The axion search landscape

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Outline

- Axions: strong CP problem and DM
- Laboratory searches
- Astrophysical and comological probes (some)
- Conclusions

based mostly on ...

1801.08127

New experimental approaches in the search for axion-like particles

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May 8, 2018

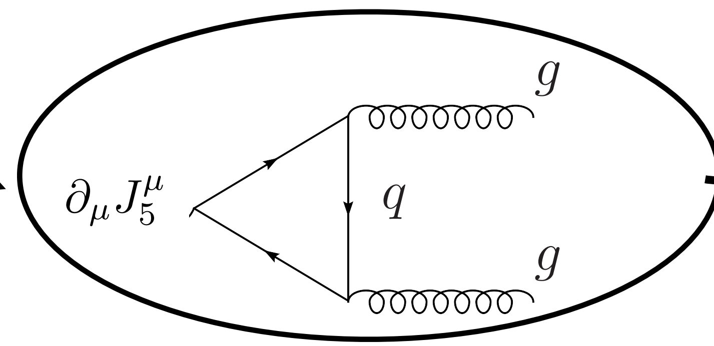
Abstract

Axions and other very light axion-like particles appear in many extensions of the Standard Model, and are leading candidates to compose part or all of the missing matter of the Universe. They also appear in models of inflation, dark radiation, or even dark energy, and could solve some long-standing astrophysical anomalies. The physics case of these particles has been considerably developed in recent years, and there are now useful guidelines and powerful motivations to attempt experimental detection. Admittedly, the lack of a positive signal of new physics at the high energy frontier, and in underground detectors searching for weakly interacting massive particles, is also contributing to the increase of interest in axion searches. The experimental landscape is rapidly evolving, with many novel detection concepts and new experimental proposals. An updated account of those initiatives is lacking in the literature. In this review we attempt to provide such an update. We will focus on the new experimental approaches and their complementarity, but will also review the most relevant recent results from the consolidated strategies and the prospects of new generation experiments under consideration in the field. We will also briefly review the latest developments of the theory, cosmology and astrophysics of axions and we will discuss the prospects to probe a large fraction of relevant parameter space in the coming decade.

The strong CP "issue"

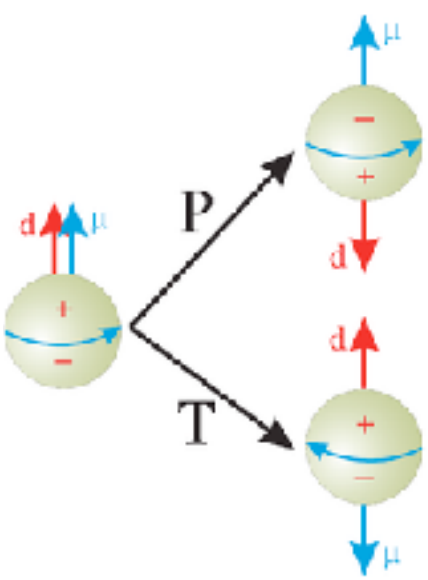
- **CP violation in QCD sector: CKM angle** $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\mathrm{QCD}} + N_f \delta$

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



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

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



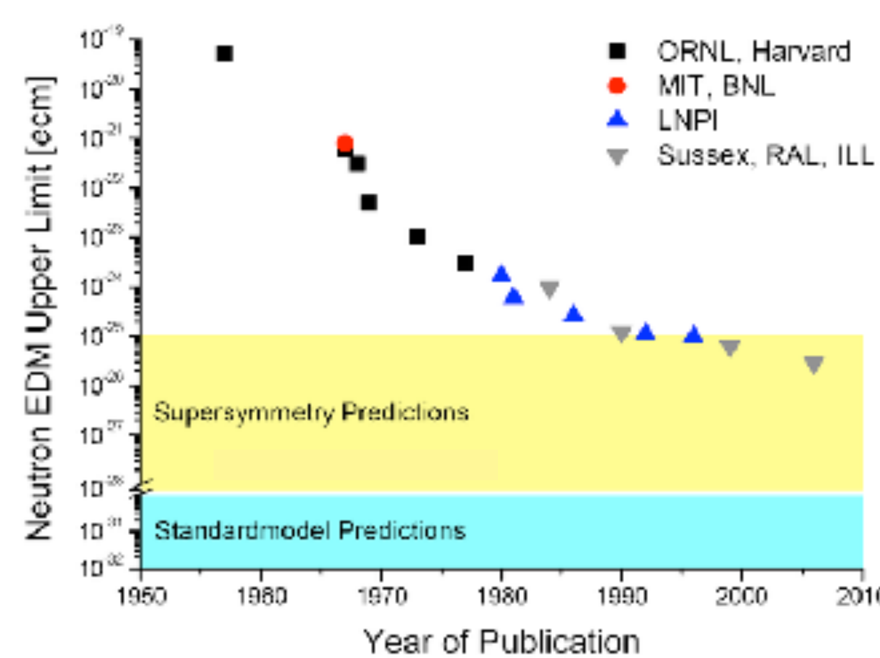
- **Neutron EDM** (Pospelov 9908508)

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

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

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

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



Driving θ dynamically to zero with BSM physics

CP Conservation in the Presence of Pseudoparticles*

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

We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

It is experimentally obvious that we live in a
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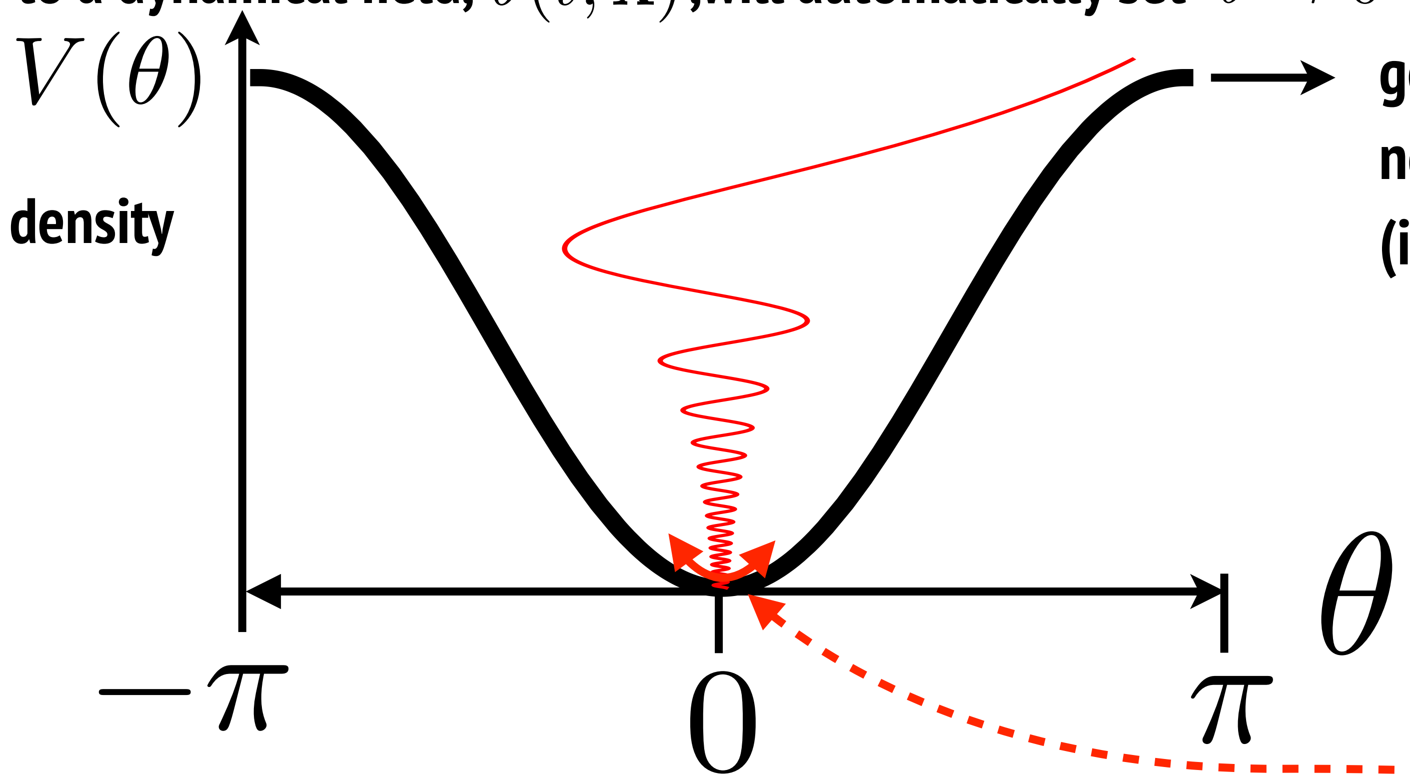
QCD vacuum energy is minimised at $\theta = 0$!

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

Potential energy density



→ generated by QCD non-perturbative dynamics (instantons)

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

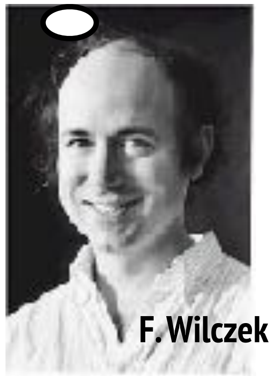
$$\mathcal{L}_\theta = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f_a^2 - \frac{\alpha_s}{8\pi} G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}\theta$$

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

New Spontaneous symmetry breaking [energy] scale f_a

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

S. Weinberg



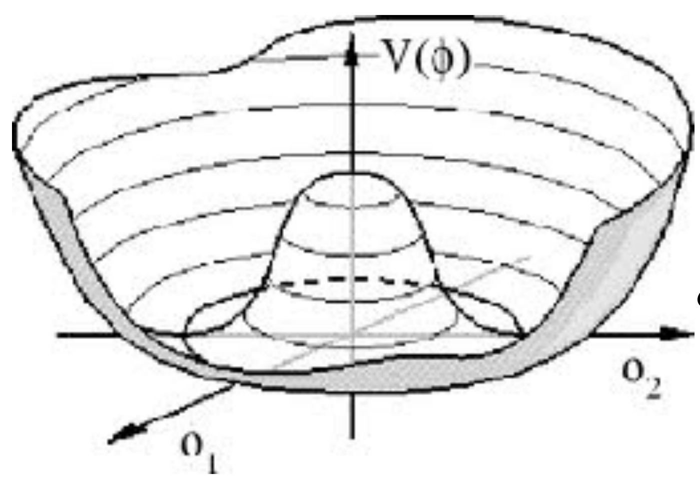
F. Wilczek

Models old and new, ALPs

- **Axions and axion-like particles are generic in BSM (not necessarily guaranteed!)**

pseudo Goldstone Bosons

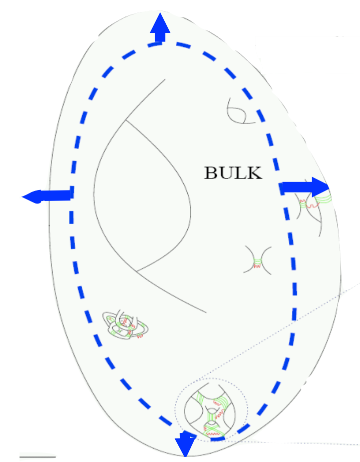
- Global symmetry spontaneously broken

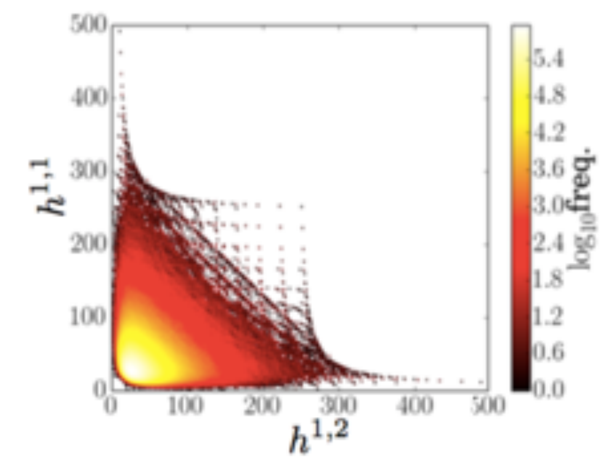


$$\phi(x) = \rho(x) e^{i\theta(x)}$$

stringy axions

- Im parts of moduli fields (control sizes)





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

- **NGB models, hadronic, 2HDMs, families, axi-majorons…**

		High-E couplings				Low-E couplings			
Model	N_{DW}	E/N	C_{Au}	C_{Ad}	C_{Ae}	$C_{A\gamma}$	C_{Ap}	C_{An}	C_{Ae}
PQWW	3	8/3	$c^2_\beta/3$	$s^2_\beta/3$	$s^2_\beta/3$	0.75	...	...	...
DFSZ I	6,3	8/3	$c^2_\beta/3$	$s^2_\beta/3$	$s^2_\beta/3$	0.75	(-0.2,-0.6)	(-0.16,0.26)	(0.024,⅓)
DFSZ II	6,3	2/3	$c^2_\beta/3$	$s^2_\beta/3$	$-c^2_\beta/3$	-1.25	(-0.2,-0.6)	(-0.16,0.26)	(-⅓,0)
KSVZ	1	0	g-loop	g-loop	0	-1.92	-0.47	-0.02(3)	$\sim 2\times10^{-4}$
Hadronic 1Q [83]	1…20	1/6…44/3	g-loop	g-loop	γ-loop	-0.25 … 12.7†	-0.47	-0.02(3)	$(0.05 \ldots 5)\times10^{-3}$
SMASH [16]	1	8/3, 2/3	g-loop	g-loop	γ-loop	0.75,-1.25	-0.47	-0.02(3)	$(-0.16, 0.16)$
MFVA [91]	9	2/3, 8/3	0	1/3	1/3	$0.75, -1.25$	~ -0.6	~ -0.26	$\sim 1/3$
Flaxion/Axi-flavon [11,12]	-	8/3	$\sim 10^{-5}$	$\sim 10^{-5}$	$\sim 10^{-5}$	(0.5,1.1)	-	-	-
Astrophobic M1,2 [93]	1,2	2/3, 8/3	∼ 2/3	∼ 1/3	∼ 0	-1.25,0.75	$\sim 10^{-2}$	$\sim 10^{-2}$	∼ 0
Astrophobic M3,4 [93]	1,2	−4/3, 14/3	∼ 2/3	∼ 1/3	∼ 0	-3.3,2.7	$\sim 10^{-2}$	$\sim 10^{-2}$	∼ 0

a recent selection from arXiv:1801.08127

couplings

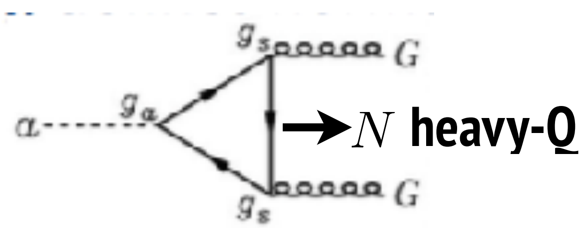
- Shift symmetry allows some generic types of interactions

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

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

(canonically normalised) $g \propto \frac{1}{f_A}$

- Color anomaly breaks explicitly shift symmetry -> axion mass + interactions (EDM+...)

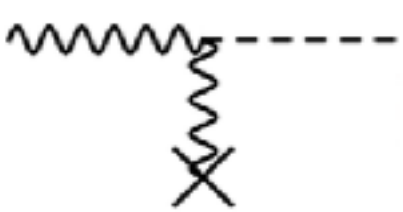


$$N\frac{\alpha}{8\pi}\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\theta \equiv \frac{\alpha_s}{8\pi}\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\frac{A}{f_A}$$

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

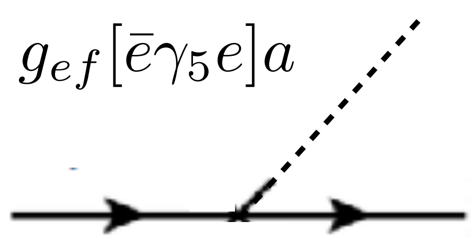
photon coupling

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



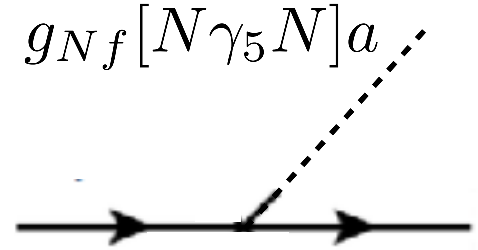
electron coupling

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



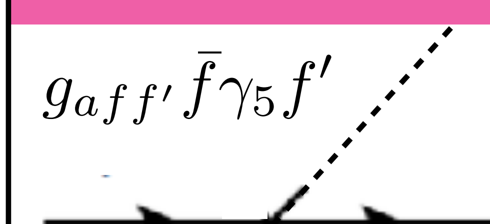
nucleon coupling

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



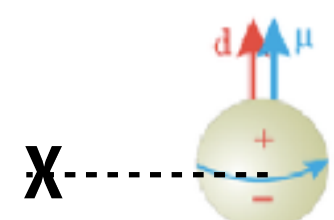
FCNC

$$g_{aff'}\bar{f}\gamma_5 f'$$

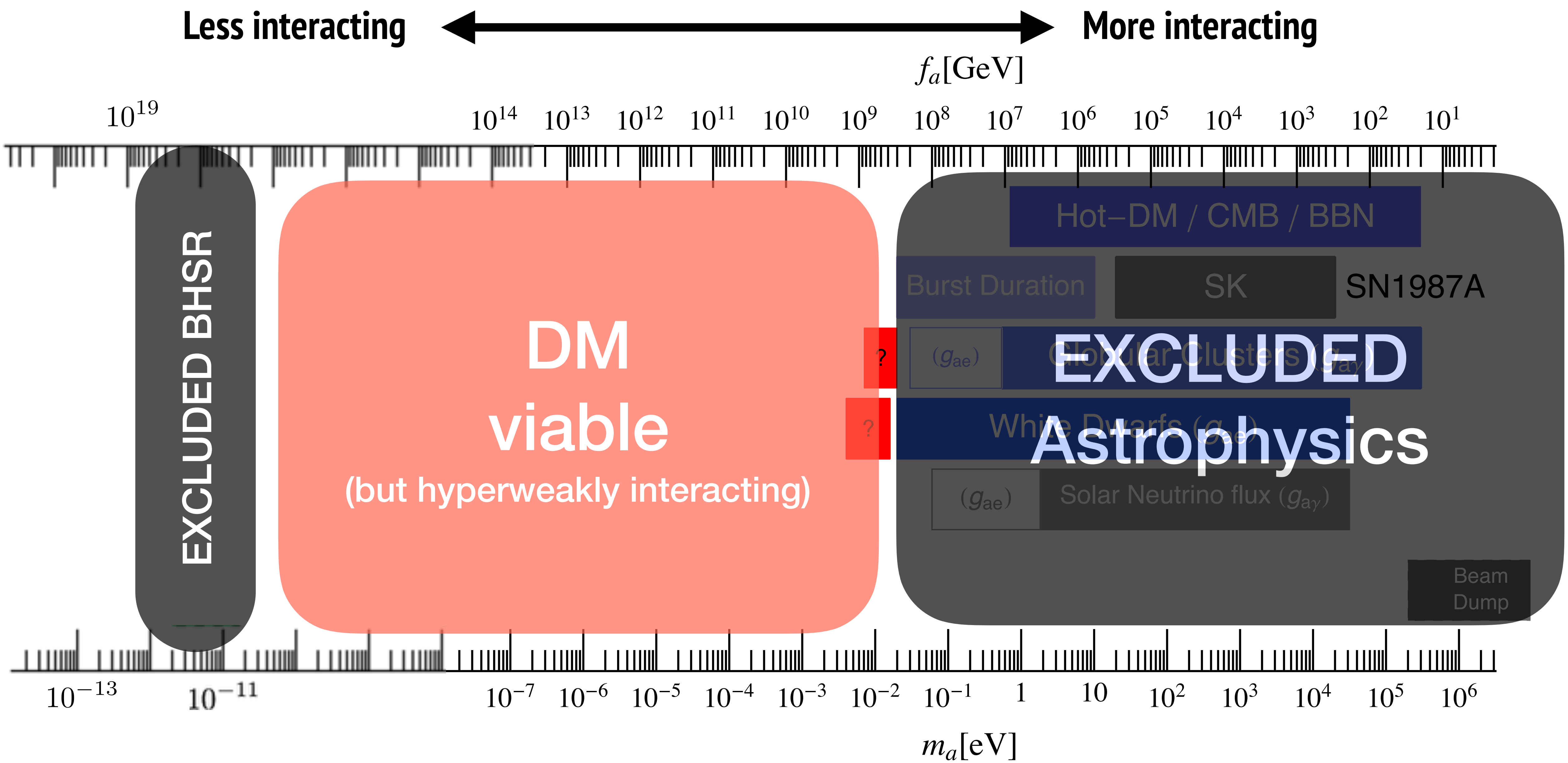


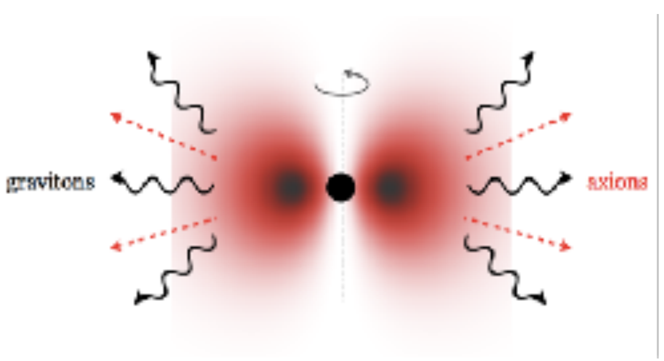
~~CP~~ Neutron electric dipole

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

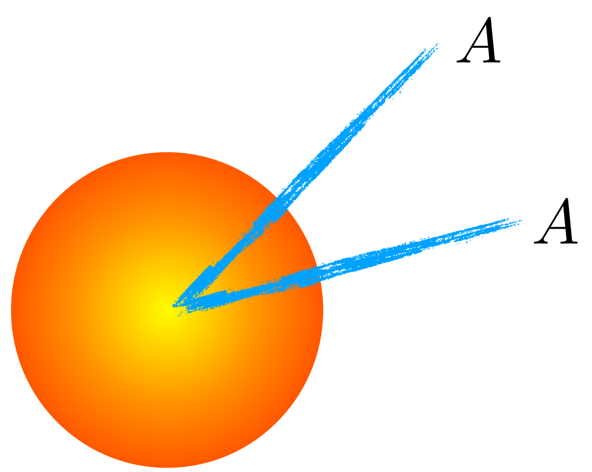


what do we know about fA





Black hole spin radiated

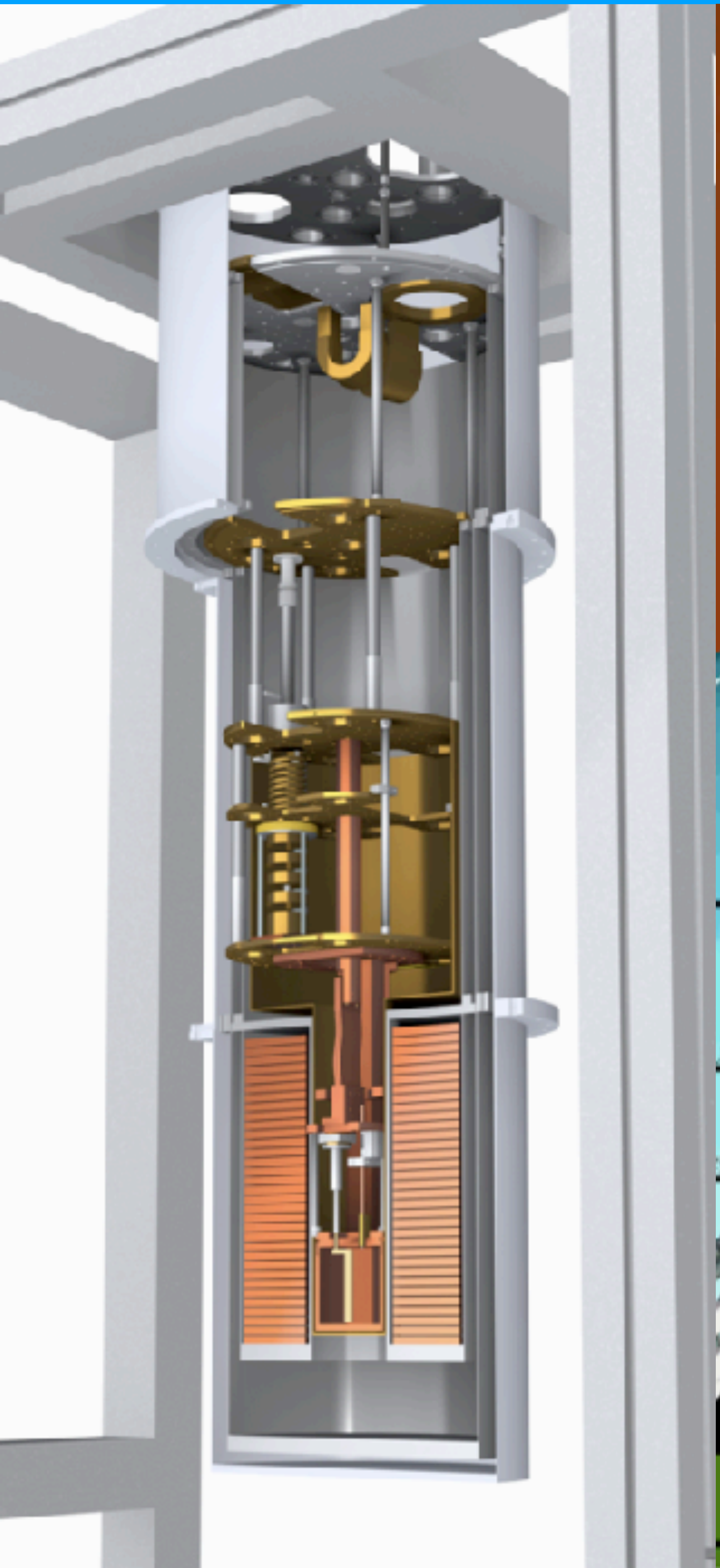


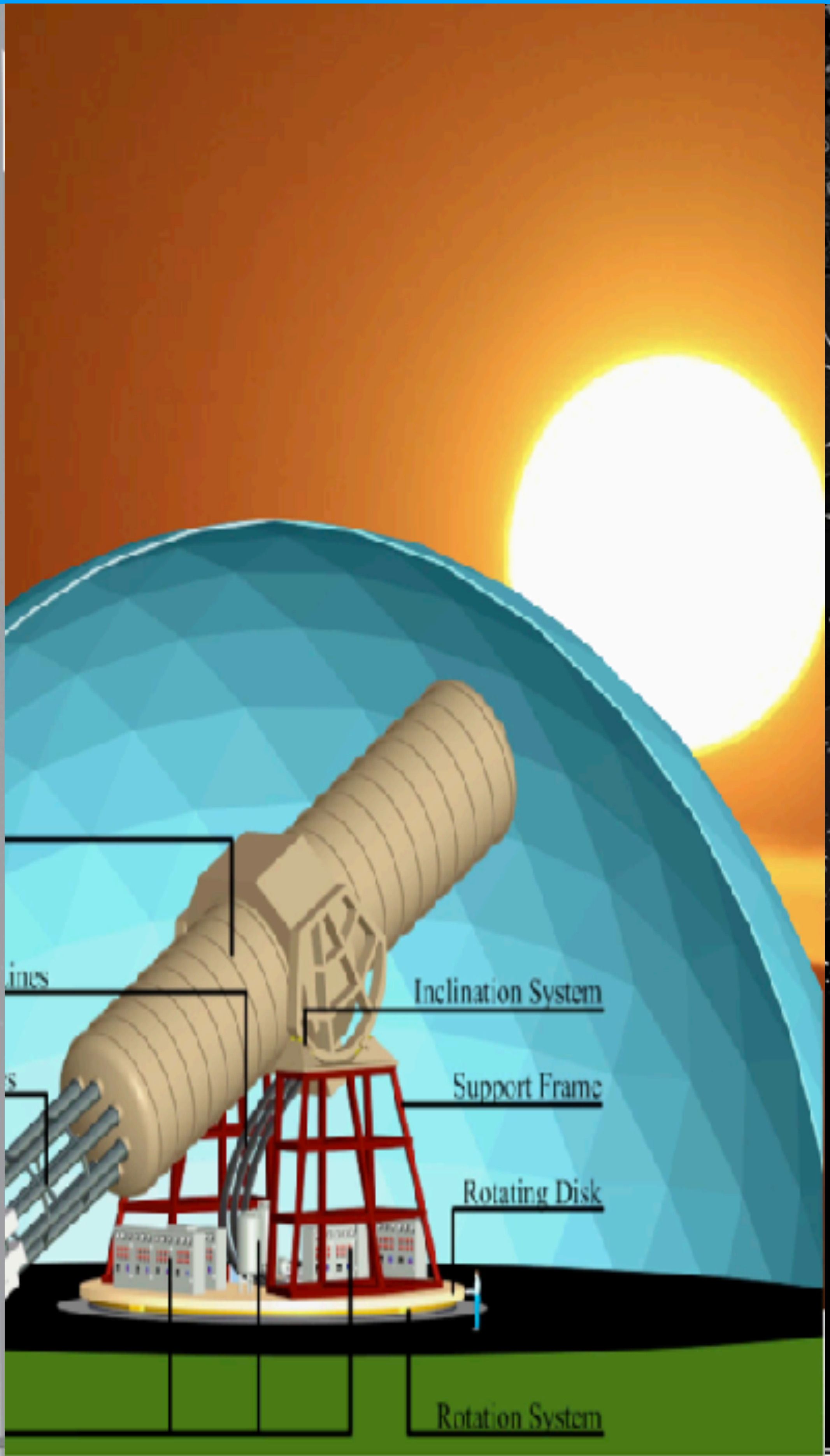
Stellar evolution accelerated*

Lab

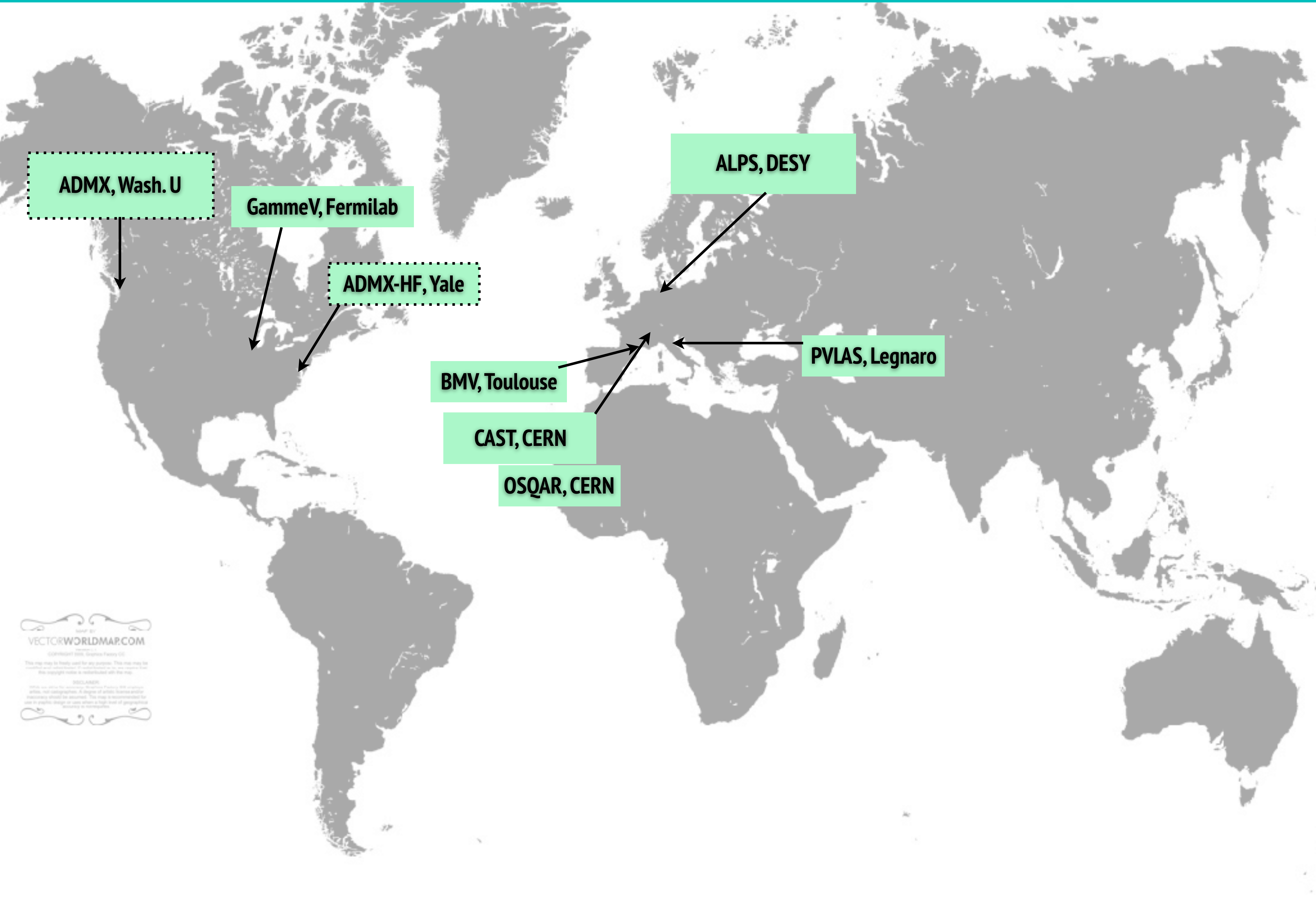
Stars

Cosmos

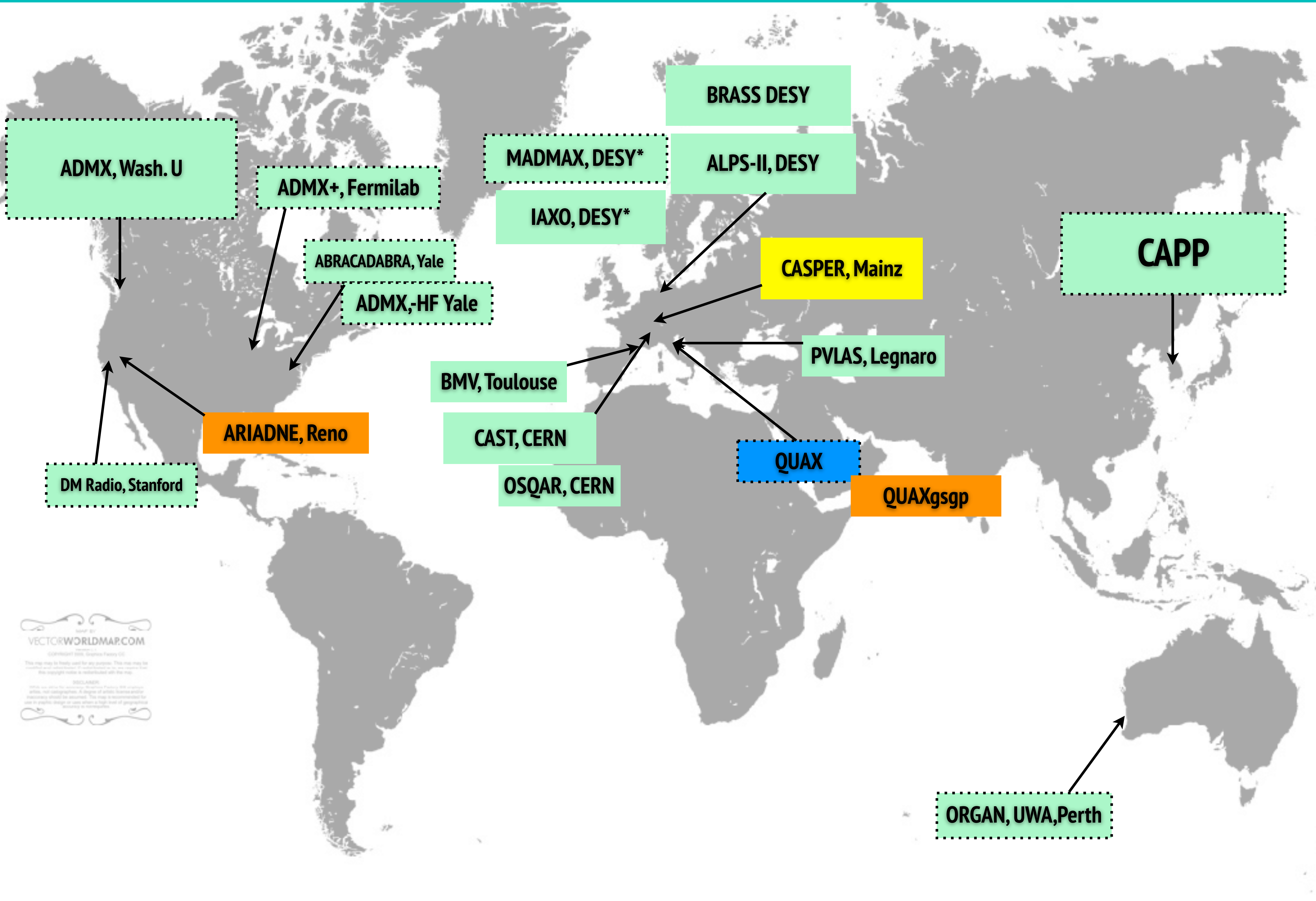




Lab experiments 2011

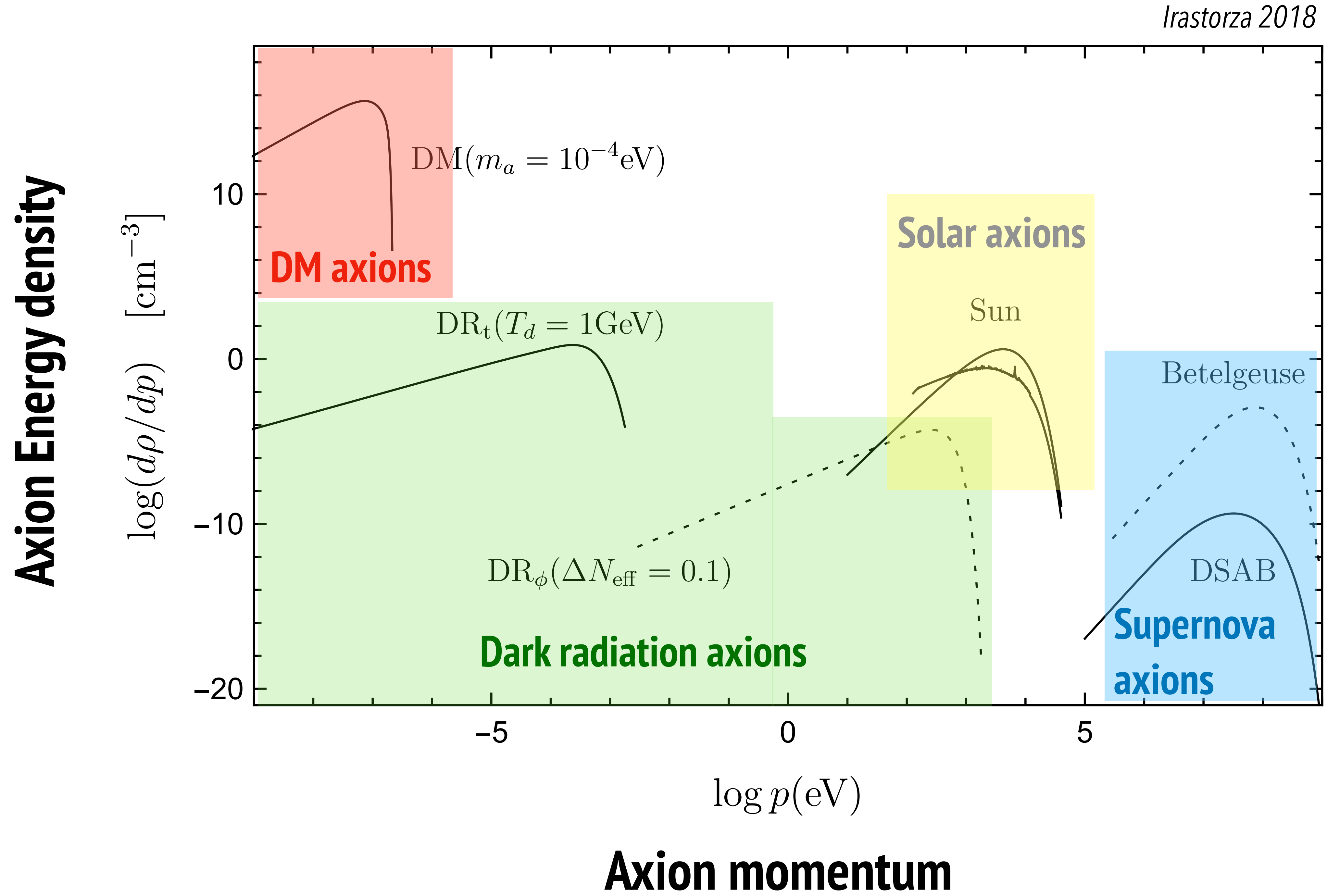


including R&D ~2017

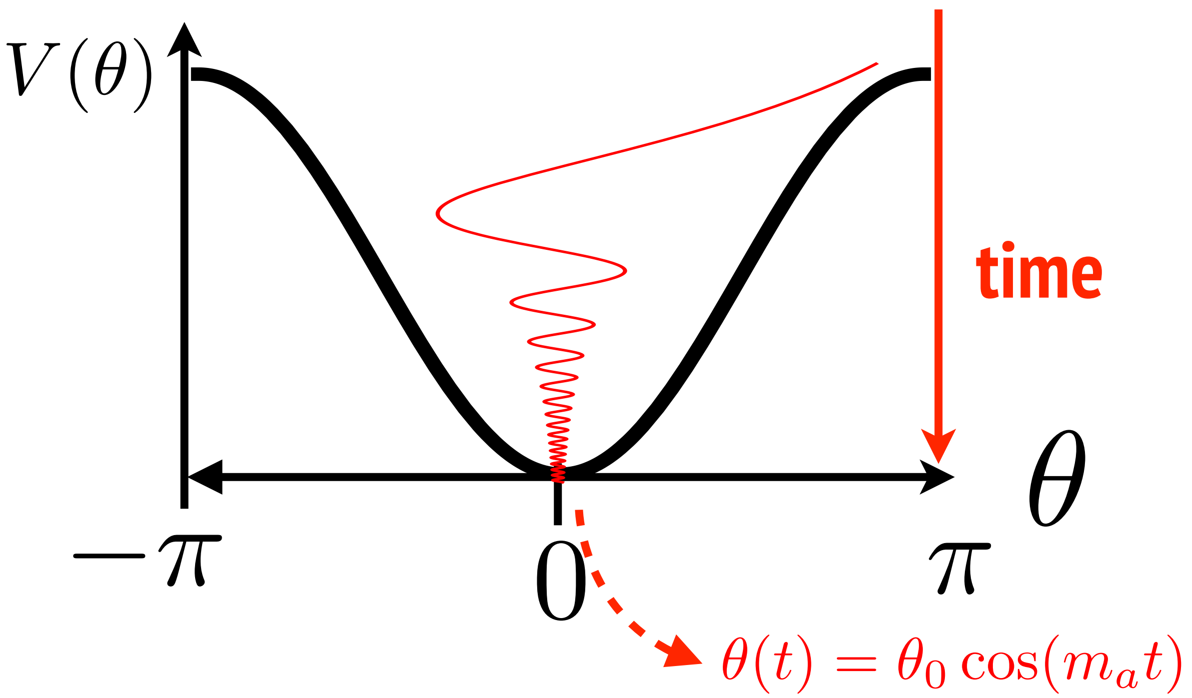


Search for Axions : Natural sources

- **Naturally produced axions could be quite copious, save production and focus on detection!**



Axion DM in the lab



Local Dark Matter density*

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

↓

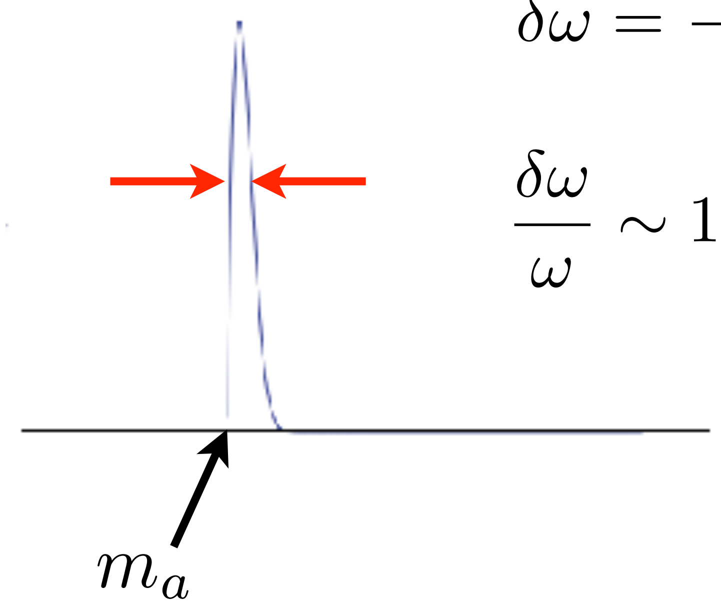
$$\theta_0 = 3.6 \times 10^{-19}$$

Detecting Axion Dark Matter

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

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

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



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

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

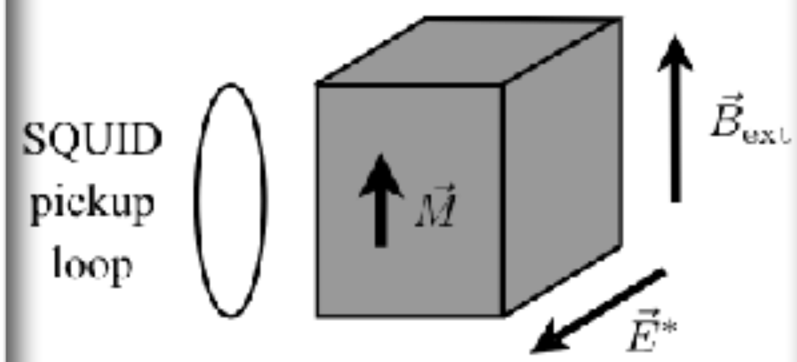
coherence time

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

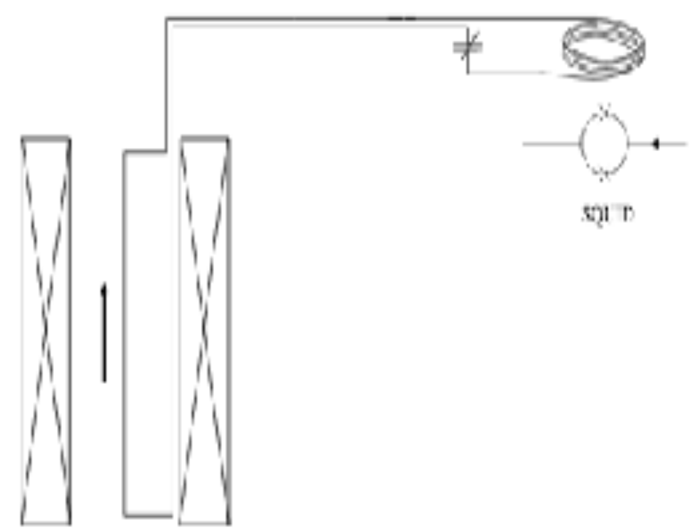
coherence length

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

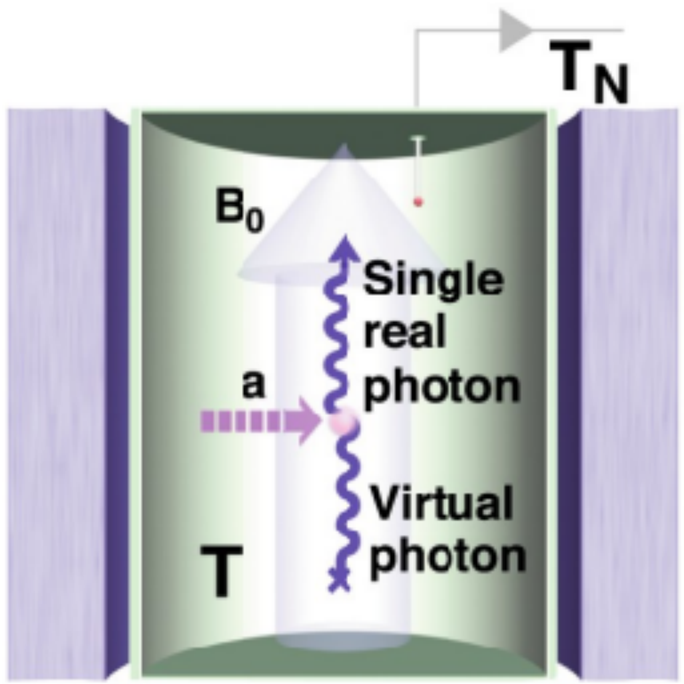
Oscillating EDM



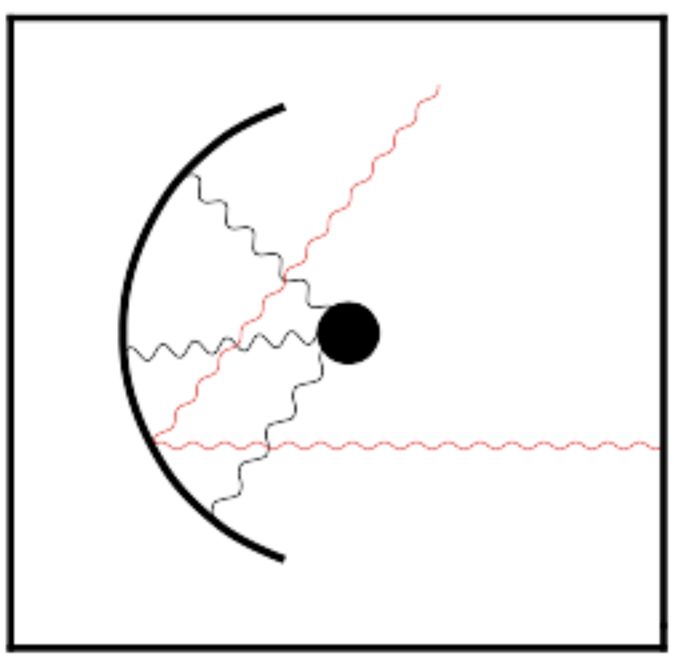
LC-circuit



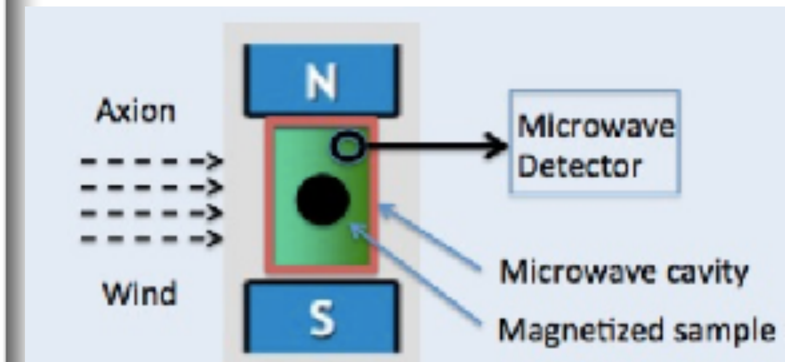
Cavities



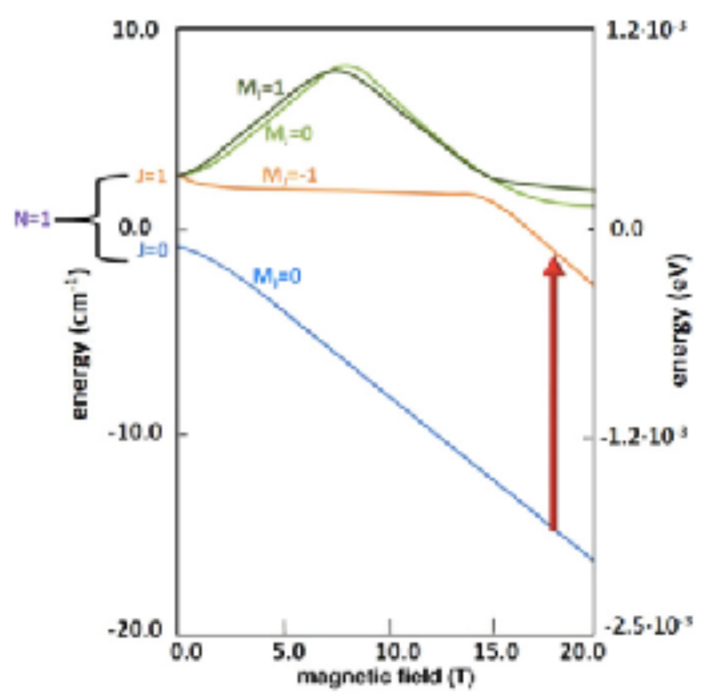
Mirrors



Ferromagnetic resonance



Atomic transitions

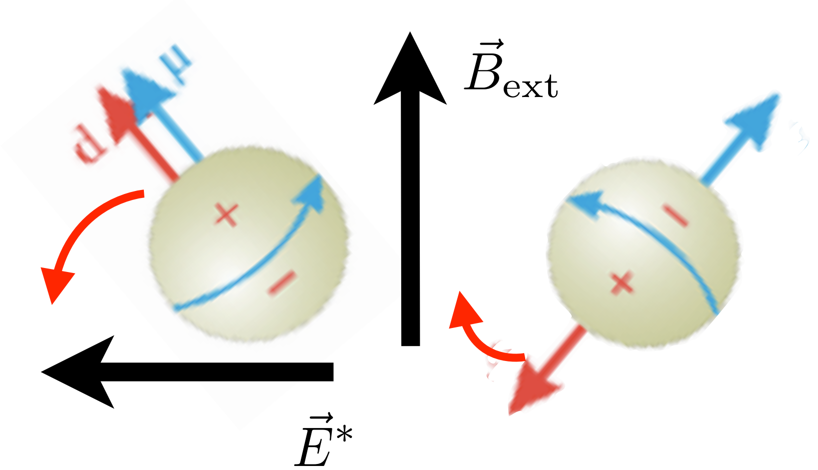


CASPER : oscillating EDM with NMR

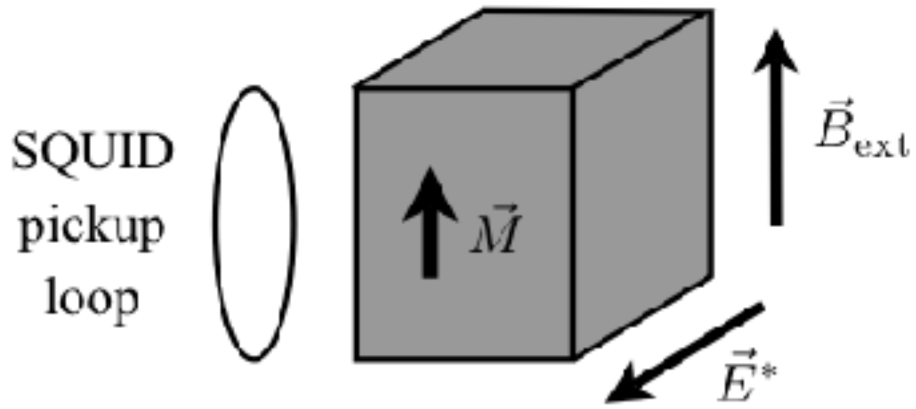
Mainz, Berkeley

D. Budker S. Rajendran P. Graham

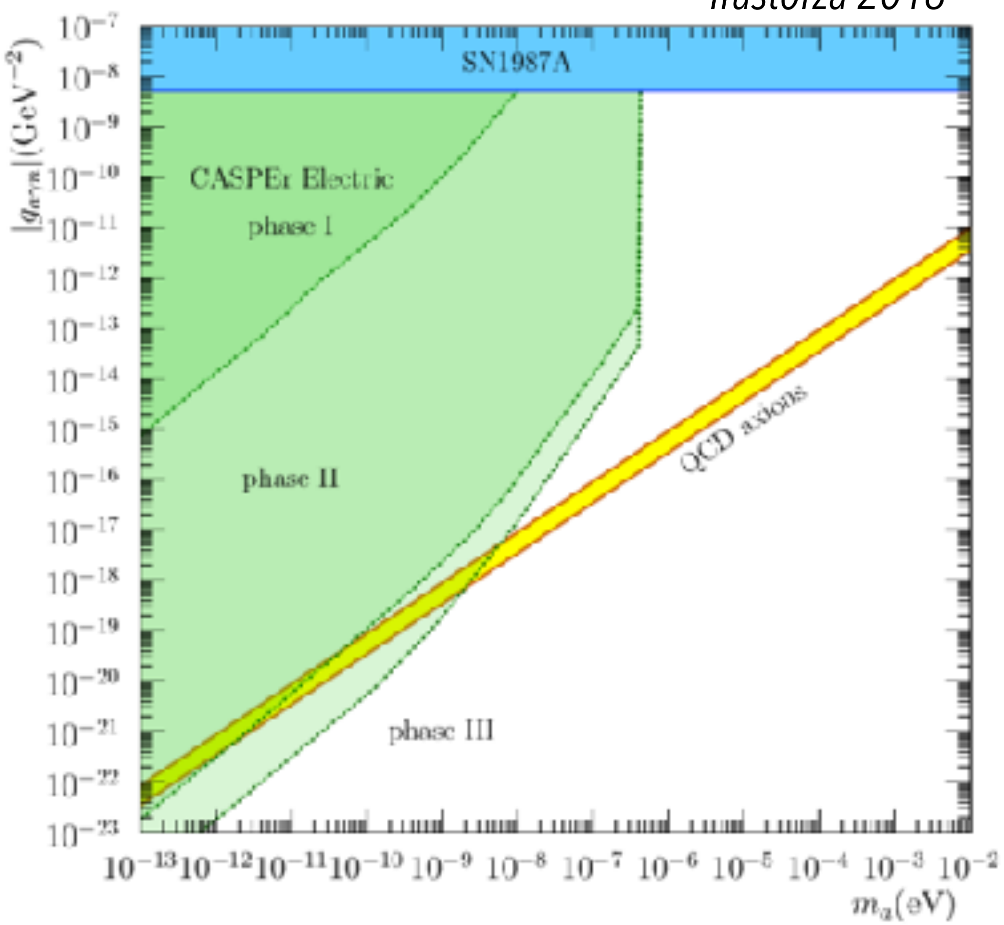
- **Oscillating neutron EDM** $d_n = -4 \times 10^{-3} \times \theta_0 \cos(m_a t)$ [e fm]



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



Irastorza 2018



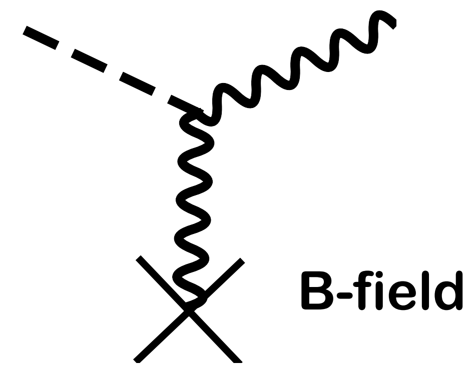
- *EDM + Large E-fields in PbTiO3*
- *Scan over frequencies, with Bext*
- *Mainz (D. Budker's group) & Berkeley*
- *Phase I starts in 2017, Phase II physics results ...*
- *Mass range limited by B-field strength*

Axion DM in a B-field

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

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

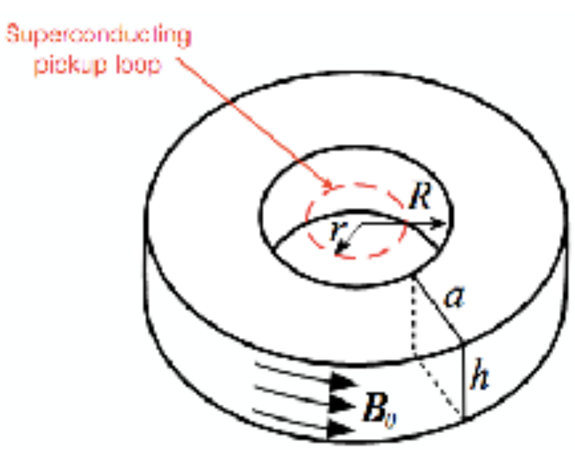
source



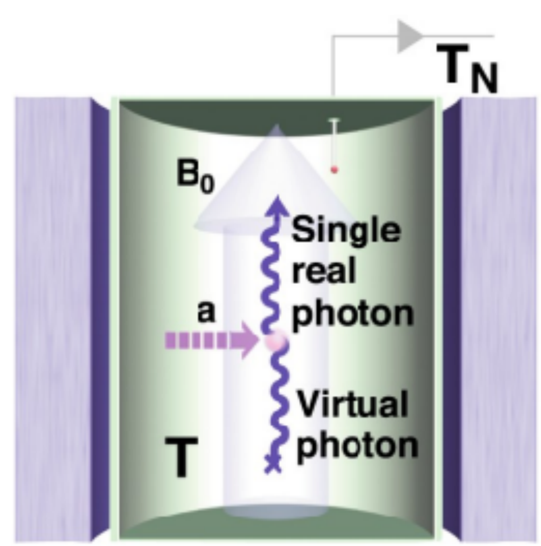
E-field $E \sim \mathcal{O}(10^{-12}\mathrm{V/m})\frac{|\mathrm{B}_{\rm ext}|}{10\,\mathrm{T}}C_{a\gamma}\times\cos(m_a t)$

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

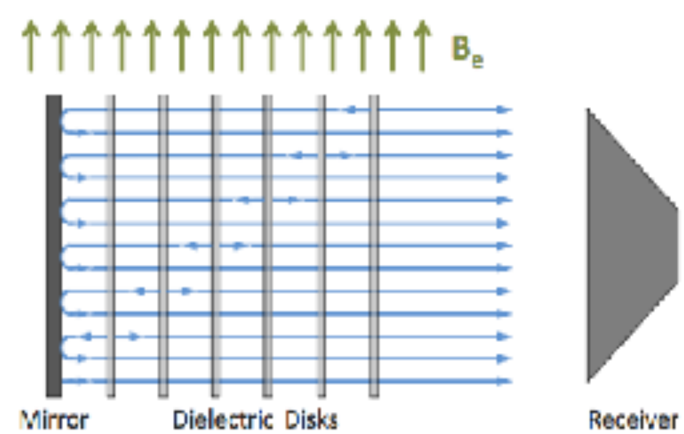
- Four different techniques:



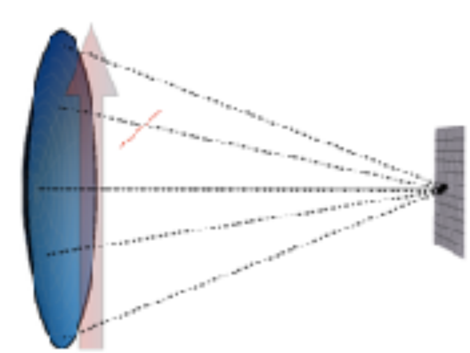
DM Radio



Cavities



Dielectric haloscope

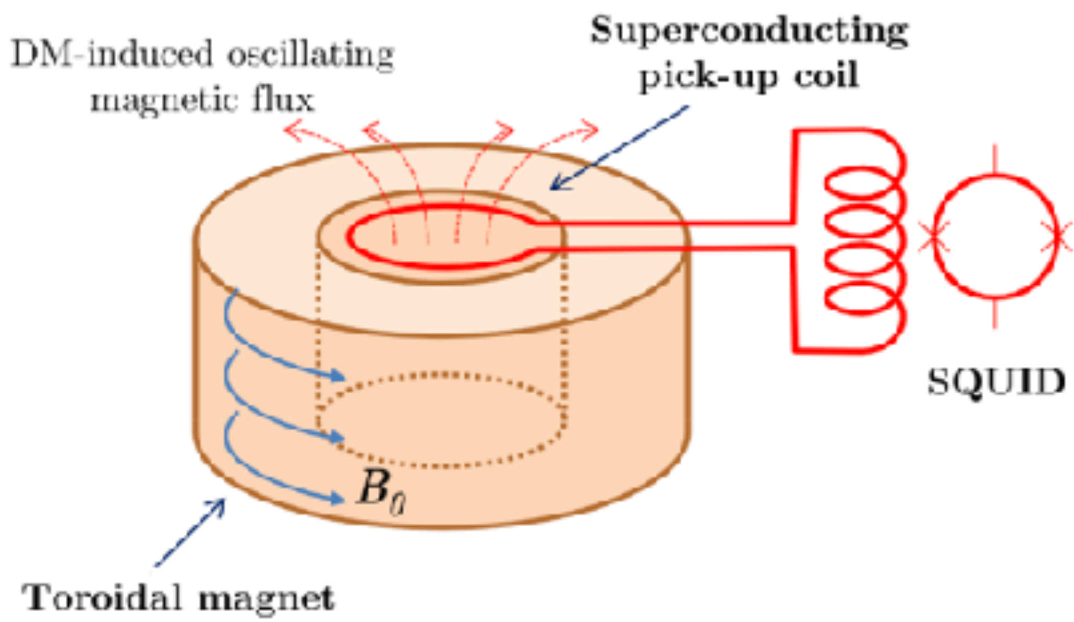


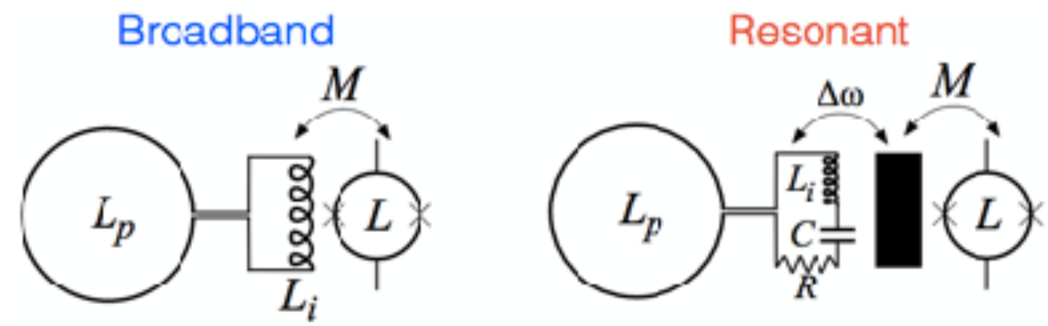
Dish antenna

DM Radio

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

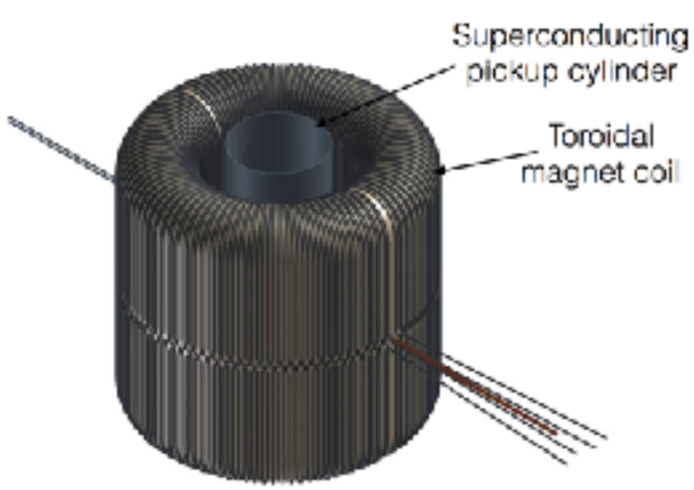
Sikivie PRL 112 (2014)
Chaudhuri PRD92 (2015)
Kahn PRL 117 (2016)



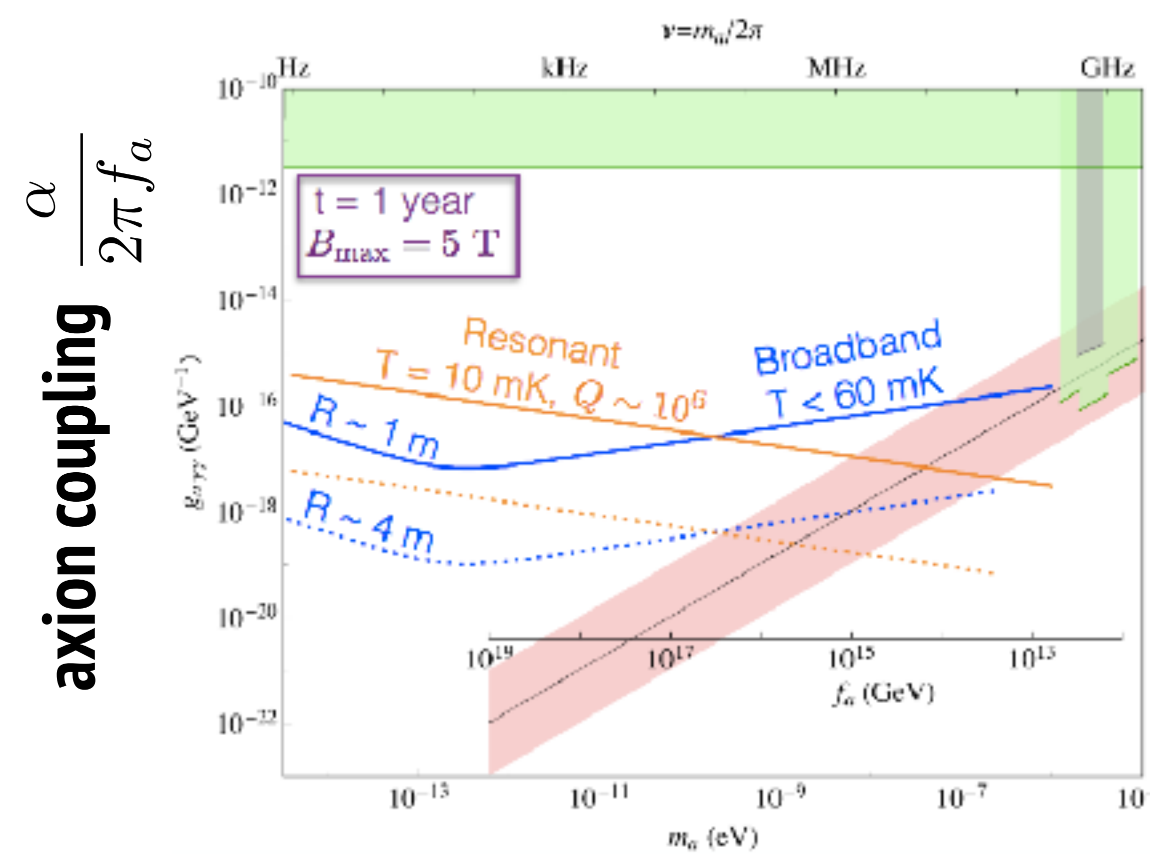


Better at low frequency

Better at high frequency



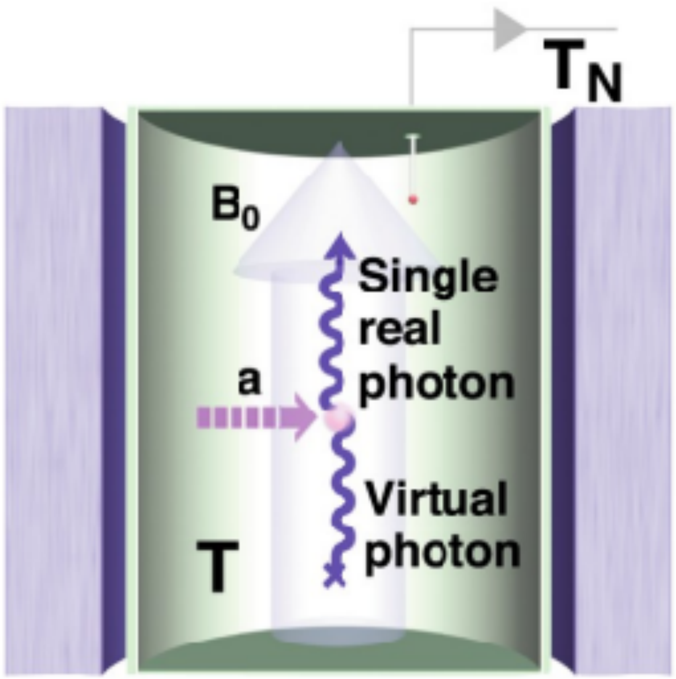
ABRACADABRA (MIT)
10 cm, 1m , 4m ...



Resonant cavities: haloscopes

P. Sikivie

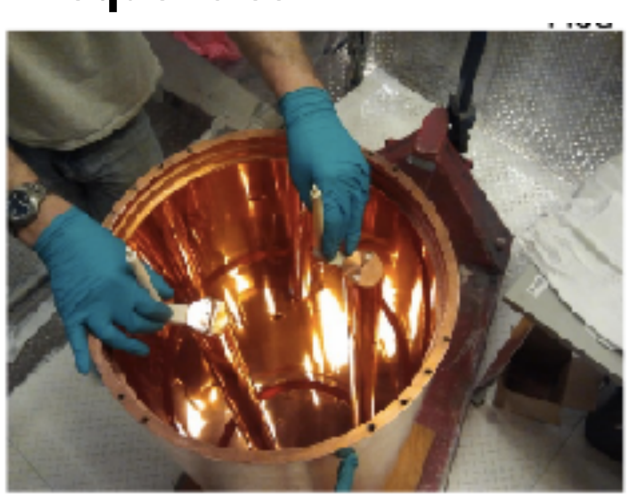
- Boost the axion-generated E-field in a tuned resonant cavity

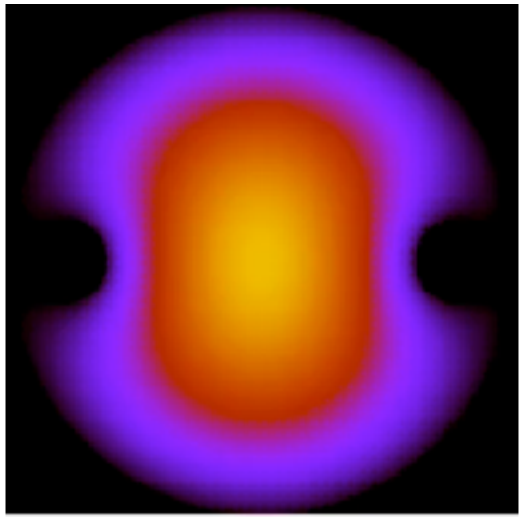


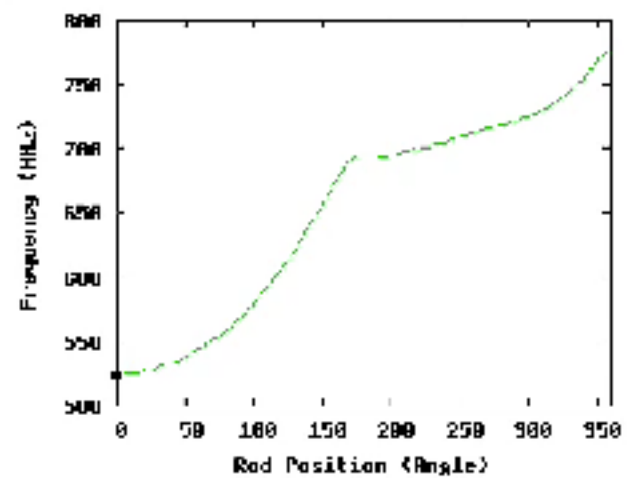
$$P_{\rm out} \sim Q|\mathbf{E}_a|^2 V m_a$$

- Cavity quality factor $Q \sim 10^5$
- B-fields $B \sim 10{\rm T}$
- Volume $\sim 1/m_a^3$ (typically a few liters)
- Temperature $T \sim 0.2 - 4\,{\rm K}$
- 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

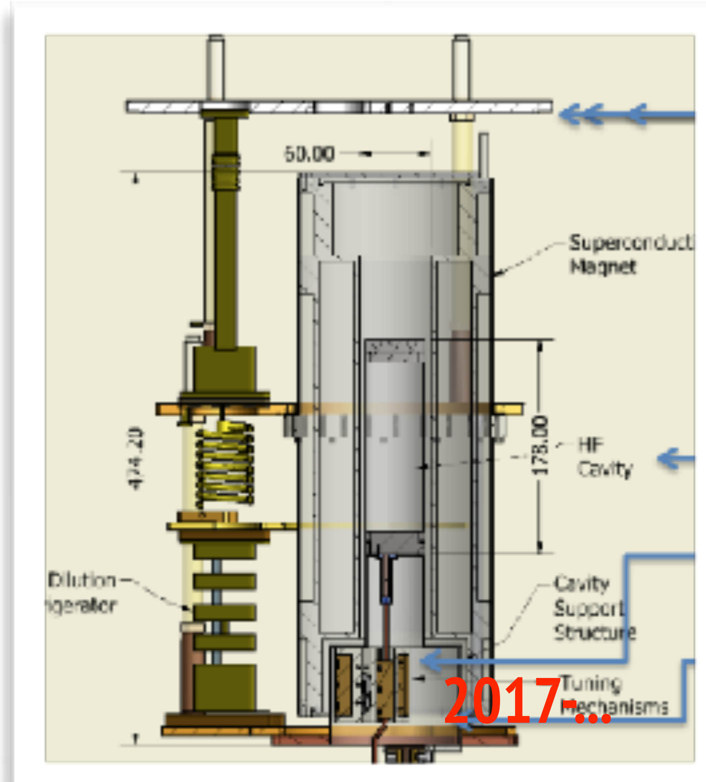
Cavity experiments

- Physical dimensions $L \sim 1/m_a$

ADMX-Seattle

new data!!!

CULTASK - CAPP -Korea



2017-...

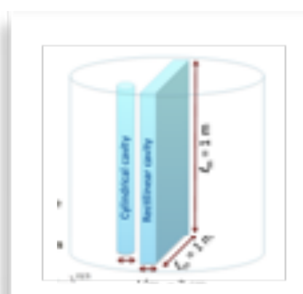
ORGAN-UWA Perth

2017-...

HAYSTAC-Yale

2016-...

ADMX-Fermilab



RADES

2017-...

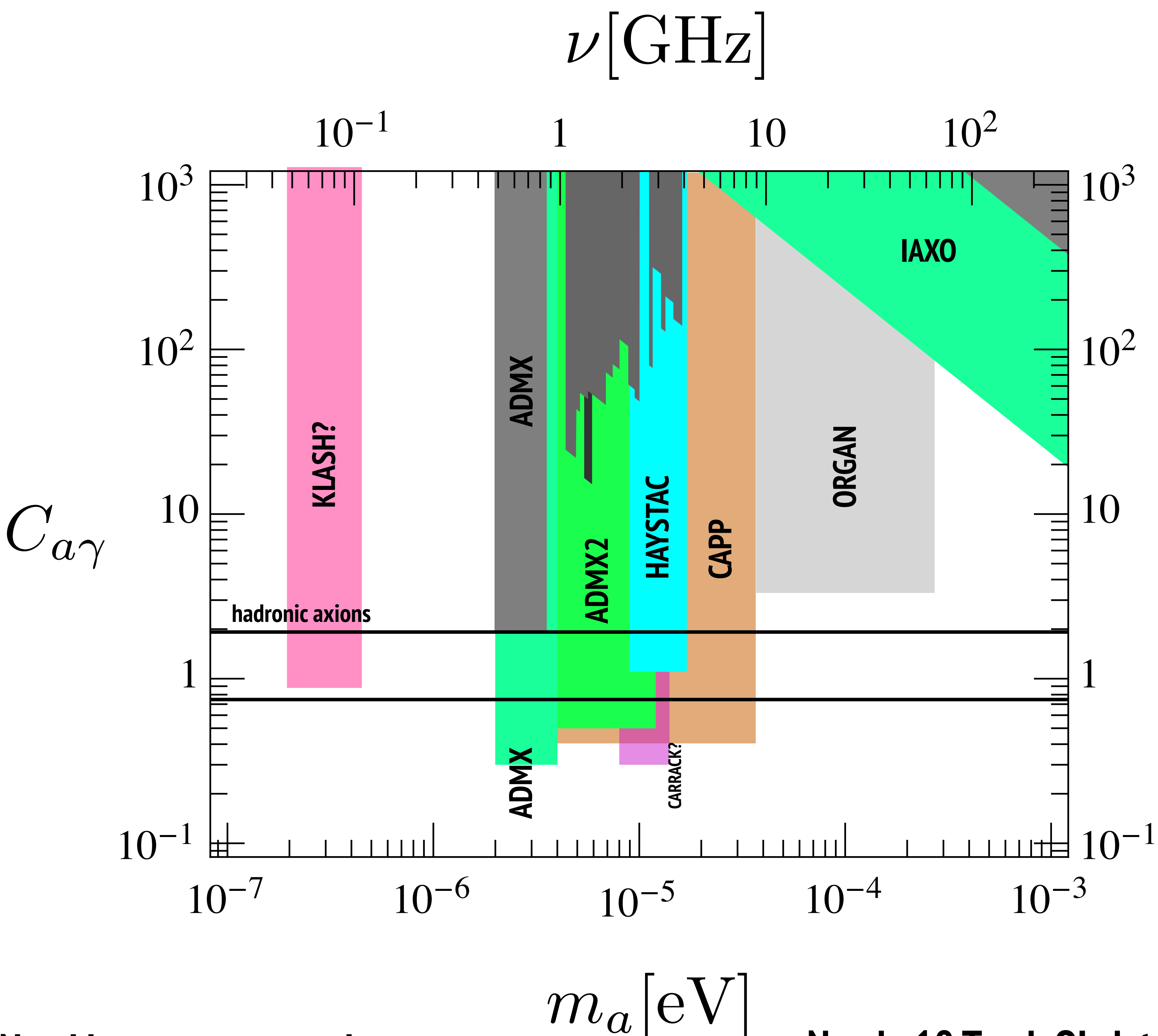
CAST-CAPP

2017-...

KLASH?

??-...

Projected optimistic sensitivities



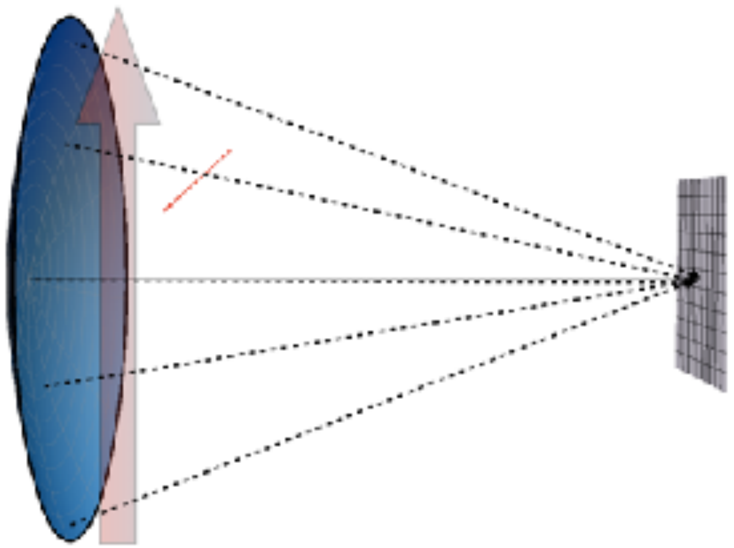
- Need larger magnet volume

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

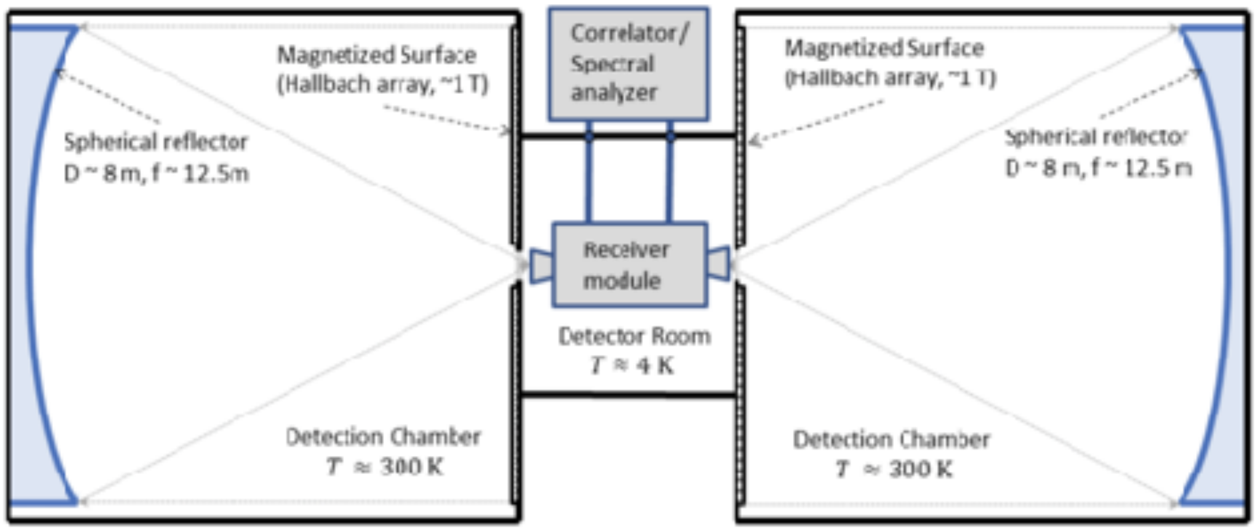
- or combine many cavities ...

Dish antenna

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



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



BRASS @ Hamburg

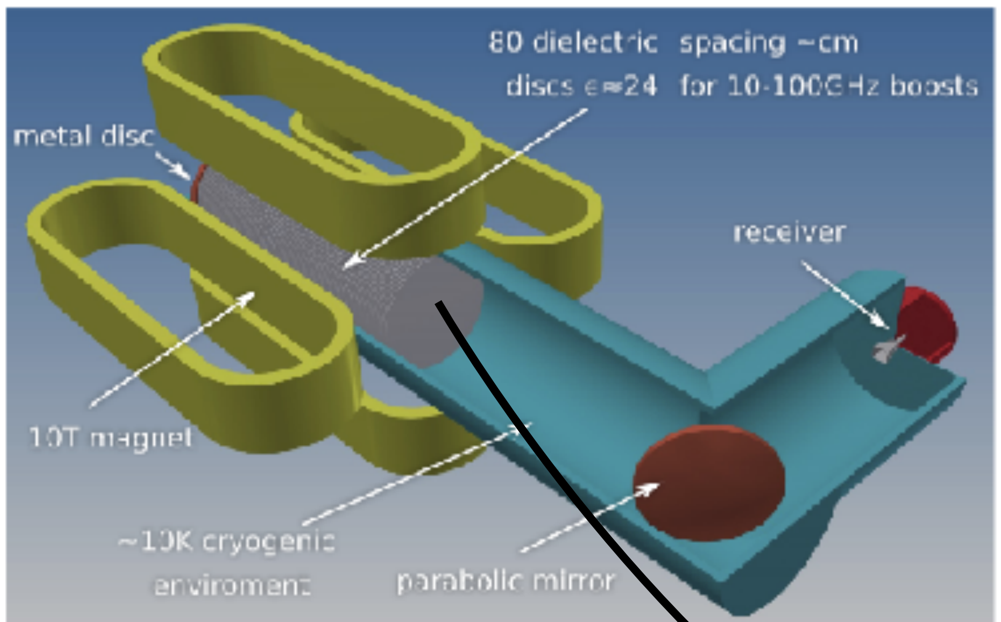
FUNK experiment (KIT)

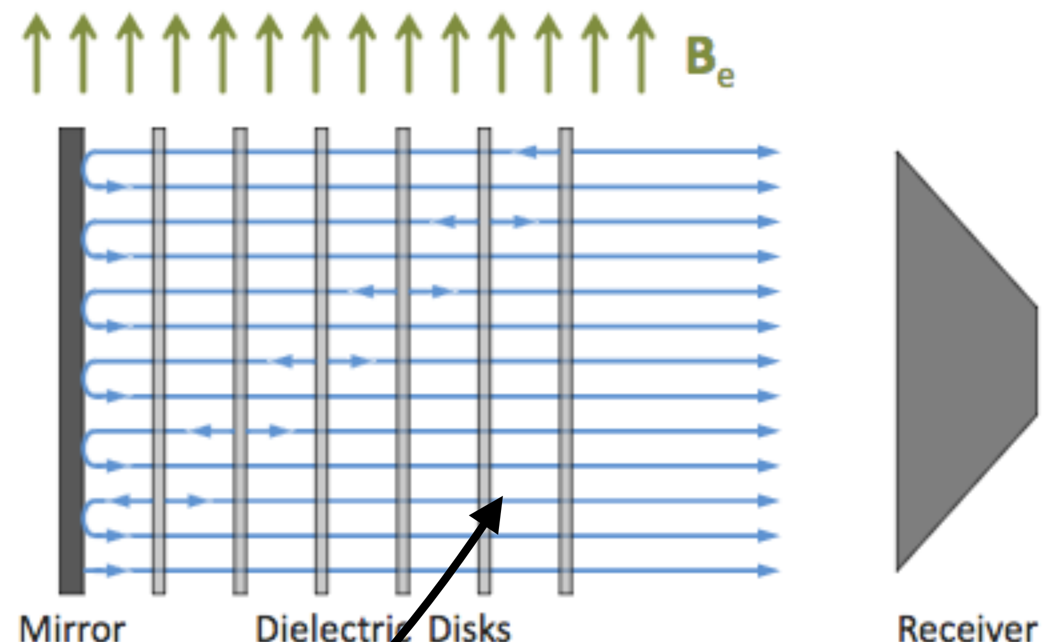
Dielectric haloscope : MADMAX

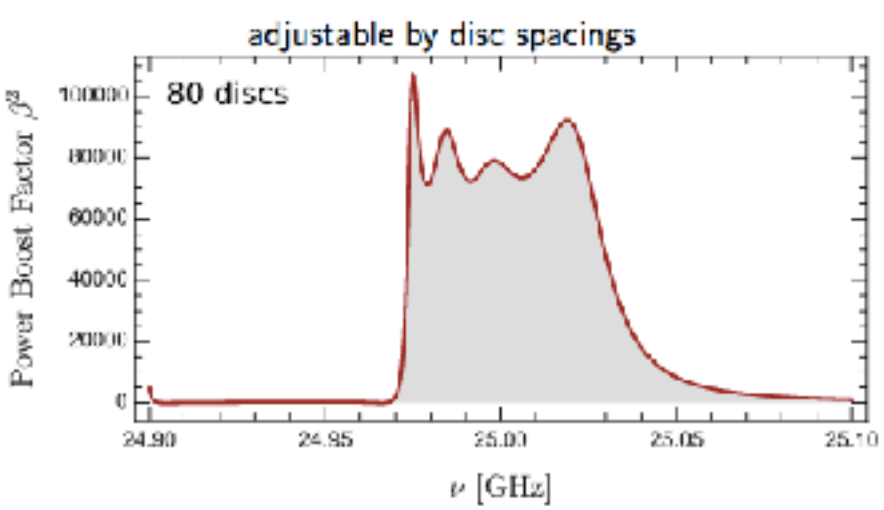
- Hybrid system, large area + multiple emitters + a bit of resonant enhancement

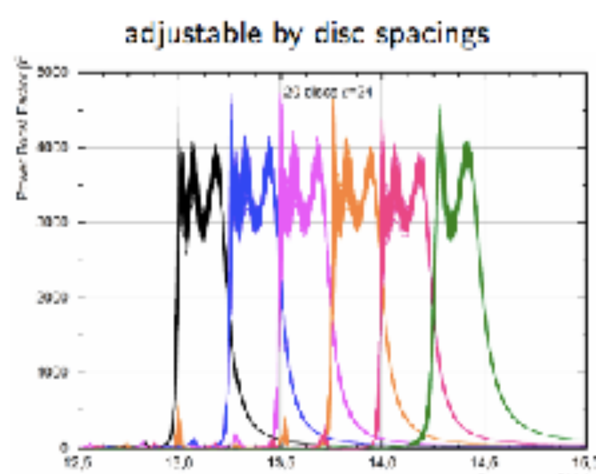
$$\frac{P}{Area} \sim 2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{c_\gamma}{2} \frac{B_{||}}{5\mathrm{T}} \right)^2 \frac{1}{\epsilon} \times \beta(\omega)$$

boost factor



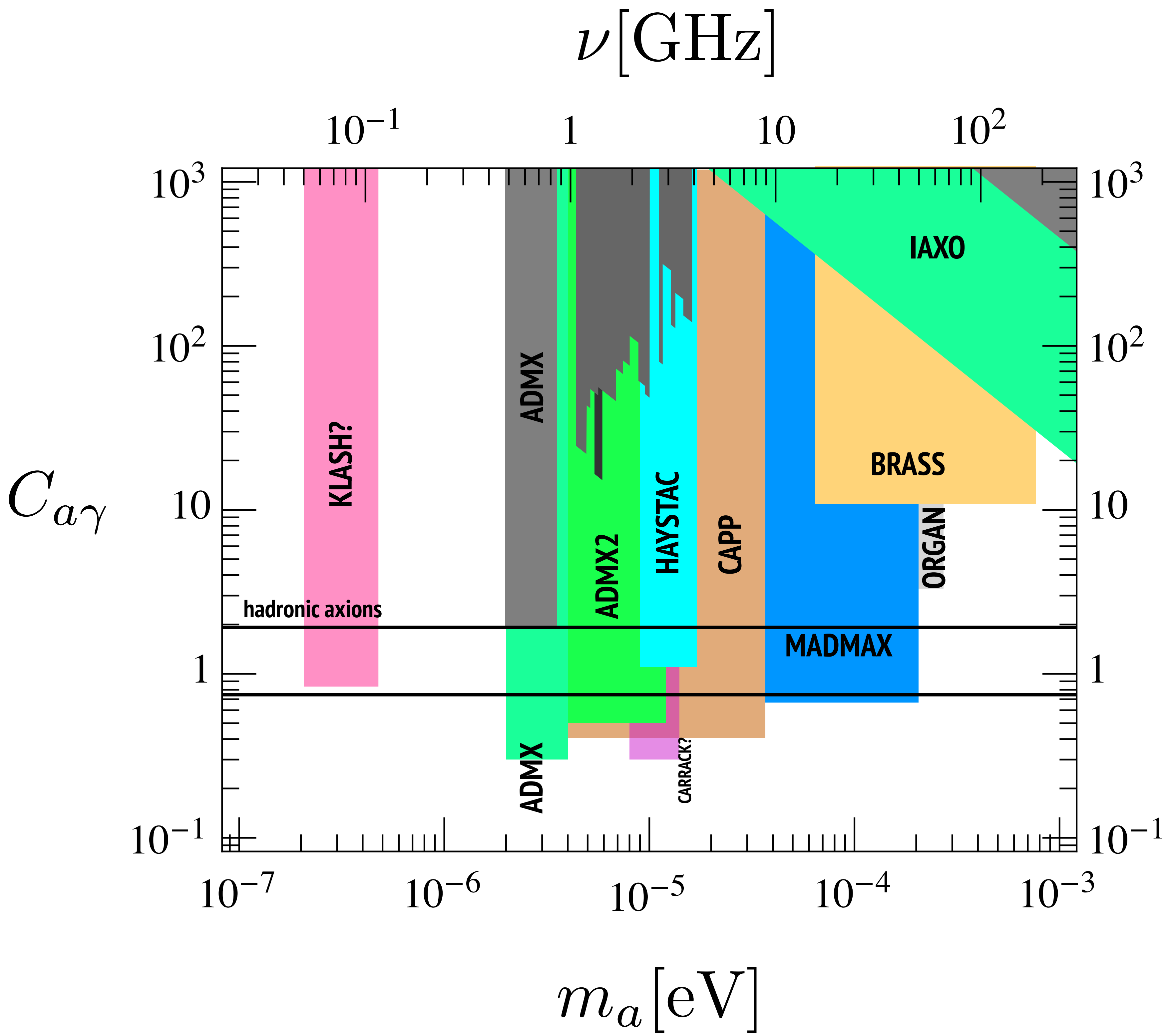




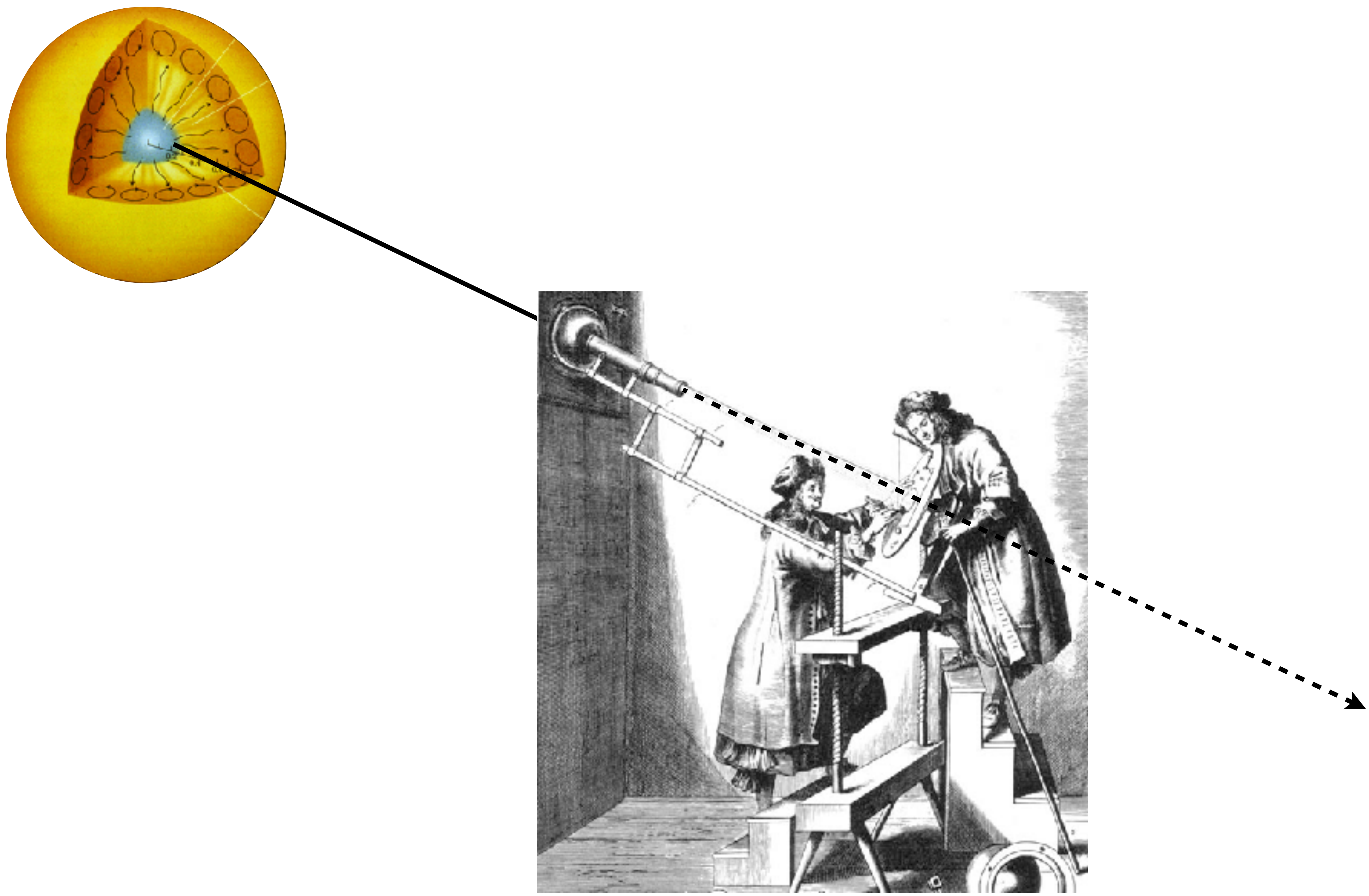


MADMAX: MAgnetised Disk and Mirror Axion eXperiment: MPP Munich, Hamburg Uni, DESY, Saclay, Zaragoza U

Projected sensitivities

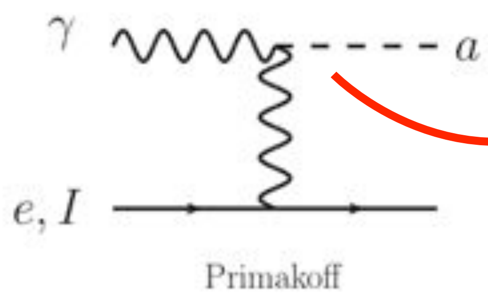


1.2 Detecting Solar Axions : Helioscopes



Axions from the Sun

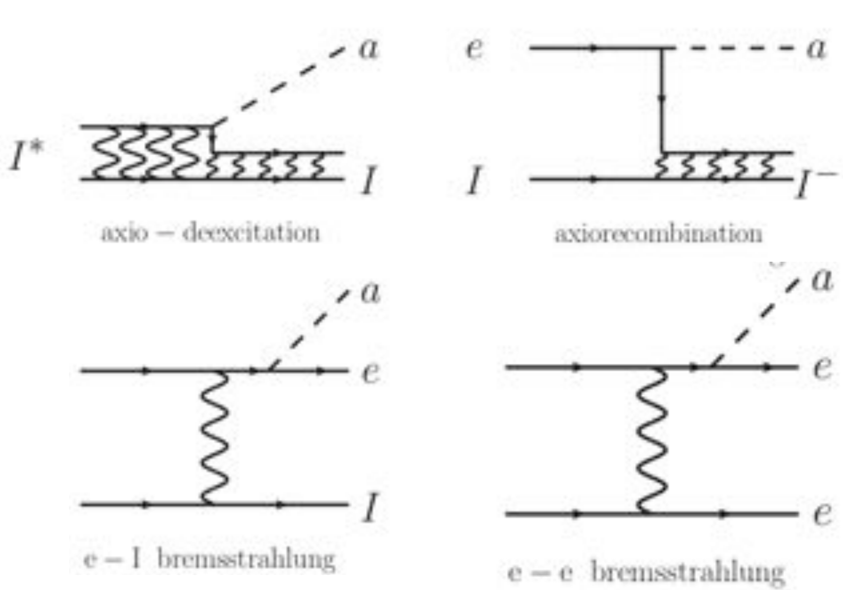
Hadronic axions (KSVZ)

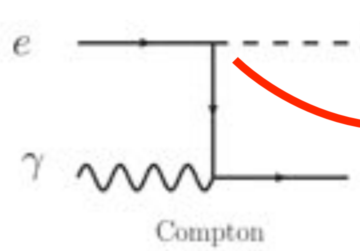


$$\frac{C_\gamma \alpha}{2\pi f_a} \frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4} a$$

$g_{a\gamma}$

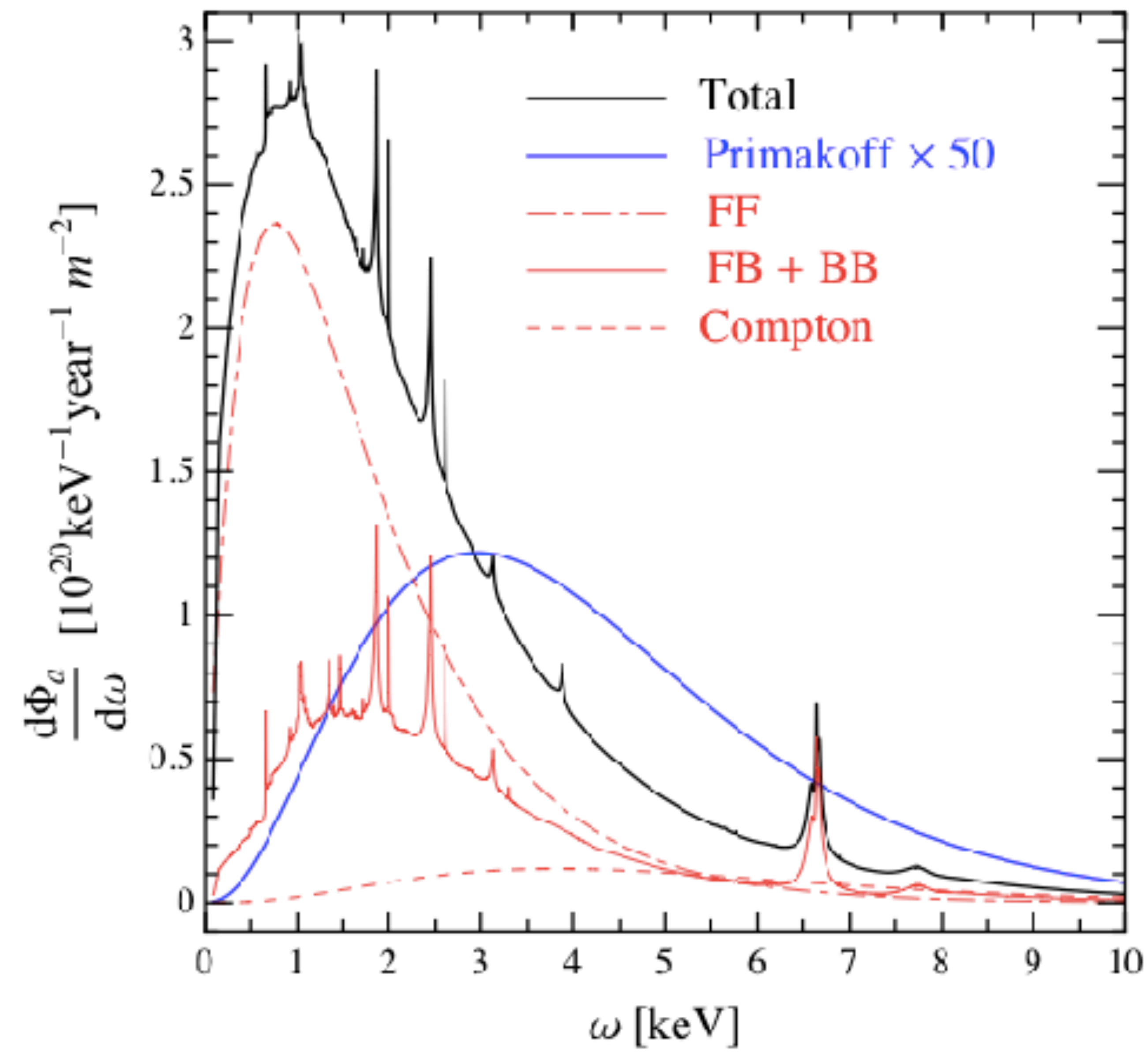
Non hadronic (DFSZ, e-coupling!)





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

g_{ae}



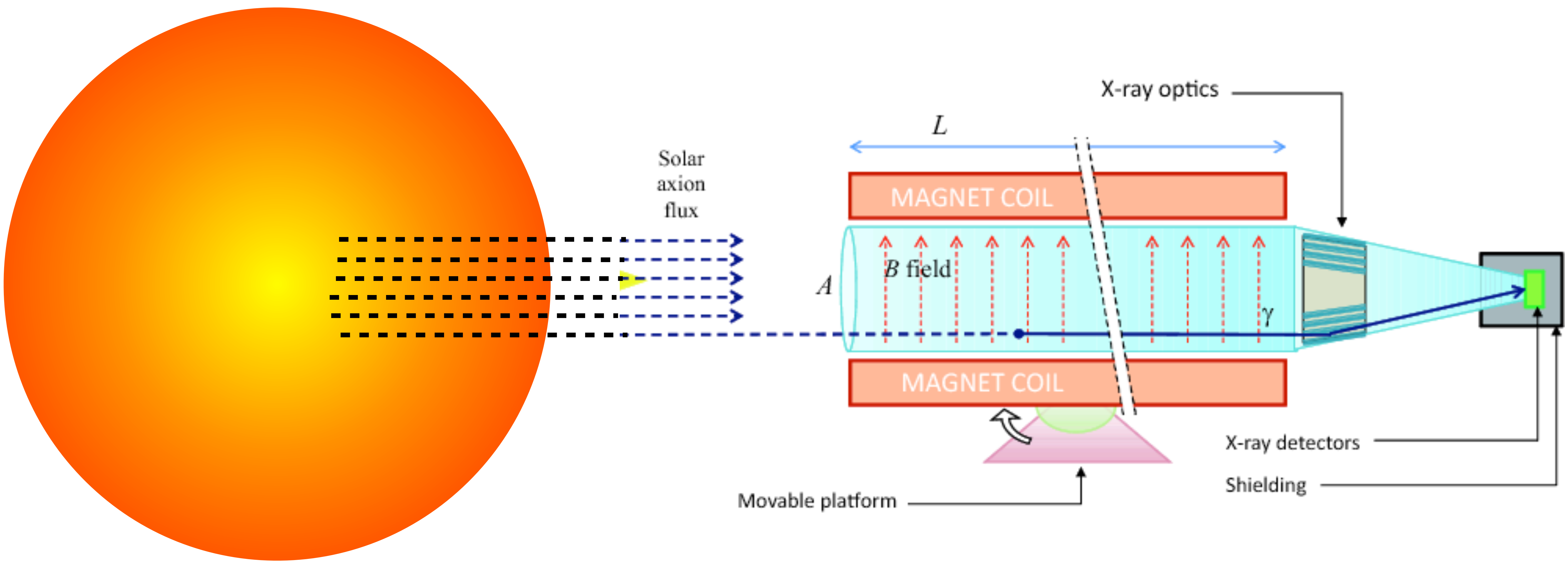
$g_{ae} = 10^{-13}$

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

typical of meV mass axions

Helioscopes

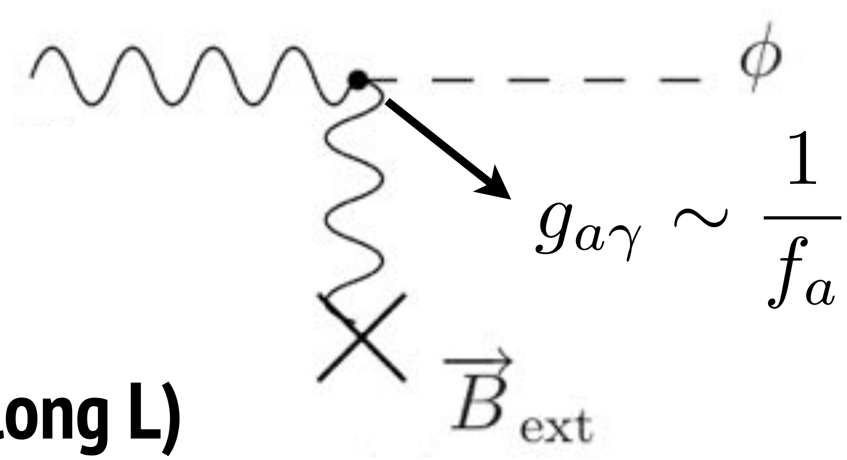
The Sun is a copious emitter of axions! **convert into X-rays** **focus** **detect**



Conversion probability

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

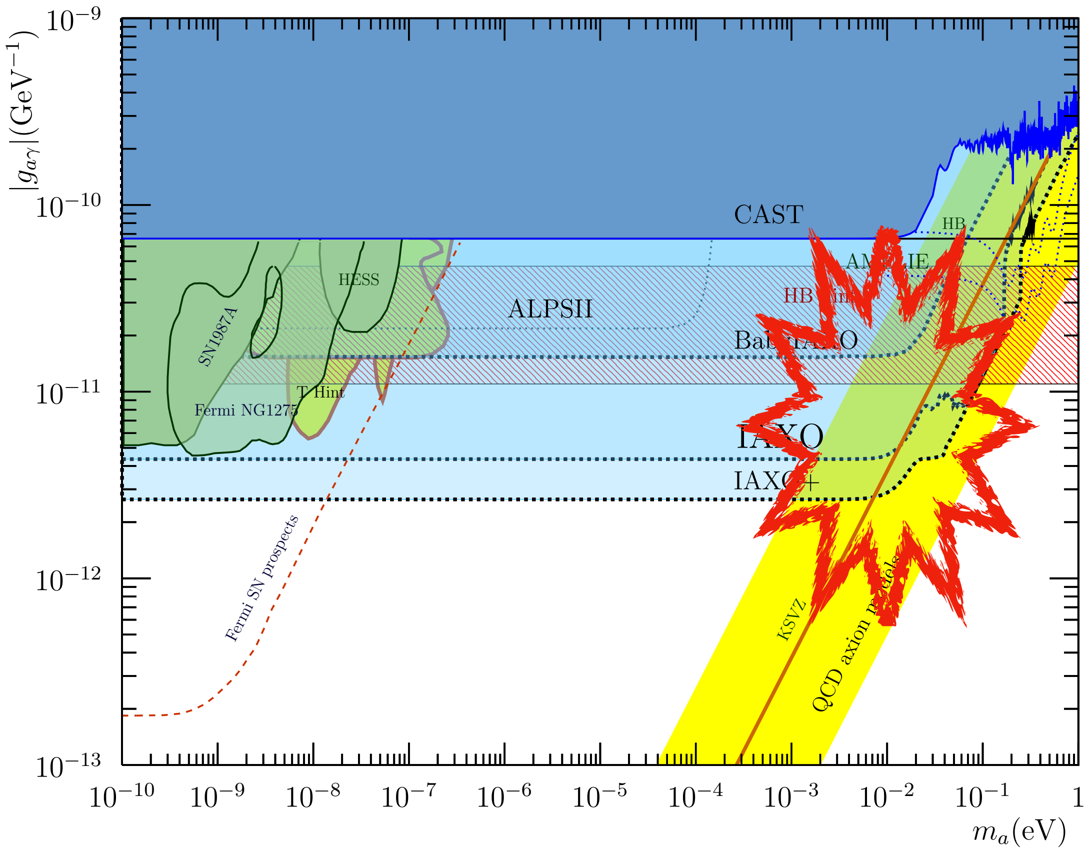
$$P(a \leftrightarrow \gamma) \sim 10^{-20} \left(\frac{B}{3\,\mathrm{T}} \frac{L}{20\,\mathrm{m}}\right)^2$$ **(coherence along L)**



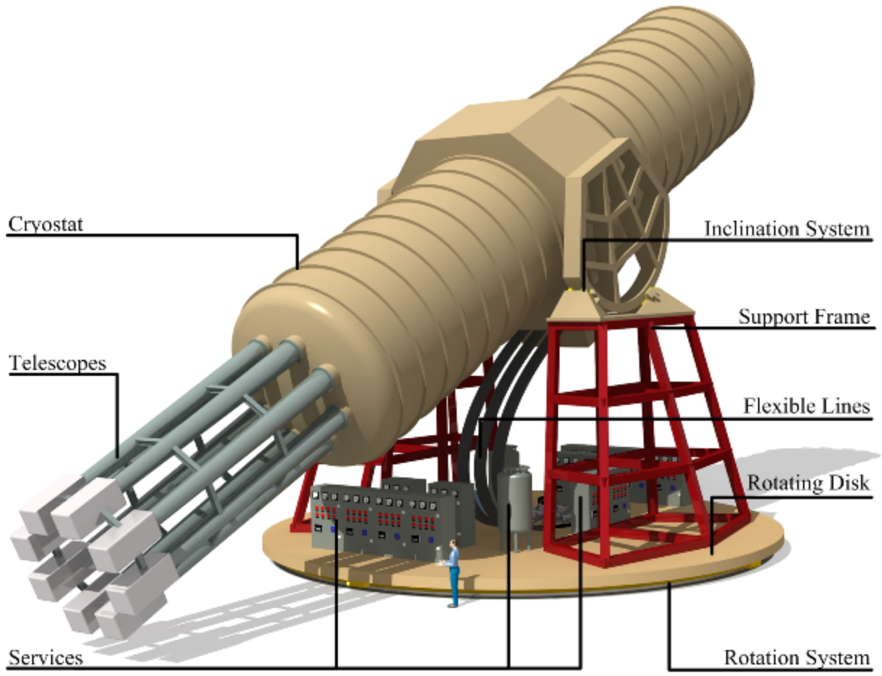
Past and the future

CAST (LHC dipole 9.3 m, 9T)

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

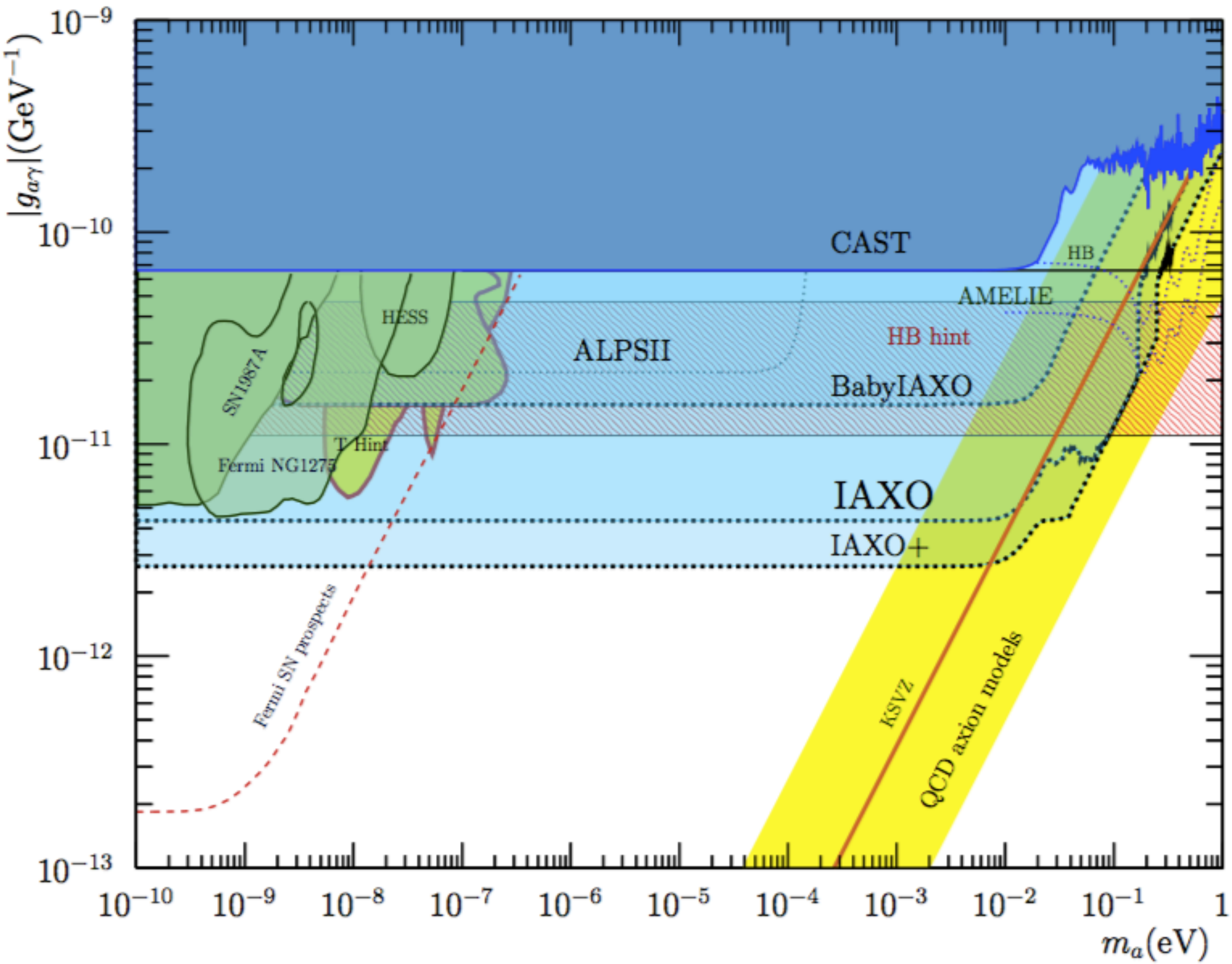


IAXO (proposed toroid) 20 m, 3T)

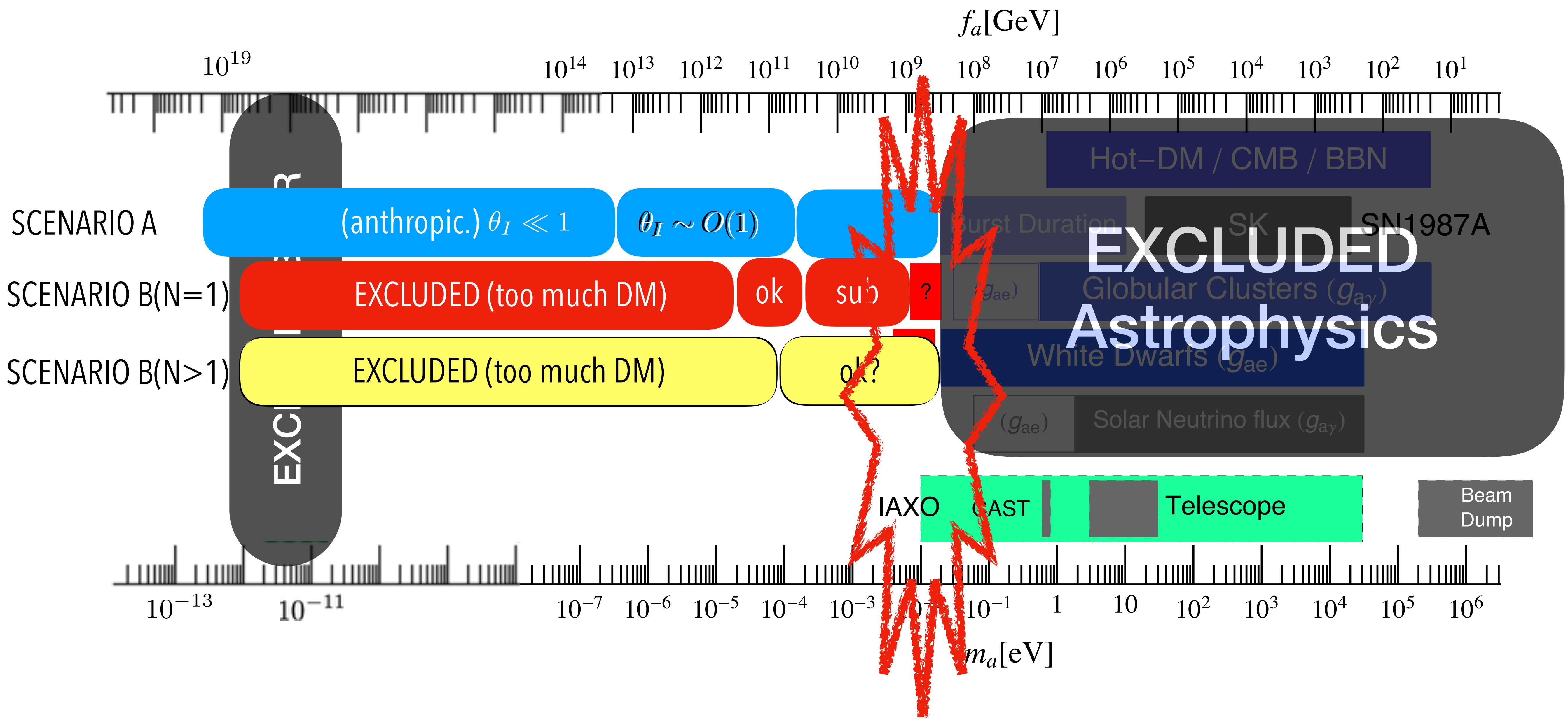


- 12 h tracking/day (sunset,dawn)
- 8 bores (60 cm diam)
- different Detectors
- dedicated X-ray optics
- Collaboration Formed 2017

In more detail

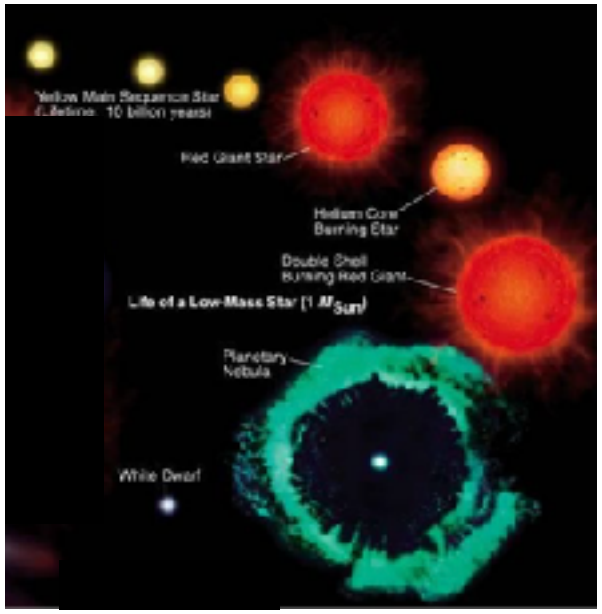


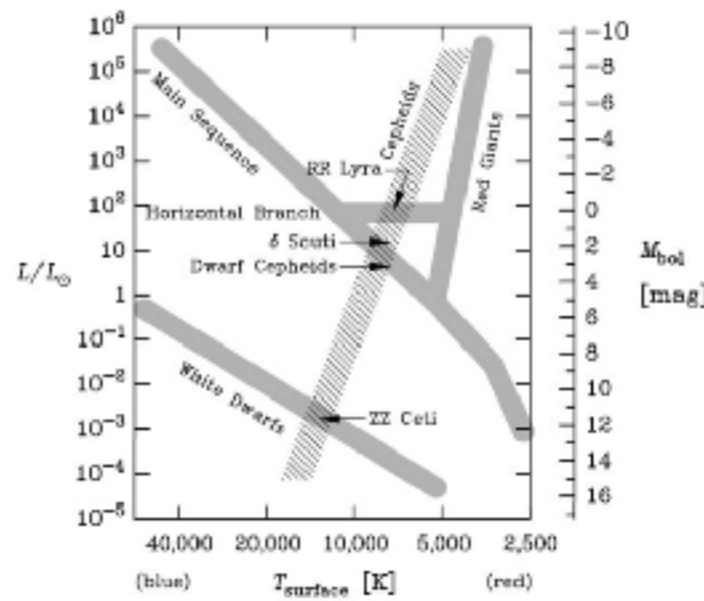
On the landscape



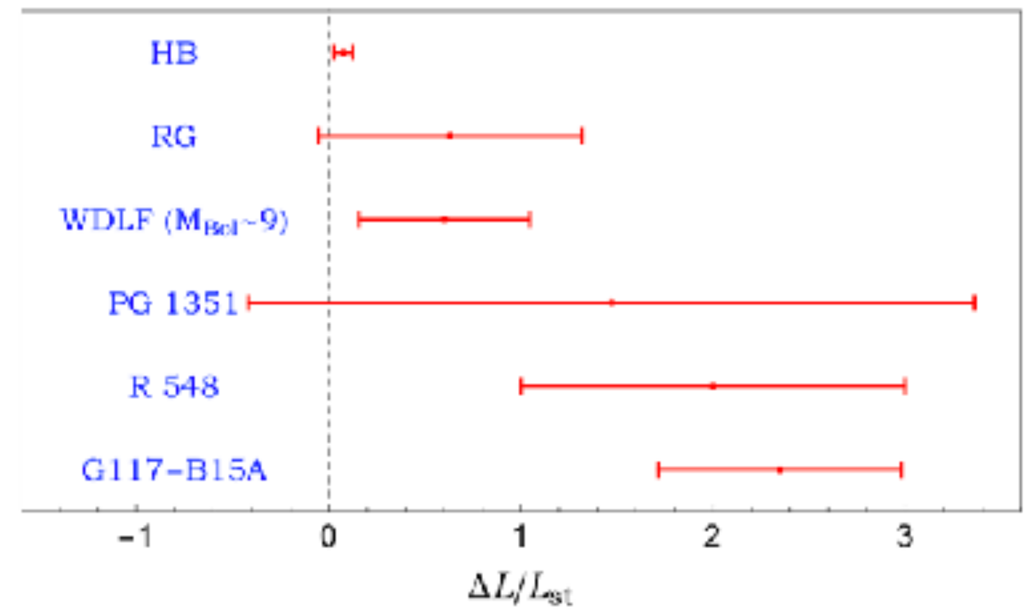
The meV frontier

- **Some stars seem to be cooling too fast; could be a sign for axion core emission!**



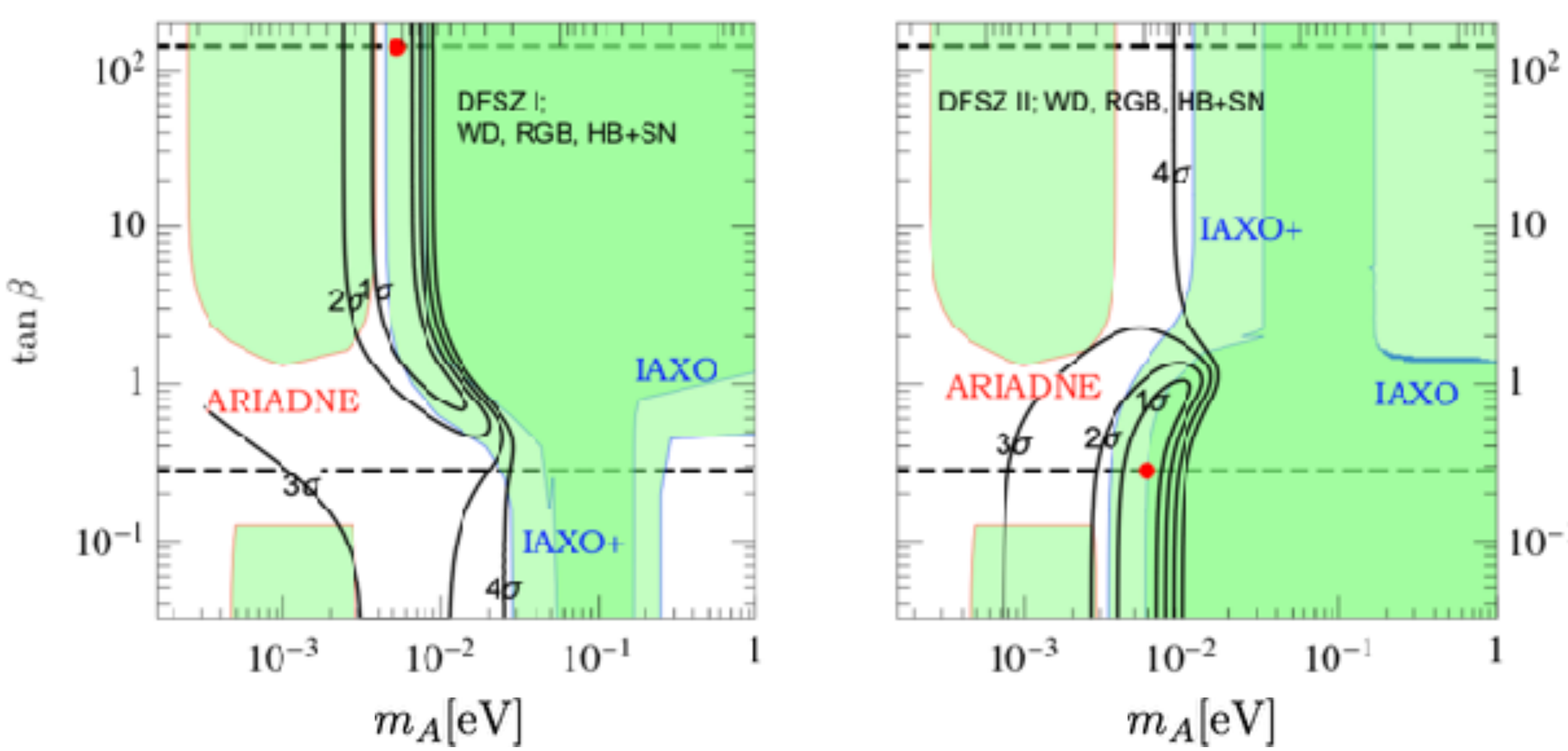


Giannotti 2015



- **Axion interpretation suggests axion-electron coupling (DFSZ?)**

Giannotti 2017



Isocontours show:

- Best region fitting the anomaly (1,2,3,4s)

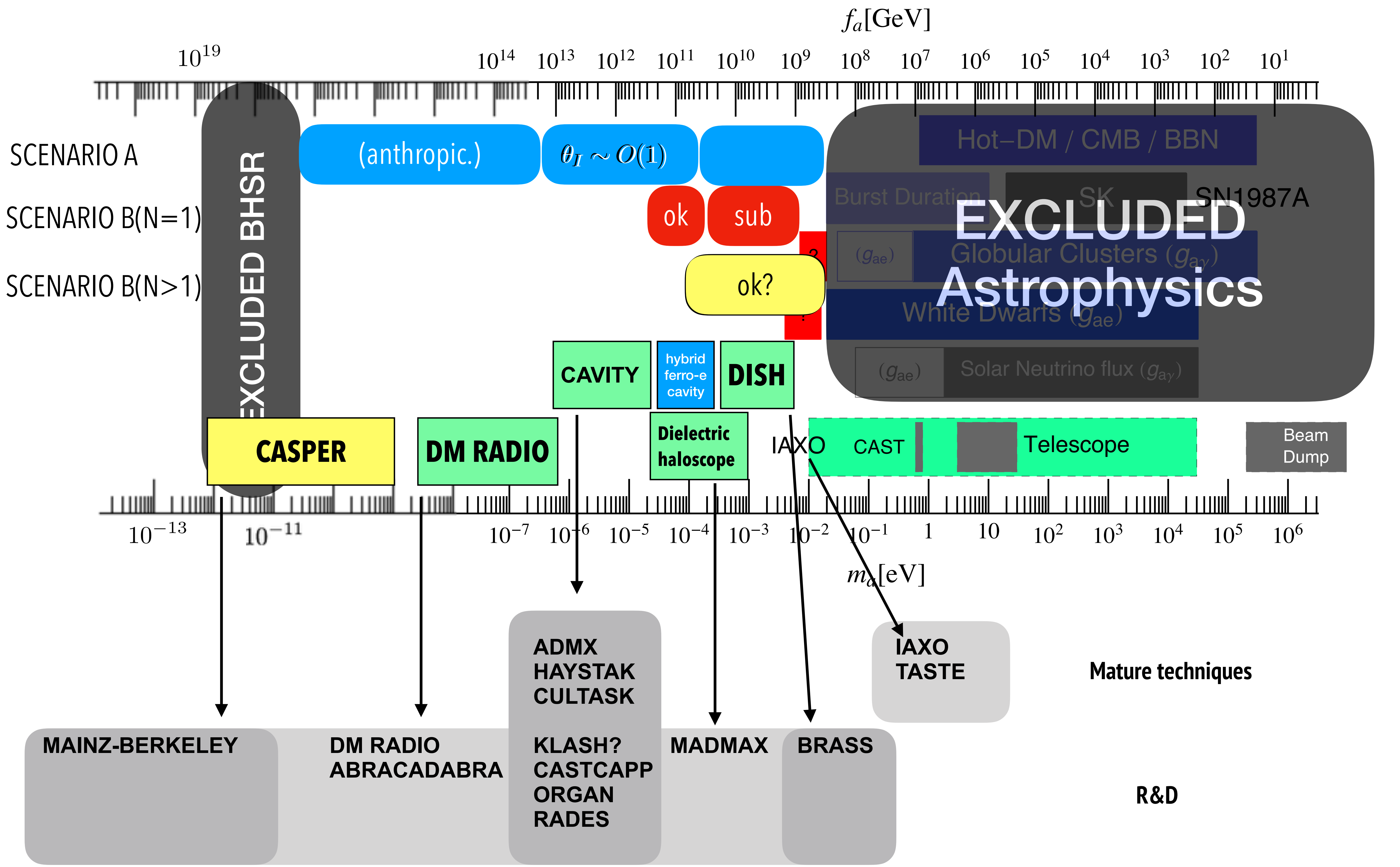
- Includes SN constraint !!!

- Dashed lines limit perturbativity of Yukawas

Clear preference for m_A~6 meV

- Detectable by IAXO!

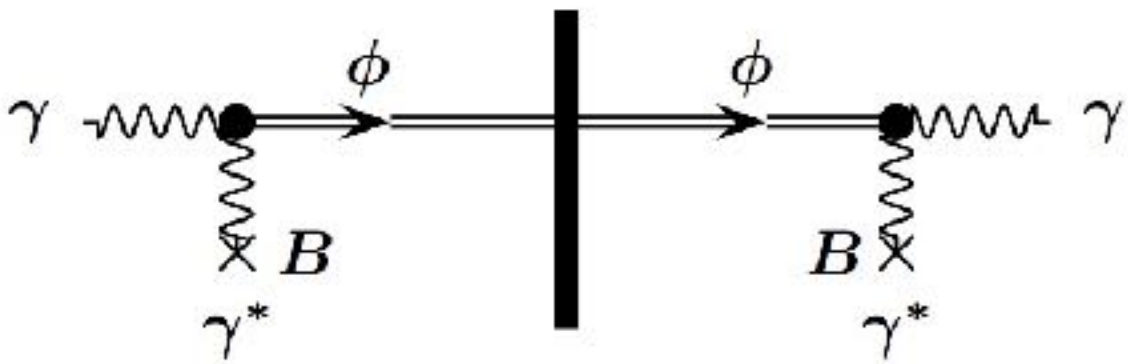
Experiments



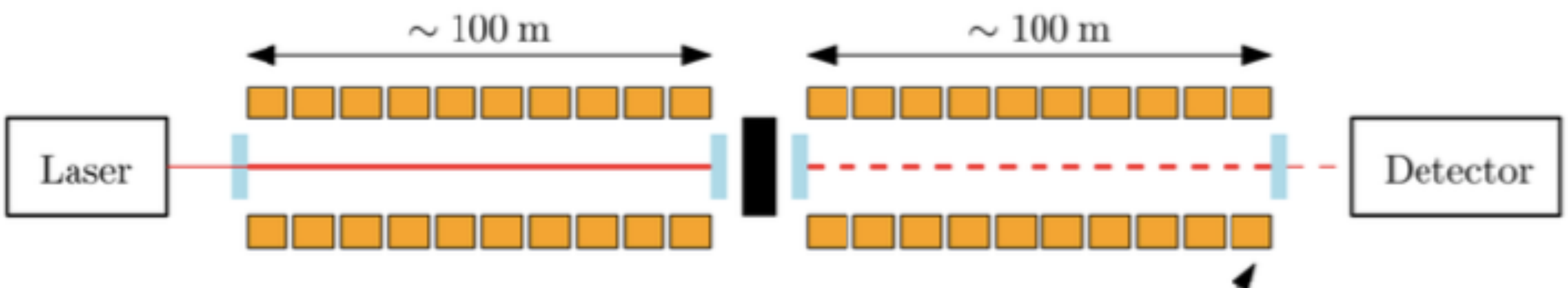
1.3 - Purely lab experiments

the ANY-Light-Particle-Search

Light shining through walls



Resonant regeneration in the receiving cavity



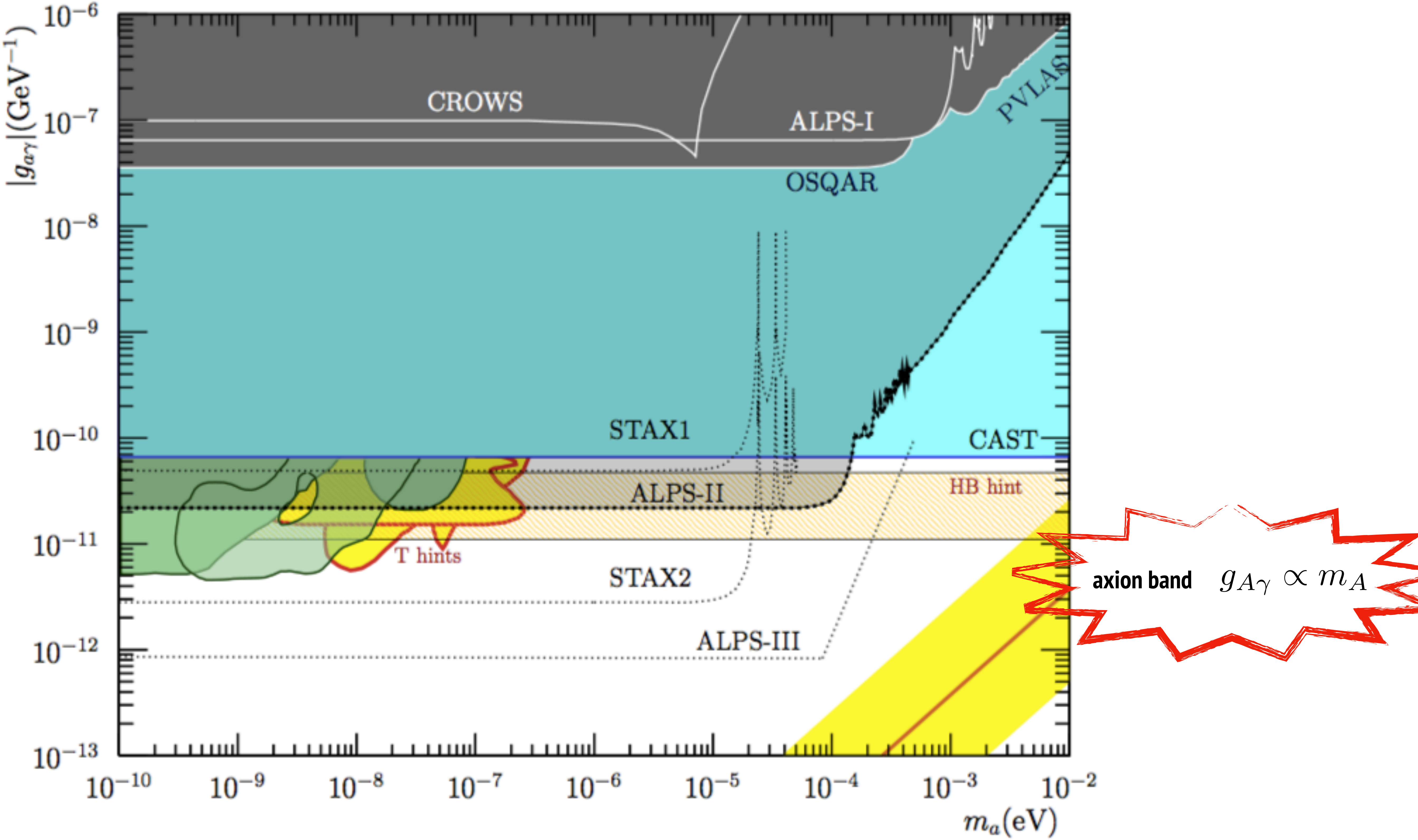
(d) ALPS-IIc

Exp.	Photon flux (1/s)	Photon E (eV)	B (T)	L (m)	B·L (Tm)	PB reg.cav.	Sens. (rel.)
ALPS I	$3.5 \cdot 10^{21}$	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

Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}$[GeV^{-1}]
ALPS-I [427]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [429]	completed	3	0.15	50	10^4	10^4	9.9×10^{-8}(*)
OSQAR [428]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [430]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [431]	concept	13	426	200	12500	10^5	10^{-12}
STAX1 [432]	concept	15	0.5	10^5	10^4	-	5×10^{-11}
STAX2 [432]	concept	15	0.5	10^6	10^4	10^4	3×10^{-12}

STAX, ALPS III and beyond

ALPS with optical lasers, STAX with Microwave cavities ... not so good for QCD...

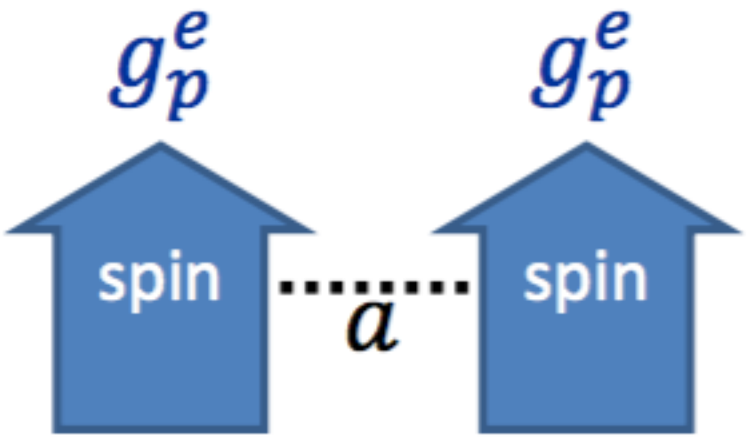


Long-range forces

Wilzcek '84, Geraci 14

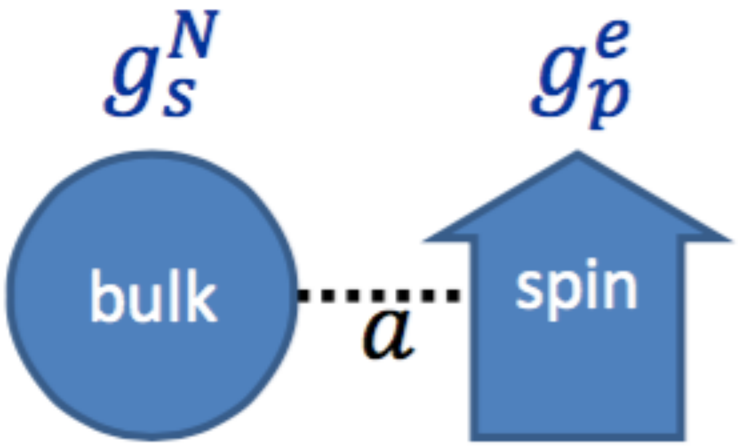
Long-range forces between macroscopic bodies

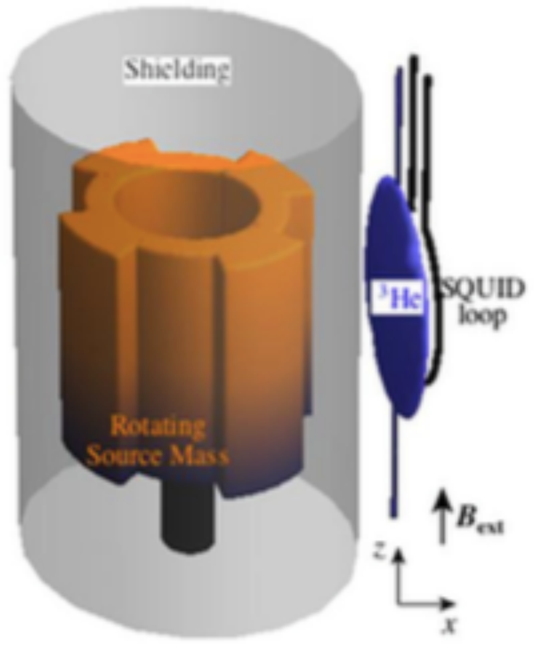
p-p forces are spin-spin ... very hard to measure!



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

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

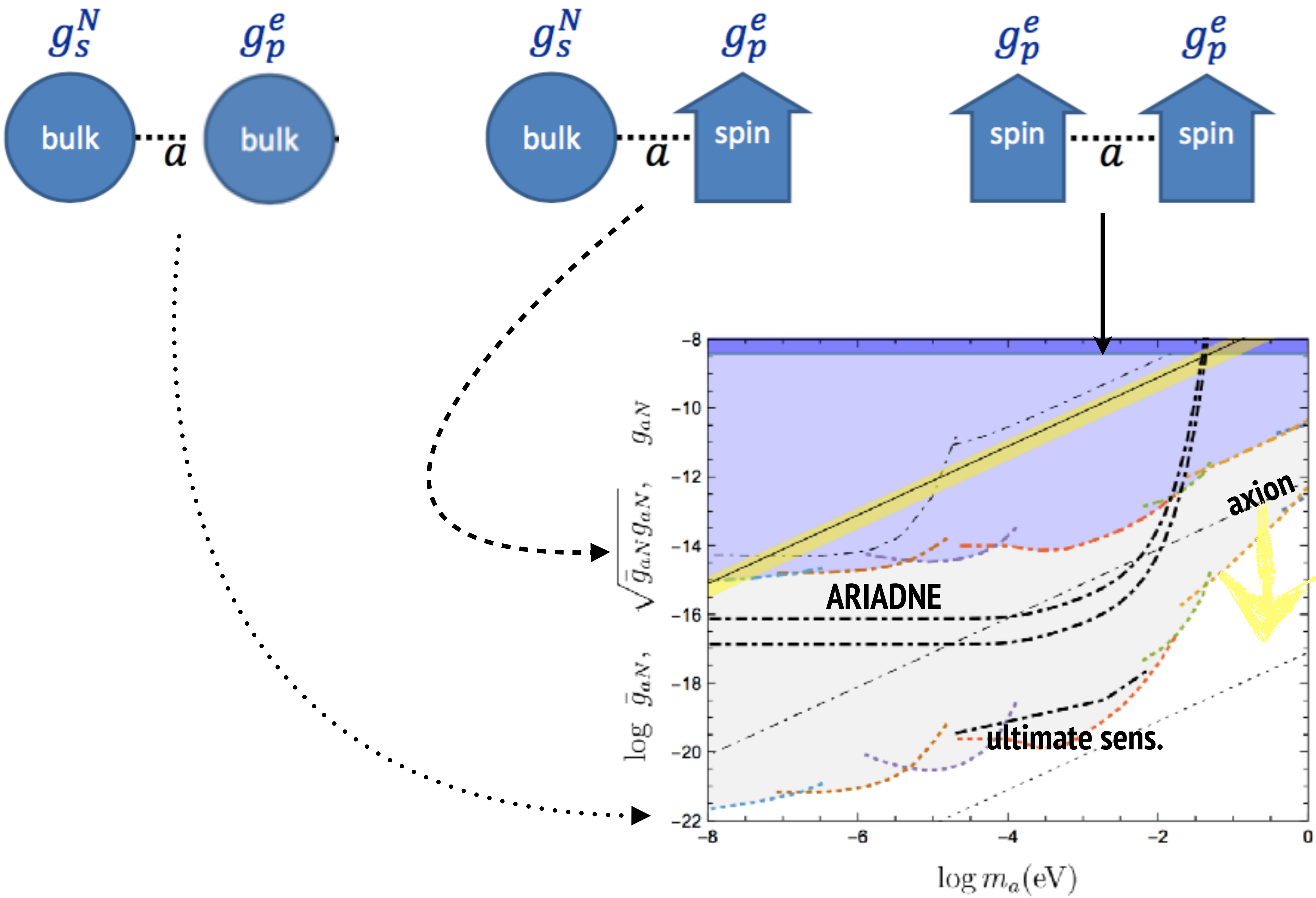




ARIADNE, University of Nevada in Reno

ARIADNE reach

Arvanitaki, Geraci 14



Flavoured axions

- Axions related to flavour/family symmetries induce Flavour violating decays

$$\Gamma(K^+ \to \pi^+ a) \simeq \frac{m_K}{64\pi} g^2_{aff'}$$

$$BR(\pi^+ a) < 7.3 \times 10^{-11} \quad (E787, E949)$$

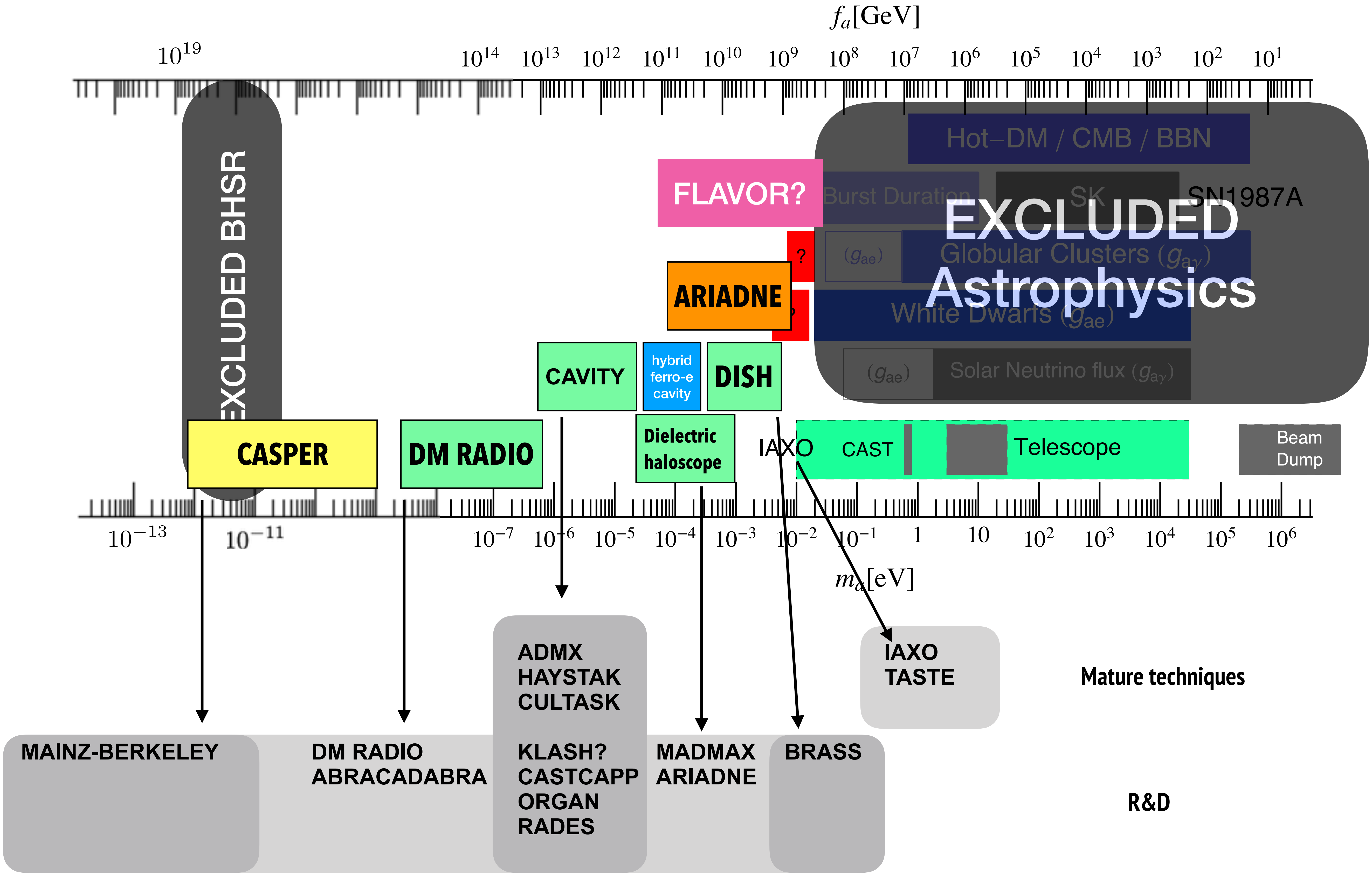
(NA62, ORKA, KOTO improvement by ~ 70 on BR)

$$f_a \gtrsim \frac{\kappa_{sd}}{N} \times 7.5 \cdot 10^{10}\,\mathrm{GeV}\,,$$

model dependent coefficient

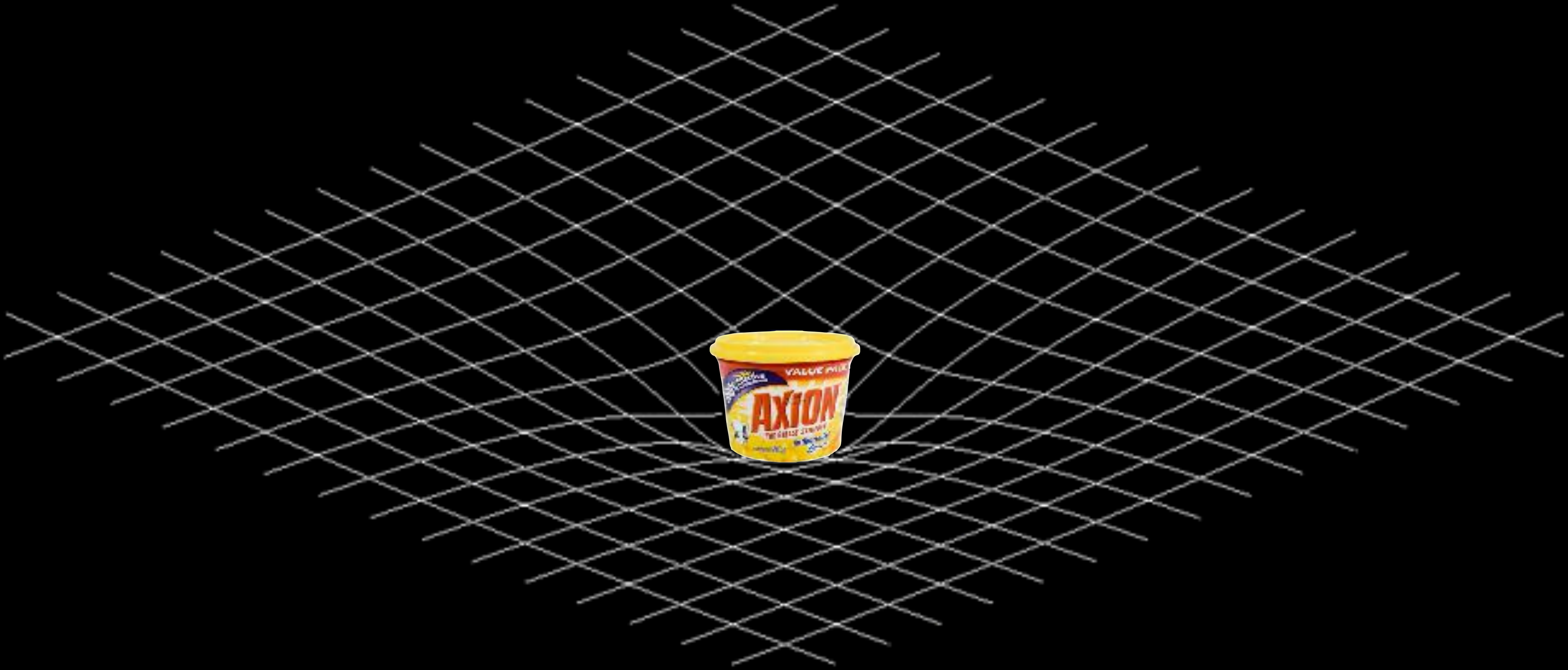
$$BR(B^+ \to K^+ a) < 10^{-8} \sim 10^{-6} \quad (Belle2?)$$

1 - Experiments



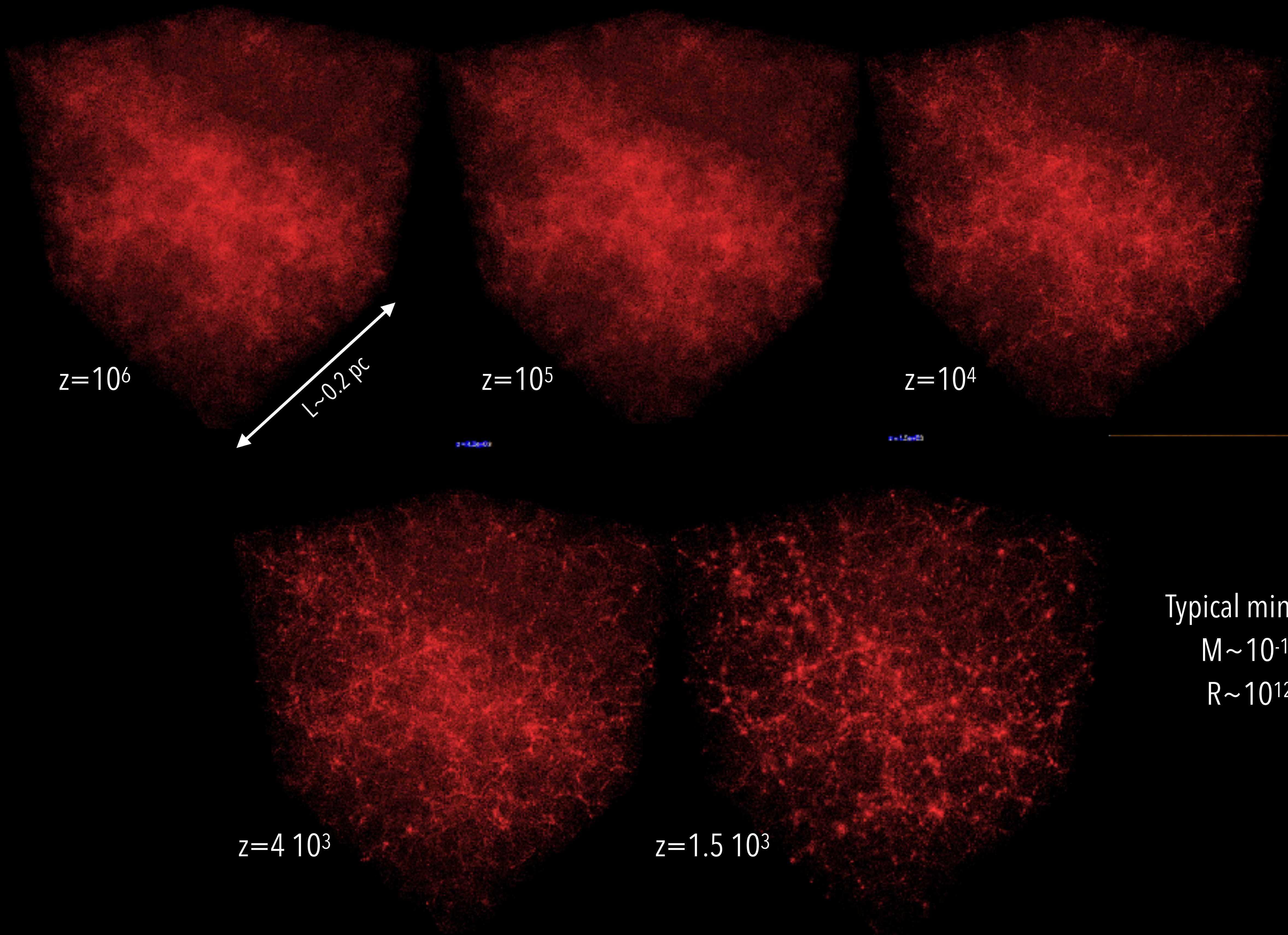
Pure gravitational phenomenology

Axion DM is different



Scenario B: miniclusters

- Axion DM inhomogeneous at ~ pc scales -> first structures form at $z \gtrsim z_{eq} \sim 4000$

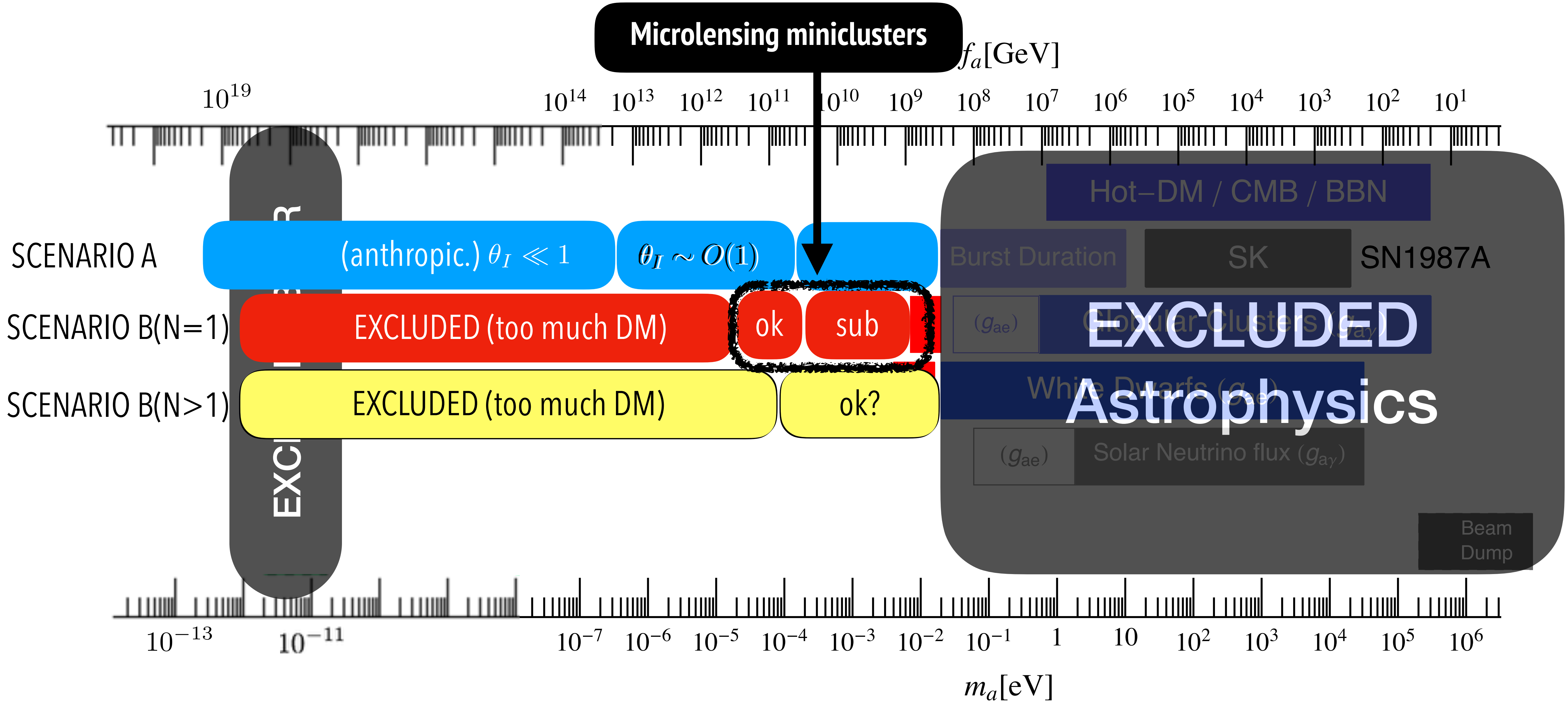


Typical minicluster

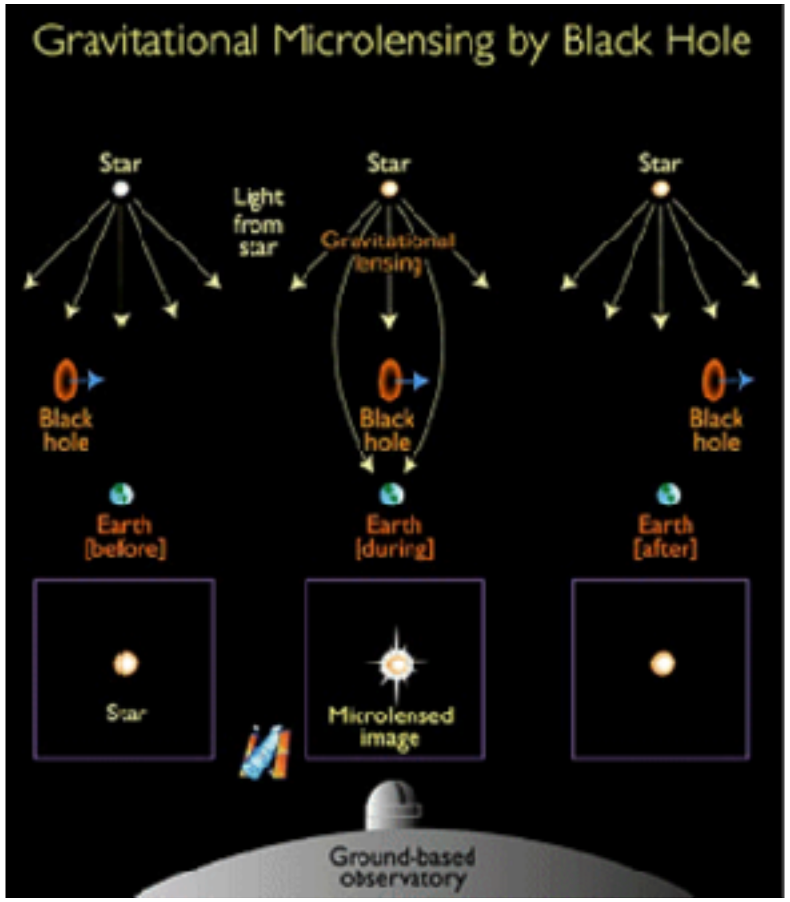
$M \sim 10^{-12}\ M_o$

$R \sim 10^{12}$ cm

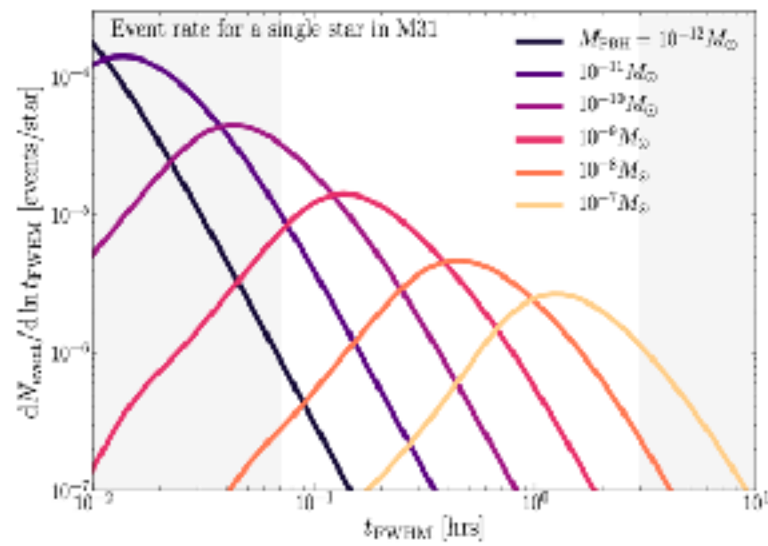
On the landscape

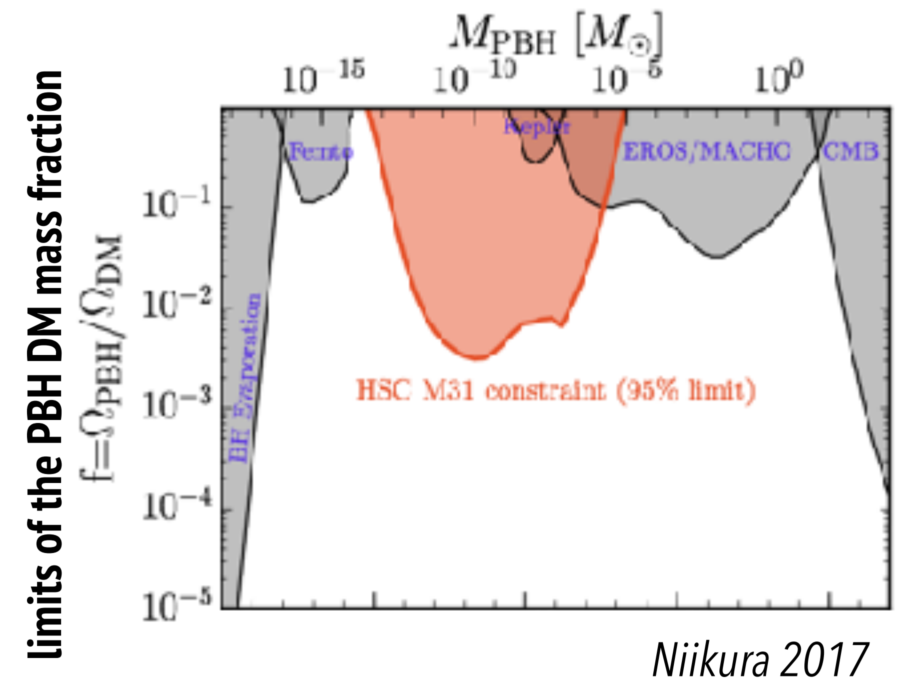


Microlensing



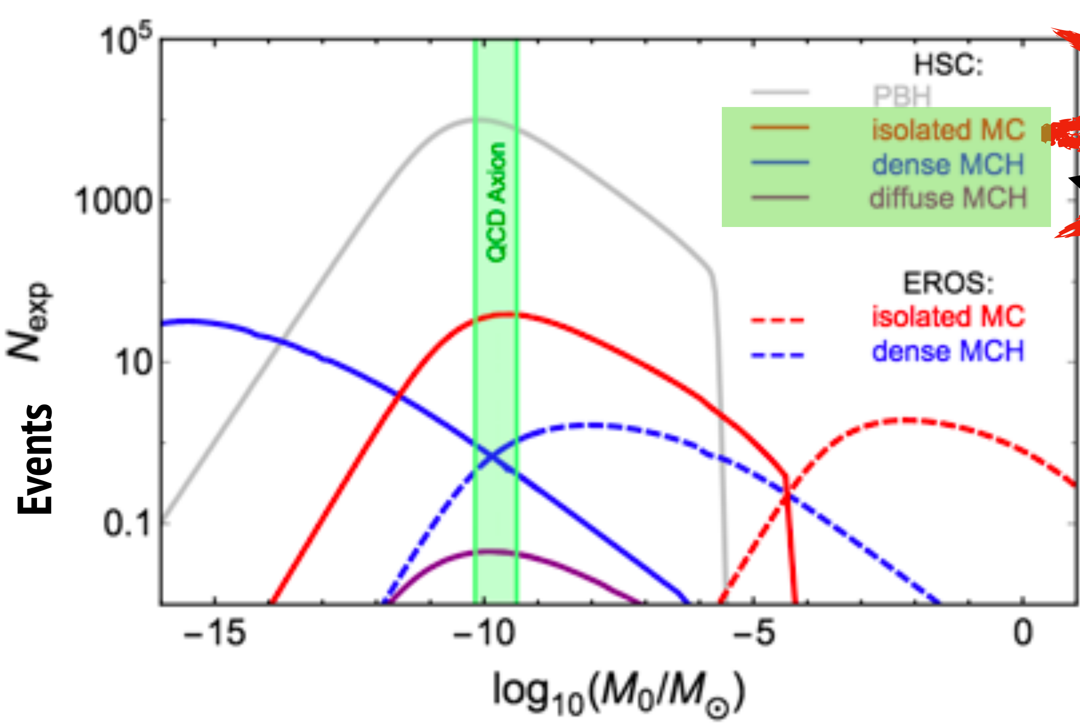
- Subaru HSC dedicated search of Primordial Planck hole events along M31
- 10^7 stars, t~2 min sampling rate

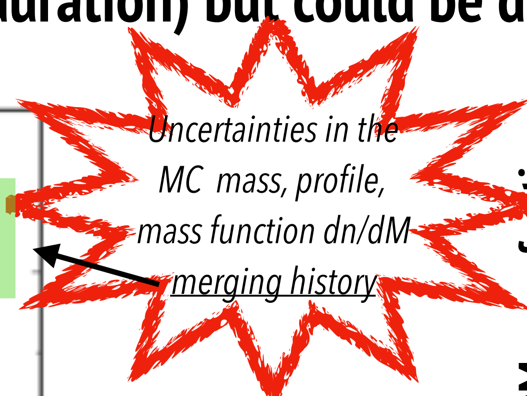


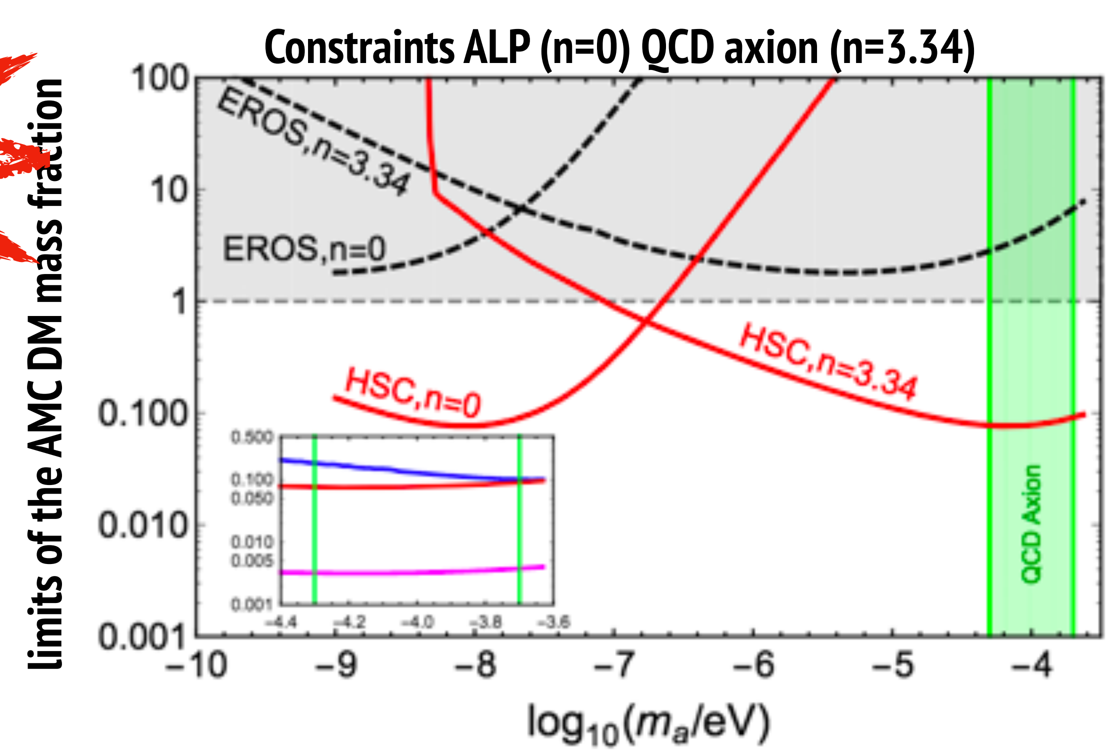


Niikura 2017

- Axion MCs are fluffy (less signal, more duration) but could be detected! *Marsh, Fairbairn , Quevillon 2017*

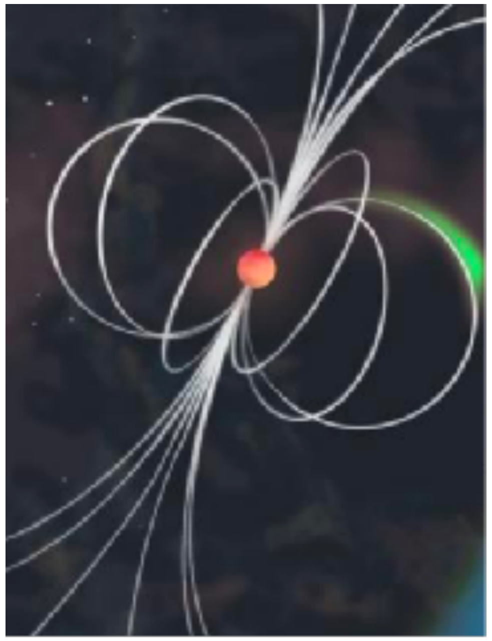






Axion photon conversion ...

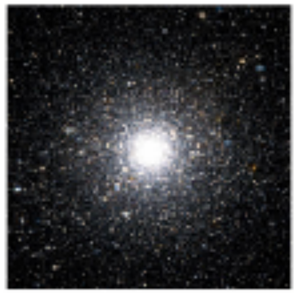
Radio signals from DM axions falling into neutron stars



RX J0806.4-4123

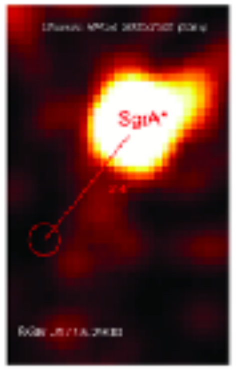
- Isolated
- Nearby (250 pc)
- Radio-quiet
- Non-pulsed

Hypothetical NS's in M54

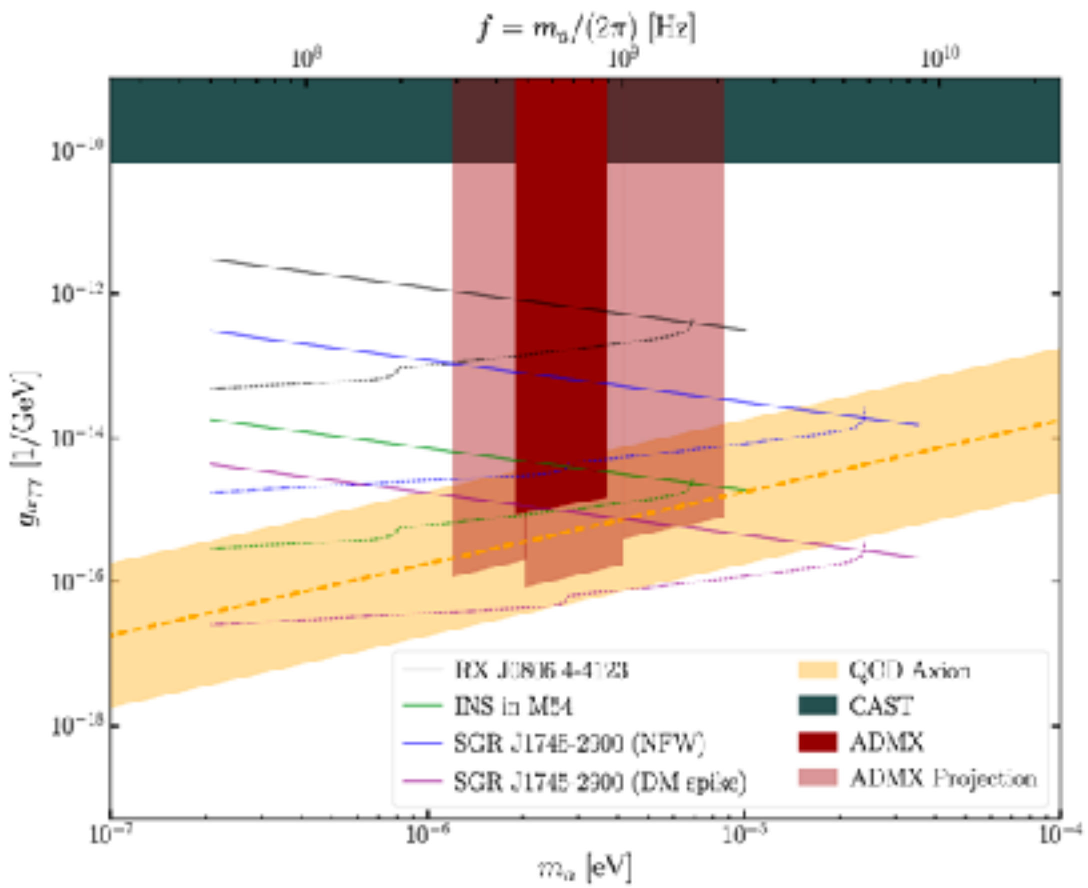


- 21 kpc away, but…
- High DM density
- Lots of NS emissions within angular res.

SJR J1745-2900

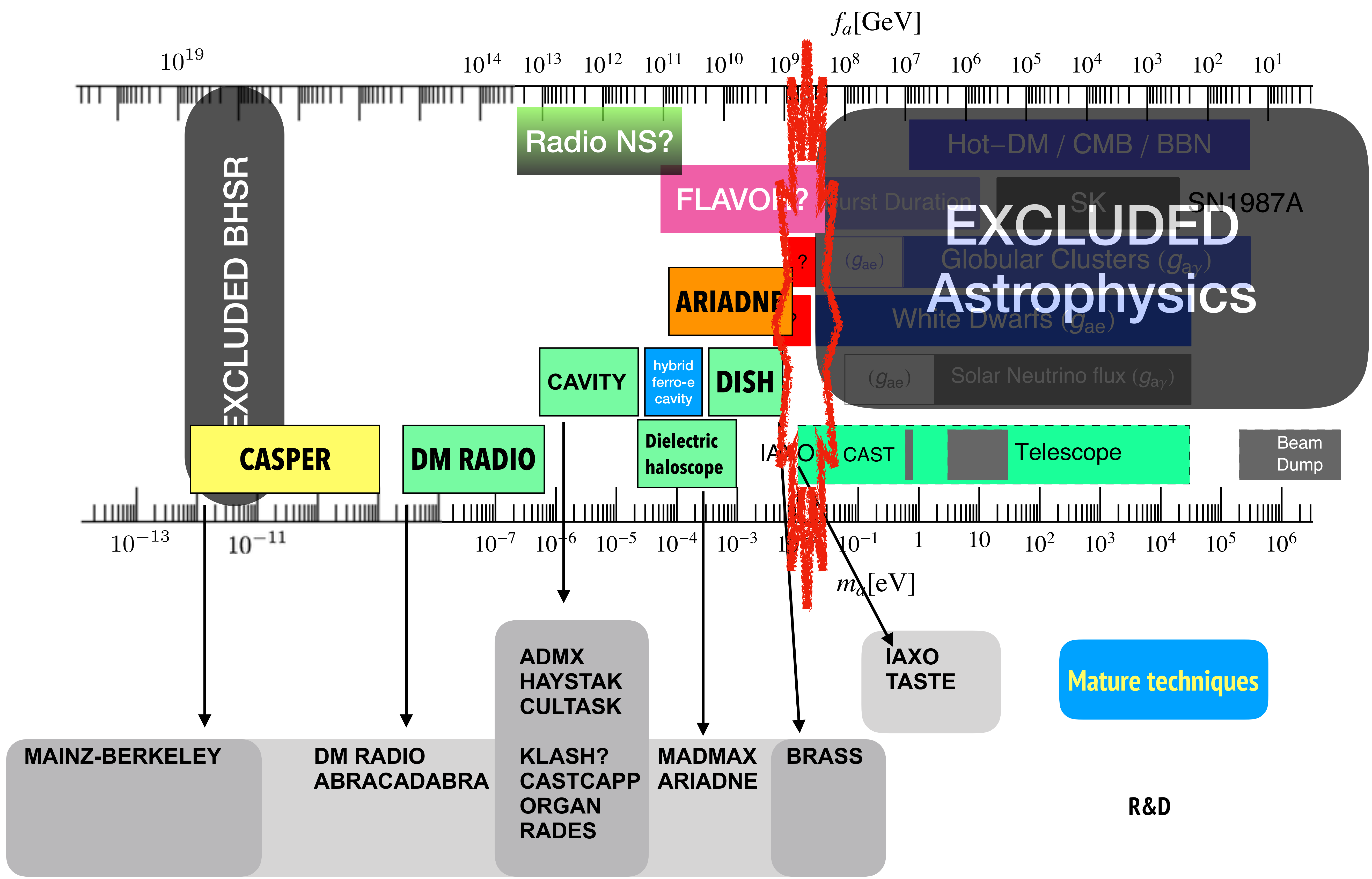


- Magnetar! $B_0 \approx 10^{10}$ T
- 0.1 pc from GC
- Potentially enormous DM density



Hook 2018

A sort of landscape



Conclusions

- Axions might be hinted by the tiny EDM of hadrons (strong CP problem!)

- Some axion dark matter is unavoidable
- Laboratory tests:
  - Direct DM experiments: cavities in the GHz (microeV)
  - Solar axions with IAXO
  - Long range forces
  - Flavour
- Cosmological probes
  - Microlensing, decay
- New experimental techniques, loads of R&D