Dark Matter Axion & ALP searches: Status and future Prospects

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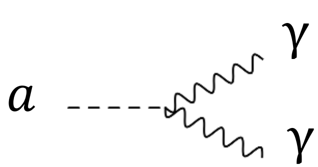
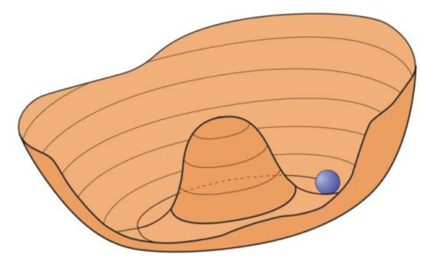
- Motivation & DM Axion mass ranges
- How to detect axions?
- Haloscopes I: Cavity experiments
- Haloscopes II: dielectric discs
- LSW and helioscope





Motivation: solution to strong CP problem

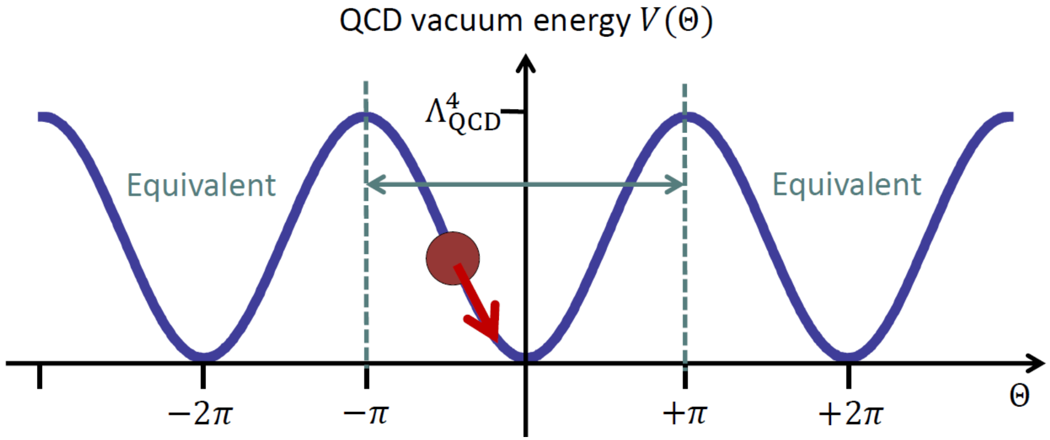
Strong force (nearly?) invariant under CP while weak force CP violating

Generically: QCD Lagrangian contains „arbitrary“ CP violating angle θ

→ induced neutron EDM: $d \sim \theta\, 10^{-16}$ e cm

Experimentally: $d < 10^{-26}$ e cm

→ $\theta < 10^{-10}$



Peccei Quinn mechanism:

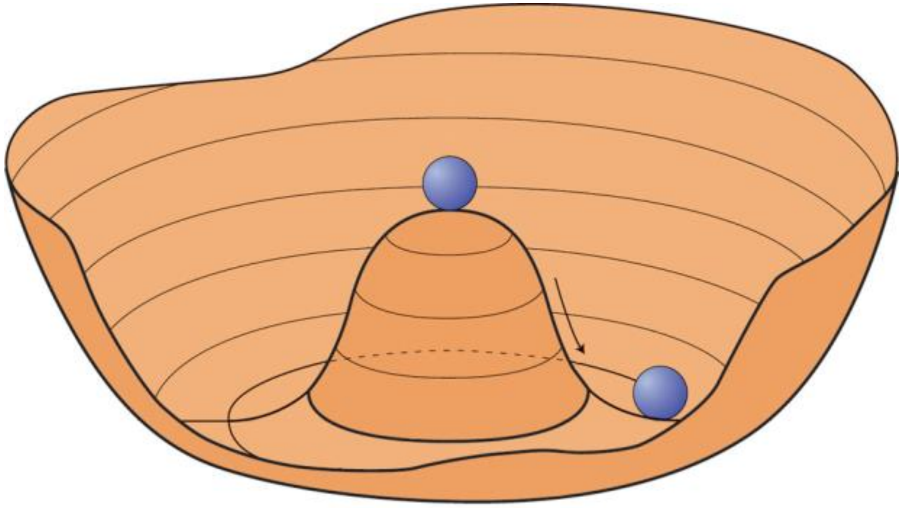
Add dynamical, spontaneously broken field

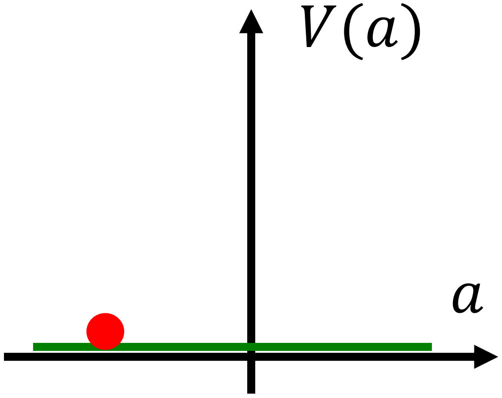
→New pseudoscalar particle: Axion (oscillation around minimum)

Solving the strong CP problem: the Axion

Peccei Quinn symmetry breaking @ T ~ $f_a > 10^9$ GeV:

- $U_{PQ}(1)$ spontaneously broken
- Field settles in Higgs like potential
- Axion field sits fixed at $a_i = \Theta_i f_a$

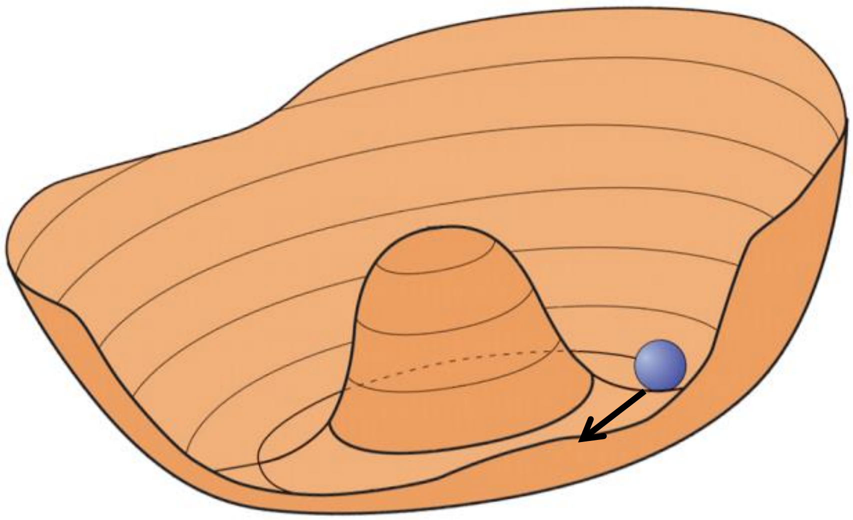




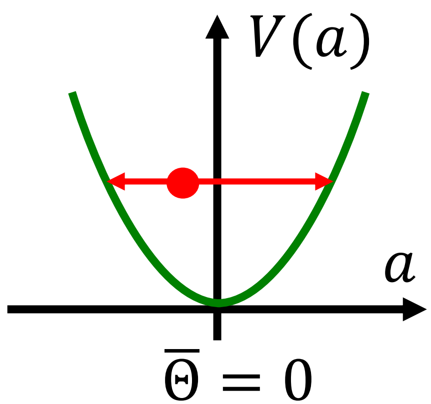
Solving the strong CP problem: the Axion

Axion acquires mass @ T ~ 1 GeV :

- **„Non-perturbative topological fluctuations of gluon field“ become relevant: topological susceptibility χ**
  $m_a = \sqrt{\chi}/f_a$ **(2nd derivative at minimum)**
- **Field rolls towards minimum**
- **Oscillations around minimum**
  → Classical field oscillations
  → axions at rest

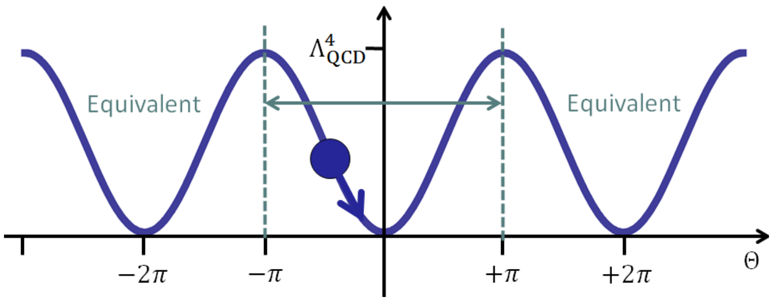


Taken from G. Raffelt

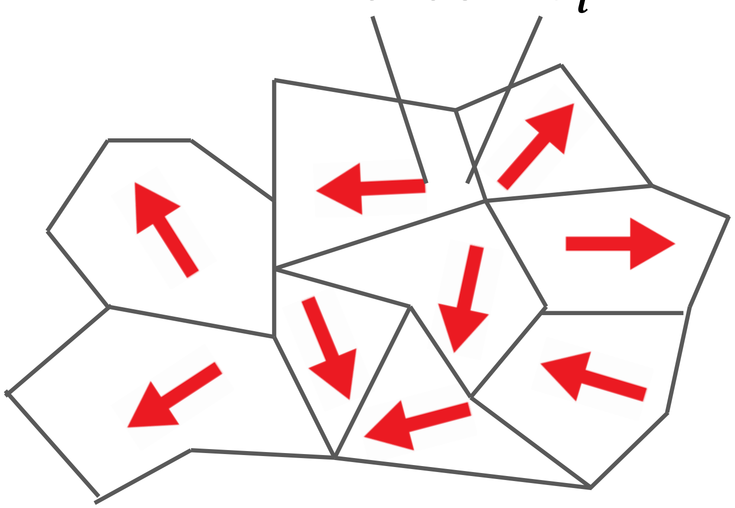


Axion DM: Pre-inflationary PQ breaking

- Observable universe "inflated" from casually connected "patch"
- All axions from this one „patch"
- Θ_i for "axion production" has a single random value
- No topological defects

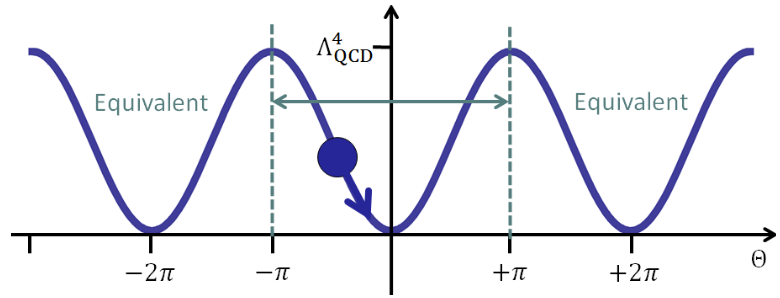


Observable Universe: Random Θ_i



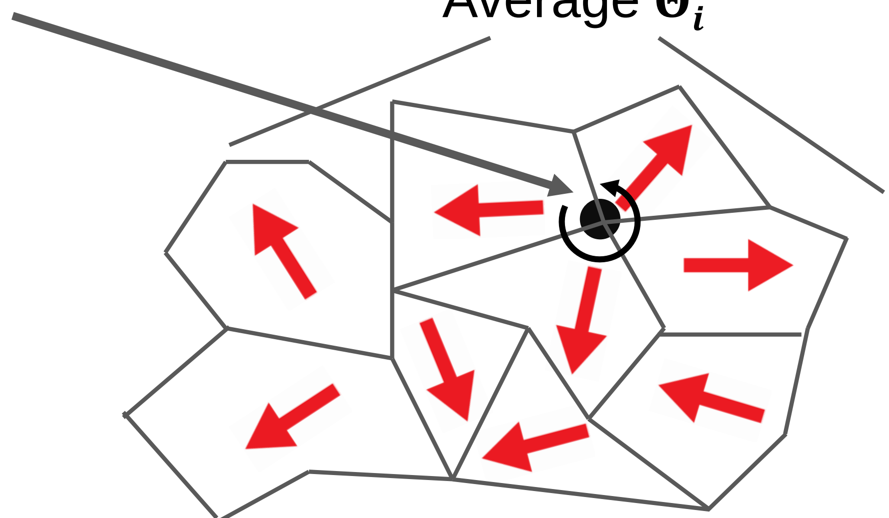
Allows for large f_a if $\Theta_i \ll 1$ (but removes justification for introduction of axion for $\Theta_i \lesssim 0.01$)

Axion DM: Post-inflationary PQ breaking



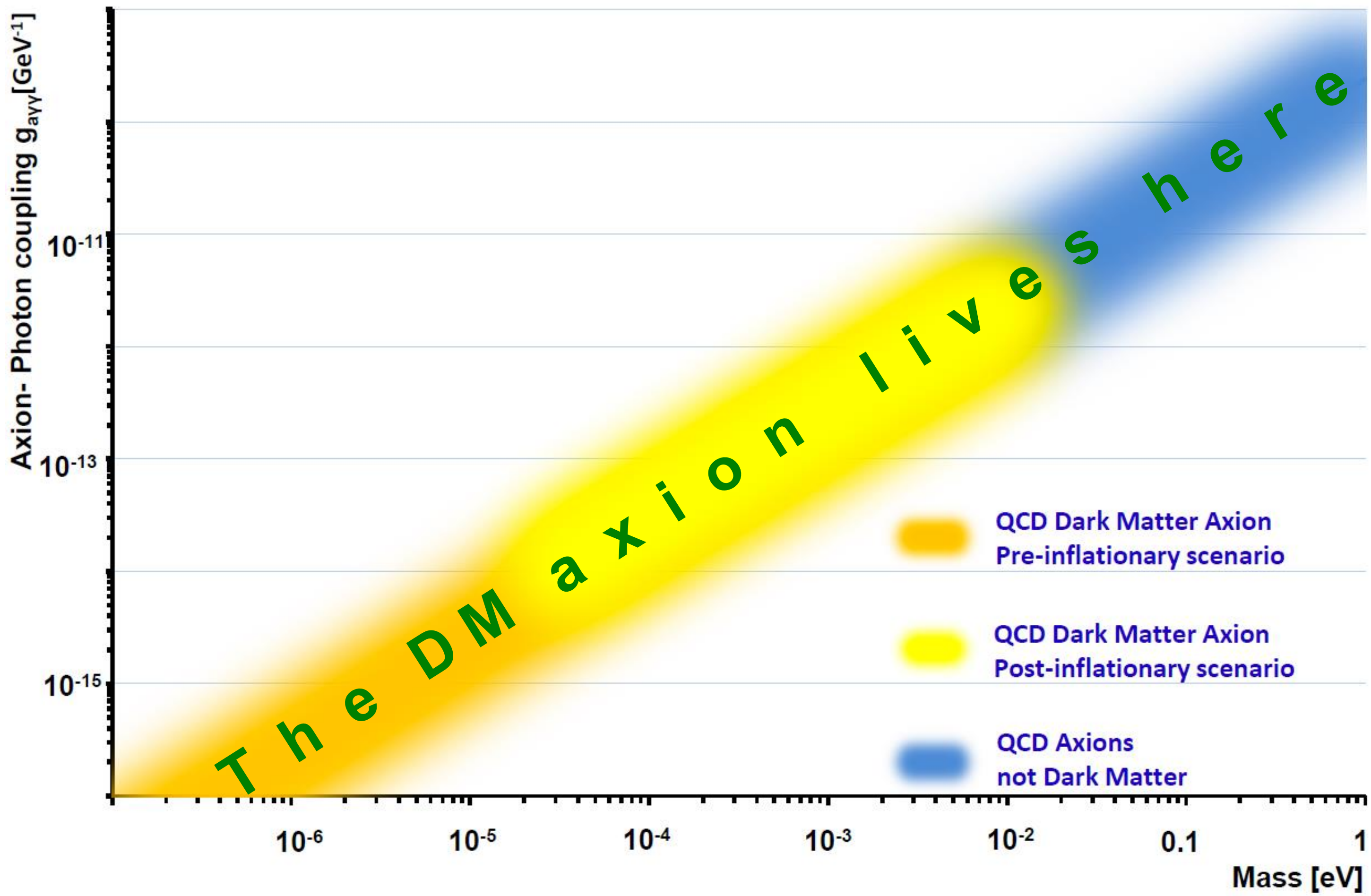
- Θ_i has random value in every casual region
- Dark matter density determined by the average $\widehat{\Theta}_i$
- Topological defects (strings and domain walls) exist in the early universe
  → decay leads to axion production
  → axion density increased!

Observable Universe Average Θ_i



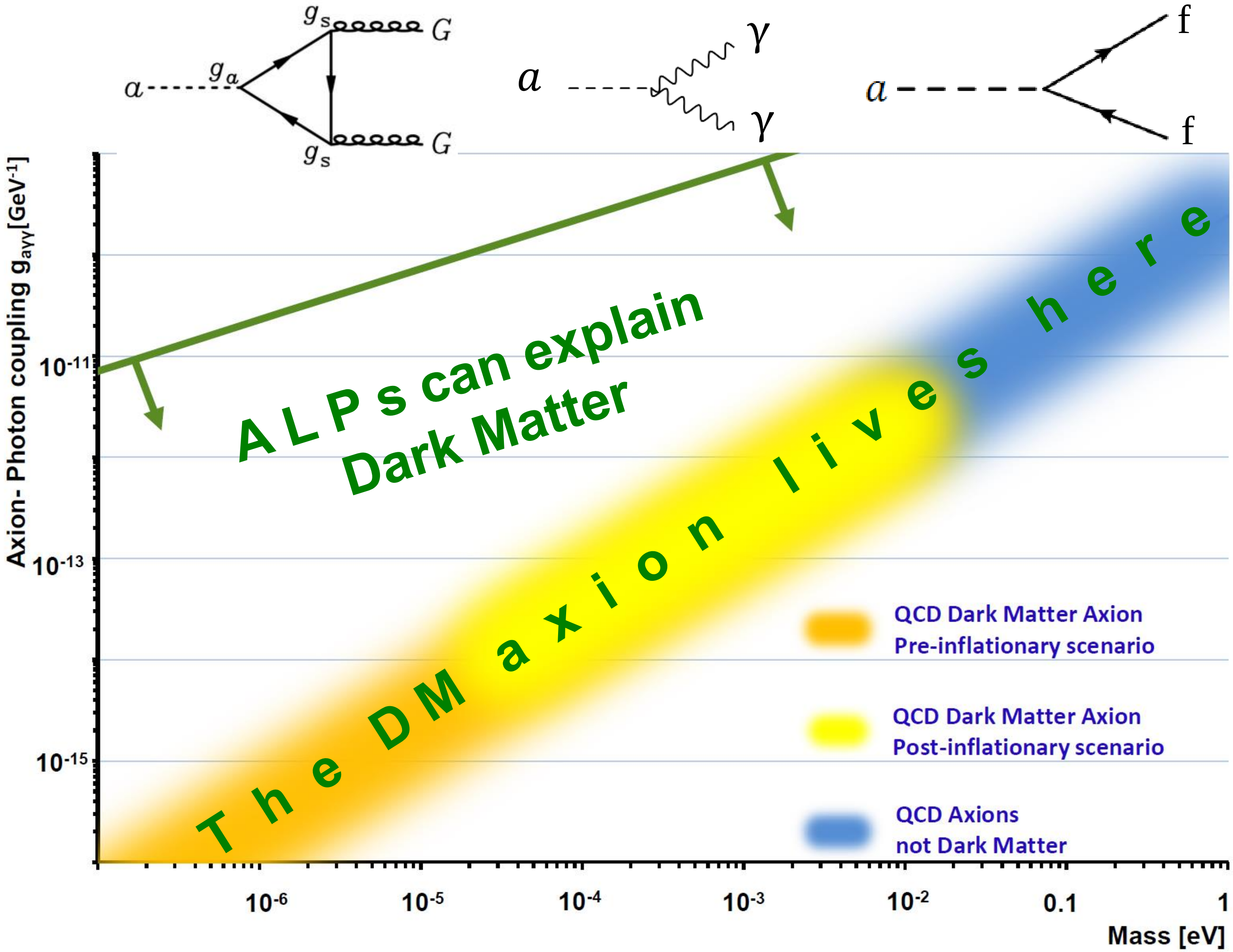
Motivation: solution to strong CP problem

$$m_a = 5.70(6)(4)\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$



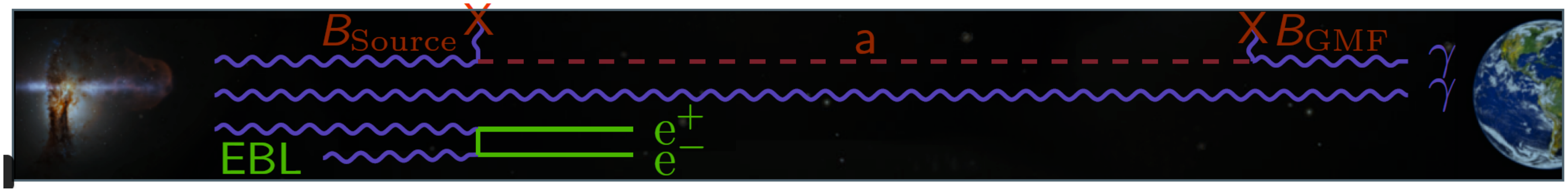
Generic Axion Like Particles:

Works for any spontaneously broken U(1) symmetry



ALPs as solution to astrophysical hints?

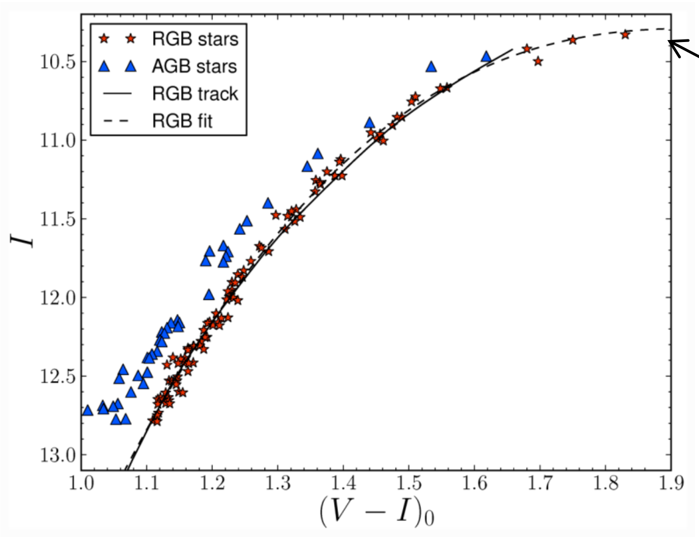
TeV transparecncy hint: ALPs



arXiv:1302.1208

Prone to systematics of source?

Stellar cooling: Could be due to QCD axions



Brightest red giants measured nonstandard energy loss

Statistically evidence for deviation from expectation arXiv:1512.08108

Could be due to ALP cooling

How well do we understand standard stellar cooling?

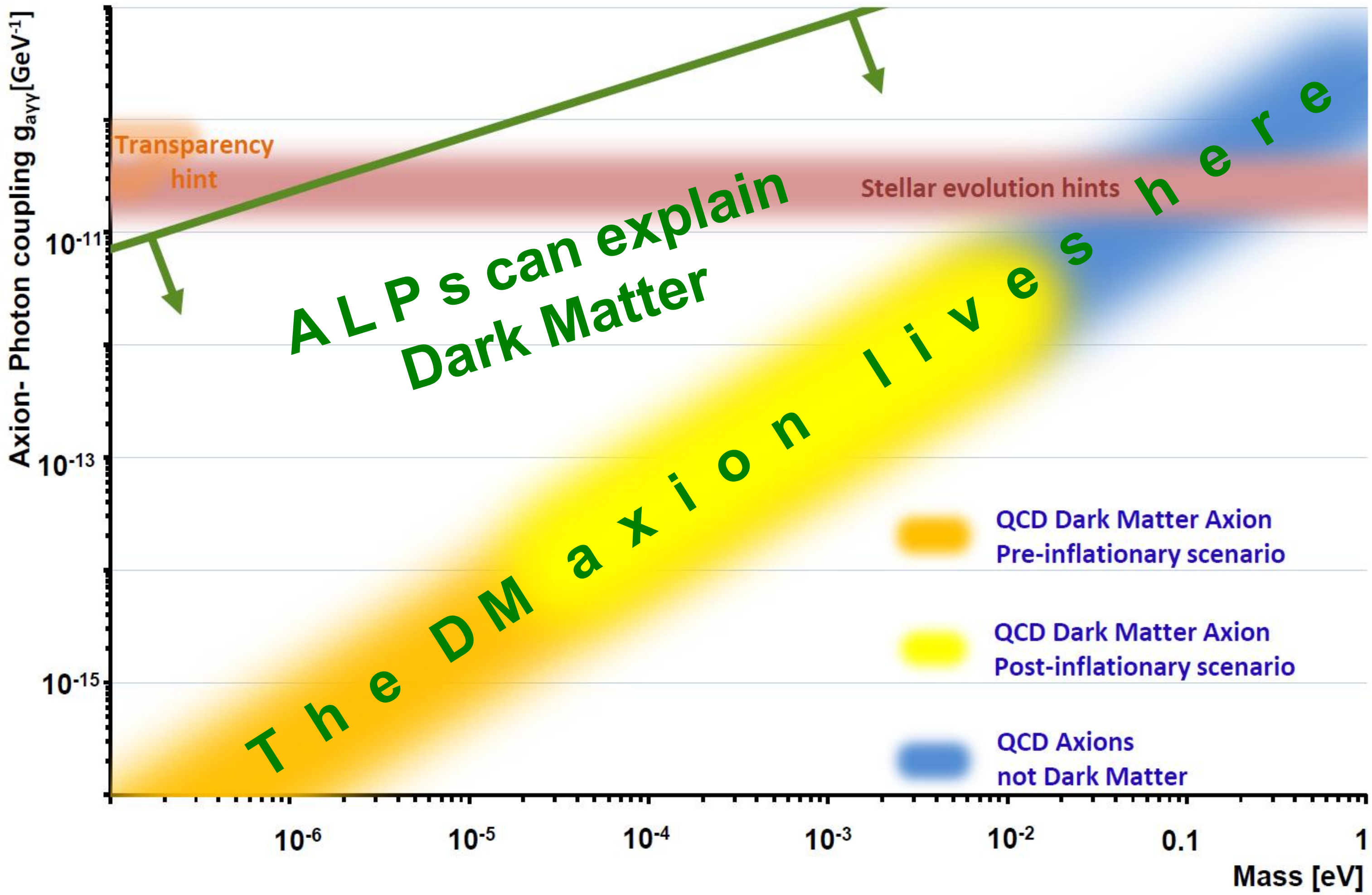
Motivations for axions and ALPs

Dark Matter

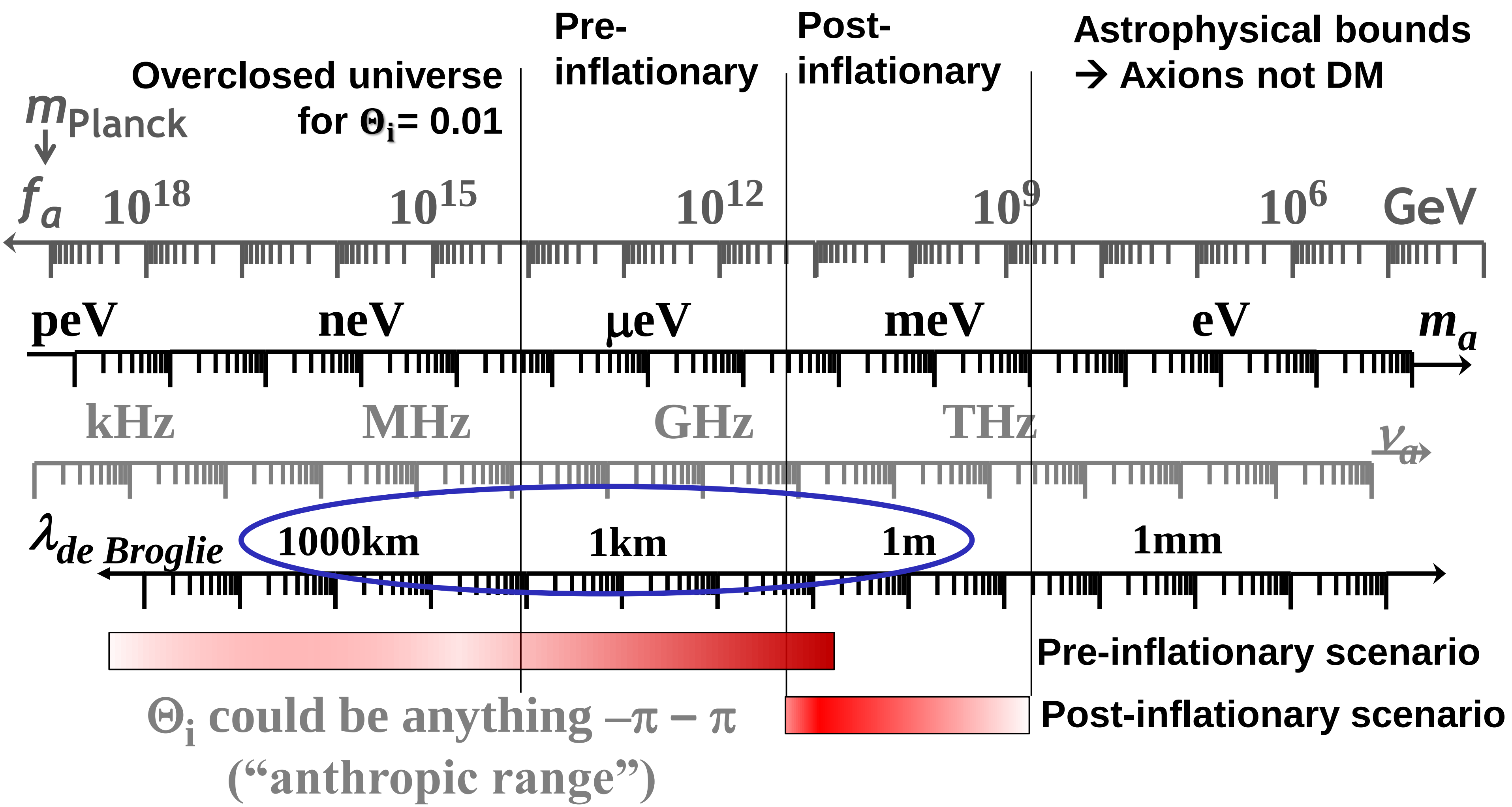
strong CP problem

Axiverse (string theory)

TeV transparency / stellar cooling

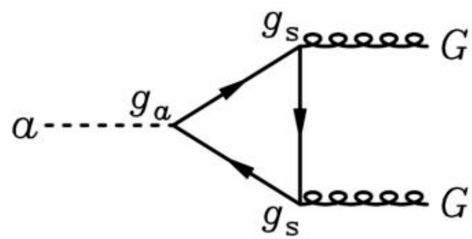


Putting DM axion properties into scale

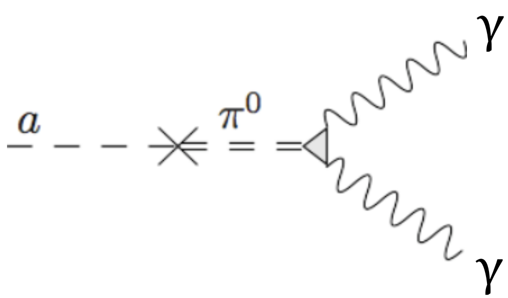


Experiment fits inside the particle!

Interactions of axions and ALPs

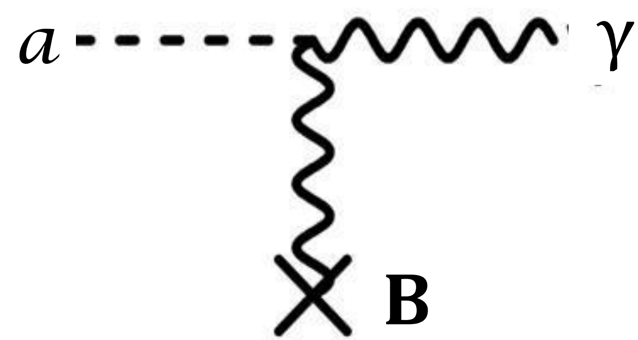


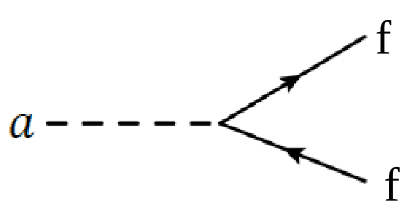
With nucleus



Mixing with photons

Primakoff effect

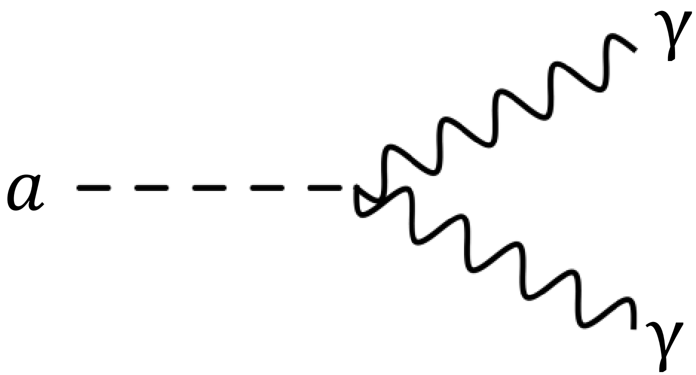




With Electron shell

Experimental approaches:

Axion to photon coupling



$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$$

$$= \frac{\alpha}{2\pi}\left(\frac{E}{N} - 1.92\right)\frac{a}{f_a}\mathbf{E}\cdot\mathbf{B} \propto \boldsymbol{m_a}$$

Modifies Maxwell equations: Additional source term

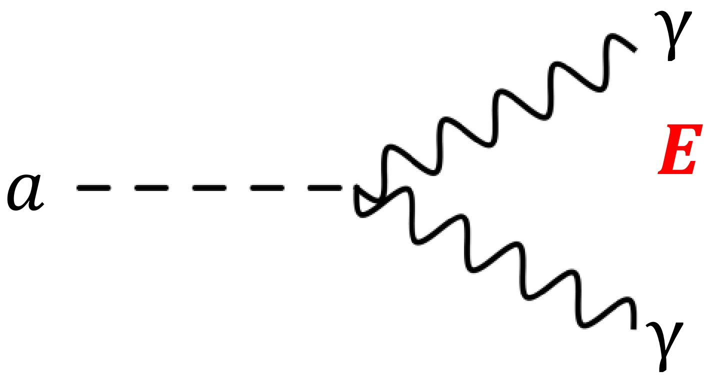
$$\nabla \times B - \dot{E} = J + g_{a\gamma}\, B\dot{a}$$

Oscillating!

in an external B-field the axion sources an E-field

Experimental approaches:

Axion to photon coupling



$$\boldsymbol{E(t) = -\frac{g_{a\gamma} B_{\text{ext}} a(t)}{\epsilon} = E_0 cos(m_a t)}$$

ϵ: dielectric constant

With local dark matter density:

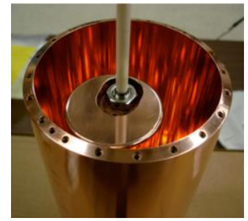
$$\rho_a = \frac{m_a^2 a_0^2}{2} = f_{\text{DM}} \frac{300\ \text{MeV}}{\text{cm}^3}$$

$$\boldsymbol{E_0 = 1.3 \times 10^{-12} \frac{Volts}{meter} \frac{B_{ext}}{10\ Tesla} C_{a\gamma} f_{DM}^{1/2}}$$

Experimental efforts worldwide

For sure not complete!

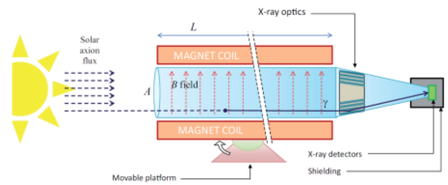
Experimental approaches:



Haloscopes - DM

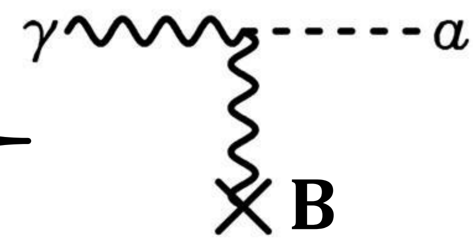
Cavity Dish antenna

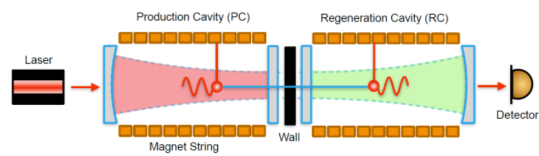
Dielectric haloscope



Helioscope – solar axions

Primakoff effect





Lab experiments - ALPs

Light shining through walls

LC circuit

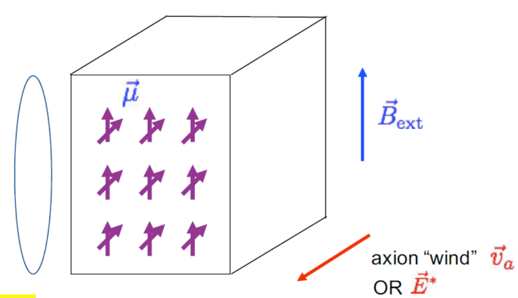
NMR methods

Beam dump

5^{th} force

Long range forces,

atomic transitions,…



Other couplings

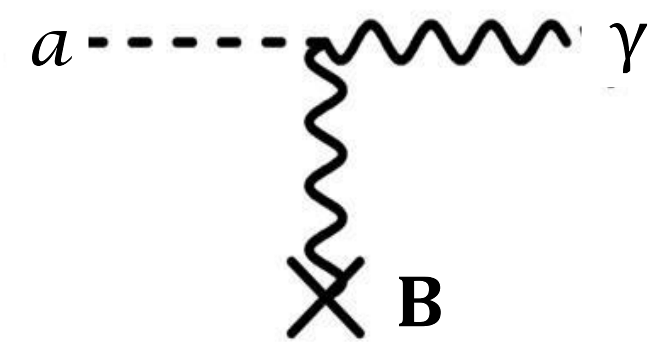
Experimental approaches
Cavity haloscope:

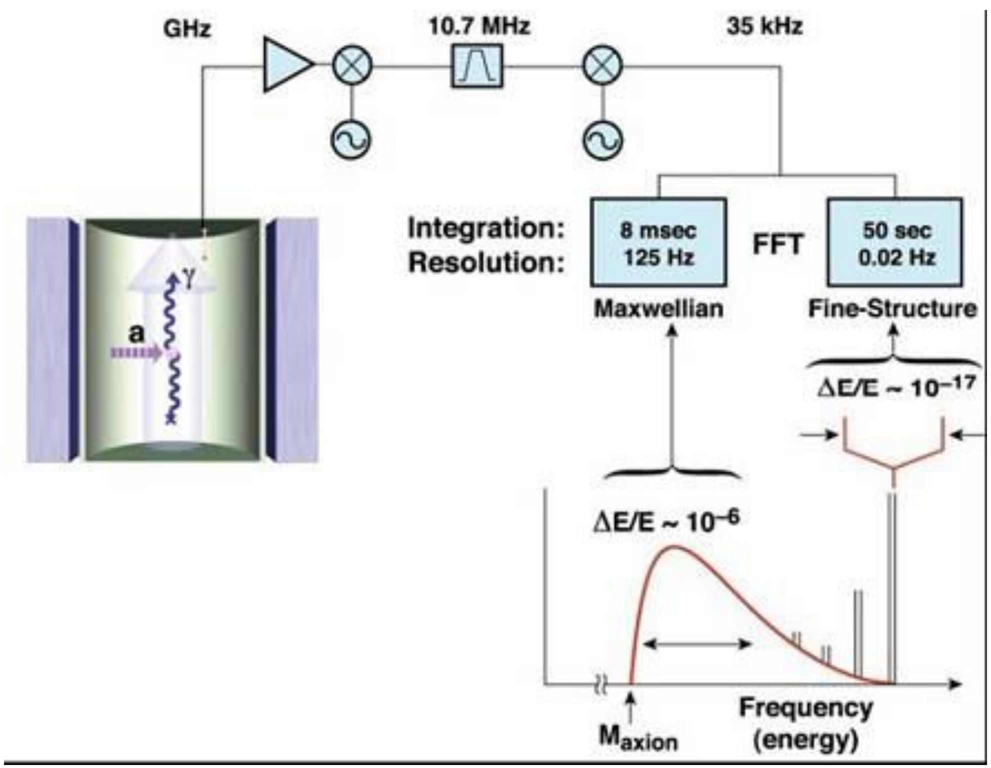
Primakoff effect

→ DM axion in static B field

→ Coherent E-field oscillation

In resonant cavity: enhancement of photon signal by quality factor of cavity





$$P_{sig} = (B^2 V\, Q_{cav})(g_{a\gamma\gamma}{}^2 m_a\, \rho_a)$$

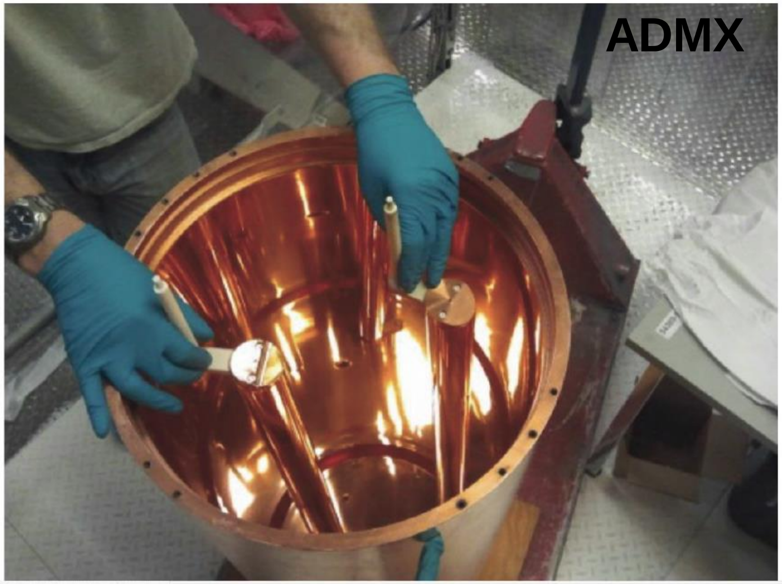
ADMX:

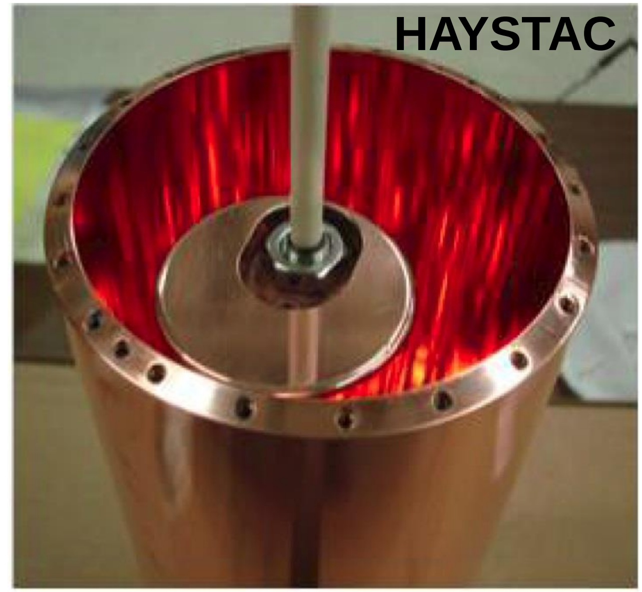
Q-factor $\sim 10^5$ $\quad$ $B = 8\,T$

$$P_{sig,ADMX} \approx 10^{-22}\, Watts$$

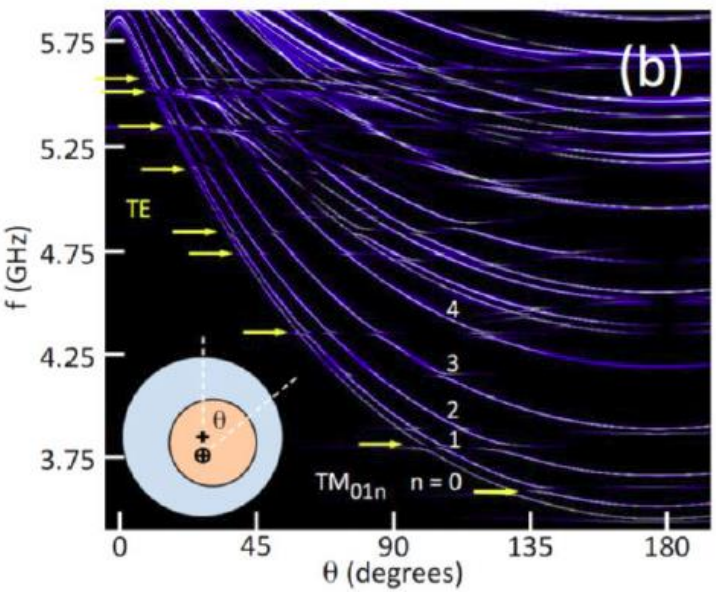
ADMX and Haystack cavity experiments

Taken from G. Rybka, presentation at ECT, Trento workshop **Axions at the crossroads: QCD, dark matter, astrophysics** 20 Nov, 2017 to 24 Nov.

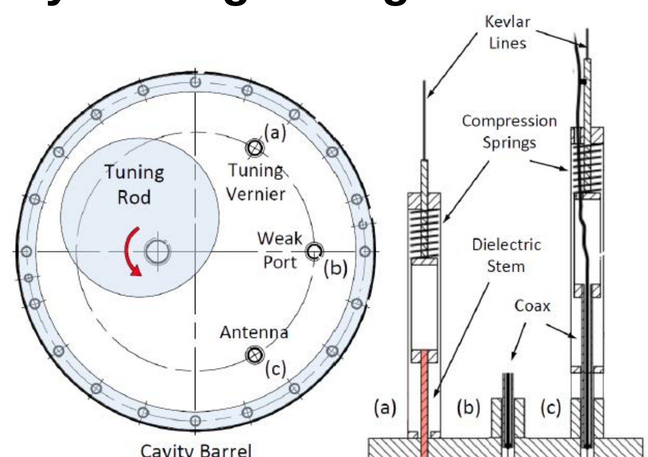




Brubaker et al., Phys. Rev. D 96, 123008 (2017)

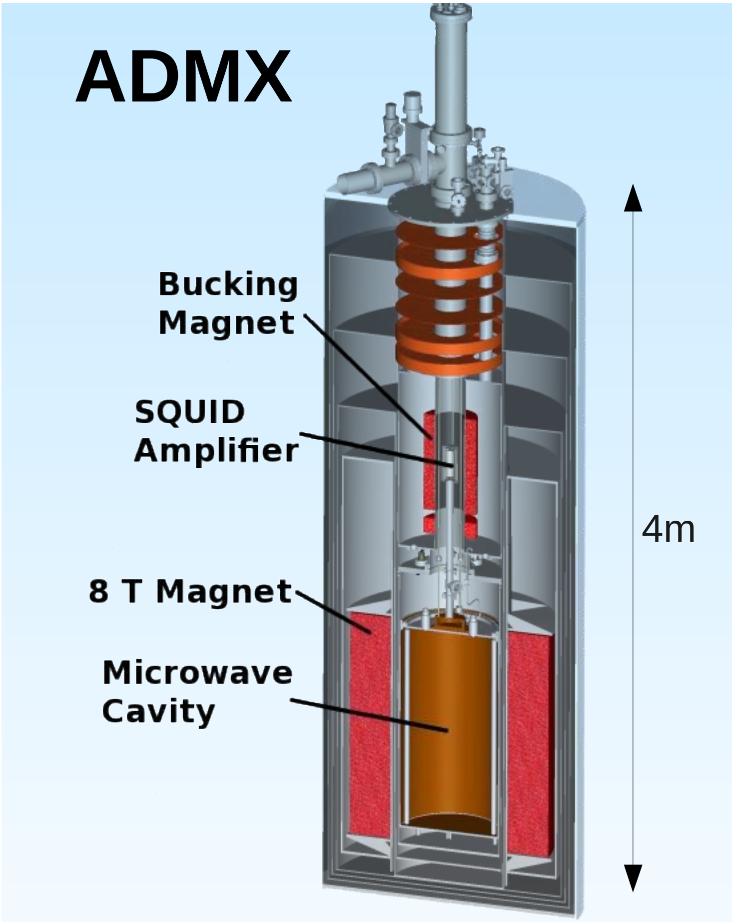


Tune cavity resonance frequency by turning tuning rod



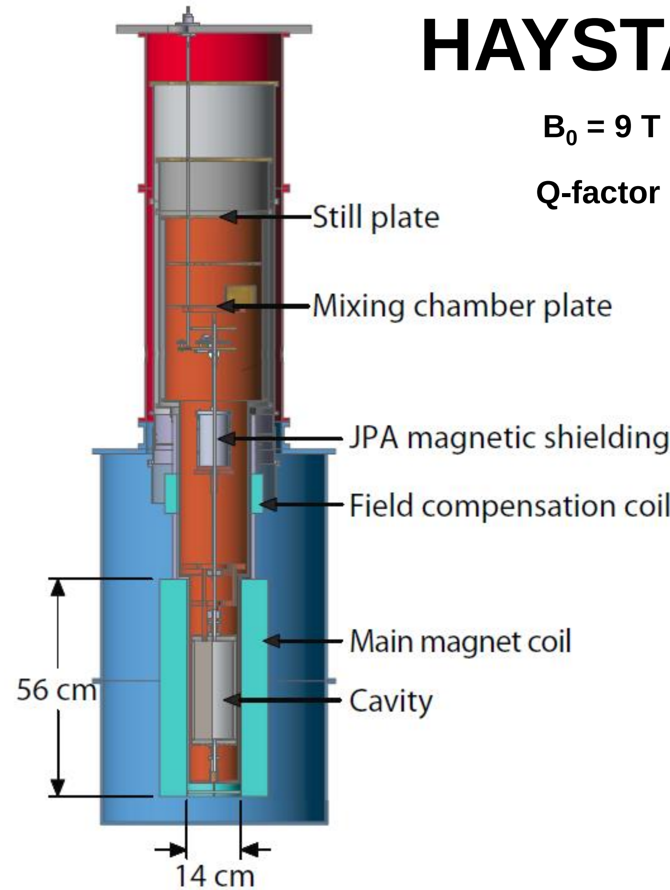
ADMX and HAYSTAC experiments

Axion Dark Matter eXperiment



LLNL, U. Washington, U. Florida,
U.C. Berkeley, NRAO, Sheffield U.

Haloscope at Yale Sensitive to Axion CDM



HAYSTAC

B_0 = 9 T @3.6K

Q-factor ~ $3 \cdot 10^4$

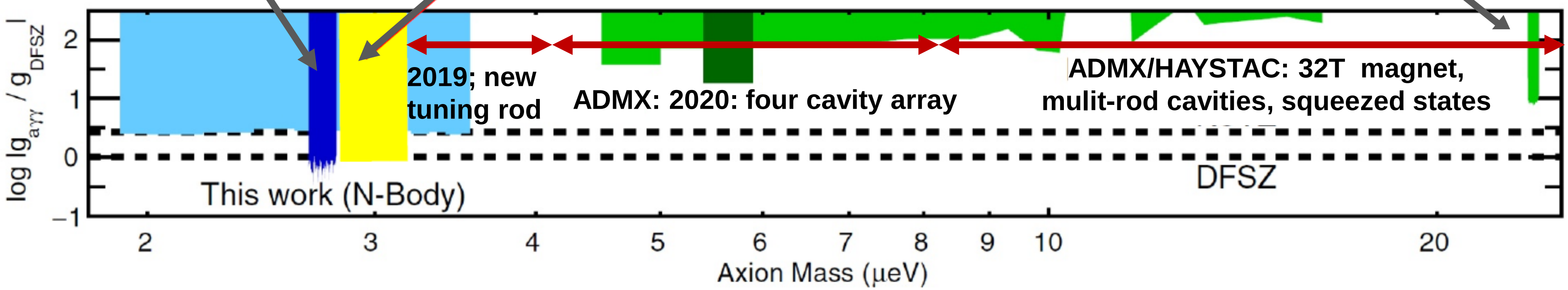
Preamps near quantum noise limit: Operate at ~50 mK

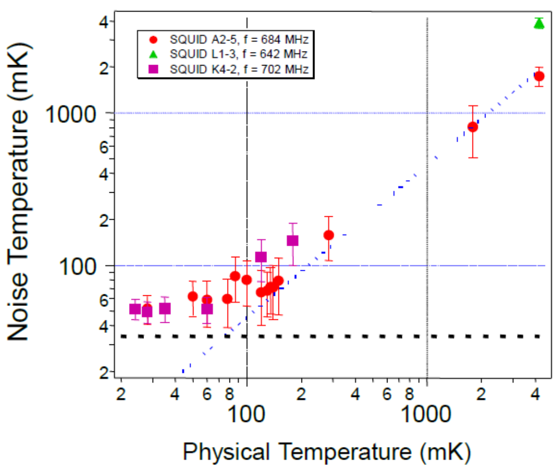
ADMX and Haystack cavity experiments

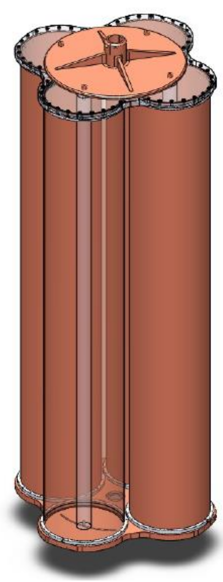
ADMX Limit **Region scanned**

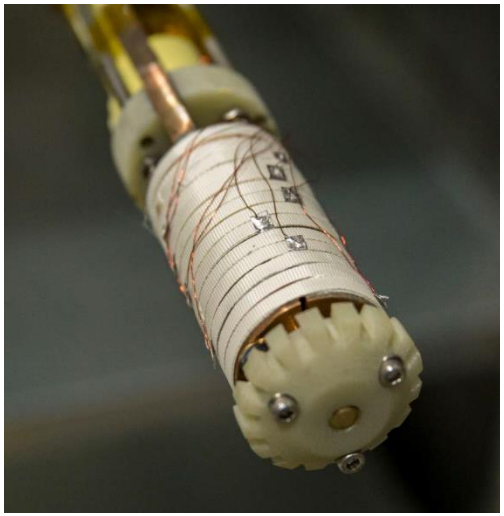
HAYSTAC Limit

Brubaker et al., Phys. Rev. D 96, 123008 (2017)









Axion searches in South Korea

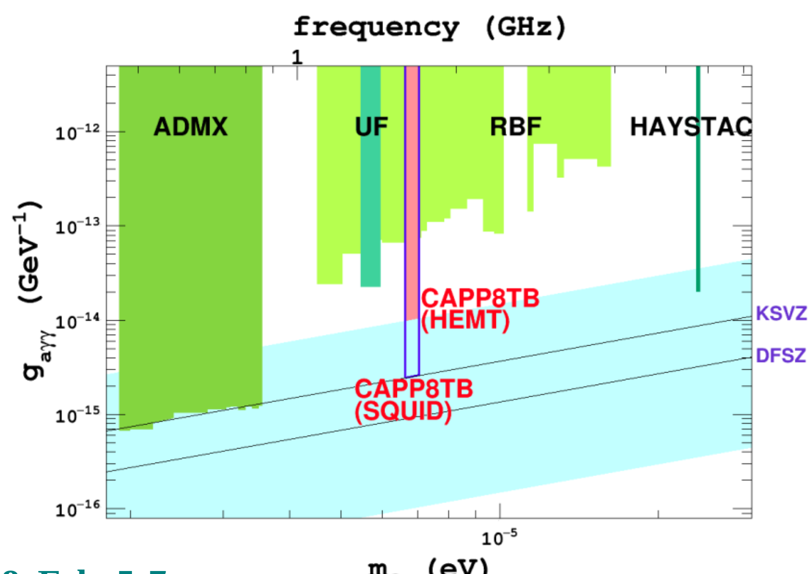
Center for Axion and Precision Physics Research
Institute for Basic Science

CAPP Ultra Low Temp. Axion Search in Korea - CULTASK

- *High B-field magnets* up to ***25T***
- *Quantum limited amplifiers*
- *High Q Superconducting cavities*
- *Large Volume Multi-cell cavities*

Experimets:

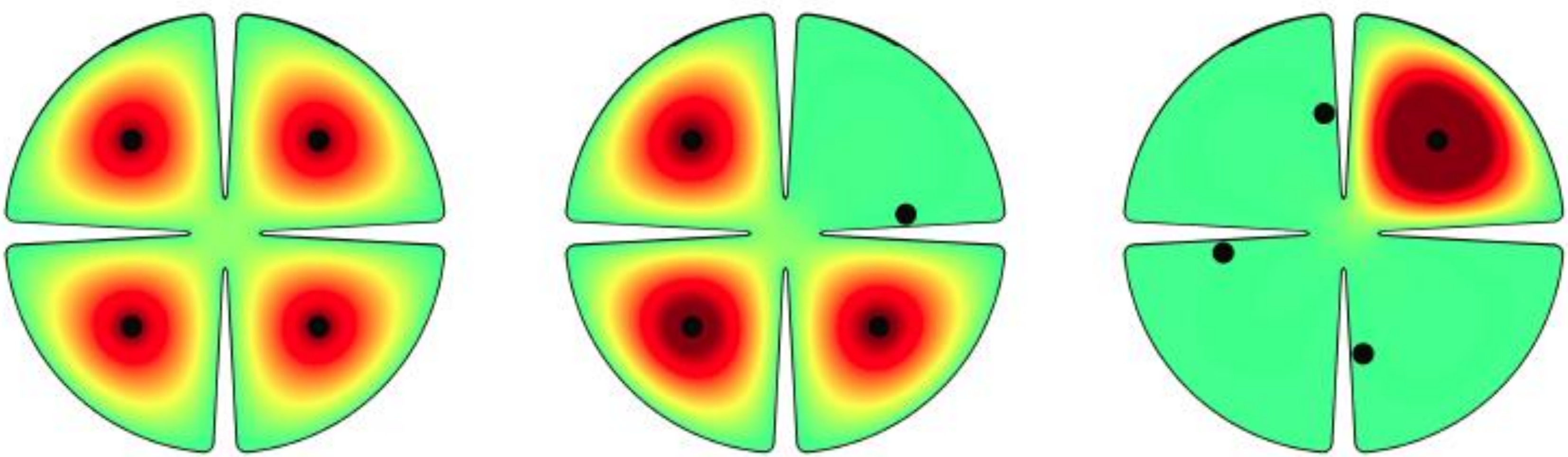
- **CAPP haloscopes - CULTASK**
- **CAST-CAPP - cavity in helioscope**
- **ARIADNE g_{aN}**
- **srEDM, GNOME, …**



Cavities for higher frequencies:

Higher frequency → smaller cavity
→ smaller Q-factor → less sensitivity

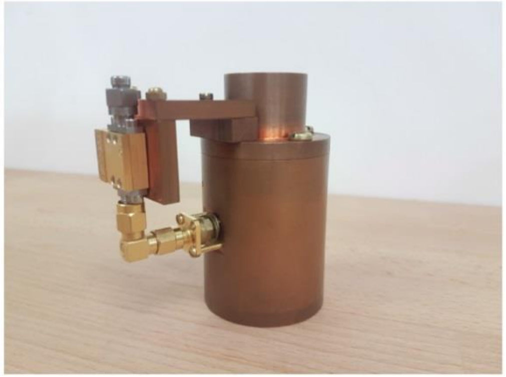
Investigtion of way around:
Phase matched multi cavity experiments: „Pizza cavity“ to reach higher masses:
CAPP / ORGAN / ADMX



See for example: arXiv:1710.06969v2

Organ cavity experiments

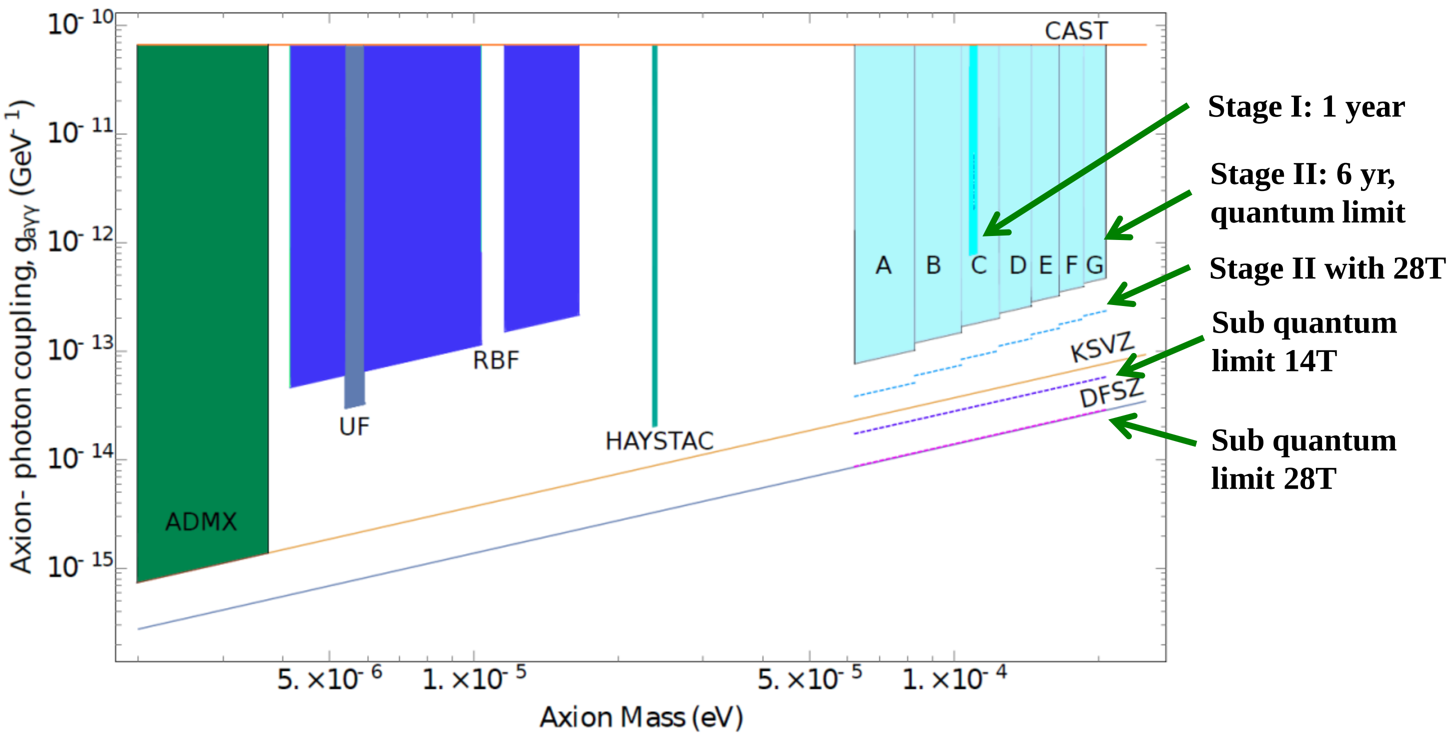
Oscillating Resonant Group AxioN
Perth, Australia

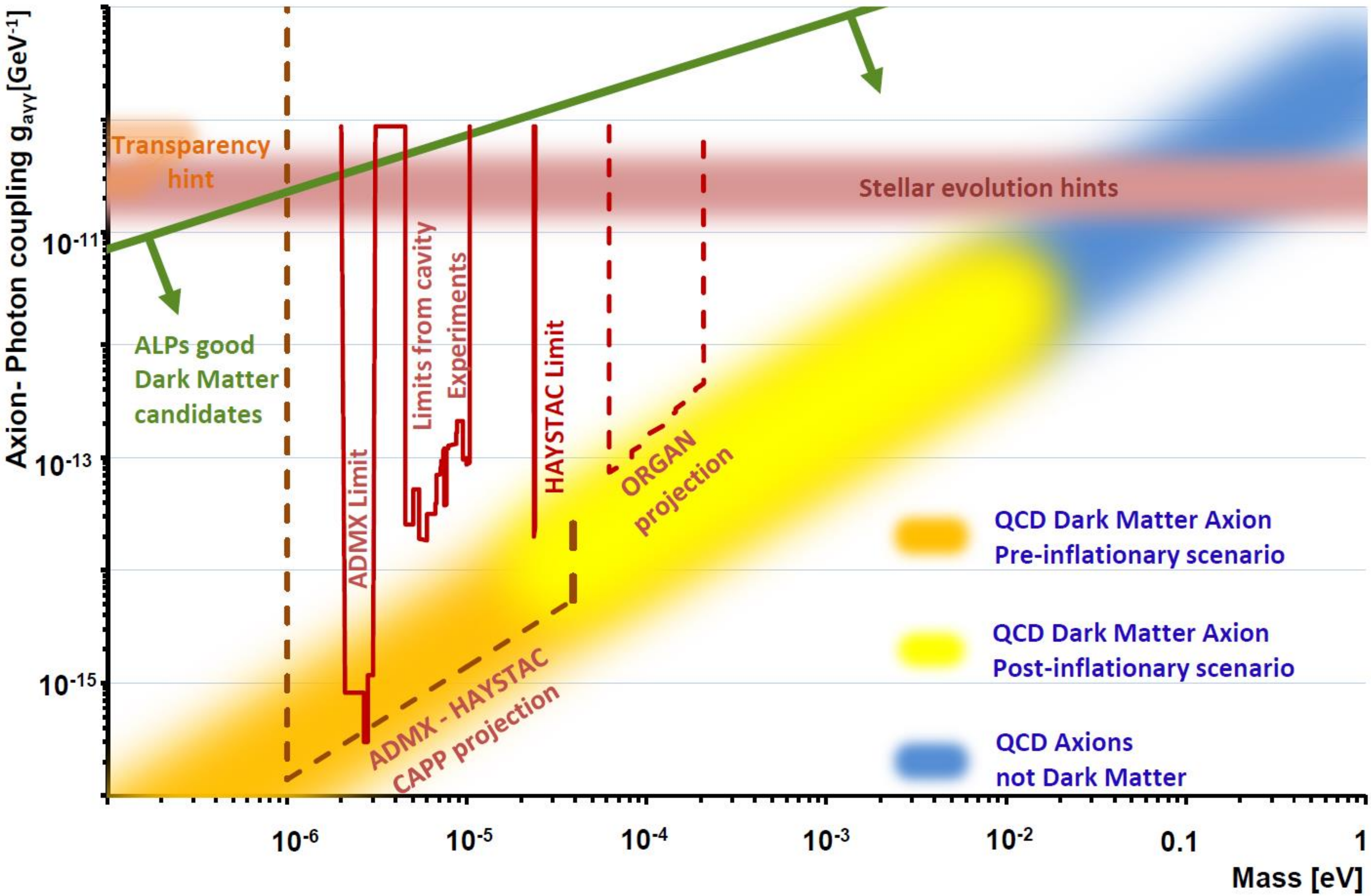


Stage I:
B=14 T, t= 1 yr Tsys=10K (HEMT), Q=50.000,
tuning with dielectric rod, → 26.1-27.1 GHz

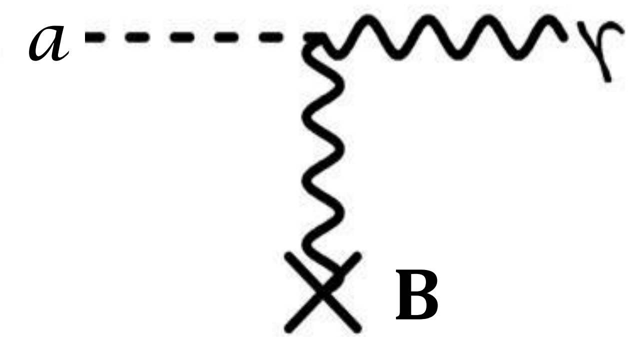
Possible upgrades:
T_{sys}= quantum limites,
B=28T, T_{sys}=sub quantum (squeezed vacuum)
Multiple cavity approach for higher frequencies

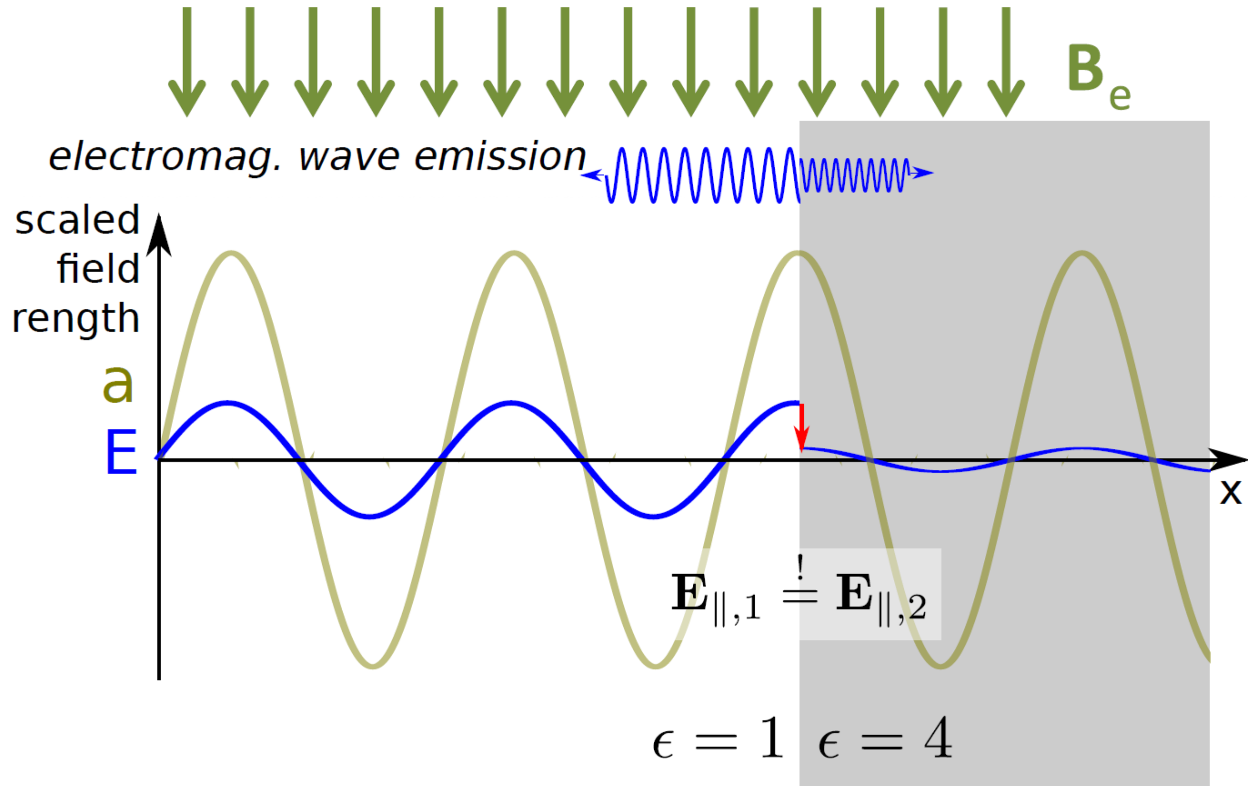
arXiv:1706.00209v2 [physics.ins-det]




Axion- Photon coupling $g_{a\gamma\gamma}$[GeV^{-1}]
10^{-11}
10^{-13}
10^{-15}
Transparency hint
ALPs good Dark Matter candidates
ADMX Limit
Limits from cavity Experiments
HAYSTAC Limit
ORGAN projection
ADMX - HAYSTAC CAPP projection
Stellar evolution hints
QCD Dark Matter Axion Pre-inflationary scenario
QCD Dark Matter Axion Post-inflationary scenario
QCD Axions not Dark Matter
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
0.1
1
Mass [eV]

Effect of Dielectric



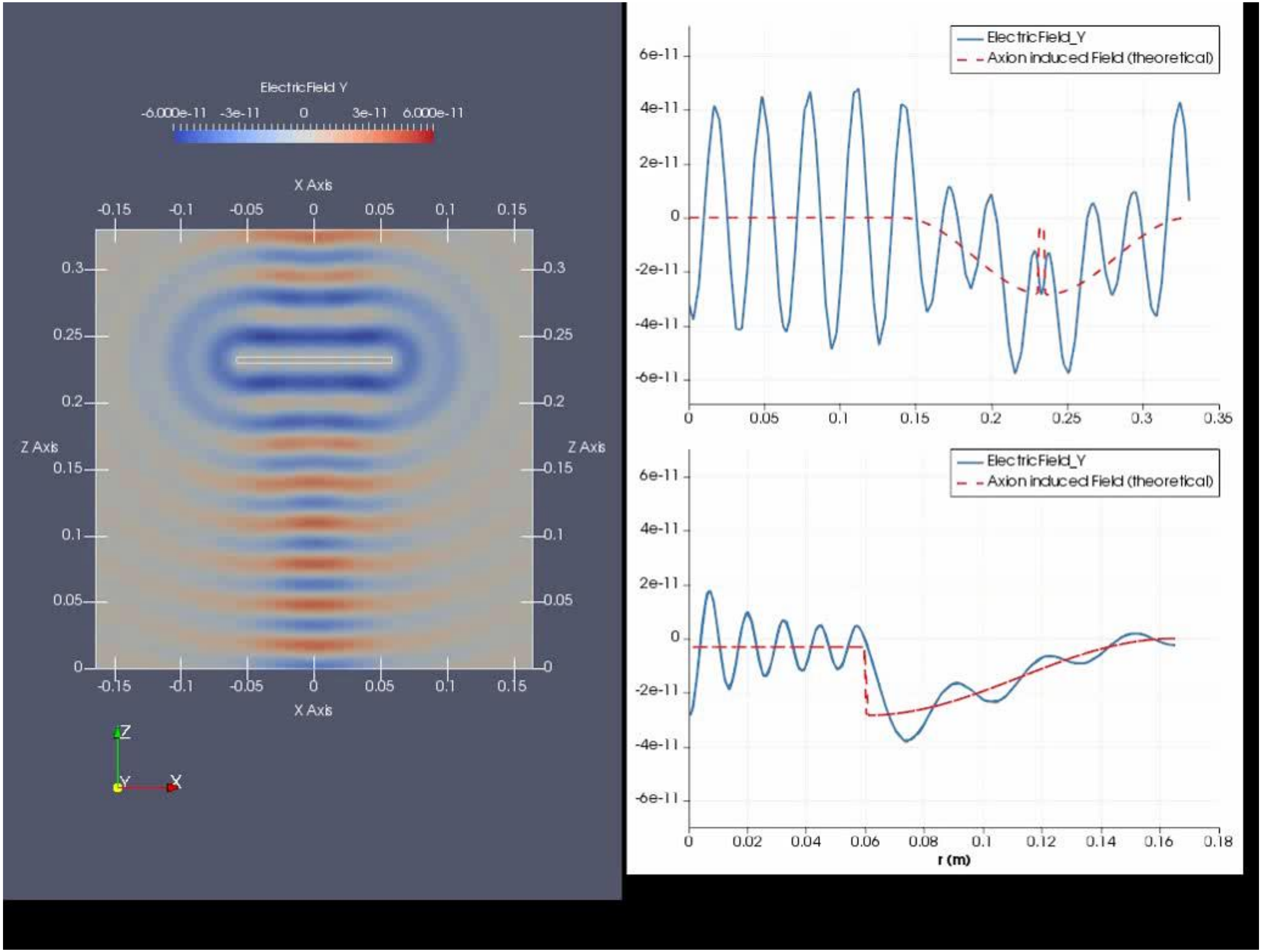


Axion in B field
→ oscillating E-field

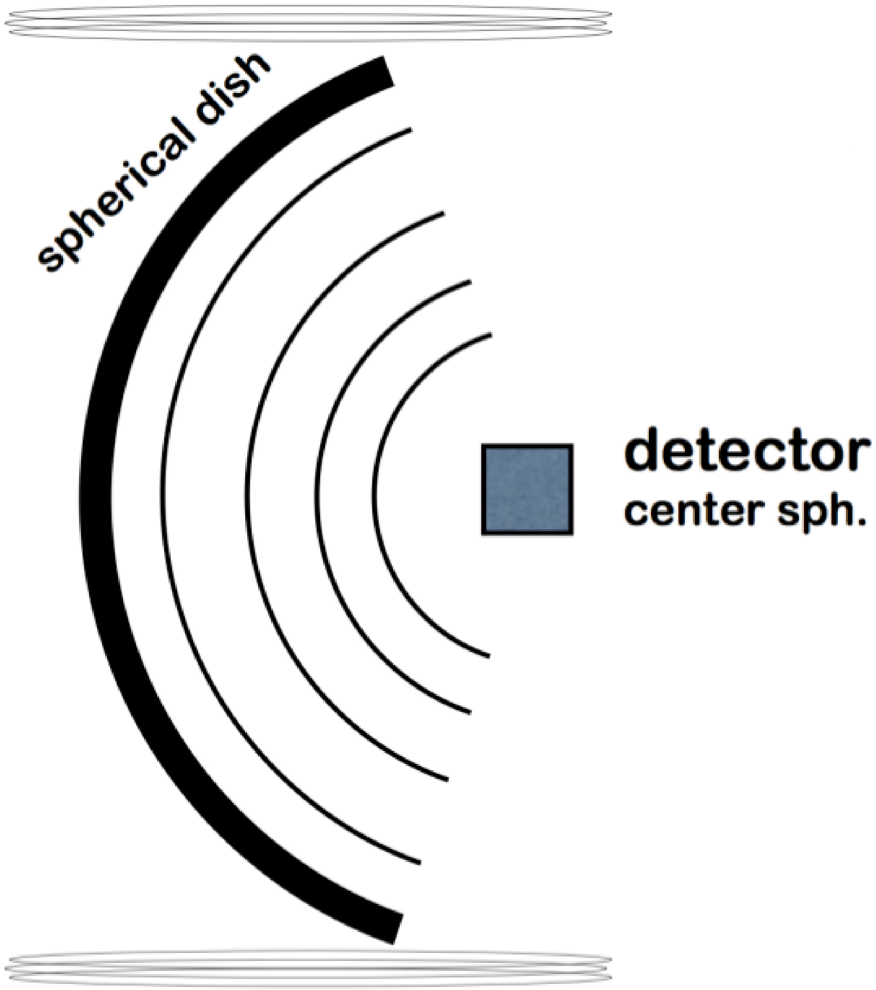
At surfaces with transition of ε:
→ Discontinuity of E-field
→ Emission of photons

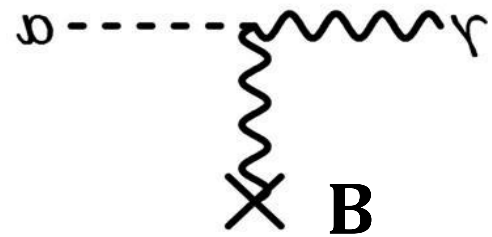
$$\left(\frac{P}{A}\right)_{mirror} \sim 2 \cdot 10^{-27} \frac{W}{m^2} \left(\frac{B_{||}}{10\ T}\right)^2 \left(g_{a\gamma\gamma} m_a\right)^2$$

D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald JCAP 1304 (2013) 016 [arXiv:1212.2970].


ElectricField Y
-6.000e-11 -3e-11 0 3e-11 6.000e-11
X Axis
Z Axis
ElectricField_Y
Axion induced Field (theoretical)
r (m)

Dish antenna haloscope:



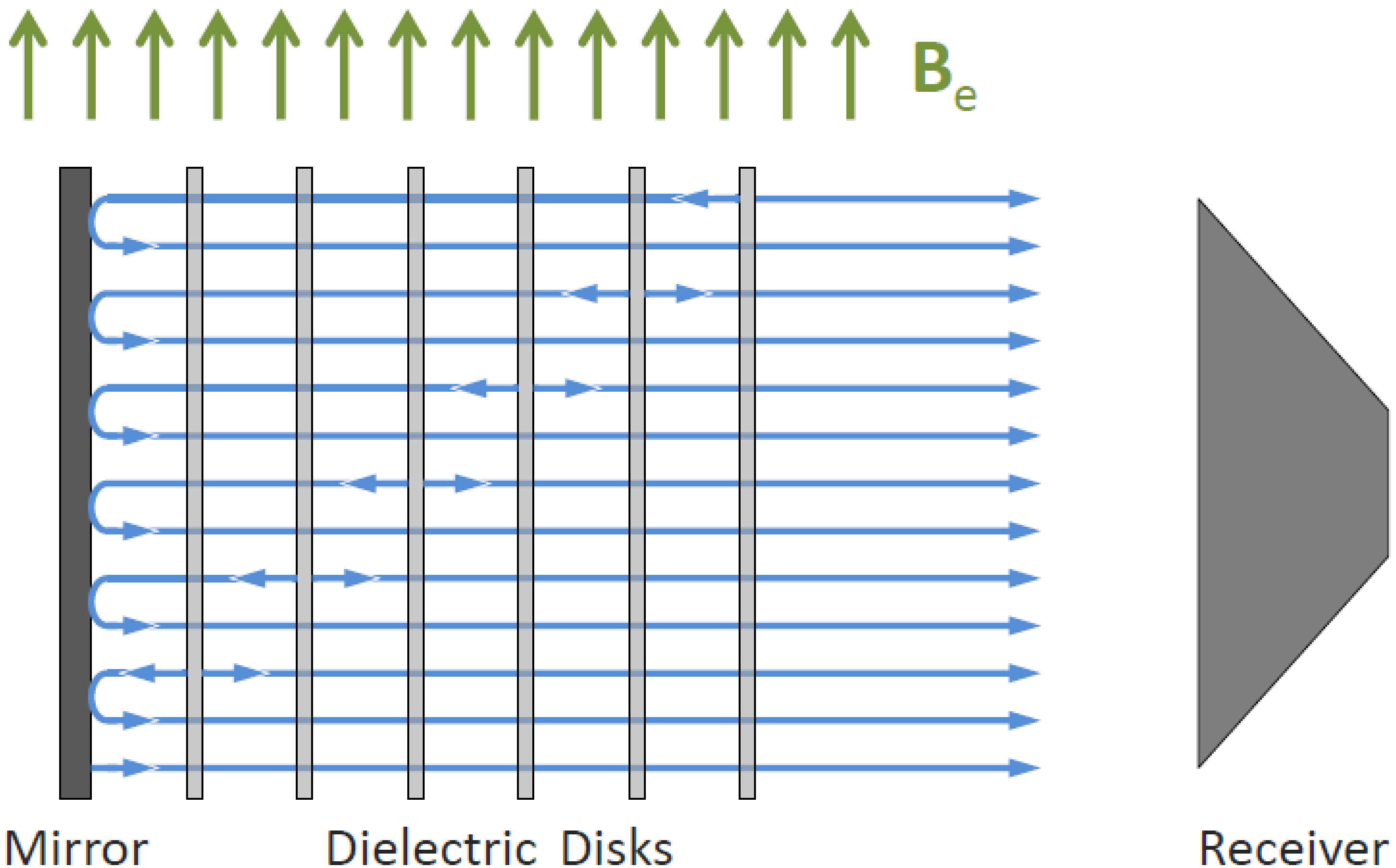


Broadband approach

Also works for kinetic mixing
→ Hidden photon search:
no B-field needed

For axion search:
Need large area or
Extremely sensitive detector
[BRASS @ Uni Hamburg/DESY]

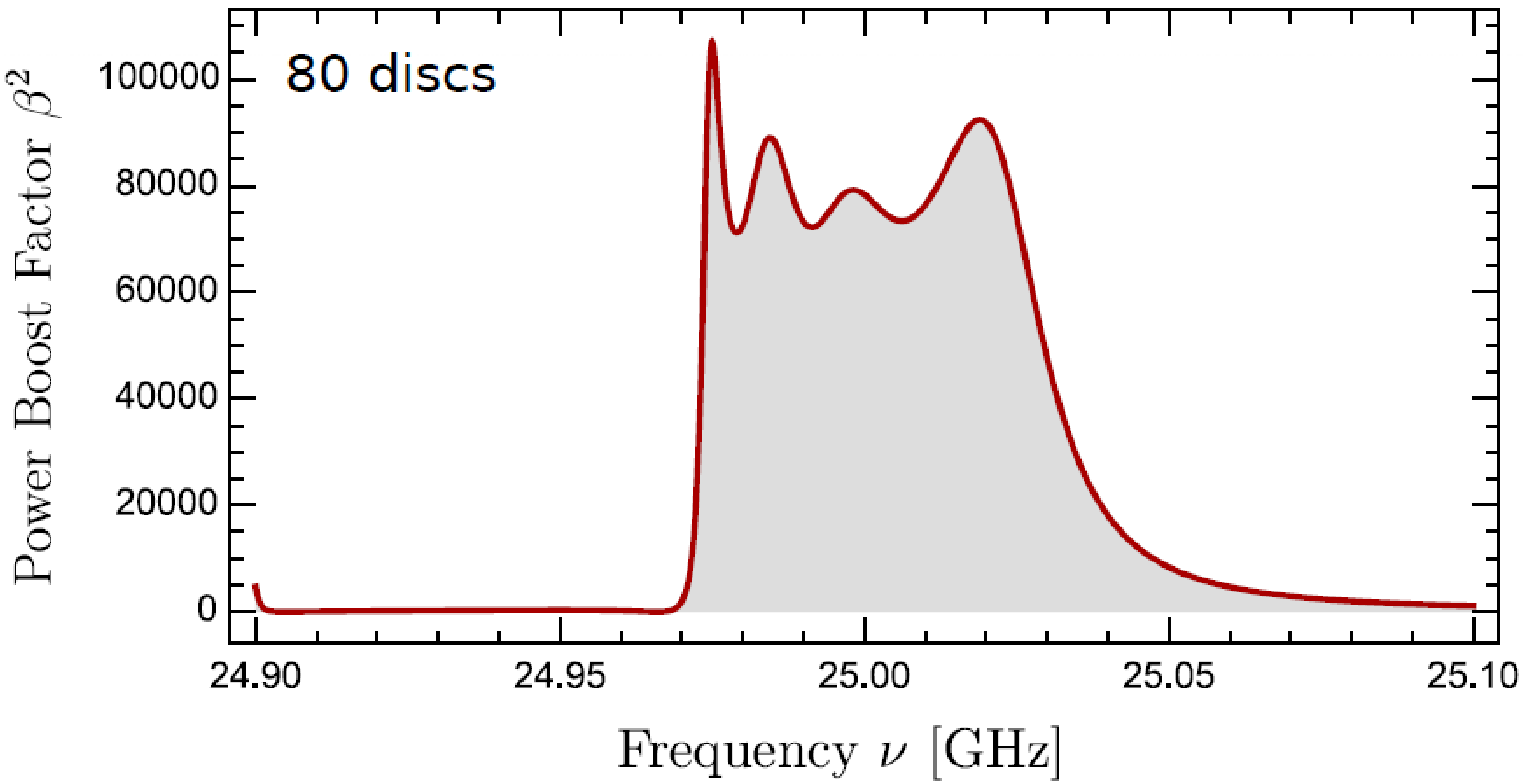
Dielectric haloscope:



$$\left(\frac{P}{A}\right)_{cavity} \sim 2\cdot 10^{-27}\frac{W}{m^2}\left(\frac{B_{||}}{10\ T}\right)^2 (g_{a\gamma\gamma}m_a)^2\beta^2$$

$$\beta^2 = \frac{P_{cavity}}{P_{mirror}}$$

Dielectric haloscope:

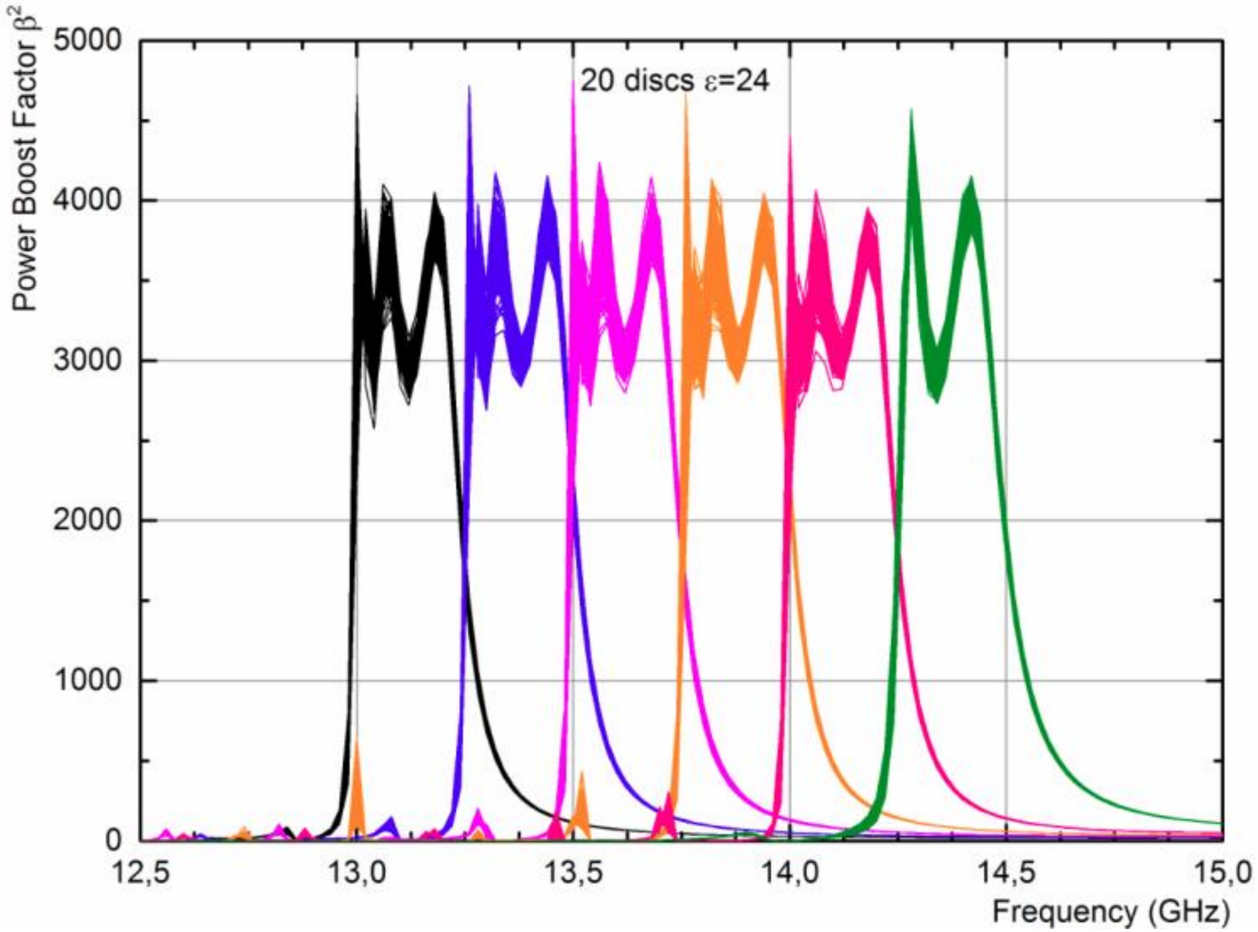


Power boost of >10^4 achievable with 80 discs of LaAlO3

“Quasi broadband” approach

The MADMAX Working Group: Phys. Rev. Lett. 118, 091801 (2017)
arXiv:1611.05865

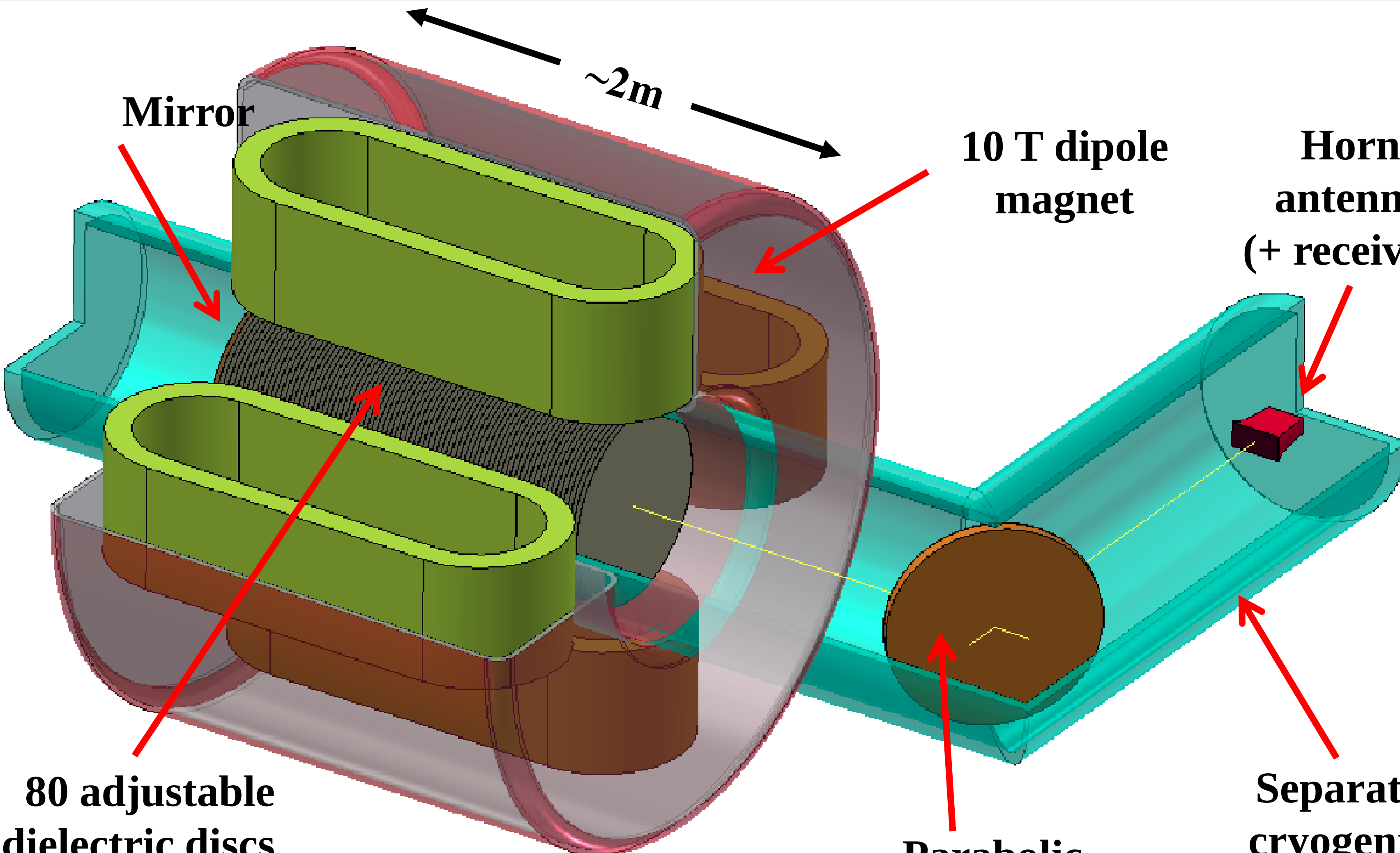
Dielectric haloscope:



Tuning of sensitive frequency range:
Disk spacings

The MADMAX Working Group: Phys. Rev. Lett. 118, 091801 (2017)
arXiv:1611.05865

MADMAX
MAgnetized Disc and Mirror Axion eXperiment



MADMAX

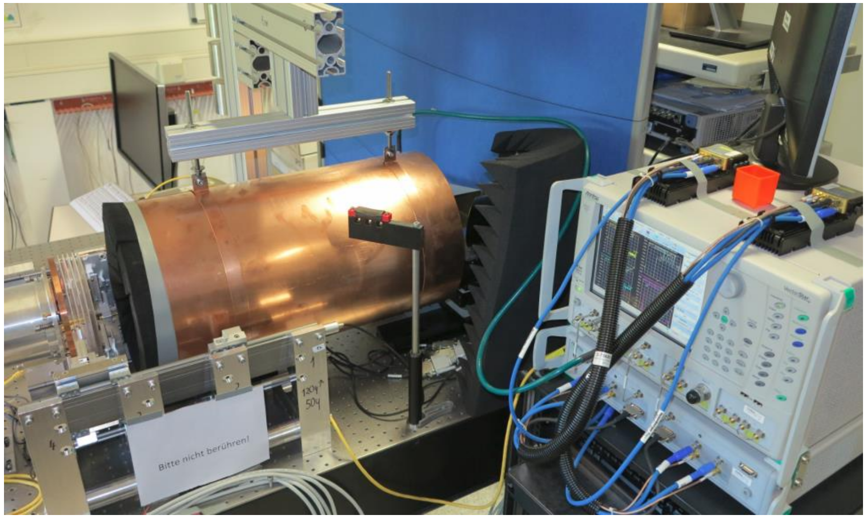
Collaboration forming at DESY, Hamburg

Site: DESY Hamburg, hall north

8 Institutes from France, Germany, Spain

RWTH AACHEN UNIVERSITY · Max-Planck-Institut für Radioastronomie · DESY · Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG · Max-Planck-Institut für Physik · Irfu - CEA Saclay Institut de recherche sur les lois fondamentales de l'Univers · cea · EBERHARD KARLS UNIVERSITÄT TÜBINGEN · Universidad Zaragoza

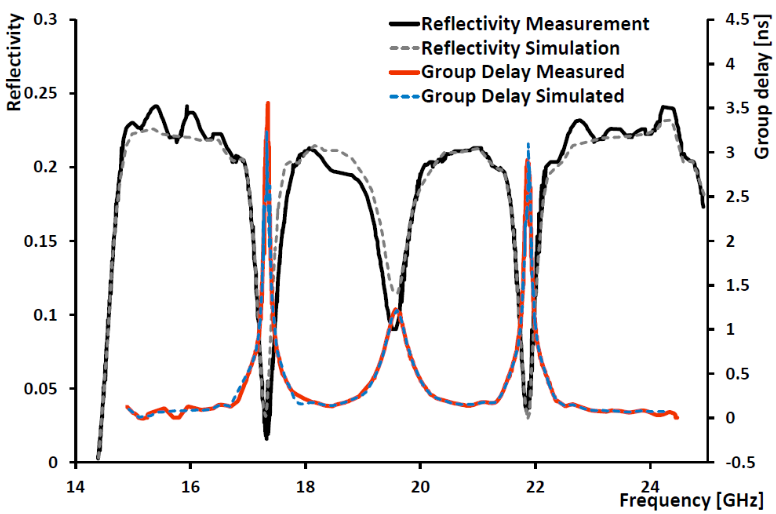
MADMAX: Prototype setup

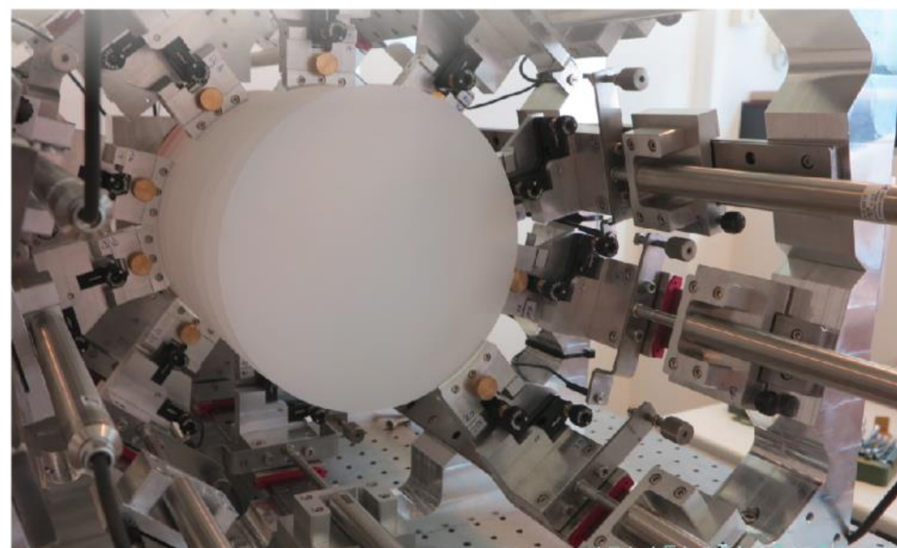


- Measurements of transmissivity and Reflectivity: Confirmed simulations
- Sensitivity: HEMT pream @ LHe: detect 10^{-23}W signal in 7 days
- Understand neede precision reproducibility ok

Excellence Cluster Universe

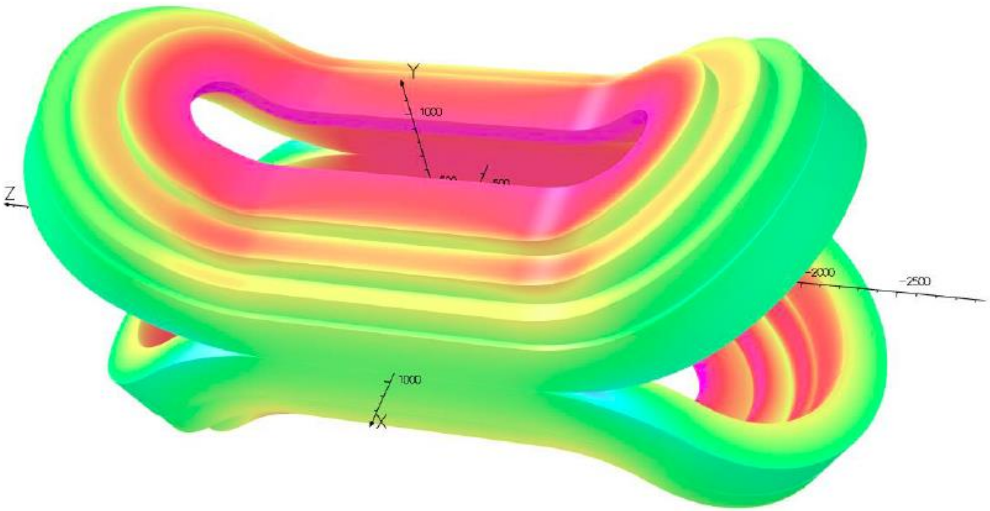
Prototype setup partly funded as seed project by:

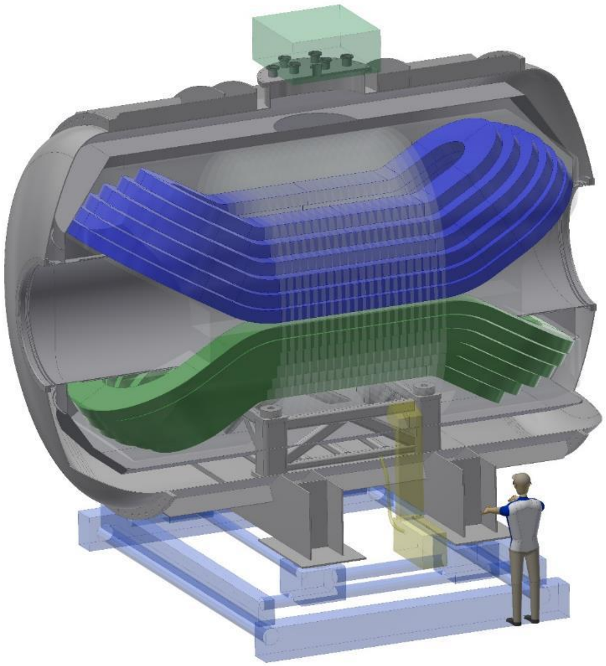




MADMAX: The magnet

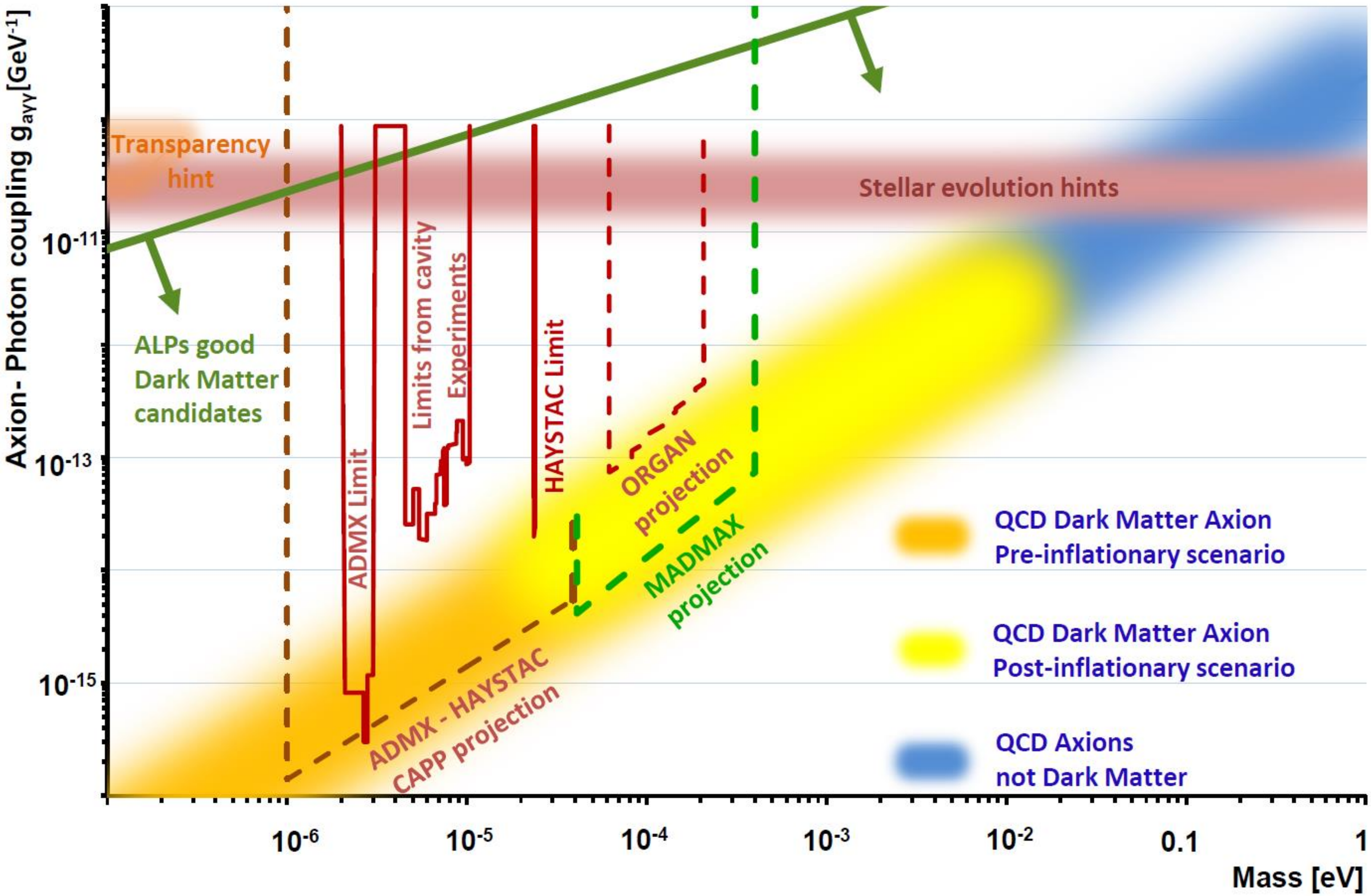
Innovation partnership with Böhringer Noell & CEA IRFU, Saclay
→ develop feasible magnet with FoM 100T²m²
Latest result: Can be done using NbTi with 9T, 1.25 m² aperture



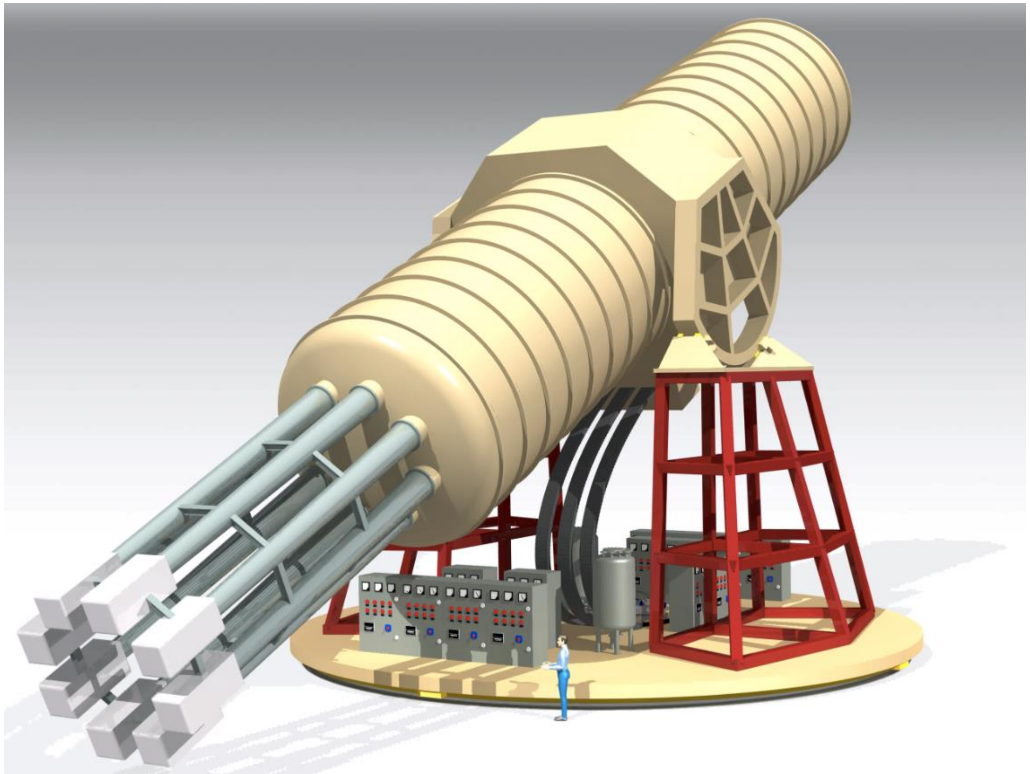


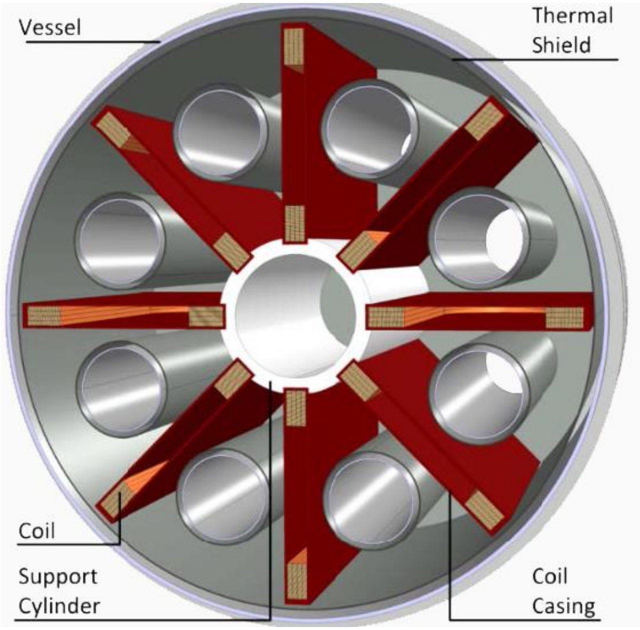
2018: **Finish magnet design & proof of principle investigations**

~ 2021: **Run prototype (3T, 30cm diameter) until 2021**
→ first physics results (ALPs Hidden photons


Axion- Photon coupling $g_{a\gamma\gamma}$[GeV^{-1}]
10^{-11}
10^{-13}
10^{-15}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
0.1
1
Mass [eV]
Transparency hint
Stellar evolution hints
ALPs good Dark Matter candidates
ADMX Limit
Limits from cavity Experiments
HAYSTAC Limit
ORGAN projection
MADMAX projection
ADMX - HAYSTAC CAPP projection
QCD Dark Matter Axion Pre-inflationary scenario
QCD Dark Matter Axion Post-inflationary scenario
QCD Axions not Dark Matter

IAXO Helioscope:

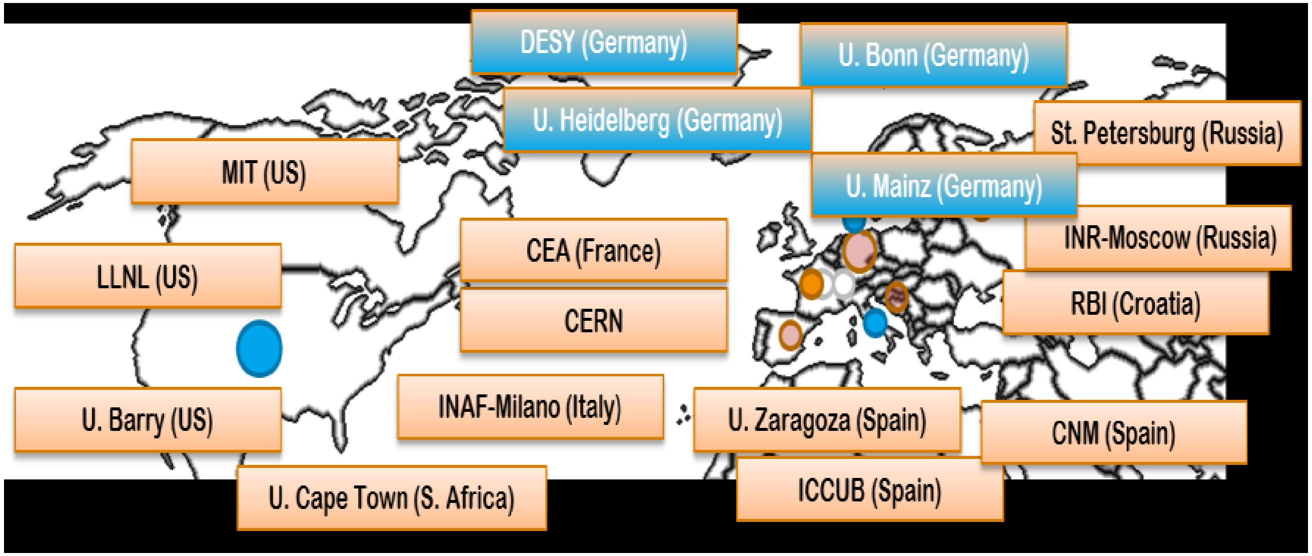




- **Worldwide first "large scale" Axion experiment.**
- **Combine expertise:**
  CAST, magnets for colliders, X-ray optics from satellites, ultra-low background X-ray detectors.
- **Toroidal 8-coil magnet L=~20m, 600mm bore, ~6T**

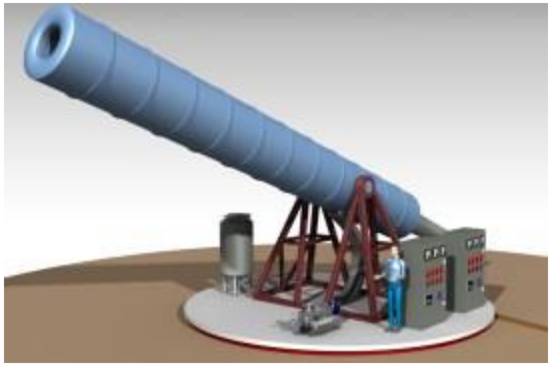
IAXO collaboration:

- Collaoration founded in July 2017 at DESY
- 17 institues from 8 countries
- DESY offered to host IAXO

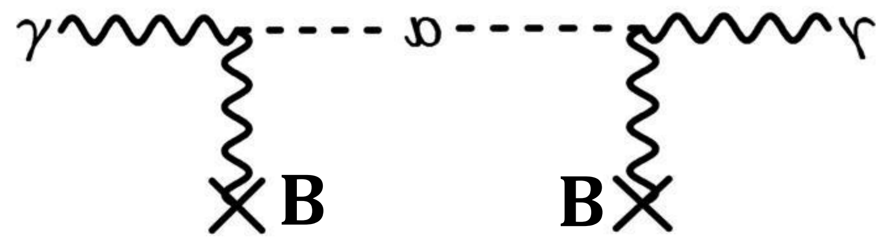


First step: babyIAXO by 2021:

- Toroidal ~6T magnet
  L=~20m, 600mm bore



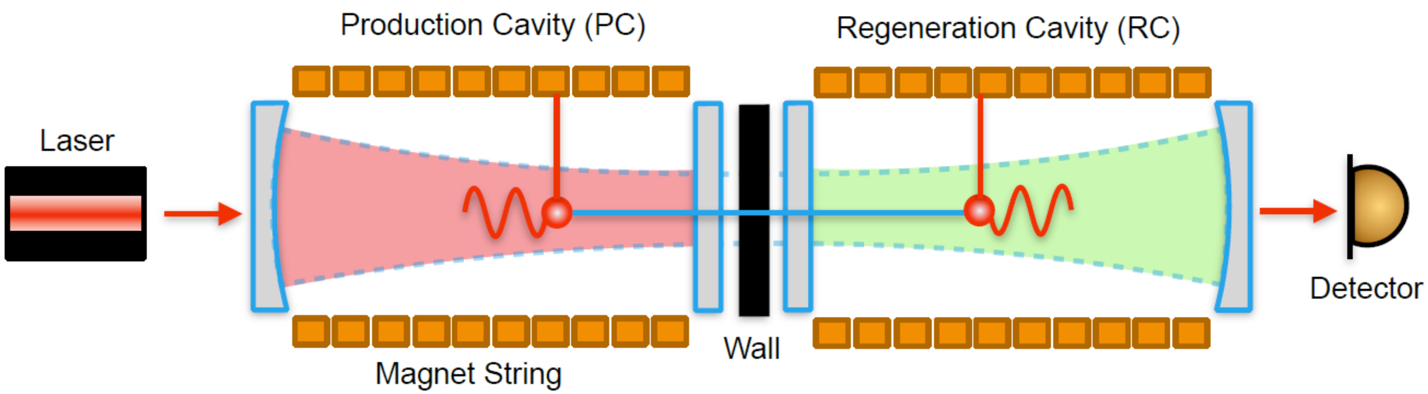
Experimental approaches
Light shining through the wall:



Primakoff effect twice

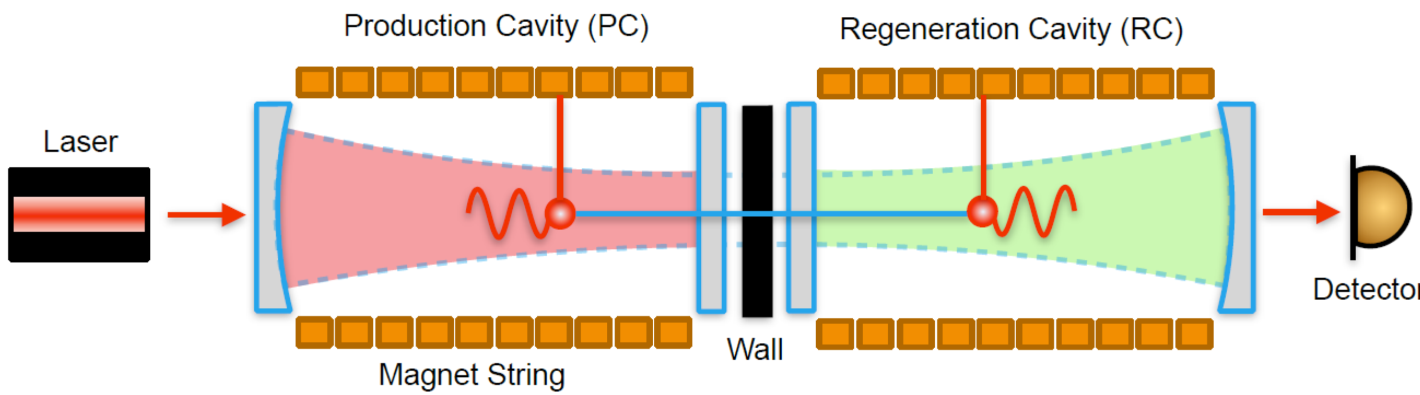
→ Convert photons into axion and reconvert behind wall

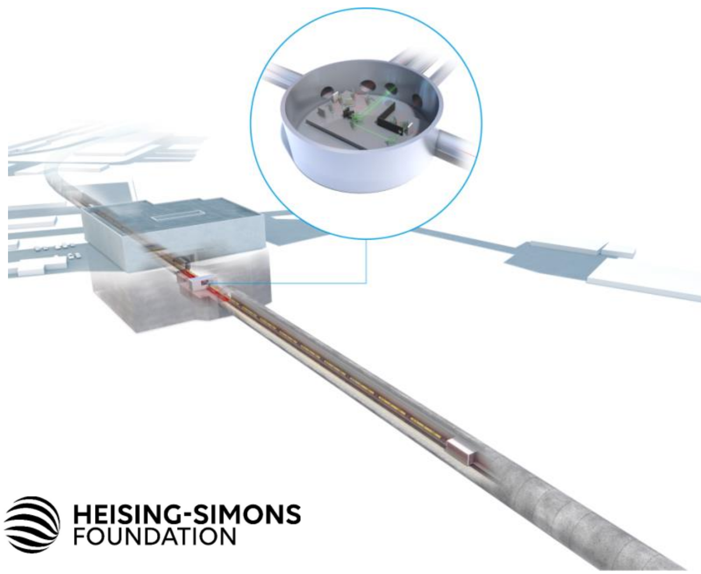
→ Detect regenerated photon behind wall



$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot 10^{-38}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\frac{B}{1\,T}\frac{l}{10m}\right)^4$$

ALPS II at DESY:





HEISING-SIMONS FOUNDATION

HELMHOLTZ ASSOCIATION

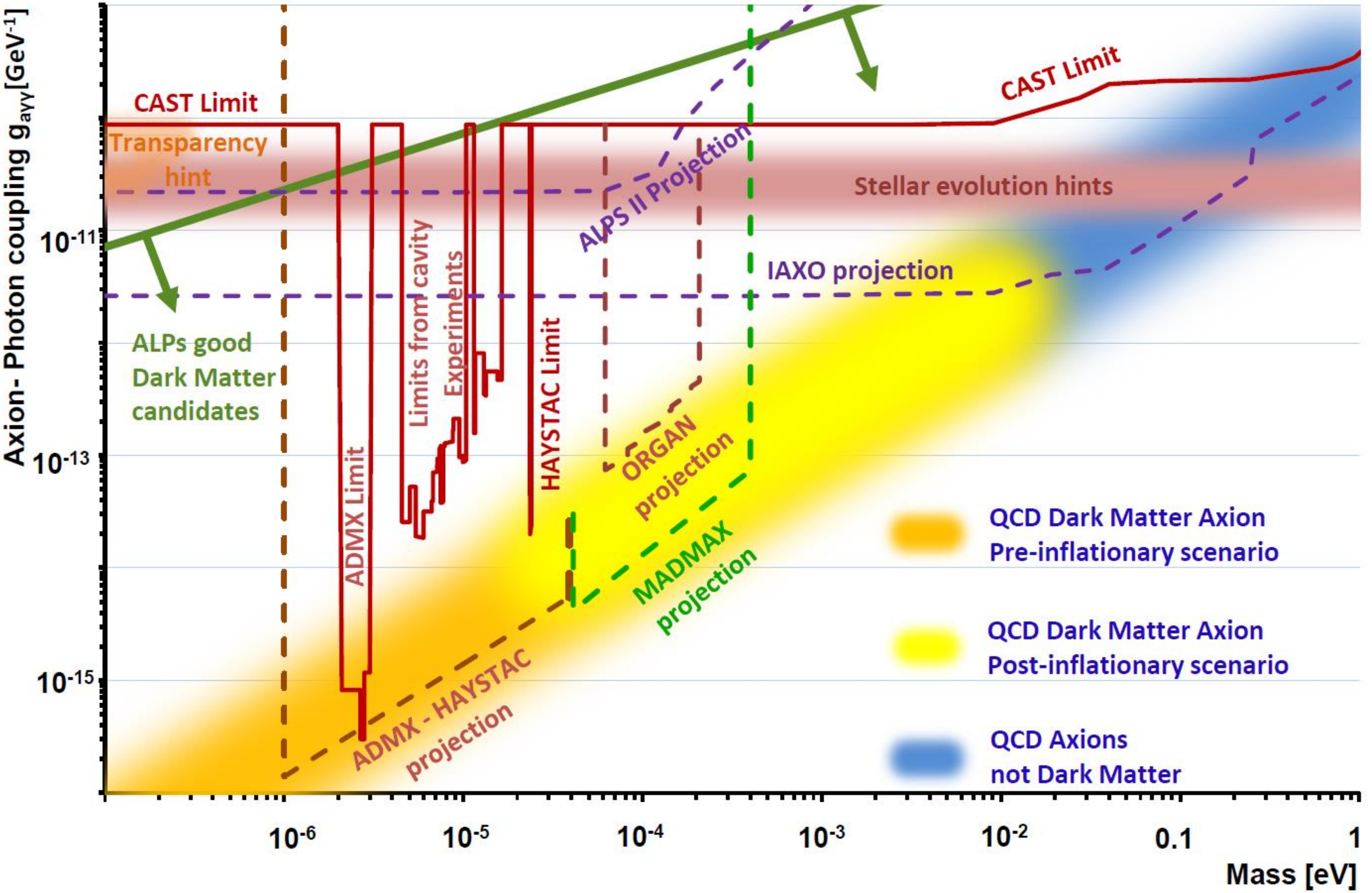
Main challenges:

Magnet – straighten 20 HERA dipoles 200m,
Optics – LIGO related concepts,
Detector – TES, heterodyne in development

Timeline:

- **Cleared HERA tunnel**
- **ALPS IIc optics commissioning beginning 2019**
- **ALPS IIc data runs in 2020**

ALPS II is a joint effort of DESY, Universität Hamburg, Albert Einstein Institute Hannover, Leibniz Universität Hannover, JOHANNES GUTENBERG UNIVERSITÄT MAINZ, UF UNIVERSITY of FLORIDA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QCD Dark Matter Axion Pre-inflationary scenario
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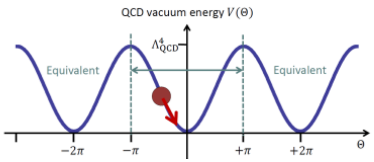
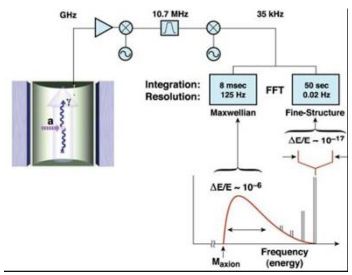
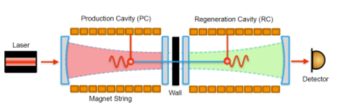
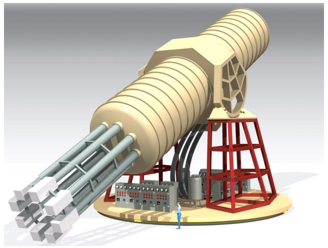
QCD Axions not Dark Matter

C O N C L U S I O N S

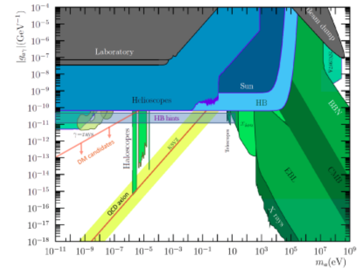


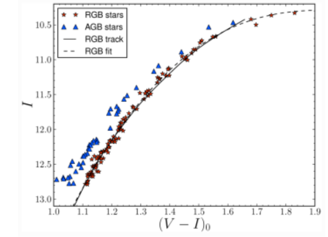


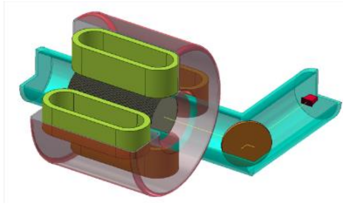


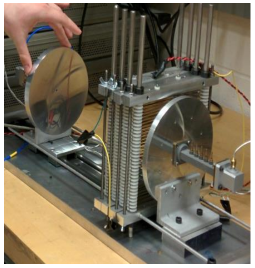


- Axions in mass range ~1-400 µeV could **solve strong CP & Dark Matter problems**
- Generic ALPs motivated by **stellar cooling and transparency anomalies**
- Cavity haloscope experiments probe DM axion masses **~ 1 – 40 µeV**
- Dielectric haloscope could be sensitive in the range **~ 40 – 400 µeV**
- Helioscopes and LSW experiments have sensitivity to DM ALPs motivated by **stellar cooling**
- Magnet issue seems solvable (price?)
- **Very complementary** axion and ALP search community!
- Next 10 years could be **very exciting!**









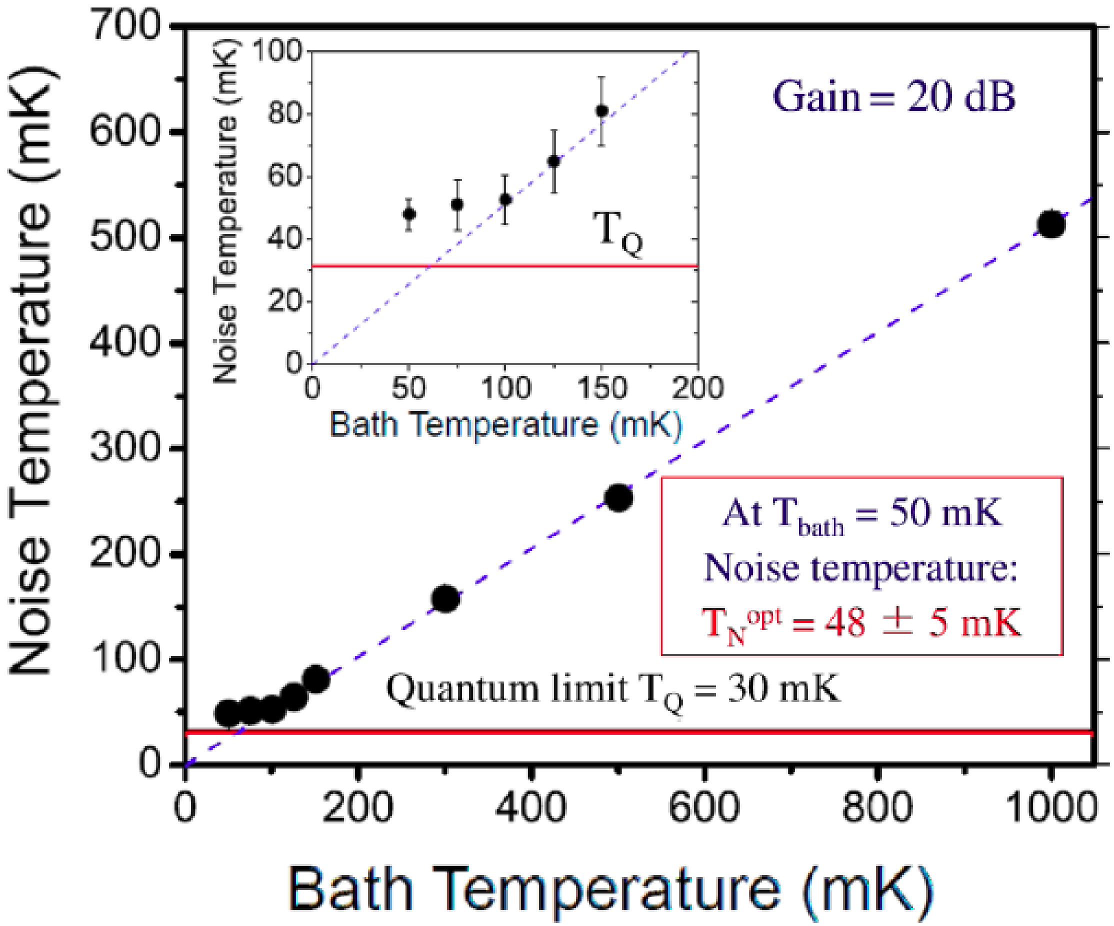
ADMX and Haystack experiments

Dicke's radiometer equation:

$$\frac{S}{N} = \frac{P_{\text{sig}}}{k_B T_{\text{sys}}} \sqrt{\frac{t_{\text{scan}}}{\Delta\nu}}$$

Quantum noise:
>1/2 photon per resolution bandwidth

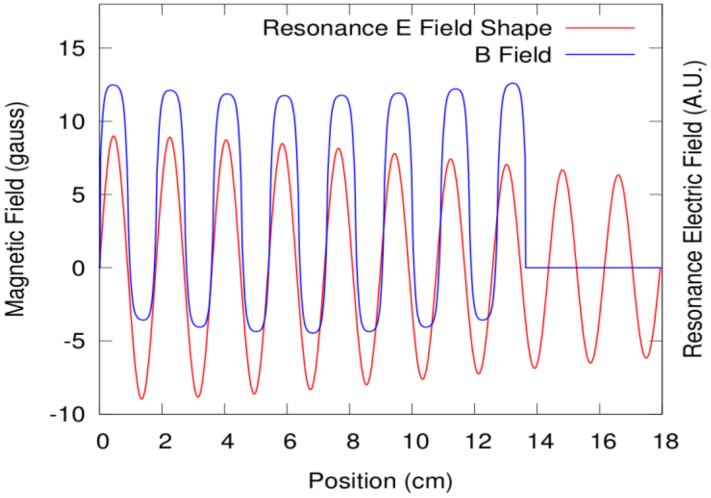
→Use amplifiers near this limit
→Operate at 50 mK



ORPHEUS R&D

University of Washington, US

Phys. Rev. D 91, 011701(R) (2015)



Match E and B fields, use dielectric discs to shorten wavelength