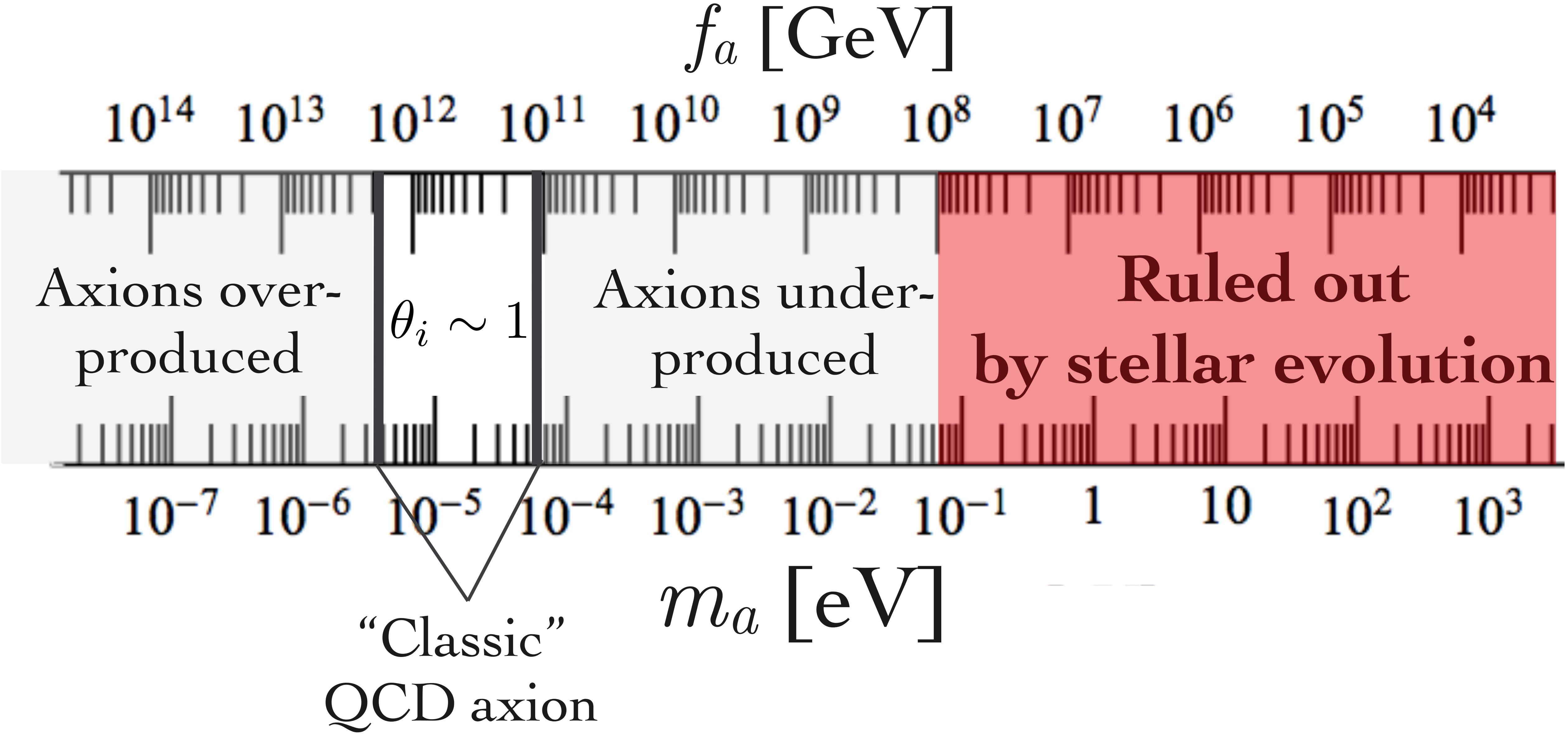
Potential tilts, axion mass switches on

Damped oscillations → cold axions produced

Relic density just depends on initial misalignment angle

$$\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{7/6} \theta_i^2$$

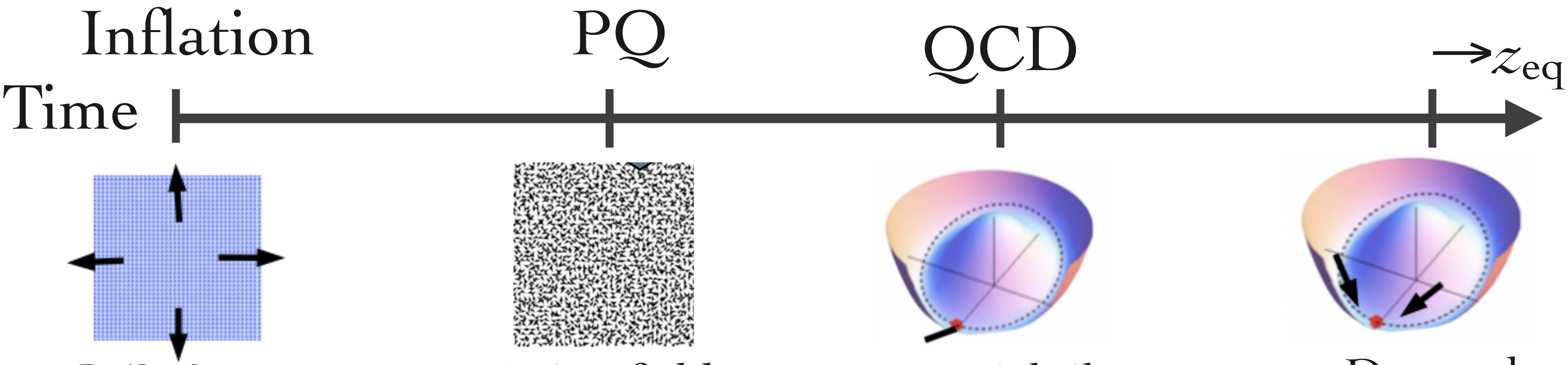
Scenario 1: Relic density



Caveats:

- Can rescue over-production by tuning initial angle → 0 ("anthropic axion")
- Details depend on axion dynamics, scale of inflation, cosmological history etc. this is far from definitive…

Scenario 2: PQ broken after inflation



Time

Inflation

PQ

QCD

$\rightarrow z_{\text{eq}}$

Inflation Happens

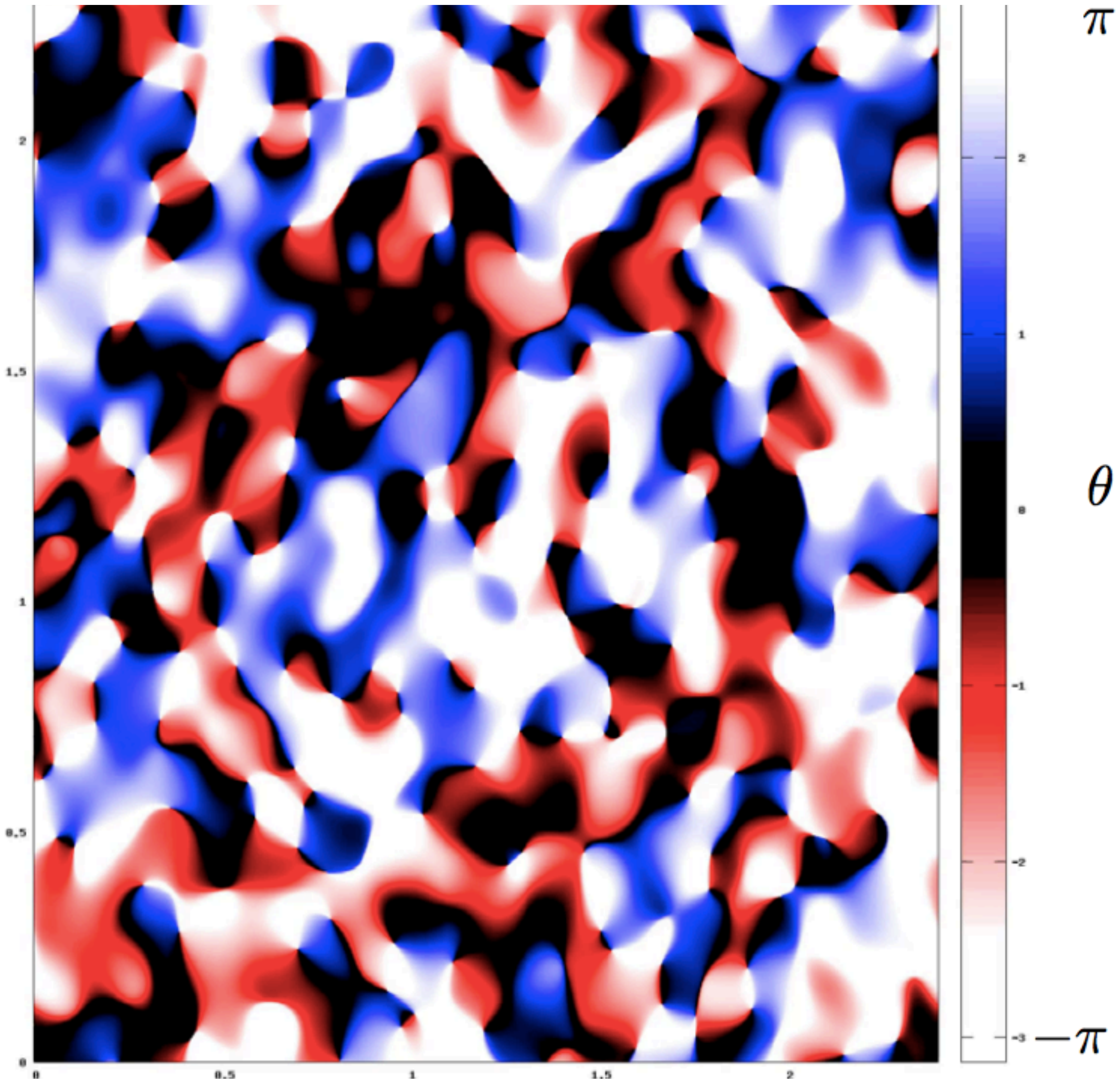
Axion field randomly distributed

Potential tilts, field tries to reconfigure to minimum

Damped oscillations → axions produced incoherently

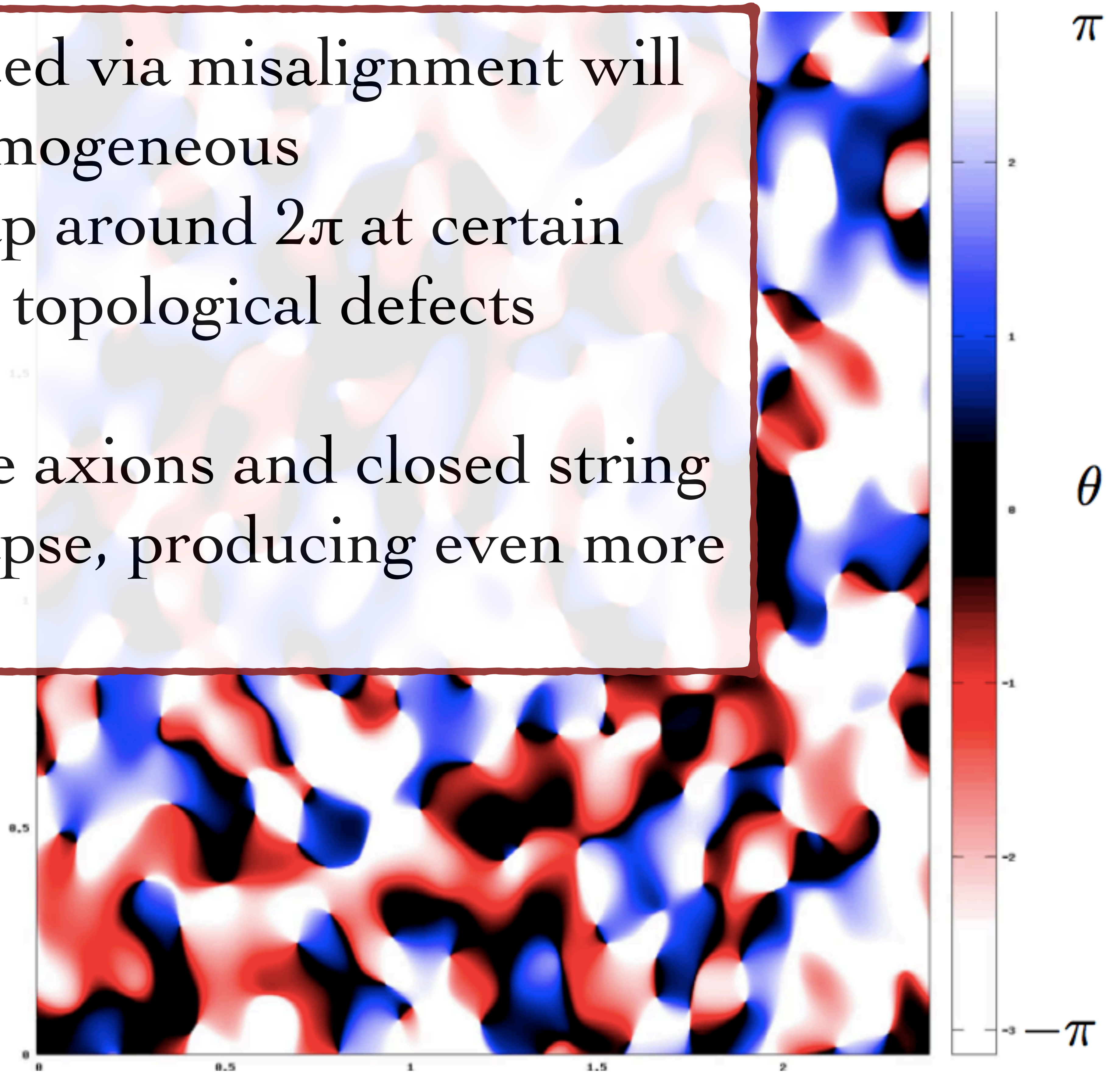
Distribution of initial misalignment angles will be highly inhomogeneous

Resulting distribution is much more complicated.



Resulting distribution is much more complicated.

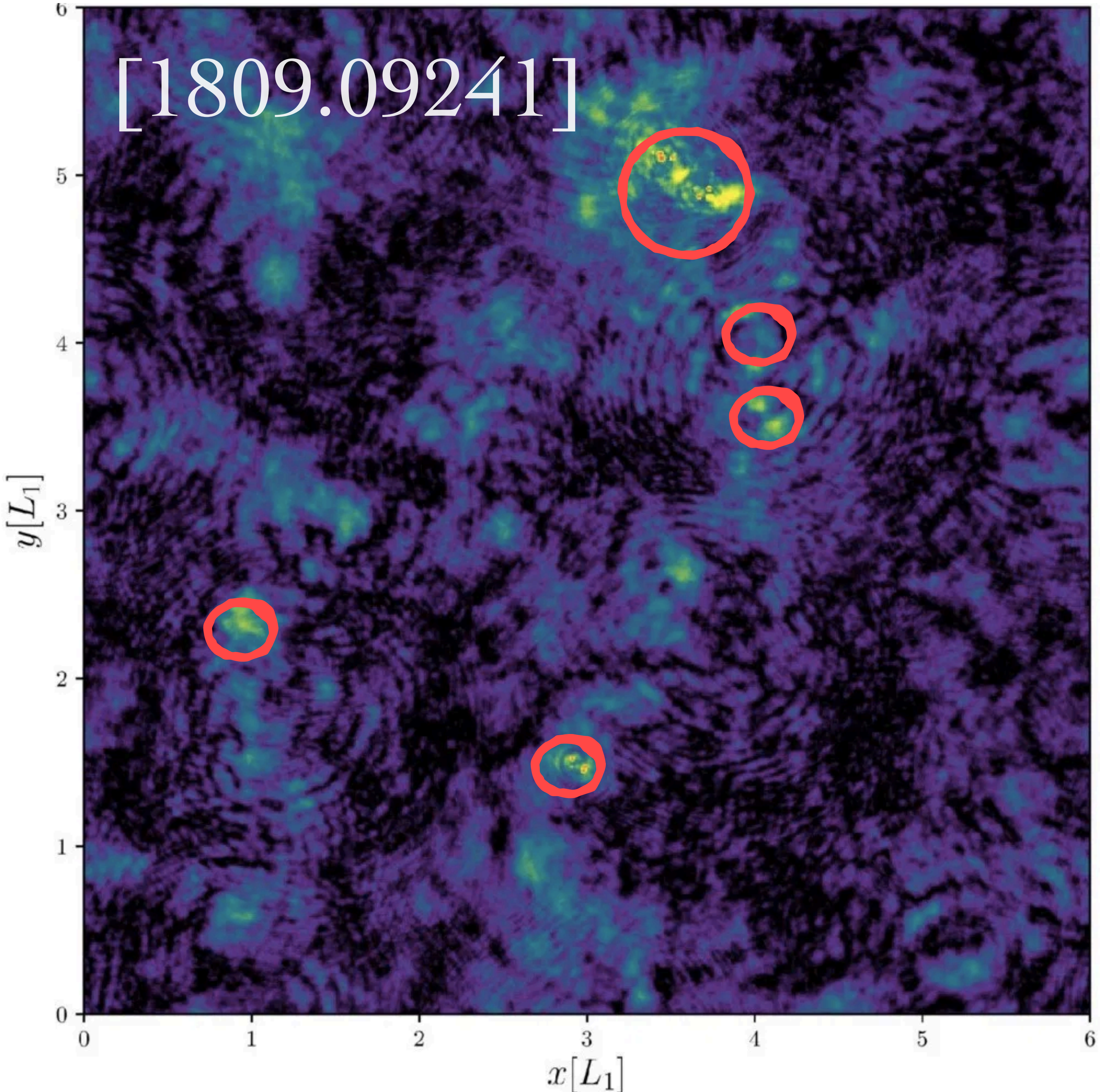
- Axions produced via misalignment will be highly inhomogeneous
- Phase will wrap around 2π at certain points forming topological defects (axion strings)
- Defects radiate axions and closed string loops will collapse, producing even more axions



Even more complications: Miniclusters

Overdensities in axion field can be so large in the post-inflationary scenario that certain patches enter matter-radiation equality early and get a head-start on growth and subsequent gravitational collapse

→ the result is small bound structures called **miniclusters**



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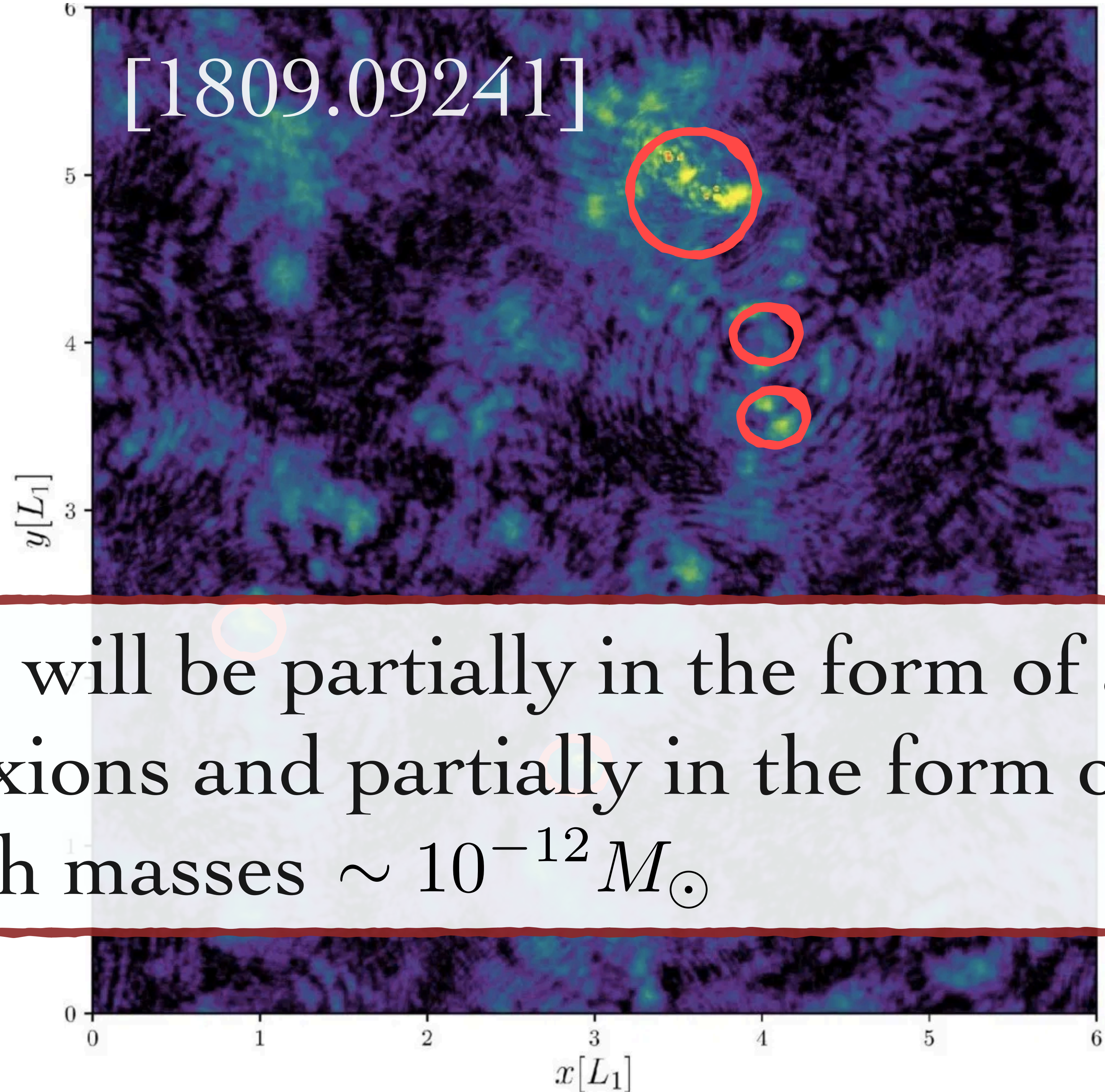
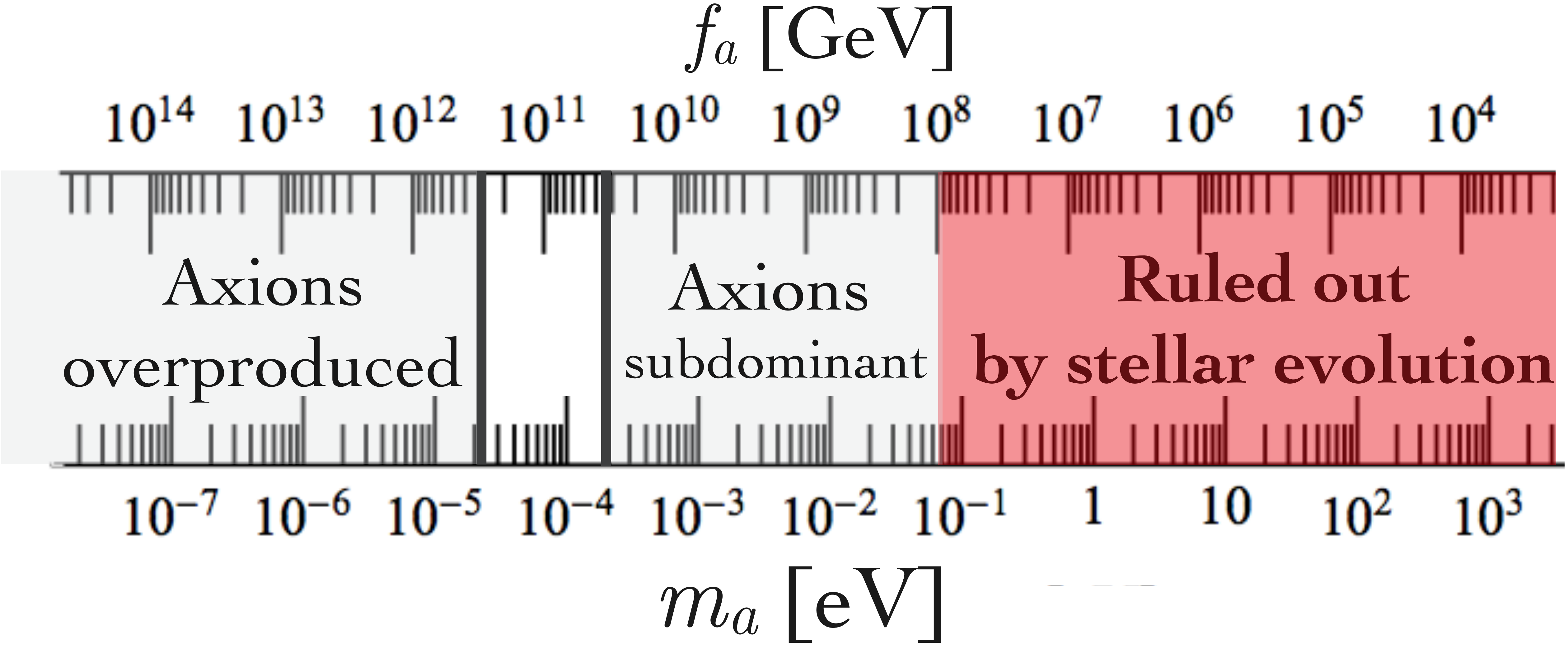


[1809.09241]

Post-inflationary axions will be partially in the form of a diffuse distribution of axions and partially in the form of tight bound clusters with masses $\sim 10^{-12} M_\odot$

Scenario 2: Can post-inflationary axions be dark matter?



- Prediction of relic density requires dedicated lattice simulations of the evolution of the axion field through the QCD phase transition, including decay of axion strings etc.
- But individual sims can given quite precise predictions for the axion mass ~ 25 μeV, e.g. 1708.07521, 1906.00967

What about those miniclusters?

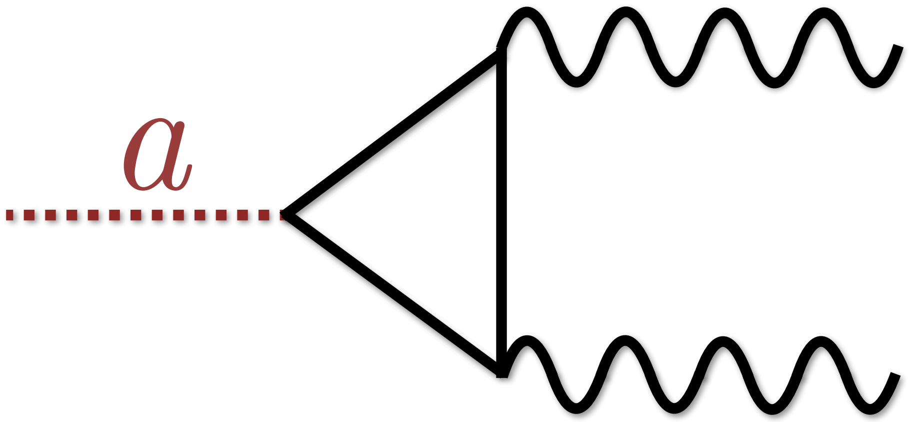
- Recent work shows that around 75% of the axions could still be bound up in miniclusters at z=100 [1911.09417]
- These miniclusters may not survive beyond that since they are small and fluffy enough to be tidally disrupted by stars [1512.02884]
- Behave as CDM on scales of galaxies, but distribution is **clumpy** on scales of <mpc
- If a large fraction do survive, this is a potential threat to direct detection of axionic DM on Earth [1701.03118]
- But—could look for them with gravitational lensing/ microlensing [1908.01773], [1701.04787]

Detecting the axion

A rather nice property (compared with other DM candidates)

Coupling to the photon: $g_{a\gamma}$

$$\mathcal{L} = \frac{1}{4} g_{a\gamma} a(\mathbf{x}, t) F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Little bit of nomenclature:

- **QCD Axion:** $g_{a\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} = 2.0 \times 10^{-16} \mathrm{C}_{a\gamma} \frac{m_a}{\mu\mathrm{eV}}\ \mathrm{GeV}^{-1}$

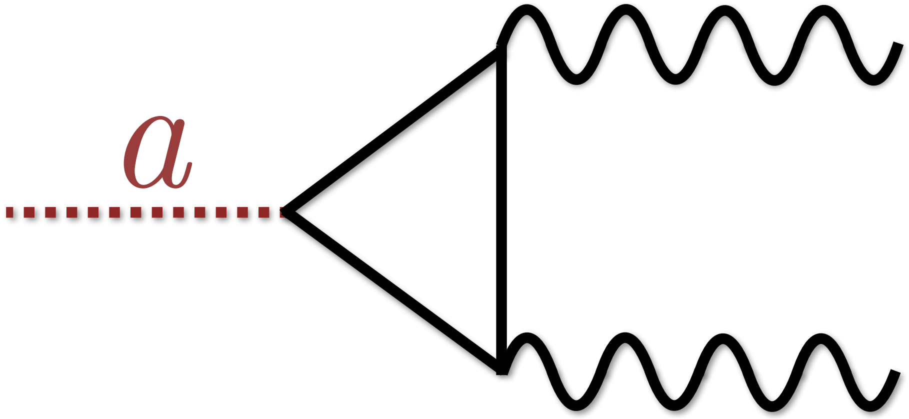
- QCD axion **models:** $\begin{array}{ll} \mathrm{KSVZ:} & C_{a\gamma} = -1.92 \\ \mathrm{DFSZ:} & C_{a\gamma} = 0.75 \end{array}$

- QCD axion "**band**": $|C_{a\gamma}| \in [0.1, 10]$

- **Axion-like particle (ALP):** $C_{a\gamma} =$ any value

Axion-photon coupling: $g_{a\gamma}$

$$\mathcal{L} = \frac{1}{4} g_{a\gamma} a(\mathbf{x},t) F_{\mu\nu}\tilde{F}^{\mu\nu}$$



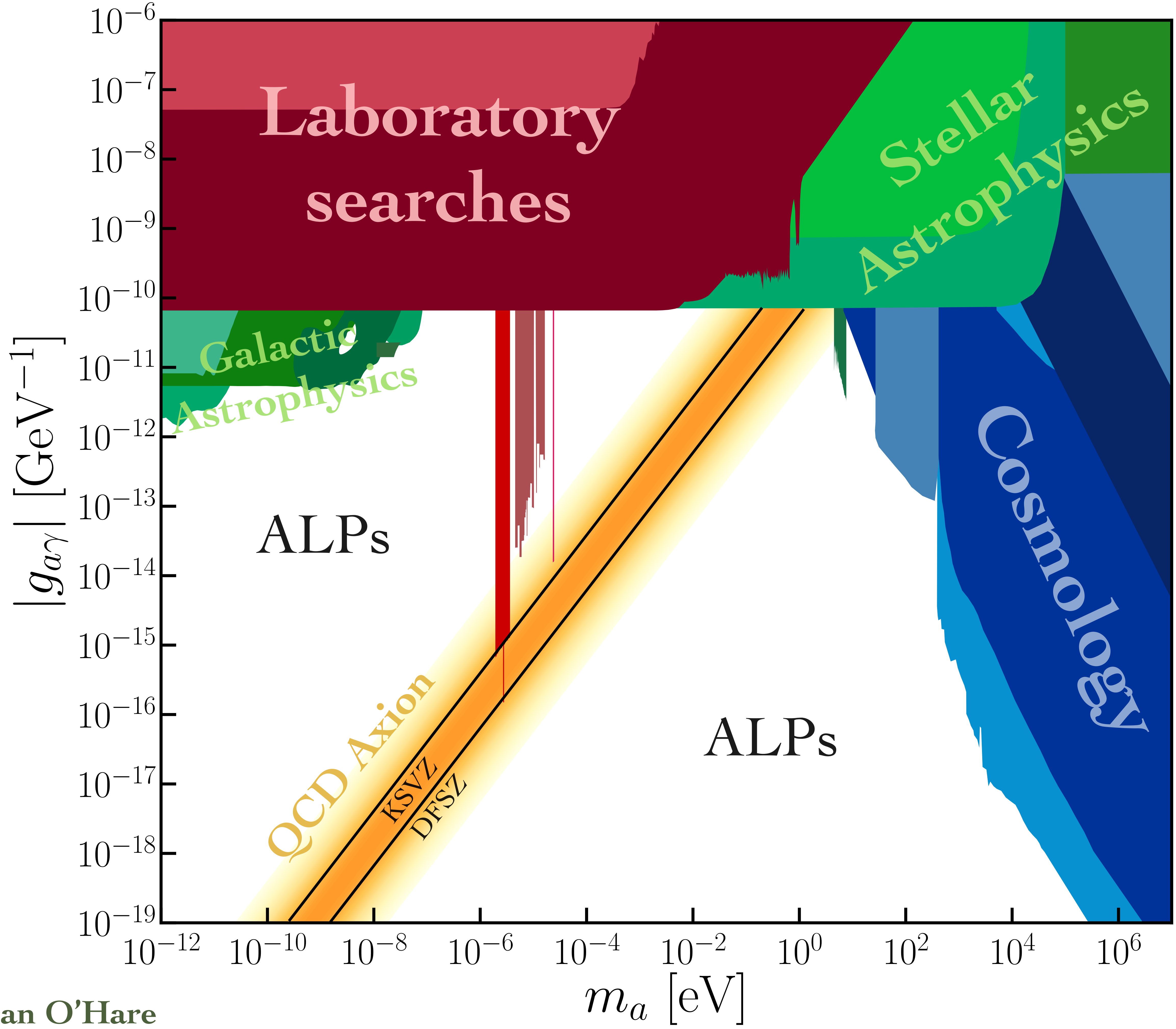
$$\nabla \cdot \mathbf{E} = \rho_q - g_{a\gamma}\mathbf{B}\cdot\nabla a$$

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

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

$$\nabla \times \mathbf{E} + \dot{\mathbf{B}} = 0$$

$$(\Box + m_a^2)a = g_{a\gamma}\mathbf{E}\cdot\mathbf{B}$$



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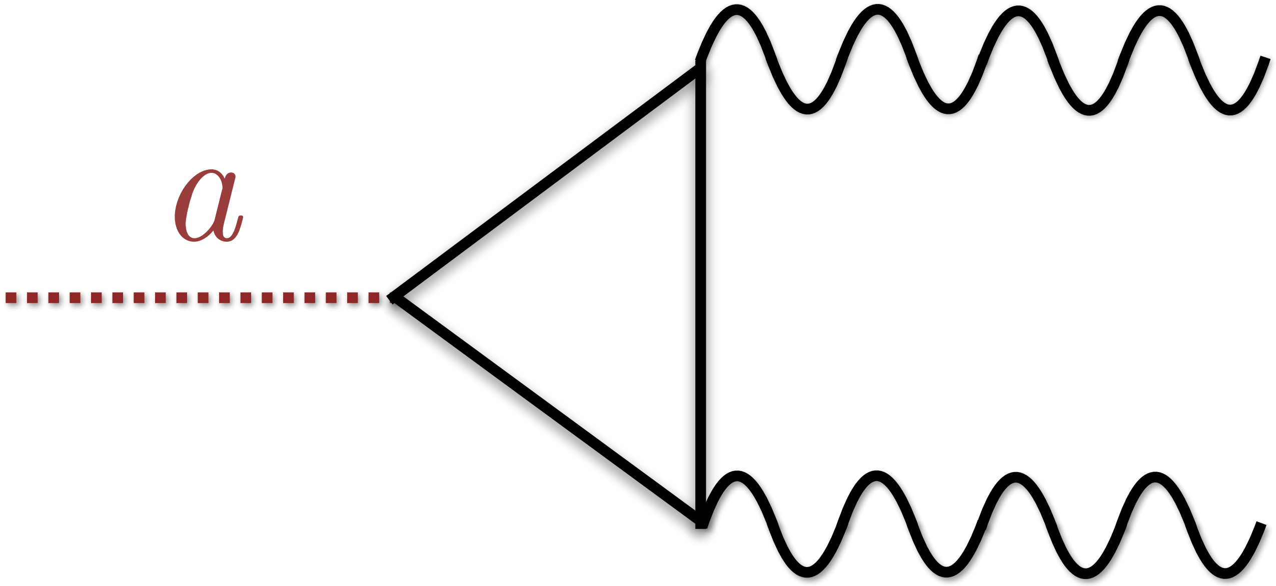
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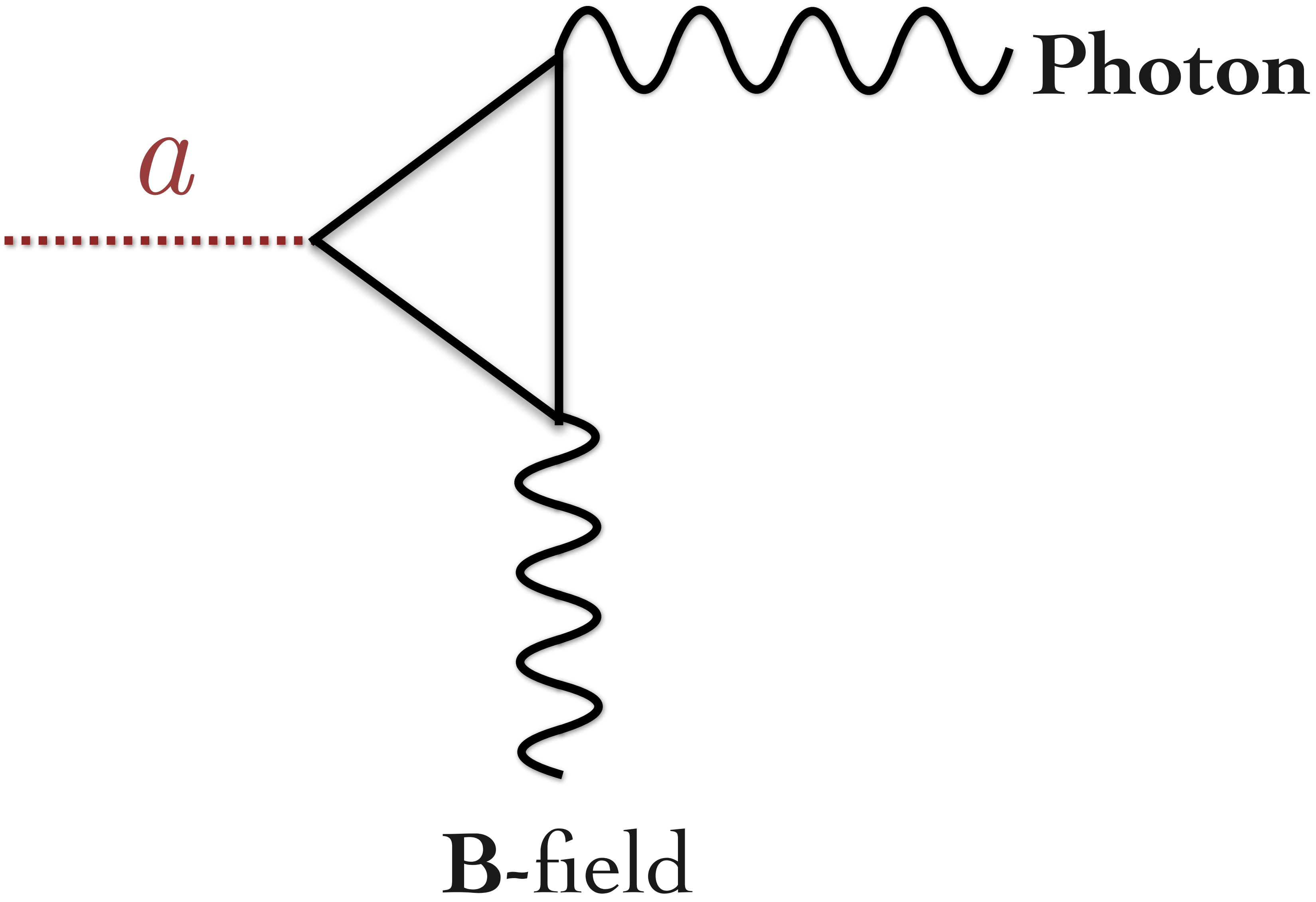
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Photon
B-field

To detect the axion we need one or more of the following:

Source of axions

Photons

Magnetic field

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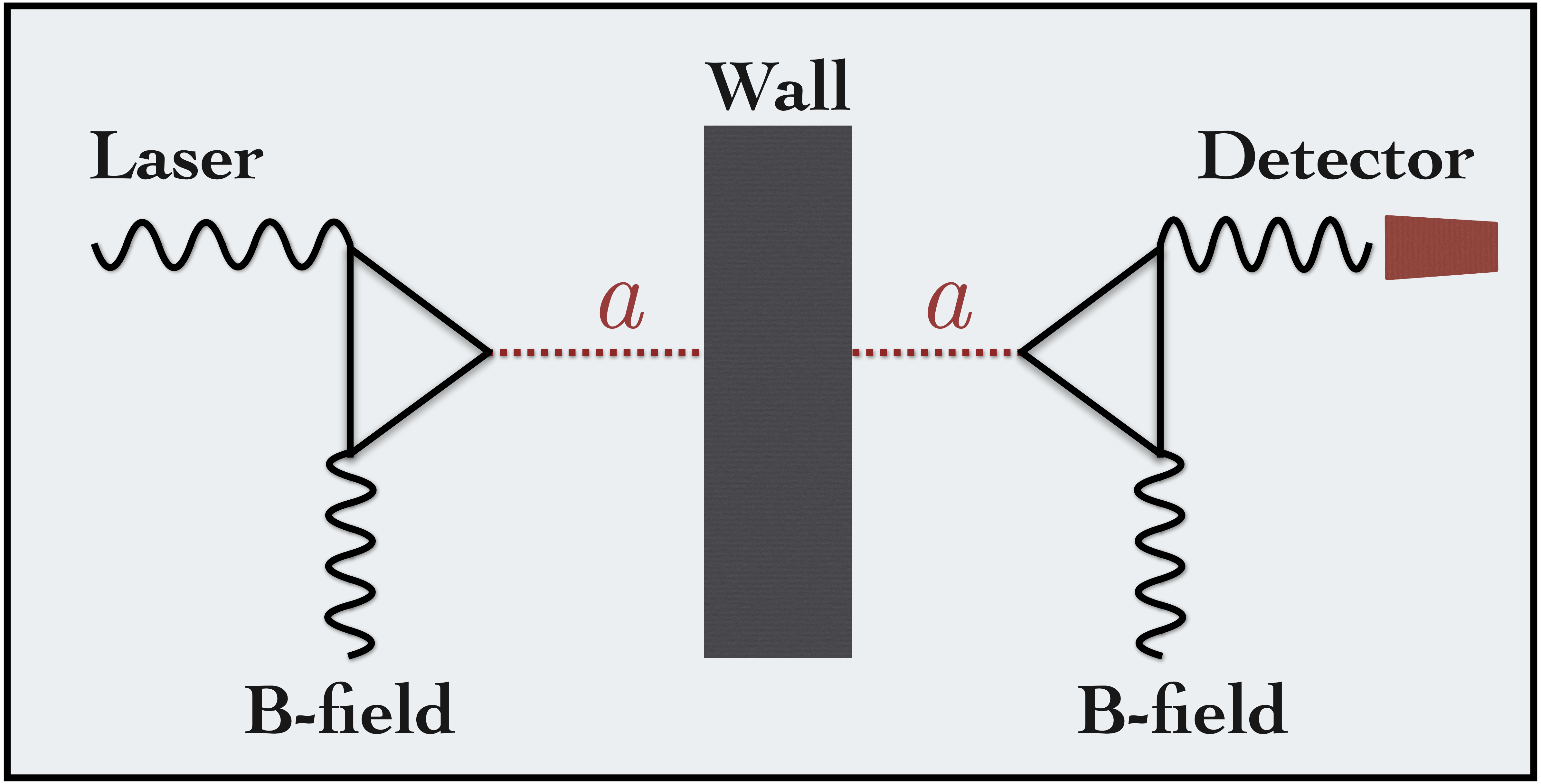
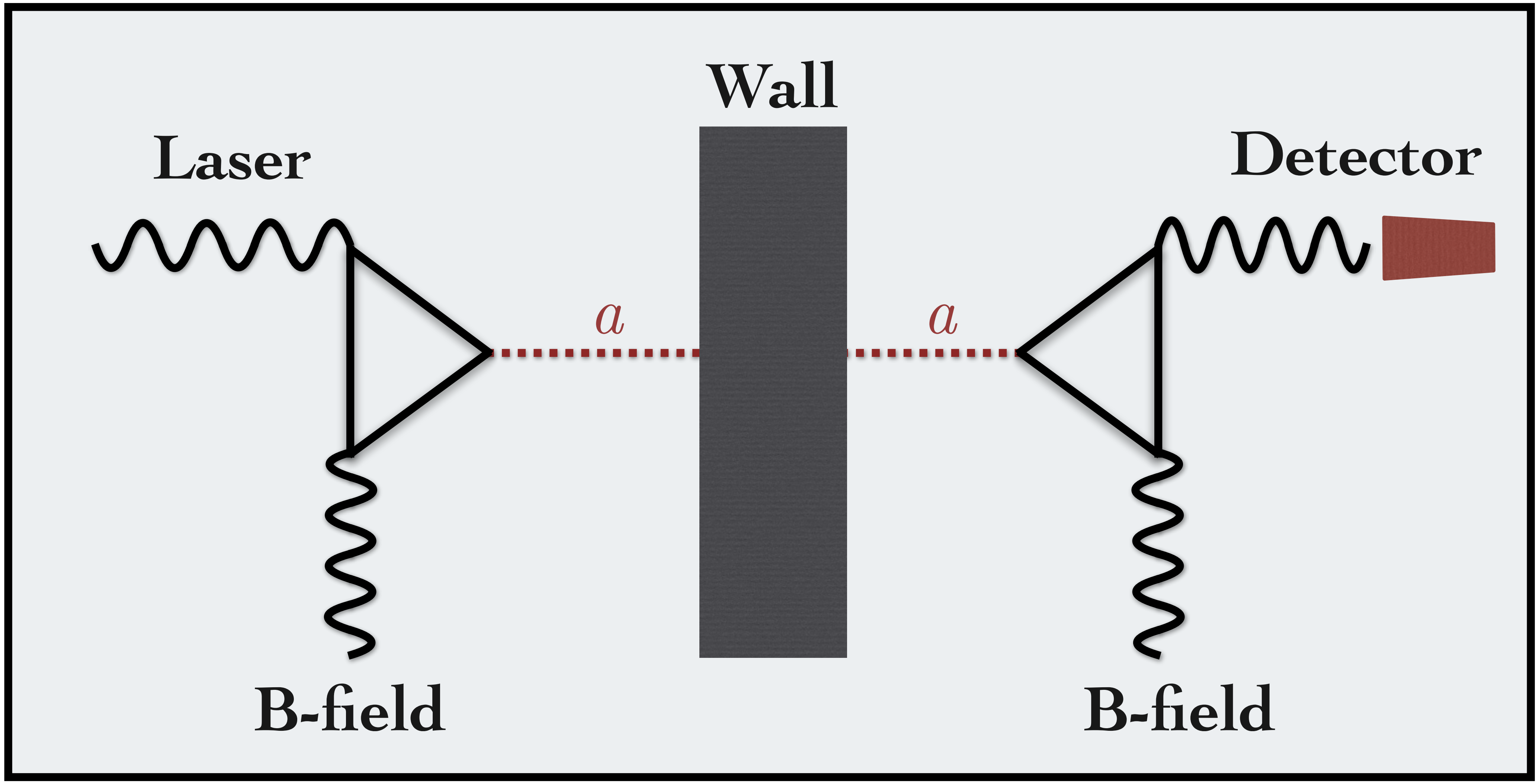
Purely lab search for the axion-photon coupling
i.e. testing Maxwell's equations in the lab

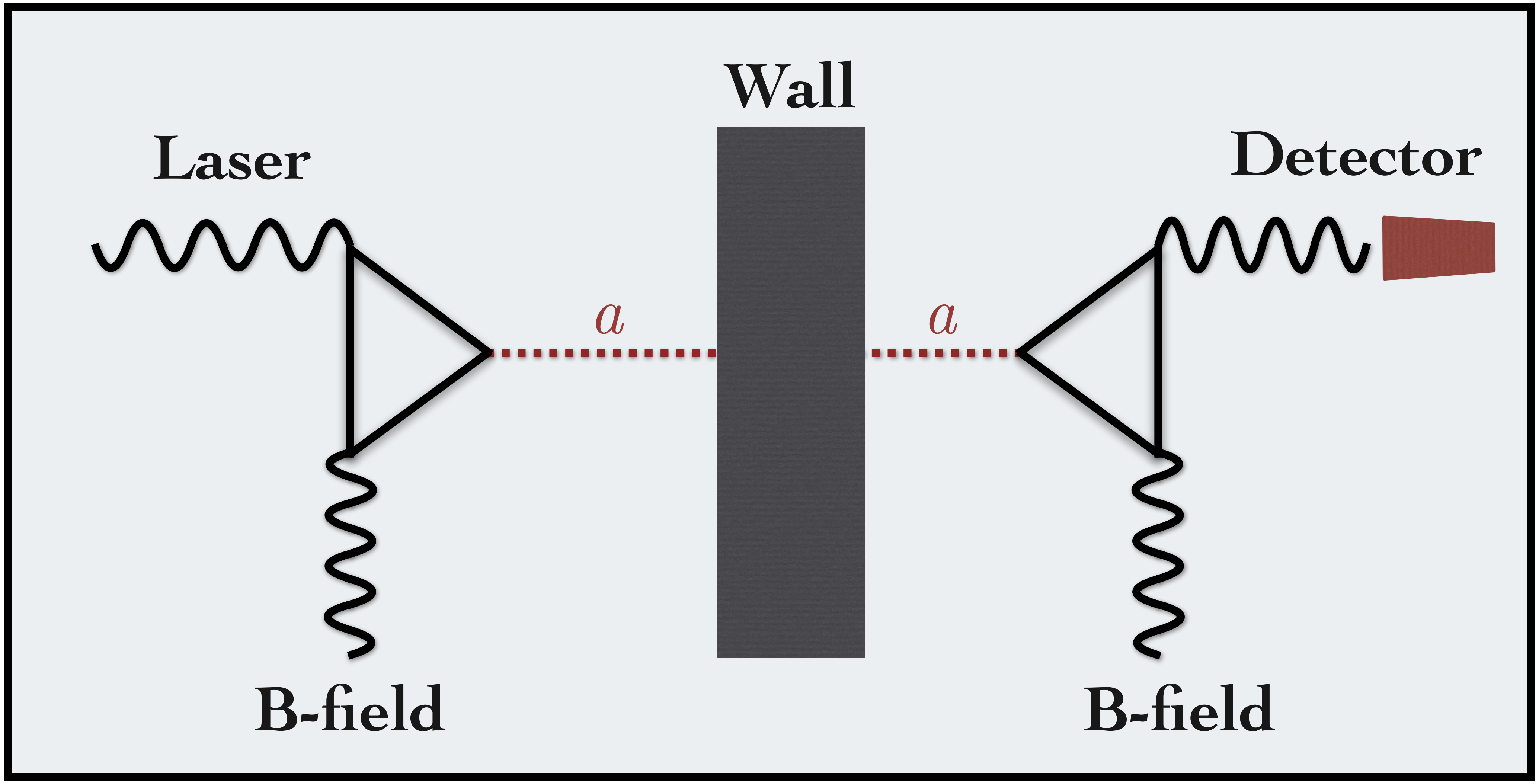
A lab test for the axion:
Light shining through a wall





Advantages:

- Conversion ~independent of axion mass below a certain value
- Sensitivity to coupling controlled by dark count rate of photodetector, strength of B-field, length of conversion region, laser power… which can all be chosen
- Completely model independent test of $\mathcal{L} = \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

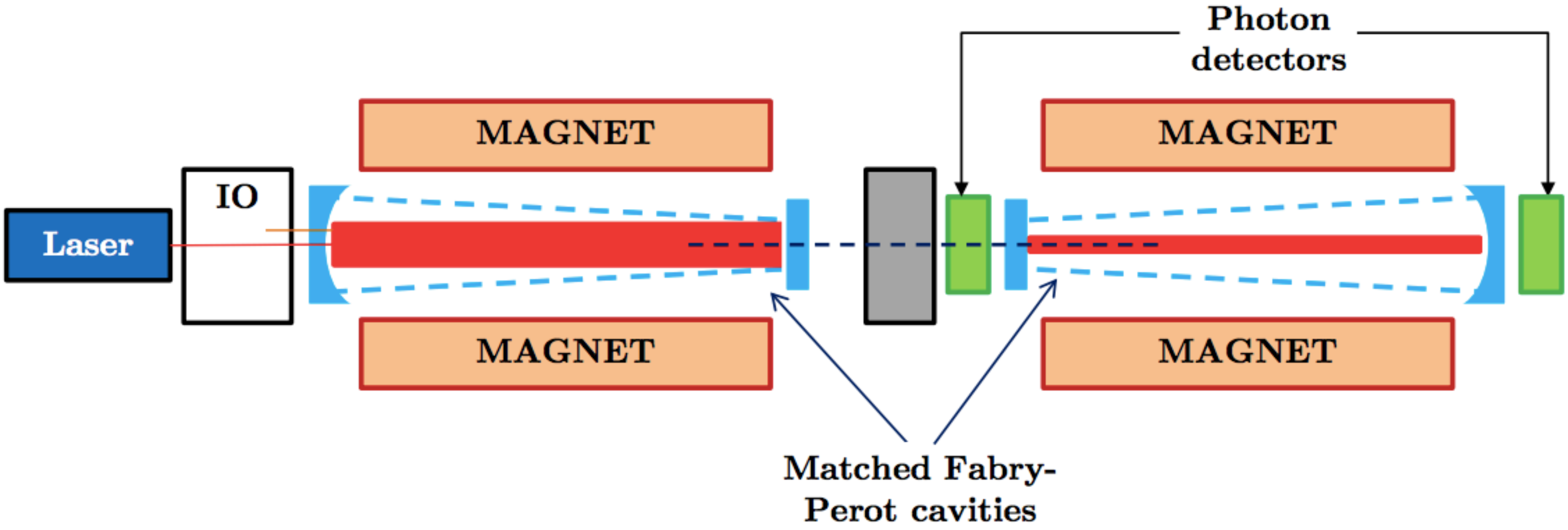


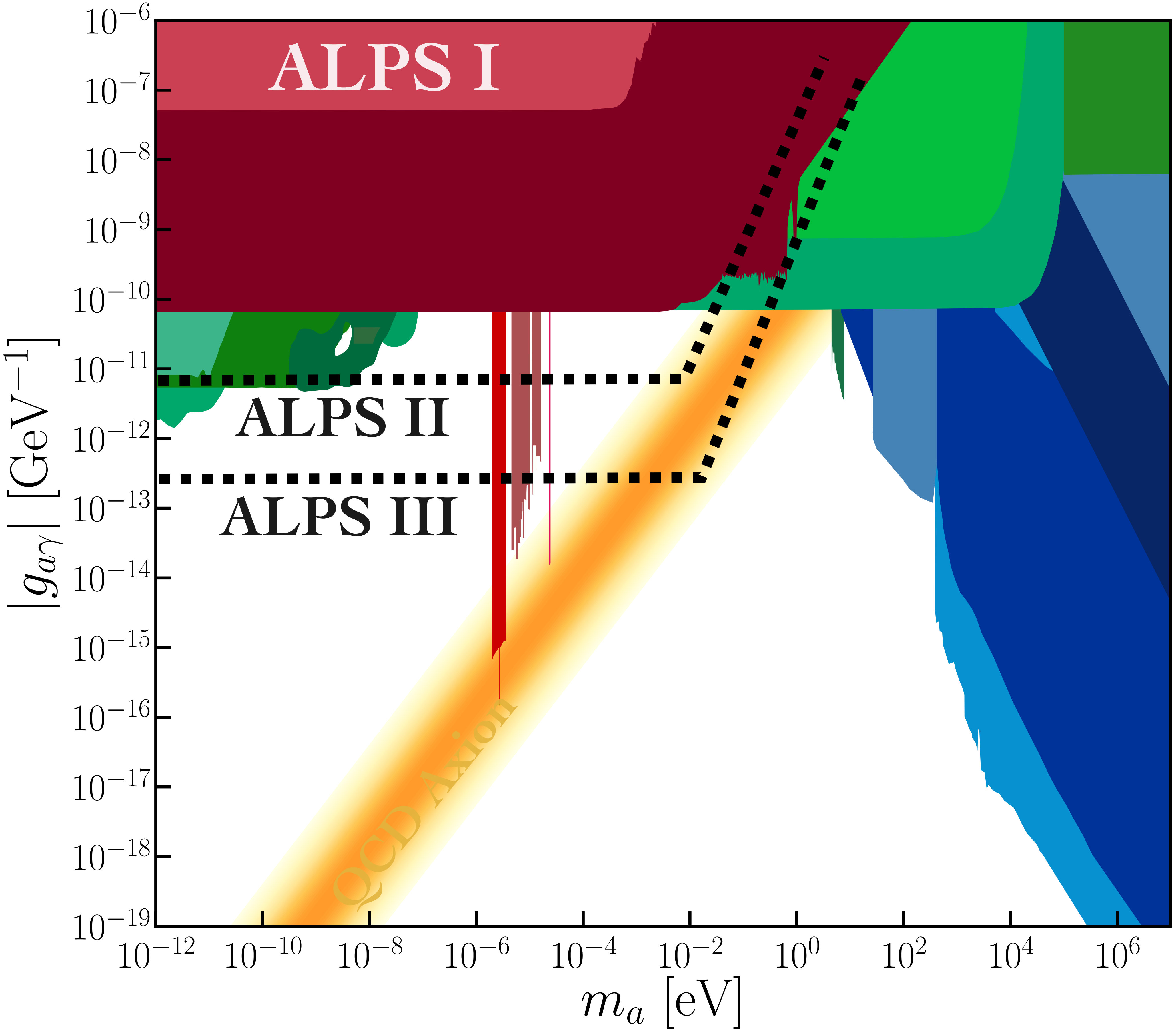
Disadvantage: (a big one)

- Axion conversion probability scales with coupling squared
- And here, axions need to convert **twice** → Power ~ g^4

LSW probability $\mathcal{P}(\gamma \to a \to \gamma) \propto \left(\frac{g_{a\gamma}B_e}{\omega}\right)^4$

ALPS (Any Light Particle Search)





ALPS I

Concluded in
2010

ALPS II

Running at
DESY, first
results soon

ALPS III

Concept for QCD
axion sensitivity

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To detect the axion we need one or more of the following:

Source of axions

Photons

Magnetic field

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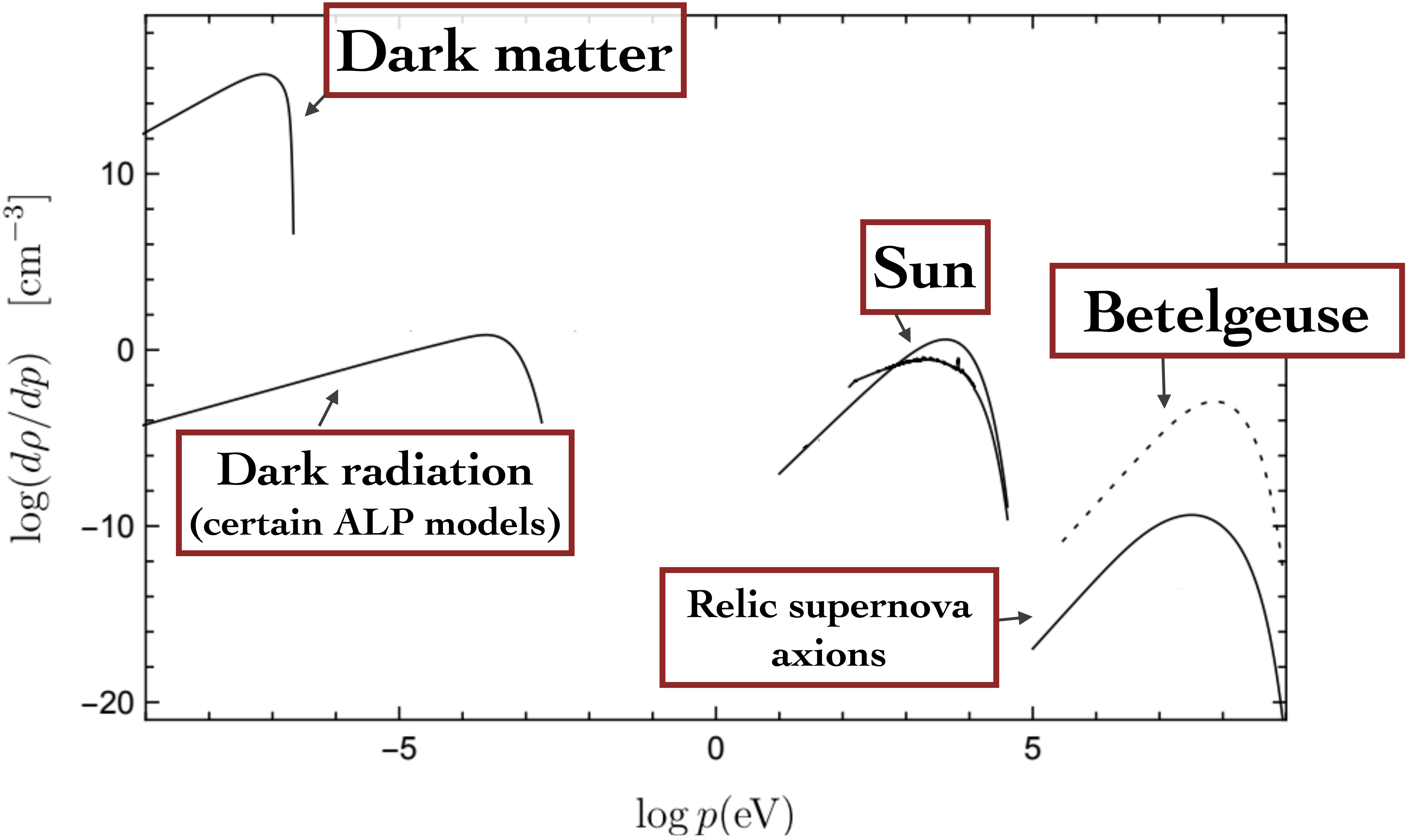
Magnetic field

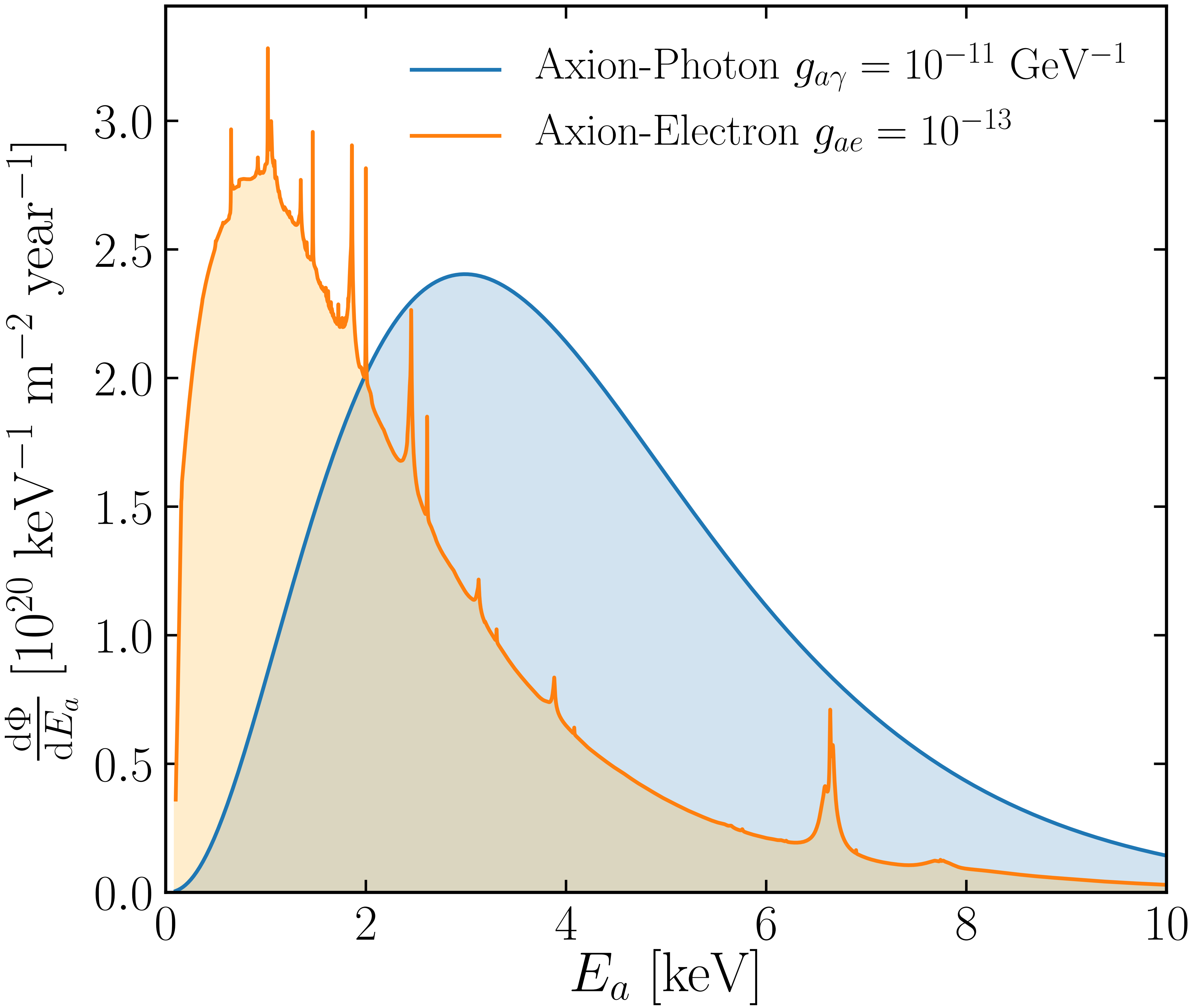
Use a **natural** source of axions interacting with a laboratory magnetic field, and detect the photons

Natural sources of axions



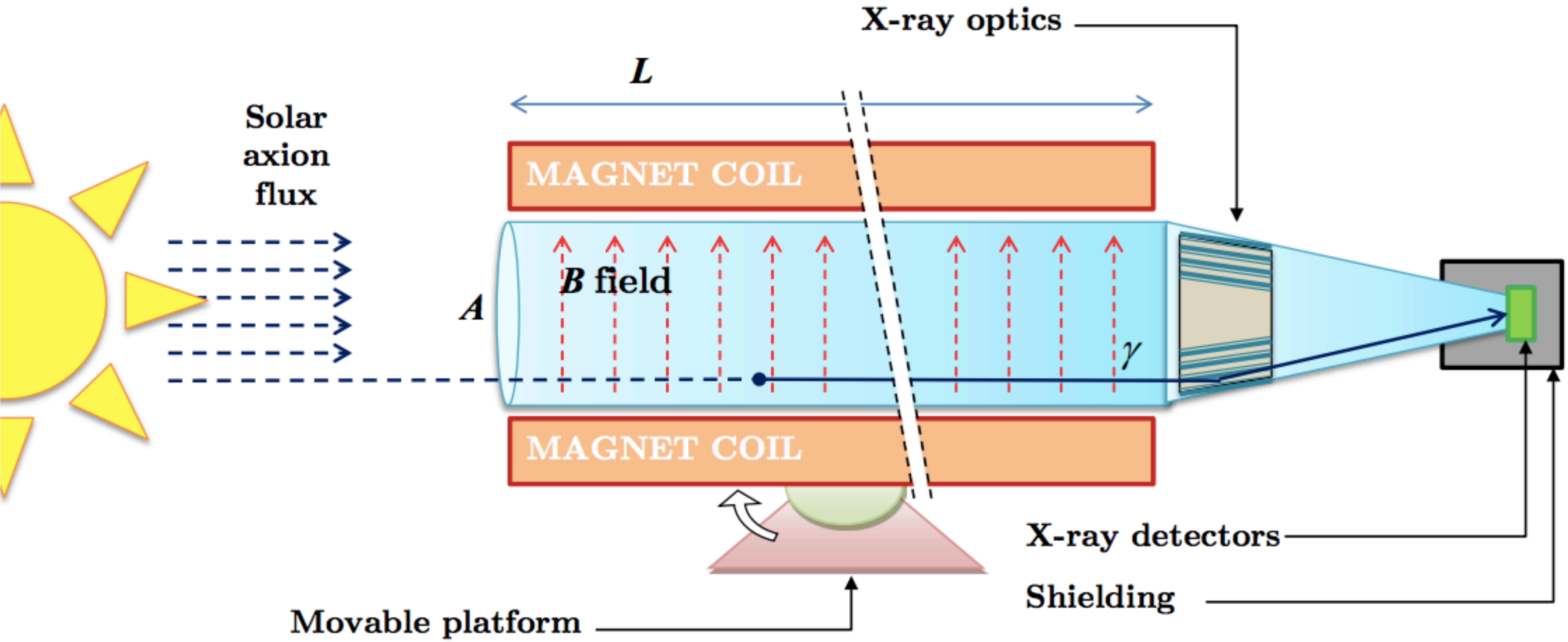
[1801.08127]

If the axion exists then the Sun is an axion factory



Helioscopes

Similar to LSW except the axions are already provided by the Sun at keV energies (X-rays)

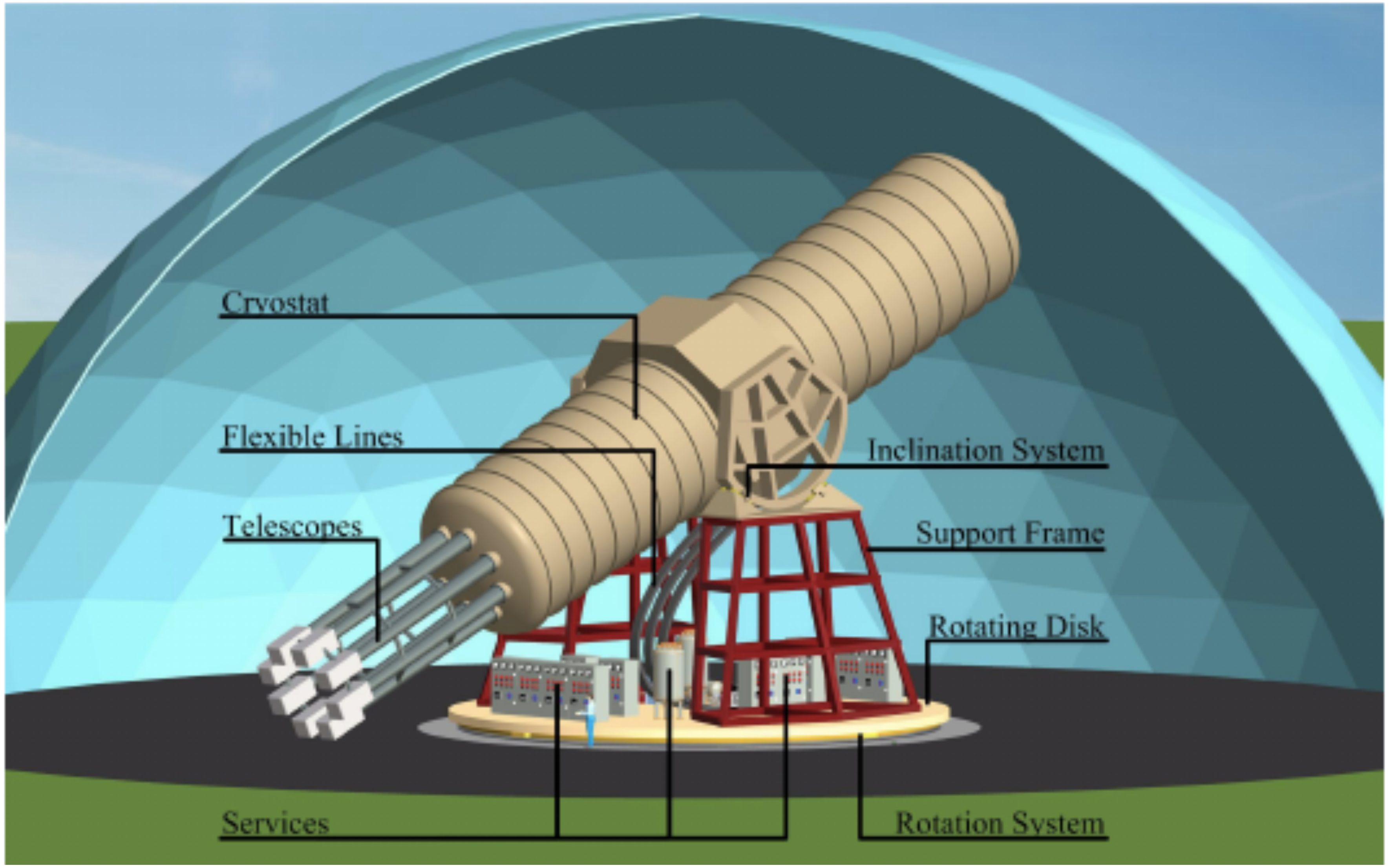


CERN Axion Solar Telescope (CAST)

- Running since 2003 at CERN
- QCD axion sensitivity for $m_a \sim 0.2$ eV

Future: International axion observatory (IAXO)

Like CAST, but bigger:



- 2.5 T field
- 20 m length
- 8 bores of 600 mm
- Rotating platform for Solar tracking

Intermediate step (babyIAXO) already funded

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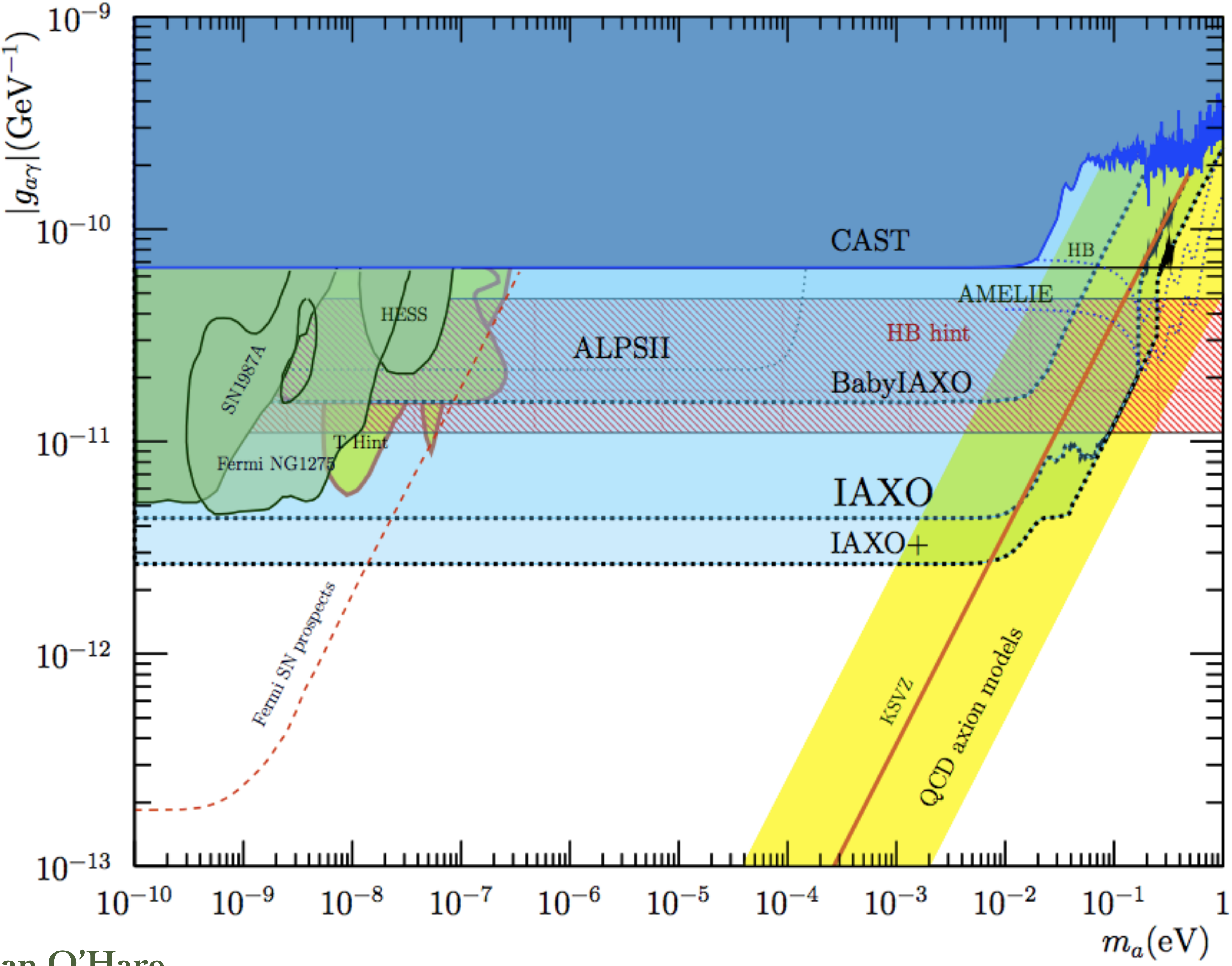
Future of non-DM searches for axions and ALPs



To detect the axion we need to supply one or more of the following:

Source of axions

Photons

Magnetic field

To detect the axion we need to supply one or more of the following:

Source of axions

Photons

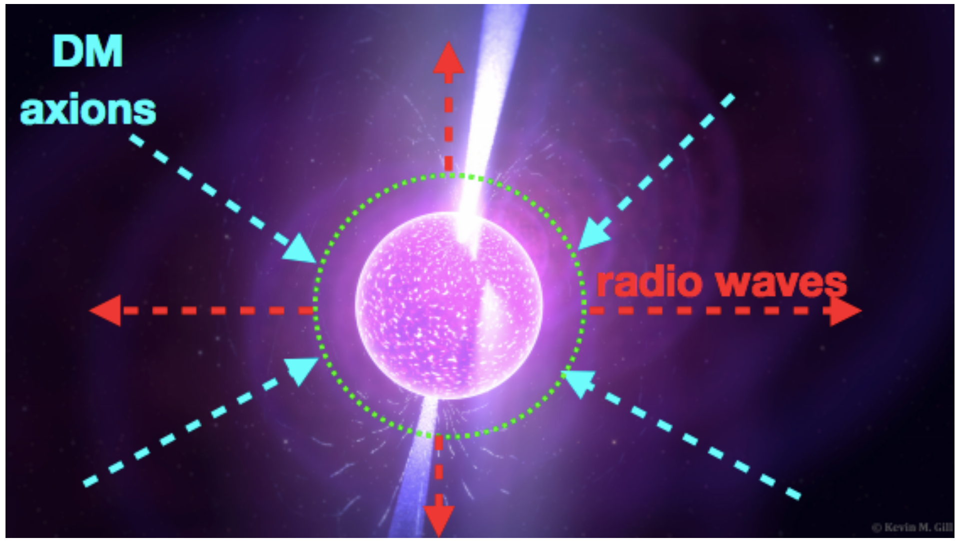
Magnetic field

All of these should already be present in space…

Astrophysical tests of axions

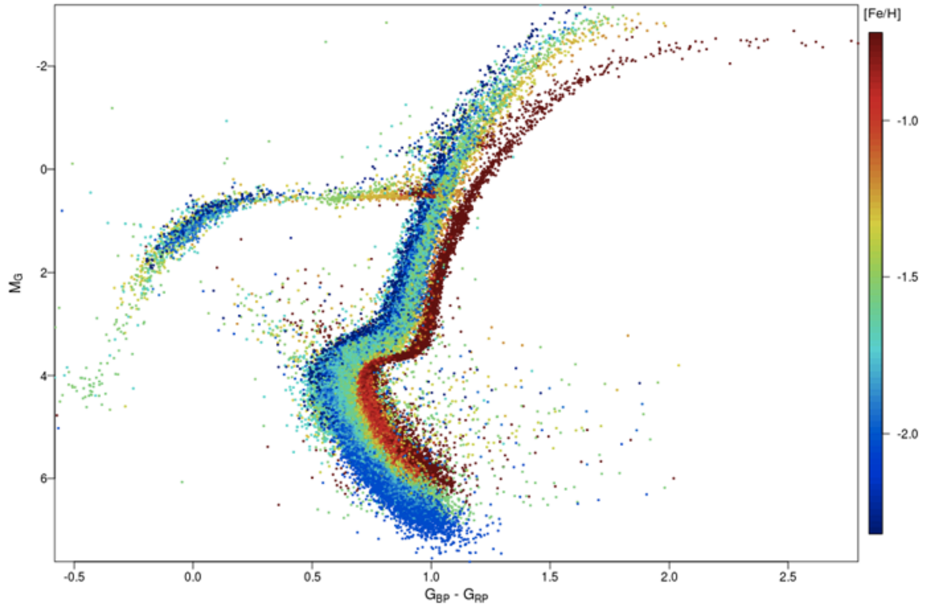
Direct signals

Can be from spontaneous axion decay, or from DM axions converting in strong magnetic fields e.g. radio lines from neutron star magnetospheres



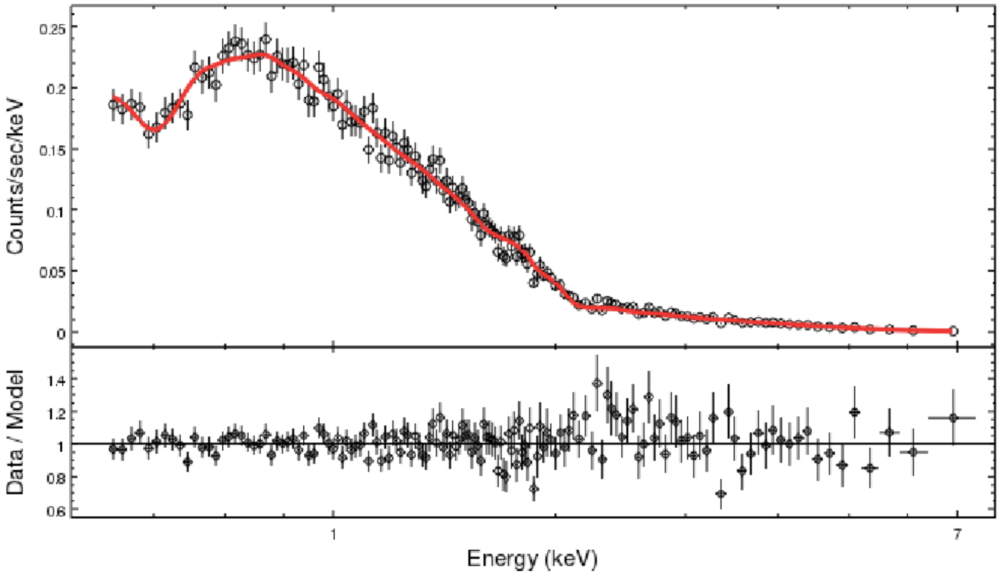
Stellar physics

Axion emission is additional channel for energy loss → impacts stellar lifetimes, emission of neutrinos, supernovae etc.



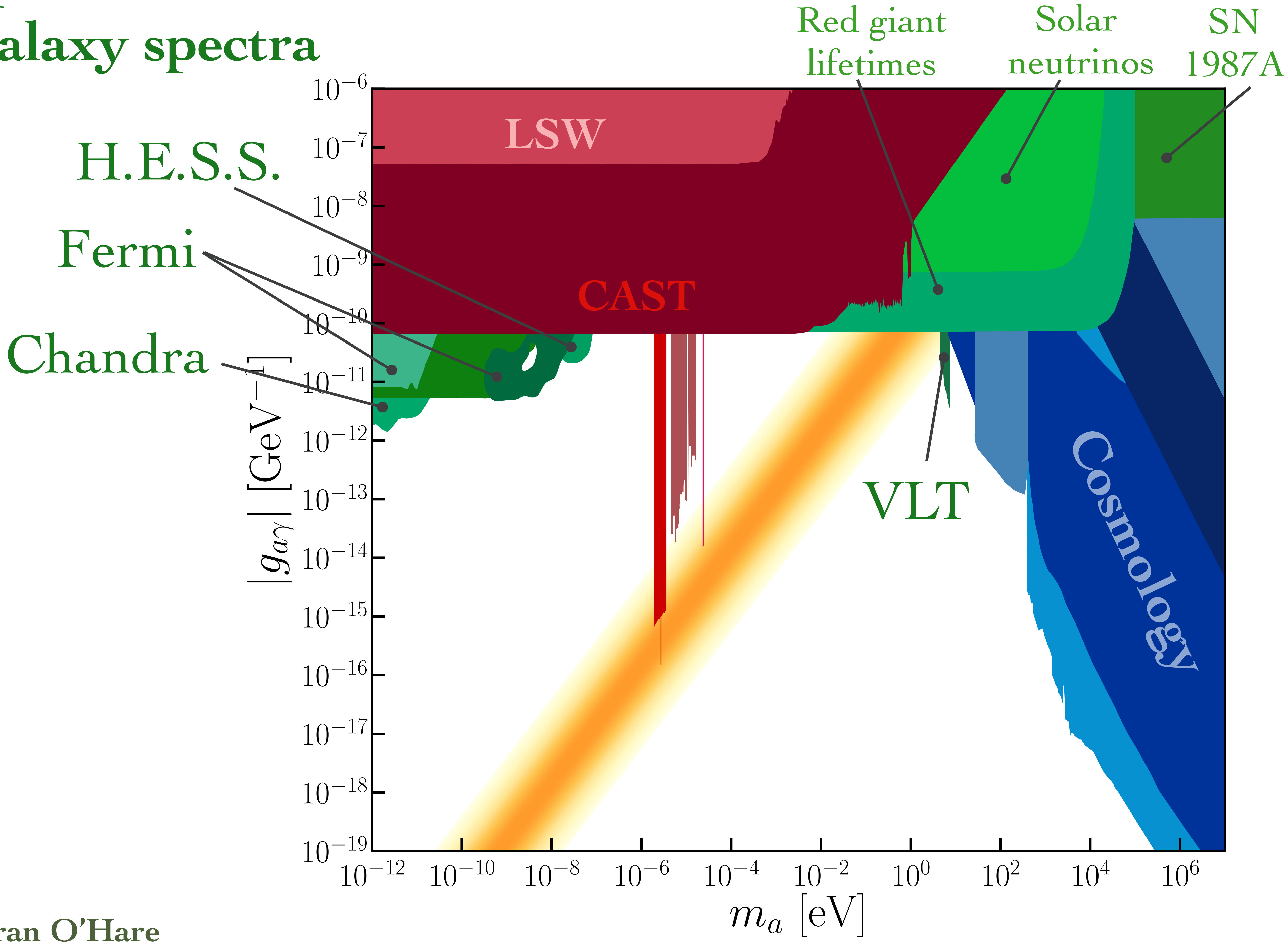
Spectral modulations

Axion-photon interconversion inside turbulent magnetic fields → oscillatory features in galaxy/cluster spectra

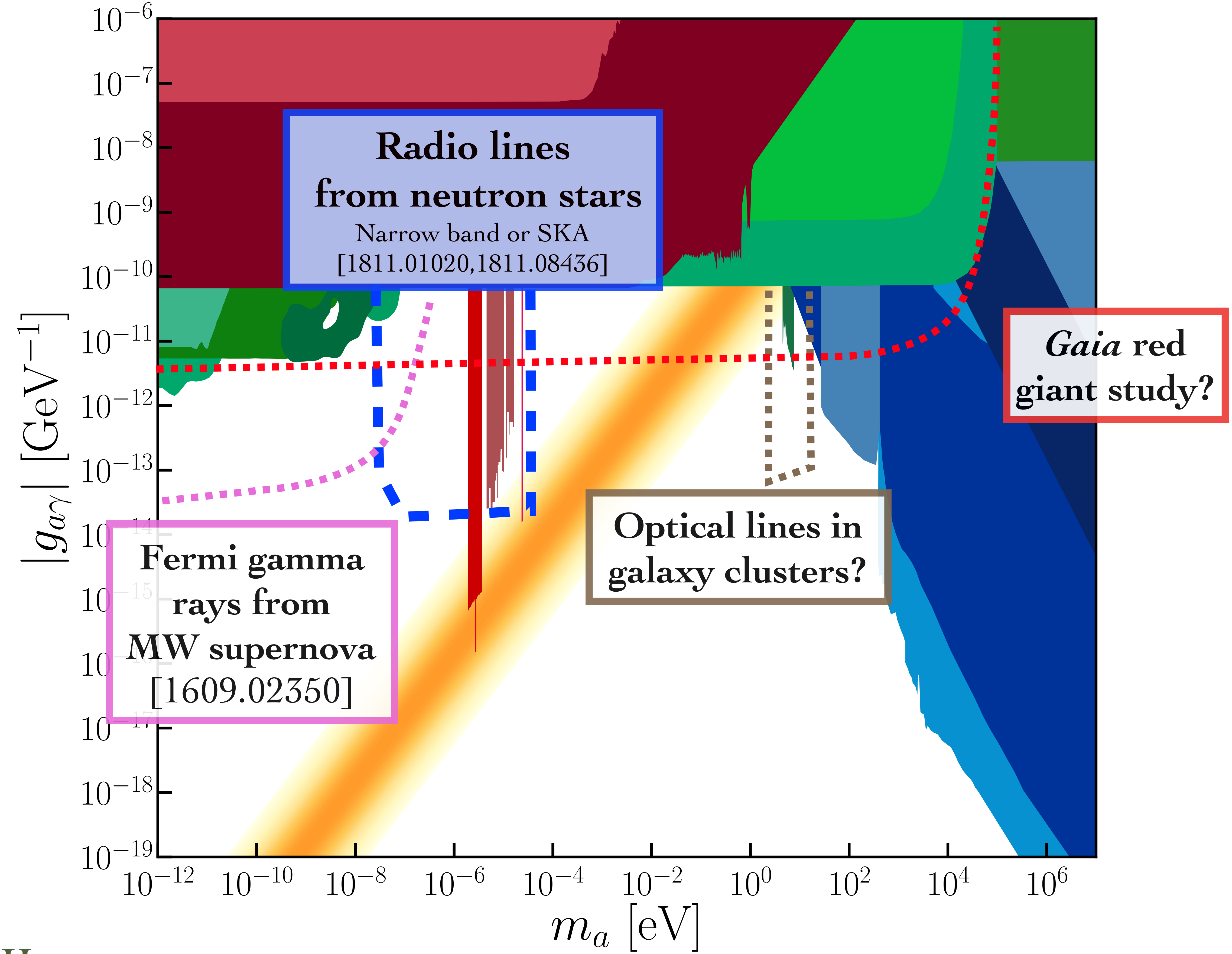


Spectral modulations in Galaxy spectra

Stellar physics constraints



Potential future constraints from astrophysics



Radio lines from neutron stars
Narrow band or SKA
[1811.01020,1811.08436]

Fermi gamma rays from MW supernova
[1609.02350]

Optical lines in galaxy clusters?

***Gaia* red giant study?**

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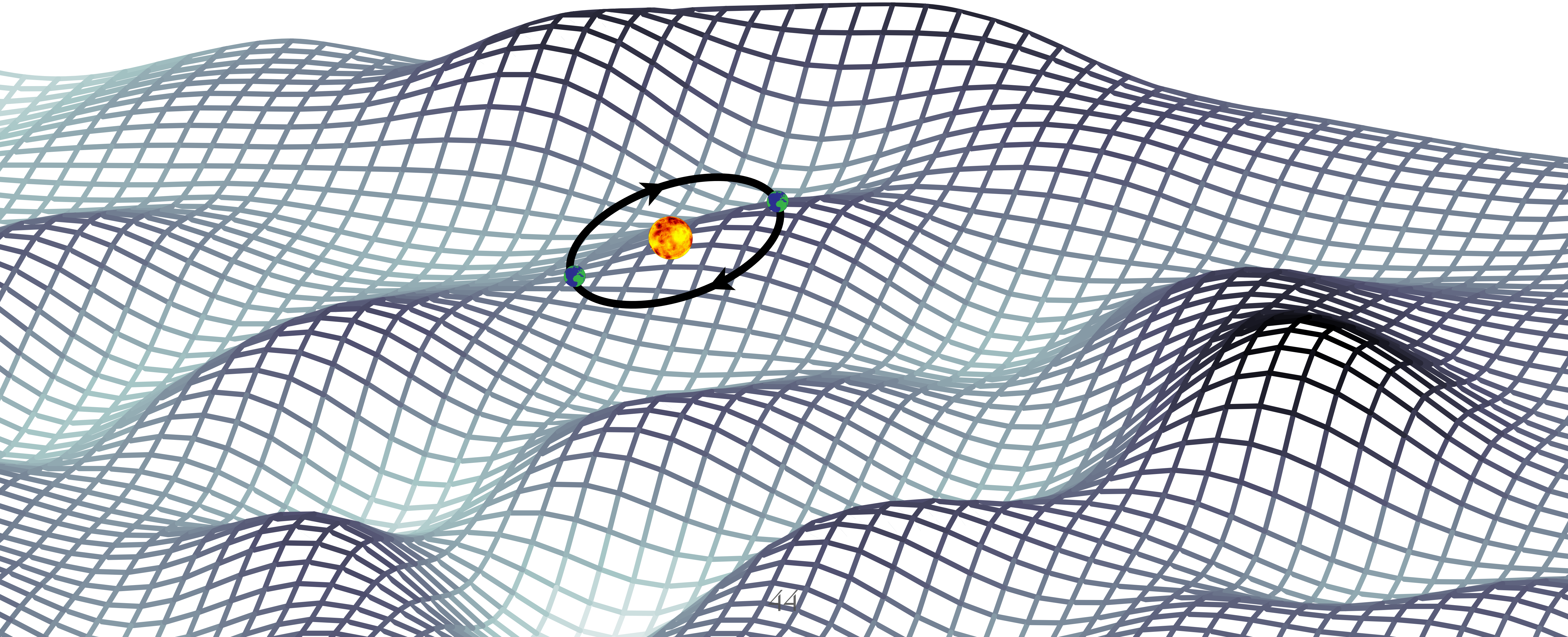
If the axion is DM…

It is so light, that must have macroscopic (huge) occupation numbers to make up local dark matter density ~ 0.5 GeV cm^{-3}

→ Describe as a classical field

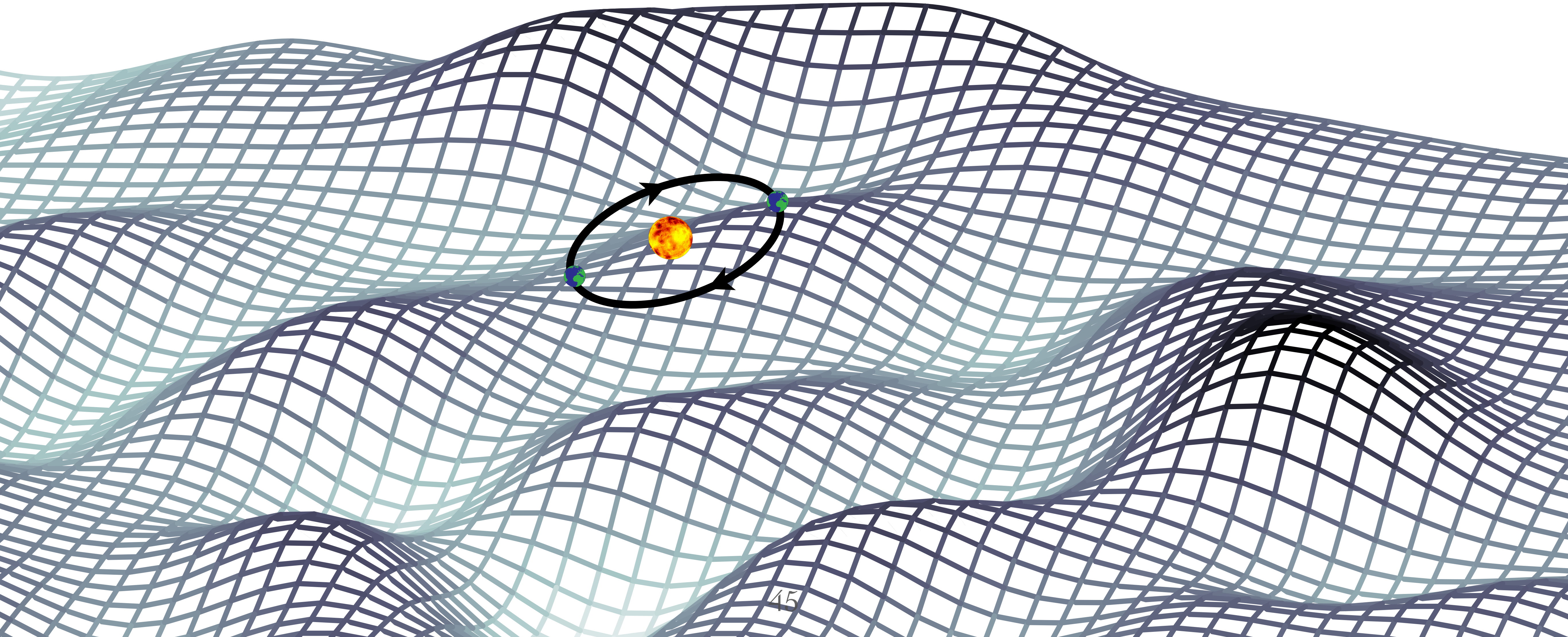


DM axion field:

$$a(\mathbf{x}, t) \approx \frac{\sqrt{2\rho_a}}{m_a} \cos\left(\omega t - \mathbf{p} \cdot \mathbf{x} + \alpha\right)$$

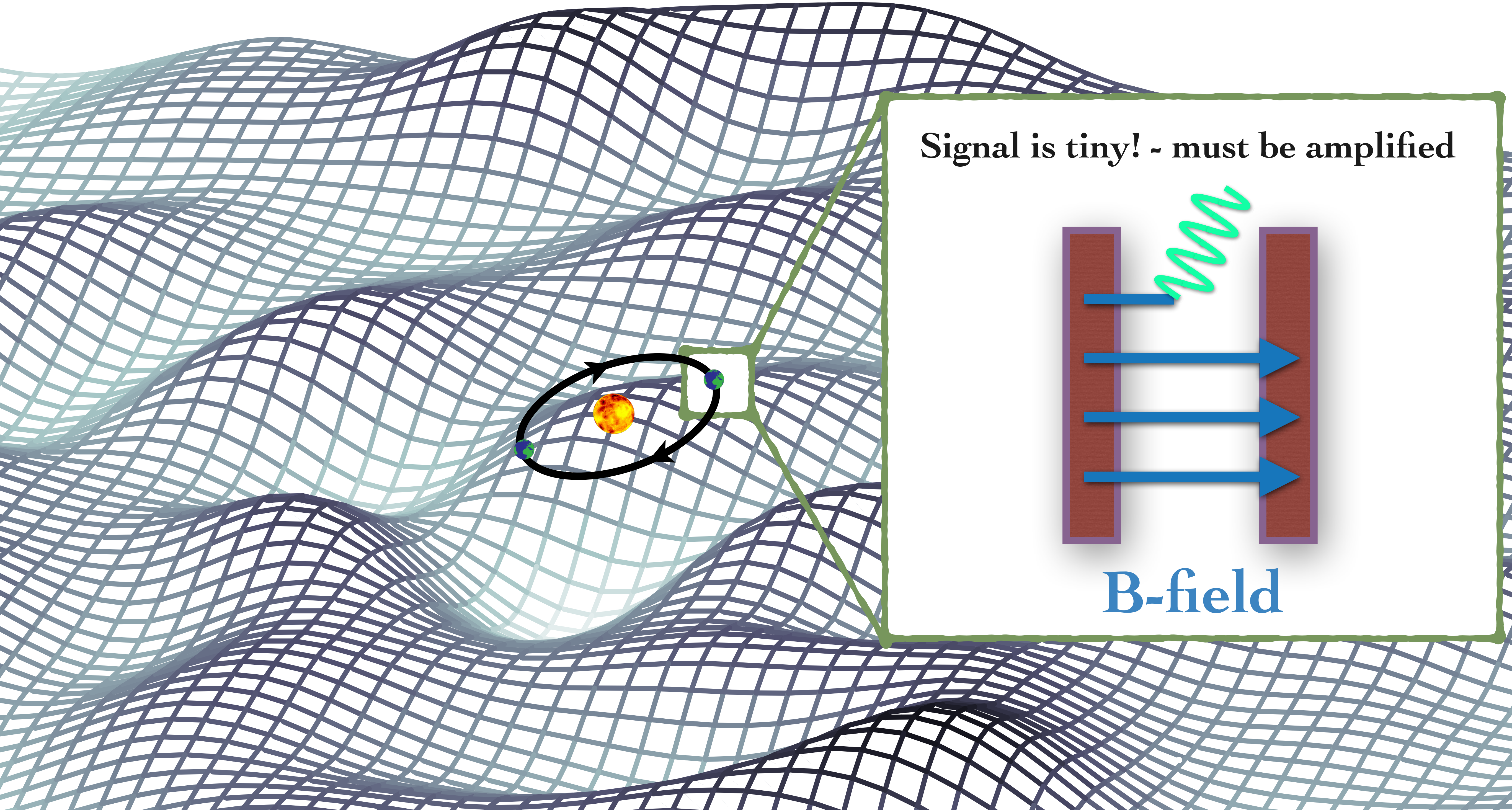
$\omega \approx m_a$

Oscillating at the axion mass



$$\omega \approx m_a$$

Searching for DM axions
→ "tune in" to EM signal oscillating at $\sim m_a$



Haloscopes

What want to apply a field B0 to the DM axion field a

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

1. Axion-induced magnetic field

2. Axion-induced electric field

3. Oscillating axion field

Haloscopes

What want to apply a field B0 to the DM axion field a

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

1. Axion-induced magnetic field

2. Axion-induced electric field

3. Oscillating axion field

What kind of experiment do we need?

→ Depends on the axion Compton wavelength (i.e. 1/mass) relative to the size of a "manageable" experiment, let's say O(metres)

Haloscopes

Light axions: Compton wavelength long relative to experiment. Axion acts as an effective current → detect induced B-field

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

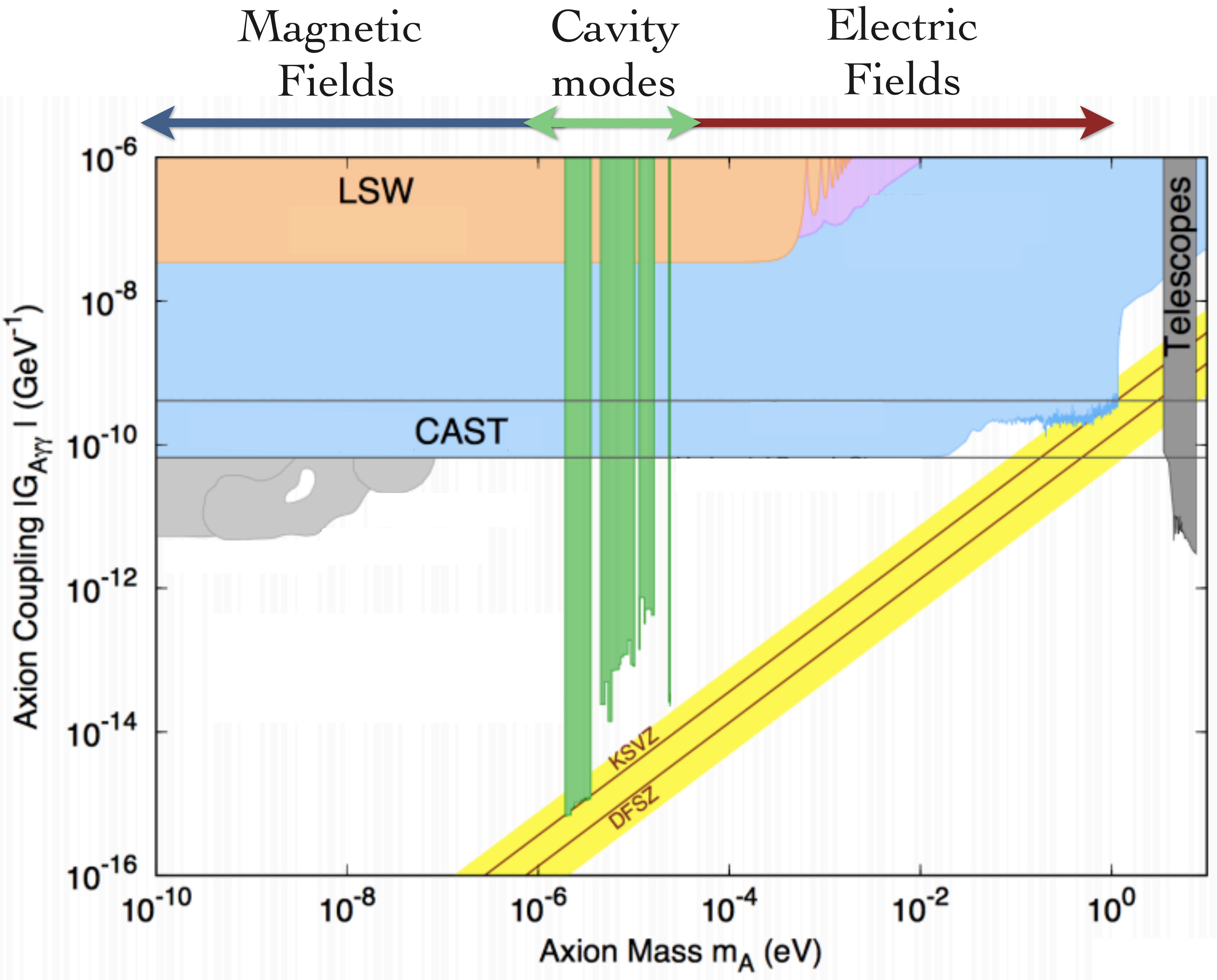
Med. axions: Compton wavelength similar scale to experiment. Axion induces oscillating EM-field → couple to a cavity mode

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

Heavy axions: Compton wavelength short relative to experiment. Axion generates radiation → arrange experiment to have constructive interference

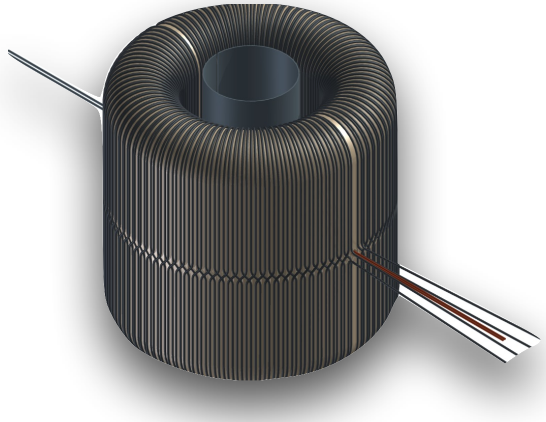
$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Haloscopes: how to probe different masses



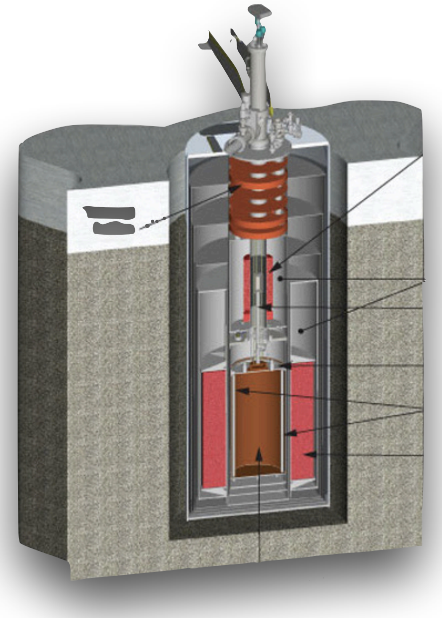
Haloscopes (basic ideas)

Magnetic fields → ABRACADBRA



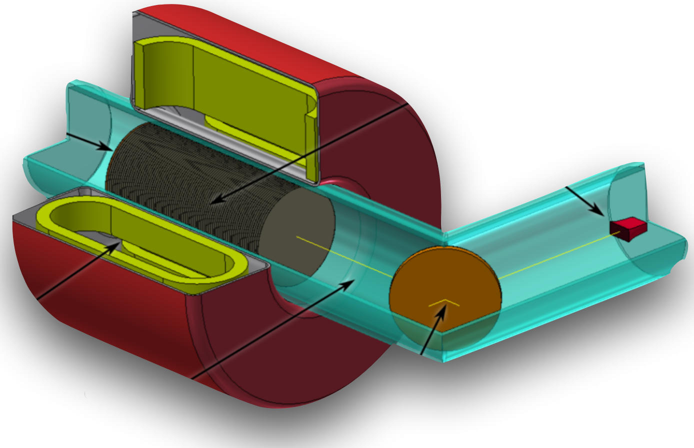
Toroidal magnet
→ axion induces B-field in centre of toroid where there should be 0 field, pick up with a SQUID magnetometer

Cavity modes → ADMX



Tunable resonant cavity
→ Detect enhanced EM-response when resonant mode is tuned precisely to axion mass

Electric fields → MADMAX



Series of dielectric disks
→ Radiation generated at magnetised dielectric interfaces, arrange series of dielectric layers to constructively interfere radiation

Ciaran O'Hare

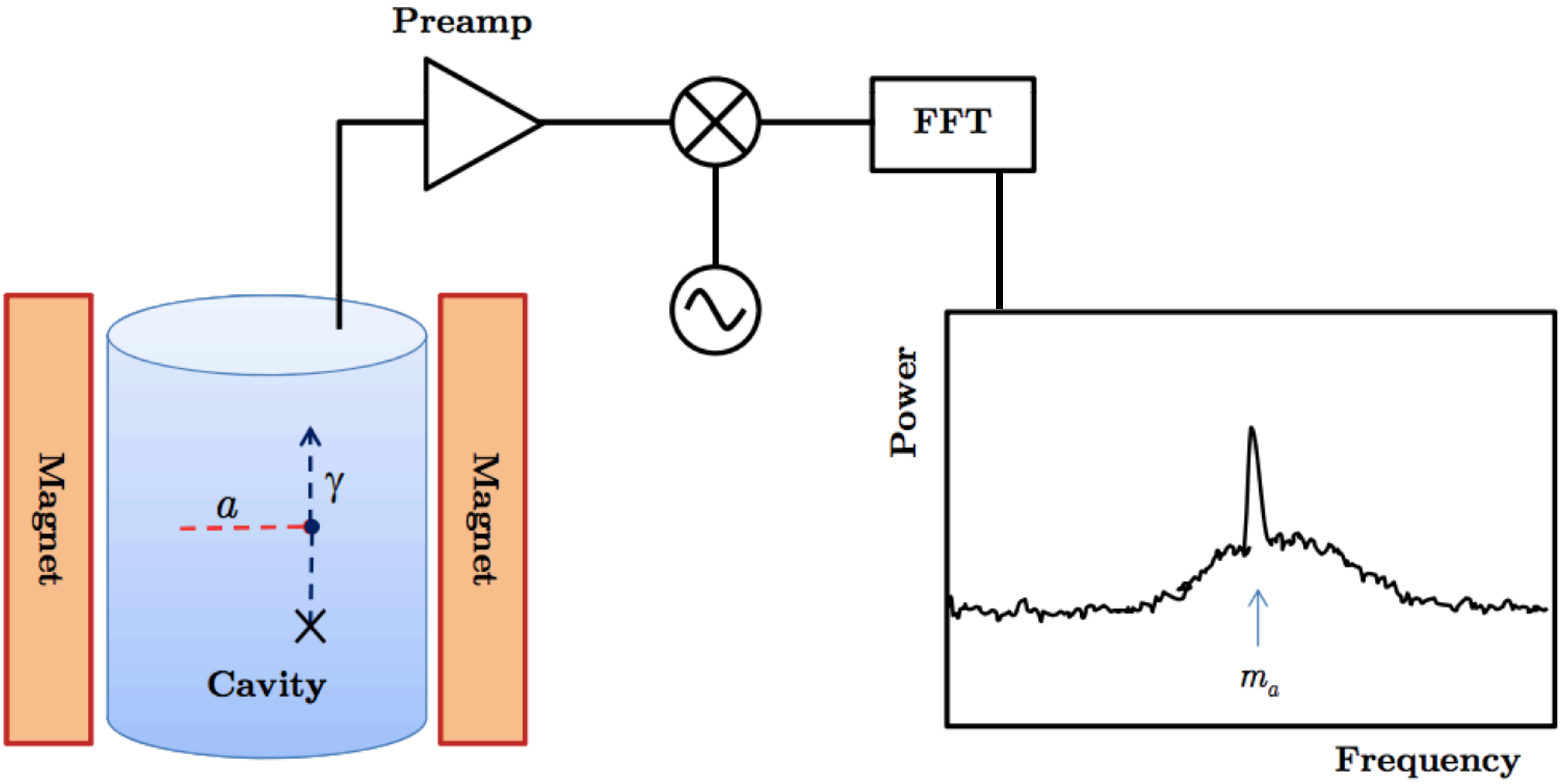
+many more I haven't mentioned

ADMX

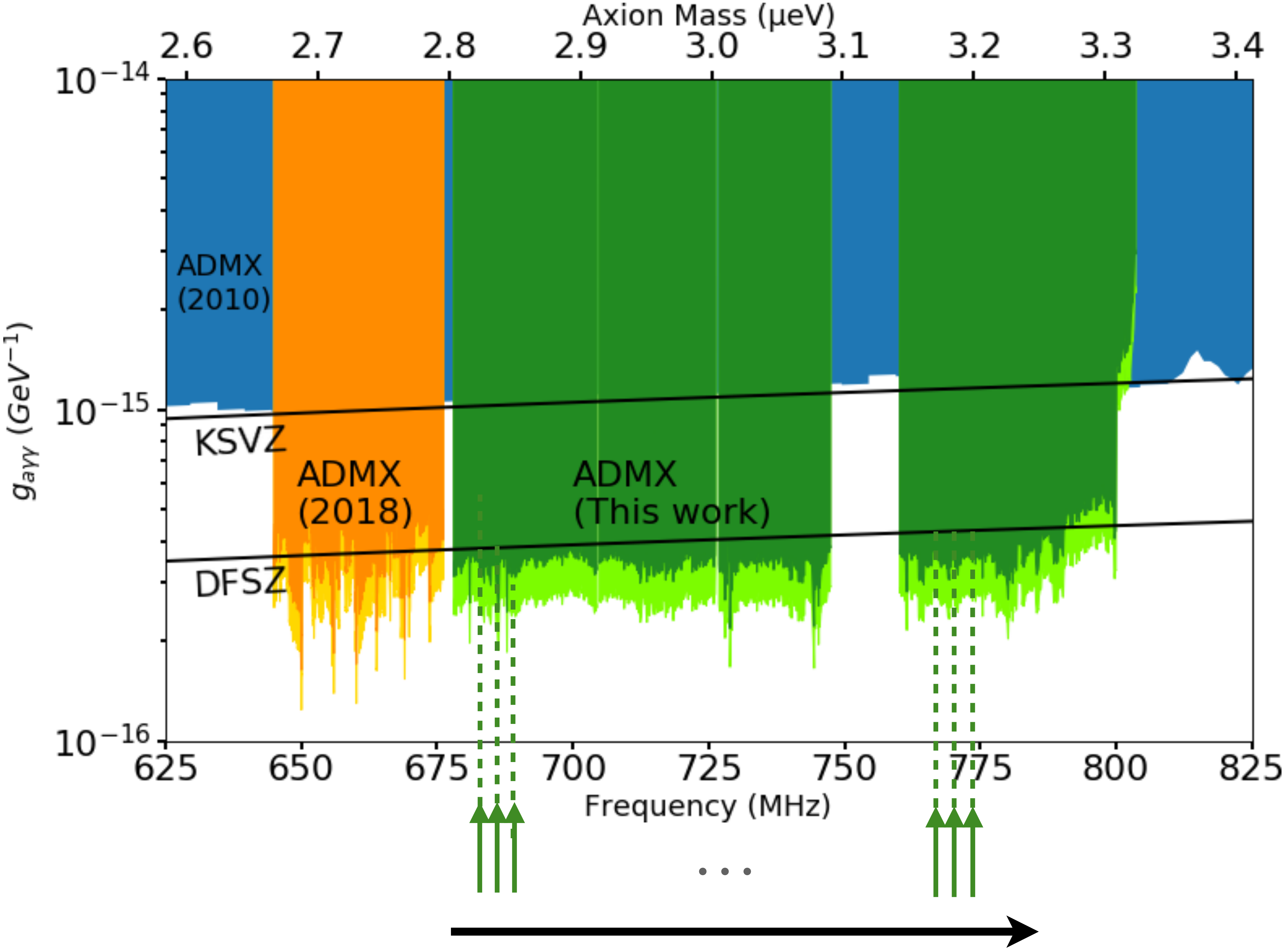
- Formed from several smaller collabs. started in the 80s
- Still the most sensitive of all haloscopes (for many years it was the only one)
- Targets the "Classic" QCD axion window ~ μeV
- B-field ~ 8 T
- Microwave cavity, $Q \sim 10^5$

Expected power for QCD axion ~ 10^{-22} W!

Resonant cavity haloscope: search for a sharp peak at the axion mass

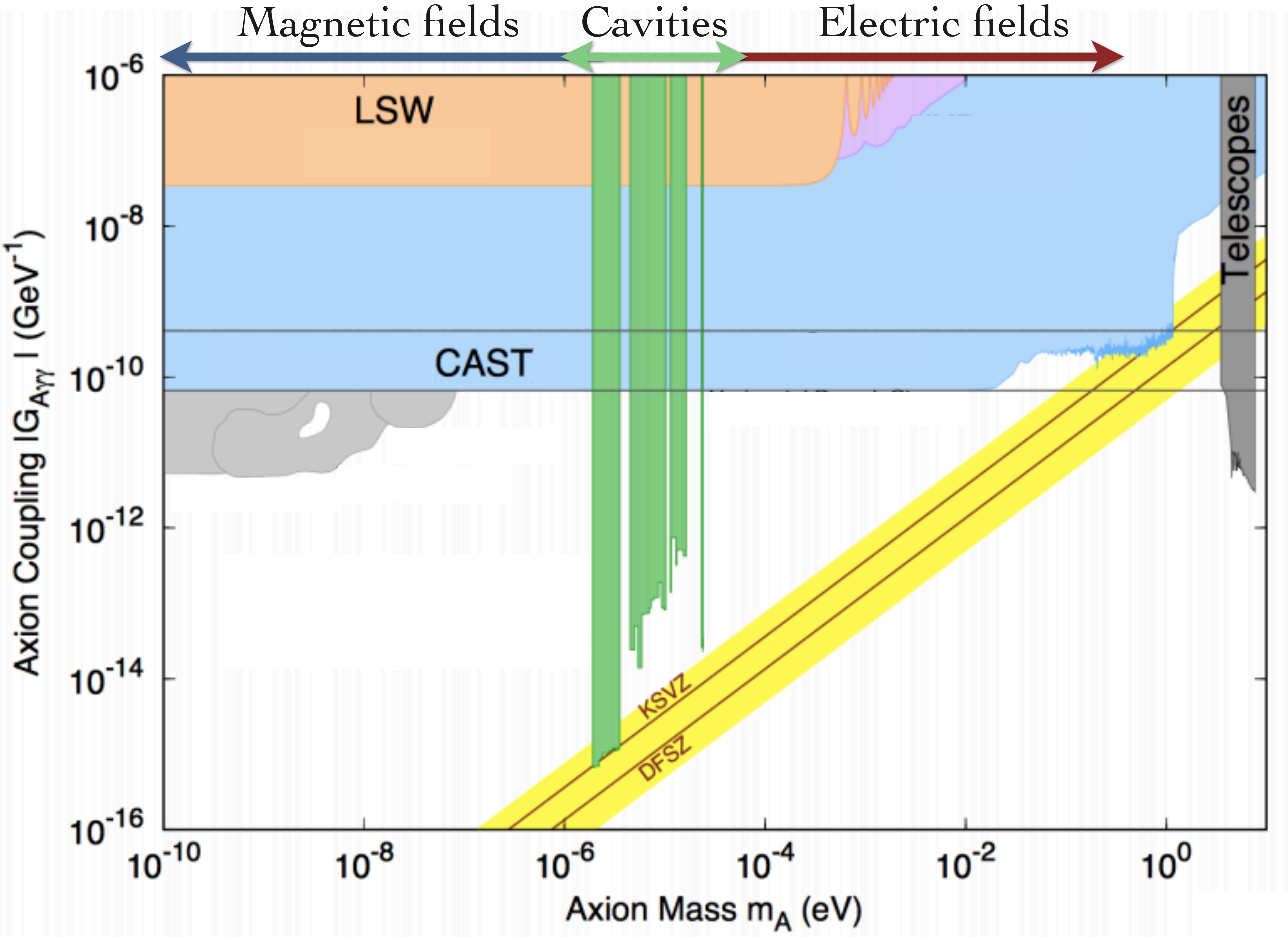


[1910.08638]

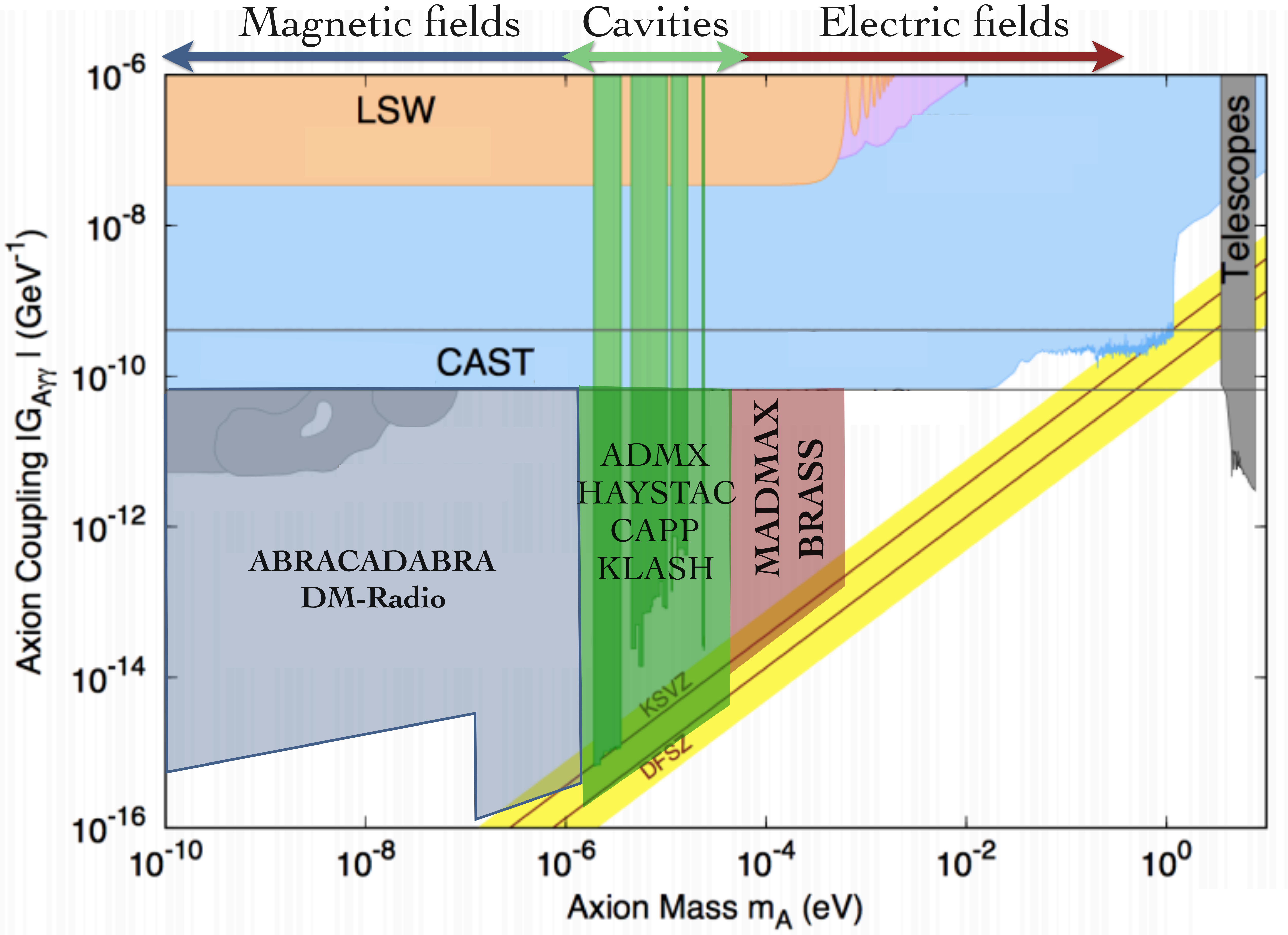


Scan over frequency, takes many days

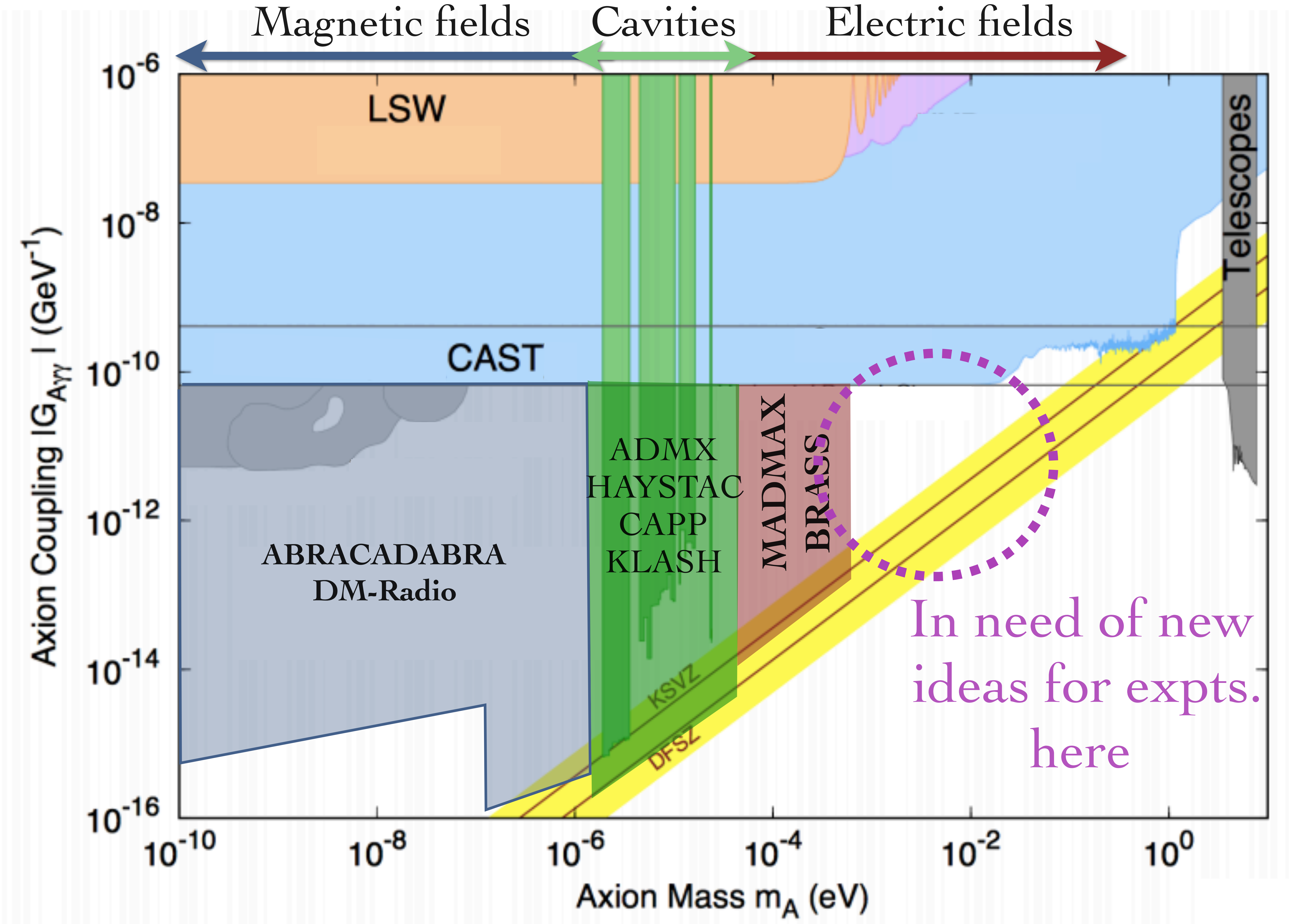
Future constraints



Future constraints



Future constraints



In need of new ideas for expts. here

Dark matter is hard to detect

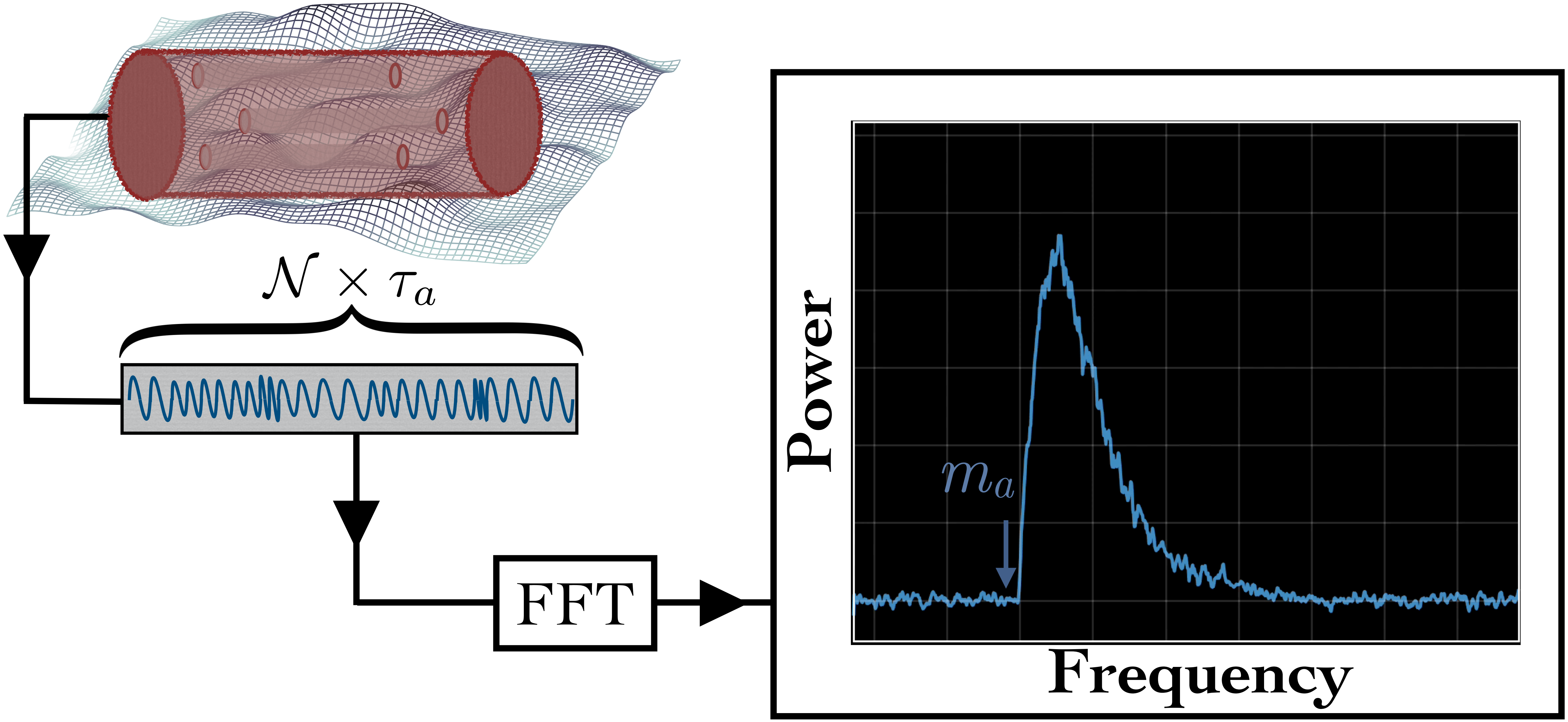
But why specifically for the axion?

If a haloscope is **resonant**, sensitivity is limited because the axion lineshape is so narrow ($Q{\sim}10^6$). Must spend significant effort to scan over just a small mass range

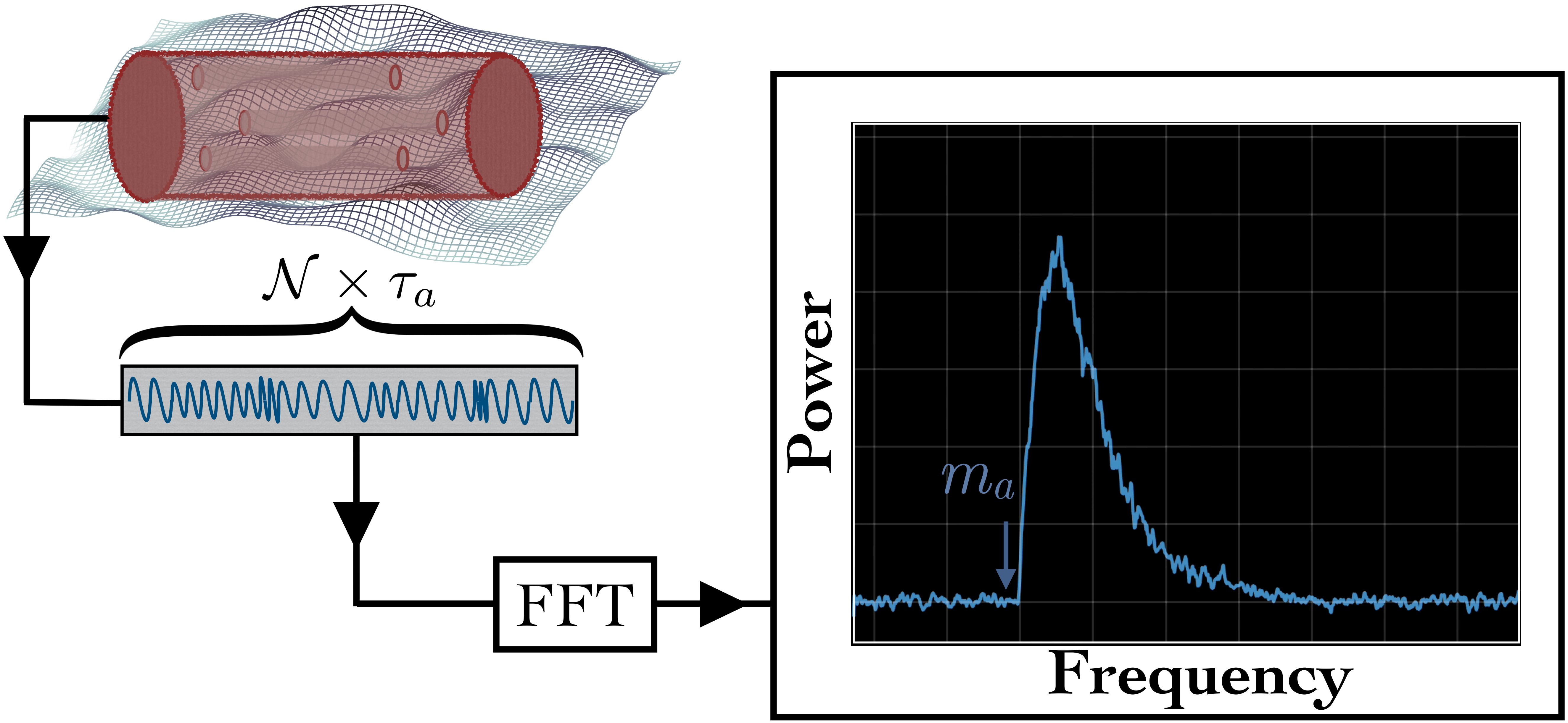
If experiment is **broadband** then a wide mass range is covered, but the signal is not resonantly enhanced, very hard to overcome such small couplings.

But everything changes once we know the right frequency…

Once we know the right frequency to resonate at, the experiment can just sit there and detect the axion for the rest of time…

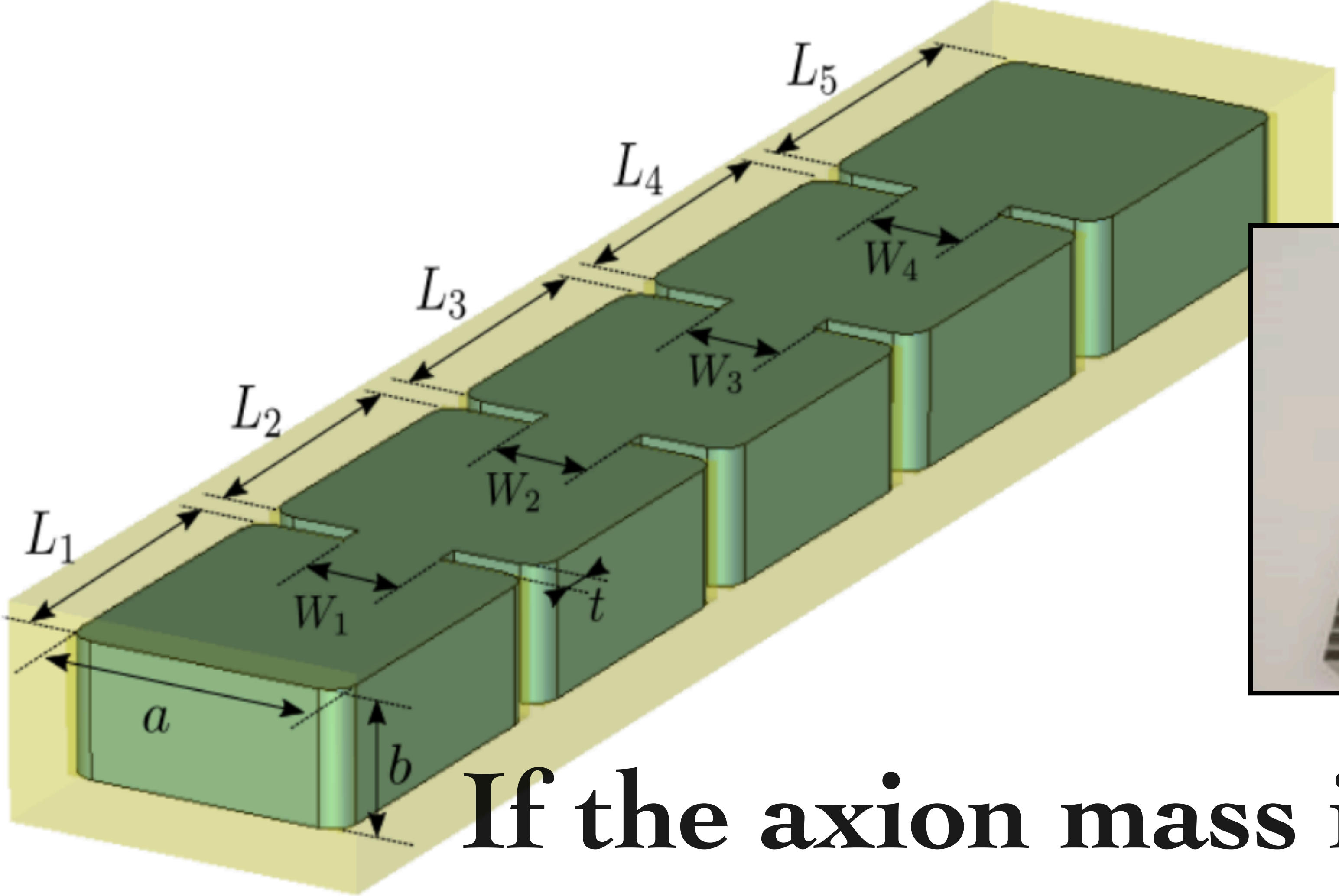


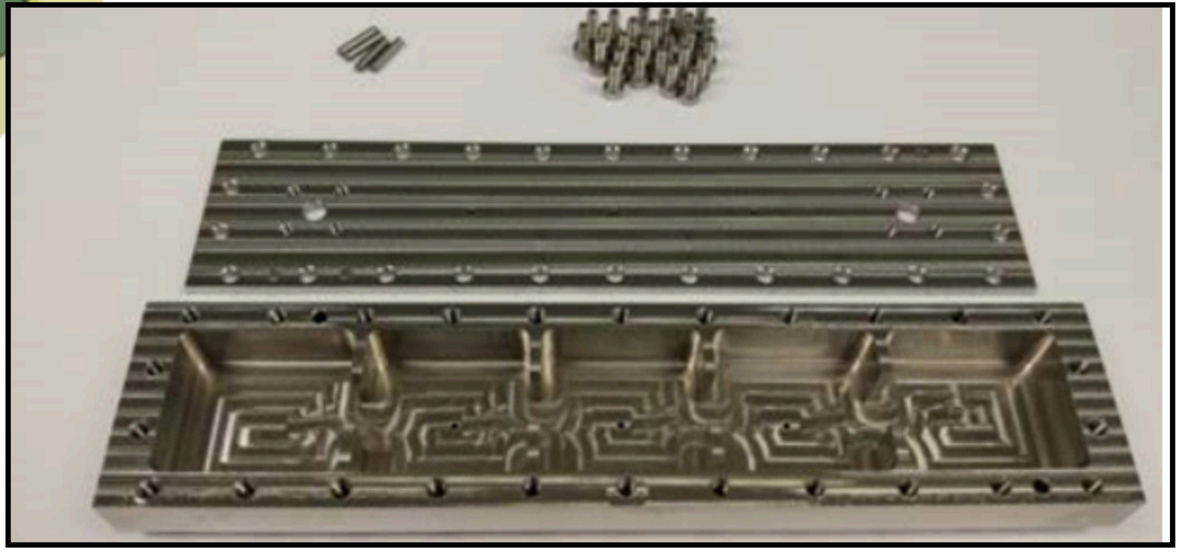
Once we know the right frequency to resonate at, the experiment can just sit there and detect the axion for the rest of time…



RADES

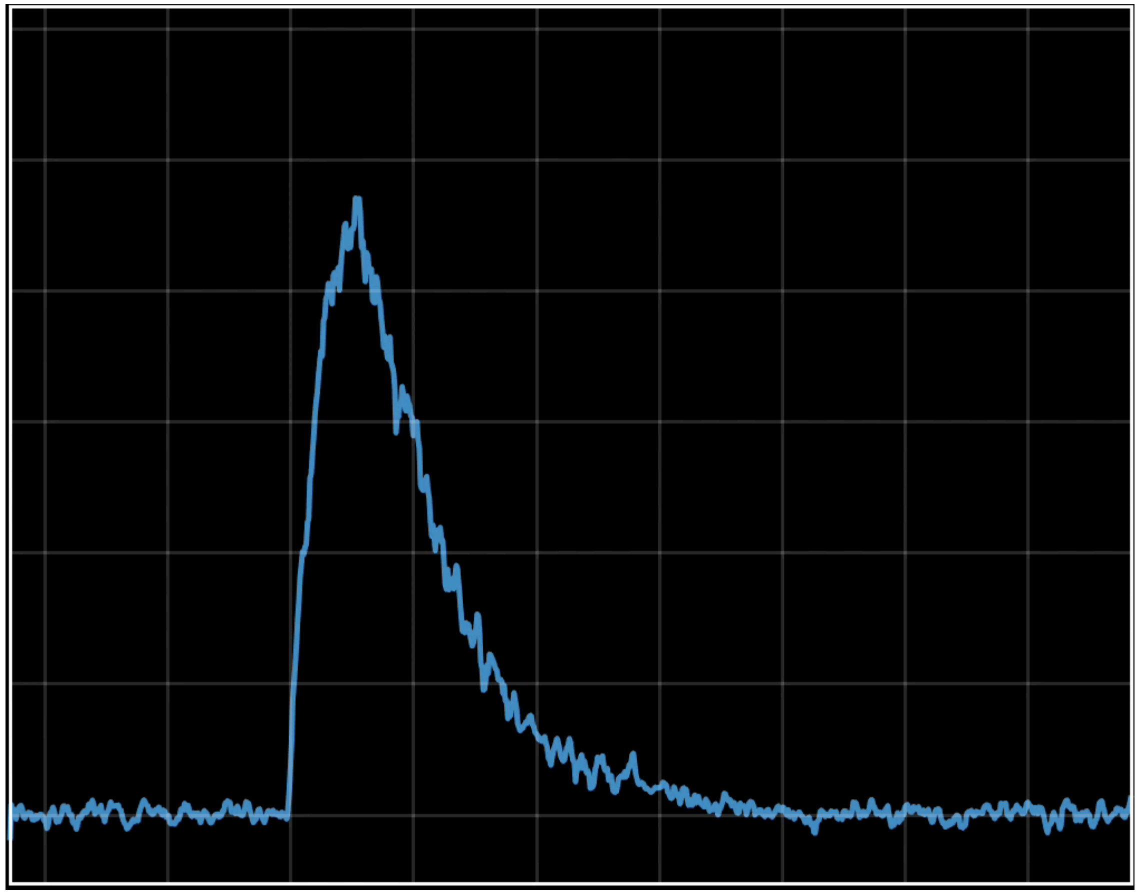
- Cavity designed to resonate at one frequency only
- Entire device is simply placed inside the magnet at CERN that CAST is already using [2002.07639]





If the axion mass is exactly 34.64 μeV this experiment would reach QCD sensitivity in ~20 weeks

Once the axion is detected the lineshape can be studied in incredible detail:



Axion-photon power spectrum

$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_a g_{a\gamma}^2}{m_a^2} f(v)$$

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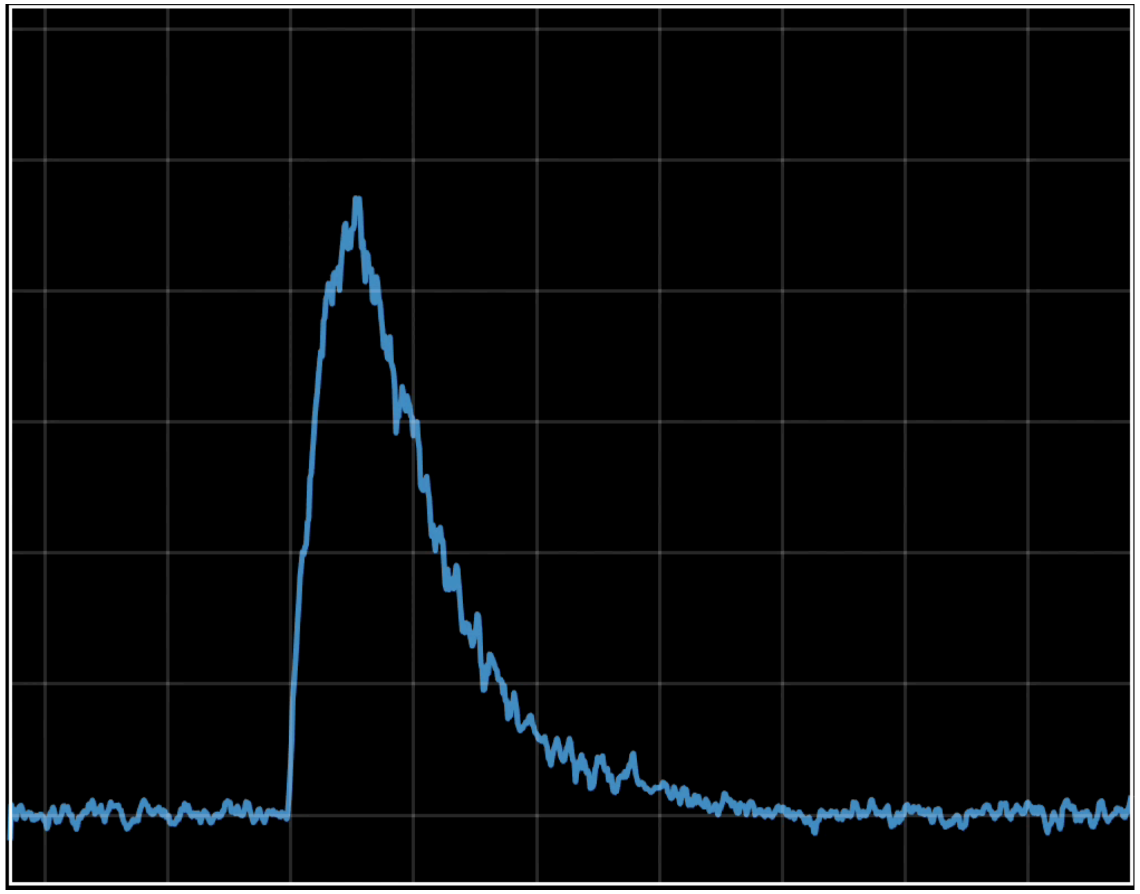

Axion-photon
power spectrum

$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_a g_{a\gamma}^2}{m_a^2} \boxed{f(v)}$$

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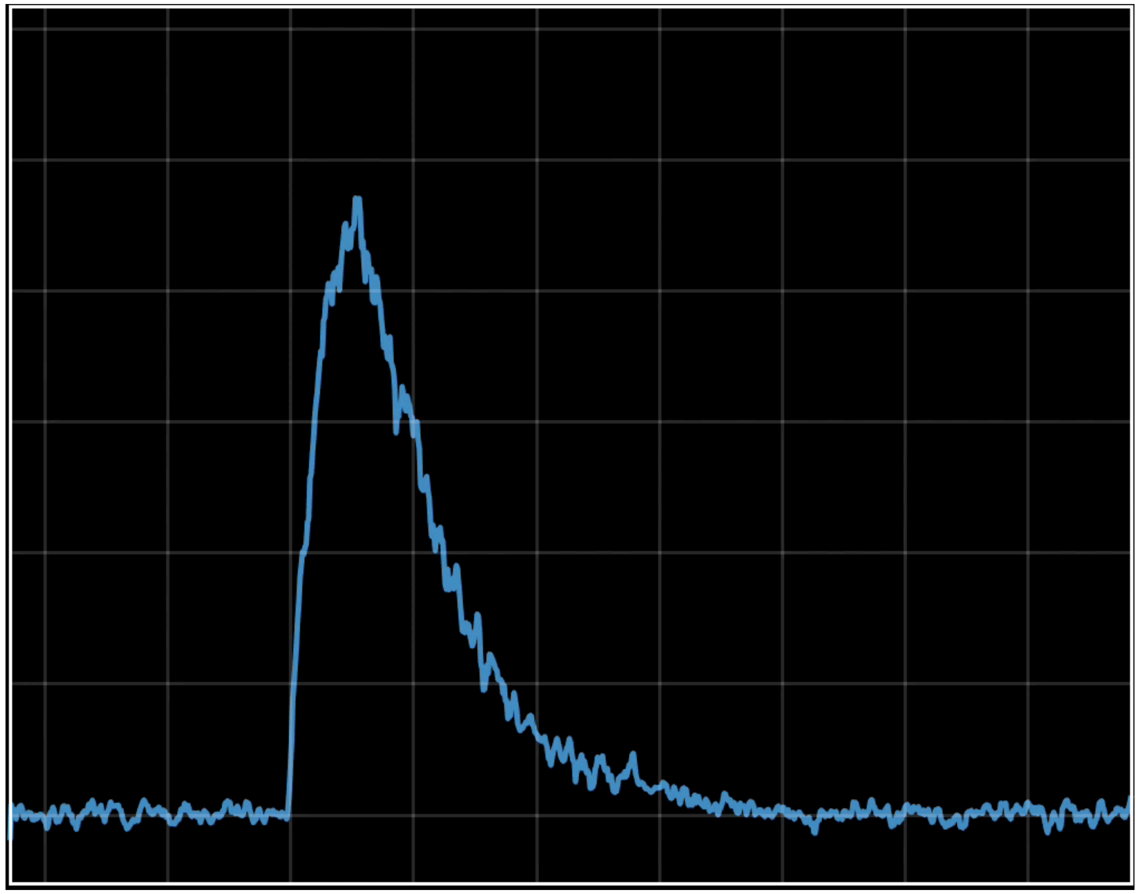


Axion-photon power spectrum

$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_a g_{a\gamma}^2}{m_a^2} \boxed{f(v)}$$

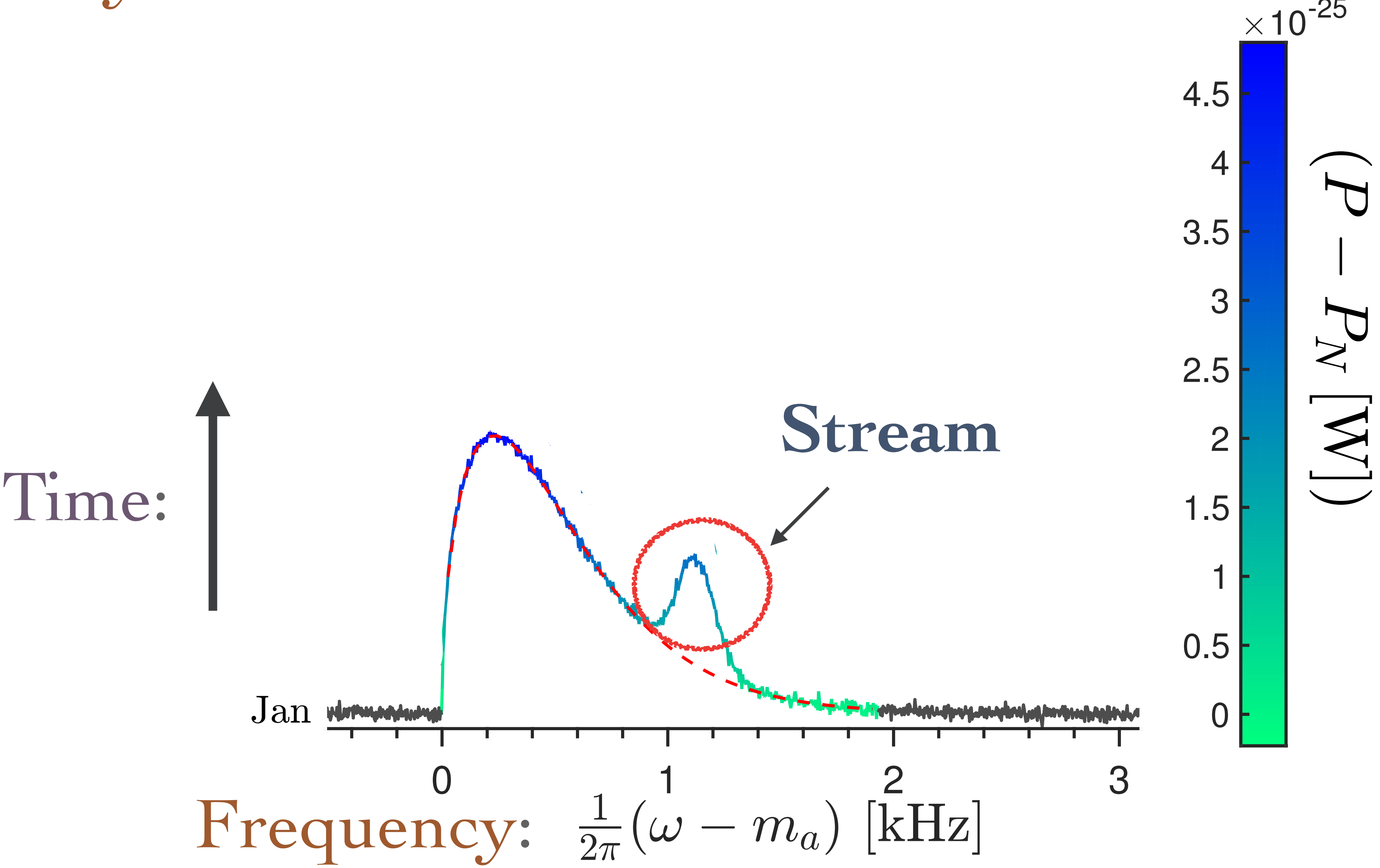
Shape of the lineshape controlled by speed distribution of DM in the galaxy, $f(v)$

→ A relatively tiny device could probe the structure of the Milky Way halo!

Axion haloscope:

Signal power
vs time
vs frequency

[1807.09004]



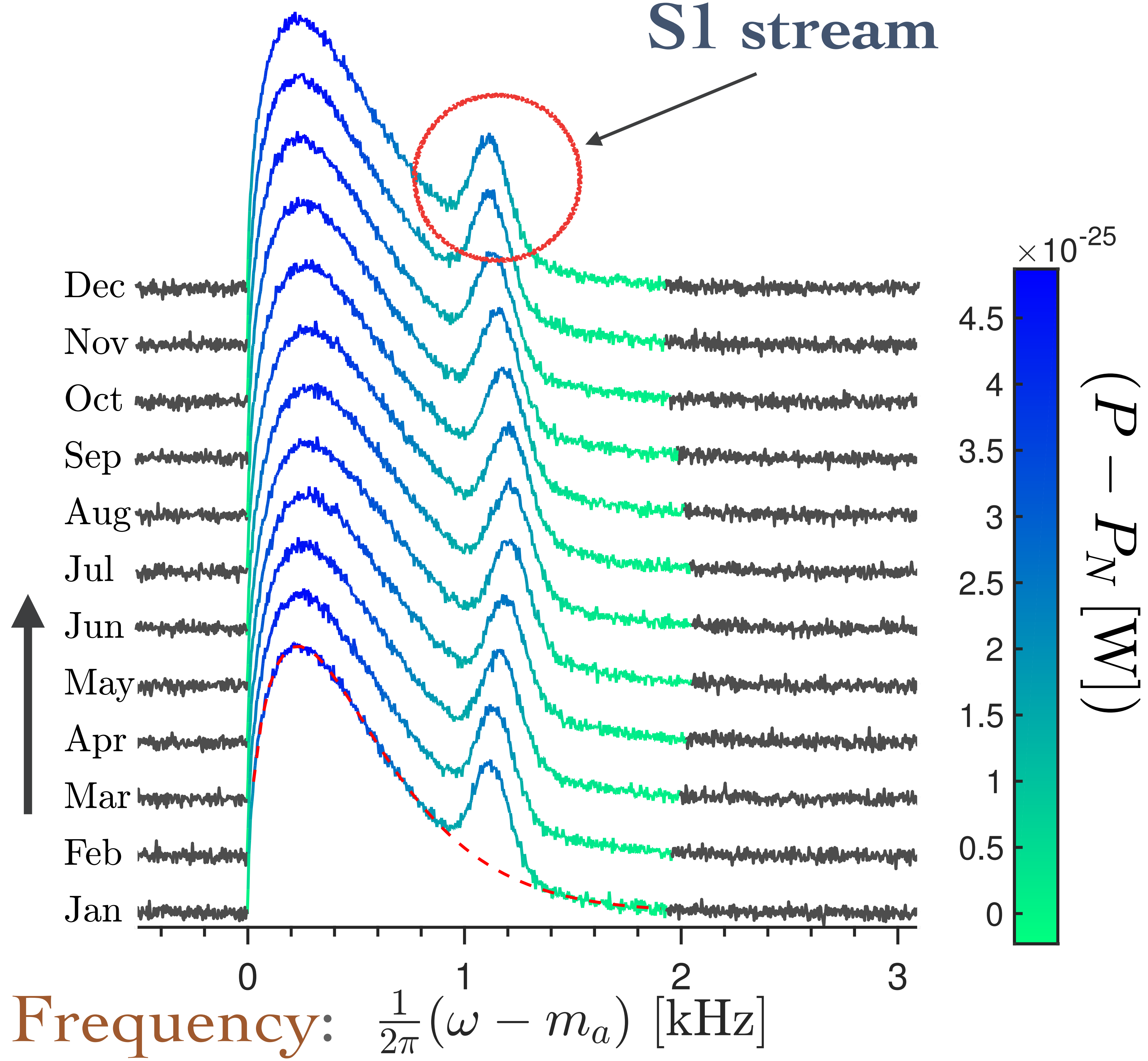
Axion haloscope:

Signal power

vs time

vs frequency

[1807.09004]



Wobble in frequency due to Earth's motion

Conservative summary

The axion is definitely dark matter

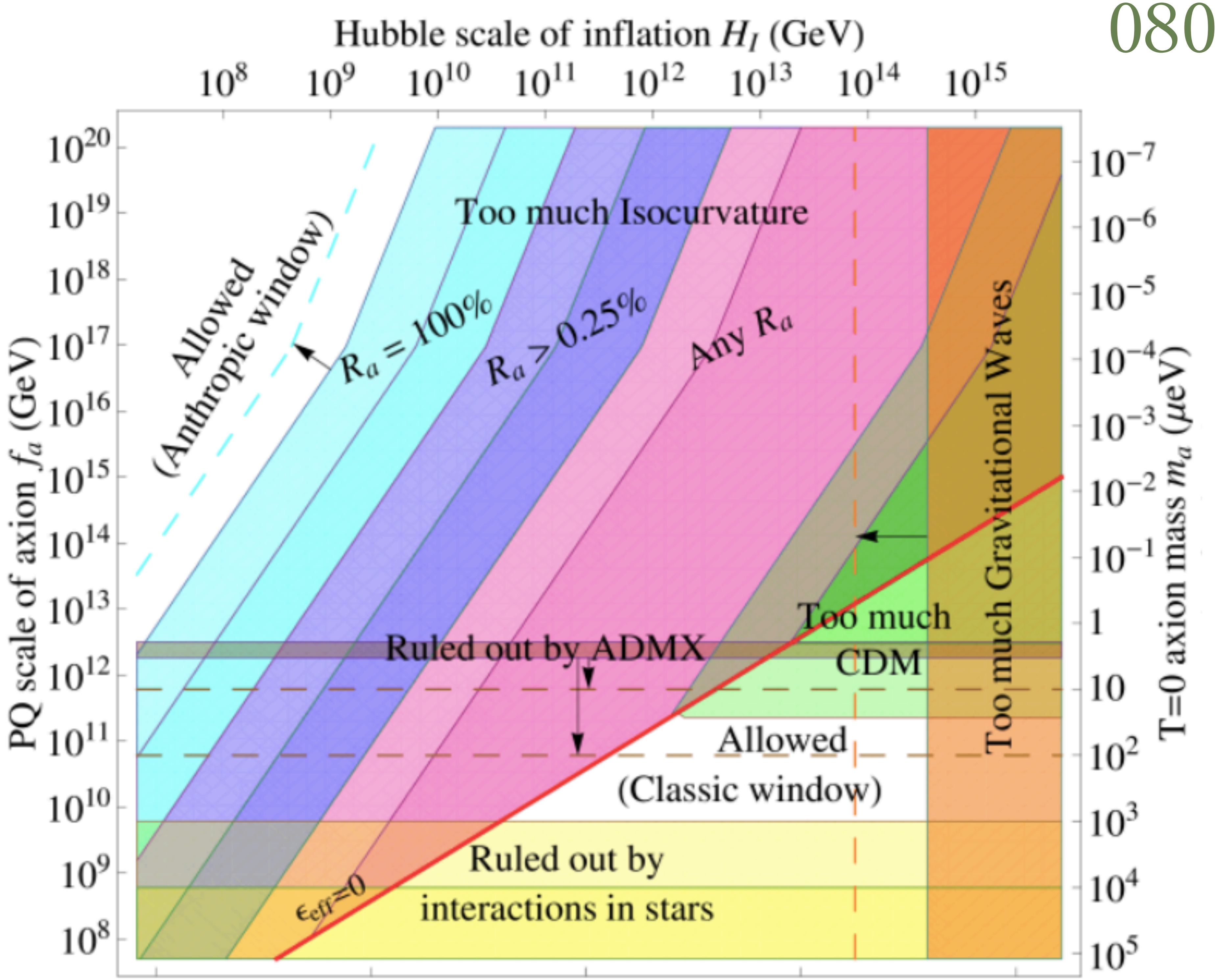
It has a mass of 25 μeV

We will find it within next ~10 years

We will soon be using the axion as a messenger of the formation of the Milky Way galaxy

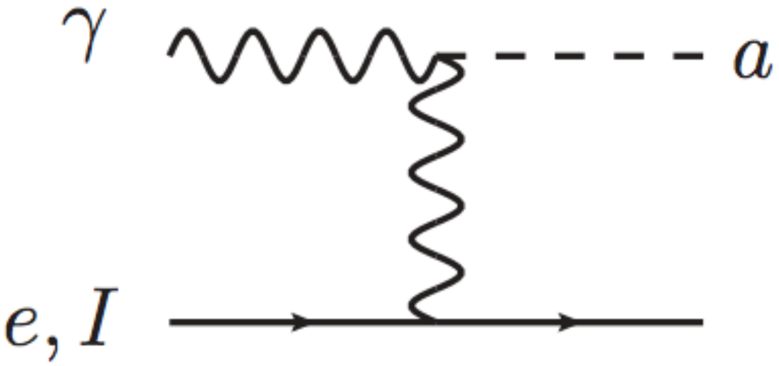
QCD axion vs Scale of inflation

0807.1726

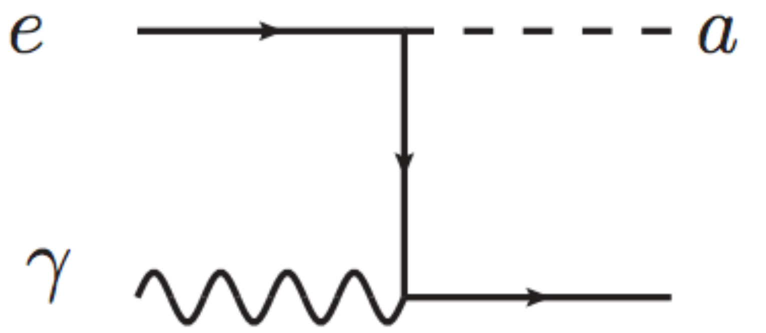


How axions are produced in the Sun

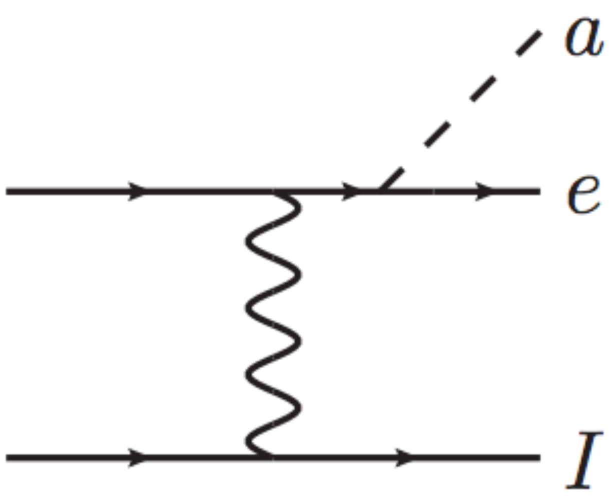
[1310.0823]



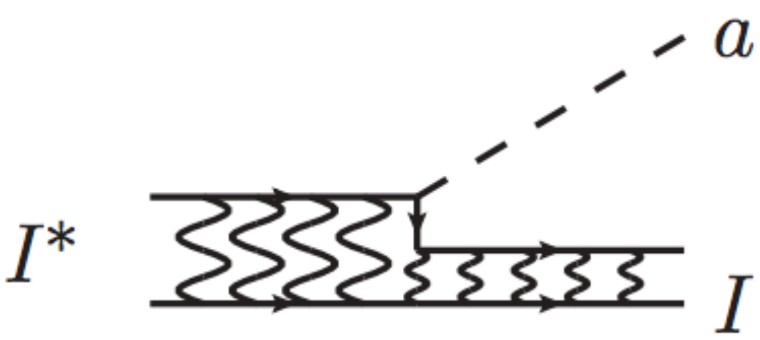
Primakoff



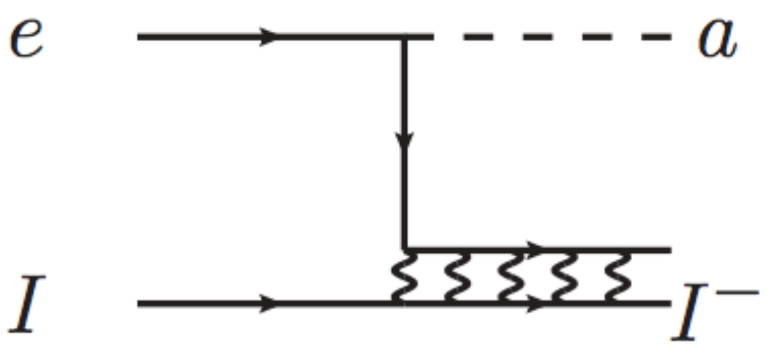
Compton



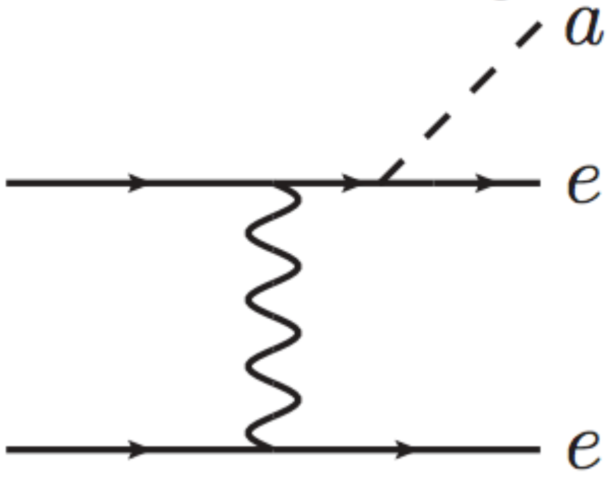
e – I bremsstrahlung



axio – deexcitation



axiorecombination



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