Axions
in the sky and the lab

Fundamental cosmology meeting
Teruel 11-13 Sep 2017

Javier Redondo
(Zaragoza U. & MPP Munich)

The strong CP "issue"

- CP violation in QCD sector: CKM angle $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\mathrm{QCD}} + N_f \delta$

$$\mathcal{L}_{\mathrm{SM}} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta/2} & 0 & \dots \\ 0 & m_d e^{i\delta/2} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\,\theta_{\mathrm{QCD}}$$

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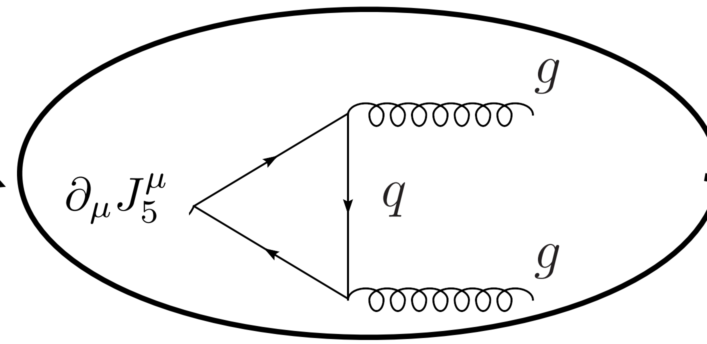

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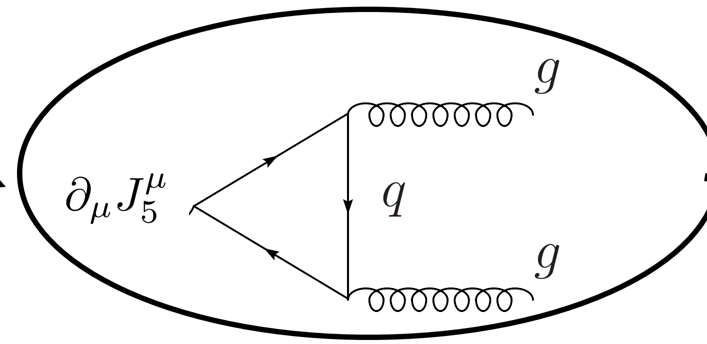

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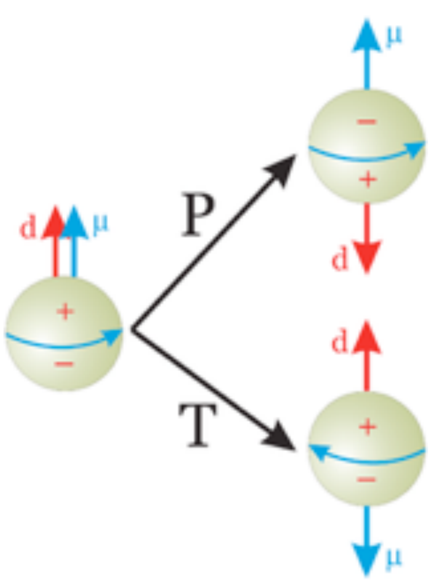
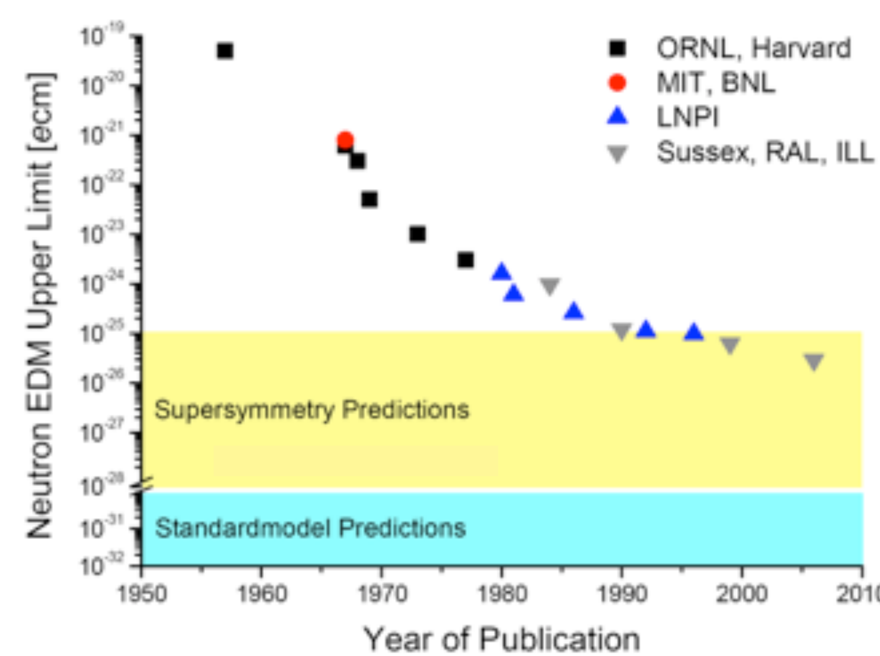


- **Neutron EDM** (Guo 1502.02295)

$$d_n = -4 \times 10^{-3} \times \theta\,[\mathrm{e\,fm}]$$

- **Experimental upper limit** (Grenoble hep-ex/0602020)

$$|d_n| < 3 \times 10^{-13}\,[\mathrm{e\,fm}]$$



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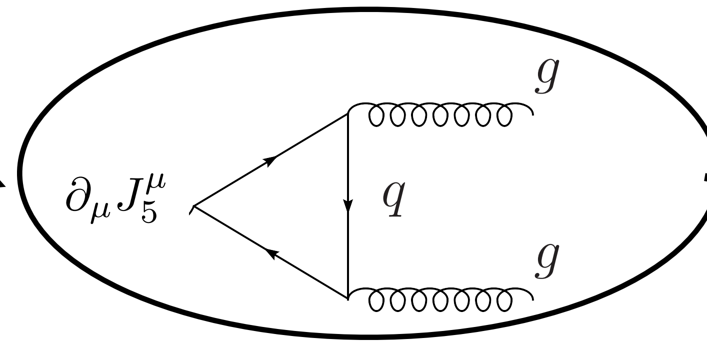

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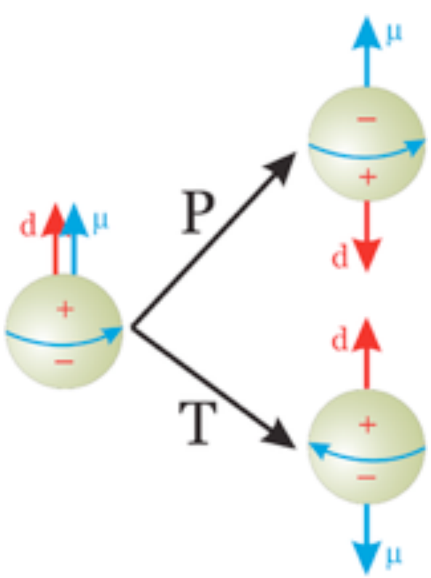

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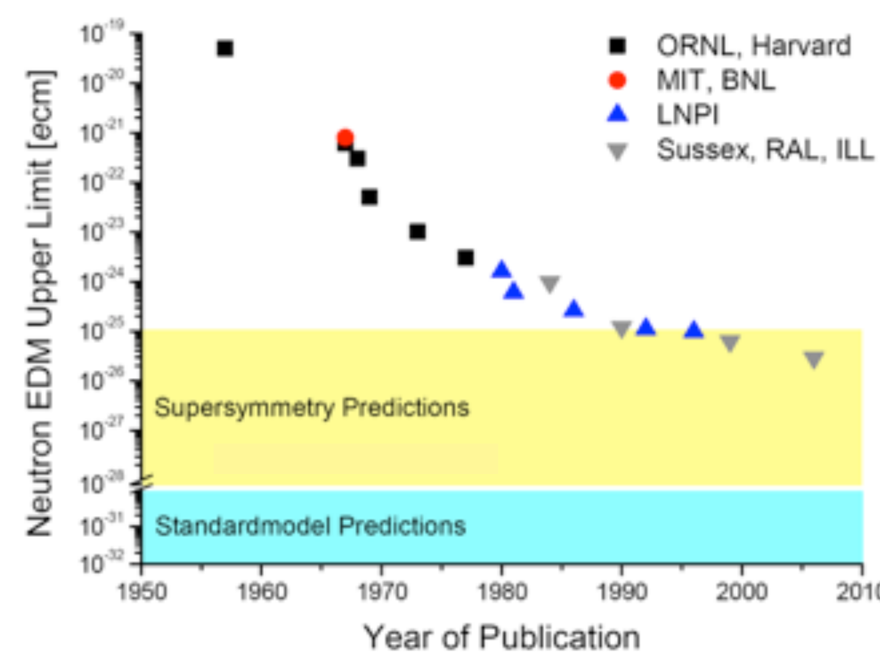
- **Why is** $\theta < 10^{-10}$ **?**



Driving θ dynamically to zero with BSM physics

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

It is experimentally obvious that we live in a

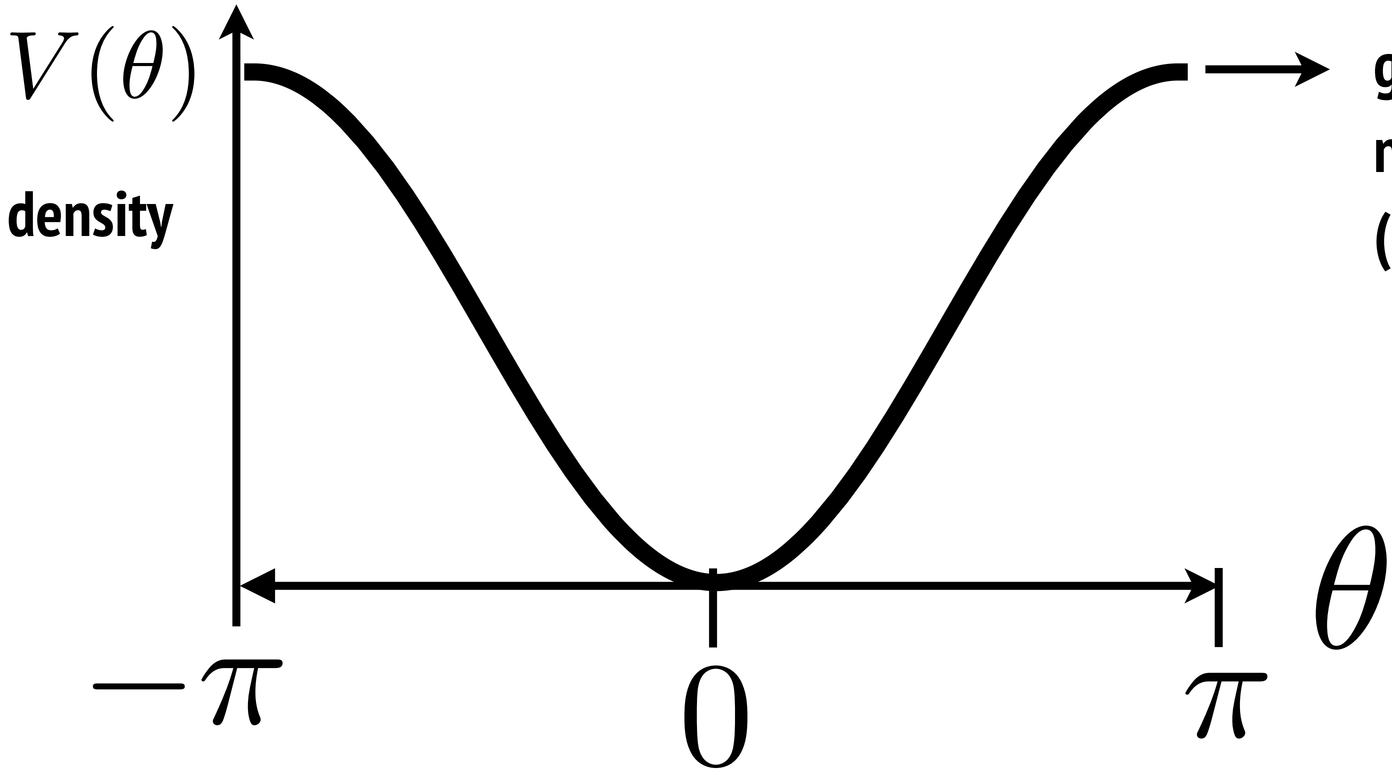
grangian.

If all fermions which couple to the non-Abelian

QCD vacuum energy is minimised at $\theta = 0$!

- Any theory promoting θ to a dynamical field, $\theta(t, \mathbf{x})$,will automatically set $\theta \to 0$ after some time...

Potential energy density



generated by QCD non-perturbative dynamics (instantons)

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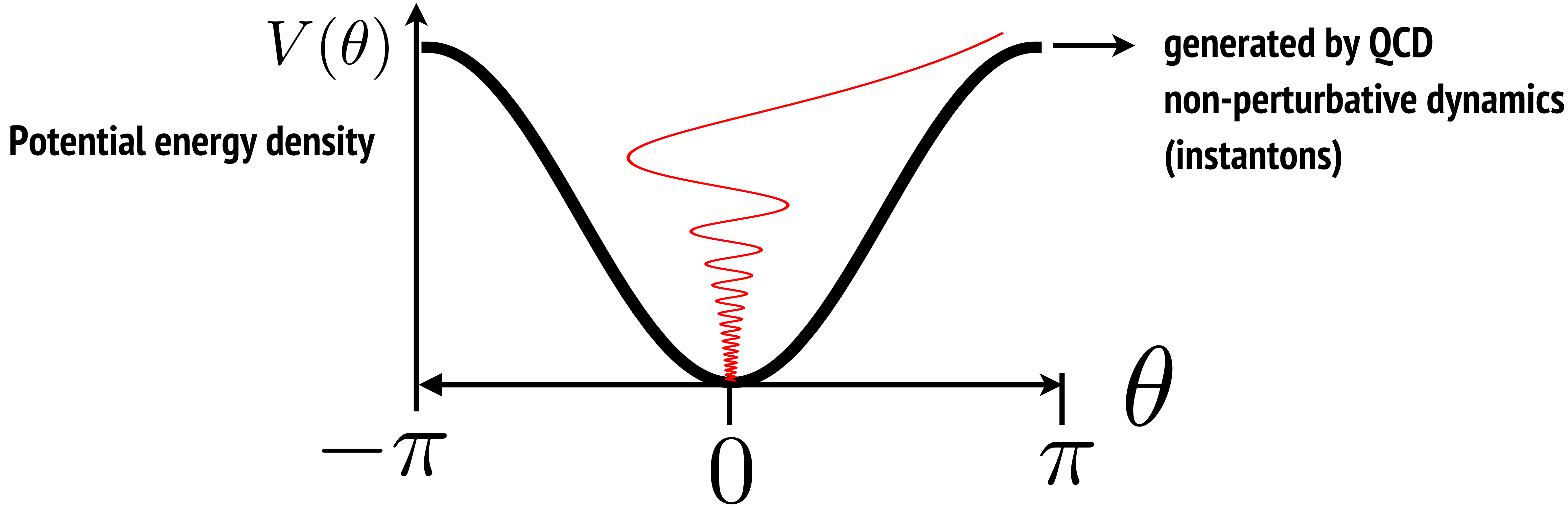

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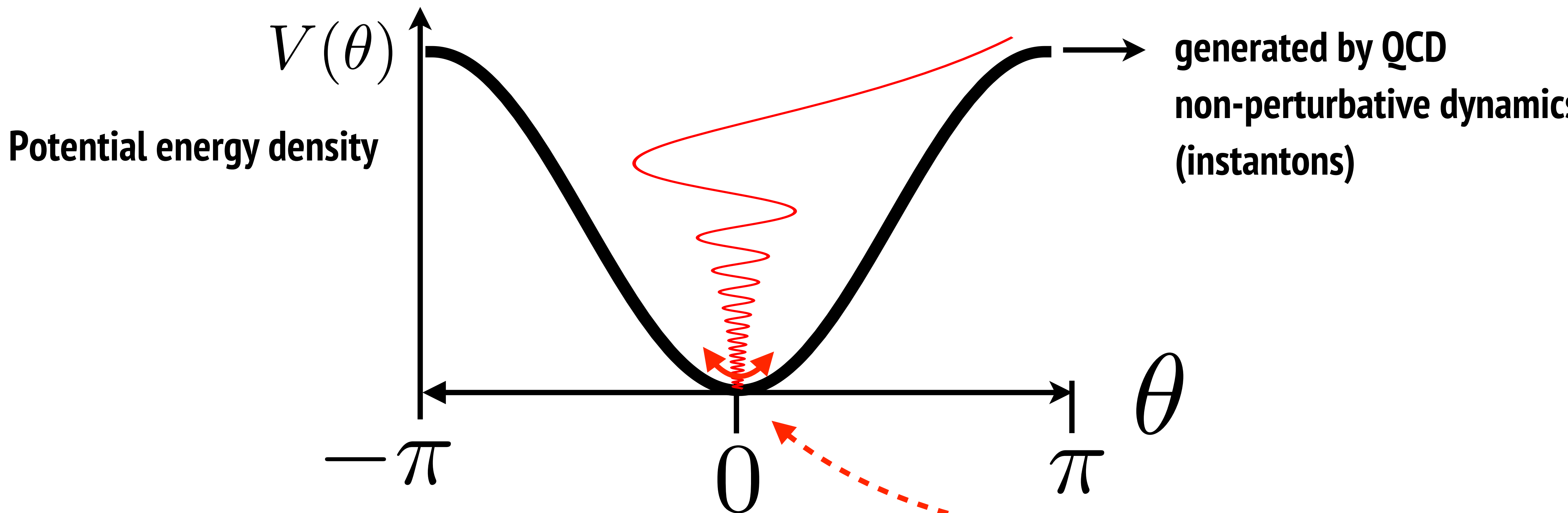

- PQ Mechanism: Global U(1) axial symmetry, spontaneously broken, colour anomalous -> Goldstone boson

$$\mathcal{L}_\theta = \frac{1}{2}(\partial_\mu\theta)(\partial^\mu\theta)f_a^2 - \frac{\alpha_s}{8\pi}G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}\theta$$

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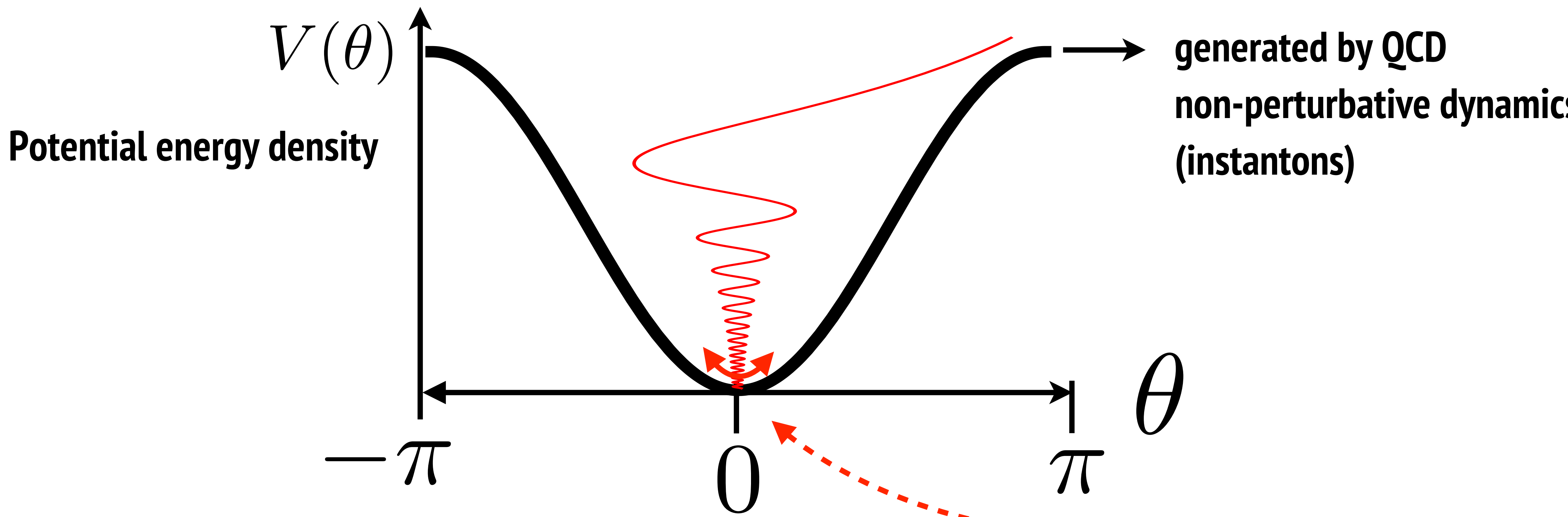

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New Spontaneous symmetry breaking [energy] scale f_a

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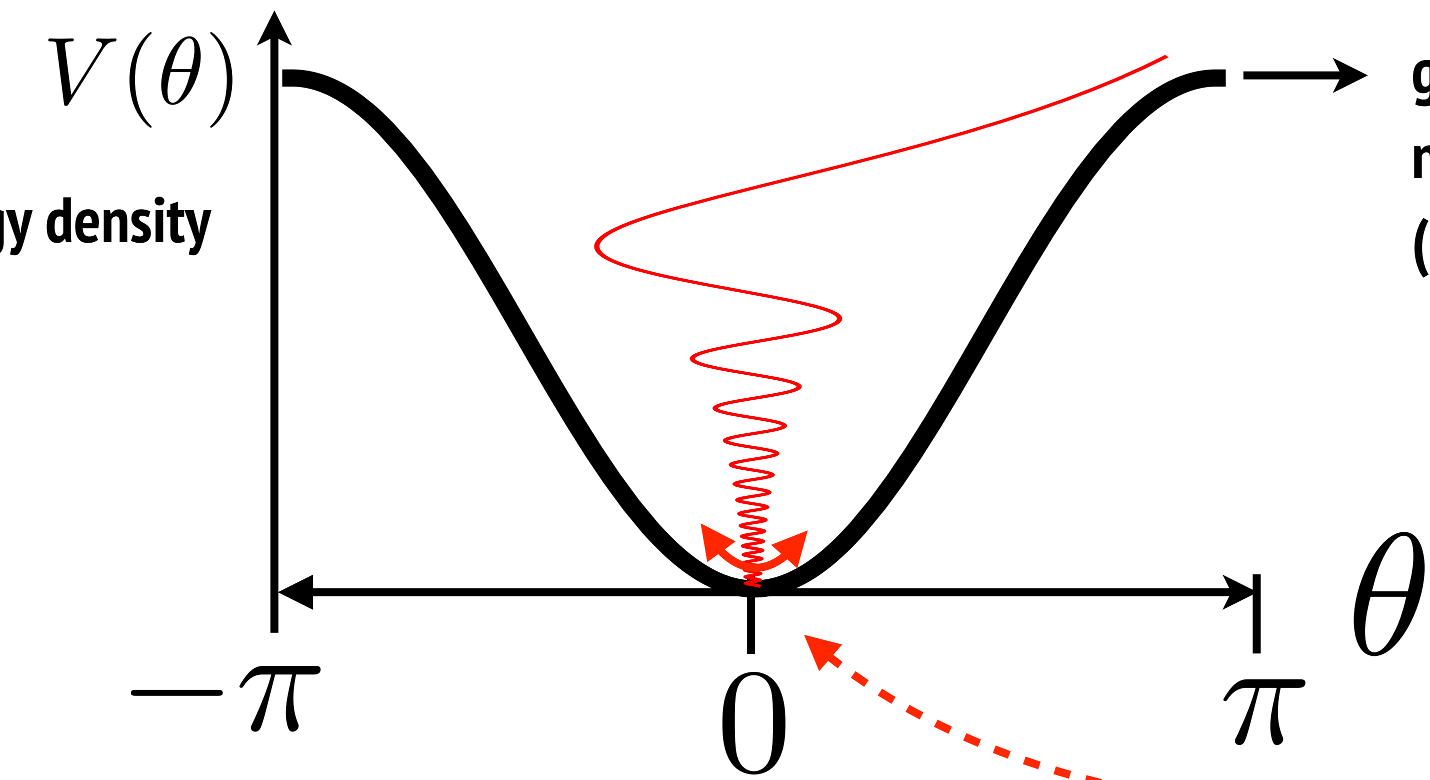

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Canonically normalised θ-field is the QCD AXION! $a(x) = \theta(x) f_a$

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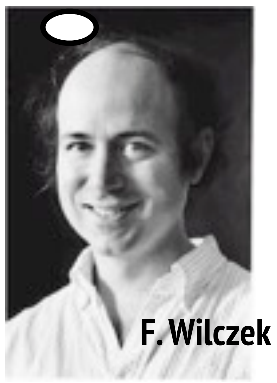

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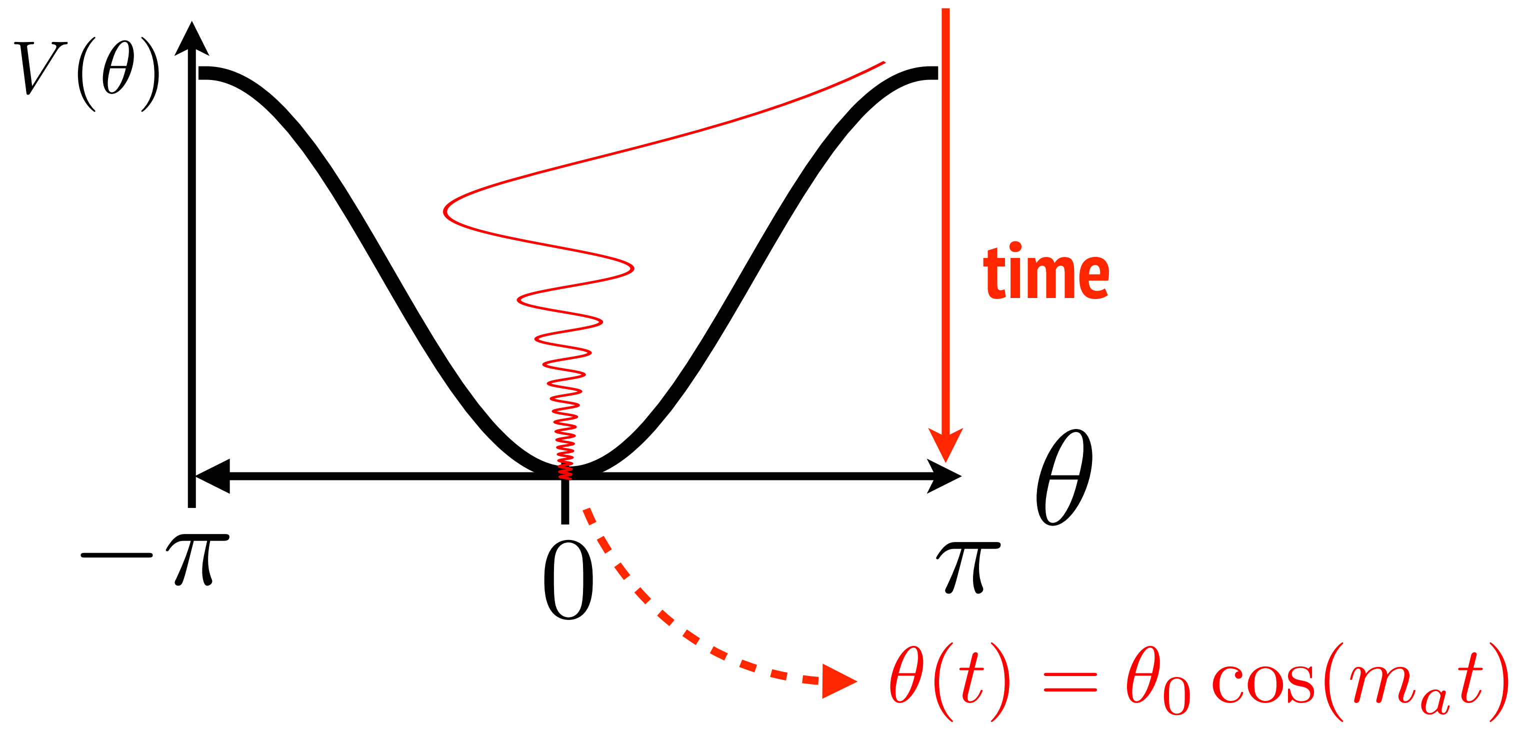
Dark Matters

Axions are dark matter ... to some extent

- High T, no preference for Initial Conditions! At time $t \sim 1/m_a$ axion field seeks its minimum



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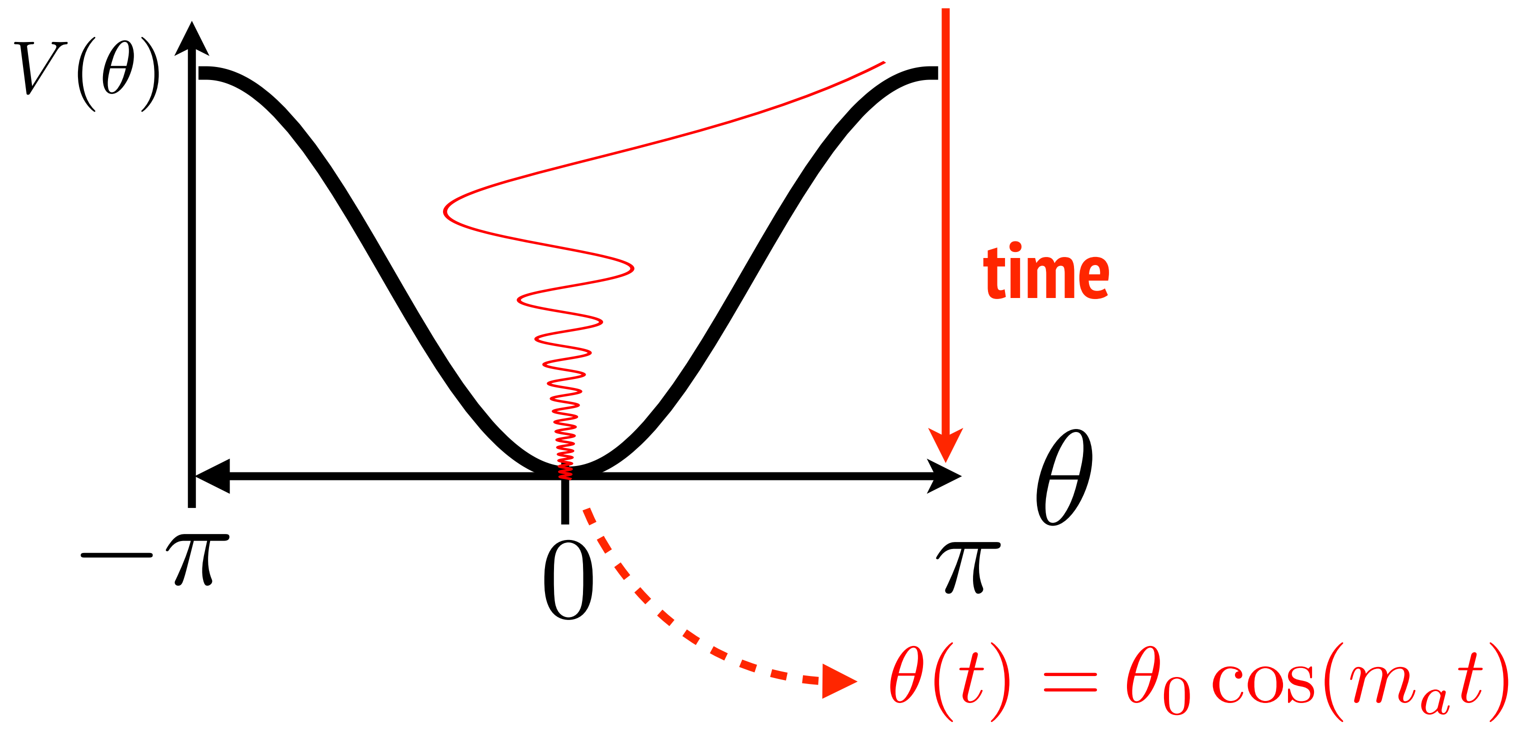

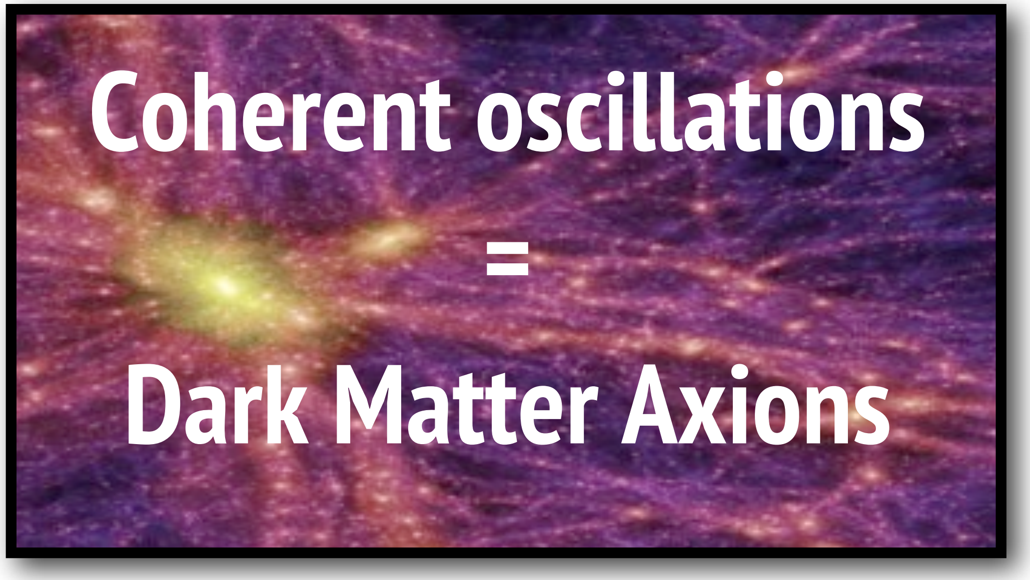

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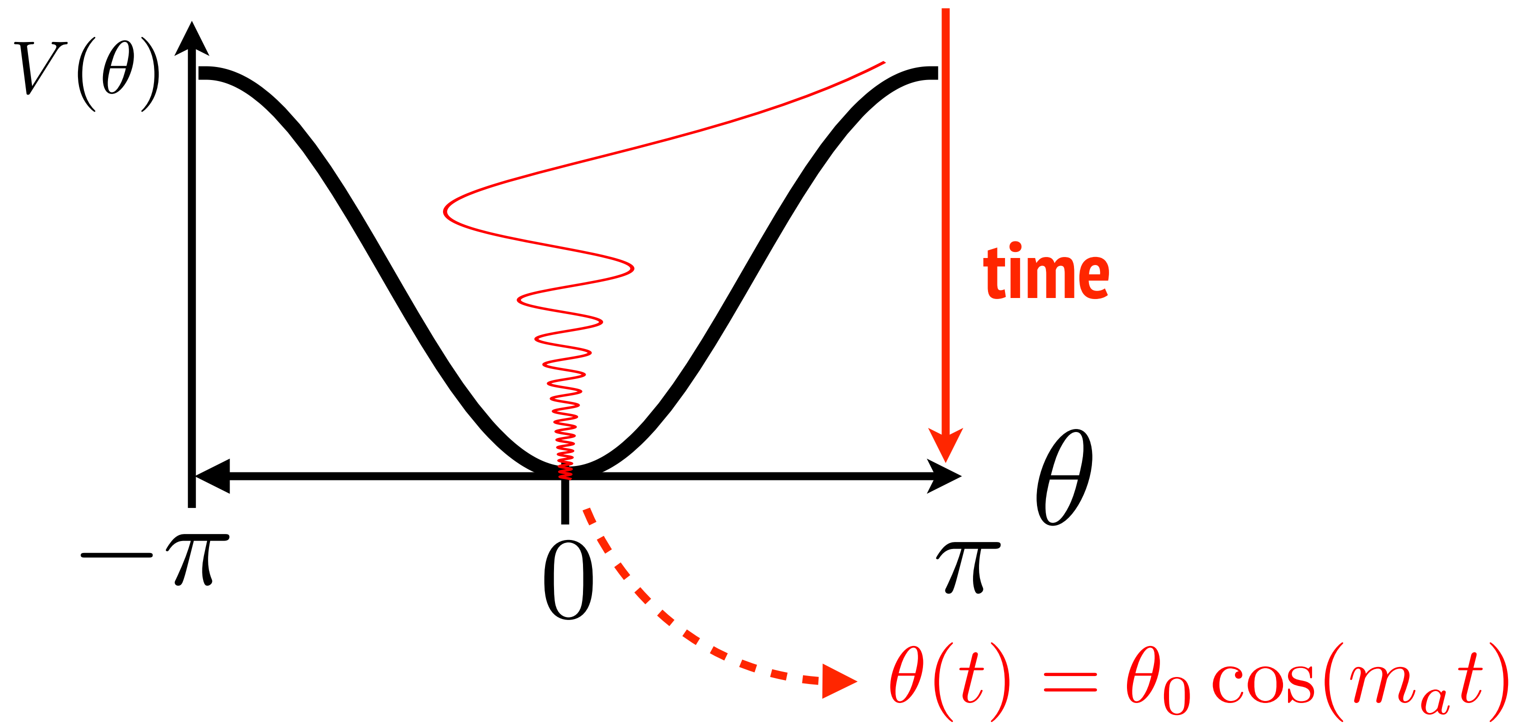

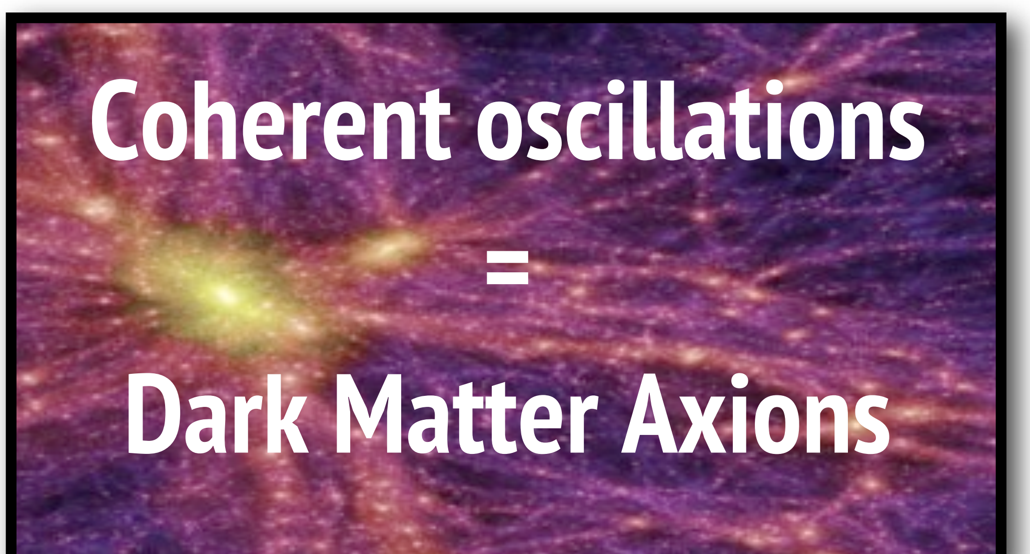

Oscillation frequency

$$\omega = m_a$$

Energy density (harm. oscillator)

$$\rho_{\rm aDM} = \frac{1}{2} m_a^2 f_a^2 \theta_0^2 = \frac{1}{2} (75{\rm MeV})^4 \theta_0^2$$

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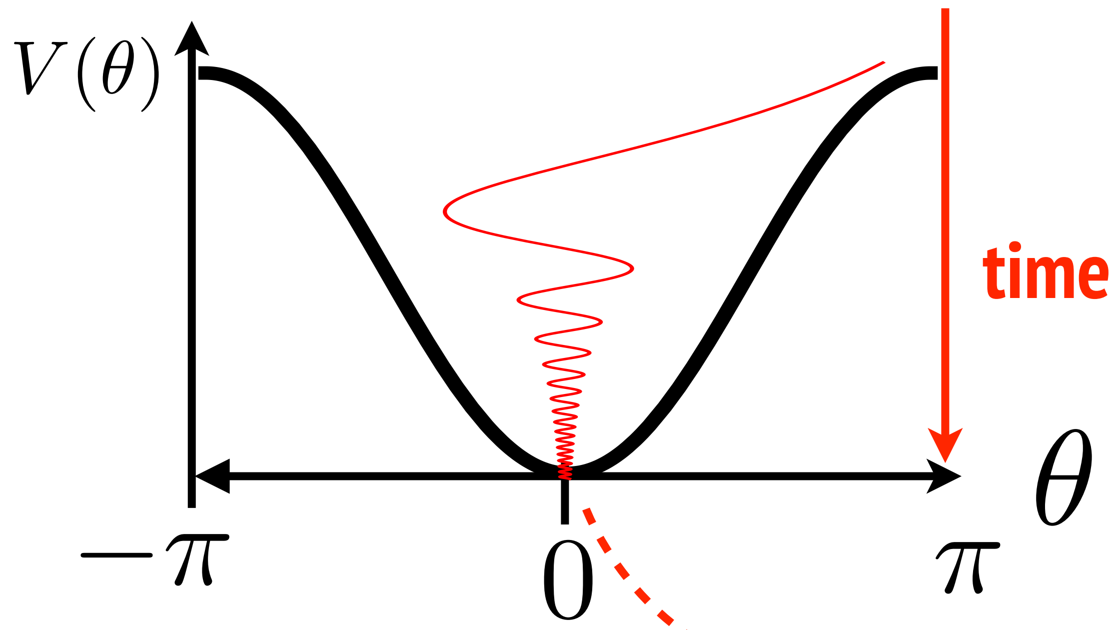
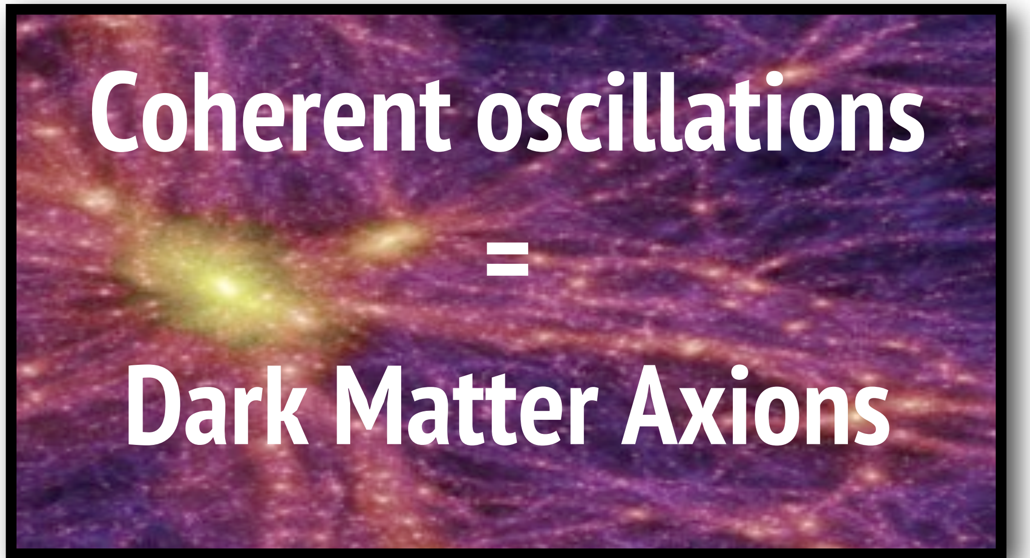


$\theta(t) = \theta_0 \cos(m_a t)$



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- **Some amount of axion Dark matter is unavoidable!**

Axion dark matter

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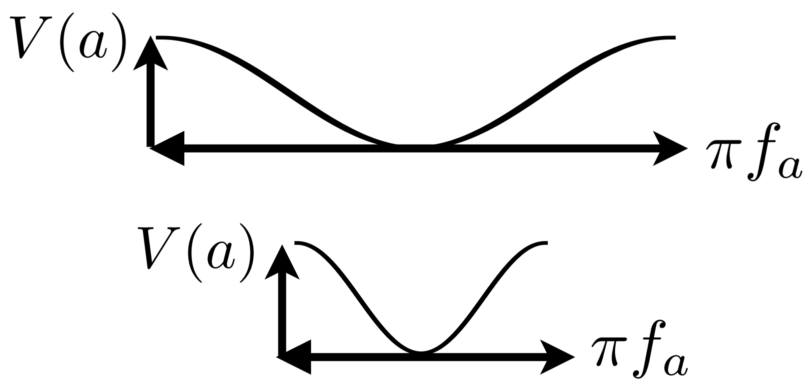
large fa, small acceleration, energy stored longer



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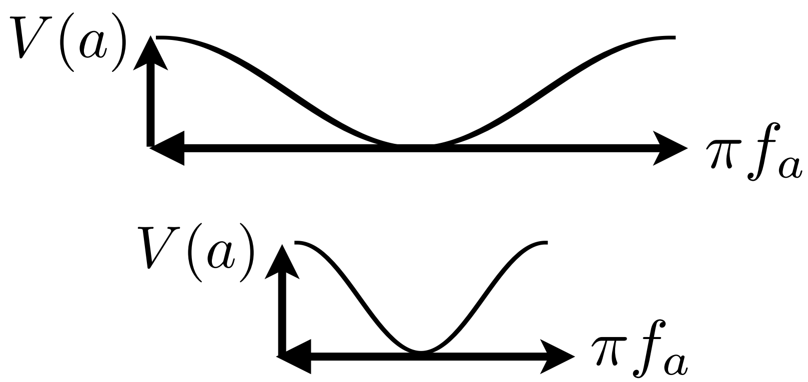
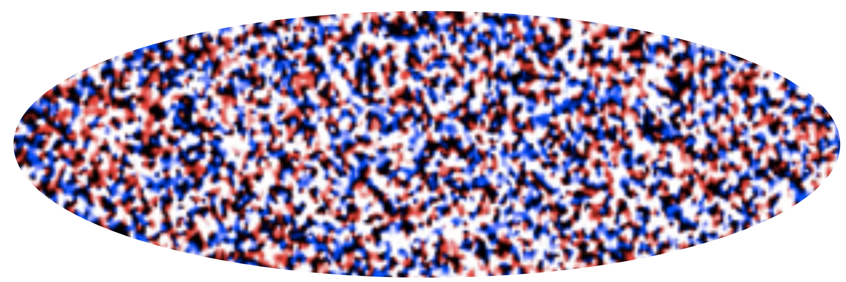


After PQ phase transition, theta IC conditions
no-correlation beyond causal horizon



average over initial conditions! -> prediction!

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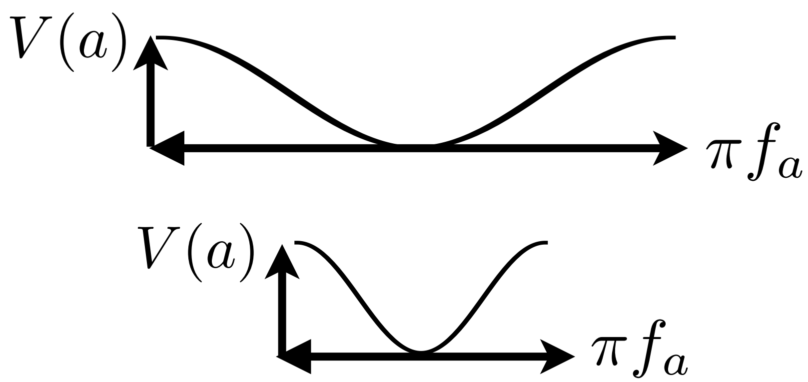

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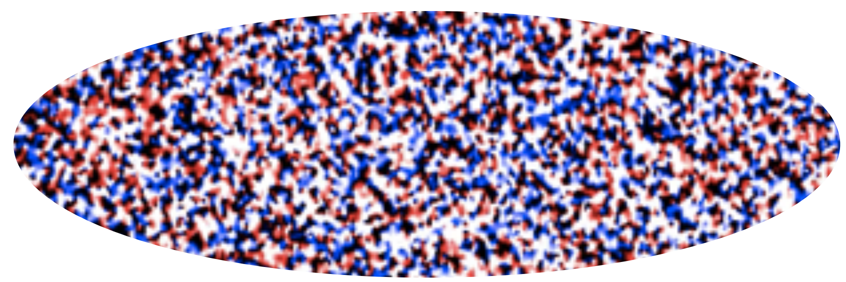

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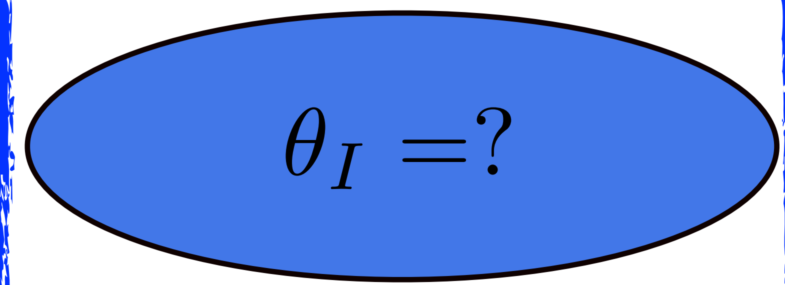
Inflation after PQ phase transition...
one domain stretched beyond our horizon!



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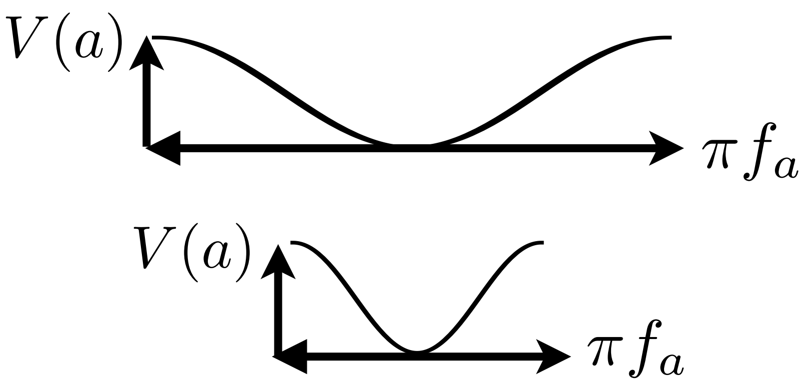

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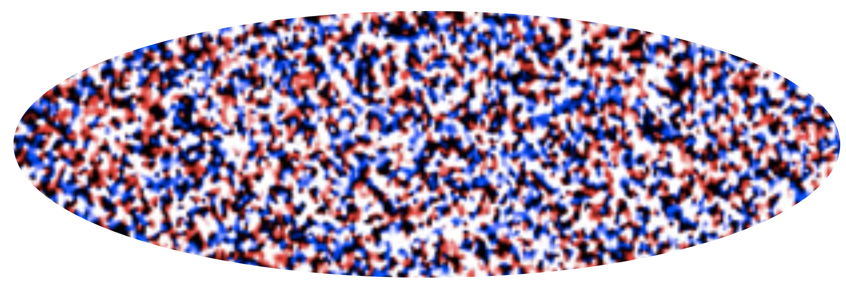

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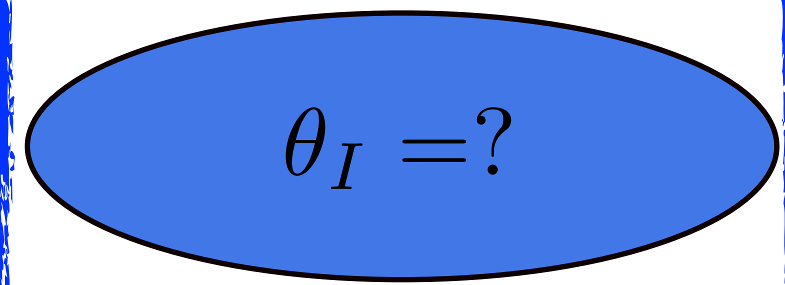

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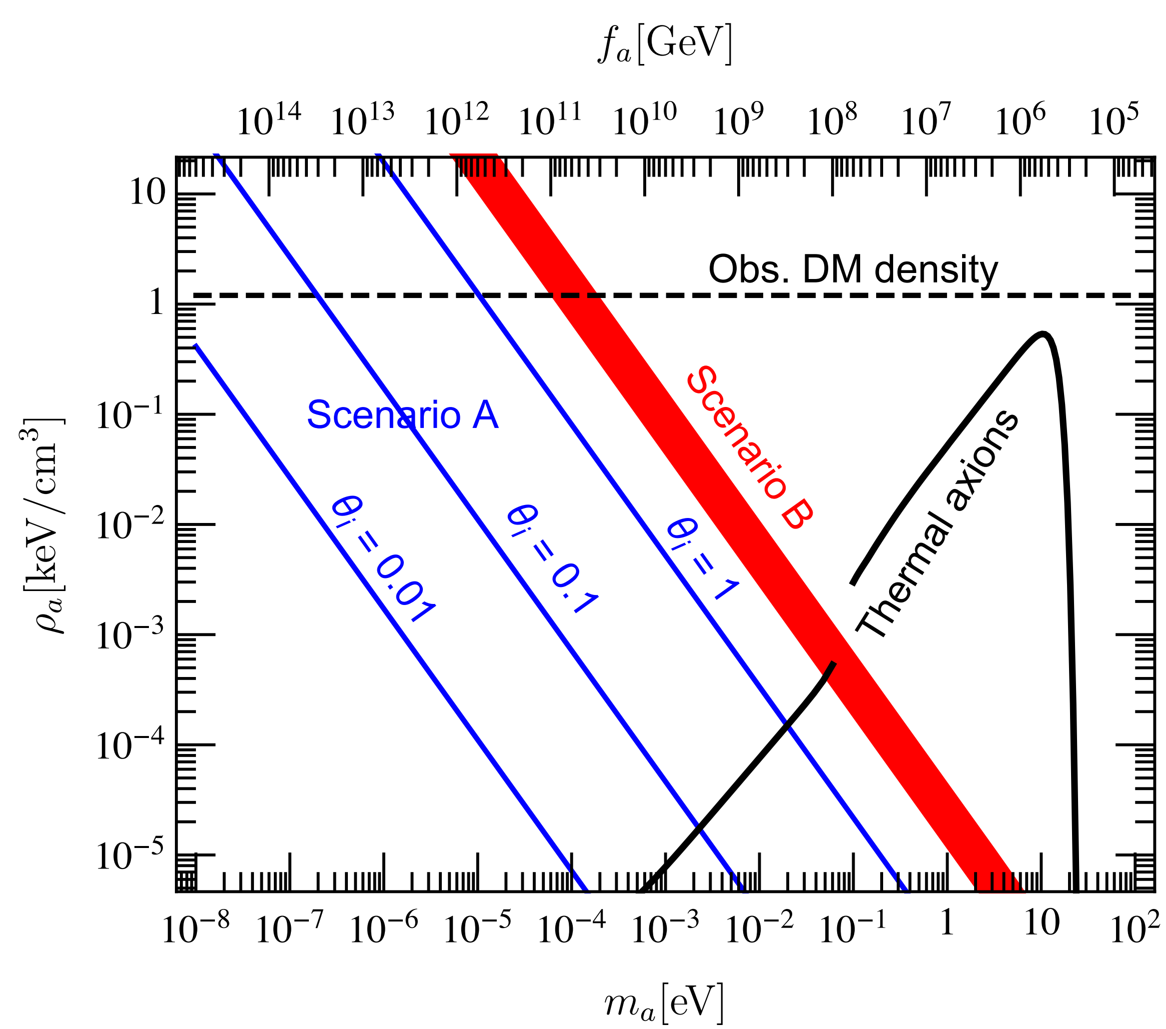
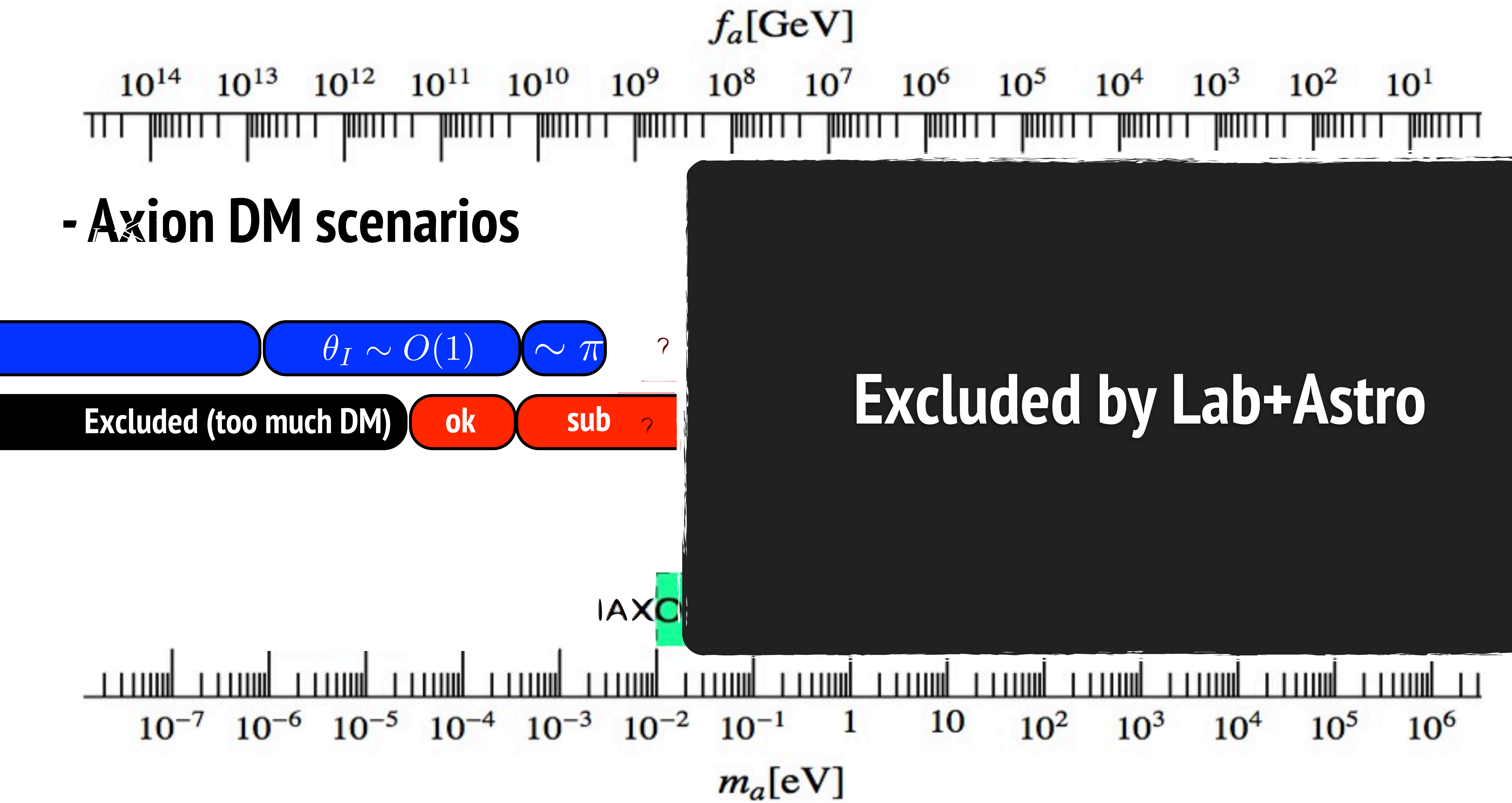


What value of f_a for $\Omega_{cdm} h^2 = 0.12$?

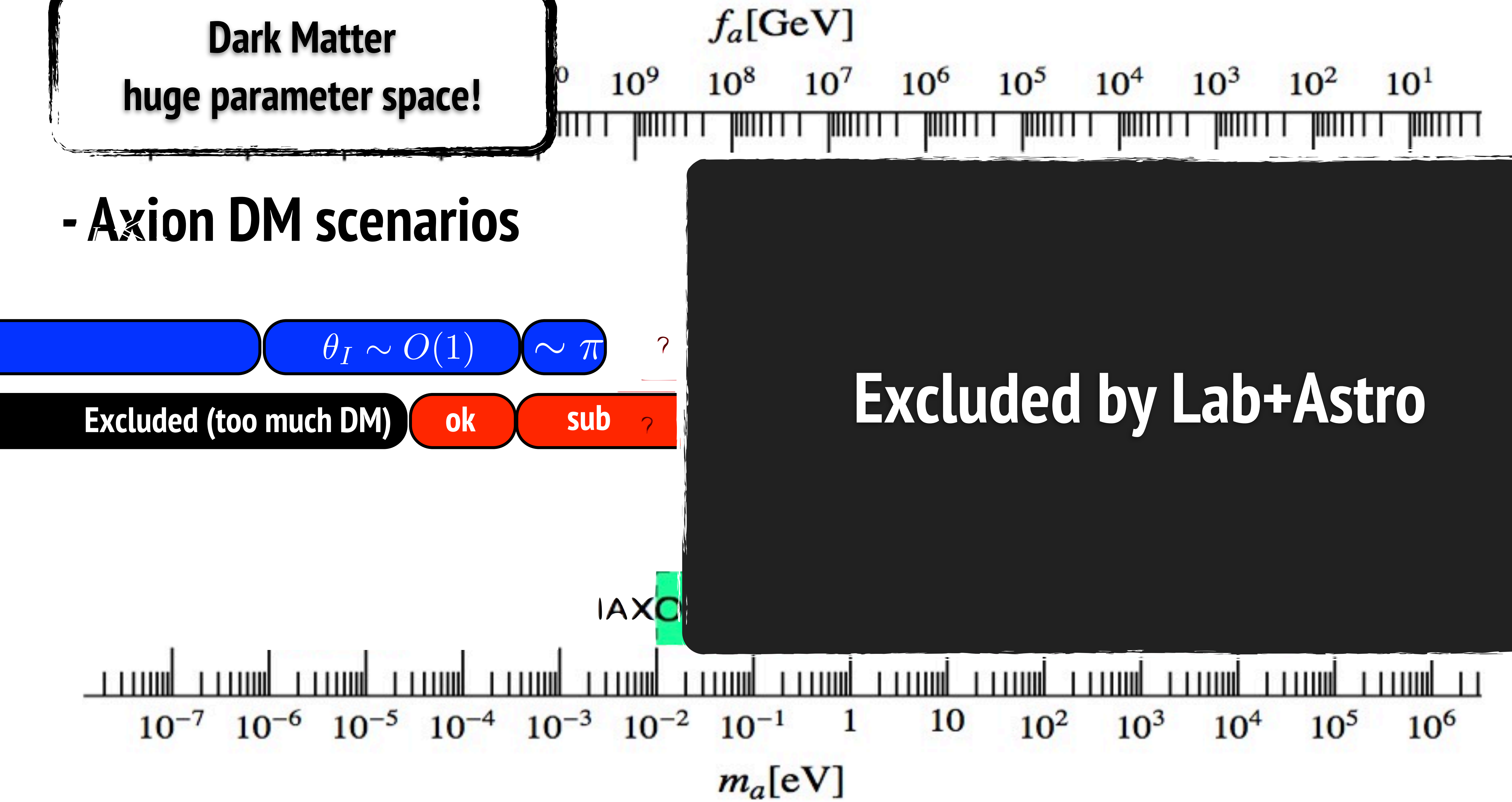


- Less minimal axion models have further possibilities ....

What value of f_a for $\Omega_{cdm}h^2 = 0.12$?

Dark Matter
huge parameter space!

- Axion DM scenarios



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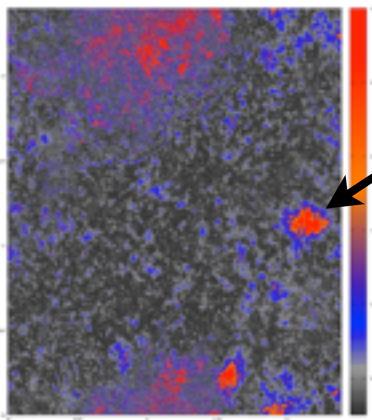
Most important constraints

- PQ breaking after inflation

-> DM inhomogeneous, Axion miniclusters



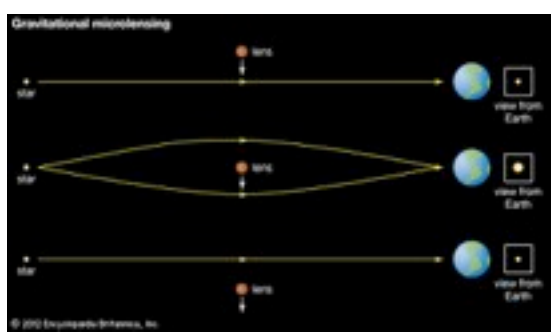
DM density contrast

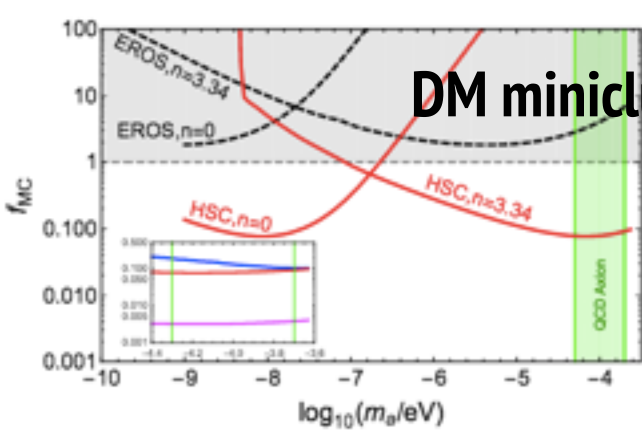
~ 0.1 comoving pc

Mass ~ $M \sim 10^{-12} M_{\odot}$

Merging to heavier masses? $10^{-7} M_{\odot}$?

Microlensing



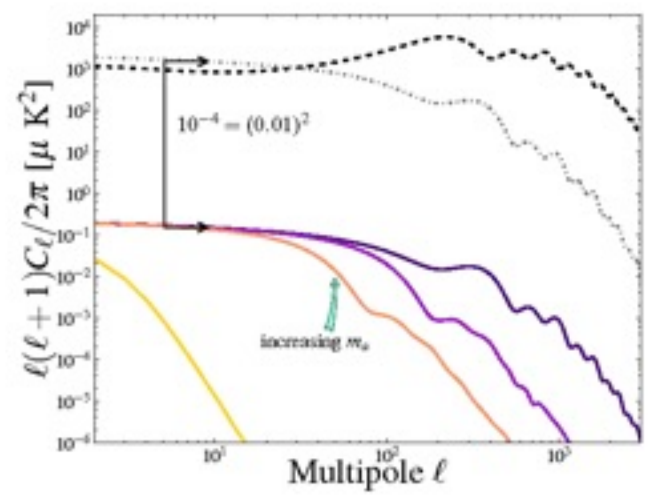


DM minicluster fraction <0.1

Marsh 1701.04787

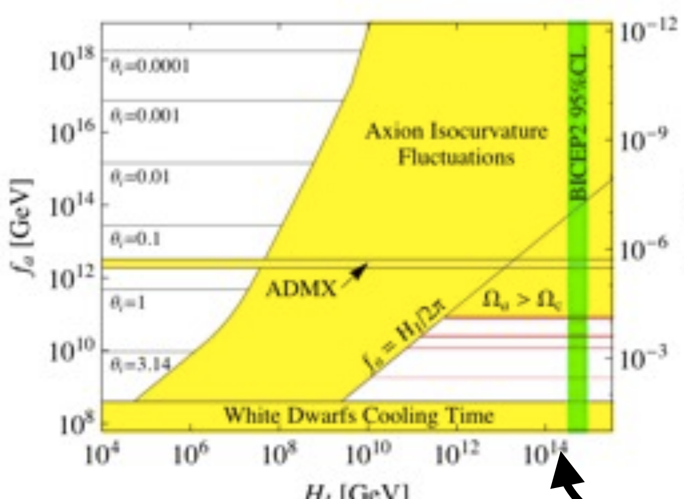
- PQ breaking before inflation

*** Axion fluctuations during inflation -> CMB isocurvature**



- Planck sees no Isocurvature fluctuations, strong limit!

$$P_{\rm iso} = \frac{d\langle n_a \rangle}{n_a} \sim \frac{d\langle a^2 \rangle}{a_I^2} = \frac{H_I^2}{\pi^2 a_I^2} = \frac{H_I^2}{\pi^2 f_a^2 \theta_I^2} < 0.039 P_s = 0.88 \times 10^{-10}$$



Depends on Hubble rate during inflation ... H_I

- If H_I **is measured by next generation CMB Polarisation axion DM is excluded (avoided in some models)**

SMASH : “minimal model” of particle physics and cosmology

- A/J model + non-minimal coupling of scalars to gravity + Higgs portal coupling

- New complex scalar:

- Inflation (mixed direction with Higgs, small non-minimal coupling -> unitarity ok!)
- Reheating calculable (high TR)
- Cures Higgs potential instability (threshold stabilisation mechanism)
- Strong CP problem (with new Quark)
- RN Majorana masses -> seesaw
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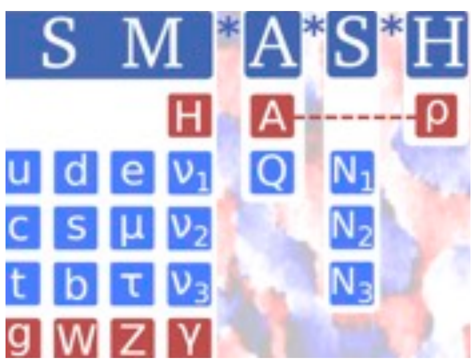

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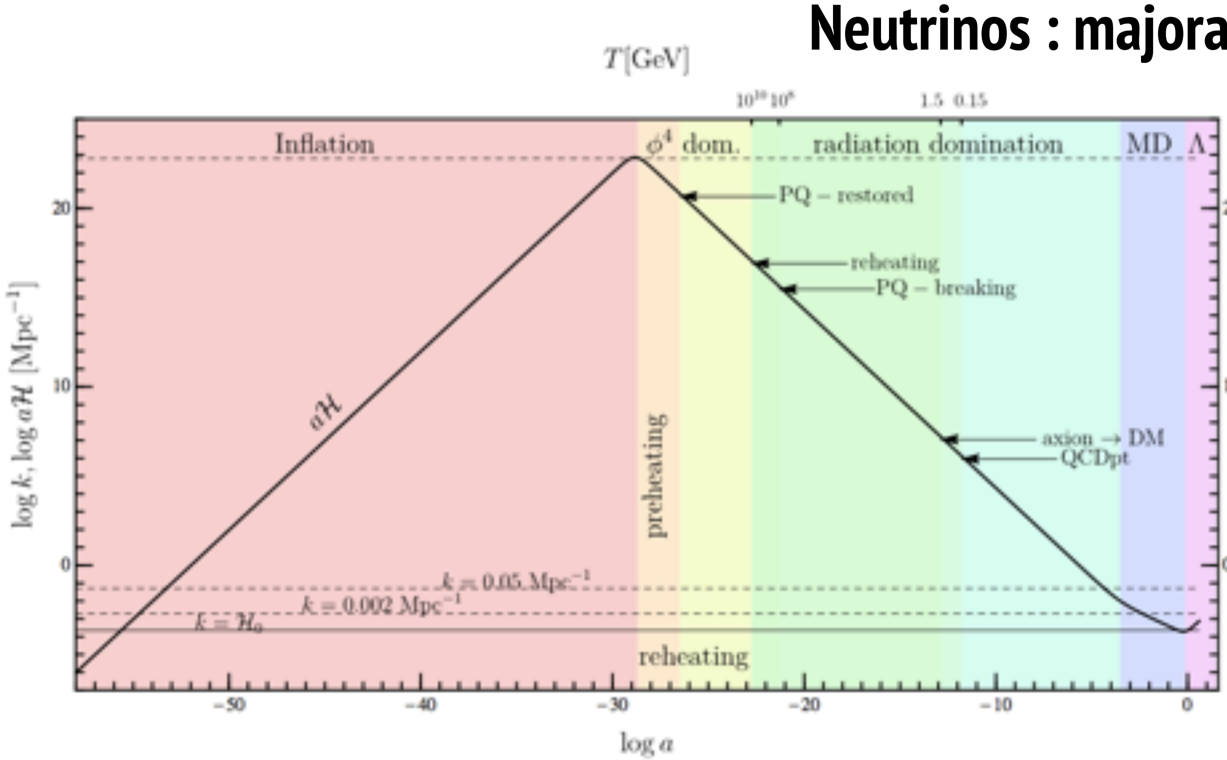
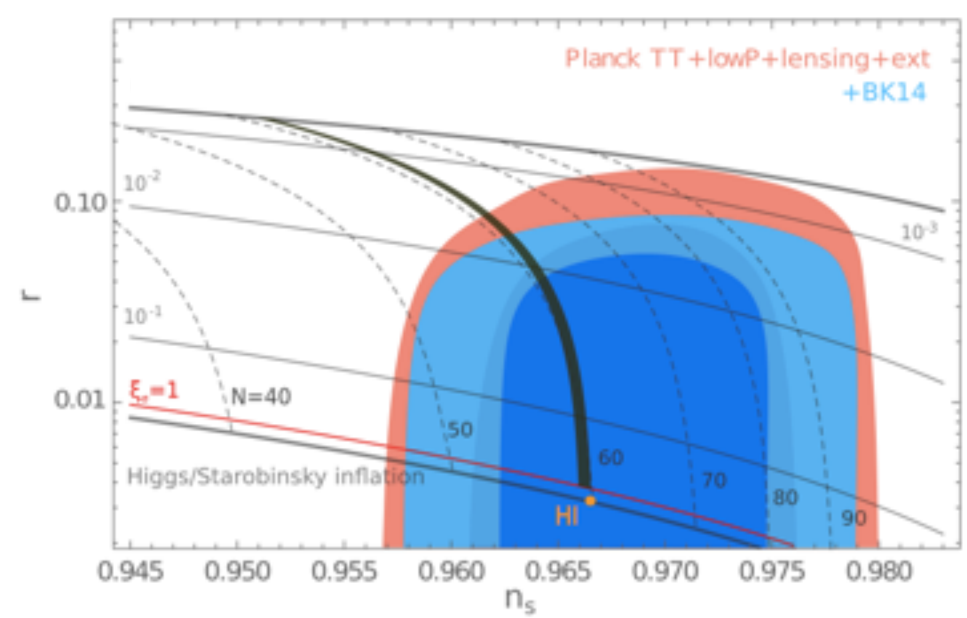
- Very clear predictions :

  CMB : $r > 0.004 \quad n_s = 0.9645 \pm 0.0015 \quad \Delta N_\nu^{\rm eff} \simeq 0.03 \quad P_{\rm iso} = 0$
  $\alpha \sim -7 \times 10^{-4}$

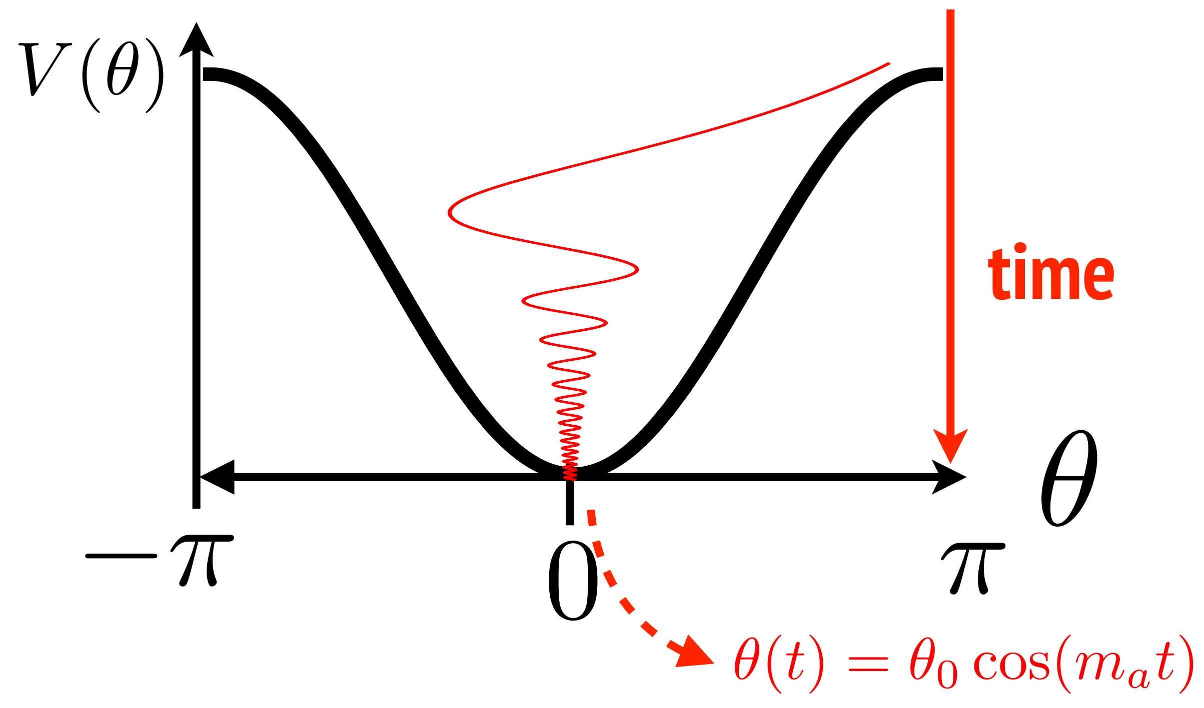
  Axion Dark Matter (scenario I: post inflation) : $m_a \sim 100\,\mu{\rm eV}$, miniclusters

  Neutrinos : majorana, typically $M_2 \sim M_3$ top mass : $m_t < 175\,{\rm GeV}$





Detecting Axion Dark matter



Local Dark Matter density

$$\rho_{\rm aDM} = 0.3 \frac{\rm GeV}{\rm cm^3}$$

$$\theta_0 = 3.6 \times 10^{-19}$$

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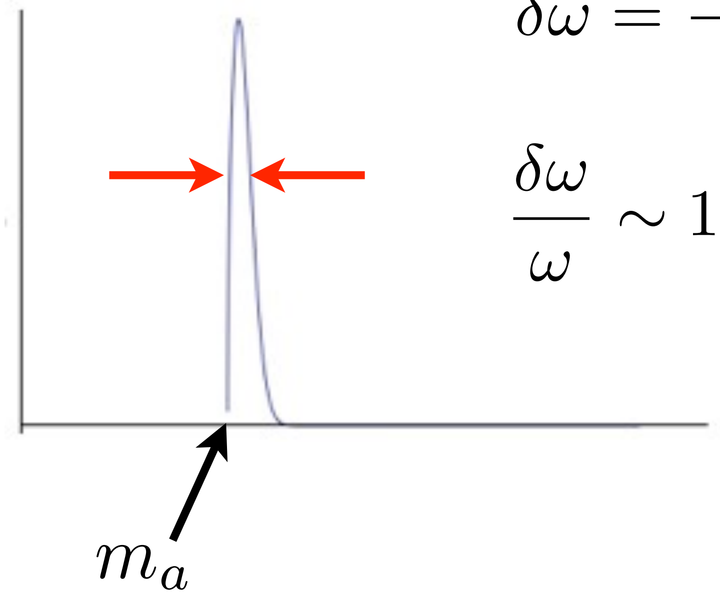
frequency $\omega \simeq m_a(1 + v^2/2 + ...)$



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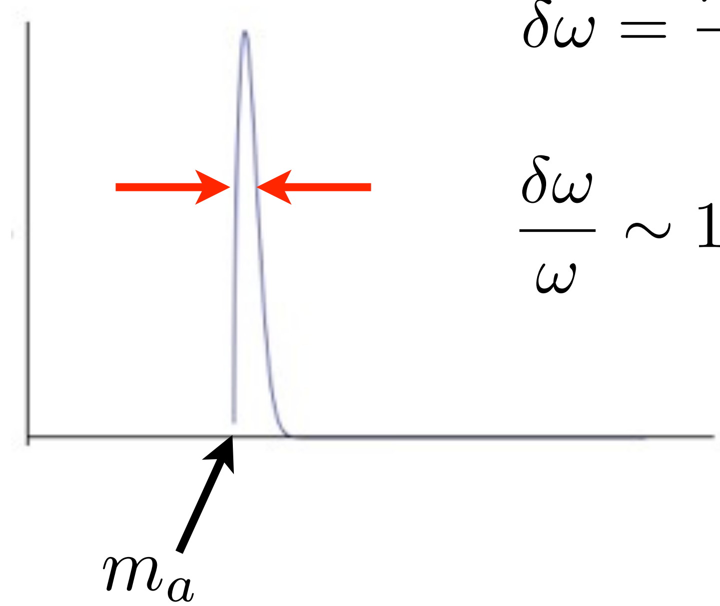

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coherence time

$$\delta t \sim \frac{1}{\delta\omega} \sim 0.13\text{ms}\left(\frac{10^{-5}\text{eV}}{m_a}\right)$$

coherence length

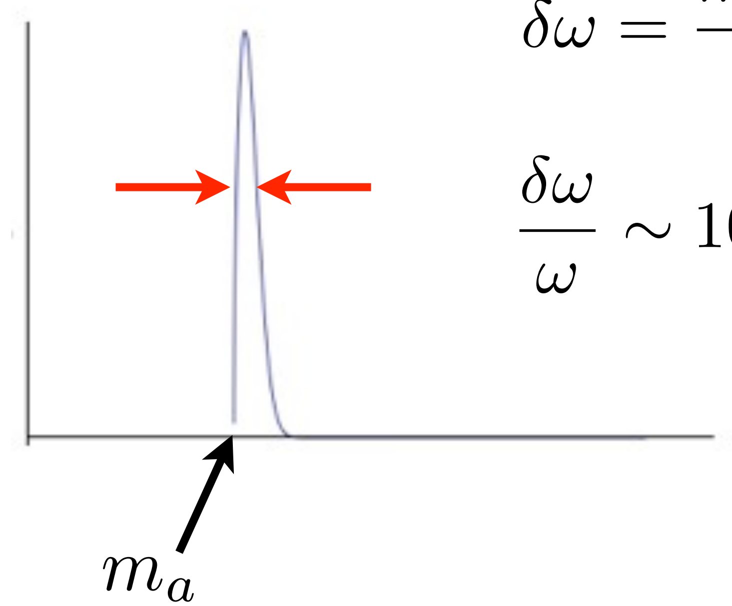
$$\delta L \sim \frac{1}{\delta p} \sim 20\text{m}\left(\frac{10^{-5}\text{eV}}{m_a}\right)$$

Detecting Axion Dark Matter

- $\theta_0 = 3.6 \times 10^{-19}$ **is a very small number but, oscillations allow for coherent detection!**

- **Axion spectrum is not exactly monochromatic, non-zero velocity of DM in the galaxy -> finite width**

frequency $\omega \simeq m_a(1 + v^2/2 + \ldots)$



$$\delta\omega = \frac{m_a v^2}{2}$$

$$\frac{\delta\omega}{\omega} \sim 10^{-6}$$

coherence time

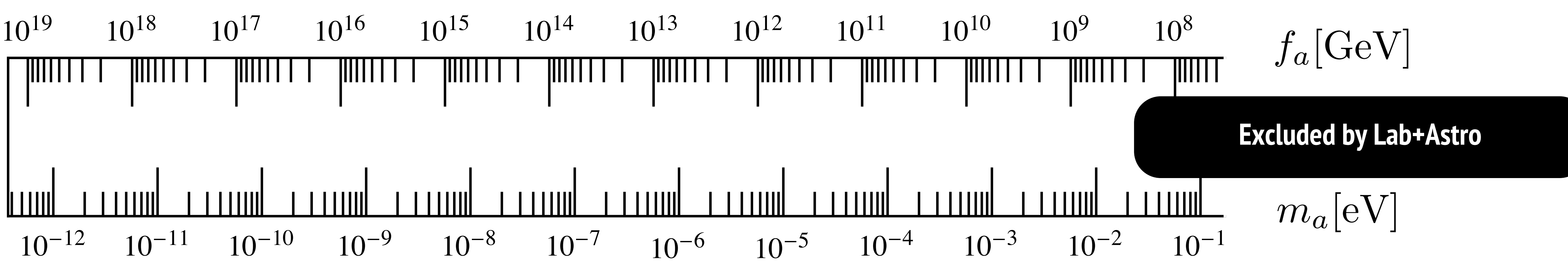
$$\delta t \sim \frac{1}{\delta\omega} \sim 0.13\text{ms}\left(\frac{10^{-5}\text{eV}}{m_a}\right)$$

coherence length

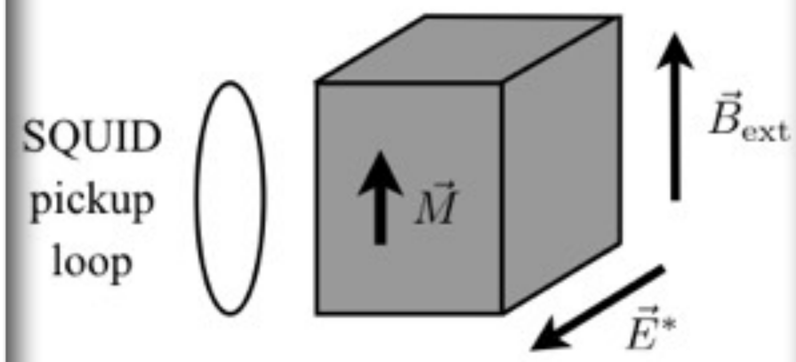
$$\delta L \sim \frac{1}{\delta p} \sim 20\text{m}\left(\frac{10^{-5}\text{eV}}{m_a}\right)$$

- **From** $f_a \sim 10^{19}\,\text{GeV}$ **to** $f_a \sim 10^{8}\,\text{GeV}$ **11 orders of magnitude in axion mass to scan ...**

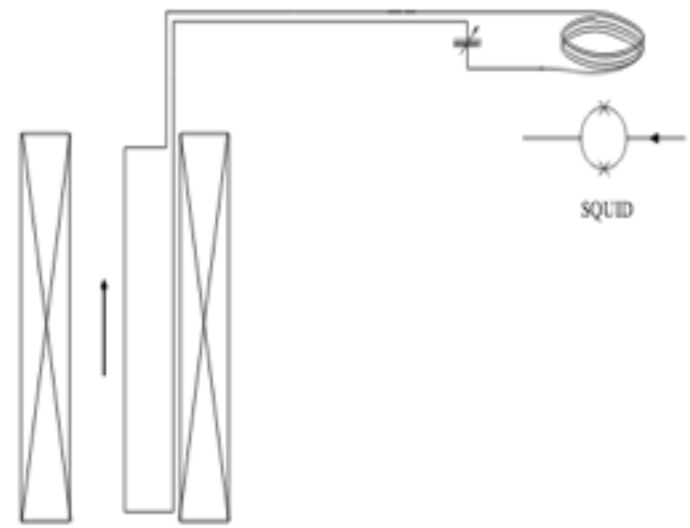
10^{17} **channels in mass ....**



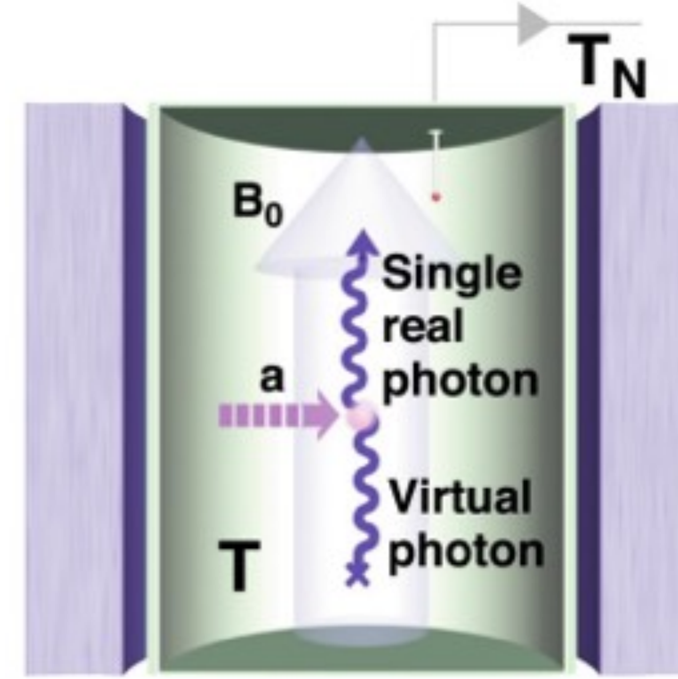
Oscillating EDM



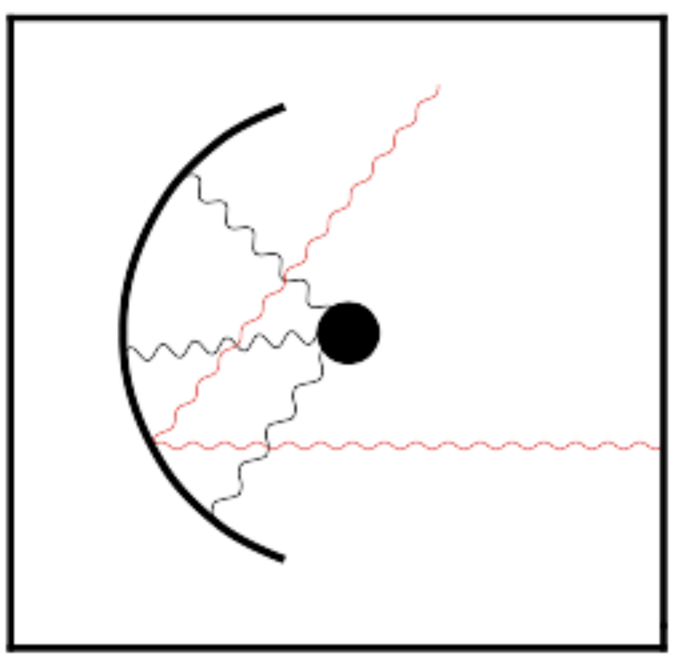
LC-circuit



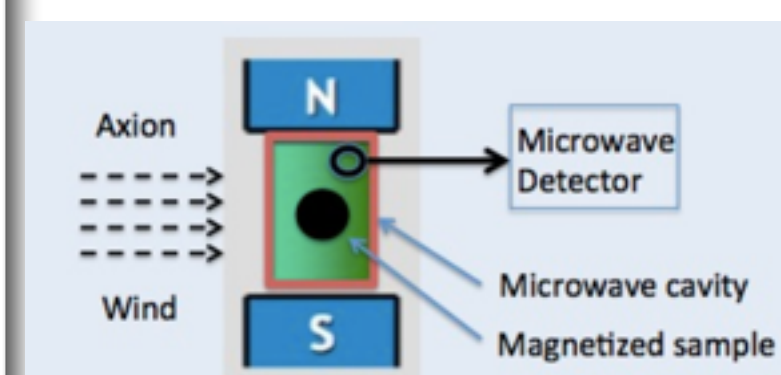
Cavities



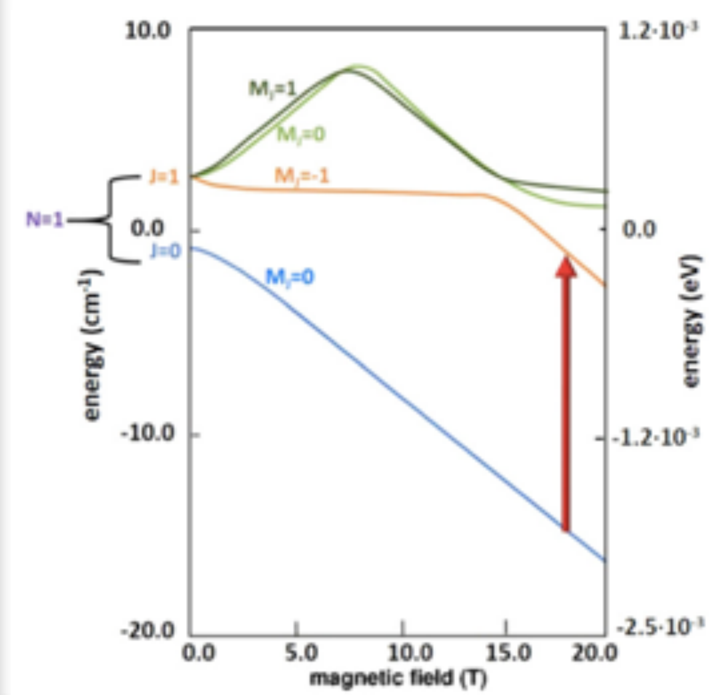
Mirrors



Ferromagnetic resonance



Atomic transitions



CASPER : oscillating EDM with NMR

Mainz, Berkeley

- **Oscillating neutron EDM** $d_n = -4 \times 10^{-3} \times \theta_0 \cos(m_a t)\,[\mathrm{e\,fm}]$

CASPER : oscillating EDM with NMR

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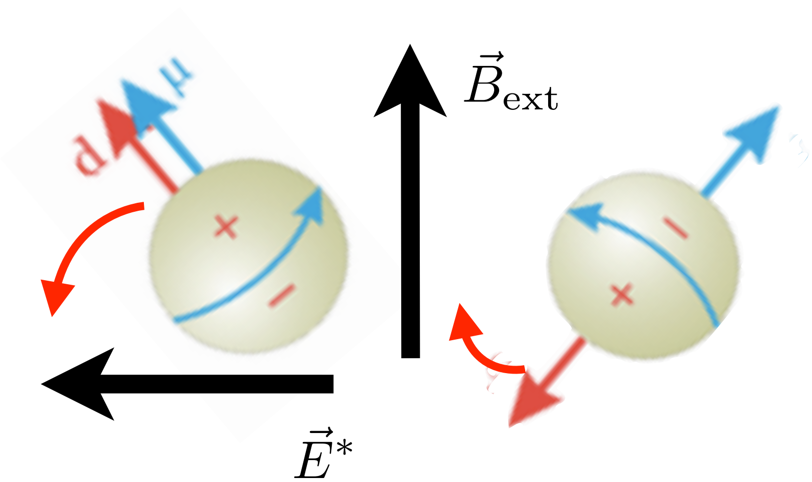
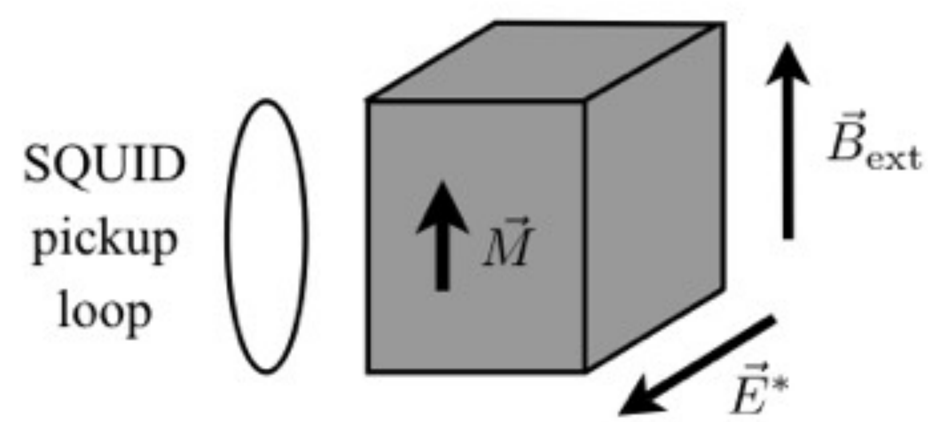


Oscillating EDM, effects add up, transverse magnetisation grows on resonance $m_a = \omega = \mu|\vec{B}_{\mathrm{ext}}|$



II

CASPER : oscillating EDM with NMR

Mainz, Berkeley

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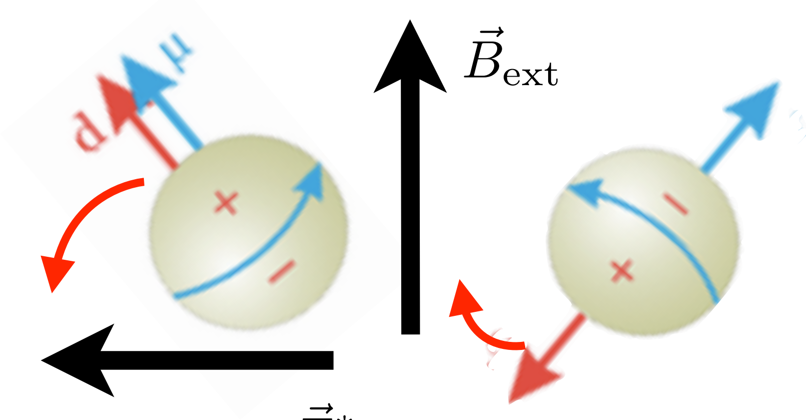

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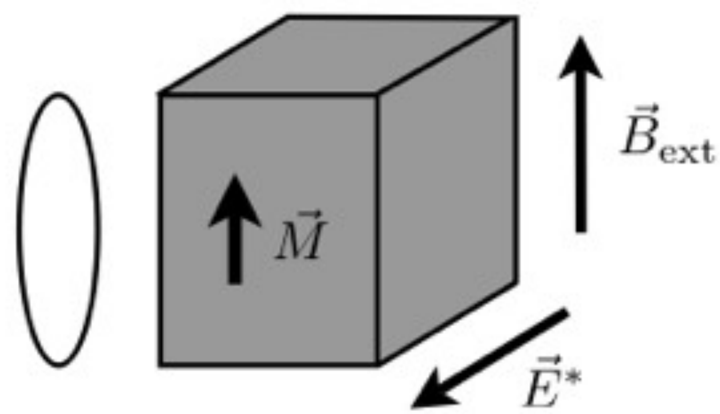

II

CASPER : oscillating EDM with NMR

Mainz, Berkeley


D. Budker


S. Rajendran


P. Graham

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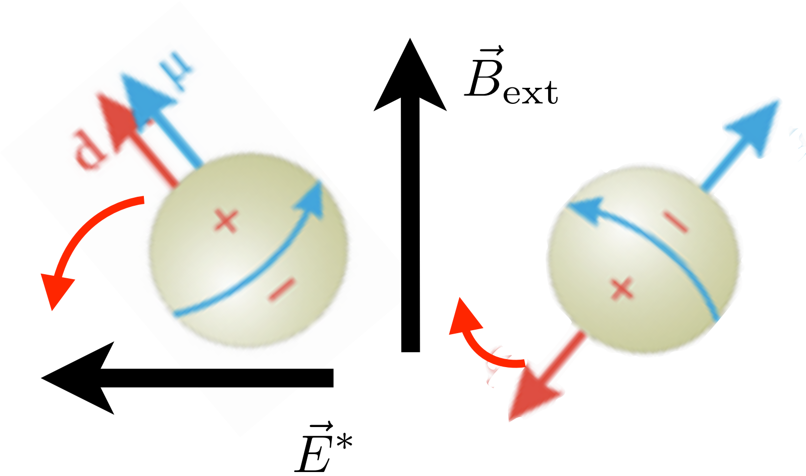

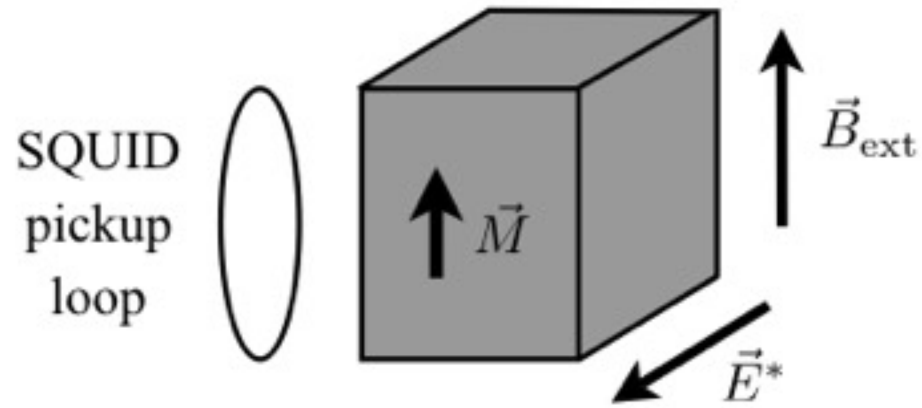

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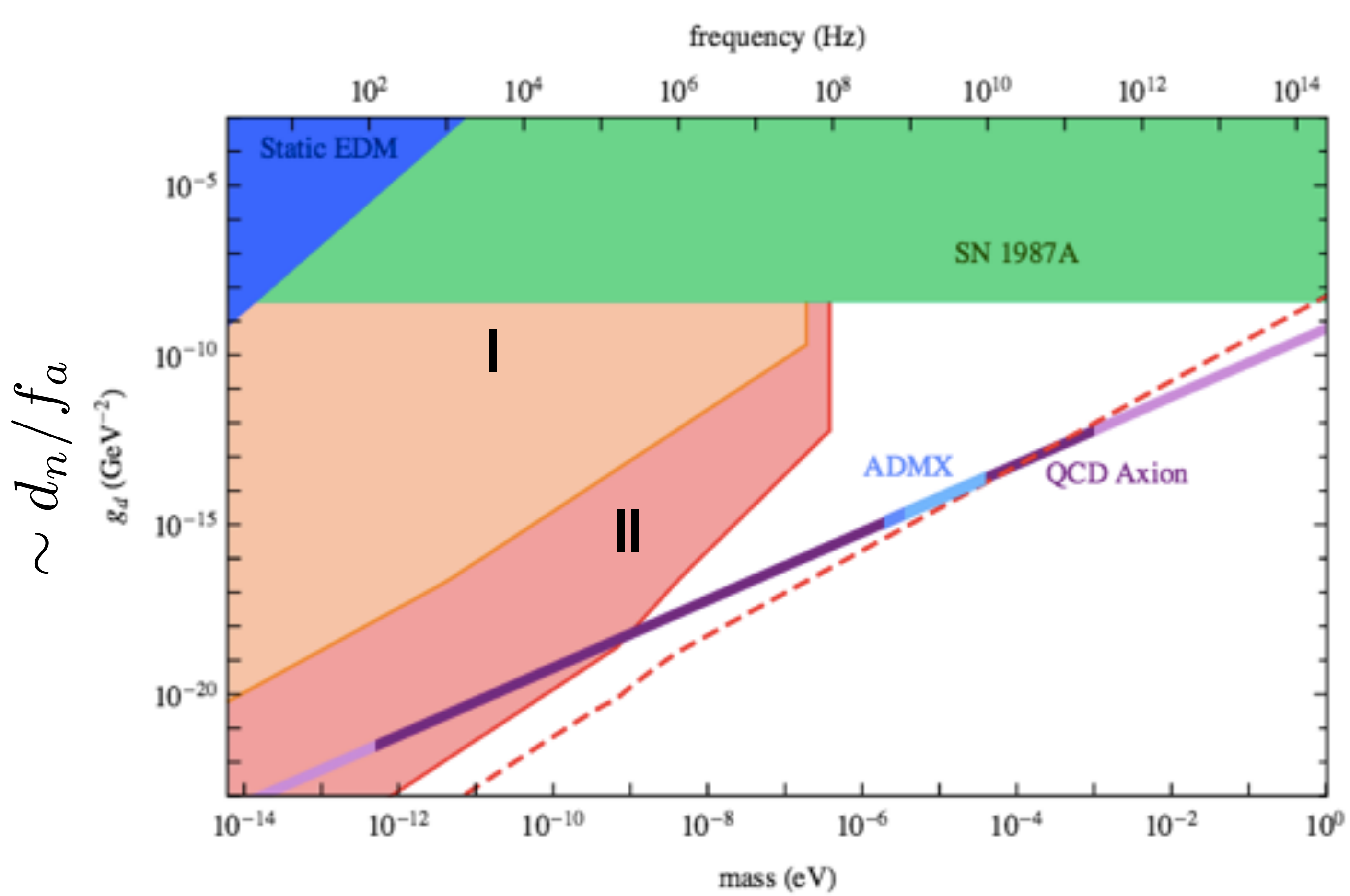
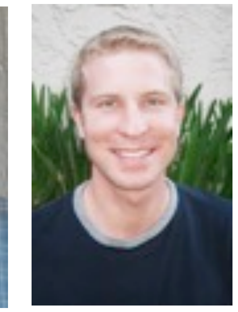


CASPER : oscillating EDM with NMR

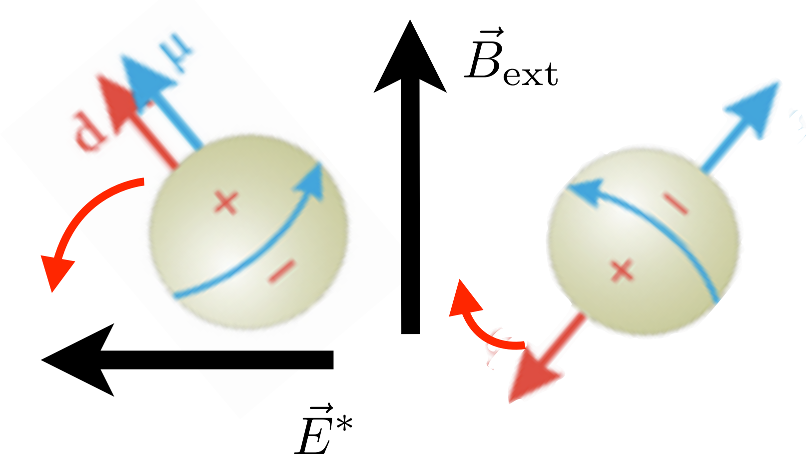
Mainz, Berkeley



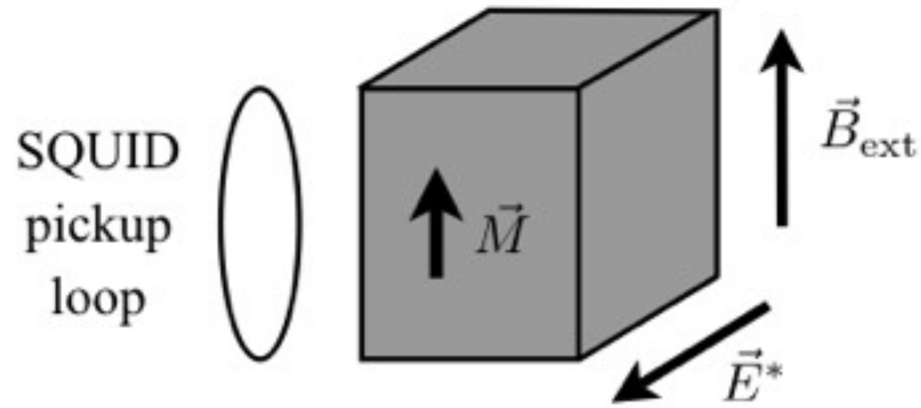


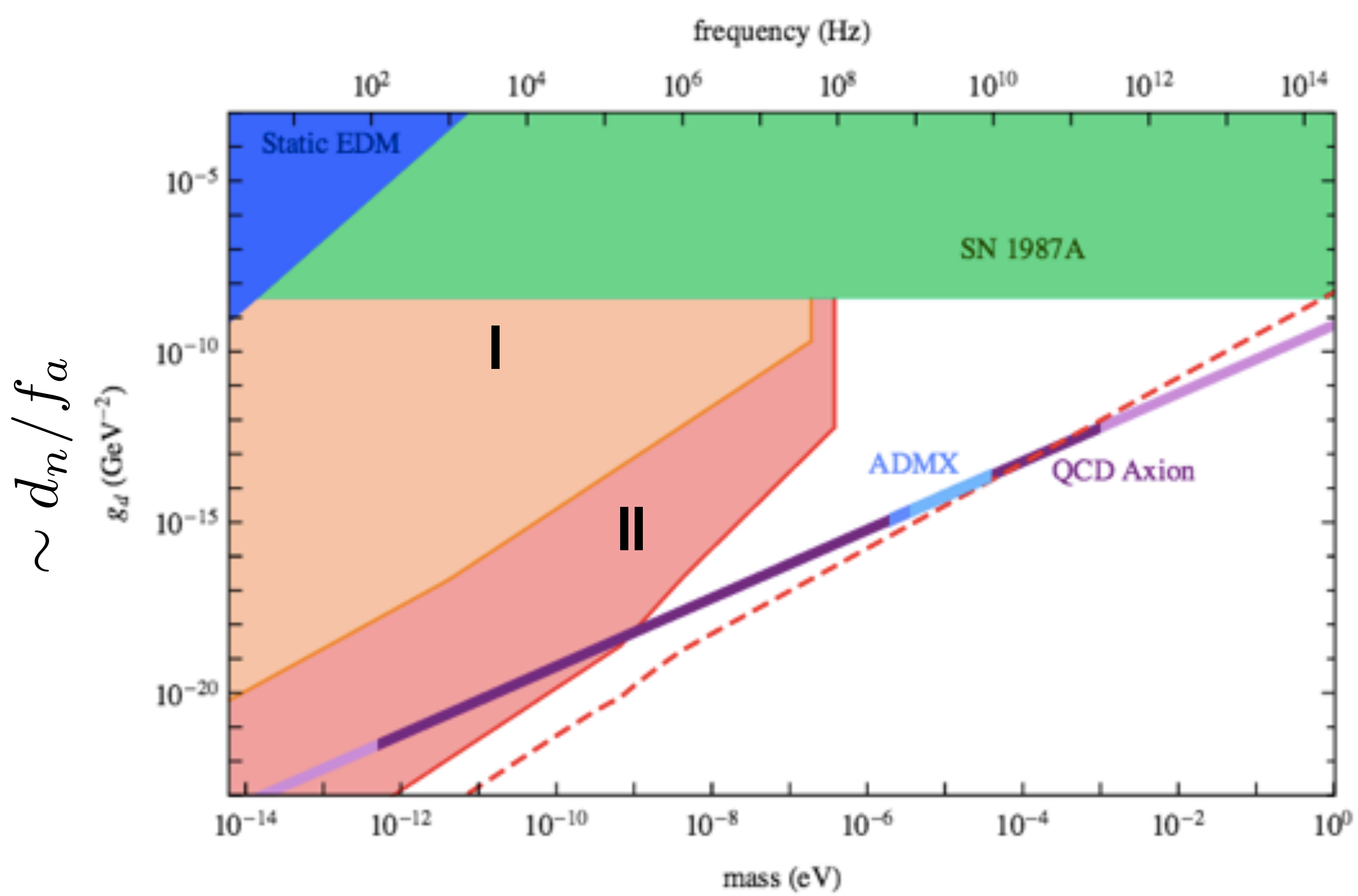
D. Budker S. Rajendran P. Graham

- **Oscillating neutron EDM** $d_n = -4 \times 10^{-3} \times \theta_0 \cos(m_a t)\ [\mathrm{e\,fm}]$



Oscillating EDM, effects add up, transverse magnetisation grows on resonance $m_a = \omega = \mu|\vec{B}_{\mathrm{ext}}|$

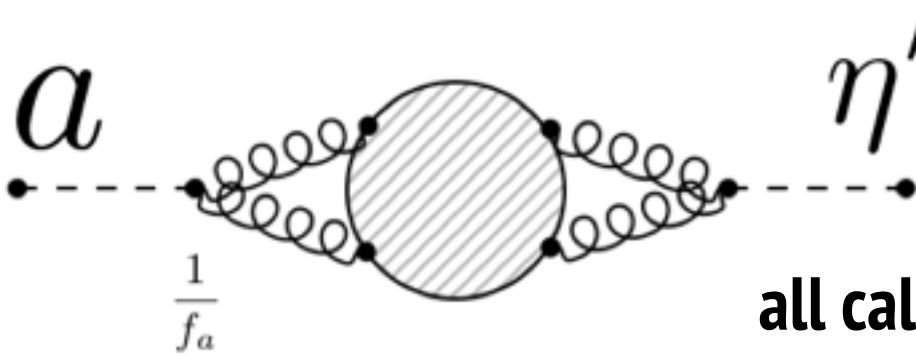




- EDM + Large E-fields in PbTiO3
- Scan over frequencies, with Bext
- Mainz (D. Budker's group) & Berkeley
- Phase I starts in 2017, Phase II physics results
- Mass range limited by B-field strength

Axion interactions

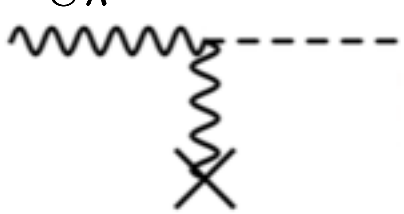
- The rest of the axion DM detection techniques rely on less-direct axion couplings
- The QCD axion mixes with eta' and the rest of mesons, acquiring couplings to photons and hadrons



all calculable and suppressed by $\frac{1}{f_a}$

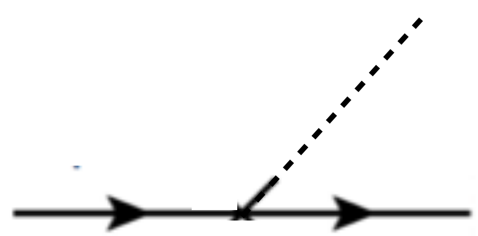
photon coupling

$$-\frac{C_{a\gamma}\alpha}{8\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}\theta$$



nucleon coupling

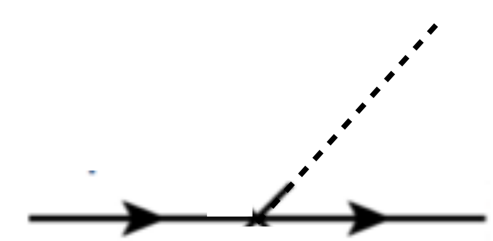
$$C_{Nf}m_N[\bar{N}\gamma_5 N]\theta$$



$$C_{a\gamma} = -1.92$$

electron coupling

$$C_{ef}m_e[\bar{e}\gamma_5 e]\theta$$



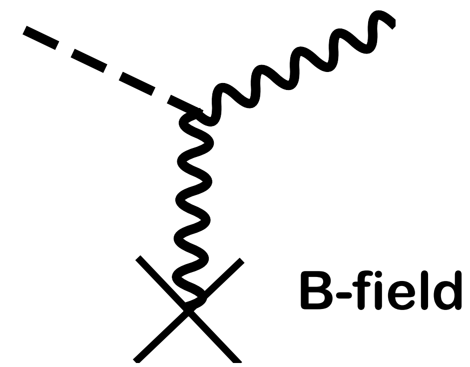
- Depending on the axion UV model, model dependent contributions ~O(1)
- But also coupligns to electrons are possible

Axion DM in a B-field

- Axion photon coupling in a strong B-field becomes a source of E-field

$$\mathcal{L}_I = -C_{a\gamma}\frac{\alpha}{2\pi}\theta(t)\,\mathbf{B}_{\rm ext}\cdot\mathbf{E}$$

source



E-field $E \sim \mathcal{O}(10^{-12}\mathrm{V/m})\frac{|\mathrm{B}_{\rm ext}|}{10\,\mathrm{T}}C_{a\gamma}\times\cos(m_a t)$

Power $P/Area \sim |\mathbf{E}_a|^2 \sim 2\times 10^{-27}\left(\frac{\mathrm{B}}{5\mathrm{T}}\frac{C_{a\gamma}}{2}\right)^2\frac{\mathrm{Watt}}{1\,\mathrm{m}^2}$

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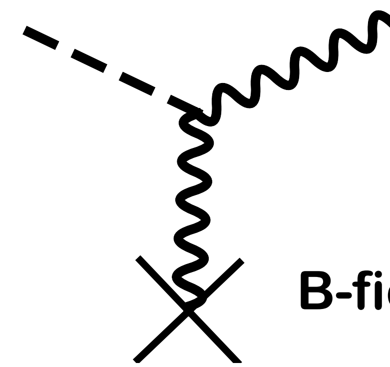

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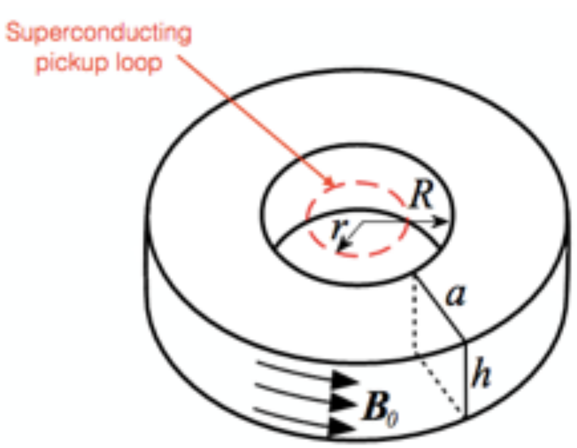
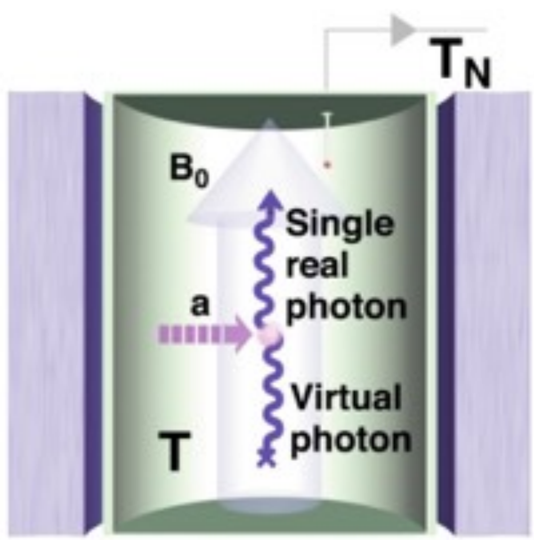
Power $P/Area \sim |\mathbf{E}_a|^2 \sim 2\times10^{-27}\left(\frac{\rm B}{5{\rm T}}\frac{C_{a\gamma}}{2}\right)^2\frac{\rm Watt}{1\,{\rm m}^2}$

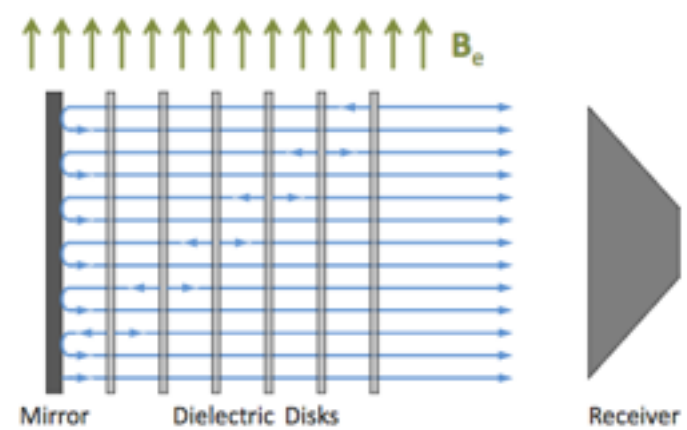
- Four different techniques:



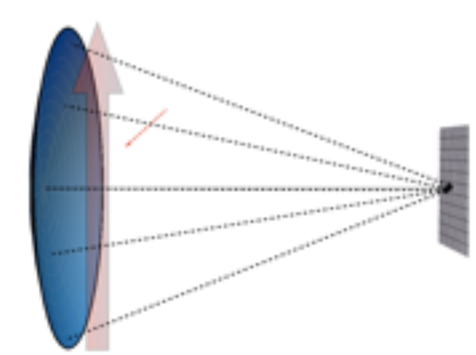
DM Radio



Cavities



Dielectric haloscope

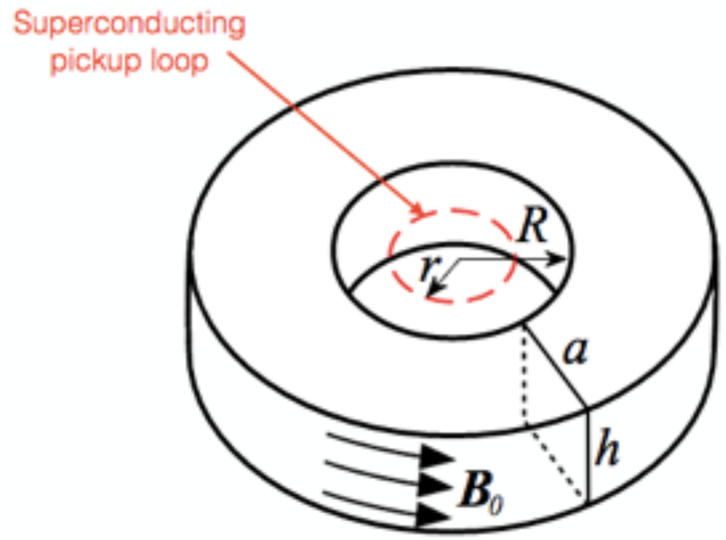


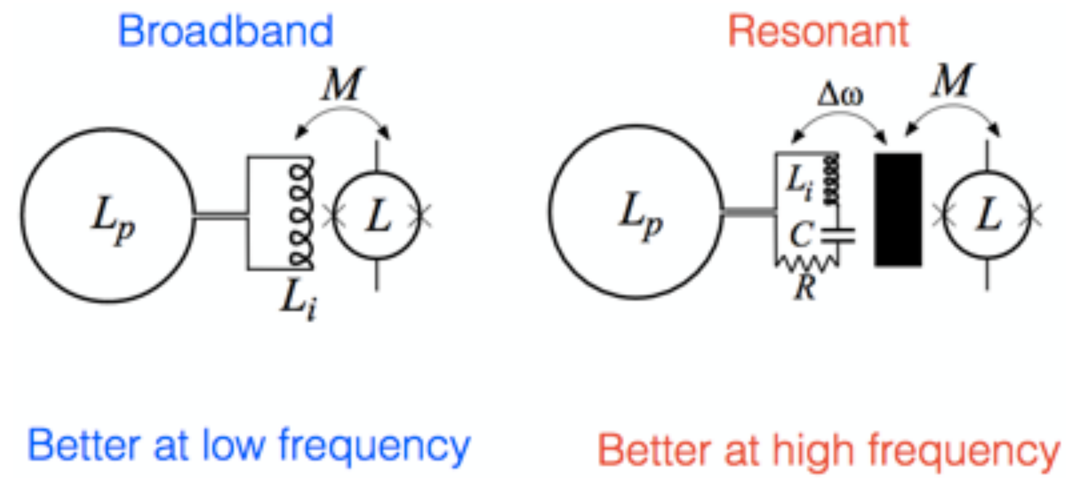
Dish antenna

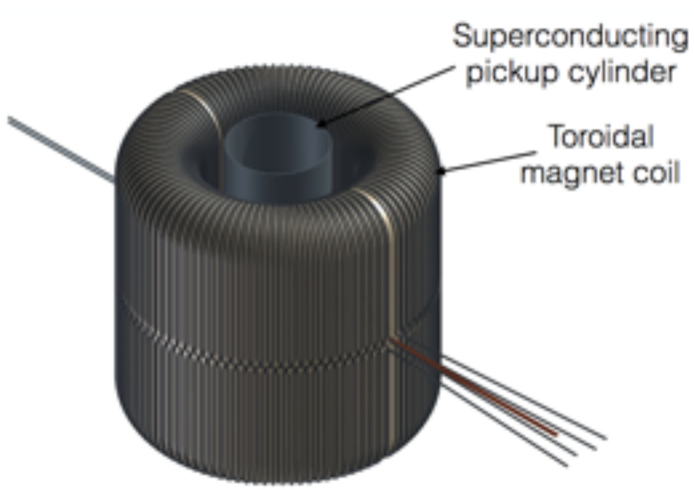
DM Radio

- Toroidal axion-induced E-field generates oscillating B-field along z

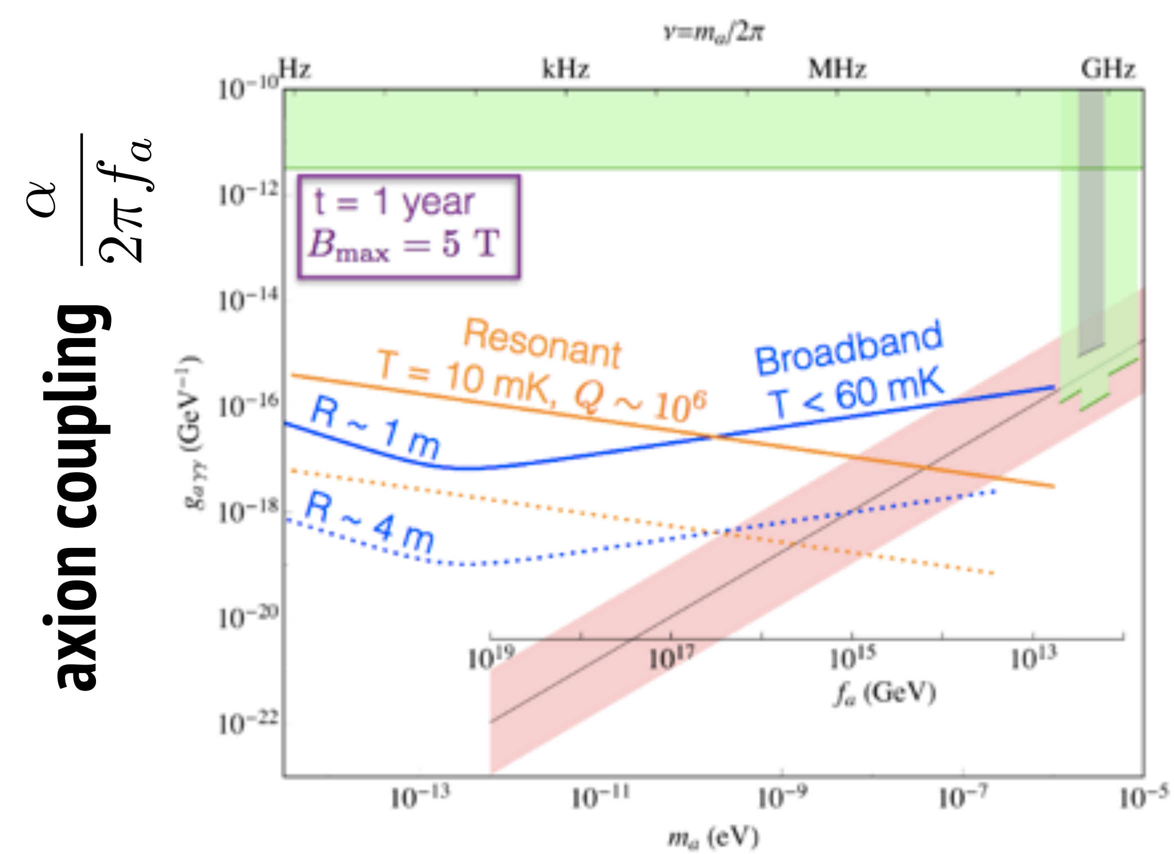
Sikivie PRL 112 (2014)
Chaudhuri PRD92 (2015)
Kahn PRL 117 (2016)







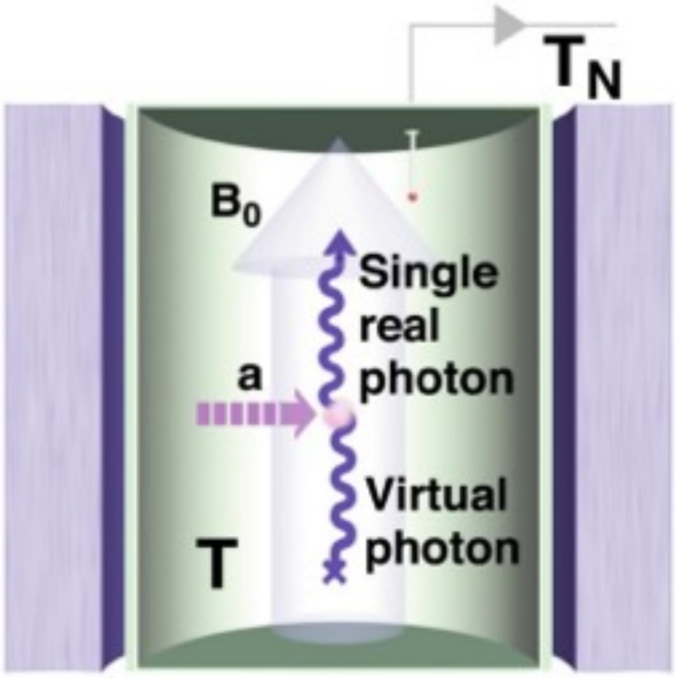
ABRACADABRA (MIT)
10 cm, 1m , 4m ...



Resonant cavities: haloscopes

P. Sikivie

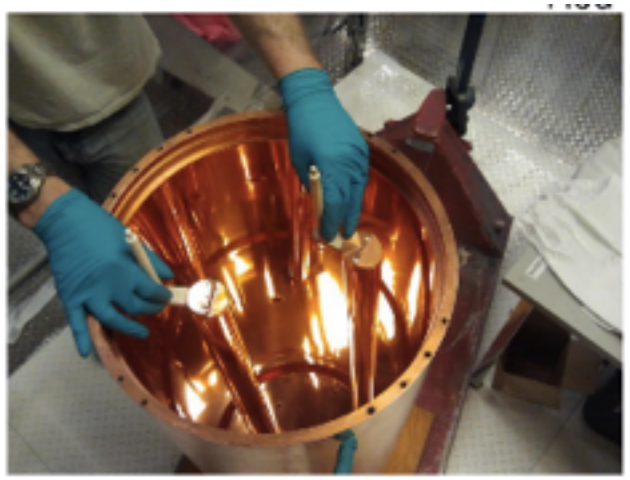
- Boost the axion-generated E-field in a tuned resonant cavity

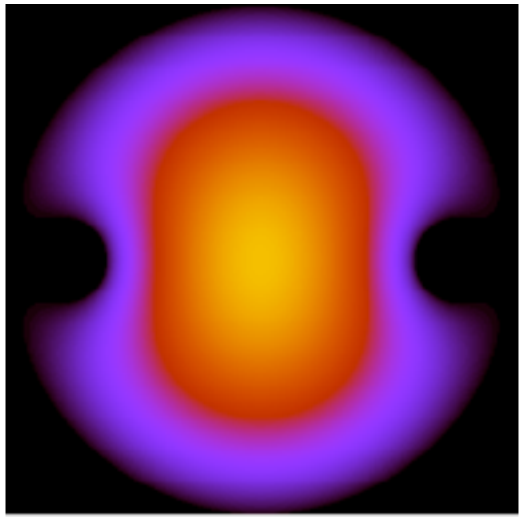


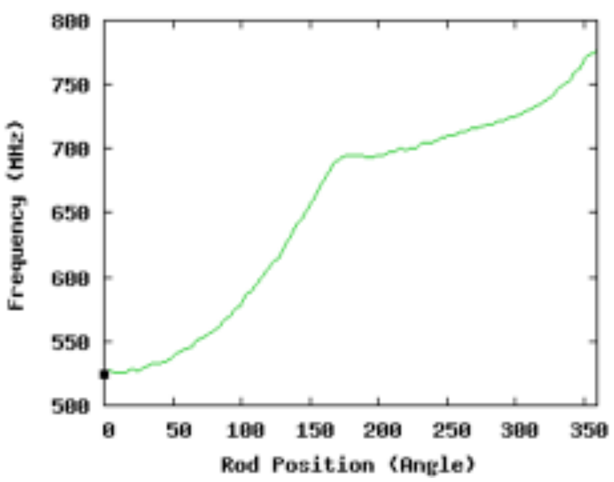
$$P_{\rm out} \sim Q|\mathbf{E}_a|^2 V m_a$$

- Cavity quality factor $Q \sim 10^5$
- B-fields $B \sim 10\mathrm{T}$
- Volume $\sim 1/m_a^3$ (typically a few liters)
- Temperature $T \sim 0.2 - 4\,\mathrm{K}$
- System T ~ Quantum limited (SQUID, JPA)

Scanning over frequencies



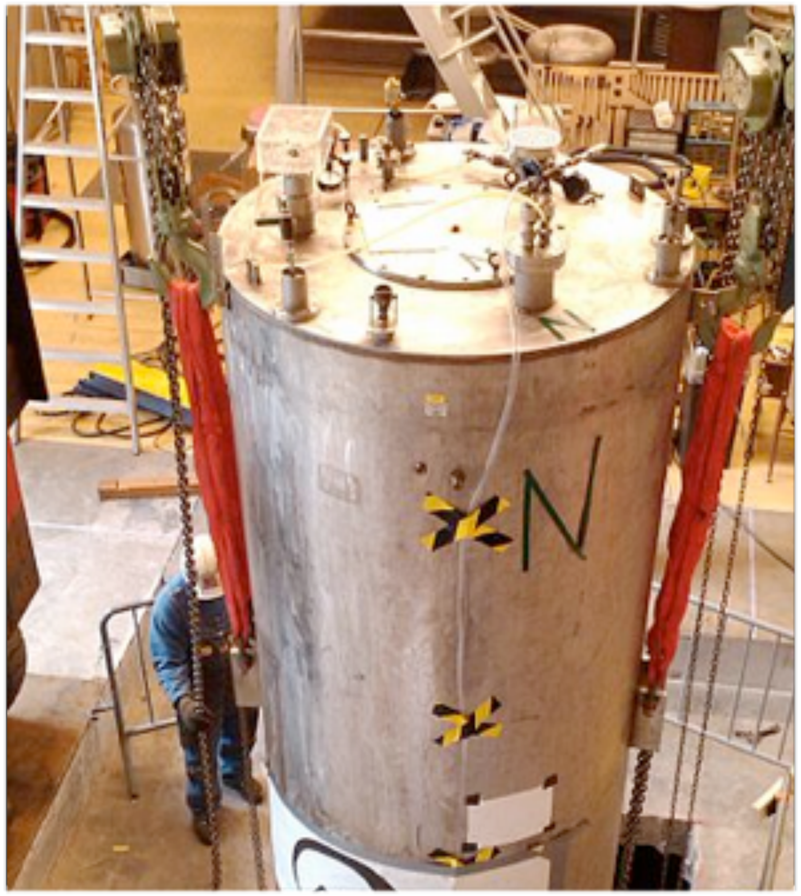




- At high freq. limited by small volume and high noise
- At low freq. by getting a large enough B-field

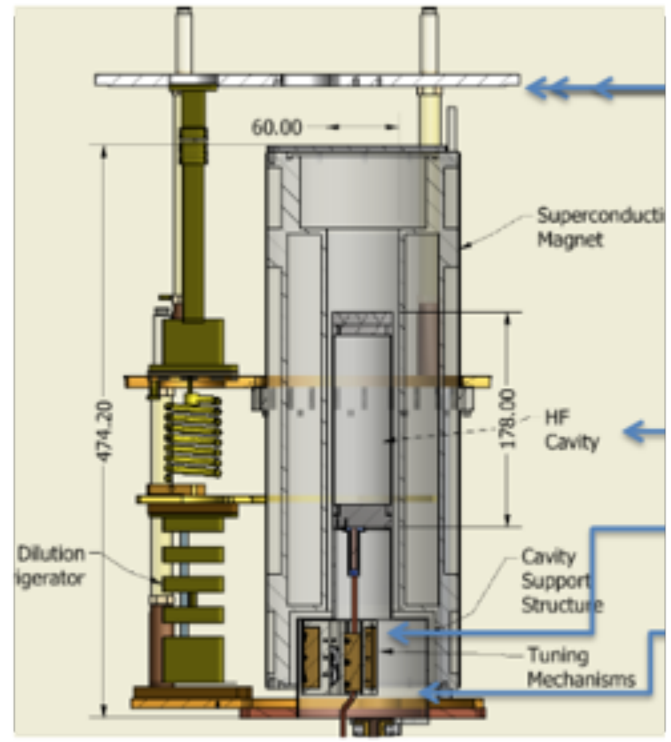
Cavity experiments

ADMX-Seattle



running!

CULTASK - CAPP -Korea

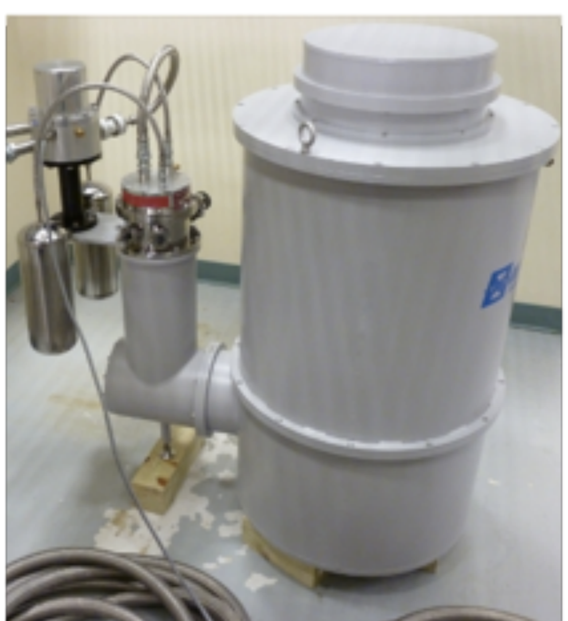


2017-...

ORGAN-UWA Perth

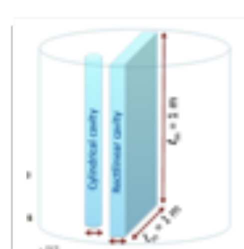
2017-...

HAYSTAC-Yale

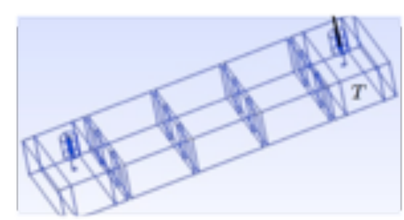


2016-...

ADMX-Fermilab



RADES



2017-...

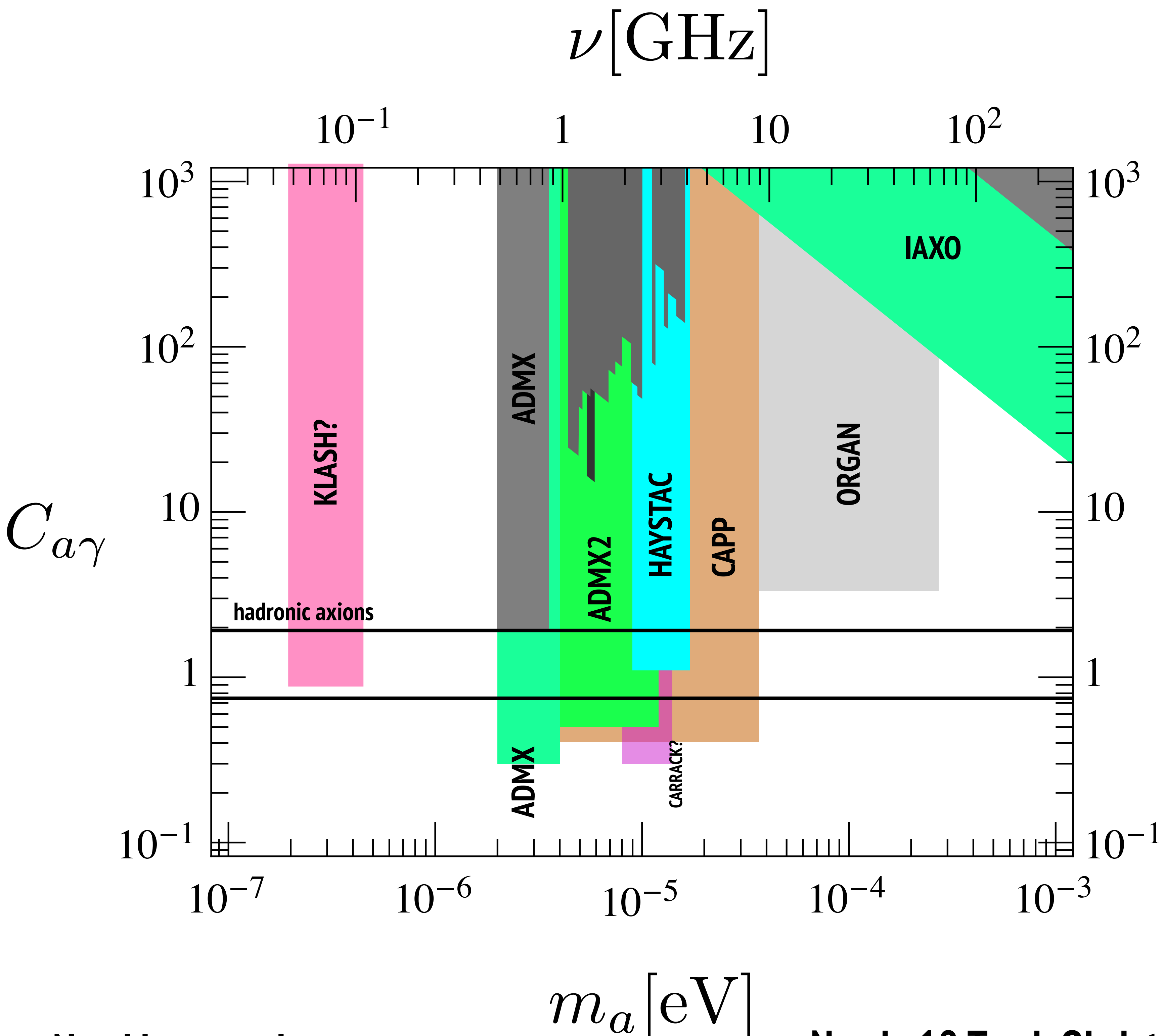
CAST-CAPP

2017-...

KLASH?

??-...

Projected sensitivities

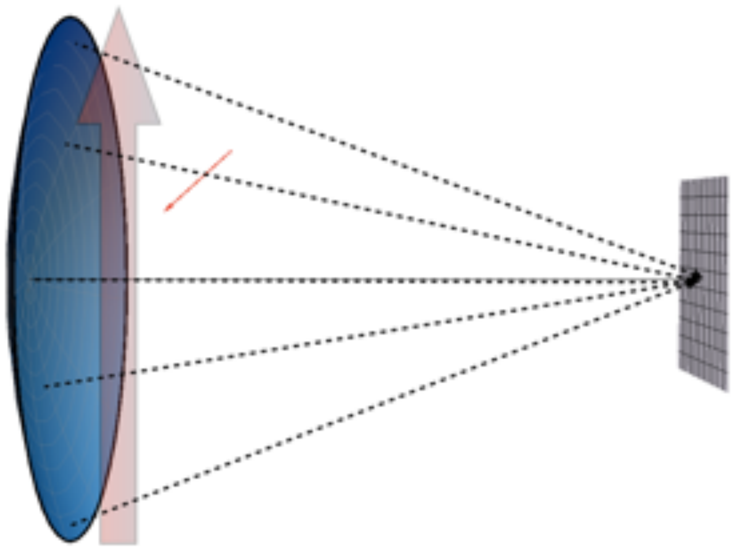


- Need larger volume

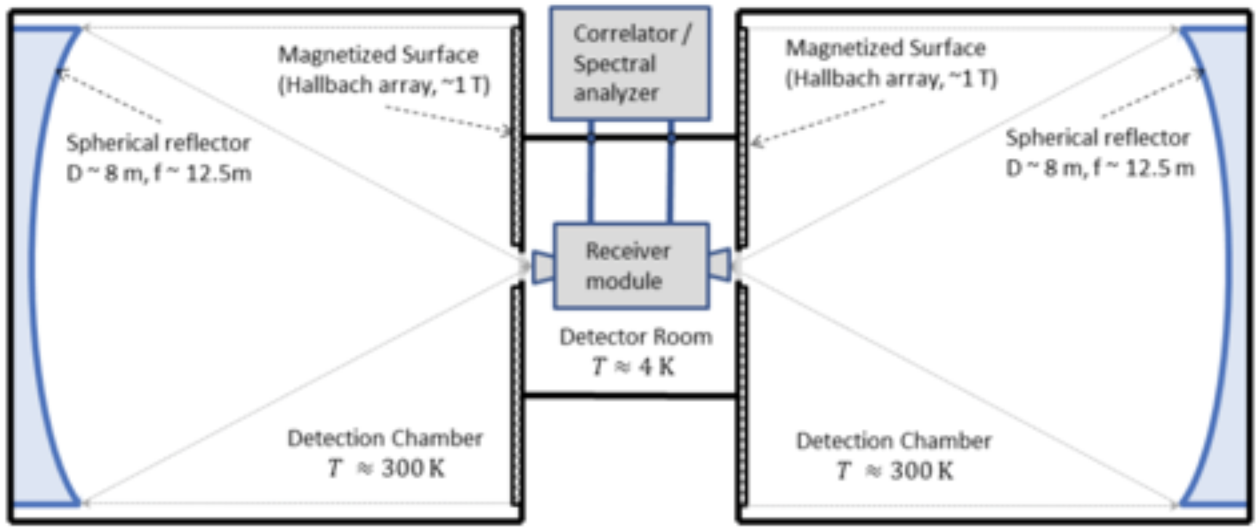
- Need >10 T, sub QL detection, Q~10^6

Dish antenna

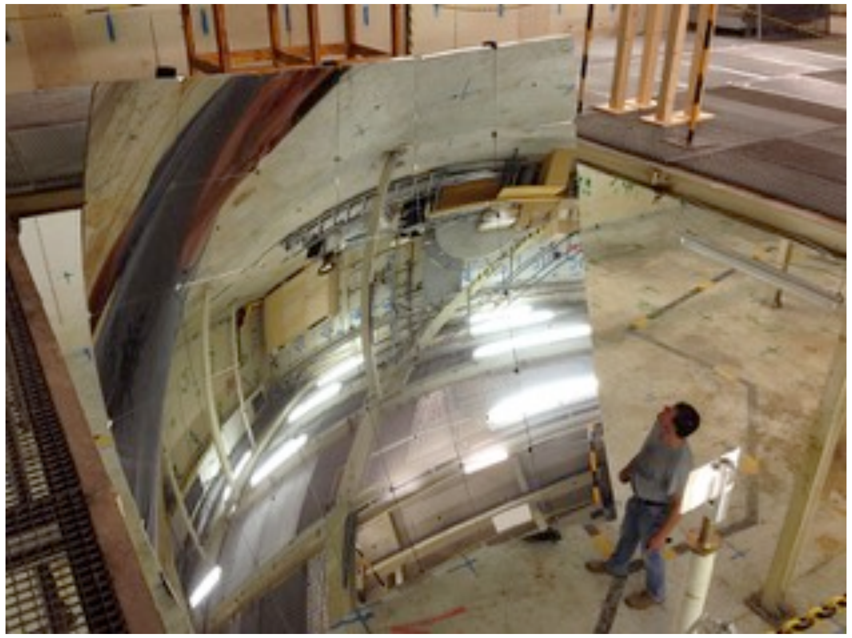
- Detect radiated power from a huge ($Am_a^2 \gg 10^6$) magnetised dish
- Broadband, no resonance enhancement; Only detector needs to be at T~mK (high reflectivity dish)
- Magnetise Area with permanent-magnets, photon counting?



$$P/Area \sim |\mathbf{E}_a|^2 \sim 2\times 10^{-27}\left(\frac{\mathrm{B}}{5\mathrm{T}}\frac{C_{a\gamma}}{2}\right)^2 \frac{\mathrm{Watt}}{1\,\mathrm{m}^2}$$



BRASS @ Hamburg

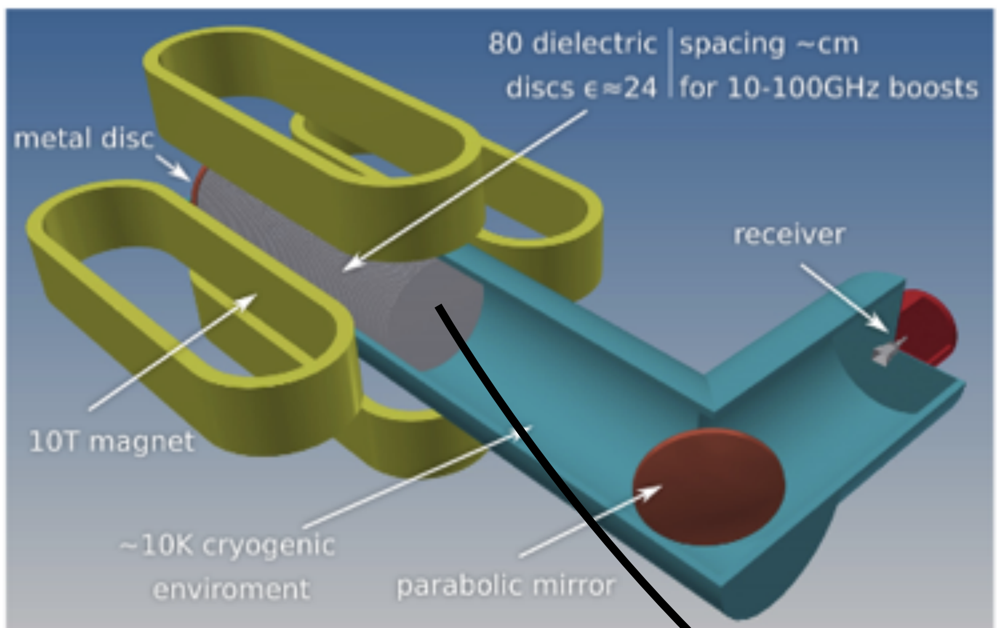


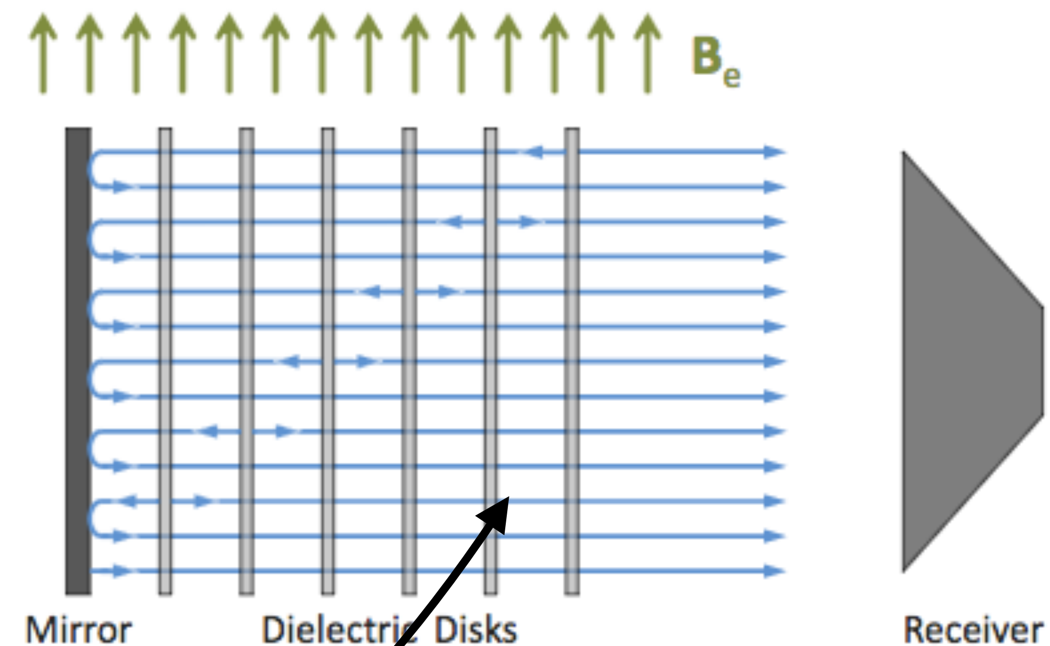
FUNK experiment (KIT)

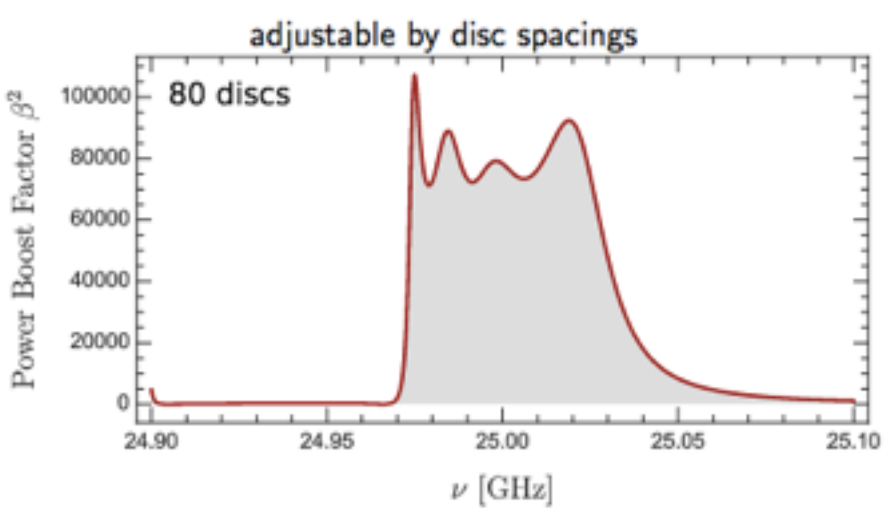
Dielectric haloscope : MADMAX

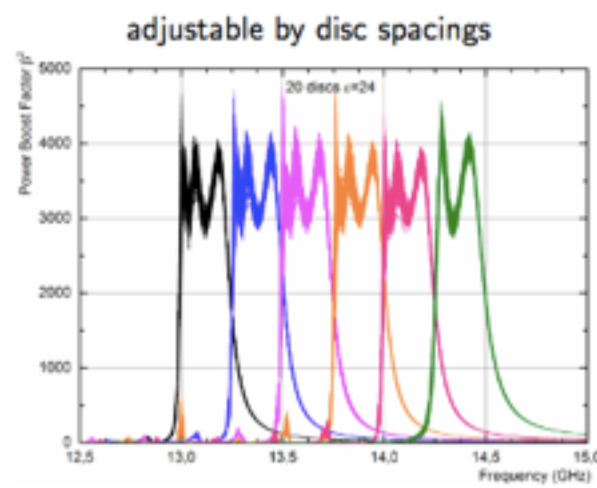
- **Hybrid system, large area + multiple emitters + a bit of resonant enhancement**

$$\frac{P}{Area} \sim 2\times 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{c_\gamma}{2}\,\frac{B_{||}}{5\mathrm{T}}\right)^2 \frac{1}{\epsilon} \times \beta(\omega)$$ **boost factor**



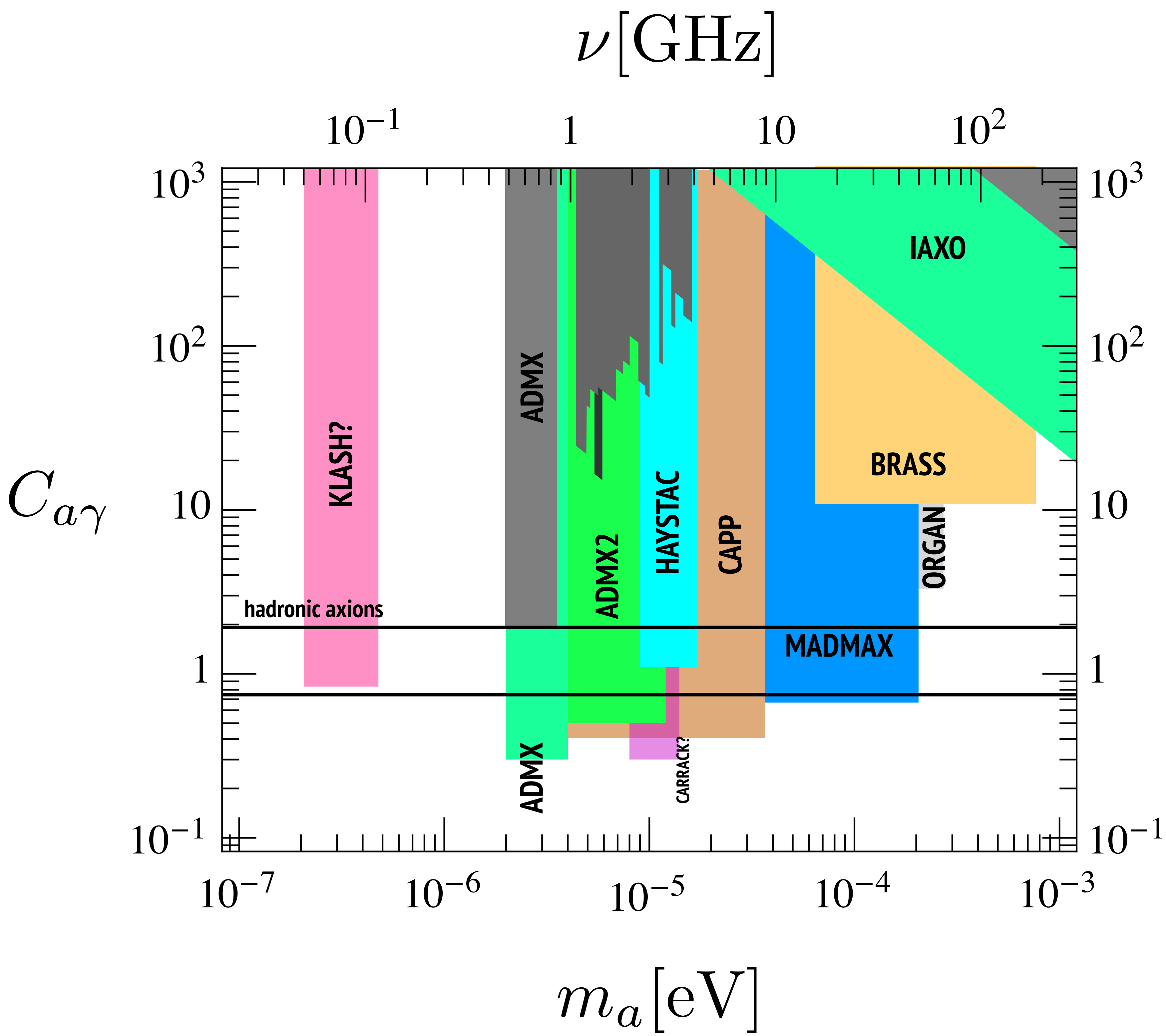






MADMAX: MAgnetised Disk and Mirror Axion eXperiment: MPP Munich, Hamburg Uni, DESY, Saclay, Zaragoza U

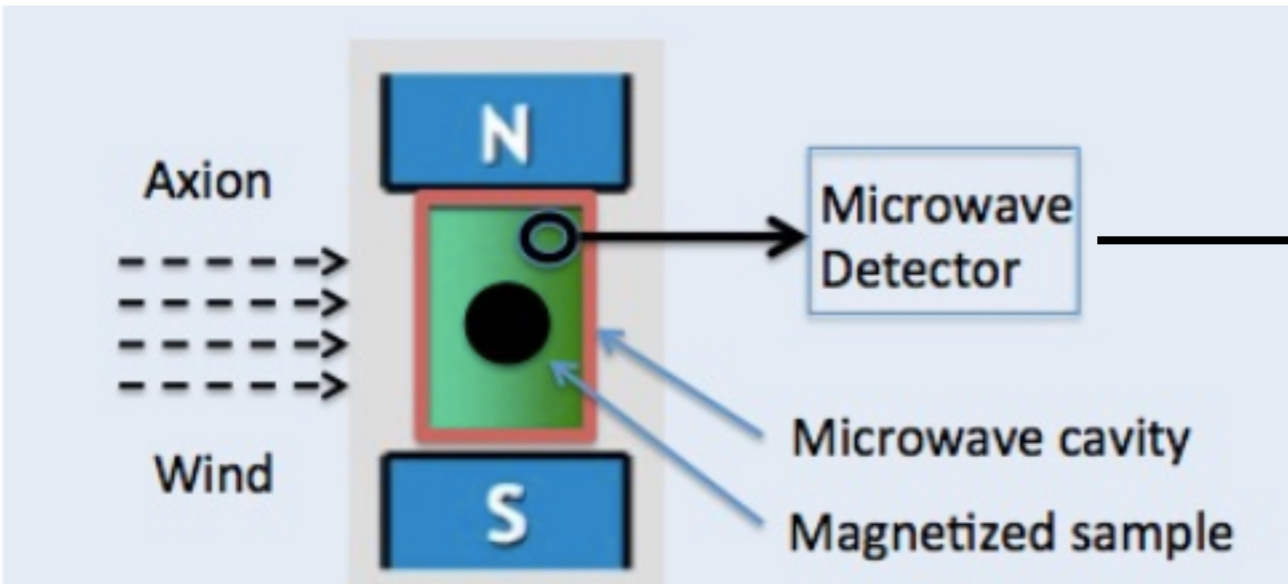
Projected sensitivities



Ferromagnetic resonance: QUAX

Barbieri 1606.02201

- Axion coupling to electron spin; hybrid magnetisation-RF mode

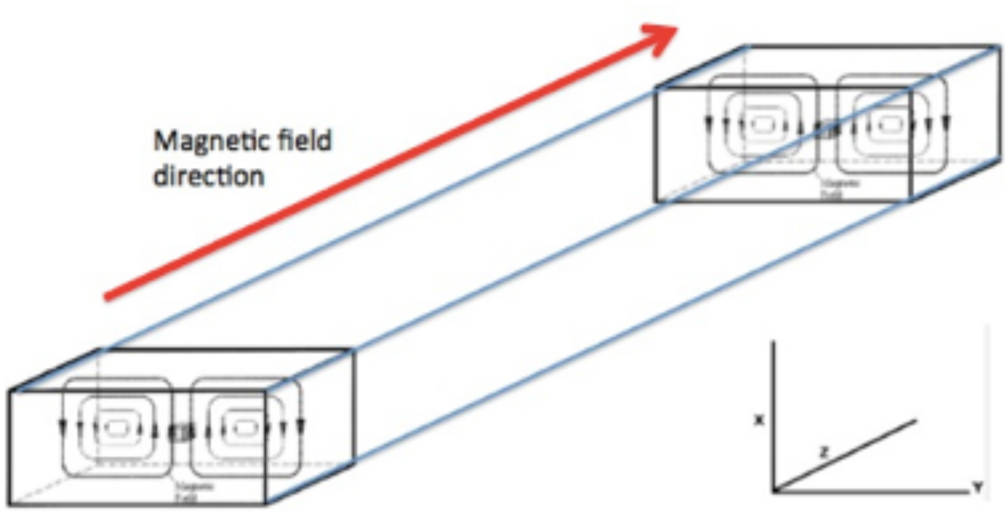


Photon counting rate

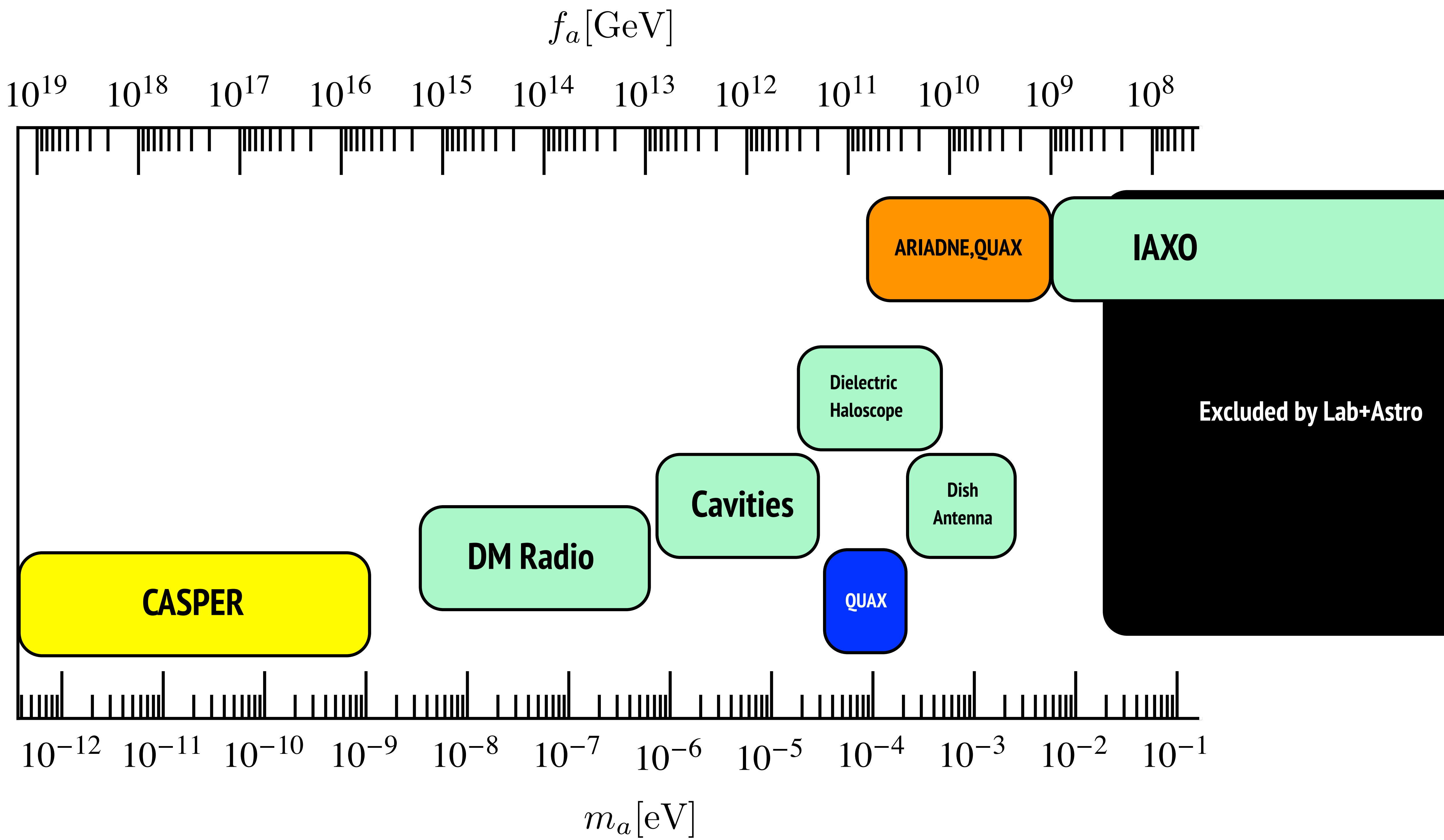
$$R_a^* = \frac{1}{2}\gamma^2 B_a^2 \tau n_S V_s =$$

$$= 5.0 \times 10^{-3} \left(\frac{m_a}{2 \cdot 10^{-4}\,\mathrm{eV}}\right)^2 \left(\frac{V_s}{1\ \mathrm{liter}}\right) \left(\frac{n_S}{10^{28}/\mathrm{m}^3}\right) \left(\frac{\tau_{\min}}{10^{-6}\,\mathrm{s}}\right) \mathrm{Hz}.$$

Scannig rate... 200 MHz/year

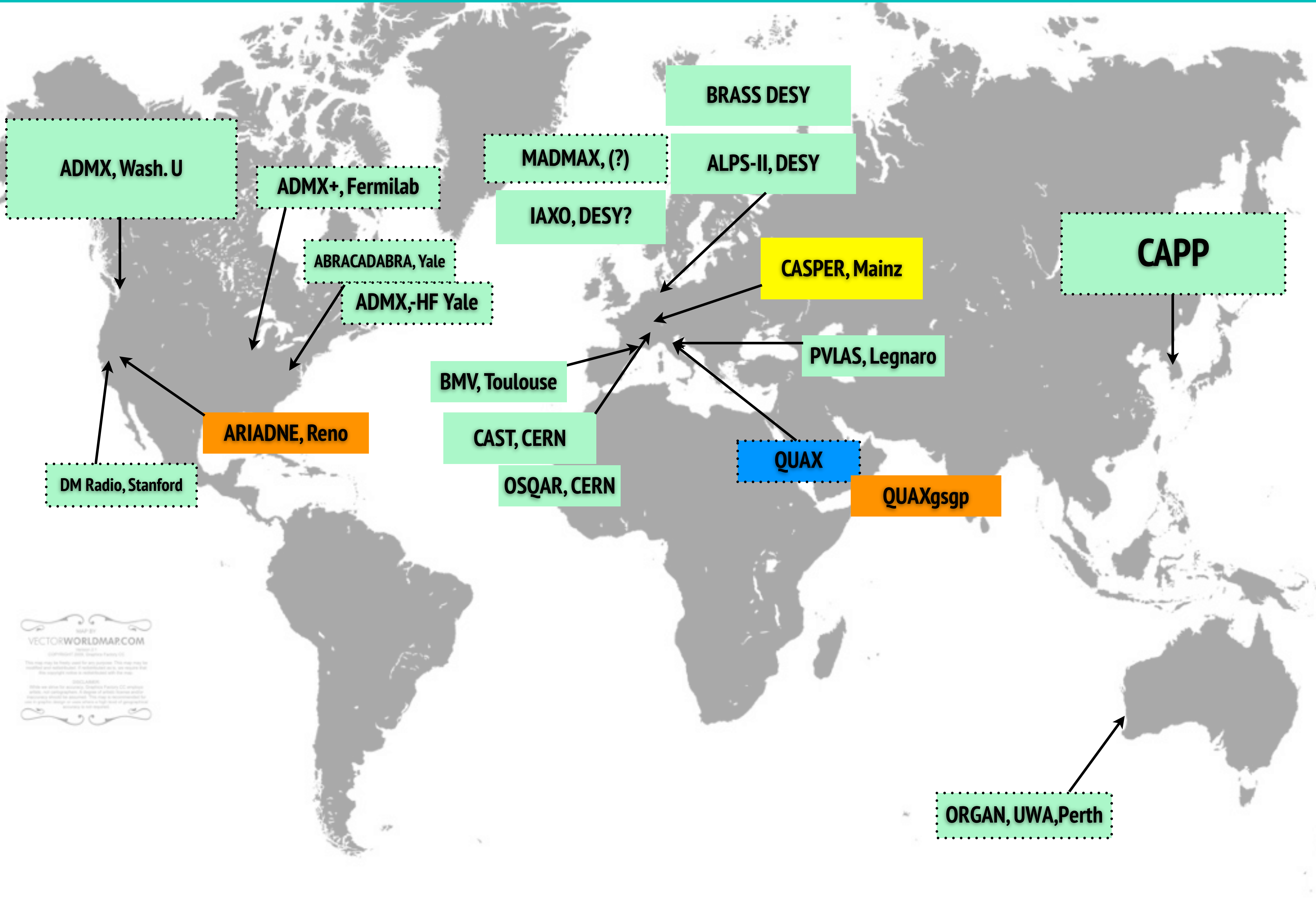


In the big picture



- Axion non-dark matter experiments ... solar axions (IAXO), long range forces (ARIADNE, QUAX), Light shining through walls (ALPSII)

In a small context



Conclusions

- Axions might be hinted by the tiny EDM of hadrons (strong CP problem!)

- Axion dark matter is unavoidable

- Cavity experiments on the run

- New experimental techniques blooming, loads of R&D

- Need for high-B-field magnets, large volumes, quiet RF receivers

- Until recently, only one axion DM experiment: ADMX in the USA