Axions and Axion-like Particles

Javier Redondo
(Zaragoza U. & MPP)

Outline

- 1 big picture
- 2 types of ALPs
- 3 types of interactions
- 4 ~ hints of existence
- 5 ... Experiments to find them
- 6 Conclusions

structure based on ...

New experimental approaches in the search for axion-like particles

Igor G. Irastorza, Javier Redondo. Jan 24, 2018.

e-Print: arXiv:1801.08127 **[hep-ph]** | PDF

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

ADS Abstract Service

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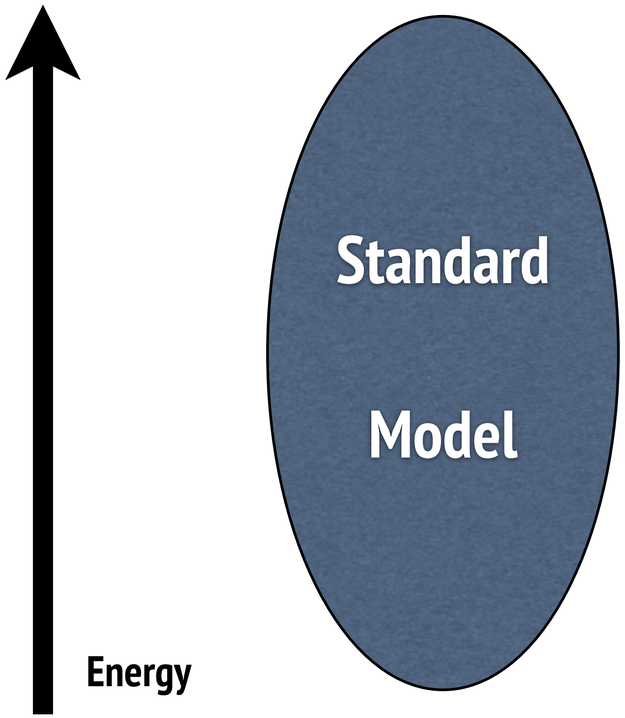
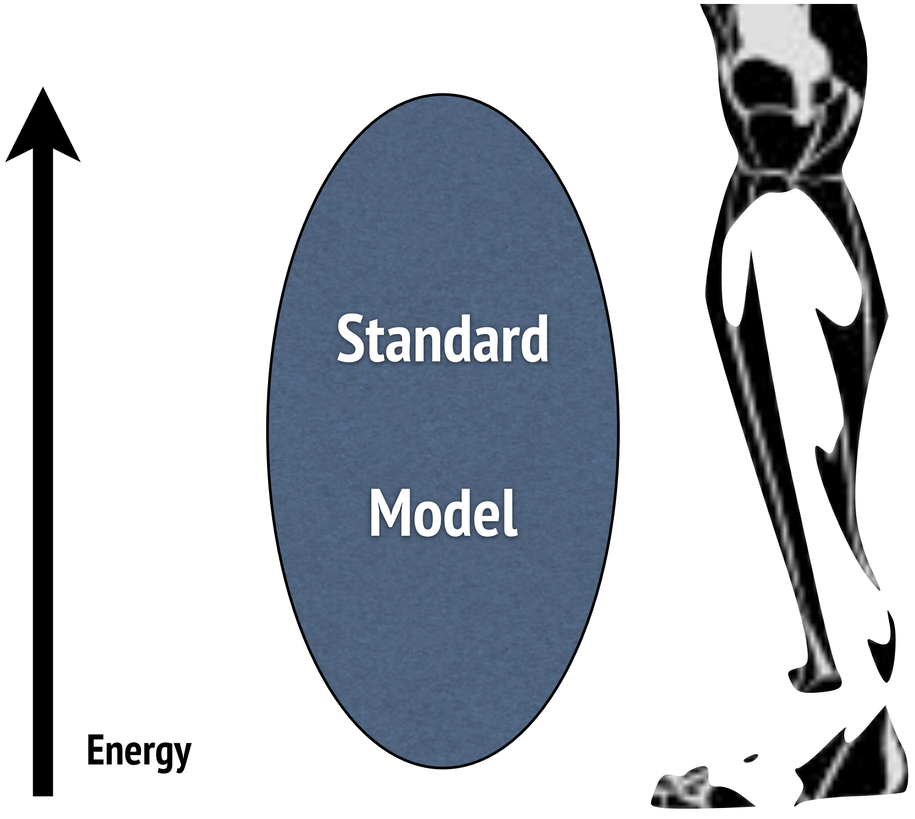


Describes extremely well
particle physics
(at low energies)



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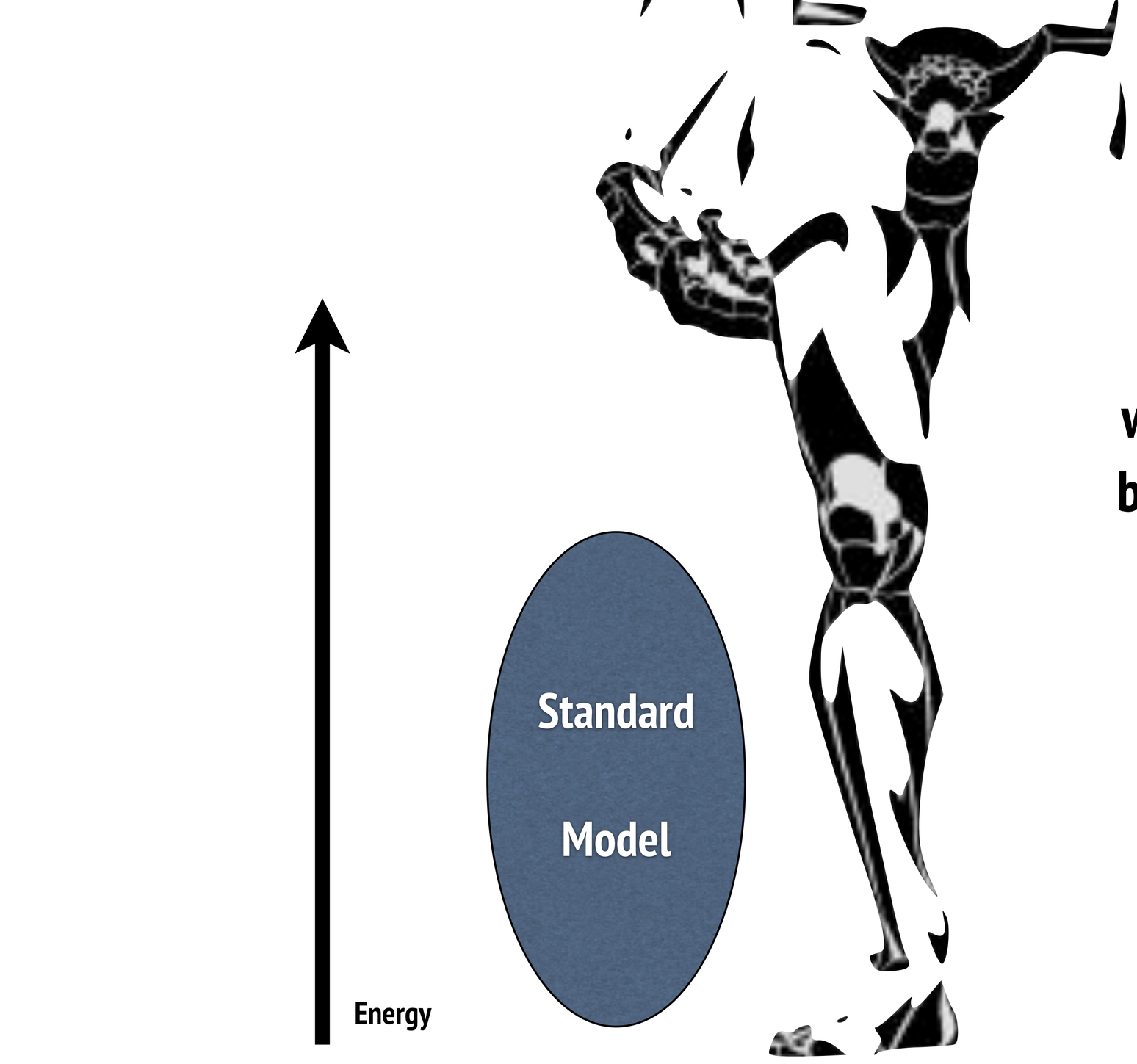
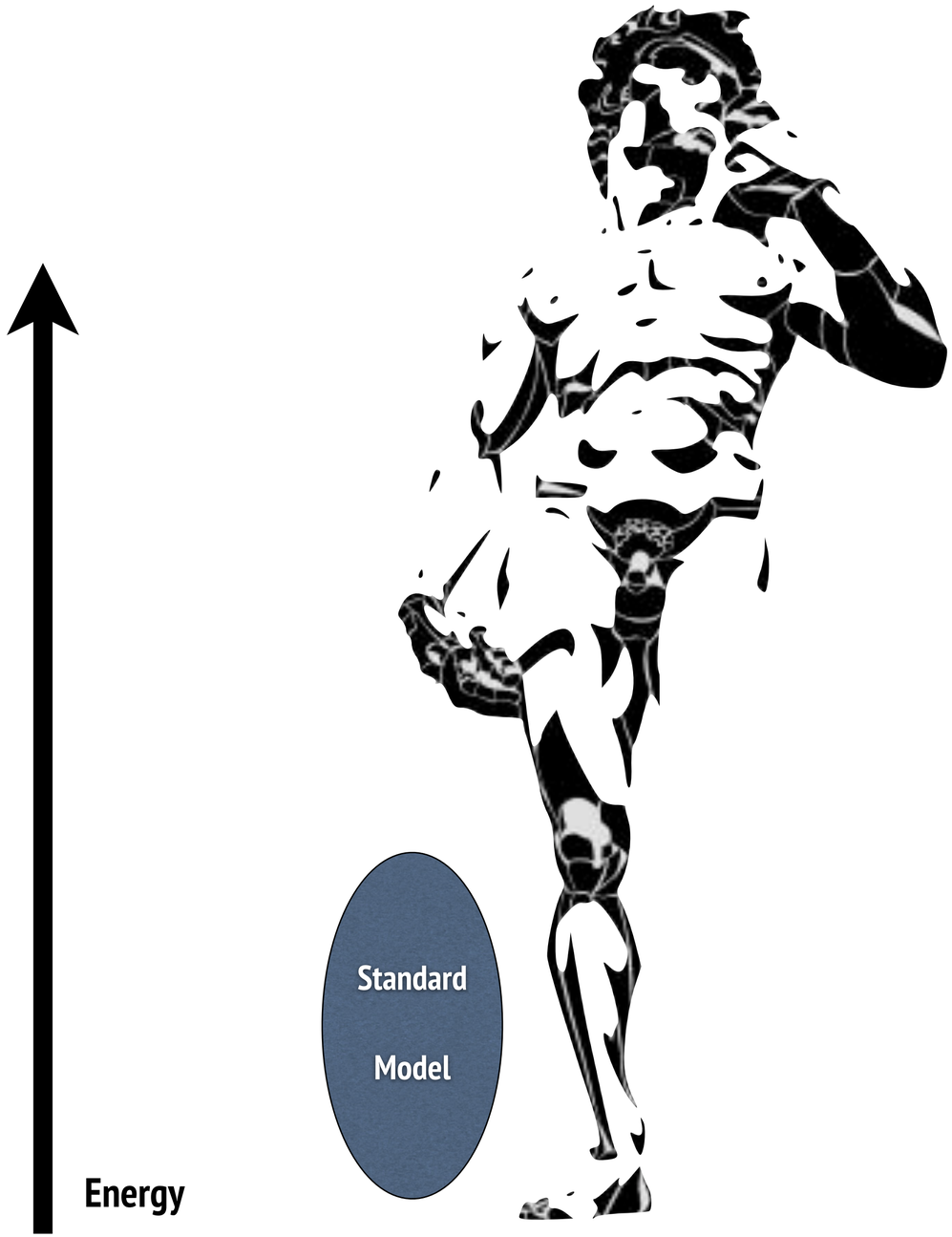
but it is certainly …

INCOMPLETE



Answers wait in the high energy frontier where more symmetric beautiful theories arise



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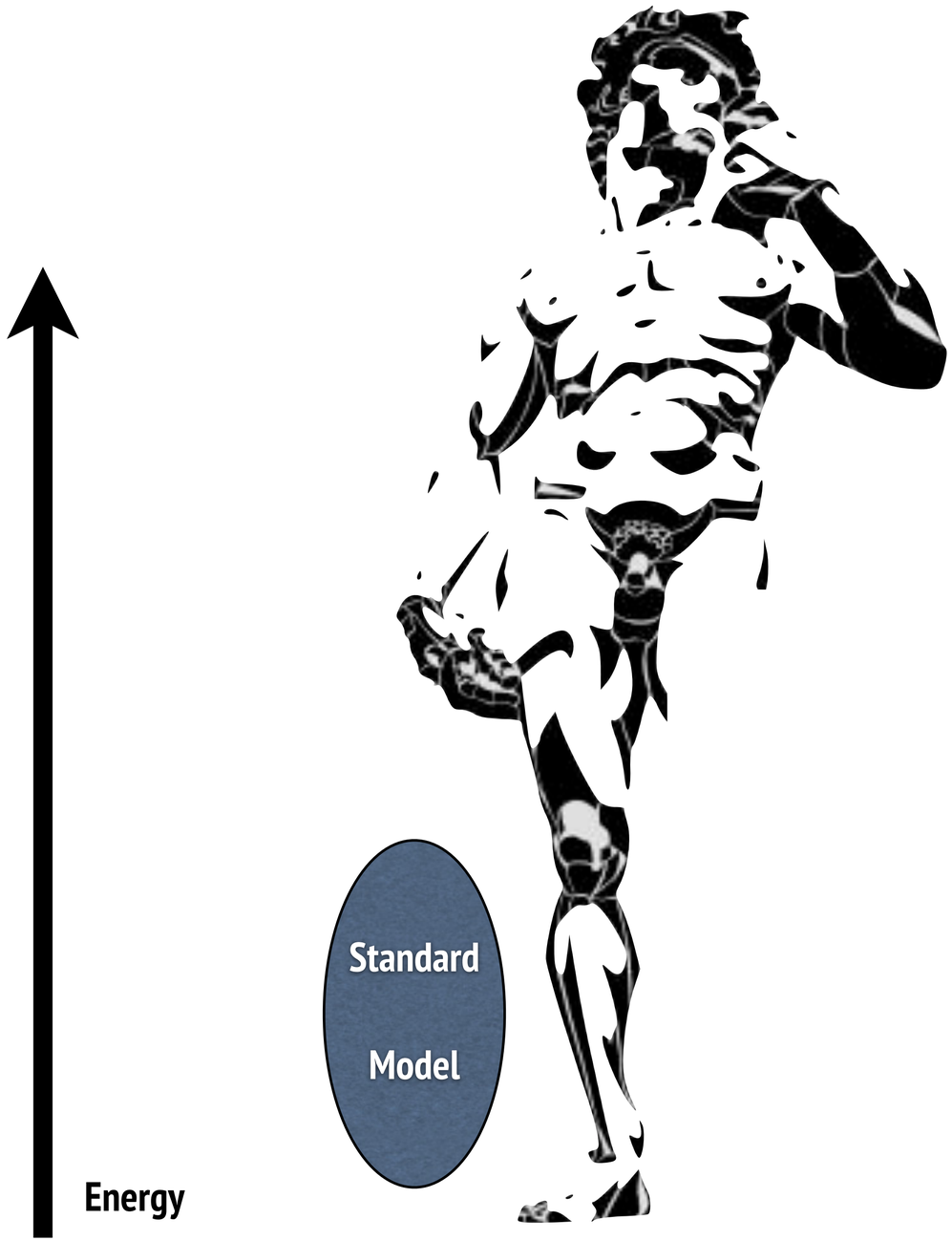

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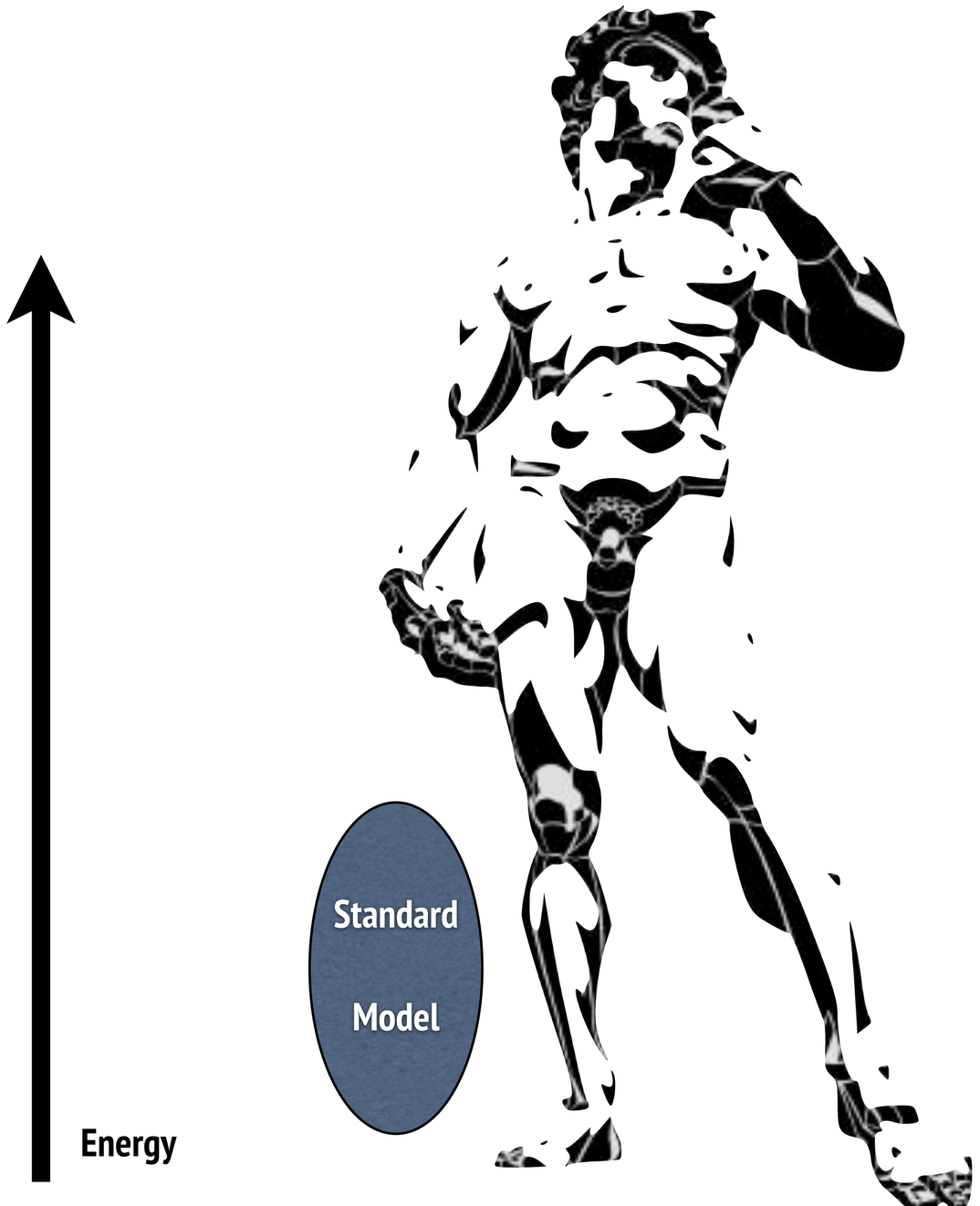

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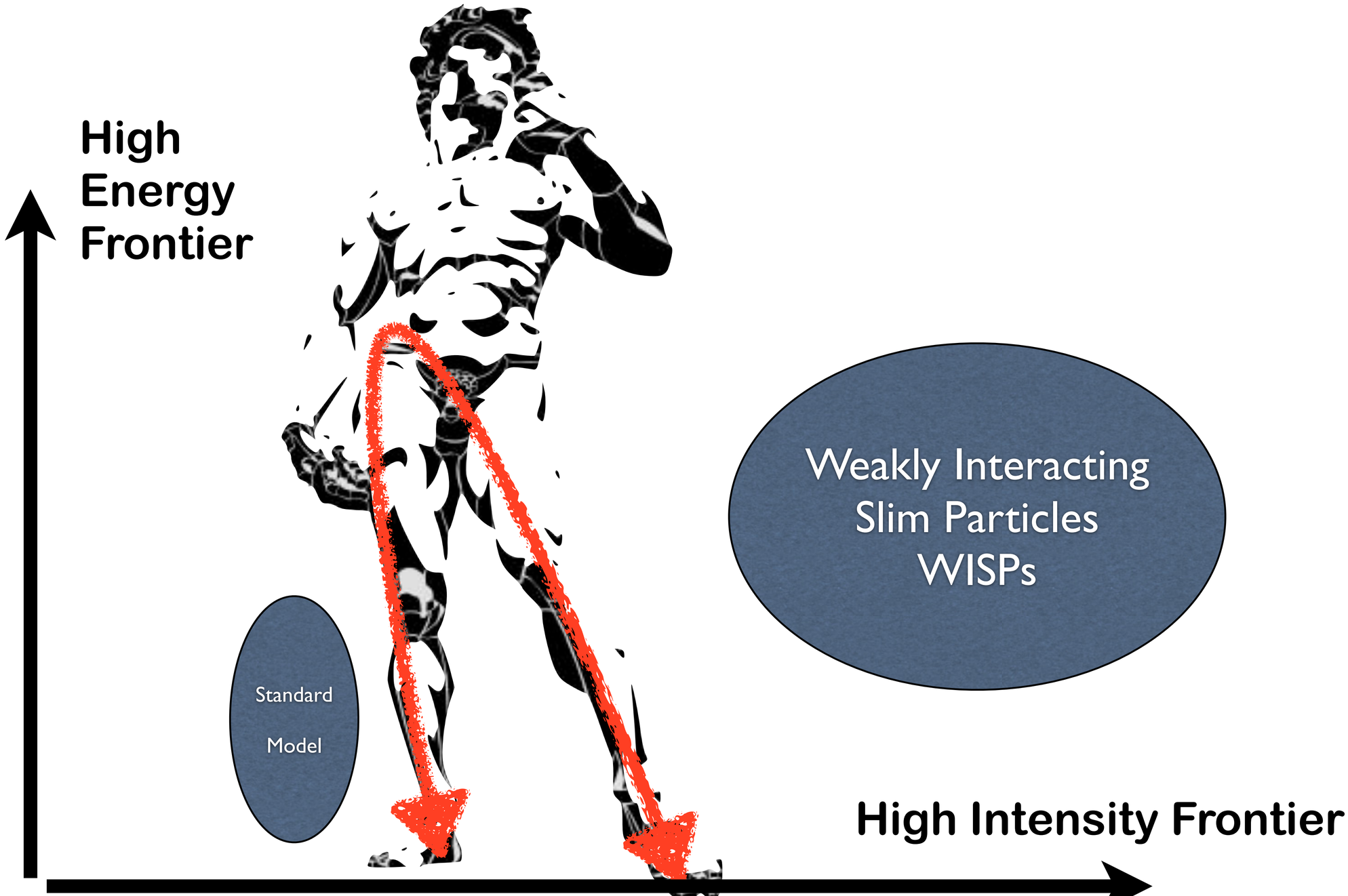
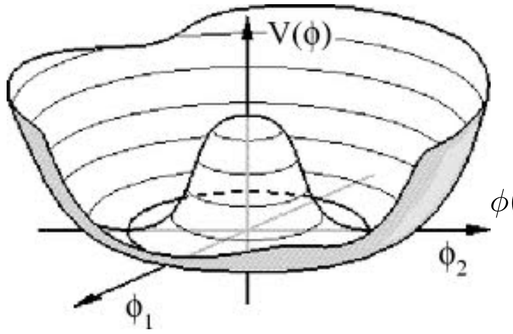

High
Energy
Frontier
Standard
Model
Weakly Interacting
Slim Particles
WISPs
High Intensity Frontier

2 types of Axion-like particles (ALPs)

pseudo Goldstone Bosons

- Global symmetry spontaneously broken



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

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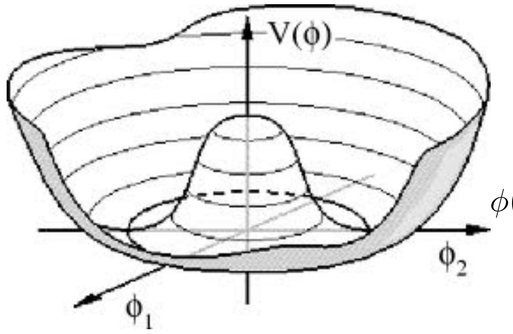

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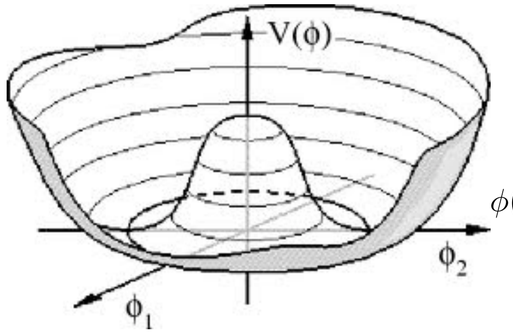

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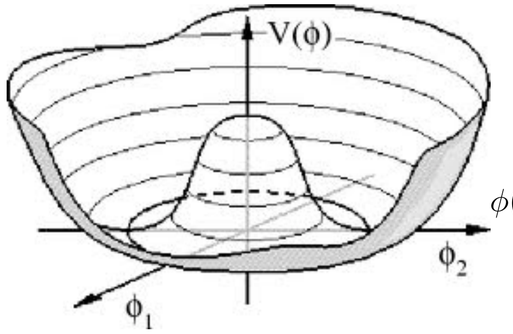

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  quantum gravity violations

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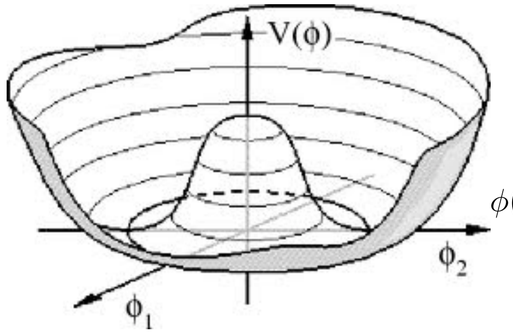

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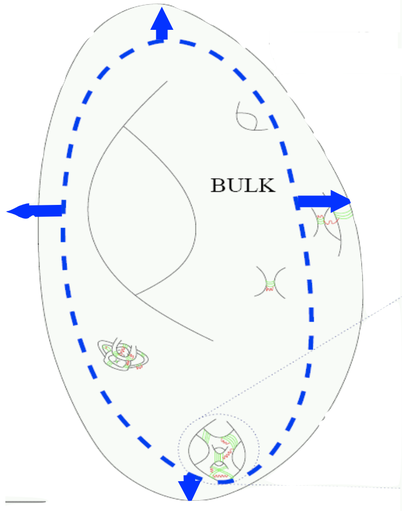
stringy axions

- Im parts of moduli fields (control sizes)



- O(100) candidates in compactification

- "decay constant", string scale M_s

- masses from non-perturbative effects

3 interactions: Low-energy effective action

- Shift symmetry allows some generic types of interactions

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

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- Most relevant interactions at low energies ...

electron coupling	nucleon coupling
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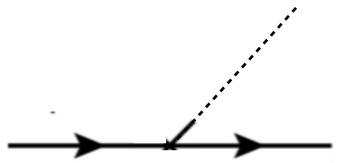	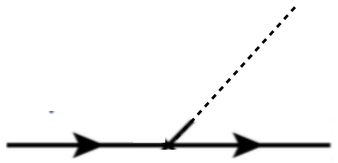

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	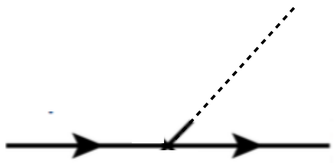	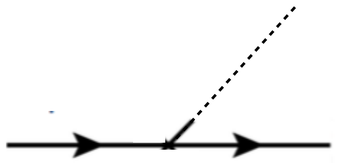

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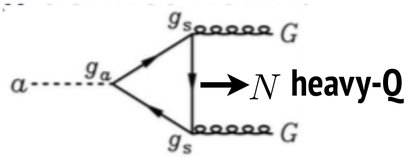

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	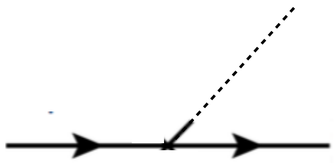	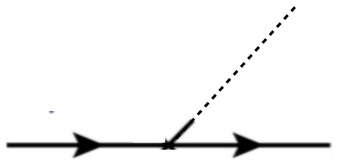

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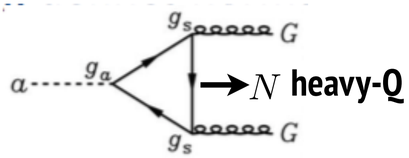

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$$V(\theta) \sim -\chi_{\rm QCD}\cos\theta \to \frac{1}{2}\frac{\chi_{\rm QCD}}{f_A^2}A^2 + \ldots = \frac{1}{2}m_A^2A^2$$

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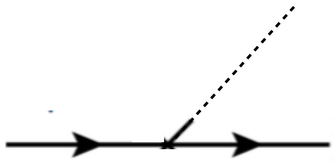

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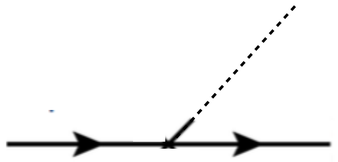
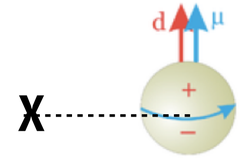


~~CP~~ Neutron electric dipole

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



The lighter the more weakly interacting

$$g_{ai} \sim \frac{c_i}{f_a} \longrightarrow \text{new high energy scale}$$

$$m_A^2 \sim \frac{\chi_{\rm QCD}}{f_A^2} \longrightarrow \text{(perturbation energy scale ... QCD, EW ...)} \longrightarrow \text{new high energy scale}$$

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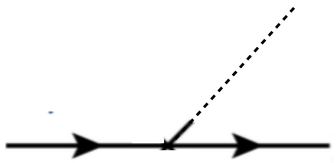

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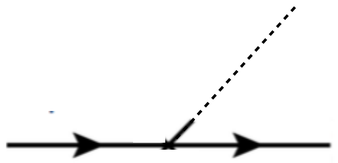

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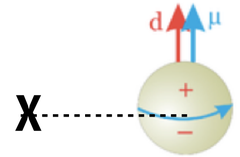

4 hints

Strong CP problem / PQ solution

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

Prediction Experiment

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

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$$\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\left(\theta_{\rm SM}+\frac{A}{f_A}\right) \quad \Rightarrow \quad d_n \propto \left(\theta_{\rm SM}+\frac{\langle A\rangle}{f_A}\right)$$

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

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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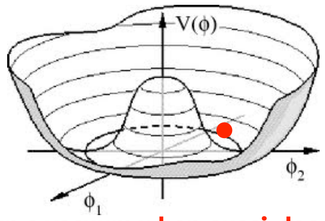
Dark matter / vacuum realignment



pick up a vacuum when quasi-degenerate

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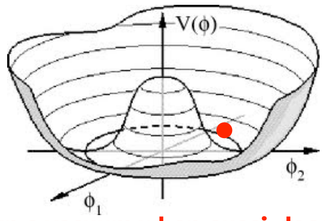

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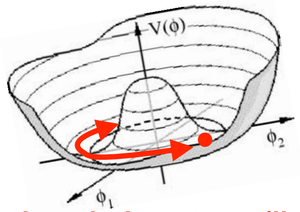

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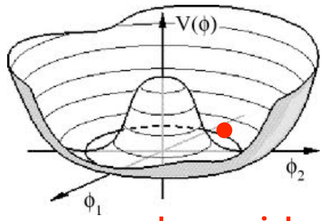

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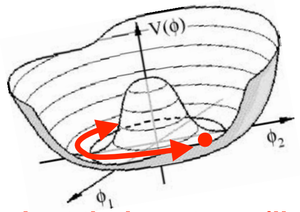

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cold DM in oscillations [cosmology dependent]

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

4 hints

Strong CP problem / PQ solution

$$\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\left(\theta_{\rm SM}+\frac{A}{f_A}\right) \quad \Rightarrow \quad d_n \propto \left(\theta_{\rm SM}+\frac{\langle A\rangle}{f_A}\right)$$

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

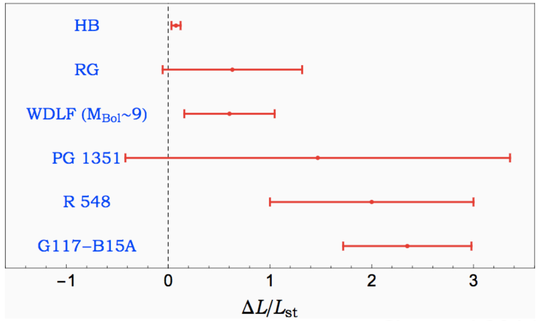
potential min.

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

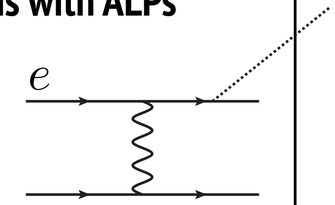
The QCD Axion cancels the effect of any constant $\theta_{\rm SM}$

Anomalous Star cooling / ALP emission

Theory fits better some observations with ALPs

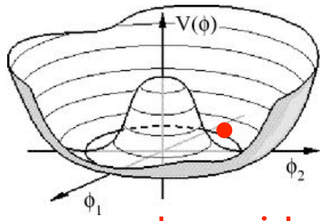


Giannotti 2016

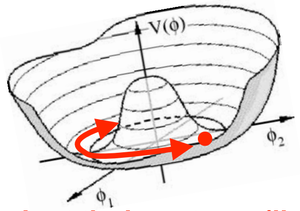


ALP bremstrahlung

Dark matter / vacuum realignment



pick up a vacuum when quasi-degenerate



ups! not the lowest ... oscillate!

cold DM in oscillations [cosmology dependent]

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

4 hints

Strong CP problem / PQ solution

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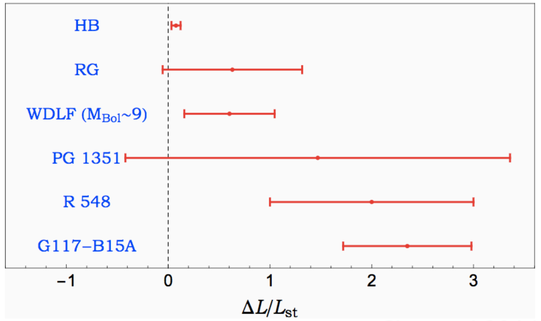
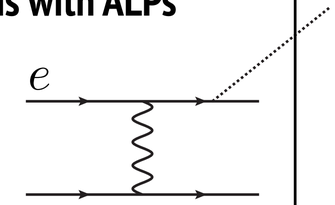


Giannotti 2016



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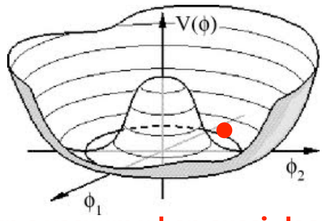

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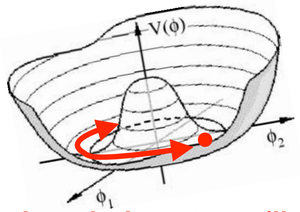

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γ -ray transparency / photon regeneration

Too many gamma-rays from far away sources?

low estimate of opacity vs ALP-mediated regeneration

Trostski 2017

4 hints

Strong CP problem / PQ solution

$$N \neq 0$$

$$\longrightarrow \quad m_A = \frac{\sqrt{\chi}}{f_A} = 5.7\,\mathrm{meV}\frac{10^9\mathrm{GeV}}{f_A}$$

$$\longrightarrow \quad g_{a\gamma}, g_{ap}, g_{an} \neq 0$$

Anomalous Star cooling / ALP emission

$$g_{ae} \sim 10^{-13}$$

$$(f_a \lesssim 10^9\mathrm{GeV})$$

Giannotti 2016

Dark matter / vacuum realignment

$$a_i \sim 10^{12}\mathrm{GeV}\left(\frac{\mathrm{meV}}{m_a}\right)^{1/4} \lesssim f_a$$

QCD axion $f_A \sim 10^9\mathrm{GeV}$

Many other production mechanisms

γ -ray transparency / photon regeneration

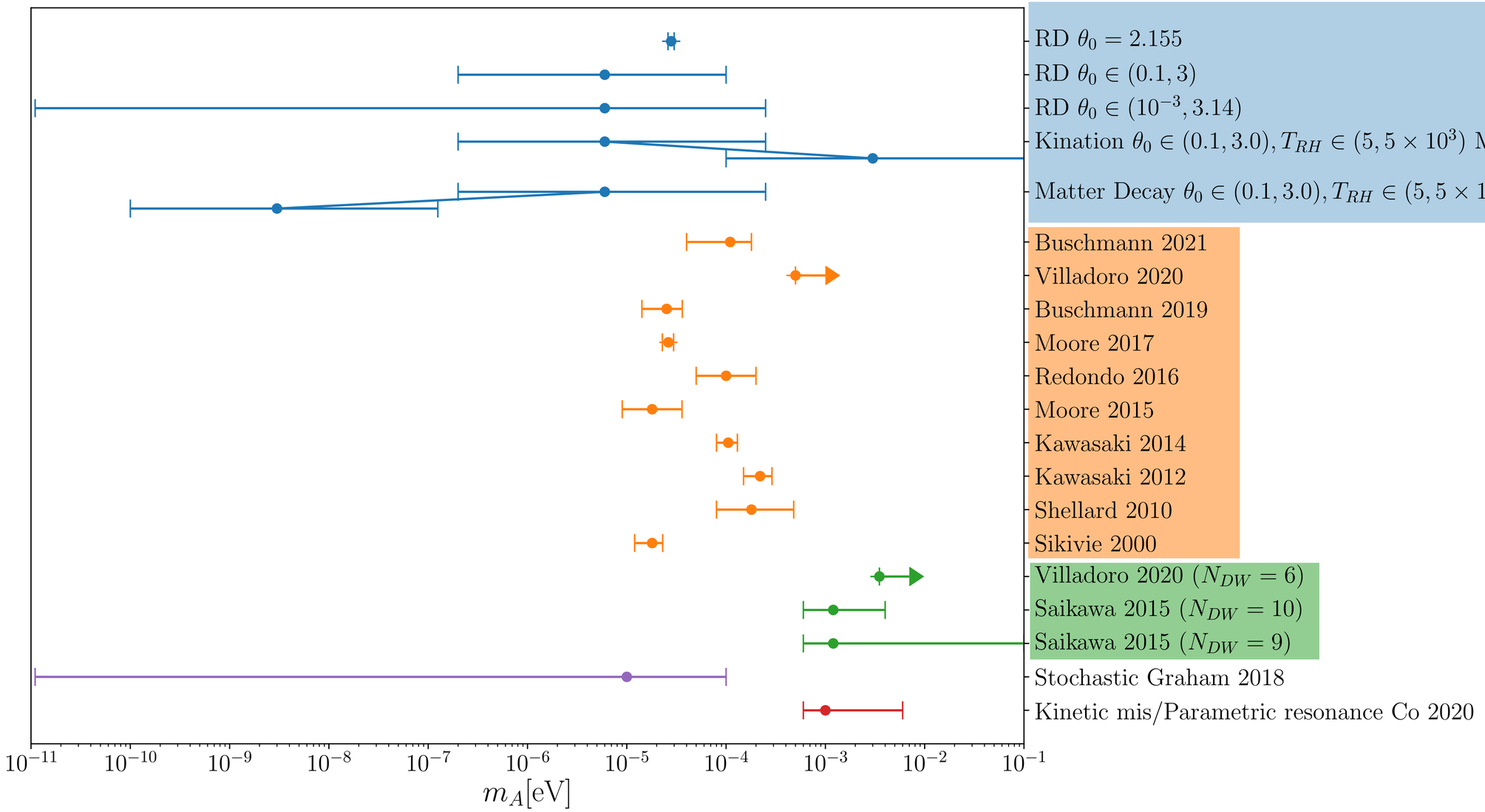
$$g_{a\gamma} \sim 10^{-11}\mathrm{GeV}^{-1}$$

$$(f_a \sim 10^8\mathrm{GeV})$$

$$m_a \lesssim 10^{-9}\mathrm{eV}$$

Predicting the DM mass

- Early-Universe and axion-model dependent!

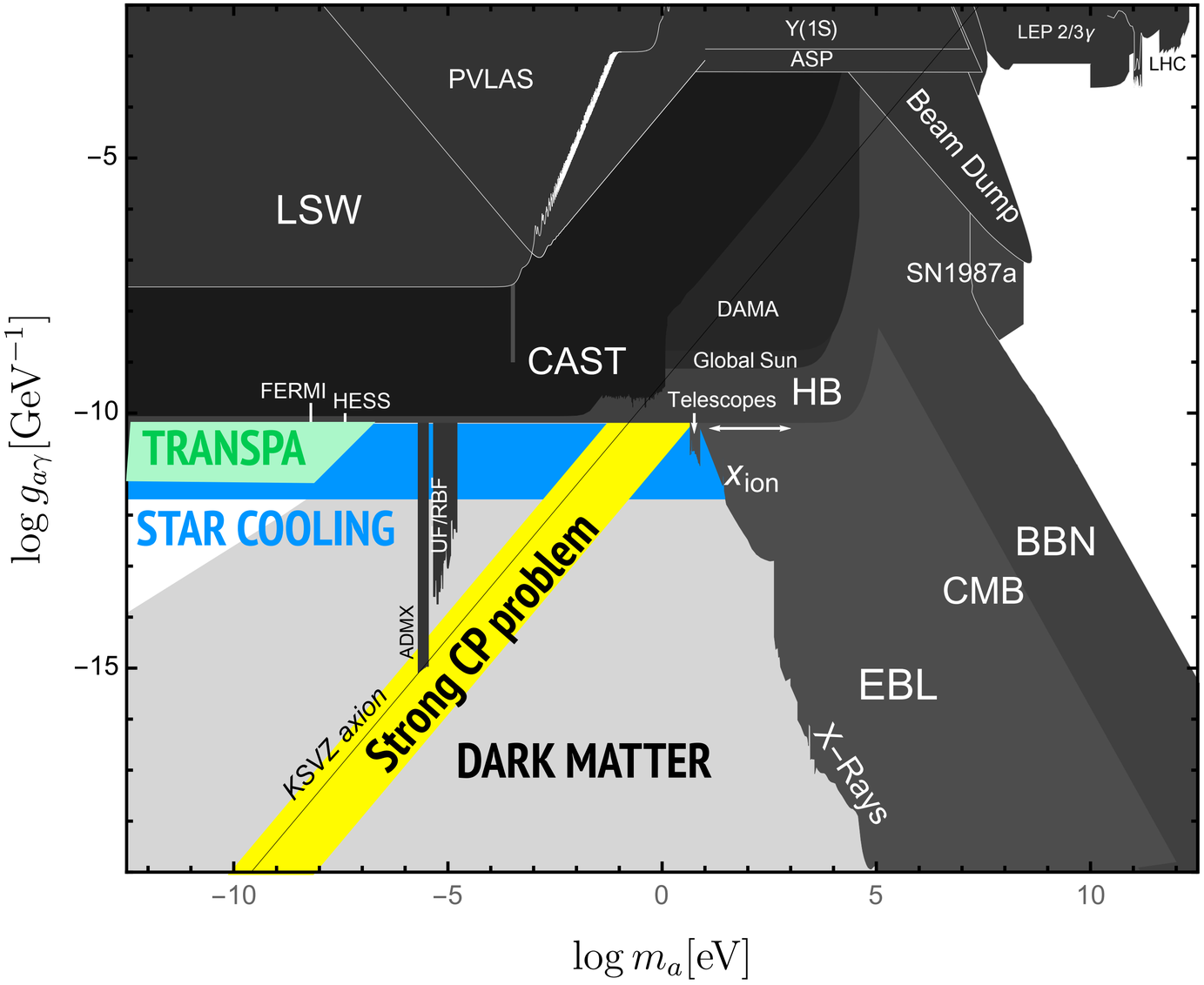


Pre-inflation (misalignment)

Post-inflation N=1 (mis.+topological defects)

Post-inflation N>1 (mis.+topological defects)

Hints and constraints (example)



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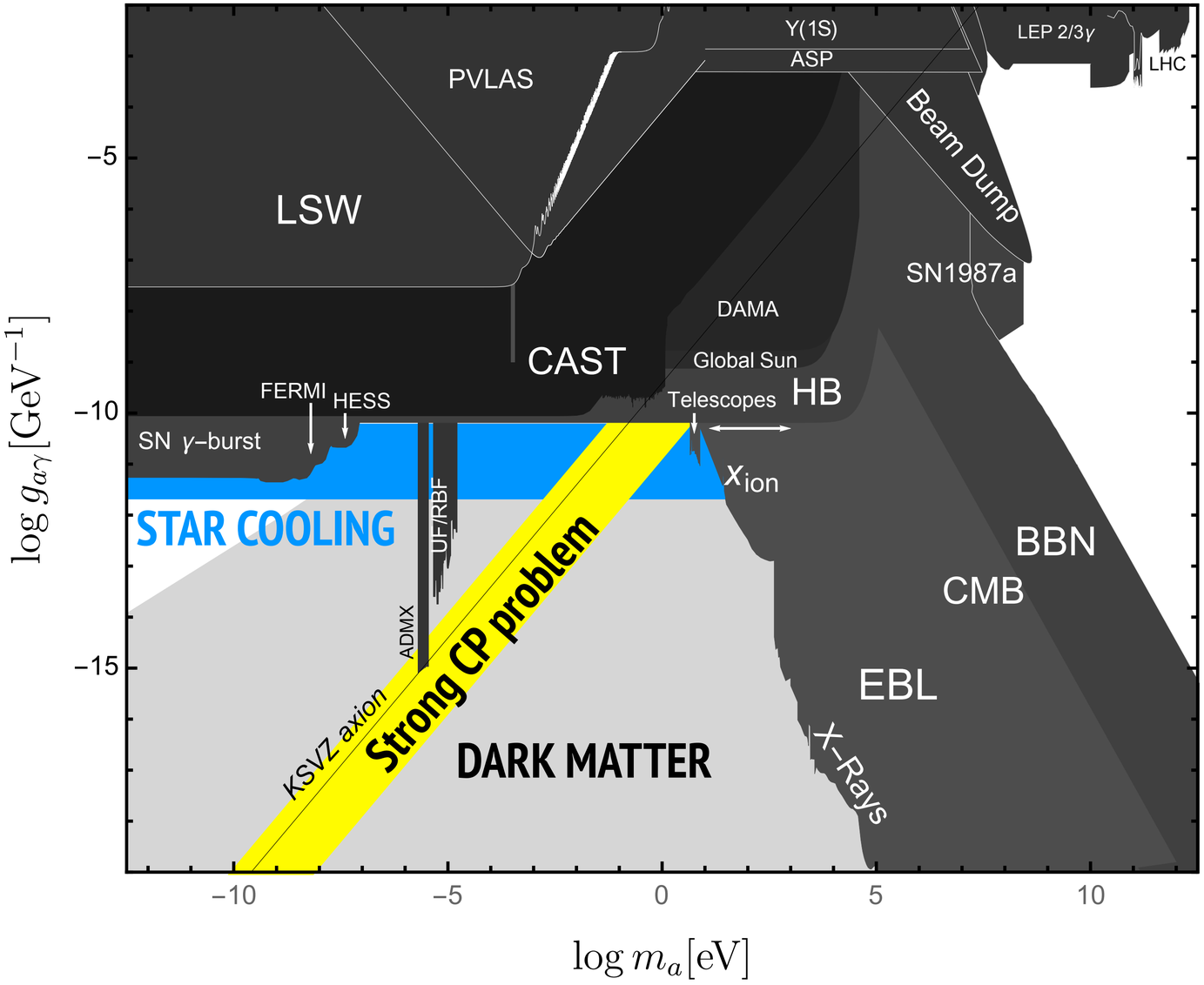
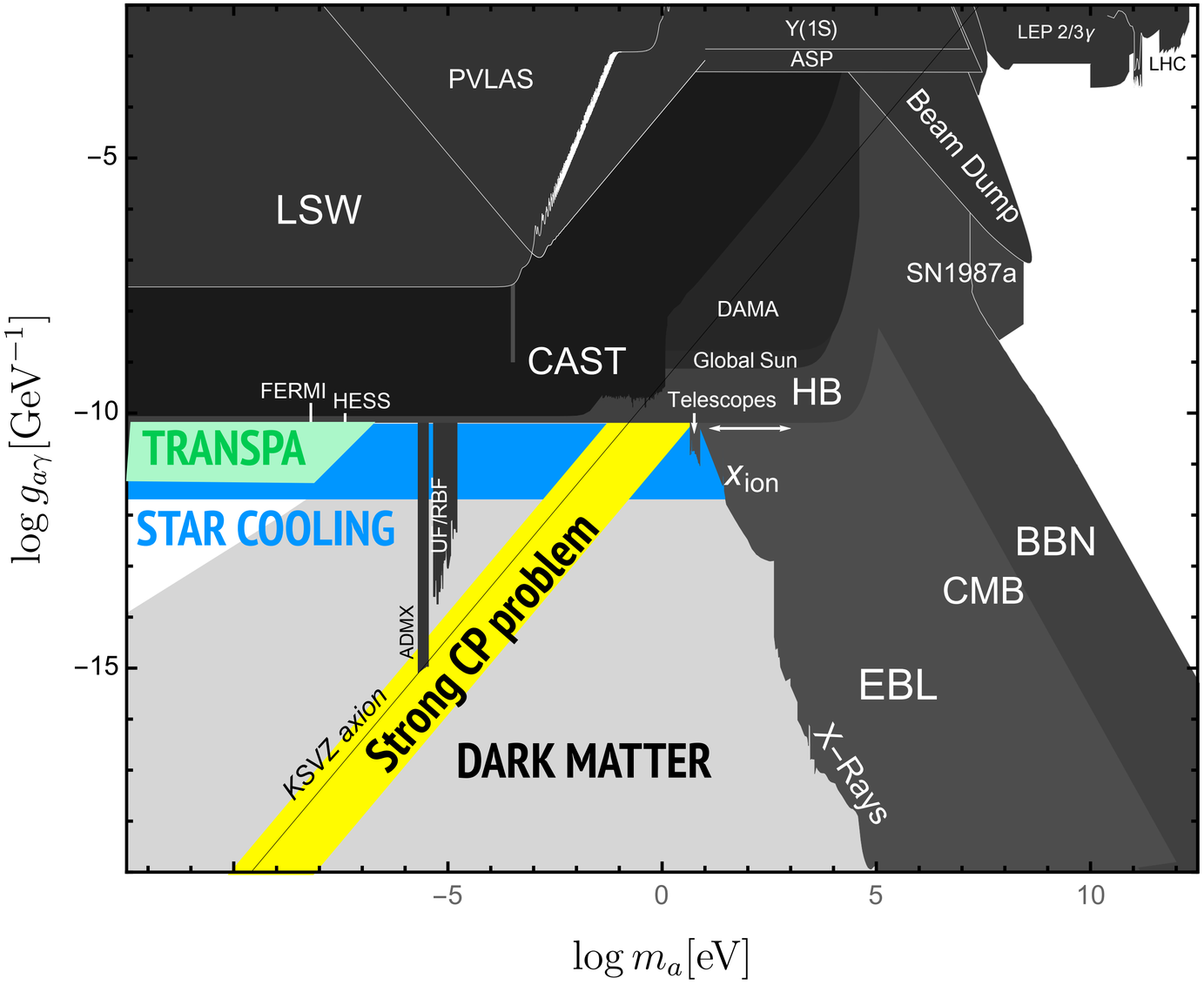


birds and stones ...



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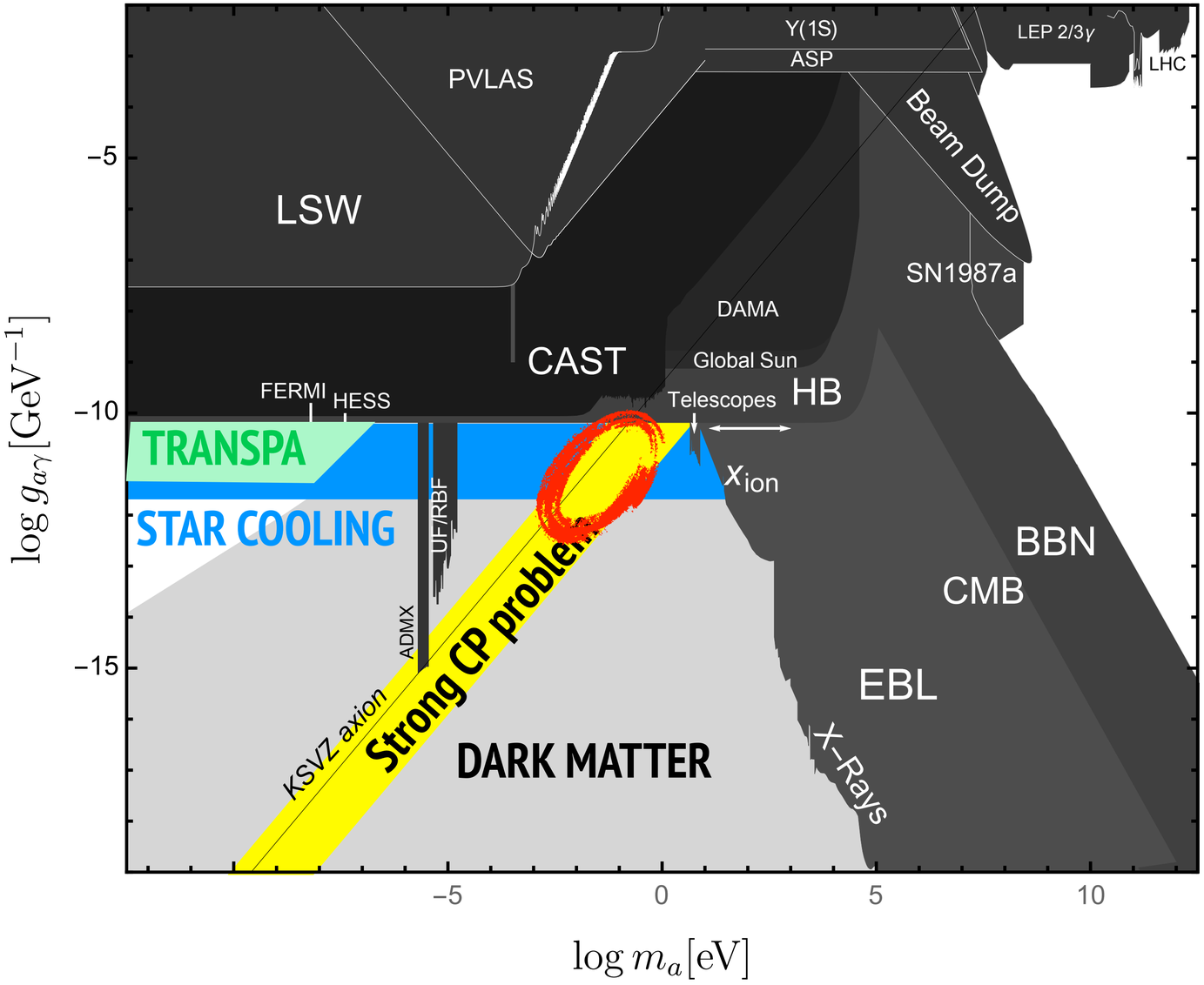

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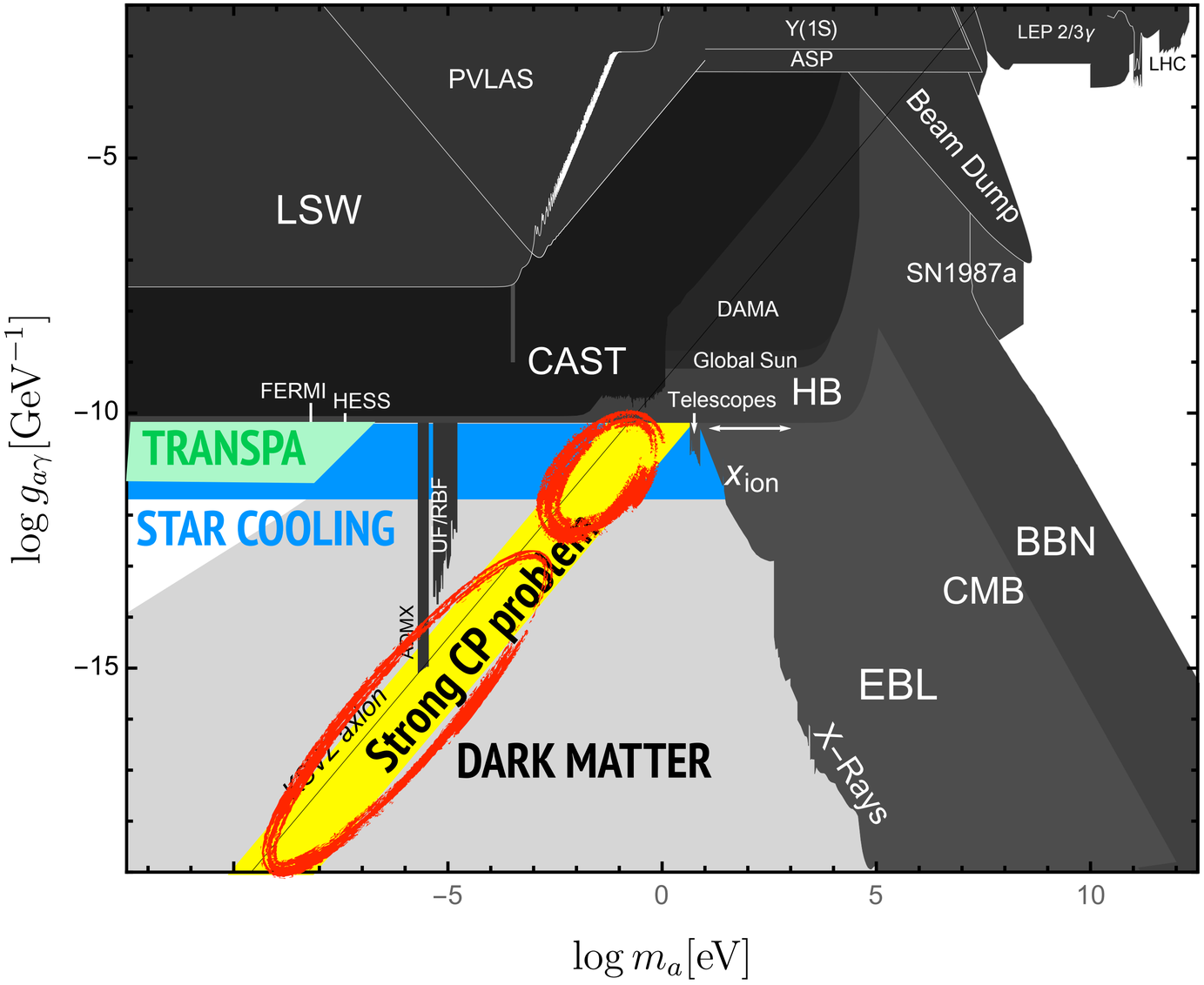

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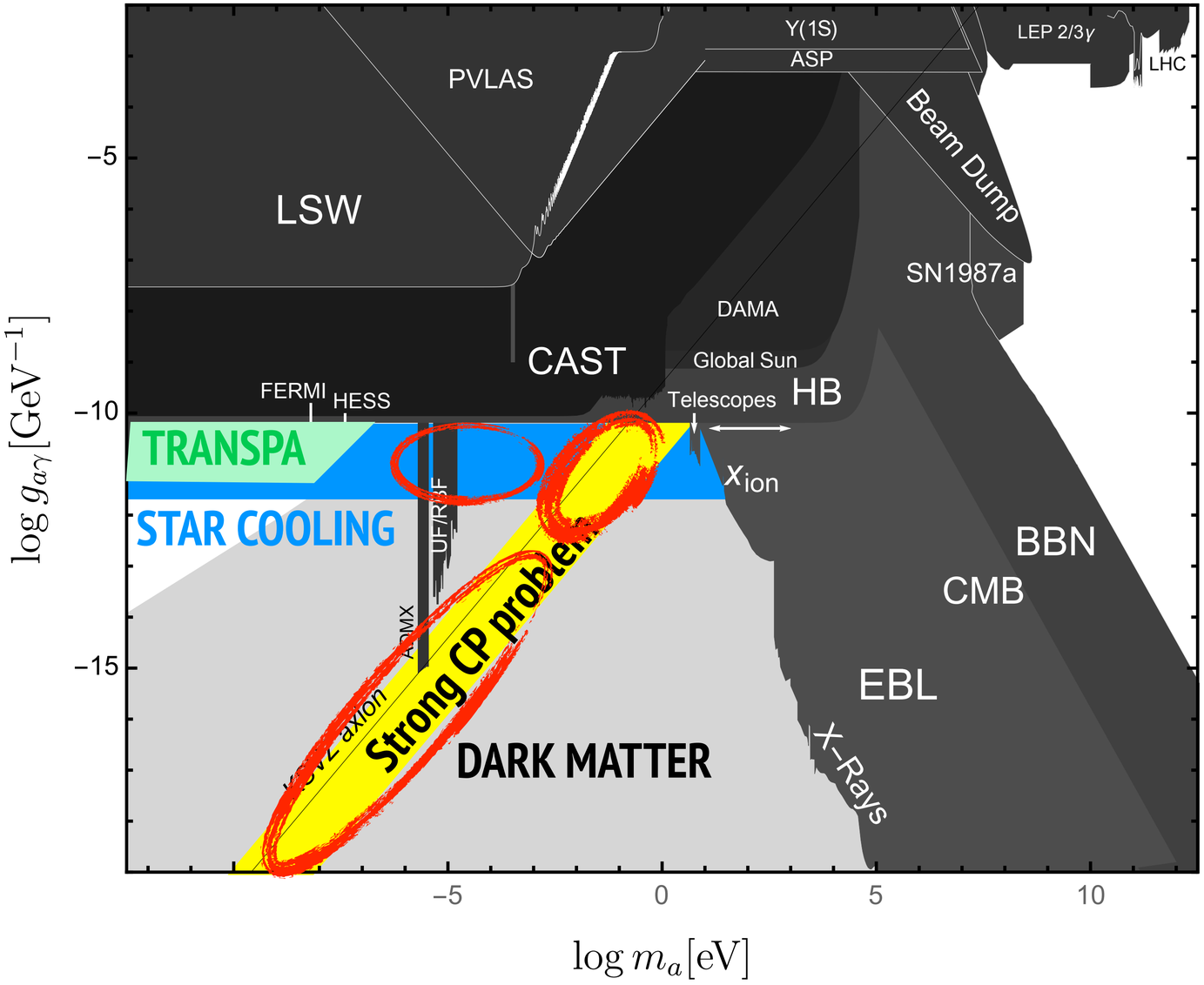

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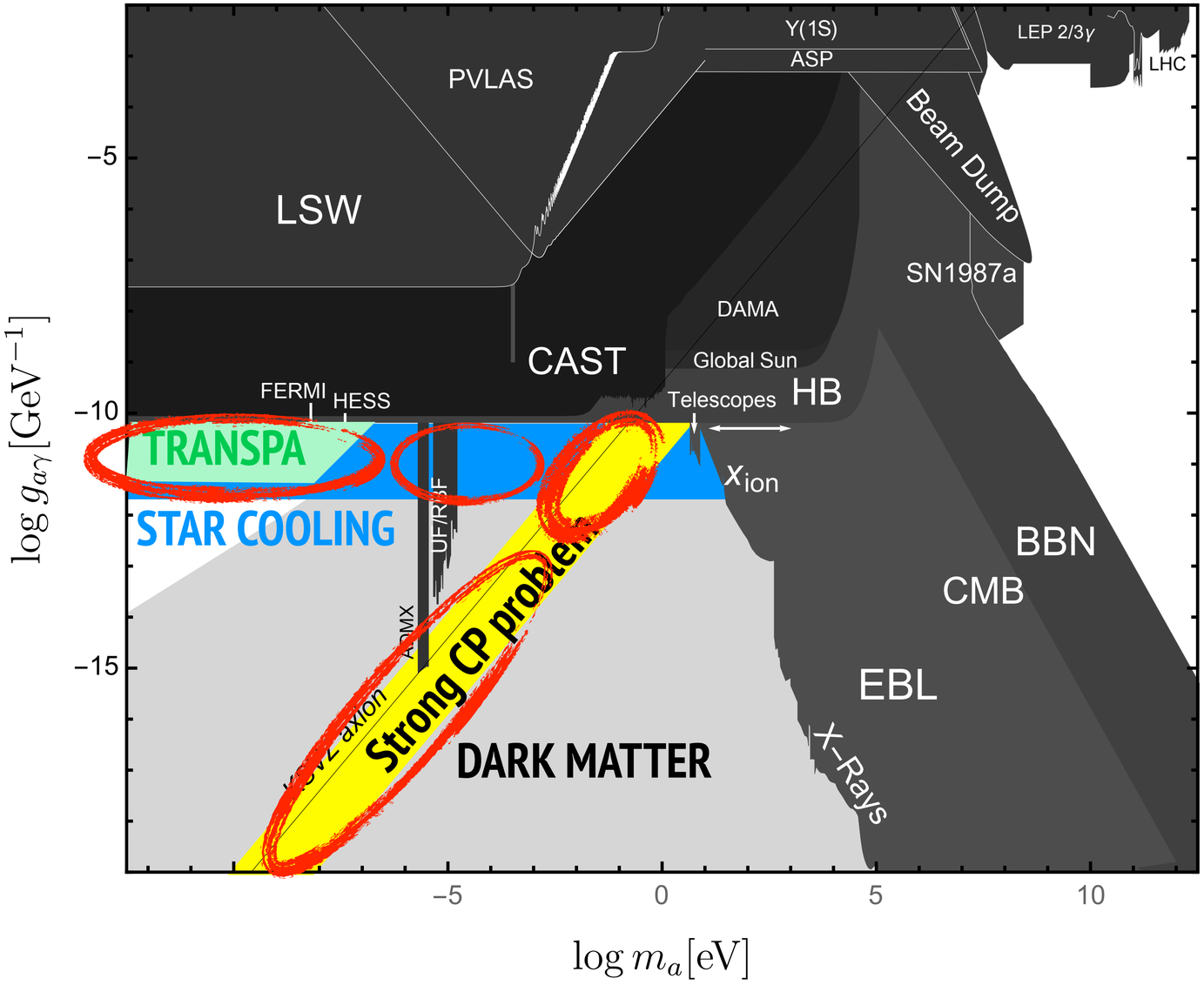

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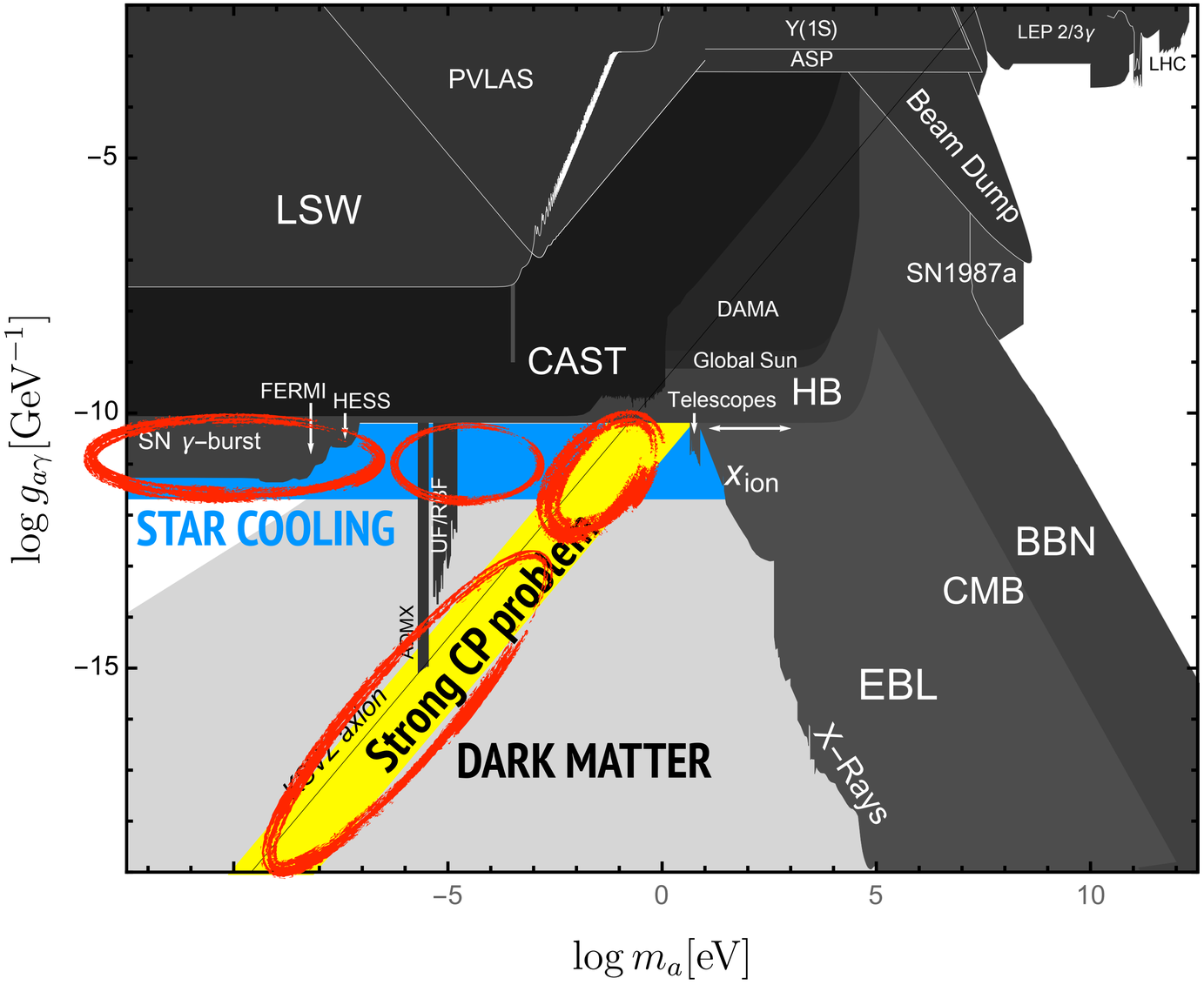
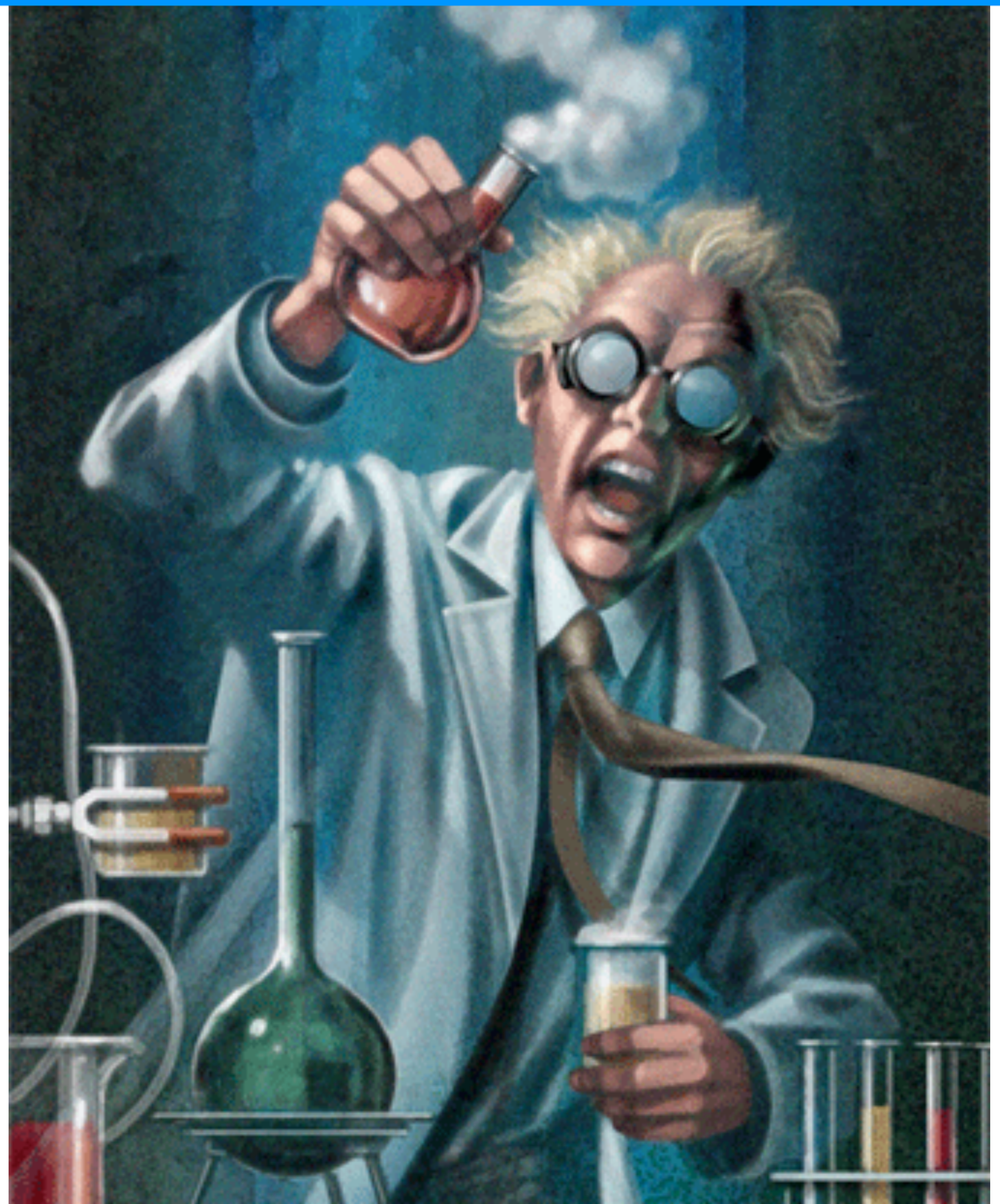
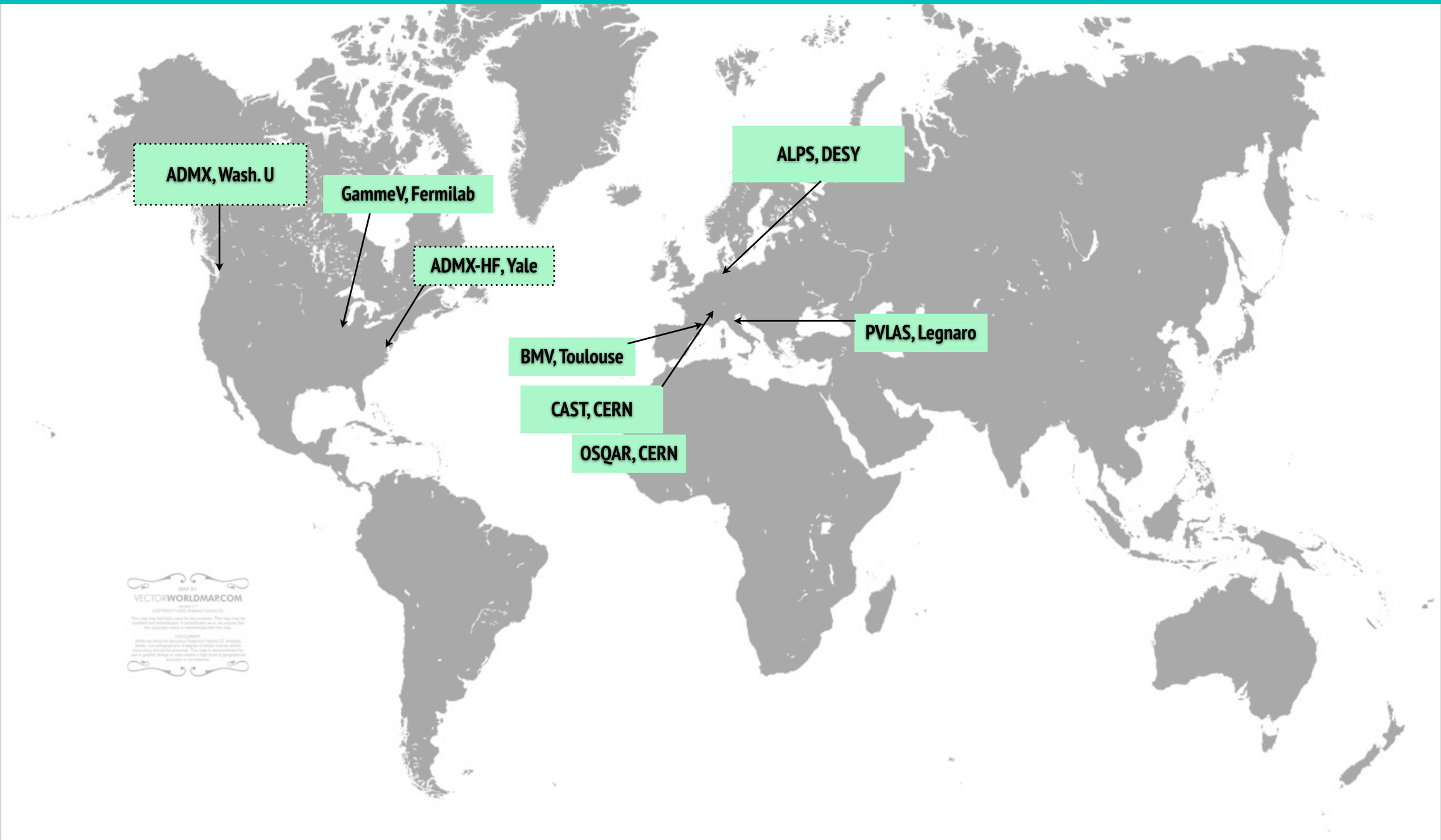


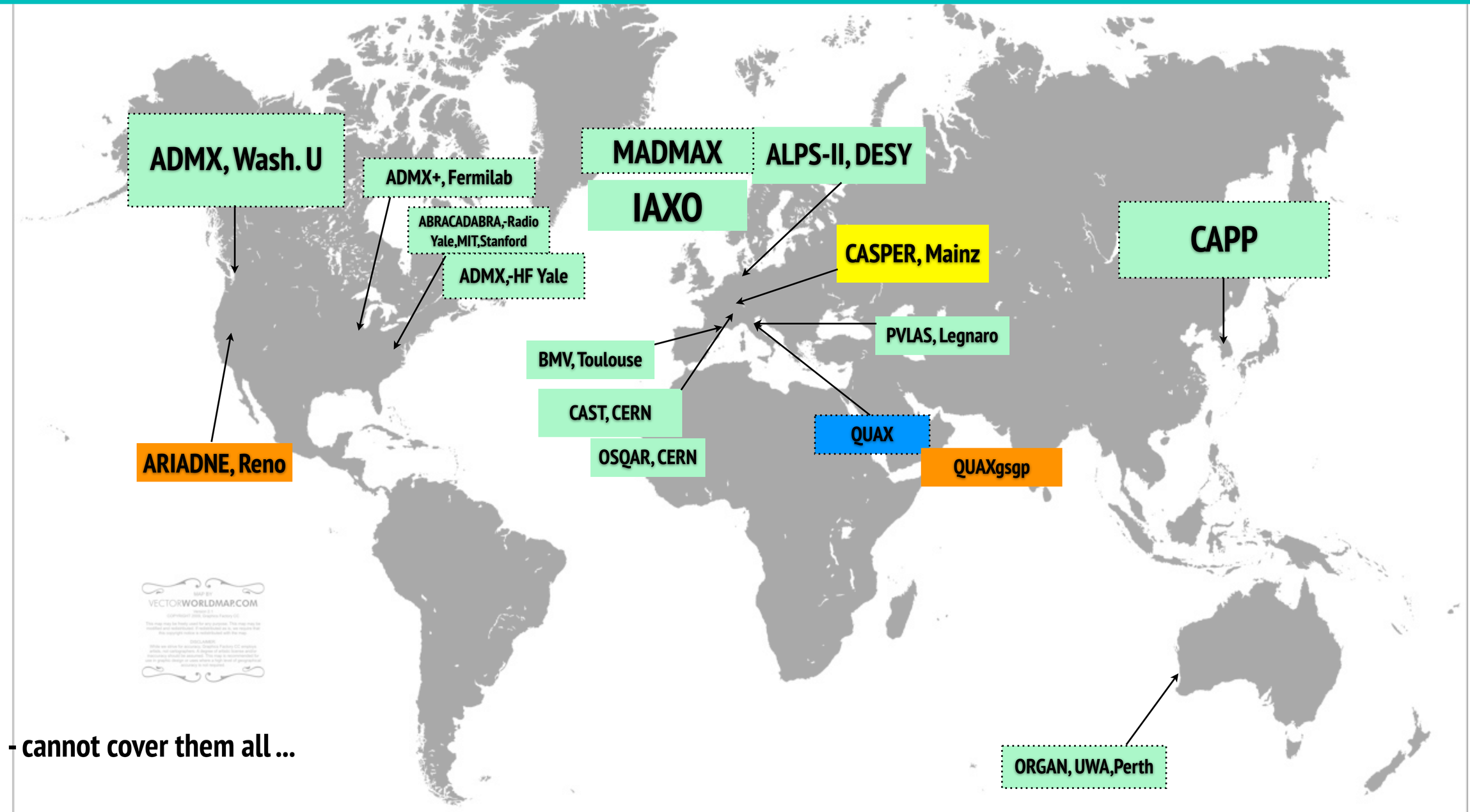
Direct Detection of ALPs : 5 key experiments



Lab experiments 2011



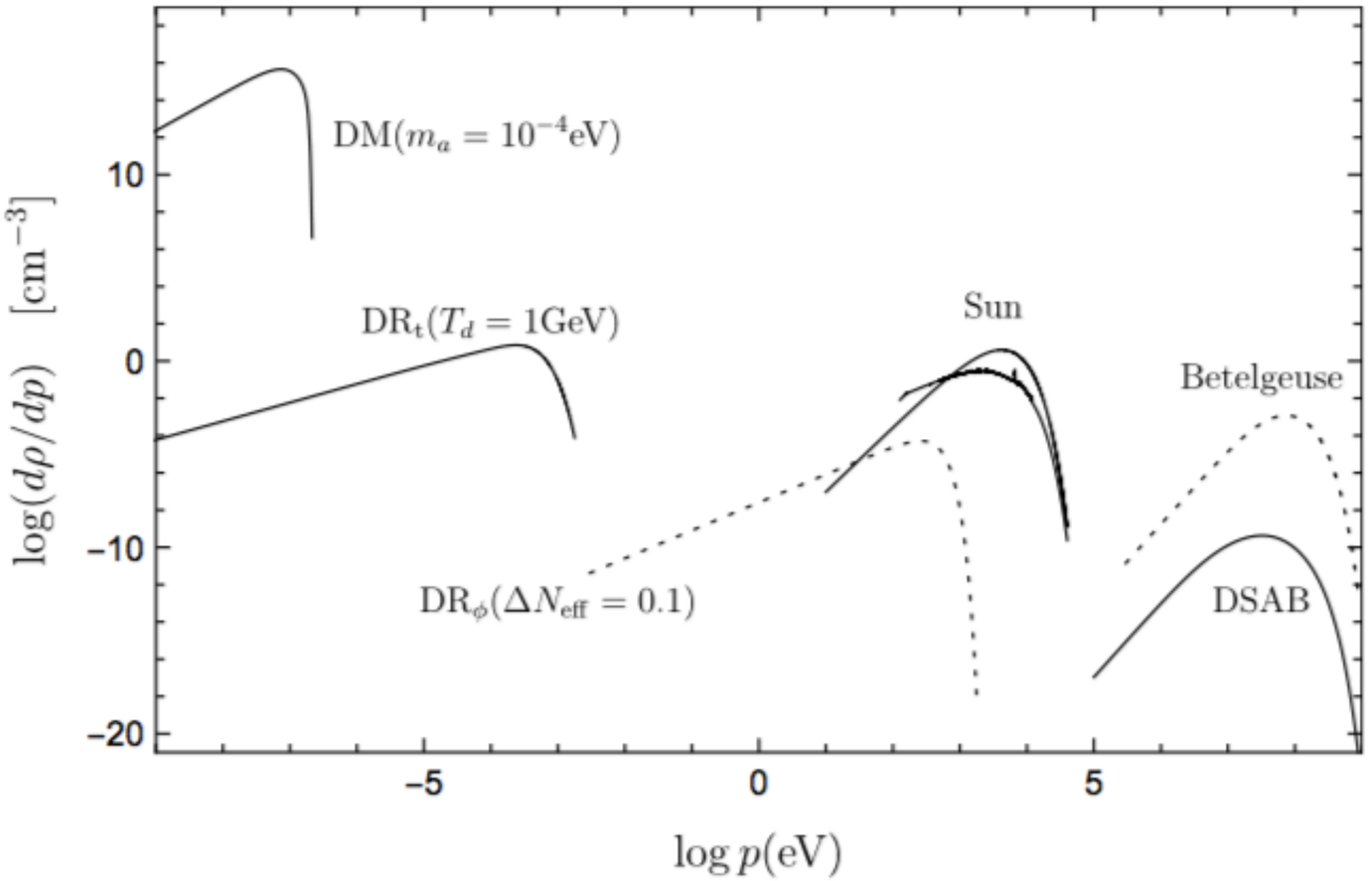
Lab experiments 2022 (a selection ...)



- cannot cover them all ...

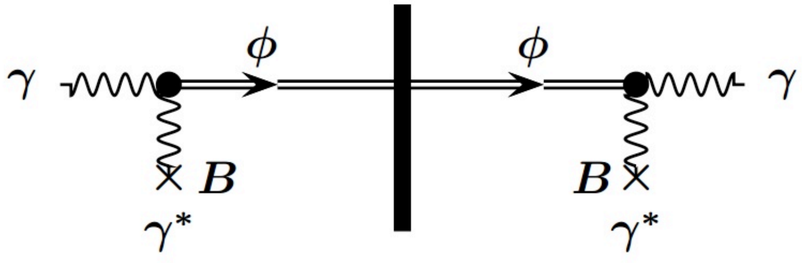
Natural sources

- Axions and ALPs are very weakly interacting... advantageous to use <u>already produced</u> (natural) axions but add extra uncertainties
- We want to explore purely - lab experiments as welll

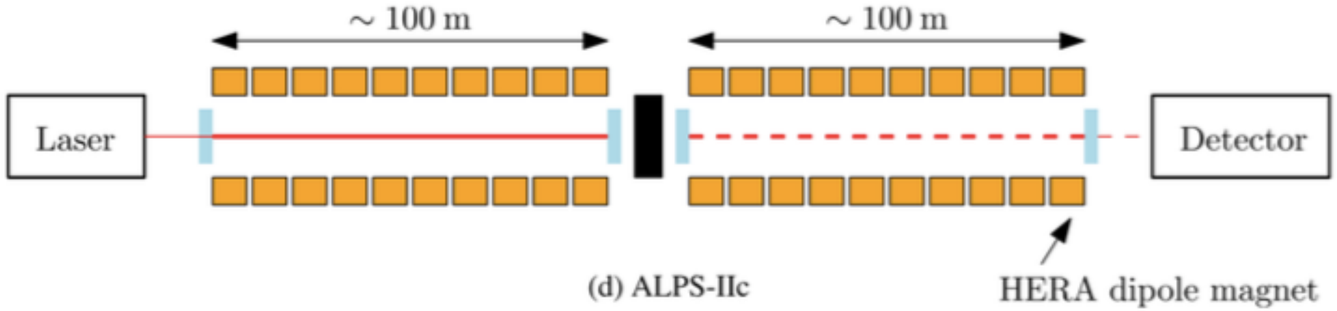


the ANY-Light-Particle-Search

Basic Light shining through walls



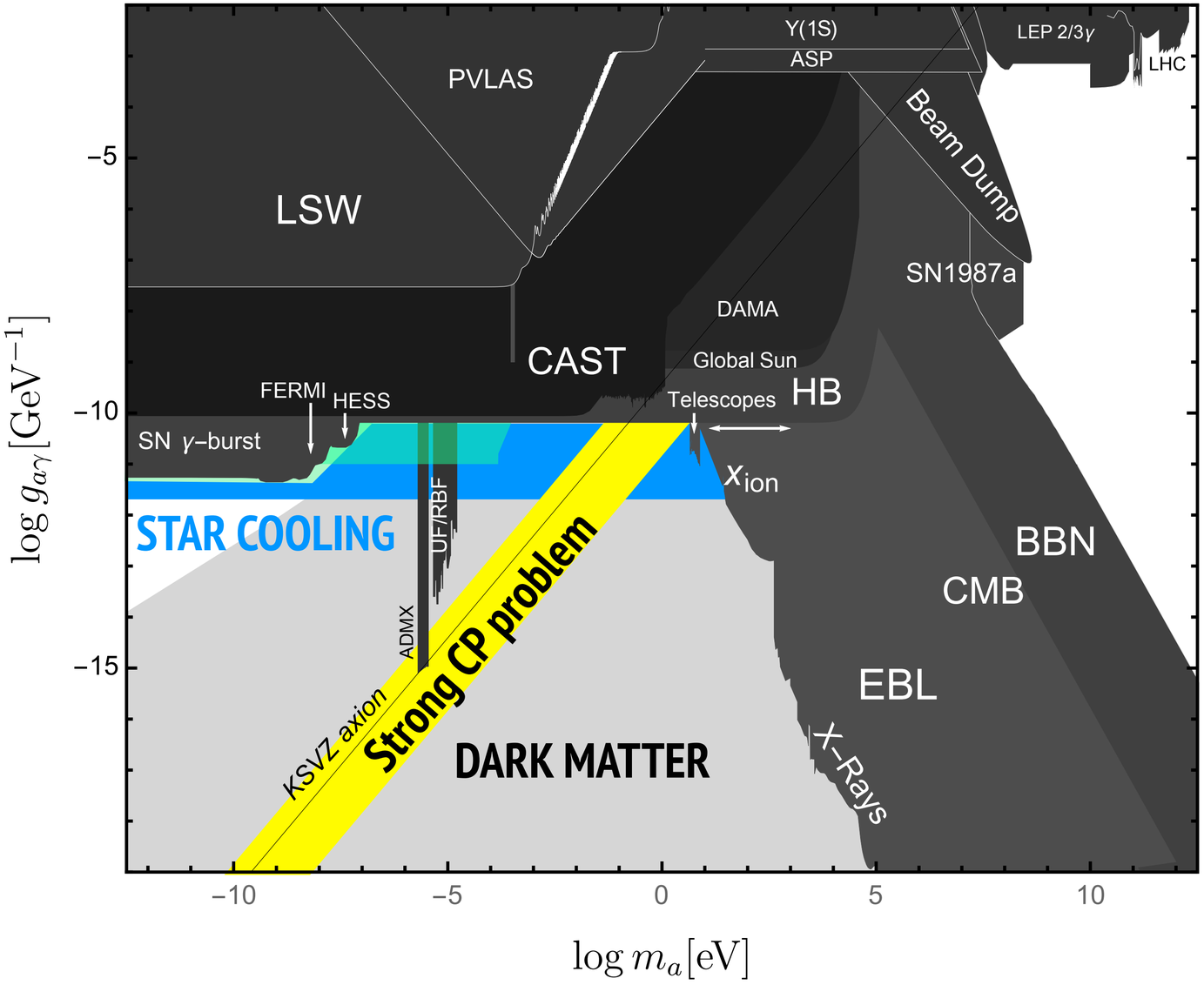
Boosted version : Emission cavity recicles photons + Resonant regeneration in the receiving cavity



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

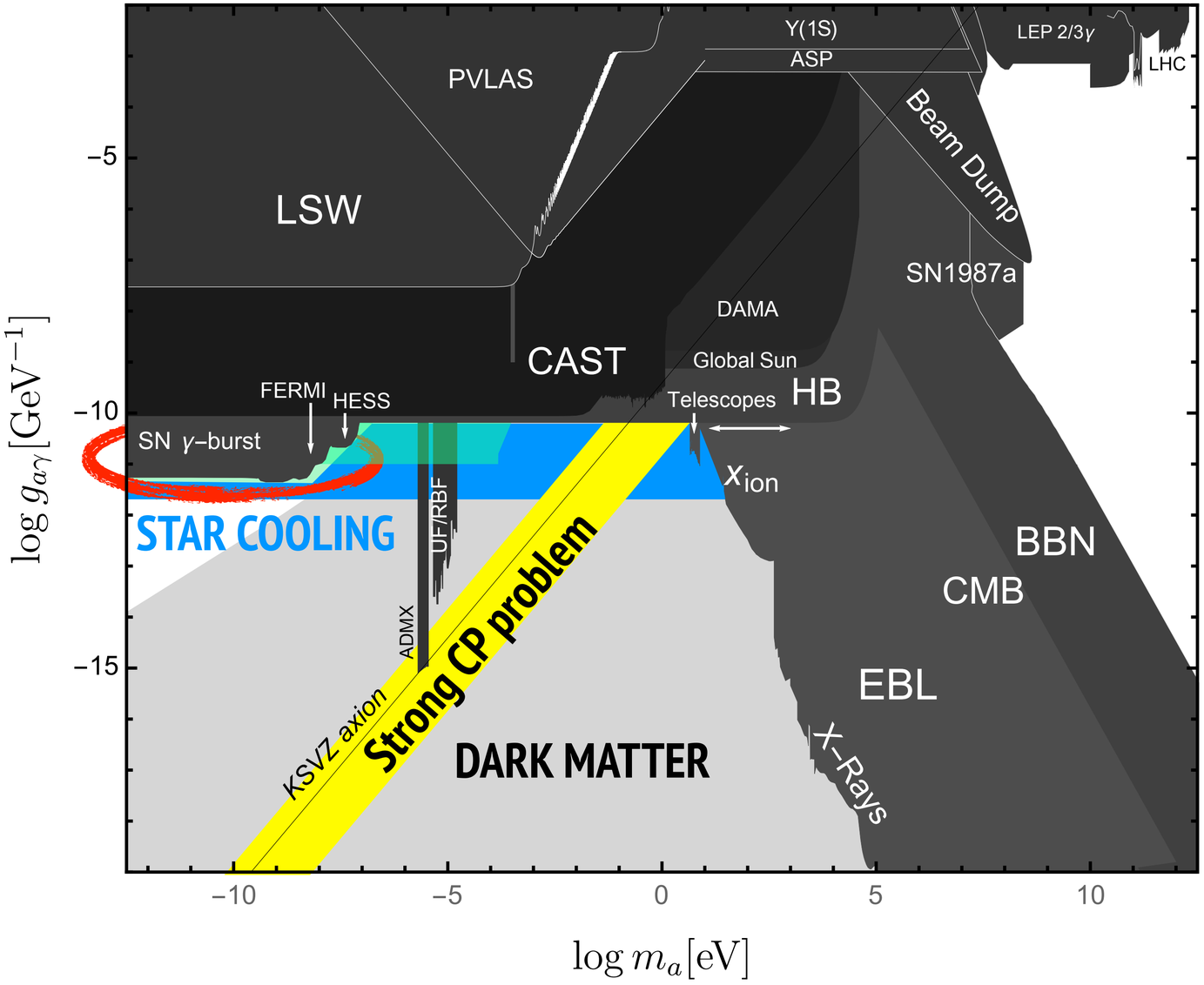
Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}$ [GeV^{-1}]
ALPS-I [427]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [429]	completed	3	0.15	50	10^4	10^4	9.9×10^{-8}(*)
OSQAR [428]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [430]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [431]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

ALPS IIc reach



but much earlier than IAXO …

ALPS IIc reach



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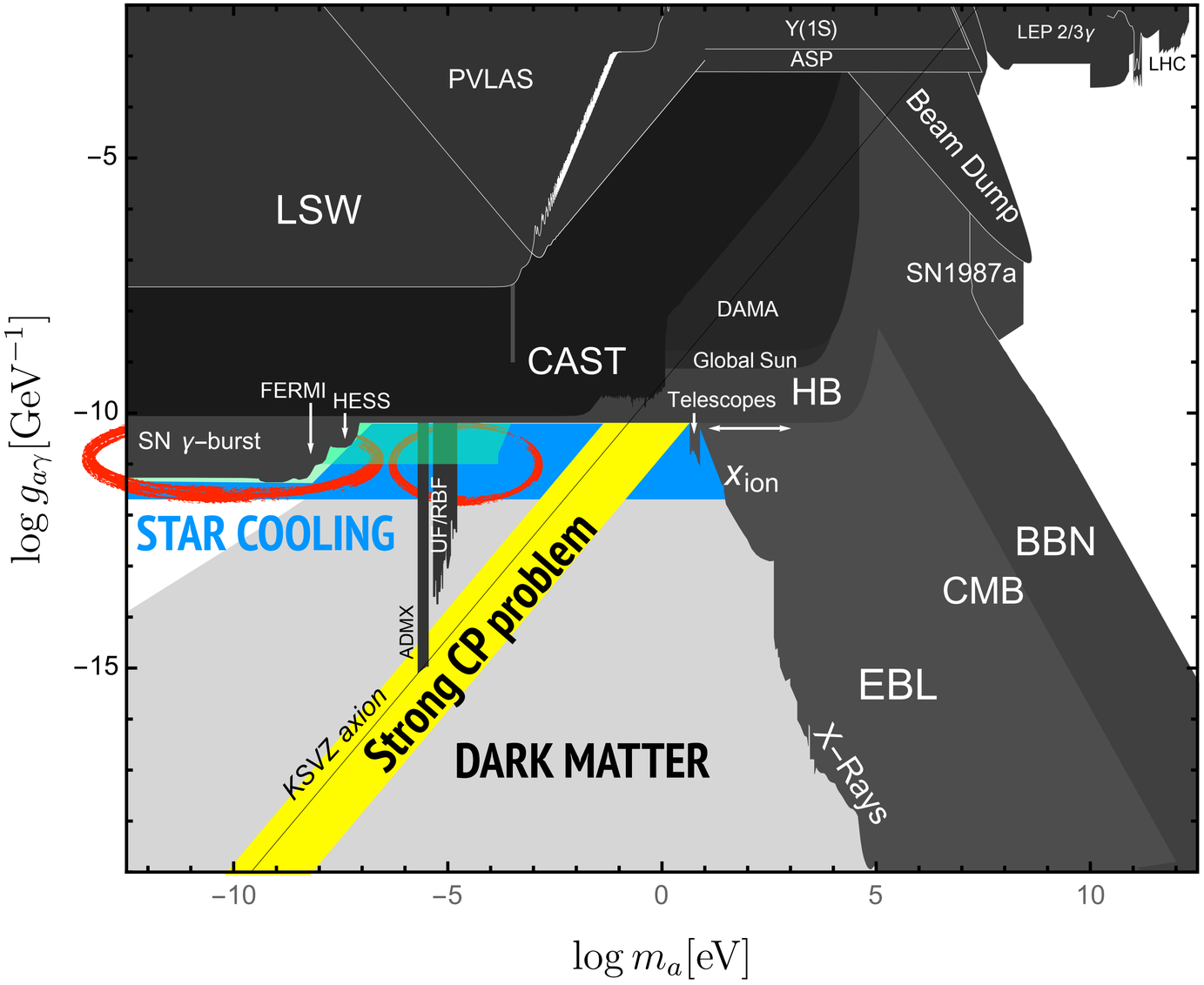

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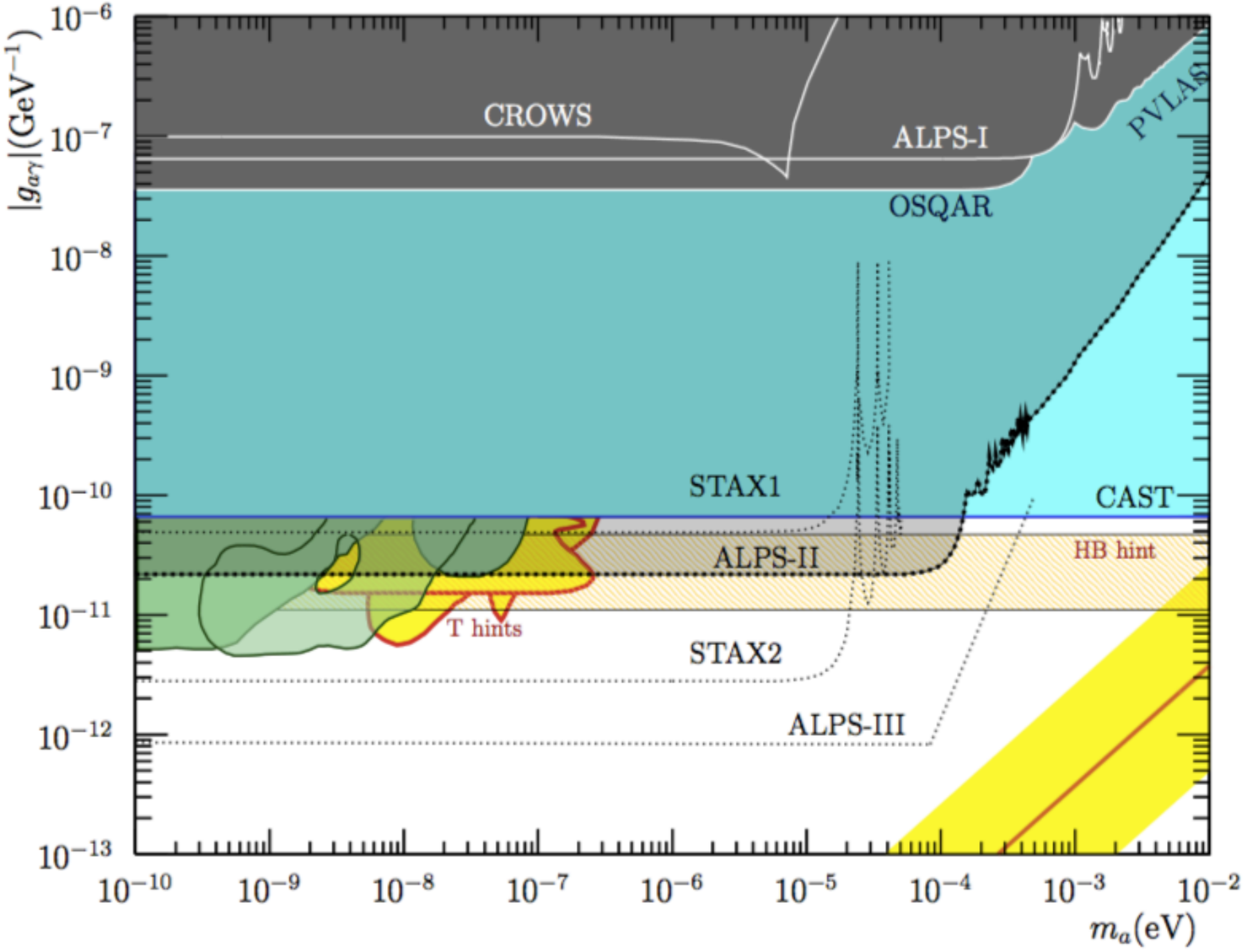
STAX, ALPS III and beyond

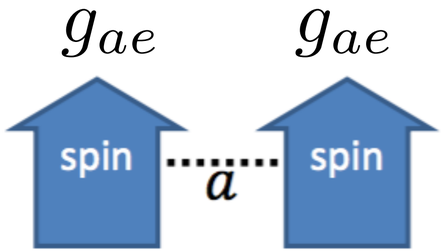


Long-range forces between macroscopic bodies

Wilzcek'84, Geraci 14

Pseudoscalar^2 forces are spin-spin ... very hard to measure! (EM background, polarised bodies...)

$$g_{a\psi}[\bar{\psi}\gamma^5\psi]a$$



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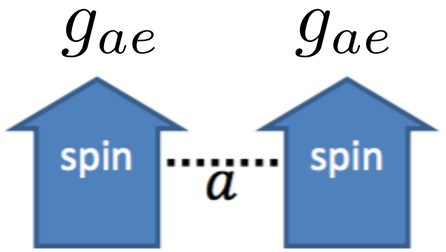
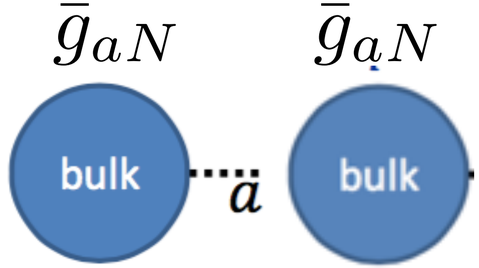


Scalar couplings are number-number ... coherent over macroscopic bodies ... strong!

$$\bar{g}_{a\psi}[\bar{\psi}\psi]a$$

Compete with gravity
Violations of Equivalence principle...
Very much constrained



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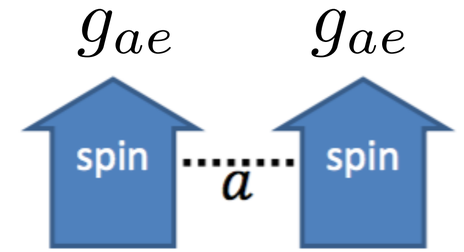

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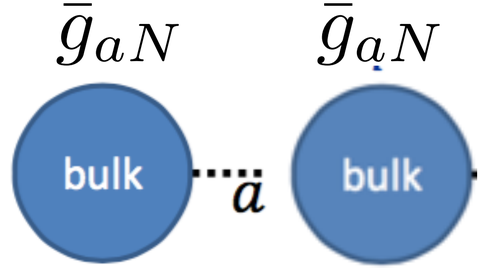
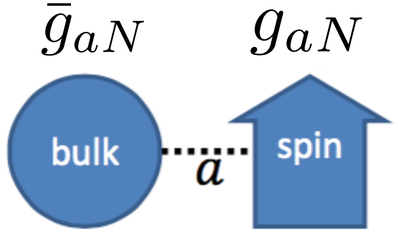


s-p forces are number-spin ... not very promising until ARIADNE experiment



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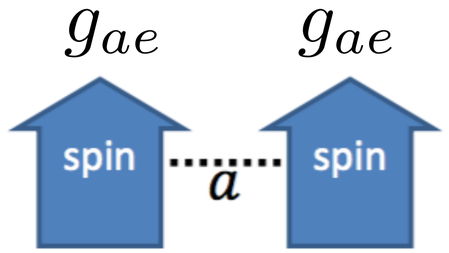

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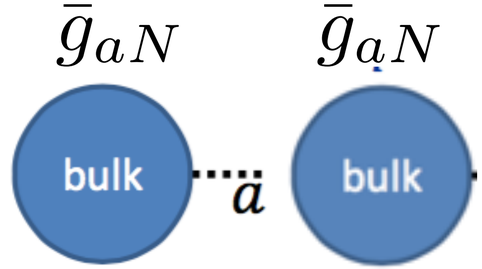
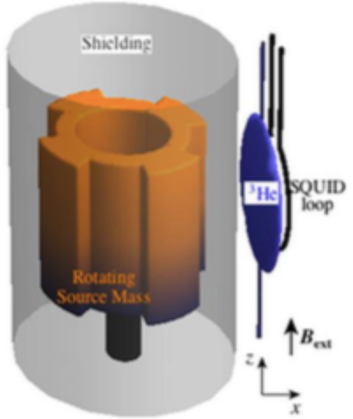


s-p forces are number-spin ... not very promising until ARIADNE experiment

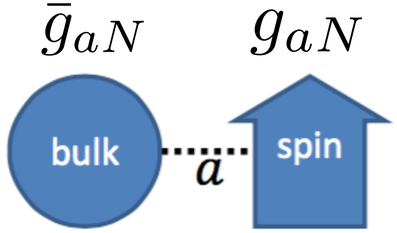
p-coupling, ficticious B-field coupled to spin

$$g_{a\psi}[\bar{\psi}\gamma^5\psi]a \sim g_{a\psi}\mathbf{S}\cdot\nabla a$$

Use asymmetric rotating body as source of a detect the spin-force with ultra sensitive NMR!



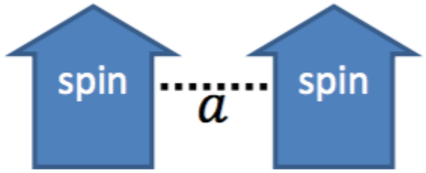
ARIADNE, University of Nevada in Reno

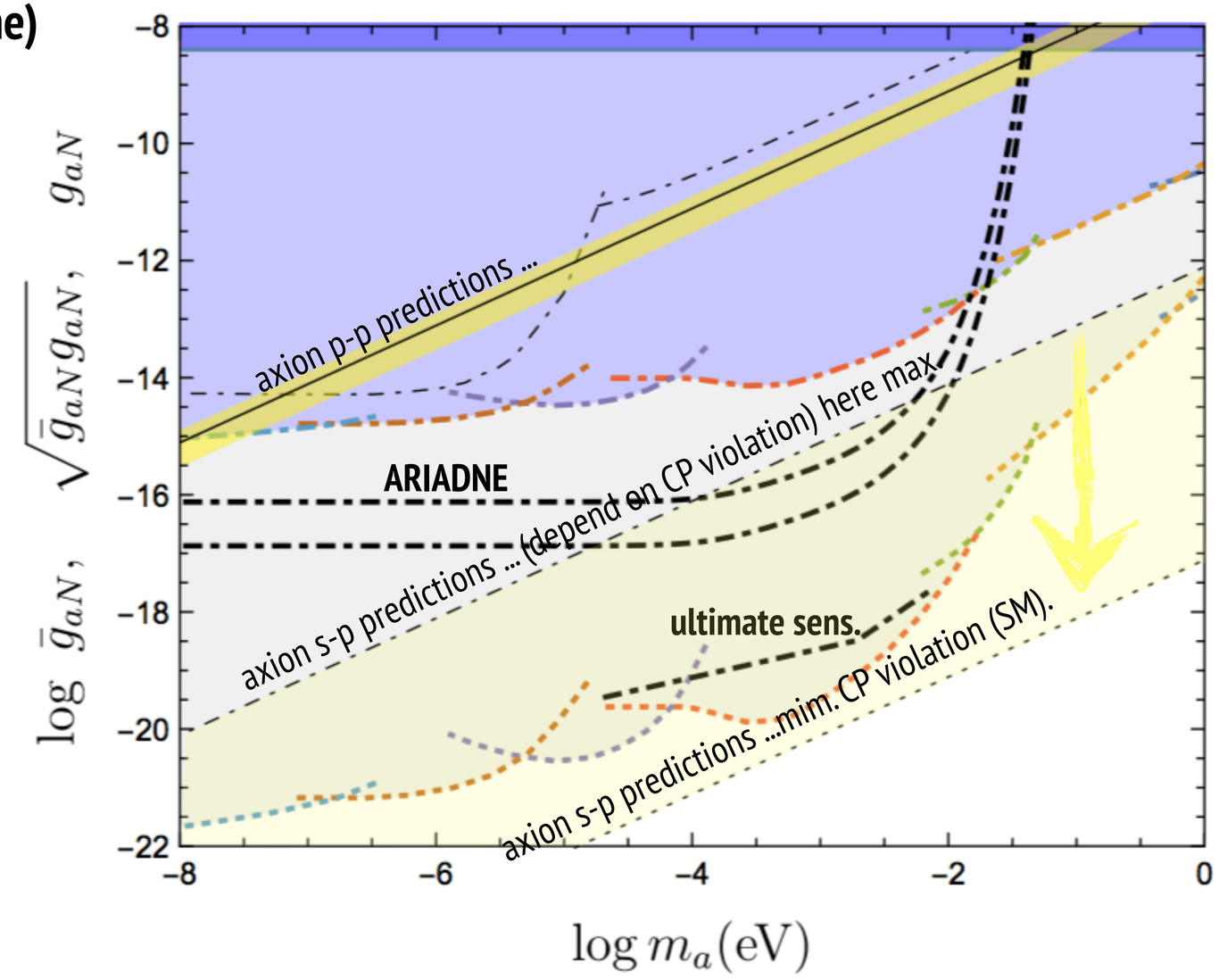


ARIADNE reach

Arvanitaki, Geraci 14

Pseudoscalar^2 forces, astrophysics exclusion (solid line)





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Arvanitaki, Geraci 14

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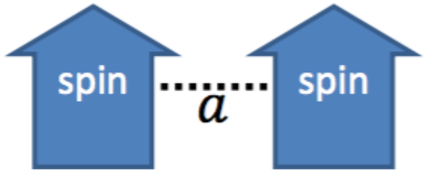
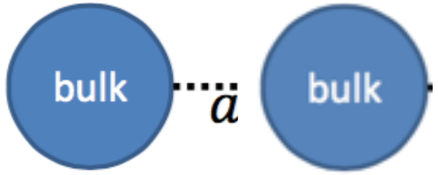
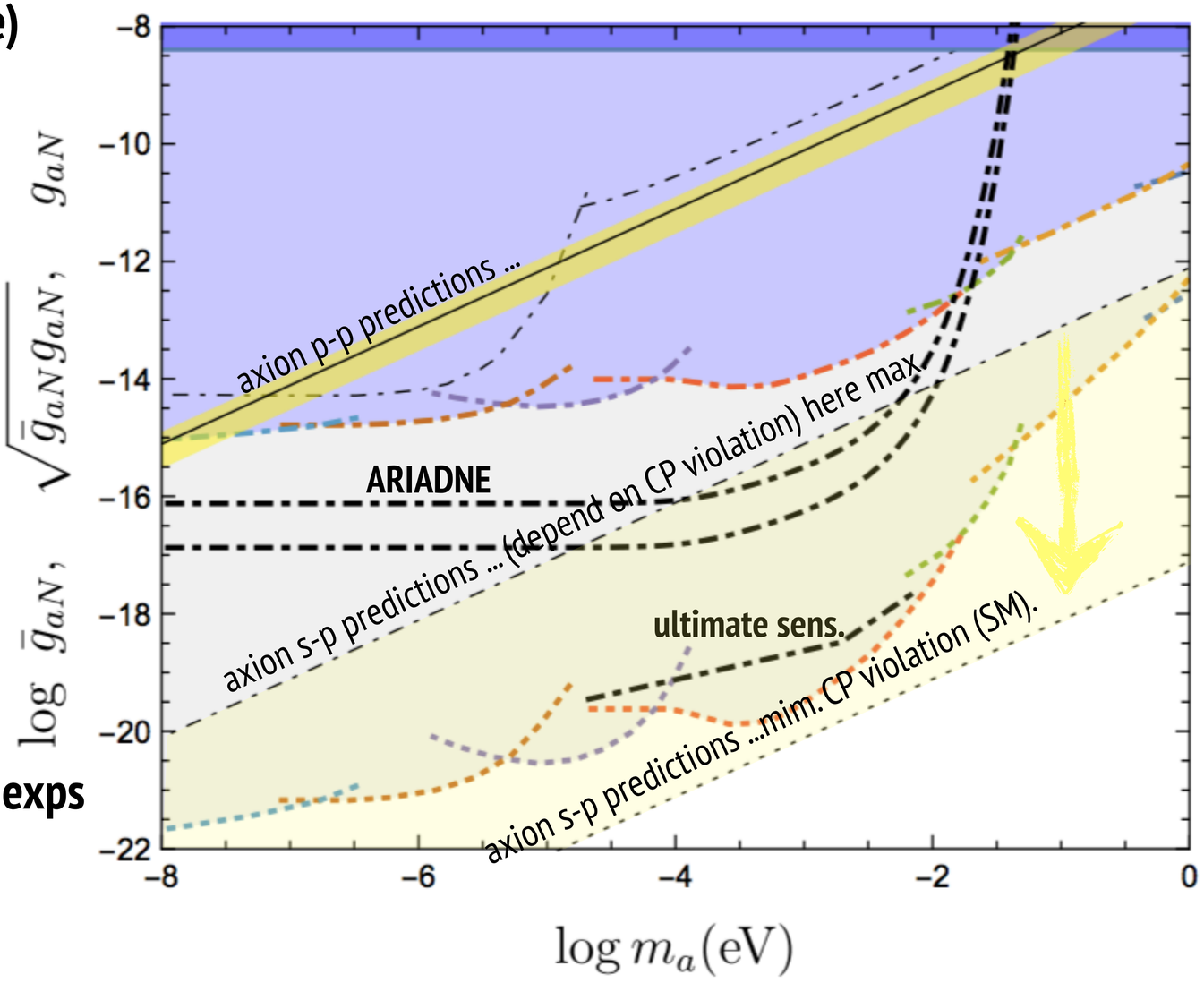


Scalar^2 forces (dotted lines) exclusion from 5th-force exps





ARIADNE reach

Arvanitaki, Geraci 14

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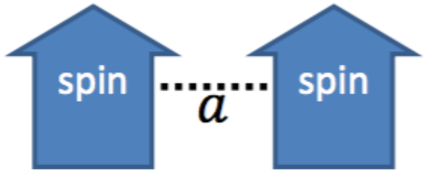
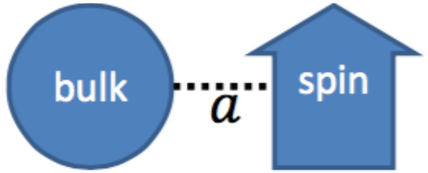


p-s forces (dash-dotted)

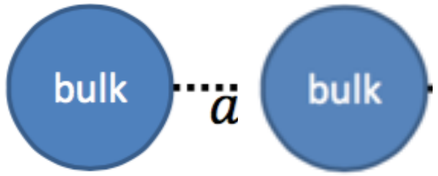
Limits from astrophysics+5th force)

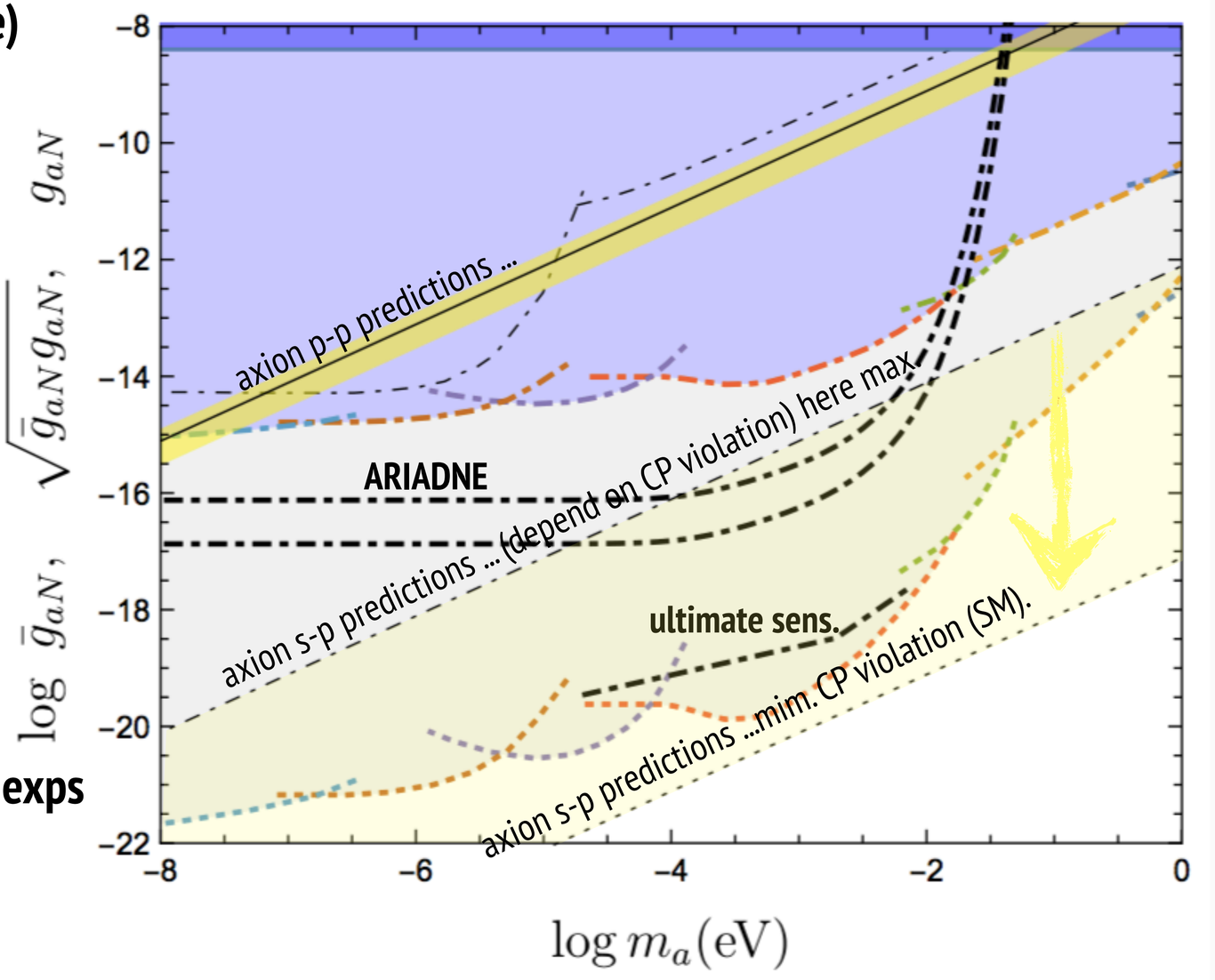
ARIADNE REACH

QCD axion prediction (depends on CP violation)



Scalar^2 forces (dotted lines) exclusion from 5th-force exps

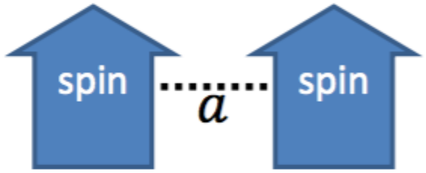




ARIADNE reach

Arvanitaki, Geraci 14

Pseudoscalar^2 forces, astrophysics exclusion (solid line)

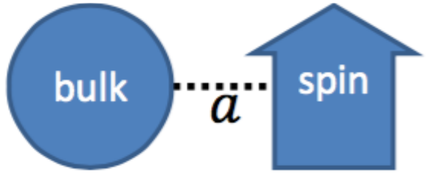


p-s forces (dash-dotted)

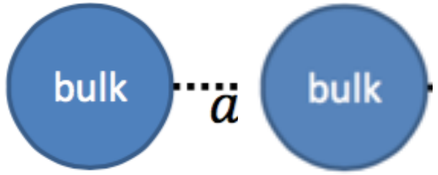
Limits from astrophysics+5th force)

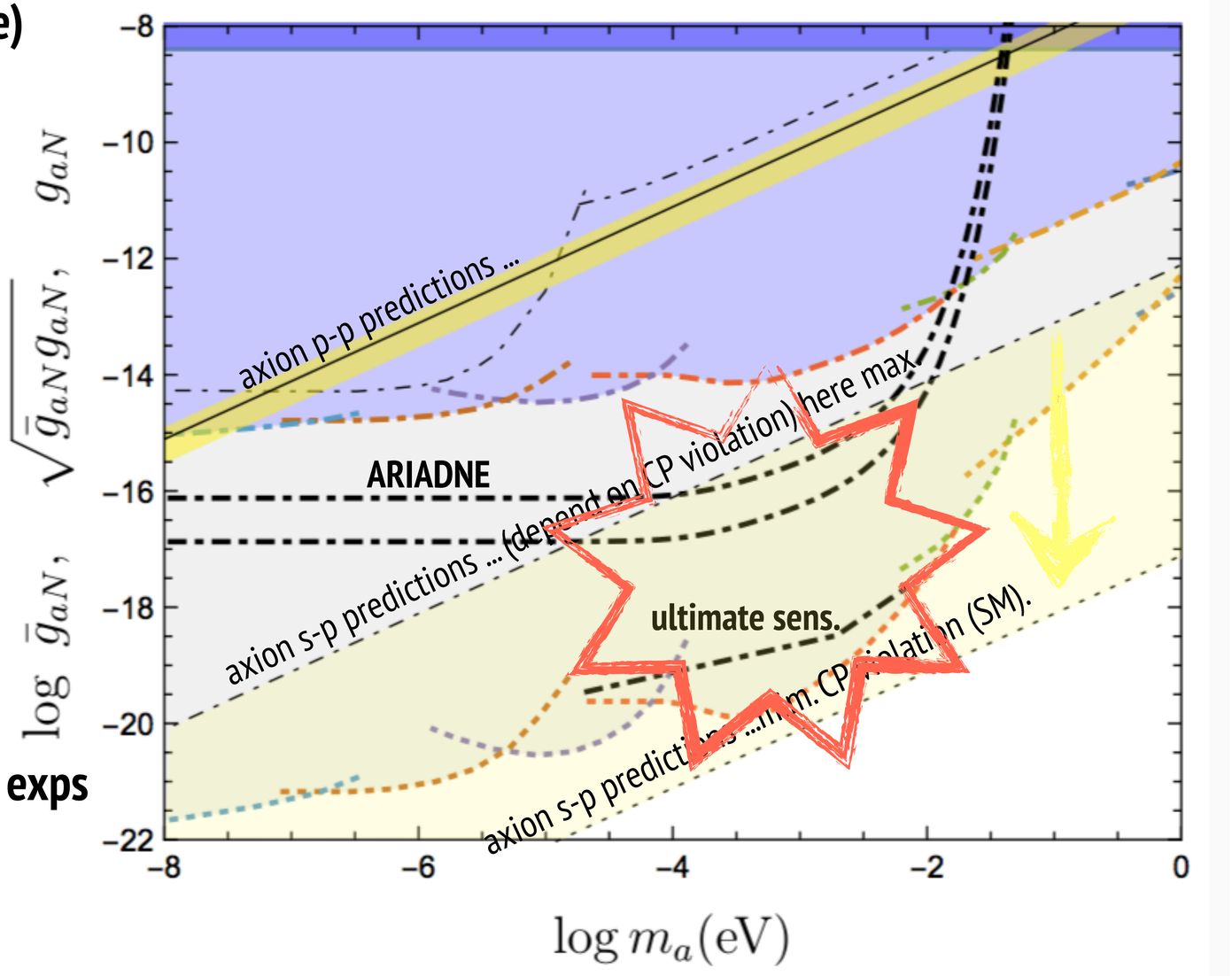
ARIADNE REACH

QCD axion prediction (depends on CP violation)



Scalar^2 forces (dotted lines) exclusion from 5th-force exps

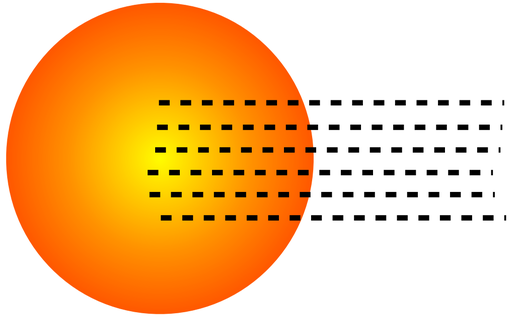




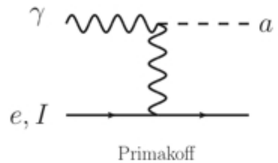
Helioscopes (search solar ALPs)

Sikivie PRL 1983

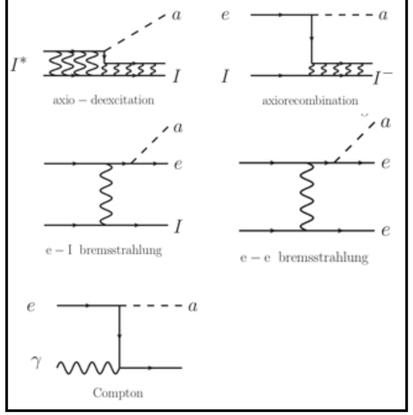
The Sun is a copious emitter of ALPs!

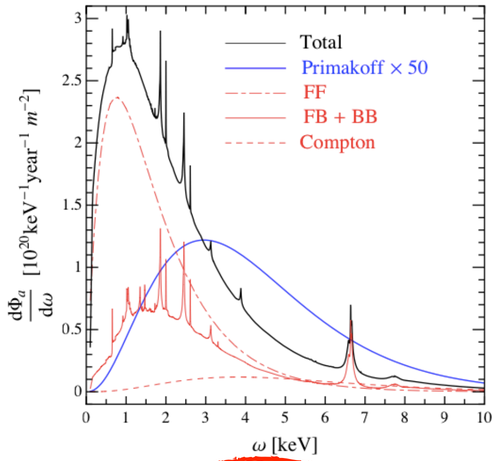


photon coupling



electron coupling





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

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

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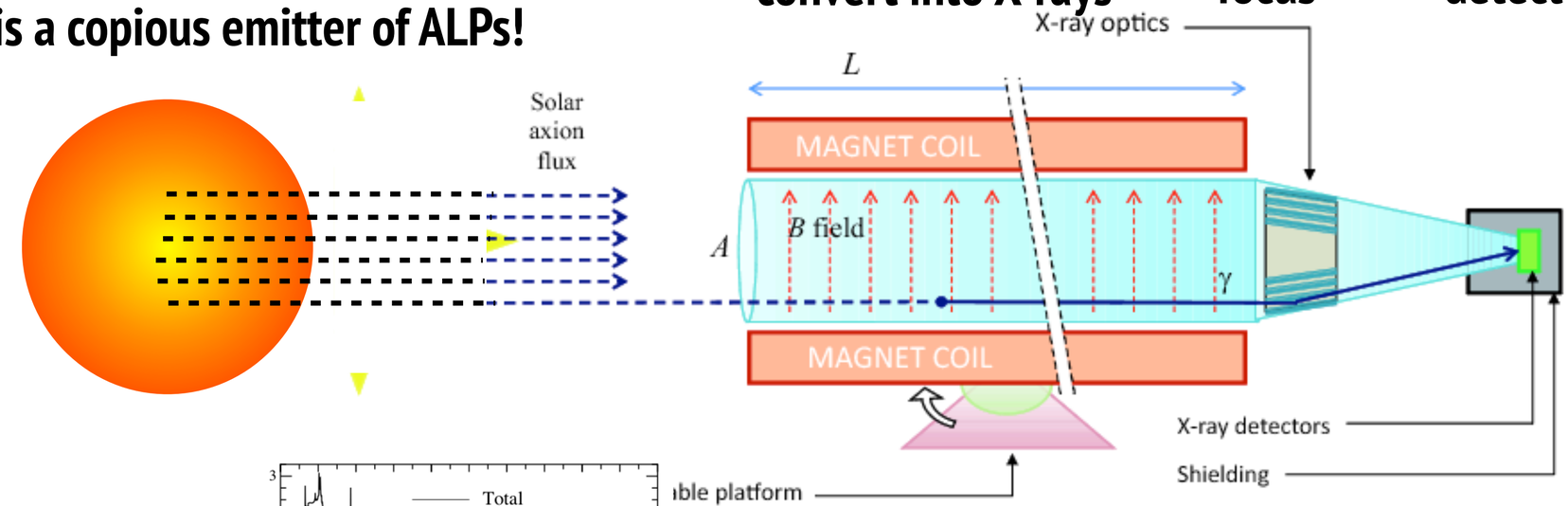
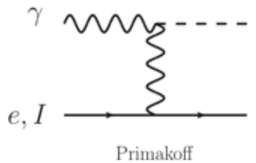
Sikivie PRL 1983

The Sun is a copious emitter of ALPs!

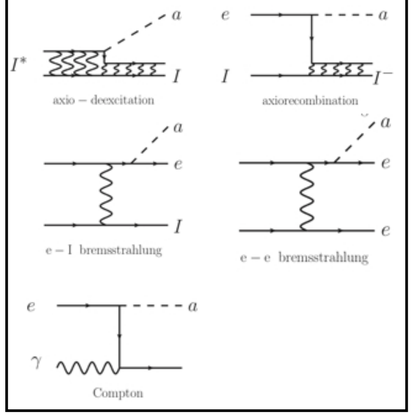
convert into X-rays | focus | detect

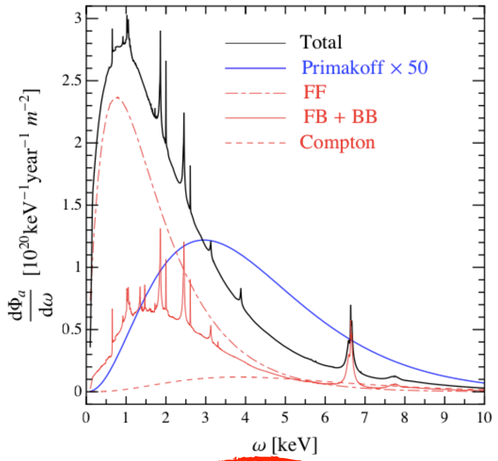


photon coupling



electron coupling





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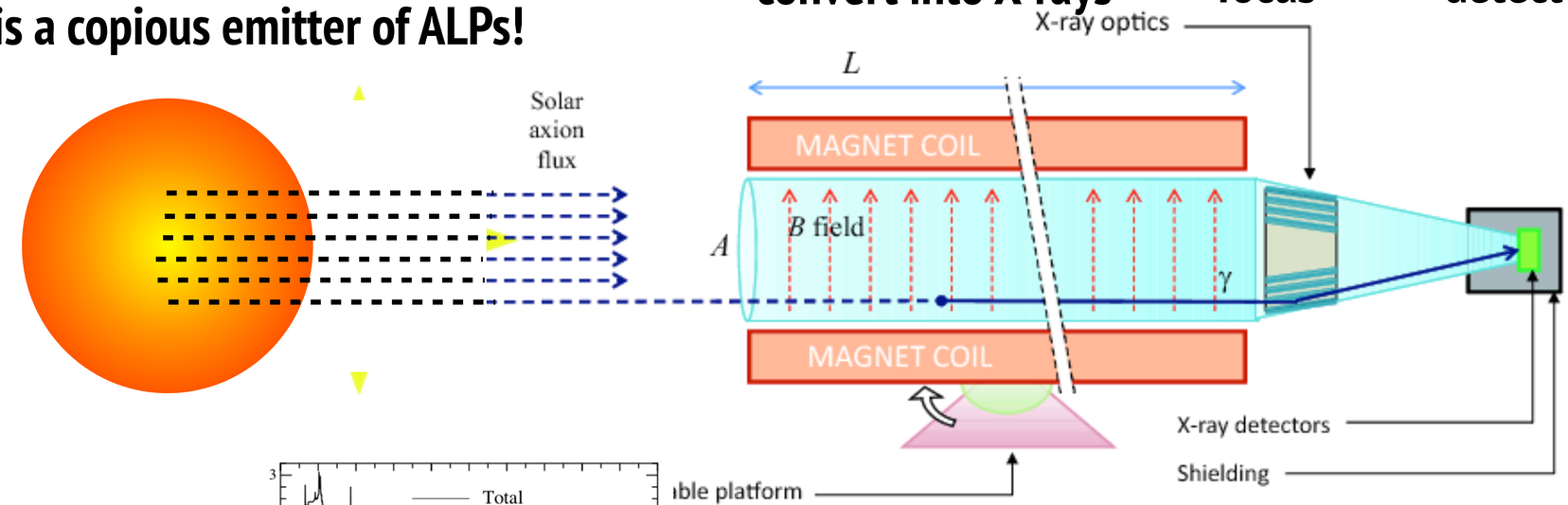

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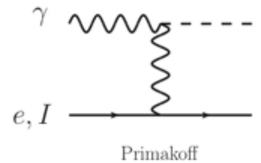

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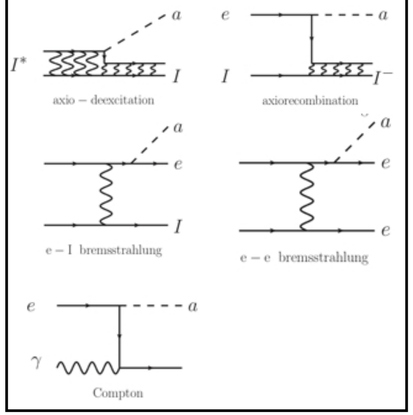
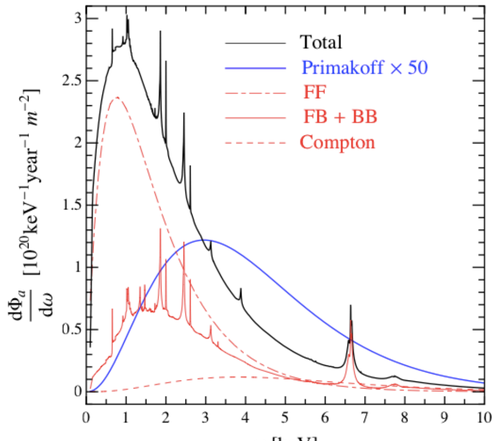


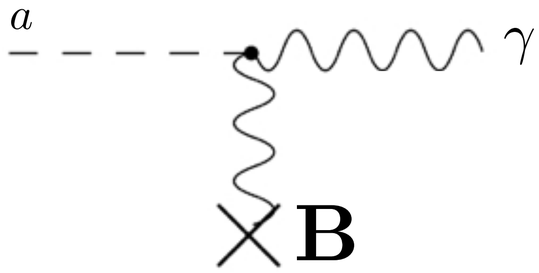


$g_{ae} = 10^{-13}$

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

Coherent Conversion along the B-field

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

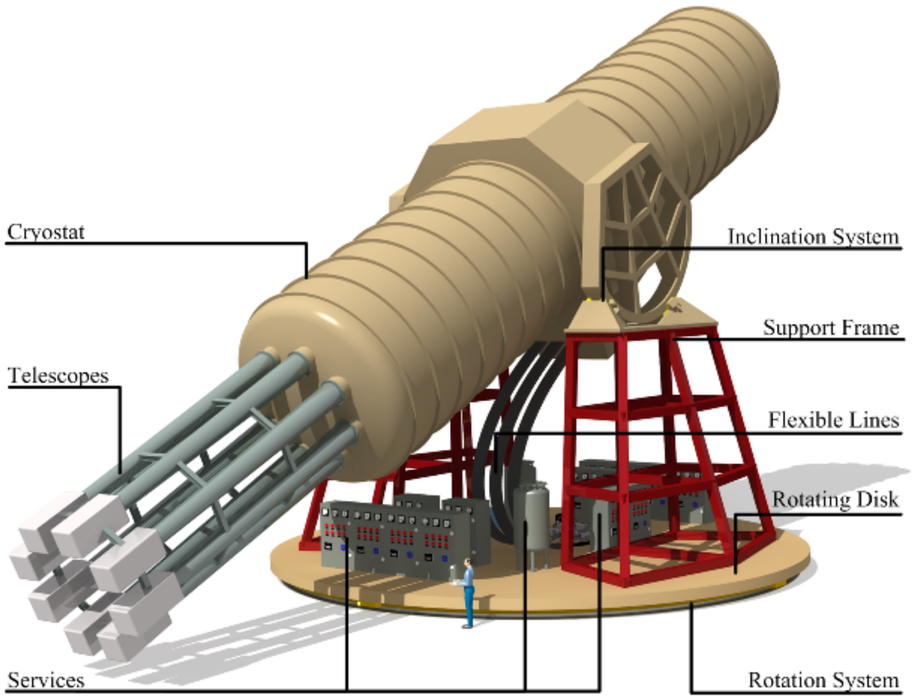


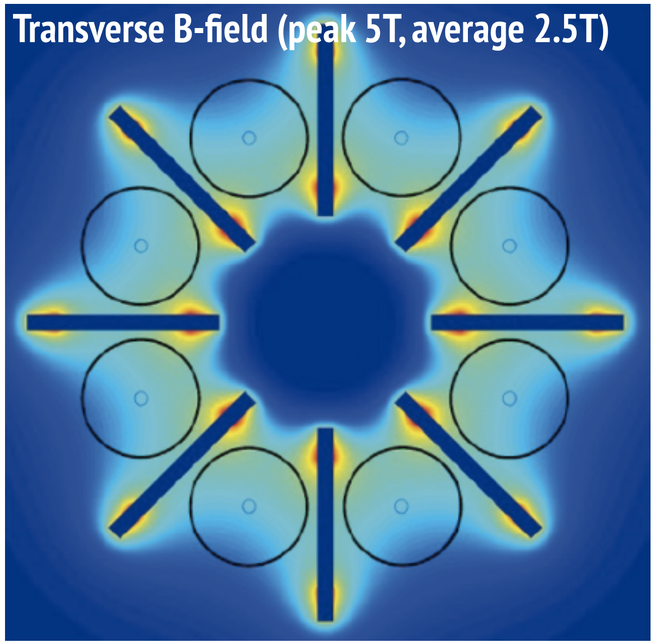
International AXion Observatory

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)



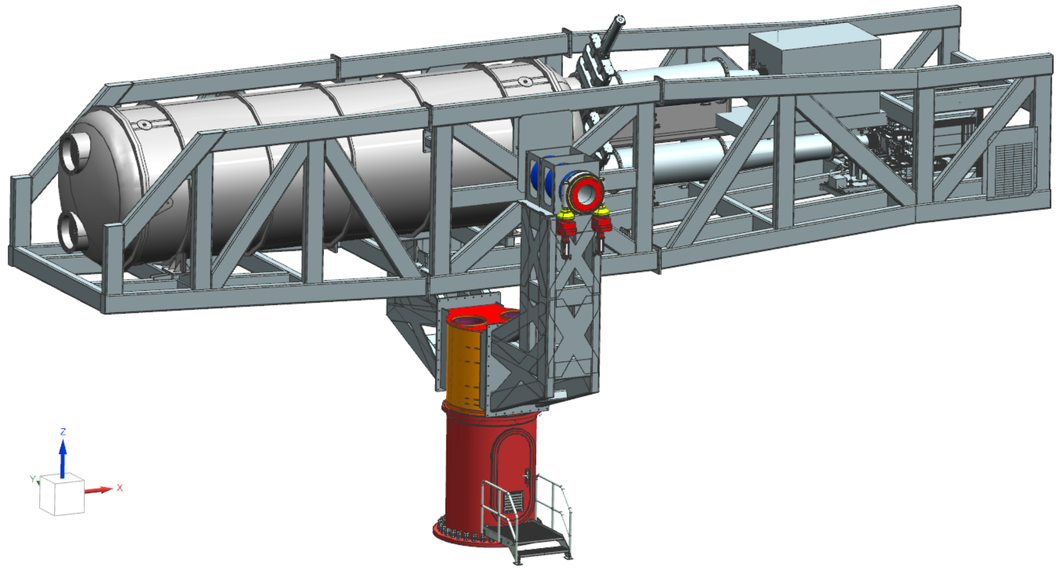


babyIAXO

IAXO is too expensive... scale slowly

IAXO collaboration 2010

- 10 m long racetracks, 2 bores
- 70cm diameter bores (!)
- B-field ~3 T
- Astronomical mount, 50% day tracking
- Dedicated X-ray telescopes
- Dedicated ultra-low-background dets.



Expected commisioning 2026

IAXO detectors

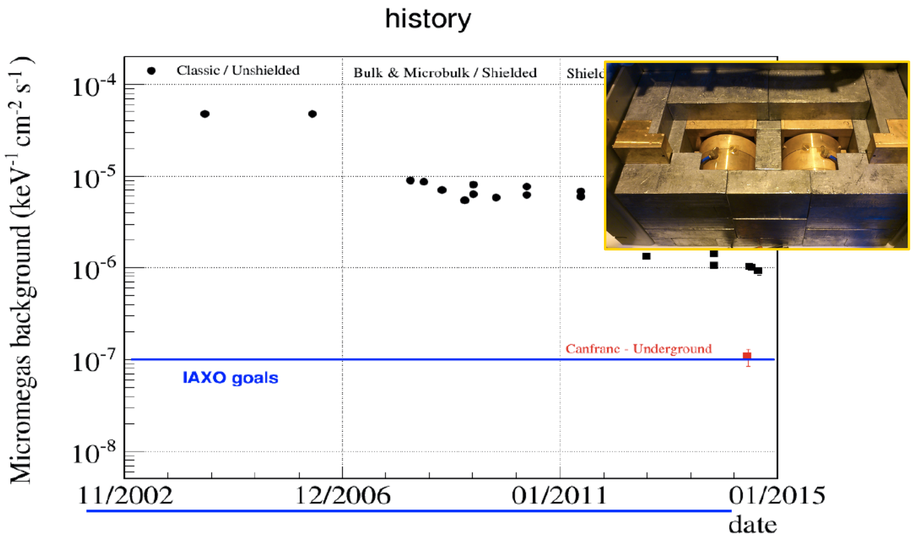
Goal background level for IAXO: $\dfrac{10^{-7} \rightarrow 10^{-8}}{\mathrm{keV\,cm^2\,s}}$

- Small Micromegas-TPC chambers:

Shielding

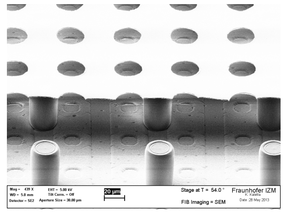
Radiopure components

Offline discrimination

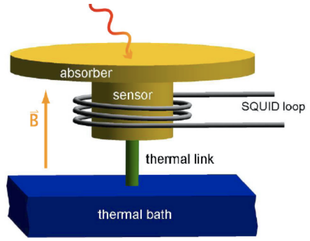


Already demonstrated: $\dfrac{8 \times 10^{-7}}{\mathrm{keV\,cm^2\,s}}$ **(in CAST 2014 result)** $\dfrac{10^{-7}}{\mathrm{keV\,cm^2\,s}}$ **(underground at LSC)**

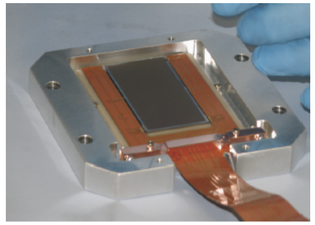
- Gridpix/InGrid,



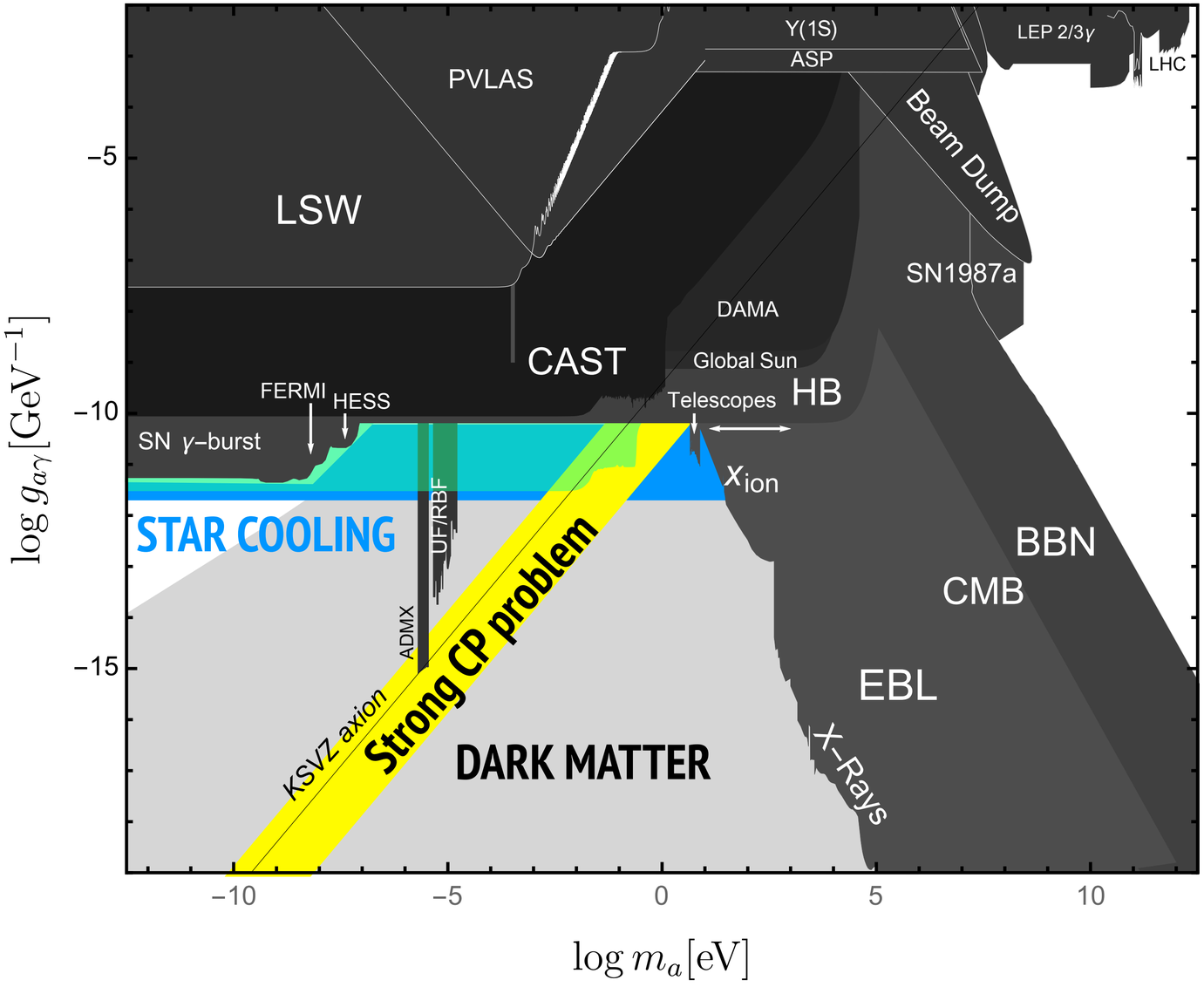
- MMC



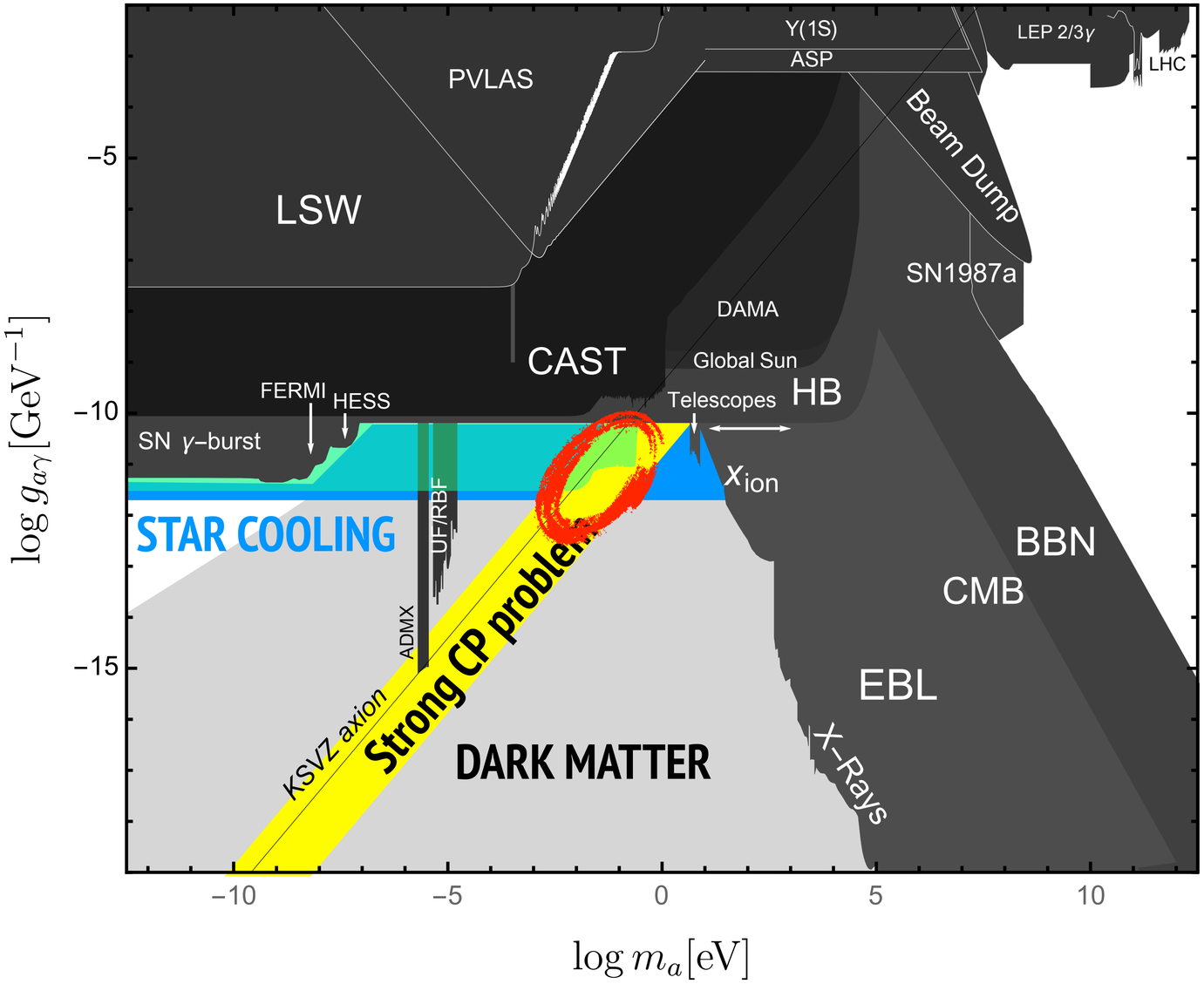
- Low noise CCDs



IAXO reach


PVLAS
Y(1S)
ASP
LEP 2/3γ
LHC
Beam Dump
LSW
SN1987a
DAMA
CAST
Global Sun
Telescopes
HB
FERMI
HESS
SN γ–burst
x_{ion}
STAR COOLING
UF/RBF
ADMX
BBN
CMB
EBL
X-Rays
KSVZ axion
Strong CP problem
DARK MATTER
−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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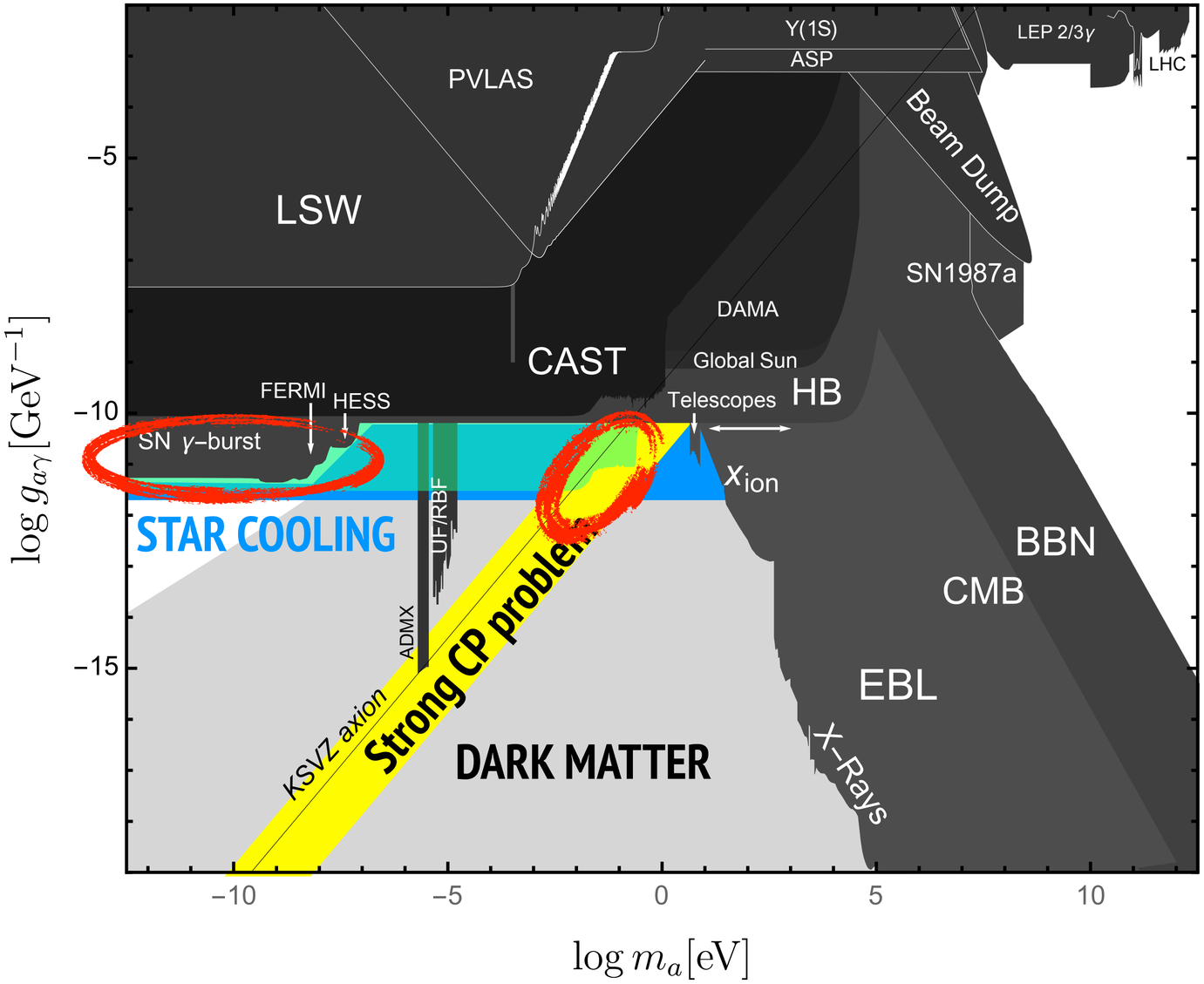
IAXO reach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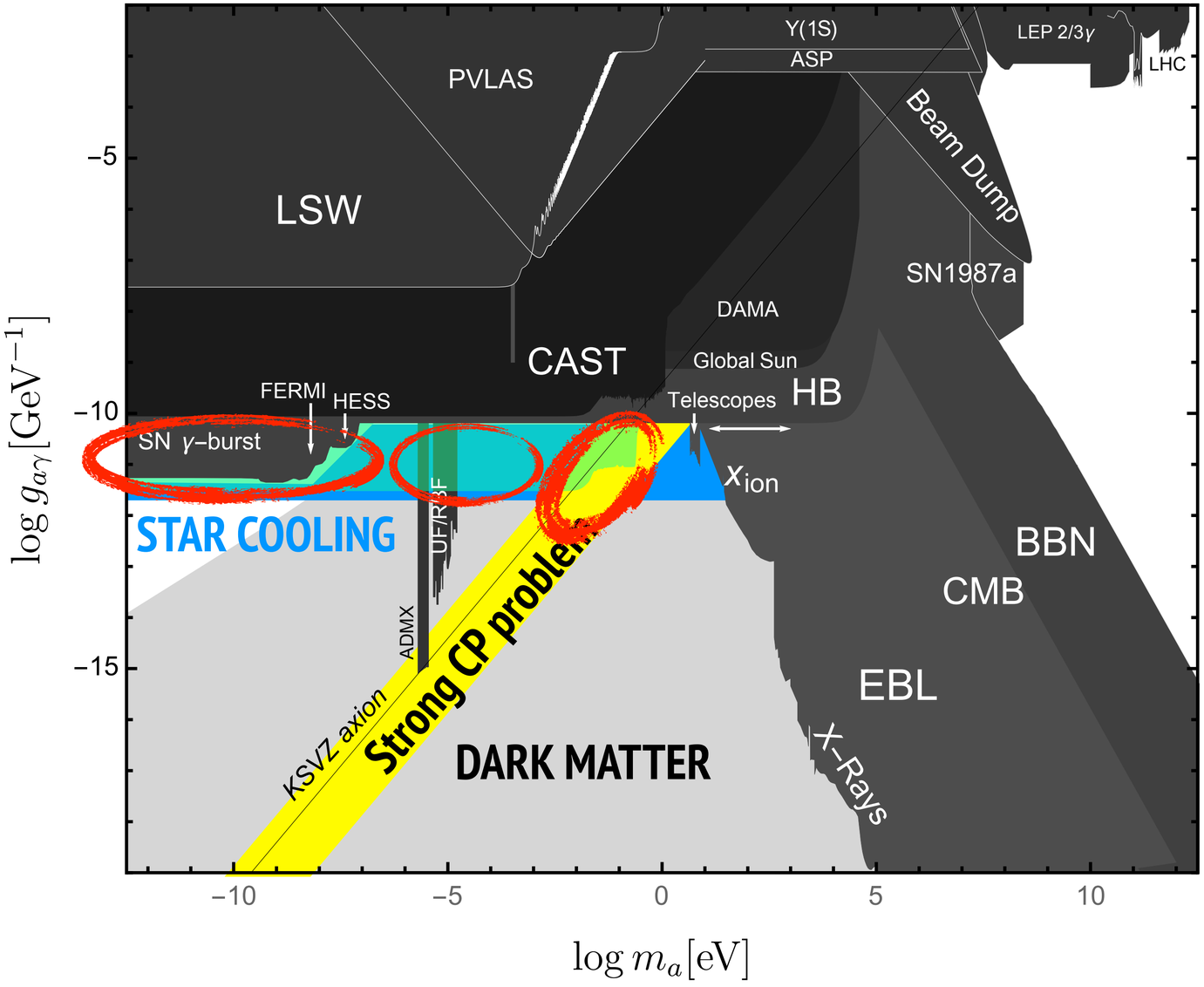
IAXO reach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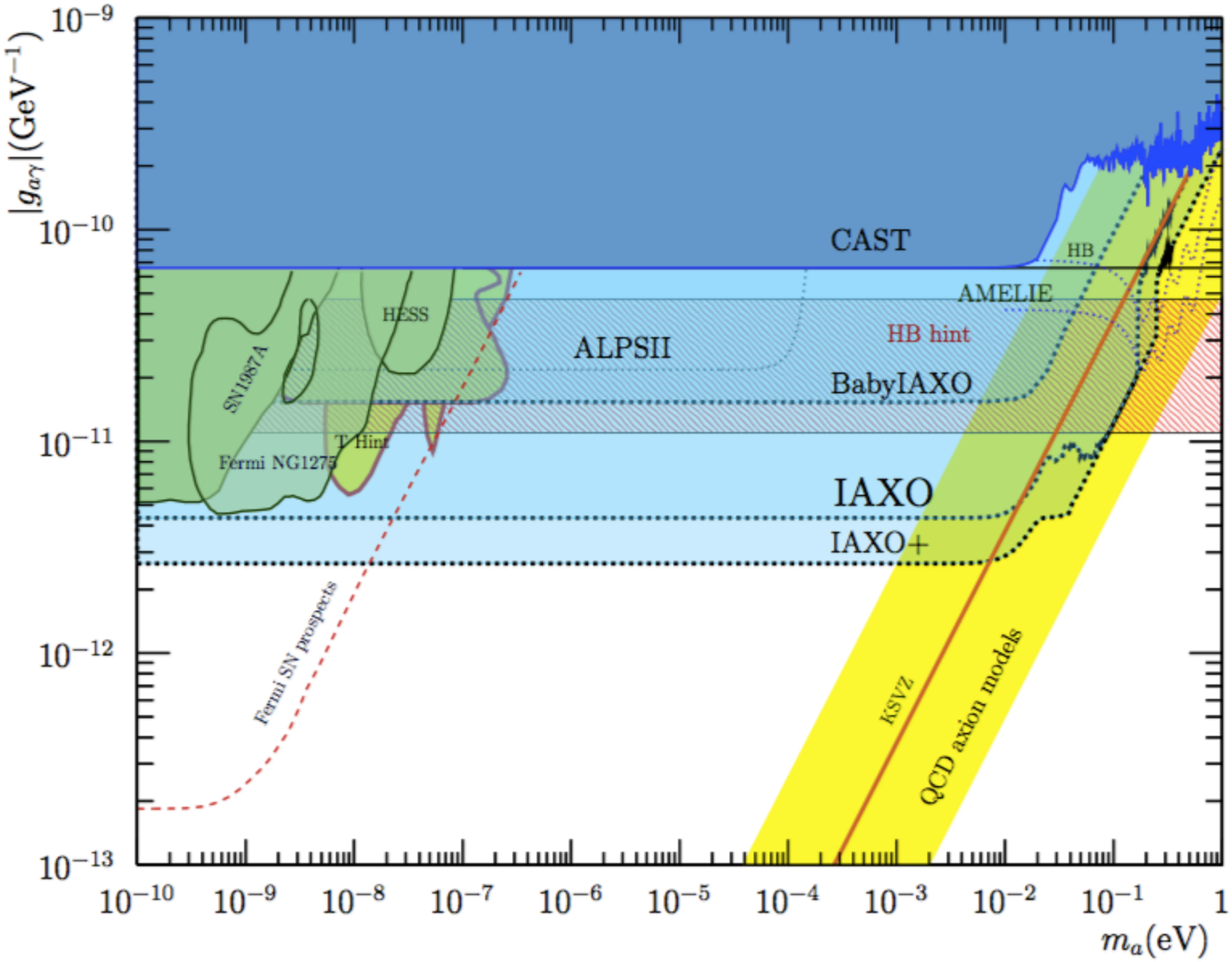
In mode detail

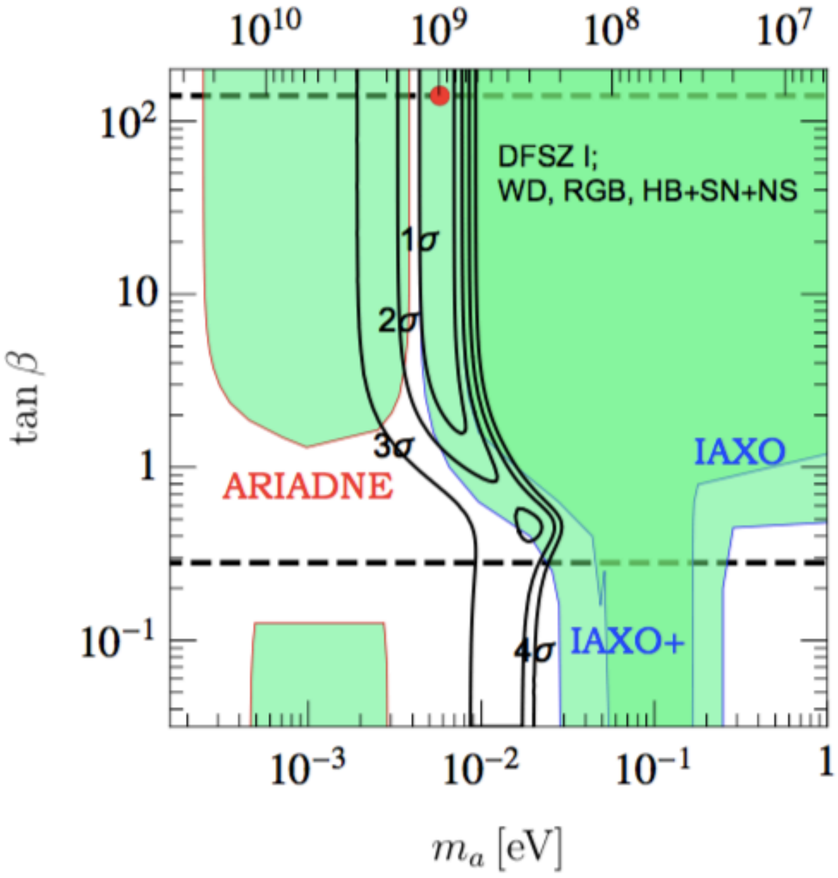


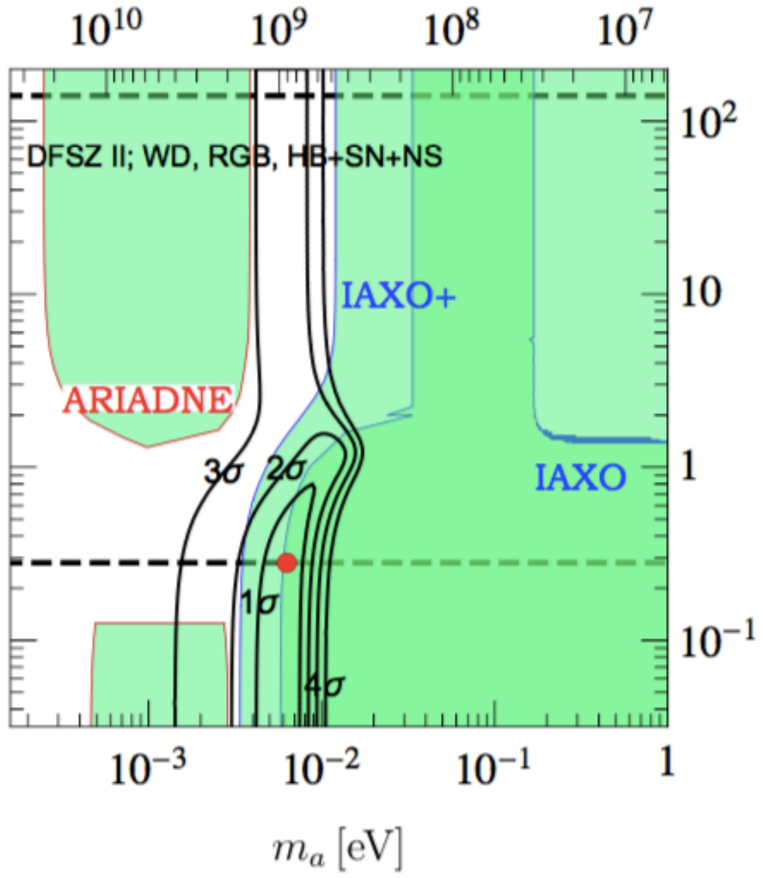
IAXO, ARIADNE and stelar hints

Example DFSZ axion model, 1-free parameter tanbeta

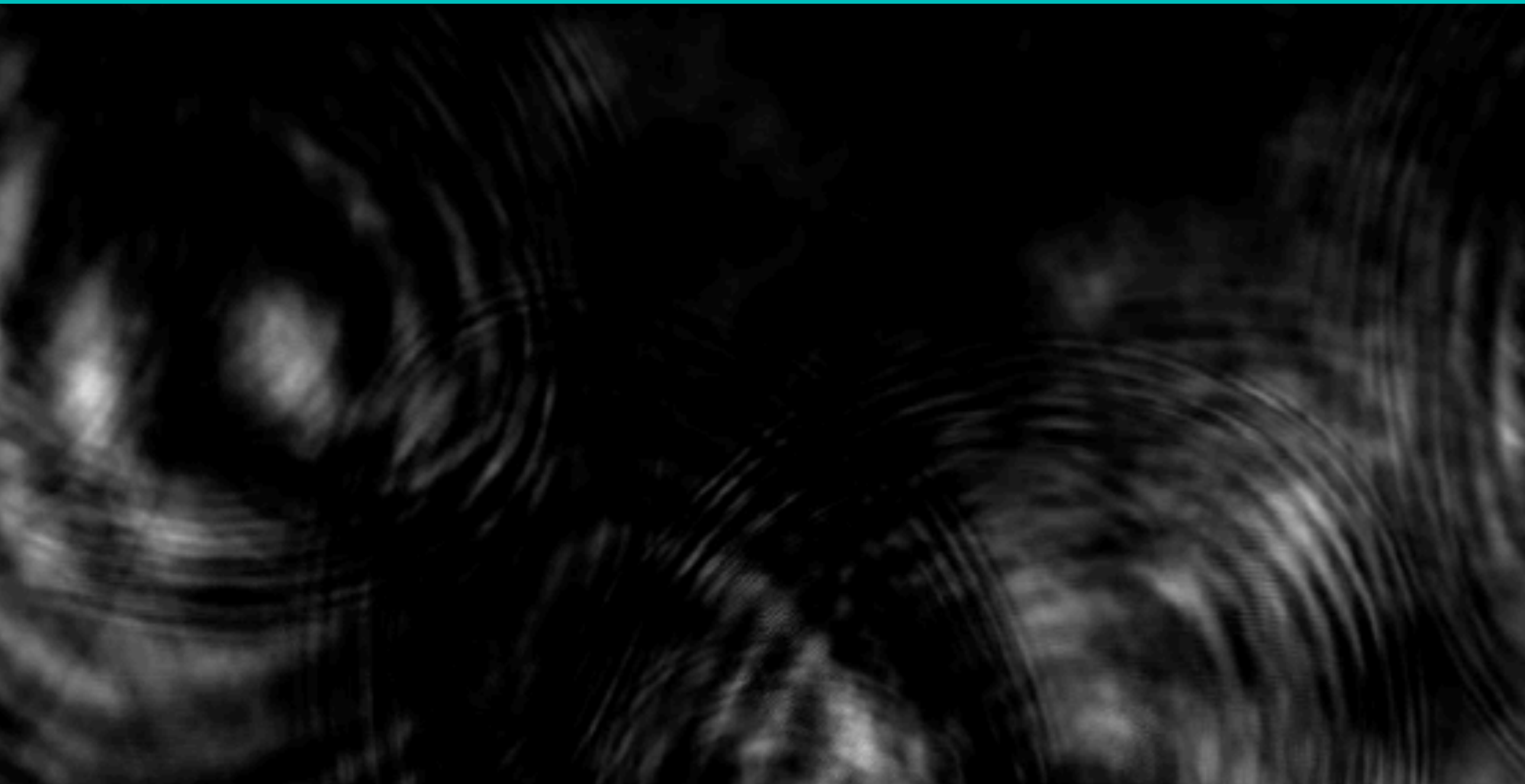
M. Giannotti et al JCAP10(2017)010

f_a [GeV]



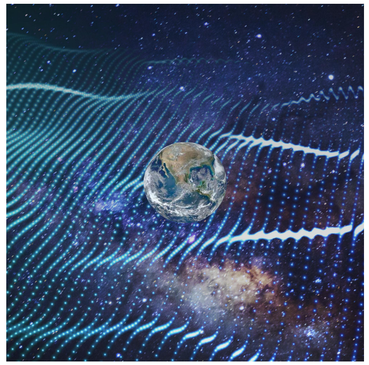


Detecting Dark Matter



Detecting axion DM

$$\theta = \sum_k \theta_k \cos(\omega t - \vec{k} \cdot \vec{x})$$



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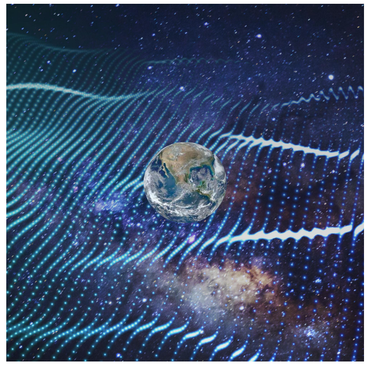

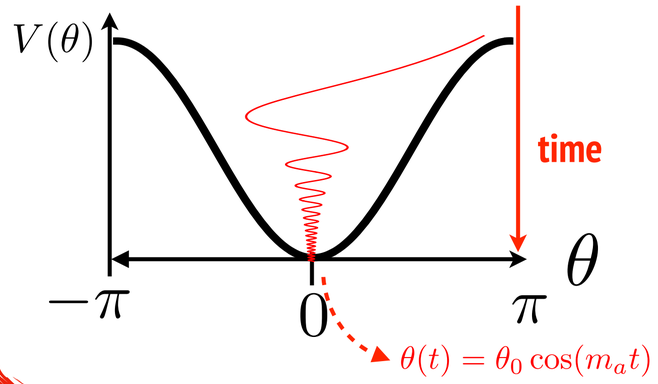

Local Dark Matter density*

$$\rho_{c,0} \simeq \frac{1}{2}\dot{a}^2 + \frac{1}{2}m_a^2 a^2 = 0.4 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

Tiny local amplitude !!!

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

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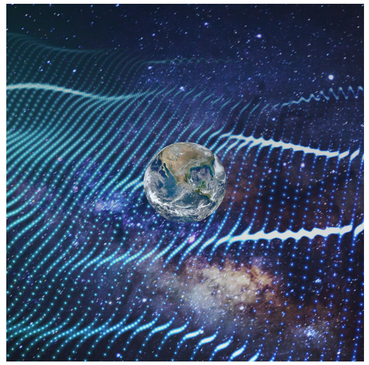

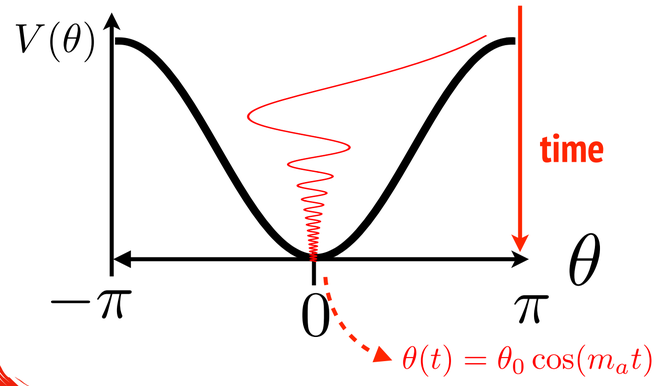

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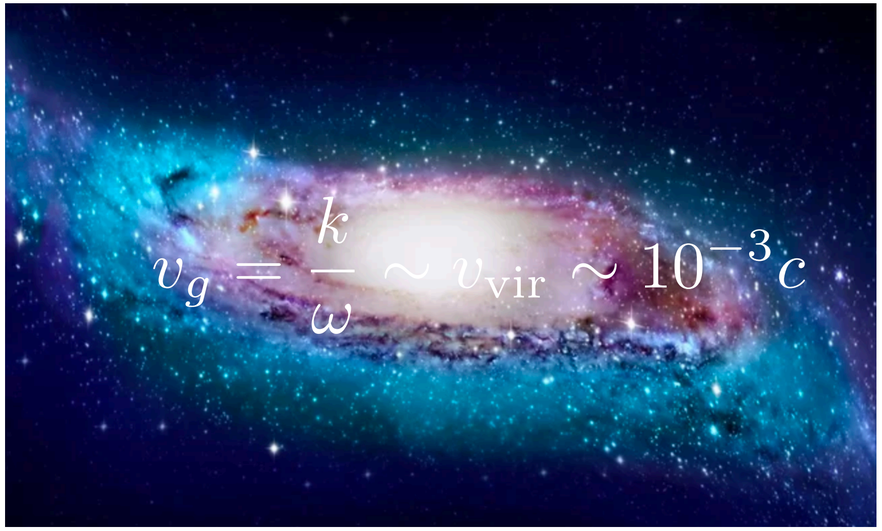
- BUT HUGE COHERENCE TIME (and LENGTH)



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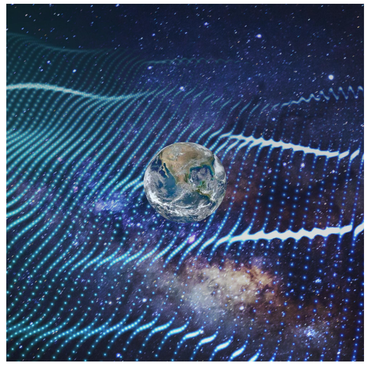

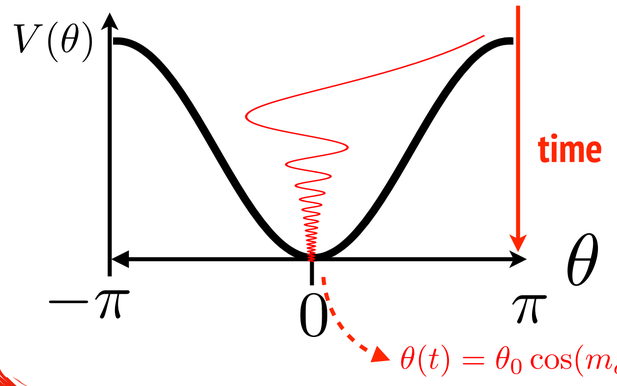

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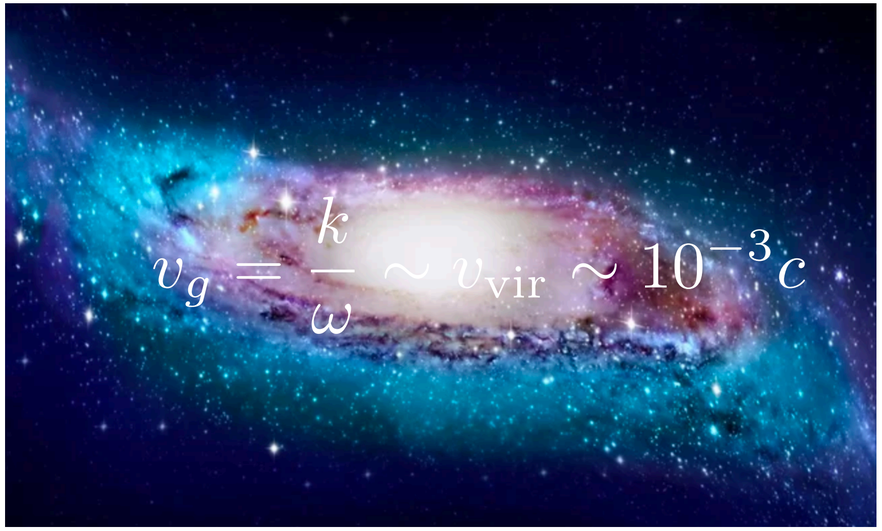
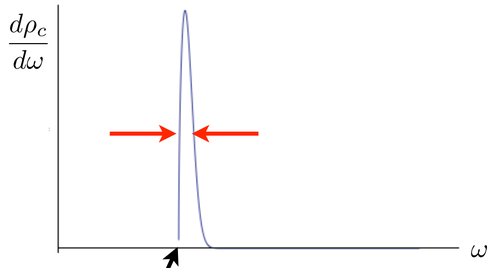


frequency $\omega \simeq m_a(1 + v^2/2 + ...)$



$$m_a \sim 4\mu\text{eV}\frac{\nu}{1\text{GHz}}$$

Detecting axion DM

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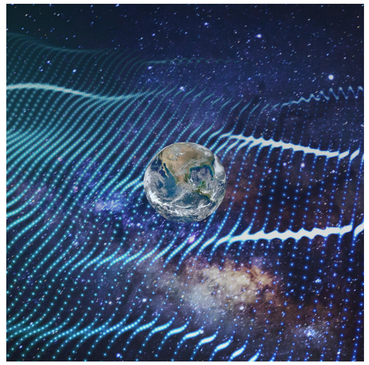

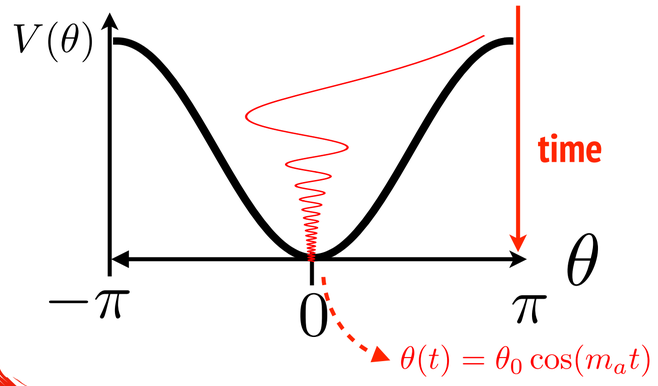

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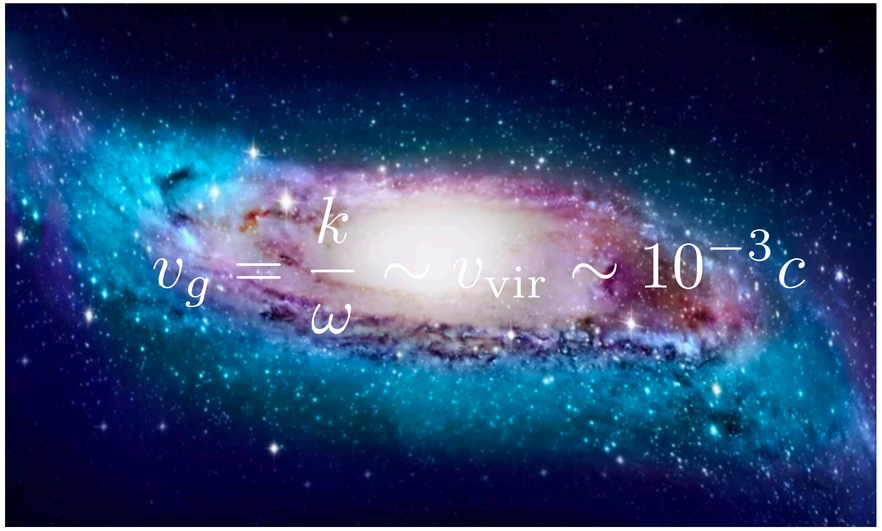
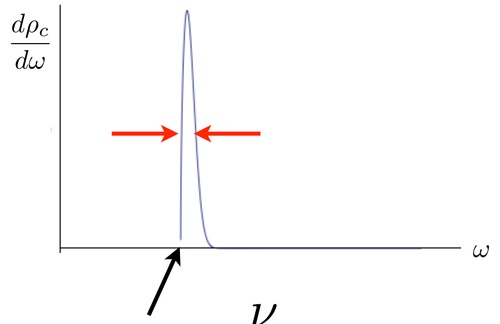
- BUT HUGE COHERENCE TIME (and LENGTH)



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



$$m_a \sim 4\mu\mathrm{eV}\frac{\nu}{1\mathrm{GHz}}$$

coherence time

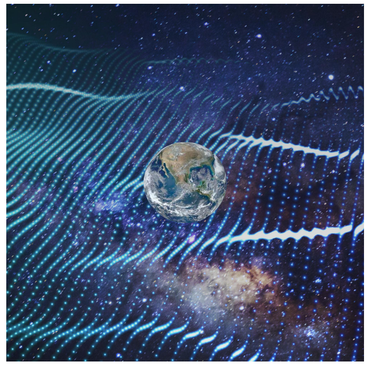
$$\delta t \sim \frac{1}{\delta\omega} \sim \frac{10^6}{m_a} = 10^6 \mathrm{cycles}$$

coherence length

$$\delta L \sim \frac{1}{\delta p} \sim \frac{10^3}{m_a} \sim 10^3 \lambda_C$$

Detecting axion DM

$$\theta = \sum_k \theta_k \cos(\omega t - \vec{k}\cdot\vec{x})$$



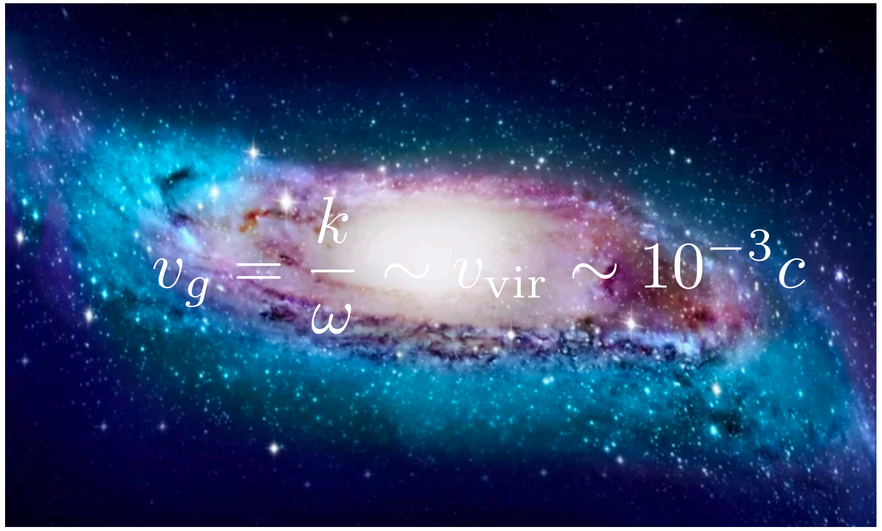
$V($

tude !!!

10^{-19}

tiny amplitude but long coherence time, use resonant detection!

- BUT HUGE COHERENCE TIME (and LENGTH)



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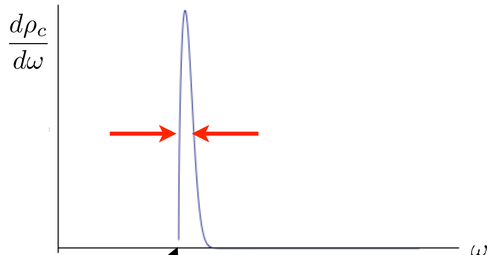

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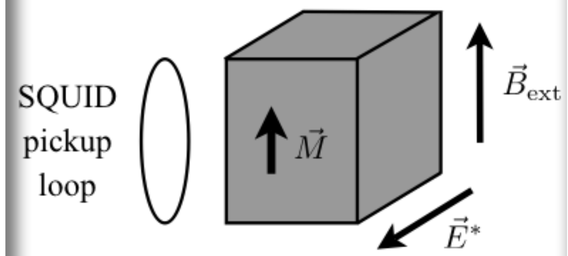
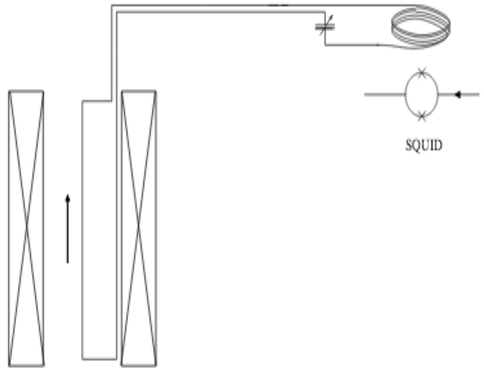
Experimental techniques

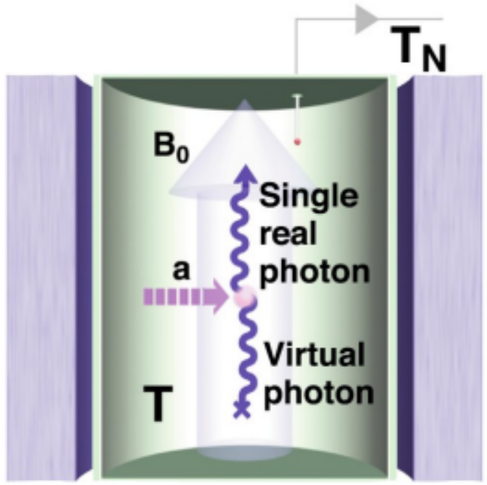
Oscillating EDM



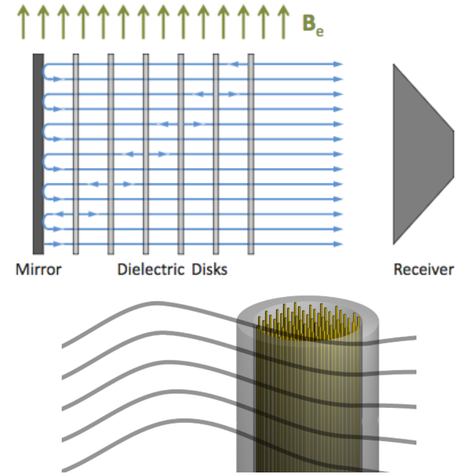
DM-Radio



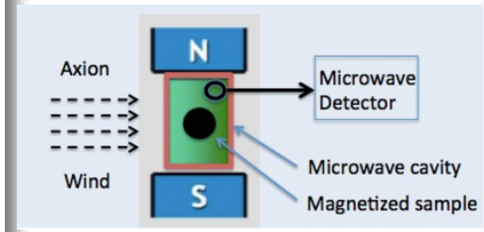
Cavities



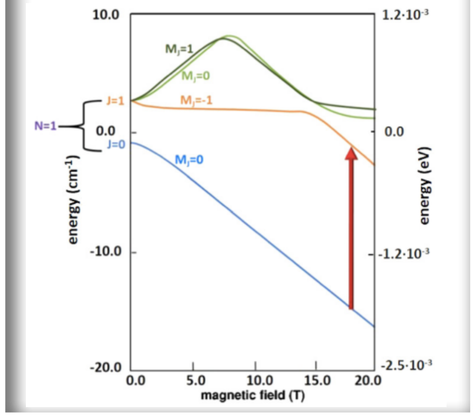
Dielectric/Plasma haloscopes



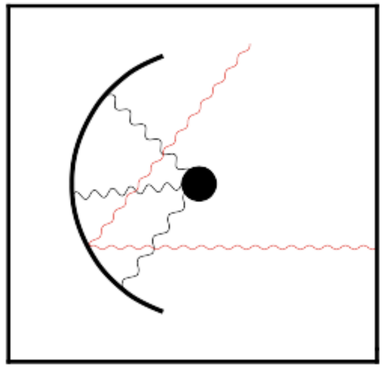
Ferromagnetic resonance



Atomic transitions

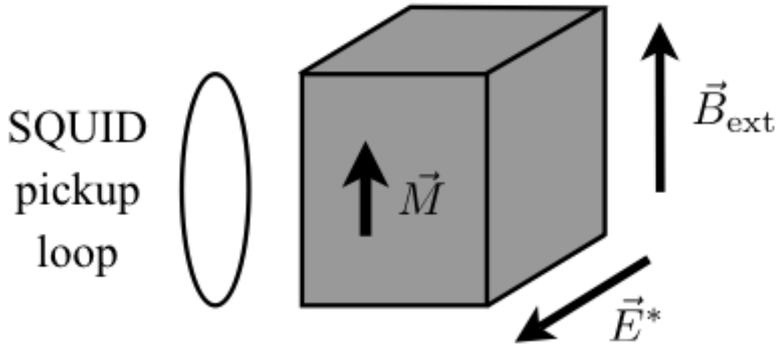


Mirrors*



CASPER at Mainz

Graham 2012



magnetic signal $\propto np\varepsilon_S dE^* T_2$

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

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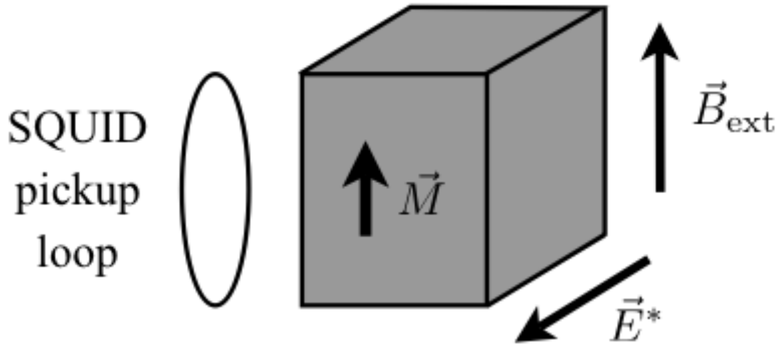

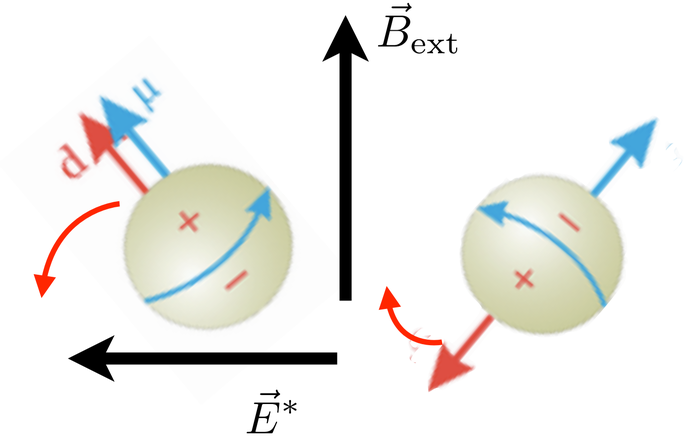

Oscillating EDM, effects add up, transverse magnetisation grows

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

magnetic signal $\propto np\varepsilon_S dE^* T_2$

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

- **EDM + Large E-fields in PbTiO3**
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- **B-field, coherence time, sensitivity to m < neV**
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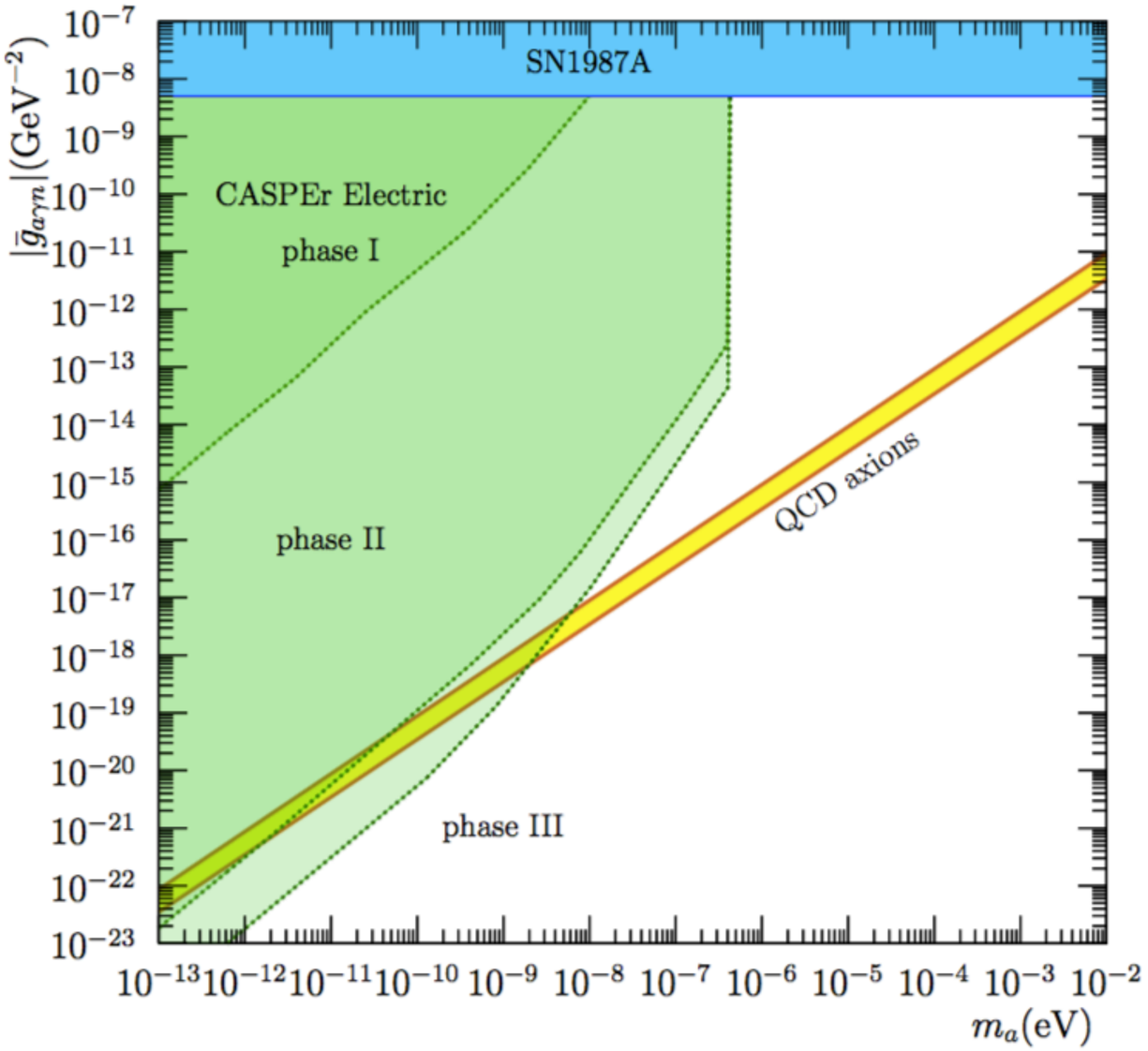
CASPER reach

Graham 2012



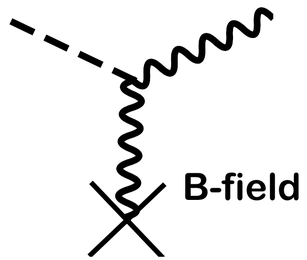
Axion DM in a B-field

$$\mathcal{L}_I = -C_{a\gamma}\frac{\alpha}{2\pi}\frac{a}{f_a}\mathbf{B}\cdot\mathbf{E}$$

- In a static magnetic field, the oscillating axion field generates EM-fields

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

source



- Electric fields $\mathbf{E}_a = C_{a\gamma}\frac{\alpha\mathbf{B}_{\rm ext}}{2\pi}\theta_0\cos(m_a t)$

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

- B-fields $\propto \nabla\theta$ $\qquad |\mathbf{B}_a| \sim \langle v\rangle |\mathbf{E}_a|$

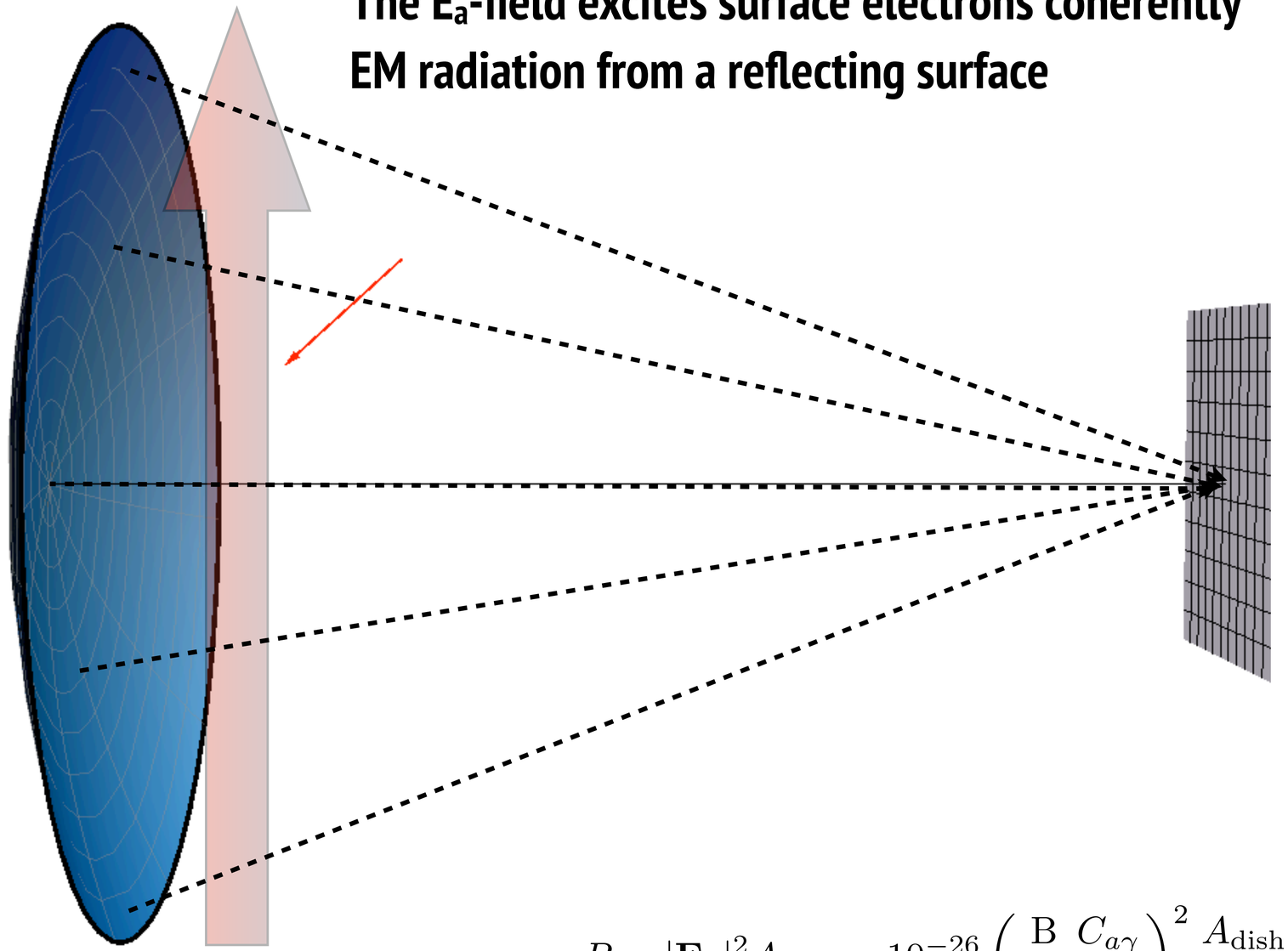
- All experiments are sensitive to light dark photon dark matter! (kin. mix)

Dish antenna experiment?

Horns 2012

The E_a-field excites surface electrons coherently

EM radiation from a reflecting surface



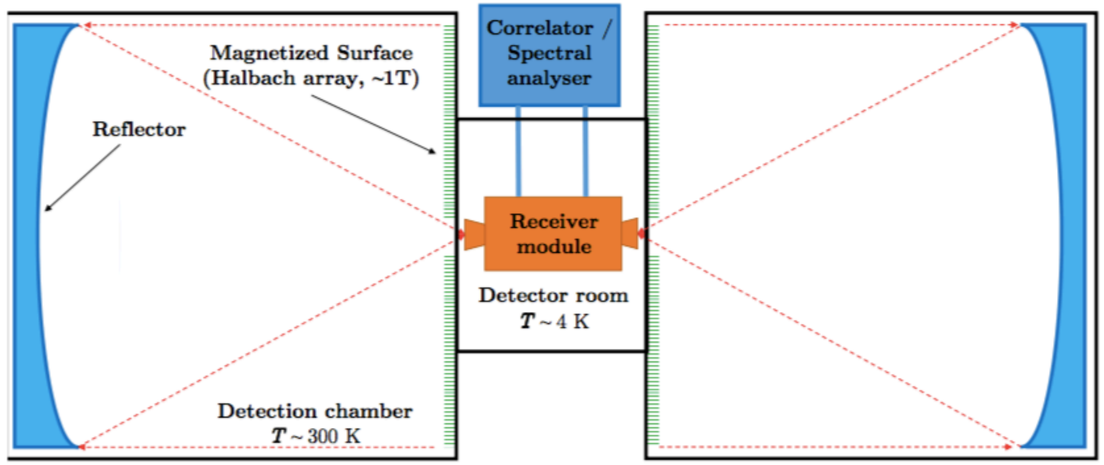
spherical reflecting dish

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

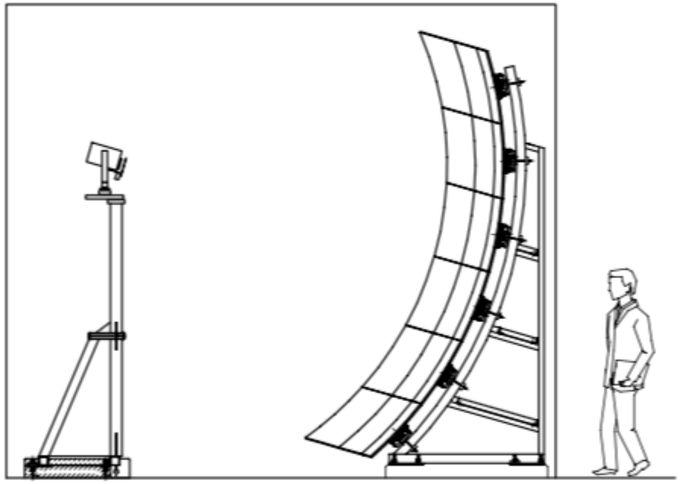
BRASS, FUNK

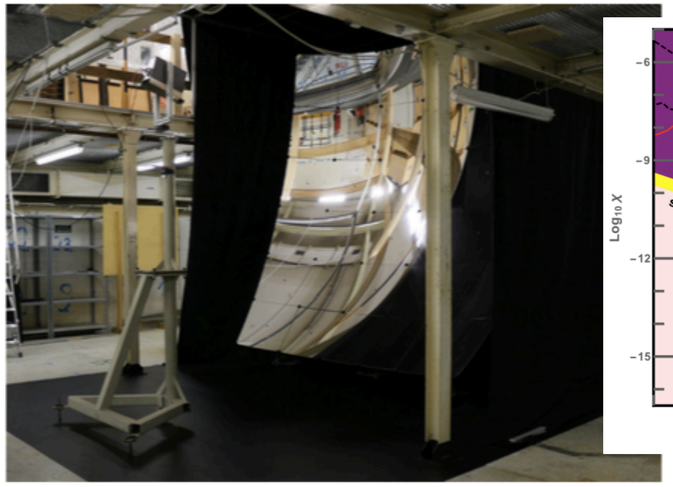
Horns/Lobanov

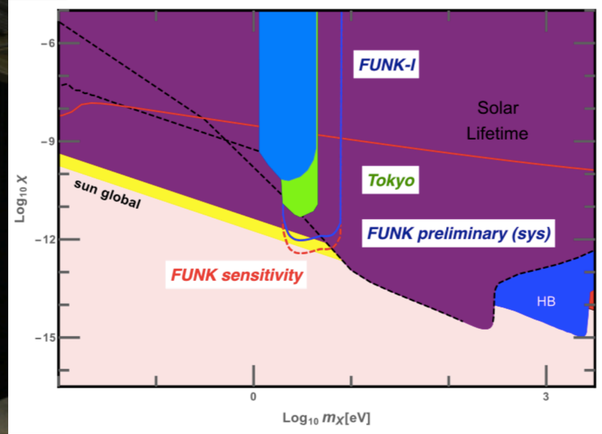
Magnetised surface (Hamburg U.)



FUNK (KIT Karlsruhe) (1711.02961)







Cavity resonators (Haloscopes)

- Haloscope (Sikivie 83)

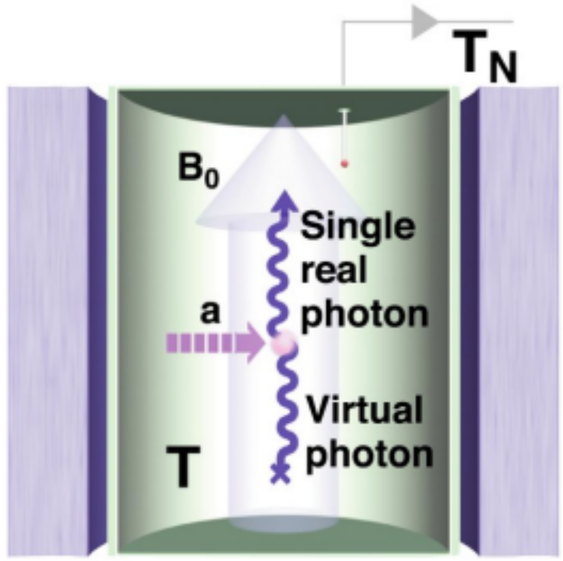
$$P \sim Q|\mathbf{E}_a|^2(Vm_a)\mathcal{G}\kappa$$ (ON RESONANCE)

- comparison with Dish antenna ($P \sim |\mathbf{E}_a|^2 A_{\rm dish}$)

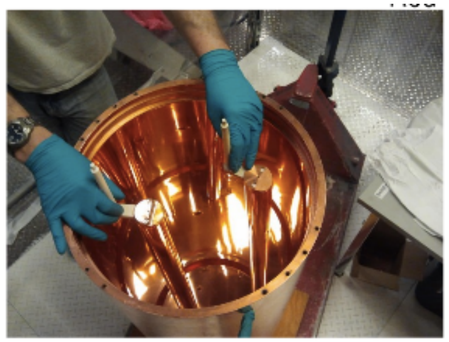
$V \sim 1/m_a^3$

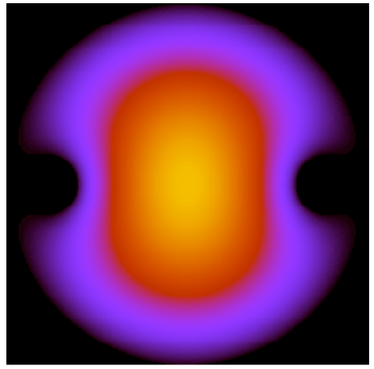
extra factor of Q~10^5

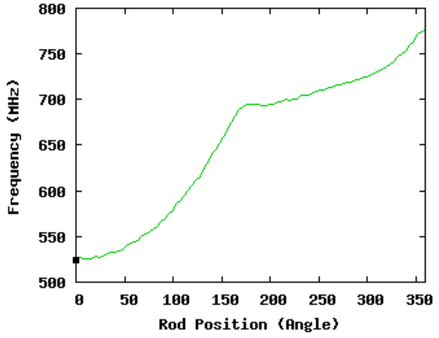
on a m_a/Q band



Scanning over frequencies







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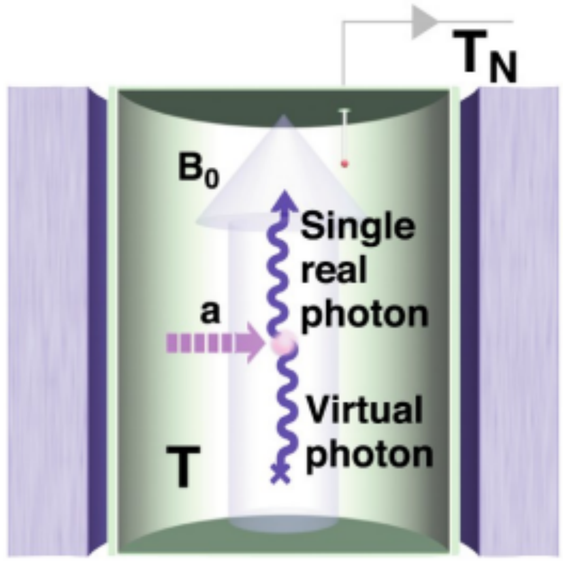

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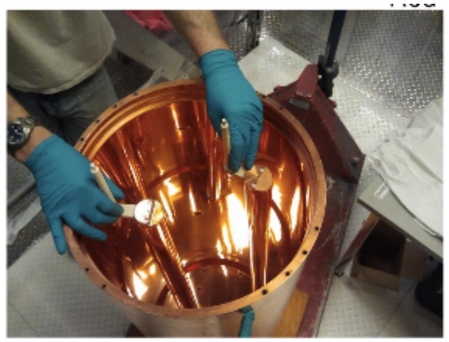
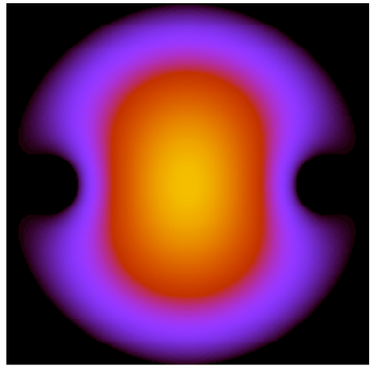
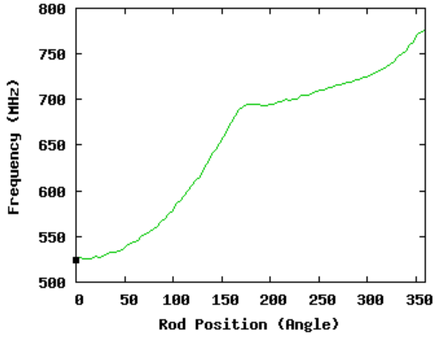


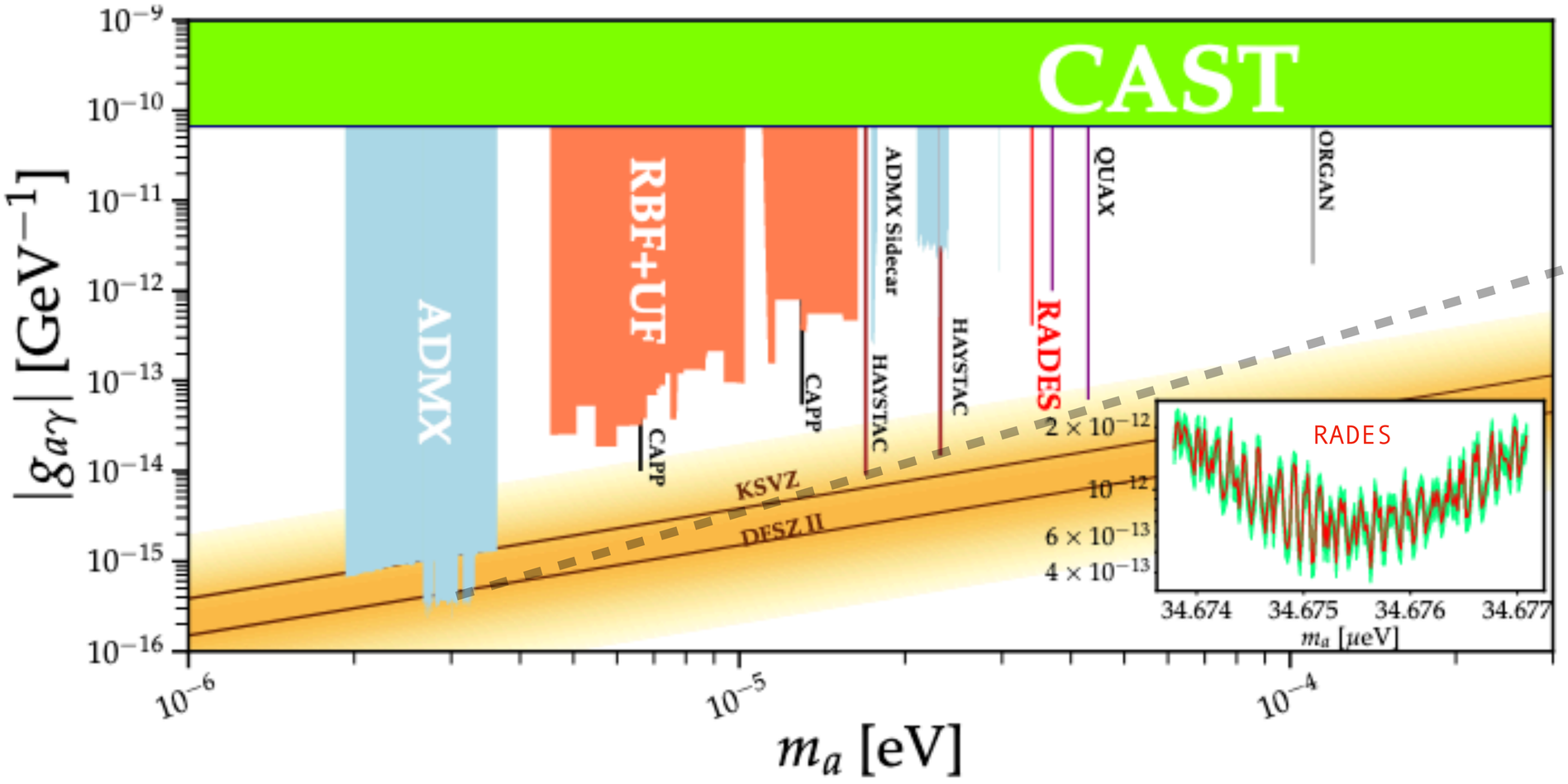




Experiments and results

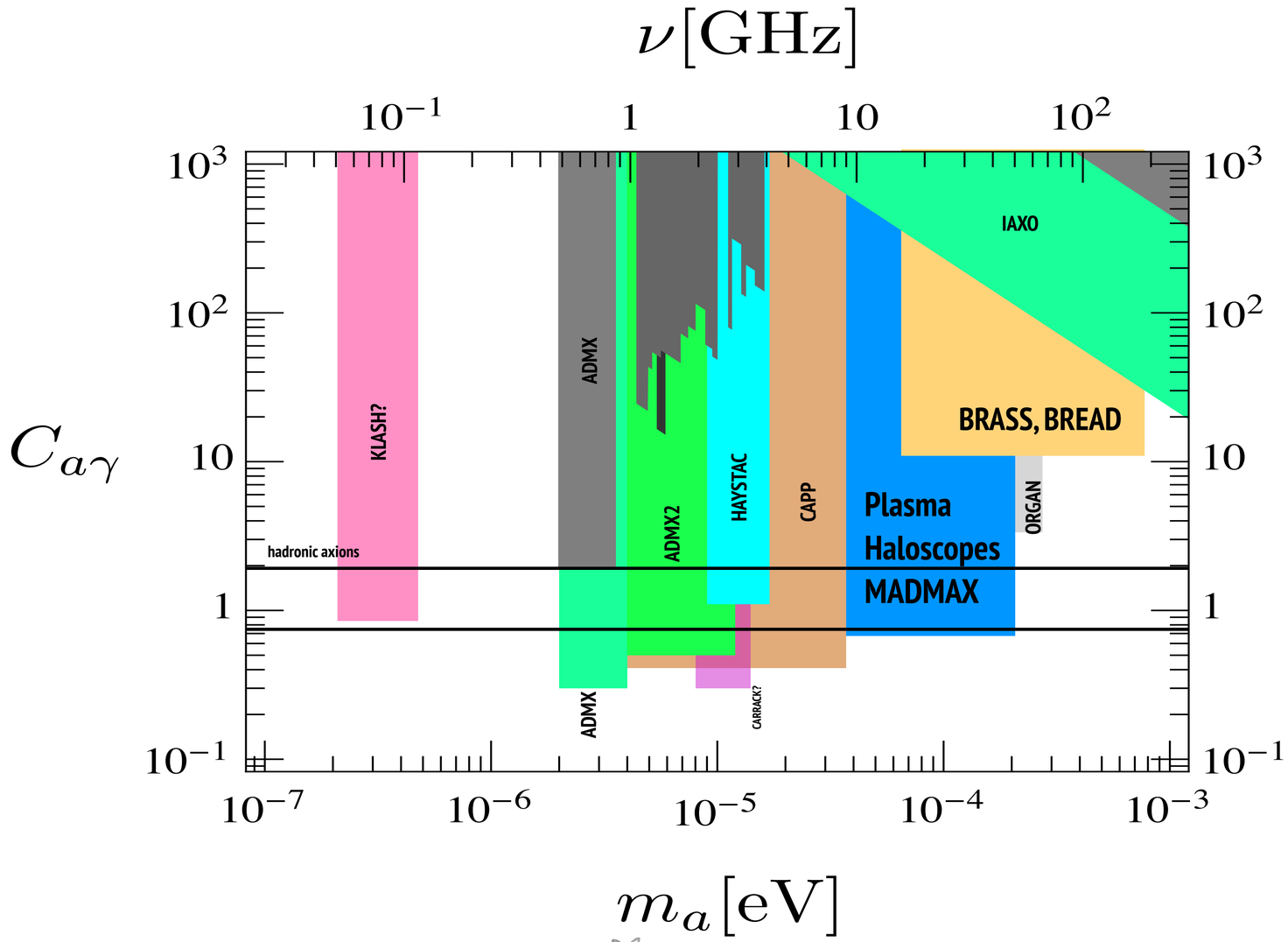
- ADMX reached DFSZ sensitivity in O(1) band, HAYSTAC, CAPP, QUAX on the way, (RADES, ORGAN @ R&D)

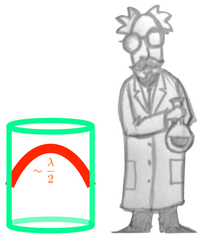
Alvarez Melcon 2021



$$g_{a\gamma} \propto m_a^{7/4}$$

Prospects, issues, solutions





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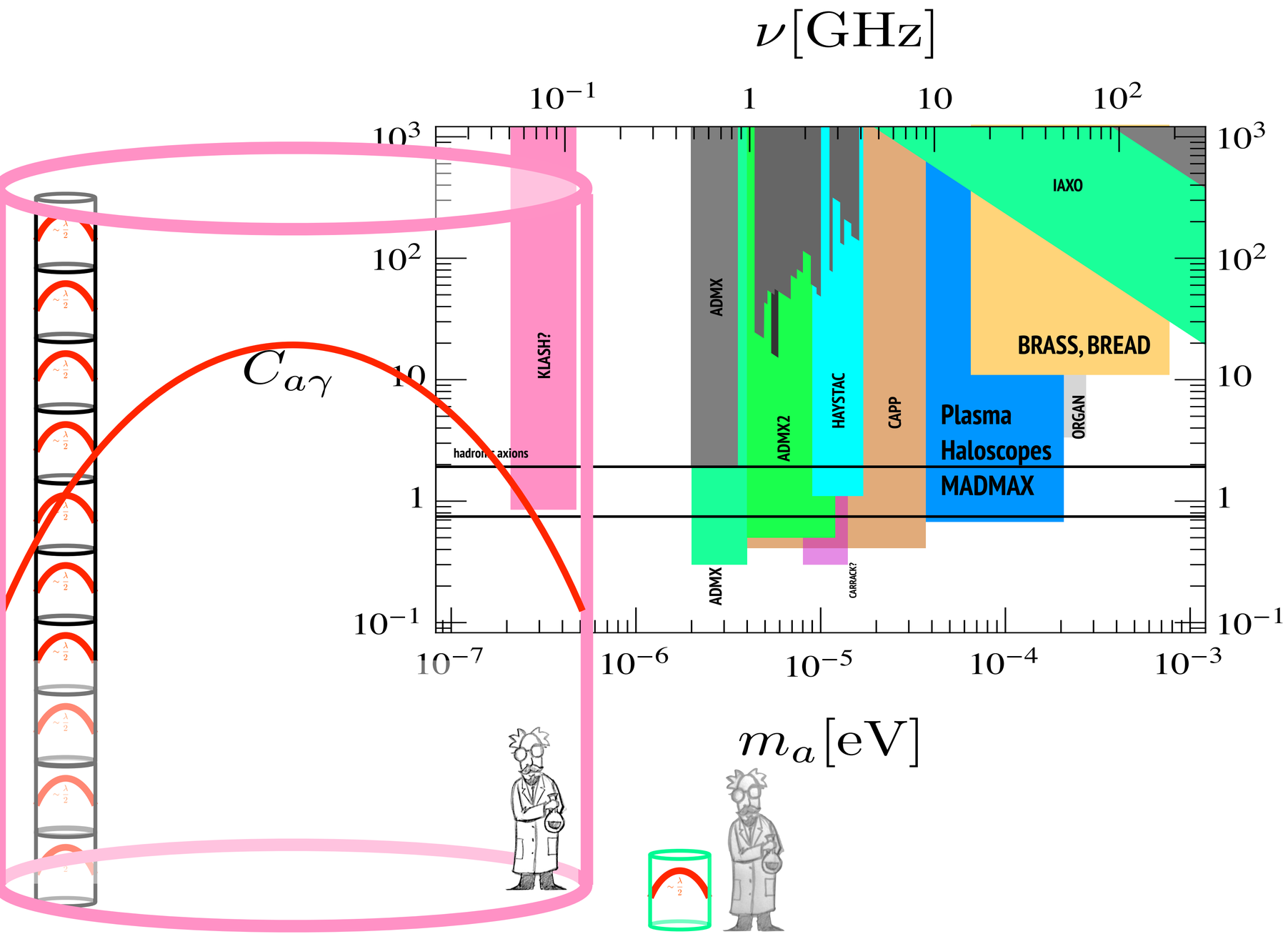
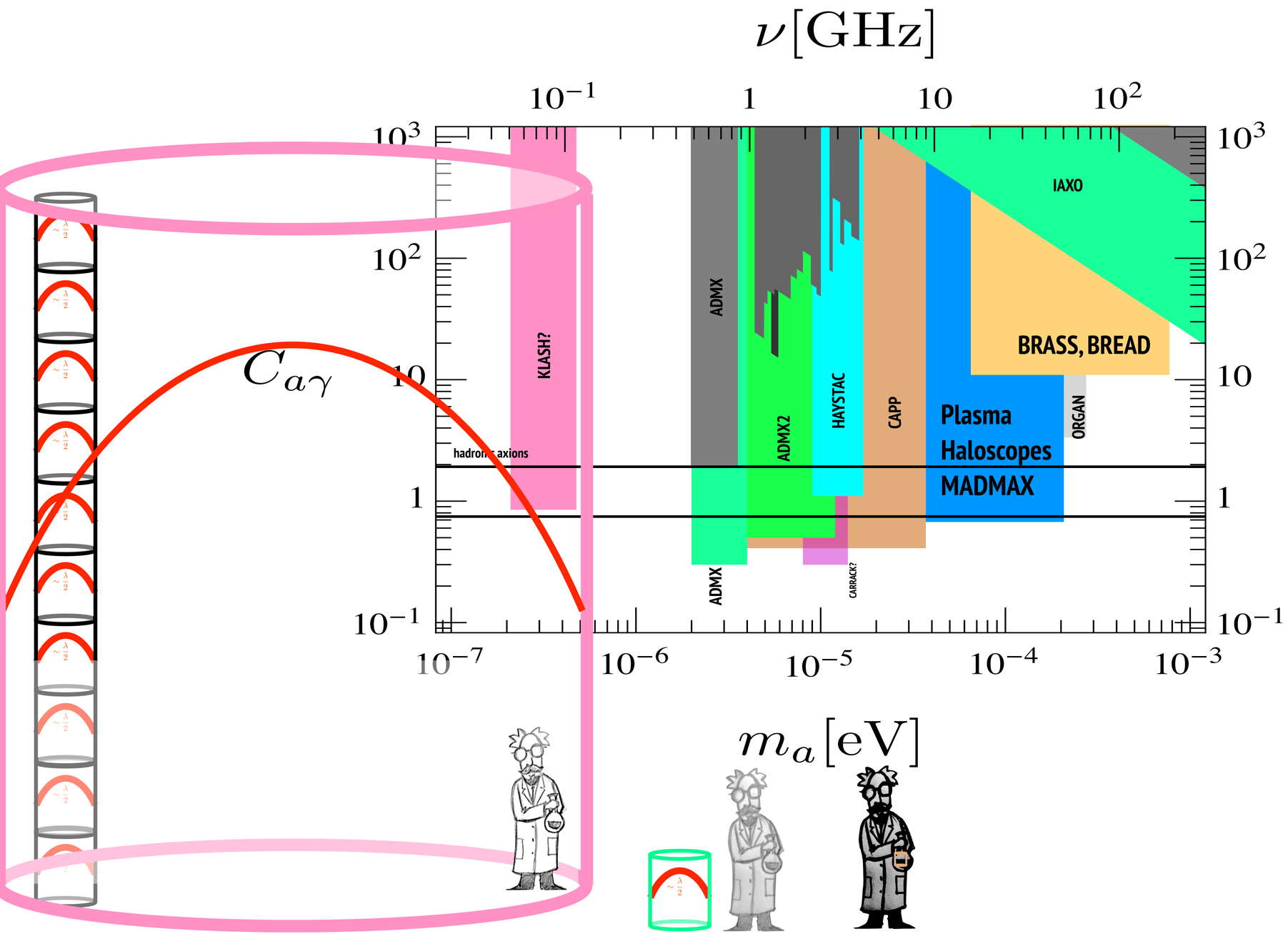


- Use HE particle physics tech
- B-fields and cavities

Prospects, issues, solutions



- Use HE particle physics tech
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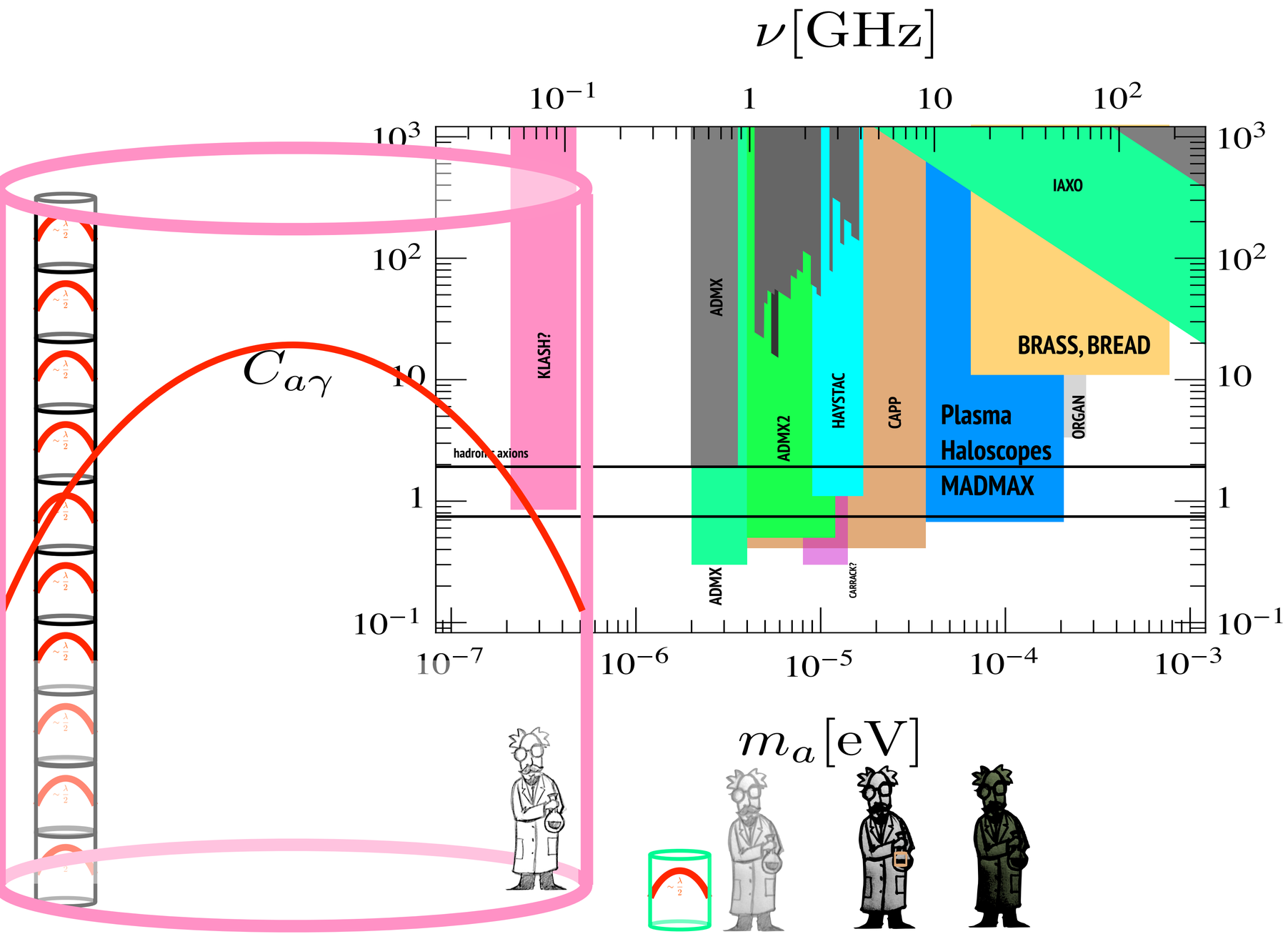
- 20-30 T fields with HTC superconductors
- QL detectors, mK Temperatures
- SC cavities to reach Q~10^6
- new photon counters
- add up signal from many cavities

Prospects, issues, solutions



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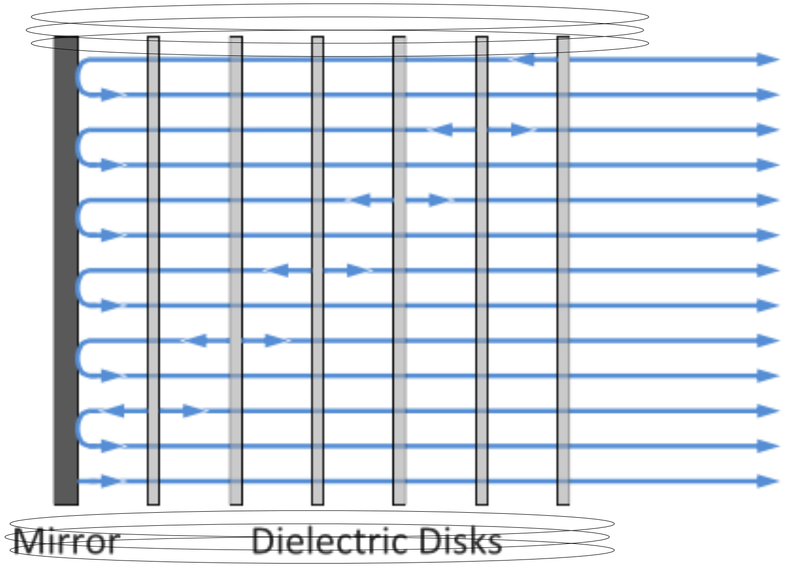
- Huge volume experiments
  - Photonic band gap
  - Brain cavities
- new photon counters?
- ALTERNATIVES
  - Dielectric haloscopes (res. + large Area)
  - Dish antenna (BRASS, BREAD)
  - Plasma Haloscopes (enhace E_a)

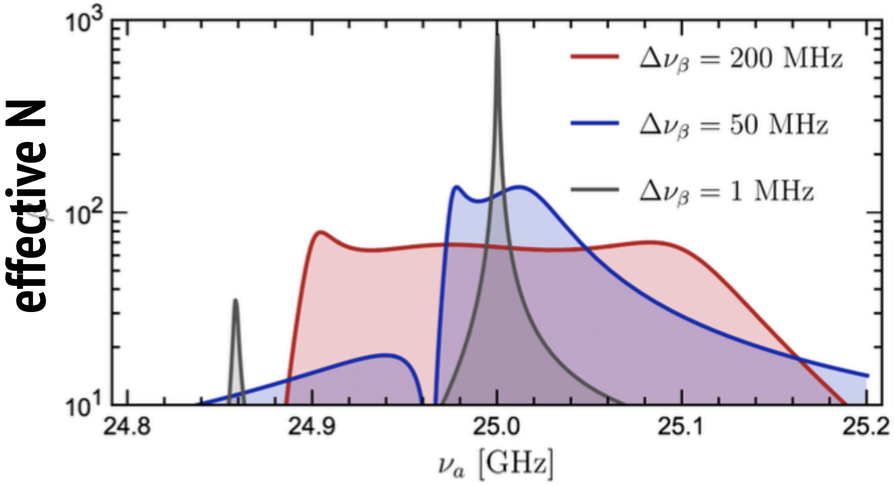
MADMAX: MAgnetised Disk and Mirror Axion eXperiment



Emitted EM-waves from each interface + internal reflections ...

$$P \sim |\mathbf{E}_a|^2 \mathrm{Area} \times \mathcal{O}(N^2)$$

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



Caldwell 2017

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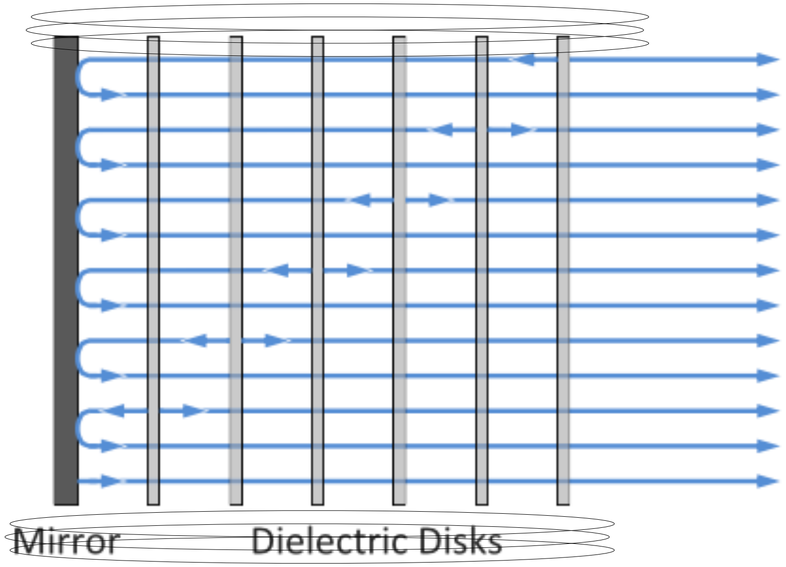

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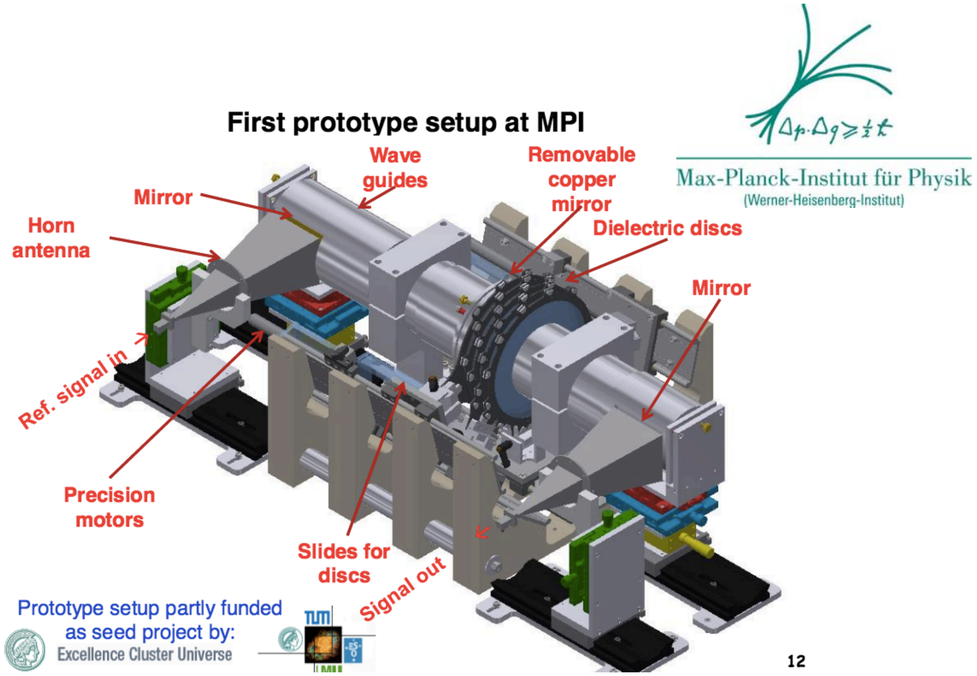
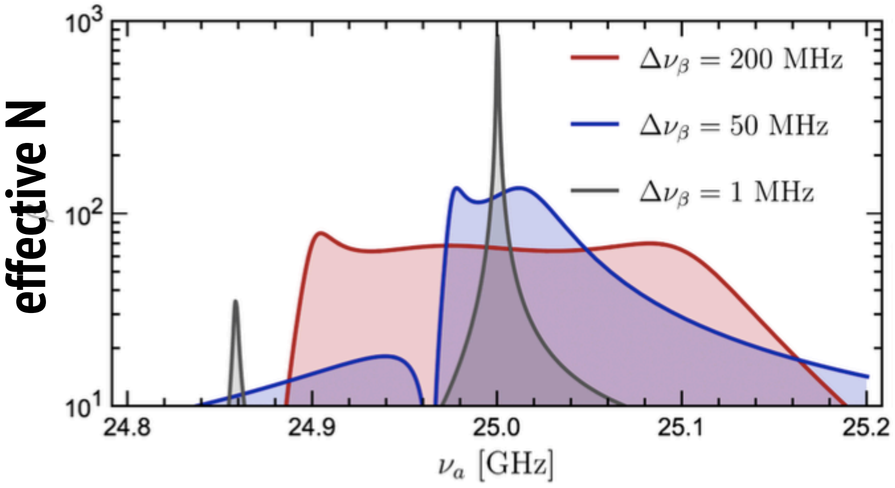
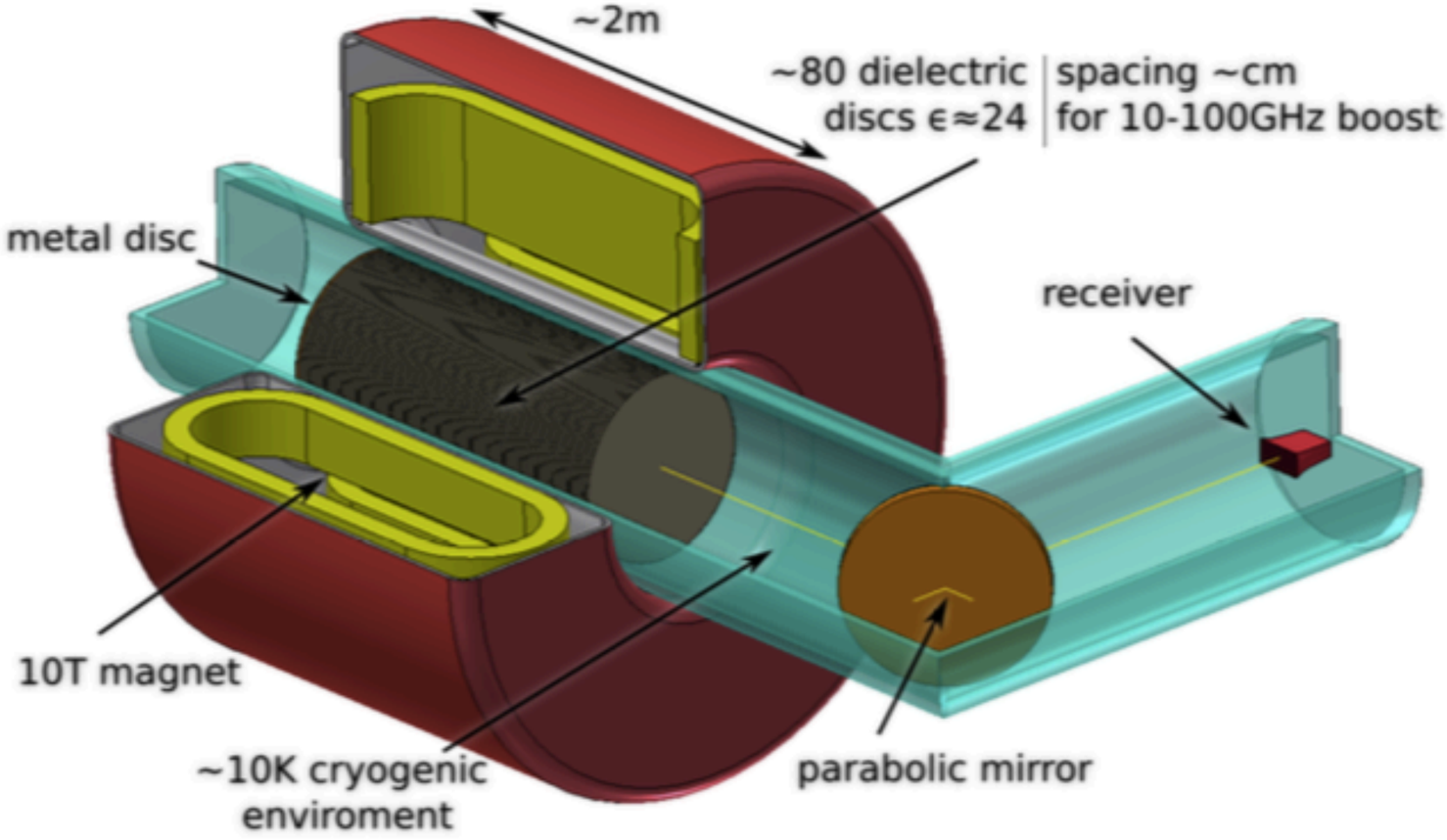
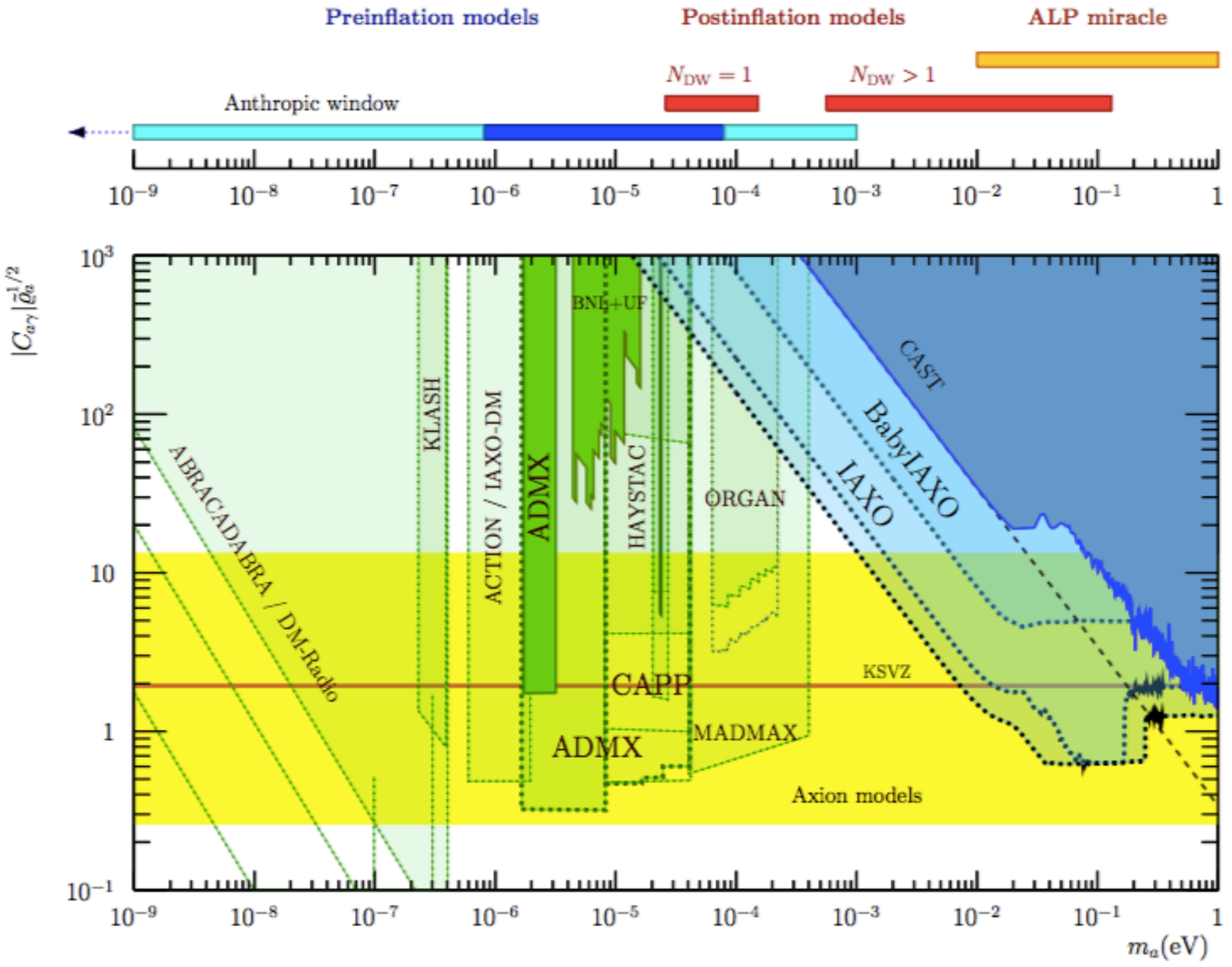




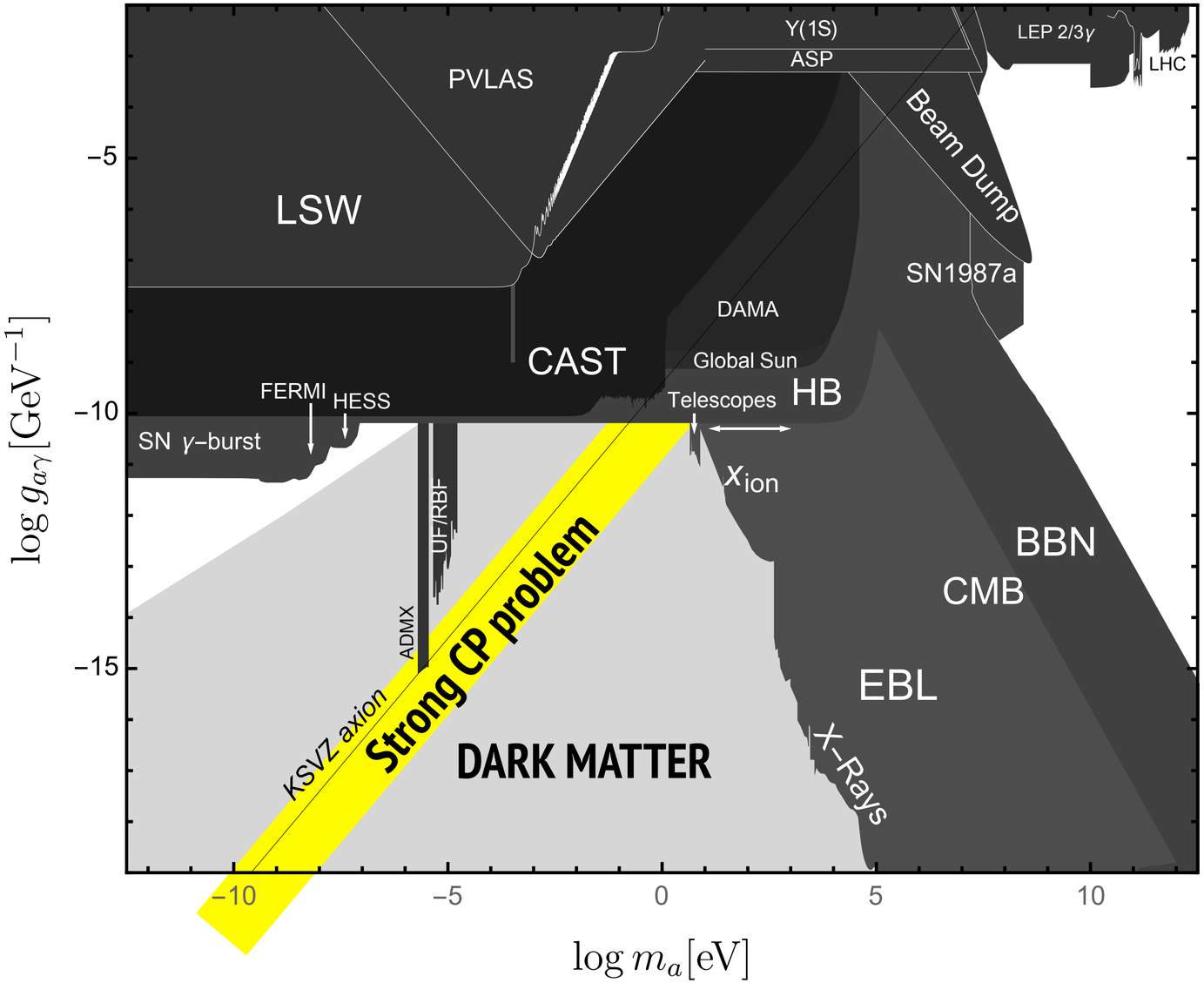
Caldwell 2017

MADMAX concept




Preinflation models
Postinflation models
ALP miracle
$N_{\rm DW}=1$
$N_{\rm DW}>1$
Anthropic window
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1
$|C_{a\gamma}|\tilde{g}_a^{1/2}$
10^3
10^2
10
1
10^{-1}
BNL+UF
CAST
BabyIAXO
IAXO
KLASH
ACTION / IAXO-DM
ADMX
HAYSTAC
ORGAN
ABRACADABRA / DM-Radio
KSVZ
CAPP
ADMX
MADMAX
Axion models
m_a(eV)

Summary plot



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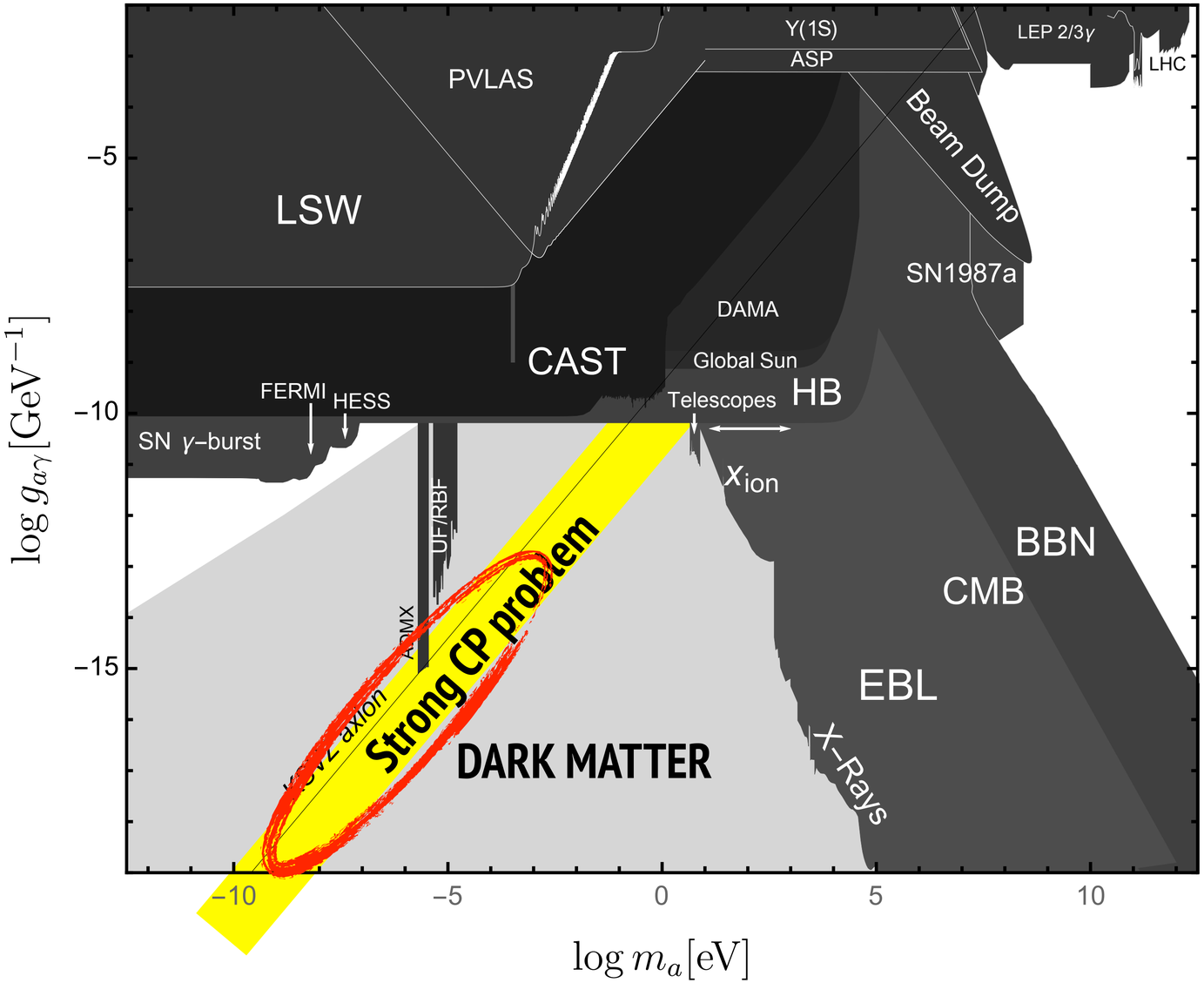

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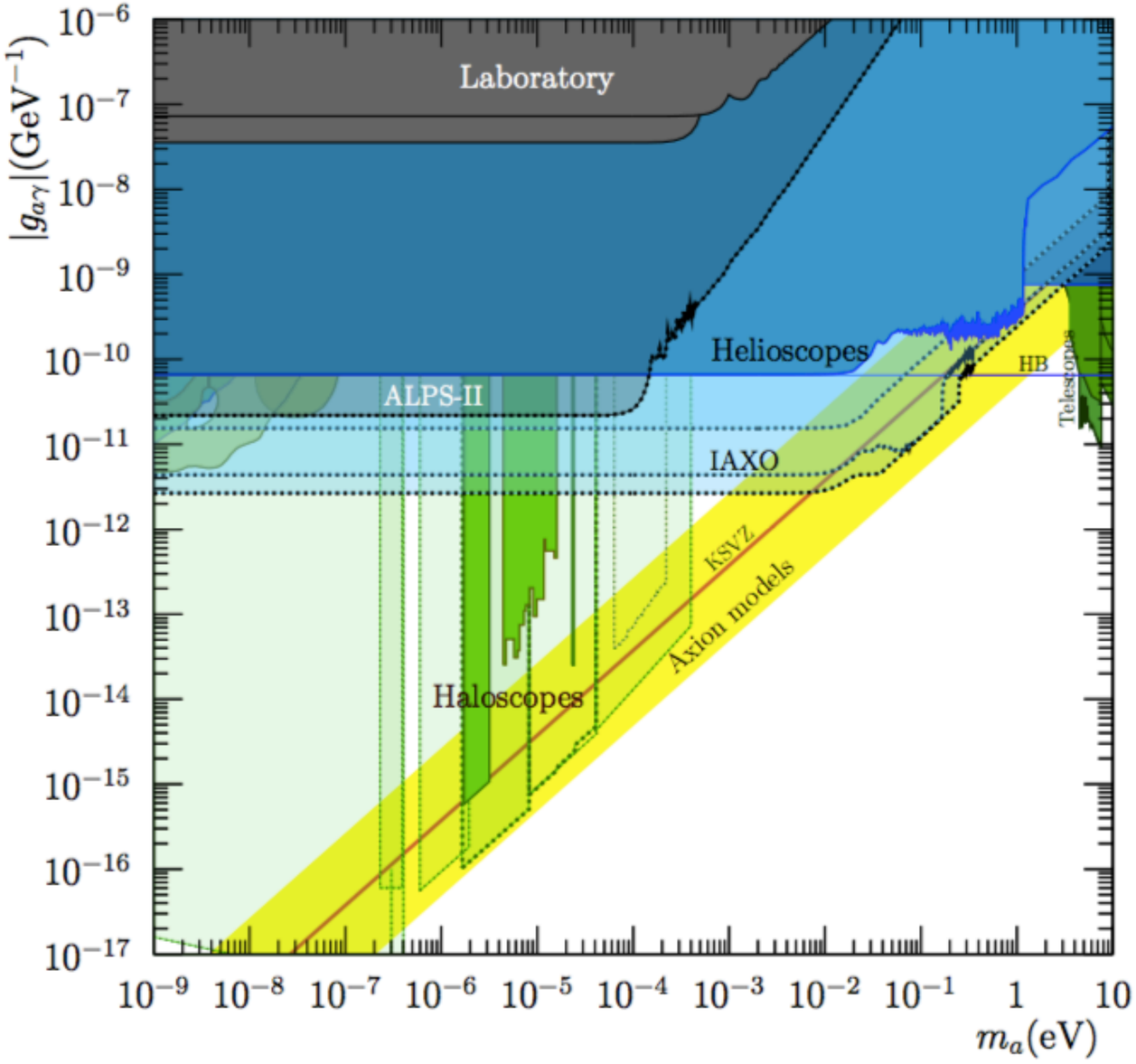
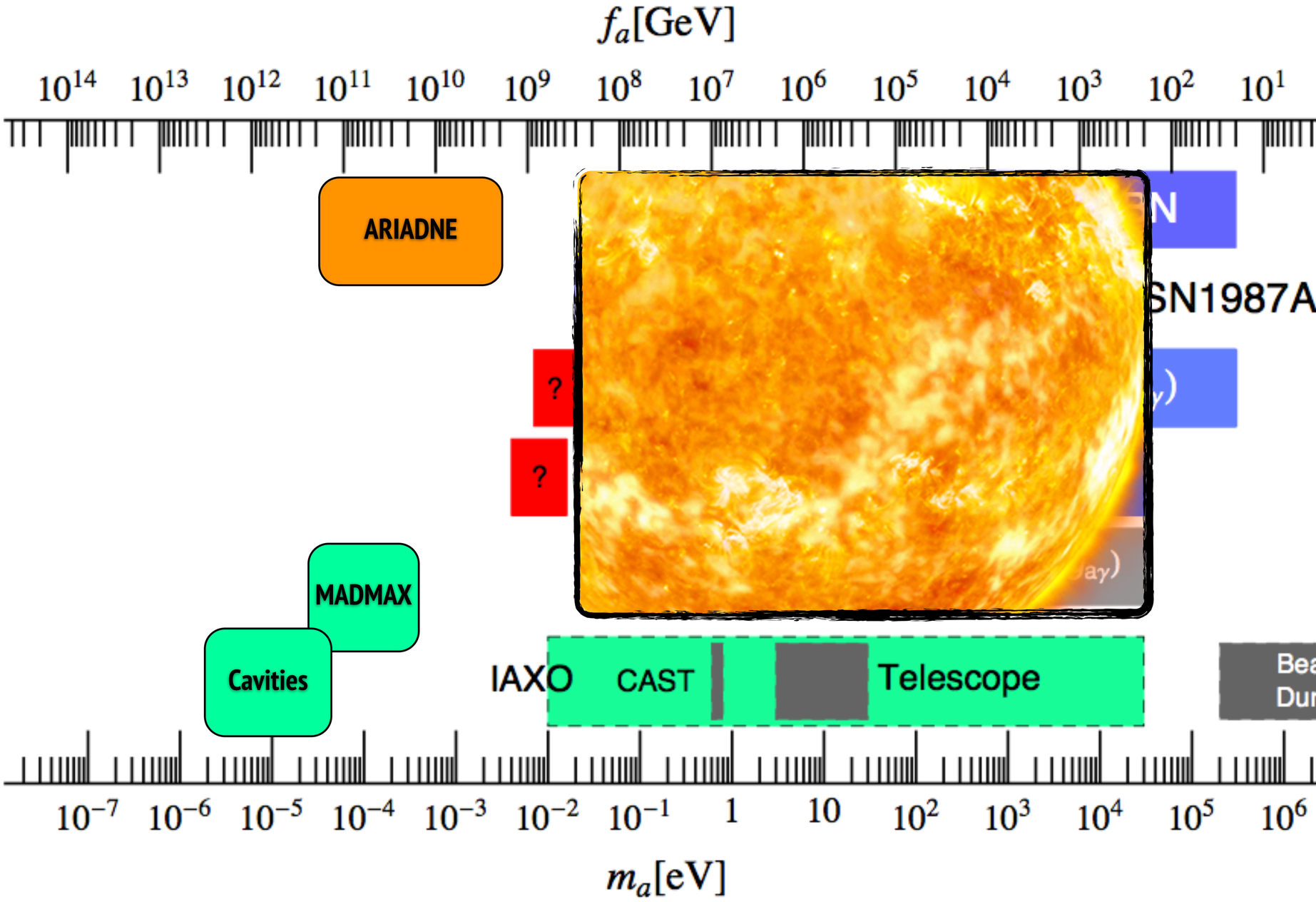
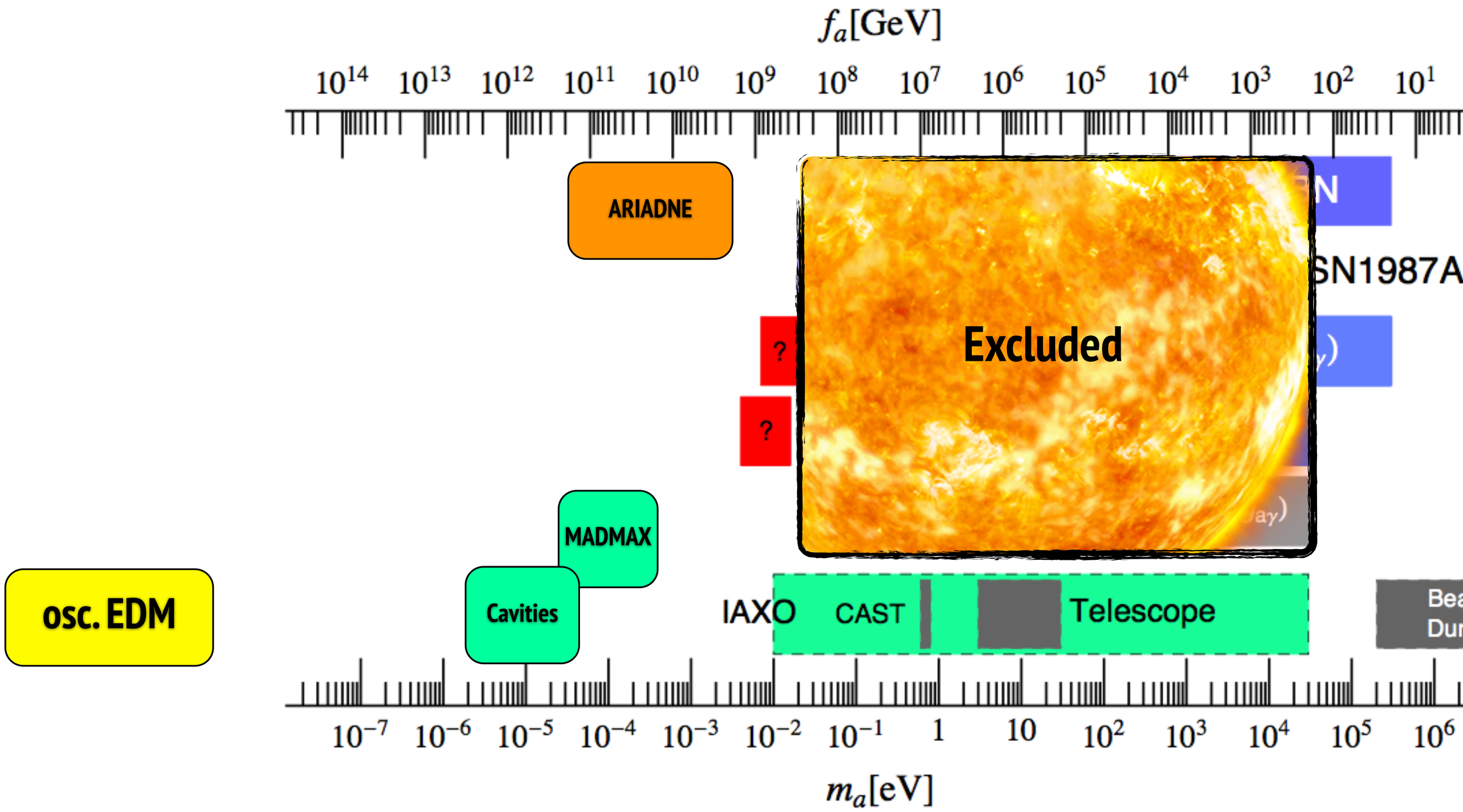


Summary plot



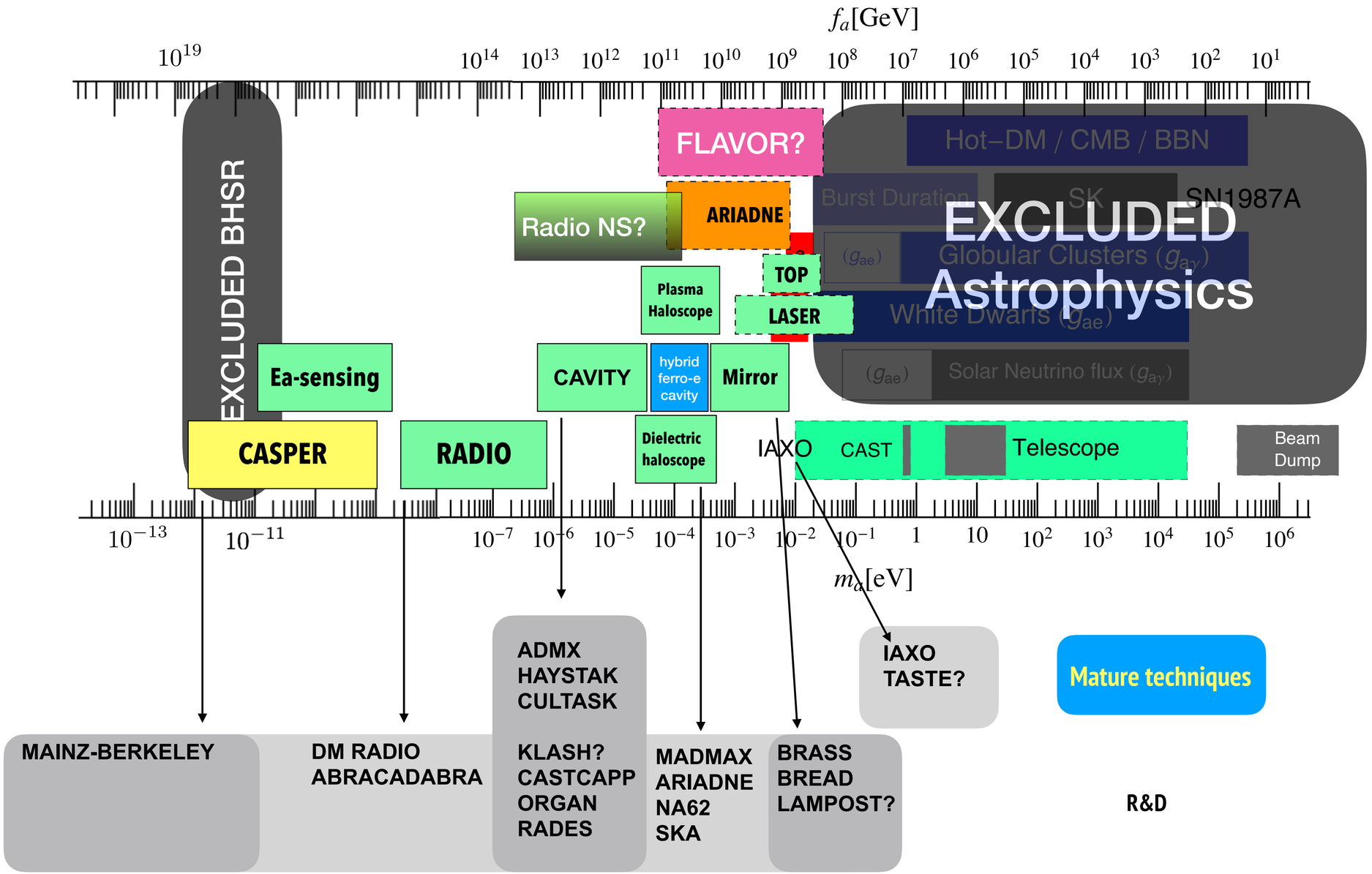
osc. EDM

Summary plot



More complete experimental Landscape

DM nonDM



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!