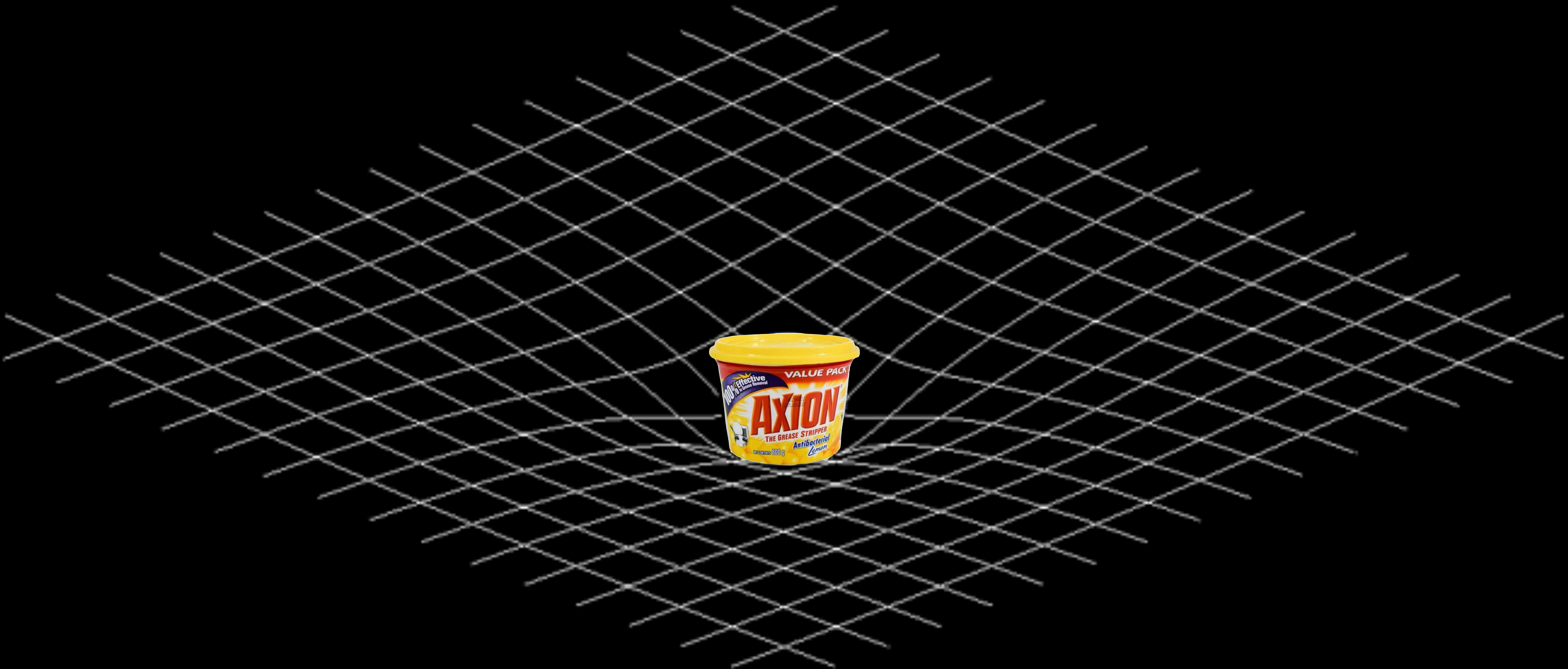
Axions,
another dark matter candidate

Javier Redondo

X CPAN days in Salamanca 30/10/2018

outline

Axion DM is different



Axions

- **Motivated by the strong CP problem,** $\mathcal{L}_{\rm SM} \in -\frac{\alpha_s}{8\pi}{\rm tr}\{G_{a\mu\nu}\widetilde{G}^{\mu\nu}_a\}\theta$ **why are nuclear EDMs sooo small?**

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f_a → **new energy scale (decay constant)**

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If Cag is non-zero, you ALP is the QCD axion $\frac{a(x)}{f_a} \equiv \theta(x)$

Shift-symmetry breaking corrections can generate a small mass + ...

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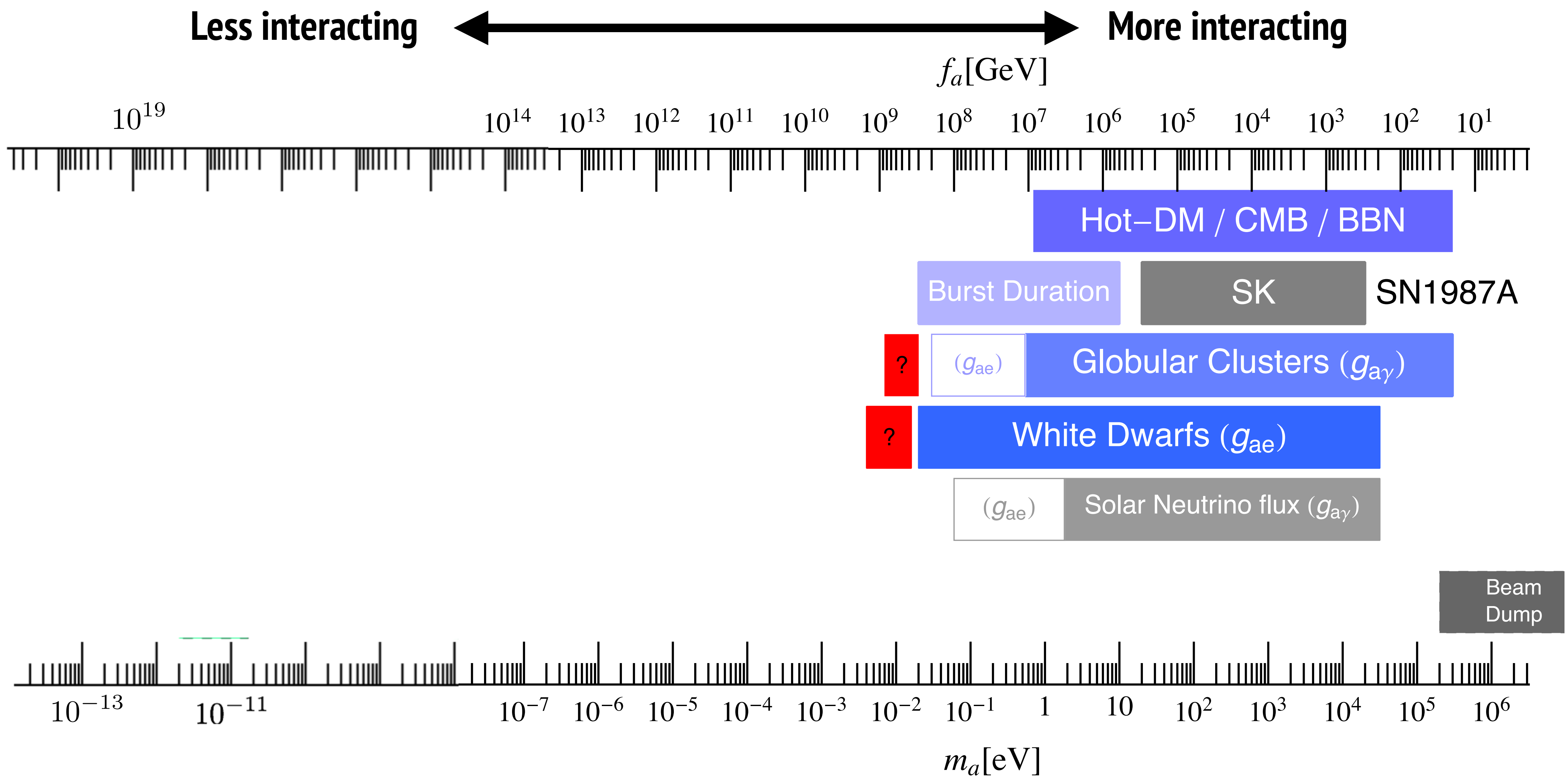
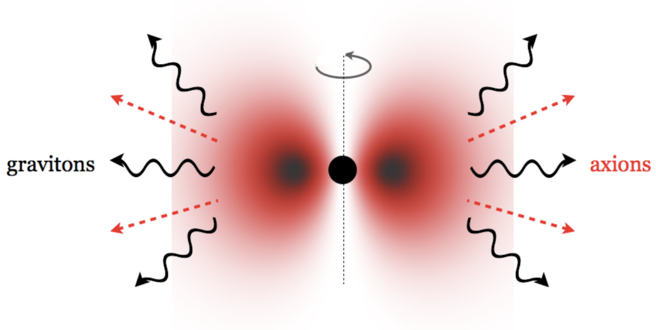
At low-energies $V_{\rm QCD}(\theta) \sim \chi(1-\cos\theta)$

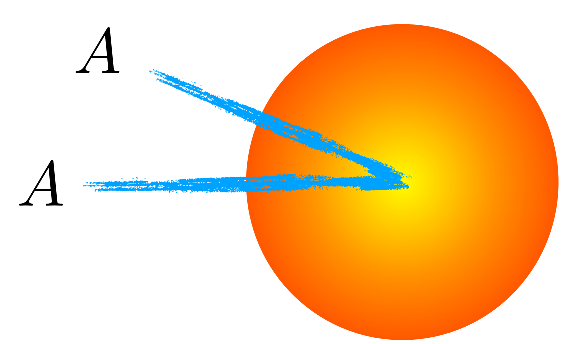
$$m_A = \frac{\sqrt{\chi}}{f_A} \sim 60\,\mu{\rm eV}\frac{10^{12}{\rm GeV}}{f_a}$$

what do we know about f_A ?

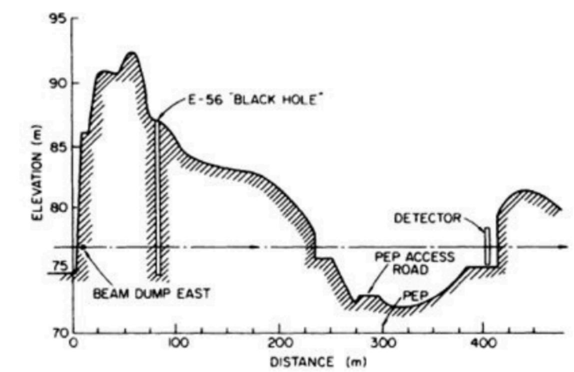




Black hole spin radiated



Stellar evolution accelerated*



beam dumps

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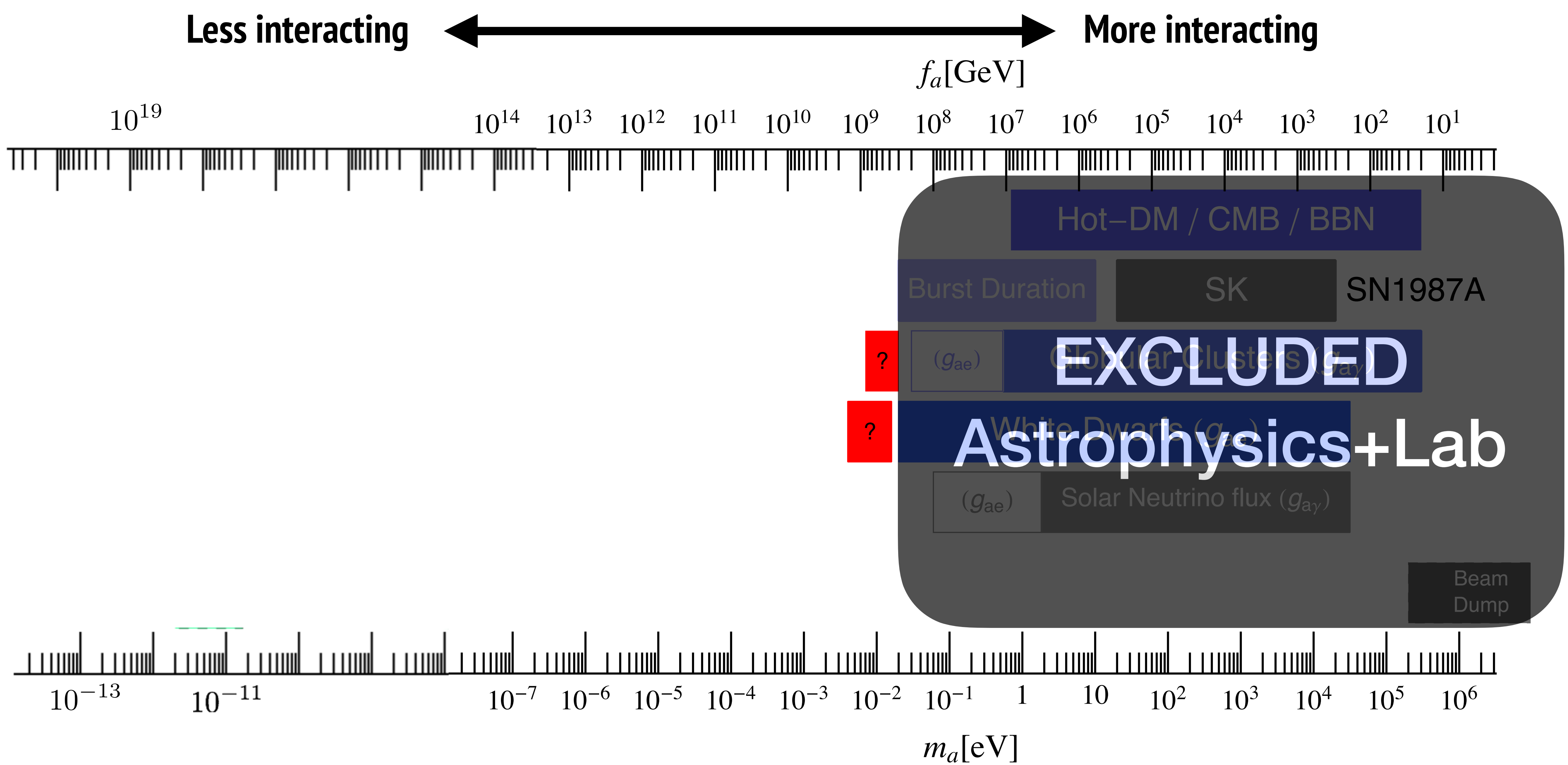

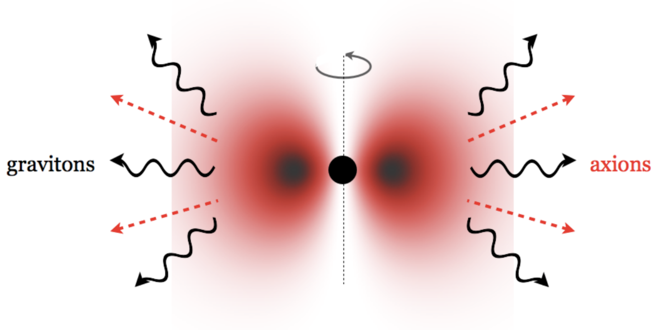

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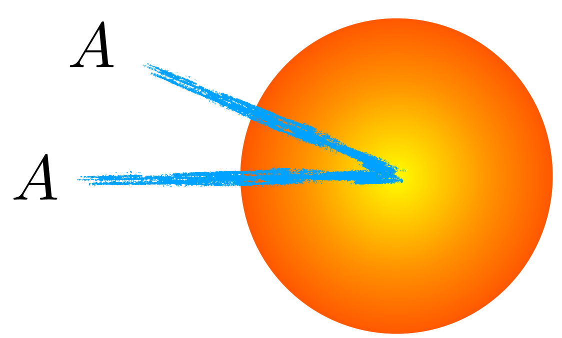

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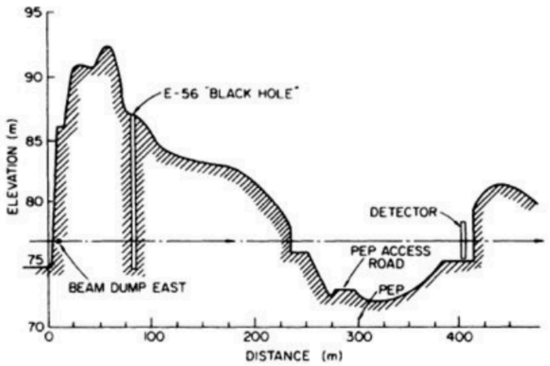

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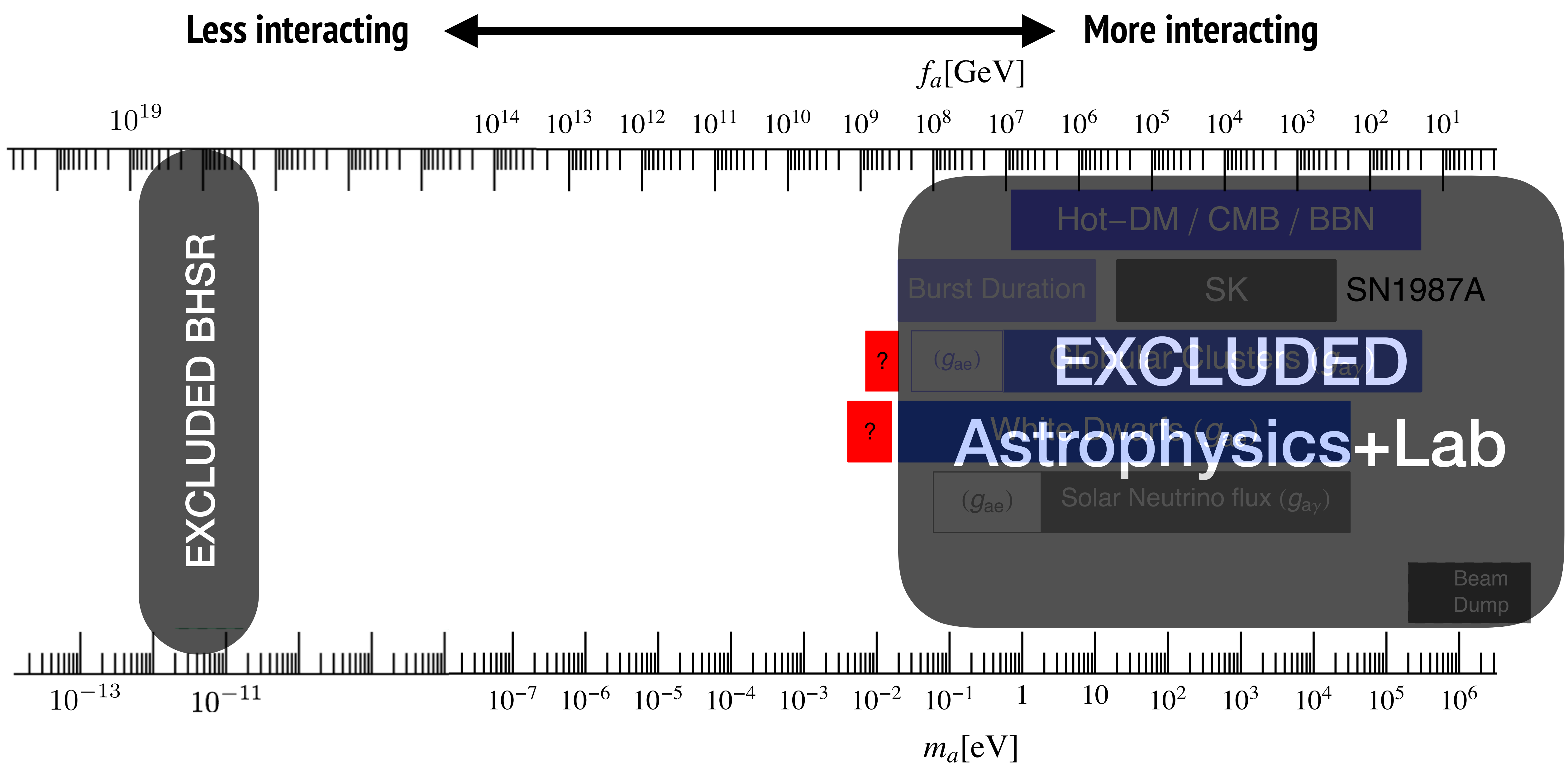

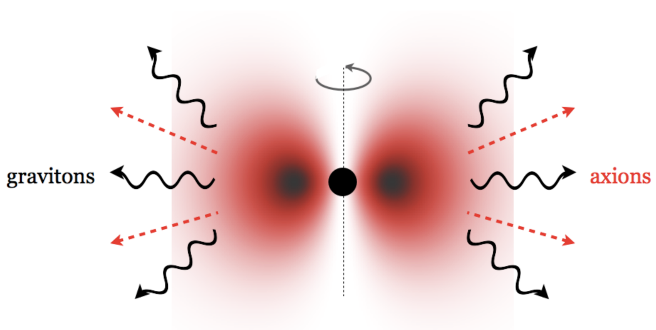

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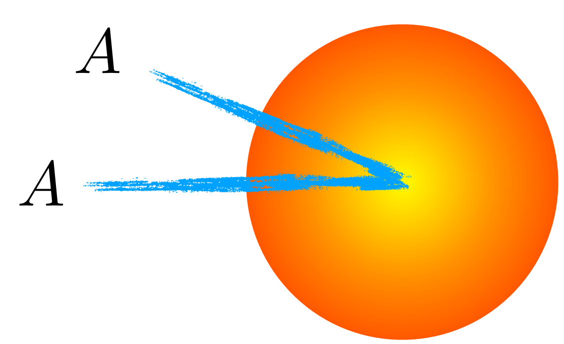

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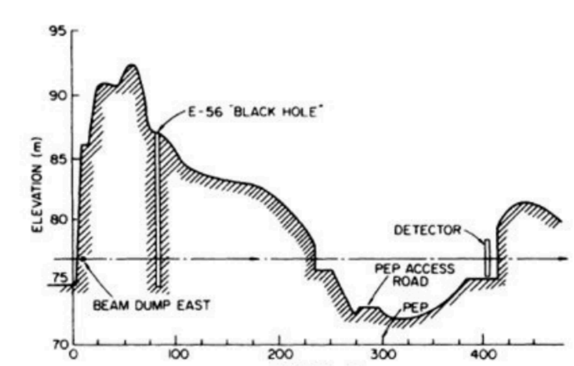

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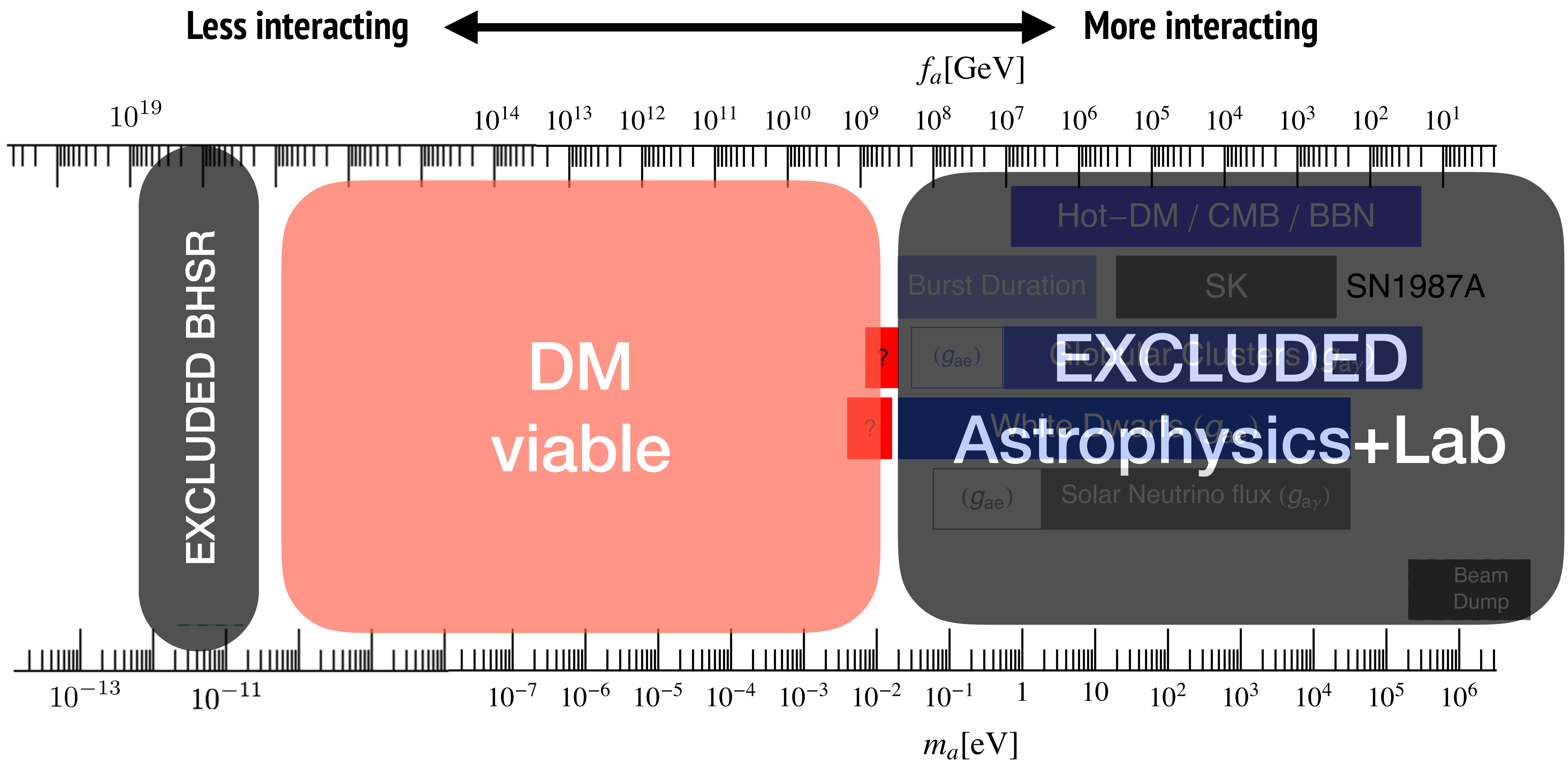

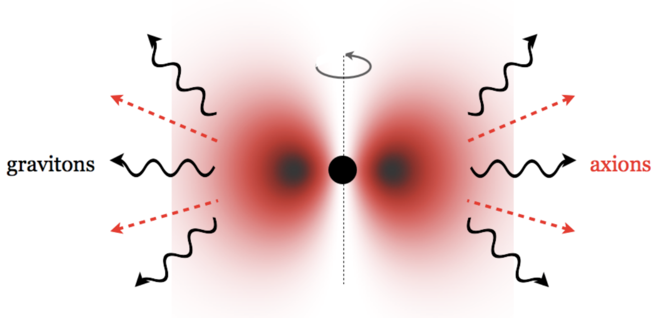

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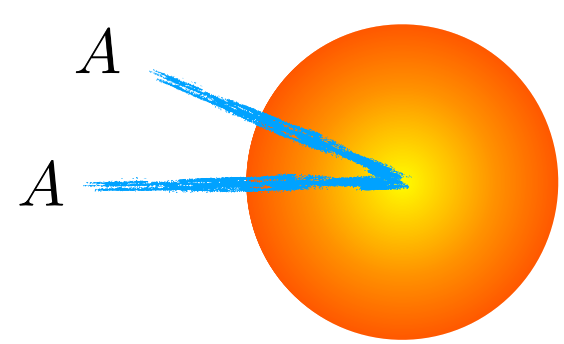

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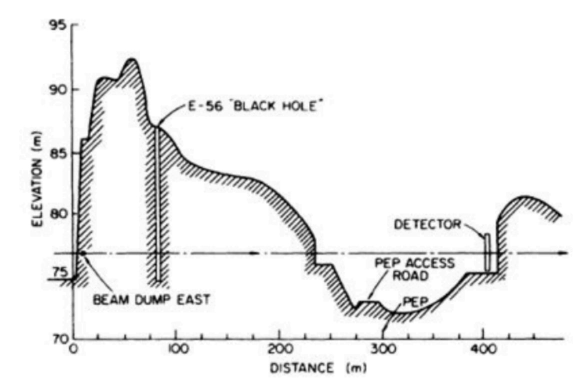
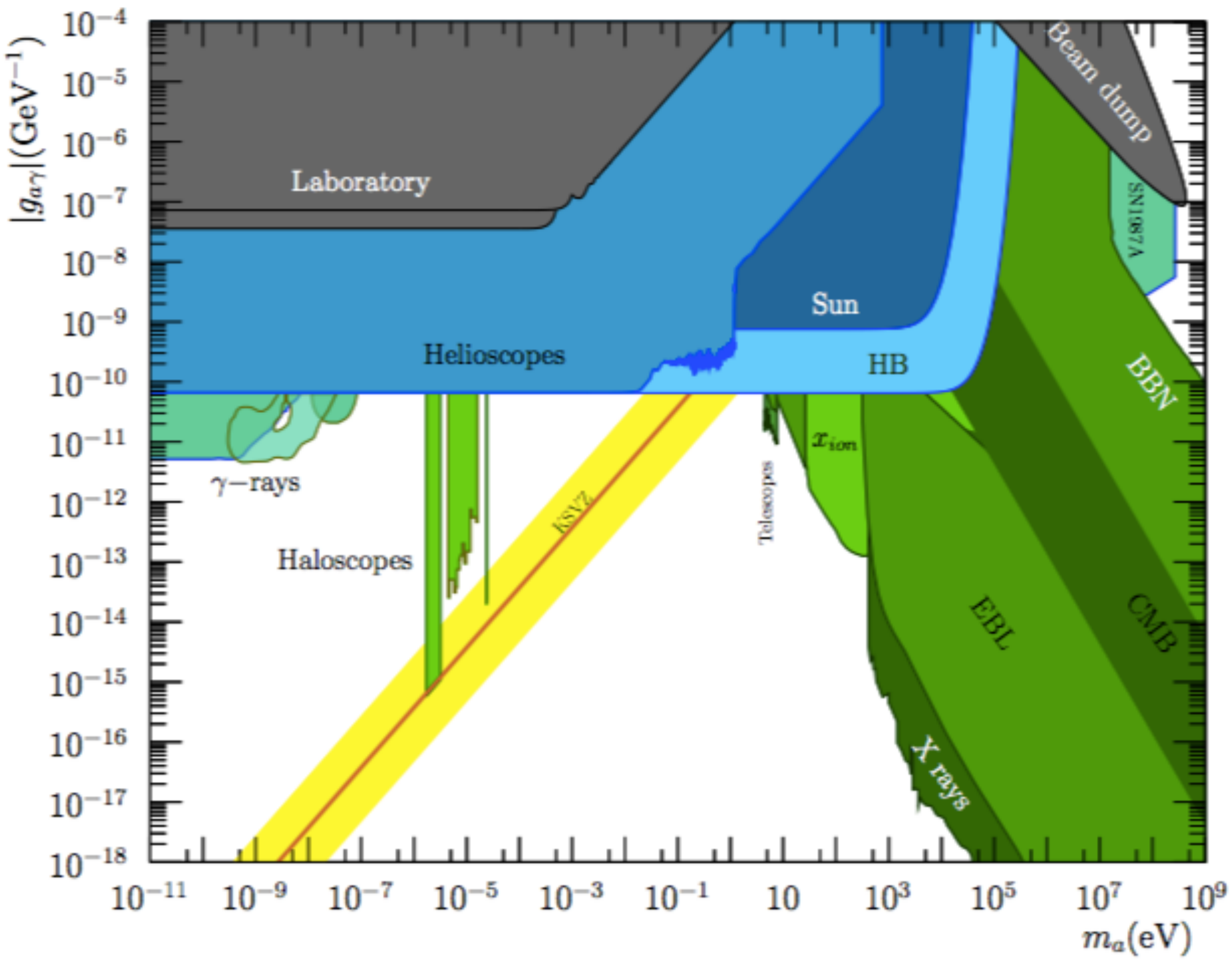
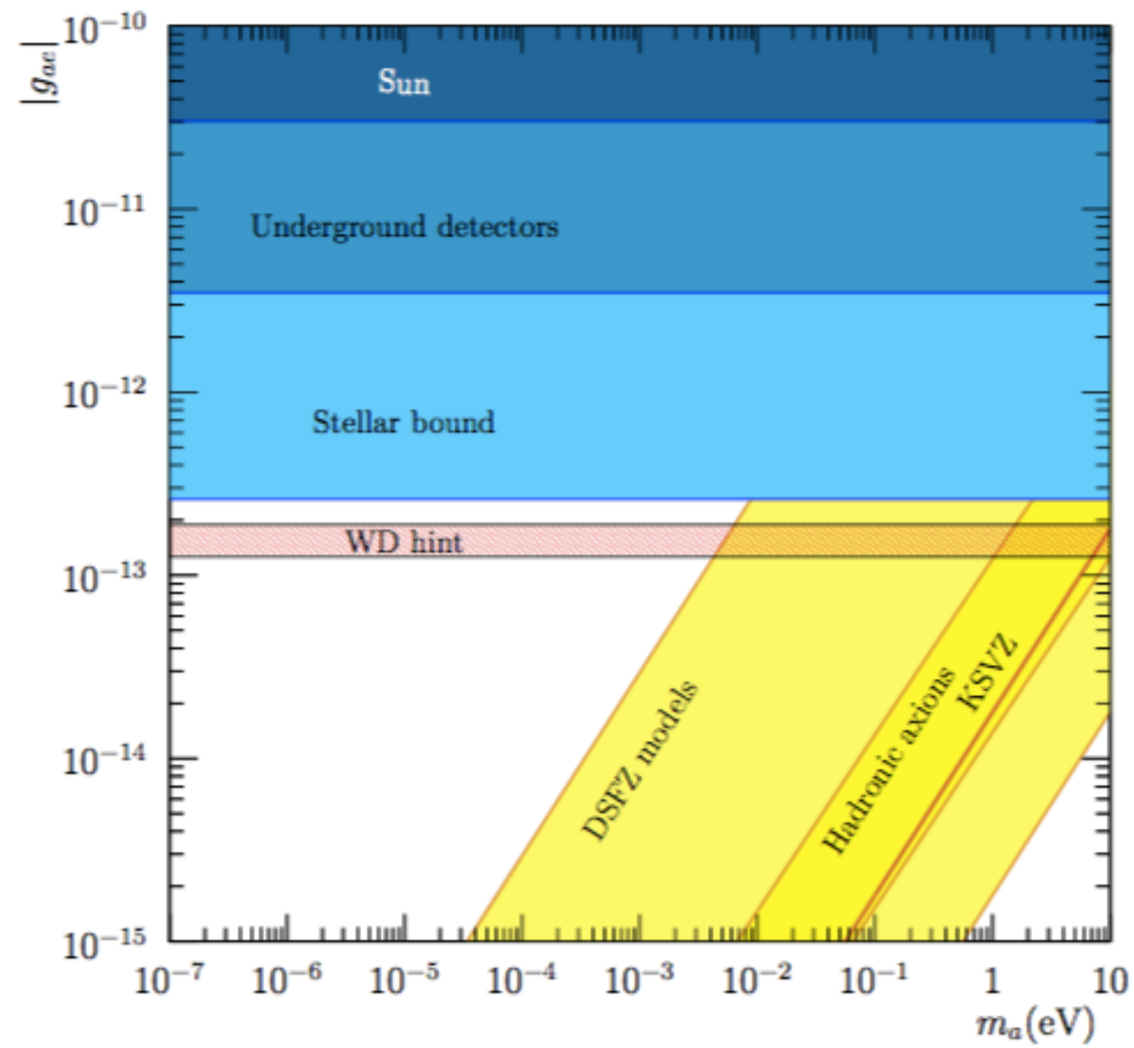


beam dumps

axion-like … broader parameter spaces

Irastorza 2018





photon coupling

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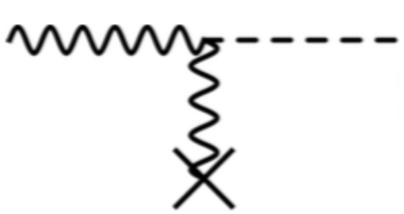

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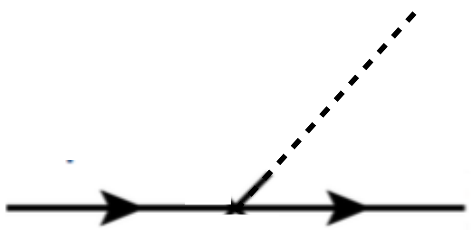

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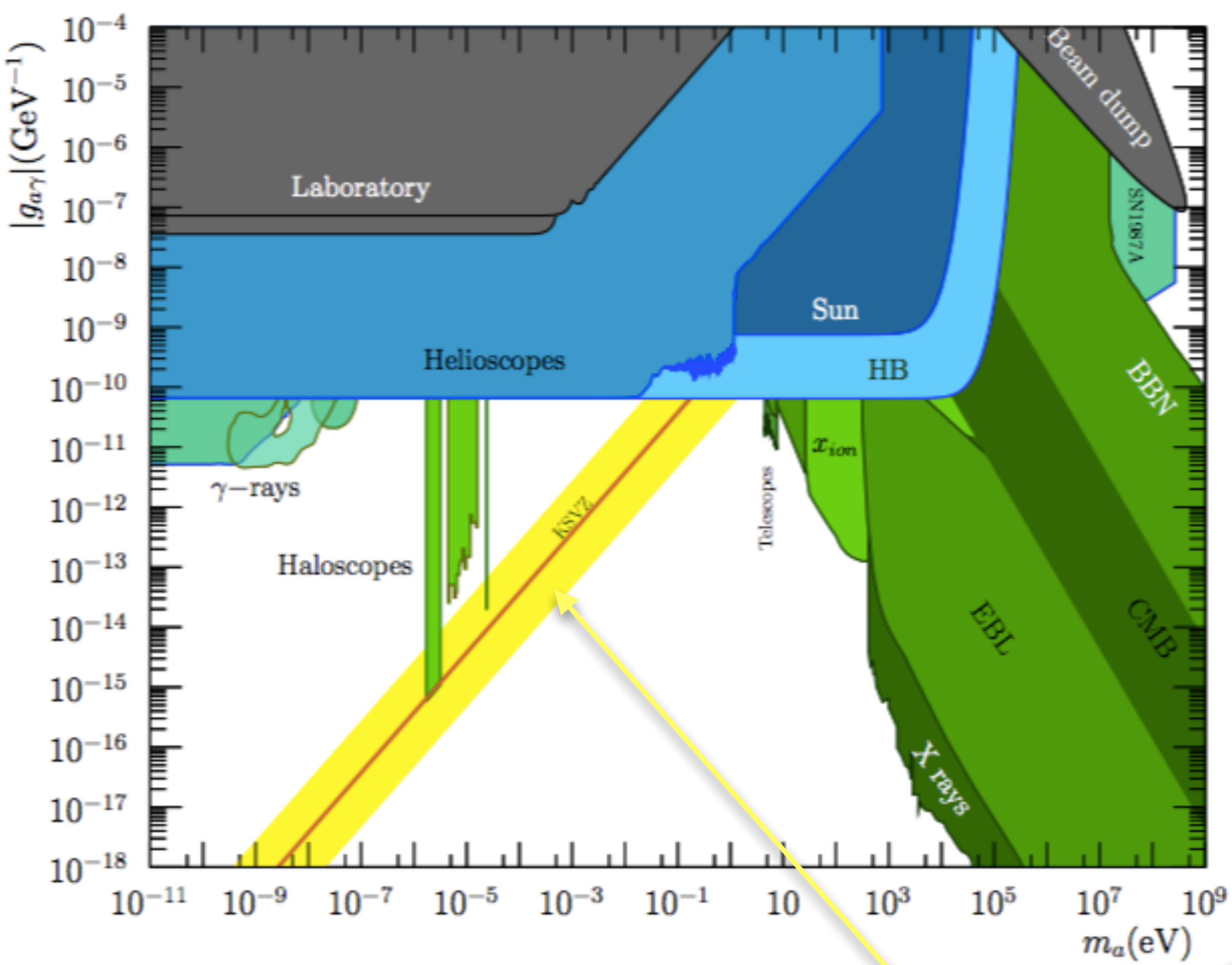

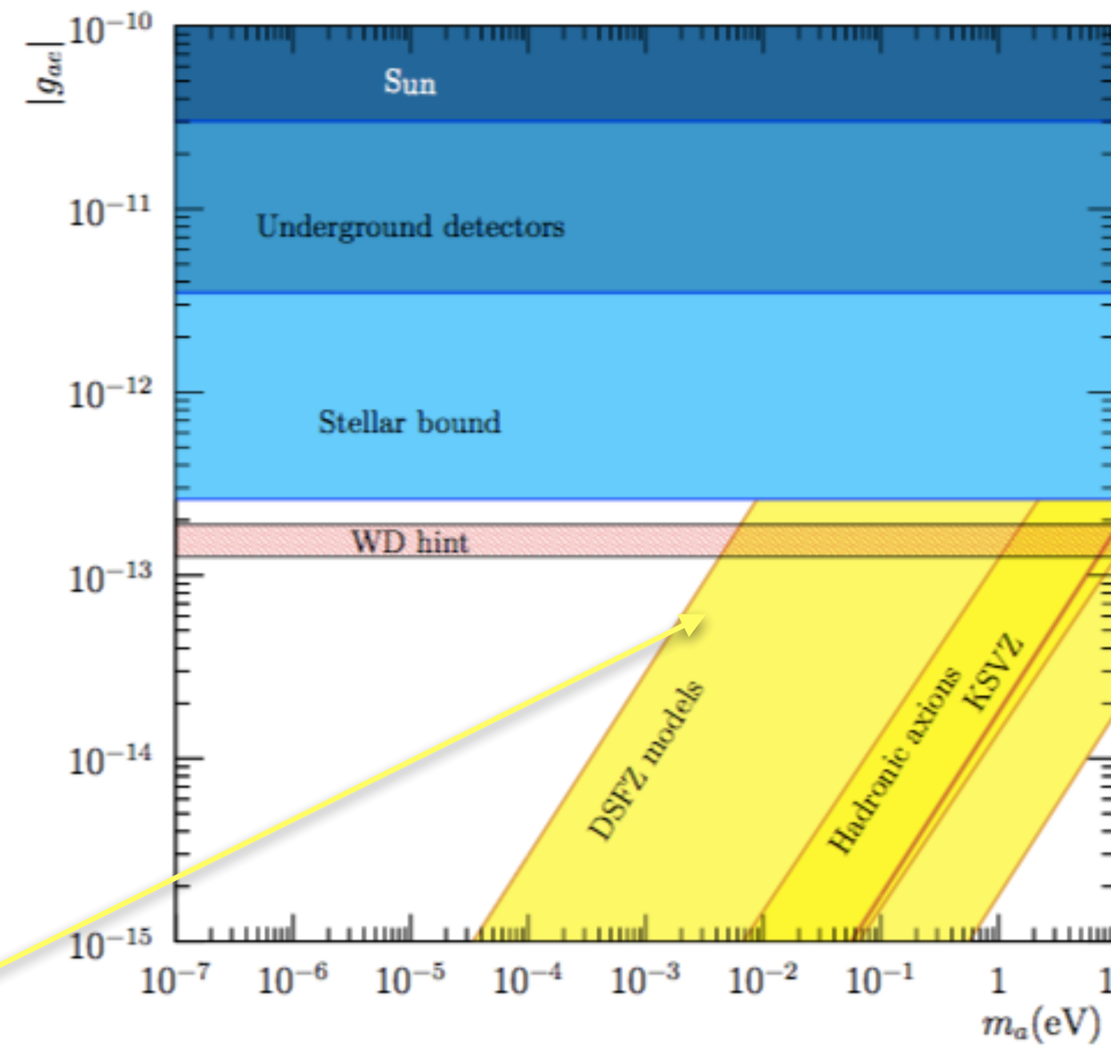

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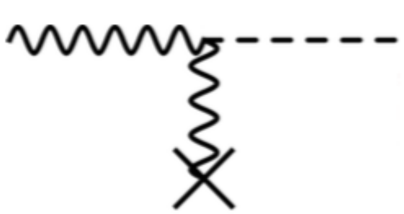

Your obliging QCD axions lie in ~ bands

$$g_{A\gamma}, g_{Ae} \propto \frac{C_{A\gamma}, C_{Ae}}{f_A} \quad m_A \propto \frac{\mathrm{QCD}}{f_A}$$

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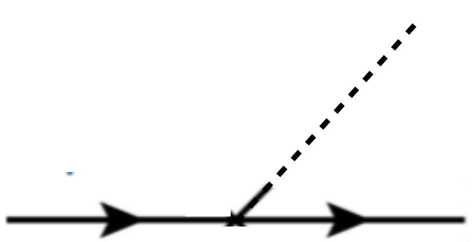

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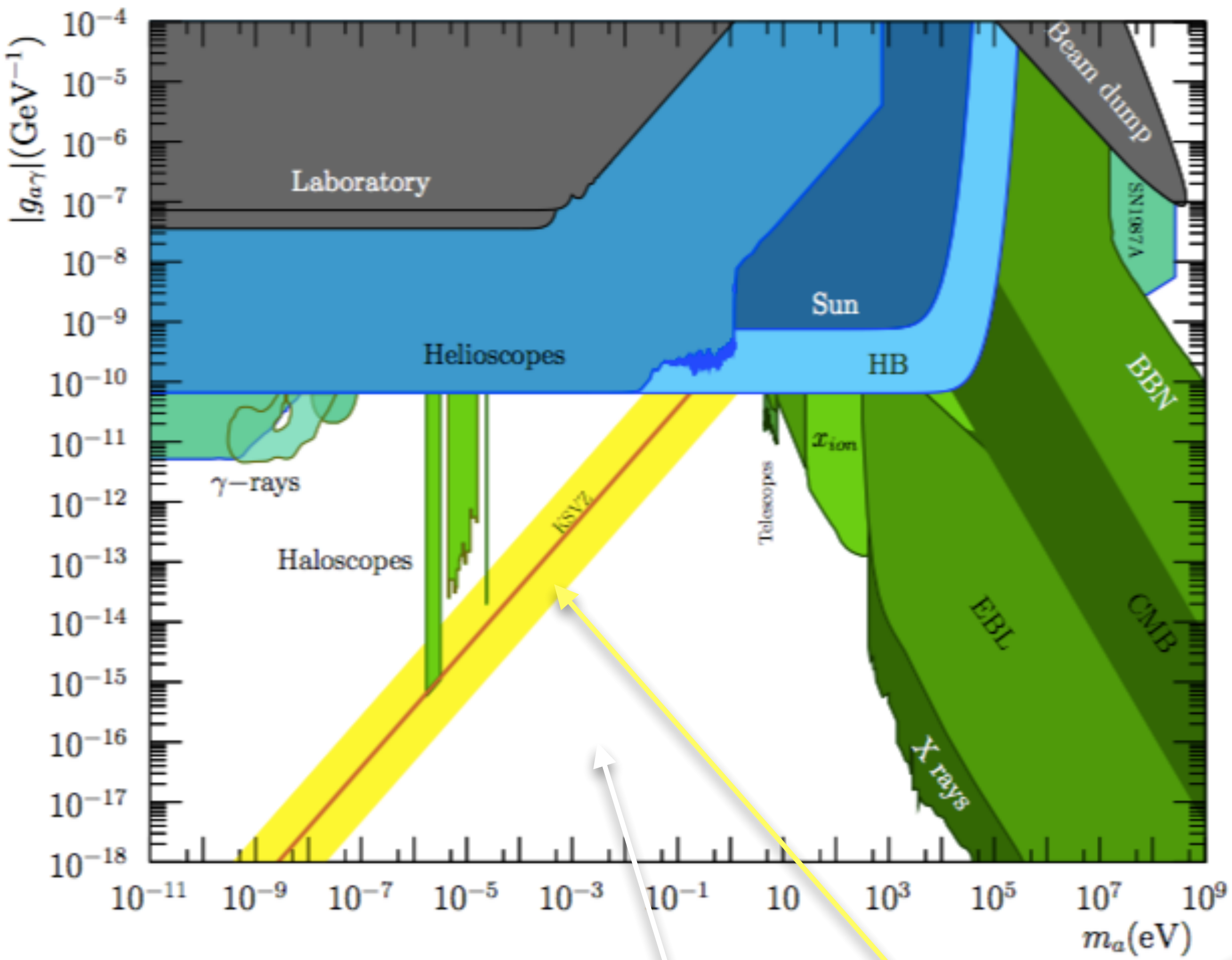

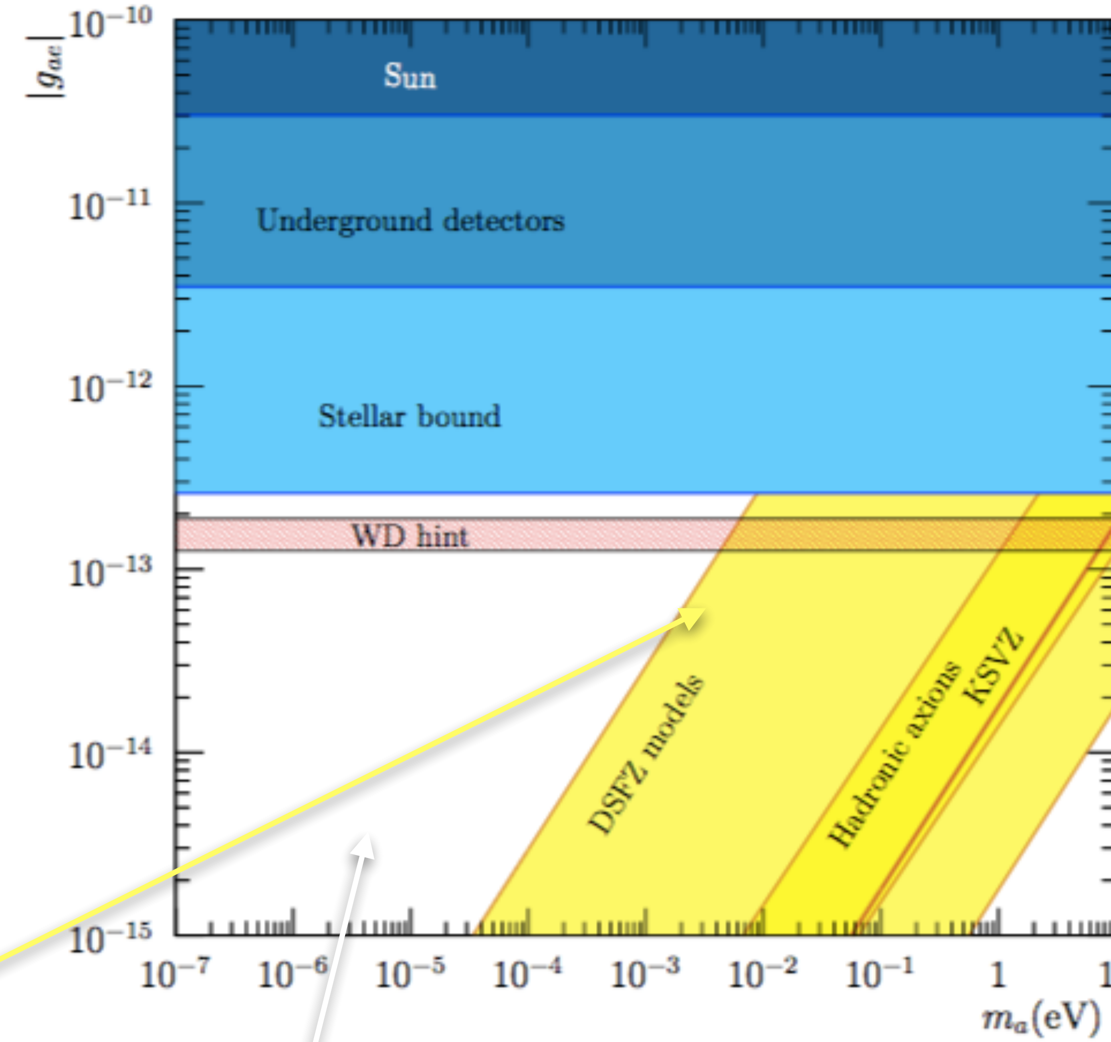

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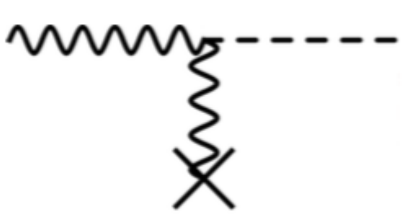

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Your maverick ALP model can be anywhere

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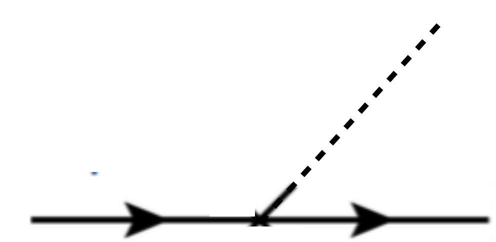
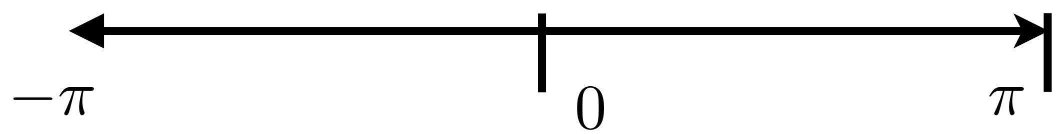


Axion dark matter in a nutshell

1: The axion field (A) is the dynamical version of the theta angle of QCD

We observe $\theta \simeq 0$



$$\theta = \frac{A}{f_A}$$

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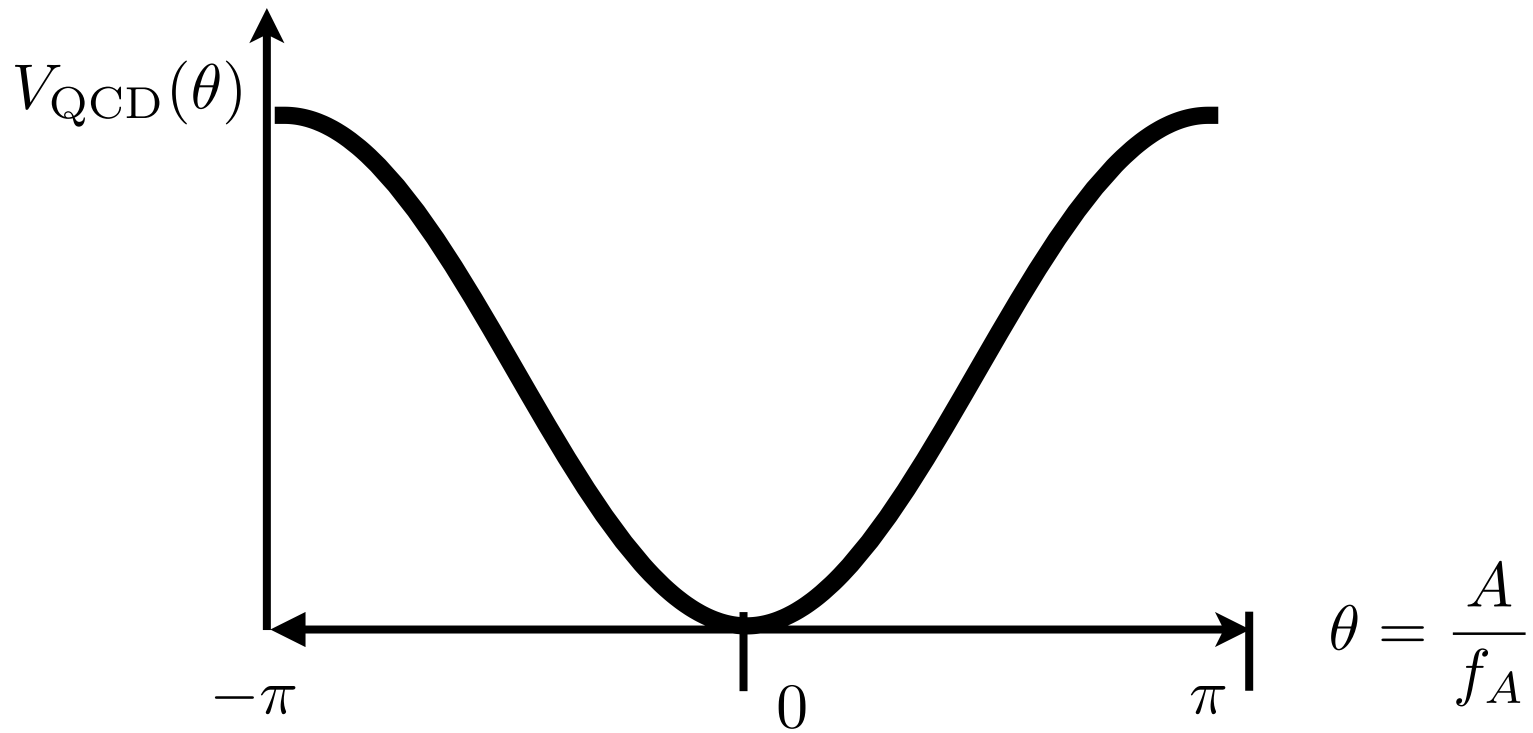

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and becomes dark matter (like inflaton)

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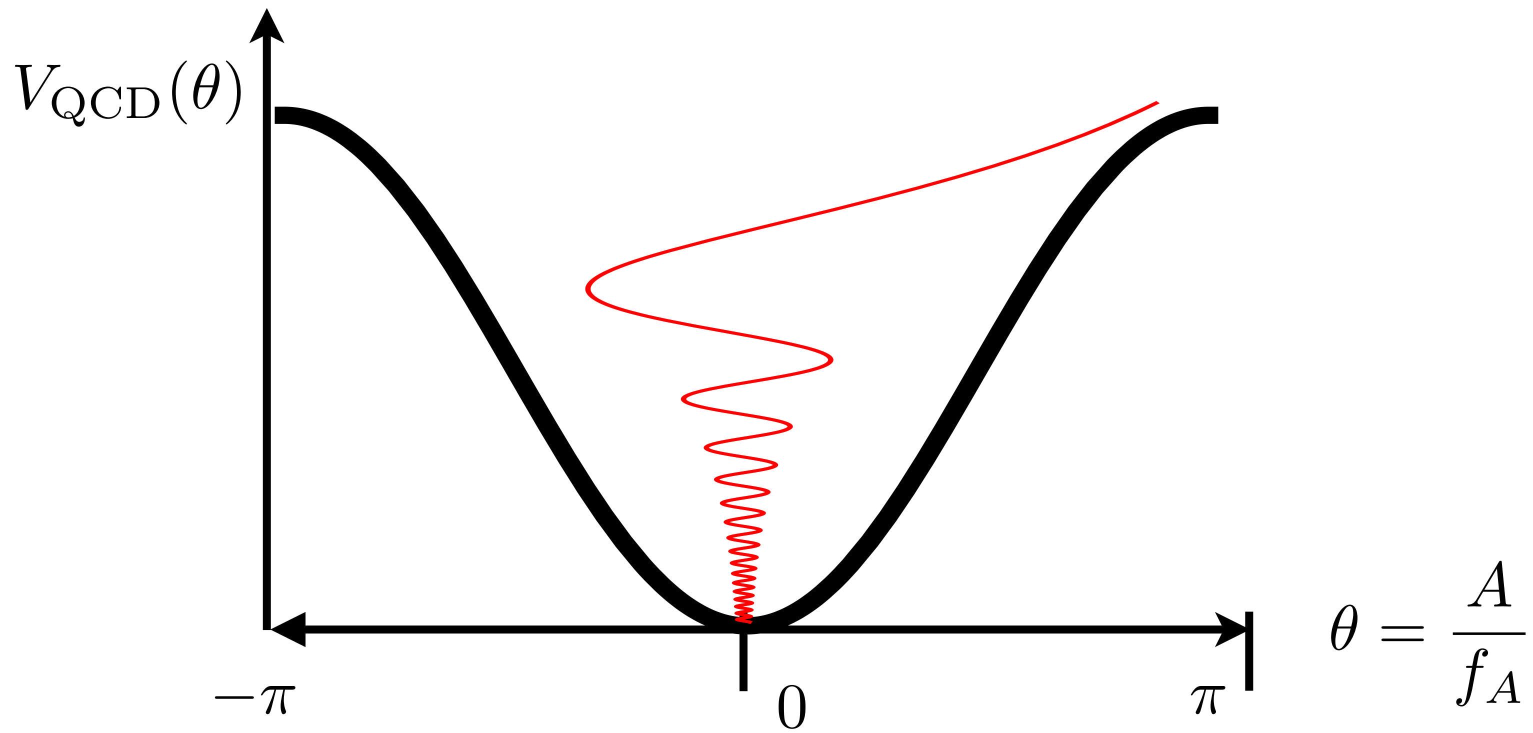

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- Axion mass
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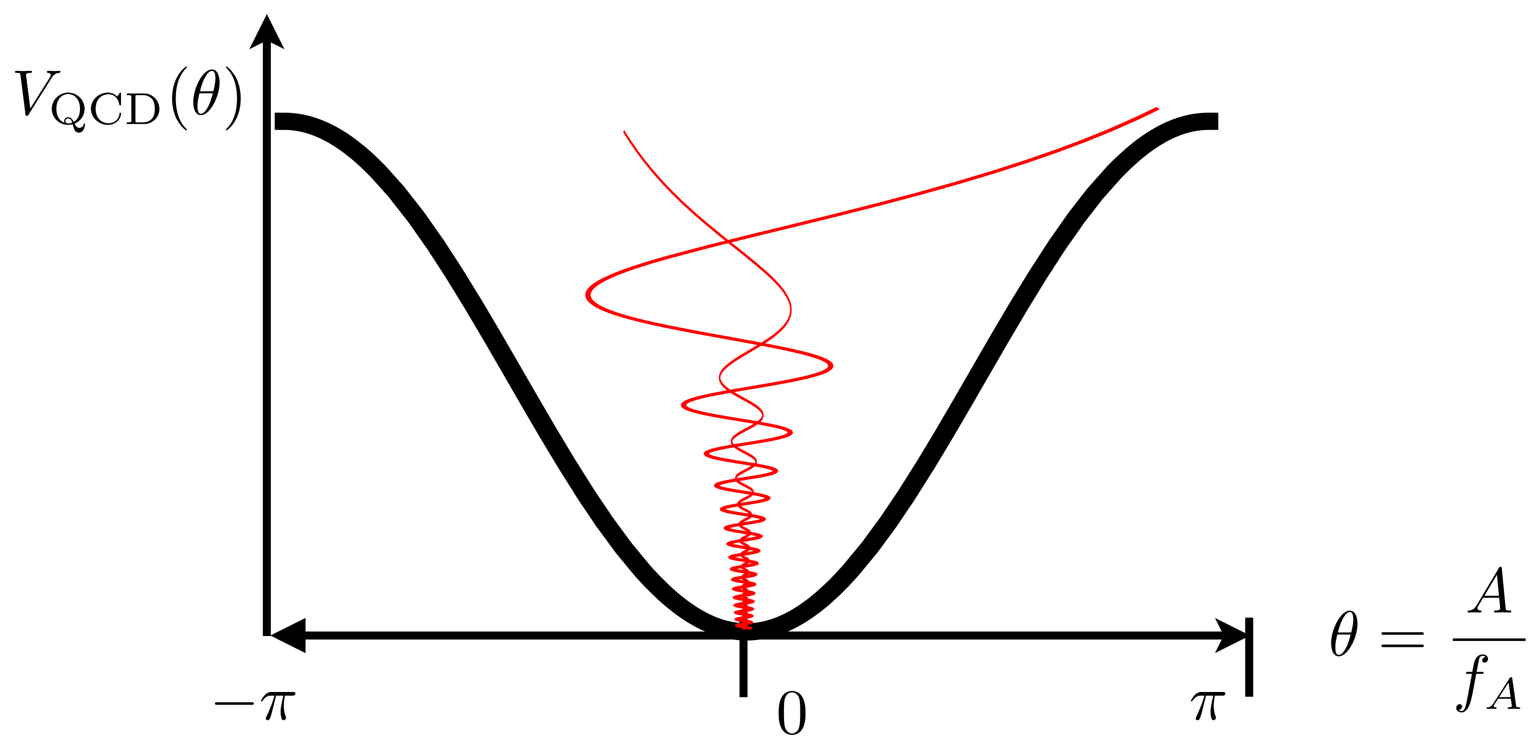

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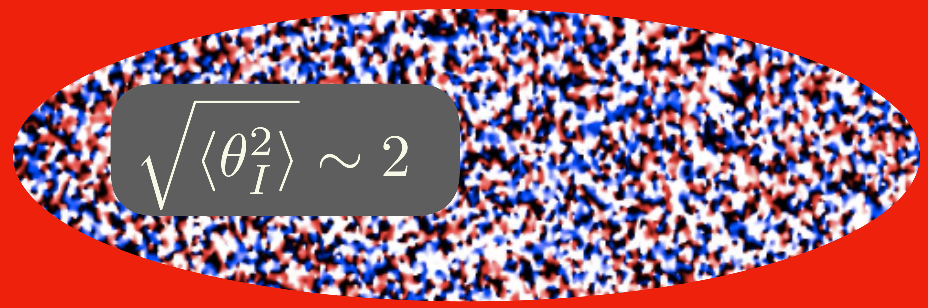

dark matter inhomogeneous at scales below ~ pc

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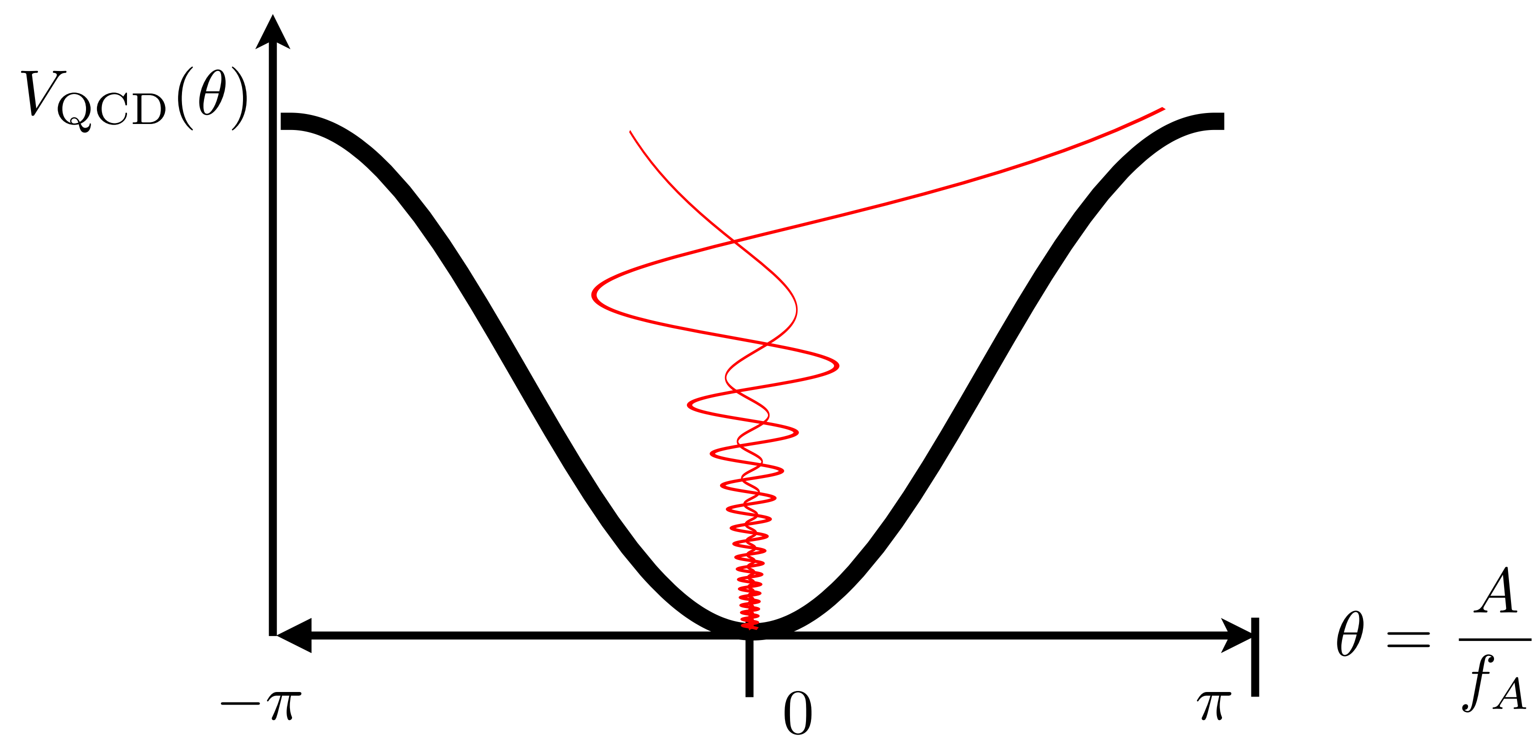

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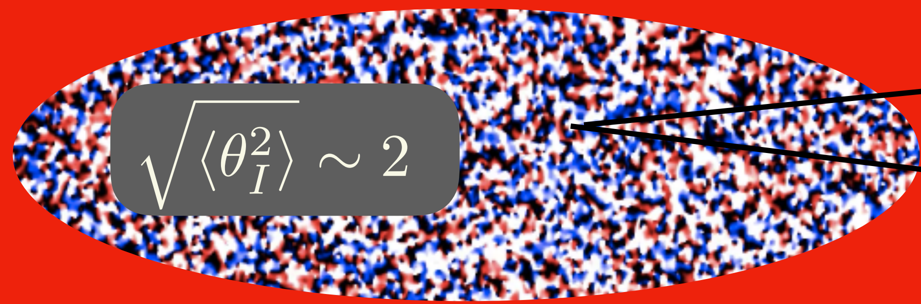

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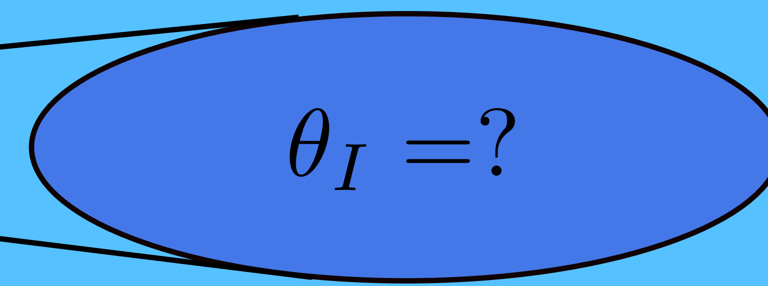
6: Scenario A : Inflation AFTER initial conditions



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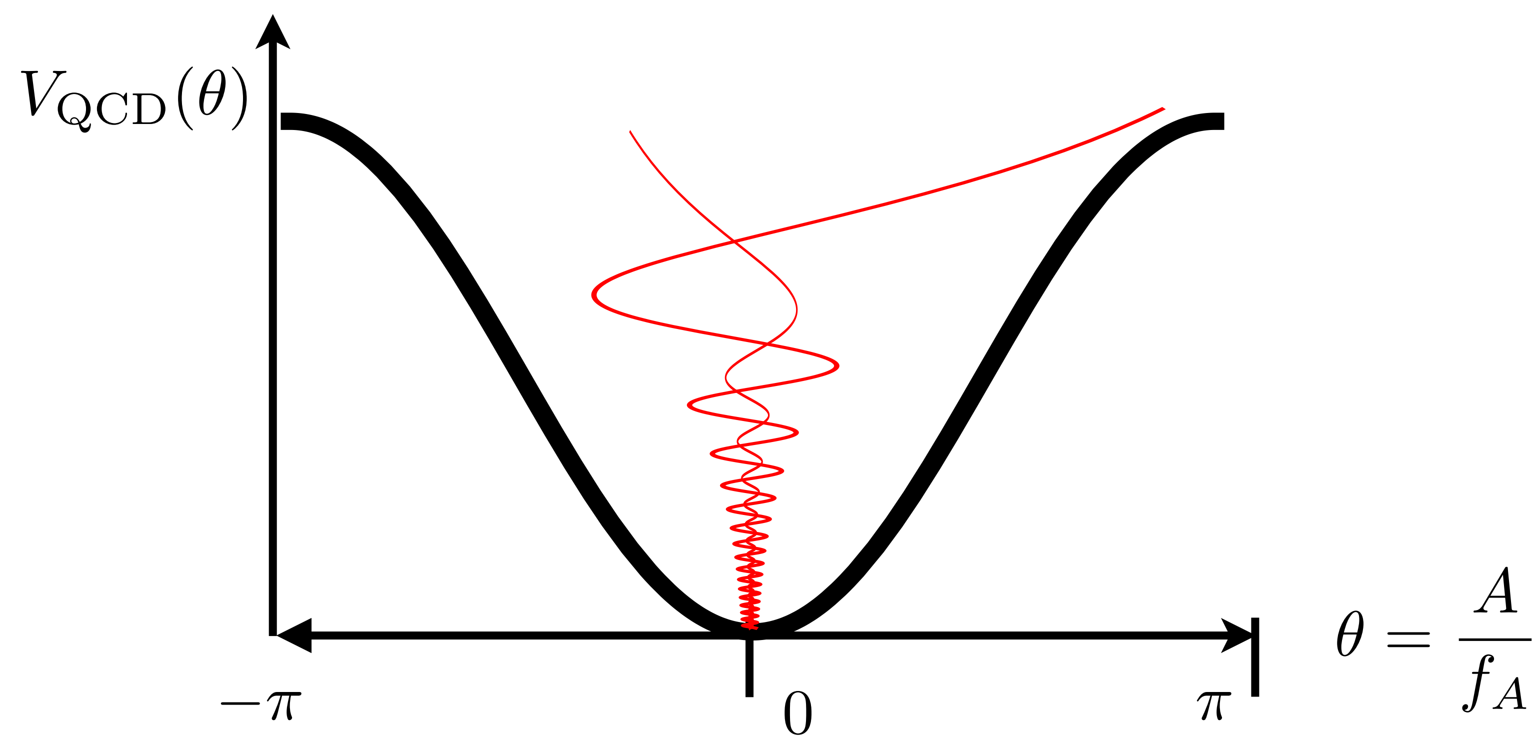

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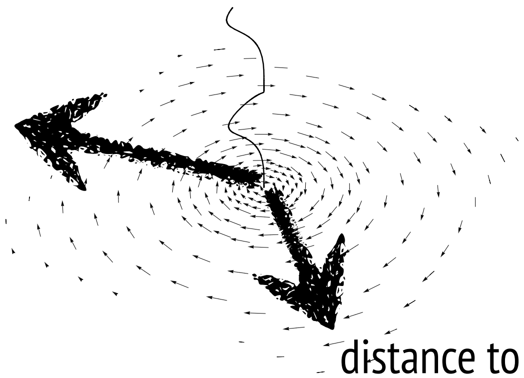

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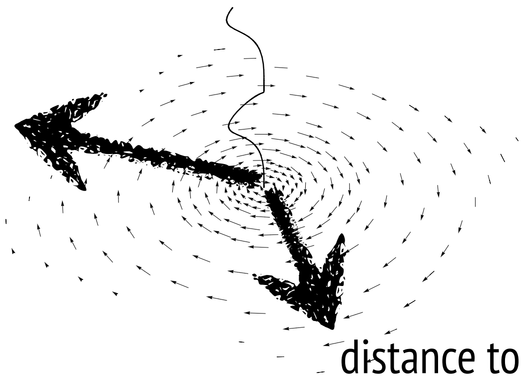

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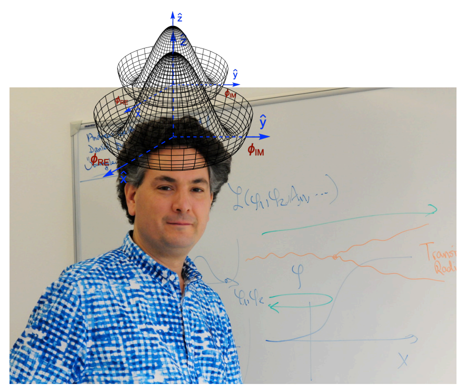
- **Effective tension approach**

$$m_A = 26.2 \pm 3.4 \mu\text{eV}$$

Klaer & Moore 2017



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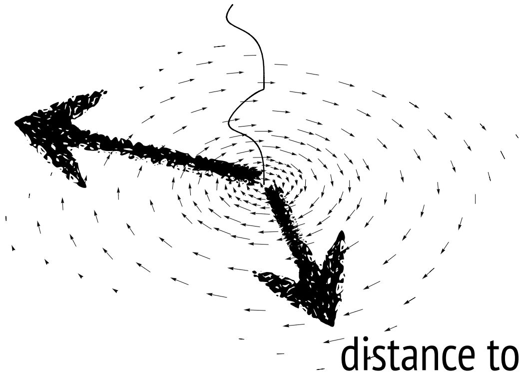
- A prediction $\Omega_c h^2 = \Omega_c h^2(f_a)$ is possible -> AXION DM MASS

- **Problems with dynamical range of simulations (cosmic strings)**

core $\sim \frac{1}{f_a}$



$$\frac{f_a}{H_1} \sim 10^{30}$$

distance to other string $\sim \frac{1}{H}$

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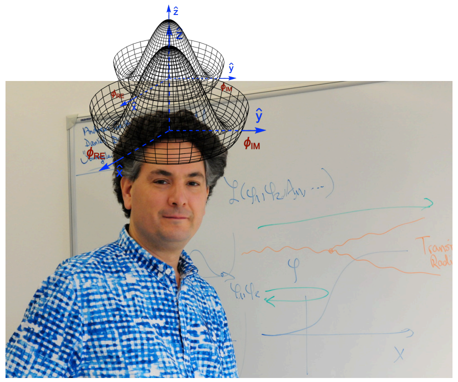

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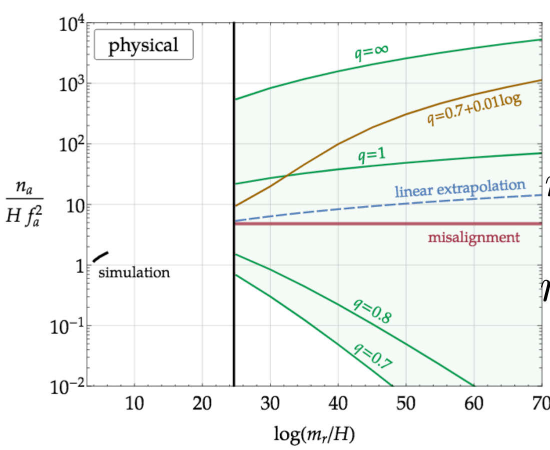

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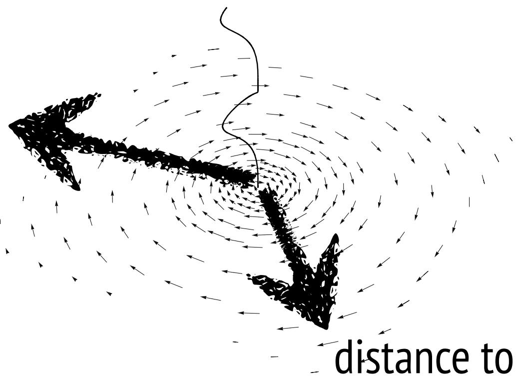

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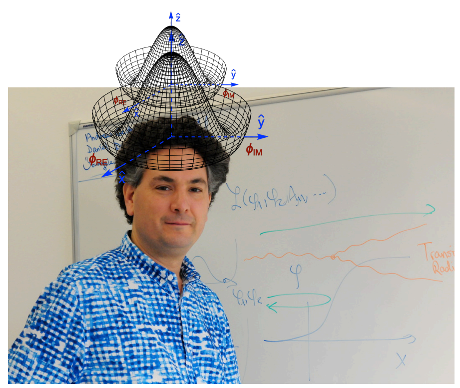

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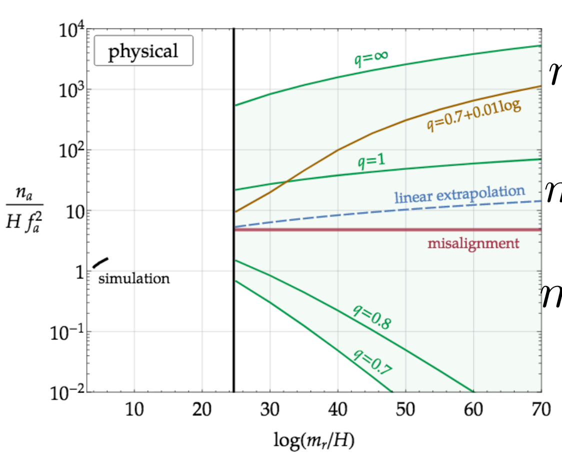

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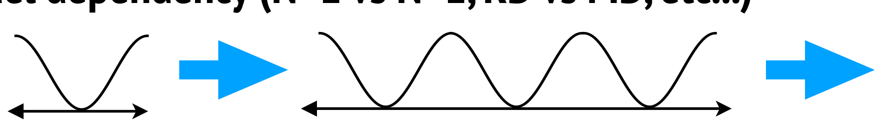

$\Omega_a h^2 \uparrow$

Scenario B	Scenario A
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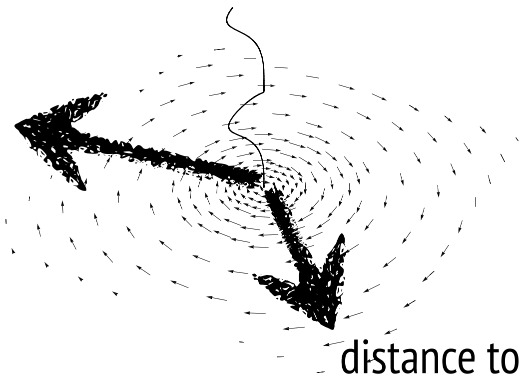

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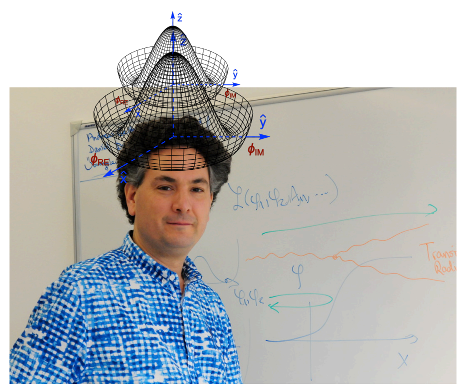
Klaer & Moore 2017



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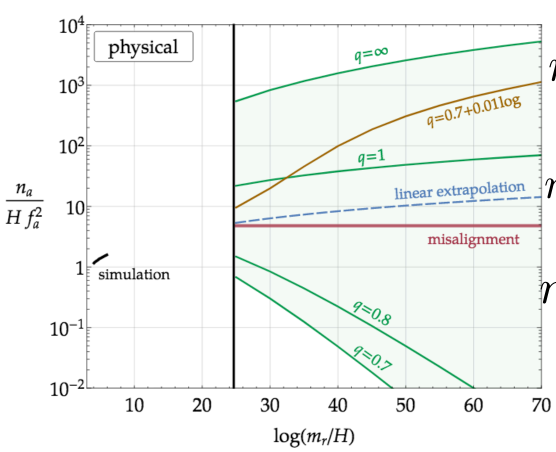

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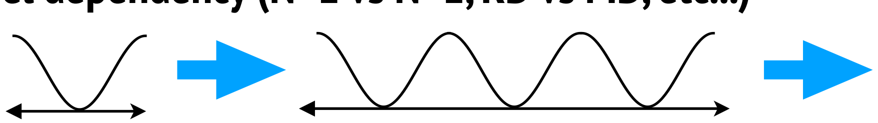

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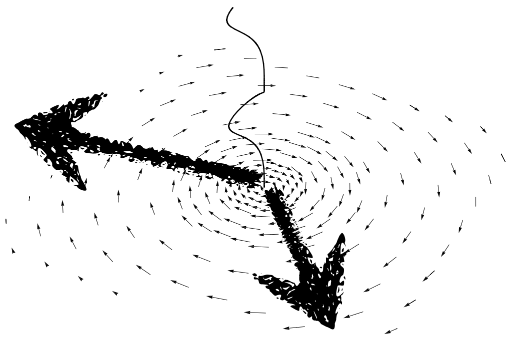

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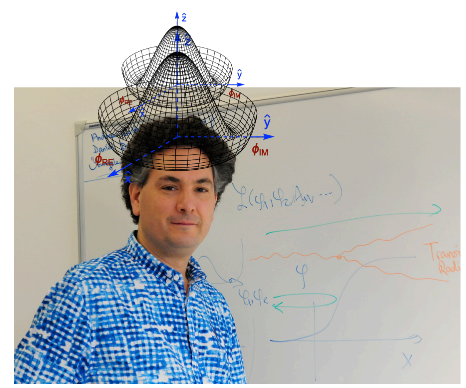

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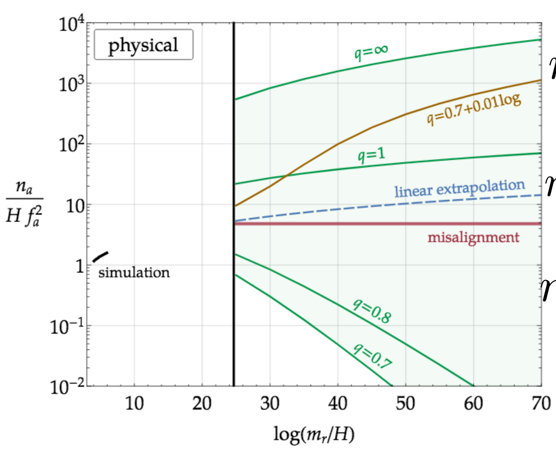

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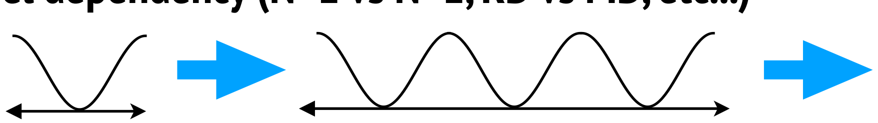

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Scenario A

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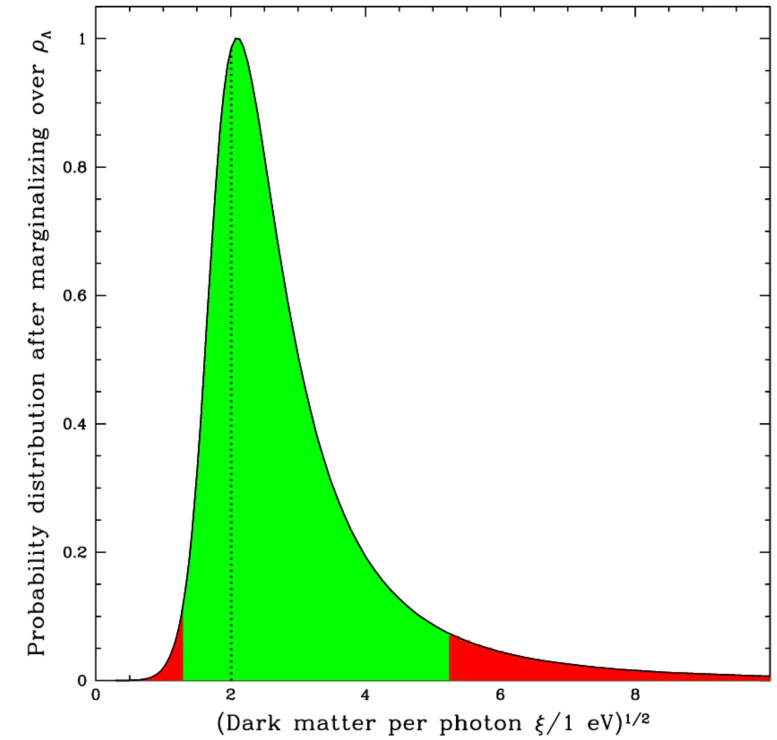
- Anthropic Axion window (Tegmark 2006)



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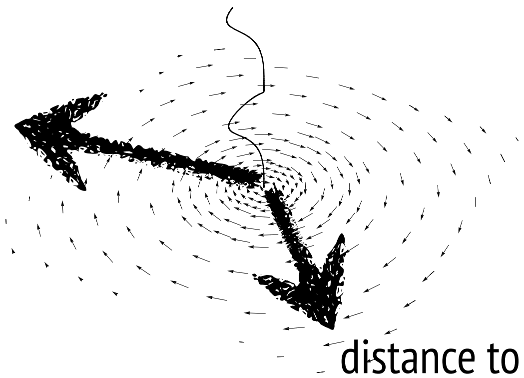

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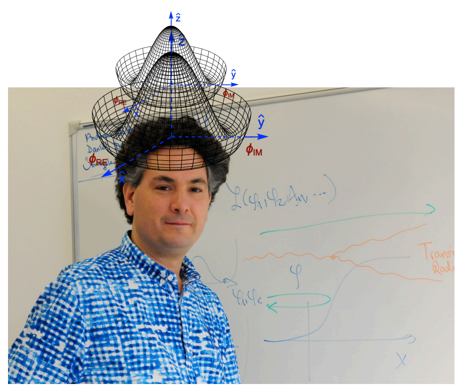

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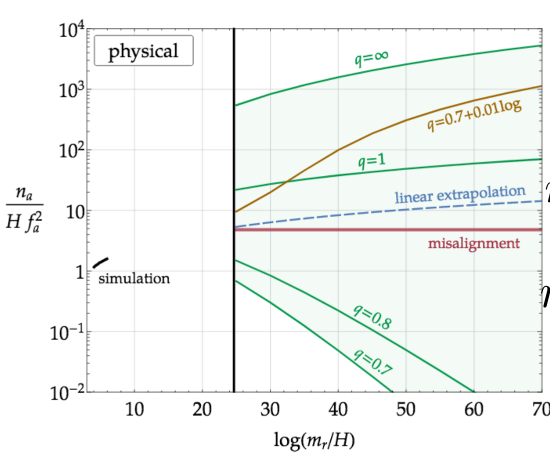

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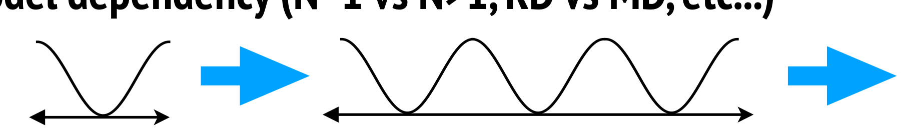

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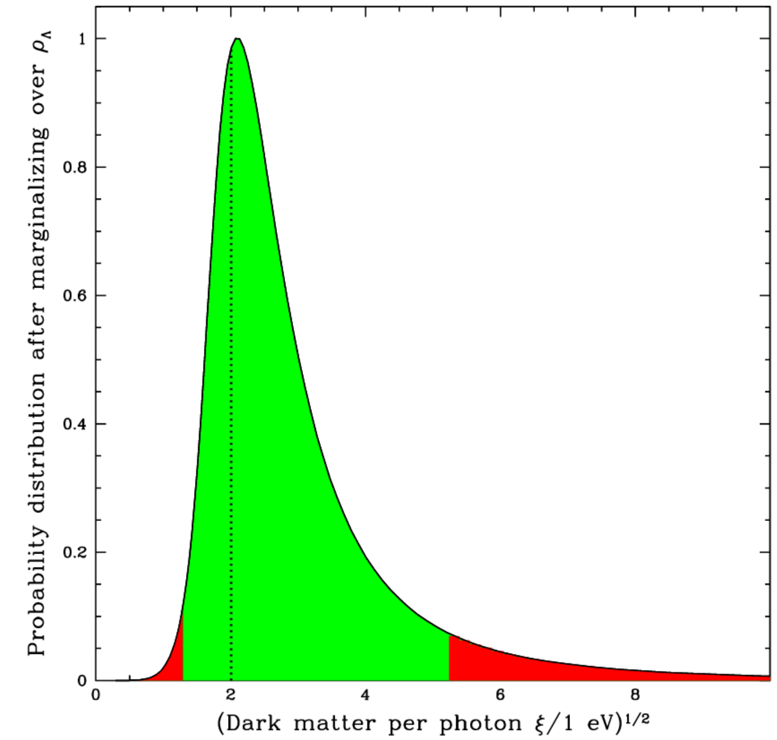
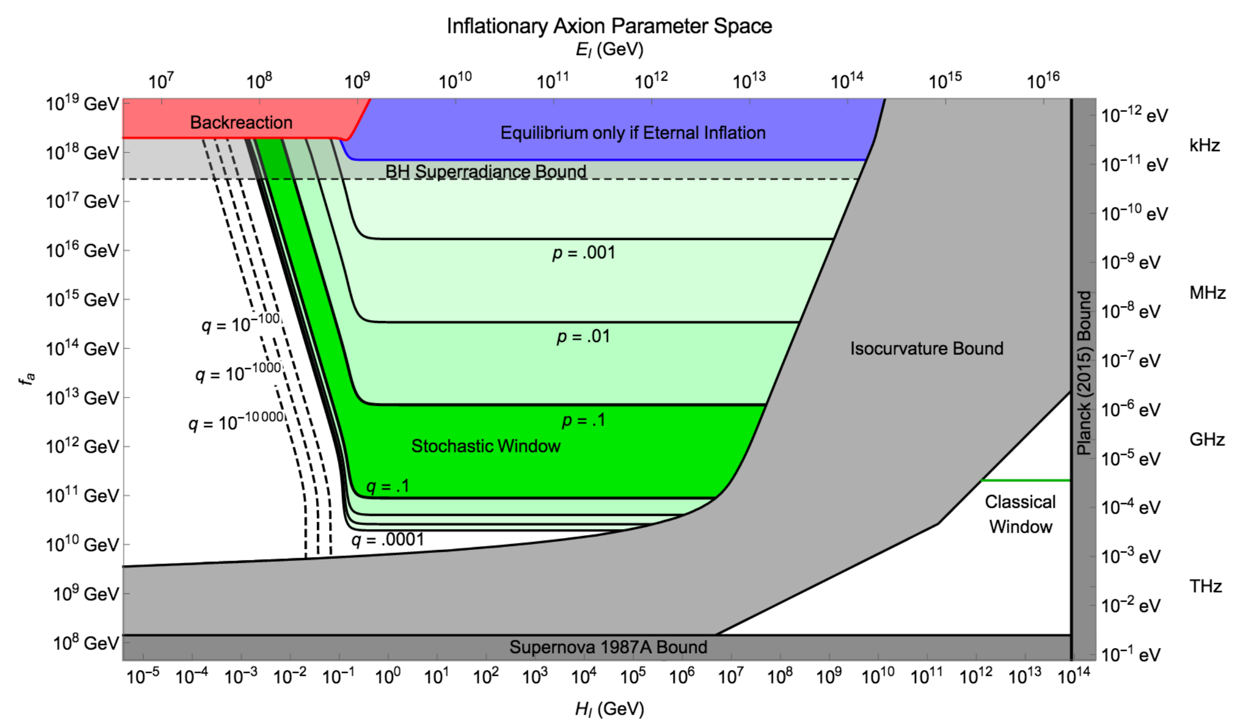
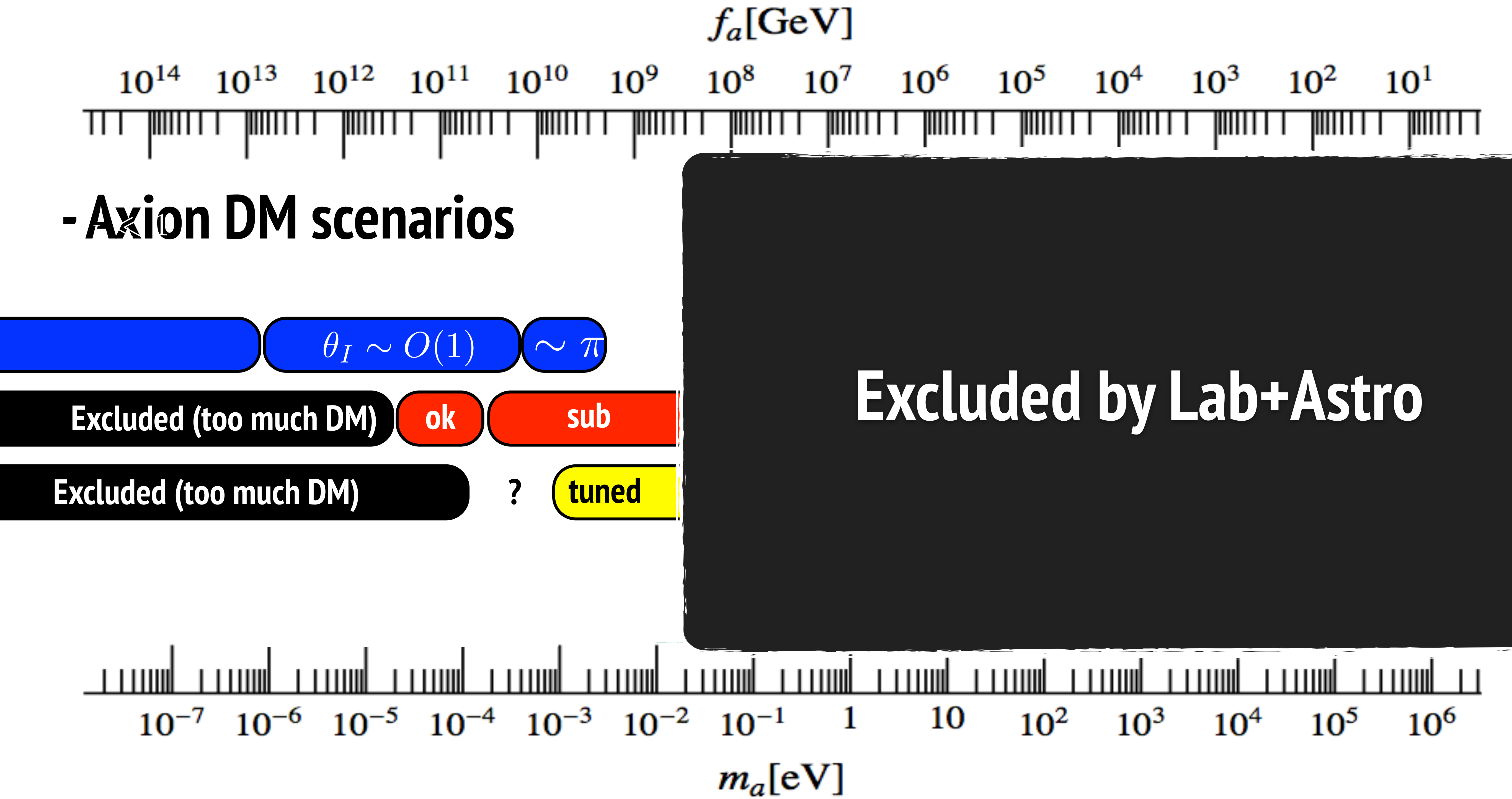


- **Stochastic Axion scenario (Scherlis 2018) Low-scale of inflation**



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

- **Axion DM scenarios**

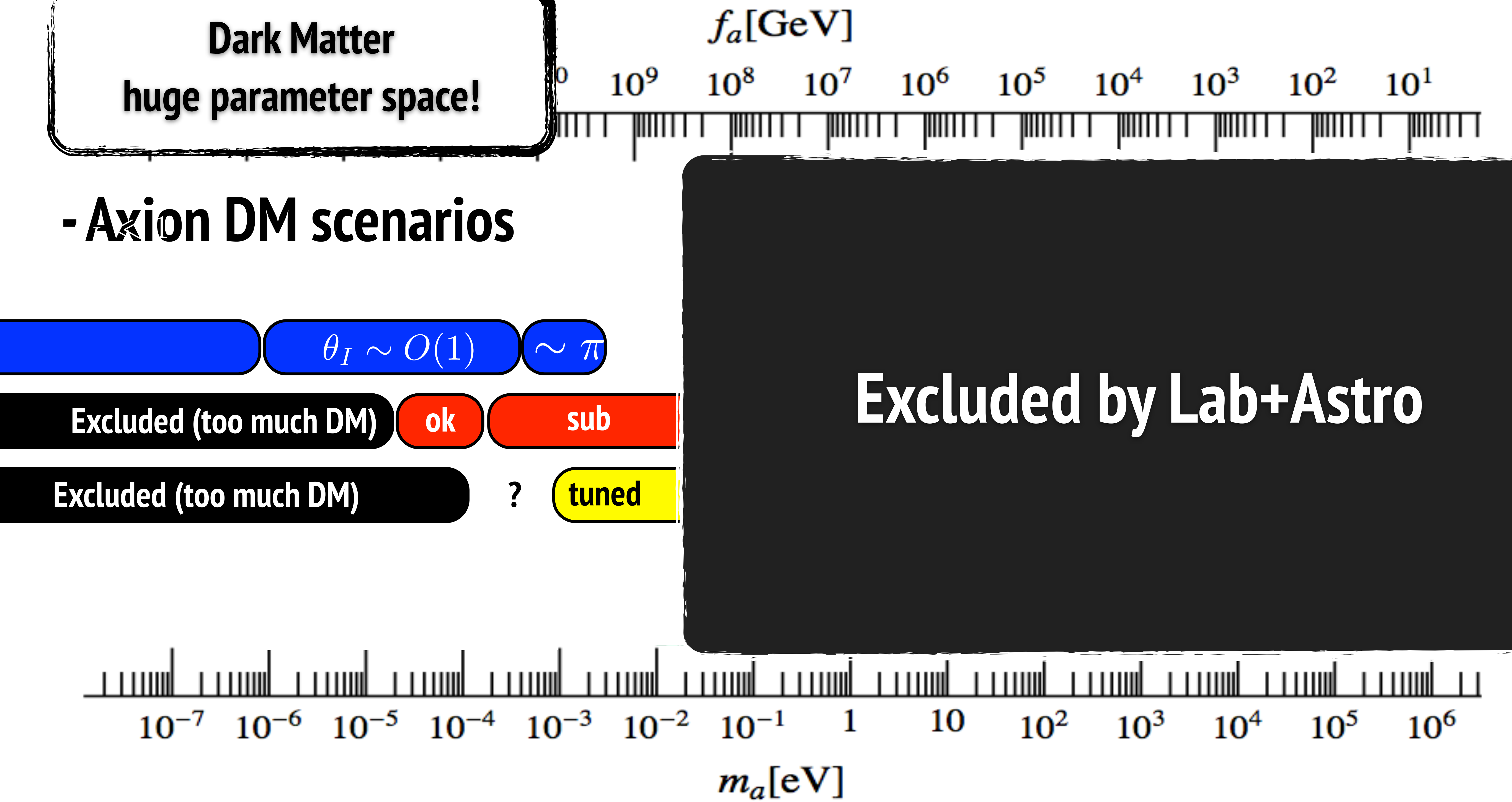


- Less minimal axion models have further possibilities ....

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

Dark Matter
huge parameter space!

- Axion DM scenarios

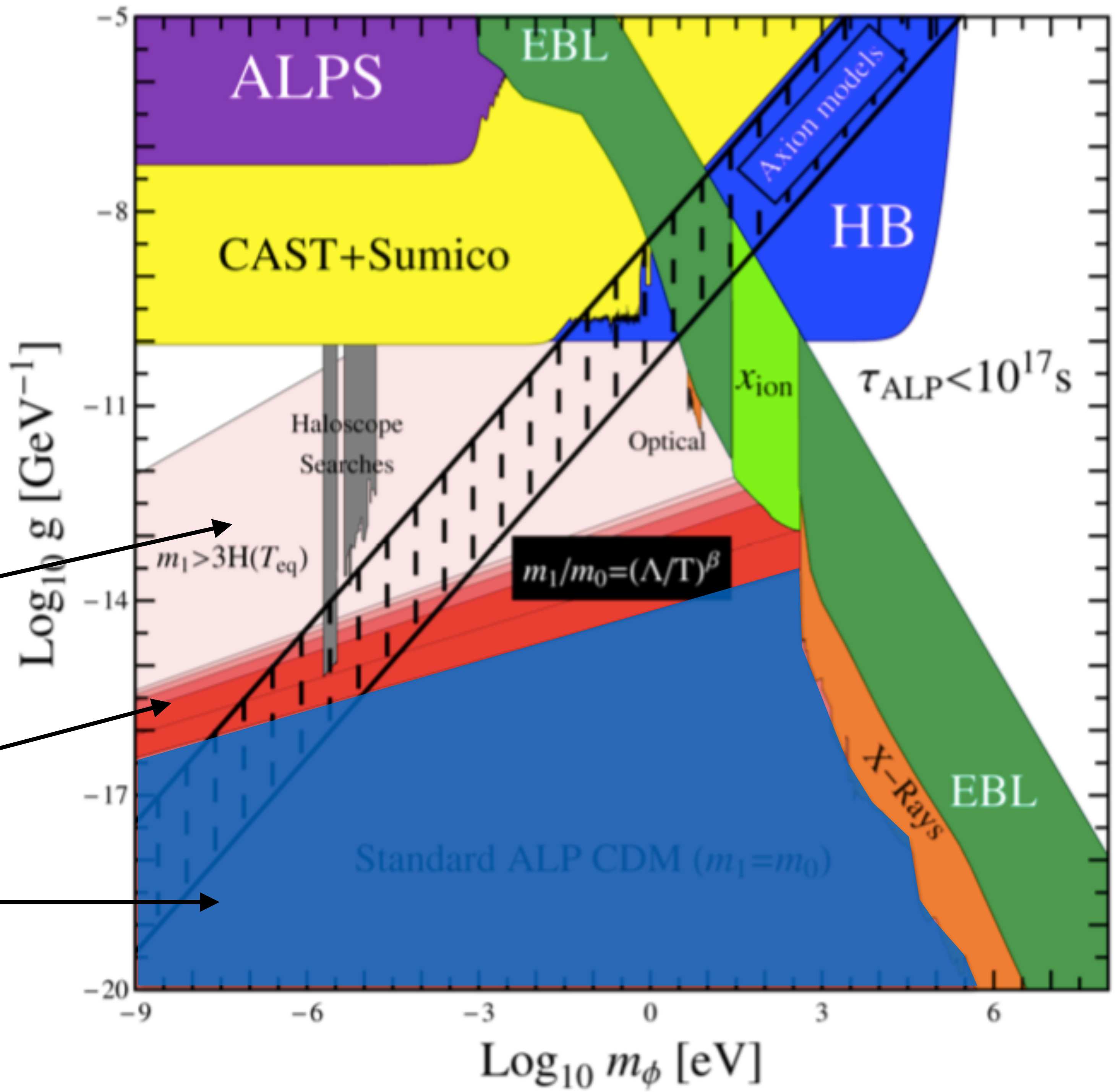


- Less minimal axion models have further possibilities ....

axion-like parameter space

$\phi_I \sim f$

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



possible?
(N>1,...)

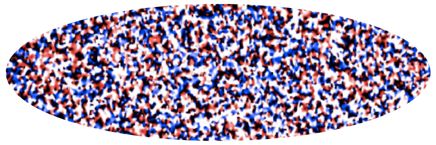
post-inflation

preinflation

Axion ALP DM is different

Scenario B

- Axion DM inhomogeneous at ~ pc scales (different for ALP/ nonstandard Ax)



Vaquero 2018

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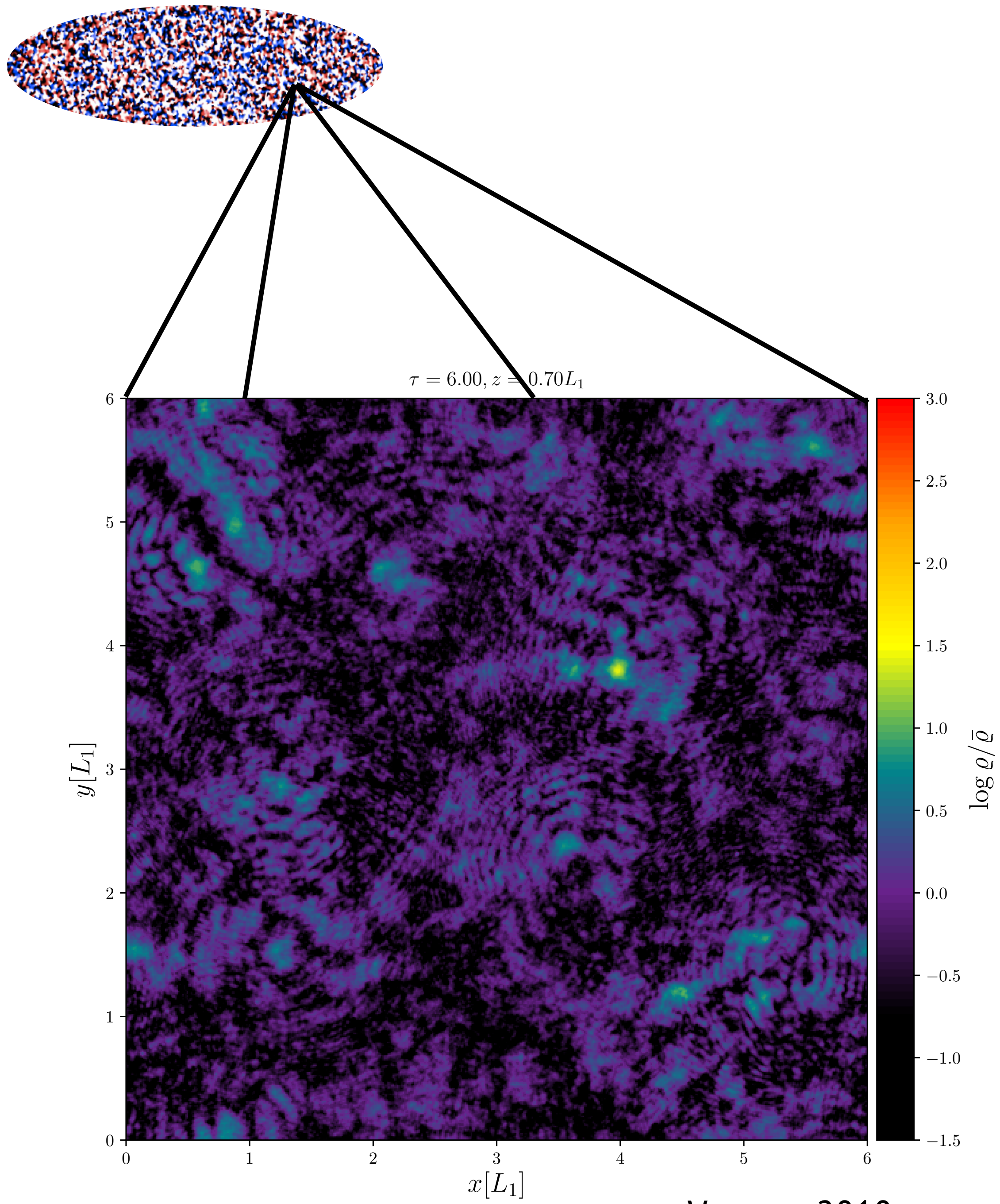

Vaquero 2018

T~ GeV

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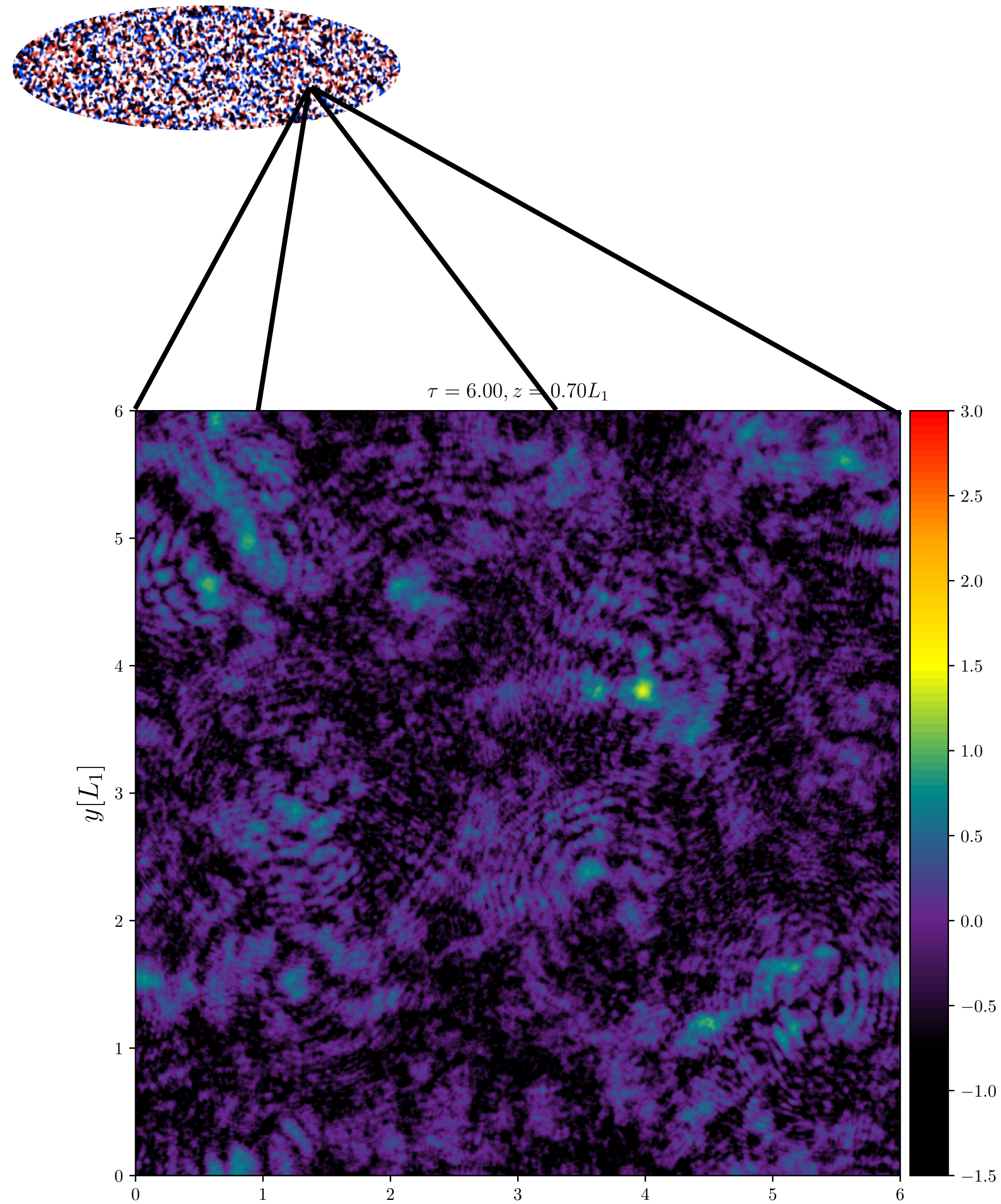
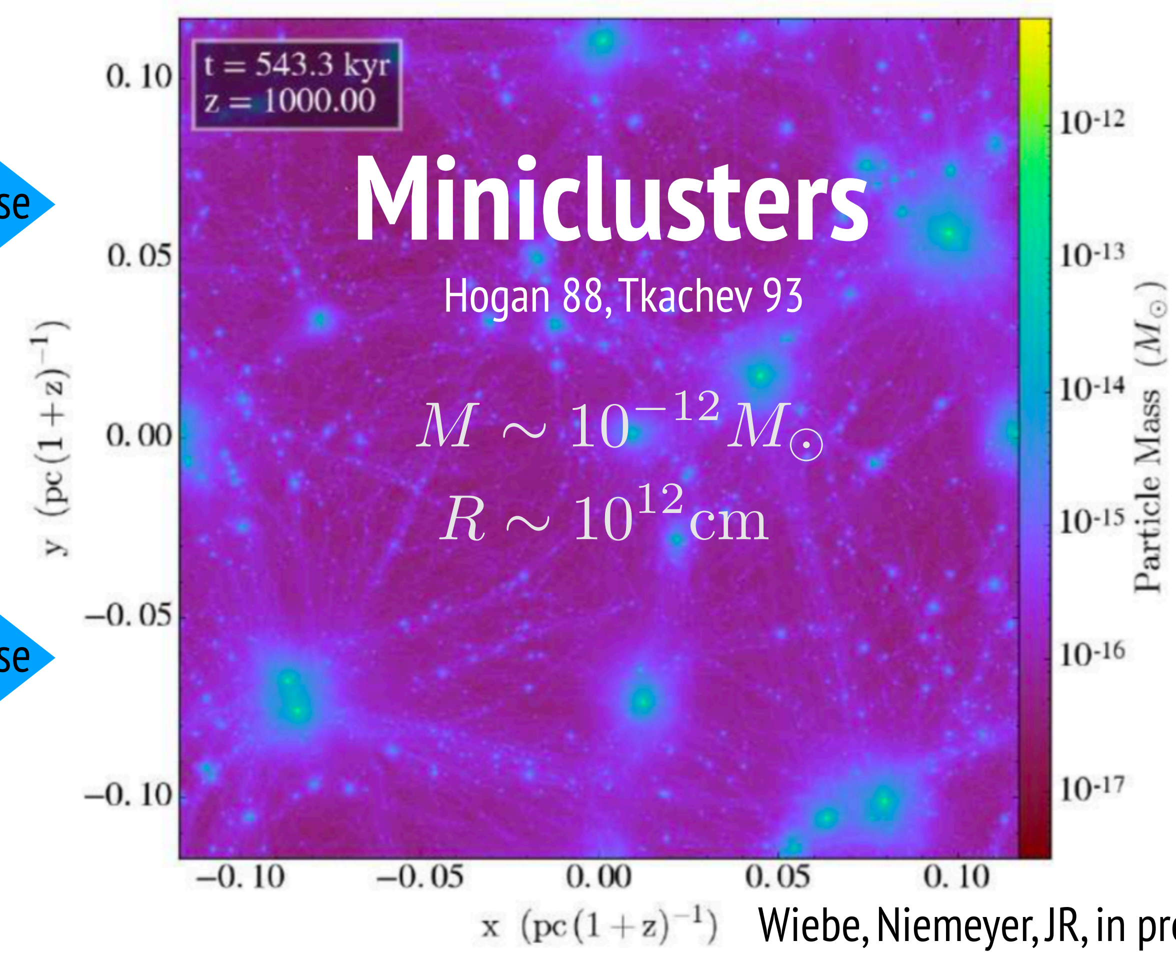


Vaquero 2018

T~ GeV

gravitational collapse

gravitational collapse



Miniclusters

Hogan 88, Tkachev 93

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

$R \sim 10^{12}\mathrm{cm}$

Wiebe, Niemeyer, JR, in prep

T~ T_{eq}

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Scenario B

Scenario A

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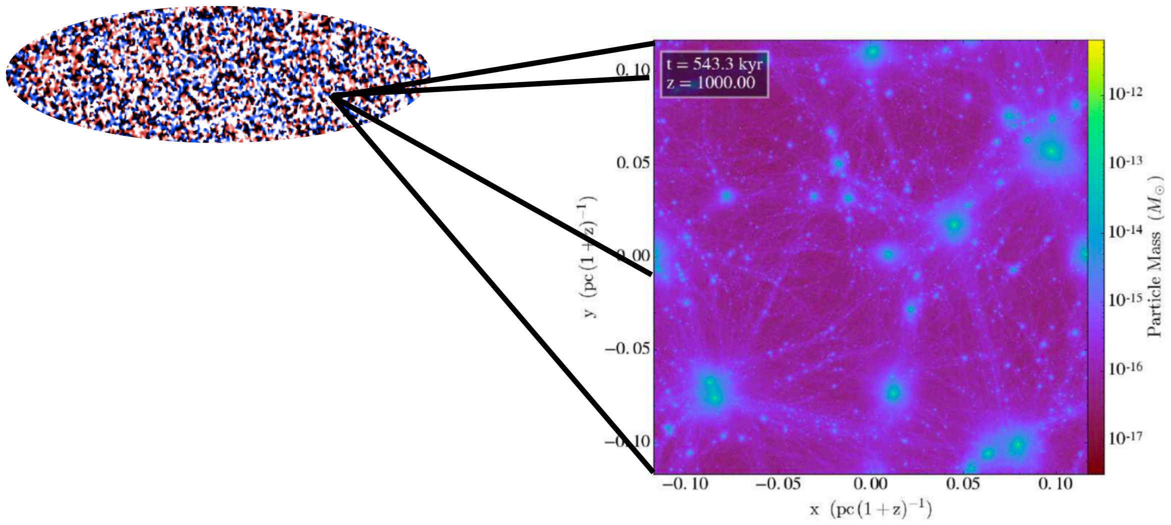

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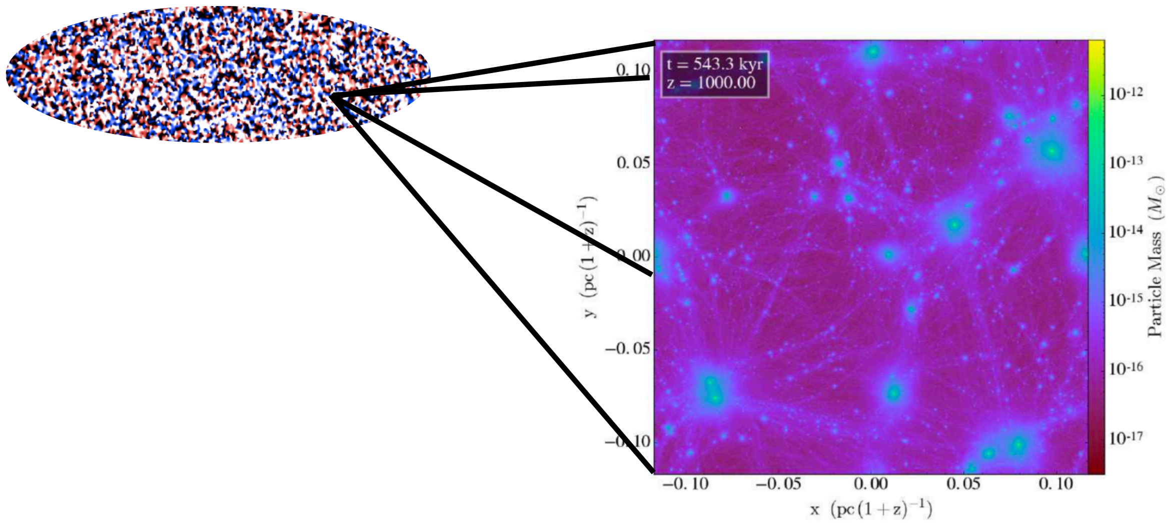
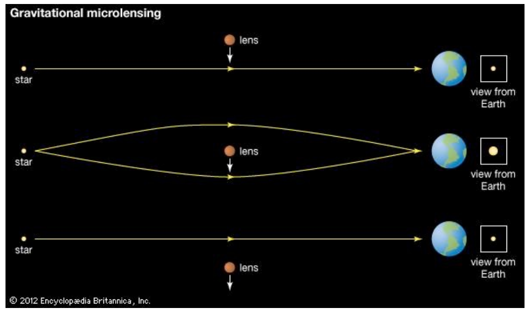


- Microlensing



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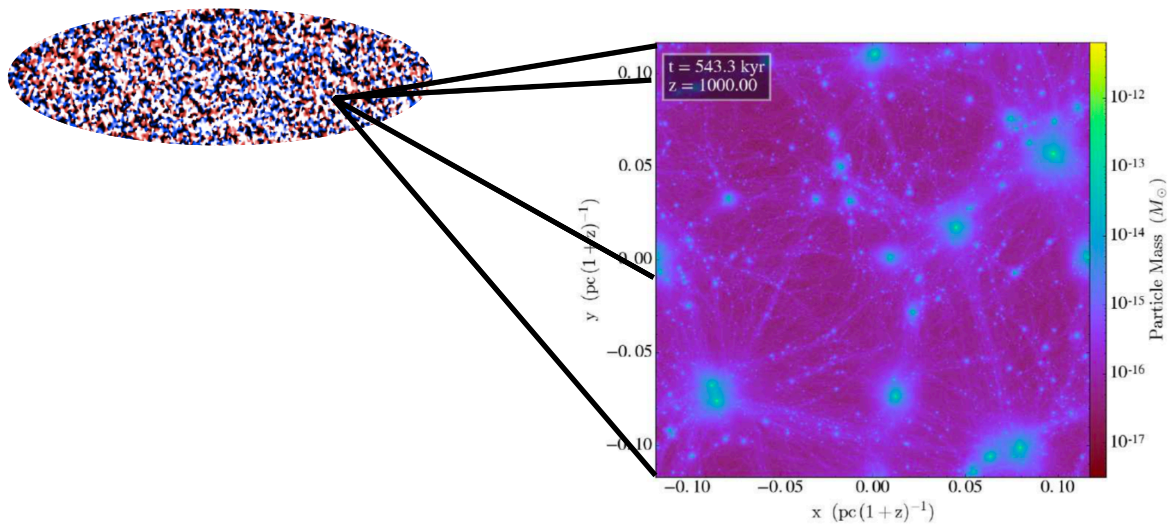

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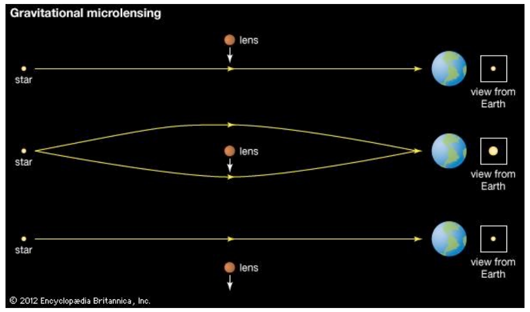
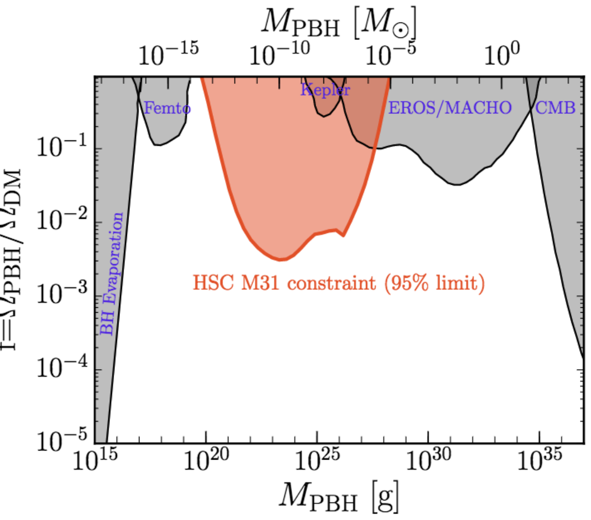


HSC M31 PBHs *Niikura 2017*



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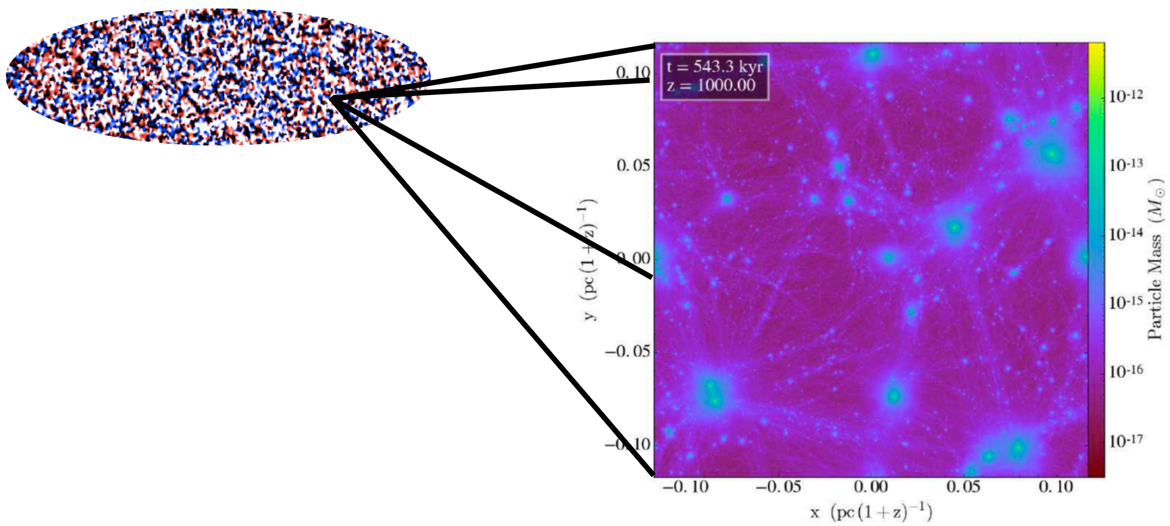

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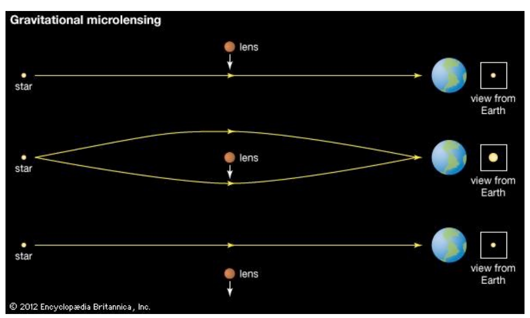

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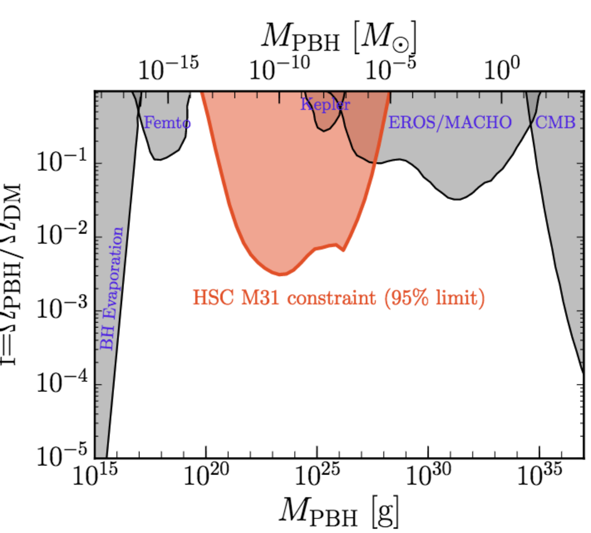
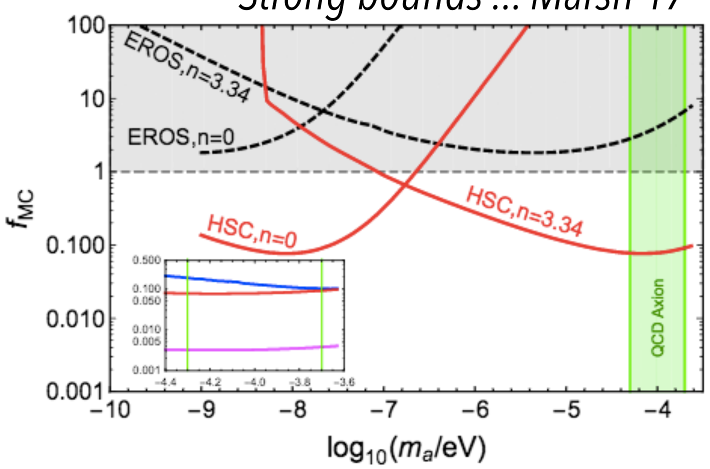


Strong bounds … Marsh 17



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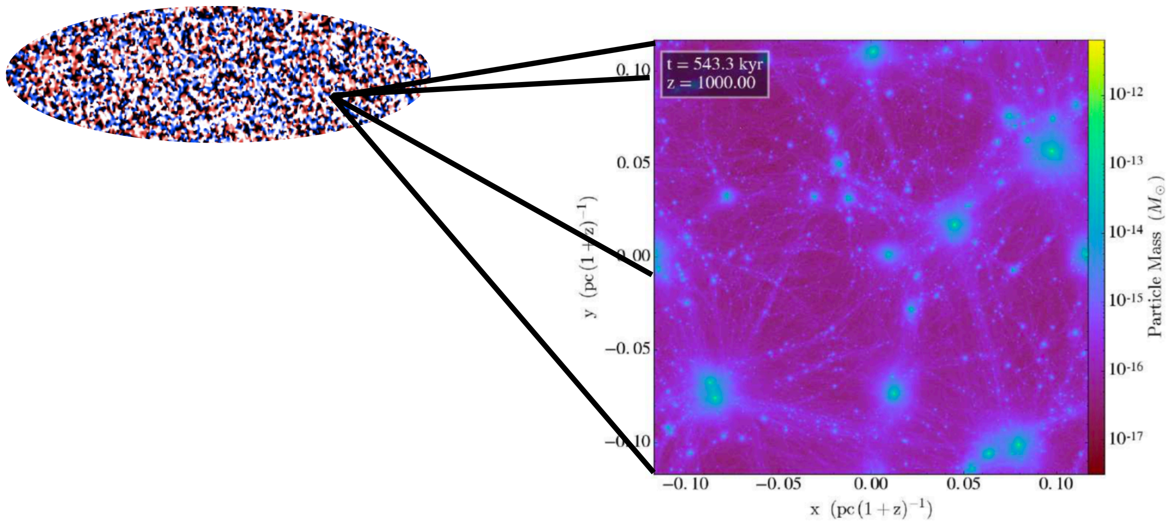

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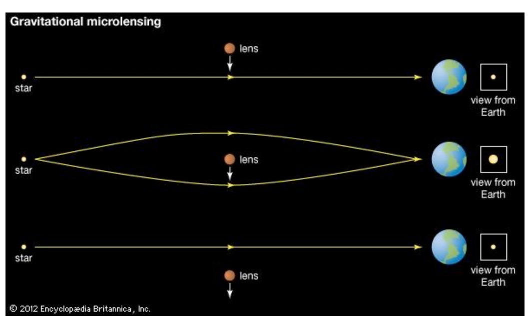

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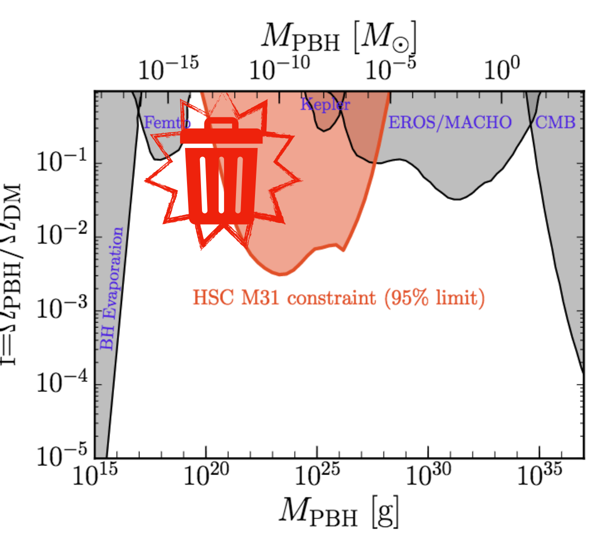

Inomata 2018

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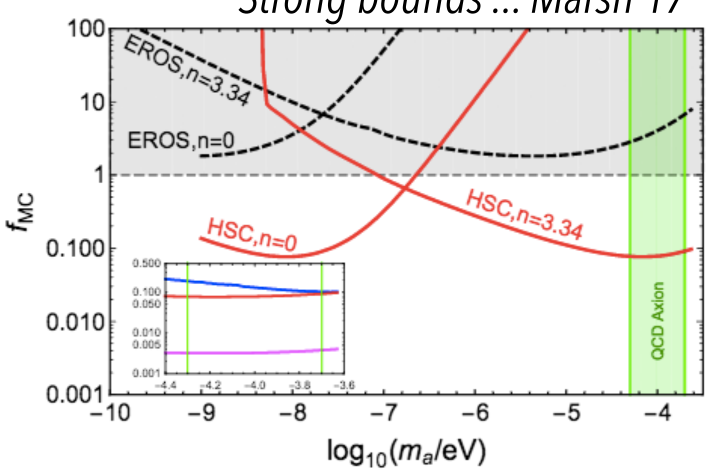

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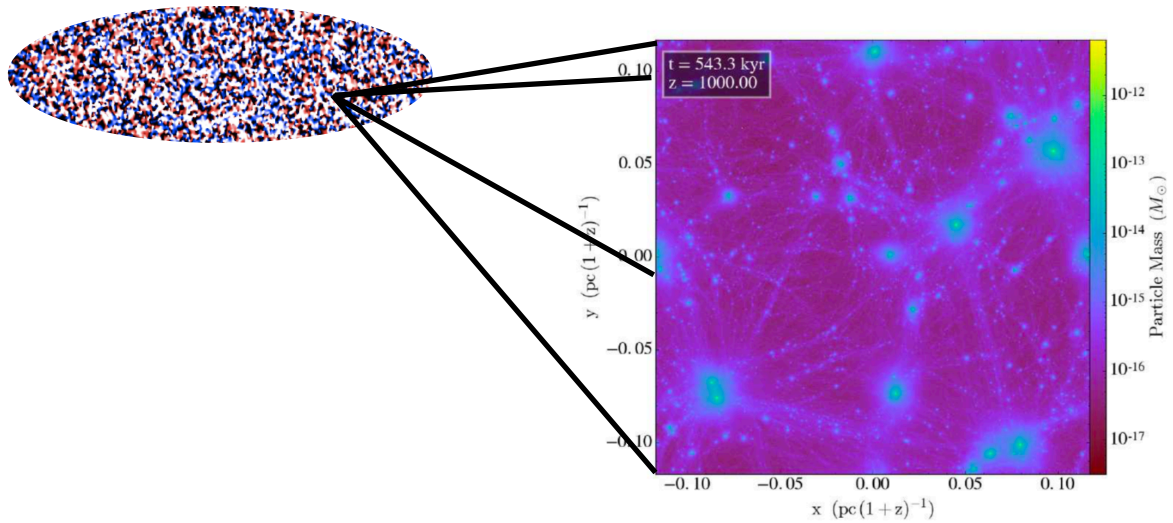

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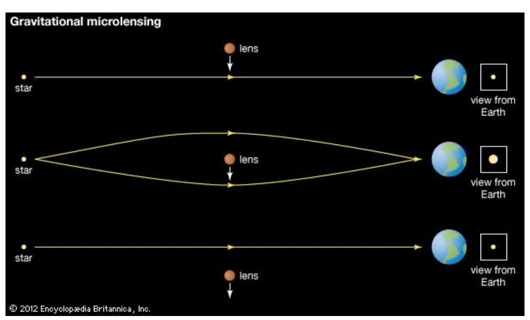

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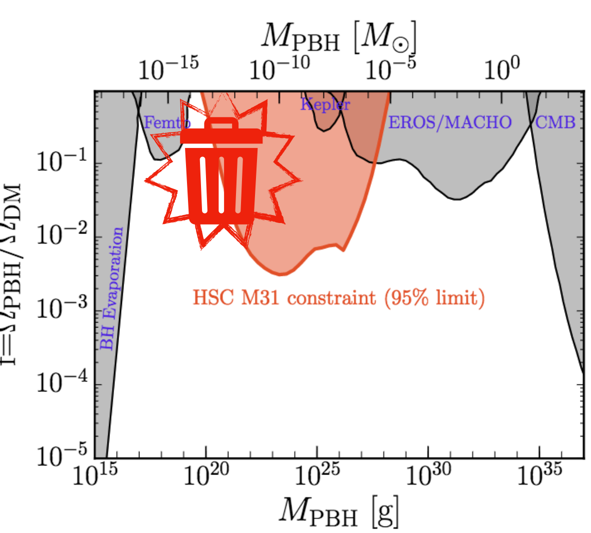

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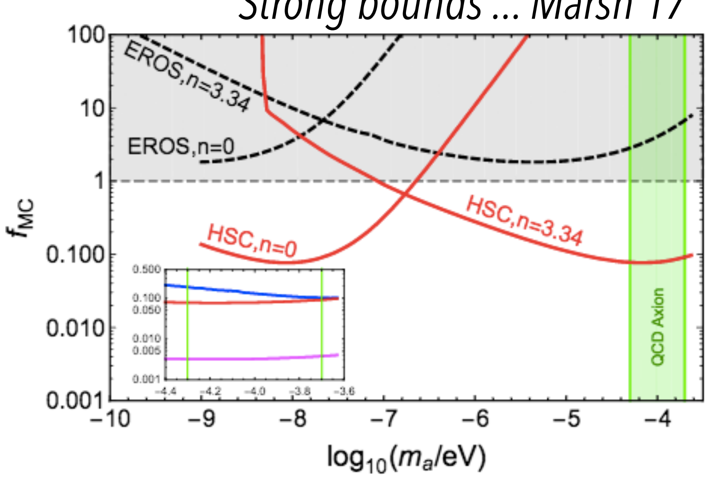
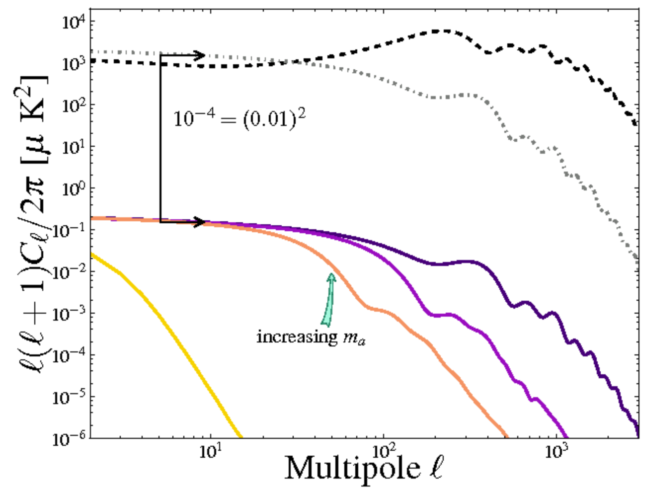


Scenario A

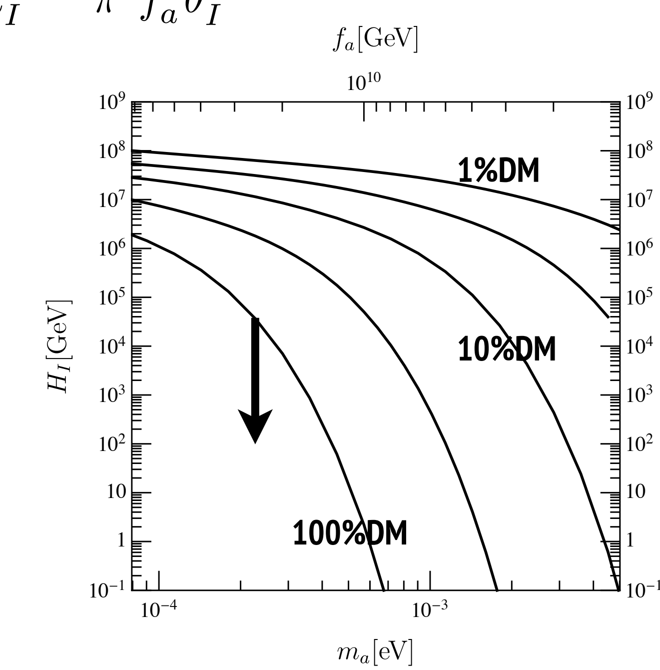
- Axion fluctuations during inflation ->>> CDM fluc. >>> isocurvature fluc. CMB!



- Planck sees no Isocurvature fluctuations, strong limit!

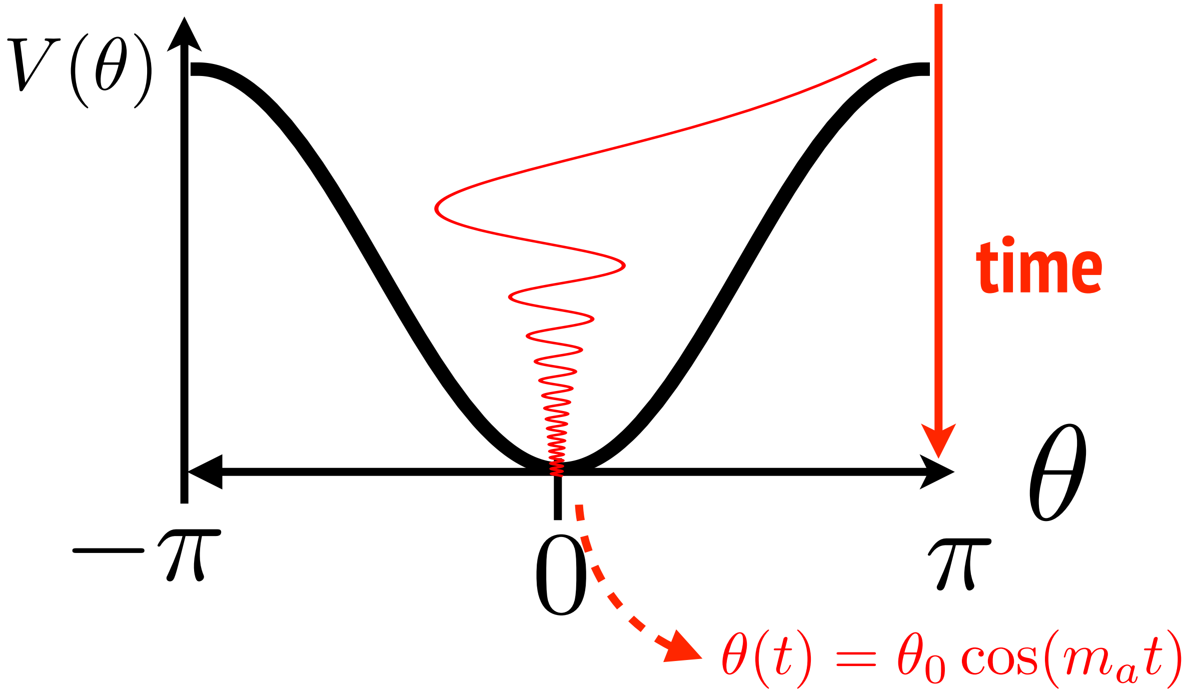
$$P_{\rm iso} = \frac{d\langle n_a\rangle}{n_a} \sim \frac{d\langle a^2\rangle}{a_I^2} = \frac{H_I^2}{\pi^2 a_I^2} = \frac{H_I^2}{\pi^2 f_a^2 \theta_I^2} < 0.039 P_s = 0.88\times 10^{-10}$$

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)

Axion DM in the lab

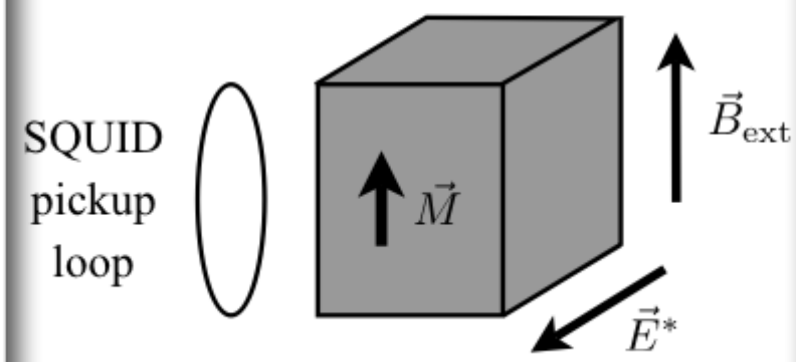


Local Dark Matter density*

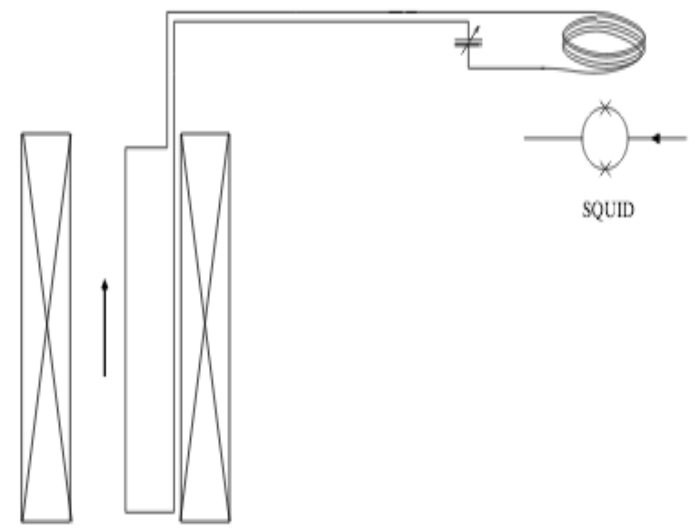
$$\rho_{\rm aDM} = 0.3 \frac{\rm GeV}{\rm cm^3}$$

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

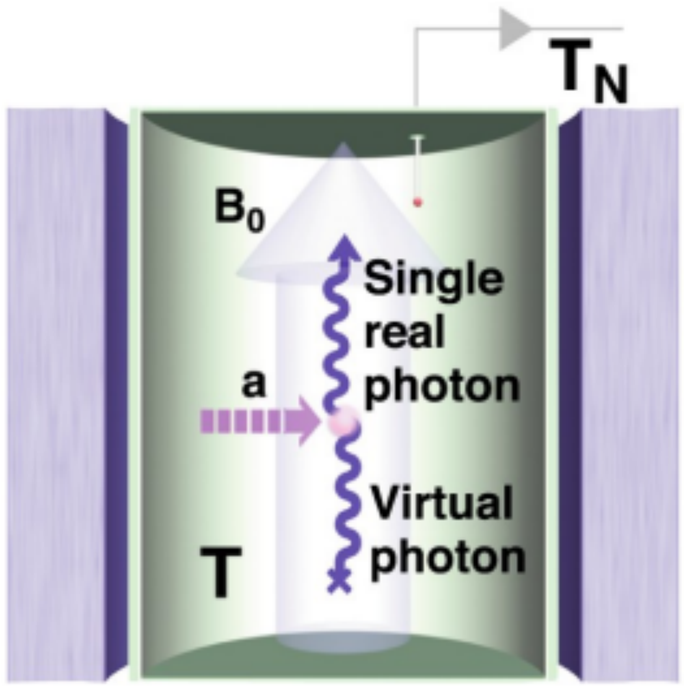
Oscillating EDM



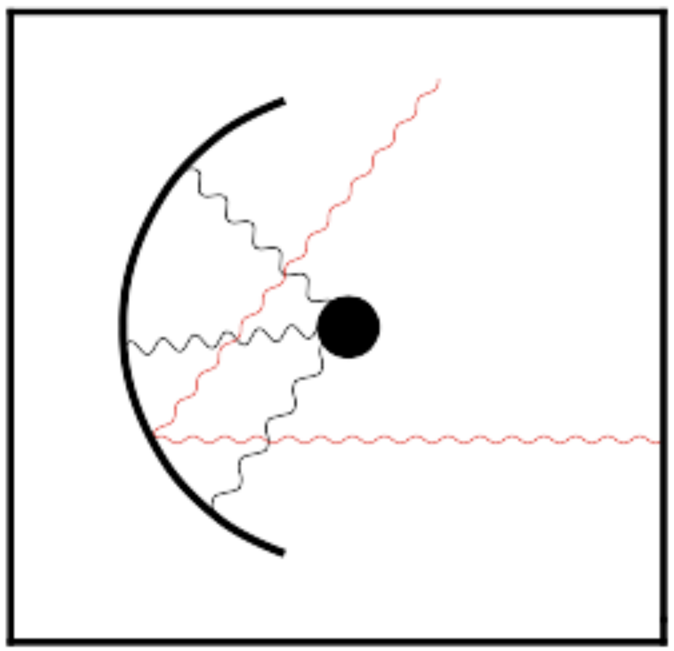
LC-circuit



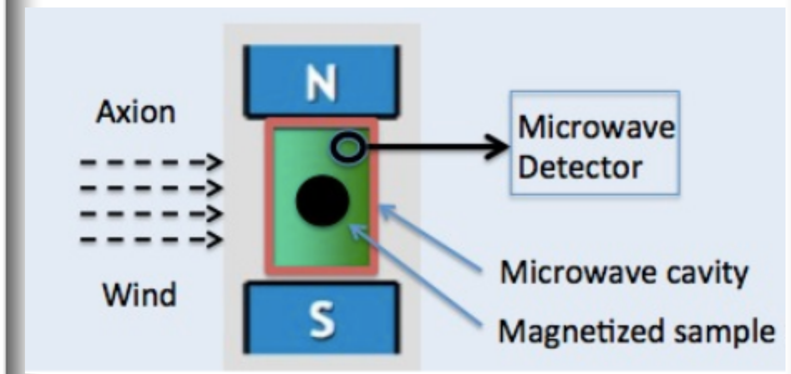
Cavities



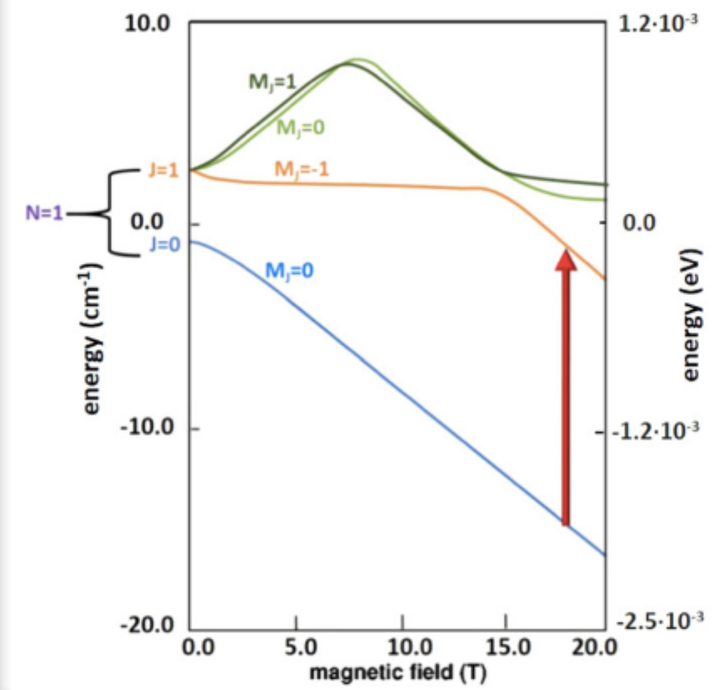
Mirrors



Ferromagnetic resonance



Atomic transitions



CASPER : oscillating EDM with NMR

Mainz, Berkeley

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

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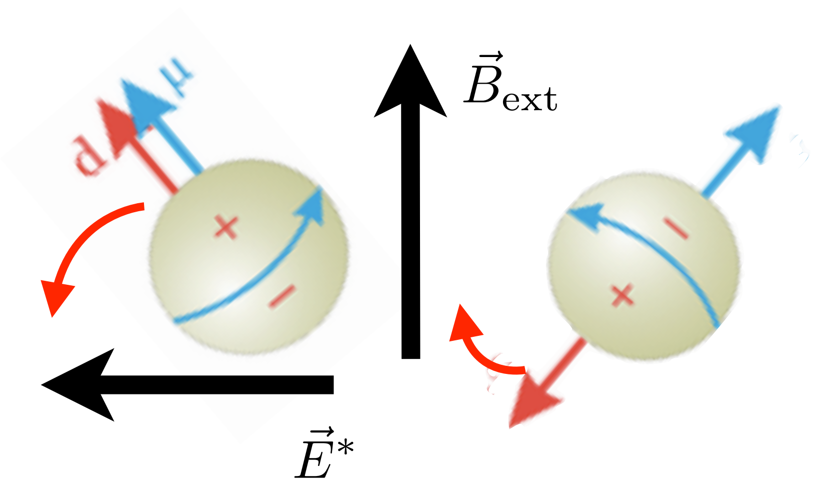
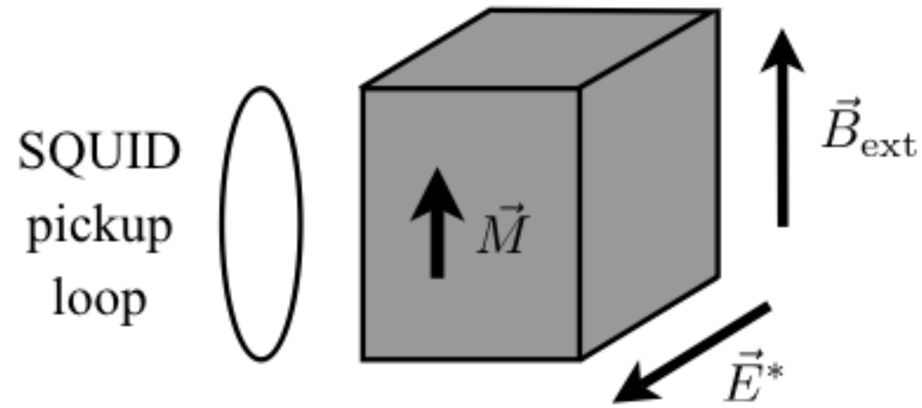


Oscillating EDM, effects add up, transverse magnetisation grows on resonance $m_a = \omega = \mu|\vec{B}_{\rm ext}|$



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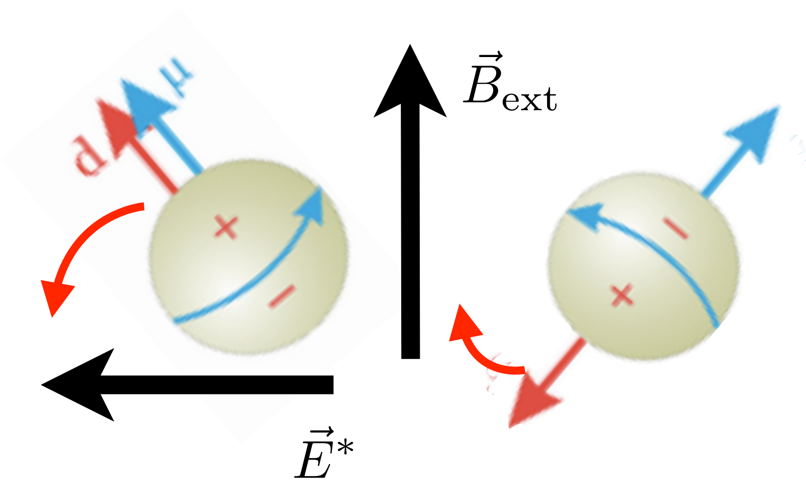

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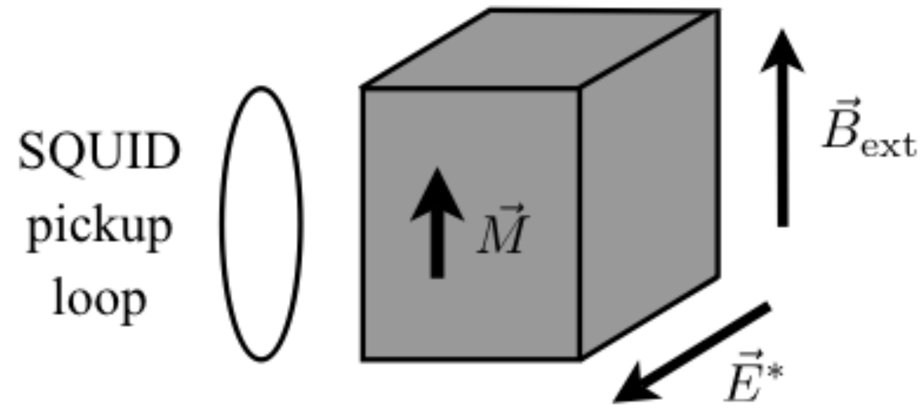


D. Budker


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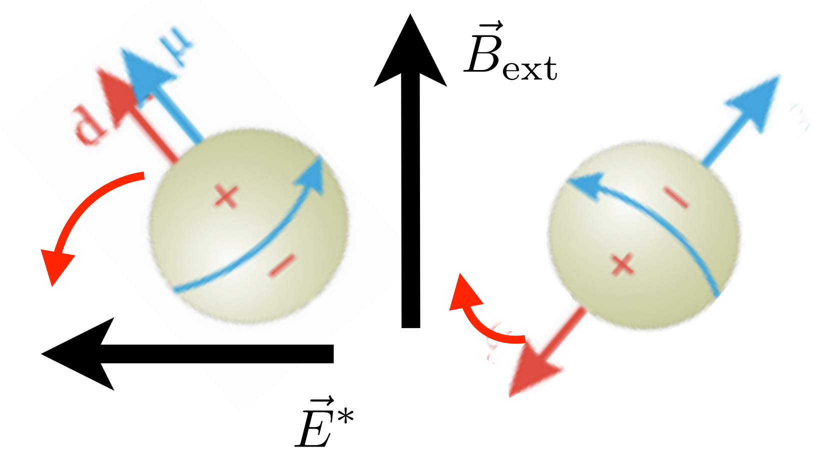

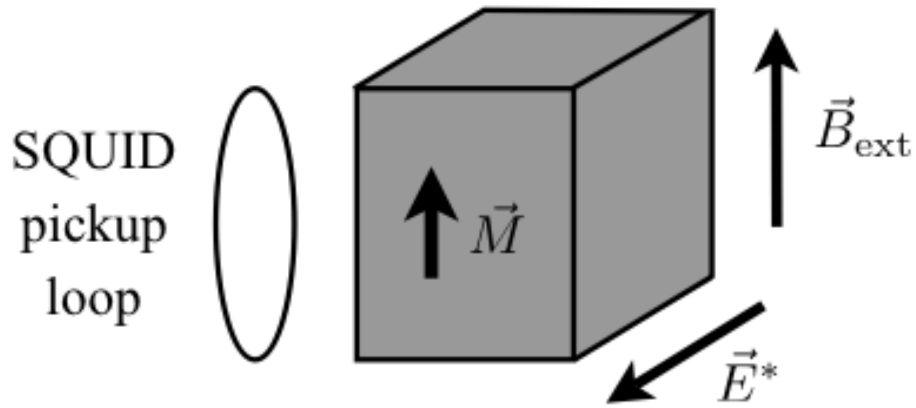

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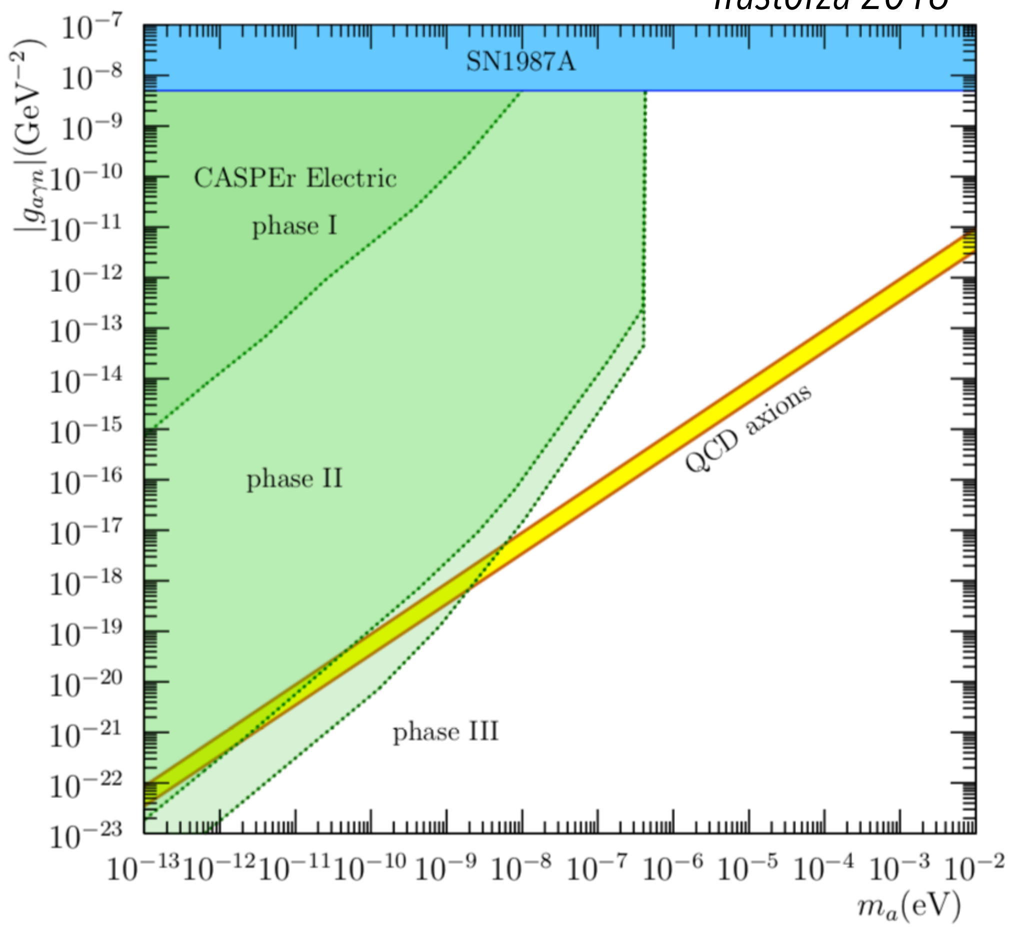
Irastorza 2018



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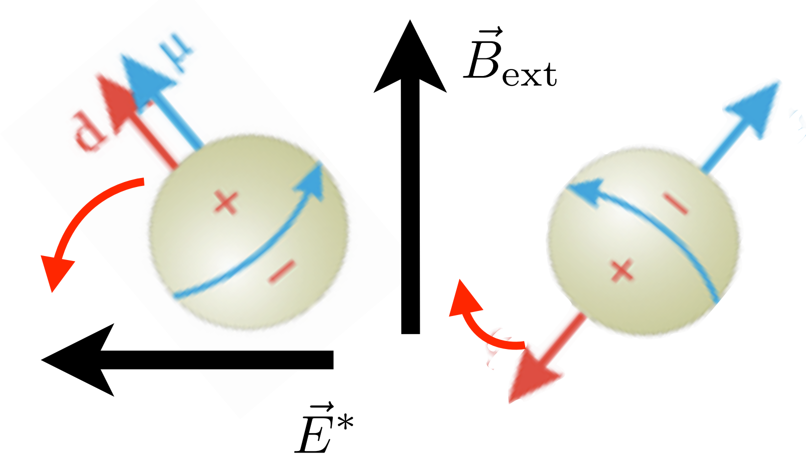

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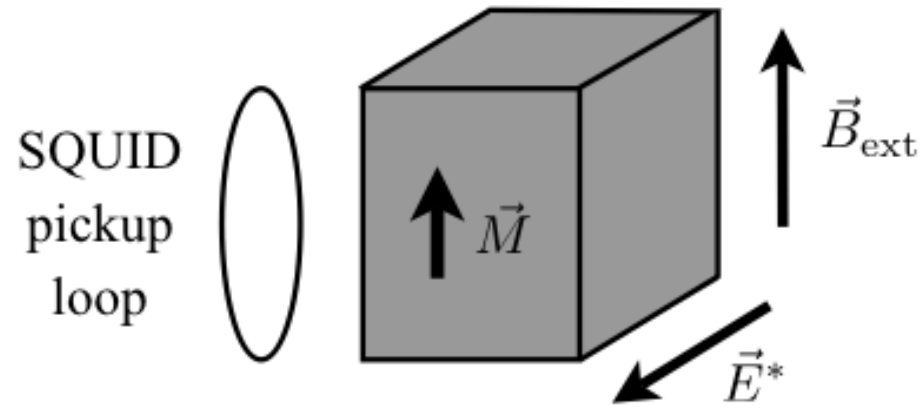

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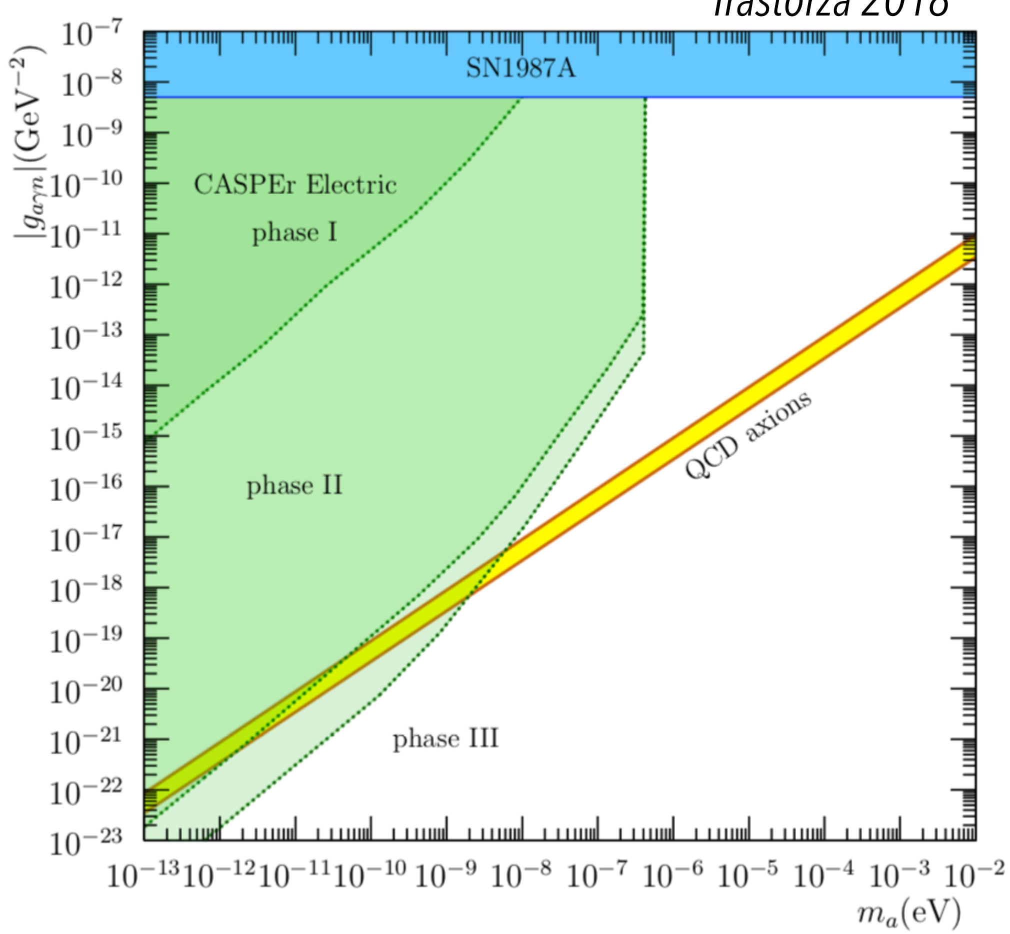


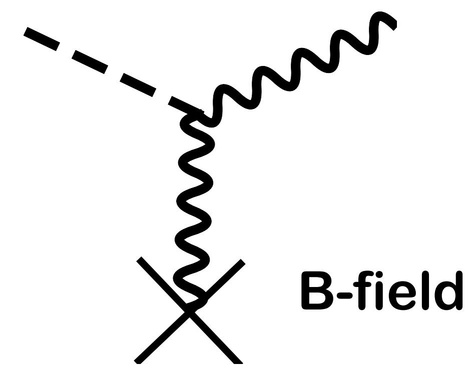
- *EDM + Large E-fields in PbTiO3*
- *Scan over frequencies, with Bext*
- *Mainz (D. Budker's group) & Berkeley*
- *Phase I starts in 2017, Phase II physics results …*
- *Mass range limited by B-field strength*

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

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

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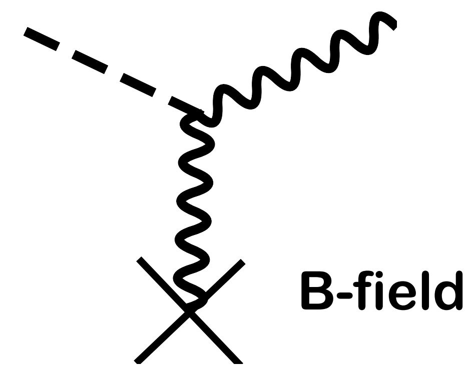

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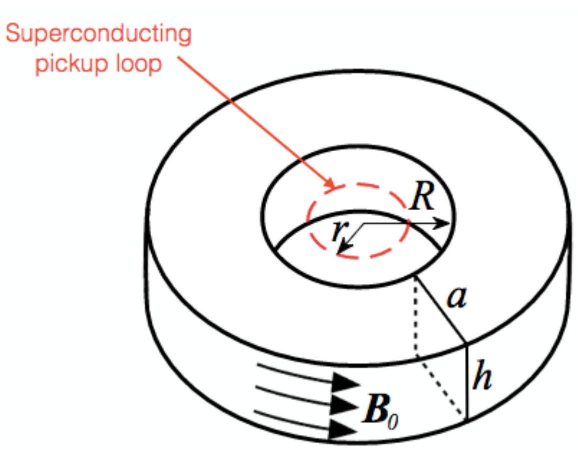
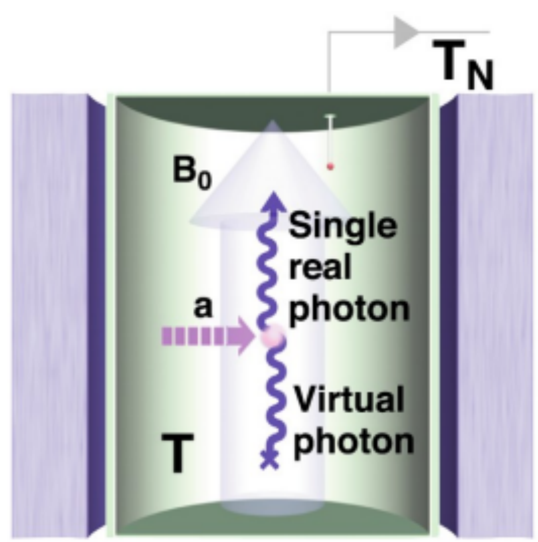
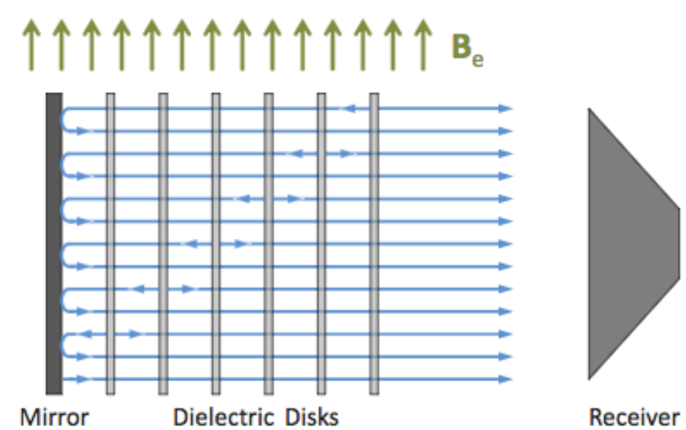
- Four different techniques:



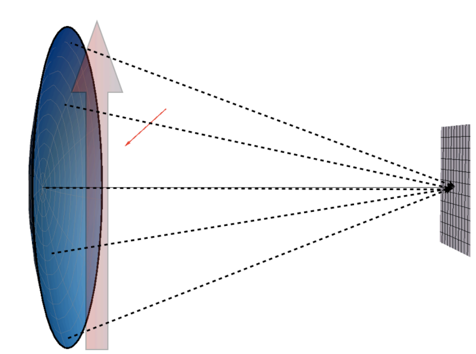
DM Radio



Cavities



Dielectric haloscope

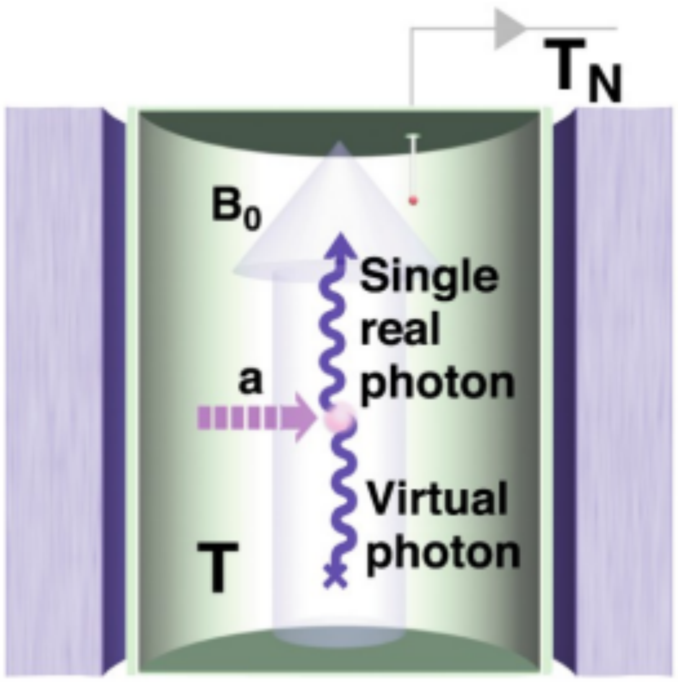


Dish antenna

Resonant cavities: haloscopes

P. Sikivie

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



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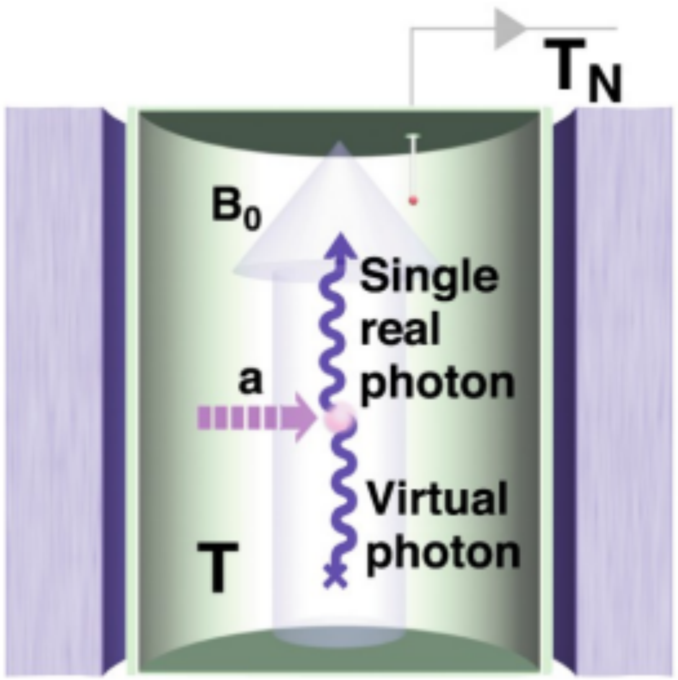

$$P_{\rm out} \sim Q|\mathbf{E}_a|^2 V m_a$$

- 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 $T \sim 0.2 - 4\,\mathrm{K}$
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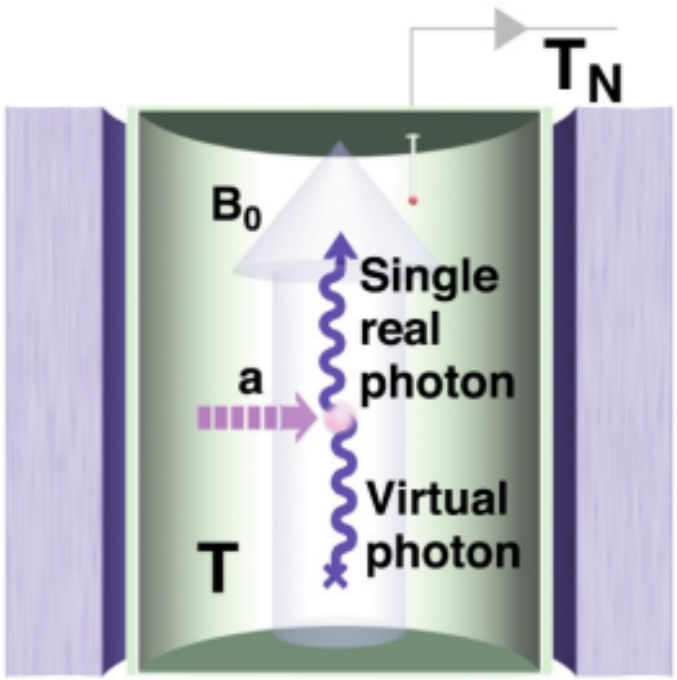

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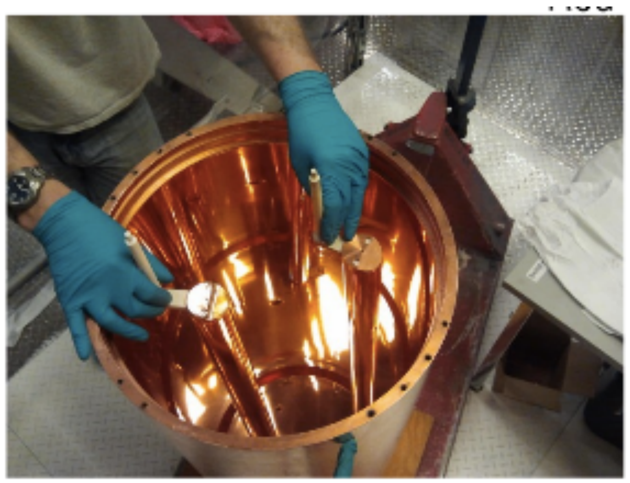

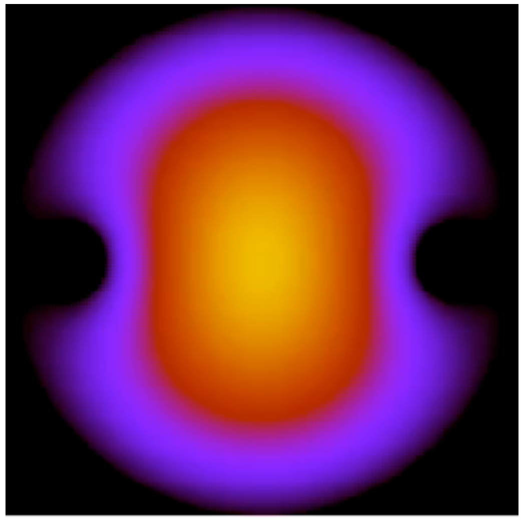

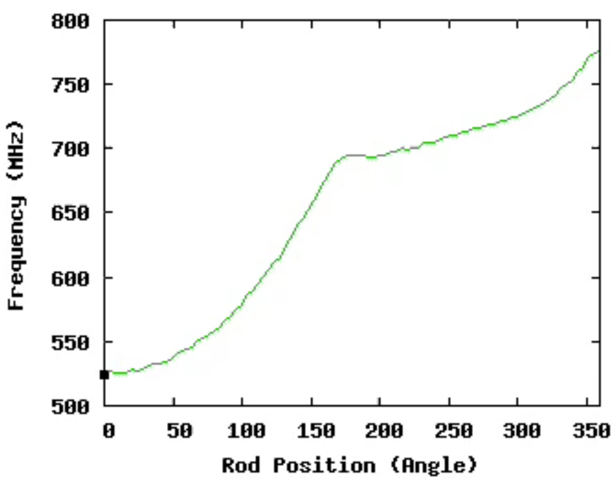

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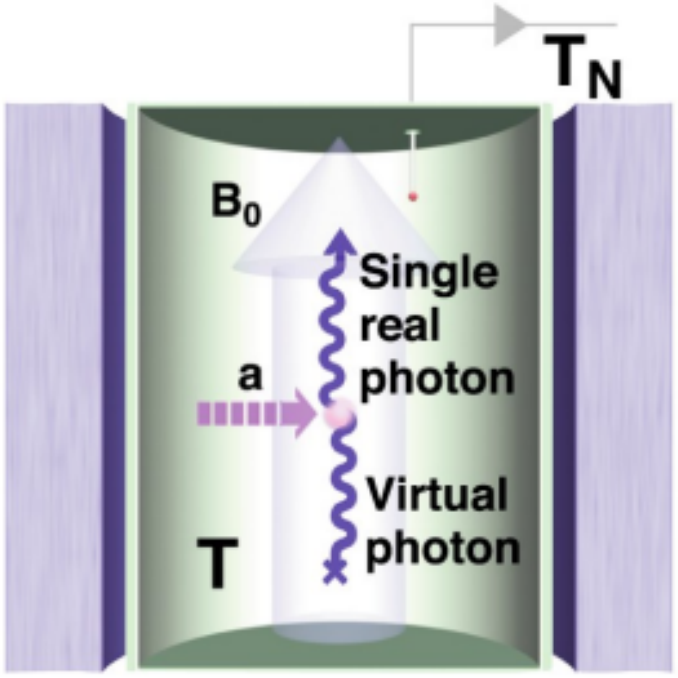

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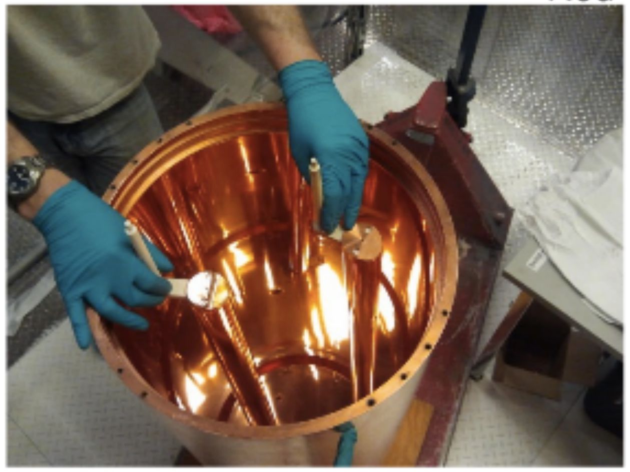
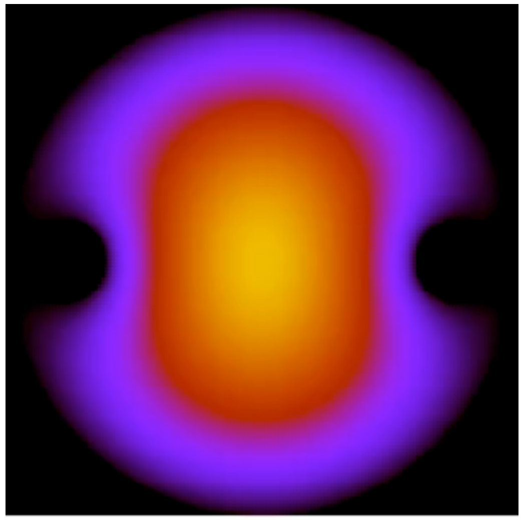
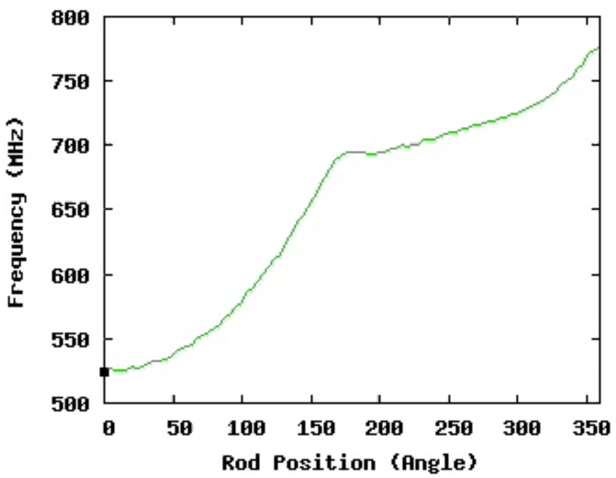






- At high freq. limited by small volume and high noise
- At low freq. by getting a large enough B-field

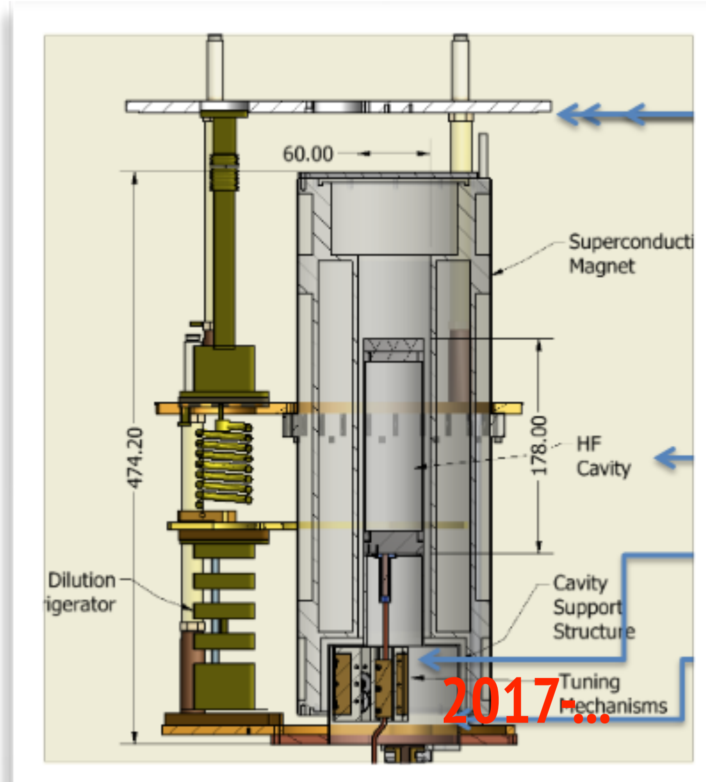
Cavity experiments

- Physical dimensions $L \sim 1/m_a$

ADMX-Seattle

new data!!!

CULTASK - CAPP -Korea



2017-...

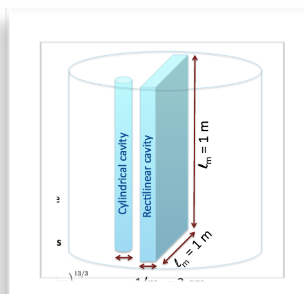
ORGAN-UWA Perth

2017-...

HAYSTAC-Yale

2016-...

ADMX-Fermilab



RADES

2017-...

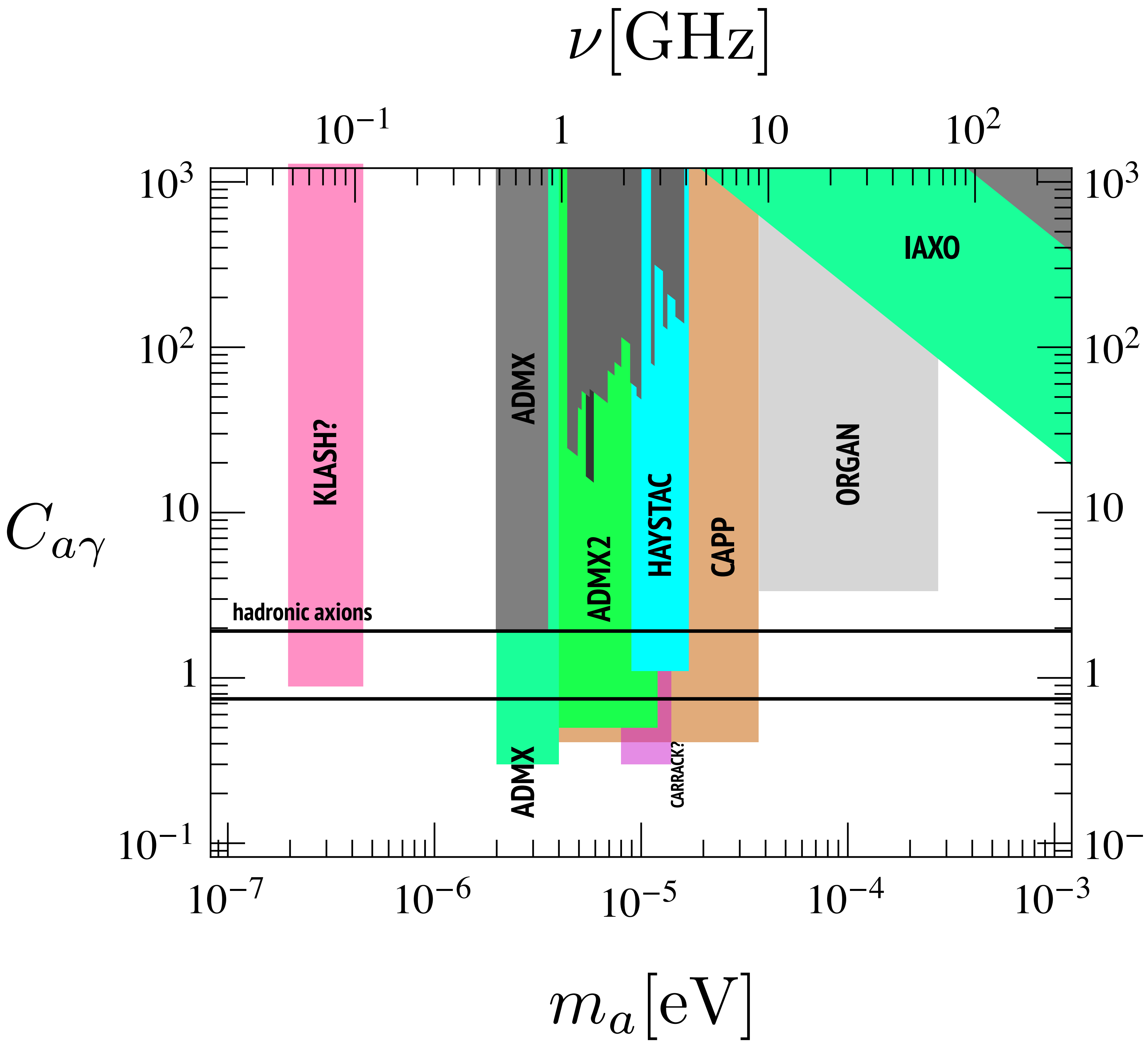
CAST-CAPP

2017-...

KLASH?

??-...

Projected optimistic sensitivities



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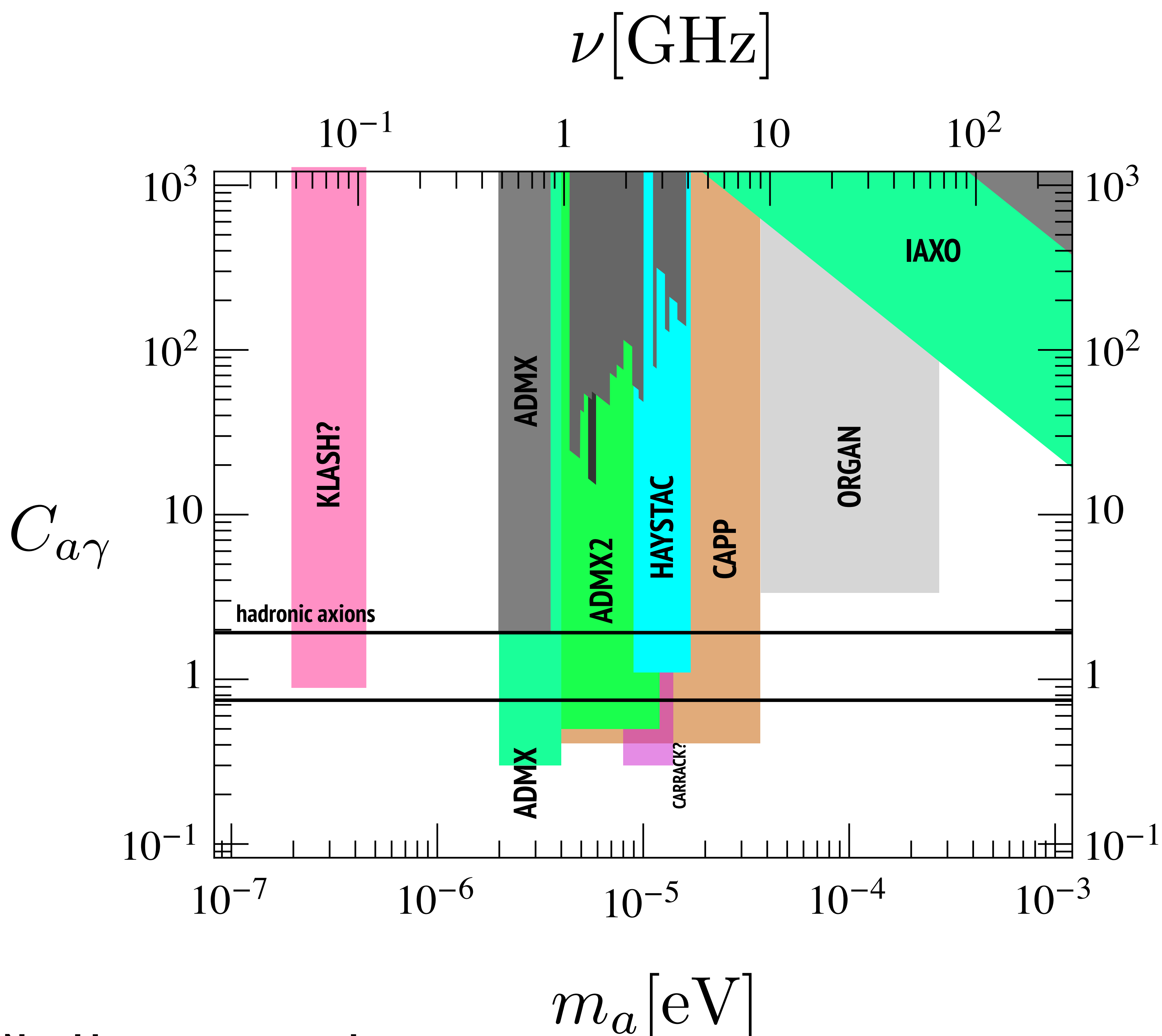
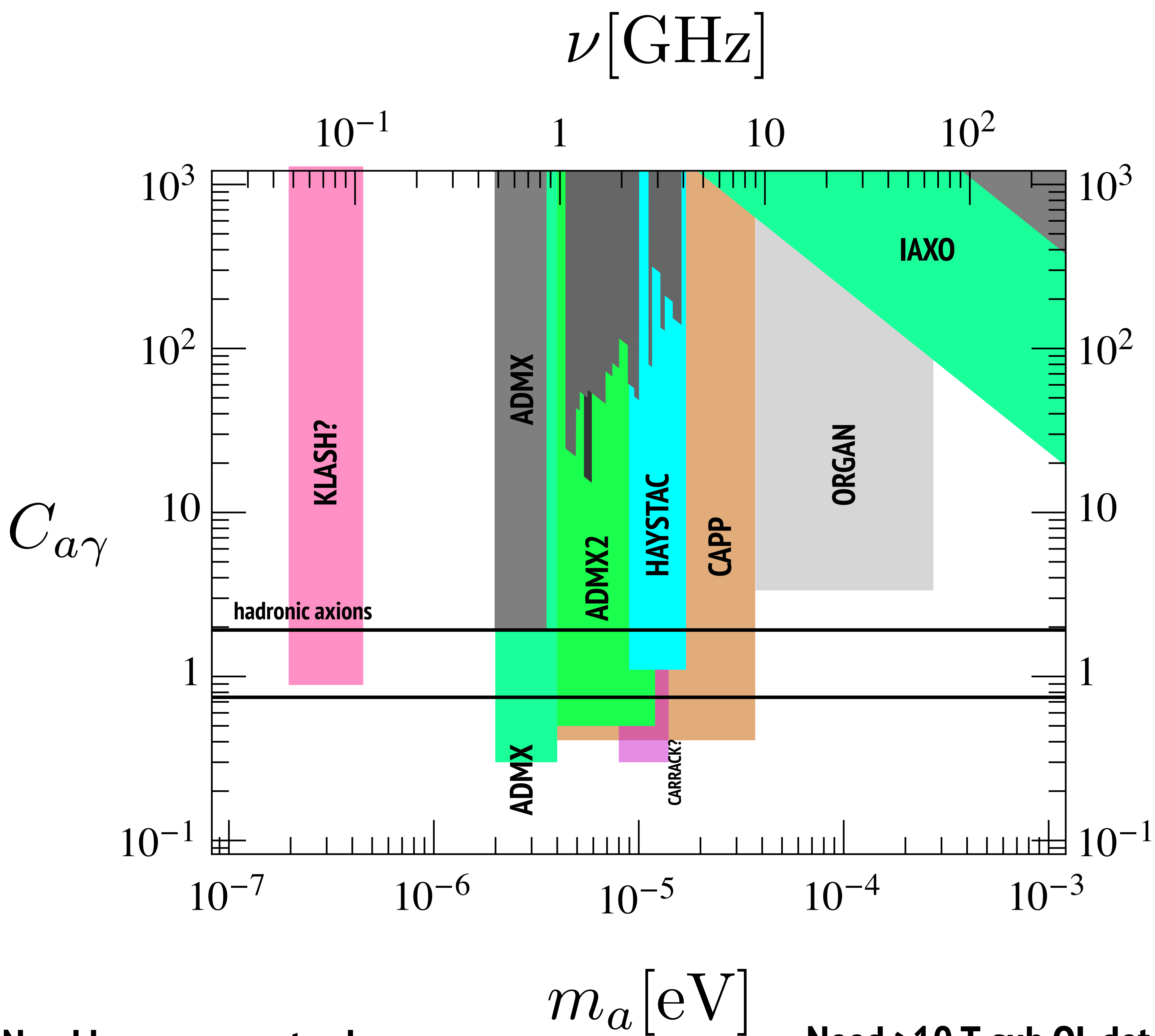


- Need larger magnet volume

Projected optimistic sensitivities



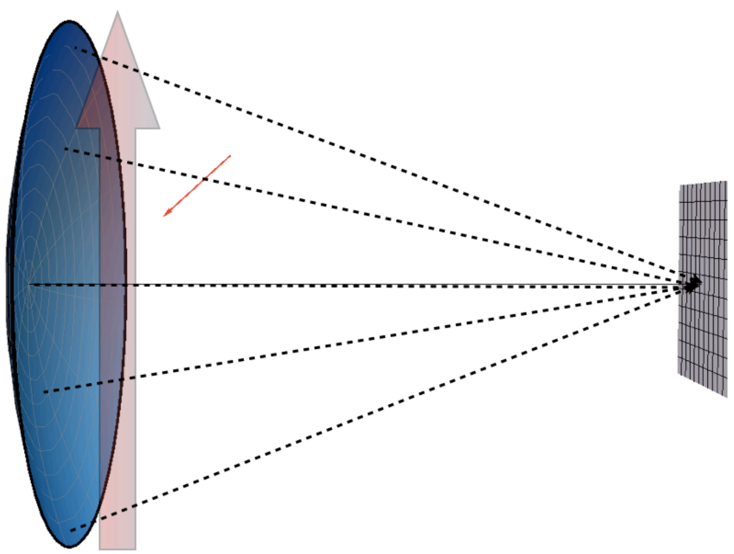
- Need larger magnet volume

- 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?



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

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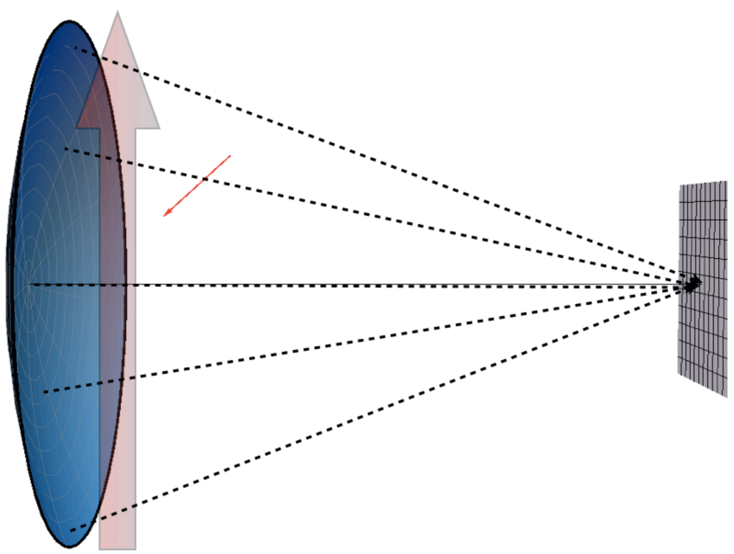

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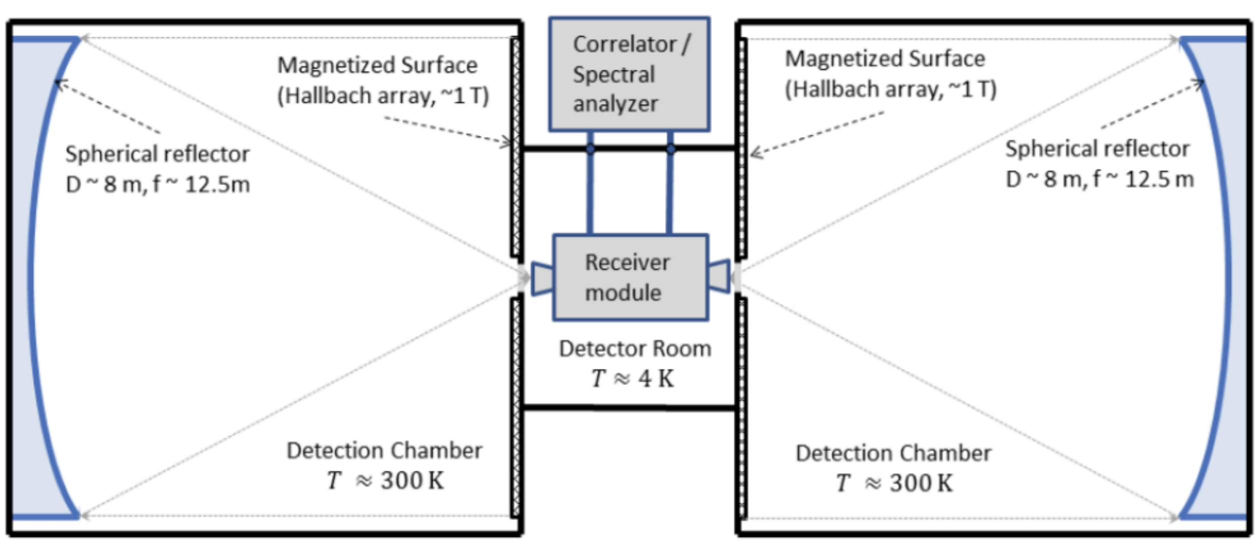

BRASS @ Hamburg

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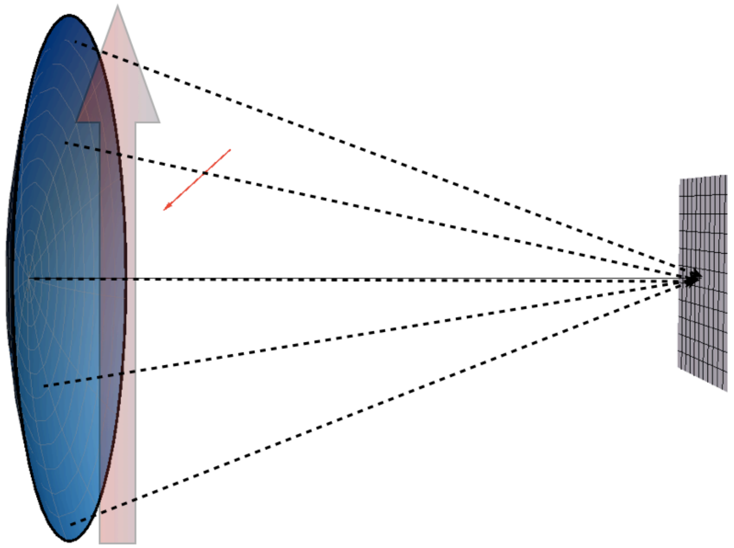

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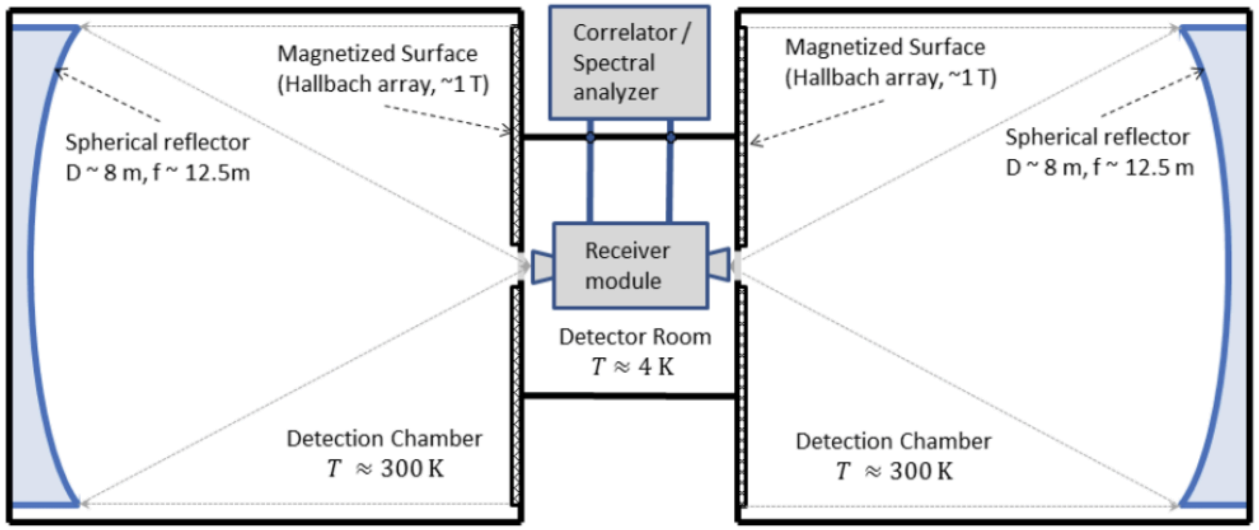

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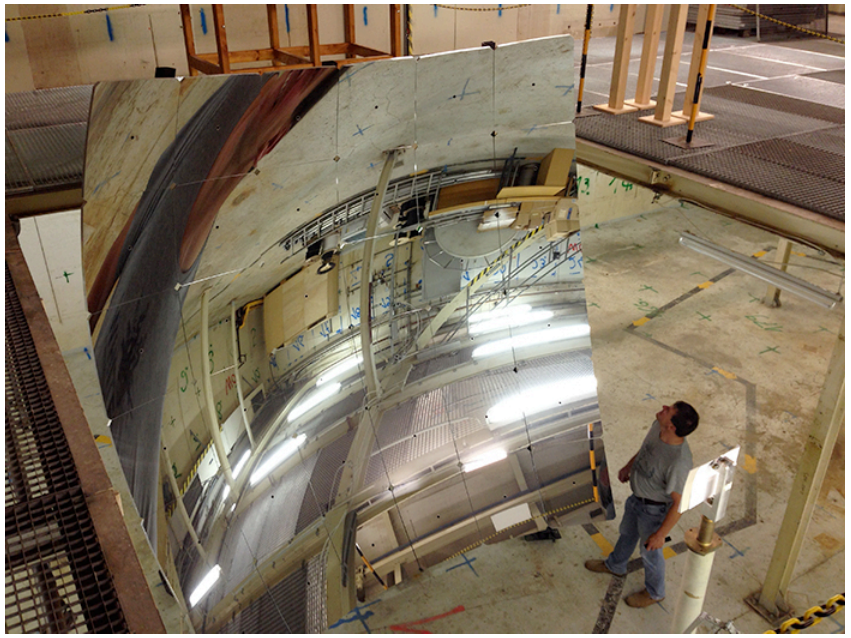


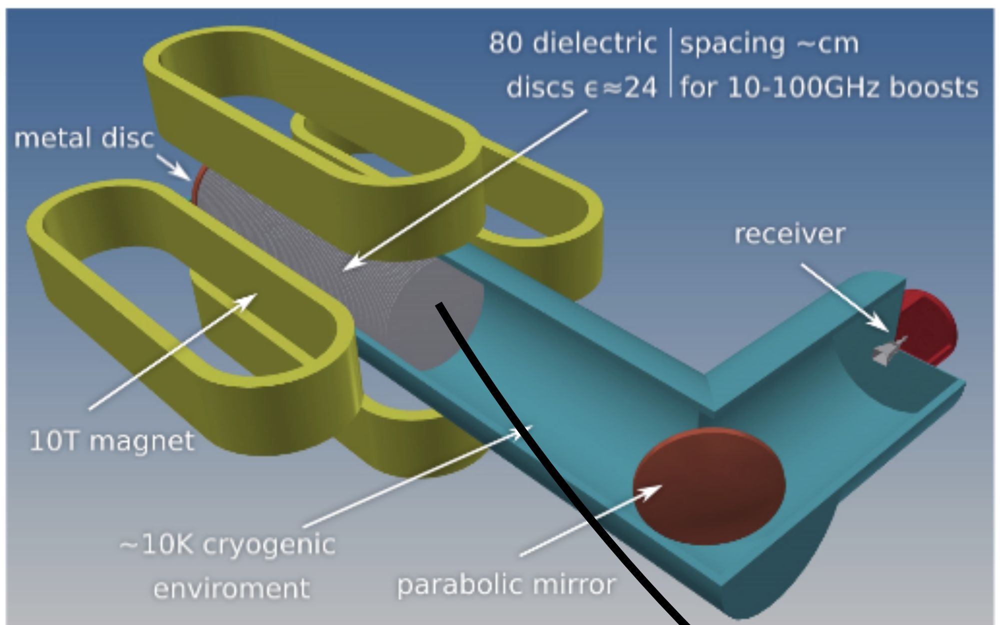
FUNK experiment (KIT)

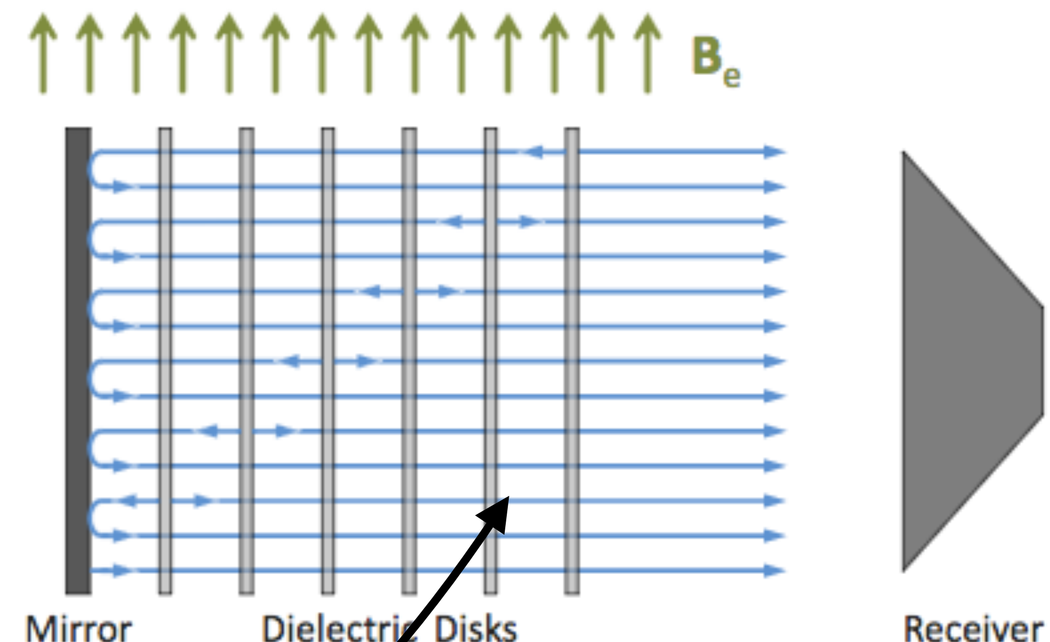
Dielectric haloscope : MADMAX

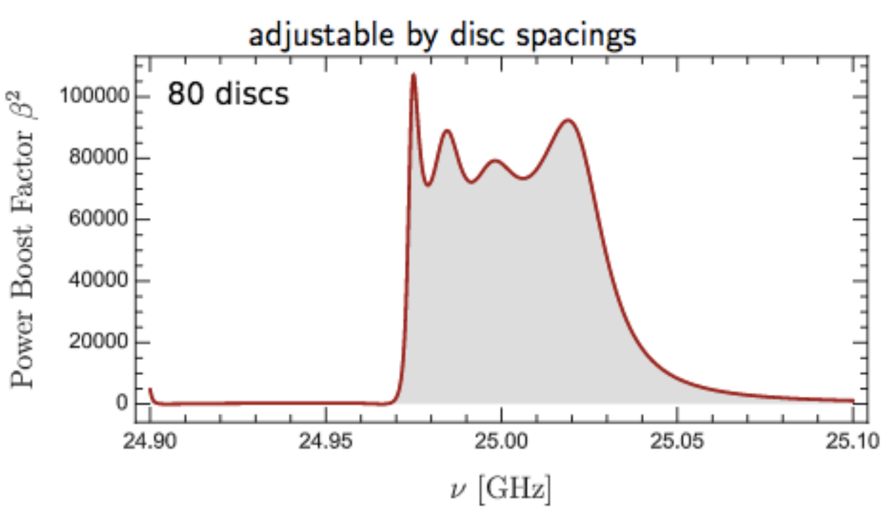
- Hybrid system, large area + multiple emitters + a bit of resonant enhancement

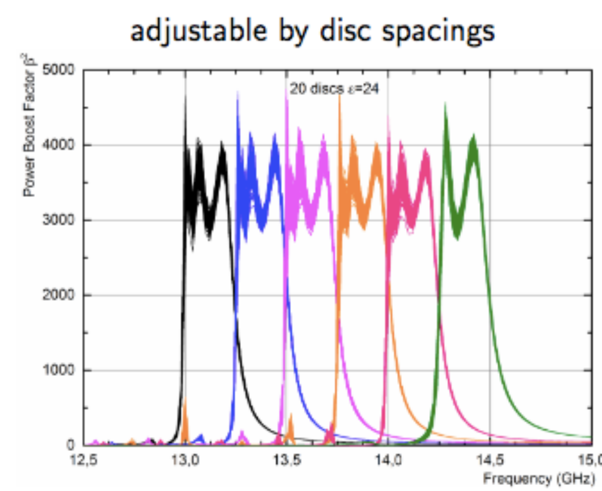
$$\frac{P}{Area} \sim 2\times 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{c_\gamma}{2}\,\frac{B_{||}}{5\mathrm{T}}\right)^2 \frac{1}{\epsilon} \times \beta(\omega)$$

boost factor



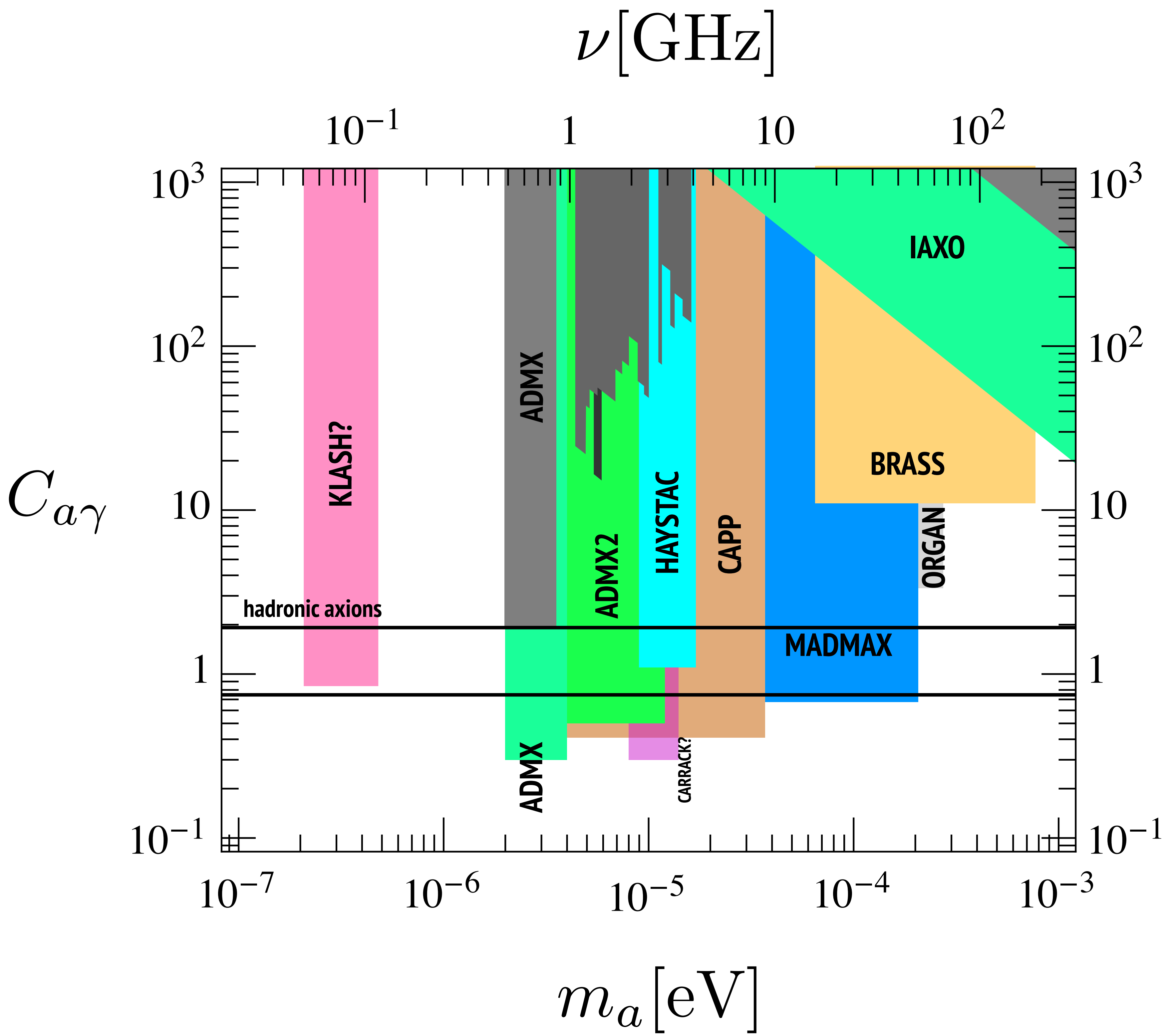




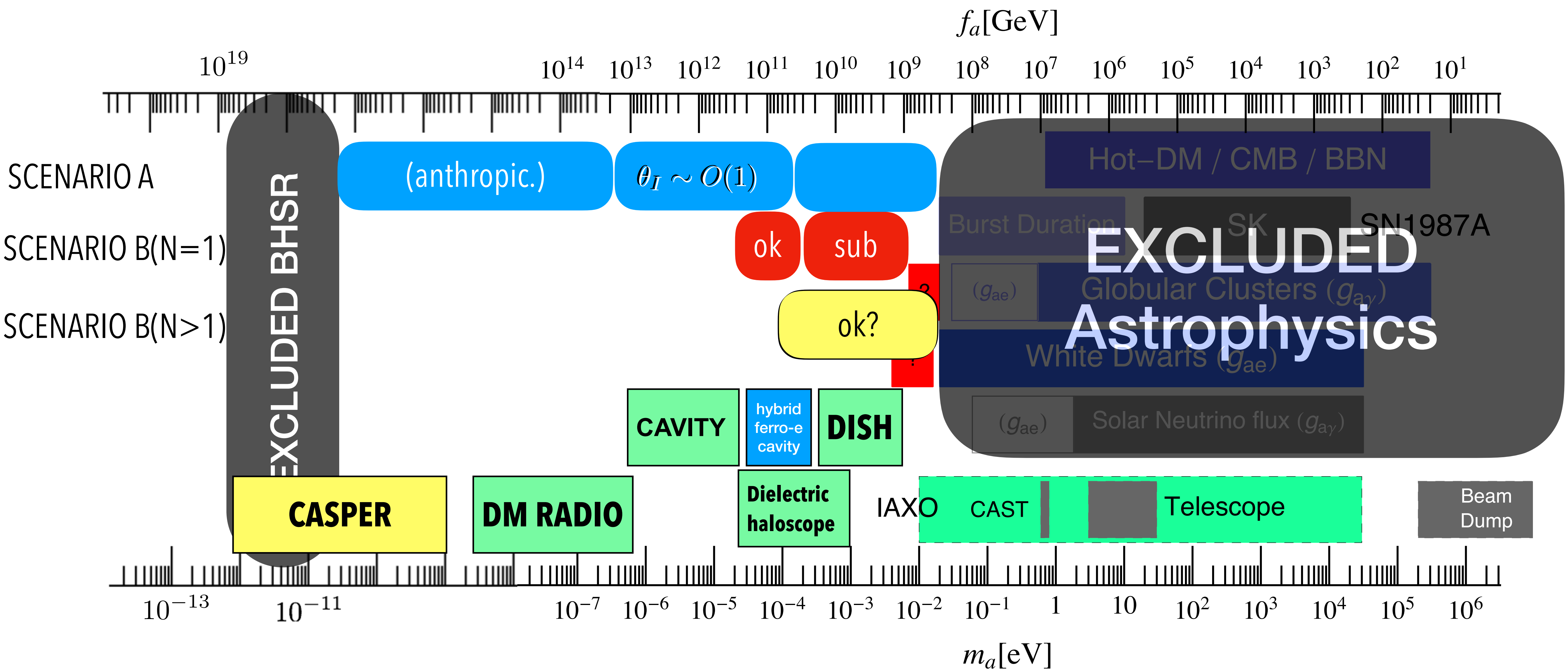


MADMAX: MAgnetised Disk and Mirror Axion eXperiment: MPP Munich, Hamburg Uni, DESY, Saclay, Zaragoza U

Projected sensitivities



DM experiments (and lab experiments)



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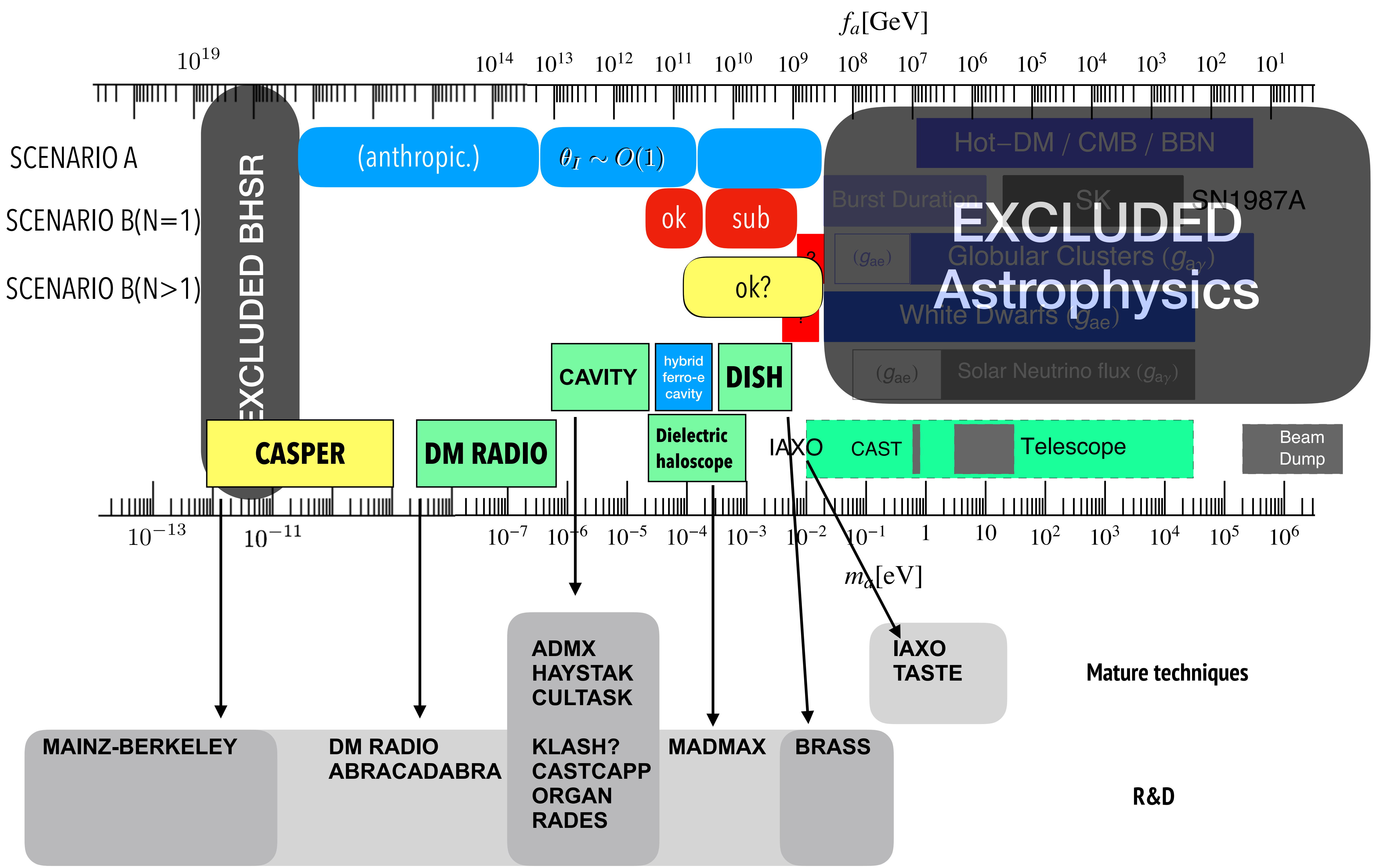
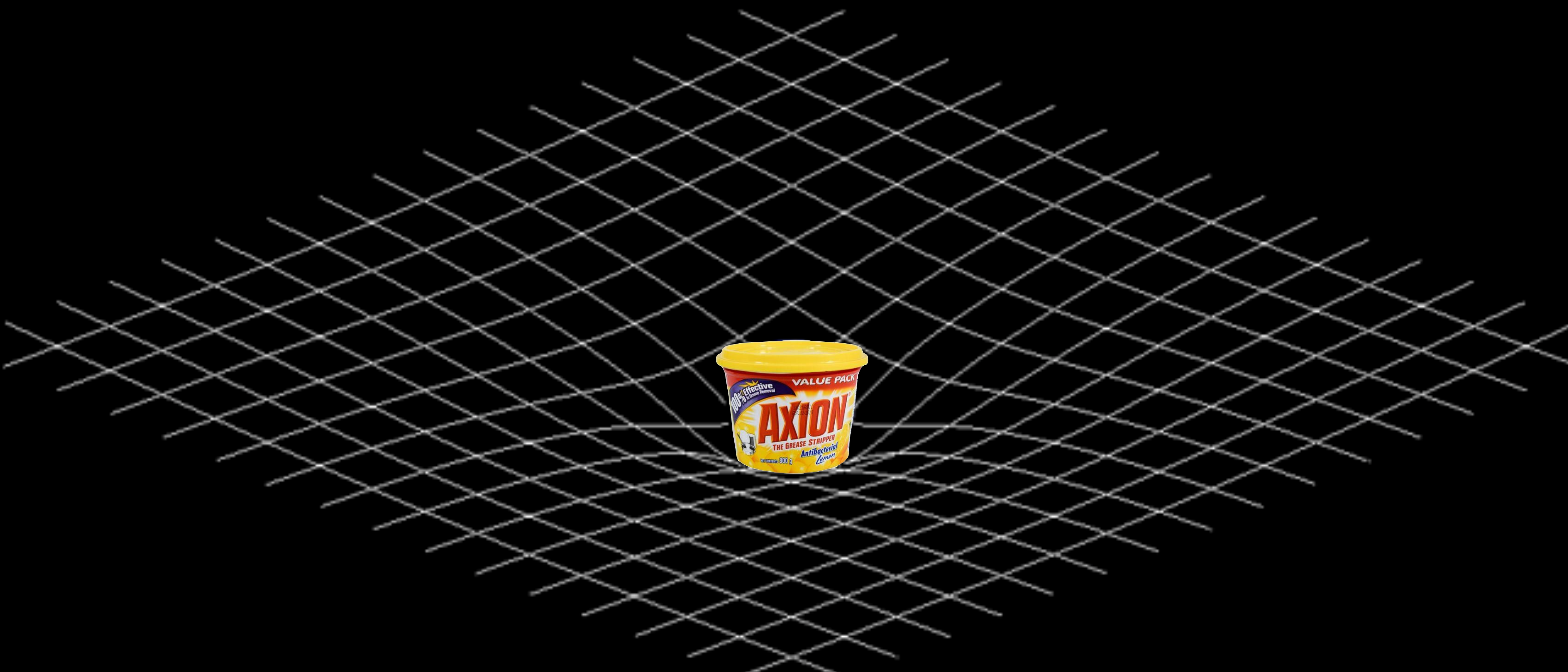


Axion DM is very different

Beyond SM

Cosmology



Dark matter

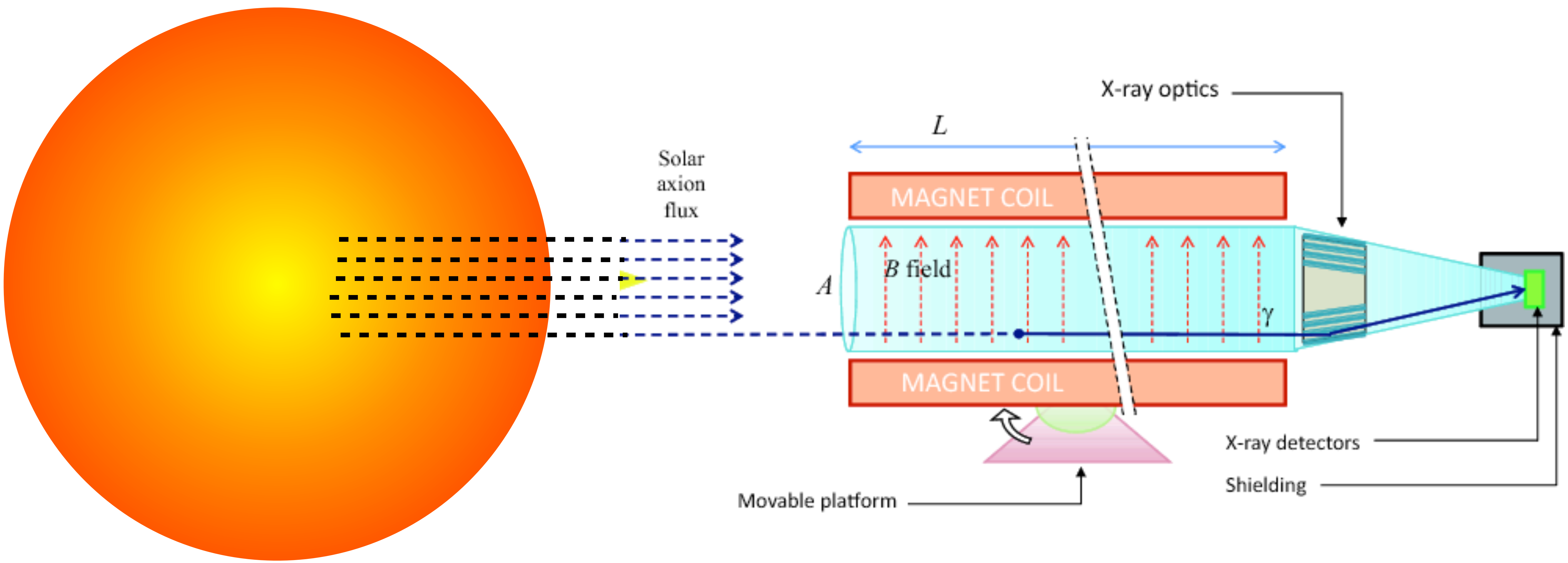
low-background,
high-B fields, NMR

and lab experiments

Helioscopes

The Sun is a copious emitter of axions!

convert into X-rays focus detect



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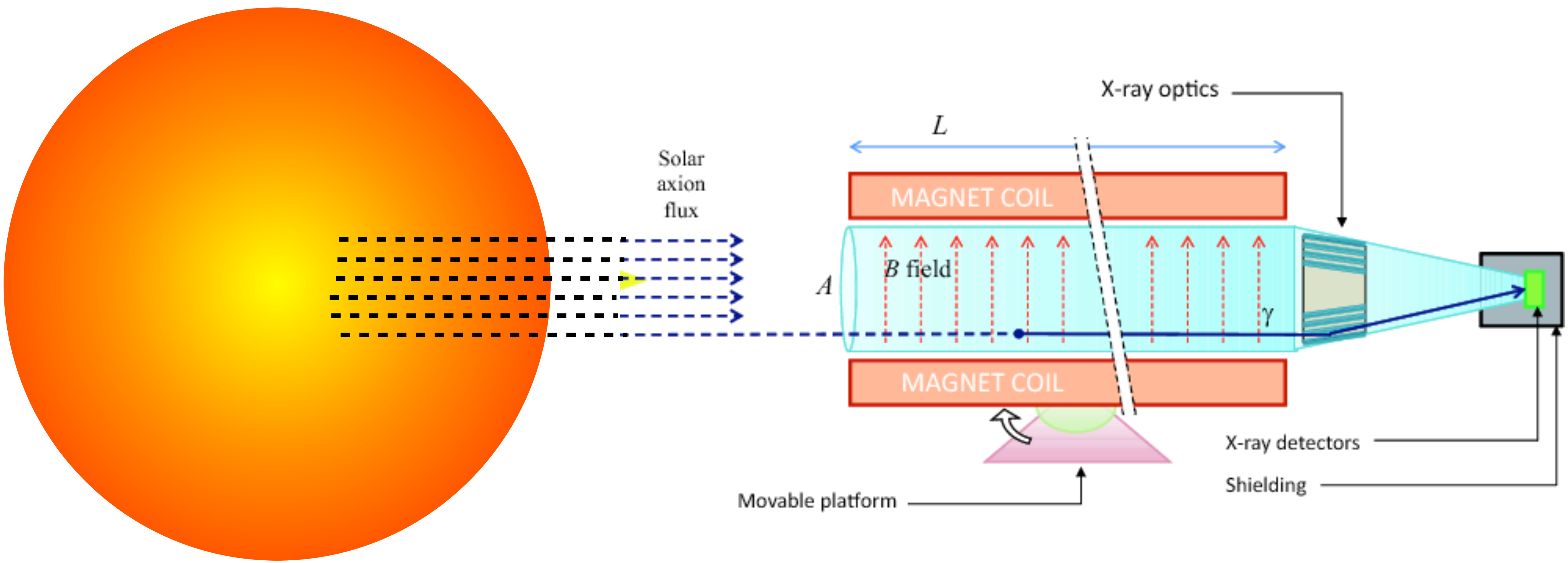
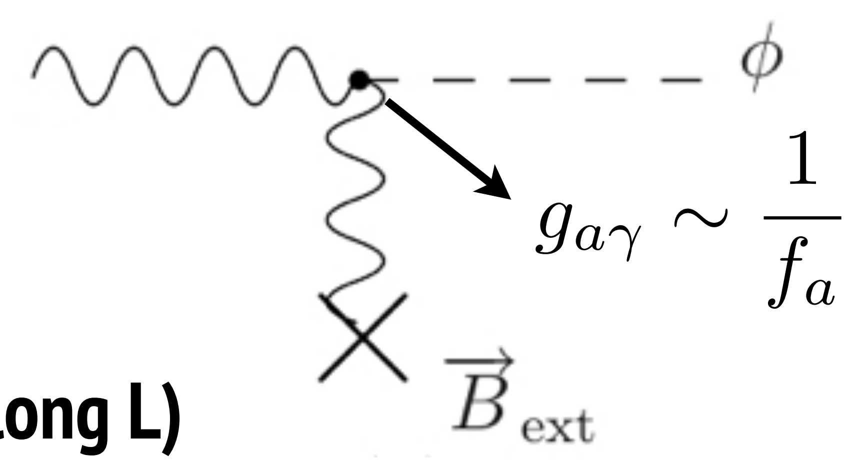


Conversion probability

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

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

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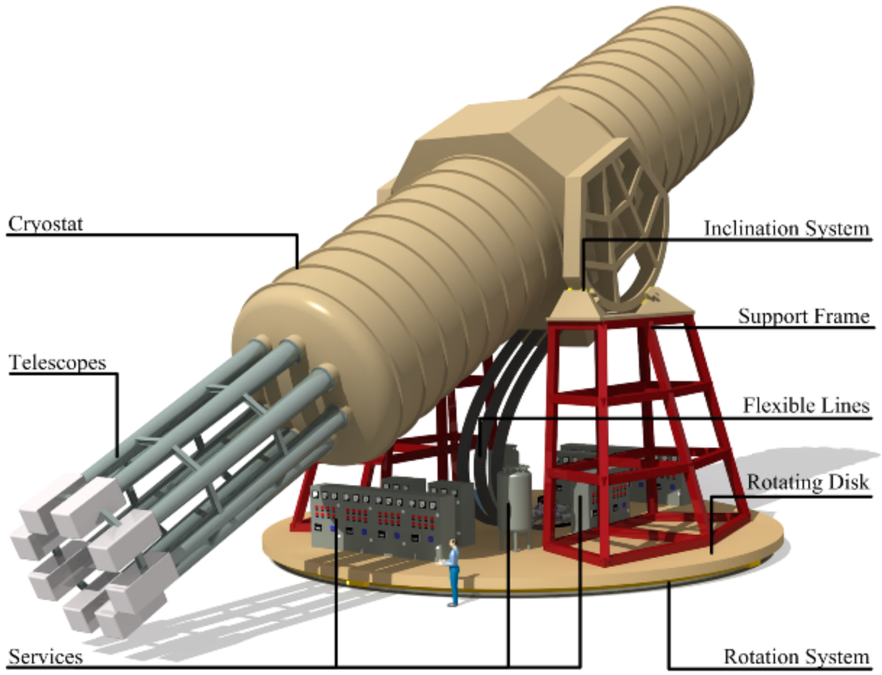
IAXO (proposed toroid) 20 m, 3T)



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

Past and the future

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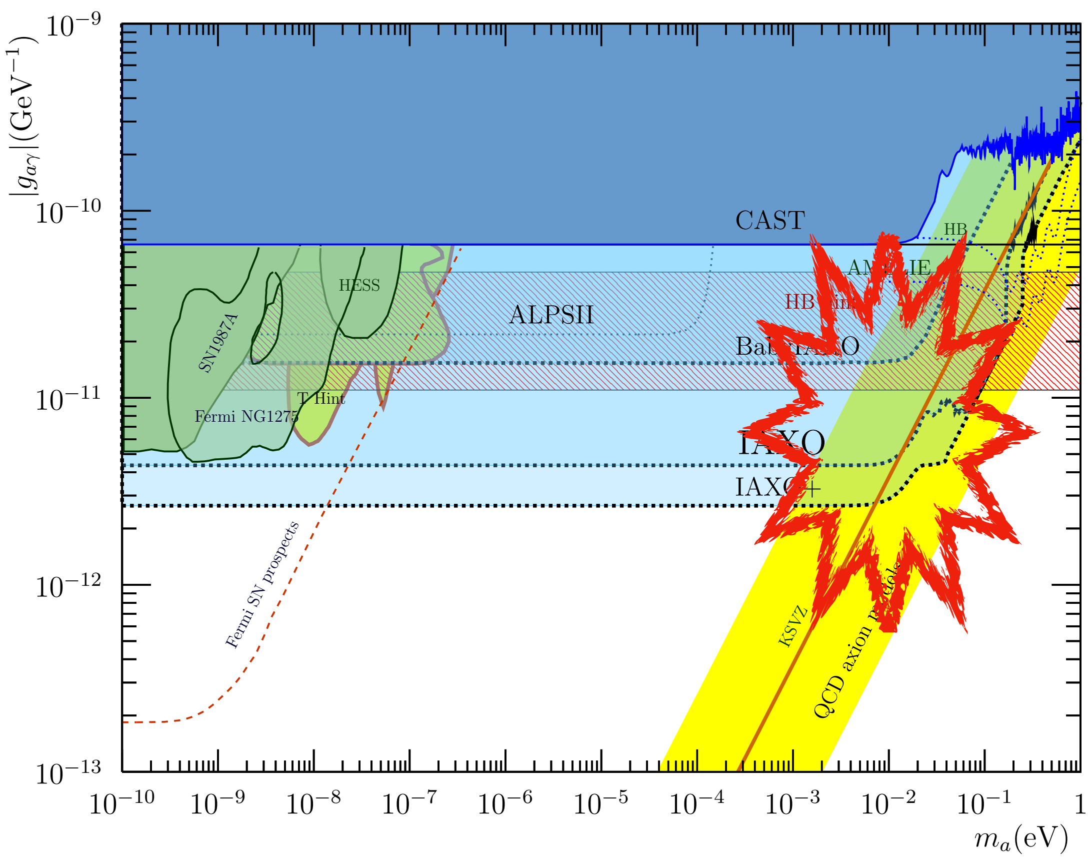
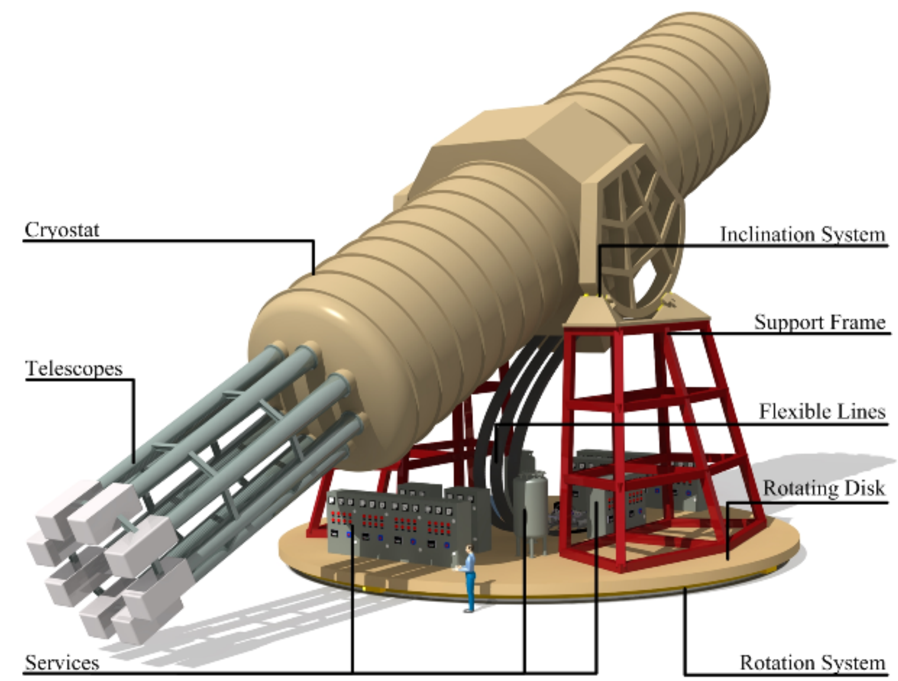
- X-ray optics
- small aperture



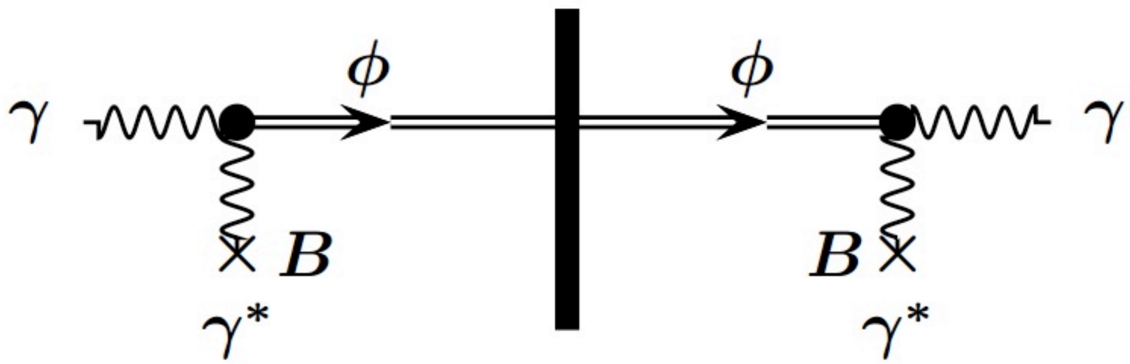
IAXO (proposed toroid) 20 m, 3T)



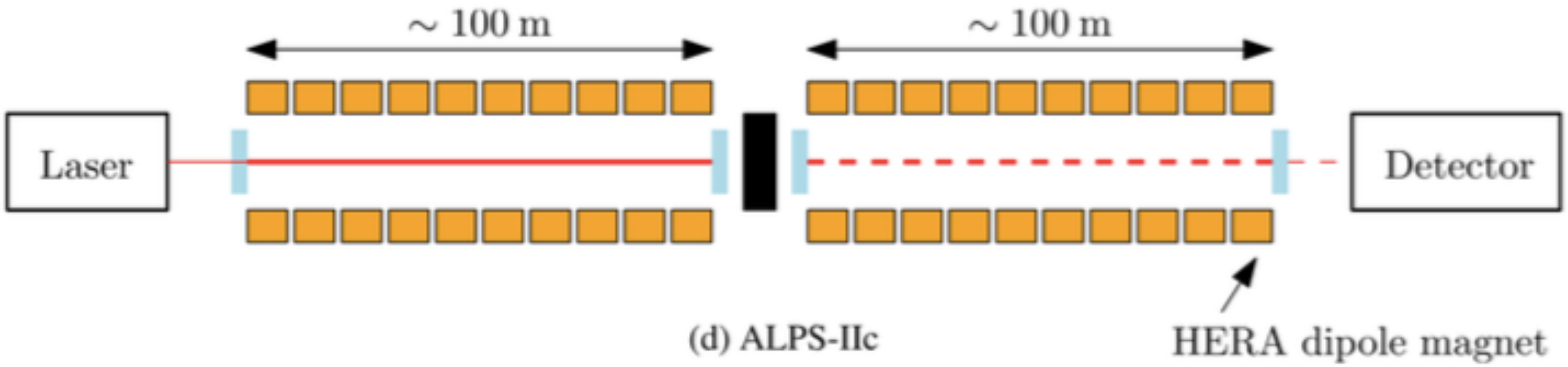
- 12 h tracking/day (sunset,dawn)
- 8 bores (60 cm diam)
- different Detectors
- dedicated X-ray optics
- Collaboration Formed 2017

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	$3.5\cdot10^{21}$	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

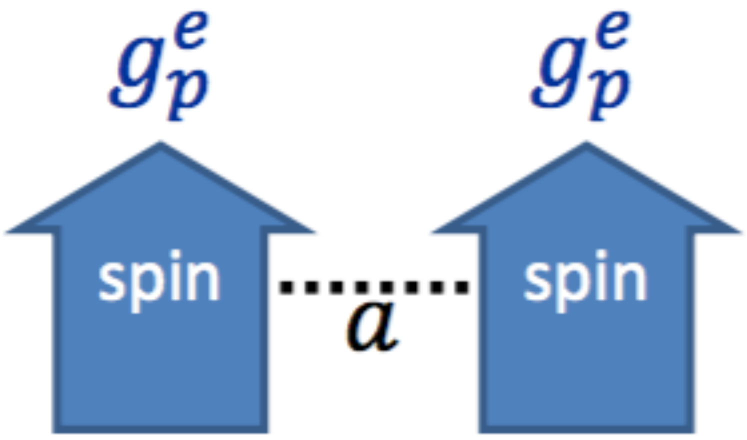
Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}$[GeV^{-1}]
ALPS-I [427]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [429]	completed	3	0.15	50	10^4	10^4	9.9×10^{-8}(*)
OSQAR [428]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [430]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [431]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

Long-range forces

Wilczek '84, Geraci 14

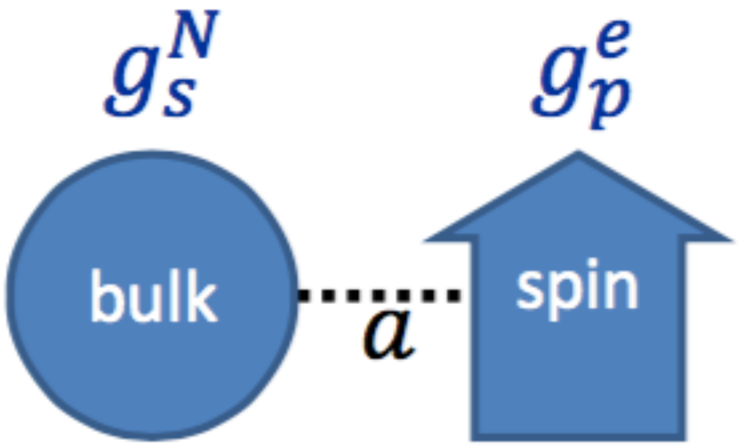
Long-range forces between macroscopic bodies

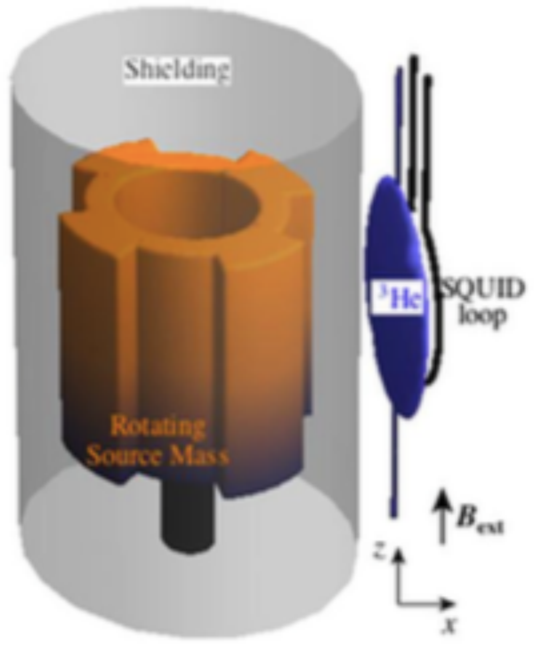
p-p forces are spin-spin ... very hard to measure!



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

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





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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