Axions and ALP motivation, hints and searches

Dark side of the Universe, Annecy 26/06/2018

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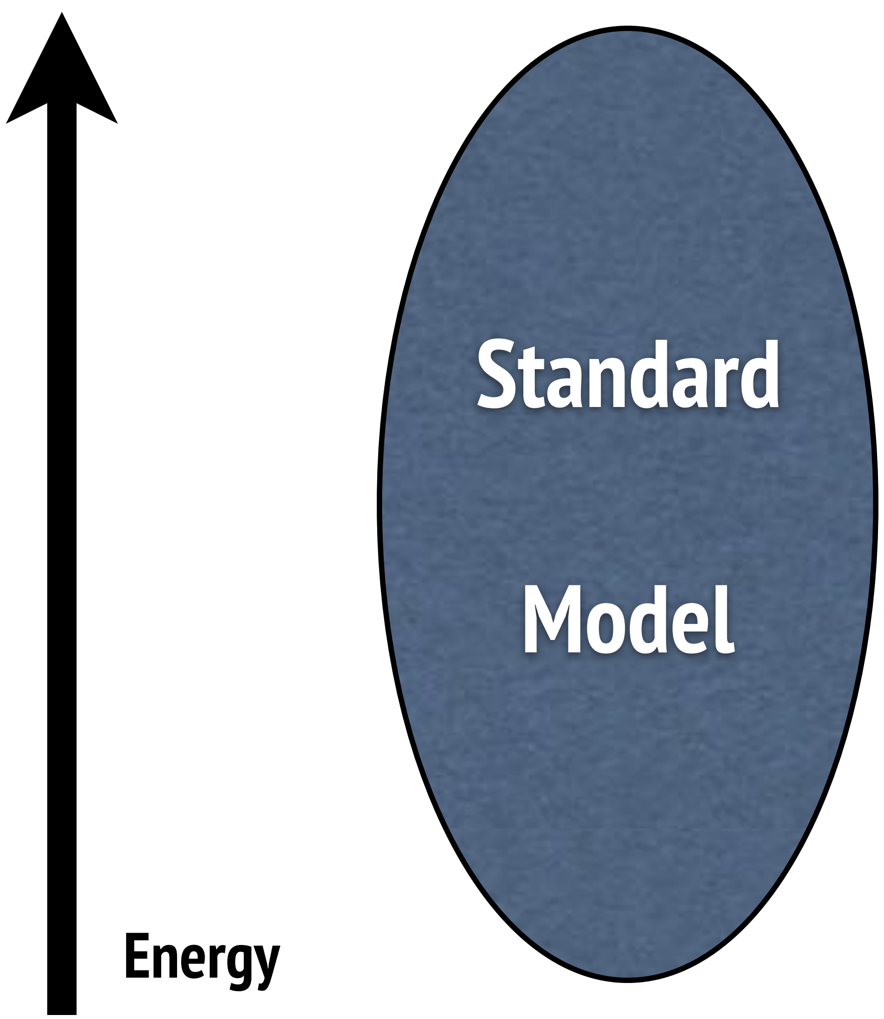
Outline

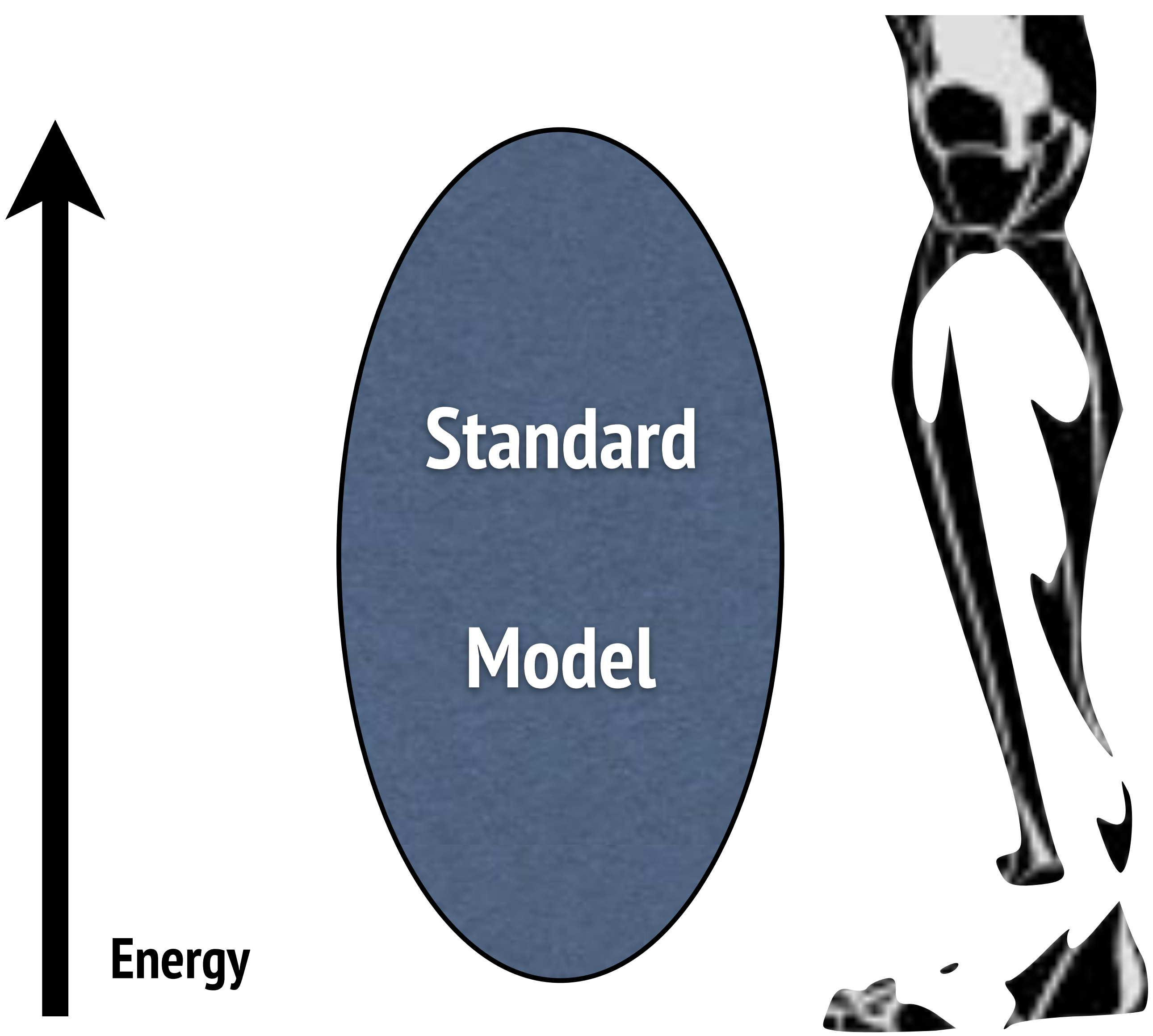
- 1 big picture
- 2 types of ALPs
- 3 types of interactions
- 4 ~ hints of existence
- 5 ... Experiments to find them
- 6 Conclusions

Based on ...

2. **New experimental approaches in the search for axion-like particles**
Igor G. Irastorza (Zaragoza U.), Javier Redondo (Zaragoza U. & Munich, Max Planck Inst.). Jan 24, 2018. 111 pp.
e-Print: arXiv:1801.08127 **[hep-ph]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 19 records



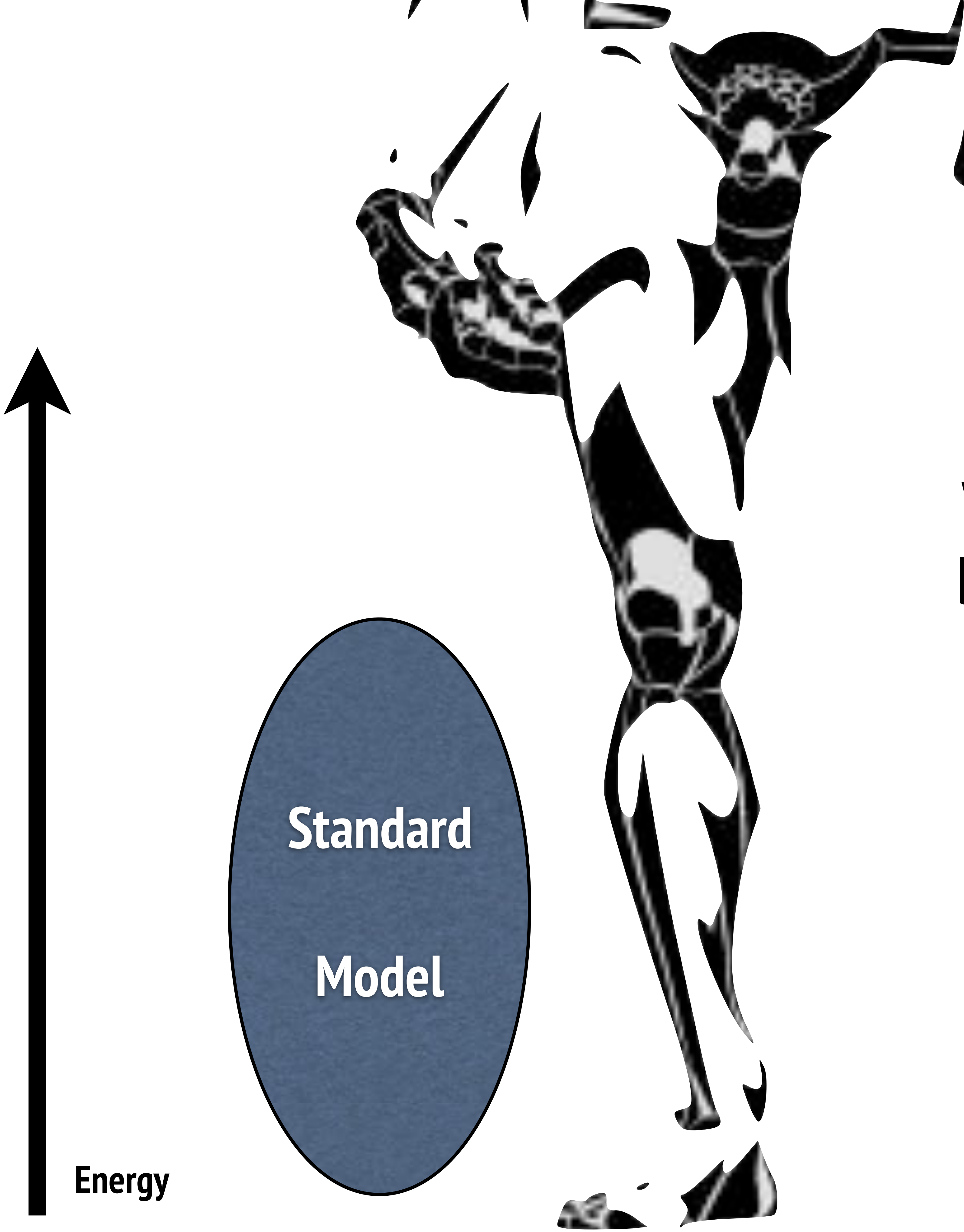
Describes extremely well particle physics (at low energies)



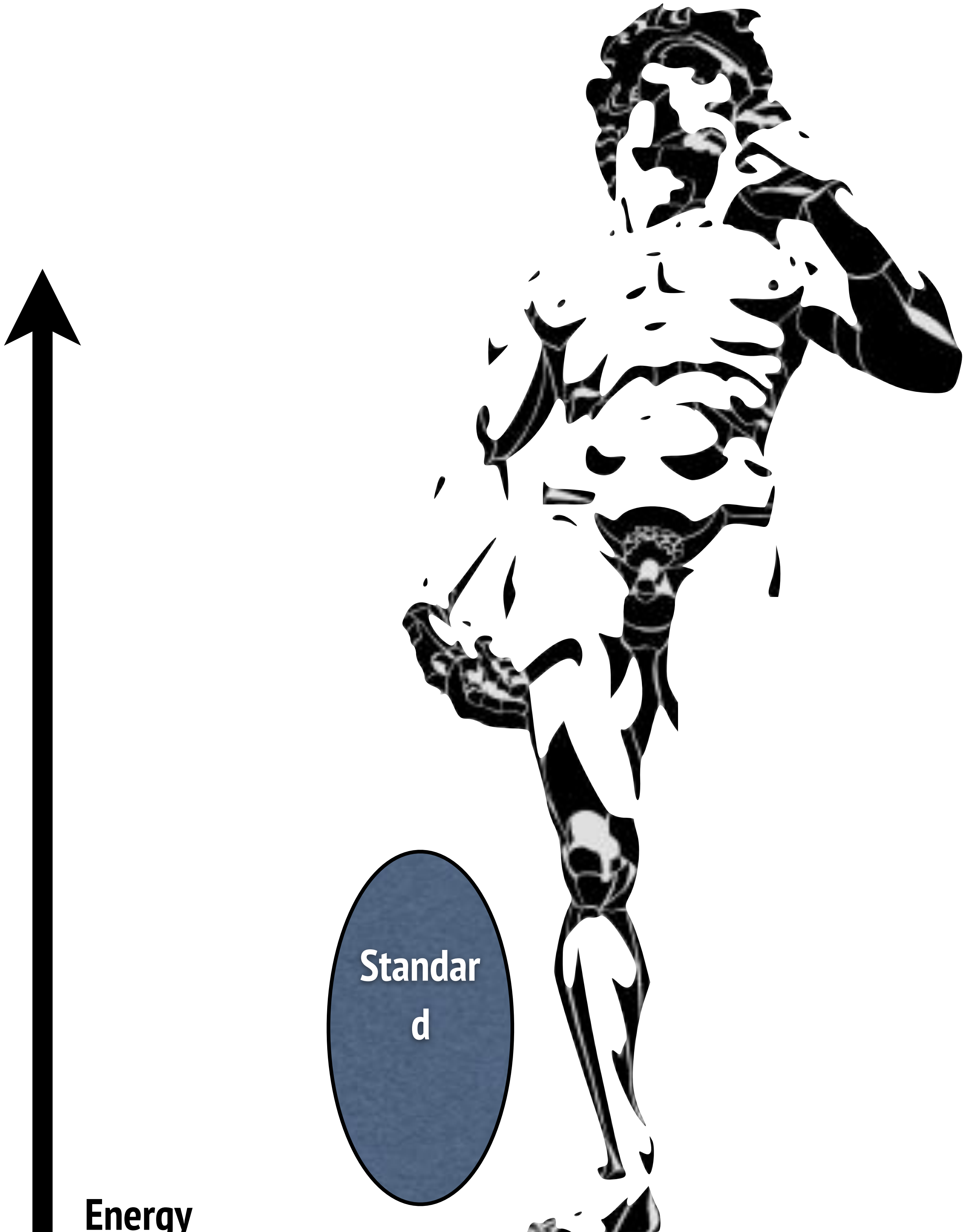
Describes extremely well particle physics (at low energies)

but it is certainly…

INCOMPLETE



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

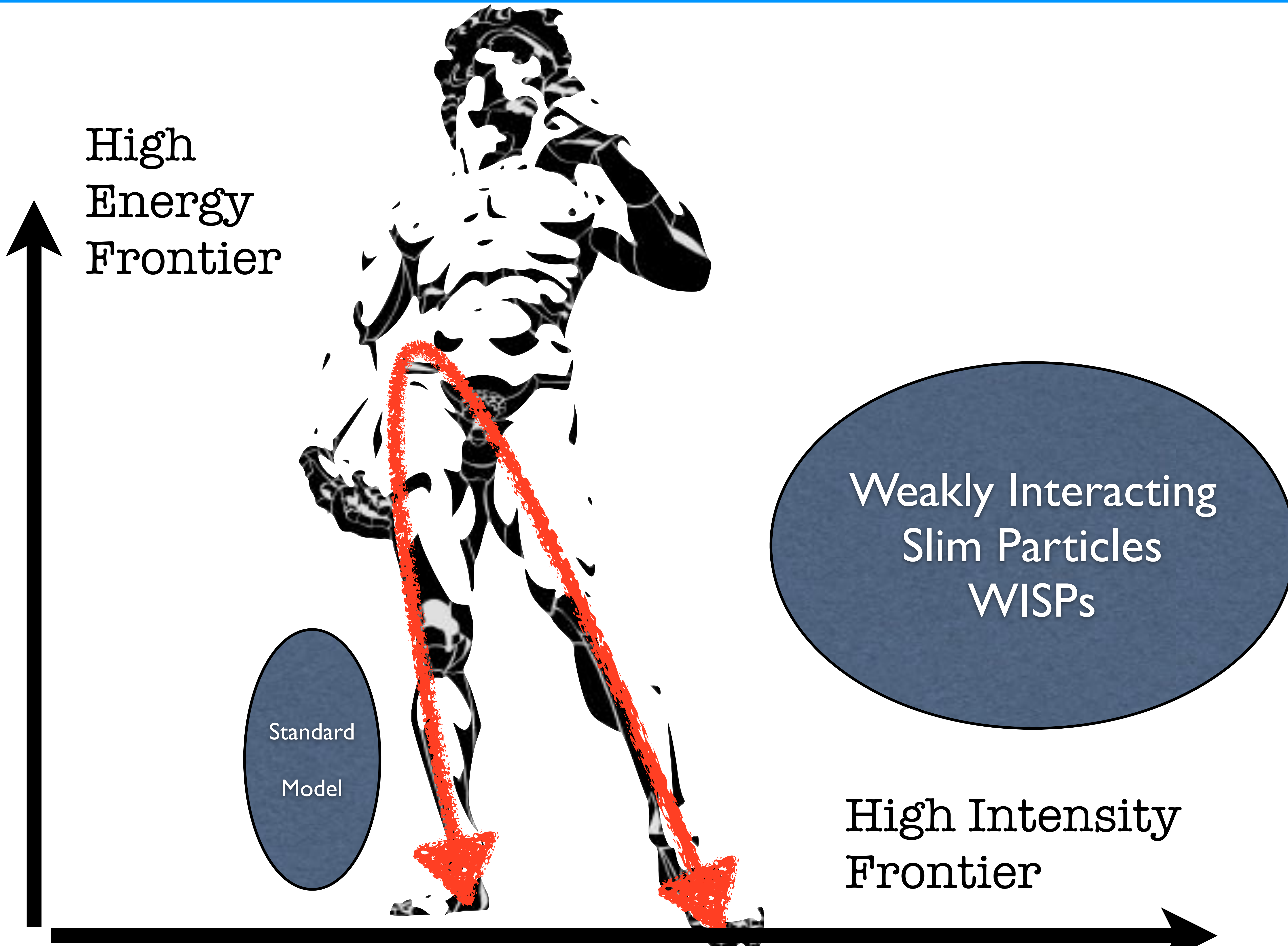


Answers wait in the high energy frontier where more symmetric beautiful theories arise

… often implying

new low energy physics!

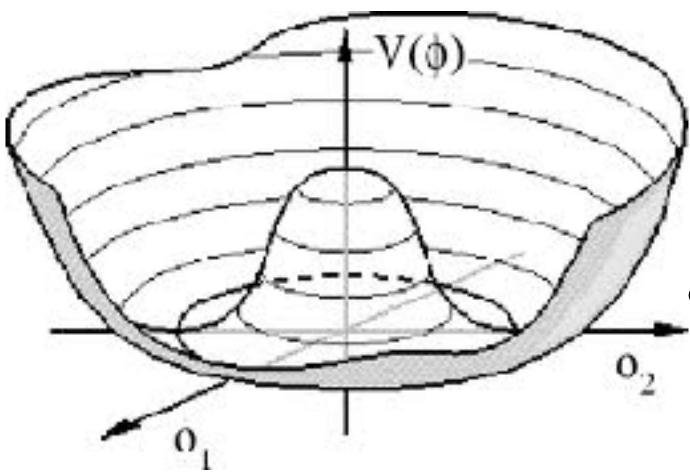
aaaaa


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

Axion-like particles (ALPs)

pseudo Goldstone Bosons

- Global symmetry spontaneously broken



- massless Goldstone Boson @ Low Energy

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

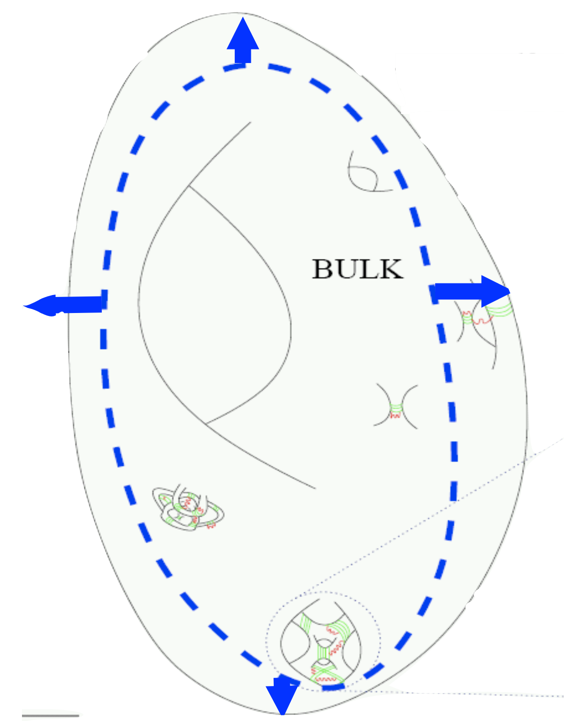
$$\mathcal{L}_{\rm kin} = \frac{1}{2}(\partial_\mu\theta)(\partial^\mu\theta)f^2$$

- 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

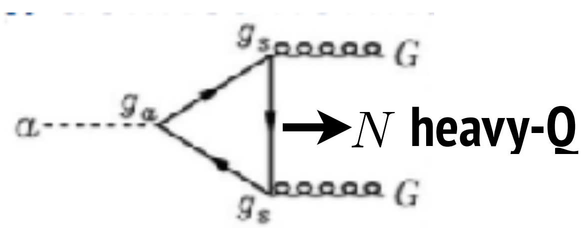
- Shift symmetry allows some generic types of interactions

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

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

(canonically normalised)

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

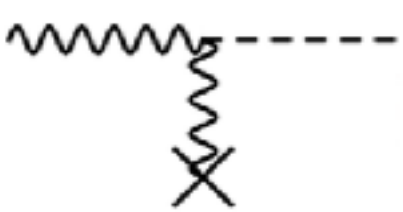


$$N\frac{\alpha}{8\pi}\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\theta \equiv \frac{\alpha_s}{8\pi}\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\frac{A}{f_A}$$

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

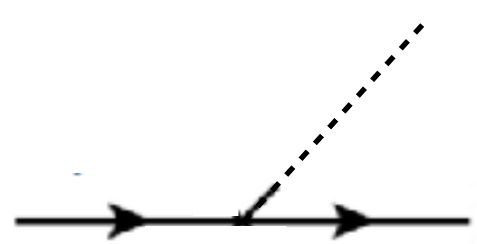
photon coupling

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



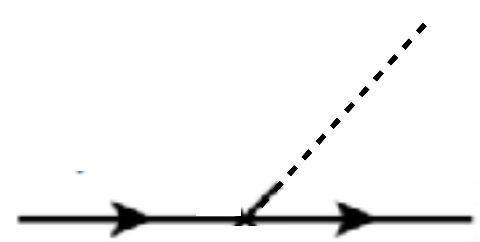
electron coupling

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



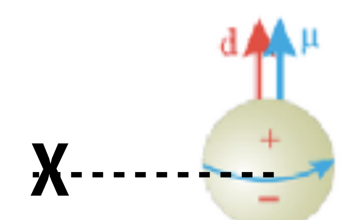
nucleon coupling

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



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

4 hints

Strong CP problem / PQ solution

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

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

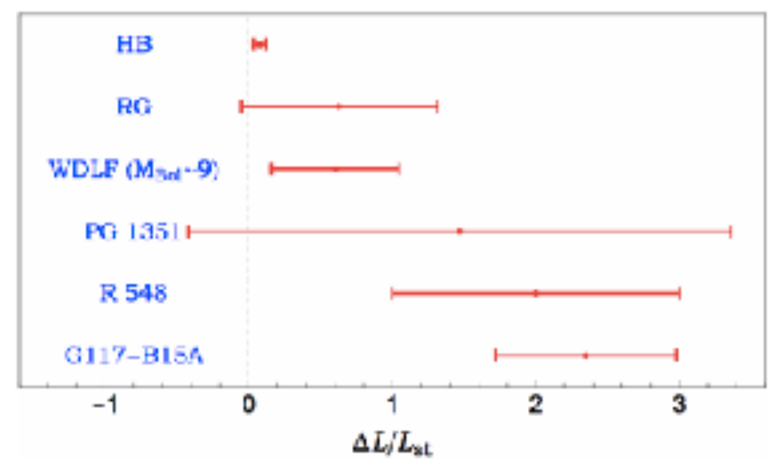
potential min.

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

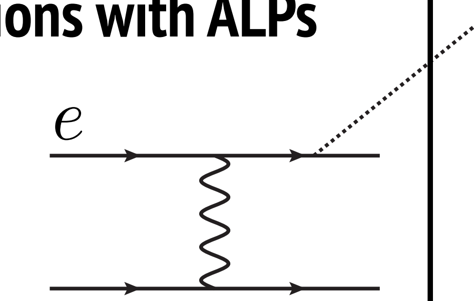
The QCD Axion cancels the effect of any constant $\theta_{\rm SM}$

Anomalous Star cooling / ALP emission

Theory fits better some observations with ALPs

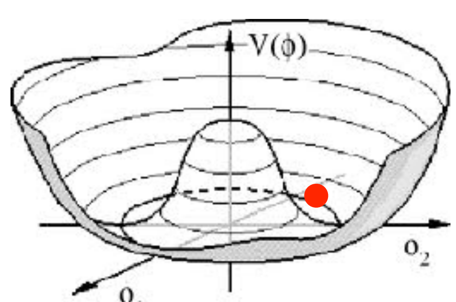


Giannotti 2016

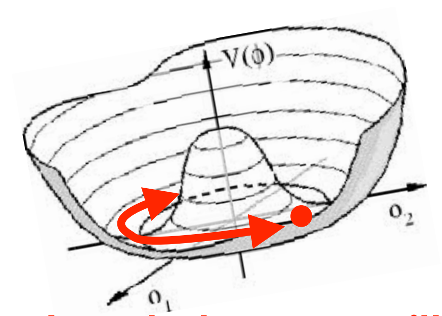


ALP bremstrahlung

Dark matter / vacuum realignment



pick up a vacuum when quasi-degenerate



ups! not the lowest ... oscillate!

cold DM in oscillations [cosmology dependent]

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

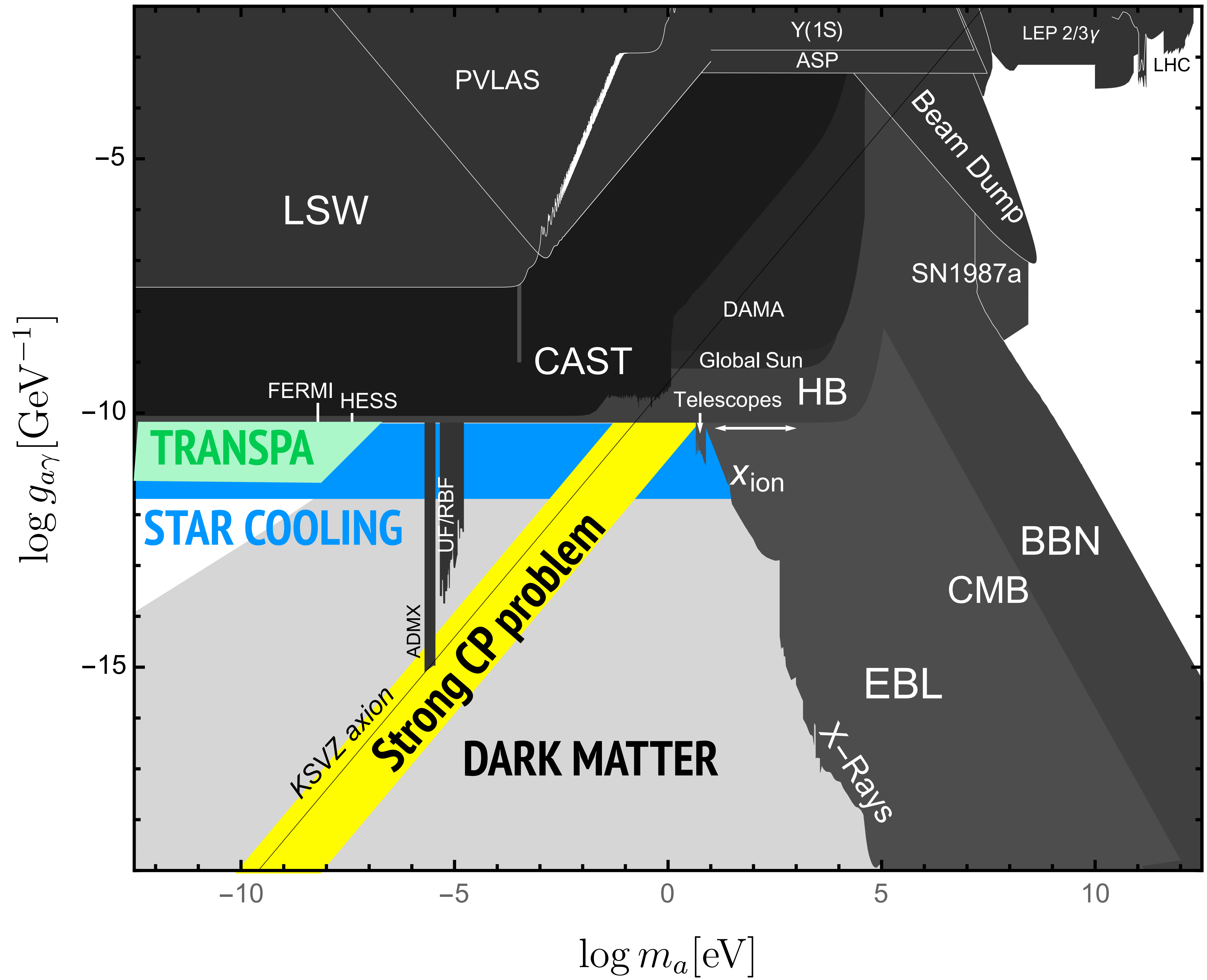
γ-ray transparency / photon regeneration

Too many gamma-rays from far away sources?

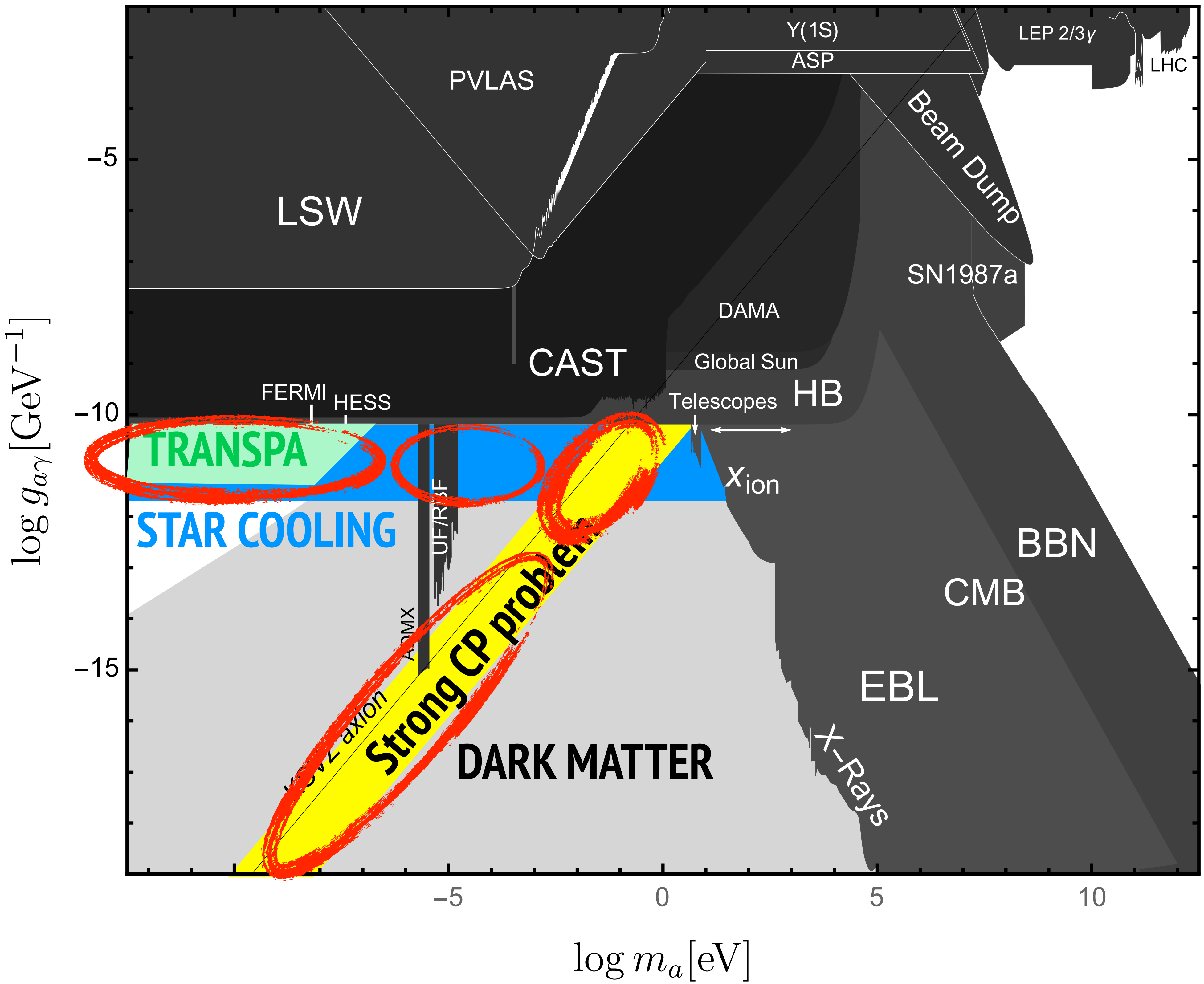
low estimate of opacity vs ALP-mediated regeneration

Trostski 2017

Hints and constraints (example)

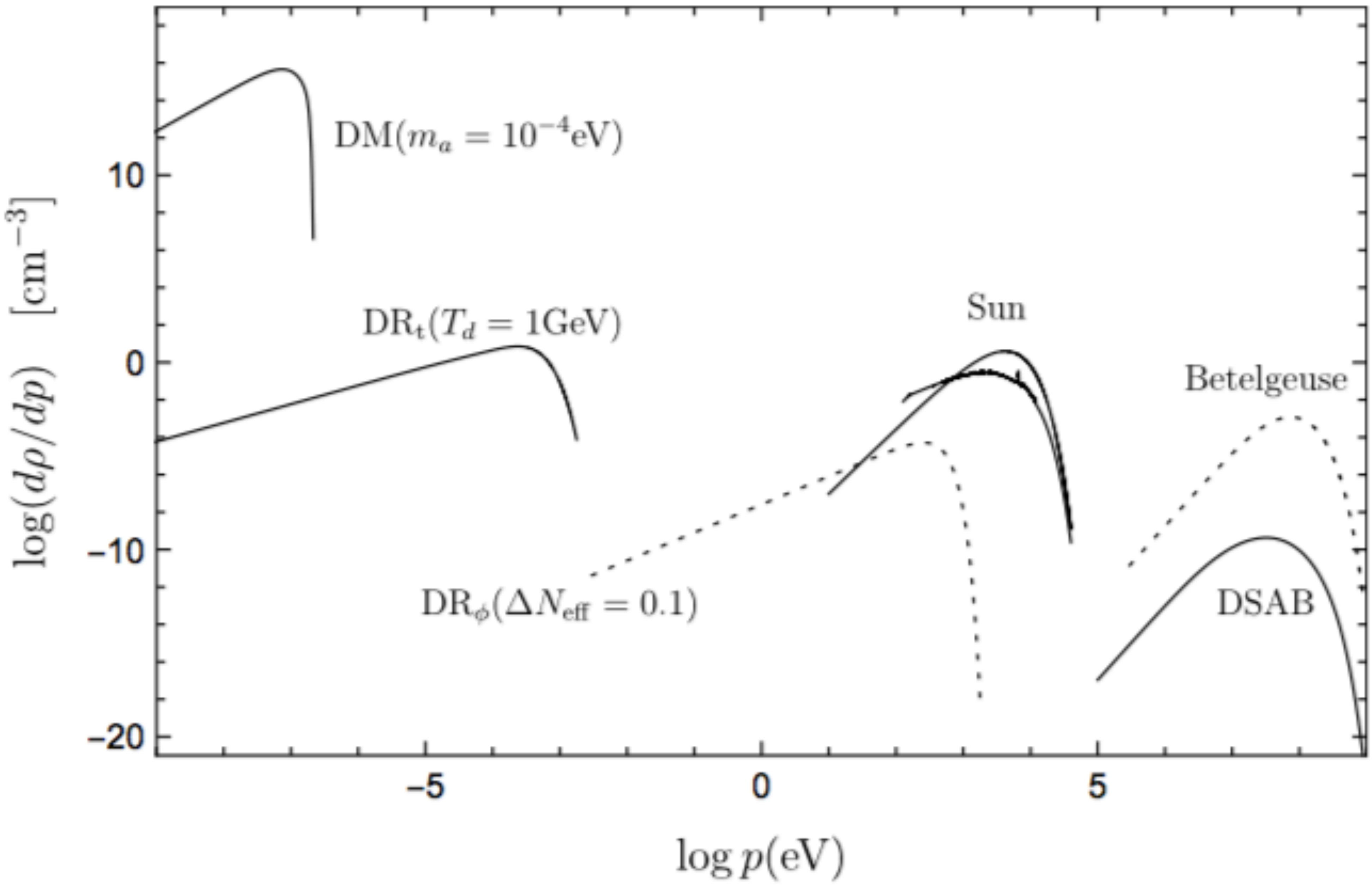


birds and stones ...



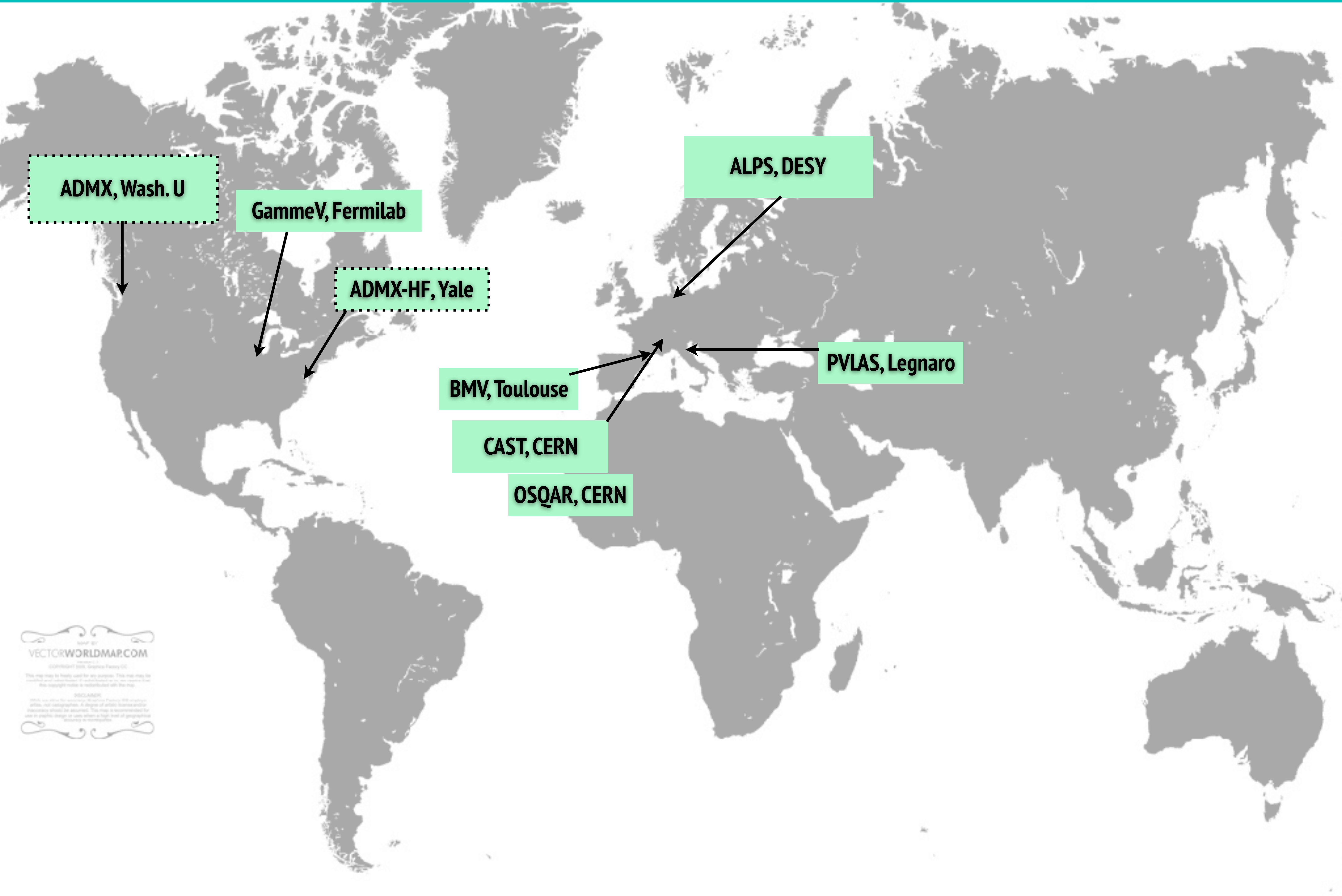
Direct Detection of ALPs

Natural sources

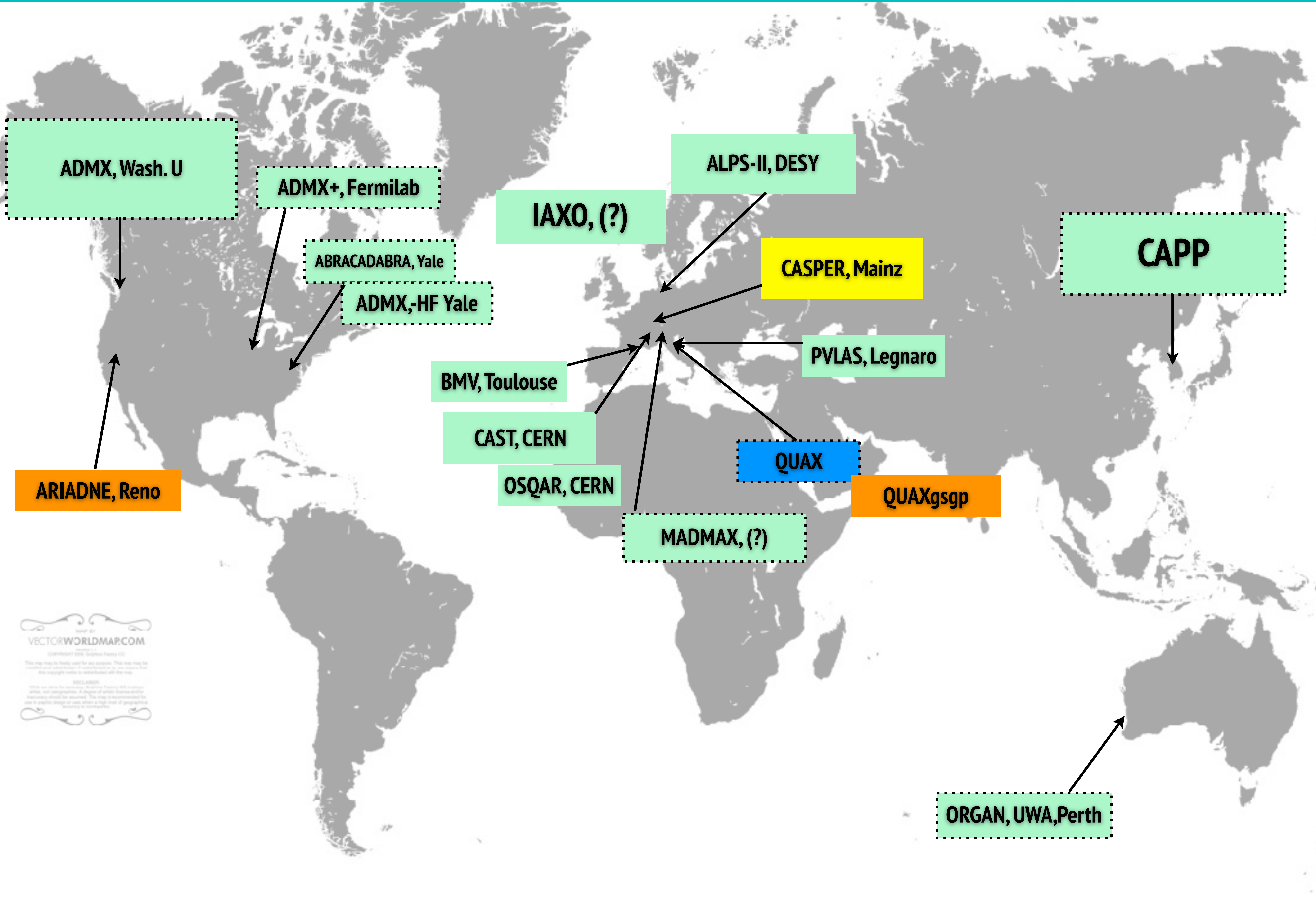


~ upper limits (predictions vary!)

Lab experiments 2011

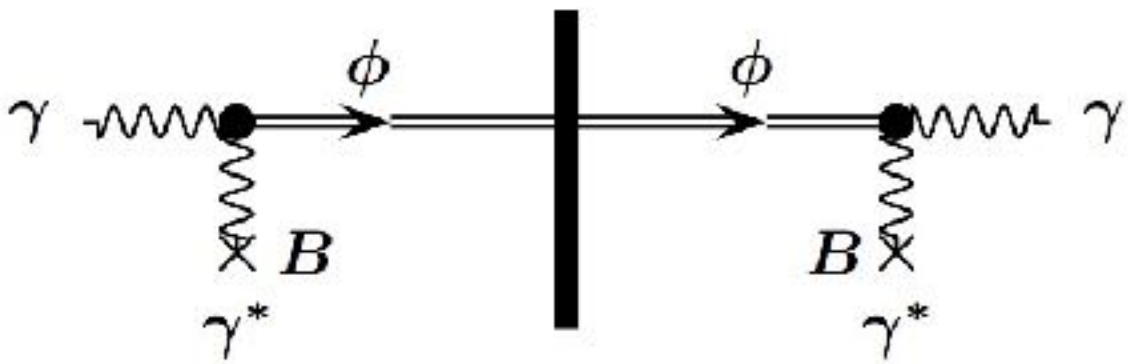


Lab experiments 2017

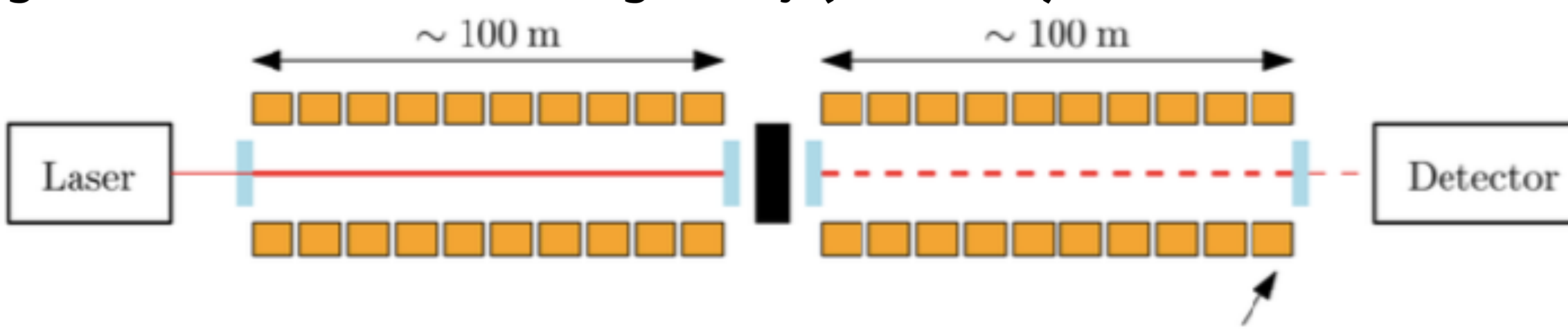


the ANY-Light-Particle-Search

Light shining through walls



Resonant regeneration in the receiving cavity (see later)

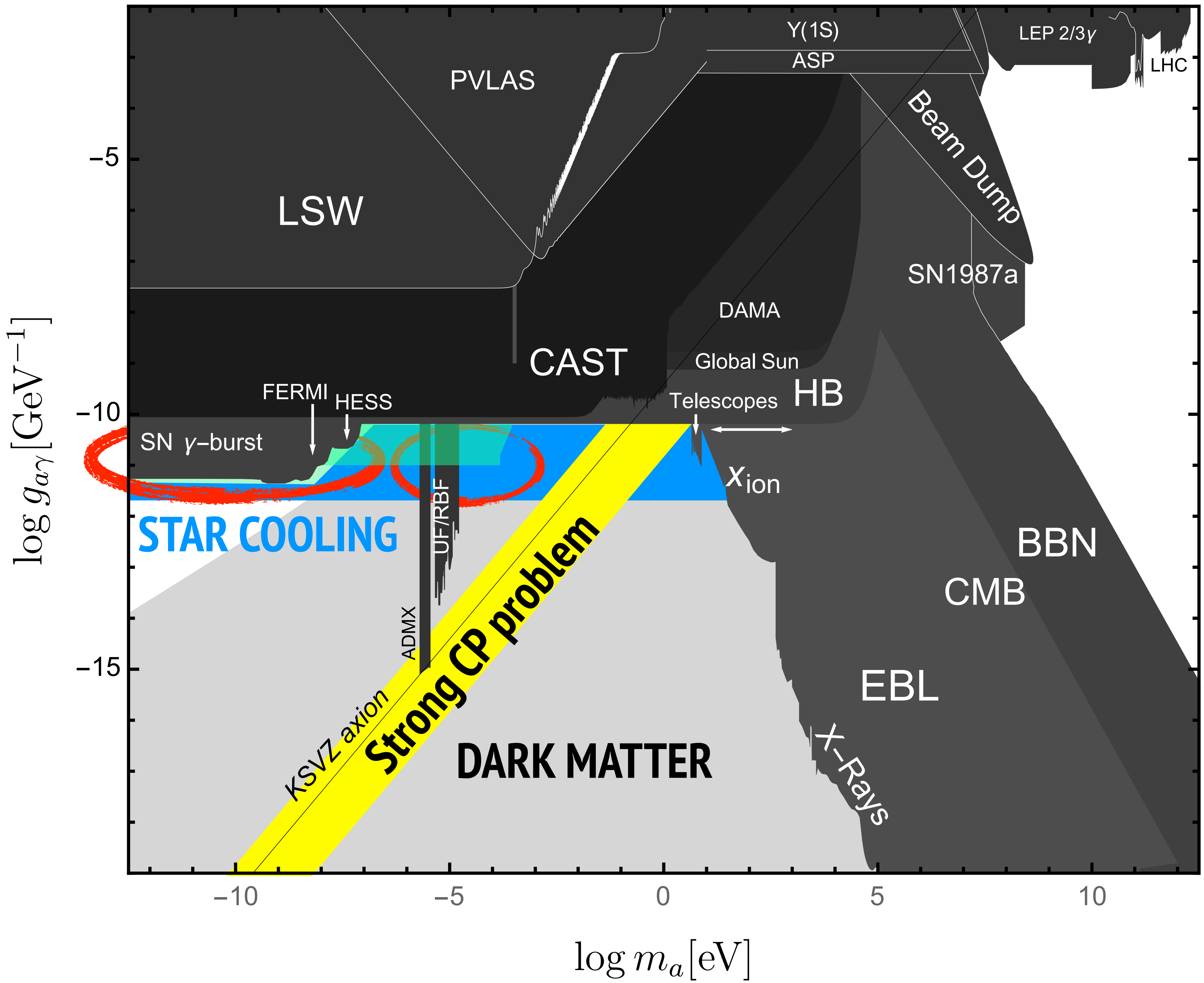


(d) ALPS-IIc

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

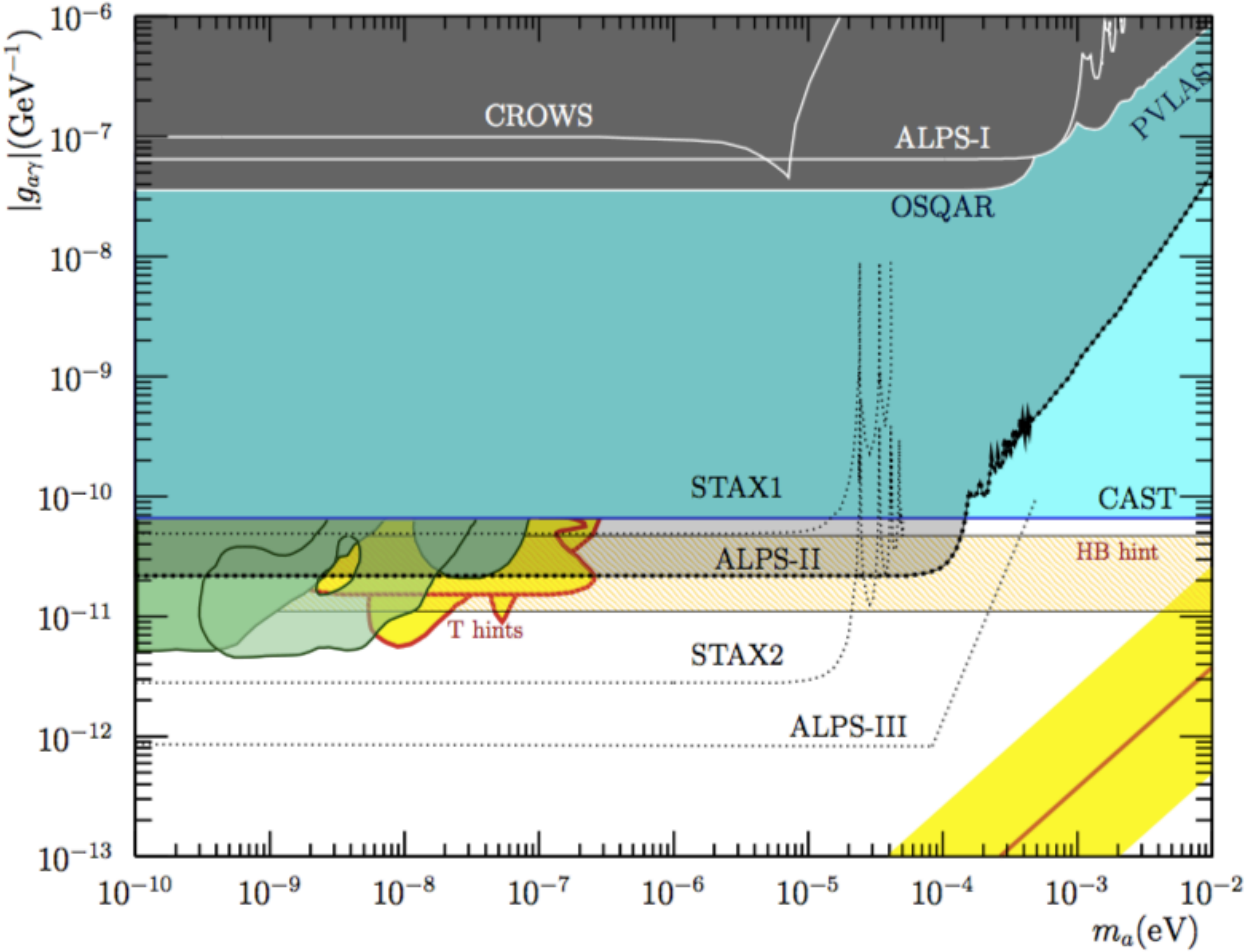
Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}$[GeV^{-1}]
ALPS-I [427]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [429]	completed	3	0.15	50	10^4	10^4	9.9×10^{-8}(*)
OSQAR [428]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [430]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [431]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

STAX, ALPS III and beyond

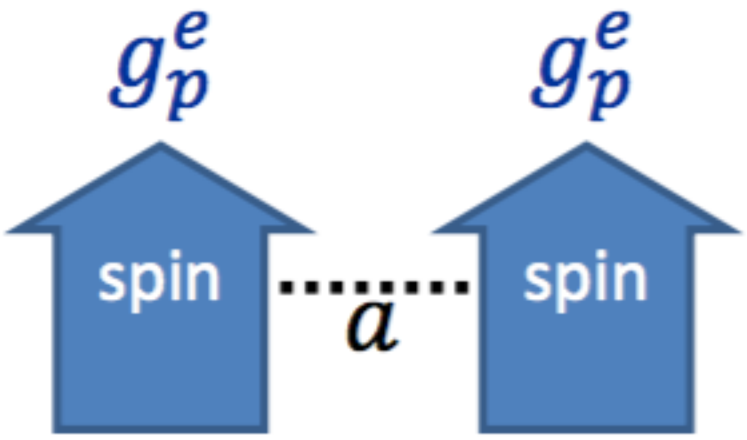


Long-range forces

Wilzcek '84, Geraci 14

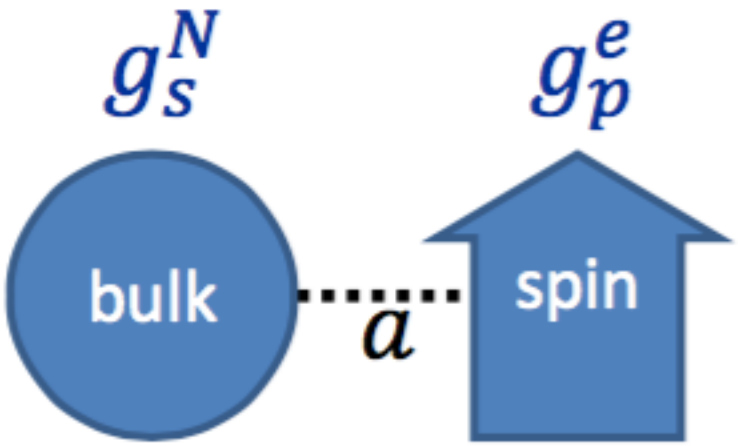
Long-range forces between macroscopic bodies

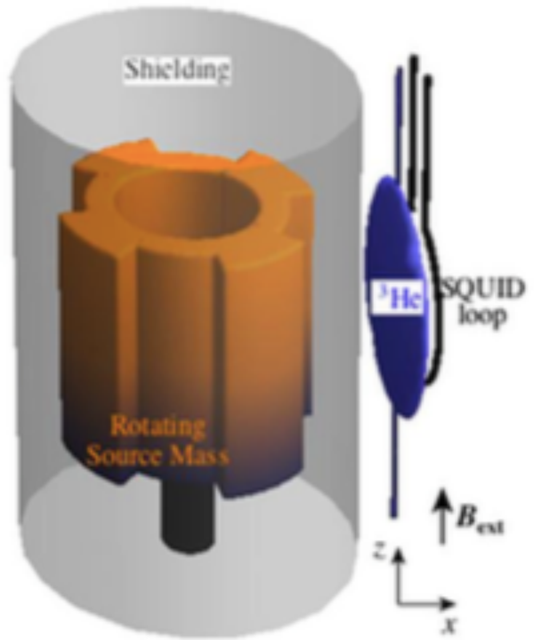
p-p forces are spin-spin ... very hard to measure!



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

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

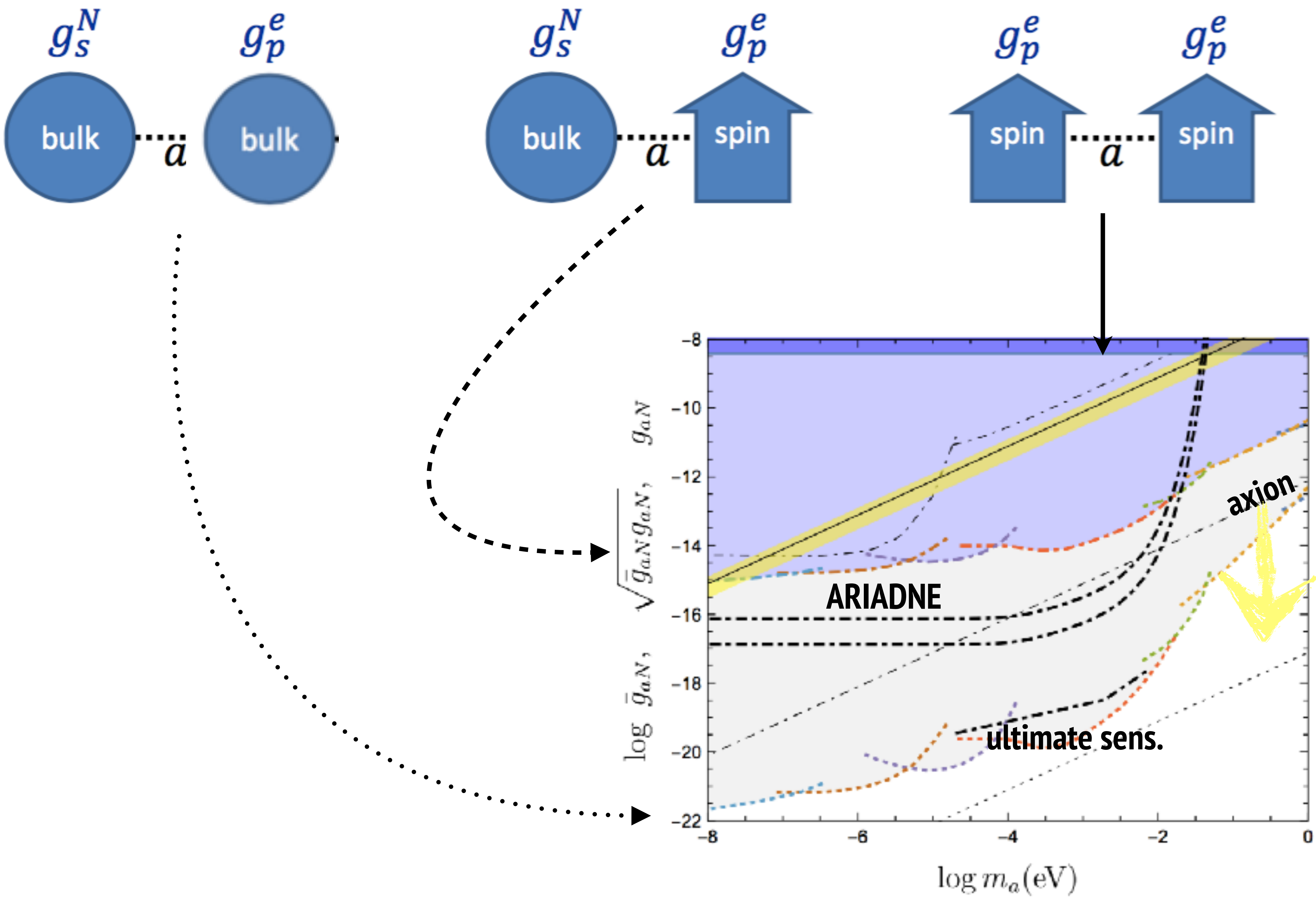




ARIADNE, University of Nevada in Reno

ARIADNE reach

Arvanitaki, Geraci 14

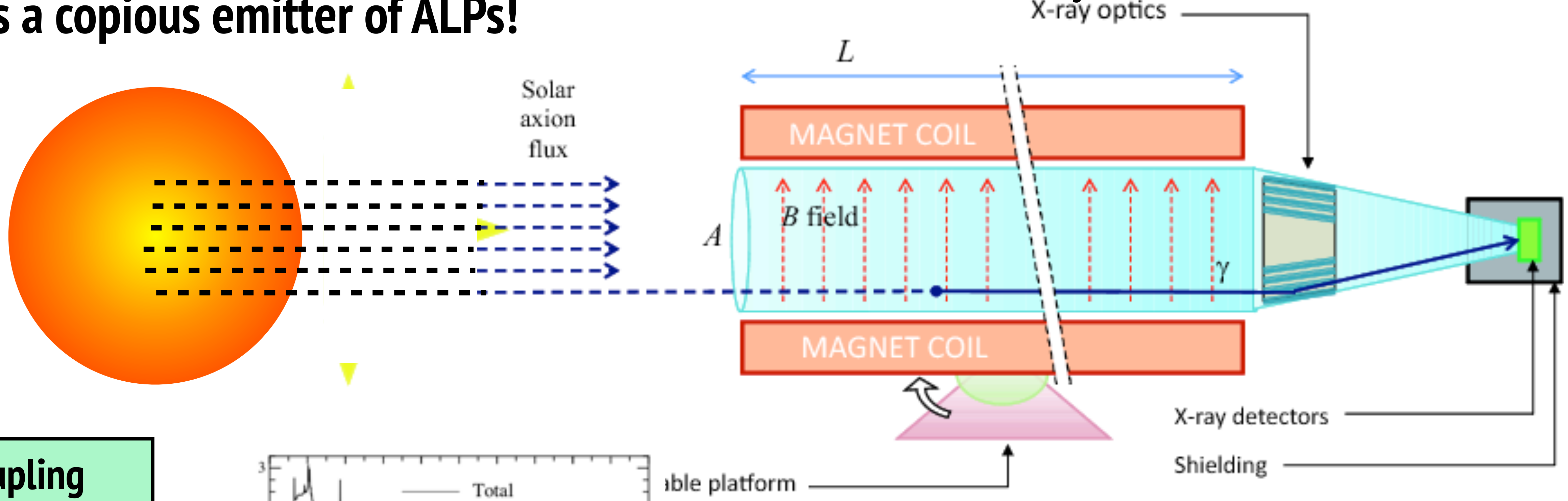


Helioscopes (search solar ALPs)

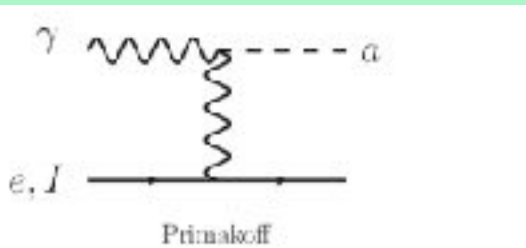
Sikivie PRL 1983

convert into X-rays   focus   detect

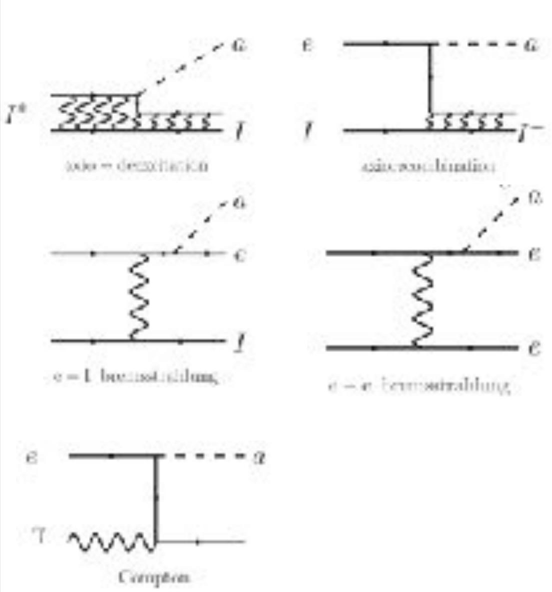
The Sun is a copious emitter of ALPs!

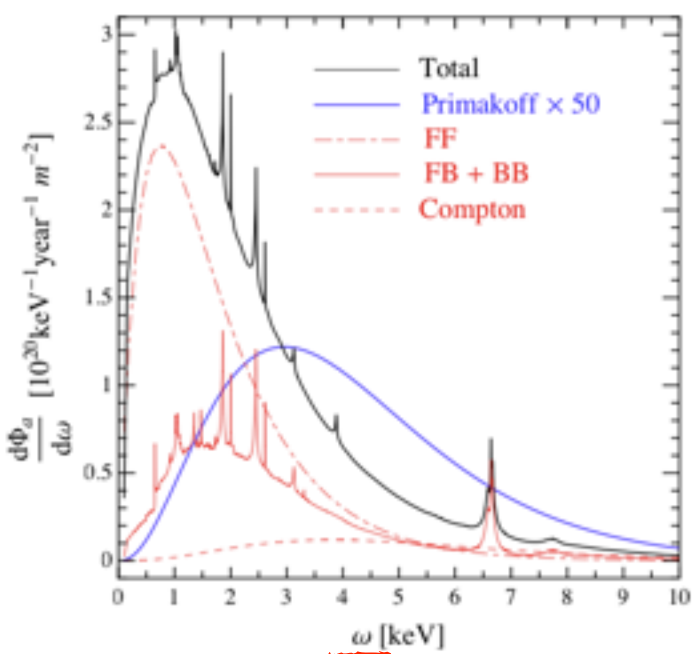


photon coupling



electron coupling



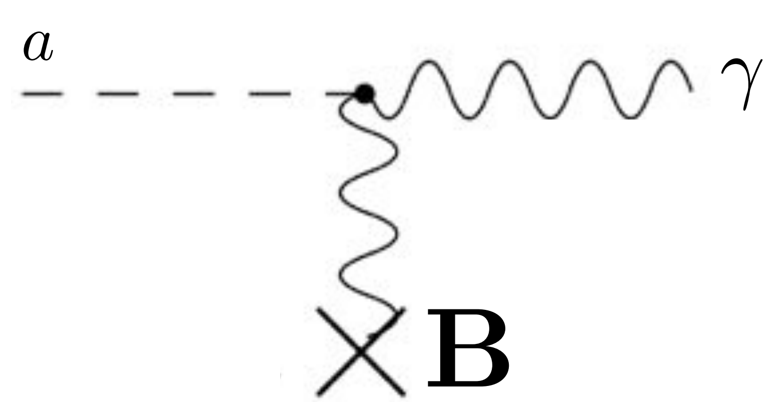


$$g_{ae} = 10^{-13}$$

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

Coherent Conversion along the B-field

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

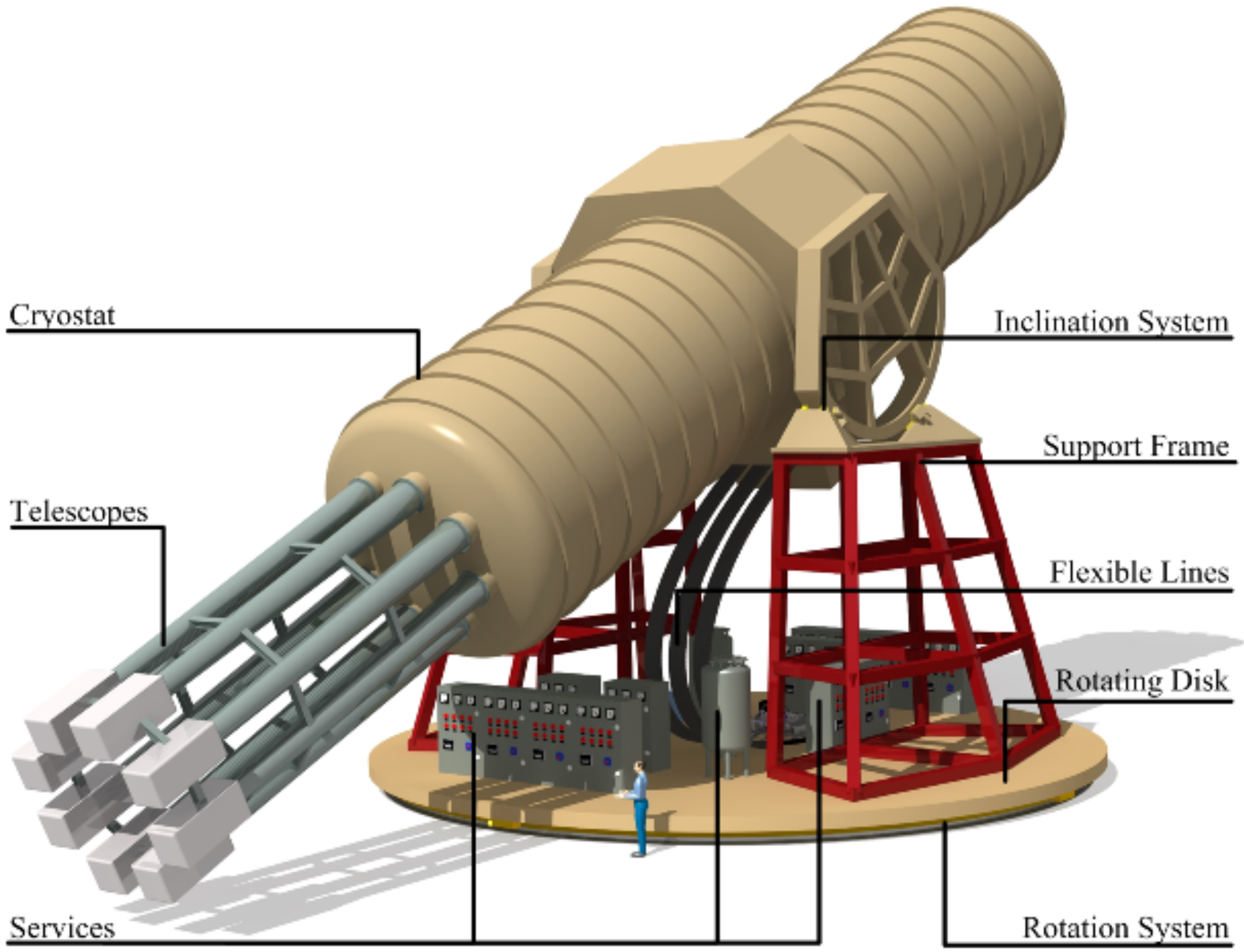


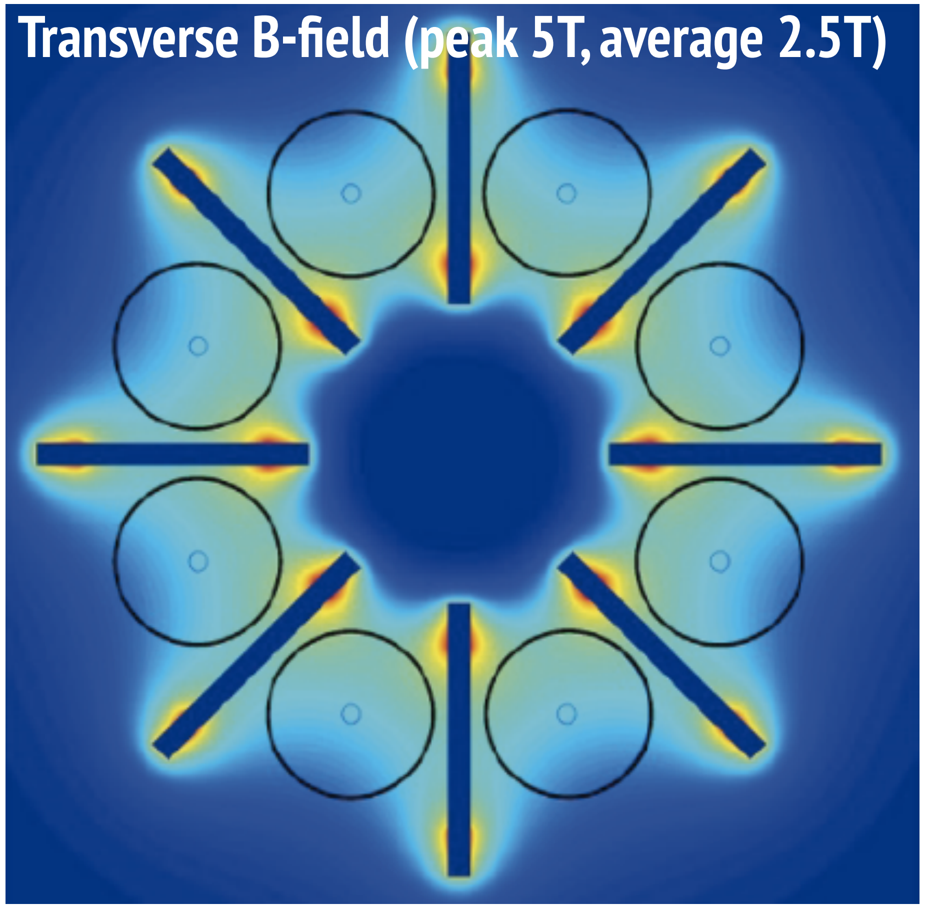
International AXion Observatory

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

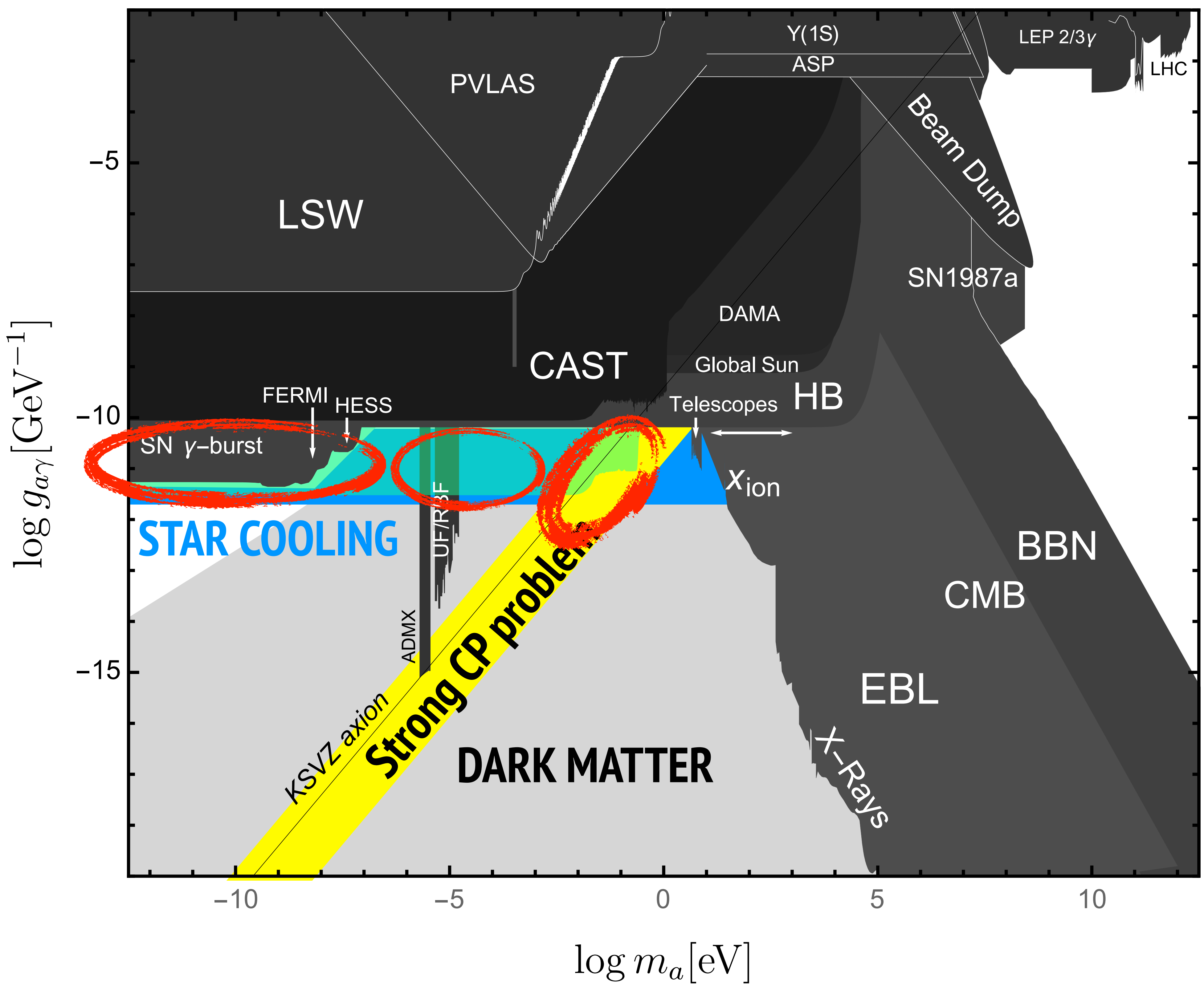
-NGAG paper JCAP 1106:013,2011
-Conceptual design report IAXO 2014 JINST 9 T05002
-LOI submitted to CERN, TDR in preparation

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



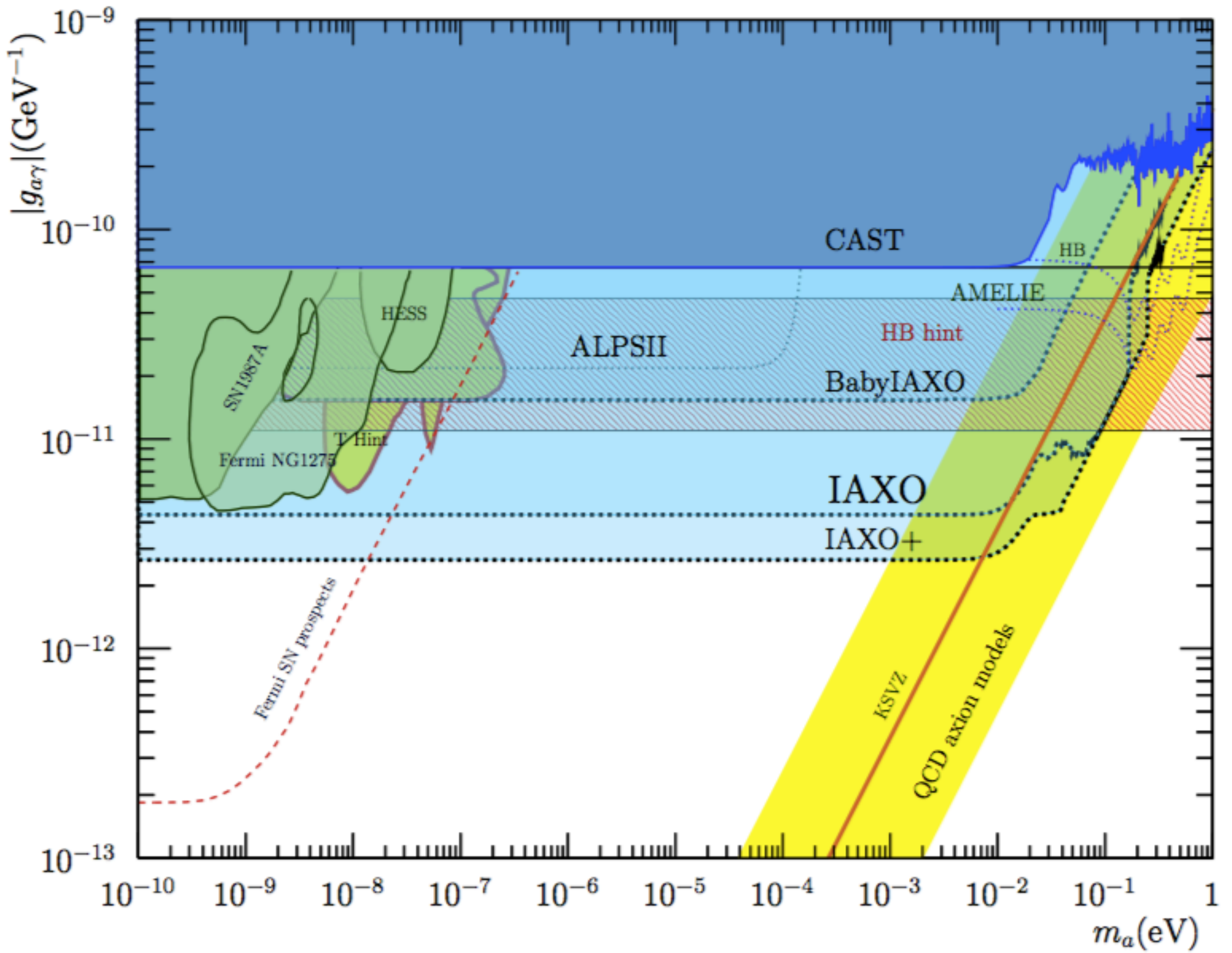


IAXO reach



PVLAS
Y(1S)
ASP
LEP 2/3γ
LHC
LSW
Beam Dump
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
$\log g_{a\gamma}[\mathrm{GeV}^{-1}]$
$\log m_a[\mathrm{eV}]$

In mode detail

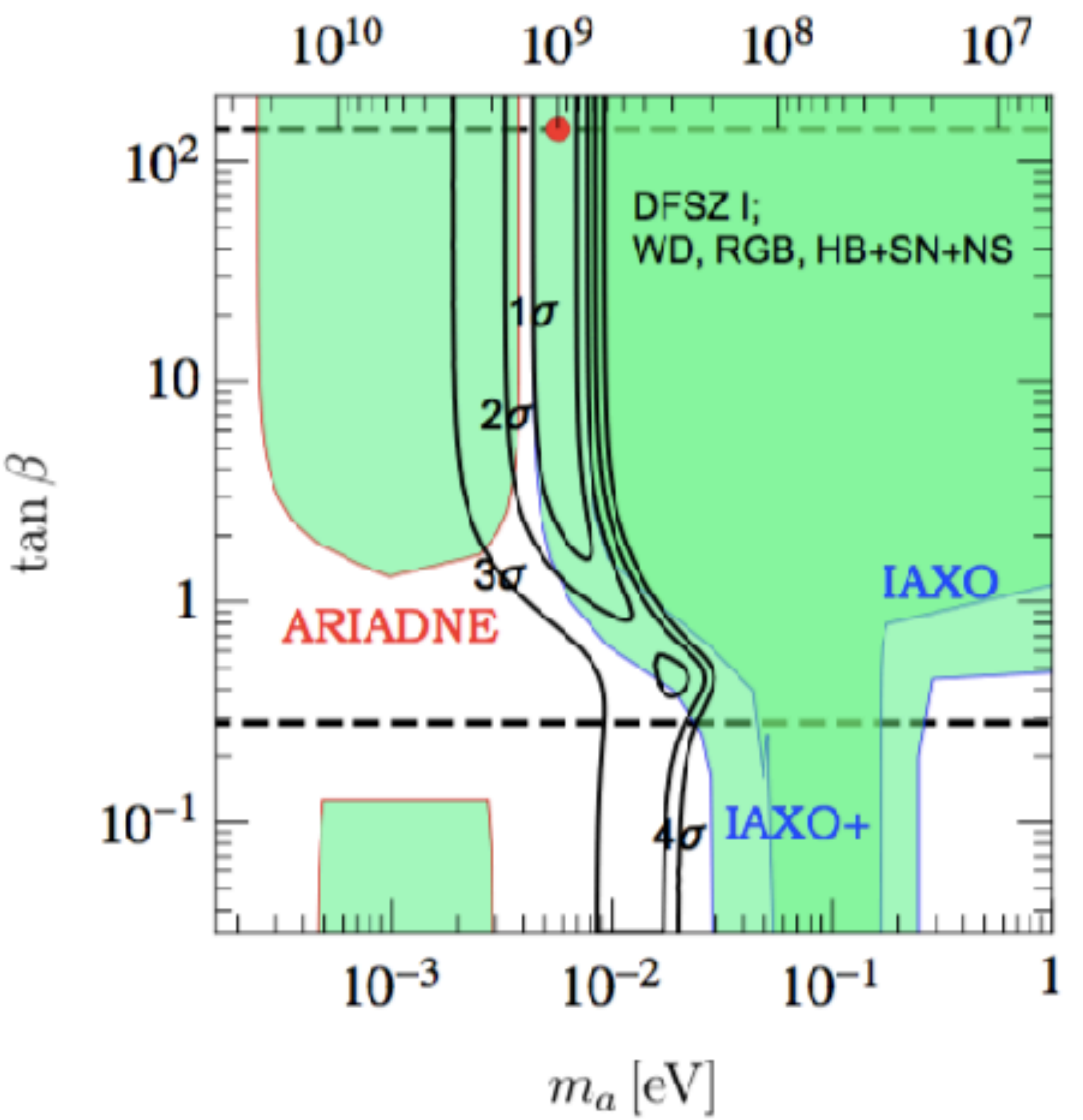


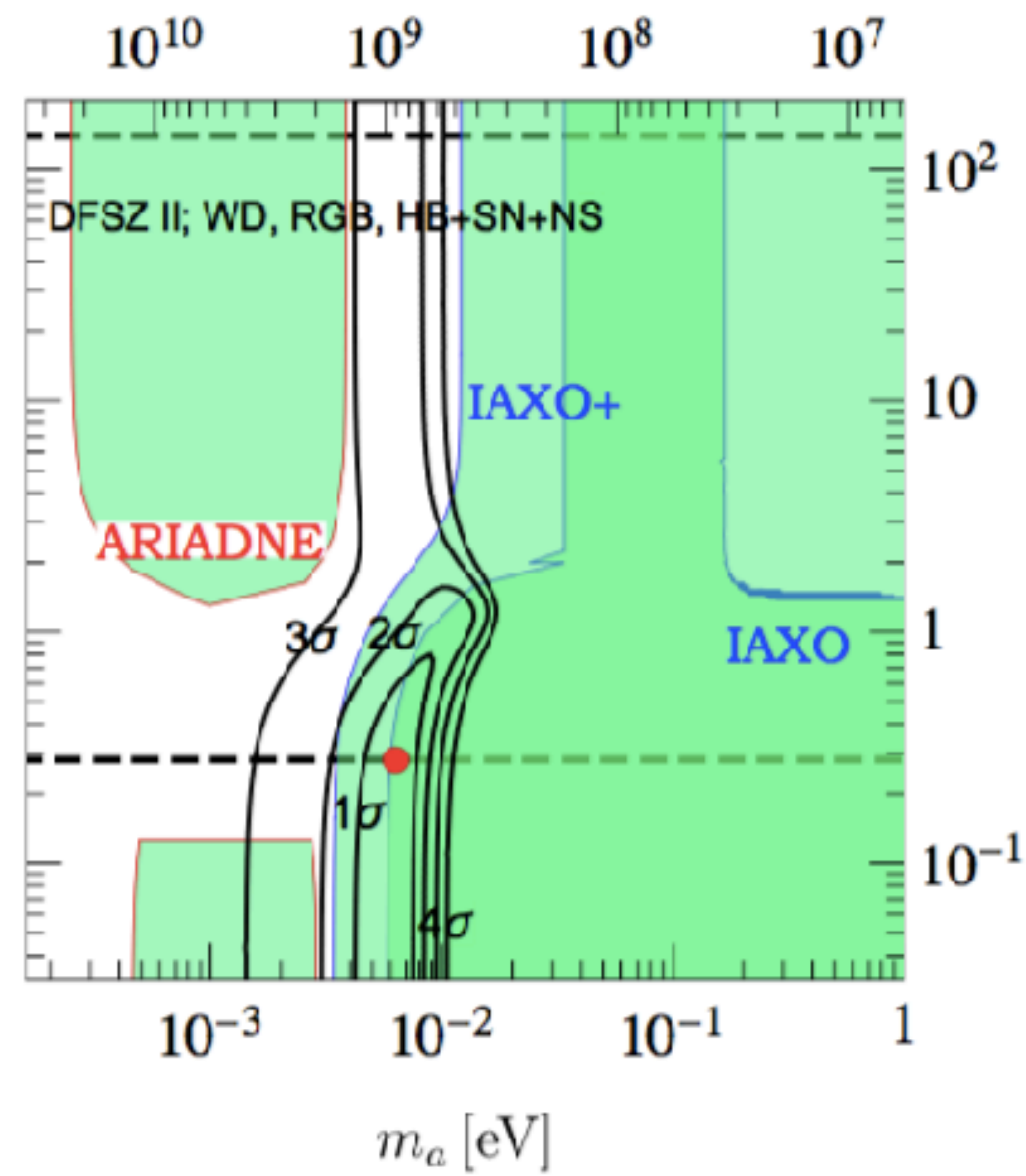
QCD axions, IAXO and ARIADNE

Example DFSZ axion model, 1-free parameter tanbeta

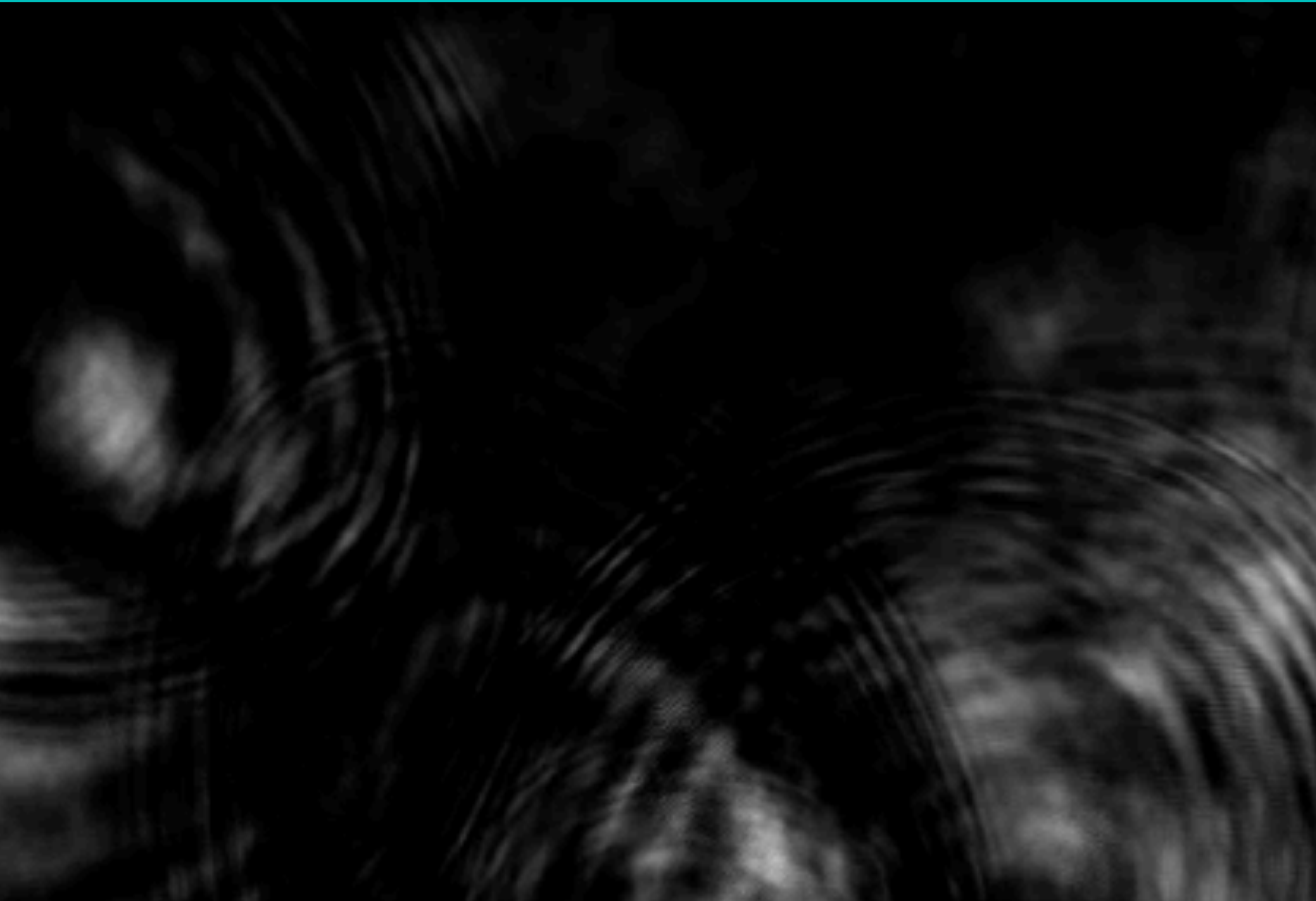
M. Giannotti et al JCAP10(2017)010

f_a [GeV]



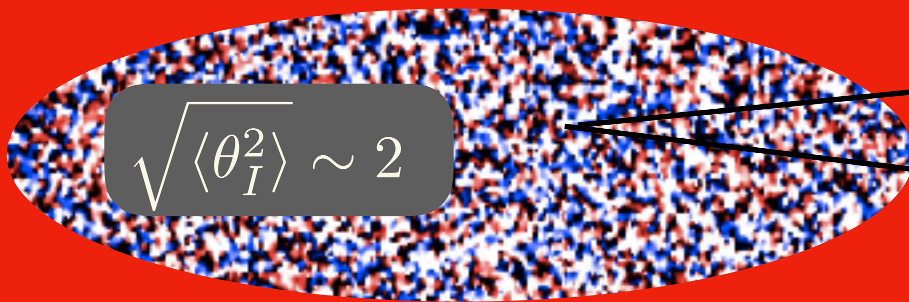


Detecting Dark Matter



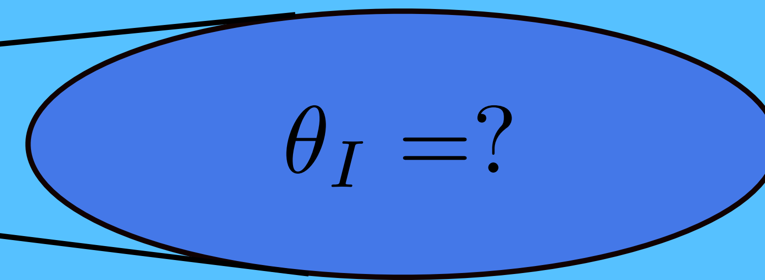
Axion dark matter in a nutshell

5: Scenario B : Initial conditions after inflation



dark matter inhomogeneous at scales below ~ pc

6: Scenario A : Inflation AFTER initial conditions



dark matter homogeneous

4: Axion dark matter abundance depends:
- Axion mass
- Initial angle

$$\Omega_c h^2 \sim 0.12\theta_I^2 \left(\frac{10\mu\text{eV}}{m_A}\right)^{1.17}$$

3: Axions field rolls down potential at

$$t_{\rm osc} \sim 1/m_A$$

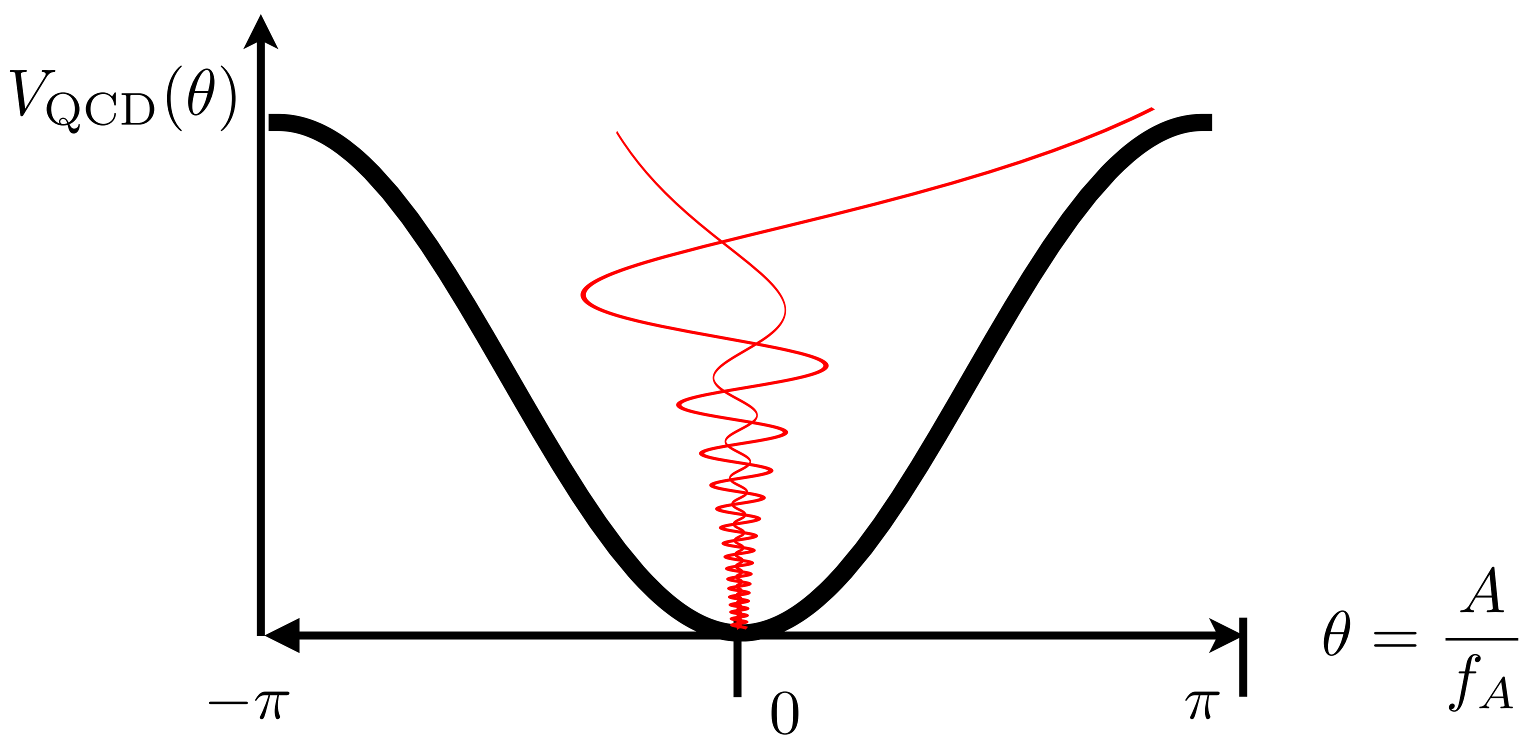
and becomes dark matter (like inflaton)

2: The QCD vacuum energy depends on θ

it has a minimum at $\theta = 0$!!!!

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

We observe $\theta \simeq 0$



Detecting Dark Matter

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

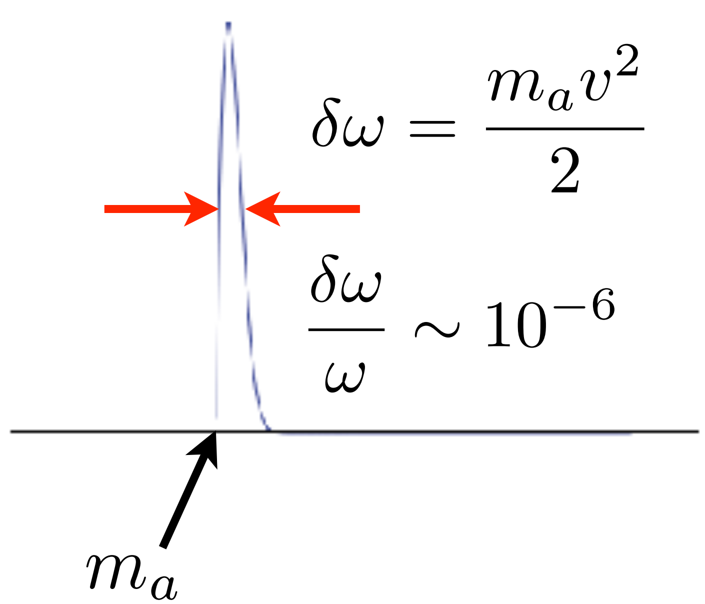
$$\rho_{\rm CDM} = 0.3 \frac{\rm GeV}{\rm cm^3} \equiv \frac{1}{2}(\dot{a})^2 + \frac{1}{2} m_a^2 a^2 = \frac{1}{2} m_a^2 f_a^2 \theta_0^2$$

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

Non-zero velocity in galaxy -> finite width

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

~ 10^-6



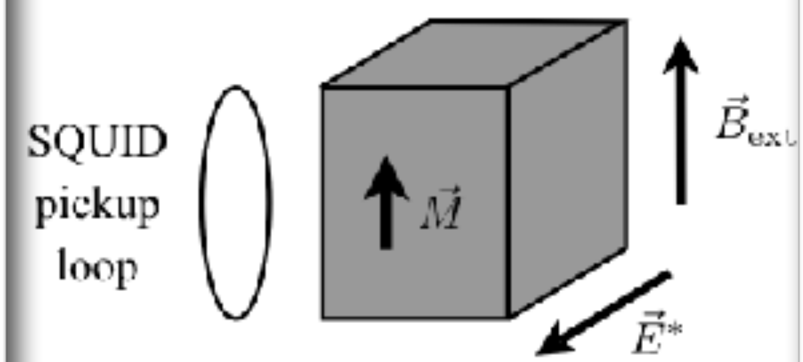
coherence time

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

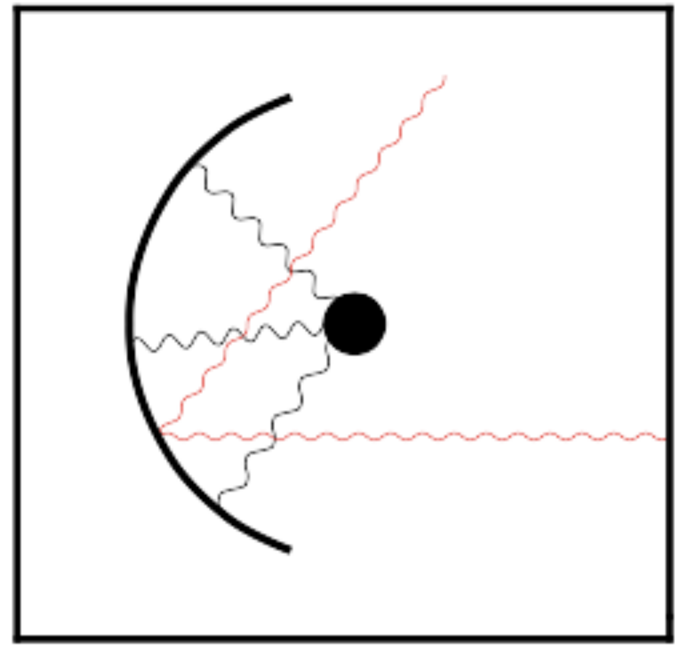
coherence length

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

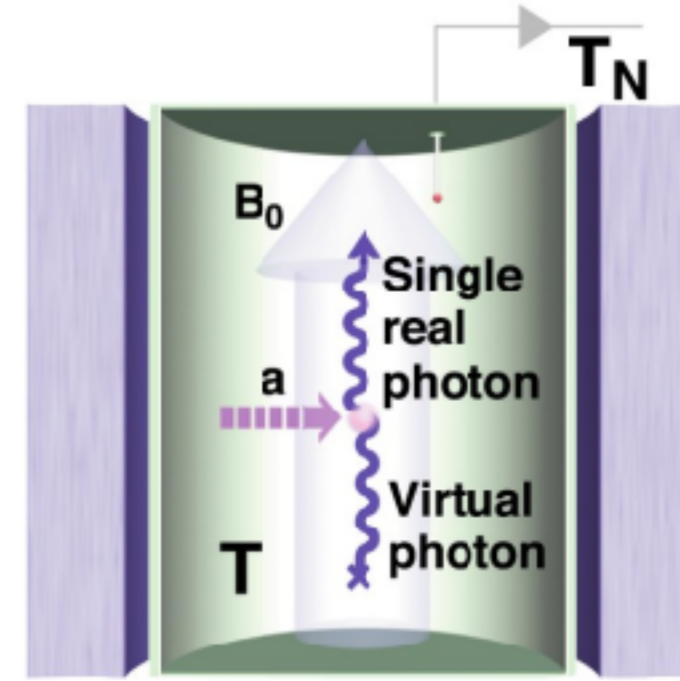
Spin precession



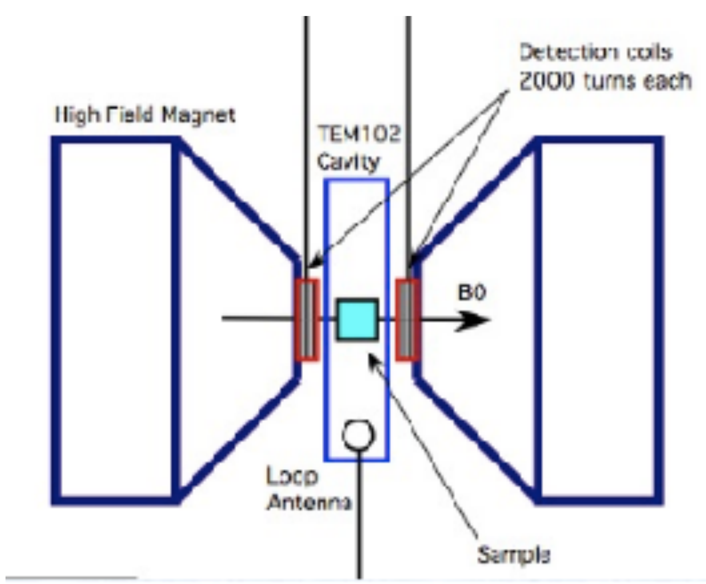
Mirrors+



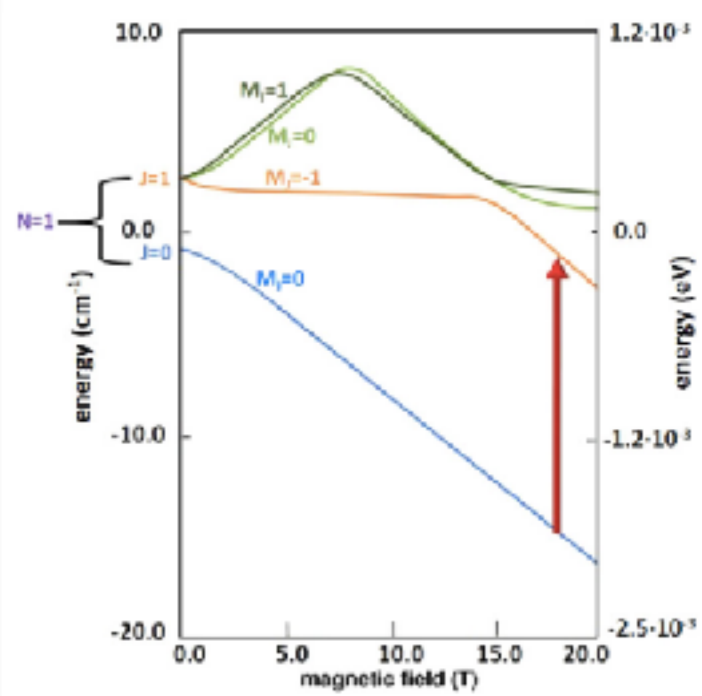
Cavities



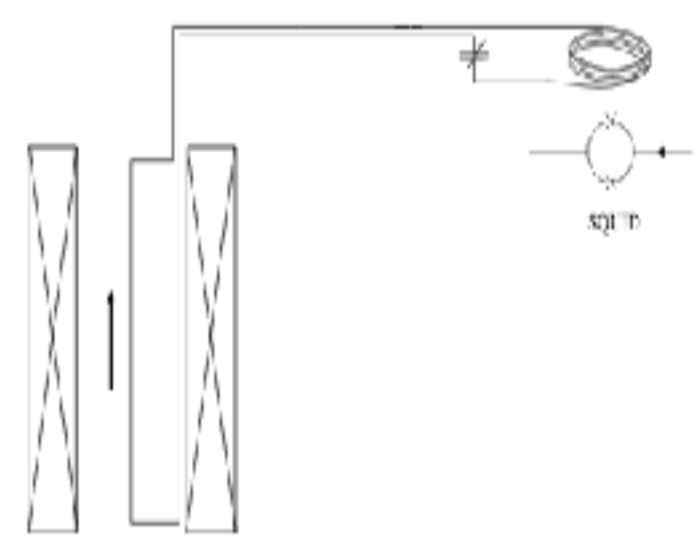
e-spin precession



Atomic transitions

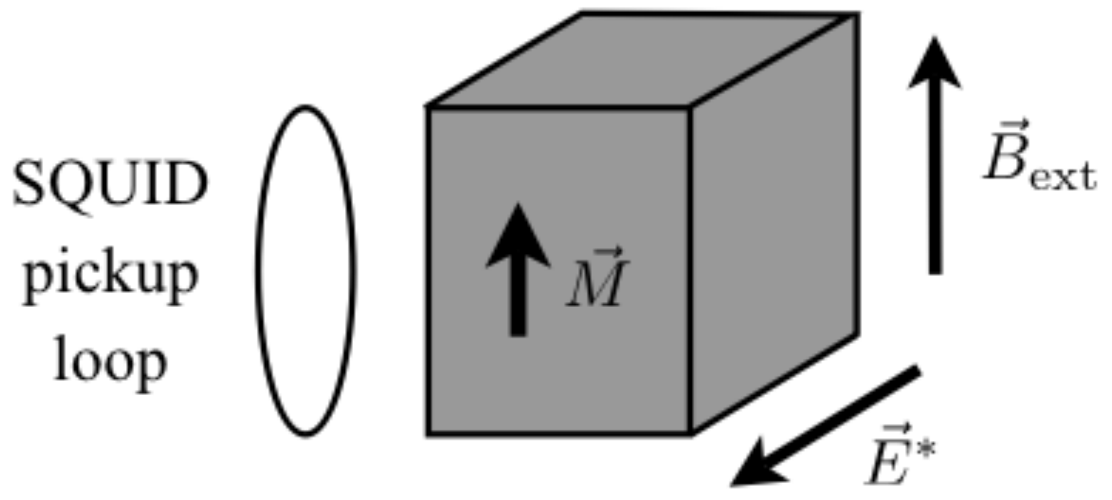


LC-circuit



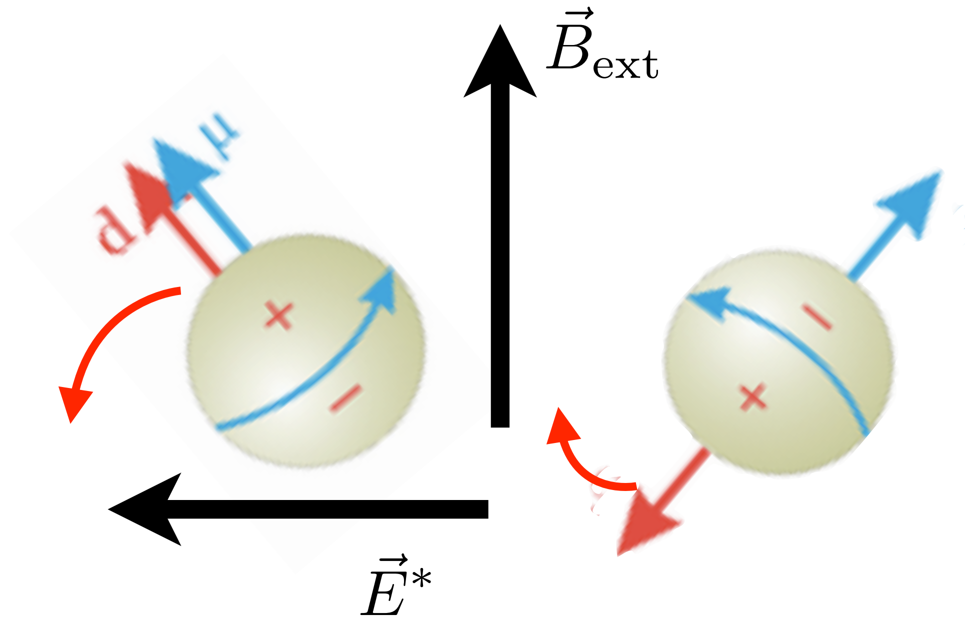
CASPER at Mainz

Graham 2012



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

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

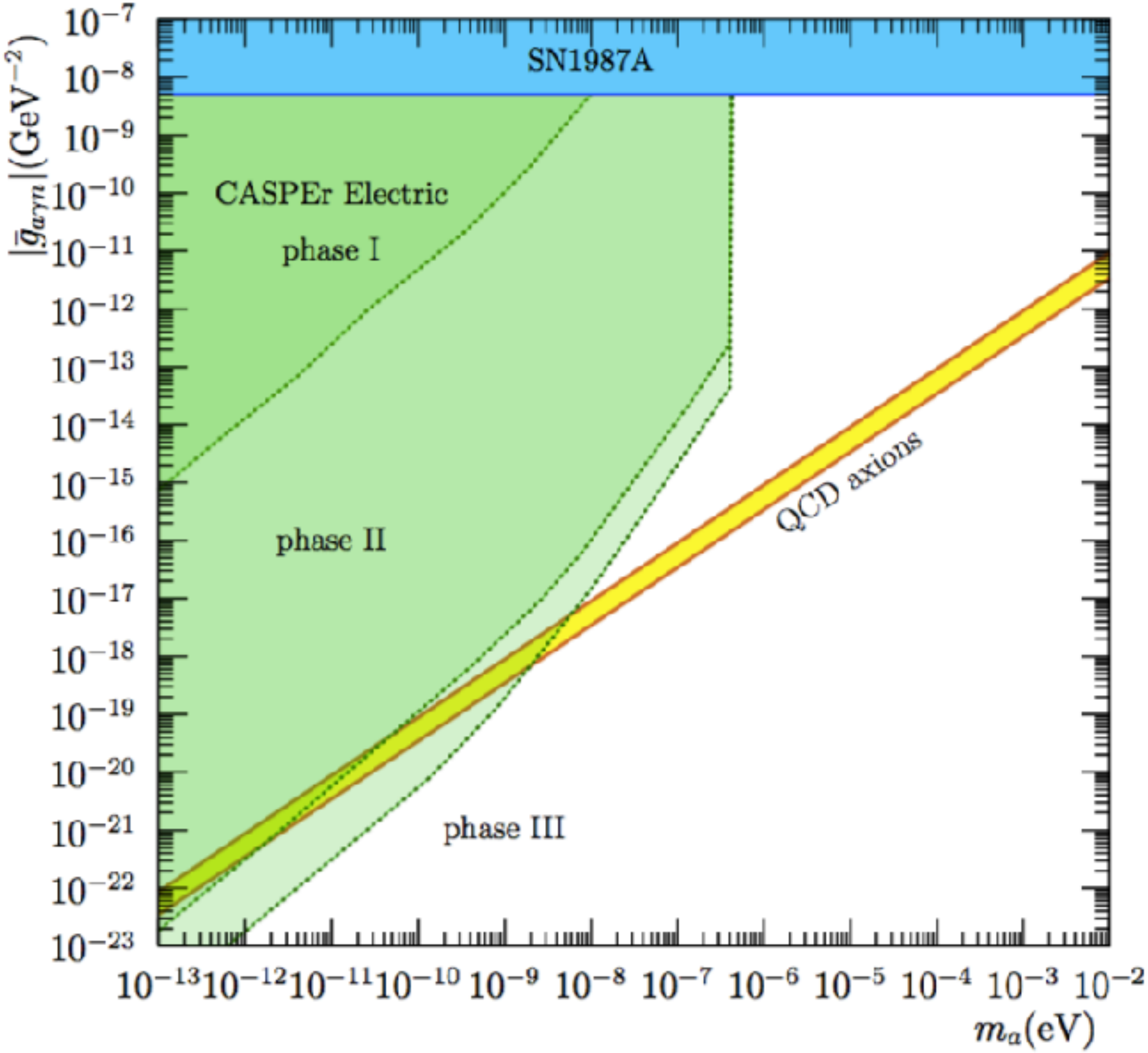


Oscillating EDM, effects add up, transverse magnetisation grows if $m_a = \omega = \mu|\vec{B}_{\mathrm{ext}}|$

- 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



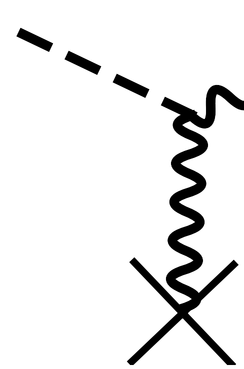
Axion DM in a B-field

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

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

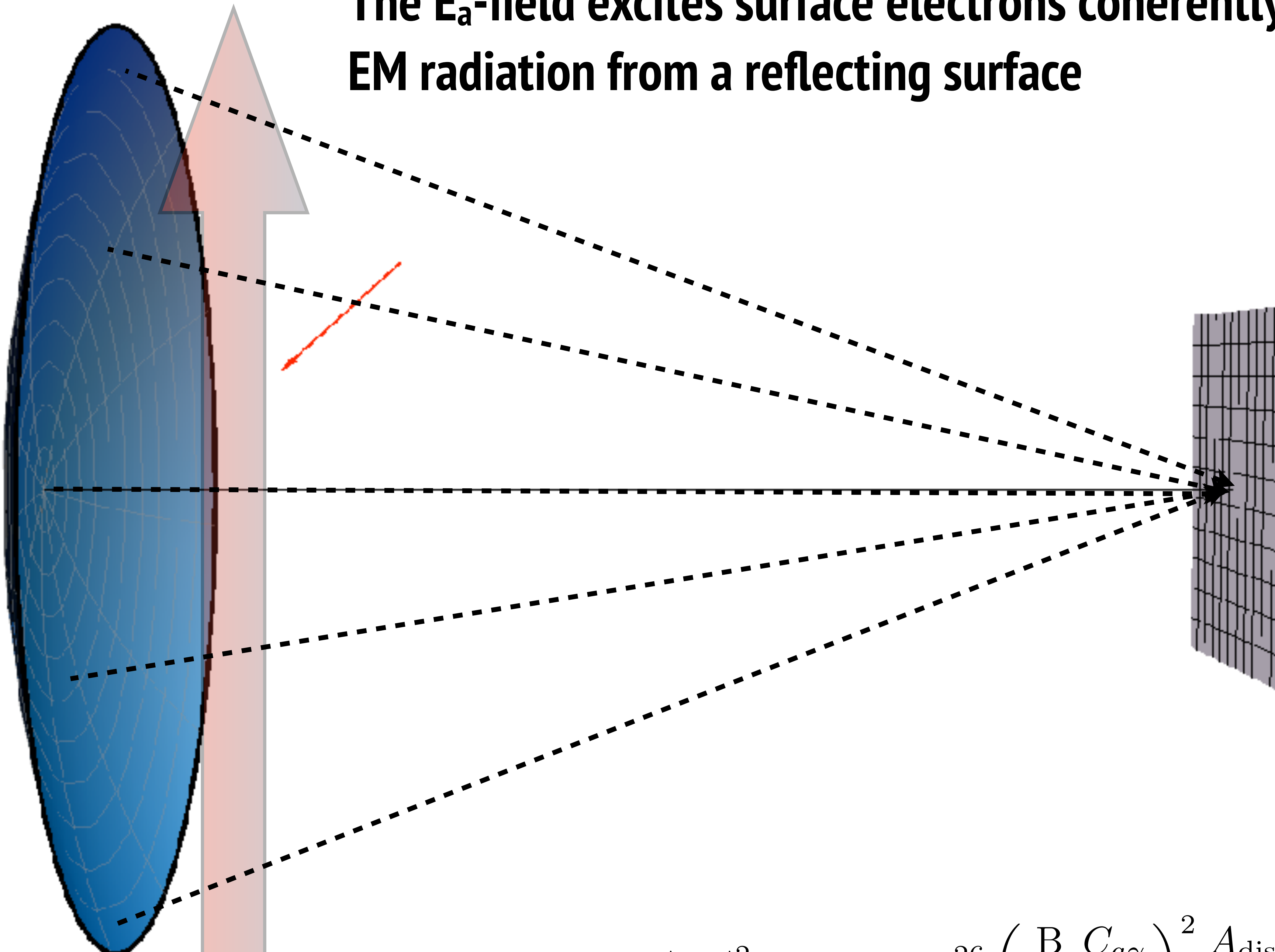
- **All experiments are sensitive to light dark photon dark matter! (kin. mix)**

Dish antenna experiment?

Horns 2012

The E_a-field excites surface electrons coherently

EM radiation from a reflecting surface

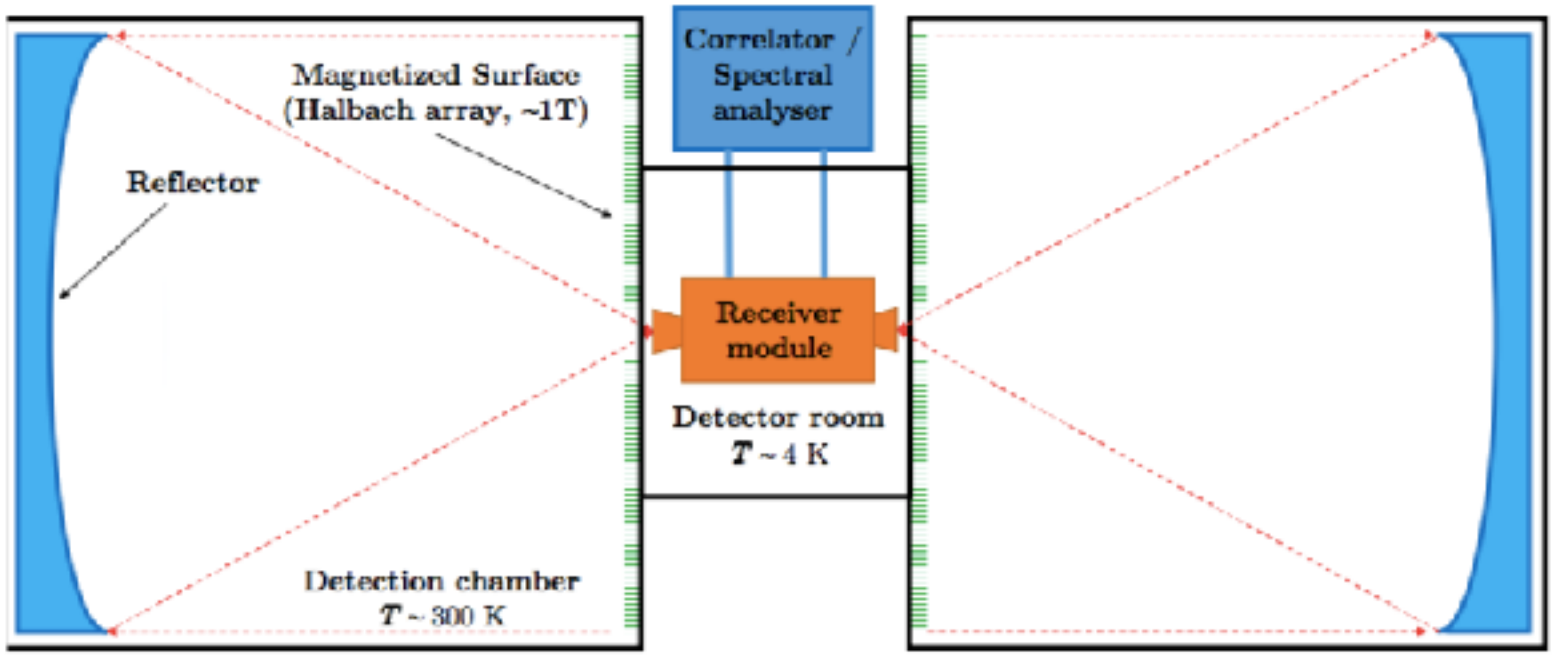


spherical reflecting dish

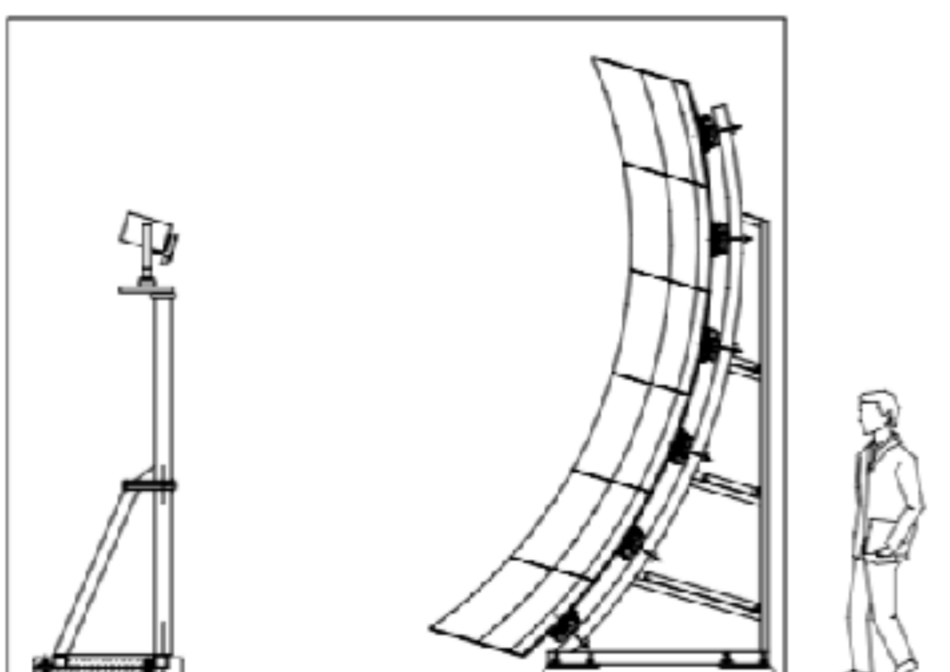
$$P \sim |\mathbf{E}_a|^2 A_{\rm dish} \sim 10^{-26} \left(\frac{\rm B}{5\rm T}\frac{C_{a\gamma}}{2}\right)^2 \frac{A_{\rm dish}}{1\,{\rm m}^2}{\rm Watt}$$

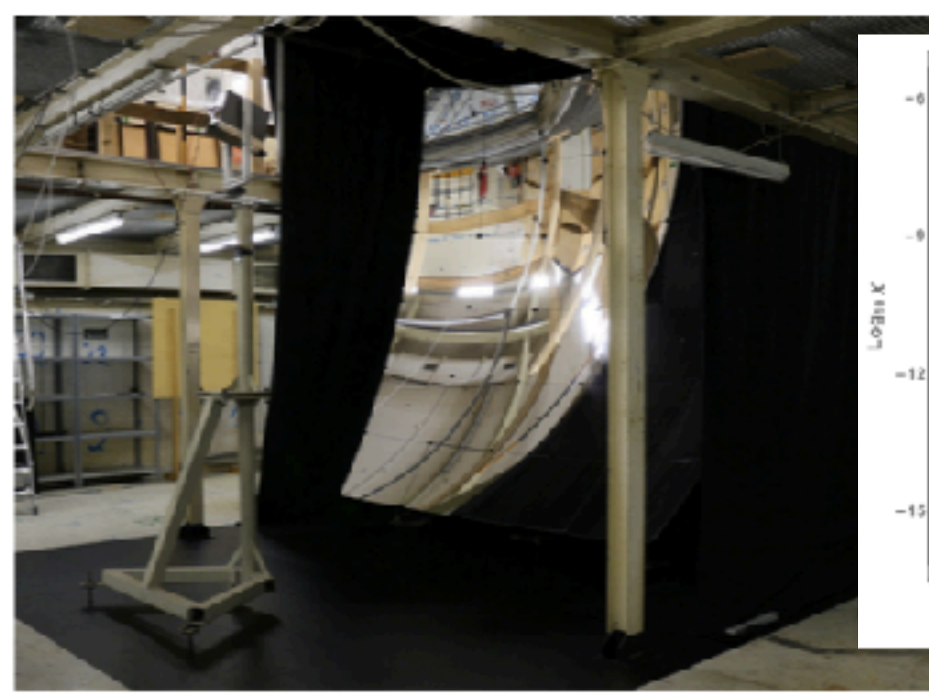
BRASS, FUNK

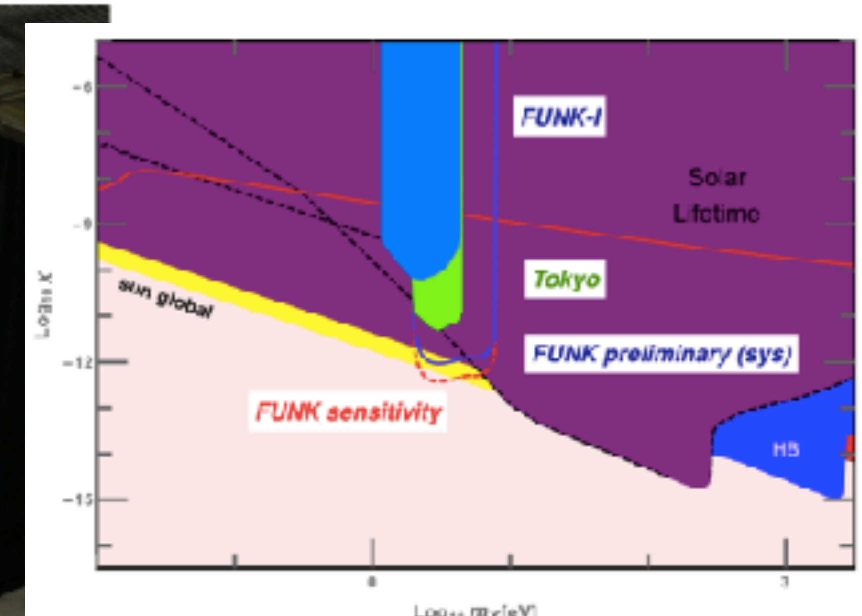
Magnetised surface (Hamburg U.)



FUNK (KIT Karlsruhe) (1711.02961)







Cavity resonators (Haloscopes)

- Haloscope (Sikivie 83)

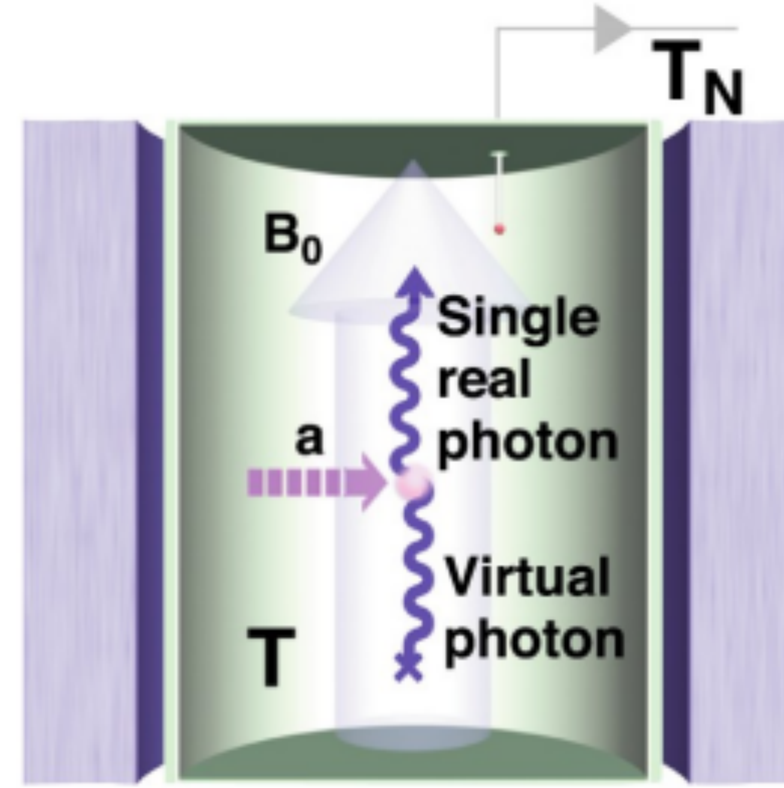
$$P \sim Q|\mathbf{E}_a|^2 (V m_a)\mathcal{G}\kappa \quad \text{(on resonance)}$$

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

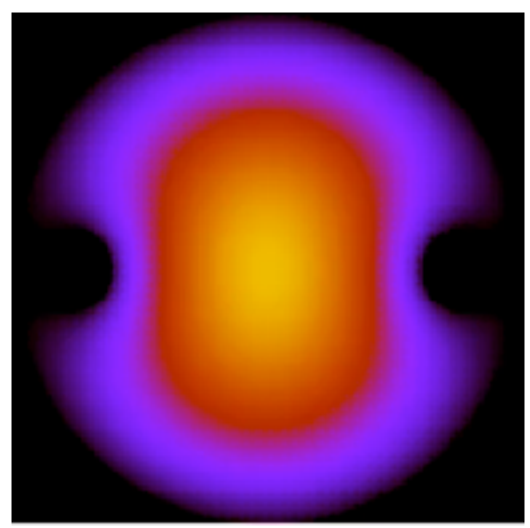
$V \sim 1/m_a^3$

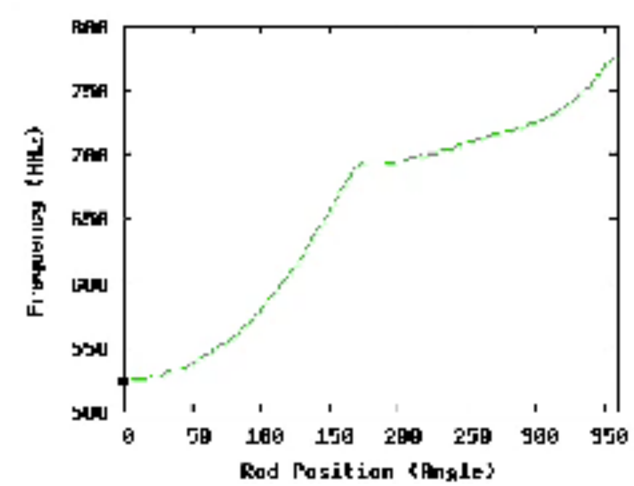
extra factor of Q~10^5

on a m_a/Q band



Scanning over frequencies





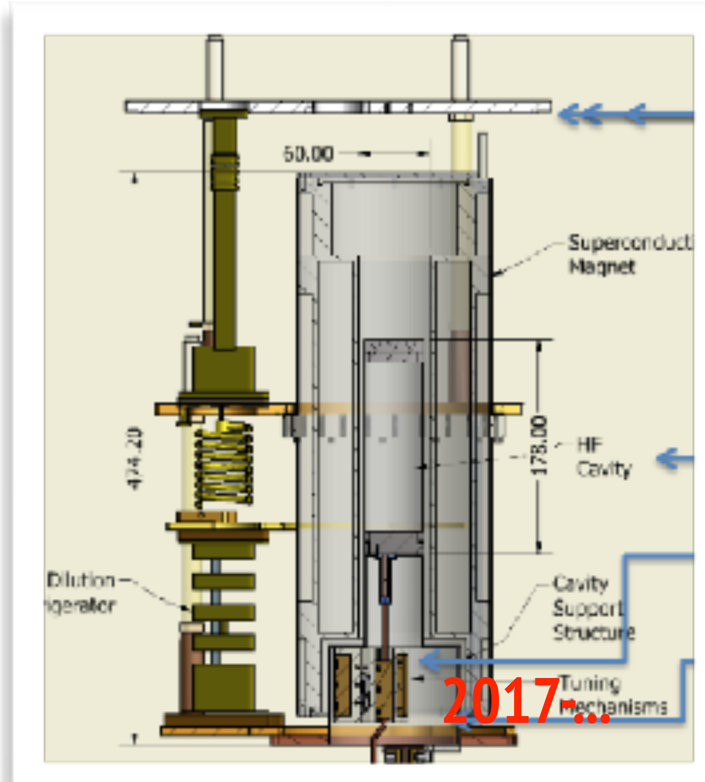
Cavity experiments

- Physical dimensions $L \sim 1/m_a$

ADMX-Seattle

new data!!!

CULTASK - CAPP -Korea



2017-...

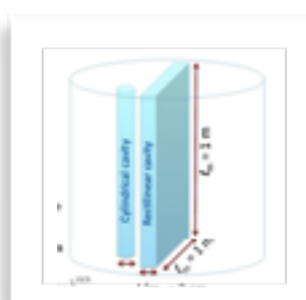
ORGAN-UWA Perth

2017-...

HAYSTAC-Yale

2016-...

ADMX-Fermilab



RADES

2017-...

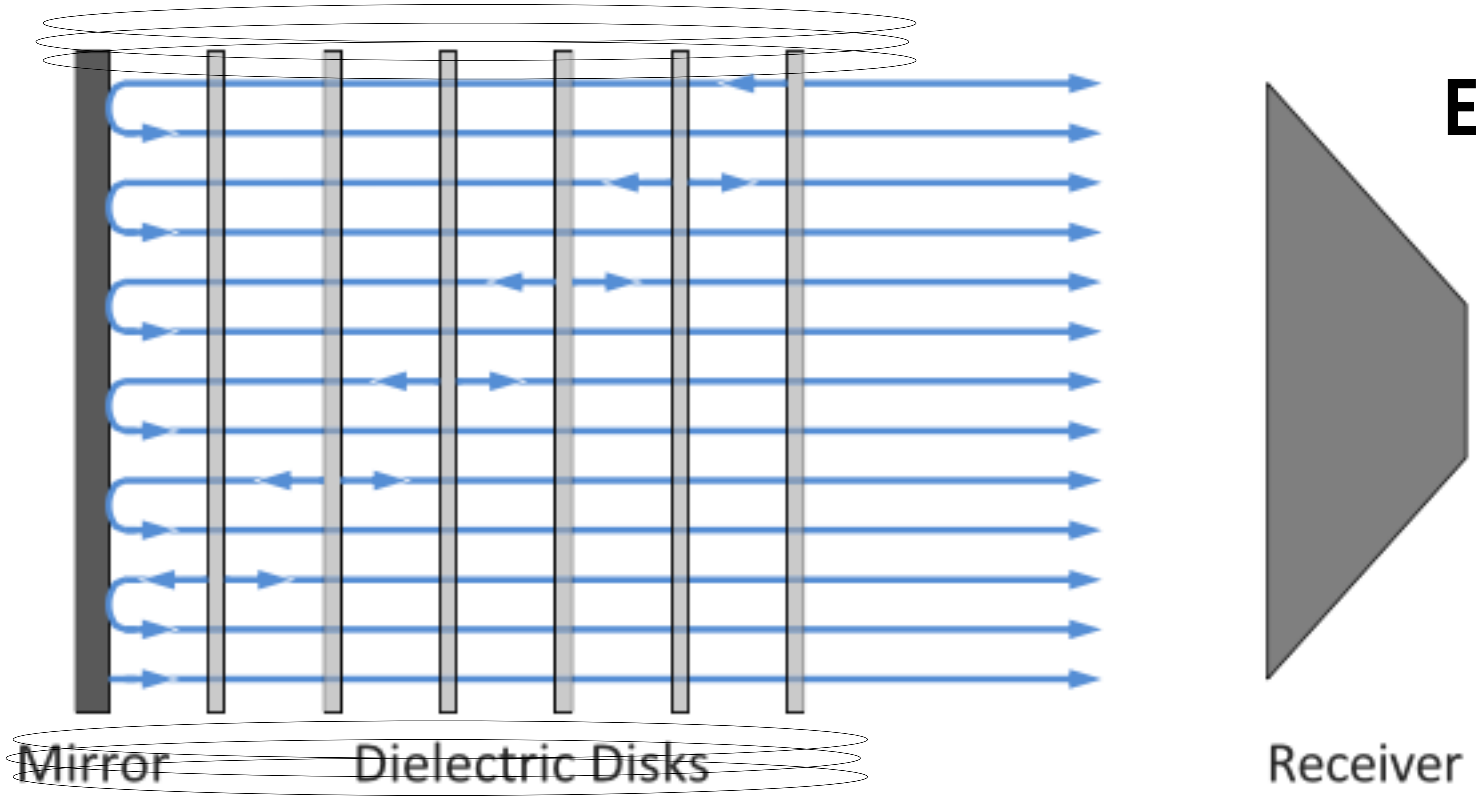
CAST-CAPP

2017-...

KLASH?

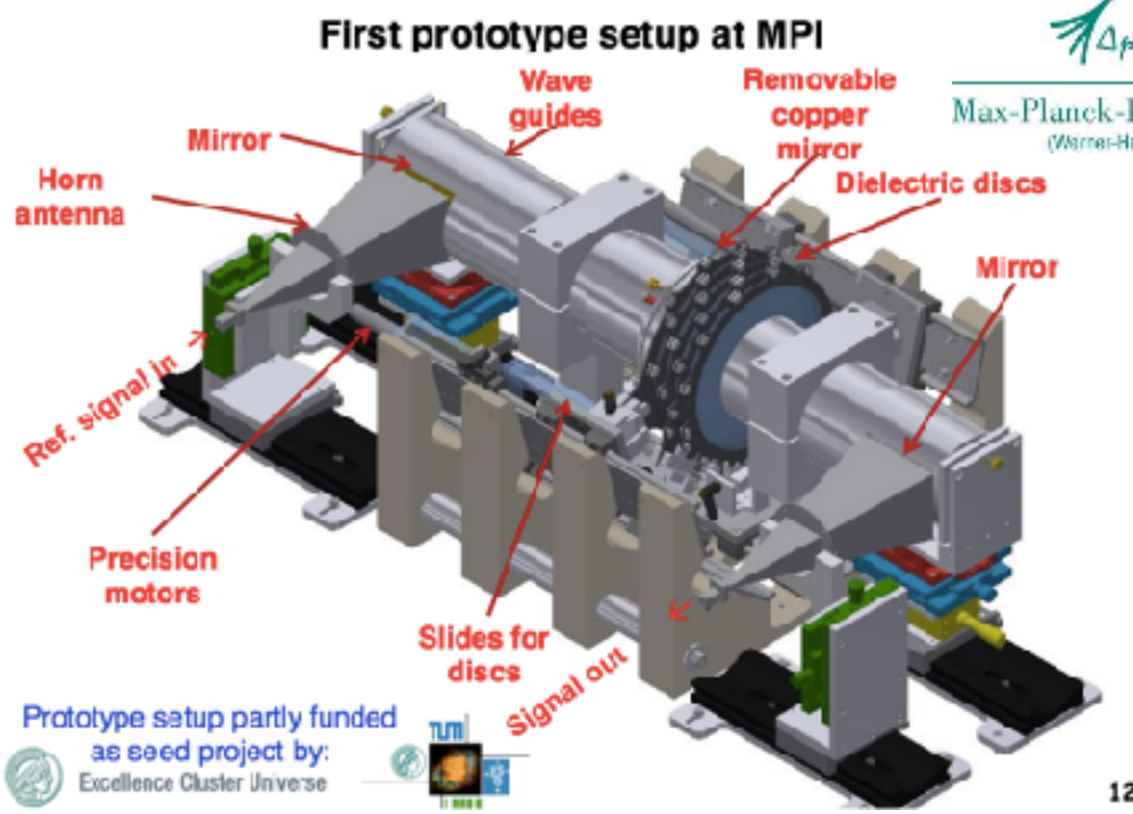
??-...

MADMAX: MAgnetised Disk and Mirror Axion eXperiment

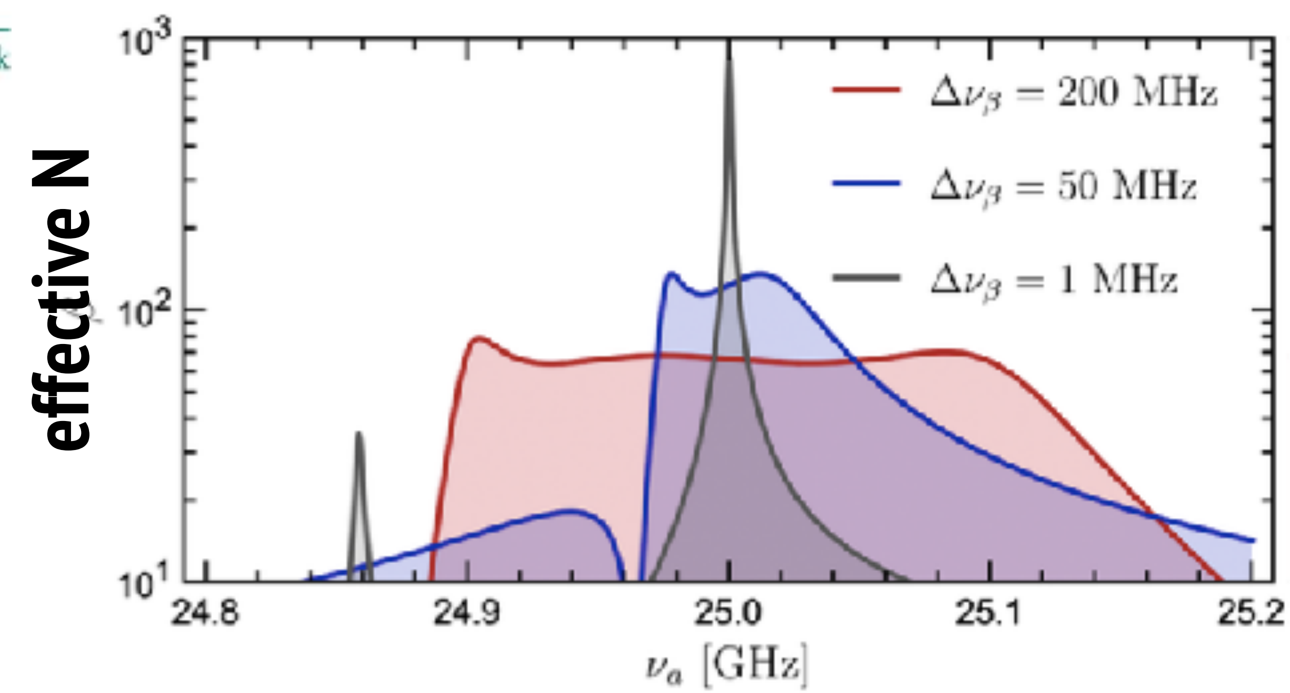


Emitted EM-waves from each interface + internal reflections ...

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

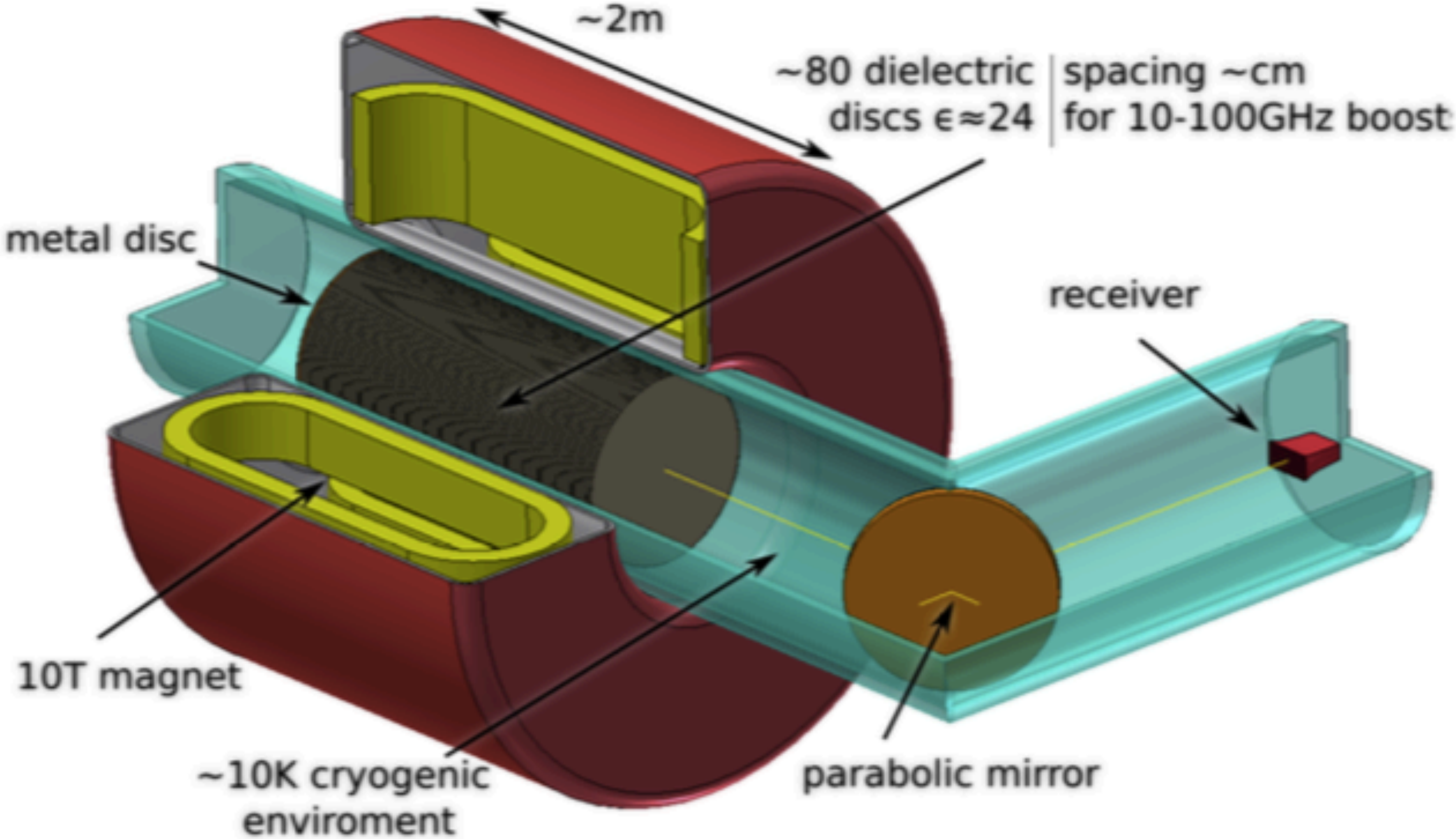


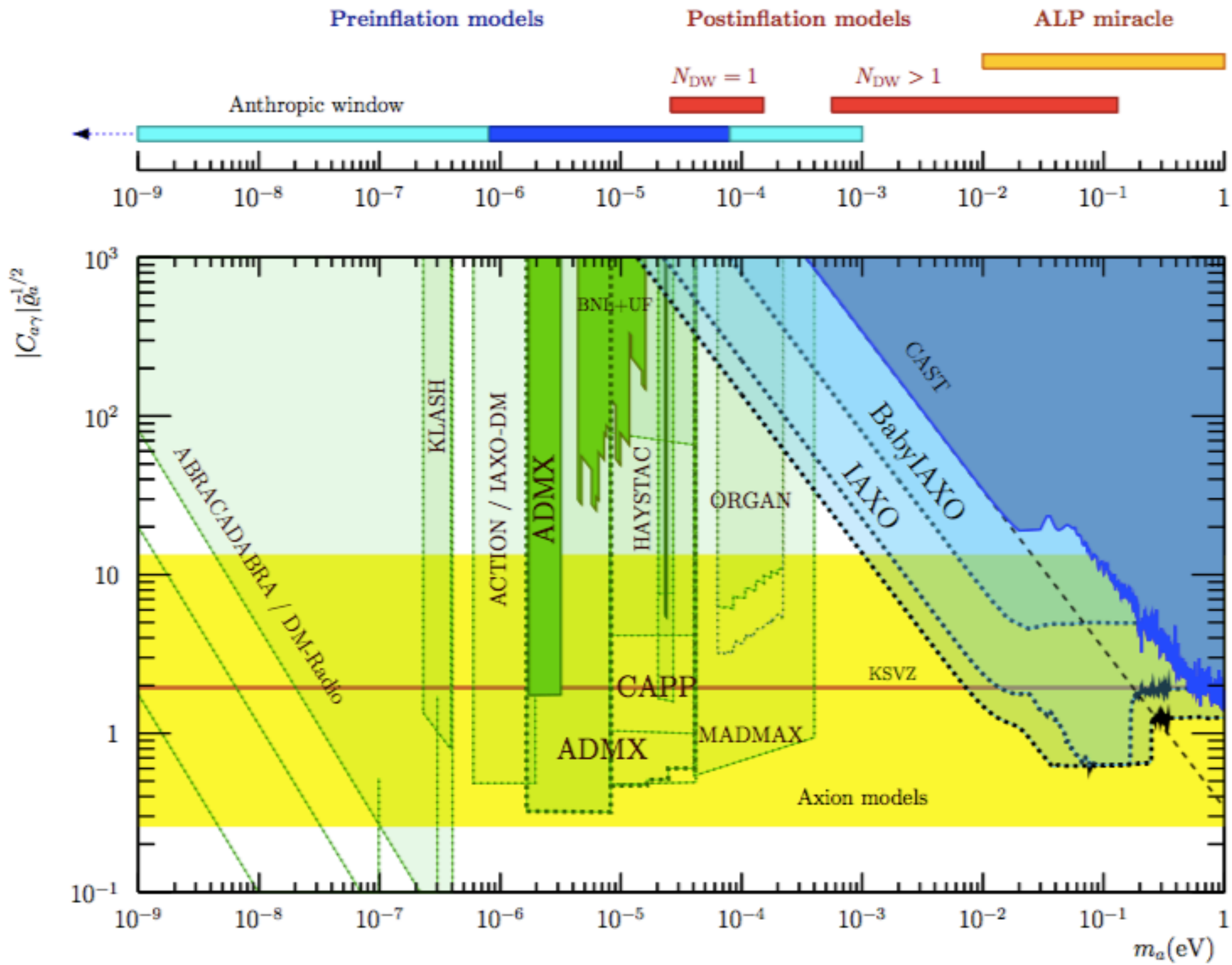
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)



Caldwell 2017

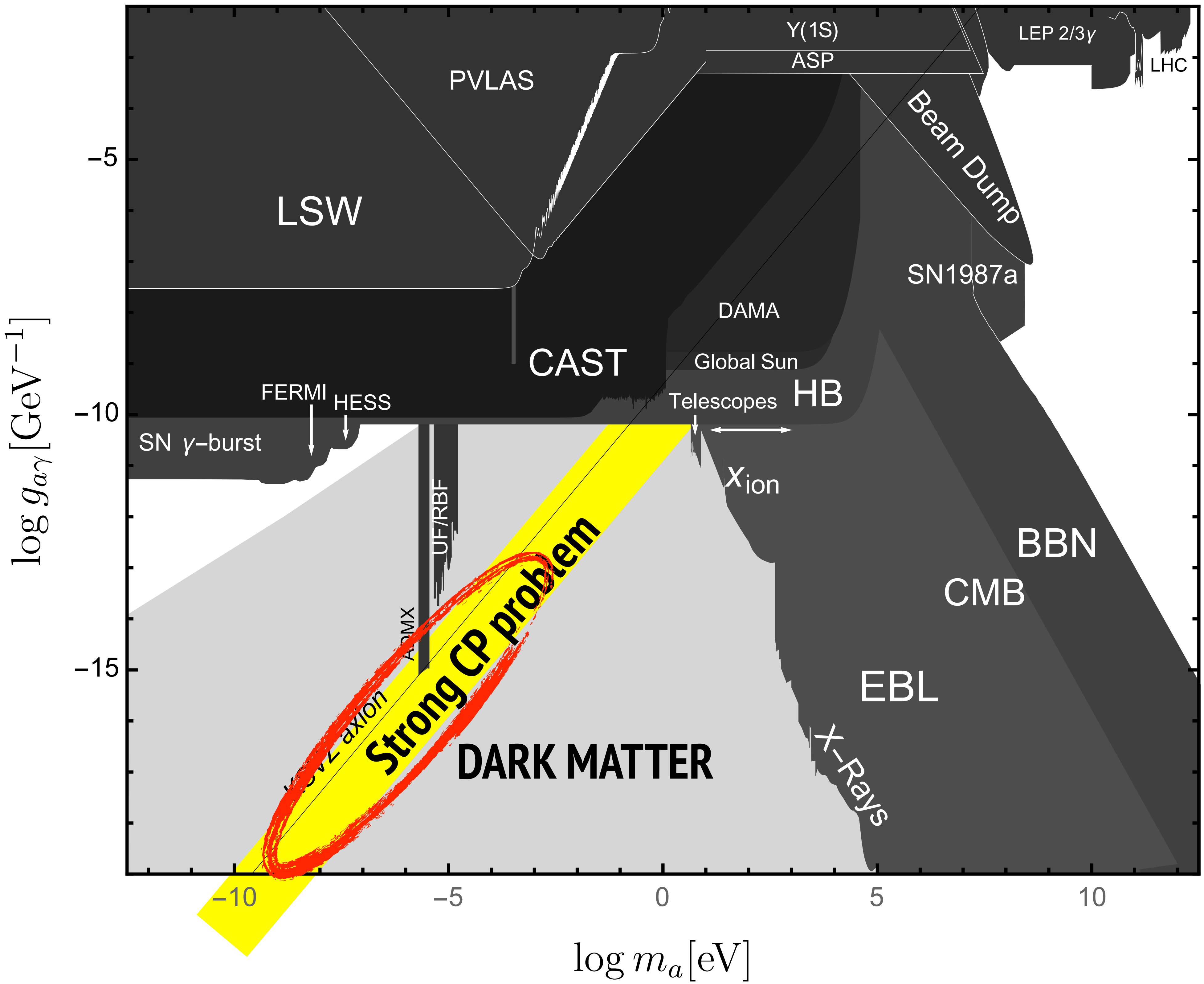
MADMAX


~2m
~80 dielectric discs ϵ≈24
spacing ~cm for 10-100GHz boost
metal disc
receiver
10T magnet
~10K cryogenic enviroment
parabolic mirror

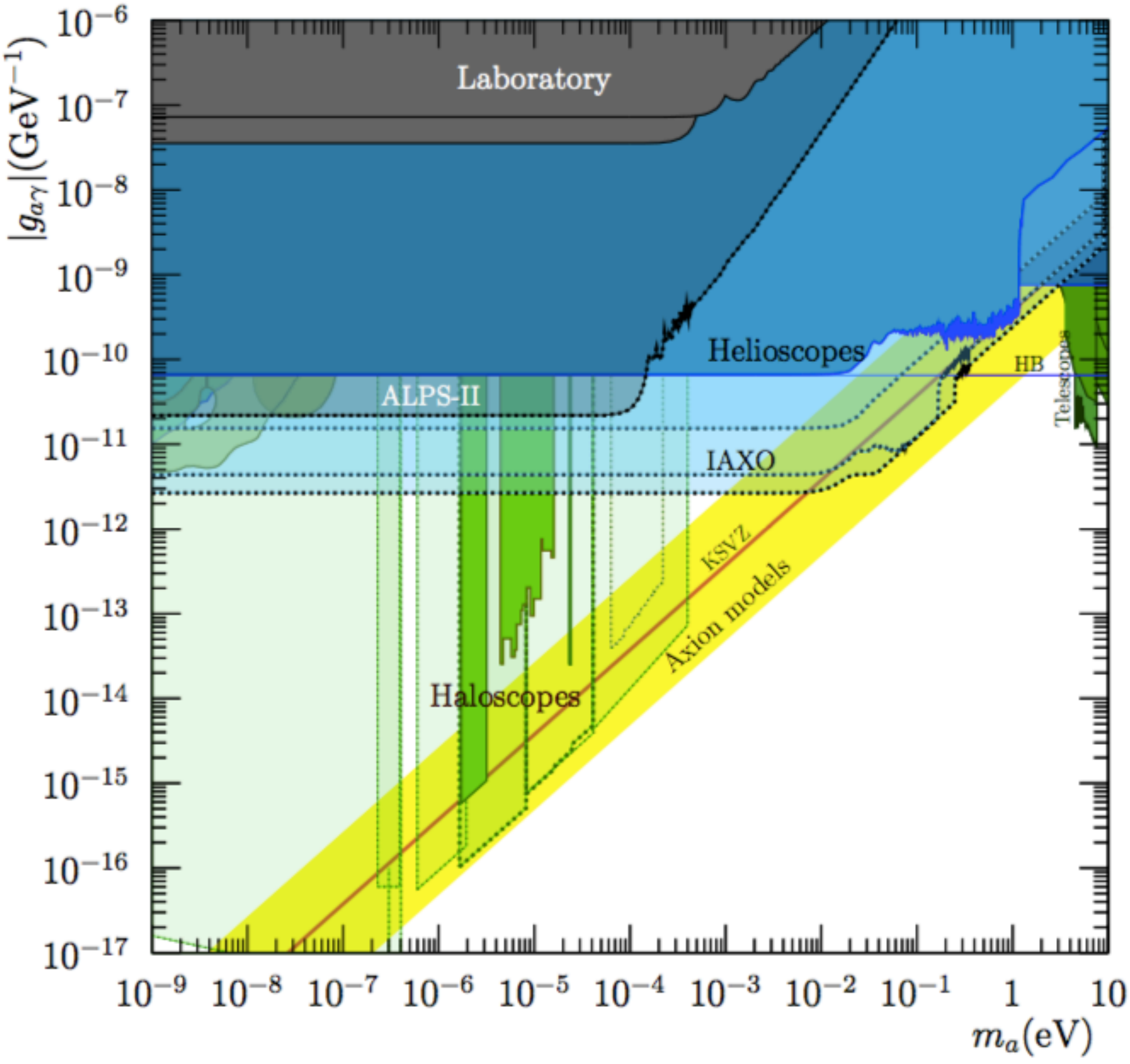


Preinflation models
Postinflation models
ALP miracle
$N_{DW} = 1$
$N_{DW} > 1$
Anthropic window
$|C_{a\gamma}|\bar{\varrho}_a^{-1/2}$
KLASH
ACTION / IAXO-DM
ADMX
BNL+UF
HAYSTAC
ORGAN
CAST
BabyIAXO
IAXO
ABRACADABRA / DM-Radio
KSVZ
CAPP
MADMAX
ADMX
Axion models
m_a(eV)

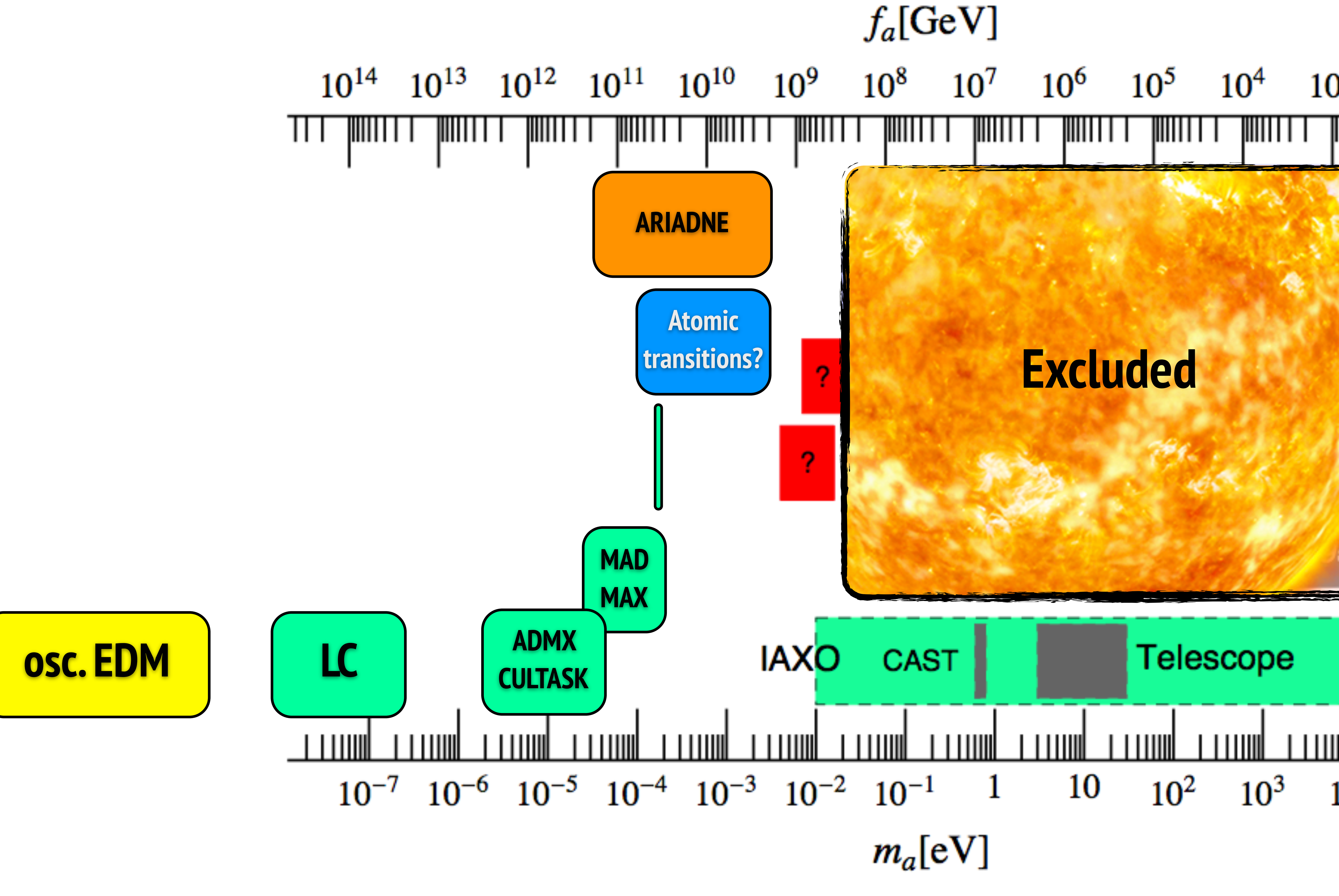
Summary plot



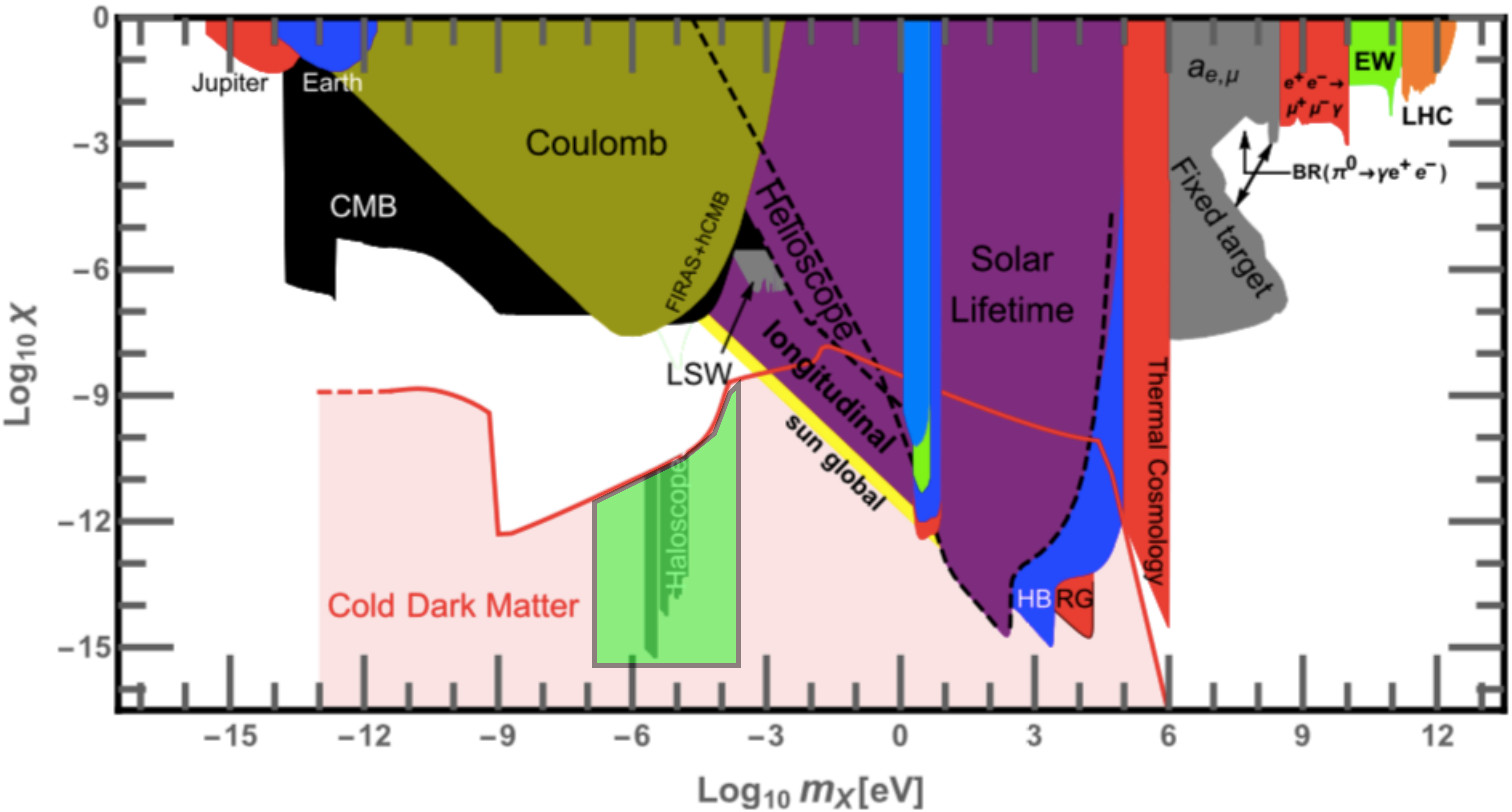
Summary plot



Summary plot



Low mass Dark Photons



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!