# Axion Physics

Andreas Ringwald
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

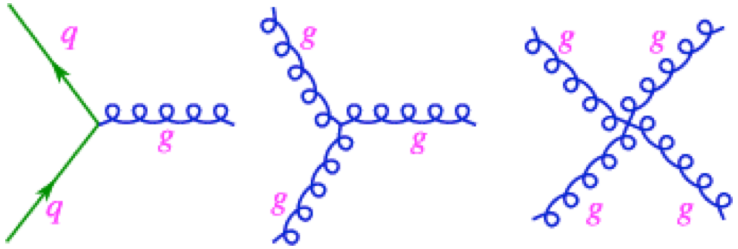
# Strong CP Puzzle

## Theta term in Quantum Chromodynamics

- Quantum Chromodynamics (QCD):

[Gross,Wilczek 73;Politzer 73; Fritzsch,Gell-Mann,Leutwyler 73]

$$S_{\rm QCD} = \int d^4x \left\{ \overline{q}\left(i\gamma_\mu D^\mu - \mathcal{M}_q\right) q - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} \right\}$$



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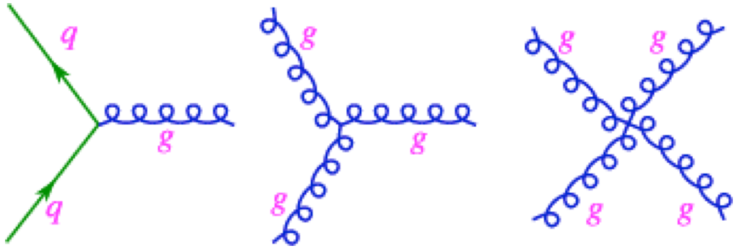

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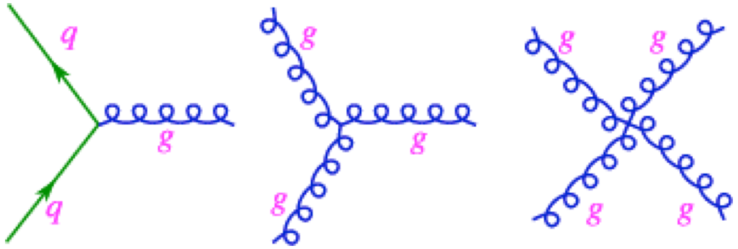

$$\int d^4x\,\partial_\mu J^\mu_{\rm CS} = 0, \pm 1, \pm 2, \ldots$$

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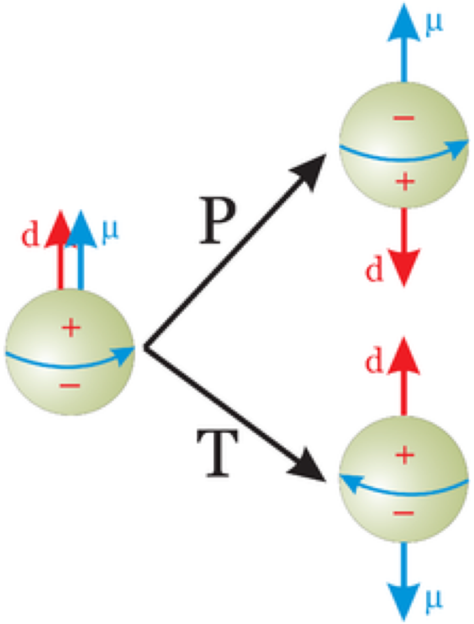

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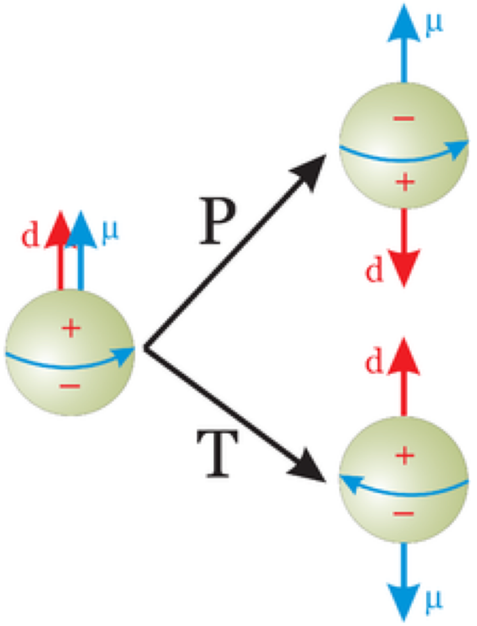
$$d_n(\overline{\theta}) = 2.4(1.0) \times 10^{-16}\, \overline{\theta}\, e\, {\rm cm}$$



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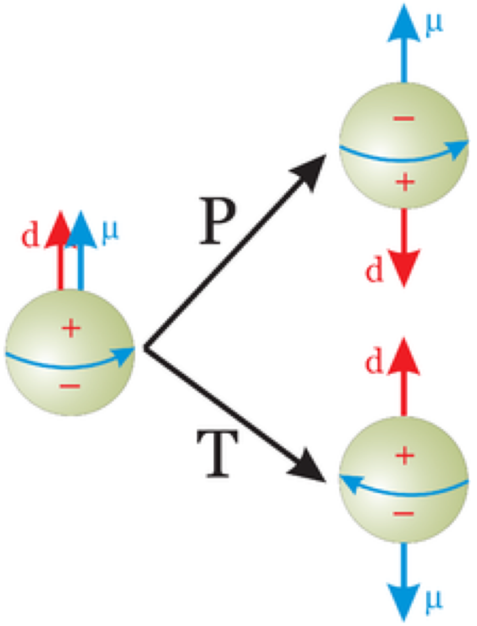
- Experiment: [Abel et al. 20]

$$|d_n| < 1.8 \times 10^{-26}\,e\,{\rm cm}$$

$$\Rightarrow |\overline{\theta}| < 10^{-10}$$



# Axionic Solution of Strong CP Puzzle

## In a nutshell: replace theta parameter by dynamical theta field

- Add to SM Nambu-Goldstone field, $\theta(x) \equiv A(x)/f_A \in [-\pi, \pi]$, respecting a non-linearly realized $U(1)_{\rm PQ}$ symmetry ($\theta(x) \to \theta(x) + {\rm const.}$), broken by coupling to gluonic topological charge density: [Peccei,Quinn 77]

$$\mathcal{L} \supset -\theta(x)\, q(x)\,; \qquad q(x) \equiv \frac{\alpha_s}{8\pi}\, G^b_{\mu\nu}(x)\tilde{G}^{b,\mu\nu}(x)$$

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$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\left[\overline{\theta} + \theta(x)\right] G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$

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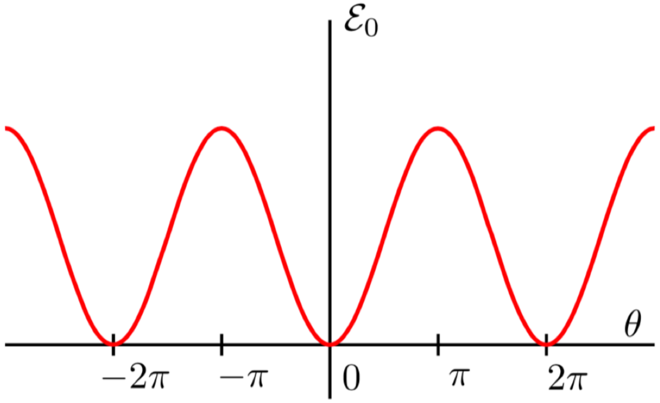
  - Effective potential at energies below $\Lambda_{\rm QCD}$ has absolute minimum at $\theta = 0$ and thus predicts vanishing vev, $\langle\theta(x)\rangle = 0$
    No strong CP violation in vacuum [Vafa,Witten 84]



$$V(\theta) = \Sigma\ (m_u + m_d) \left(1 - \frac{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos\theta}}{m_u + m_d}\right)$$

$$\Sigma \equiv -\langle \bar{u}u \rangle = -\langle dd \rangle$$

[Di Vecchia,Veneziano `80; Leutwyler,Smilga 92]

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  - Particle excitation: pseudo Nambu-Goldstone boson "axion" [Weinberg 78; Wilczek 78]
  - Topological susceptibility in QCD, $\chi \equiv \int d^4x \langle q(x) q(0) \rangle$, determines mass in units of decay constant: $m_A = \sqrt{\chi}/f_A$
  - Recent precise determination (ChPT; lattice QCD):

$$m_A = 5.691(51) \left(\frac{10^9\,{\rm GeV}}{f_A}\right) {\rm meV}$$

[Grilli di Cortona et al. `16;
Borsanyi et al. `16;
Gorghetto, Villadoro `19]

# Peccei-Quinn Extension of Standard Model

## Simple way to get dynamical theta field

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

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

  - Mass of particle excitation of modulus: $m_\rho \sim v_{\rm PQ}$
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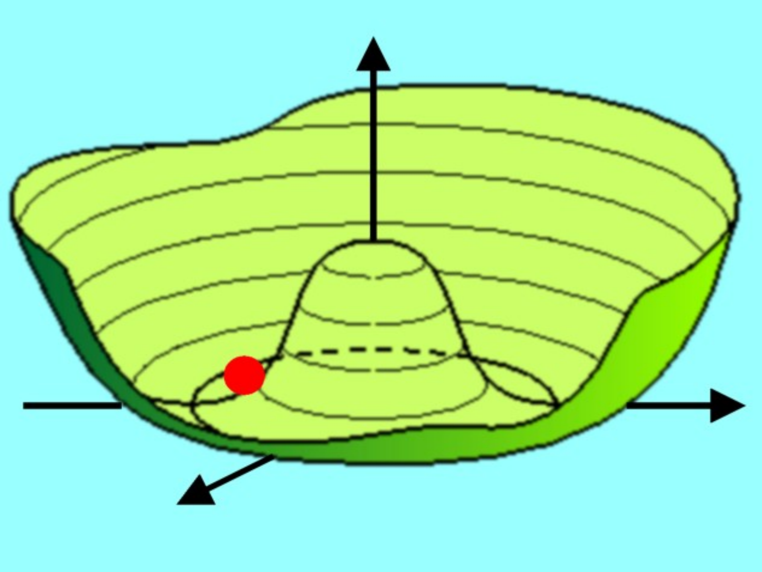

[Raffelt]

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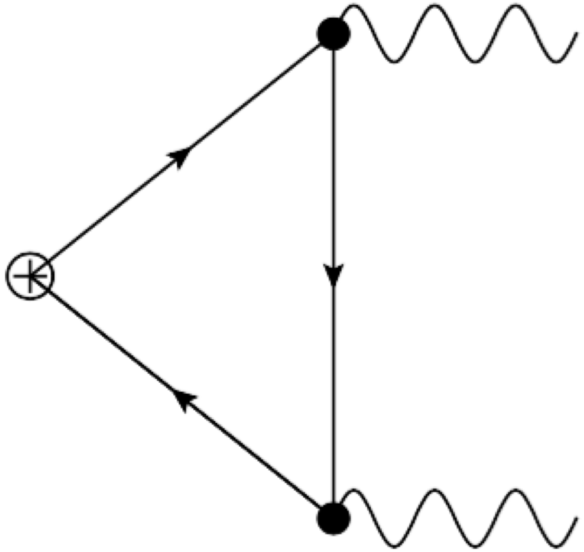
$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} \supset -\frac{\alpha_s}{8\pi} N\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$



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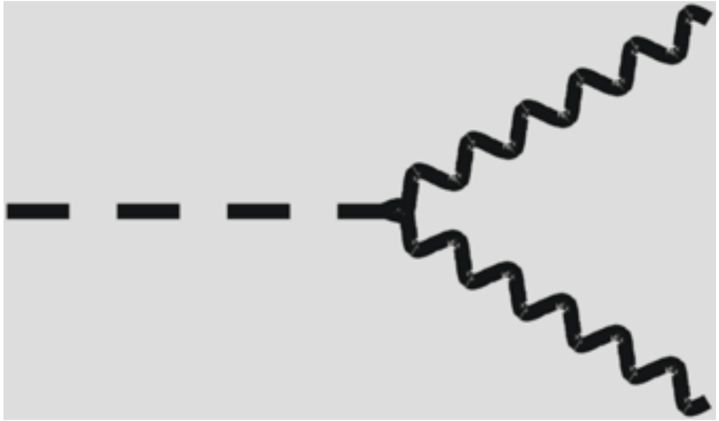

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- Low energy effective field theory at energies above $\Lambda_{\rm QCD}$ but below $v\ (\ll v_{\rm PQ})$: [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

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

[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

$$\mathcal{L}_A \supset -\frac{i}{2}\frac{C_{AD}}{f_A}\,A\,\overline{\Psi}_N\sigma_{\mu\nu}\gamma_5\Psi_N F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A}\,A\,F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{C_{Af}}{f_A}\,\partial_\mu A\,\overline{\Psi}_f\gamma^\mu\gamma_5\Psi_f$$

- „Invisible axion“: couplings to SM suppressed by inverse power of $f_A = v_{\rm PQ}/N \gg v = 246\,{\rm GeV}$

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

- EDM coupling: $C_{AD} = 2.4(1.0)\times 10^{-16}\,e\,{\rm cm}$ [Pospelov,Ritz `00]
- Photon coupling: $C_{A\gamma} = \frac{E}{N} - 1.92(4)$ [Kaplan 85;Srednicki `85; Grilli di Cortona et al. `16]
- Nucleon couplings:

$$\begin{aligned} C_{Ap} &= -0.47(3) + 0.88(3)C_{Au} - 0.39(2)C_{Ad} - 0.038(5)C_{As} \\ &\quad - 0.012(5)C_{Ac} - 0.009(2)C_{Ab} - 0.0035(4)C_{At}\,, \\ C_{An} &= -0.02(3) + 0.88(3)C_{Ad} - 0.39(2)C_{Au} - 0.038(5)C_{As} \\ &\quad - 0.012(5)C_{Ac} - 0.009(2)C_{Ab} - 0.0035(4)C_{At} \end{aligned}$$

- Electron coupling very model-dependent
- Strong CP problem solved for any value of $f_A$ $(m_A)$!

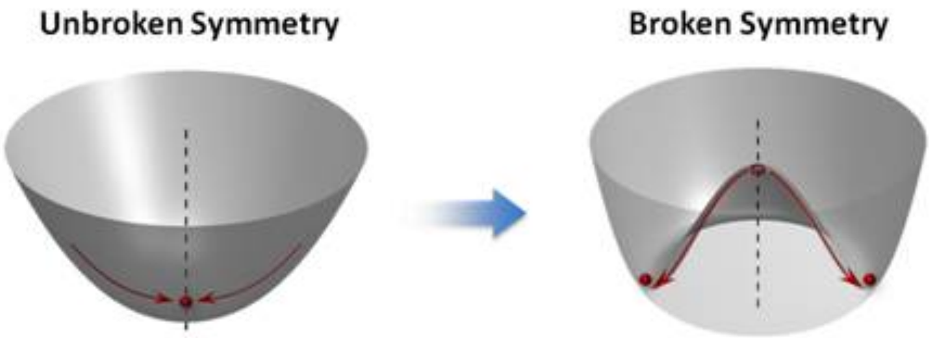
# Axion Dark Matter

## Vacuum re-alignment mechanism

- PQ phase transition takes place at

$$T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$$

- Axion takes random initial values in causally connected domains



[Peking University]

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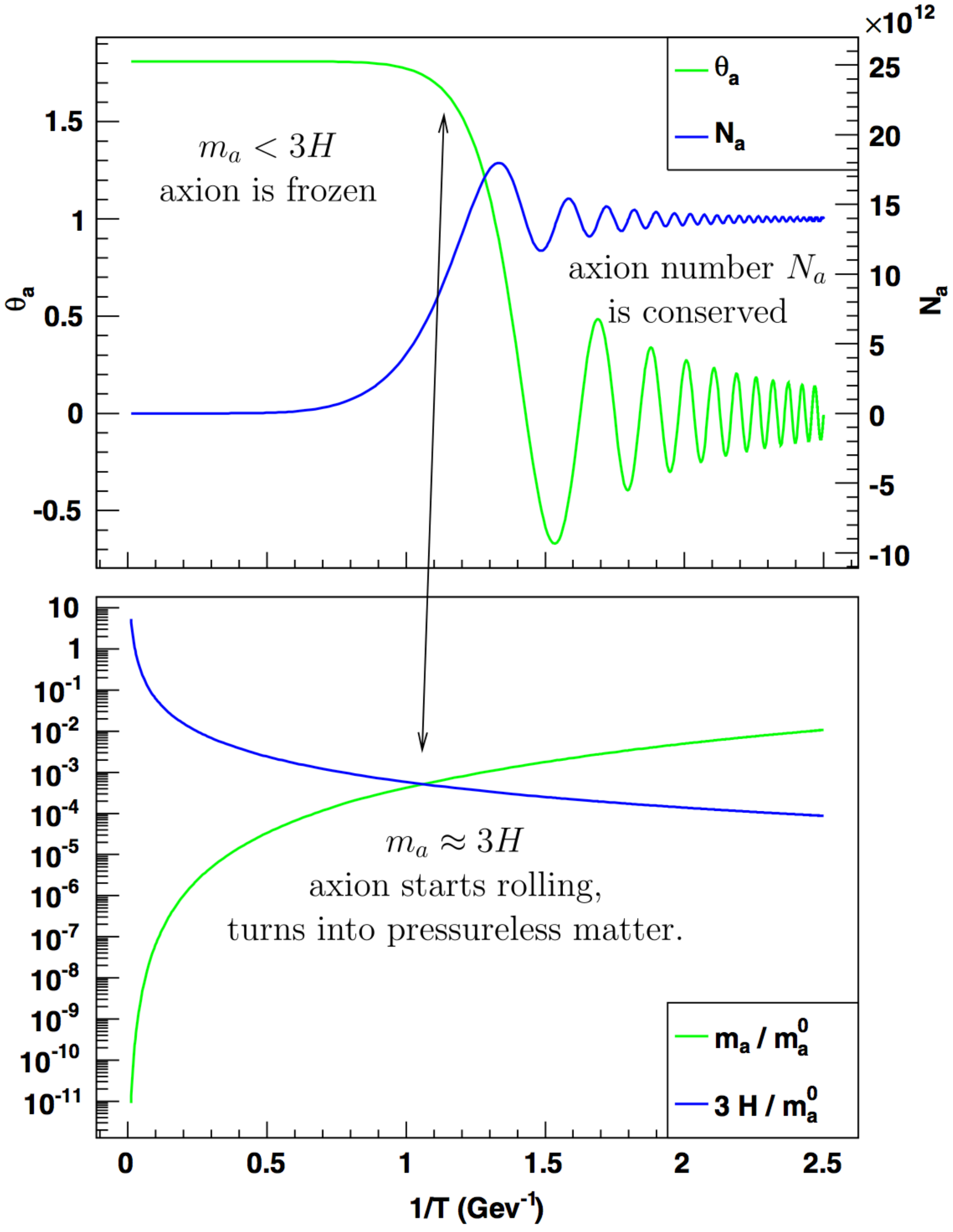
[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]



[Wantz,Shellard `09]

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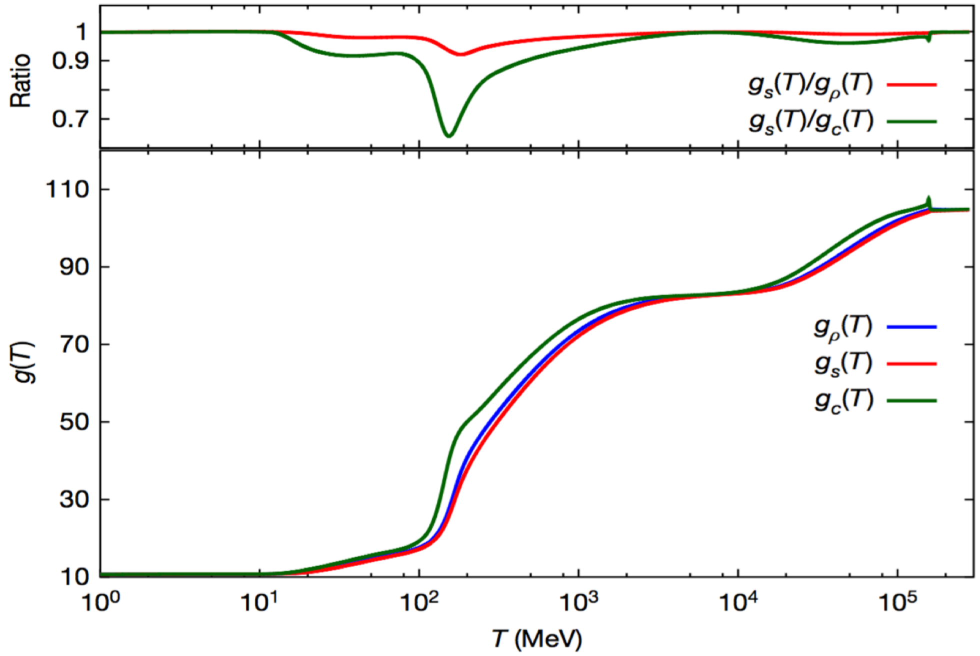

[Borsanyi et al., Nature `16 [1606.0794]]

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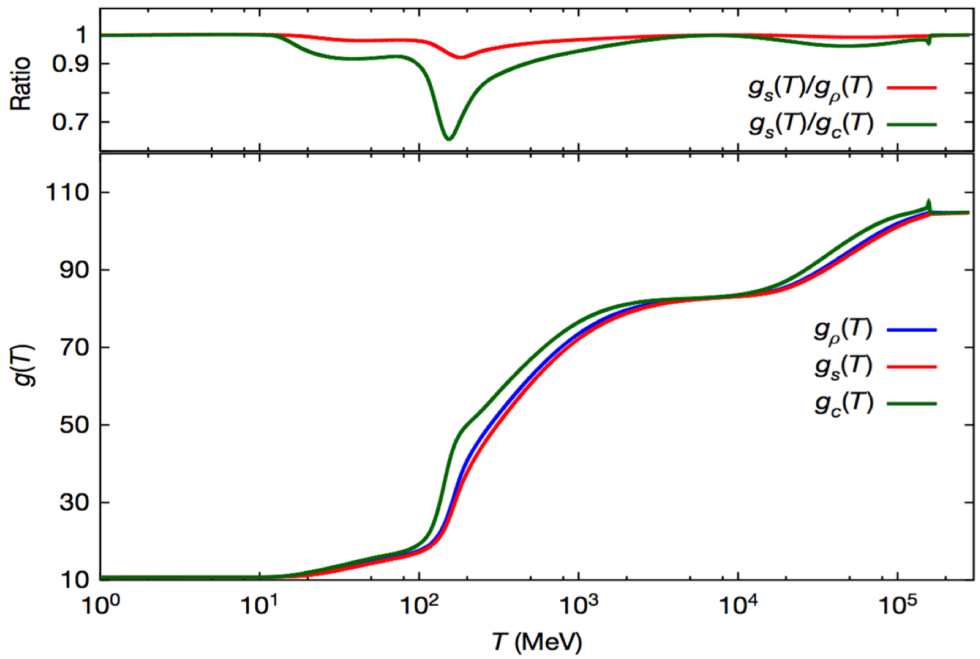
  - Topological susceptibility $\Rightarrow m_A(T) = \dfrac{\sqrt{\chi(T)}}{f_A}$



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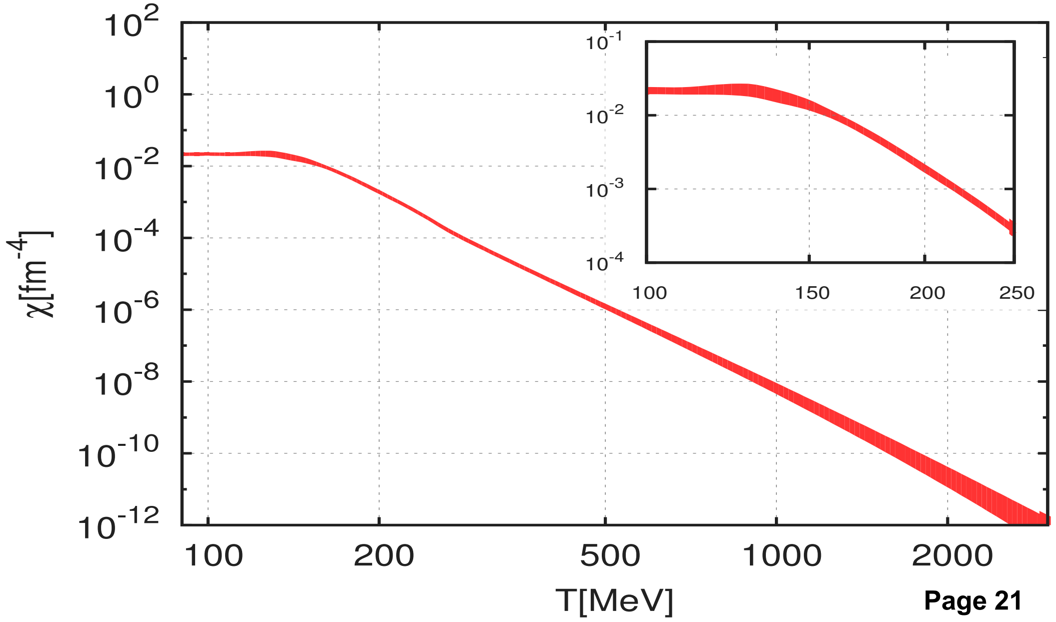
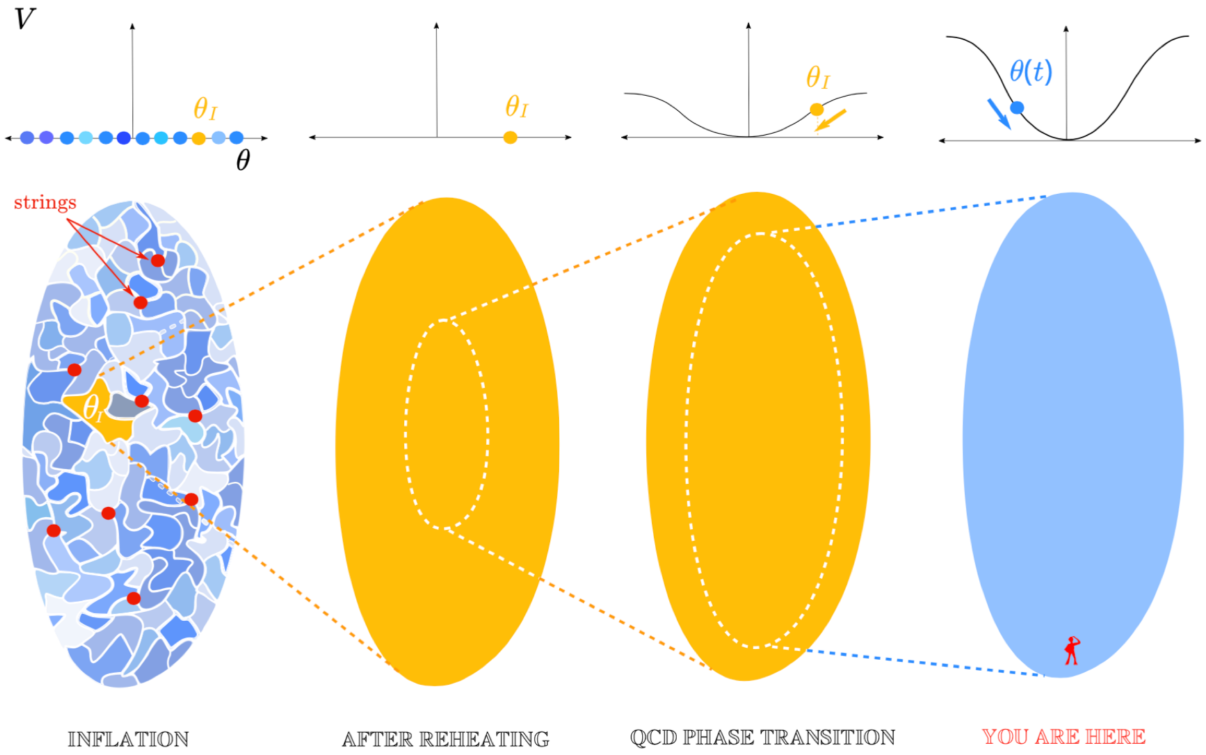


# Axion Dark Matter

## Pre-inflationary PQ SSB scenario

- If PQ symmetry broken before or during inflation $(f_A > H_I/(2\pi))$ and not restored afterwards
  - Axion CDM density depends on single initial value in patch which becomes observable universe and $f_A$

Pre-inflationary scenarios



For illustration purposes only. Resemblance to the actual product might be limited

[Tamarit]

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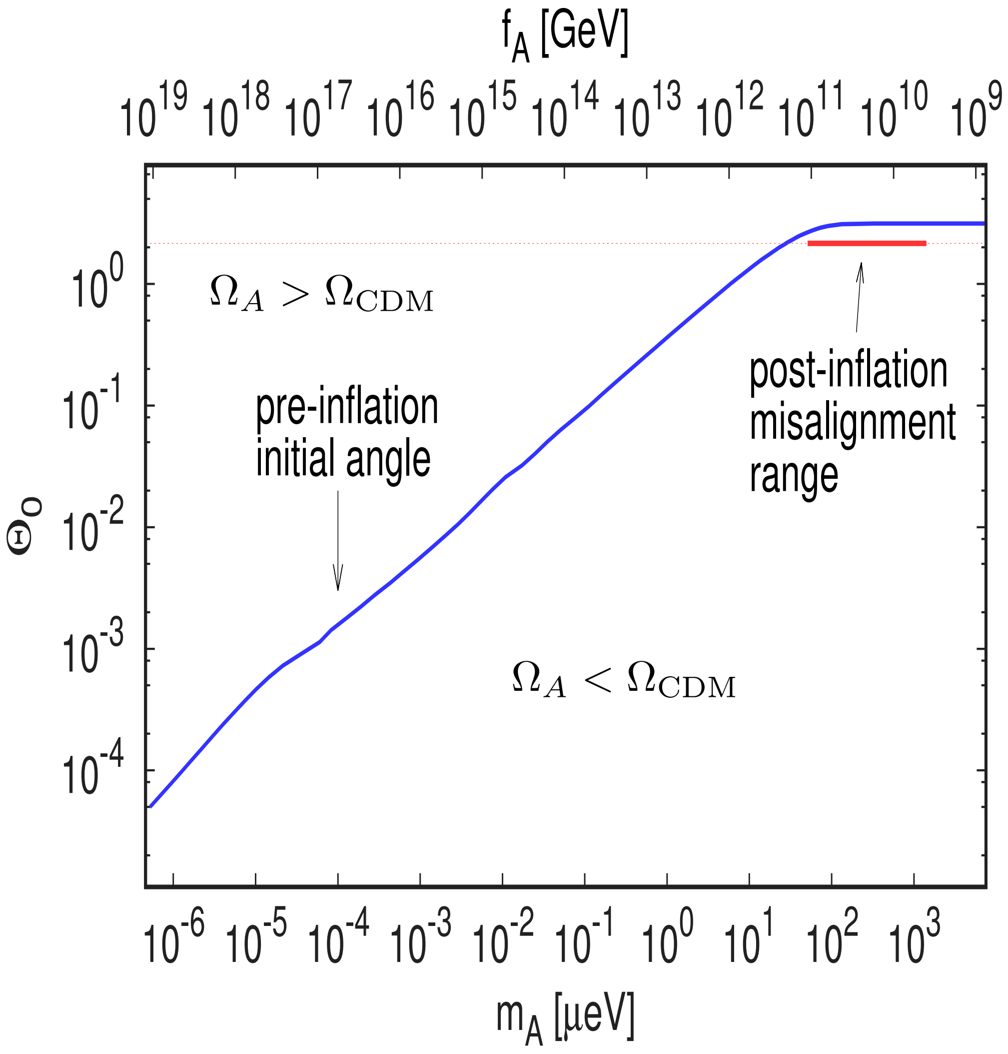
$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{f_A}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \theta_{\rm i}^2$$
$$\approx 0.12 \left(\frac{6\ \mu{\rm eV}}{m_A}\right)^{1.165} \theta_{\rm i}^2 ,$$



[Borsanyi et al., Nature `16]

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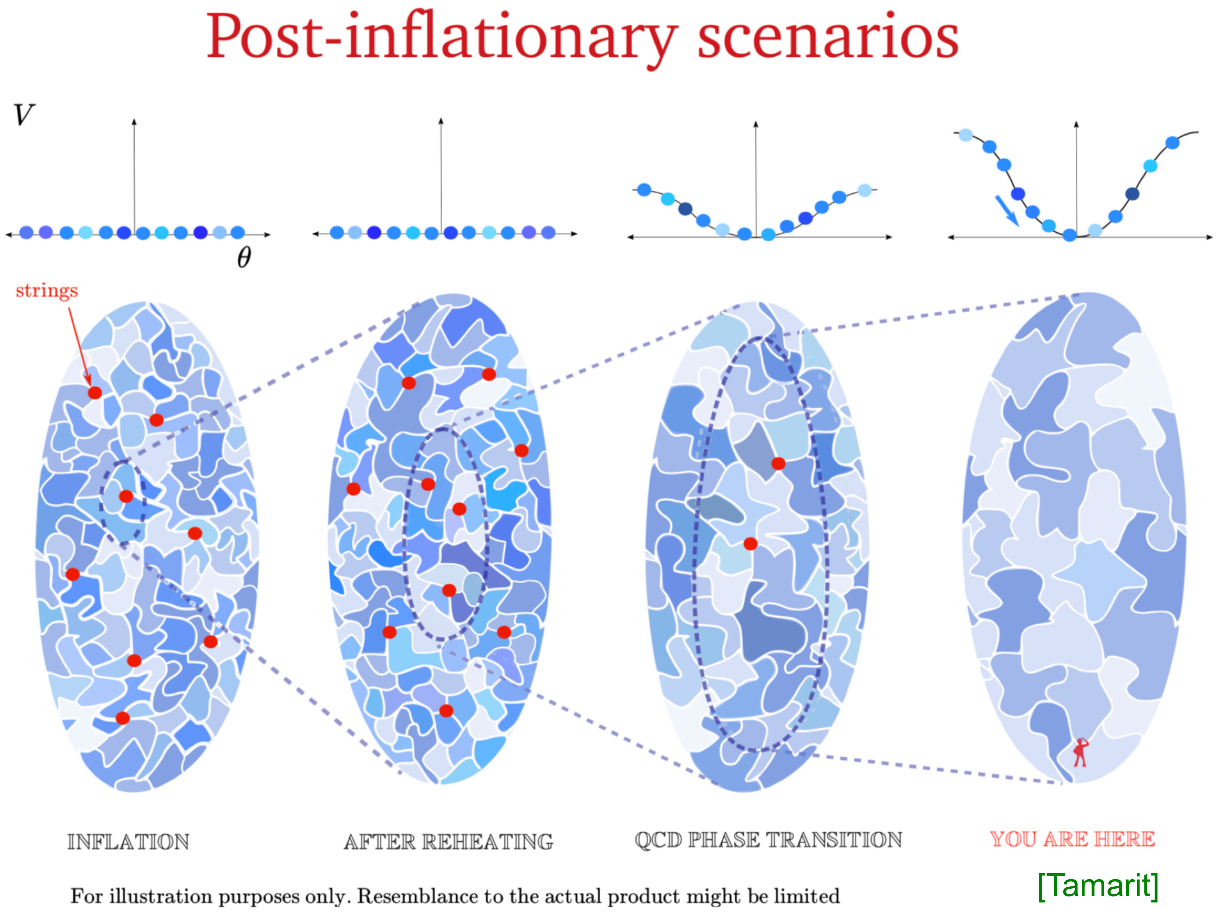
## Post-inflationary PQ SSB scenario

- Averaging over random initial axion field values

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{30\ \mu{\rm eV}}{m_A}\right)^{1.165}$$

- Does not exceed observed CDM abundance for

$$m_A > 28(2)\,\mu{\rm eV}$$ [Borsanyi et al., Nature `16]



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[Borsanyi et al., Nature `16 [1606.0794]]

- Axions also produced by collapse of network of topological defects – strings and domain-walls –

- Axion can be 100% of DM for

$$m_A \approx 25\ \mu{\rm eV} - 40\ {\rm meV}$$

[Hiramatsu et al. 11,12,13;
Kawasaki,Saikawa,Segikuchi 15;
Ballesteros et al. 16;
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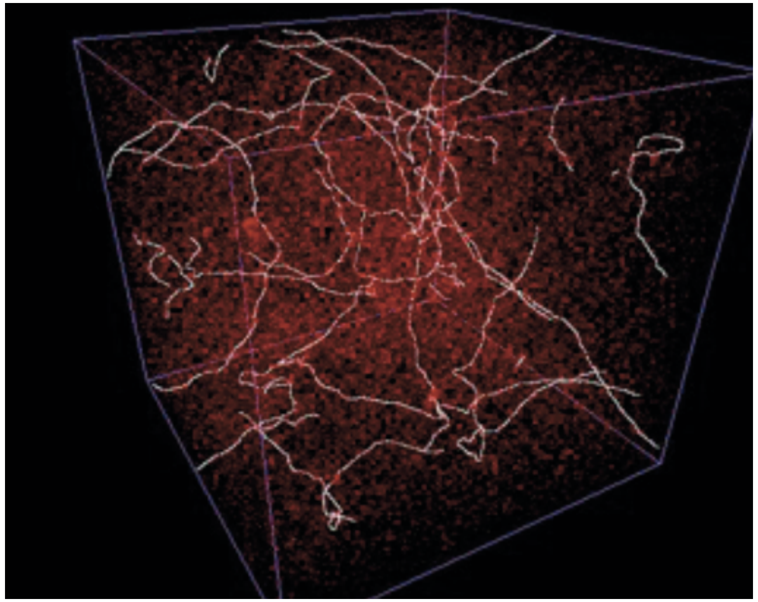
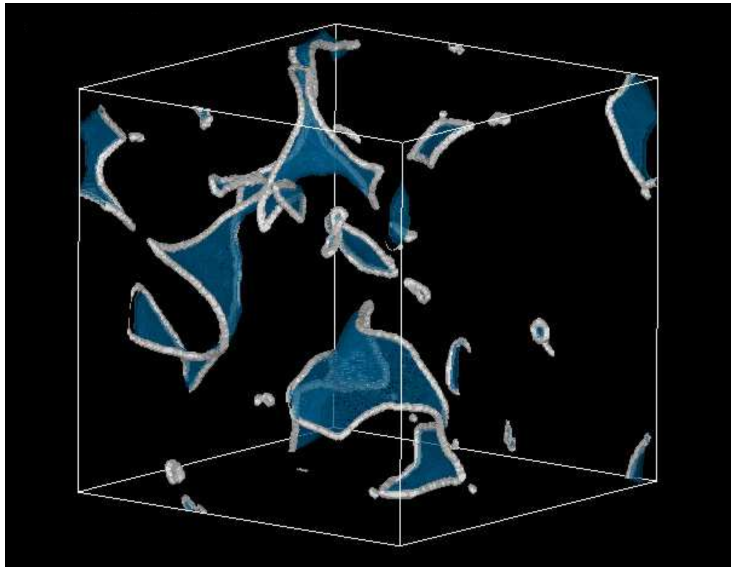
Klaer,Moore `17;
Gorghetto,Hardy,Villadoro `18;
Buschmann et al. 19;
Hindmarsh 19]



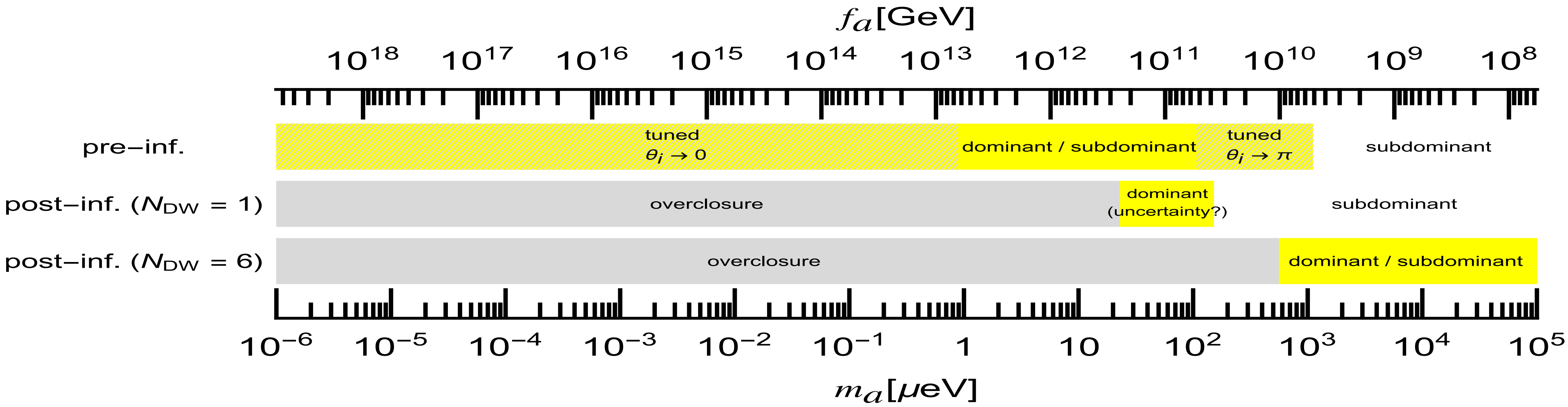
[Hiramatsu et al. ]



# Axion Dark Matter

## Worldwide experimental efforts

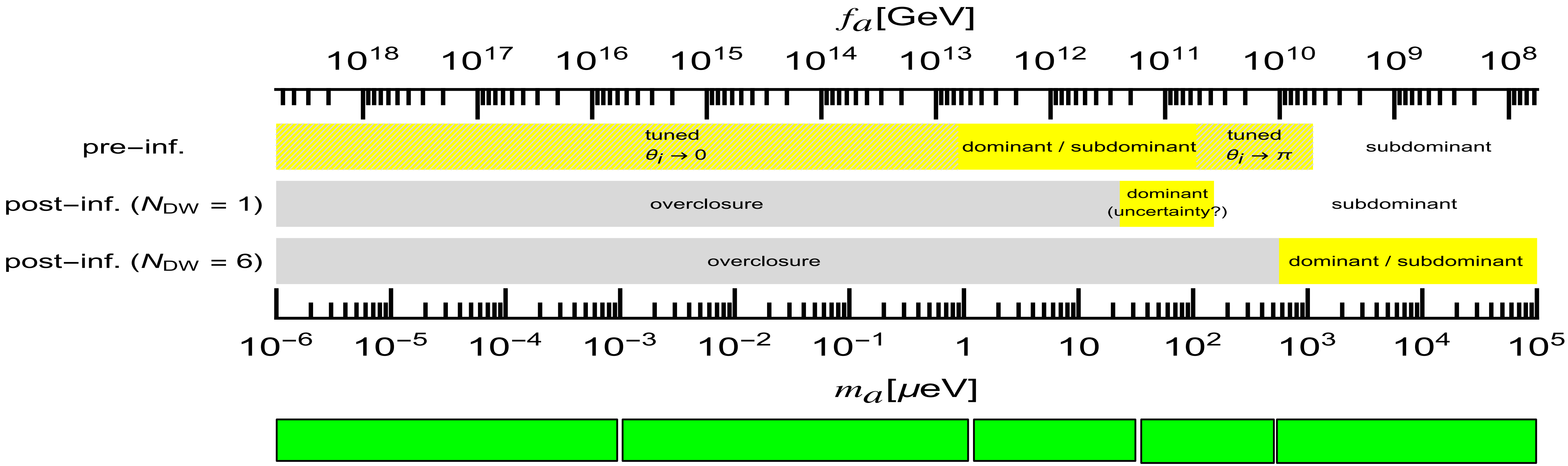
- Dark-matter axion mass spans a huge range:



# Axion Dark Matter

## Worldwide experimental efforts

- Strong motivation for current und upcoming axion DM experiments:



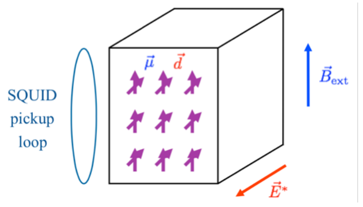
CASPEr

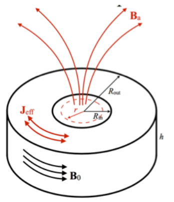
ABRACADABRA

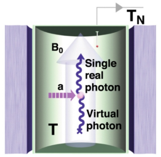
**ADMX**
**HAYSTAC**
**CAPP**

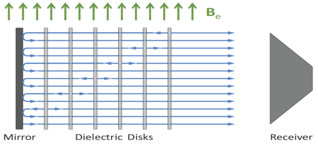
MADMAX
ORPHEUS
**ORGAN**
QUAX

BRASS





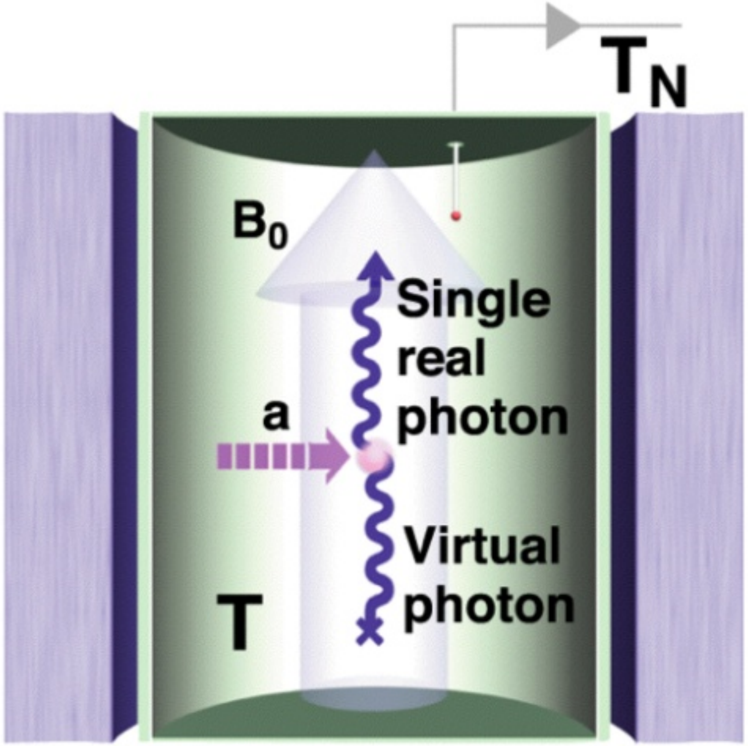




# Searches for Dark Matter Axions

## Microwave Cavities

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

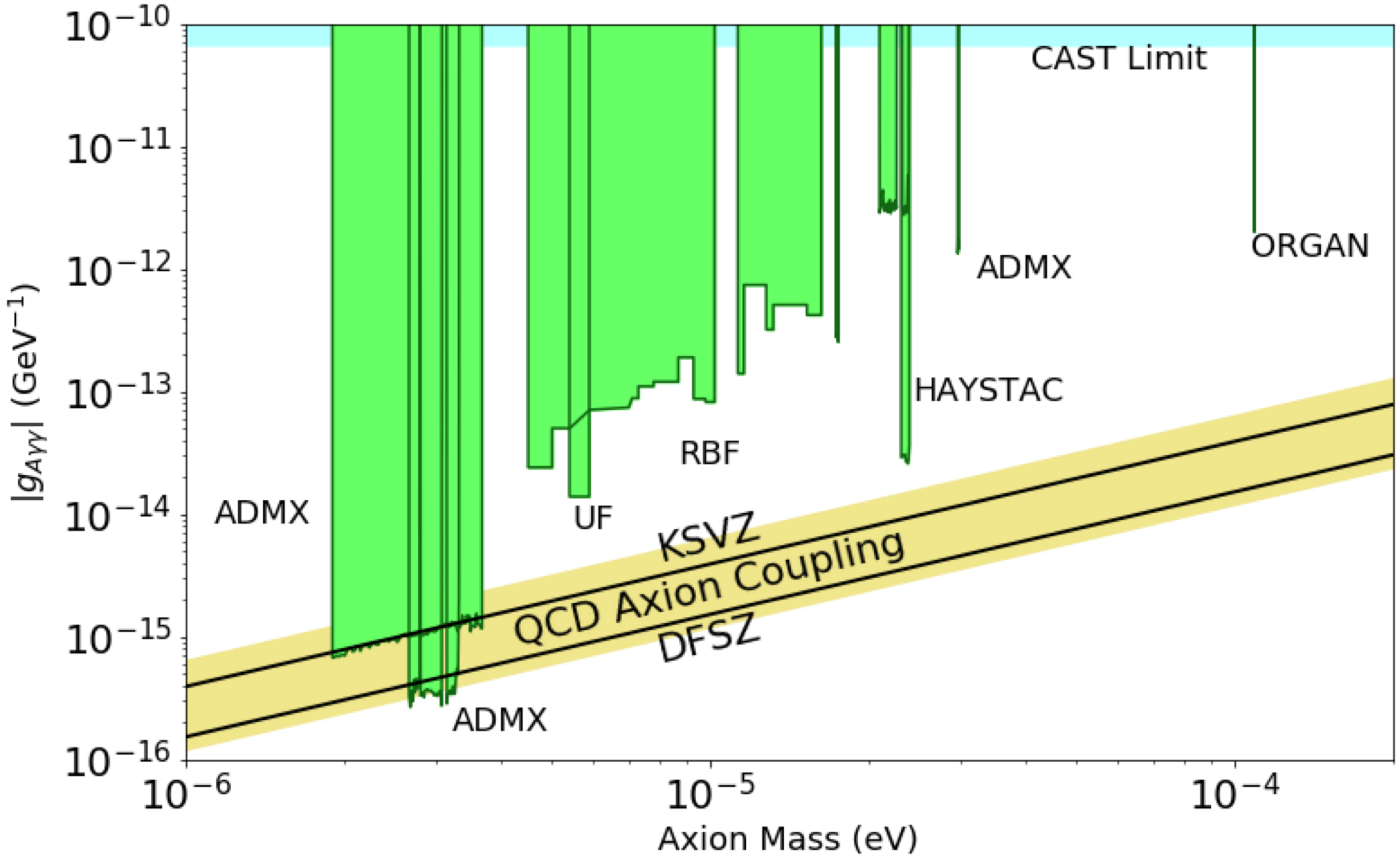


$$P_{\rm out} \sim g^2 \mid \mathbf{B}_0 \mid^2 \rho_{\rm DM} V Q / m_a$$

# Searches for Dark Matter Axions

## Microwave Cavities

- Currently running:
  - ADMX
  - HAYSTAC
  - ORGAN
  - CAST-CAPP
  - RADES

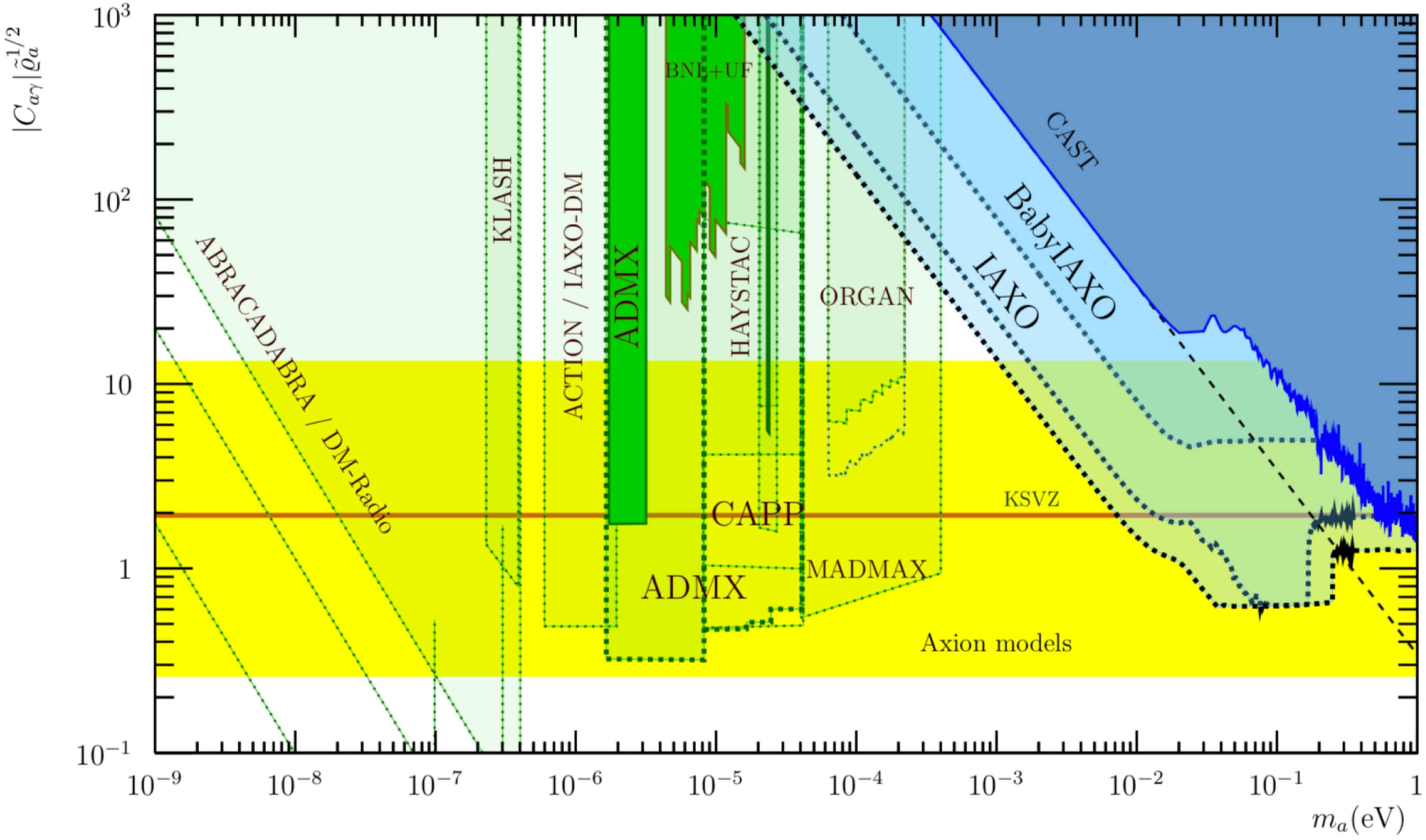


[AR,Rybka,Rosenberg in 2019 update PDG RPP]

# Searches for Dark Matter Axions

## Microwave Cavities

- Currently running:
  - ADMX
  - HAYSTAC
  - ORGAN
  - CAST-CAPP
  - RADES
- Currently in construction:
  - CULTASK
- Proposed:
  - KLASH
  - ACTION
  - IAXO-DM

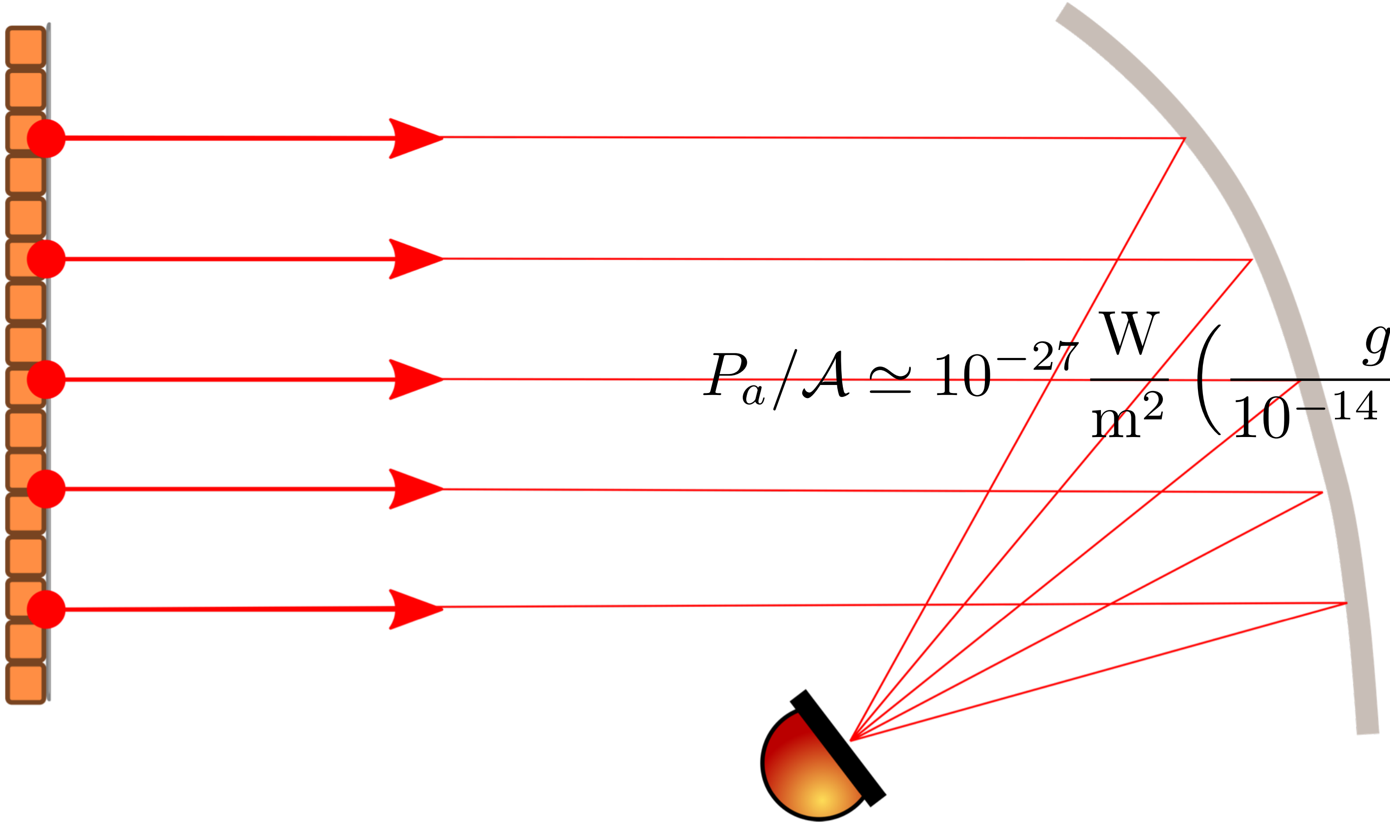


[Irastorza,Redondo 18]

# Searches for Dark Matter Axions

## Dish Antennas

- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component
- A magnetised mirror in axion/ALP DM background radiates photons [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]

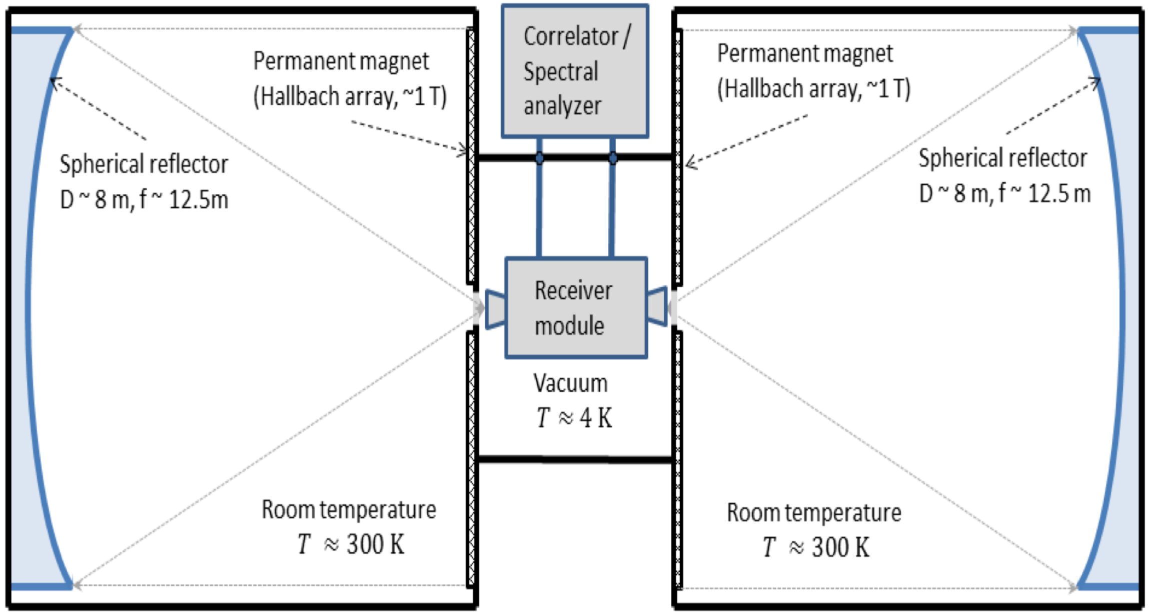


$$P_a/\mathcal{A} \simeq 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{g_{a\gamma}}{10^{-14}\,\mathrm{GeV}^{-1}}\right)^2\left(\frac{10^{-4}\,\mathrm{eV}}{m_a}\right)^2\left(\frac{B}{10\,\mathrm{T}}\right)^2$$

# Searches for Dark Matter Axions

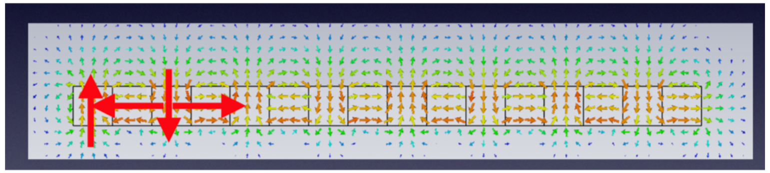
## Dish Antennas

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



[Horns et al. (unpublished)]

- Permanently magnetized surface for axion/ALP photon conversion (Halbach array)

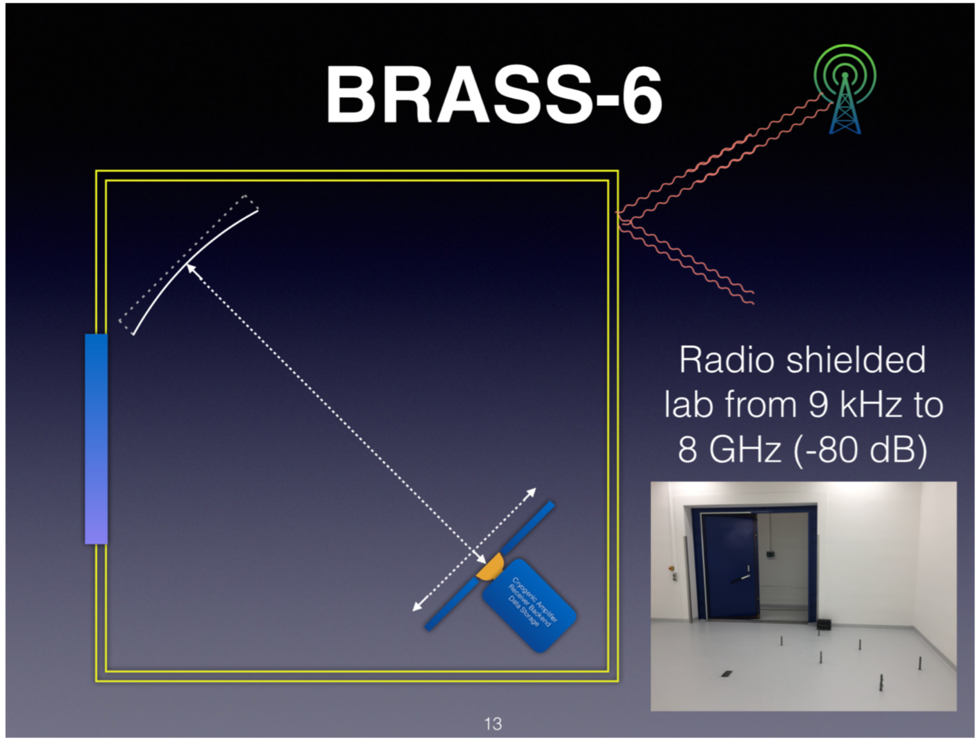


- Dish antenna for photon signal concentration
- Broadband acquisition (16 GHz bandwidth, $10^7$ channels)

# Searches for Dark Matter Axions

## Dish Antennas

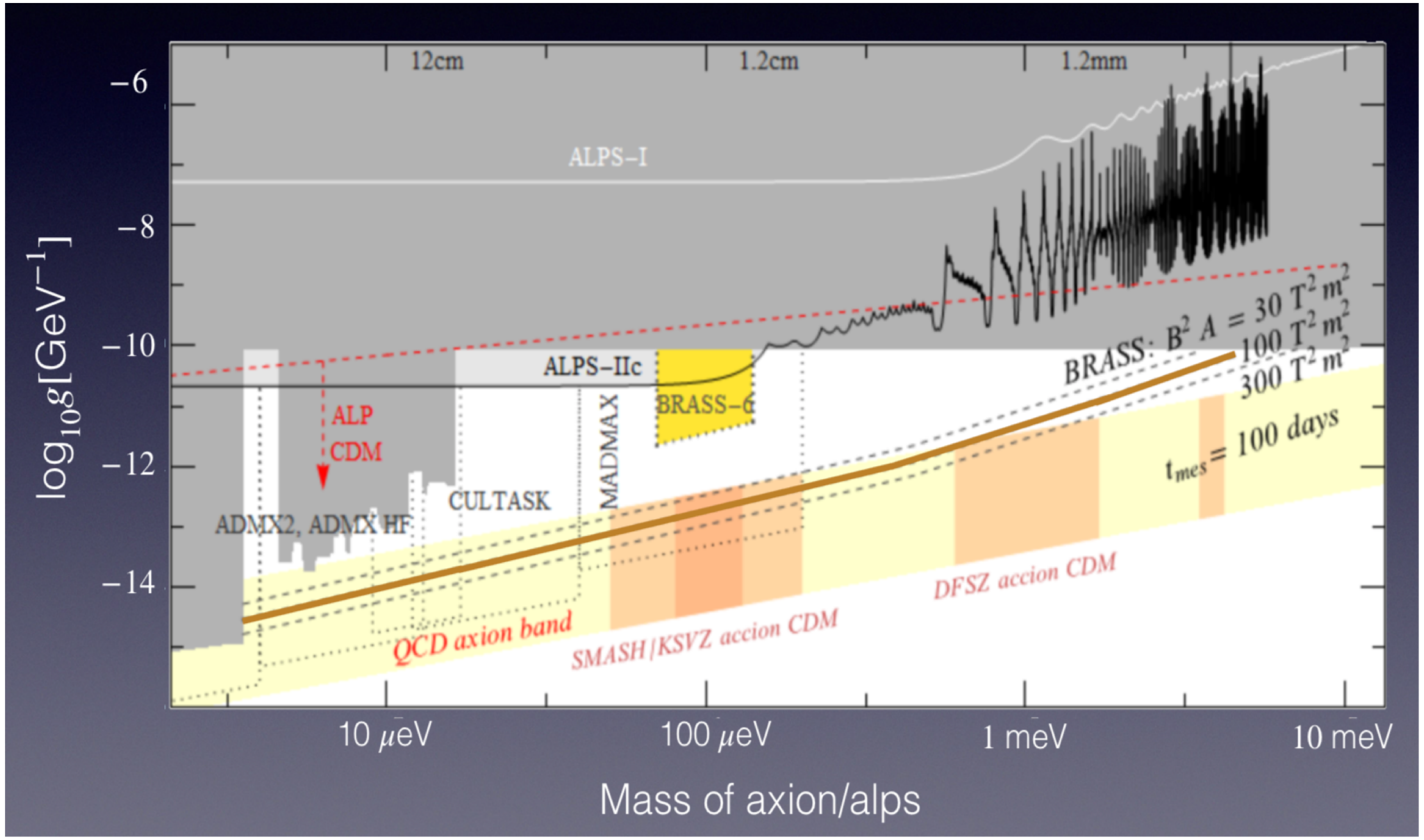
- Prototype BRASS-6 in construction, data taking starting 2021



BRASS-6

Radio shielded lab from 9 kHz to 8 GHz (-80 dB)

13



[Le Hoang Nguyen, Patras Workshop 2019]

# Searches for Dark Matter Axions

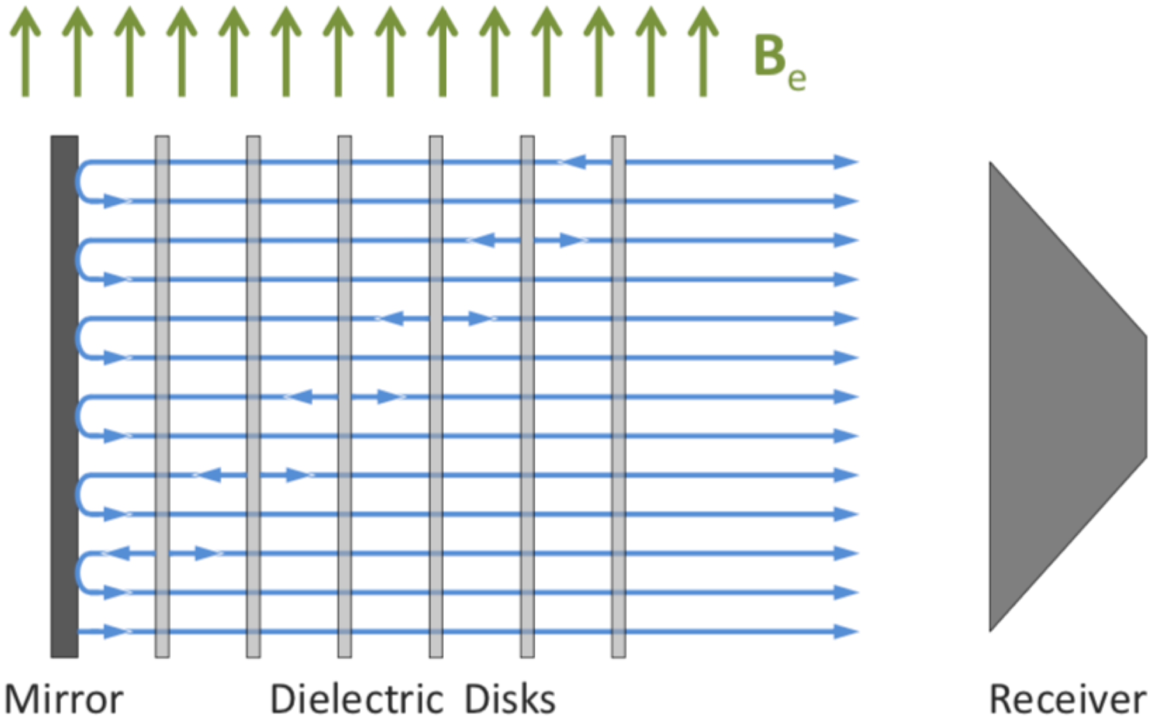
## Dish Antennas

- Boosted dish antenna: Open dielectric resonator
  - Add stack of dielectric disks with $\sim \lambda/2$ spacing in front of mirror (all immersed in magnetic field)
  - Constructive interference of photon part of wave function

[Jaeckel,Redondo 13]

[Millar,Raffelt,Redondo,Steffen 16]

[Baryakhtar,Huang,Lasenby18]



[Caldwell et al. `16]

# Searches for Dark Matter Axions

## Dish Antennas

- Boosted dish antenna: Proposed MADMAX experiment [Caldwell et al. `16; Bruns et al. 19]

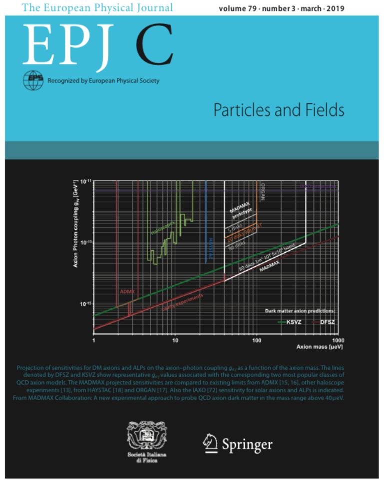
2017 -2019
Design

2020 -2025
Prototype

2025 -2035
Experiment

@CERN

@DESY


The European Physical Journal

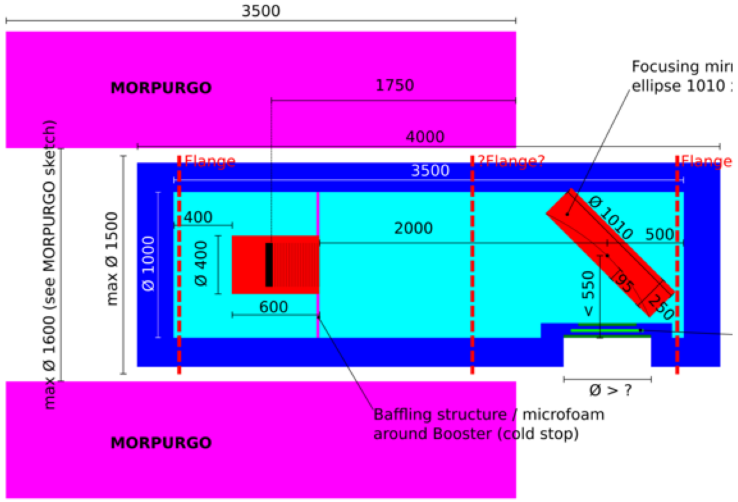
volume 79 · number 3 · march · 2019

EPJ C

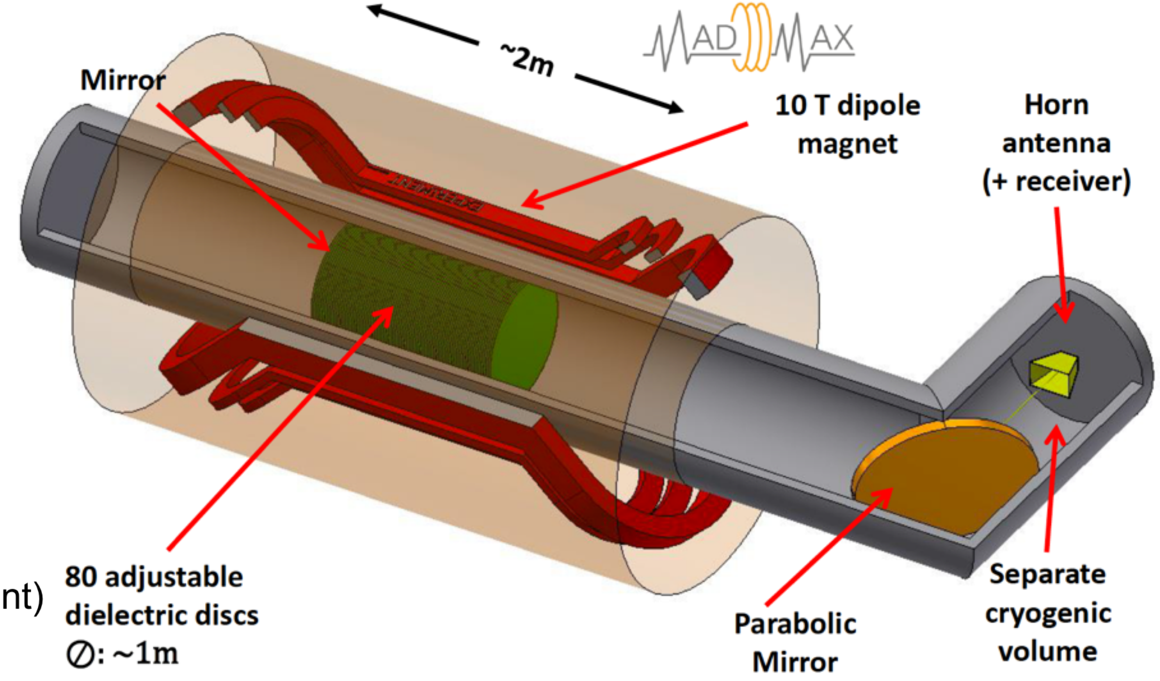
Recognized by European Physical Society

Particles and Fields

Springer



Scaling: Area 1/10 (of final experiment)
# discs 1/4
B [T] 1/5

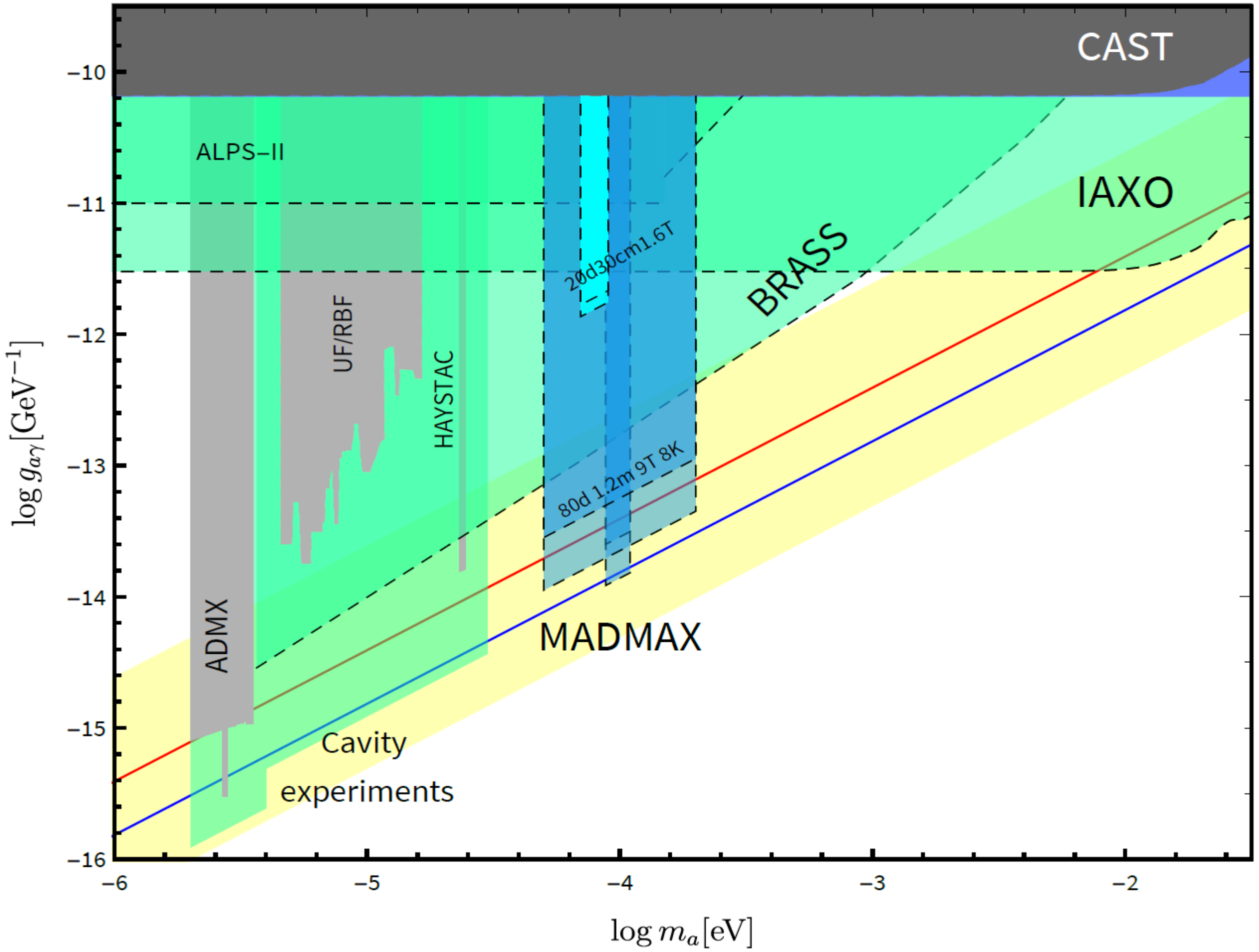


# Searches for Dark Matter Axions

## Dish Antennas

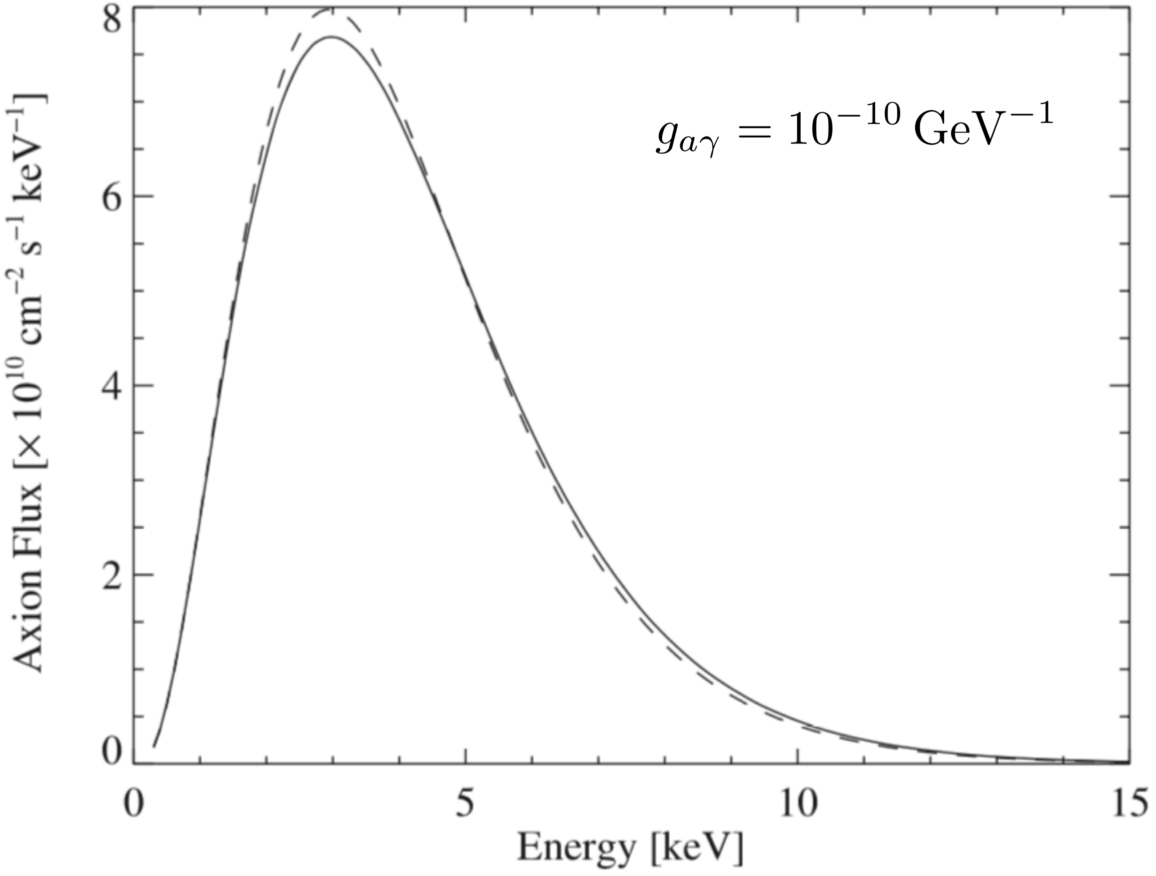
- Projected sensitivity of MADMAX experiment

[Caldwell et al. `16; Bruns et al. 19]

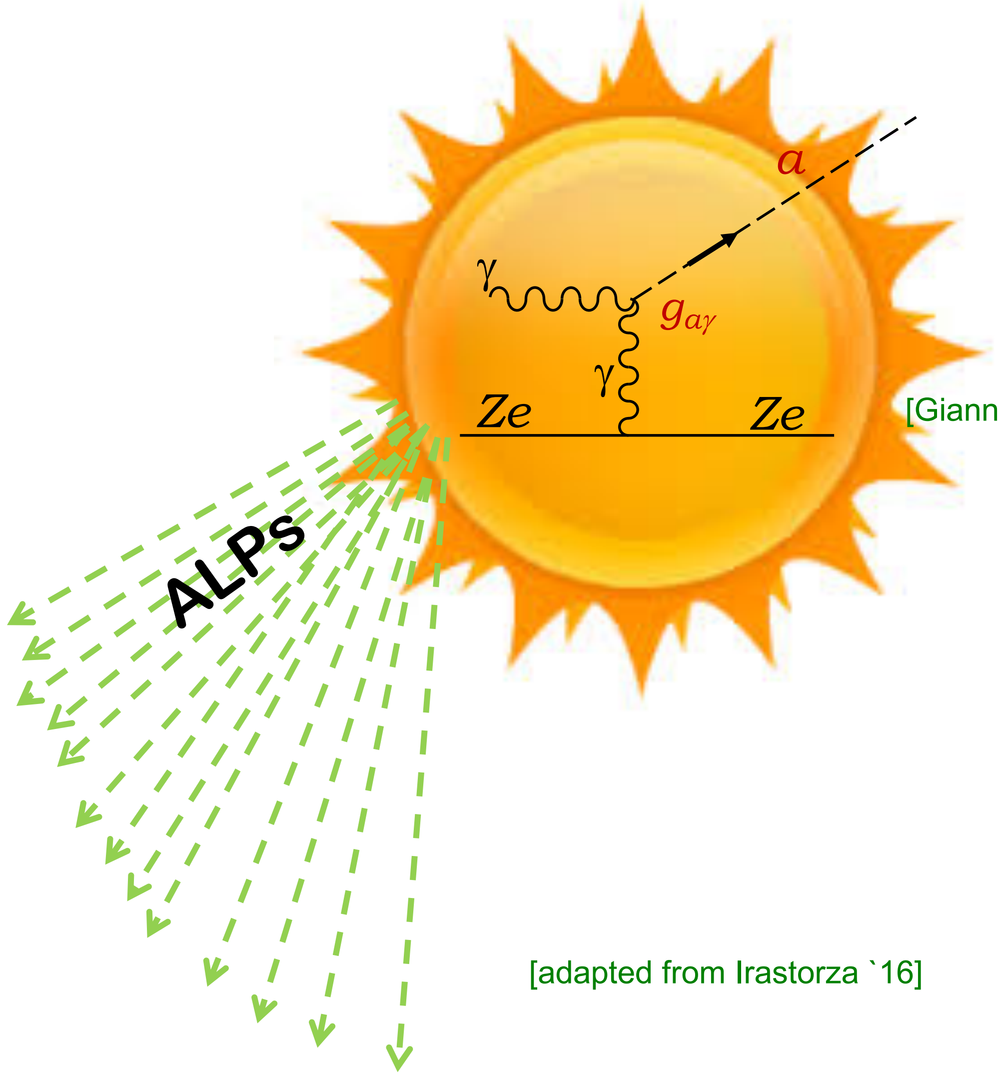


# Searches for Solar Axions

- Flux of solar axions/ALPs produced by two photon process in core:



[Adriamonje et al. \`07]

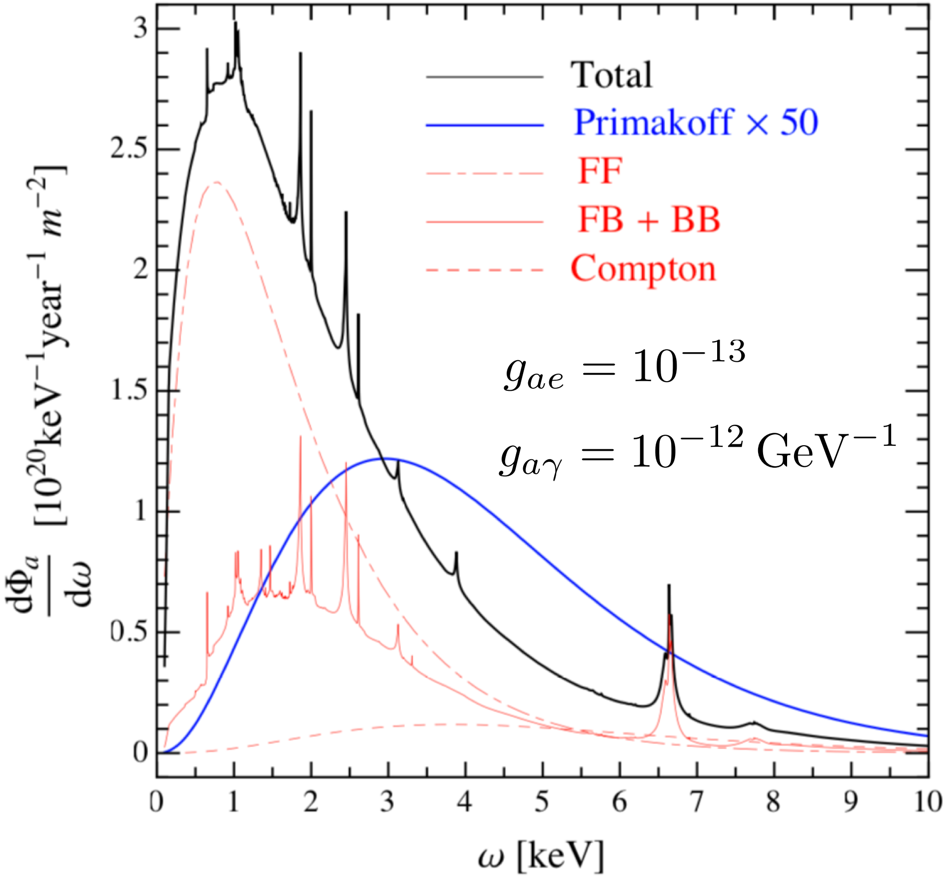


[Giannotti \`16]

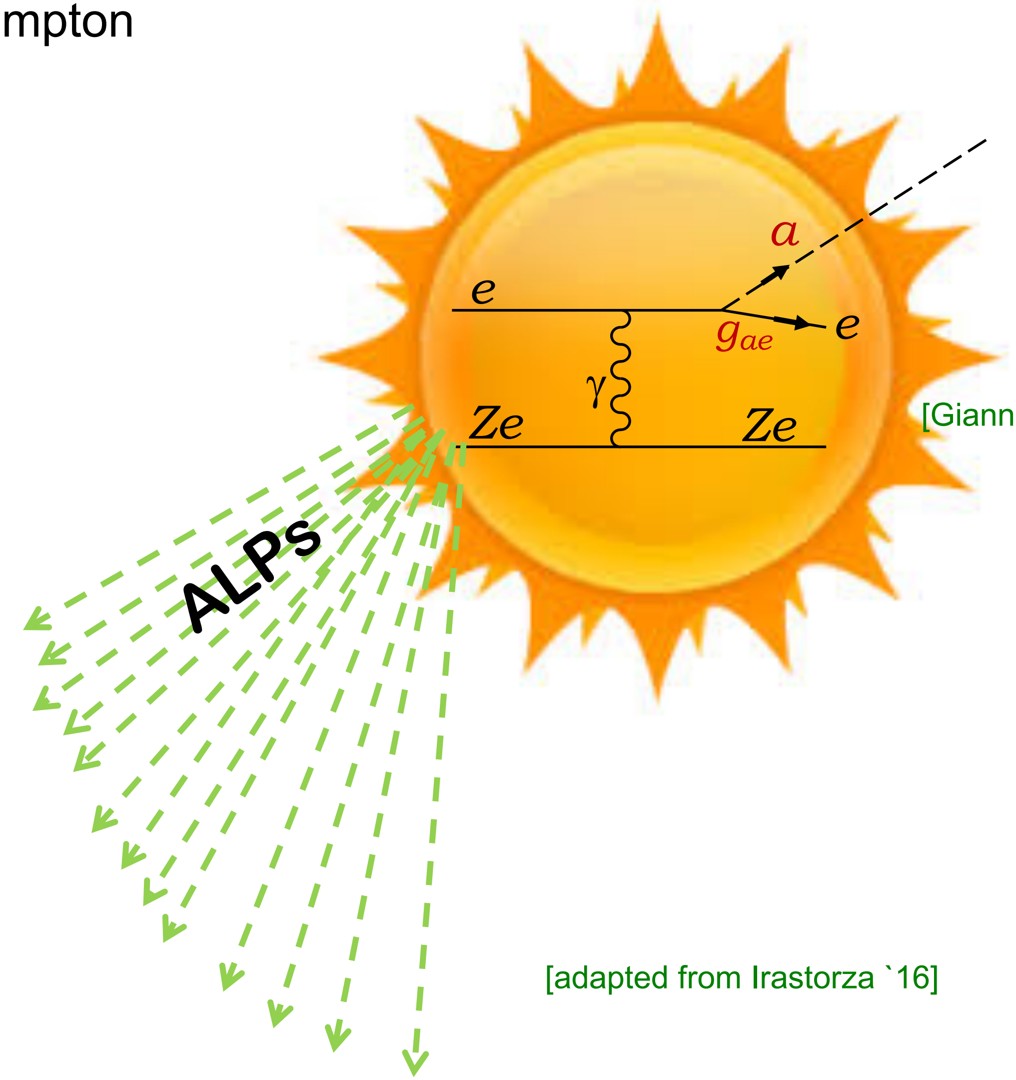
[adapted from Irastorza \`16]

# Searches for Solar Axions

- If axion/ALP couples to electron, even higher flux of solar axion/ALPs produced by atomic recombination and deexcitation (FB+BB), Bremsstrahlung (FF) and Compton



[Redondo `13]



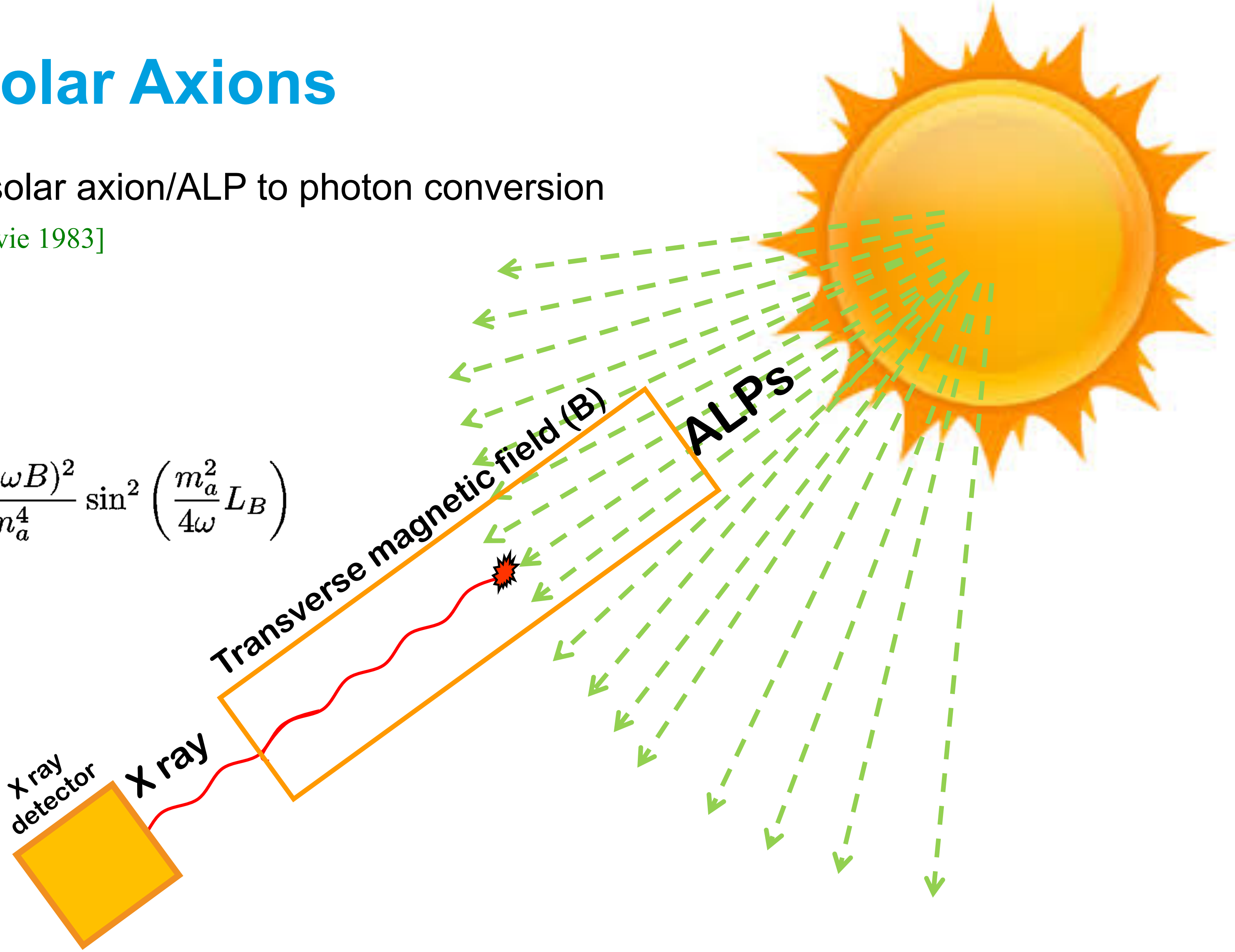
[Giannotti `16]

[adapted from Irastorza `16]

# Searches for Solar Axions

- Helioscope concept: solar axion/ALP to photon conversion in magnetic field [Sikivie 1983]

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



[adapted from Irastorza `16]

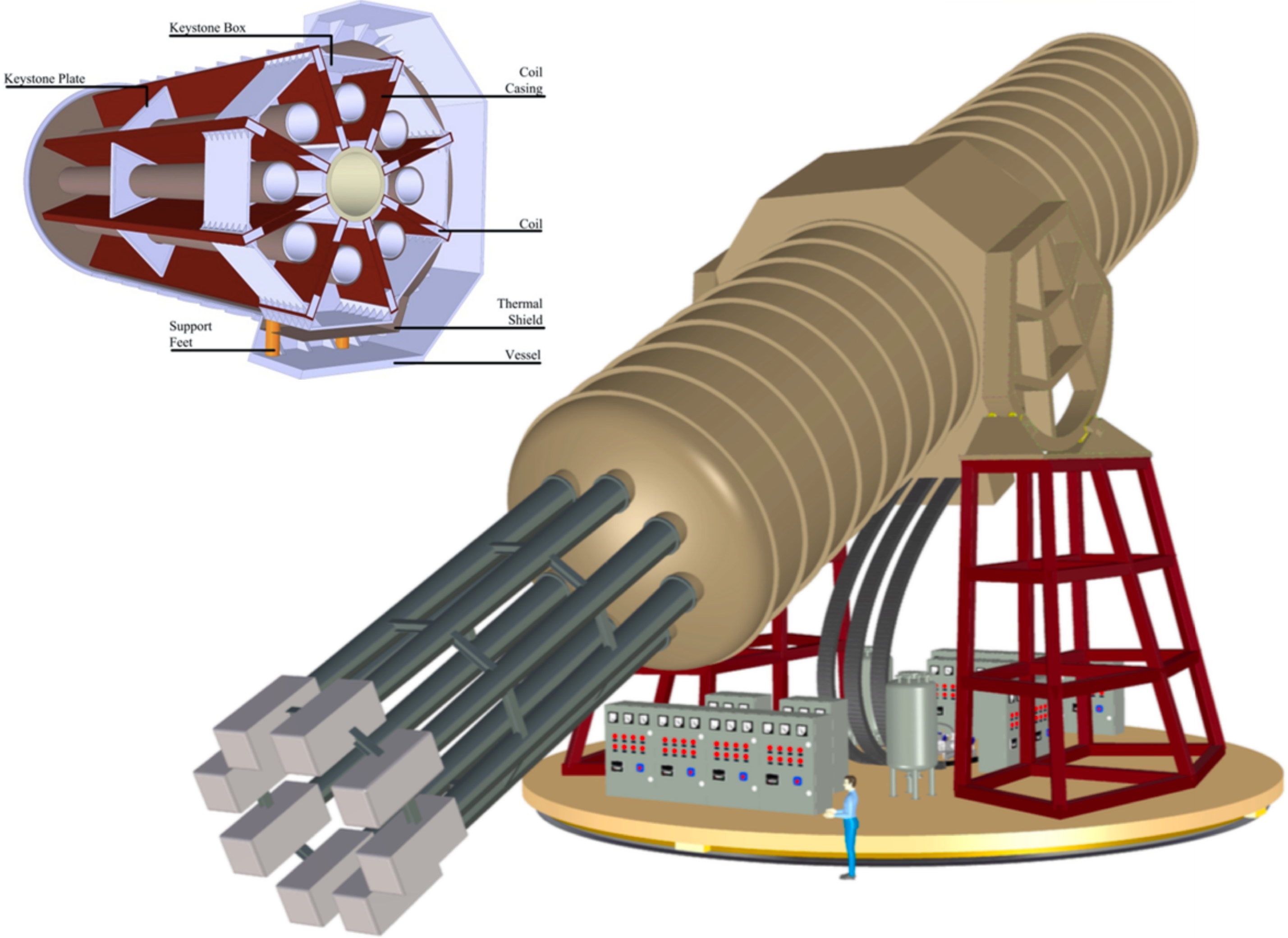
# Searches for Solar Axions

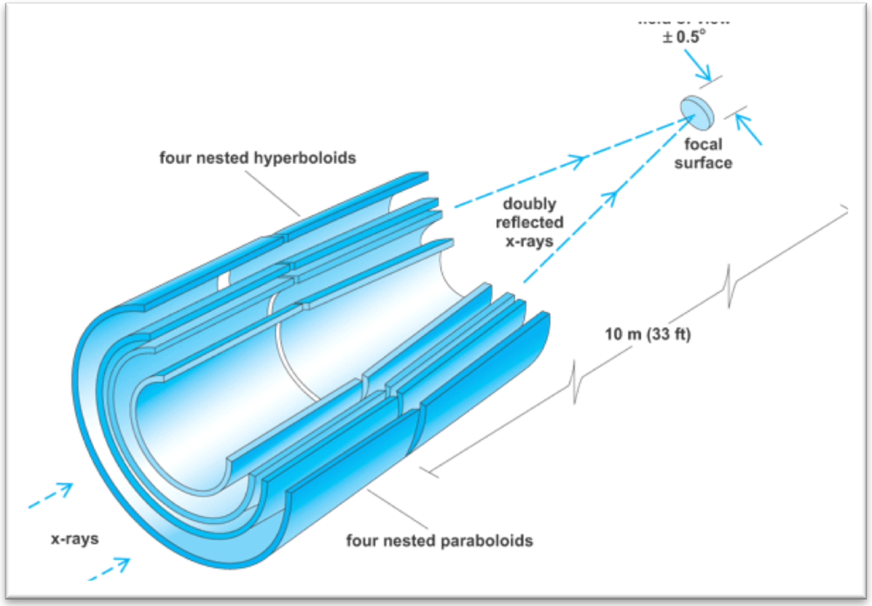
- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (axion band)

# Searches for Solar Axions

- International Axion Observatory (IAXO)
  - Large toroidal 8-coil magnet L = ~20 m
  - 8 bores: 600 mm diameter each
  - 8 X-ray telescopes + 8 detection systems
  - Rotating platform with services

[IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]





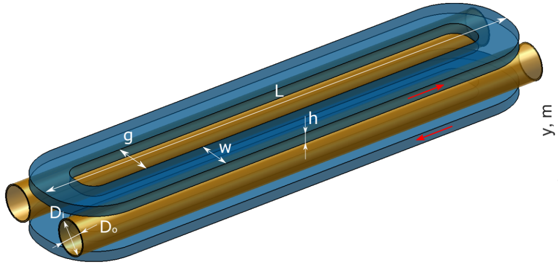
# Searches for Solar Axions

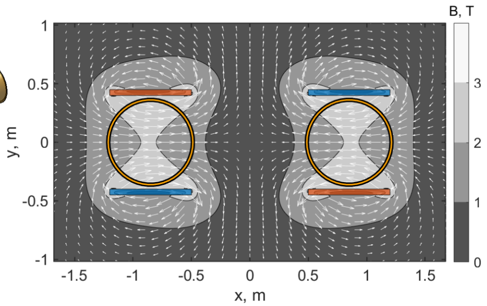
- International Axion Observatory (IAXO)
  - Large toroidal 8-coil magnet L = ~20 m
  - 8 bores: 600 mm diameter each
  - 8 X-ray telescopes + 8 detection systems
  - Rotating platform with services
- Proposed site: DESY

[IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]

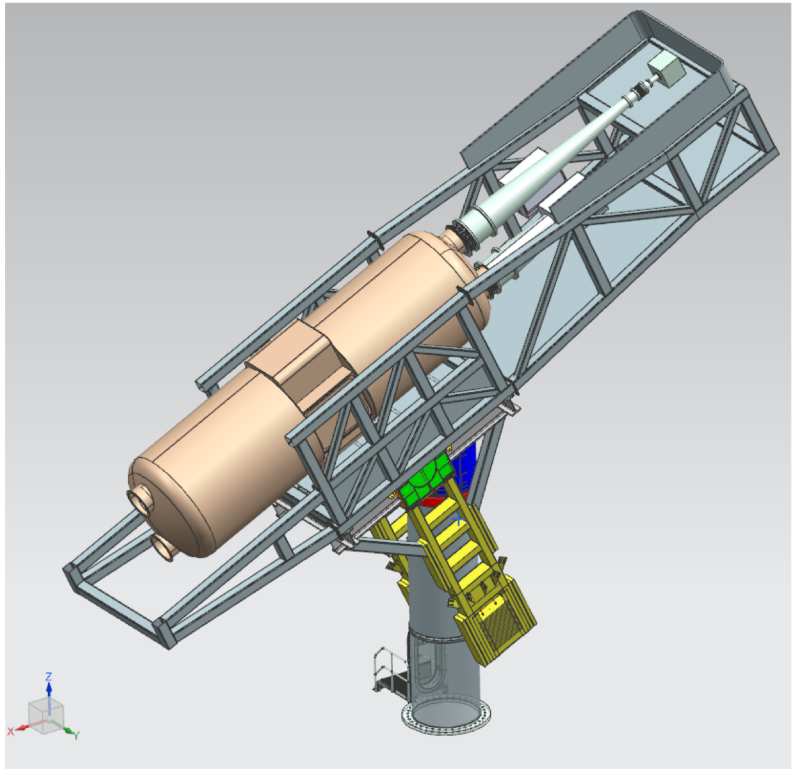
# Searches for Solar Axions

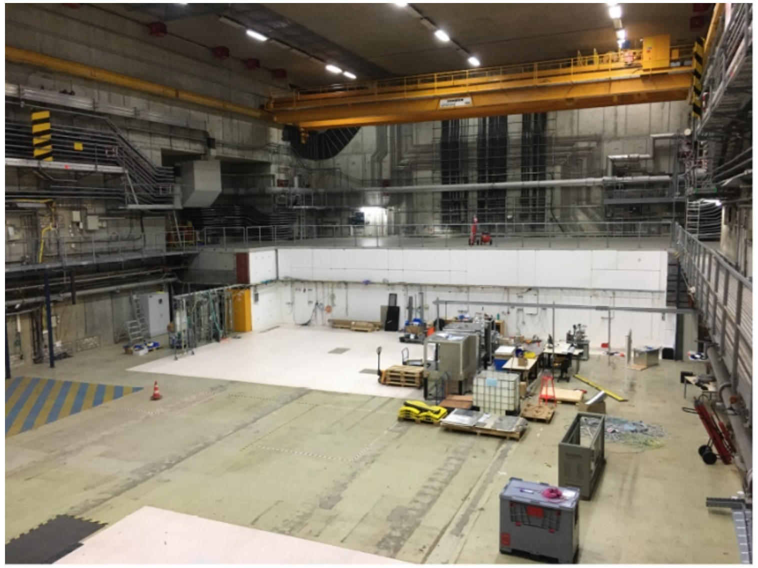
- Prototype for IAXO: BabyIAXO
    - Two bores of dimensions similar to final IAXO bores
    - Detection lines representative of final ones
    - Test & improve all systems
- Magnet technical design ongoing at CERN





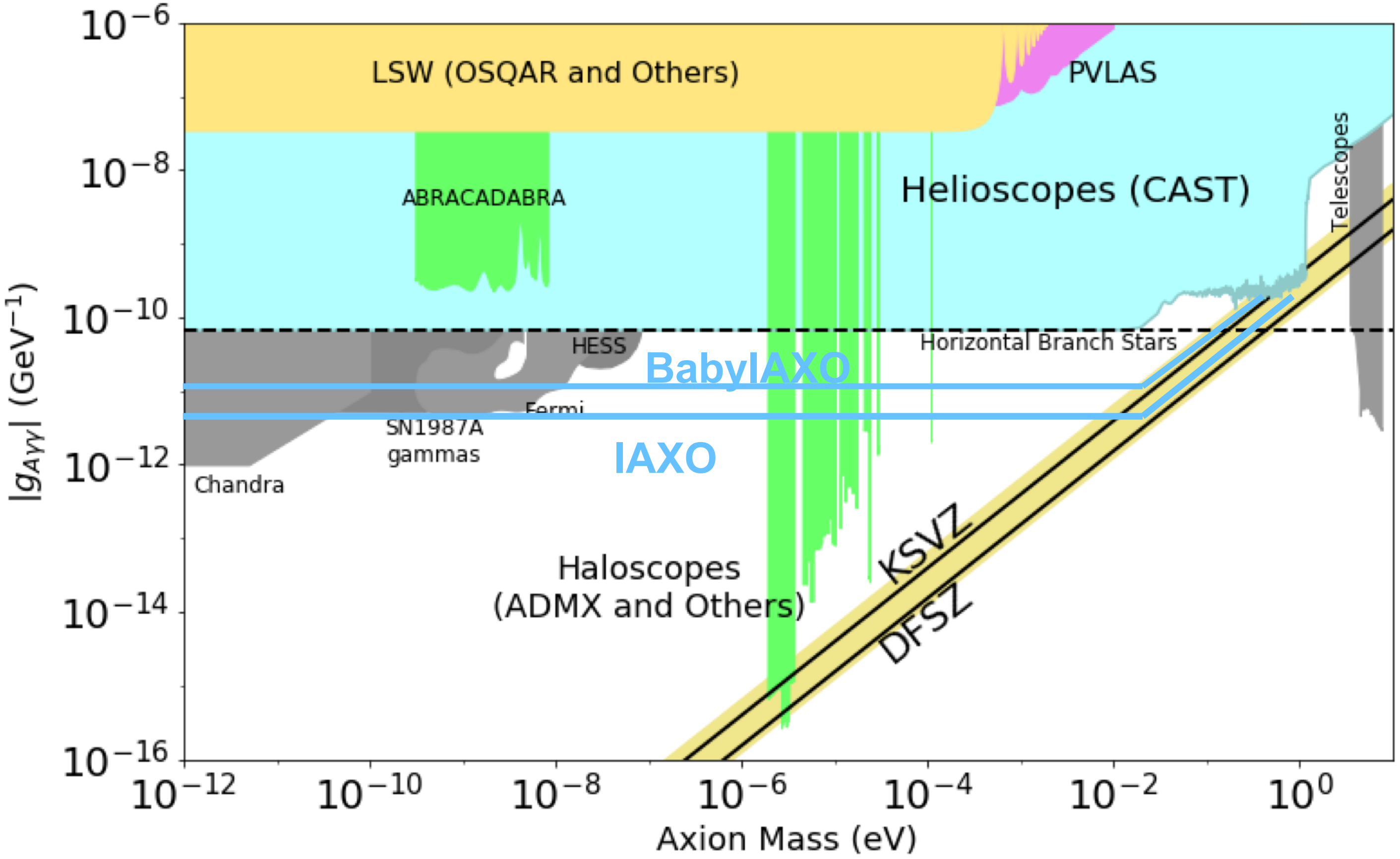
- HERA South Hall being prepared for BabyIAXO
- Funded mainly via Irastorza: ERC-AvG 2017 IAXO+
- Preparations have already started in 2020
- Data taking may start in 2024/25





# Searches for Solar Axions

- (Baby)IAXO probes meV mass QCD axion



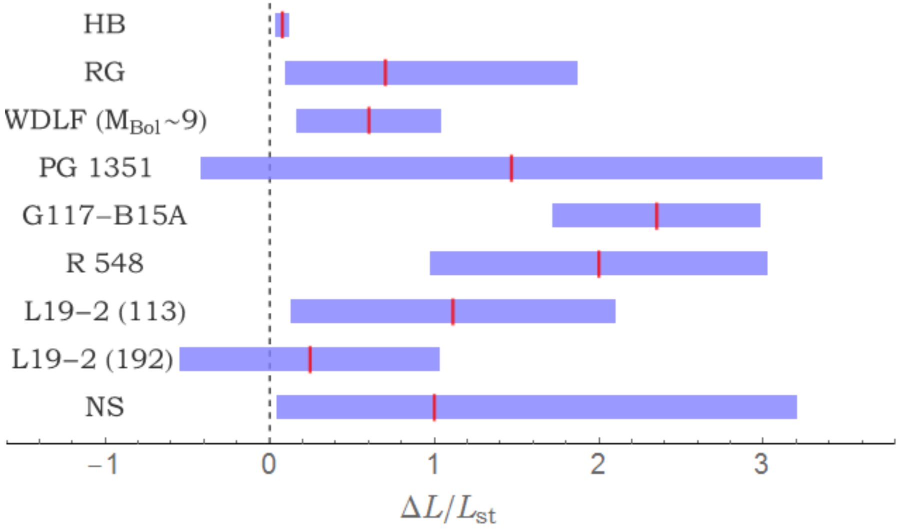
[adapted from AR,Rybka,Rosenberg in 2019 update PDG RPP]

# Searches for Solar Axions

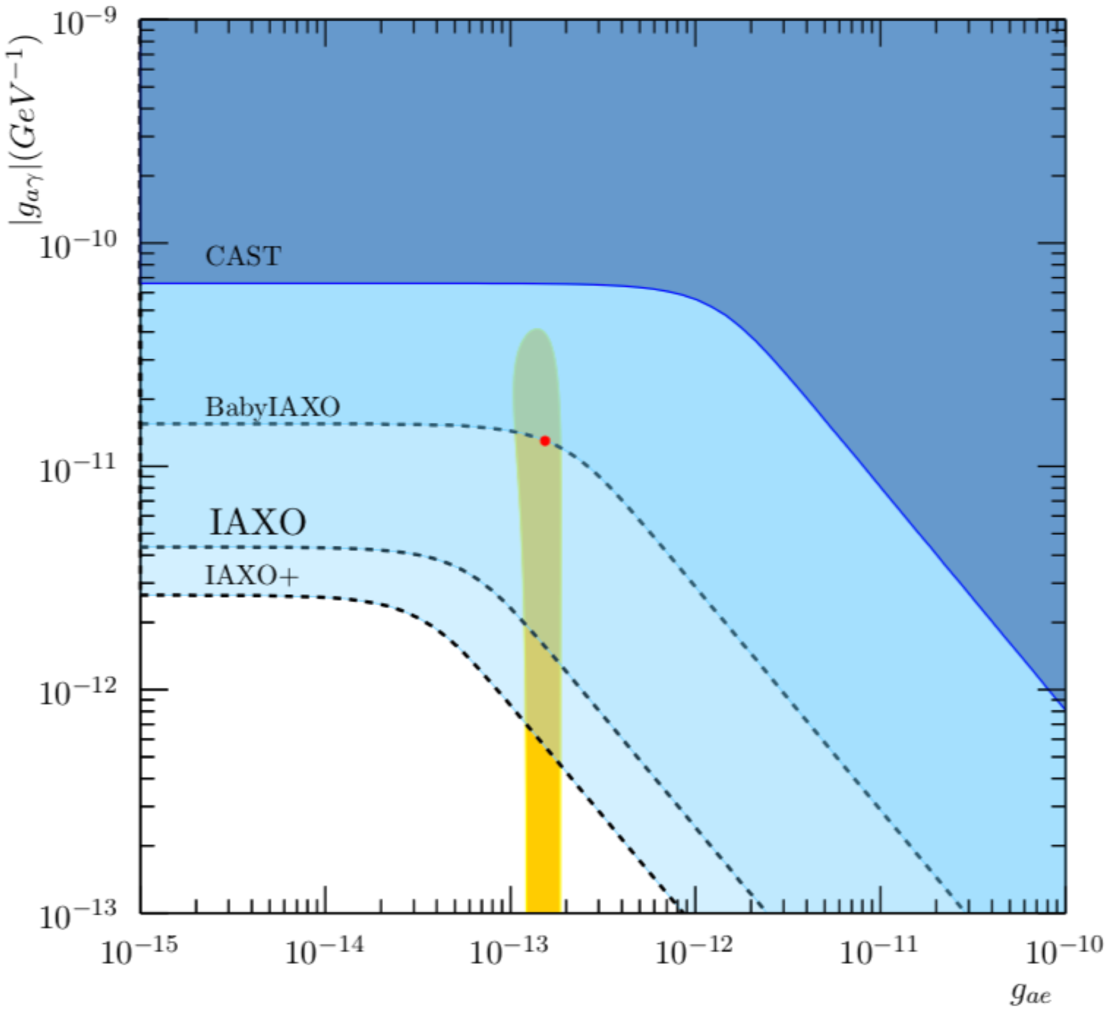
- (Baby)IAXO also sensitive to electron coupling
- Probes parameter region which is suggested by explanation of stellar cooling excess

[Giannotti, Irastorza, Redondo, AR, Saikawa 17]

  - Stellar cooling excess: Practically every stellar systems seems to be cooling a bit faster than predicted by models based on SM:



[Giannotti, Irastorza, Redondo, AR 15]

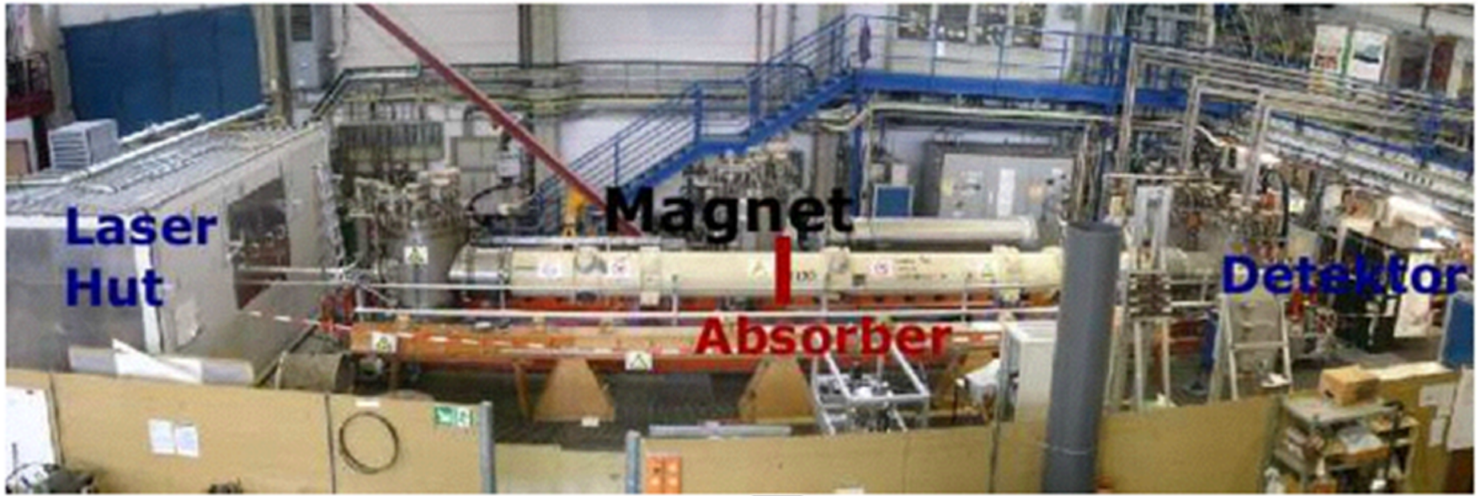


[Armengaud et al. 19]

# Light-Shining-through-a-Wall Searches

[Sikivie 1983, Ansel‘m 1985, van Bibber et al. 1987]

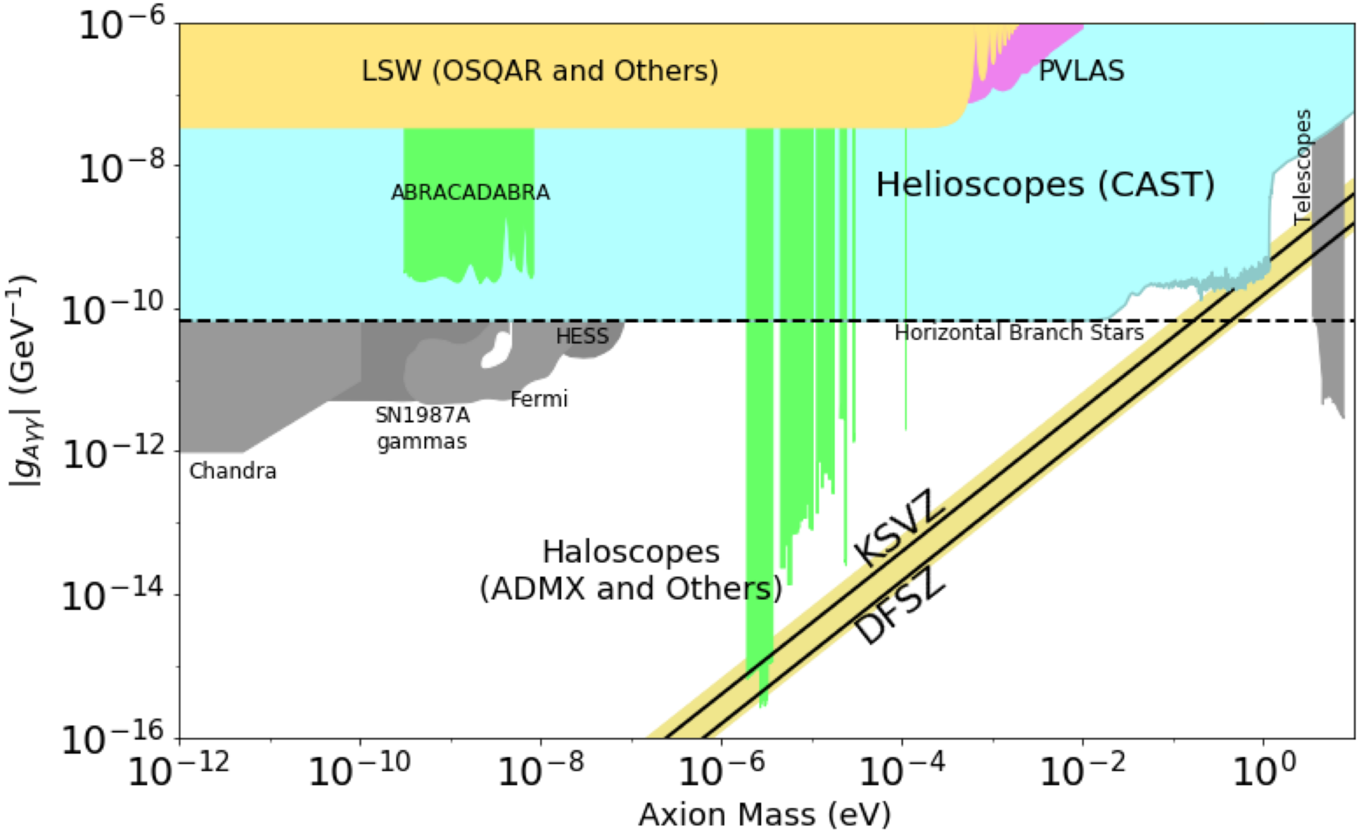
- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg) [AR 03;....;Ehret et al. 10]



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

# Light-Shining-through-a-Wall Searches

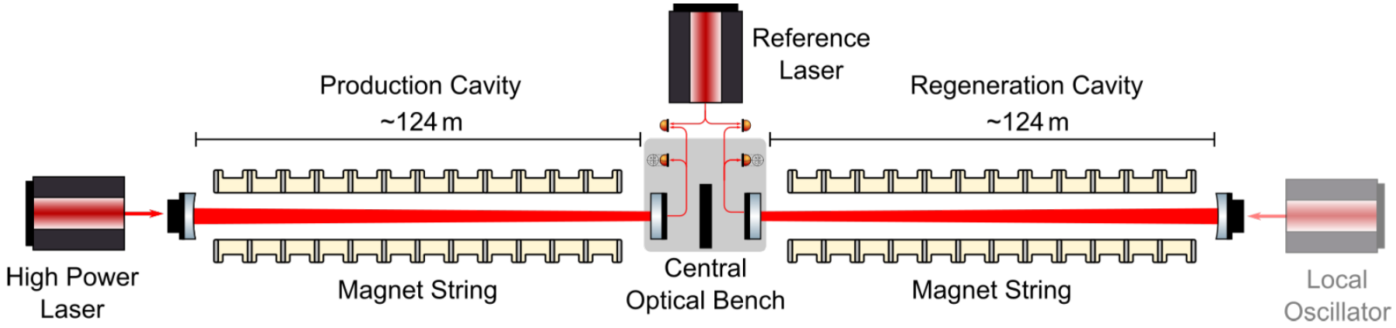
- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg) [AR 03;...;Ehret et al. 10]
  - LSW experiments ALPS I and OSQAR @ CERN give currently the best purely laboratory limit on low mass axions:

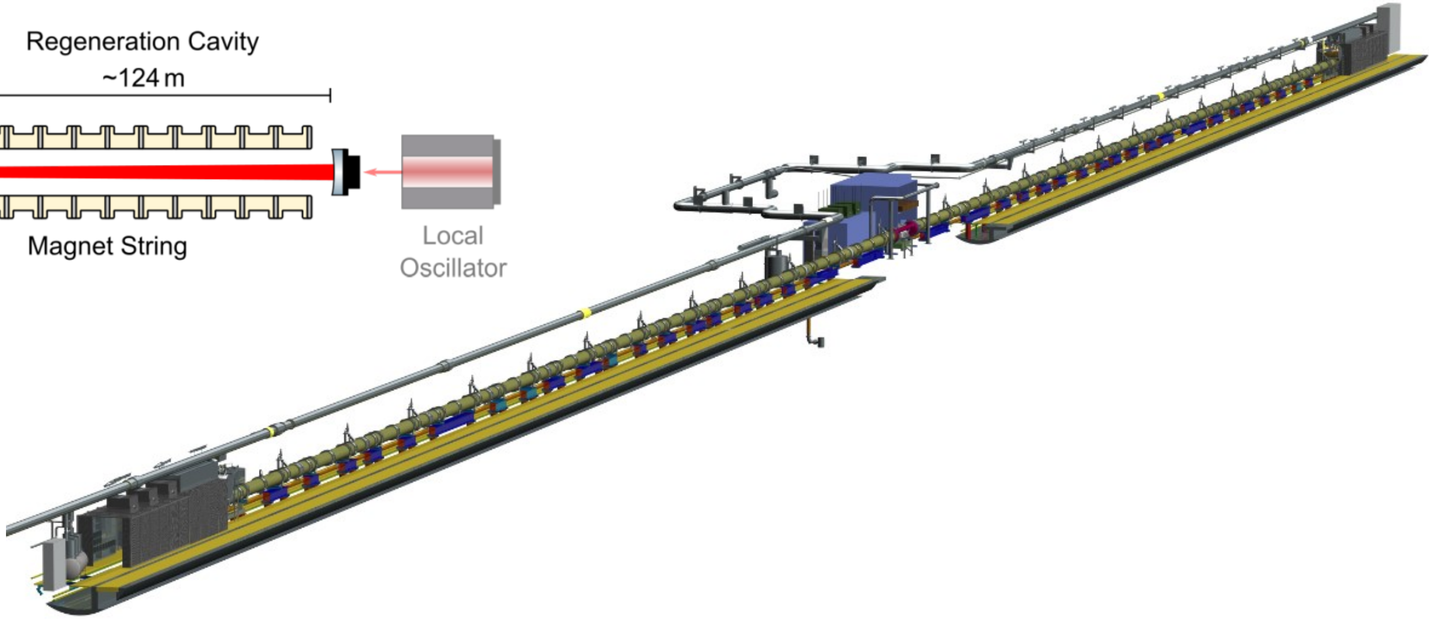


[AR,Rybka,Rosenberg in 2019 update PDG RPP]

# Light-Shining-through-a-Wall Searches

- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz) [Bähre et al (ALPS II TDR) 13]
  - Increase sensitivity in photon coupling by a factor of more than $10^3$ by exploiting
    - 12 + 12 straightened HERA magnets





    - Optical cavities both at production and regeneration sites

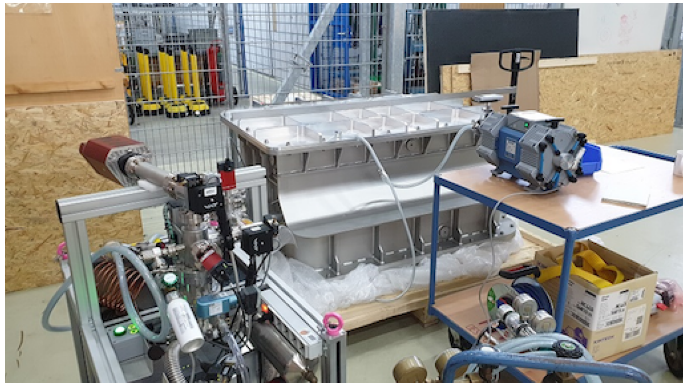
# Light-Shining-through-a-Wall Searches

## ALPS II at DESY

- HERA tunnel on about 300 m cleared

- 24 magnets straightened and tested; first magnets installed

- Everything on track for data taking in 2021



DESY

Albert Einstein Institute
Hannover

UF UNIVERSITY of FLORIDA

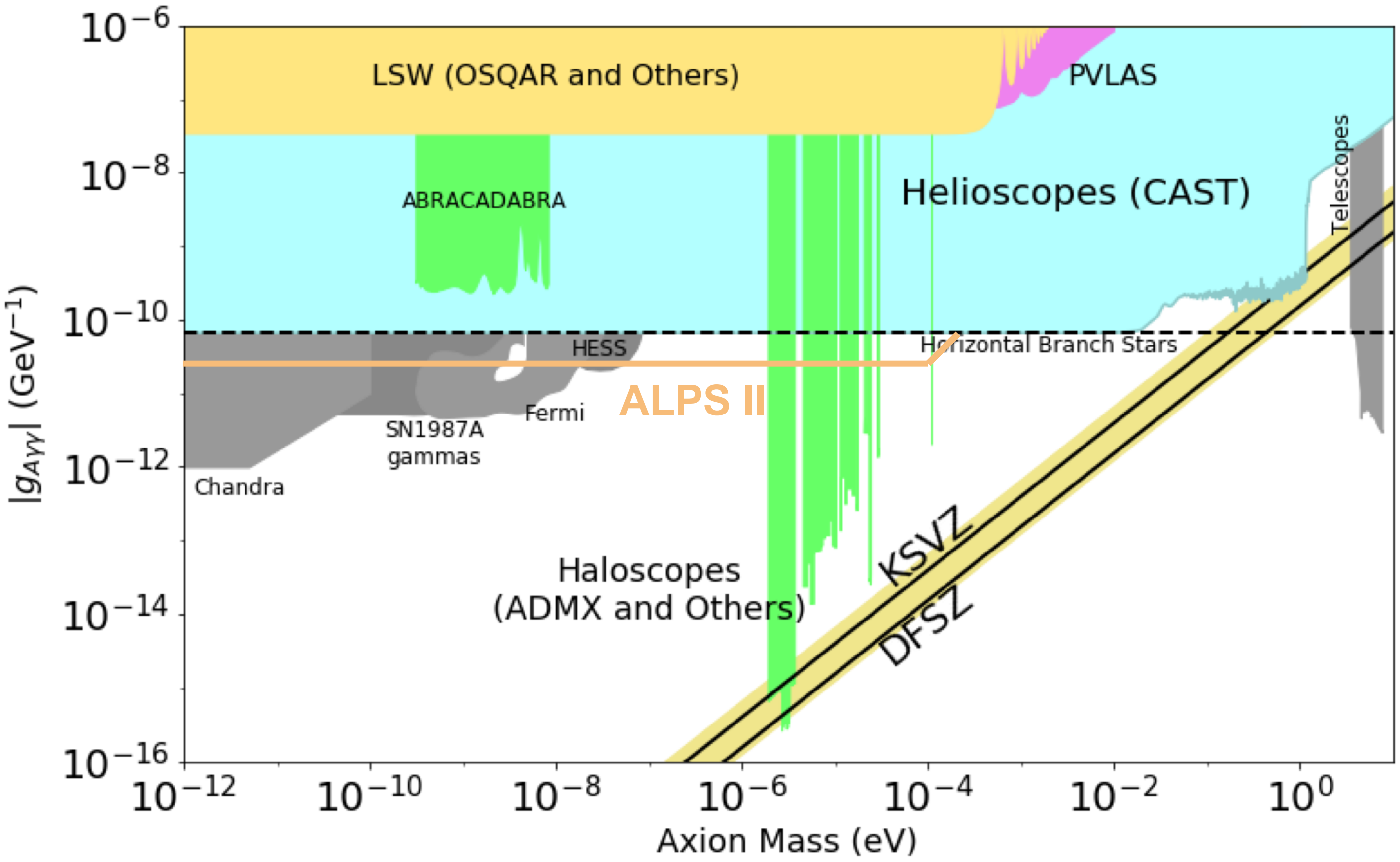
HEISING-SIMONS FOUNDATION

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

JGU
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

# Light-Shining-through-a-Wall Searches

- ALPS II will probe previously uncharted territory, in particular part of parameter space relevant for dark matter and astro hints (excessive energy losses of Horizontal Branch stars in globular clusters)



[adapted from AR,Rybka,Rosenberg in 20129 update PDG RPP]

# 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/ALP parameter space will be tackled in the upcoming decade by a number of terrestrial experiments:
  - Axion dark matter searches (ABRACADABRA, BRASS, ADMX, CASPEr, CULTASK, HAYSTAC, MADMAX, ORGAN, QUAX, ...)
  - Solar axion searches ((Baby)IAXO, ...)
  - Light-shining-through-a-wall experiments (ALPS II, ...)
  - Searches for axion-mediated forces (ARIADNE, ...)
- If 100 % of DM consists of QCD axions, one of the dark matter axion experiments likely to see a signal in the upcoming decade!

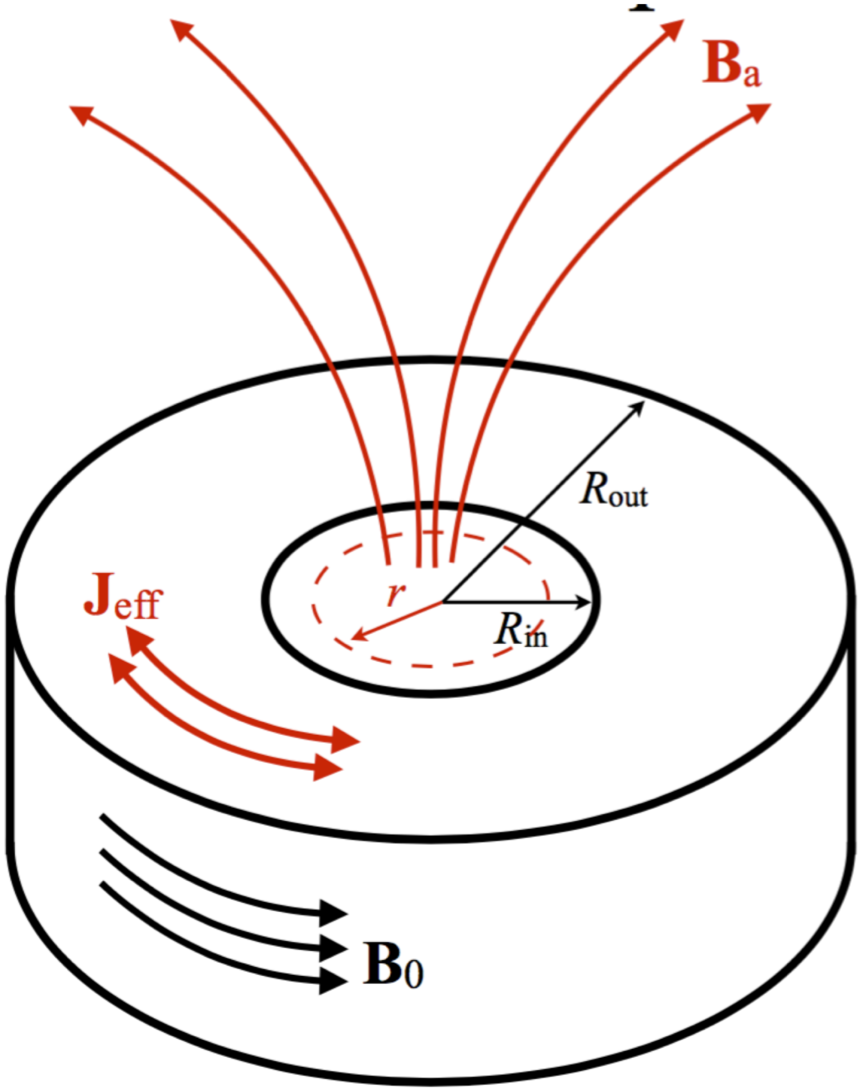
**STAY TUNED!**

# Searches for Dark Matter Axions

## 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
- DM-Radio (Stanford): similar experiment in path-finder status [Silva-Feaver et al. 16]



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

# Searches for Dark Matter Axions

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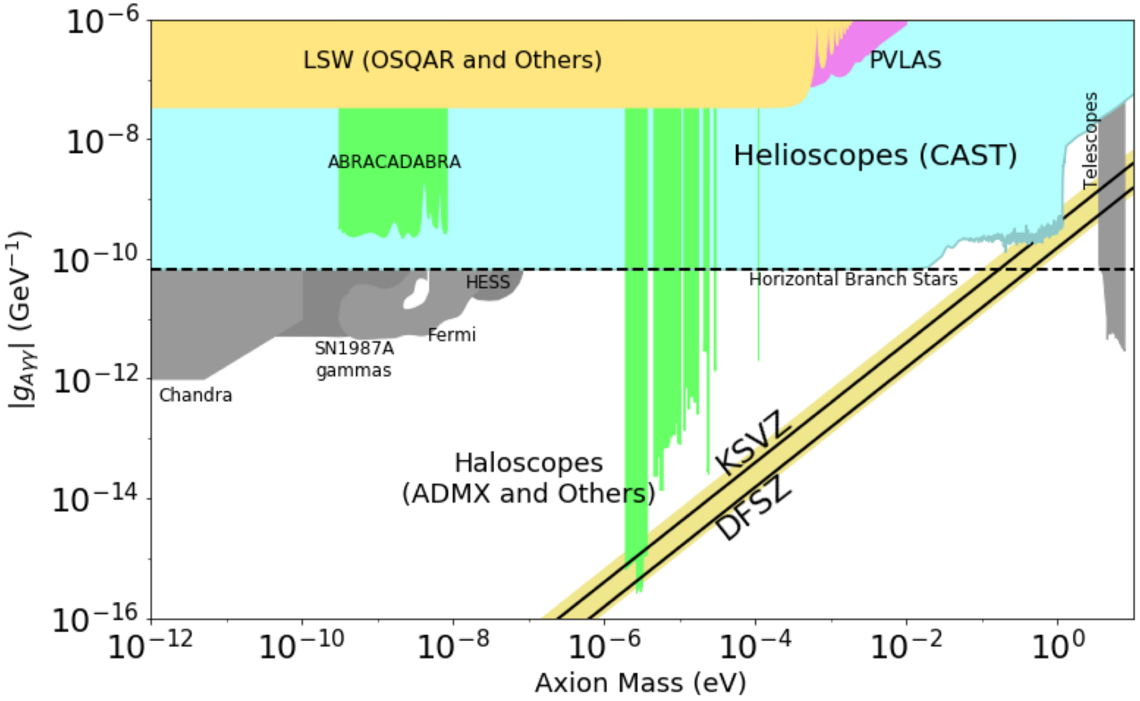
ABRACADABRA-10 cm Run 1:



[AR,Rybka,Rosenberg in 2019 update PDG RPP]

# Searches for Dark Matter Axions

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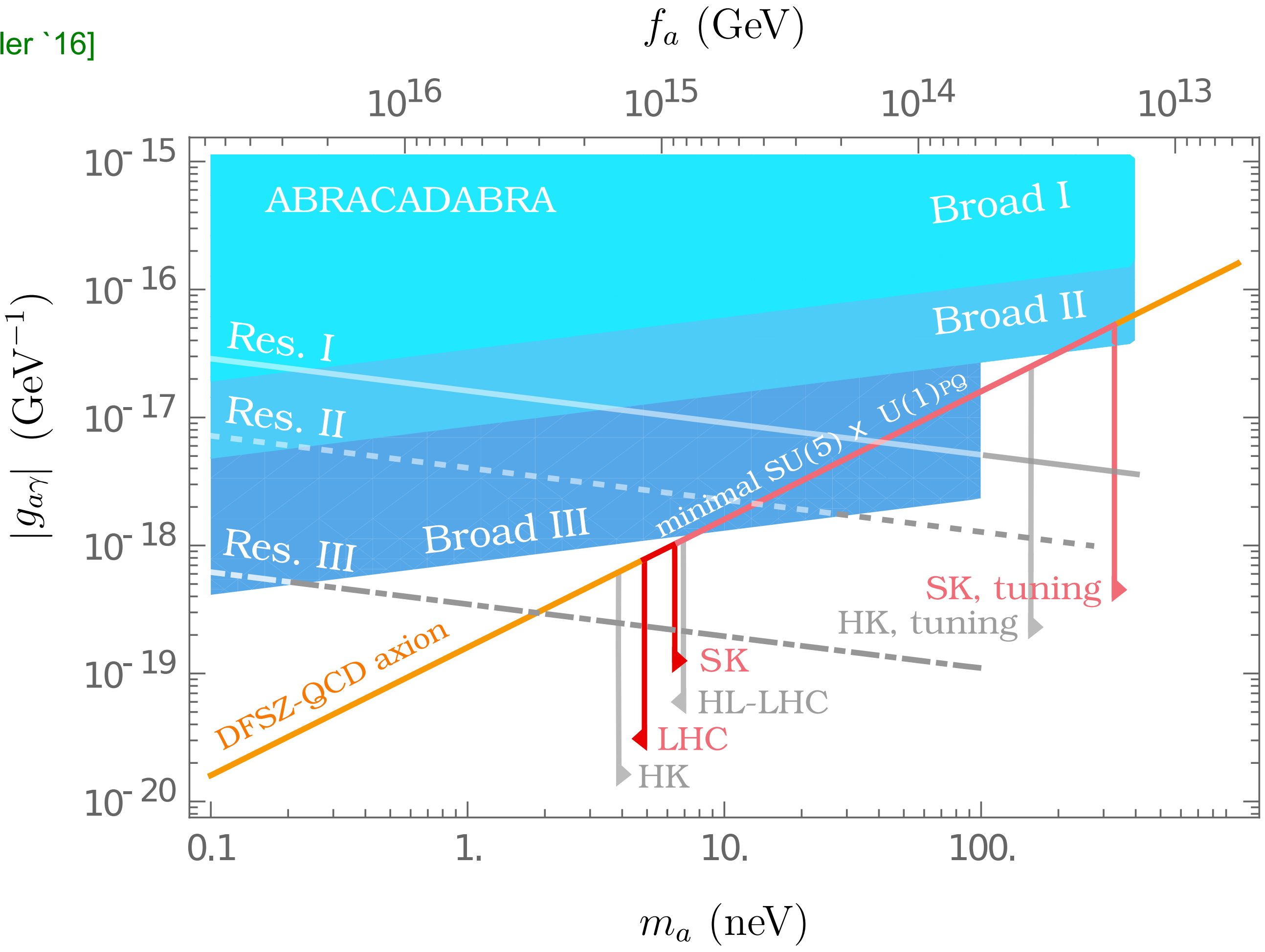
- DM-Radio (Stanford): similar experiment in path-finder status [Silva-Feaver et al. 16]
- Probe QCD axion dark matter in mass range predicted by Grand Unified Theories (GUTs)

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



[Di Luzio, AR, Tamarit, arXiv:1807.09769]

# Searches for Dark Matter Axions

## 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 external $\vec{B}_{\rm ext} \perp E^*$
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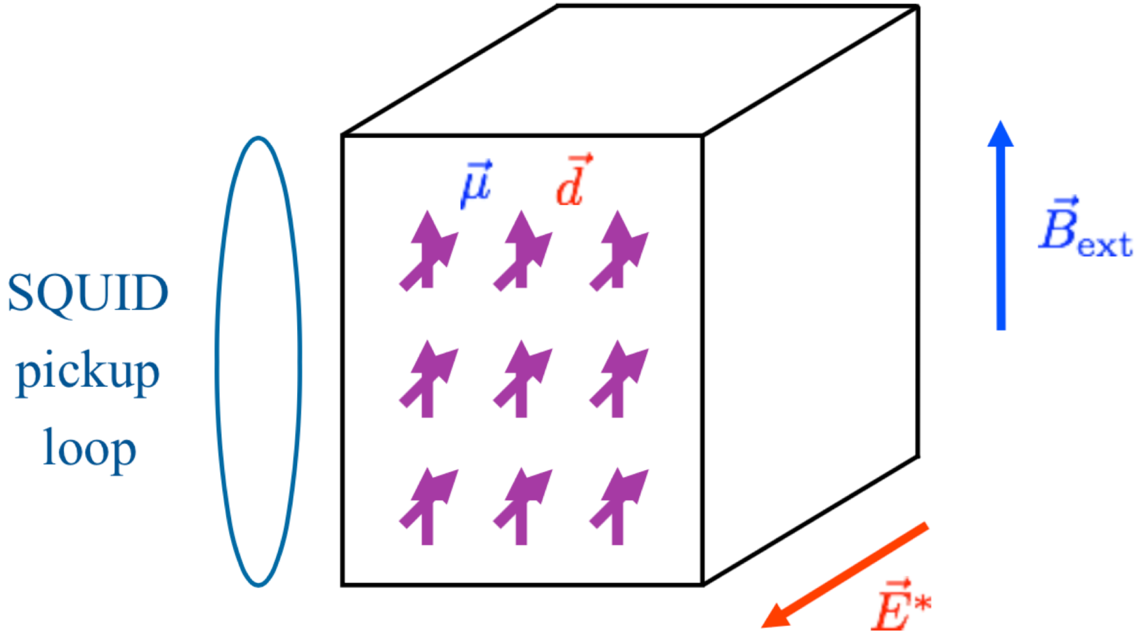
[Graham,Rajendran 13; Budker et al. 14]

- CASPEr-Electric currently being set-up in Boston



[Budker et al. 14]

# Searches for Dark Matter Axions

## Magnetic Resonance Searches

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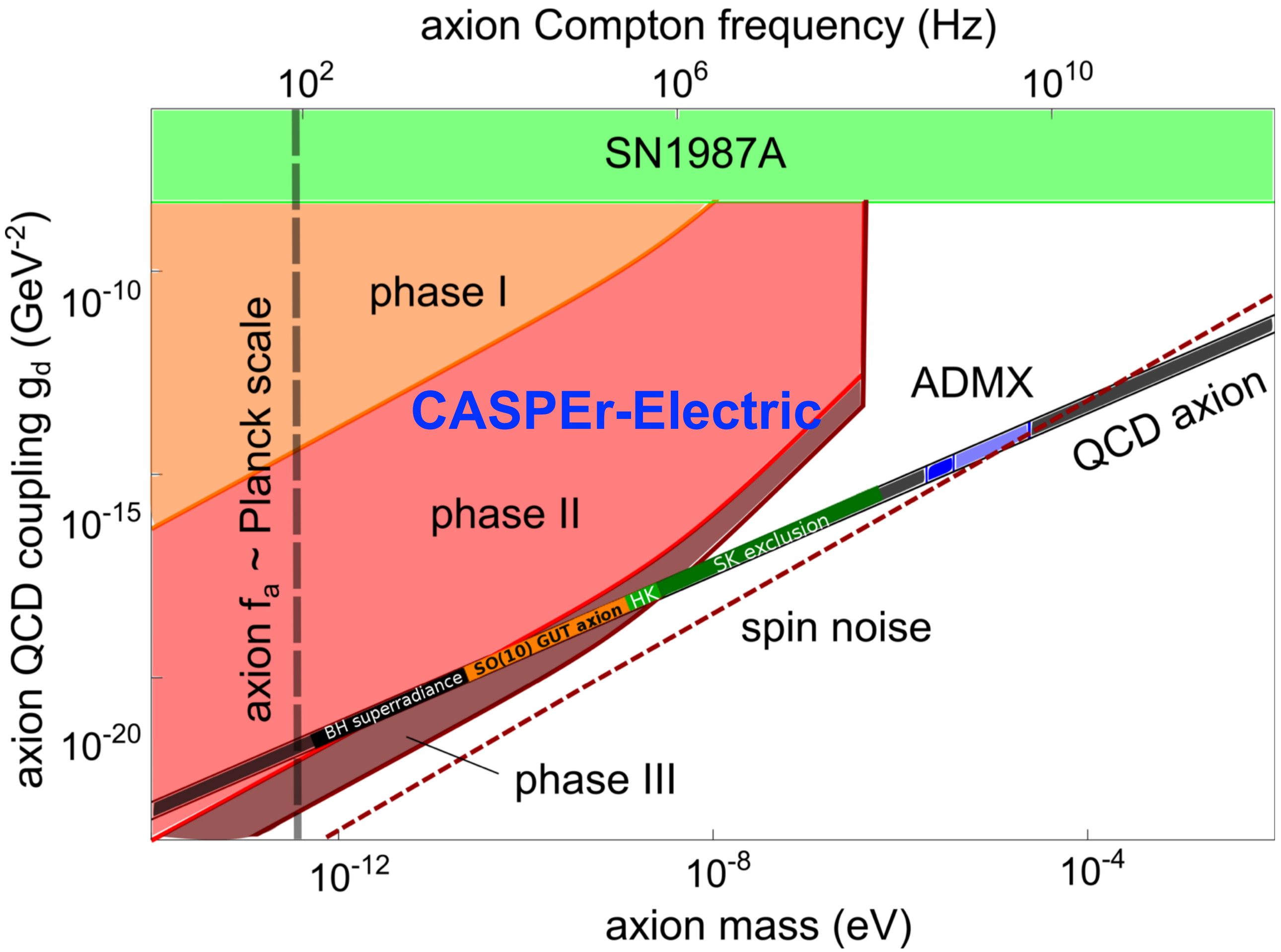

[Ernst,Di Luzio,AR,Tamarit 18]

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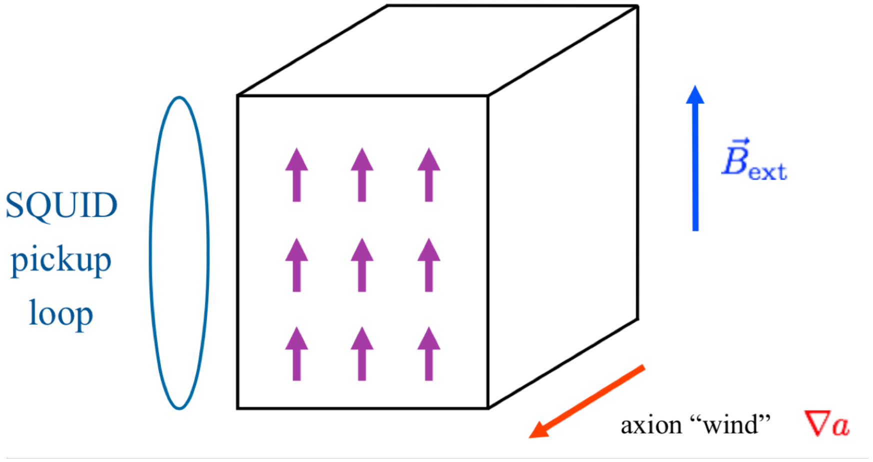
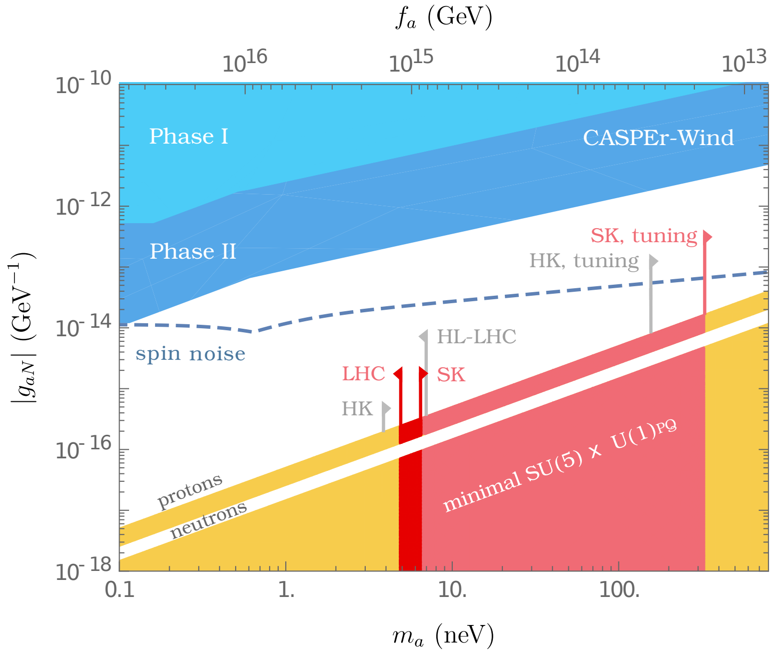


[Budker et al. 14]



[Di Luzio,AR,Tamarit 18]

# Searches for Axion Mediated Forces

## Magnetic Resonance Searches

- Experiments searching for axion mediated forces particularly effective in meV mass range
- Monopole-dipole interaction between nucleon and fermion:

$$U_{\text{mon-dip}}(r) = \frac{g_{\overline{aN\bar N}}\, g_{af\bar f}}{8\pi m_f}\left(\frac{m_a}{r} + \frac{1}{r^2}\right) e^{-m_a r}\,(\hat\sigma\cdot\hat r)$$

$$\mathcal{L}_{\text{int}} = g_{\overline{aN\bar N}}\; a\,\bar N N - i\, g_{af\bar f}\, a\, \bar f \gamma_5 f$$

- Proposed ARIADNE experiment searches for forces between a rotating cylinder, made of unpolarized material, and a vessel containing hyperpolarized $^3$He gas
  - Since $^3$He magnetic moment dominated by neutron contribution: sensitive to monopole-dipole interaction between nucleus and neutrons, $\left| g_{\overline{aN\bar N}}\, g_{an\bar n} \right|$

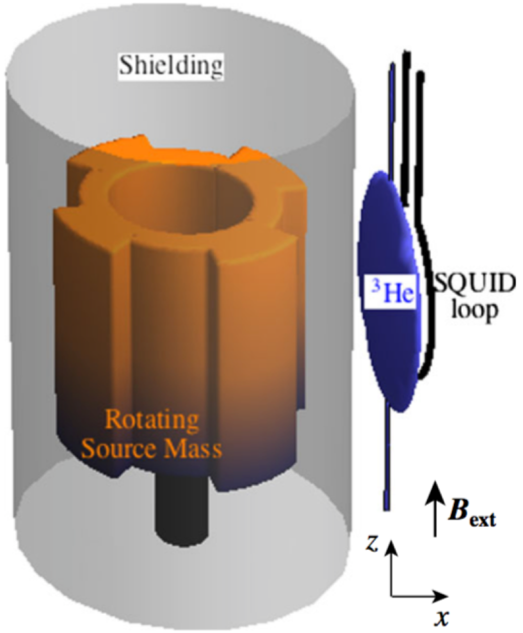


FIG. 1 (color online). A source mass consisting of a segmented cylinder with $n$ sections is rotated around its axis of symmetry at frequency $\omega_{\text{rot}}$, which results in a resonance between the frequency $\omega = n\omega_{\text{rot}}$ at which the segments pass near the sample and the resonant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

[Arvanitaki, Geraci 14]

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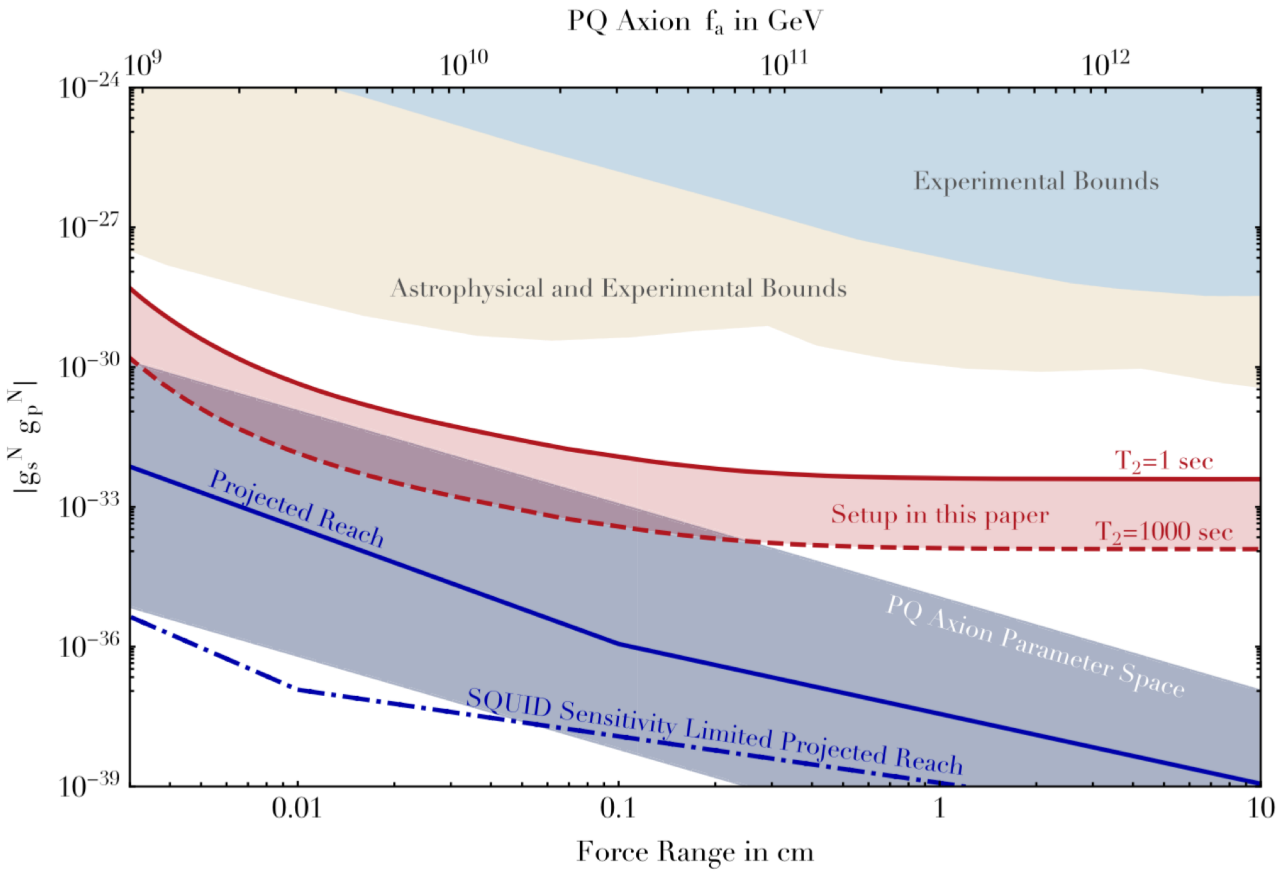

[Arvanitaki, Geraci 14]