Latest Updates on IAXO (International Axion Observatory)

TAUP 2013, Asilomar, CA
8 – 13 September 2013

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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

Towards a new generation axion helioscope

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Irastorza et al. JCAP 06 (2011) 013

Letter of Intent to the CERN SPSC

The International Axion Observatory IAXO

CERN-SPSC-2013-022; SPSC-I-242
http://cds.cern.ch/record/1567109

What is an axion? (in 70 words or less)

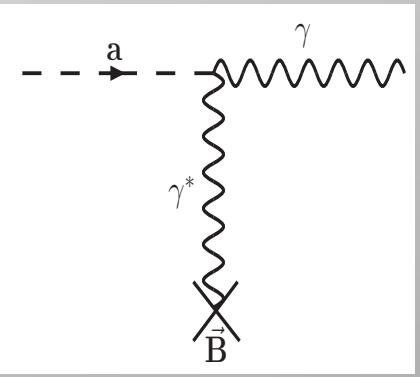
- **Strong CP problem**

  CP violation expected in QCD, but not observed experimentally (θ, nEDM)

- **Peccei-Quinn solution**
  - New global U(1) symmetry, θ into a dynamical variable, relaxes to zero

- **Axion**
  - Pseudo Goldstone-Boson results if this new symmetry is spontaneously broken at yet unknown scale f_a

- **Properties of this potential DM candidate**
  - Extremely weakly-coupled fundamental pseudoscalar
  - Generic coupling to two photons
  - Mass unknown $m_a \propto g_{a\gamma}$, Astrophysics: $g_{a\gamma} < 10^{-10}$ GeV^{-1}



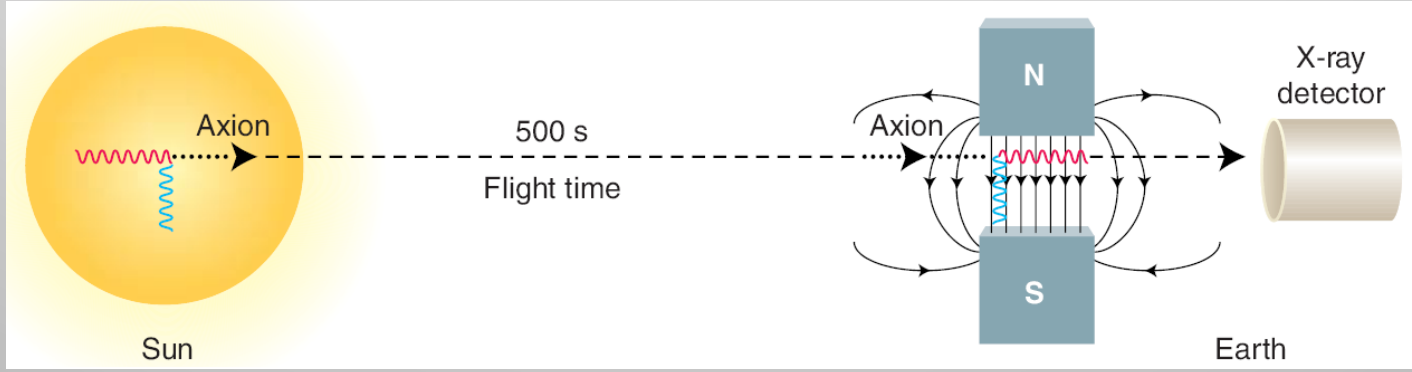
Two birds with one stone: strong CP problem & dark matter

Production and detection of axions

- First axion helioscope proposed by P. Sikivie

Sikivie *PRL* 51:1415 (1983)

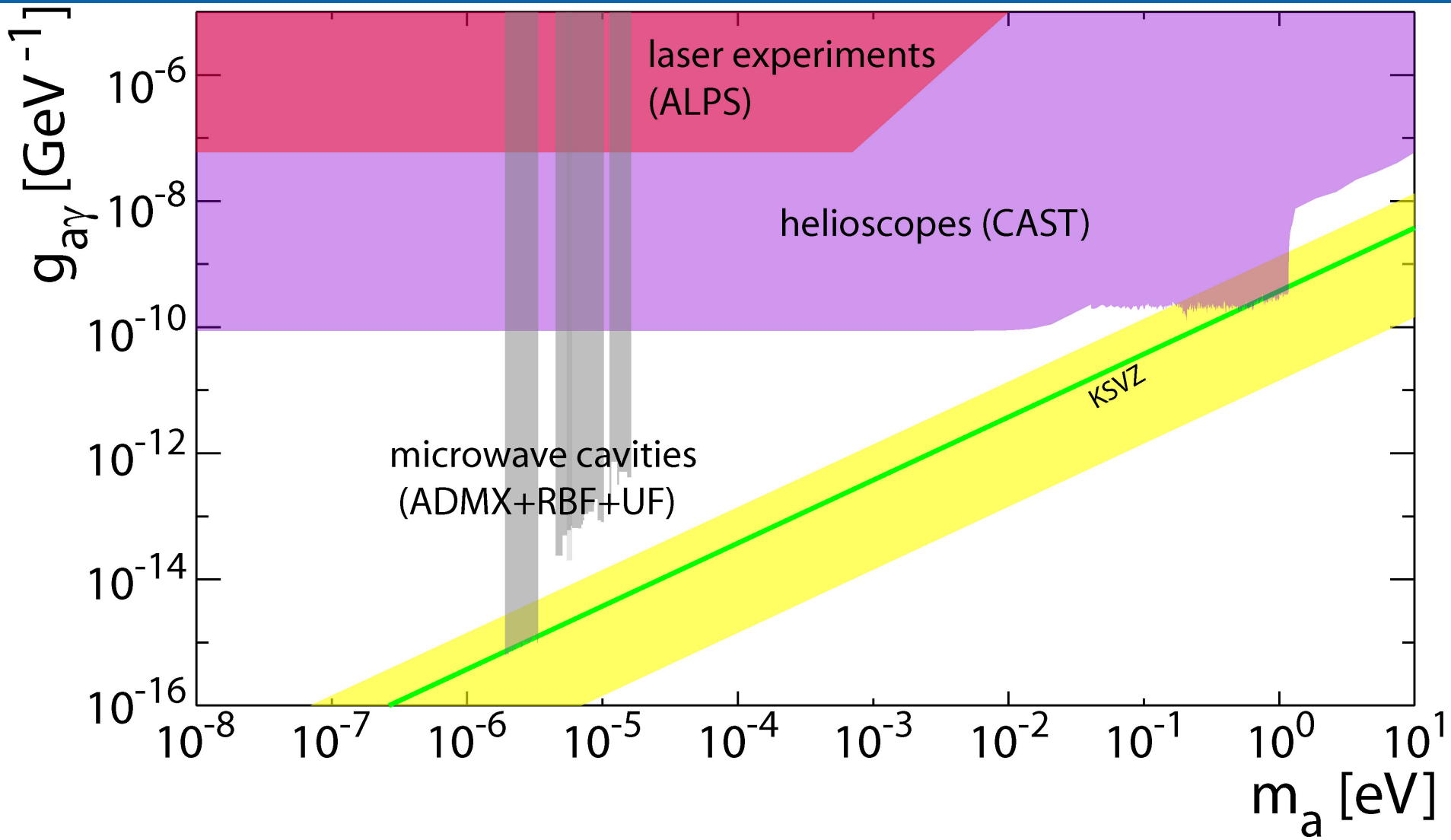
  - Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electromagentic fields in the plasma
  - Reconversions of axions into x-ray photons possible in strong laboratory magnetic field



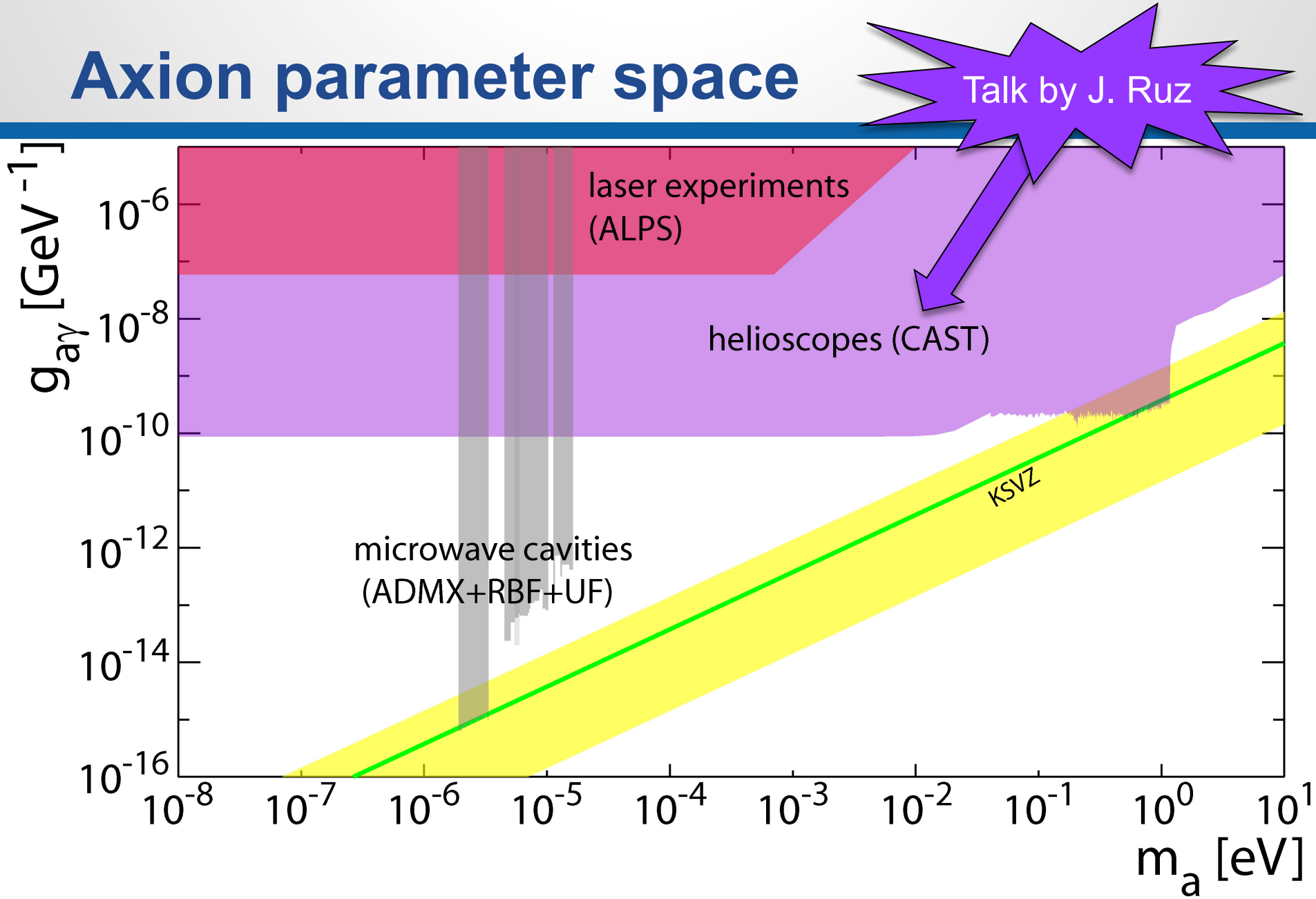
- Idea refined by K. van Bibber by using buffer gas to restore coherence over long magnetic field

Van Bibber et al. *PhysRevD* 39:2089 (1989)

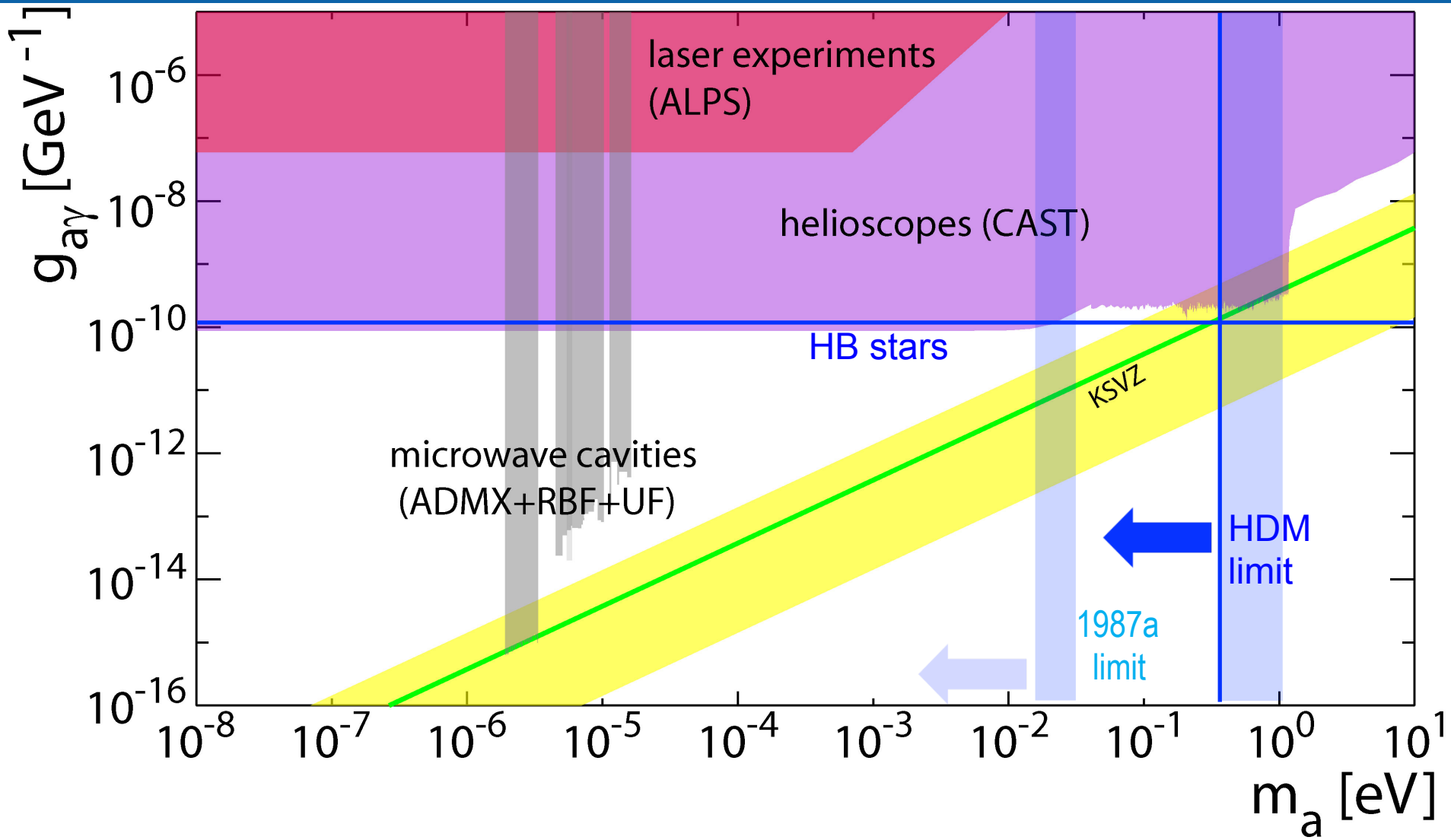
Axion parameter space



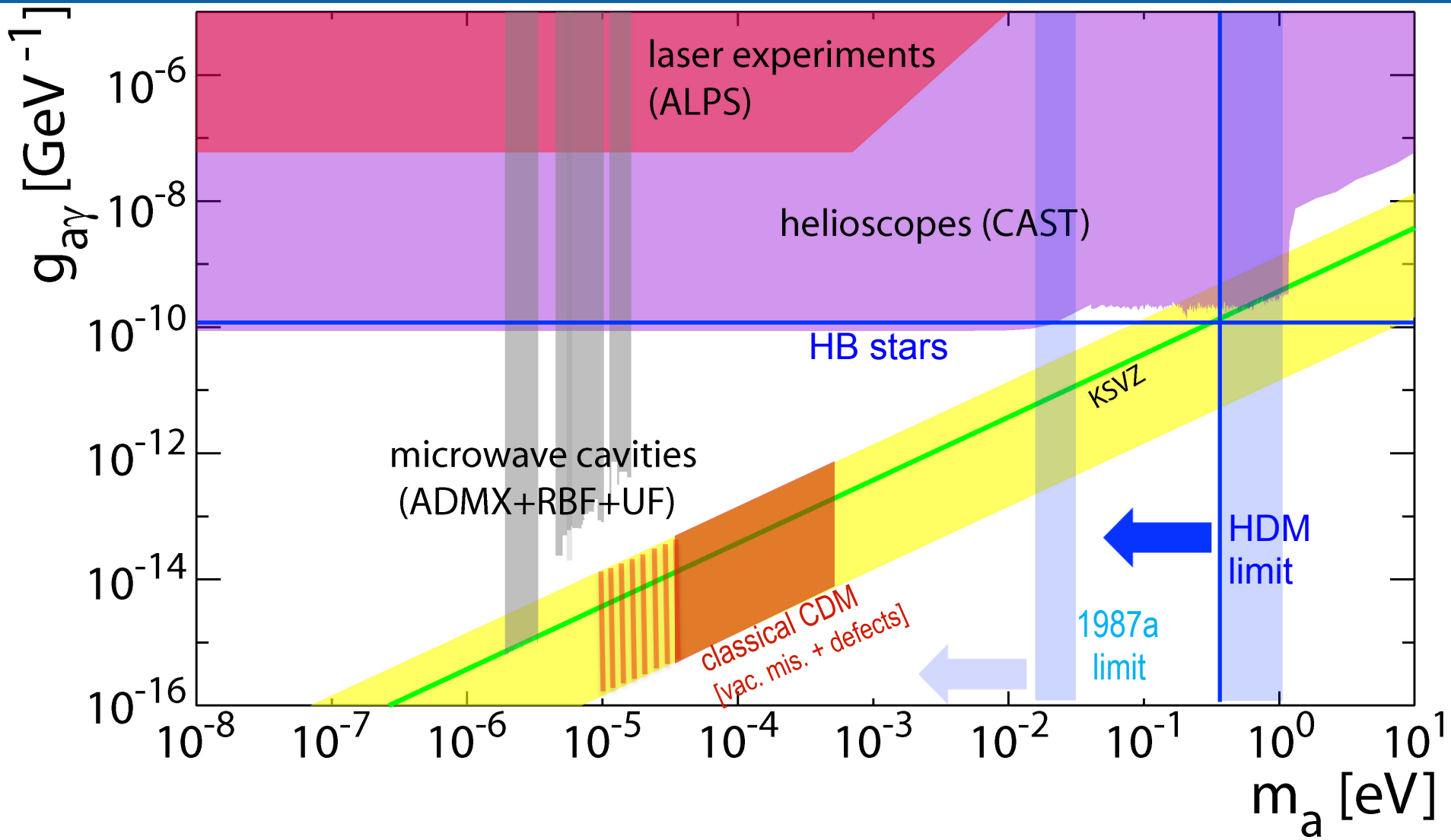
Axion parameter space



Axion parameter space



Axion parameter space



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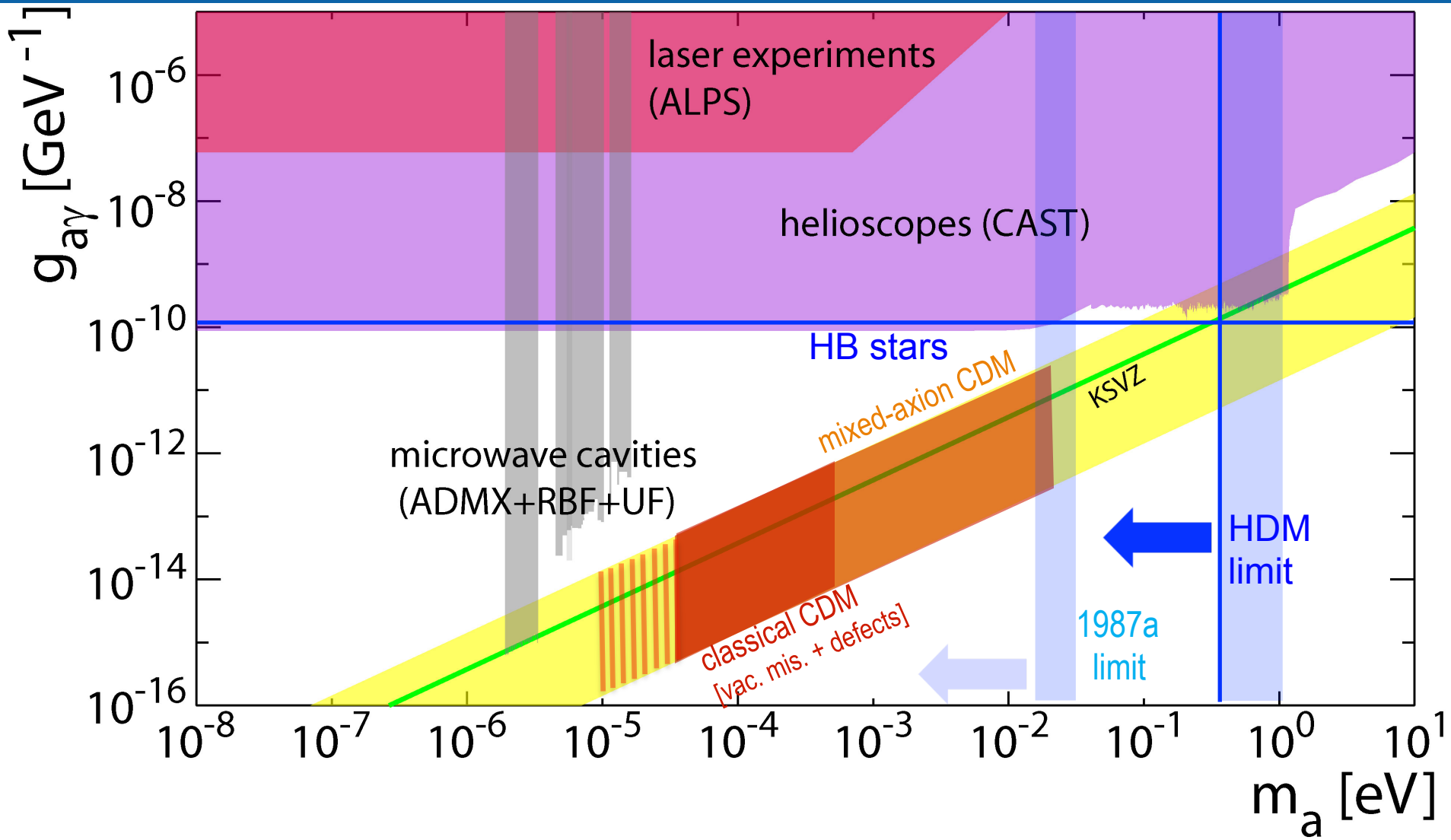

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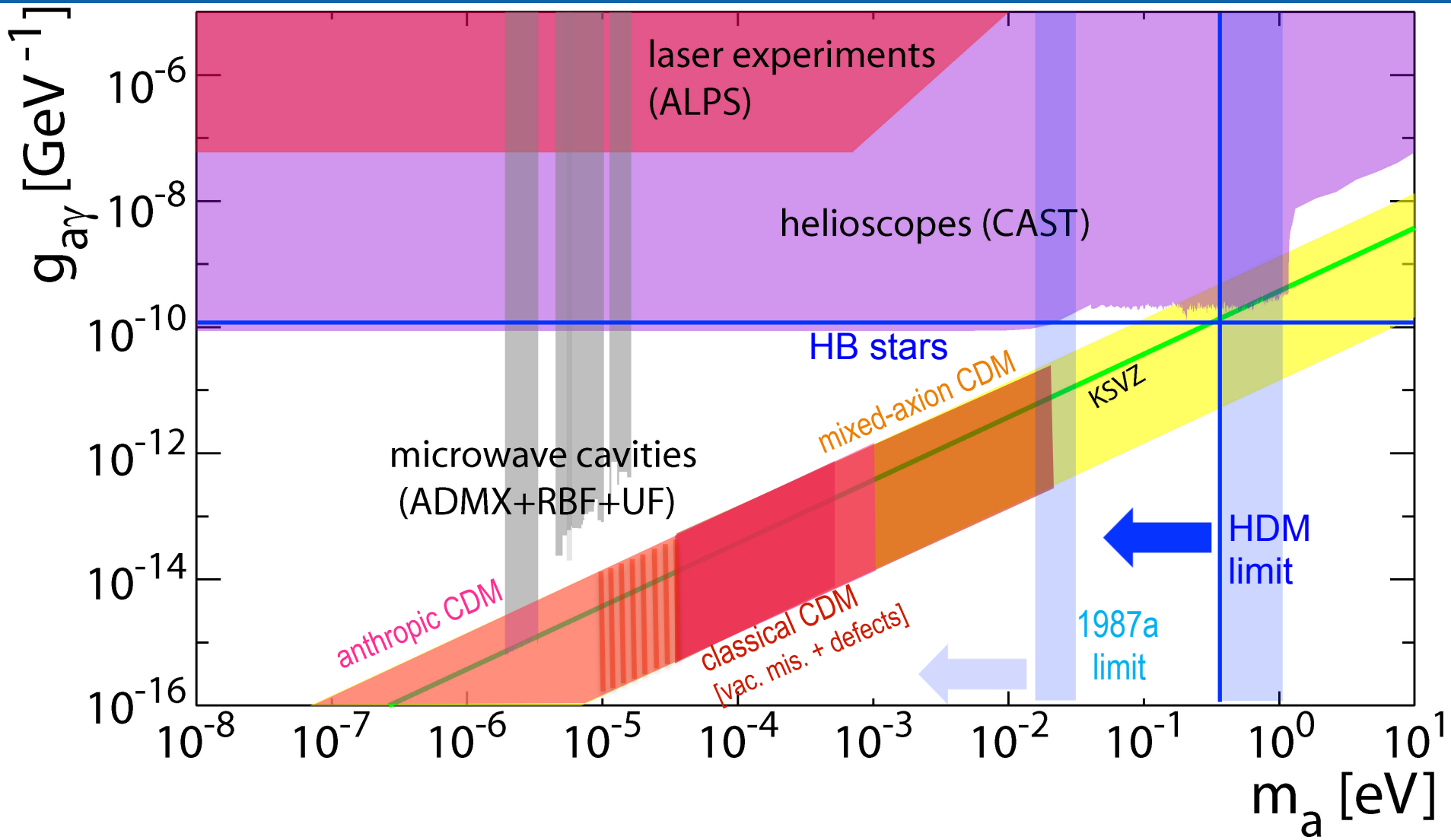

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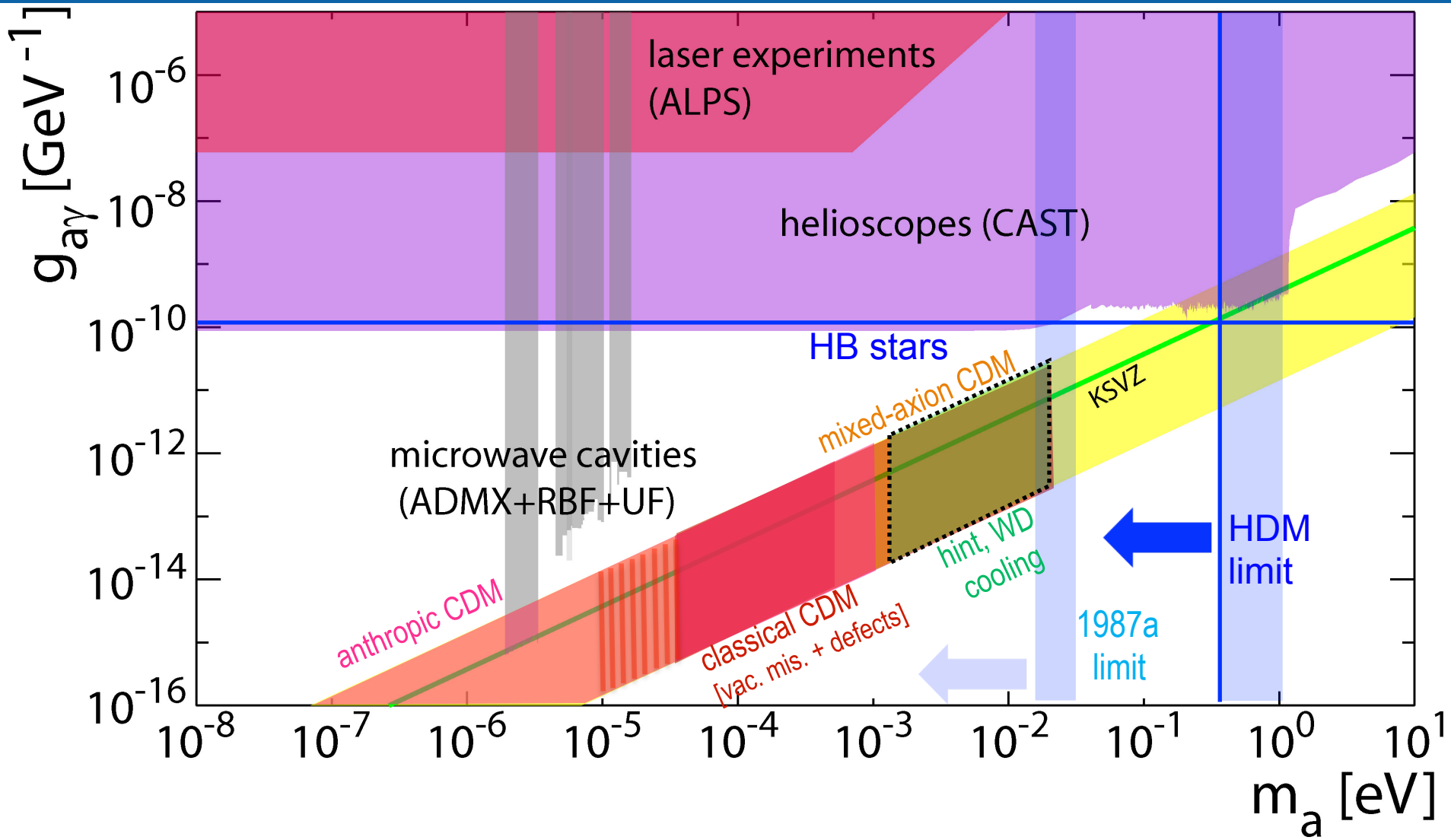

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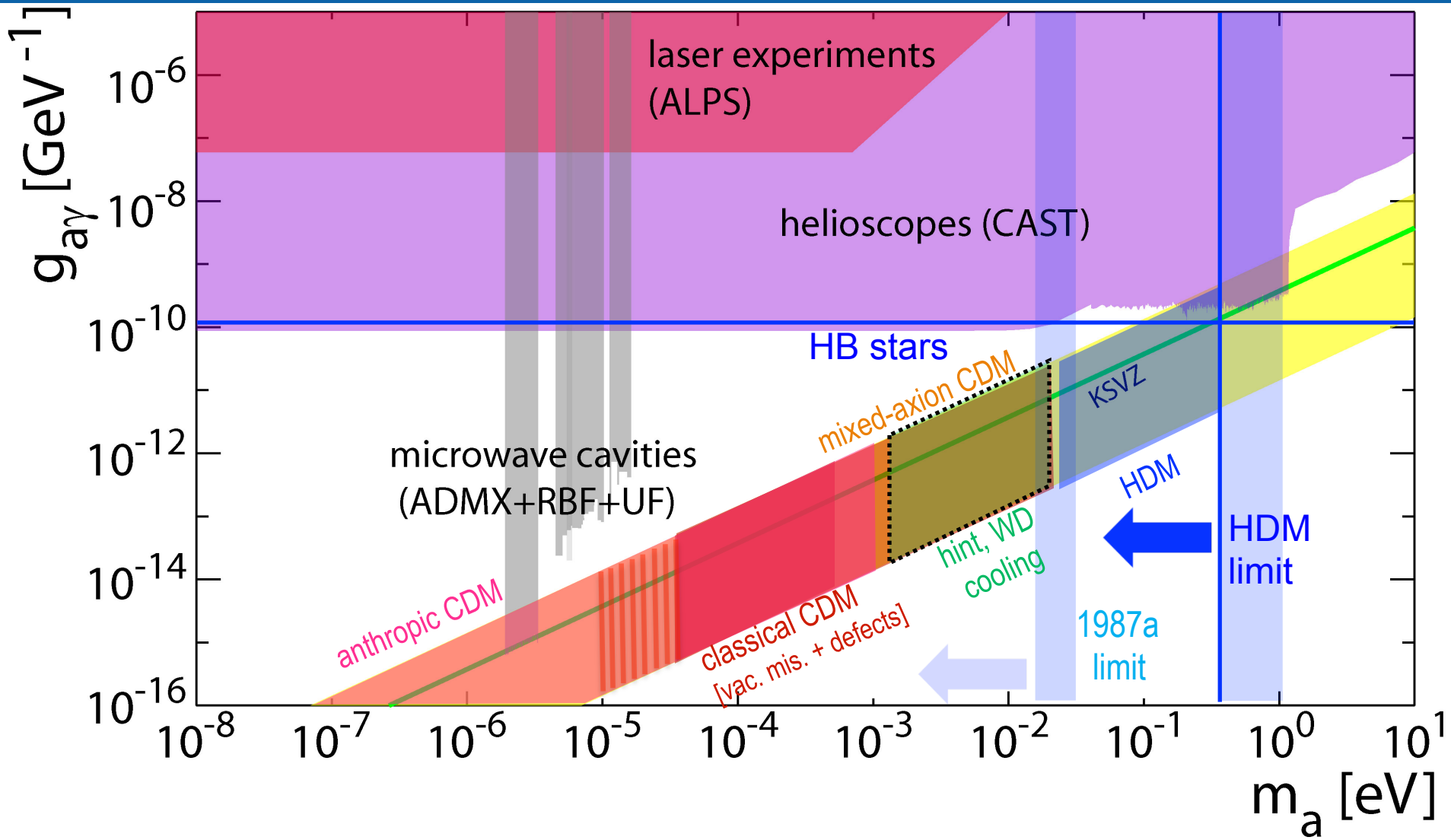

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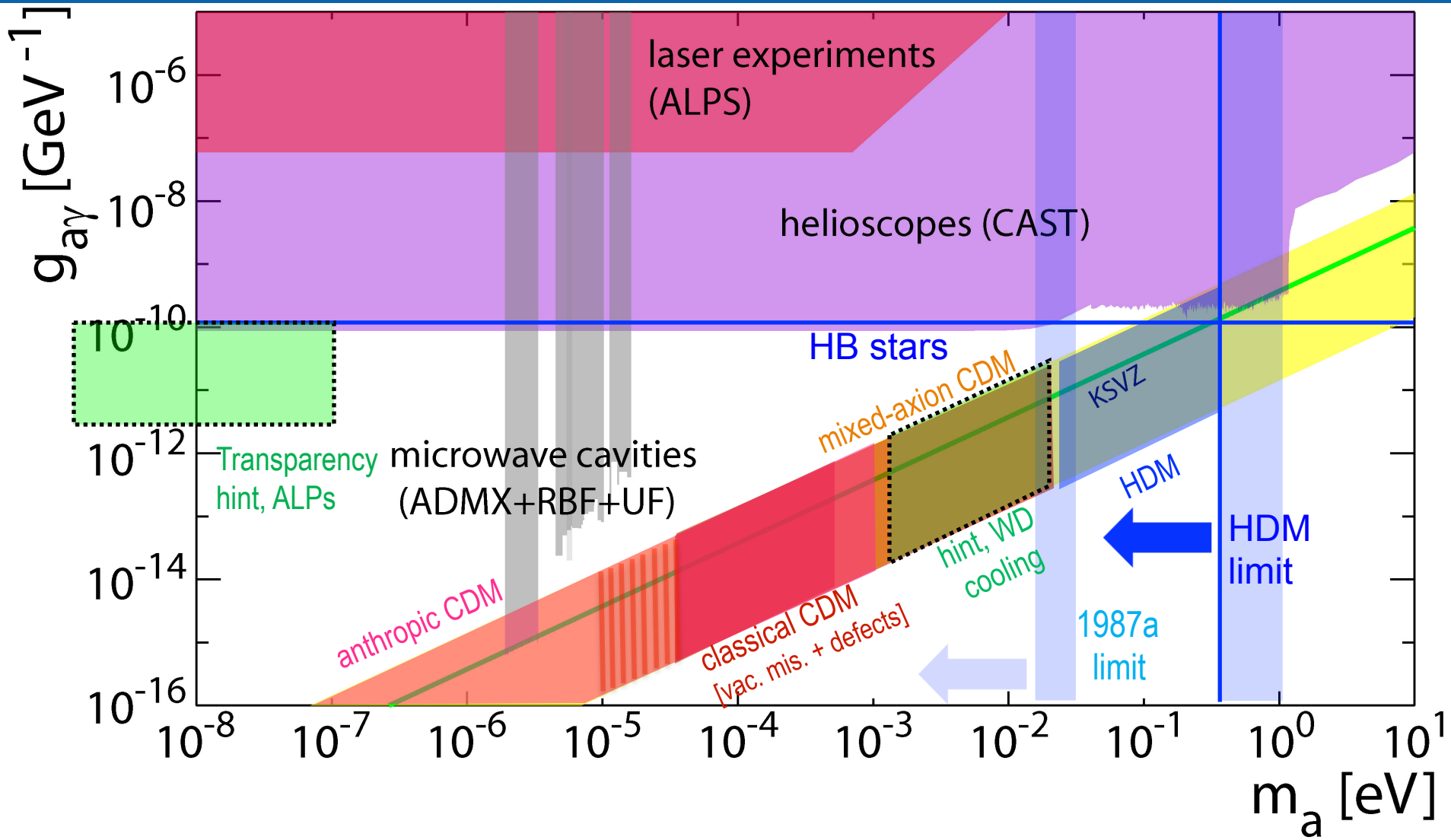

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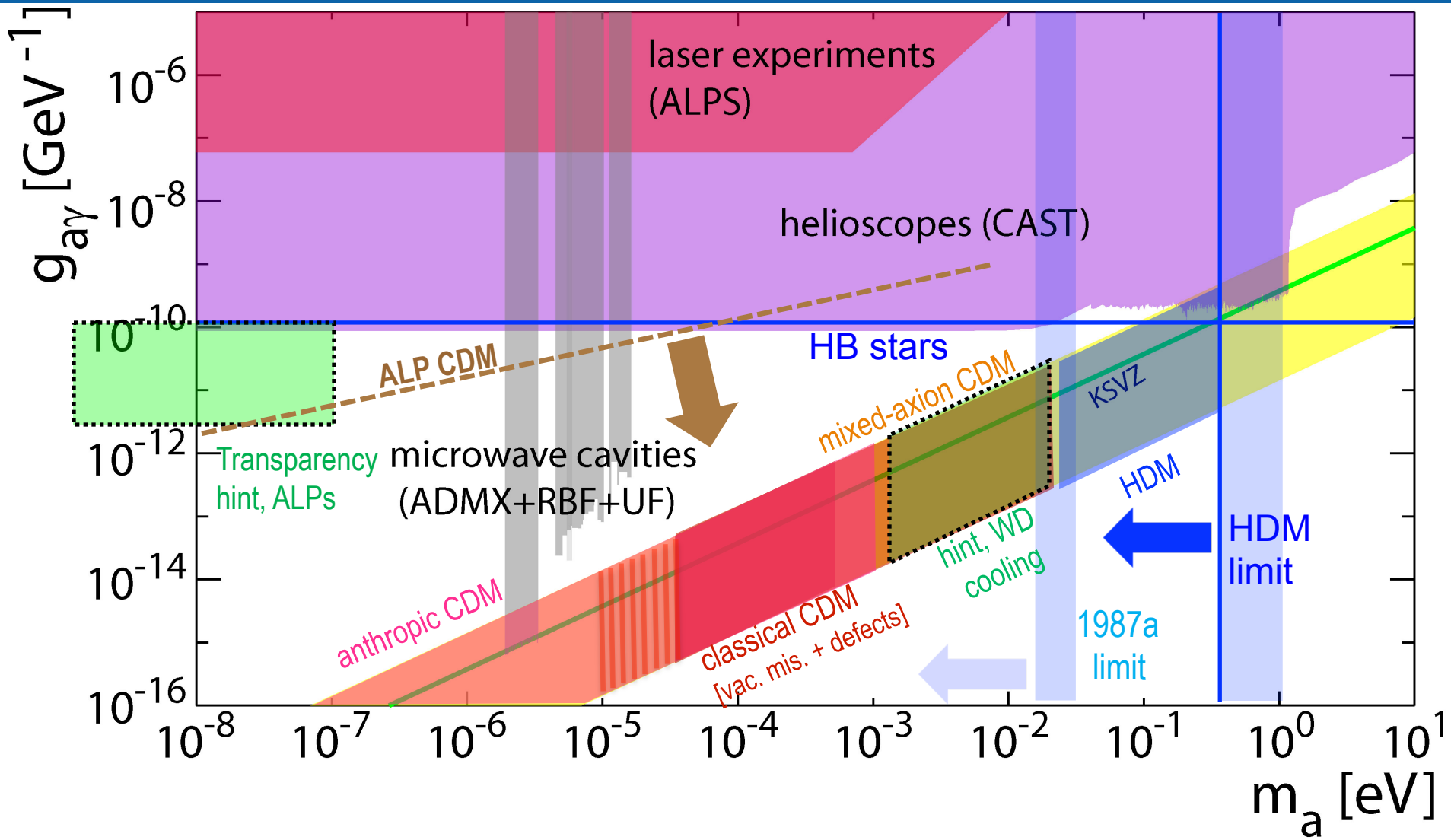


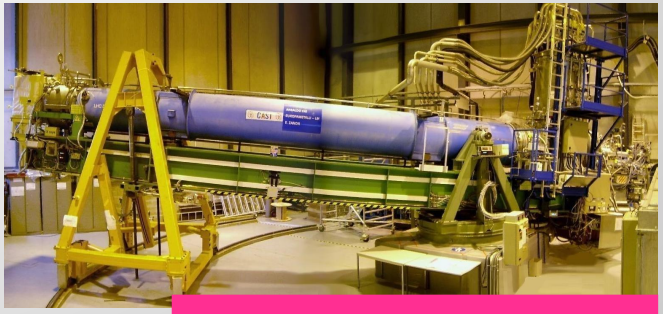
IAXO – 4th generation helioscope

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

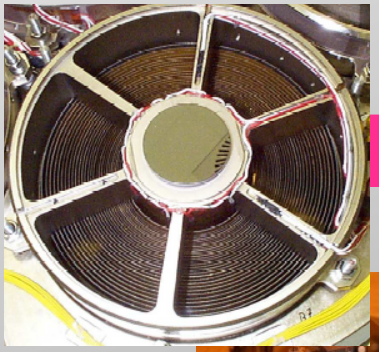
IAXO = 4th generation axion helioscope

- 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

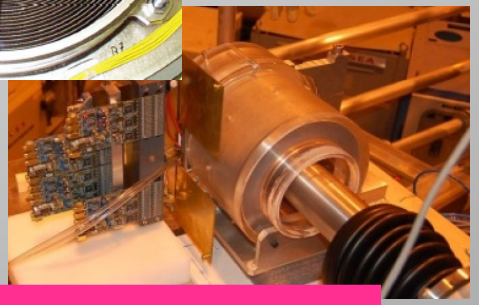
Ingredients of a successful helioscope



Large & powerful magnet...



...X-ray optics,...



...and low background detectors

IAXO – How to improve sensitivity

X-RAY DETECTORS

X-RAY OPTICS

MAGNET

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

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**

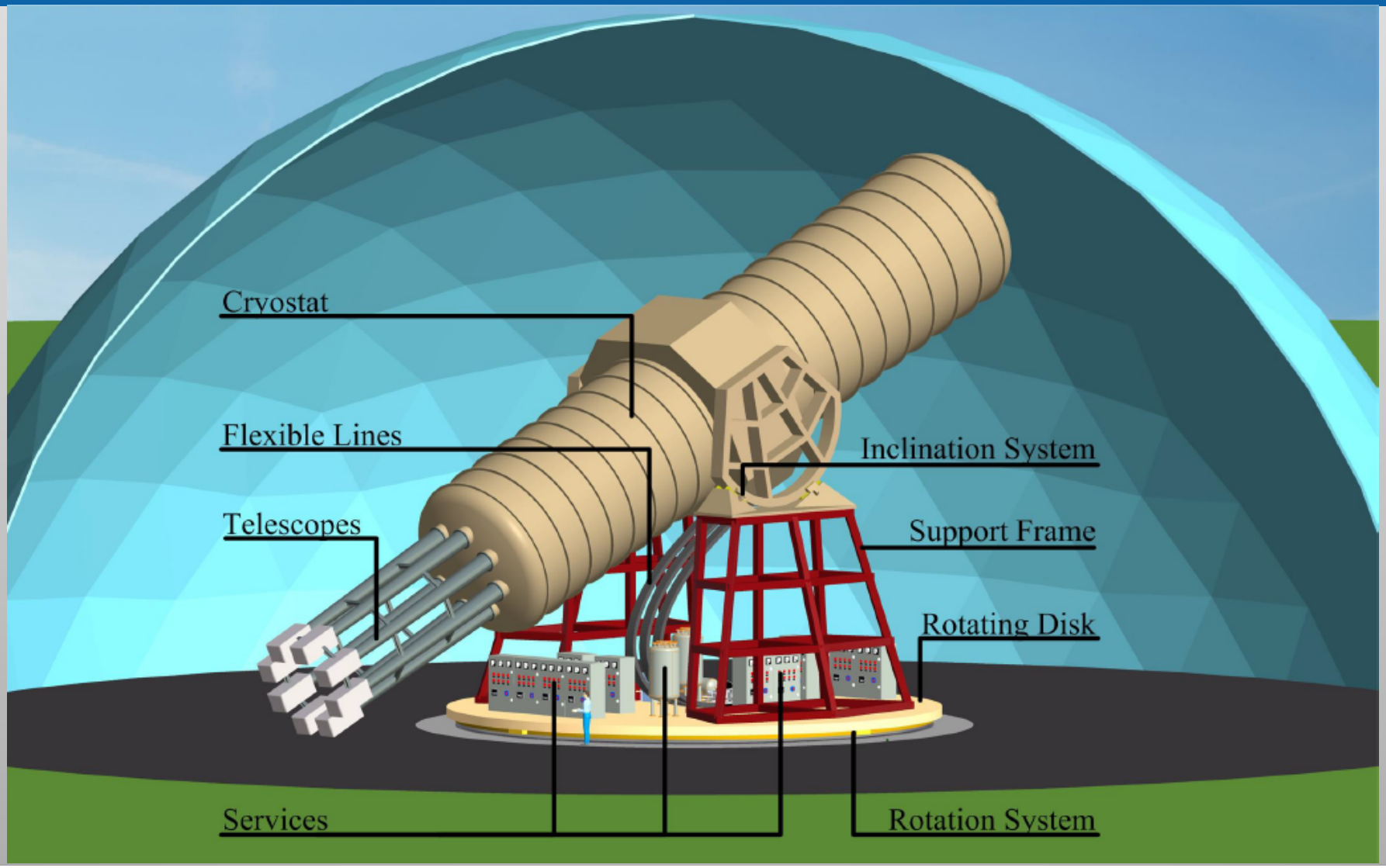
- Achieving one order of magnitude better sensitivity than CAST requires

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

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

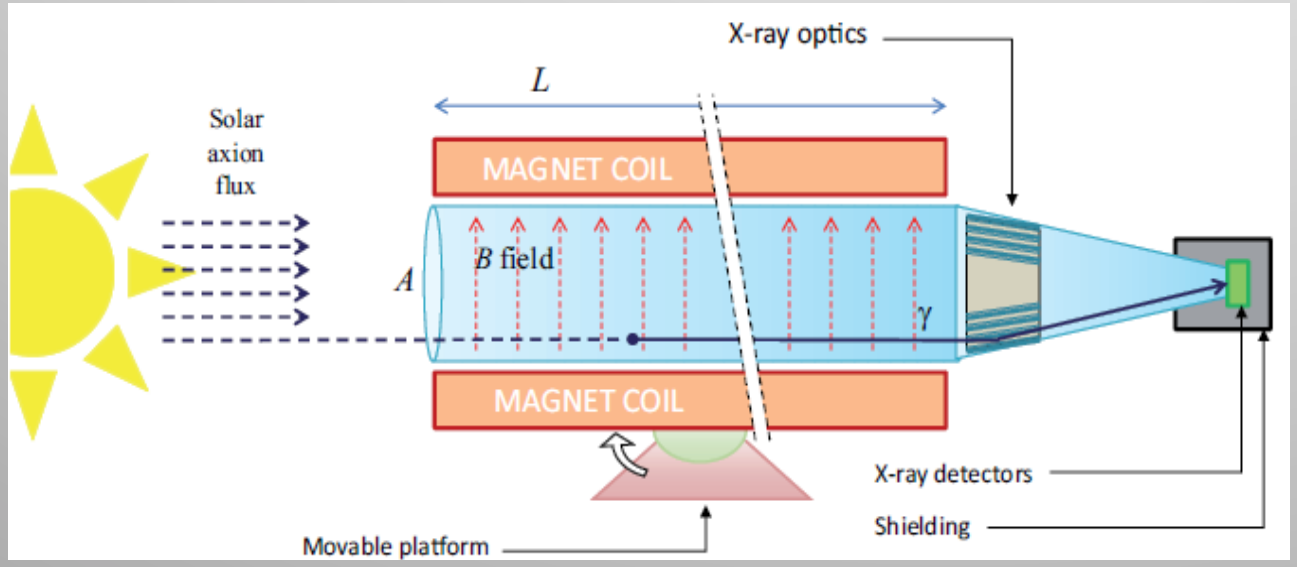
IAXO setup


Cryostat
Flexible Lines
Telescopes
Inclination System
Support Frame
Rotating Disk
Services
Rotation System

Magnet for IAXO

- CAST has pushed the limits of "recycling", by using one of the best existing magnets (LHC test magnet)
- Further improvement needs purpose-built 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 4.5 cm
  - Relatively light (no iron yoke)
  - Bores at room temperature



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)

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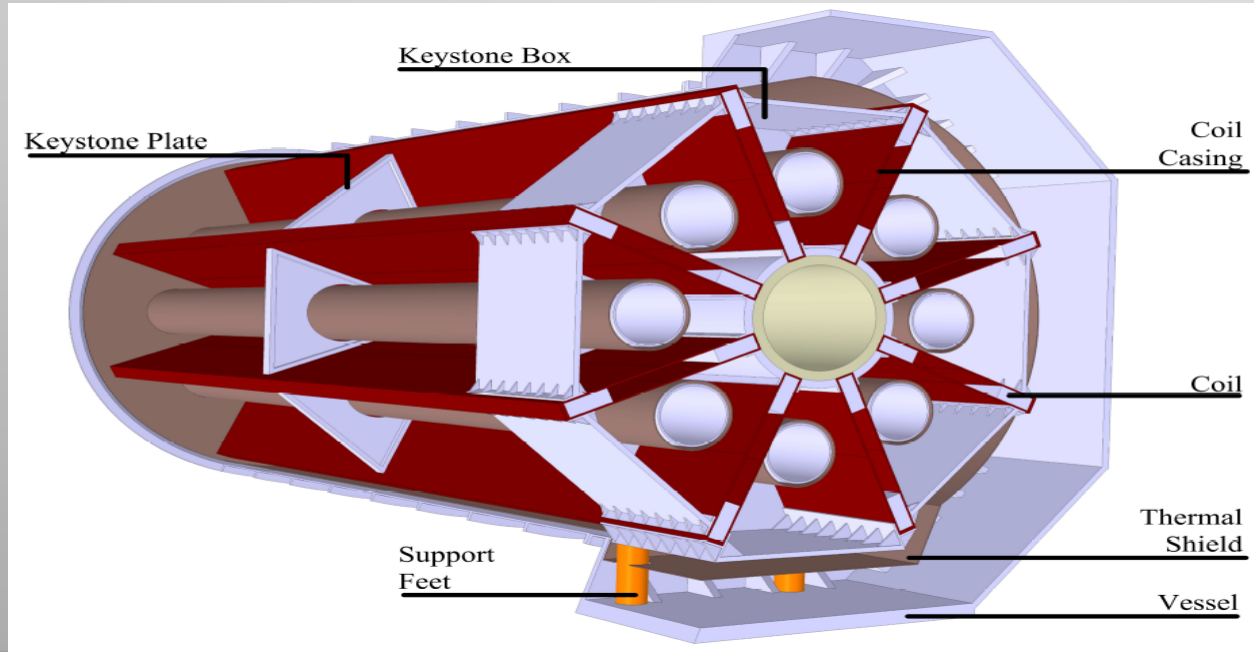
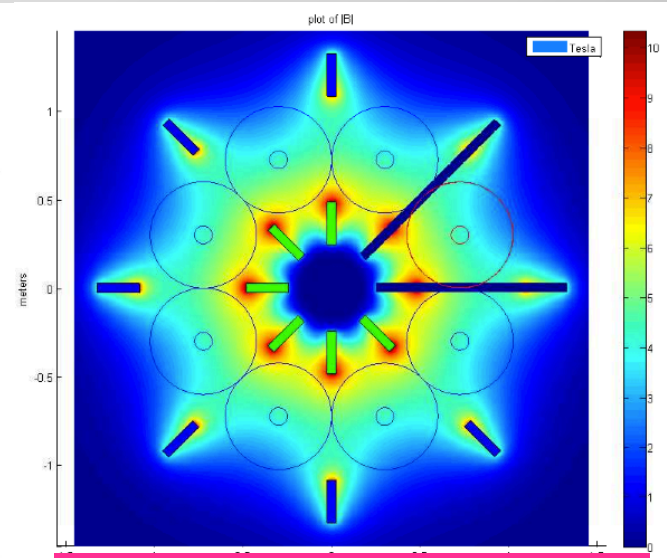
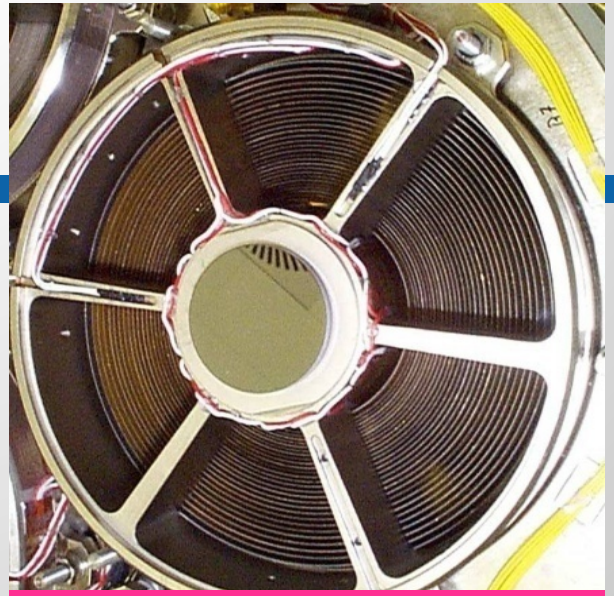




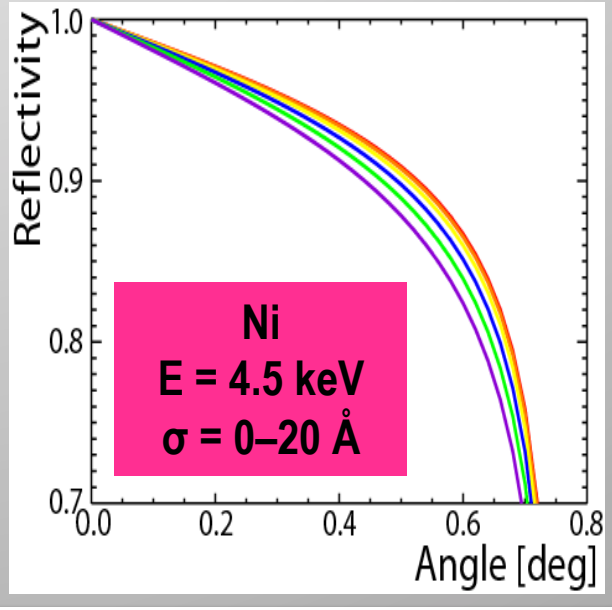
Shilon et al. arXiv:1212.4633v1
IEEE Trans Appl Supercond 23 (2013)

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



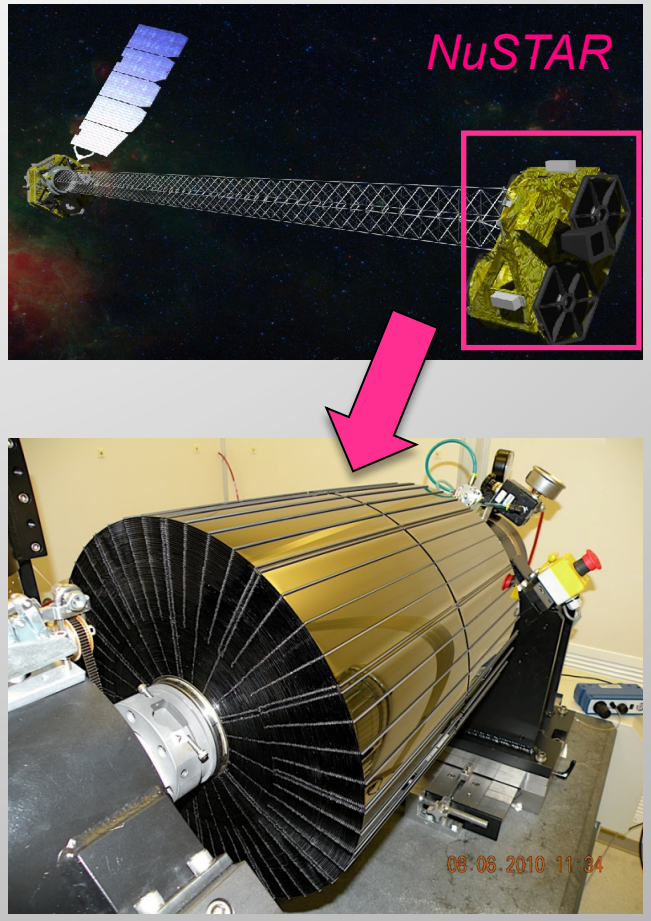
X-ray optics (2)

- 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 June 2012
  - Specialized tooling for mirror production and telescope-assembly now available
  - Hardware can be easily configured to tailor dimensions of optics

3

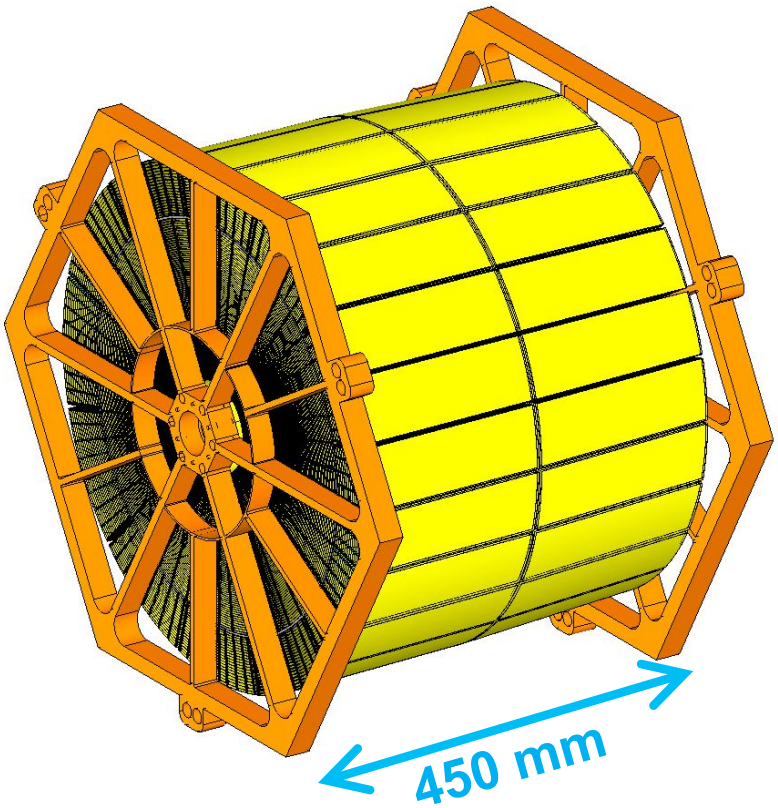
- Many institutes from *NuSTAR* optics team [Columbia U, DTU Space, LLNL] in IAXO

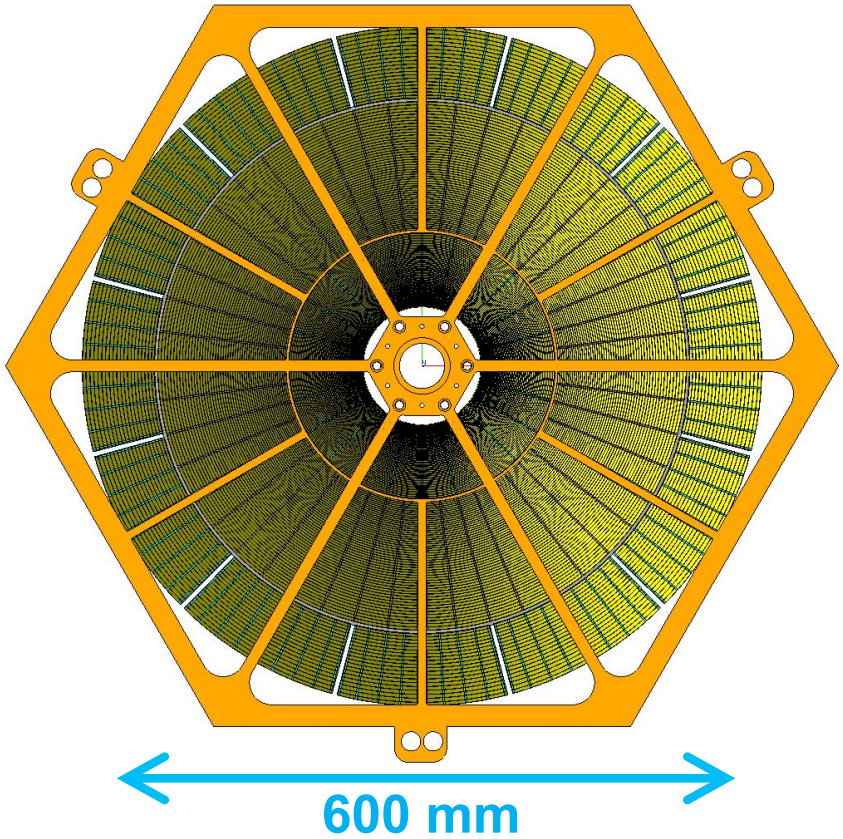


***NuSTAR* x-ray telescope**

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

X-ray optics (3)



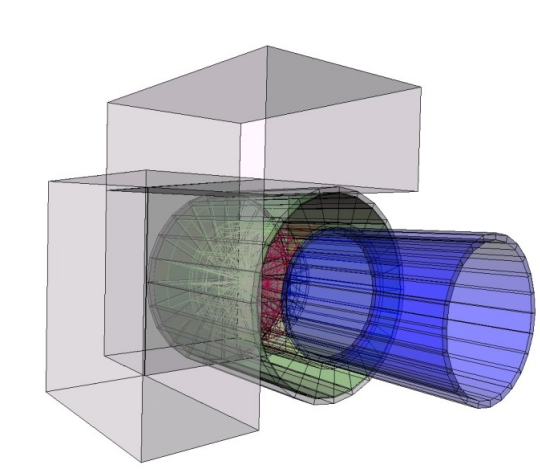


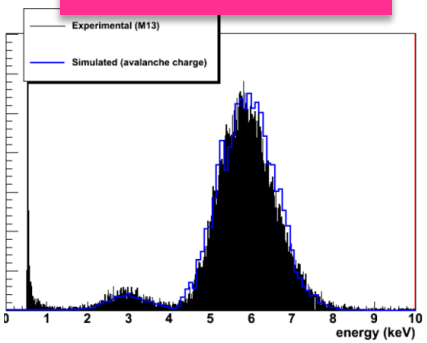
Telescopes	= 8
Layers per telescope	= 123
Mirrors per telescope	≈ 2200
Focal length	= 5 m
Coatings	= W/B_4C multilayers
Pass band	= 1–10 keV
Half-power diameter	= 60 arcsec

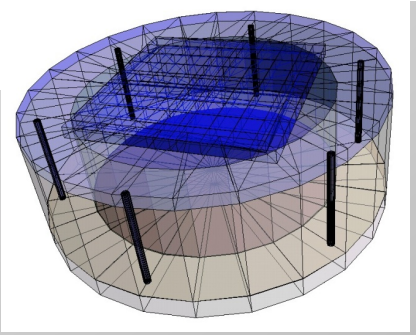
Low-background detectors

- **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

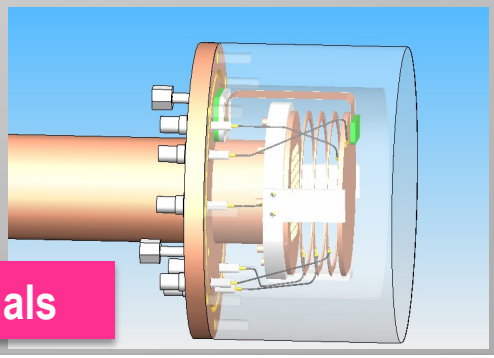
Simulations







Shielding

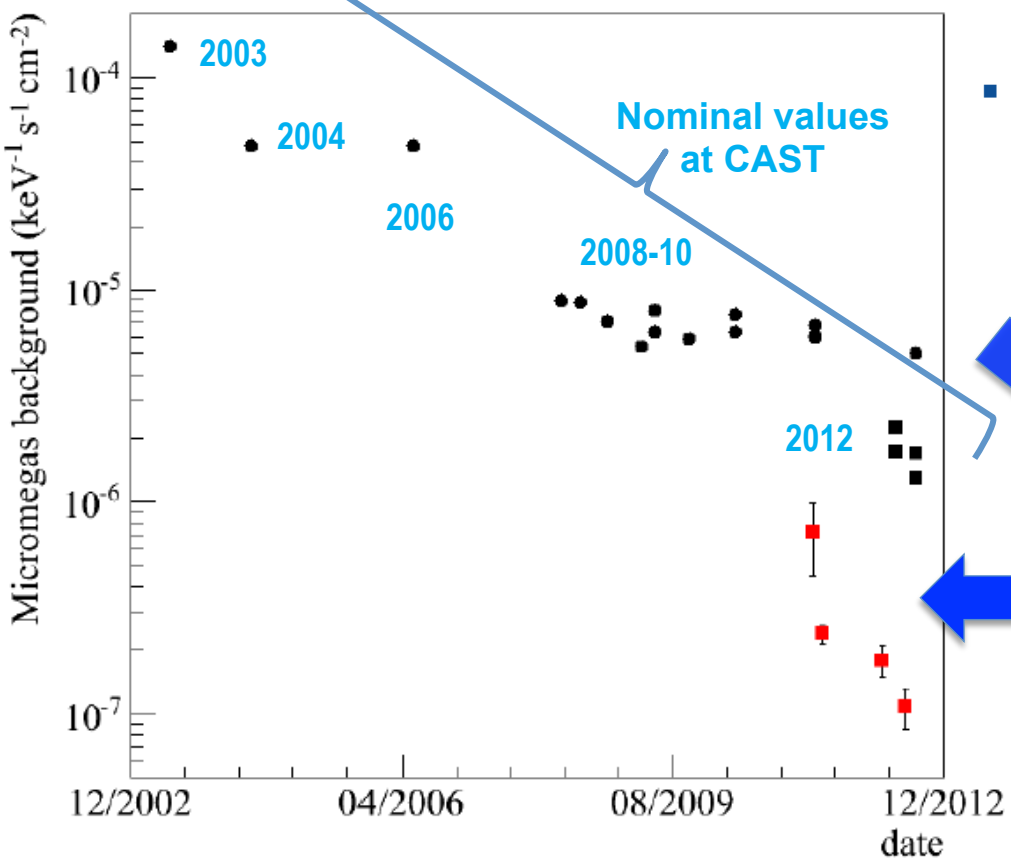


Radiopure materials

Low-background detectors (2)

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

History of background improvement of Micromegas detectors at CAST



- 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

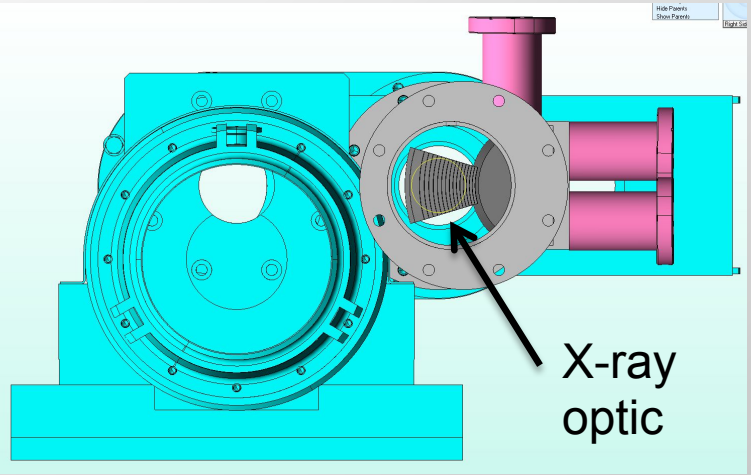
Underground testing of new configurations

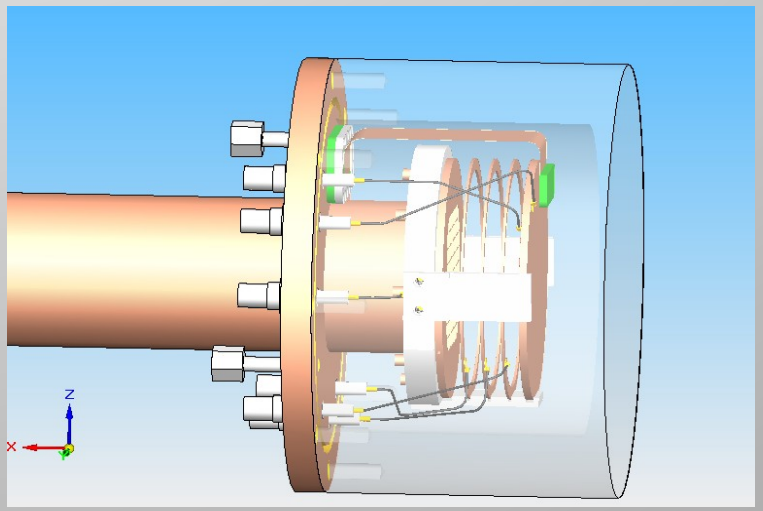
Pathfinder detector+optics for IAXO

- 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

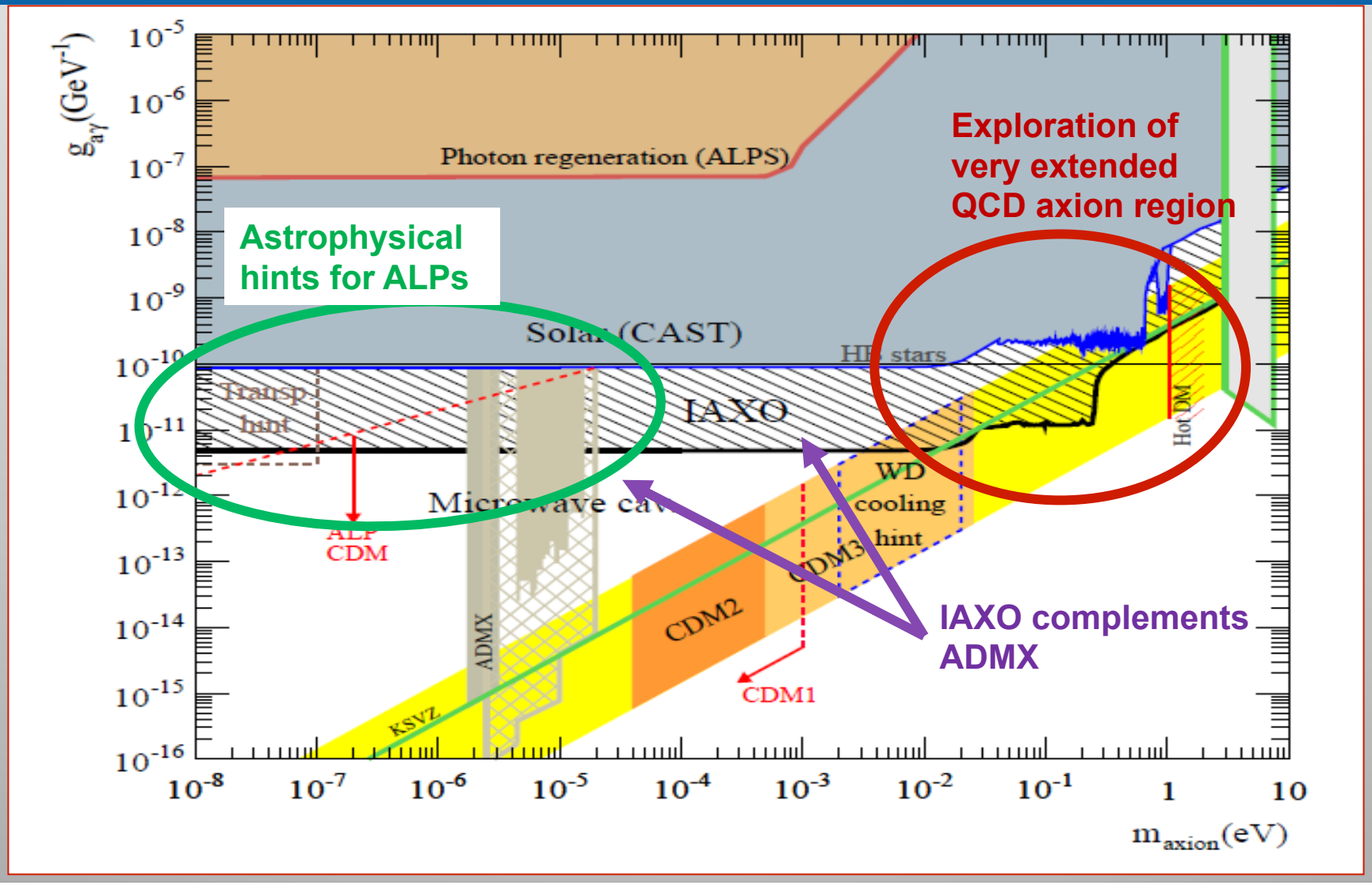
➡ Installation at CAST in 2014

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



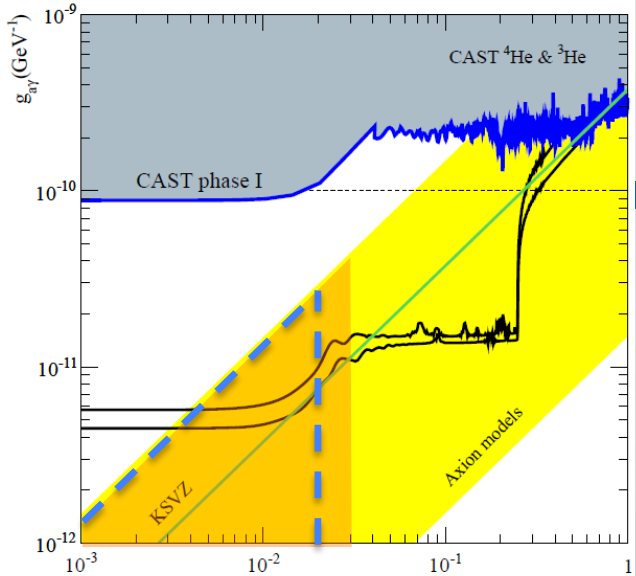


IAXO sensitivity prospects

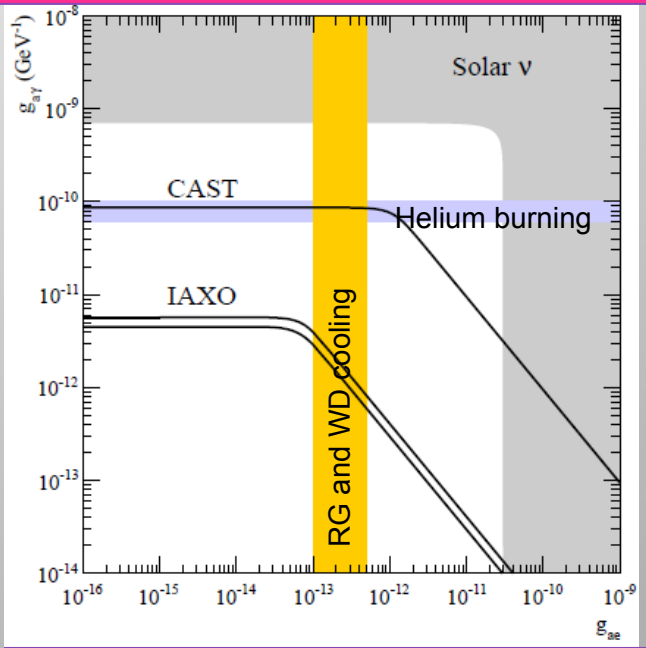


IAXO sensitivity prospects

- **Hadronic axion models**
  - Improvements of factor **8–30** in $g_{a\gamma}$ (4000 –10^6 in signal strength)
  - IAXO can probe high mass QCD axions including standard KSVZ model down to 10^{-2} eV and white dwarf anomalous cooling
- **Non-hadronic axion models** provide extra axion emission from the Sun through axion-electron Compton and bremsstrahlung processes



http://cds.cern.ch/record/1567109



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

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

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

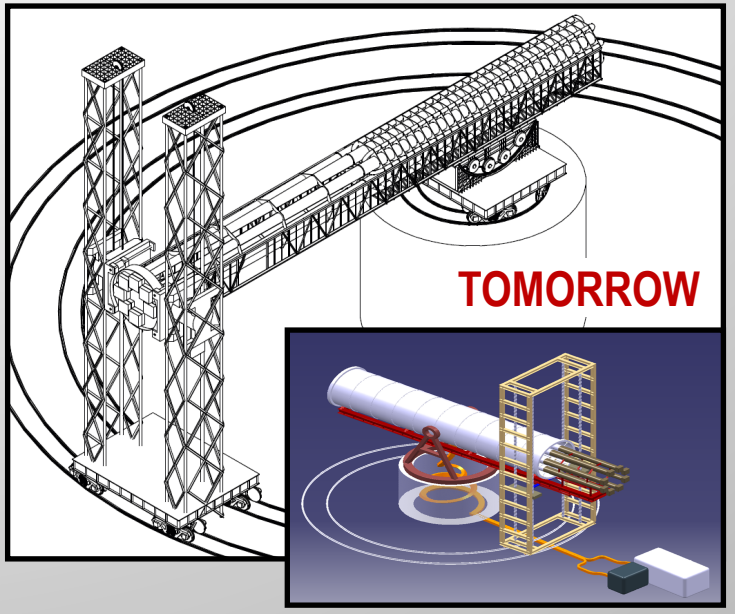
- Socializing IAXO with DOE/SC/HEP and communities of interest (dark matter, particle astrophysics, …)
- Budget [ROM] = $60−110M (dependent on cost models)
  - $30M magnet
  - $10M CF
  - $16M optics
  - $ 6M detectors

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?			

http://cds.cern.ch/record/1567109

Conclusions



- **IAXO is a proposed 4th generation axion helioscope**
  - Based on mature technologies and more than a decade of experience with a reference in axion physics (CAST PRL2004 most cited experimental paper in axion physics)
  - Excellent prospects to improve over CAST by **1−1.5 orders** of magnitude in sensitivity
  - Hot physics topics
    - → Sensitive to QCD axions at high masses
    - → Can test mixed axion-WIMP DM models/ anomalous WD cooling
    - → Probe large untested realistic ALP space
    - → Potential for more exotic physics (WISPs, hidden photons, chameleons)
    - → Possibly even capability to accommodate a haloscope

Together IAXO and haloscopes could explore a large part of the QCD axion model region in the next decade

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**