Axions and ALPs hints and experiments

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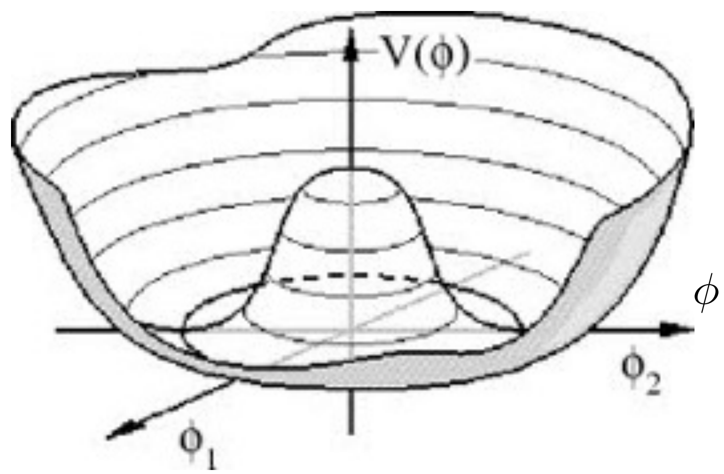
(Zaragoza U. & MPP)

DAνCo
DArk matter, νs and their Connections
28.08-01.09.
2017

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 $\theta(x) \rightarrow \theta(x) + \alpha$

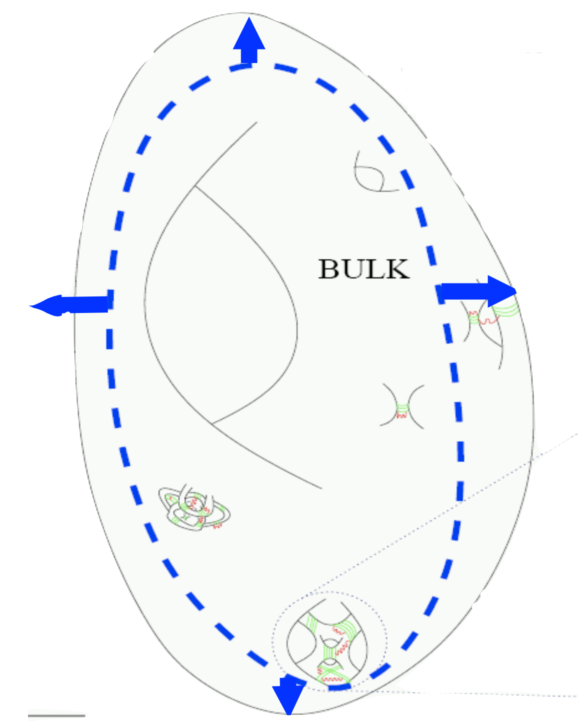
$$\mathcal{L}_{\rm kin} = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f^2$$

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

- small symmetry breaking ⟶ 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

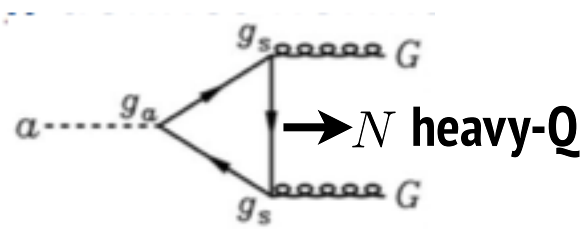
- **Shift symmetry allows some generic types of interactions**

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

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

(canonically normalised)

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



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

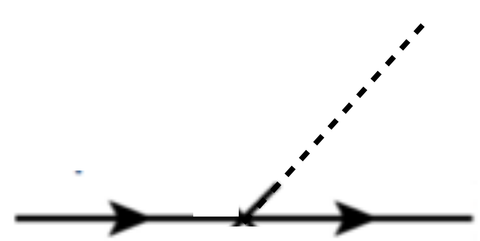
$$V(A) \sim \frac{1}{2}\chi_{\rm QCD}\left(\frac{A}{f_A}\right)^2 = \frac{1}{2}m_A^2 A^2$$

photon coupling

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

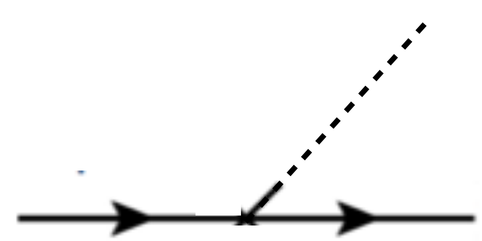
electron coupling

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



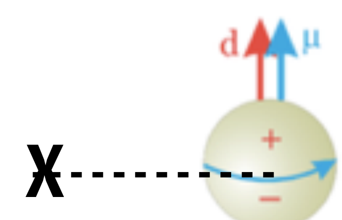
nucleon coupling

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



~~CP~~ Neutron electric dipole

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



4 hints

Strong CP problem / PQ solution

$$\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\theta_{\rm SM} \Rightarrow d_n \sim \frac{e}{m_n}\theta_{\rm SM} < 5\times 10^{-12}\frac{e}{m_n}$$

why!! $\theta_{\rm SM} < 10^{-11}$!!

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$$\Downarrow$$

$$V(A)\sim\frac{1}{2}\chi\left(\theta_{\rm SM}+\frac{A}{f_A}\right)^2$$

potential min.

$$\langle A\rangle/f_A=-\theta_{\rm SM}$$

The QCD Axion cancels the effect of any constant $\theta_{\rm SM}$

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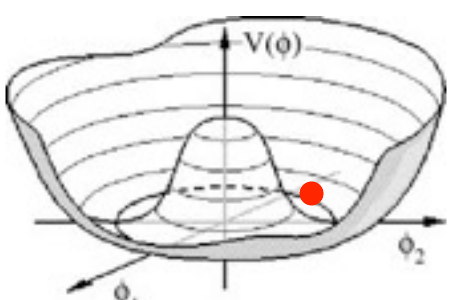
Dark matter / vacuum realignment



pick up a vacuum when quasi-degenerate

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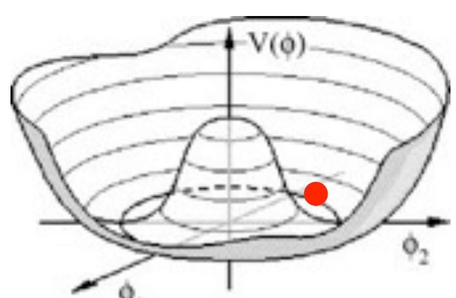

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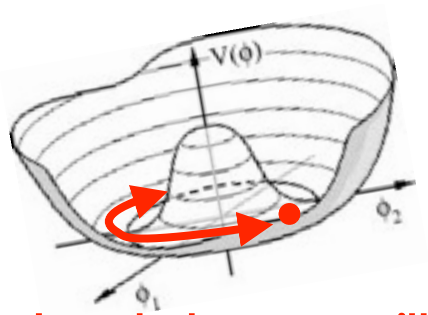

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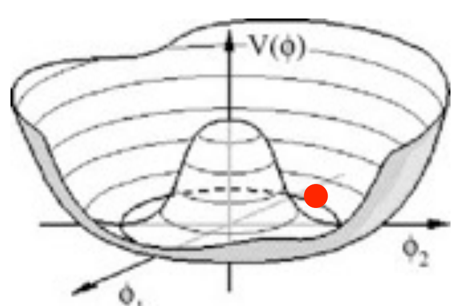

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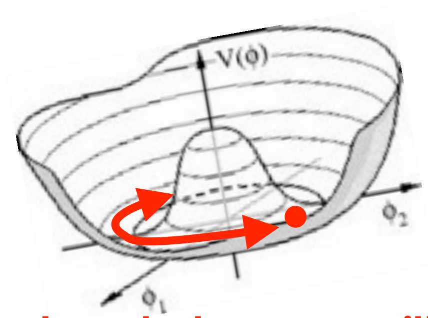

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cold DM in oscillations [cosmology dependent]

$$\Omega h_c^2 \simeq 0.12\sqrt{\frac{m_a}{\rm meV}}\left(\frac{a_i}{3\times 10^{12}\,\rm GeV}\right)^2$$

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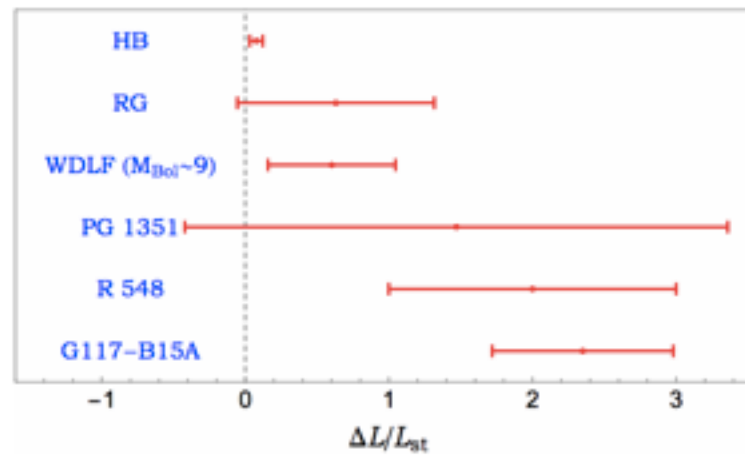
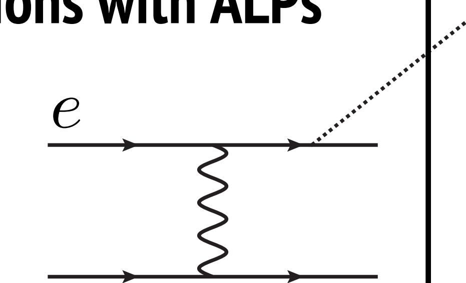
Anomalous Star cooling / ALP emission

Theory fits better some observations with ALPs



Giannotti 2016



ALP bremstrahlung

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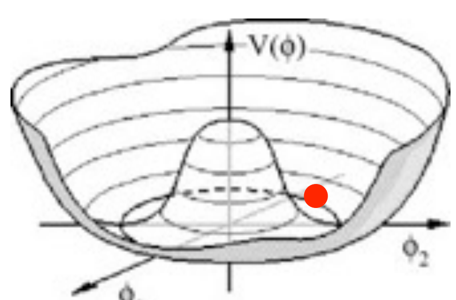

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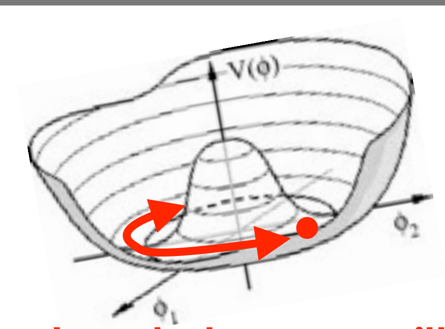

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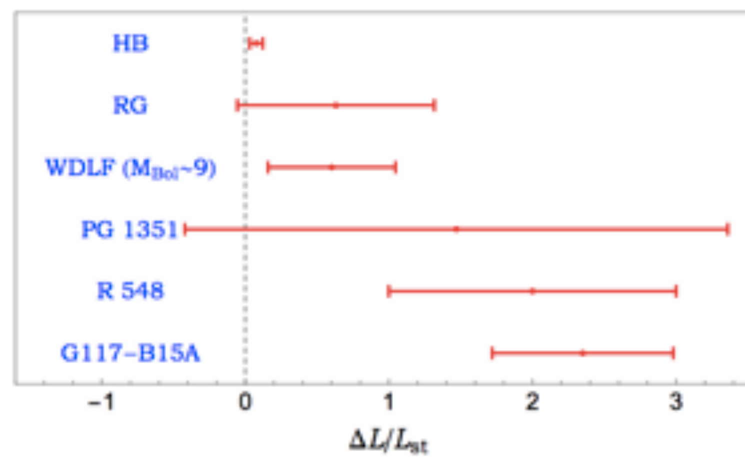

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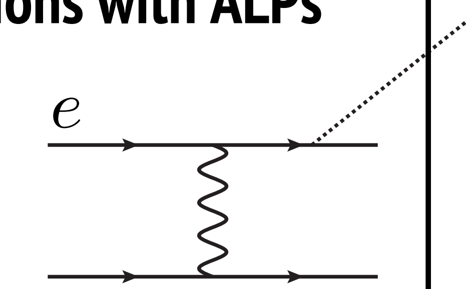

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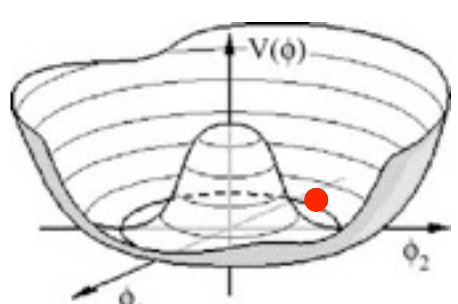

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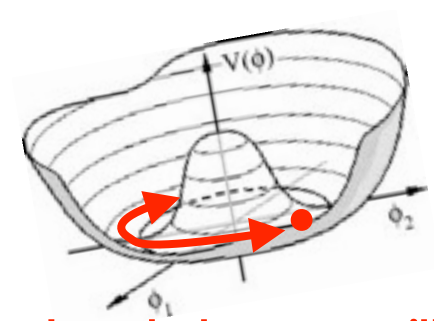

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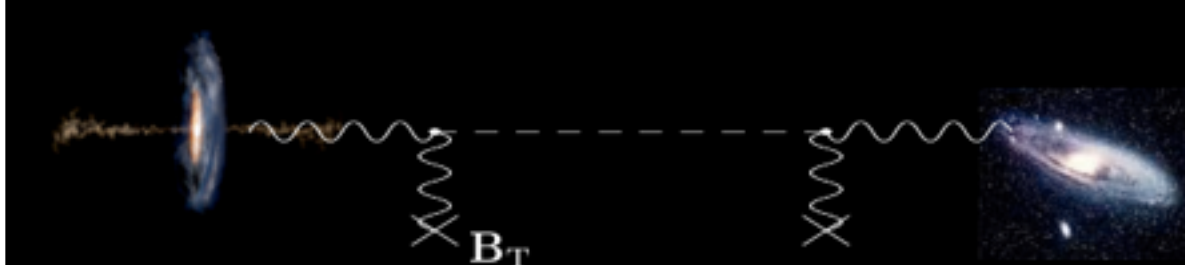
γ-ray transparency / photon regeneration

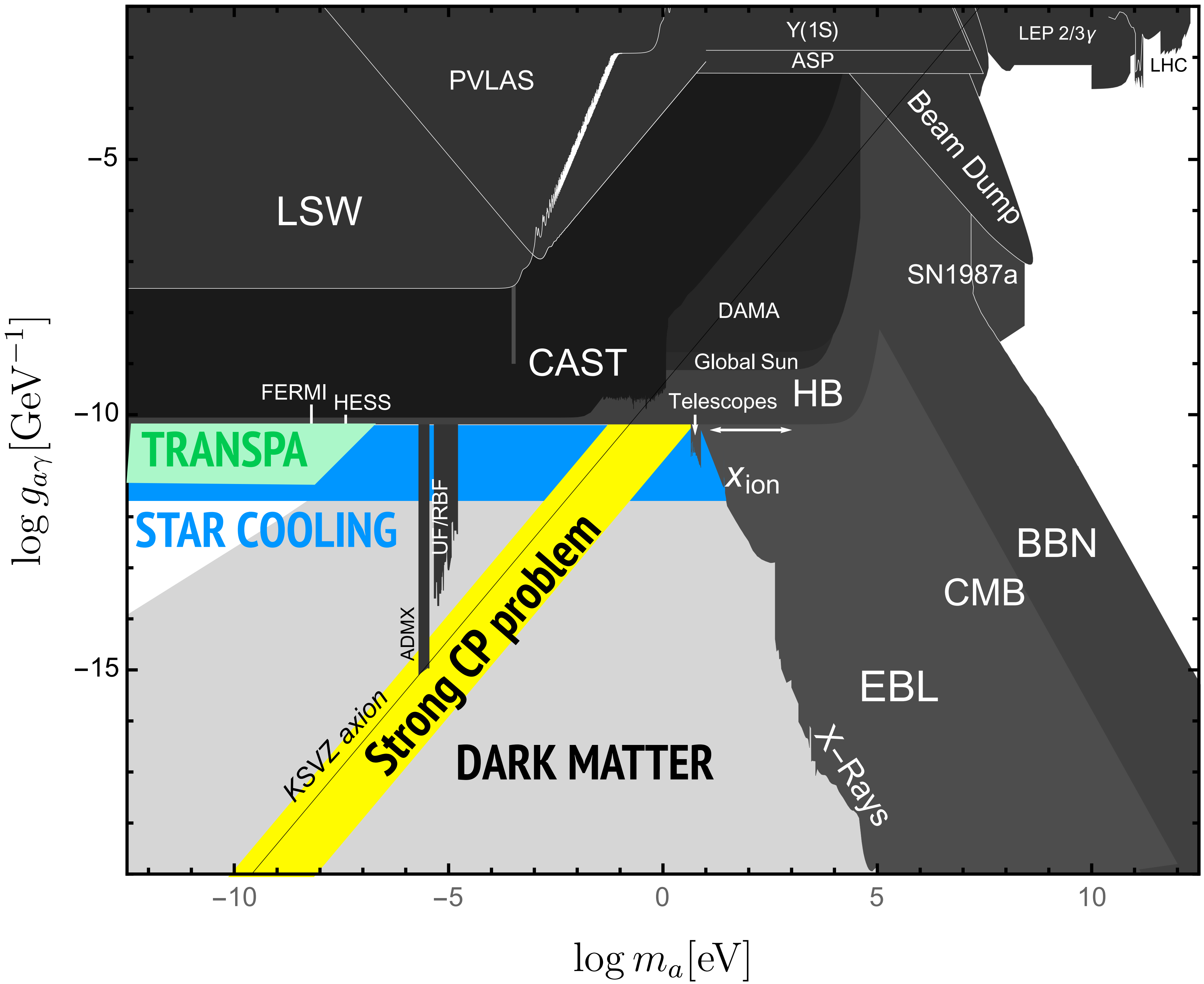
Too many gamma-rays from far away sources?



low estimate of opacity vs ALP-mediated regeneration

Trostski 2017

Hints and constraints (photon coupling example)



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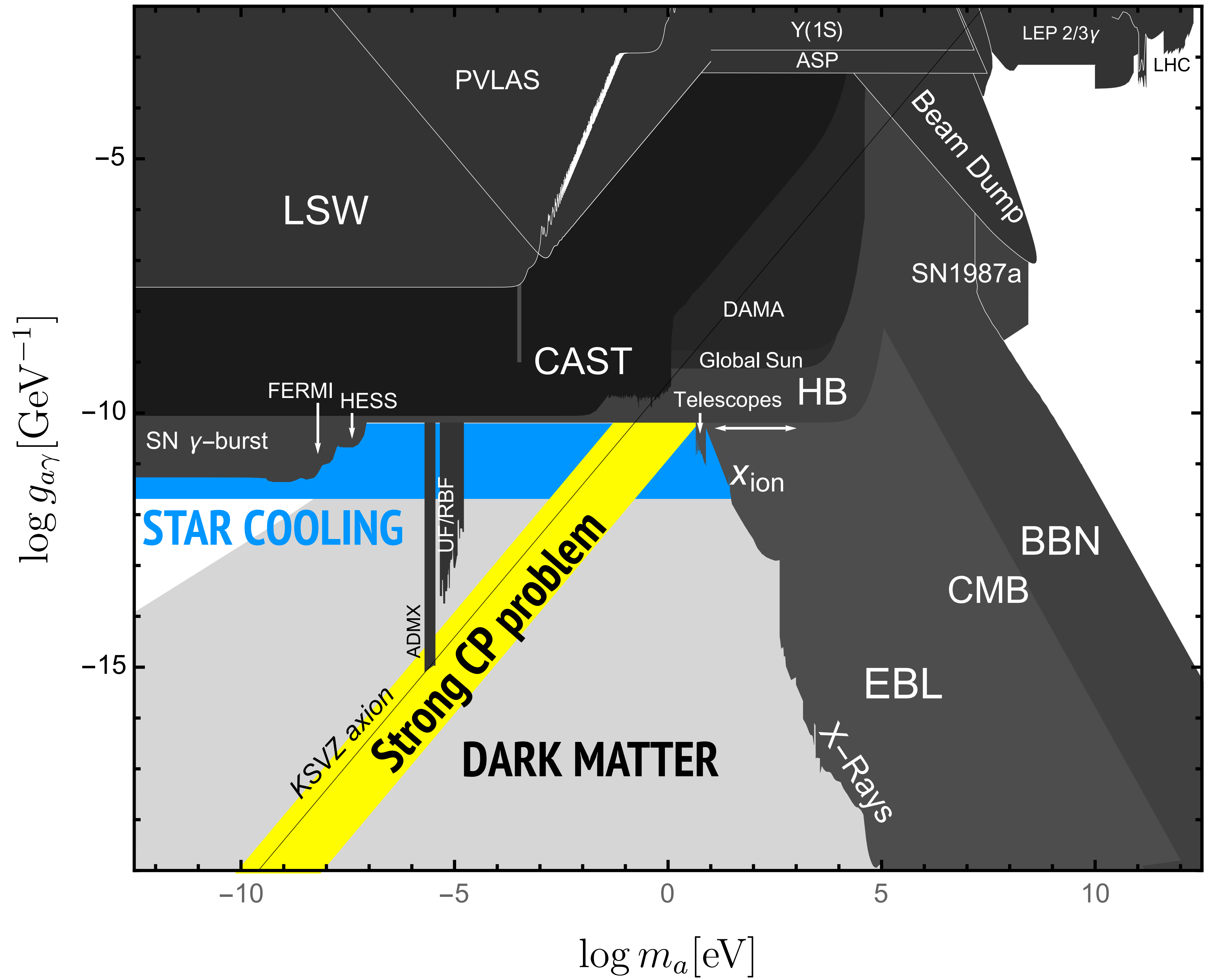
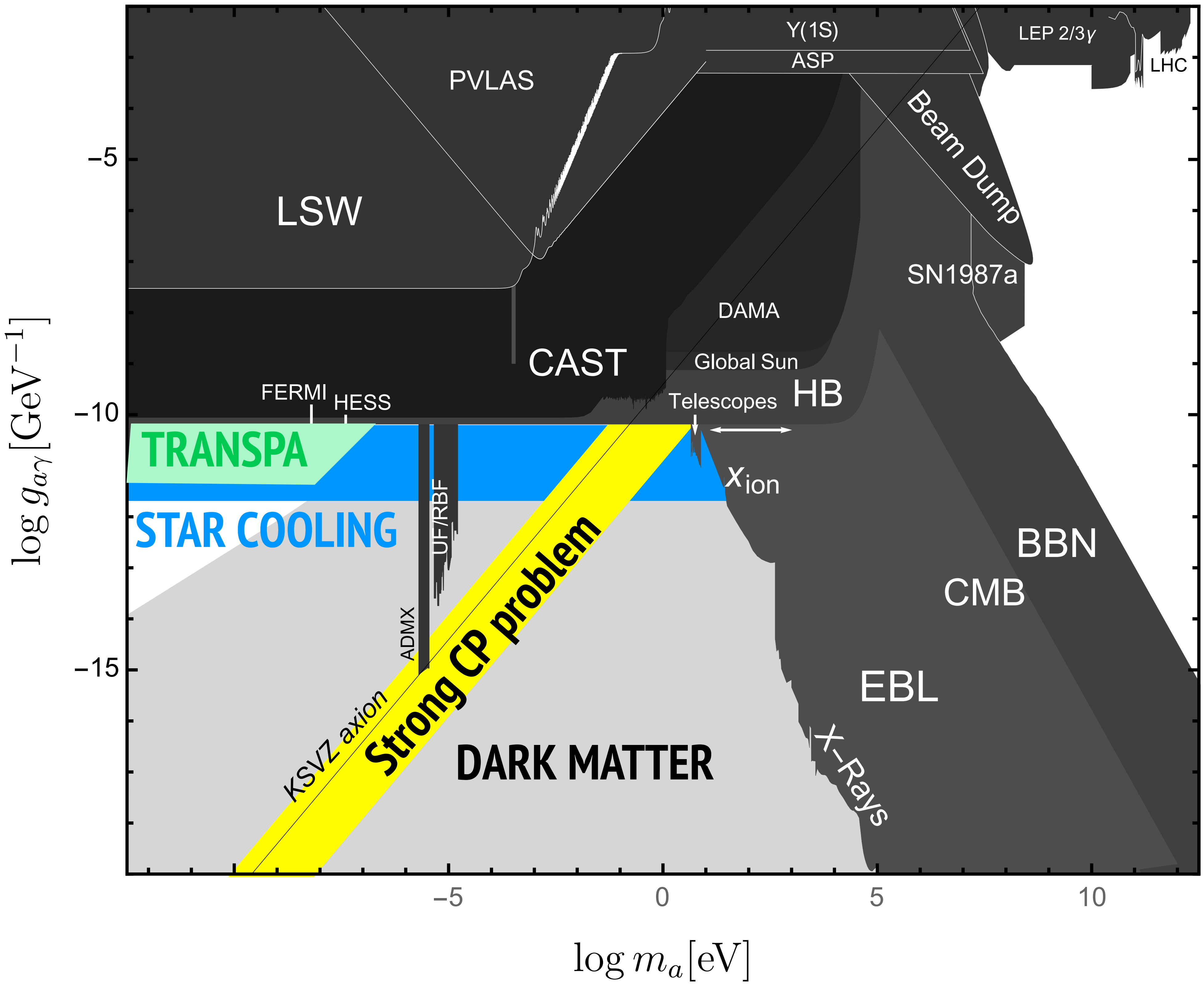


birds and stones ...



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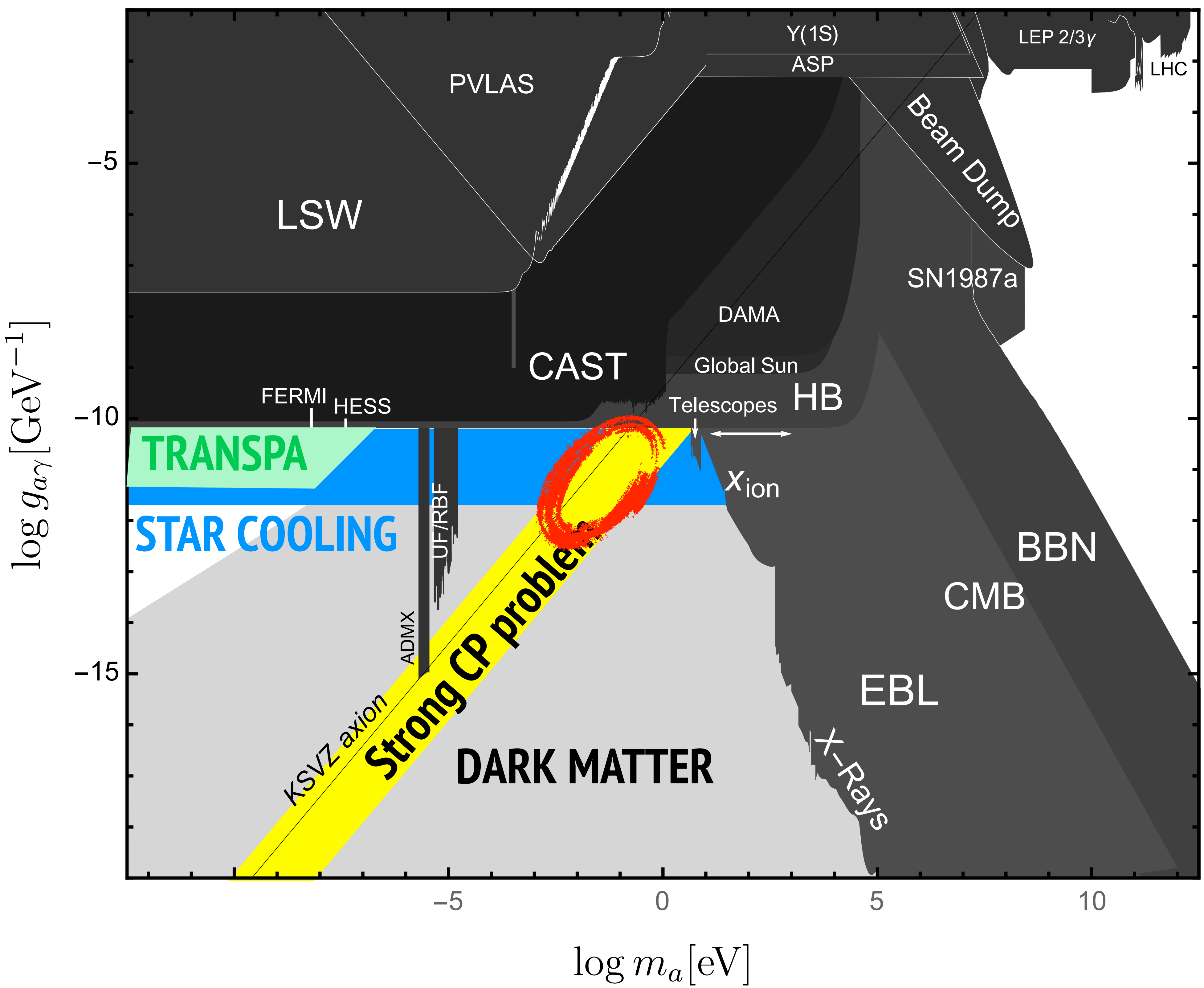

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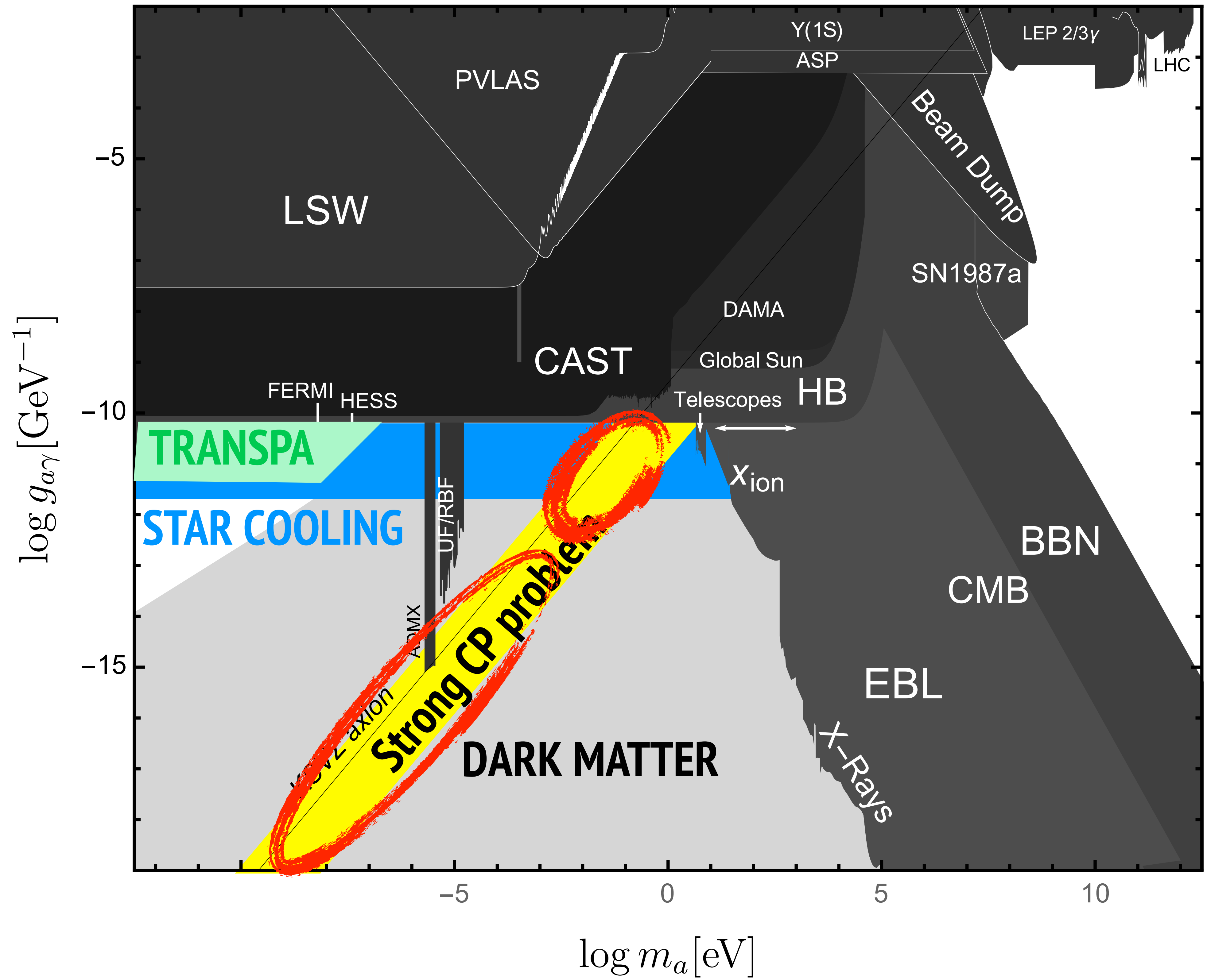

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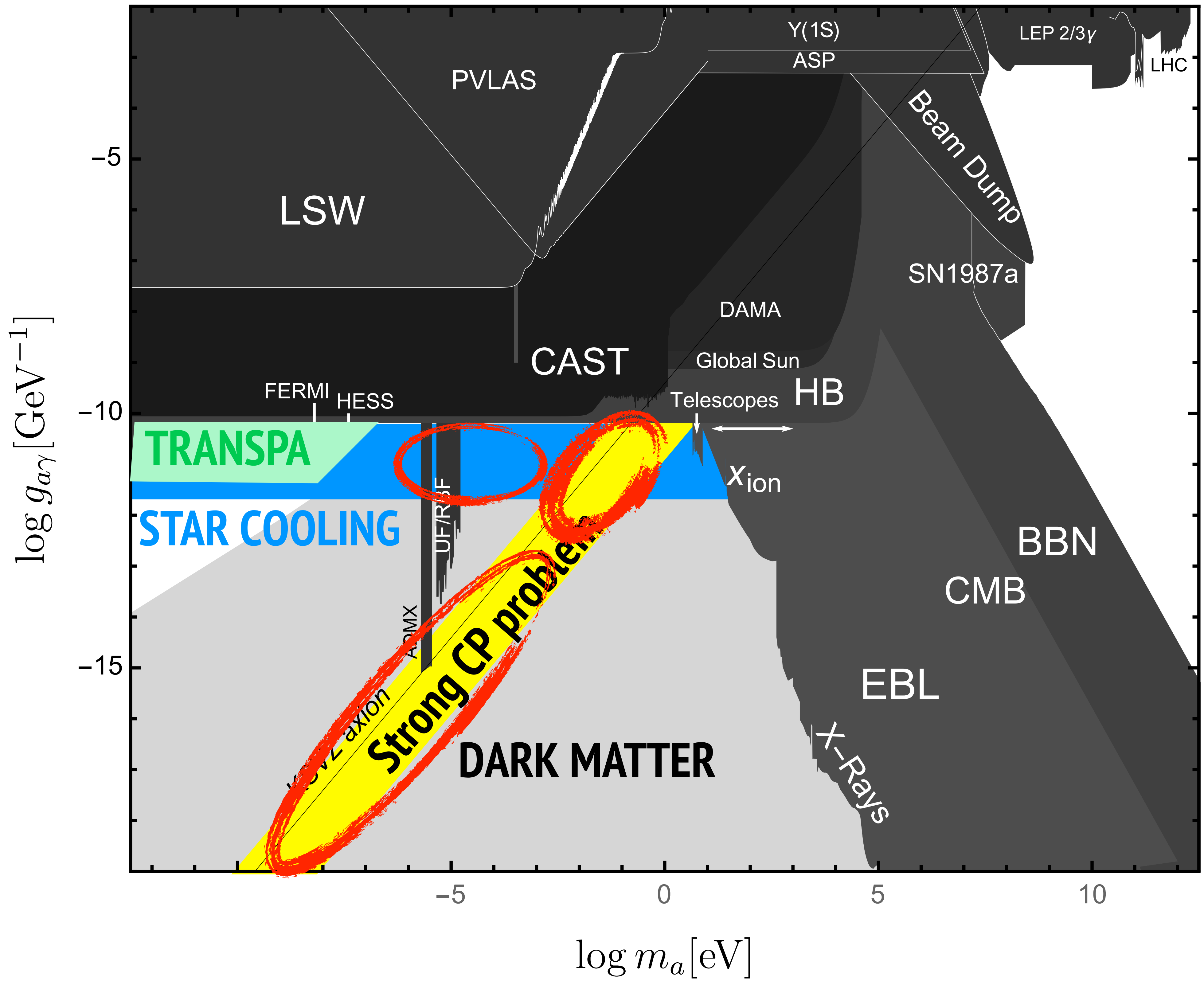

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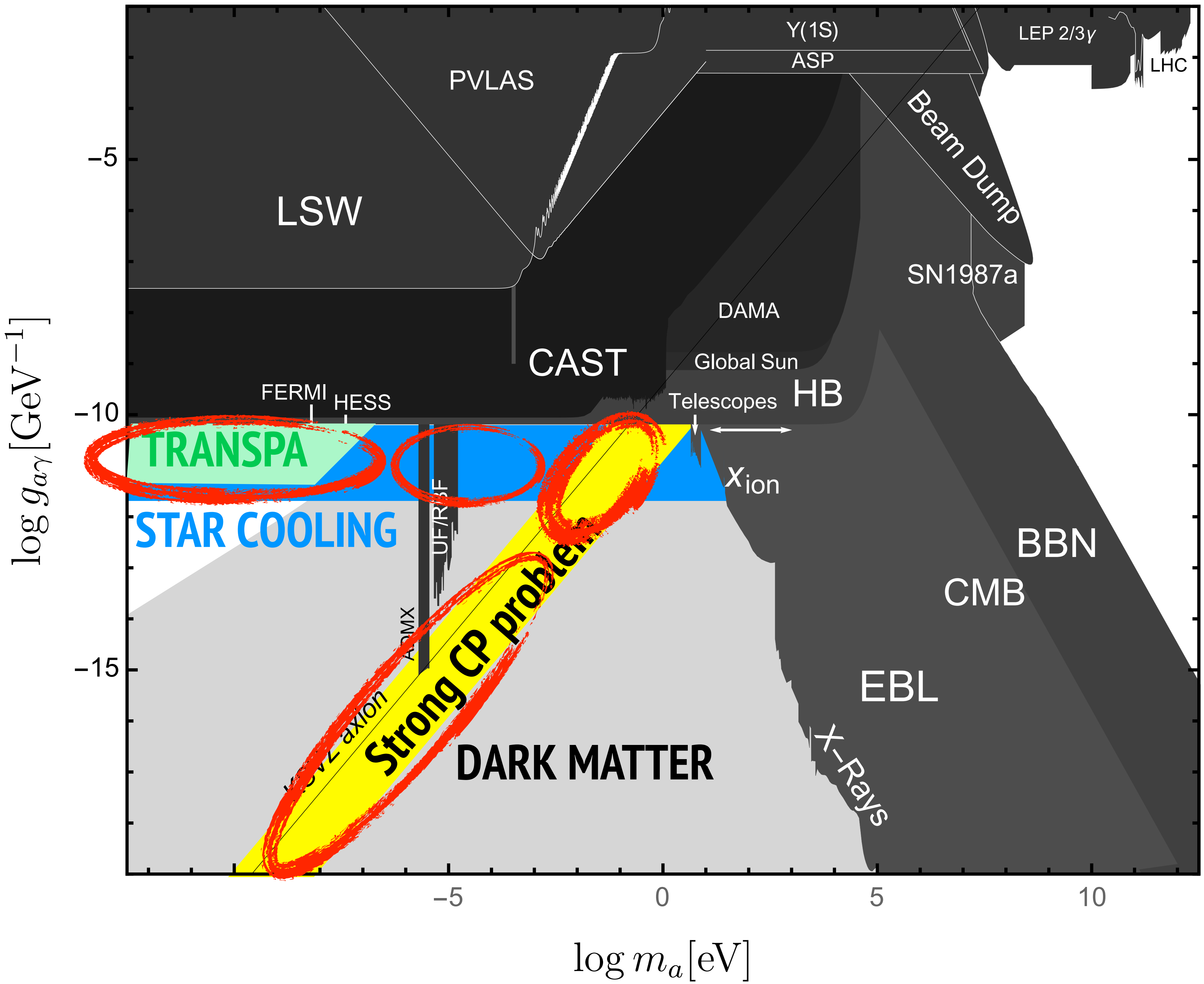

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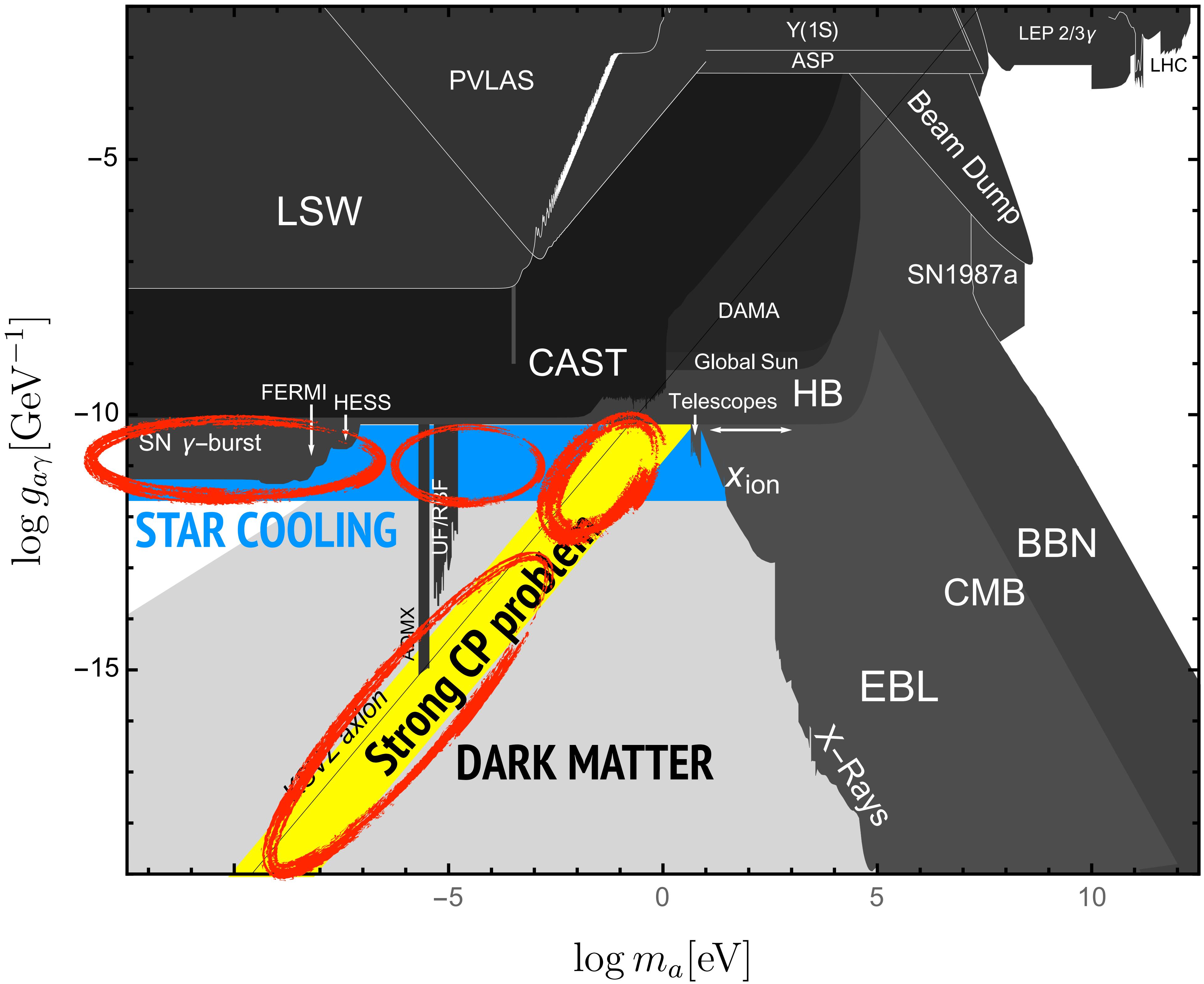

Recipes for Axion hunters

Gianotti 1708.02111

Axion models to explain stellar cooling anomalies (White dwarf, Red Giant, GC's, CAS A...)

- KSVZ model $\sigma = \rho e^{i\theta}$ **+ extra quark** $y\sigma\bar{Q}_L Q_R + \text{h.c.}$ **electron coupling too small**

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$$c_e \sim -\frac{1}{16\pi^2}(\mathrm{tr}\kappa - \kappa_{ee})$$

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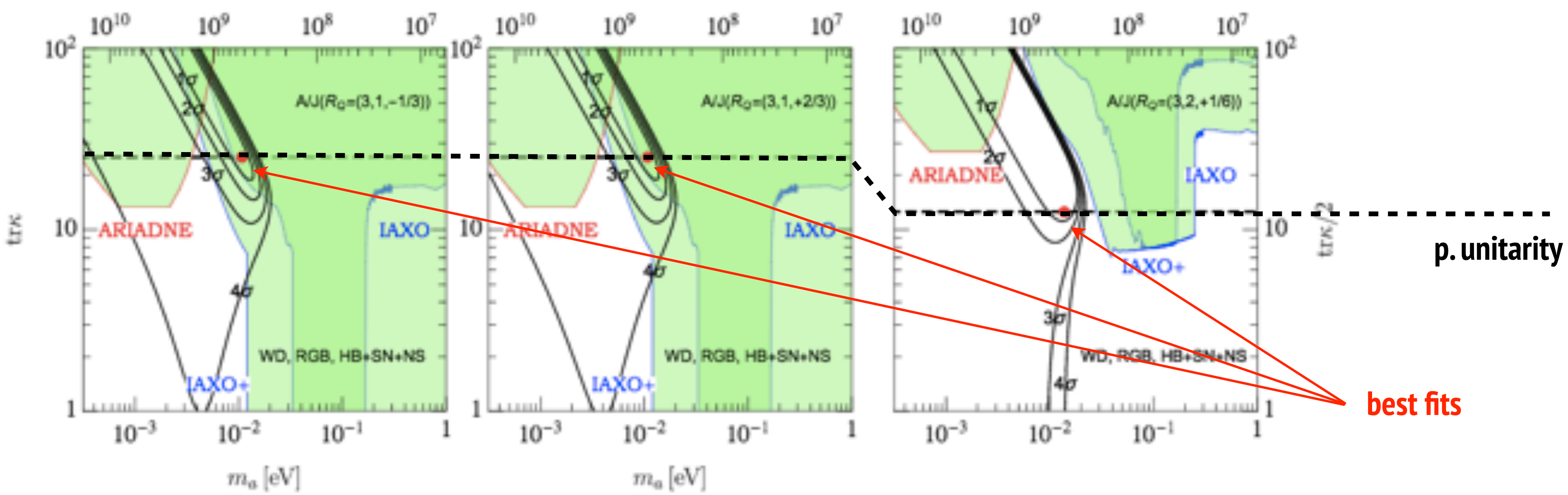

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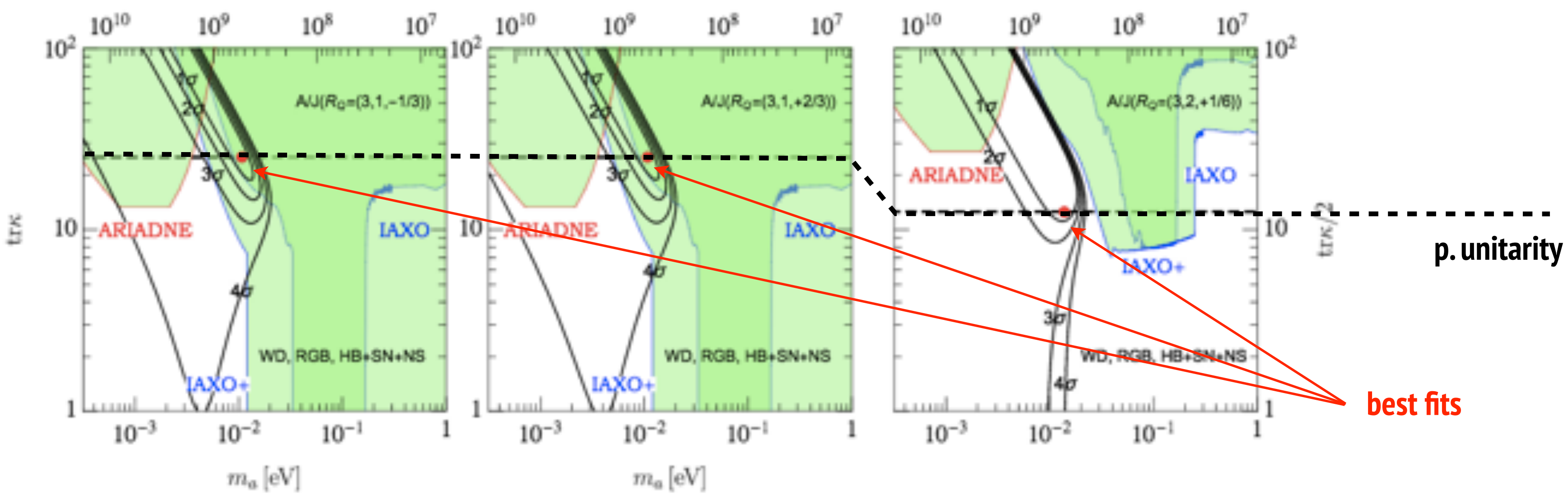

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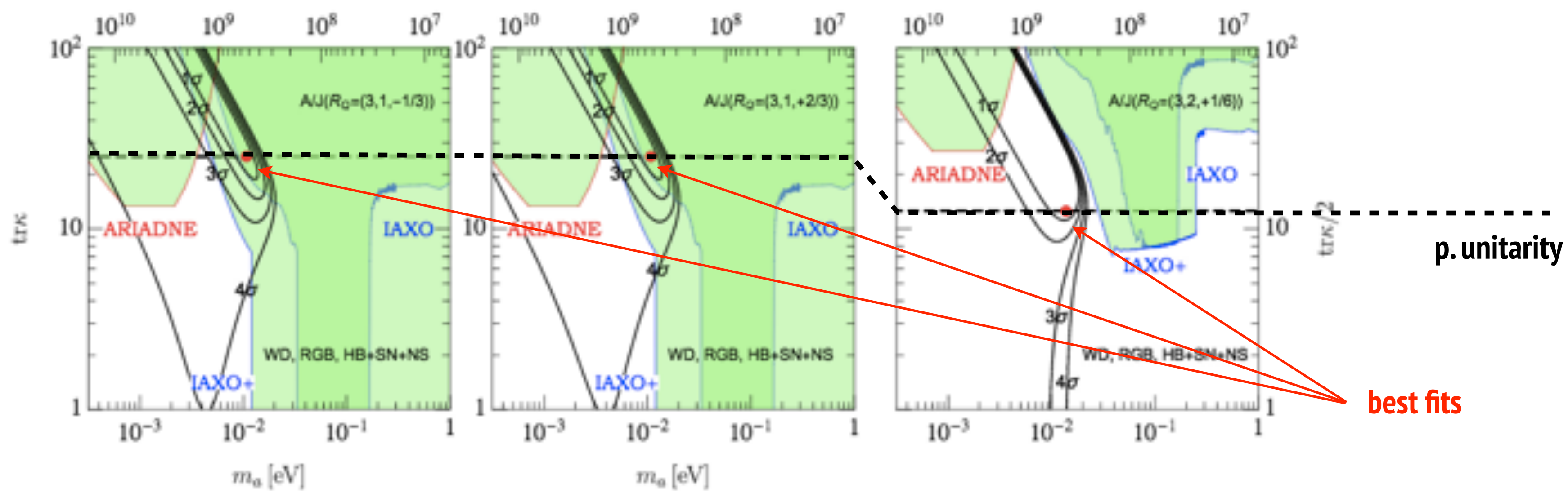

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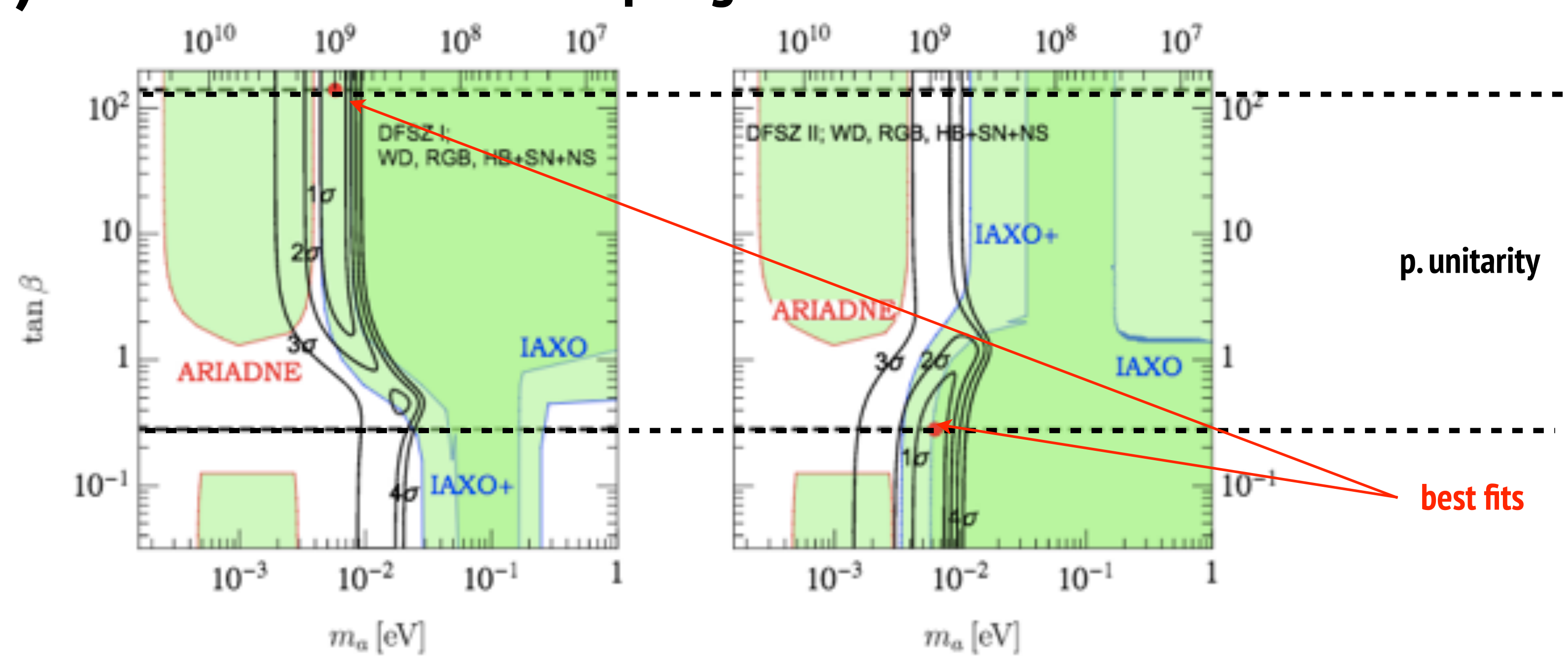
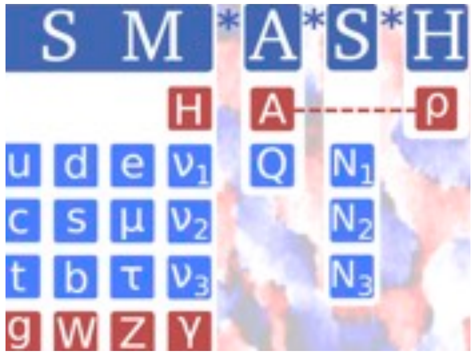


SMASH : "minimal model" of particle physics and cosmology

- A/J model + non-minimal coupling of scalars to gravity + Higgs portal coupling

  - New complex scalar:



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- Reheating calculable (high TR)
- Cures Higgs potential instability (threshold stabilisation mechanism)
- Strong CP problem (with new Quark)
- RN Majorana masses -> seesaw
- Leptogenesis (slightly resonant)

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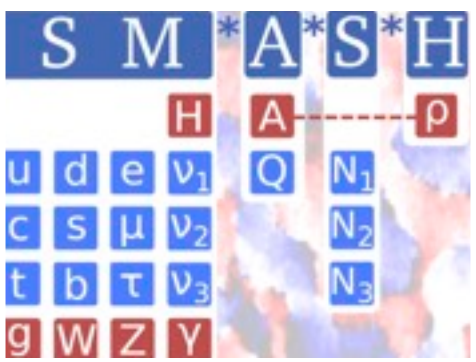

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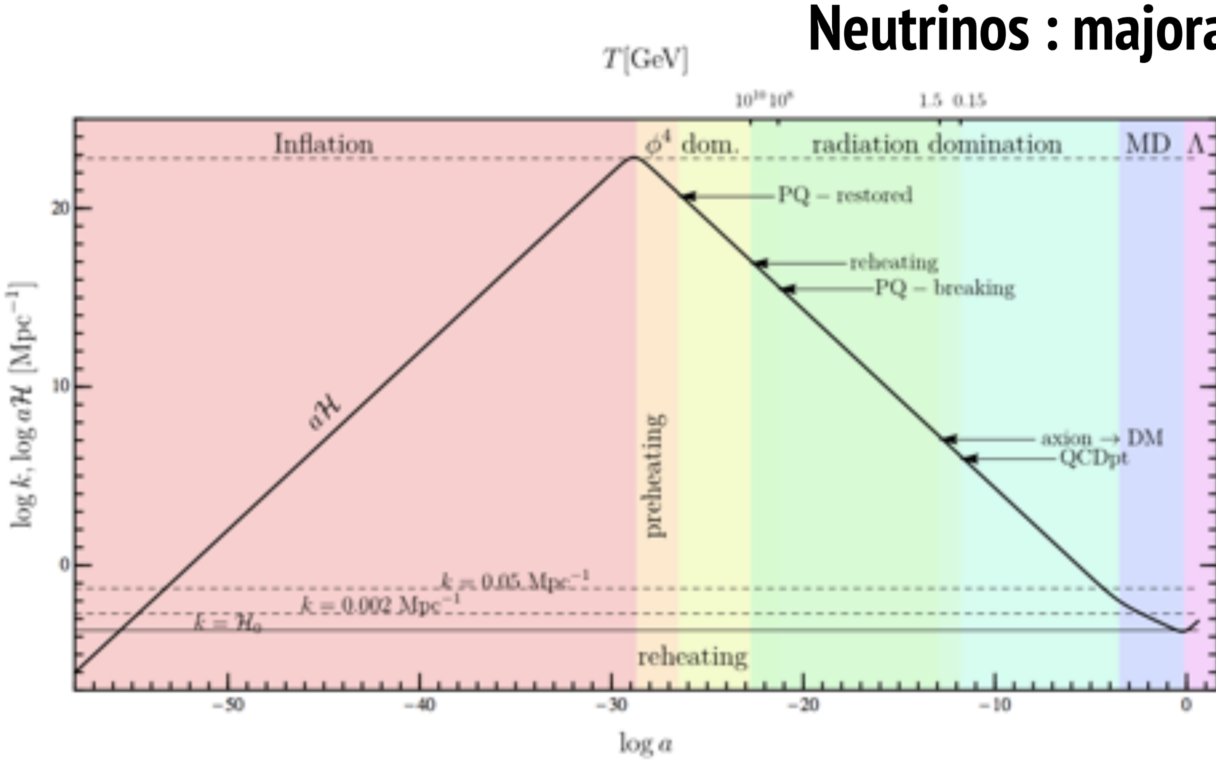
- Very clear predictions :

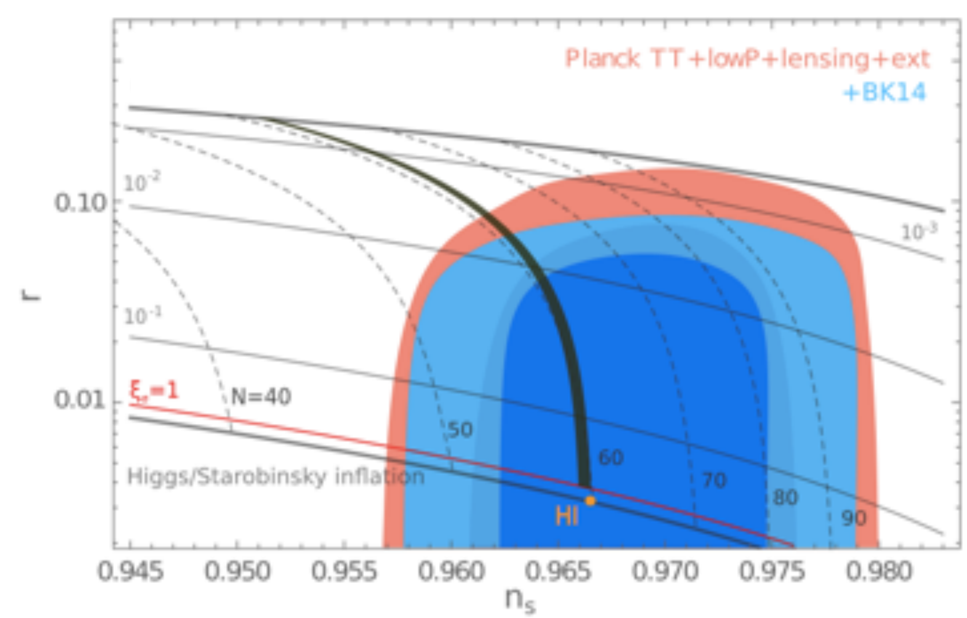
CMB : $r > 0.004 \quad n_s = 0.9645 \pm 0.0015 \quad \Delta N_\nu^{\rm eff} \simeq 0.03 \quad P_{\rm iso} = 0$

$\alpha \sim -7 \times 10^{-4}$

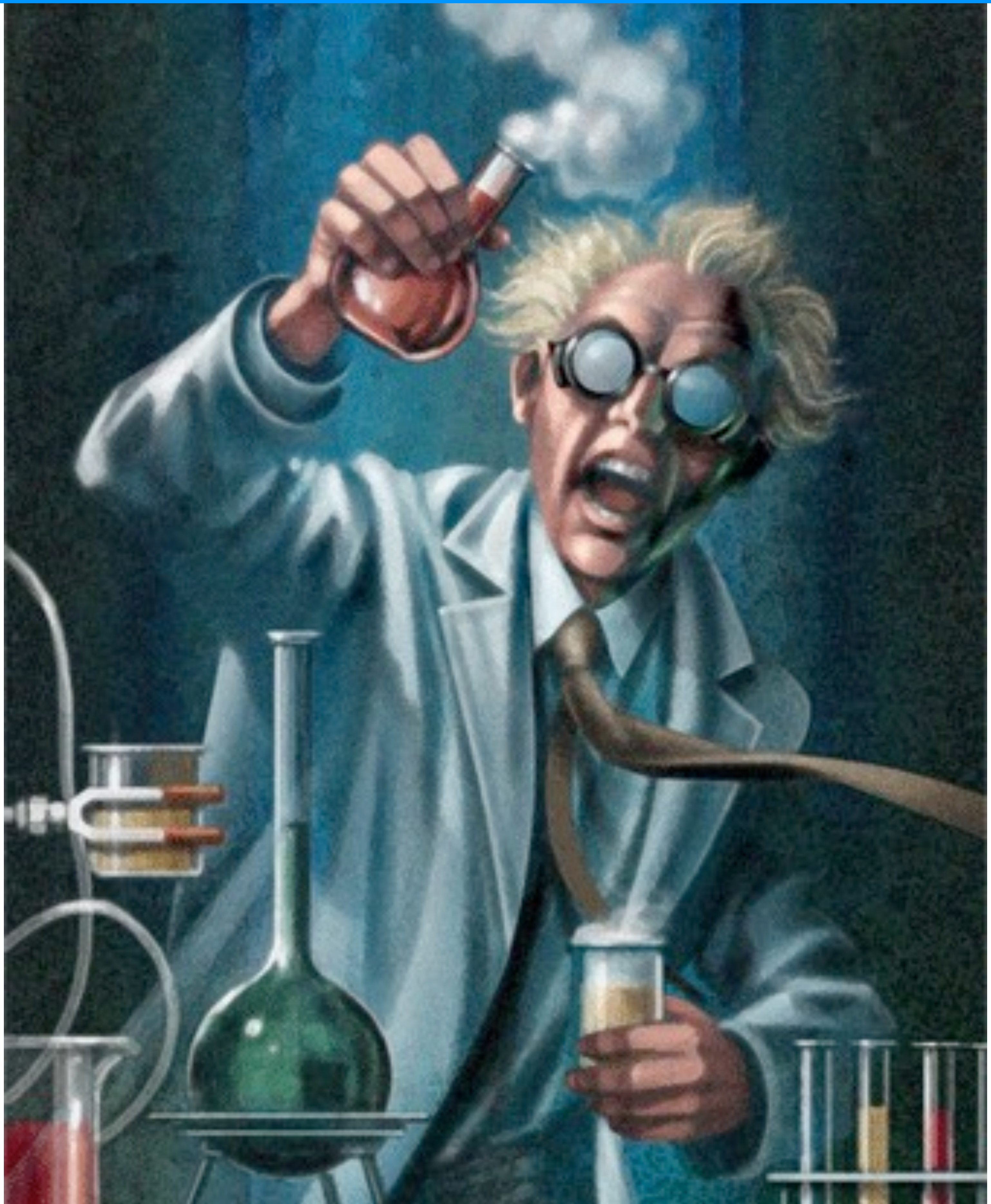
Axion Dark Matter (scenario I: post inflation) : $m_a \sim 100\,\mu{\rm eV}$, miniclusters

Neutrinos : majorana, typically $M_2 \sim M_3$ top mass : $m_t < 175\,{\rm GeV}$

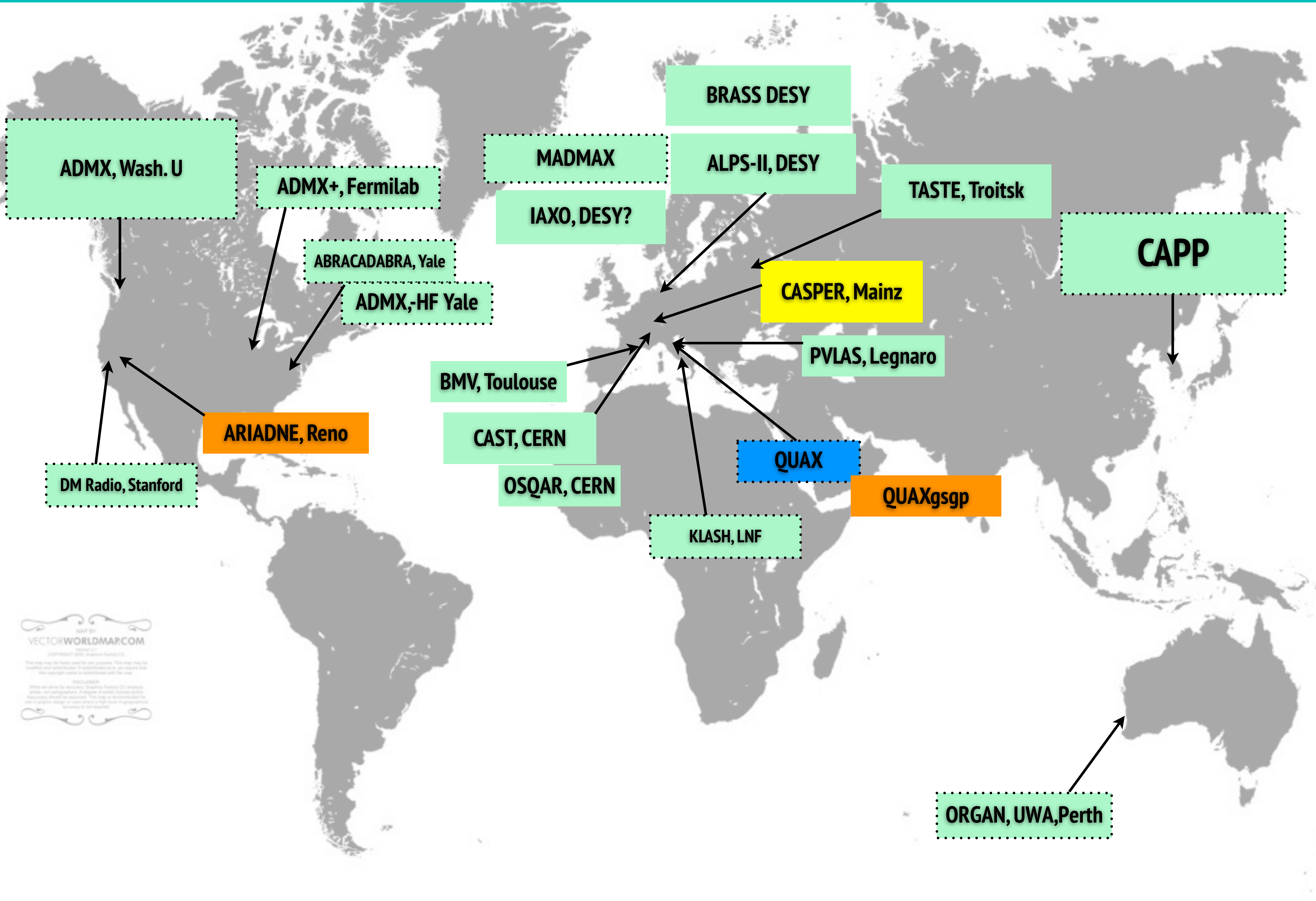




Direct Detection of ALPs



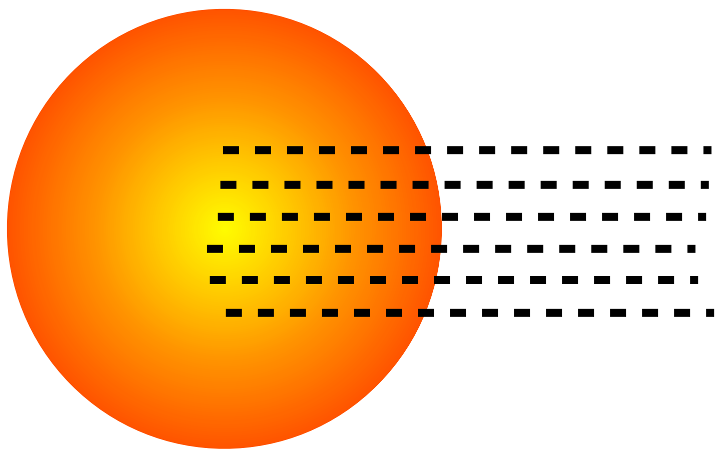
Experiments



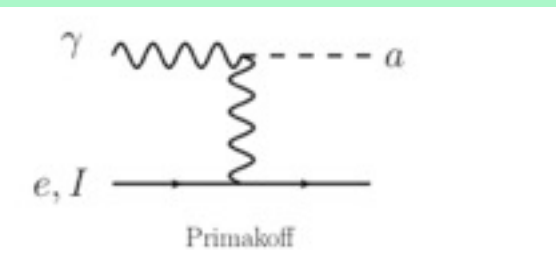
Helioscopes (search solar ALPs)

Sikivie PRL 1983

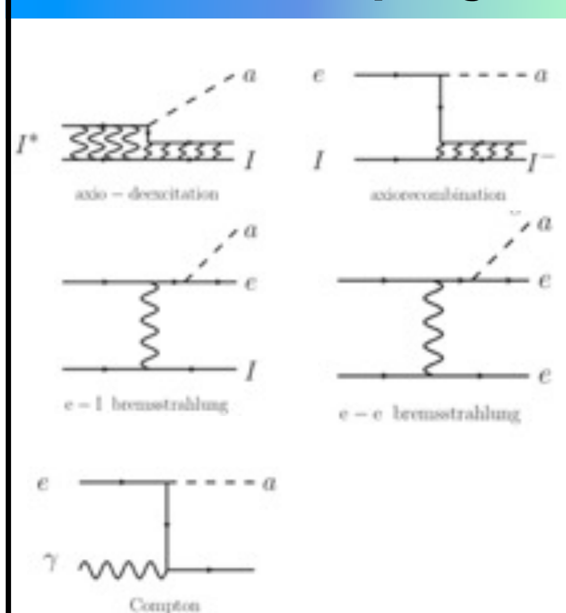
The Sun is a copious emitter of ALPs!

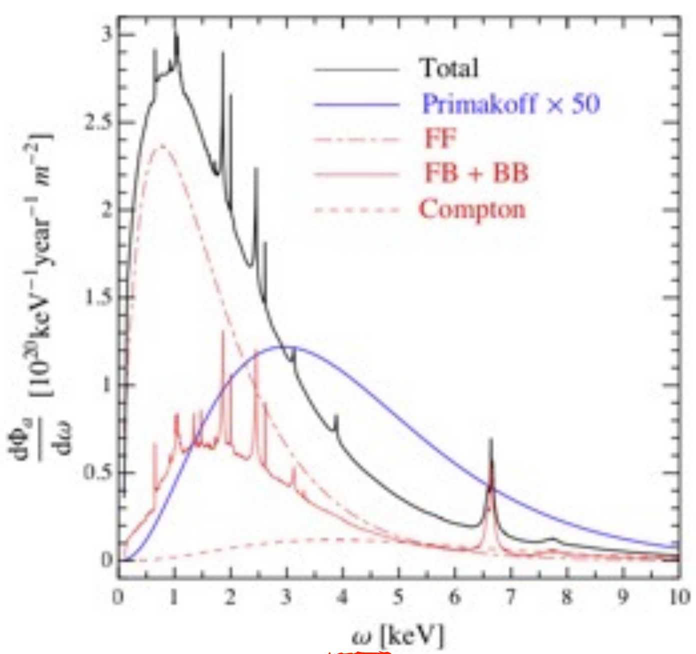


photon coupling



electron coupling





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

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

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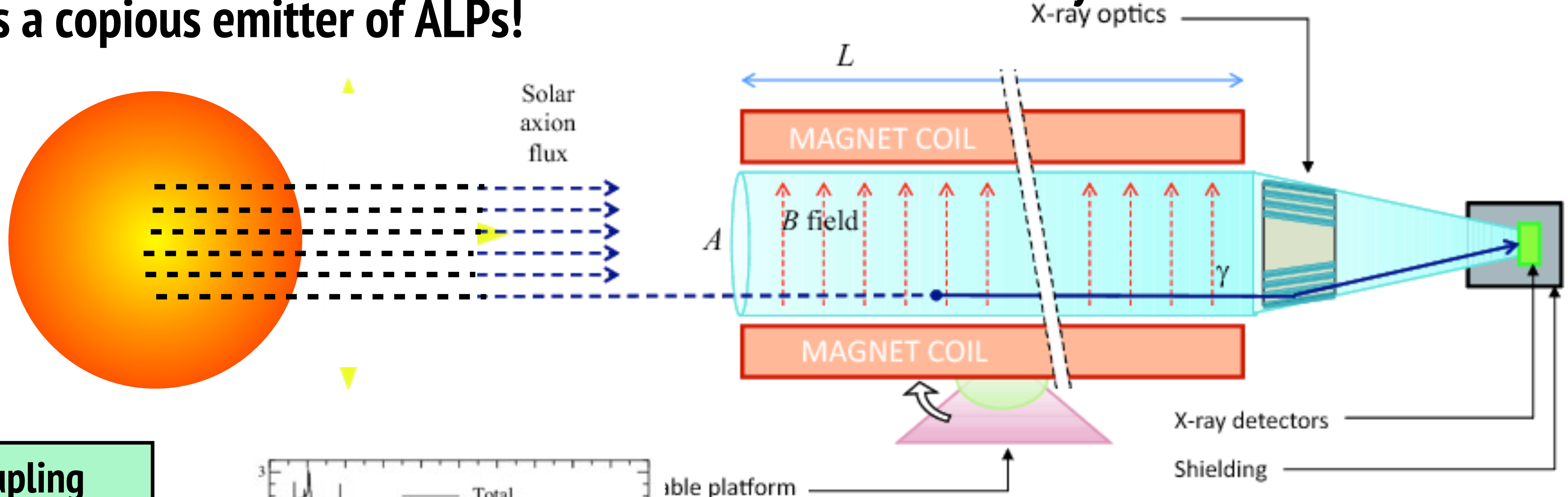
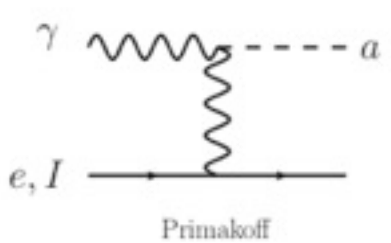
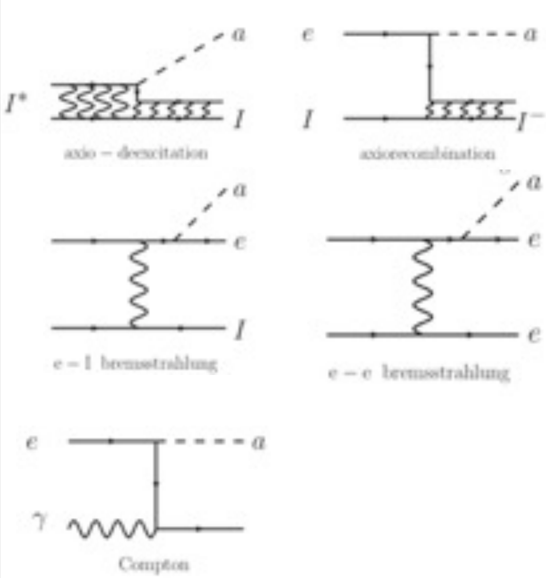
convert into X-rays **focus** **detect**

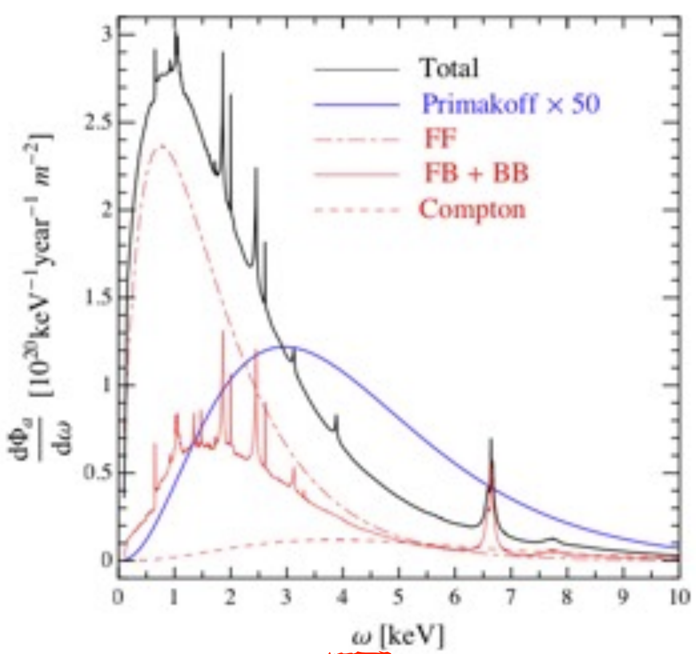


photon coupling



electron coupling





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

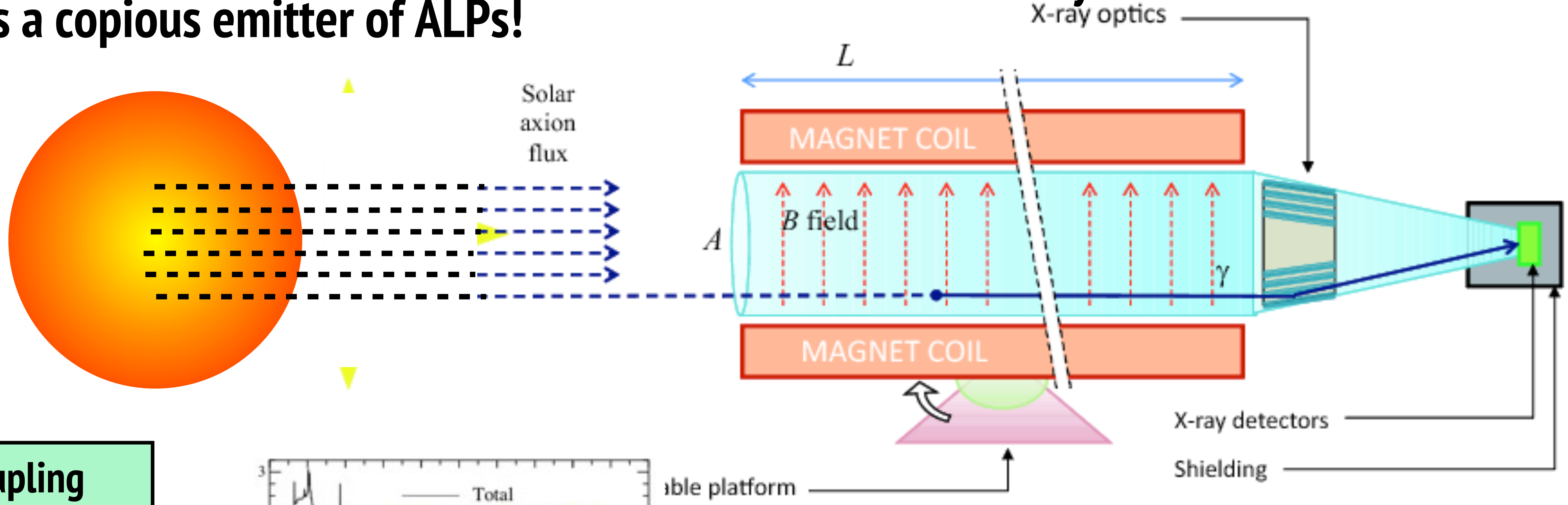
$$g_{a\gamma} = 10^{-12}$$

Helioscopes (search solar ALPs)

Sikivie PRL 1983

The Sun is a copious emitter of ALPs!

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



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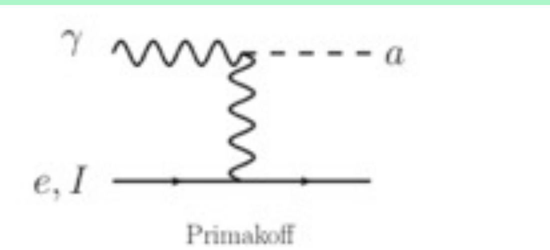
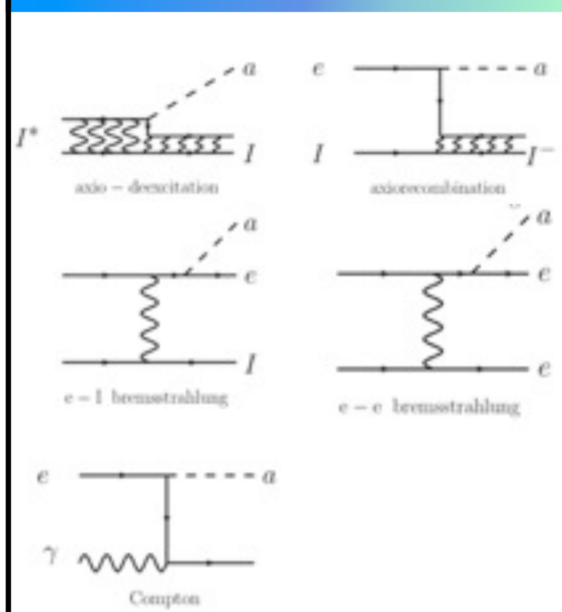
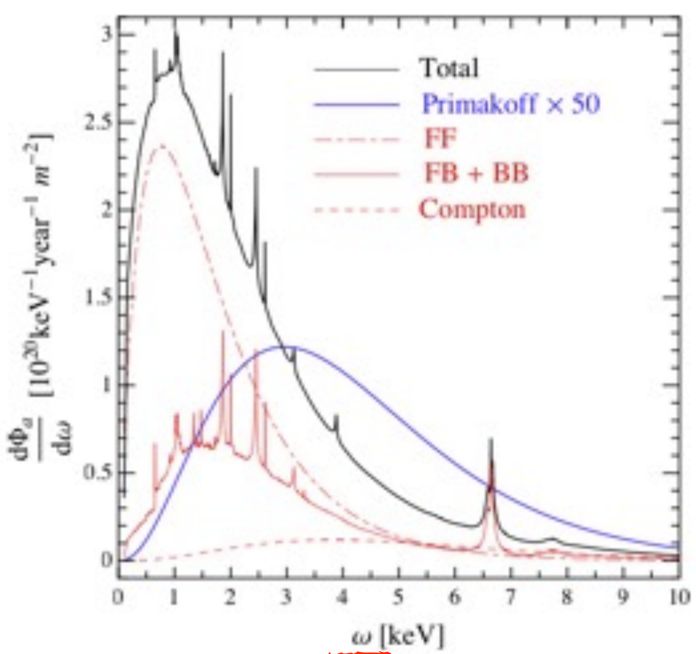


electron coupling

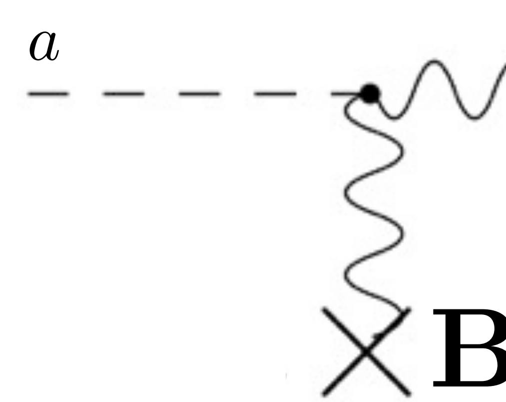




$$g_{ae} = 10^{-13}$$
$$g_{a\gamma} = 10^{-12}$$

Coherent Conversion along the B-field

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

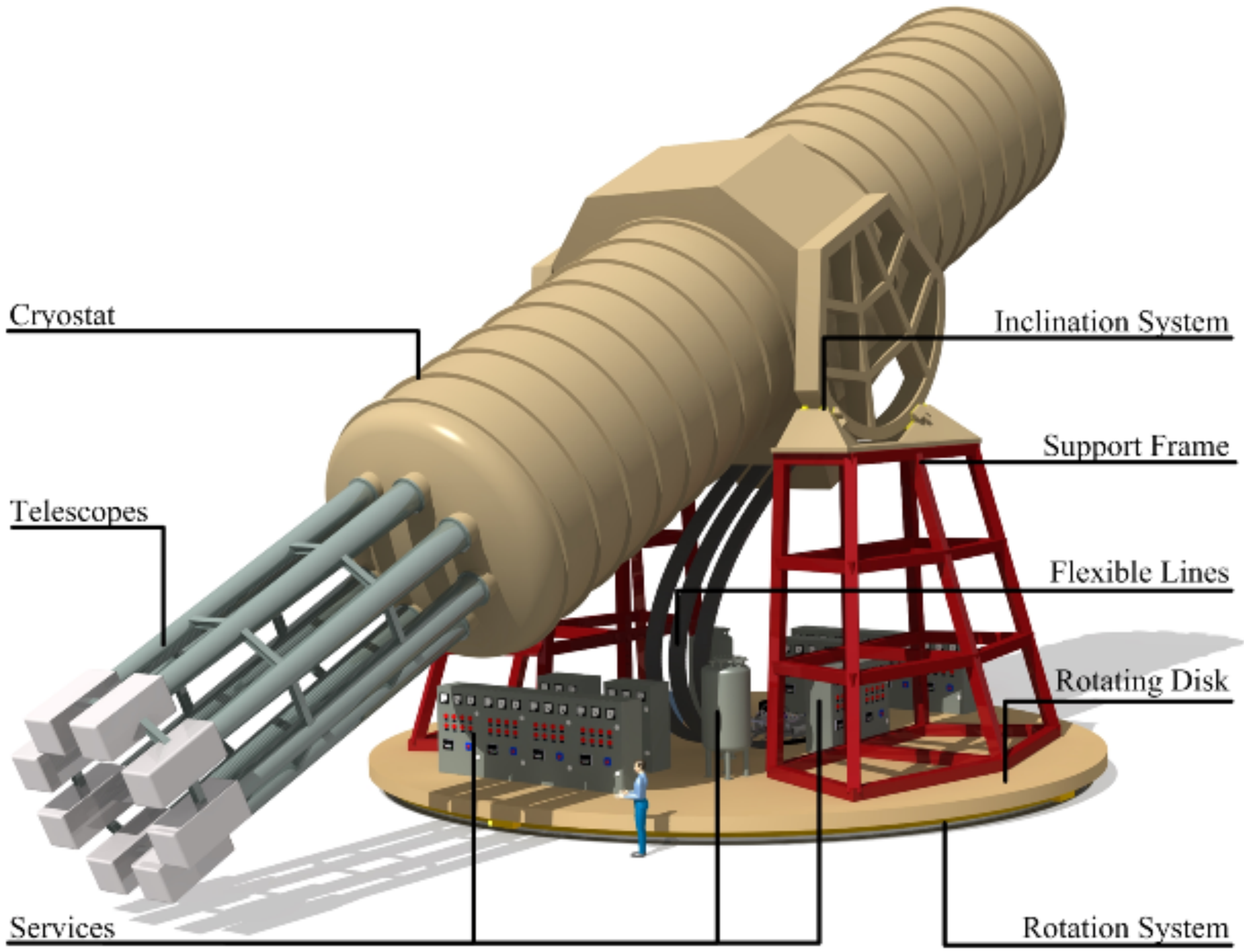


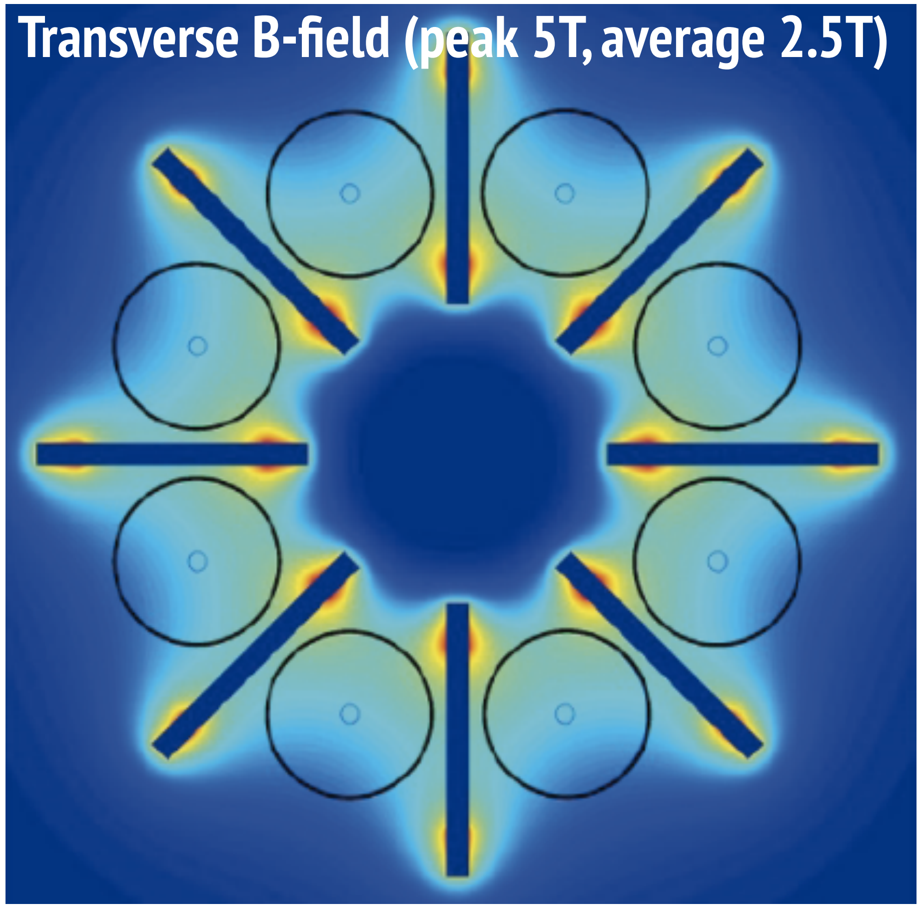
International AXion Observatory

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

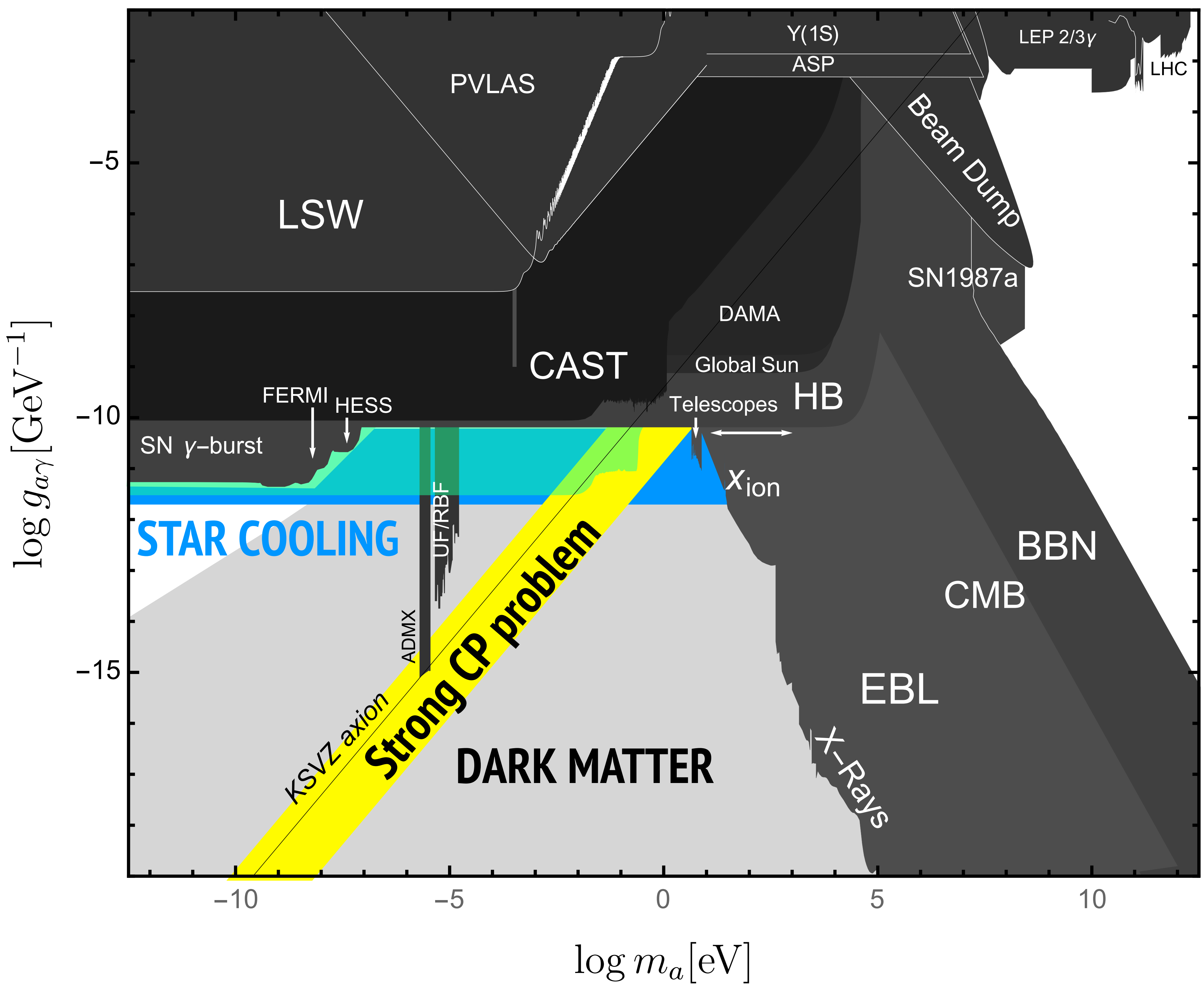
-Possibility of Direct Axion DM experiments (cavities,ABRACA)





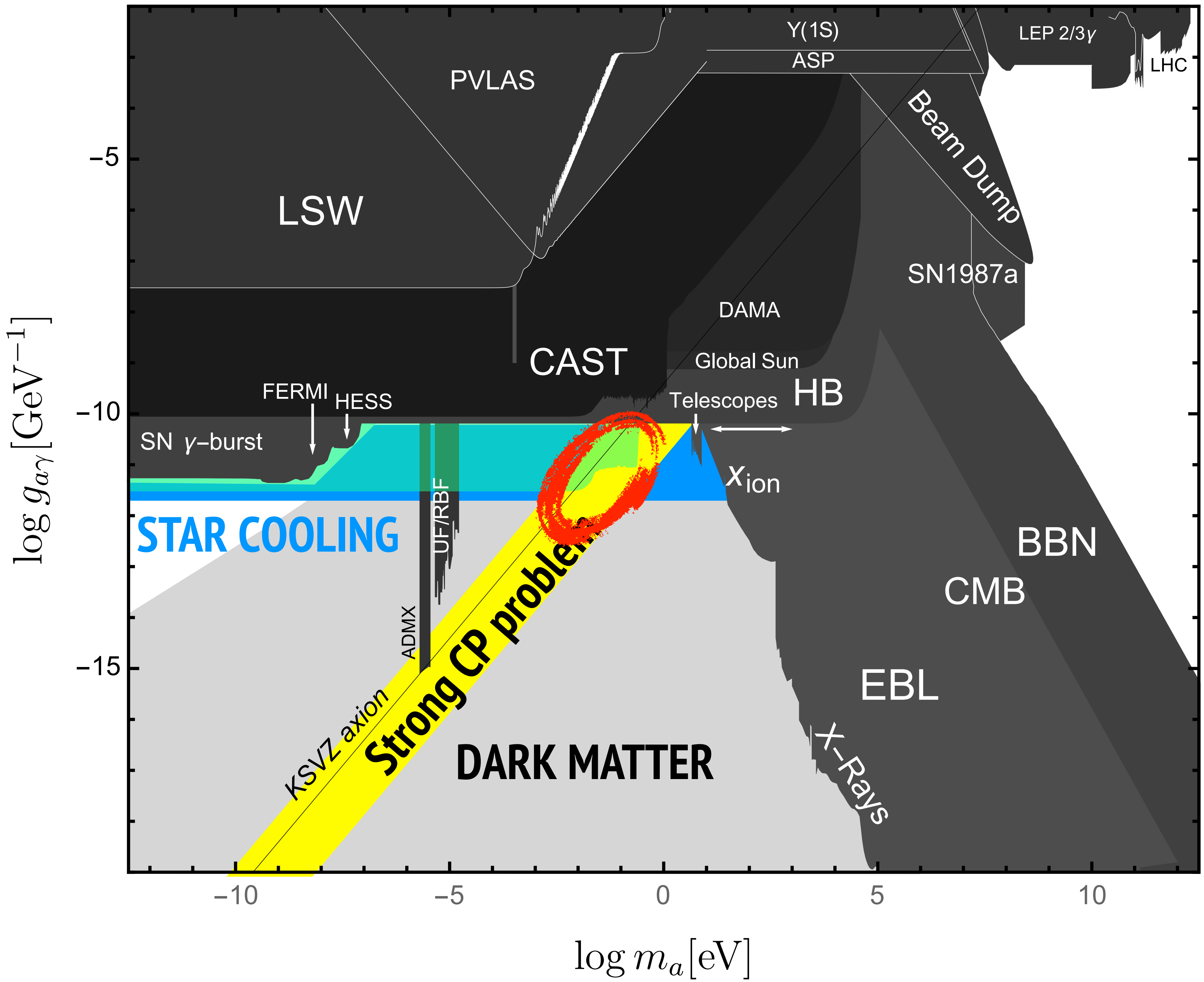
Recent Ideas for a smaller intermediate version (baby IAXO and TASTE)

IAXO reach



PVLAS
LSW
Y(1S)
ASP
LEP 2/3γ
LHC
Beam Dump
SN1987a
DAMA
CAST
Global Sun
Telescopes
HB
FERMI
HESS
SN γ–burst
x_{ion}
STAR COOLING
UF/RBF
ADMX
Strong CP problem
KSVZ axion
DARK MATTER
BBN
CMB
EBL
X-Rays
−5
−10
−15
−10
−5
0
5
10
$\log g_{a\gamma}[\mathrm{GeV}^{-1}]$
$\log m_a[\mathrm{eV}]$

IAXO reach



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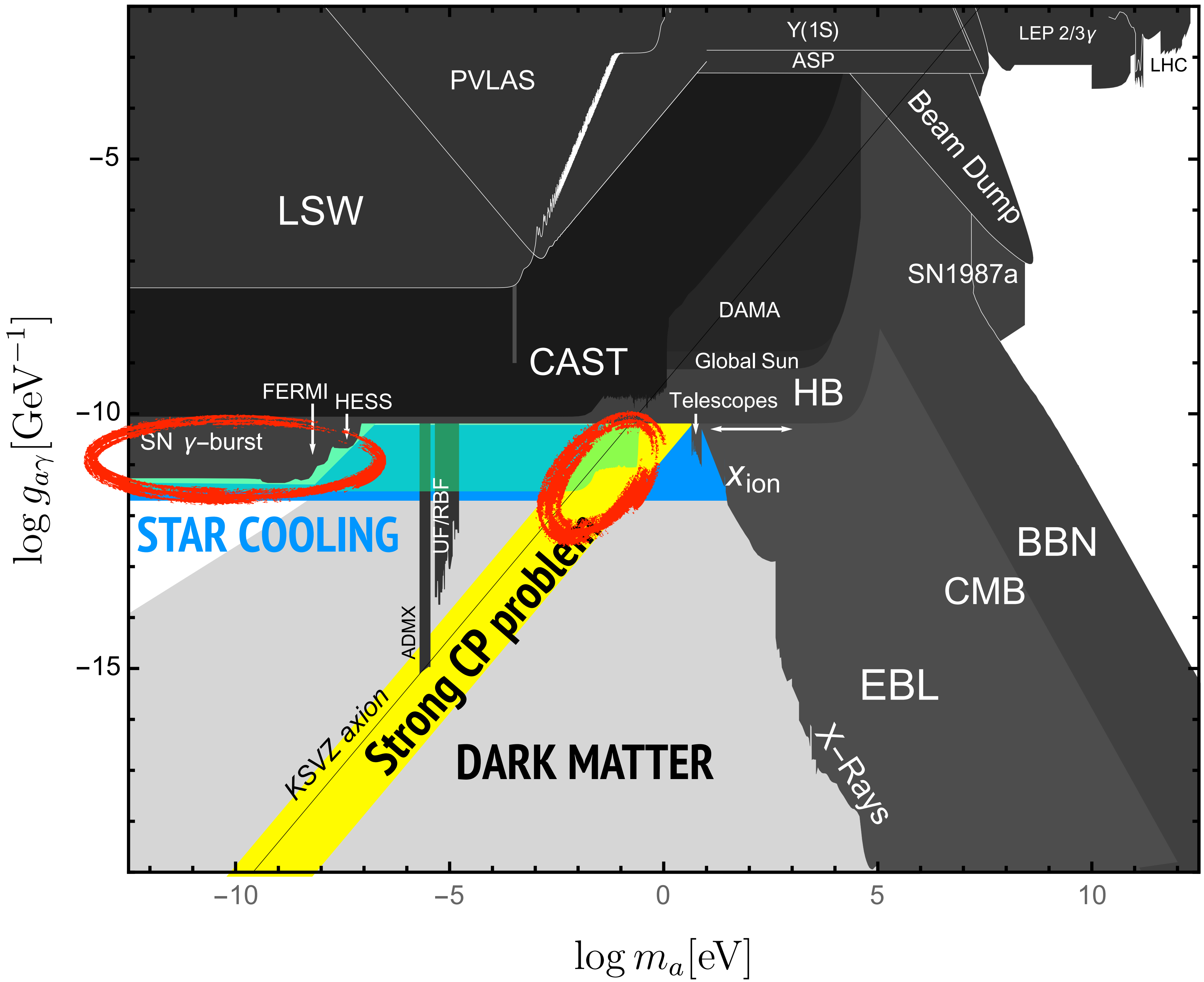
IAXO reach



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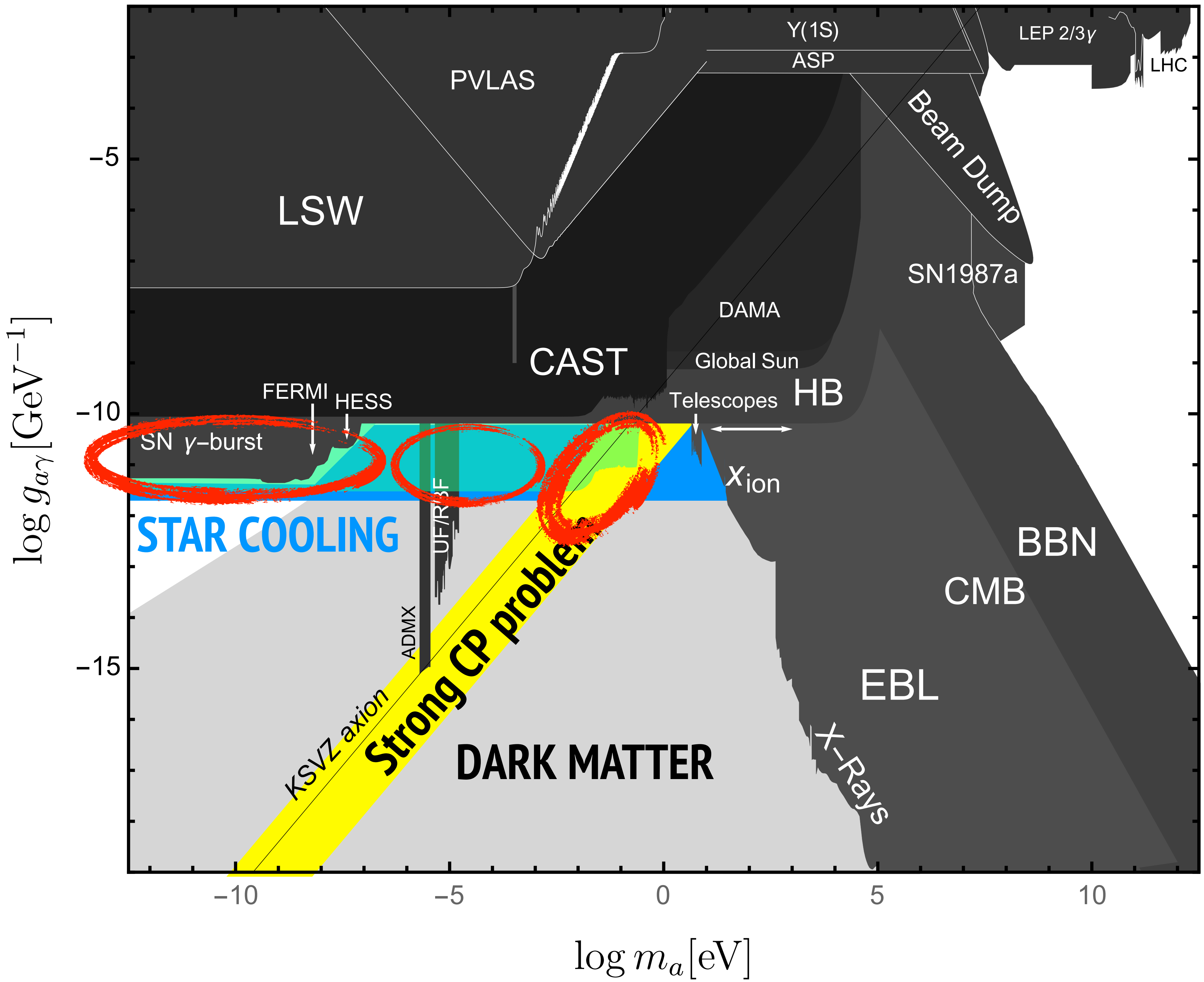
IAXO reach



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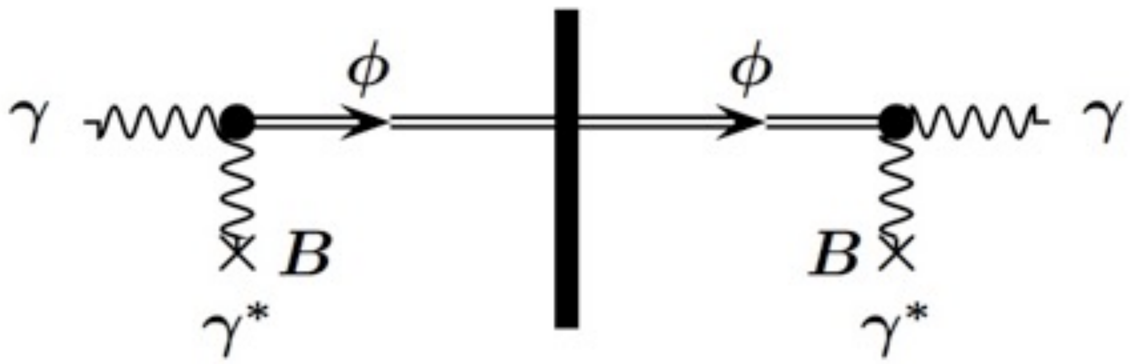
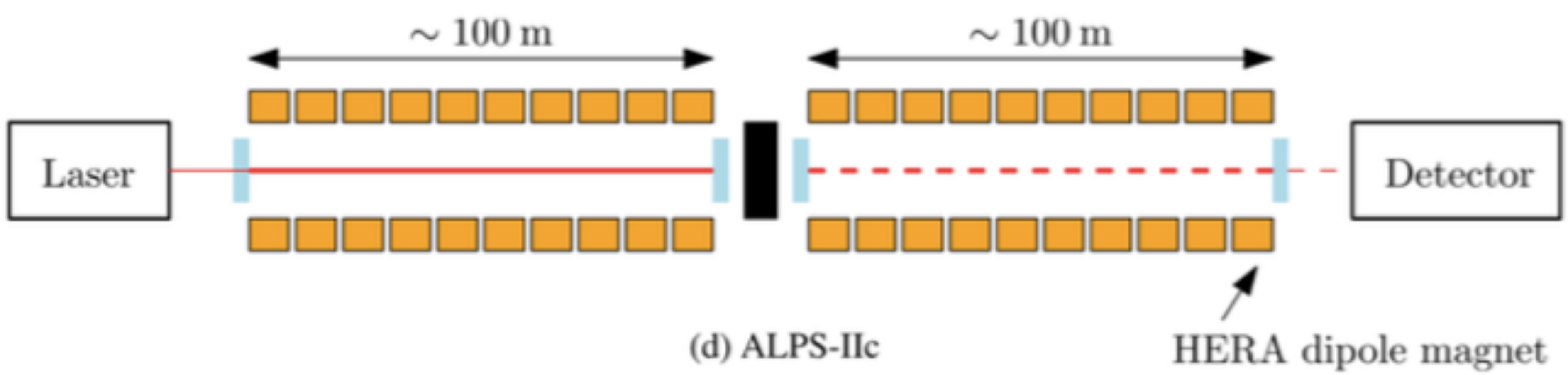
$\log m_a[\mathrm{eV}]$

the ANY-Light-Particle-Search

Light shining through walls



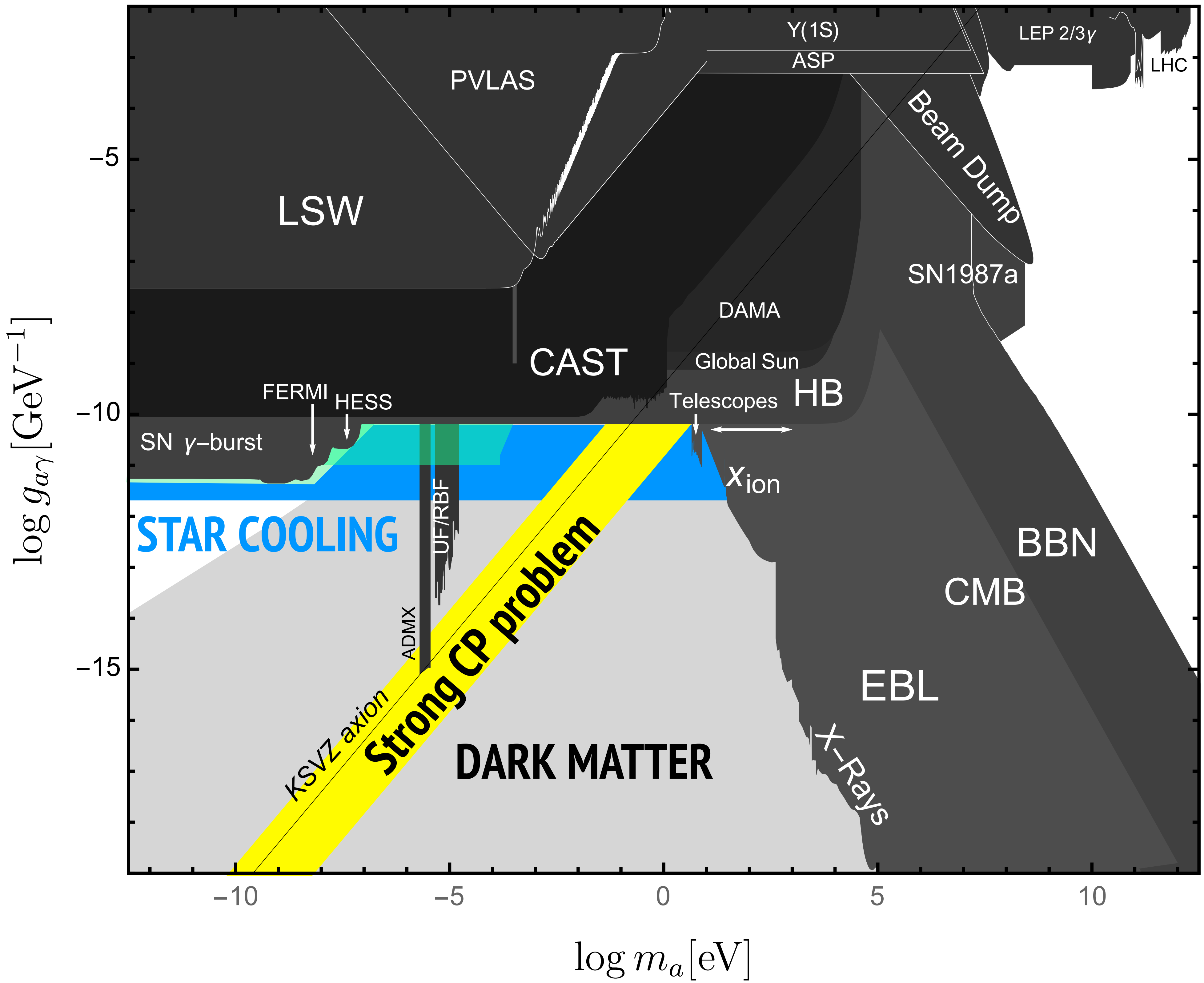
Resonant regeneration in the receiving cavity (see later)



(d) ALPS-IIc

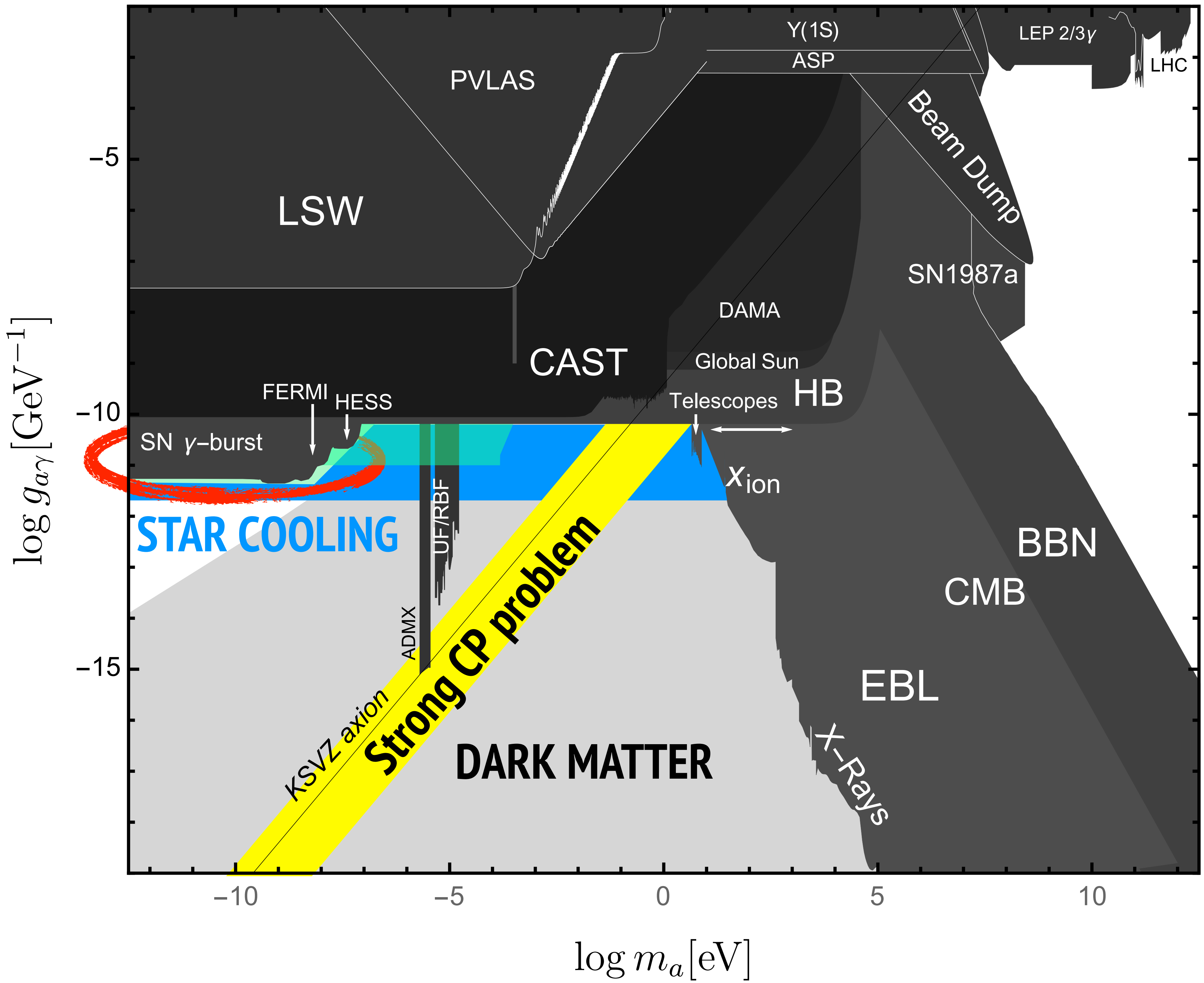
Exp.	Photon flux (1/s)	Photon E (eV)	B (T)	L (m)	B·L (Tm)	PB reg.cav.	Sens. (rel.)
ALPS I	$3.5\cdot10^{21}$	2.3	5.0	4.4	22	1	0.0003
ALPS II	$1\cdot10^{24}$	1.2	5.3	106	468	40,000	1
"ALPS III"	$3\cdot10^{25}$	1.2	13	400	5200	100,000	27

ALPS IIc reach



but much earlier than IAXO ...

ALPS IIc reach



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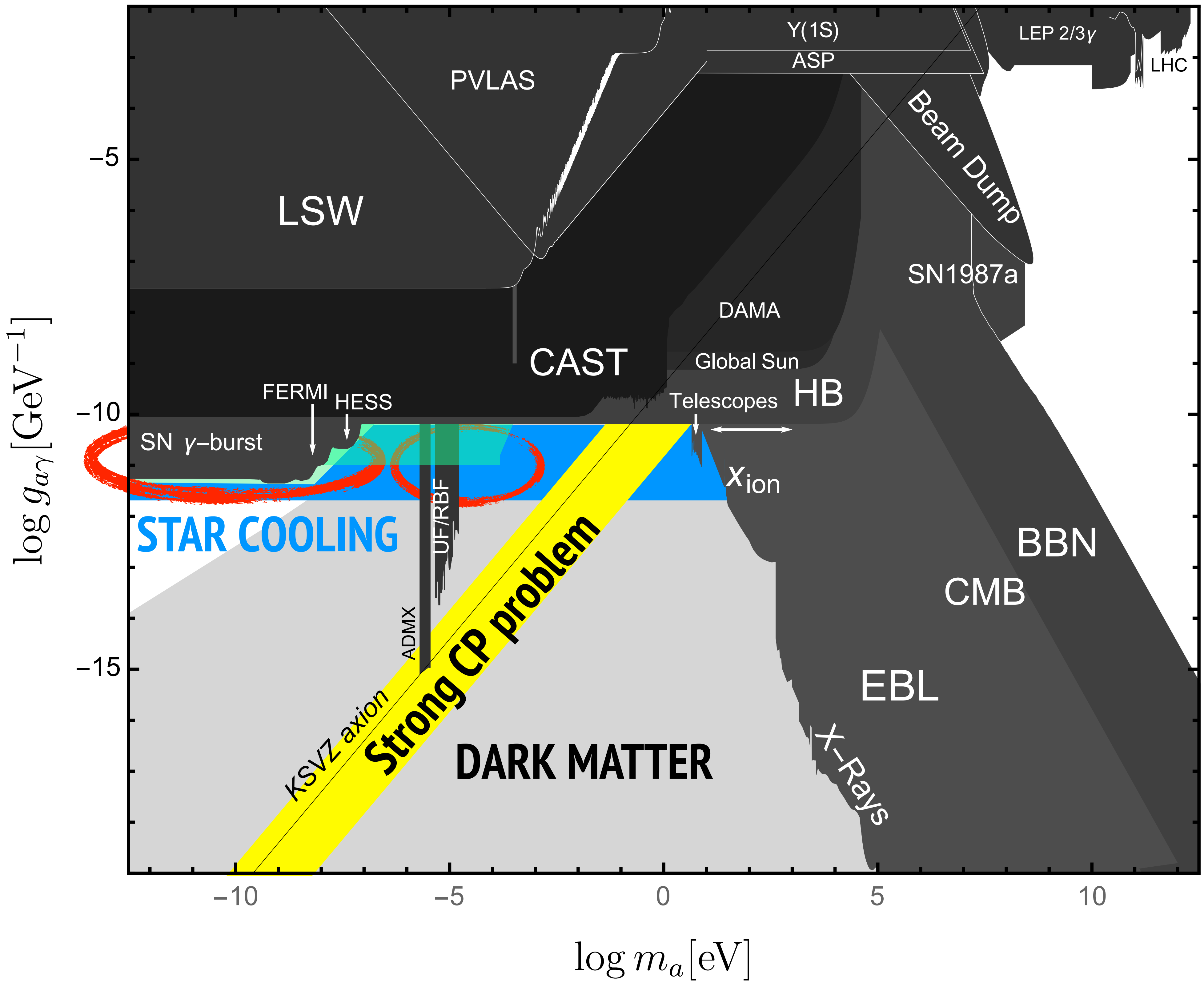
ALPS IIc reach

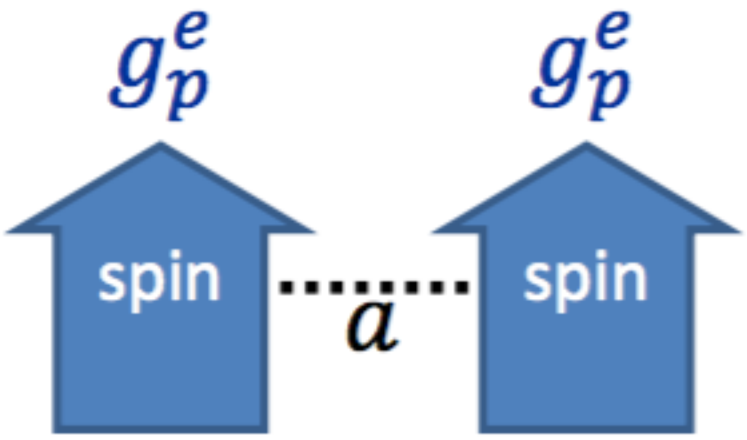


but much earlier than IAXO ...

Long-range forces

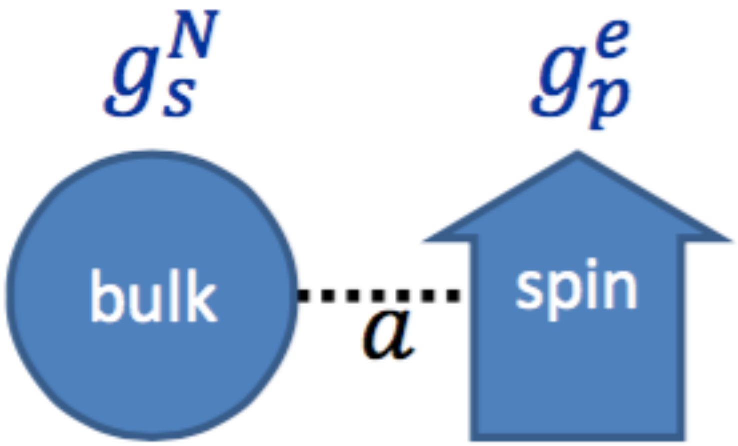
Wilzcek '84, Geraci 14

Long-range forces between macroscopic bodies

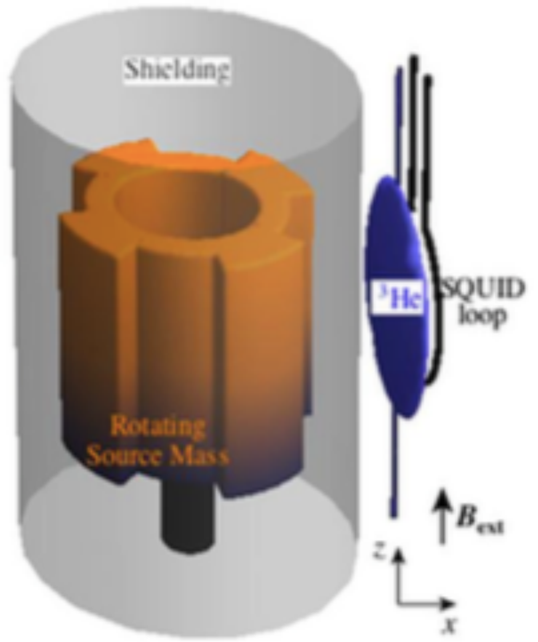


p-p forces are spin-spin ... very hard to measure!

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



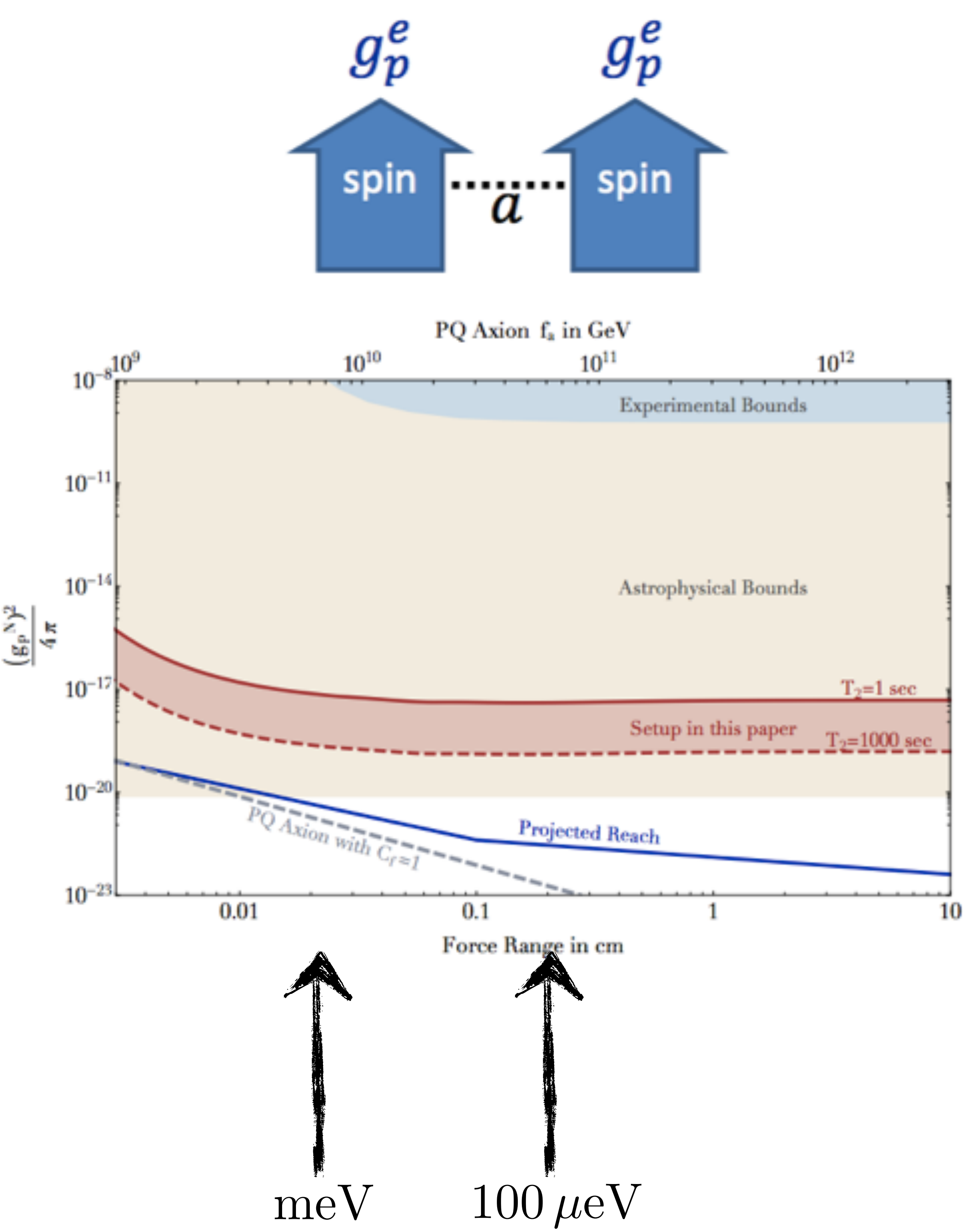
s-p forces are number-spin ... much easier

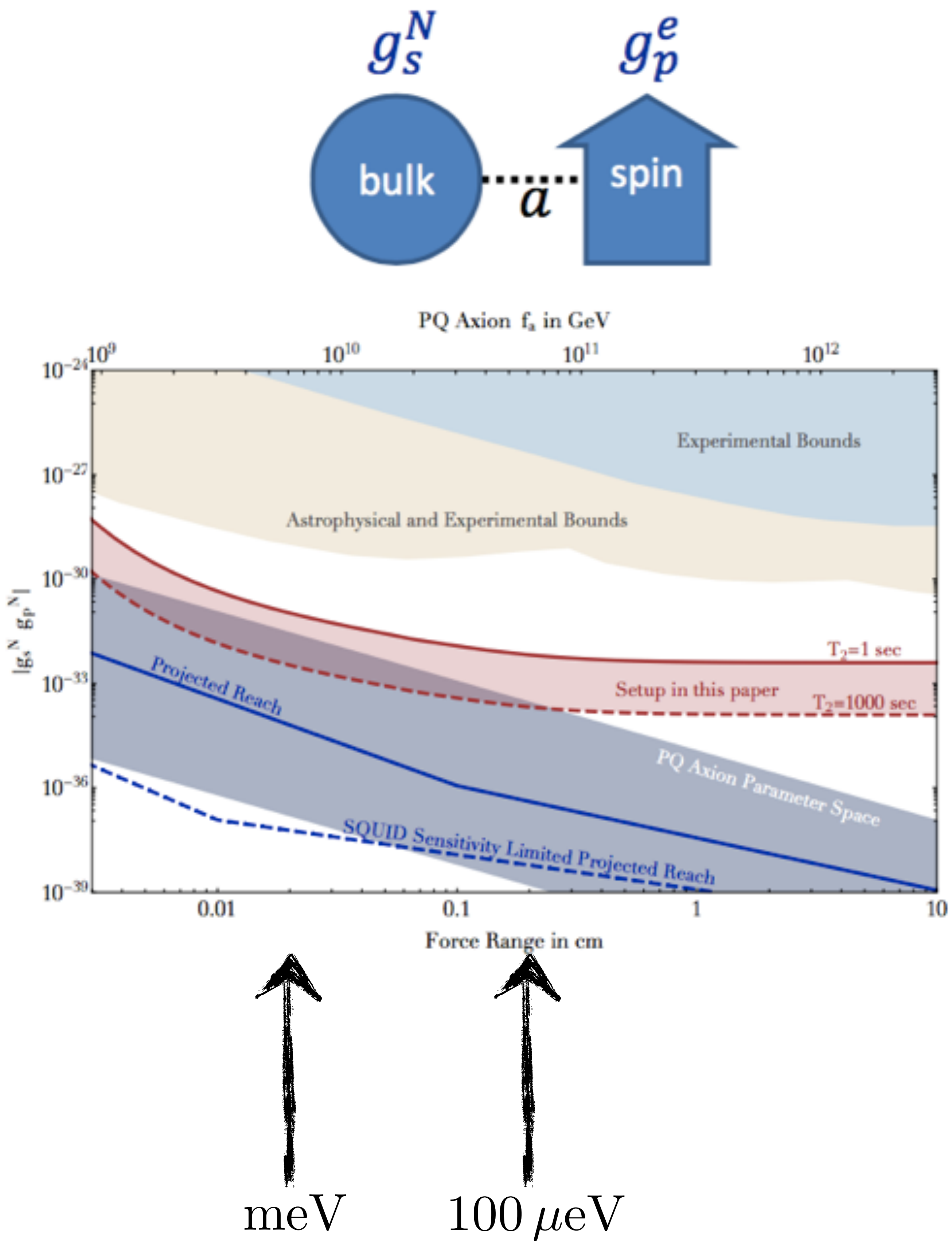


ARIADNE, University of Nevada in Reno

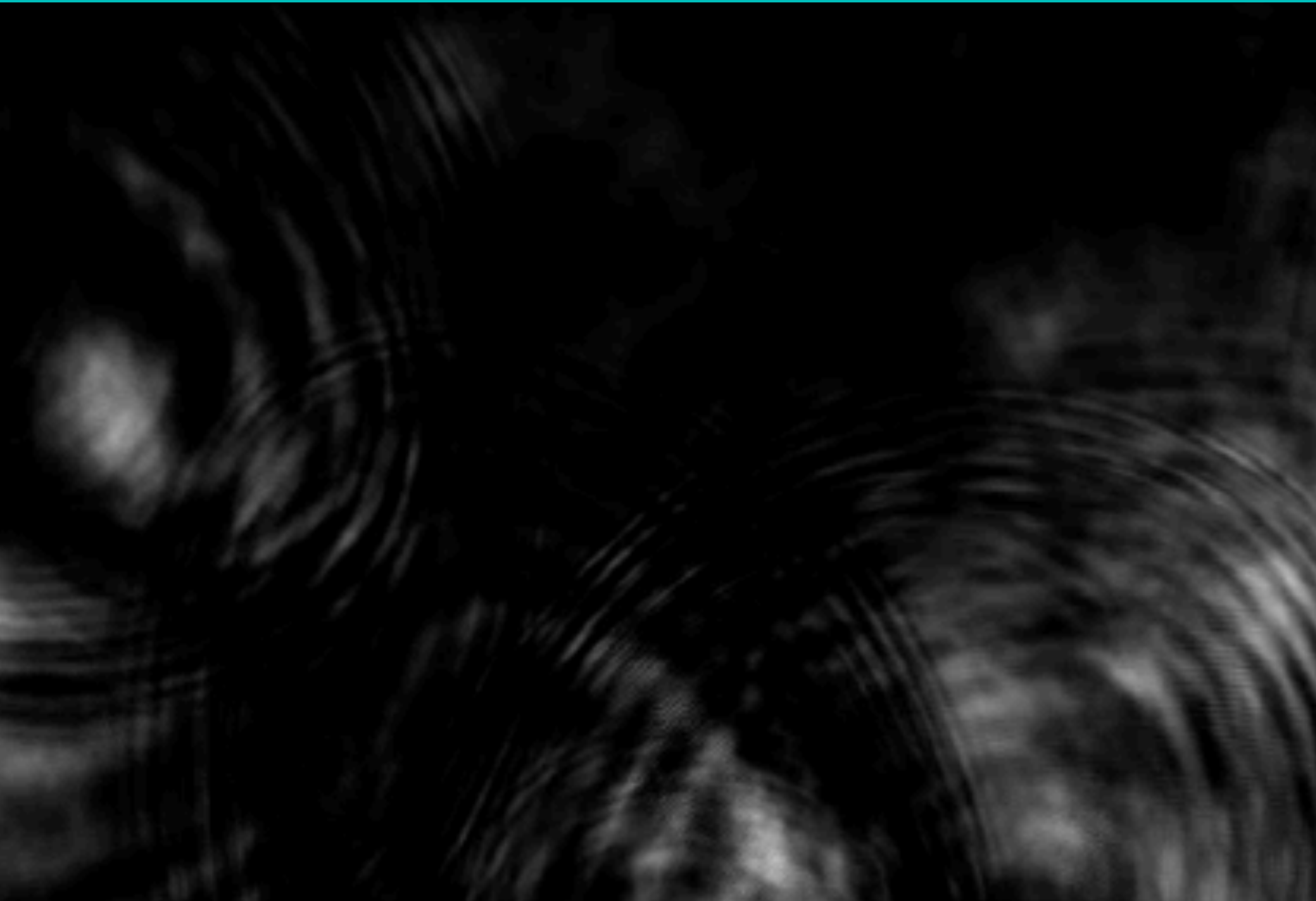
ARIADNE reach

Arvanitaki, Geraci 14





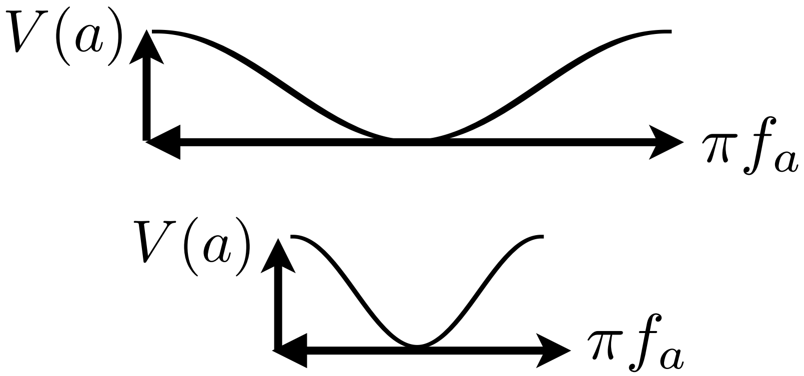
Detecting Dark Matter



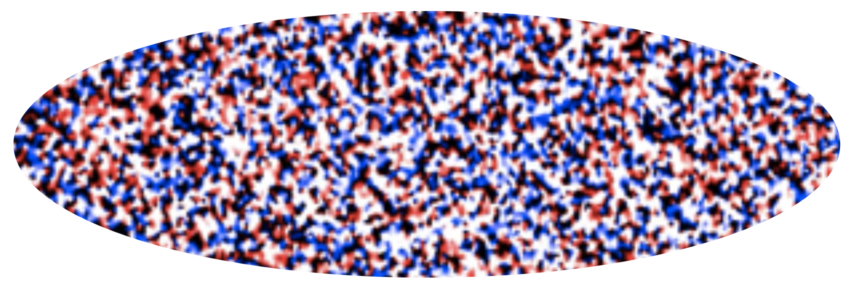
Axion dark matter

- The amount of axion DM produced depends on f_a AND on the initial conditions

large fa, small acceleration, energy stored longer

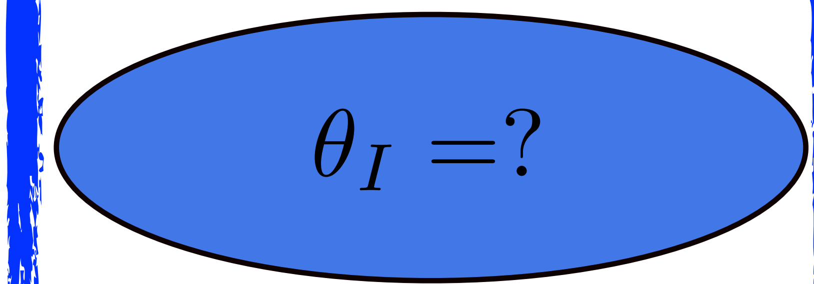


After PQ phase transition, theta IC conditions
no-correlation beyond causal horizon

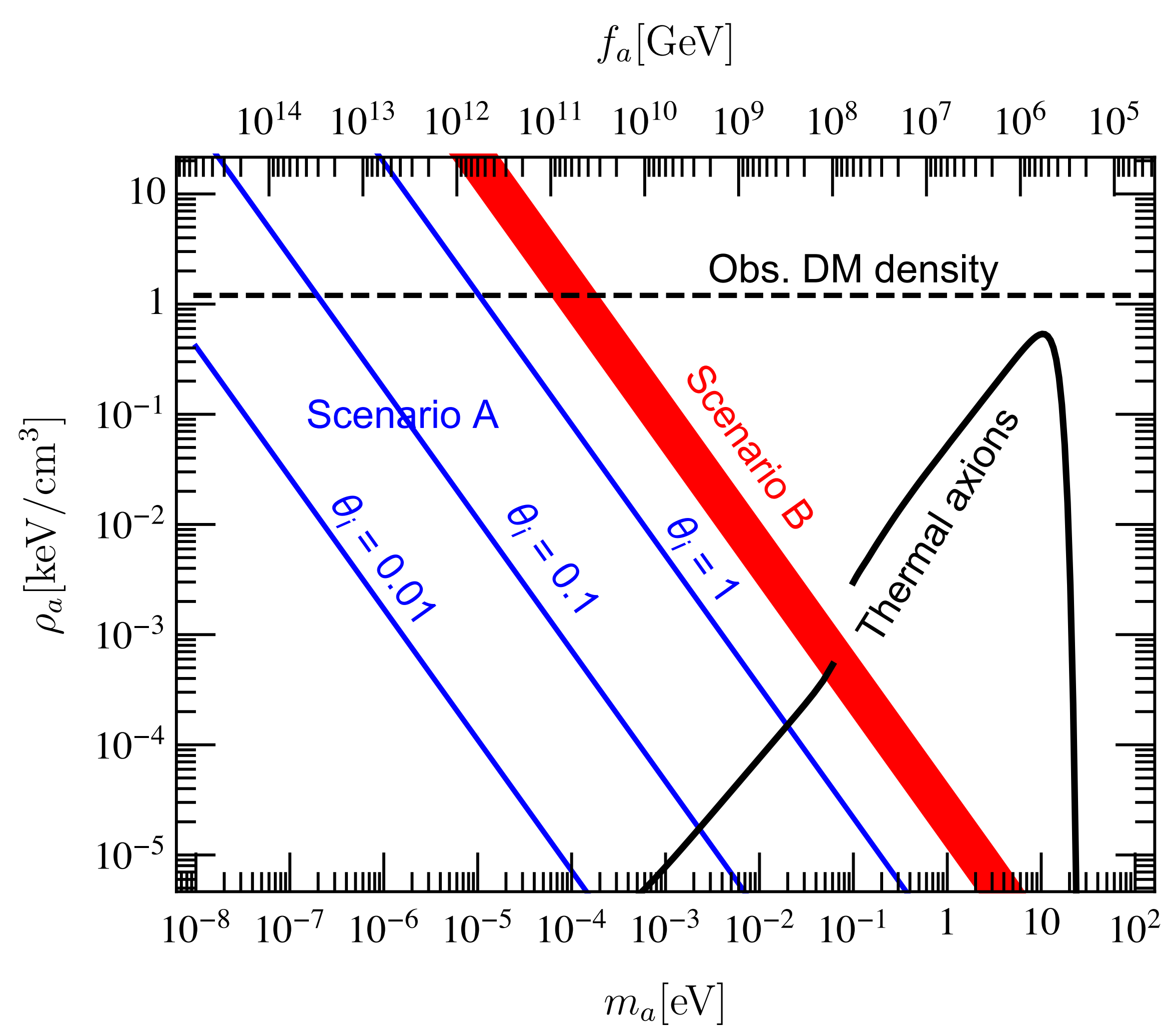


average over initial conditions! -> prediction!

Inflation after PQ phase transition...
one domain stretched beyond our horizon!



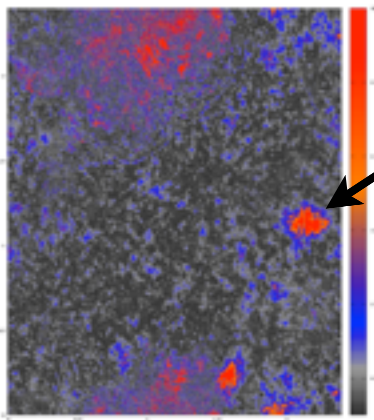
but which one??? no prediction!



Most important constraints

- PQ breaking after inflation

-> DM inhomogeneous, Axion miniclusters

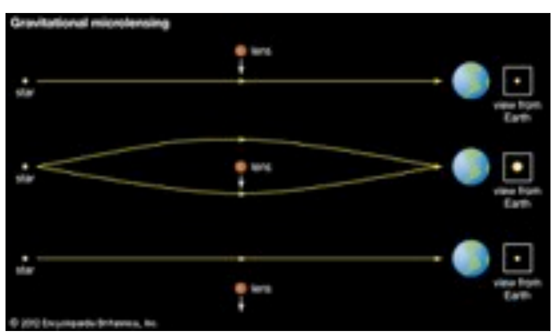


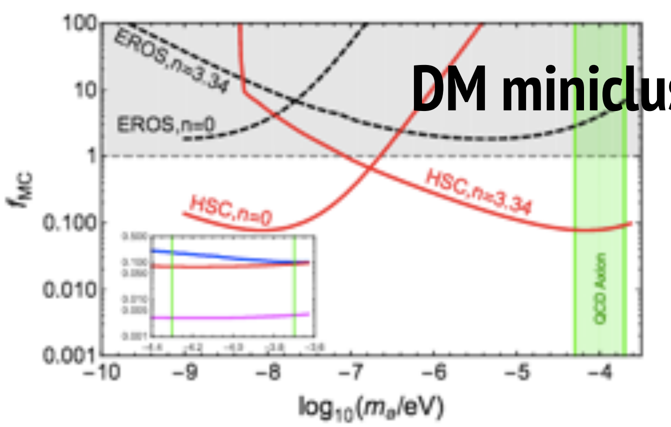
~ 0.1 comoving pc

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

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

Microlensing



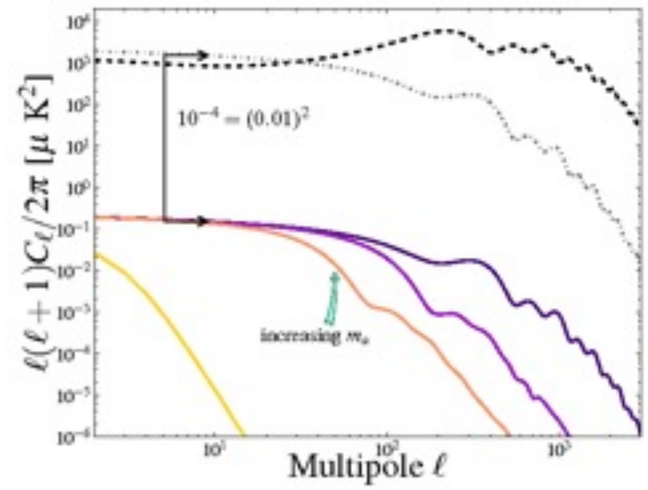


DM minicluster fraction <0.1

Marsh 1707.03310

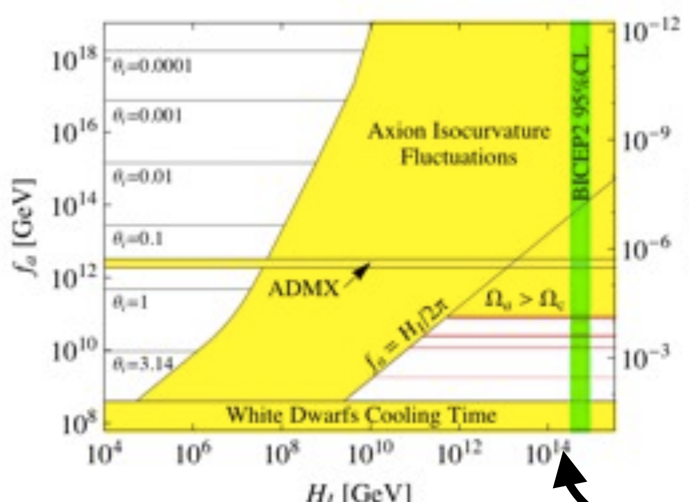
- PQ breaking before inflation

* Axion fluctuations during inflation -> CMB isocurvature



- Planck sees no Isocurvature fluctuations, strong limit!

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



Depends on Hubble rate during inflation ... H_I

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

Detecting Dark Matter

Imperfect Vacuum realignment $\theta(t) = \theta_0 \cos(m_a t)$

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

QCD axion

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

~ 10^-6

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

Non-zero velocity in galaxy -> finite width

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

~ 10^-6

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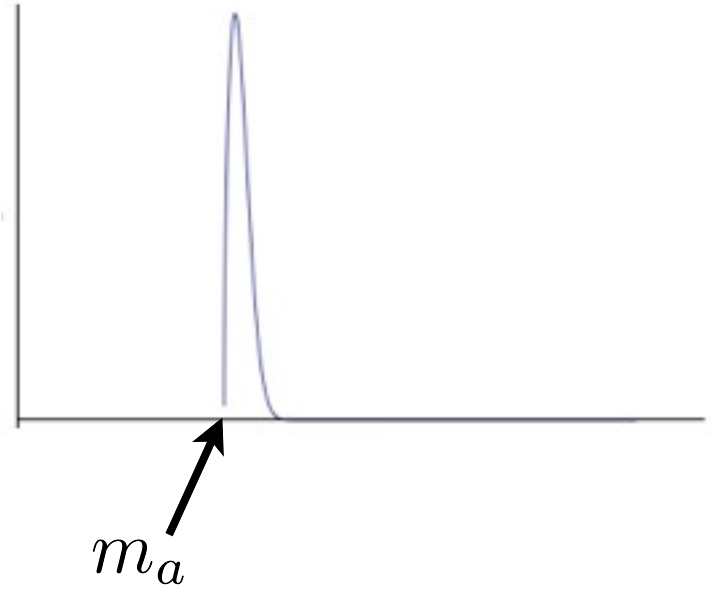

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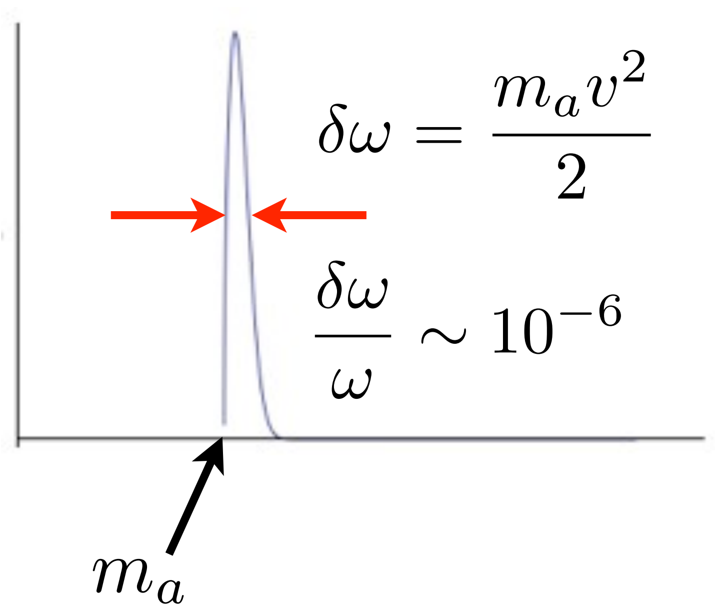

$$\delta\omega = \frac{m_a v^2}{2}$$

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

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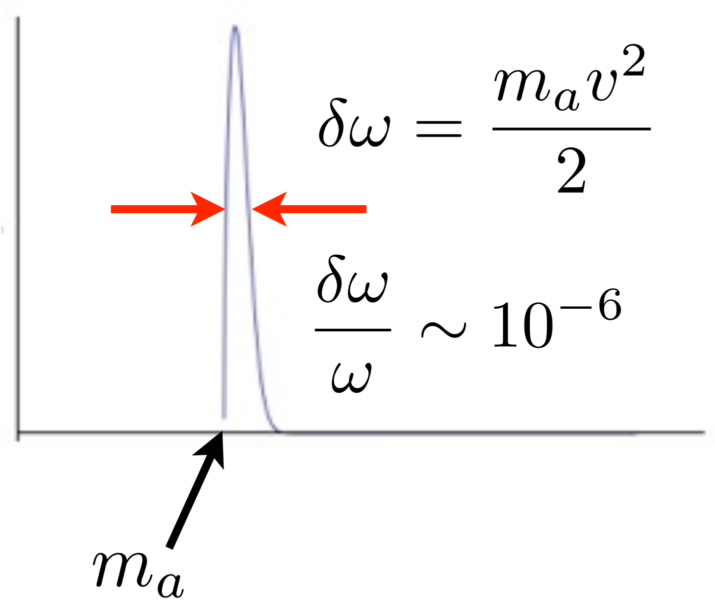
Non-zero velocity in galaxy -> finite width

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

~ 10^-6

coherence time

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



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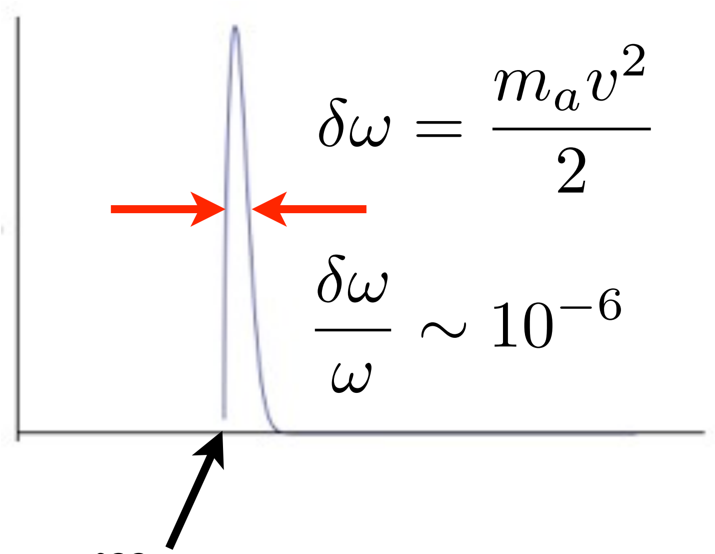
~ 10^-6



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

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

m_a

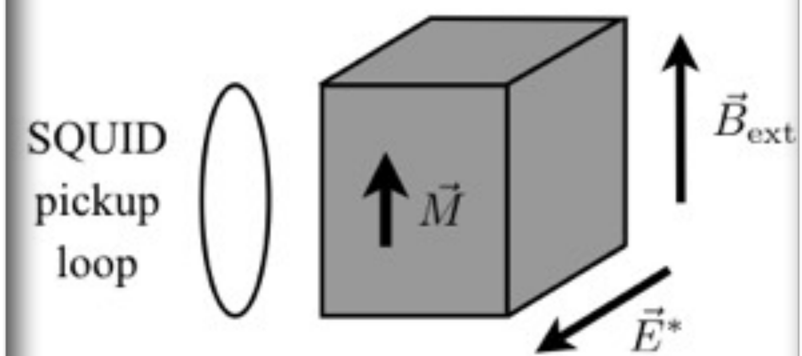
coherence time

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

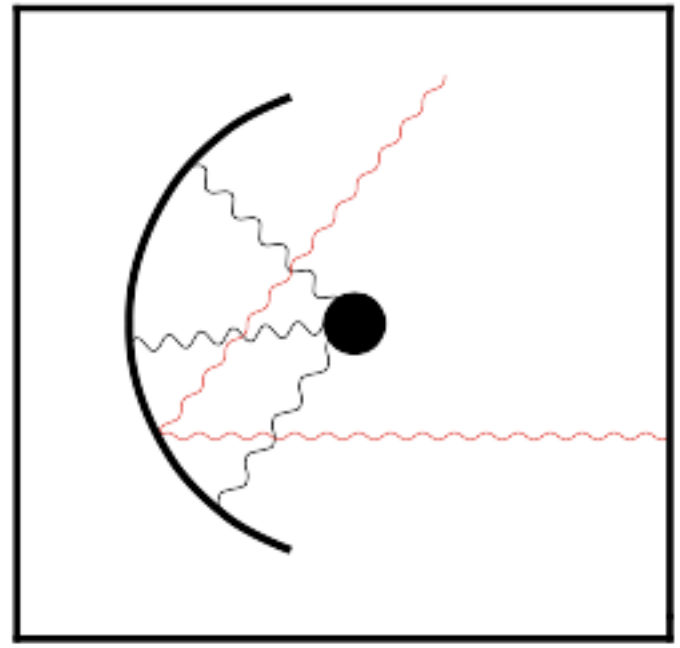
coherence length

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

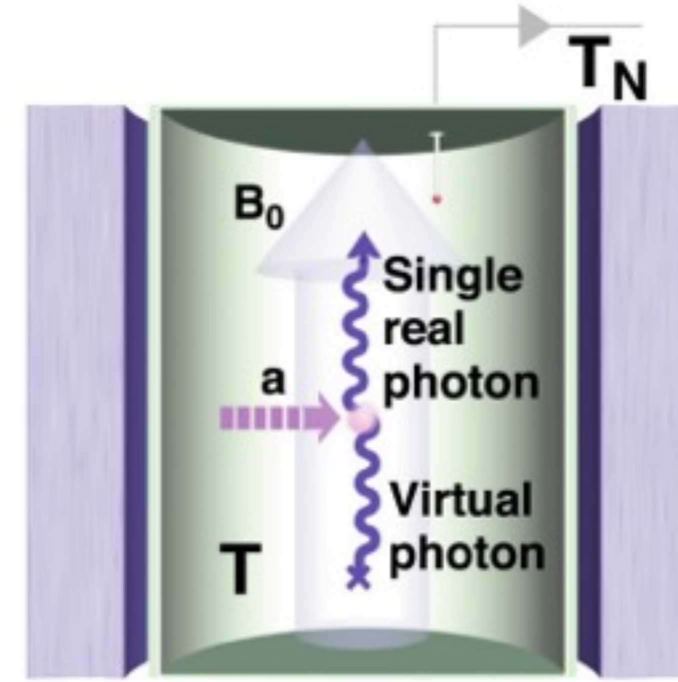
Spin precession



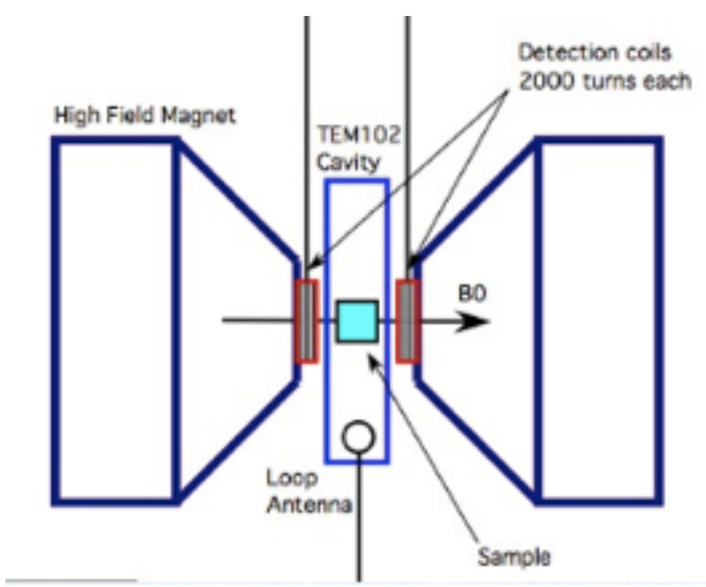
Mirrors+



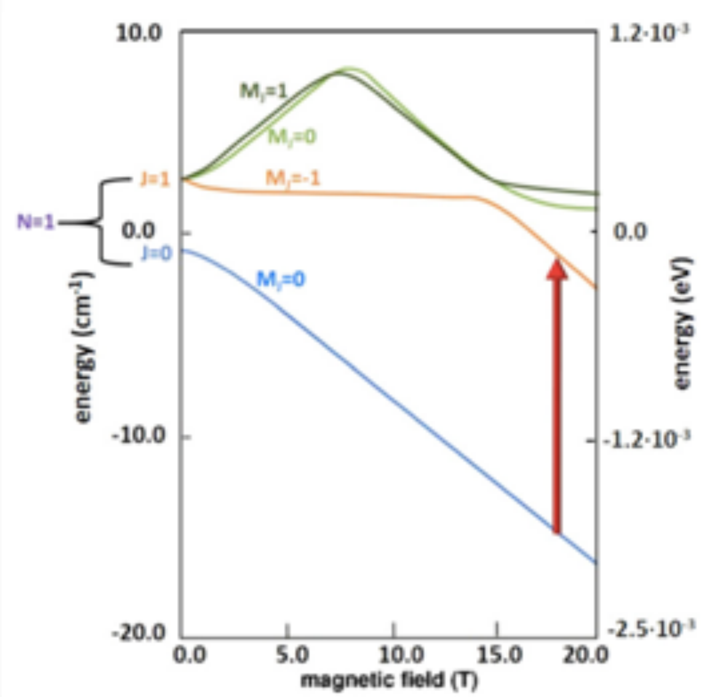
Cavities



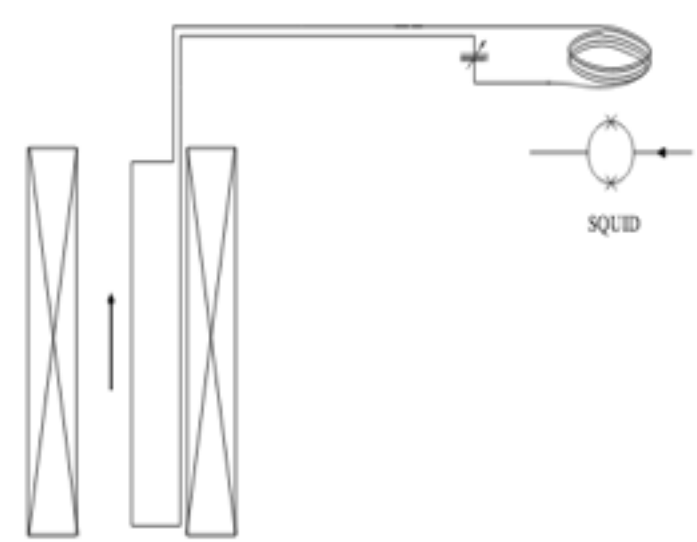
e-spin precession



Atomic transitions

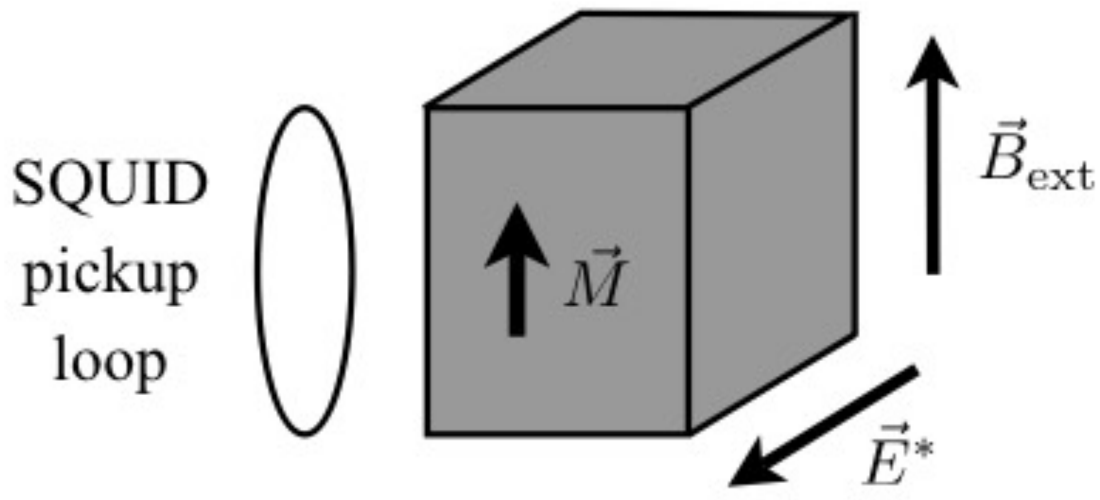


LC-circuit



CASPER at Mainz

Graham 2012



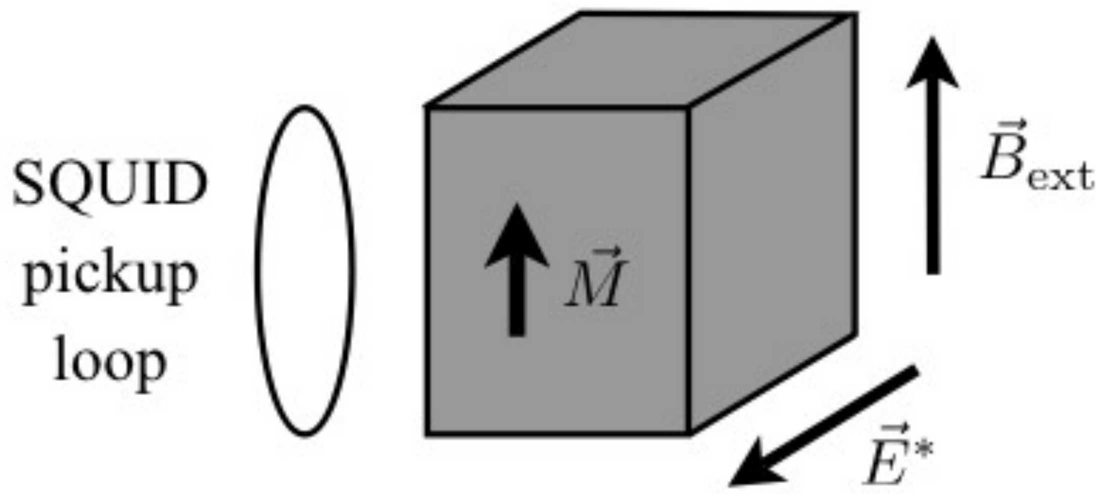
magnetic signal $\propto n p \varepsilon_S d E^* T_2$

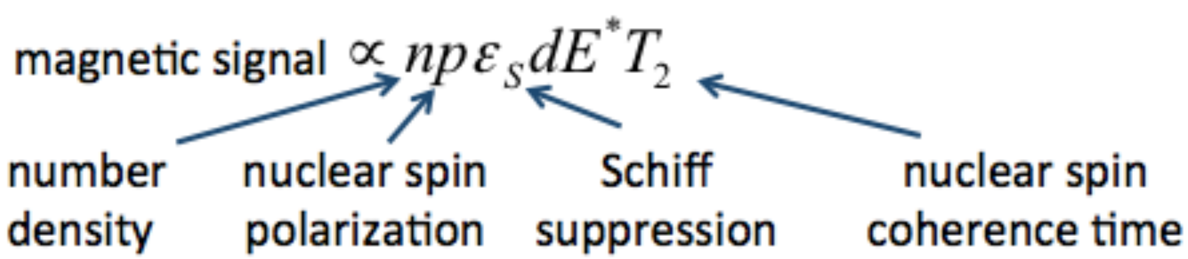
number density, nuclear spin polarization, Schiff suppression, nuclear spin coherence time

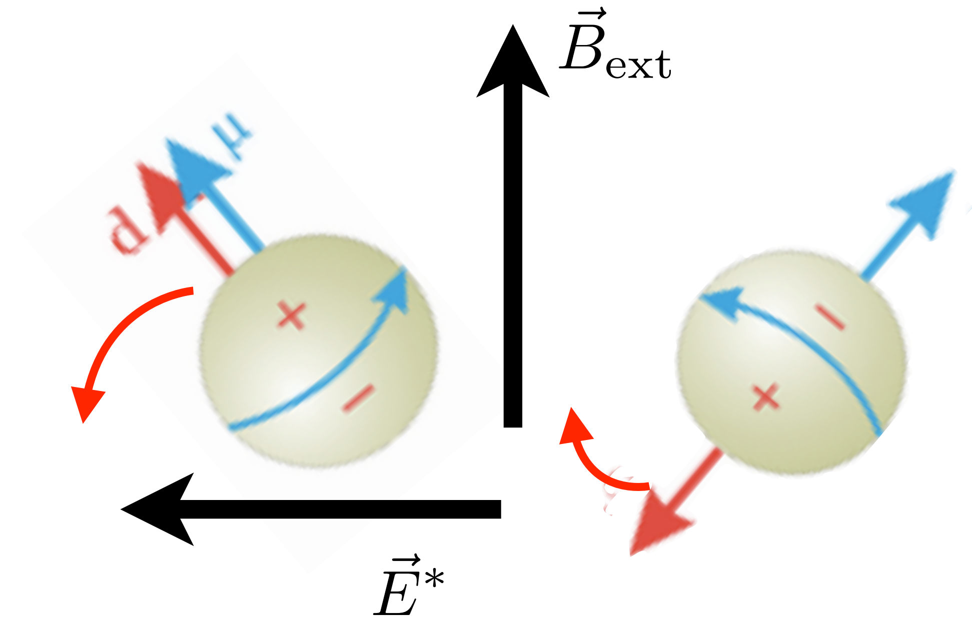
- EDM + Large E-fields in PbTiO3
- Mainz (D. Budker's group) & Berkeley
- B-field, coherence time, sensitivity to m < neV
- Mass range limited by B-field strength

CASPER at Mainz

Graham 2012







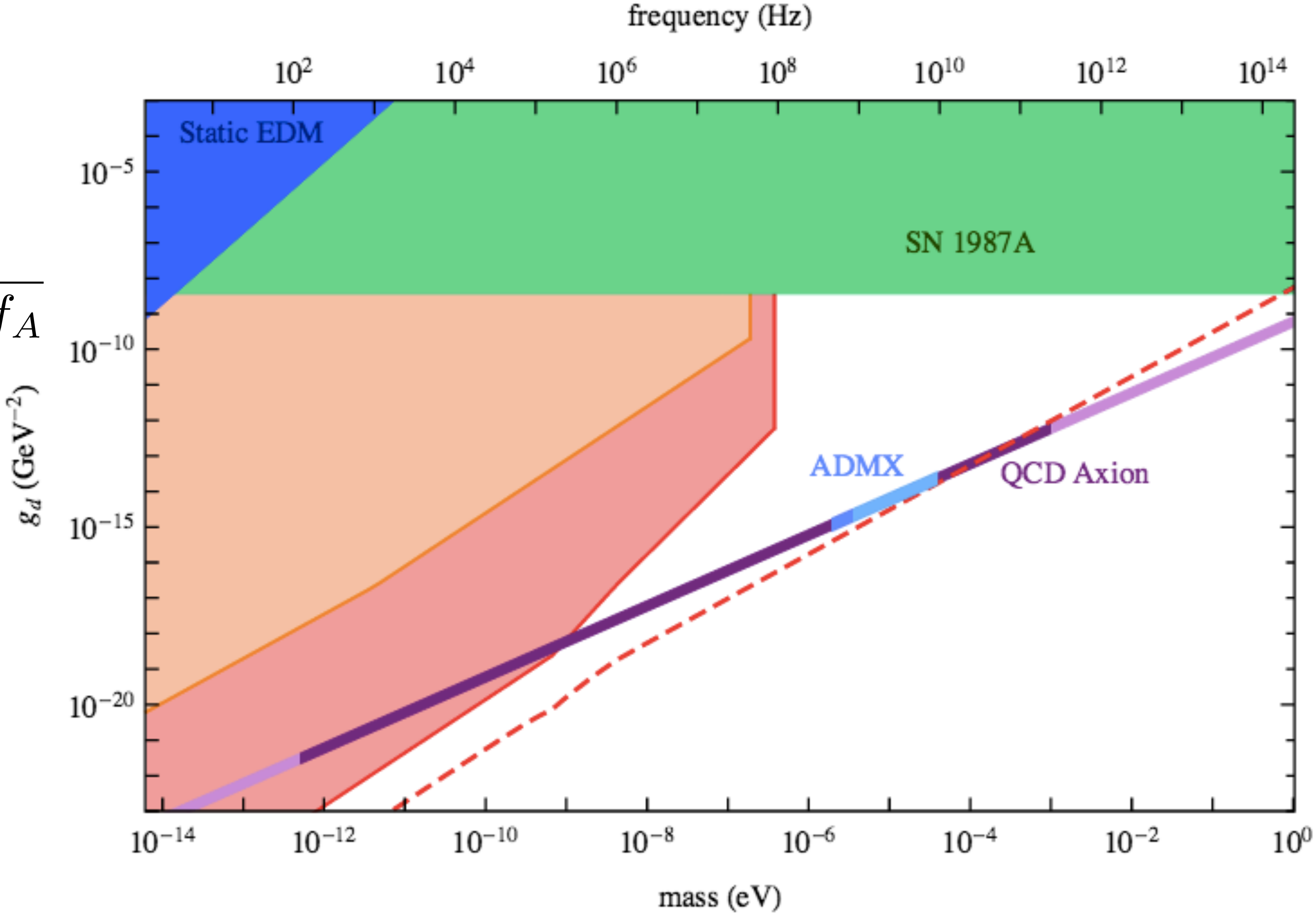
Oscillating EDM, effects add up, transverse magnetisation grows if $m_a = \omega = \mu|\vec{B}_{\rm ext}|$

- EDM + Large E-fields in PbTiO3
- Mainz (D. Budker's group) & Berkeley
- B-field, coherence time, sensitivity to m < neV
- Mass range limited by B-field strength

CASPER reach

Graham 2012

$$\sim \frac{1}{m_n f_A}$$

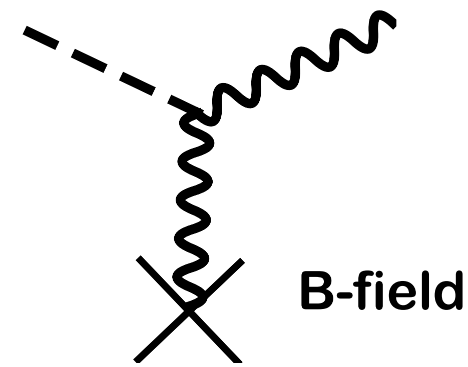


Axion DM in a B-field

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

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

source



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

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

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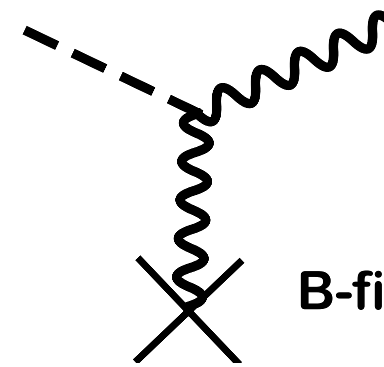

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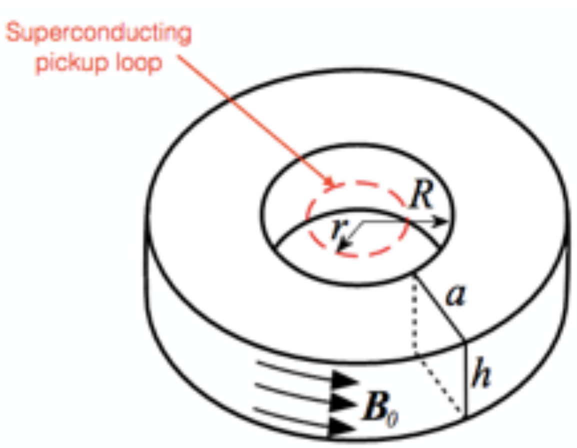
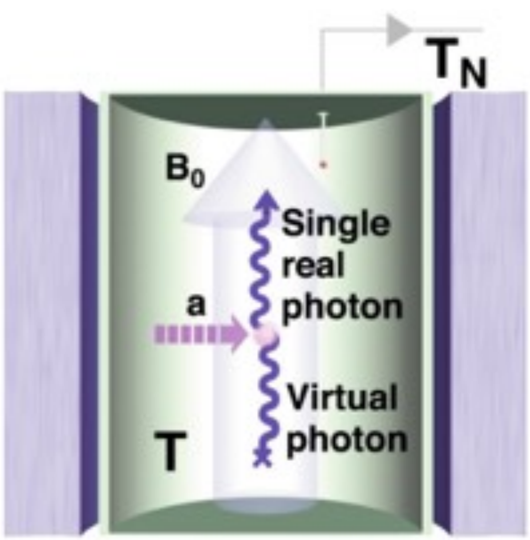
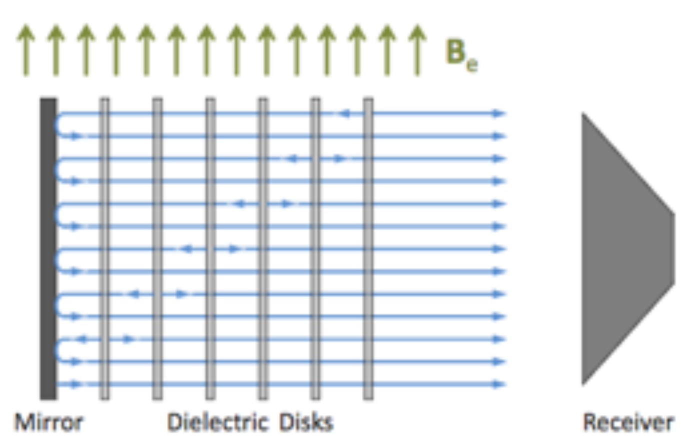
- Four different techniques:



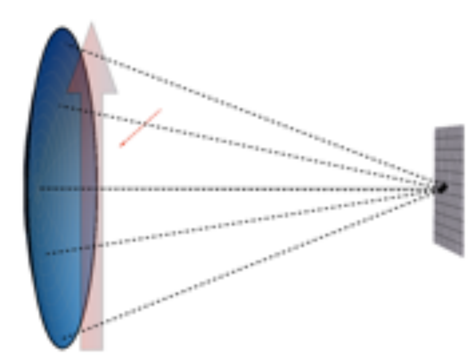
DM Radio



Cavities



Dielectric haloscope

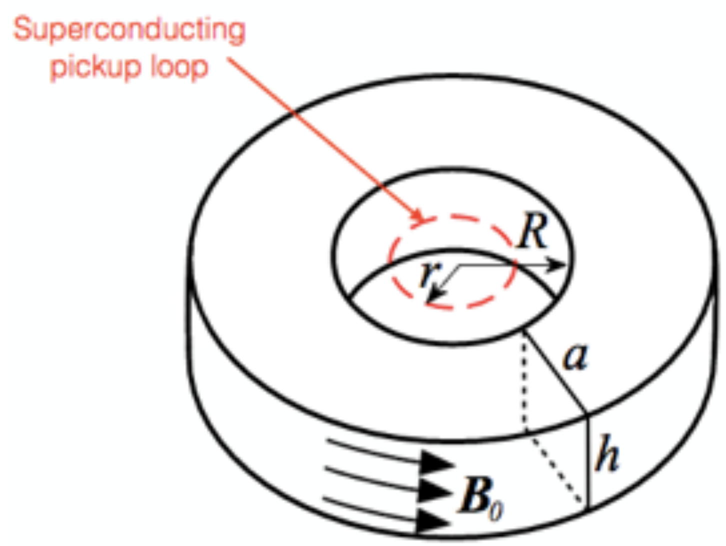


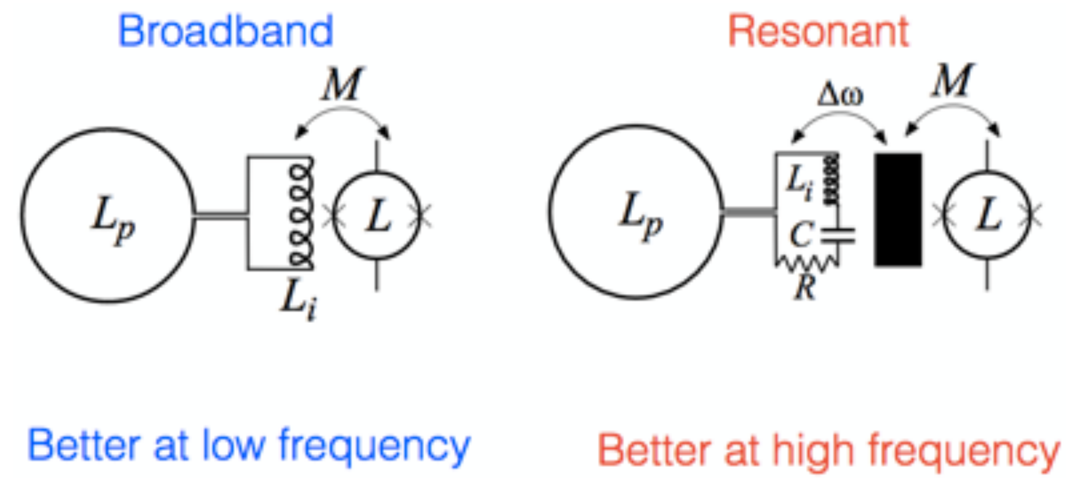
Dish antenna

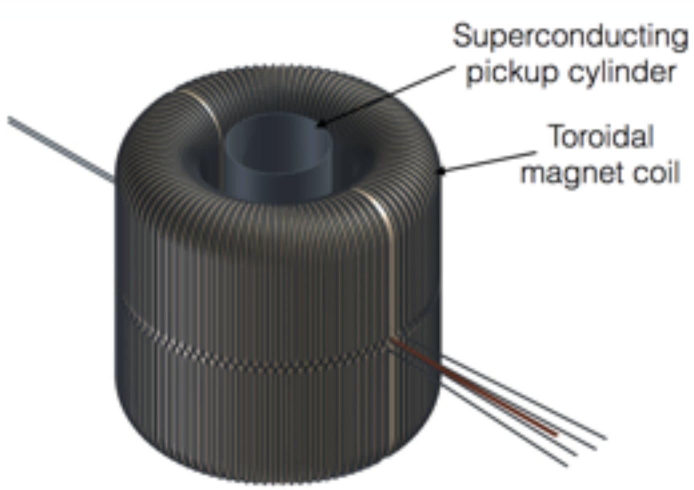
DM Radio

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

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

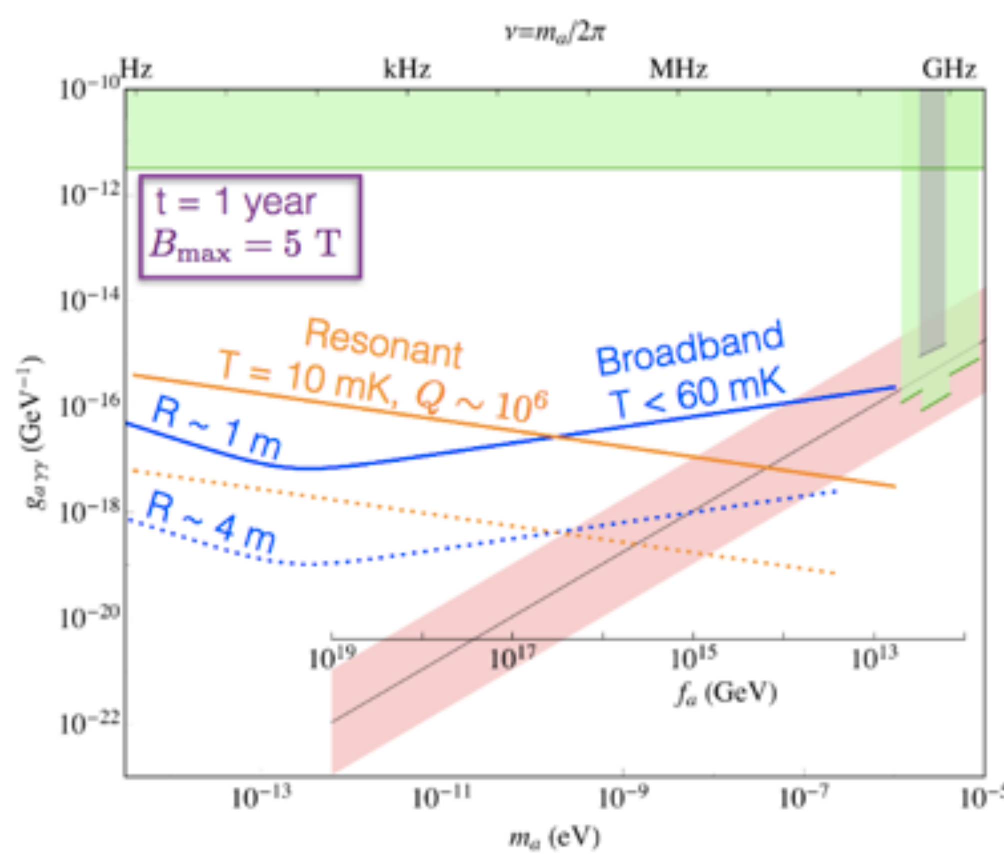






ABRACADABRA (MIT)
10 cm, 1m , 4m ...

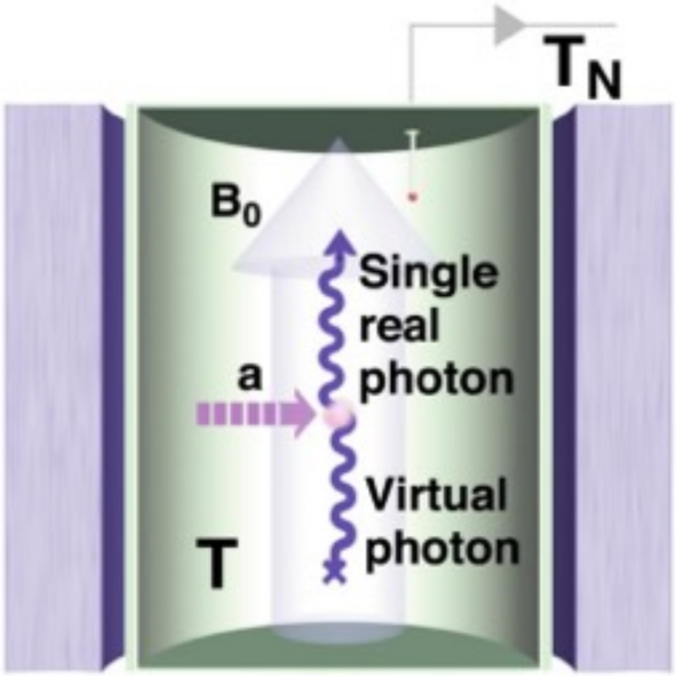
axion coupling $\frac{\alpha}{2\pi f_a}$



Resonant cavities: haloscopes

P. Sikivie

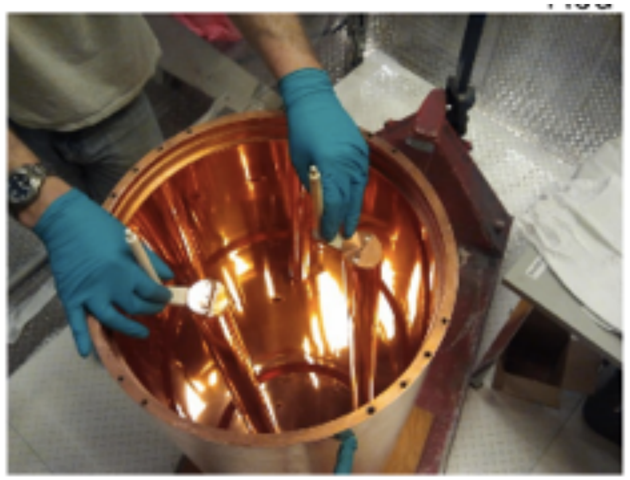
- Boost the axion-generated E-field in a tuned resonant cavity

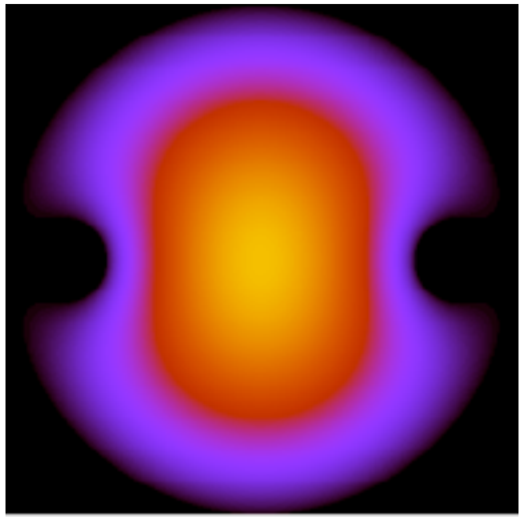


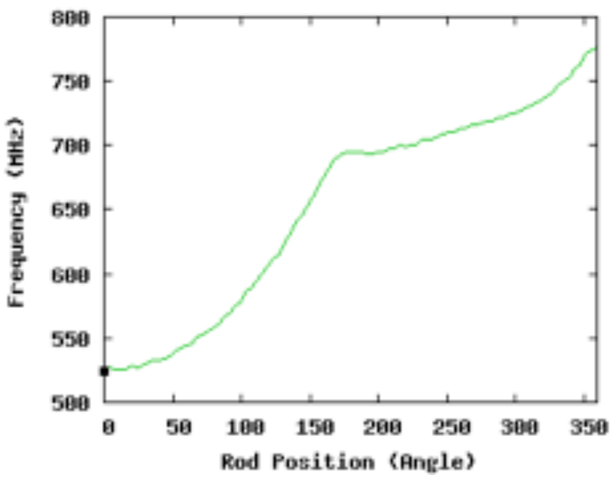
$$P_{\rm out} \sim Q|\mathbf{E}_a|^2 V m_a$$

- 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







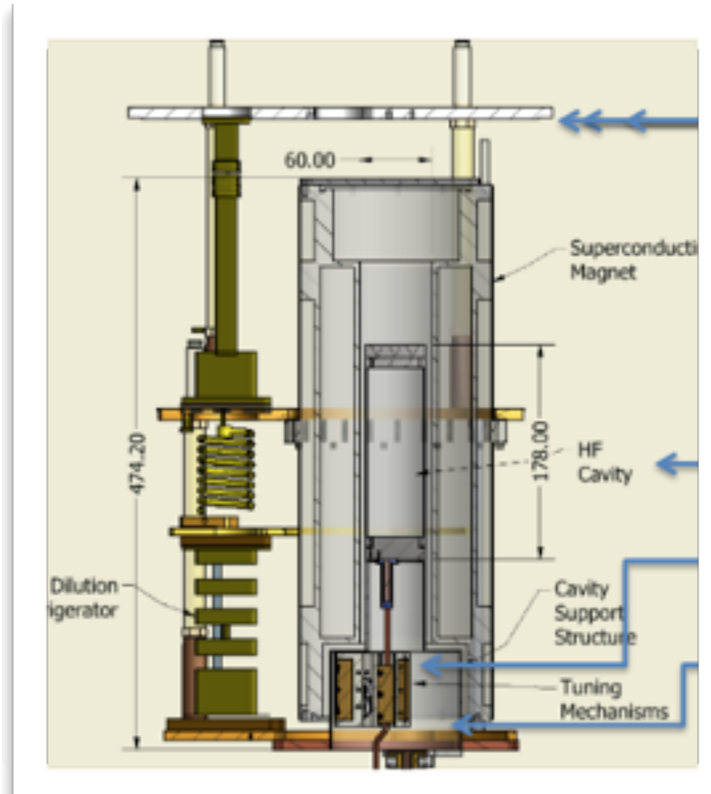
- At high freq. limited by small volume and high noise
- At low freq. by getting a large enough B-field

Cavity experiments

ADMX-Seattle

running!

CULTASK - CAPP -Korea



2017-...

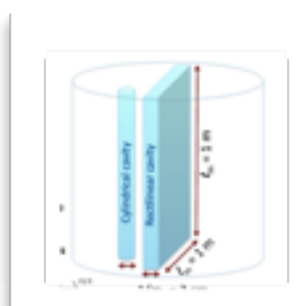
ORGAN-UWA Perth

2017-...

HAYSTAC-Yale

2016-...

ADMX-Fermilab



RADES

2017-...

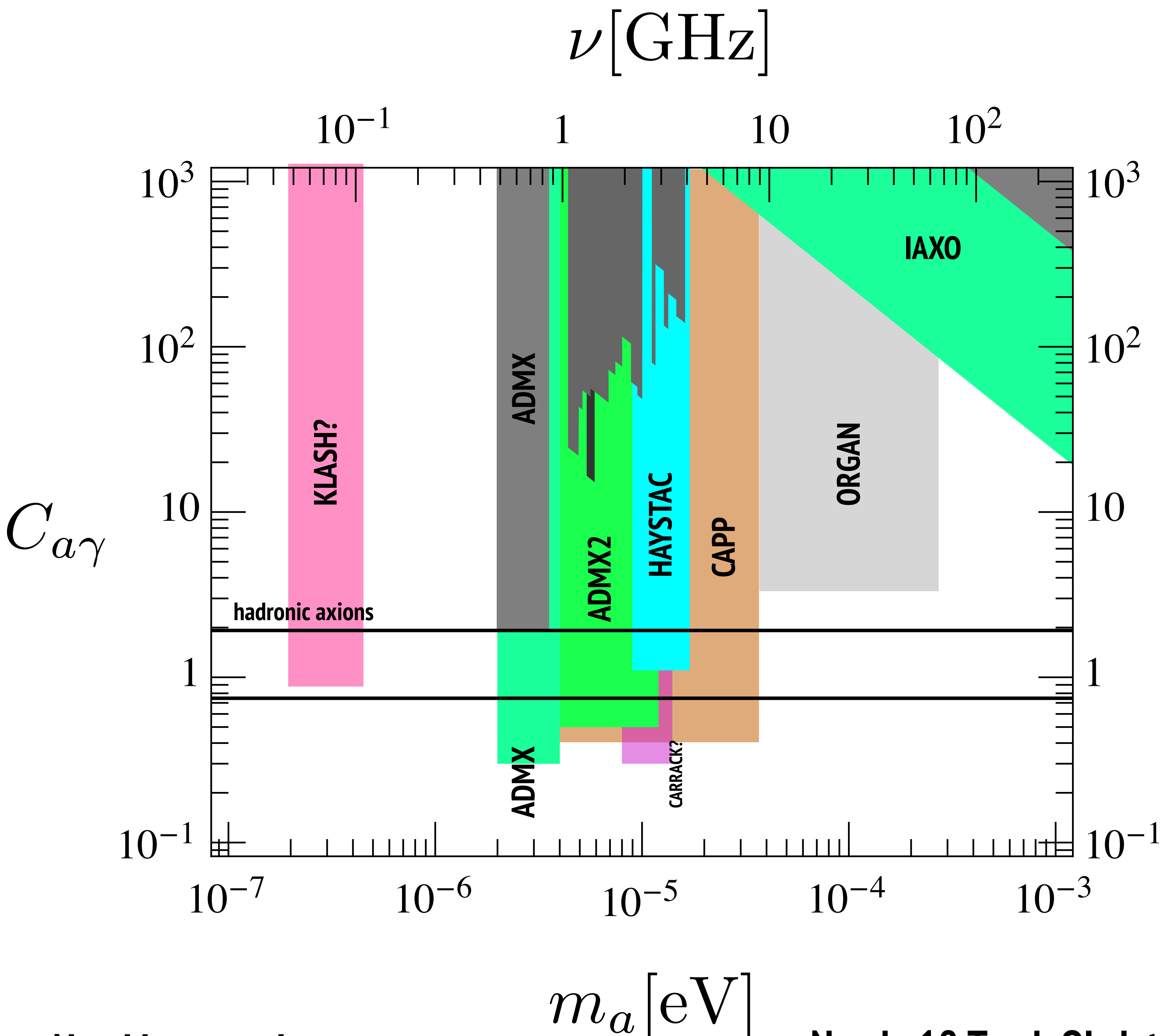
CAST-CAPP

2017-...

KLASH?

??-...

Projected sensitivities

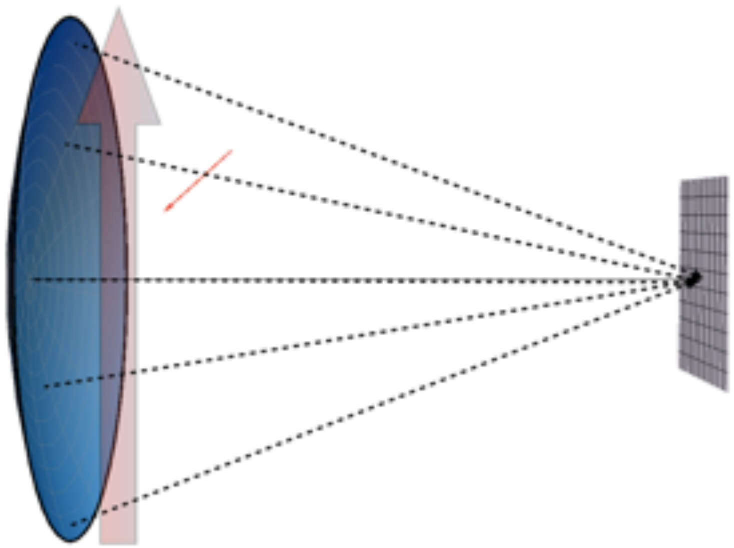


- Need larger volume

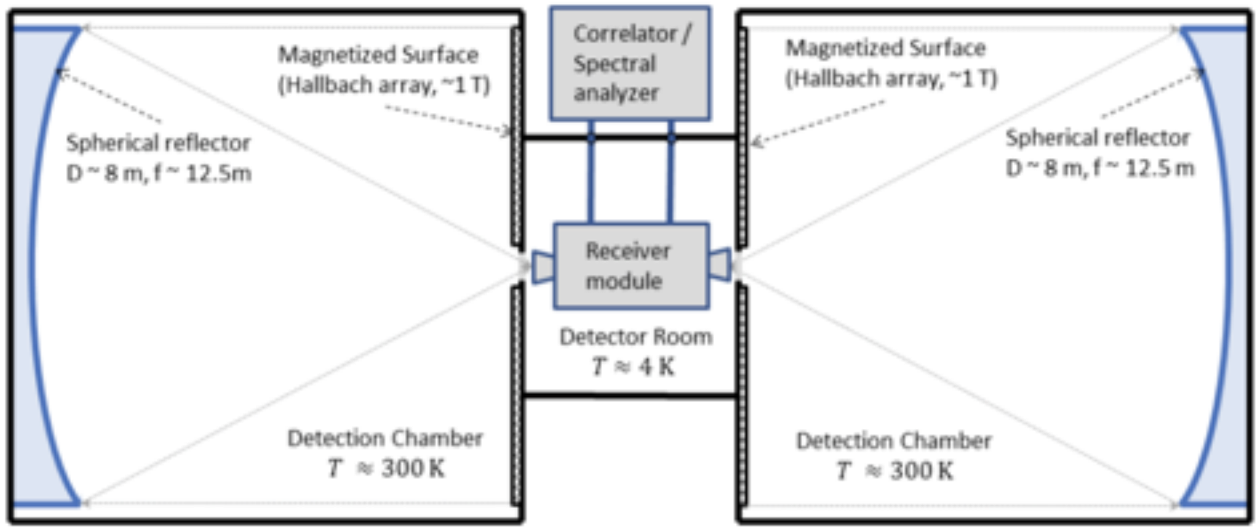
- Need >10 T, sub QL detection, Q~10^6

Dish antenna

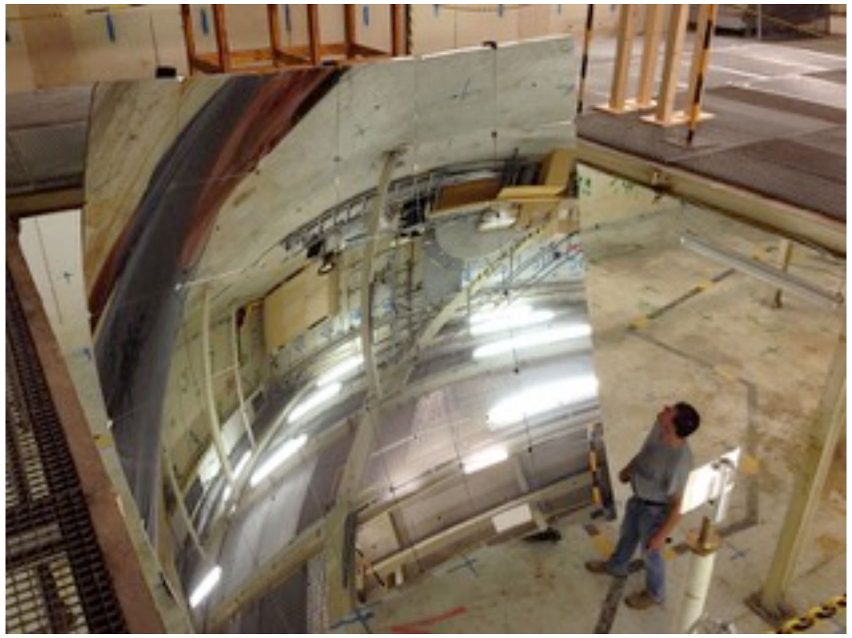
- Detect radiated power from a huge ($Am_a^2 \gg 10^6$) magnetised dish
- Broadband, no resonance enhancement; Only detector needs to be at T~mK (high reflectivity dish)
- Magnetise Area with permanent-magnets, photon counting?



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



BRASS @ Hamburg



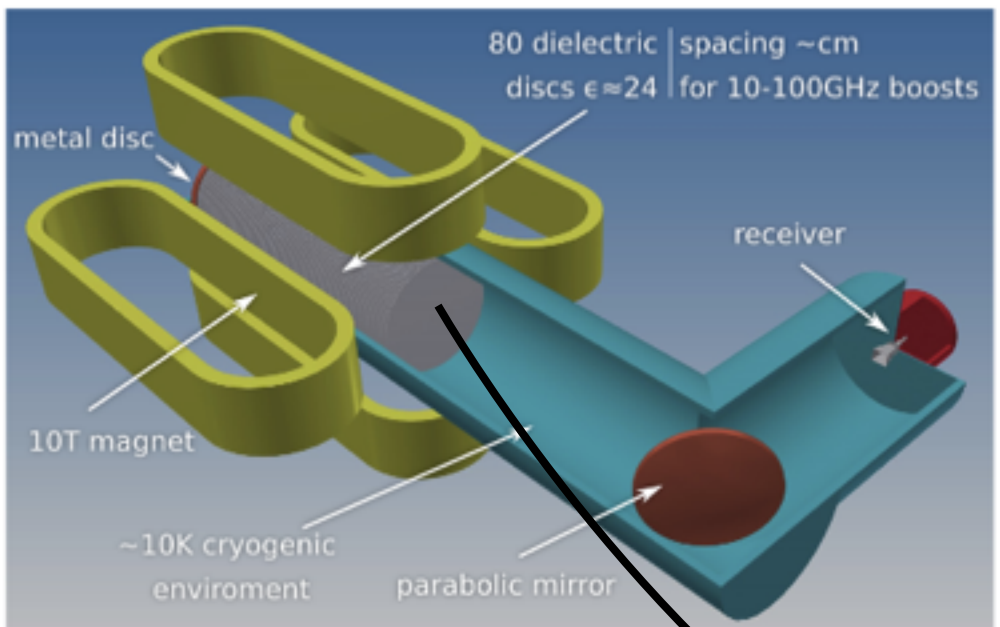
FUNK experiment (KIT)

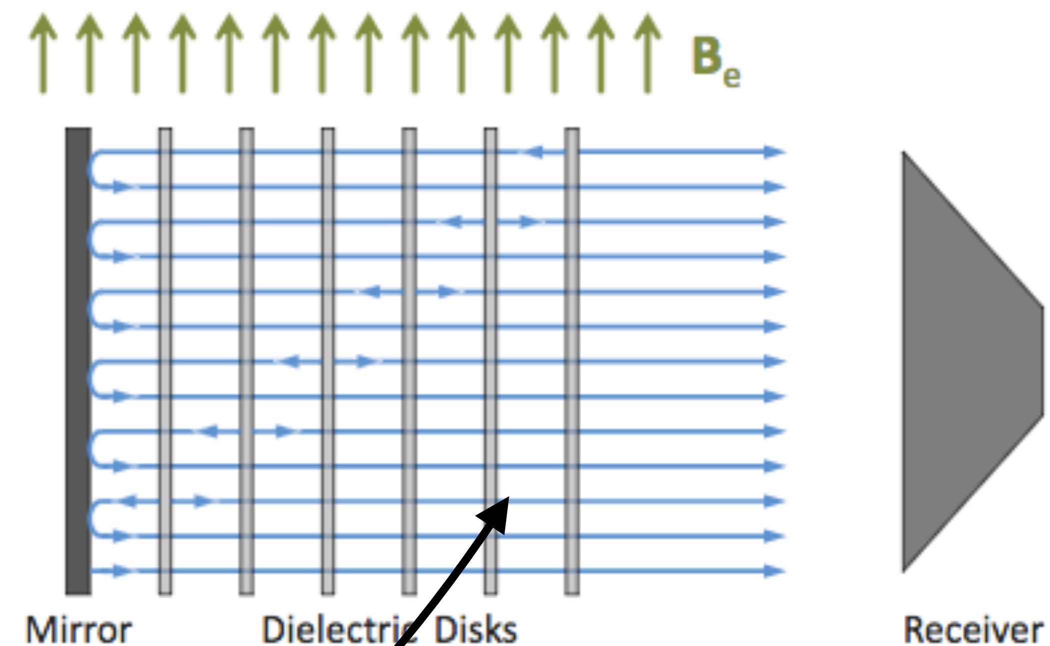
Dielectric haloscope : MADMAX

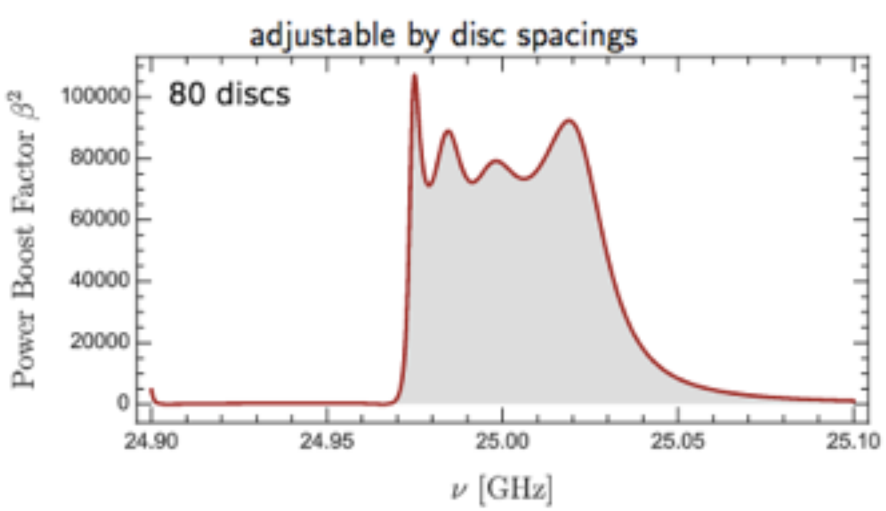
- **Hybrid system, large area + multiple emitters + a bit of resonant enhancement**

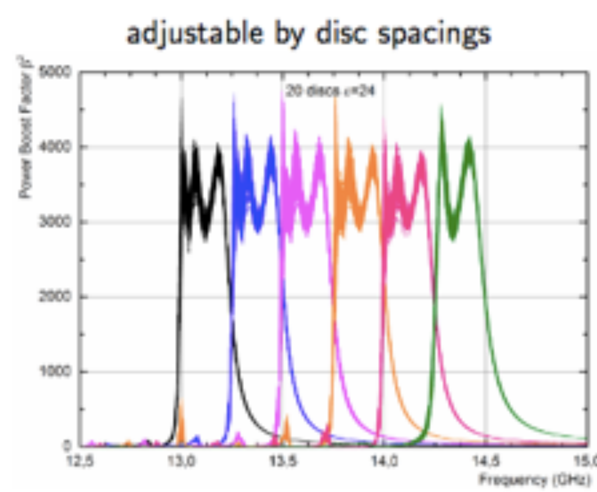
$$\frac{P}{Area} \sim 2\times 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{c_\gamma}{2}\,\frac{B_{||}}{5\mathrm{T}}\right)^2 \frac{1}{\epsilon} \times \beta(\omega)$$

boost factor



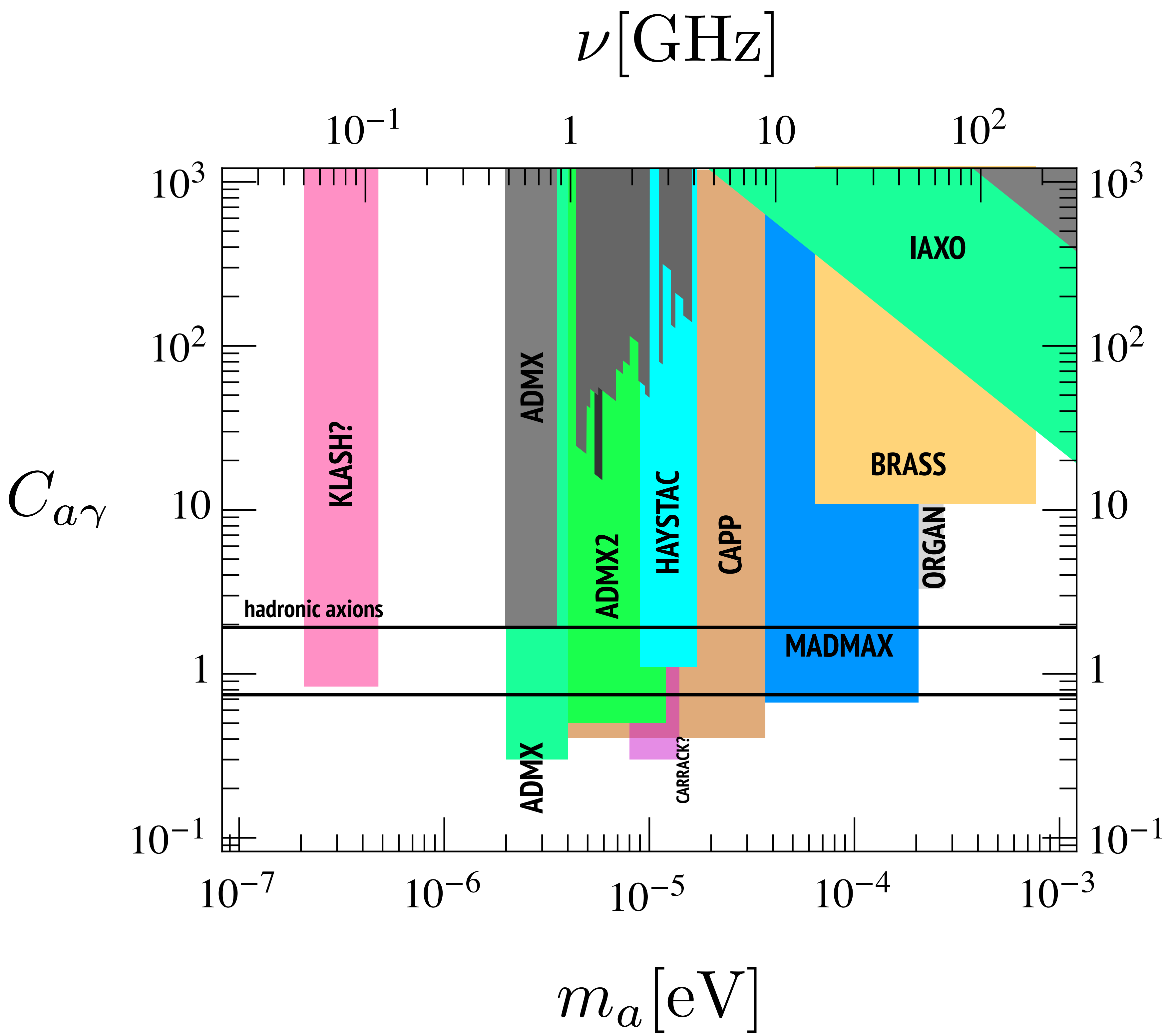




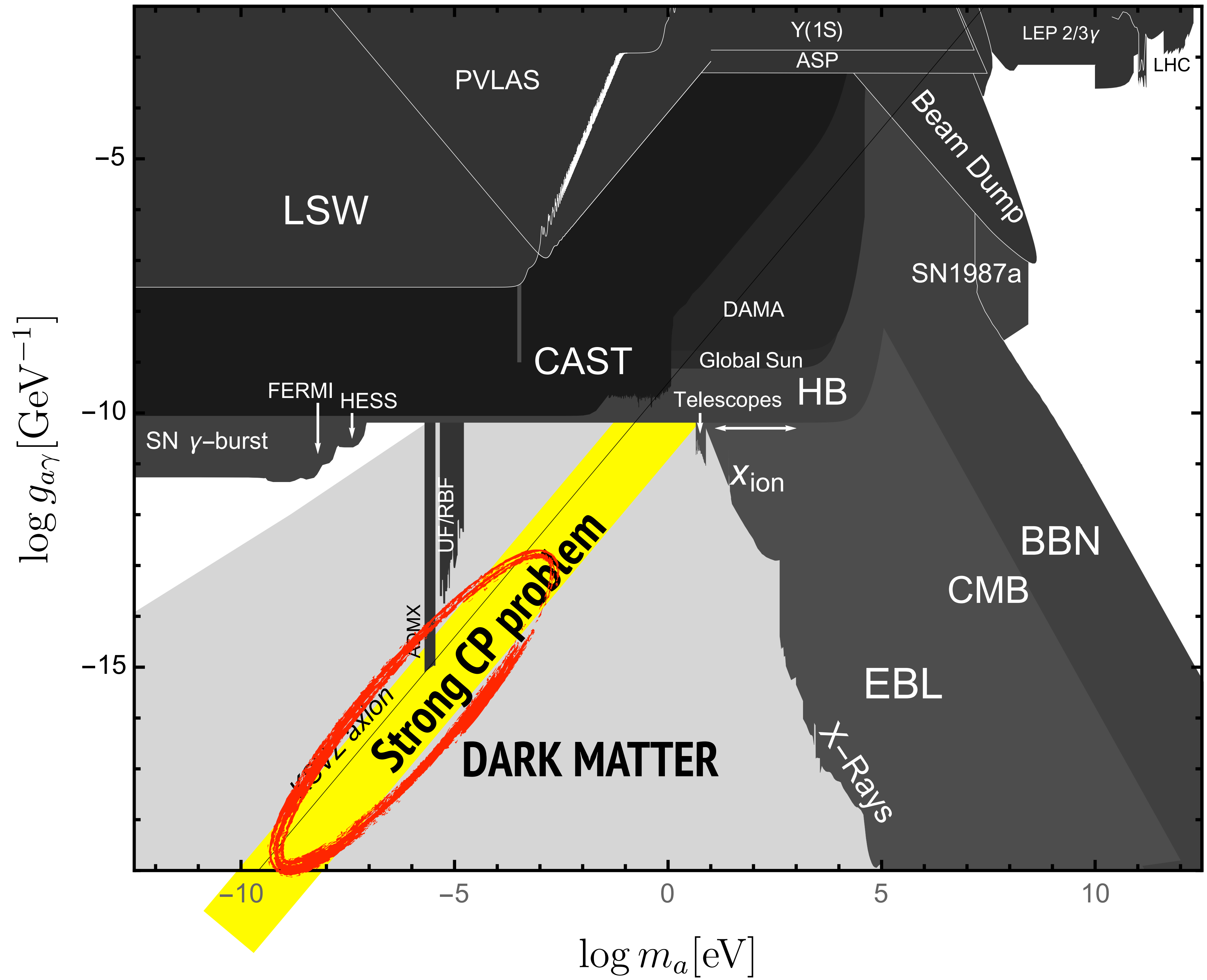


MADMAX: MAgnetised Disk and Mirror Axion eXperiment: MPP Munich, Hamburg Uni, DESY, Saclay, Zaragoza U

Projected sensitivities



Summary plot



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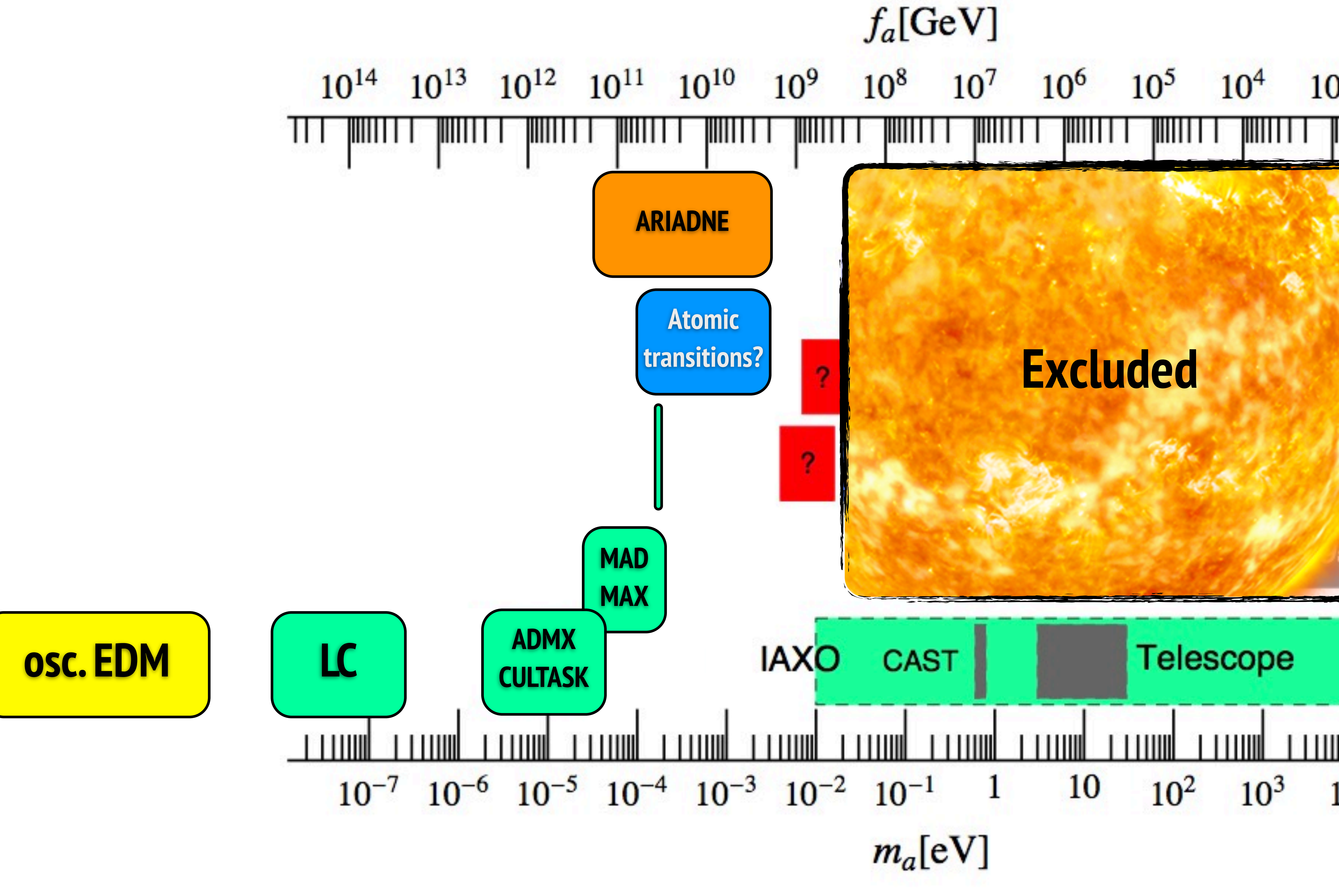

Conclusions

- Beyond the SM with extremely low energies

- Detect an ALP, new energy scale!

- Generic interactions

- hints: Strong CP problem, DM, Stellar evolution, Transparency of Gamma's

- Good Experimental ideas

- Still a lot of parameter space to explore!