IAXO at Snowmass:
Prospects for the International Axion Observatory

CSS 2013 | Snowmass on the Mississippi
29 July – 6 August 2013

Michael Pivovaroff
On behalf of the IAXO collaboration

Lawrence Livermore National Laboratory

LLNL-PRES-641561

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Overview

- Solar Axion Searches
- The International Axion Observatory (IAXO)
  - Magnet
  - X-ray optics
  - Low-background detectors
  - Prototype testing
- IAXO Science Reach
  - Sensitivity prospects
  - Collaboration and schedule
- Conclusions

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Towards a new generation axion helioscope

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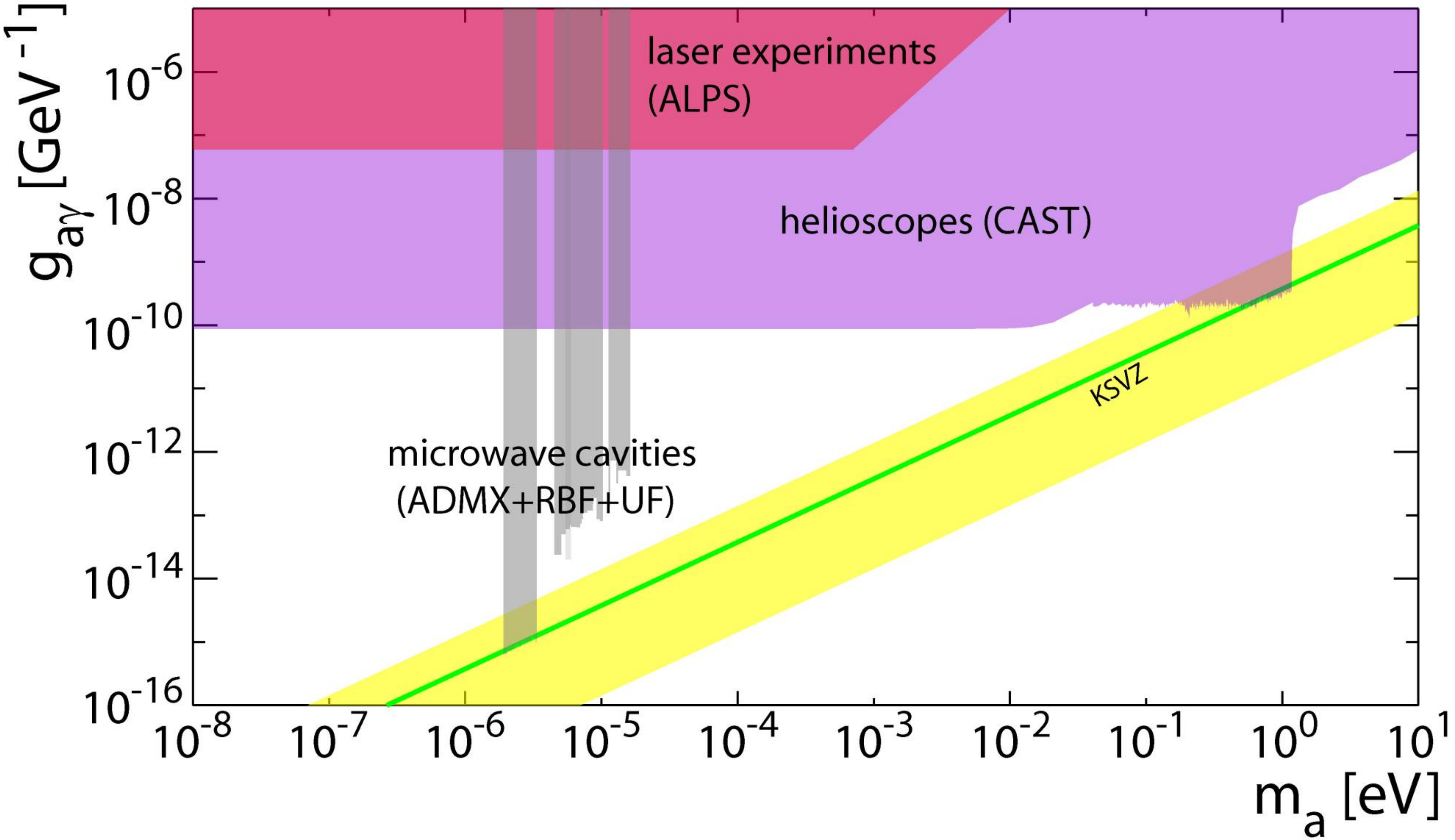
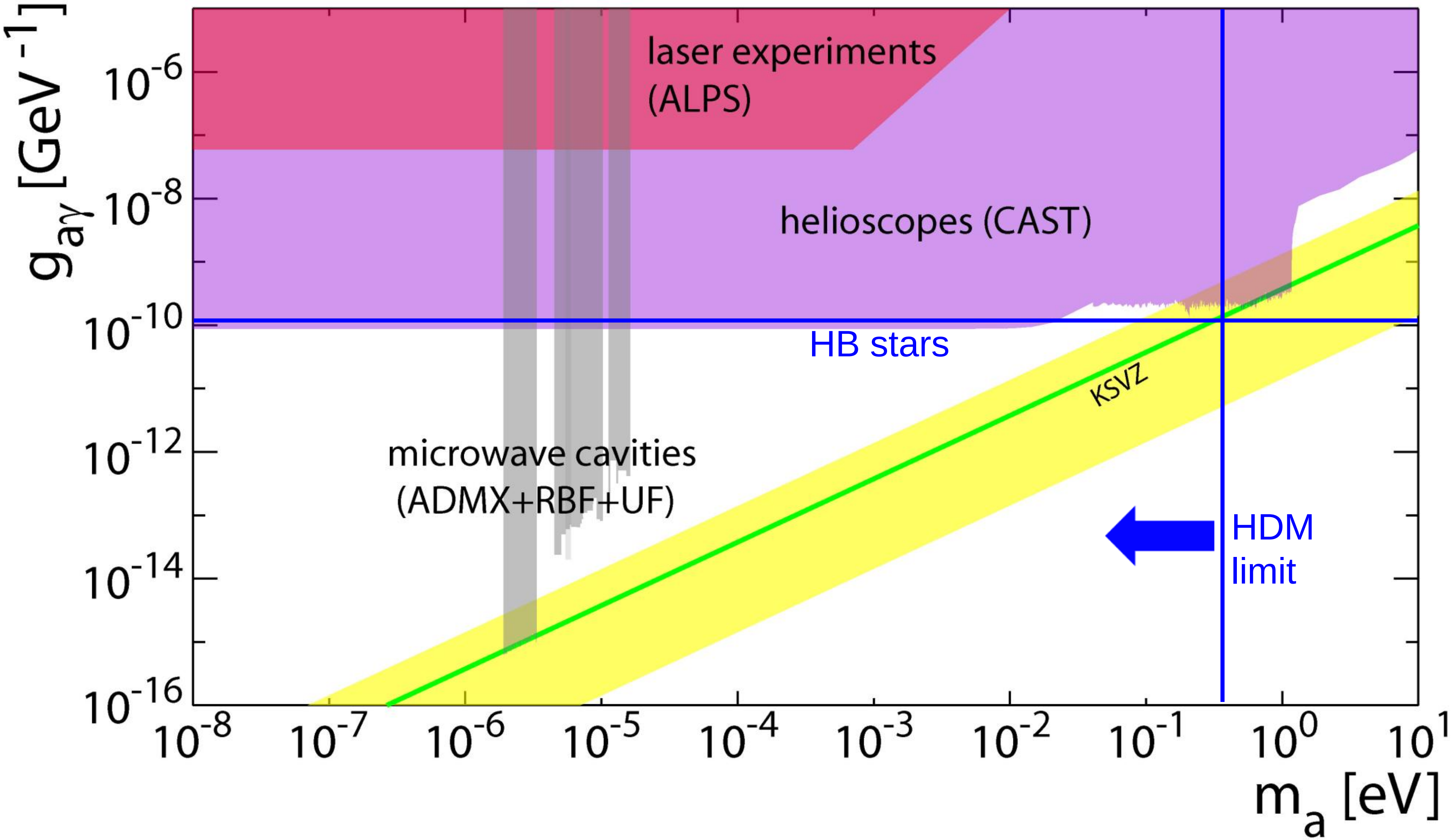
Irastorza et al. JCAP 06 (2011) 013

Axion phase space



Axion phase space



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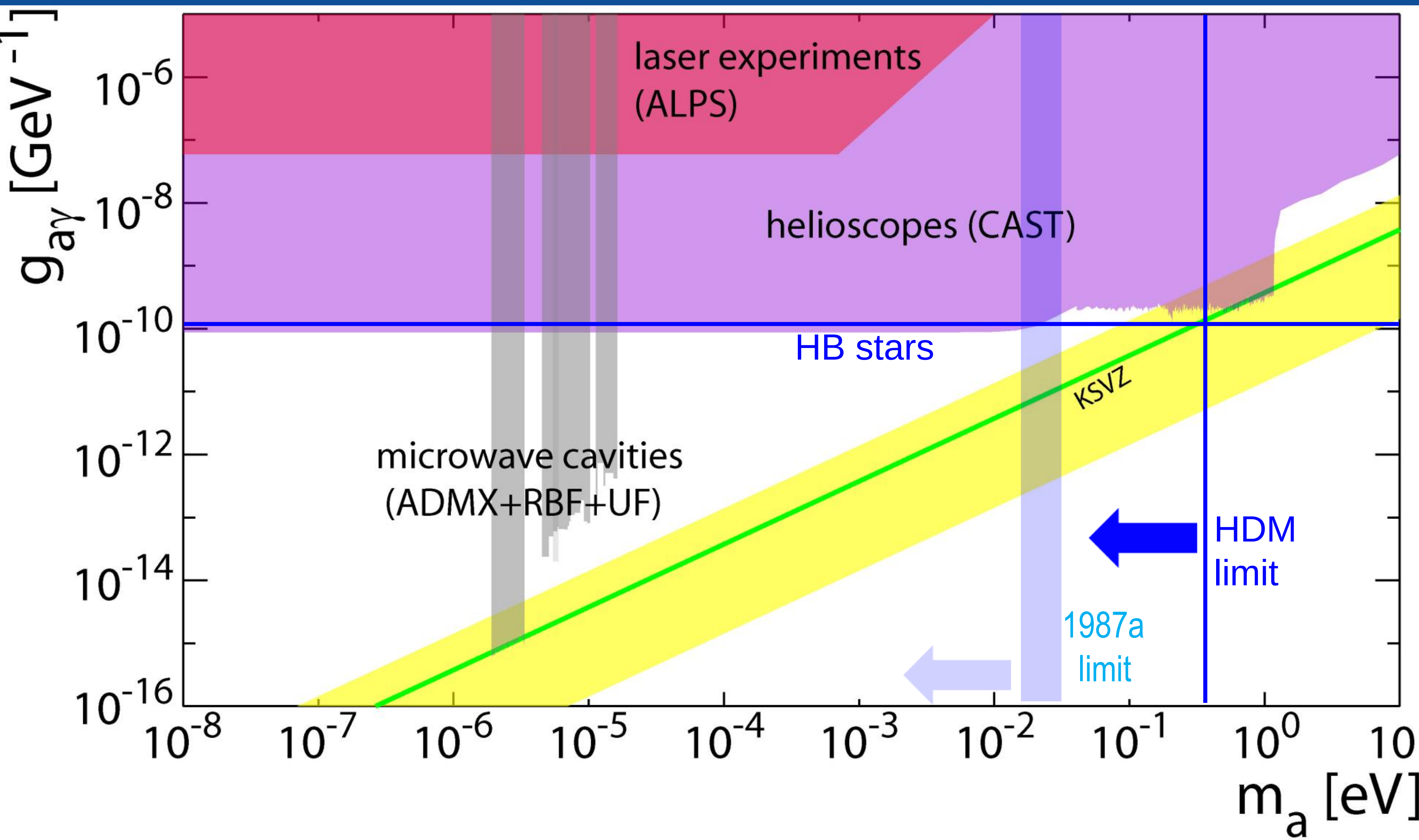

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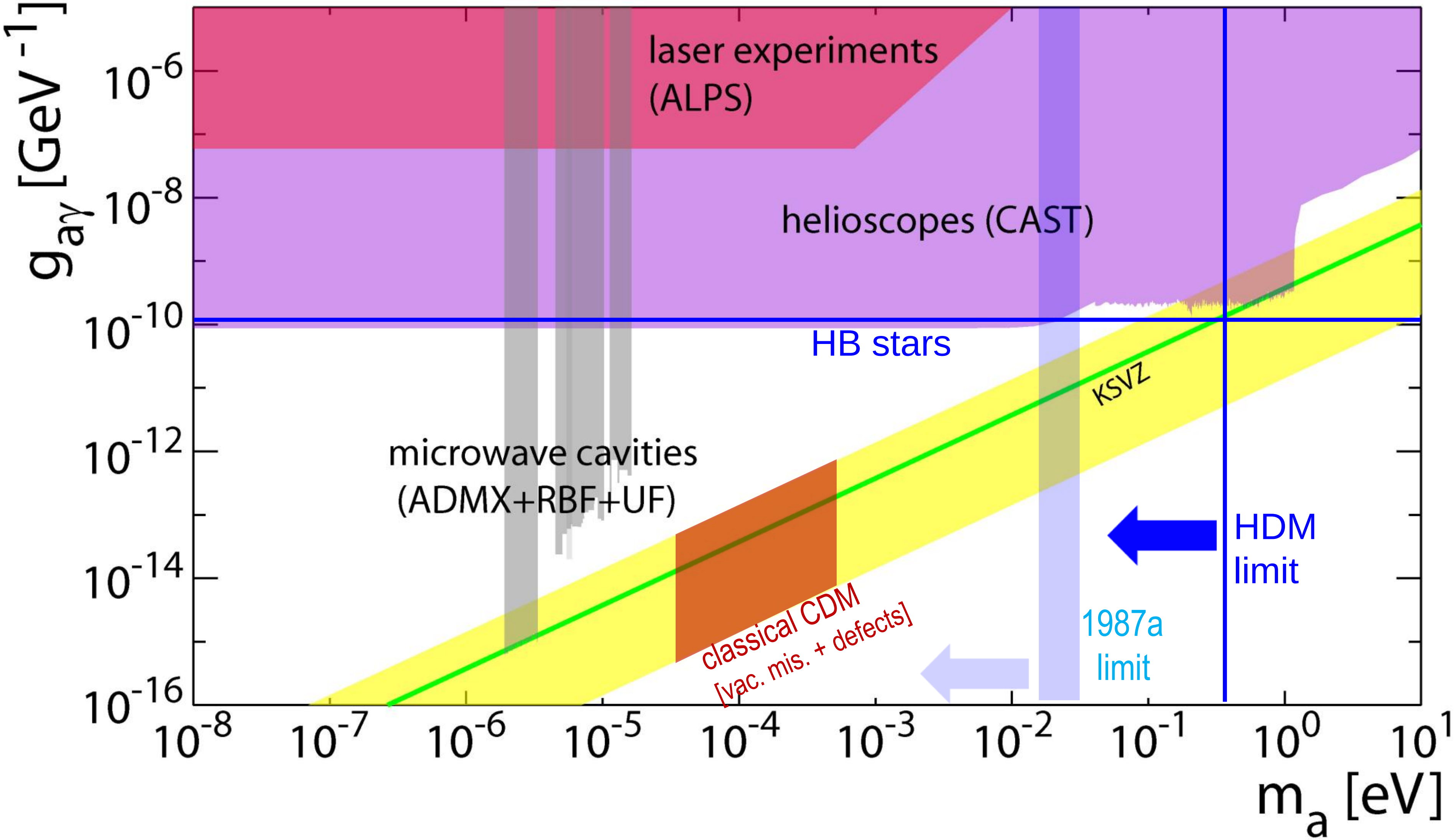

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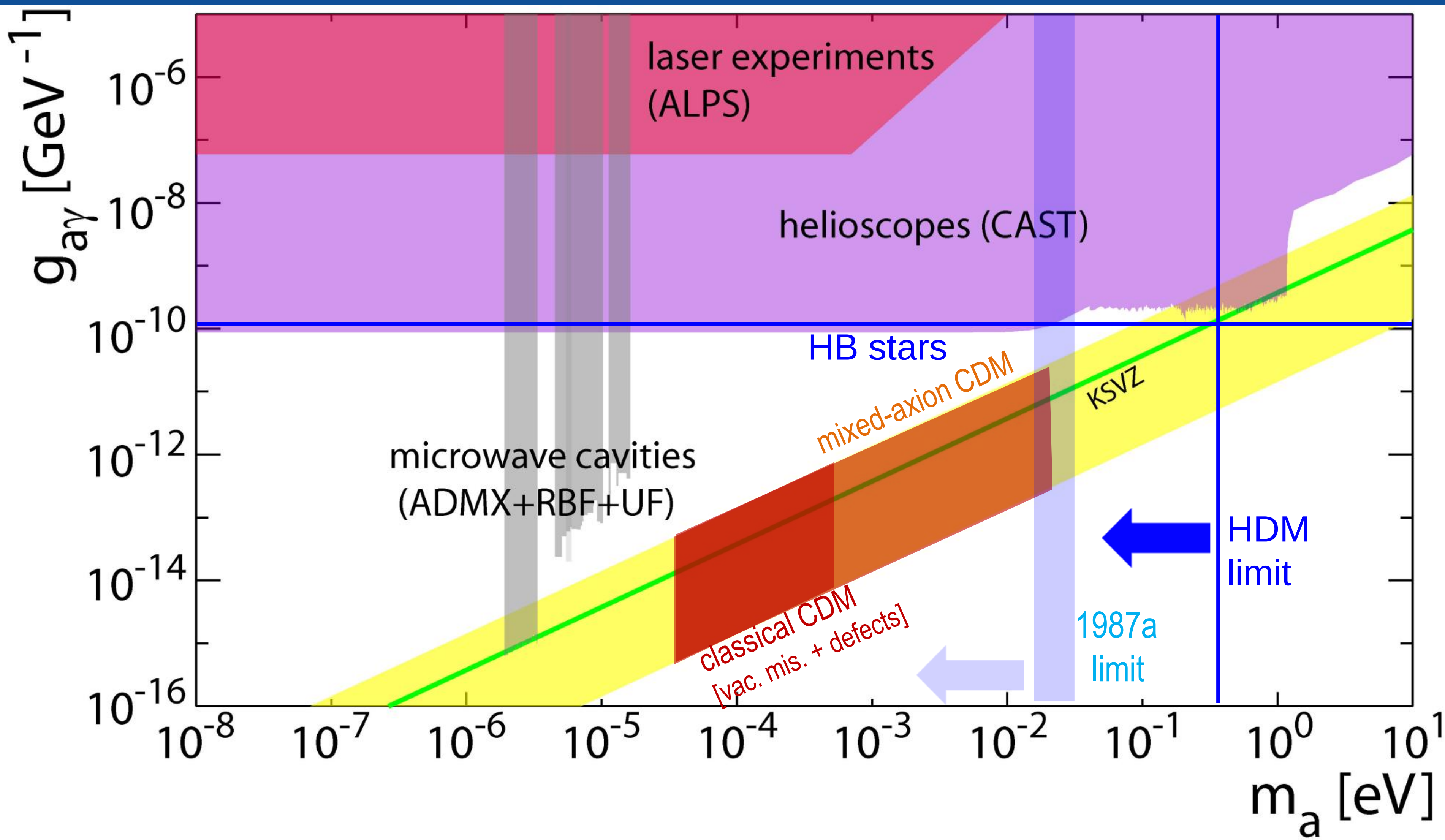

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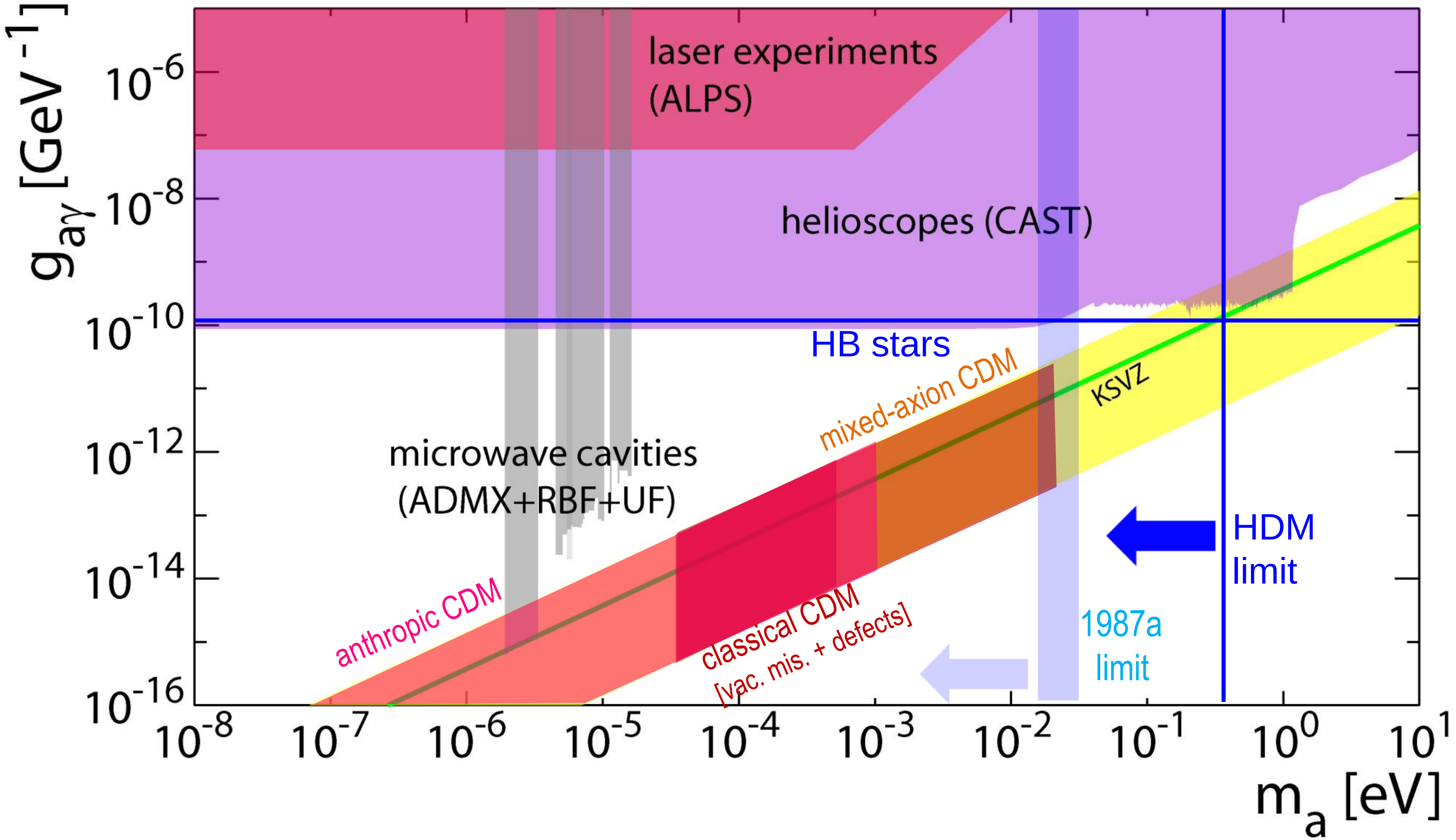
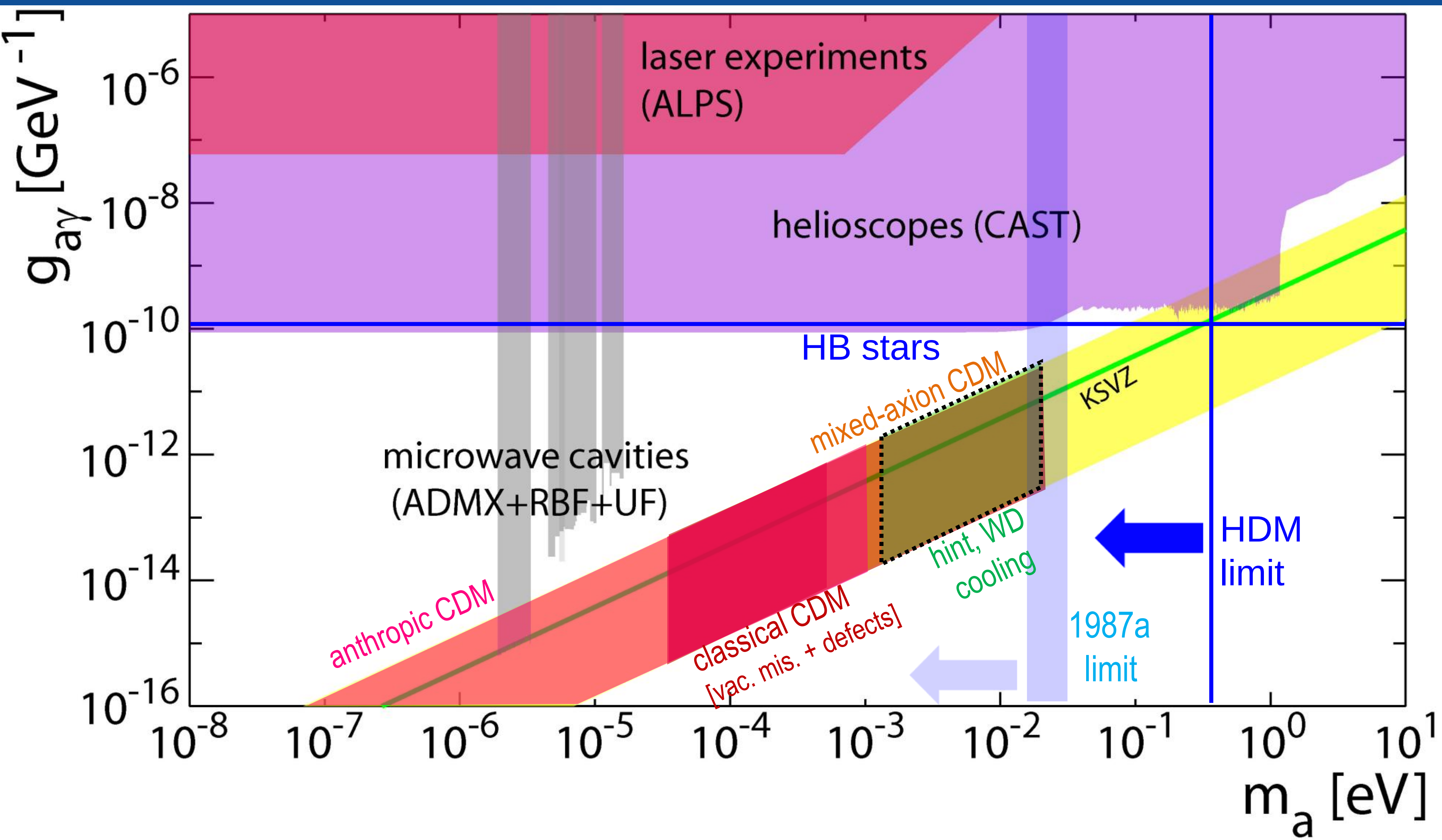
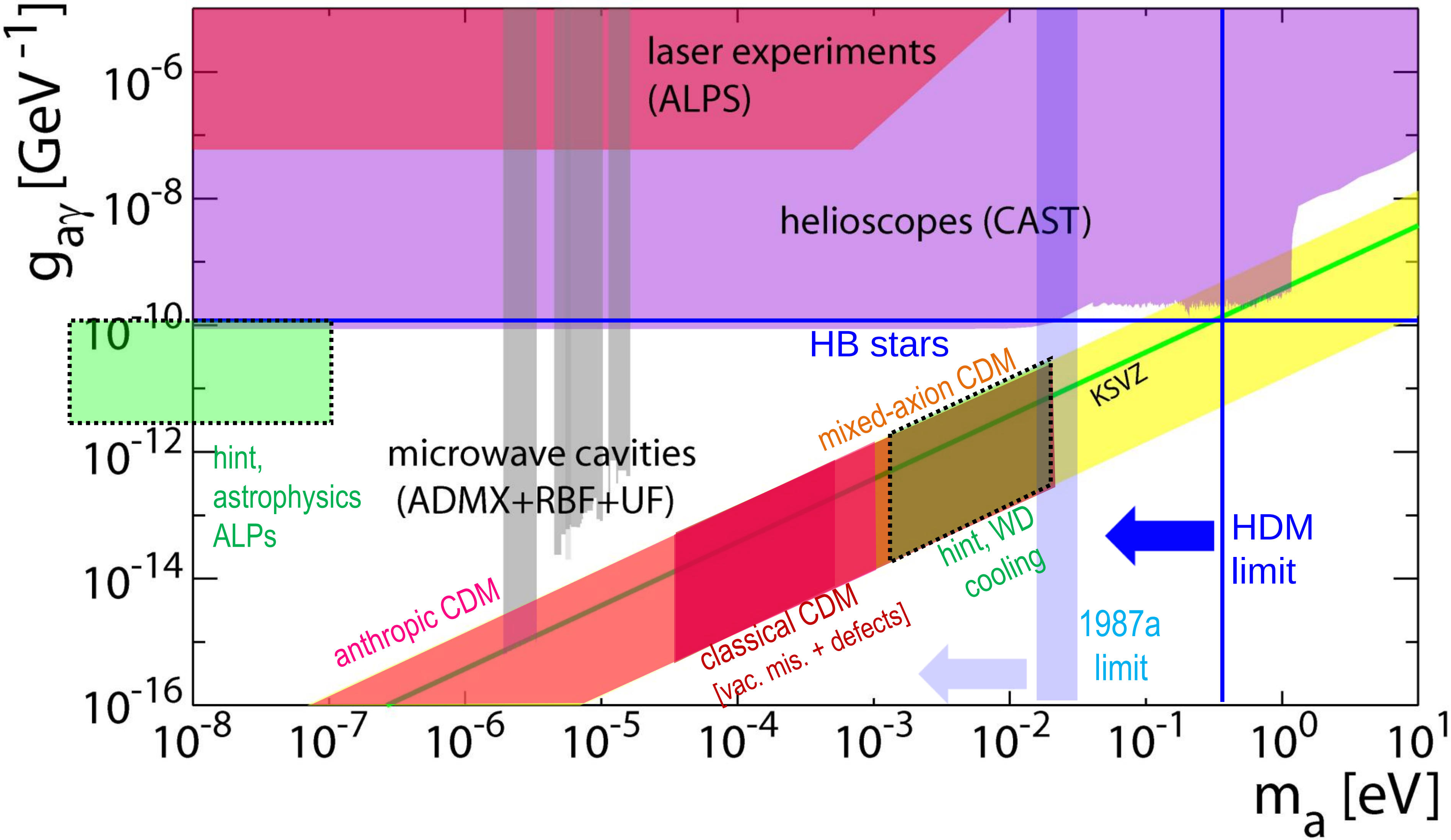


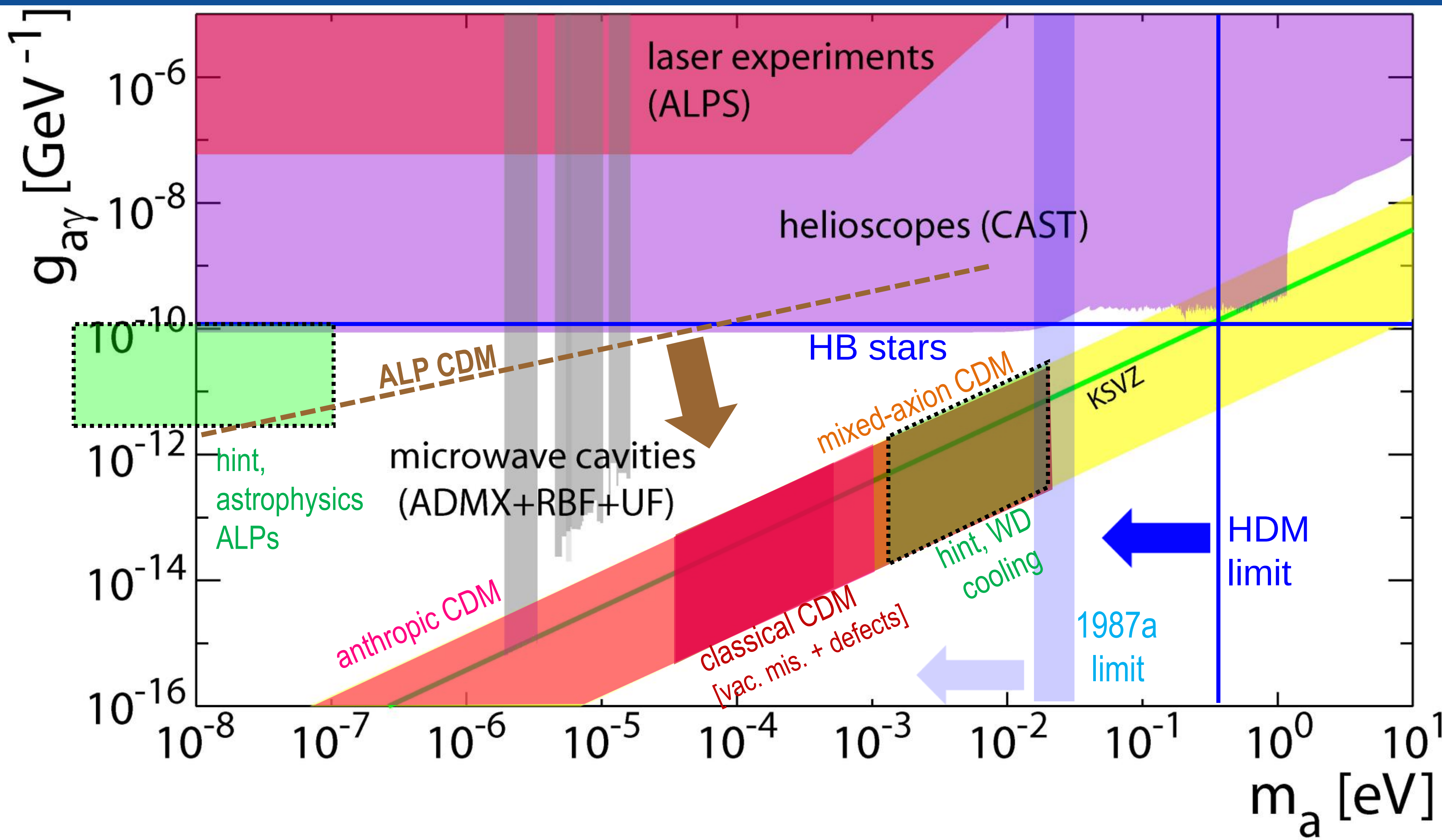
Axion phase space



Axion phase space



Axion phase space



IAXO – 4th generation helioscope

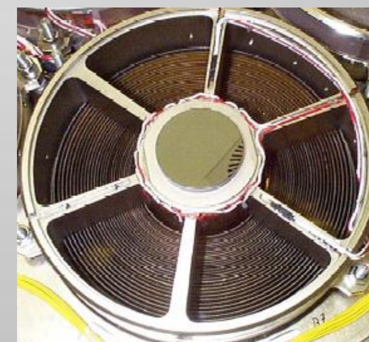
→ 1st generation: Brookhaven Experiment
→ 2nd generation: Tokyo Helioscope
→ 3rd generation: CAST

IAXO = 4th generation axion helioscope

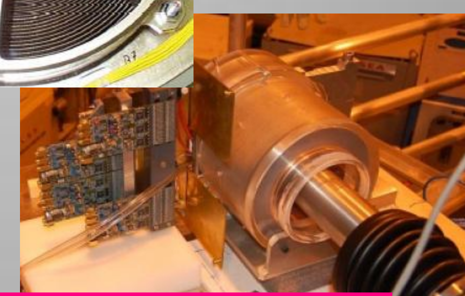
- CAST is established as a reference result in experimental axion physics
- IAXO builds on CAST innovations to improve the helioscope technique…
  - Based on the more than a decade CAST experience
  - Technologies have high maturity [TRL ≥ 6] − no fundamental challenges nor high-risk R&D required
- No other technique can realistically improve grasp over a wide mass range for γ–a coupling

Ingredients of a successful helioscope

Large & powerful magnet...

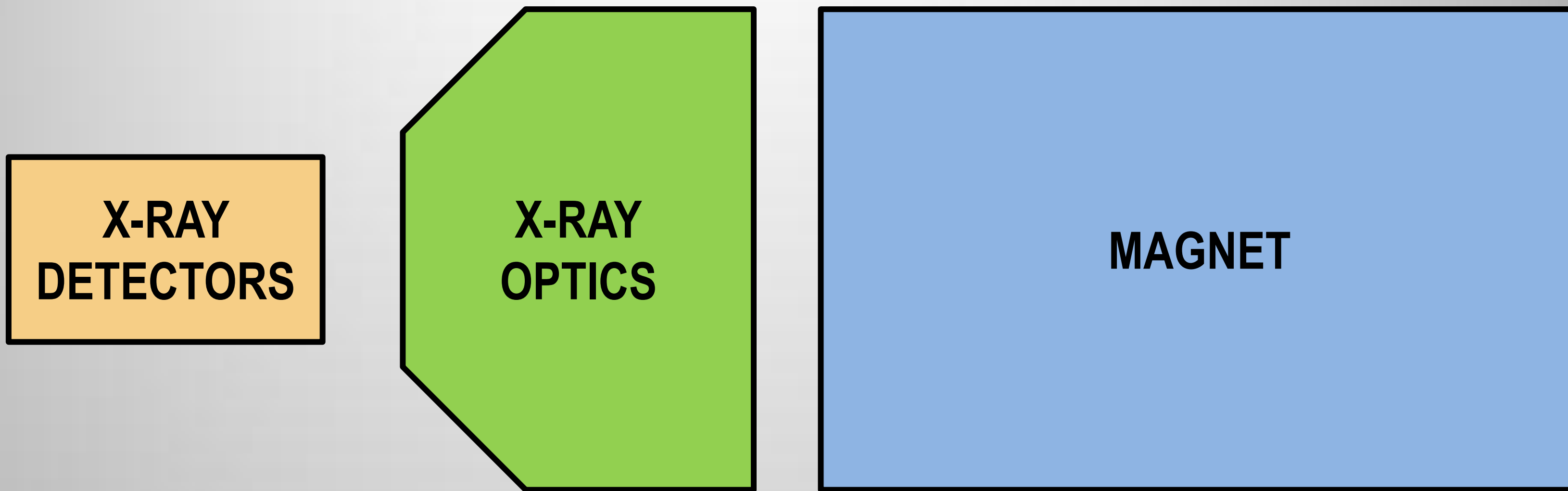


...X-ray optics,...



...and low background detectors

IAXO – How to improve sensitivity



$$g_{ag}^{4} \propto \underbrace{b^{1/2}\varepsilon^{-1}}_{\text{detectors}} \times \underbrace{s^{1/2}\varepsilon_0^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

detectors

b = background
ε = efficiency

optics

s = spot size
ε_0 = efficiency

magnet

B = magnetic field
L = magnet length
A = cross-sectional area

exposure

t = time

IAXO – How to improve sensitivity (2)

- To improve sensitivity, compared to CAST, we define a figure of merit, *f*, that accounts for improvements in sub-systems

$$f \equiv f_M \times f_{DO} \times f_T \propto g_{a\gamma}^{-4}$$

f_M **magnet**

f_{DO} **detectors + optics**

f_T **exposure**

- Achieving one order of magnitude better sensitivity than CAST requires

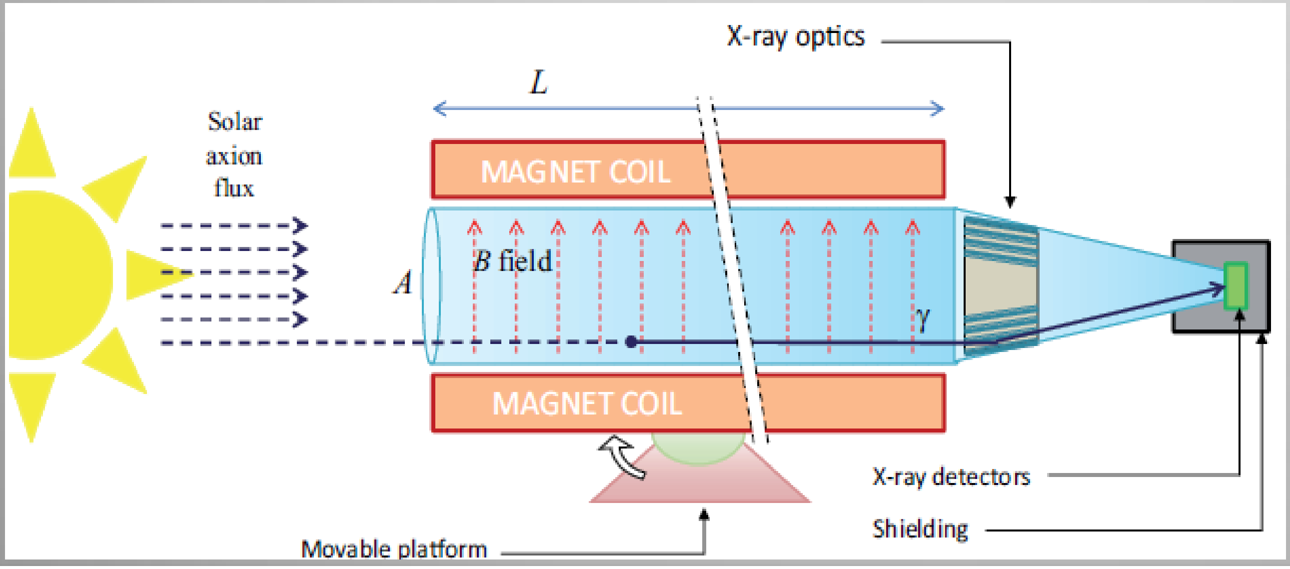
$$g_{a\gamma}^{\mathrm{IAXO}} < \frac{g_{a\gamma}^{\mathrm{CAST}}}{10} \Rightarrow \frac{f_{\mathrm{IAXO}}}{f_{\mathrm{CAST}}} > 10000$$

IAXO – How to improve sensitivity (3)

Parameter	Units	CAST-I	IAXO nominal	IAXO enhanced
B	T	9	2.5	2.5
L	m	9.26	20	20
A	m^2	2×0.0015	2.3	2.3
f_M		1	300	300
b	10^{-5}/(keV cm^2 s)	~4	5×10^{-3}	1×10^{-3}
ε_d		0.5−0.9	0.7	0.8
ε_o		0.3	0.5	0.7
s	cm^2	0.15	8×0.2	8×0.15
f_{DO}		1	17	60
ε_t		0.12	0.5	0.5
t	year	~1	3	3
f_T		1	3.5	3.5
f		1	2×10^4	6×10^4

Magnet for IAXO

- CAST has pushed the limits of "recycling", by using one of the best existing magnets (LHC test magnet)
- Only way to markedly improve reach is to build a new magnet for axions
- Significant modeling and design work completed
- Optimal design is a toroidal configuration (similar to ATLAS):
  - Much bigger bores than CAST
    - 60 cm versus 5 cm
  - Relatively light (no iron yoke)
  - Bores at room temperature
- Incorporate operational principles of a detector magnet with the performance required for axion physics



Toroid radius	**= 4.1 m**
Bore diameter	**= 600 mm**
Number of bores	**= 8**
Cryostat diameter	**= 5.2 m**
Cryostat length	**= 25 m**
Peak field	**= 5.4 T**
Stored Energy	**= 500 MJ**
Total mass	**≈ 250 Tons**

Shilon et al. arXiv:1212.4633v1
IEEE Trans Appl Supercond 23 (2013)

Magnet for IAXO (2)

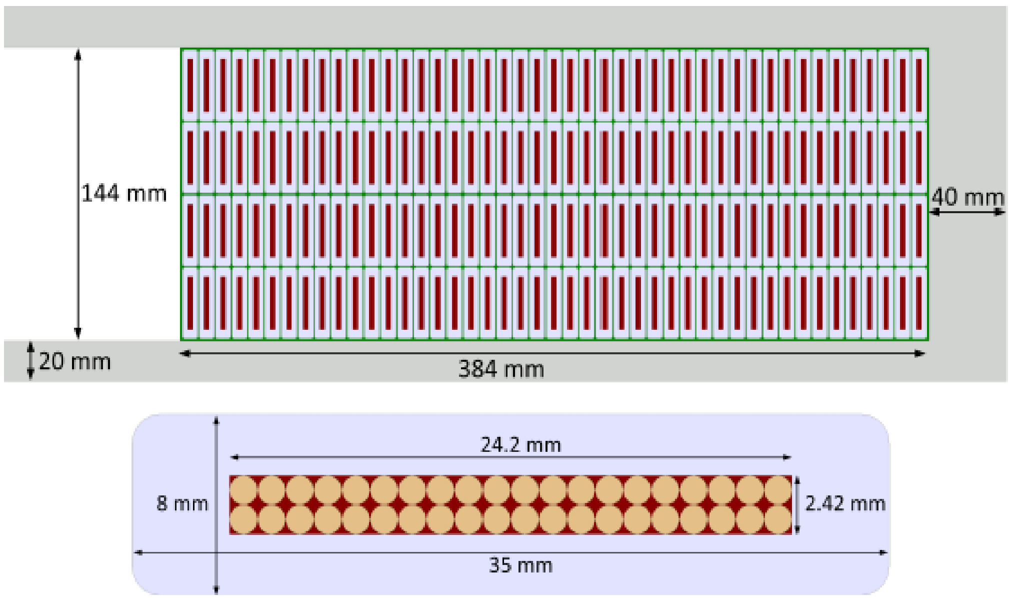
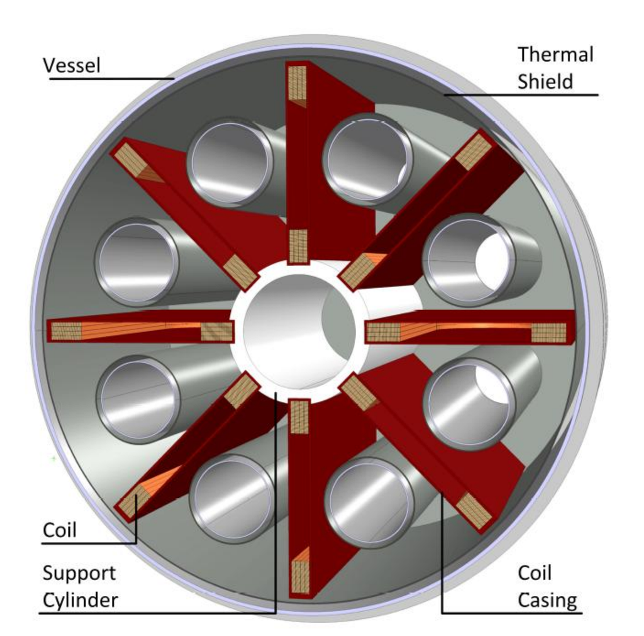
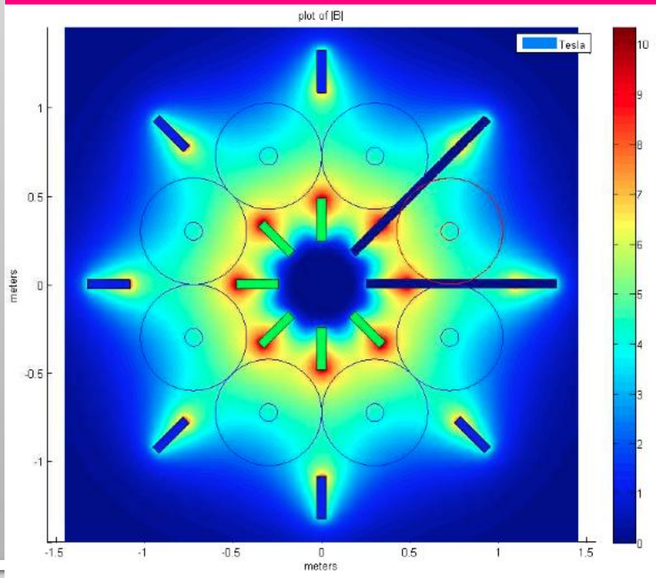


Fig. 4. Cross section of the conceptual design of the two double pancake winding pack and the coil casing (top) and the conductor with a 40 strands NbTi Rutherford cable embedded in a high purity Al stabilizer (bottom).

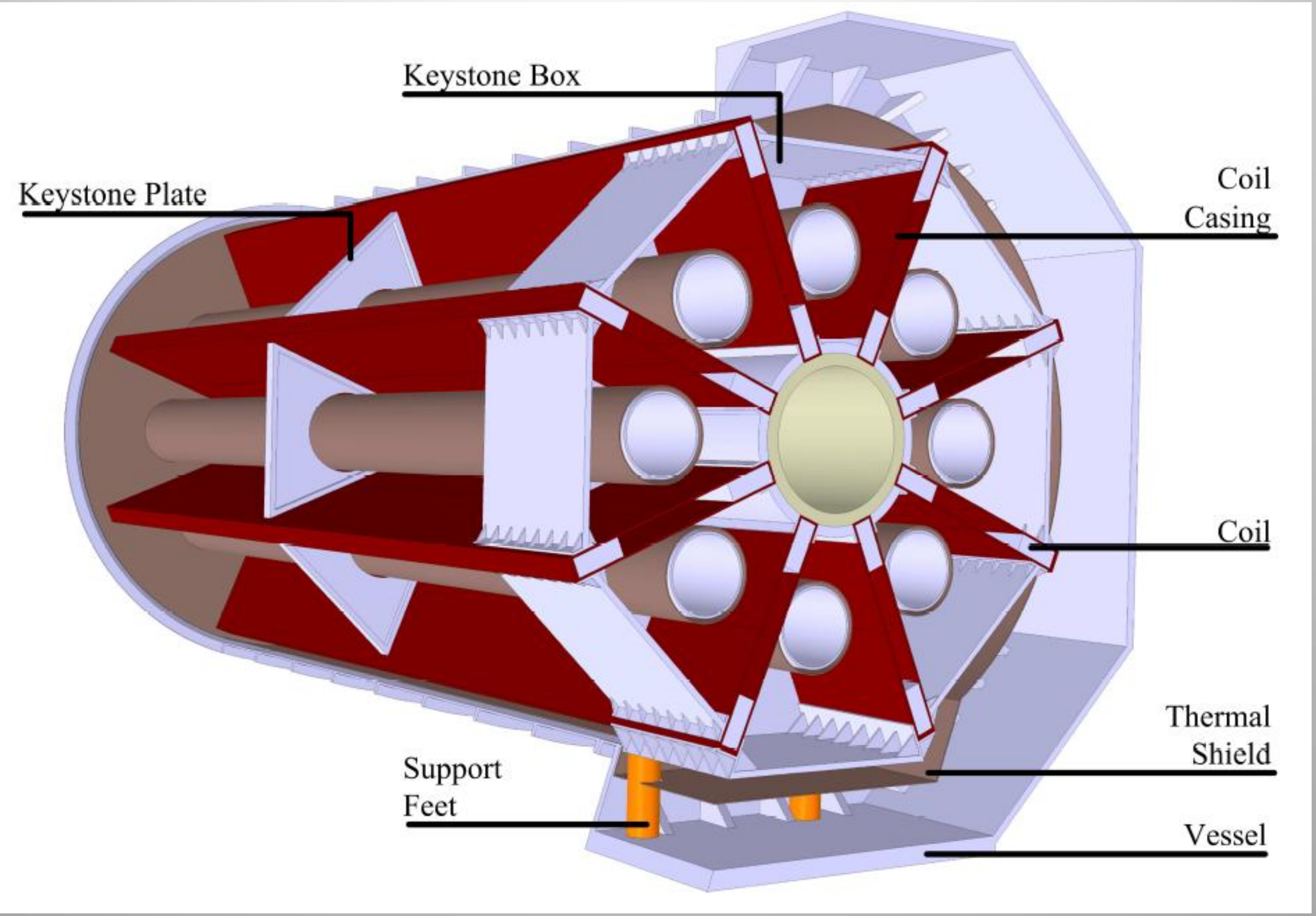
Shilon et al. arXiv:1212.4633v1
IEEE Trans Appl Superc 23 (2013)



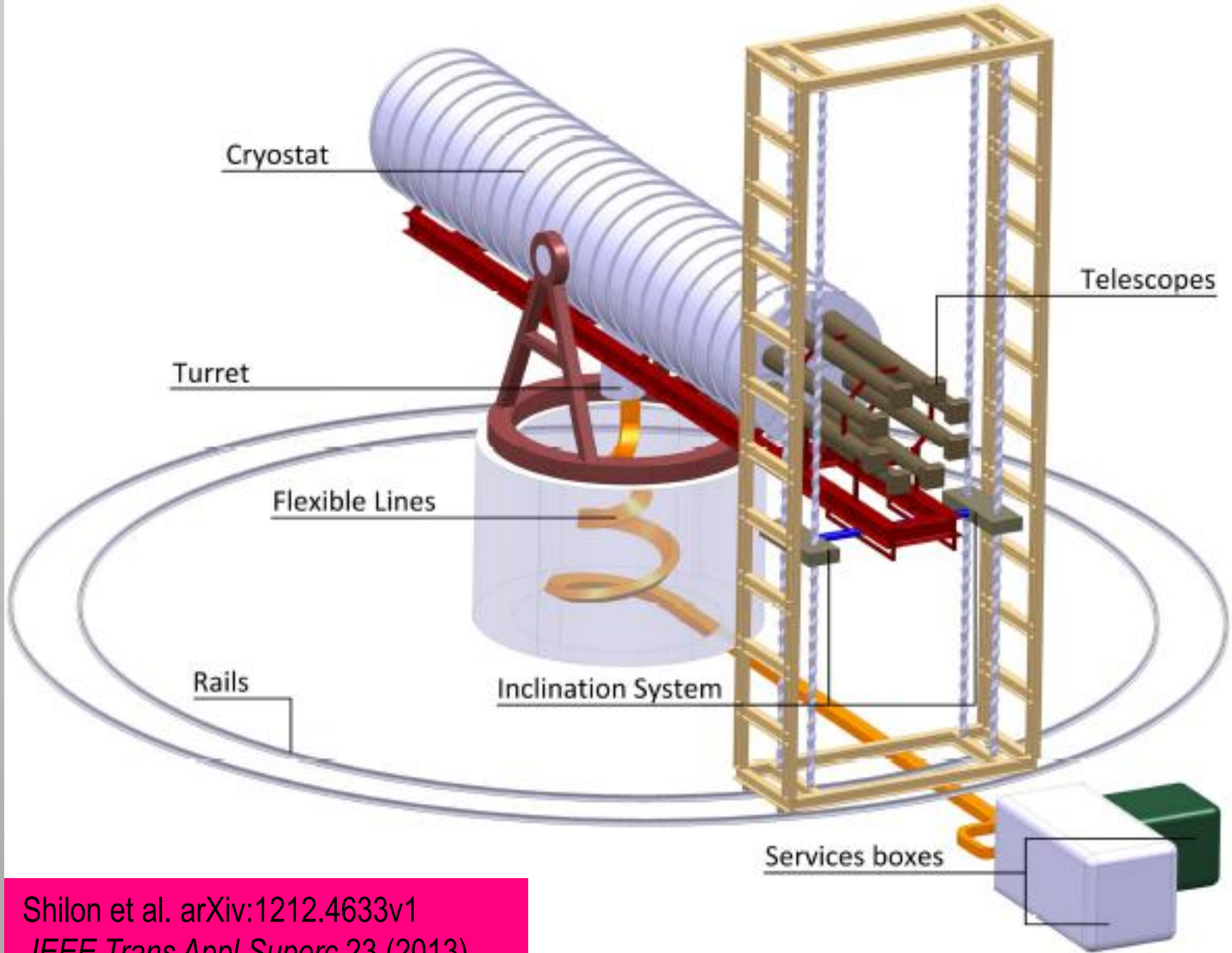
Plot of magnetic fields



Magnet for IAXO (3)

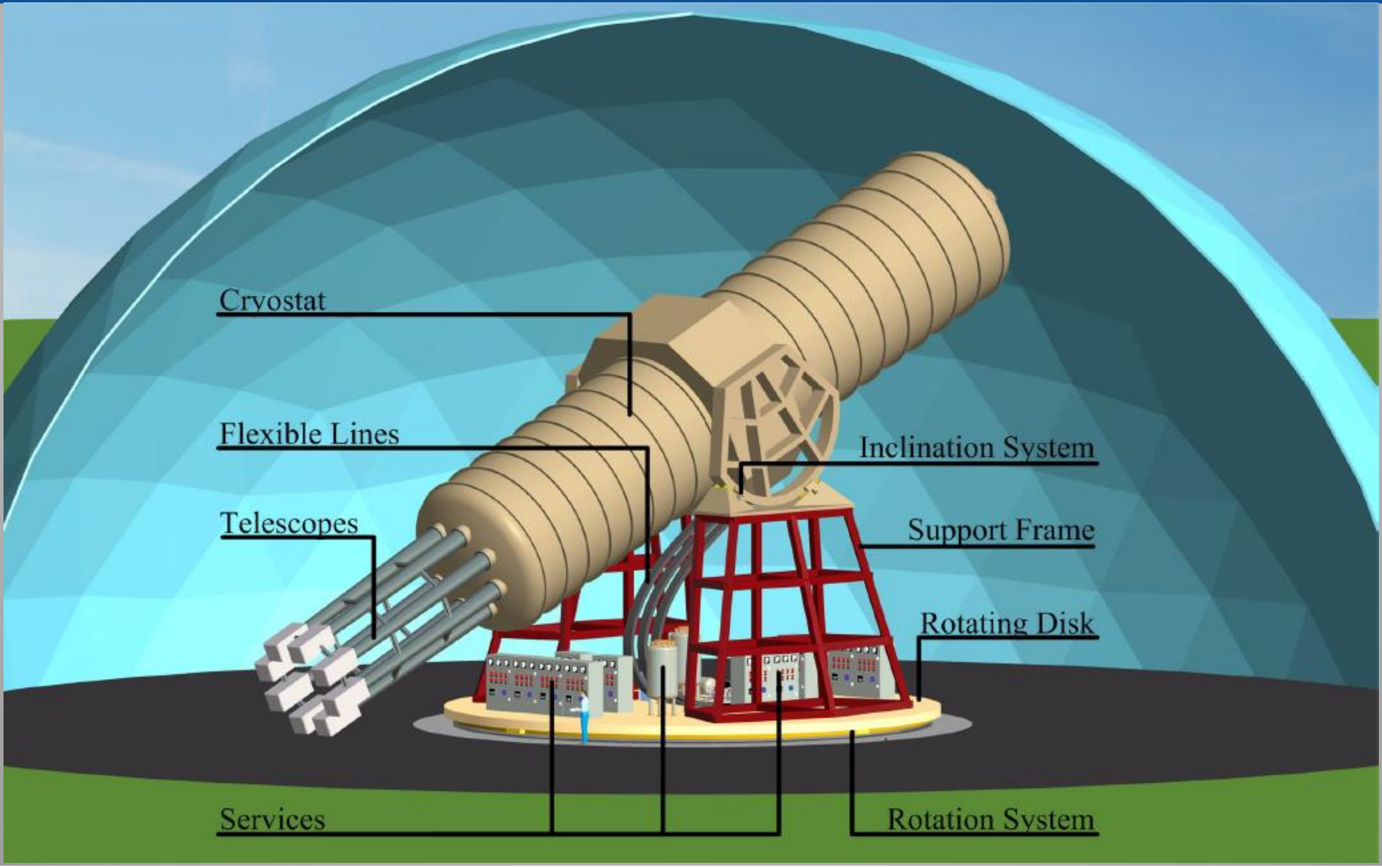


Maturing design for IAXO



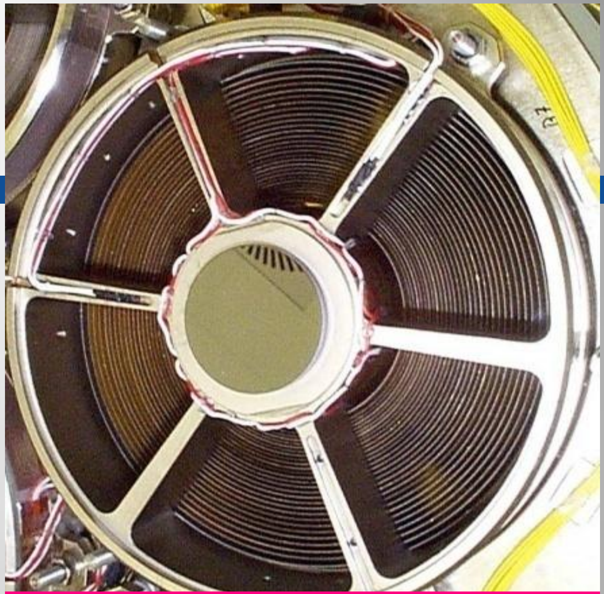
Shilon et al. arXiv:1212.4633v1
IEEE Trans Appl Superc 23 (2013)

IAXO conventional facilities

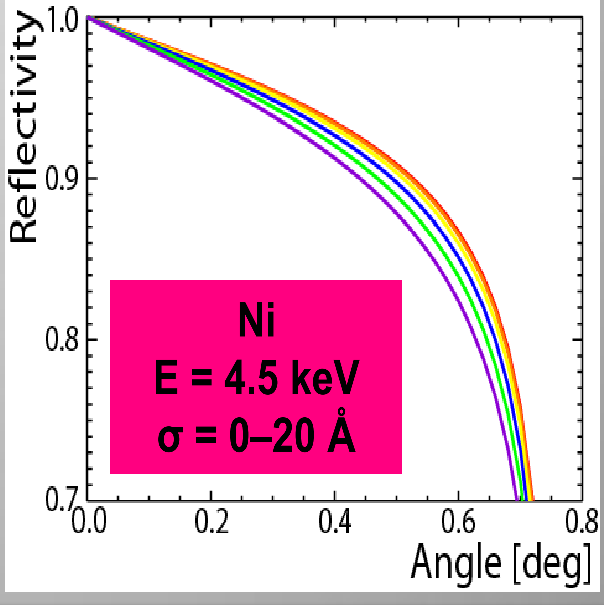


X-ray optics

- X-ray astrophysics community has invested heavily in the development of reflective x-ray optics:
  - 40+ years of telescopes in space
  - Excellent imaging capabilities
- Innovations include:
  - Nested designs (*e.g.*,Wolter telescopes)
  - Low-cost substrates
  - Highly reflective coatings
- IAXO optics requirements:
  - Exquisite imaging not needed for solar studies
  - Optics aperture matched to magnet bore size
    → IAXO requires dedicated but cost-effective optics
  - Good throughput (30–50% integrated reflectivity)

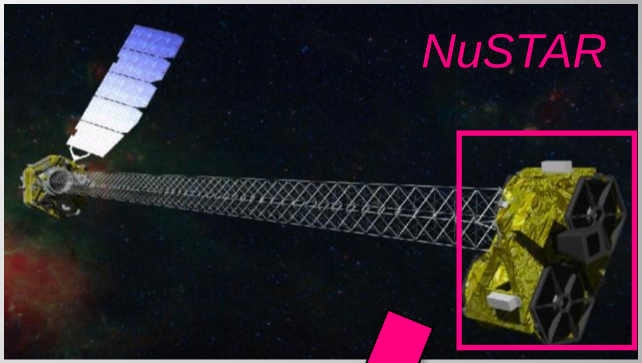


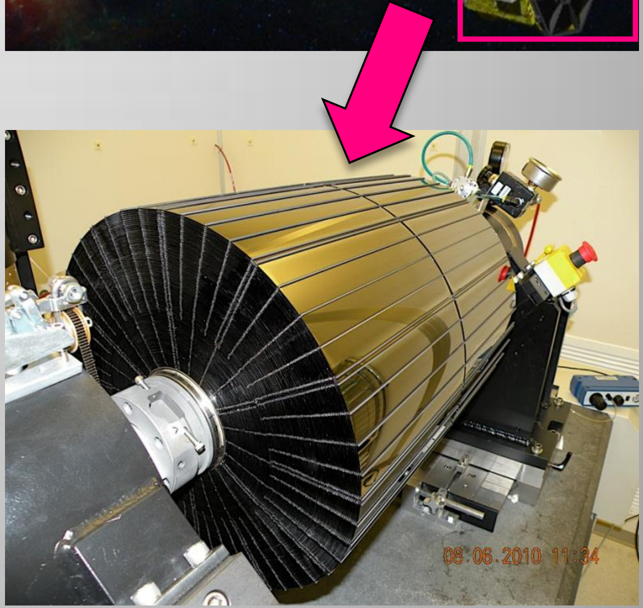
ABRIXAS flight-spare telescope



X-ray optics (2)

- Thermally-formed glass substrates optics
  - Successfully used for NASA's *NuSTAR*
  - Leverage of existing infrastructure
    → Minimize costs & risks
  - Allows for optimization of the reflective coating (multilayers or thin metal films)
- *NuSTAR* launched 13 June 2012
  - Specialized tooling for mirror production and telescope-assembly now available
  - Hardware can be easily configured to tailor dimensions of optics
- Many institutes from *NuSTAR* optics team [Columbia U, DTU Space, LLNL] in IAXO

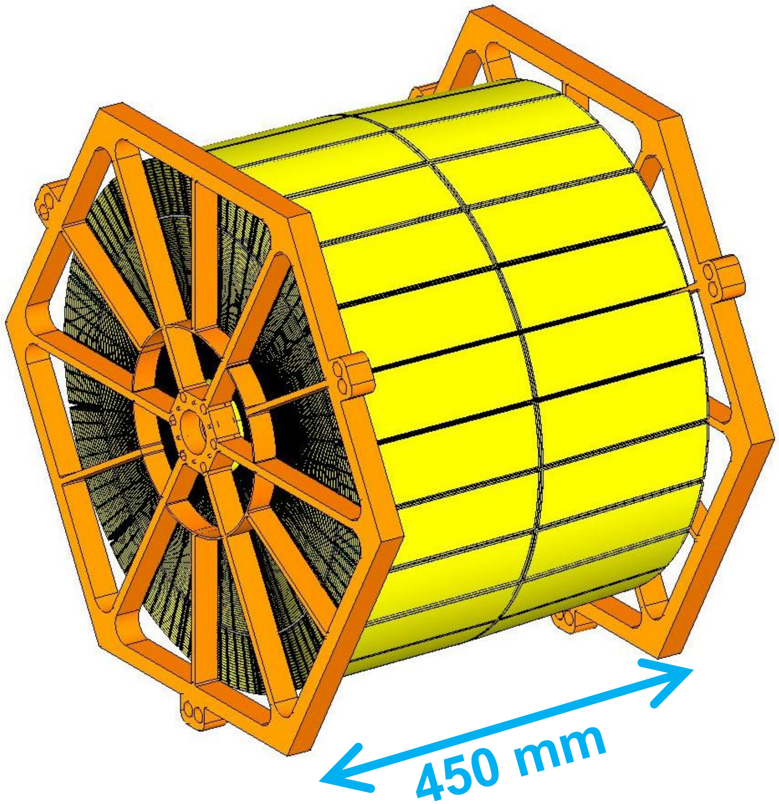


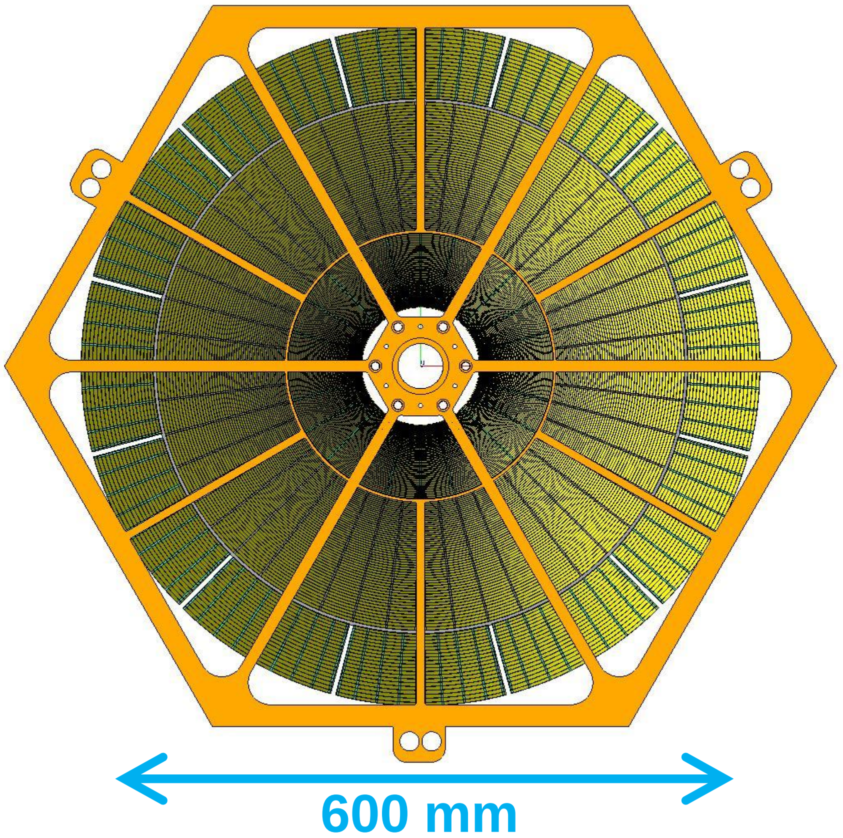


***NuSTAR* x-ray telescope**

J Koglin *et al., Proc SPIE*, **8147,** (2011)
W Craig *et al., Proc SPIE*, **8147,** (2011)

X-ray optics (3)



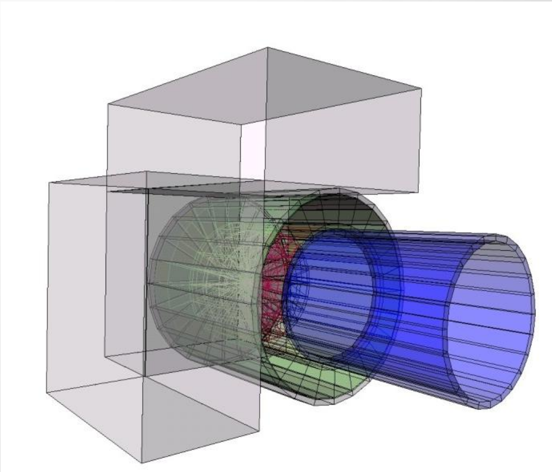


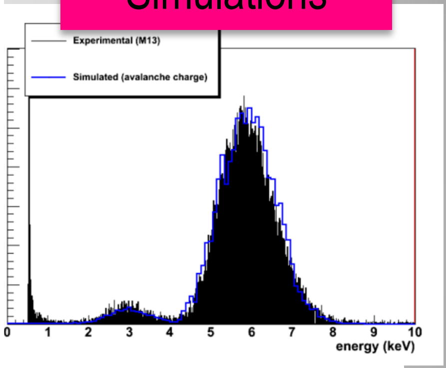
Telescopes	= 8
Layers per telescope	= 123
Mirrors per telescope	≈ 2200
Focal length	= 5 m
Coatings	= W/B_4C multilayers
Pass band	= 1−10 keV
Half-power diameter	= 60 arcsec

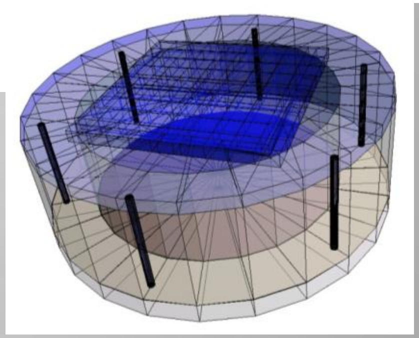
Low-background detectors

- **Goal**
  - Micromegas detectors with at least 10^{-7} cts/(keV×cm^2×s)
  - May be possible to reach 10^{-8} cts/(keV×cm^2×s)
- **Work ongoing**
  - Experimental tests with current micromegas detectors at CERN, Saclay & Zaragoza
  - Underground setup at Canfranc
  - Simulation works to build up a background model
  - Design a new detector with improvements implemented

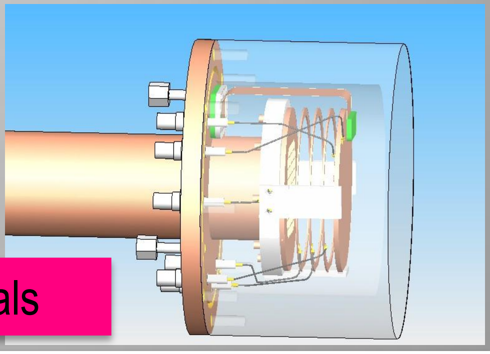
Simulations







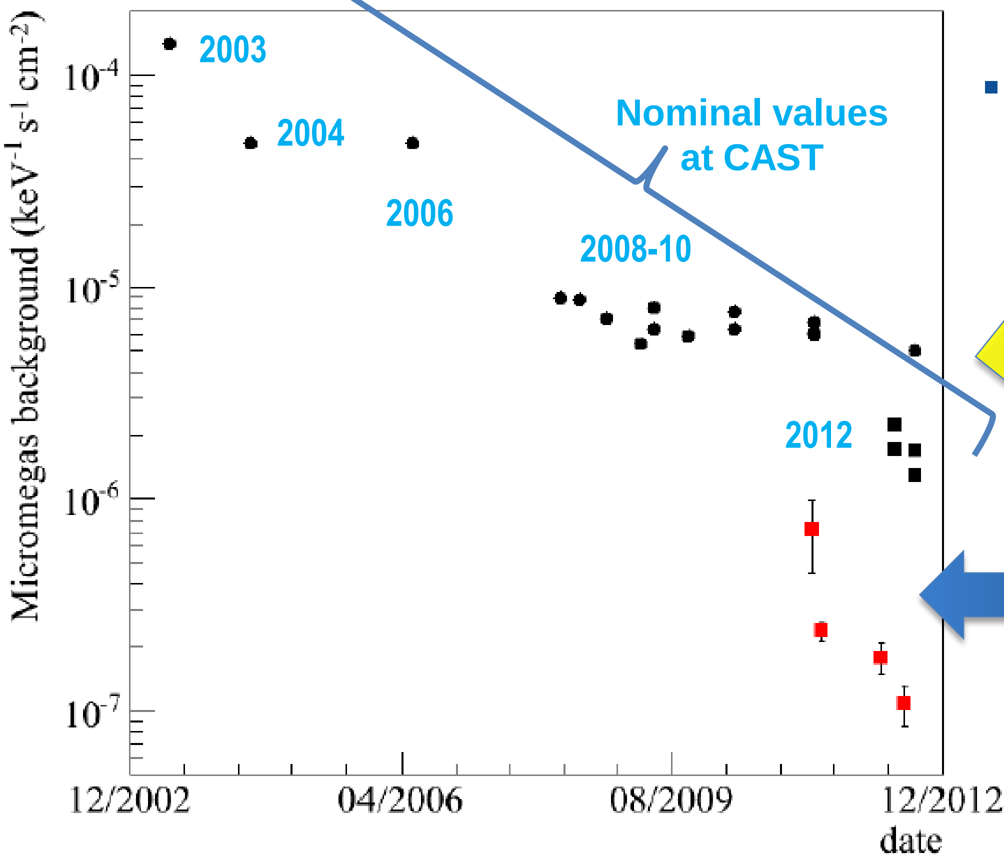
Shielding



Radiopure materials

Low-background detectors (2)

History of background improvement of Micromegas detectors at CAST



- Latest Micromegas background improved by 20×
  - Shielding & radiopure materials
  - New fabrication methods (microbulk readouts)
  - More powerful post-processing methods

- Tests in controlled conditions underground at Canfranc:
  - Better shielding coverage
  - Thicker shielding

Backgrounds around ~10-7 cts/keV/s/cm^2 with improved shielding ~ 30× better than CAST

Underground testing of new configurations

Low-background detectors (3)

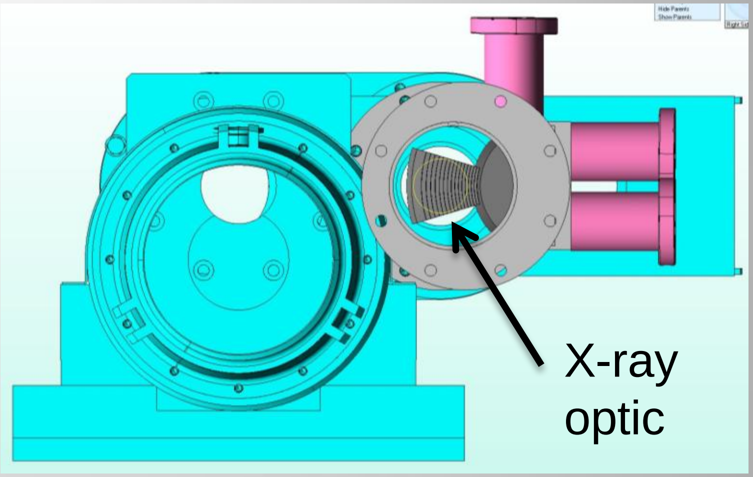
As implemented in CAST [2013]

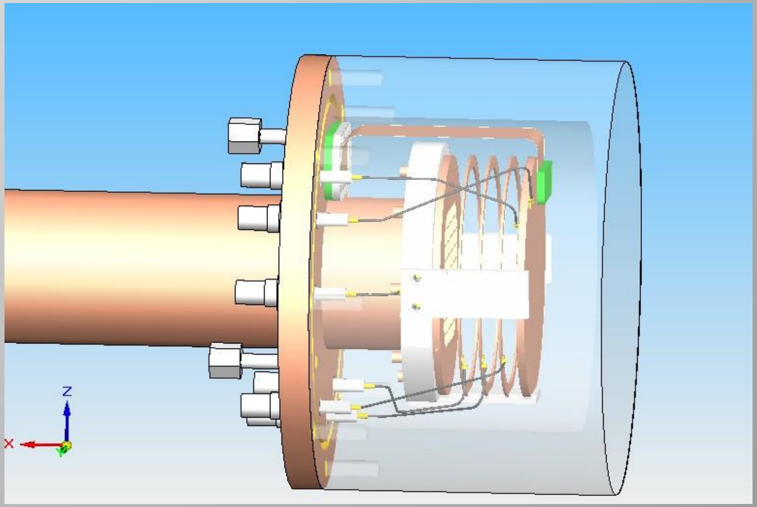
Pathfinder detector+optics for IAXO

- Small x-ray optics
  - Fabricated purposely using thermally-formed glass substrates (NuSTAR-like)
- Micromegas low background detector:
  - Apply lessons learned from R&D: compactness, better shielding, radiopurity,…
  - Aim for background of 10^{-7} cts/(keV×cm^2×s) or lower
- Collaboration of key groups:
  Saclay, Zaragoza, LLNL, DTU, Columbia

➡ Installation at CAST in 2014

➡ Tests of techniques and instrumentation; gain operational knowledge for IAXO

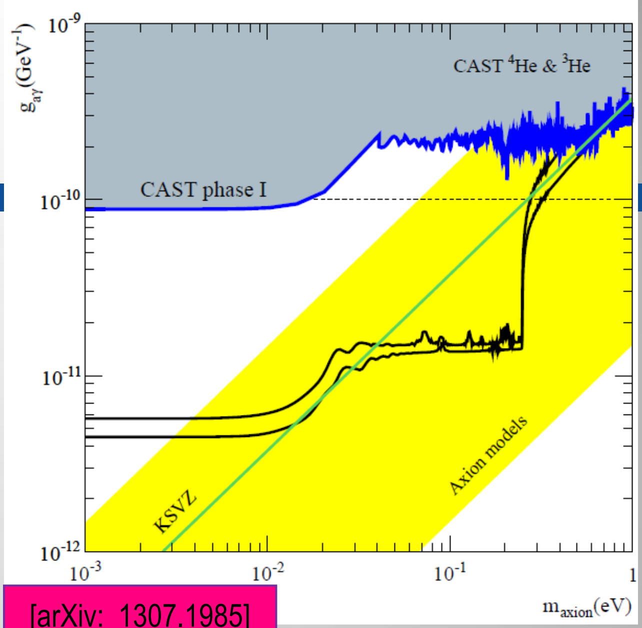




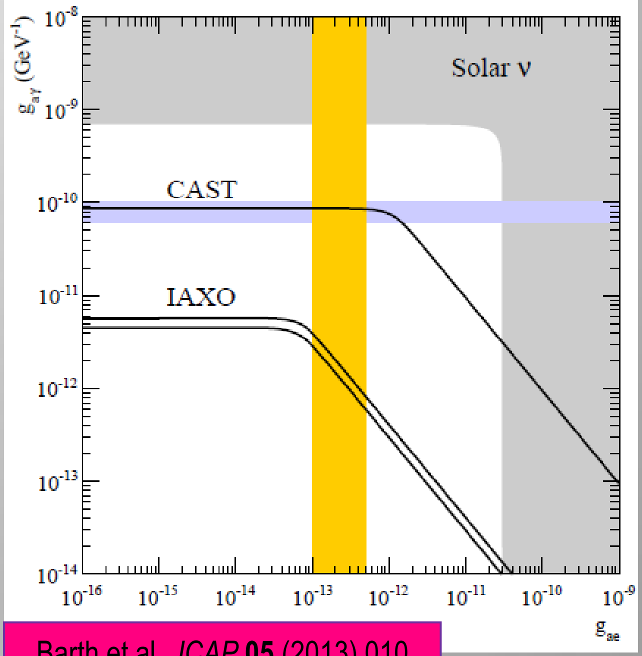
IAXO sensitivity prospects

- **Hadronic axion models**
  - Improvements of **8−30×** in $g_{a\gamma}$ (4×10^3 -1×10^6 in signal stregnth)
  - QCD axions at masses of ~1 meV seem out of reach even for an improved axion helioscope **but …**
- **Non-hadronic axion models** provide extra axion emission from the Sun through axion-electron Compton and bremsstrahlung processes

IAXO could improve current CAST sensitivity to non-hadronic axions by about 3 orders of magnitude

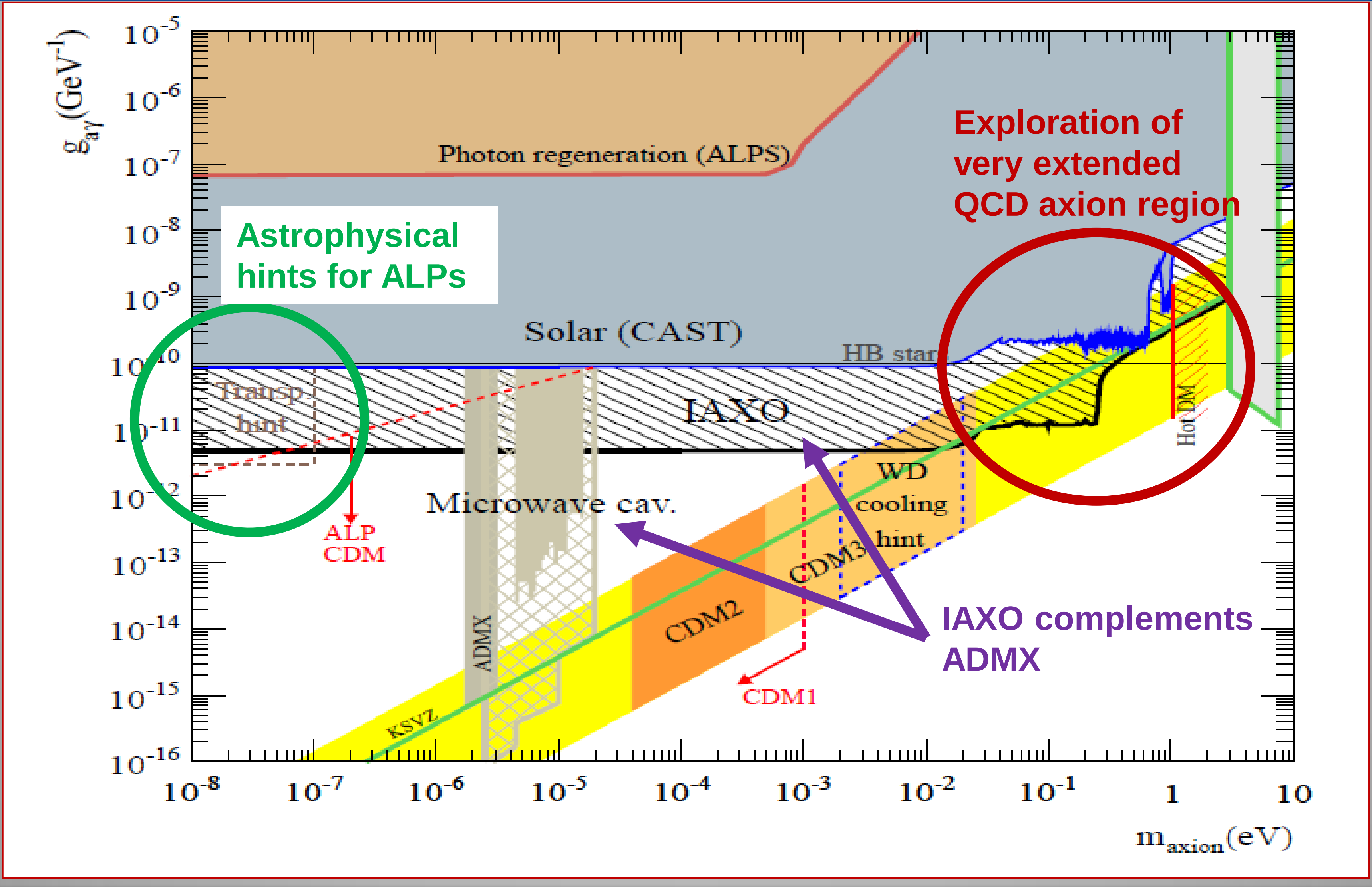


[arXiv: 1307.1985]



Barth et al. *JCAP* **05** (2013) 010

IAXO sensitivity prospects (2)



Collaboration status and schedule

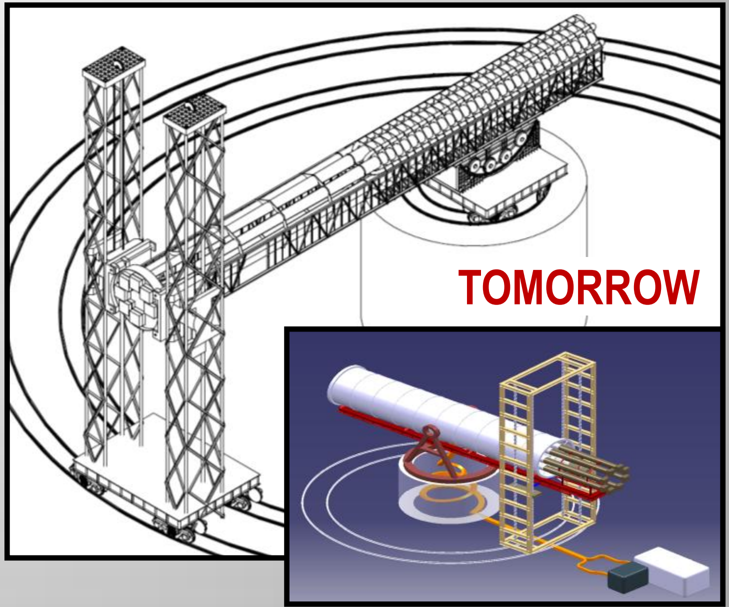
- Collaboration formed and growing
  - 100 physicists, 20 institutions, 15 countries
- Conceptual design report in preparation; LOI solicited by CERN and **submitted August 2013**
- 4th gen helioscope supported in 2011 ASPERA roadmap

- Socializing IAXO with DOE/SC/HEP and communities of interest (dark matter, particle astrophysics, …)
- Budget [ROM] = $60−110M (dependent on cost models)
  - $30M magnet
  - $10M CF
  - $16M optics
  - $ 6M detectors

} does not include labor

Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10
Phase I		Phase II			Phase III		Phase IV		
Reduce risk Prototype: optics, detector, magnet		**Construction** Build: conventional facilities, magnet, optics detectors			**Commission** Integrate elements, calibrate, test operations		**Science observations:** Solar searches Extragalactic? Microwave cavities?		

Conclusions



- **CAST is at the forefront of experimental axion physics**
  - CAST PRL2004 most cited experimental paper in axion physics
  - Expertise gathered in magnet, optics, low background detectors, gas systems
  - No other technique can realistically improve on CAST sensitivity over a wide mass range.
- **IAXO is a proposed 4th generation axion helioscope**
  - Good prospects to improve CAST by 1−1.5 orders of magnitude in sensitivity
  - Conceptual design effort is underway and will be completed in 2013
  - Together IAXO and haloscopes (ADMX) could explore a large part of the QCD axion model region in the next decade
  - Potential for other physics (White Dwarfs, ALPs,…)

Additional physics potential

- More specific ALP or WISP (weakly interacting slim particle) models could be searched for at the low energy frontier of particle physics:
  - Paraphotons / hidden photons
  - Chameleons
  - Non-standard scenarios of axion production
- Axions will also have more subtle implications on other astrophysical objects:
  - Neutron stars
  - SNe
  - Red Giants in Globular Clusters
- If equipped with microwave cavities, dark matter halo axions could be searched for, extending the sensitivity to lower masses.
  - under study → Baker et al. (PRD **85** 035018 [2012])
- **IAXO is a true “axion facility” open to the community**
- **Groups are invited to contribute and enrich the science program of IAXO**