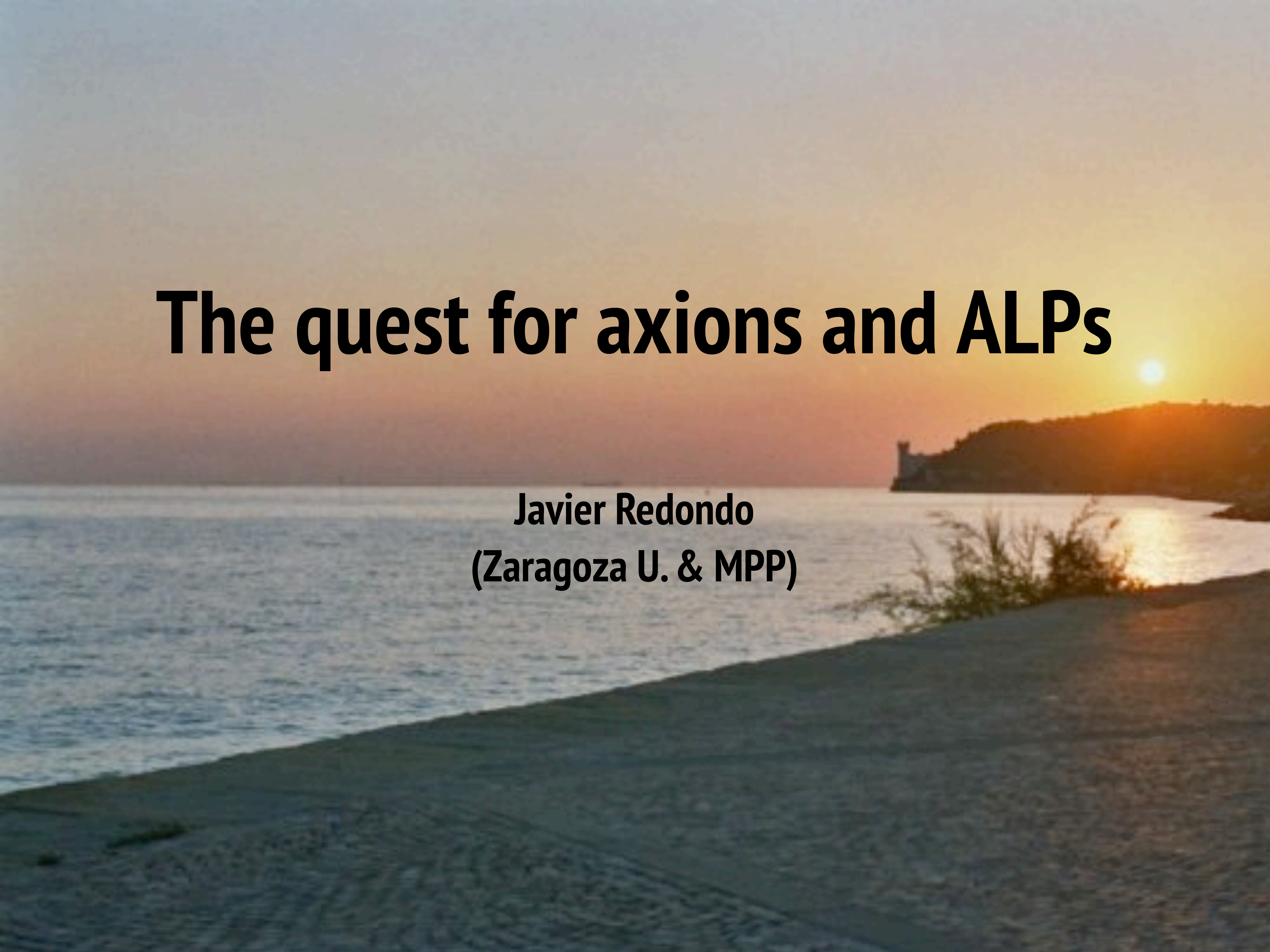
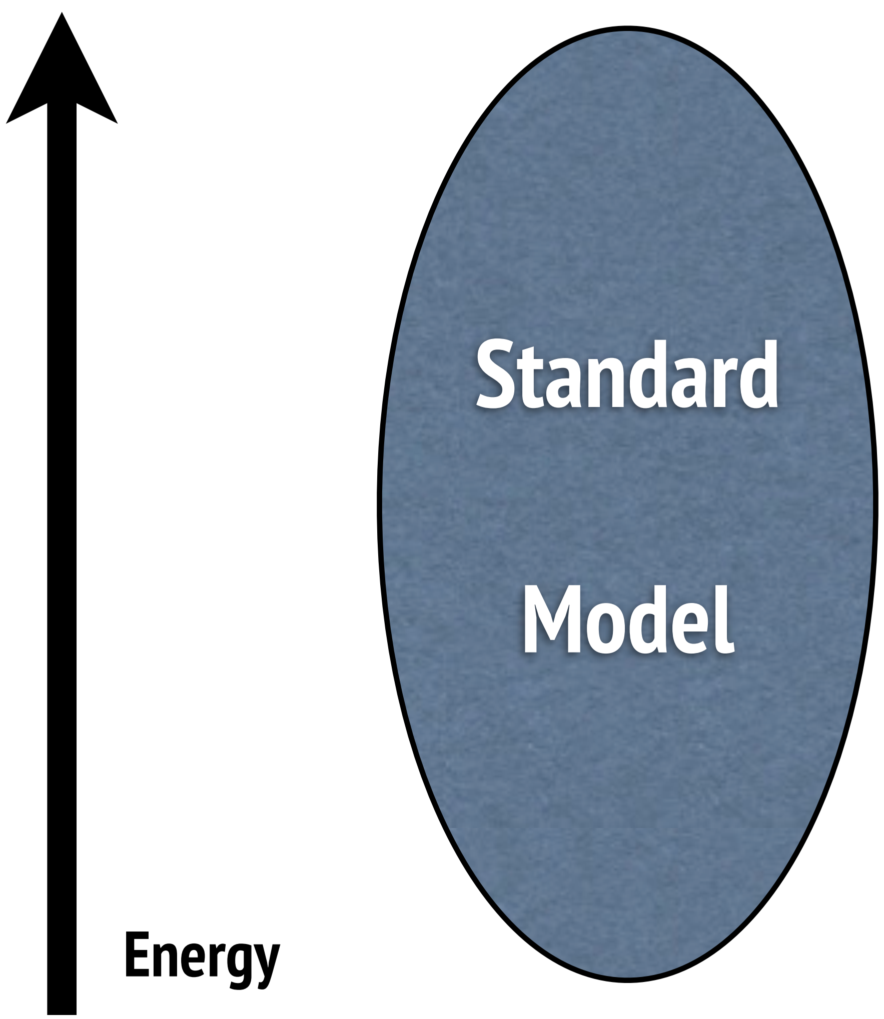


The quest for axions and ALPs

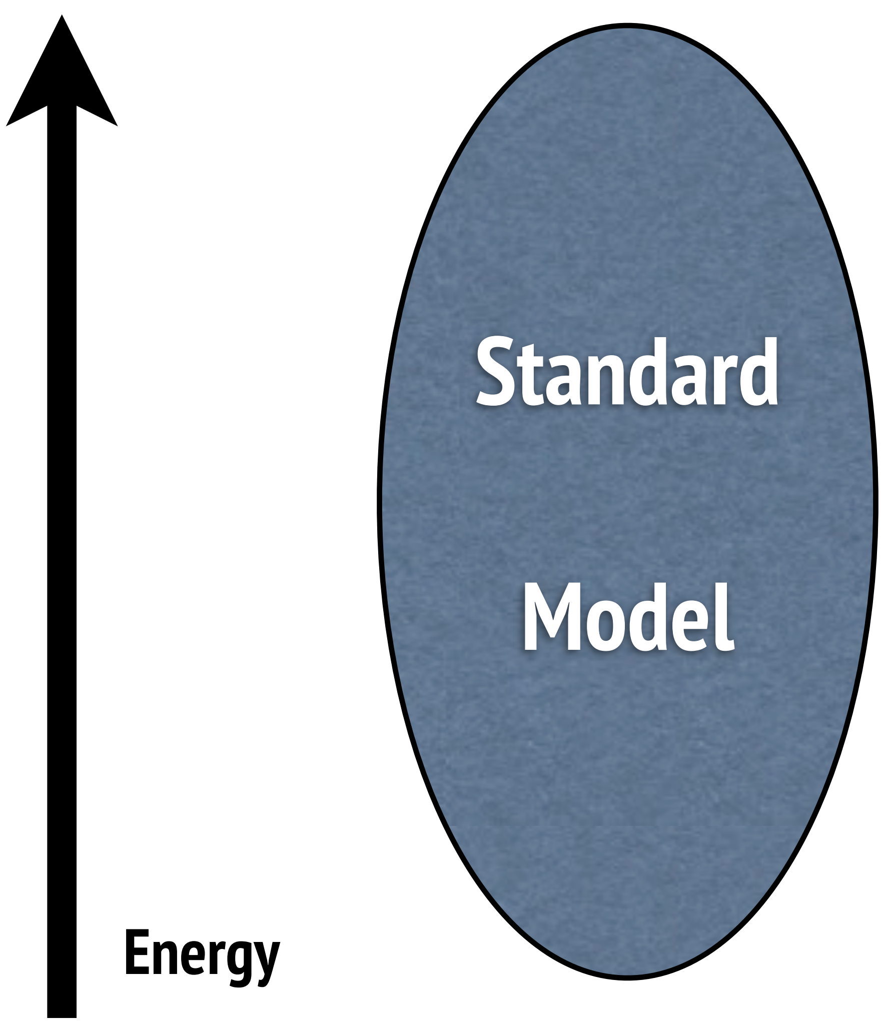
Javier Redondo
(Zaragoza U. & MPP)

Outline

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



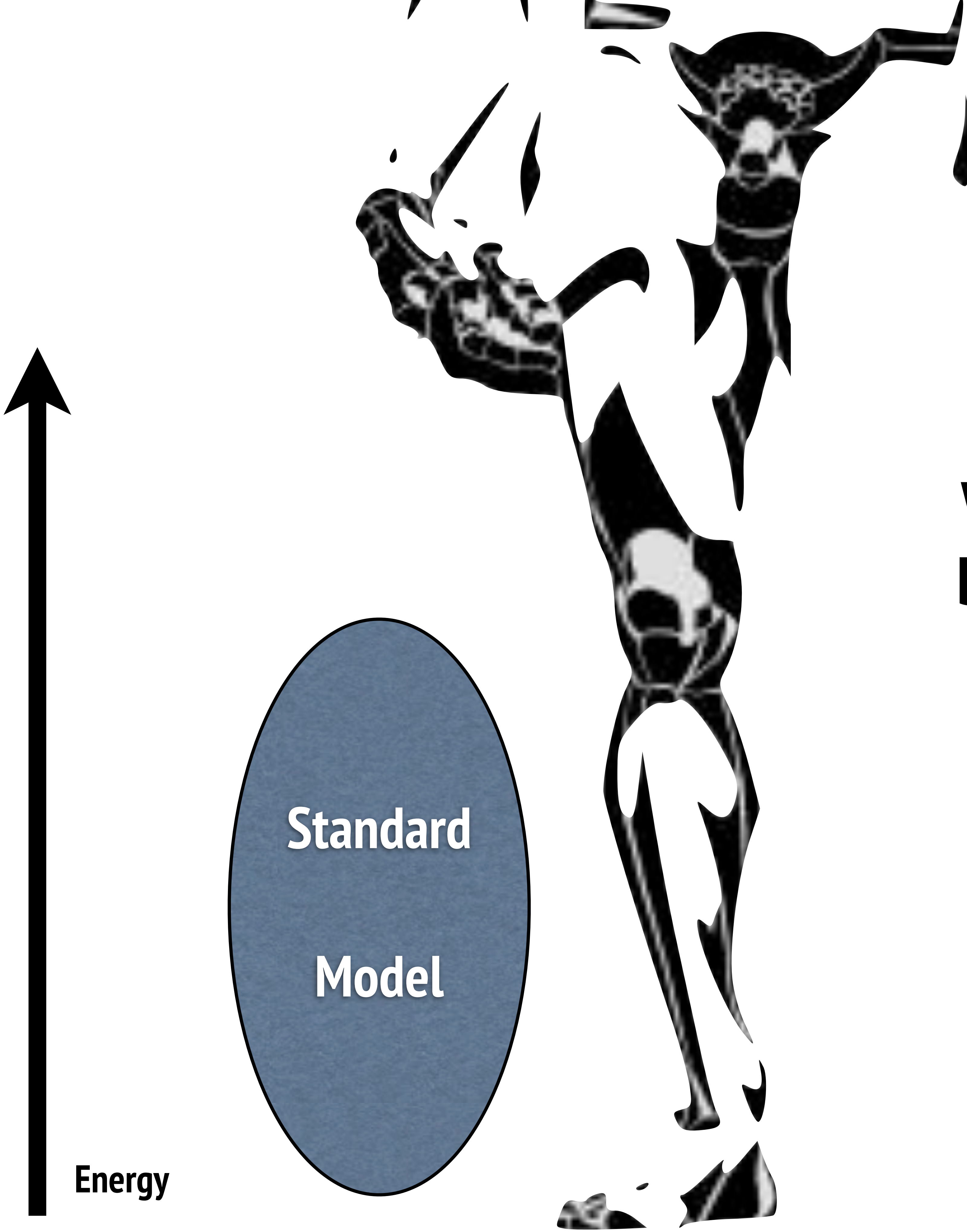
Describes extremely well particle physics (at low energies)



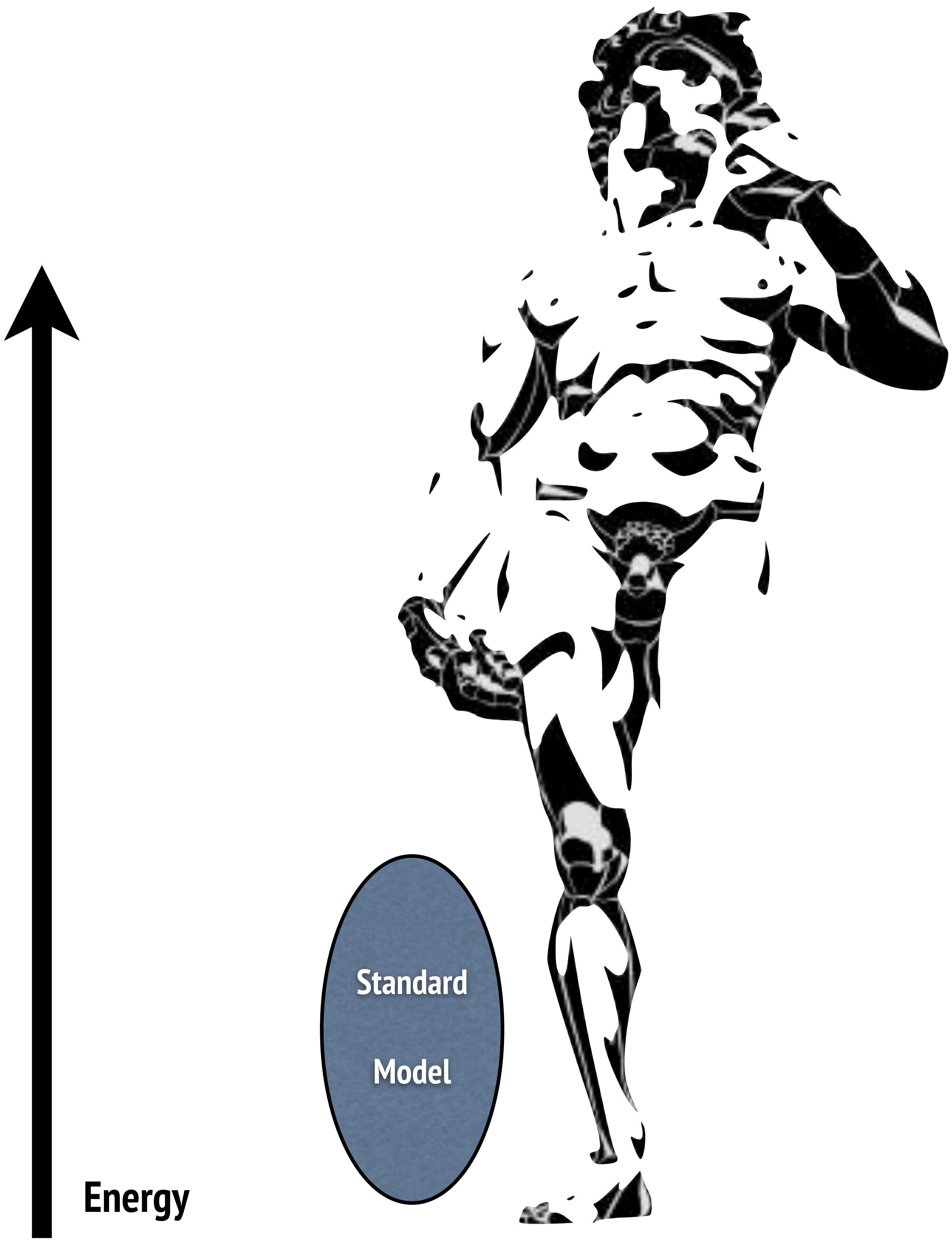
Describes extremely well particle physics (at low energies)

but it is certainly ...

INCOMPLETE



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



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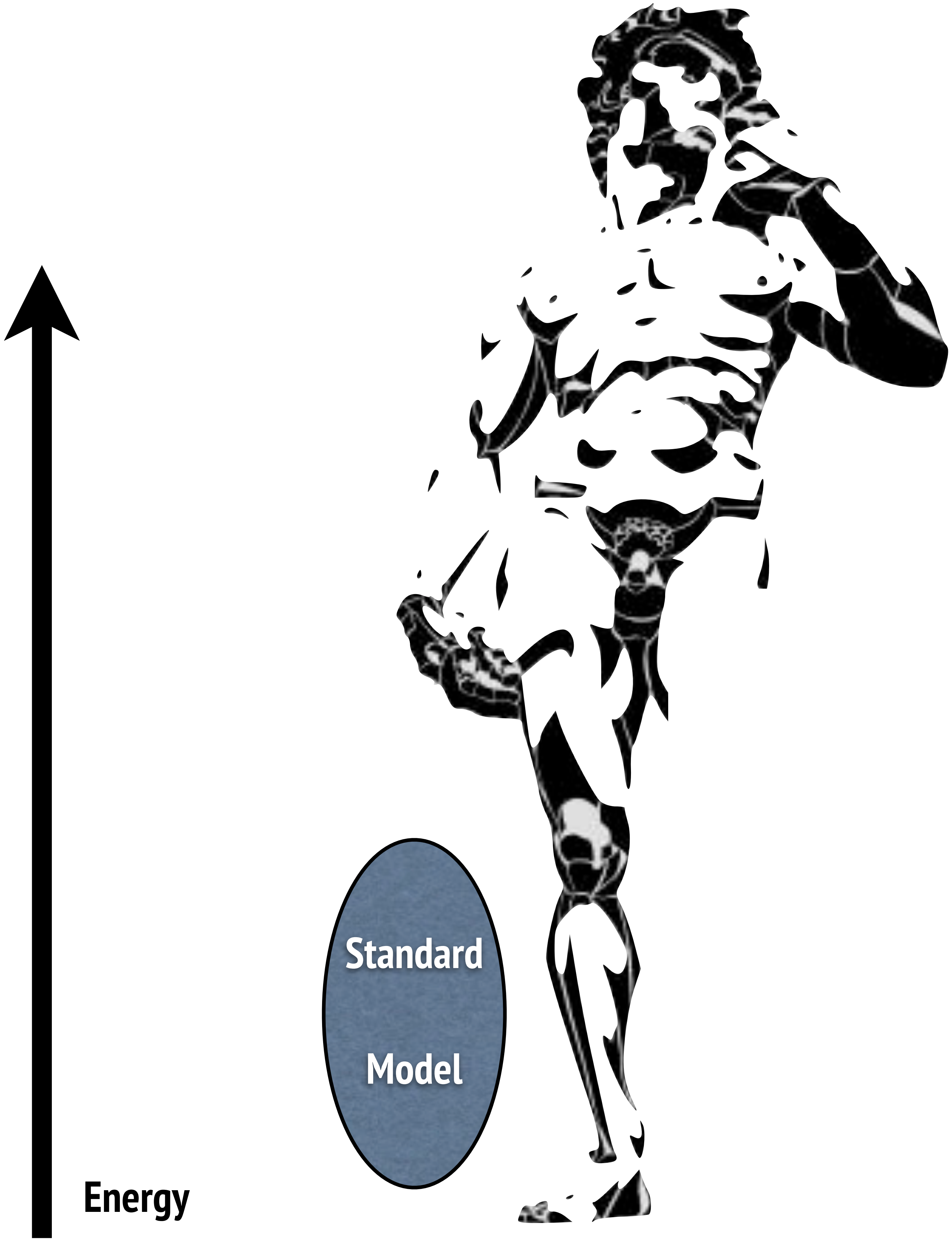
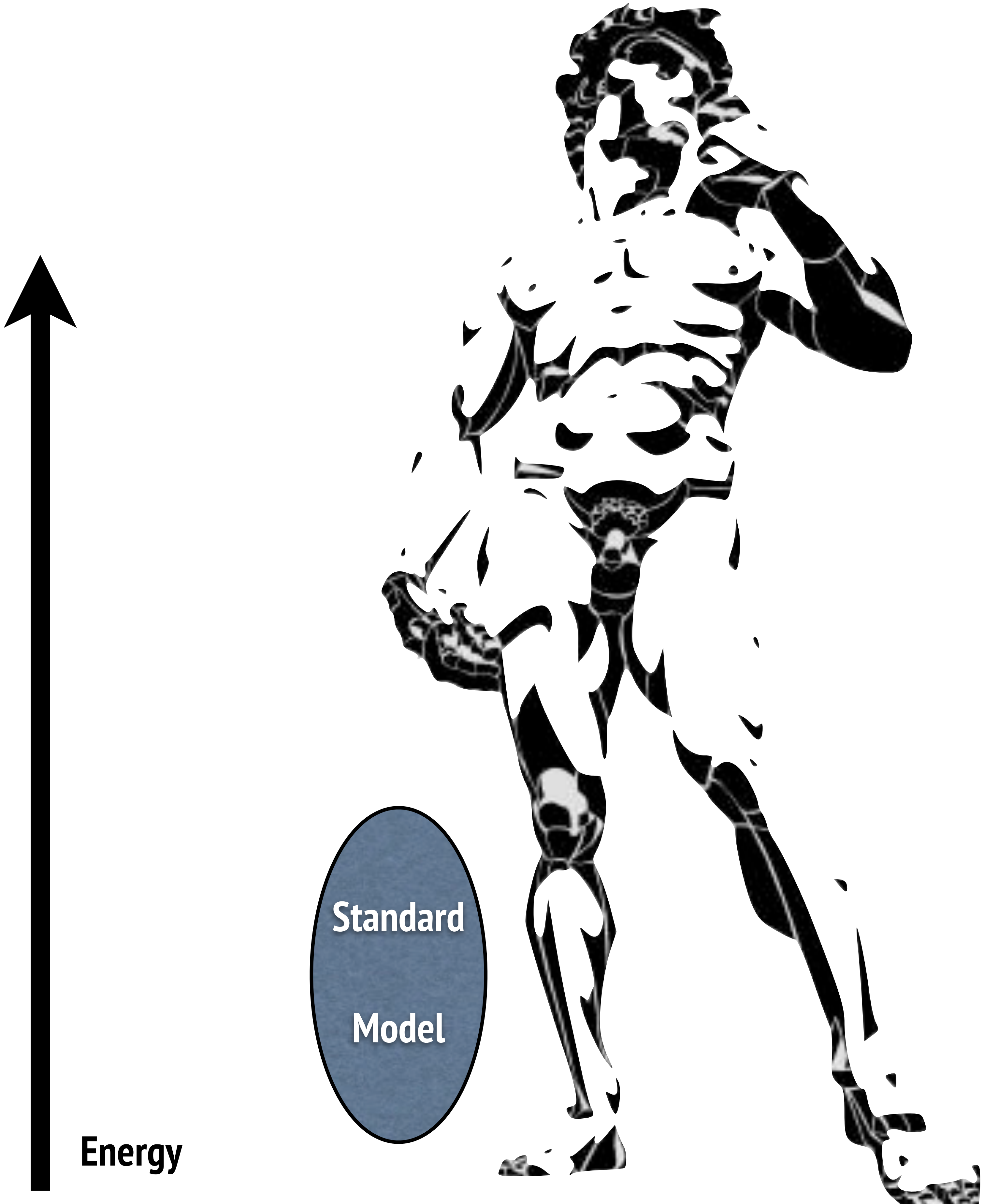


Answers wait in the high energy frontier where more symmetric beautiful theories arise ... often implying



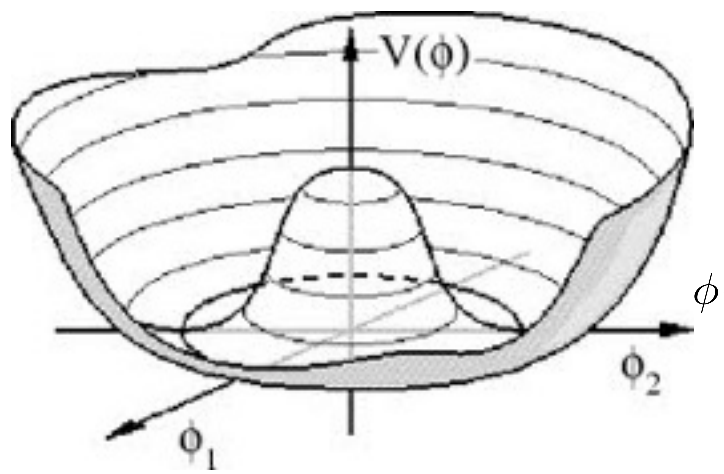
Answers wait in the
high energy frontier
where more symmetric
beautiful theories arise
… often implying

new low energy physics!

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

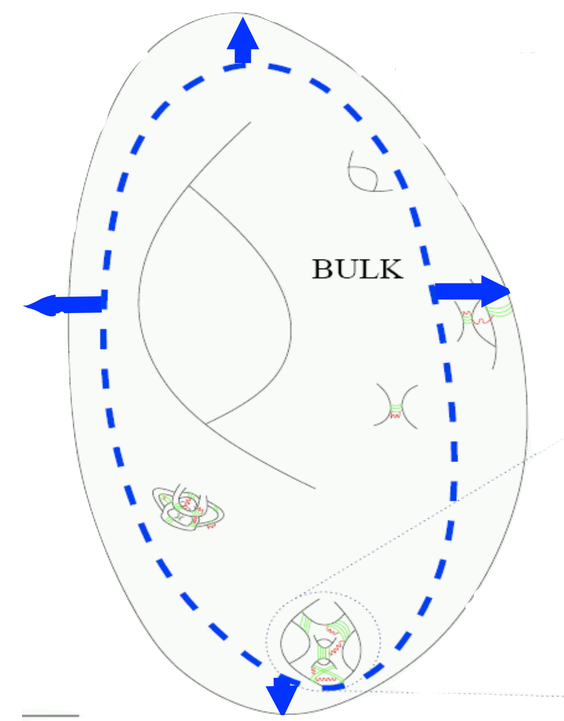
$$\mathcal{L}_{\rm kin} = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f^2$$

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

- small symmetry breaking $\longrightarrow$ 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

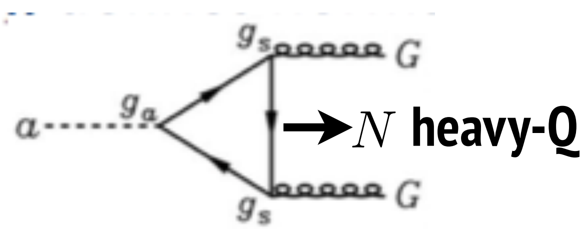
- **Shift symmetry allows some generic types of interactions**

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

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

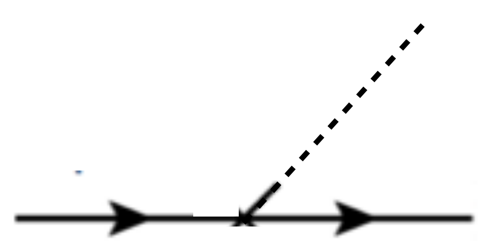
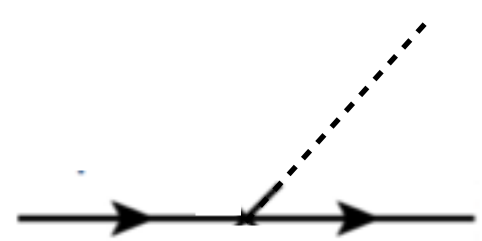
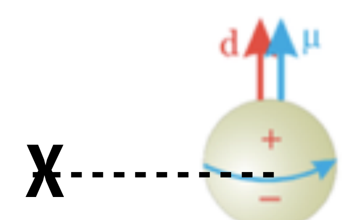
(canonically normalised)

- **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	electron coupling	nucleon coupling	$\not{CP}$ Neutron electric dipole
$-\frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a$	$g_{ef}[\bar{e}\gamma_5 e]a$	$g_{Nf}[\bar{N}\gamma_5 N]a$	$\propto \frac{1}{m_n}[F_{\mu\nu}\bar{n}\sigma^{\mu\nu}\gamma_5 n]\frac{A}{f_A}$
			

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

$$\Downarrow$$

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

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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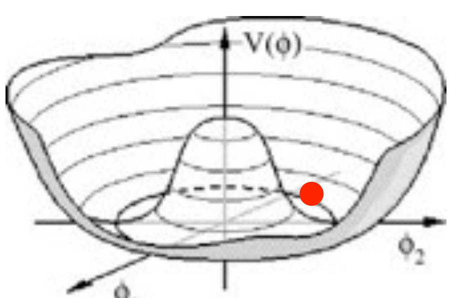
Dark matter / vacuum realignment



pick up a vacuum when quasi-degenerate

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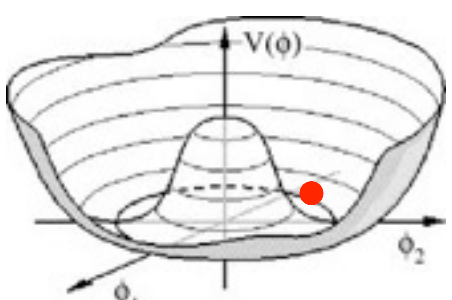

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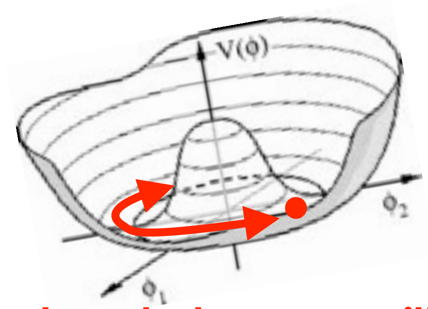

ups! not the lowest ... oscillate!

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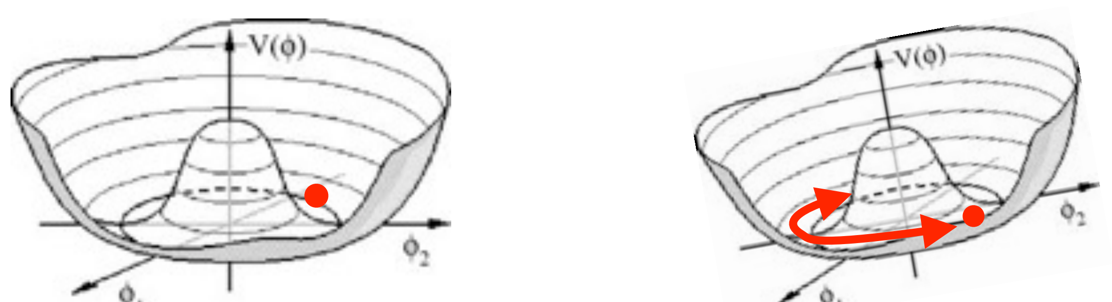

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cold DM in oscillations [cosmology dependent]

$$\Omega h_c^2 \simeq 0.12\sqrt{\frac{m_a}{\rm meV}}\left(\frac{a_i}{3\times10^{12}\,{\rm GeV}}\right)^2$$

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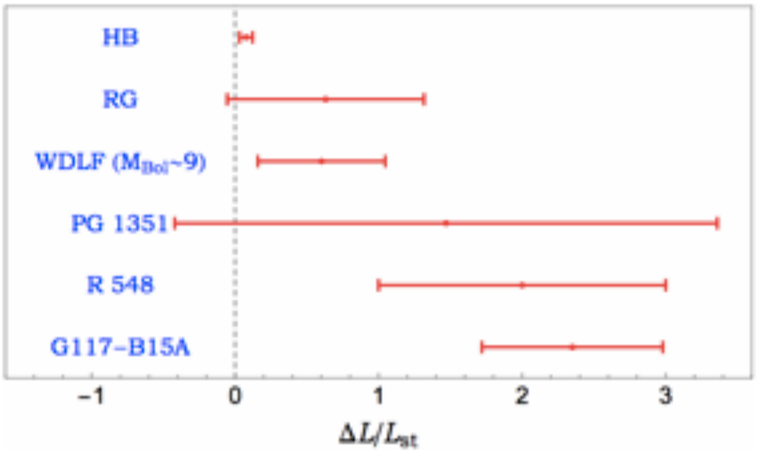
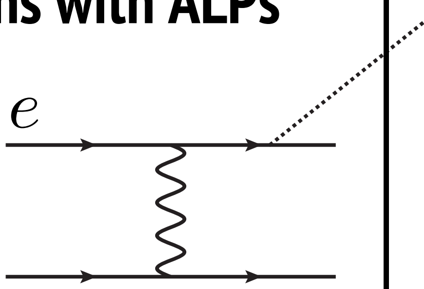
Anomalous Star cooling / ALP emission

Theory fits better some observations with ALPs

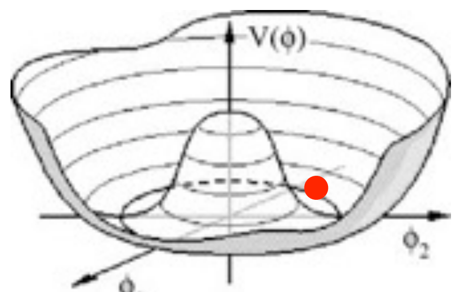


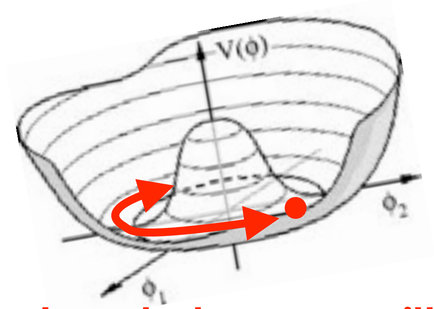


ALP bremstrahlung

Giannotti 2016

Dark matter / vacuum realignment





pick up a vacuum when quasi-degenerate   ups! not the lowest ... oscillate!

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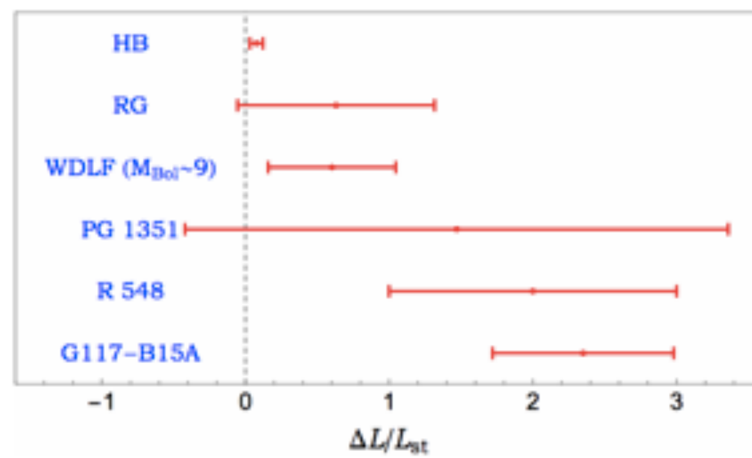
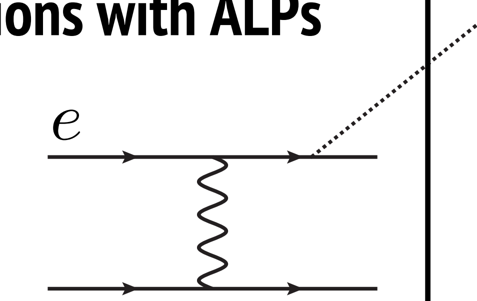


Giannotti 2016



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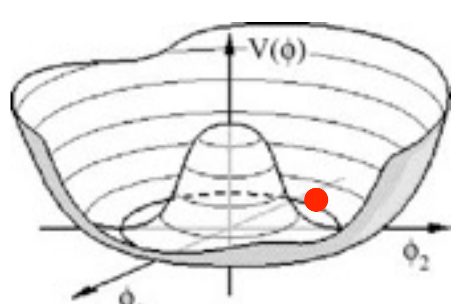

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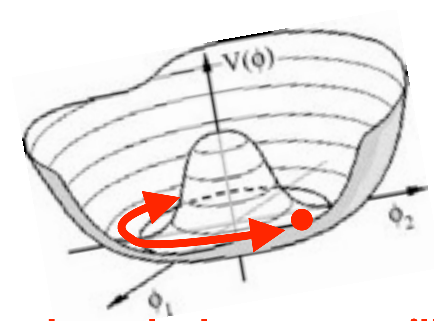

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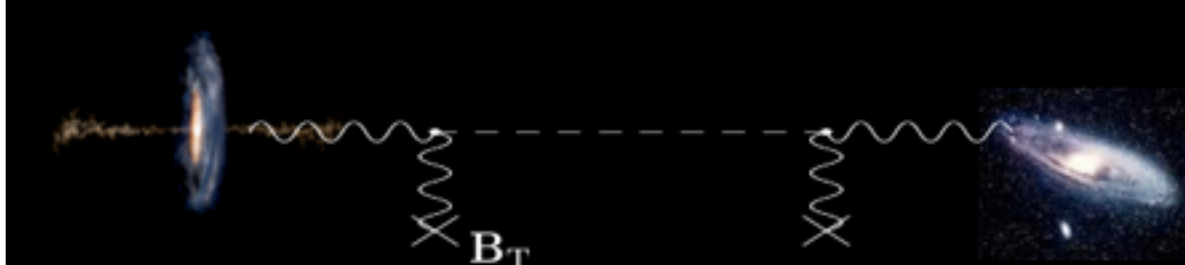
γ-ray transparency / photon regeneration

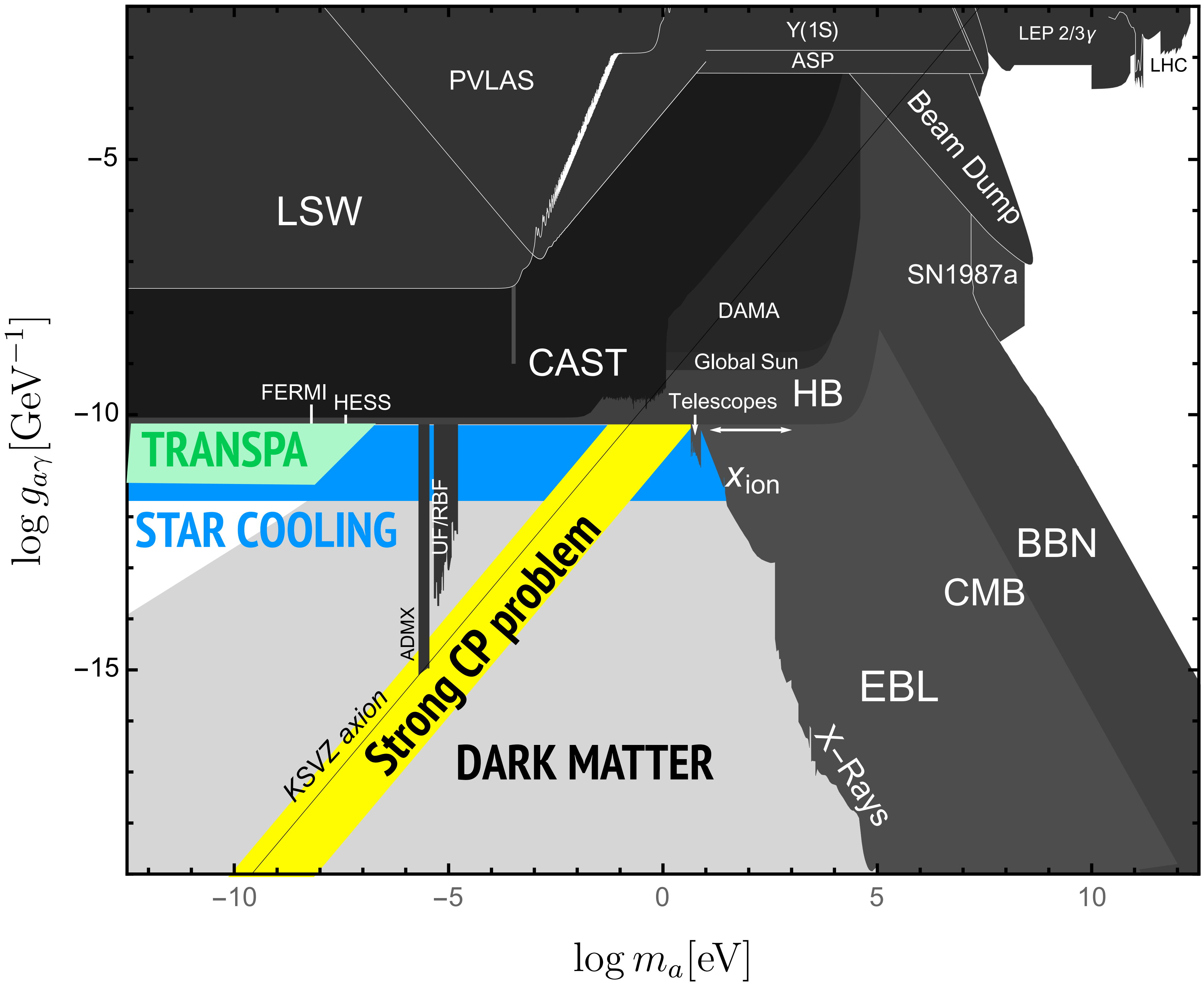
Too many gamma-rays from far away sources?



low estimate of opacity vs ALP-mediated regeneration

Trostski 2017

Hints and constraints (example)



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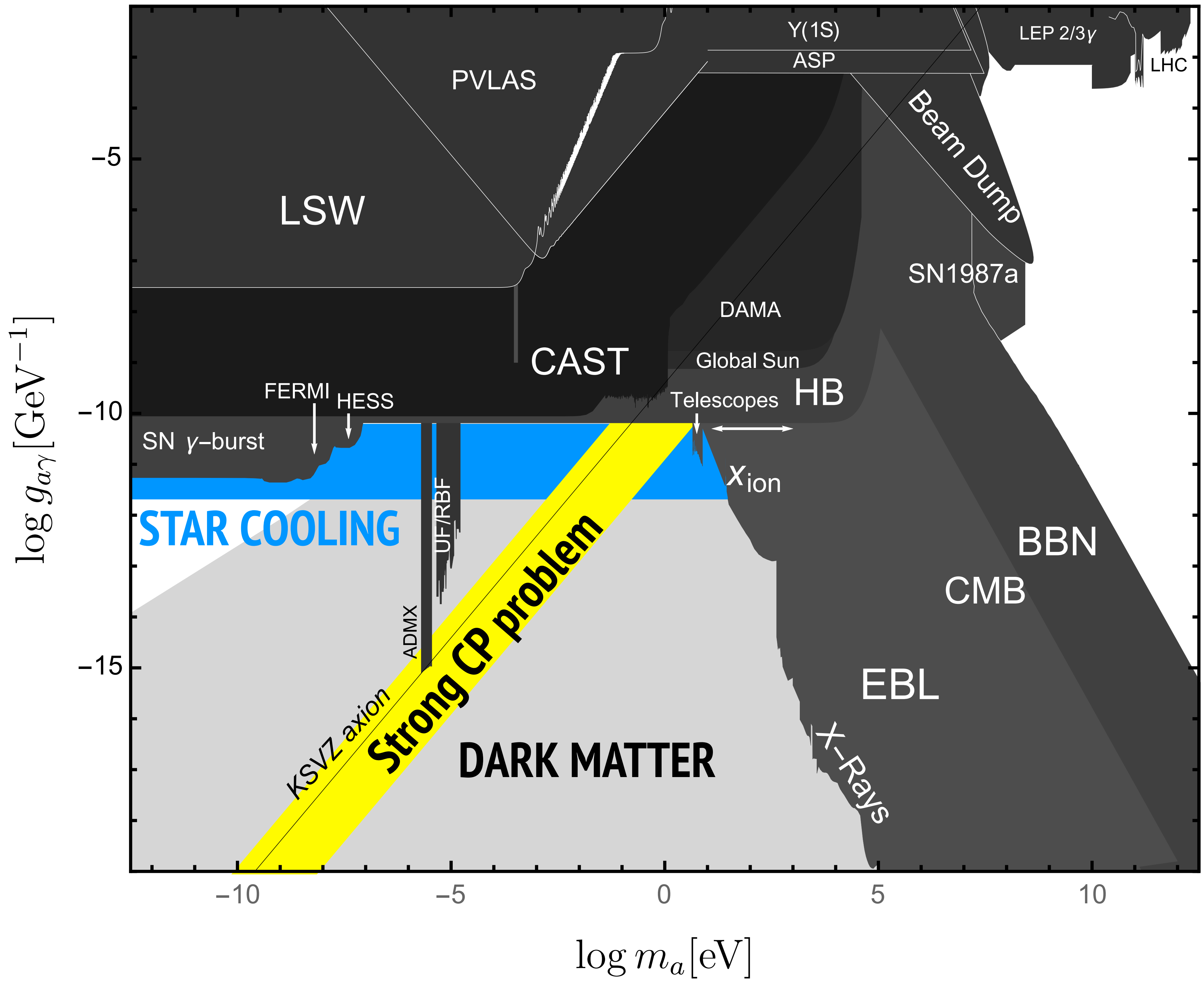
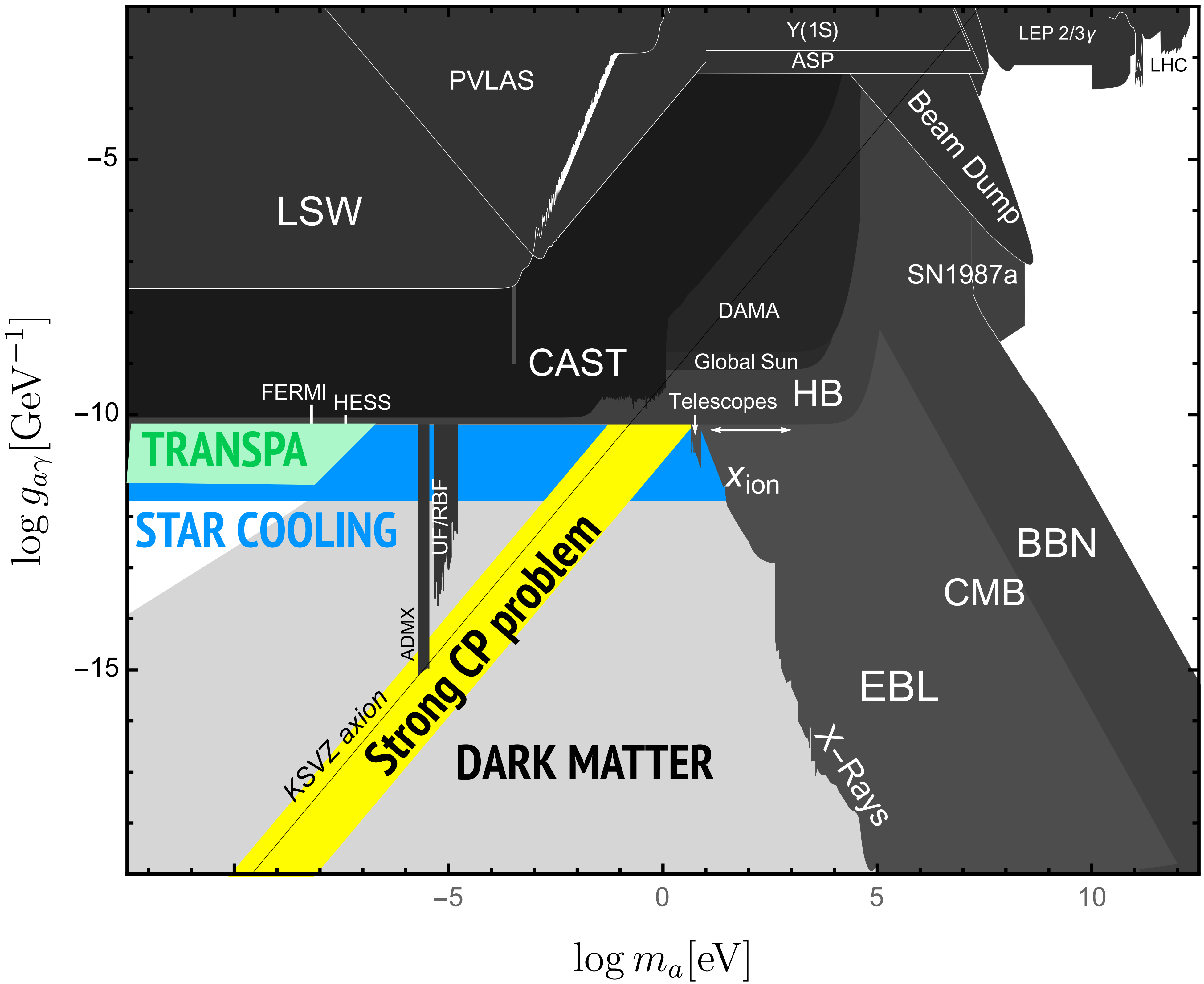


birds and stones ...



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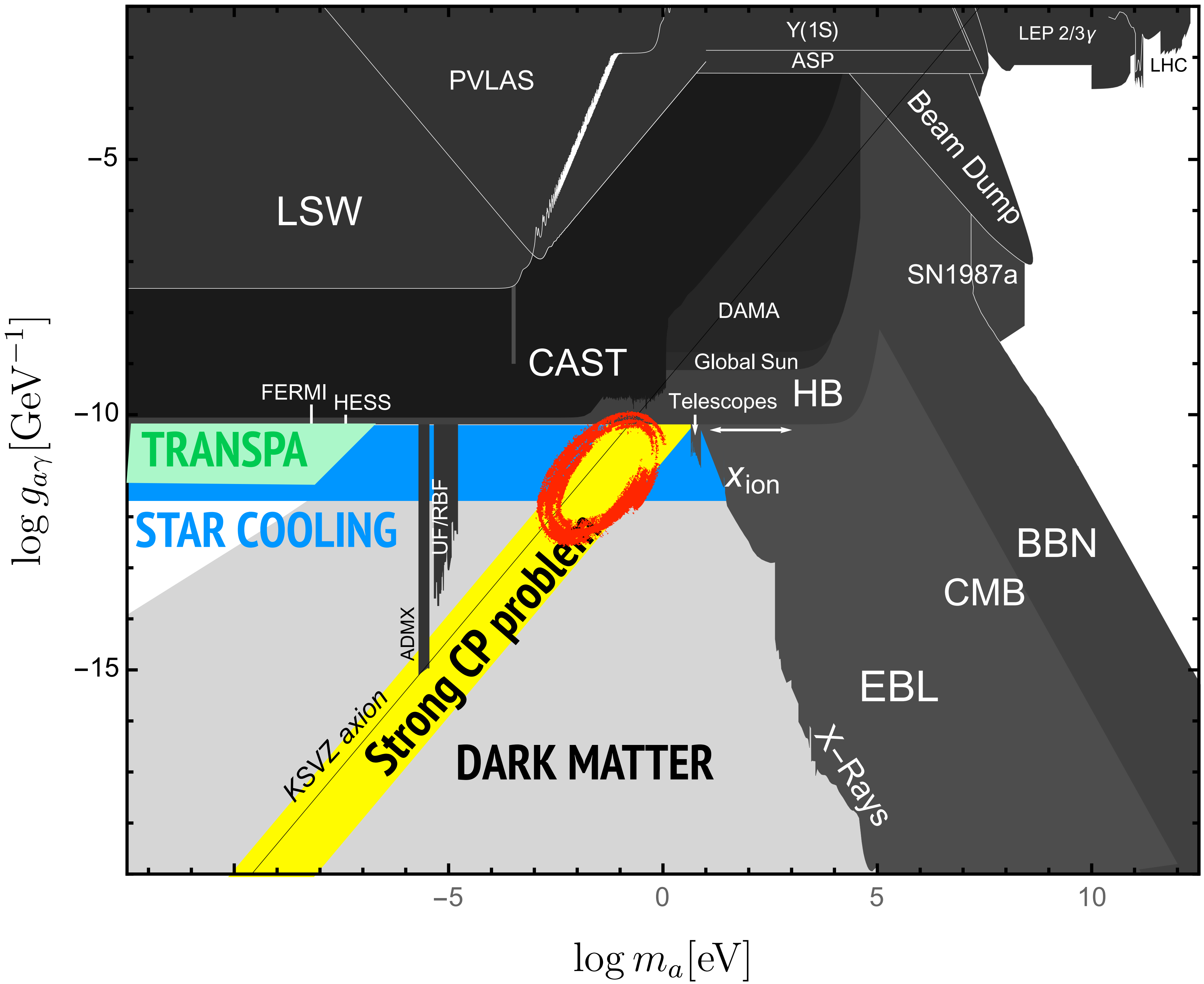

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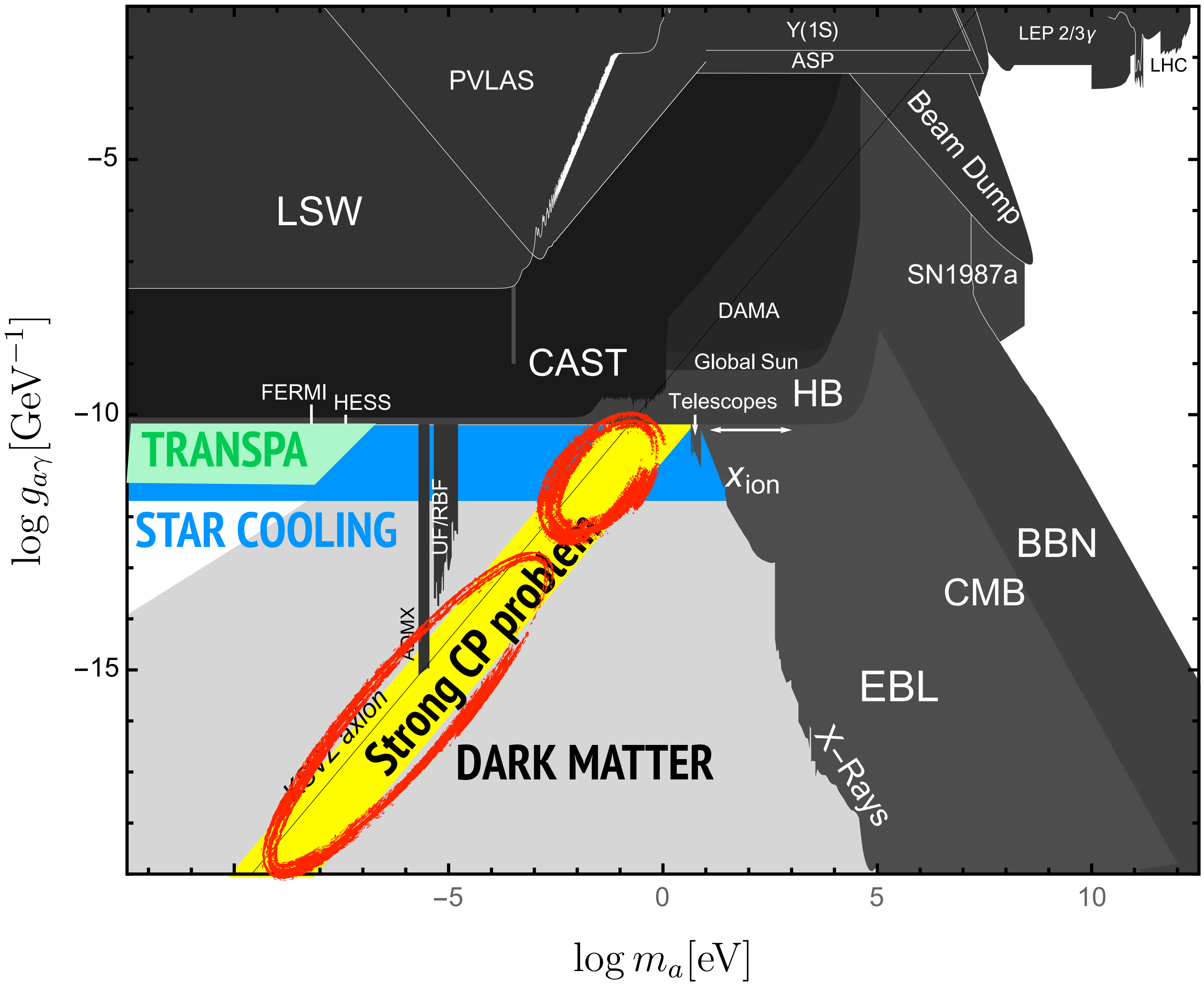

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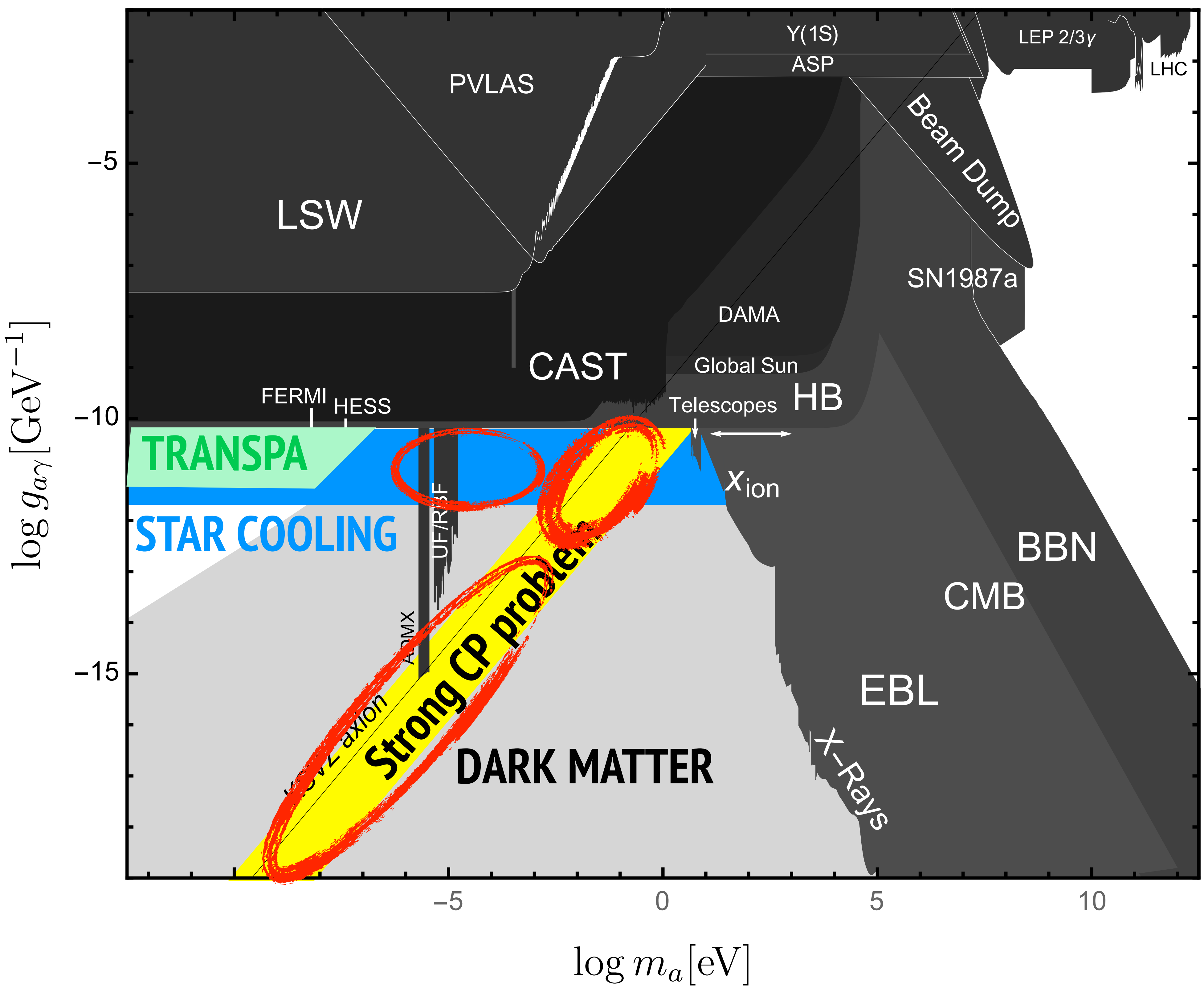

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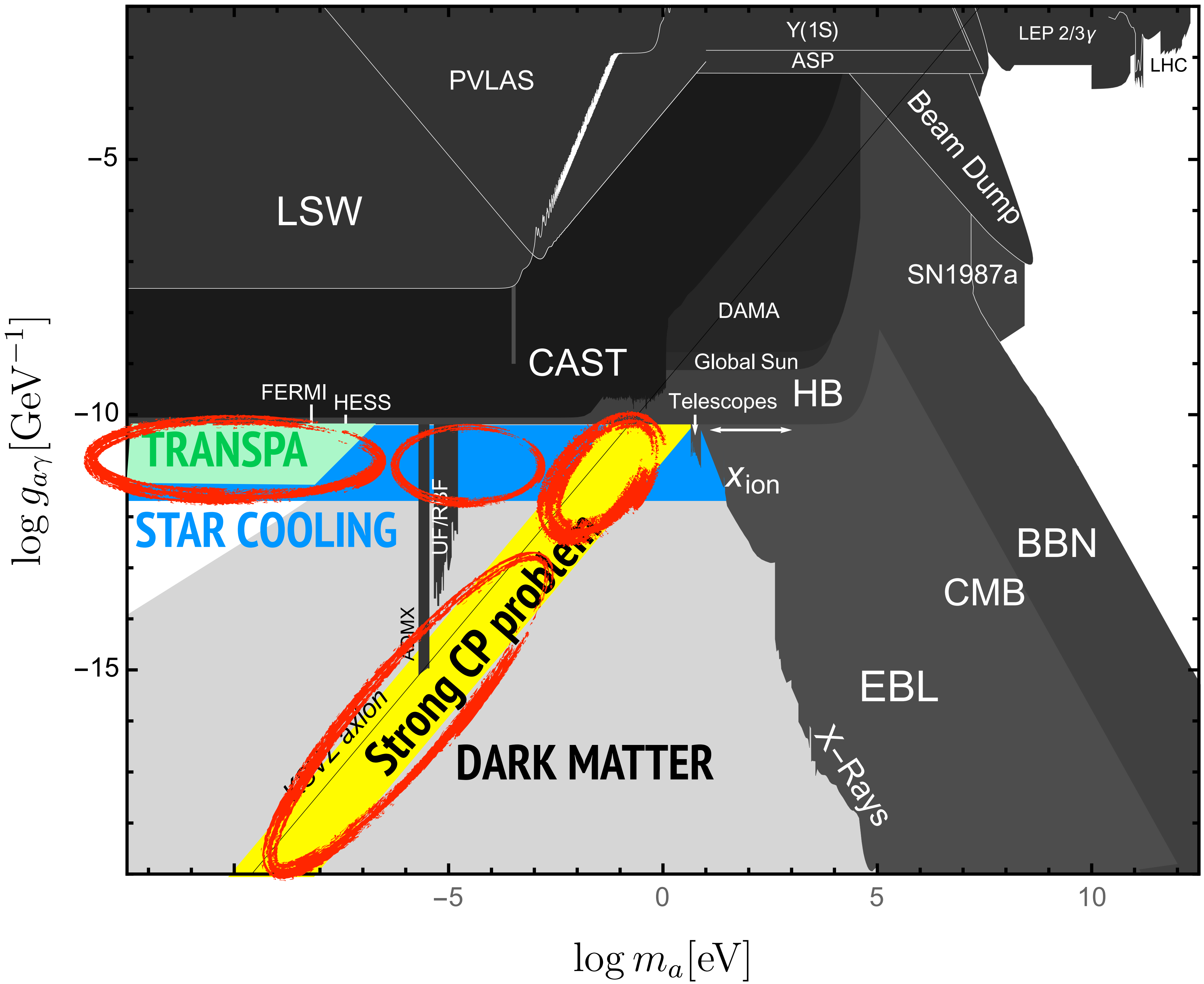

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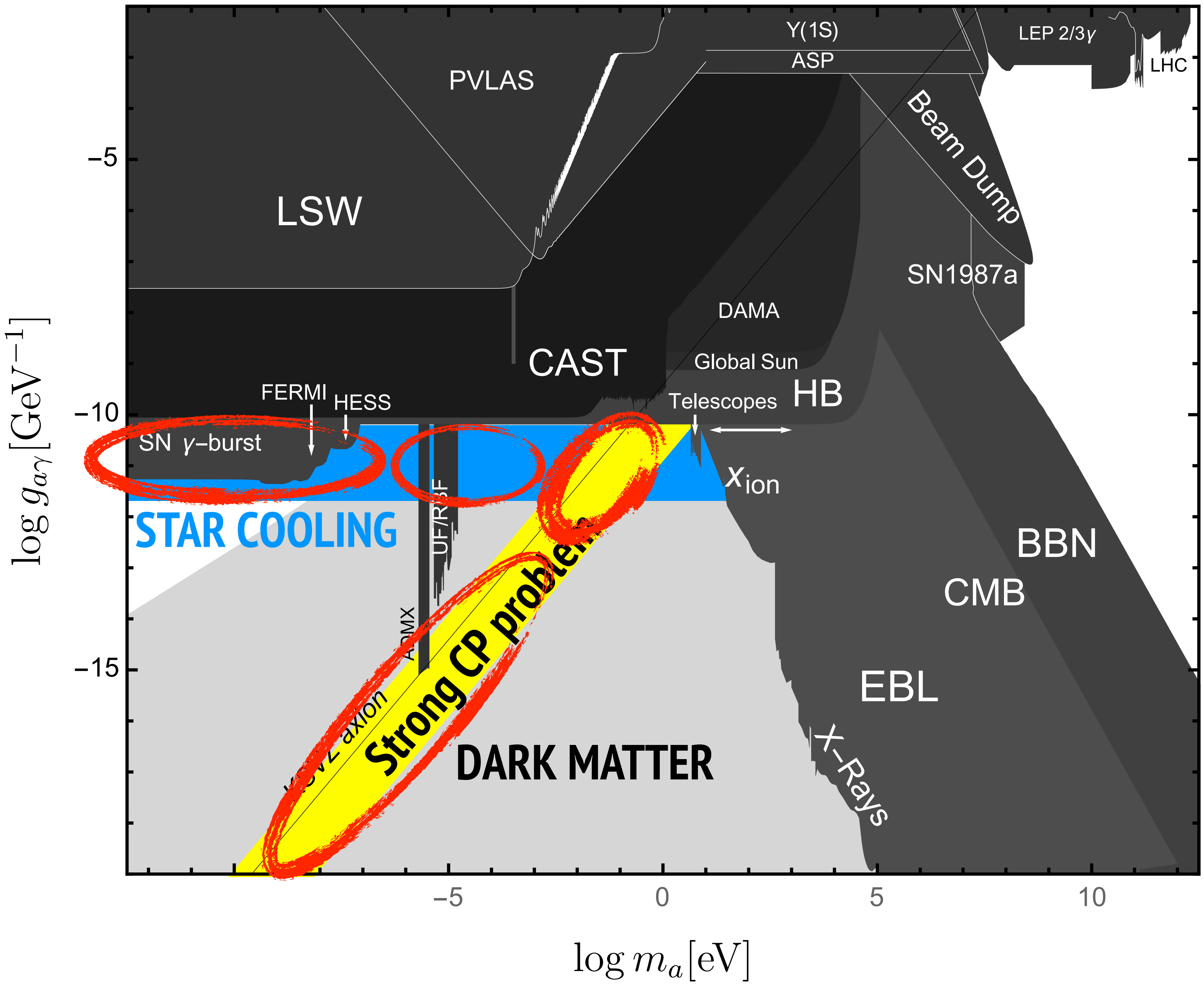
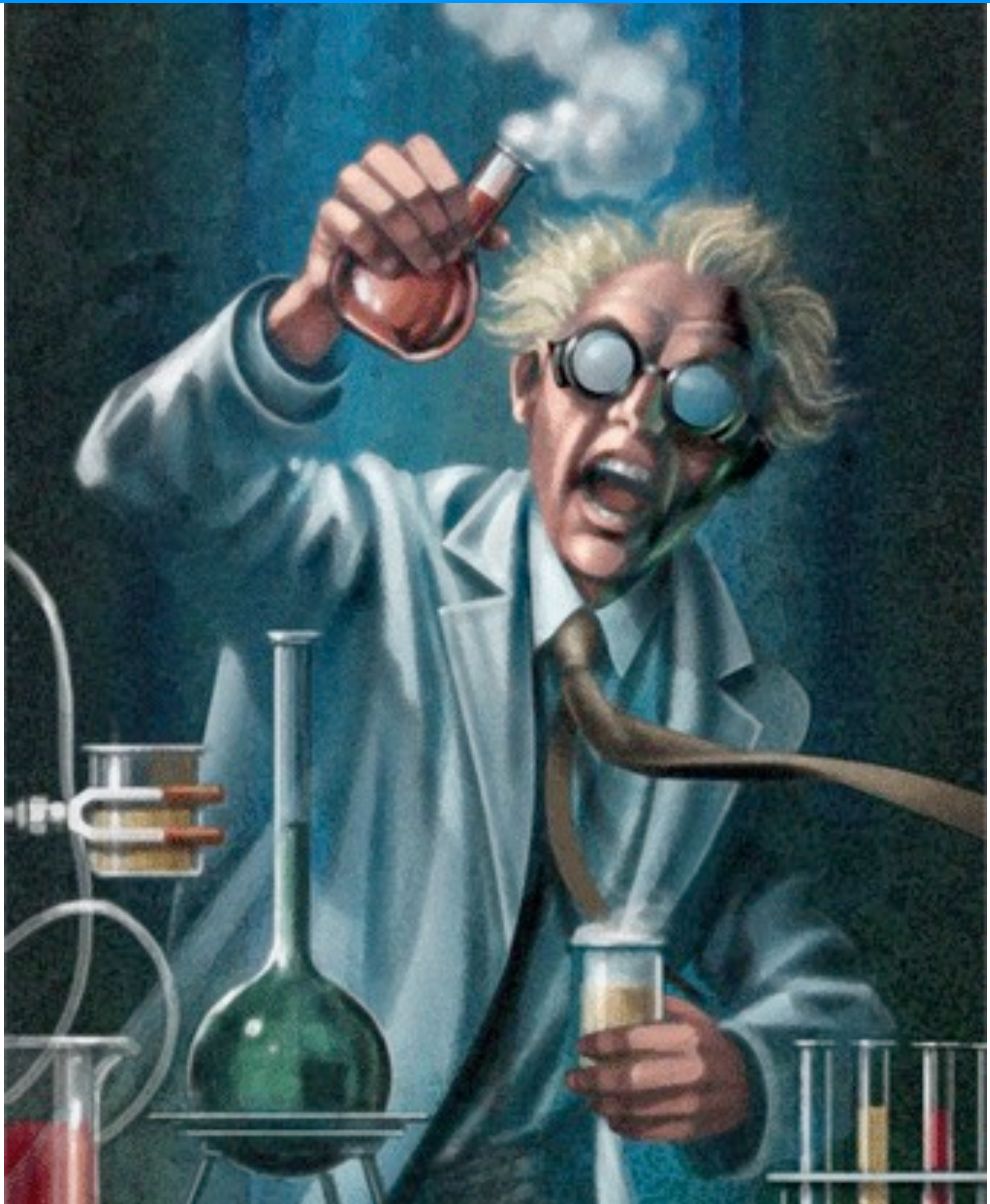
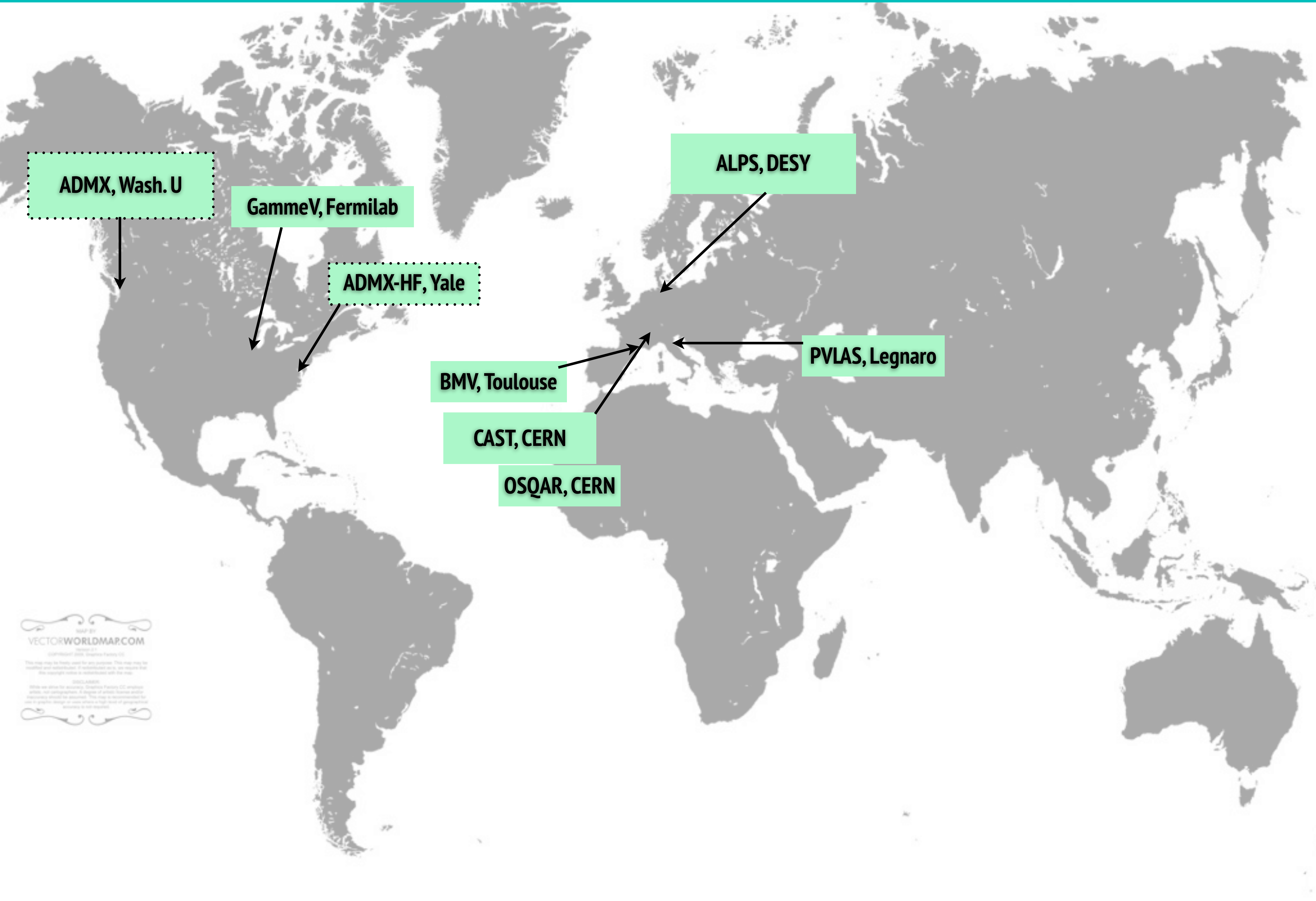


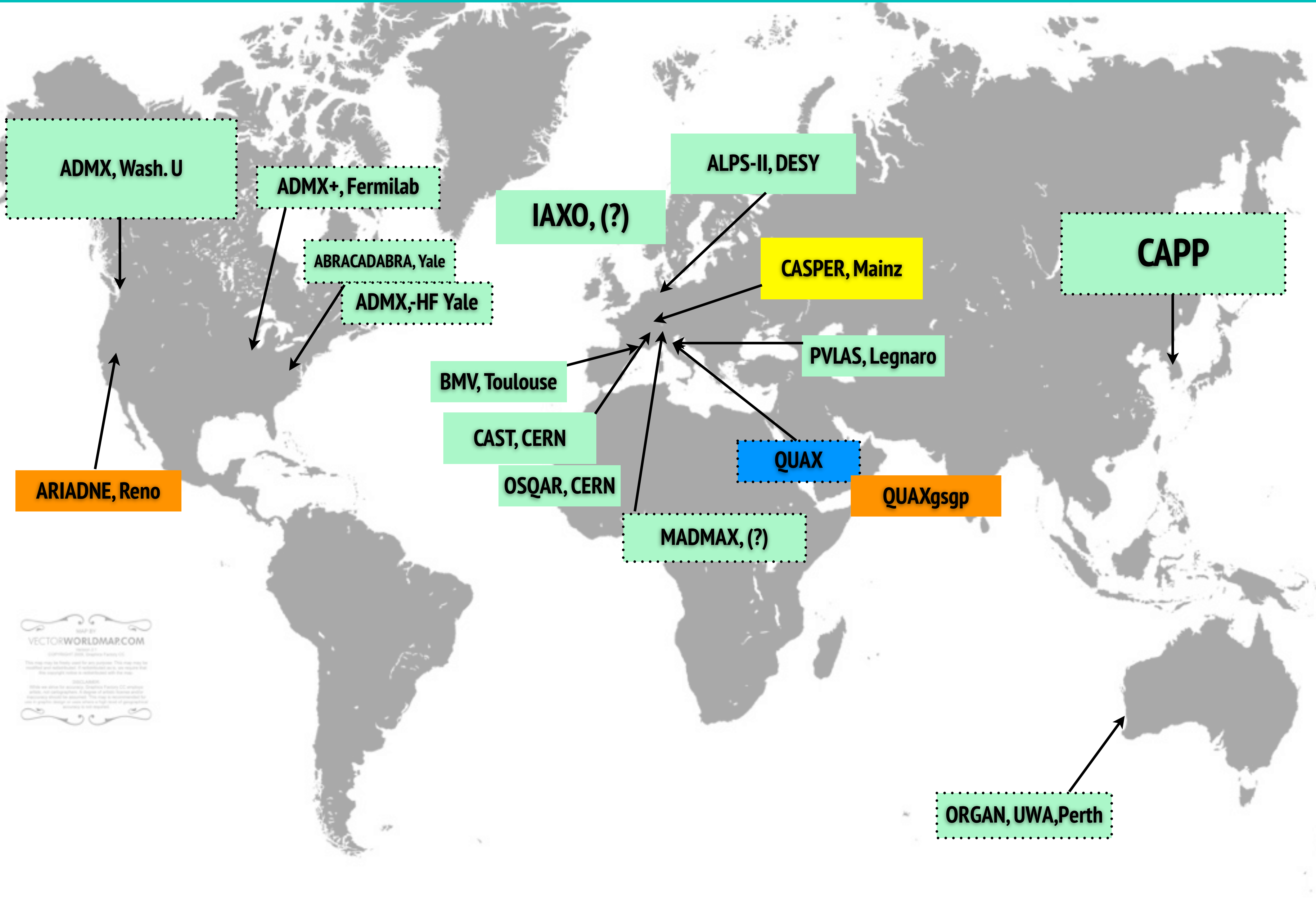
Direct Detection of ALPs



Lab experiments 2011



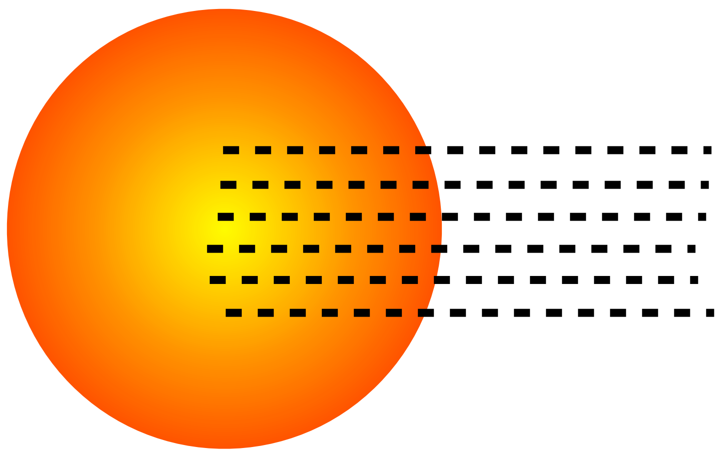
Lab experiments 2017



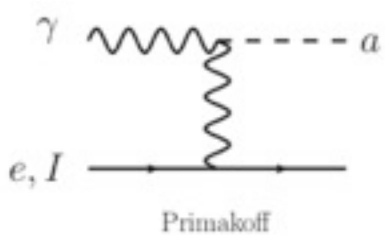
Helioscopes (search solar ALPs)

Sikivie PRL 1983

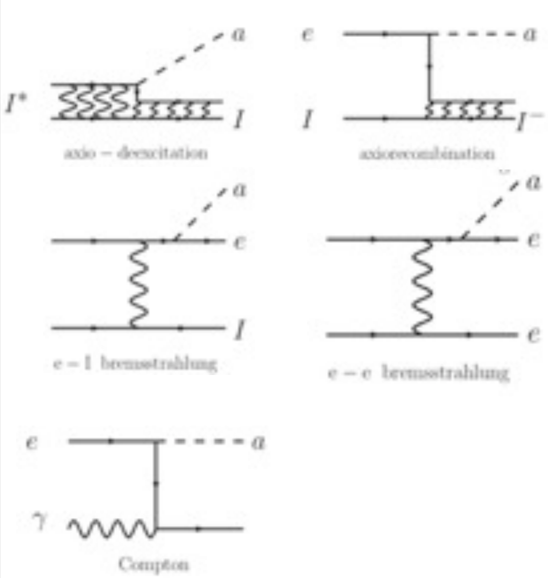
The Sun is a copious emitter of ALPs!

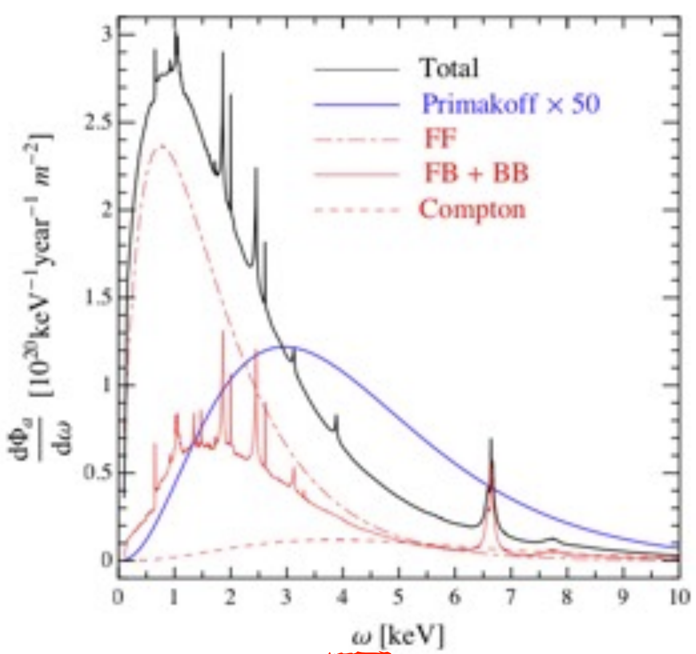


photon coupling



electron coupling





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

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

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convert into X-rays　　focus　　detect

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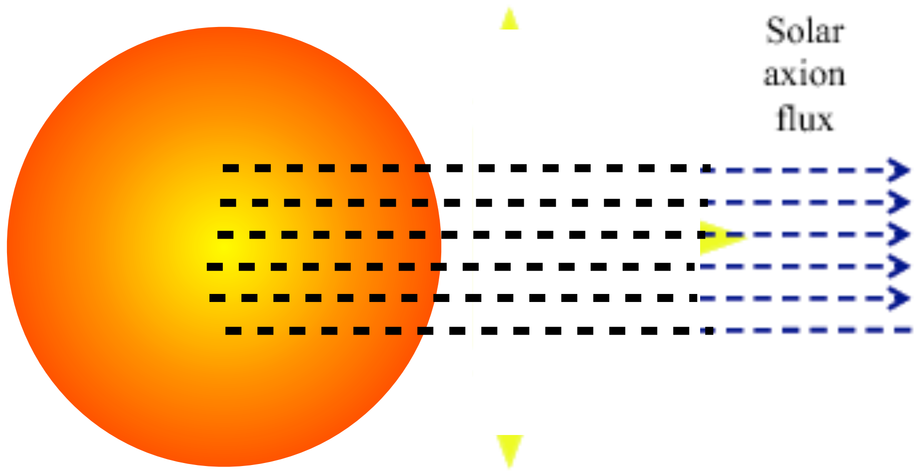

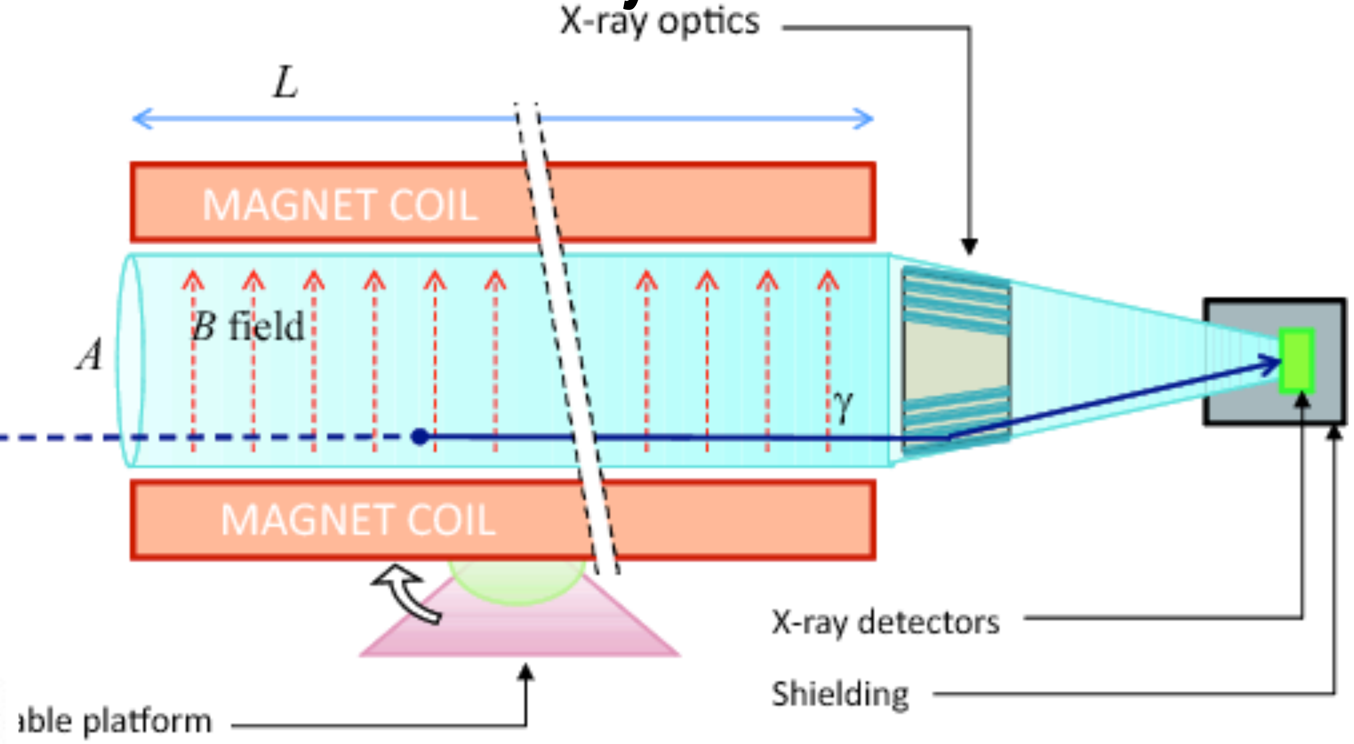

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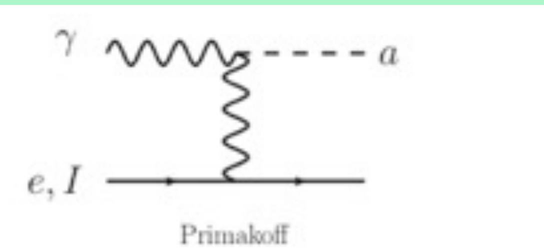

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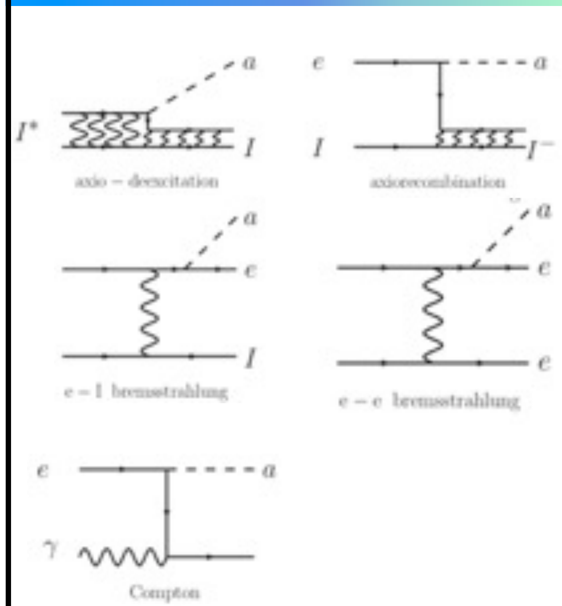

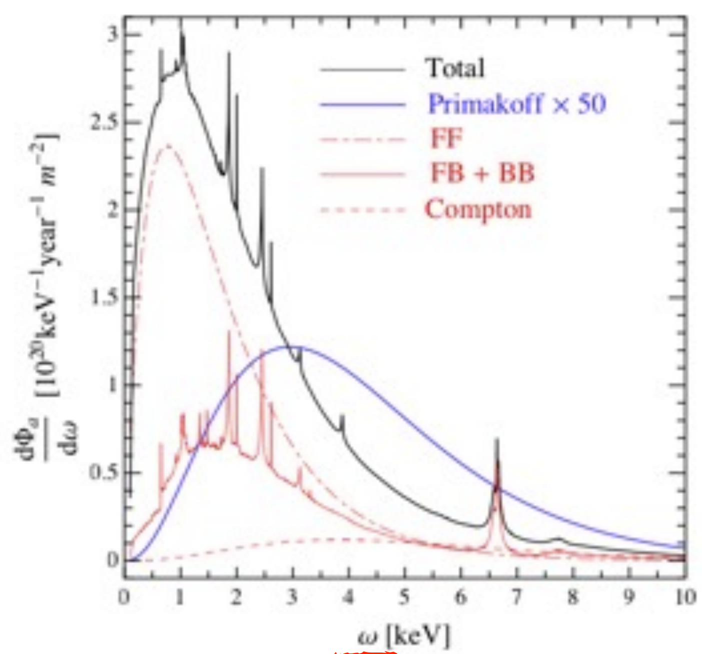

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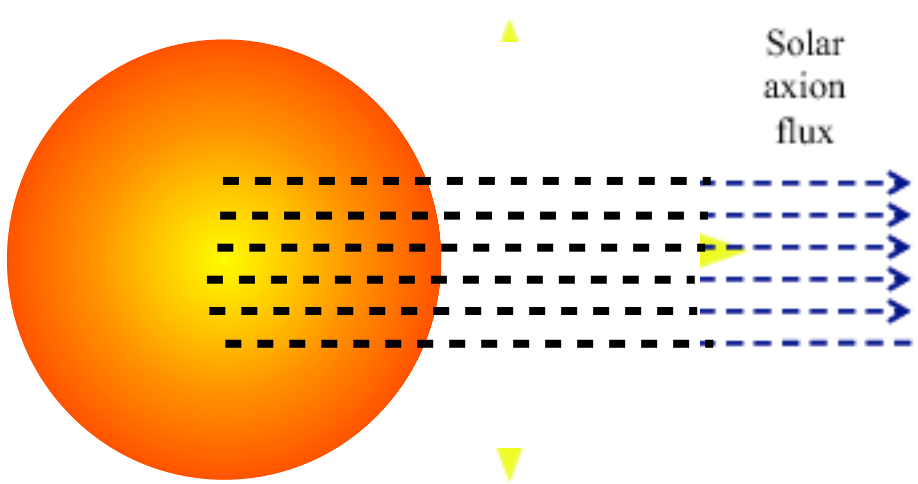

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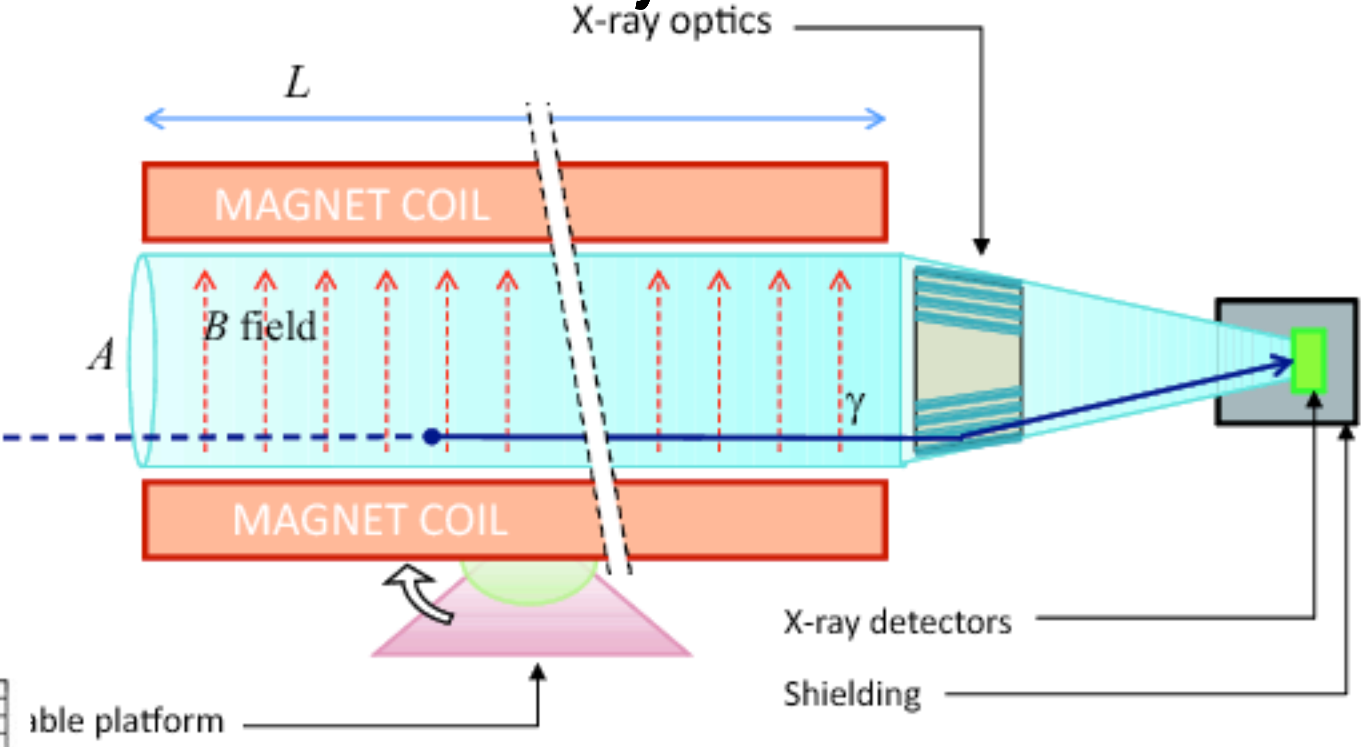

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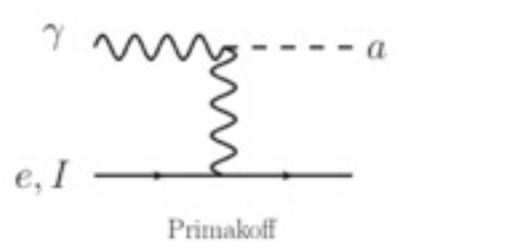

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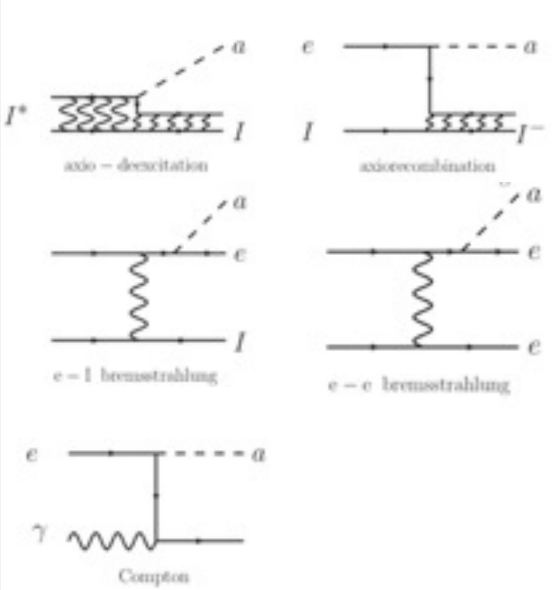

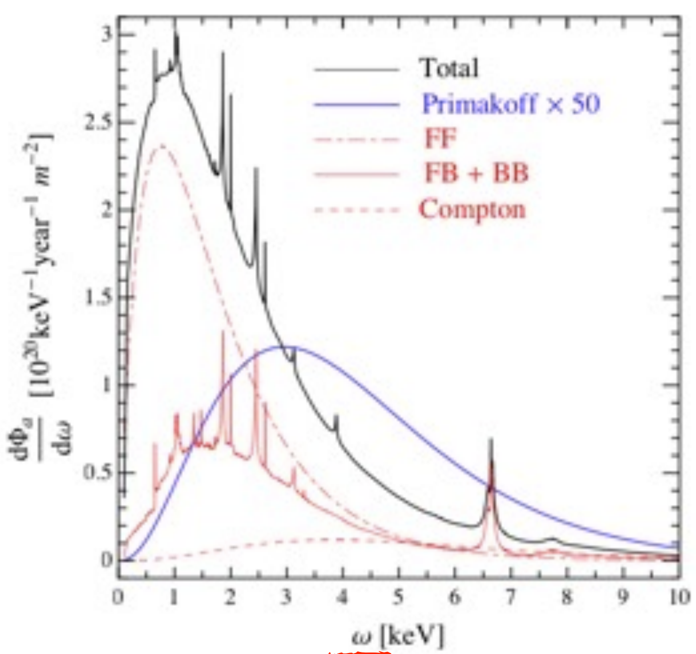

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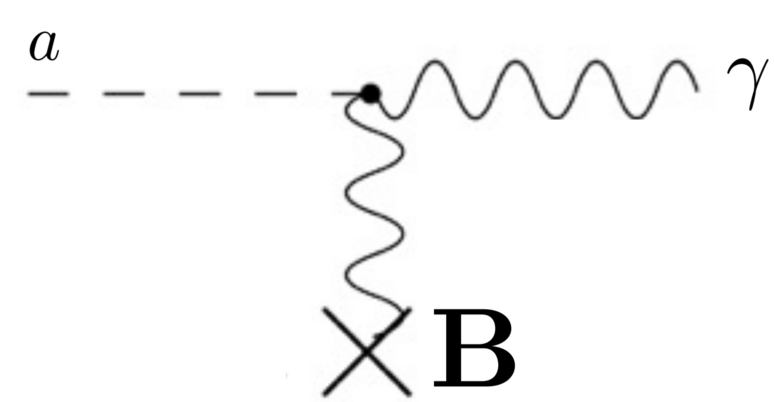
Coherent Conversion along the B-field

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

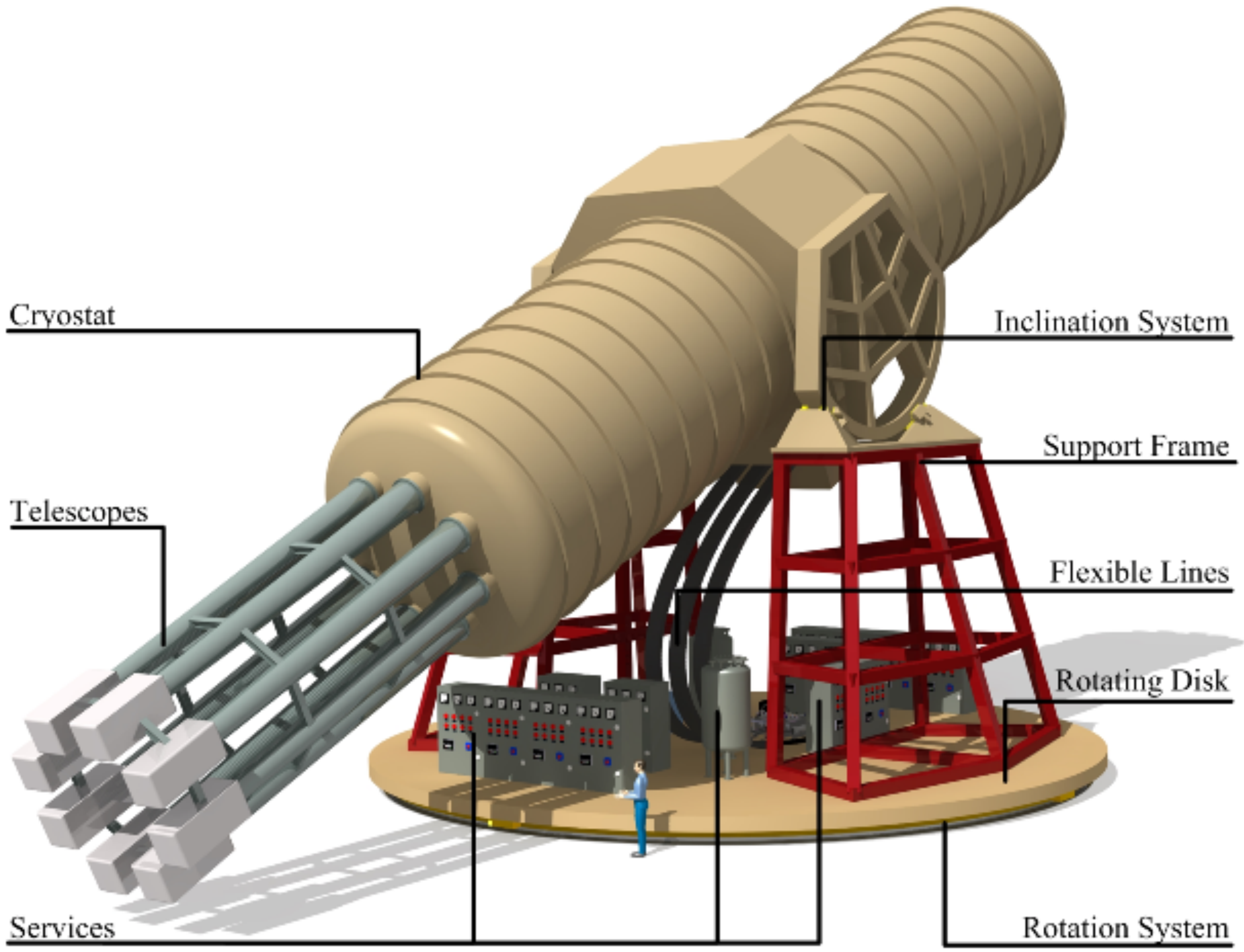


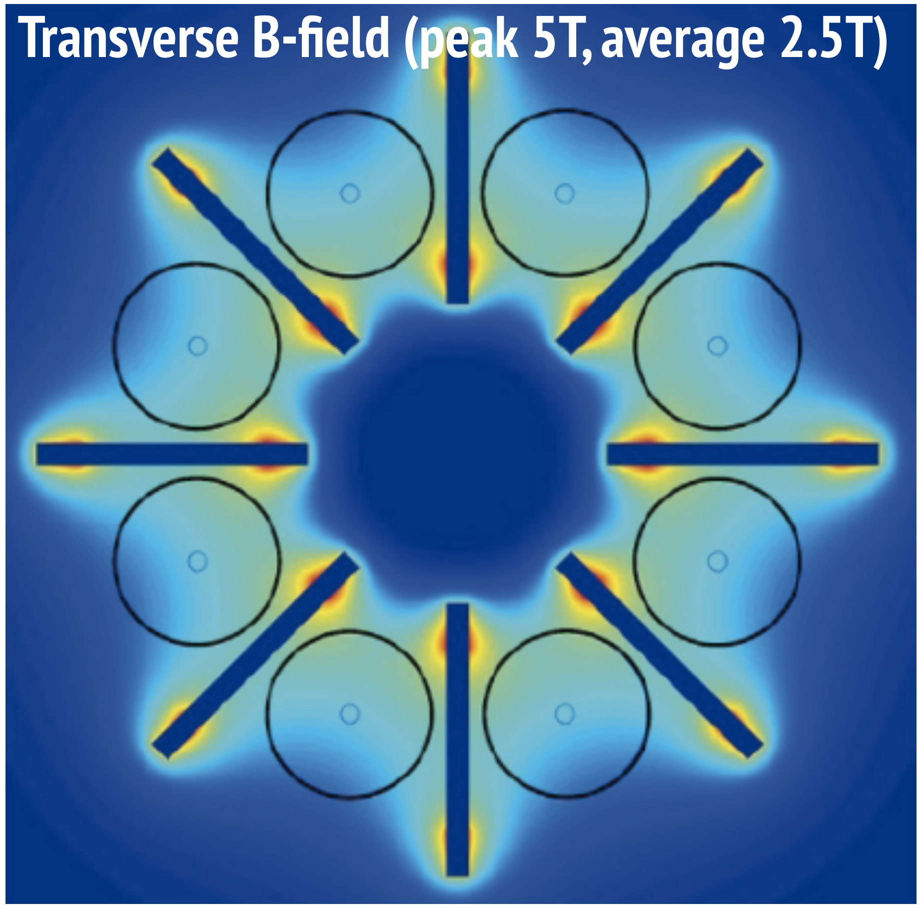
International AXion Observatory

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)

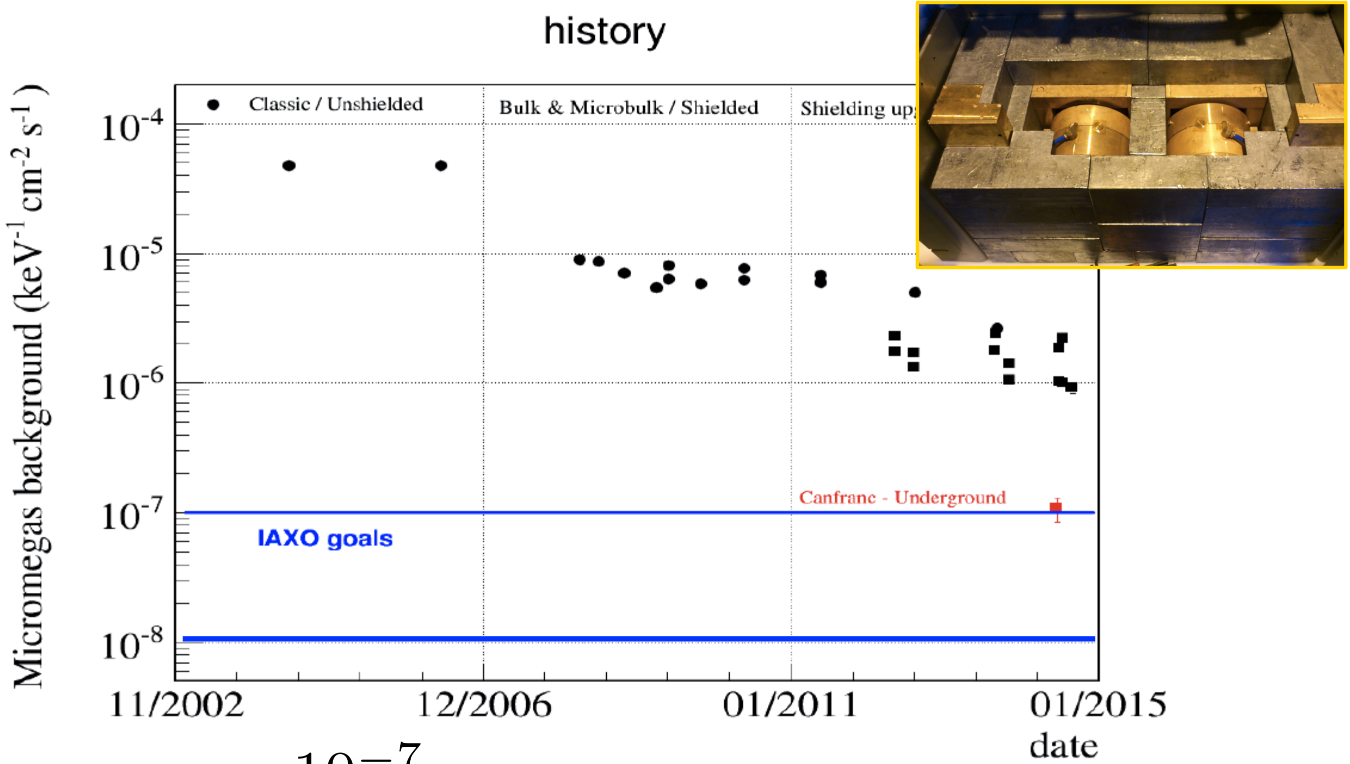




IAXO detectors

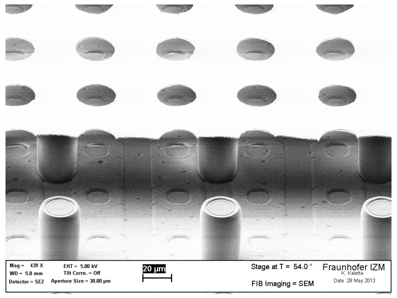
Goal background level for IAXO: $\dfrac{10^{-7} \rightarrow 10^{-8}}{\mathrm{keV\ cm^2\ s}}$

- **Small Micromegas-TPC chambers:**
  - **Shielding**
  - **Radiopure components**
  - **Offline discrimination**

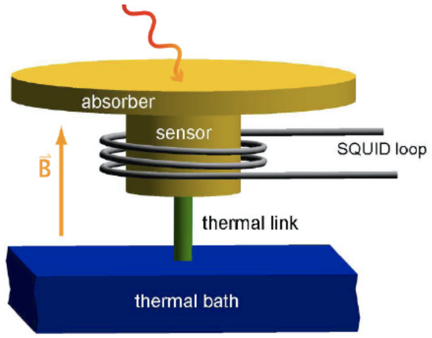


Already demonstrated: $\dfrac{8 \times 10^{-7}}{\mathrm{keV\ cm^2\ s}}$ **(in CAST 2014 result)** $\dfrac{10^{-7}}{\mathrm{keV\ cm^2\ s}}$ **(underground at LSC)**

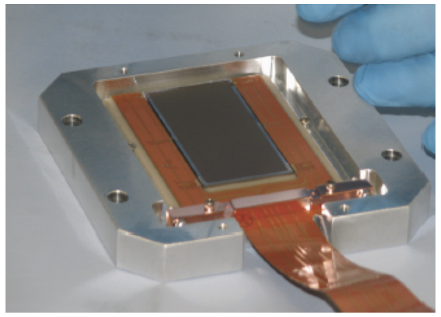
- **Gridpix/InGrid,**



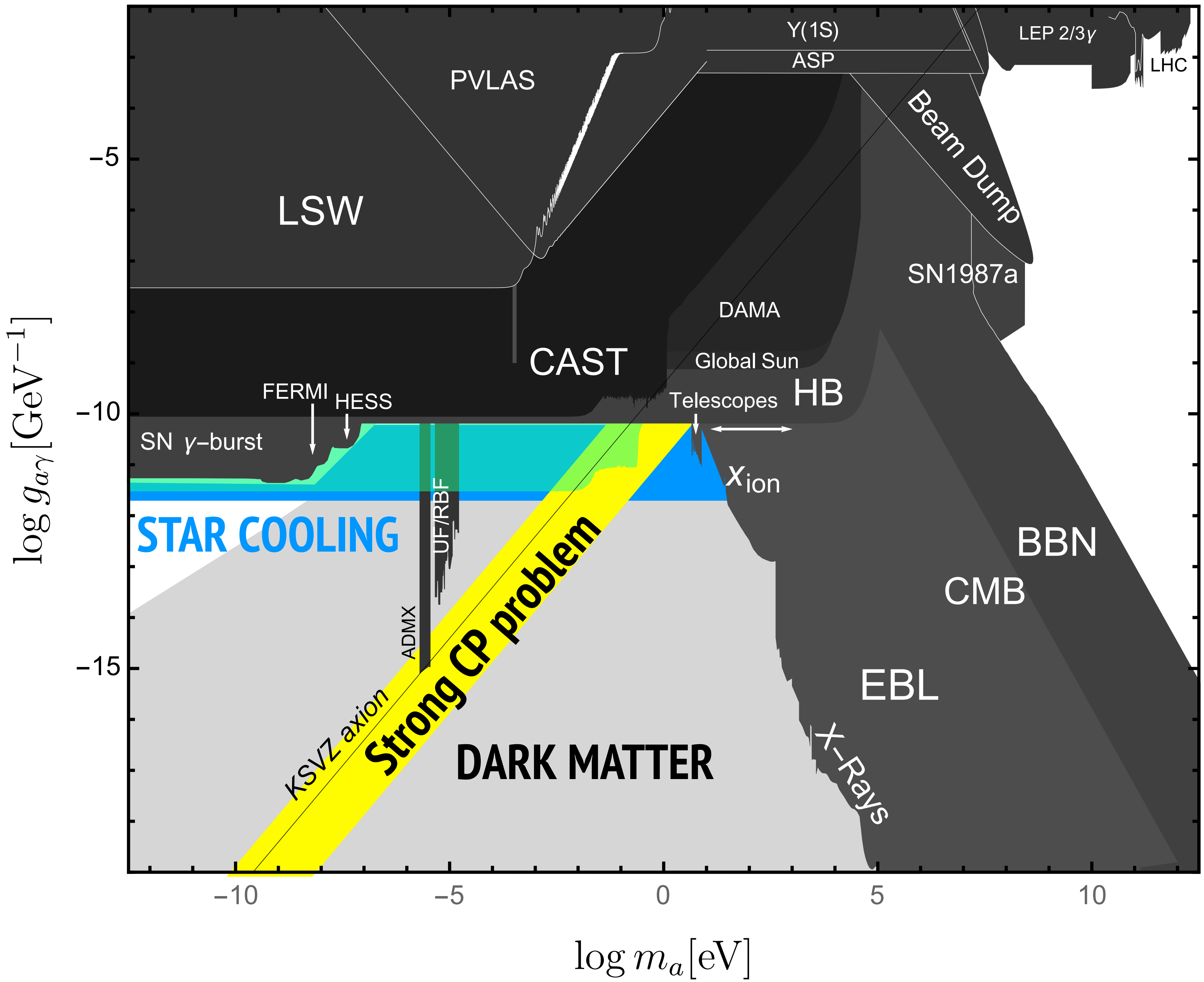
- **MMC**



- **Low noise CCDs**



IAXO reach



PVLAS
Y(1S)
ASP
LEP 2/3γ
LHC
LSW
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
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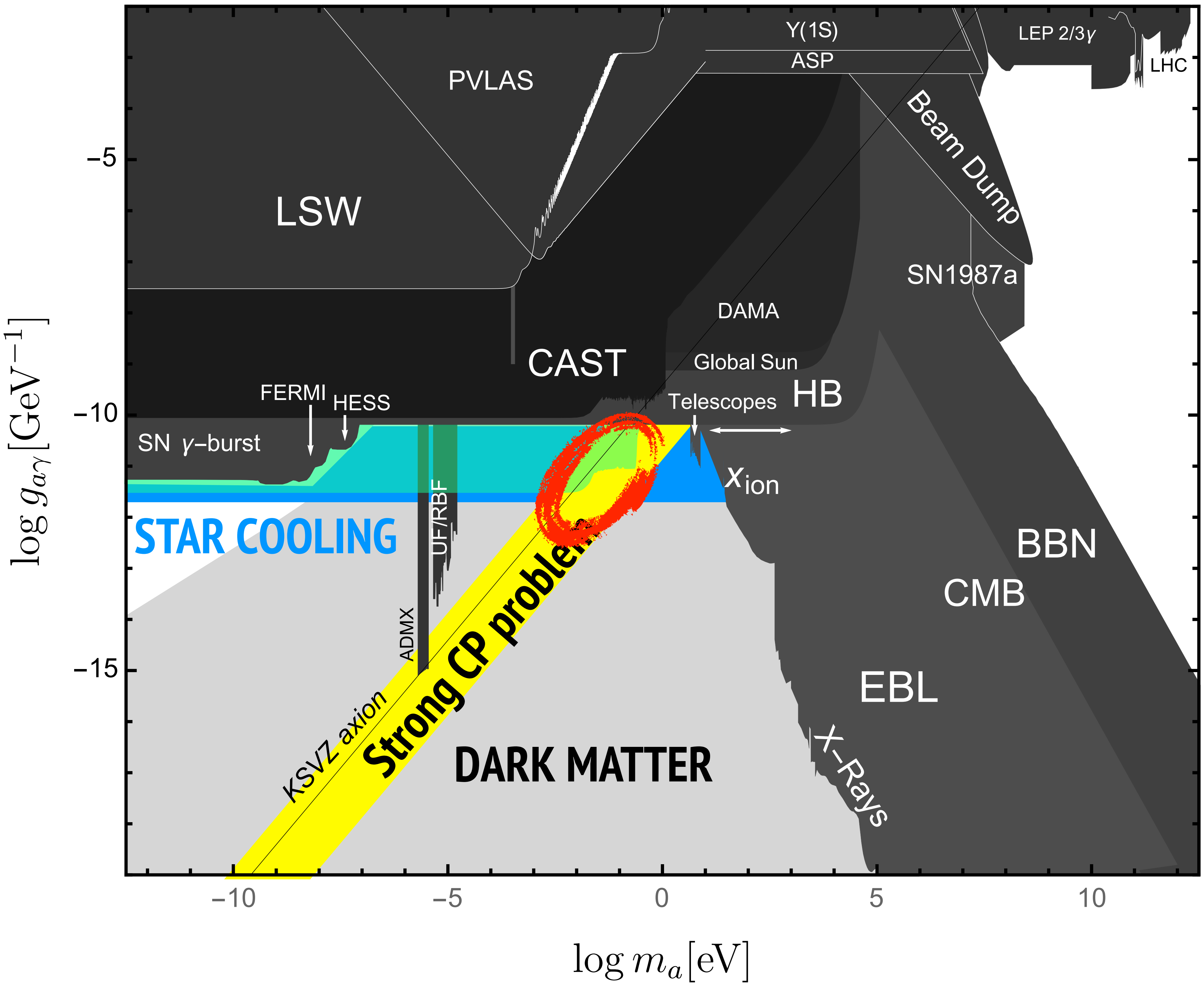
0
5
10
$\log g_{a\gamma}[\mathrm{GeV}^{-1}]$
$\log m_a[\mathrm{eV}]$

IAXO reach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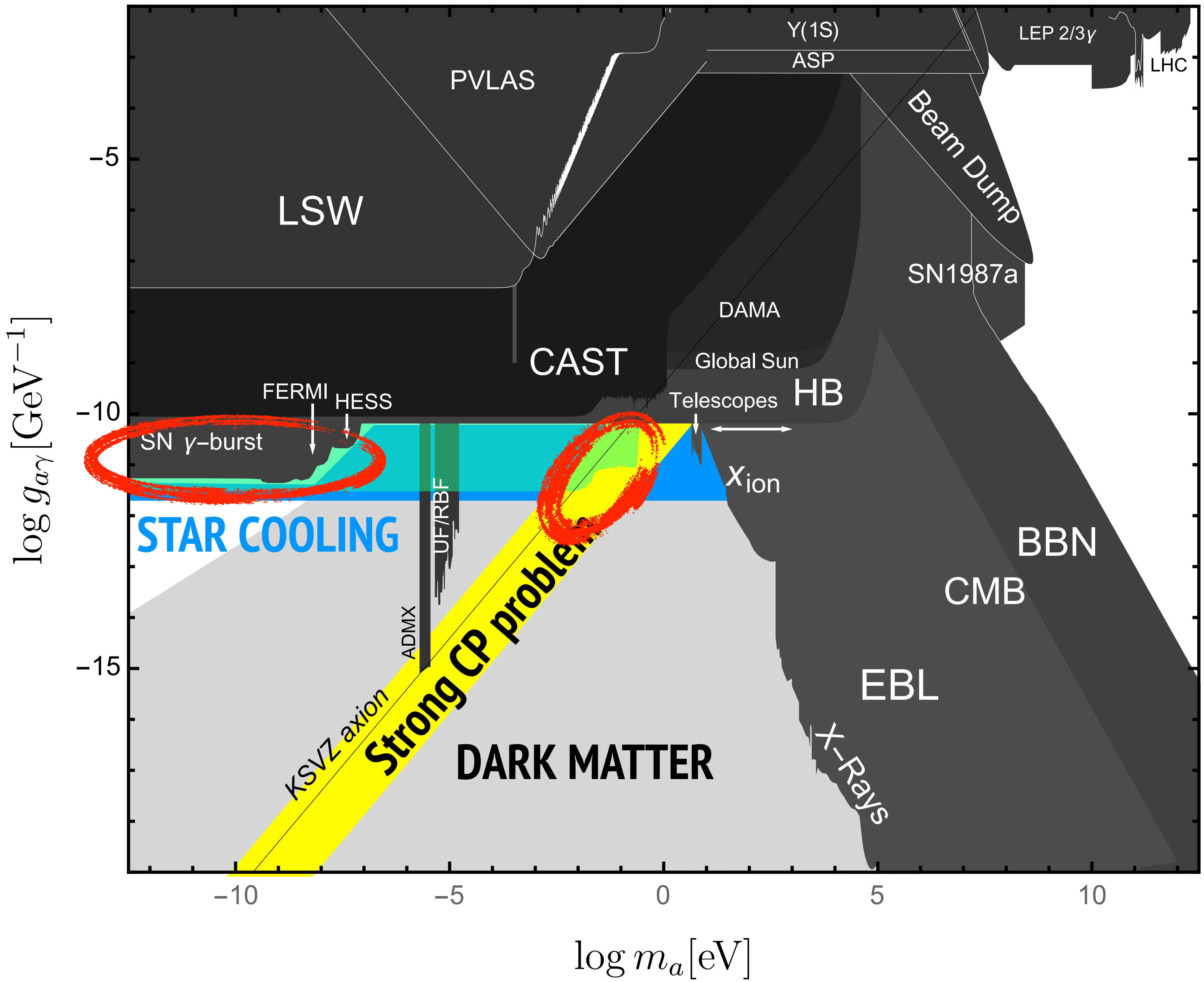

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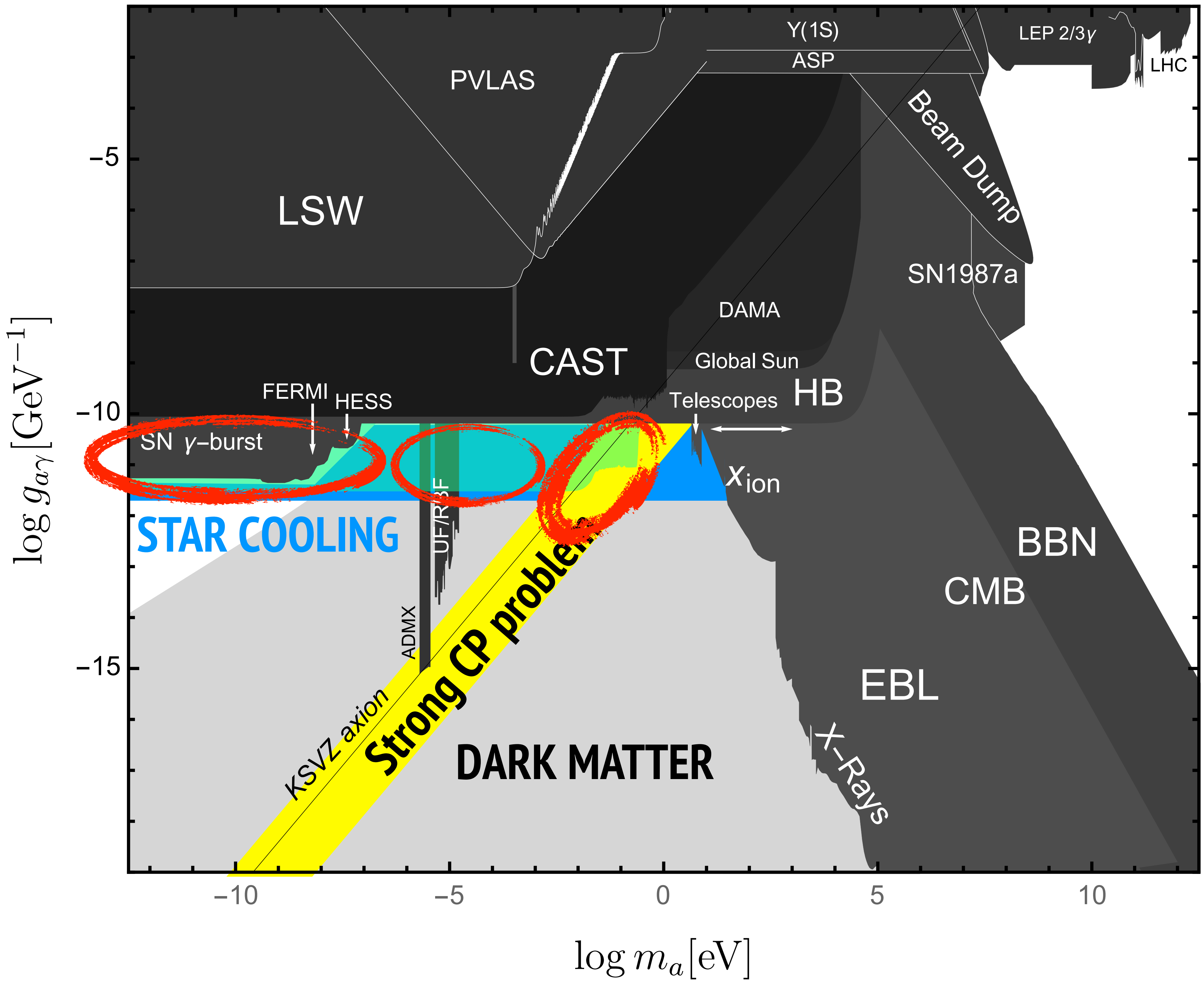

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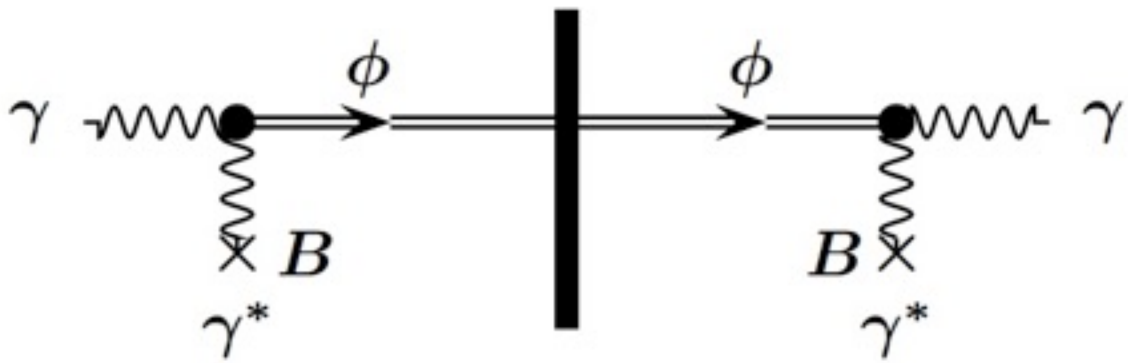
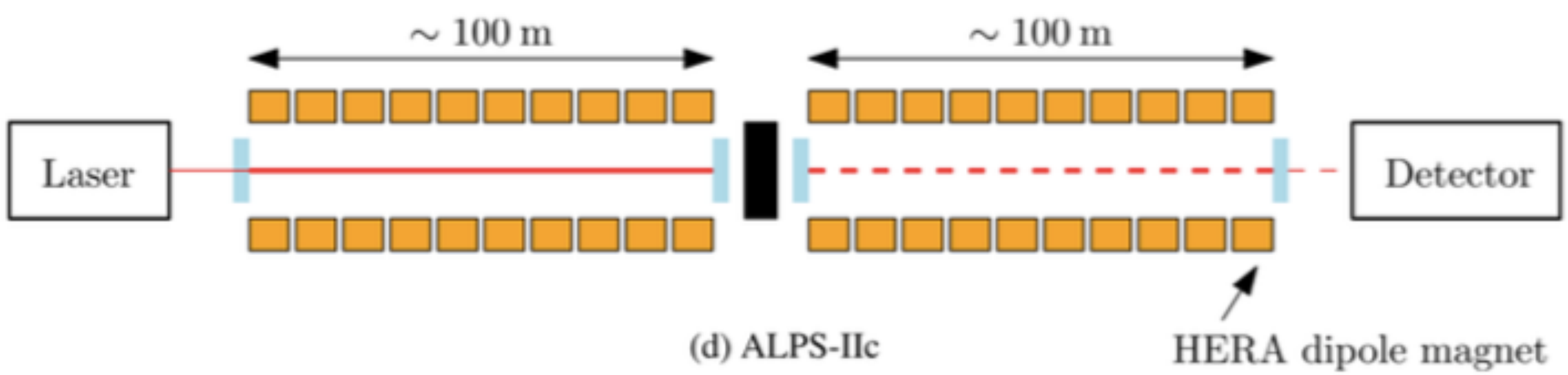
the ANY-Light-Particle-Search

Light shining through walls



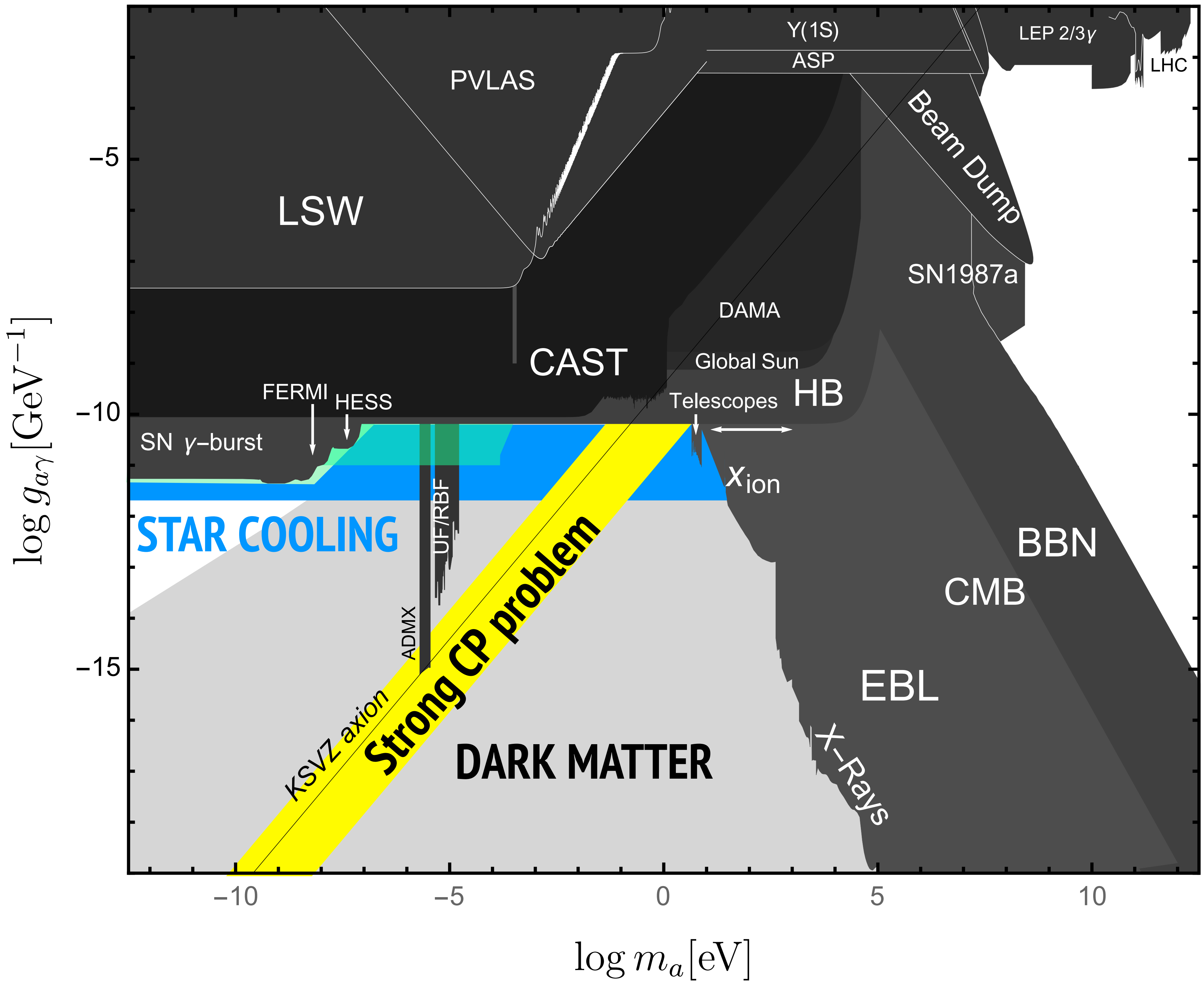
Resonant regeneration in the receiving cavity (see later)



(d) ALPS-IIc

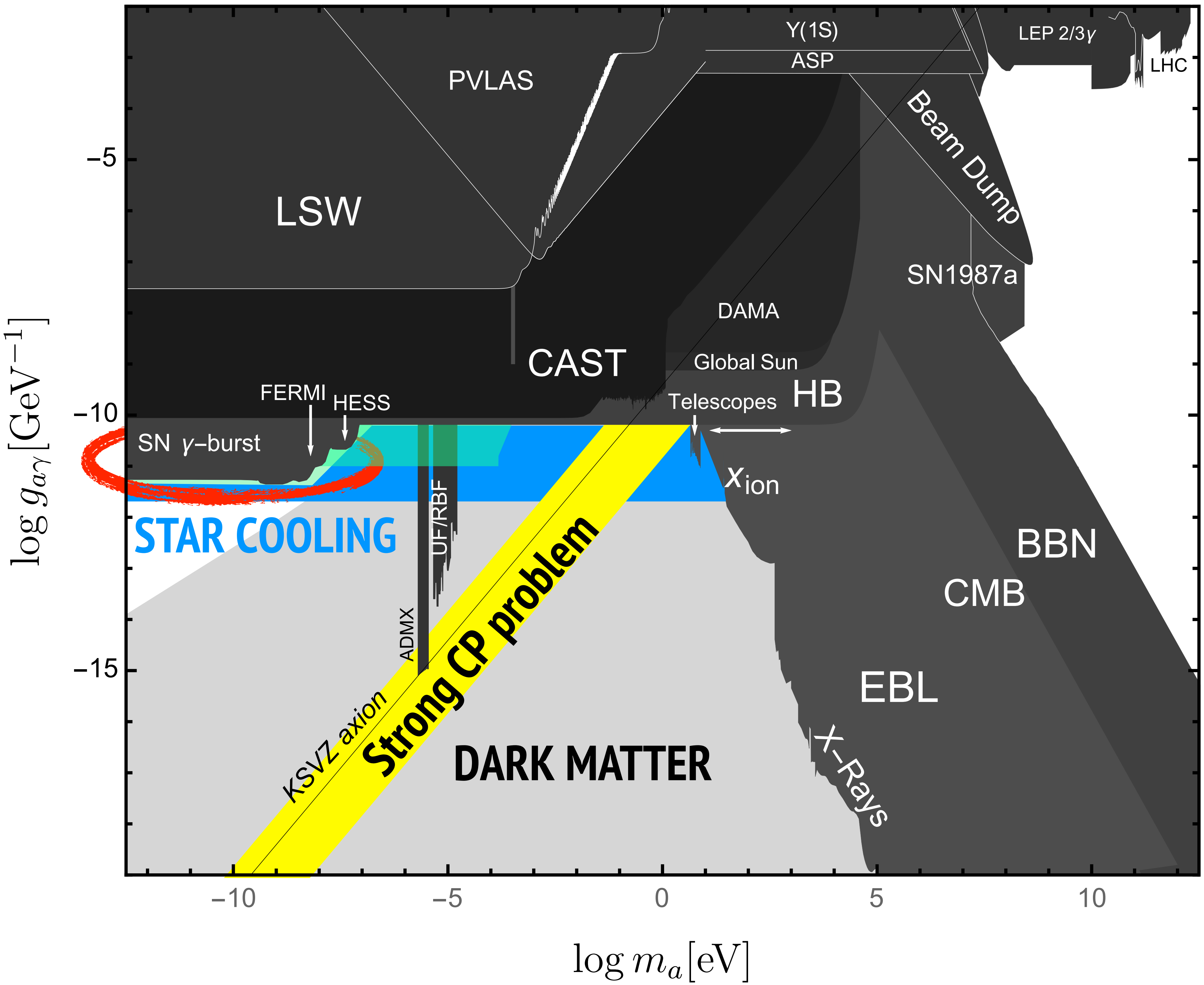
Exp.	Photon flux (1/s)	Photon E (eV)	B (T)	L (m)	B·L (Tm)	PB reg.cav.	Sens. (rel.)
ALPS I	$3.5 \cdot 10^{21}$	2.3	5.0	4.4	22	1	0.0003
ALPS II	$1 \cdot 10^{24}$	1.2	5.3	106	468	40,000	1
"ALPS III"	$3 \cdot 10^{25}$	1.2	13	400	5200	100,000	27

ALPS IIc reach



but much earlier than IAXO ...

ALPS IIc reach



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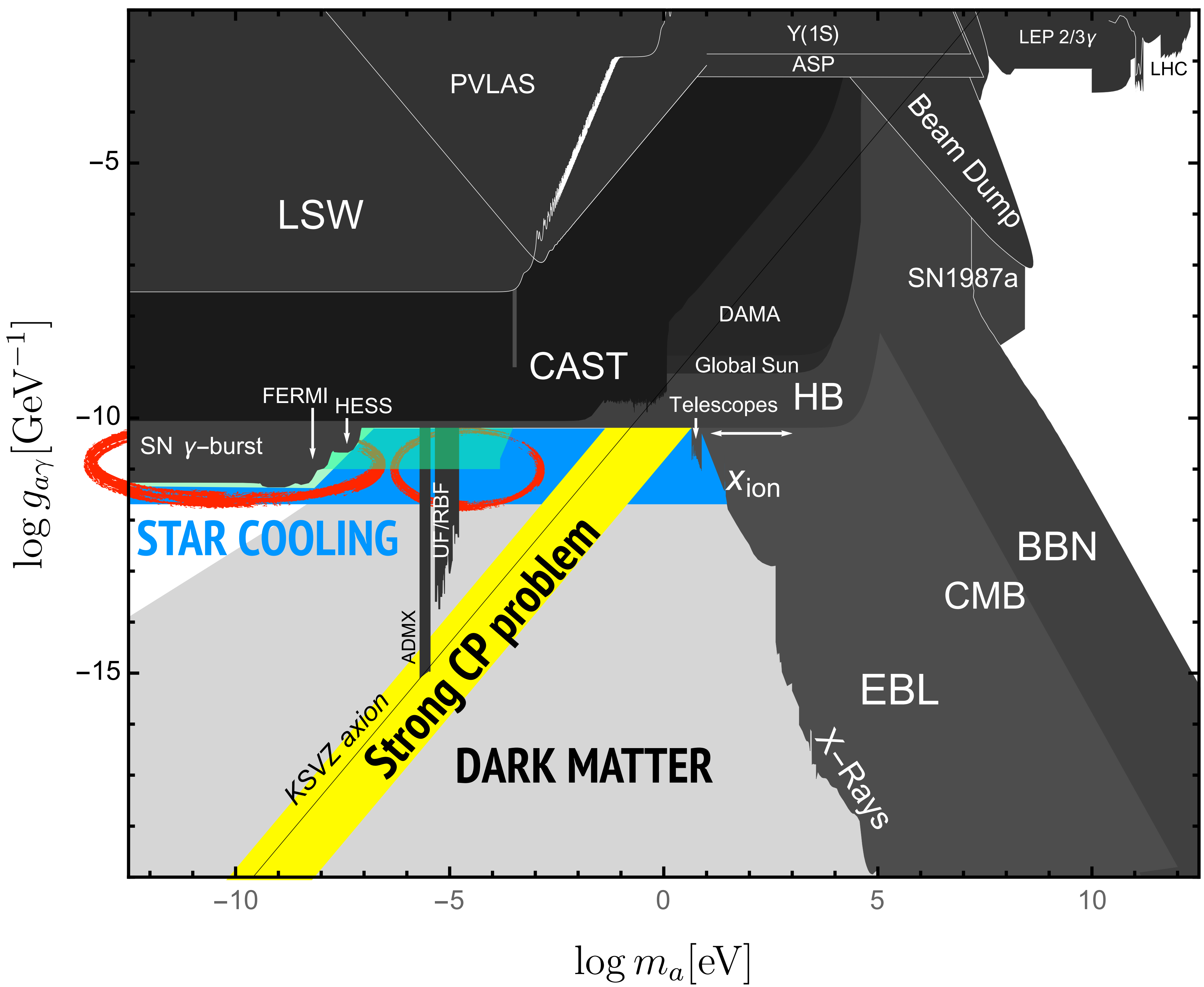


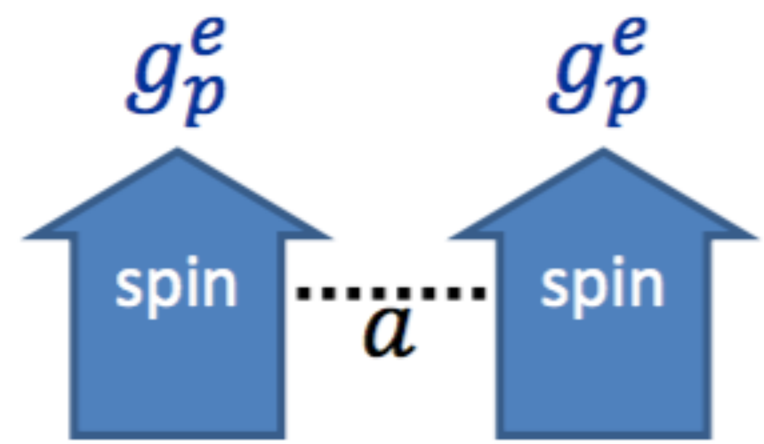
but much earlier than IAXO ...

Long-range forces

Wilczek '84, Geraci 14

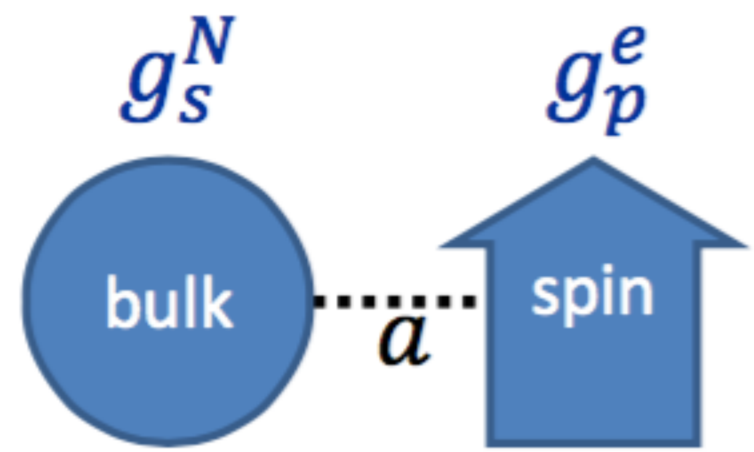
Long-range forces between macroscopic bodies

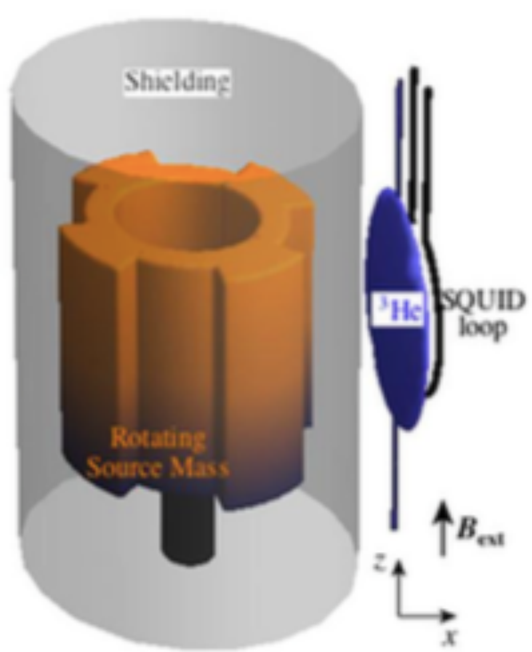
p-p forces are spin-spin … very hard to measure!



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

s-p forces are number-spin … much easier

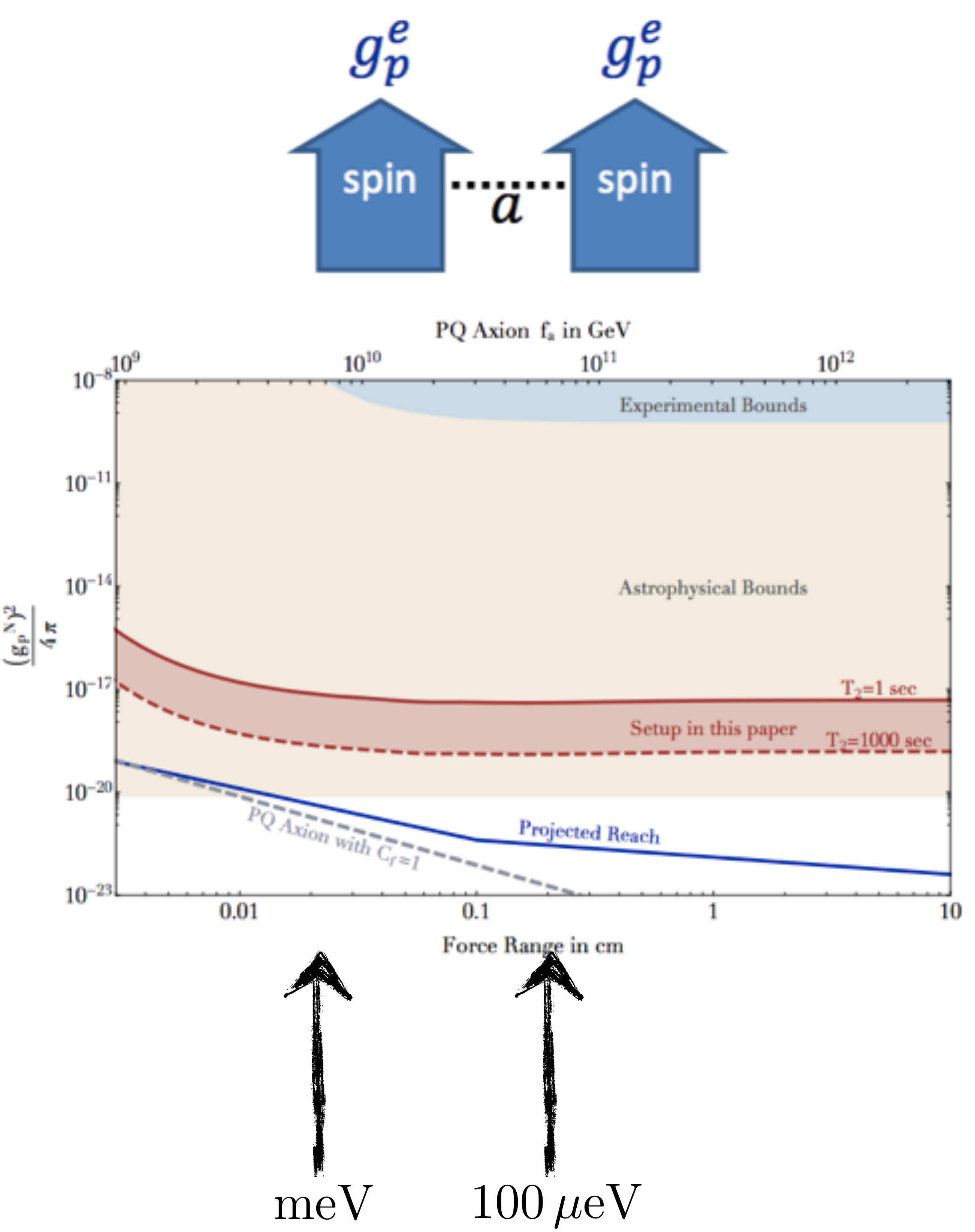


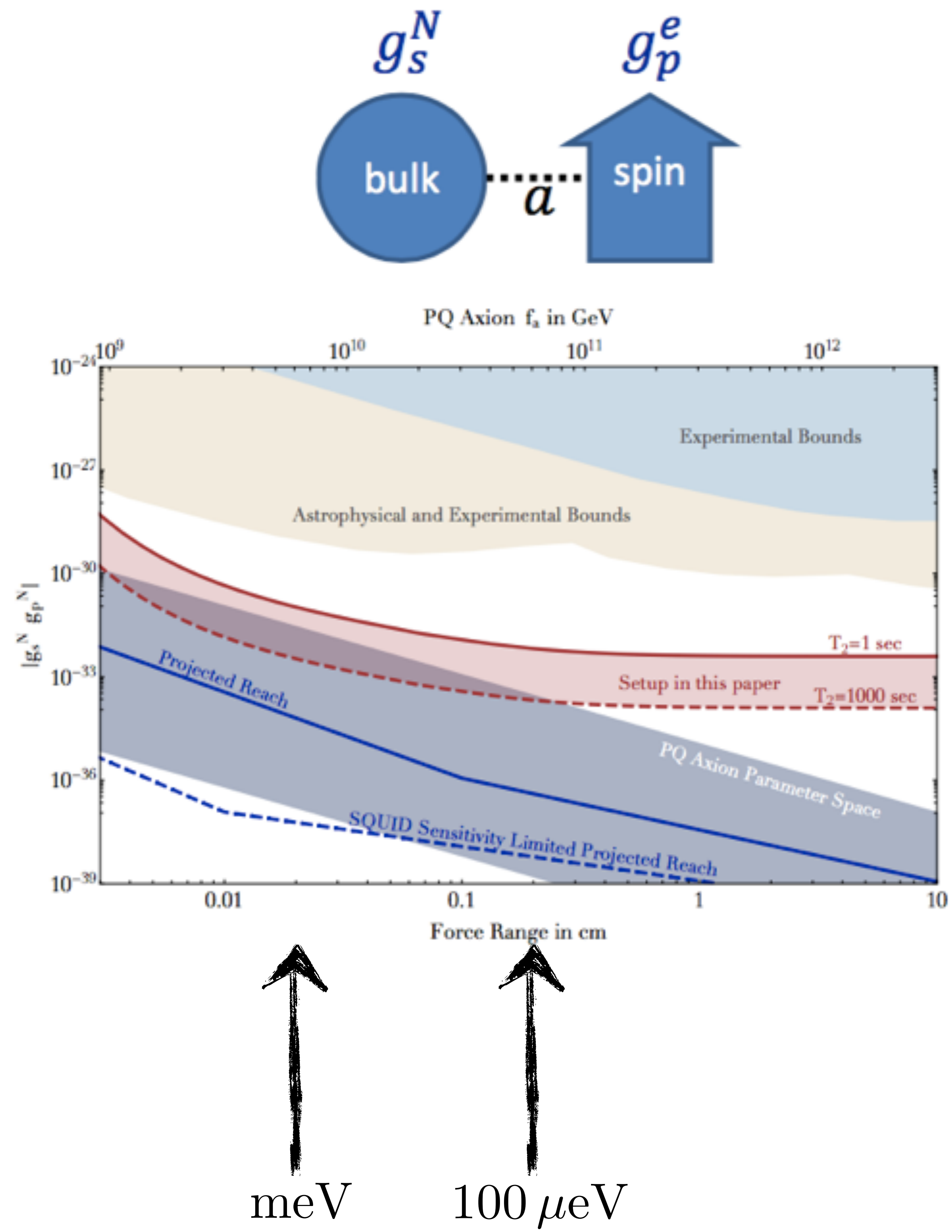


ARIADNE, University of Nevada in Reno

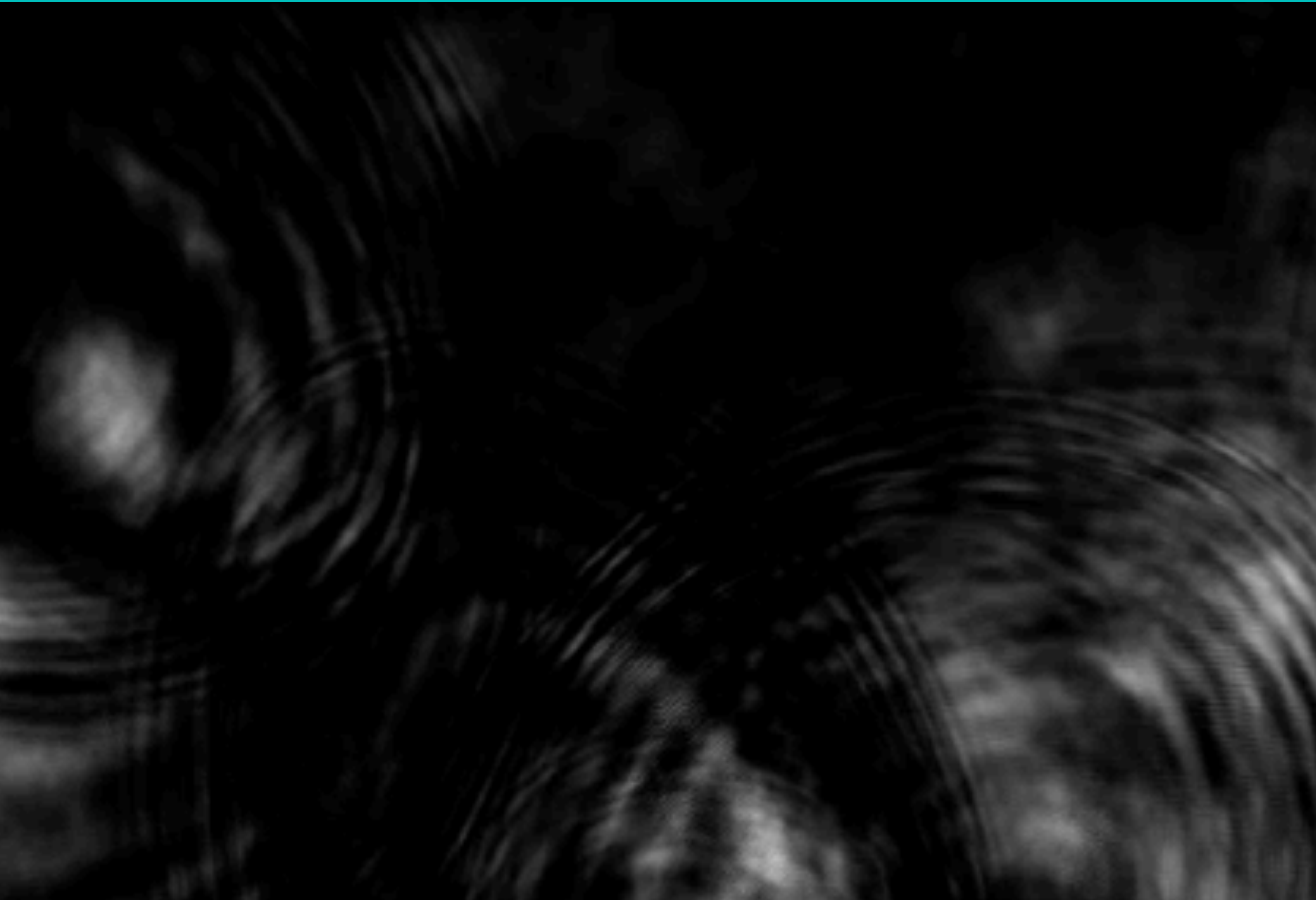
ARIADNE reach

Arvanitaki, Geraci 14





Detecting Dark Matter



Detecting Dark Matter

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

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

QCD axion

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

~ 10^-6

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Non-zero velocity in galaxy -> finite width

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

~ 10^-6

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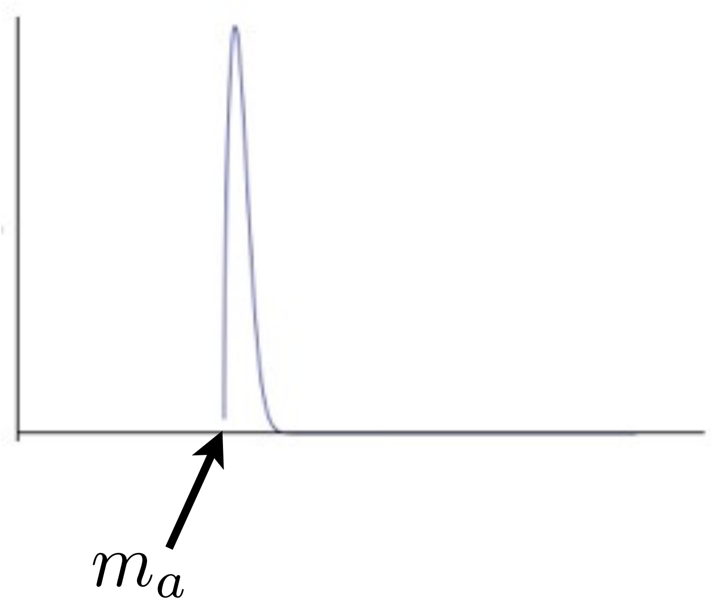

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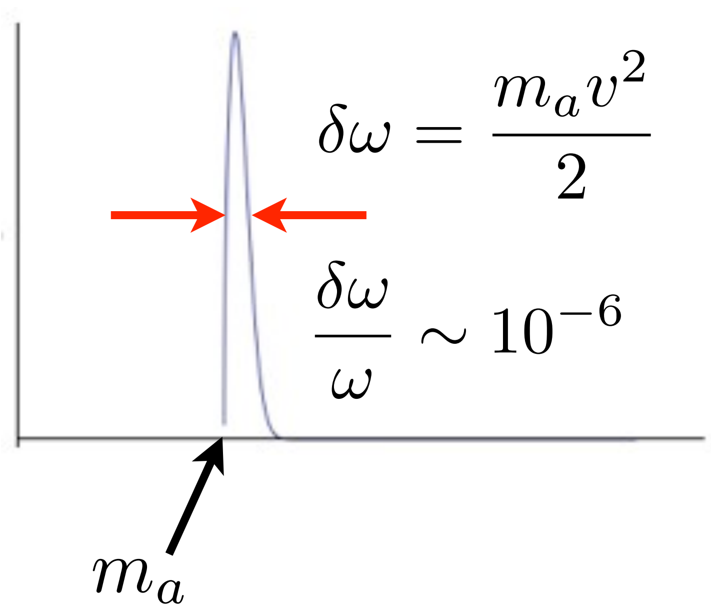

$$\delta\omega = \frac{m_a v^2}{2}$$

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

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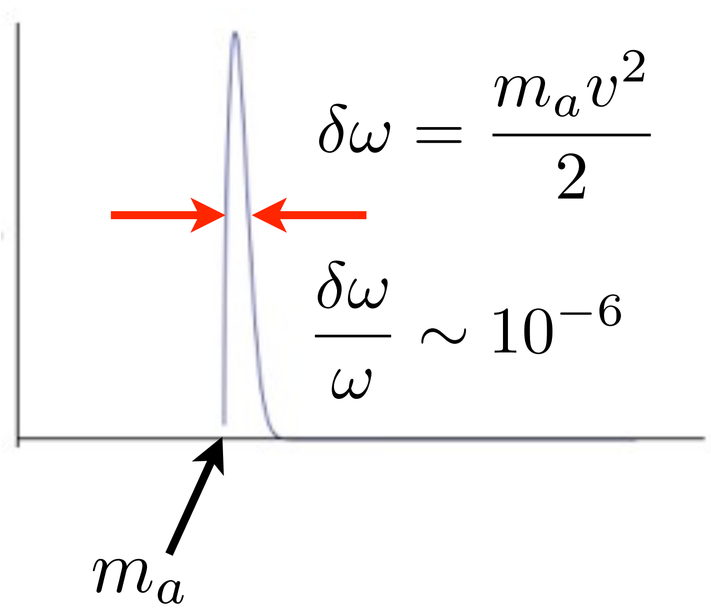
~ 10^-6

coherence time

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



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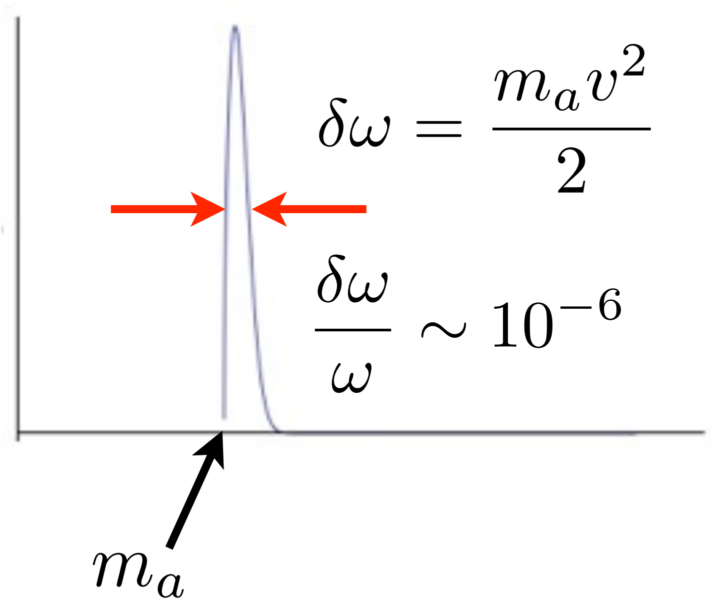
~ 10^-6



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

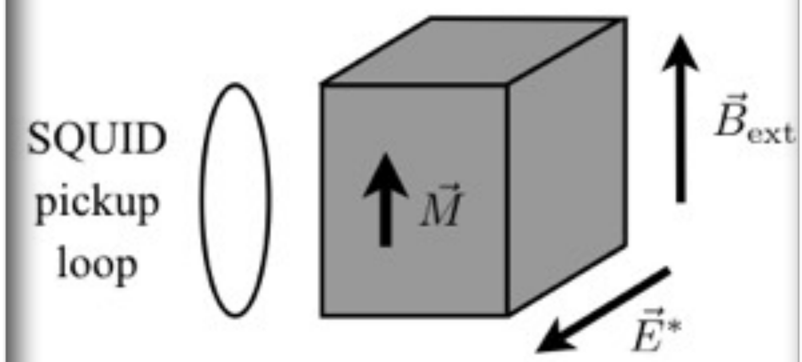
coherence time

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

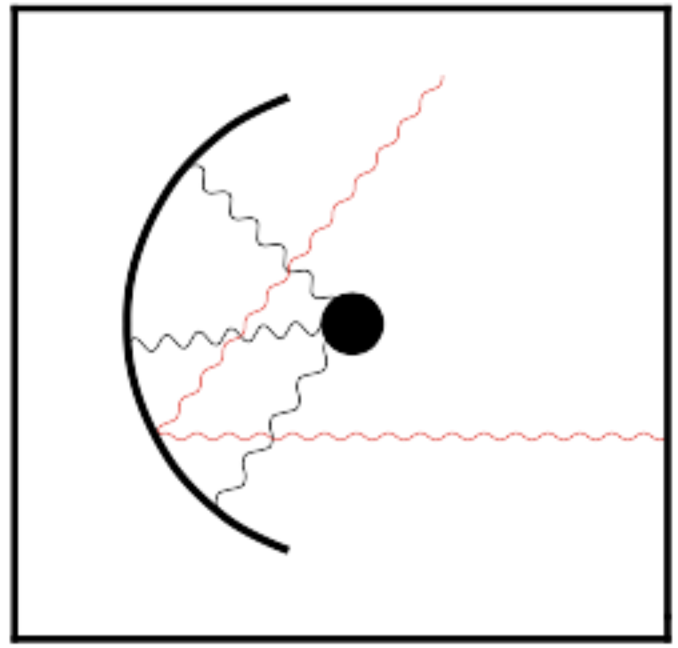
coherence length

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

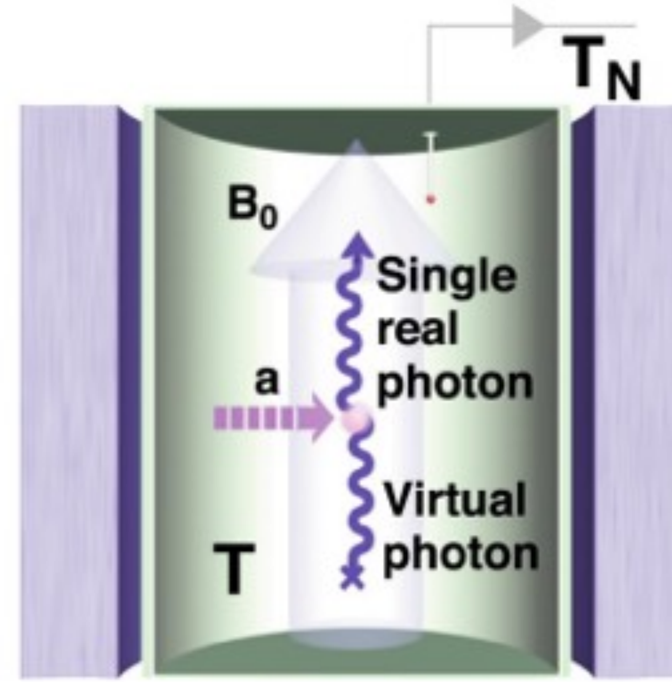
Spin precession



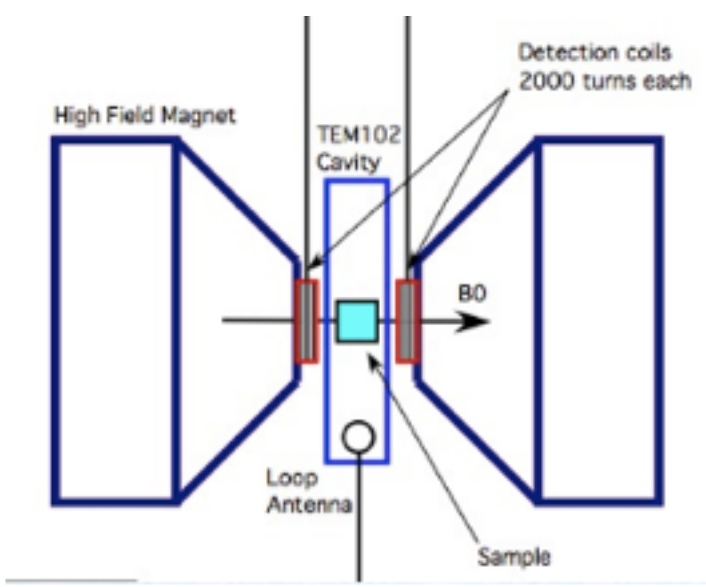
Mirrors+



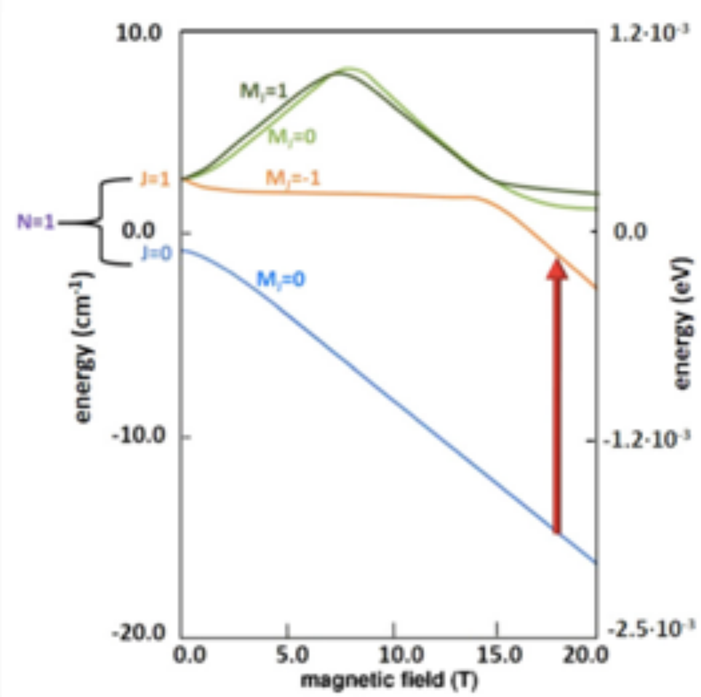
Cavities



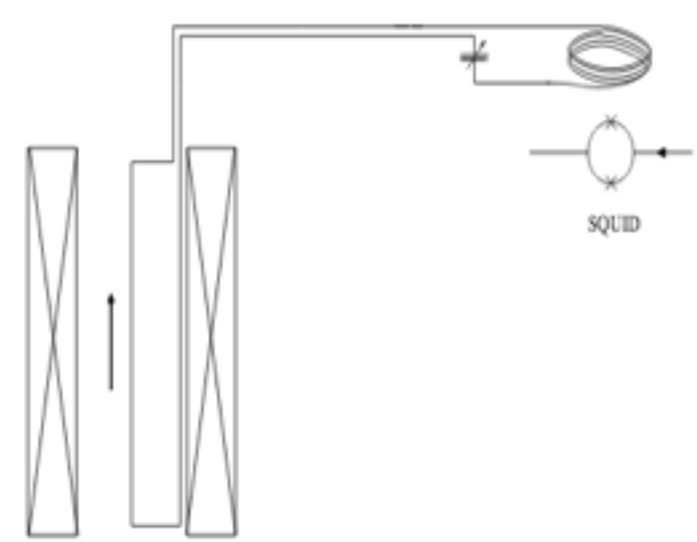
e-spin precession



Atomic transitions

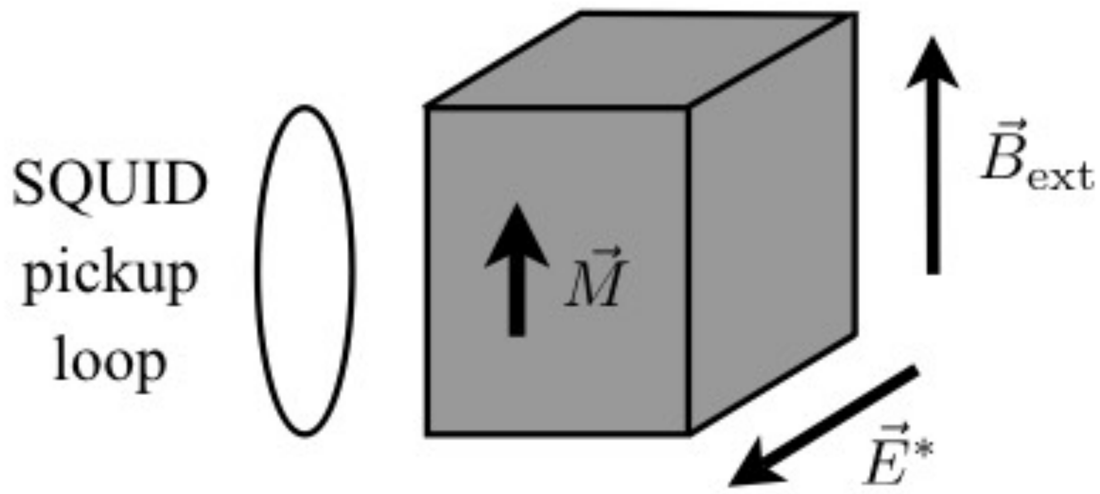


LC-circuit



CASPER at Mainz

Graham 2012



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

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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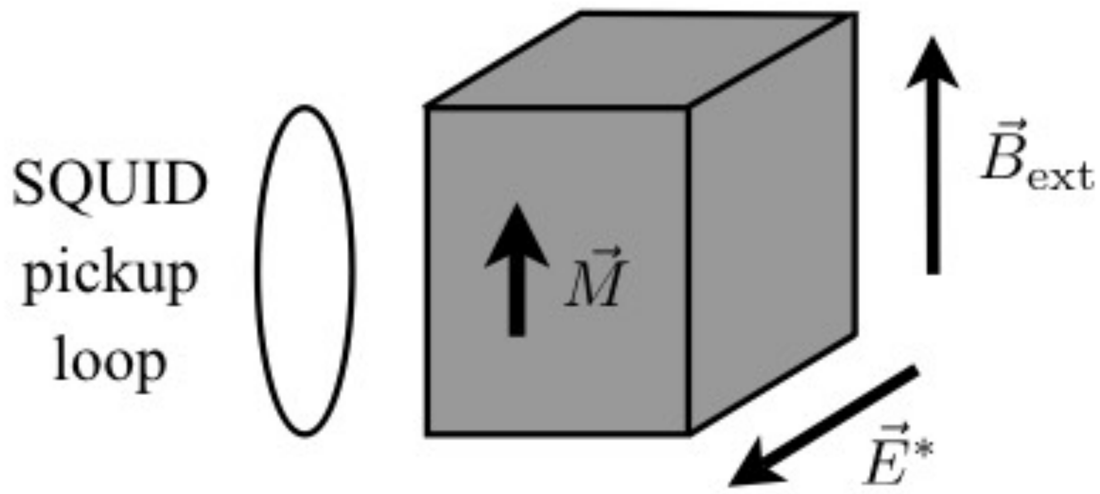
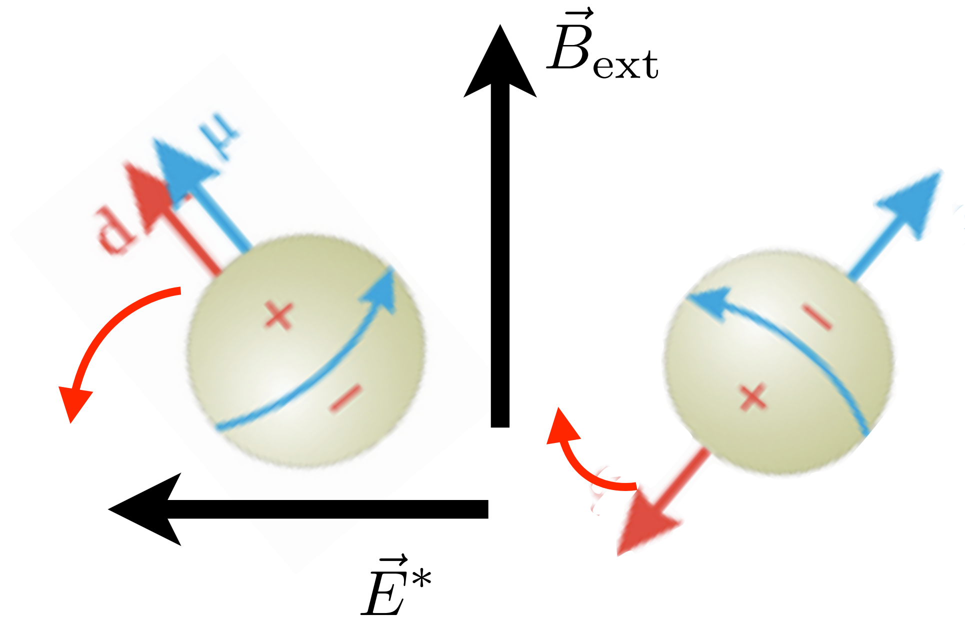
Graham 2012





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

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

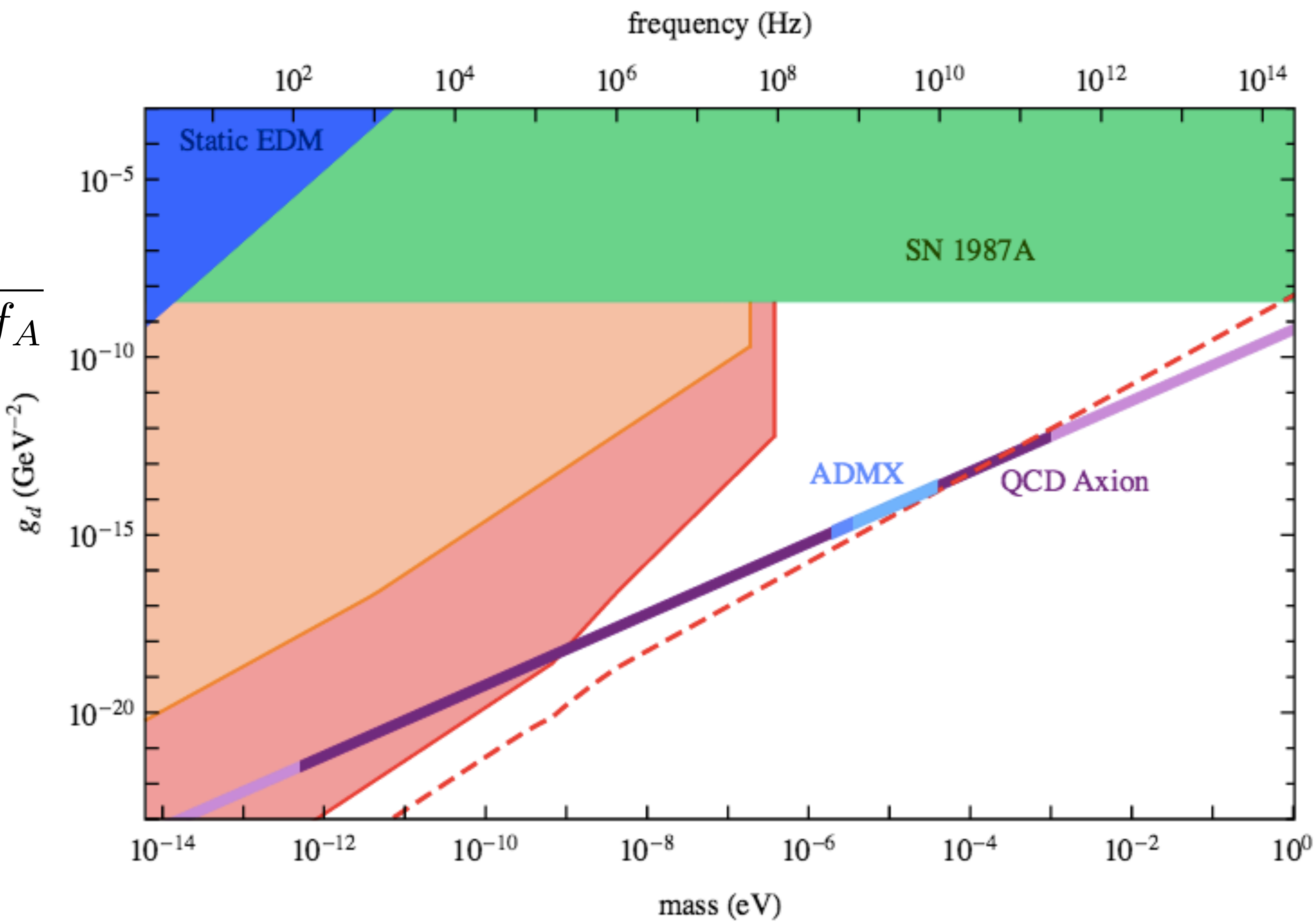
Oscillating EDM, effects add up, transverse magnetisation grows if $m_a = \omega = \mu|\vec{B}_{\rm ext}|$

- 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

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



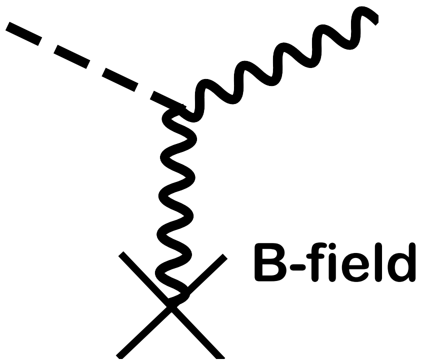
Axion DM in a B-field

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

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

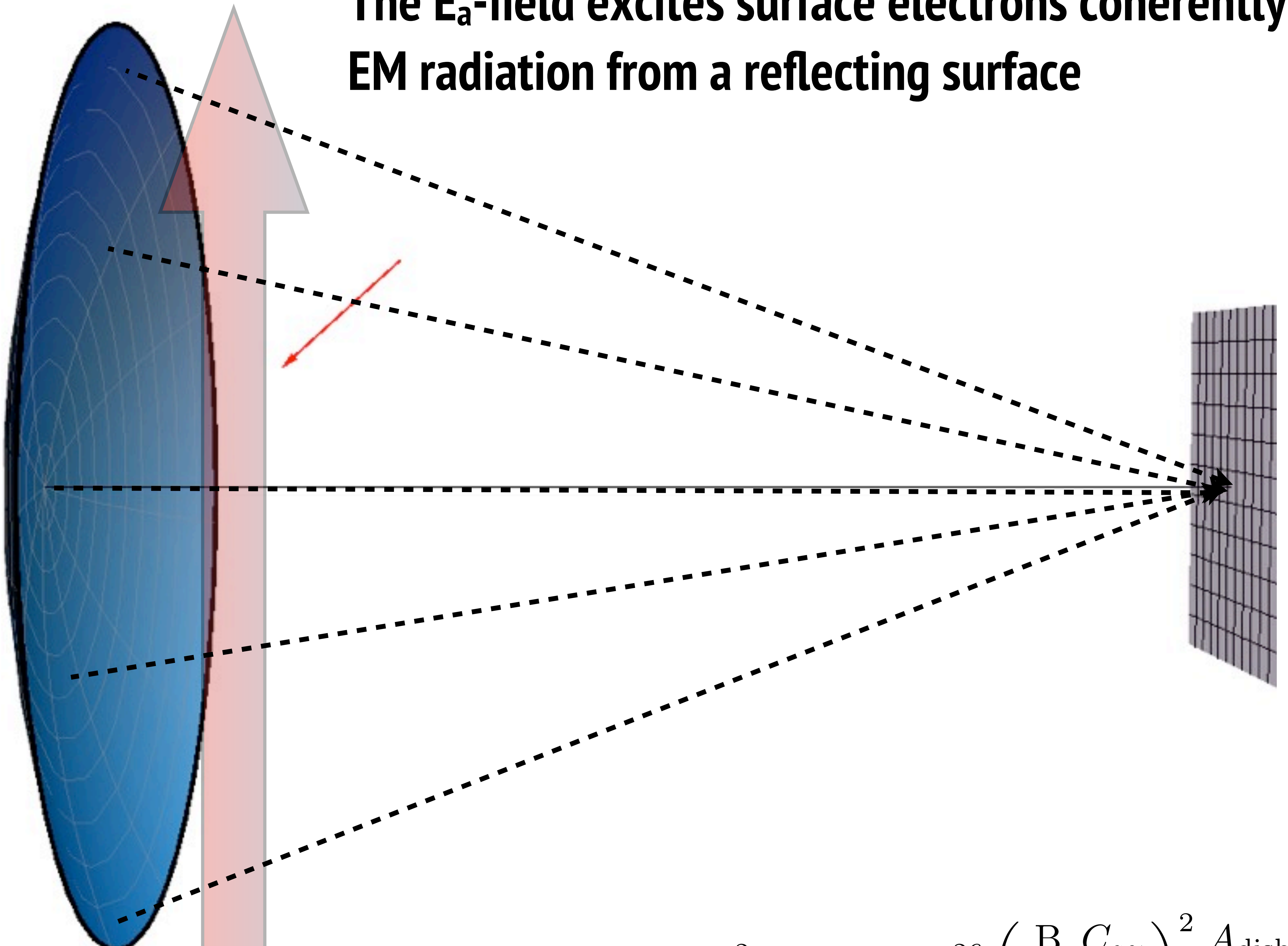
- Oscillating at a frequency $\omega \simeq m_a$

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

Dish antenna experiment?

Horns 2012

The E_a-field excites surface electrons coherently
EM radiation from a reflecting surface



spherical reflecting dish

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

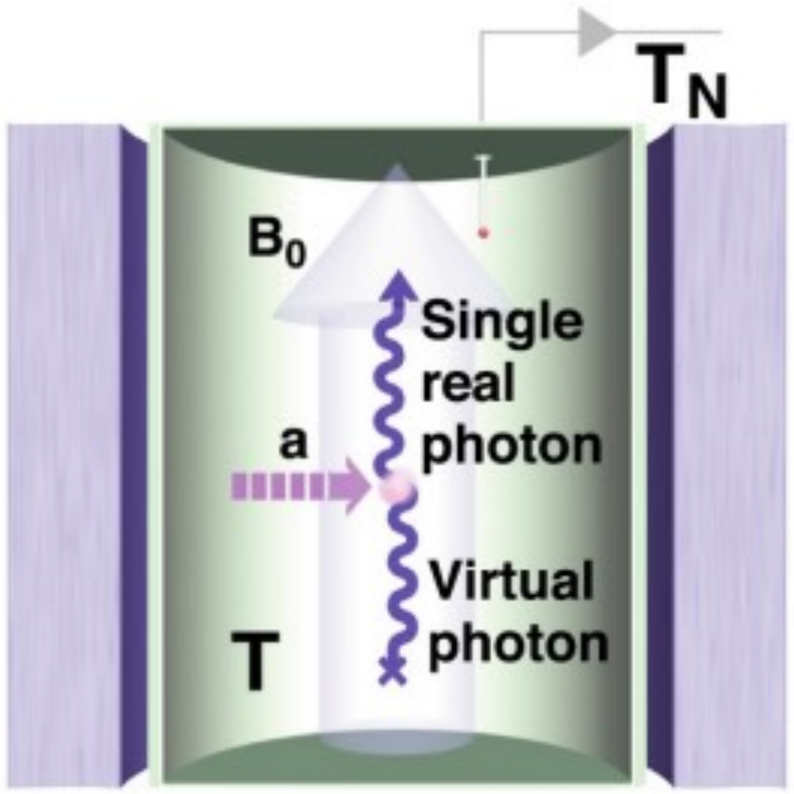
Cavity resonators (Haloscopes)

- Haloscope (Sikivie 83)

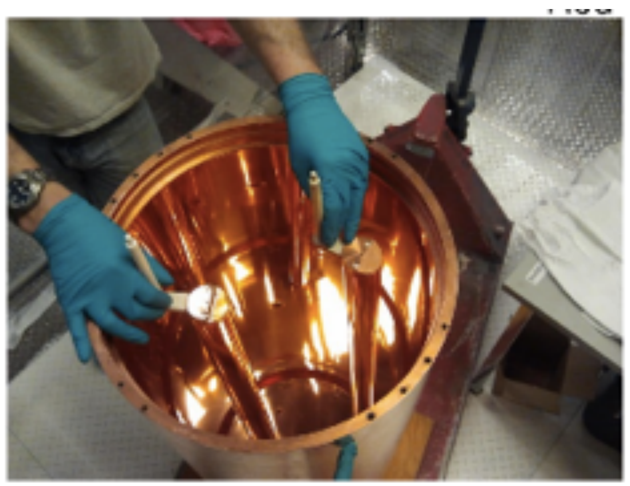
$$P \sim Q|\mathbf{E}_a|^2 (V m_a)\mathcal{G}\kappa$$ (ON RESONANCE)

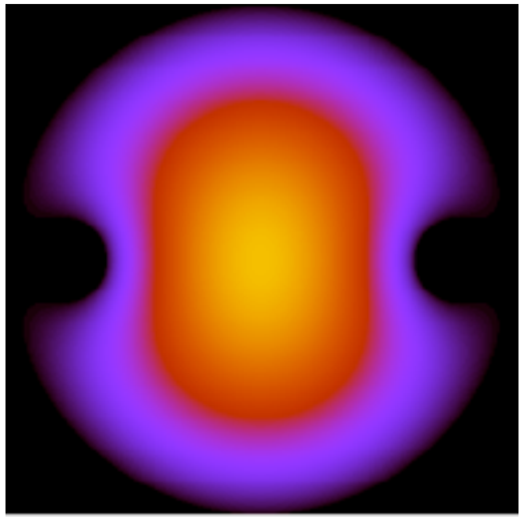
- Naive ADMX scaling (e.g. an ADMX every octave)

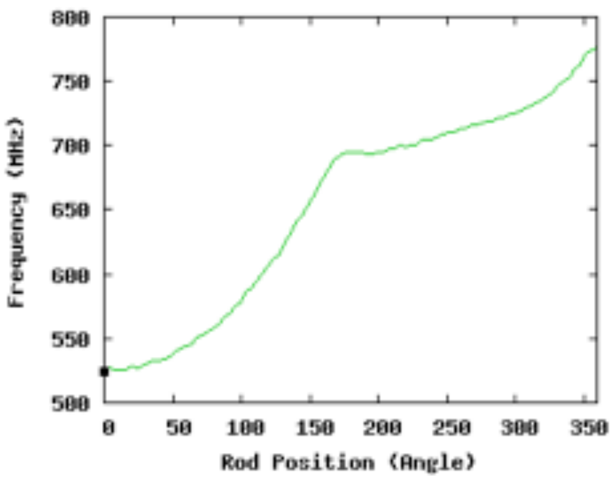
- Signal $(V \propto m_a^{-3})$ $\quad P_{\rm out} \propto V m_a \sim \frac{1}{m_a^2}$
- Noise $\quad P_{\rm noise} = T_{\rm sys}\Delta\nu_a \propto m_a^2$
- Signal/noise in $\Delta\nu_a$ of time, t, $\quad \frac{S}{N} = \frac{P_{\rm out}}{P_{\rm noise}}\sqrt{\Delta\nu_a t}$
- Scanning rate $\quad \frac{1}{m_a}\frac{d\Delta m_a}{dt} \propto \frac{C_{A\gamma}^4}{m_a^7}$



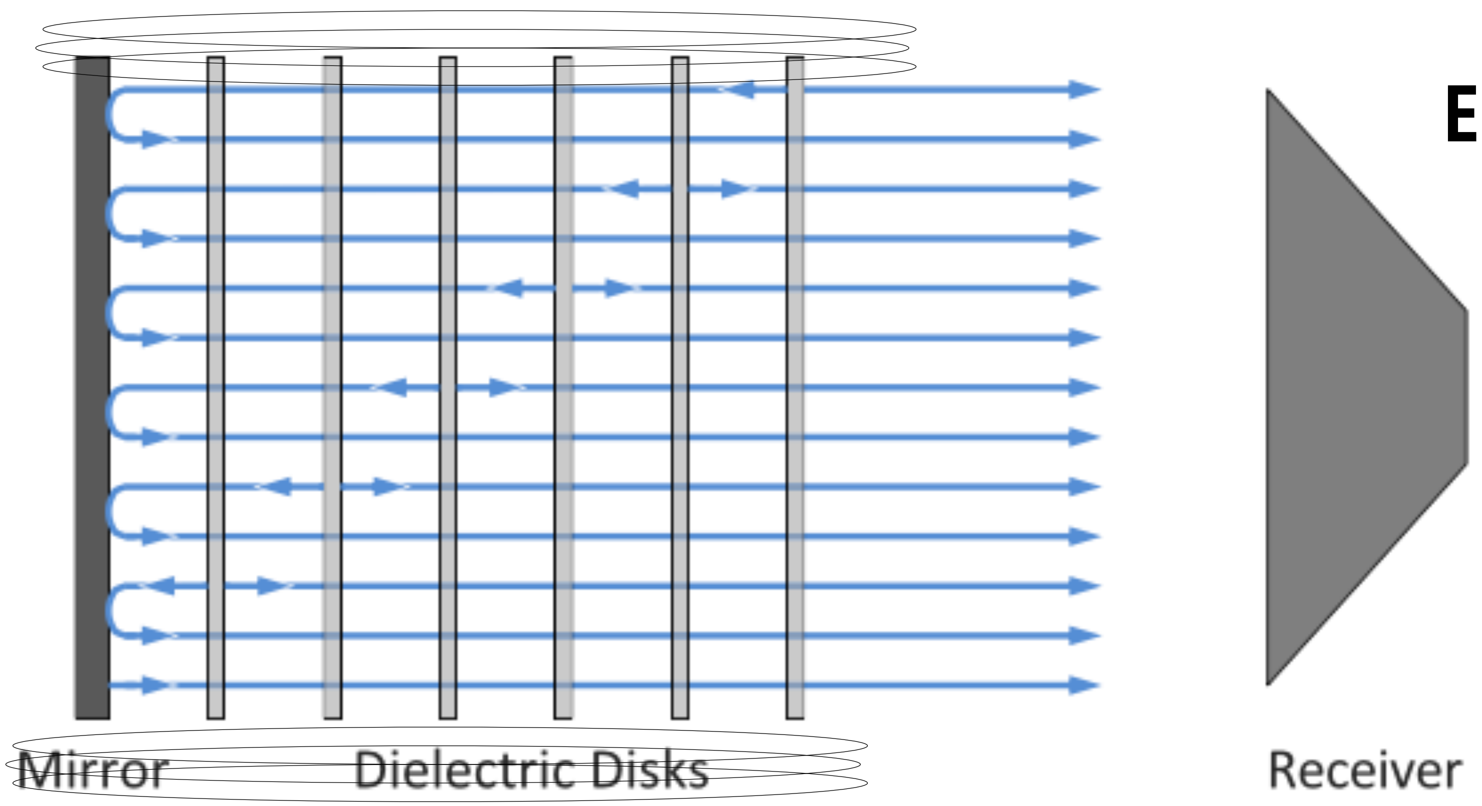
Scanning over frequencies







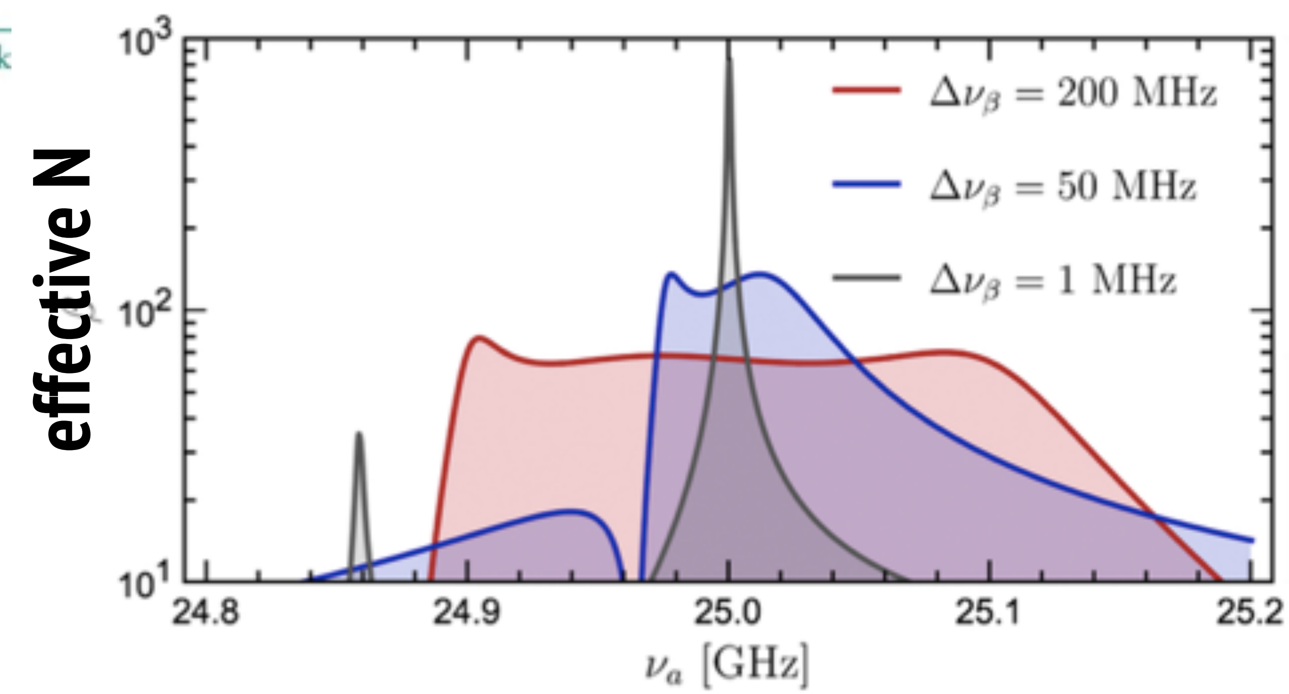
MADMAX: MAgnetised Disk and Mirror Axion eXperiment



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

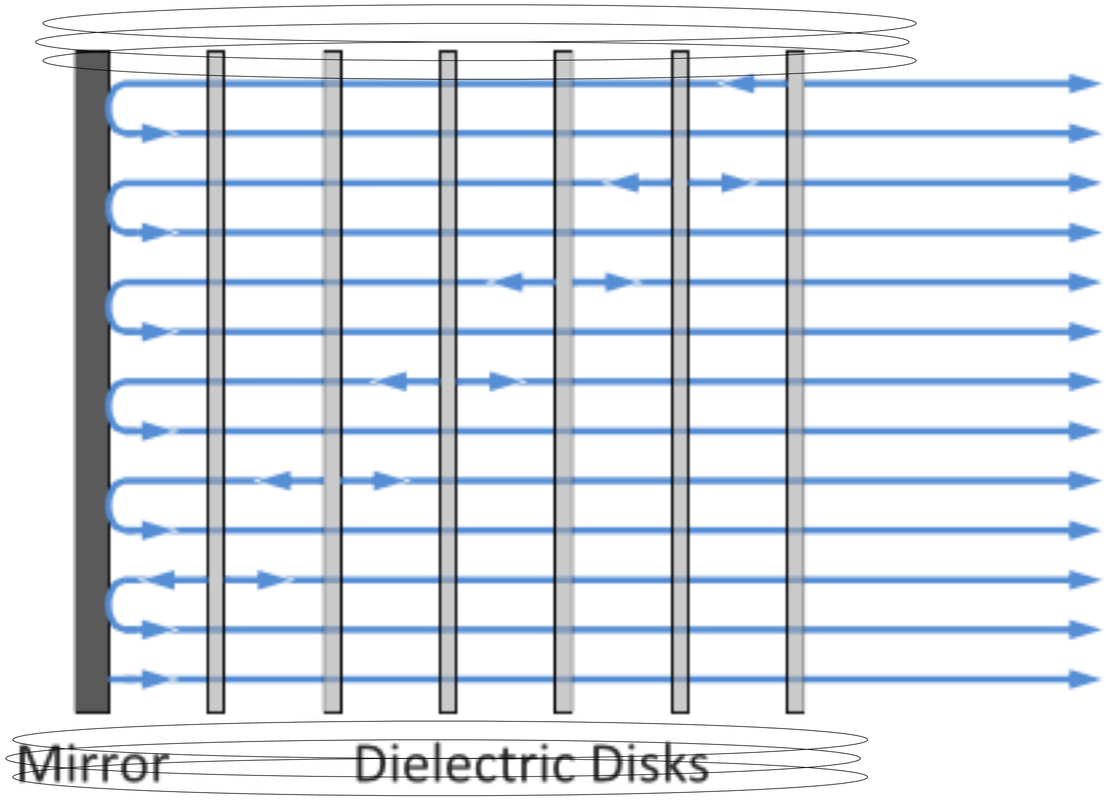
$$P \sim |\mathbf{E}_a|^2 \mathrm{Area} \times \mathcal{O}(N^2)$$

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



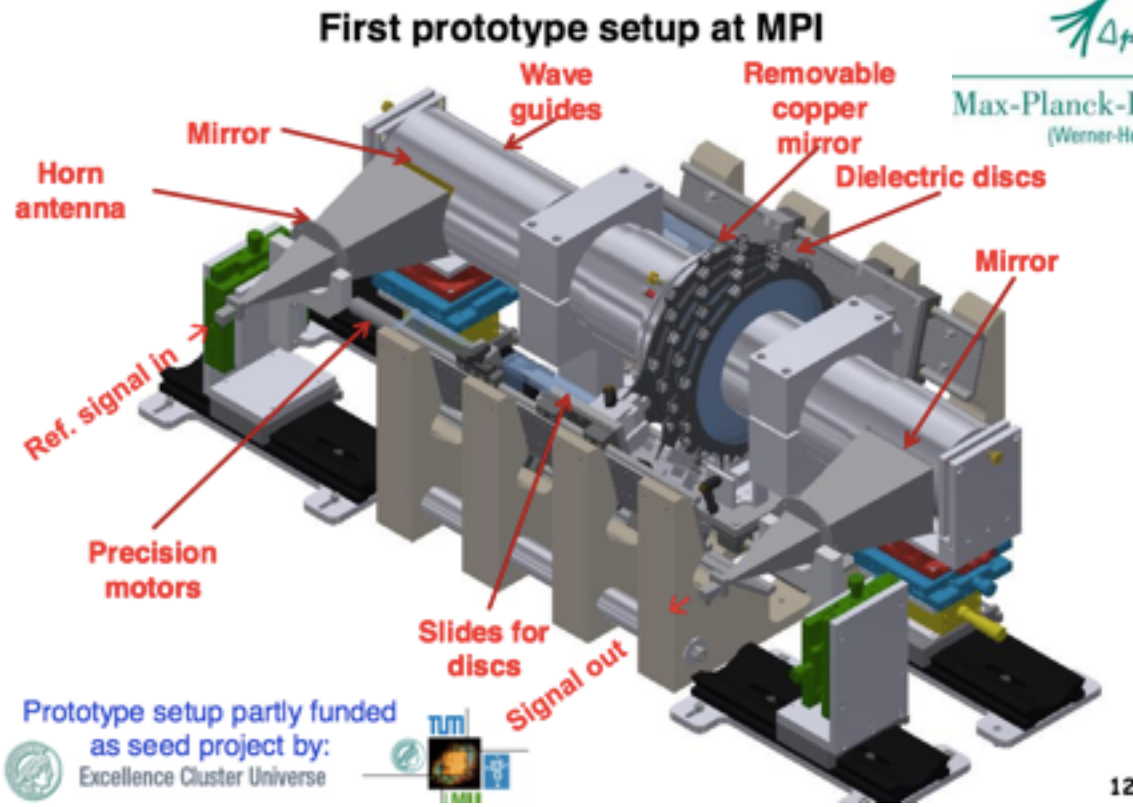
Caldwell 2017

MADMAX: MAgnetised Disk and Mirror Axion eXperiment

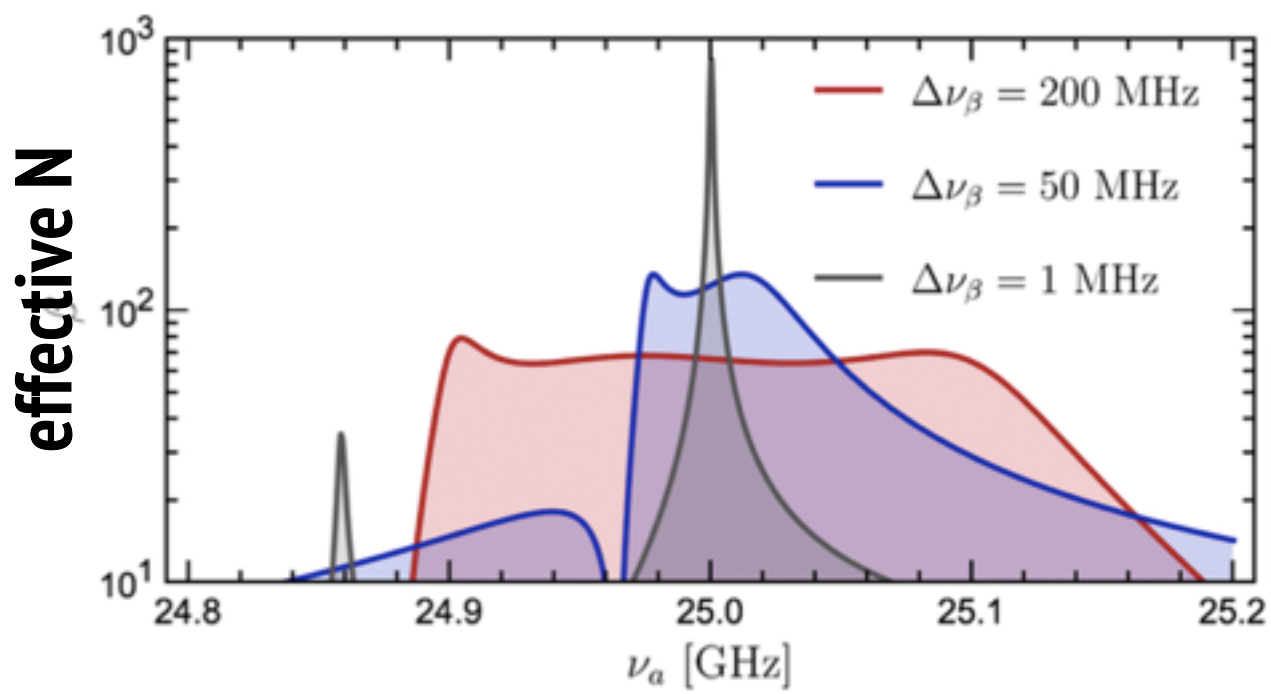


Emitted EM-waves from each interface + internal reflections ...

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



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



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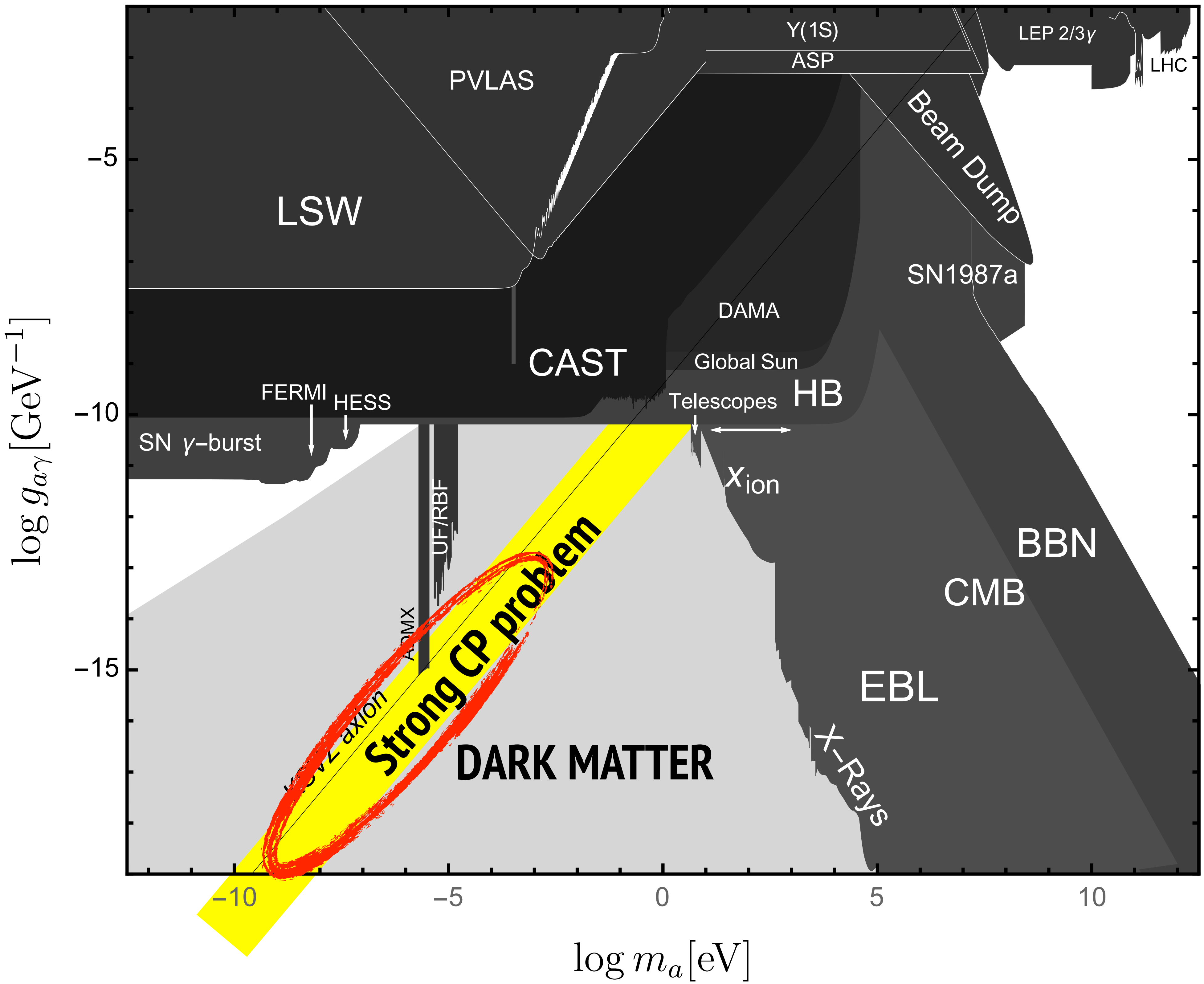
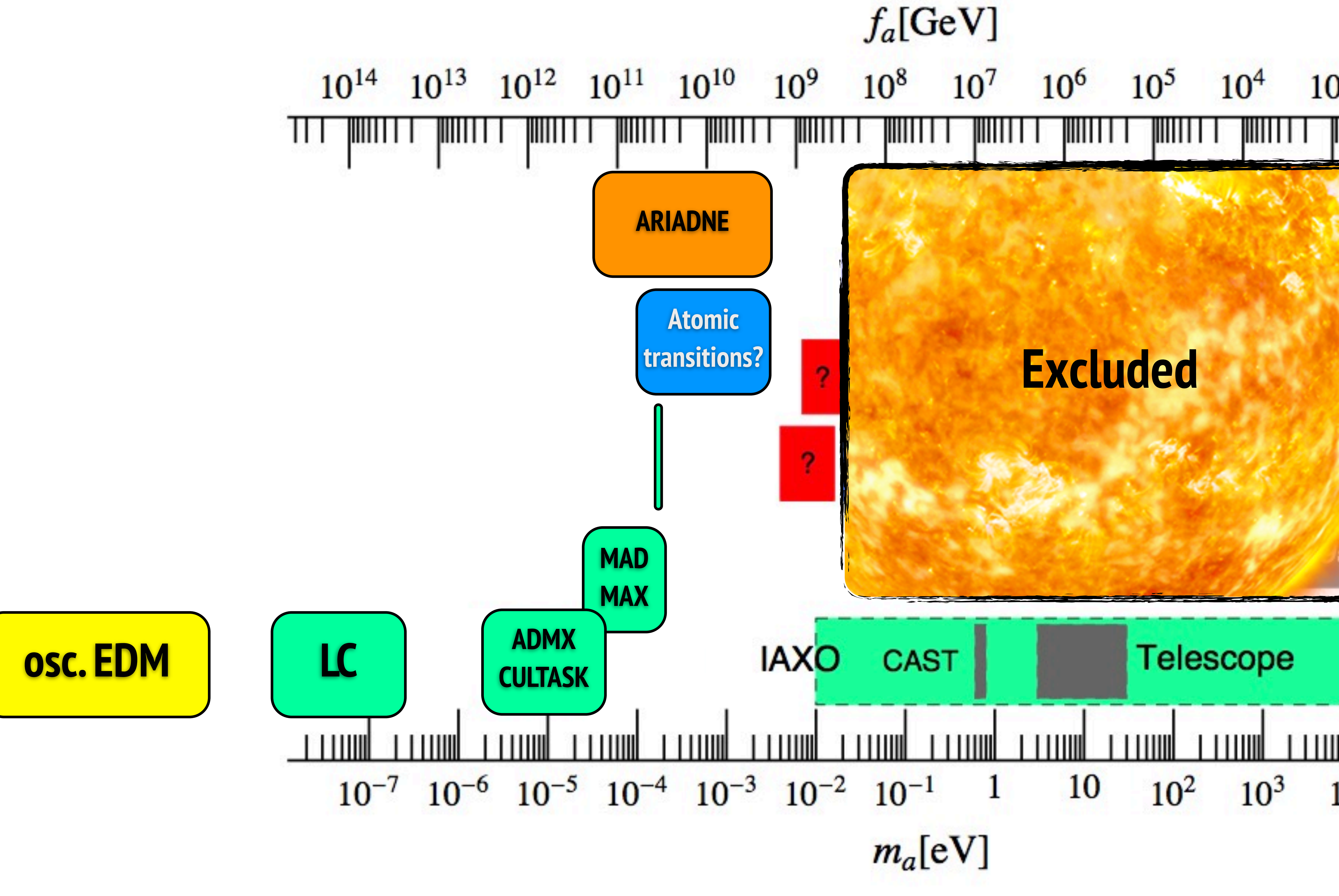
Summary plot



Summary plot



Conclusions

- Beyond the SM with extremely low energies

- Detect an ALP, new energy scale!

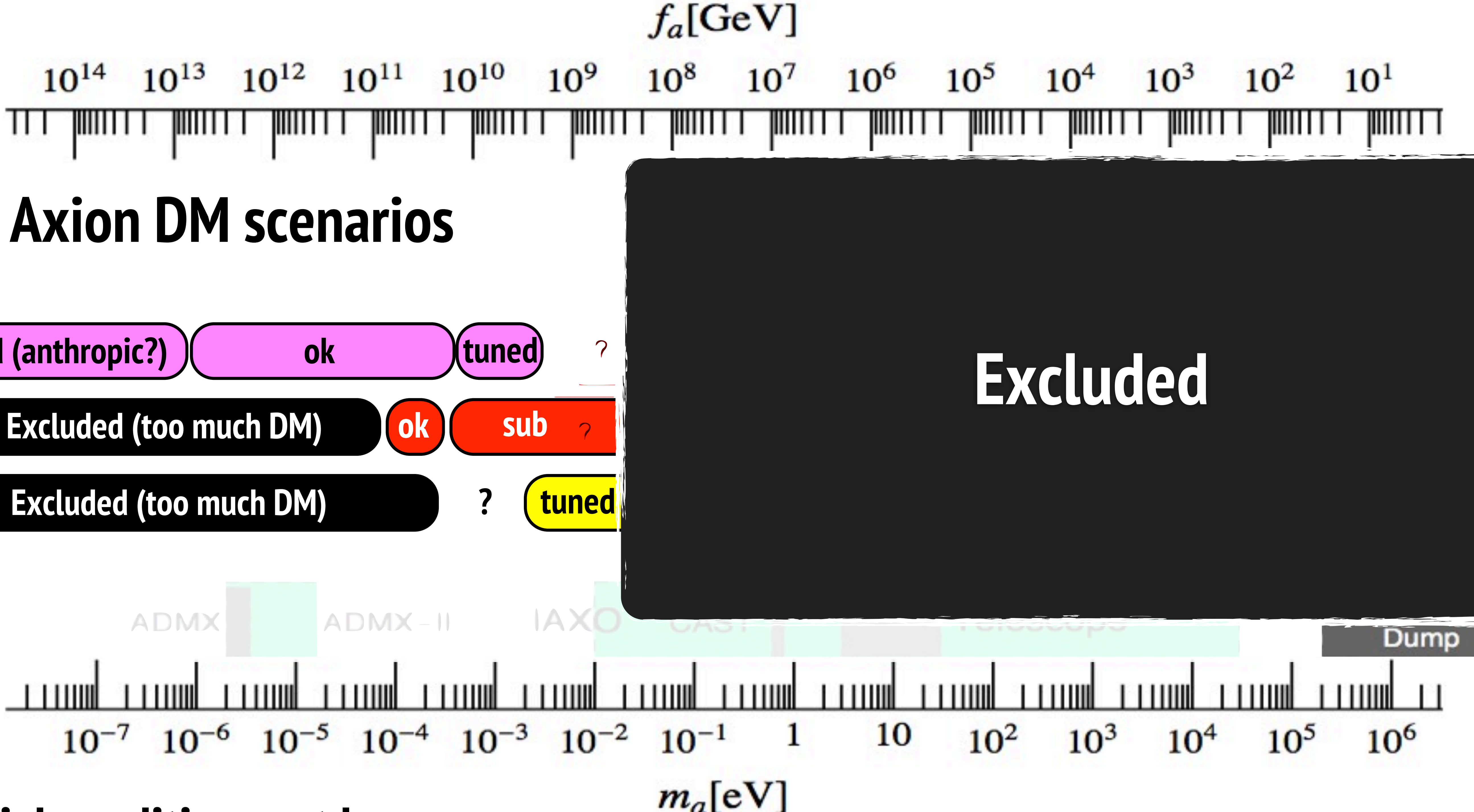
- Generic interactions

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

- Good Experimental ideas

- Still a lot of parameter space to explore!

Axion dark matter scenarios



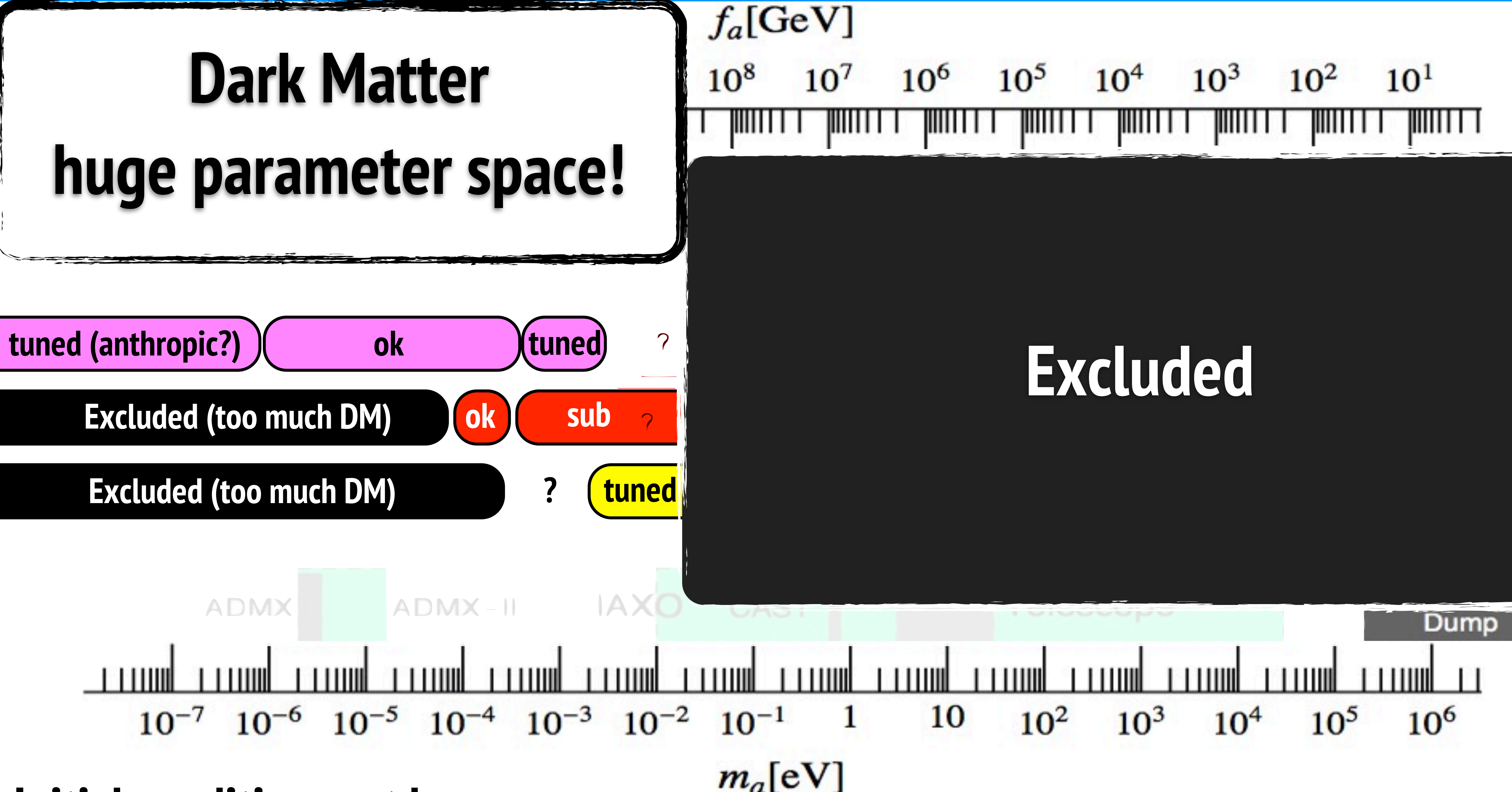
Initial conditions set by :

Inflation smooth	Phase transition (N=1)	Phase transition (N>1)
$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu\text{eV}}{m_a}\right)^{1.19}$	strings+unstable DW's	strings+long-lived DWs

Axion dark matter scenarios

Dark Matter

huge parameter space!



Initial conditions set by :

Inflation smooth

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Phase transition (N=1)

strings+unstable DW's

Phase transition (N>1)

strings+long-lived DWs