Searches for Axions: motivation, status and future

Joint particle & astroparticle seminar KIT
Karlsruhe 20/06/2017

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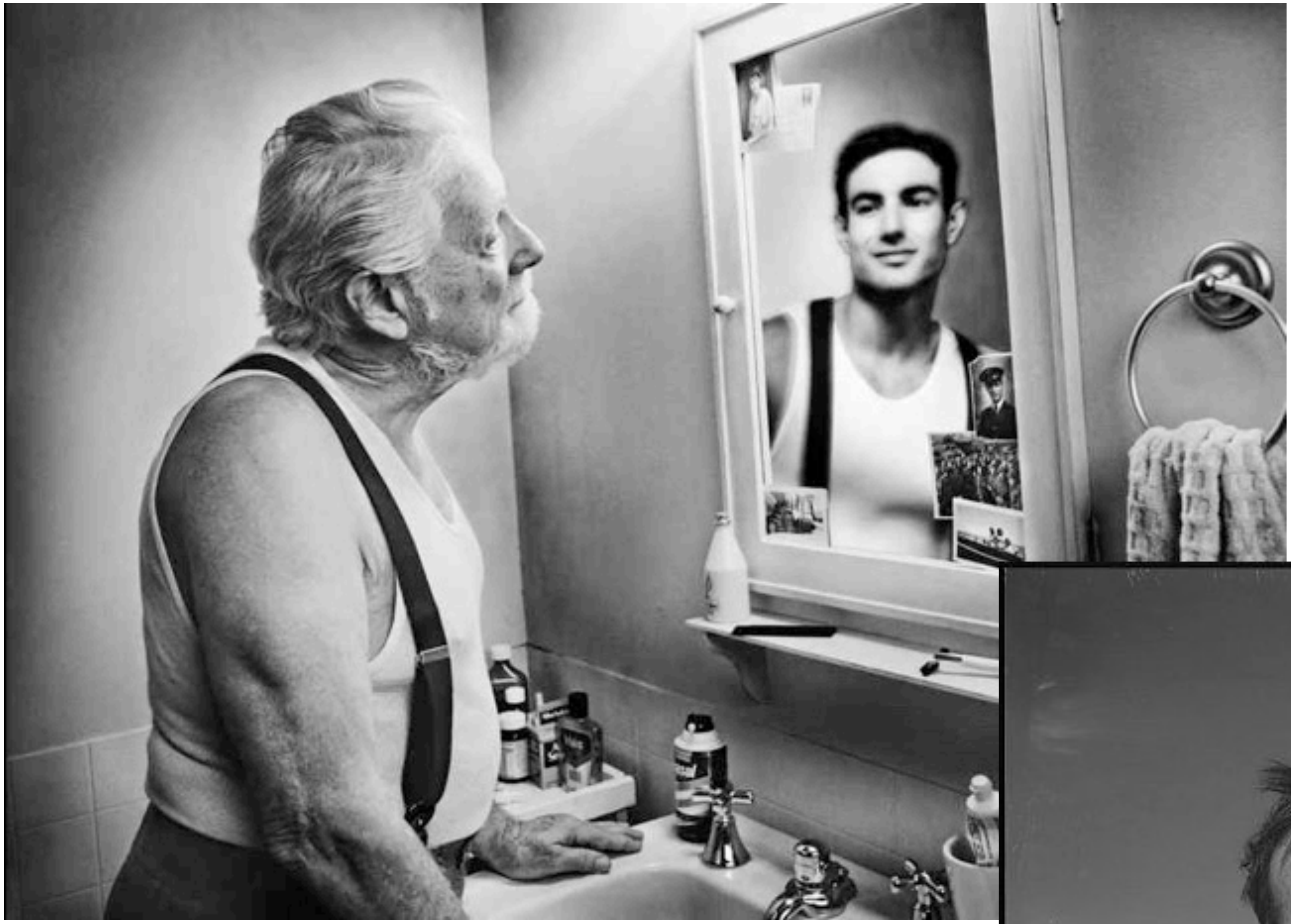
Overview

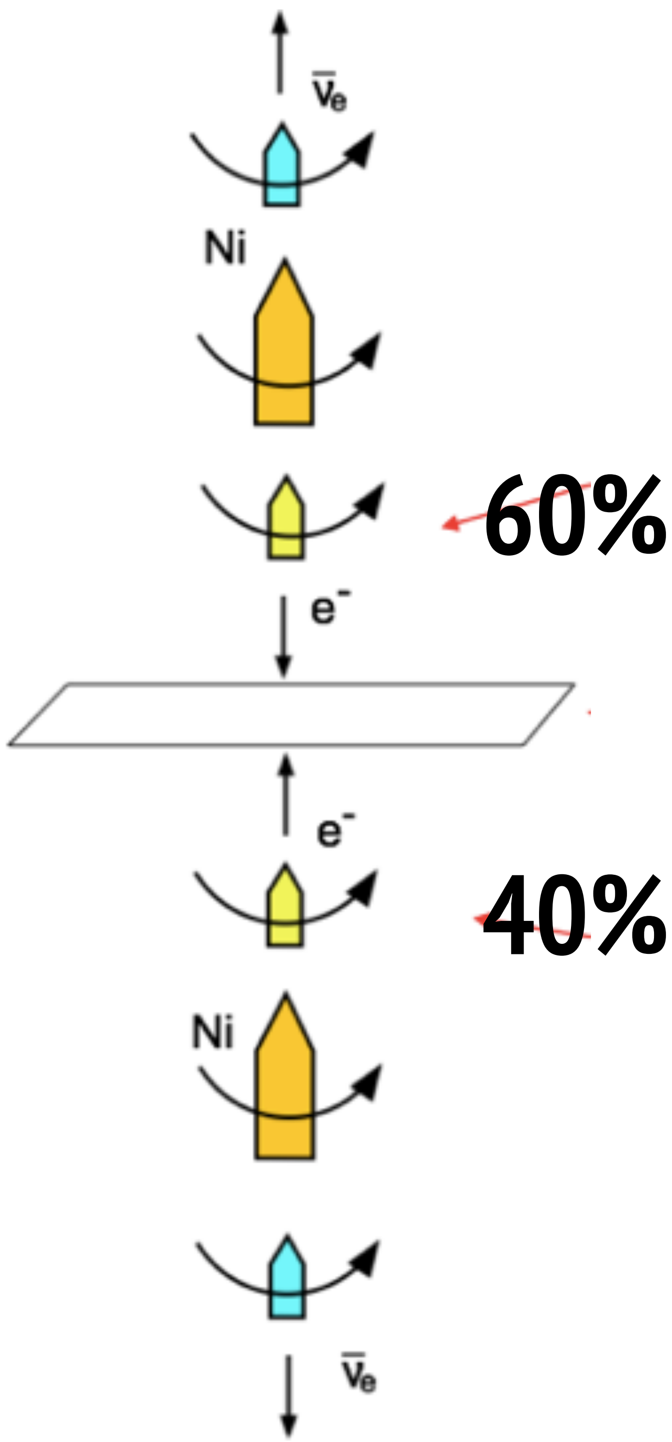
- Strong CP problem
- Axions and ALPs
- Dark matter
- Dark matter experiments
- Lab experiments

Parity and Time reversal



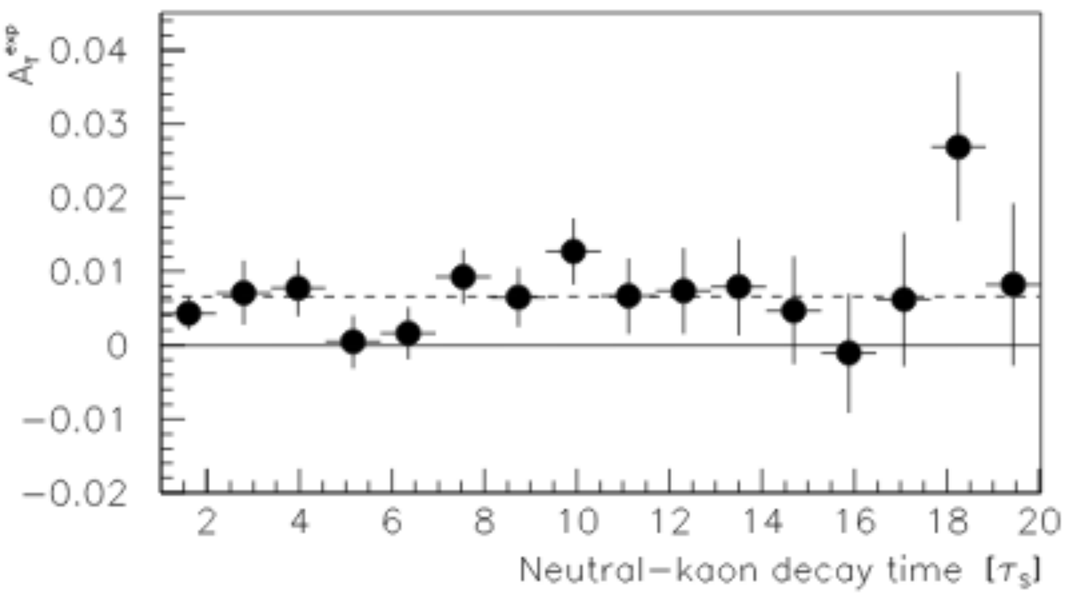
in particle physics (electroweak interactions)

P-violation (Wu 56)



T-violation (CPLEAR 90's)

$$\frac{R(\bar{K}^0 \to K^0) - R(K^0 \to \bar{K}^0)}{R(\bar{K}^0 \to K^0) + R(K^0 \to \bar{K}^0)}$$



... but not in the strong interactions

many theories based on SU(3)c (QCD)

$$\mathcal{L}_{\rm QCD} = \underbrace{-\frac{1}{4}G_{\mu\nu a}G^{\mu\nu}_{a} + \sum_q i\bar{q}\gamma^\mu D_\mu q - \bar{q}mq}_{\text{P,T conserving}} + \underbrace{\frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\widetilde{G}^{\mu\nu}_{a}}_{\text{P,T violating}}$$

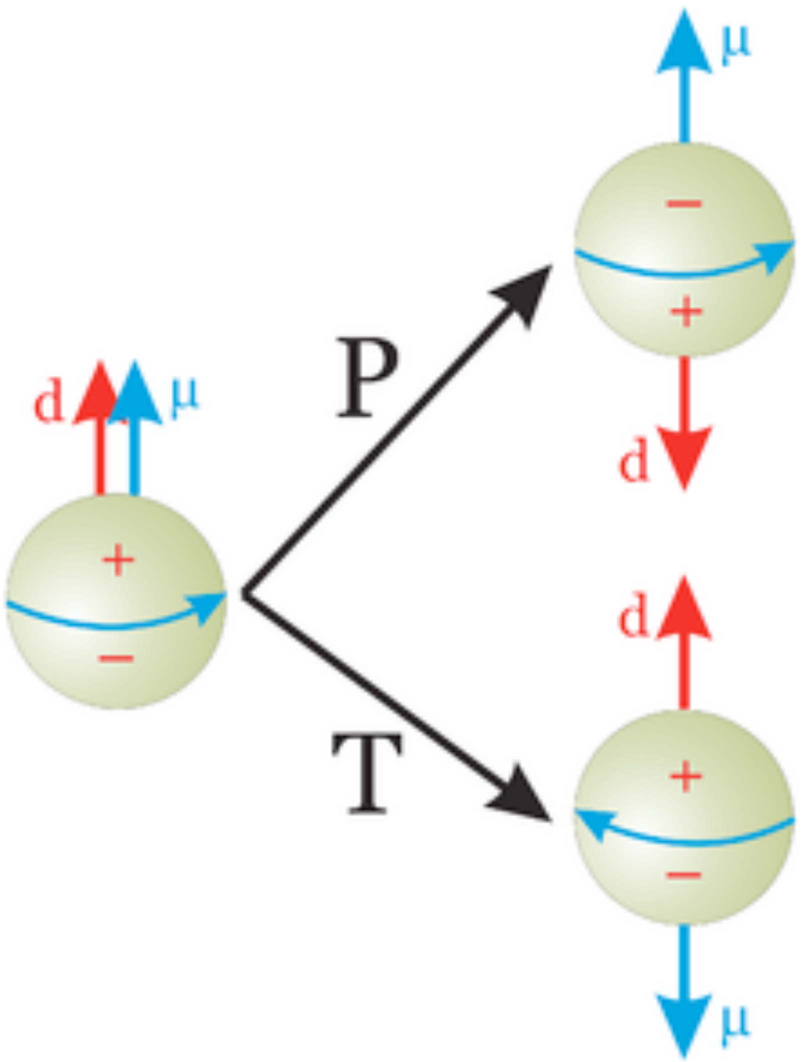
we tend to forget this

$\frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\widetilde{G}^{\mu\nu}_{a}$ **induces P and T (CP) violation** $\propto \theta$

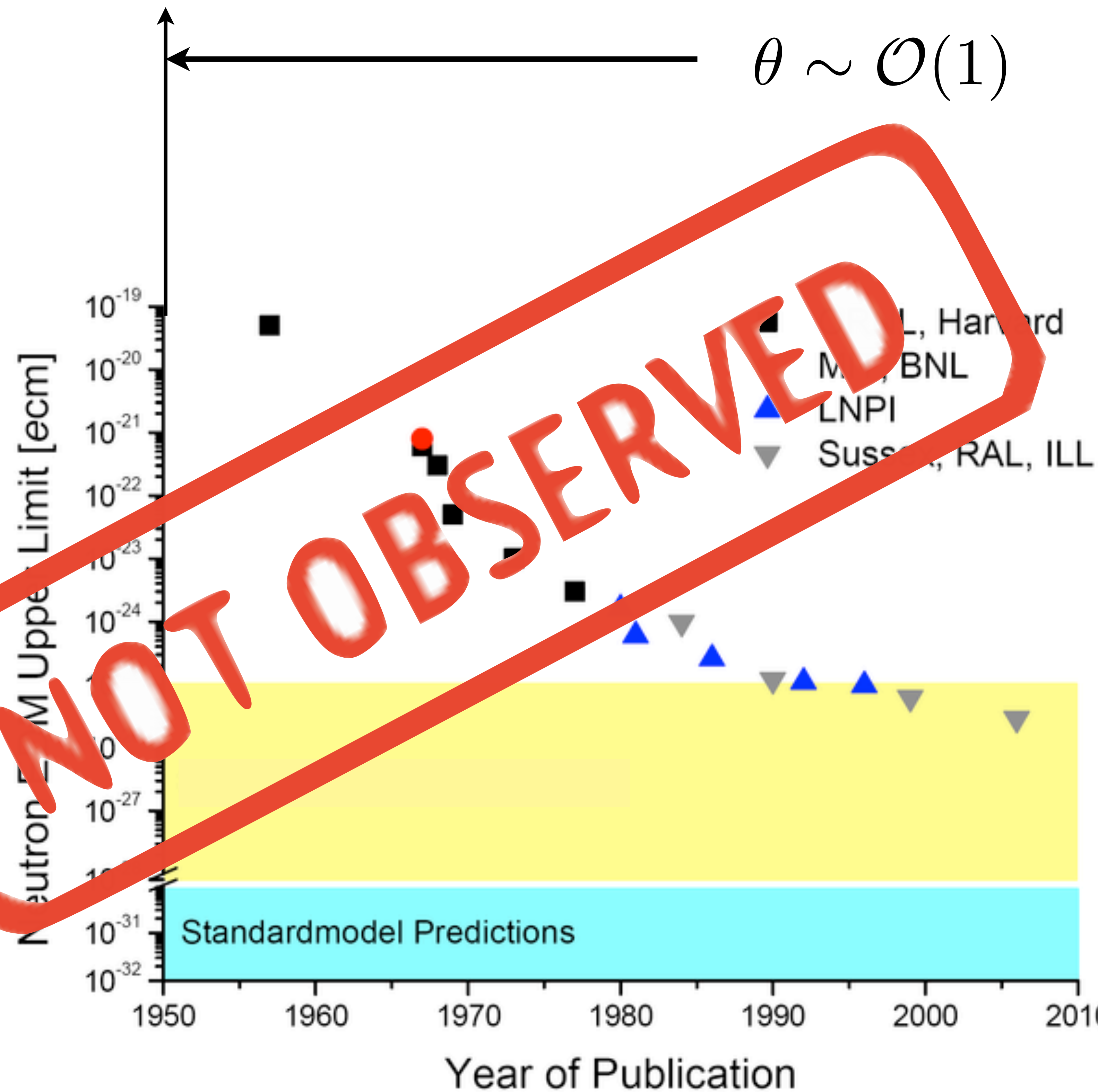
$\theta \in (-\pi, \pi)$ **infinitely versions of QCD... all are P,T violating**

Neutron EDM

Most important P, T violating observable $d_n \sim \theta \times \mathcal{O}(10^{-15})\mathrm{e\,cm}$

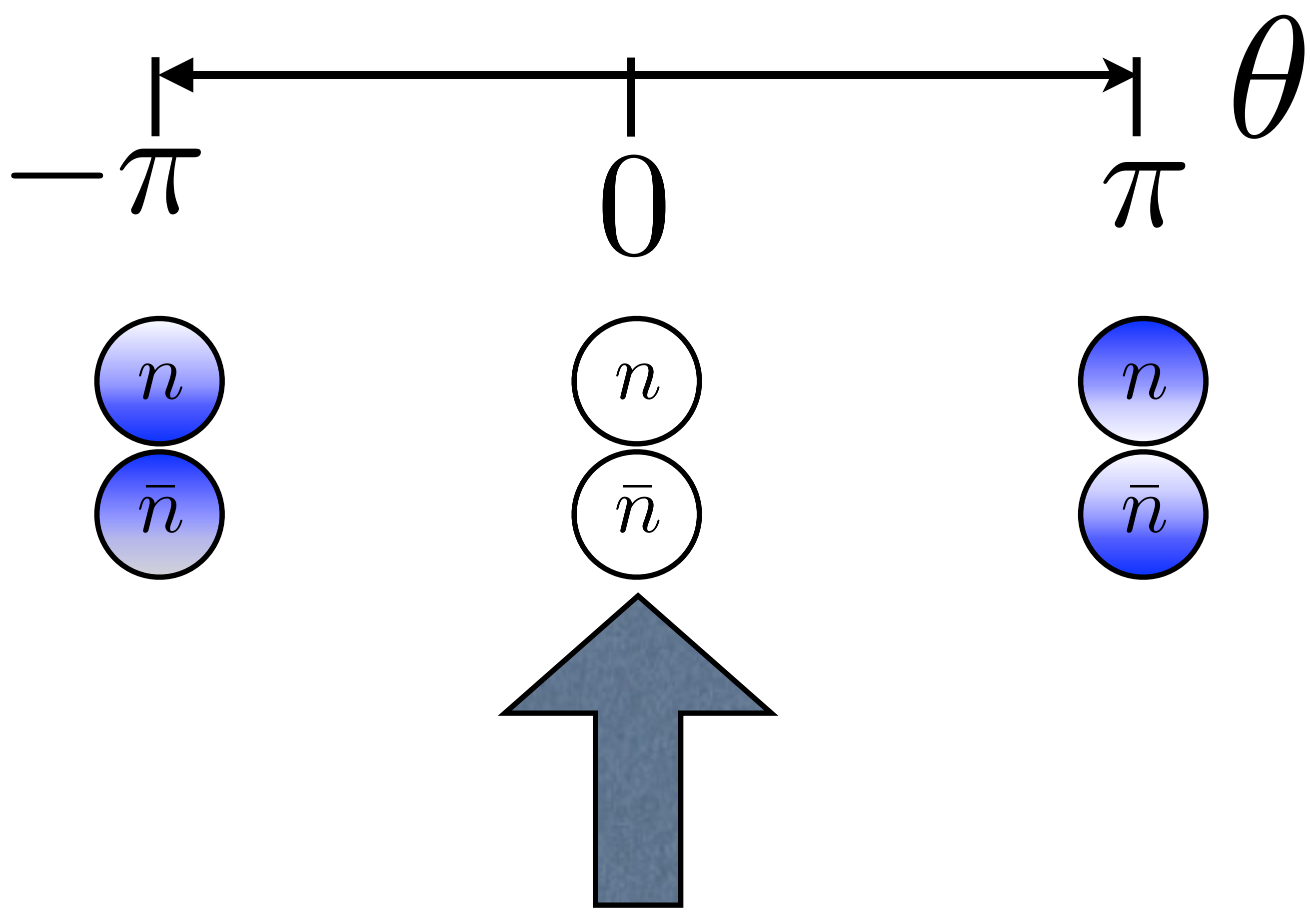


EDM violates P,T



The theta angle of the strong interactions

- The value of θ controls P,T violation in QCD



Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Roberto Peccei and Helen Quinn 77

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.

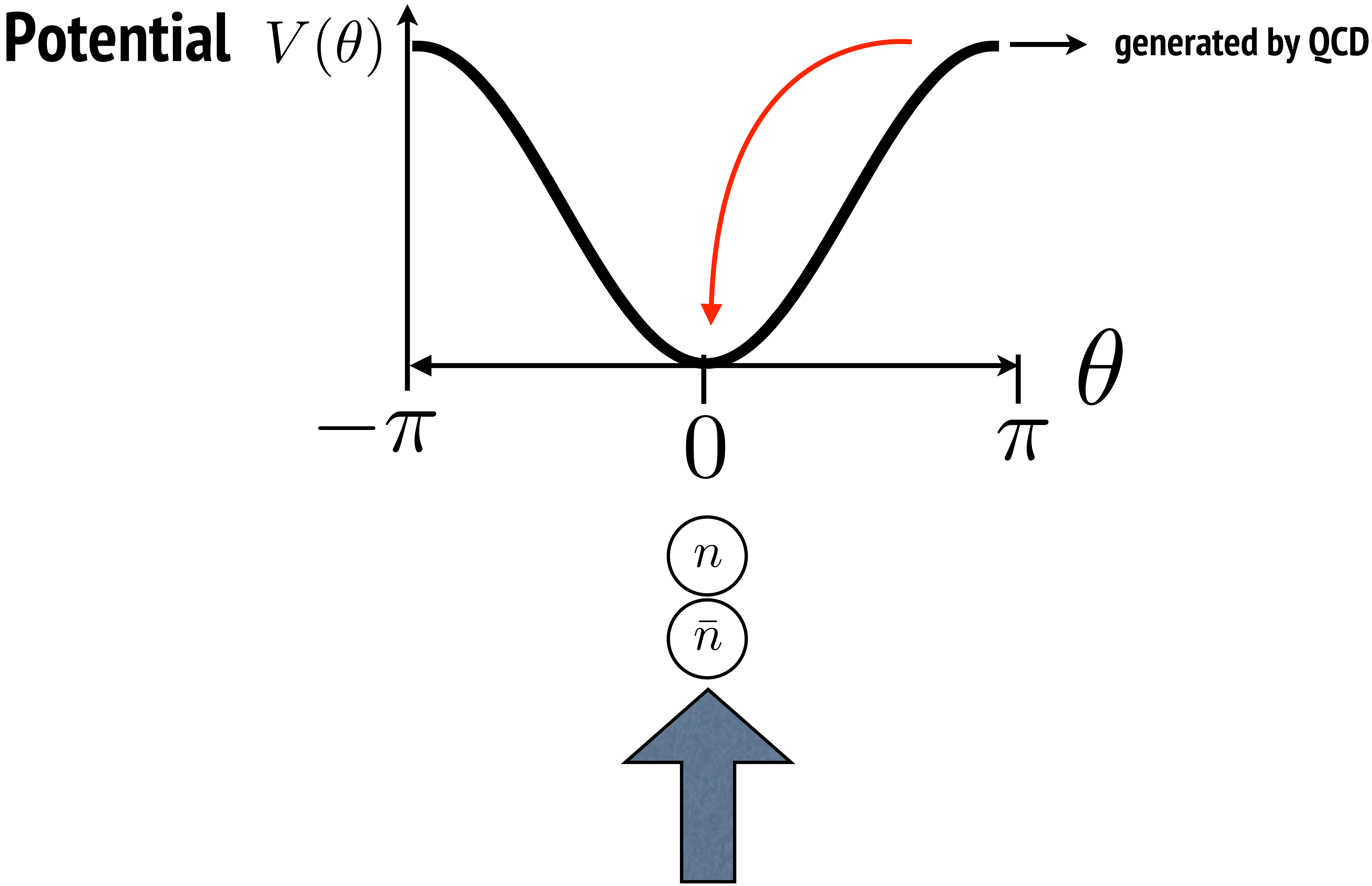
It is experimentally obvious that we live in a

grangian.

If all fermions which couple to the non-Abelian

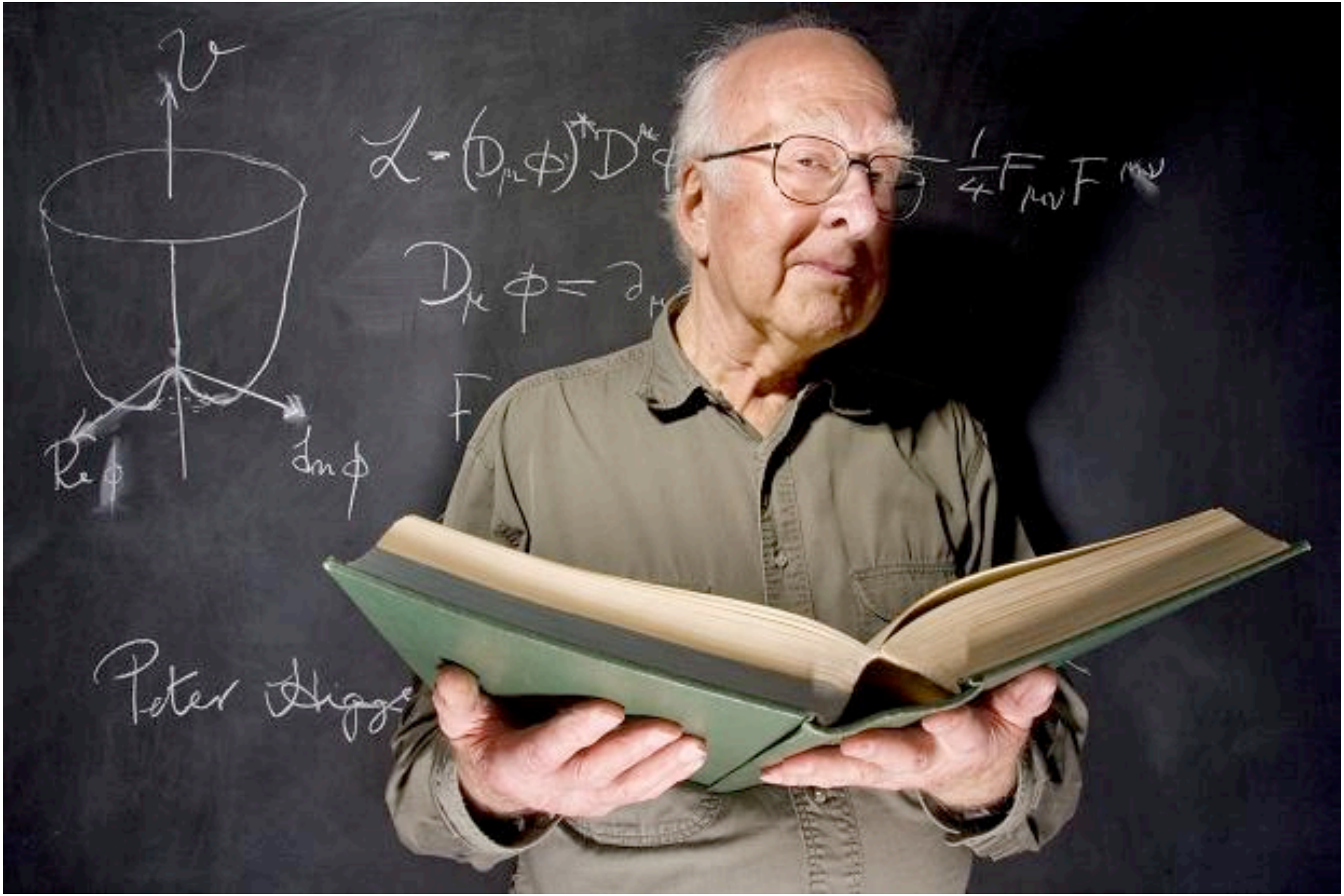
QCD vacuum energy minimised at theta = 0

- ... if $\theta(t, \mathbf{x})$ is dynamical field, relaxes to its minimum



Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

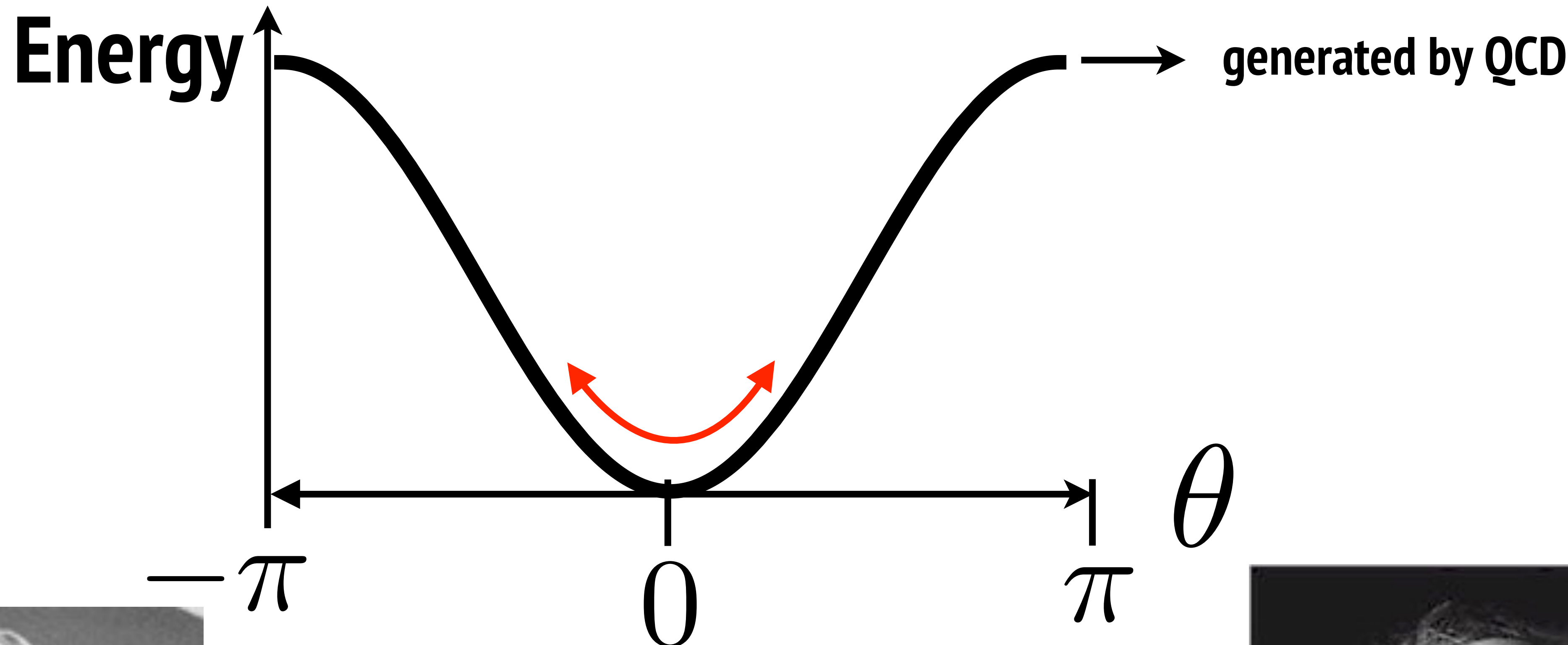
ain’t you forgetting something?



P. Higgs

and a new particle is born ...

- if $\theta(t, \mathbf{x})$ is dynamical field



Field Excitations around the vacuum are particles

S. Weinberg

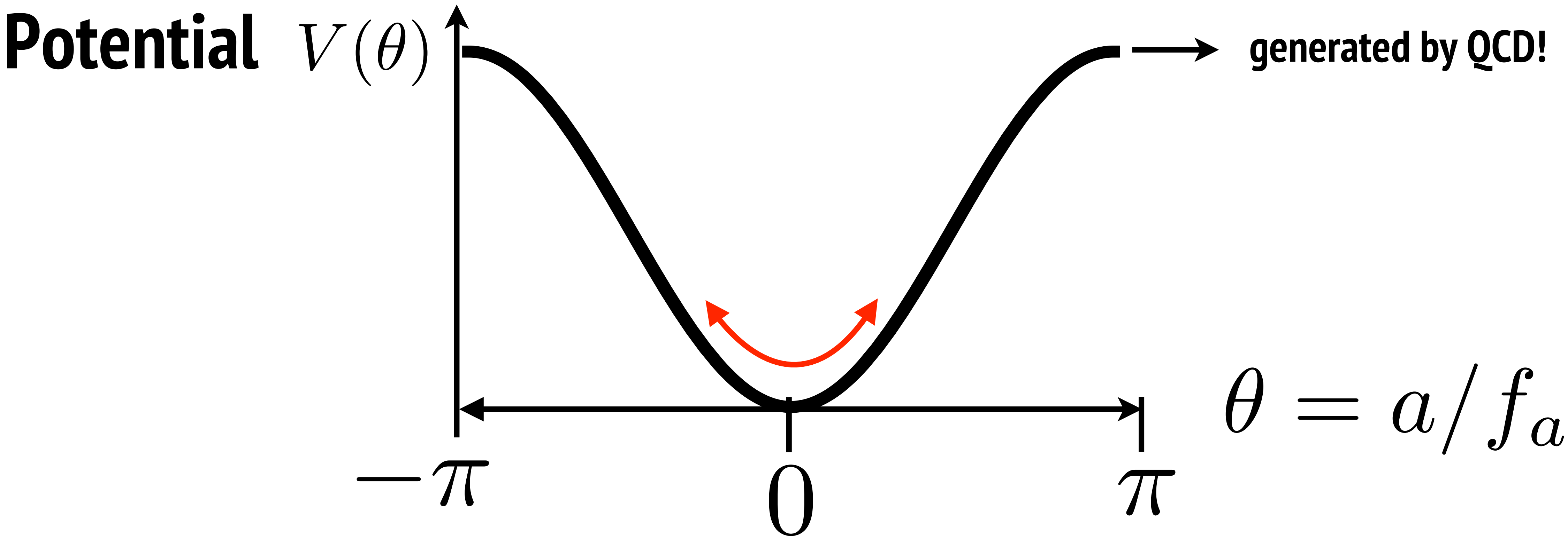
F. Wiczek

and a new particle is born ... the axion

- if $\theta(t, \mathbf{x})$ is dynamical field

and a new scale sets the game, fa

- **kinetic term for θ requires a new energy scale, f_a**



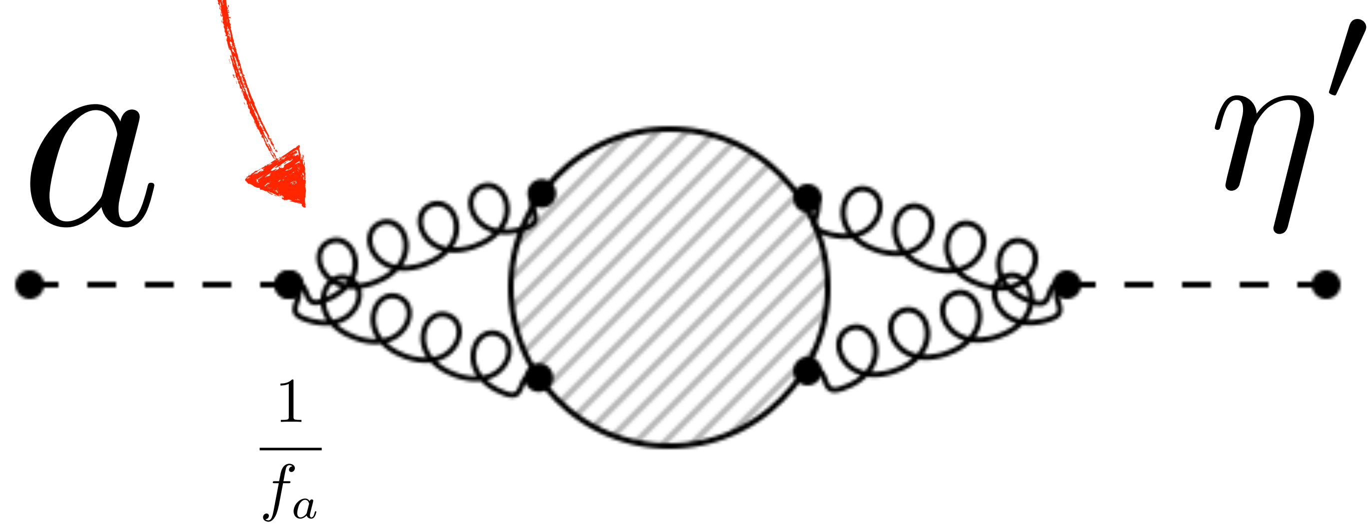
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}^{\mu\nu}_a \theta + \frac{1}{2} (\partial_\mu \theta)(\partial^\mu \theta) f_a^2$$

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

Axion couplings at low energy

- From θ-term, axion mixes with eta' and the rest of mesons

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

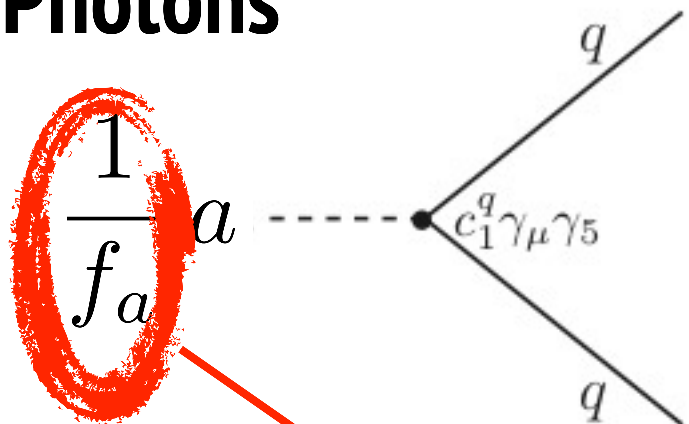


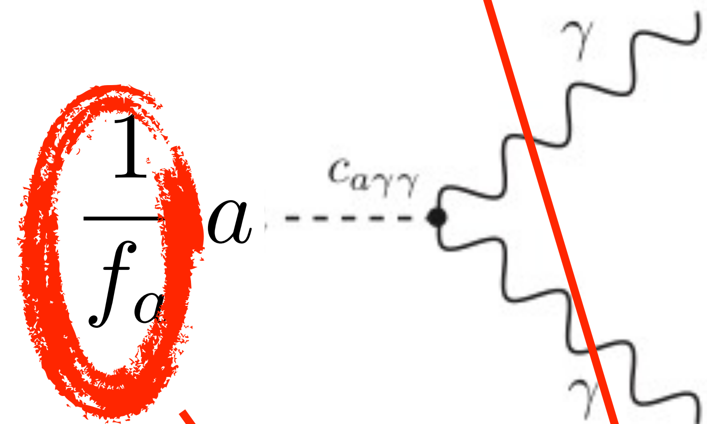
Axion couplings at low energy

Mass

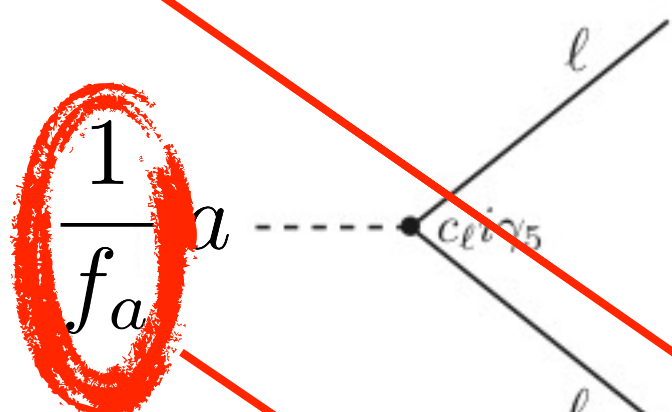
$$m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6 \text{ meV} \frac{10^9 \text{GeV}}{f_a}$$

hadrons, Photons



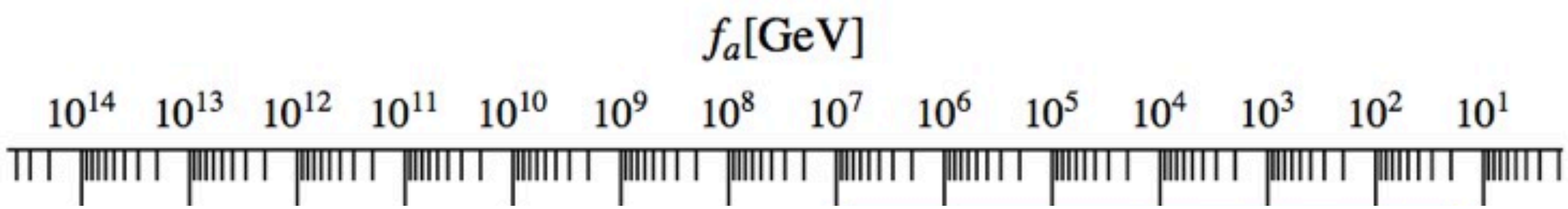


Leptons (in some models)



The lighter the more weakly interacting

Axion Landscape

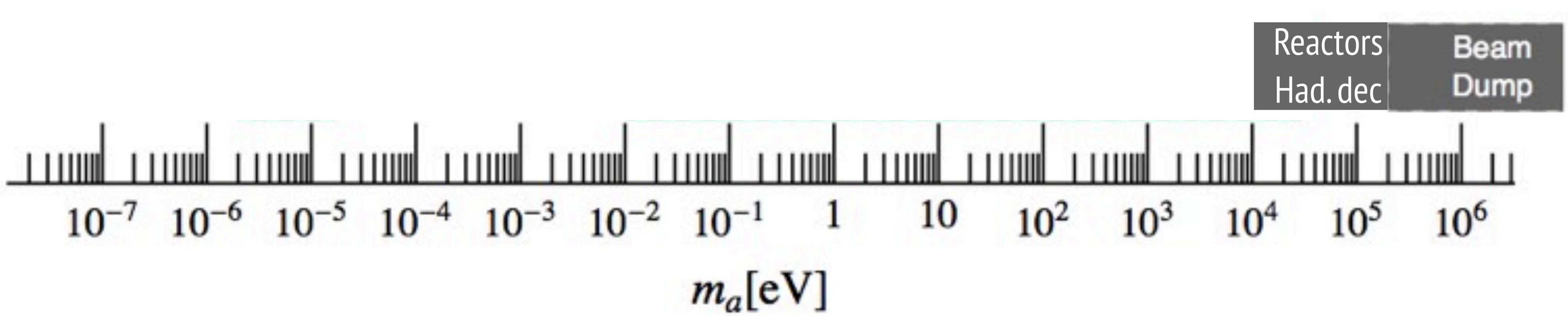


$f_a \gg v_{\mathrm{EW}}$

Invisible models

$f_a \sim v_{\mathrm{EW}}$

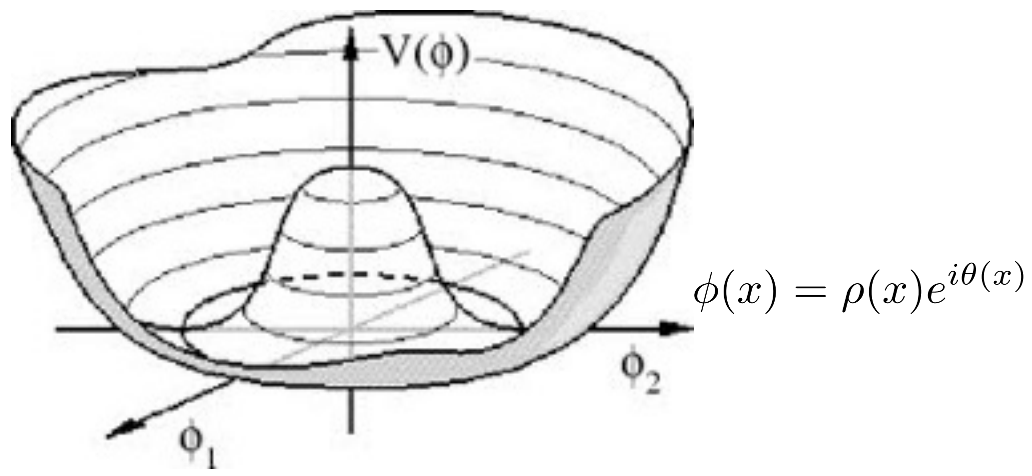
PQWW models



Axion-like particles (ALPs)

pseudo Goldstone Bosons

- Global symmetry spontaneously broken



- massless Goldstone Boson @ Low Energy

shift symmetry $\theta(x) \to \theta(x) + \alpha$

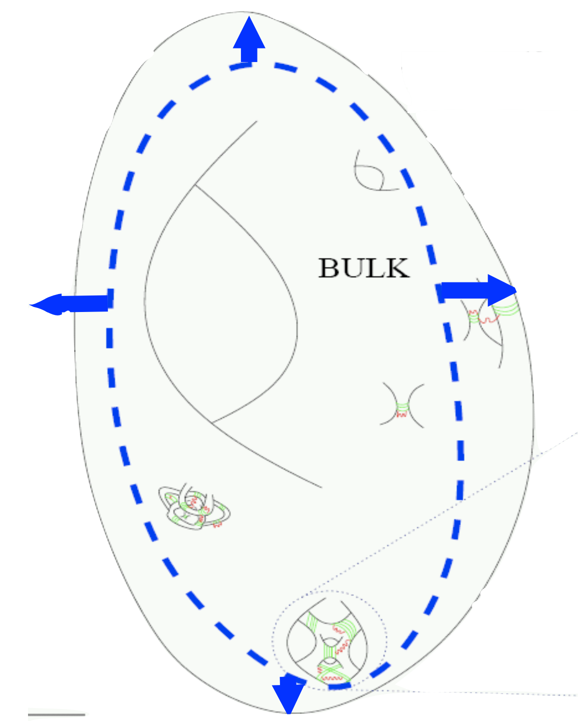
$$\mathcal{L}_{\rm kin} = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f^2$$

- HE decay constant, $f = \langle \rho \rangle$

- small symmetry breaking $\longrightarrow$ small mass

stringy axions

- Im parts of moduli fields (control sizes)



- O(100) candidates in compactification

- "decay constant", string scale M_s

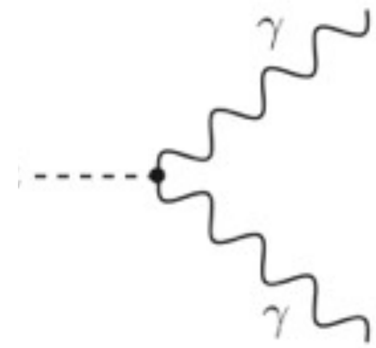
- masses from non-perturbative effects

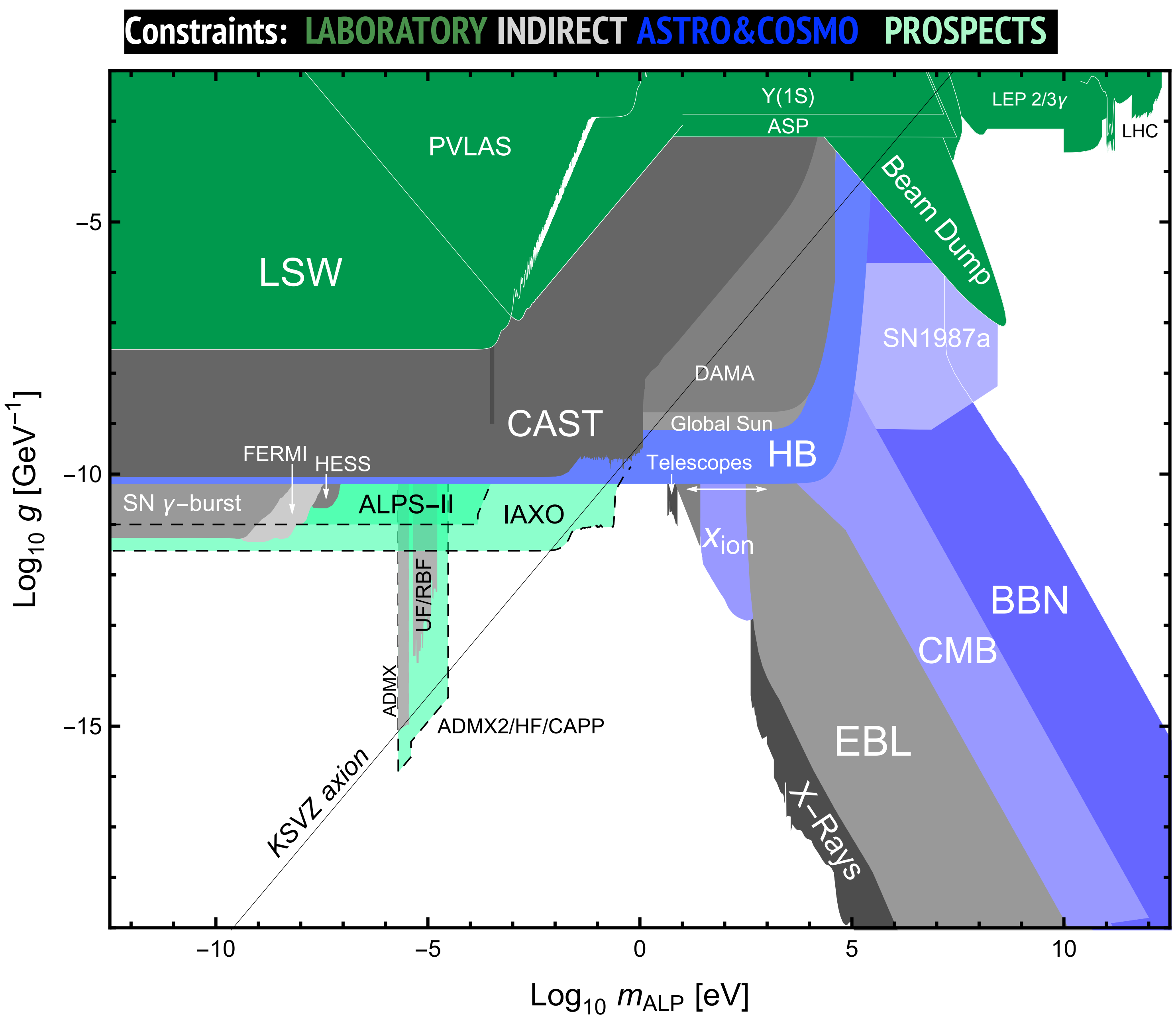
- Couplings, $\propto 1/f$, MASS $\sim \Lambda^2_{\rm breaking}/f$, different relation than QCD axions

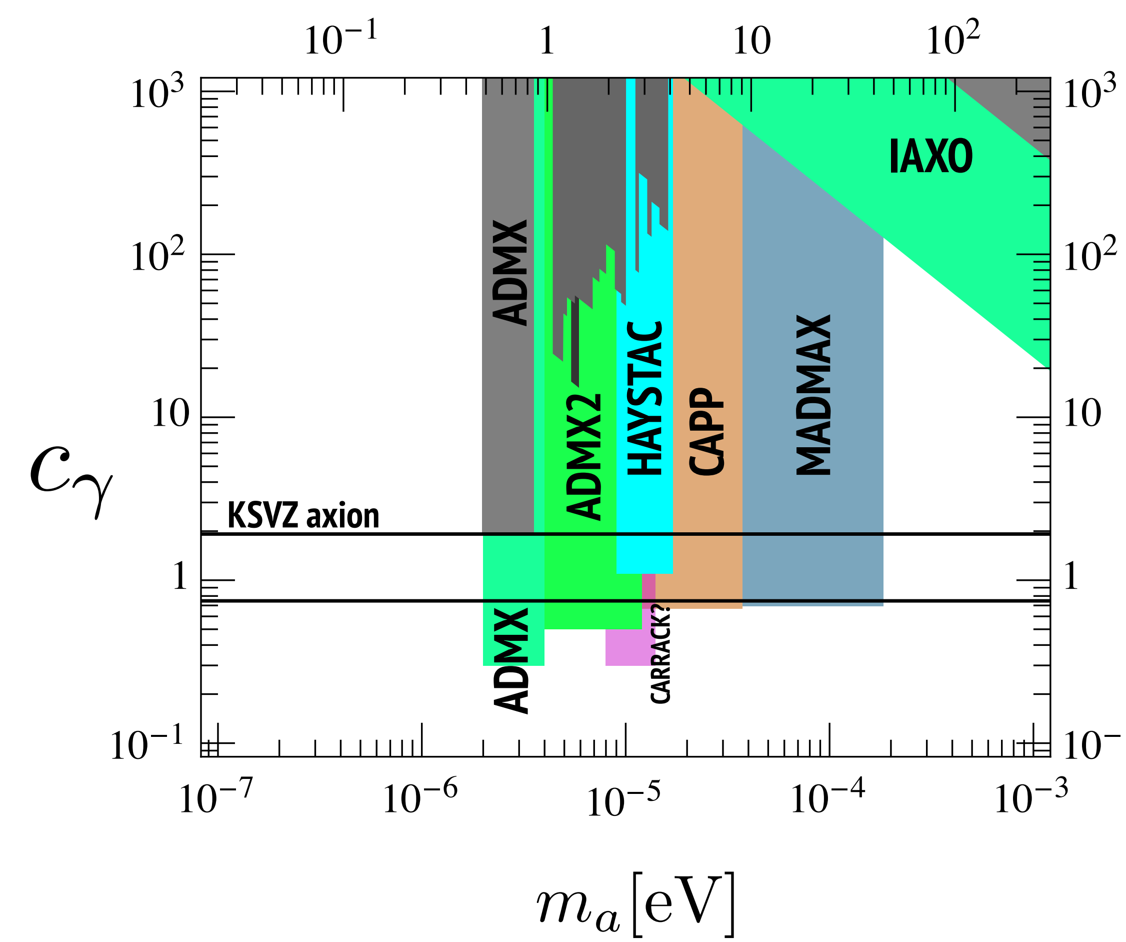
Axion, ALP parameter space

- Coupling vs Mass, QCD axions in a band
- Important example: photon coupling

$$g_{a\gamma} = c_\gamma \frac{\alpha}{2\pi f_a}$$





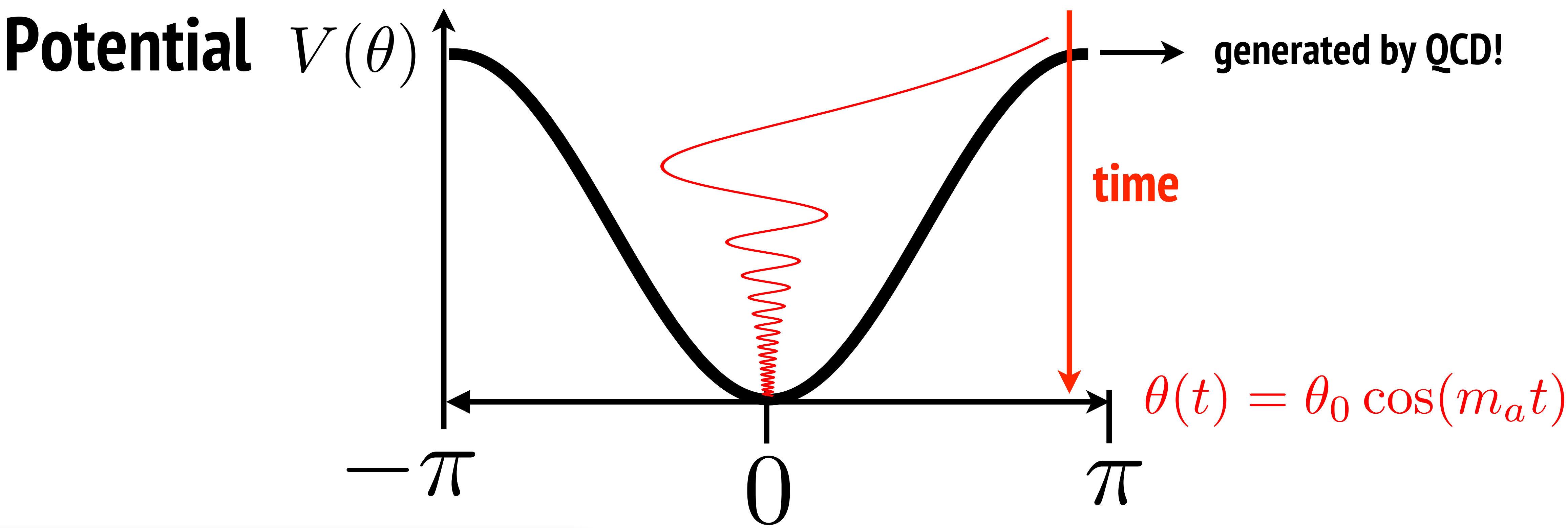


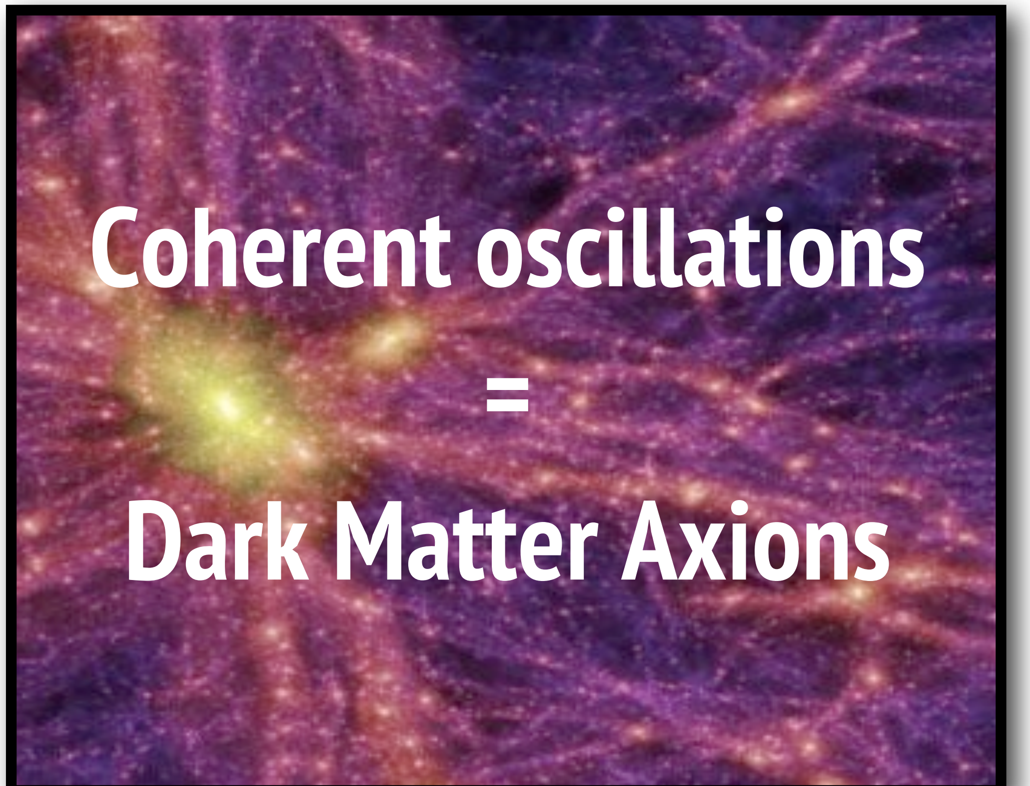
*KSVZ axion model, couplings come only from eta' mixing, $c_\gamma = -1.92$

Dark Matters

Axions and dark matter

- axion field relaxes to minimum & oscillates (DARK MATTER!), damping due to expansion of the Universe





Oscillation frequency

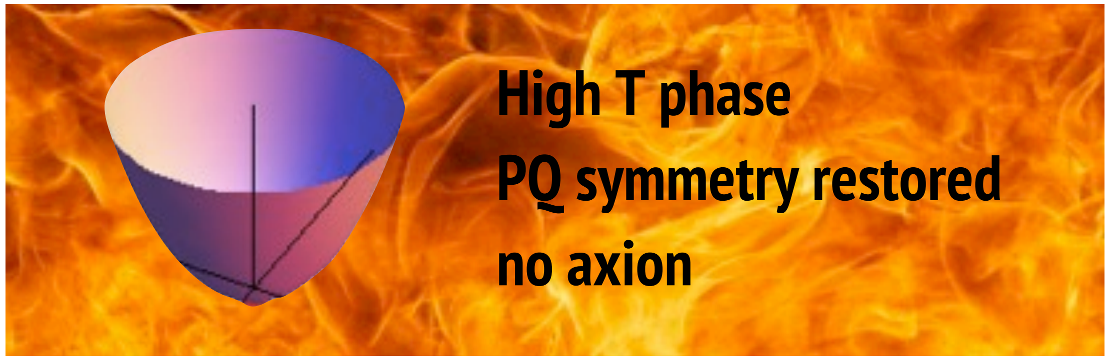
$$\omega = m_a$$

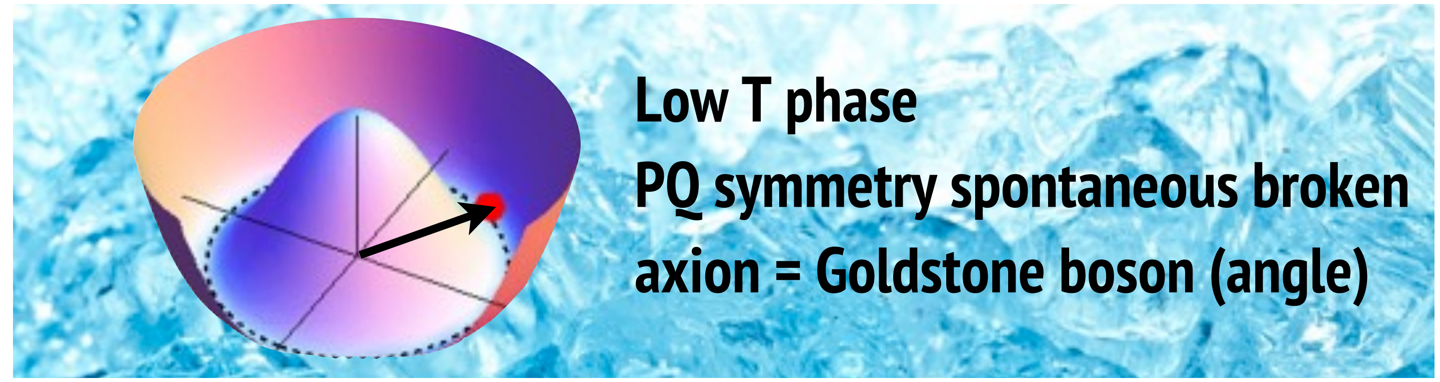
Energy density (harm. oscillator)

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

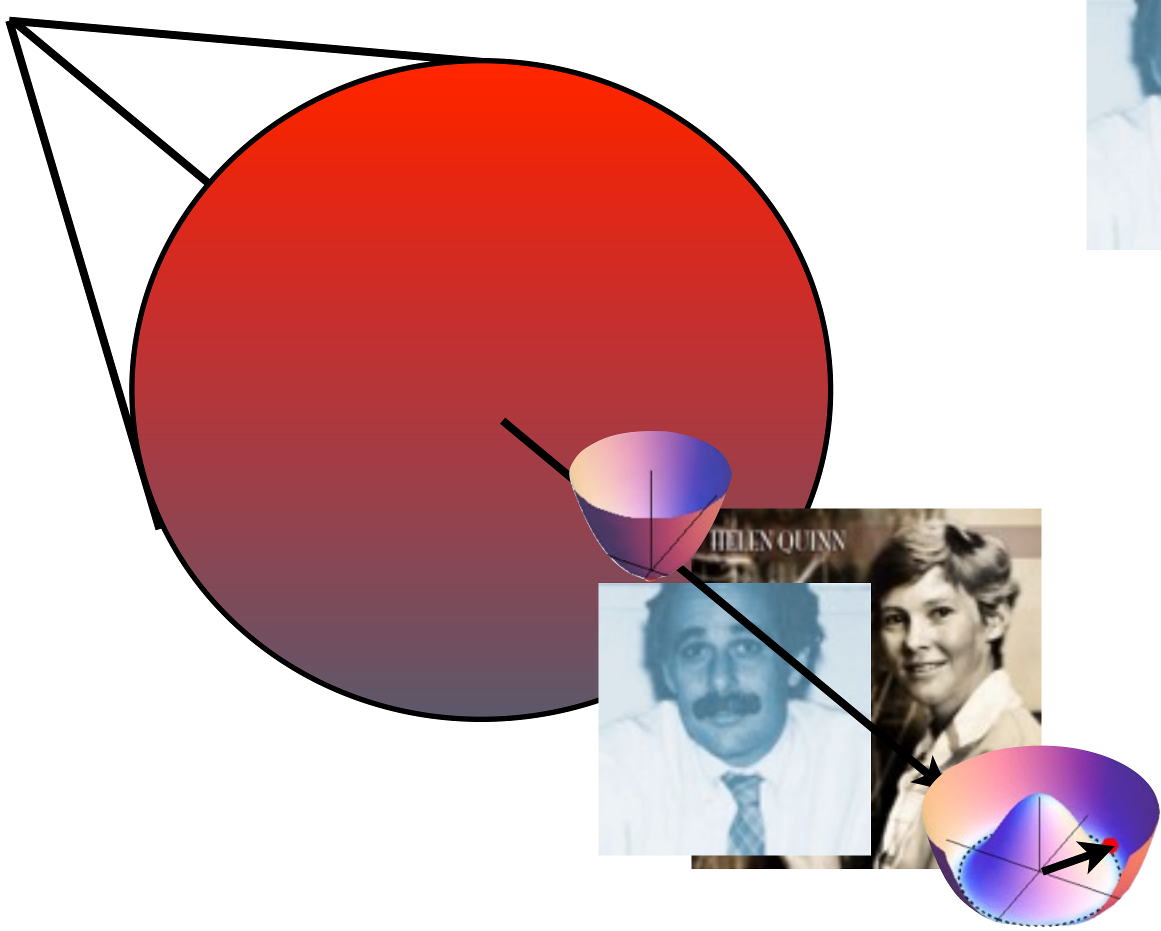
Two scenarios

- Consider axion as a Goldstone boson: exists only below spontaneous symmetry breaking (PQ symmetry)

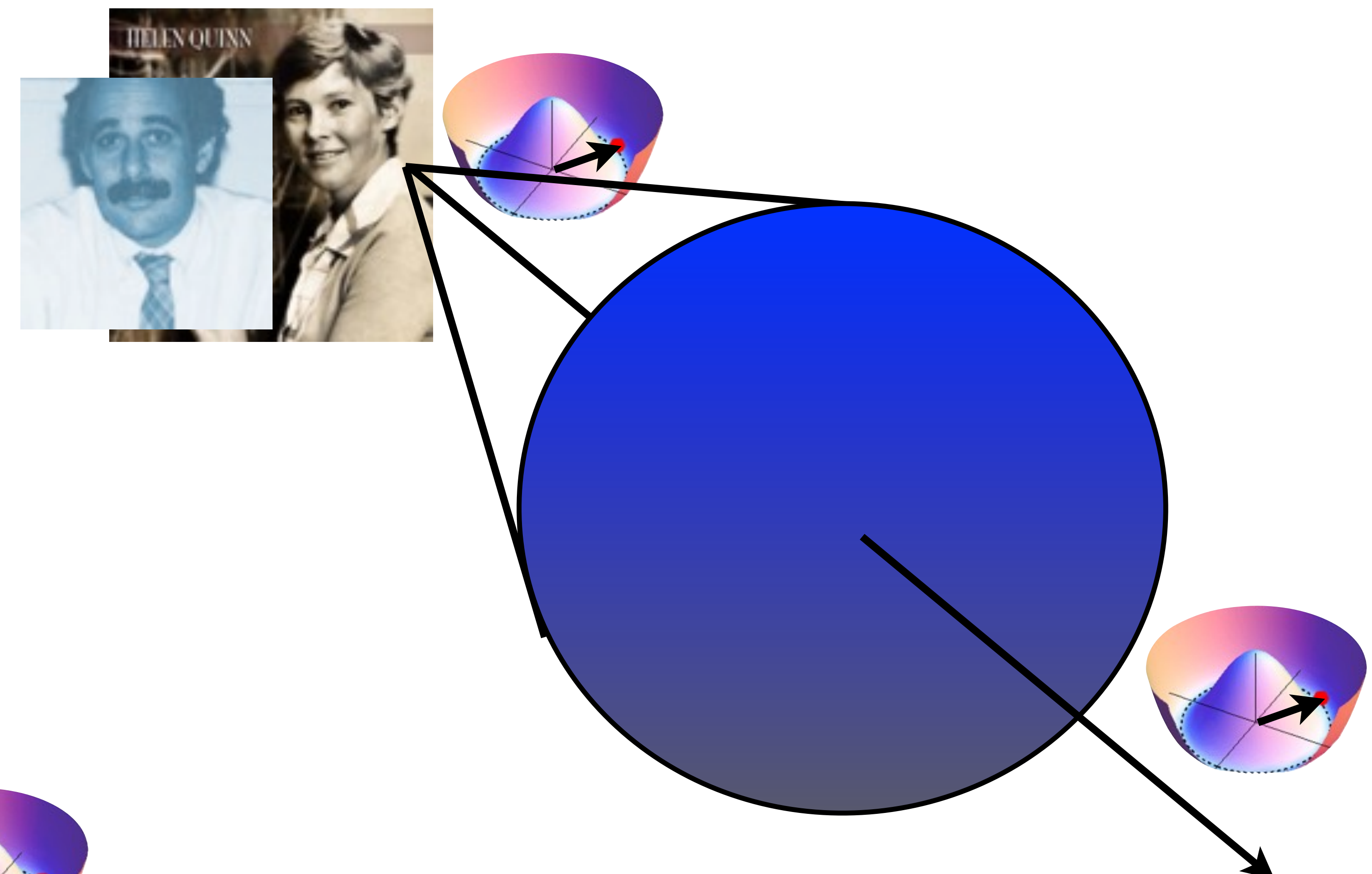




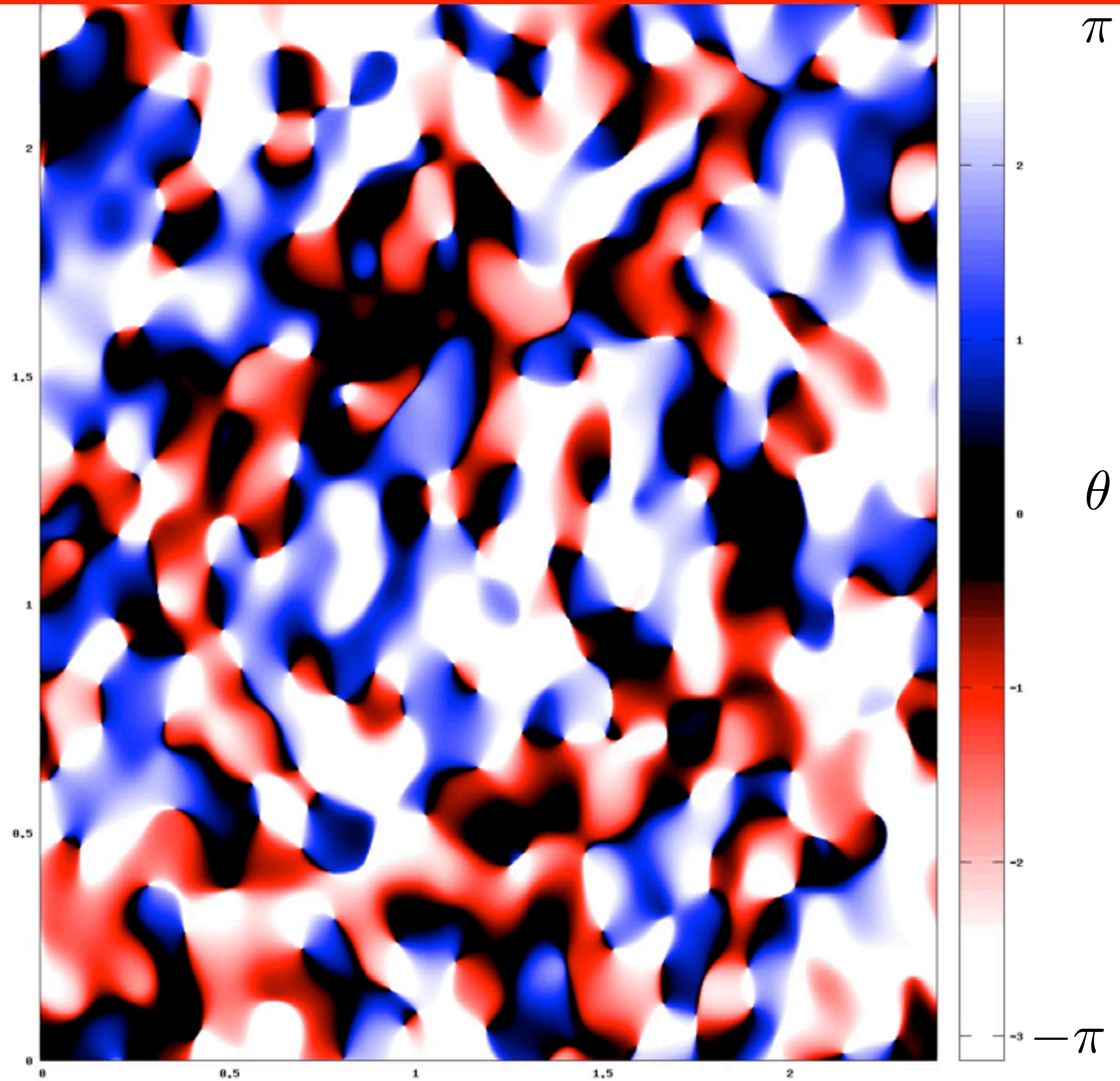
- PQ breaking after inflation



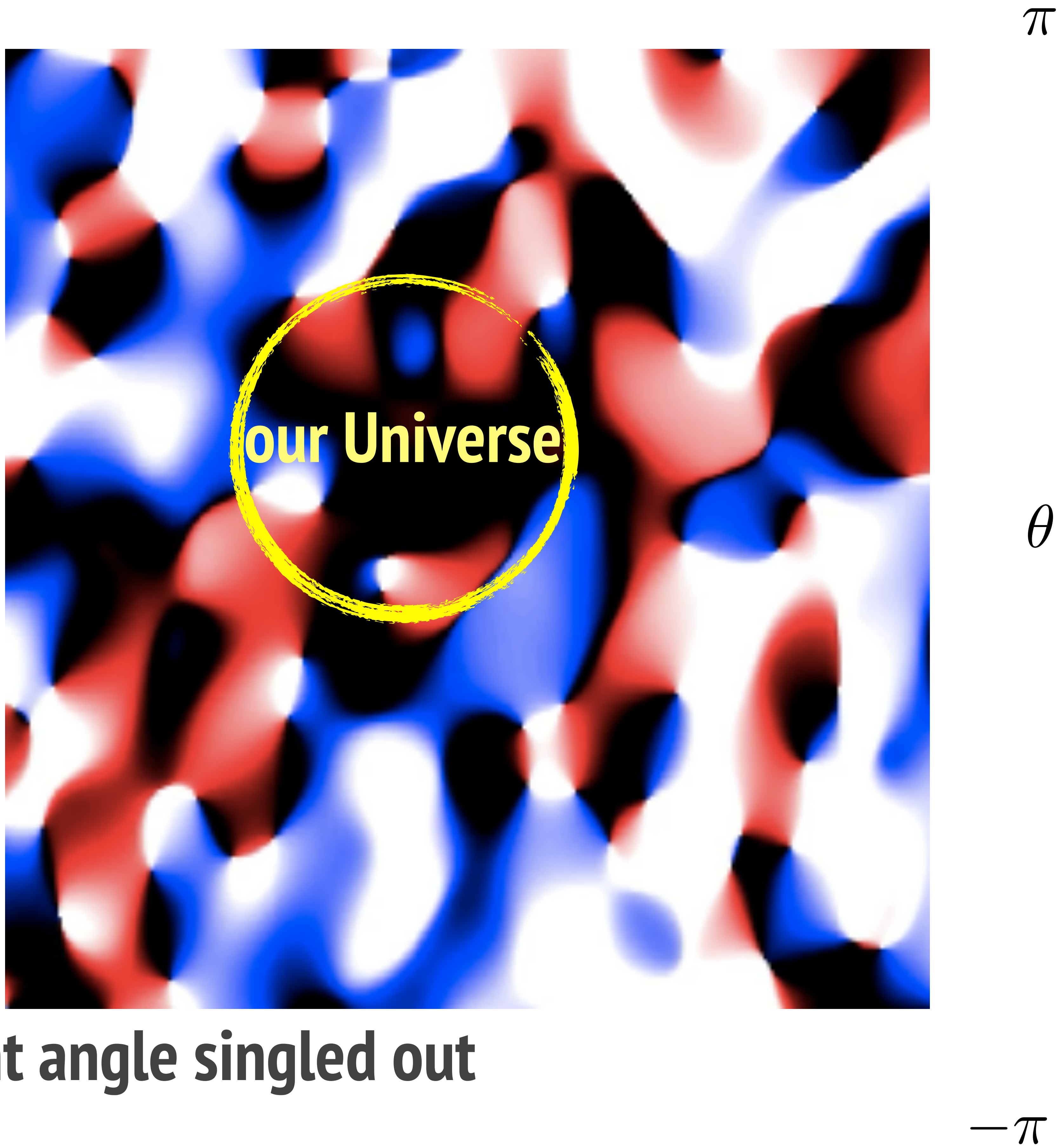
- PQ breaking before inflation



After inflation, PQ phase transition, misaligned patches



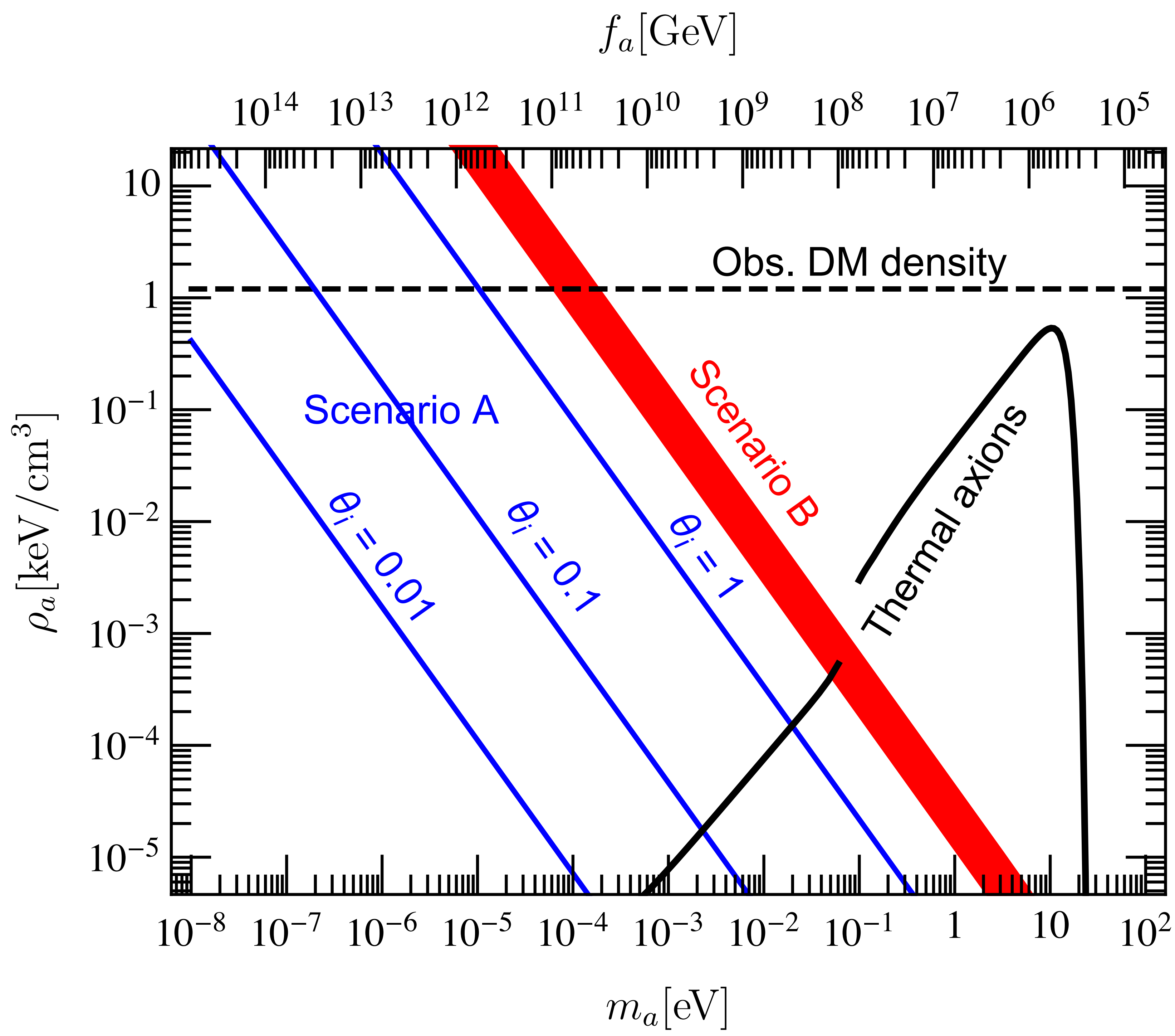
PQ Before inflation, one patch stretched to be our Universe



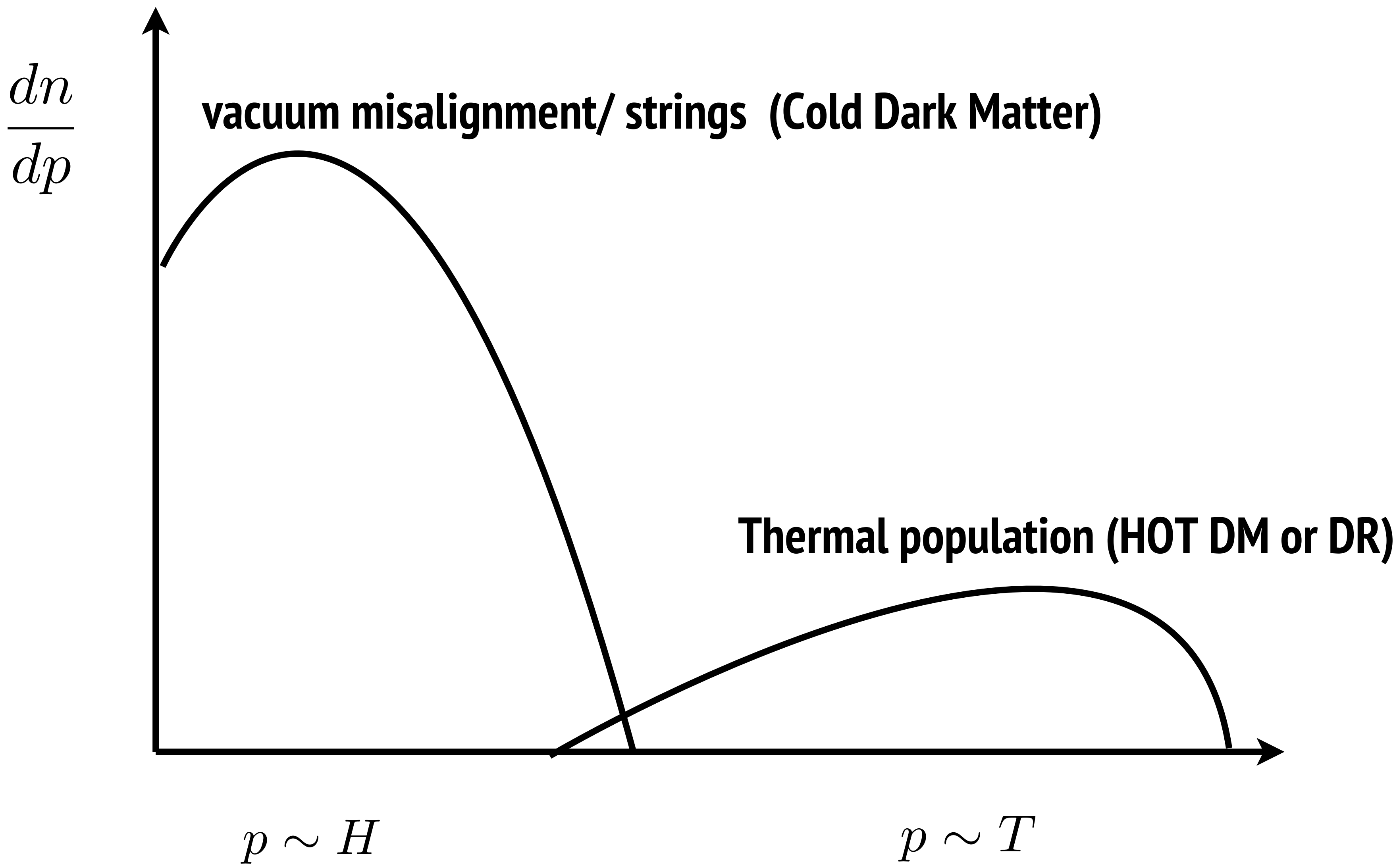
One misalignment angle singled out

Axion dark matter

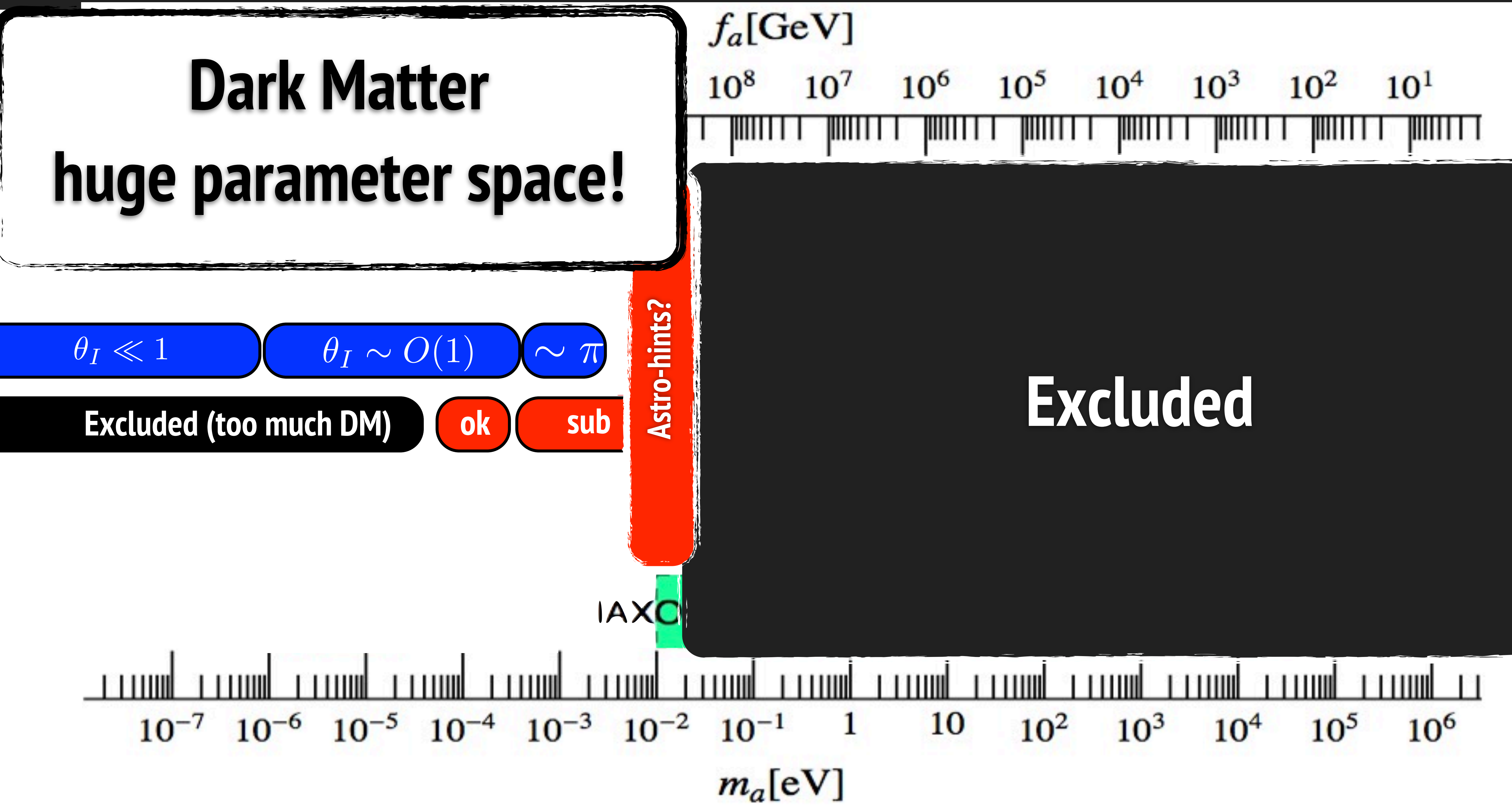
- The amount of axion DM produced depends on fa



Momentum distribution



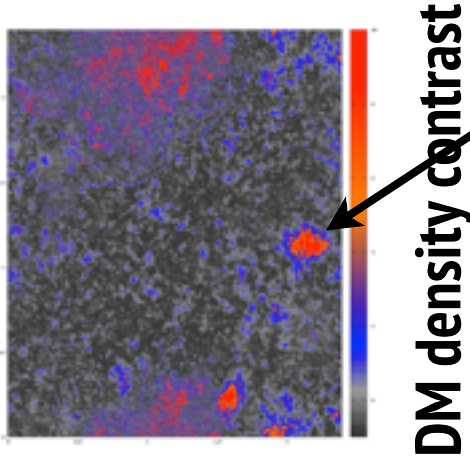
What value of f_a for $\Omega_{cdm}h^2 = 0.12$?



Most important constraints

- PQ breaking after inflation

-> DM inhomogeneous, Axion miniclusters

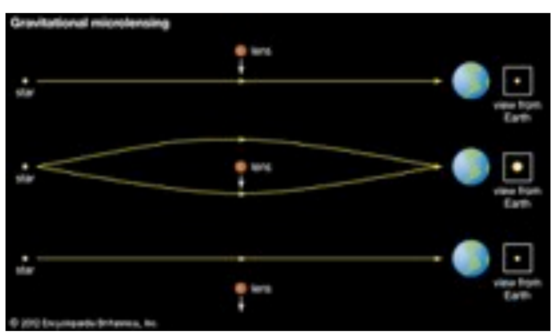


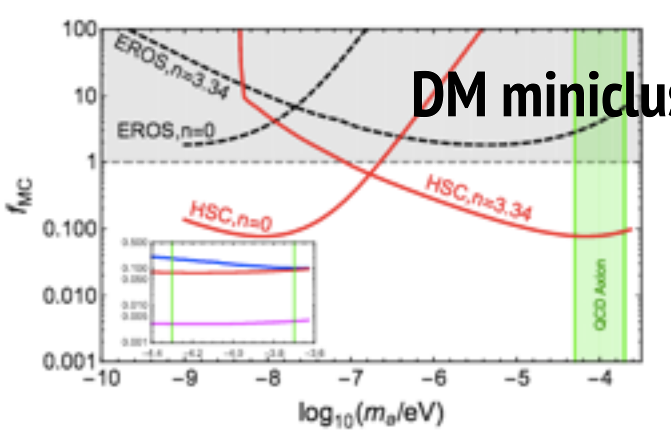
~ 0.1 comoving pc

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

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

Microlensing



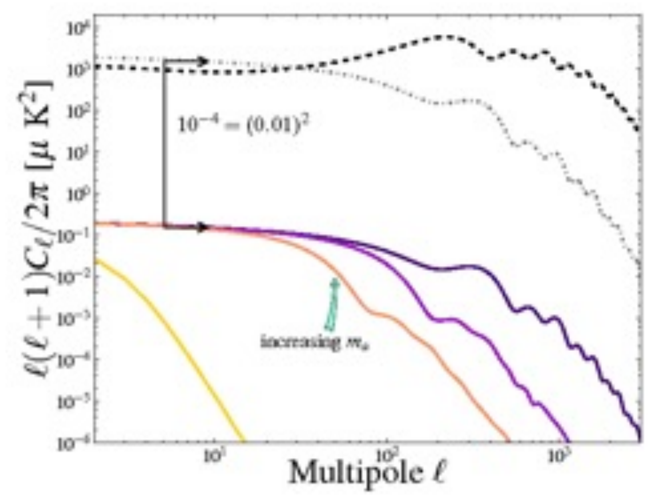


DM minicluster fraction <0.1

Marsh 1701.04787

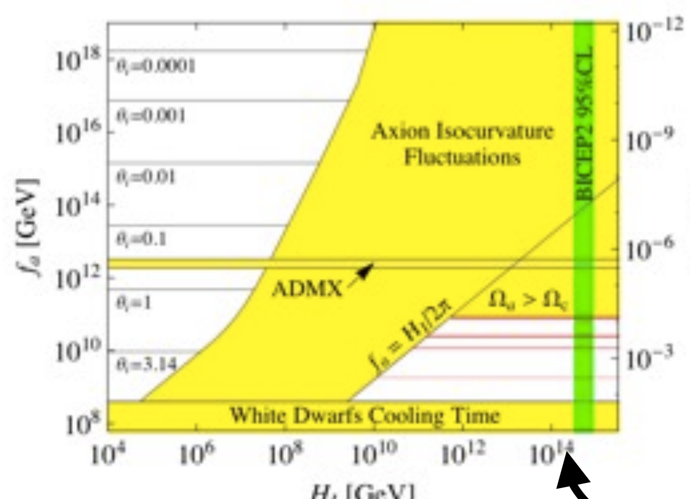
- PQ breaking before inflation

* Axion fluctuations during inflation -> CMB isocurvature



- Planck sees no Isocurvature fluctuations, strong limit!

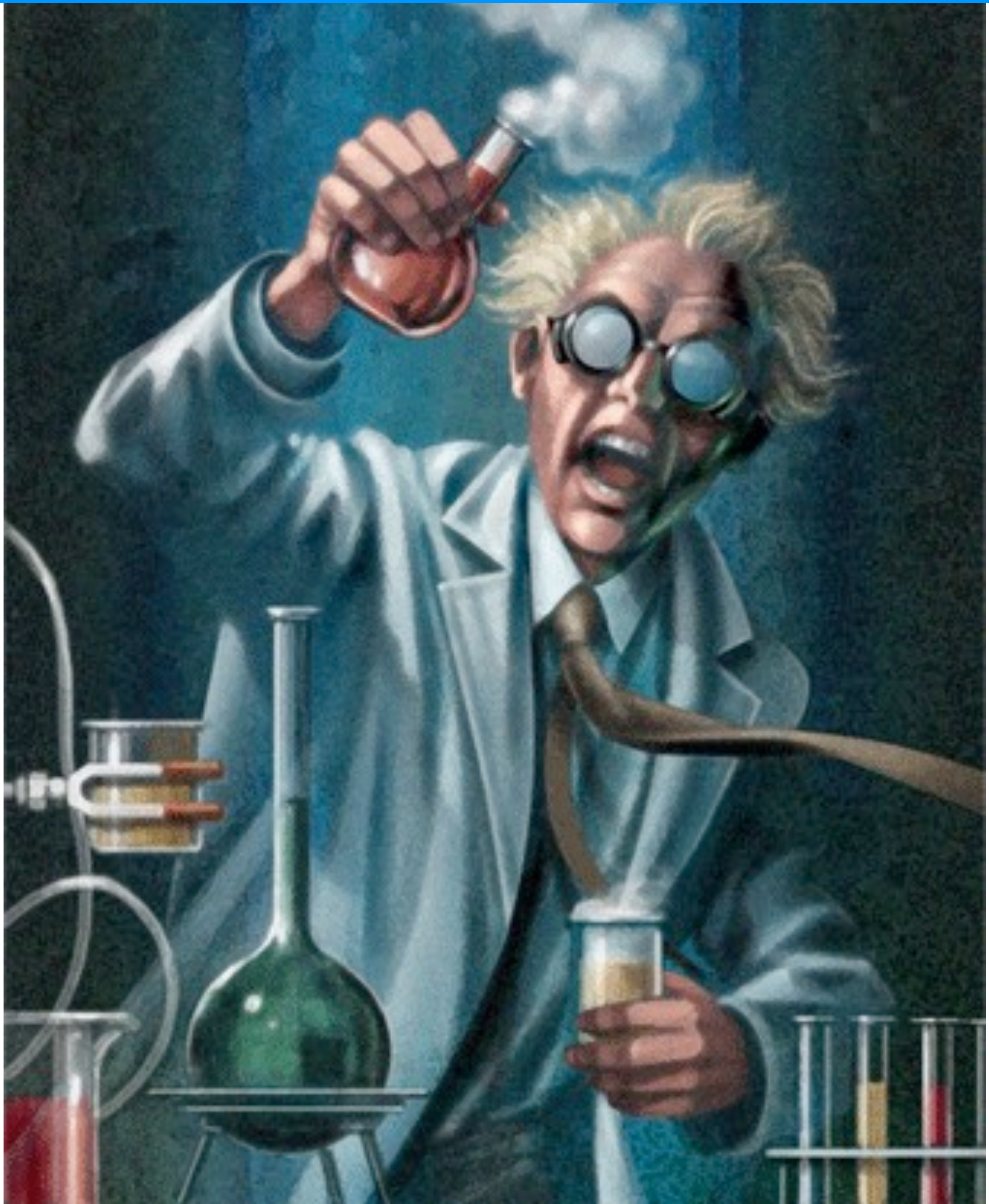
$$P_{\rm iso} = \frac{d\langle n_a\rangle}{n_a} \sim \frac{d\langle a^2\rangle}{a_I^2} = \frac{H_I^2}{\pi^2 a_I^2} = \frac{H_I^2}{\pi^2 f_a^2 \theta_I^2} < 0.039 P_s = 0.88 \times 10^{-10}$$



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)

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 Dark Matter

Imperfect Vacuum realignment

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

$$\rho_{\mathrm{CDM}} = 0.3\frac{\mathrm{GeV}}{\mathrm{cm}^3} \equiv \frac{1}{2}(\dot{a})^2 + \frac{1}{2}m_a^2 a^2 = \frac{1}{2}m_a^2 f_a^2 \theta_0^2$$

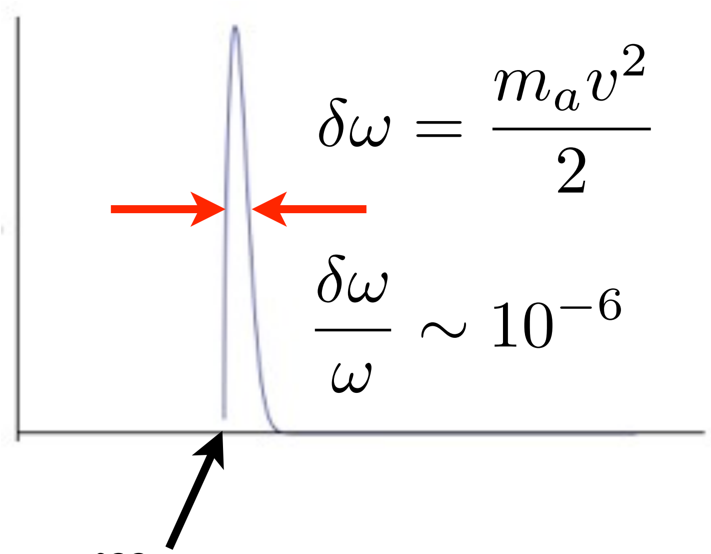
QCD axion

$$\xrightarrow[m_A^2 f_A^2 = \chi_{\mathrm{QCD}}]{} \theta_0 \sim 3.6 \times 10^{-19}$$

Non-zero velocity in galaxy -> finite width

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

~ 10^-6



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

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

m_a

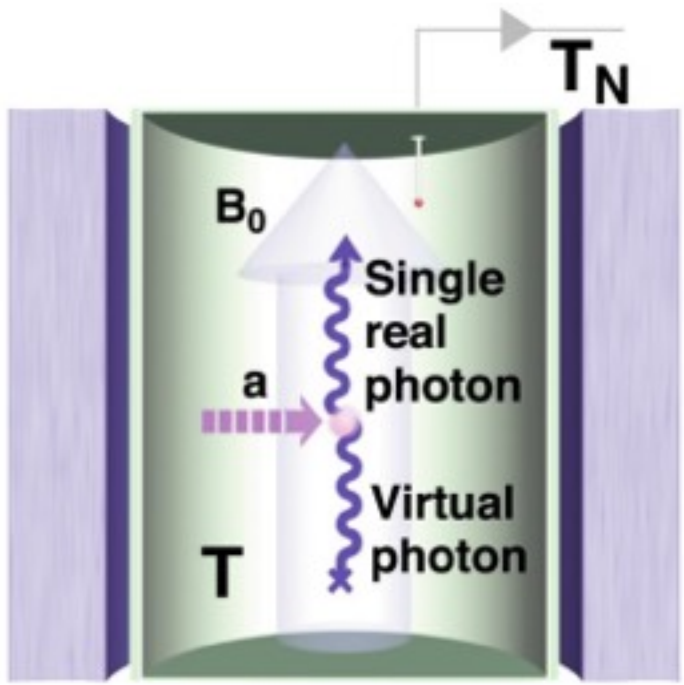
coherence time

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

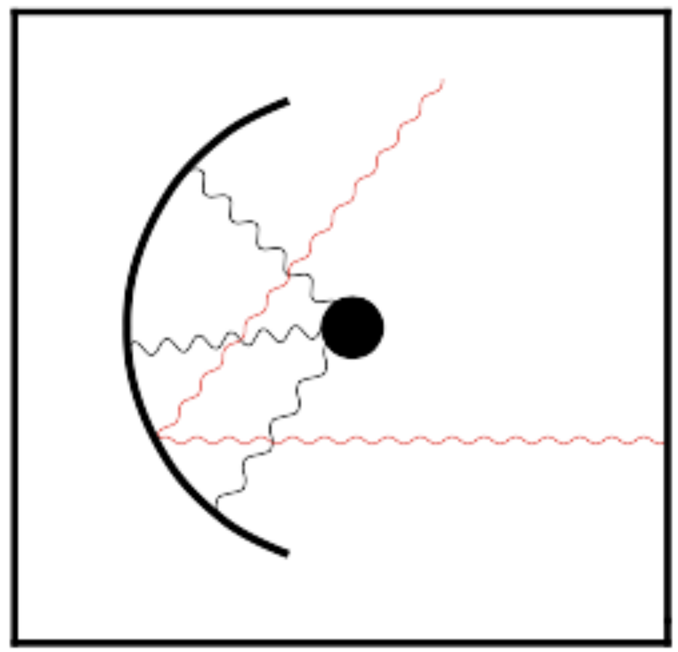
coherence length

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

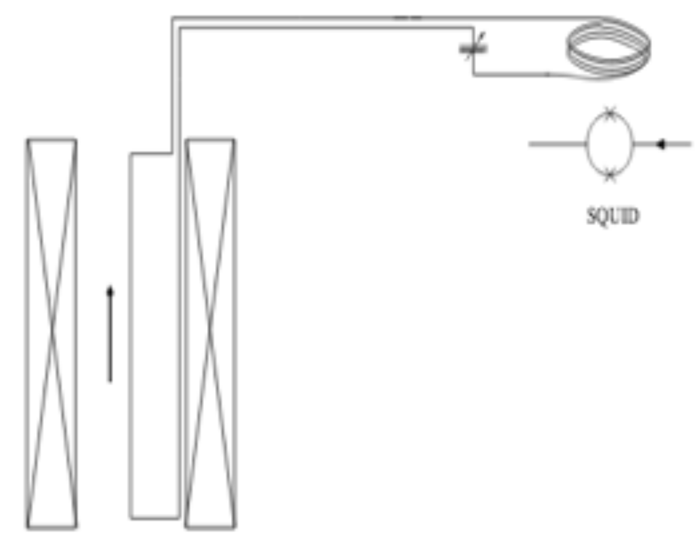
Cavities



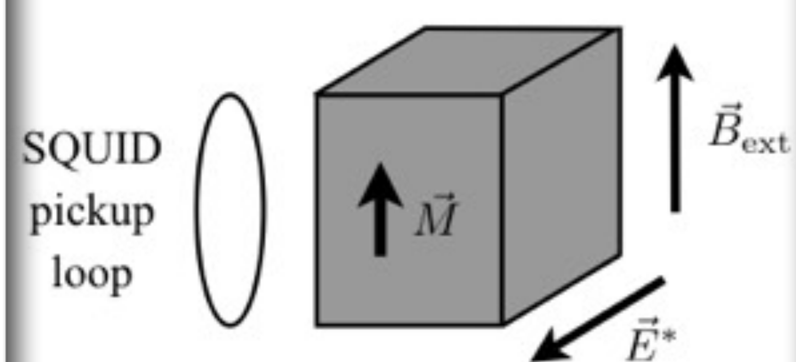
Mirrors



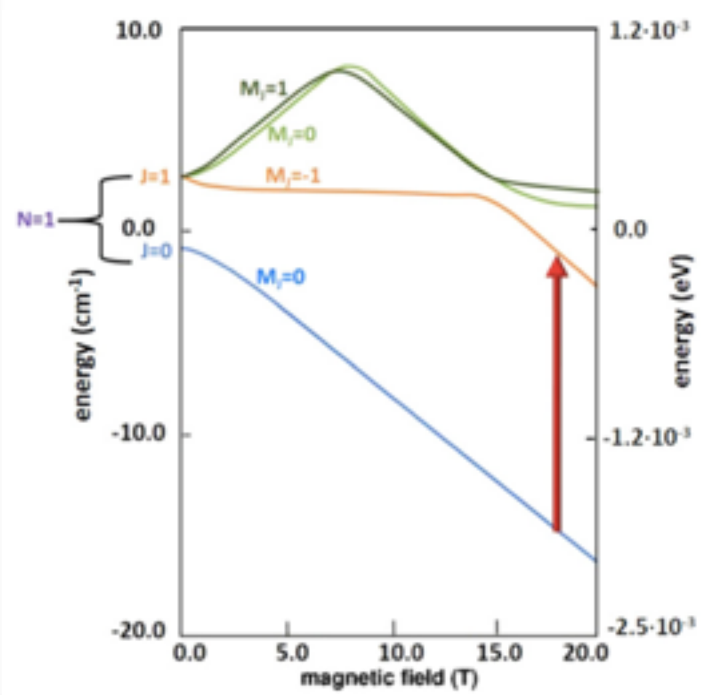
LC-circuit



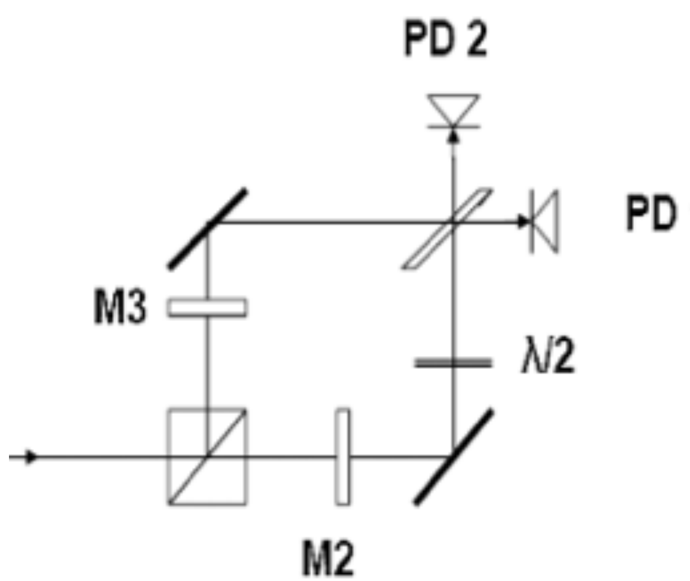
Spin precession



Atomic transitions

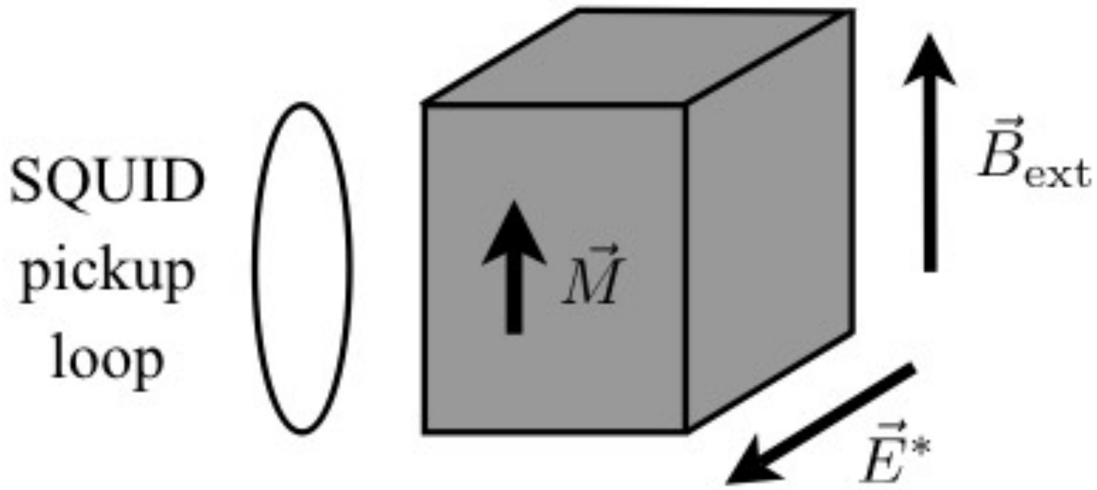


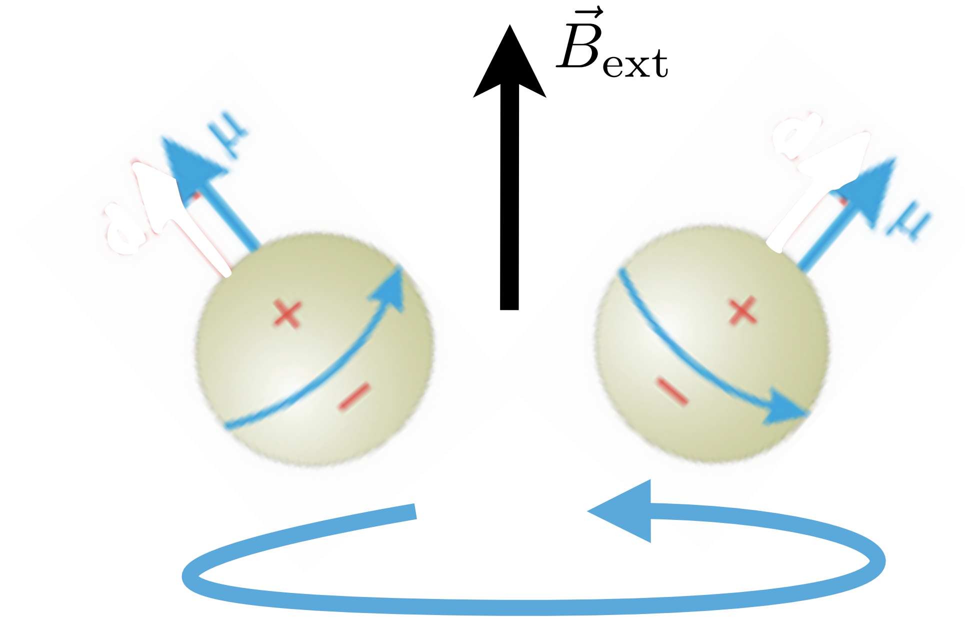
Optical



CASPER: Cosmic Axion Spin Precession exPERiment

Graham 2012



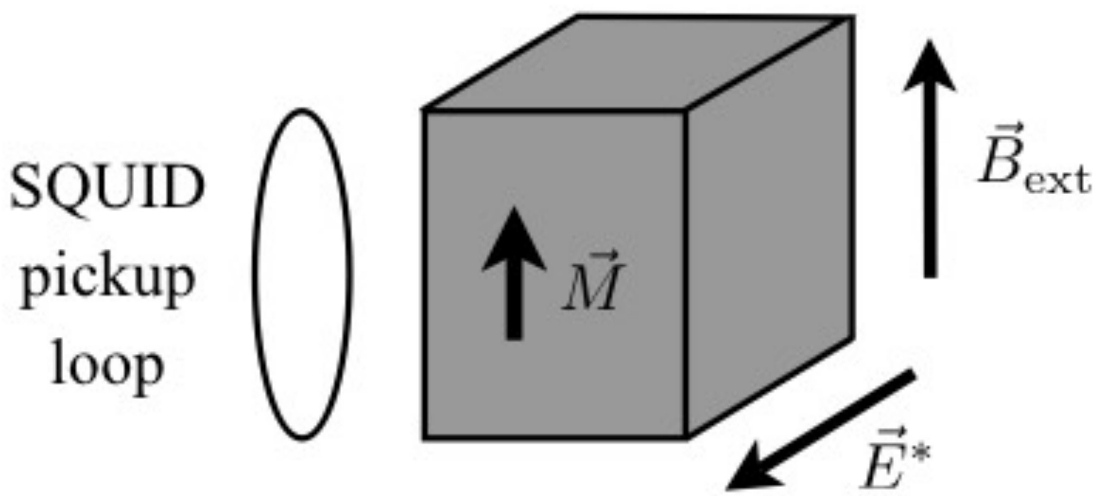


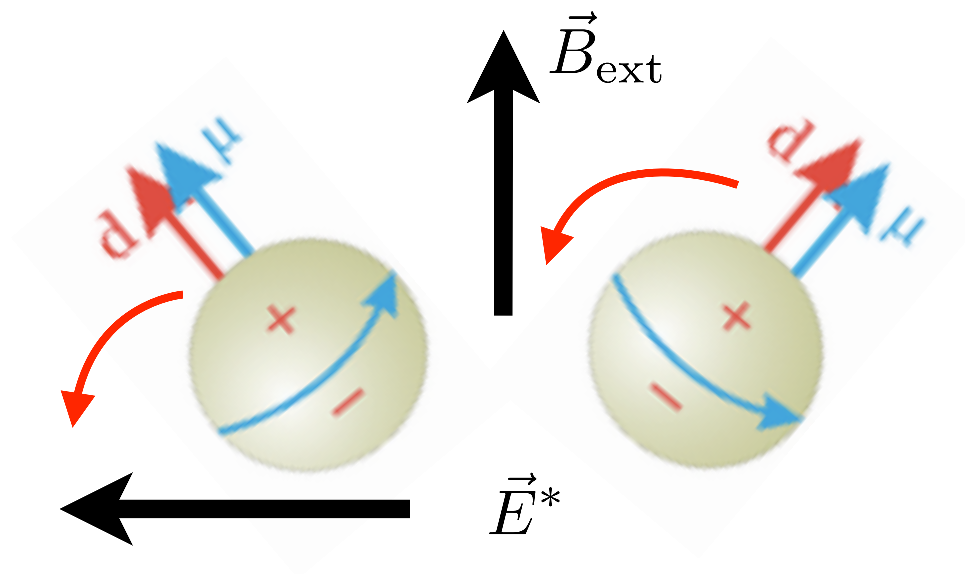
Spin precesion

$$\omega = \mu|\vec{B}_{\rm ext}|$$

CASPER : Spin precession

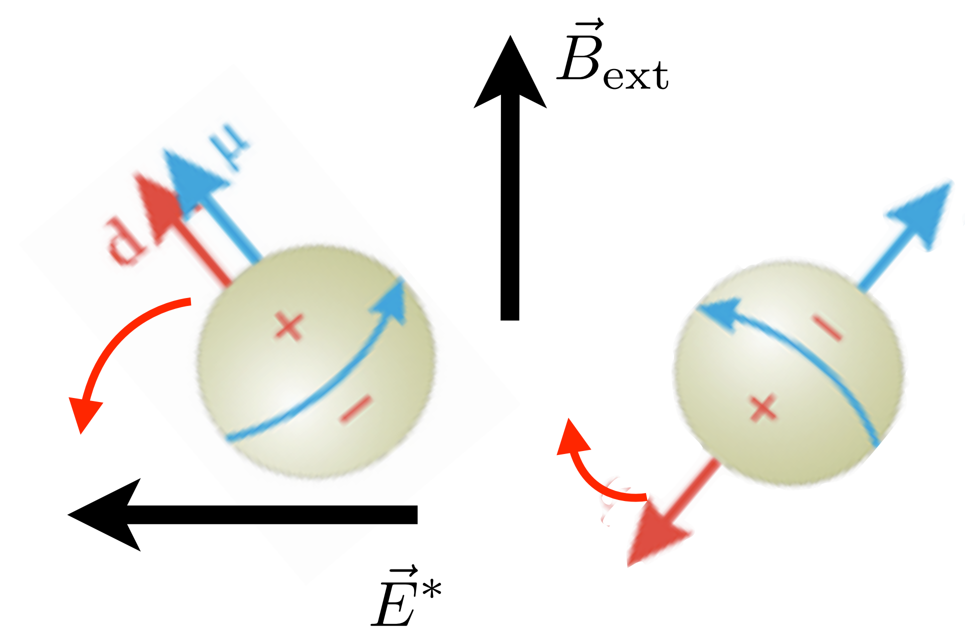
Mainz, Berkeley





Static EDM, effects cancel in a period

- EDM + Large E-fields in PbTiO3
- Scan over frequencies, with Bext
- Mainz (D. Budker's group) & Berkeley
- Phase I starts in 2016, Phase II physics results
- Mass range limited by B-field strength

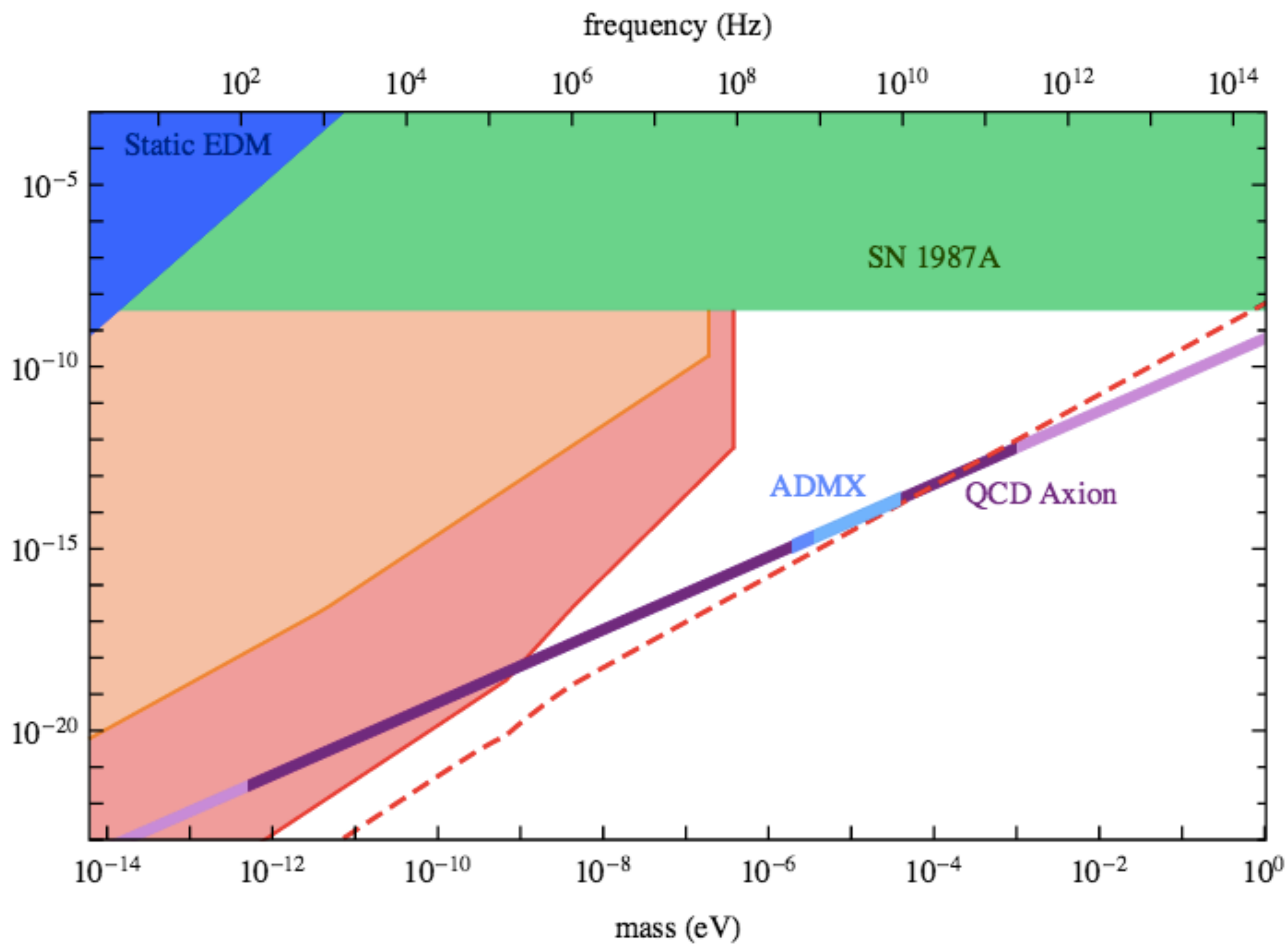


Oscillating EDM, effects add up, transverse magnetisation grows if $m_a = \omega = \mu|\vec{B}_{\text{ext}}|$

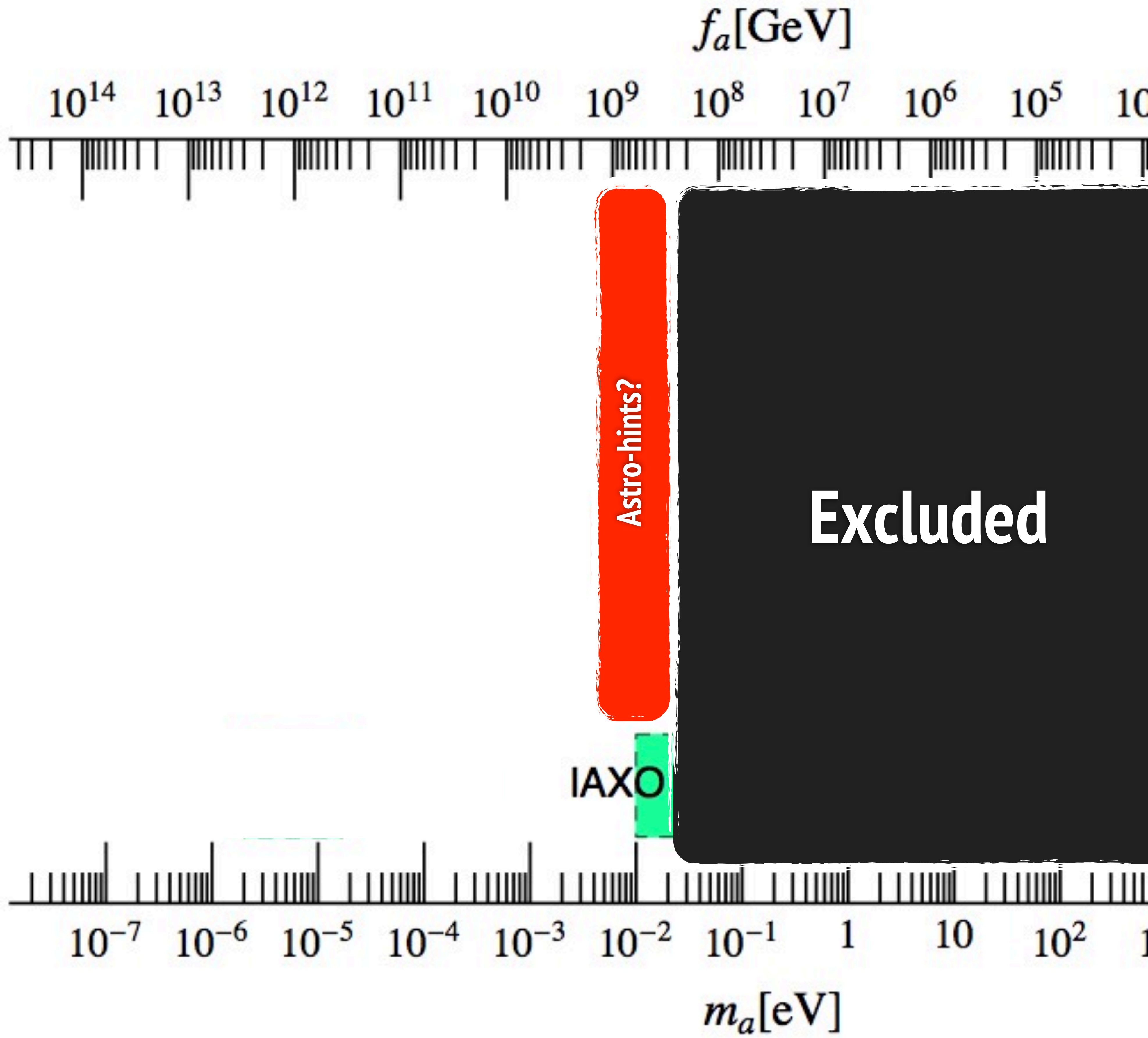
Future sensitivity

Mainz, Berkeley

Coupling to neutron EDM



In the big picture



osc. EDM

DM Axion Photon conversion

- Axion DM, $\theta = \theta_0 \cos(m_a t)$, in a B-field is a source in Maxwell's eq.

$$
\begin{aligned}
\nabla \cdot \mathbf{D} &= \rho_f \\
\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} &= \mathbf{J}_f - c_\gamma \frac{\alpha}{2\pi} \mathbf{B} \frac{\partial \theta}{\partial t} \\
\nabla \cdot \mathbf{B} &= 0 \\
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} &= 0
\end{aligned}
$$

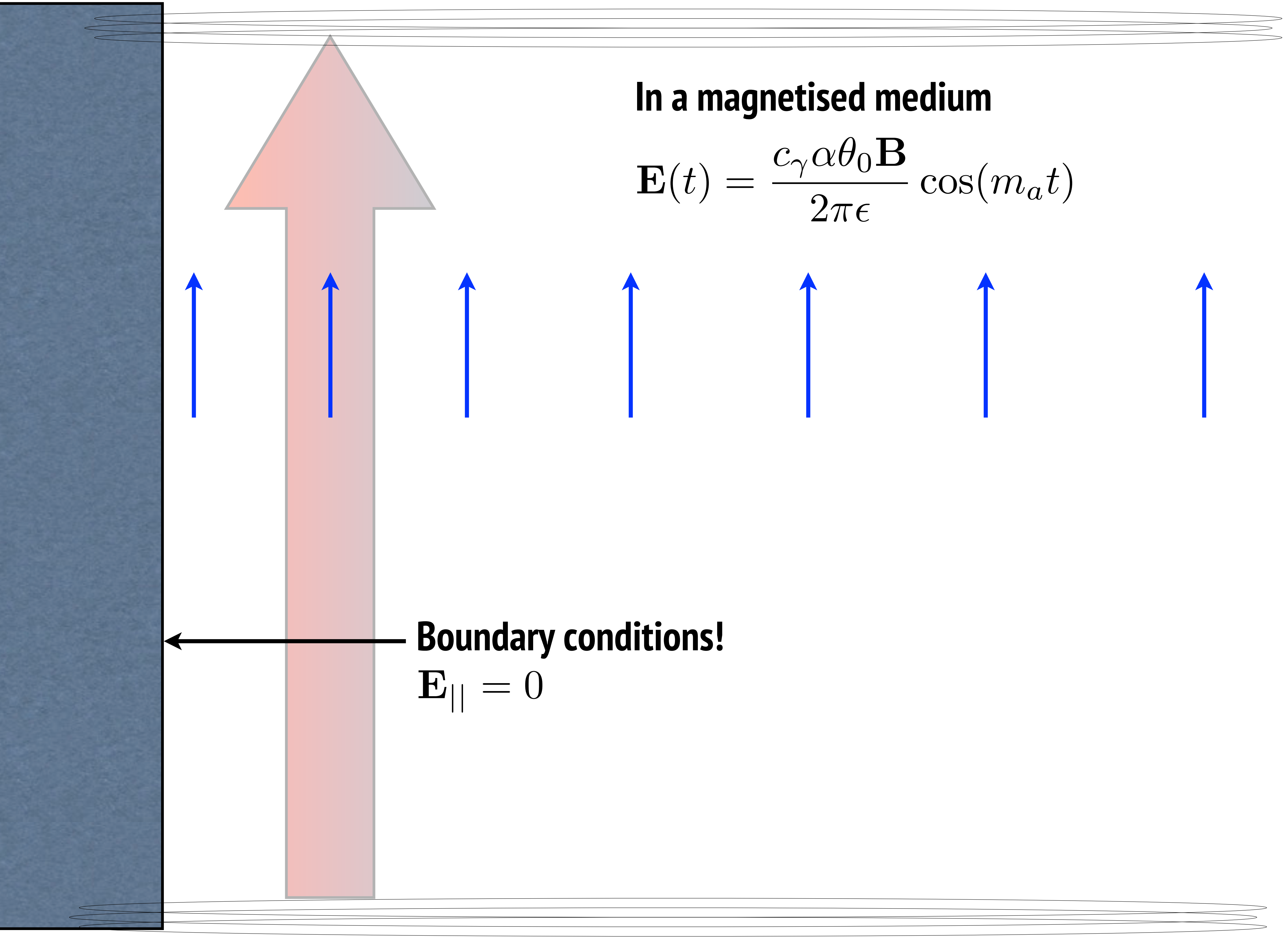
$$\Longrightarrow \quad \mathbf{E}_a(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

In a constant B-field ... ADM generates an oscillating E-field

Radiation from a magnetised mirror

In a magnetised medium

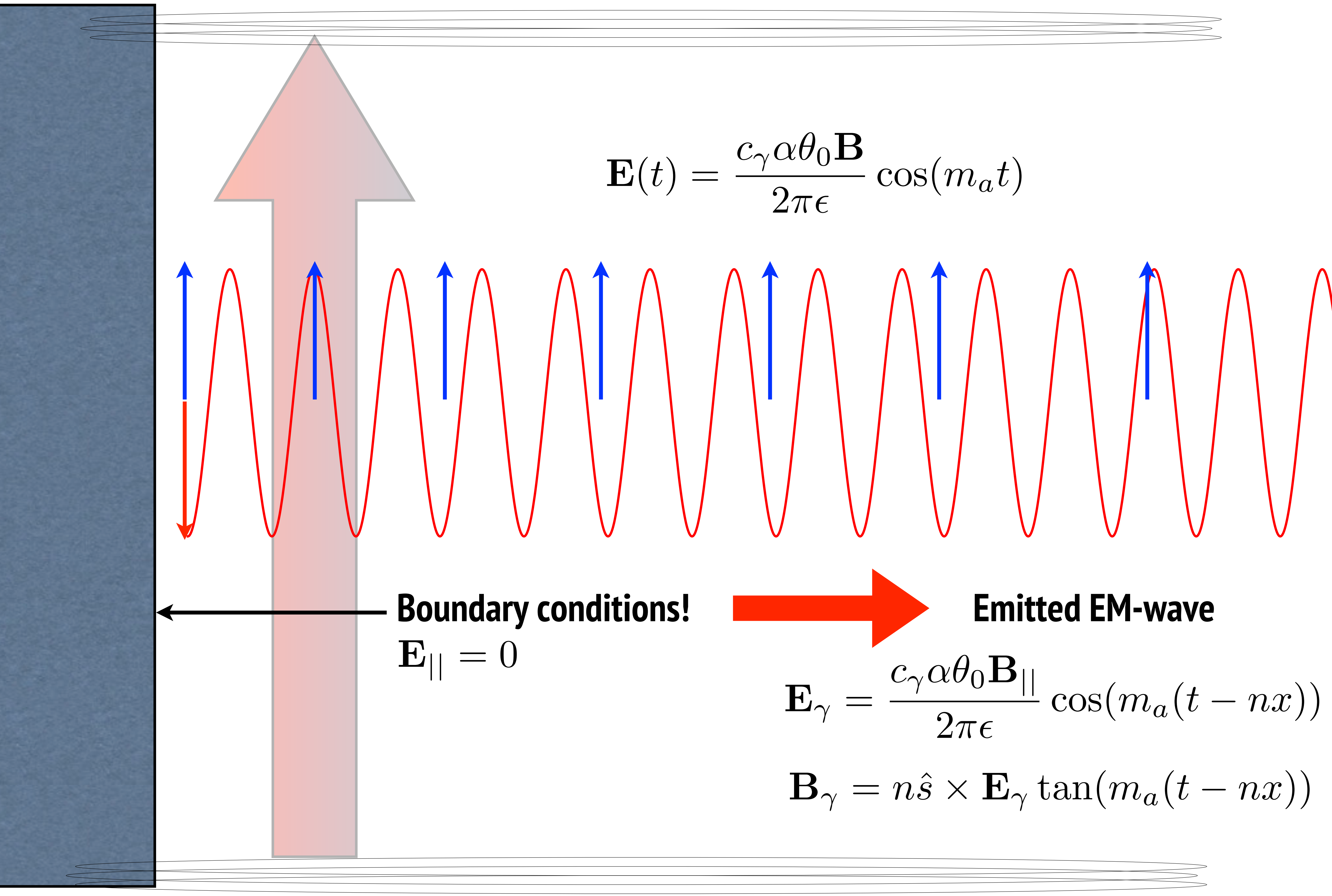
$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$



Boundary conditions!

$$\mathbf{E}_{||} = 0$$

Radiation from a magnetised mirror



$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

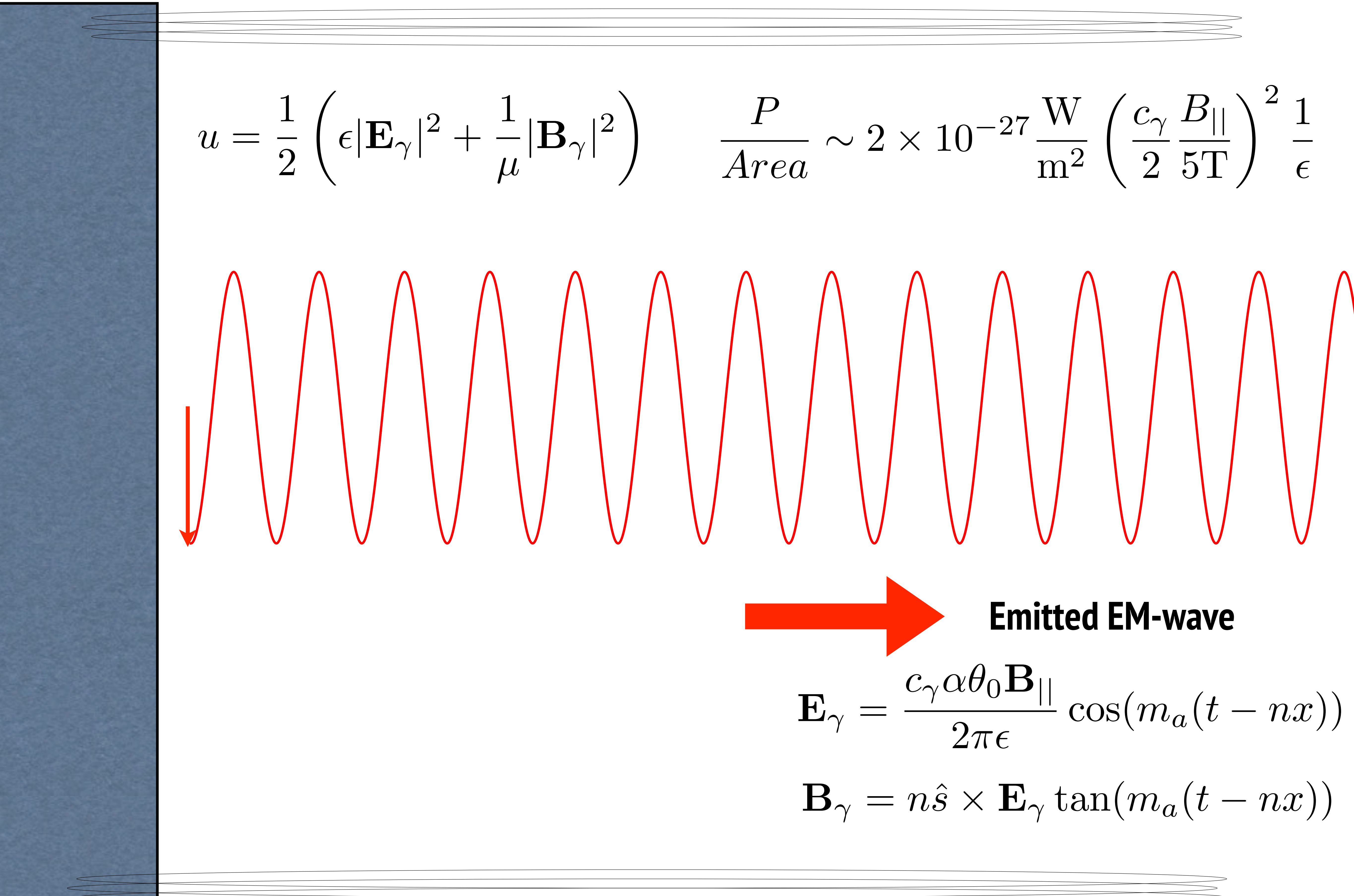
$$\mathbf{E}_{||} = 0$$

$$\mathbf{E}_\gamma = \frac{c_\gamma \alpha \theta_0 \mathbf{B}_{||}}{2\pi\epsilon} \cos(m_a(t - nx))$$

$$\mathbf{B}_\gamma = n\hat{s} \times \mathbf{E}_\gamma \tan(m_a(t - nx))$$

Radiation from a magnetised mirror : Power

$$u = \frac{1}{2}\left(\epsilon|\mathbf{E}_\gamma|^2 + \frac{1}{\mu}|\mathbf{B}_\gamma|^2\right) \qquad \frac{P}{Area} \sim 2\times 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{c_\gamma}{2}\,\frac{B_{||}}{5\mathrm{T}}\right)^2 \frac{1}{\epsilon}$$



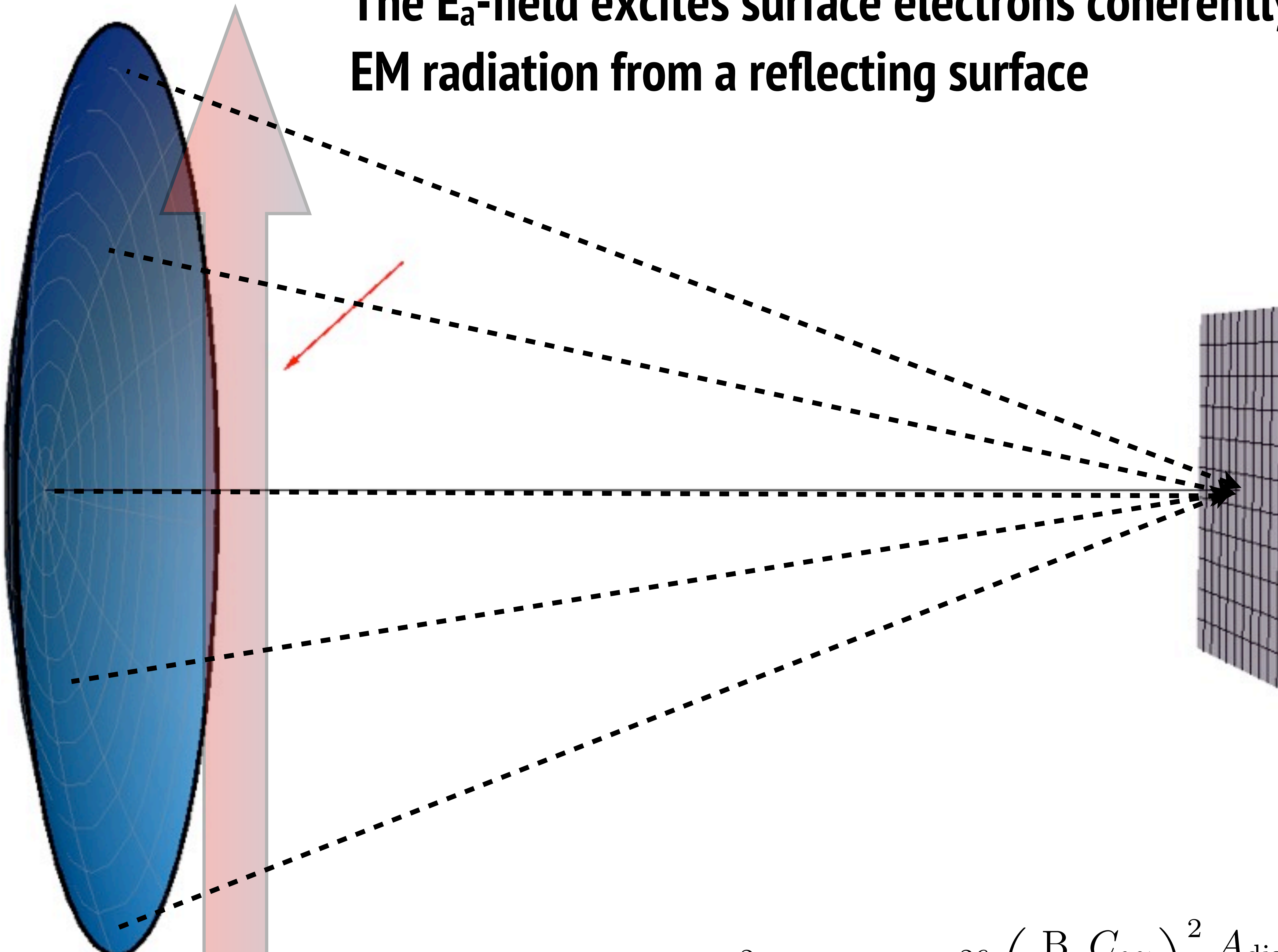
$$\mathbf{E}_\gamma = \frac{c_\gamma \alpha \theta_0 \mathbf{B}_{||}}{2\pi\epsilon}\cos(m_a(t - nx))$$

$$\mathbf{B}_\gamma = n\hat{s}\times\mathbf{E}_\gamma \tan(m_a(t - nx))$$

Dish antenna experiment?

Horns 2012

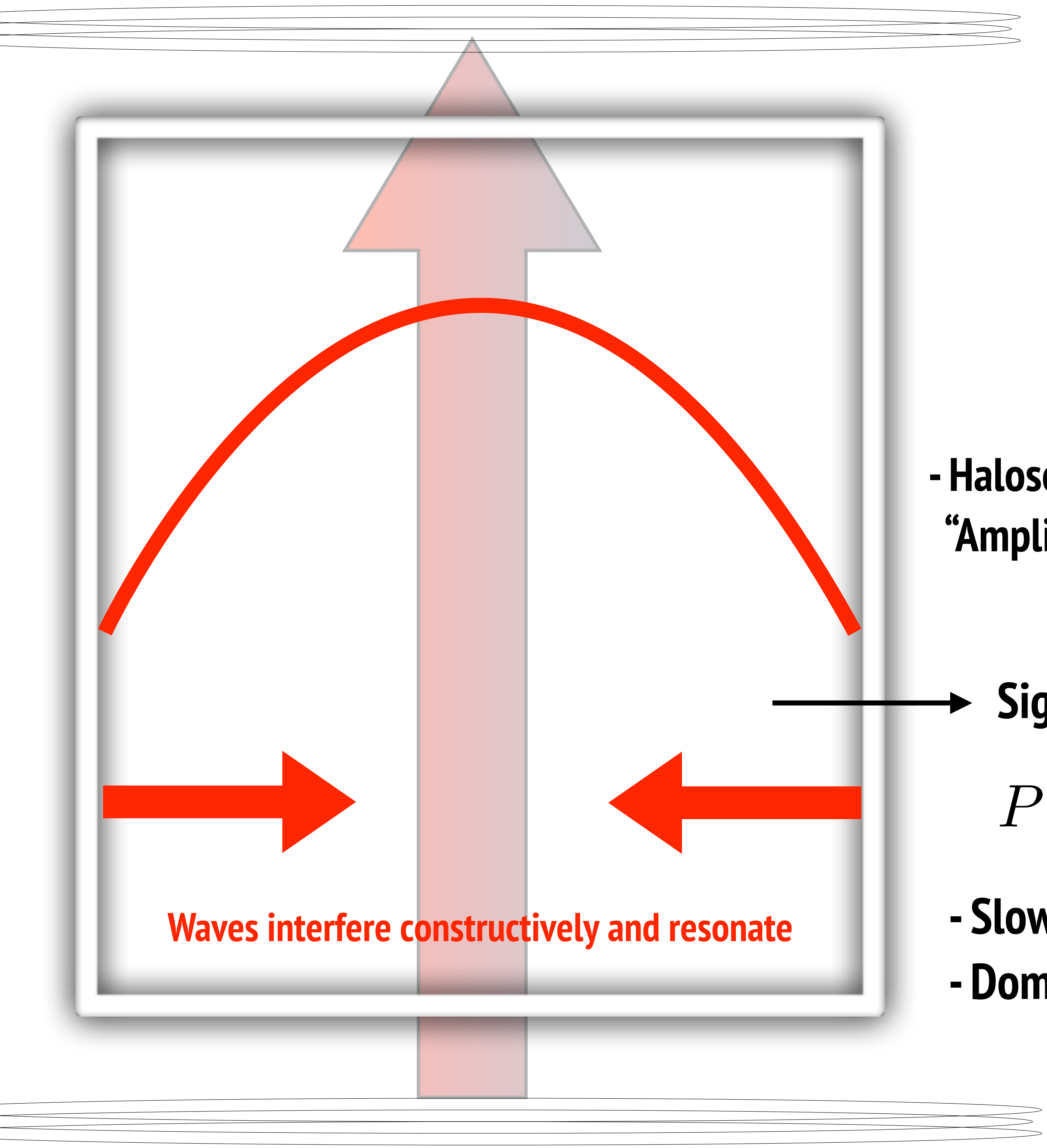
The E_a-field excites surface electrons coherently
EM radiation from a reflecting surface



spherical reflecting dish

$$P \sim |\mathbf{E}_a|^2 A_{\rm dish} \sim 10^{-26} \left(\frac{\rm B}{5\rm T}\frac{C_{a\gamma}}{2}\right)^2 \frac{A_{\rm dish}}{1\,{\rm m}^2} \rm Watt$$

Cavity experiments



- Haloscope (Sikivie 83)
  "Amplify resonantly the EM field in a cavity"

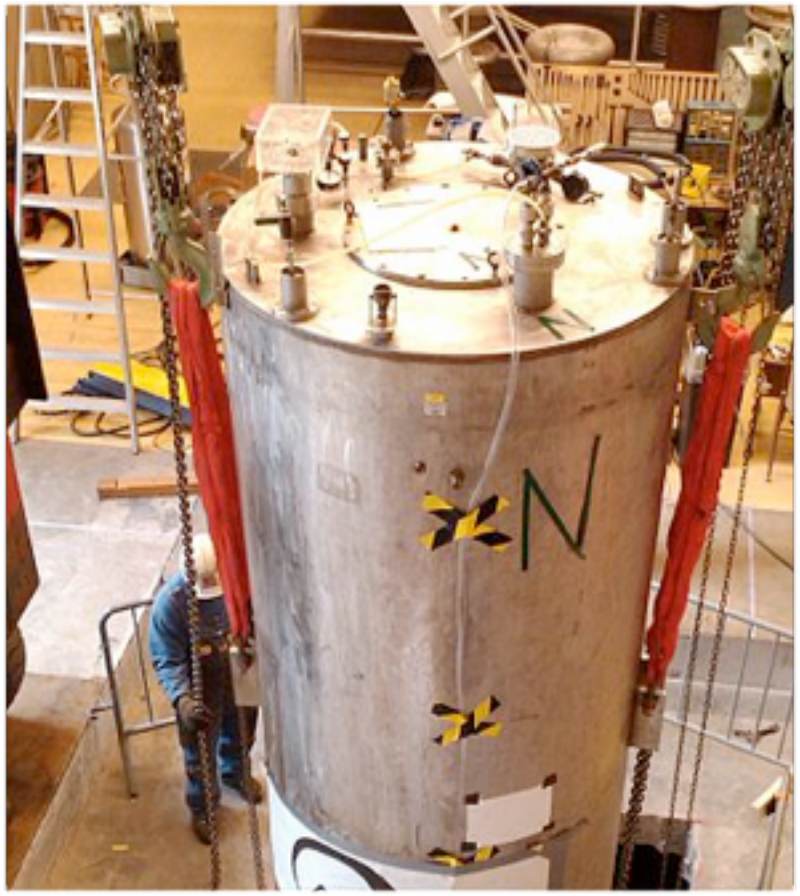
Signal if tuned

$$P \to P \times Q$$

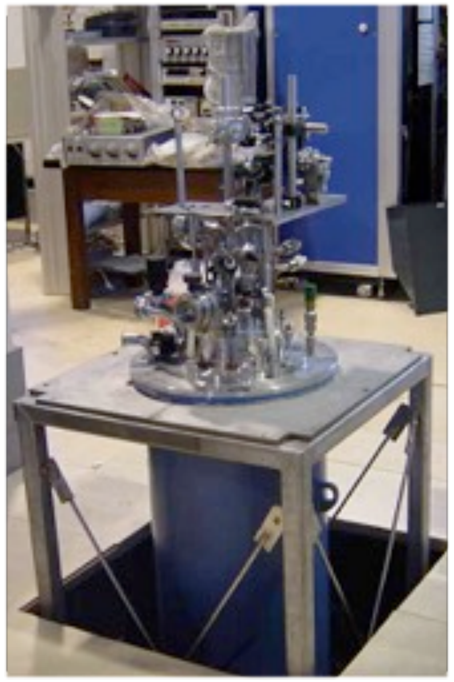
- Slow scan over frequencies
- Dominated by thermal+preamp noise

Cavity experiments

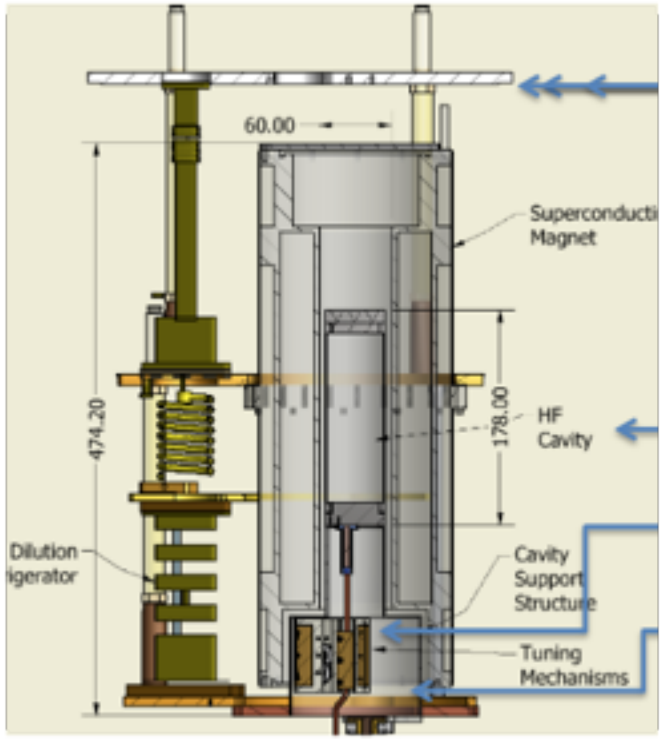
ADMX



CARRACK (discontinued)

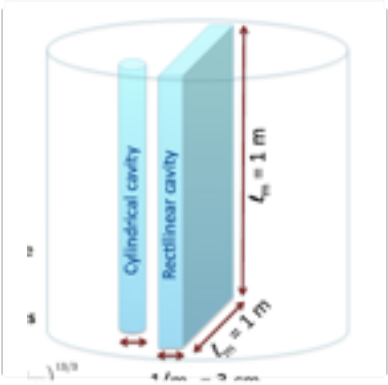


CULTASK - CAPP -Korea

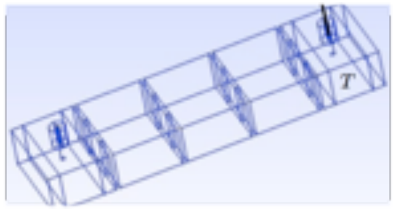


ADMX-HF

ADMX-Fermilab



RADES



CAST-CAPP

Signal power in cavity experiments (haloscopes)

$$c_\alpha = \frac{c_\gamma \alpha}{2\pi}$$

Combine MW equations into an oscillator

$$\ddot{\mathbf{E}} - \nabla^2 \mathbf{E} = -\frac{c_\gamma \alpha}{2\pi} \mathbf{B}_{\rm ext}\, \ddot{\theta}$$

Expand in eigenmodes of the cavity satisfy (with appropriate boundary conditions)

$$\mathbf{E}(t, \mathbf{x}) = \sum_i E_i(t) \mathbf{e}_i. \qquad -\nabla^2 \mathbf{e}_i = \omega_i^2 \mathbf{e}_i.$$

Equation for the amplitude of one mode

geometric factor ...

$$\ddot{E}_i + \omega_i^2 E_i + \Gamma \dot{E}_i = -c_\alpha B C_i \ddot{\theta}. \qquad C_i = \frac{1}{VB} \int dV \mathbf{e}_i \cdot \mathbf{B}_{\rm ext}.$$

damping (energy loss by walls and pick up signal)

damping (energy loss by walls and pick up signal)

Forced oscillator solution

$$E_i = -\frac{c_\alpha B m_a^2 C_i}{(m_a^2 - \omega_i^2)^2 + (m_a \Gamma)^2} \left(\theta(t)(m_a^2 - \omega_i^2) + \dot{\theta}(t) \Gamma \right),$$

Resonance quality factor $Q = \omega_i / \Gamma$

Off-resonance $m_a \gg \omega_i$

$$\boxed{E_i \sim c_\alpha B C_i \theta(t) \sim |\mathbf{E}_a|}$$

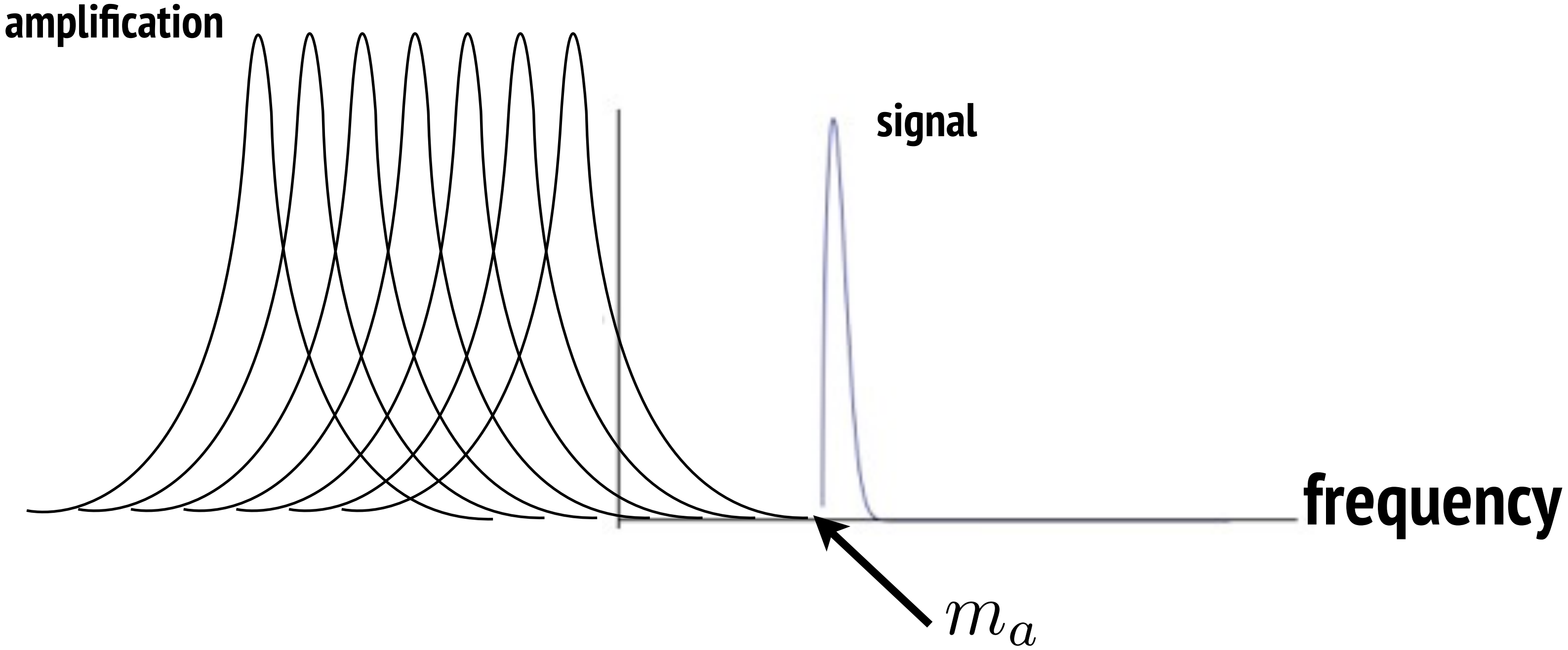
On resonance $m_a = \omega_i$

$$\boxed{E_i \sim |\mathbf{E}_a| Q}$$

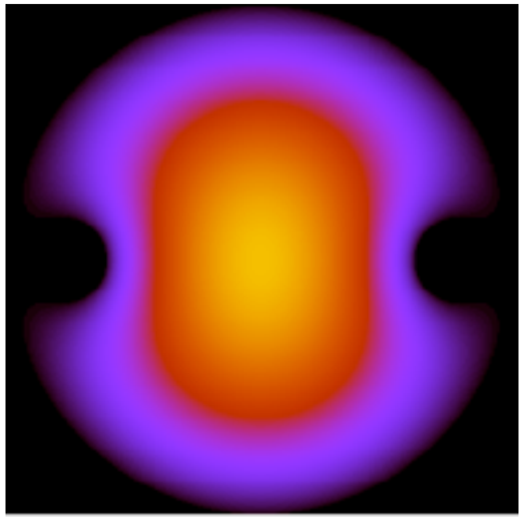
but needs tuning!

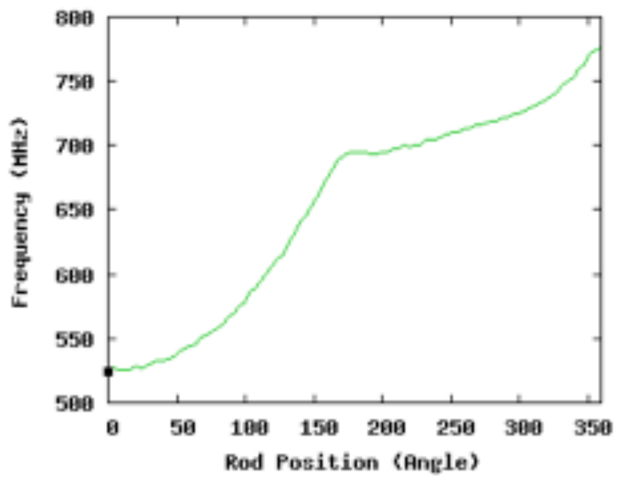
Power extracted from cavity on resonance $$P \sim \frac{\Gamma}{m_a} E^2 \sim Q|\mathbf{E}_a|^2$$

But we do not know axion mass ... need to tune cavity and do different experiments

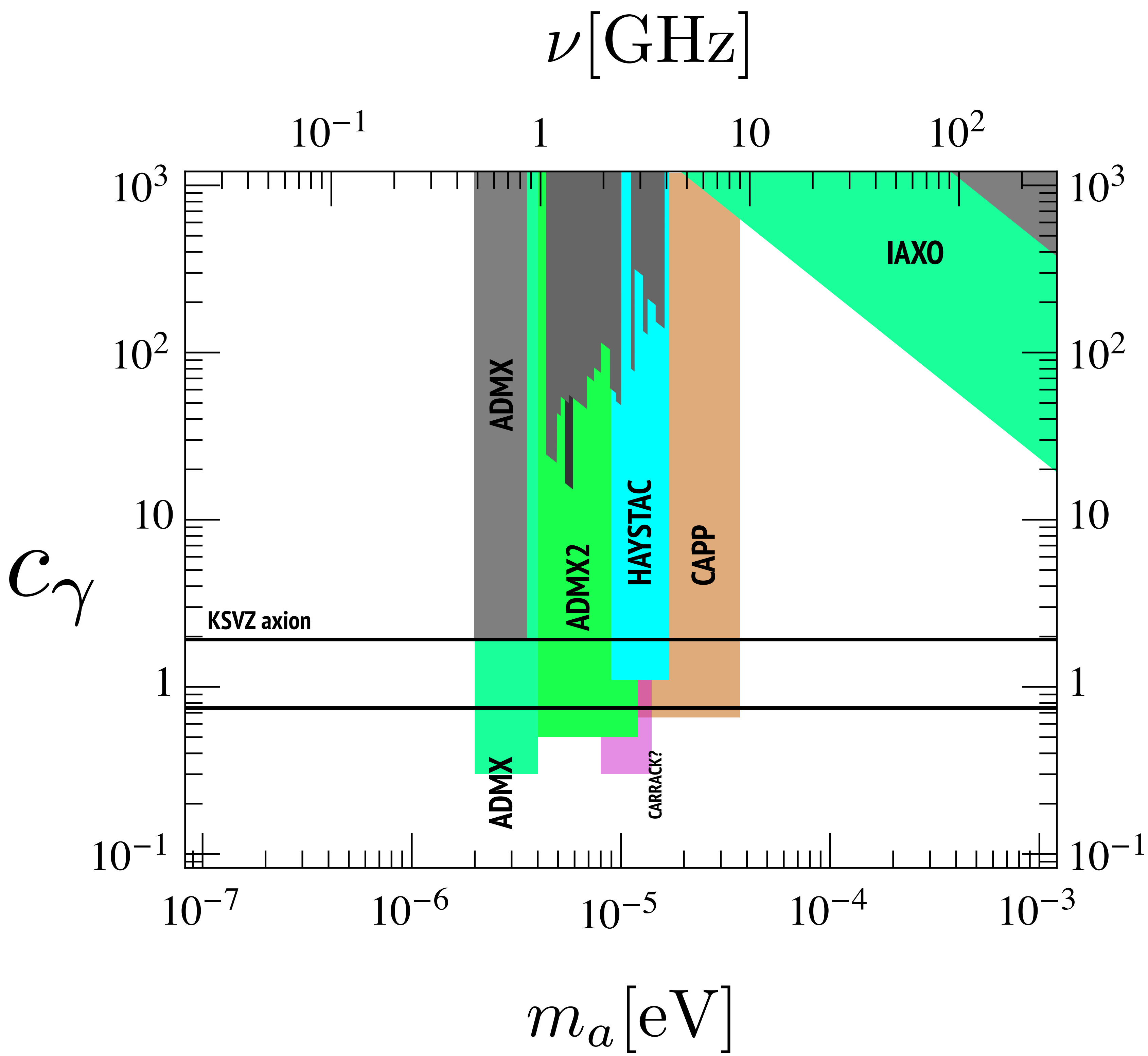


Scanning over frequencies moving metalic rods (ADMX)





Cavity experiments



Problem at high mass

- Haloscope

$$P \sim Q|\mathbf{E}_a|^2(Vm_a)\mathcal{G}\kappa$$ (ON RESONANCE)

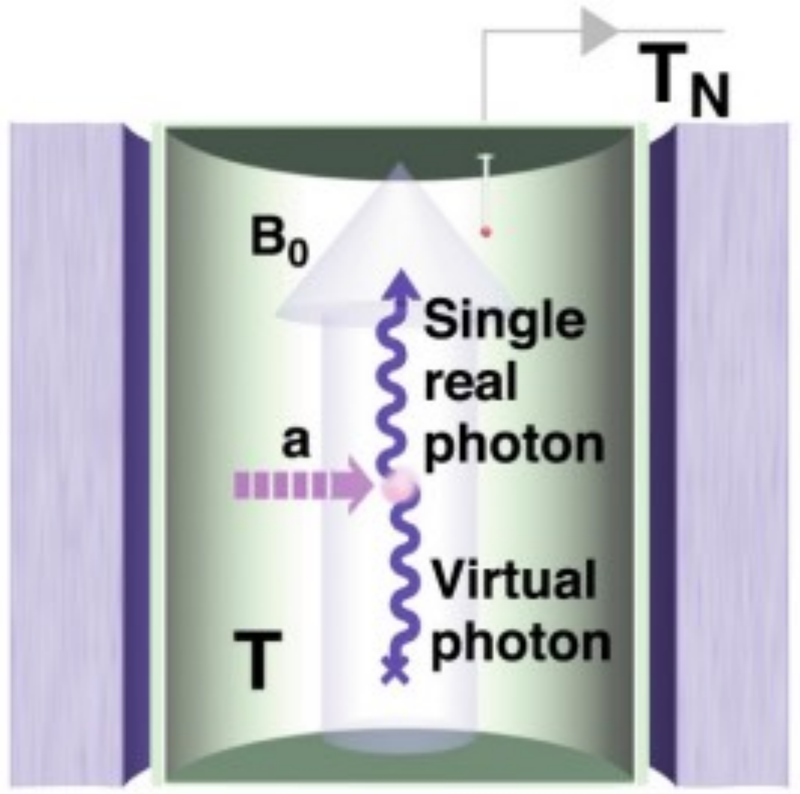
- Naive ADMX scaling (e.g. an ADMX every octave)

- Signal $(V \propto m_a^{-3})$ $$P_{\rm out} \propto V m_a \sim \frac{1}{m_a^2}$$

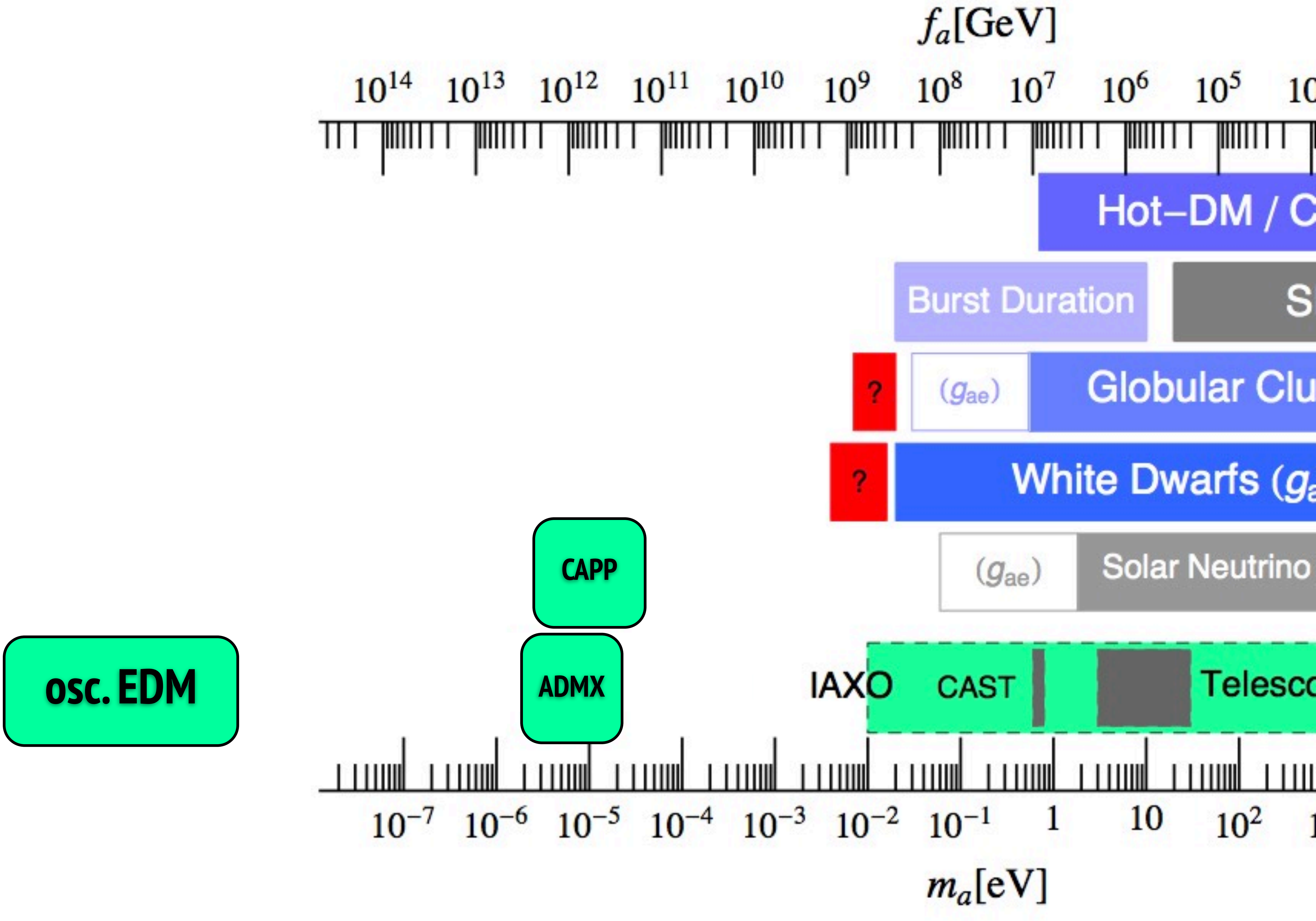
- Noise $$P_{\rm noise} = T_{\rm sys}\Delta\nu_a \propto m_a^2$$

- Signal/noise in $\Delta\nu_a$ of time, t, $$\frac{S}{N} = \frac{P_{\rm out}}{P_{\rm noise}}\sqrt{\Delta\nu_a t}$$

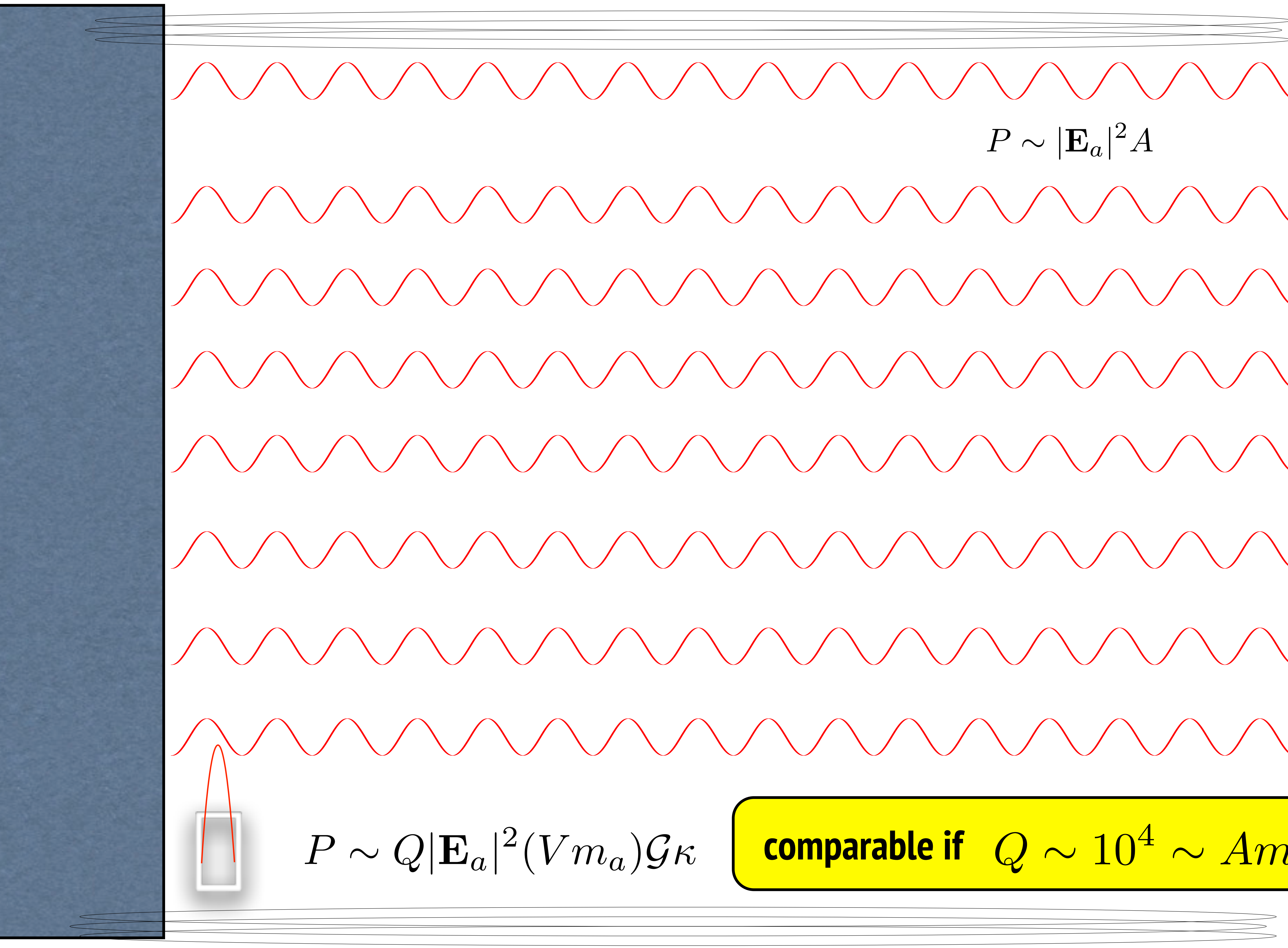
- Scanning rate $$\frac{1}{m_a}\frac{d\Delta m_a}{dt} \propto \frac{C_{A\gamma}^4}{m_a^7}$$



Conclusions : a developing picture



Large freq ... Area vs volume



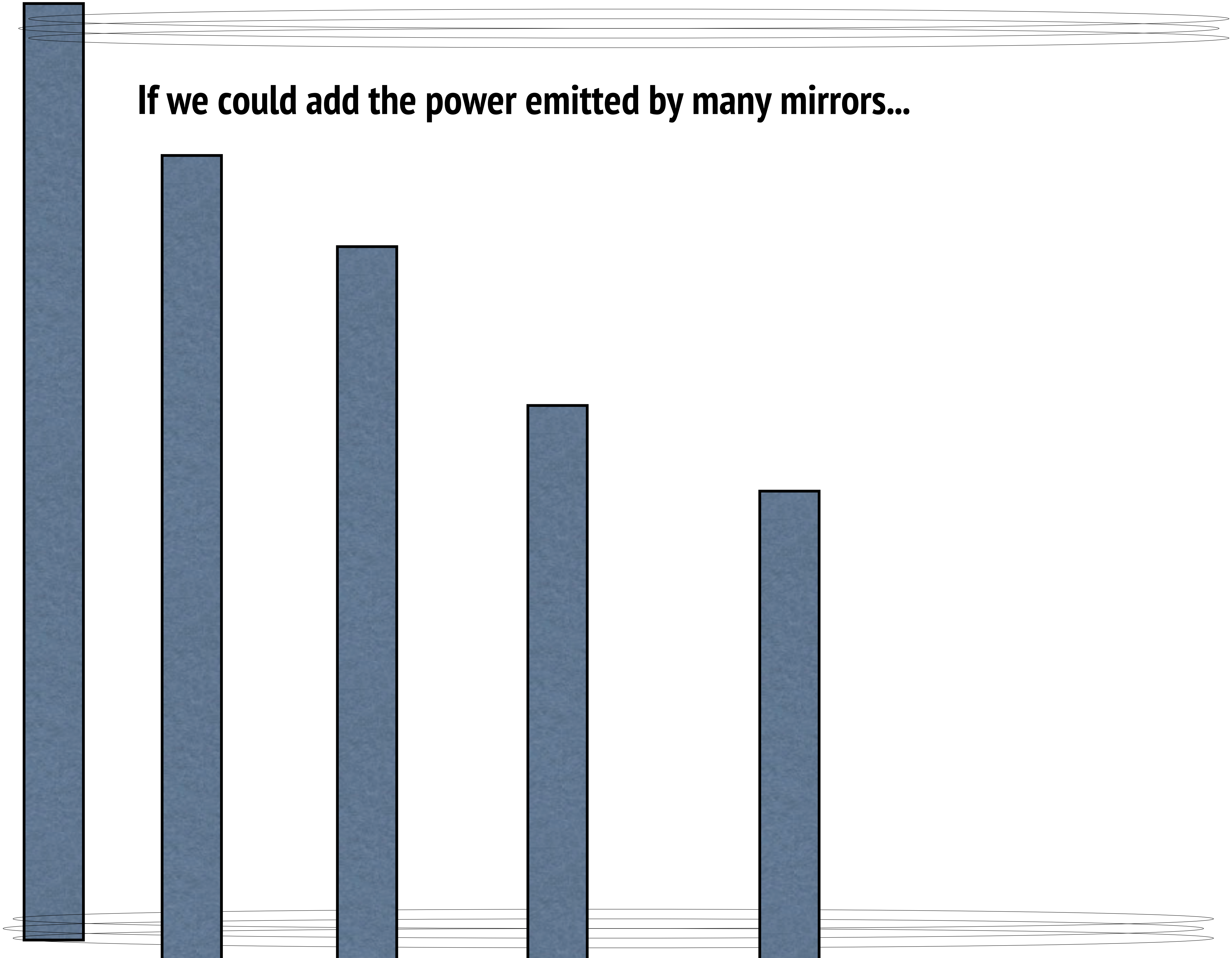
$P \sim |\mathbf{E}_a|^2 A$

$P \sim Q|\mathbf{E}_a|^2 (V m_a) \mathcal{G} \kappa$

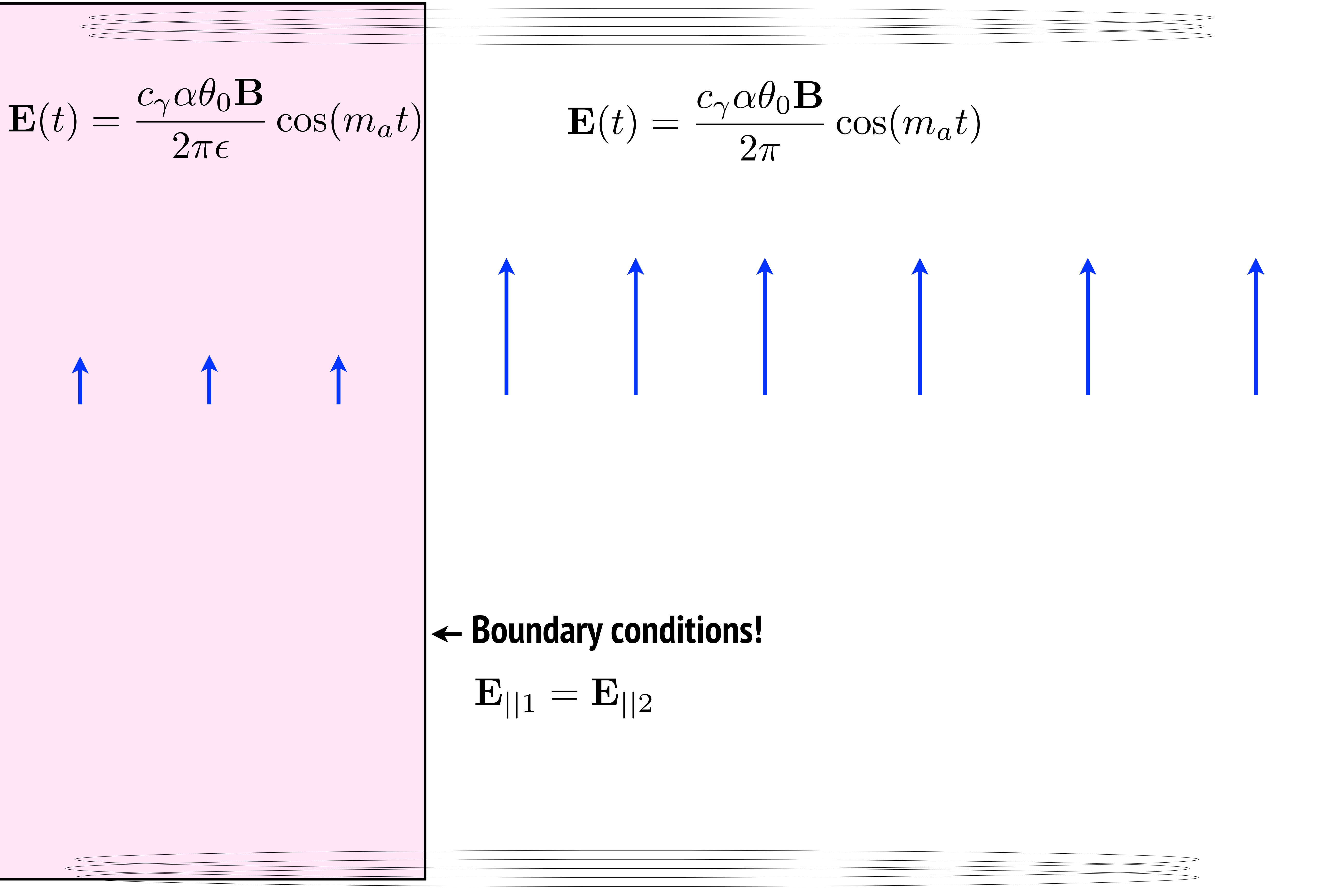
comparable if $Q \sim 10^4 \sim A m_a^2$

Mixed scheme?

If we could add the power emitted by many mirrors...



Radiation from a dielectric interface ...



$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi} \cos(m_a t)$$

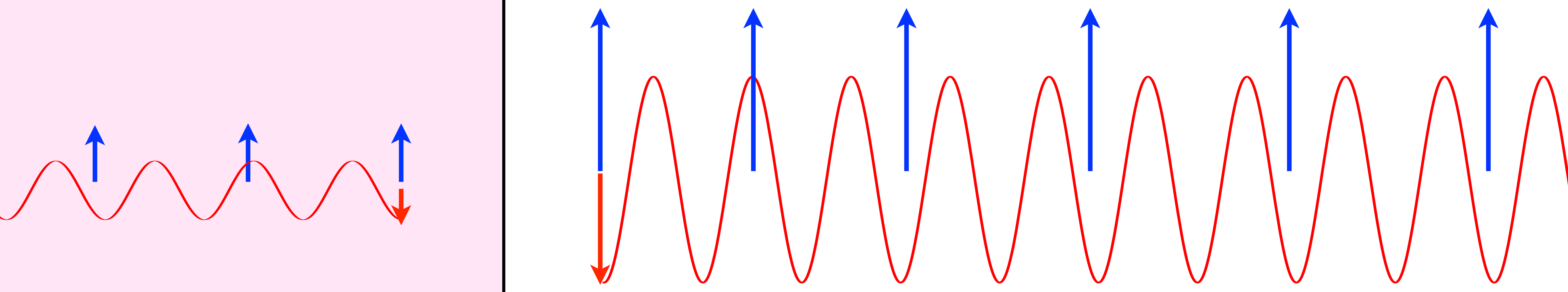
← **Boundary conditions!**

$$\mathbf{E}_{||1} = \mathbf{E}_{||2}$$

Radiation from a dielectric interface ...

$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi} \cos(m_a t)$$



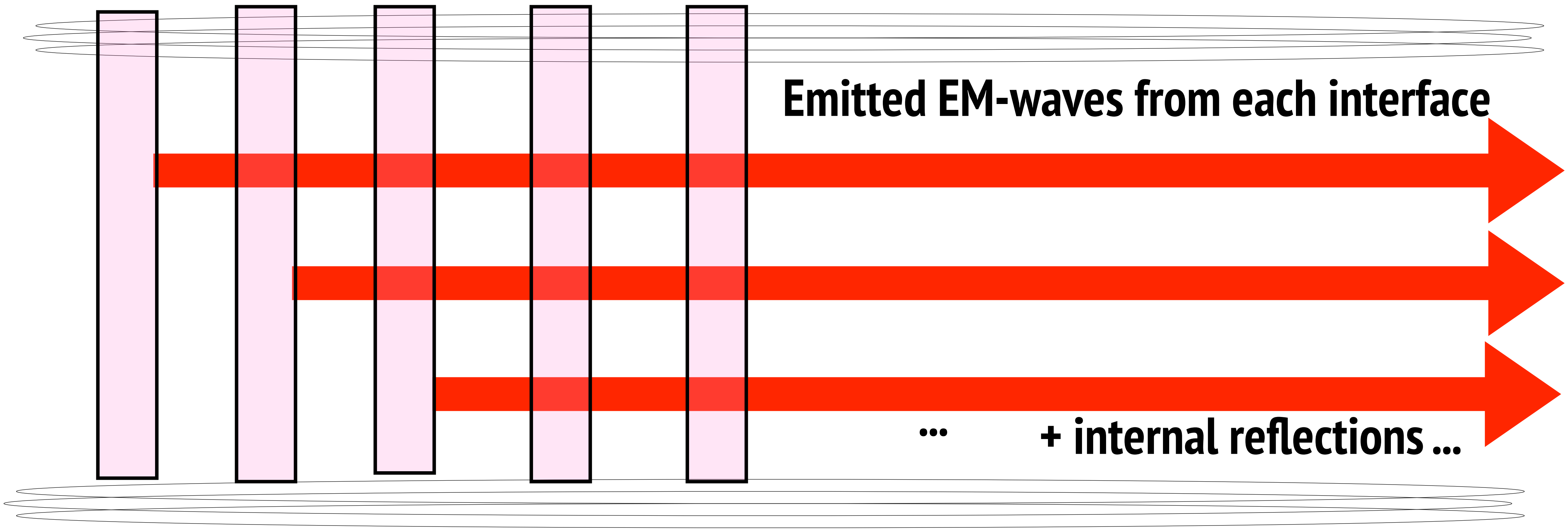
Emitted EM-wave

← Boundary conditions!

$$\mathbf{E}_{||1} = \mathbf{E}_{||2}$$

Emitted EM-wave

Many dielectrics : MADMAX at MPP Munich

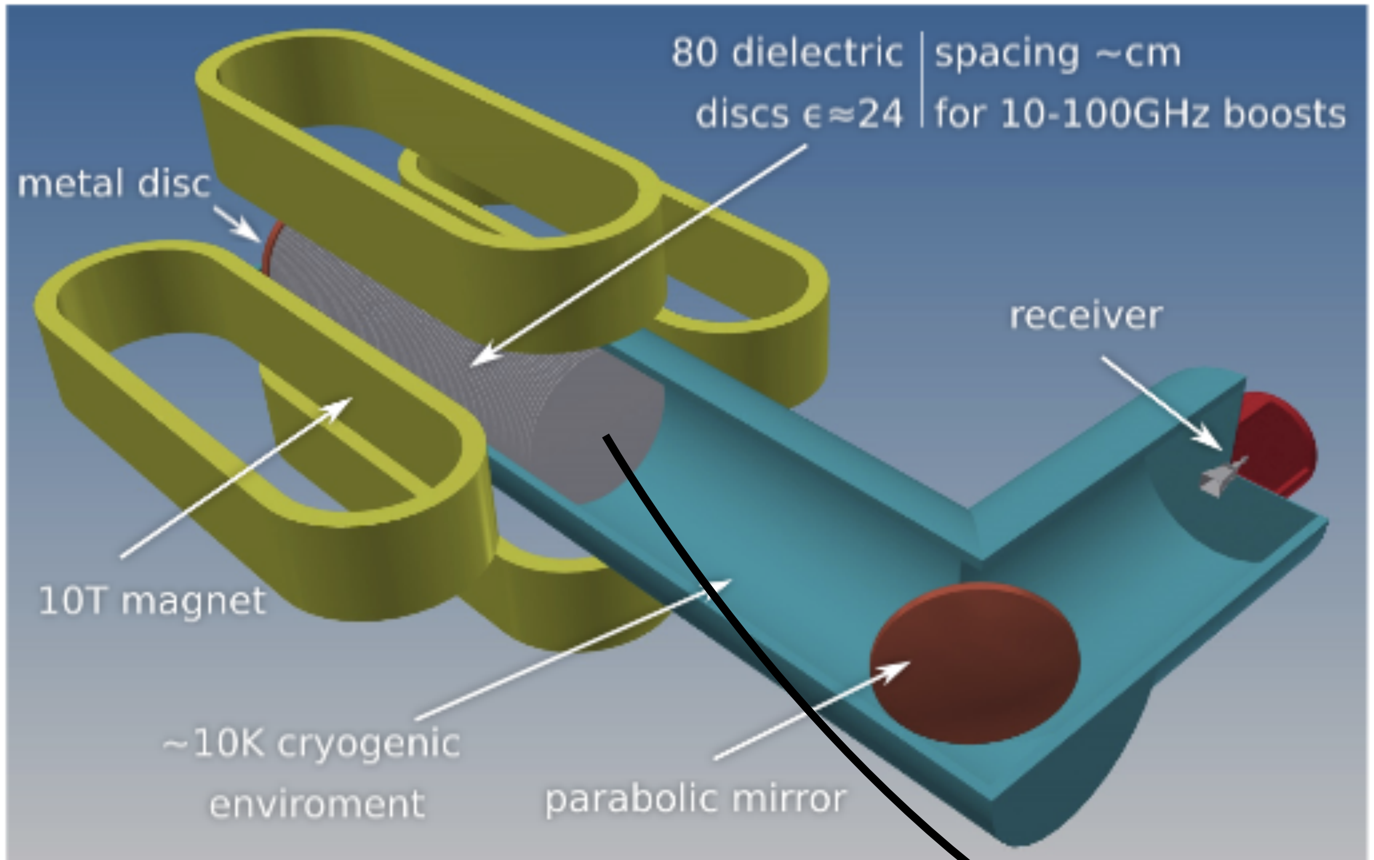


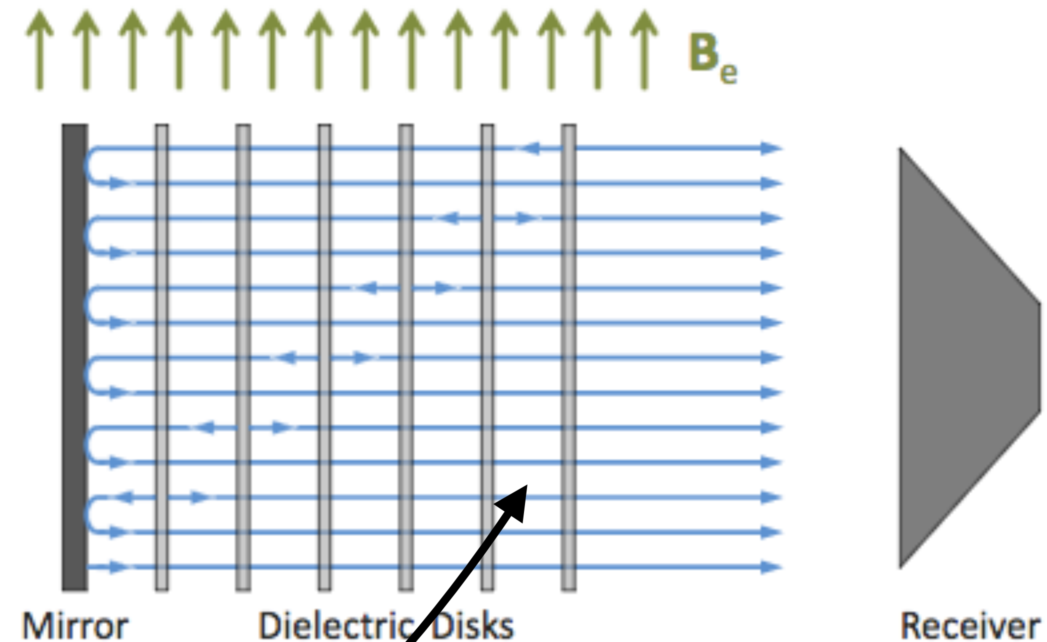
- Emission has large spatial coherence; adjusting plate separation -> coherence

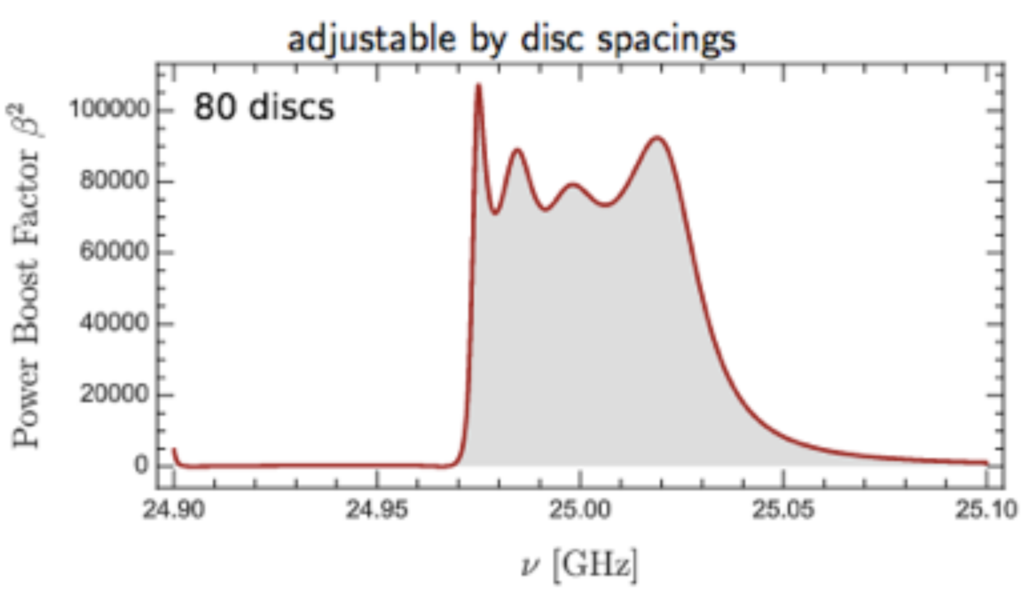
$$\frac{P}{Area} \sim 2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{c_\gamma}{2} \frac{B_{||}}{5\mathrm{T}} \right)^2 \frac{1}{\epsilon} \boxed{\times \beta(\omega) \quad \text{boost factor}}$$

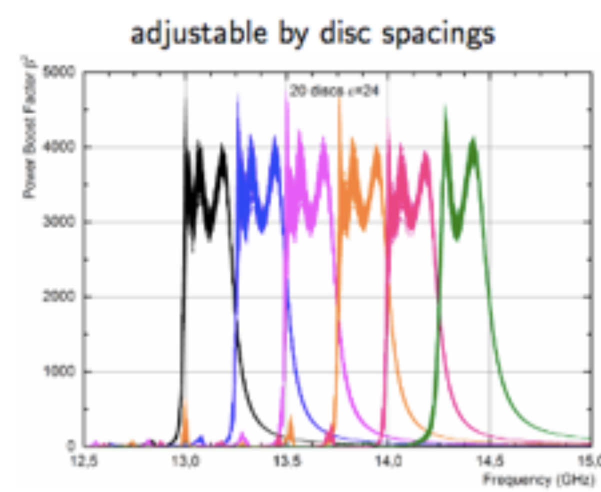
- Work in progress at Max Planck Institute fur Physik (Conceptual design)

MADMAX (2022?)

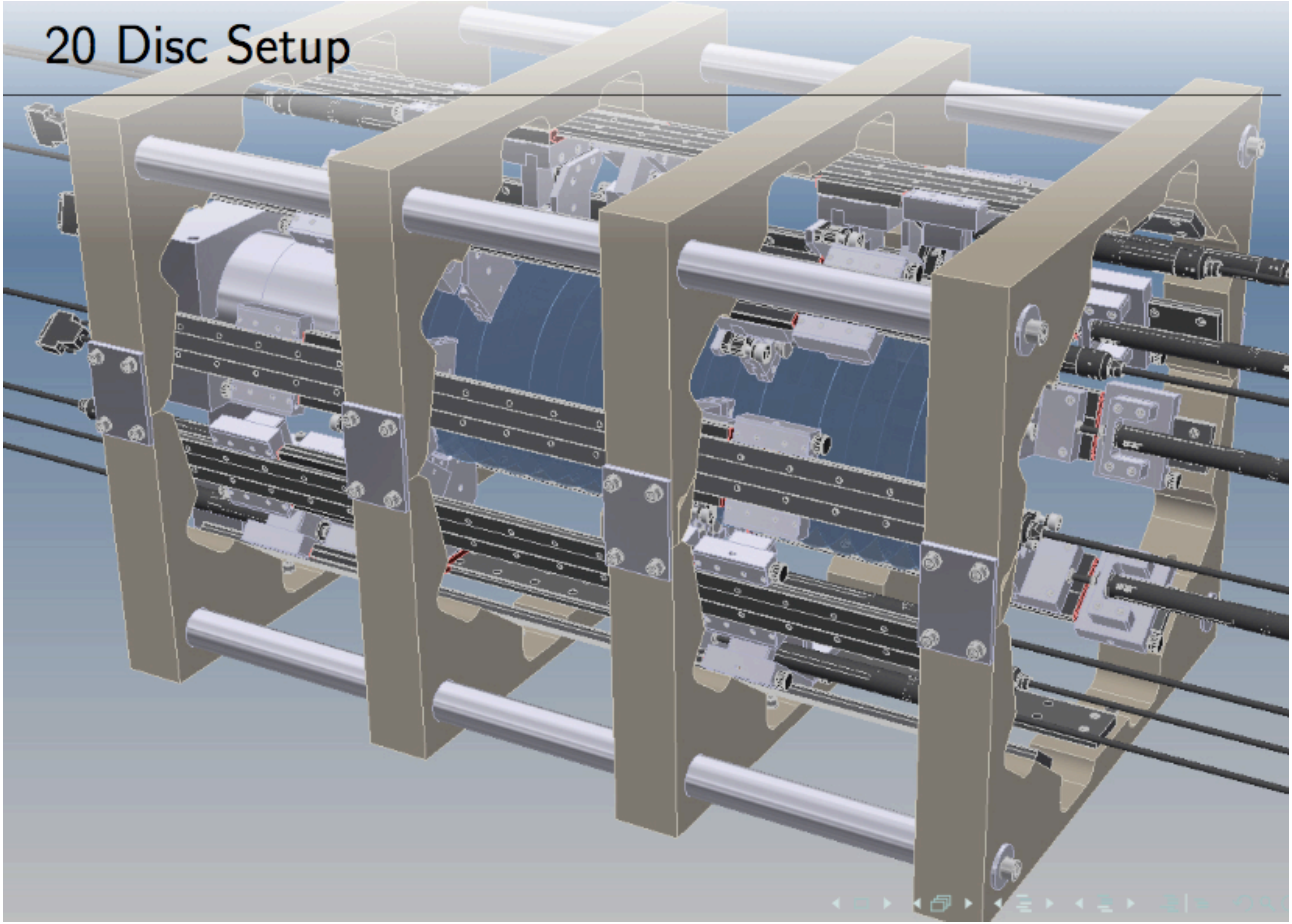

80 dielectric discs ϵ≈24
spacing ~cm for 10-100GHz boosts
metal disc
receiver
10T magnet
~10K cryogenic enviroment
parabolic mirror


B_e
Mirror
Dielectric Disks
Receiver

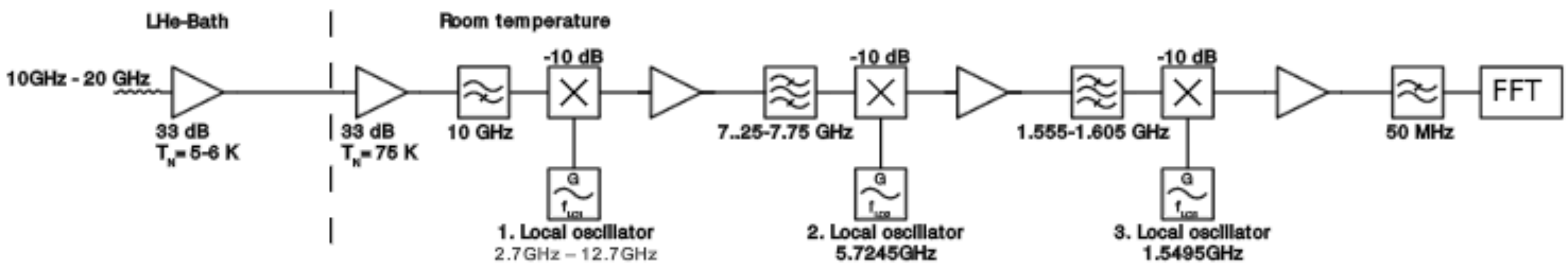

adjustable by disc spacings
80 discs
Power Boost Factor β^2
100000
80000
60000
40000
20000
0
24.90
24.95
25.00
25.05
25.10
ν [GHz]

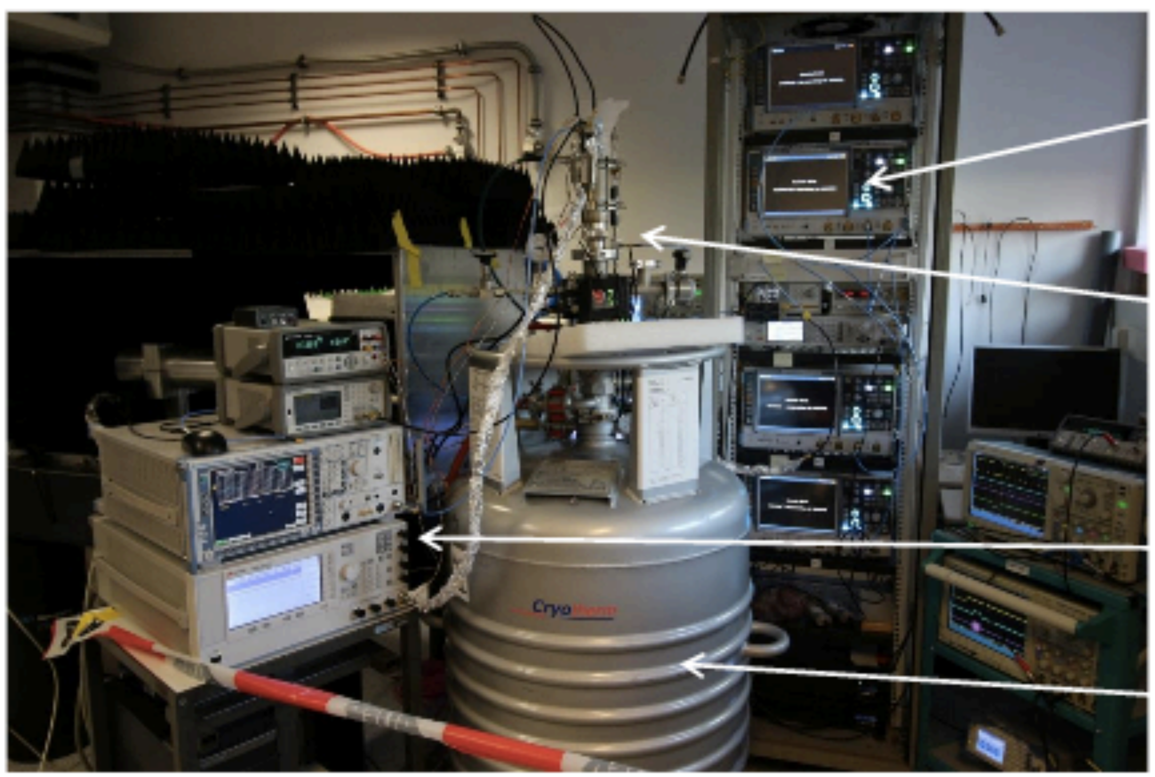

adjustable by disc spacings
20 discs ε=24
Power Boost Factor β^2
Frequency (GHz)

MADMAX current setup



MADMAX receiver system





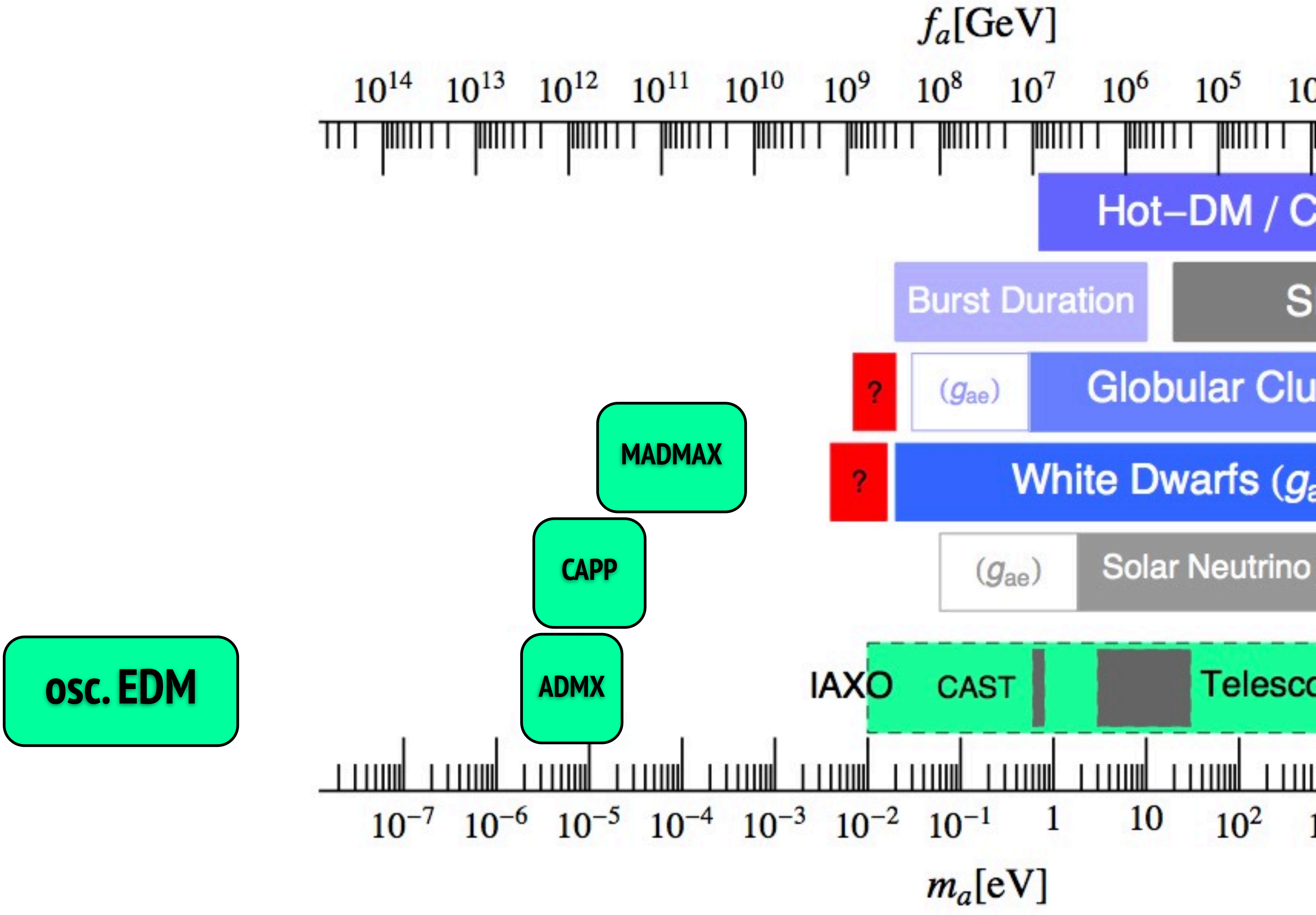
signal analyzer
(4 samplers, 1.4% dead time)

front end mixers
and amps

“Fake Axion”

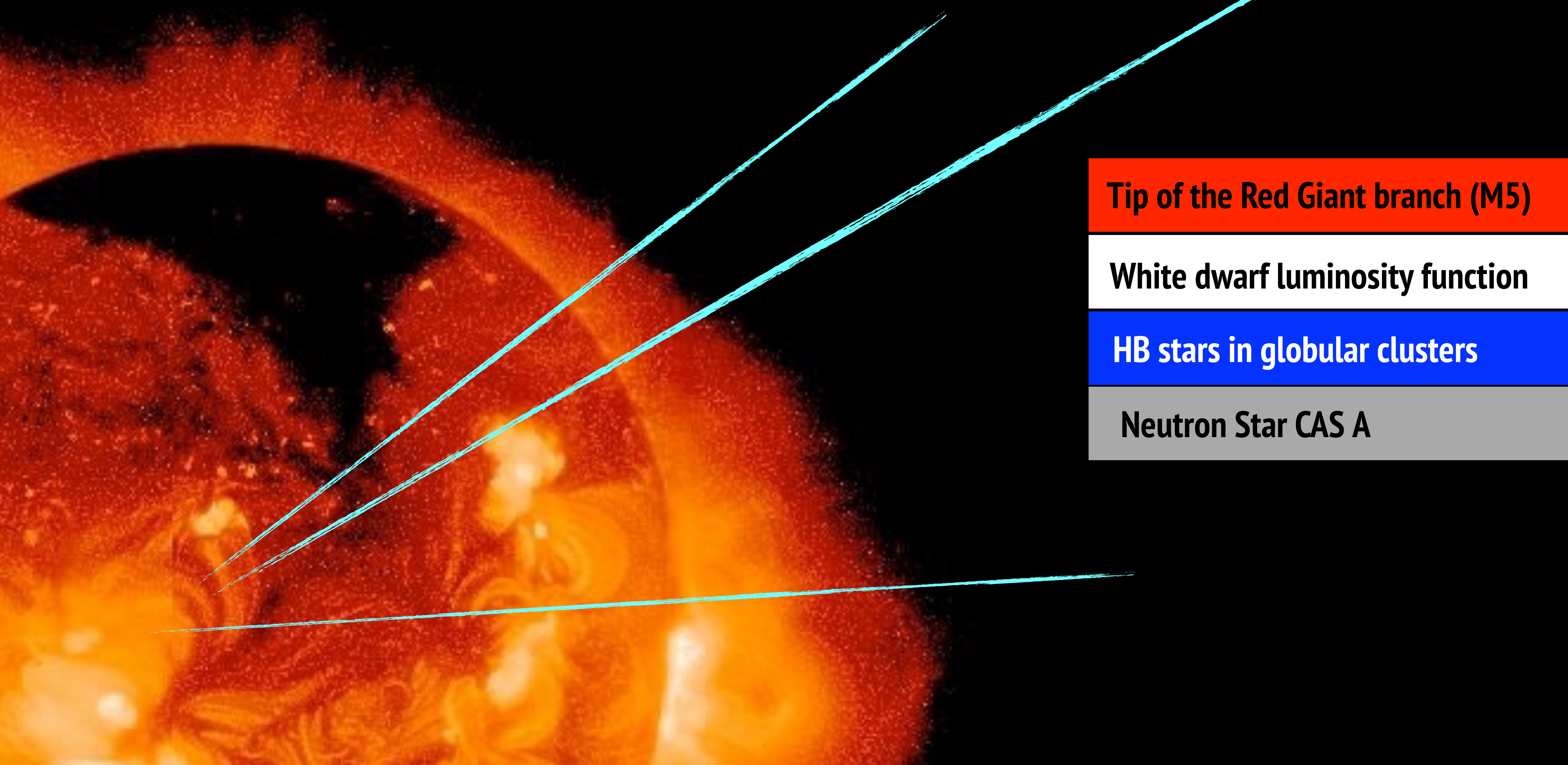
LHe bath
$\rightarrow$ 4K T_{He} + 5.5K T_{Amp} $\approx$ 9.5K T_{Sys}

Conclusions : a developing picture

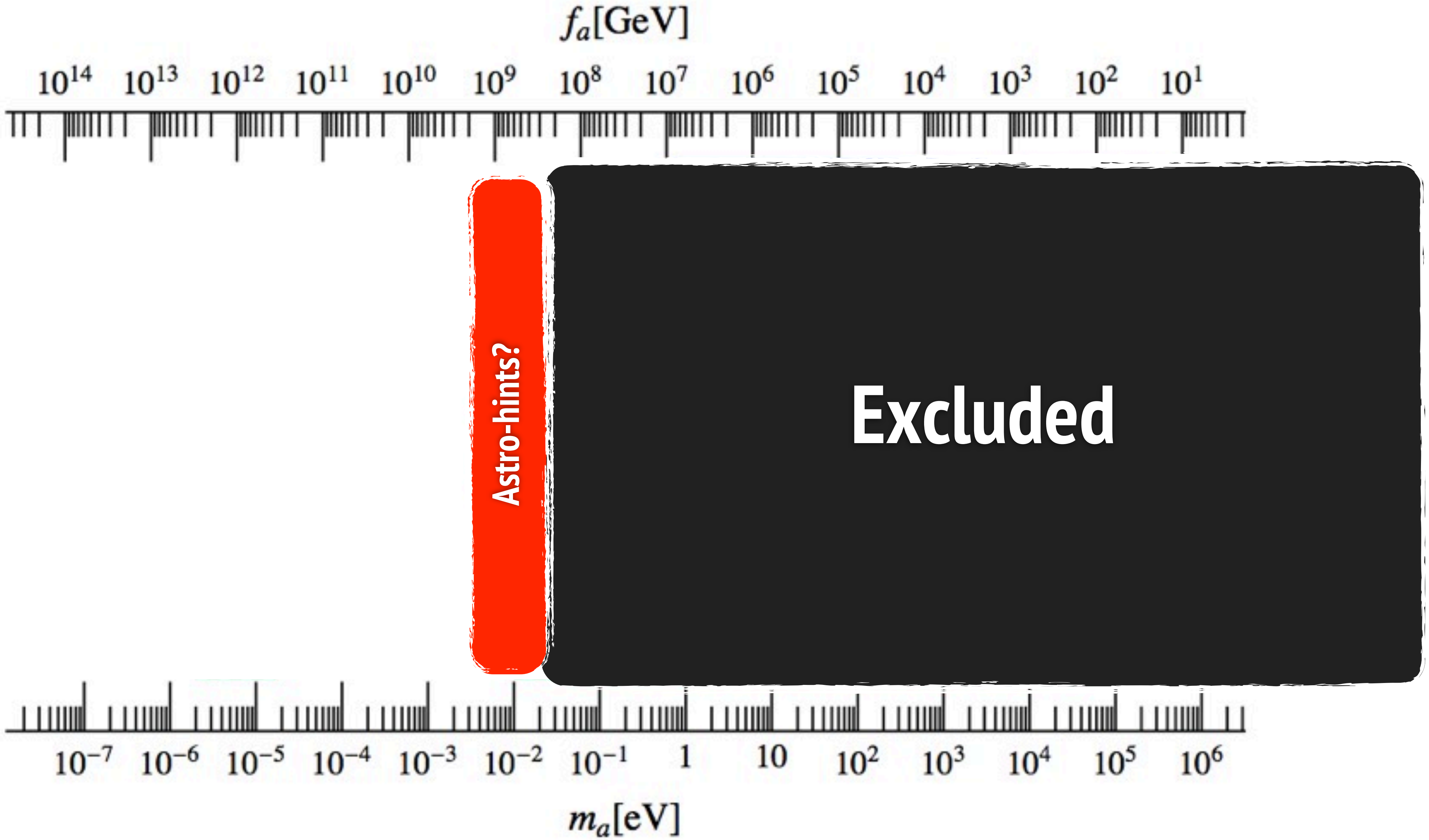


Bounds and hints from astrophysics

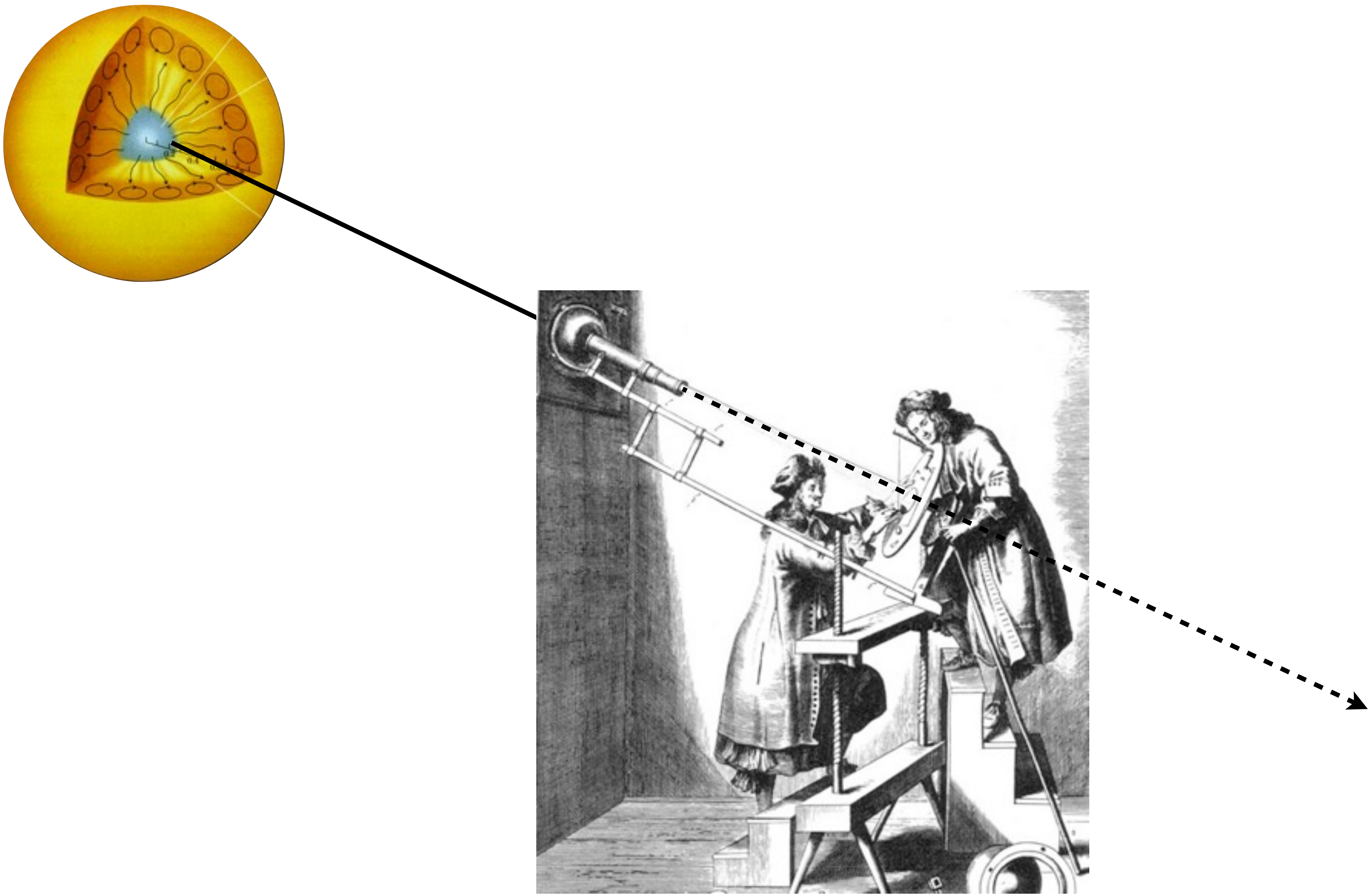
- Axions emitted from stellar cores accelerate stellar evolution
- Too much cooling is strongly excluded (obs. vs. simulations)
- Some systems improve with additional axion cooling!



Axion Landscape

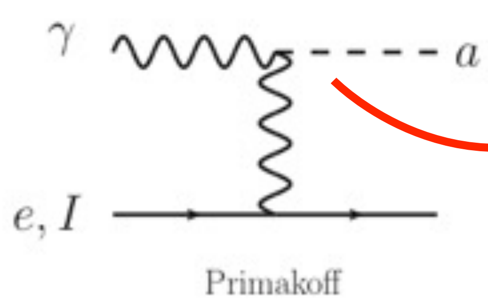


Detecting Solar Axions : Helioscopes



Flux of Solar axions/ALPs well understood

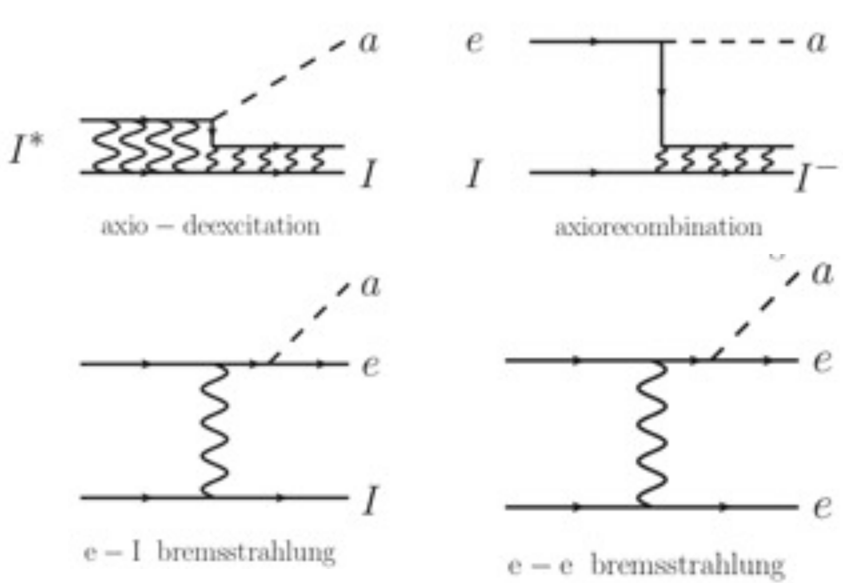
From axion 2-Photon coupling

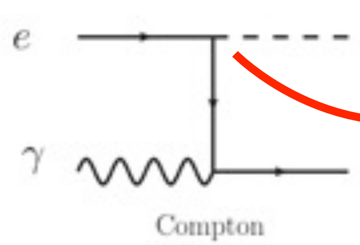


$$\frac{C_\gamma \alpha}{2\pi f_a}\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4}a$$

$g_{a\gamma}$

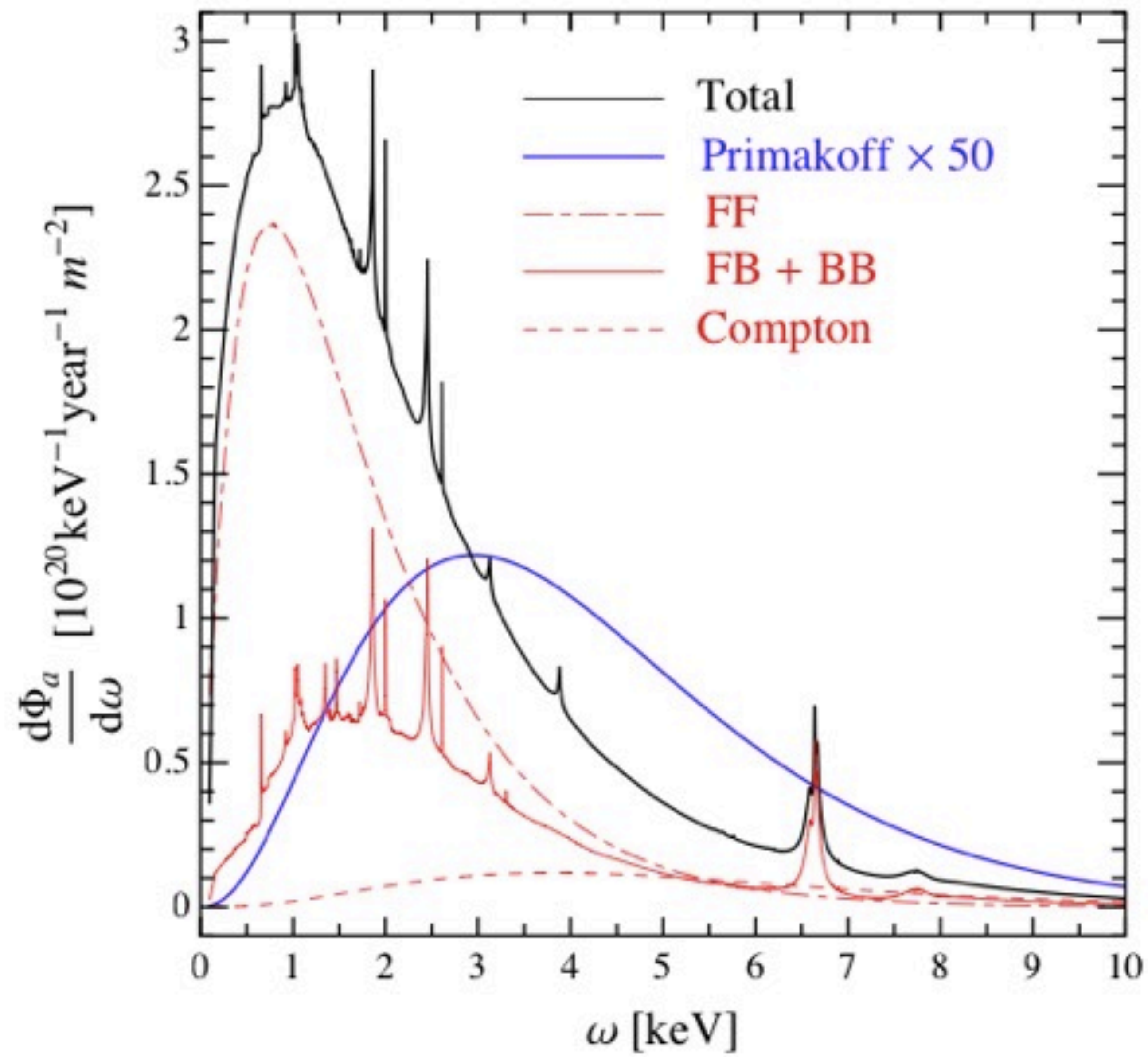
From axion-Electron coupling





$$\frac{C_e m_e}{f_a} i\bar{e}\gamma_5 e\, a$$

g_{ae}



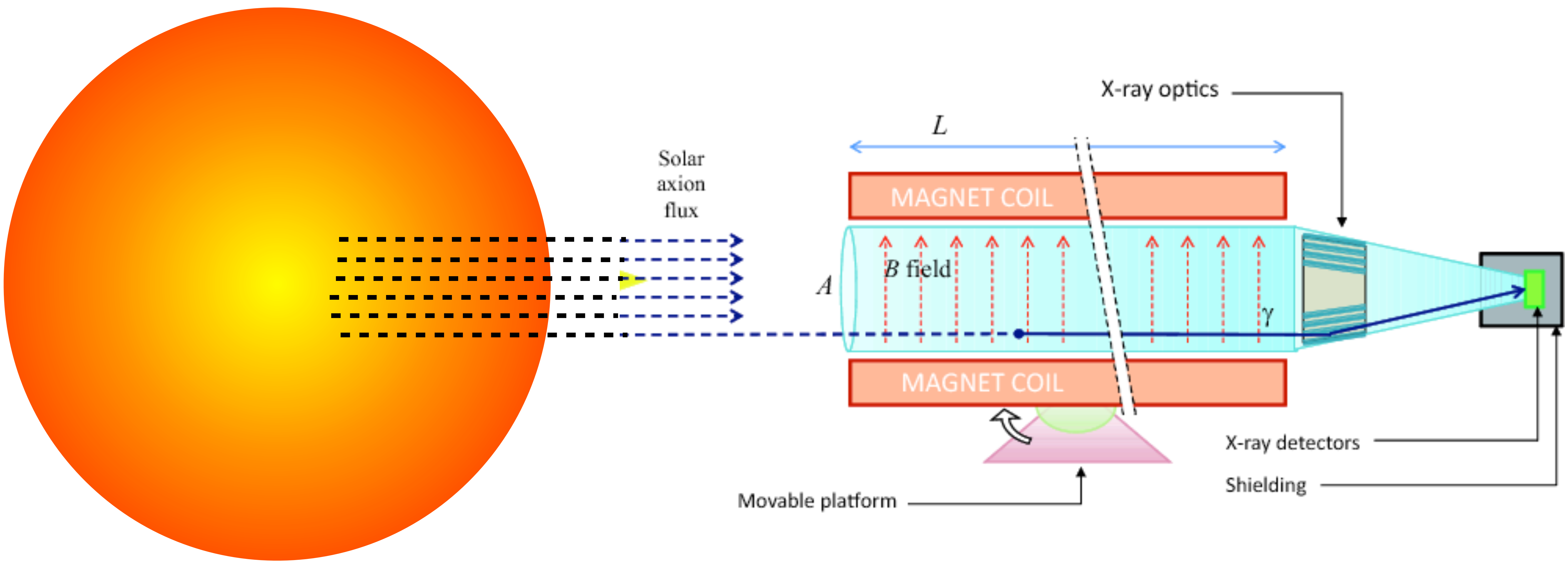
$$g_{ae} = 10^{-13}$$
$$g_{a\gamma} = 10^{-12}\mathrm{GeV}^{-1}$$

- couplings safe below exclusion bounds
- values typical of meV-mass axions

Detection with Helioscopes

The Sun is a copious emitter of axions!

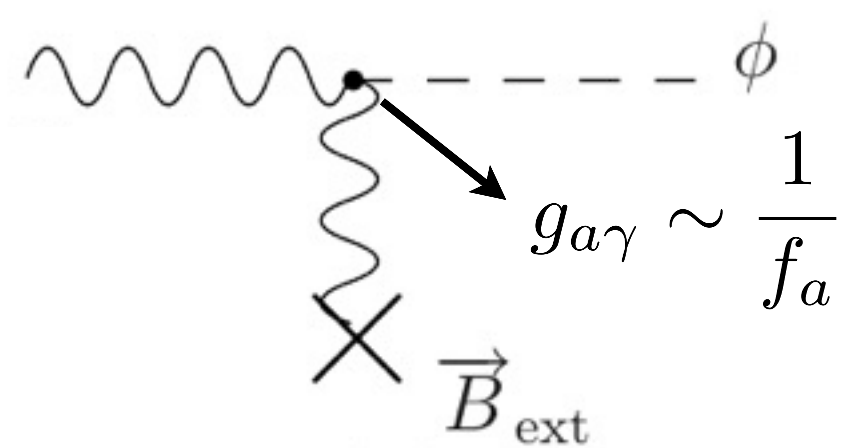
convert into X-rays **focus** **detect**



Conversion probability

$$P(a \leftrightarrow \gamma) = \left(\frac{2 g_{a\gamma} B_T \omega}{m_a^2}\right)^2 \sin^2\left(\frac{m_a^2 L}{4\omega}\right)$$

$$P(a \leftrightarrow \gamma) \sim 10^{-20} \left(\frac{B}{3\,\mathrm{T}}\frac{L}{20\,\mathrm{m}}\right)^2$$

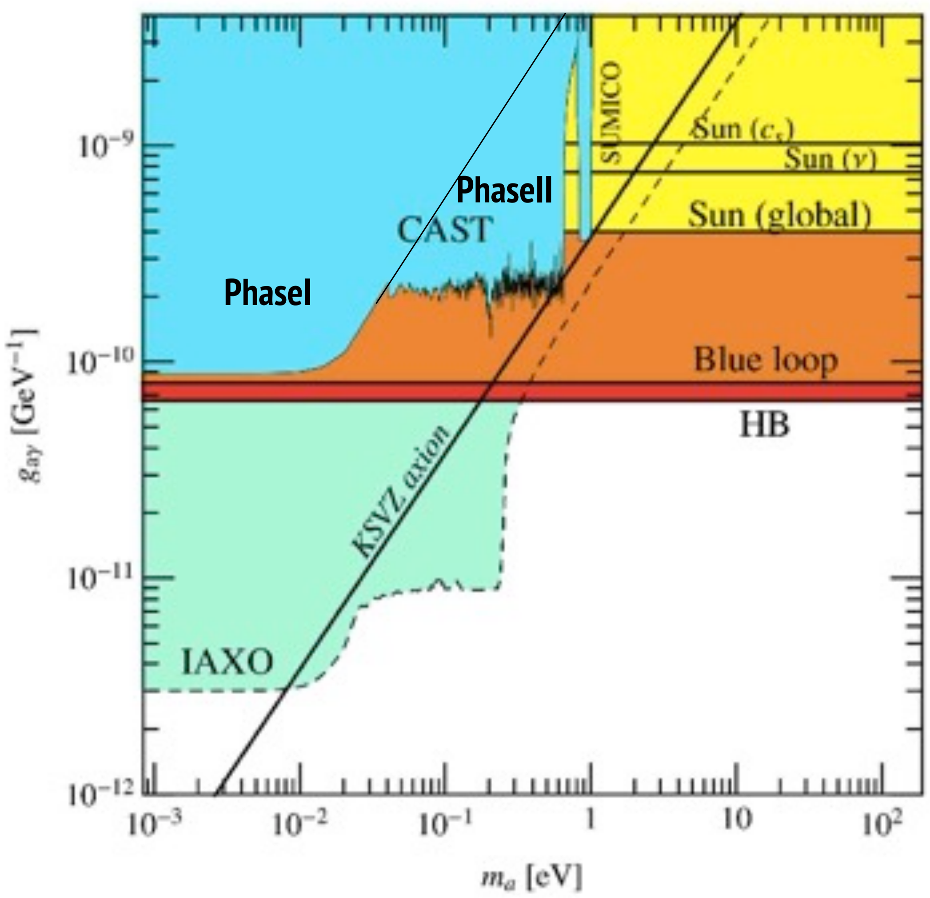


CAST Helioscope

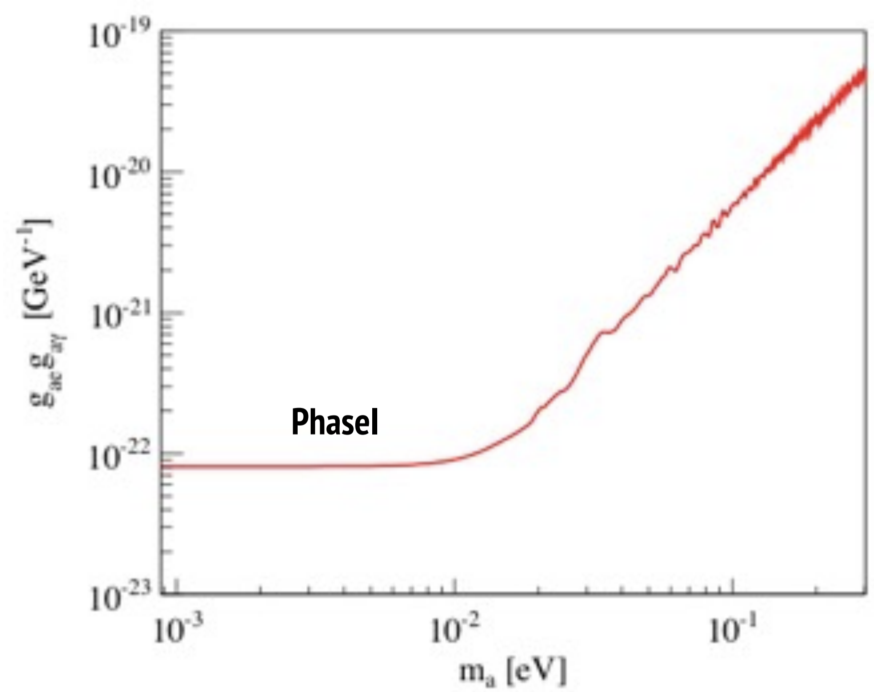
CAST (LHC dipole 9.3 m, 9T)

- 1~2 h tracking/day (sunset,dawn)
- 3 Detectors (2 bores)
  CCD, Micromegas
- X-ray optics

Photon coupling

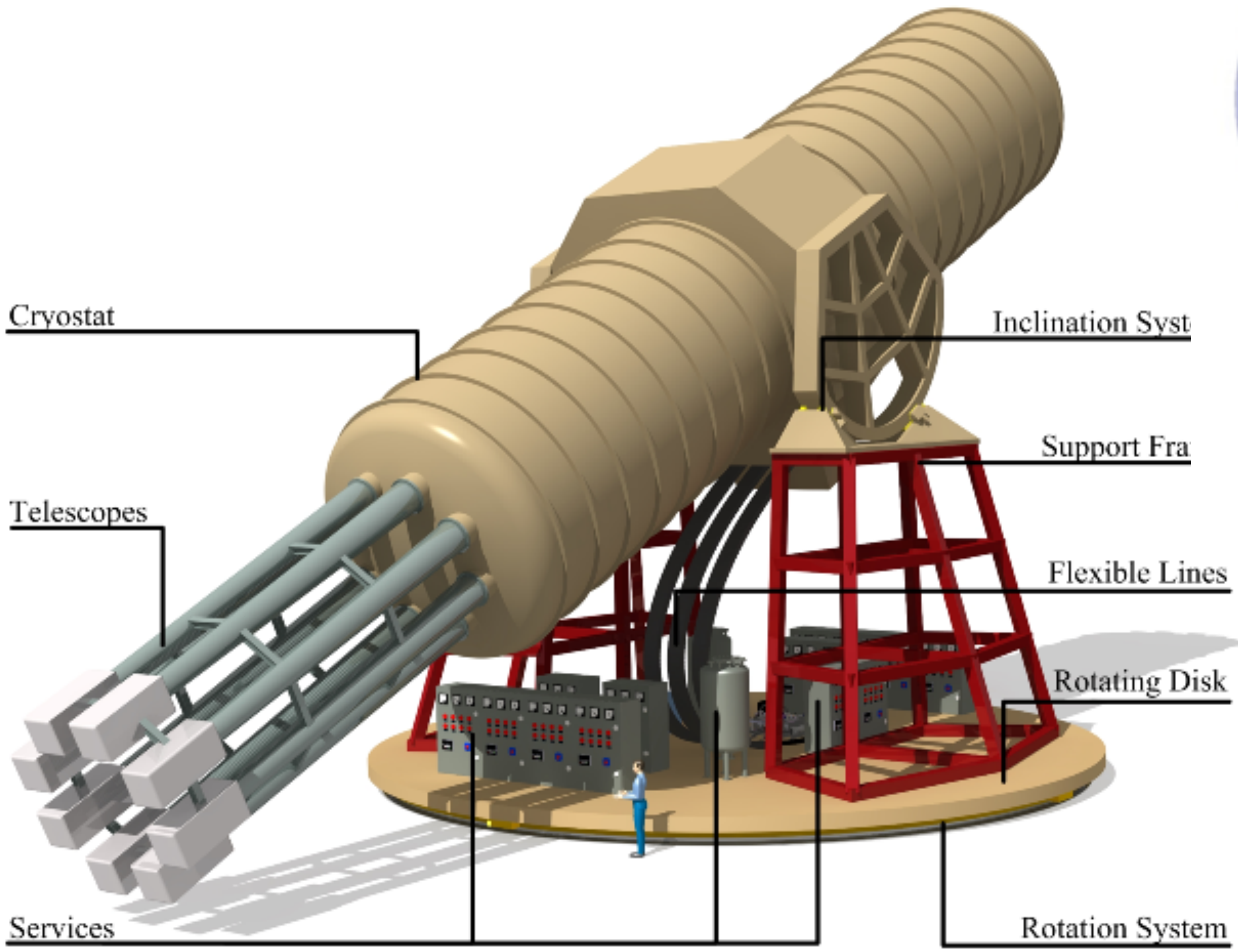


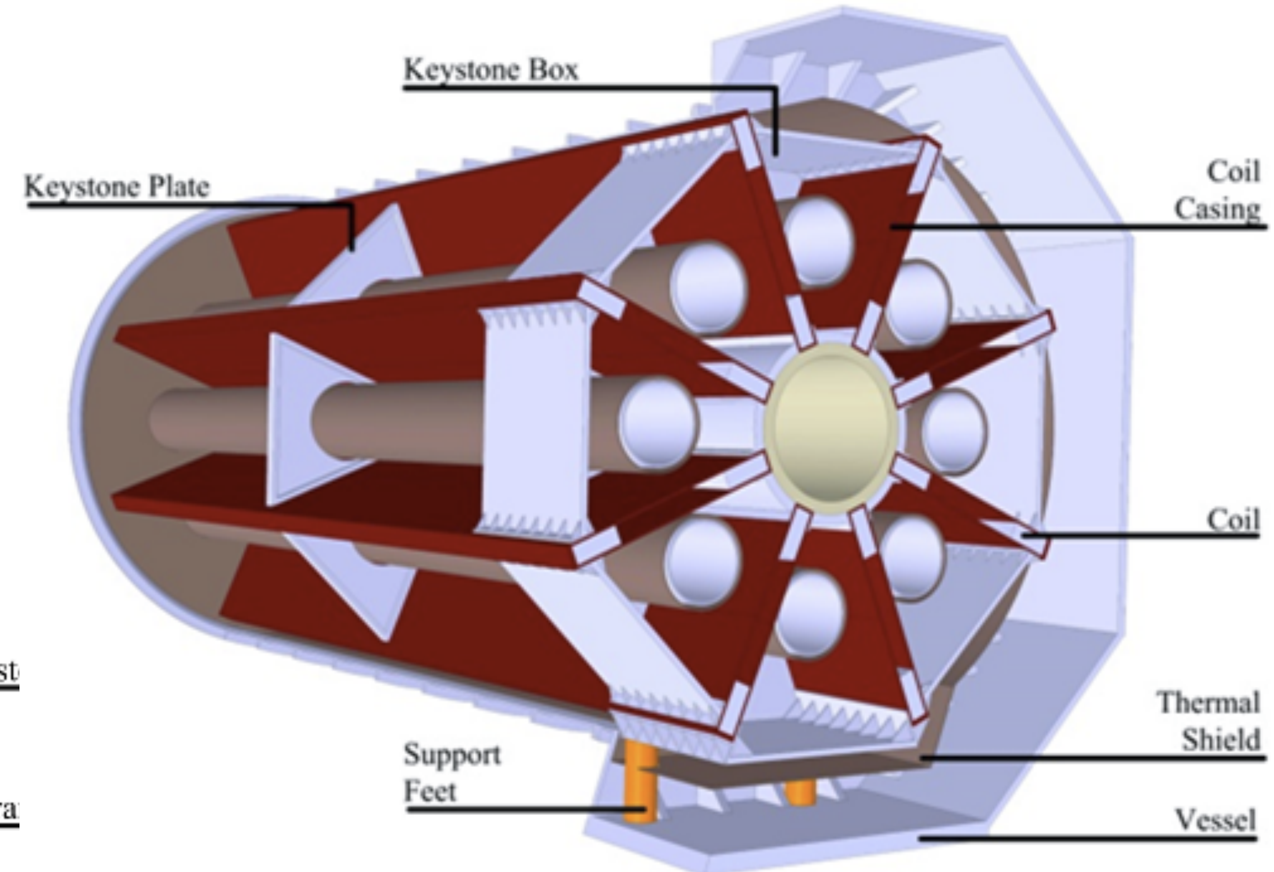
Electron(production) photon (detection)

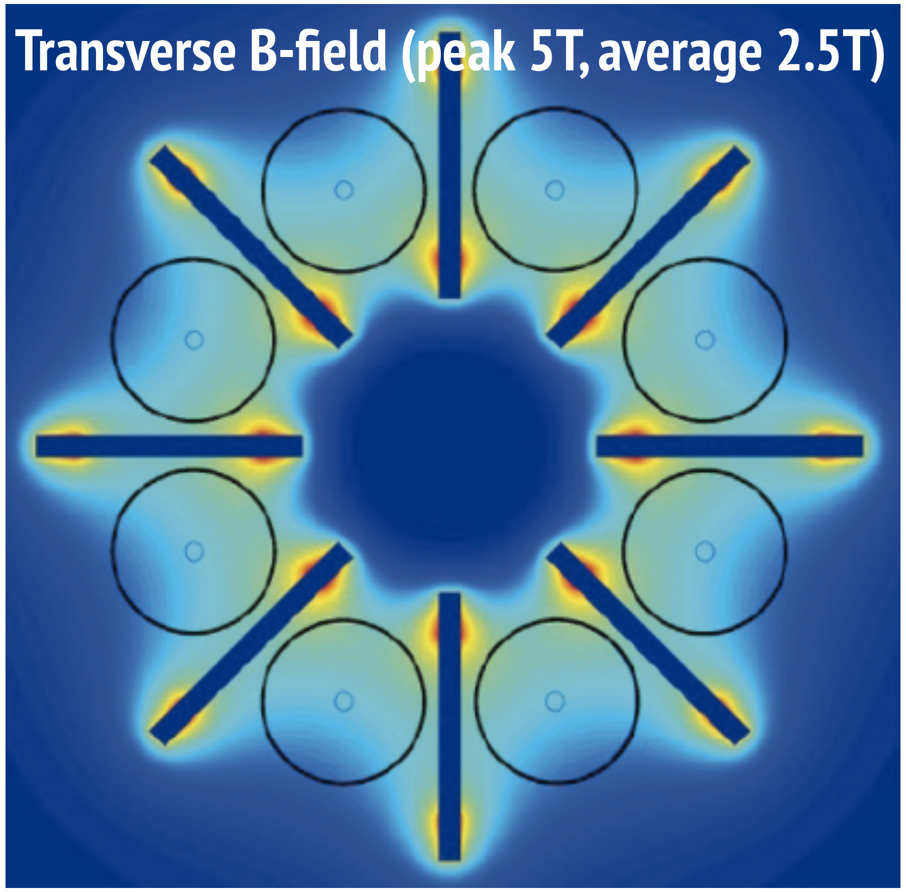


The future : International Axion observatory (IAXO)

Large toroidal 8-coil magnet L = ~20 m
Large AREA : 8 bores x 600 mm diameter
8 x-ray optics + 8 detection systems
Rotating platform with services





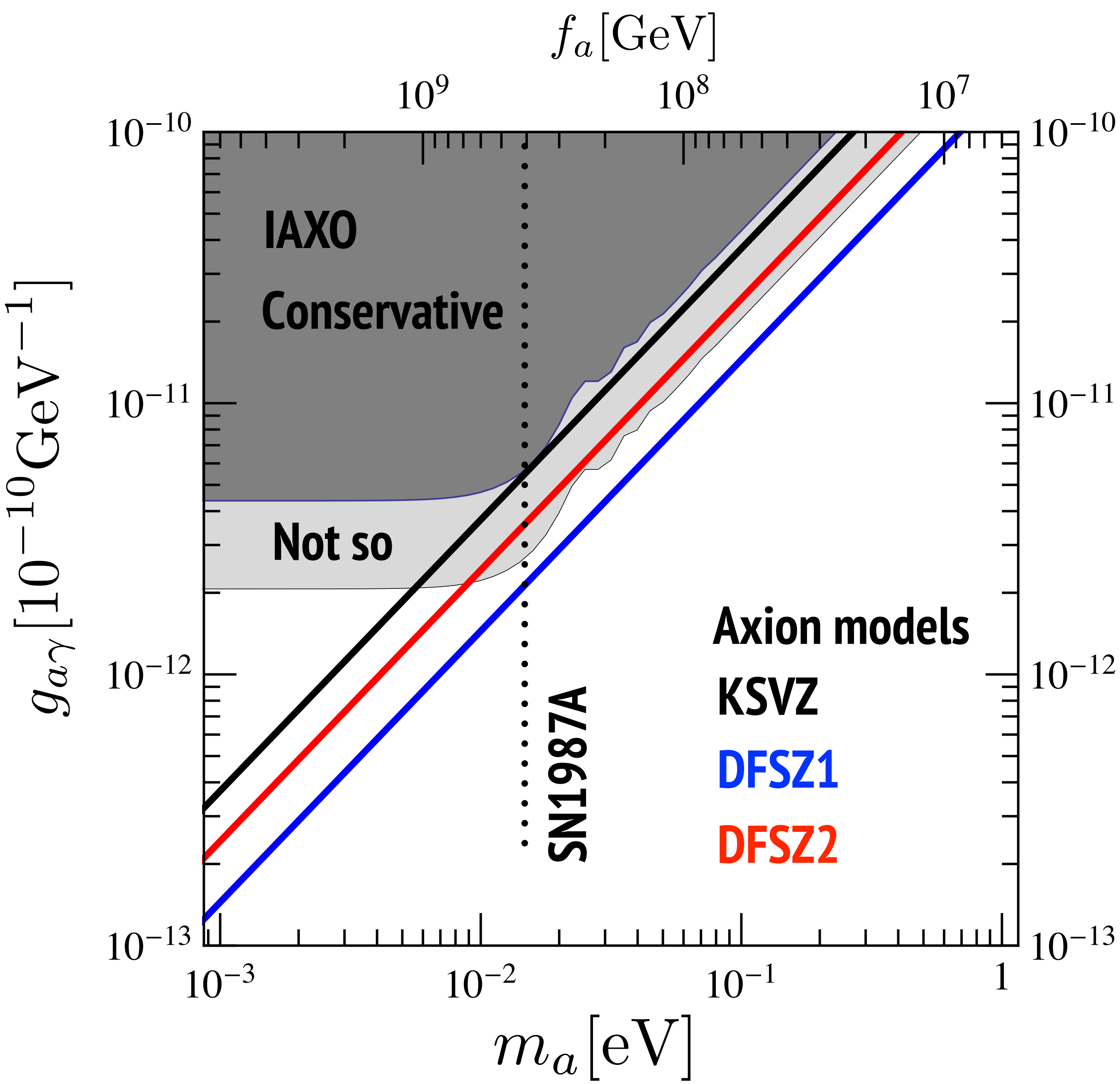


-NGAG paper JCAP 1106:013,2011
-Conceptual design report IAXO 2014 JINST 9 T05002
-LOI submitted to CERN, TDR in preparation

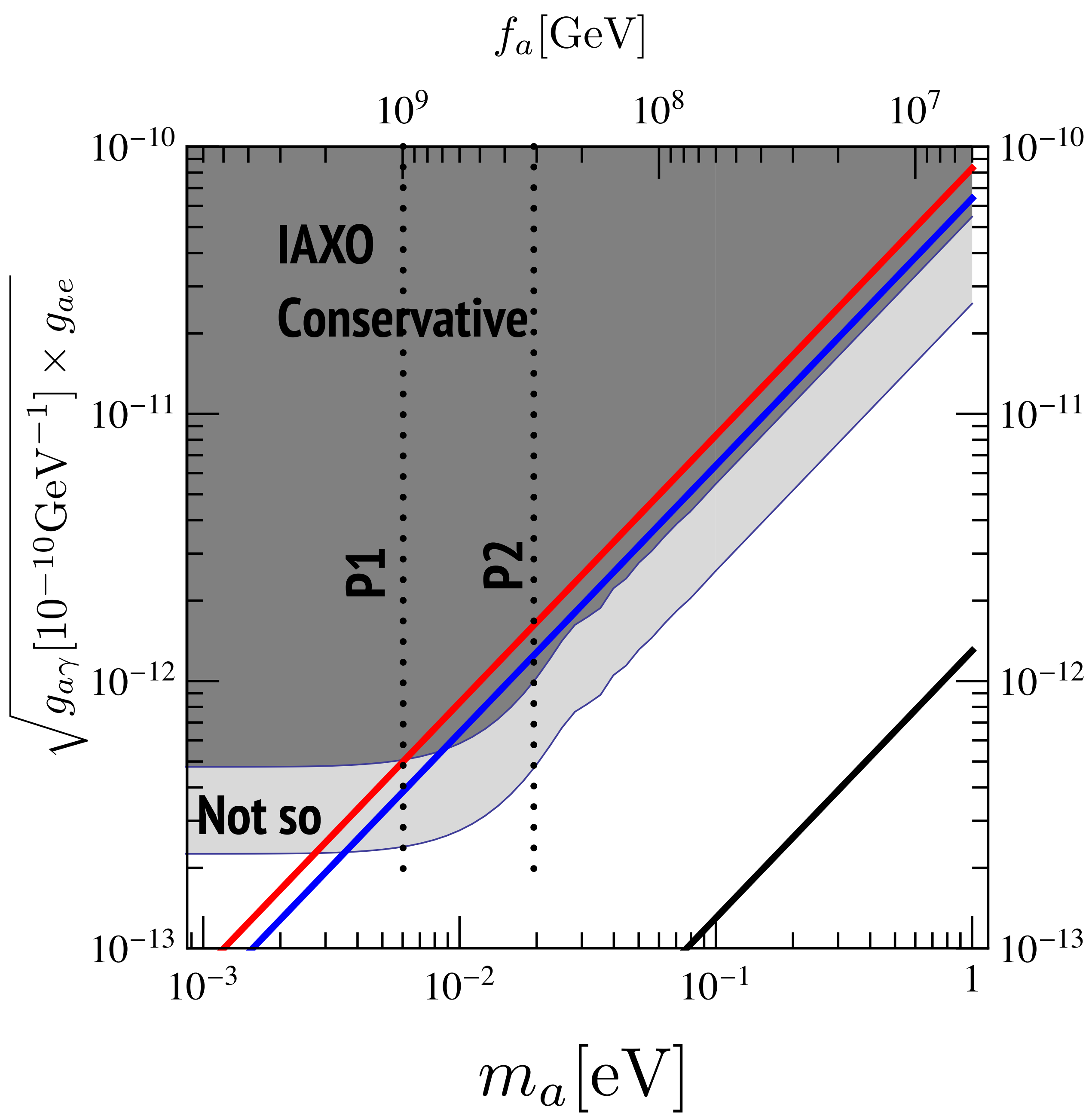
-Possibility of Direct Axion DM experiments (cavities)

Physics reach (preliminary)

Photon coupling

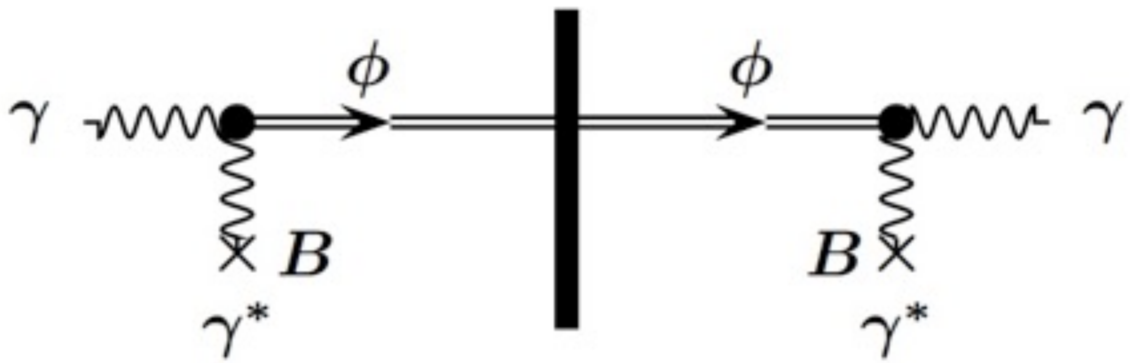


Electron and Photon coupling

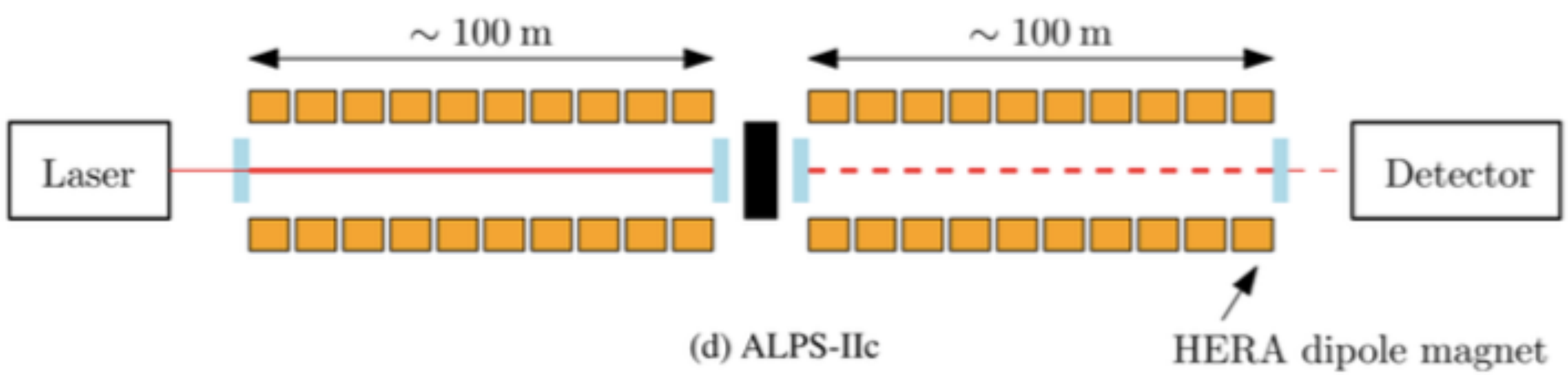


the ANY-Light-Particle-Search

Light shining through walls

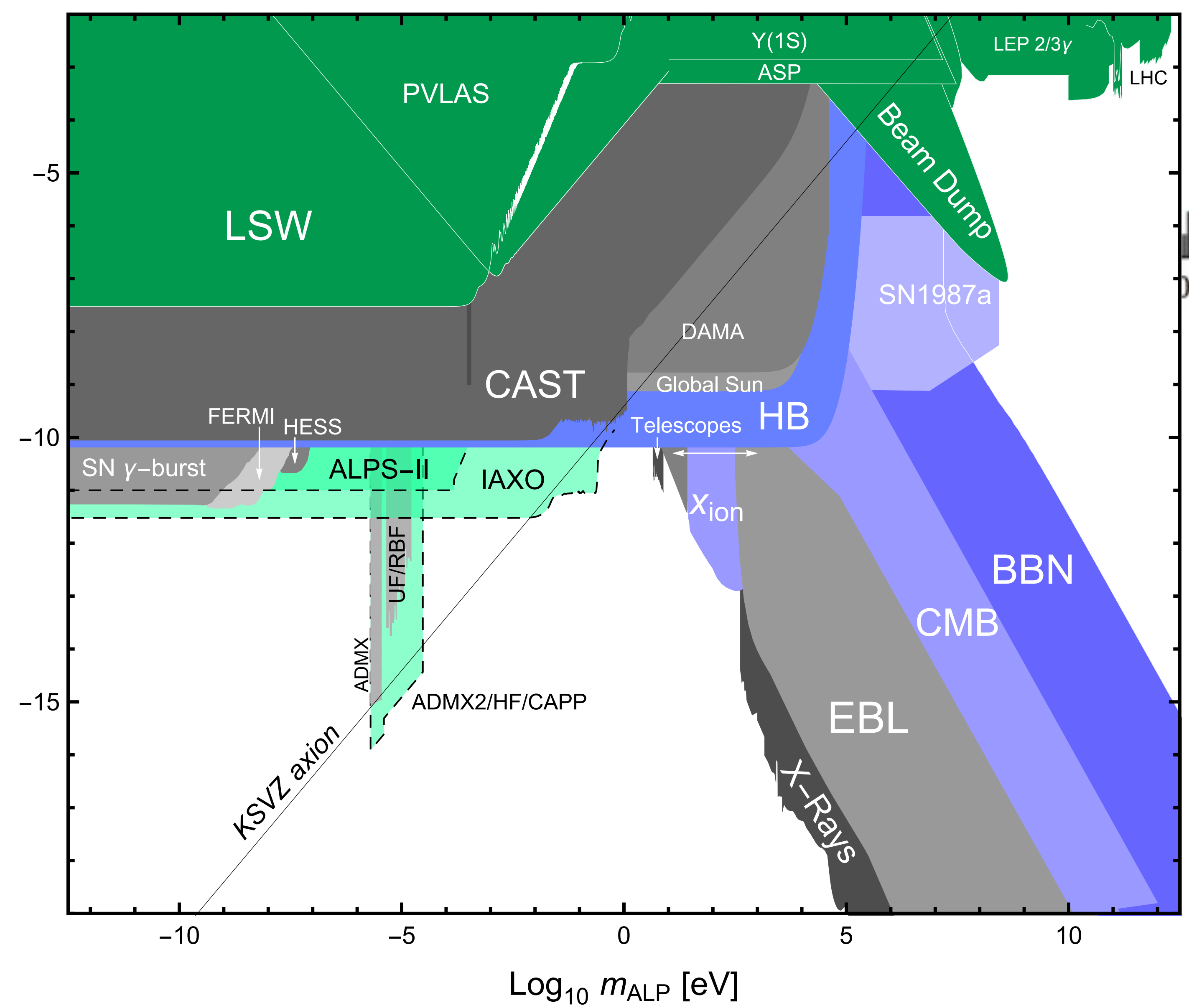


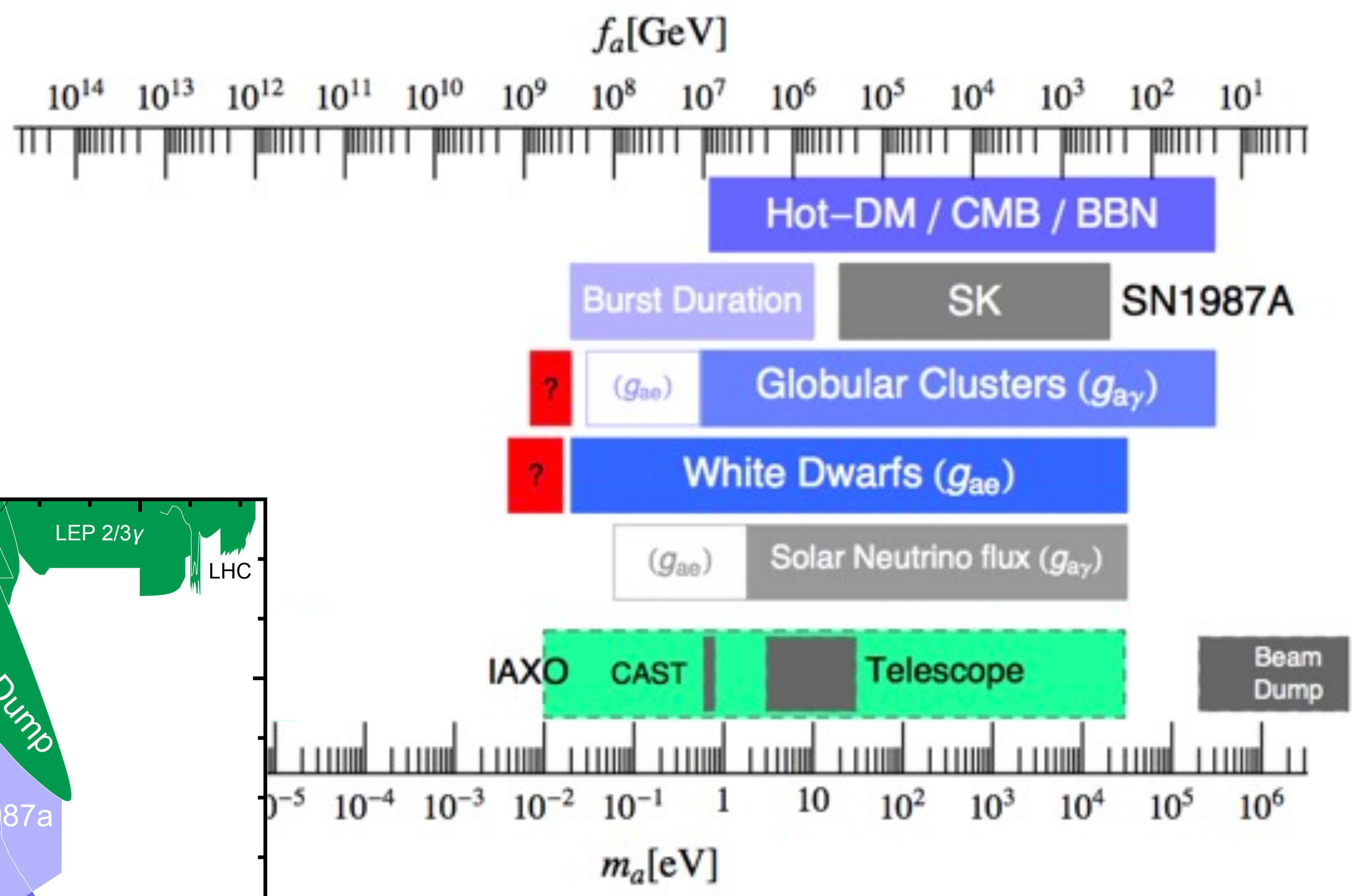
Resonant regeneration in the receiving cavity (see later)



Exp.	Photon flux (1/s)	Photon E (eV)	B (T)	L (m)	B·L (Tm)	PB reg.cav.	Sens. (rel.)
ALPS I	$3.5 \cdot 10^{21}$	2.3	5.0	4.4	22	1	0.0003
ALPS II	$1 \cdot 10^{24}$	1.2	5.3	106	468	40,000	1
"ALPS III"	$3 \cdot 10^{25}$	1.2	13	400	5200	100,000	27

Axion/ALP Landscape



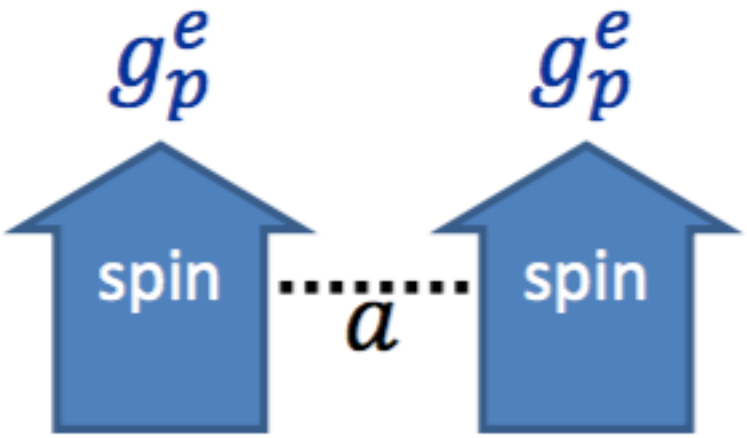


Long-range forces

Wilczek '84, Geraci 14

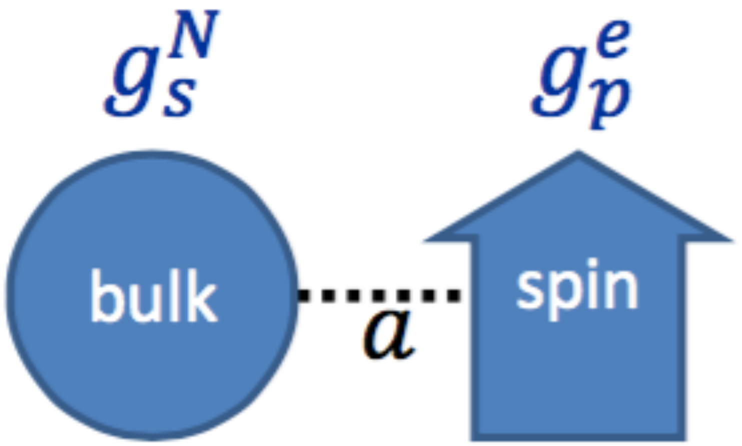
Long-range forces between macroscopic bodies

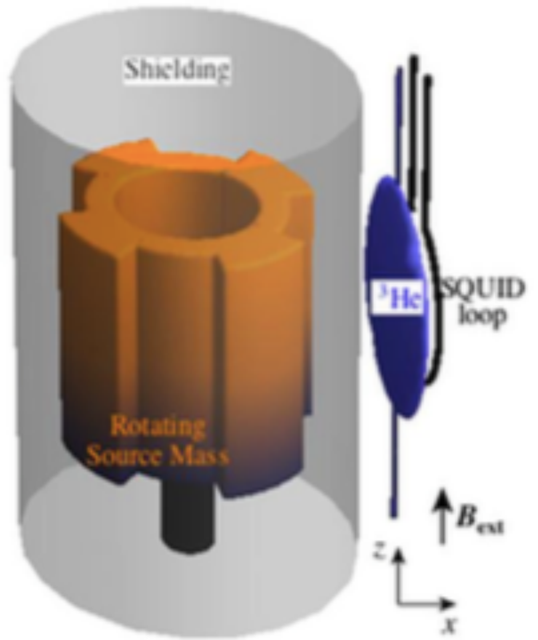
p-p forces are spin-spin ... very hard to measure!



In some case a tiny s-coupling can lead to a larger effect

s-p forces are number-spin ... much easier

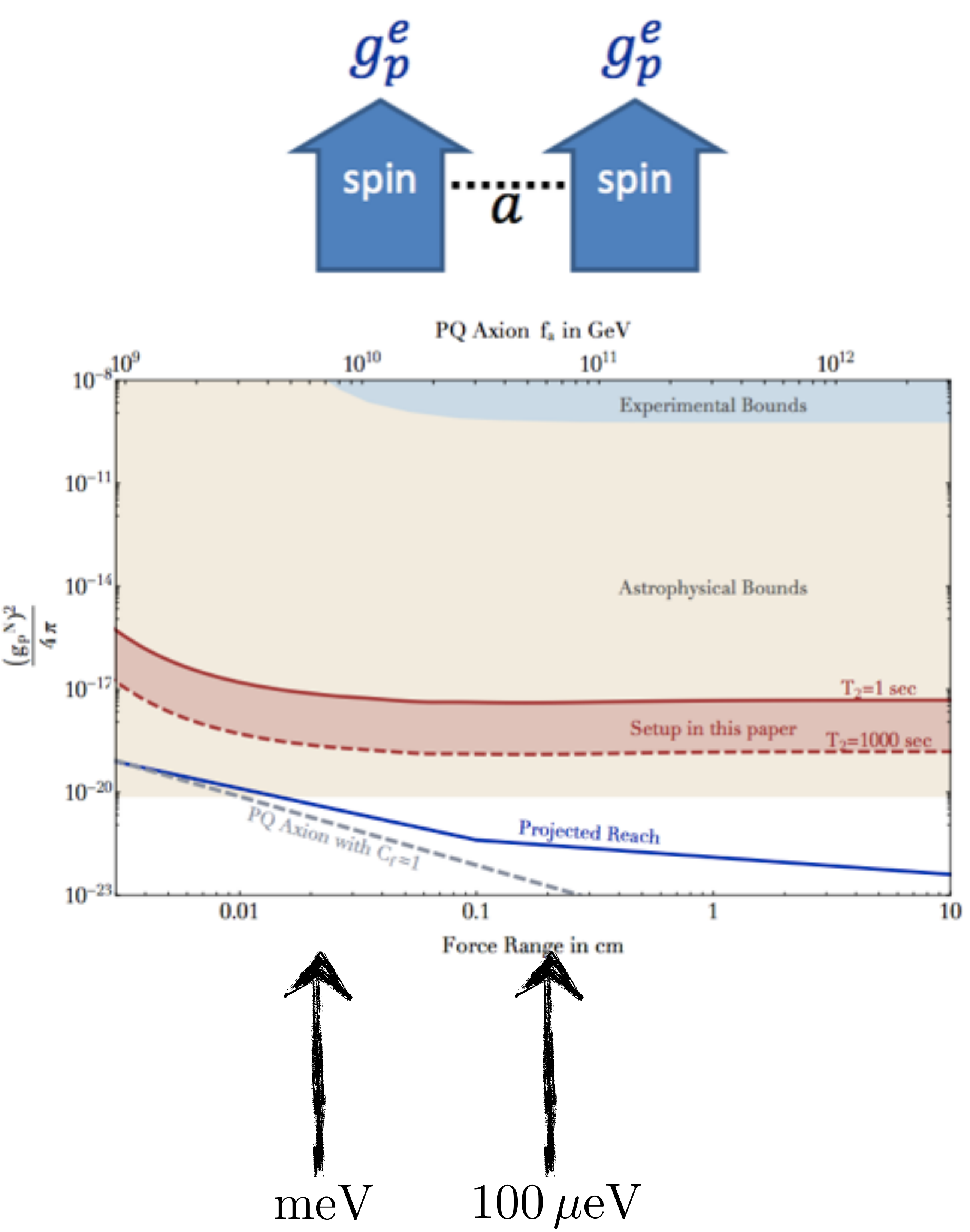


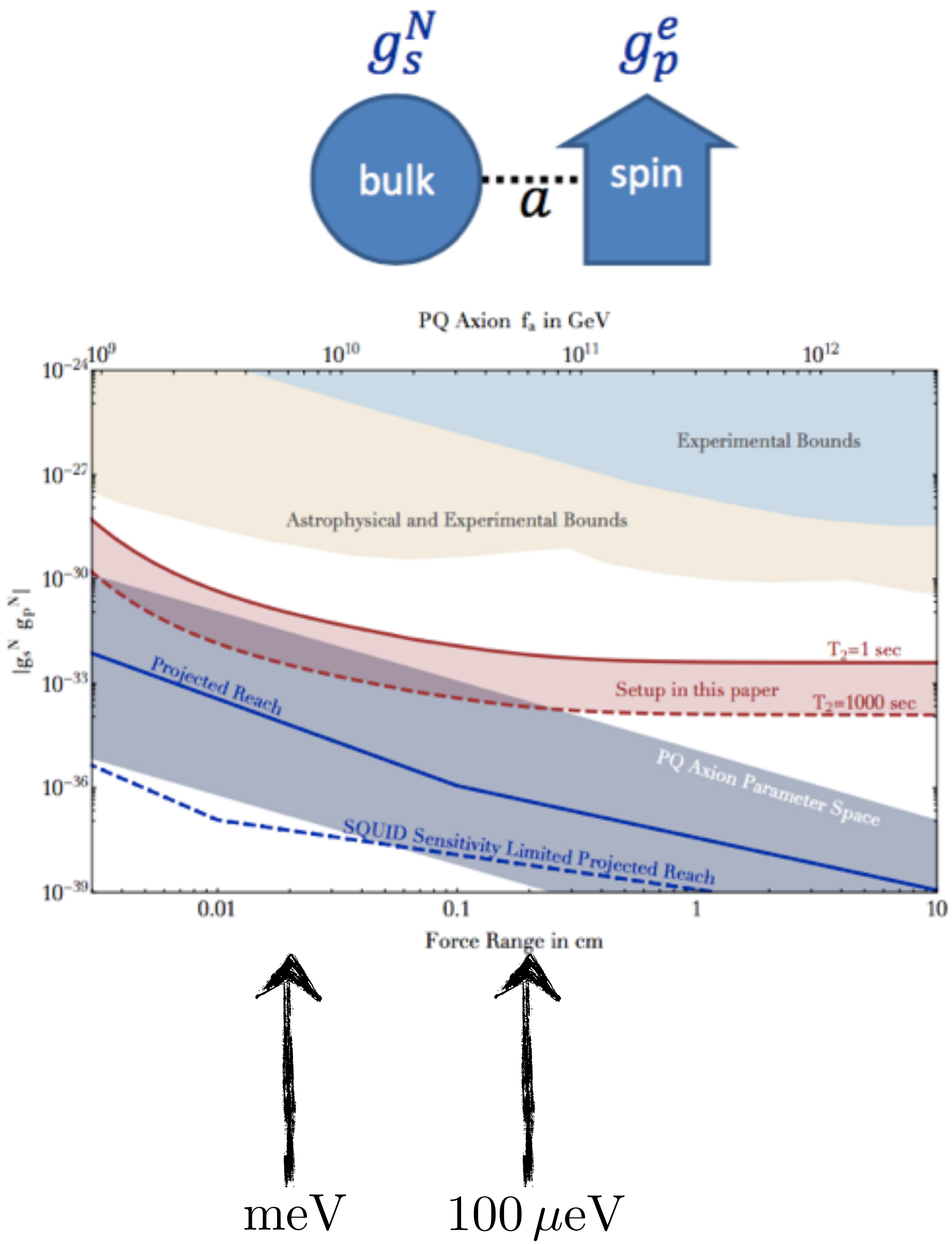


ARIADNE, University of Nevada in Reno

ARIADNE reach

Arvanitaki, Geraci 14





Axion DM : A developing picture