ALPernative DM candidates:
Axions and ALPs

NOW 2018

15 Sep 2018, Rosa Marina, Italy

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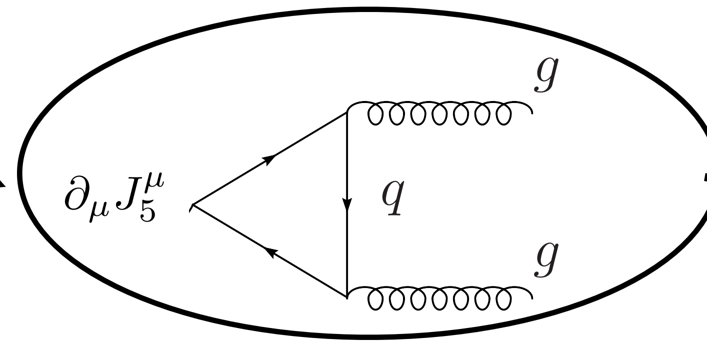
MAX-PLANCK-GESELLSCHAFT

The strong CP "issue"

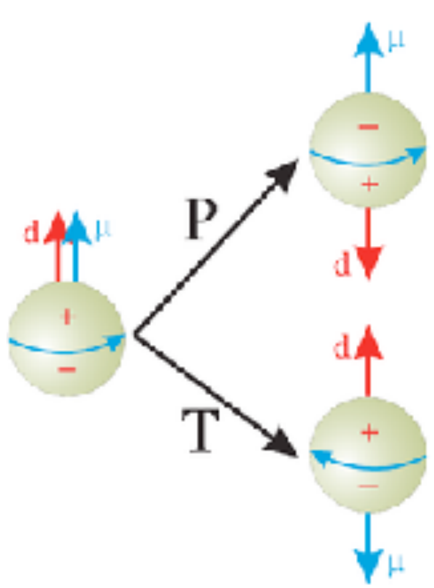
- **CP violation in QCD sector: CKM angle** $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\rm QCD} + N_f \delta$

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



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!**



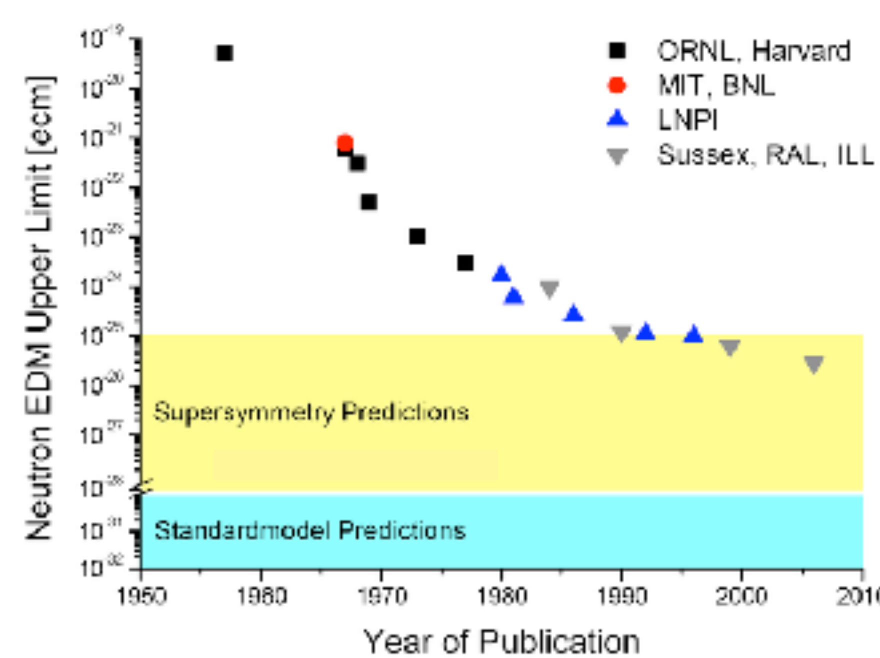
- **Neutron EDM** (Pospelov 9908508)

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

- **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*

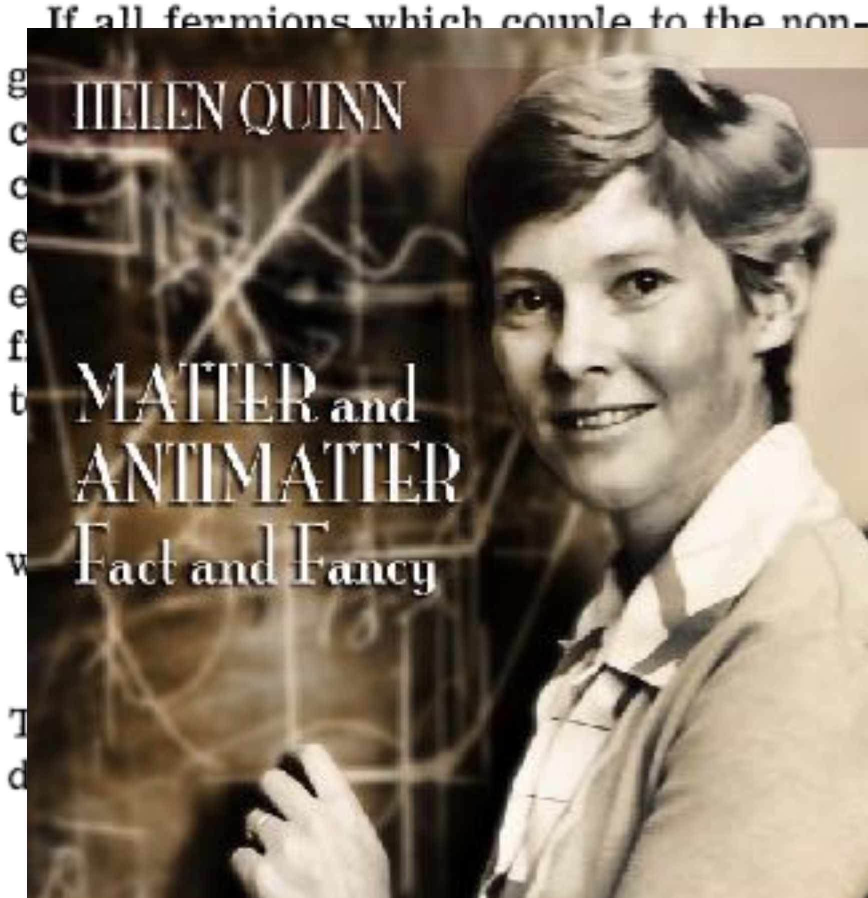
R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

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.

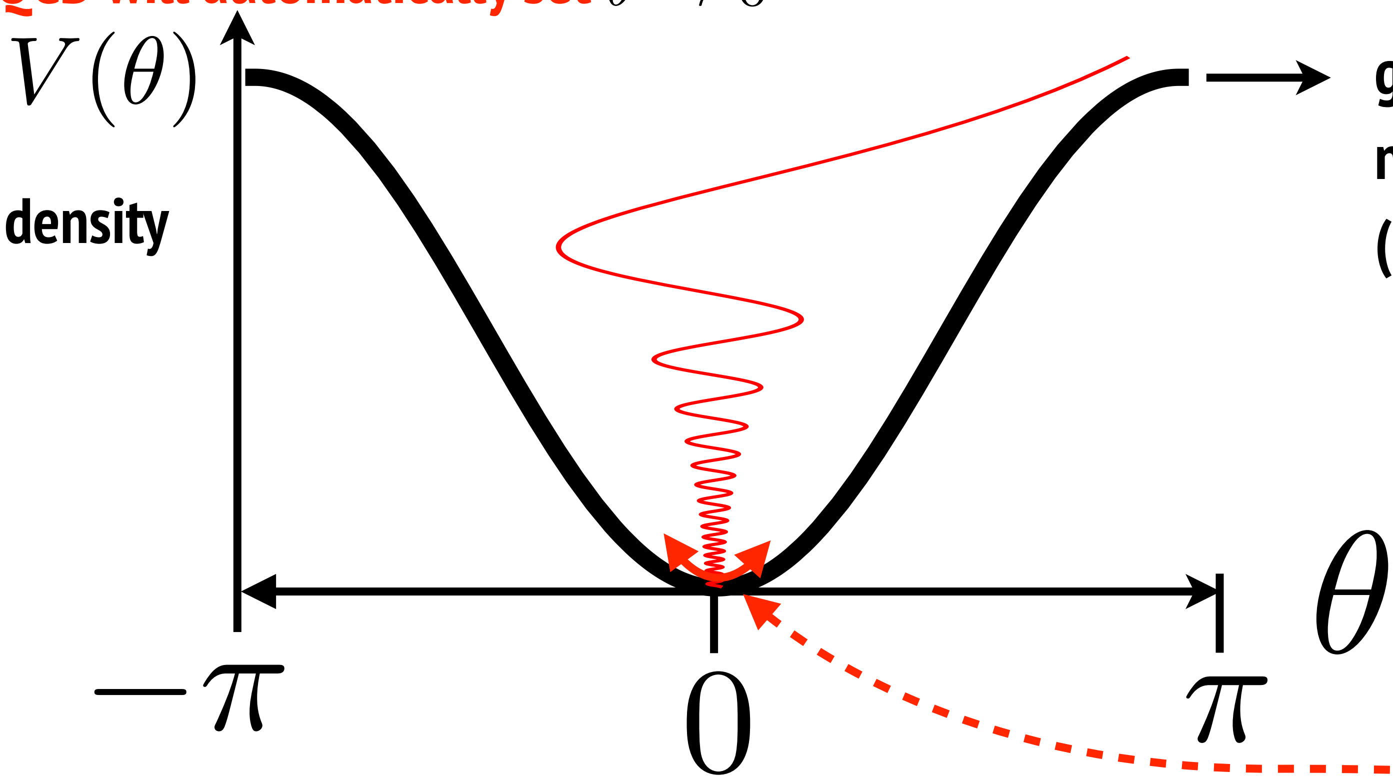
If all fermions which couple to the non-Abelian



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

- If θ is a dynamical field, QCD will automatically set $\theta \to 0$

Potential energy density



generated by QCD non-perturbative dynamics (instantons)

- PQ Mechanism: 1: Global U(1) symmetry spontaneously broken-> Goldstone boso

2: symmetry color anomalous -> gluon coupling!

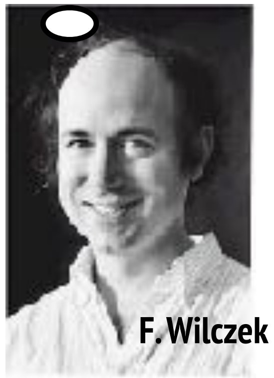
$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f_a^2 - \frac{\alpha_s}{8\pi} G_{\mu\nu a} G_a^{\mu\nu} \theta$$

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)


S. Weinberg


F. Wilczek

couplings

- U(1) symmetry (axion shift symmetry) restricts interactions

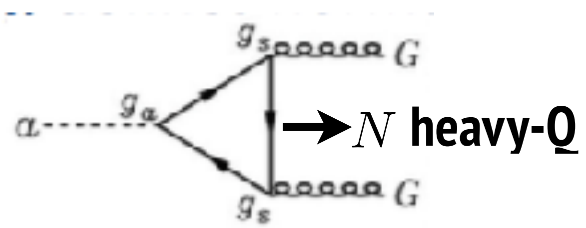
$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu\theta)(\partial^\mu\theta)f^2 + \sum_f C_{af}[\bar{f}\gamma^\mu\gamma_5 f]\partial_\mu\theta - E\frac{\alpha}{8\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}\theta$$

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_f g_{af}[\bar{f}\gamma_5 f]a - \frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a$$

interaction strength

$$g_{aX} \propto \frac{C_{aX}}{f_a}$$

- SS breaking terms induce mass, mixings + new interactions (one example ...

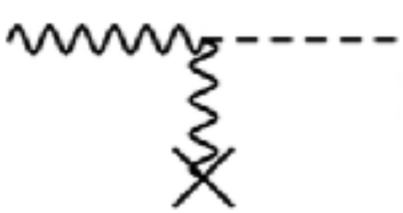


$$N\frac{\alpha}{8\pi}\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\theta \equiv \frac{\alpha_s}{8\pi}\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\frac{A}{f_A}$$

$$V(A) \sim \frac{1}{2}\chi_{\mathrm{QCD}}\left(\frac{A}{f_A}\right)^2 = \frac{1}{2}m_A^2 A^2$$

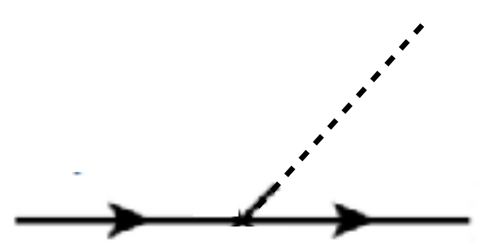
photon coupling

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



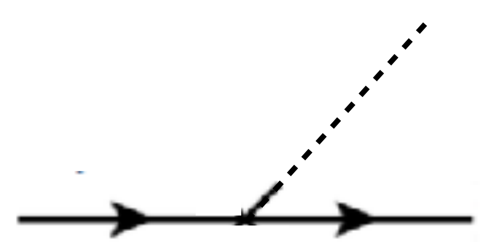
electron coupling

$$g_{ef}[\bar{e}\gamma_5 e]a$$



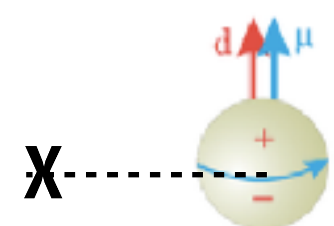
nucleon coupling

$$g_{Nf}[\bar{N}\gamma_5 N]a$$



~~CP~~ Neutron electric dipole

$$\propto \frac{1}{m_n}[F_{\mu\nu}\bar{n}\sigma^{\mu\nu}\gamma_5 n]\frac{A}{f_A}$$

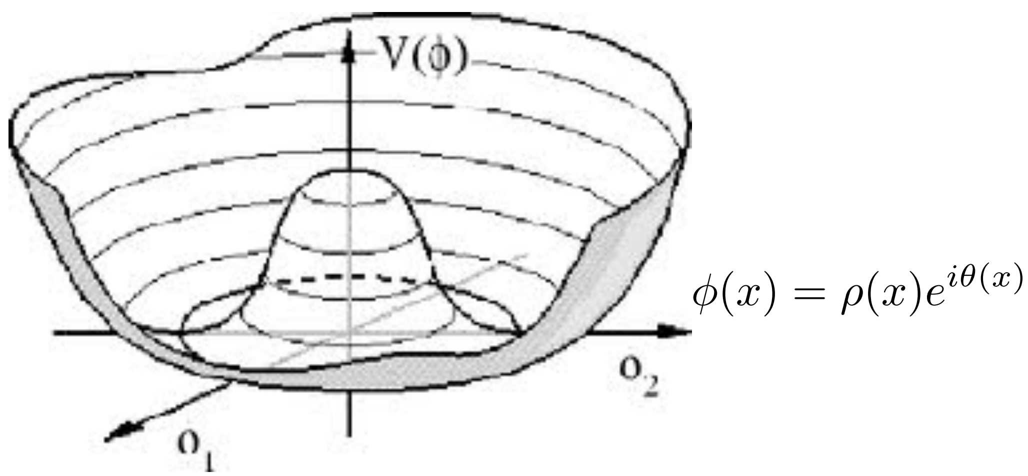


Models old and new, ALPs

- Axions and "axion-like" particles are generic in BSM + compatible with SUSY, GUTs and String Theories

pseudo Goldstone Bosons

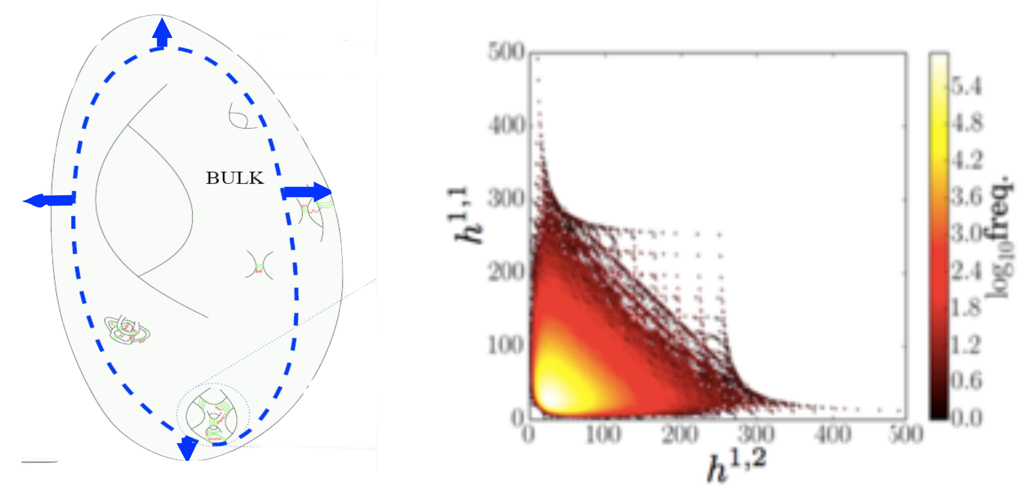
- Global symmetry spontaneously broken



Examples: QCD mesons,..., QCD axion, Majoron, R-axion, Familon ...

stringy axions

- Im parts of moduli fields (control sizes)



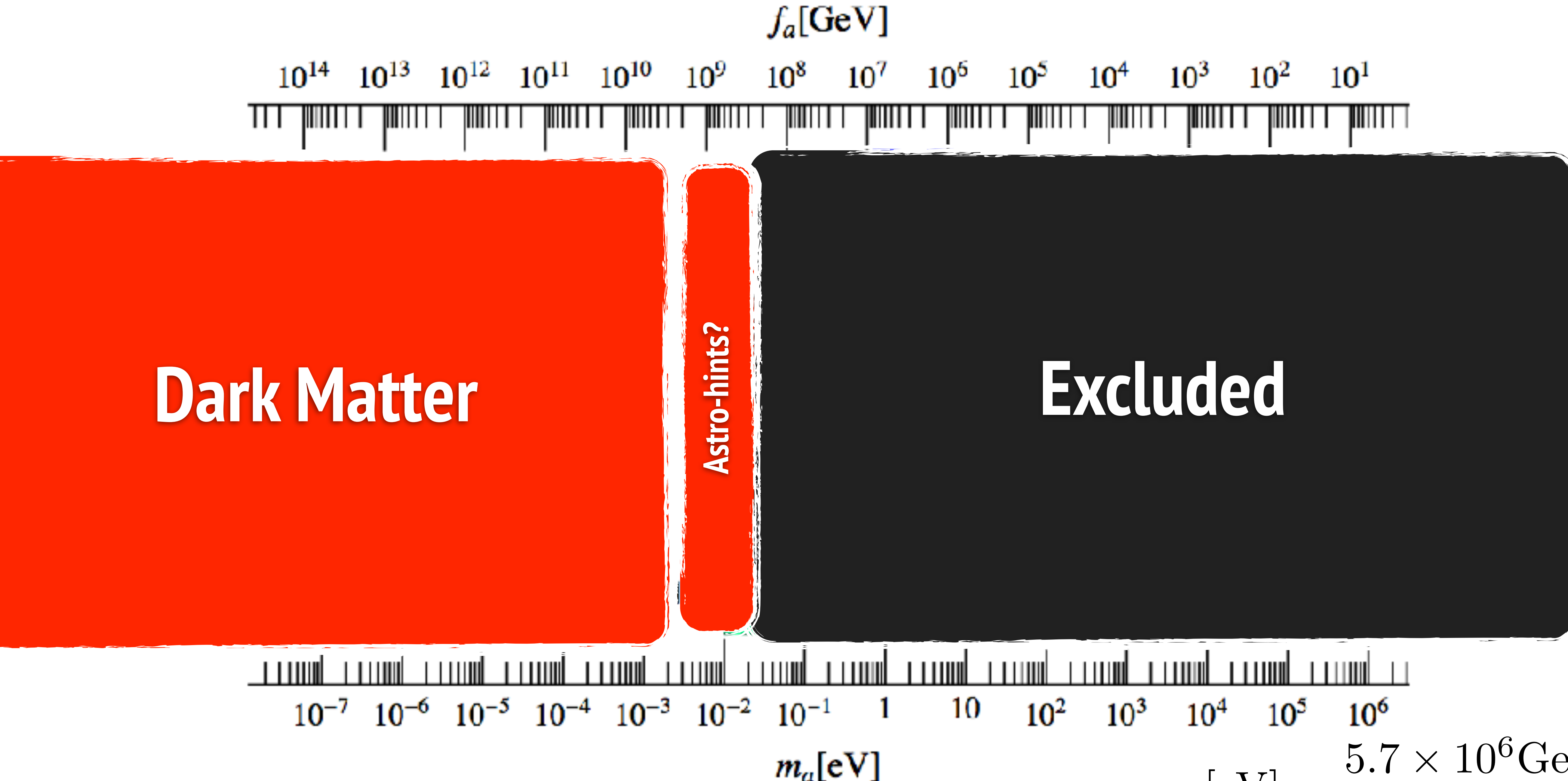
- O(100) candidates in typical compactifications
- masses from non-perturbative effects

- QCD axion models: hadronic, 2-Higgs-Doublet-models, familons, axi-majorons...

a recent selection from arXiv:1801.08127

Model	N_{DW}	High-E couplings E/N	C_{Au}	C_{Ad}	C_{Ae}	Low-E couplings $C_{A\gamma}$	C_{Ap}	C_{An}	C_{Ae}
PQWW	3	8/3	$c_\beta^2/3$	$s_\beta^2/3$	$s_\beta^2/3$	0.75	...	...	...
DFSZ I	6,3	8/3	$c_\beta^2/3$	$s_\beta^2/3$	$s_\beta^2/3$	0.75	(-0.2,-0.6)	(-0.16,0.26)	(0.024,⅓)
DFSZ II	6,3	2/3	$c_\beta^2/3$	$s_\beta^2/3$	$-c_\beta^2/3$	-1.25	(-0.2,-0.6)	(-0.16,0.26)	(-⅓,0)
KSVZ	1	0	g-loop	g-loop	0	-1.92	-0.47	-0.02(3)	$\sim 2\times10^{-4}$
Hadronic 1Q [83]	1...20	1/3...44/3	g-loop	g-loop	γ-loop	-0.25 ... 12.7†	-0.47	-0.02(3)	(0.05 ... 5) $\times10^{-3}$
SMASH [16]	1	8/3, 2/3	g-loop	g-loop	γ-loop	0.75,-1.25	-0.47	-0.02(3)	(−0.16, 0.16)
MFVA [91]	9	2/3, 8/3	0	1/3	1/3	0.75, −1.25	∼ −0.6	∼ −0.26	∼ 1/3
Flaxion/Axi-flavon [11, 12]	-	8/3	$\sim10^{-5}$	$\sim10^{-5}$	$\sim10^{-6}$	(0.5,1.1)	-	-	-
Astrophobic M1,2 [93]	1,2	2/3, 8/3	∼ 2/3	∼ 1/3	∼ 0	-1.25,0.75	$\sim10^{-2}$	$\sim10^{-2}$	∼ 0
Astrophobic M3,4 [93]	1,2	−4/3, 14/3	∼ 2/3	∼ 1/3	∼ 0	-3.3,2.7	$\sim10^{-2}$	$\sim10^{-2}$	∼ 0

Landscape, what do we know?

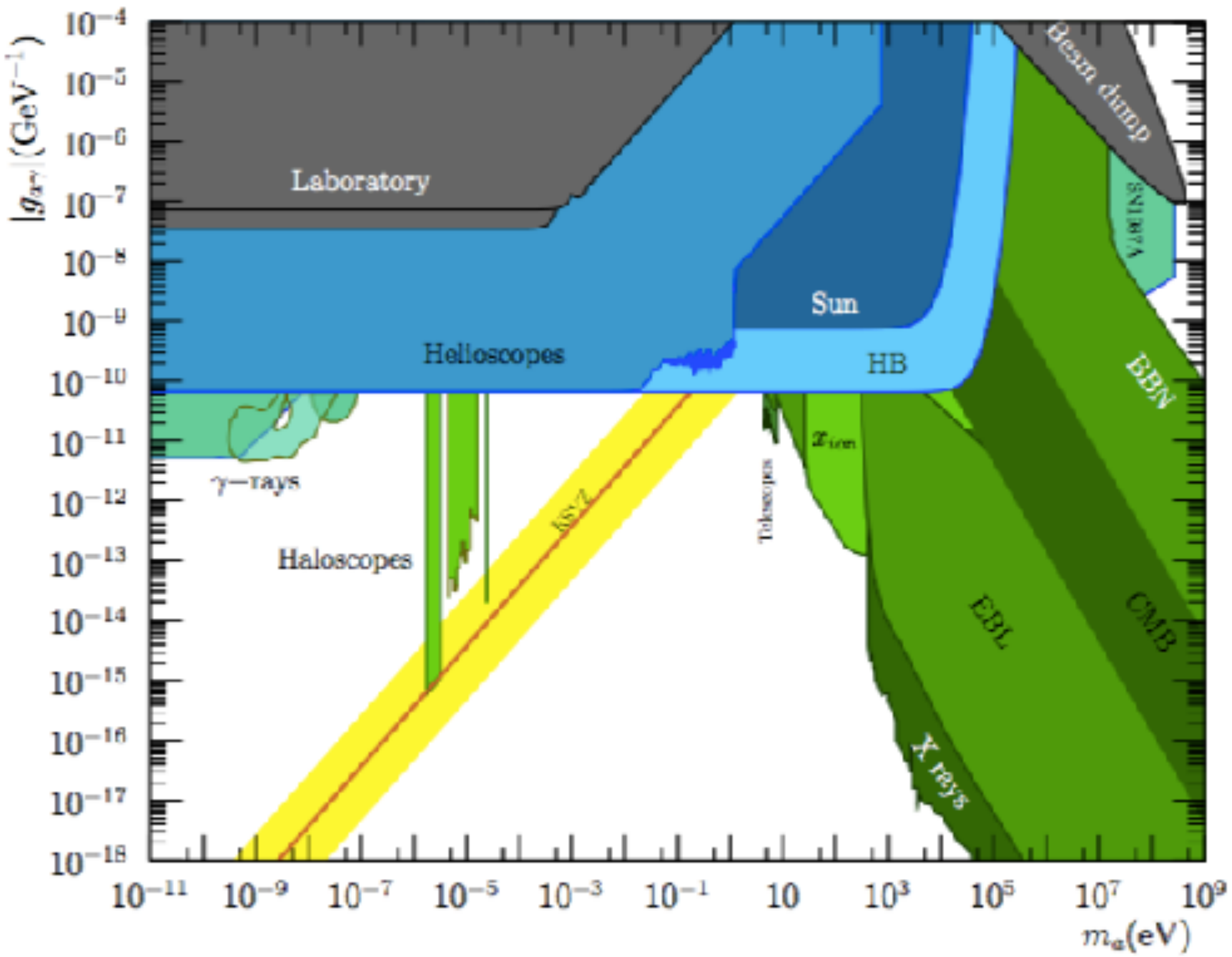


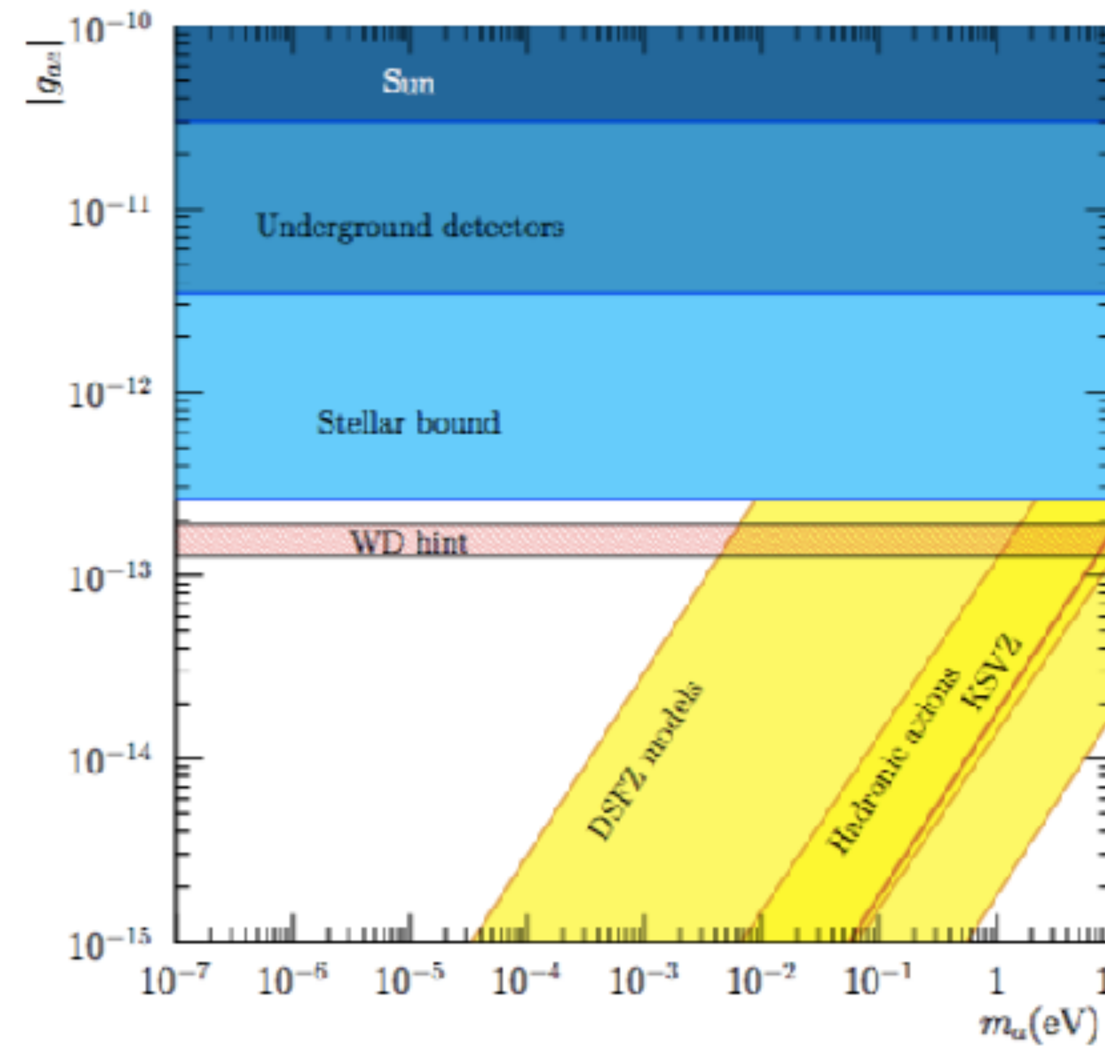
$$m_a[\mathrm{eV}] = \frac{5.7 \times 10^6 \mathrm{GeV}}{f_a}$$

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

axion-like … broader parameter spaces

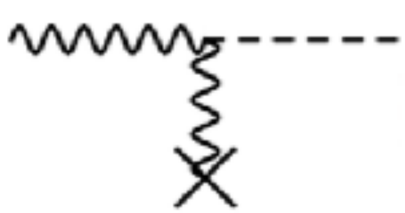
arXiv:1801.08127





photon coupling

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



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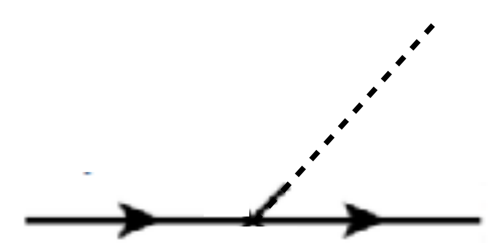
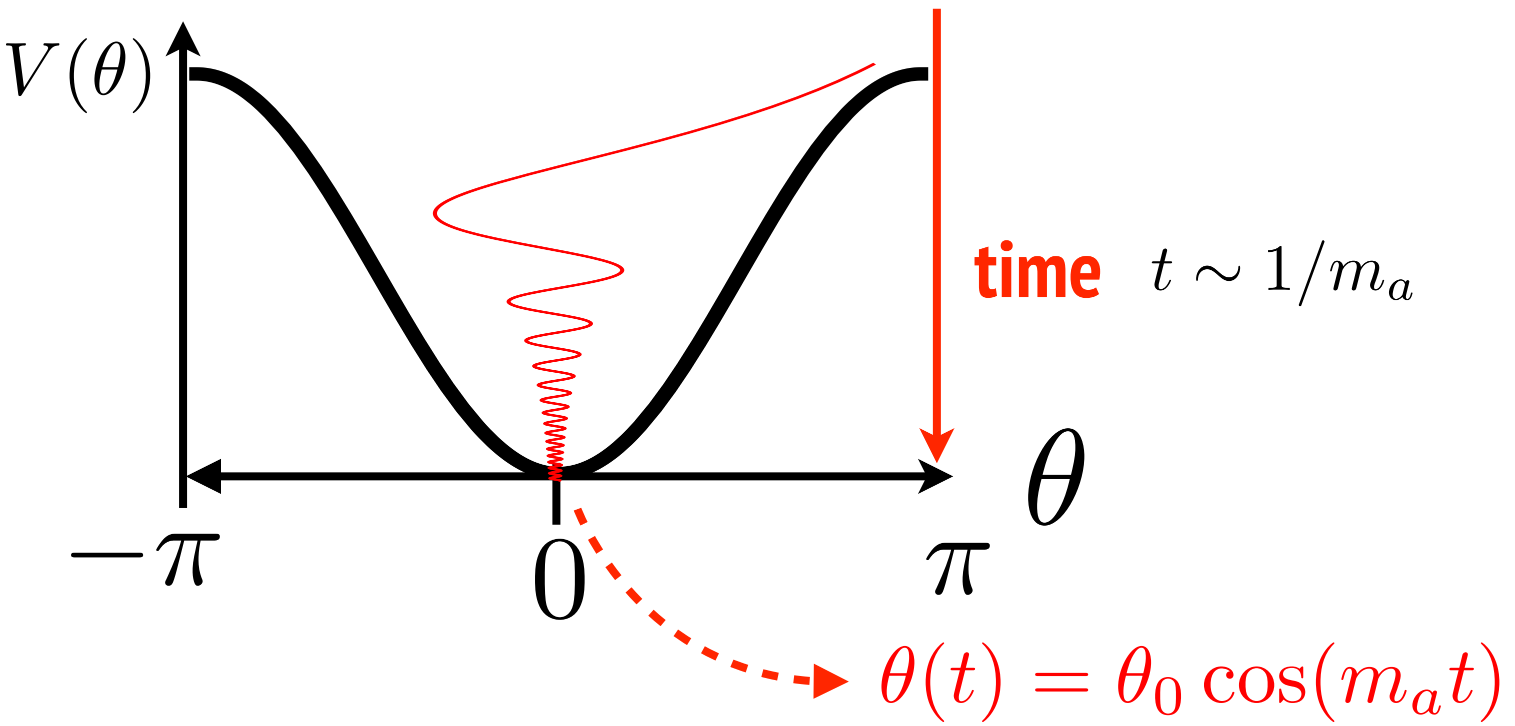
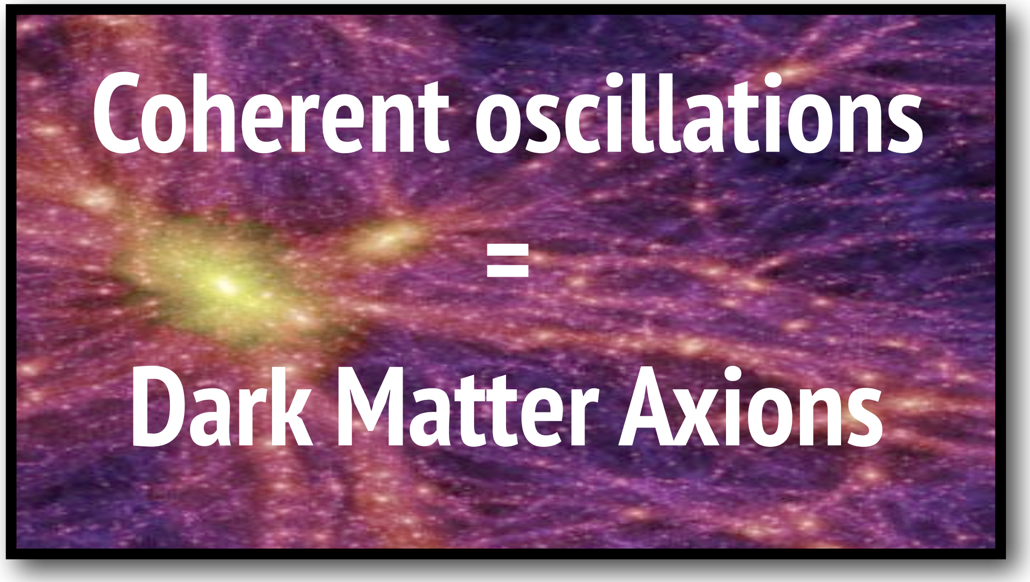


Dark Matters

Axions are dark matter … to some extent

- Weakly interacting, no thermalisation with SM particles, ALPs follow their potential
- low mass … flat potentials





Oscillation frequency

$$\omega = m_a$$

Energy density (harm. oscillator)

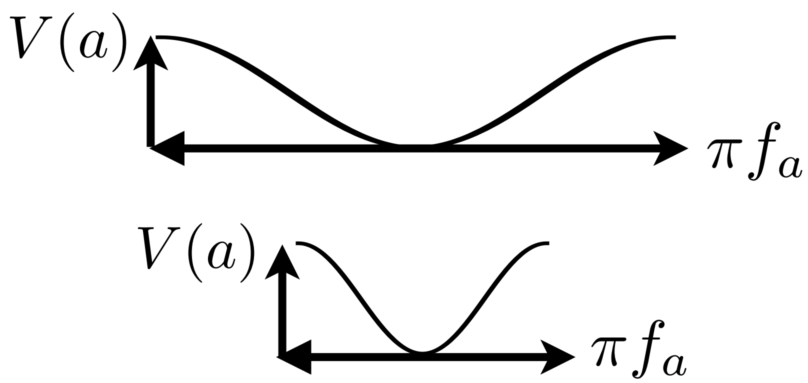
$$\rho_{\mathrm{aDM}} = \frac{1}{2} m_a^2 f_a^2 \theta_0^2 = \frac{1}{2} (75\mathrm{MeV})^4 \theta_0^2$$

- Some amount of axion Dark matter is unavoidable!
- t1~teq … ALP is not DM

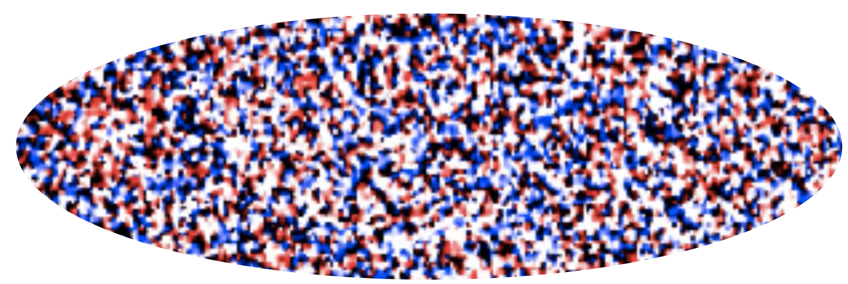
Axion dark matter

- The ALP DM YIELD depends on f_a AND on the initial conditions

large fa, small acceleration, energy stored longer

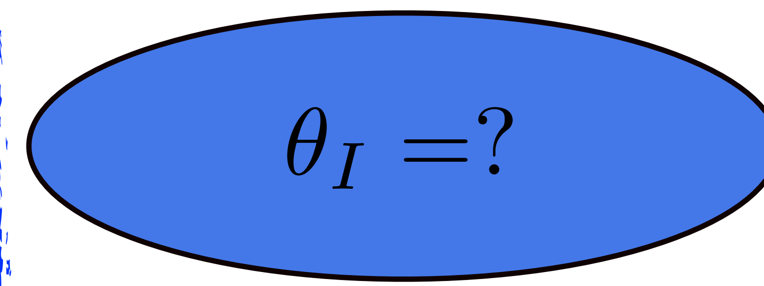


After PQ phase transition, theta IC conditions
no-correlation beyond causal horizon

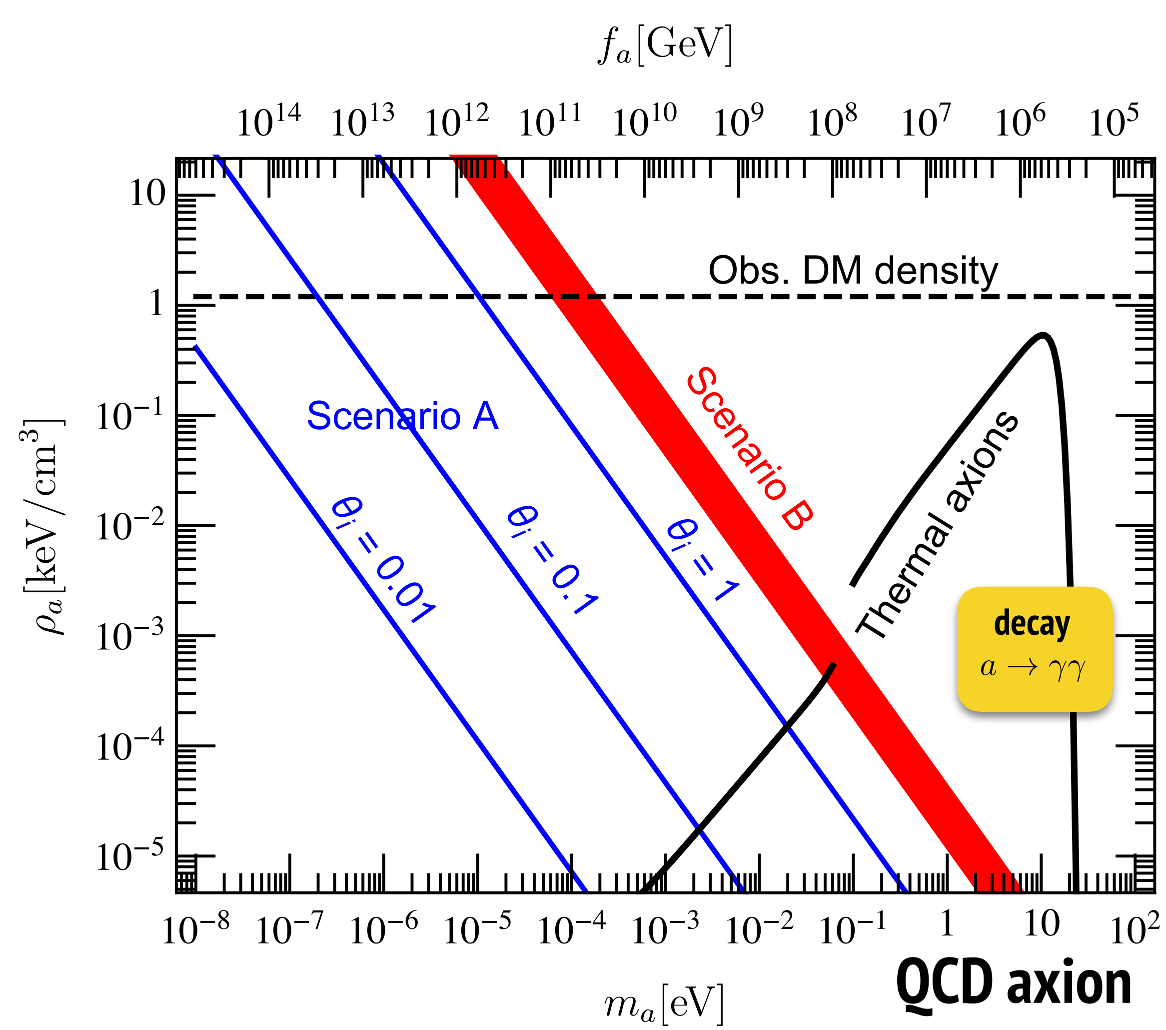


average over initial conditions! -> prediction!

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

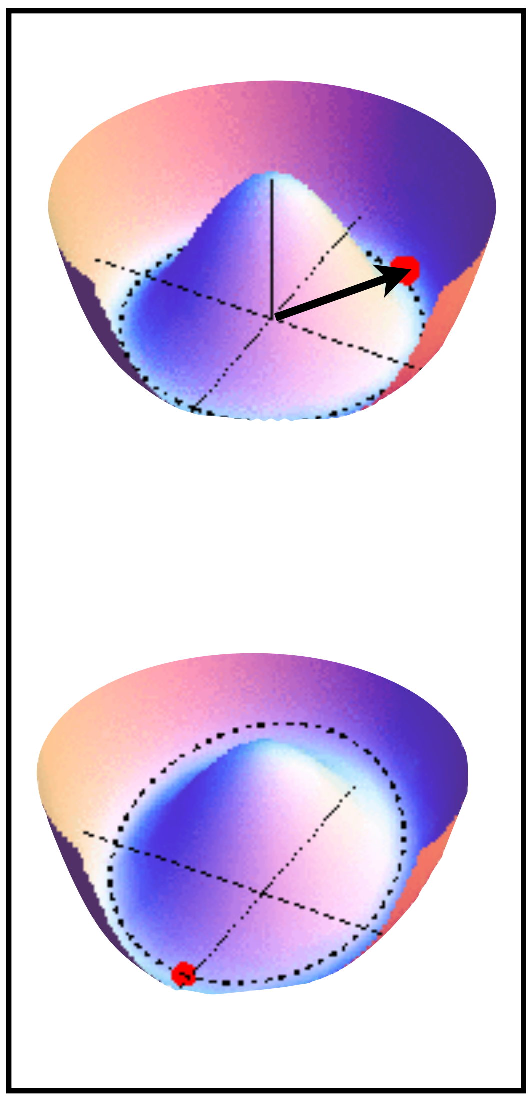


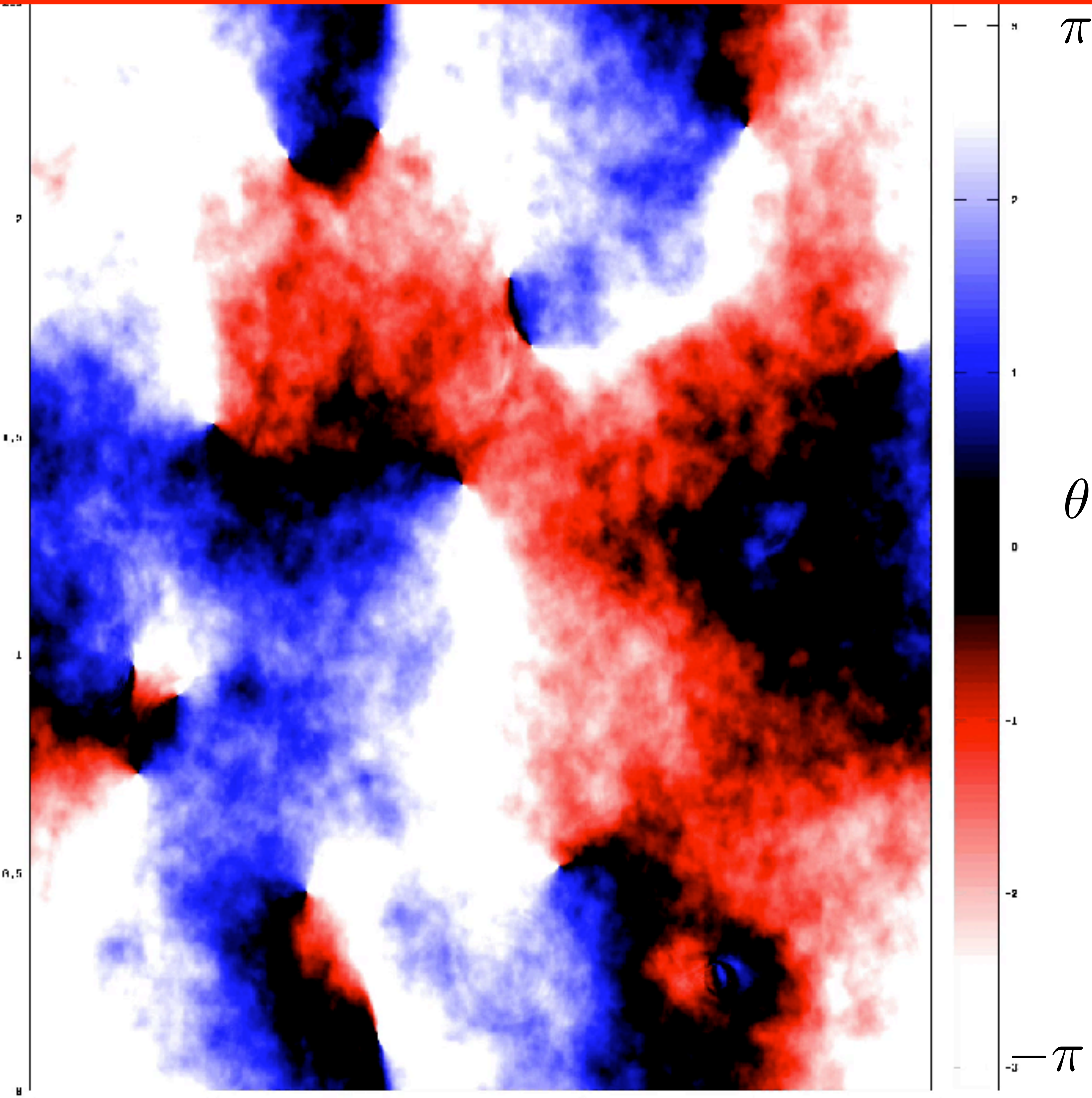
but which one??? no prediction!



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

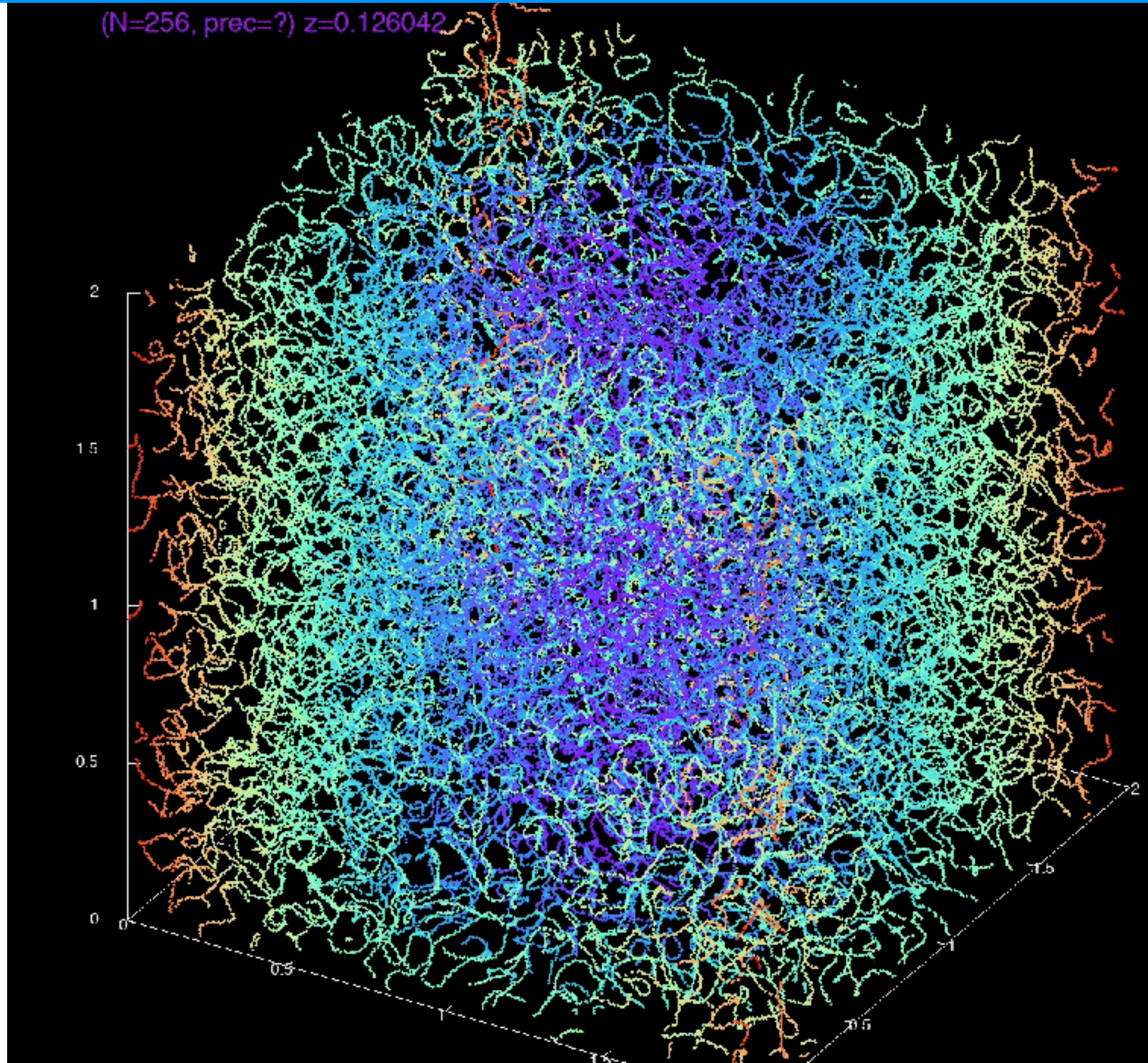
- 2D slice axion
- Correlation length increases
- cosmic strings (resolution!)
- at t_1, theta->0
- inhomogeneus DM





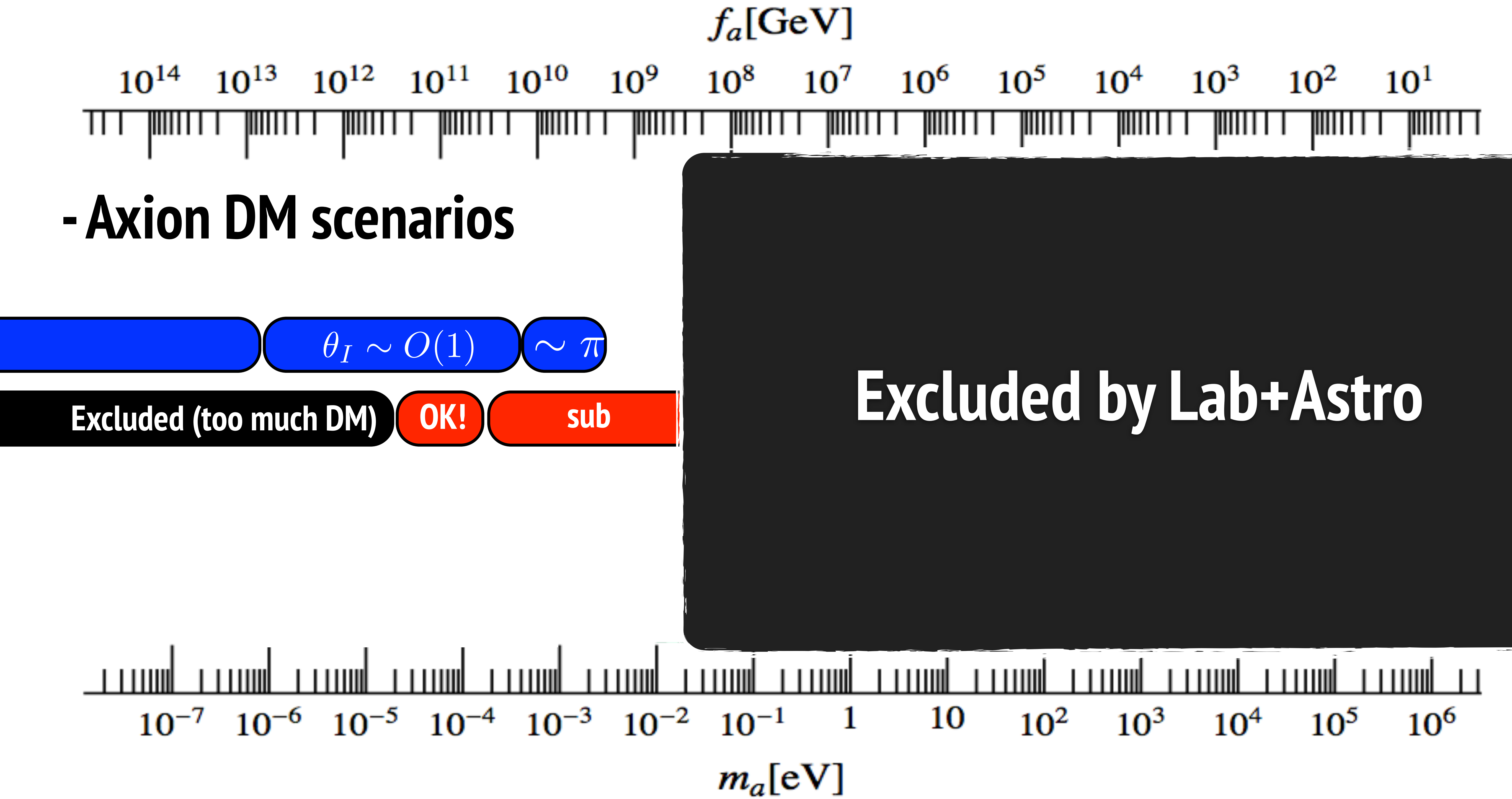
3 D string network

- UV completion when Theta=0...2pi



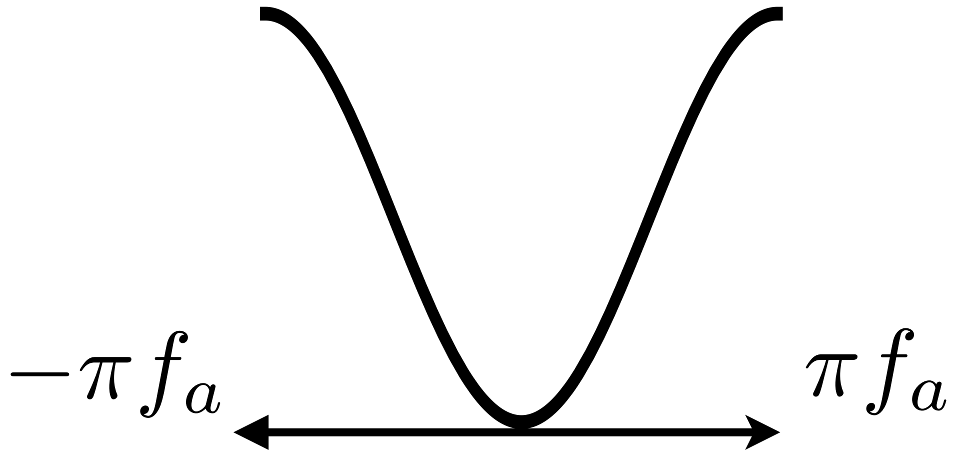
What value of f_a for $\Omega_{cdm} h^2 = 0.12$?

- Axion DM scenarios



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

SCENARIO I, N=1



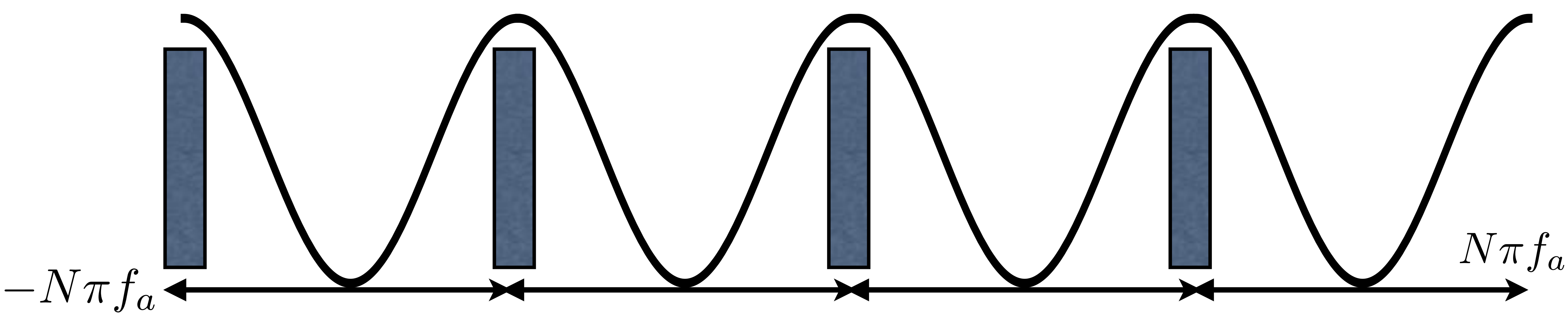
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}^{\mu\nu}_a \theta$$

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

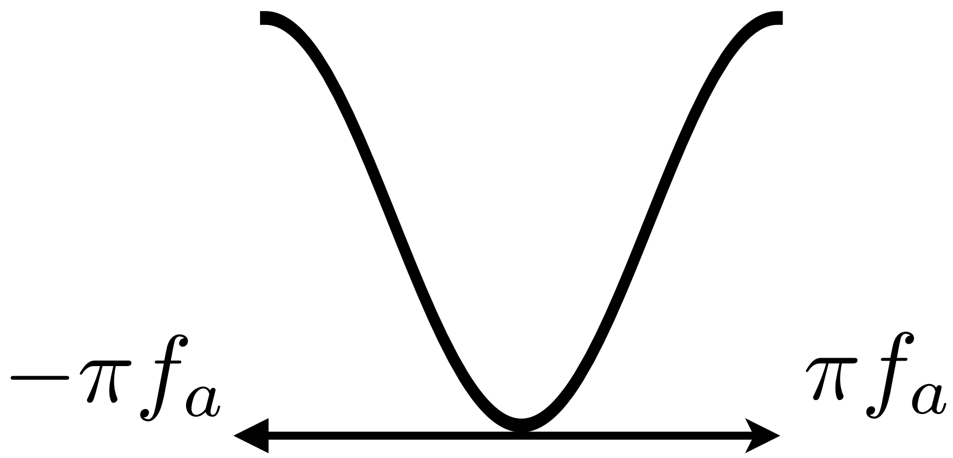
SCENARIO I, N>1, Domain Walls stable-> cosmological disaster

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**

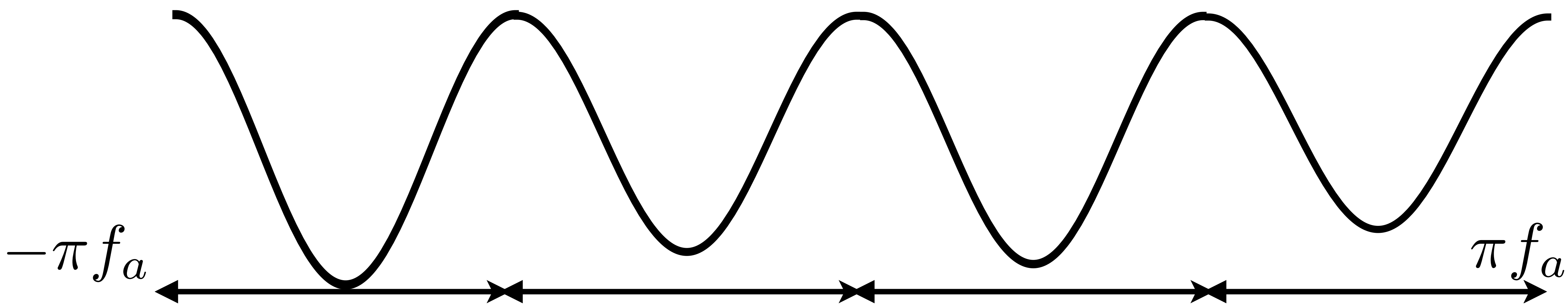


SCENARIO I, N=1



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

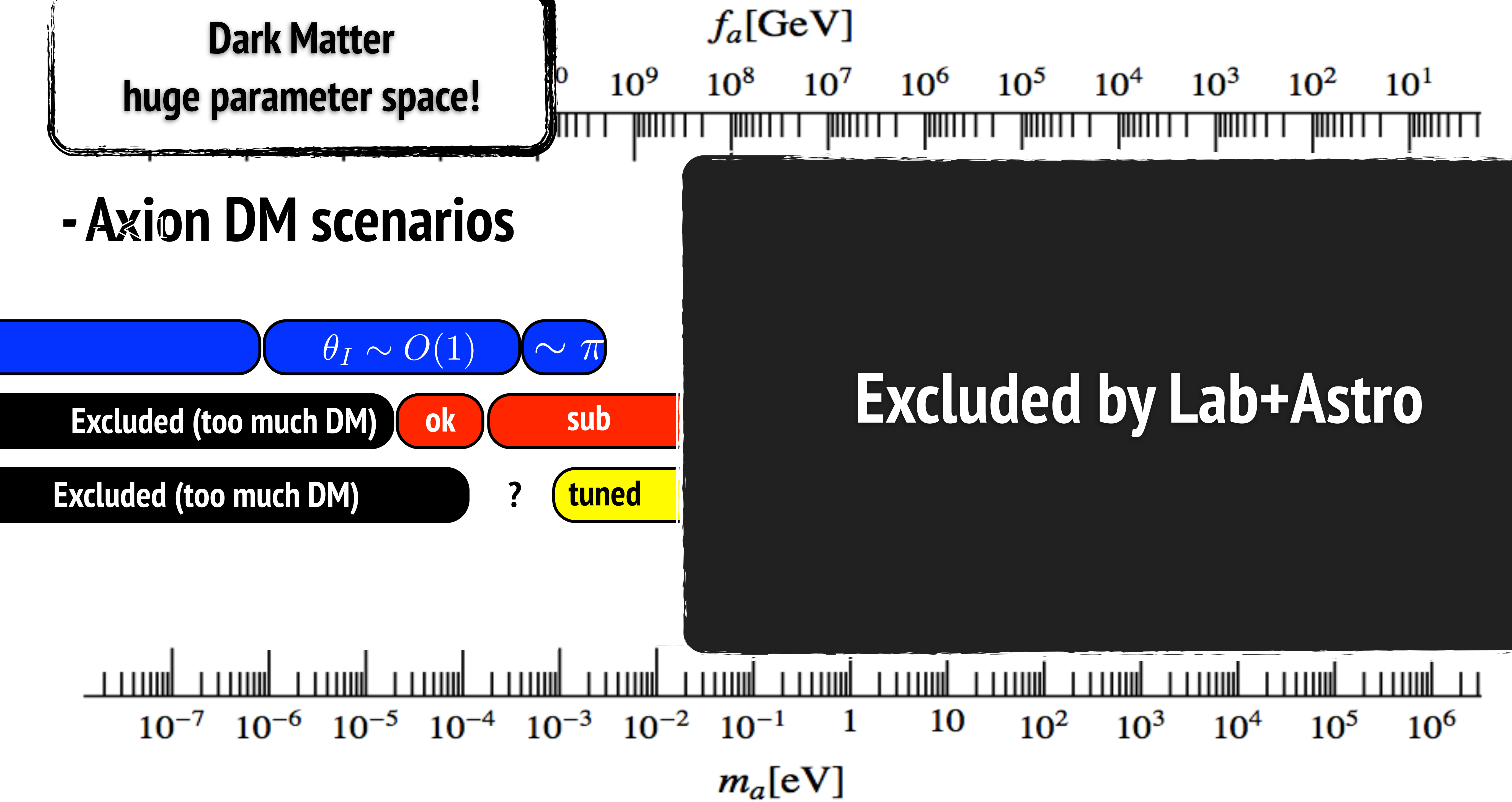
SCENARIO I, N>1, break slightly degeneracy (but tuning...)



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

Dark Matter
huge parameter space!

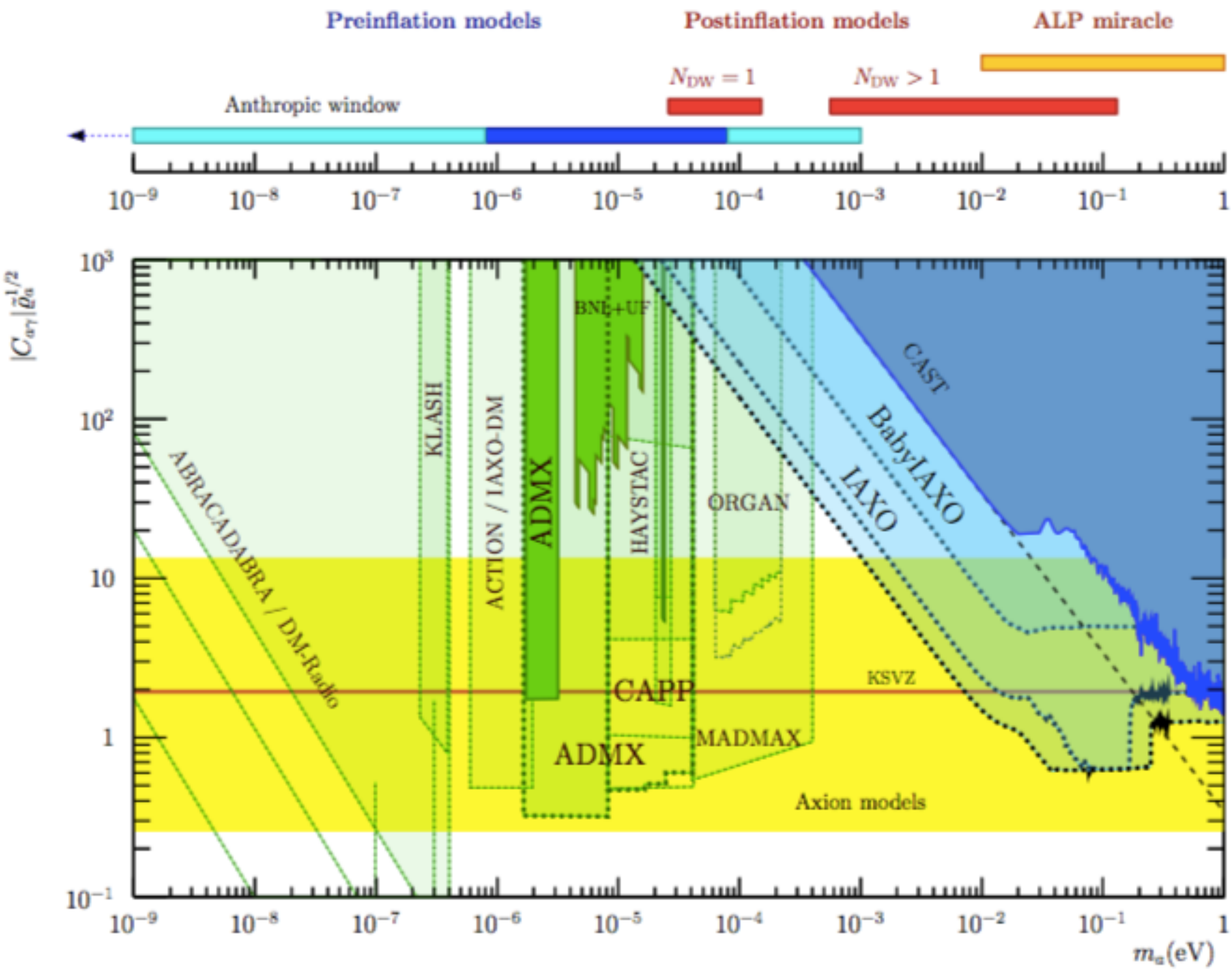
- Axion DM scenarios



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

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

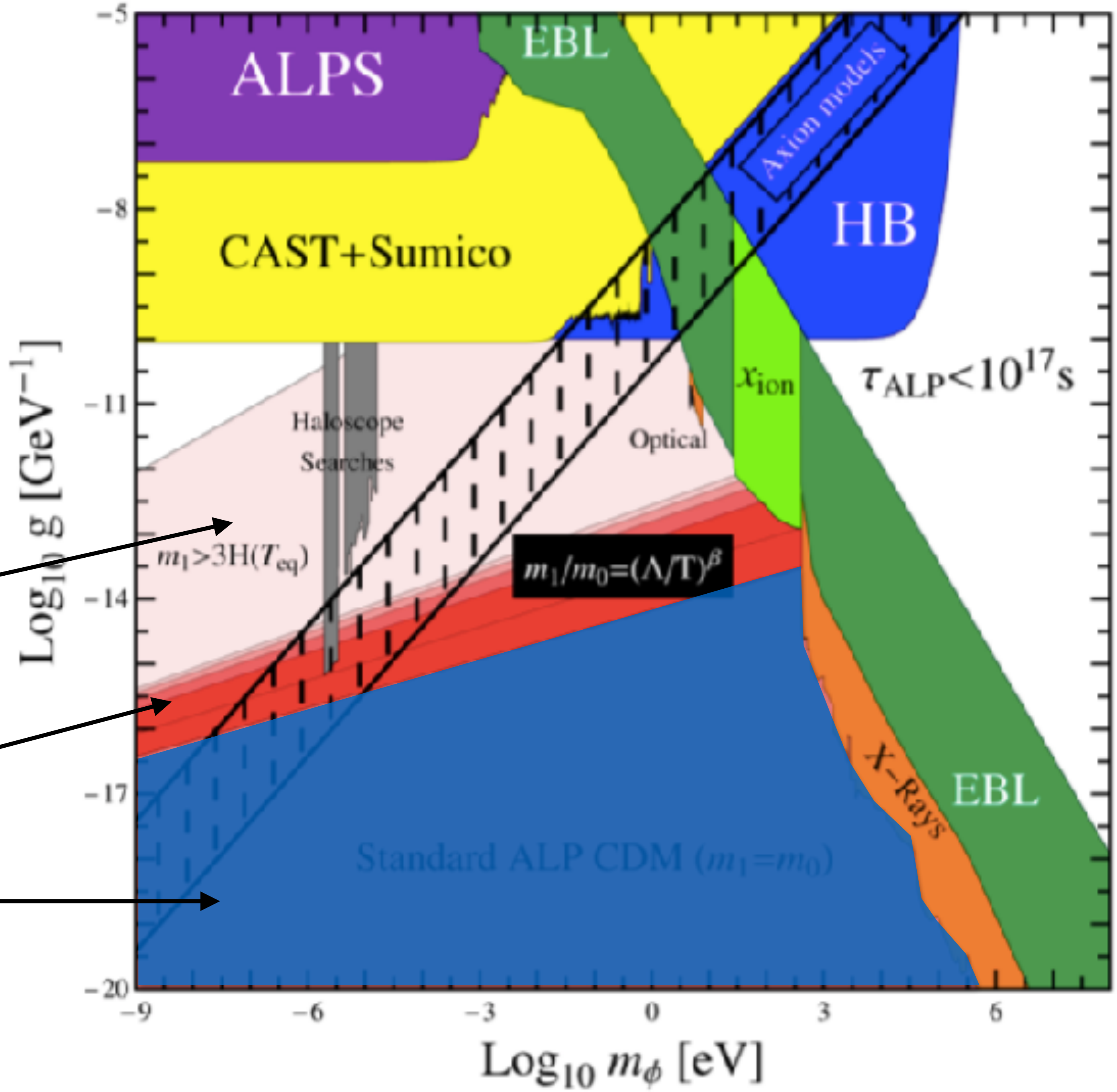
arXiv:1801.08127



axion-like parameter space

$$\phi_I \sim f$$

$$g_{\phi\gamma} \sim \frac{\alpha}{2\pi f}$$



possible?
(N>1,...)

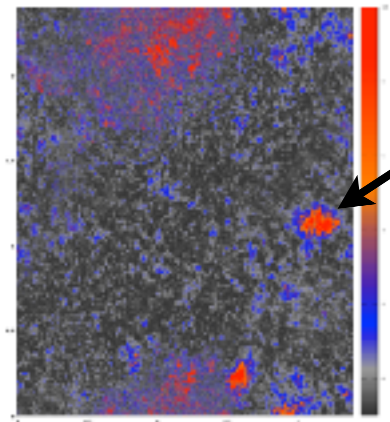
post-inflation

preinflation

Most important constraints I

- PQ breaking after inflation

-> DM inhomogeneous, Axion miniclusters



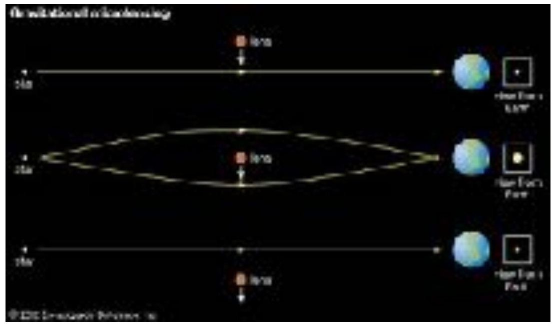
DM density contrast

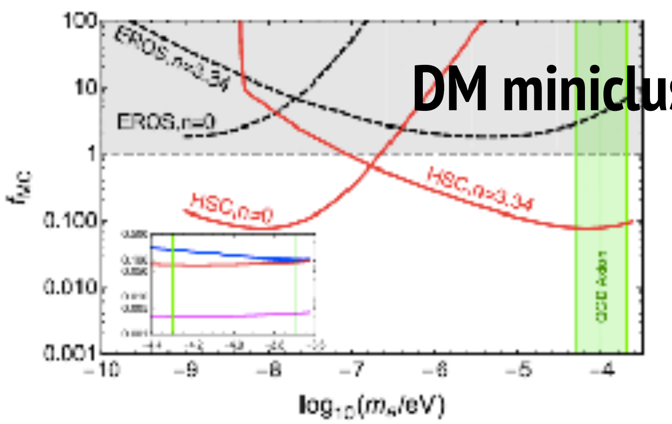
~ 0.1 comoving pc

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

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

Microlensing





DM minicluster fraction <0.1

Marsh 1701.04787

Miniclusters

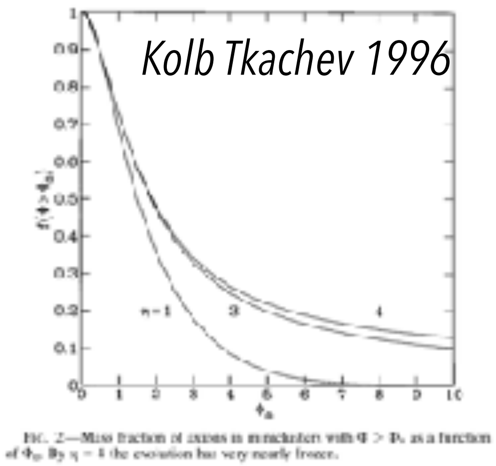
Important issues are quantitative:

- how many MCs or which mass and radius?
- how void is the space between them?
- encounter rates with Earth?
- sensitivity to lensing

Kolb-Tkachev, properties determined by δ and $M_0 \sim \bar{\rho} \times R_1^3$ (mass inside typical causal patch)

$$M \sim (1+\delta)M_0 \ \sim 10^{-12} M_\odot$$
$$R \sim L/(z_{\rm eq}\delta) \ \sim 10^{12}{\rm cm}$$
$$\rho \sim \rho_{\rm eq}\delta^3(1+\delta) \sim 10^{-12}{\rm g/cm}^3$$

Kolb Tkachev 1994

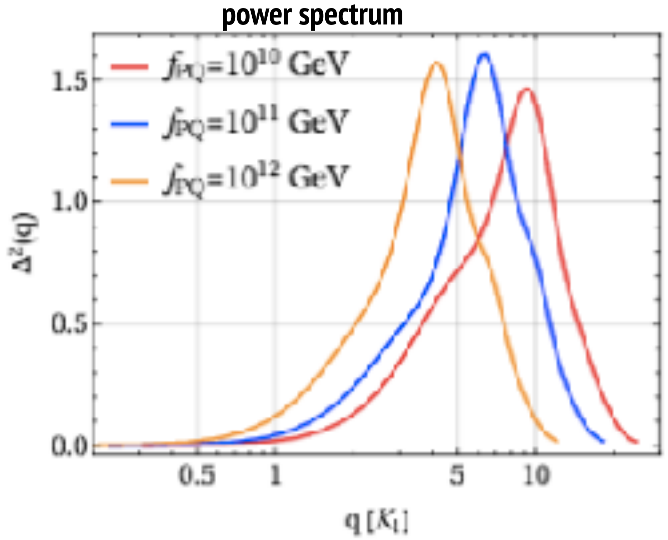


overdensity distribution?

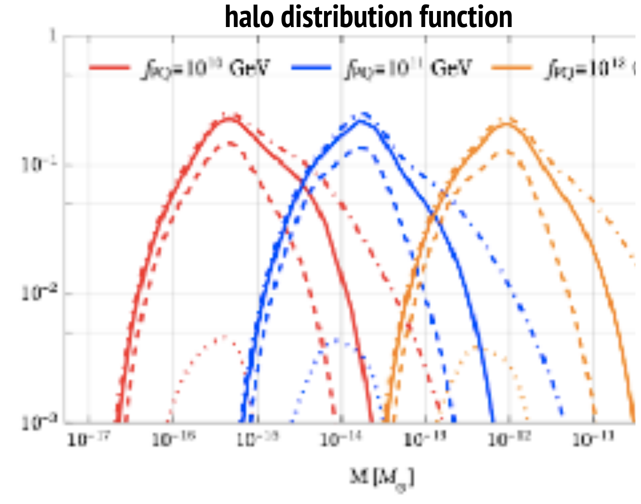
Enander-Schwetz, linear approximation

1708.04466

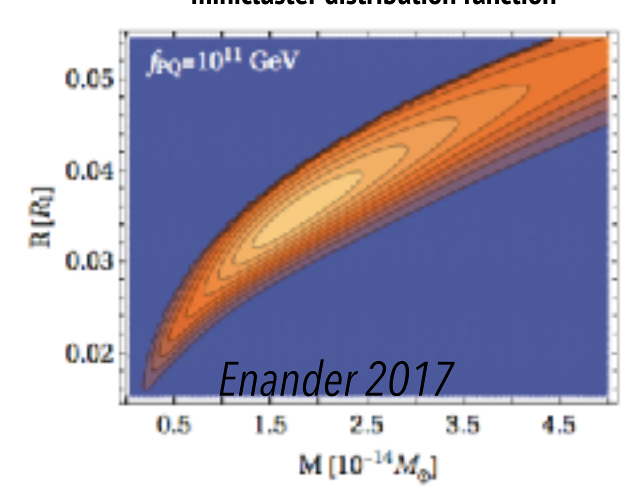
power spectrum



halo distribution function



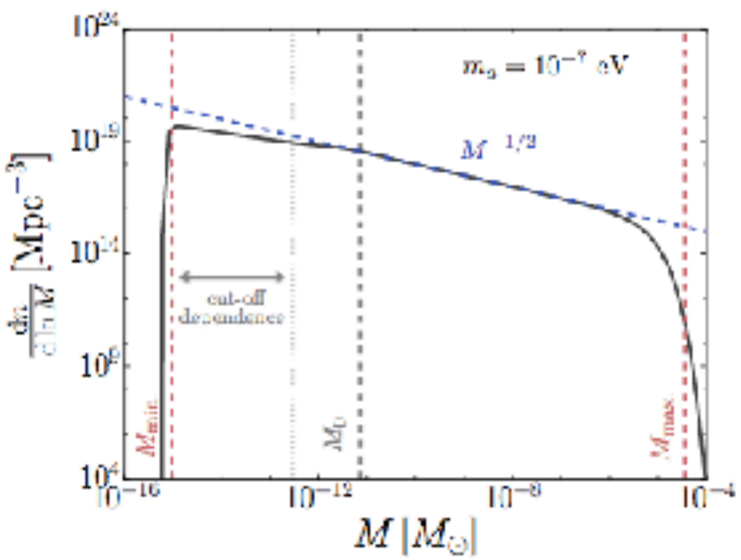
minicluster distribution function



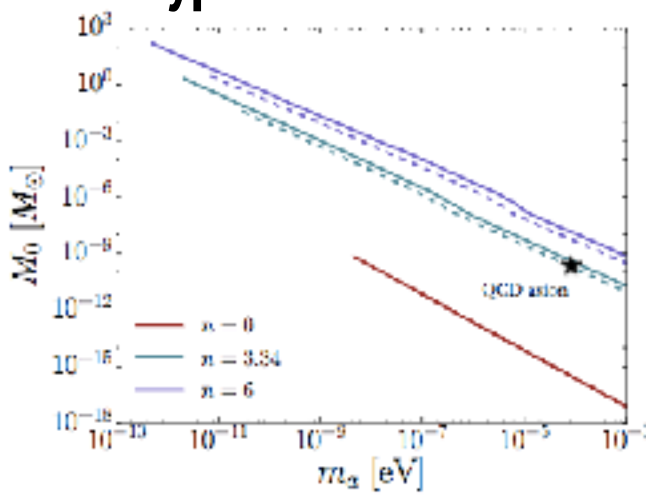
Minicluster Microlensing ...

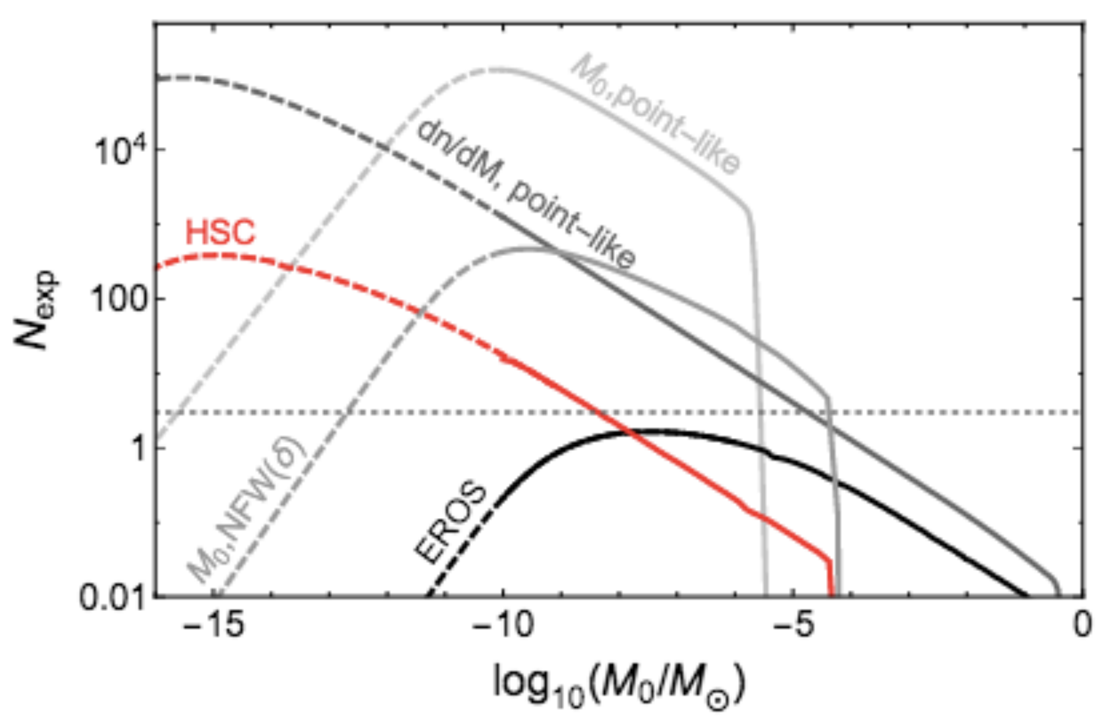
- Microlensing can be used to detect miniclusters with slightly optimistic parameters
- Fairbairn, Marsh, Quevillon arXiv:1701.04787v1

simplest MC mass function

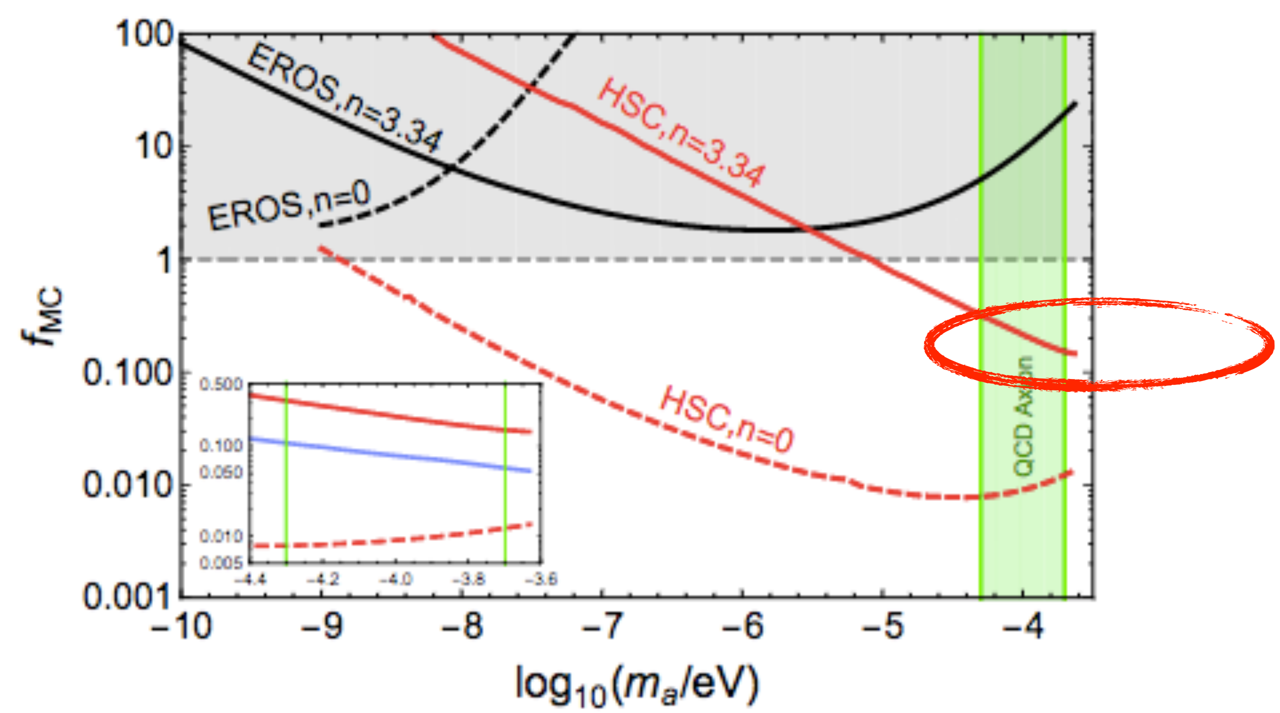


typical MC mass ???





Fraction of DM in miniclusters



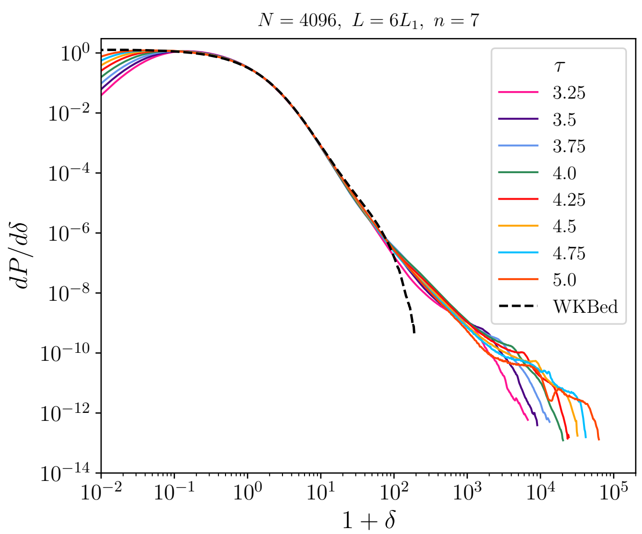
- Problems: too large M_0 mass [?], Kolb-distribution for M_0 miniclusters,
- HSC interpretation below 10^-10 M_sun. (1711.06129)

New axion DM simulations

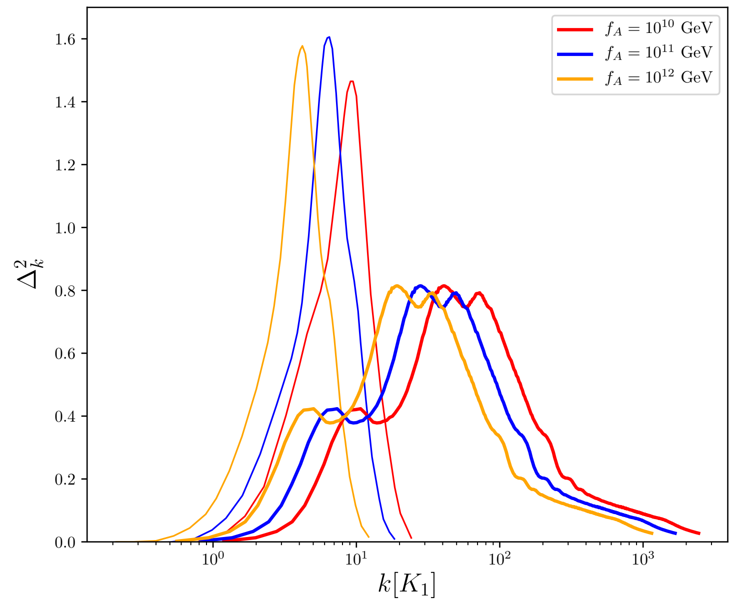
Redondo, Stadler, Vaquero 2018

- **-Cosmic-string simulation ->axion until freeze-out**
- **- Huge grids 8192^3, further sensitivity**

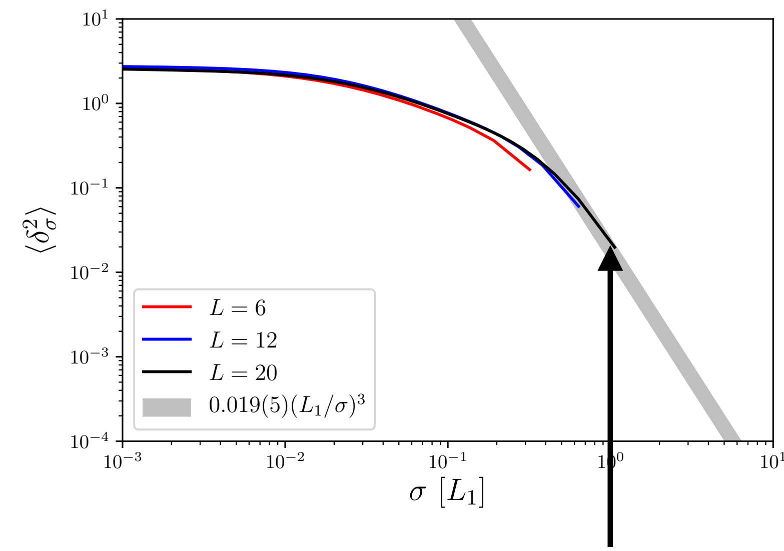
we see very large overdensities and non-linear effects



but power is at small scales, even smaller than enander

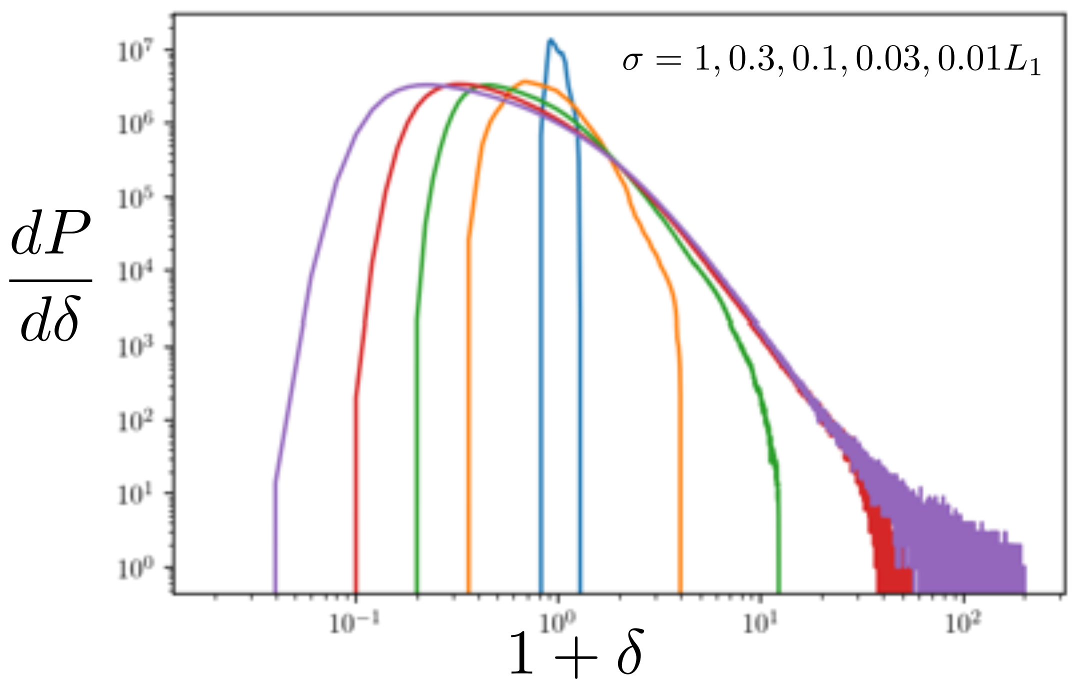


typical contrast as a function of minicluster seed radius



but at length (mass scales) related to horizon, variance small!!

distribution of density contrasts for different Radii



- conclusions:

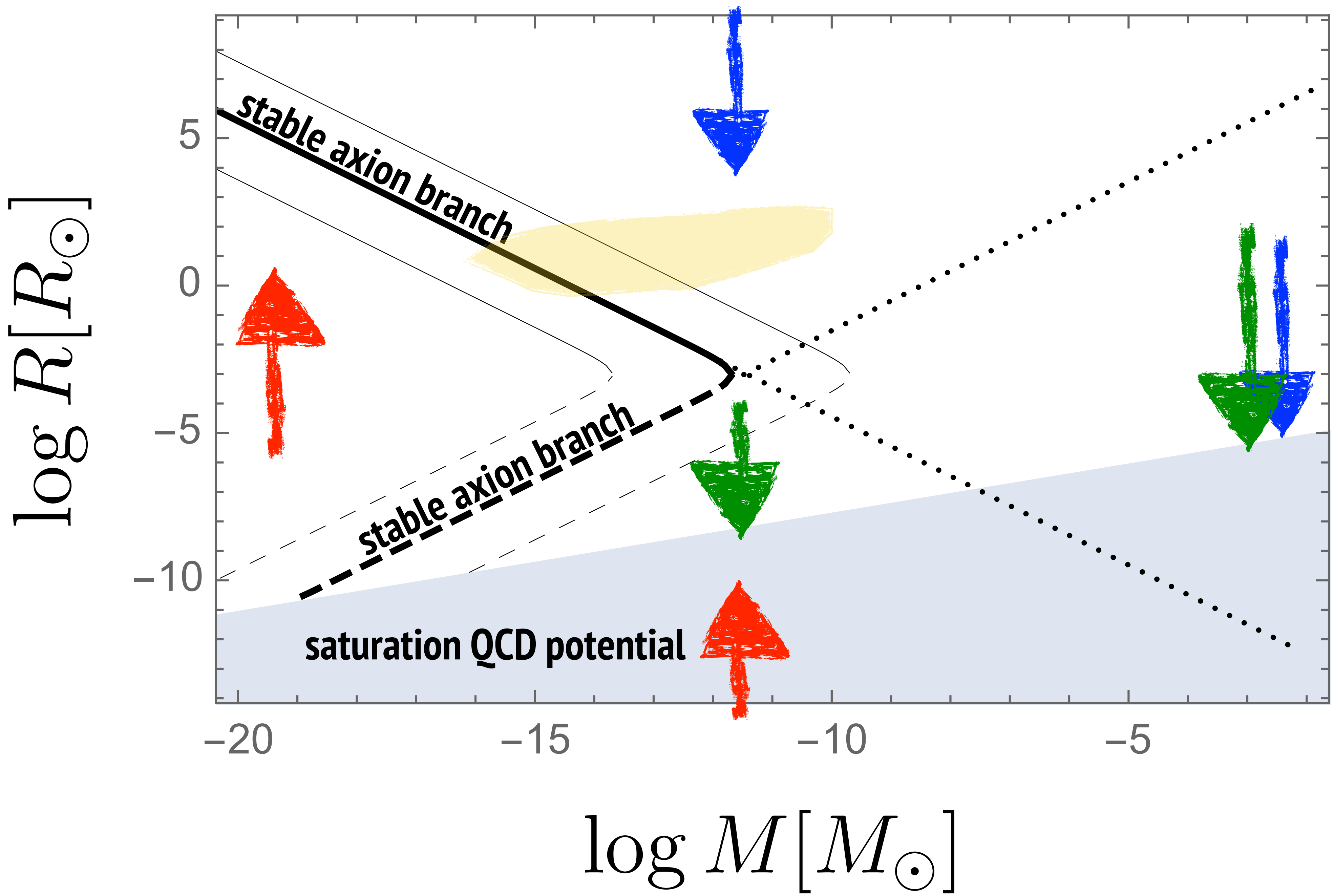
current microlensing constraints relaxed

many compact small-mass MCs

MC mass function coming soon! *RSV, Niemeyer 2018*

Axion stars ... gravitationally bound coherent lumps

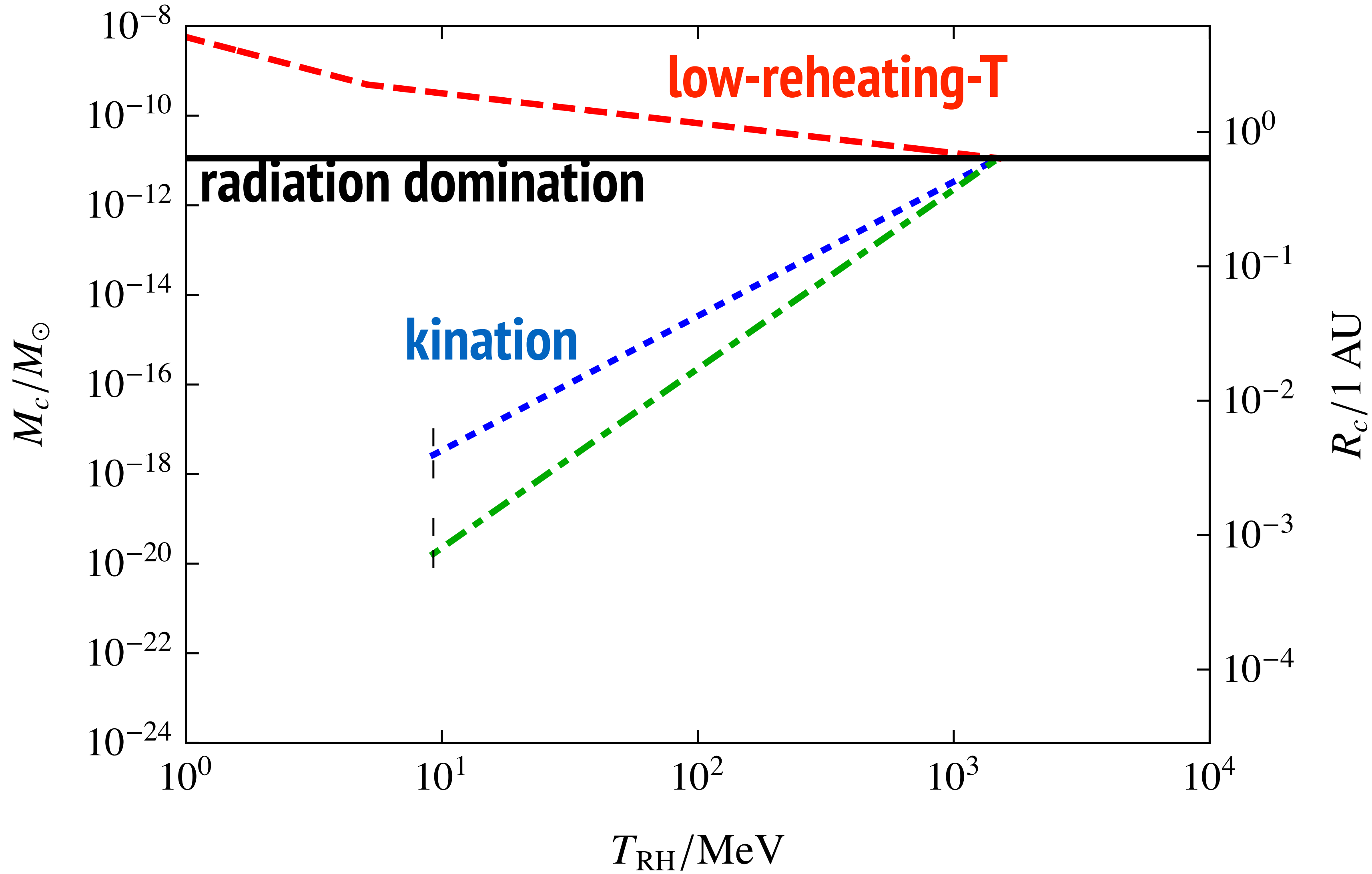
- Gradient-pressure vs axion-attractive-self-interactions vs gravity
- Axion miniclusters not far from axion stars (Bose-stars, oscillotons)
- Our small compact MC seeds -> low mass axion stars
- Exciting cosmology to explore



Different cosmological histories

Visinelli 2018

- Radiation domination assumed during t1
- Alternative cosmologies change strongly the MC mass and bring back constraints!



Most important constraints II

- PQ breaking after inflation

-> DM inhomogeneous, Axion miniclusters

~ 0.1 comoving pc

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

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

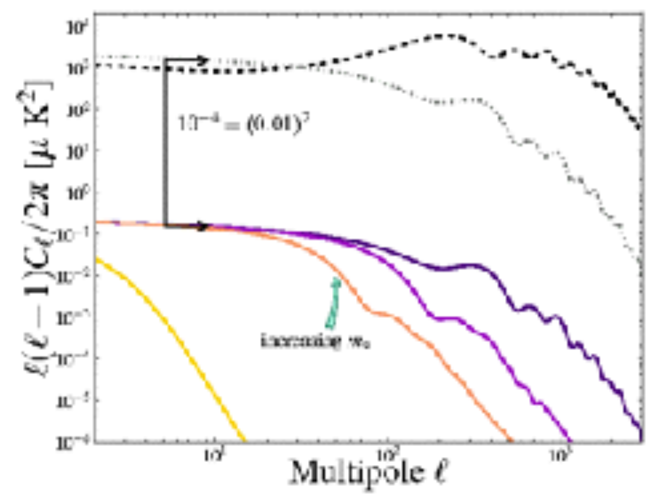
Microlensing

DM minicluster fraction <0.1

Marsh 1701.04787

- PQ breaking before inflation

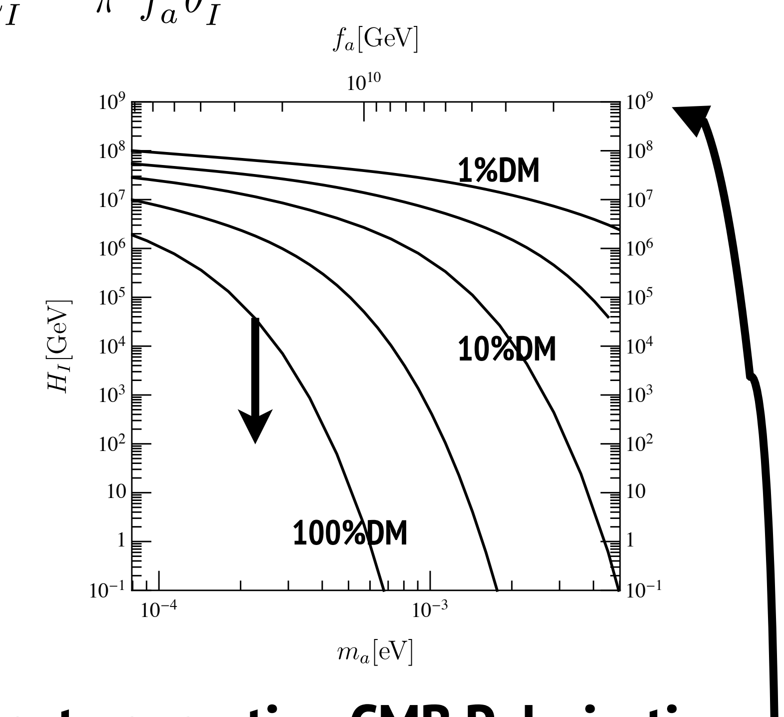
* Axion fluctuations during inflation -> CMB isocurvature



- Planck sees no Isocurvature fluctuations, strong limit!

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

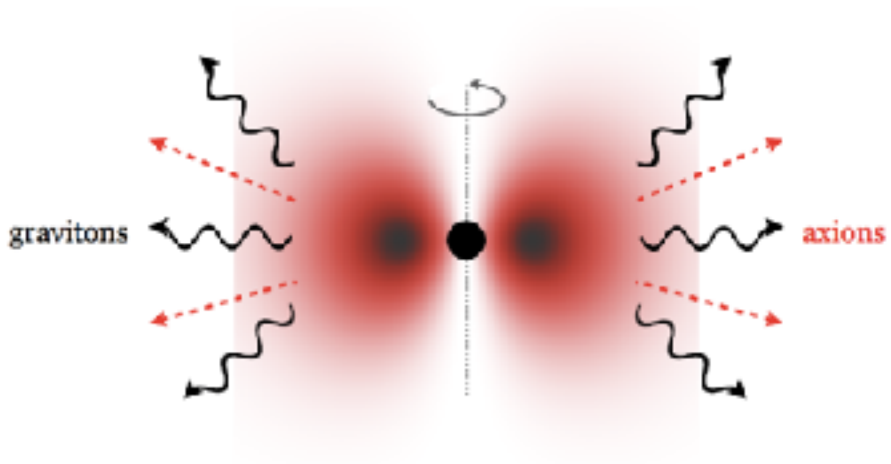
Depends on Hubble rate during inflation ... H_I

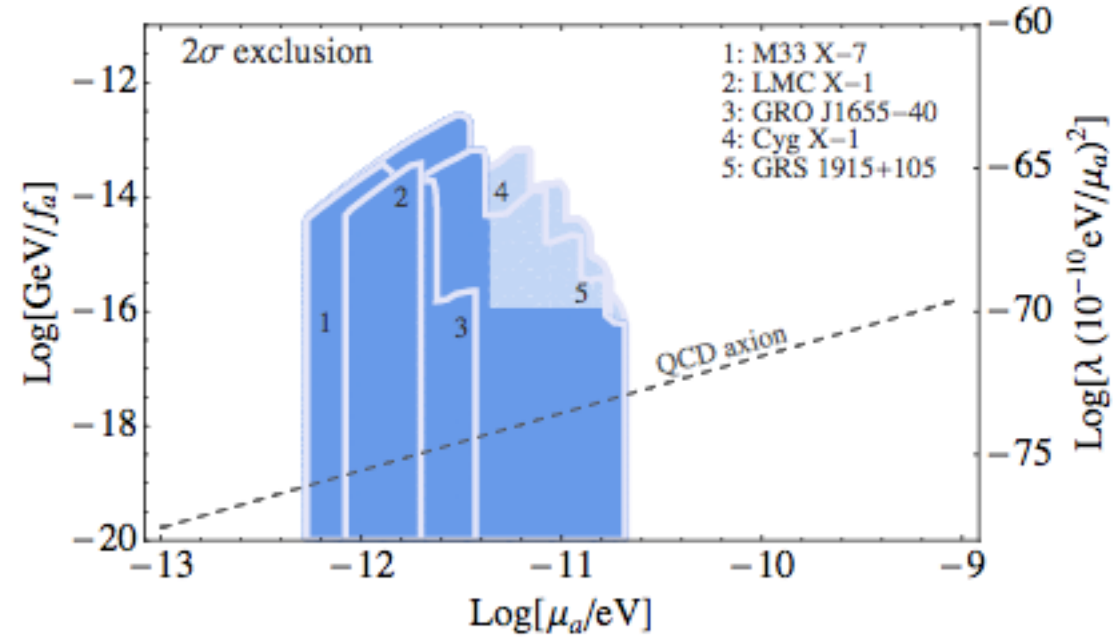


- If H_I is measured by next generation CMB Polarisation axion DM is excluded (avoided in some models)

Most important constraints III

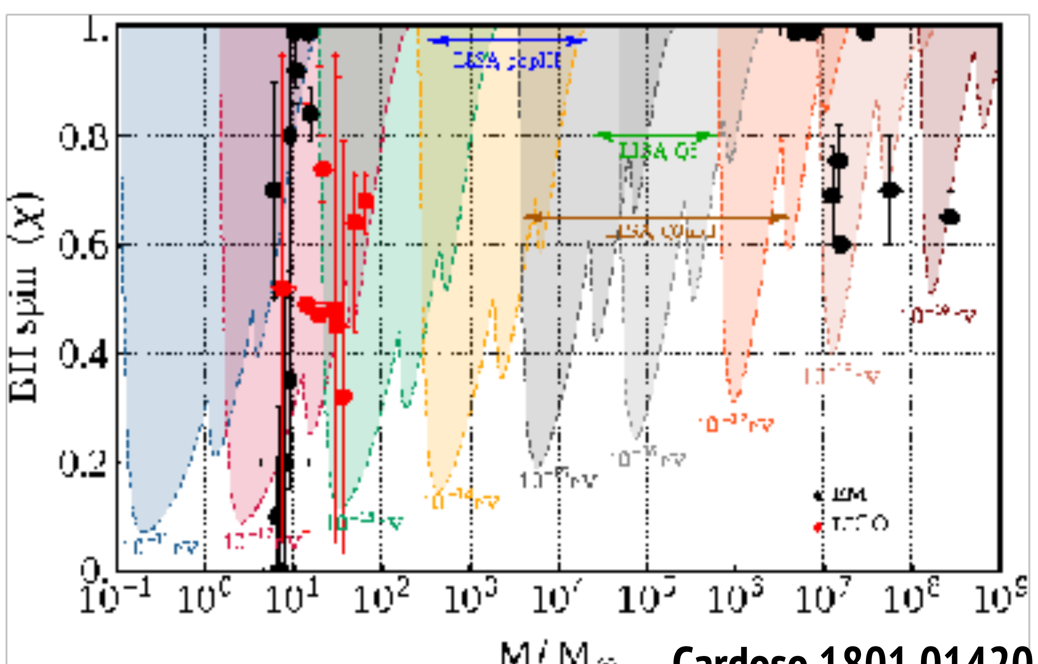
-Black-hole super radiance 1411.2263



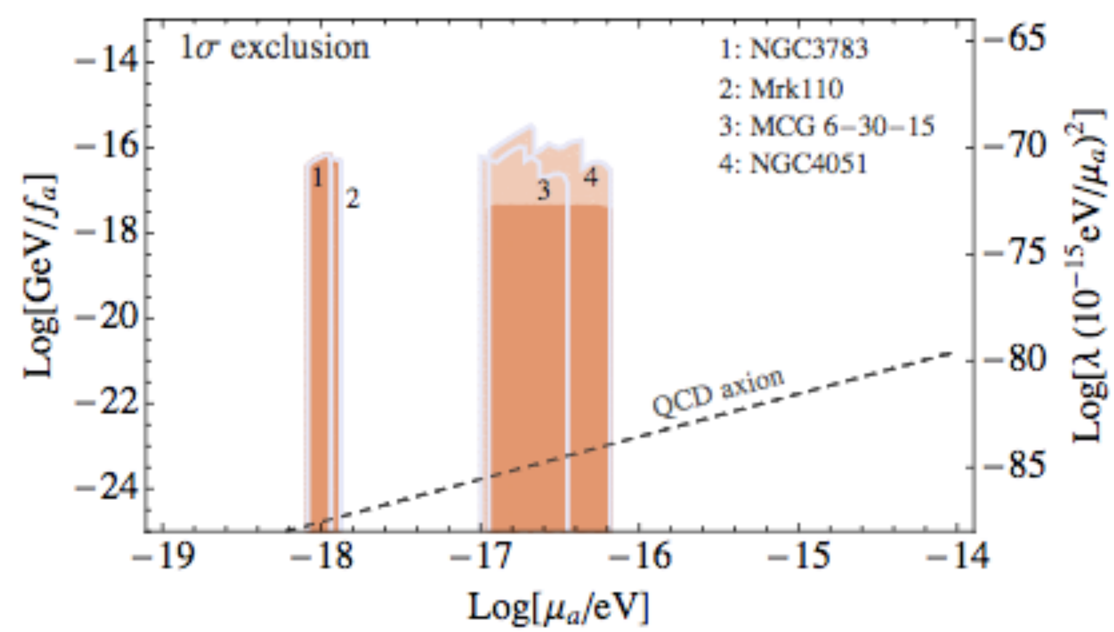


(a)

BHs with spin can radiate it into axions quite efficiently, we observe spin BH's so we can put constraints…



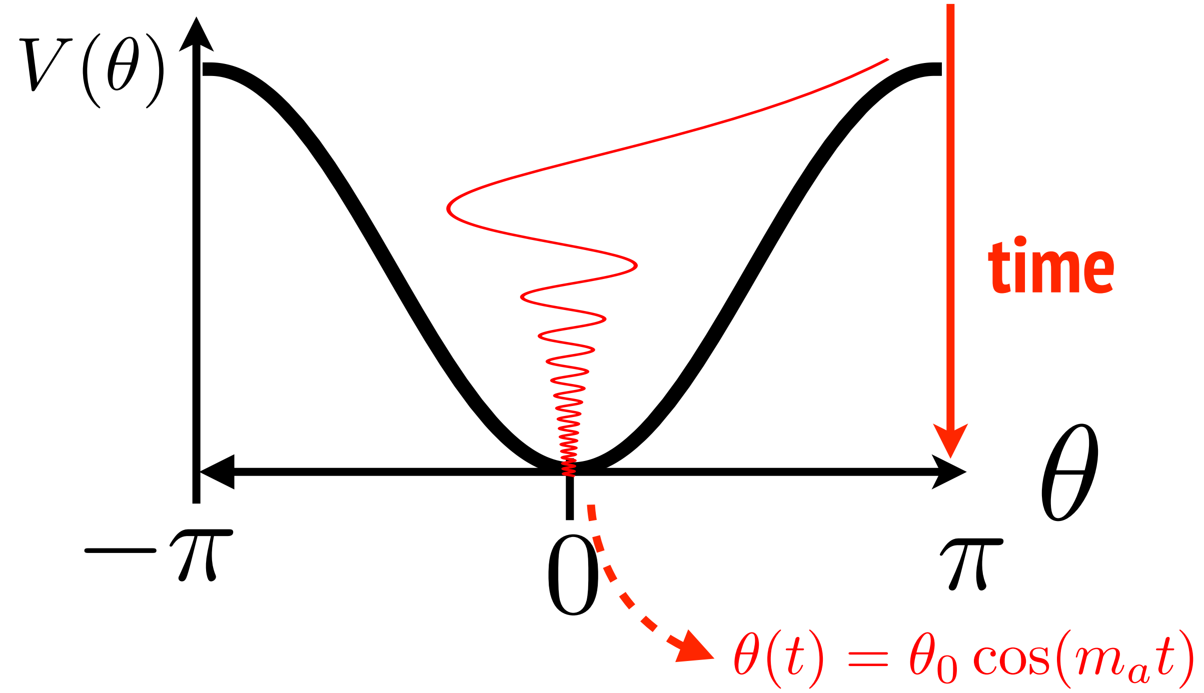
Cardoso 1801.01420



(b)

Arvanitaki 1411.2263

Axion DM in the lab



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

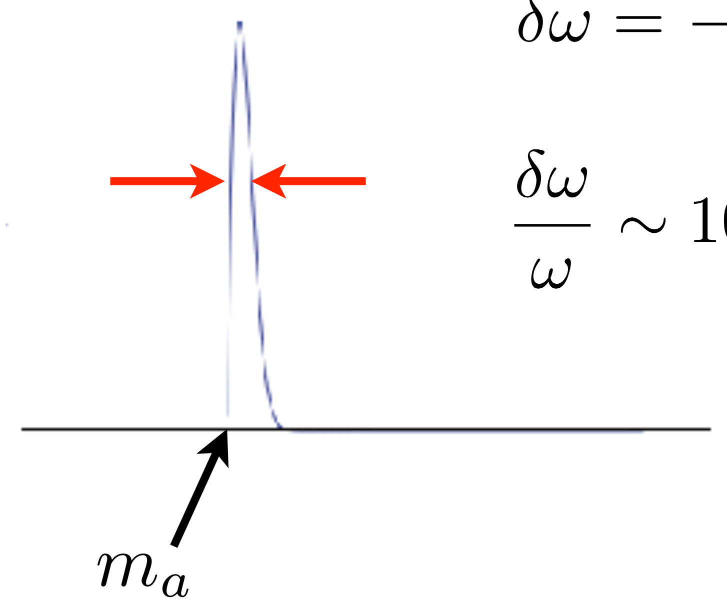
- $\theta_0 = 3.6 \times 10^{-19}$ **is a very small number but, oscillations allow for coherent detection!**

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

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

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

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



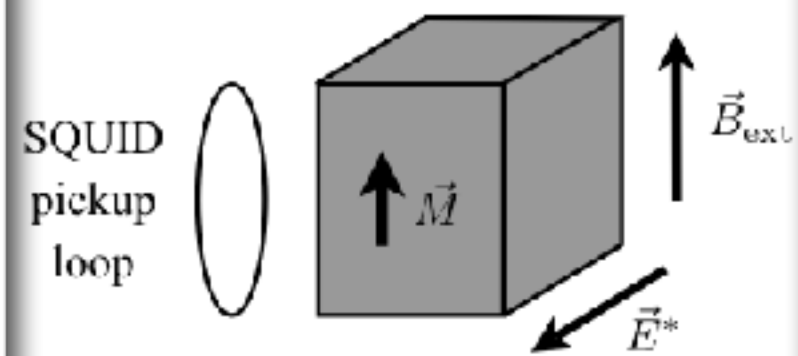
coherence time

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

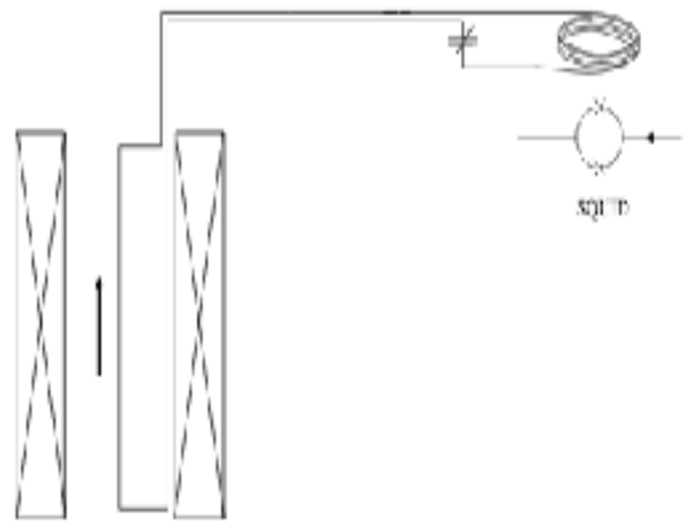
coherence length

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

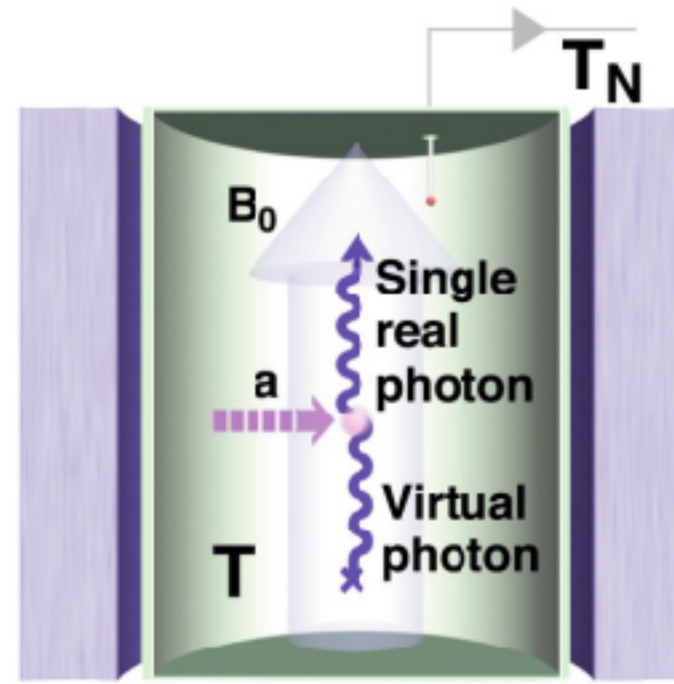
scillating EDM



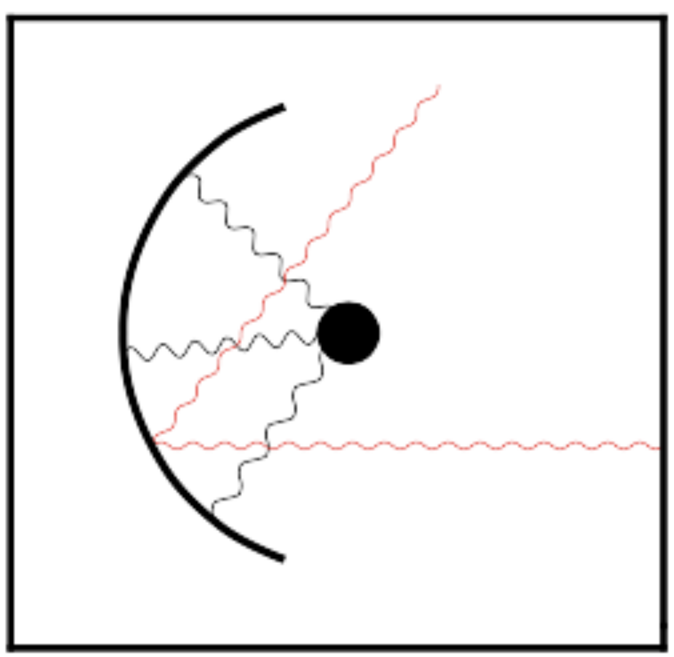
C-circuit



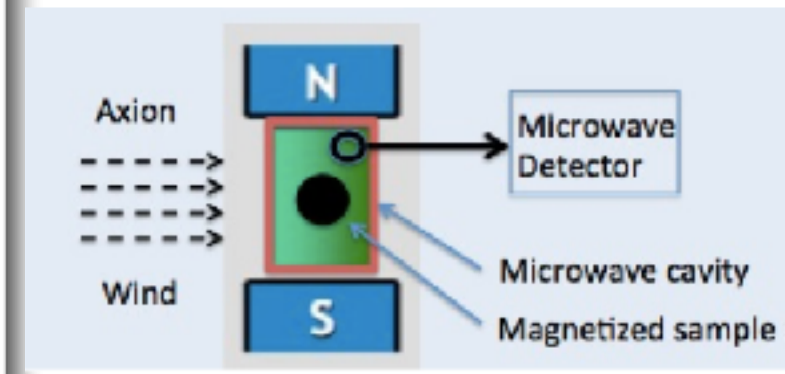
avities



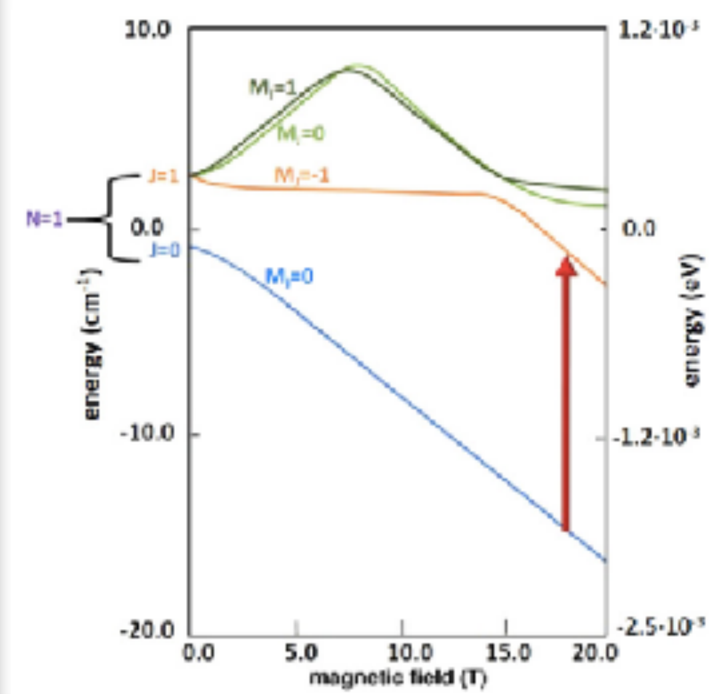
irrors



rromagnetic resonance



tomic transitions

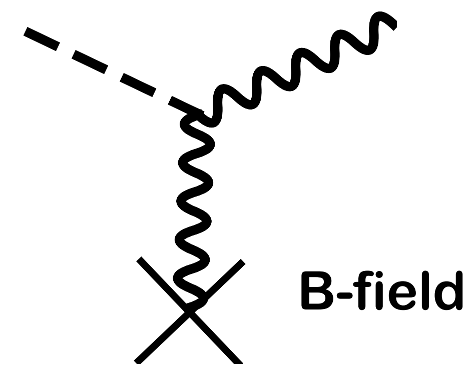


Axion DM in a B-field

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

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

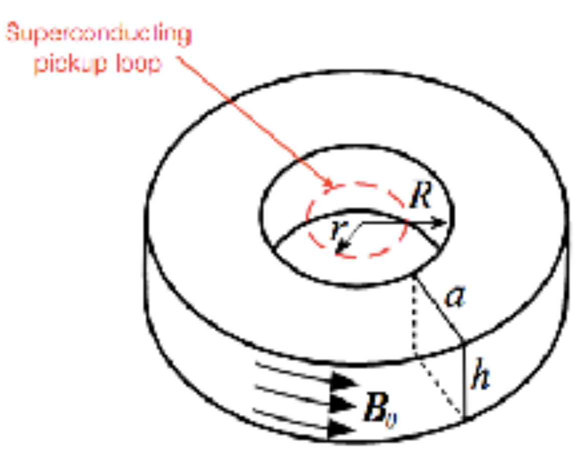
source



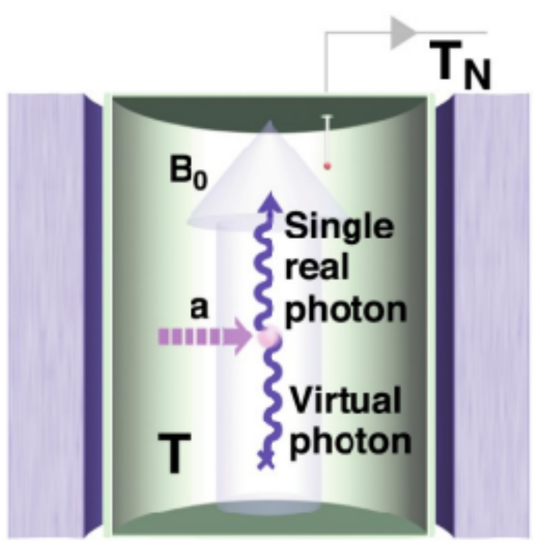
E-field $E \sim \mathcal{O}(10^{-12}\text{V/m})\frac{|\text{B}_{\text{ext}}|}{10\,\text{T}}C_{a\gamma}\times\cos(m_a t)$

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

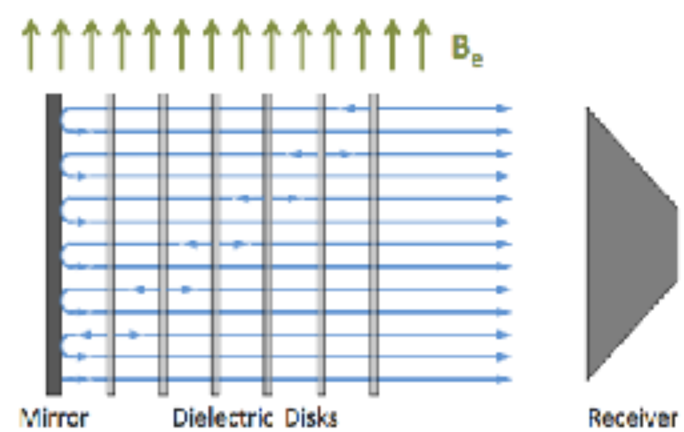
- Four different techniques:



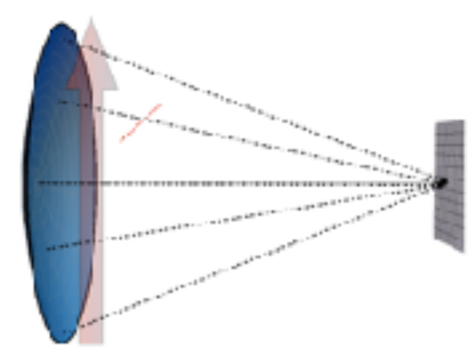
DM Radio



Cavities

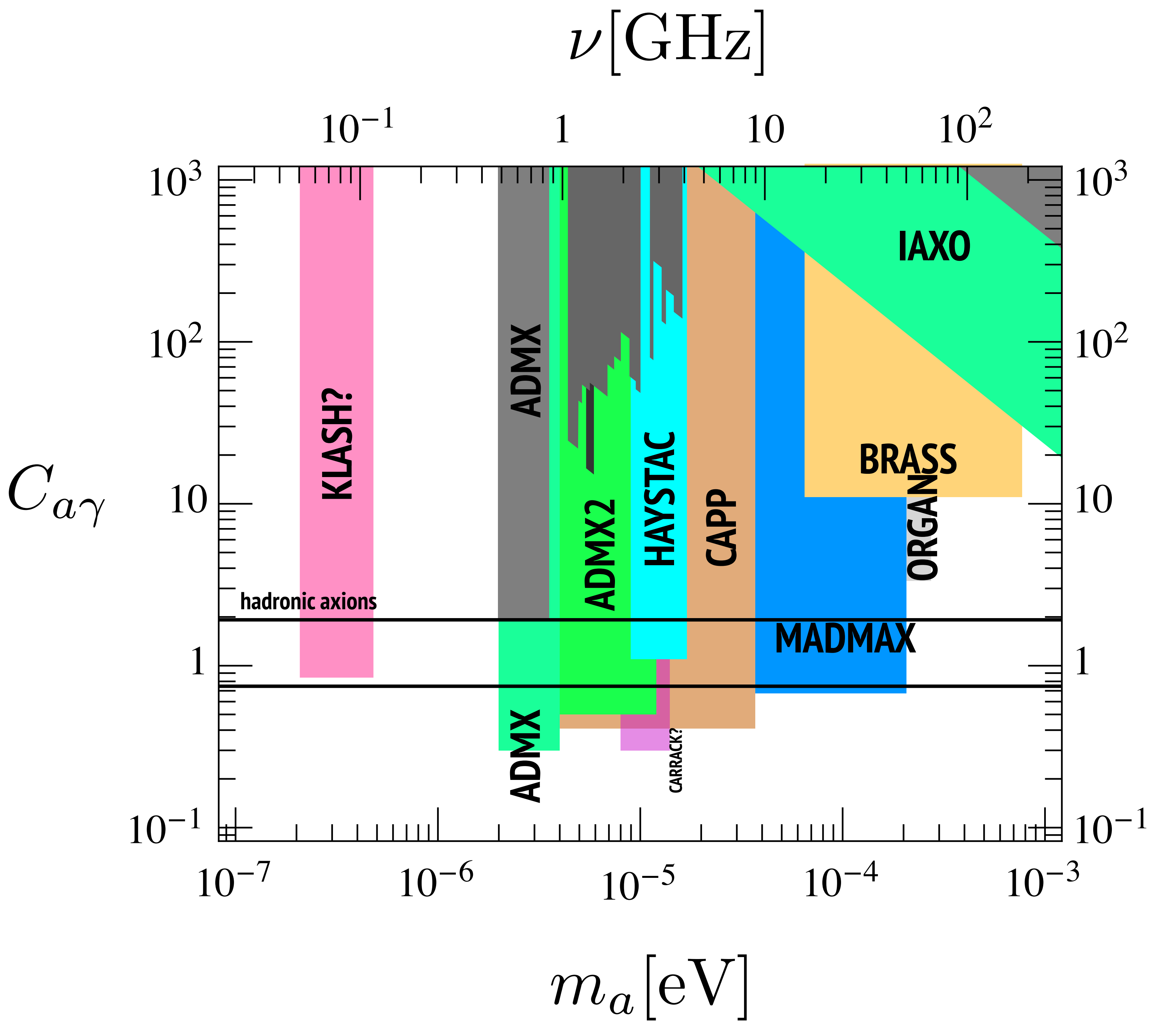


Dielectric haloscope

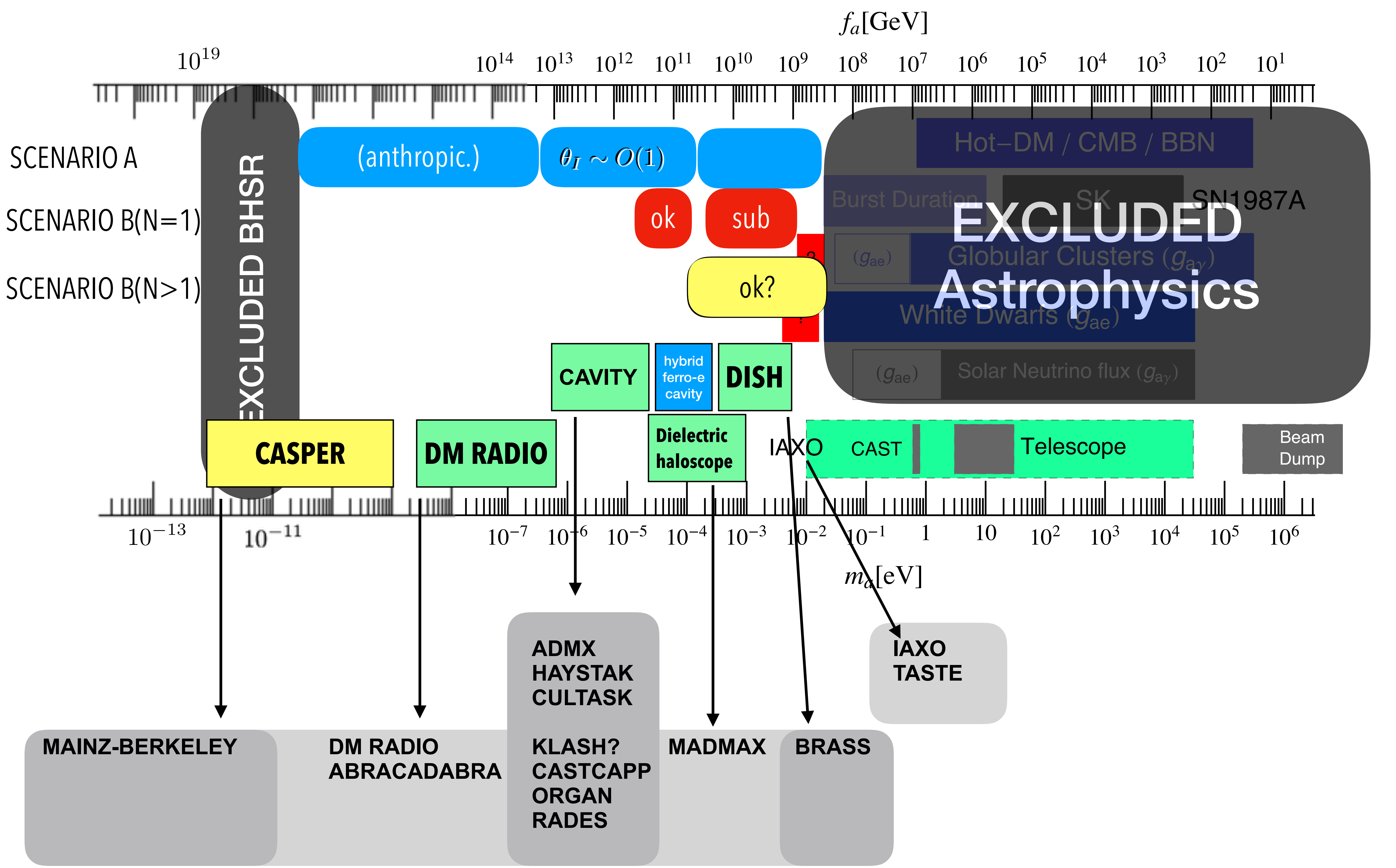


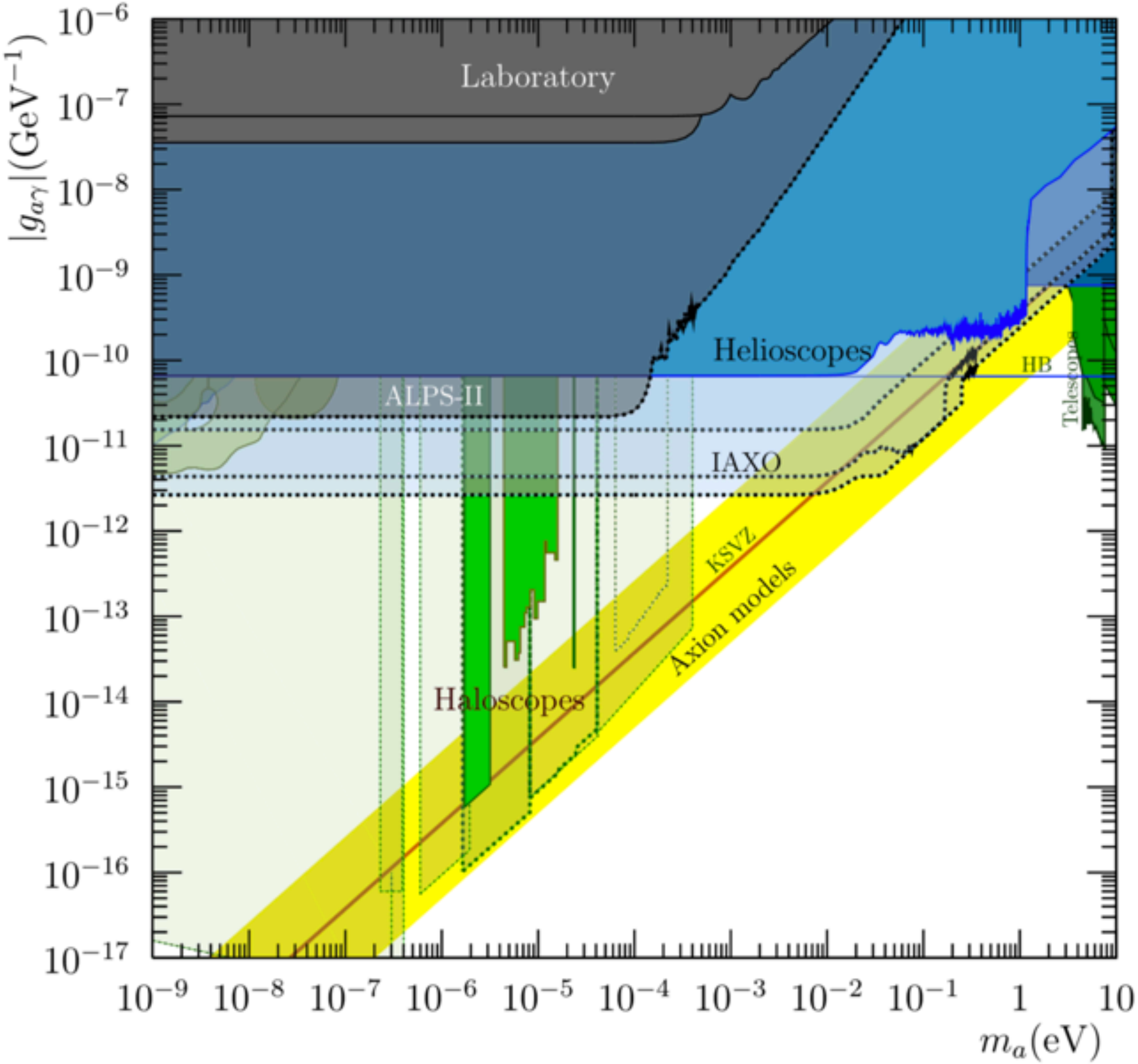
Dish antenna

Projected sensitivities



Experiments





Laboratory
Helioscopes
ALPS-II
IAXO
HB
Telescopes
KSVZ
Axion models
Haloscopes
$|g_{a\gamma}|(\mathrm{GeV}^{-1})$
$m_a(\mathrm{eV})$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10

Conclusions

- Axions: Strong CP -> dark matter

- Axions and ALPs are generic BSM, generic couplings

- DM abundance controlled by initial conditions and early cosmology (inflation?)

- two grand scenarios:
  pre-inflation : any QCD axion mass works ... -> isocurvature perturbations in the CMB?
  post-inflation: 25-100 micro-eV favoured -> miniclusters... microlensing?

- Several detection schemes: most on R&D

- other 'gravitational probes available': BH super radiance at ultra-low masses