Axions

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Benasque

Outline

- Strong CP problem

- Peccei-Quinn mechanism and Axions

- Dark Matter

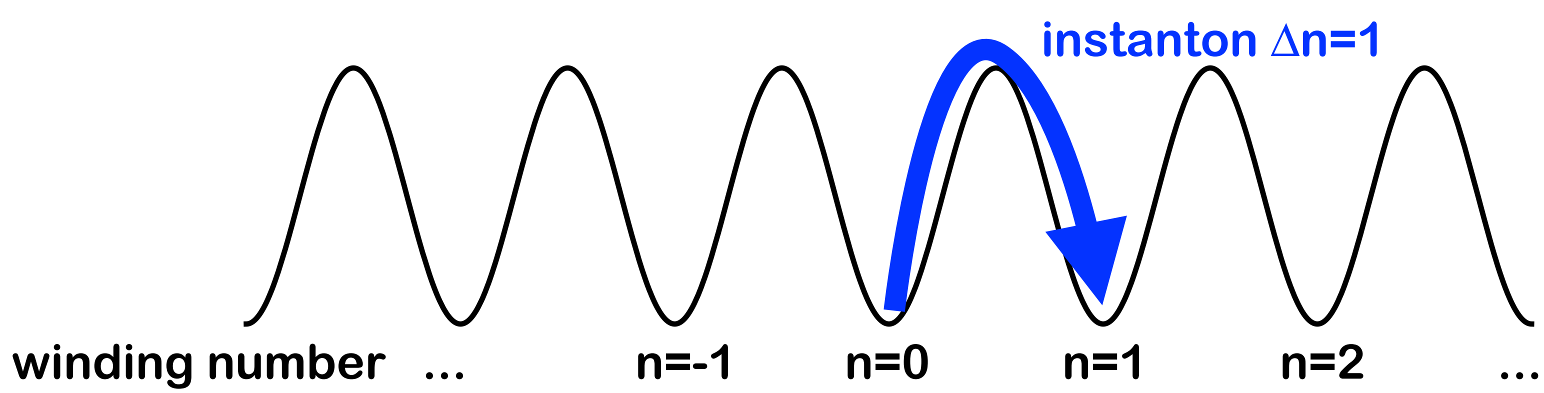
- Solar axions

The strong CP “problem”

- **P, T violated in the SM, consider** $\mathcal{L}_\theta = -\frac{\alpha_s}{8\pi} G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}\theta$

  $G_a^{\mu\nu}\widetilde{G}_{a\mu\nu} = \partial_\mu K^\mu$ **but cannot be disregarded!**

- **gauge-invariant QCD Vacua** $|\theta\rangle = \sum_n e^{-i\theta n}|n\rangle$



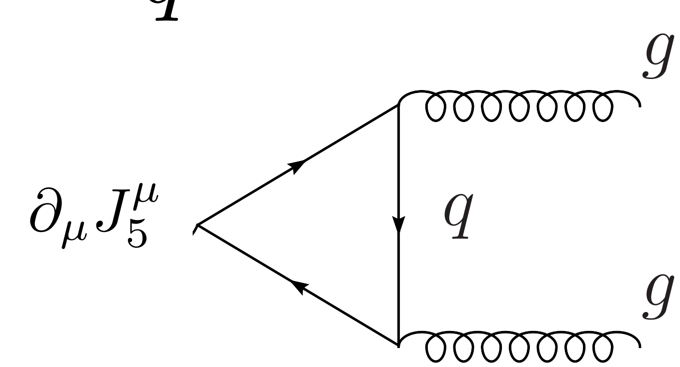
instantons contribute to $G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}$

including them in Path Integrals $\rightarrow \mathcal{L}_\theta$

- **quark phases, axial U(1)** $q \rightarrow e^{i\gamma_5\alpha} q$

$$\mathcal{L}_{\rm QCD} \rightarrow \mathcal{L}_{\rm QCD} + \alpha(\partial_\mu J_5^\mu)$$

$$\partial_\mu J_5^\mu = 2im_q\bar{q}\gamma_5 q + \frac{\alpha_s}{8\pi}G\widetilde{G}$$



redefining quark phases I shift theta!

Theta shifts

$$\mathcal{L}_{\rm SM} \ni -m_u \bar{u} e^{i\gamma_5 \delta_u} u - m_d \bar{d} e^{i\gamma_5 \delta_d} d - \frac{\alpha_s}{8\pi} G\widetilde{G}\,\theta$$

$$u \to e^{-i\gamma_5 \frac{\delta_u}{2}} u \qquad\qquad d \to e^{-i\gamma_5 \frac{\delta_d}{2}} d$$

$$\mathcal{L}_{\rm SM} \ni -m_u \bar{u} u + m_d \bar{d} d - \frac{\alpha_s}{8\pi} G\widetilde{G}\,(\theta + \delta_u + \delta_d)$$

$$\theta_{\rm SM} = \underline{\theta_{\rm QCD\ vacuum}} + \underline{\arg(\rm trM_q)}$$

comes from QCD... from Yukawa sector

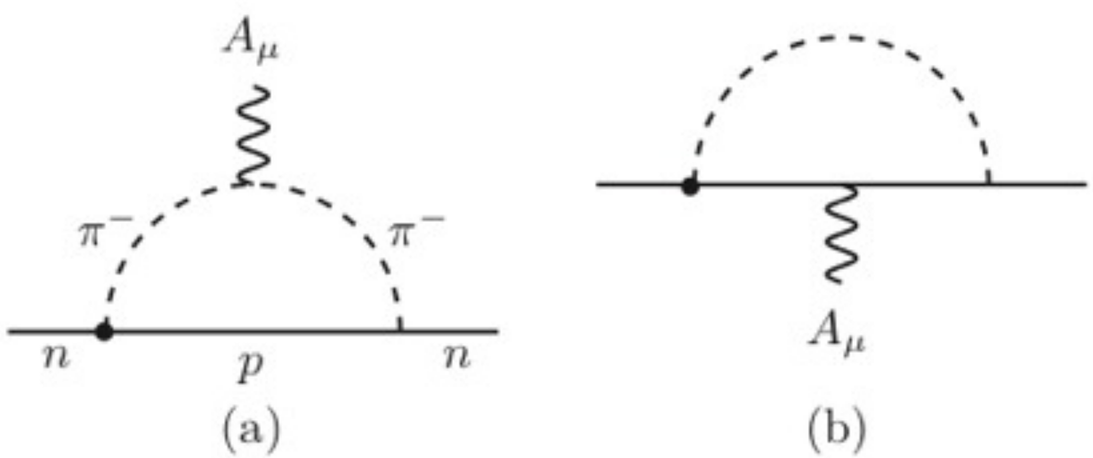
$$\mathcal{L}_{\rm SM} \ni -m_u \bar{u} e^{i\gamma_5 \theta} u + m_d \bar{d} d$$ **etc...**

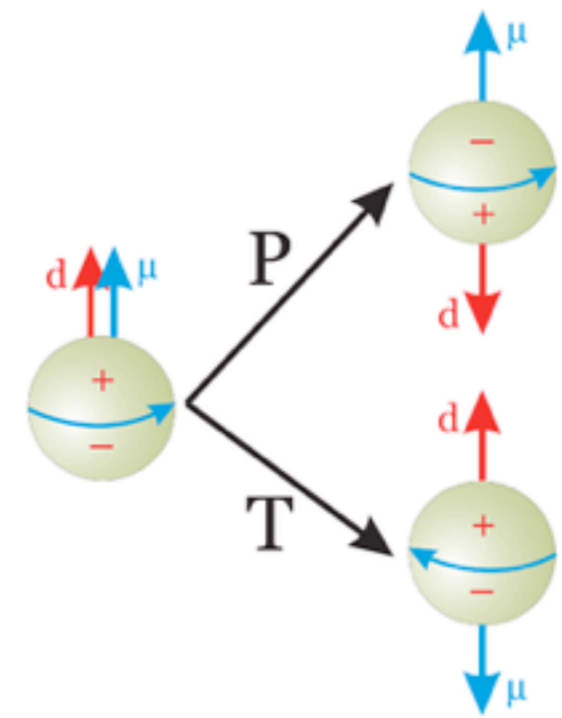
massless quark, θ unphysical!

The strong CP "surprise"

- $\theta \neq 0 \rightarrow$ **Parity and Time-reversal violation (CP)**

- **Neutron Electric Dipole moment**





$$d_n \sim \theta \times \mathcal{O}(10^{-2})[e\,\mathrm{fm}]$$

$$d_n^{\mathrm{exp}} < 3 \times 10^{-13}[e\,\mathrm{fm}]$$ Baker et al. 2006 ILL Grenoble

Non Observation:

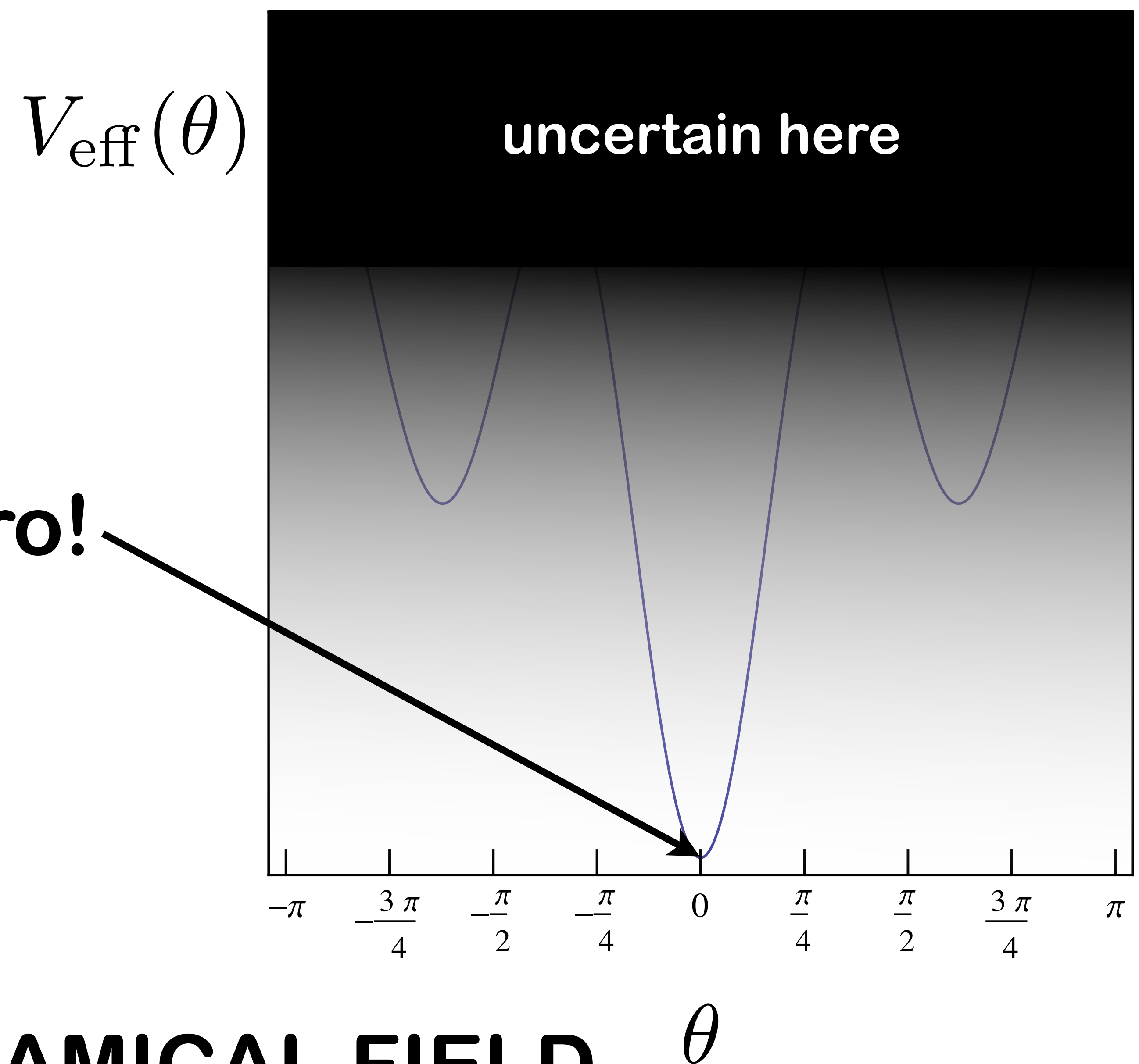
$\theta \lesssim 10^{-11}$ **Why ?????**

The strong CP “hint”

- **there is a certain bias towards** $\theta = 0$

Vafa-Witten NPB 1984, see also Azcoiti-Galante PRL1999

QCD vacuum energy has a minimum at zero!



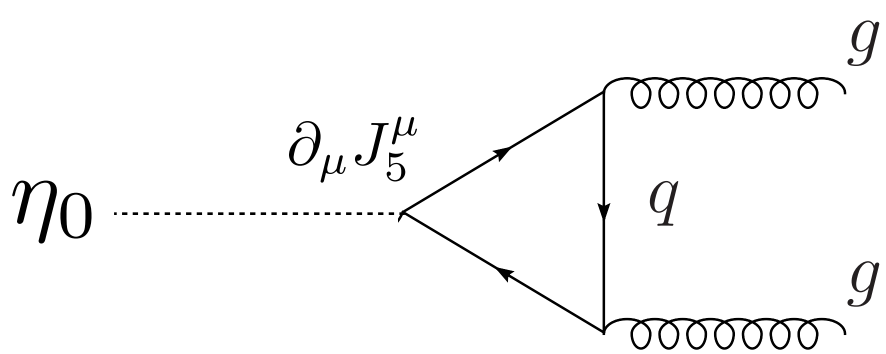
- **But theta is NOT A DYNAMICAL FIELD**

The strong CP "hint" II

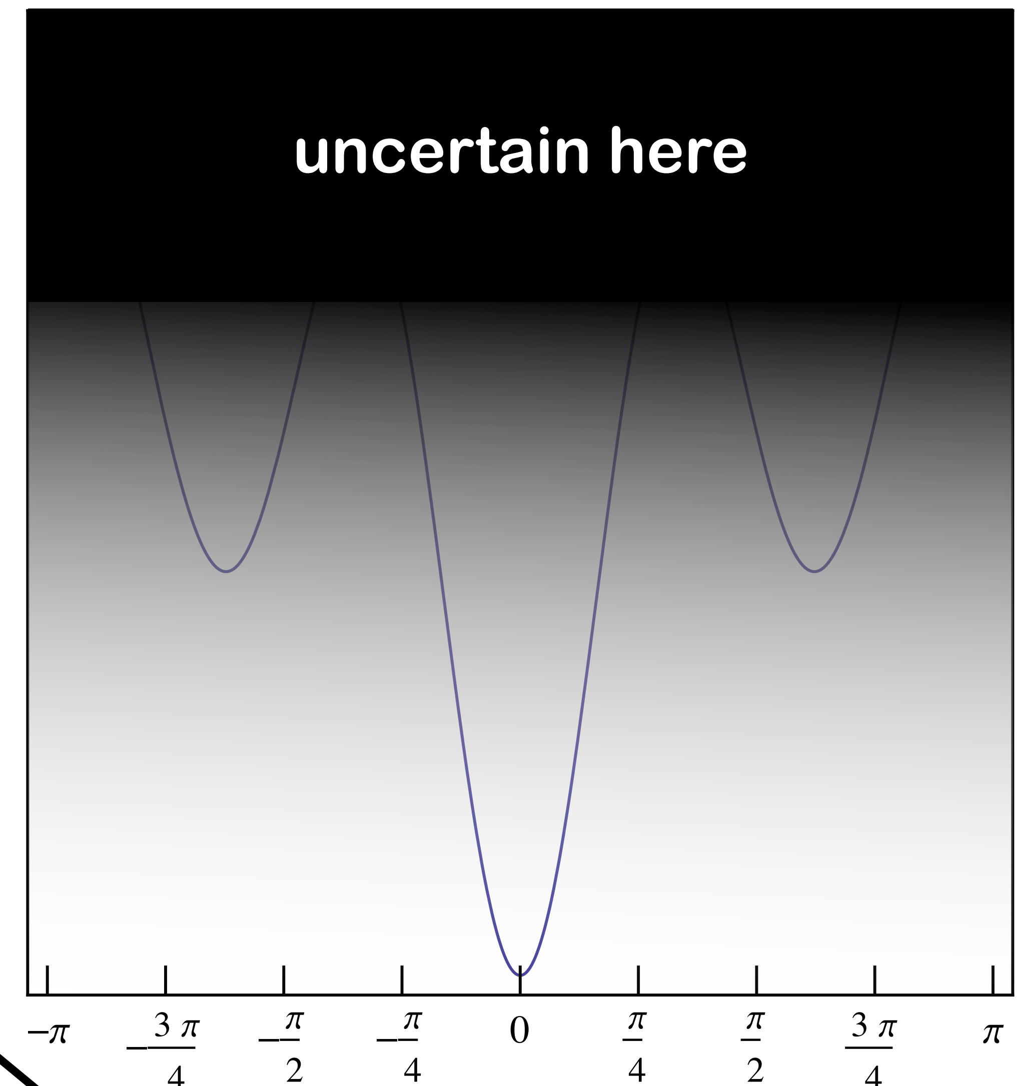
(DANGER!)
This is an illustrative slide, don't take it too seriously

- $U(1)_A$ is <u>spontaneously broken</u> and <u>color anomalous</u>

- $\langle \bar{q} q \rangle \neq 0$
- **Goldstone boson couples to** $G\widetilde{G}$ **!!!**



$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G\widetilde{G} \left(\theta + \frac{\eta_0}{f_\eta} \right)$$



$$\theta_{\rm eff} = \theta + \langle \eta_0 \rangle / f_\eta$$

The minimum of the potential of η_0 **corresponds to** $\theta_{\rm eff} = 0$

The strong CP "hint" II

(DANGER!)
This is an illustrative slide, don't take it too seriously

- U(1)$_A$ … is also explicitly violated by quark masses

$$V(\eta_0) \simeq V_{\rm QCD} + \frac{1}{2} m^2 \eta_0^2 + \dots$$

supersimplified model … one needs including pi0!

Toy calculation

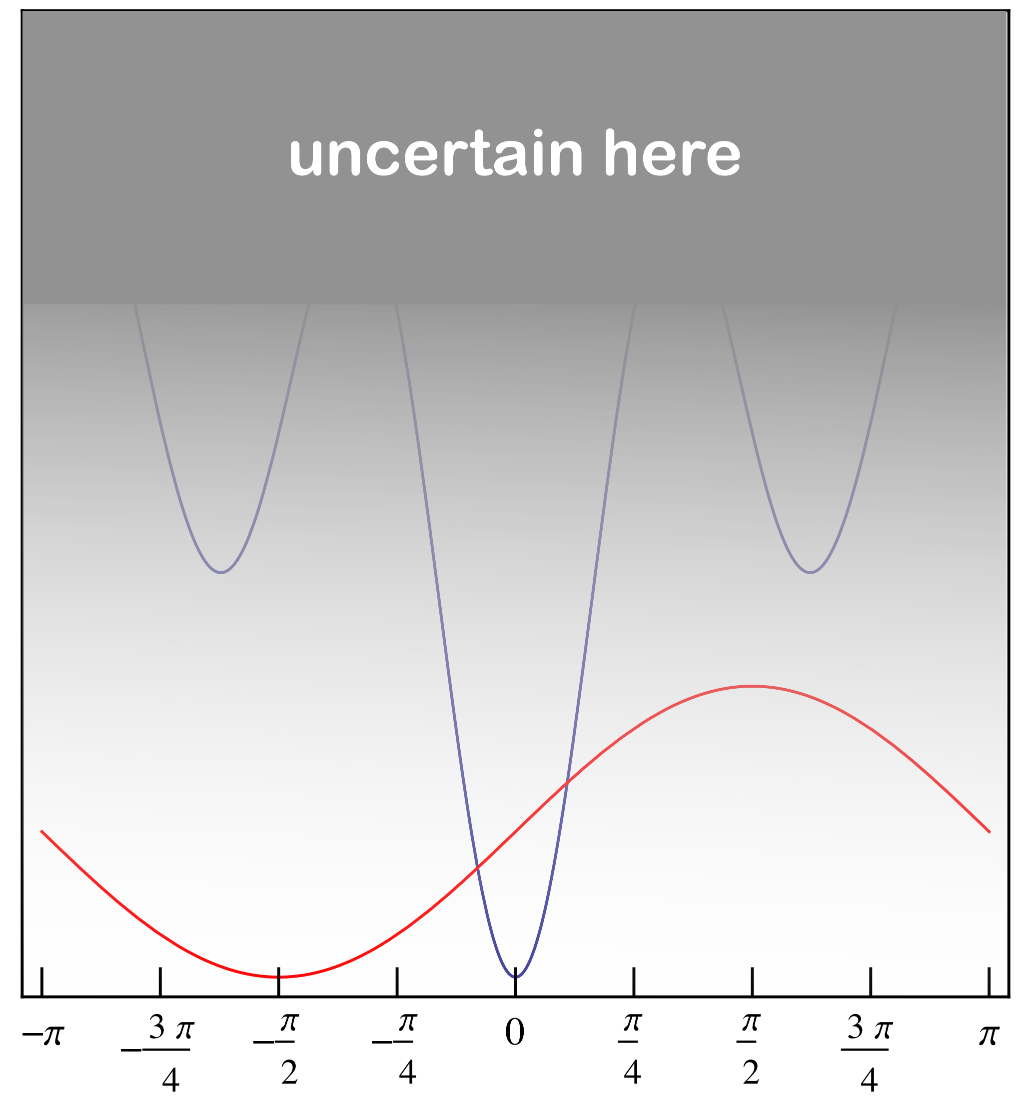
$$V(\eta_0) \simeq \frac{1}{2} M^2_{\rm QCD} (\theta f_\eta + \eta_0)^2 + \frac{1}{2} m^2 \eta_0^2 + \dots$$

$$\Rightarrow \quad \theta_{\rm eff} = \theta \frac{m^2}{m^2 + M^2}$$

$$m \sim \mathcal{O}(m_\pi)$$
$$M \sim m_{\eta'}$$

$$\Rightarrow \quad \theta_{\rm eff} \sim \mathcal{O}(10^{-2})\theta$$

remember other 10^-2 suppression of theta effects?



$$\theta_{\rm eff} = \theta + \langle \eta_0 \rangle / f_\eta$$

Note $m \propto m_q$ (1 massless quark = no CP)

The strong CP “hint” III : AXIONS

Peccei and Quinn 77, Weinberg Wilczek 78

- New spontaneously broken $U(1)_A$ (extra quarks?)

- New Goldstone boson: ϕ
- New SSB energy scale f_a

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G\widetilde{G} \left(\theta + \frac{\eta_0}{f_\eta} + \frac{\phi}{f_a} \right)$$

- NOT explicitly broken!!!!!!!

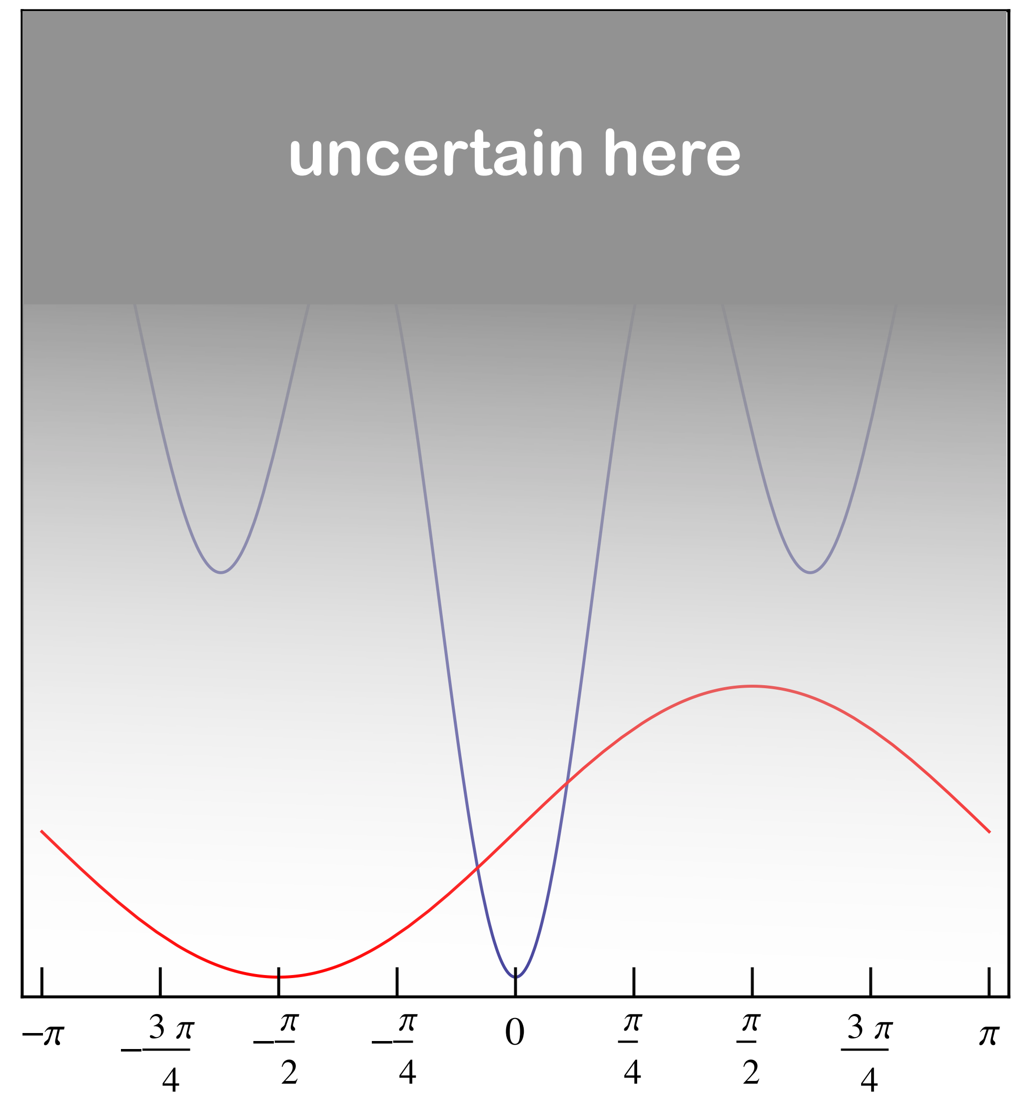
$$V(\eta_0, \phi) = \frac{1}{2} M^2 (\theta f_\eta + \eta + \phi\beta)^2 + \frac{1}{2} m^2 \eta_0^2$$

The minimum of the potential is now P,T conserving

$$\langle \eta' \rangle = 0$$

$$\langle \phi \rangle / f_a = -\theta$$

$$\theta_{\rm eff} = 0!!!!!$$



$$\theta_{\rm eff} = \theta + \langle \eta' \rangle / f_\eta + \langle \phi \rangle / f_a$$

The axion and its mass

- **Including** π^0 and taking for simplicity $f_\pi = f_\eta$ $\quad \beta = \dfrac{f_\pi}{f_a}$

$$V(\eta_0, \pi^0, \phi) = \frac{1}{2}M^2(\theta f_\eta + \eta_0 + \phi\beta)^2 + \frac{1}{2}m_u v^3(\eta_0 + \pi^0)^2 + \frac{1}{2}m_d v^3(\eta_0 - \pi^0)^2$$

$$m_{\eta'} \gg m_{\pi^0} \gg m_a \qquad \eta' \sim \eta_0 + \beta\phi \qquad m_{\eta'} \simeq M$$

$$V(\pi^0, \phi) = \frac{1}{2}m_u v^3(\pi^0 - \beta\phi)^2 + \frac{1}{2}m_d v^3(\pi^0 + \beta\phi)^2$$

$$m_\pi^2 \simeq (m_u + m_d)v^3$$

$$m_a^2 \simeq \frac{m_u m_d}{m_u + m_d} v^3 \beta^2 = \frac{m_u m_d}{(m_d + m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a} \simeq \left(0.006\text{meV}\frac{10^9\text{GeV}}{f_a}\right)^2$$

$$a \simeq \phi - \beta\left(\eta_0 - \frac{m_d - m_u}{m_u + m_d}\pi_0\right)$$

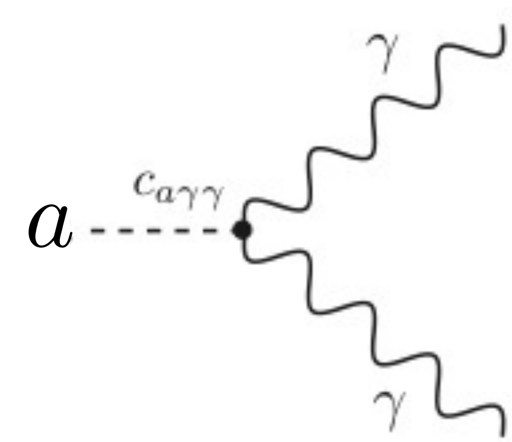
Axion couplings

- Simplest model, from mixing with mesons derived as before

$$\mathcal{L}_{a,I} = \sum_N c_{N,a} \bar{N} \gamma^\mu \gamma_5 N \frac{a}{f_a} + c_{a\gamma} \frac{\alpha}{2\pi} F_{\mu\nu} \widetilde{F}^{\mu\nu} \frac{a}{f_a} + ...$$

nucleons ... **photons ...** **mesons ...**

$c_{\gamma a} = -1.92$



- more involved models have model-dependent contributions

A simple axion model (KSVZ)

Kim 78, Shifman-Vainstein-Zakharov 80

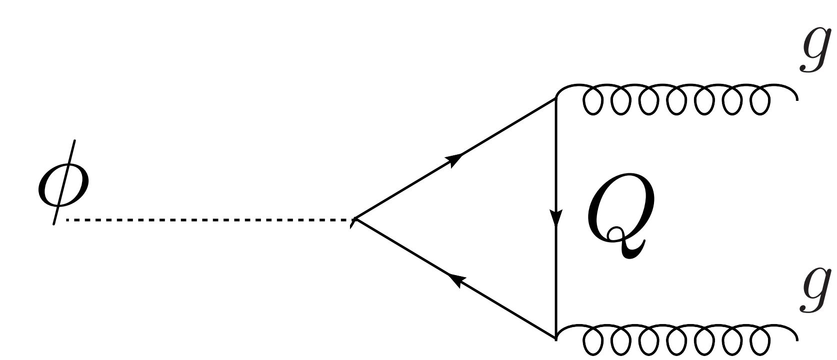
New vector quark (EW singlet) + charged scalar

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{Q} \not{D} Q - (y \bar{Q}_L Q_R \Phi + {\rm h.c}) - \lambda |\Phi|^4 + \mu^2 |\Phi|^2$$

U(1)$_A$ symmetry $\quad Q \to e^{i\gamma_5 \alpha} Q, \quad \Phi \to e^{-2i\alpha} \Phi$

(color anomalous again)

SSB $\quad \Phi(x) = e^{i\phi(x)} \rho(x) \to e^{i\phi(x)} \langle \rho \rangle$

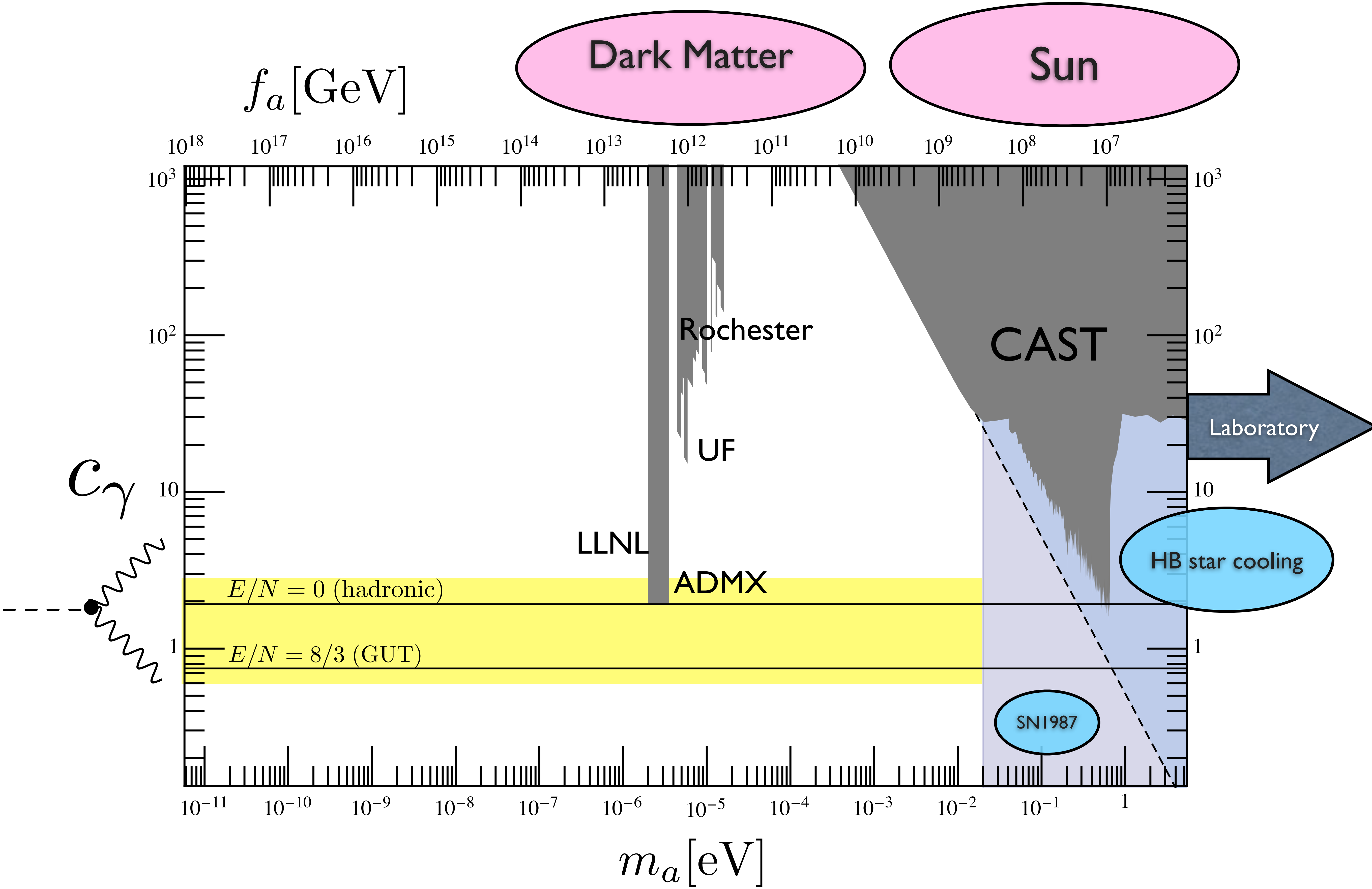


Low energy lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2} (\partial_\mu \phi)^2 - \frac{\alpha_s}{8\pi} G \widetilde{G} \frac{\phi}{f_a}$$

$$f_a = \langle \rho \rangle$$

Parameter space

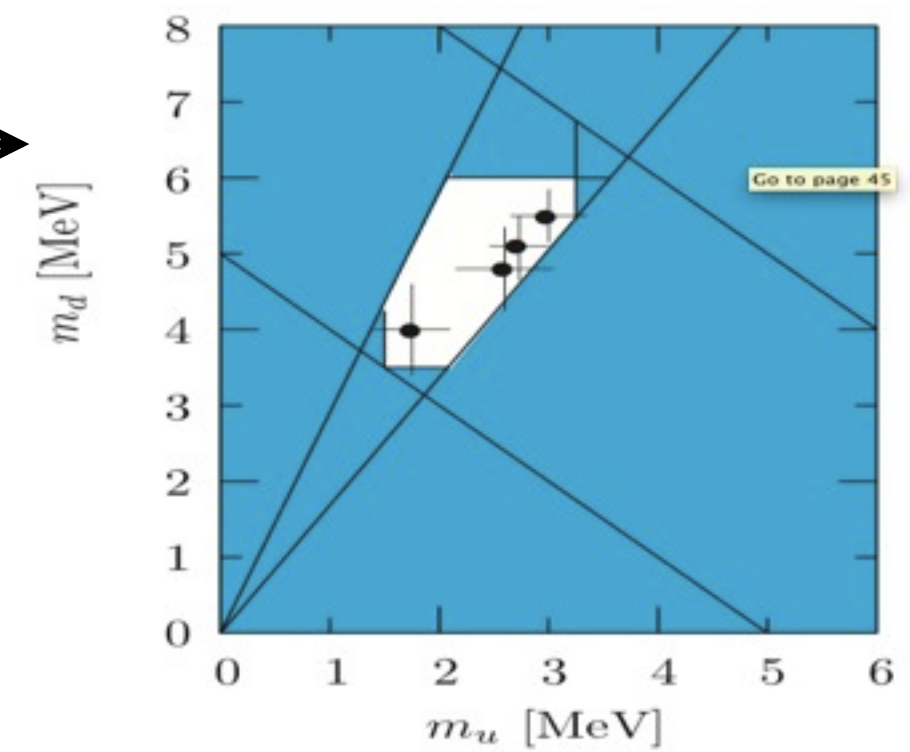


Partial summary

- Lack of CP violation in QCD...

  - one quark could be massless (ruled out) →
  - Theta = 0 from some BSM (loop effects)
  - there is an axion (make θ dynamical)

From Kim and Carosi 2009



- axions, simple to obtain BSM
  - Goldstone bosons, compatible with GUT, SUSY
  - stringy axions

- axions, predictable properties

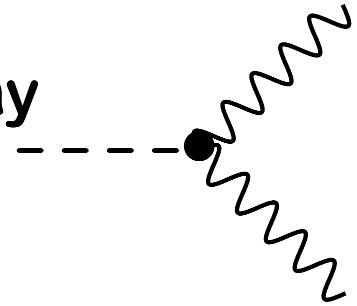
  (like pi0's but lighter and more weakly interacting)

- can be searched for: dark matter and solar axion exps

- imply physics at energy scales $f_a \gtrsim 10^9 \mathrm{GeV}$

Axion cold dark matter

- Axions decay



$$\tau \sim \frac{1}{g_{a\gamma}^2 m_a^3} \propto \frac{1}{m_a^5}$$

only low mass axions can be DM!

- THERMAL PRODUCTION $p_{\rm today} \sim T_{\rm today} \sim {\rm meV}$

~~$m_a \sim$ eV ???~~

- NON-THERMAL → $p \sim H \lll T$

$$\Phi(x) = \rho(x) e^{i\frac{a(x)}{f_a}}$$

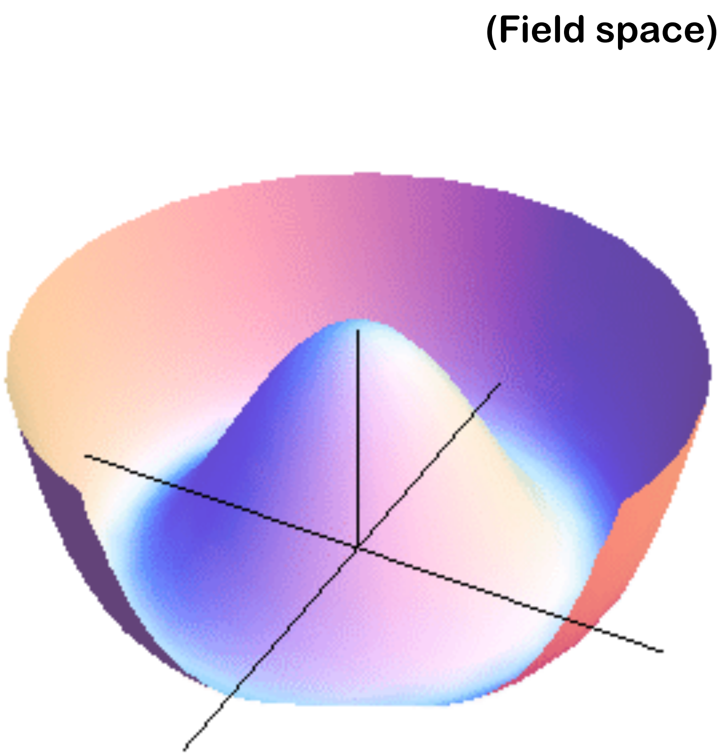
  - initial conditions
  - decay of cosmic strings, domain walls

$$\frac{a(t_0)}{f_a} \in (-\pi, \pi)$$

At PQ phase transition

Axion cold dark matter I

Realignment mechanism



$$\Phi(x) = \rho(x) e^{i\frac{a(x)}{f_a}}$$

$$\frac{\Omega_{a,VR}}{\Omega_{\text{obs}}} \sim \left(\frac{40\mu\text{eV}}{m_a}\right)^{1.184}$$

Axion cold dark matter I

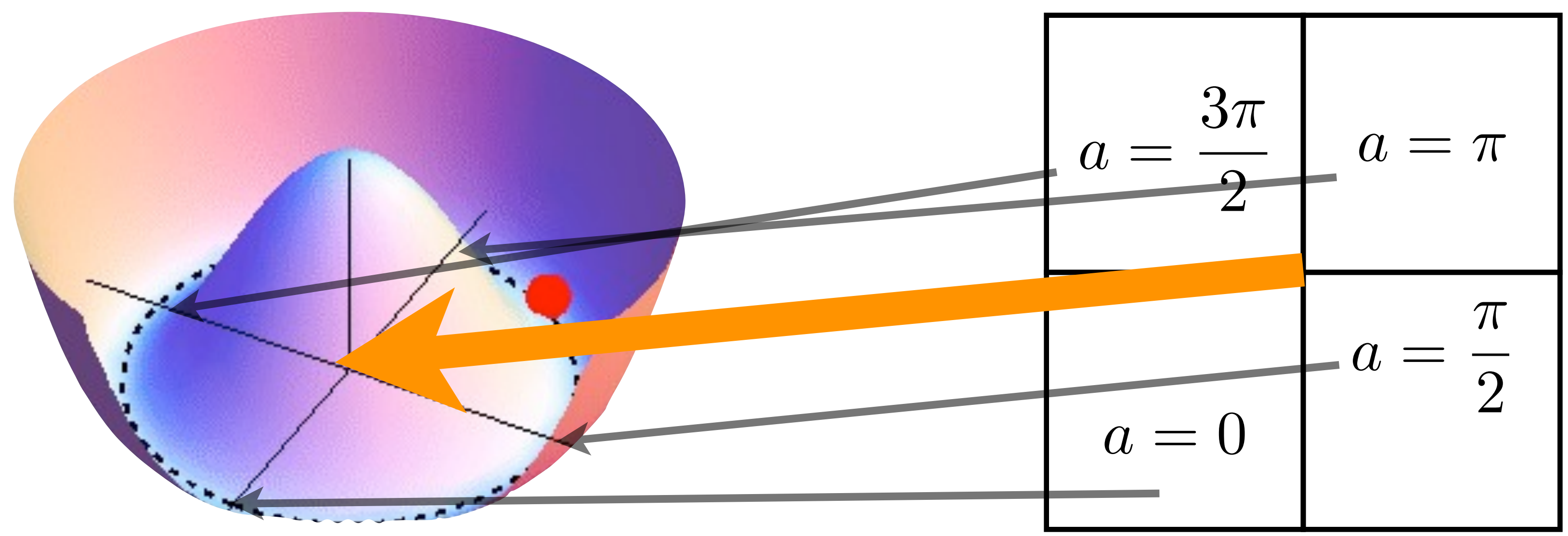
Realignment mechanism

Cosmic Strings

(Field space)

(Position space)

(T>QCD)



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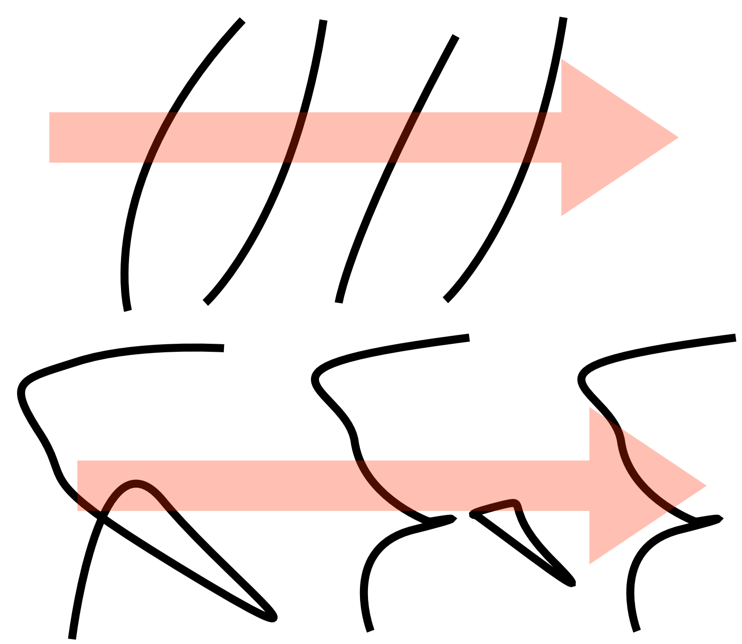


Axion cold dark matter I

Realignment mechanism

Cosmic Strings

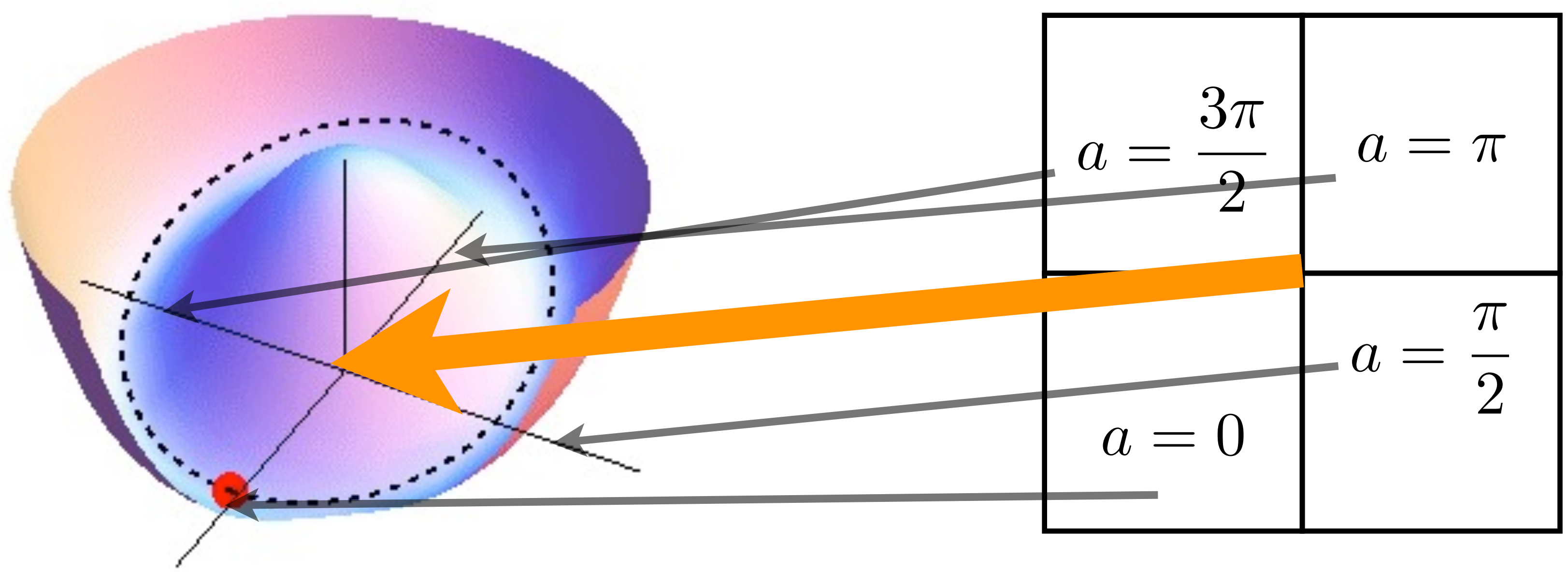
Domain Walls

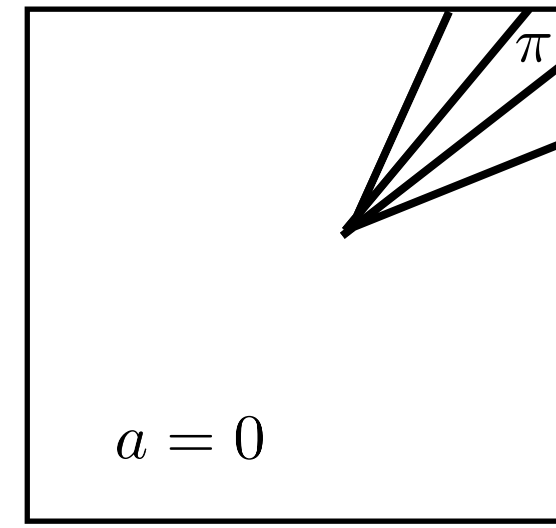
(Field space)

(Position space)

(T>QCD)

(T<QCD)





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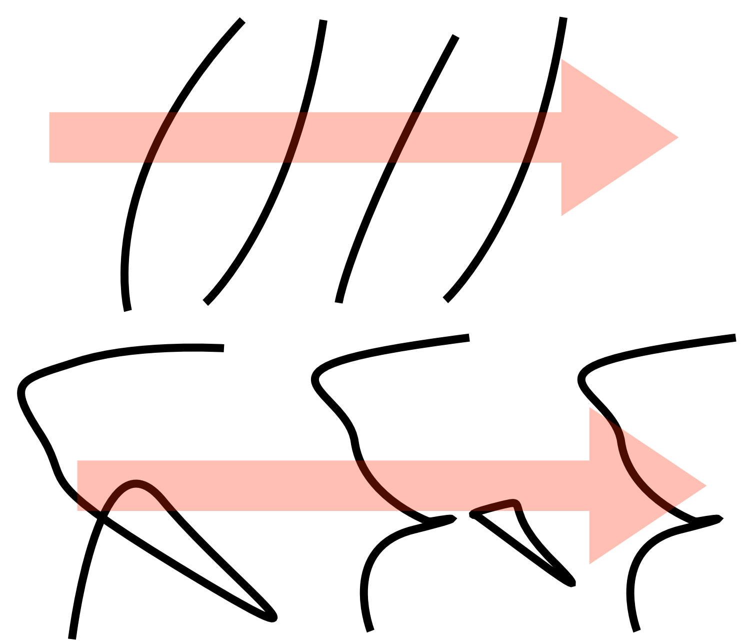
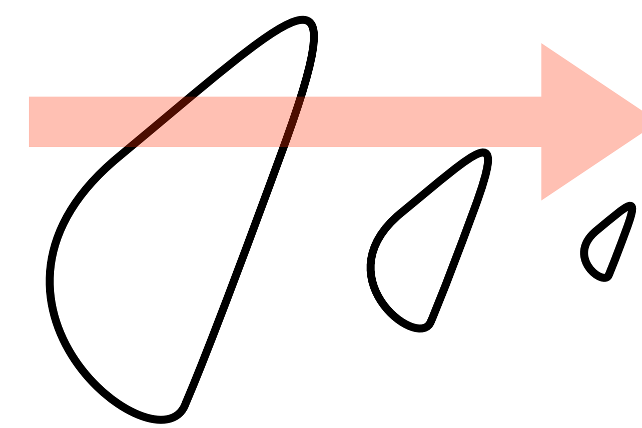


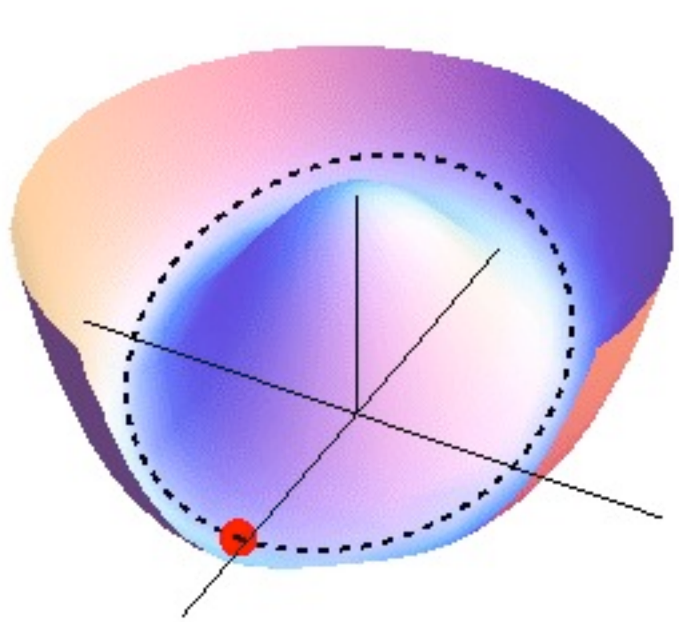


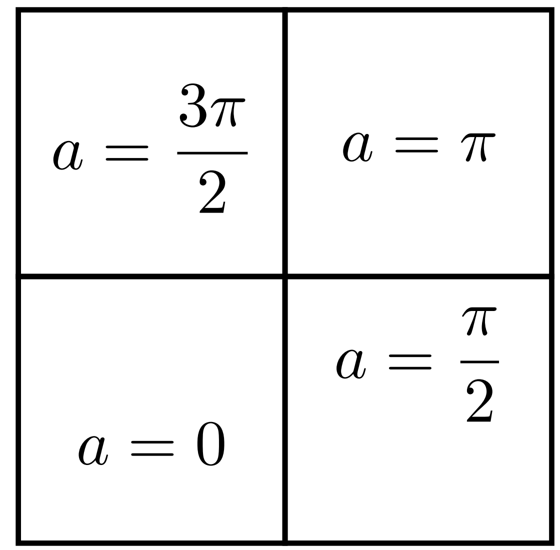
Axion cold dark matter I

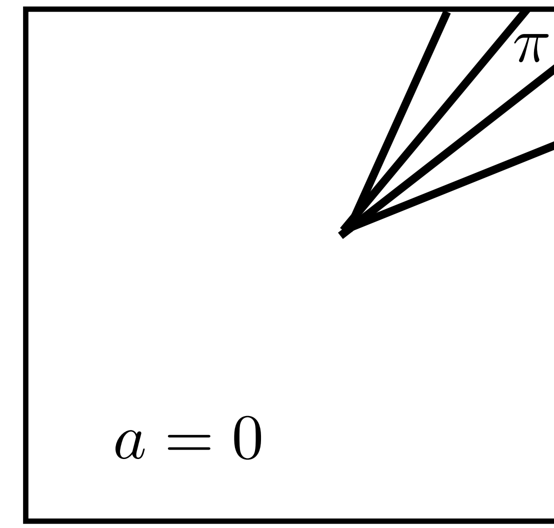
Realignment mechanism	Cosmic Strings	Domain Walls

(Field space) (Position space)

(T>QCD) (T<QCD)







$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu{\rm eV}}{m_a}\right)^{1.184}$$

$$\frac{\Omega_{a,DW+ST}}{\Omega_{\rm obs}} \begin{cases} \sim \left(\frac{40\mu{\rm eV}}{m_a}\right)^{1.184} \\ \sim \left(\frac{400\mu{\rm eV}}{m_a}\right)^{1.184} \end{cases}$$

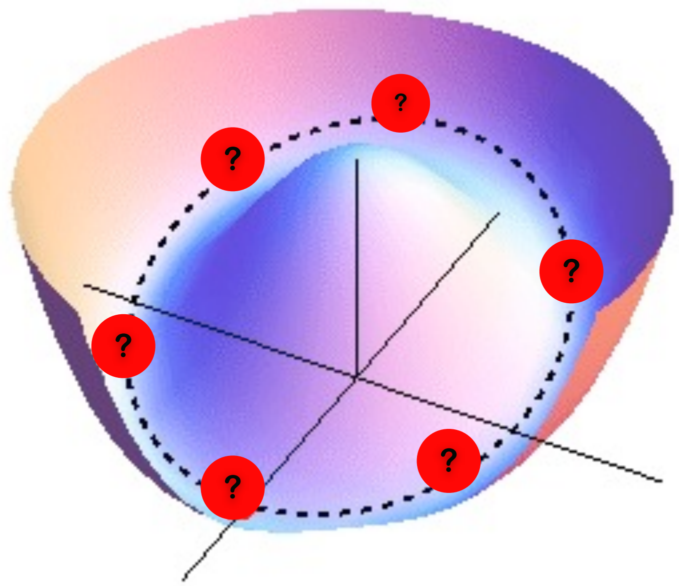
Sikivie, Harari et at.

Shellard, Davis et at.
Kawasaki, Hiramatsu et at

Axion cold dark matter II (PQ before inflation)

Realignment mechanism

(Field space)



$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{a_0}{f_a}\right)^2 \left(\frac{10\mu{\rm eV}}{m_a}\right)^{1.184}$$

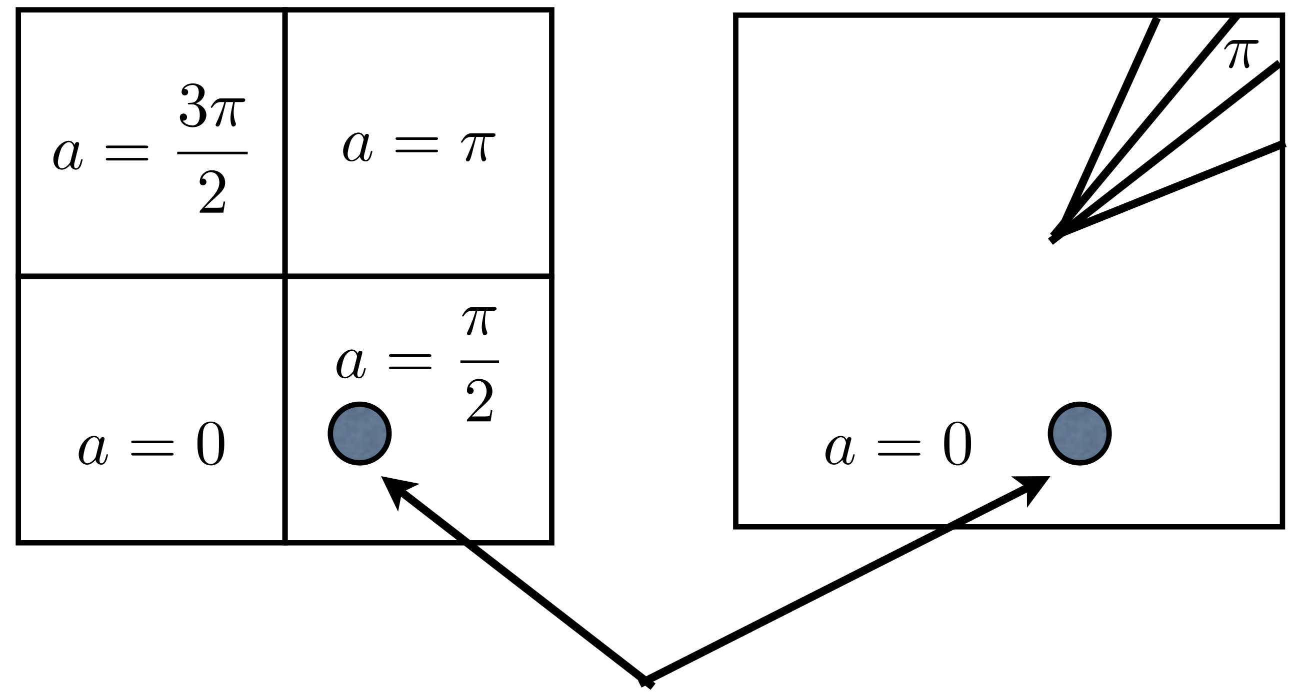
Cosmic Strings

Domain Walls

(Position space)

(T>QCD)

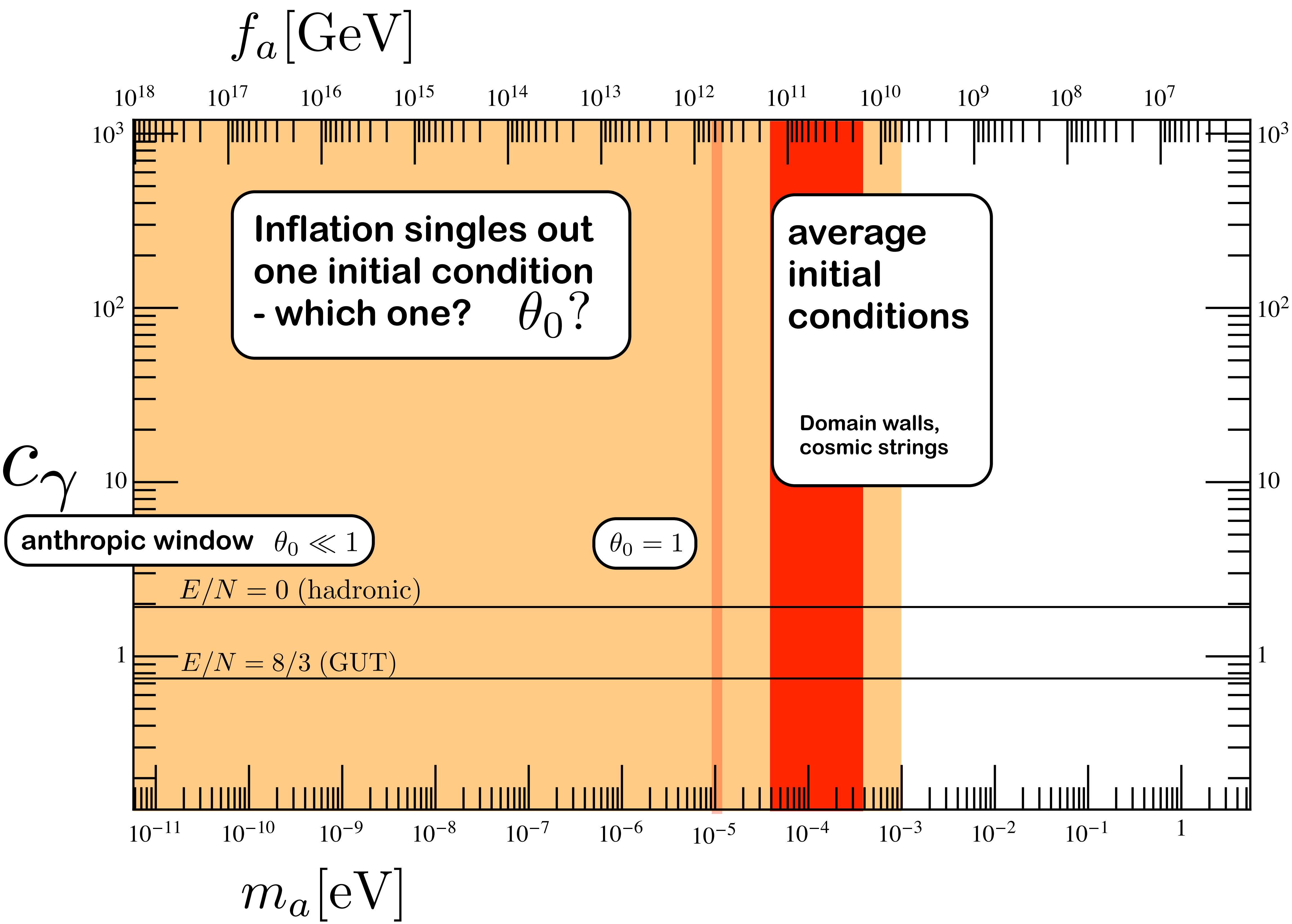
(T<QCD)



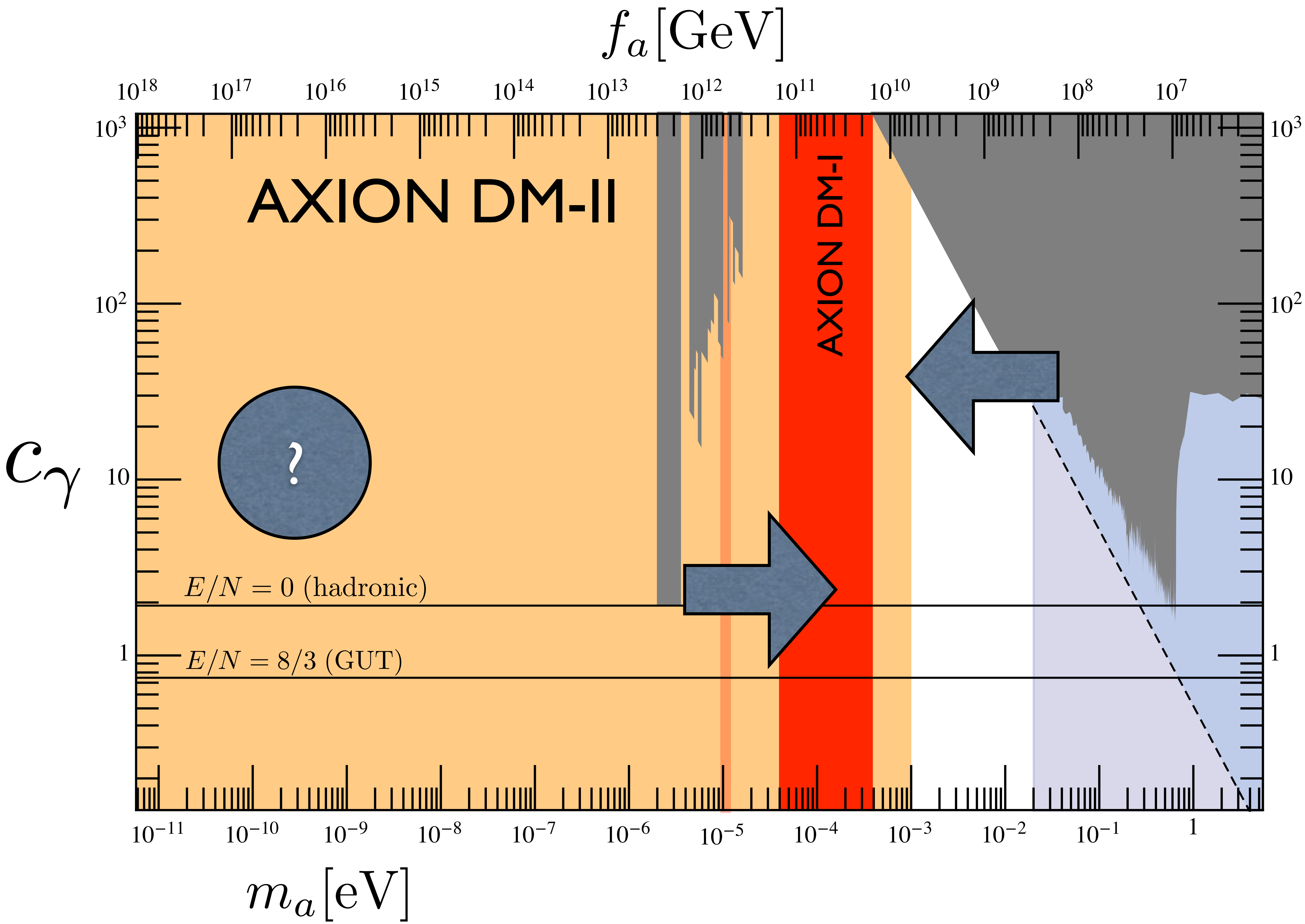
Size of our universe after inflation fits inside one of these domains

- **CSs and DWs are diluted by expansion**
- **Whole universe has 1 initial value for a**

All the observed DM in Axions? where?



First conclusions and roadmap



Axion - photon mixing in a magnetic field

Raffelt, PRD'88

- In a magnetic field one photon polarization Q-mixes with the axion

$$\mathcal{L}_I = \frac{g_{a\gamma}}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} a = -g_{a\gamma} \mathbf{B} \cdot \mathbf{E}\, a$$

Not axions, nor photons are propagation eigenstates!

- Equations of motion can be easily diagonalised

$$\left[(\omega^2 - k^2) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & -g_{a\gamma}|\mathbf{B}|\omega \\ -g_{a\gamma}|\mathbf{B}|\omega & m_a^2 \end{pmatrix} \right] \begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} .$$

- Dark matter solution $\quad v = \dfrac{k}{\omega} \quad ; \quad \omega \simeq m_a (1 + v^2/2 + ...)$

$$\left. \begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix} \right|_{\rm DM} \propto \begin{pmatrix} -\chi \\ 1 \end{pmatrix} \exp(-i(\omega t - kz)).$$

It has a small E field!

$$\chi \sim \frac{g_{a\gamma}|\mathbf{B}|}{m_a}$$

Dark Matter cavity experiments

- In a magnetic field B, DM axions trigger electric fields of order

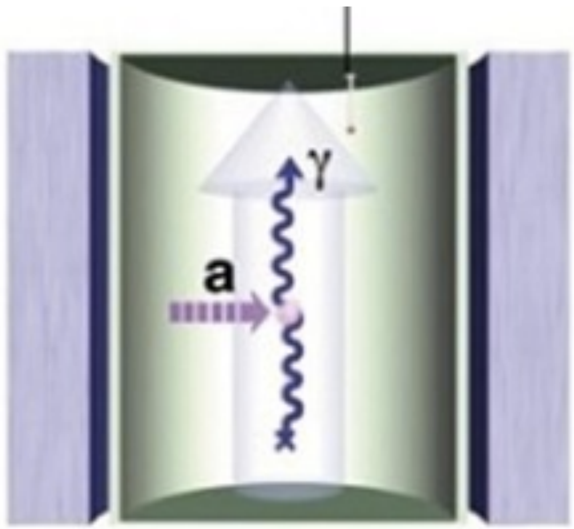
$$|\mathbf{E}| \sim \frac{10^{-12}\mathrm{V}}{\mathrm{m}} \frac{\mathrm{B}}{5\mathrm{Tesla}} \times \frac{c_\gamma}{2}$$

$$P \sim 10^{-26} \left(\frac{\mathrm{B}}{5\mathrm{T}} \frac{c_\gamma}{2}\right)^2 \frac{\mathrm{A}}{1\mathrm{m}^2} \mathrm{Watt}$$

with frequency $\omega \simeq m_a$

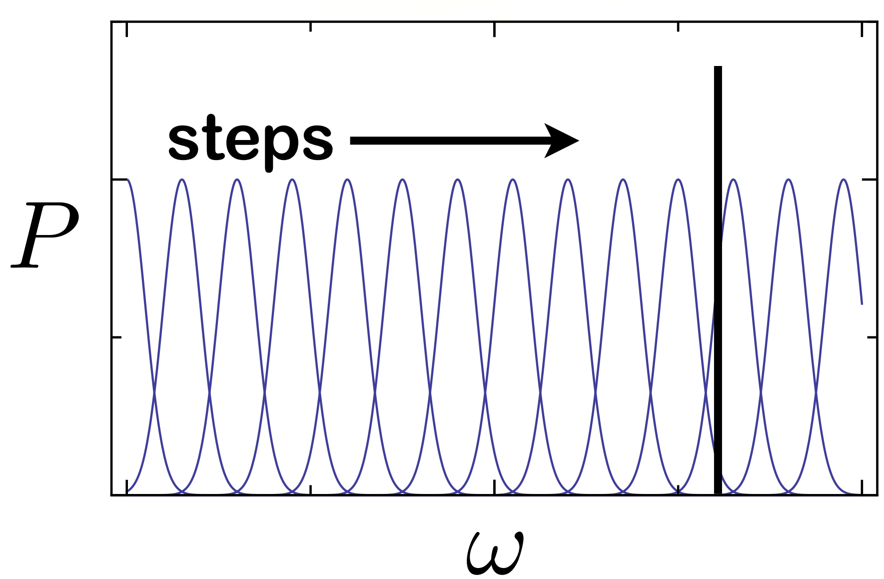
and bandwidth $\delta\omega \sim 10^{-6} m_a$

- Haloscope technique (Sikivie 1982)



-RESONANT CAVITY
(boost by the quality factor Q of the cavity, up to $Q \sim 10^6$)

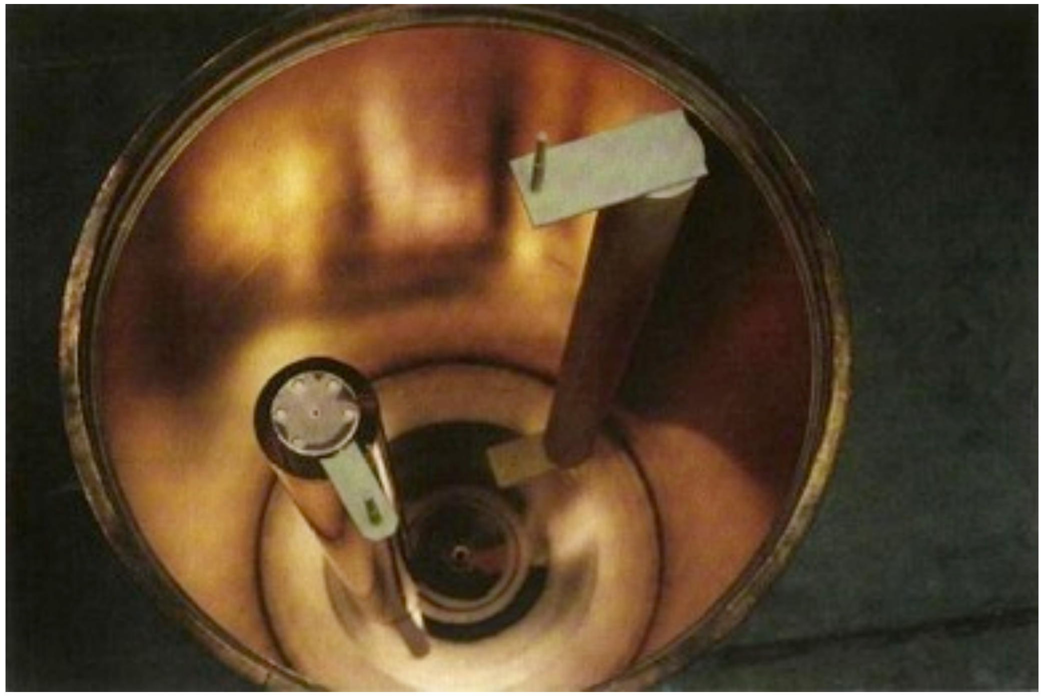
-ULTRALOW NOISE MW DETECTORS
(signal close to quantum limit)



- PROBLEM: boost only in a small $\delta\omega$ around resonant frequency
- Need to scan over resonant frequencies in small steps
- NEED MANY EXPERIMENTS (mass ranges)

Today's cavity experiments

ADMX @ Seattle

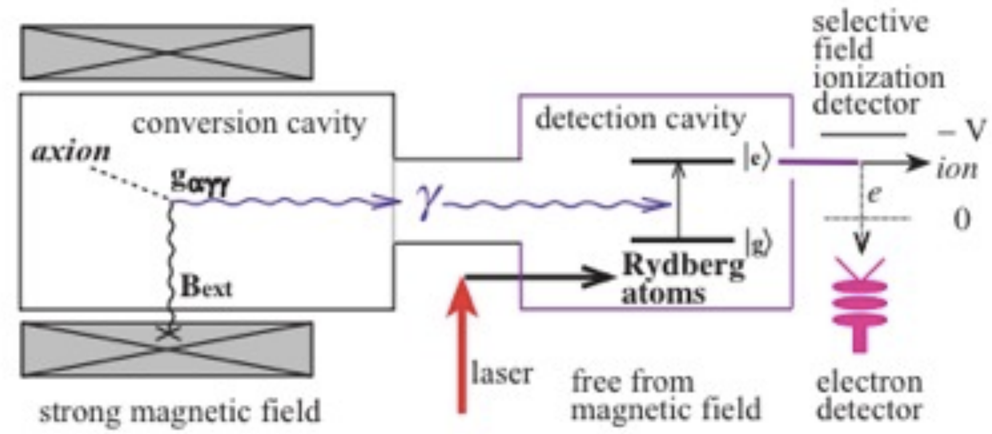


- 8T field, 1m L, 0.5 m D
- Tuning range 2-4 micro eV
- TM020 up to 9 microeV

- SQUID detector - TS - 0.4 K

- Data already taken at T =2 K
- Dilution refrigerator to mK 2014
- Data taking run 2015

CARRACK @ Kyoto



- 8T field, 0.73 m L, 0.09 m D
- 2.55 GHz + 15% (10 microeV)

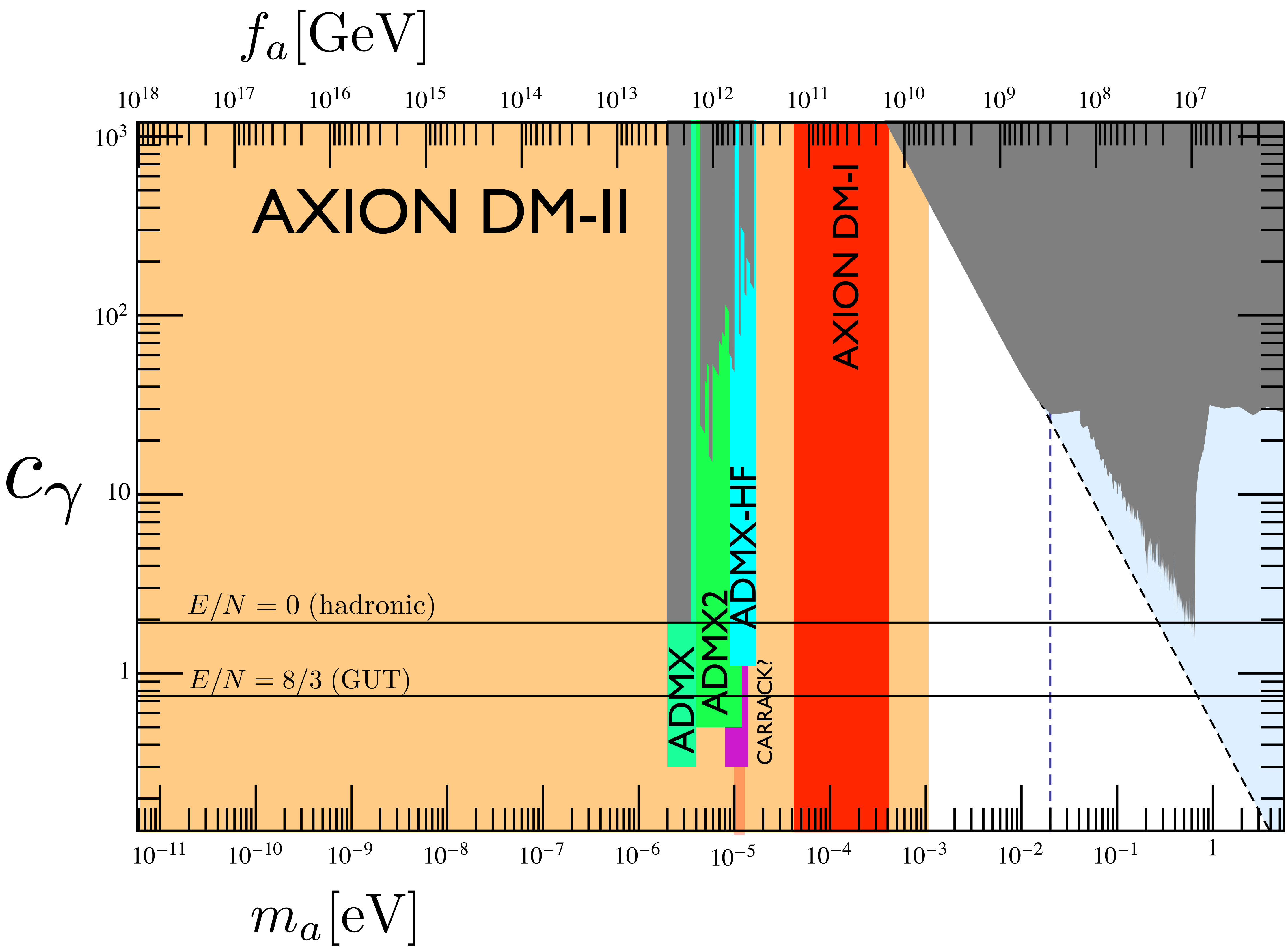
- Rydberg atoms (down to 10 mK?)
- No known plans!

ADMX-HF at Yale NEW!

- Towards HIGH FREQUENCY
- Hybrid cavities to improve Q
- Josephson amplifiers

Prospects

- New experiments are insufficient to cover parameter space



Limitations and Ideas

- At high masses:
  1 - cavities are small $P \propto A$
  2 - Q's decrease (conductivity of copper, ASD)
  3 - Quantum noise limit increases $T_{\rm QL} = \omega$

- Ideas:
  1 - Long cavities (mode overlapping!)
  1 - Dish antenna (forget about Q, make A huge)
  2 - hybrid cavities (superconducting parts)
  3 - Photon counting (short noise lim) CARRACK

- Groups at Yale, LLNL, DESY, CERN, interested on these possibilities

- At low masses: (signal is stronger)
  1 - cavities and B-field regions become huge

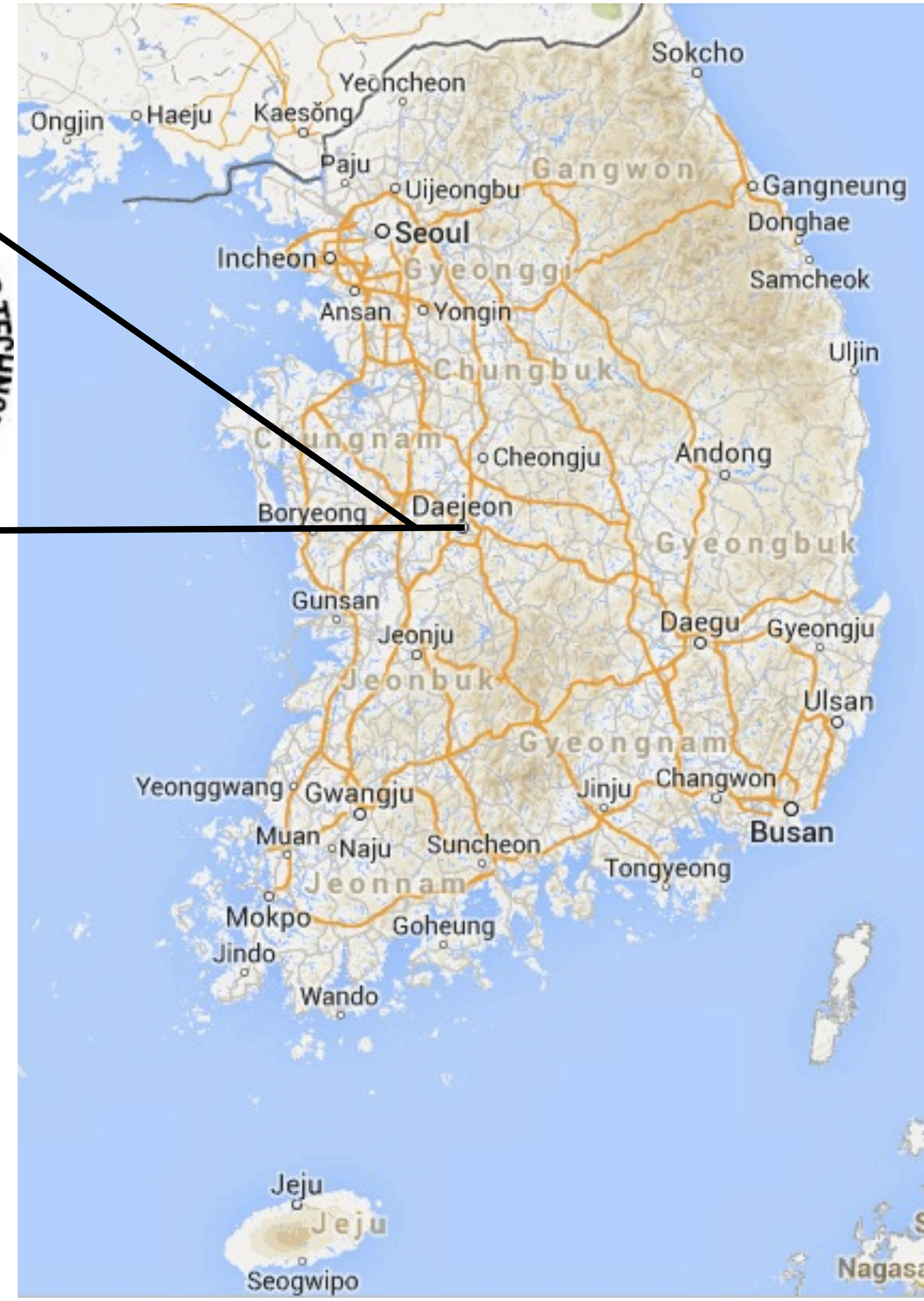
- Group at DESY and MPRA Bonn working on 1 microeV cavities. (WISPDMX)

Mode	ν [MHz]	Q_0	Mode	ν [MHz]	Q_0
TM_{010}	199	53360	TM_{014}	579	122500
TM_{011}	295	44830	TM_{015}	707	60950
TM_{012}	433	47450	TM_{016}	765	105070
TM_{013}	524	47710	TM_{017}	832	102230

and some news ...

- New AXION INSTITUTE being created in Korea (KAIST Campus)
- CAPP (Center for Axion and Precision Physics)
- Innitiative of Y. Semerzidis (now director)

KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
KAIST
한국과학기술원
SINCE 1971



- 10 years + renewable ad inf

- Target:

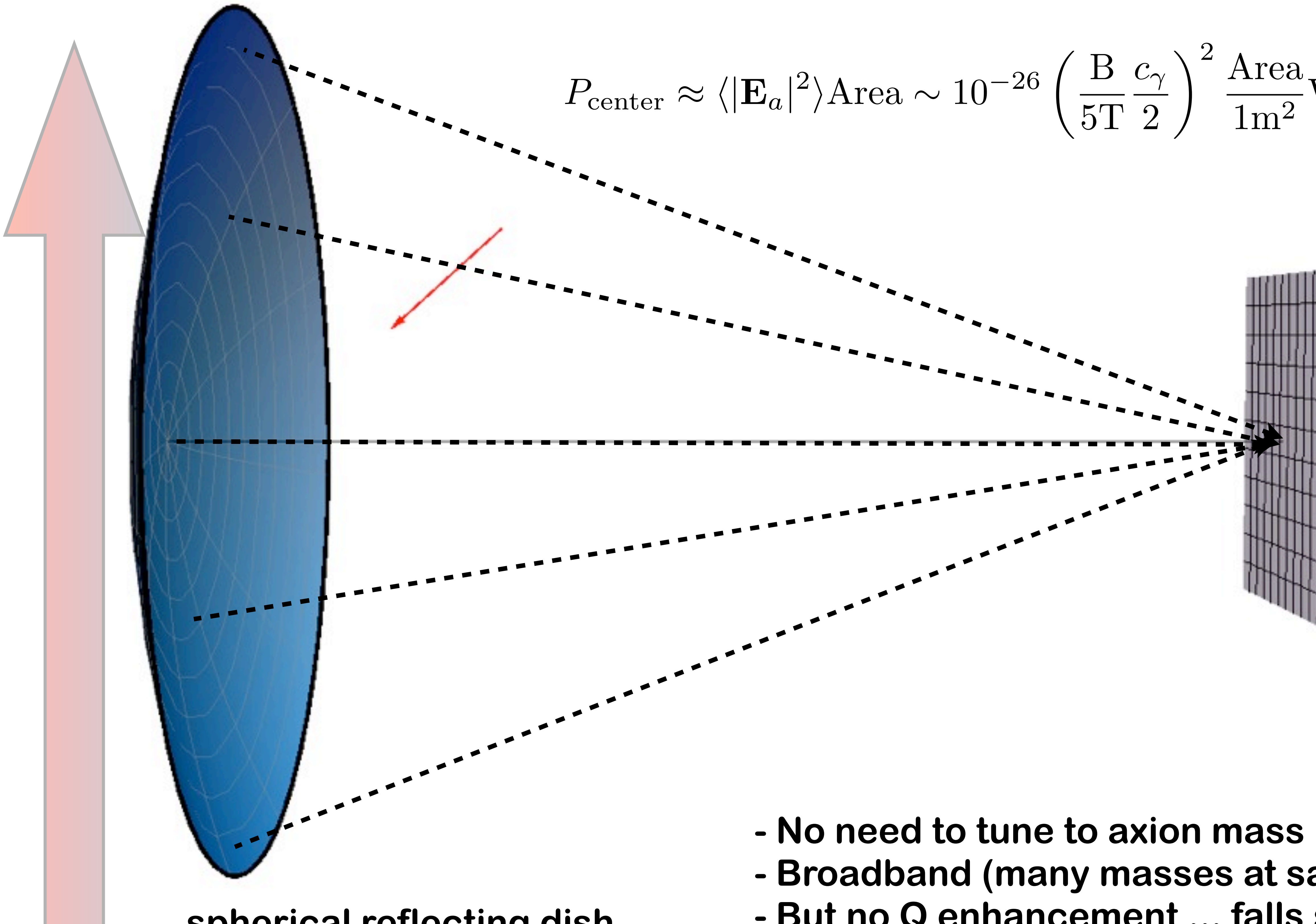
… *to establish a competitive axion dark matter experiment in Korea and be involved in state of the art axion dark matter experiments around the world.*
The institute will be involved in the muon g-2 experiments at Fermilab and J-PARC and will play a leading role in the proton EDM experiment.

- Y. Semerzidis is our Colloquium speaker (11th March)

Dish antenna

Horns at al JCAP04(2013)016

$$P_{\rm center} \approx \langle |\mathbf{E}_a|^2 \rangle \mathrm{Area} \sim 10^{-26} \left(\frac{\mathrm{B}}{5\mathrm{T}} \frac{c_\gamma}{2} \right)^2 \frac{\mathrm{Area}}{1\mathrm{m}^2} \mathrm{Watt}$$

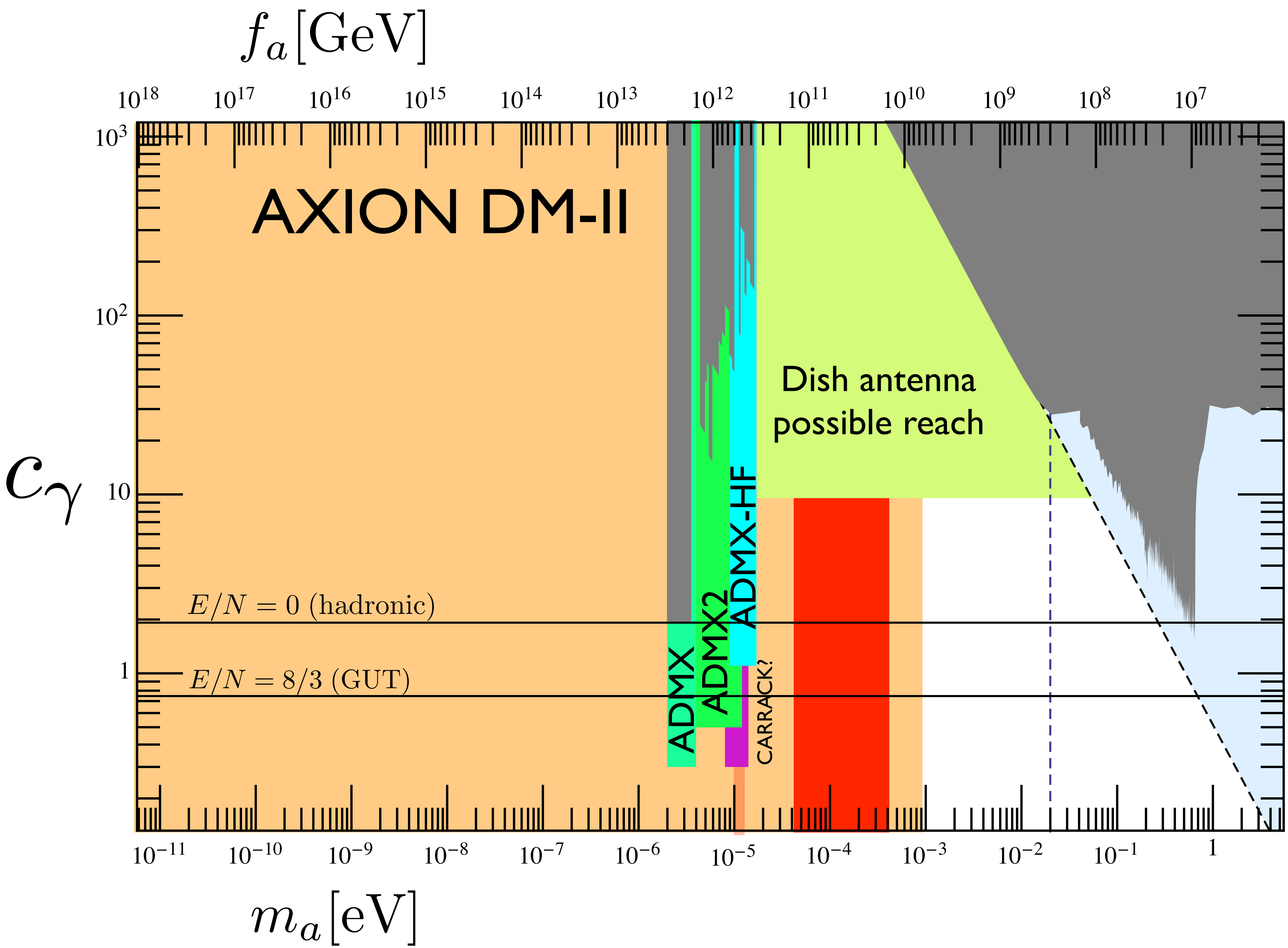


spherical reflecting dish

- No need to tune to axion mass
- Broadband (many masses at same time)
- But no Q enhancement … falls short

Prospects

- Still insufficient to cover all the parameter space



Oscillating EDM

Graham and Rajendran 2010

- **Axion DM implies an oscillating neutron EDM** $\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\mathrm{tr}\left\{G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}\right\}\frac{m_\pi^2}{M^2}\frac{a}{f_a}$

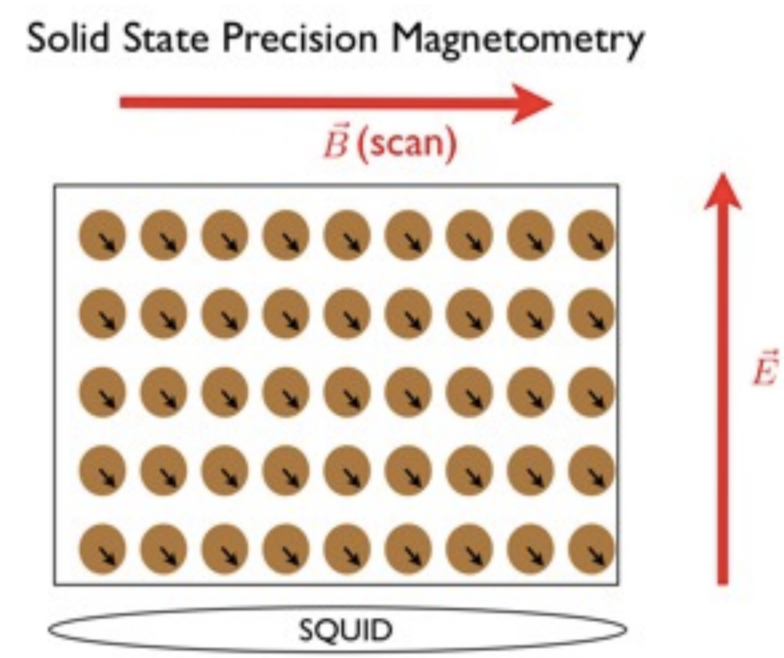
$$\frac{a(t)}{f_a} \sim 10^{-19}\cos(m_a t) \rightarrow d_n \sim 10^{-34}\ \cos(m_a t)\mathrm{ecm}$$

8 orders of magnitude below the (static) experimental constraint but OSCILLATING

- **CASPEr experiment arXiv:1306.6089: Using precise magnetometry to measure tiny deviations from Larmor frequency.**

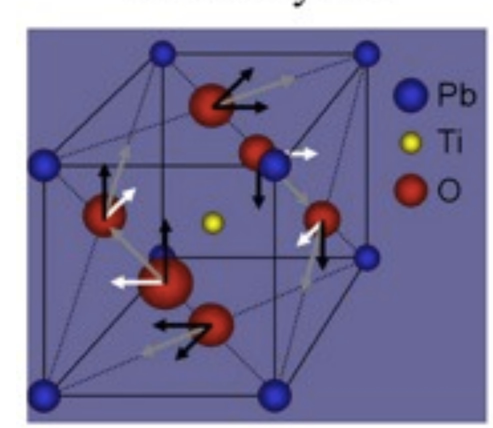
- **High electric fields in special crystals**
- **High Z atoms (E=0 in nucleus, coupling to higher moments)**

- **Dmitry Budker, new W3 at Mainz University and Helmholtz Institute (Feb 2014) will develop these experiments (and others) at Mainz.**



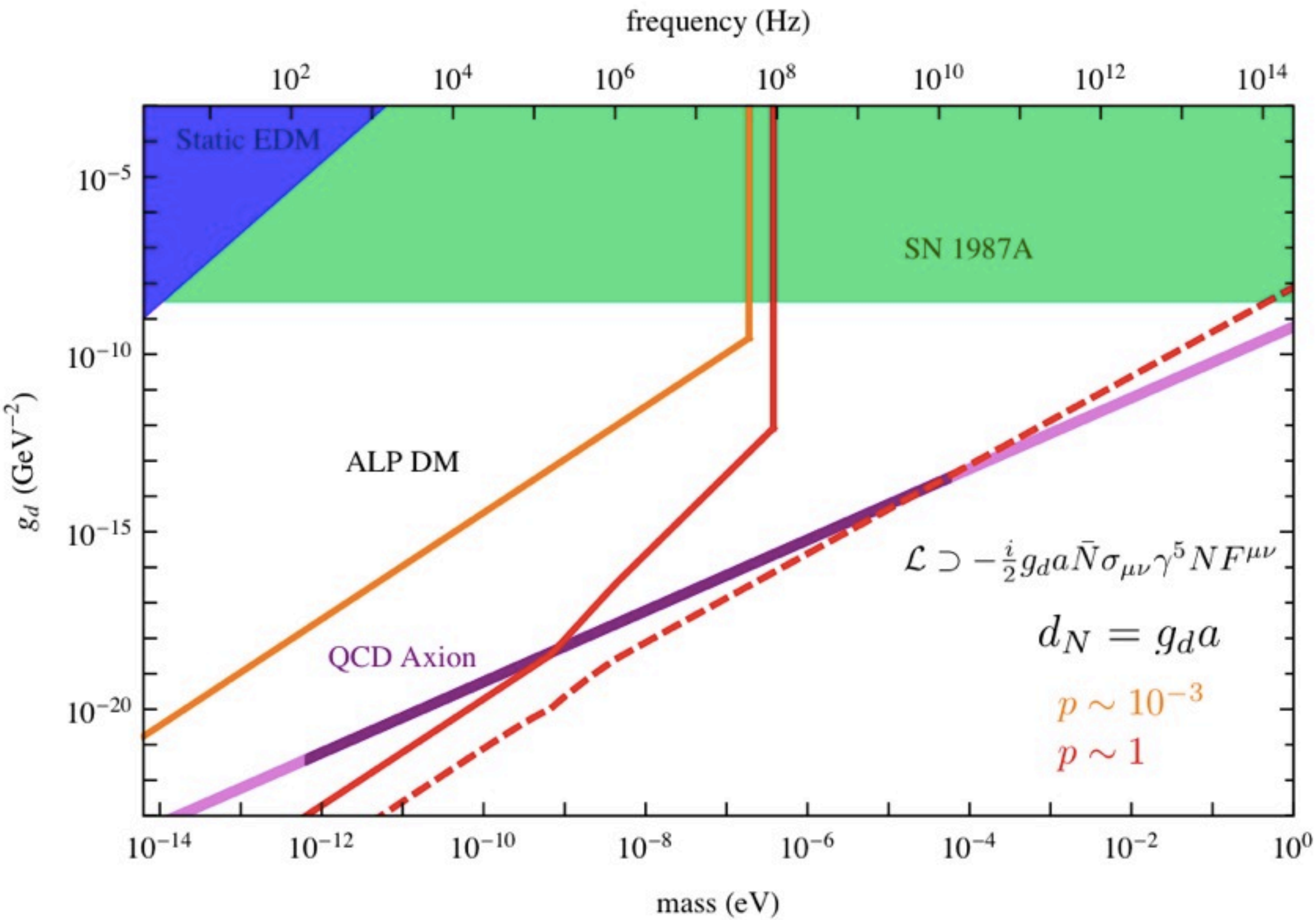
$$\delta B \sim n\mu_N \frac{d_N E}{2\mu_N B - m_a}\sin\left((2\mu_N B - m_a)t\right)\sin\left(2\mu_N B t\right)$$

Polar Crystal



Lead Titanate

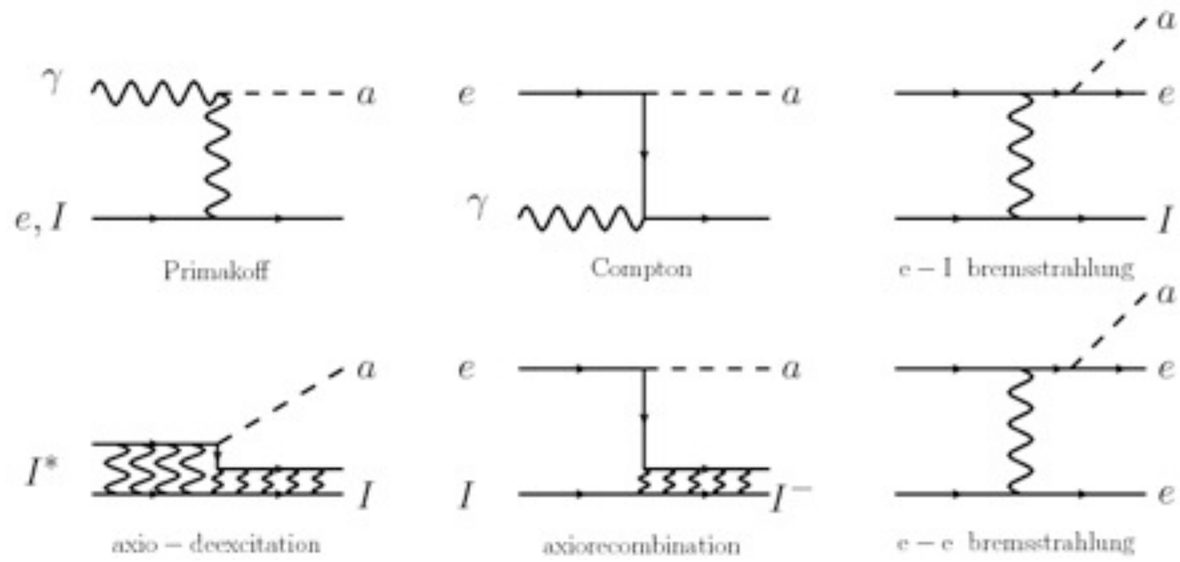
Projected Sensitivity in Lead Titanate

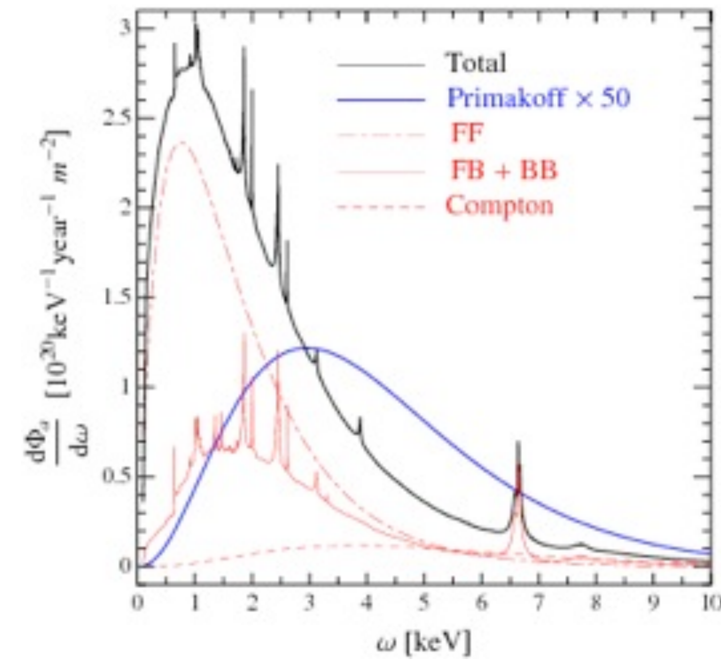


$$\delta B = 0.1 \frac{\text{fT}}{\sqrt{\text{Hz}}},\ n = \frac{10^{22}}{\text{cm}^3},\ V = 1000\ \text{cm}^3,\ T_2 = 1\ \text{s}$$

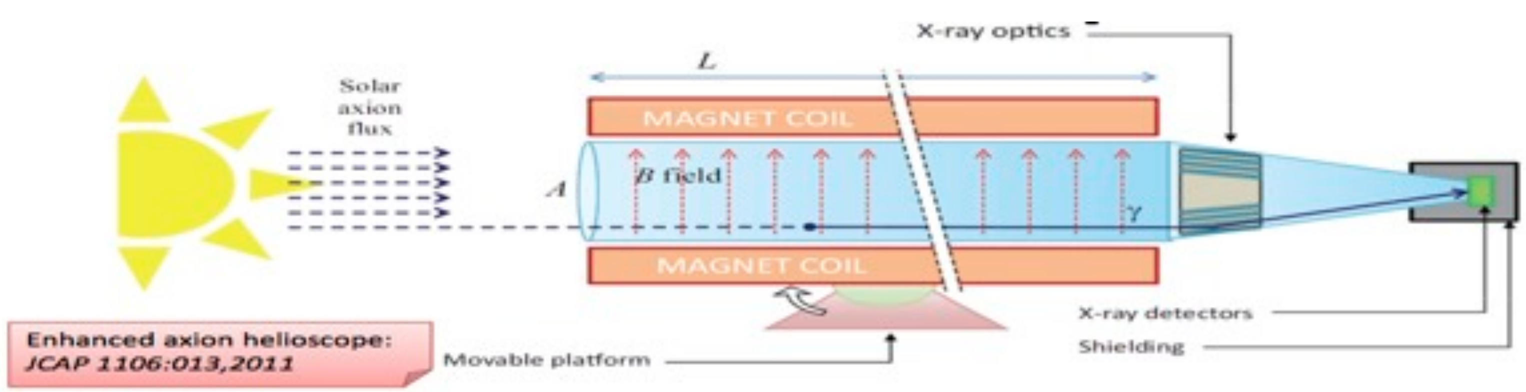
Solar axions

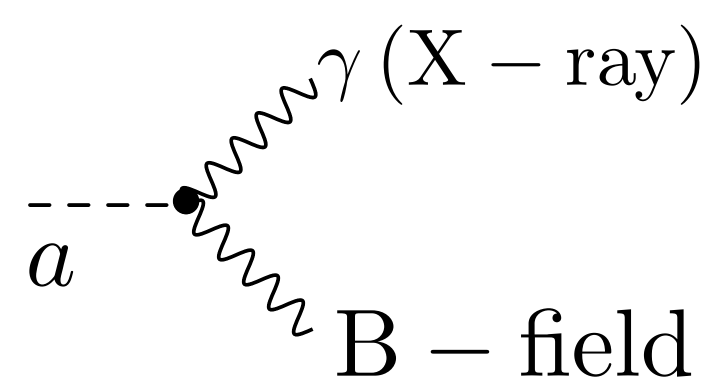
- solar axion flux well understood





- Helioscope technique (Sikivie 1982)

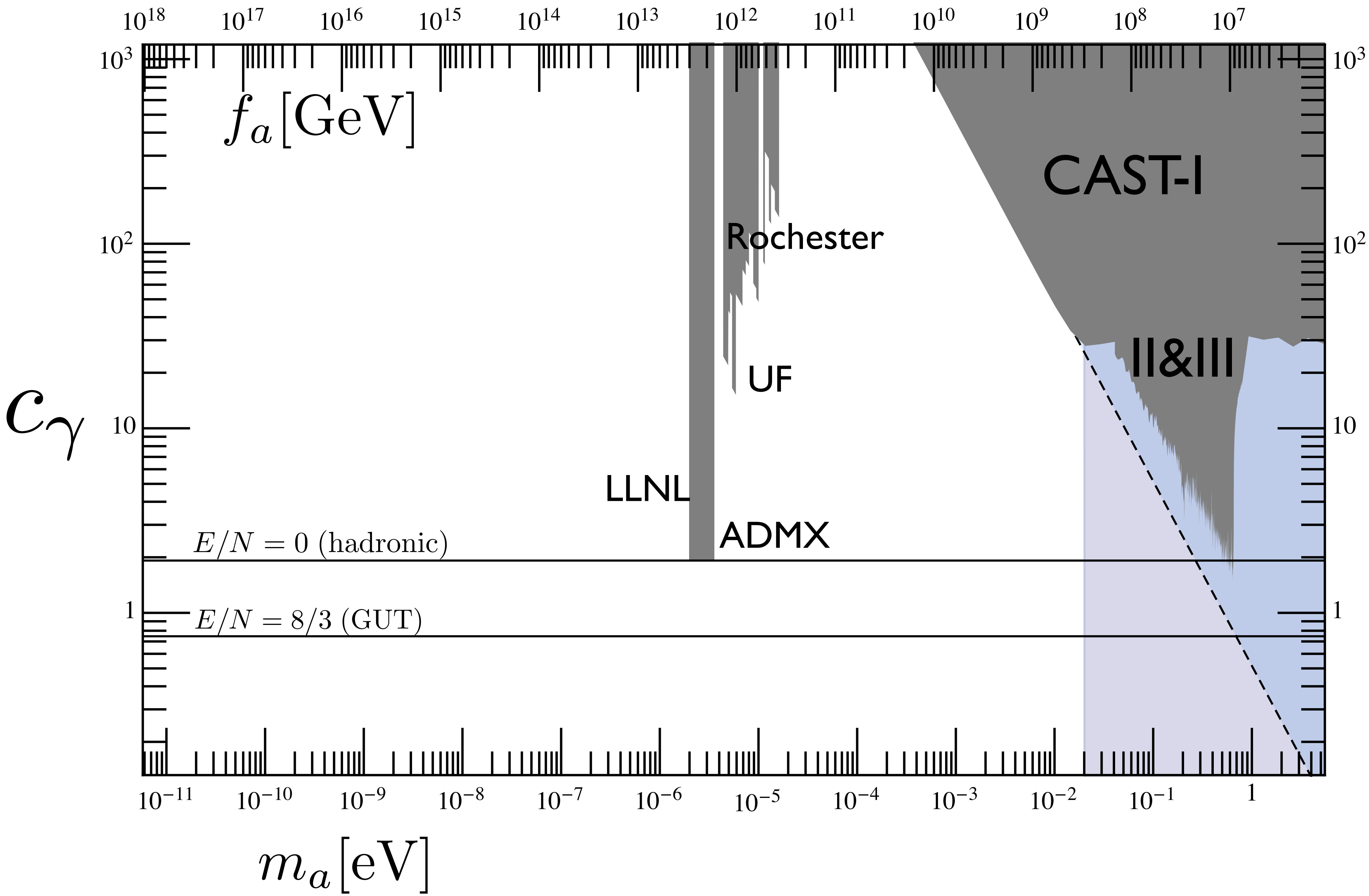




- Most sensitive helioscope CAST@CERN
- LHC decommisioned dipole (L=10 m, B=9 T)
- CCD and Micromegas detectors
- 3 h/day Sun tracking
- X-ray optics

CAST reach

$$N_\gamma \propto (c_\gamma m_a)^4 \times B^2 \times \text{Area} \times \frac{\sin^2(qL)}{(qL)^2} \qquad q = \frac{m_a^2 - m_\gamma^2}{4\omega}$$



How much better than CAST can be done?

Towards a next generation axion heliocope (Irastorza et al. JCAP06(2011)013)

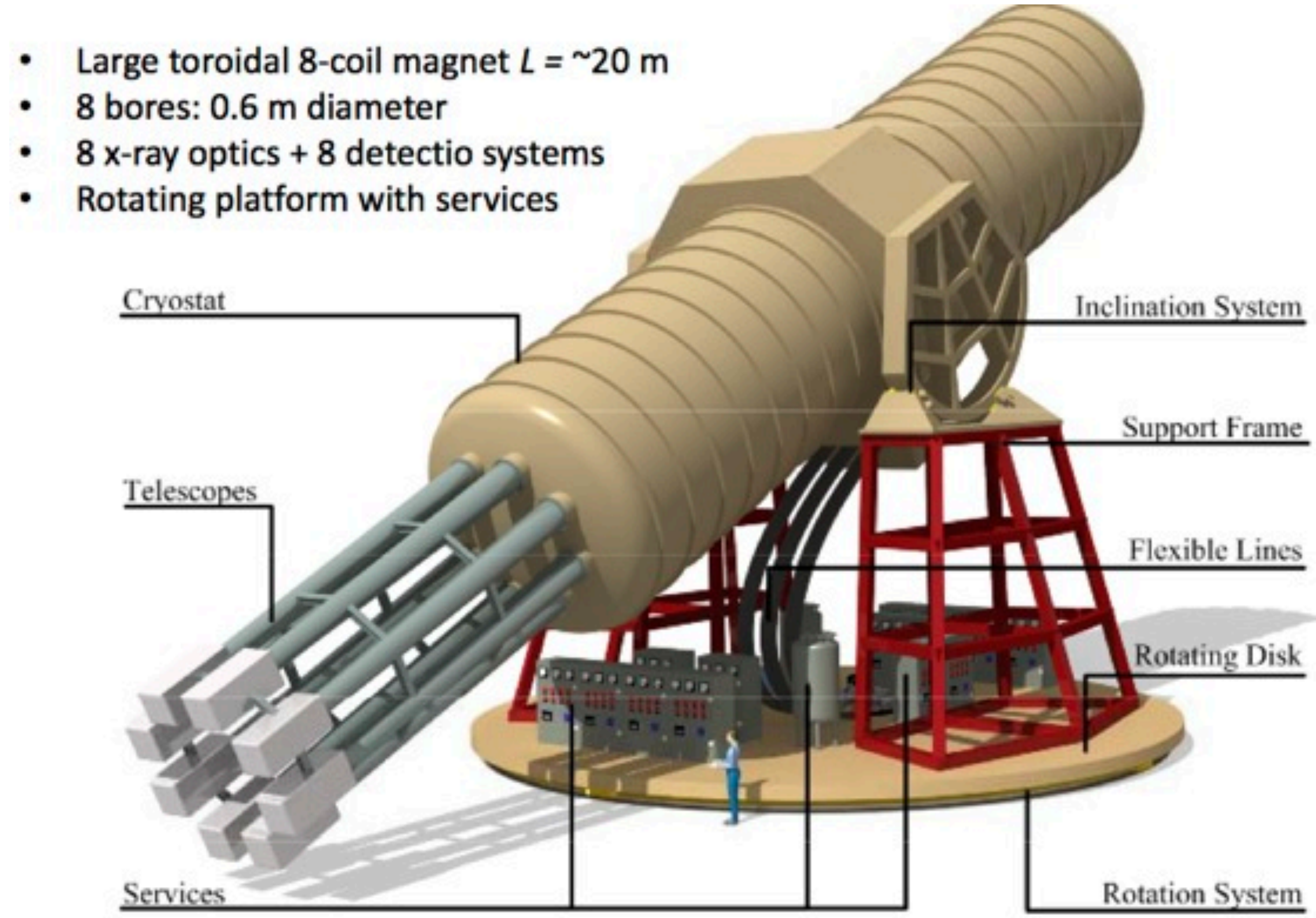
Parameter	Unit	CAST-I	NGAH 1	NGAH 2	NGAH 3	NGAH 4
B	T	9	3	3	4	5
L	m	9.26	12	15	15	20
A	m^2	2×0.0015	1.7	2.6	2.6	4.0
f^*_M		1	100	260	450	1900
b	$\frac{10^{-5}\,c}{keV\,cm^2\,s}$	~ 4	3×10^{-2}	10^{-2}	3×10^{-3}	10^{-3}
ϵ_d		0.5–0.9	0.7	0.7	0.7	0.7
ϵ_o		0.3	0.3	0.3	0.6	0.6
a	cm^2	0.15	3	2	1	1
f^*_{DO}		1	6	14	40	40
ϵ_t		0.12	0.3	0.3	0.5	0.5
t	year	~ 1	3	3	3	3
f^*_T		1	2.7	2.7	3.5	3.5
f^*		1	1.6×10^3	9.8×10^3	6.3×10^4	2.7×10^5

very significant boost!

IAXO (International AXion Observatory)

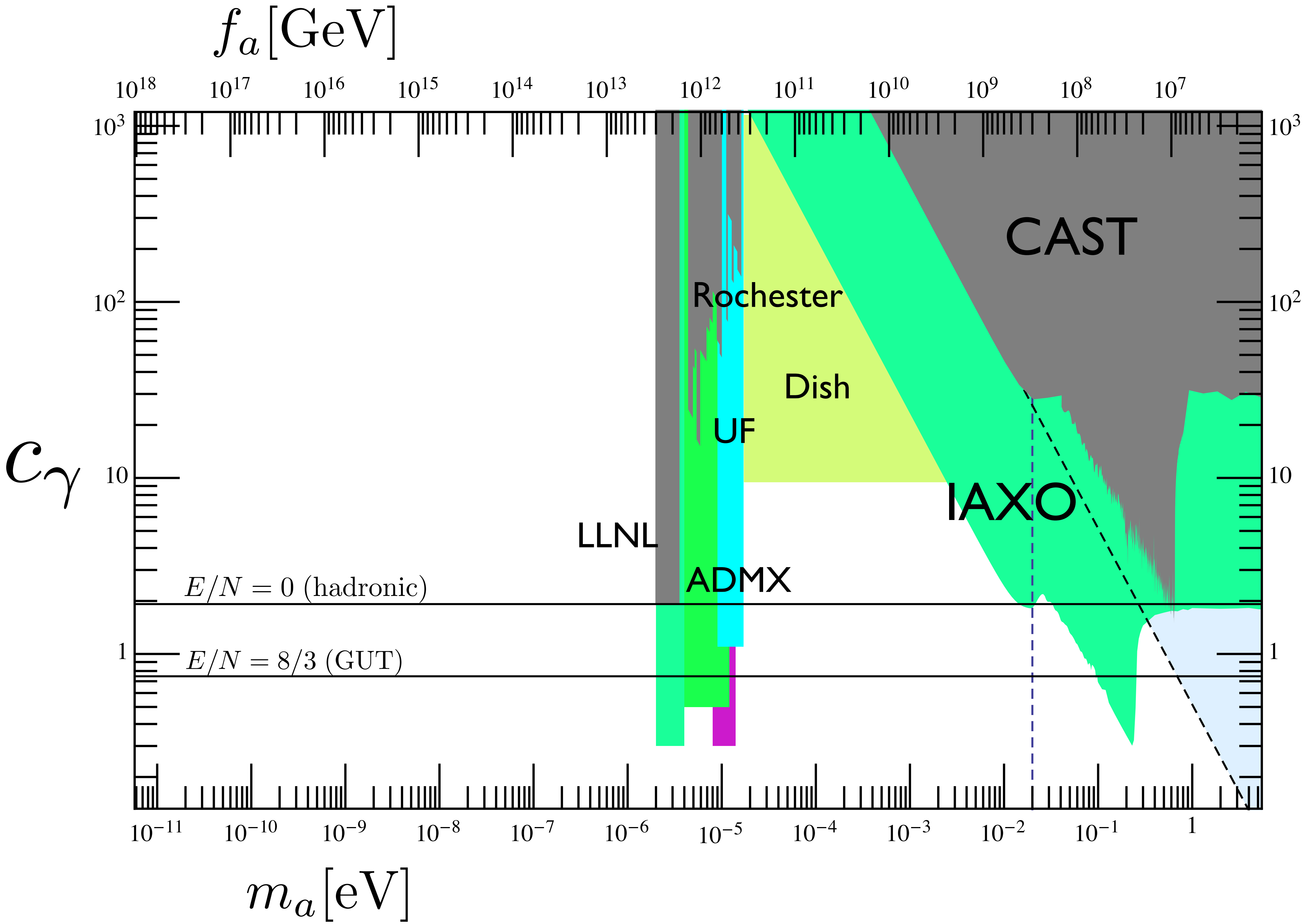
- A NGAH is feasible! but a major step ...
- New collaboration being build
- IAXO requires a DEDICATED MAGNET
  - superconducting toroid designed (arXiv:1308.2526)

- L = 20 m
- B = 4 T
- 8 independent warm bores (60 cm diameter)
- X-ray optics
- MICROmegas detectors

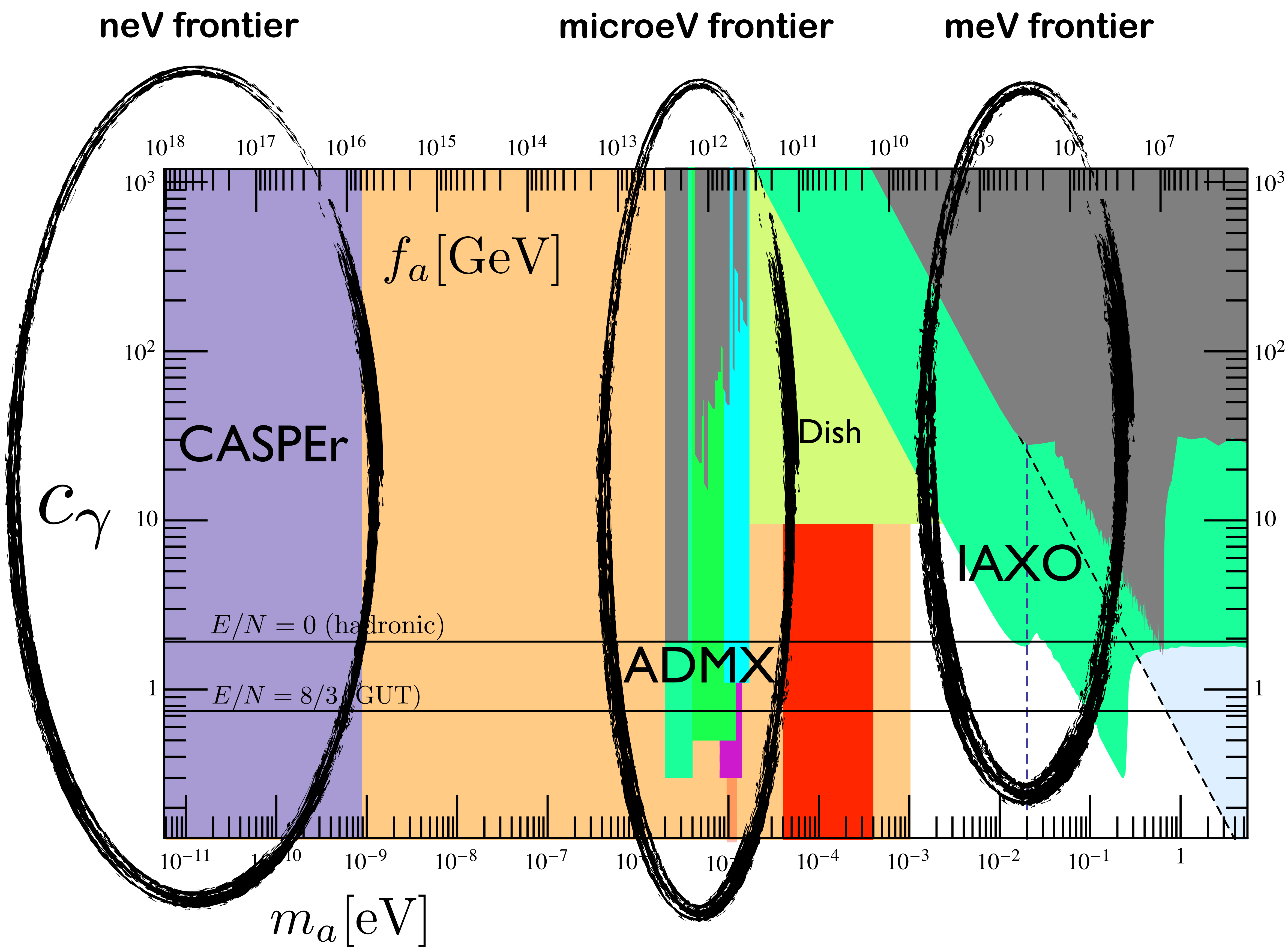


- Letter of Intent to CERN's SPSC
  - positive feedback (new!)
    - recommendations:
      - encourages to prepare TDR
      - enlarge collaboration
      - extend physics reach with new detectors (axion DM?)

IAXO realistic prospects



3 front-lines ...



Conclusions

- Strong CP hint, is there are axion?

- it implies very HEP

- axions are cold dark matter

- DM experiments on the way,
    - ADMX, ADMX-HF, CARRACK test microeV DM a’s
    - oscillating EDM (CASPEr) will test nanoeV a’s
    - other well motivated masses not covered

- solar axions (meV mass) can be searched with IAXO
    - model-independent search
    - IAXO’s huge magnetic volume ideal for new DM exps
    - very strong involvement of Zaragoza U.

- BSM physics can appear at very low energies!