Axion Dark Matter

"Axions at the crossroads: QCD, dark matter, astrophysics"

ECT Trento, 20-24 Nov 2017

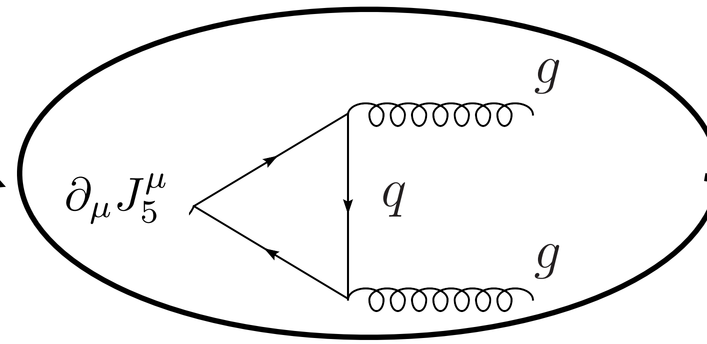
Javier Redondo

MAX-PLANCK-GESELLSCHAFT

The strong CP "issue"

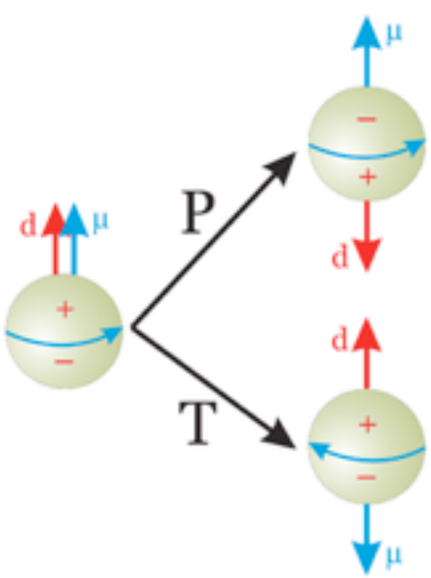
- **CP violation in QCD sector: CKM angle** $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\rm QCD} + N_f \delta$

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



quark phase redefinition shifts between quark mass phase and QCD vacuum because of the axial anomaly

- **The** θ**-angle produces flavour-neutral CP violation like Electric Dipole Moments ... never observed!**



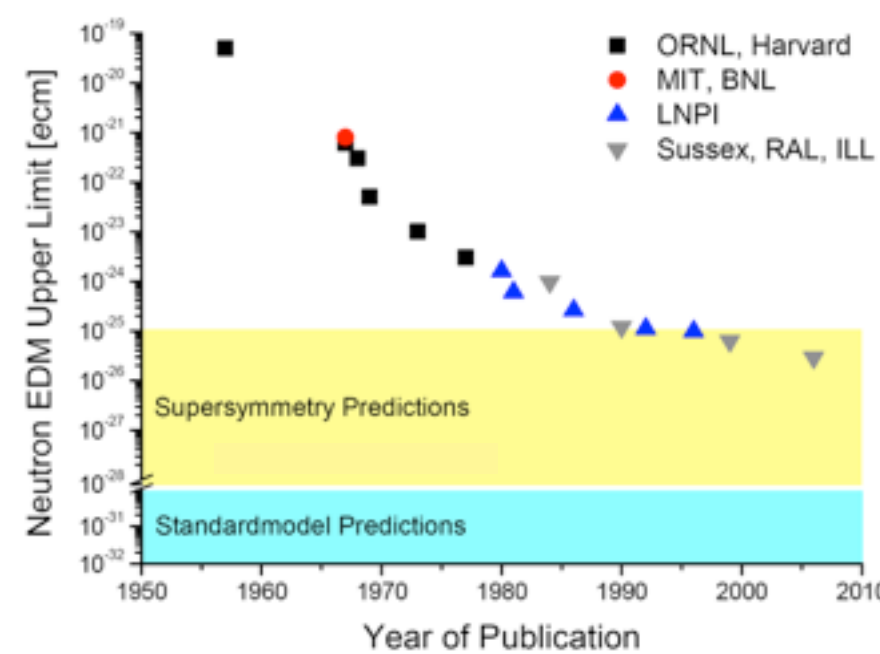
- **Neutron EDM** (Guo 1502.02295)

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

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

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

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



Driving θ dynamically to zero with BSM physics

CP Conservation in the Presence of Pseudoparticles*

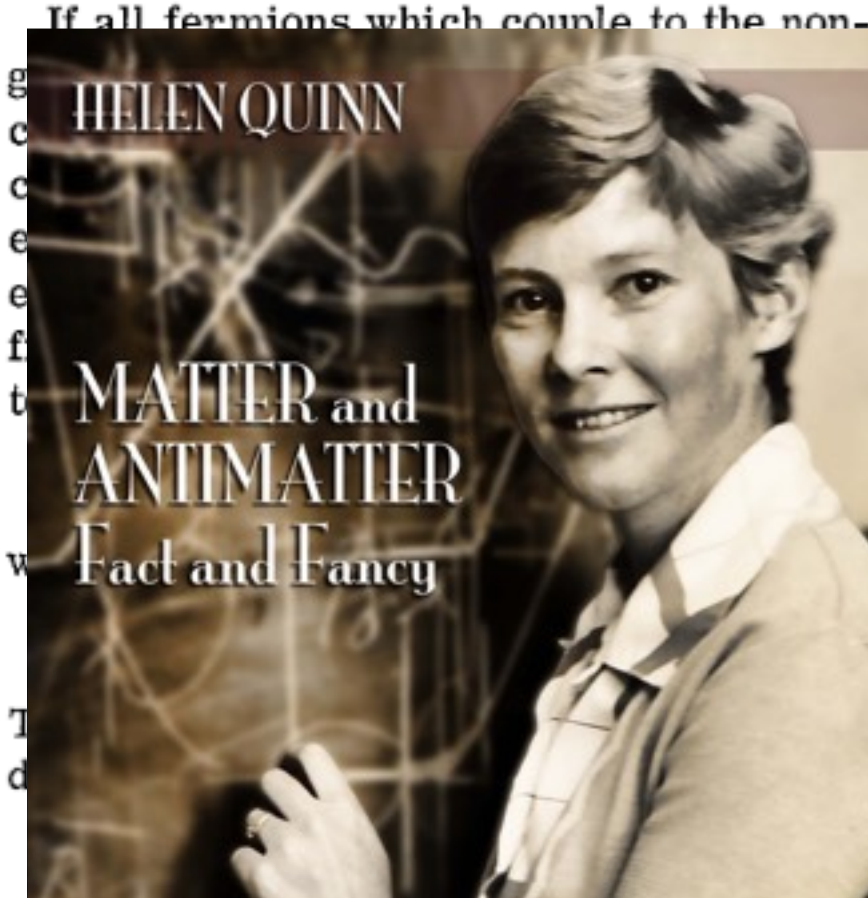
R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

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.

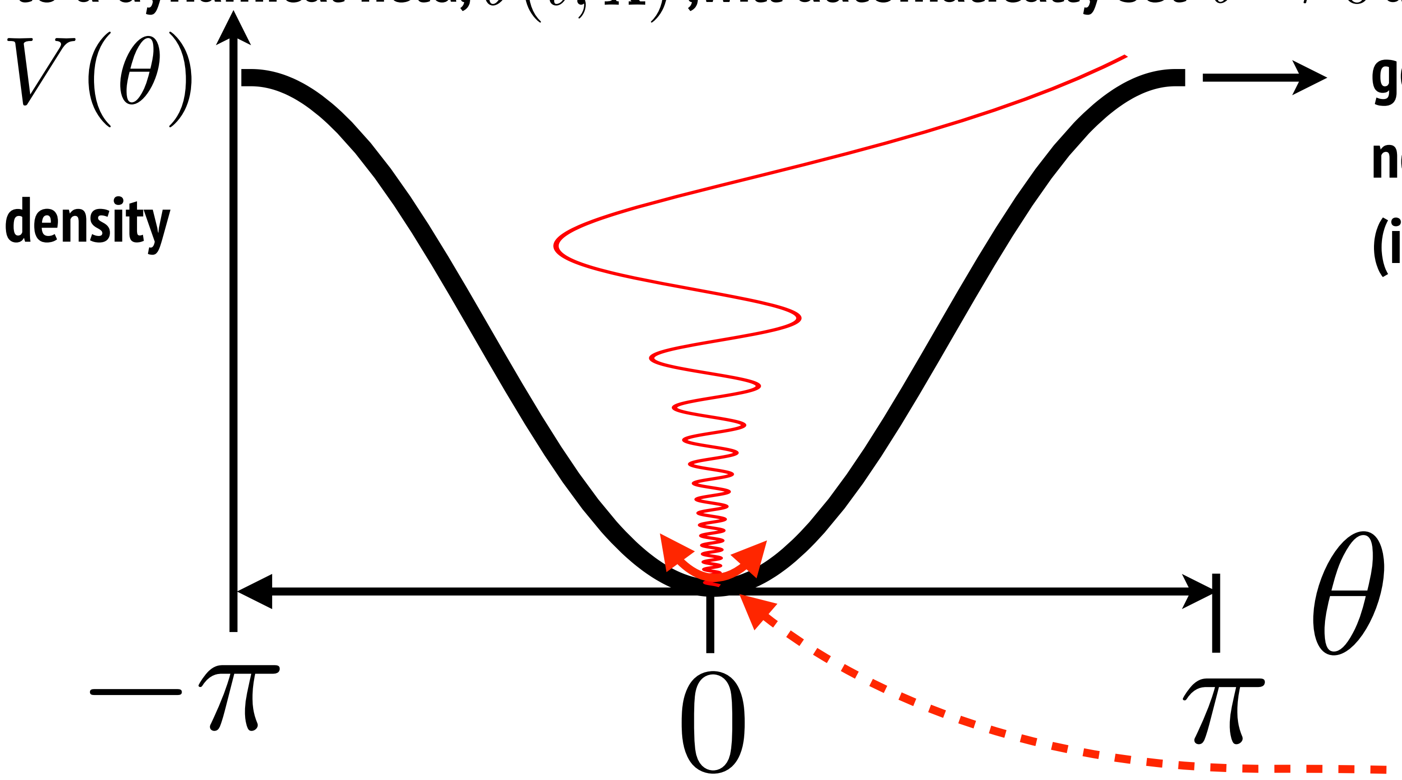
If all fermions which couple to the non-Abelian



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

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

Potential energy density



generated by QCD non-perturbative dynamics (instantons)

- PQ Mechanism: Global U(1) axial sym spontaneously broken-> Goldstone boson

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

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

New Spontaneous symmetry breaking [energy] scale f_a

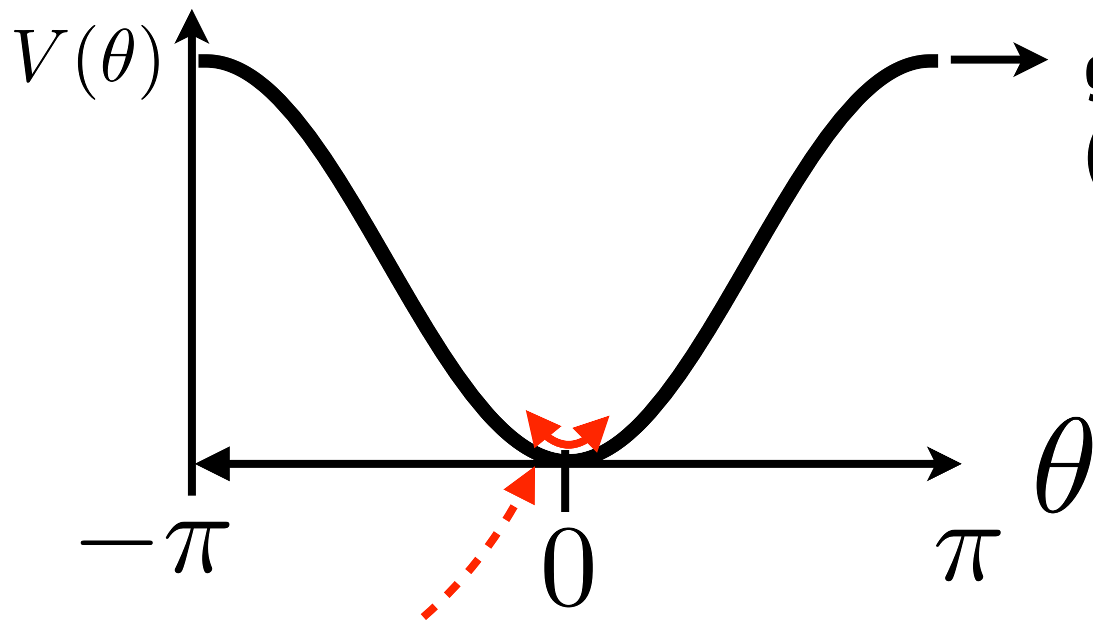
New scale f_a can relate to fundamental scales (string, flavor)

F. Wilczek

Talks by Cicoli, Hollik

The axion mass

- QCD potential gives the axion a mass -> pseudoGoldstone boson $m_a^2 = \frac{\partial^2 V}{\partial a^2} = \frac{1}{f_a^2}\frac{\partial^2 V}{\partial \theta^2} = \frac{1}{f_a^2}\chi$



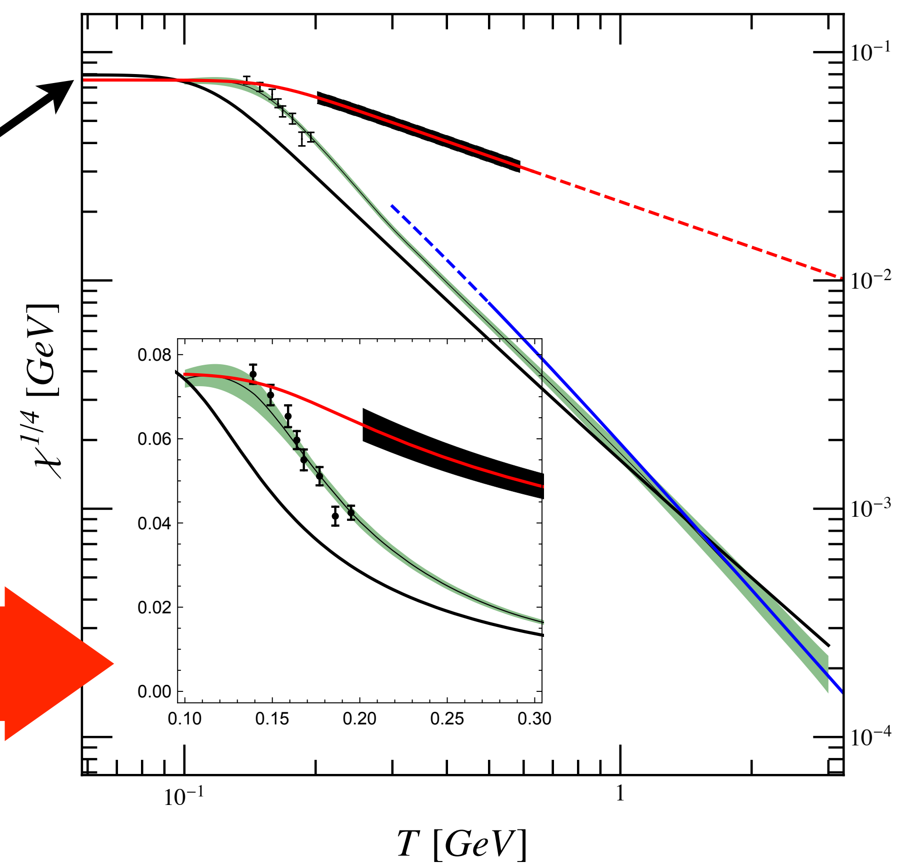
generated by QCD (instantons)

- Topological susceptibility depends strongly on temperature! high T axions are ~ massless!

$\chi = (75.5\,\mathrm{MeV})^4$

ChiPT, Grilli di Crotona JHEP 1601 (2016) 034

Lattice QCD, Borsanyi Nature 539 (2016)



Lattice QCD 2+1 (T~Tc) Bonati et al JHEP 1603 (2016) 155

Lattice QCD 2+1+1 (T~Tc) Borsanyi et al Nature 539 (2016)

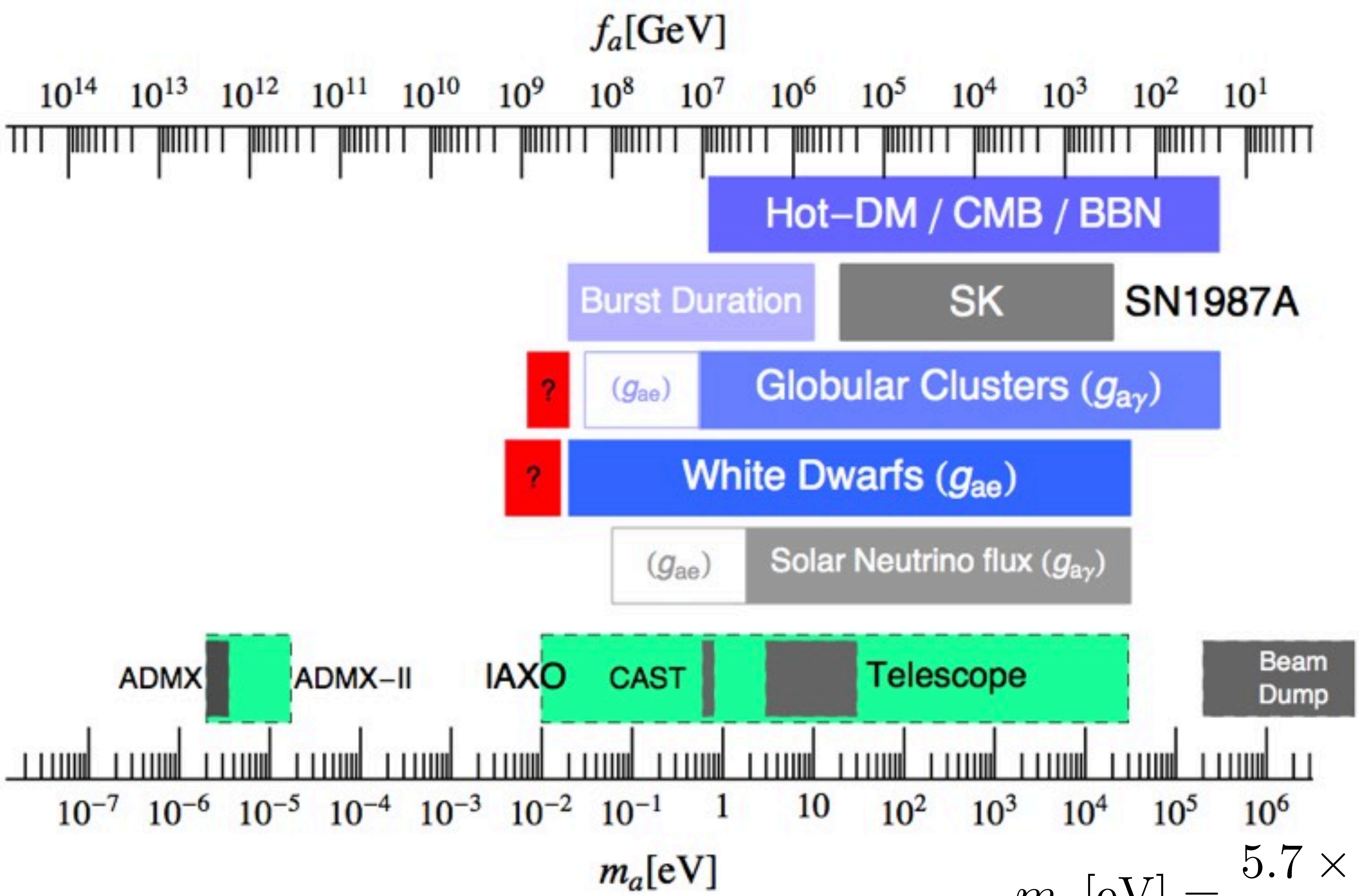
DIGA (analytical) (valid T>>Tc) Borsany at al PLB 2015

Lattice QCD 2+1 Petreczky at al arXiv:1606.03145

Lattice QCD (DWF) 2+1 Buchoff et al PRD 89 2014

Interacting Instanton Liquid (Model) Wantz/Shellard PRD 82 2010

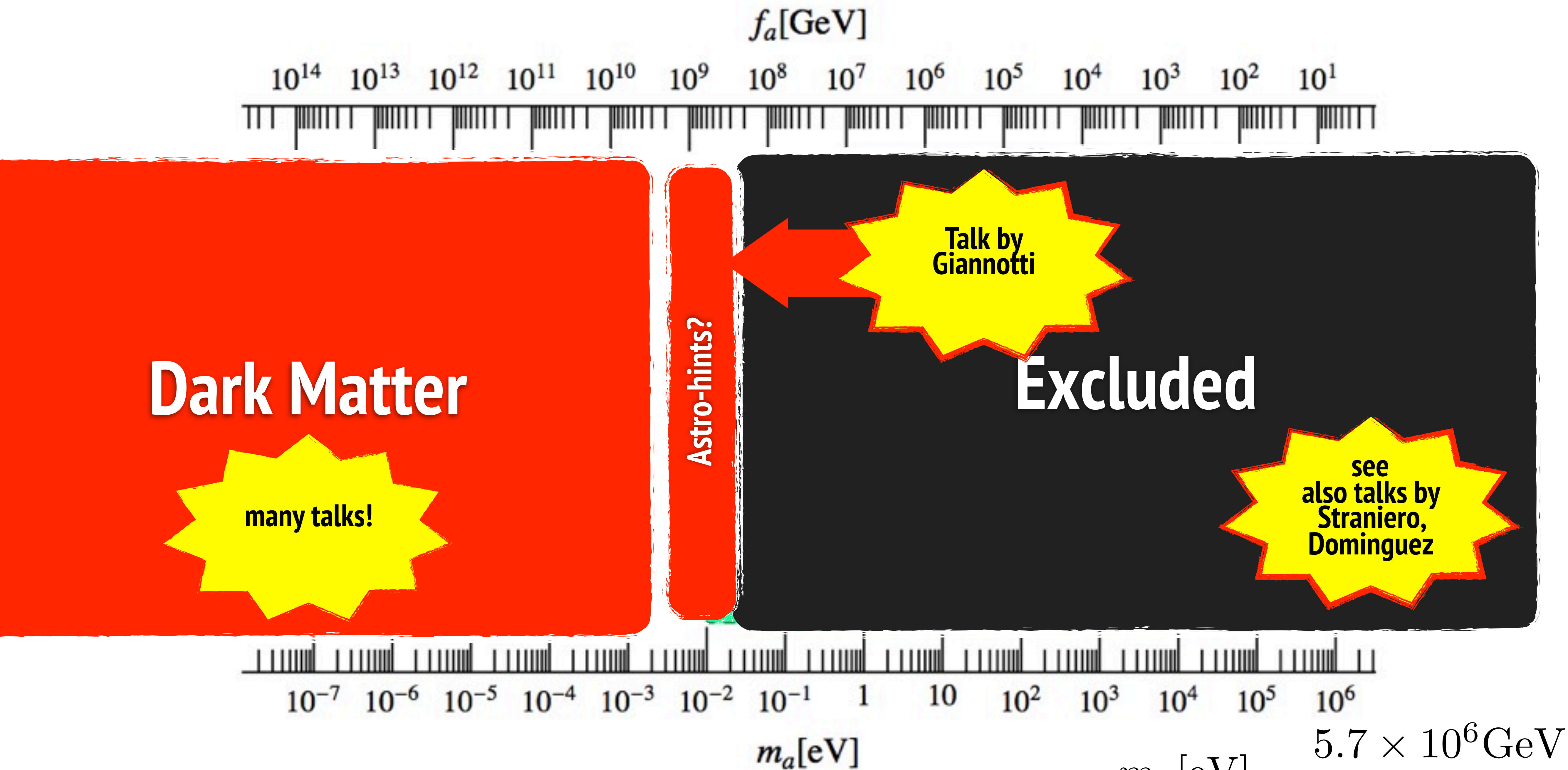
Landscape, what do we know?



$$m_a[\mathrm{eV}] = \frac{5.7 \times 10^6 \mathrm{GeV}}{f_a}$$

If axions exist, they are very light and VERY weakly interacting!

Landscape, what do we know?



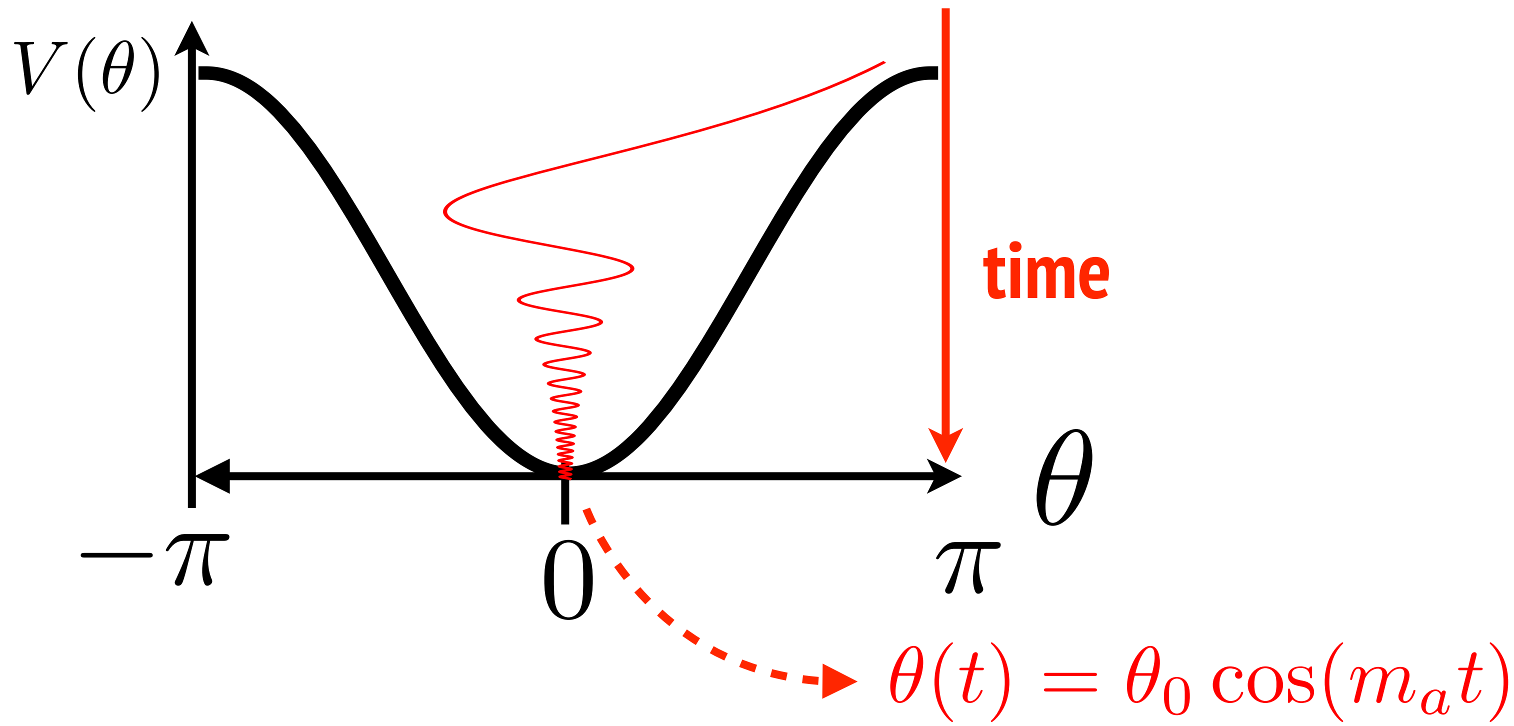
$$m_a[\mathrm{eV}] = \frac{5.7\times 10^6\,\mathrm{GeV}}{f_a}$$

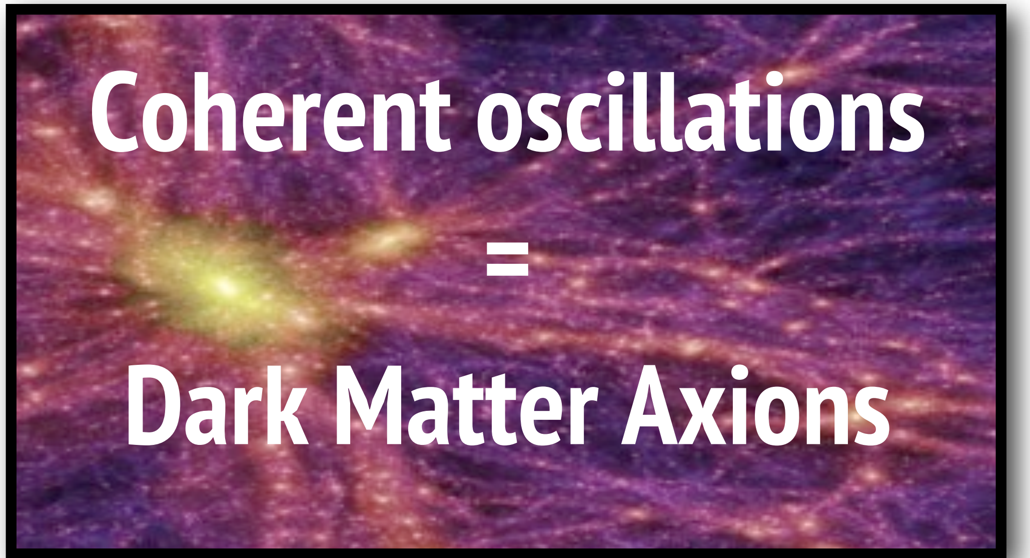
If axions exist, they are very light and VERY weakly interacting!

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





Oscillation frequency

$$\omega = m_a$$

Energy density (harm. oscillator)

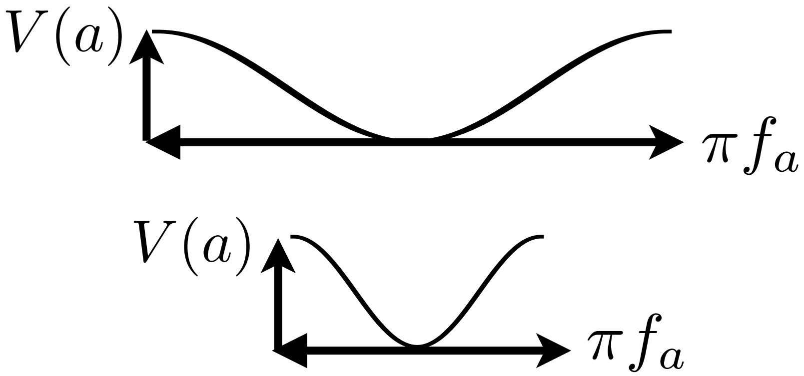
$$\rho_{\rm aDM} = \frac{1}{2} m_a^2 f_a^2 \theta_0^2 = \frac{1}{2} (75 {\rm MeV})^4 \theta_0^2$$

- Some amount of axion Dark matter is unavoidable!

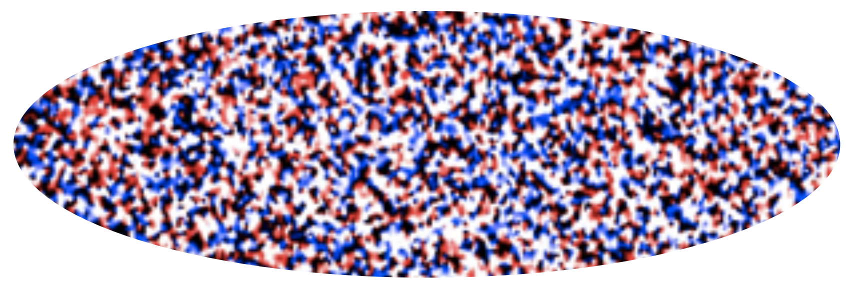
Axion dark matter

- The amount of axion DM produced depends on f_a AND on the initial conditions

large fa, small acceleration, energy stored longer

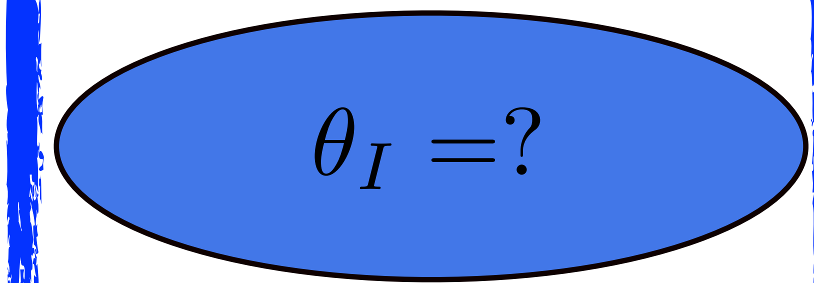


After PQ phase transition, theta IC conditions no-correlation beyond causal horizon

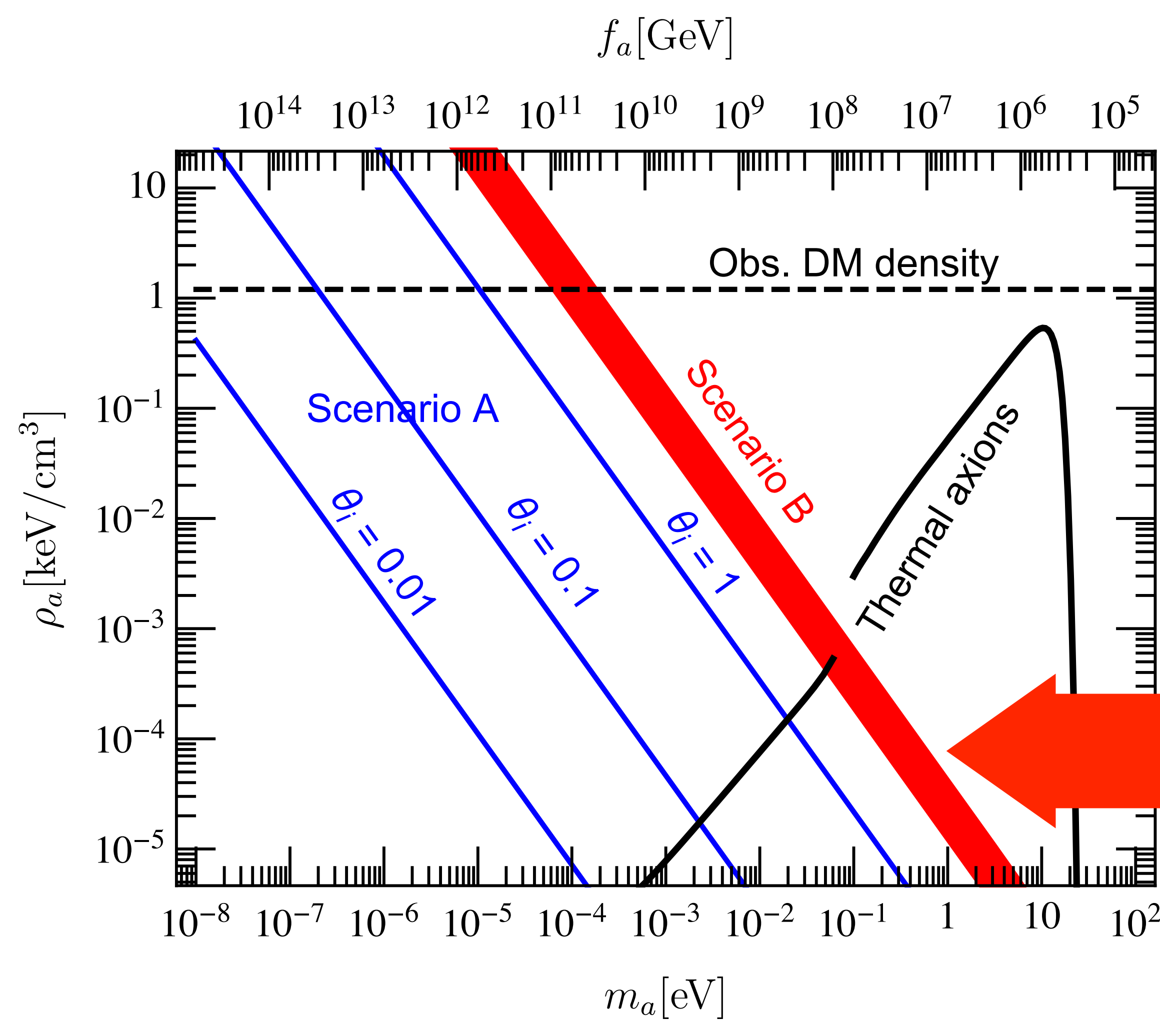


average over initial conditions! -> prediction!

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

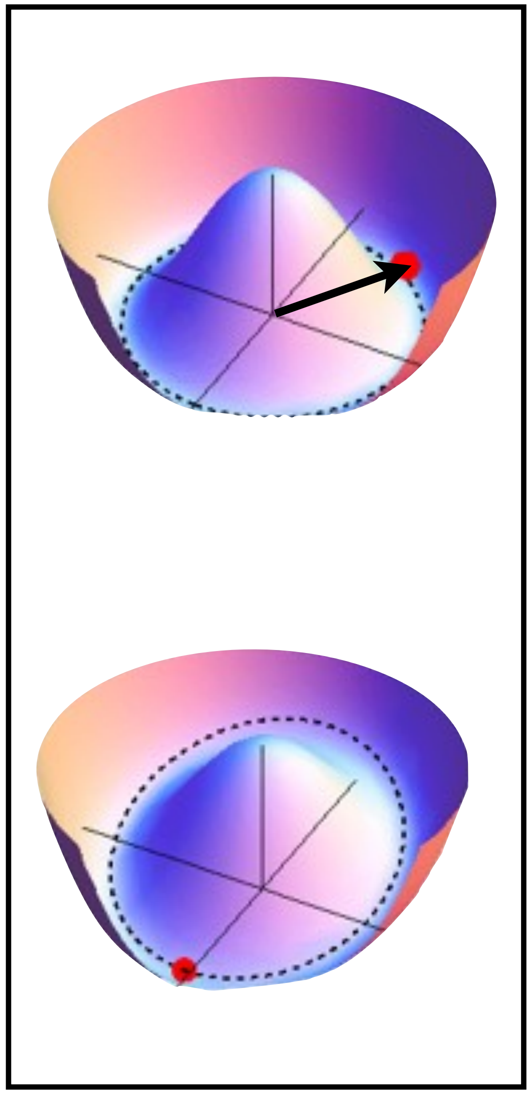


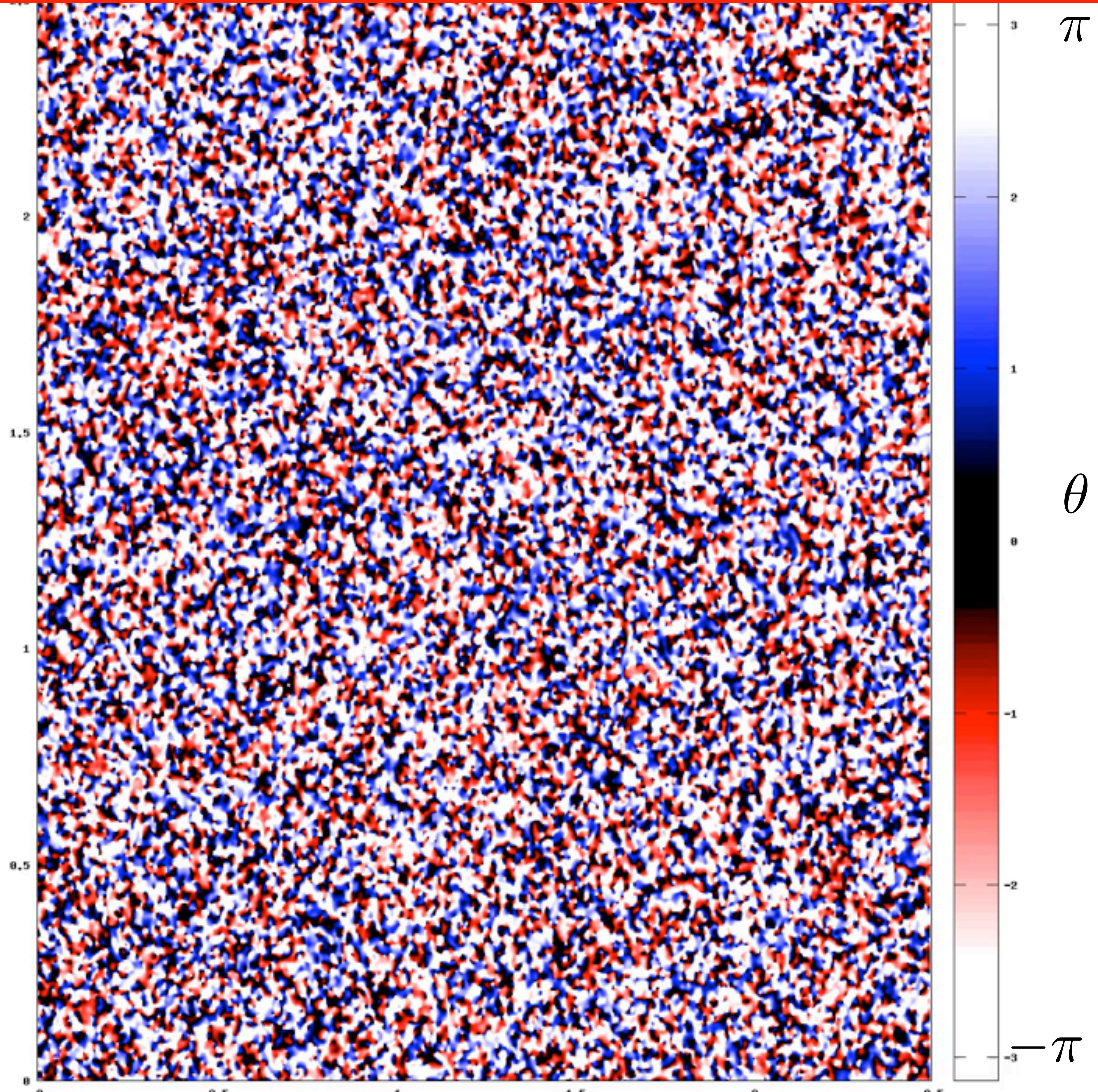
but which one??? no prediction!



Talks by Gorghetto, Klaer

SCENARIO I (N=1): axion evolution around t1

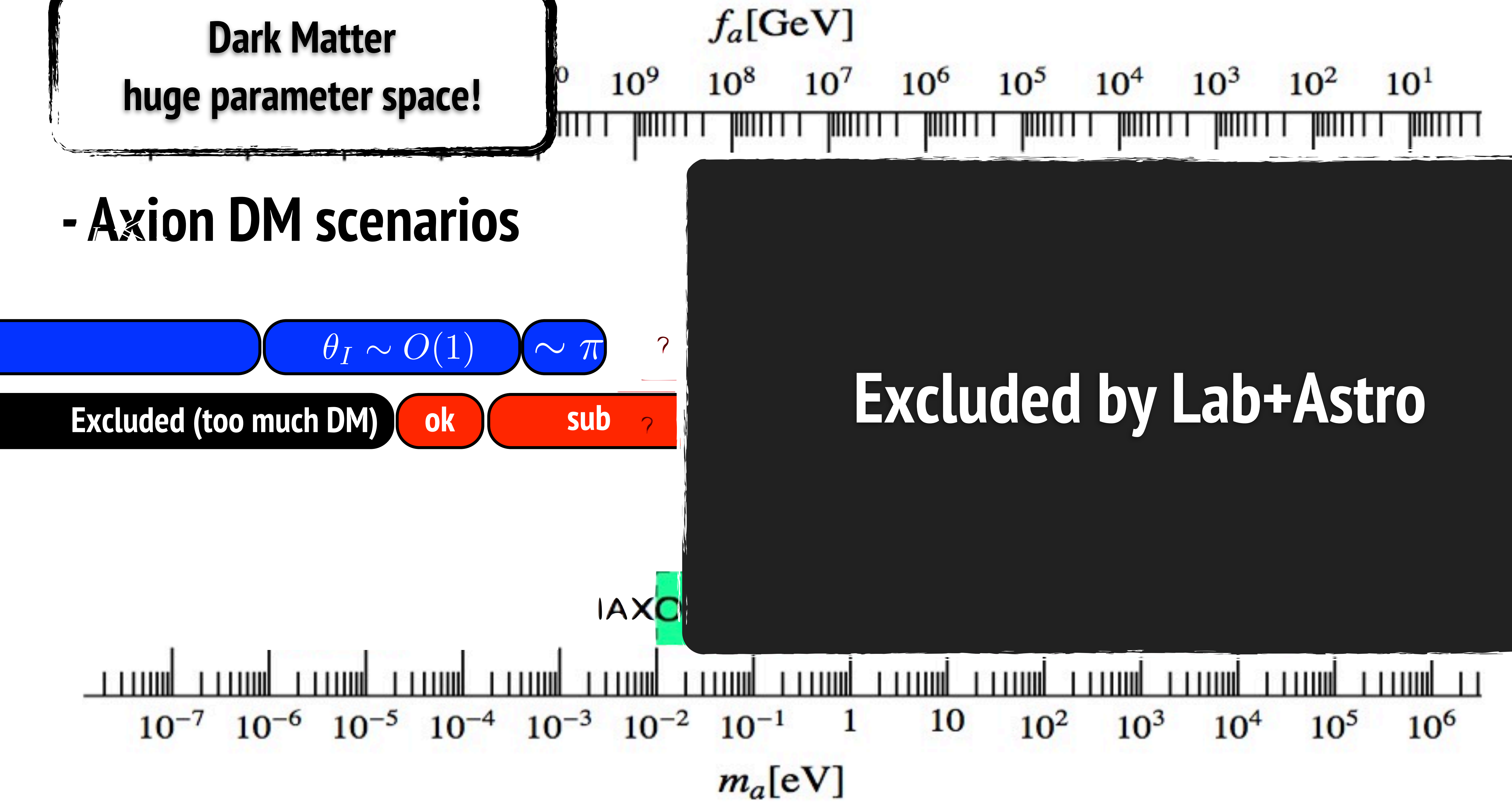




What value of f_a for $\Omega_{cdm} h^2 = 0.12$?

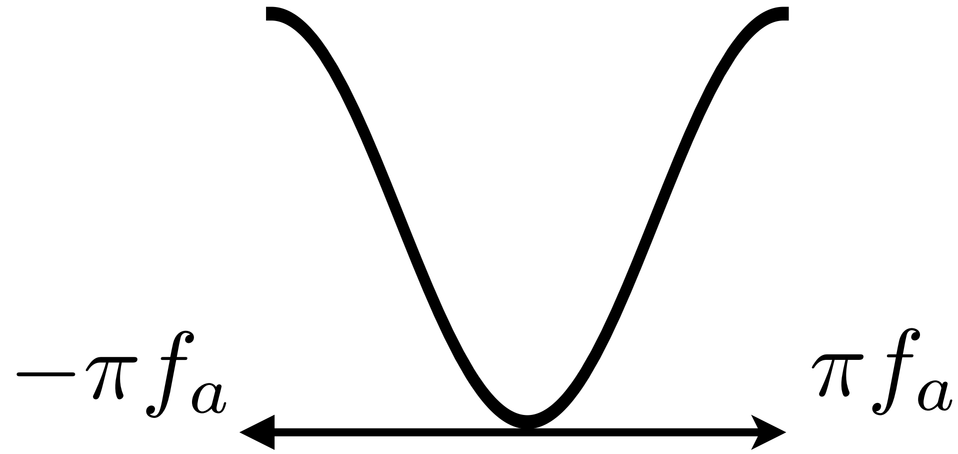
Dark Matter
huge parameter space!

- Axion DM scenarios



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

SCENARIO I, N=1



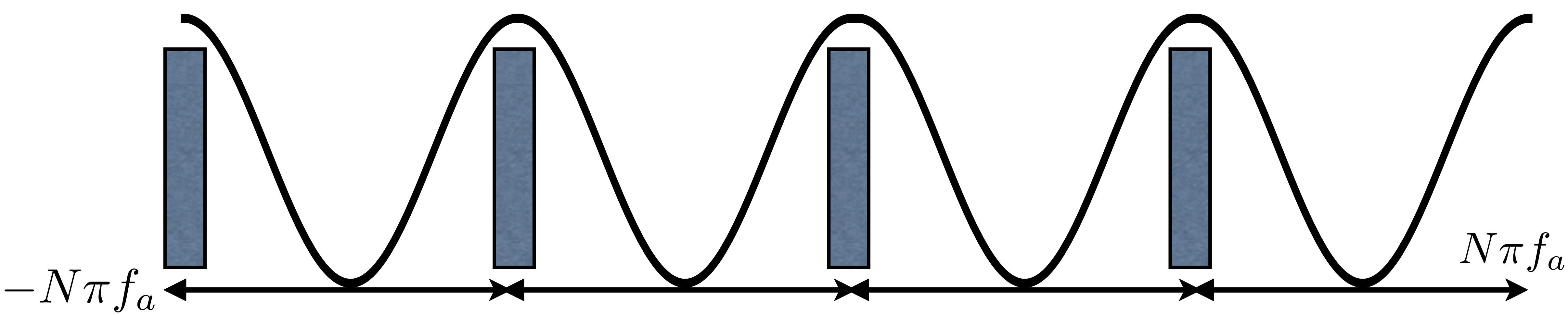
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}^{\mu\nu}_a \theta$$

$$\theta \in (-\pi, \pi)$$

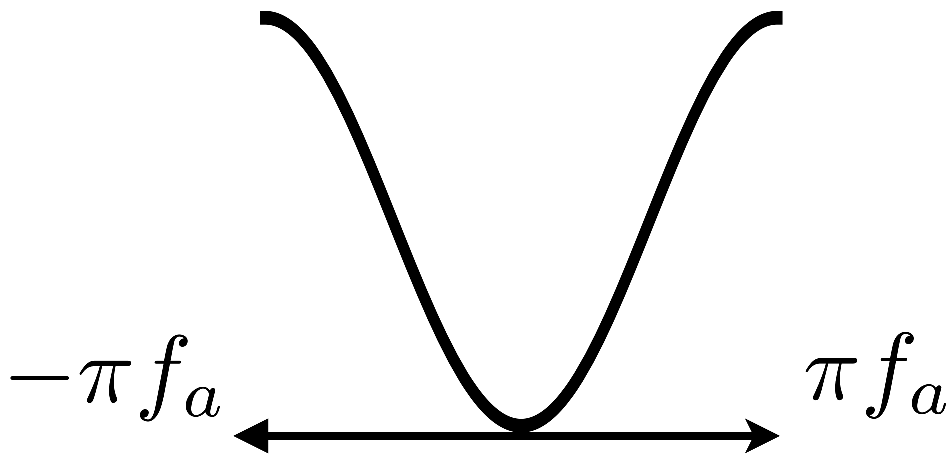
SCENARIO I, N>1, Domain Walls stable-> cosmological disaster

In some axion models, the Goldstone is $\theta_g \in (-\pi, \pi)$ **but the anomaly leads to** $\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}^{\mu\nu}_a \theta_g N$

-> the axion field is defined $\theta = \theta_g N$ **up to Npi and has thefore N degenerate (CP conserving) minima**

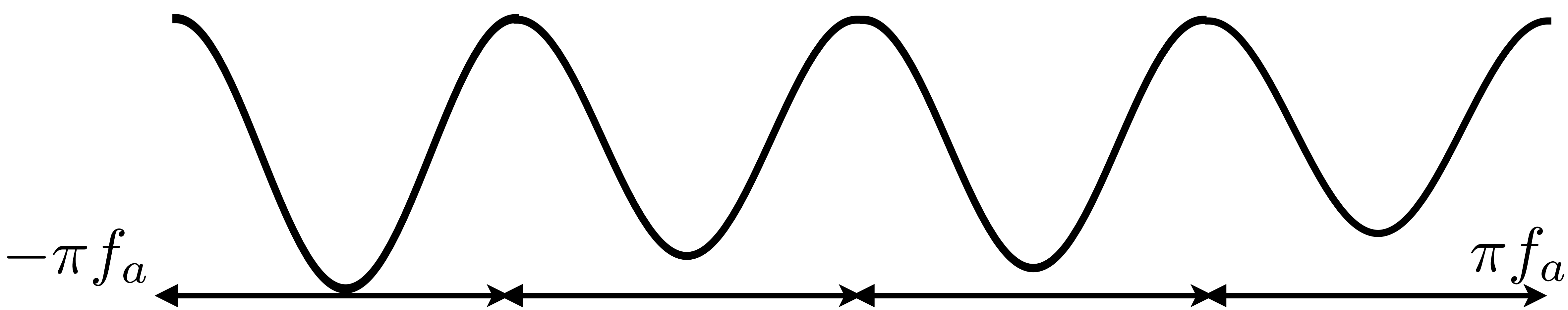


SCENARIO I, N=1



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

SCENARIO I, N>1, break slightly degeneracy (but tuning...)



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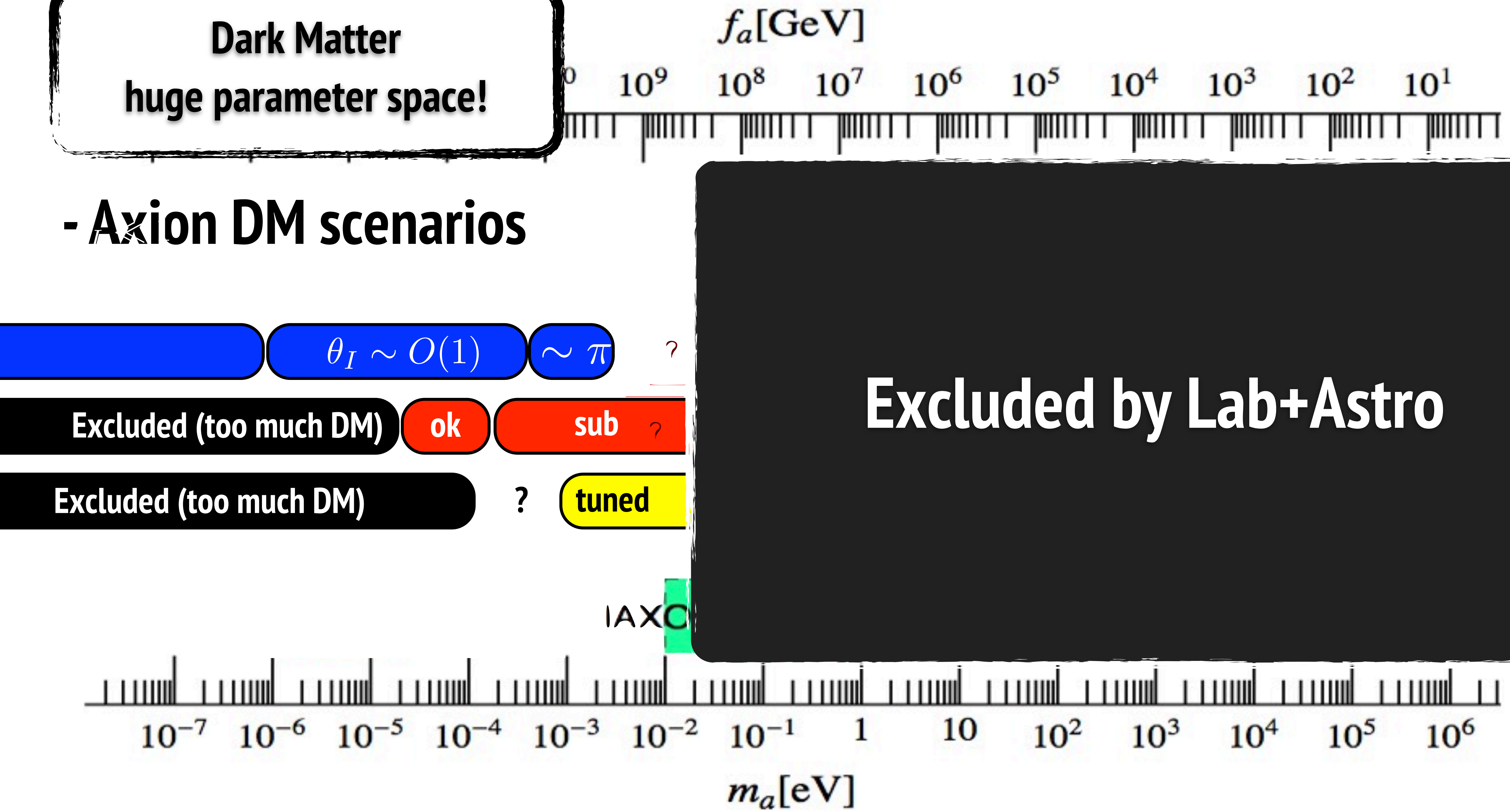
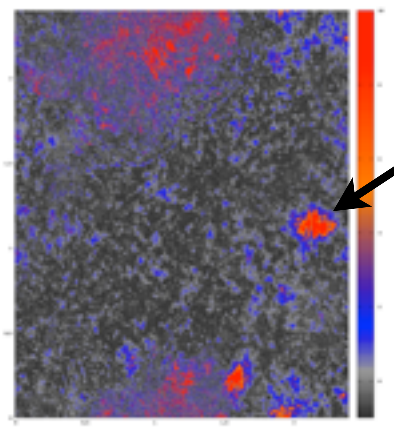


- Less minimal axion models have further possibilities ....

Most important constraints I

- PQ breaking after inflation

-> DM inhomogeneous, Axion miniclusters



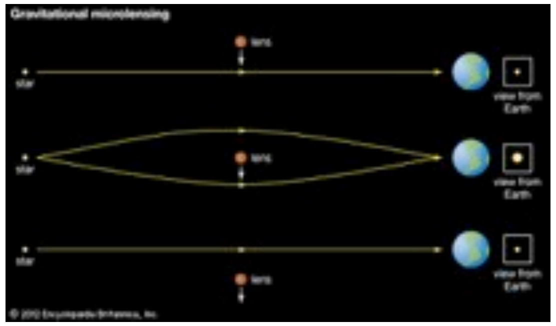
DM density contrast

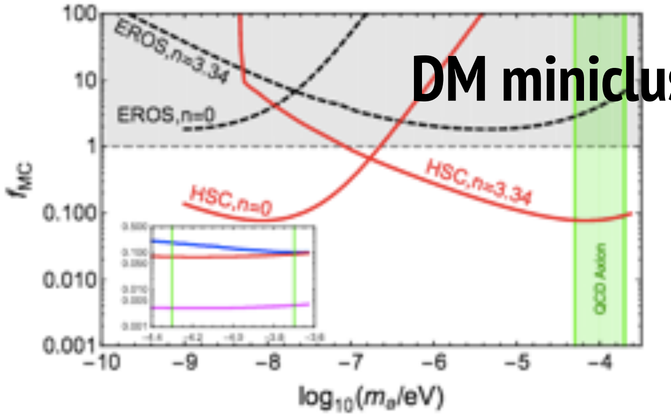
~ 0.1 comoving pc

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

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

Microlensing





DM minicluster fraction <0.1

Marsh 1701.04787

Scenario I Length scales

- **Time scale**

$$3H(T_1) = m_a(T_1) \qquad t_1 \sim \frac{1}{2H_1}$$

- **Horizon size (shorter wavelengths decay)**

$$L_1 = 2t_1 \sim \frac{1}{H_1}$$

- **Full Axion DM in this model** $f_a \sim 10^{11}\mathrm{GeV}$

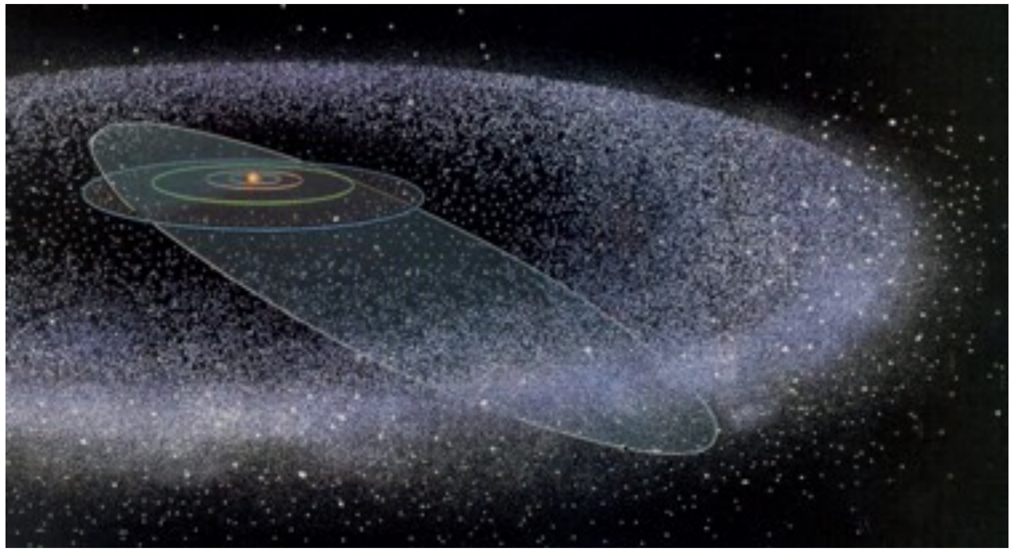
$$T_1 \sim 1.5\,\mathrm{GeV}\left(\frac{10^{11}\mathrm{GeV}}{f_a}\right)^{0.16}$$

- **Horizon scale at t1**

$$L \sim 10^4\ \mathrm{AU}$$ **(comoving)**

- **Mass scale in L-cube**

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

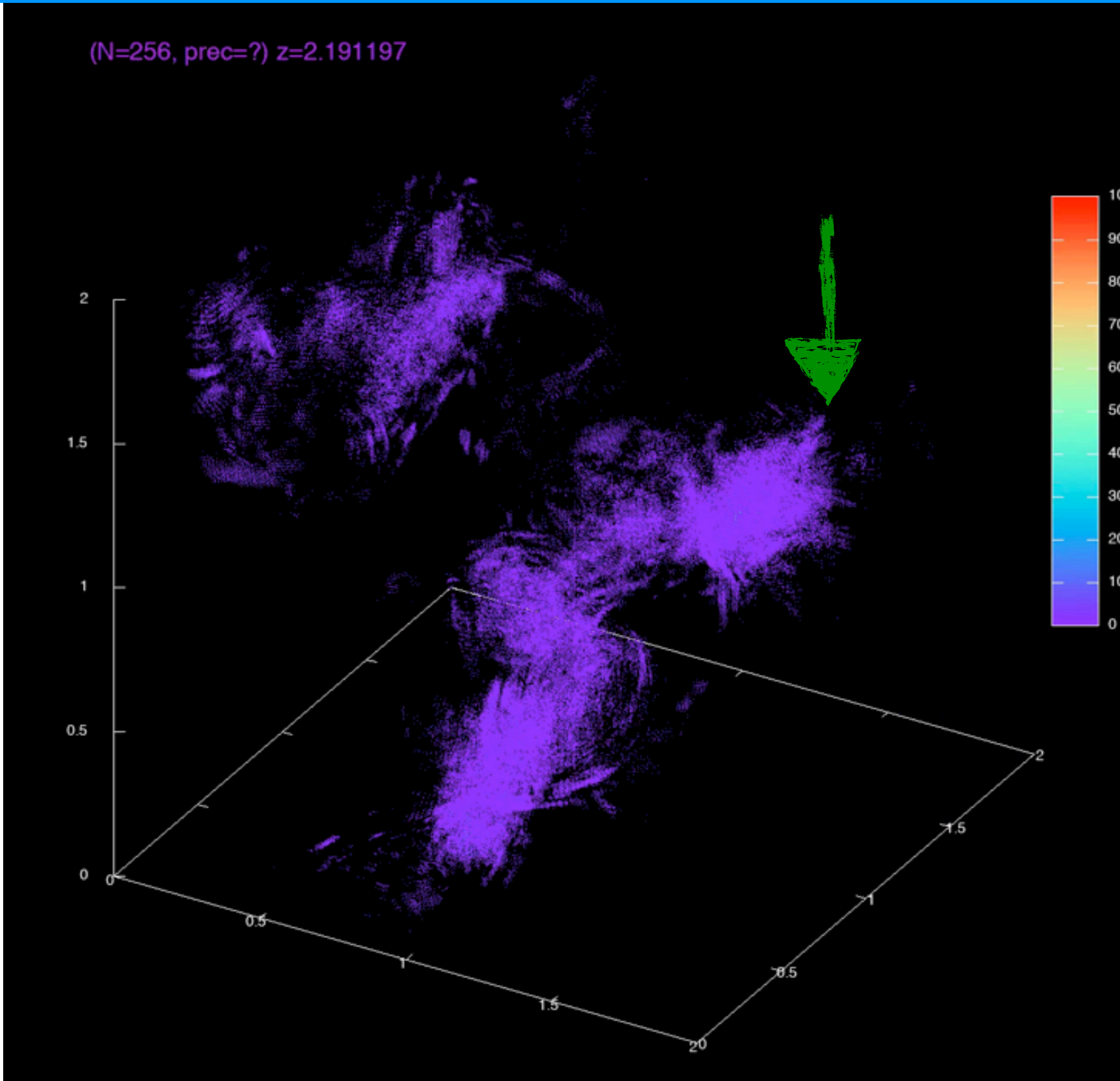


today corresponds to distances ~ Oort cloud

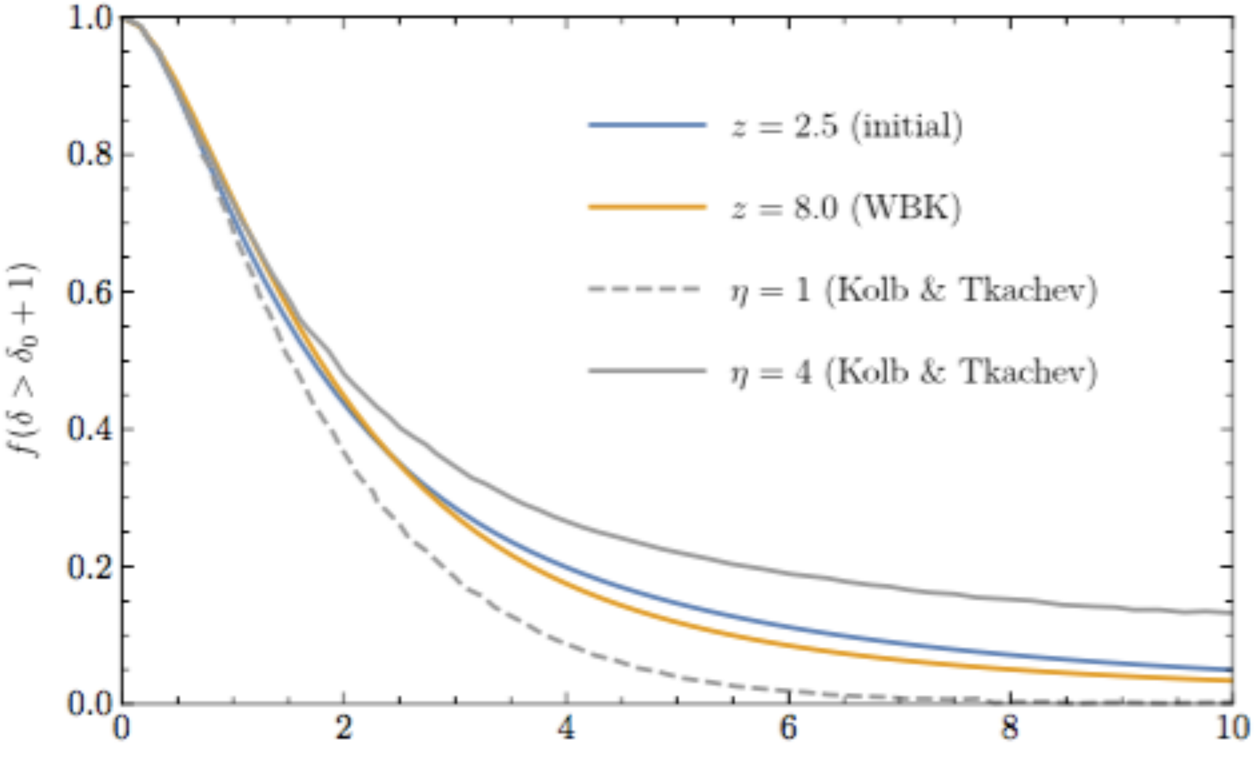
3 D energy density

$$\delta = \frac{\rho - \langle\rho\rangle}{\langle\rho\rangle} > 10$$

- axion miniclusters
- axitons (axion stars in core)



Distribution of overdensities



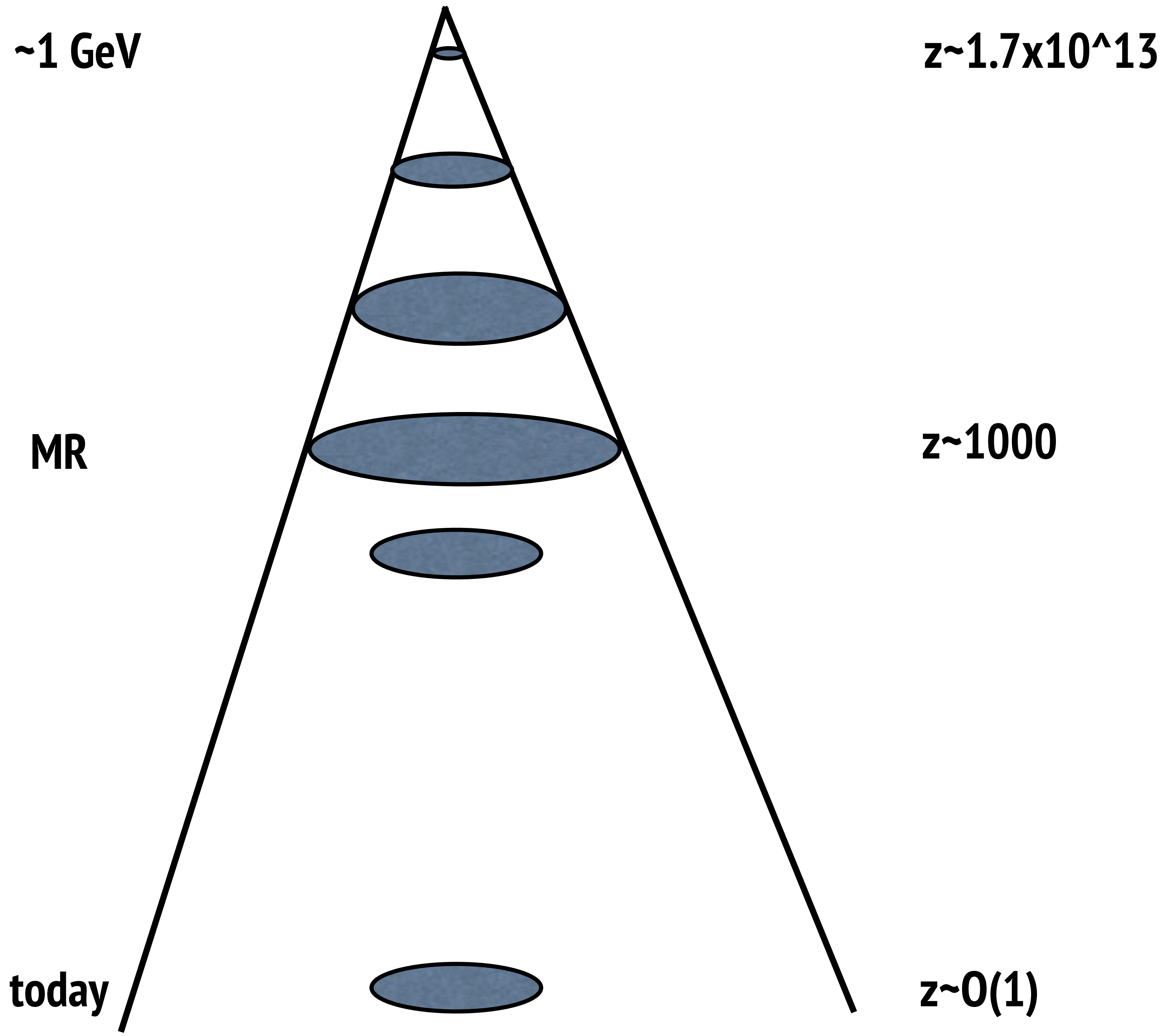
density contrast +1

Miniclaster size

frozen

size expands with the Universe

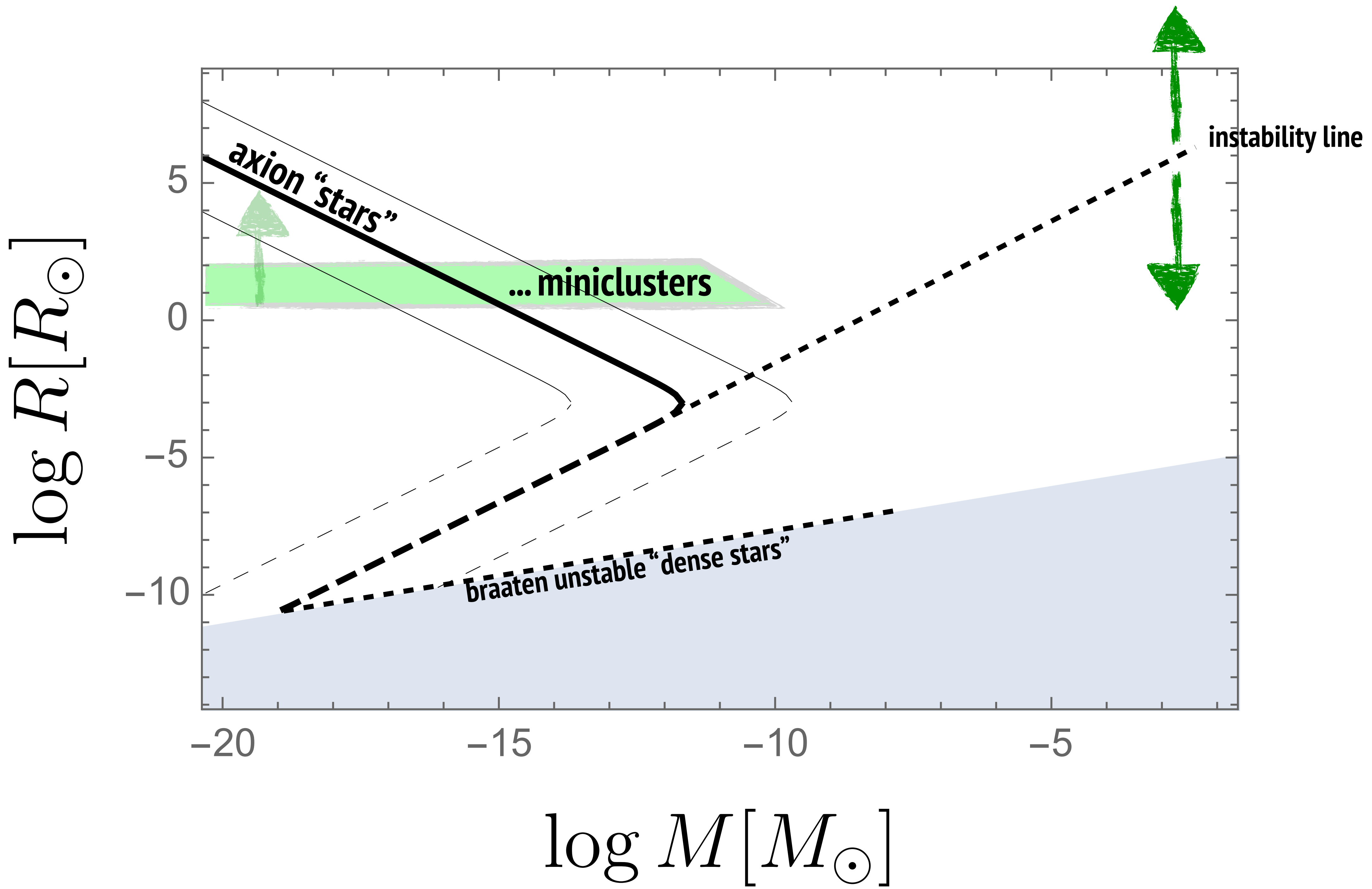
local $\rho_m = \rho_r$ collapse $z \sim \delta z_{\rm eq}$



They expand with the Universe until ~ Matter-radiation equality (z~1000)

$L \sim \mathcal{O}(1)\mathrm{A.U.}$

A picture

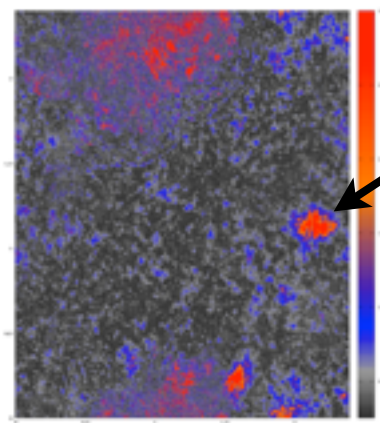


Braaten 2016
Visinelli 2017
JR work in progress ...

Most important constraints II

- PQ breaking after inflation

-> DM inhomogeneous, Axion miniclusters



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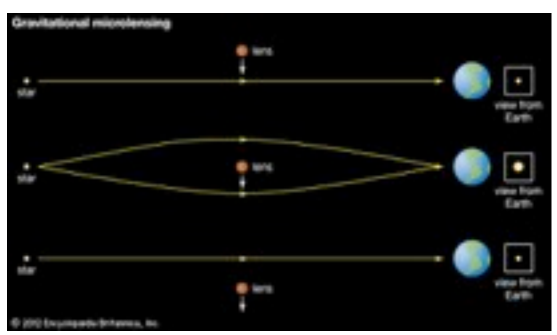
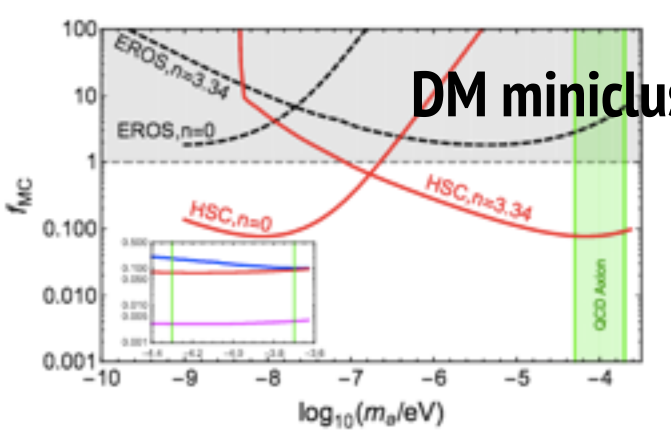


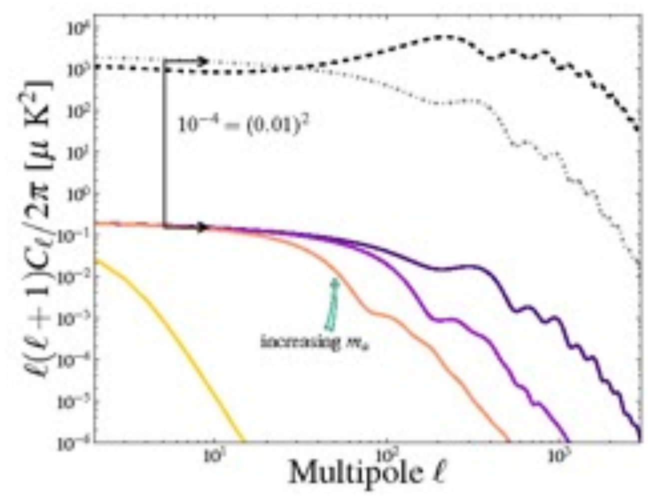


DM minicluster fraction <0.1

Marsh 1701.04787

- PQ breaking before inflation

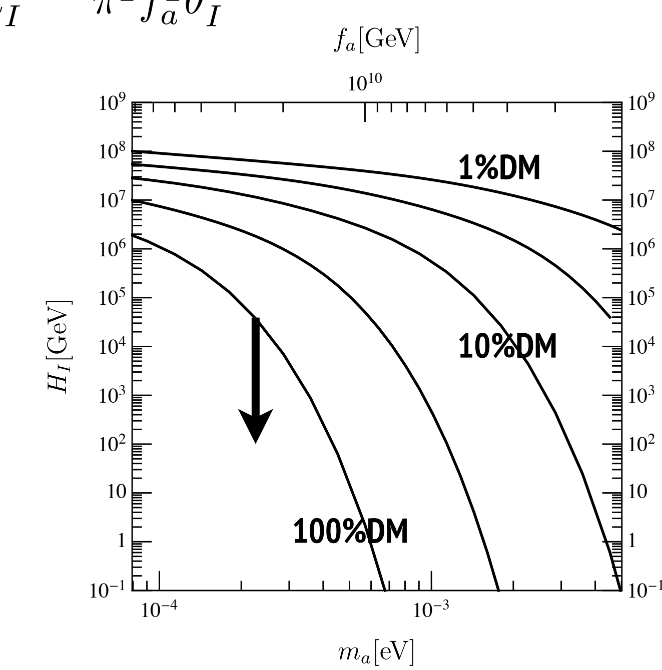
*** Axion fluctuations during inflation -> CMB isocurvature**



- 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

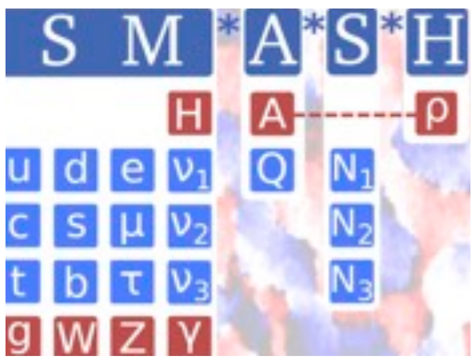


- If H_I **is measured by next generation CMB Polarisation axion DM is excluded (avoided in some models)**

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
- Leptogenesis (slightly resonant)

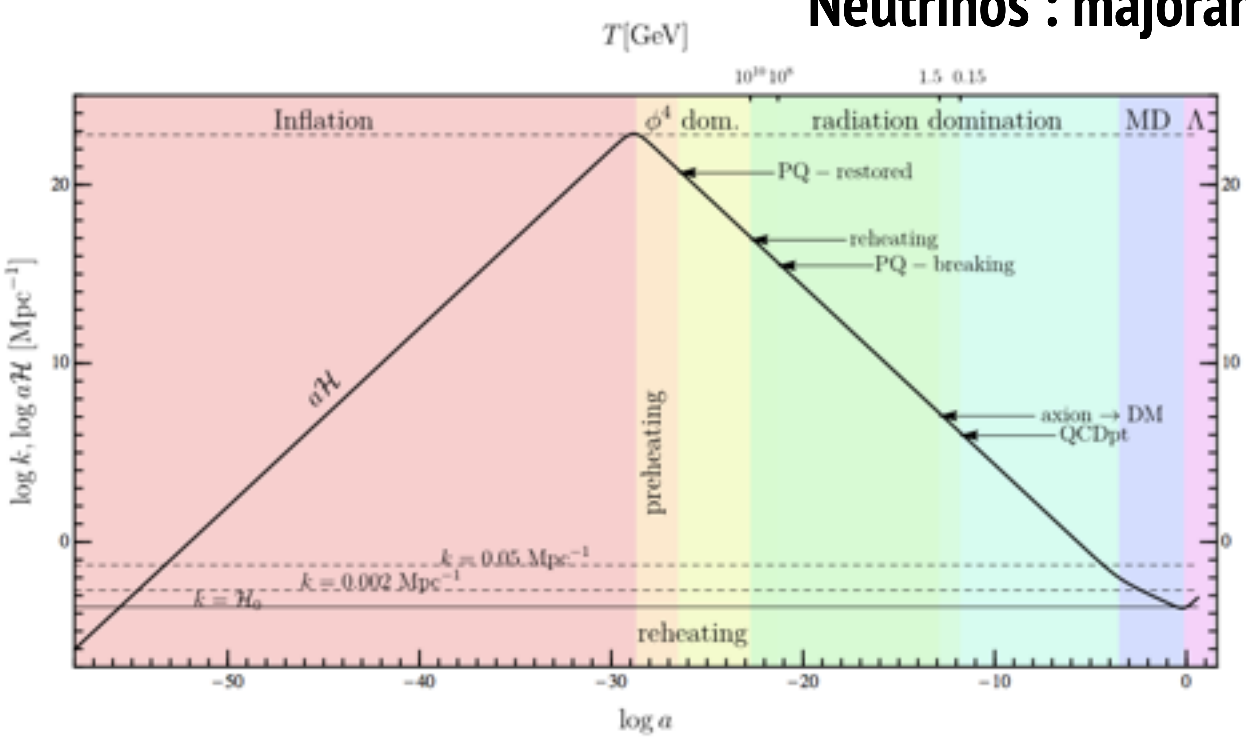
- Very clear predictions :

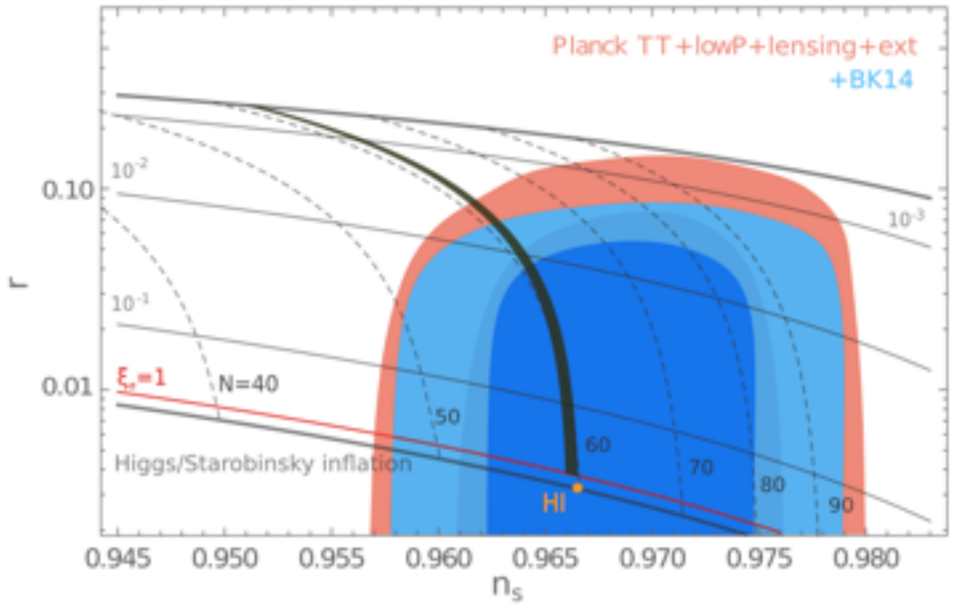
CMB : $r > 0.004 \quad n_s = 0.9645 \pm 0.0015 \quad \Delta N_\nu^{\rm eff} \simeq 0.03 \quad P_{\rm iso} = 0$

$\alpha \sim -7 \times 10^{-4}$

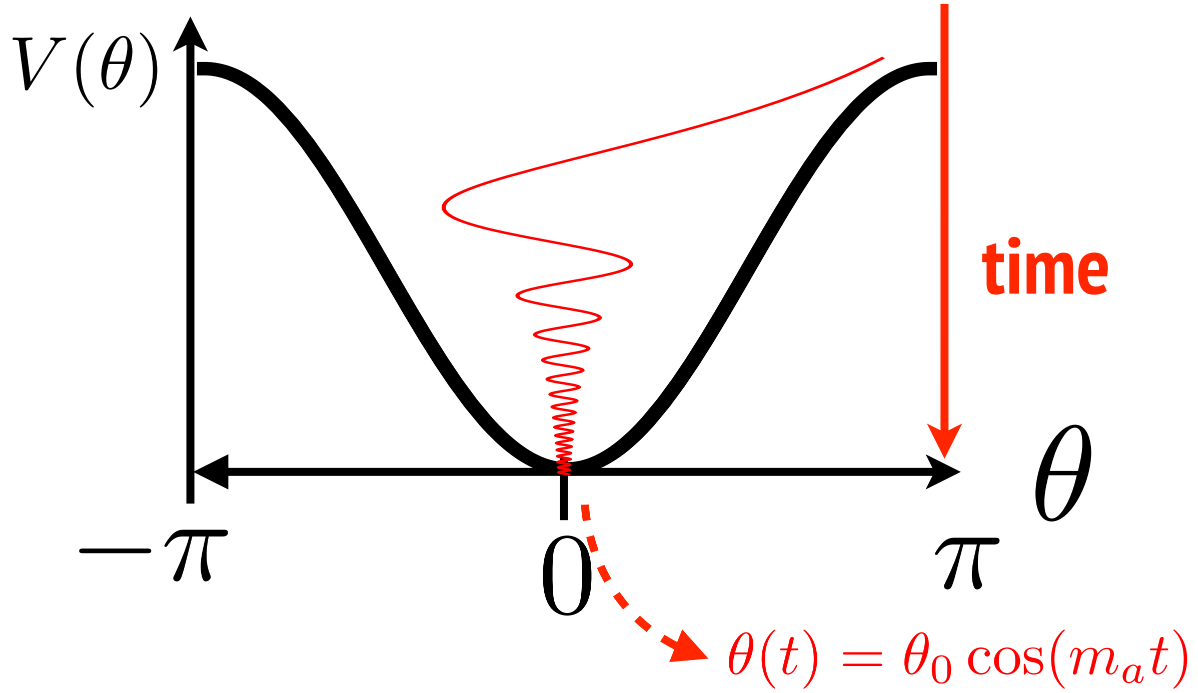
Axion Dark Matter (scenario I: post inflation) : $m_a \sim 100\,\mu{\rm eV}$, miniclusters

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





Detecting Axion Dark matter



Local Dark Matter density*

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

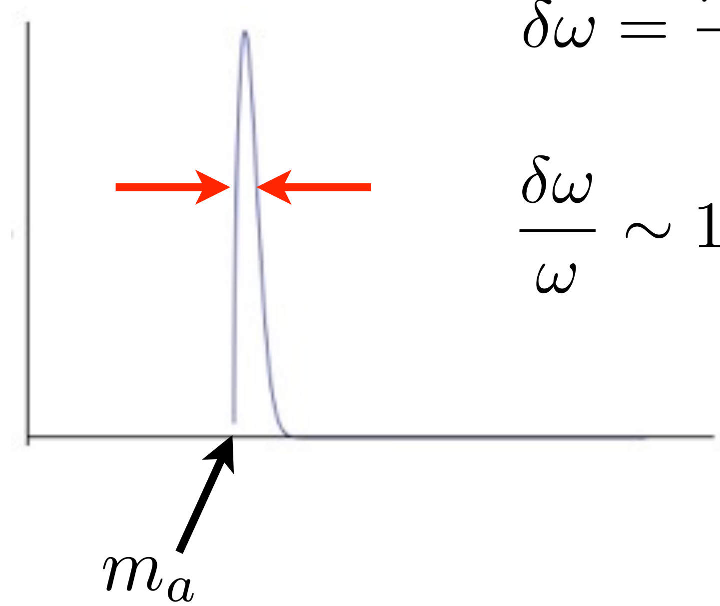
$$\theta_0 = 3.6 \times 10^{-19}$$

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



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

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

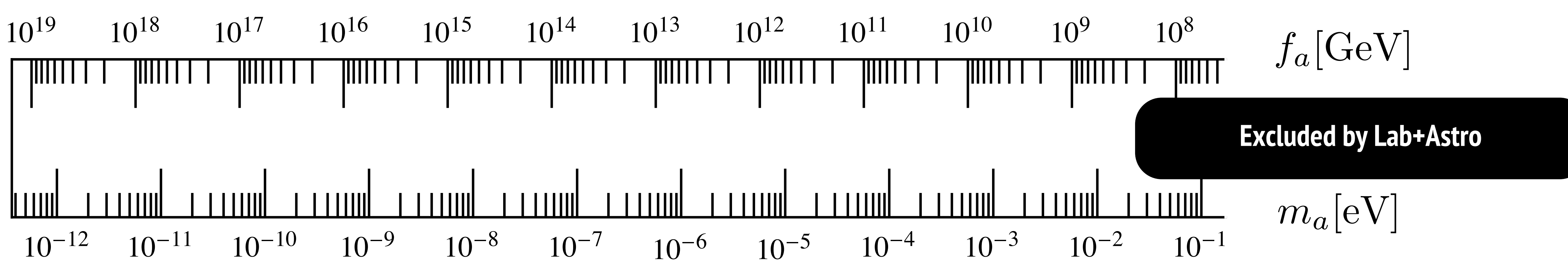
coherence time

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

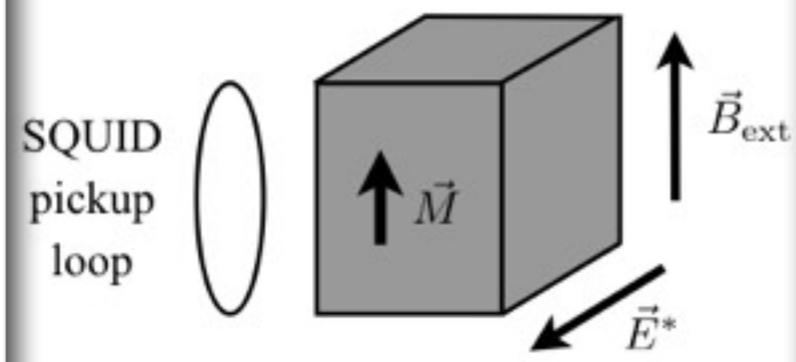
coherence length

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

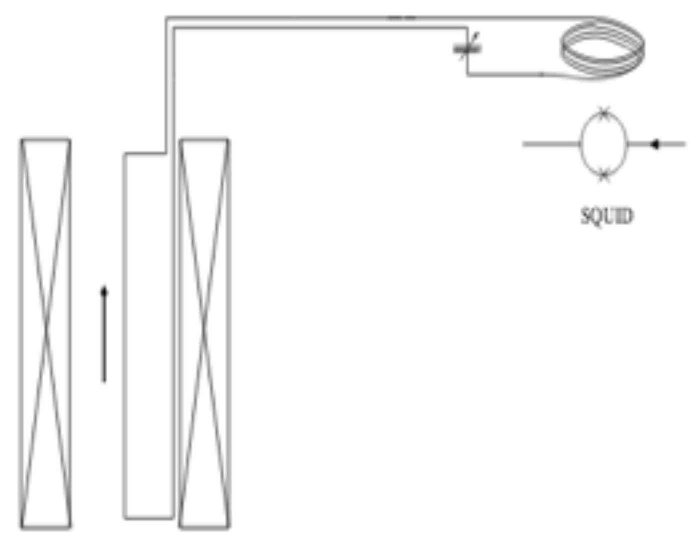
- **From** $f_a \sim 10^{19}\,\text{GeV}$ **to** $f_a \sim 10^{8}\,\text{GeV}$ **11 orders of magnitude in axion mass to scan ...**
10^{17} **channels in mass ....**



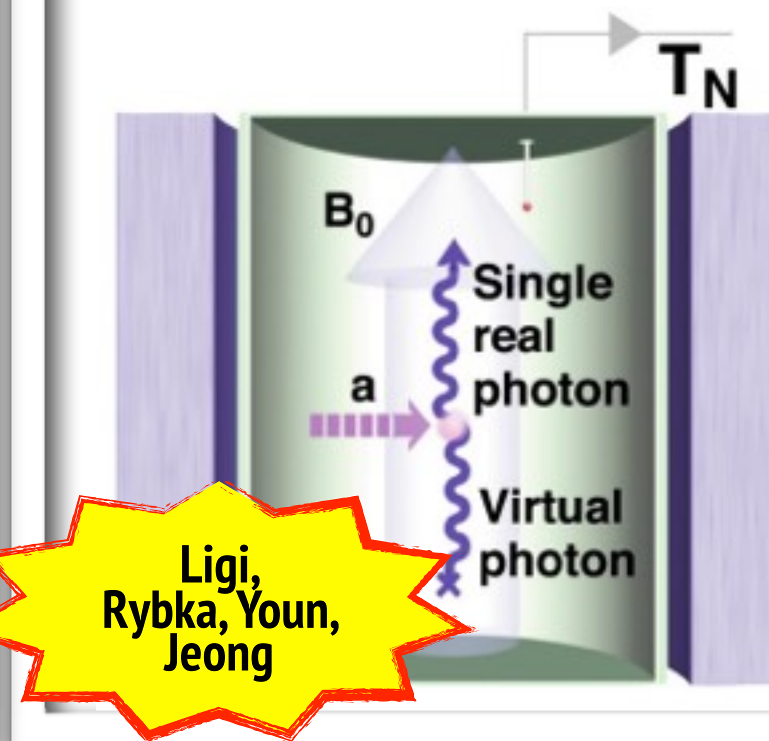
Oscillating EDM



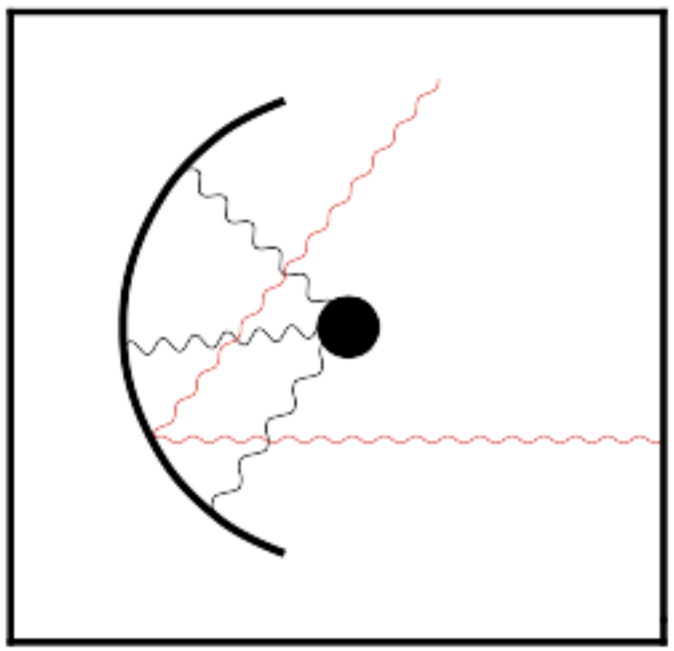
LC-circuit



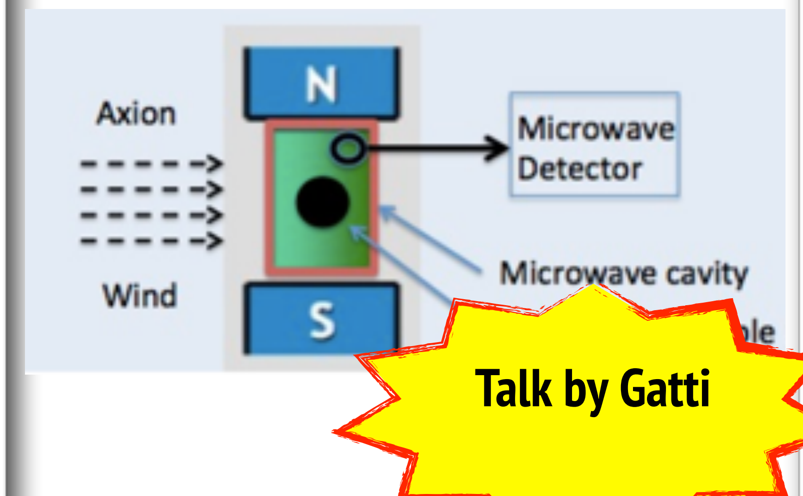
Cavities



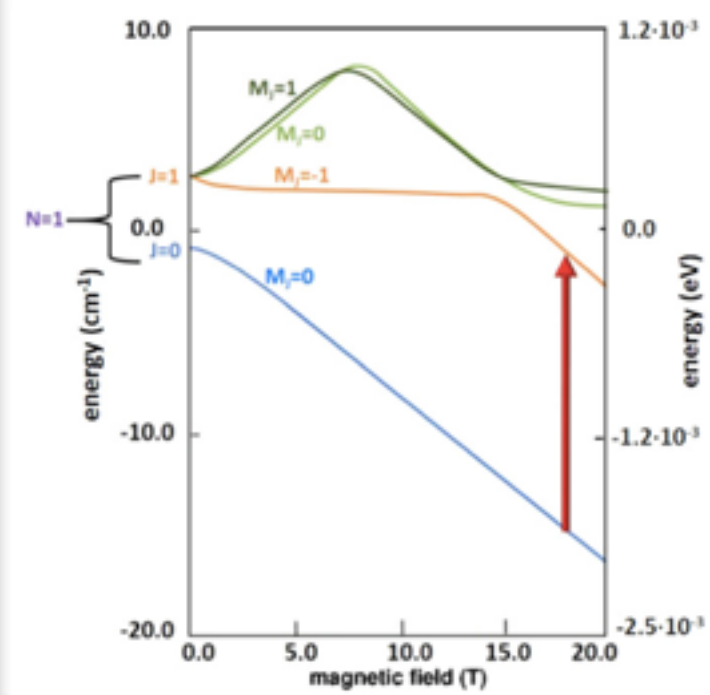
Mirrors



Ferromagnetic resonance



Atomic transitions

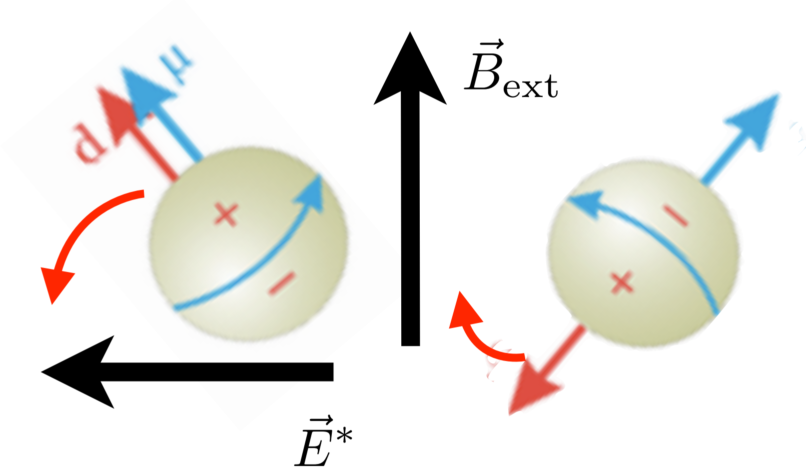


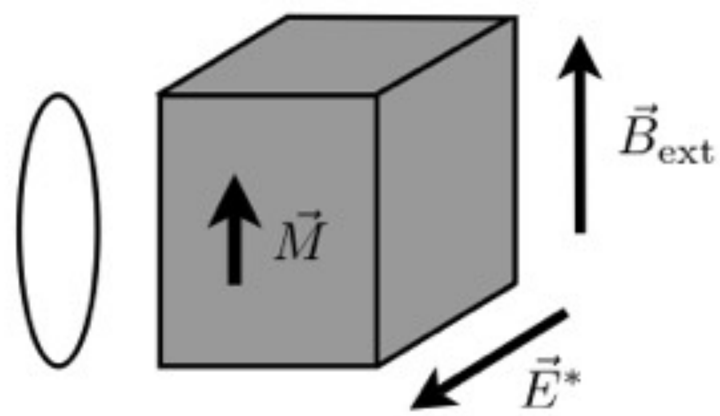
CASPER : oscillating EDM with NMR

Mainz, Berkeley

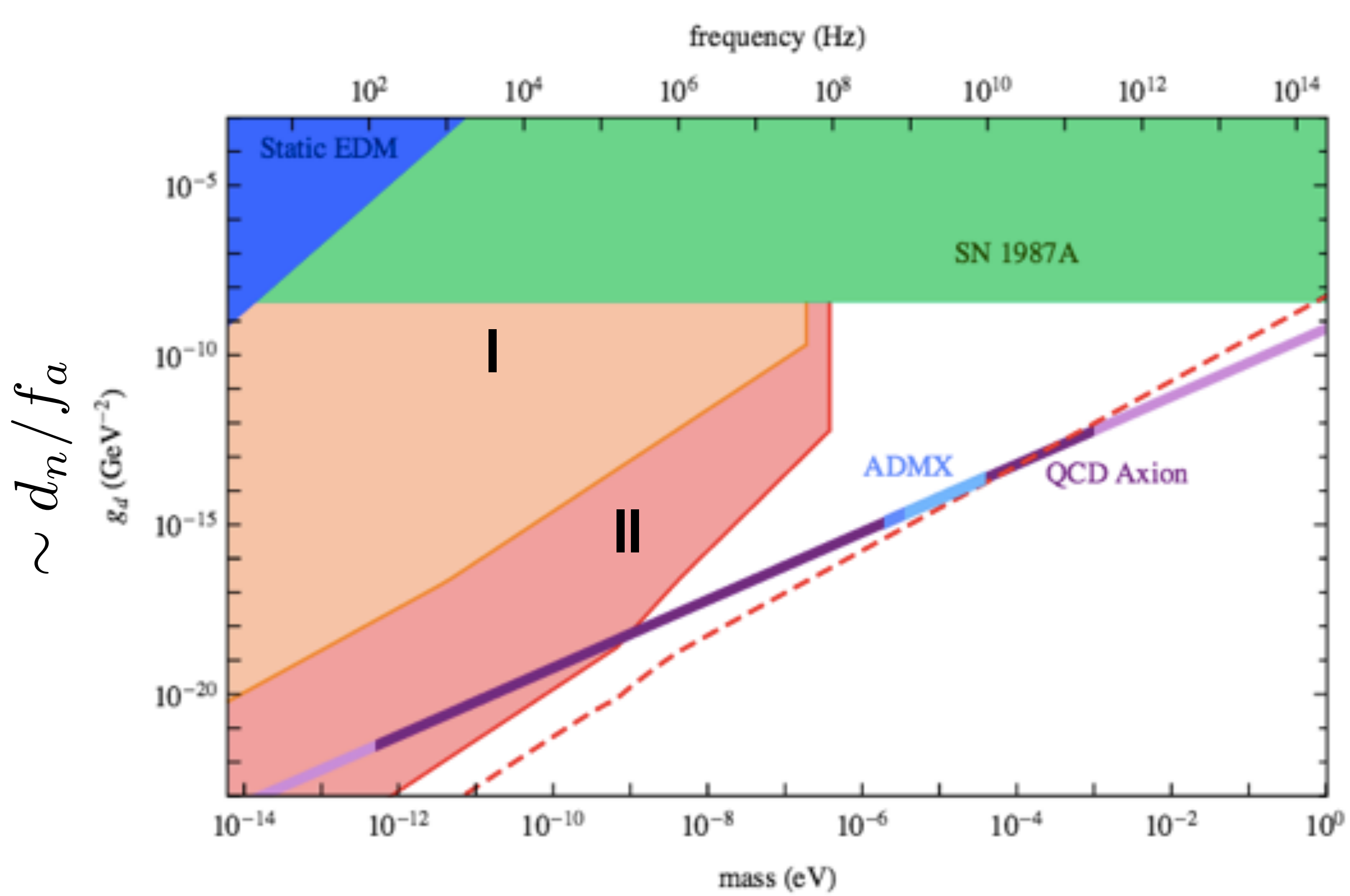
D. Budker S. Rajendran P. Graham

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



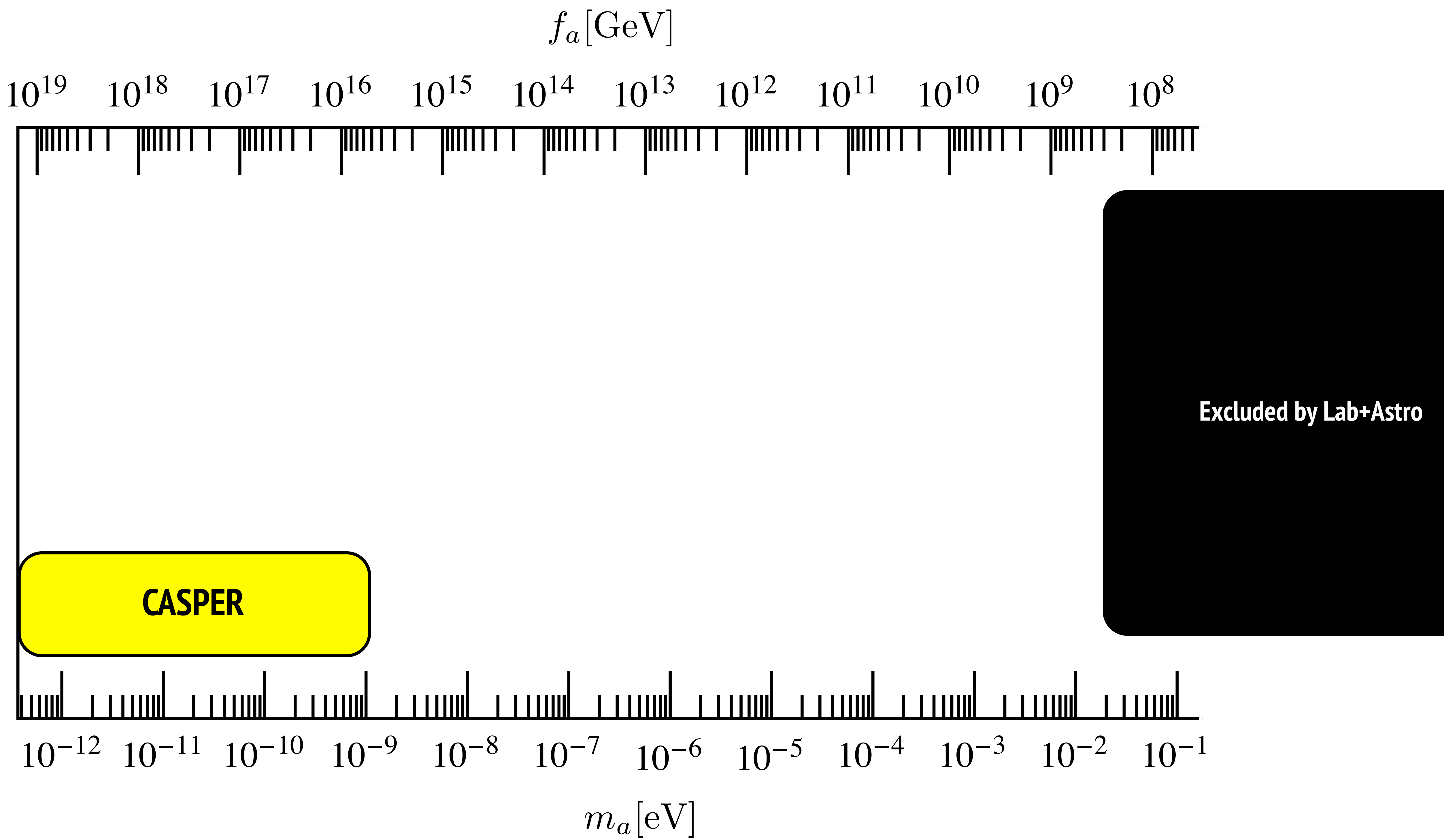


Oscillating EDM, effects add up, transverse magnetisation grows on resonance $m_a = \omega = \mu|\vec{B}_{\text{ext}}|$



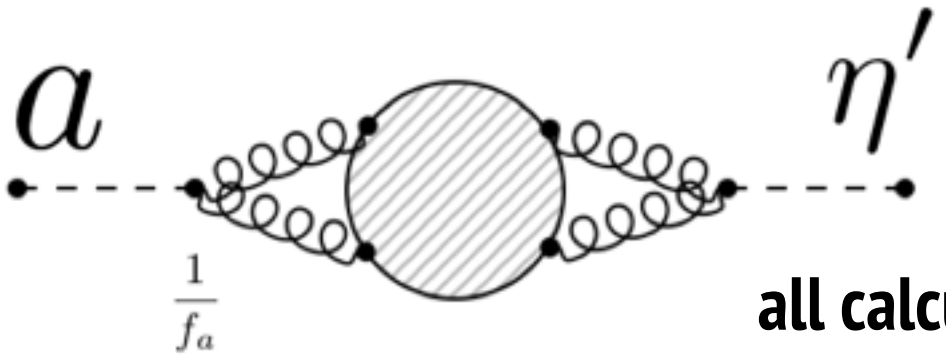
- EDM + Large E-fields in $PbTiO_3$
- Scan over frequencies, with Bext
- Mainz (D. Budker's group) & Berkeley
- Phase I starts in 2017, Phase II physics results
- Mass range limited by B-field strength

In the big picture



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



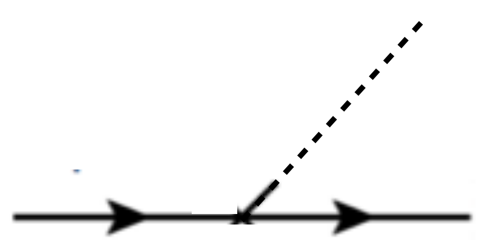
all calculable and suppressed by $\frac{1}{f_a}$

photon coupling

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

nucleon coupling

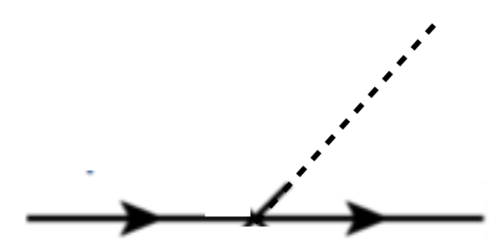
$$C_{Nf}m_N[\bar{N}\gamma_5 N]\theta$$



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

electron coupling

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



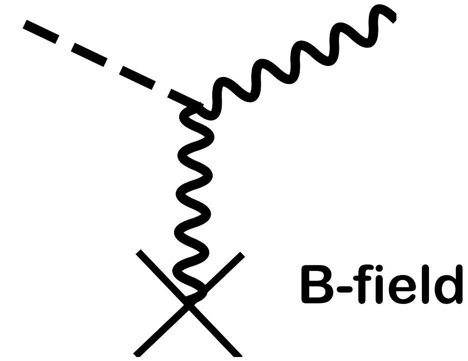
- Depending on the axion UV model, model dependent contributions ~O(1)
- But also coupligns to electrons are possible

Axion DM in a B-field

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

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

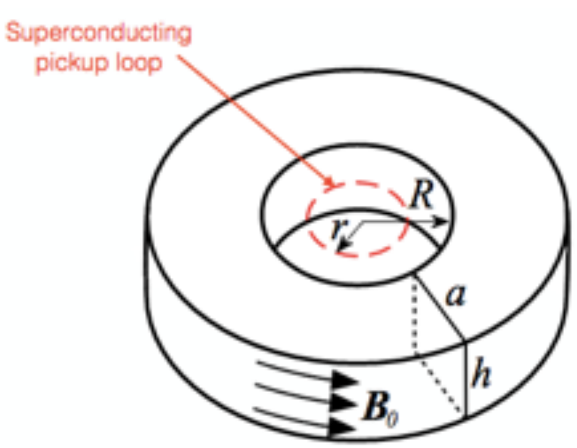
source



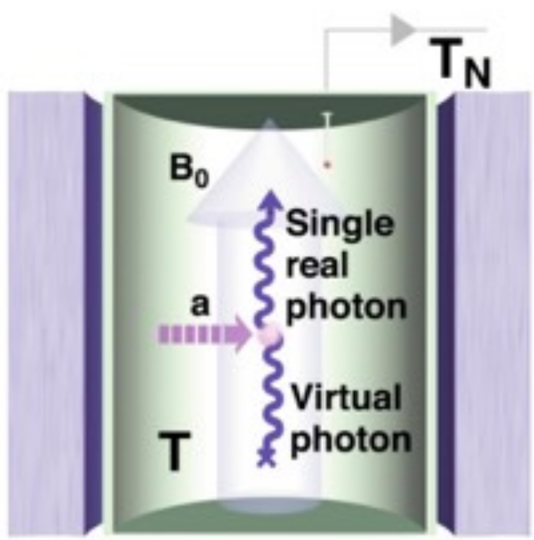
E-field $E \sim \mathcal{O}(10^{-12}\mathrm{V/m})\frac{|\mathrm{B_{ext}}|}{10\,\mathrm{T}}C_{a\gamma}\times\cos(m_a t)$

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

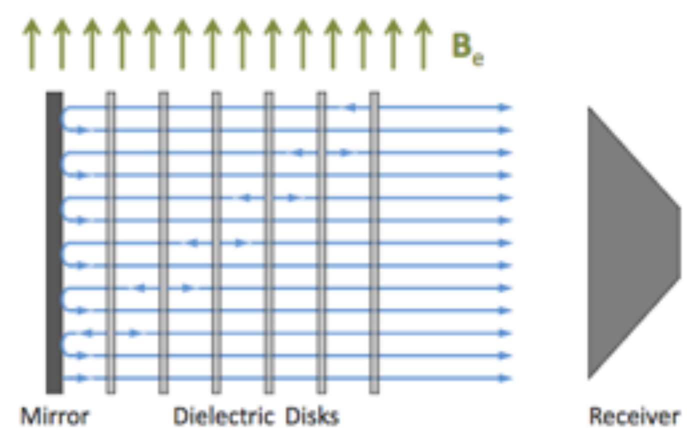
- Four different techniques:



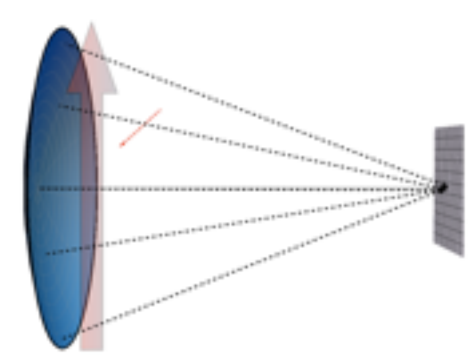
DM Radio



Cavities



Dielectric haloscope

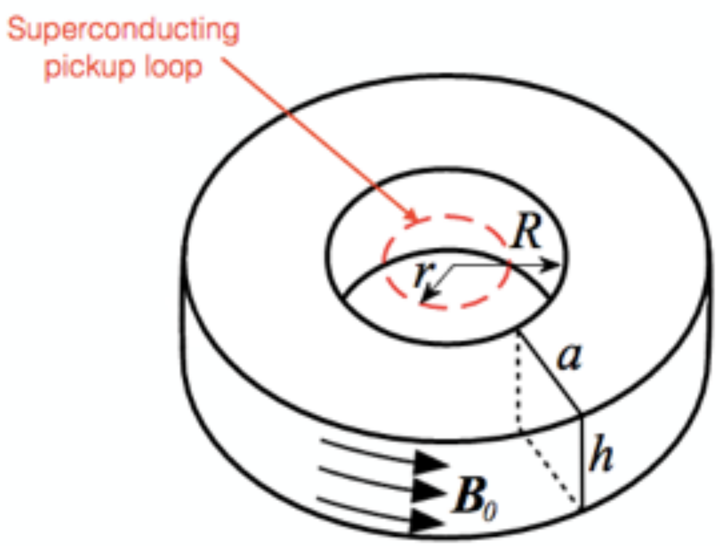


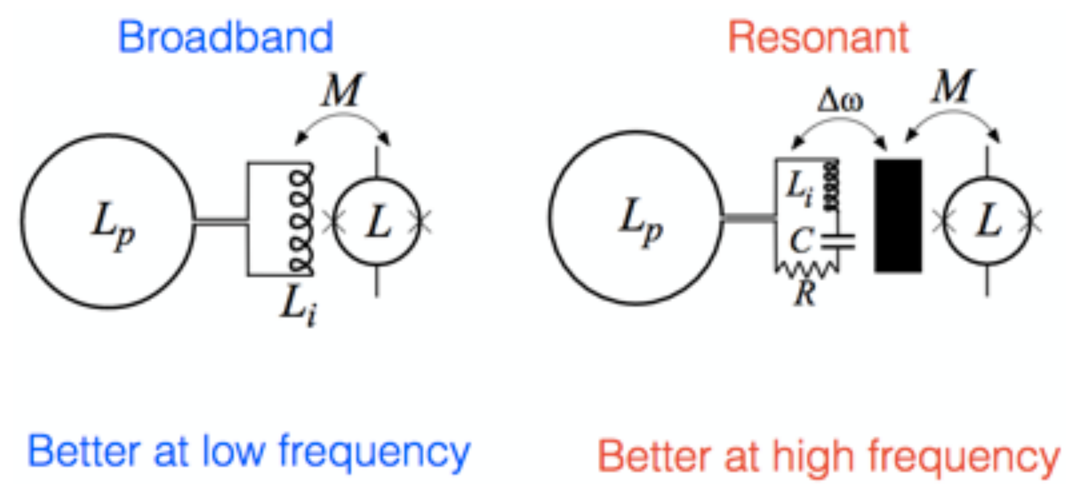
Dish antenna

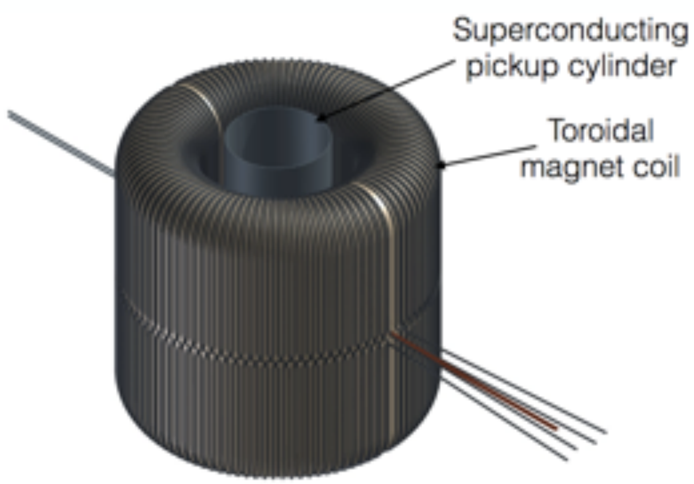
DM Radio

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

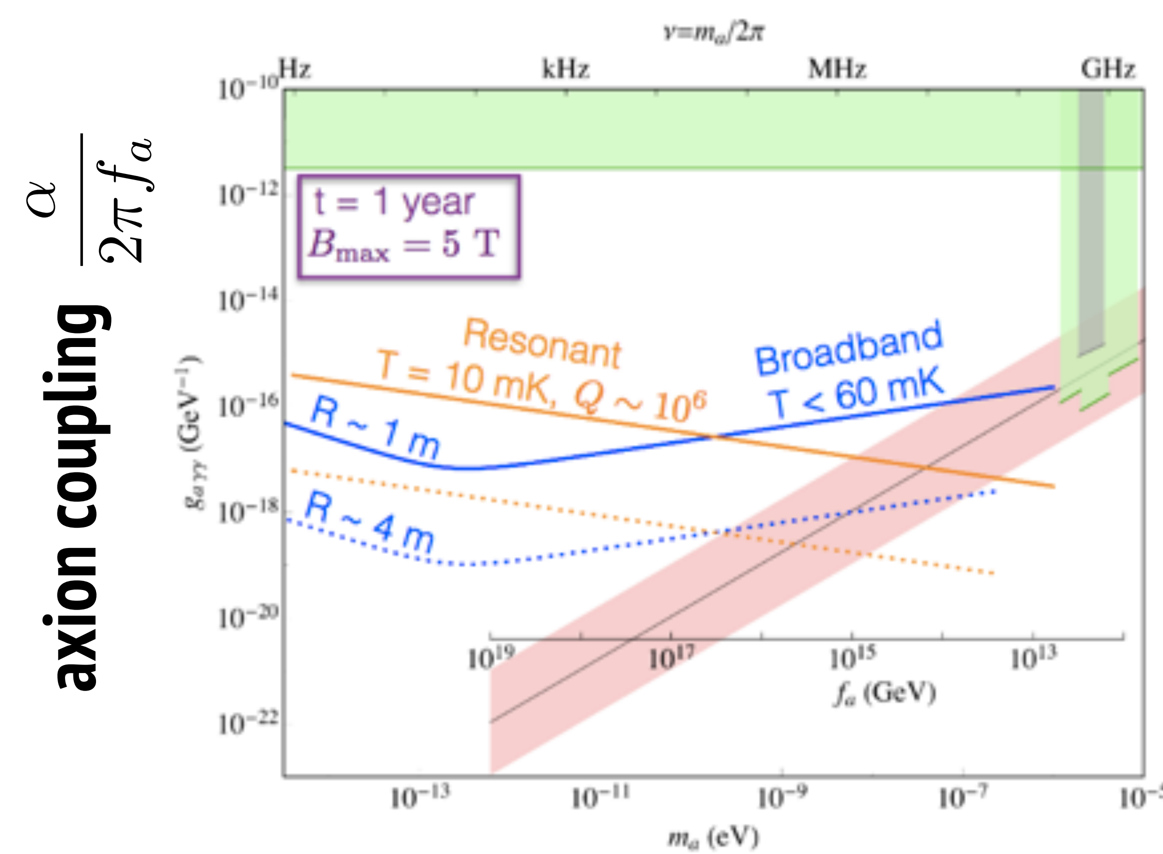
Sikivie PRL 112 (2014)
Chaudhuri PRD92 (2015)
Kahn PRL 117 (2016)







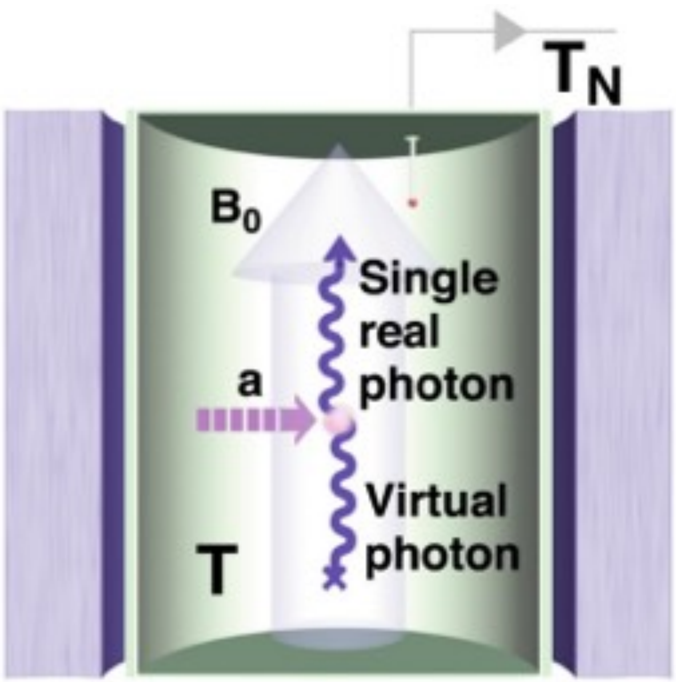
ABRACADABRA (MIT)
10 cm, 1m , 4m ...



Resonant cavities: haloscopes

P. Sikivie

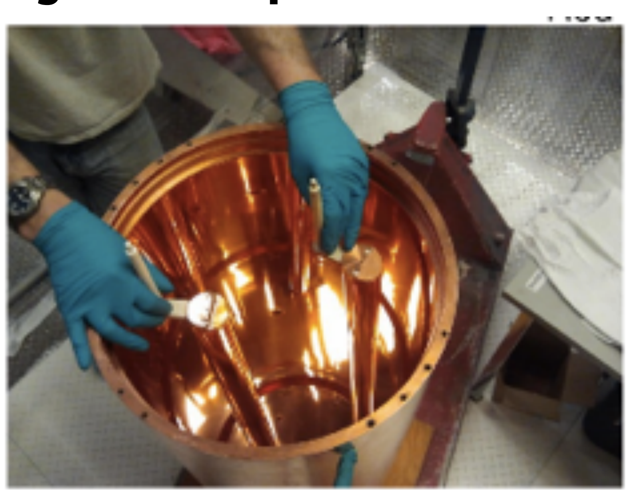
- Boost the axion-generated E-field in a tuned resonant cavity

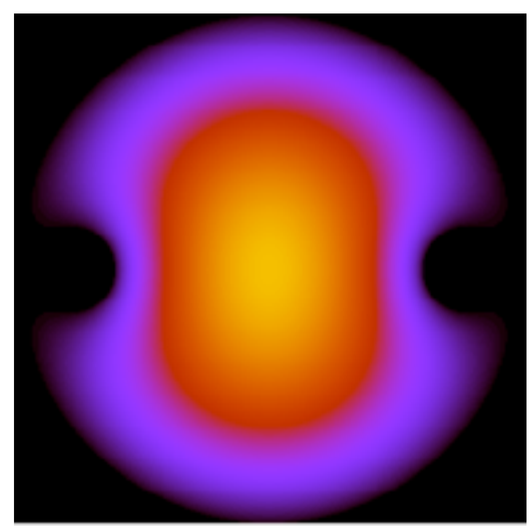


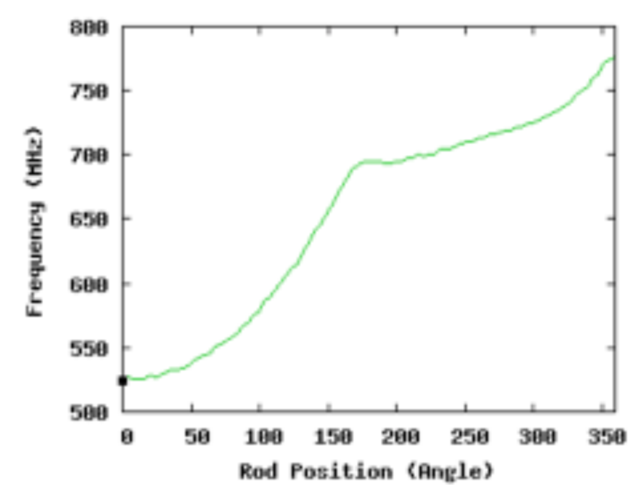
$$P_{\rm out} \sim Q|\mathbf{E}_a|^2 V m_a$$

- 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

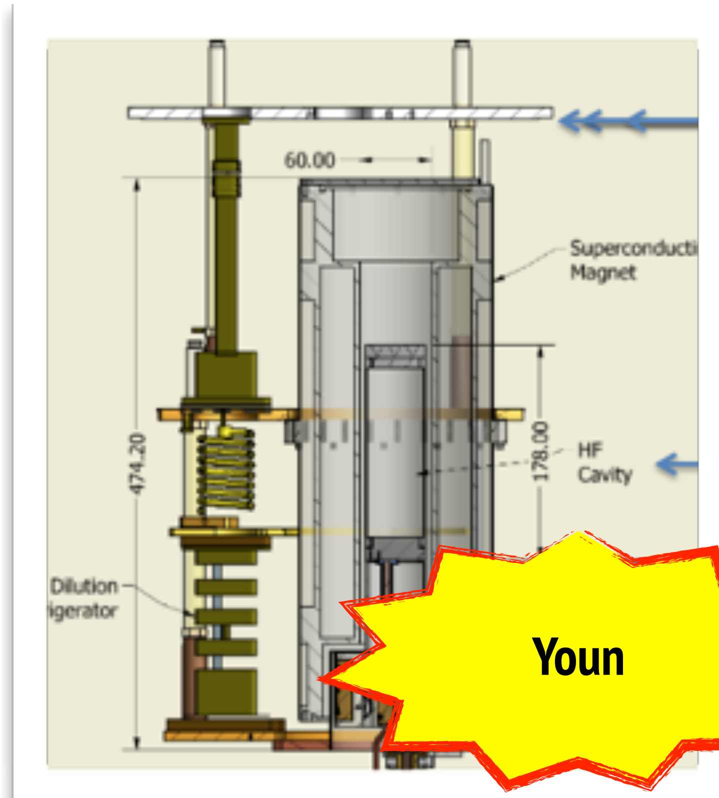
Cavity experiments

ADMX-Seattle

Rybka

running!

CULTASK - CAPP -Korea



Youn

2017-...

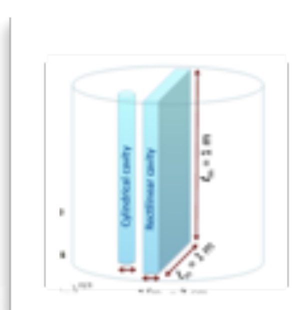
ORGAN-UWA Perth

2017-...

HAYSTAC-Yale

2016-...

ADMX-Fermilab



RADES

2017-...

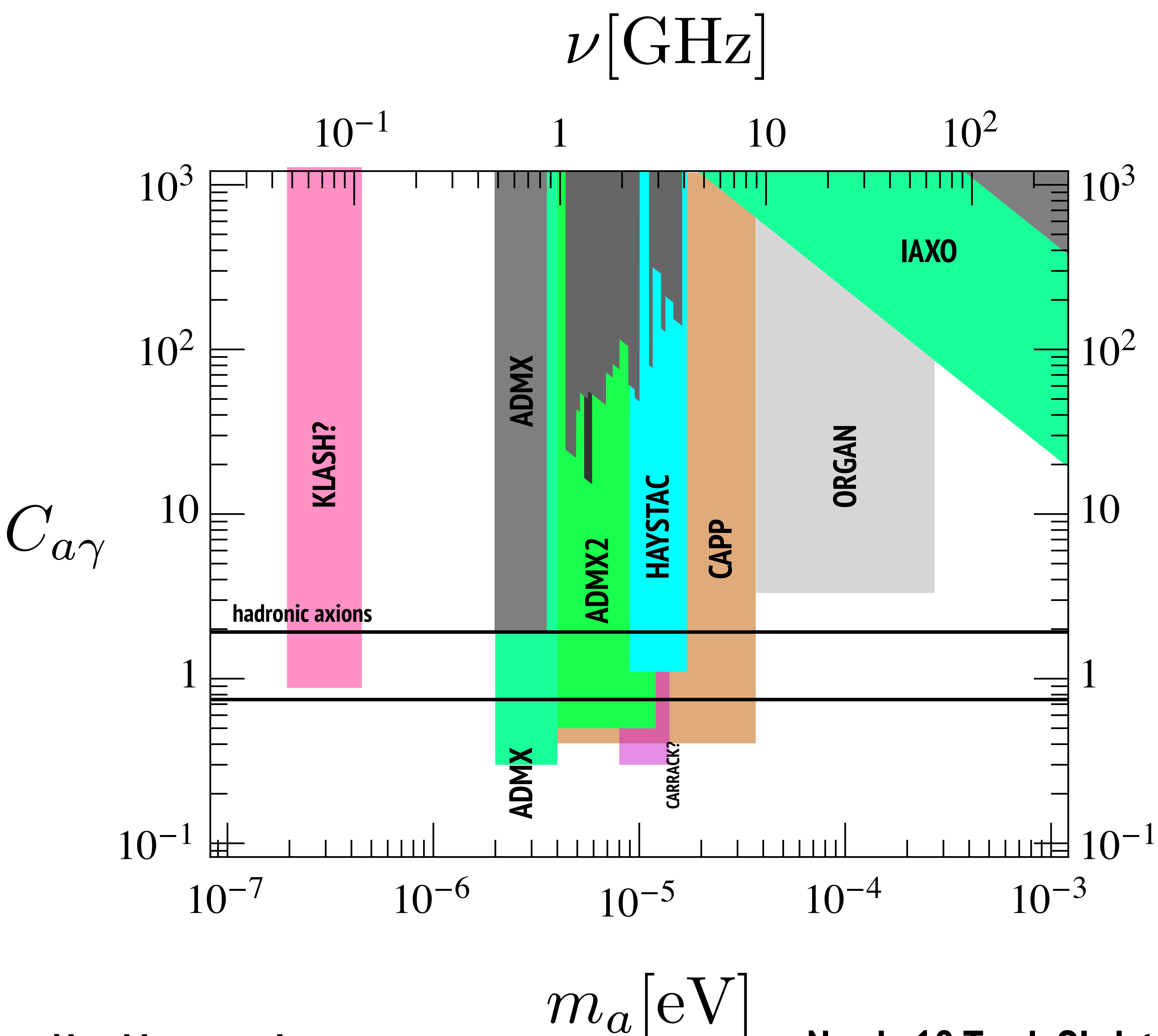
CAST-CAPP

2017-...

KLASH?

Ligi

Projected sensitivities

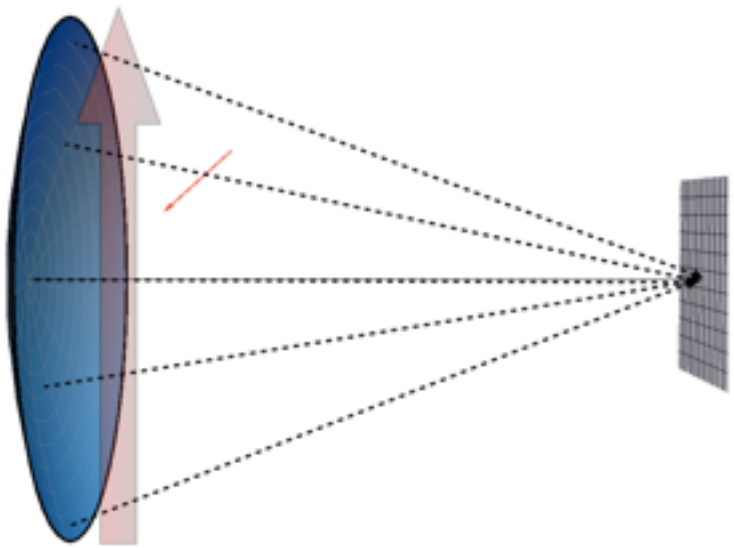


- Need larger volume

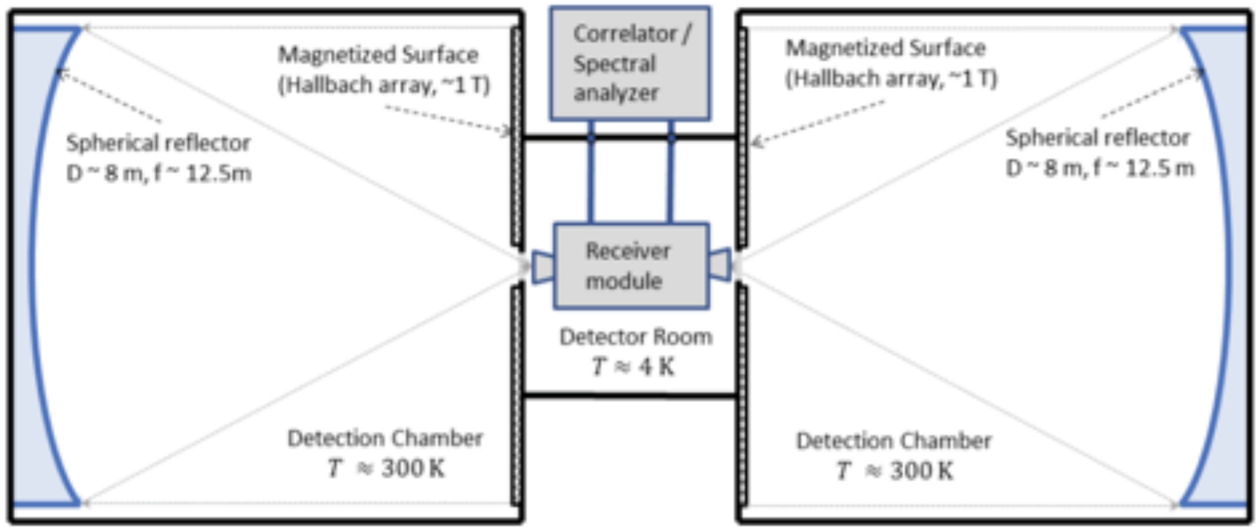
- Need >10 T, sub QL detection, Q~10^6

Dish antenna

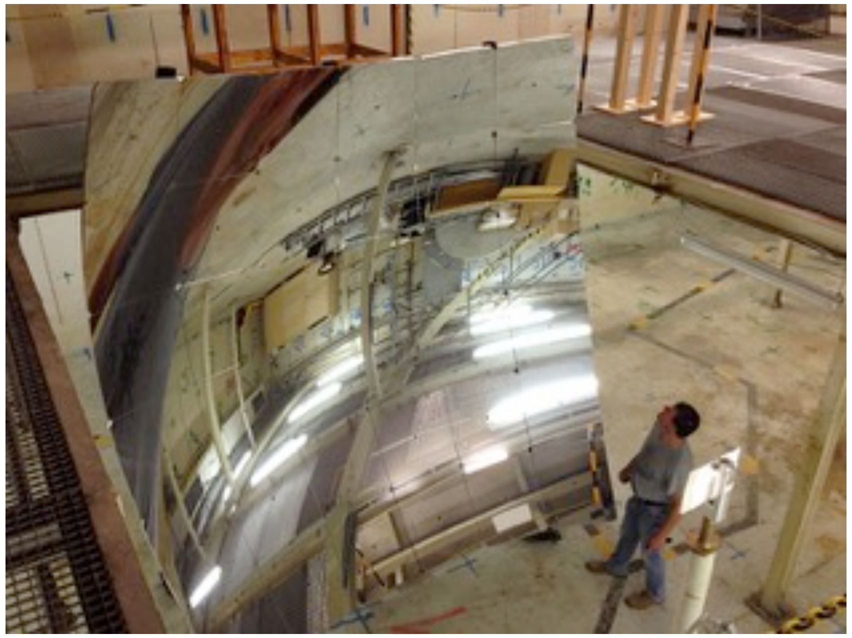
- Detect radiated power from a huge ($Am_a^2 \gg 10^6$) magnetised dish
- Broadband, no resonance enhancement; Only detector needs to be at T~mK (high reflectivity dish)
- Magnetise Area with permanent-magnets, photon counting?



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



BRASS @ Hamburg



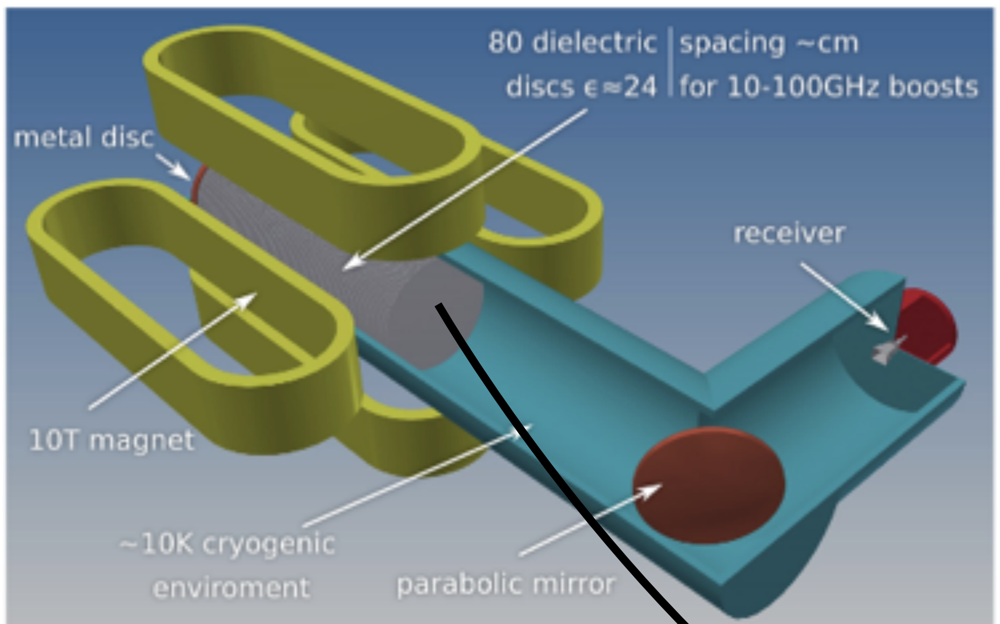
FUNK experiment (KIT)

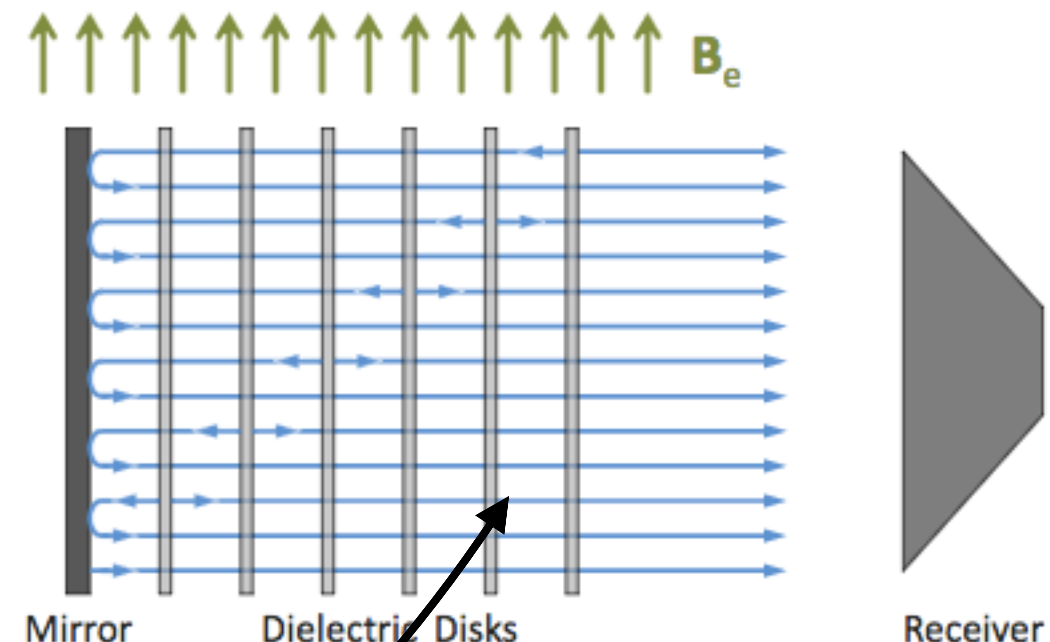
Dielectric haloscope : MADMAX

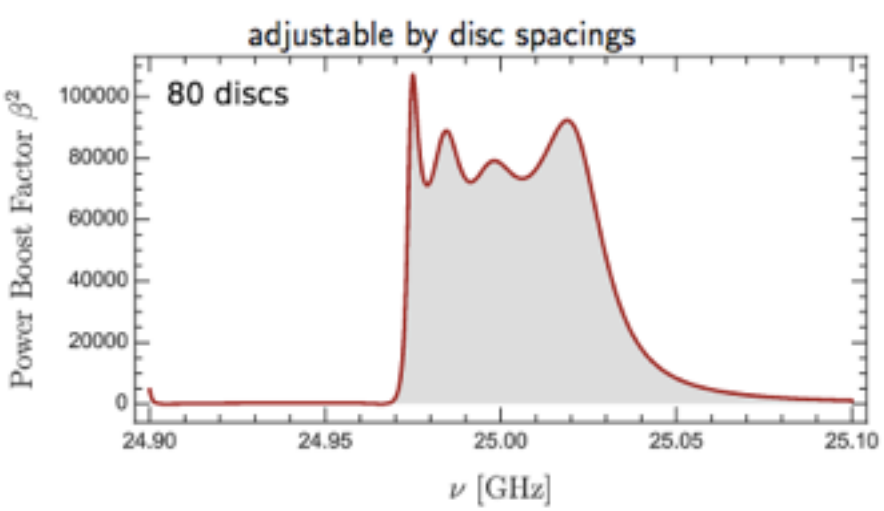
- **Hybrid system, large area + multiple emitters + a bit of resonant enhancement**

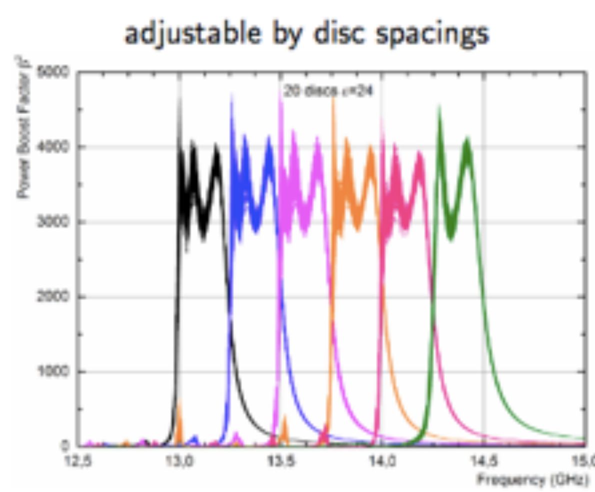
$$\frac{P}{Area} \sim 2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{c_\gamma}{2} \frac{B_{||}}{5\mathrm{T}} \right)^2 \frac{1}{\epsilon} \times \beta(\omega)$$

boost factor



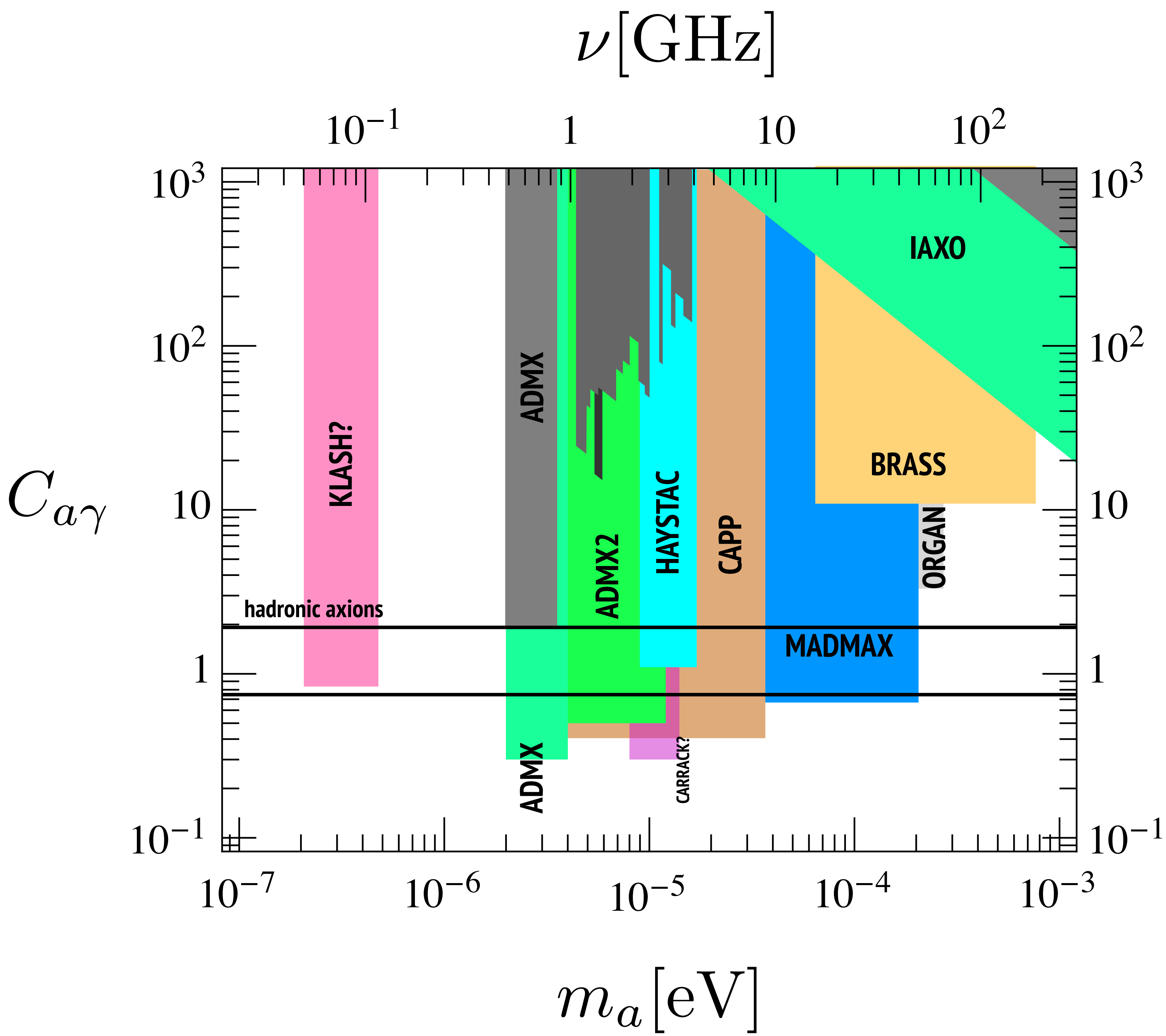




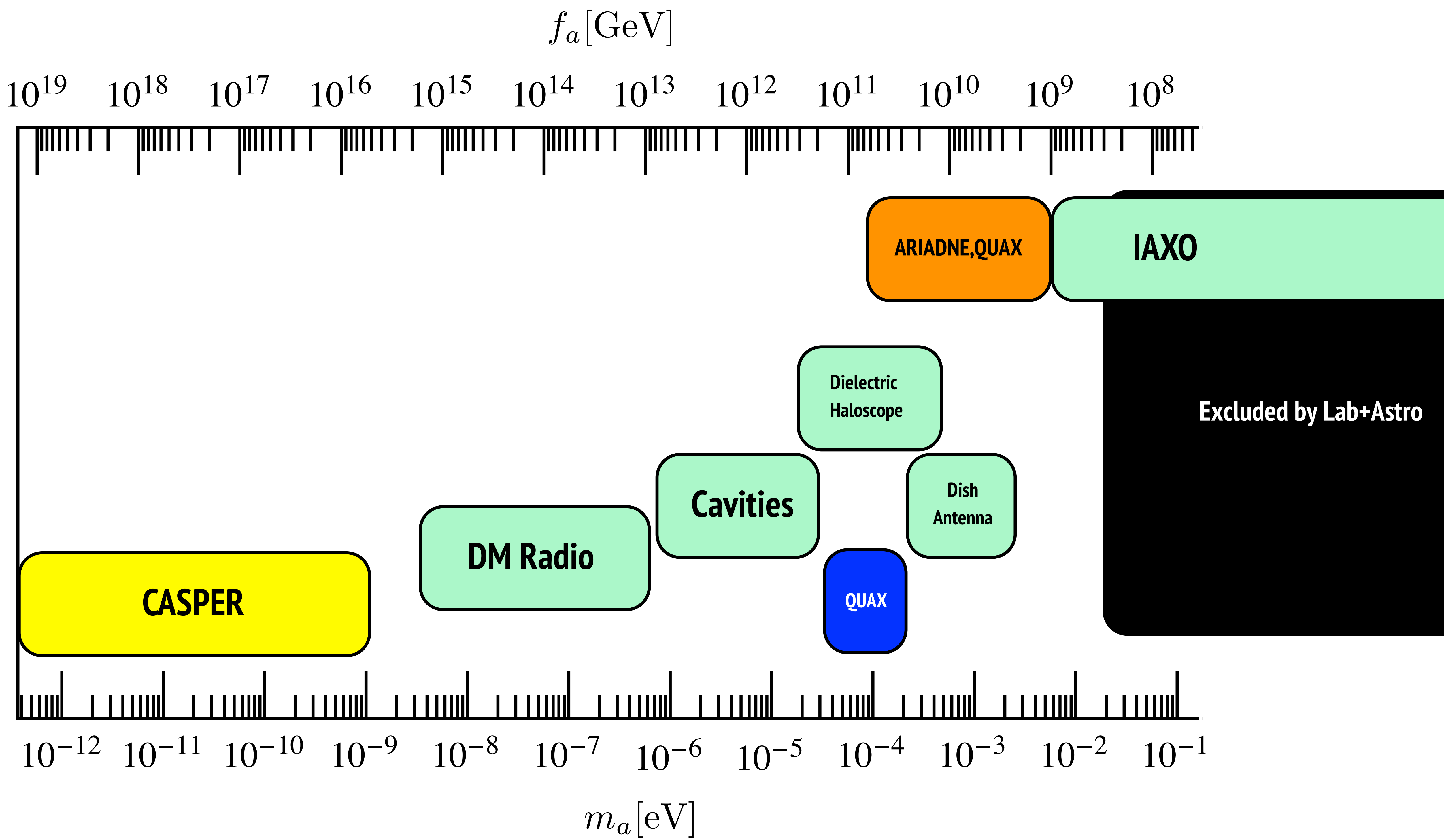


MADMAX: MAgnetised Disk and Mirror Axion eXperiment: MPP Munich, Hamburg Uni, DESY, Saclay, Zaragoza U

Projected sensitivities

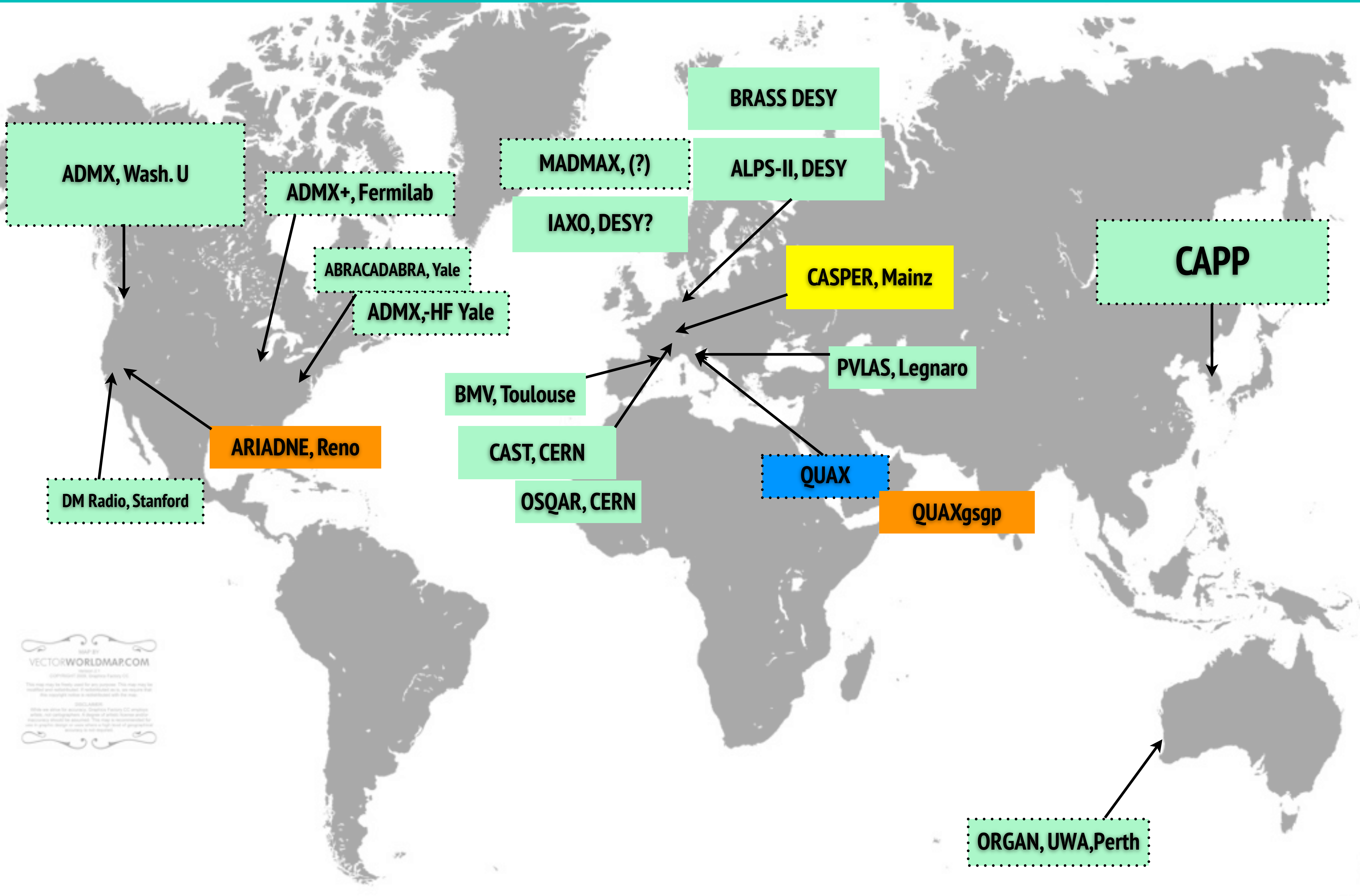


In the big picture



- 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!)

- Some axion dark matter is unavoidable

- Two scenarios and two predictions: miniclusters or isocurvature

- Cavity experiments on the run

- New experimental techniques blooming, loads of R&D