# Axions, dark photons, and light DM

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# Why new light particles?

*Motivated from UV and IR perspectives*

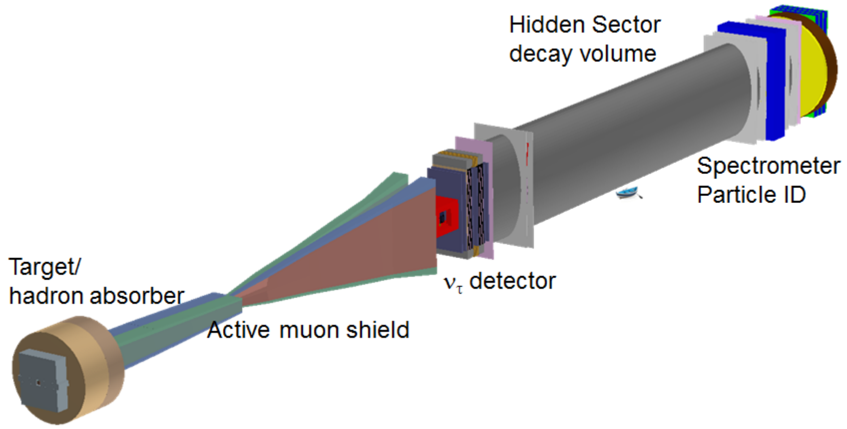
- Solve problems with the SM (QCD axion)
- Dark Matter candidates or portals to dark sectors/ mediate DM self-interactions
- Plausible in typical string compactifications
- Various almost interesting experimental anomalies

Less explored than other possibilities, experimental progress likely

No sharp prediction for where to look

# What can theory contribute?

Many interesting experiments:


Highlight especially well motivated parts of parameter space

Determine existing limits from e.g. astrophysical systems

Understand physics implications of new searches

In case of an anomaly or discovery interpret what has been seen

# QCD axion

$$\mathcal{L} \supset \theta_0 \frac{\alpha_S}{8\pi} G\tilde{G}$$

Experiment $\theta_0 + \arg\left(\mathrm{Det}\, M_q\right) \lesssim 10^{-10}$

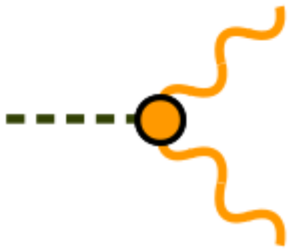
*Strong CP Problem!*

Best solution, QCD Axion, spontaneously broken anomalous U(1) symmetry

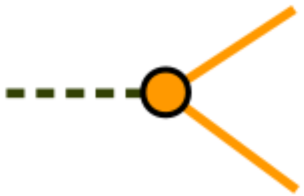
$$a \rightarrow a + \delta_{\mathrm{PQ}}$$

$$\mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G}$$

$$\frac{1}{4}\, a\, g^0_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



$$c^0_q \bar{q}\gamma^\mu\gamma_5 q\, \frac{\partial_\mu a}{2 f_a}$$



Naturally appears in UV models, especially string theory

# Axion properties

Mass: NLO chiral perturbation theory calculation

[Grilli di Cortona, EH, Vega, Villadoro, 1511.02867]

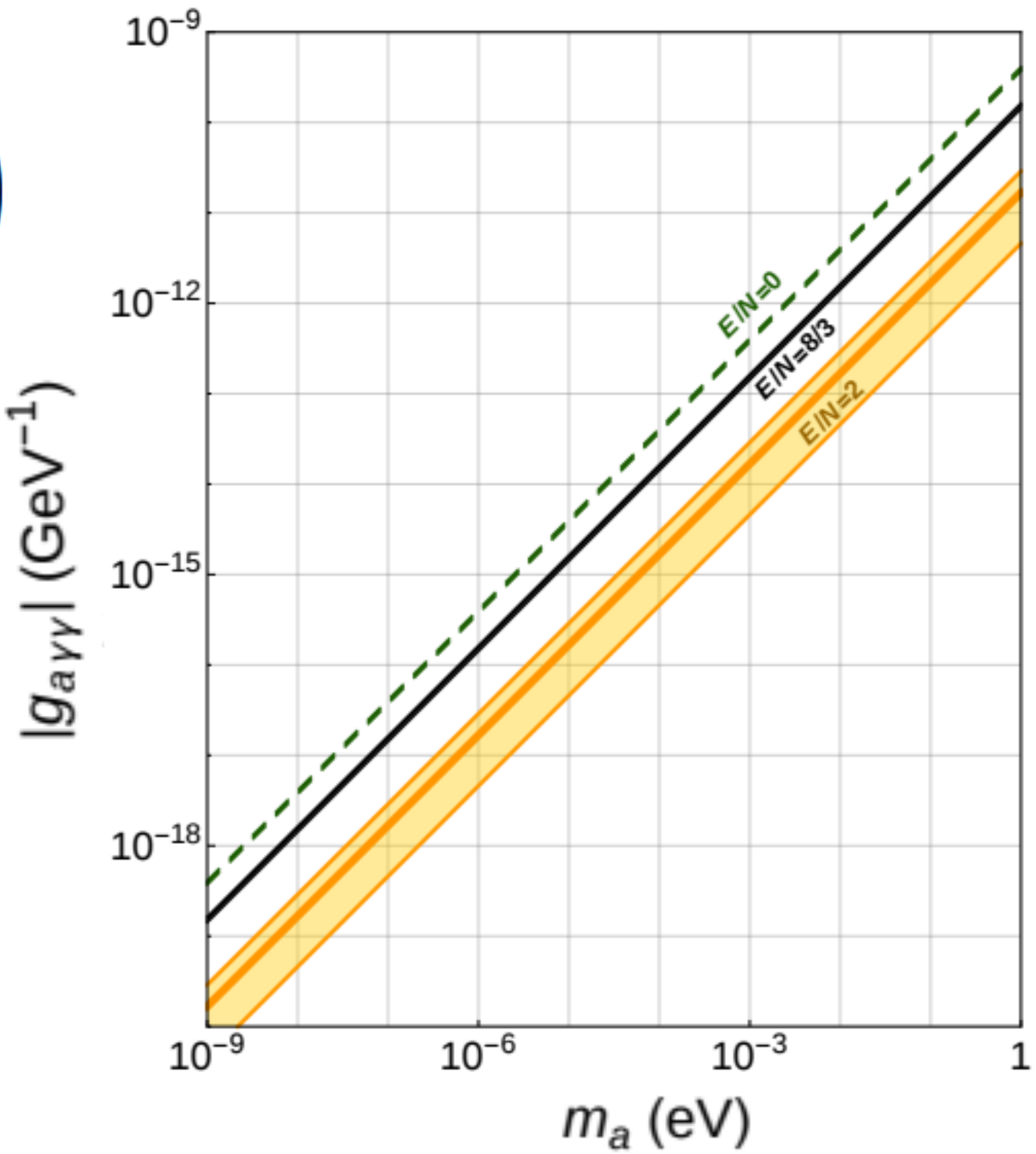
$$m_a^2 = \frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2}\left[1+2\frac{m_\pi^2}{f_\pi^2}\left(h_1^r - h_3^r - l_4^r + \frac{m_u^2 - 6 m_u m_d + m_d^2}{(m_u+m_d)^2} l_7^r\right)\right]$$

lattice

$$m_a = 5.70(6)(4)\ \mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

Mixing with the pion leads to a minimum coupling to the photon for a given axion mass

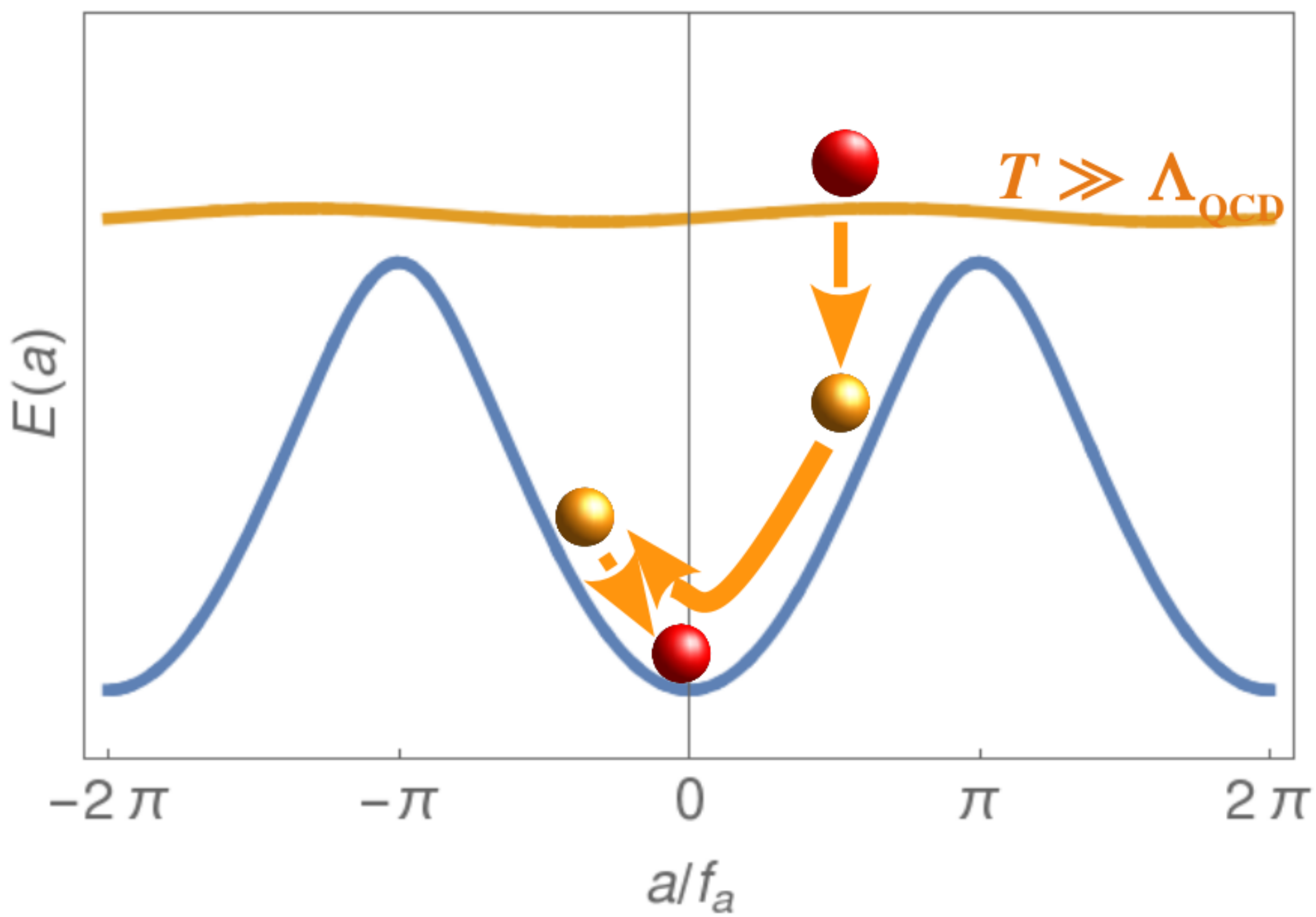
$$g_{a\gamma\gamma} = \left[0.203(3)\frac{E}{N} - 0.39(1)\right]\frac{m_a}{\text{GeV}^2}$$



# Dark matter

Extra bonus feature, can automatically be the dark matter

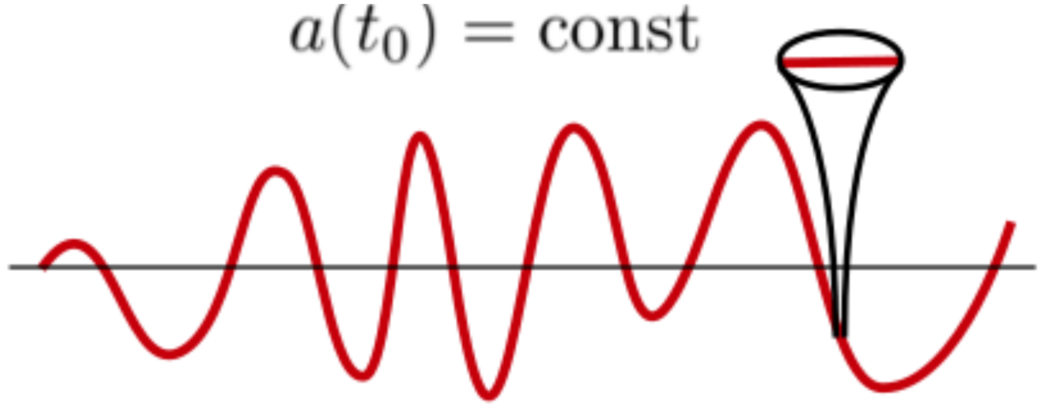
$$\ddot{a} + 3H(T)\dot{a} + m_a^2\,(T)\,a = 0$$



# Dark matter scenarios

$f_a > \max\{H_I, T_R\}$

$a(t_0) = \text{const}$



only contribution from misalignment
but not calculable

$\theta_0 < \pi \quad \Leftrightarrow \quad f_a \gtrsim 10^{10}\ \text{GeV}$

$f_a < \max\{H_I, T_R\}$

$a(t_0) = \text{random}$

misalignment contribution fixed

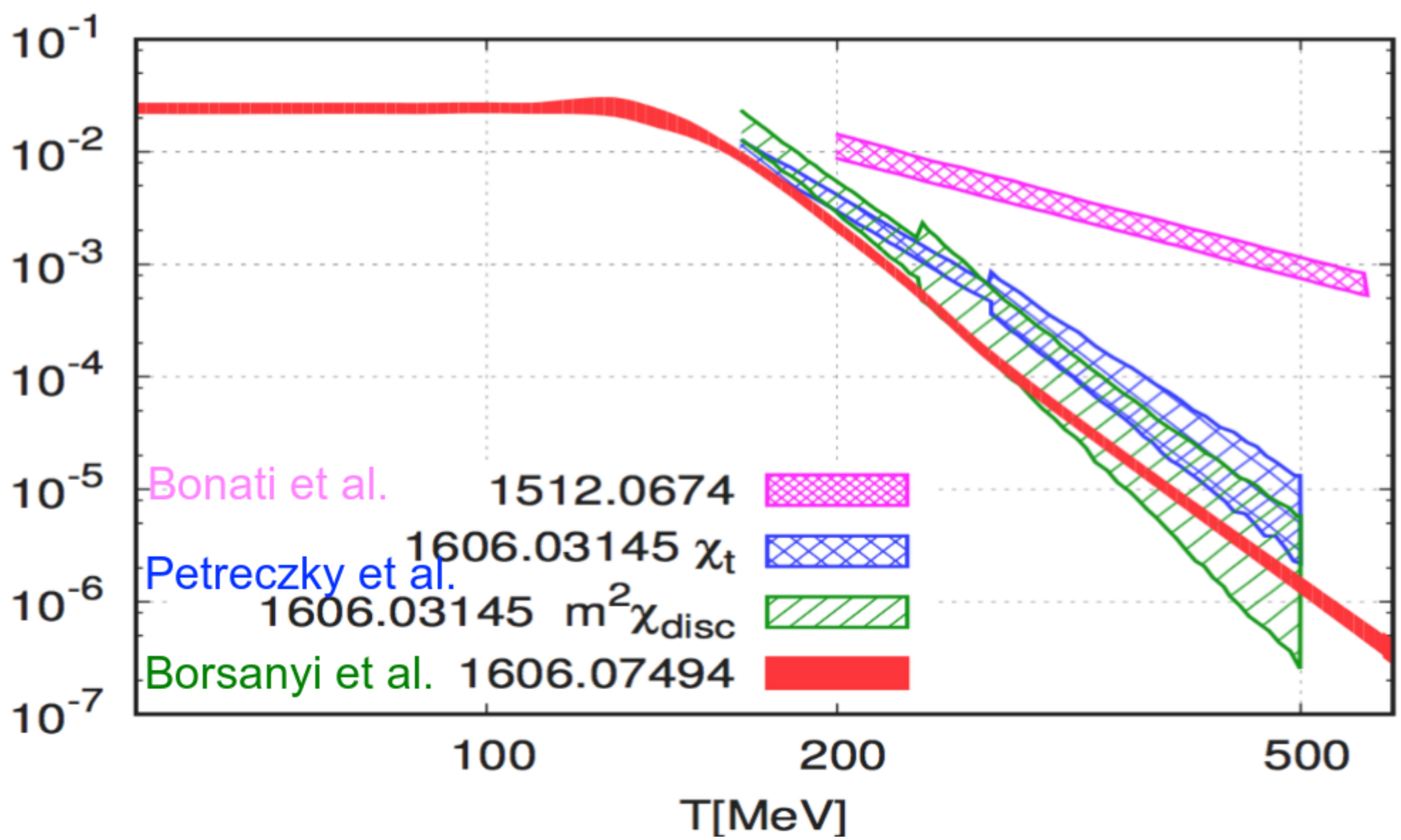
$$\theta_0^2 \approx \frac{\langle a^2 \rangle}{f_a^2} \approx (2.2)^2$$

extra axion from strings + domain walls
large uncertainties

$\Omega_a > \Omega_a^{mis} \quad \Leftrightarrow \quad f_a < f_a^{mis} \sim 10^{12}\ \text{GeV}$

# Temperature dependence of mass

$\sim m_a^2(T)$

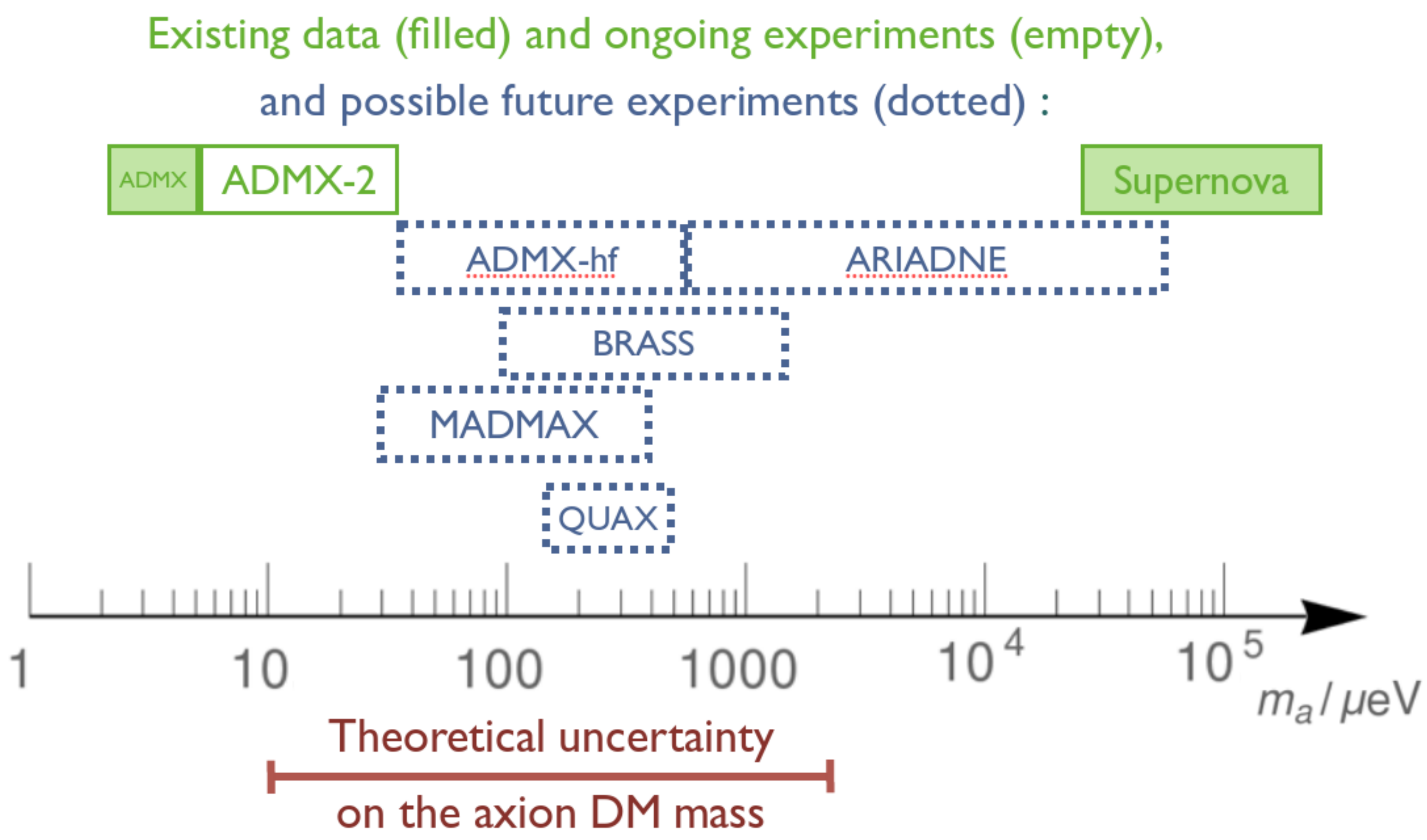



[Borsanvi et al. 1606.079411]

Dominant uncertainty in minimum DM axion mass if PQ breaking before inflation

# PQ breaking after inflation

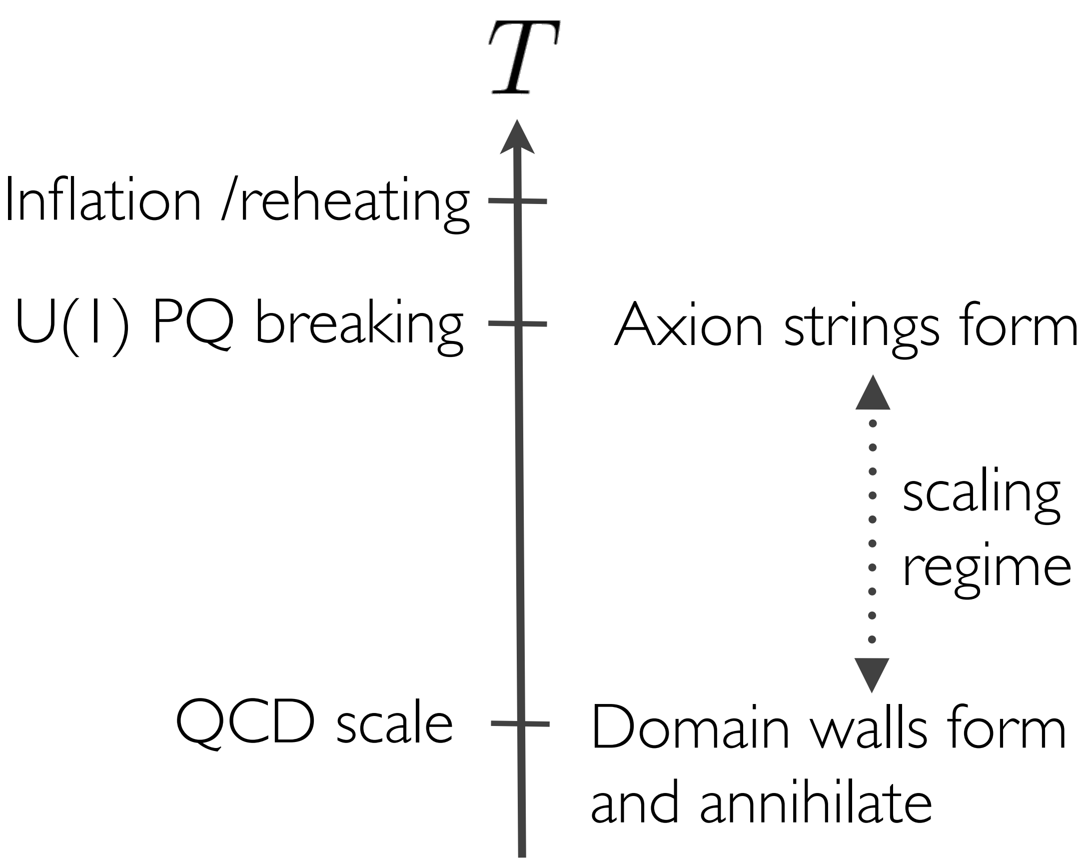
In principle an extremely predictive scenario, unique DM axion mass

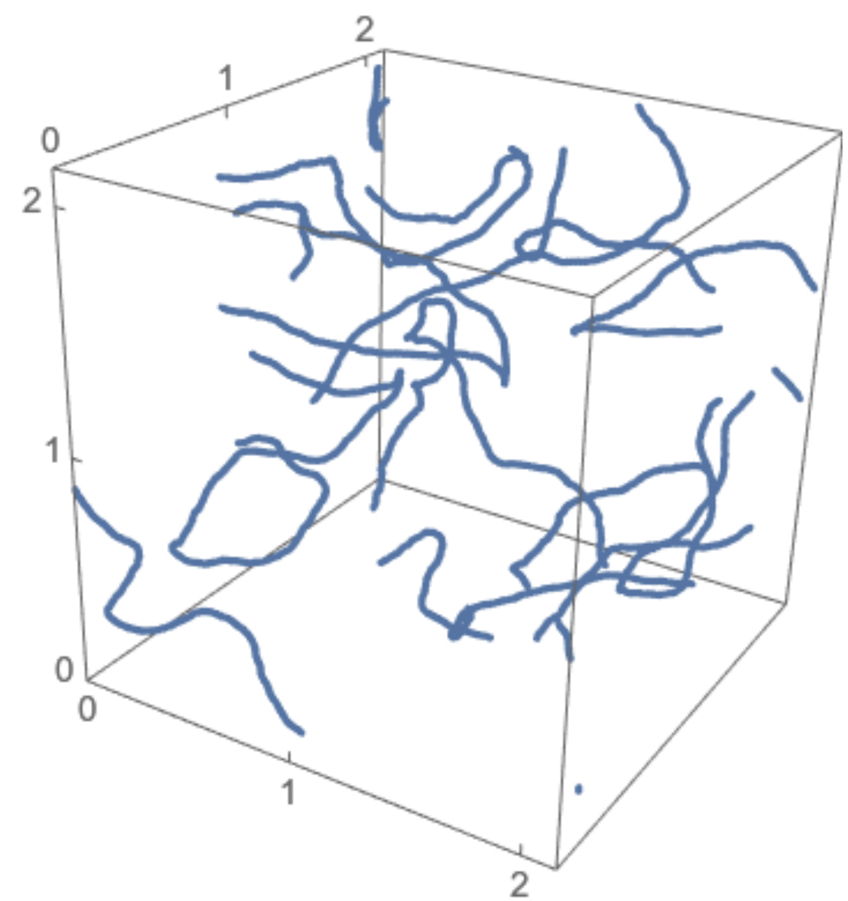



Reliable prediction is crucial to interpret ongoing experiments, design future experiments to target motivated parameter space

Precise agreement with an experimental discovery would hint towards a minimum inflation scale

# String and domain walls




Significant proportion of DM axions produced by strings and domain walls

Hard to study analytically, can help with qualitative understanding of dynamics, but full network has complicated interactions and dynamics

Instead resort to numerical simulations

# Why it's hard

String tension depends on the ratio of string core size and Hubble scale

$$\text{tension} = \frac{E}{L} \sim \pi f_a^2 \log\left(\frac{f_a}{H}\right) =: \pi f_a^2 \log(\alpha)$$

Physical scale separation $\alpha \sim 10^{30}$

Numerical simulations have to have at least one lattice point per string core, and simultaneously have to include at least a few Hubble patches

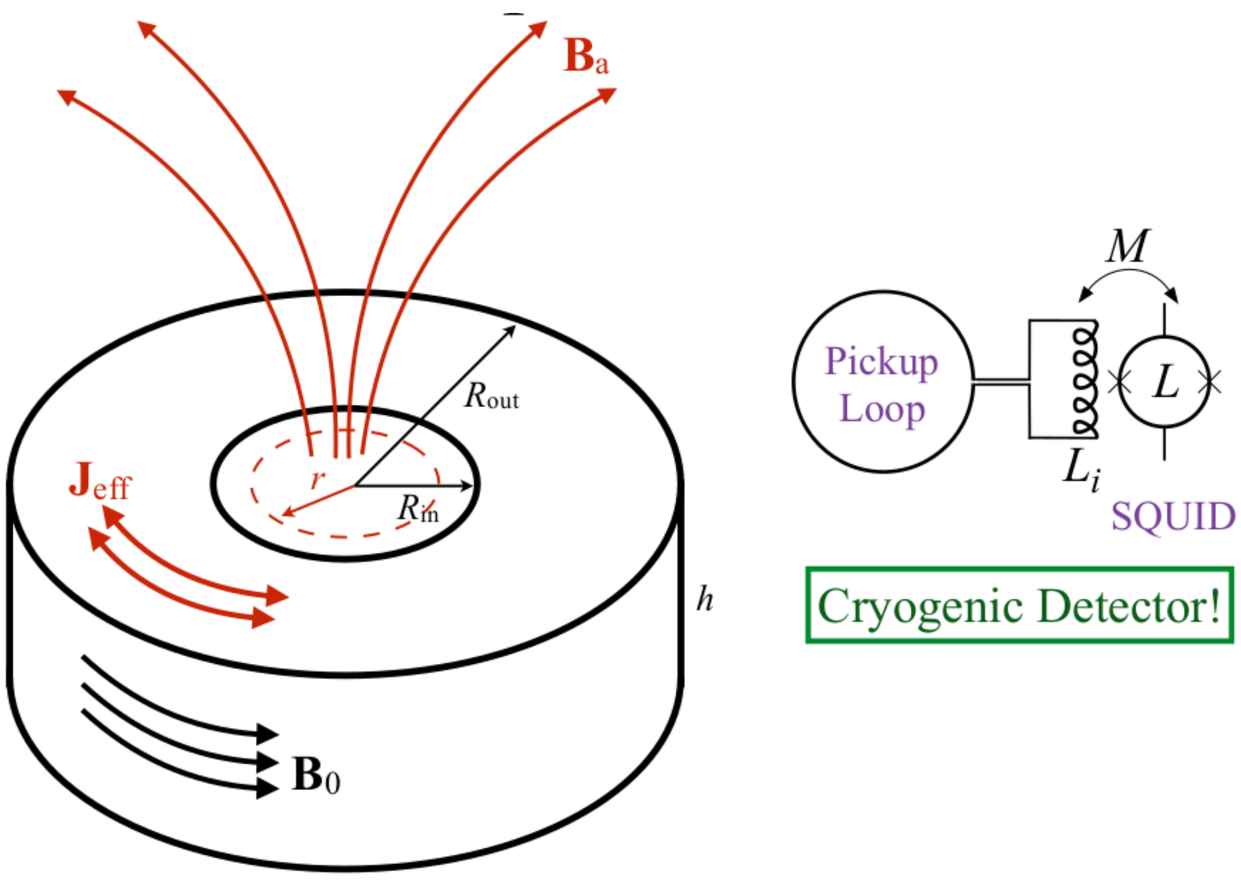
Even using clusters/ parallelisation, can only simulate grids with $\sim 1000^3$ points

Current attempts just study with small separation $\alpha \sim 100$

[Ongoing work, e.g. Redondo et al./ Moore et al./ Kawasaki et al.]

# Experimental searches

Many interesting ideas, e.g. Abracadabra [Kahn et al. 1602.01086]



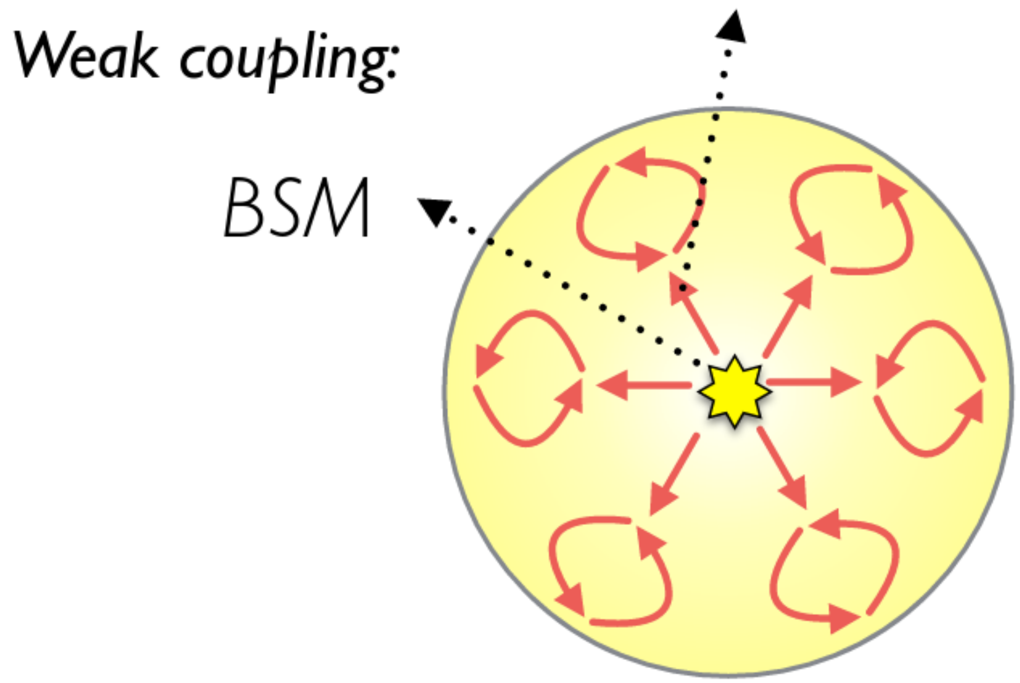

- Toroidal magnet with fixed magnetic field
- Axion DM generates oscillating current around the ring
- Leads to oscillating magnetic field
- Detected by an extremely sensitive pickup loop

Other approaches sensitive to light axions, e.g. using NMR,
Ariadne [Arvanitaki & Geraci 1403.1290]

Often will be able to determine axion mass very precisely $\delta m/m \sim 10^{-6}$

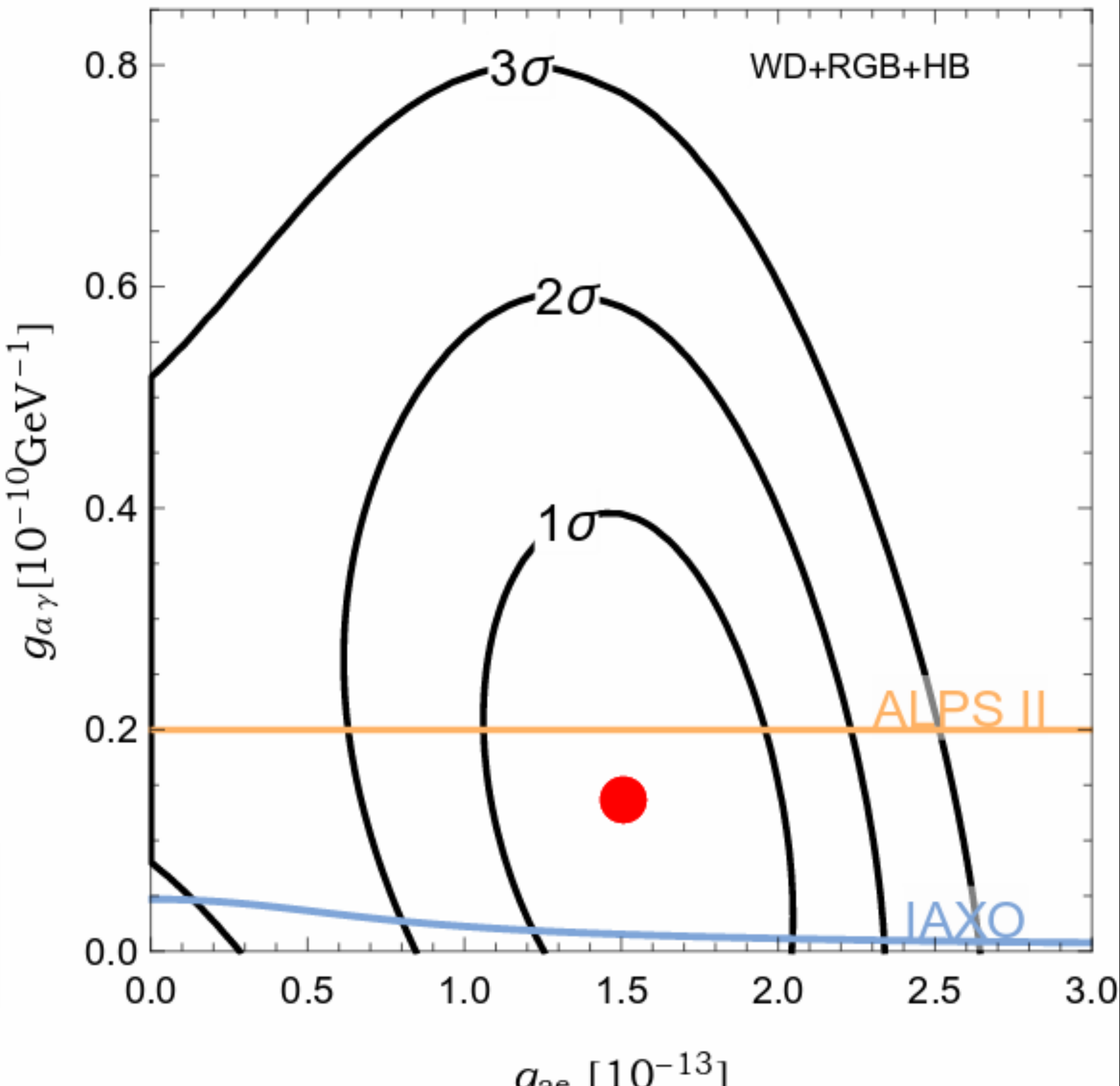
Insight into velocity distribution of axions in the galaxy / dark matter streams
[O'Hare & Green 1701.03118]

# Cooling hints?




BSM volume emission

[Giannotti et al. 1708.02111]




White dwarfs e.g. [Isern et al. 0806.2807]

There are variable, pulsating WDs: cooling rate can be related to the number of stars per luminosity interval

Additional channels seem to help when comparing observations to expectations

# Variant QCD axion modes

Many attempts to modify the standard predictions:

- Change abundance with a modified cosmology
  [Giudice et al 0005123, Visinelli & Gondolo 0912.0015, Acharya et al. 1004.5138]
- Heavy axions by introducing a mirror QCD sector
  [early papers by Dimpoulos & Susskind, Rubakov, recent interest e.g. Dimopoulos et al.1606.03097]
- Visible QCD axions, by looking right at a part of parameter space that seems to be safe from all constraints?!
  [Alves & Weiner 1710.03764]
- Dissipate axion abundance to light hidden sector photon in the early universe?
  [Agrawal et. al., 1708.05008]

# Axion like particles

More general couplings

$$\mathcal{L} = \frac{1}{2}\partial_\mu a_i' \partial^\mu a_i' - \frac{\alpha_s}{8\pi}\left(\sum_{i=1}^{n_{\rm ax}} C_{ig}' \frac{a_i'}{f_{a_i'}}\right) G_{\mu\nu}^b \tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\left(\sum_{i=1}^{n_{\rm ax}} C_{i\gamma}' \frac{a_i'}{f_{a_i'}}\right) F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\left(\sum_{i=1}^{n_{\rm ax}} C_{ie}' \frac{\partial_\mu a_i'}{f_{a_i'}}\right) \bar{e}\gamma^\mu\gamma_5 e + \ldots .$$

Reviewed in e.g. [Ringwald 1407.0546]

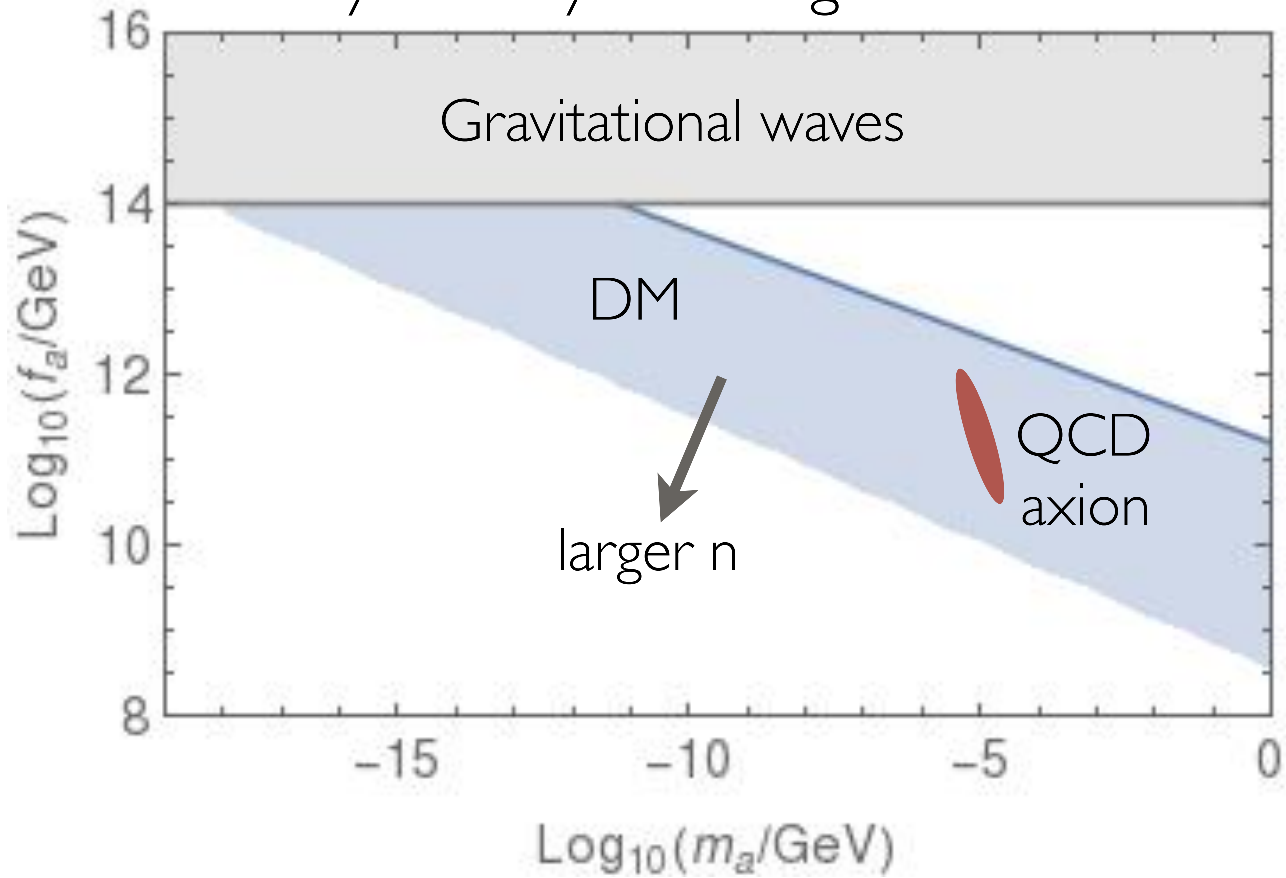
$$m_a^2(T) = m_a^2\left(\frac{\Lambda}{T}\right)^n$$

Can act as dark matter
or as dark radiation

Appear from string theory as:

- Open string axions
- Closed string axions

If symmetry breaking after inflation:



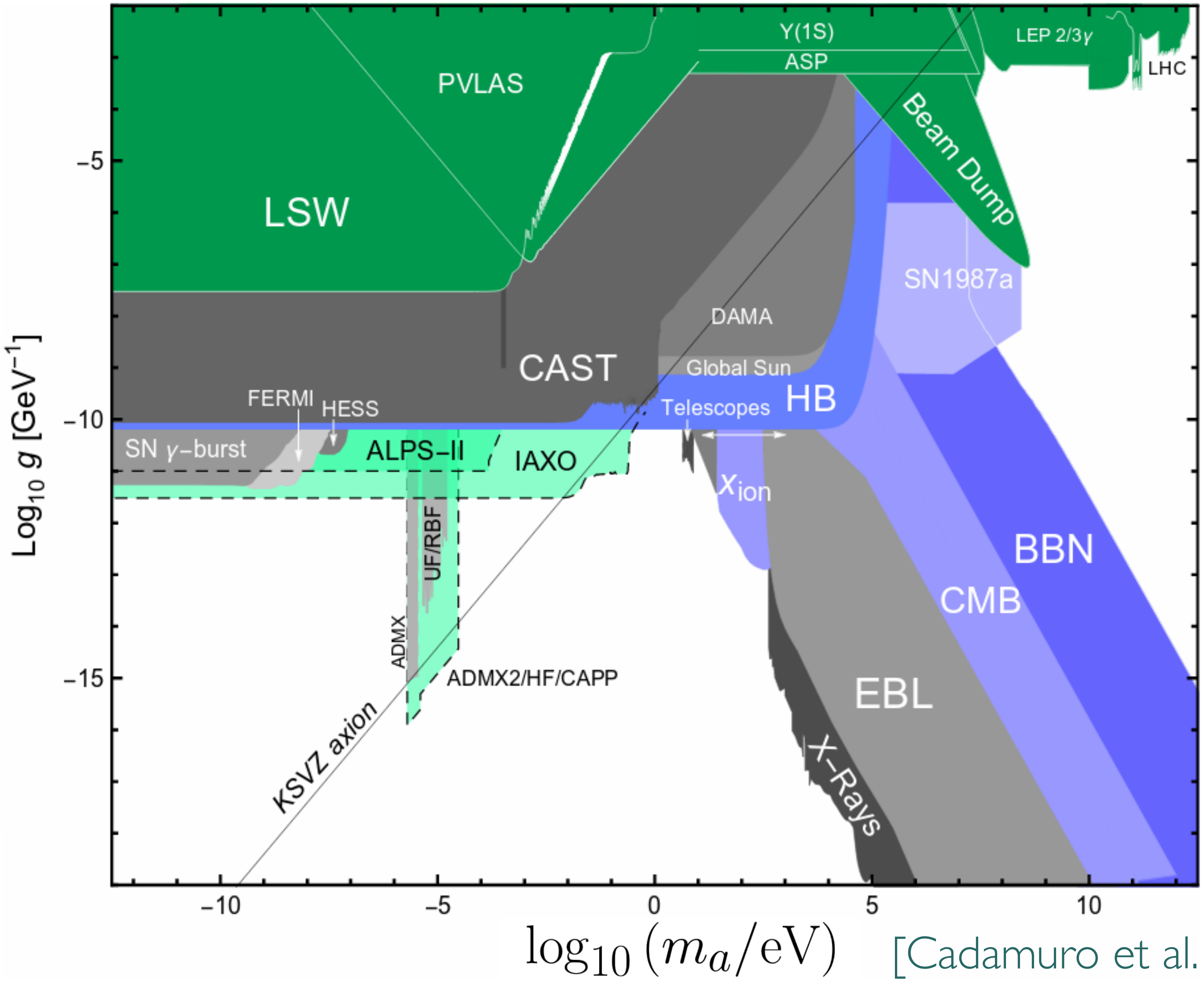
# Constraints

Constrained by QCD axion searches

+ other possibilities in the extended parameter space

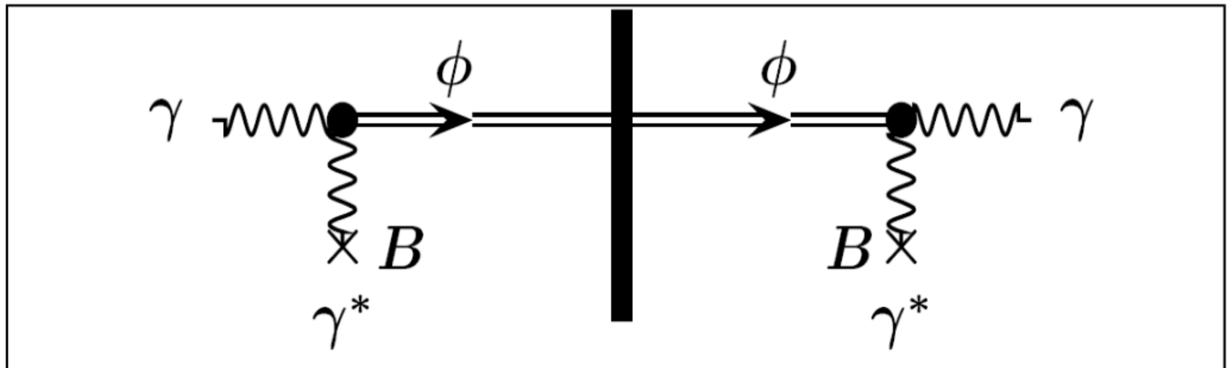
At large masses and small coupling to photons significant cosmological constraints from:

- Extragalactic background light
- X-rays from galaxies
- CMB distortion
- decays during BBN




[Cadamuro et al. 1201.5902]

# Experiments: Light shining through walls

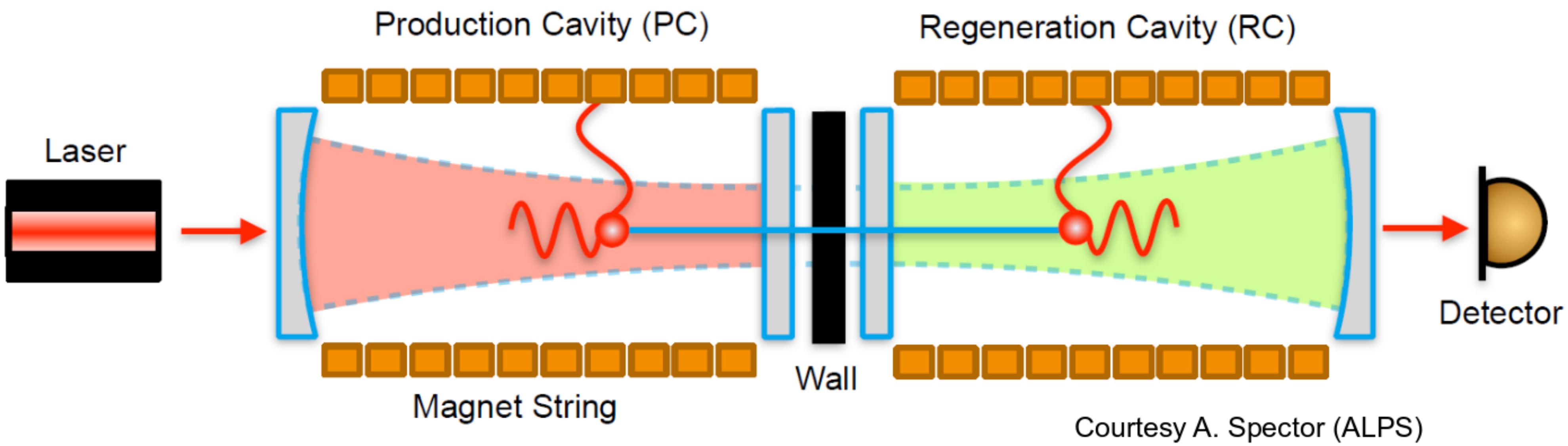


Okun 1982, Skivie 1983, Ansel‘m 1985, Van Bibber et al. 1987

Requires:

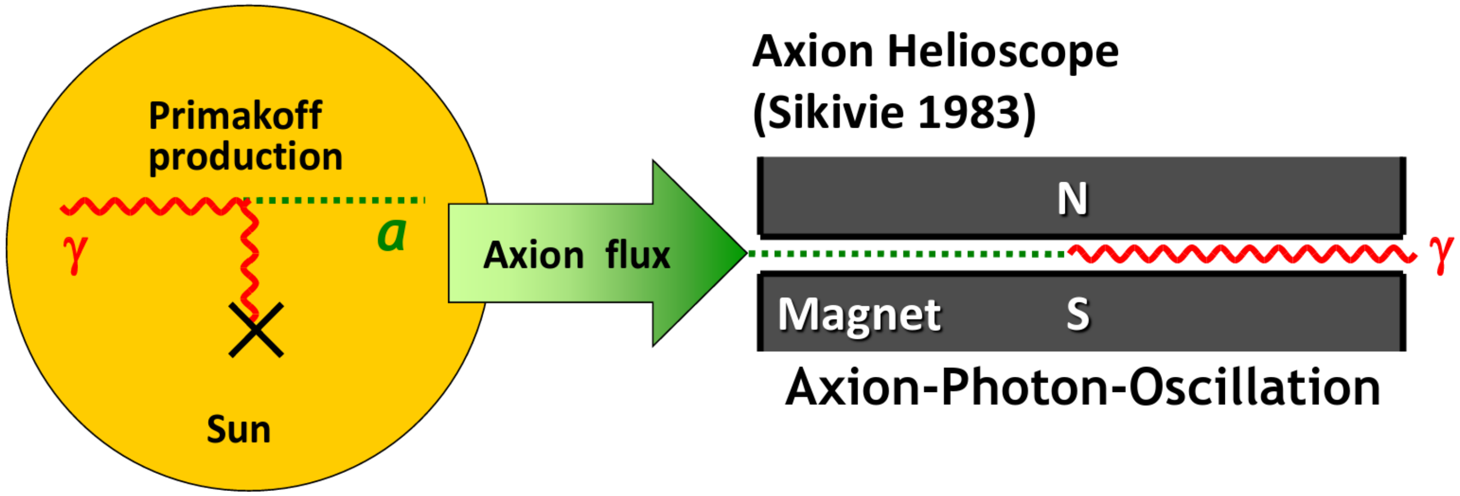
- Strong laser & sensitive detector
- Background rejection
- Strong magnets

Current best is ALPS, ALPS-II in development



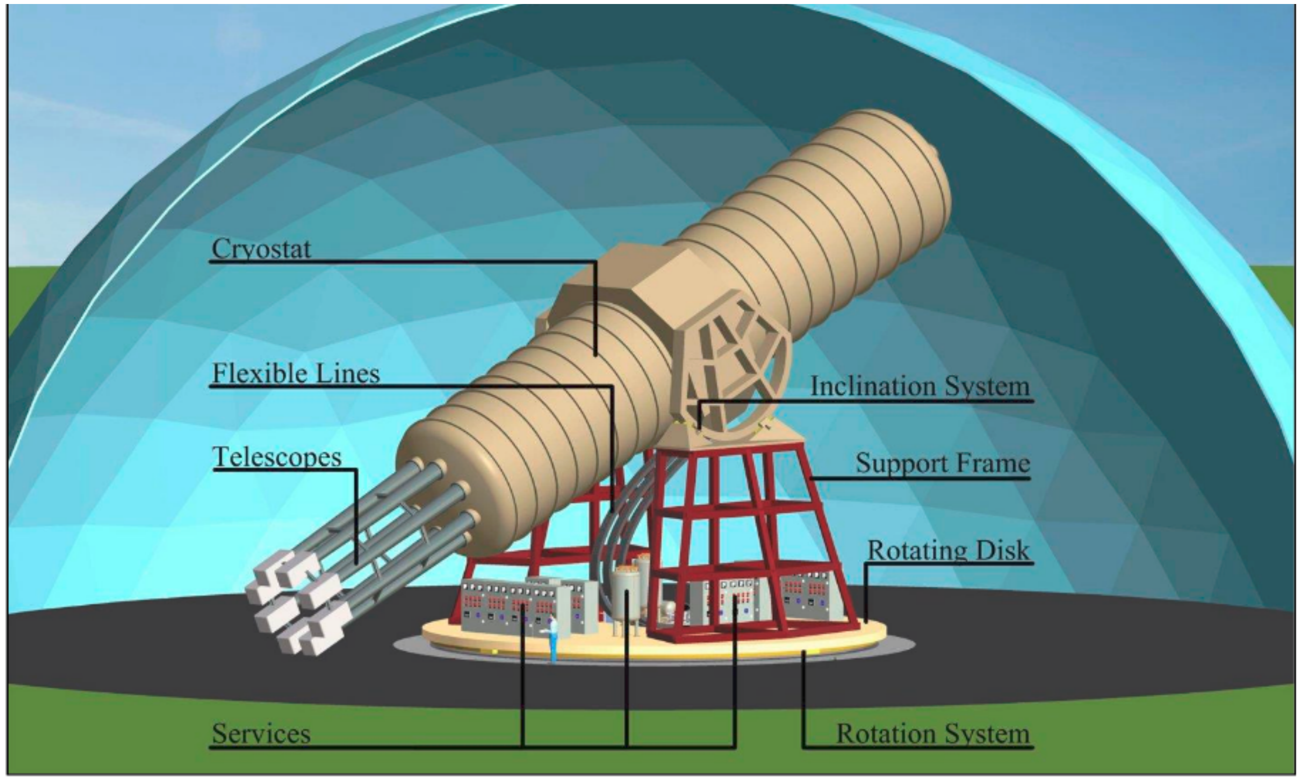

[Bahre et al. 1302.5647]

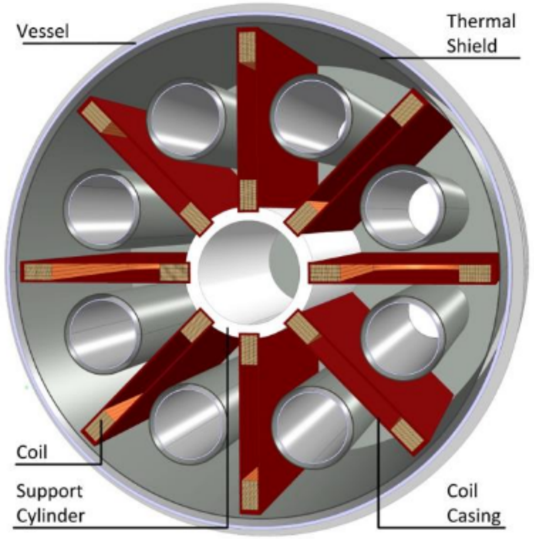
# Experiments: helioscopes




Explore a potentially large mass range

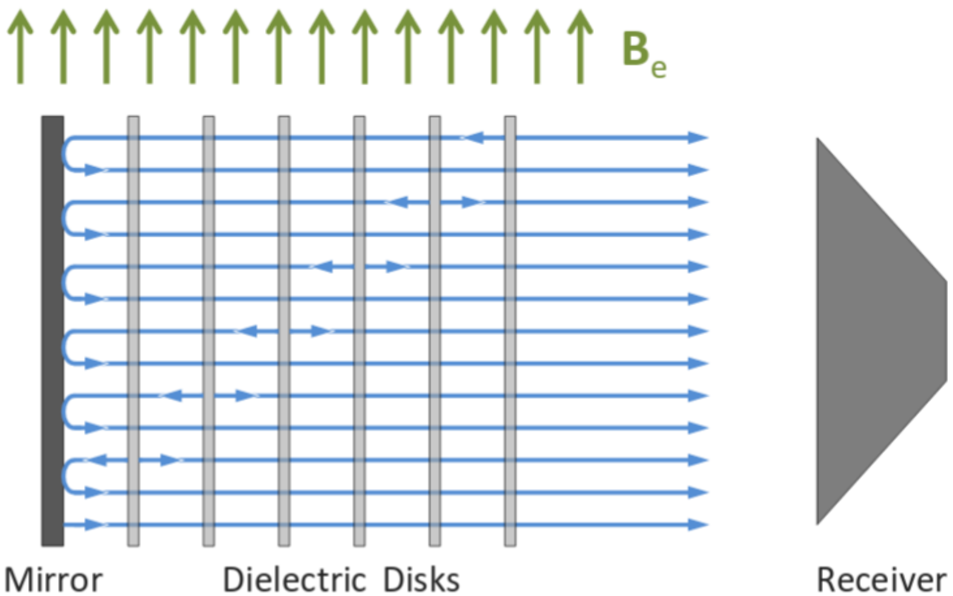
IAXO currently in development




[Armengaud et al. 1401.3233 ]

# New experimental ideas



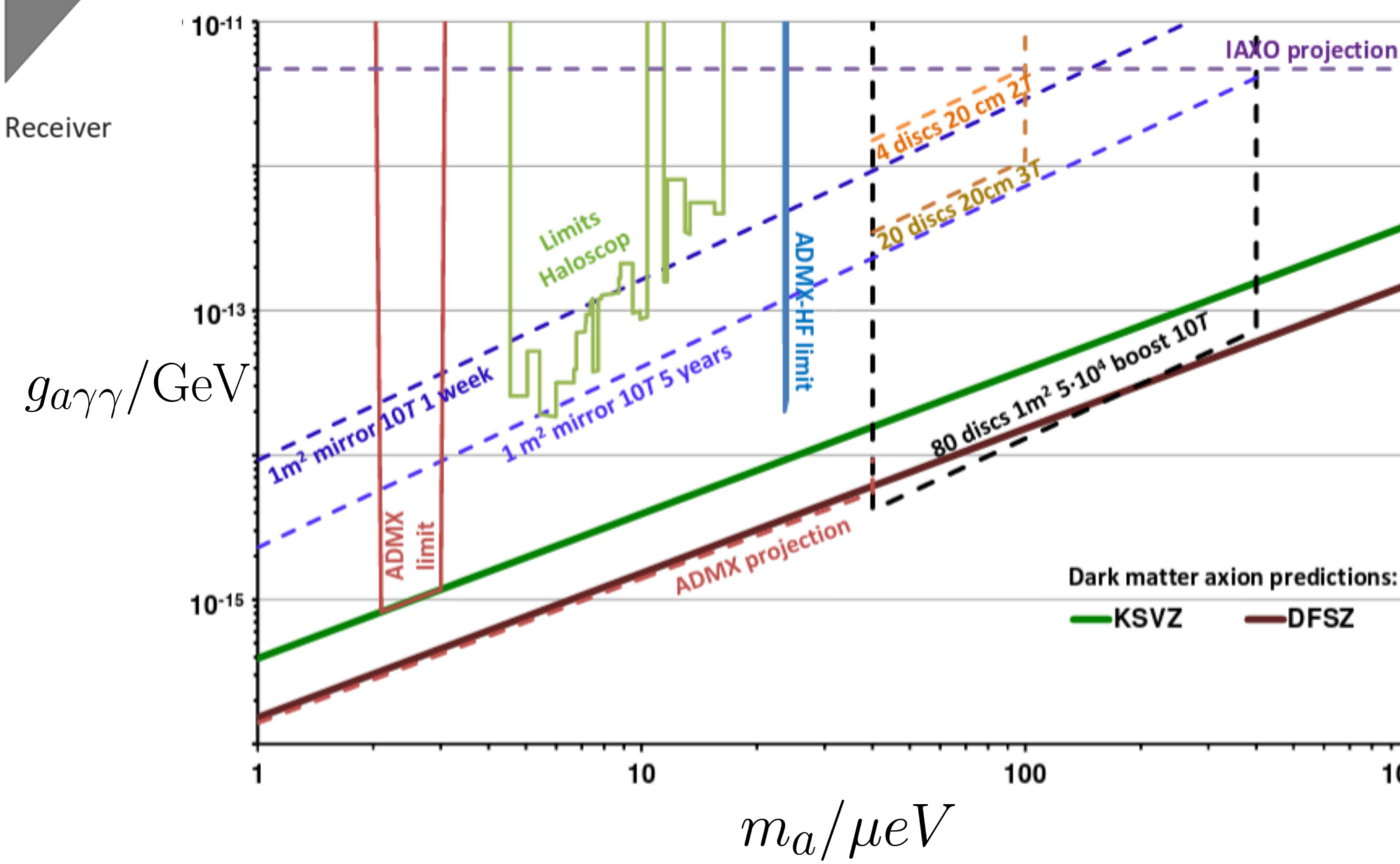

Axion in external magnetic field sources an electric field

Produces EM waves at surface of each dielectric disk, which add coherently

[Horns et al. 1212.2970,
The MADMAX interest group
1611.05865]

E.g. MADMAX

dielectric haloscope, sensitive to high mass region (and reaches typical QCD axion-photon coupling)

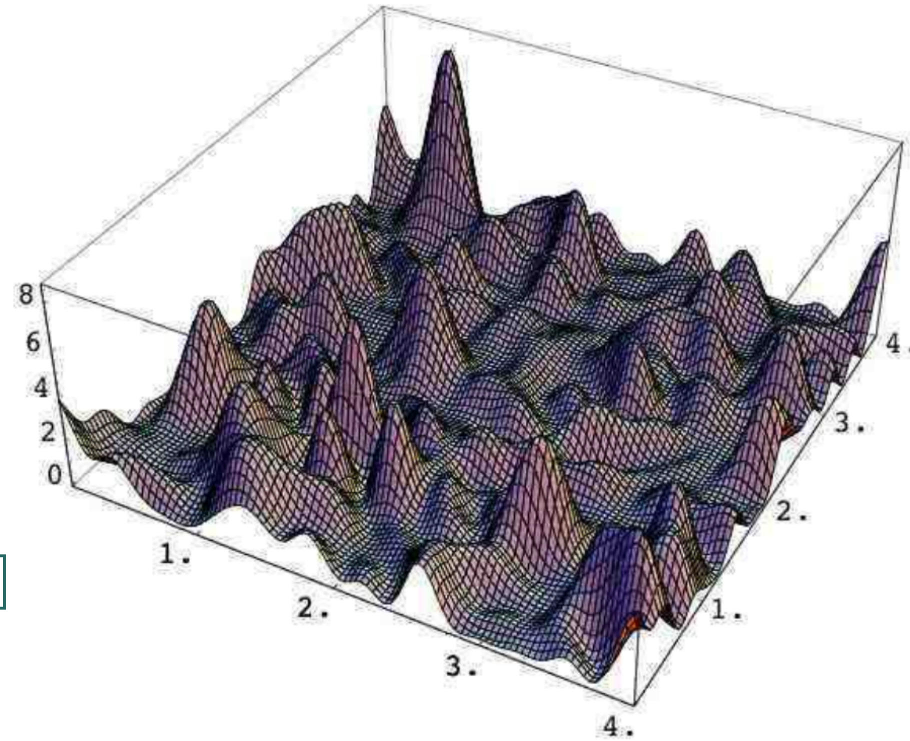


# Miniclusters and microlensing

Density perturbations due to PQ symmetry breaking

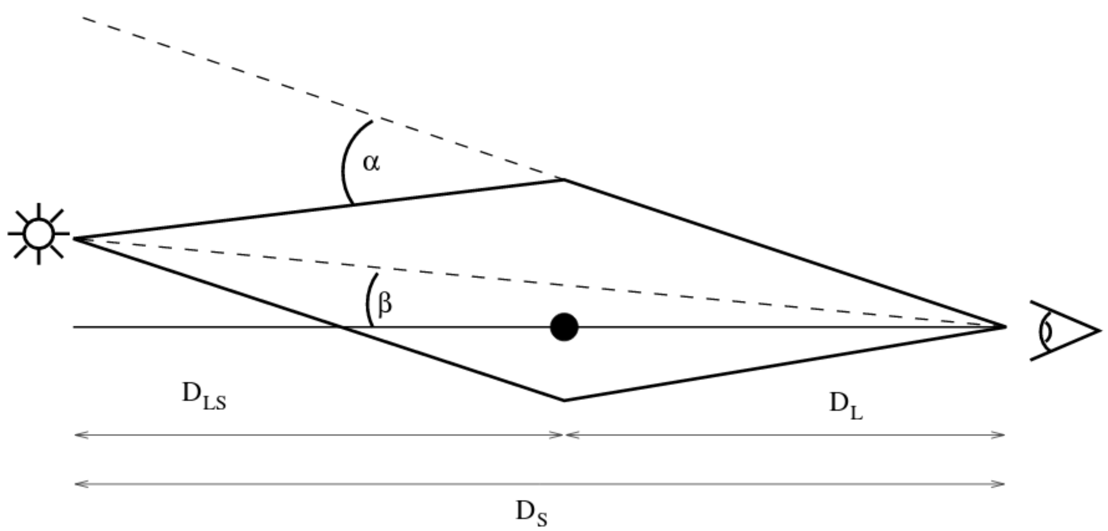
Collapse to miniclusters at matter-radiation equality

[Zurek et. al. 0607341]

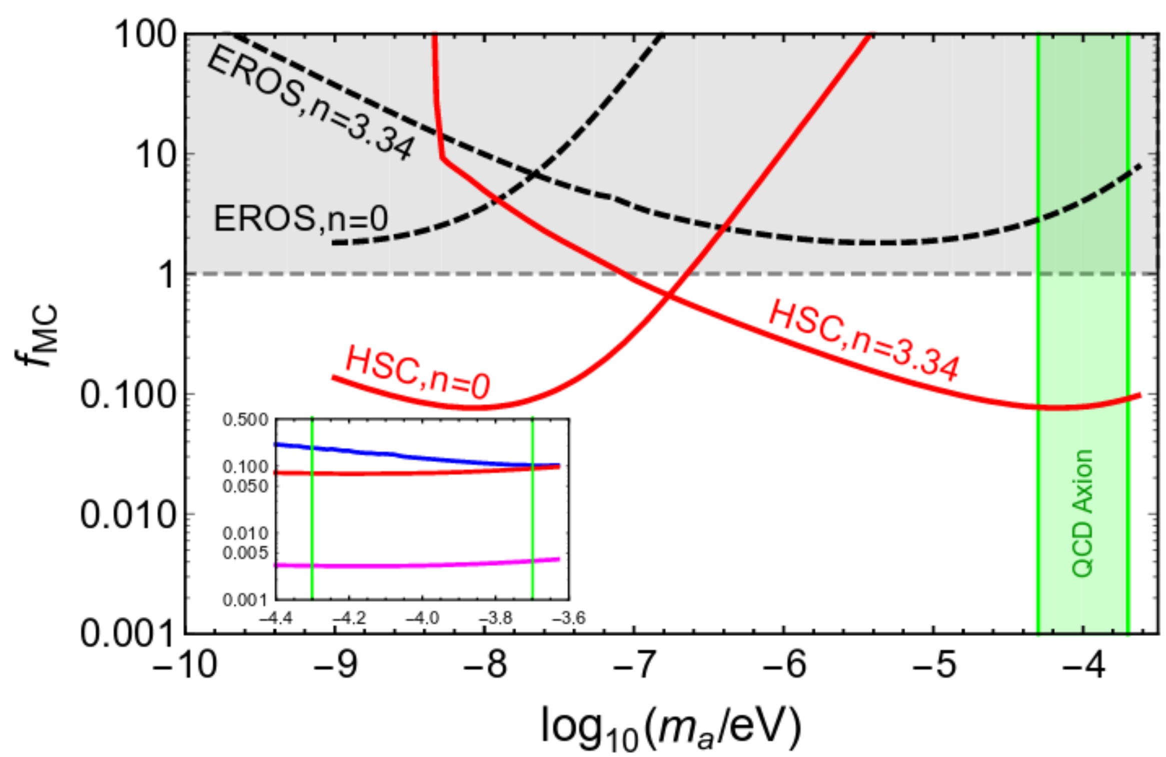



Potentially observable microlensing signals

Evolution and survival rate after production still unclear




[Fairbairn et. al.1701.04787]



# Dark Photons

Extra U(1): $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times U(1)'$

$$\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{1}{4}F'^2 + \frac{1}{2}m^2 X^2 + eJ(A + \epsilon X)$$

(same as $-\frac{\epsilon}{2}FF'$ )

Kinetic mixing induced by heavy states charged under visible and hidden sector U(1)s not suppressed

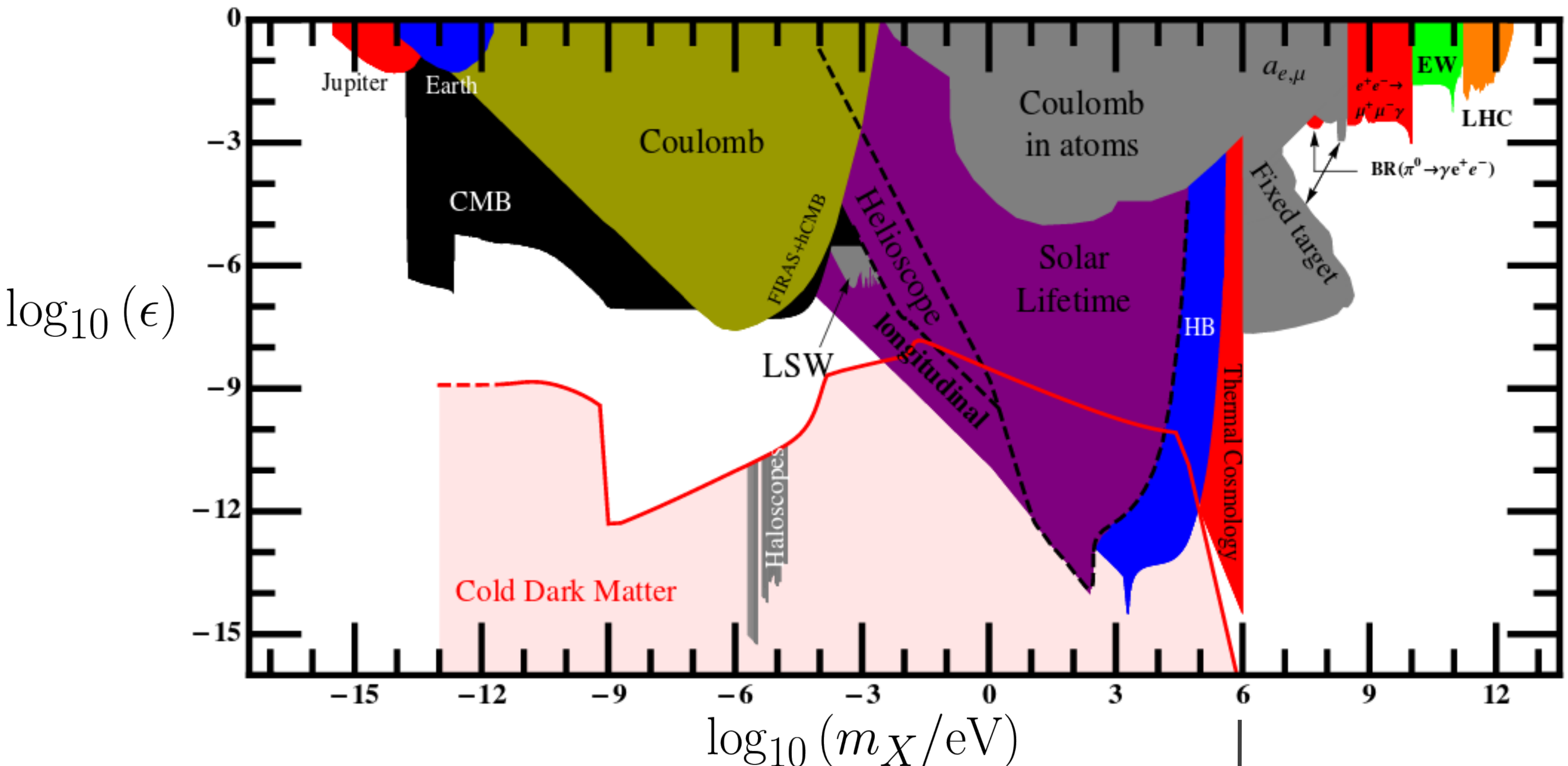
$$\Delta\epsilon \sim g' e/(12\pi^2) \times \log(\Lambda_{UV}^2/M)^2$$

Extra U(1)'s common in many string theory compactifications, e.g. models with D-branes

Mixing can be calculated in some compactifications, and is often non-zero

e.g. [Bullimore et al. 1009.2380]

# Experimental searches

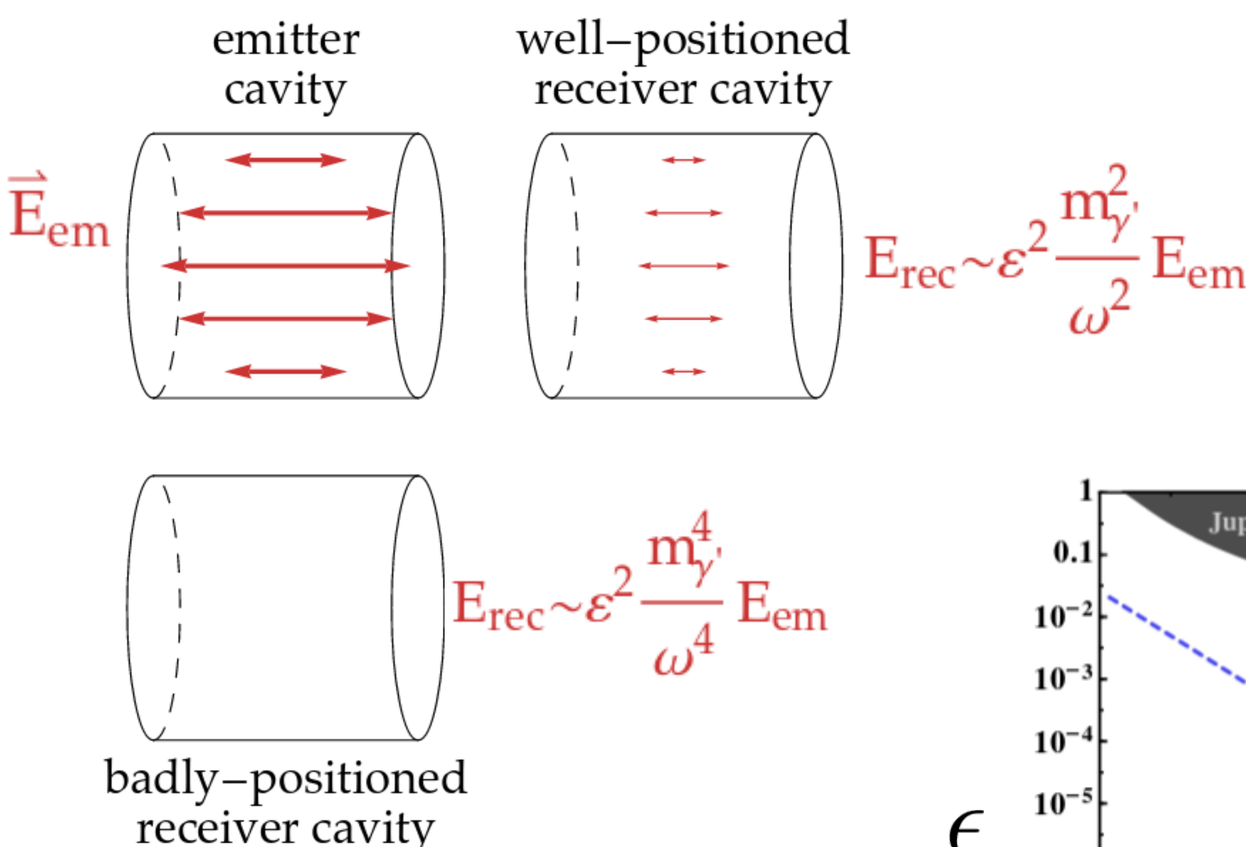



[Jaeckel 1303.1821]

Dark matter candidate ⟵ ⟶ Decays to leptons

- DM produced by misalignment
- or by quantum fluctuations during inflation [Graham et al 1504.02102]

# Experimental design- L dark photons

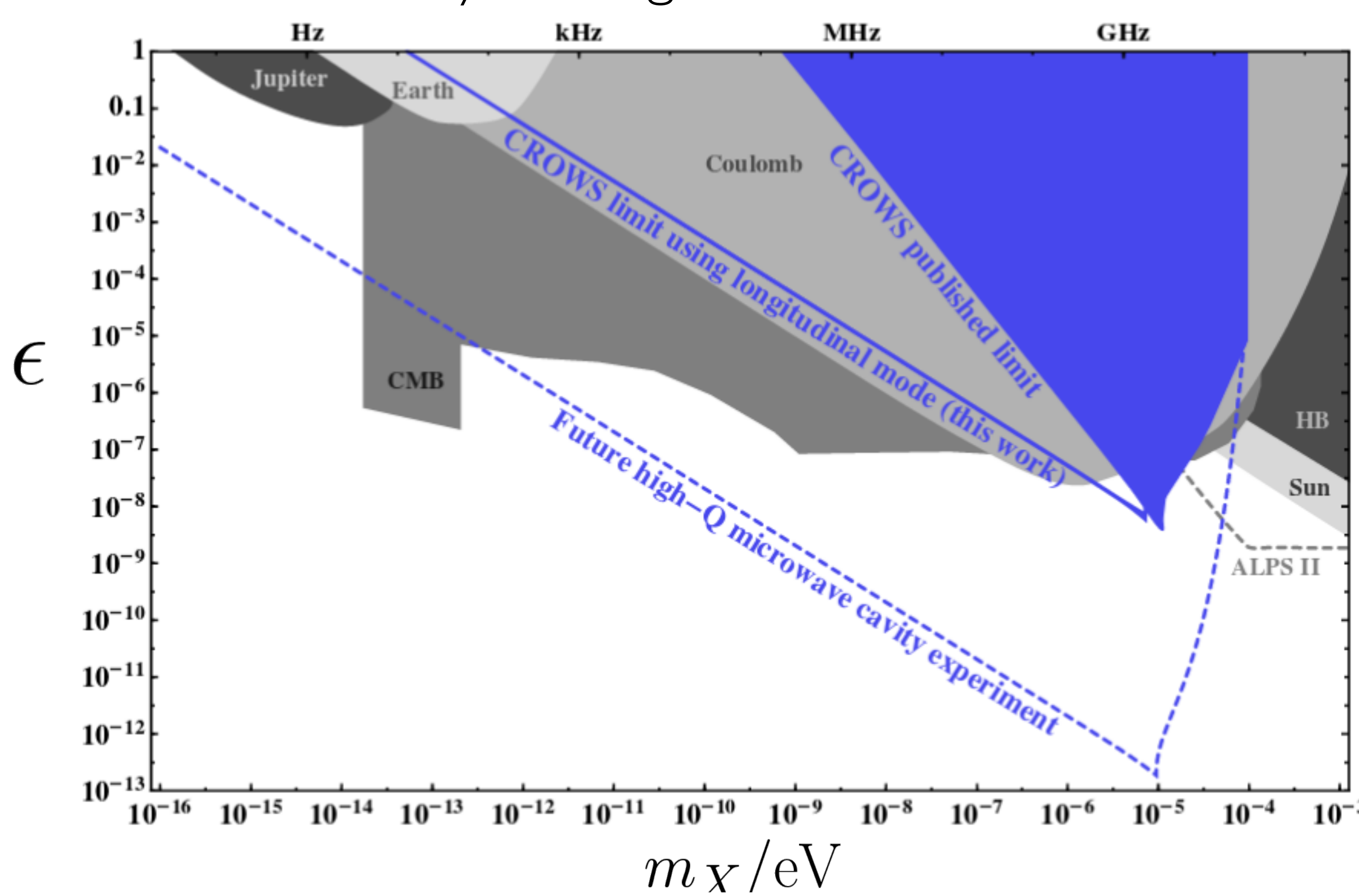



Light shining through wall experiments with resonant cavities

Effects have to be suppressed by some power of hidden photon mass

But suppression weaker for production and decay of longitudinal mode

E-field of the emitter-cavity mode should point in the direction of the receiver cavity



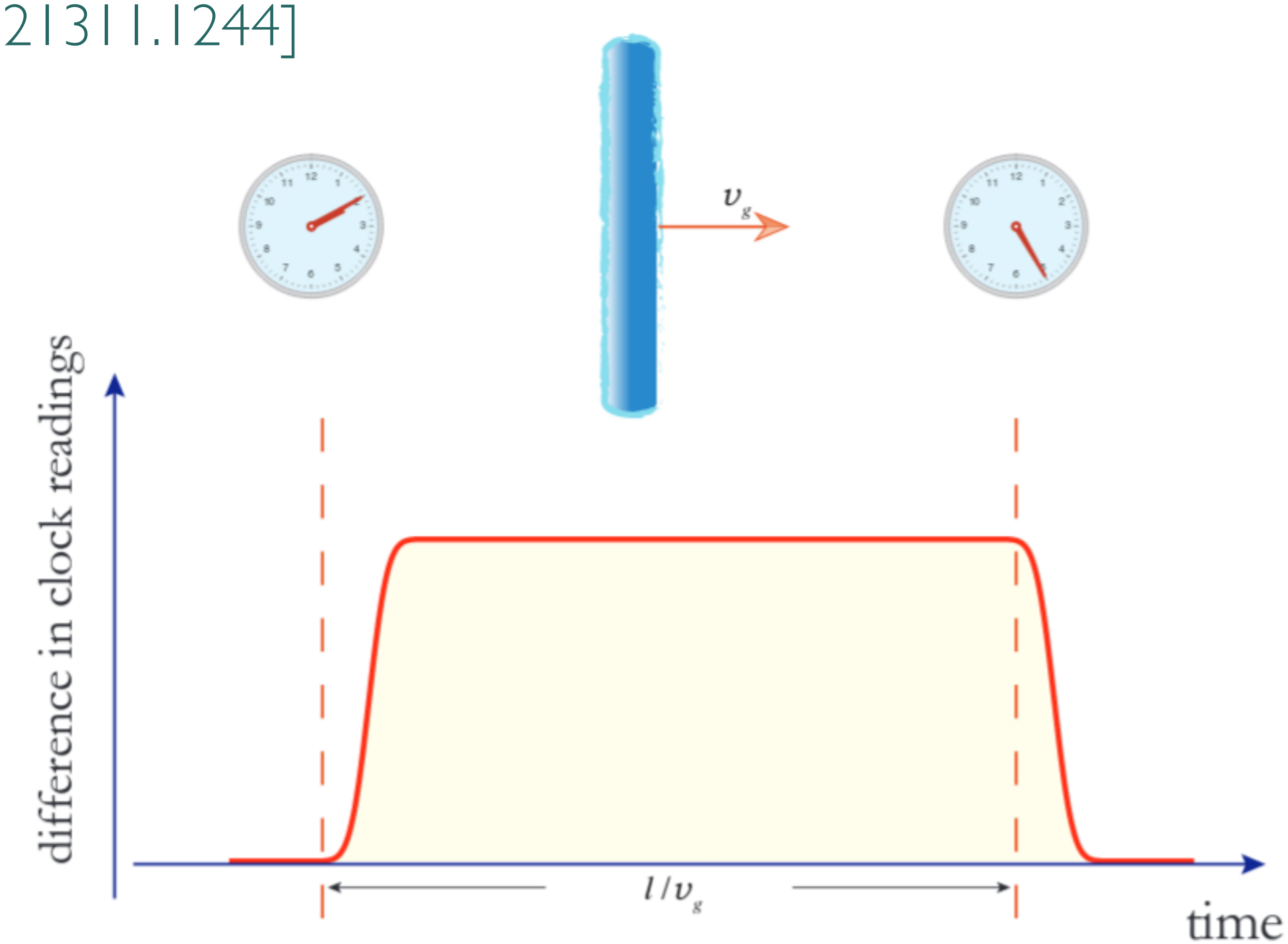

[Graham et al. 1407.4806]

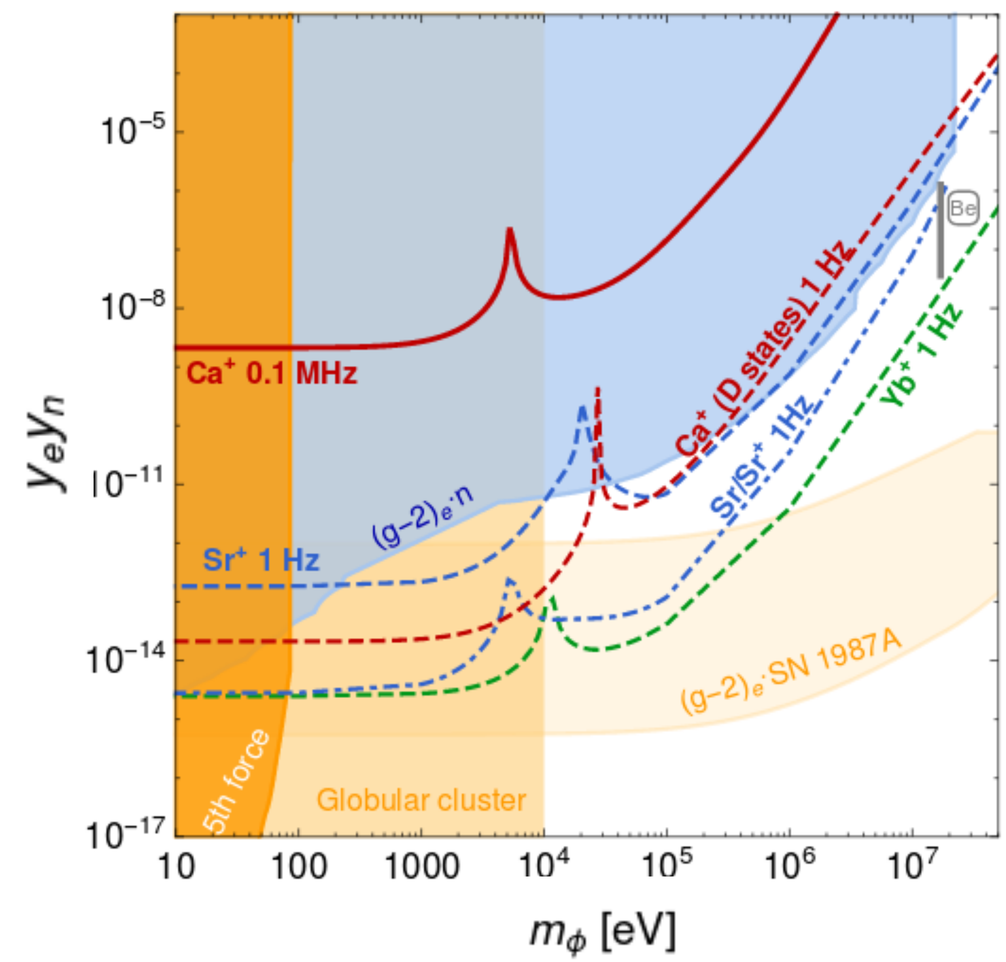
# New experiments: light scalars

Interesting proposals using high precision low energy experiments (along with existing constraints)

Atomic clocks

Transient change in speed due to dark matter objects/ e.g. domain walls, dilaton DM [Derevianko & Pospelov, 1213.11.1244]



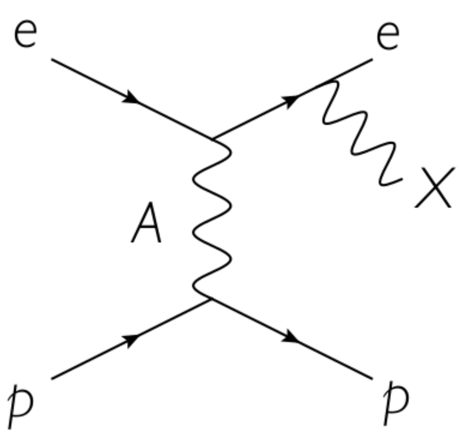




Precision spectroscopy

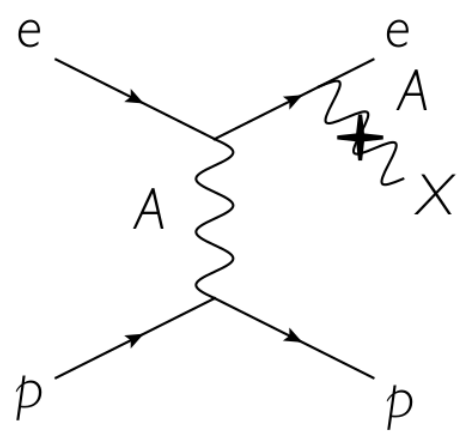
Compare measurements and theory predictions of spectral lines

[Delaunay et al. 1709.02817]

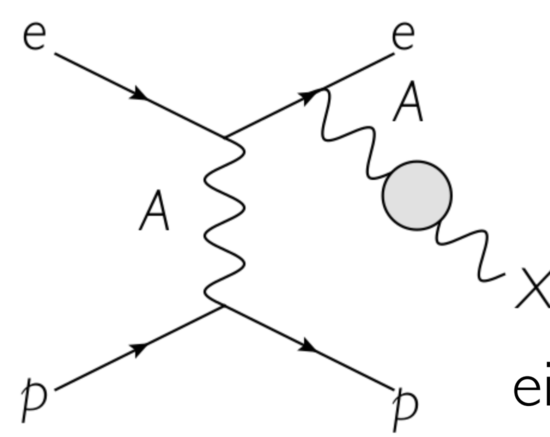
# Cooling Bounds




"Naive"
production rate




If X not a propagation eigenstate, have mixing contributions

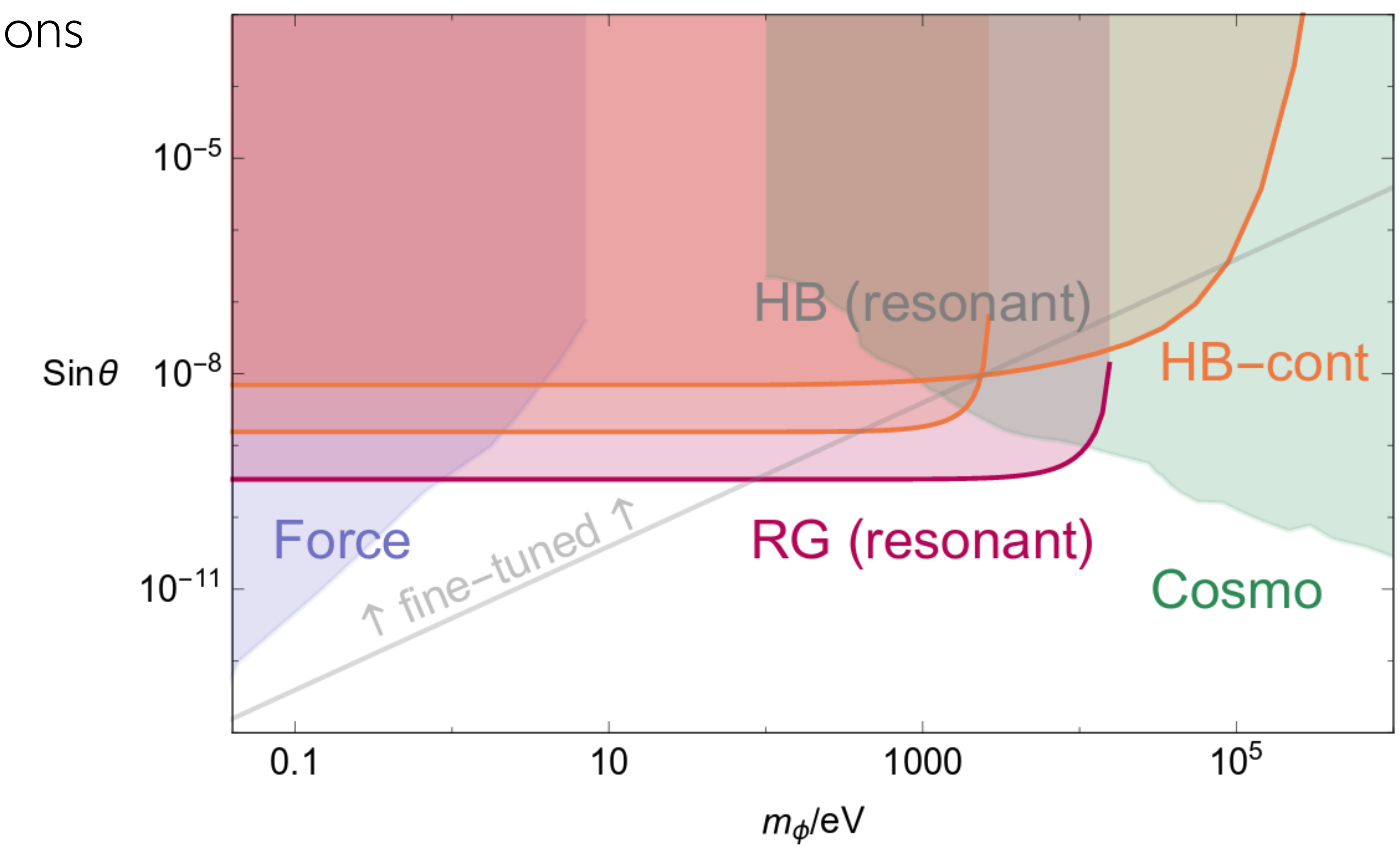



Propagation eigenstates in medium not the same as those in vacuum

E.g. Higgs portal scalar:

$$(m_f/v)\sin\theta\phi\bar{f}f$$

Including resonant production strengthens constraints from cooling of stars by factor ~ 10




[EH & Lasenby 1611.05852]

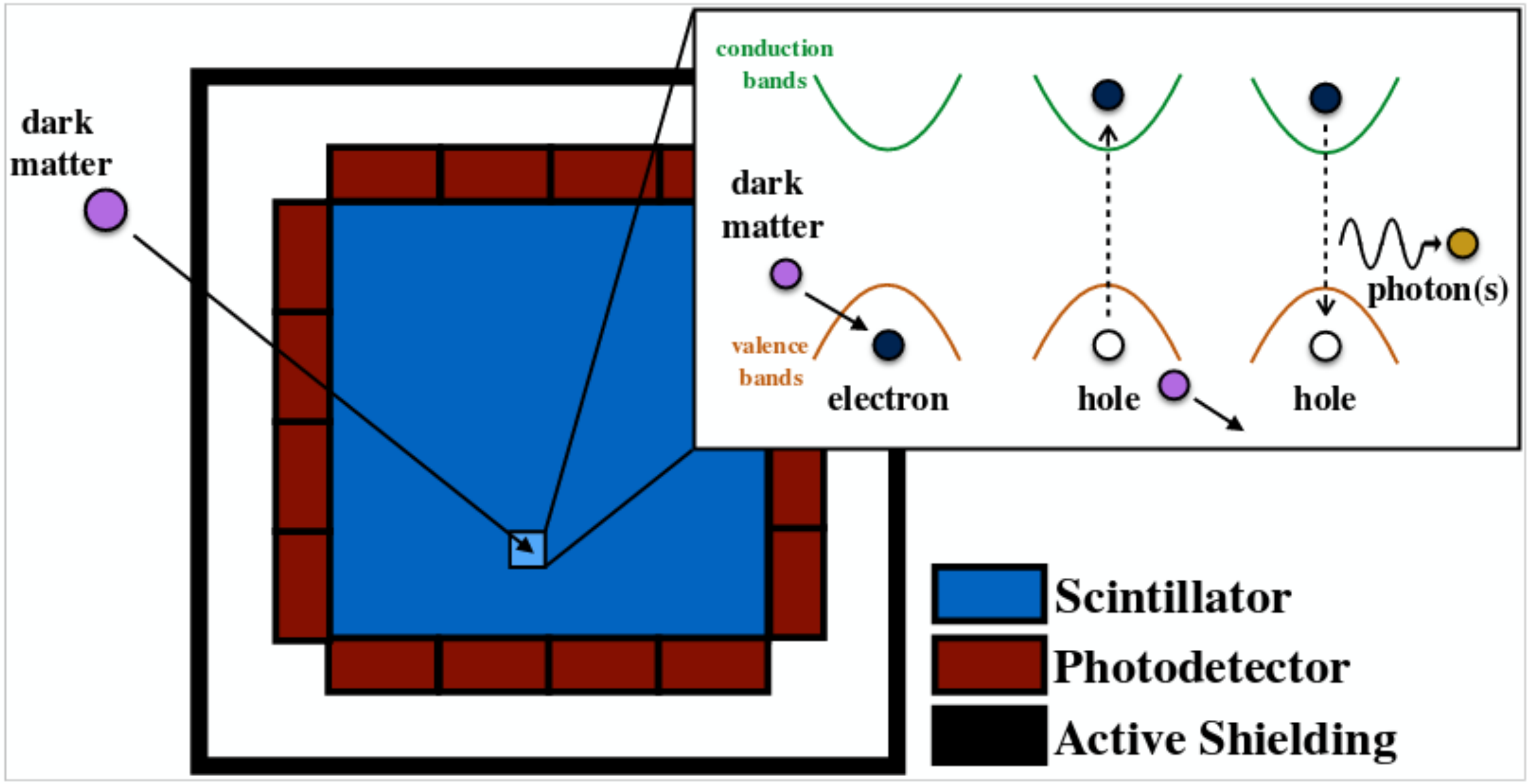
# Light-ish DM

DM candidates with mass between meV and GeV are also reasonable

Typically not probed by normal direct detection experiments

Many proposals for new experiments, including

- Semiconductors
- Scintillators
- Carbon nano-tubes
- Superfluid helium
- Superconductors



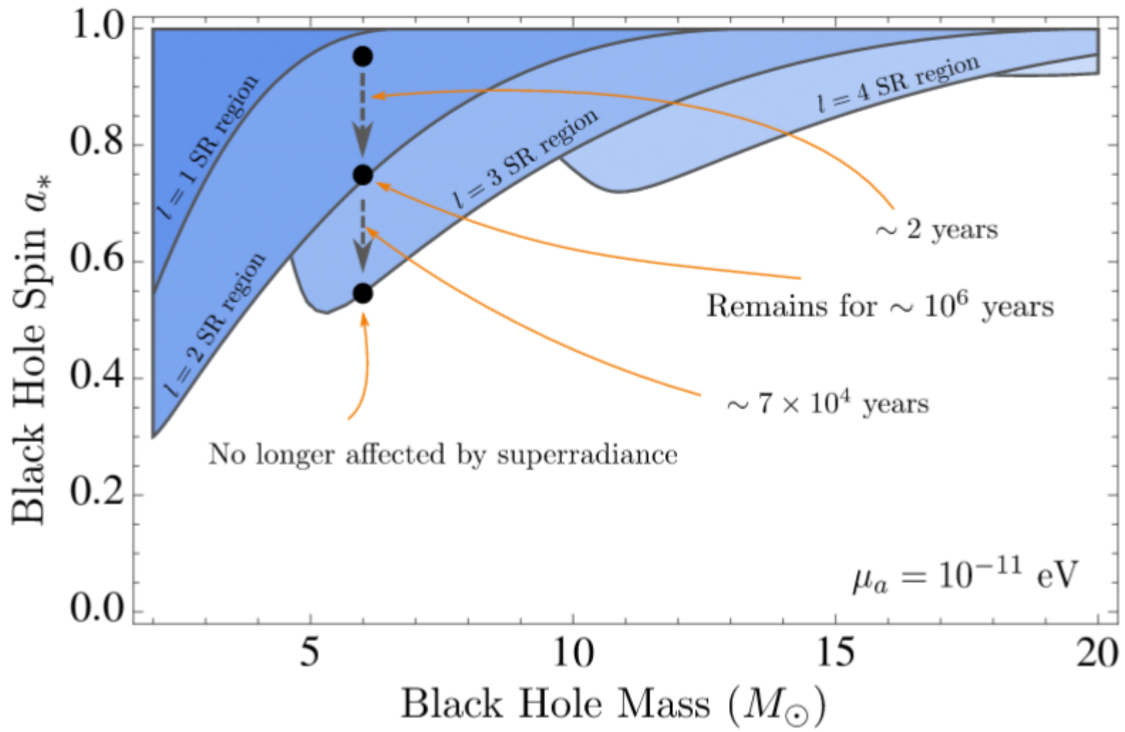

[Derenzo et al. 1607.01009]

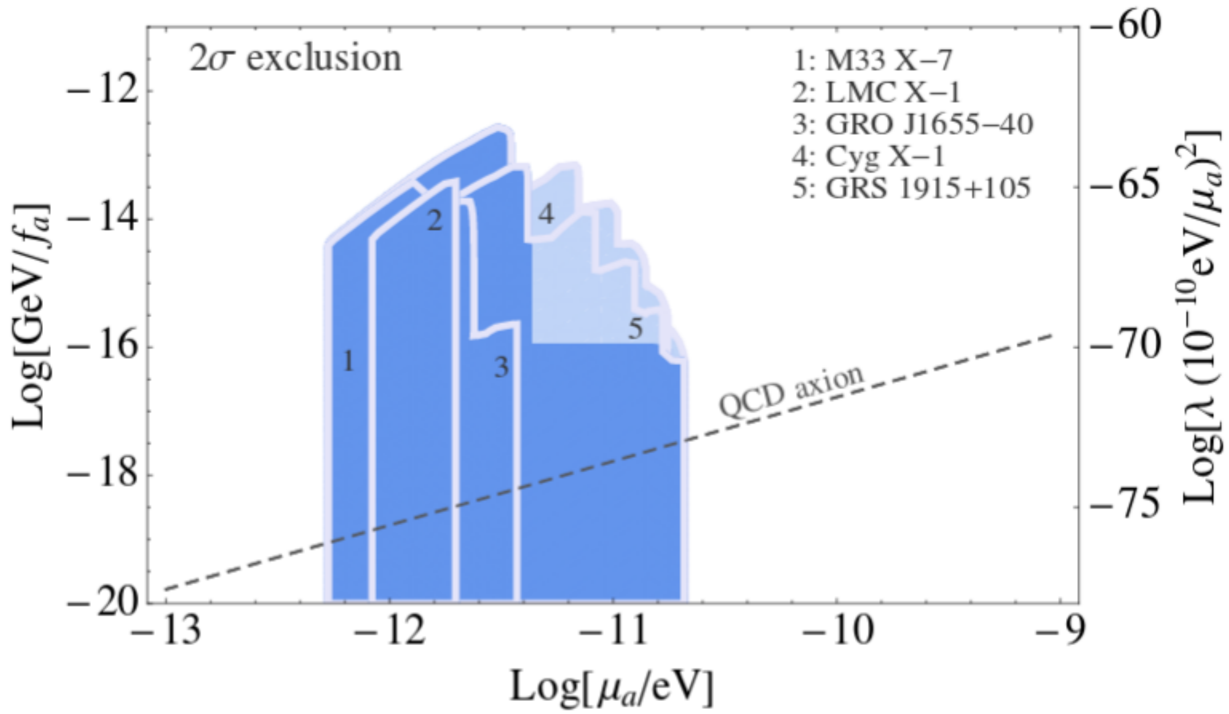
# Conclusions

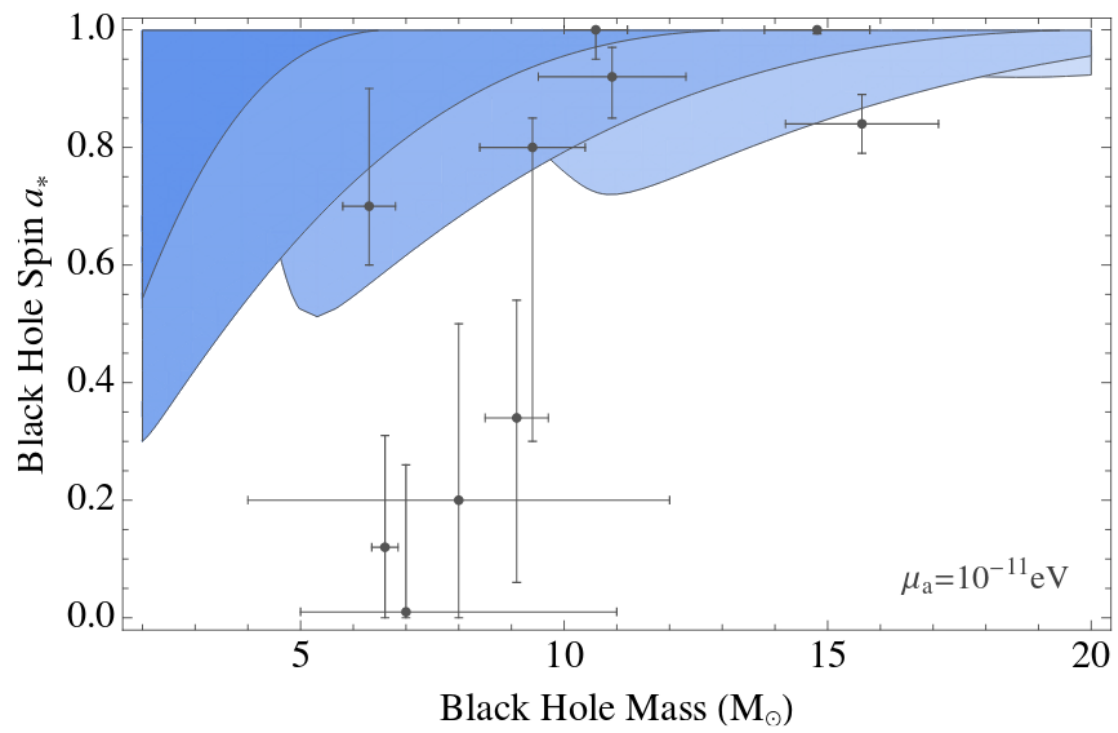
- Light particles are a motivated scenario for new physics, both from UV model building and phenomenology perspectives
- Experimental progress is reasonably cheap and fast, many new ideas
- Theoretical input is important, and significant uncertainties remain

# Thanks

# Black hole superradiance



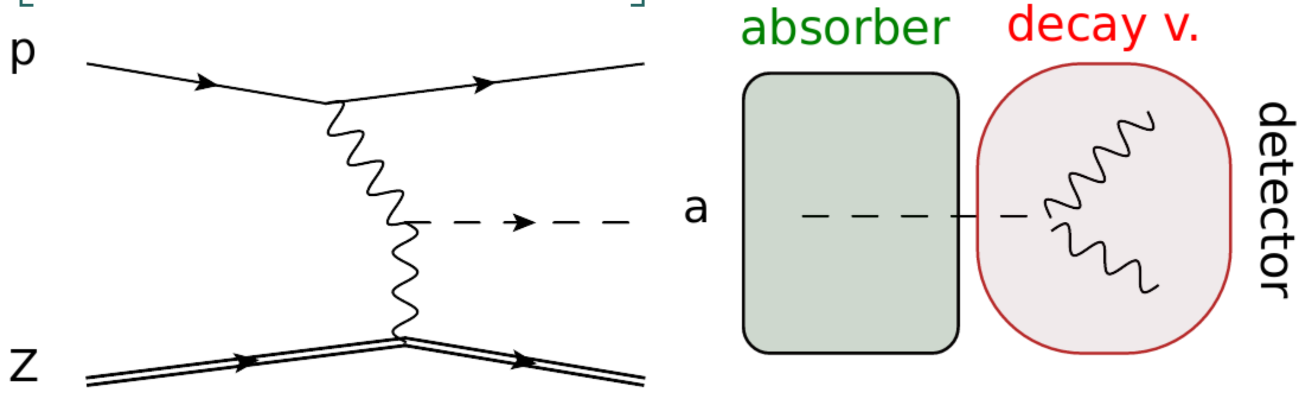

Observation of fast spinning black holes rules out very light axions [Arvanitaki et al. 1411.2263]

GW signals from the cloud are also possible:

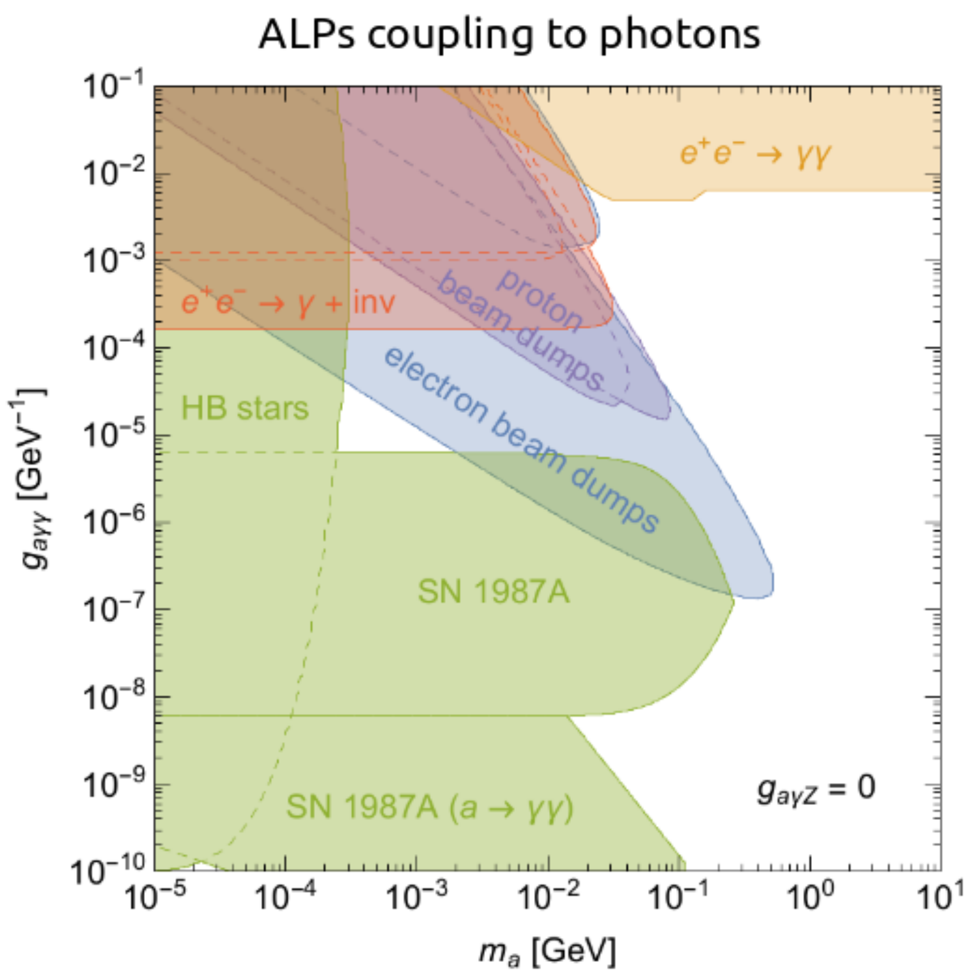
- graviton emission from level transitions
- axion annihilations into gravitons
- bosenova collapse of the axion cloud

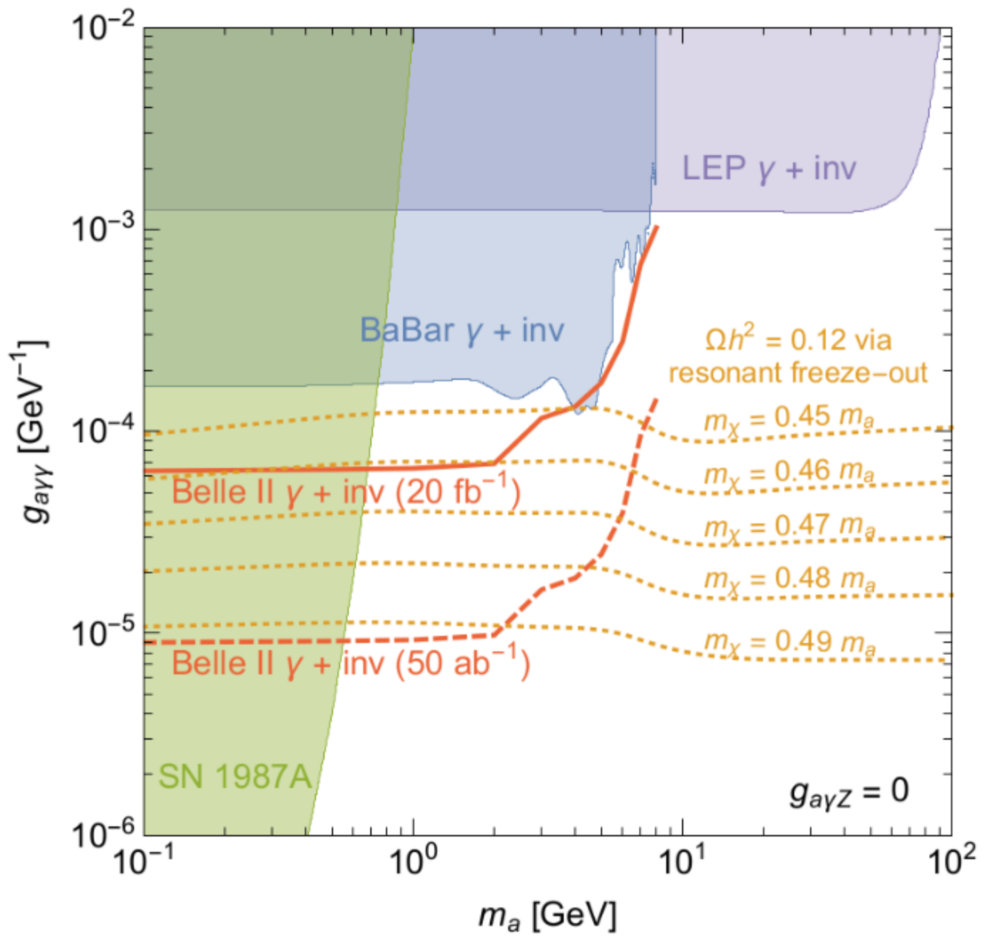
# Beam dumps/ colliders

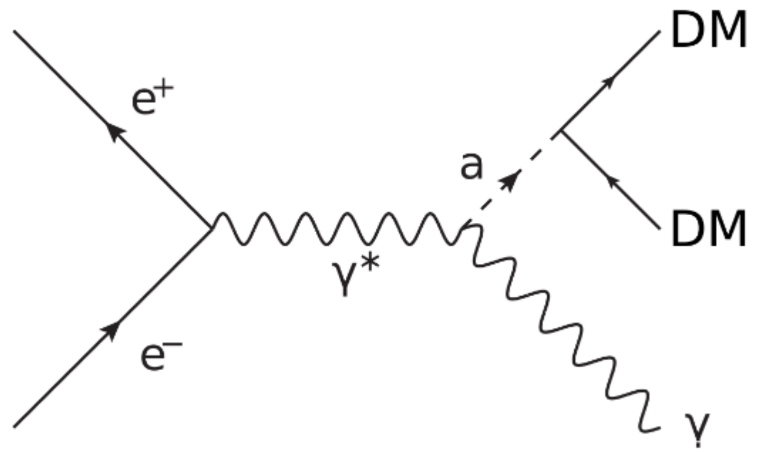
[Masso & Toldra 9503293]




[Fig. from Dobrich]




[Dolan et al. 1709.00009]

# Galactic scale dynamics

Ultralight/ fuzzy dark matter axions $m \sim 10^{-22}$–$10^{-21}$ eV E.g. [Hui et al.1610.08297]

Macroscopic de Broglie wavelength ~ kpc , expect a solitonic core in DM halos

Could be related to the cusp-core problem? also the missing-satellite problem?

Suppression of small-scale perturbations

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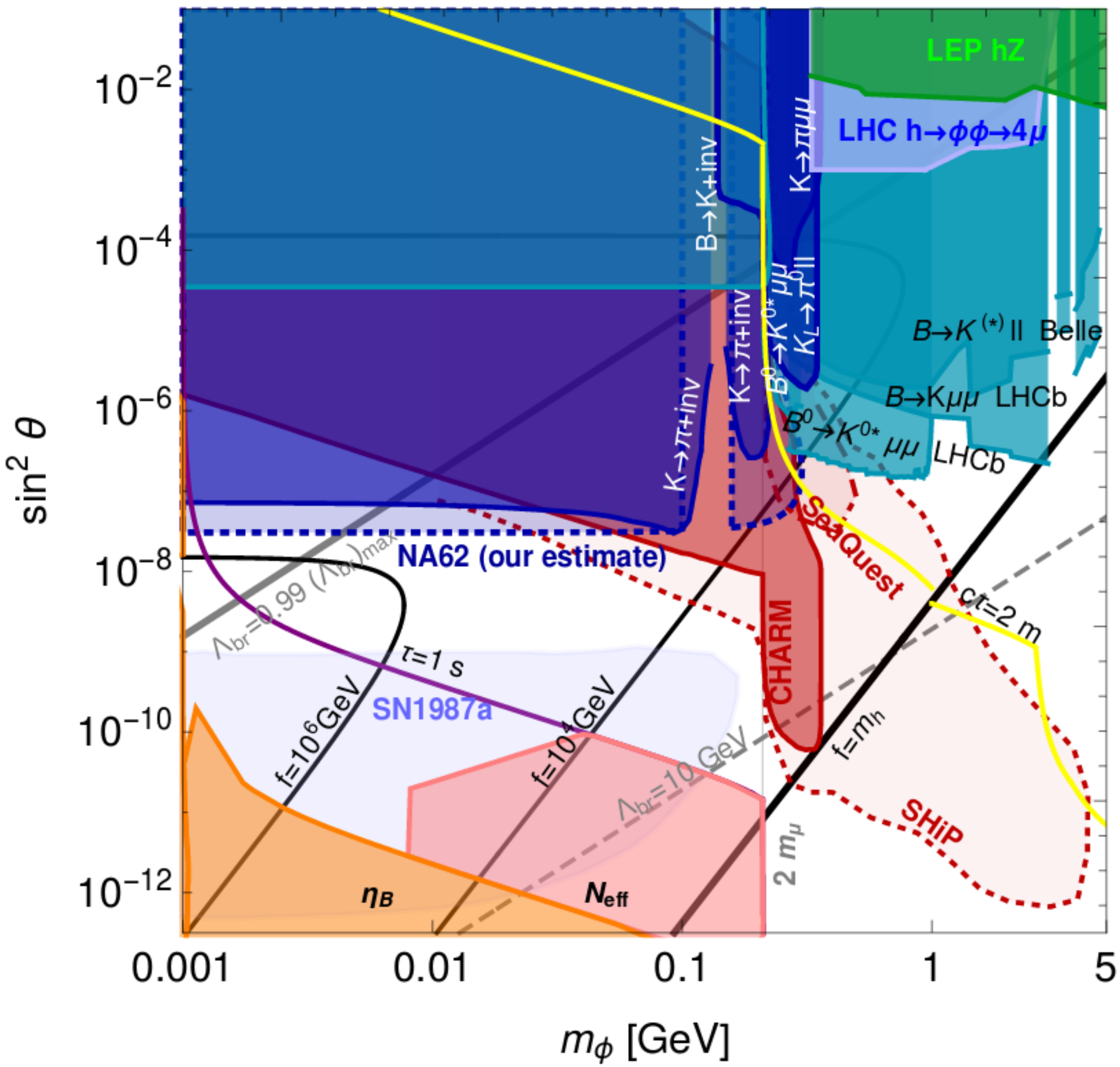
Do QCD axions undergo bose condensation? [Erken et al.1111.1157]

Does rethermalization of axions falling into gravitational potential change the dynamics and produce DM caustic rings in galactic halo?

# Experimental constraints on relaxions

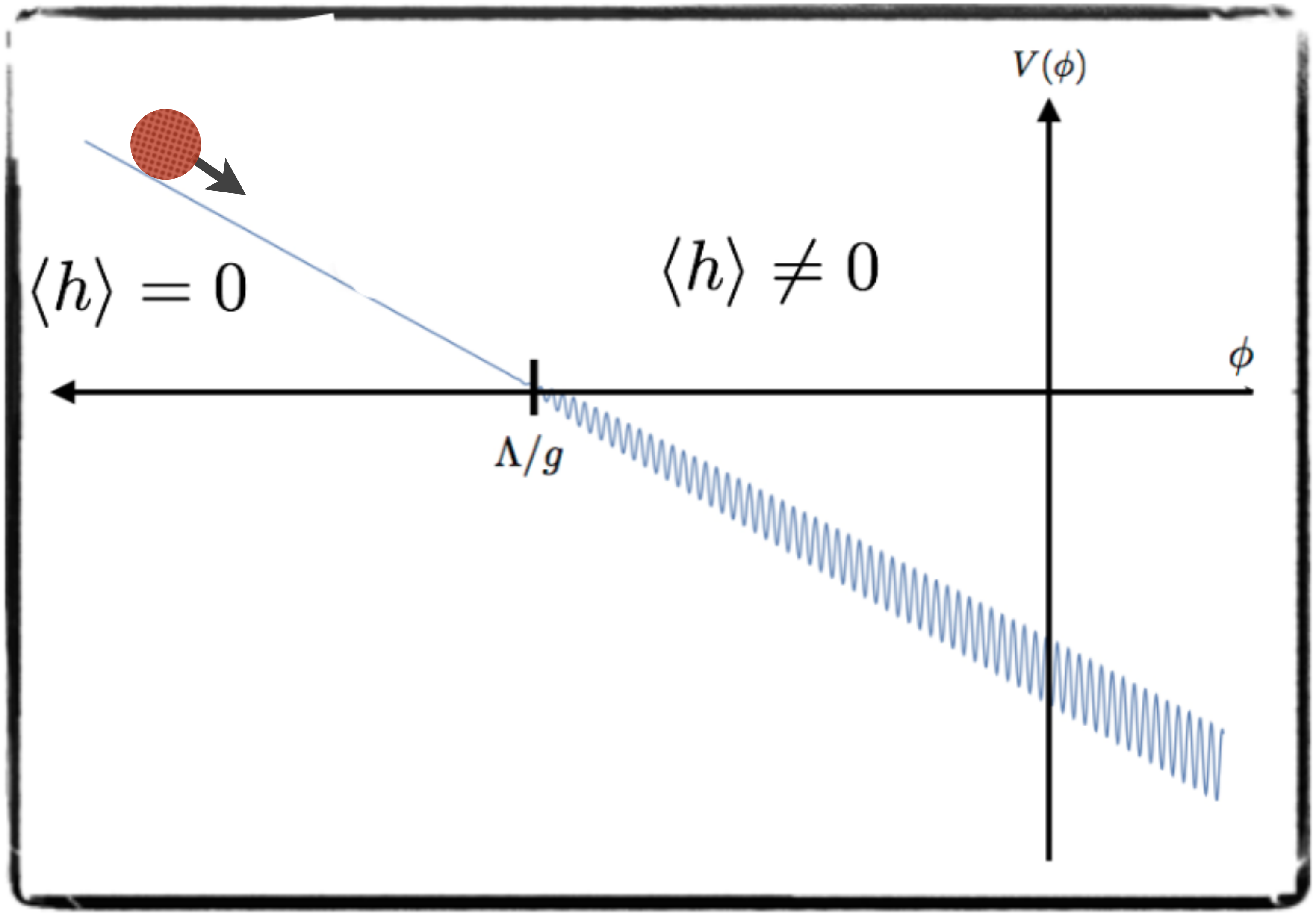



Many constraints:

- Fifth force,
- Astrophysical
- Cosmological
- Beam dumps
- Flavour
- LEP and LHC

[Flacke et al. 1610.02025]

# Relaxions




Attempt to solve the EW hierarchy problem with cosmological history

Very worrying theoretical problem, e.g. exponentially many e-folds of inflation needed

But still a new approach, maybe improvements in the model are possible?

[Graham et al. 1504.07551]

$$m_\phi \sim (10^{-20} - 10^2)\,\mathrm{GeV}$$

- New light scalar with very weak couplings
- No signals at the LHC,
- Mixes with the Higgs, detection in precision experiments/ astrophysics/ cosmology

# Astrophysical constraints

Many interesting effects, e.g.

- ALP photon conversion in Milky Way's magnetic field after emission from SN

$$g_{a\gamma} \lesssim 5.3 \times 10^{-12}\ \text{GeV}^{-1}, \quad \text{for} \quad m_a \lesssim 4.4 \times 10^{-10}\ \text{eV}$$

[Payez et al. 1410.3747]

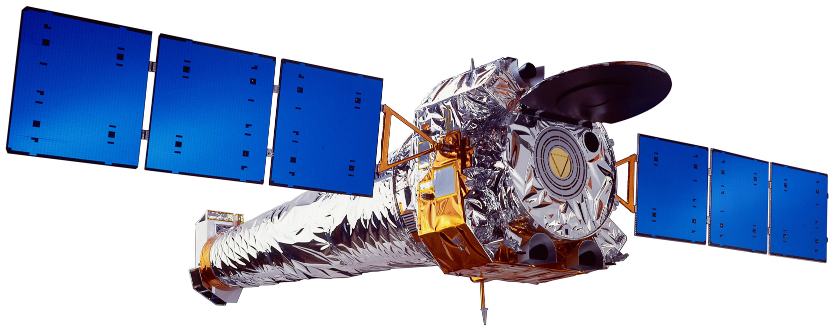
- Reduced opacity of the universe to very high energy photons, energy > 50 GeV

Photons from blazars oscillate into axions and back again

Assumptions about the extra-galactic magnetic field? [De Angelis et al. 0707.4312]

- Constraints from X-ray spectrum of the centre of the radio galaxies in the Virgo cluster

Observations by Chandra



[M.C. David Marsh et al. 1703.07354]

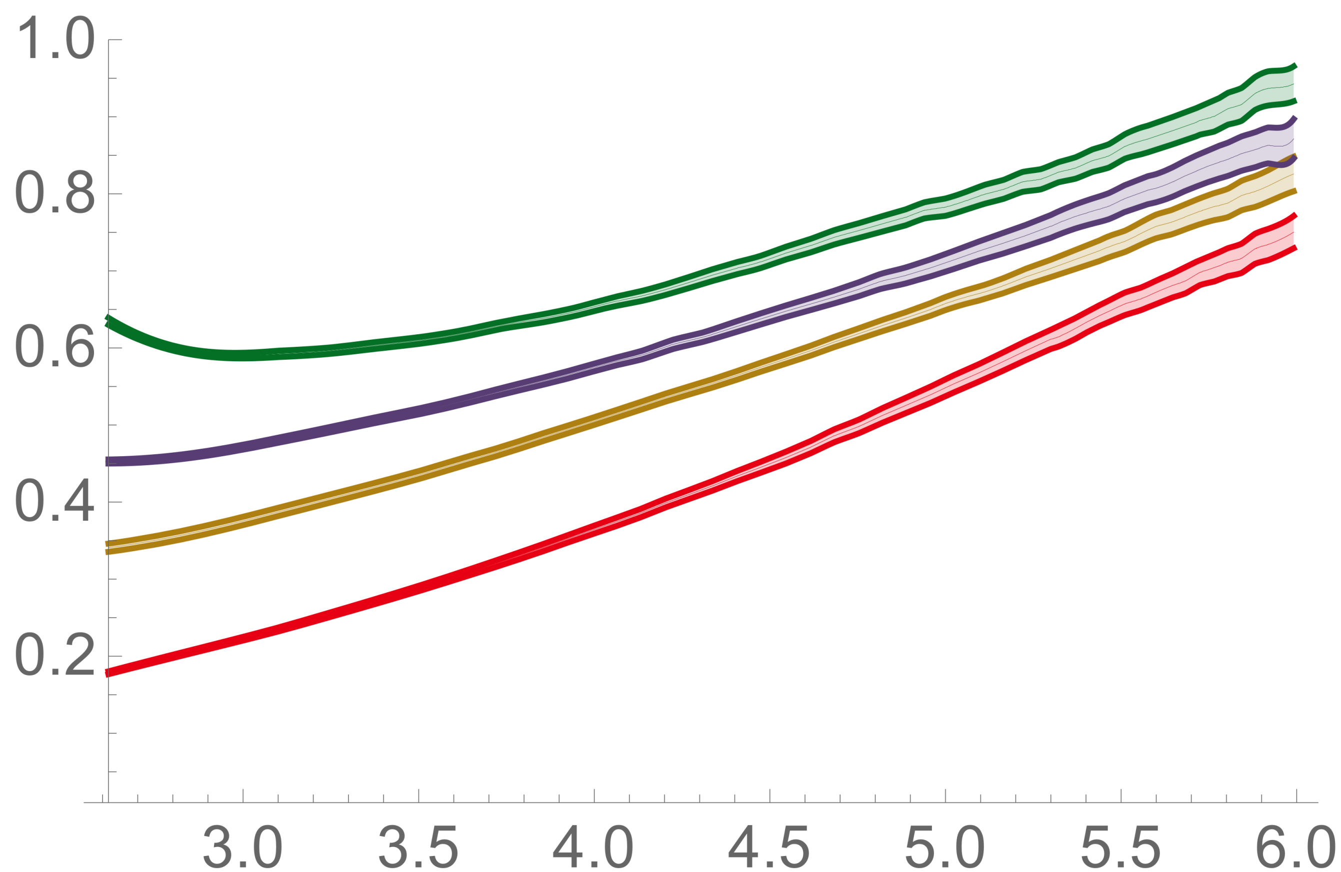
# QCD axion details

# String length per Hubble volume

Energy stored in string network at the time of QCD phase transition proportional to average length of strings per Hubble patch

We find a log increase in this, robust to changing the initial conditions

string length per Hubble patch




$\log(\alpha)$

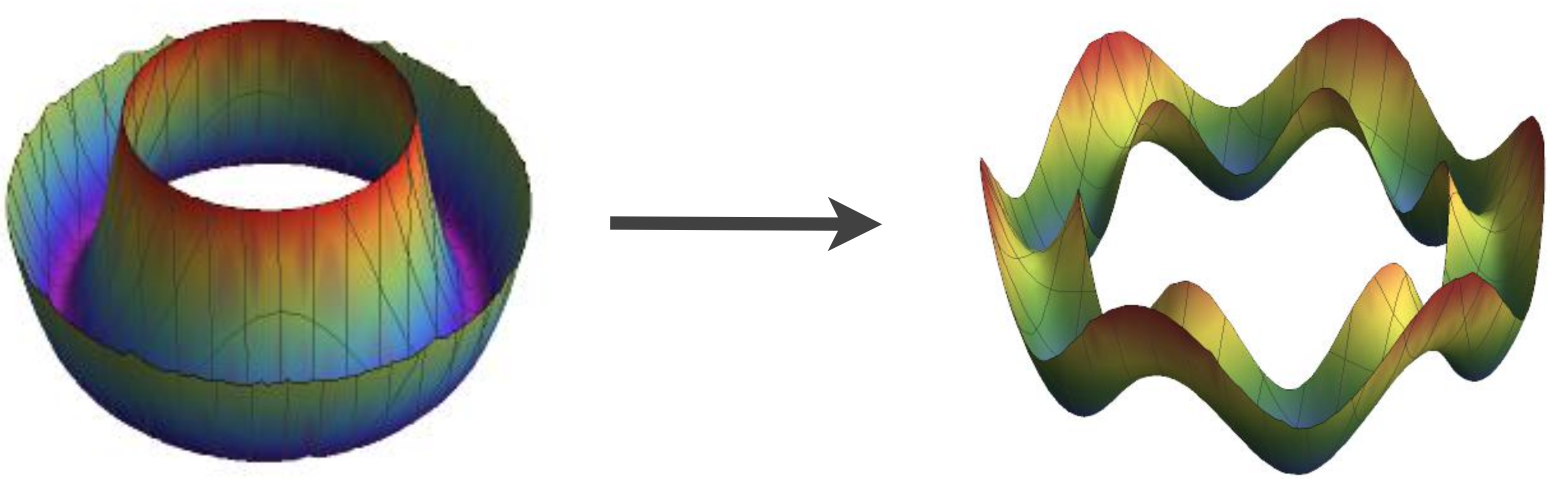
If extrapolation is valid, grows to ~15 at QCD scale!

Changes the prediction for the axion DM mass by a factor ~ 10

# Domain walls

Two populations of axions released due to topology: those emitted by strings just before axion mass turns on, and those emitted when the network is destroyed (along with the misalignment contribution)

Need to also study the dynamics of domain walls



Depends on the anomaly coefficient:

- $N = 1$, unstable, automatically decay
- $N > 1$, stable in the absence of extra PQ breaking, current simulations seems marginally ruled out unless fine-tuned

# Spectrum of axions emitted

Makes a difference of another factor of log in the relic abundance

If string energy is emitted with momentum strongly peaked around the Hubble scale

$$\frac{dP}{dk} \sim \frac{1}{k^m} \qquad \text{with } m > 1$$

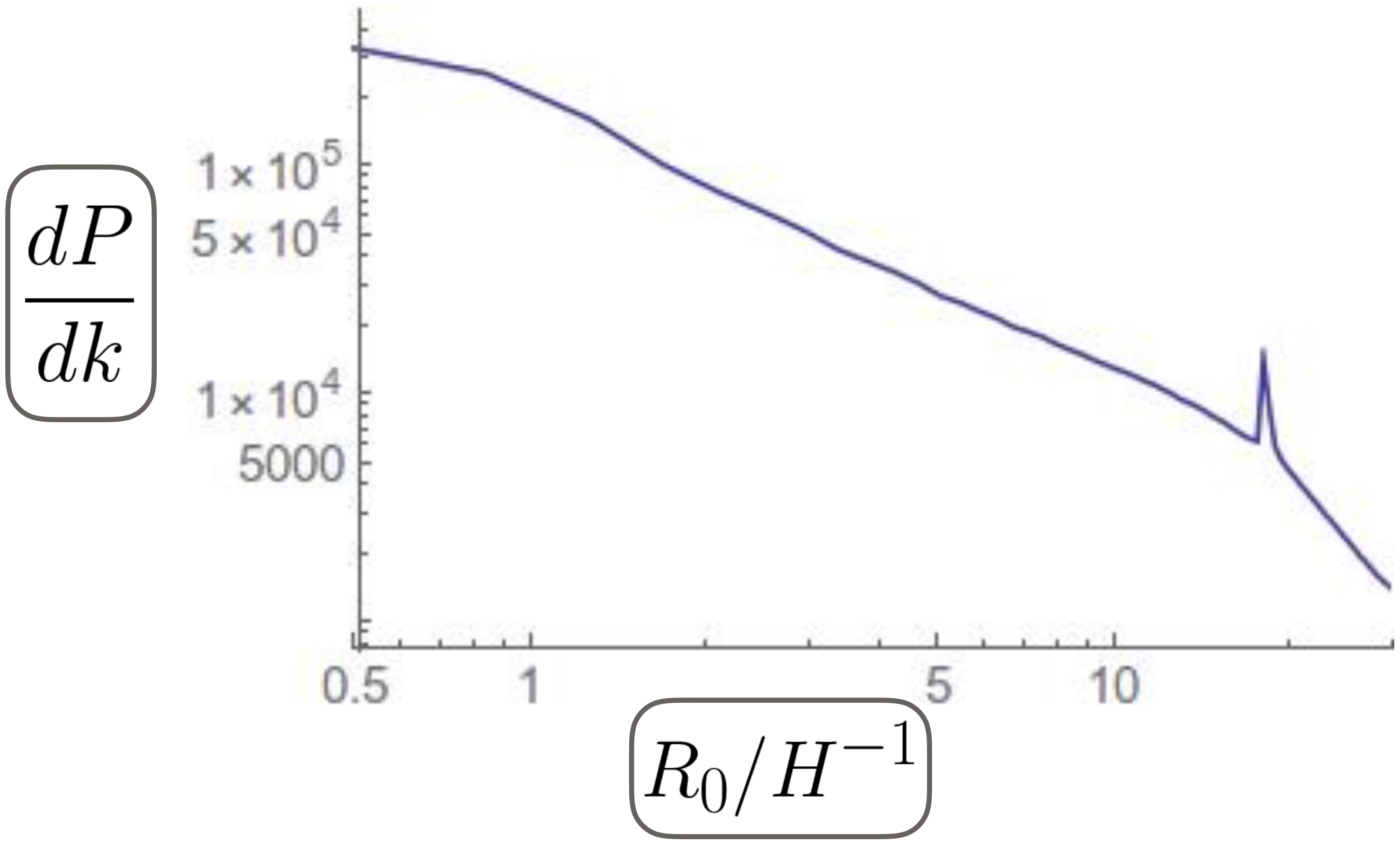
then average momentum of emitted DM axions $\sim H\left(T \simeq \mathrm{GeV}\right)$

Whereas if $$\frac{dP}{dk} \sim \frac{1}{k}$$

The average momentum is $\sim \log \alpha \times H\left(T \simeq \mathrm{GeV}\right)$

# By loops/ full simulation

Studying individual loops, we find a power spectrum ~1/k at small $\log \alpha$ and hints of a stronger power law as the scale separation increases




Matches theoretical belief that as $\log \alpha$ increases behave more like local strings

Collapse time starts to match solution with Nambu-Goto action, and shows more signs of bouncing

# Domain walls

Possibly crucial dynamics have previously been neglected

Axion mass becomes cosmologically relevant when

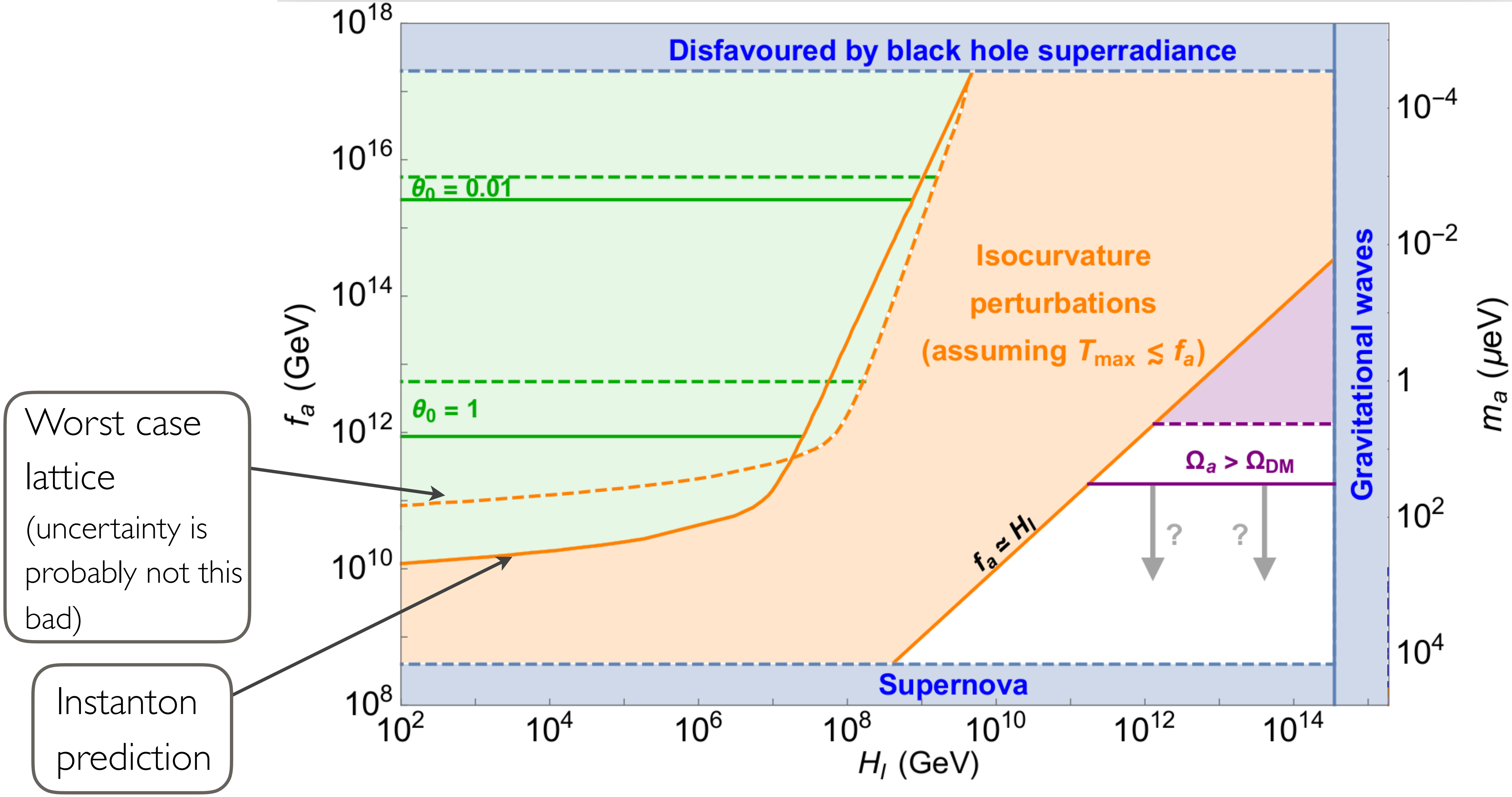
$$m_a(T_0) \simeq H(T_0)$$

Subsequently it increases fast, and quickly $m_a(T) \gg H(T_0)$

But typical size of domain walls still $\sim 1/H(T_0)$, momentum of lowest harmonics $\sim H(T_0)$ emission at higher harmonics strongly suppressed

Could this delay the destruction of the domain wall network? Potentially a big effect on the relic abundance?

# Cosmology




If PQ symmetry is broken before inflation, constant axion VEV over observable universe