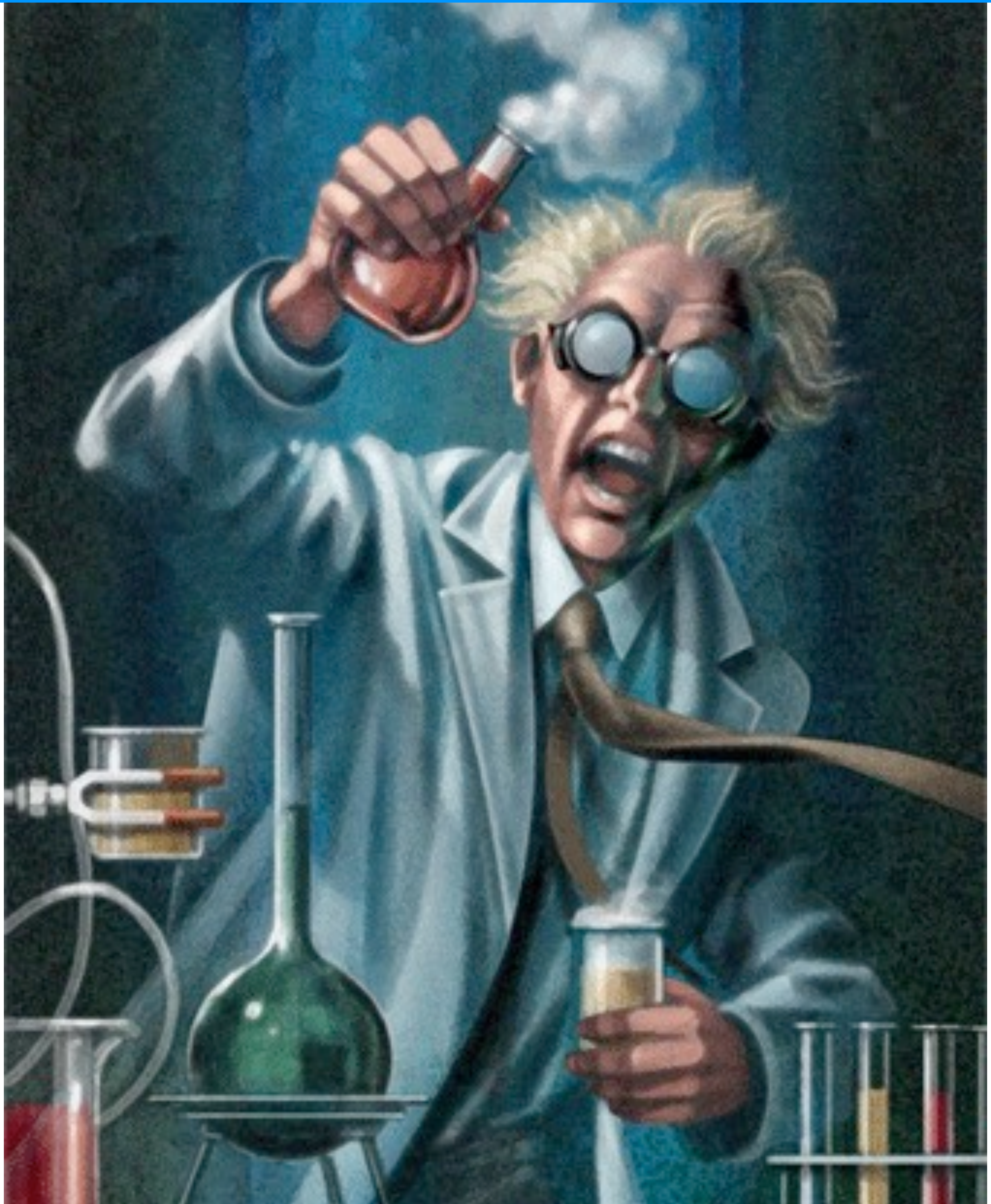
Axion searches



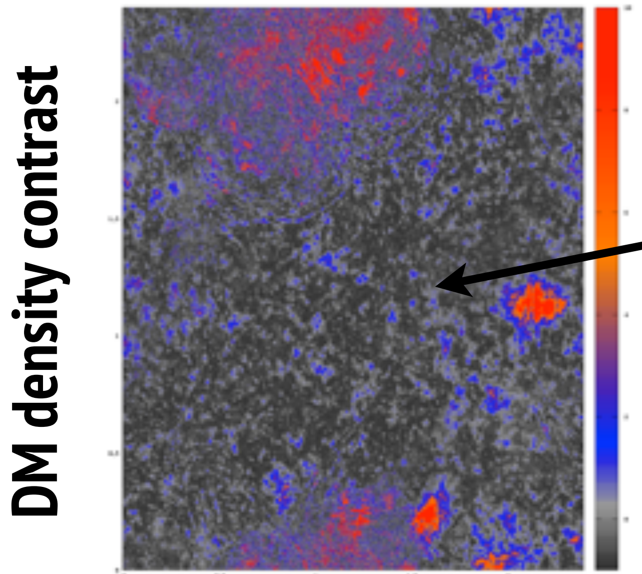
Axion searches

- Gravitational (Indirect)
    - CMB anisotropies (isocurvature) - Axion DM in SC2
    - Lensing - Axion DM Miniclusters in SC1
    - Bose Einstein DM Galactic Halo (?)
- Based on axion couplings
    - Indirect : ~ Stellar evolution
    - Direct :
        - Haloscopes (Axion DM)
        - Helioscopes (Solar Axions)

    - Purely Lab experiments :
        - Light shining through walls
        - 5th forces

Axion DM implications

PQ breaking after inflation -> DM inhomogeneous, Axion miniclusters

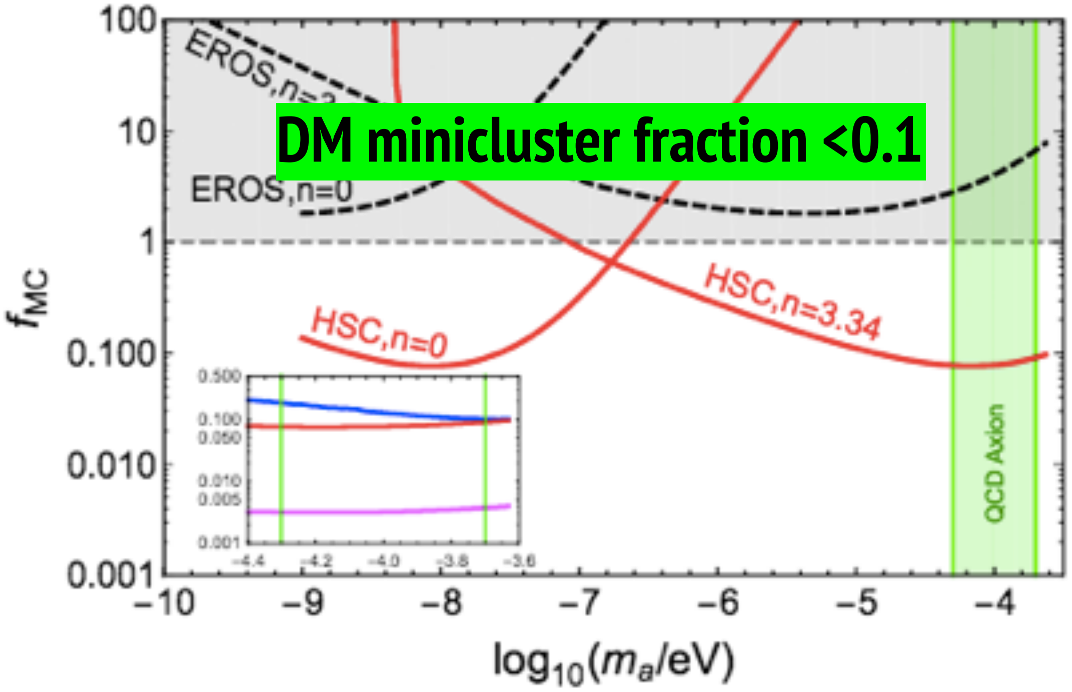


~ 0.1 comoving pc

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

do they Merge to heavier masses? $10^{-7} M_\odot$?

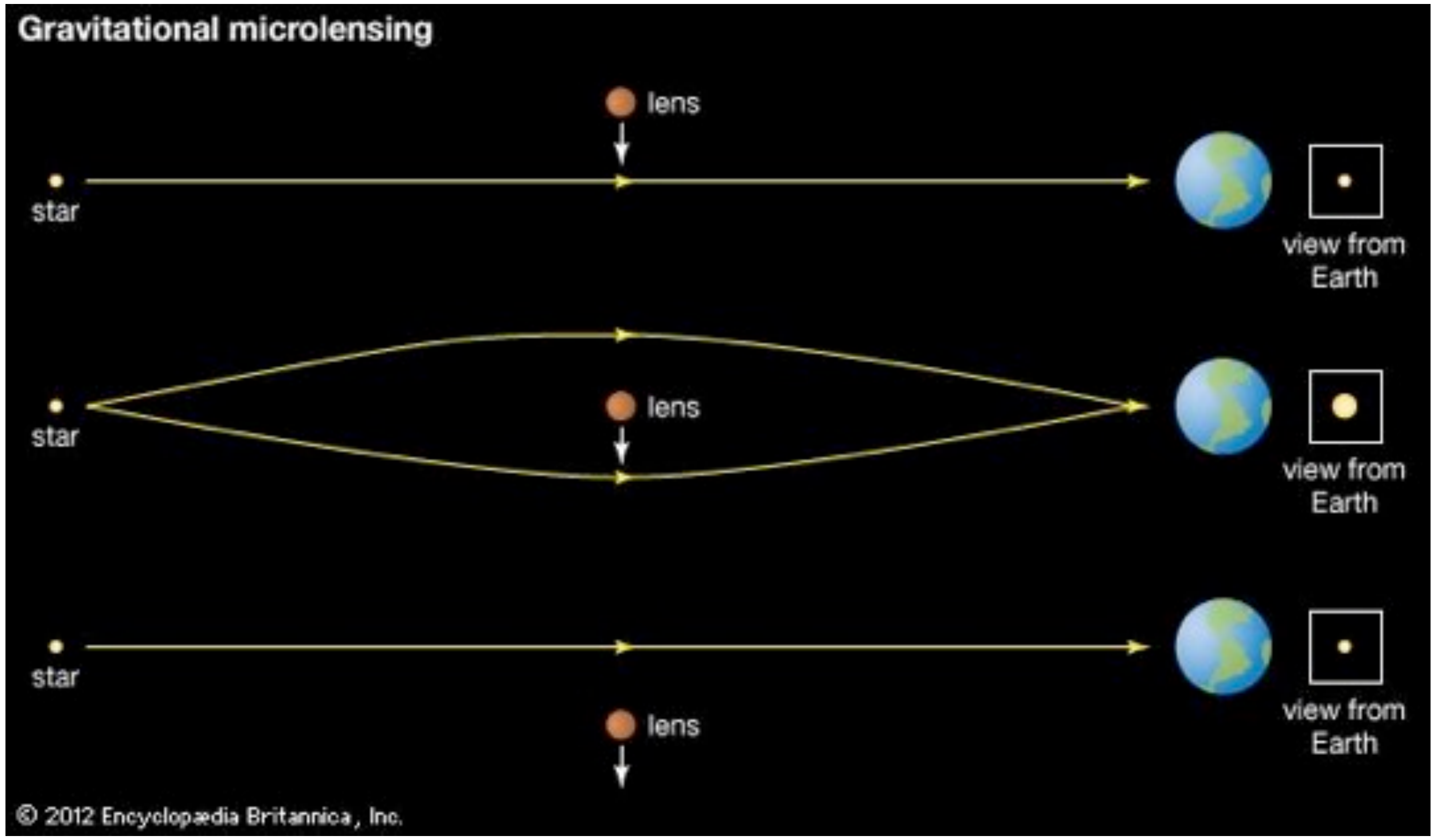
do they Survive until today?



DM minicluster fraction <0.1

Marsh 1701.04787

Microlensing



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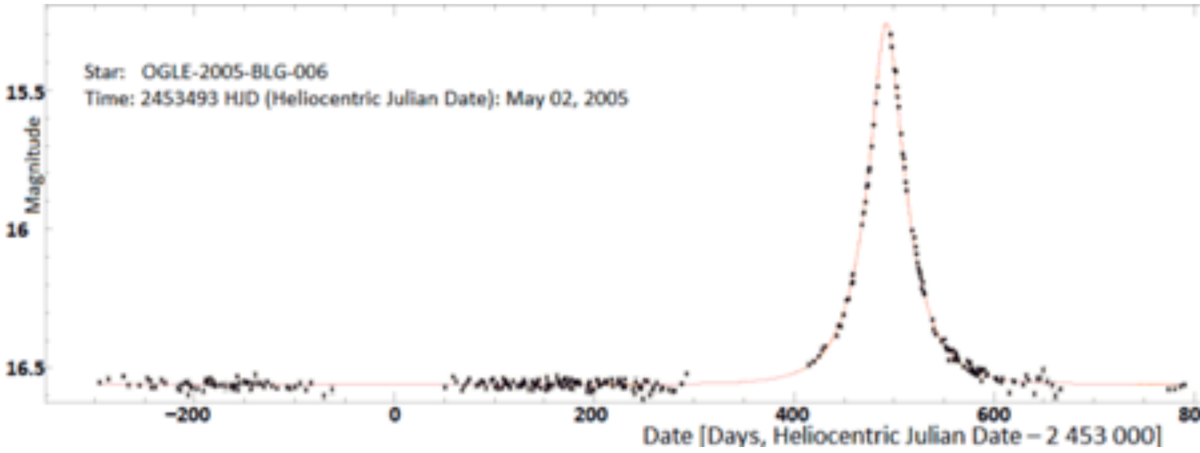
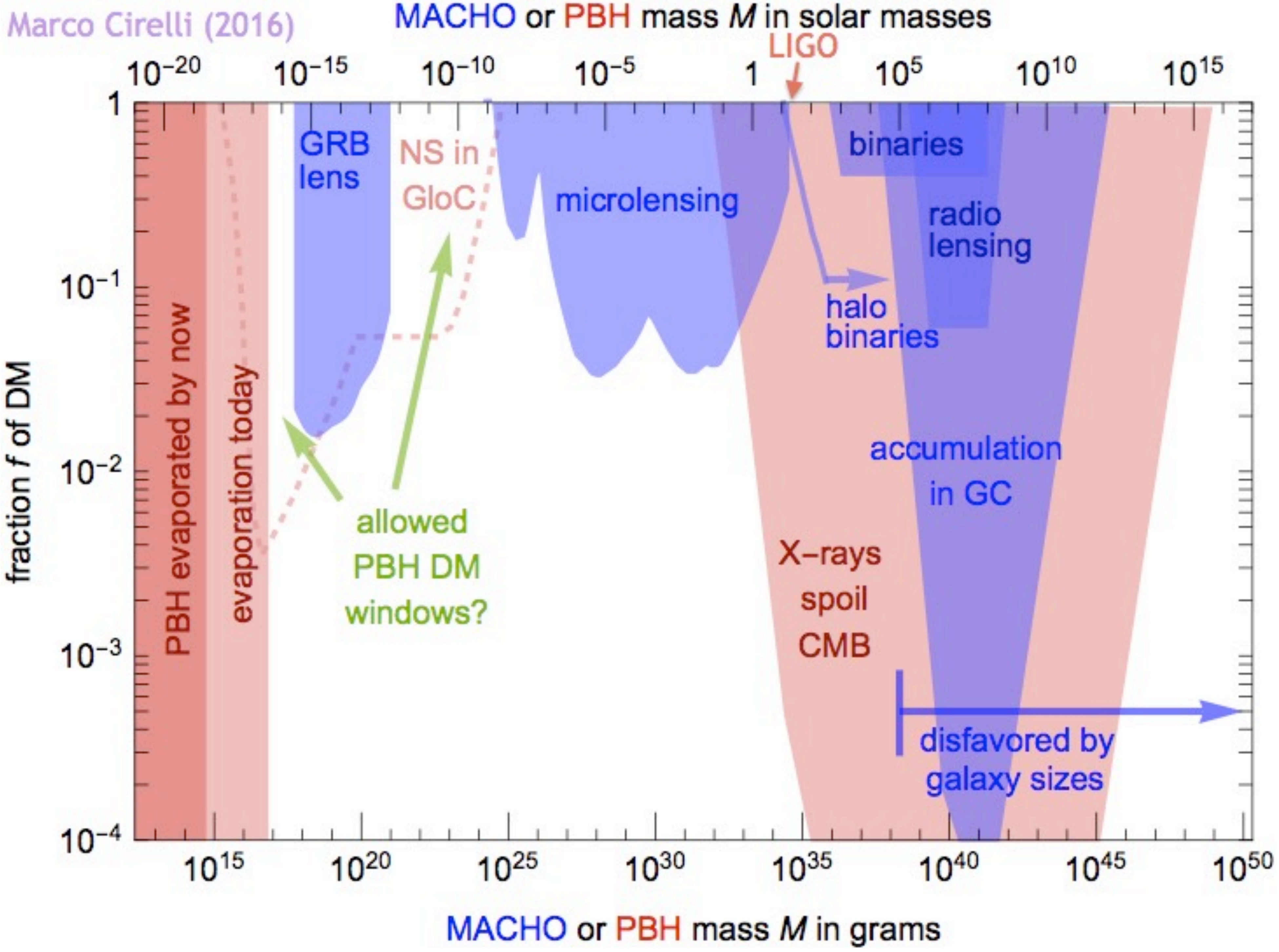


Recall searches for massive compact objects (MACHOs) like primordial BH's



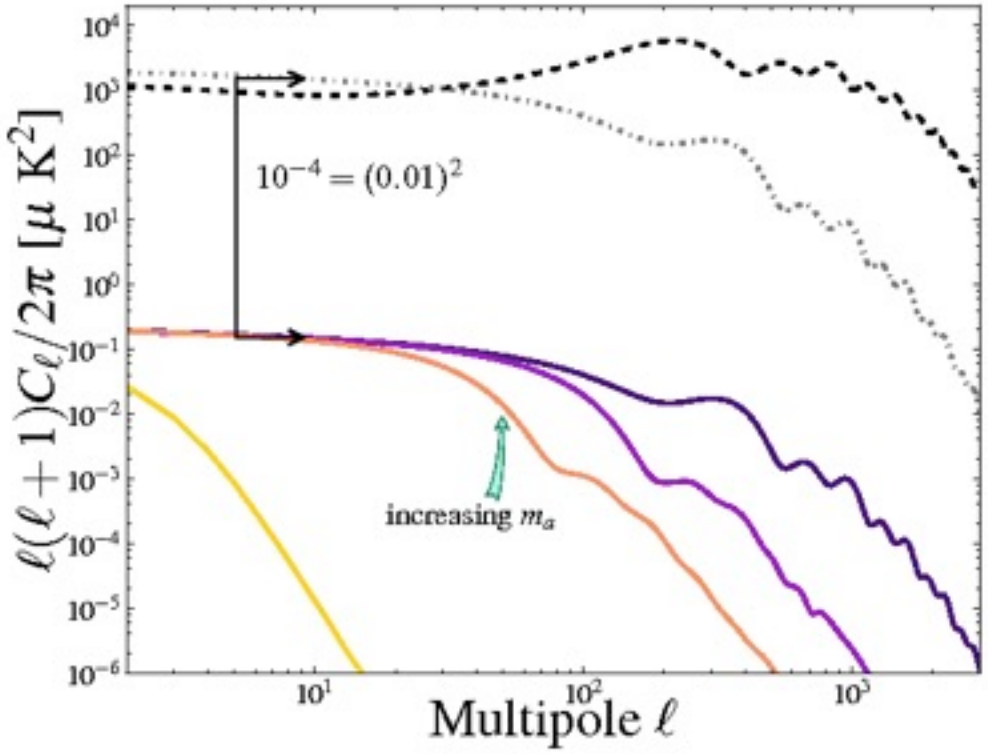
Axion DM implications

- PQ breaking before inflation

* Axion fluctuations during inflation

Axion is DM -> fluctuations imprinted in the CMB temperature

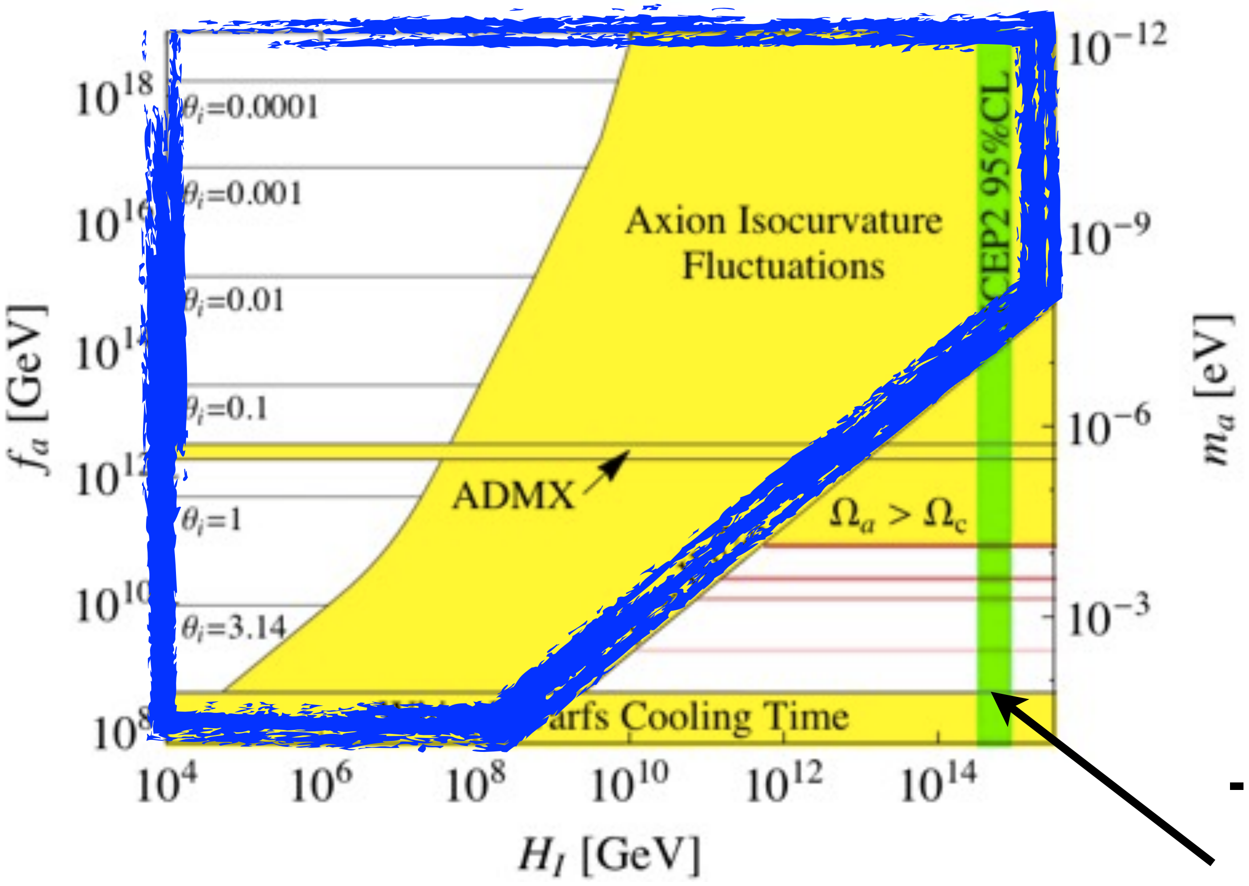
Isocurvature!!! Uncorrelated with the Inflaton fluctuations!



- 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 H_I during inflation ...

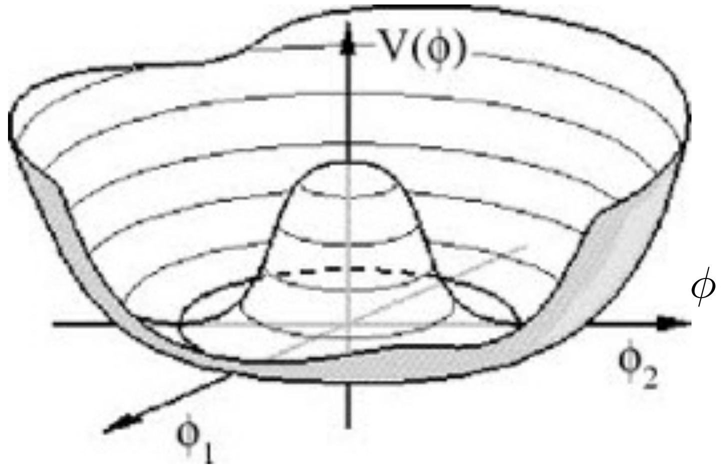


-If H_I is measured by next generation CMB experiments axion DM is excluded (avoided in some models)

Searching for Axion-like particles (ALPs)

pseudo Goldstone Bosons

- Global symmetry spontaneously broken



$\phi(x) = \rho(x) e^{i\theta(x)}$

- massless Goldstone Boson @ Low Energy

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

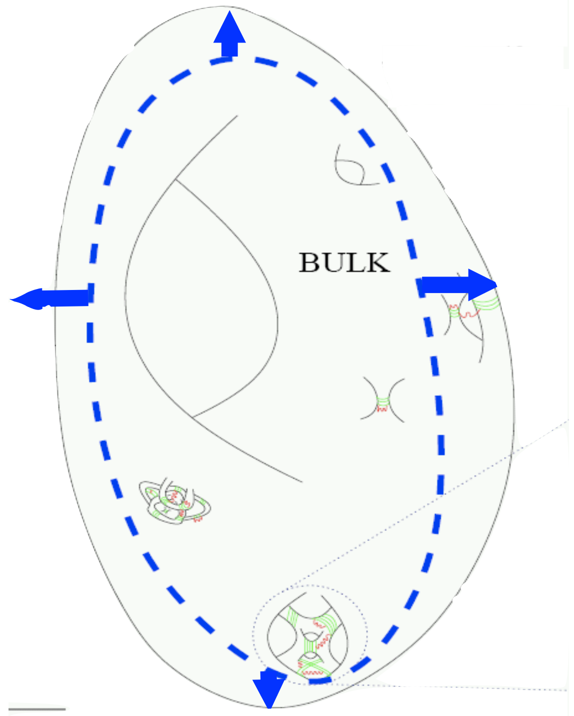
$$\mathcal{L}_{\text{kin}} = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f^2$$

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

- small symmetry breaking ⟶ 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

Low-energy effective action

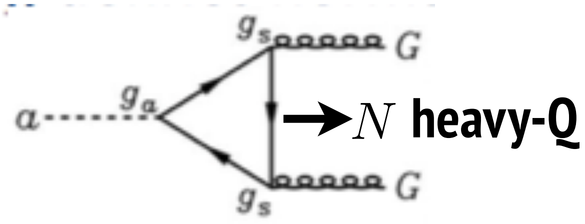
- Shift symmetry allows some generic types of interactions

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

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

(canonically normalised)
(EOM for fermion couplings)

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



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

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

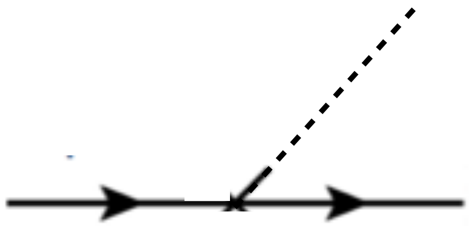
If our ALP shift symmetry is broken "only" by GGtilde -> QCD Axion

photon coupling

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

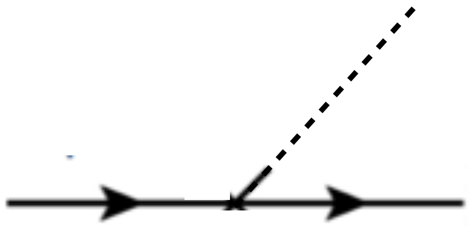
electron coupling

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



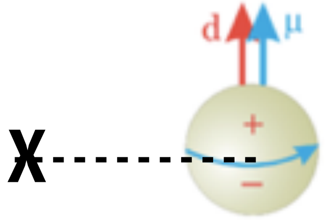
nucleon coupling

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

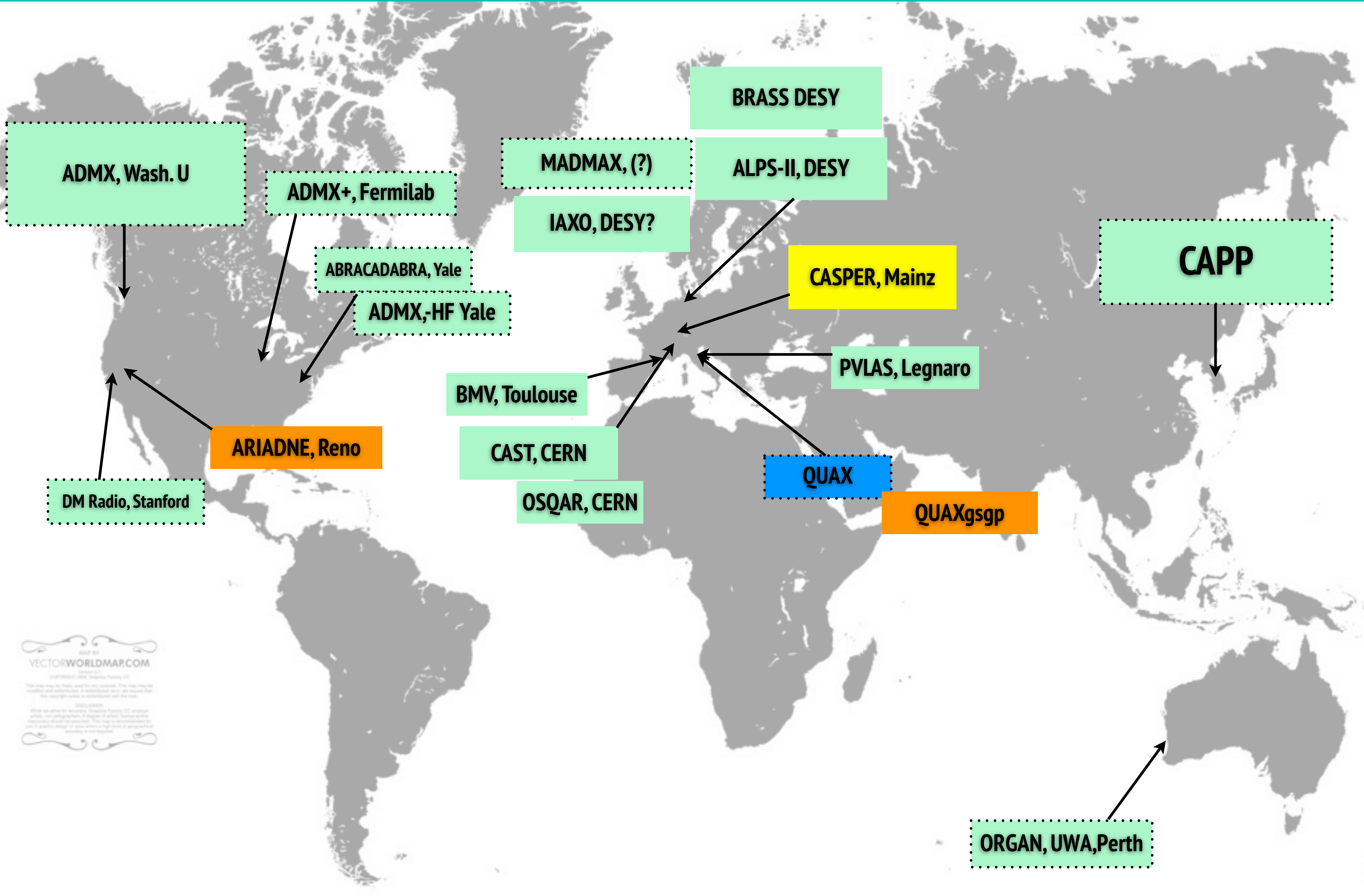


~~CP~~ Neutron electric dipole

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



Axion (ALP) experiments



BRASS DESY

ADMX, Wash. U

ADMX+, Fermilab

MADMAX, (?)

ALPS-II, DESY

IAXO, DESY?

ABRACADABRA, Yale

CASPER, Mainz

CAPP

ADMX,-HF Yale

PVLAS, Legnaro

BMV, Toulouse

ARIADNE, Reno

CAST, CERN

QUAX

DM Radio, Stanford

OSQAR, CERN

QUAXgsgp

ORGAN, UWA,Perth

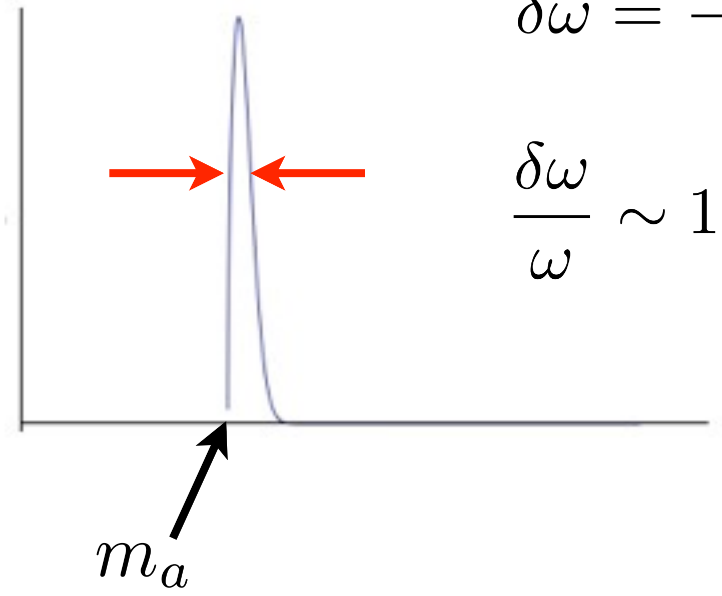
Dark matter searches

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



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

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

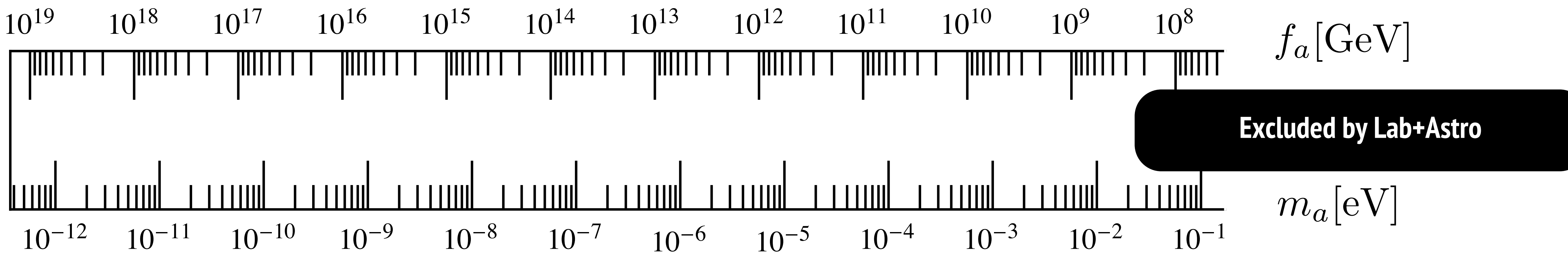
coherence time

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

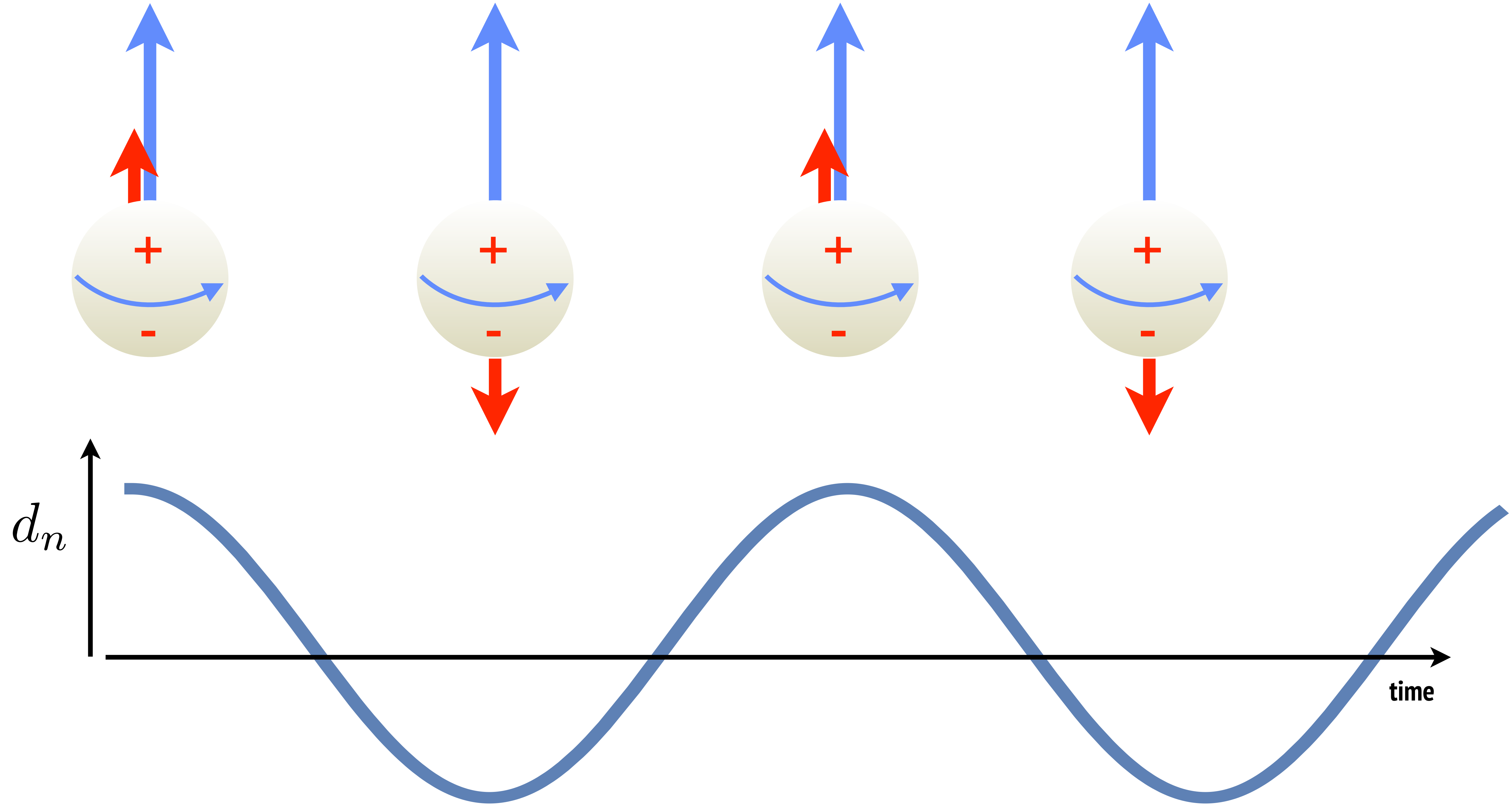
coherence length

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

- **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 nEDM!



$$d_n \sim \cos(m_a t) 10^{-34}\ \text{ecm}$$

CASPER : oscillating EDM with NMR

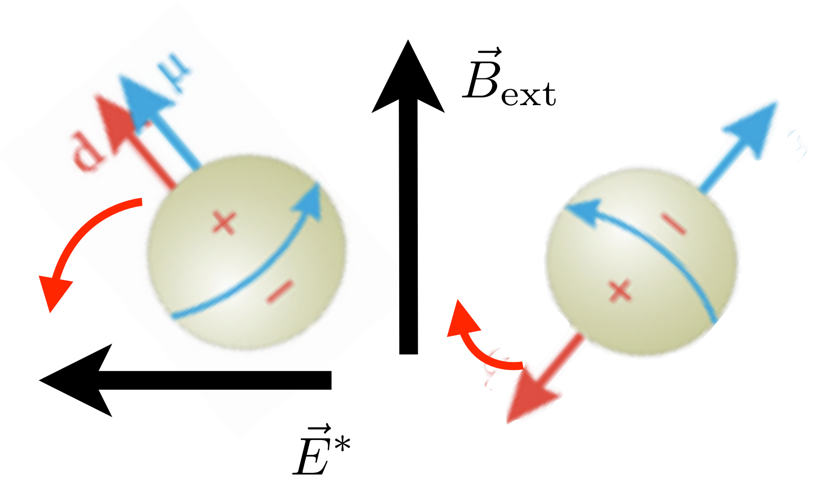
Mainz, Berkeley

D. Budker

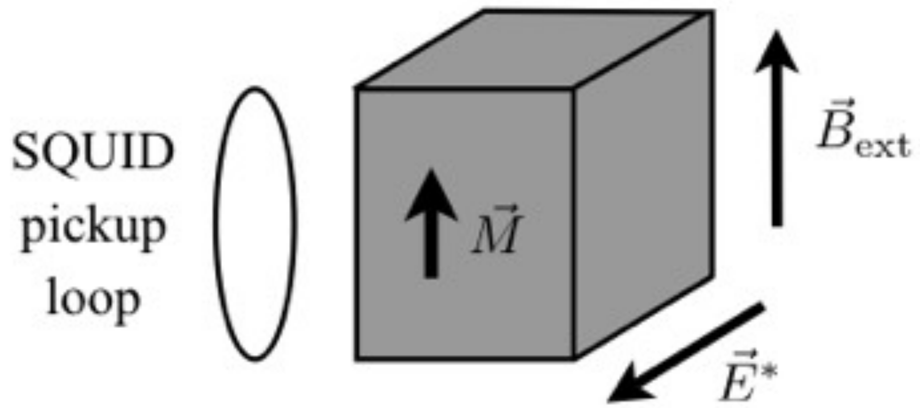
S. Rajendran

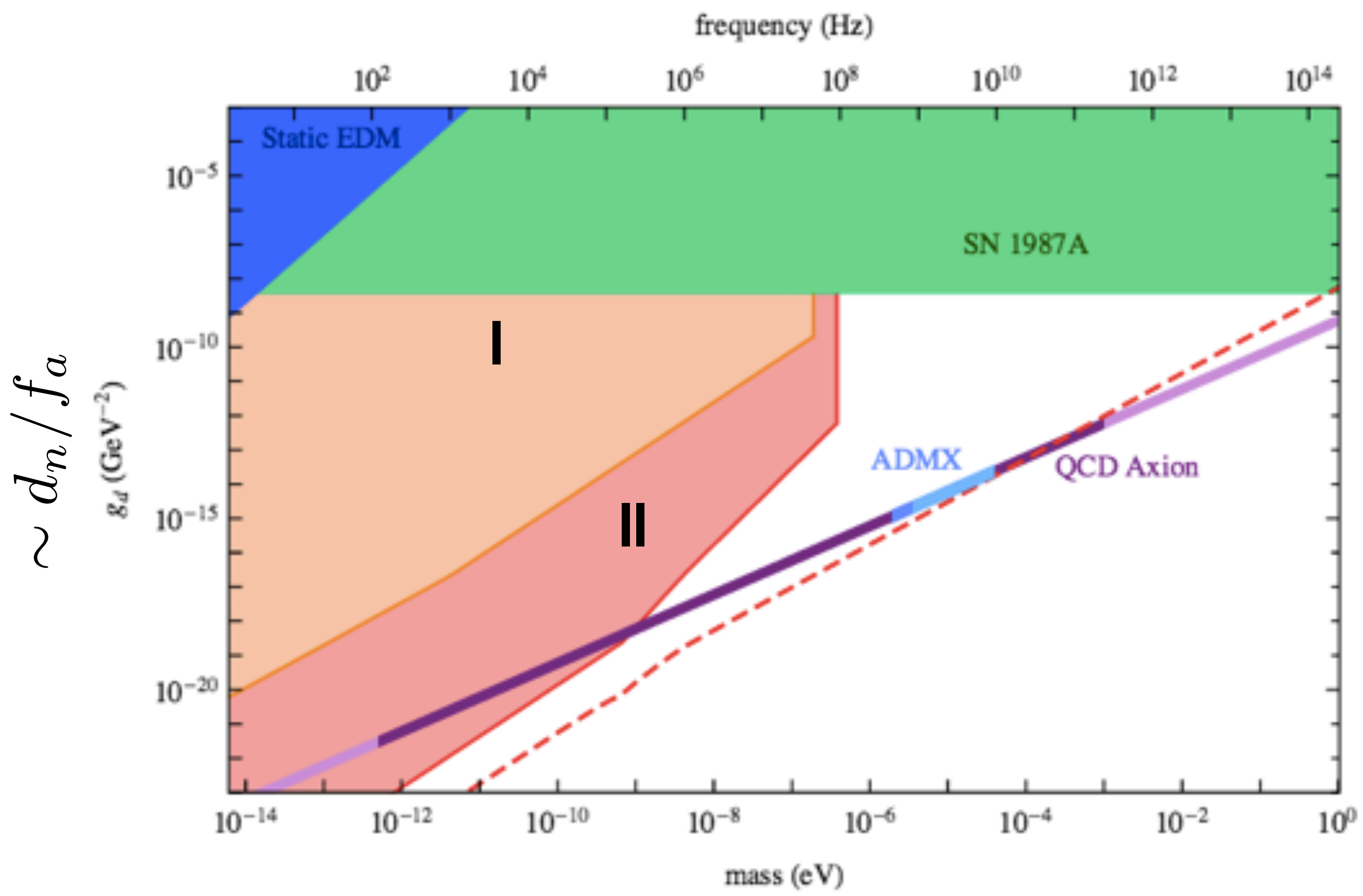
P. Graham

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



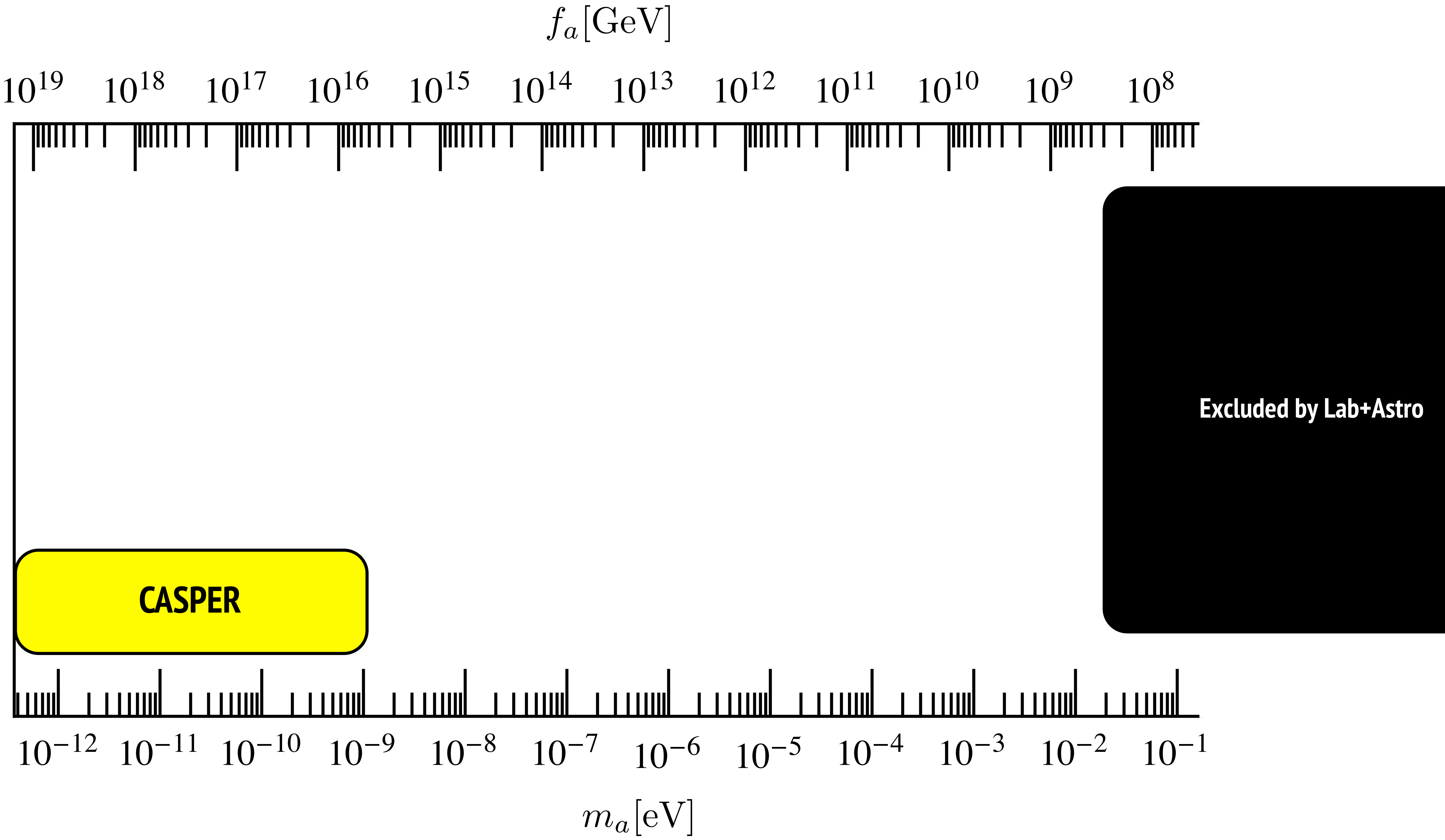
Oscillating EDM, effects add up, transverse magnetisation grows on resonance $m_a = \omega = \mu|\vec{B}_{\mathrm{ext}}|$





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

In the big picture

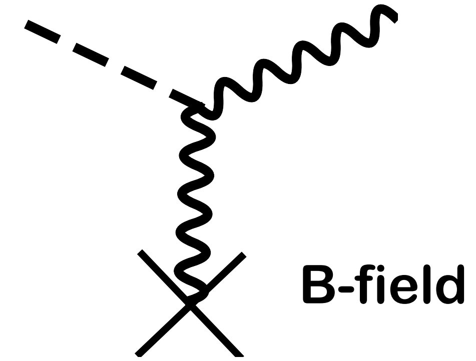


Axion DM in a B-field

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

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

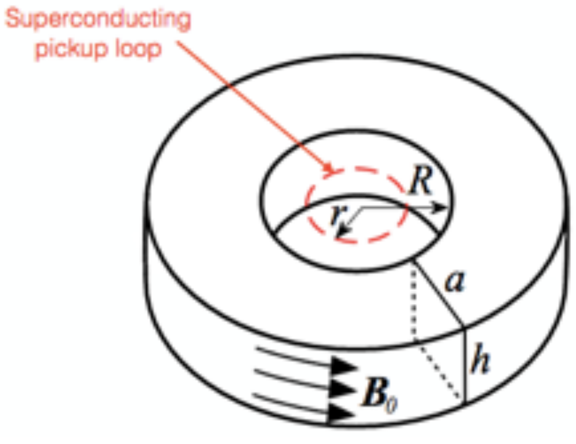
source



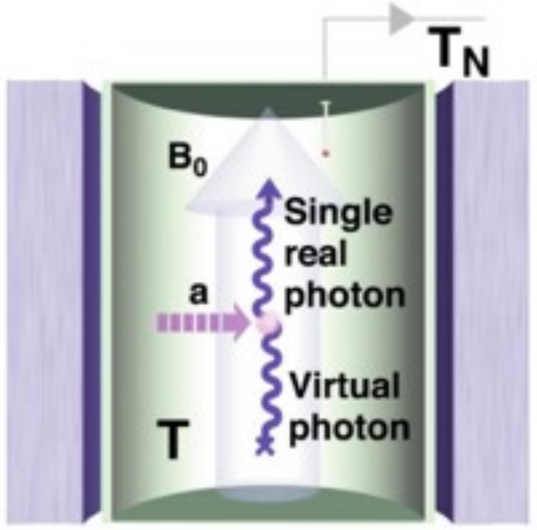
E-field $E \sim \mathcal{O}(10^{-12}{\rm V/m})\frac{|{\rm B}_{\rm ext}|}{10\,{\rm T}}C_{a\gamma}\times\cos(m_a t)$

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

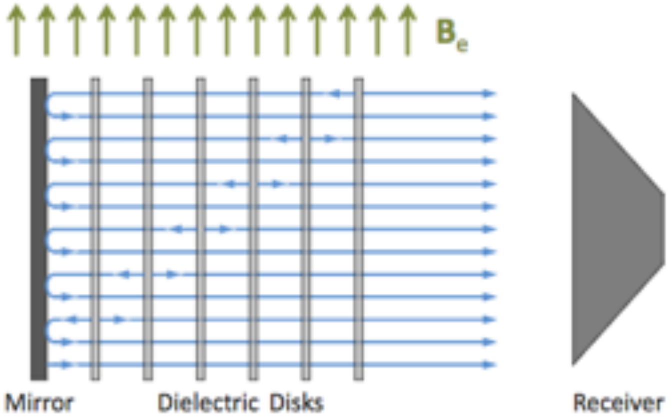
- Four different techniques:



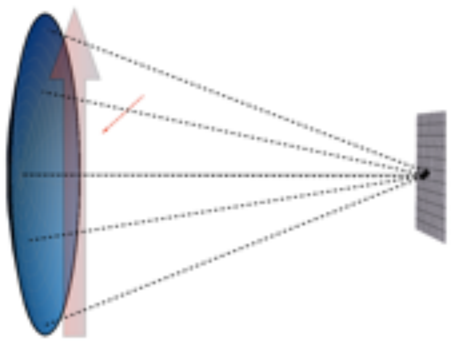
DM Radio



Cavities



Dielectric haloscope



Dish antenna

Detecting axion DM

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

$$\begin{aligned} \nabla \cdot \mathbf{E} &= \rho_f \\ \nabla \times \mathbf{H} - \dot{\mathbf{E}} &= \mathbf{J}_f - C_{a\gamma}\frac{\alpha}{2\pi}\mathbf{B}\,\dot{\theta} \\ \nabla \cdot \mathbf{B} &= 0 \\ \dot{\mathbf{B}} + \nabla \times \mathbf{E} &= 0 \end{aligned}$$

In a magnetised medium

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

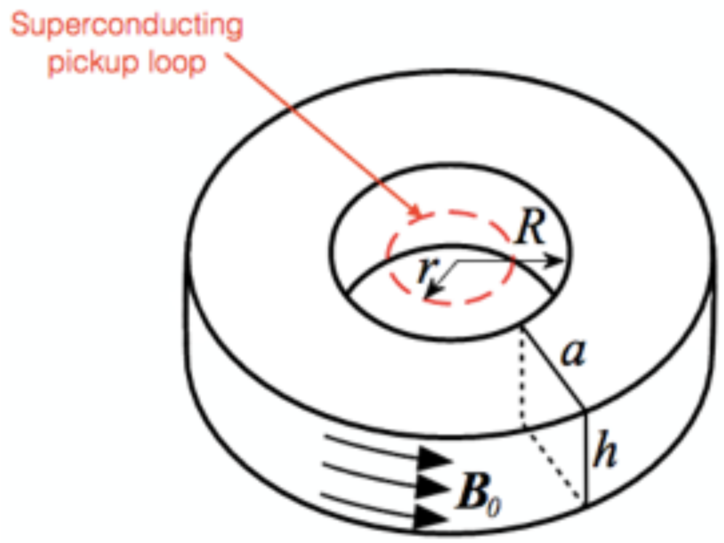
- **Electric fields** $|\mathbf{E}_a| = 1.3 \times 10^{-12}\ \mathrm{V/m}\ \frac{B_\mathrm{e}}{10\ \mathrm{T}}\ C_{a\gamma}\,.$ **(independent of mass!)**

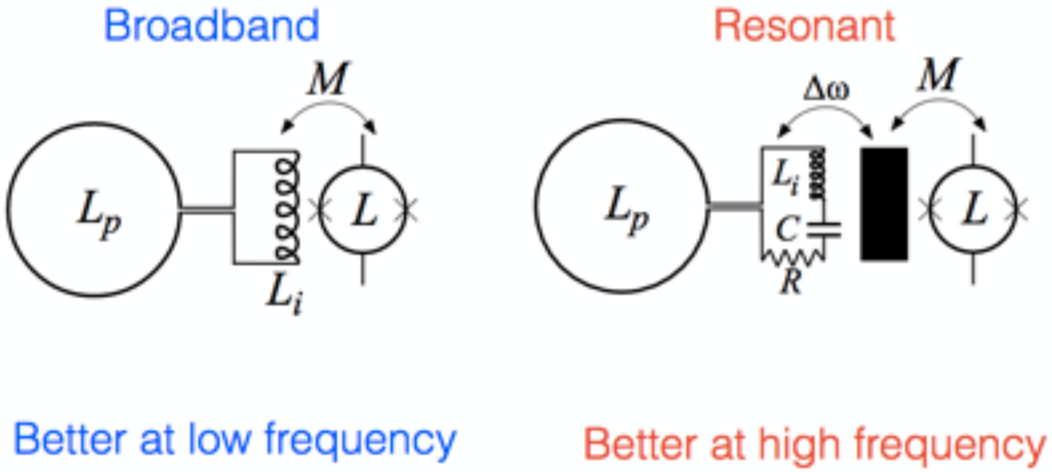
- **Oscillating at a frequency** $\omega \simeq m_a$

DM Radio

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

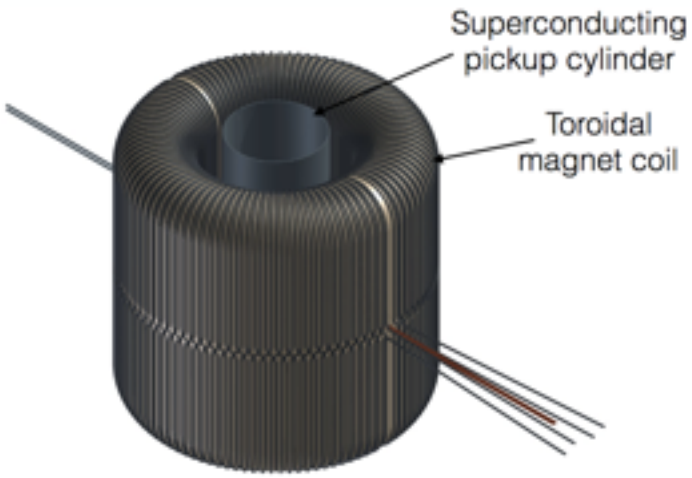
Sikivie PRL 112 (2014)
Chaudhuri PRD92 (2015)
Kahn PRL 117 (2016)



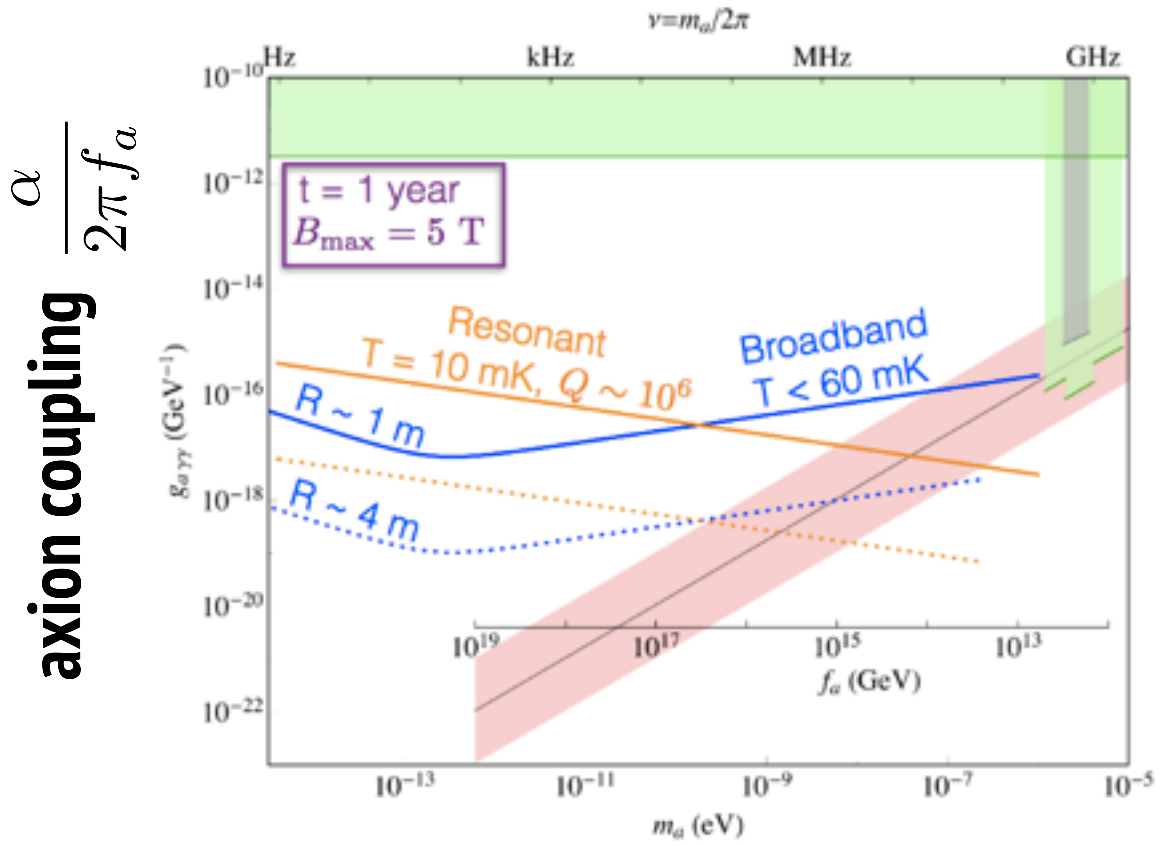


Better at low frequency

Better at high frequency



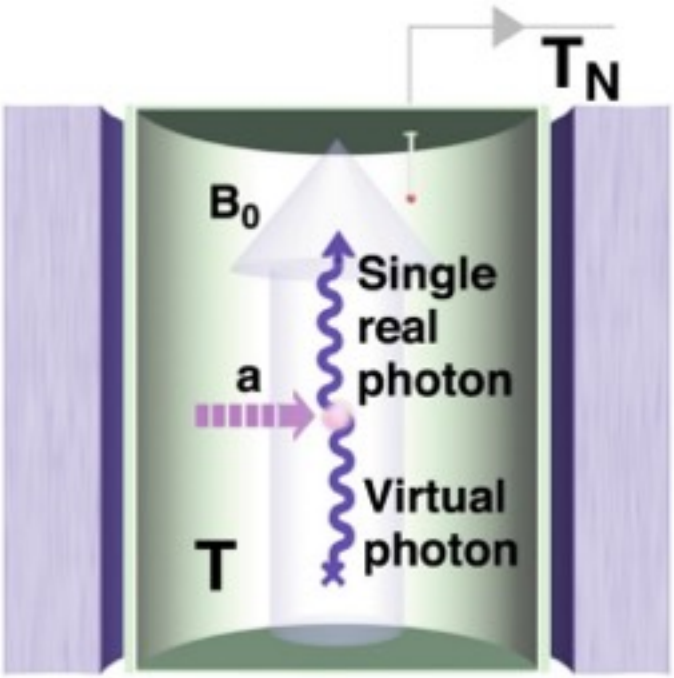
ABRACADABRA (MIT)
10 cm, 1m , 4m …



Resonant cavities: haloscopes

P. Sikivie

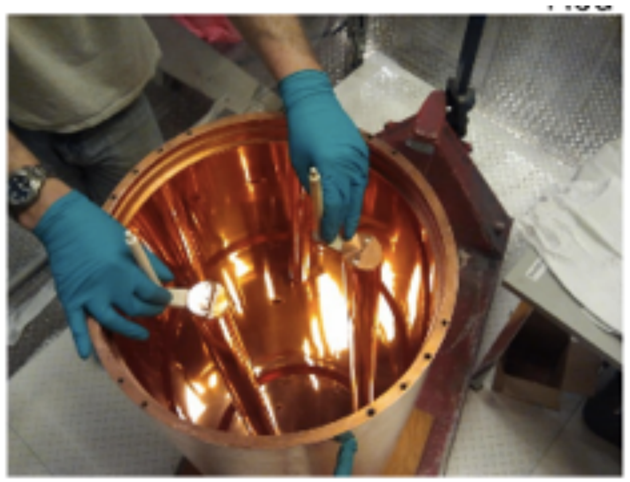
- Boost the axion-generated E-field in a tuned resonant cavity

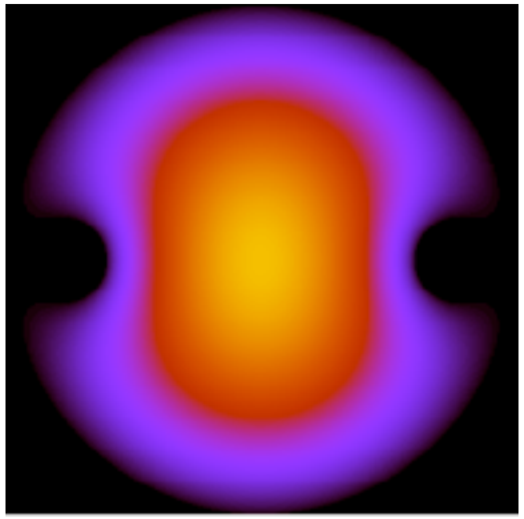


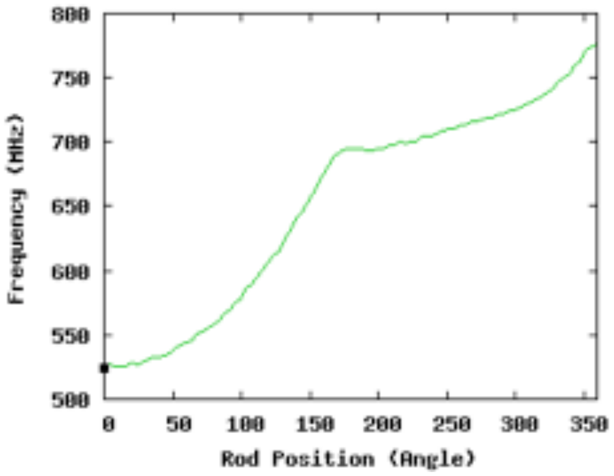
$$P_{\rm out} \sim Q|\mathbf{E}_a|^2 V m_a$$

- 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





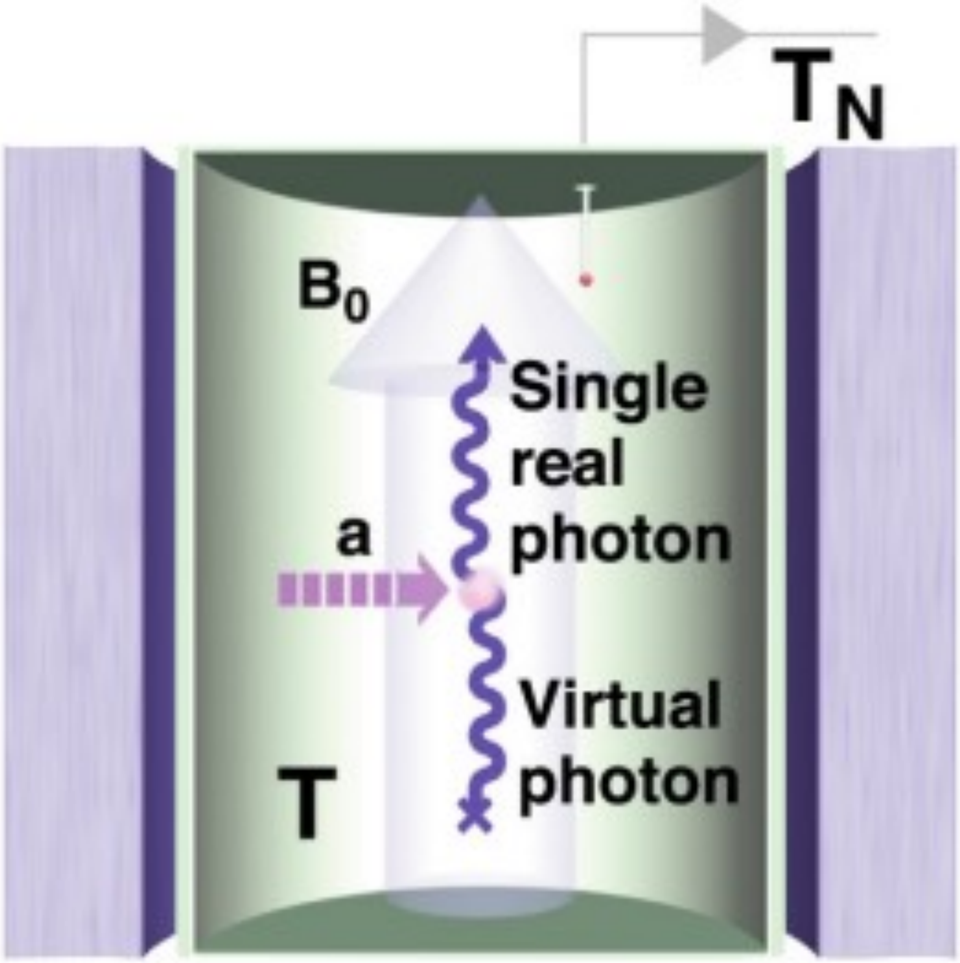


- At high freq. limited by small volume and high noise
- At low freq. by getting a large enough B-field

Cavity experiments

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

$$\mathrm{Power}_{\mathrm{out}} \sim Q|\mathbf{E}_a|^2(Vm_a)\mathcal{G}\kappa$$ **(on resonance)**



Cavity equation (forced damped EM oscillator)

$$\ddot{\mathbf{E}} - \nabla^2\mathbf{E} + \Gamma\ \dot{\mathbf{E}} = -\frac{C_{a\gamma}\alpha}{2\pi}\mathbf{B}_{\mathrm{ext}}\ \ddot{\theta}$$

Axions in magnetised cavities

Cavity equation (forced damped EM oscillator)

$$\ddot{\mathbf{E}} - \nabla^2\mathbf{E} + \Gamma\ \dot{\mathbf{E}} = -\frac{C_{a\gamma}\alpha}{2\pi}\mathbf{B}_{\rm ext}\,\ddot{\theta}$$

$$\ddot{\mathbf{E}} - \nabla^2\mathbf{E} + \Gamma\ \dot{\mathbf{E}} = m_a^2\mathbf{E}_a\mathbf{b}$$

➡

$$E_i = \frac{\int dV\,\mathbf{e}_i\cdot\mathbf{b}}{V}\,\frac{m_a^2\mathbf{E}_a}{(-m_a^2+\omega_i^2-im_a\Gamma)}$$

Normal modes ...

$$\mathbf{E}(t,\mathbf{x}) = \sum_i E_i(t)\mathbf{e}_i(\mathbf{x})$$

$$-\nabla^2\mathbf{e}_i = \omega_i^2\mathbf{e}_i$$ **+ b.c.**

$$\int dV\,\mathbf{e}_i\cdot\mathbf{e}_j = V\delta_{ij}$$

Energy in a mode

$$U_i = VE_i^2$$

Energy loss (Power loss)

$$U_i = U_i(0)e^{-\Gamma t}$$

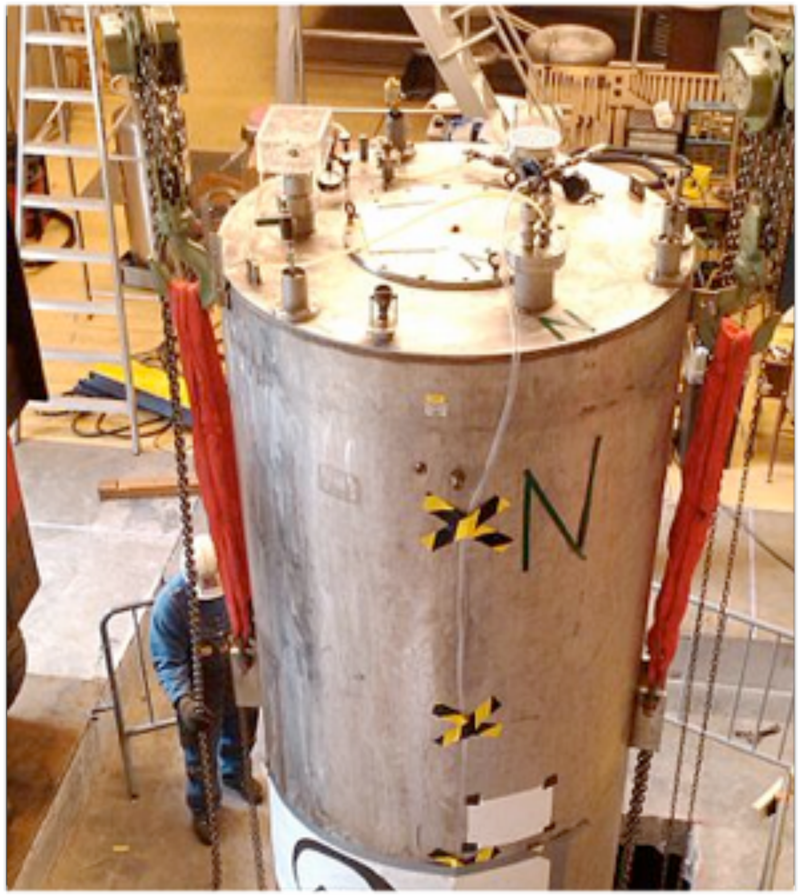
$$\Gamma = \Gamma_{out} + \Gamma_{dissipation}$$

Quality factor

$$Q_i = \frac{\omega_i}{\Gamma}$$

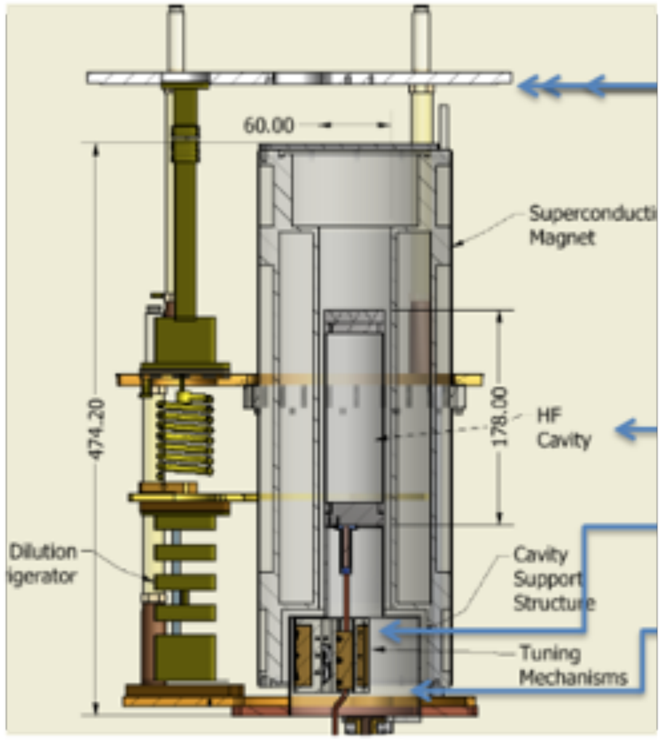
Cavity experiments

ADMX-Seattle



running!

CULTASK - CAPP -Korea



2017-...

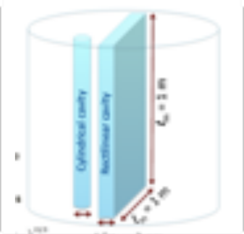
ORGAN-UWA Perth

2017-...

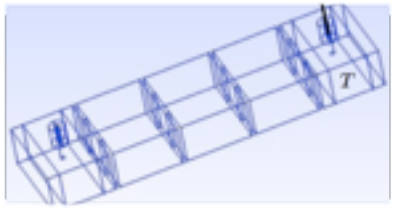
HAYSTAC-Yale

2016-...

ADMX-Fermilab



RADES



2017-...

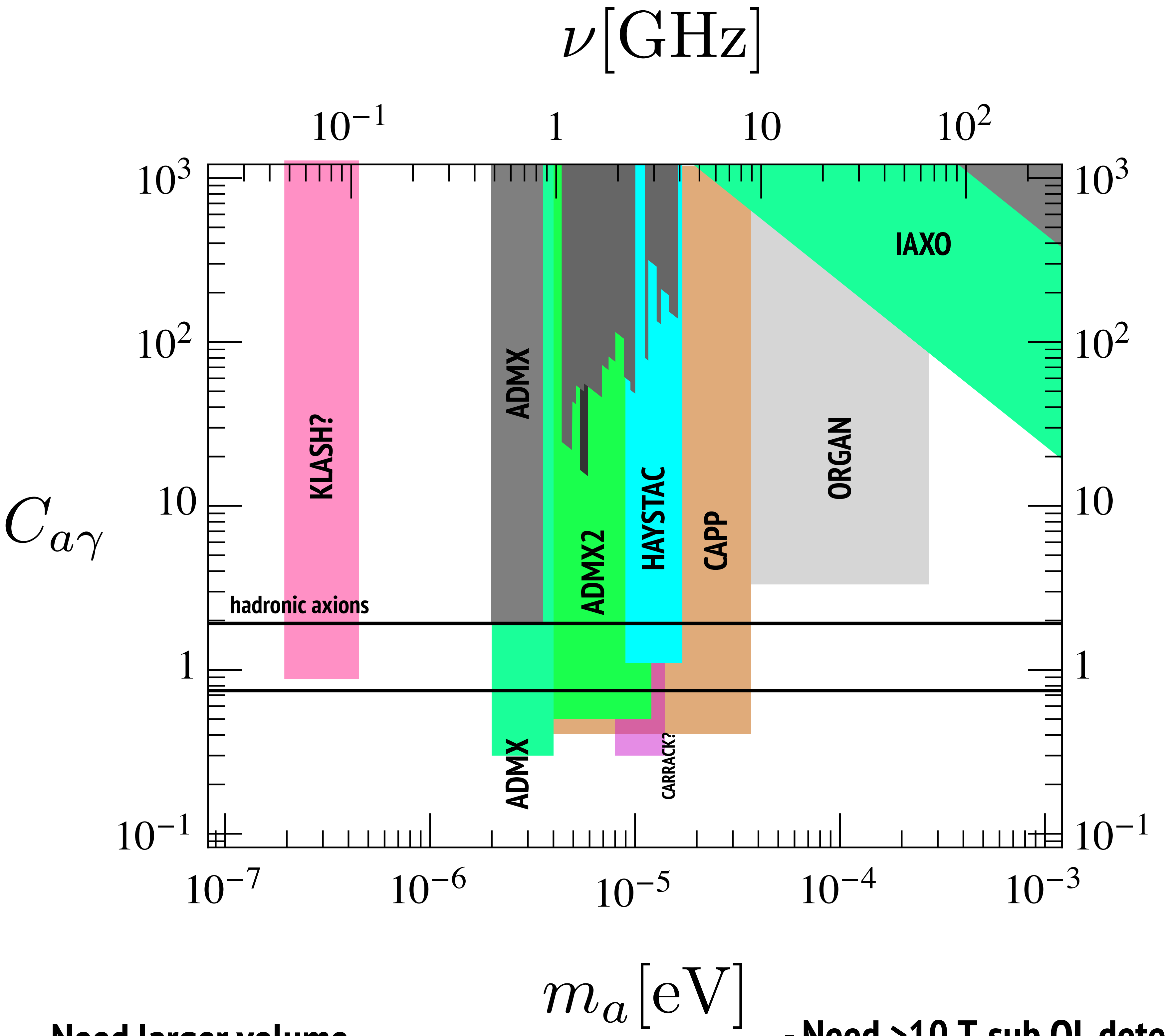
CAST-CAPP

2017-...

KLASH?

??-...

Projected sensitivities

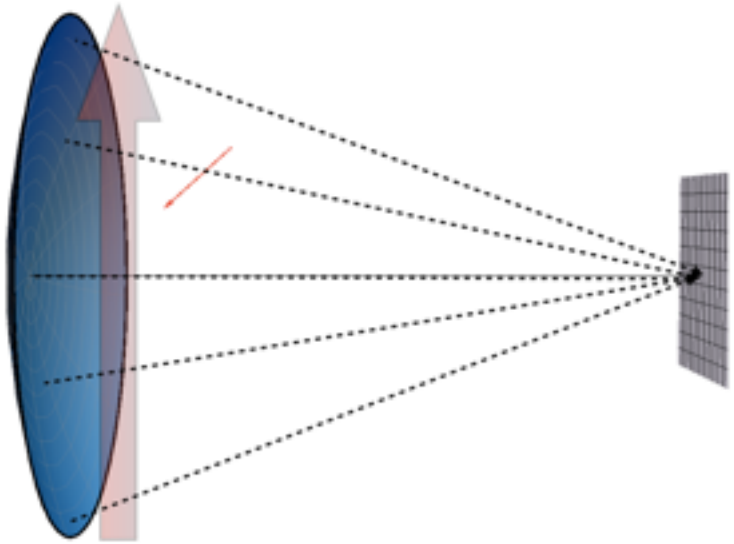


- Need larger volume

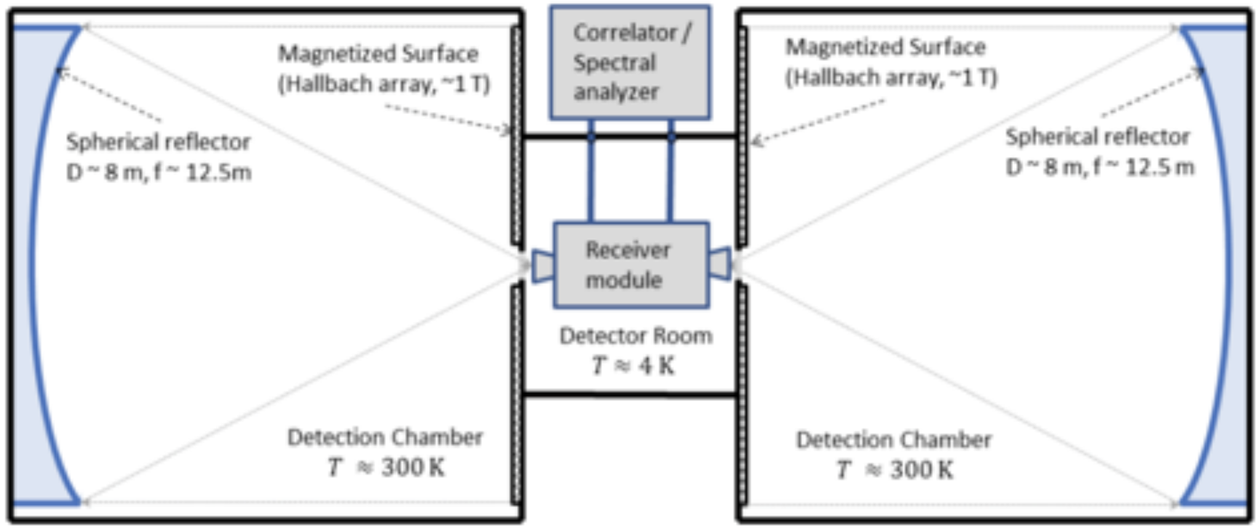
- Need >10 T, sub QL detection, Q~10^6

Dish antenna

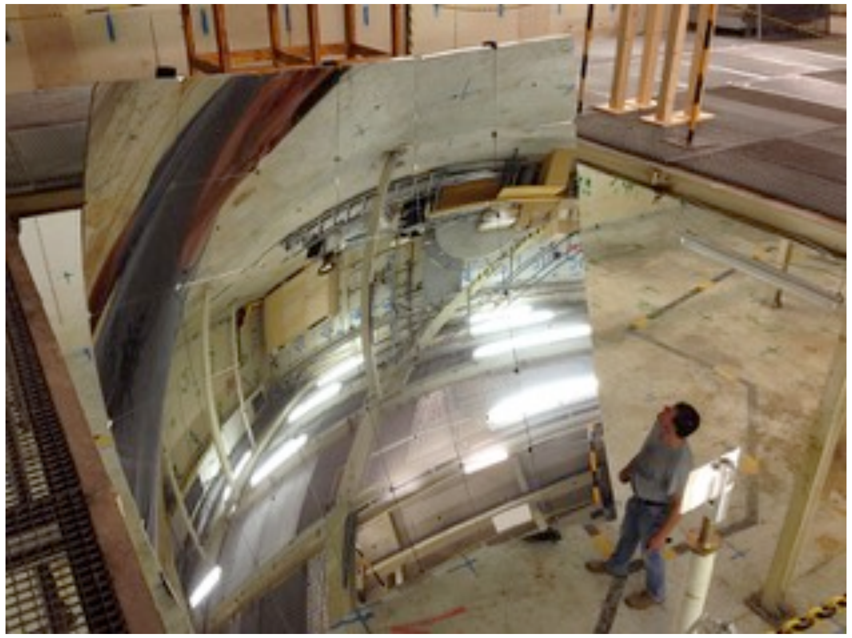
- Detect radiated power from a huge ($Am_a^2 \gg 10^6$) magnetised dish
- Broadband, no resonance enhancement; Only detector needs to be at T~mK (high reflectivity dish)
- Magnetise Area with permanent-magnets, photon counting?



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



BRASS @ Hamburg



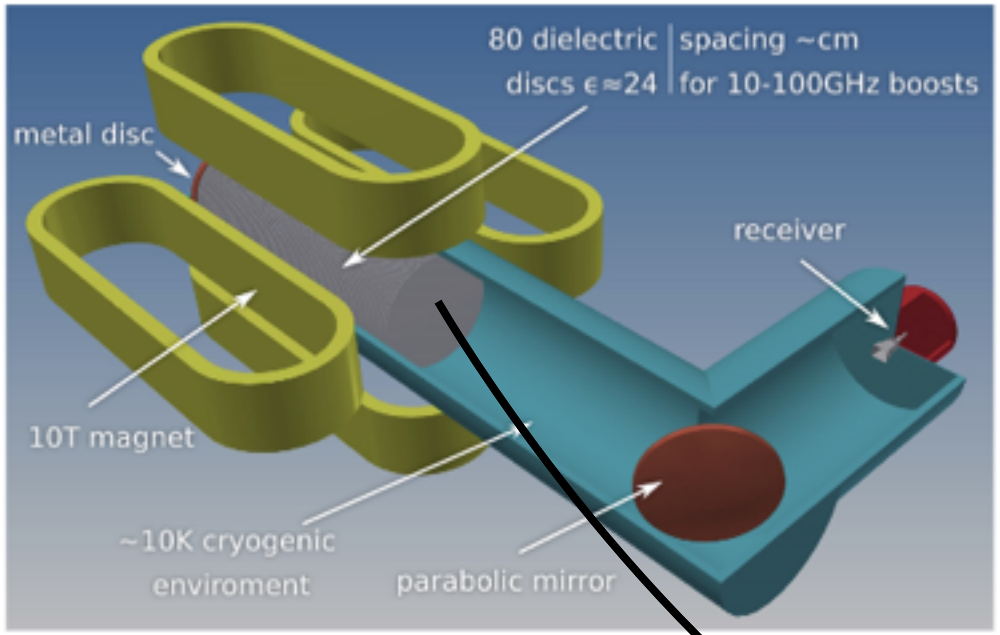
FUNK experiment (KIT)

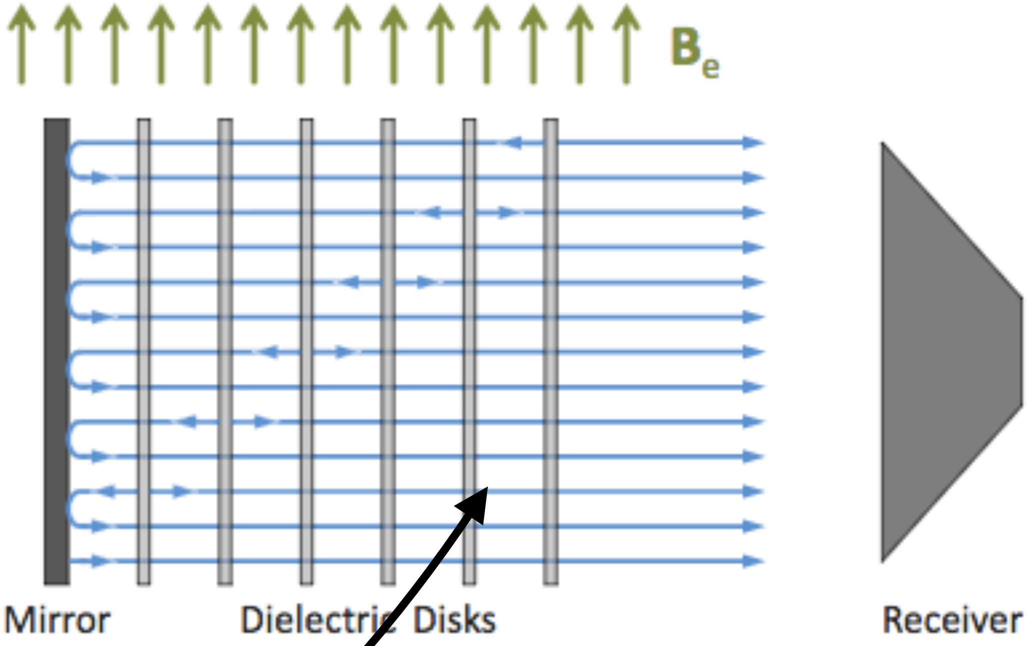
Dielectric haloscope : MADMAX

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

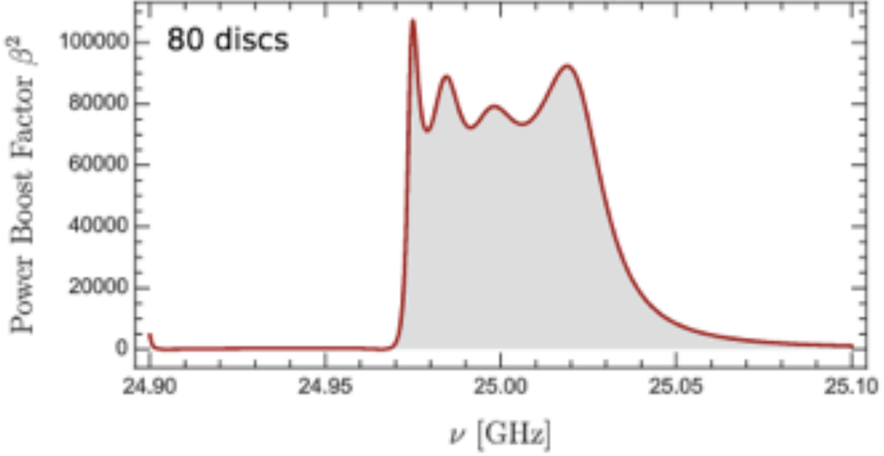
$$\frac{P}{Area} \sim 2\times 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{c_\gamma}{2}\,\frac{B_{||}}{5\mathrm{T}}\right)^2\frac{1}{\epsilon}\times\beta(\omega)$$

boost factor

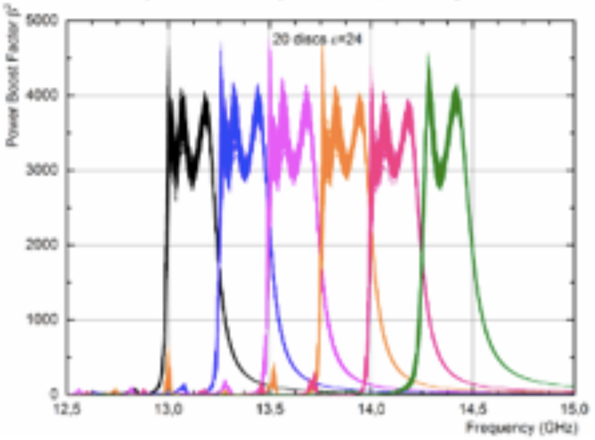




adjustable by disc spacings

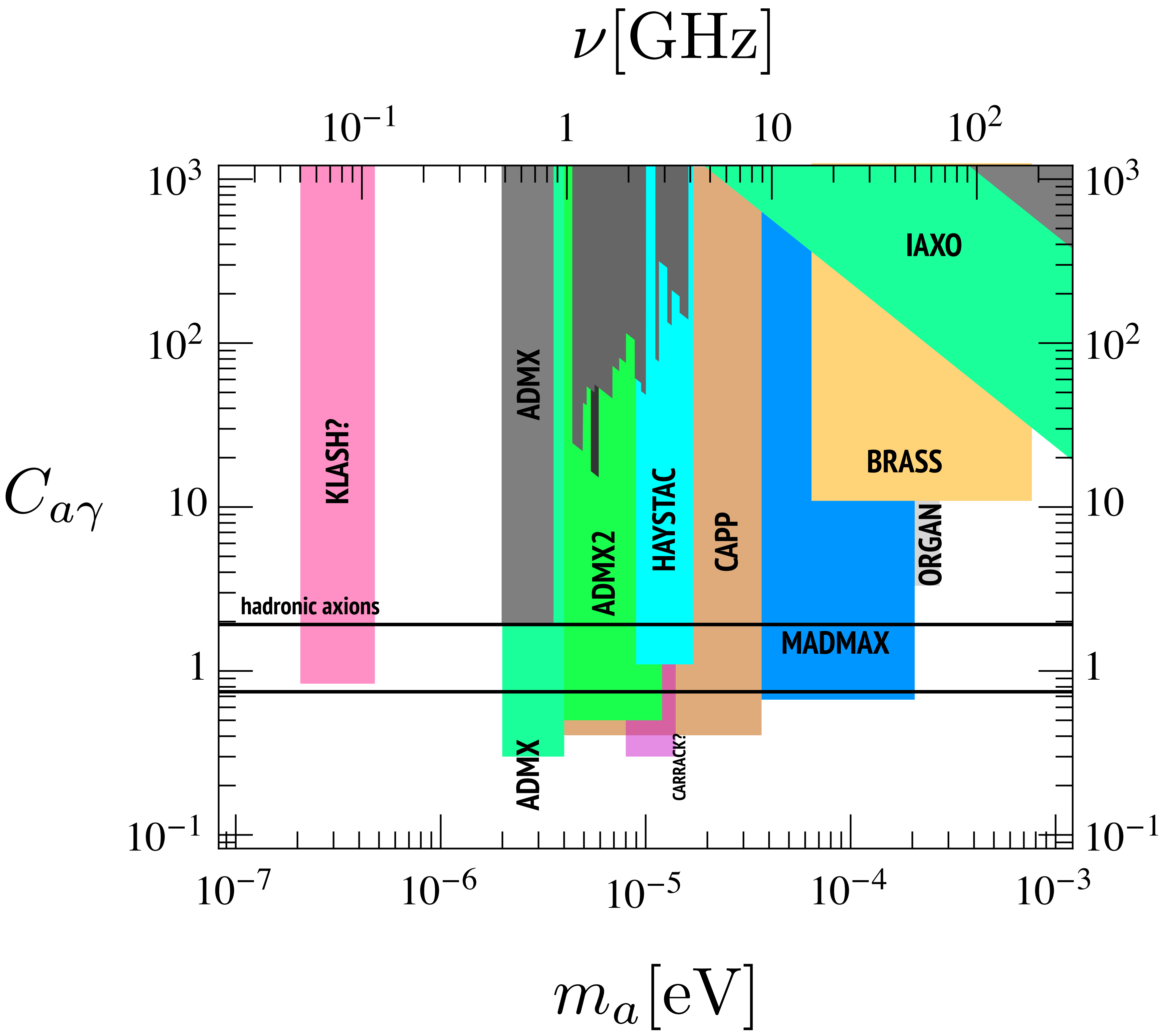


adjustable by disc spacings



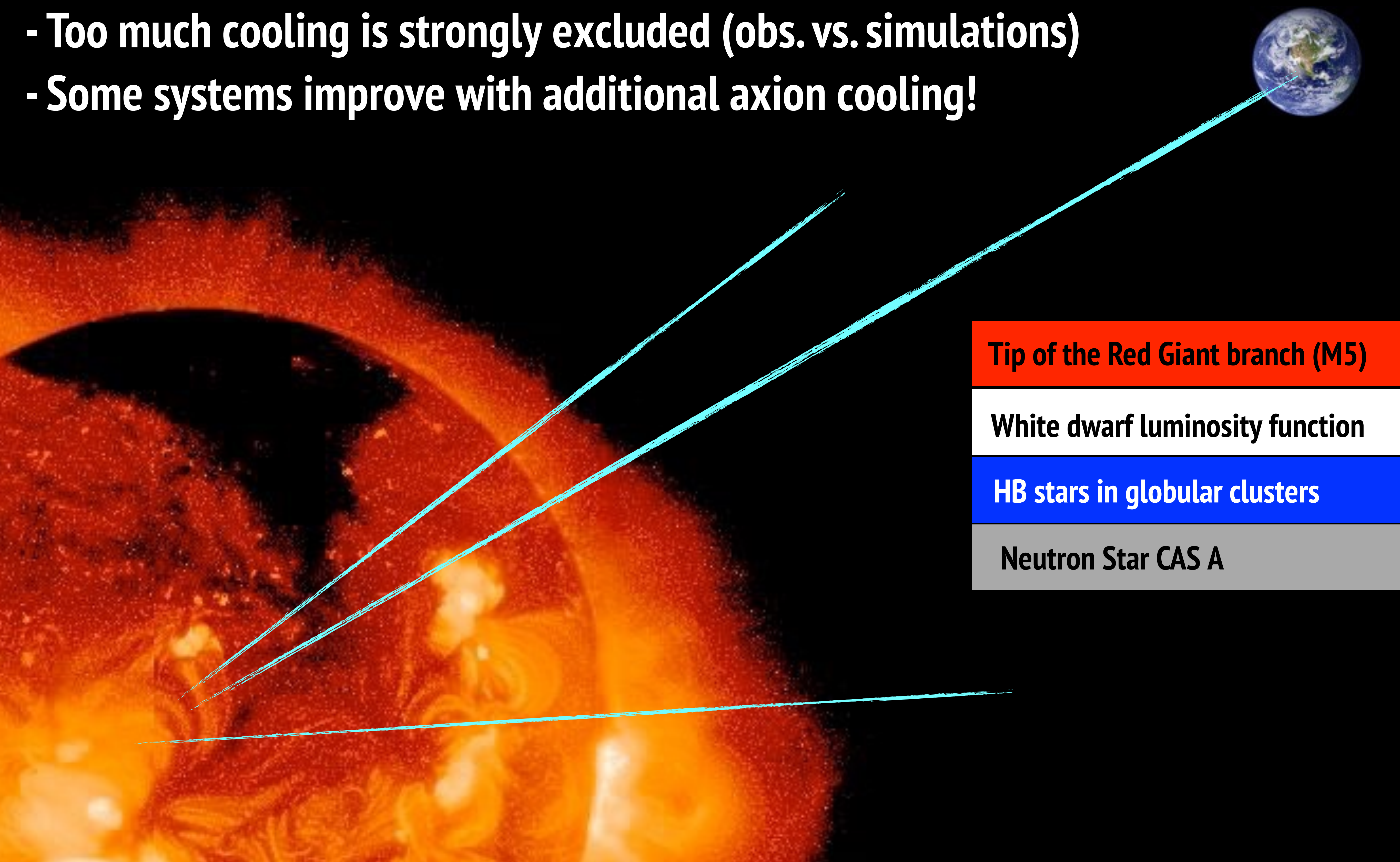
MADMAX: MAgnetised Disk and Mirror Axion eXperiment: MPP Munich, Hamburg Uni, DESY, Saclay, Zaragoza U

Projected sensitivities



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!



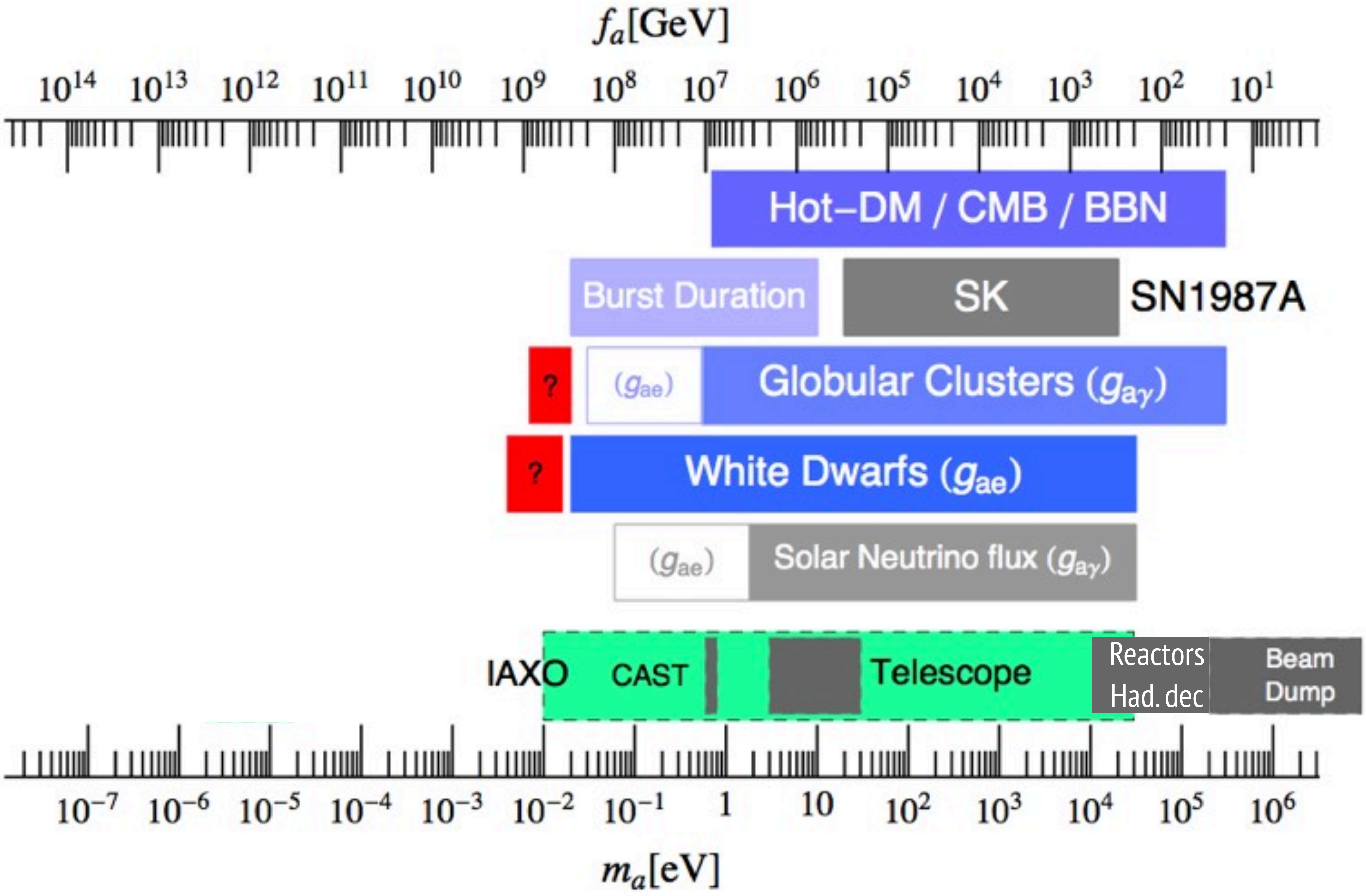
Tip of the Red Giant branch (M5)

White dwarf luminosity function

HB stars in globular clusters

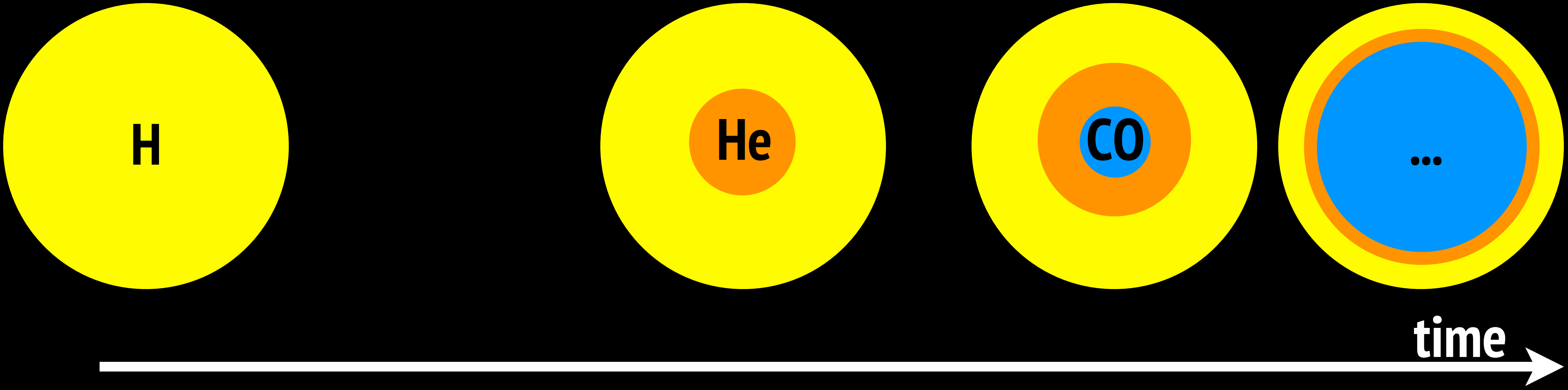
Neutron Star CAS A

Axion Landscape

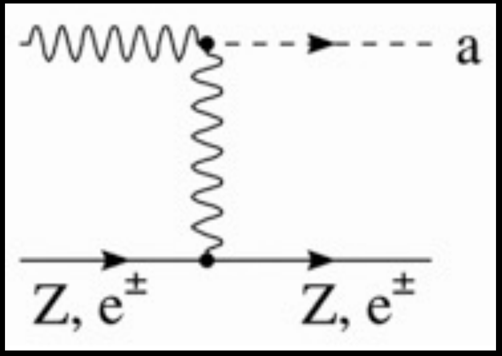


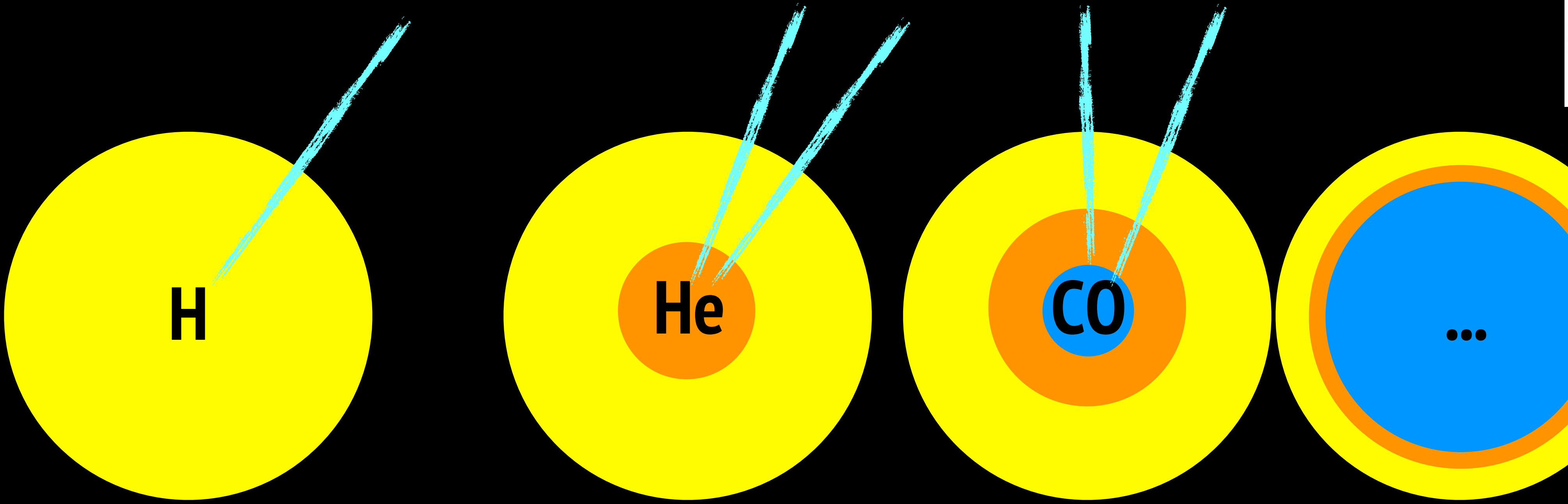
Stellar evolution and axions

- Stellar evolution (speed limited by energy loss)



- Axions emitted from stars accelerate stellar evolution





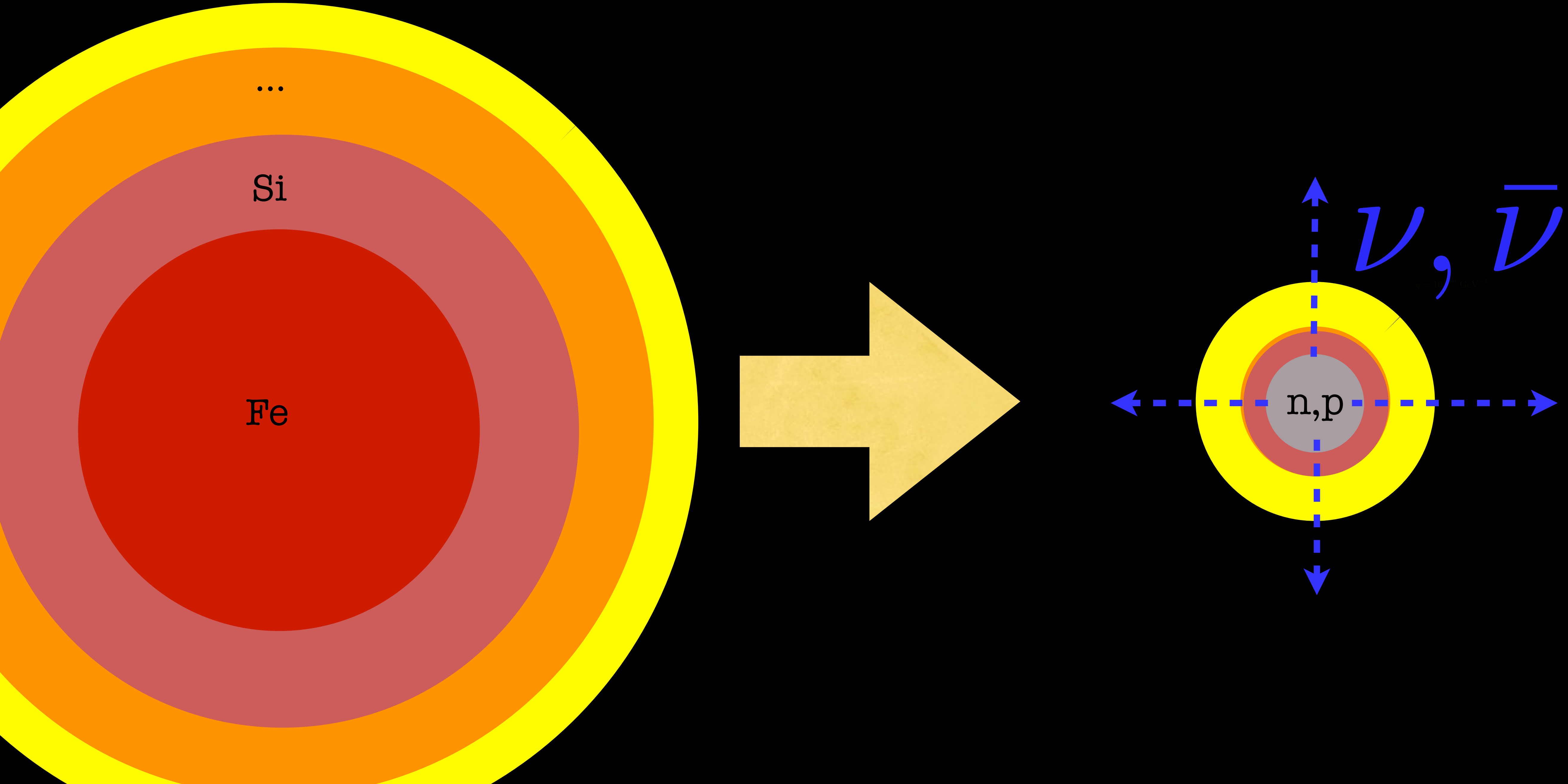
Core collapse SN

Iron Core collapse when electron degeneracy pressure cannot support its grav. pull

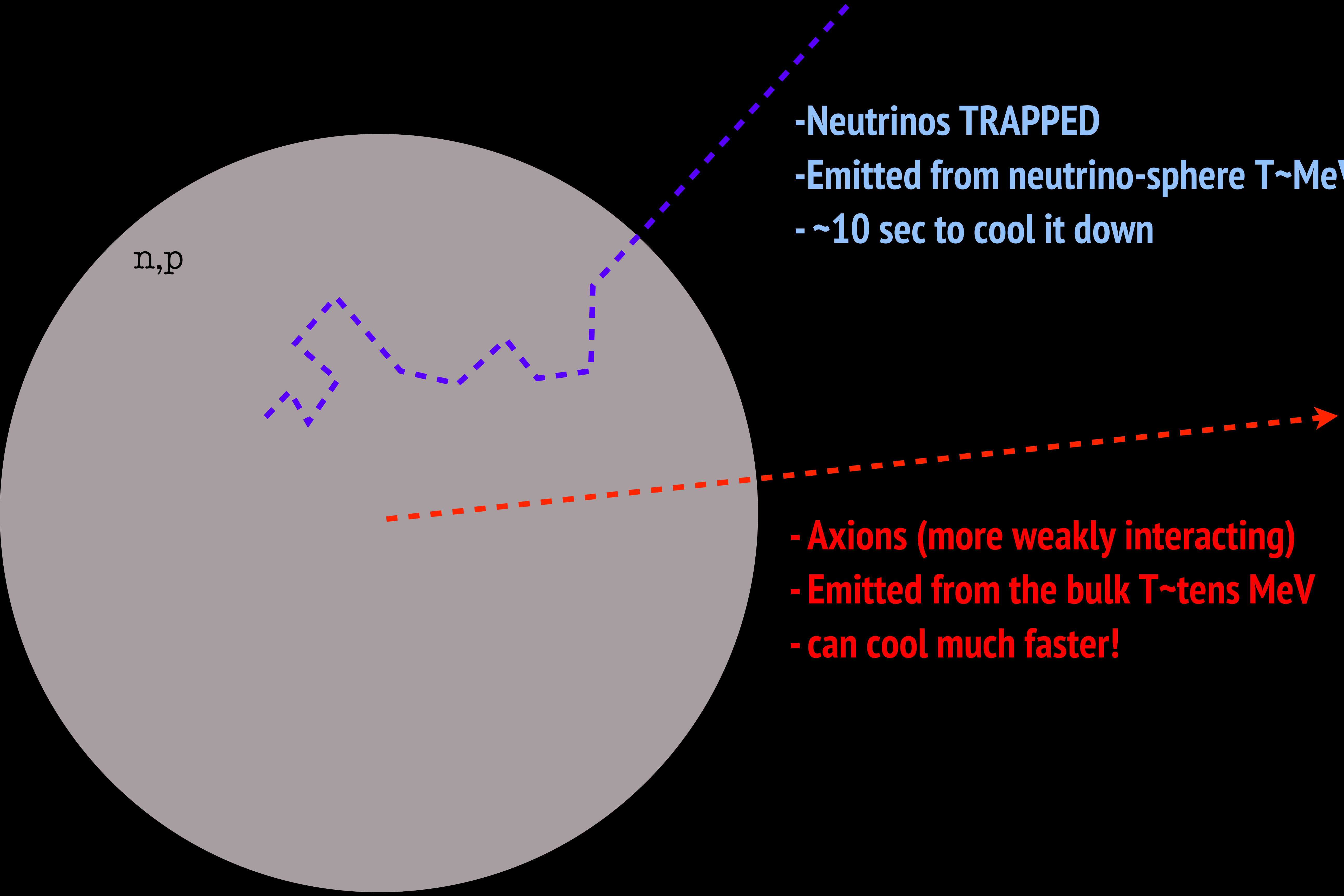
$$\mathcal{M}_{\mathrm{core}} \sim 1.4\mathcal{M}_{\odot}$$

The gravitational energy of the core is mainly to be radiated away in neutrinos

$$E = 3 \times 10^{53}\ \mathrm{erg}$$



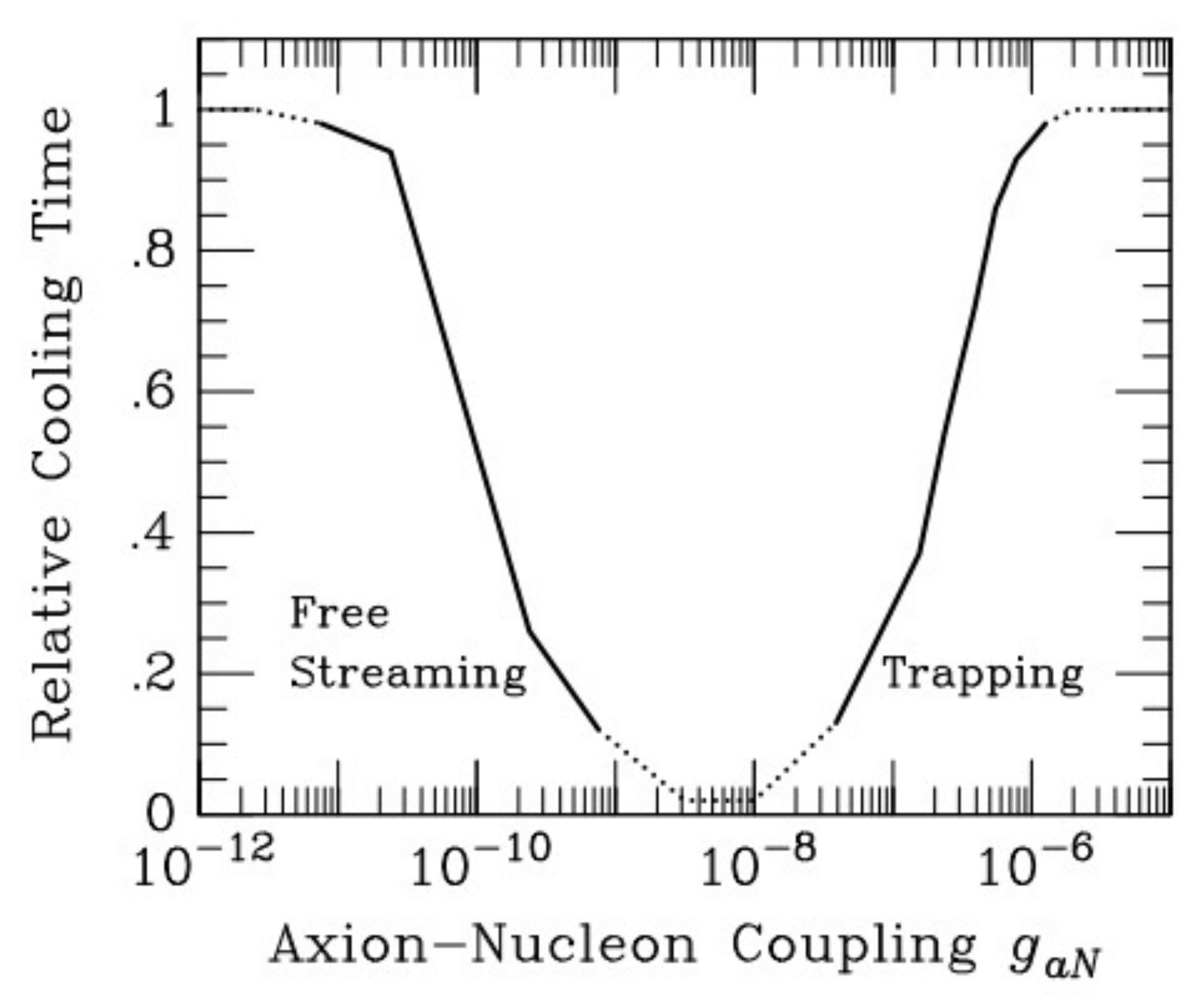
Neutrino burst



-Neutrinos TRAPPED
-Emitted from neutrino-sphere T~MeV
- ~10 sec to cool it down

- Axions (more weakly interacting)
- Emitted from the bulk T~tens MeV
- can cool much faster!

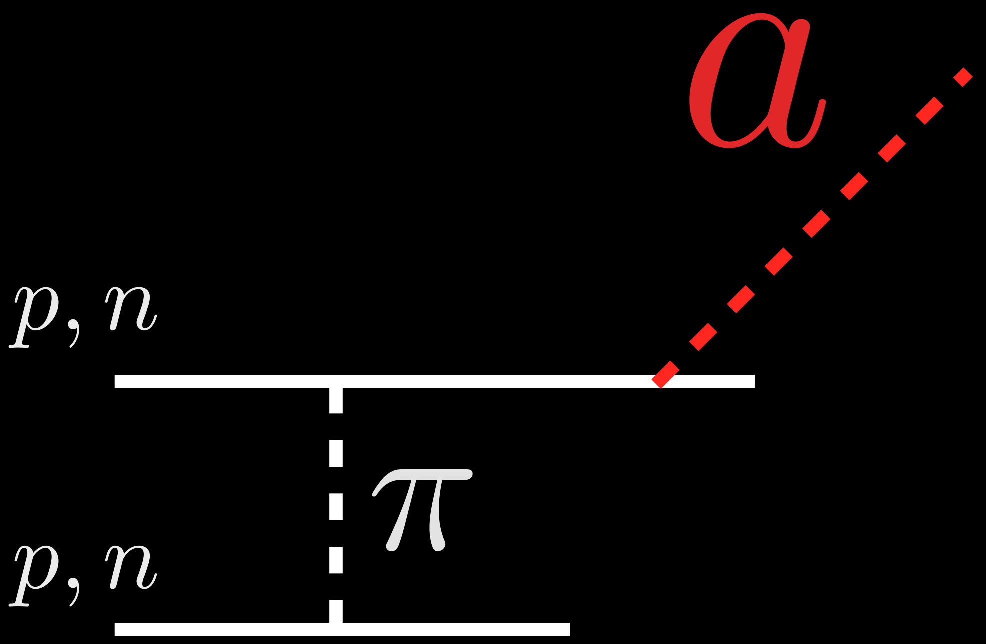
Reduction of nu burst $N + N \to N + N + a$



axion production
not significant

Cool the PNS
eficiently
reduce the
neutrino burst!

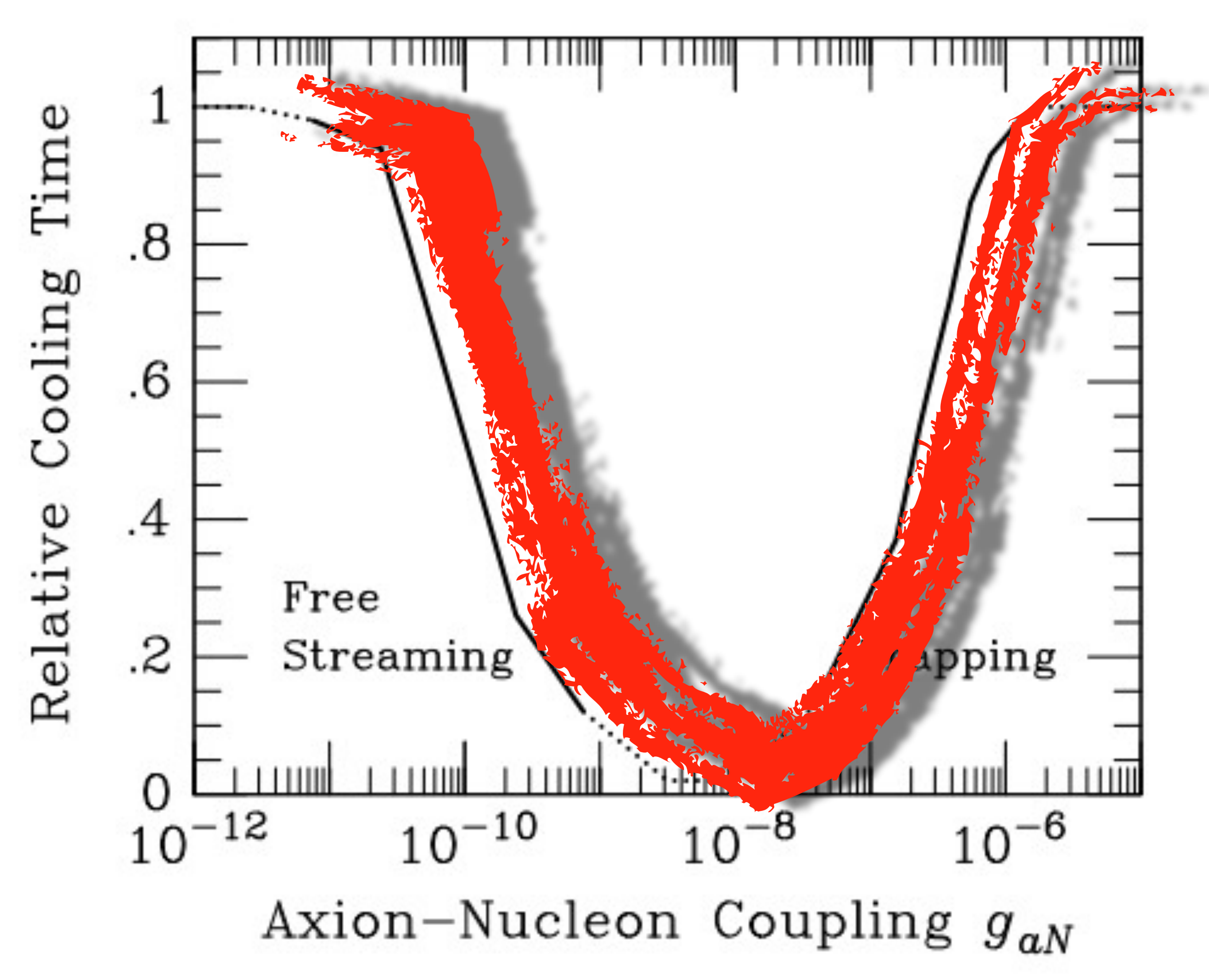
axions are
reabsorbed
inside the SN

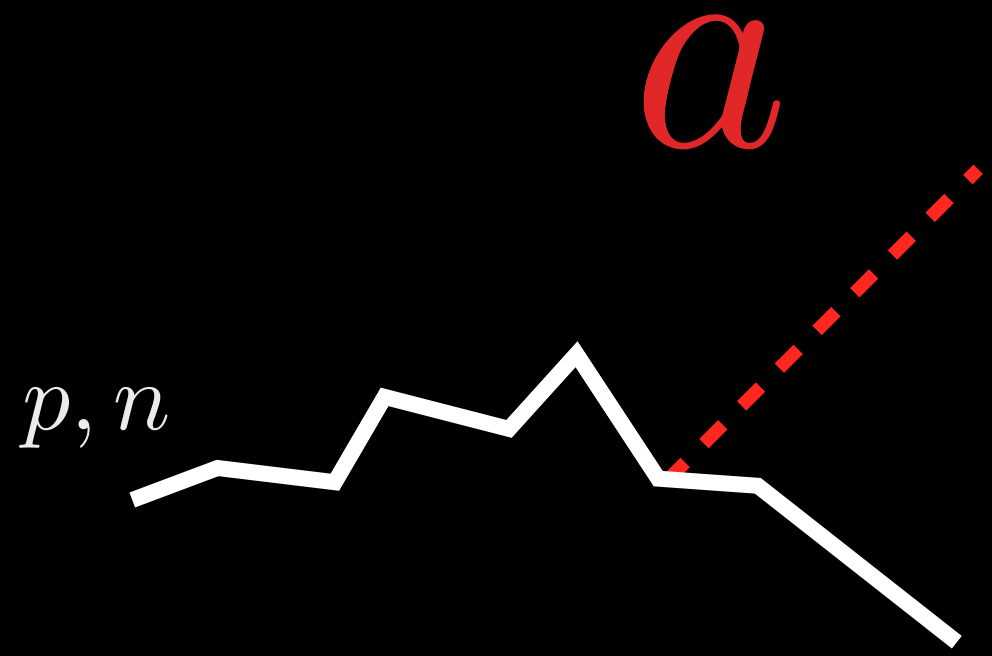


first approx. (pi pole too hard...)

$g = 10^{-10}\ \mathrm{GeV}^{-1}$

Reduction of nu burst $N + N \to N + N + a$





axion emission is suppressed due to high density effects !

$g = 10^{-10}\ \mathrm{GeV}^{-1}$

SN1987A

- Cooling ~ 10 s
- Exotics, Eloss/mass and time

$$\epsilon \lesssim 10^{19} \mathrm{erg/gs}$$

- Axion emission …

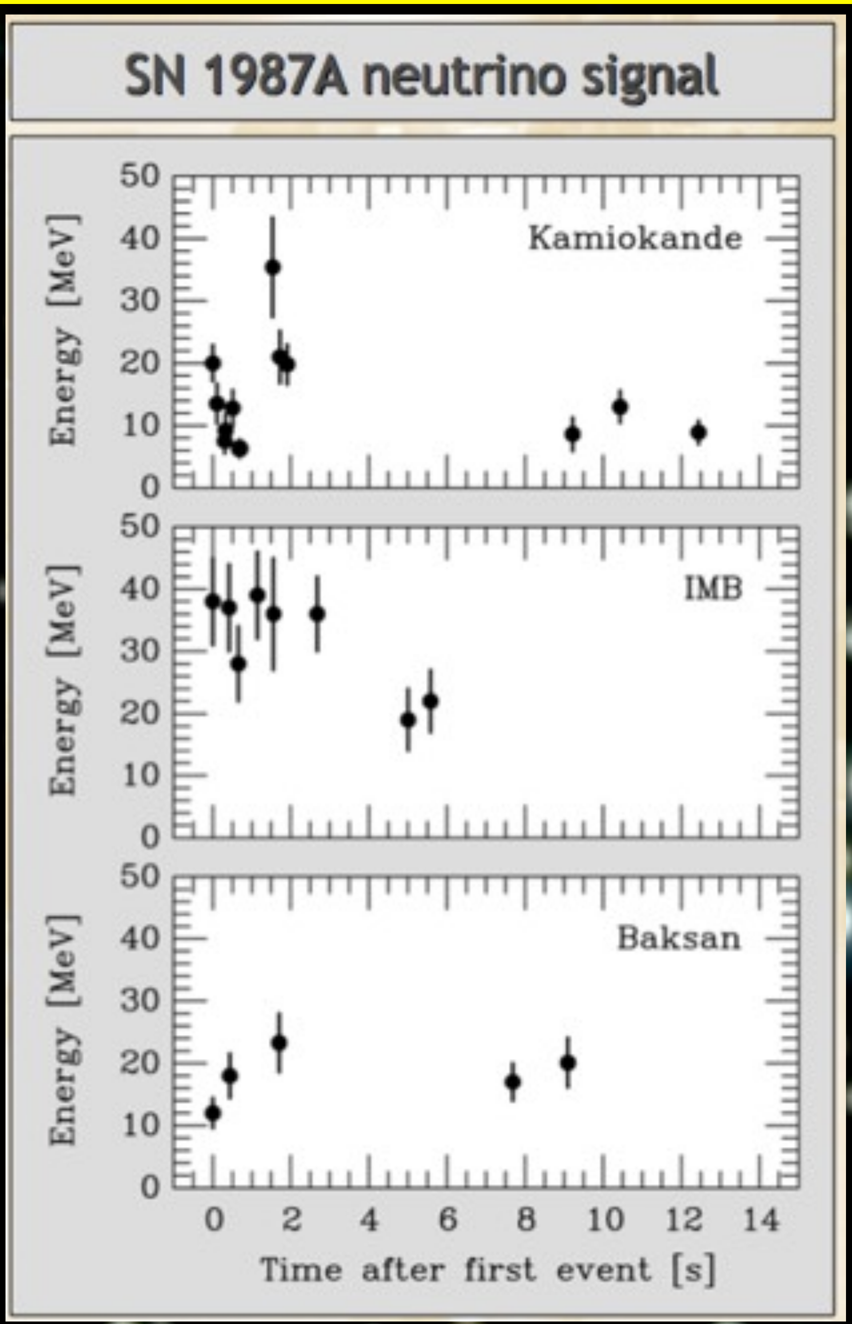
$$\epsilon_a \sim g_{ap}^2 1.6 \times 10^{37} \mathrm{erg/gs} \left(\frac{T}{30 \mathrm{MeV}} \right)^4$$

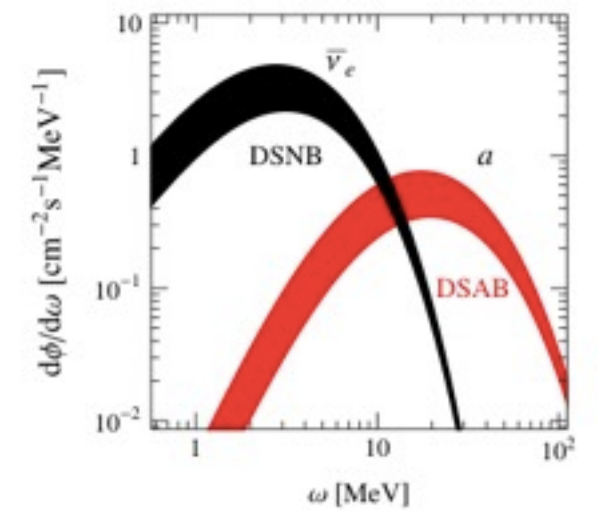
- Constraint …

$$g_{ap} \lesssim 8 \times 10^{-9}$$

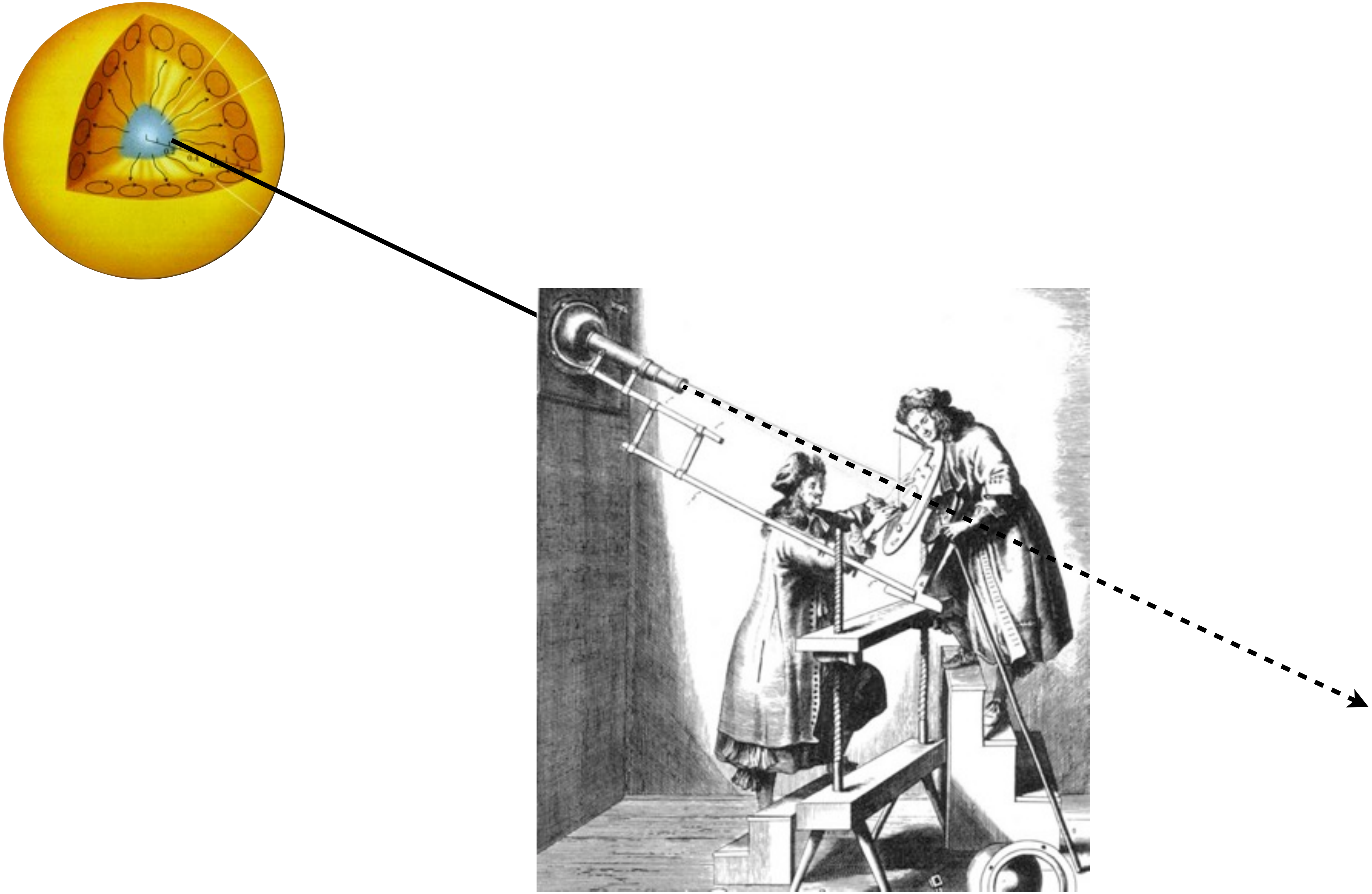
- Axions saturating the bound take ~50% Ecore

Diffuse Supernova Axion Background


SN 1987A neutrino signal

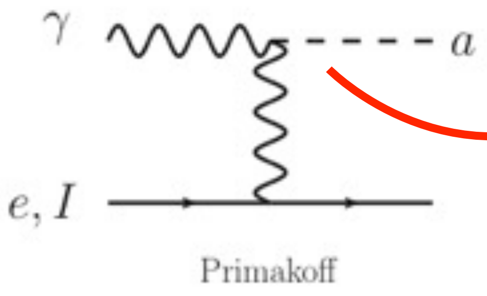


Detecting Solar Axions : Helioscopes



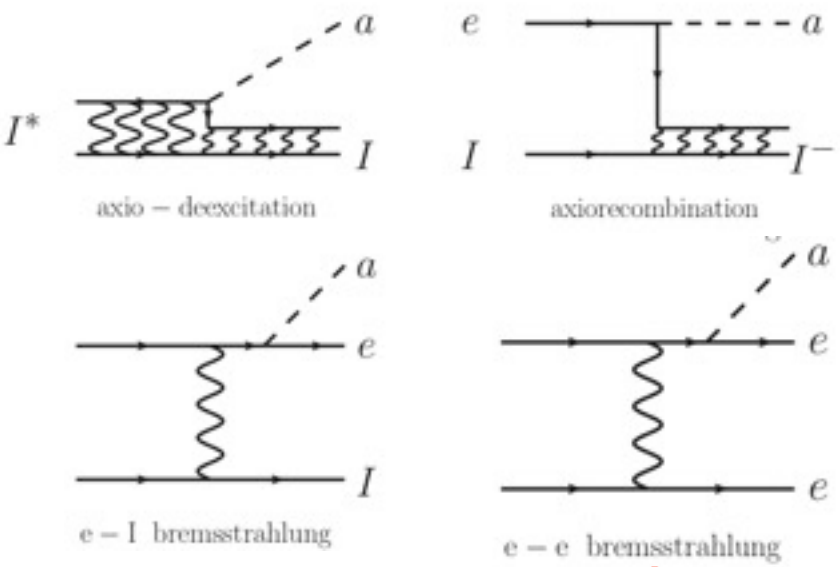
Axions from the Sun

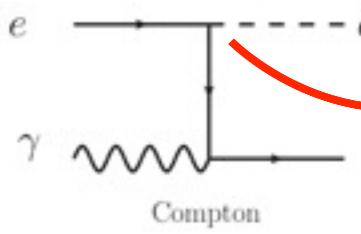
Hadronic axions (KSVZ)



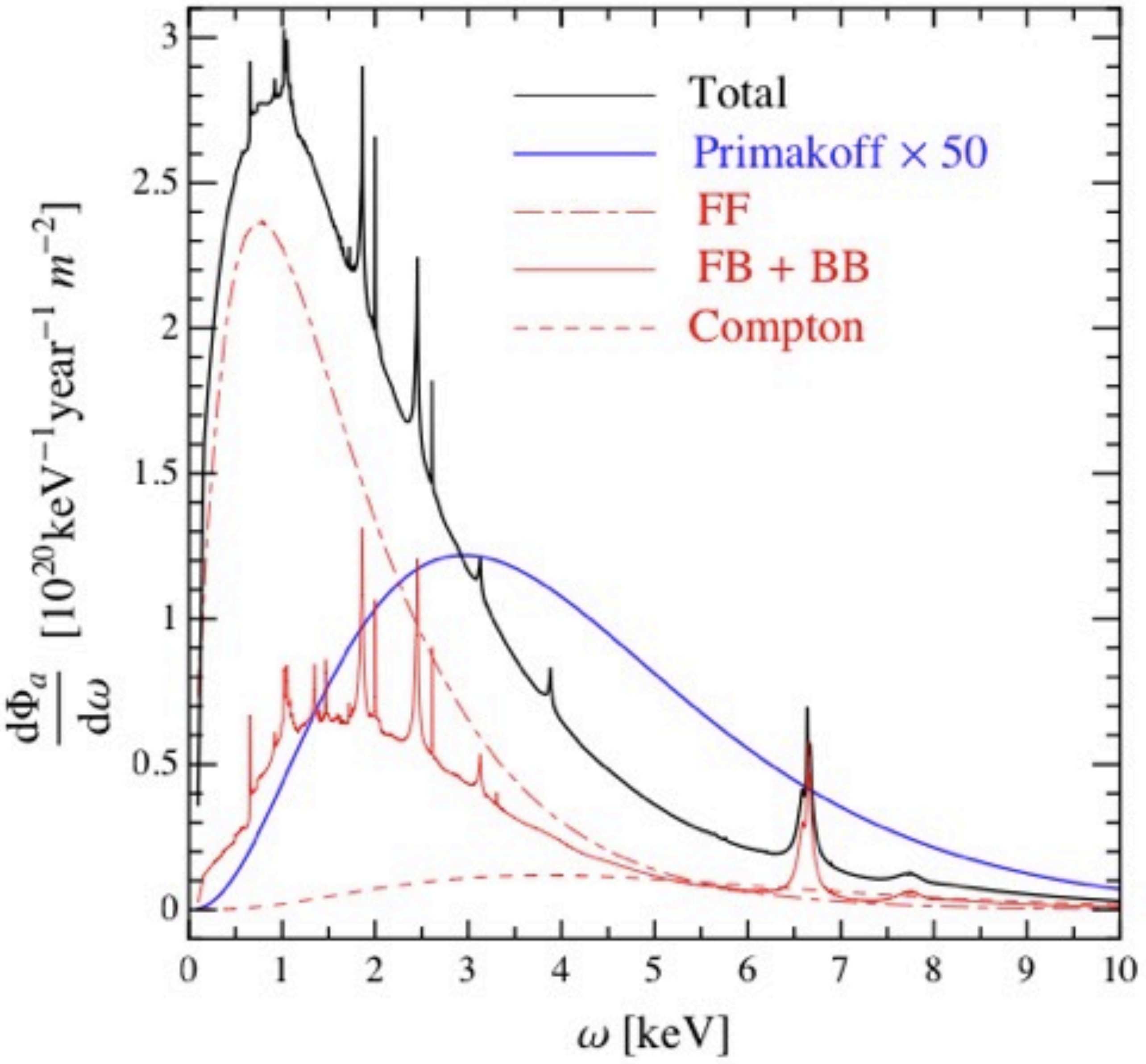
$$\underbrace{\frac{C_\gamma \alpha}{2\pi f_a}}_{g_{a\gamma}} \frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4} a$$

Non hadronic (DFSZ, e-coupling!)





$$\underbrace{\frac{C_e m_e}{f_a}}_{g_{ae}} i\bar{e}\gamma_5 e\, a$$



$$g_{ae} = 10^{-13}$$

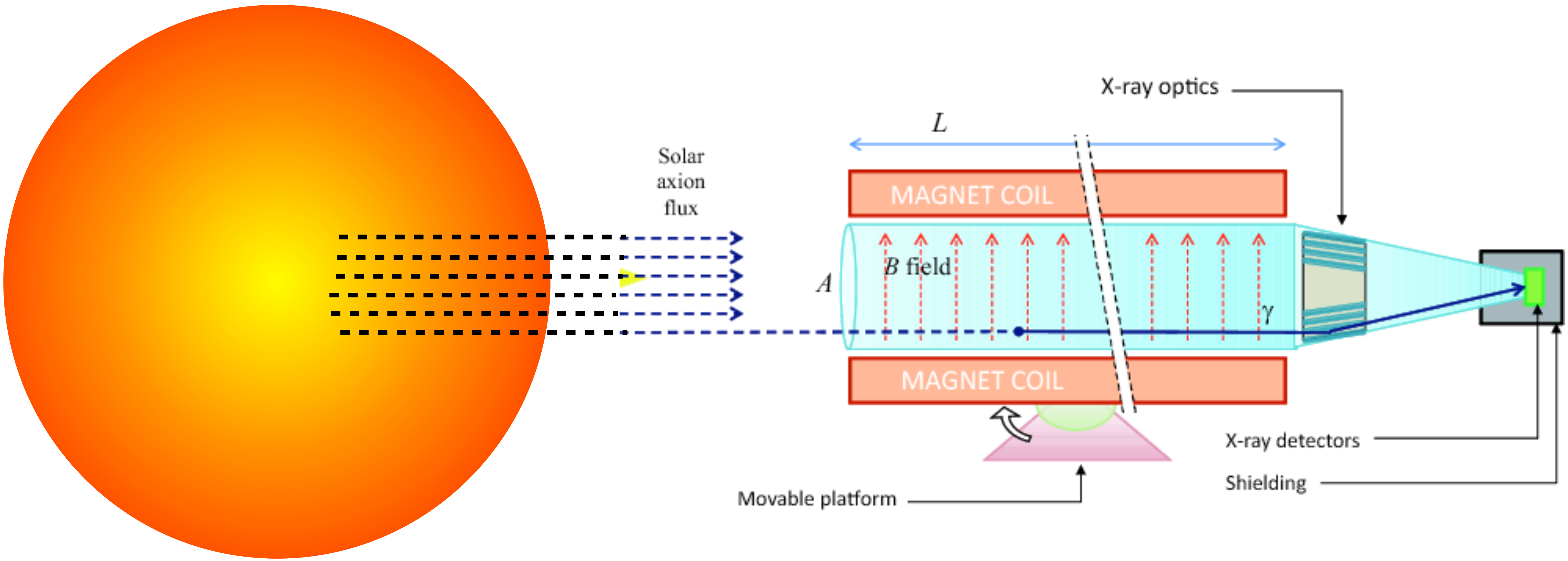
$$g_{a\gamma} = 10^{-12}\mathrm{GeV}^{-1}$$

typical of meV mass axions

Helioscopes

The Sun is a copious emitter of axions!

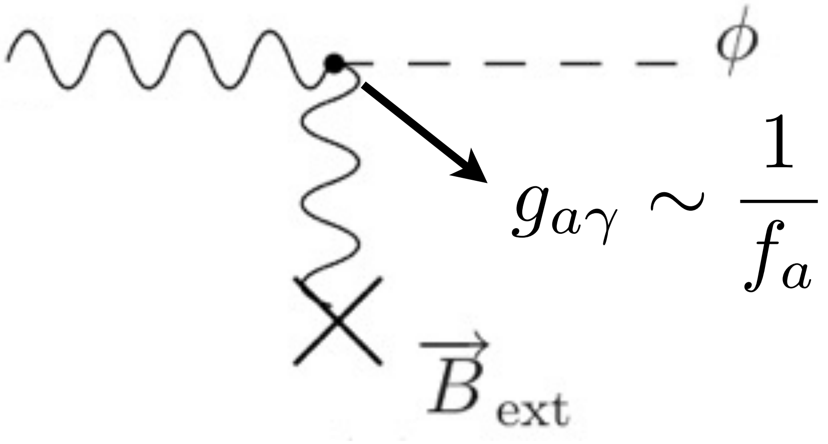
convert into X-rays **focus** **detect**



Conversion probability (exercise!)

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

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



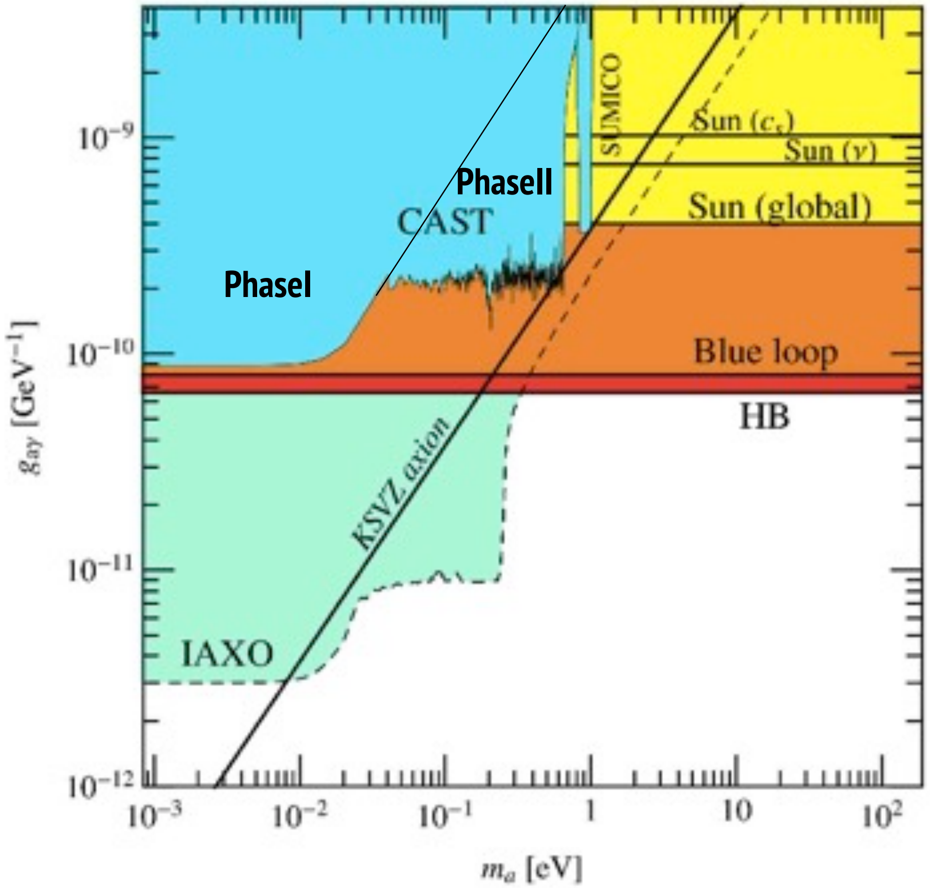
$$g_{a\gamma} \sim \frac{1}{f_a}$$

CAST Helioscope

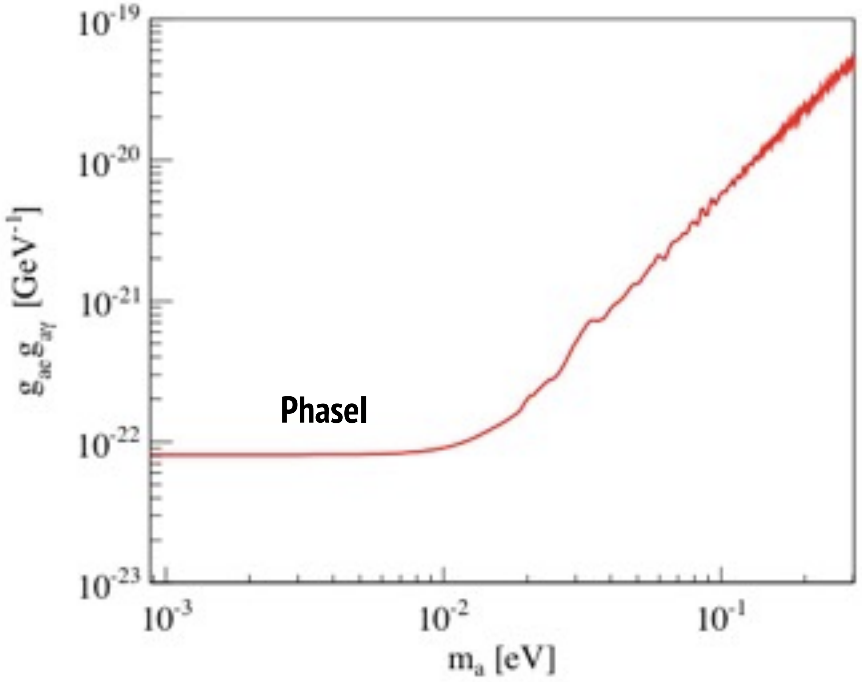
CAST (LHC dipole 9.3 m, 9T)

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

hadronic axions



non-hadronic axions



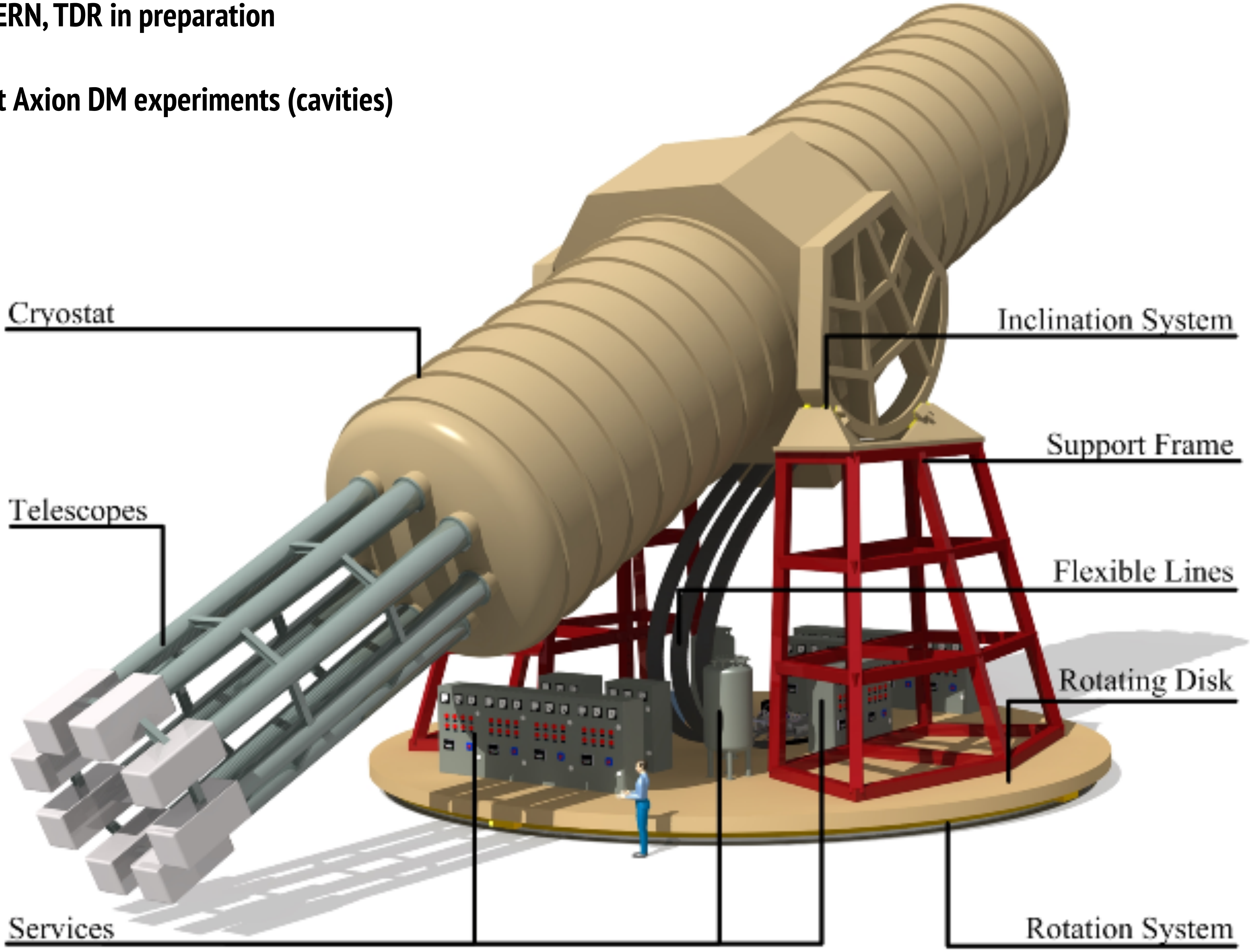
Next generation (proposed) IAXO

Boost parameters to the maximum

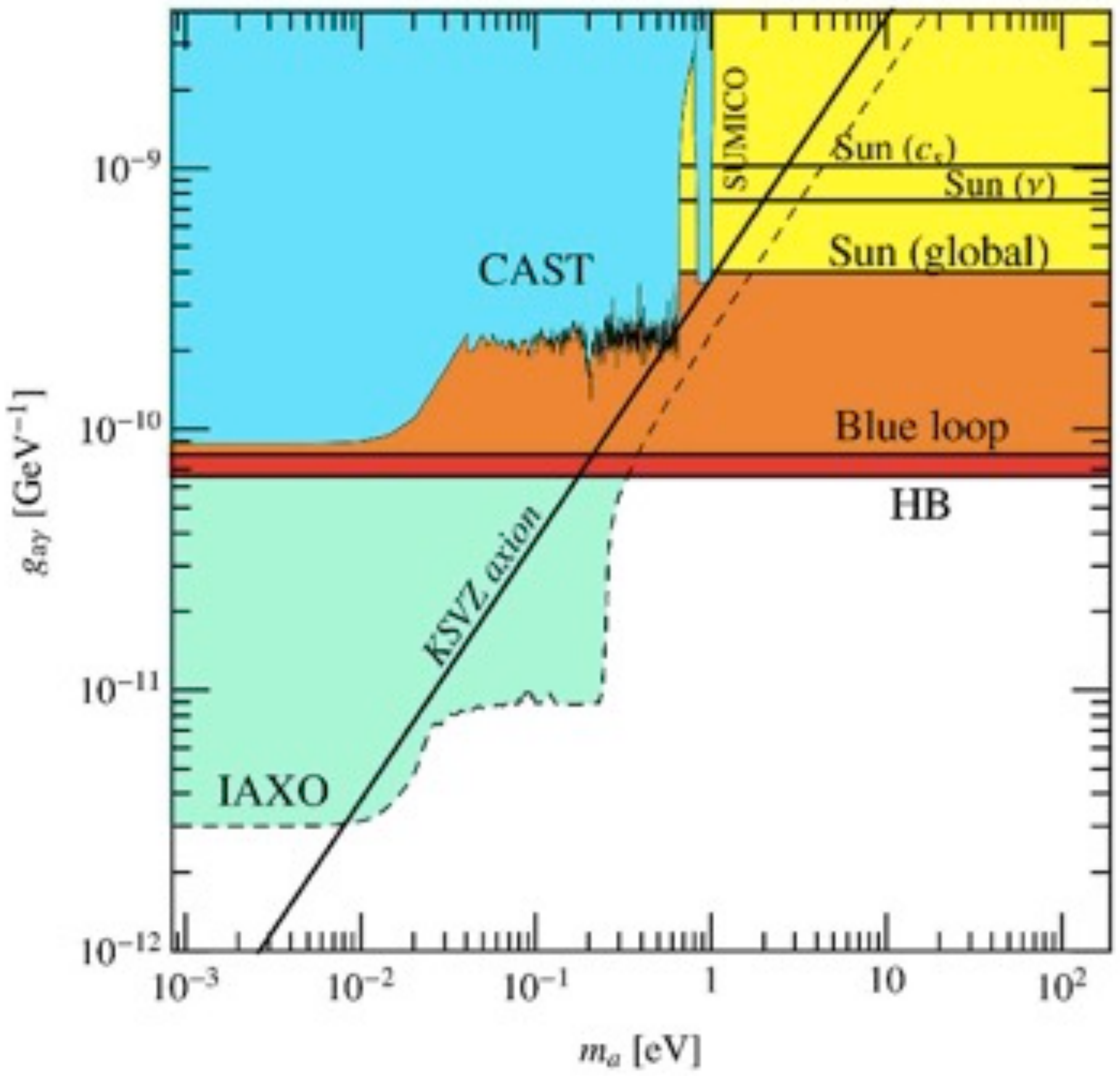
Large toroidal 8-coil magnet L = ~20 m
8 bores: 600 mm diameter each
8 x-ray optics + 8 detection systems
Rotating platform with services

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

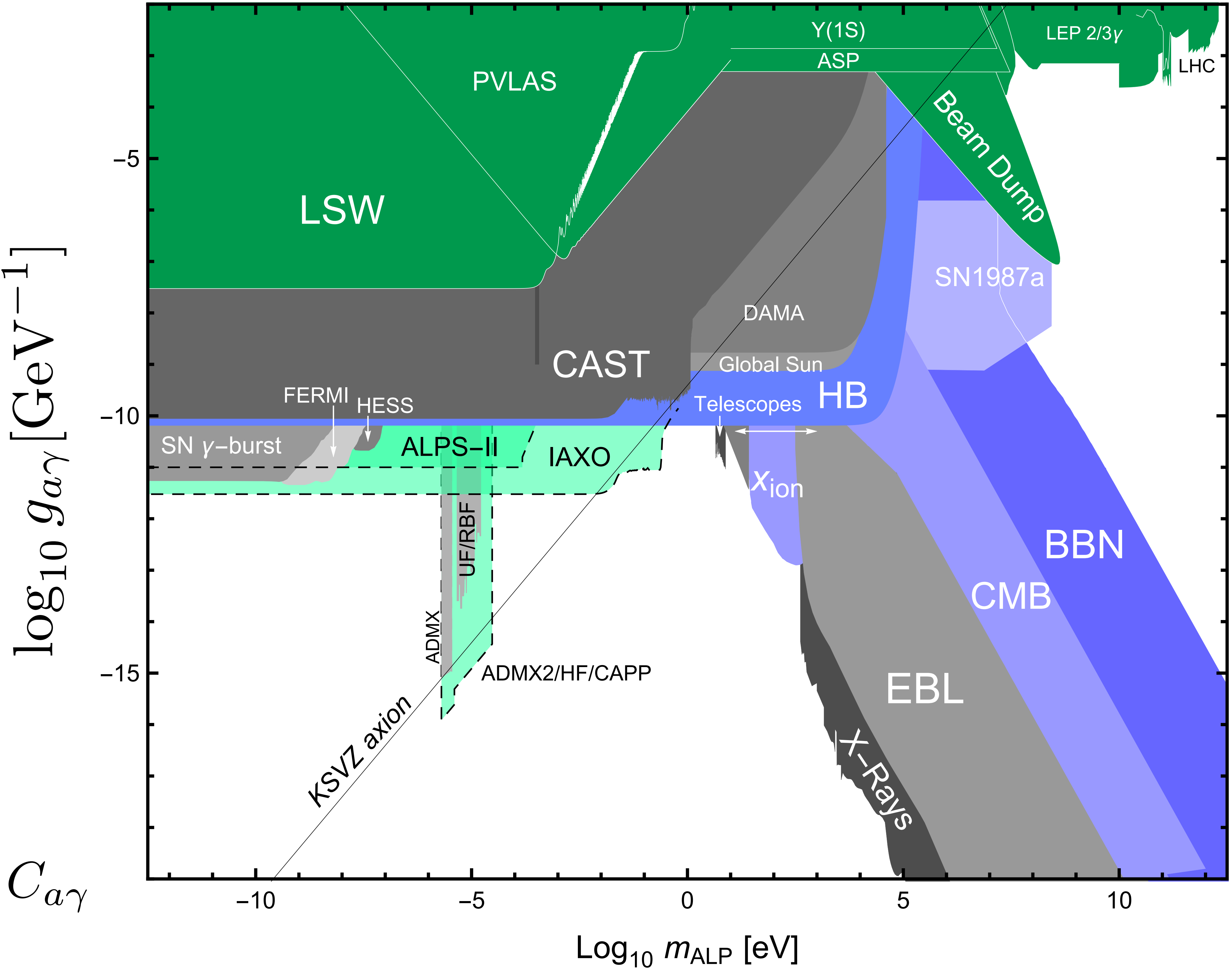
-Possibility of Direct Axion DM experiments (cavities)



IAXO sensitivity

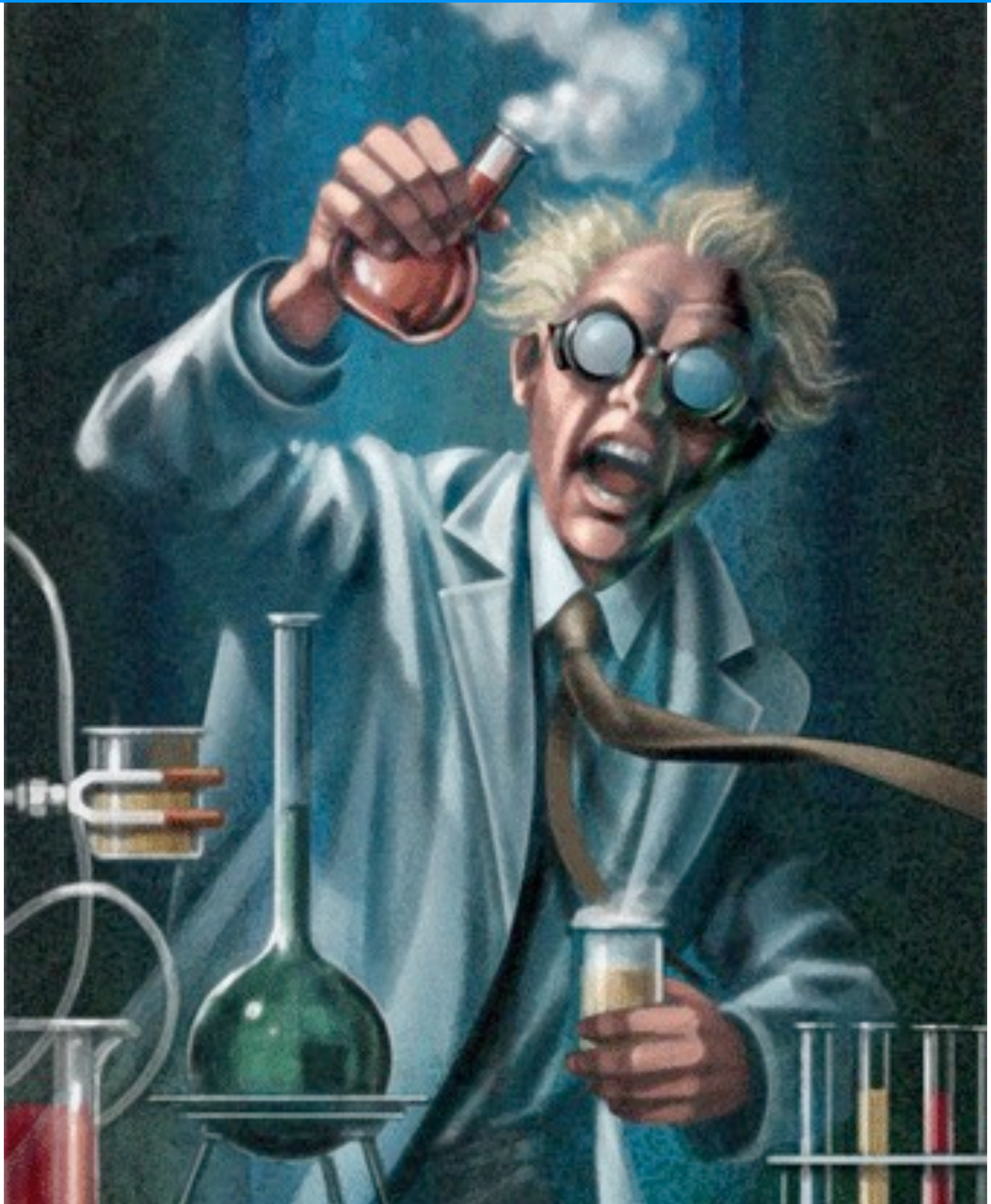


2-Photon coupling (general ALP)



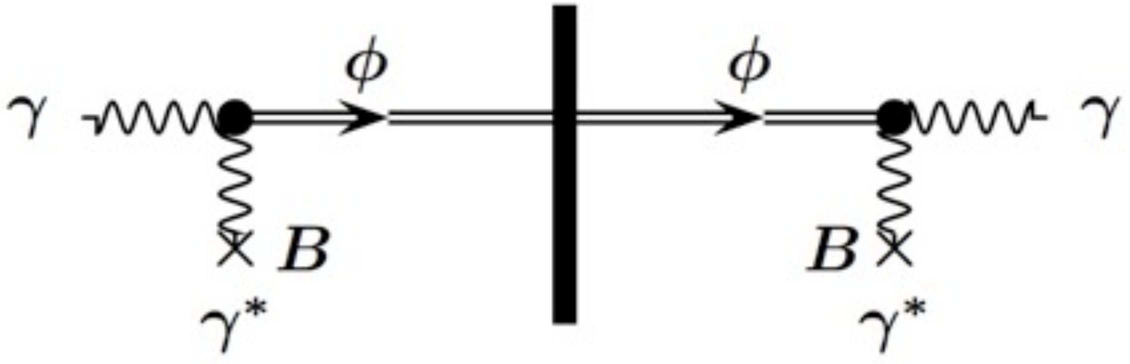
$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} C_{a\gamma}$$

Purely lab searches

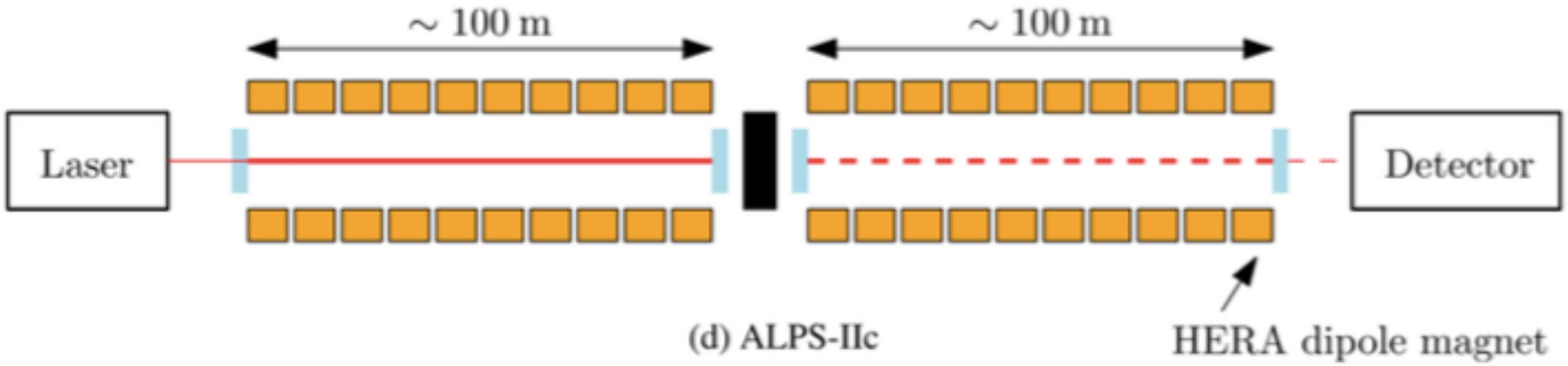


the ANY-Light-Particle-Search

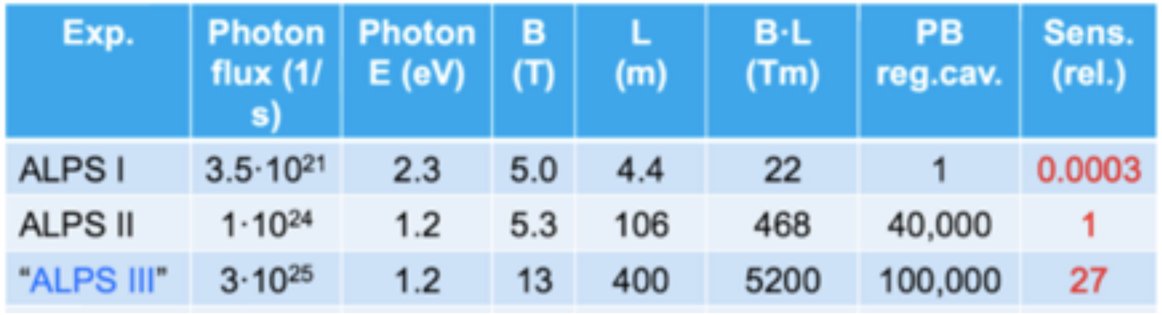
Light shining through walls



Resonant regeneration in the receiving cavity (see later)



(d) ALPS-IIc



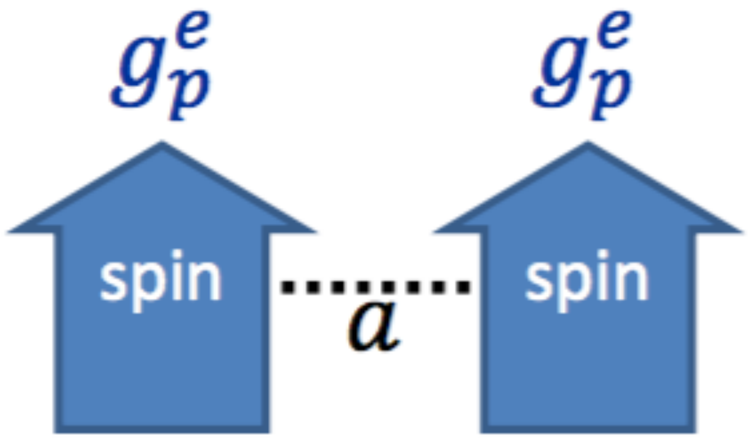
Exp.	Photon flux (1/s)	Photon E (eV)	B (T)	L (m)	B·L (Tm)	PB reg.cav.	Sens. (rel.)
ALPS I	$3.5\cdot10^{21}$	2.3	5.0	4.4	22	1	0.0003
ALPS II	$1\cdot10^{24}$	1.2	5.3	106	468	40,000	1
"ALPS III"	$3\cdot10^{25}$	1.2	13	400	5200	100,000	27

Long-range forces

Wilzcek '84, Geraci 14

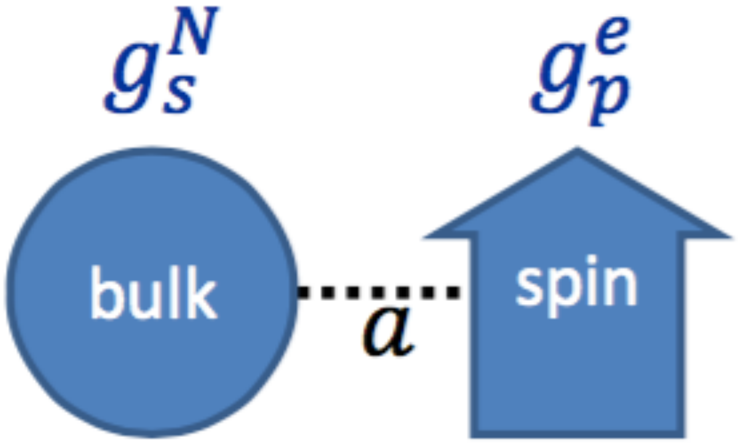
Long-range forces between macroscopic bodies

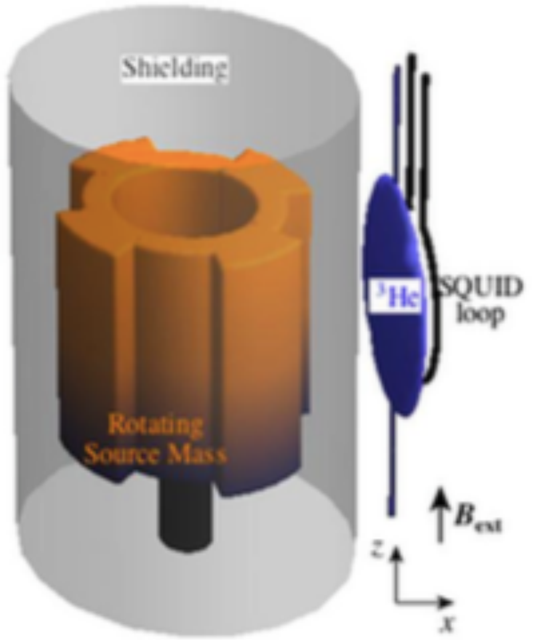
p-p forces are spin-spin ... very hard to measure!



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

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

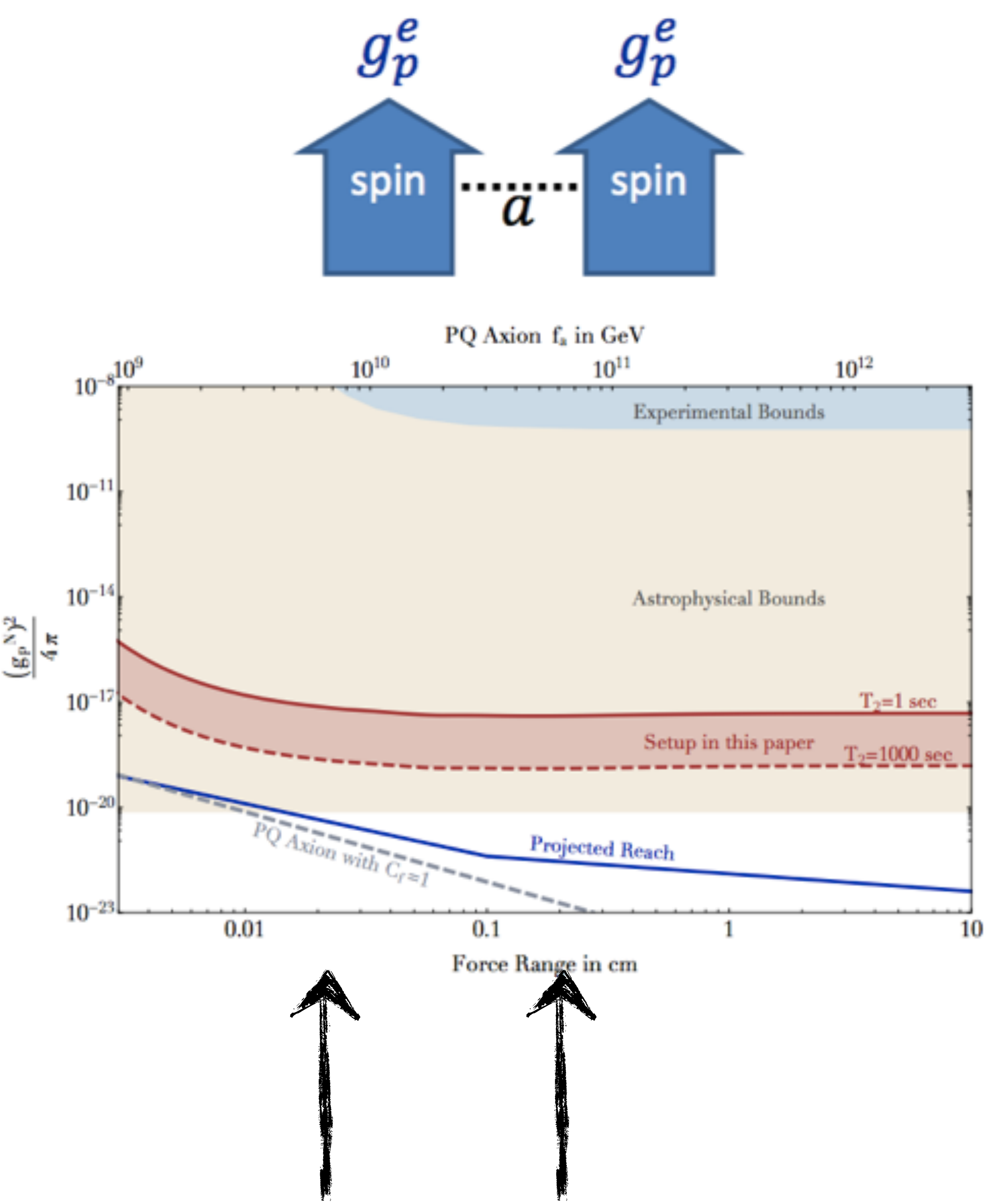




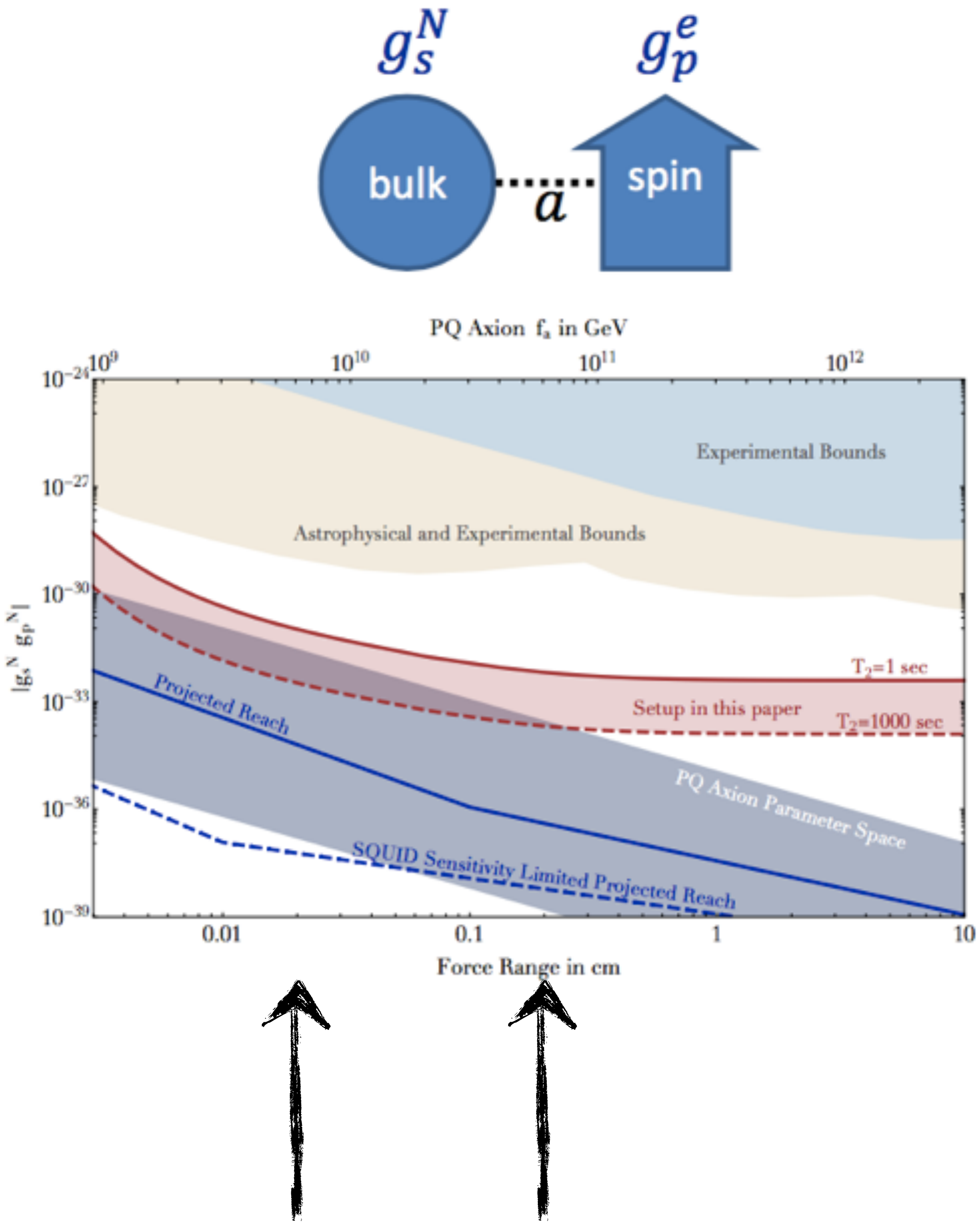
ARIADNE, University of Nevada in Reno

ARIADNE reach

Arvanitaki, Geraci 14

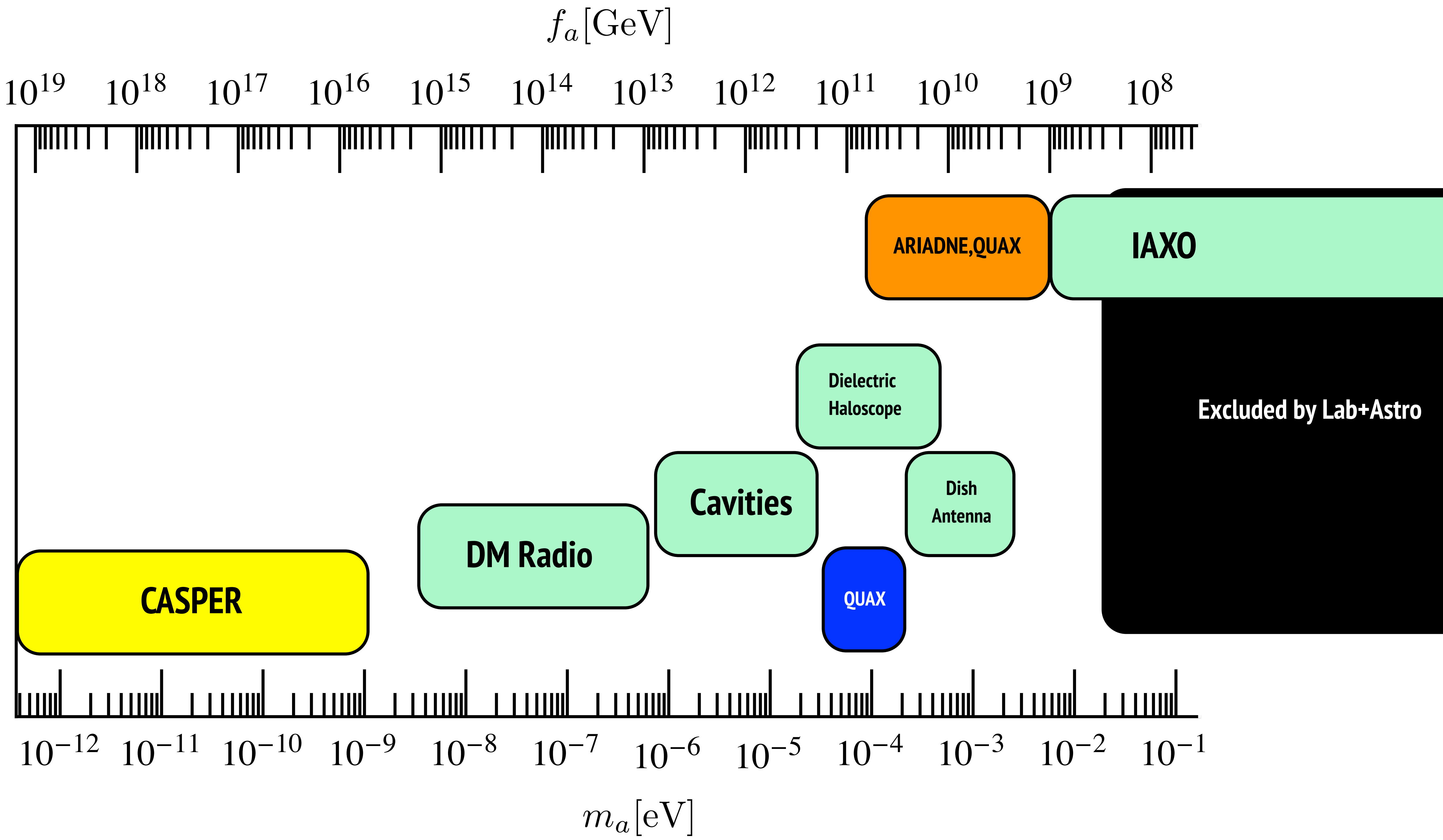


meV 100 μeV



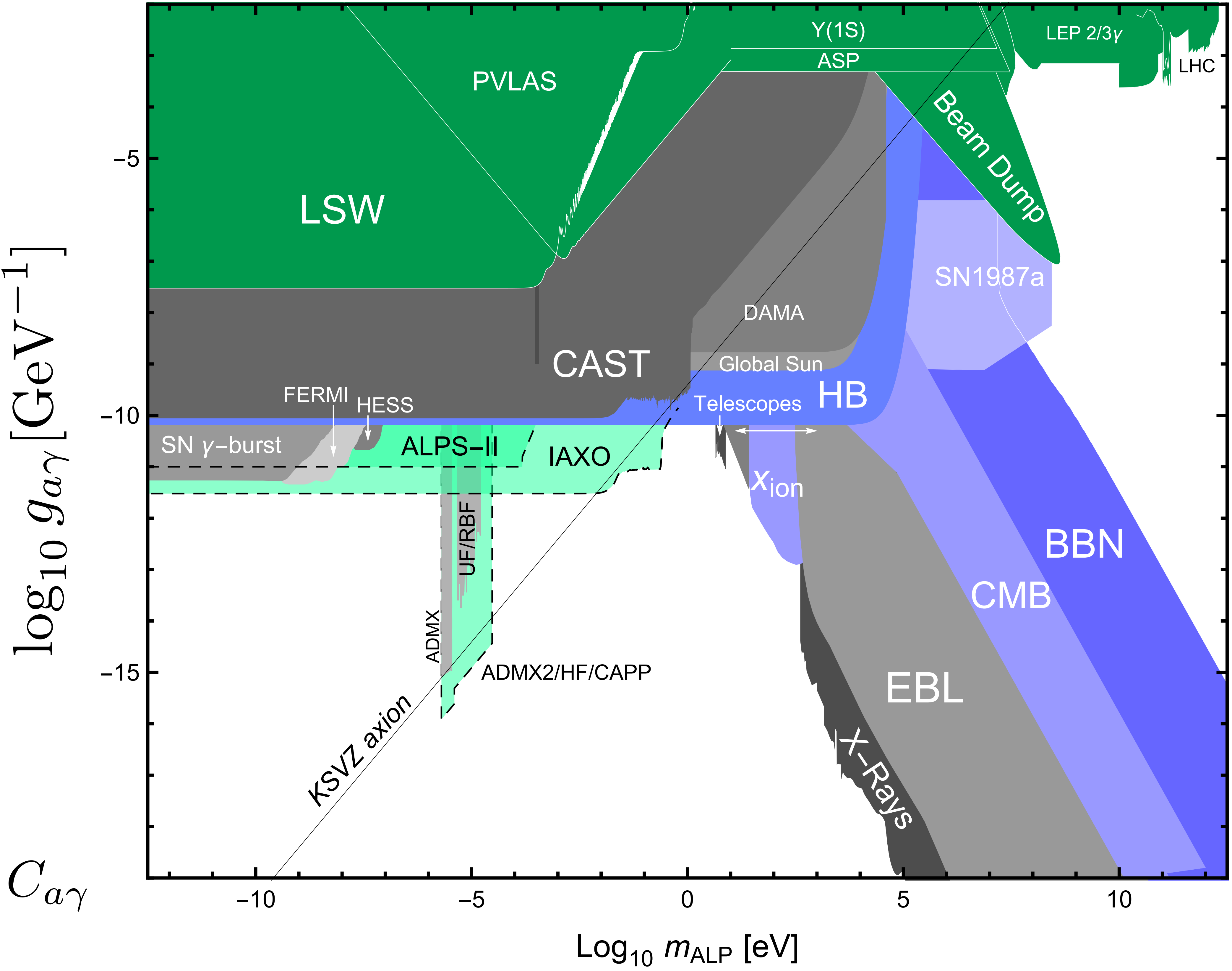
meV 100 μeV

In the big picture



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

2-Photon coupling (general ALP)



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

Conclusions

- Many Experimental consequences of "almost invisible" axions

- Many experimental routes :

  Very promising :
  - Axion DM, (ADMX, CAPP and others)
  - Solar axions (IAXO)
  - Oscillating nEDM (CASPER)
  - 5th forces (ARIADNE)

  Many other (new) ideas being explored

- Axion DM could be discovered tomorrow ... but the experimental landscape is not completely covered... a lot of work for you folks!