Axions/ALPs: overview of experimental approaches in the low mass range

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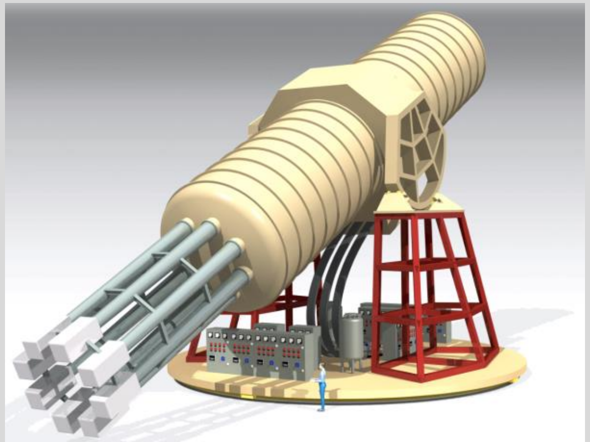
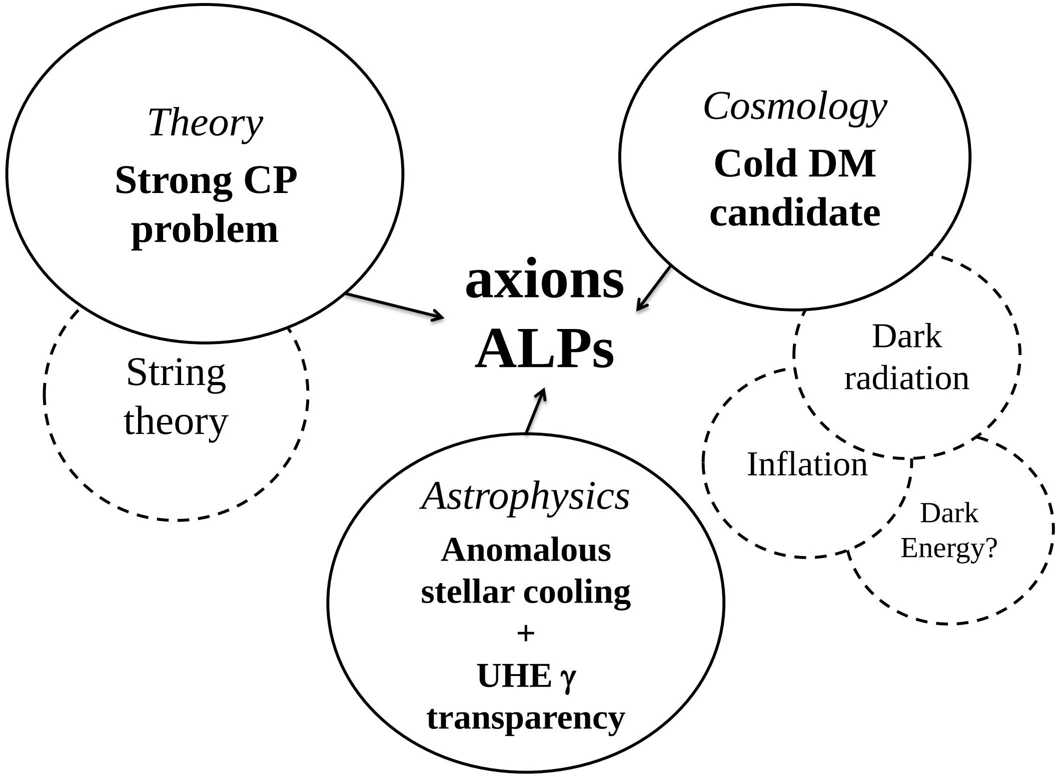


Why axions?

- Most compelling solution to the **Strong CP problem** of the SM
- Axion-like particles (ALPs) **predicted by many extensions** of the SM (e.g. string theory)
- Axions, like WIMPs, may **solve the DM problem** ***for free***. (i.e. not *ad hoc* solution to DM)
- **Astrophysical hints** for axion/ALPs?
  - Transparency of the Universe to UHE gammas
  - Stellar anomalous cooling → $g_{a\gamma}$ ~ few 10^{-11} GeV^{-1} / m_a ~few meV ?
- Relevant axion/ALP parameter space at **reach of current and near-future experiments**
- Still too little experimental efforts devoted to axions



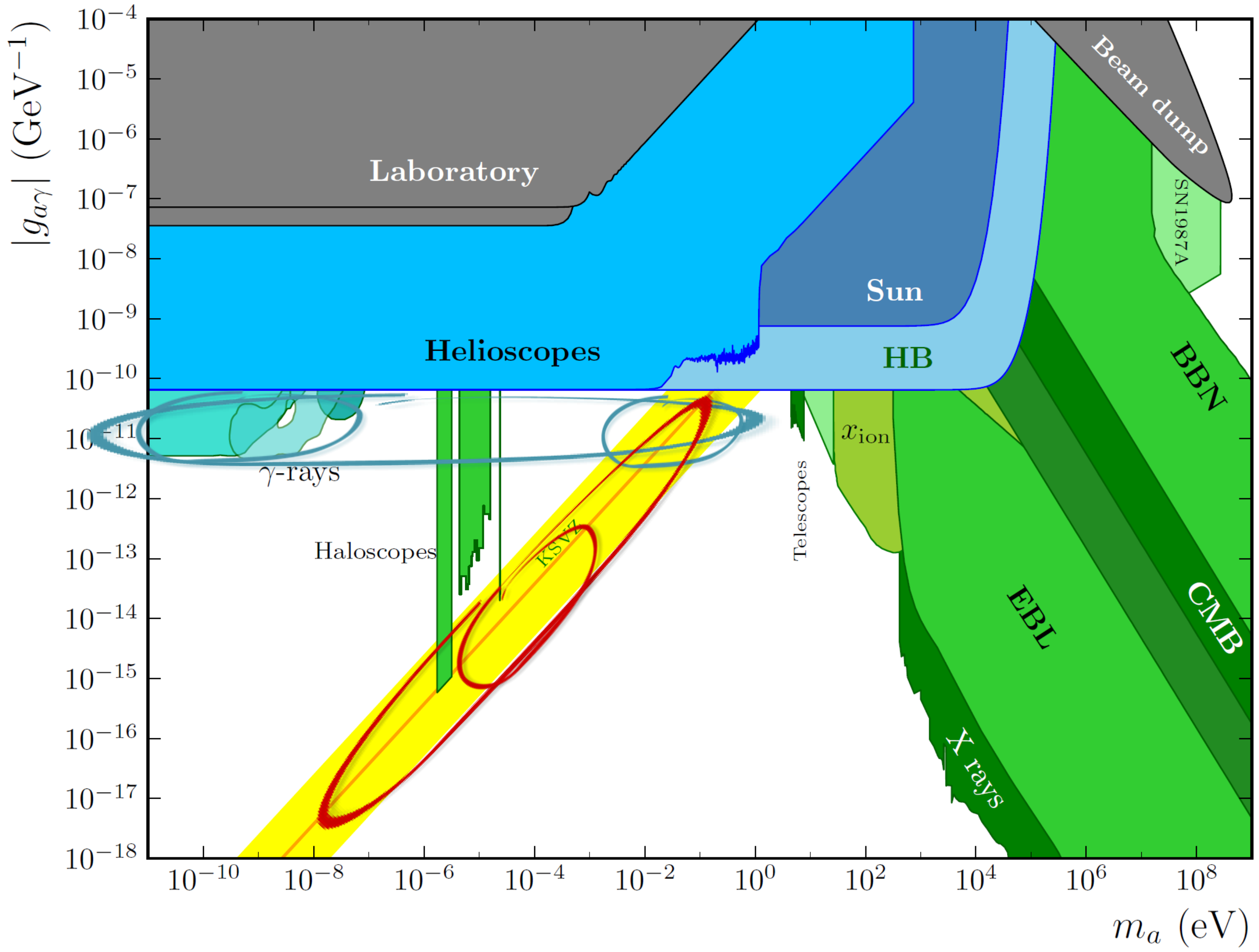
Axion/ALP searches motivation

"Focuses of interest" in the ALP parameter space

Theory

Astrophysics

Cosmology

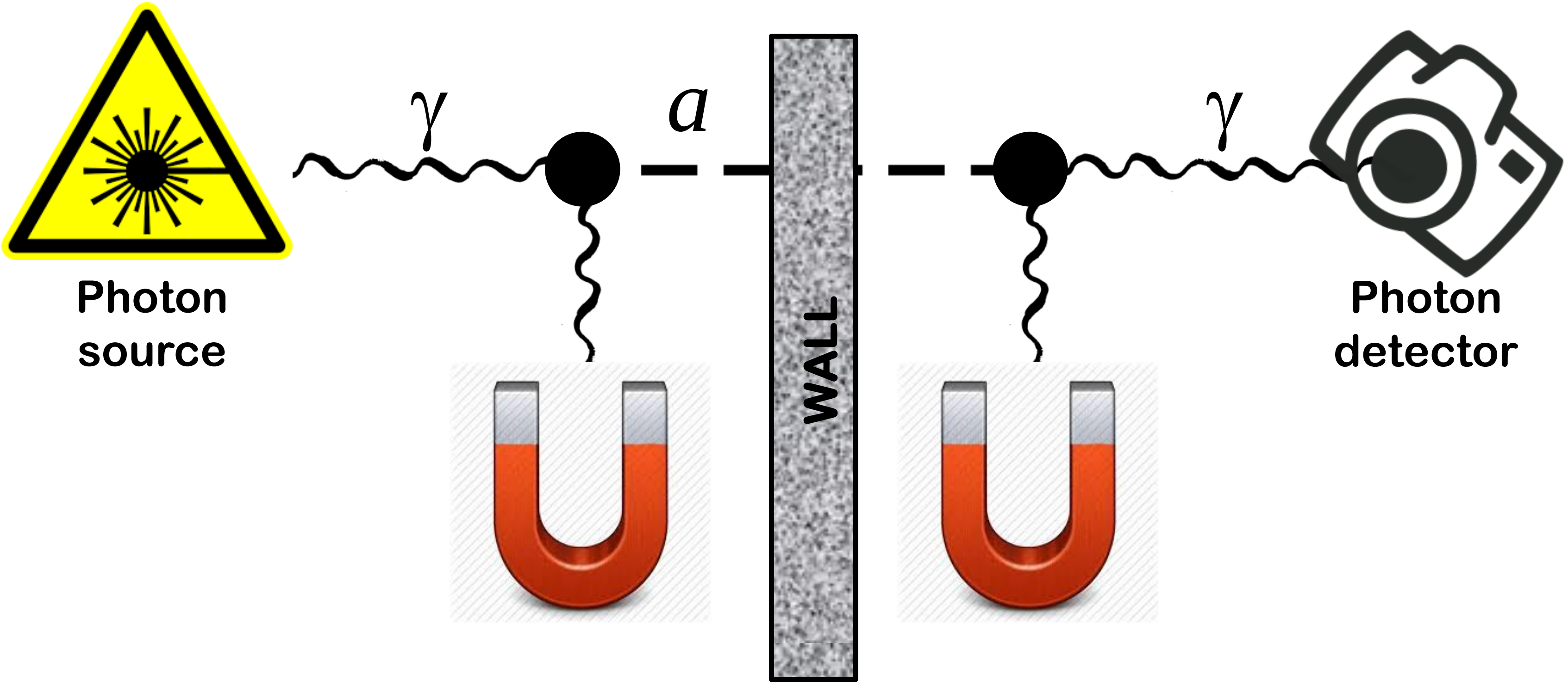


Detection of axions

Large complementarity among categories

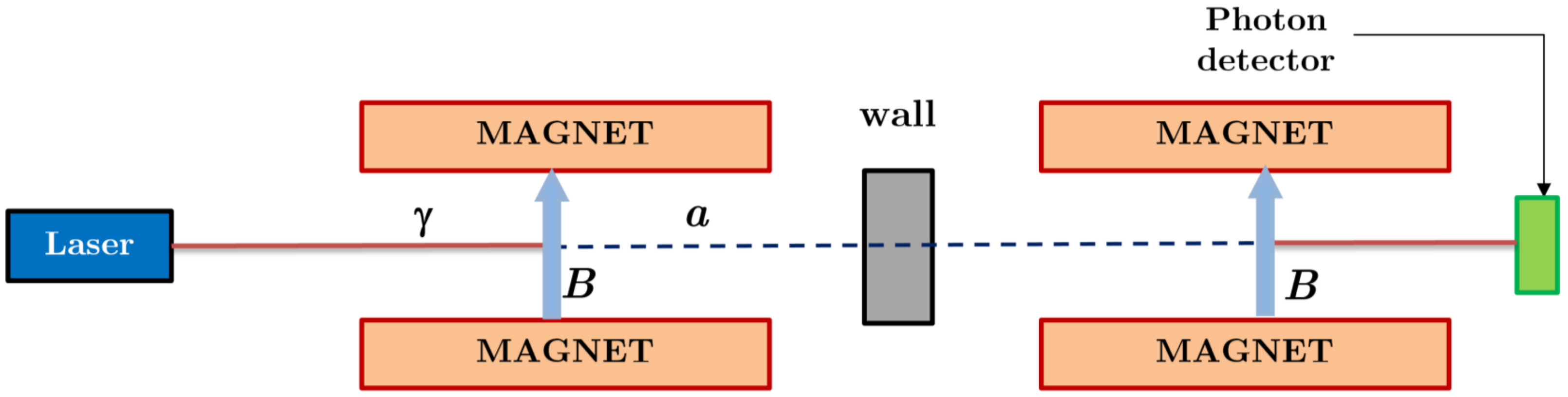
Source	Experiments	Model & Cosmology dependency	Technology
Relic axions 	ADMX, HAYSTAC, CAPP, MADMAX, BRASS, ORGAN, RADES, QUAX, CASPEr, SHAFT, ABRA, DM-Radio, …	High	New ideas emerging, Active R&D going on,…
Lab axions 	ALPS, JURA, OSQAR, PVLAS, ARIADNE,…	Very low	Ready for large scale experiment
Solar axions 	SUMICO, CAST, (Baby)IAXO	Low	Ready for large scale experiment

Laboratory axions

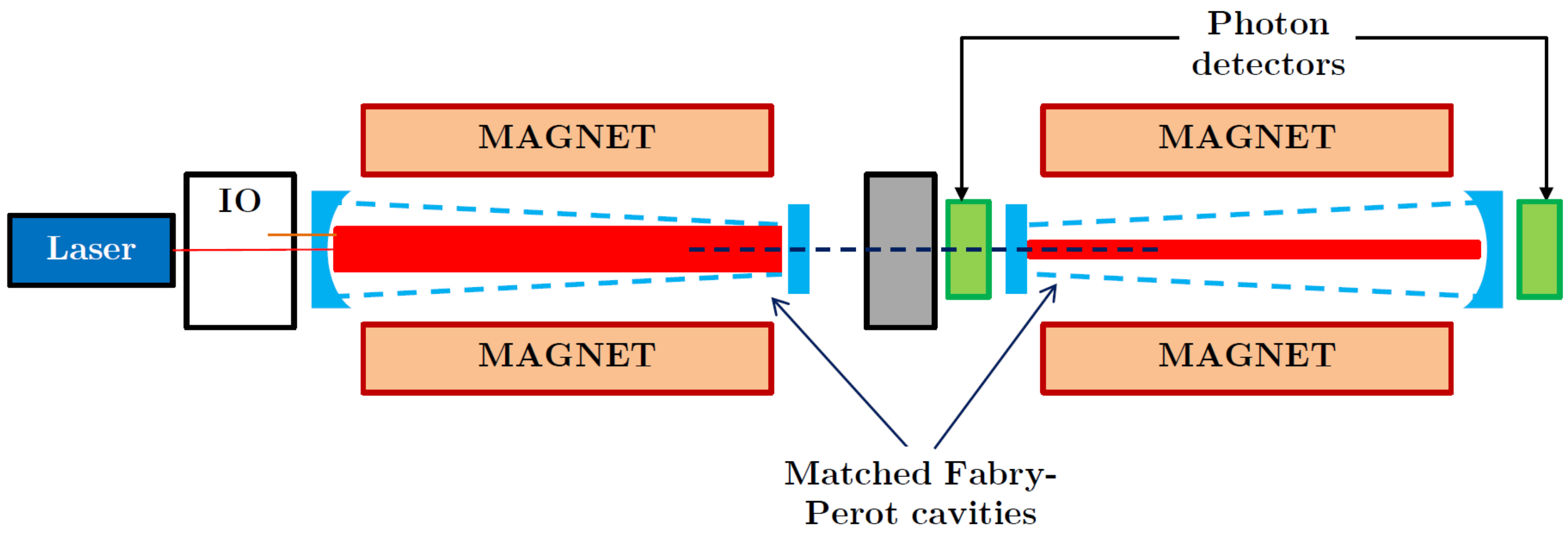


Light-shining-through-wall (LSW)

Standard configuration →



Enhanced “resonant” configuration (future) →

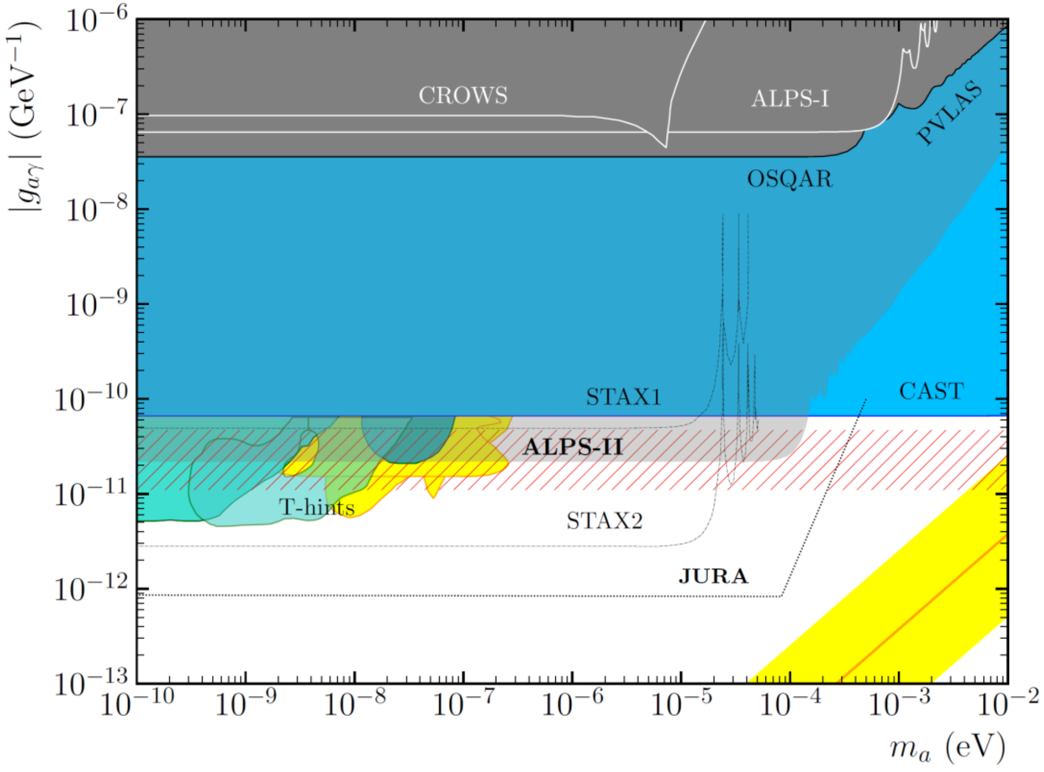


ALPS experiment

Any Light Particle Search @ DESY: ALPS I concluded in 2010

ALP II under construction (resonant, 10+10 magnets,…)

parameter	scaling	ALPS I	ALPS IIc	sens. gain
BL (total)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
PC built up ($P_{\text{laser,eff.}}$)	$g_{a\gamma} \propto \beta_{\text{PC}}^{-1/4}$	1 (kW)	150 (kW)	3.5
rel. photon flux $\dot{n}_{\text{prod}}$	$g_{a\gamma} \propto \dot{n}_{\text{prod}}^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
RC built up β_{RC}	$g_{a\gamma} \propto \beta_{\text{RC}}^{-1/4}$	1	40,000	14
detector eff. DE	$g_{a\gamma} \propto DE^{-1/4}$	0.9	0.75	0.96
detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	$1.8 \cdot 10^{-3}\,\text{s}^{-1}$	$10^{-6}\,\text{s}^{-1}$	2.6
combined				3082



Also: OSQAR@CERN, CROWS@CERN, GammeV & REAPR @ Fermilab, US, BMV @ Toulouse,…

also polarization experiments: PVLAS @ Ferrara, …

Future: VMB@CERN

Possible future extrapolation: JURA (& also STAX with MW)

Axion-mediated macroscopic forces

Axions could be detected as short-range deviation of gravity…

(but traditionally though without enough sensitivity to QCD axions)

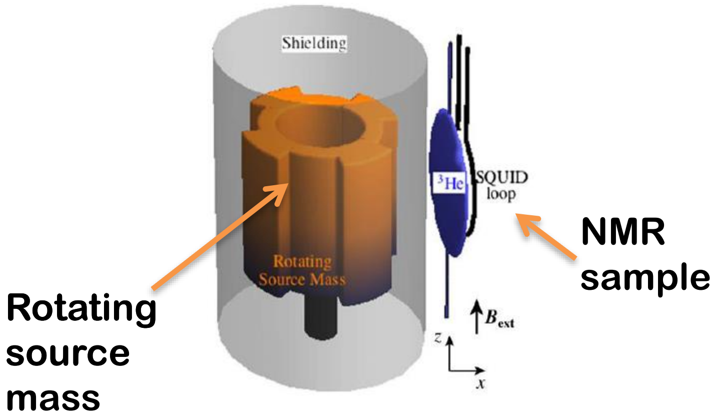
Recently proposed: ARIADNE experiment

Short-range force by NMR technique

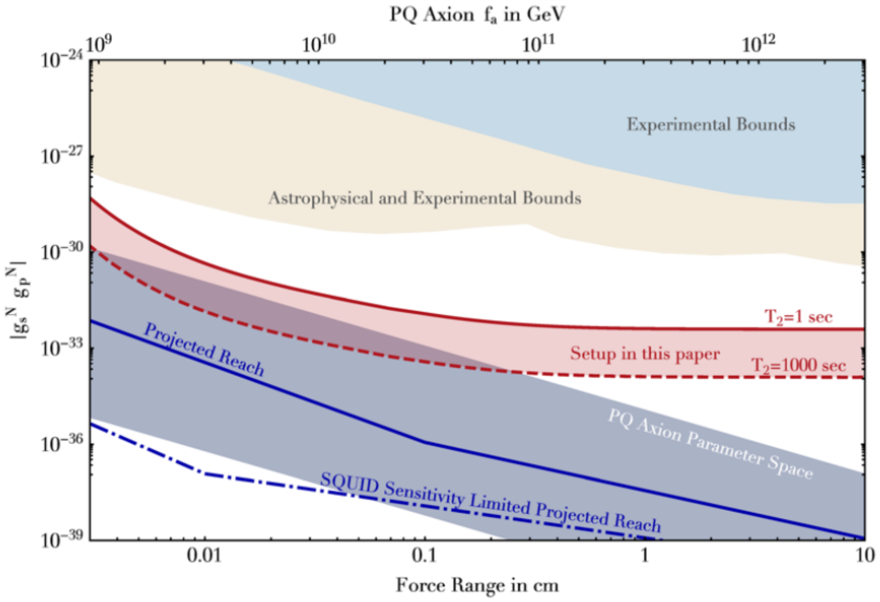
Sensitive to (products of) fermion couplings

Good prospects for sub-meV axion

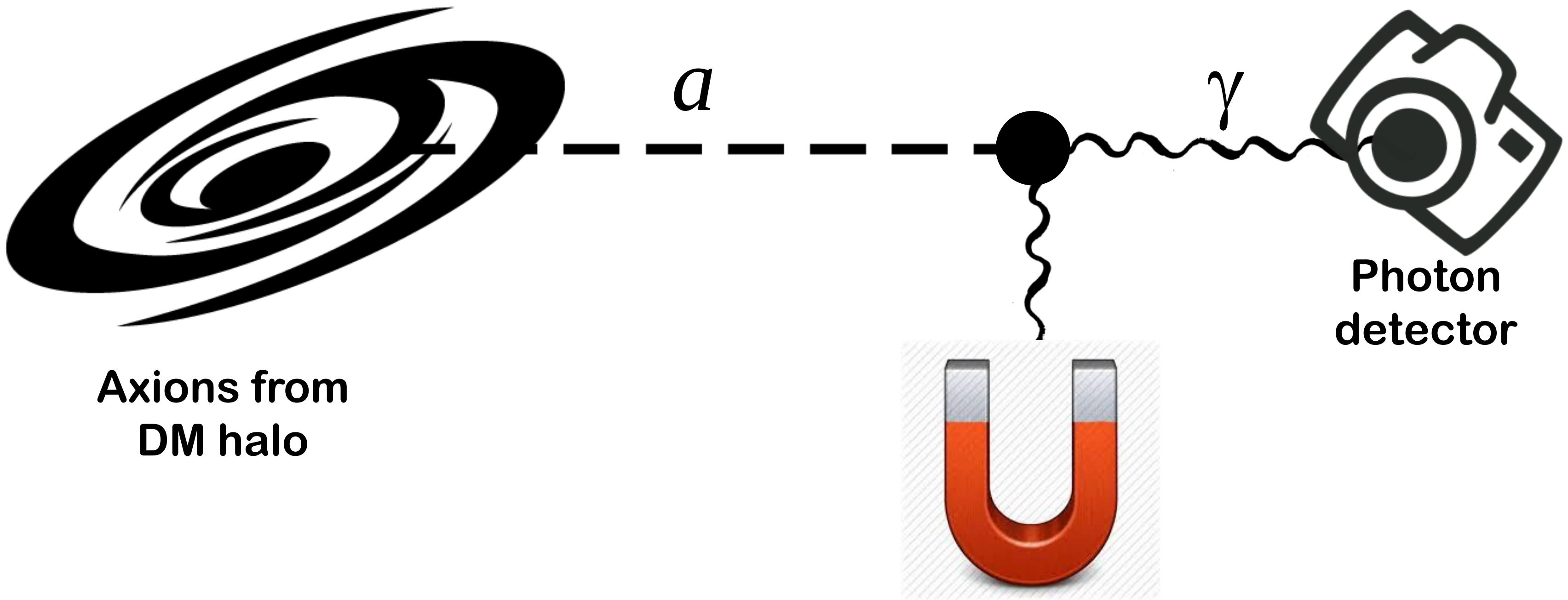
(assuming CP-violating effects not far from current bound on θ)



Arvanitaki, Geraci
Phys. Rev. Lett. 113, 161801 (2014)



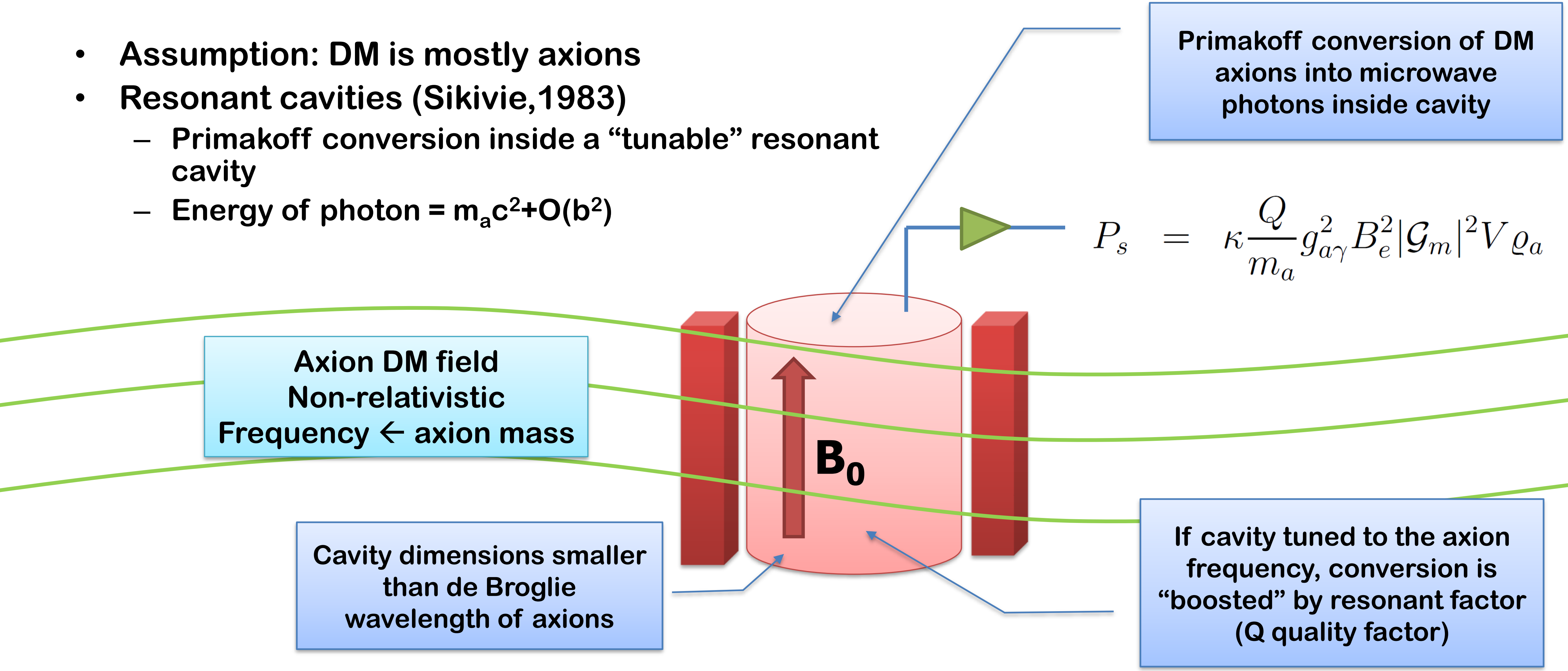
Dark matter axions



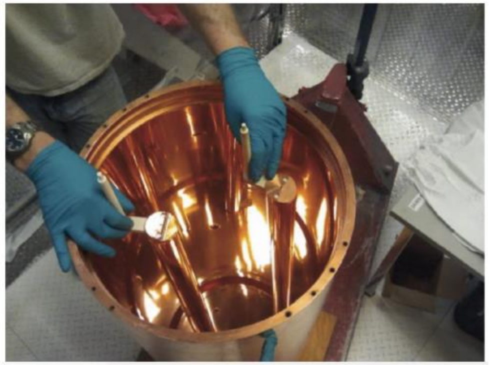
Detecting DM axions: “haloscopes”

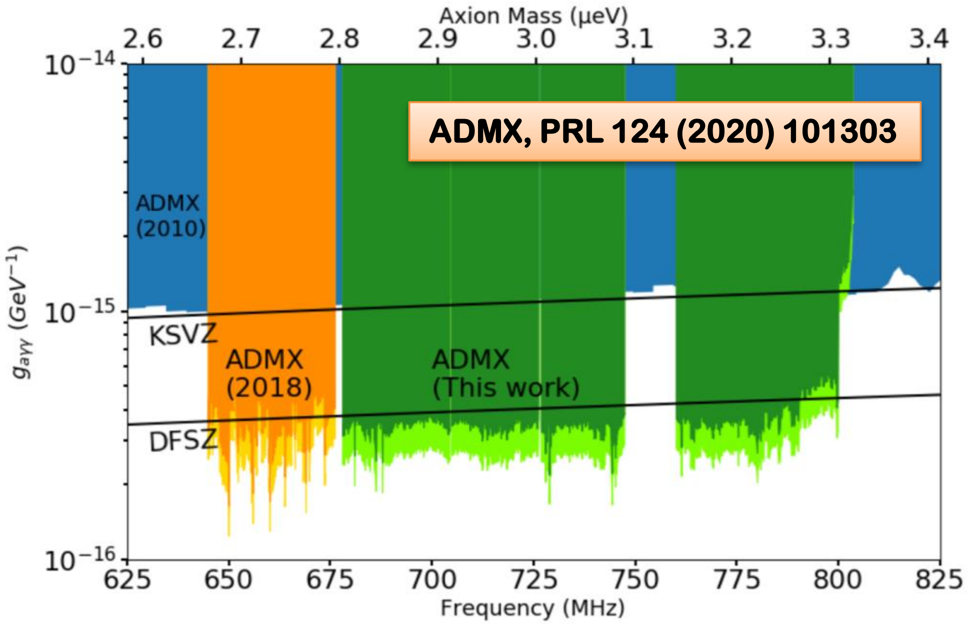
- Assumption: DM is mostly axions
- Resonant cavities (Sikivie,1983)
  - Primakoff conversion inside a “tunable” resonant cavity
  - Energy of photon = $m_a c^2 + O(b^2)$

$$P_s = \kappa \frac{Q}{m_a} g_{a\gamma}^2 B_e^2 |\mathcal{G}_m|^2 V \varrho_a$$

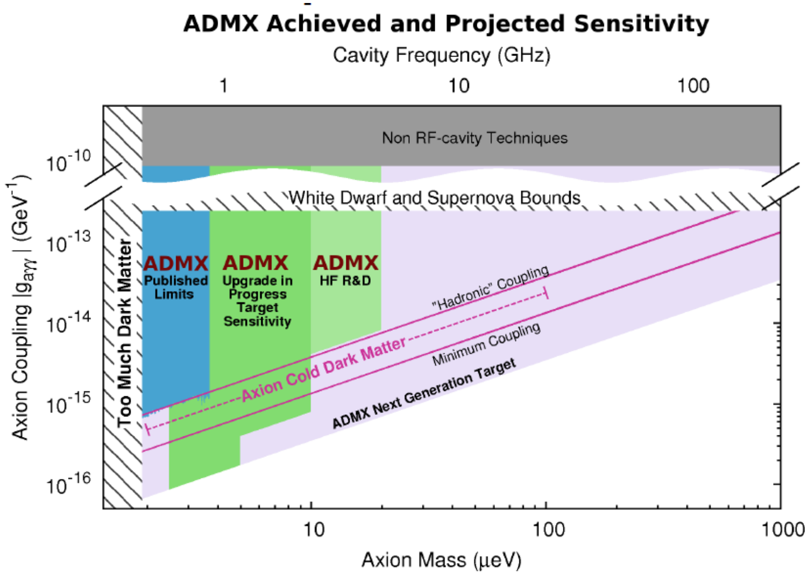


ADMX





- Leading haloscope
  - Many years of R&D
  - First results >10 years ago.
- Sensitivity to **few μeV** proven
- Now producing new results:
  - First data down to DFSZ coupling (2.7 to 3.3 μeV)…



- Current program will surely cover 1-10 μeV with high sensitivity (i.e. reaching even pessimistic coupling).
- What about higher masses?

Higher-m_a haloscopes

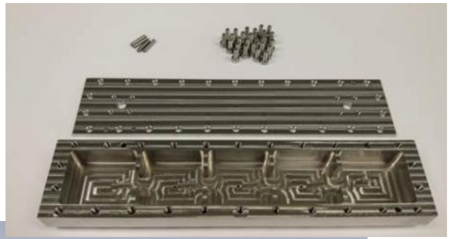
- **Problematic:**

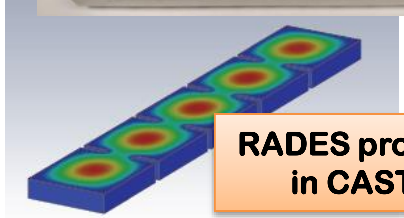
higher m_a → lower V → lower sensitivity

$$F \sim \varrho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{sys}^{-2} |\mathcal{G}|^4 Q$$

- **R&D to go to:**
  - Higher B magnets
  - Larger instrumented volumes
  - Lower noise sensors
  - Higher Q cavities

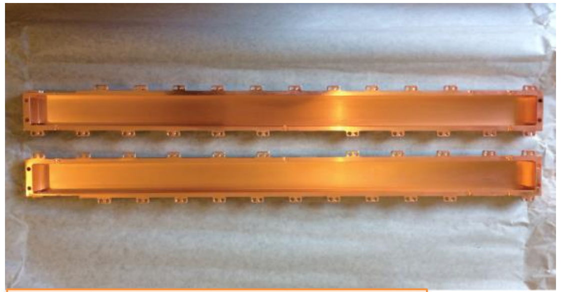
Very active R&D in many groups!





RADES project in CAST

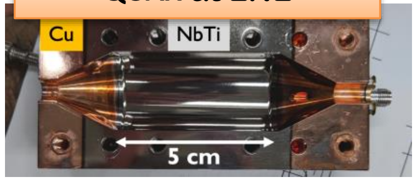
- More powerful magnets
- Multicell structures:
  - Phase-matched
  - Filter-like
  - Dielectric loading
  - Photonic bandgap
  - …

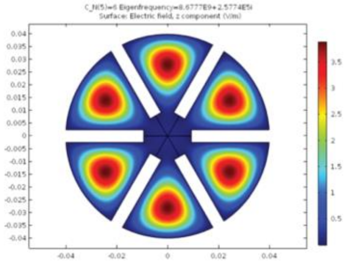


CAST-CAPP project In the CAST magnet

- SC deposited cavities

QUAX at LNL





"Pizza cavity" at CAPP → 2008.10141

Higher-m_a haloscopes

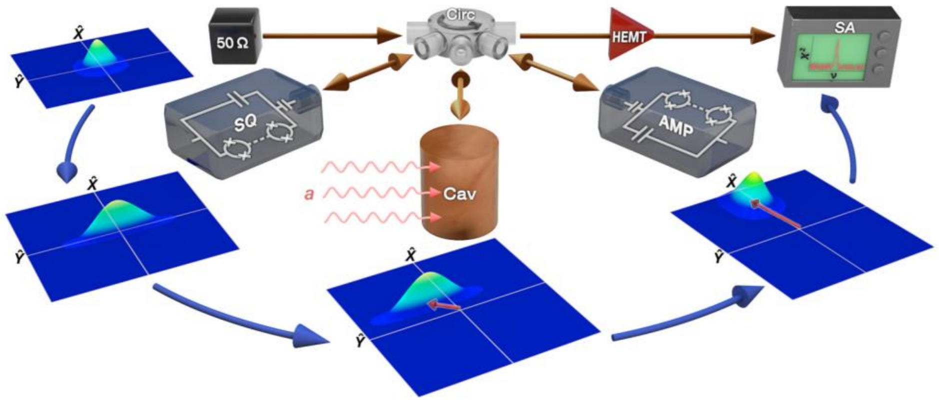
- **Problematic:**

higher m_a → lower V → lower sensitivity

$$F \sim \varrho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{sys}^{-2} |\mathcal{G}|^4 Q$$

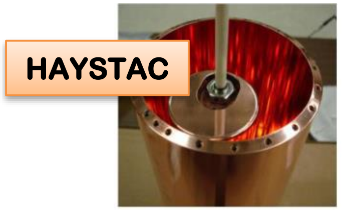
- **R&D to go to:**
  - Higher B magnets
  - Larger instrumented volumes
  - Lower noise sensors
  - Higher Q cavities

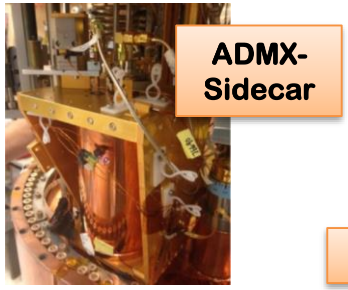
- Squeezed state to reduce noise beyond quantum limit
- Quantum information technologies for axion search
- First experimental application HAYSTAC 2008.01853:
  - factor x2 effective faster scan rate
  - 17.14-17.28 μeV scanned down to 1.38 x $g_{a\gamma}^{KSVZ}$

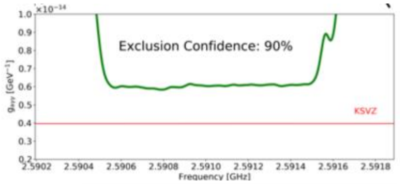


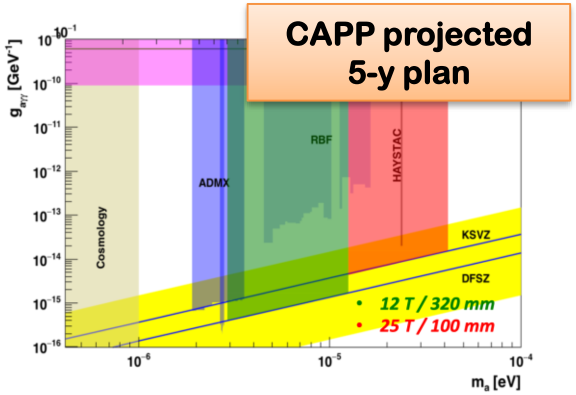
Higher-m_a haloscopes

- HAYSTAC @ Yale: started as ADMX test bed for new ideas.
  - First results released in 2018 (1803.03690)
  - Very recent: first result with squeeze states very recent (2008.01853)
- CAPP: recently created "Center for Axion and Precision Physics" at South Korea
  - Recent first results released CAPP-PACE
  - Also multicell setup (pizza cavity)
  - + a lot of R&D lines
- ADMX-Sidecar: small demonstrator adjacent to main ADMX (PRL121)
- Many other projects exploring new cavity designs:
  - QUAX @ LNL: SC coated cavity. Also setups sensitivity to g_{ae} coupling
  - RADES & CAST-CAPP @ CERN
  - Also ORGAN in Australia

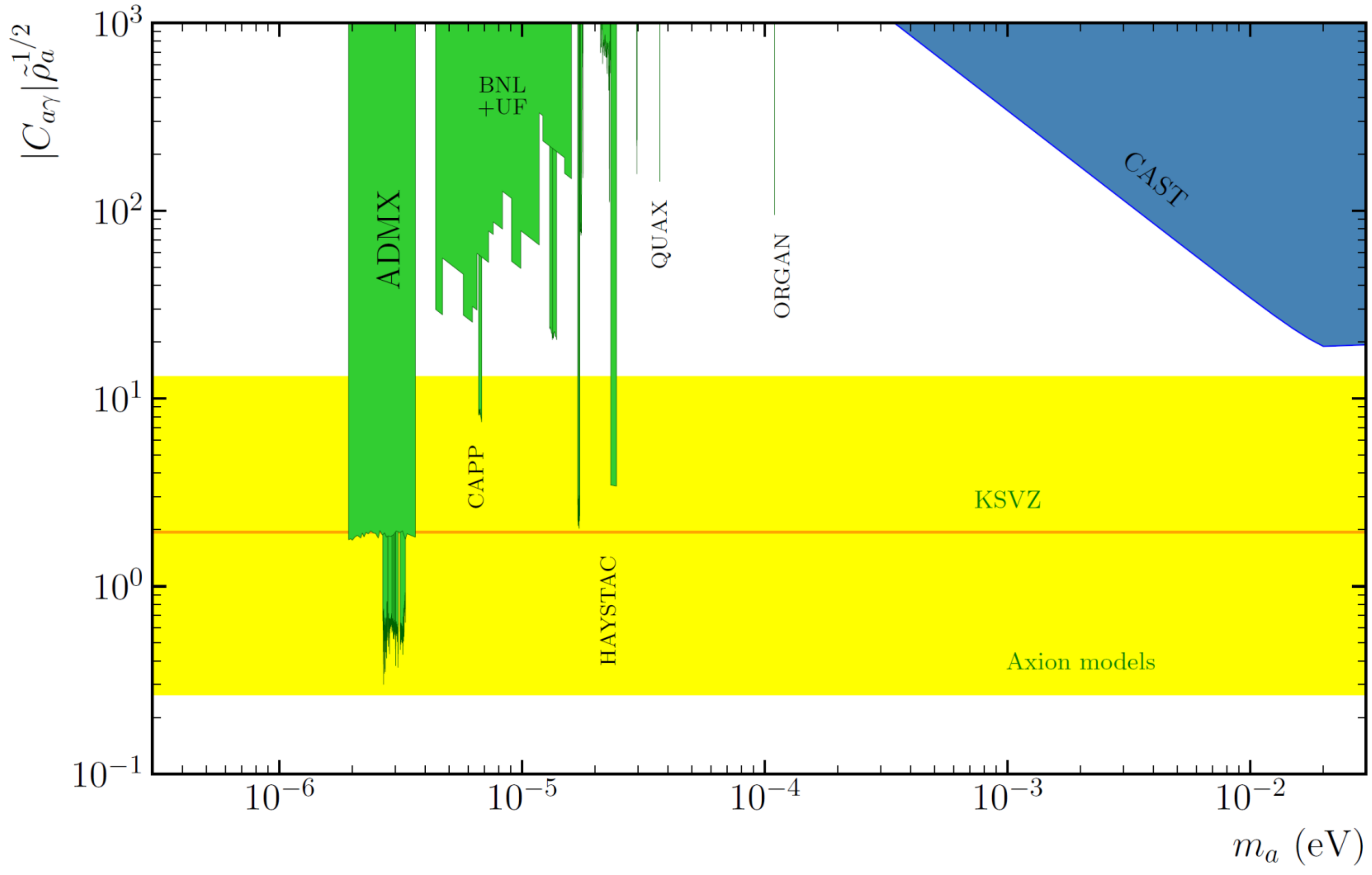








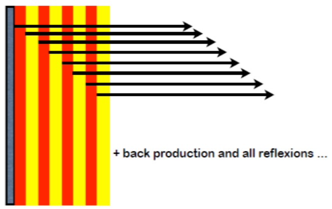
Haloscopes - current results

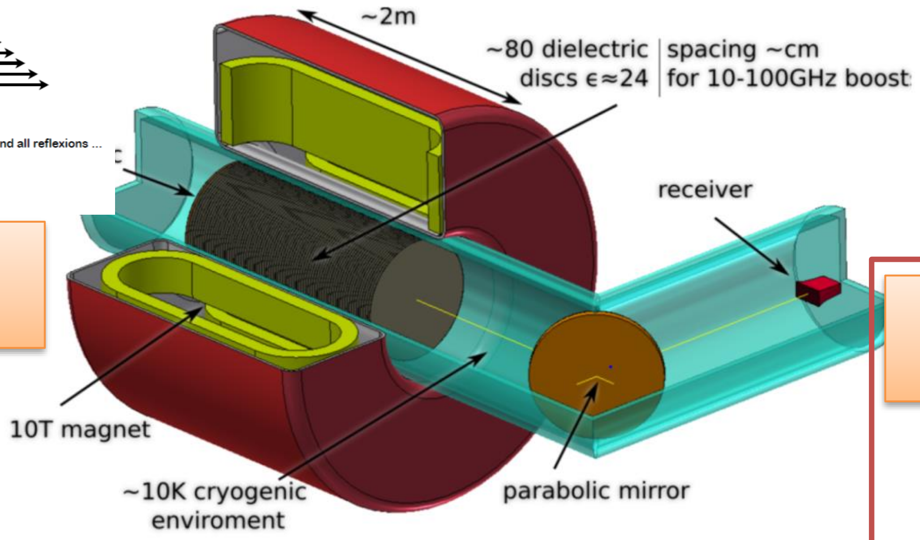


Beyond haloscopes…
Dish antennas & dielectric haloscopes

- **Dish antennas:**

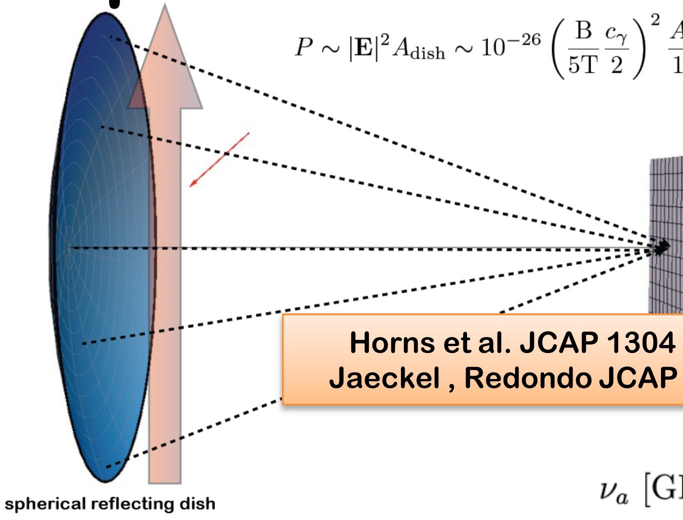
  No resonance, but large area possible…
- **Realistic sensitivity limited, but boost possible with dielectric multilayer**





MADMAX dielectric haloscope

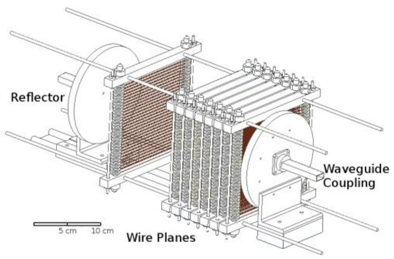
$$P \sim |\mathbf{E}|^2 A_{\rm dish} \sim 10^{-26} \left(\frac{\rm B}{5\rm T}\frac{c_\gamma}{2}\right)^2 \frac{A_{\rm dish}}{1\,\rm m^2}\,\rm Watt$$

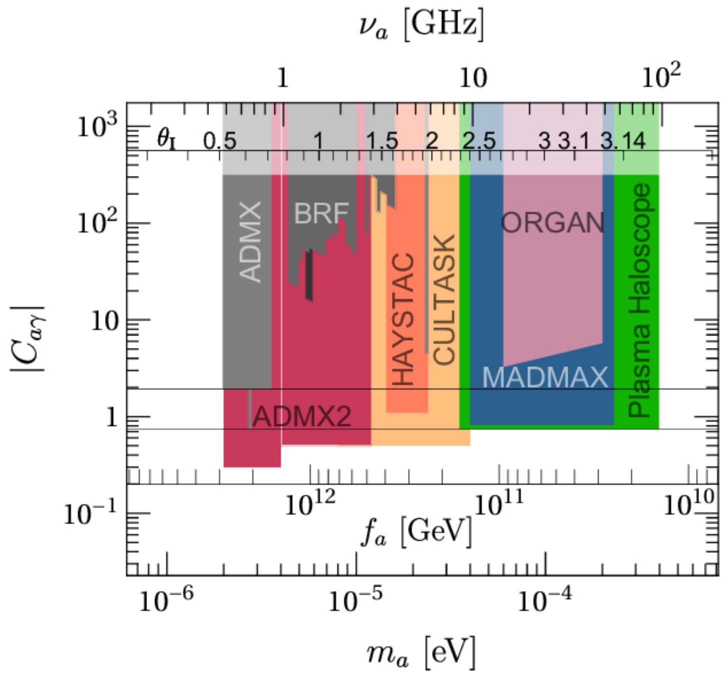


BRASS @ Hamburg

Horns et al. JCAP 1304 (2013) 016
Jaeckel , Redondo JCAP 1311 (2013)

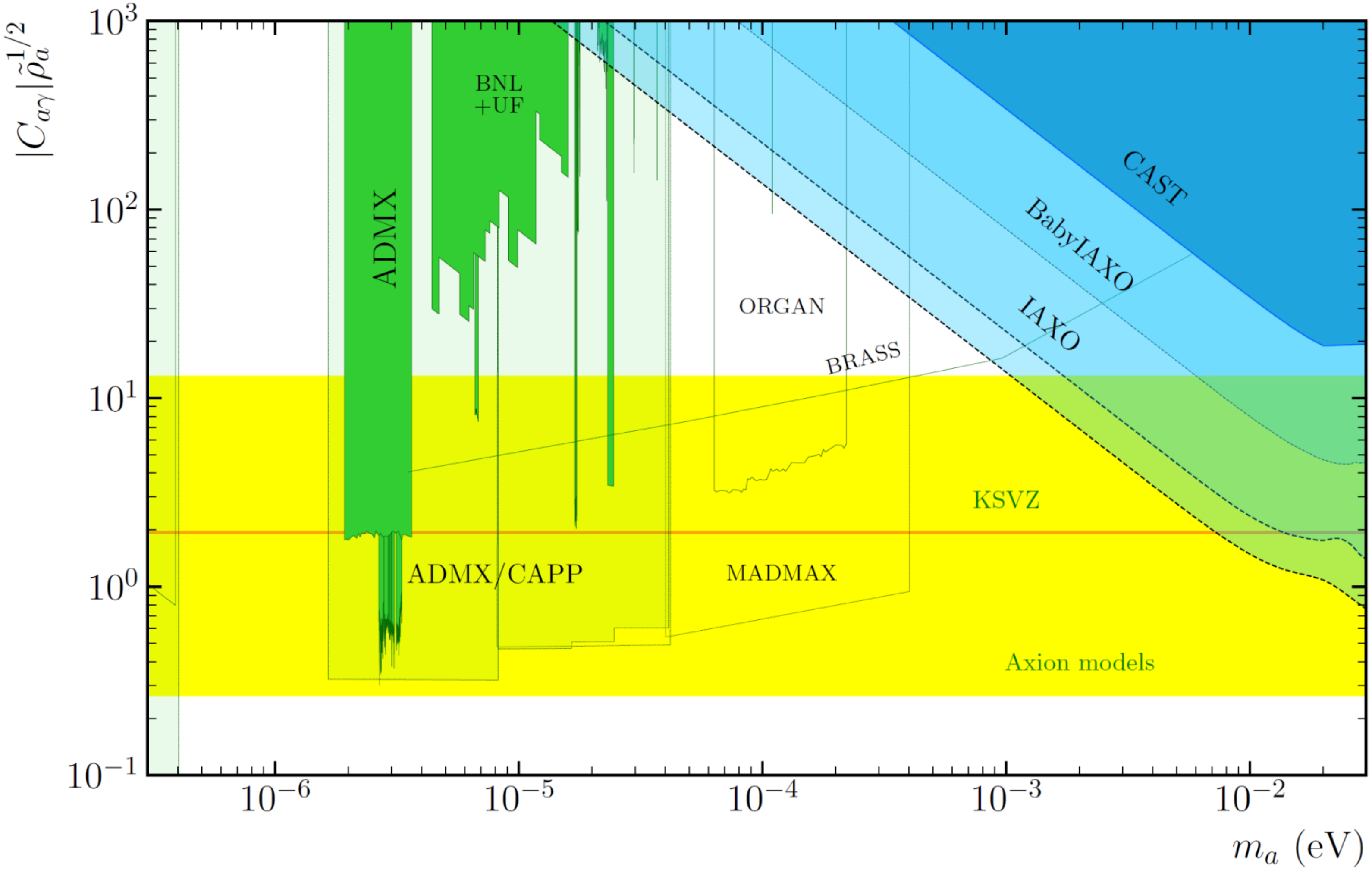
Similar high-m_a structures: ORPHEUS and Electric-Tiger in US





- **Even newer ideas:**
  - DM-induced atomic transitions (AXIOMA)
  - dielectric haloscope at visible λ (PRD98 (2018))
  - plasmas haloscopes… (arXiv:1904.11872)

Haloscopes – future prospects

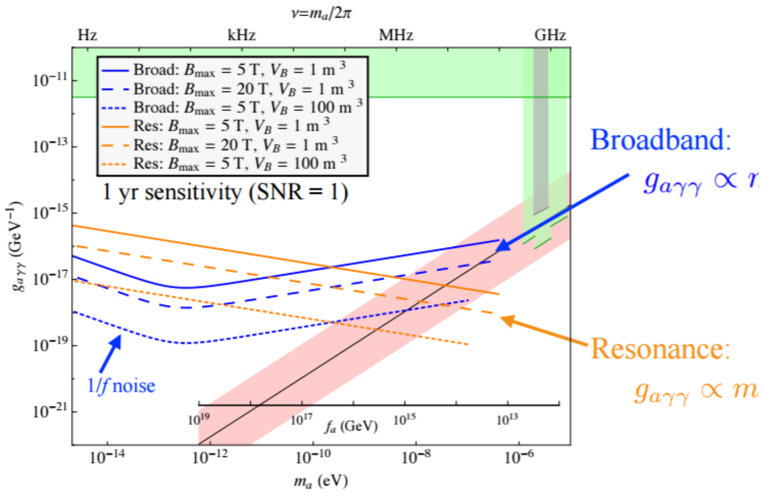


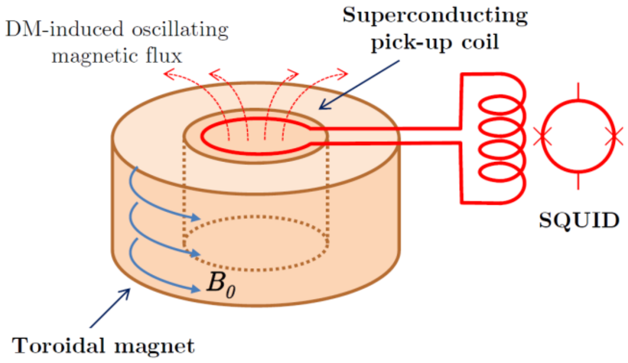
Towards lower m_a

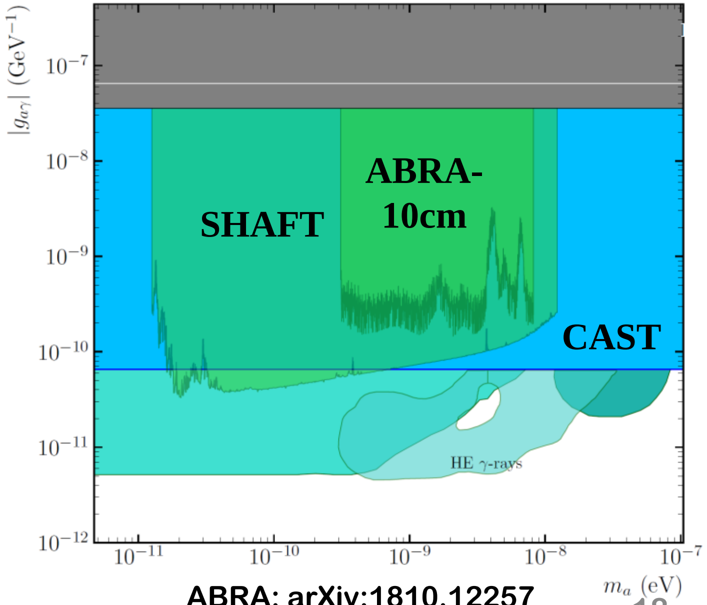
KLASH proposal: use of 50 m^3, 0.6T, KLOE magnet at LNF

- **Large V haloscopes** are technologically simpler, but expensive → huge magnet needed. Use of existing magnets could be an effective strategy

- **Pick-up coil & resonant circuits** → ABRACADABRA @ MIT, SHAFT @ Boston, DM-RADIO @ Stanford prototypes R&D ongoing



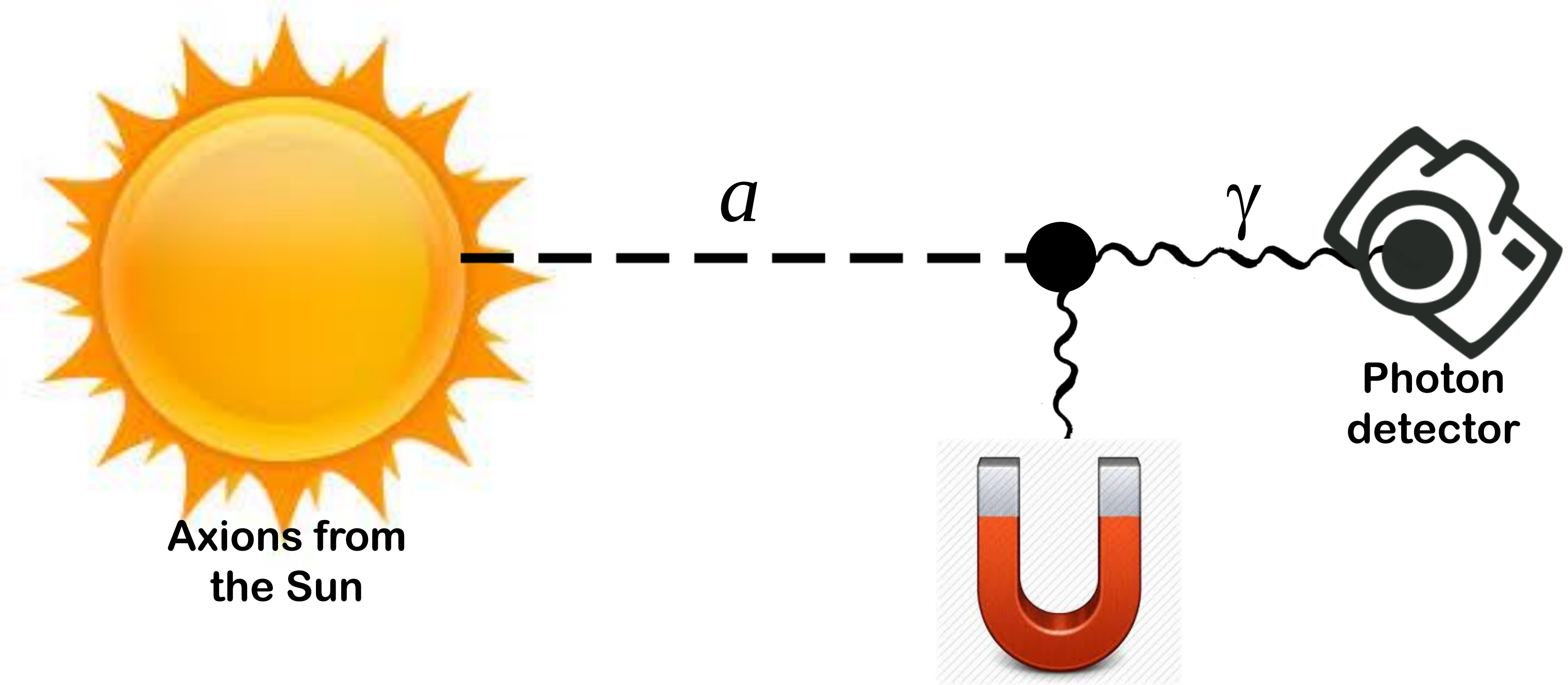




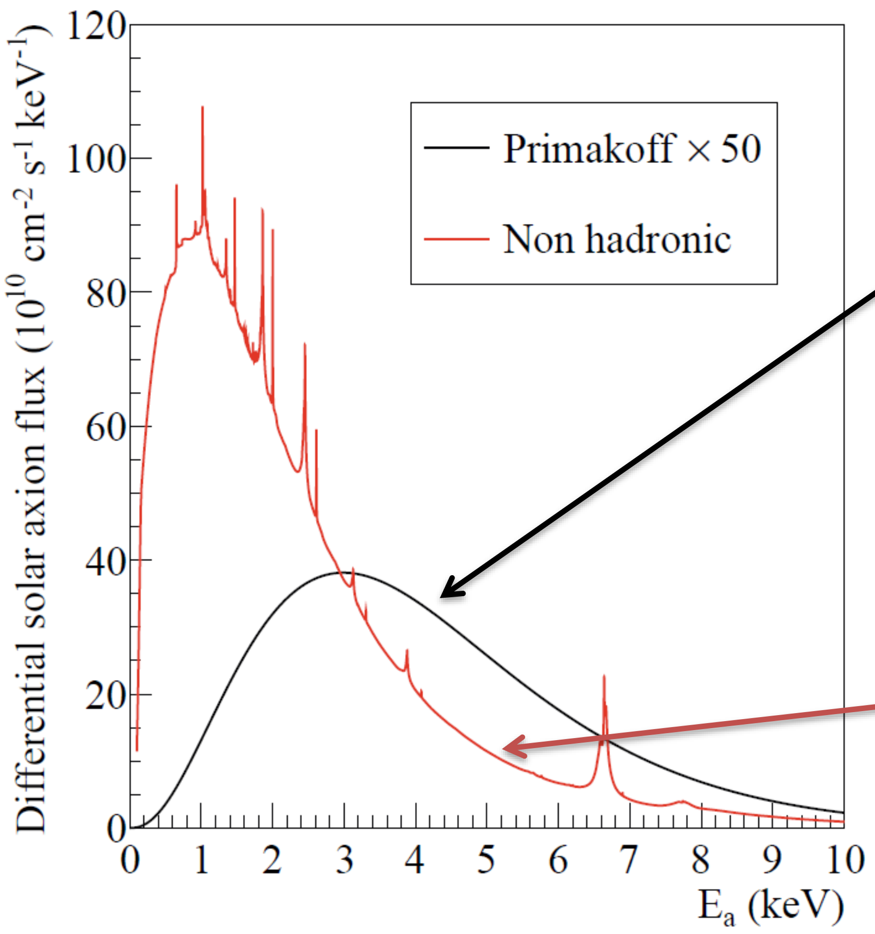
ABRA: arXiv:1810.12257
SHAFT:arXiv:2003.03348

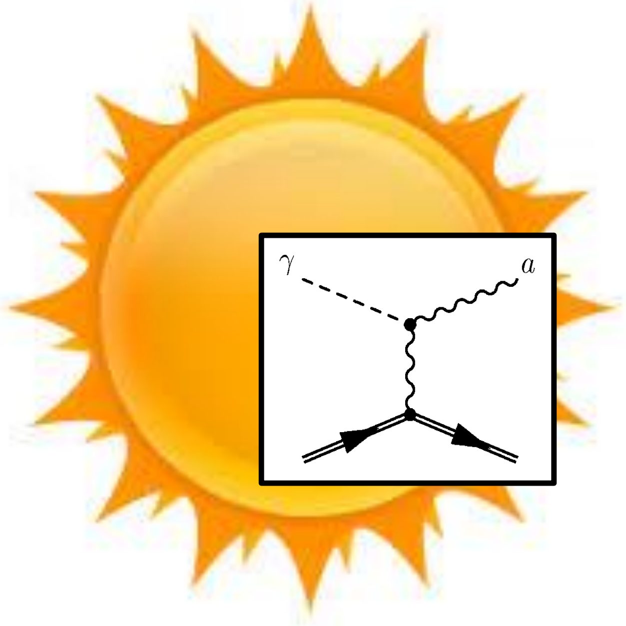
- DM-induced spin precession (NMR) → CASPER
  - Sensitive to gluon term & fermionic couplings

Solar axions



Solar Axions





Standard Primakoff spectrum

Robust prediction from axion models. Conversion of solar plasma fotons into axion (only axion-photon coupling involed)

van Bibber PRD 39 (89)
CAST JCAP 04(2007)010

Non-hadronic "ABC" Solar axion flux at Earth
(only if axion couples to electron)

Redondo, JCAP 1312 008

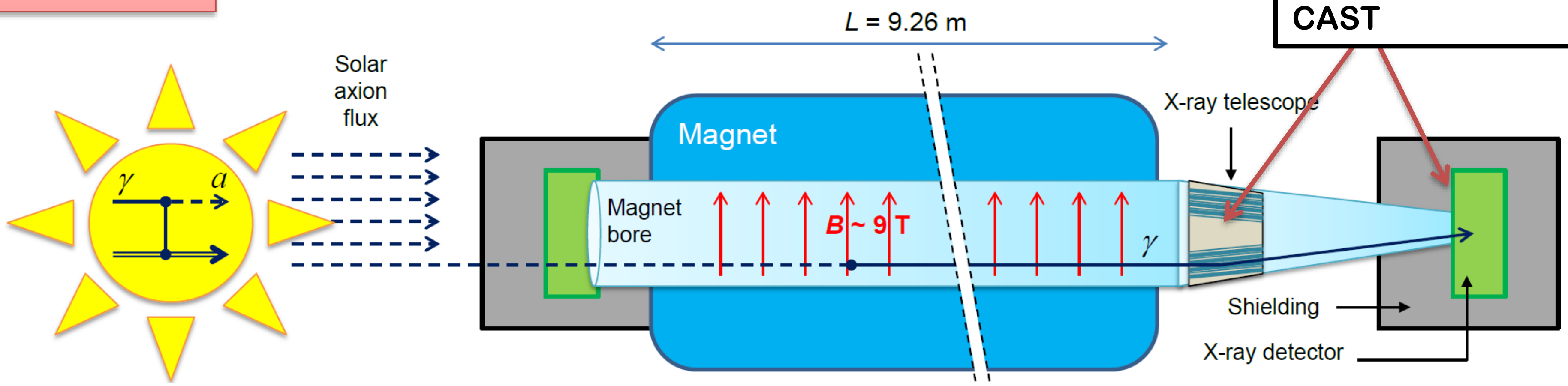
Axion helioscopes

Axion helioscope concept
P. Sikivie, 1983
+ K. van Bibber, G. Raffelt, et al. (1989)
(use of buffer gas)

Pioneer implementations of helioscope concept:
Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet

Current state-of-the-art: CERN Axion Solar Telescope (CAST)

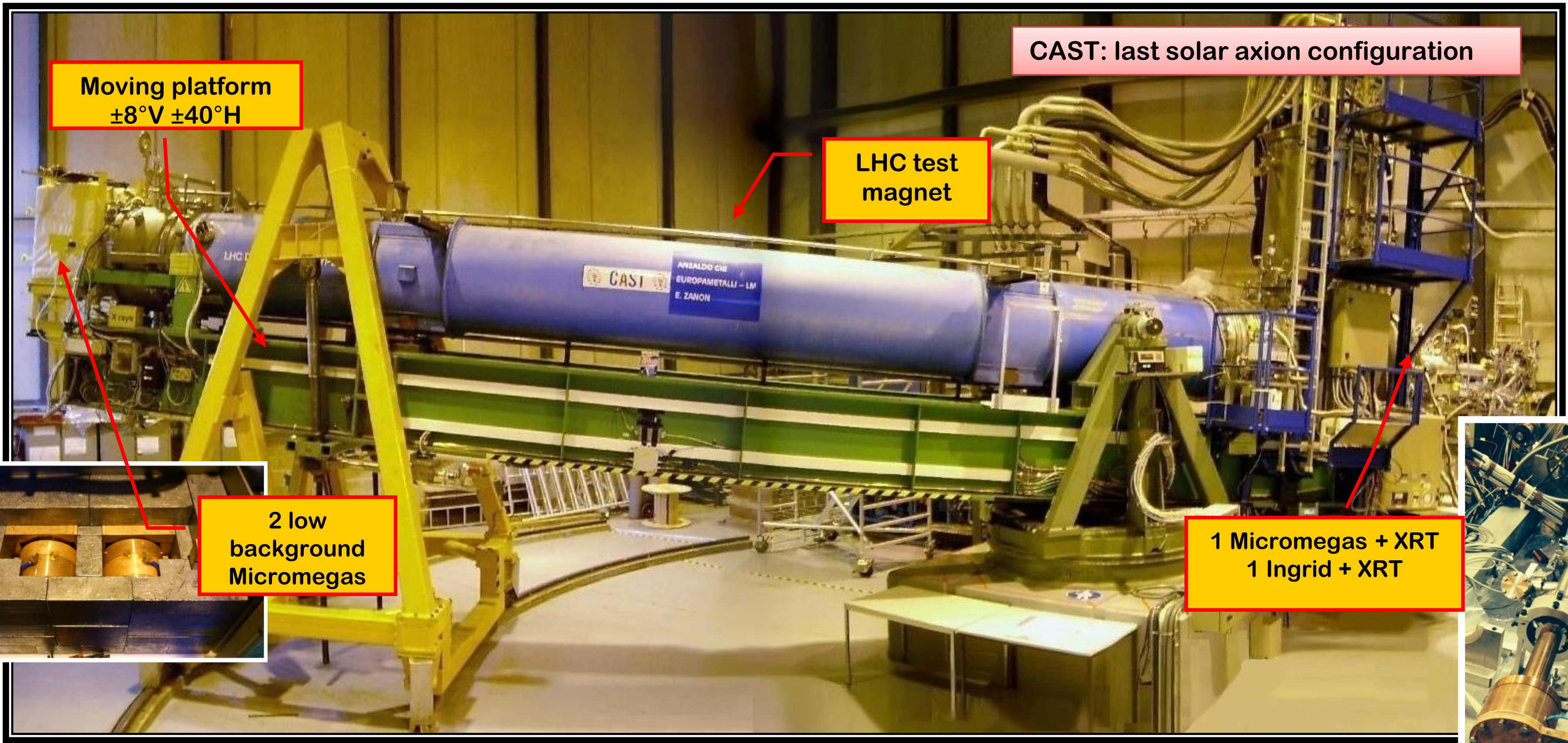
X-ray Focussing & low-background
Later innovations by CAST

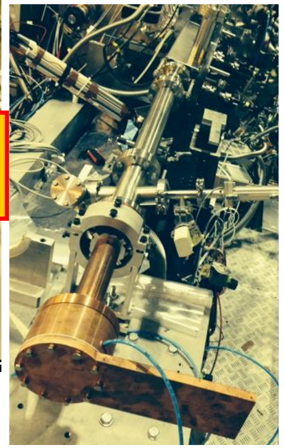


$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

CAST experiment @ CERN

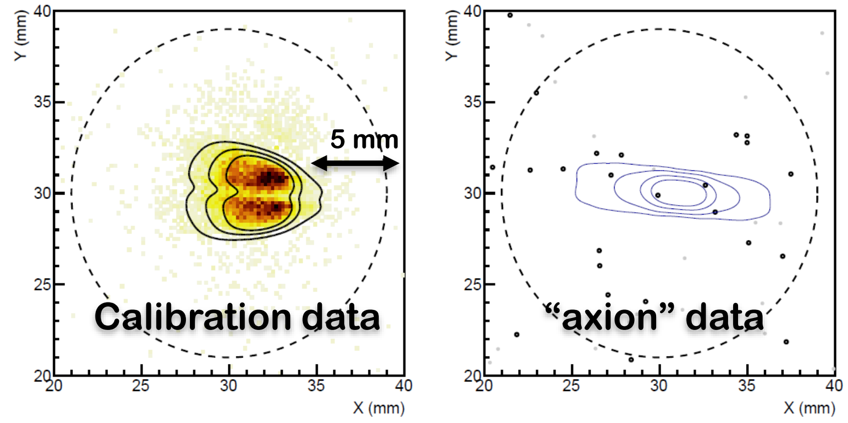
- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 3 X rays detector prototypes used.
- X ray Focusing System to increase signal/noise ratio.





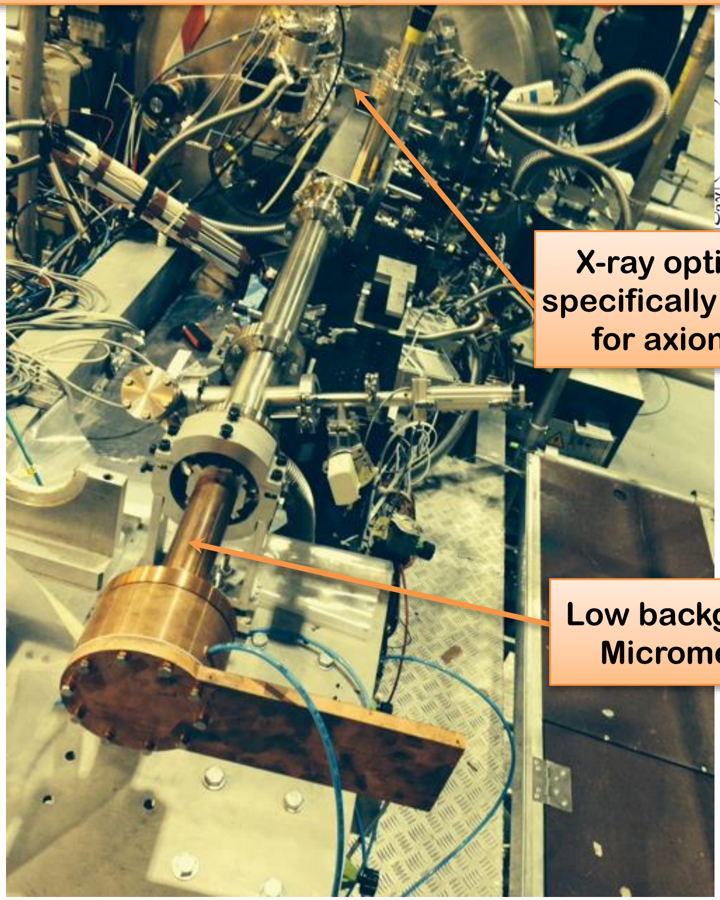
Latest CAST limit

Detector: JCAP12 (2015)
Physics: Nature Physics 13 (2017) 584-590



- Best SNR of any previous detector
- 290 tracking hour acquired (6.5 months operation)
- 3 counts observed in RoI (1 expected)

Enabled by the IAXO pathfinder system

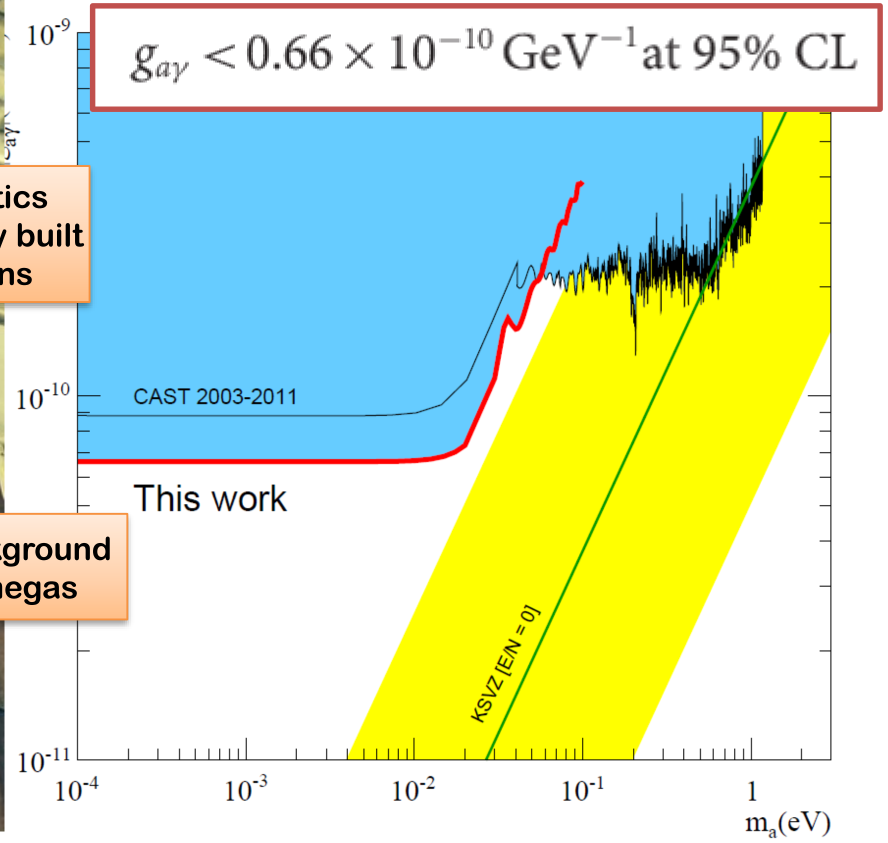



nature physics
ARTICLES
PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109
OPEN

New CAST limit on the axion–photon interaction

CAST Collaboration†

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such

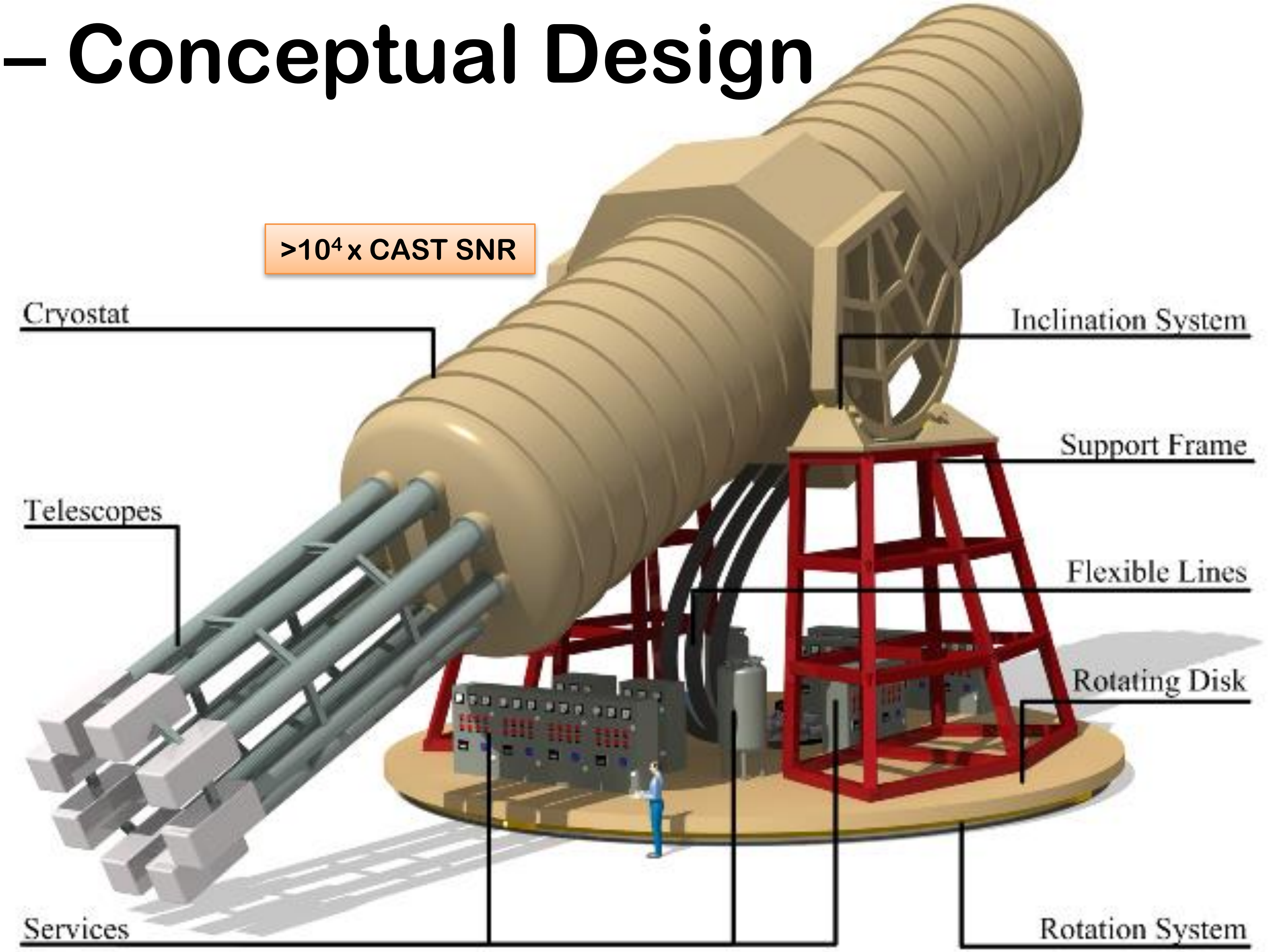


IAXO – Conceptual Design

- **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**

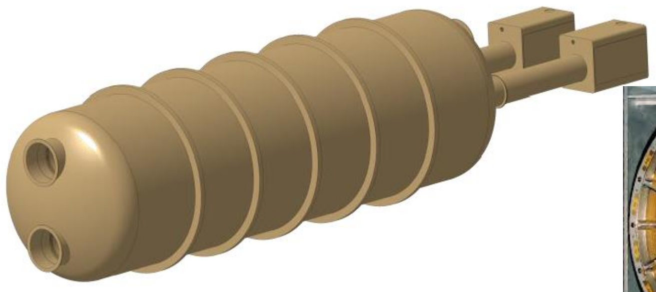
IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)

>10^4 x CAST SNR

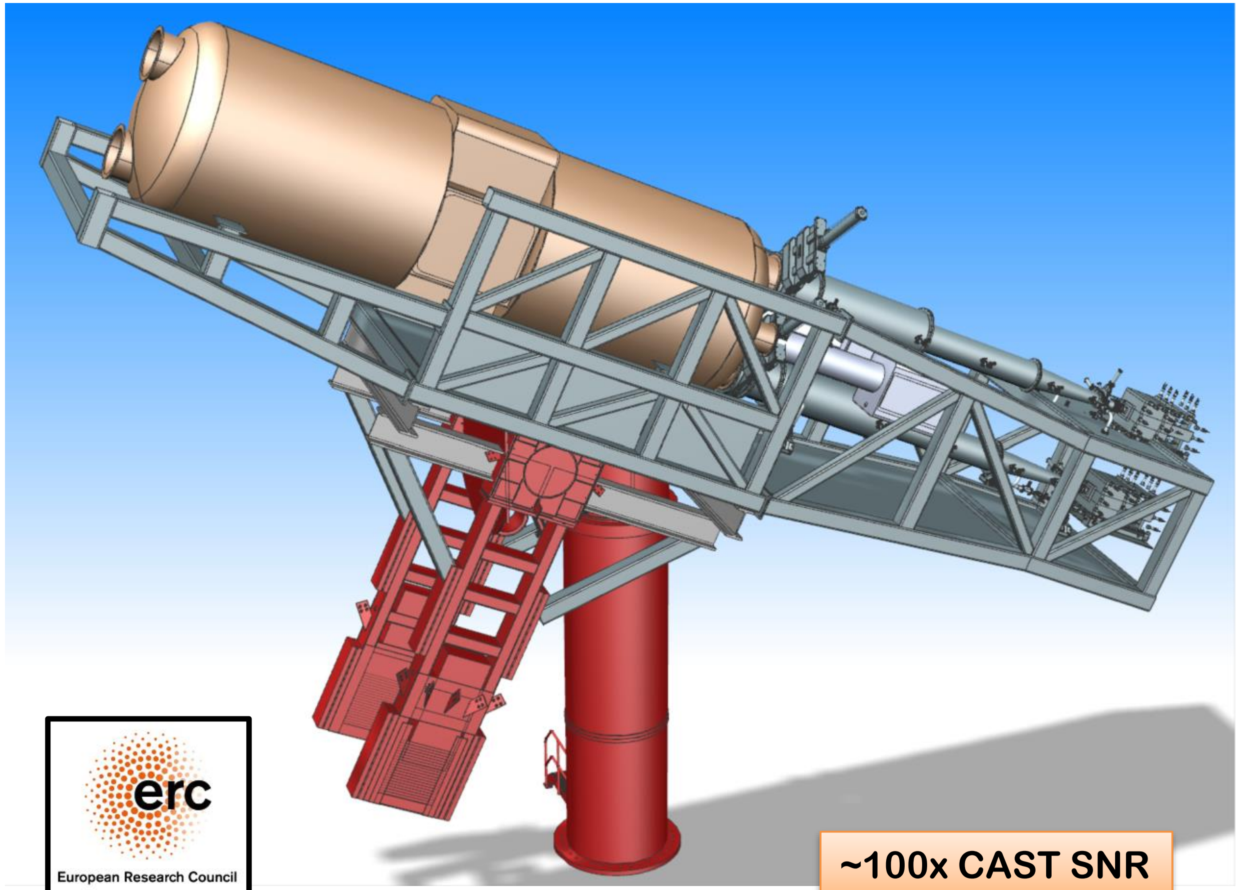


BabyIAXO

- Intermediate experimental stage before IAXO:
  - Prototype of final IAXO system
  - Relevant physics

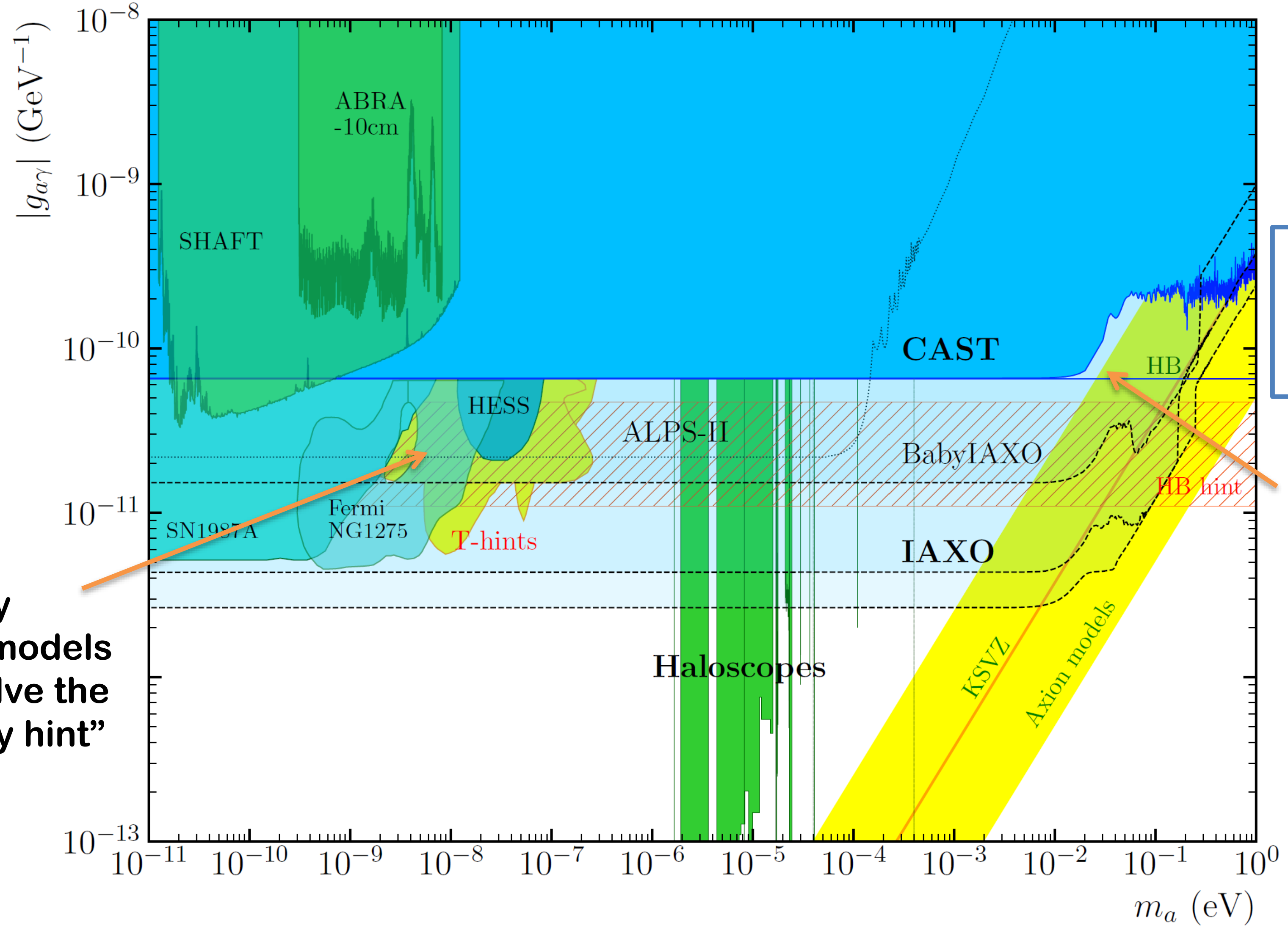


- Approved by DESY PRC last year.
- Rely on CERN magnet SC expertise & experience with CAST
- Commissioning expected by 2023



European Research Council
Established by the European Commission

Helioscopes & astrophysics



IAXO+: enhanced scenario with x10 (x4) higher FOM (MFOM) with respect to LoI

IAXO will fully explore ALP models invoked to solve the "transparency hint"

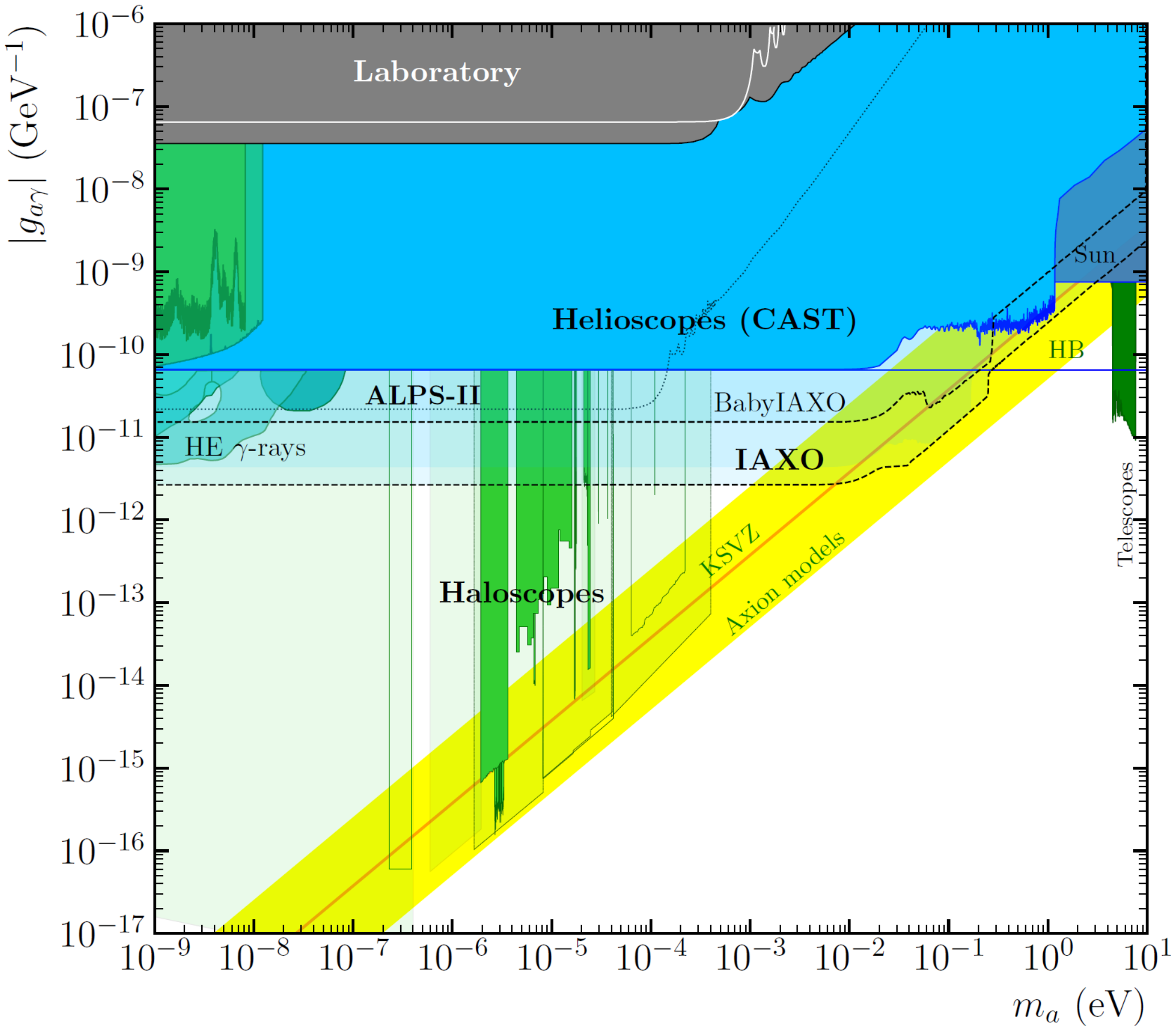
... as well as a large fraction of the axion & ALP models invoked in the "stellar cooling anomaly"

But for this the g_{ae} is particularly interesting (see backup slides)

MFOM = Magnet FOM

Overall picture (for $g_{a\gamma}$)

- Helioscopes (IAXO) will probe ALP models motivated by astrophysics
  - Haloscopes will soon probe 1-10 μeV QCD axions
    - Promising new haloscopes R&D to substantially expand explorable mass range



- Helioscopes (IAXO) will probe meV – eV QCD axion models
- … and most of the region hinted by stellar cooling

- In overall, a large fraction of the ALP parameter space may be explored in the future

Conclusions

- Experimental search for axions → attracting new interest
- Increasing efforts: experimental (& phenomenology/theory)
  - Singular combination of technologies: magnets, RF, x-ray astro, low noise, …
- Consolidation of classical detection lines: ADMX, CAST, ALPS,…
  - ADMX and CAST have firstly probed interesting (small) fraction of par space.
  - Helioscopes: next gen IAXO clear step ahead
  - Haloscopes: ADMX, CAPP + vigorous multiple R&D approach
- New ideas to tackle new regions
  - Dielectric haloscopes (MADMAX), "DM-radios", NMR…
- Large fraction of parameter space at reach of near-future experiments
  - chances of discovery!

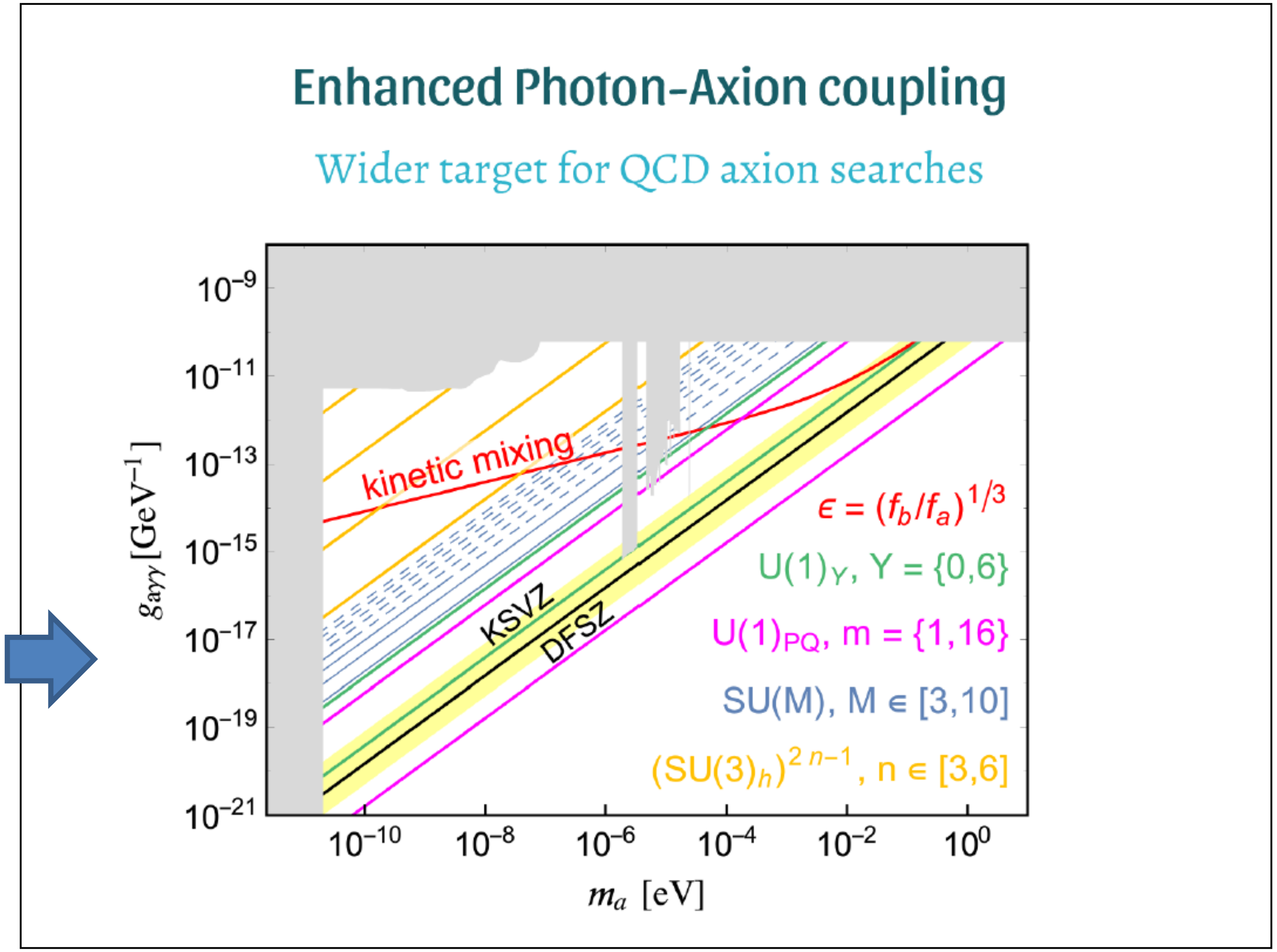
Good times for axions… stay tuned

Backup slides

Axion models

- Conventional QCD axion models lie on the "yellow band"
  - KSVZ, DSFZ benchmarks
- Outside the band typically ALPs

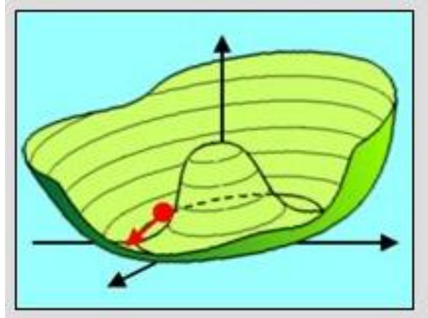
- **BUT** a lot of "model building" activity in recent years, leading to QCD axion models outside the conventional band…
  - Normally populating higher $g_{a\gamma}$.
  - Very interesting for experiments!



P. Agrawal, ESPP 2019 Granada

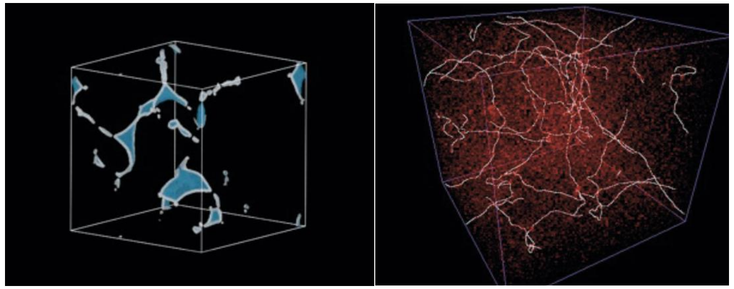
Axions as cold dark matter

Axion realignment… (AR)



PQ before or after inflation?

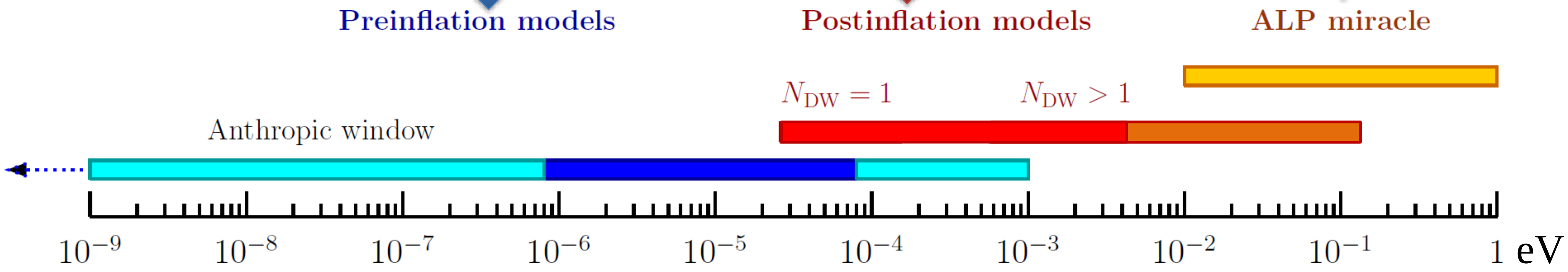
… AND decay of topological defects. (TD)



- Only well-known AR
- BUT, initial misalignment angle unknown…
- Large range of masses possible, even very low ones (→ anthopically finetuned?)

- TD contributes, potentially dominating…
- Not initial AR uncertainty
- BUT TD computation very complex
- Still large range of masses possible

ALP as inflaton AND dark matter?



→ Right axion DM density is possible for a wide range range of masses

Axion phenomenology

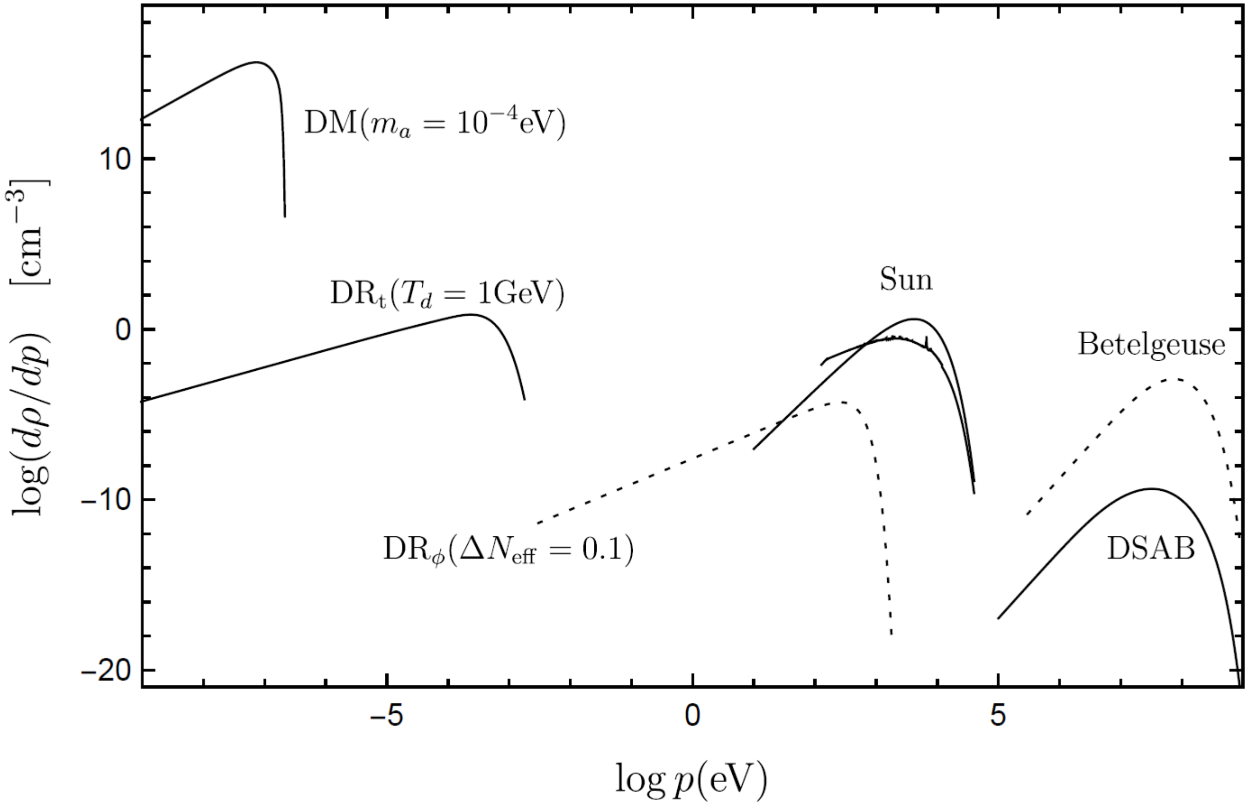
- Some phenomenology depends on the **"axion model"**, e.g.
  - KSVZ axions are "hadronic axions" (no coupling with leptons at tree level)
  - DFSZ axions couple to electrons

Gluon coupling	Mass	Photon coupling	Fermion couplings
$\frac{\alpha_s}{8\pi f_a} a G \tilde{G}$	$m_A = 5.70(7)\mu\text{eV} \times \left(\frac{10^{12}\text{GeV}}{f_A}\right)$	$g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a$ $g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	Electron coupling Nucleon coupling …
generic	*generic*	*generic but value model dependent*	*Model dependent*

Sources of axions

Natural sources

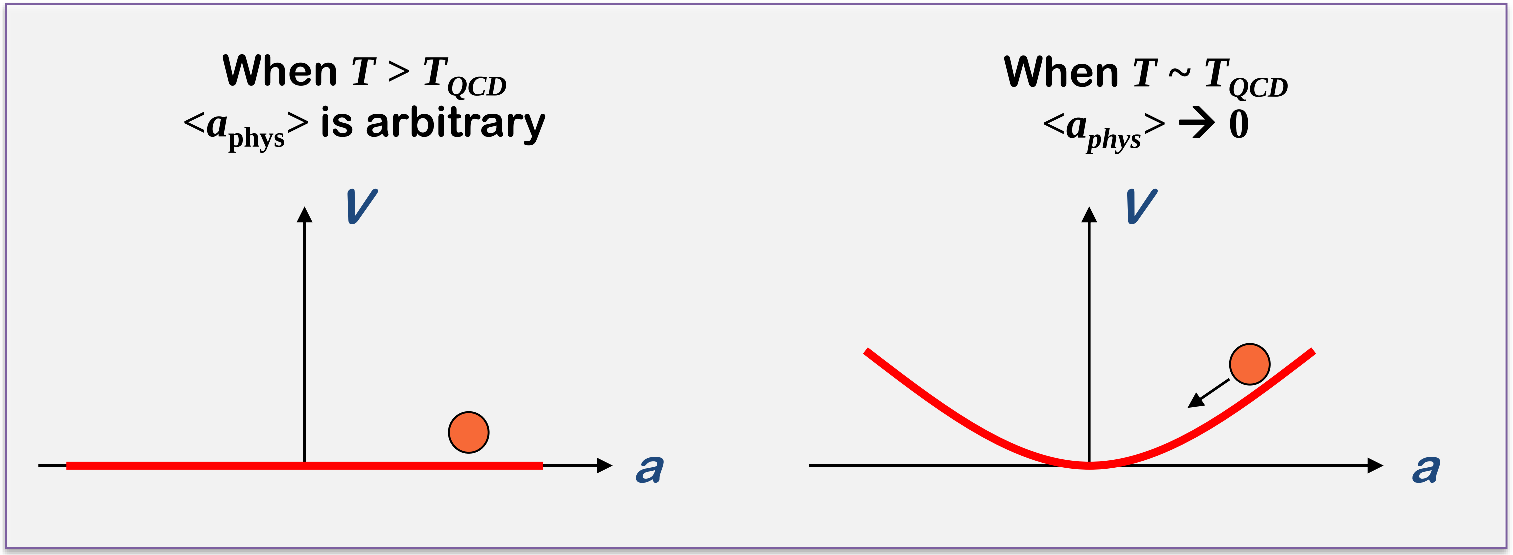
Dark matter **Dark radiation** **Stellar**

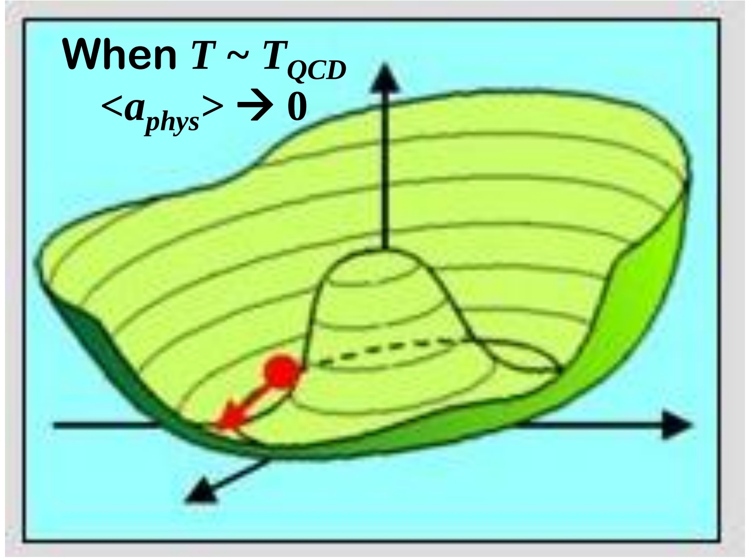


Laboratory sources

- Photon-ALP conversion in strong magnetic fields (axion-photon coupling)
- ALP fields from macroscopic bodies (fermionic couplings)

Cosmological axions: axion realignment



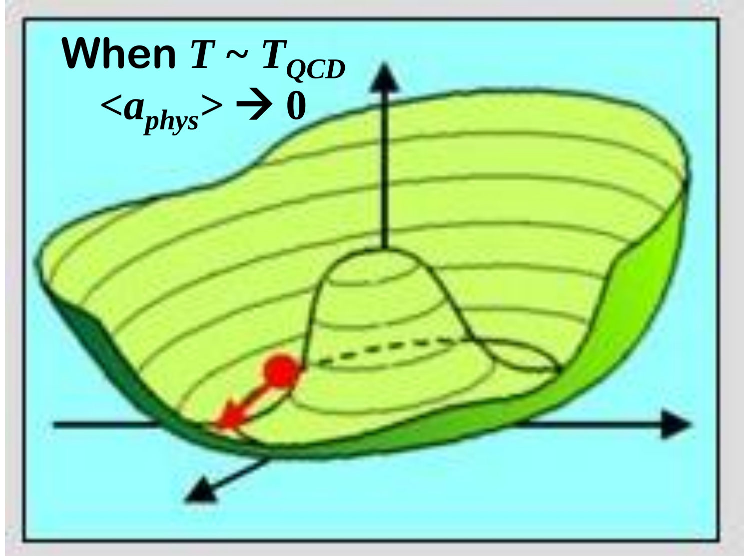


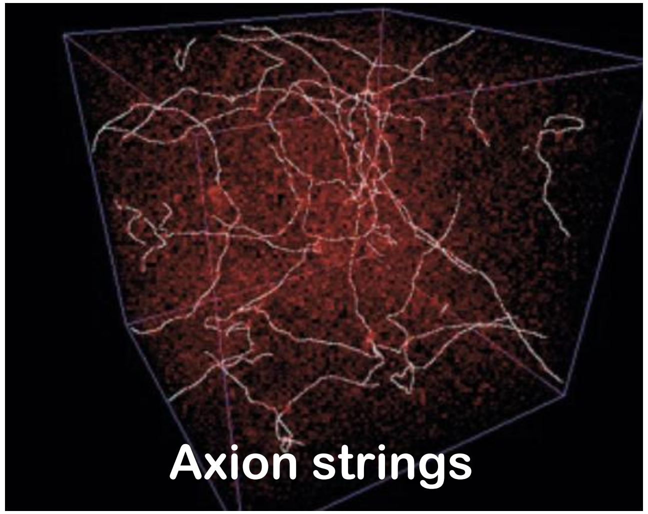
As the Universe cools down below T_{QCD}, space is filled with low energy axion field fluctuations → act as cold dark matter

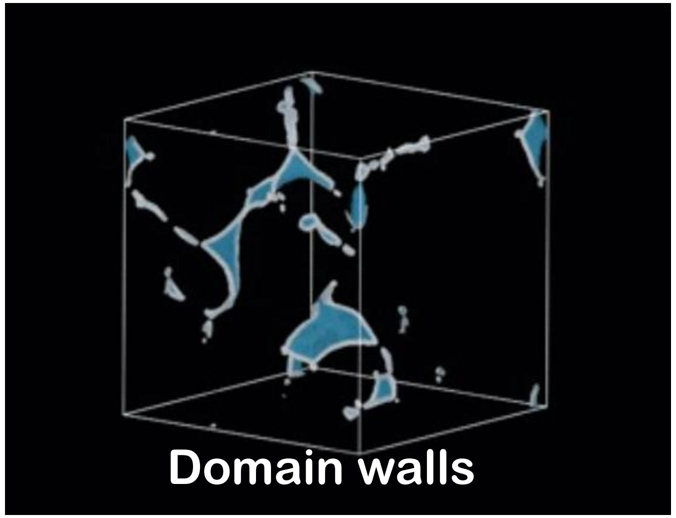
Their density depends on the initial value of $<a_{phys}>$ ("misalignment angle") which:

- Unique (but unknown) for all visible Universe in pre-inflation models
- Effectively averaged away in post-inflation models $\langle \theta_a^2 \rangle = \pi^2/3$

Cosmological axions: topological defects







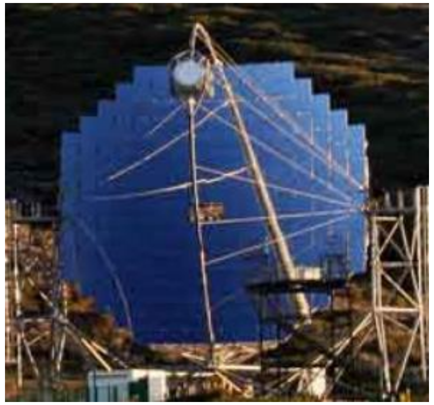
But inflation may "wipe out" topological defects… Did inflation happen before or after the creation of defects (PQ transition) ?

pre-inflation or post-inflation scenarios

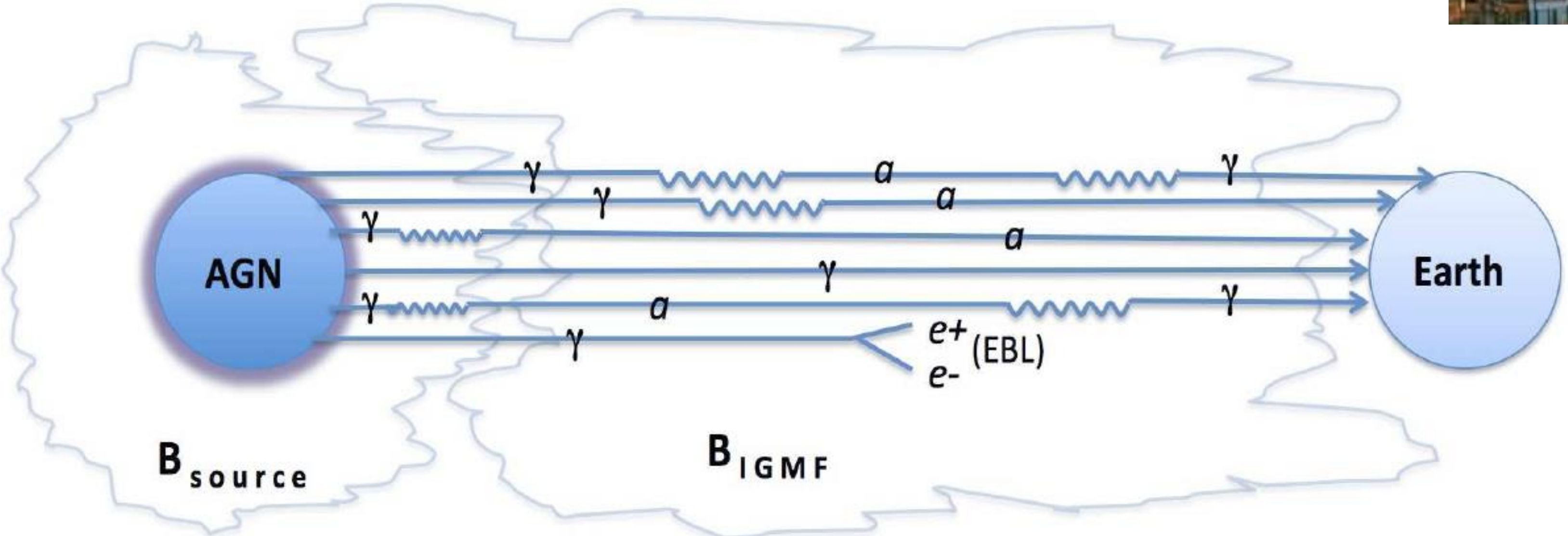
Computation of axion DM density from defect decay is complicated (→ big uncertainty)

Astrophysical hints for axions

- **Gama ray telescopes like MAGIC or HESS observe HE photons from very distant sources…**

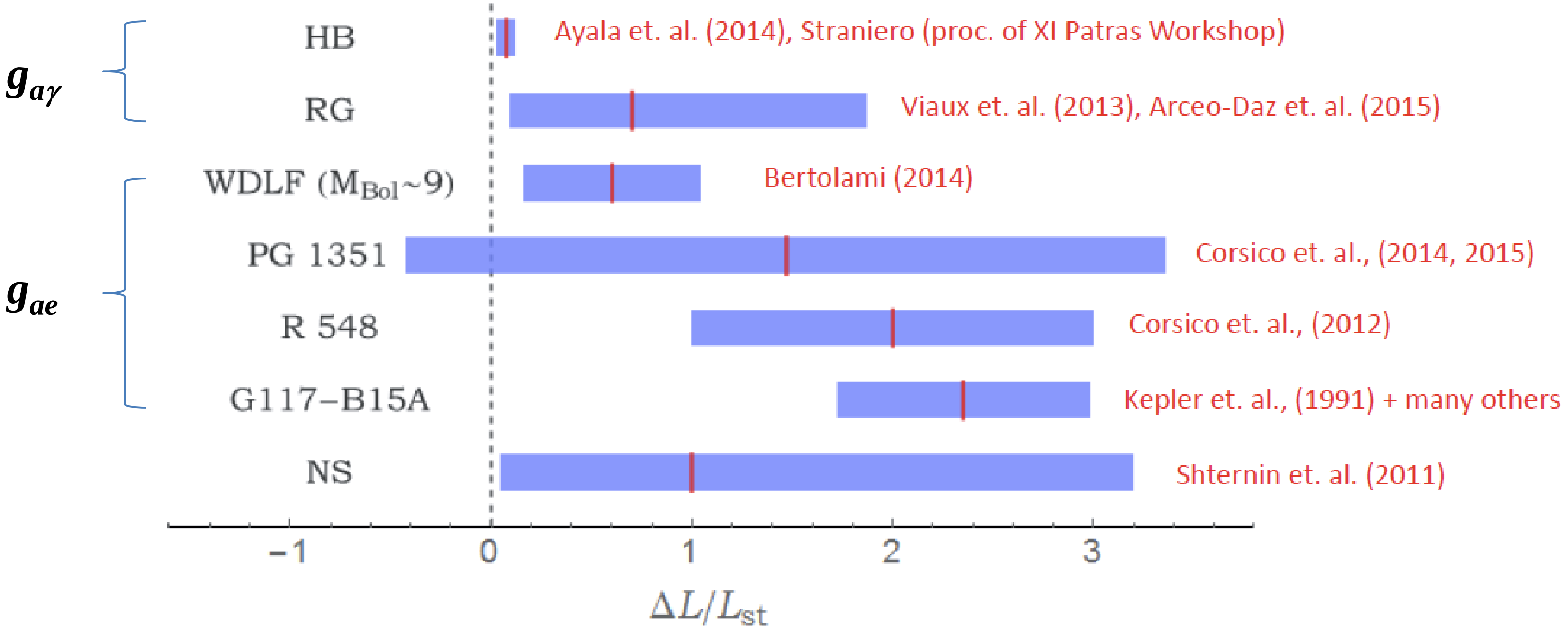


ALP: $$g_{a\gamma} \sim 10^{-12}\text{–}10^{-10}\ \mathrm{GeV}^{-1}$$
$$m_a \lesssim 10^{-(10-7)}\ \mathrm{eV}$$



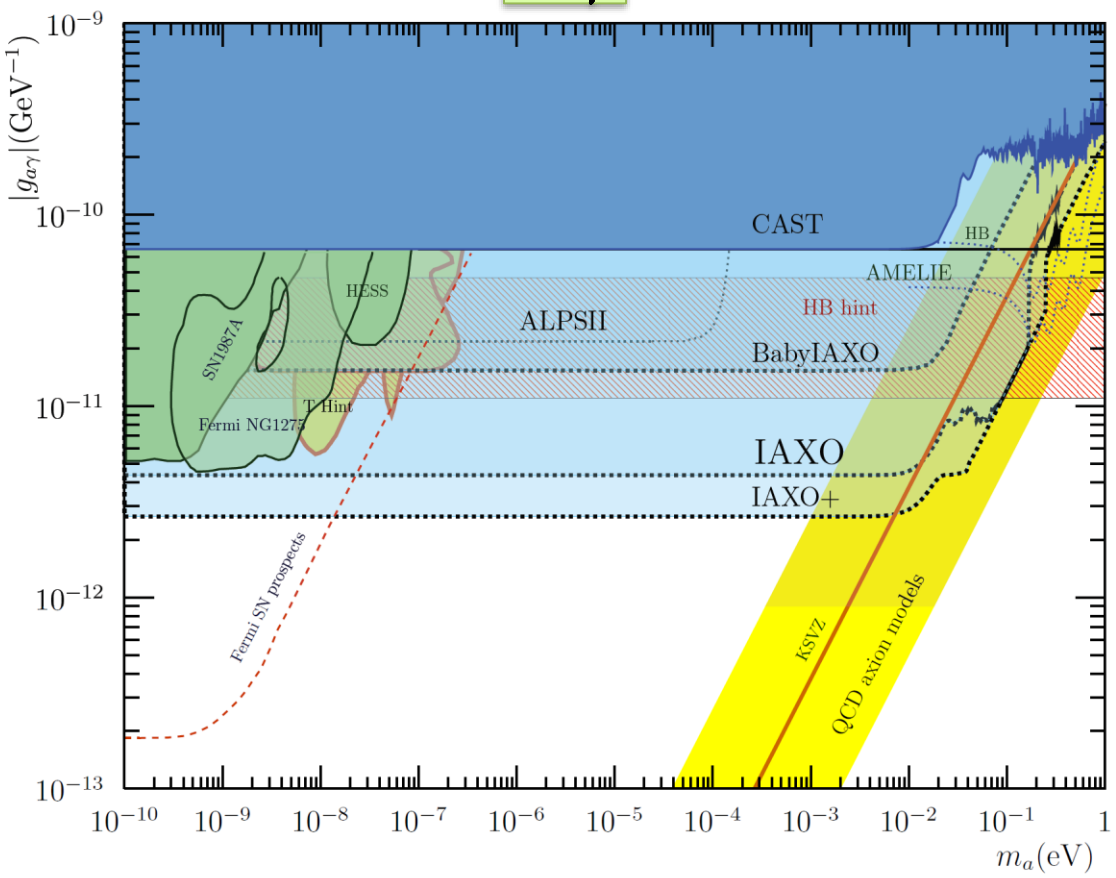
Astrophysical hints for axions

- Most stellar systems seem to cool down faster than expected.
- Presence of axions/ALPs offer a good joint explanation (M. Giannotti et al. JCAP 1710 (2017) 010, arXiv:1708.02111)

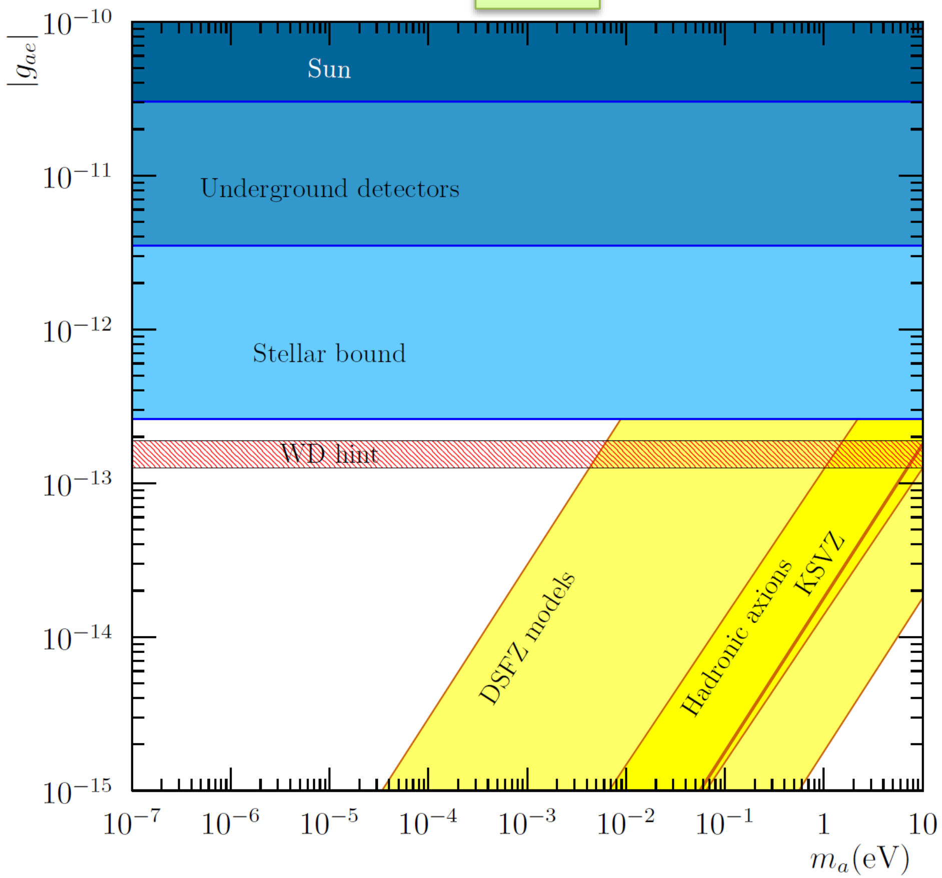


Astrophysical hints for axions

$g_{a\gamma}$

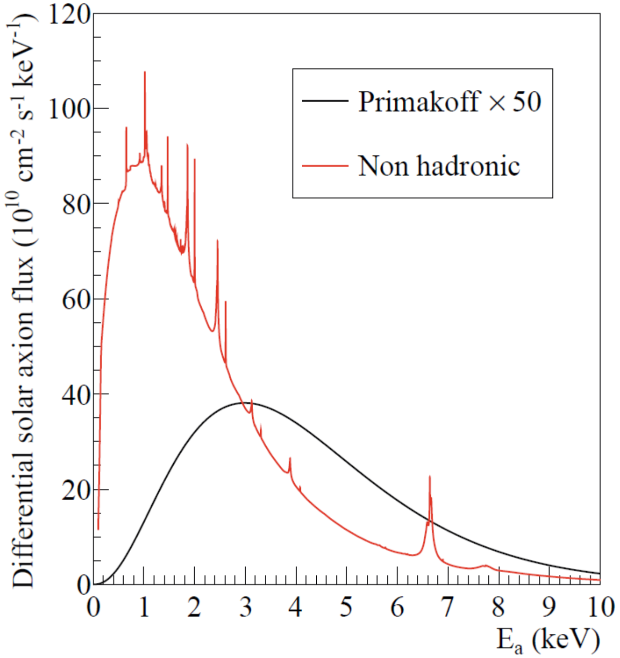


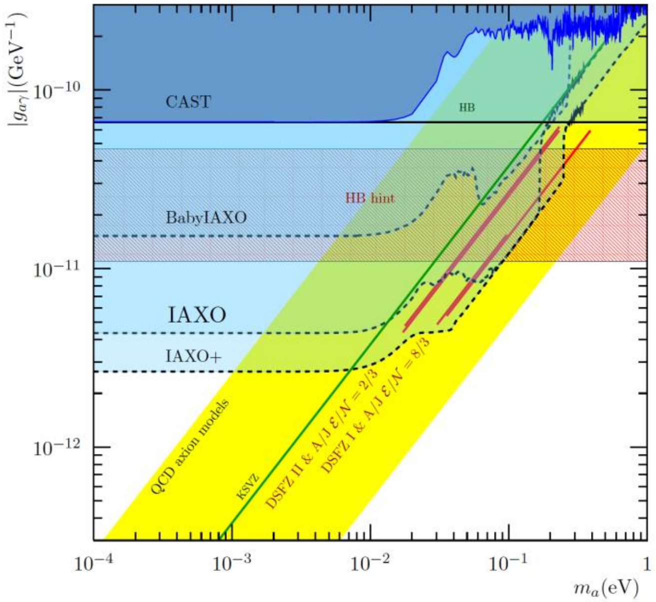
g_{ae}

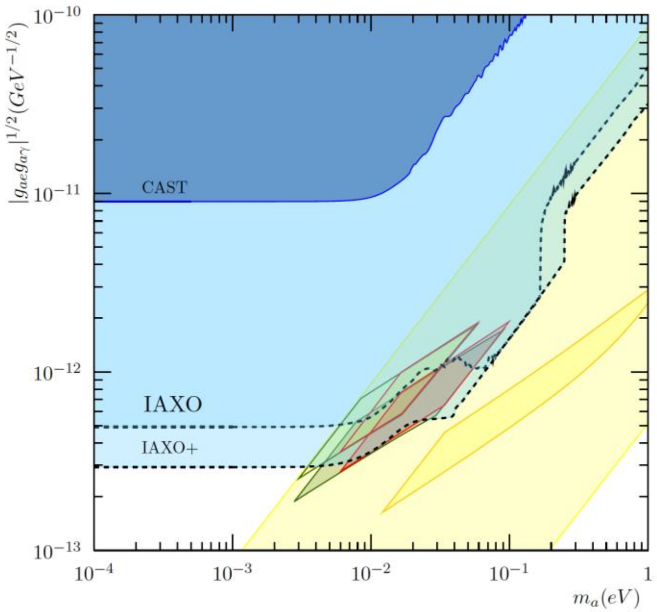


IAXO & stellar cooling hints

- IAXO can detect "ABC" solar axions (i.e. non-hadronic, g_{ae}-mediated)
- Boost in sensitivity for models featuring g_{ae}- coupling.
- Will probe QCD axion models invoked to solve all stellar cooling anomalies







Most detection strategies rely on the axion-photon conversion

Axion detection strategies

Detection method	$g_{a\gamma}$	g_{ae}	g_{aN}	$g_{A\gamma n}$	$g_{a\gamma}g_{ae}$	$g_{a\gamma}g_{aN}$	$g_{ae}g_{aN}$	$g_N\bar{g}_N$	Model dependency
Light shining through wall	×								no
Polarization experiments	×								no
Spin-dependent 5th force			×				×	×	no
Helioscopes	×				×	×			Sun
Primakoff-Bragg in crystals	×				×				Sun
Underground ion. detectors	×	×	×			×	×		Sun*
Haloscopes	×								DM
Pick up coil & LC circuit	×								DM
Dish antenna & dielectric	×								DM
DM-induced EDM (NMR)			×	×					DM
Spin precession in cavity		×							DM
Atomic transitions		×	×						DM

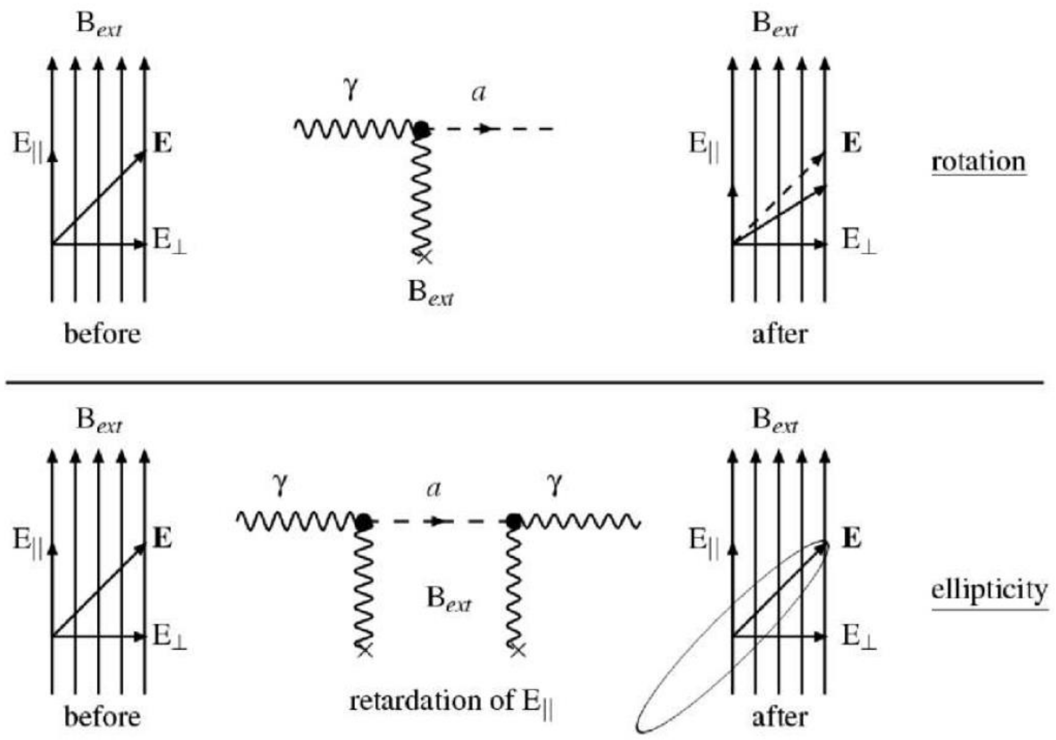
Table 3: List of the axion detection methods discussed in the review, with indication of the axion couplings (or product of couplings) that they are sensitive to, as well as whether they rely on astrophysical (axions/ALPs are produced by the Sun) or cosmological (the dark matter is made of axions/ALPs) assumptions. *Also "DM" when searching for ALP DM signals, see section 6.2

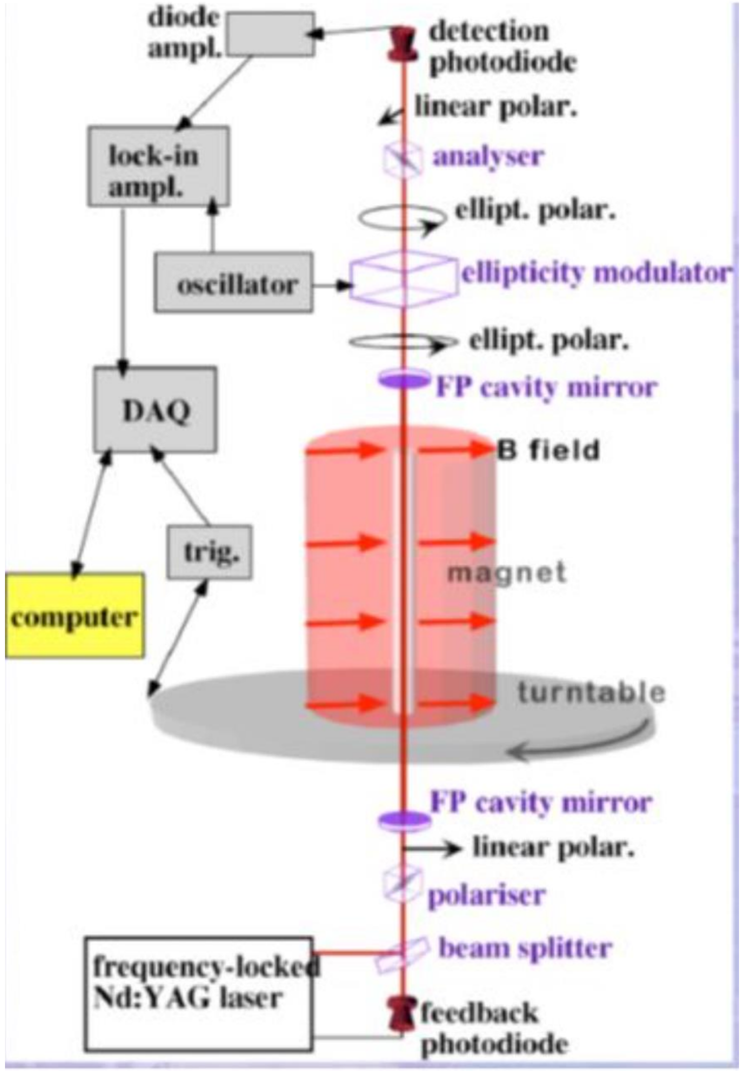
Polarization experiments

PVLAS experiment: study QED vacuum birrefringence (standard effect), but also sensitivty to ALPs:

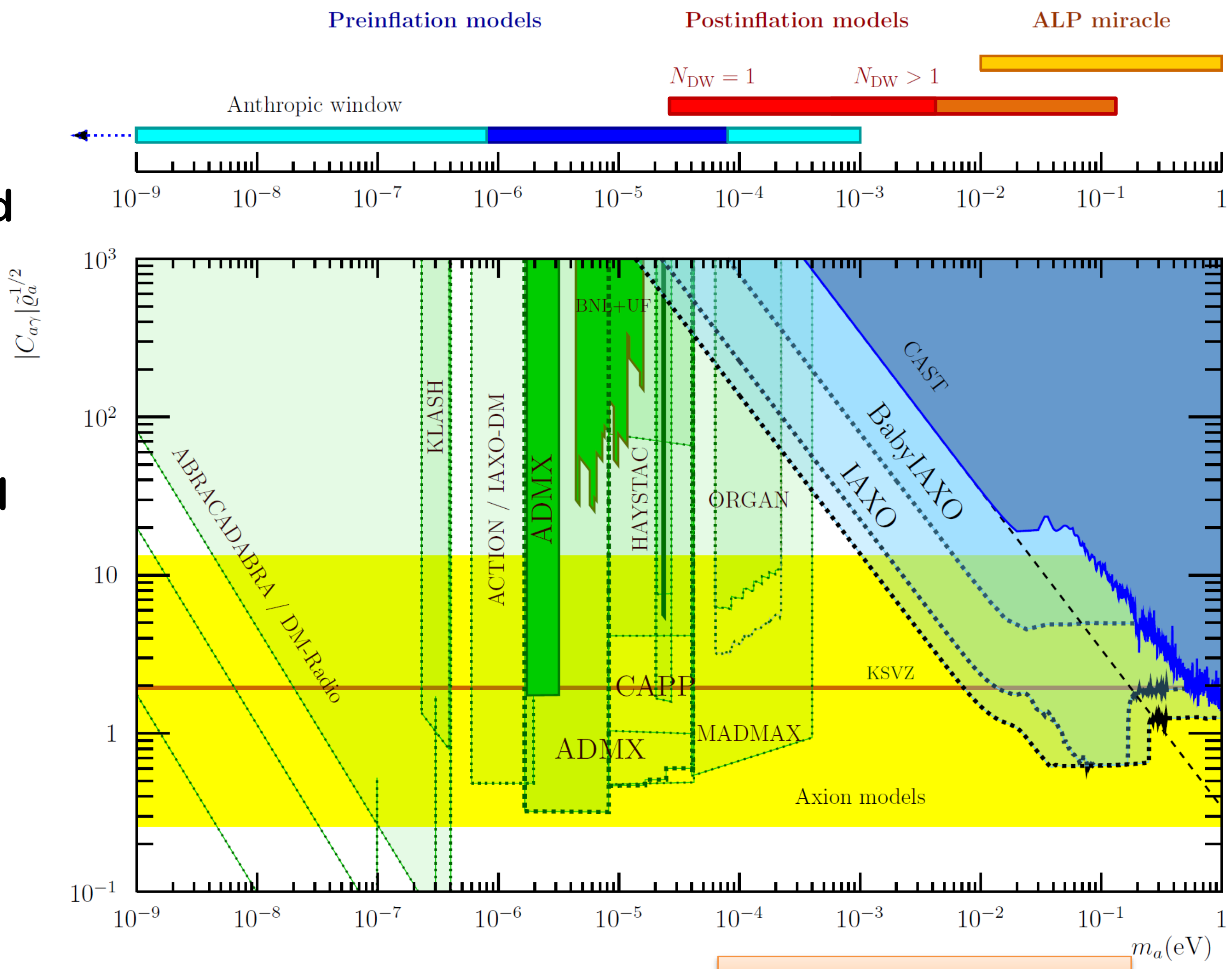
Dichroism: Production of real particles

Ellipticity: Production of massive virtual particles





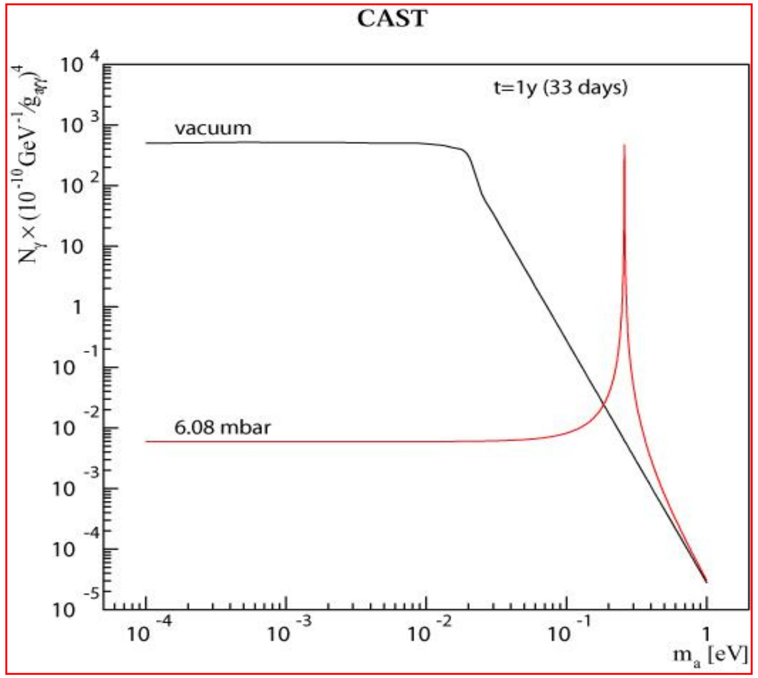
- Summary of current status and future prospects…
- A diverse experimental landscape has emerged with potential to cover a substantial fraction of parameter space
- **Caution**: many of these prospects still rely on a prior succesful R&D phase
- **Caution**: Green areas rely on axion as DM hypothesis…



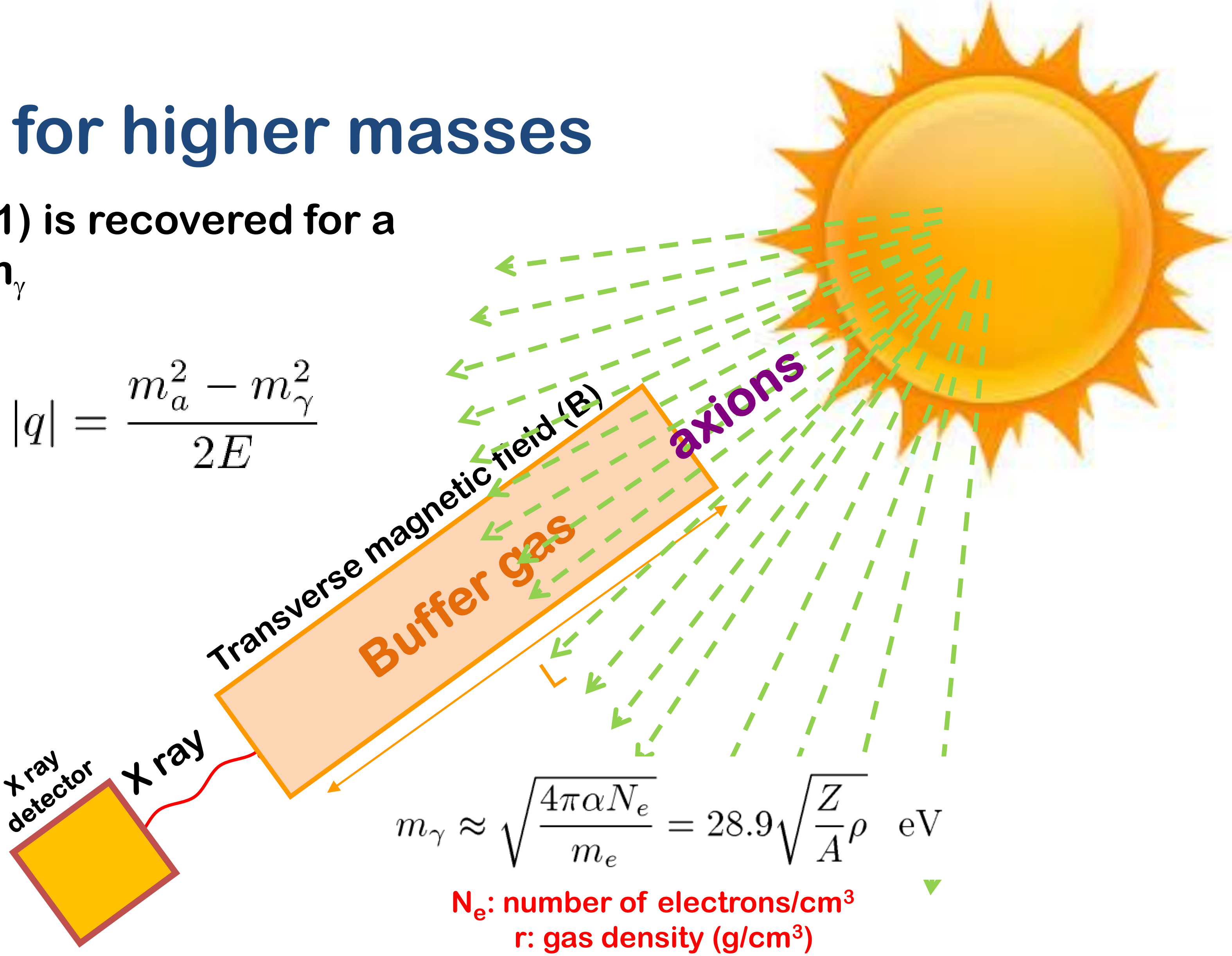
From arXiv:1801.08127

Buffer gas for higher masses

Coherence condition (qL << 1) is recovered for a narrow mass range around m_γ



$$|q| = \frac{m_a^2 - m_\gamma^2}{2E}$$

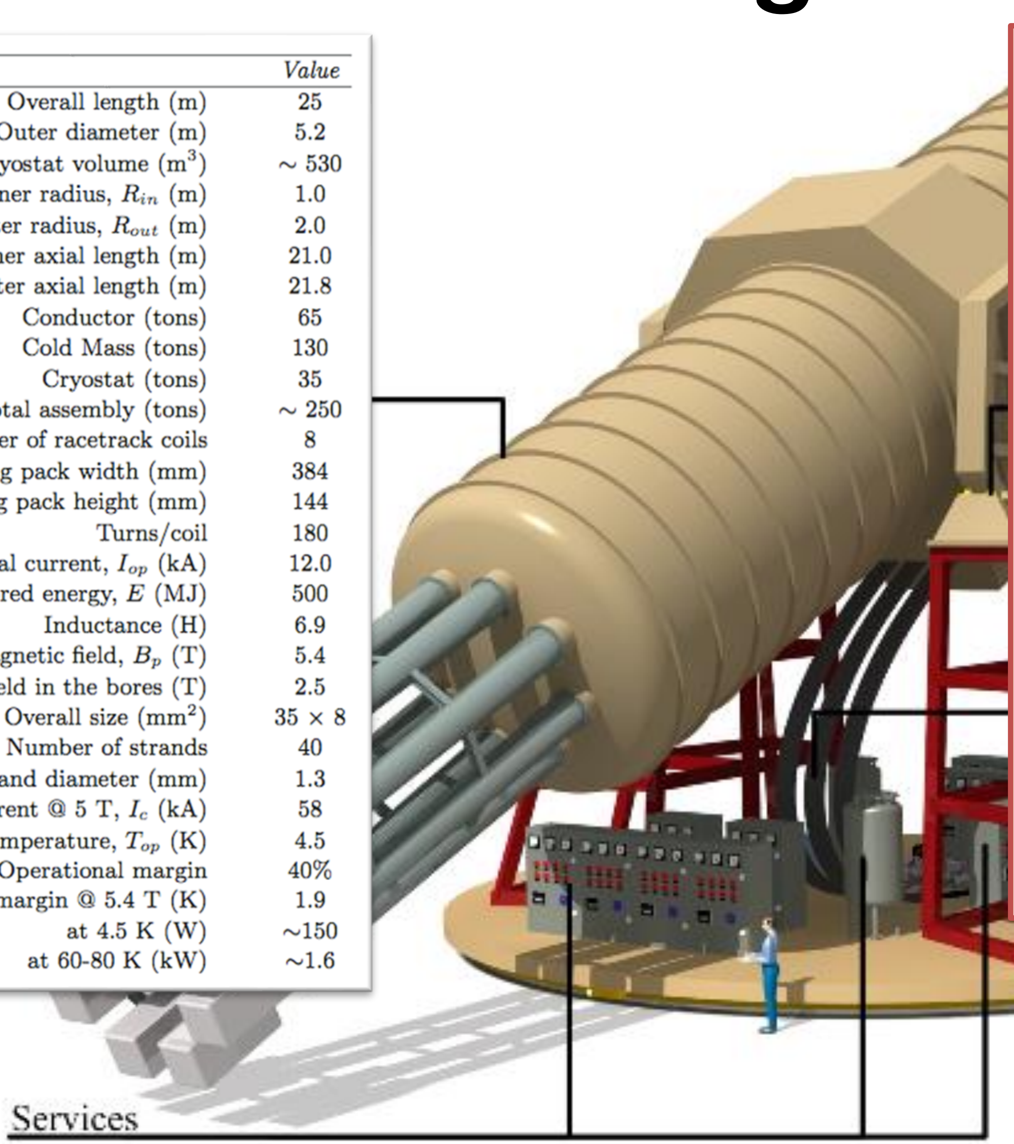


$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \text{eV}$$

N_e: number of electrons/cm^3
r: gas density (g/cm^3)

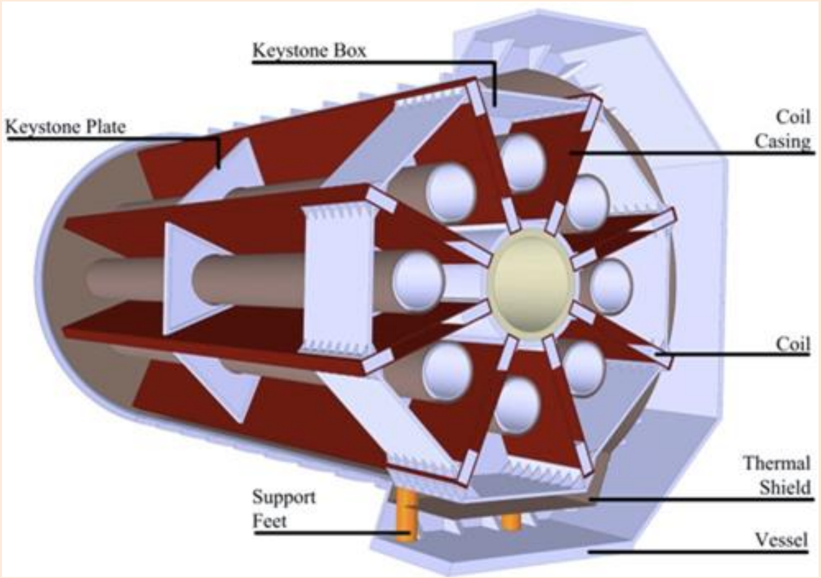
IAXO technologies – magnet

Property		*Value*
Cryostat dimensions:	Overall length (m)	25
	Outer diameter (m)	5.2
	Cryostat volume (m^3)	~ 530
Toroid size:	Inner radius, R_{in} (m)	1.0
	Outer radius, R_{out} (m)	2.0
	Inner axial length (m)	21.0
	Outer axial length (m)	21.8
Mass:	Conductor (tons)	65
	Cold Mass (tons)	130
	Cryostat (tons)	35
	Total assembly (tons)	~ 250
Coils:	Number of racetrack coils	8
	Winding pack width (mm)	384
	Winding pack height (mm)	144
	Turns/coil	180
	Nominal current, I_{op} (kA)	12.0
	Stored energy, E (MJ)	500
	Inductance (H)	6.9
	Peak magnetic field, B_p (T)	5.4
	Average field in the bores (T)	2.5
Conductor:	Overall size (mm^2)	35 × 8
	Number of strands	40
	Strand diameter (mm)	1.3
	Critical current @ 5 T, I_c (kA)	58
	Operating temperature, T_{op} (K)	4.5
	Operational margin	40%
	Temperature margin @ 5.4 T (K)	1.9
Heat Load:	at 4.5 K (W)	~150
	at 60-80 K (kW)	~1.6



IAXO magnet

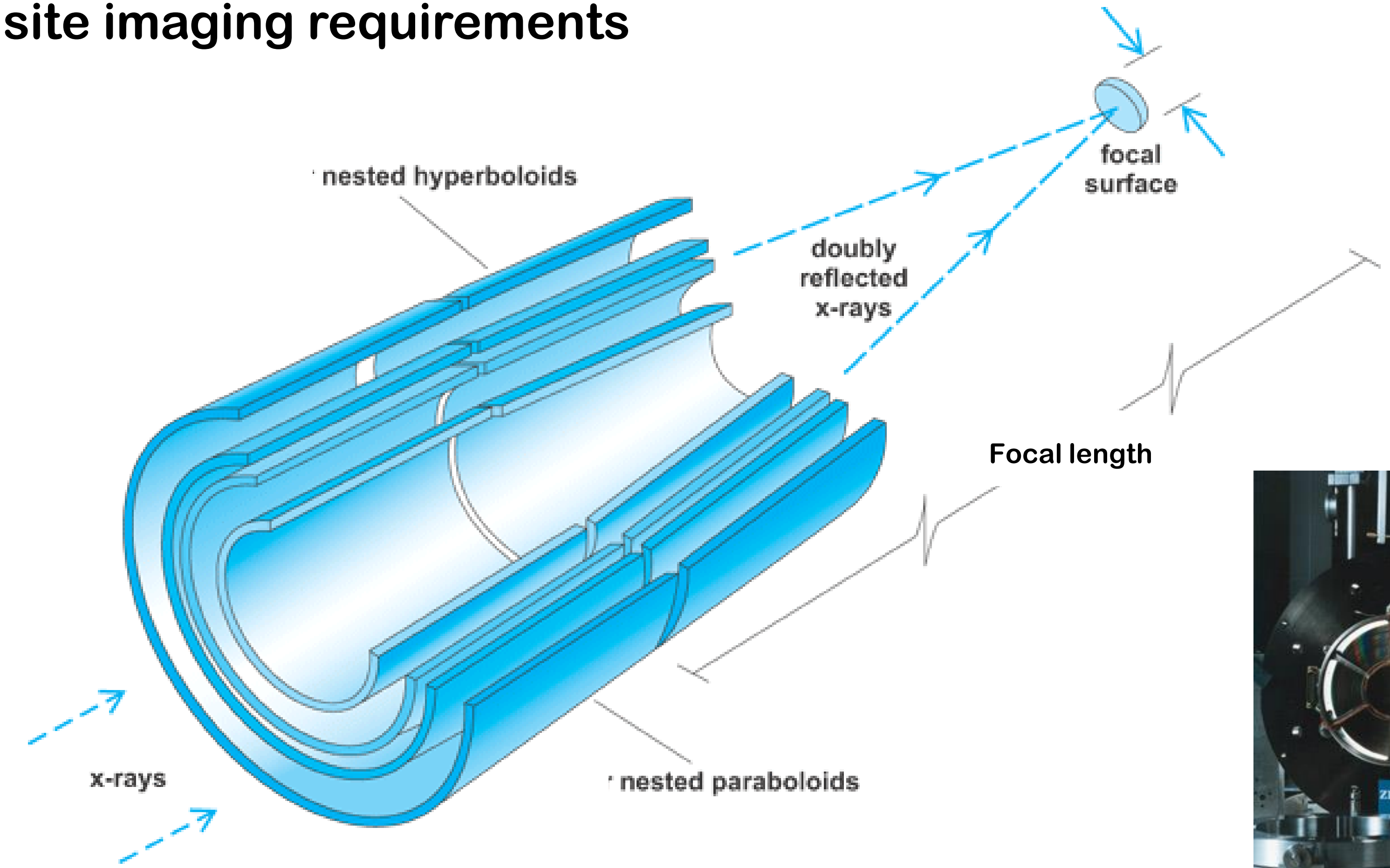
- Superconducting "detector" magnet.
- Toriodal geometry (8 coils)
- Based on ATLAS toroid technical solutions.
- CERN+CEA expertise
- 8 bores / 20 m long / 60 cm Ø per bore



Baseline developed at:
IAXO Letter of Intent: CERN-SPSC-2013-022
IAXO Conceptual Design: JINST 9 (2014) T05002 (arXiv:1401.3233)

IAXO x-ray optics

- **X-rays are focused by means of grazing angle reflection (usually 2)**
- **Many techniques developed in the x-ray astronomy field. But usually costly due to exquisite imaging requirements**

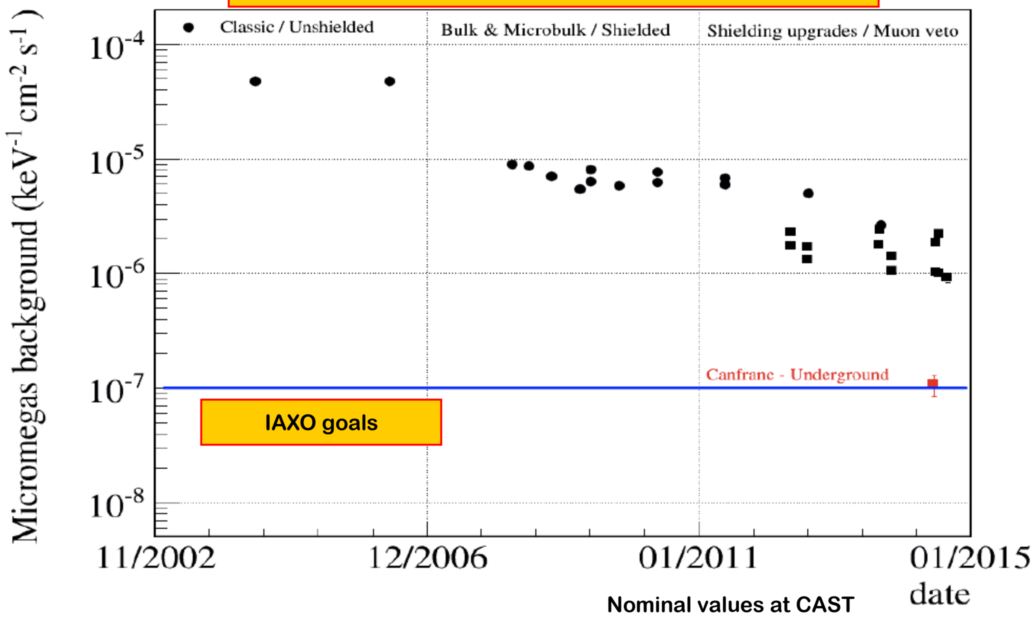


ABRIXAS spare telescope, in use in one of the 4 bores of CAST (pioneer use of x-ray optics in axion research)

IAXO low background MM detectors

- Goal background level for IAXO:
  - $10^{-7} – 10^{-8}$ c keV^{-1} cm^{-2} s^{-1}
- Already demonstrated:
- ~8×10^{-7} c keV^{-1} cm^{-2} s^{-1}
  (in CAST 2014 result)
  - 10^{-7} c keV^{-1} cm^{-2} s^{-1}
    (underground at LSC)

History of background improvement of Micromegas detectors at CAST



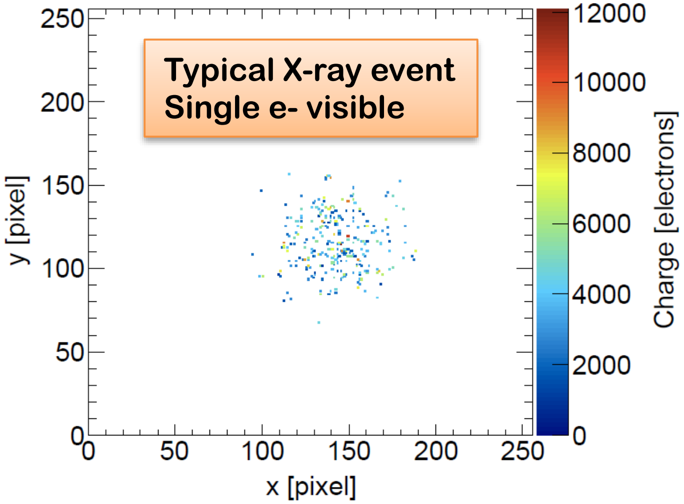
Nominal values at CAST

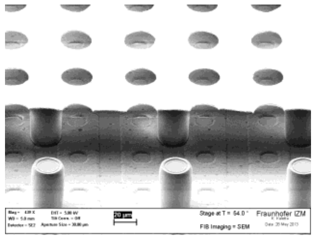
- Active program of development.
- IAXO-D0 test-platform to explore background sources and improve levels

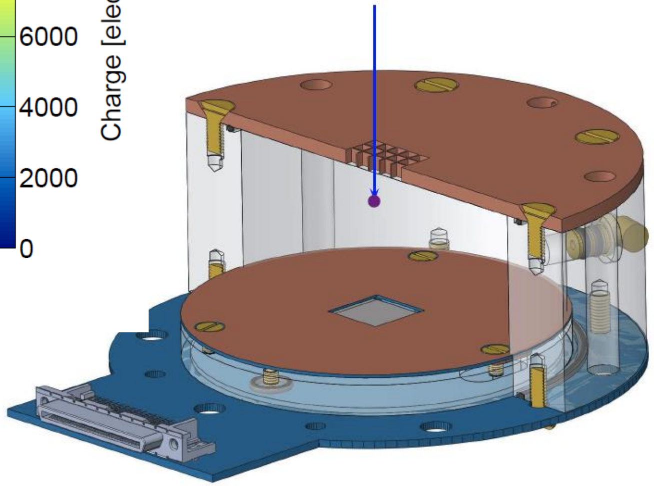
Additional detector technologies for IAXO

Ingrid detectors (U. Bonn):

- Micromegas on top of a CMOS chip (Timepix)
- Very low threshold (tens of eV)
- Tested in CAST

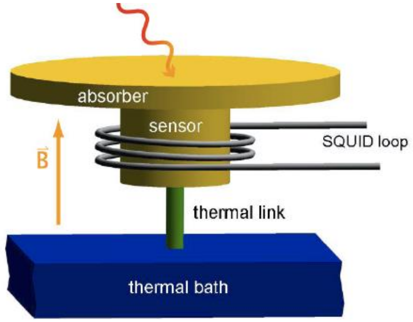


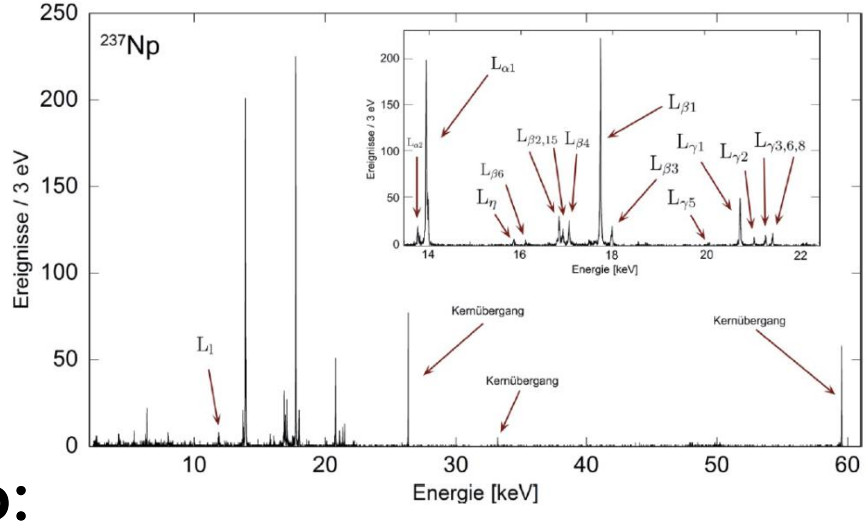




MMC detectors (U. Heidelberg):

- Extremely low threshold and energy resolution (~eV scale)
- Low background capabilities under study

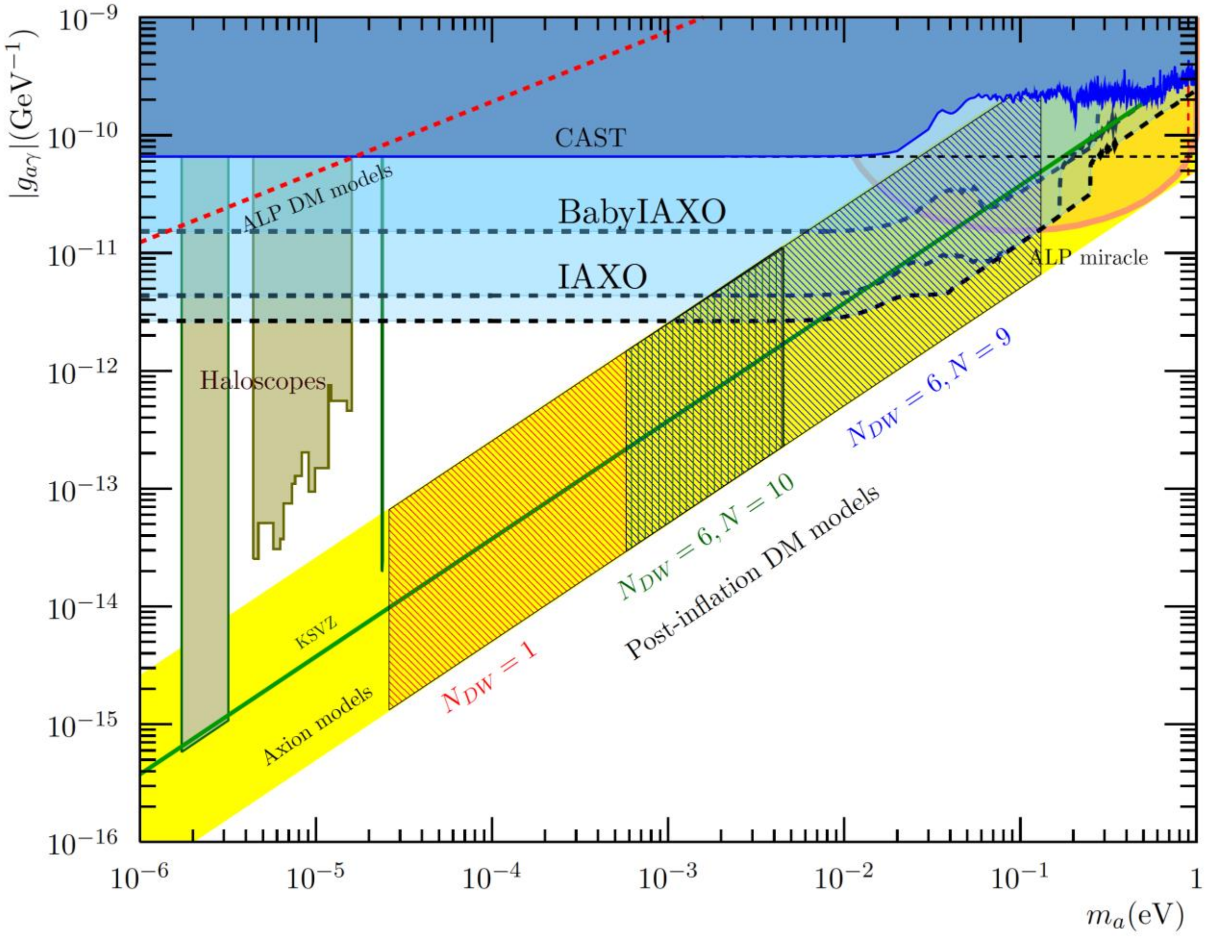




Also:

- Transition Edge Sensors (TES)
- Si- detetors

IAXO & axion cosmology



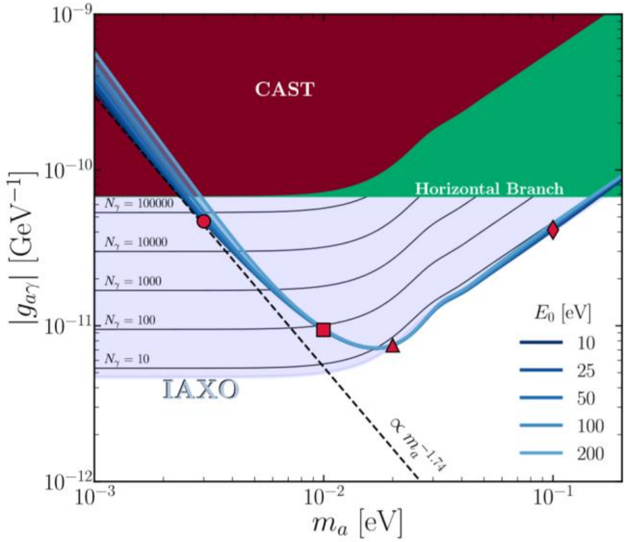
- **Axion post-inflation mass window overlaps with astro window**
  - **Uncertainty in topological defect decay is large (Gorghetto et al 2018)**
  - **NDW>1 models (Saikawa, Ringwald 2016)**

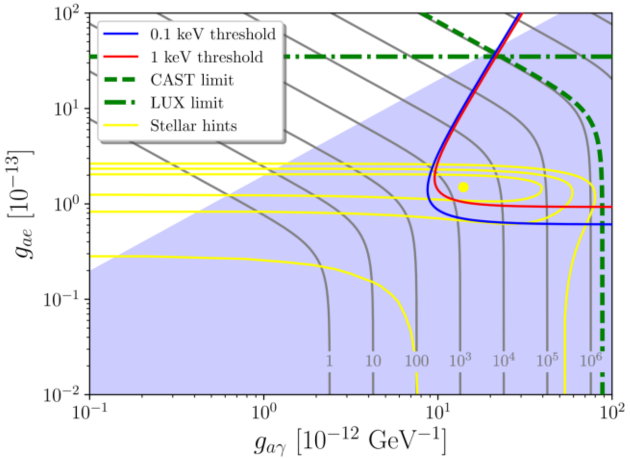
- **Also:**
  - **If axions only subdominant DM component, axion mass moves to higher values.**
  - **"ALP miracle" (ALP inflation + DM) models @ 0.01 to 1 eV**
  - **EDGES anomaly interpretation with DM axions at 0.01-1 eV range**

- **IAXO will probe interesting DM axion & ALP models**

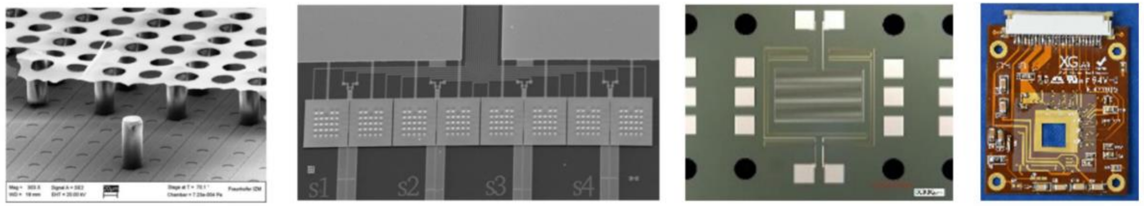
Post-discovery physics

- A positive signal in BabyIAXO will be seen >100x stronger in IAXO
- With sufficient statistics and precision detectors IAXO can determine axion model parameters:
  - Axion mass: "Weighing" the solar axion" [Dafni et al. arXiv:1811.09278]
  - Axion couplings: "Distinguishing axion models with IAXO" [Jaeckel et al. arXiv:1811.09278]

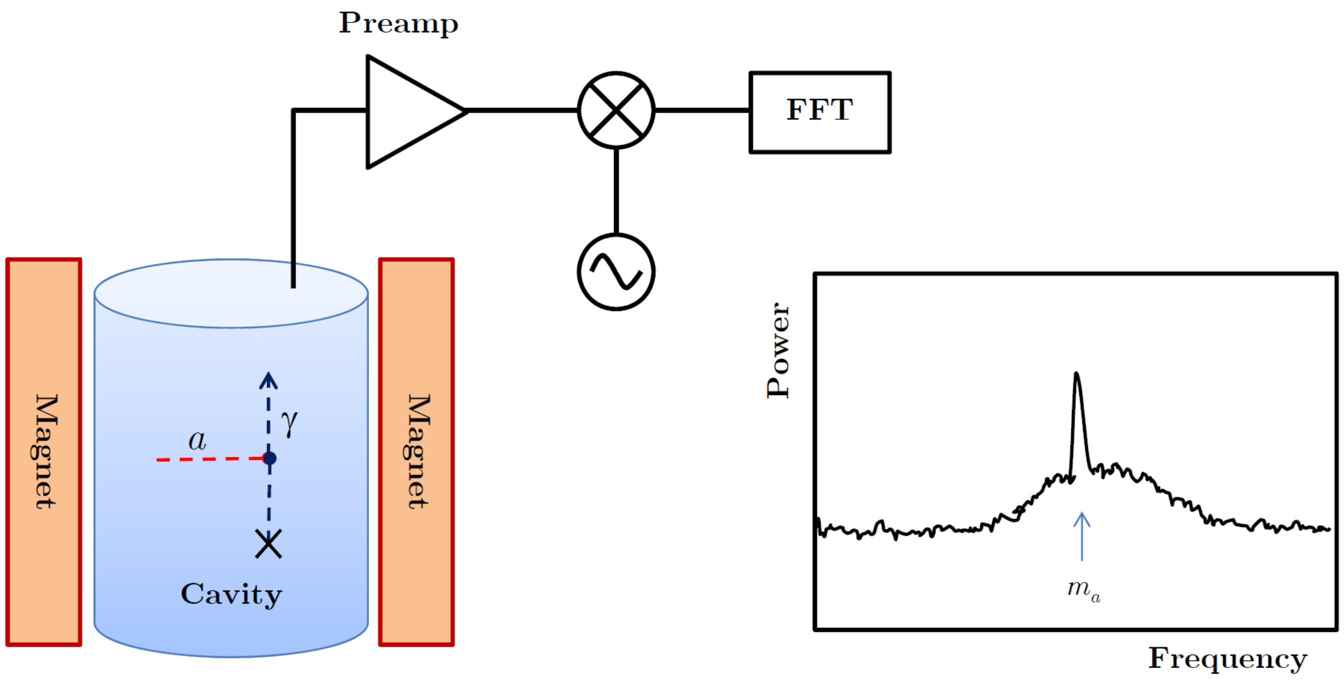




- IAXO collaboration is developing high-precision ("post-discovery") detectors (e.g. MMCs or TES)



Detecting DM axions: "haloscopes"



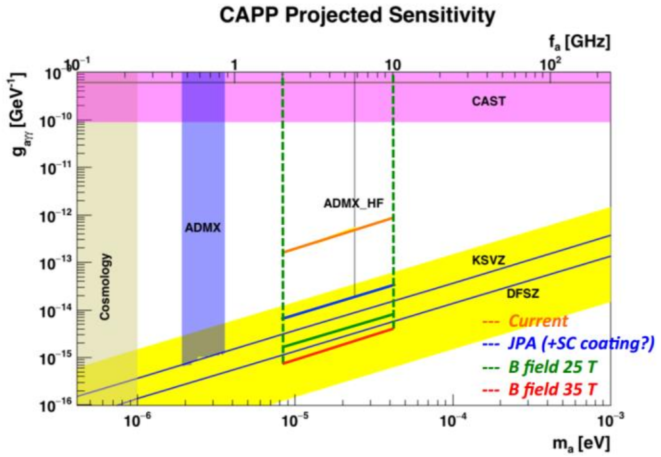
Data taking proceeds by scanning small (1/Q) mass steps and taking limited data a each step

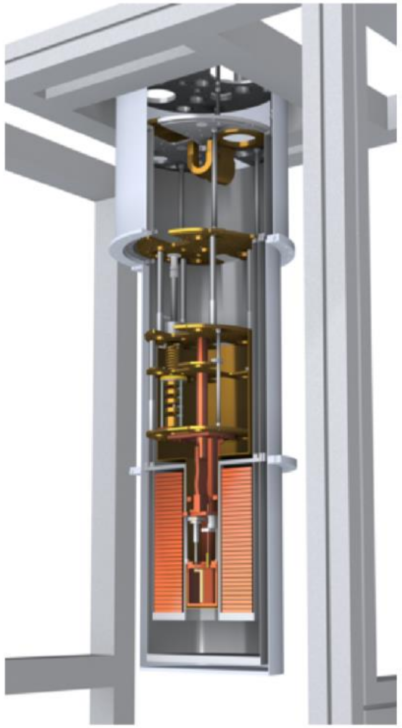
- **Figure of merit:** $$F \sim \varrho_a^2 g_{a\gamma}^4 m_a^2 B_e^4 V^2 T_{\rm sys}^{-2} |\mathcal{G}|^4 Q$$

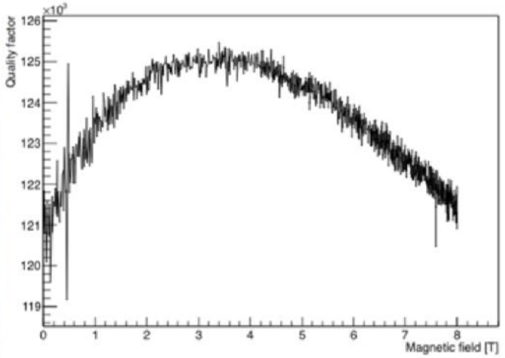
(proportional to "time needed to scan a given mass range")

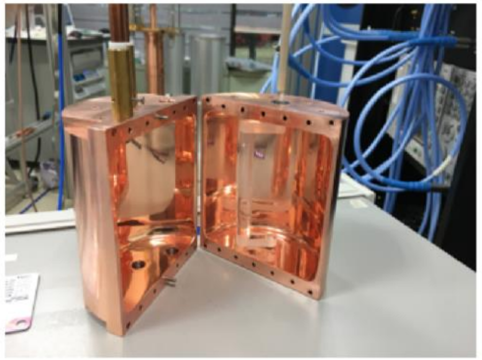
CULTASK @ CAPP

- **CAPP: recently created "Center for Axion and Precision Physics" at South Korea**
- **Main goal to "build a large axion DM experiment in Korea"**
- **Many R&D lines ongoing:**
  - Ultrahigh field superconducting magnets
  - Superconducting films to get high G cavities
  - Low noise sensors (SQUIDs)
  - New cavity designs & multi-cavity phase locking schemes



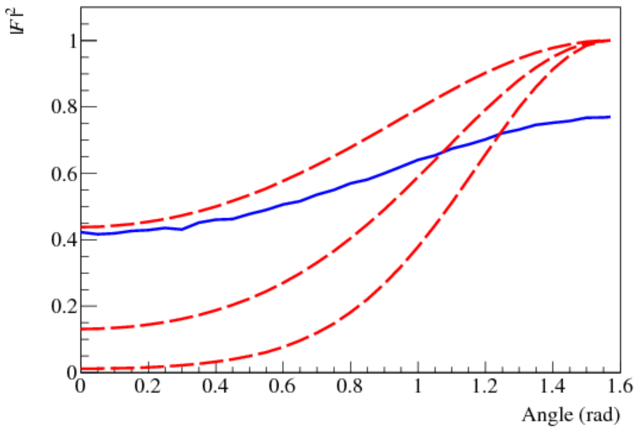


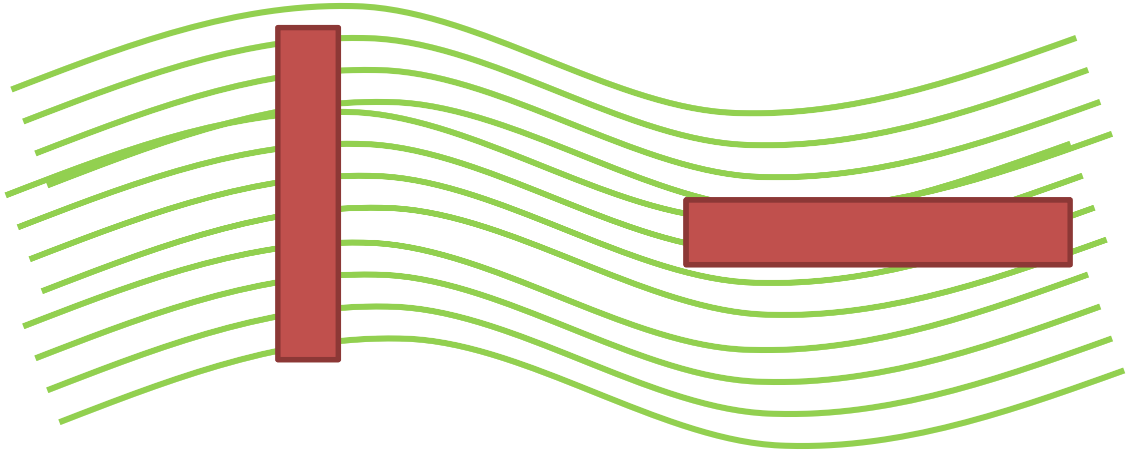


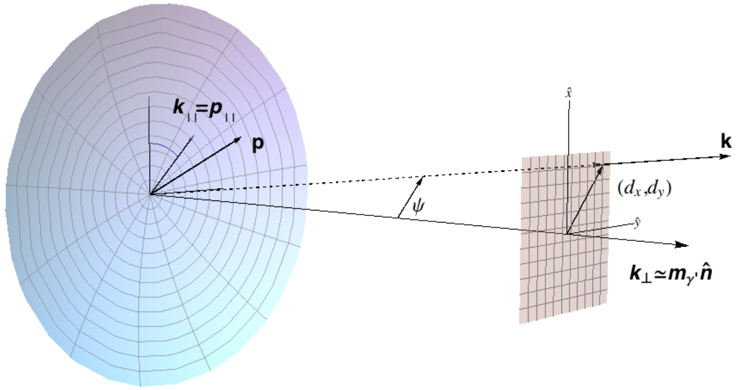


Directional effects

- DM directionality would be a powerful signature to confirm a putative signal
- Long aspect-ratio cavities should show a directional dependence if L > ldeBroglie
- Dish antennas: small parallel component proportional to axion momentum
  - pixelised detector at the focal point could image velocity distribution







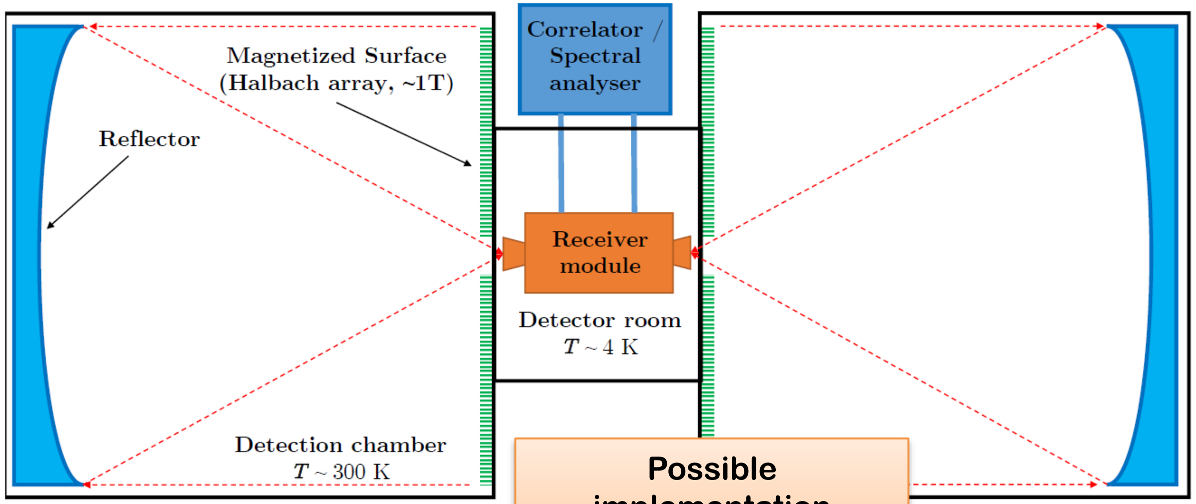
An "axion astronomy" era would follow a discovery

Magnetized dish antenna

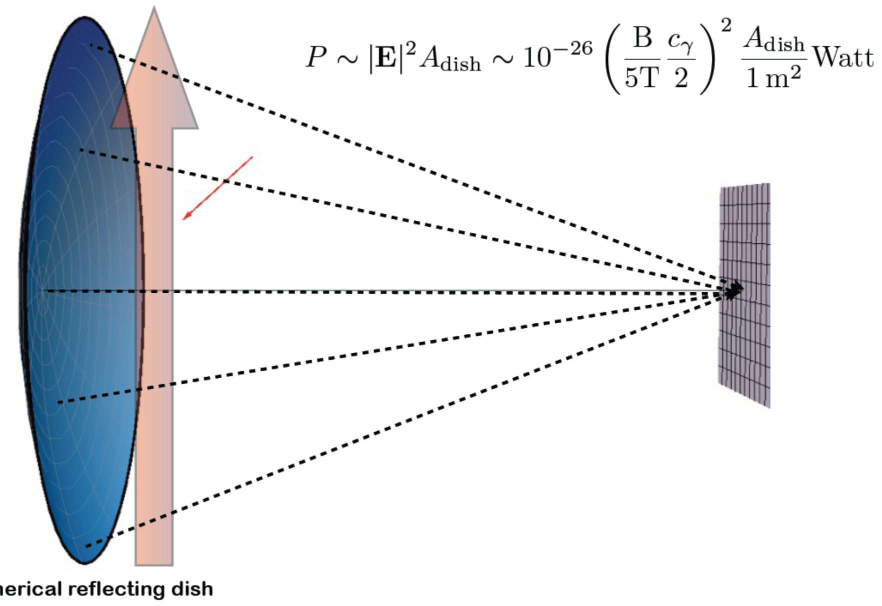
- **DM field + B field + boundary condition in the dish → photon emission normal to surface**
- **No resonance (loss a factor Q) BUT may be compensated with very large areas ?**

Resonance versus area

$$\frac{P_{\rm dish}}{P_{\rm haloscope}} \propto \frac{m_a^2 A}{Q},$$

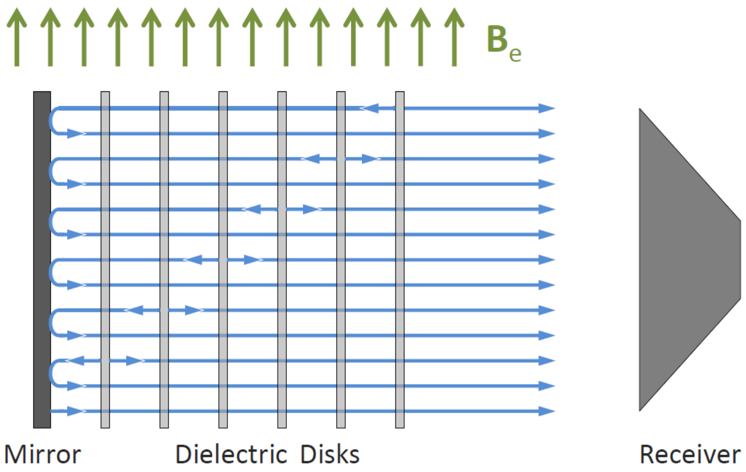


Possible implementation (BRASS Project at Hamburg)

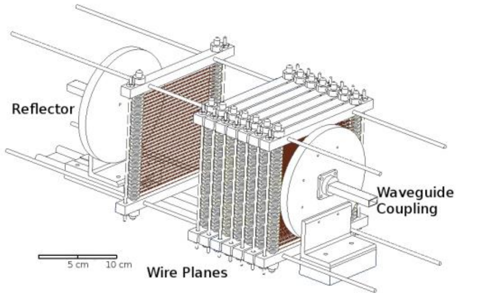


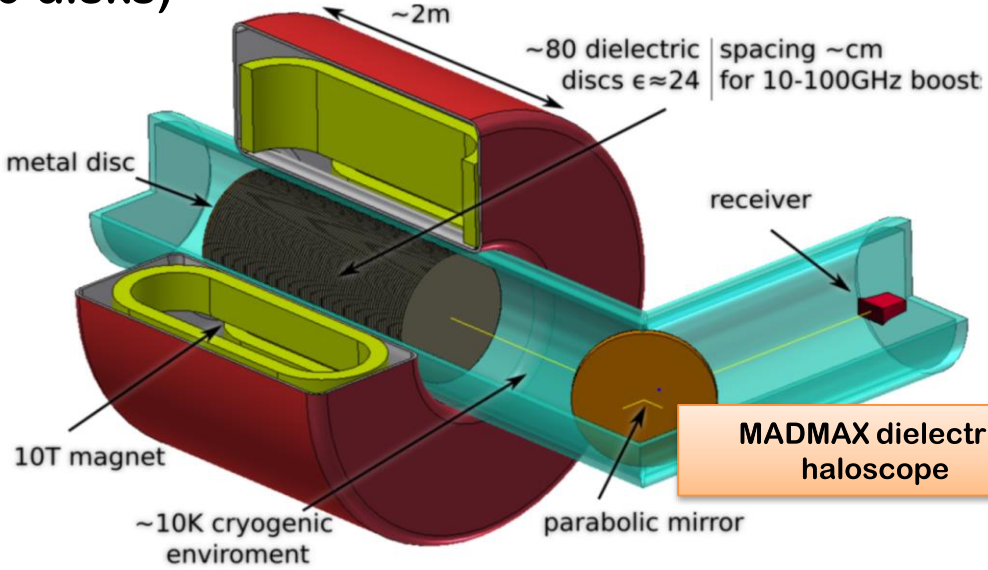
Dielectric haloscopes

- Effect of dish antenna "boosted" by the addition of many dielectric disks
- Some "mild" resonance
  - Concept between a haloscope and a dish antenna
  - It needs tuning! (challenging)
- Relevant sensitivity in the 10^{-4} eV ballpark for a ~m^3 10T experiment (80 disks)

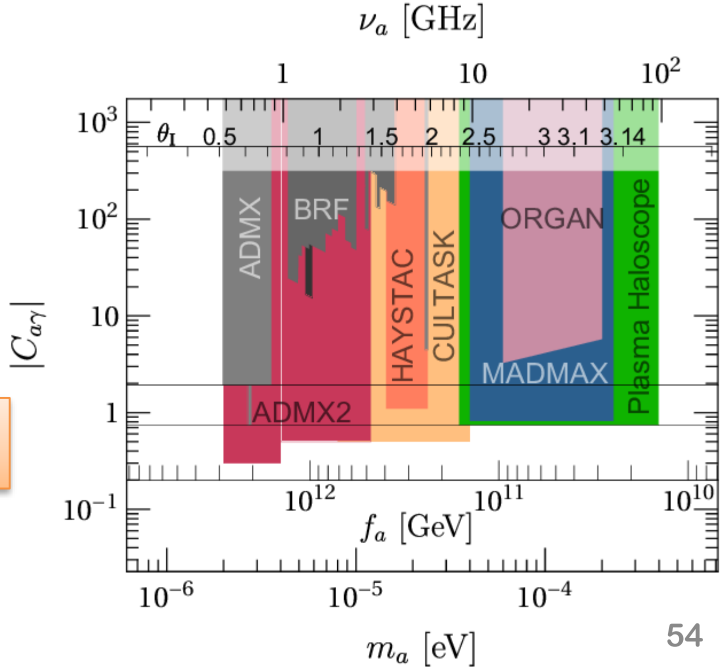


Similar high-m_a structures: ORPHEUS and Electric-Tiger in US



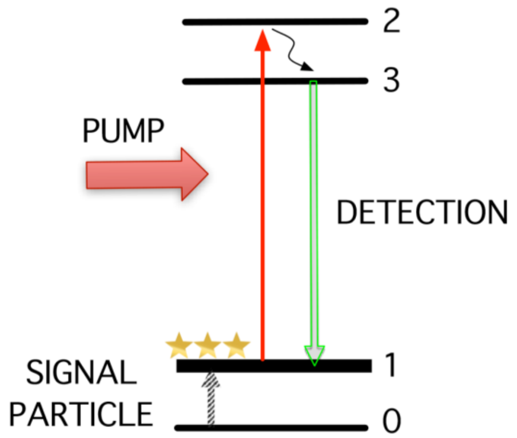


MADMAX dielectric haloscope

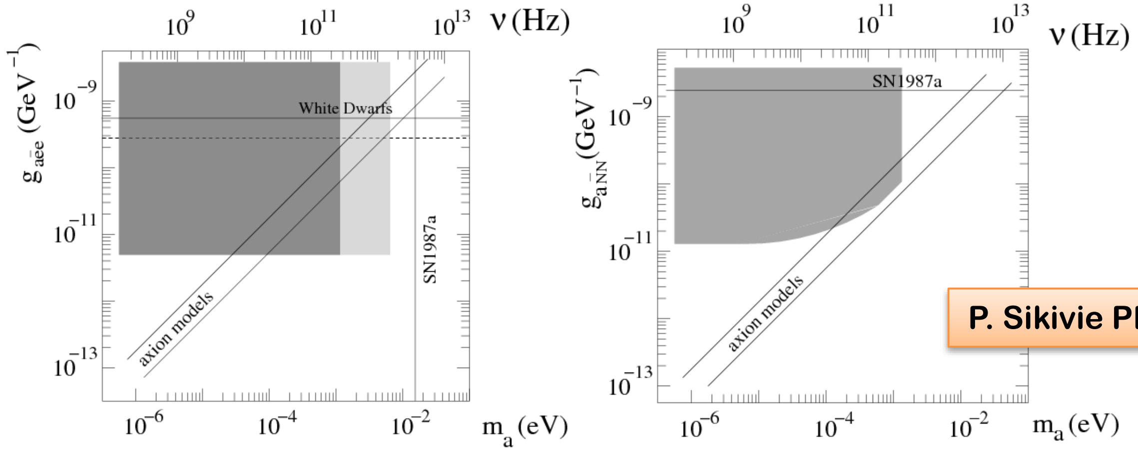


DM-induced atomic transitions

- DM can induce atomic excitations equal to m_a.
- Sensitive to axion-electron and axion-nucleon coupling
- Zeeman effect → create atomic transitions tunable to m_a
- Detection of excitation via pump laser
- AXIOMA → recent project aiming at an implementaiton



Relevant sensitivity for $m_a \sim 10^{-4}$ eV seems possible for kg-sized samples



P. Sikivie PRL 113(14)