The Quest for the Axion

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AlbaNova/NORDITA Colloquium
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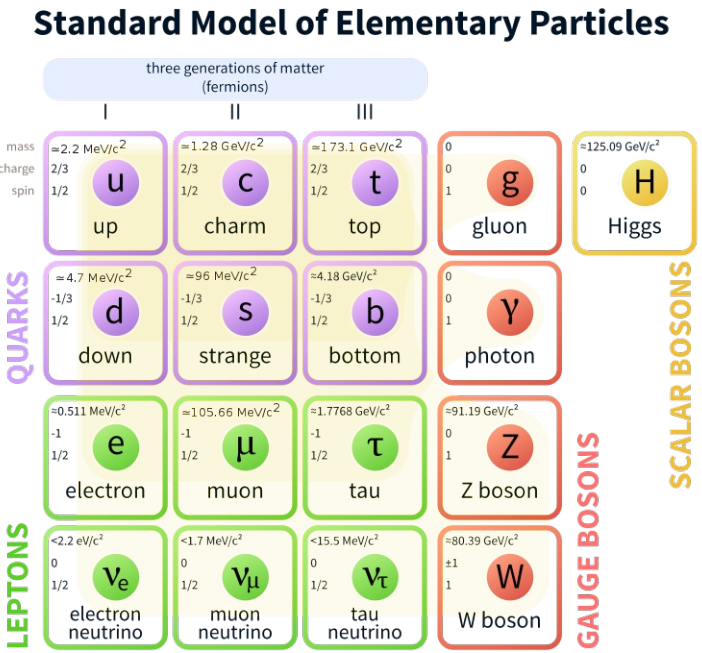
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

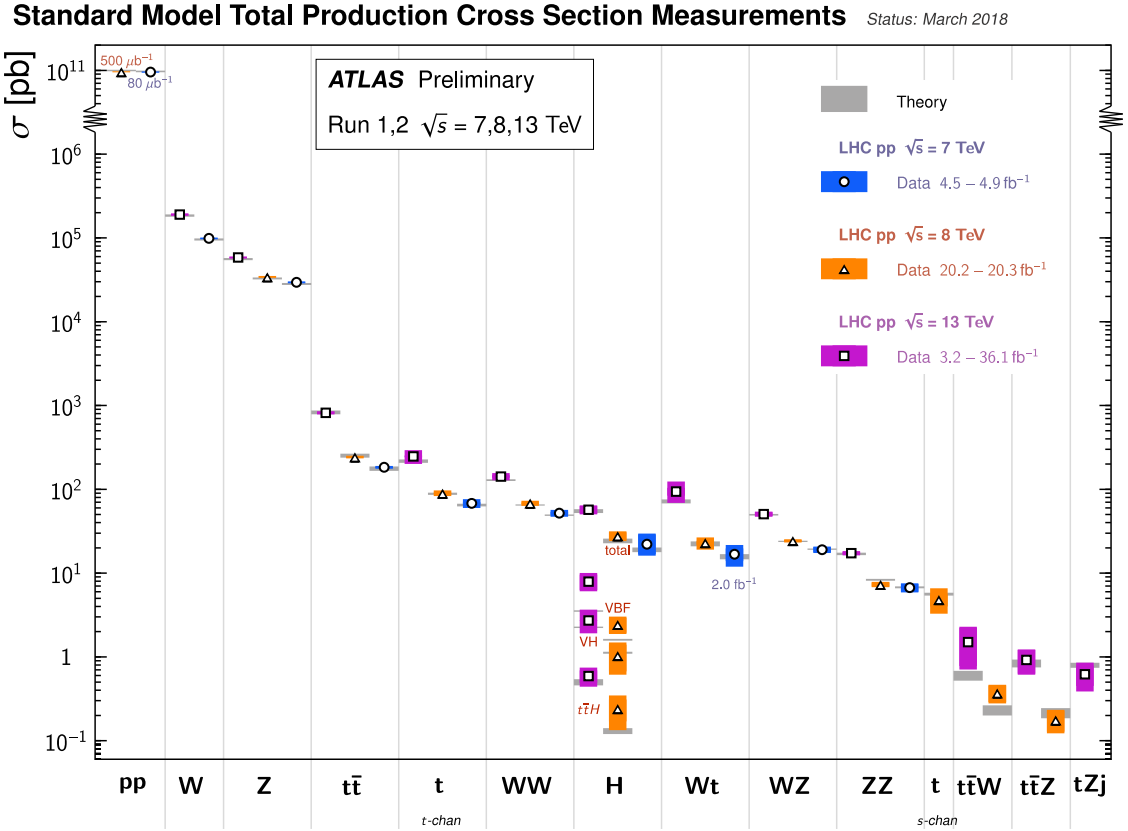
Introduction

Strong case for physics beyond the Standard Model

- Standard Model (SM) describes interactions of all known particles with remarkable accuracy



[Wikipedia]



[twiki.cern.ch]

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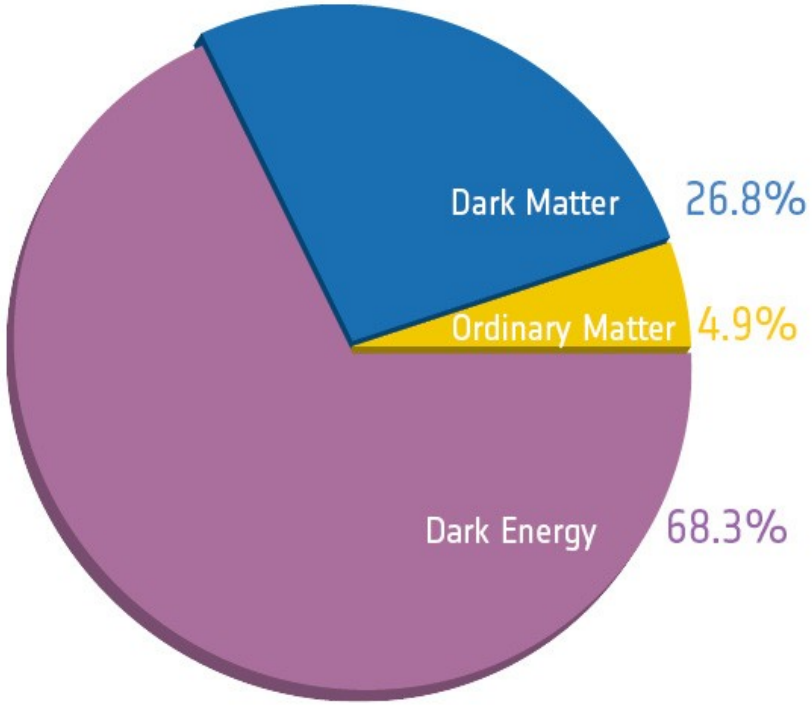

[PLANCK]

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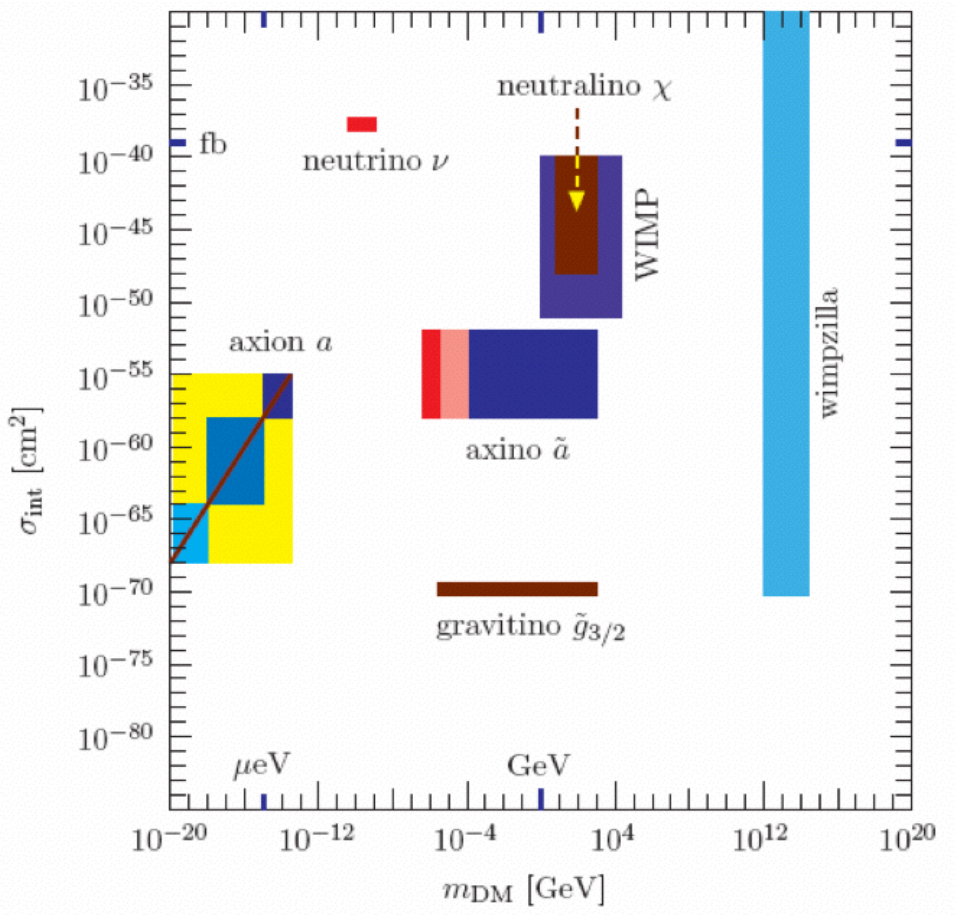

[Kim,Carosi 10]

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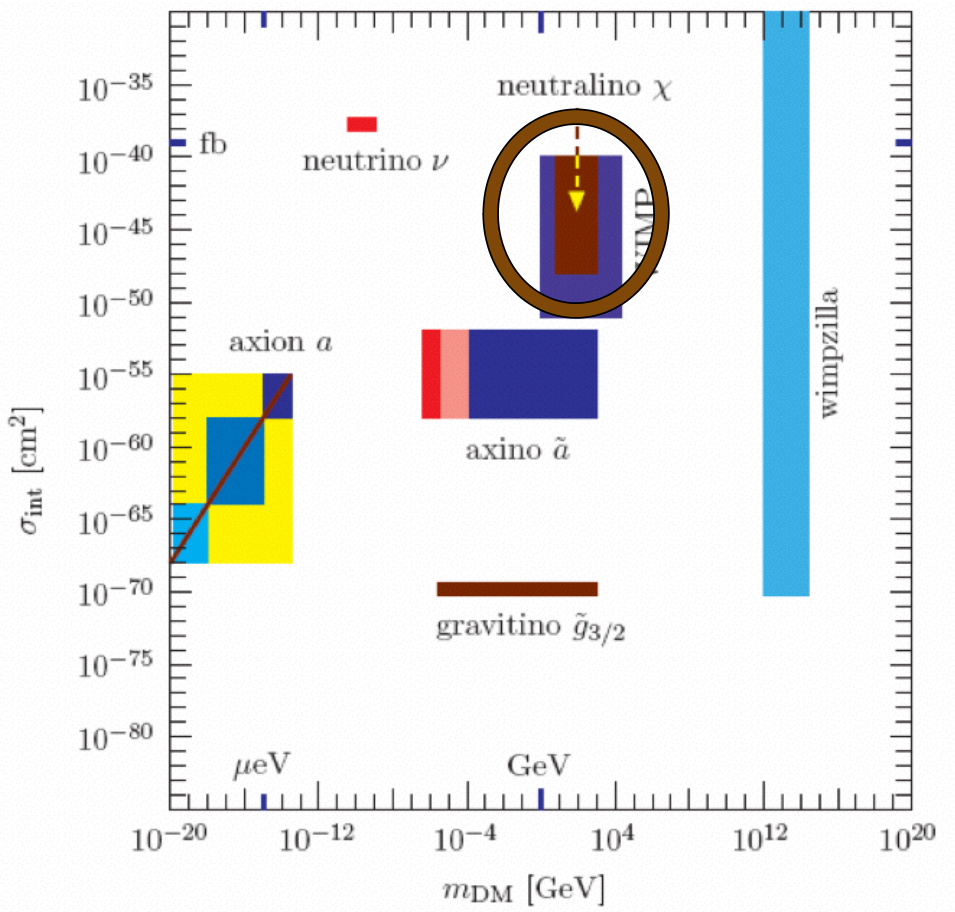

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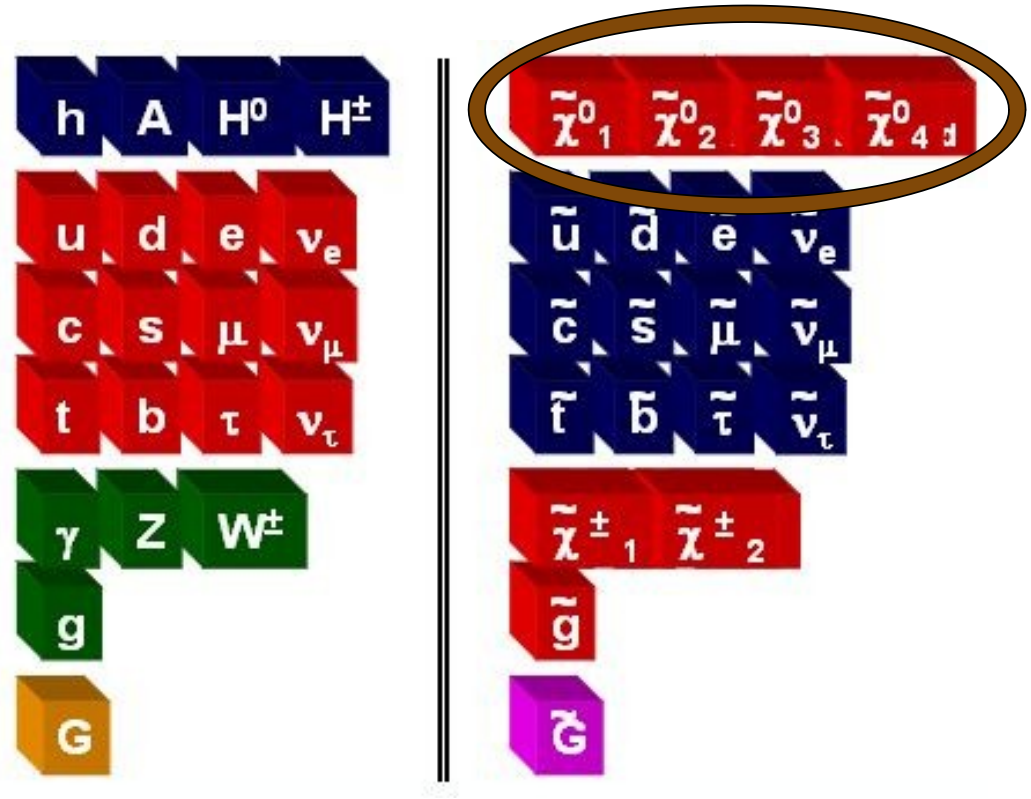
Minimal Supersymmetric Standard Model (MSSM)



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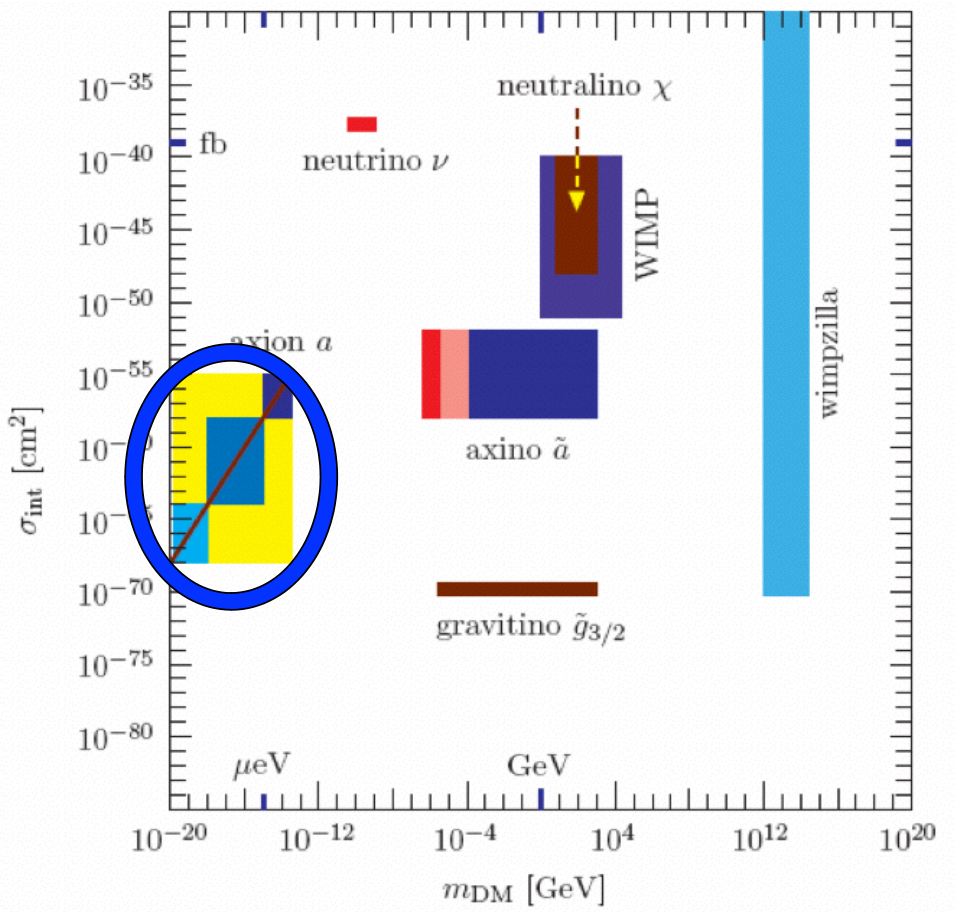

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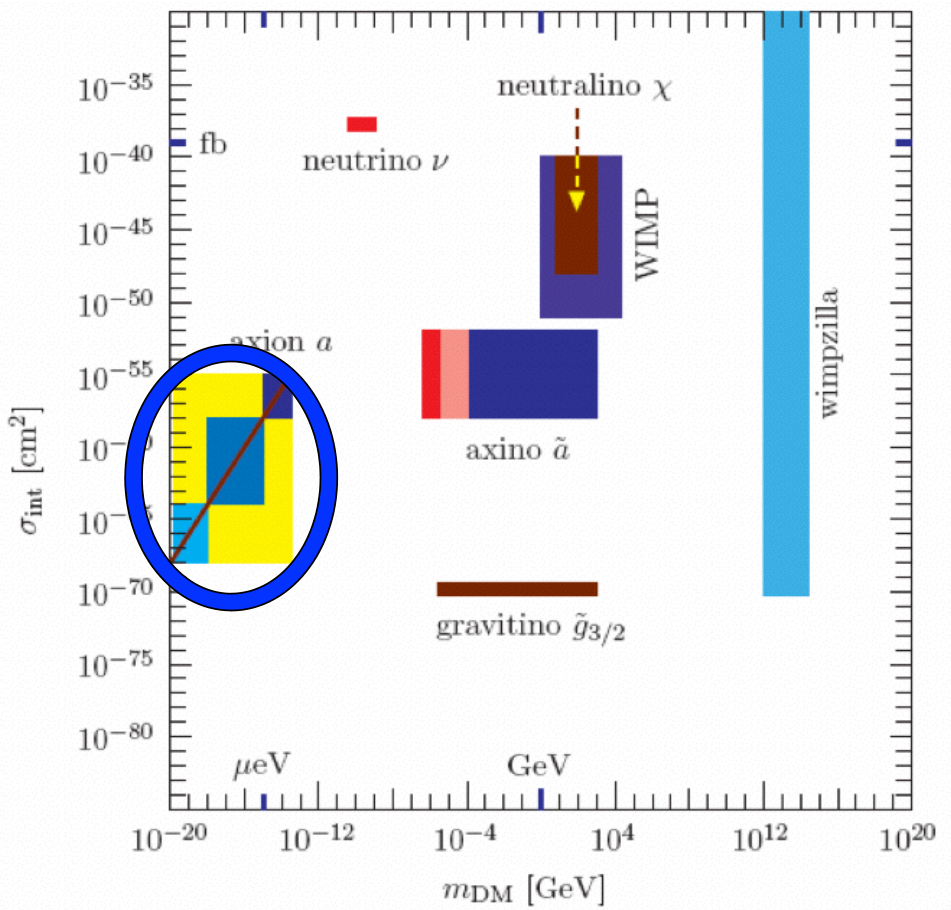
  - Strong CP problem: Axion
- Non-observation of neutralino at Large Hadron Collider (LHC) or in DM direct detection experiments strong motivation to focus more attention to axion



[Kim,Carosi 10]

Strong CP Problem

Theta term in Quantum Chromodynamics

- Quantum Chromodynamics (QCD): [Gross,Wilczek 73;Politzer 73; Fritzsch,Gell-Mann,Leutwyler 73]

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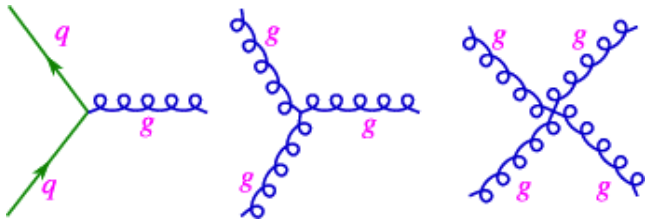

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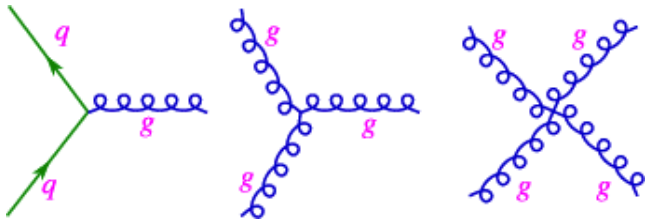

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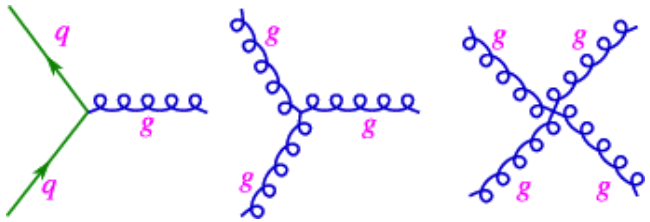

$$\int d^4x\, \partial_\mu J^\mu_{\rm CS} = 0, \pm 1, \pm 2, ...$$

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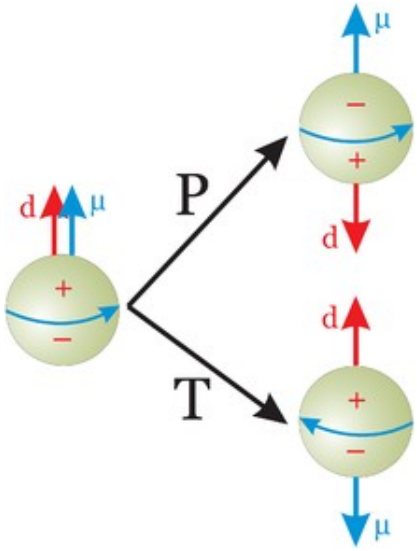

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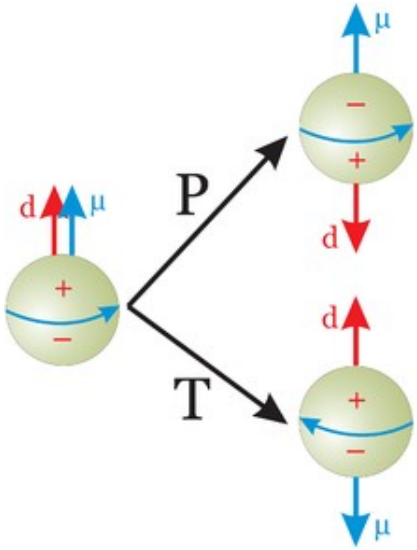
$$d_n(\overline{\theta}) = 2.4(1.0) \times 10^{-16}\,\overline{\theta}\,e\,\mathrm{cm}$$



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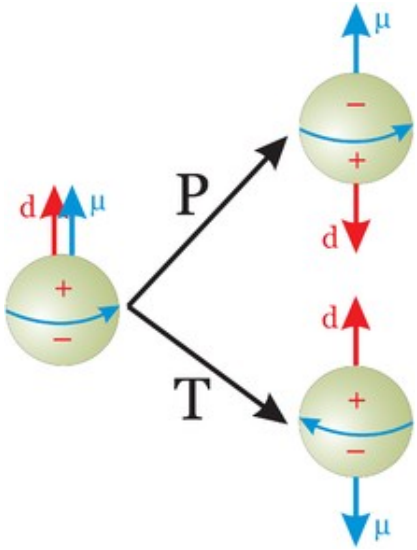
- Experiment: [Baker et al. 06]

$$|d_n| < 2.9 \times 10^{-26}\,e\,\mathrm{cm}$$



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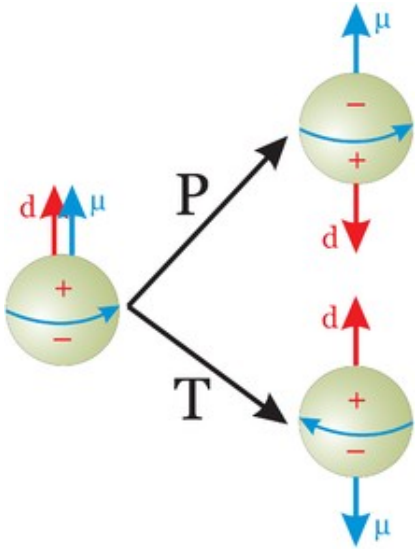

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A dynamical solution

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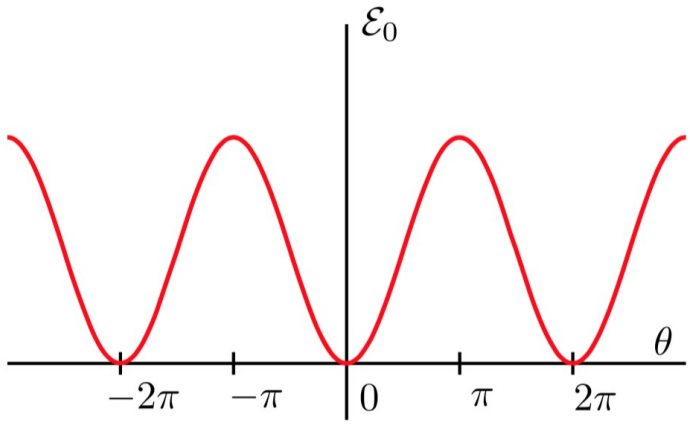
[Vafa,Witten 84]



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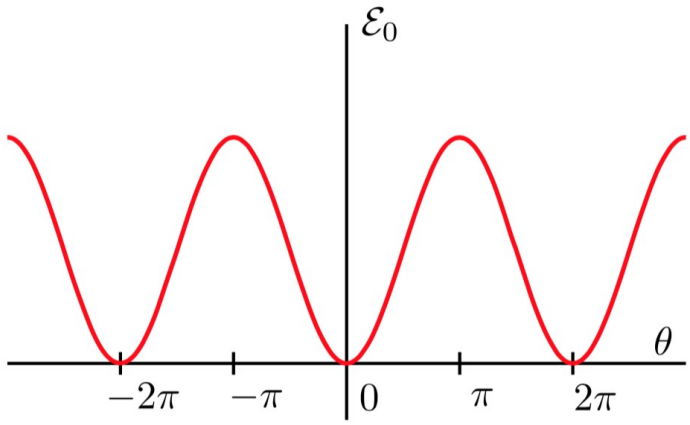

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[Peccei,Quinn 77]

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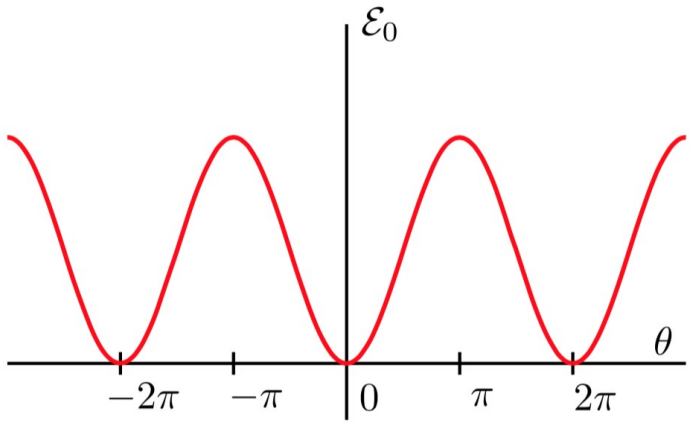

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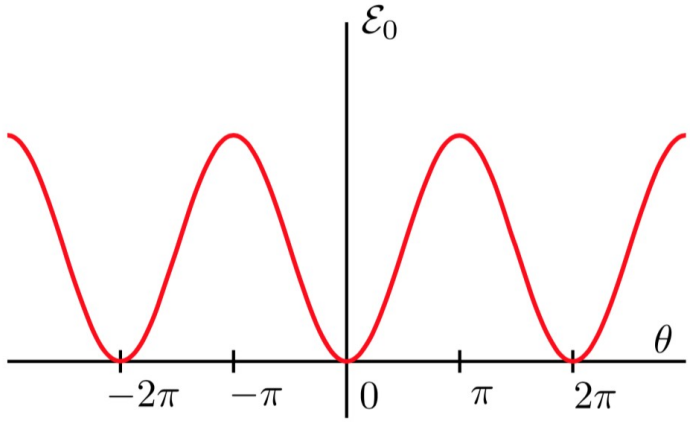

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- Mass:

$$m_A \simeq \frac{\sqrt{\Sigma}}{f_A}\sqrt{\frac{m_u m_d}{m_u + m_d}} \simeq \frac{m_\pi f_\pi}{f_A}\frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\ \text{meV}\left(\frac{10^9\ \text{GeV}}{f_A}\right)$$

Peccei-Quinn Extension of Standard Model

Simple way to get dynamical theta field

- A singlet complex scalar field σ, featuring a spontaneously broken global $U(1)_{\rm PQ}$ symmetry
- Particle excitations:

$$\sigma(x) = \frac{1}{\sqrt{2}} \left(v_{\rm PQ} + \rho(x)\right) \mathrm{e}^{iA(x)/v_{\rm PQ}}$$

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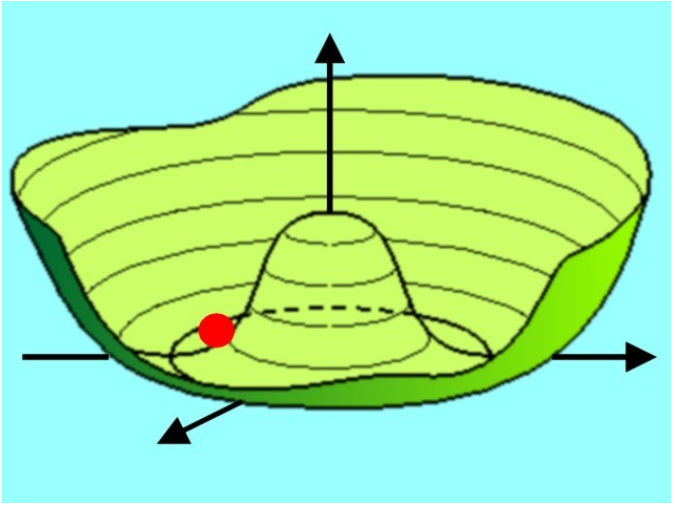

[Raffelt]

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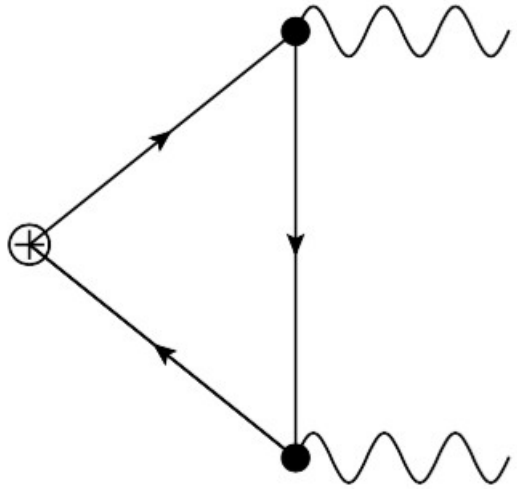
$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} \supset -\frac{\alpha_s}{8\pi} N\, G^b_{\mu\nu} \tilde{G}^{b,\mu\nu}$$



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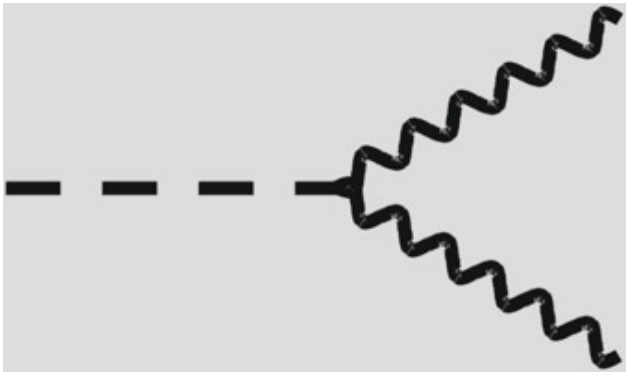
- Low energy effective field theory at energies above $\Lambda_{\rm QCD}$ but below $\left(\ll v_{\rm PQ}\right)$: [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\, \theta(x)\, G^b_{\mu\nu} \tilde{G}^{b,\mu\nu}\,; \qquad \theta(x) = A(x)/f_A\,; \qquad f_A = v_{\rm PQ}/N$$

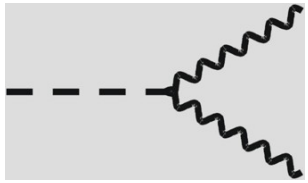
[Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]

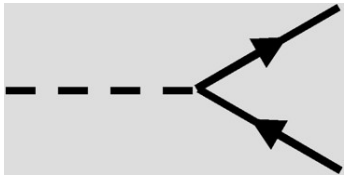


Peccei-Quinn Extension of Standard Model

Axion couplings to SM at energies below QCD scale

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu A \partial^\mu A - \frac{1}{2} m_A^2 A^2 - \frac{\alpha}{8\pi} \frac{C_{A\gamma}}{f_A} A F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \frac{C_{Af}}{f_A} \partial_\mu A \, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$





- Couplings of axion to SM suppressed by inverse power of

$$f_A = v_{\rm PQ}/N \gg v = 246\,{\rm GeV}$$

rendering the axion „invisible“

[Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]

- Since mass also inversely proportional PQ scale,

$$m_A = 57.0(7)\left(\frac{10^{11}\,{\rm GeV}}{f_A}\right)\mu{\rm eV}$$

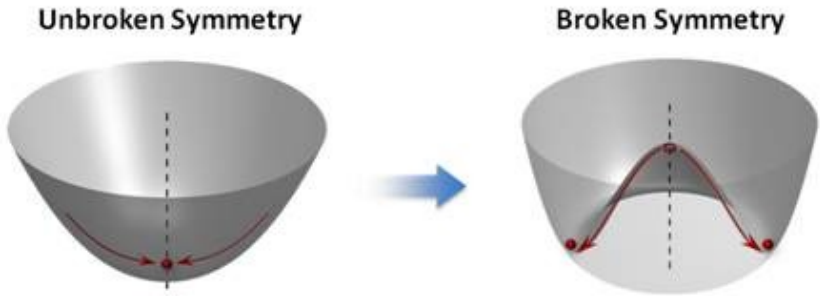
couplings to SM decrease towards lower masses

[Grilli di Cortona et al. `16; Borsanyi et al. `16]

Axion Dark Matter

- Axion field born after breaking of $U(1)_{\rm PQ}$ symmetry:

$$T \lesssim v_{\rm PQ} \sim f_A$$



[Peking University]

Axion Dark Matter

- Axion field born after breaking of $U(1)_{\rm PQ}$ symmetry:

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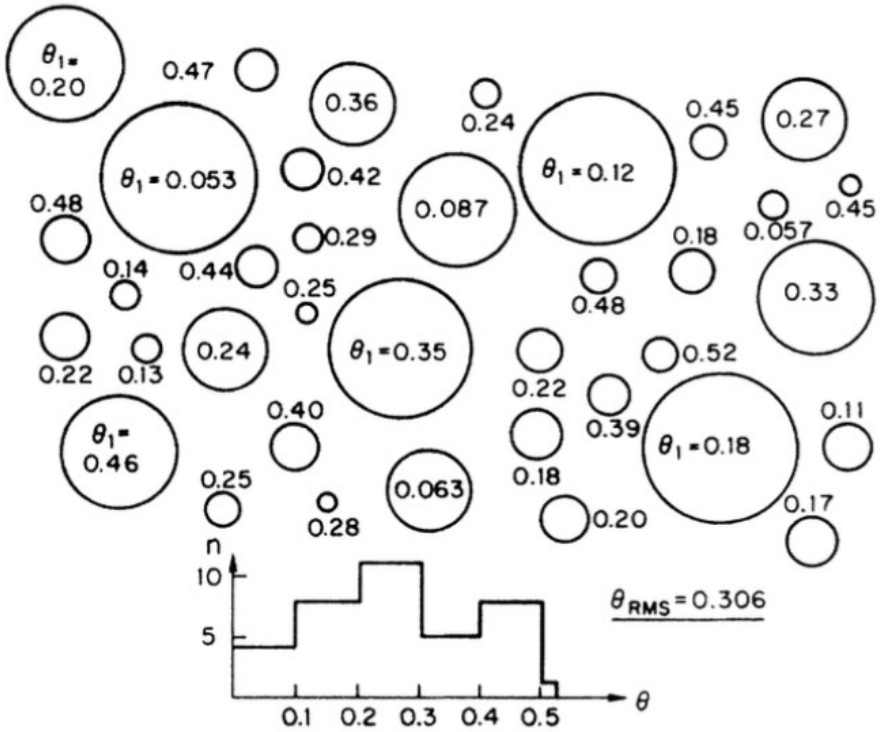
- In causally connected region at phase transition, axion field $\theta = A/f_A$ takes random initial value



[Turner `86]

Axion Dark Matter

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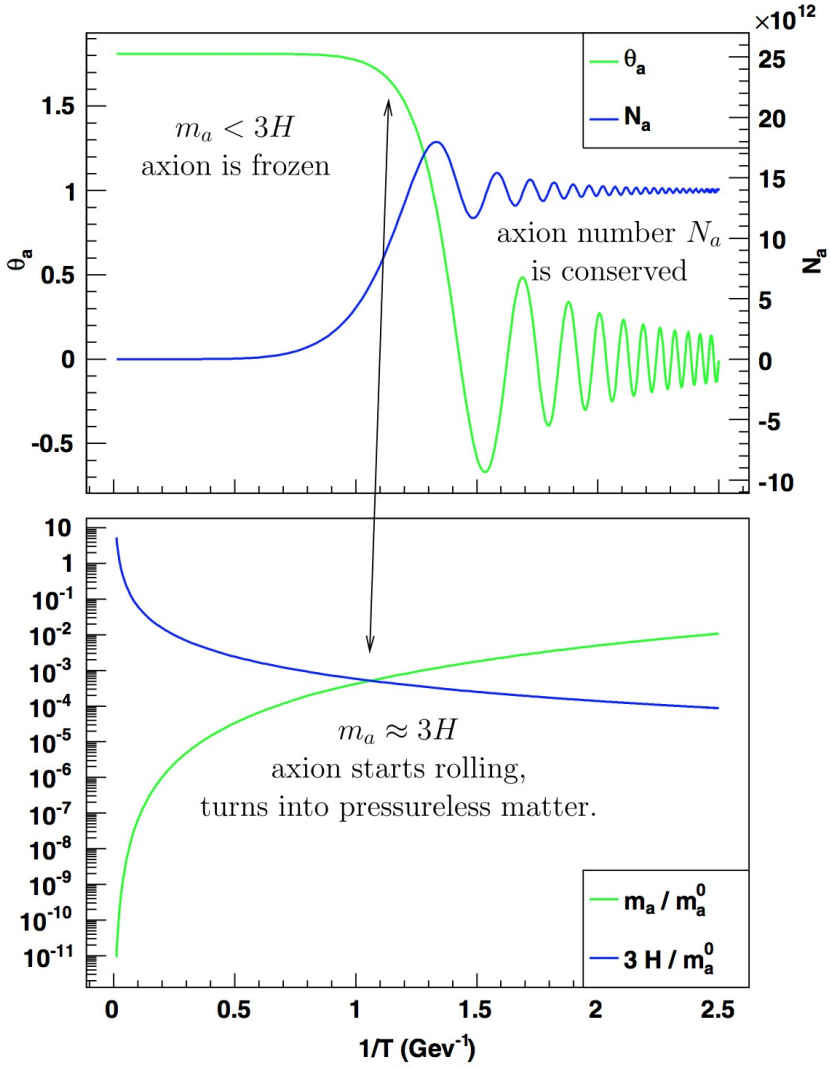
- Frozen as long as Hubble expansion rate exceeds mass, $H(T) \gtrsim m_A(T)$

- Later, when $H(T) \sim m_A(T)$, field starts to oscillate around zero; equation of state like cold dark matter:
$$w_A = p_A/\rho_A \simeq 0$$

[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83]



[Wantz,Shellard `09]

Axion Dark Matter

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$$w_A = p_A/\rho_A \simeq 0$$

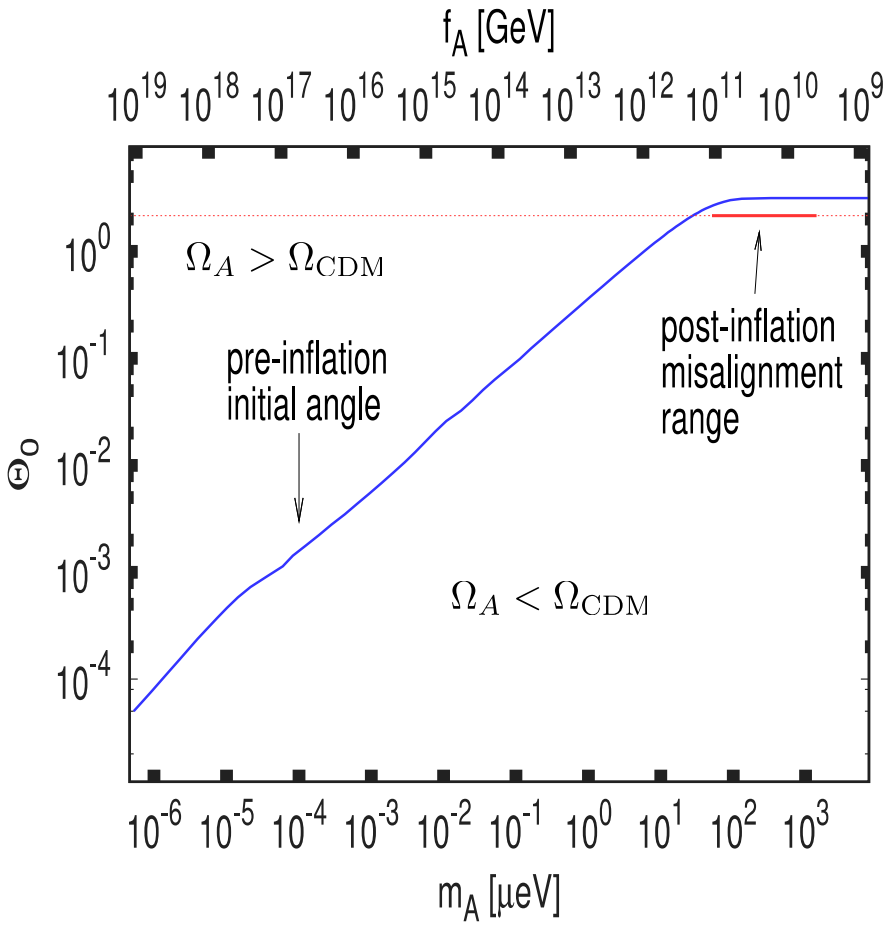
[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83]

- DM prediction:

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{f_A}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \theta_{\rm i}^2$$

$$\approx 0.12 \left(\frac{6\ \mu{\rm eV}}{m_A}\right)^{1.165} \theta_{\rm i}^2\,,$$

- Axion can be 100% of DM for $f_A \gtrsim 10^9\ {\rm GeV}$

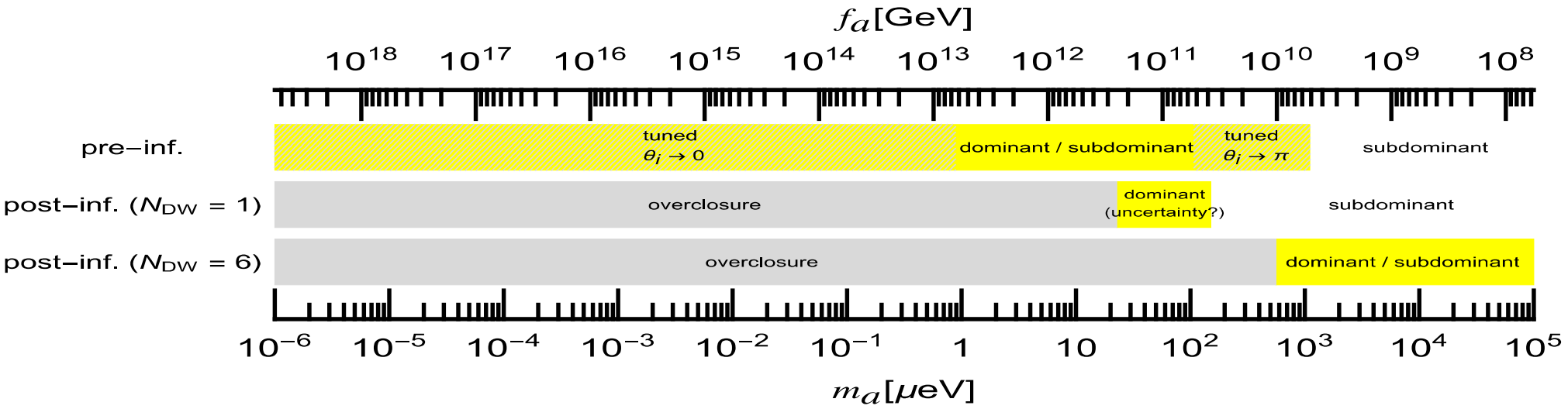


[Borsanyi et al., Nature `16]

Axion Dark Matter

Experimental hunt

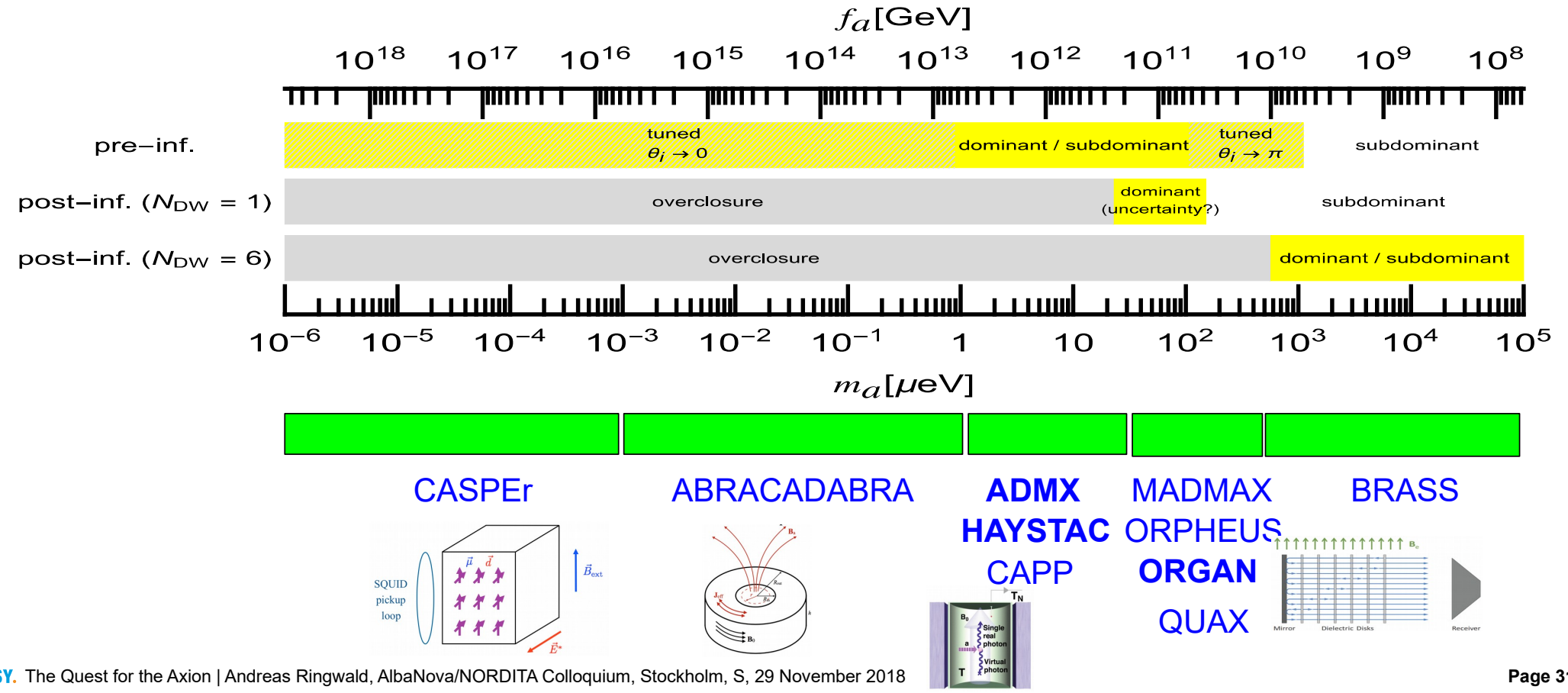
- Dark-matter axion mass spans a huge range:



Axion Dark Matter

Experimental hunt

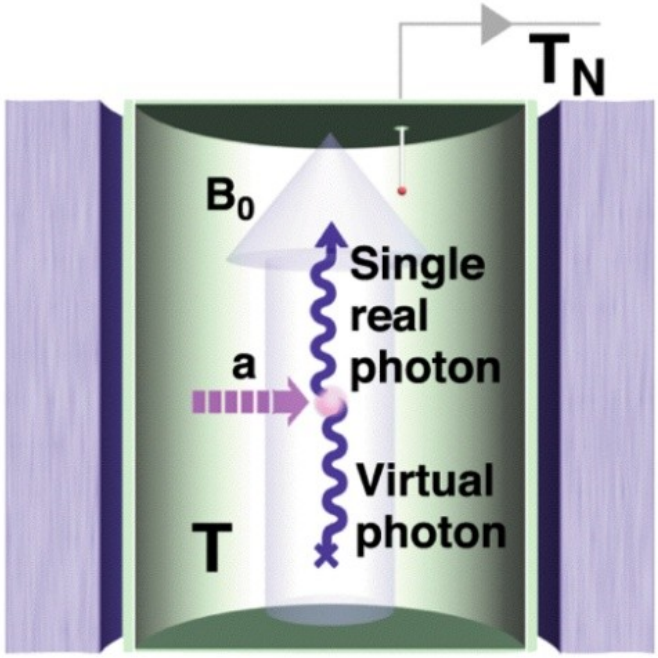
- Strong motivation for current und upcoming axion DM experiments:



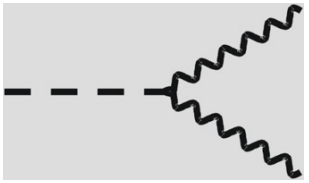
Dark Matter Axion Searches

Microwave cavities

- Axion or DM – photon conversion in microwave cavity placed in magnetic field [Sikivie 83]
- Best sensitivity: mass = resonance frequency $m_a = 2\pi\nu \sim 4\ \mu\text{eV}\left(\frac{\nu}{\text{GHz}}\right)$



$$P_{\text{out}} \sim g_{A\gamma}^2 |\mathbf{B}_0|^2 \rho_{\text{DM}} V Q / m_A$$

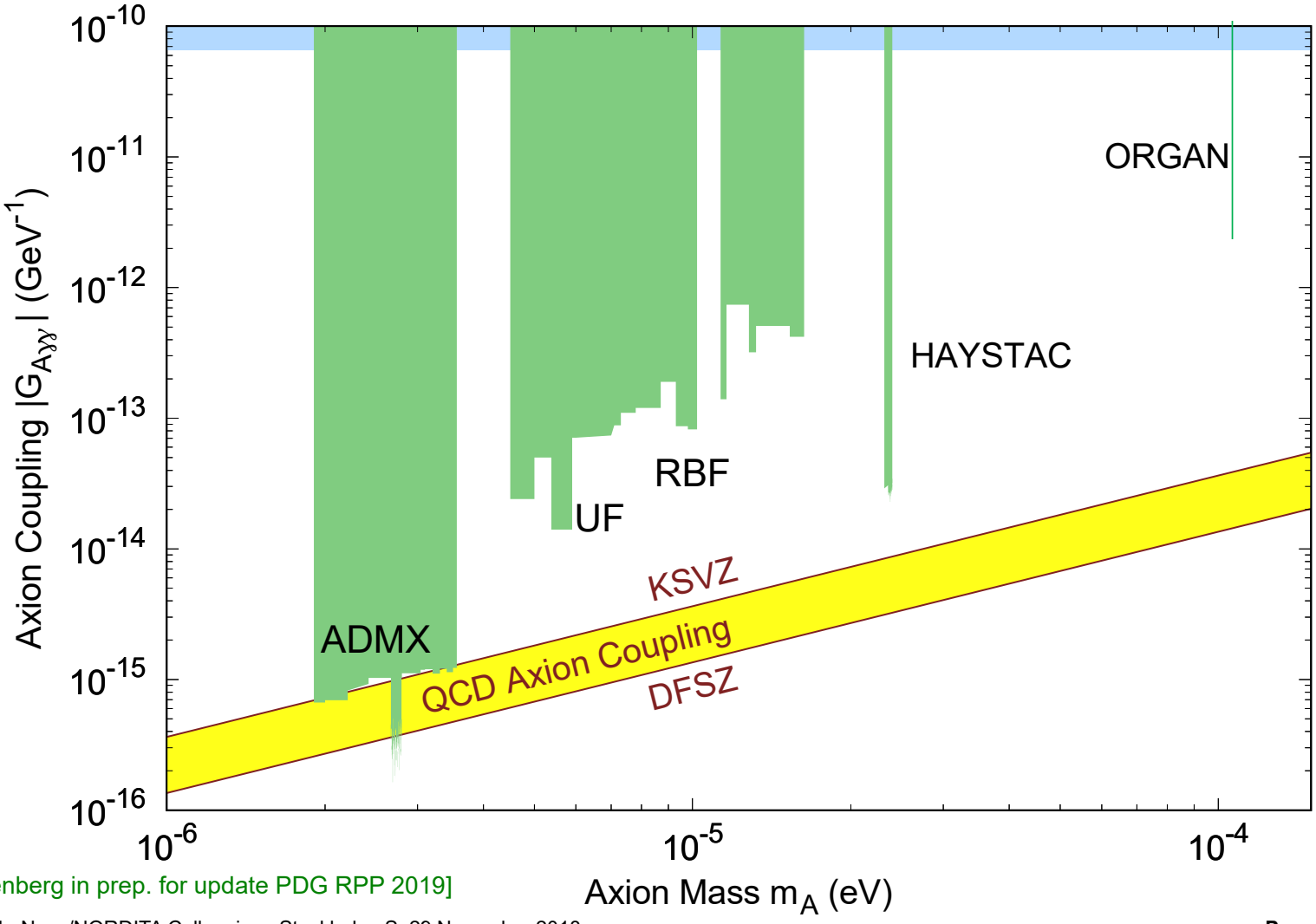


$$g_{A\gamma} = \frac{\alpha}{2\pi f_A} C_{A\gamma}$$

Dark Matter Axion Searches

Microwave cavities

- Current status:
  - ADMX
  - HAYSTAC
  - ORGAN

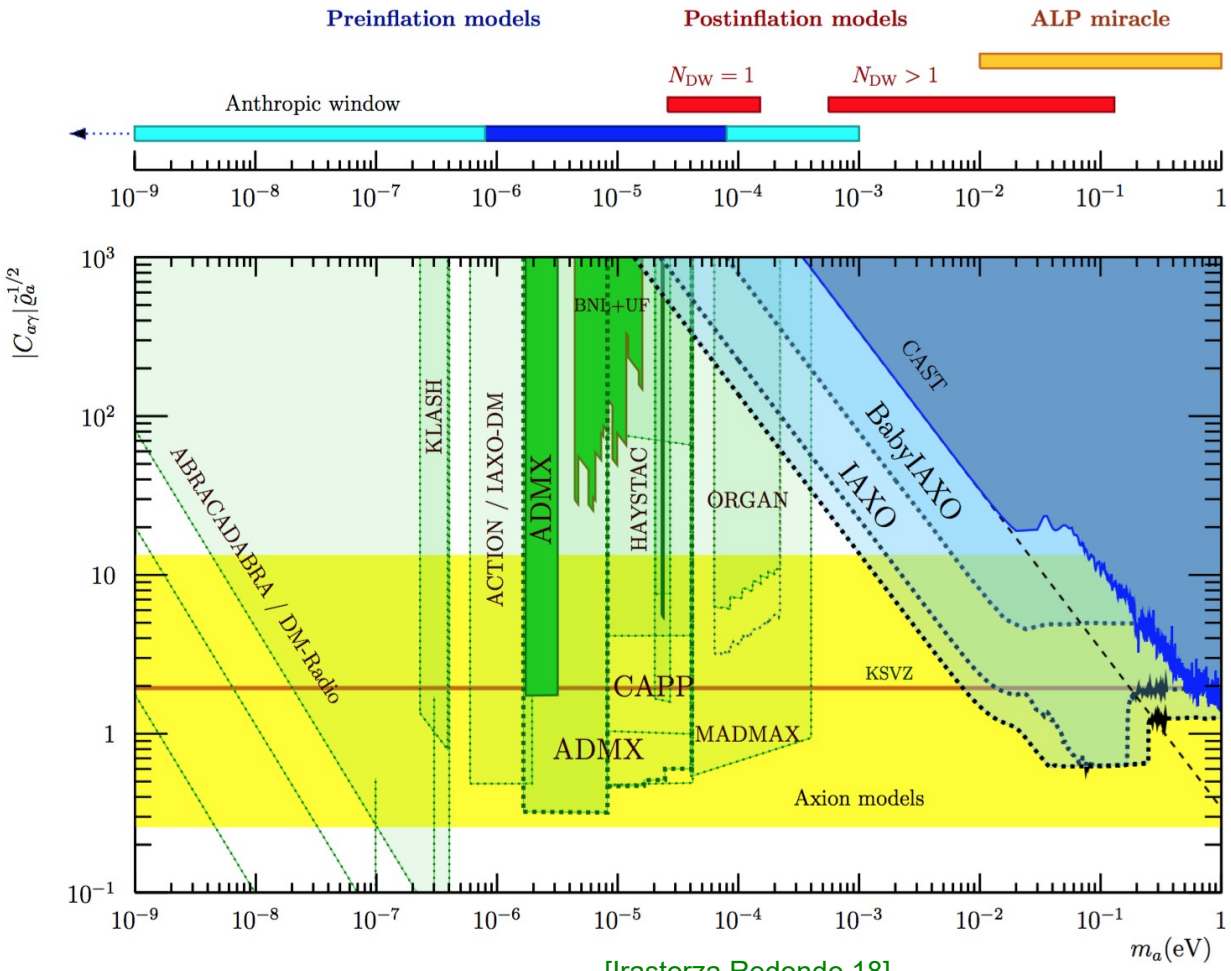


[AR,Rybka,Rosenberg in prep. for update PDG RPP 2019]

Dark Matter Axion Searches

Microwave cavities

- Current status:
  - ADMX
  - HAYSTAC
  - ORGAN
- Currently in construction:
  - CAPP (South Korea)
- Proposed:
  - KLASH (Frascati)
  - ACTION (South Korea)
  - IAXO-DM
- Axion DM searches with microwave cavities may cover $0.3\,\mu\mathrm{eV} \lesssim m_a \lesssim 30\,\mu\mathrm{eV}$
- Need other techniques in remaining mass range



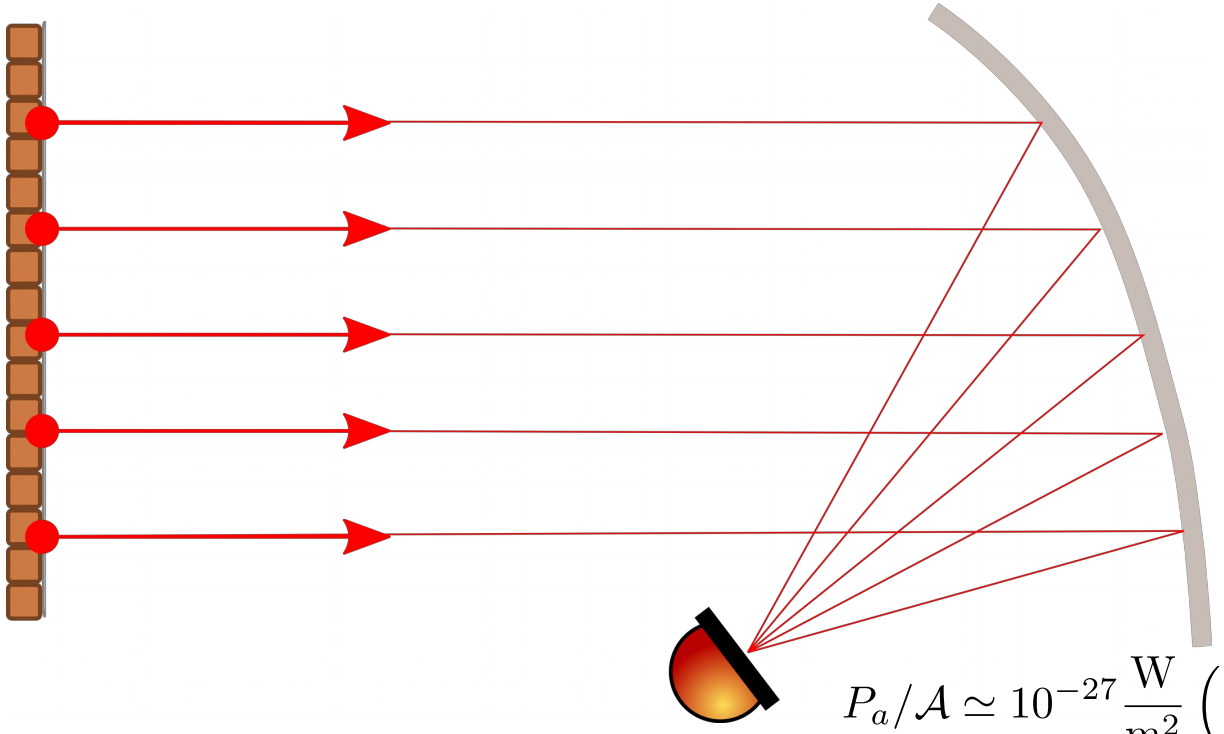
[Irastorza,Redondo 18]

Dark Matter Axion Searches

Dish antenna

- Oscillating axion DM in a background magnetic field carries a small electric field component
- A magnetised mirror in axion DM background radiates photons

[Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]

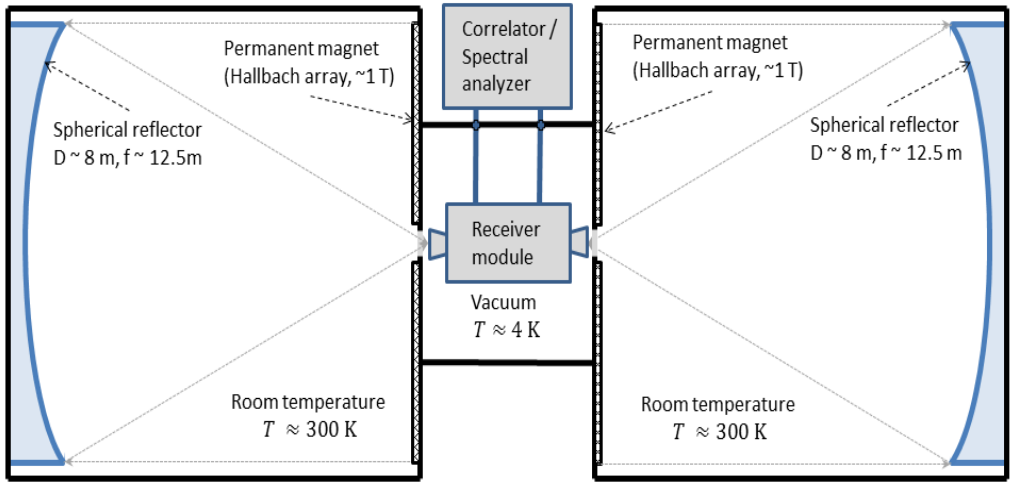


$$P_a/\mathcal{A} \simeq 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{g_{a\gamma}}{10^{-14}\,\mathrm{GeV}^{-1}}\right)^2\left(\frac{10^{-4}\,\mathrm{eV}}{m_a}\right)^2\left(\frac{B}{10\,\mathrm{T}}\right)^2$$

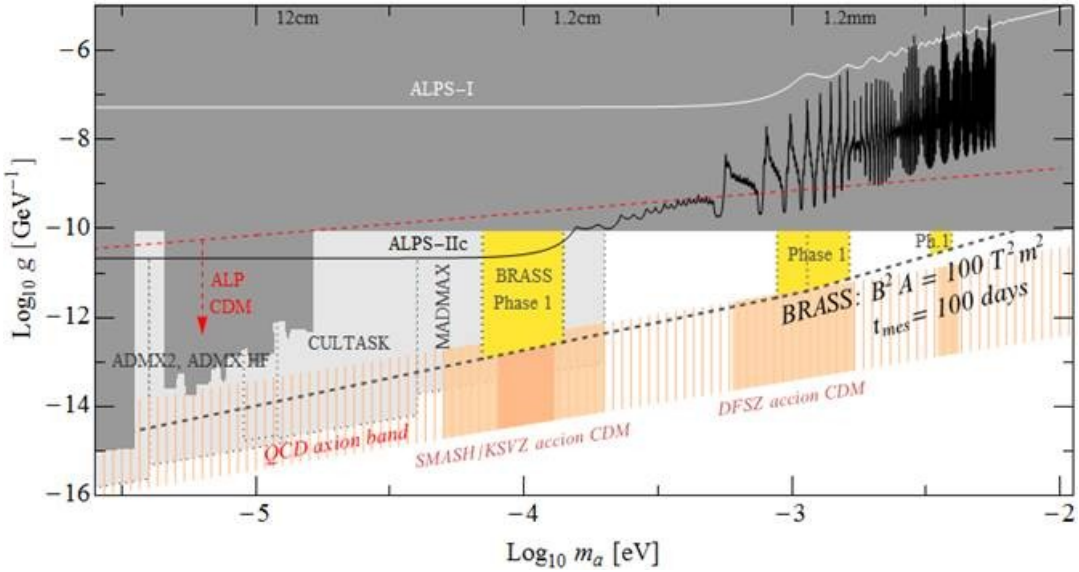
Dark Matter Axion Searches

Dish antenna

- Oscillating axion DM in a background magnetic field carries a small electric field component
- A magnetised mirror in axion DM background radiates photons [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]
- Proposed DM axion dish antenna experiment: BRASS (U Hamburg)



[Horns et al. (unpublished)]



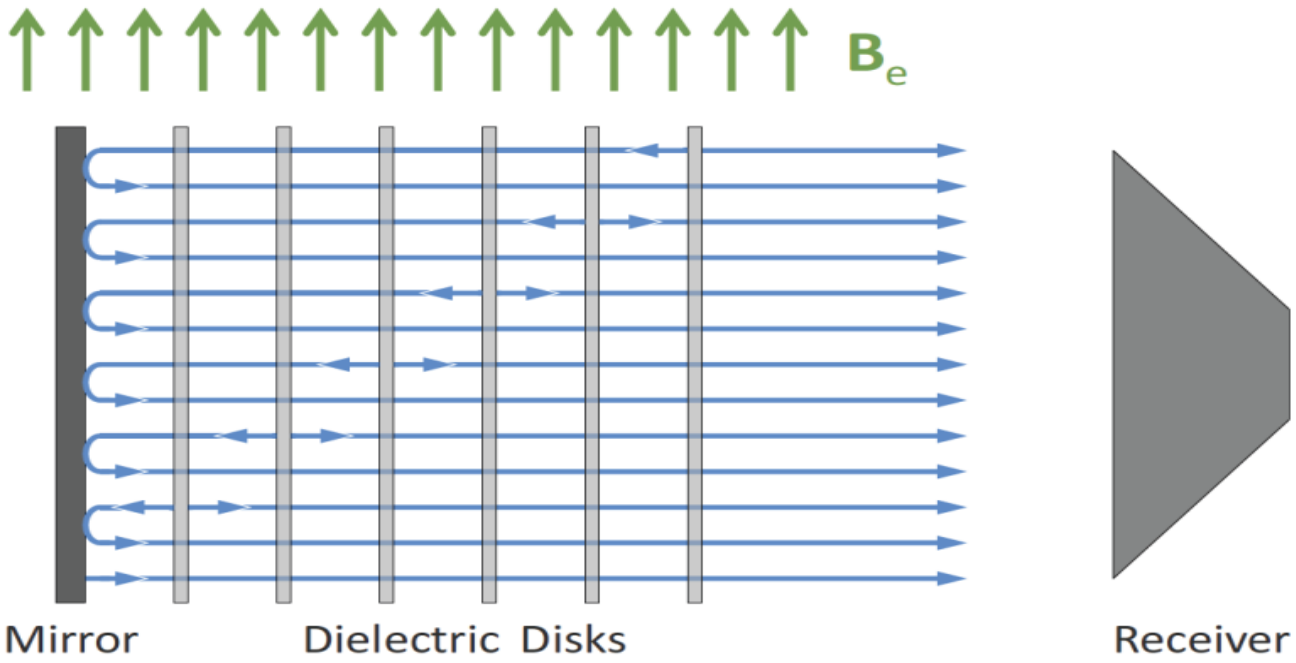
Dark Matter Axion Searches

Boosted dish antenna

- Open dielectric resonator
  - Add stack of dielectric disks in front of mirror (all immersed in magnetic field)
  - May achieve constructive interference of photon part of wave function

[Jaeckel,Redondo 13]

[Millar,Raffelt,Redondo,Steffen 16]



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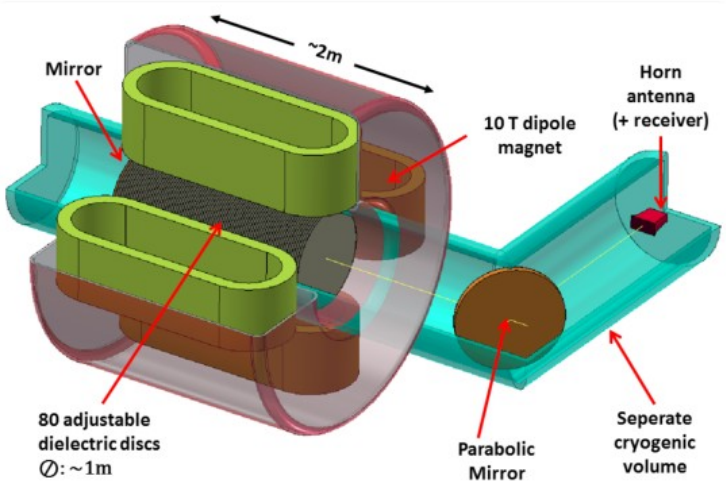
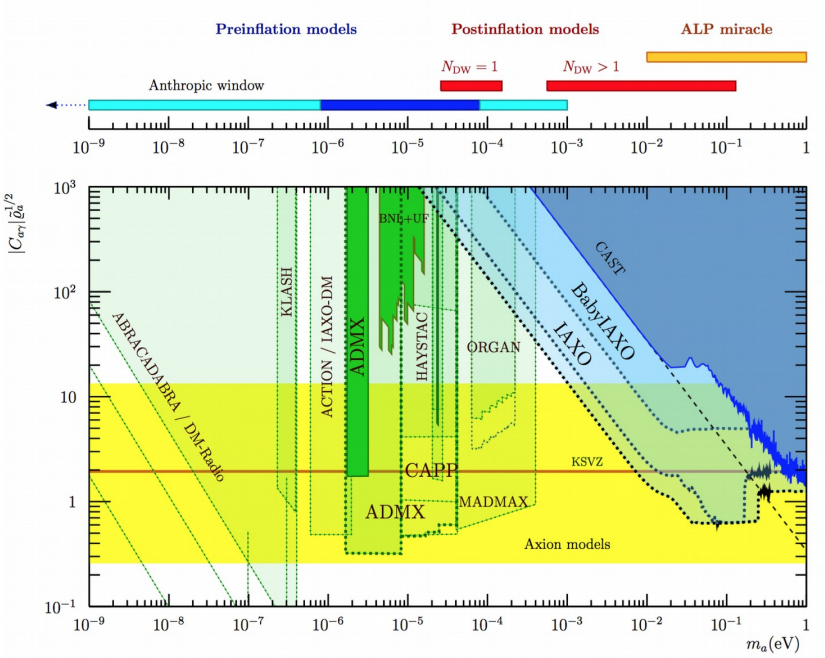
  - May achieve constructive interference of photon part of wave function [Millar,Raffelt,Redondo,Steffen 16]
- Proposed MADMAX experiment [Caldwell et al. `16]





[Irastorza,Redondo 18]

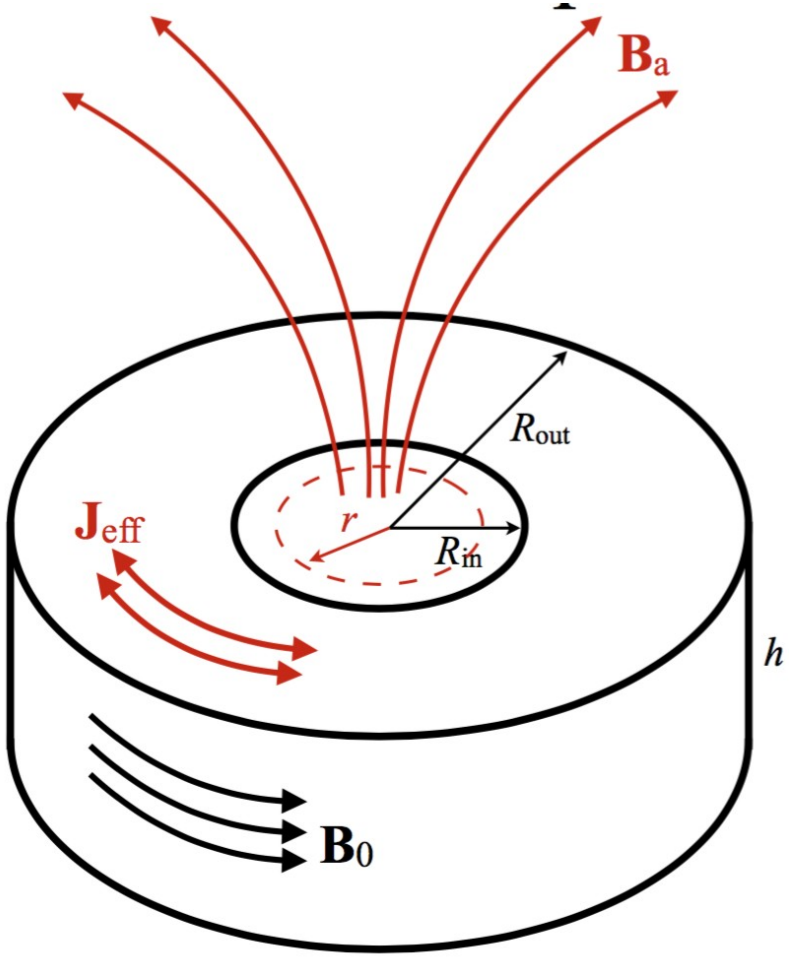
- Foreseen site: HERA Hall North at DESY

Dark Matter Axion Searches

Searching for axion-induced magnetic fields

[Sikivie,Sullivan,Tanner 14; Kahn,Safdi,Thaler `16]

- ABRACADABRA (MIT) currently being set-up
  - Exploit toroidal magnet with fixed magnetic field:
    - Axion DM generates oscillating effective current around ring
    - ... this generates oscillating magnetic field through center
    - ... this can be detected by pickup loop



[Ouellet `16; adapted from Kahn,Safdi,Thaler `16]

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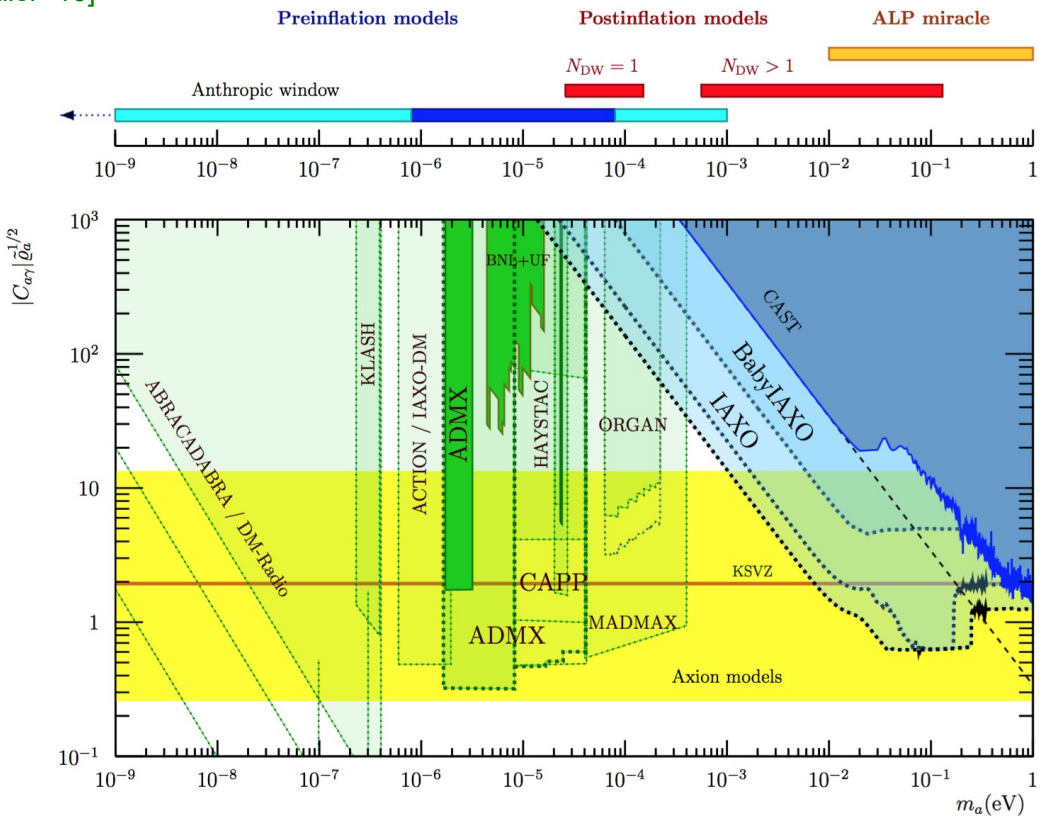

[Irastorza,Redondo 18]

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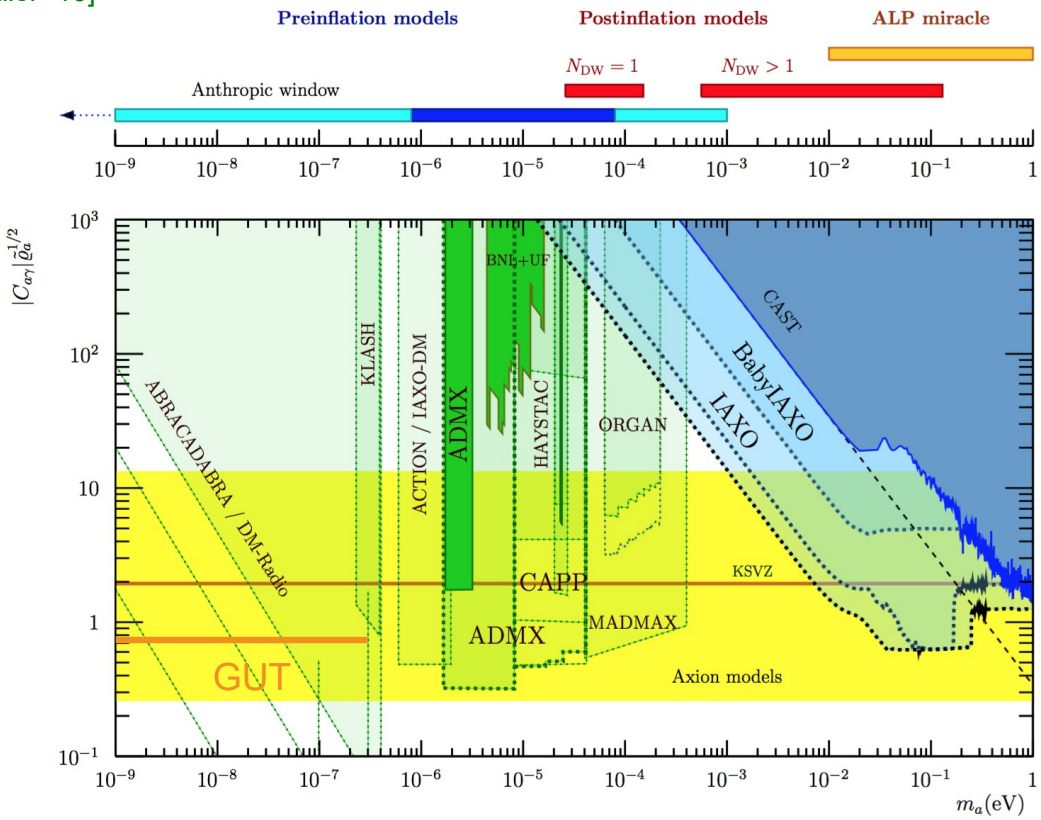
- DM-Radio (Stanford): similar experiment in path-finder status [Silva-Feaver et al. 16]
- Probe QCD axion dark matter in mass range predicted by Grand Unified Theories (GUTs)

[Ernst,AR,Tamarit 18; Di Luzio,AR,Tamarit 18]



[Irastorza,Redondo 18]

Dark Matter Axion Searches

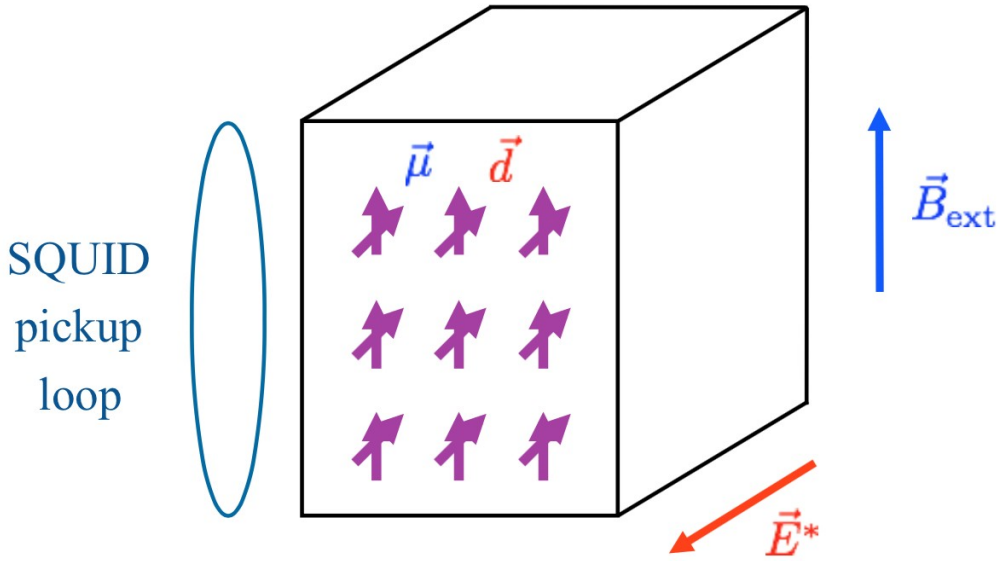
Magnetic resonance searches

- Axion DM field induces oscillating NEDMs:

$$d_N(t) = g_d \sqrt{2\rho_{\rm DM}}\cos(m_A t)/m_A$$

- Place a ferroelectric crystal (permanent electric polarisation fields $\vec{E}^*$) in an external $\vec{B}_{\rm ext} \perp E^*$
  - Nuclear spins are polarised along $\vec{B}_{\rm ext}$ and precess at Larmor frequency $\omega_L = 2\mu_N B_{\rm ext}$
  - Interaction $\epsilon_S \vec{d}_N(t) \cdot \vec{E}^*$ of DM induced NEDM with the $\vec{E}^*$-field leads to resonant increase of transverse magnetisation of sample when $\omega_L = m_A$

[Graham,Rajendran 13; Budker et al. 14]



[Budker et al. 14]

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[Graham,Rajendran 13; Budker et al. 14]

- CASPEr-Electric currently being set-up in Boston
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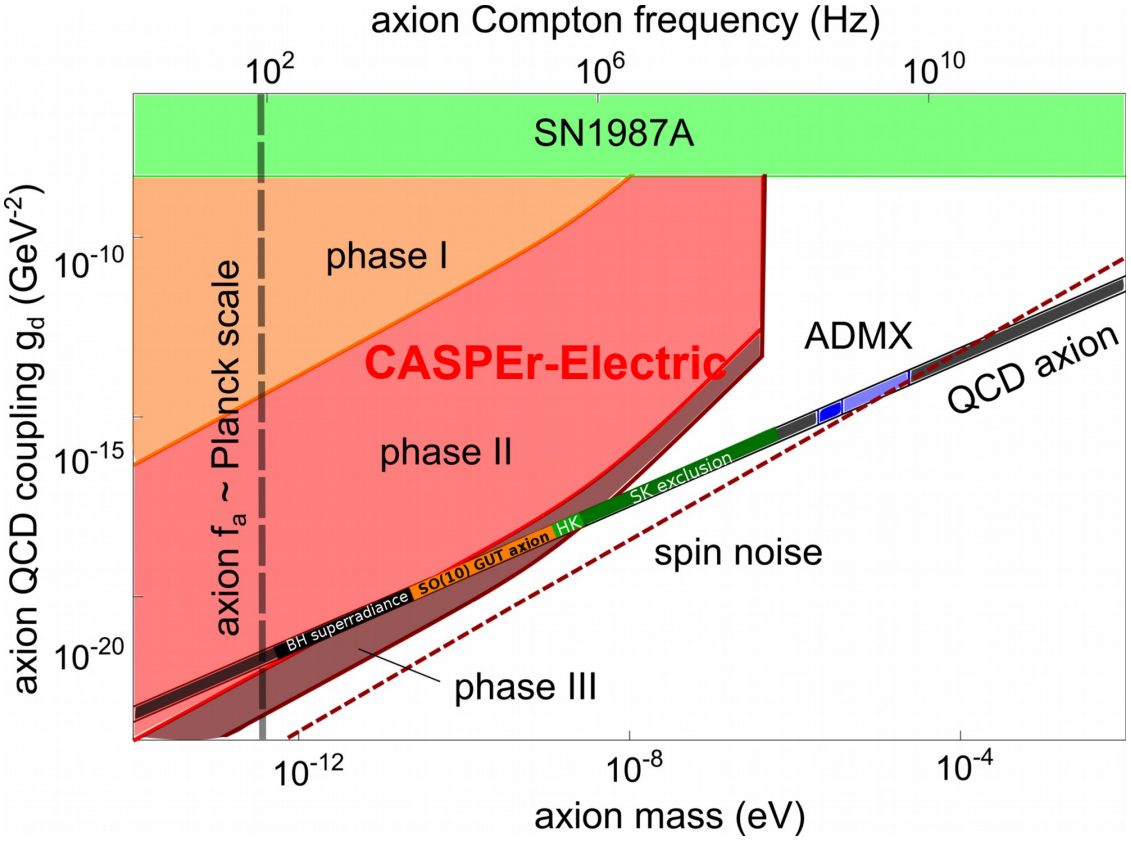
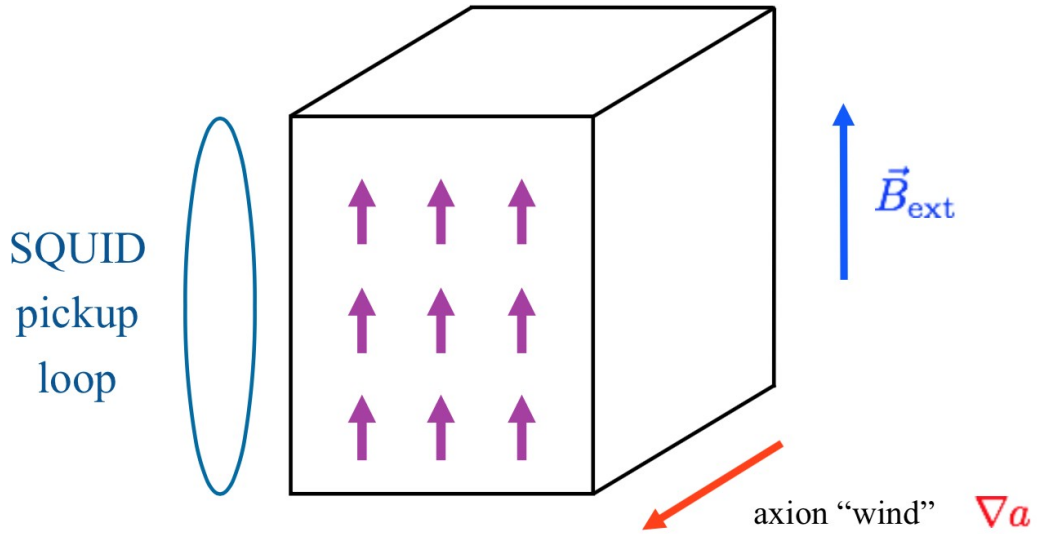


[Ernst 18; adapted from Kimball et al. 17]

Dark Matter Axion Searches

Magnetic resonance searches

- Axion nucleon (electron coupling) leads to nucleon (electron) spin precession about galactic axion DM wind
- MRT search for transverse magnetization due to precession of nuclear (electron spins) in polarized sample in DM wind [Graham,Rajendran 13]



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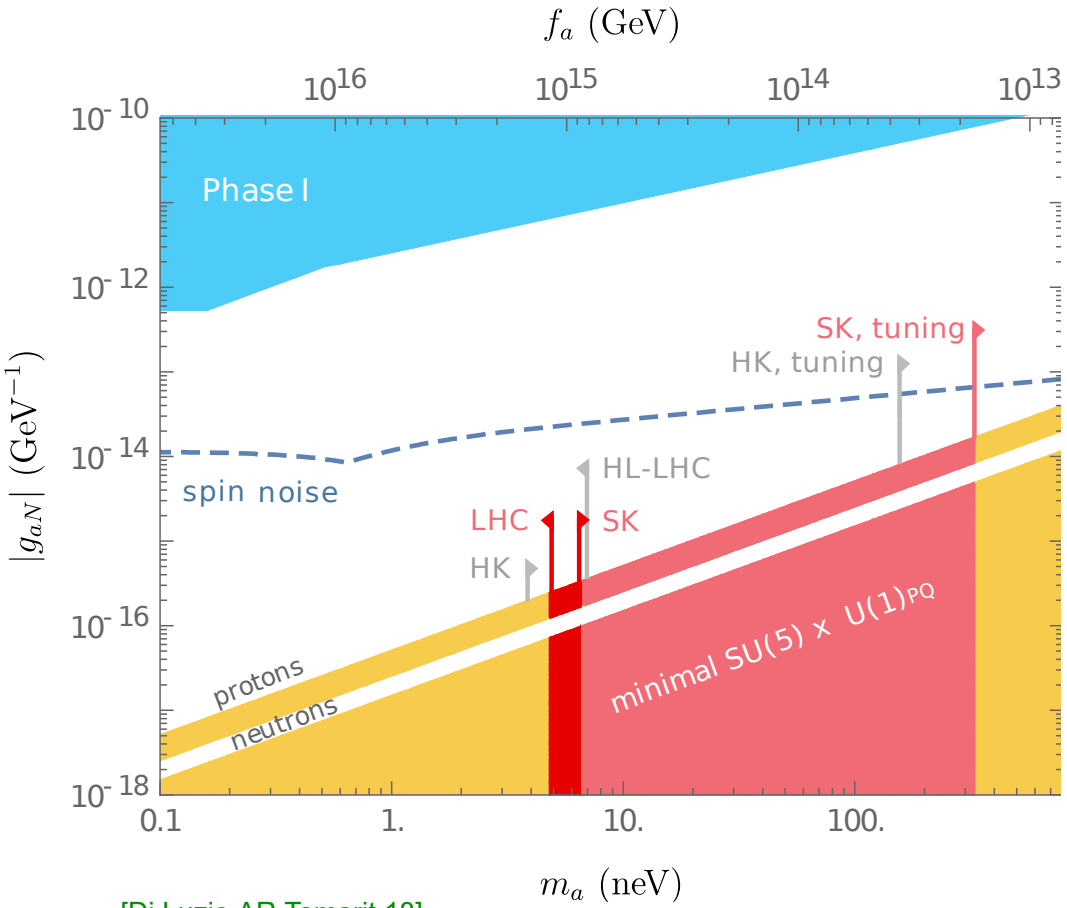
- CASPEr-Wind currently set-up at HMI Mainz [Budker et al.]
- QUAX (Legnaro): electron spin precession [Barbieri et al. 17]

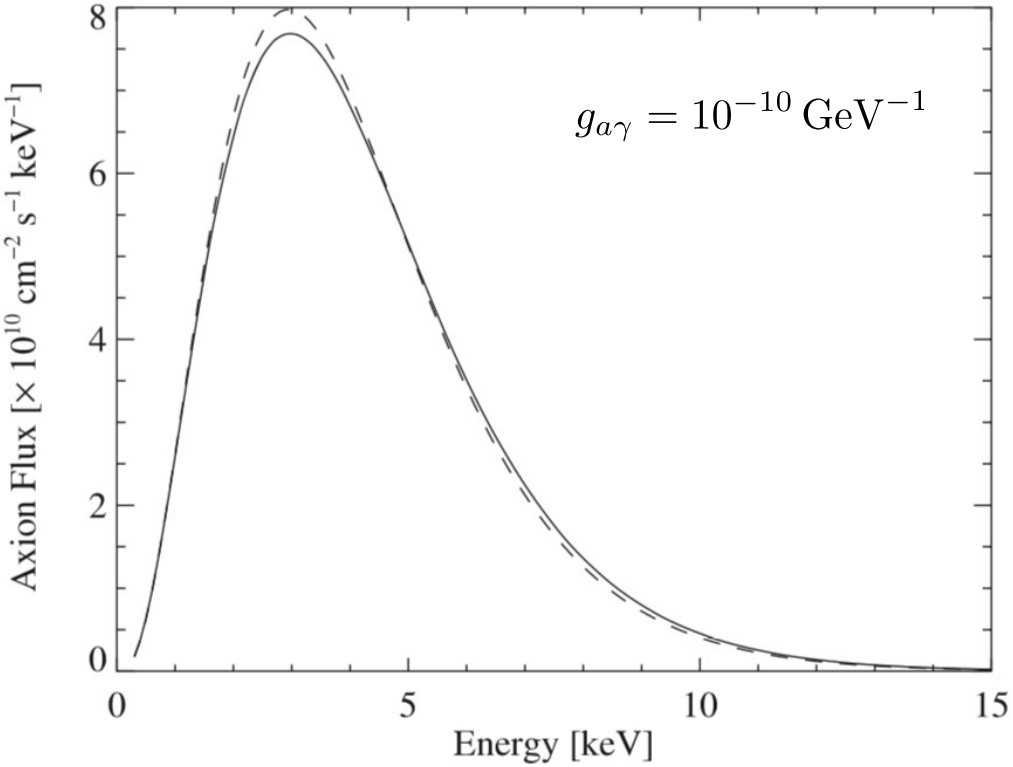


[Di Luzio,AR,Tamarit 18]

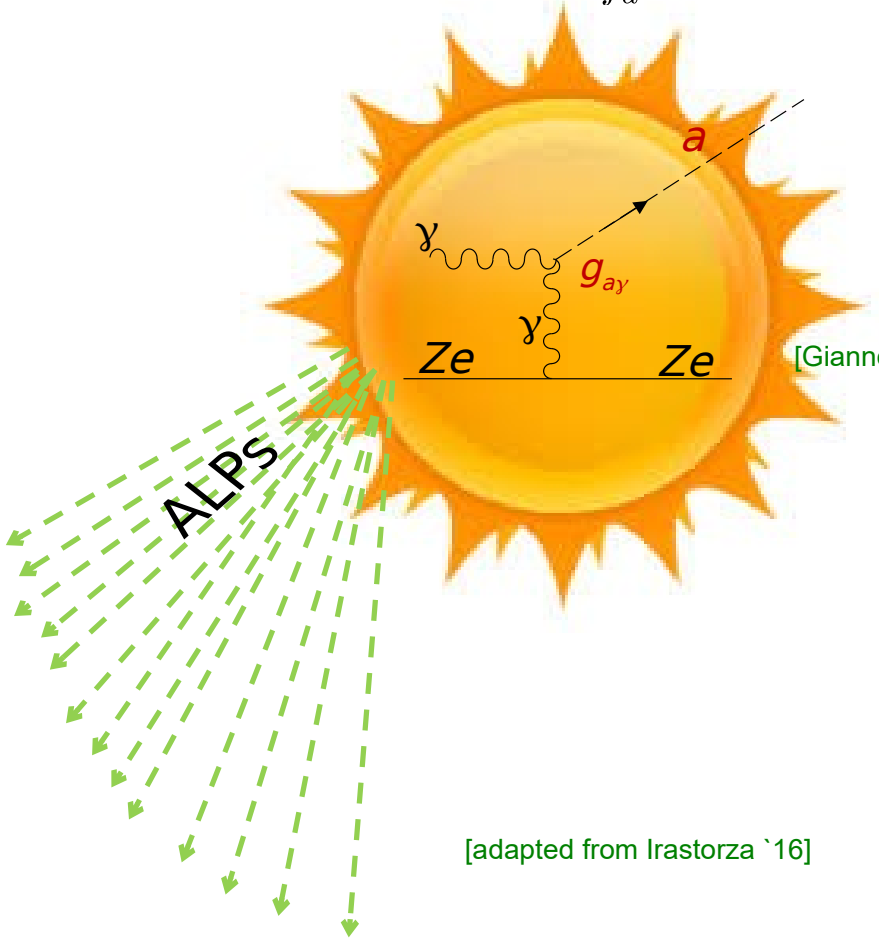
Solar Axion Searches

- Flux of solar axions produced by Primakoff process in core:

$$g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a} C_{a\gamma}$$



[Adriamonje et al. `07]



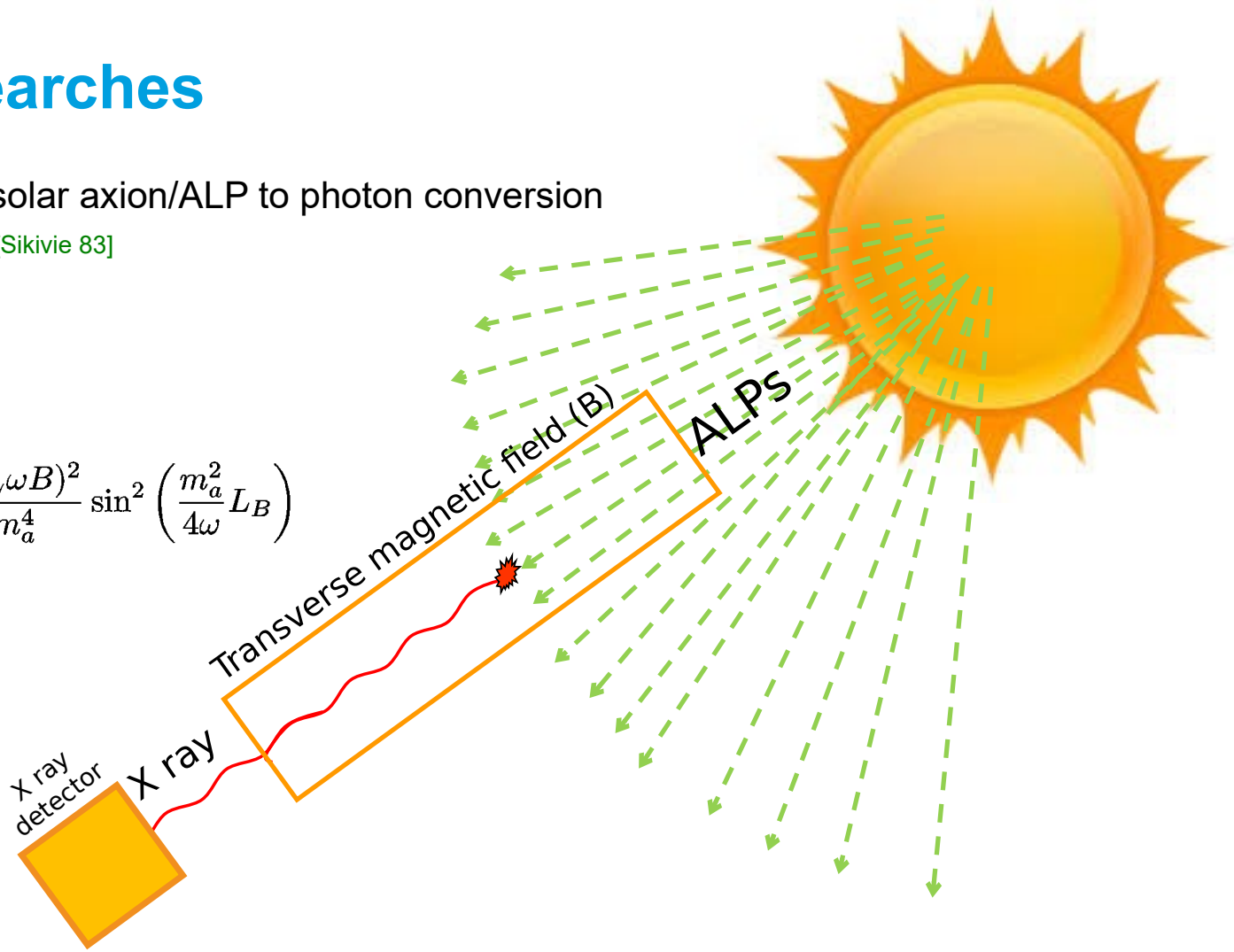
[Giannotti `16]

[adapted from Irastorza `16]

Solar Axion Searches

- Helioscope concept: solar axion/ALP to photon conversion in magnetic field [Sikivie 83]

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



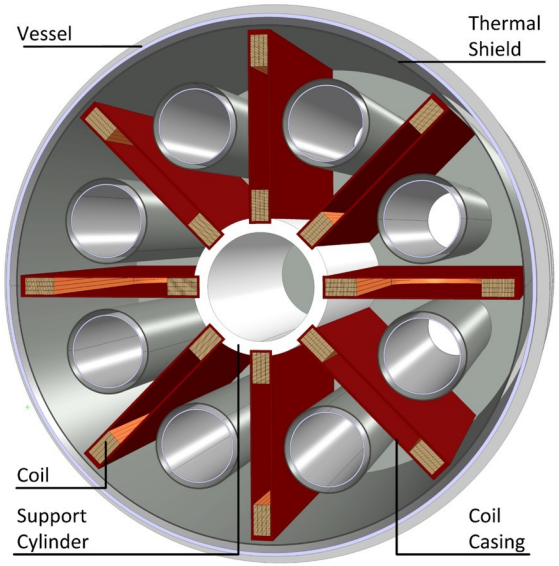
[adapted from Irastorza `16]

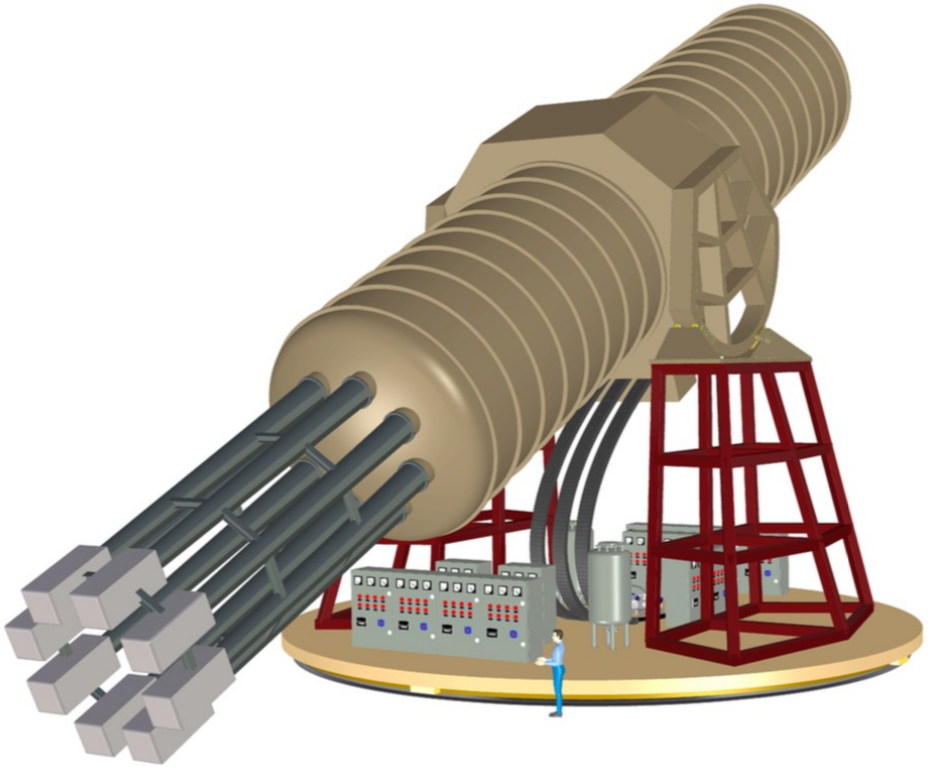
Solar Axion Searches

- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (axion band)

Solar Axion Searches

- Proposed successor: International Axion Observatory (IAXO) [Armengaud et al. (IAXO CDR) 14]
  - Dedicated superconducting toroidal magnet with much bigger aperture than CAST
  - Extensive use of X-ray optics
  - Low background X-ray detectors





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- Proposed site: DESY

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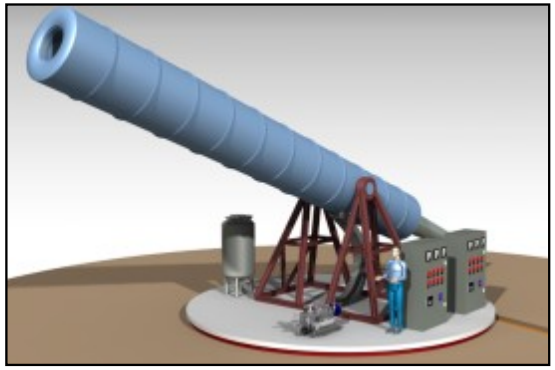
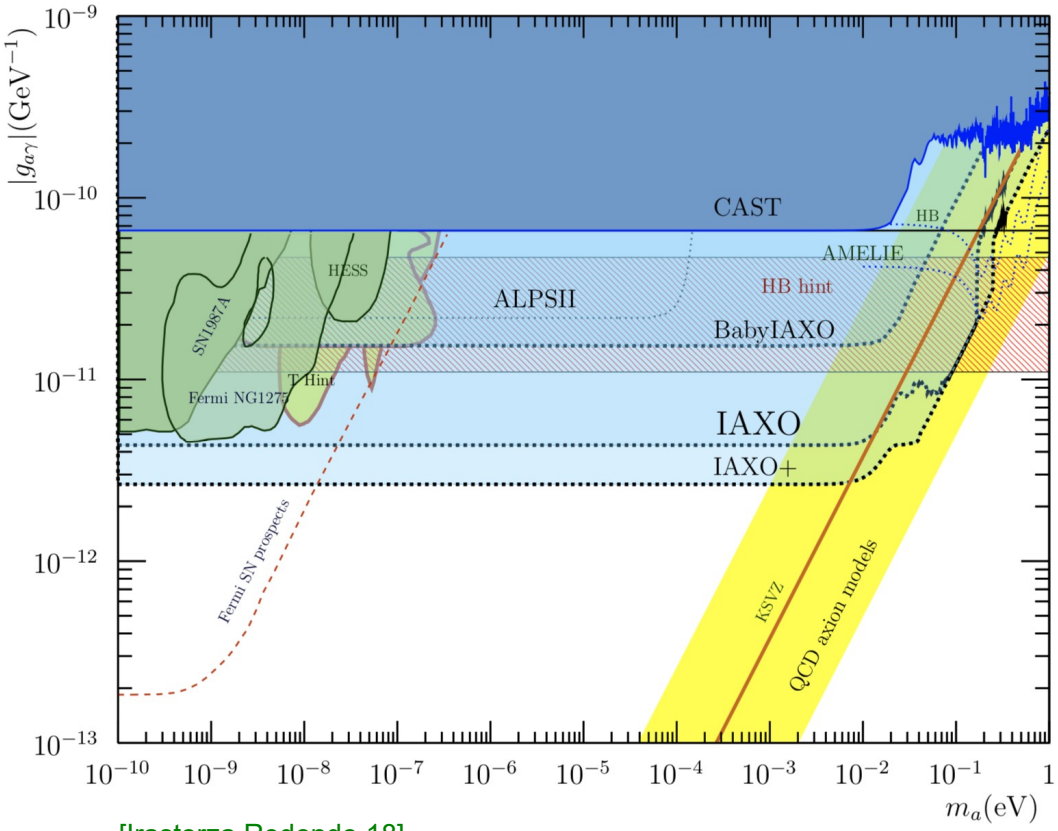
  - Dedicated superconducting toroidal magnet with much bigger aperture than CAST
  - Extensive use of X-ray optics
  - Low background X-ray detectors
- Proposed site: DESY
- Timeline:
  - Prototype BabyIAXO ready in 2021
  - Several options for locations at DESY

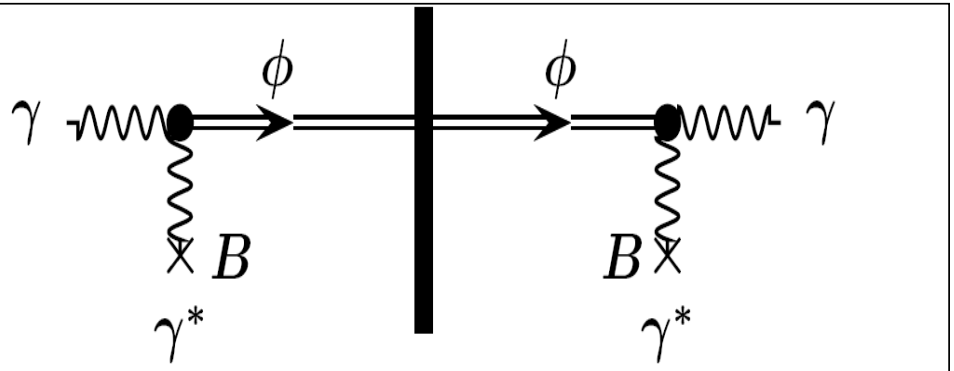




[Irastorza,Redondo 18]

Self-made Axion Searches

- Light-shining-through a wall:



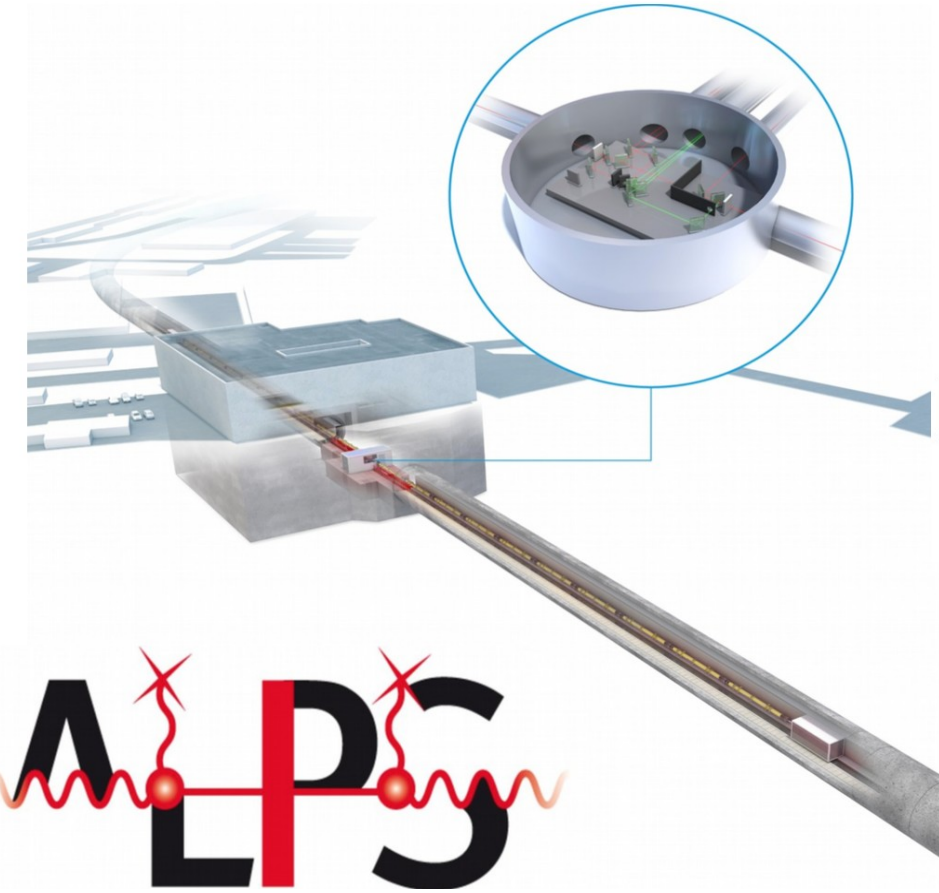
[Okun 1982, Sikivie 1983, Ansel'm 1985, van Bibber et al. 1987]

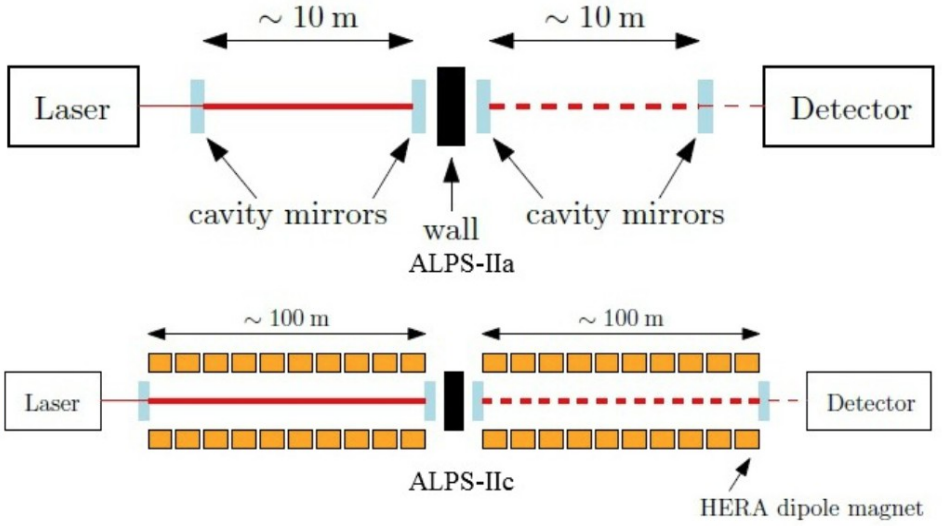
- Conversion probability:

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

Self-made Axion Searches

- ALPS II at DESY (in coll. with AEI, UFL, U Mainz): Data taking planned in 2020 [Bähre et al (ALPS II TDR) 13]

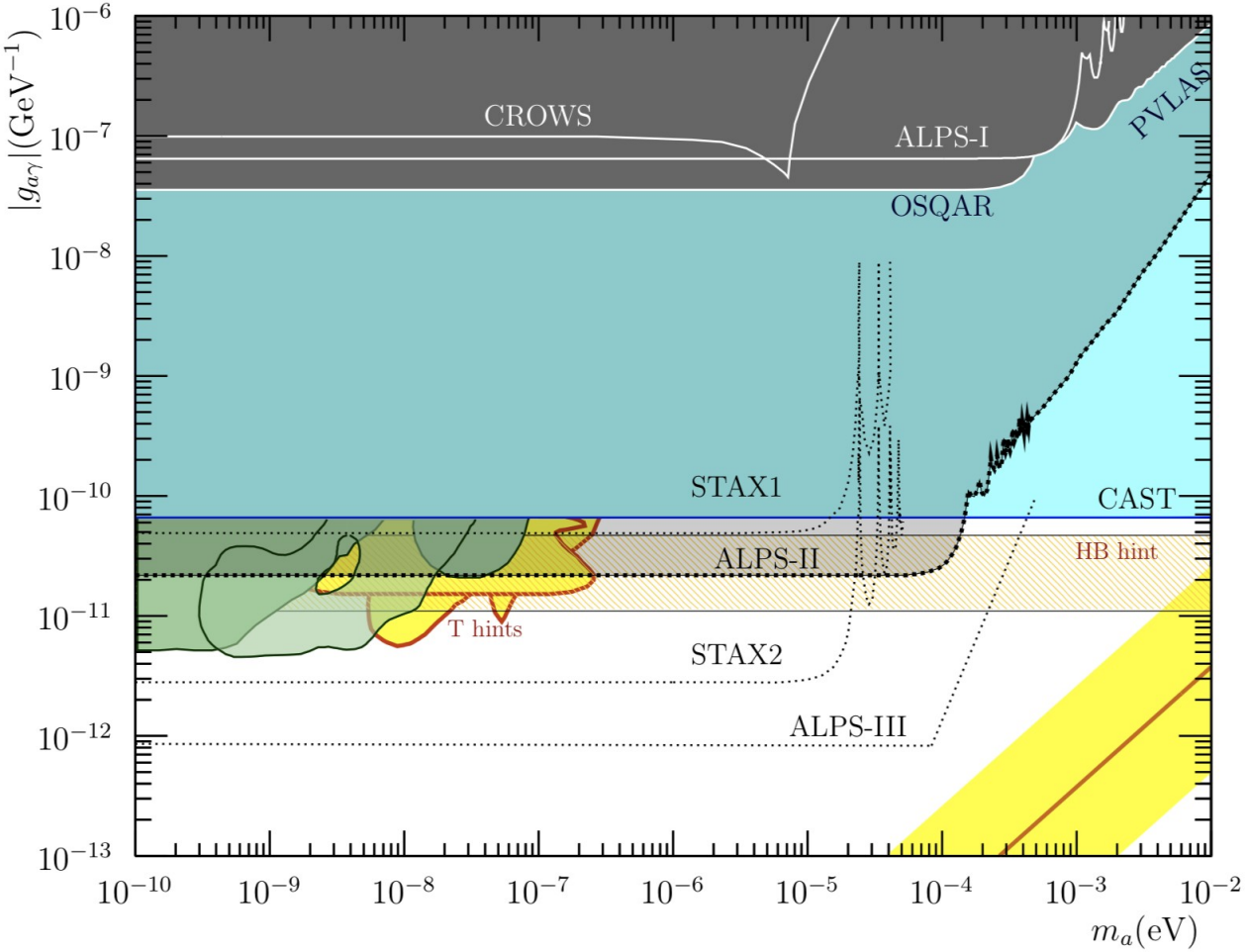




Parameter	Scaling	ALPS I	ALPS IIc	Sens. gain
Effective laser power P_{laser}	$g_{a\gamma} \propto P_{\text{laser}}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC P_{RC}	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	14
BL (before& after the wall)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
Detector efficiency QE	$g_{a\gamma} \propto QE^{-1/4}$	0.9	0.75	0.96
Detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	0.0018 s^{-1}	0.000001 s^{-1}	2.6
Combined improvements				3082

Self-made Axion Searches

- ALPS II prospects:
  - Improves current pure laboratory bounds by three orders of magnitude
- ALPS III a.k.a. JURA proposes to exploit 13 T magnets presently being developped for LHC energy upgrade or FCC-hh and a generation cavity with 2.5 MW circulating power [Lindner 14 (unp.)]
  - Could even touch axion band if one exploits “wiggler” type of magnet string [Arias et al. 10]



[Irastorza,Redondo 18]

Conclusions

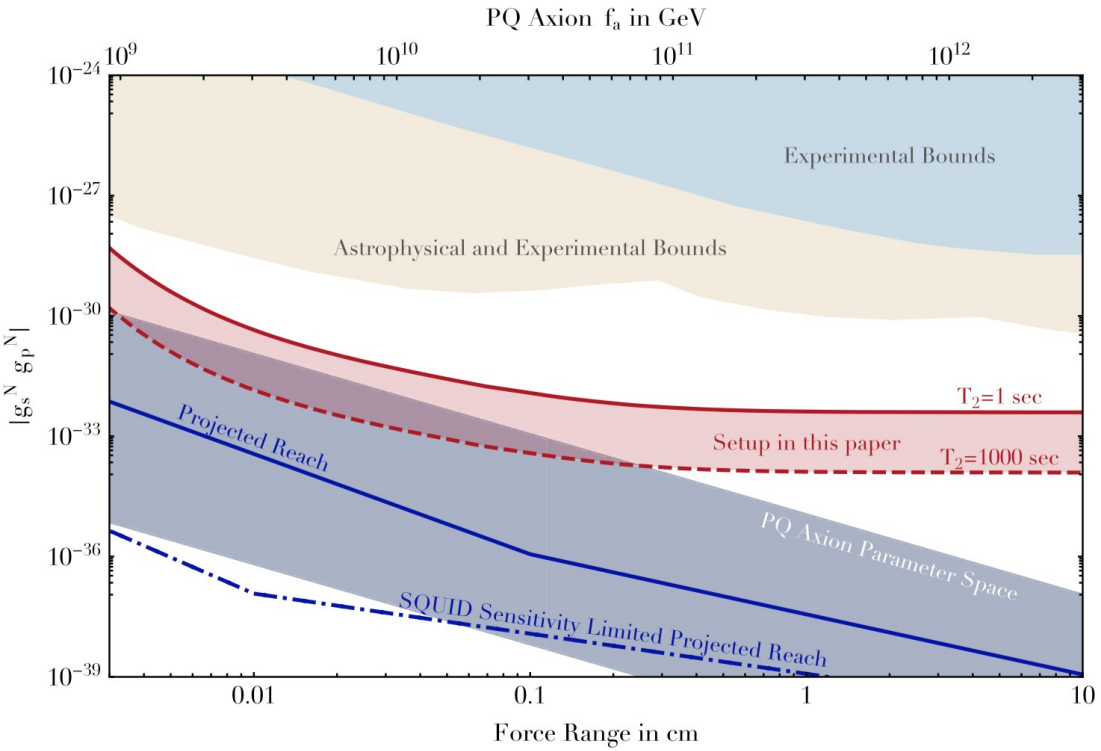
- Axion extensions of SM very attractive:
  - Axion solves strong CP puzzle
  - Axion is dark matter candidate (for $f_A \gtrsim 10^8\,\mathrm{GeV} \;\Leftrightarrow\; m_A \lesssim 60\,\mathrm{meV}$)
- Boom in axion searches!
- Large parts in axion parameter space will be tackled in the upcoming decade by a number of terrestrial experiments:
  - Light-shining-through-a-wall experiments (ALPS II, ...)
  - Helioscopes ((Baby)IAXO, ...)
  - Haloscopes (ABRACADABRA, ADMX, BRASS, CASPEr, CAPP, HAYSTAC, MADMAX, ORGAN, QUAX, ...)
- If 100 % of DM consists of QCD axions, one of the dark matter axion experiments likely to see a signal in the upcoming decade!

STAY TUNED!

Back-up: Search for Axion-Mediated Forces

- ARIADNE: Proposed experiment based on precision magnetometry to search for axion-mediated spin-dependent forces
- Combining techniques used in NMR and short-distance tests of gravity

[Arvanitaki, Geraci 14]



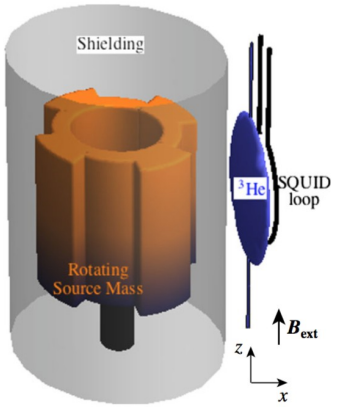
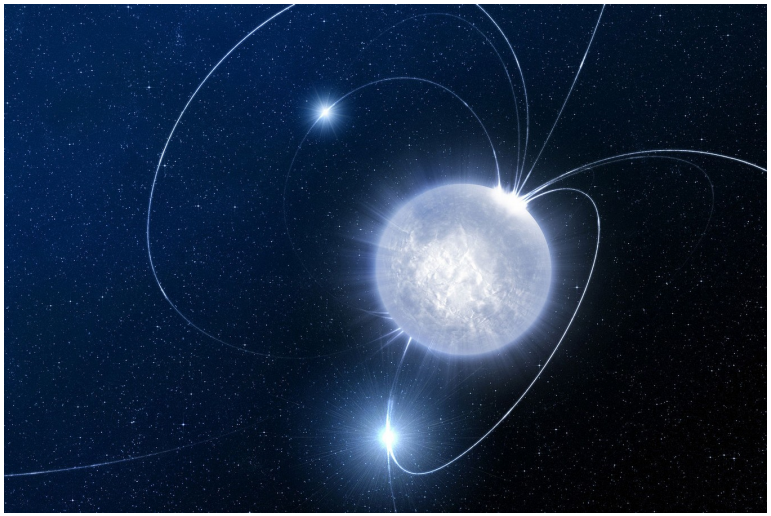


FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency ω_{rot}, which results in a resonance between the frequency $\omega = n\omega_{rot}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N \cdot \vec{B}_{ext}/\hbar$ of the NMR sample. Superconducting cylinders screen the NMR sample from the source mass and (not shown) the setup from the environment.

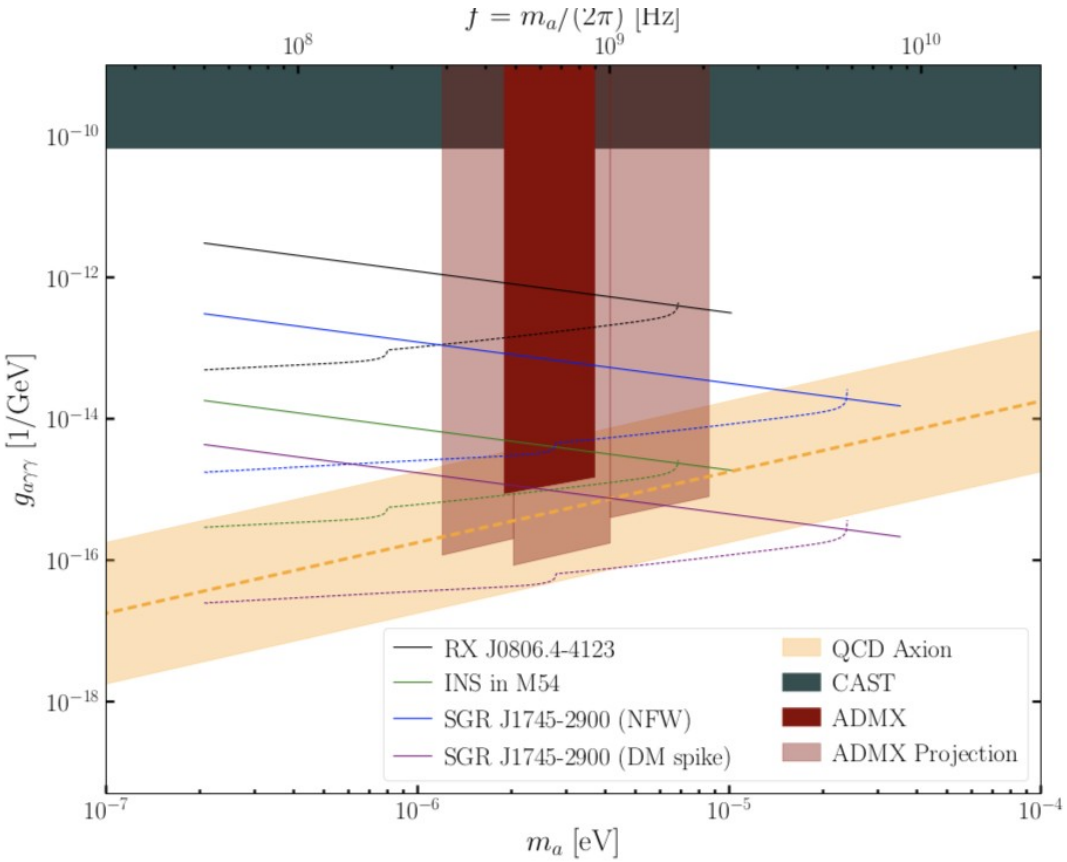
Back-up: Search for Radio Signals from Axion DM Conversion

- Radio signals from axion DM conversion in neutron star magnetospheres

[Hook et al. 18; Safdi et al. 18]



[ESO/L.Calçada https://www.eso.org/public/images/eso0831a/]

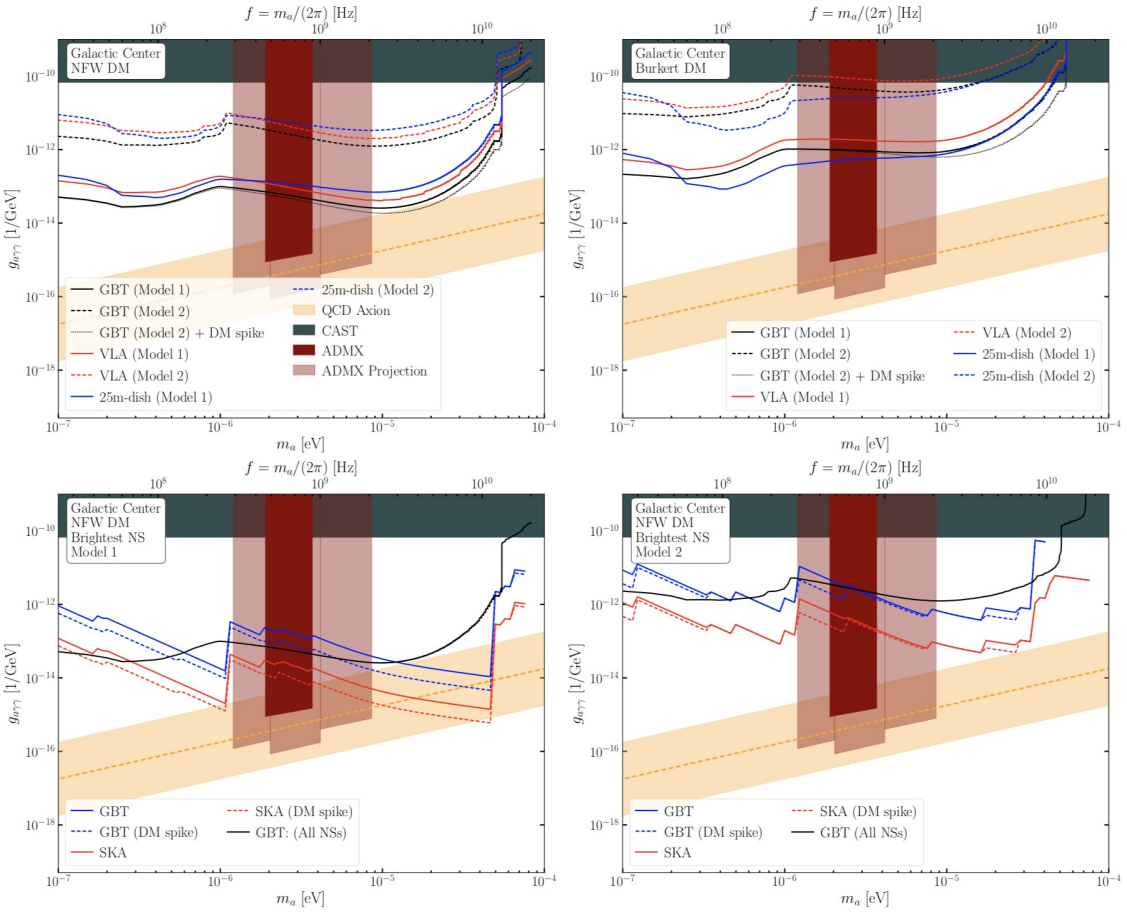


Back-up: Search for Radio Signals from Axion DM Conversion

- Radio signals from axion DM conversion in neutron star magnetospheres

[Hook et al. 18; Safdi et al. 18]

Name	$d_{\rm prim}$ [m]	G [K/Jy]	N	$r^{1\ \rm GHz}_{\rm prim}$	$r^{1\ \rm GHz}_{\rm synth}$	T_R [K]
GBT	100	2.0	1	6.3'	-	25
25m-dish	25	0.13	1	25'	-	25
VLA Config. D	25	0.13	27	25'	0.58'	25
SKA2	15	0.045	5659	42'	TBD	25



- Narrow-band radio observations with e.g. Green Bank Telescope (GBT) and future Square Kilometer Array (SKA) may probe axion over