Axion and DM Axion Searches

Explore the Unexplored
Expect the Unexpected

B.Majorovits, MPI für Physik

Outline:

- Motivation for axion(like particle)s
- Experimental approaches
- Experiments and Proposals (with German participation)
- CONCLUSIONS

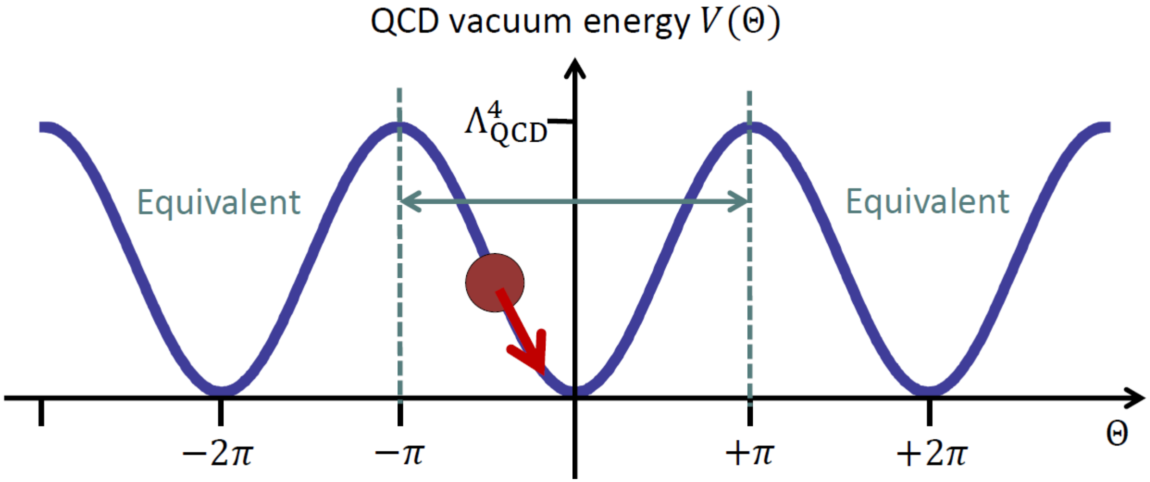
Motivation: solution to strong CP problem

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

→ $\theta < 10^{-10}$

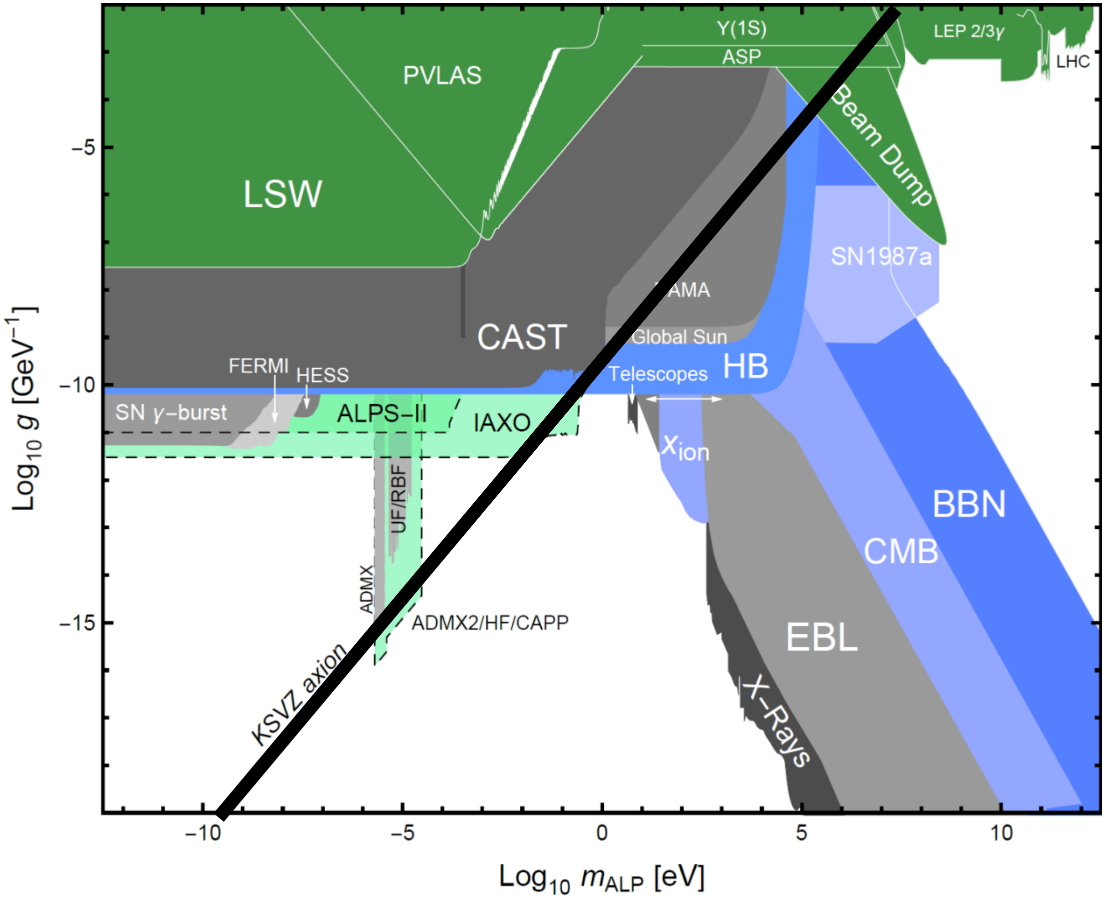


Peccei Quinn mechanism:
Add dynamical, spontaneously broken field

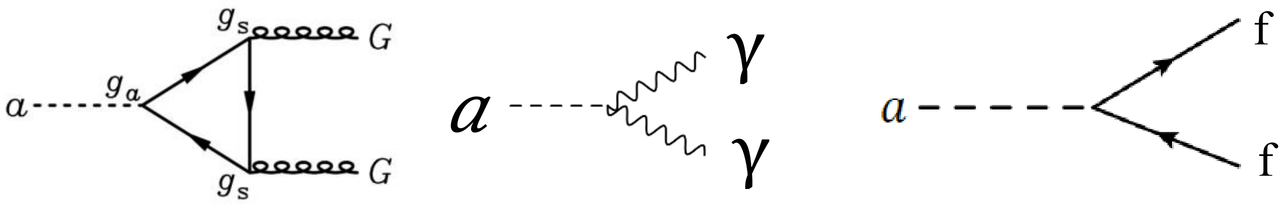
→New pseudoscalar particle: Axion (oscillation around minimum)

Motivation: solution to strong CP problem

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

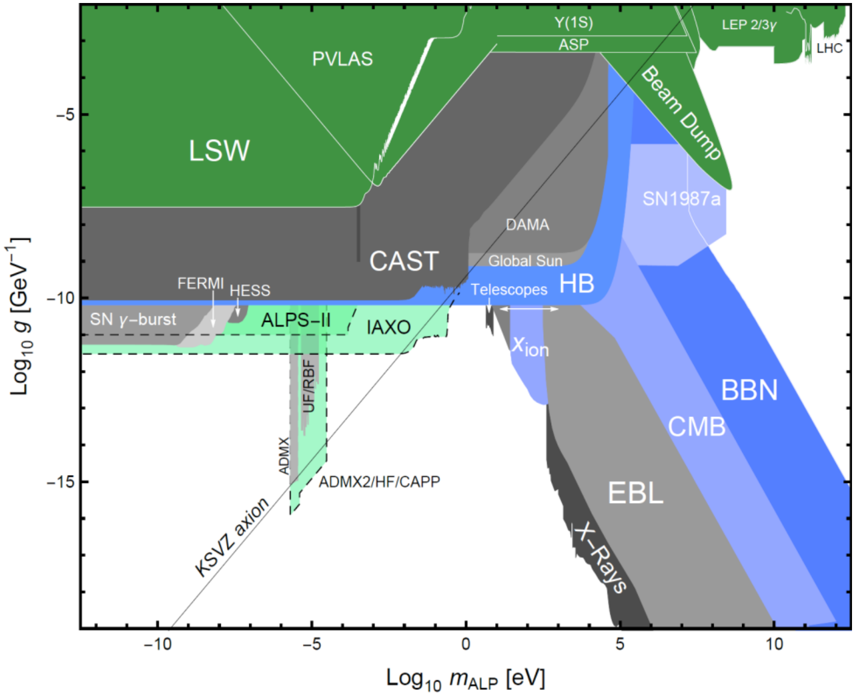


Axion Like Particles:



Generically: Axion Like Particles (ALPs):

same couplings with different coupling constants possible, no mass-coupling relation by PQ scale (not given by QCD)



Motivation: QCD axions as cold dark matter

QCD Axions could also explain dark matter!

Scenario I:

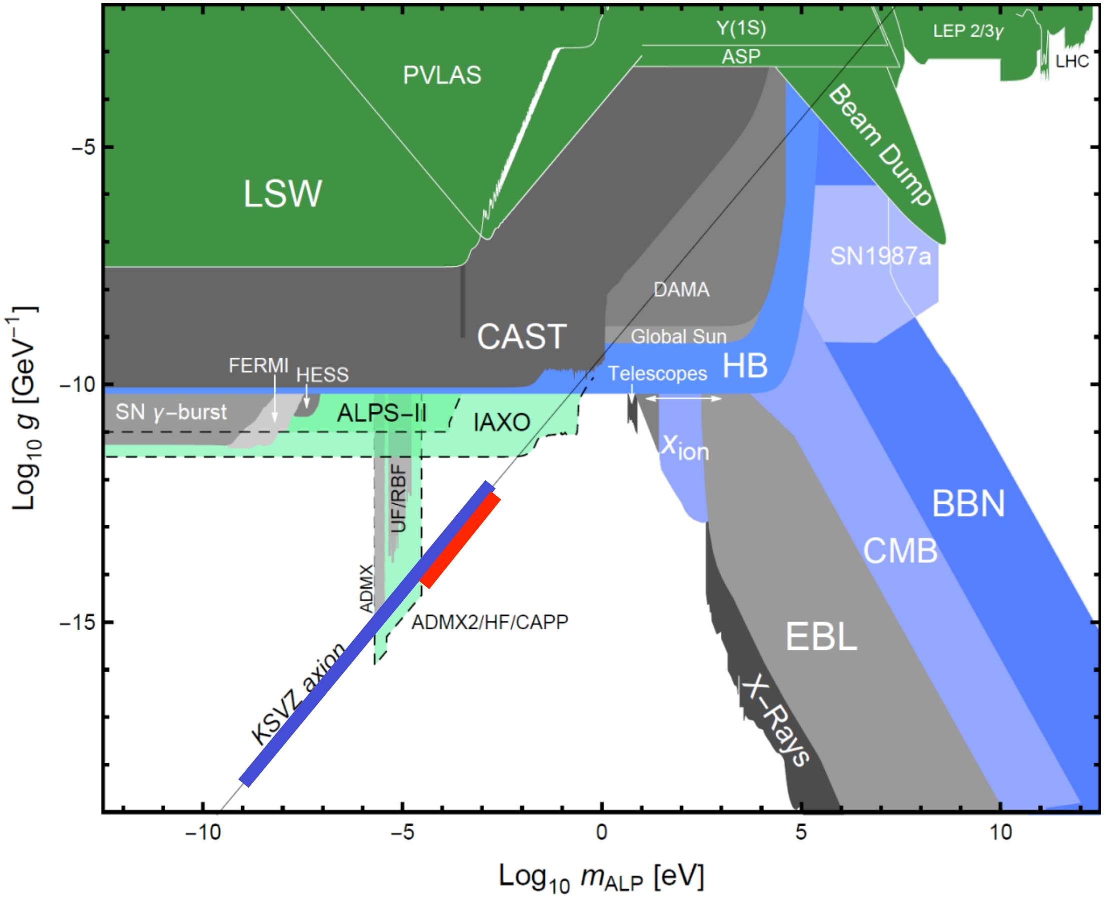
Prediction for symmetry breaking before inflation

Being experimentally covered

Scenario II:

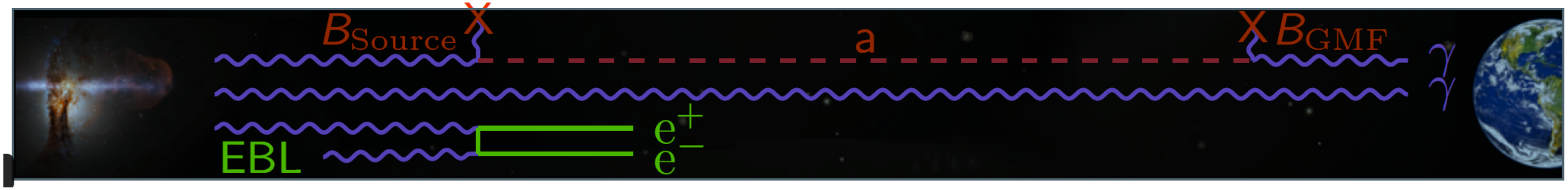
Prediction for symmetry breaking after inflation: Axion production by decay of strings and domain walls

Experimentally not covered



ALPs as solution to astrophysical hints?

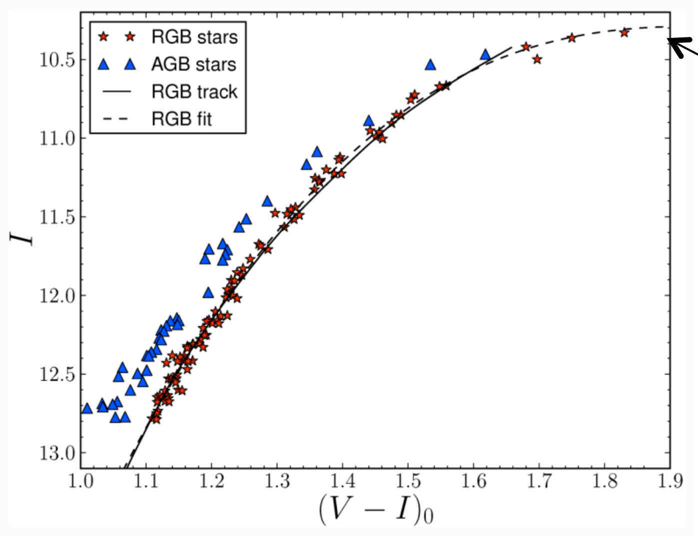
TeV transparecncy hint: ALPs



arXiv:1302.1208

Prone to systematics of source?

Stellar cooling: Could be due to QCD axions



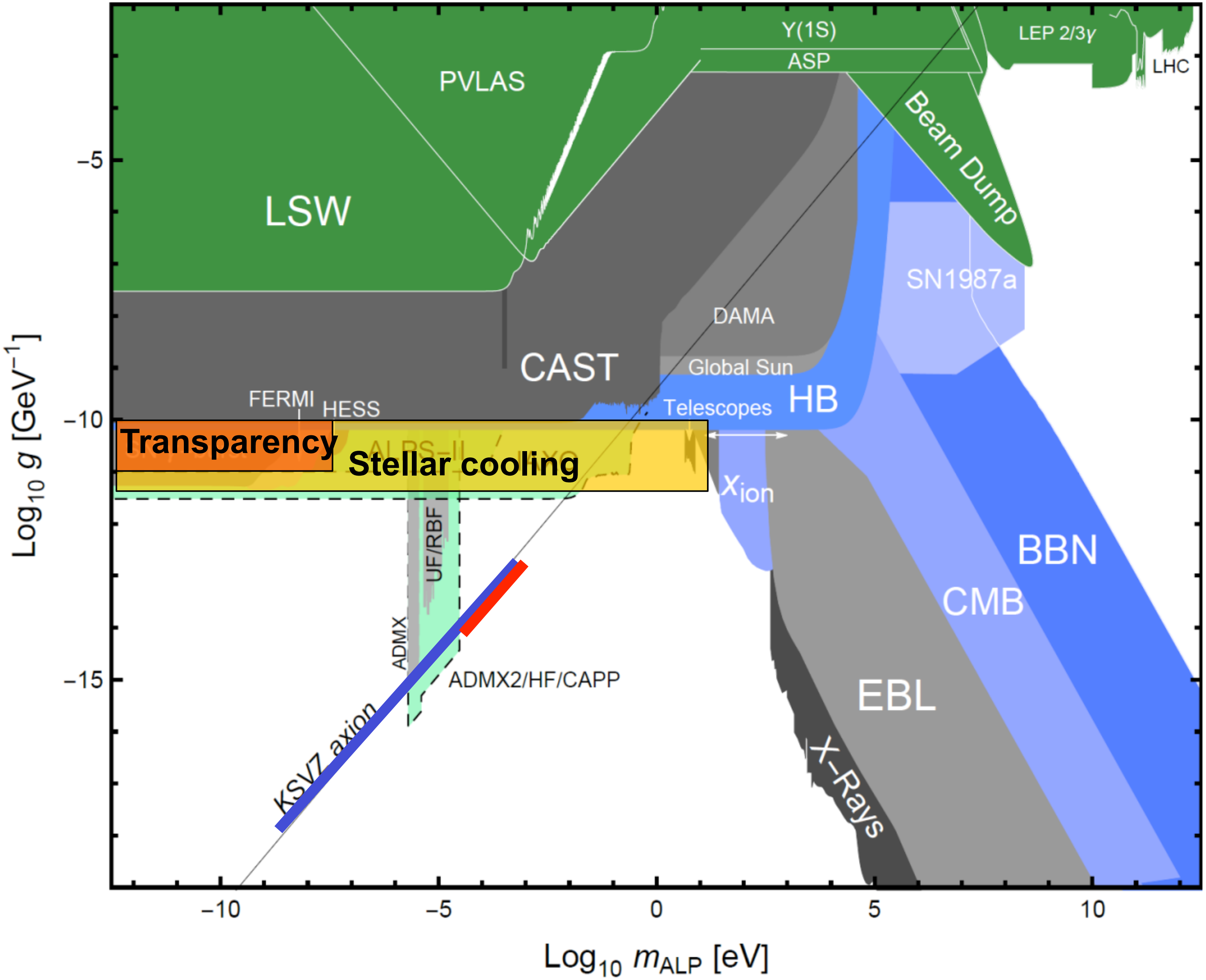
Brightest red giants measured nonstandard energy loss

Statistically evidence for deviation from expectation arXiv:1512.08108

Could be due to ALP cooling

How well do we understand standard stellar cooling?

Motivation: ALPs to resolve hints?



Motivation for axions and ALPs

strong CP problem

Solar (QCD) axions

QCD DM axion (neV-1µeV)

TeV transparency / stellar cooling

Axions and ALPs

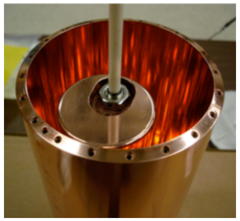
Dark Matter

Stringy axions

[Hidden/Dark photons]

New Fields (string theory)

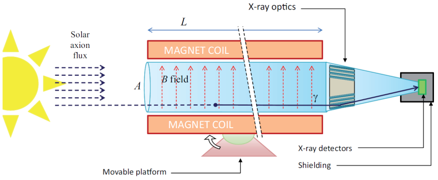
Experimental approaches:



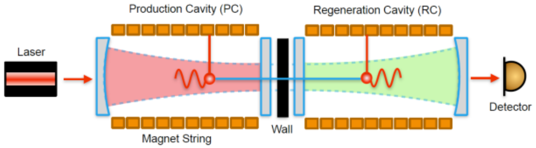
Haloscopes - DM

Cavity Dish antenna

Dielectric haloscope



Helioscope – solar axions



Lab experiments - ALPs

Light shining through walls

LC circuit

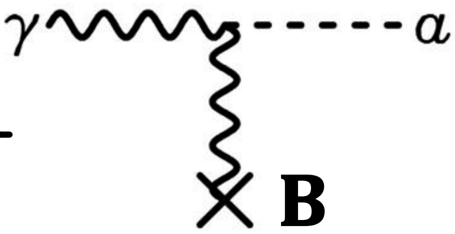
NMR methods

Beam dump

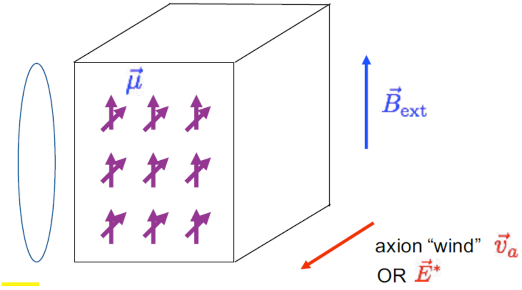
5th force

Long range forces,

atomic transitions,…

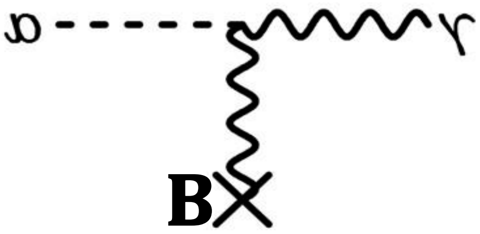


Primakoff effect



Other couplings

Experimental approaches
Cavity haloscope:



Primakoff effect

→ Mixing of DM axion with photon in static B field

→ Additional source term to Maxwell equations

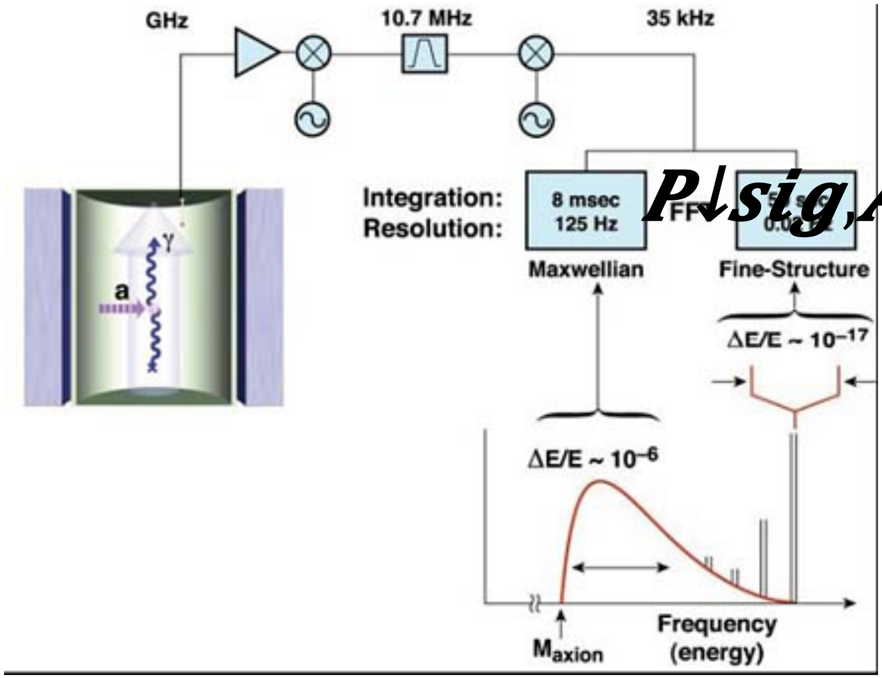
In resonant cavity: enhancement of photon signal by quality factor of cavity

$$P_{sig} = (B^2 V Q_{cav})(g$$

m_a

ADMX:

Q-factor $2\cdot10^5$ $B=8.5$

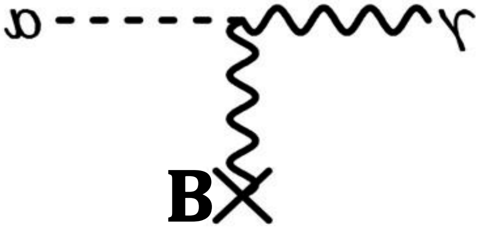


$$P_{sig,ADMX} \approx 10^{-23}\ Watts$$

Tuning of resonance frequency by movement of “tuning rod”

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

Experimental approaches
Dish antenna haloscope:

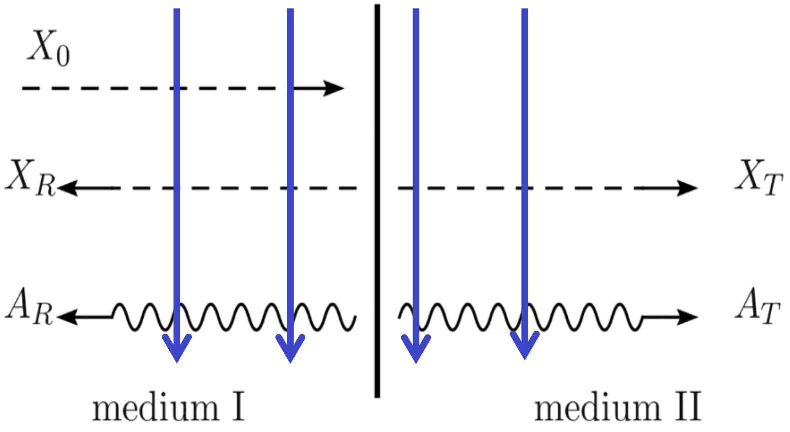


Primakoff effect

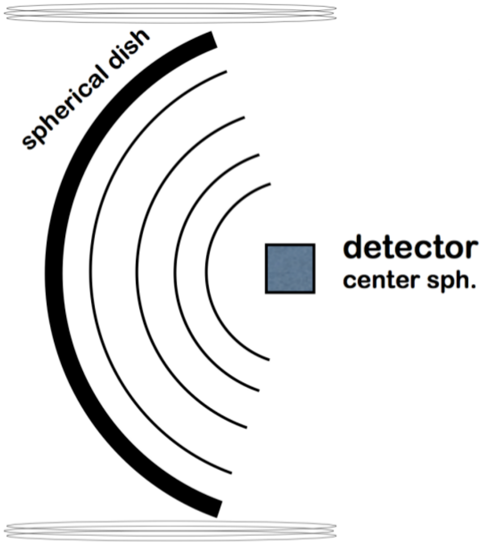
→ Mixing of DM axion with photon in static B field

→ Additional source term to Maxwell equations

→ At surfaces with transition of ε: emission of photons



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



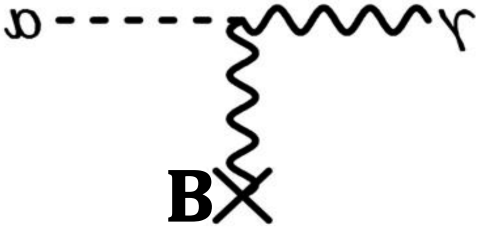
$$(P/A)_{mirror} \sim 2\cdot 10^{-27}\ W/m^2\ (B_{||}/10\ T)^2\ (g_{a\gamma\gamma} m_a)^2$$

Broadband approach

Also works for kinetic mixing

→ Hidden photon, no B-field needed

Experimental approaches
Dielectric haloscopes:



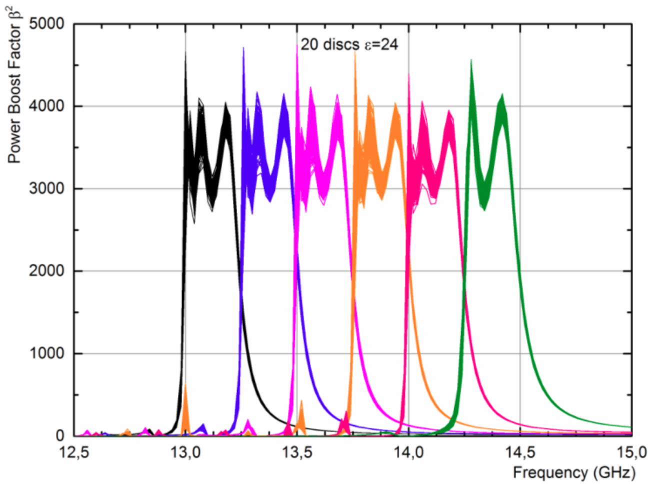
Primakoff effect

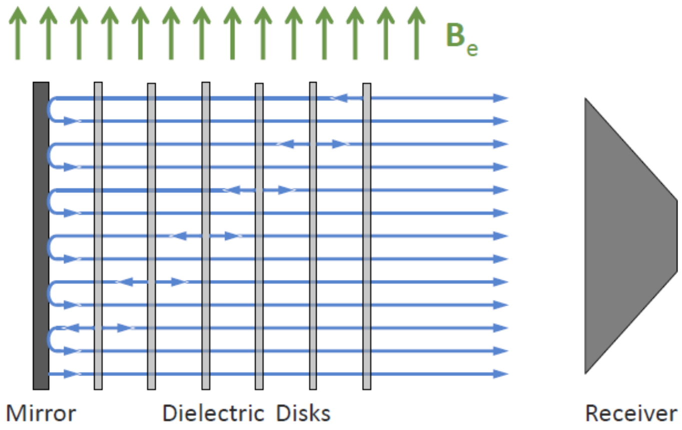
→ Mixing of DM axion with photon in static B field

→ At surfaces with transition of ε: emission of photons

→ Build layered structure with many transitions

→ "Broadband" enhancement of photon signal through interference





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

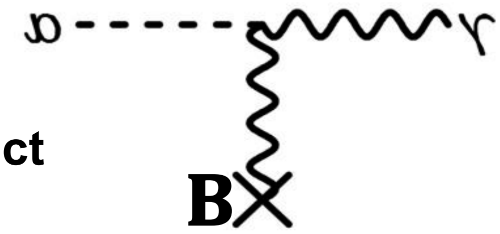
γ/P_{mirror}

"Quasi broadband" approach

Also works for kinetic mixing

→ Sensitive to hidden photon, no B-field needed

Experimental approaches
Helioscopes:



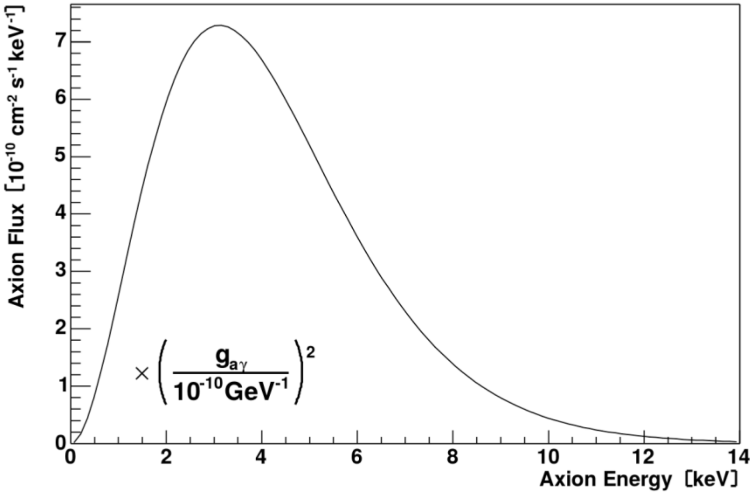
Primakoff effect (twice)

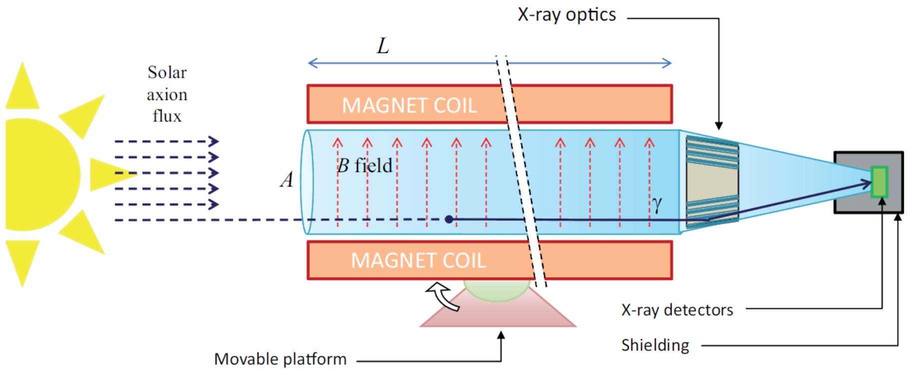
→ **Production of x-ray photons in sun by Primakoff effect**

→ **Point magnet towards sun**

→ **Mixing of solar axion with photon in static B field**

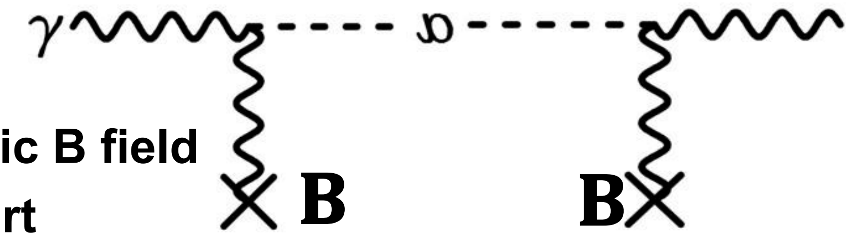
→ **X-ray optics & detectors to detect ~keV x-rays from a→γ conversion**





$$P_{a\gamma} \sim 2.6\cdot 10^{-17} \left(\frac{B}{10\ T}\right)^2 \left(\frac{L}{10\ m}\right)^2 \left(g_{a\gamma\gamma}\,10\,GeV\right)^2$$

Experimental approaches
Light shining through the wall:

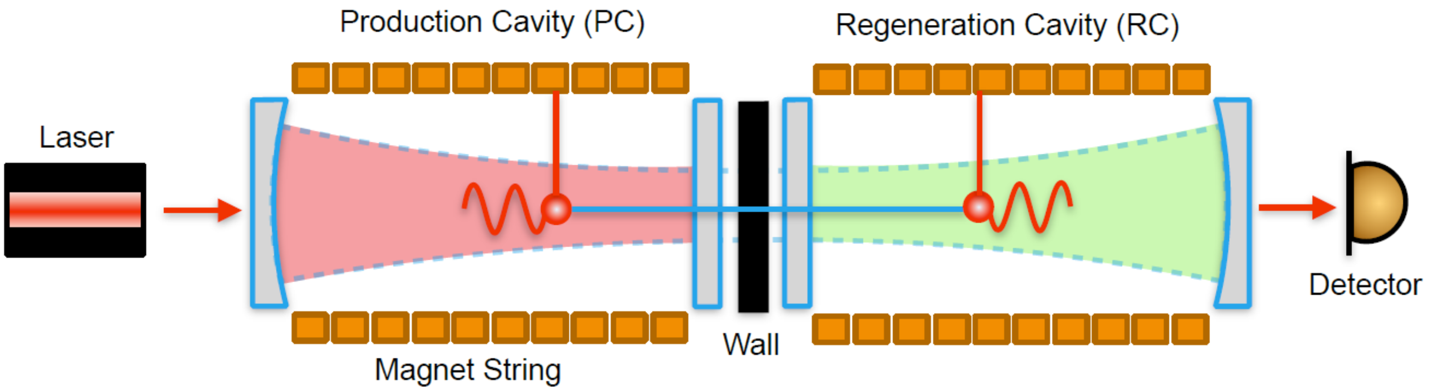


Primakoff effect twice

→ Mixing of solar axion with photon in static B field

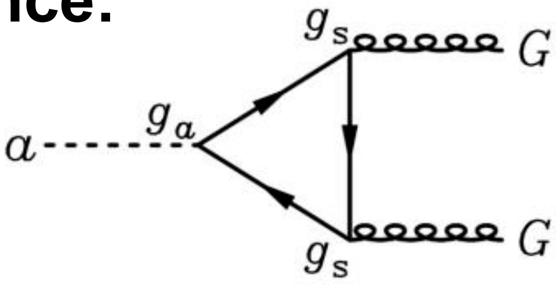
→ Convert photons into axion and reconvert behind wall

→ Detect regenerated photon behind wall



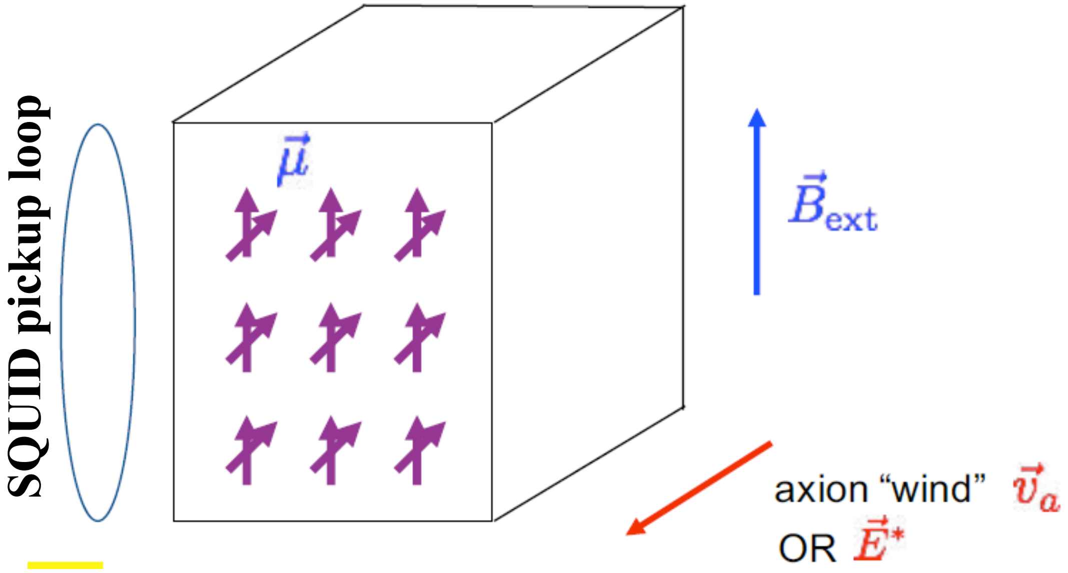
$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot 10^{-38}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\,\frac{B}{1\,T}\,\frac{l}{10m}\right)^4$$

Experimental approaches
Nuclear Magnetic Resonance:



Axion coupling with nucleus

- → Nuclei interact with background axion dark matter
- → Oscillating electric dipole moment
- → Precession of nuclear spin in material sample in presence of an electric field
- → Resonant transverse magnetization if Lamor frequency equ. m_a
- → Modify B_{ext} to scan different masses (defines sensitivity)
- → Measure via precision magnetometry



Experimental approaches

Synergies with particle and astroparticle physics

Axion (ALP) search challenges

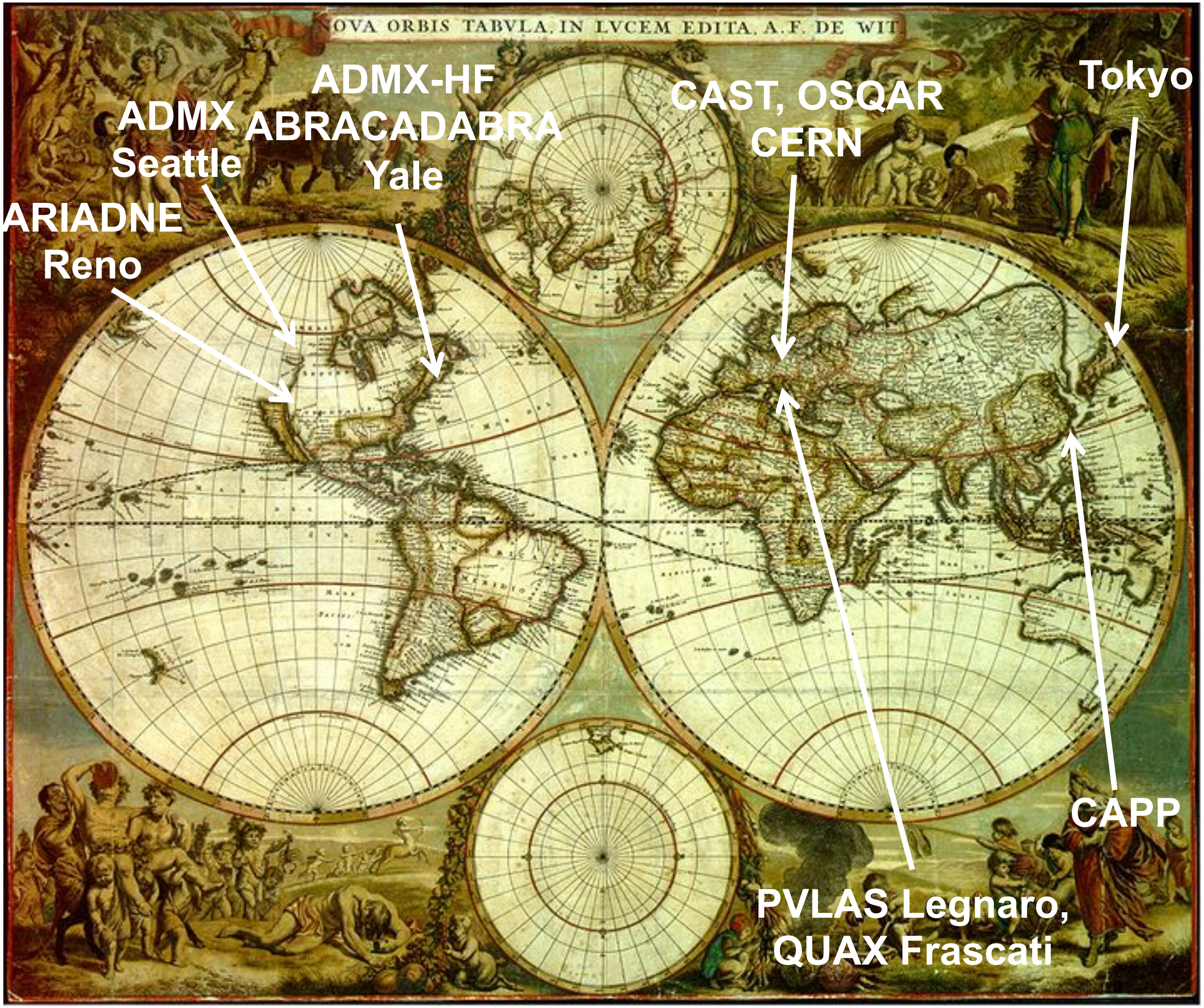
Need Strong B-fields	→	Magnets
Very weak signal expected	→	Detectors
Cold temperatures needed	→	Cryogenics

Synergies with Particle-, Astroparticle-, and Astrophysics:

→ Particle detectors: RF to x-ray (even higher for beam dump), Cryogenics, SQUIds, TES,….

→ Accelerators: Accelerator magnets, RF technology, Cryogenics

Experimental efforts worldwide outside Germany



ADMX
Seattle

ADMX-HF
ABRACADABRA
Yale

ARIADNE
Reno

CAST, OSQAR
CERN

Tokyo

CAPP

PVLAS Legnaro,
QUAX Frascati

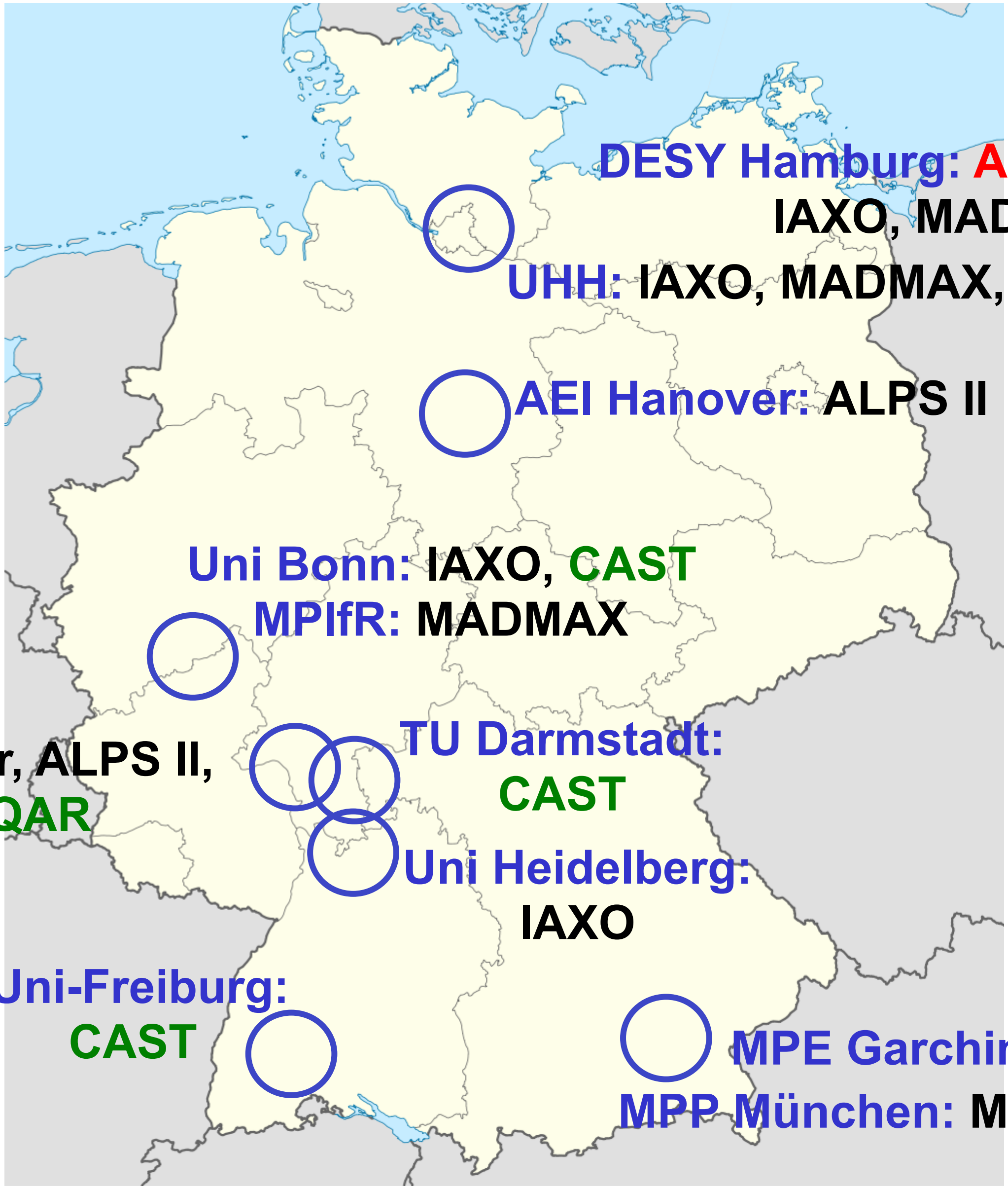
For sure not complete!

Axions and ALPs in Germany

green: running

red: past

black: future



DESY Hamburg: ALPS, ALPS II, IAXO, MADMAX

UHH: IAXO, MADMAX, BRASS (ALPS II)

AEI Hanover: ALPS II

Uni Bonn: IAXO, CAST

MPIfR: MADMAX

Uni Mainz: CASPEr, ALPS II, GNOMe, OSQAR

TU Darmstadt: CAST

Uni Heidelberg: IAXO

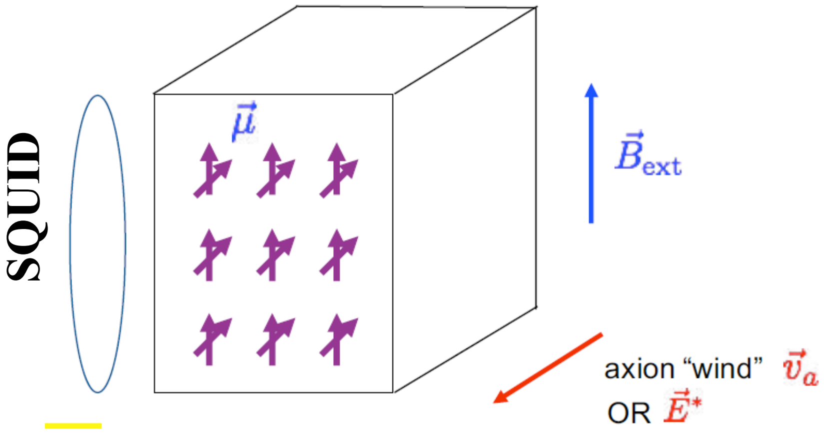
Uni-Freiburg: CAST

MPE Garching : CAST

MPP München: MADMAX, CAST

CASPEr at Mainz (and GNOME):

Cosmic Axion Spin Precession Experiment



J. Gutenberg Uni Mainz
 (Budker group)
UC Berkeley Physics NSD
LBNL

Initial phase (few years):
- proof of prinicple,
- R&D to enhance sensitivity
- First limits

Investigate example materials:
liquid 129Xe, ferroelectric PbTiO3

Second phase (few years):
- Run with improved sensitivity

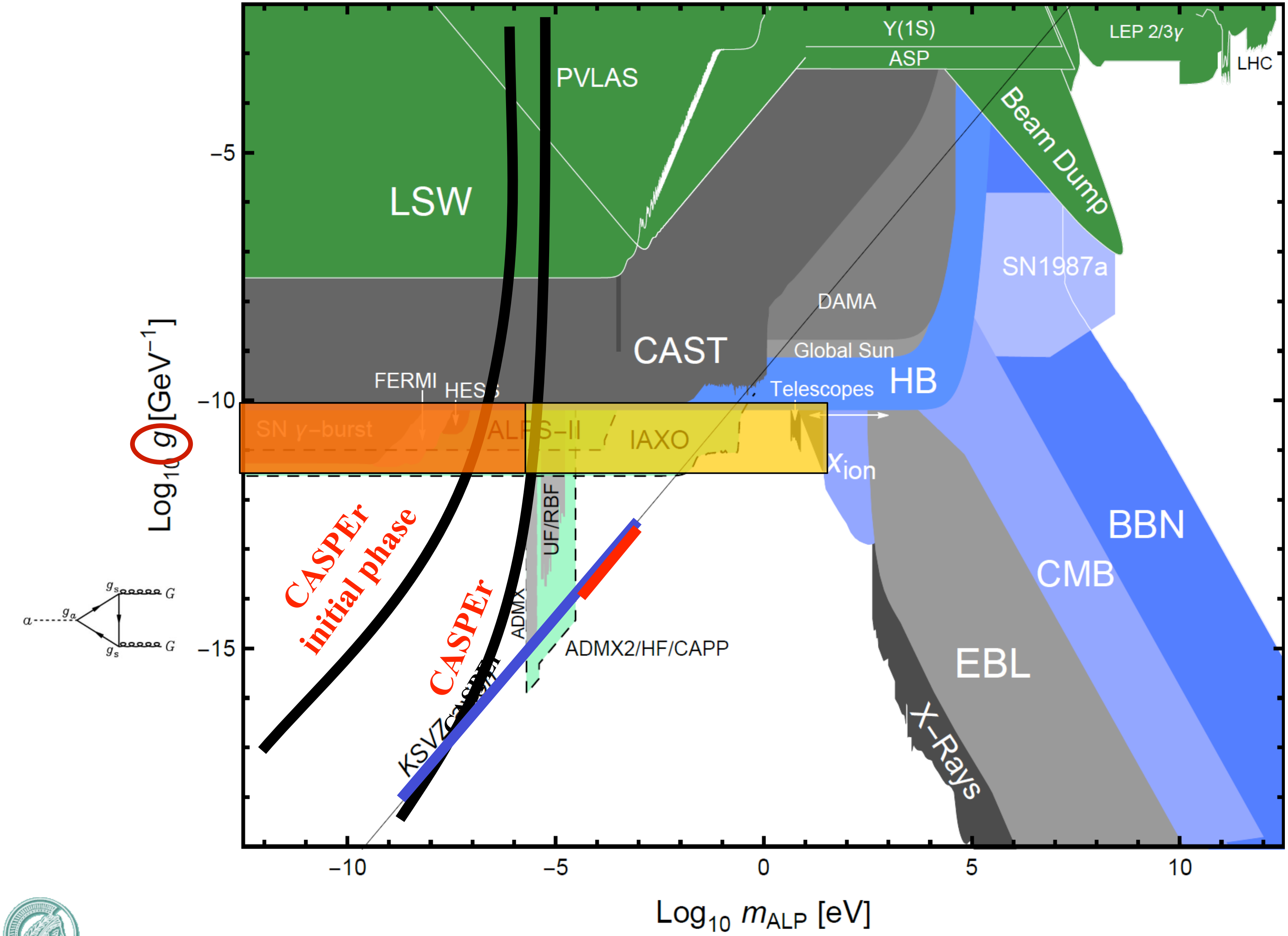
Phase I funded by:

DFG Deutsche Forschungsgemeinschaft

HEISING-SIMONS FOUNDATION

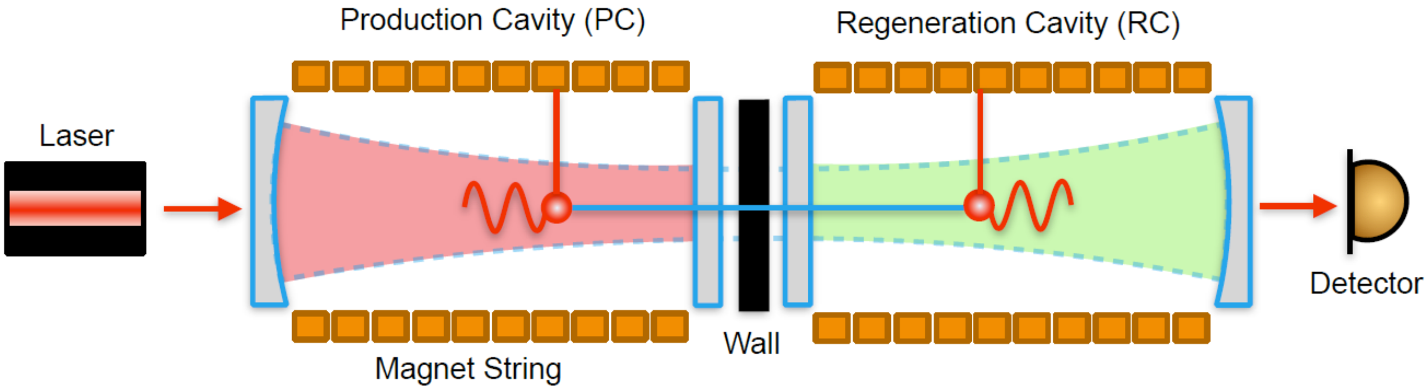
Phase II budget need: ~ 5-10 M€
Expand collaboration upon demand (cooperation with Berkeley/Stanford DM Radio?)

The Axion and ALPs landscape



Note the different coupling!

ALPS II at DESY:



ALPS II is a joint effort of

DESY-Hamburg: Infrastruktur, Magnete, Optics, TES
Hamburg University (until 07/17): TES, Optics
AEI Hannover (MPG & Hannover Uni.): Optics
Mainz University: TES-Detektor
University of Florida: Optics, Heterodyne Detection

ALPS II at DESY: Plans

ALPS IIc in 2019
in the HERA tunnel

Timeline:

- **Clearing HERA tunnel begins in May**
- **ALPS IIc optics commissioning beginning 2019**
- **ALPS IIc data runs in 2020**

Main challenges:

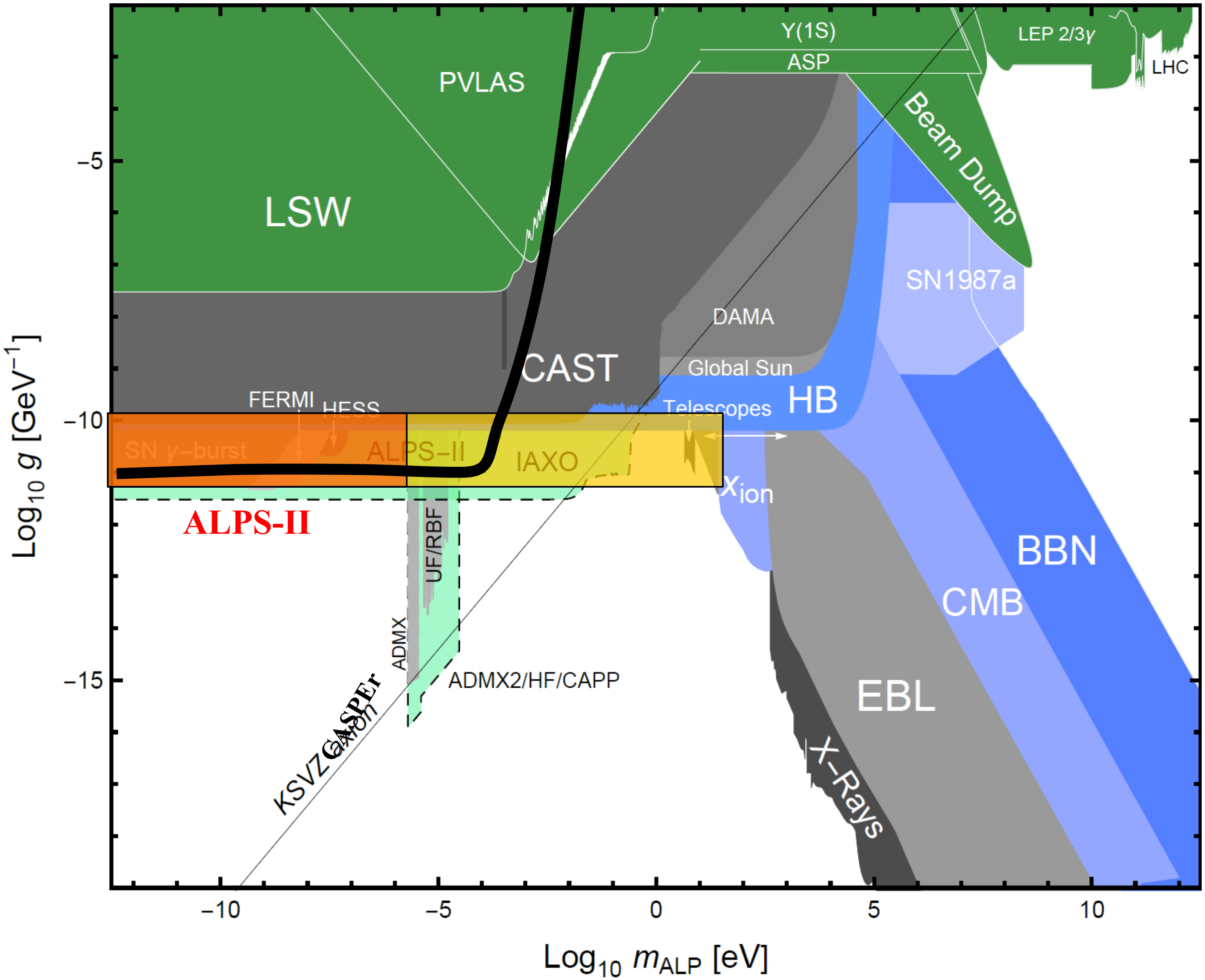
Magnet – straighten 20 HERA dipoles 200m,
Optics – LIGO related concepts,
Detector – TES, heterodyne in development

ALPS II is funded: ~2M€ investment

HEISING-SIMONS FOUNDATION

HELMHOLTZ | ASSOCIATION

ALPS II at DESY: Sensitivity



OSQAR @ CERN:

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

M. Schott

OSQAR group:
DFG Proposal for Axion- LSW search @ CERN in 2018/2019 :

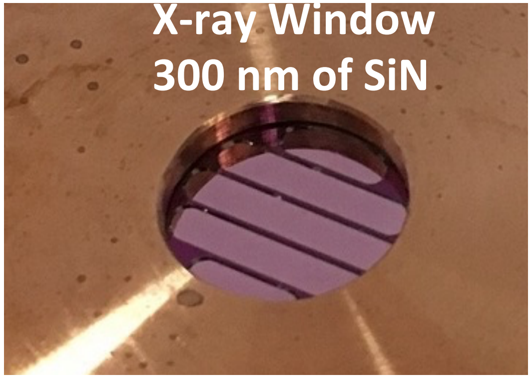
ALPS-1 scheme with 2 LHC Magnets:

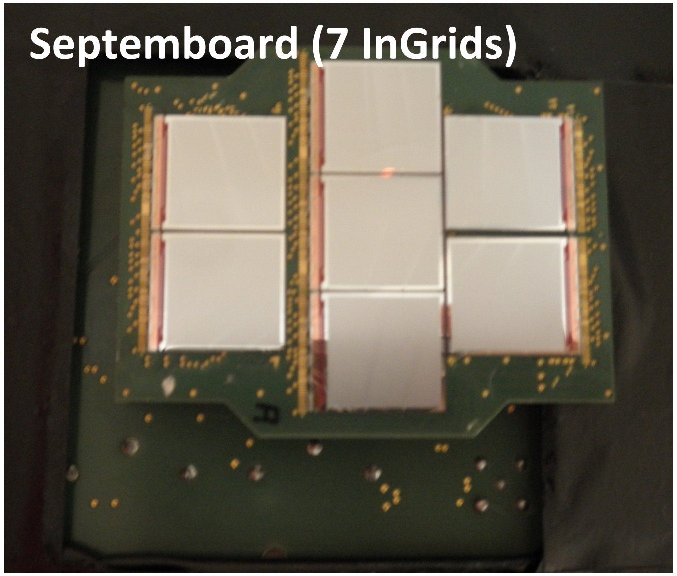
Laser-Cavity on production side and
CCD Camera without cavity on regeneration side.

→ Factor 6 in sensitivity w.r.t. existing LSW Limits

CAST @ CERN:

- Physics scope 2016-18:
  Solar chameleons ("InGrid", "KWISP")
  Relic Axions ("CAPP", "RADES")
- Important input for design of IAXO:
  detectors + X-ray optics


X-ray Window
300 nm of SiN


Septemboard (7 InGrids)

German Groups:

MPE, Garching

X-ray telescope

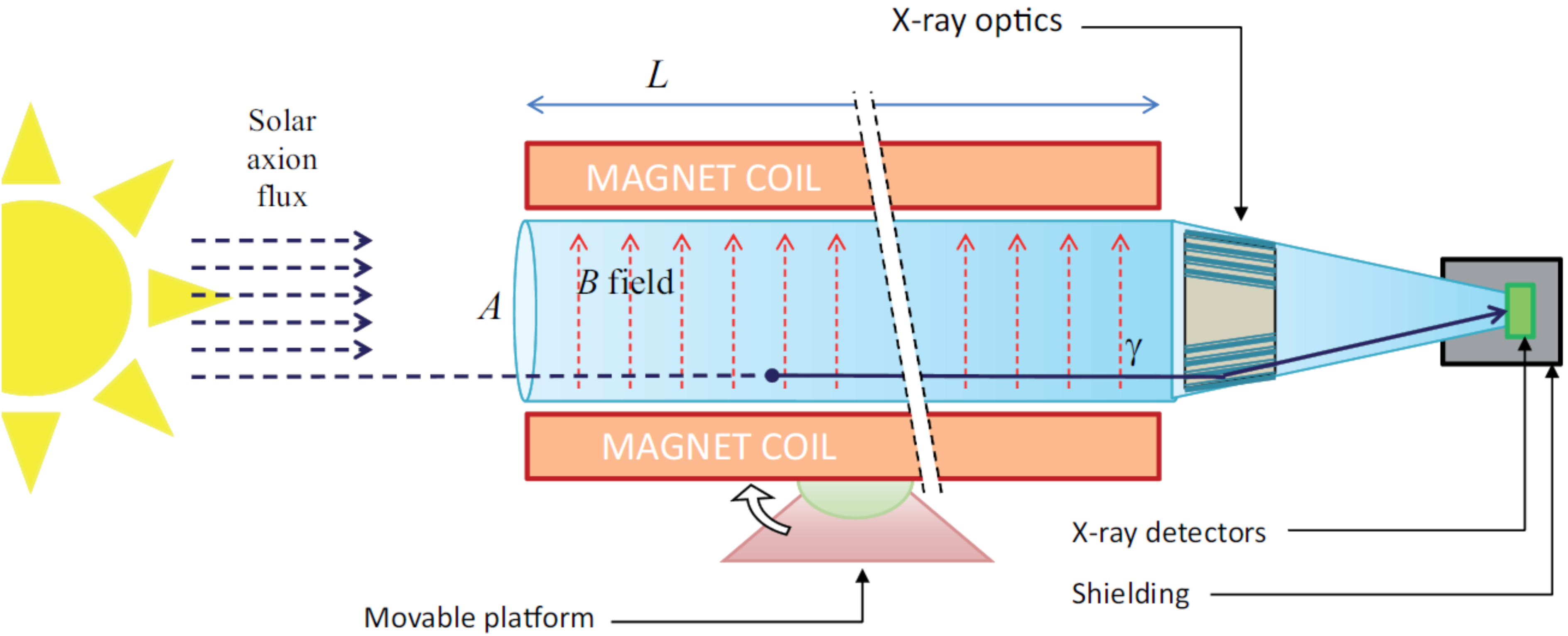
Darmstadt, Freiburg

KWISP Chameleon force sensor

Uni Bonn

InGrid detector: solar chameleons & axions

IAXO Helioscope:

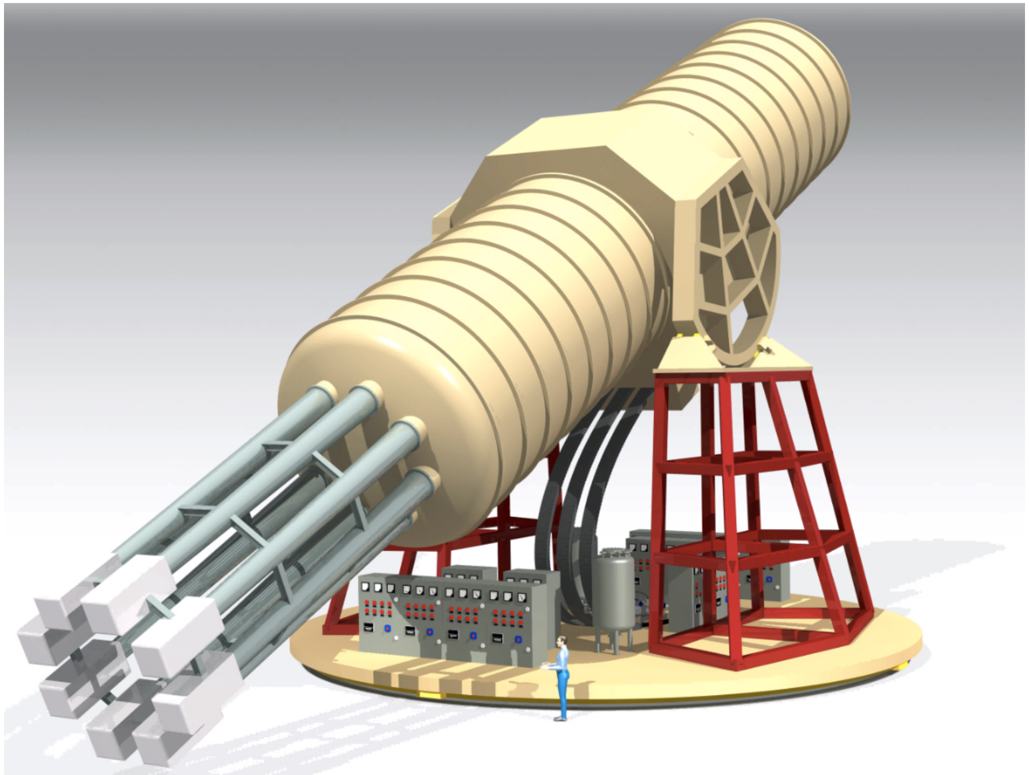


Strategy:

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

Improve:

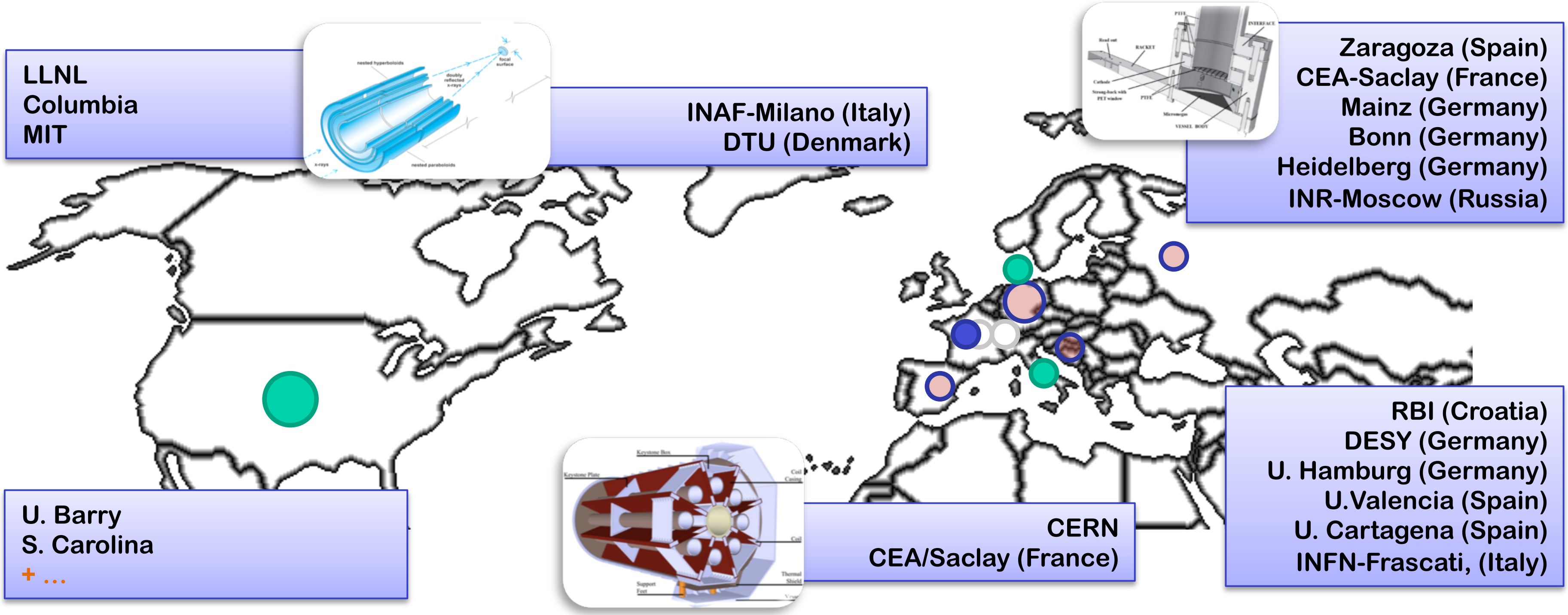
IAXO Helioscope:



- Worldwide first “large scale” Axion experiment.
- Combination of magnet expertise from particle collider experiments, X-ray optics from satellites, ultra-low background X-ray detectors.
- DESY could be the host laboratory.

IAXO proto-collaboration:

- Proto-collaboration out of 22 institutes from 9 countries.
- Big effort to strengthen collaboration → large consortium involved in a number of funding applications, covering all TDR needs



LLNL
Columbia
MIT

INAF-Milano (Italy)
DTU (Denmark)

Zaragoza (Spain)
CEA-Saclay (France)
Mainz (Germany)
Bonn (Germany)
Heidelberg (Germany)
INR-Moscow (Russia)

U. Barry
S. Carolina
+ …

CERN
CEA/Saclay (France)

RBI (Croatia)
DESY (Germany)
U. Hamburg (Germany)
U.Valencia (Spain)
U. Cartagena (Spain)
INFN-Frascati, (Italy)

(*) Only shown groups for which formal activity is ongoing or under discussion/preparation.
Potentiaal interest in more groups than shown

IAXO Timeline - Costs:

Timeline:

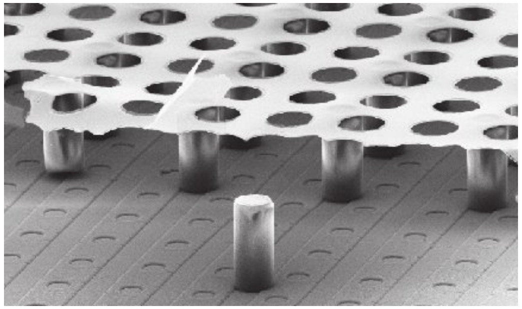
- 2014: CERN SPSC recommendation to move to a TDR.
- 2017: foundation of IAXO collaboration at DESY (July).
- 2017-2020: TDR + demonstrator phase (“BabyIAXO").
- 2024: start of data taking
  (assuming funding decisions in 2019).

Costs (CDR estimate, investments only):

- Cost driver: magnet ~ 30 M€
- Optics/ detectors / Infrastructure: ~26.0 M€

German IAXO Groups - Interests:

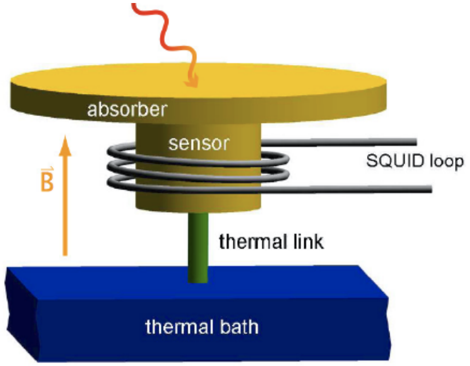
Universities: Detectors, Physics, Simulation



U Bonn (Desch)
InGrid – pixelized gaseous
X-Ray detectors comissioned in CAST

U Mainz (Budker, Büscher, Schott)
Cosmic veto detectors
Simulation, Physics studies

U Heidelberg (Enss, Gastaldo)
Metallic Micro-Calorimeters

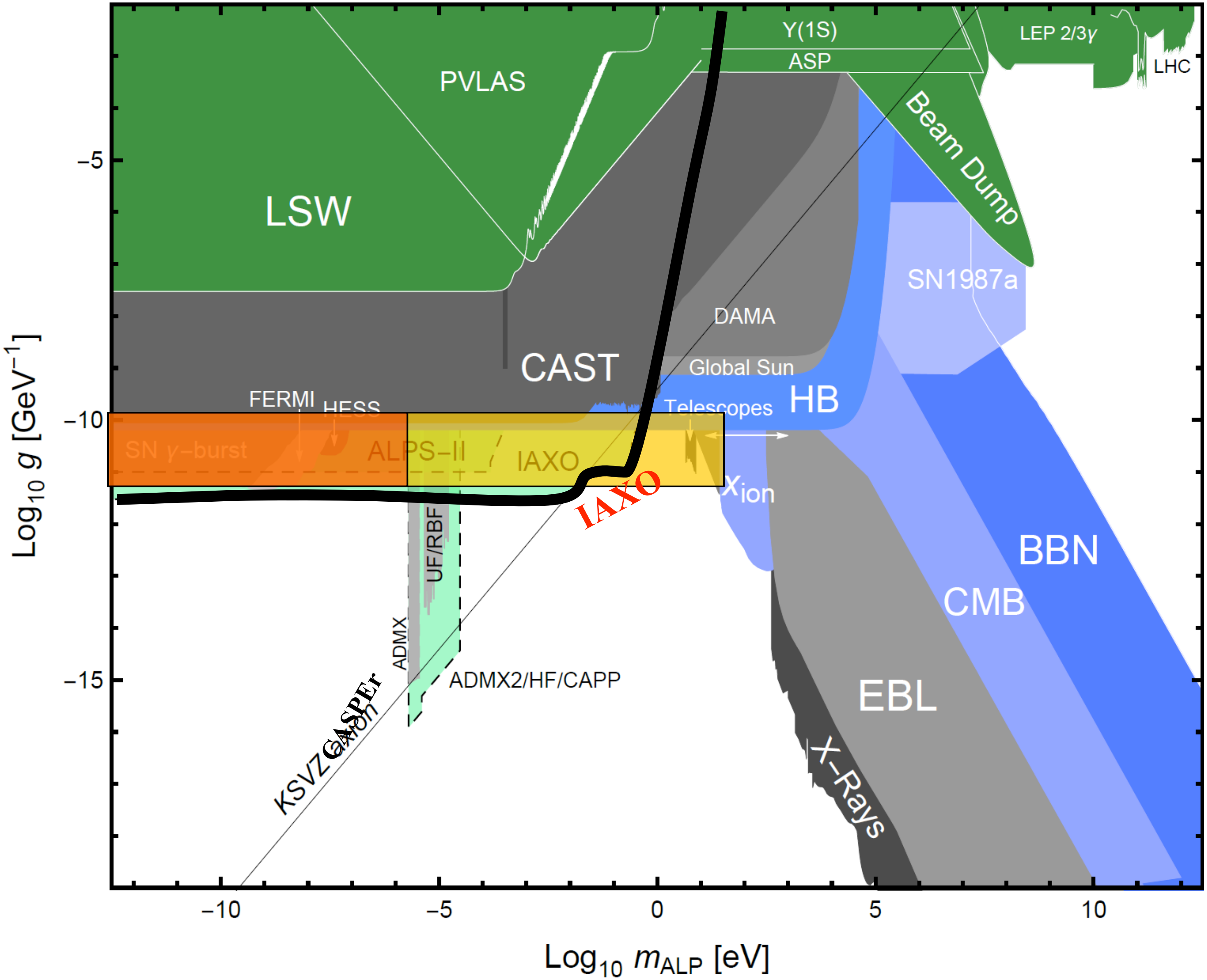


Further Universitites interested

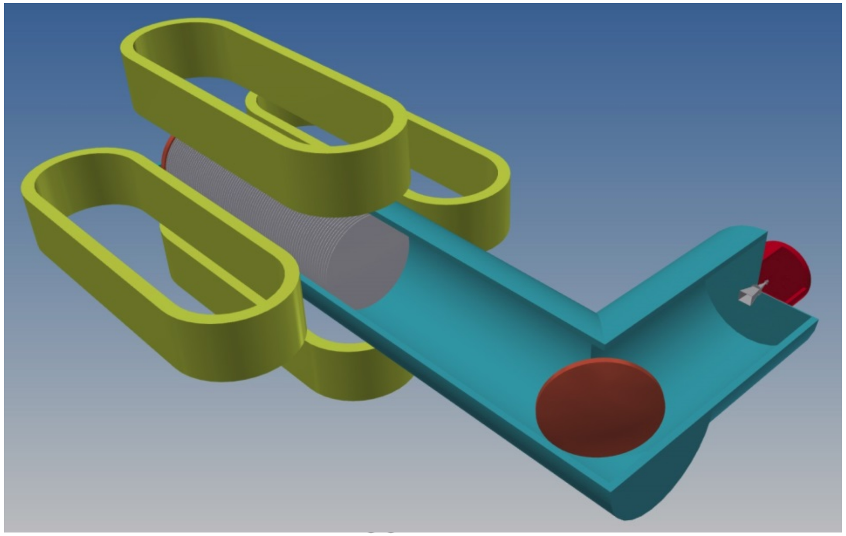
DESY: possible Host Lab

- **Synergies with ALPS II, in-line with future DESY strategy in particle physics**
- **Competence to provide infrastructure, cryogenics, operation of IAXO**
- **Encouraging first discussions on support from CERN for IAXO at DESY**

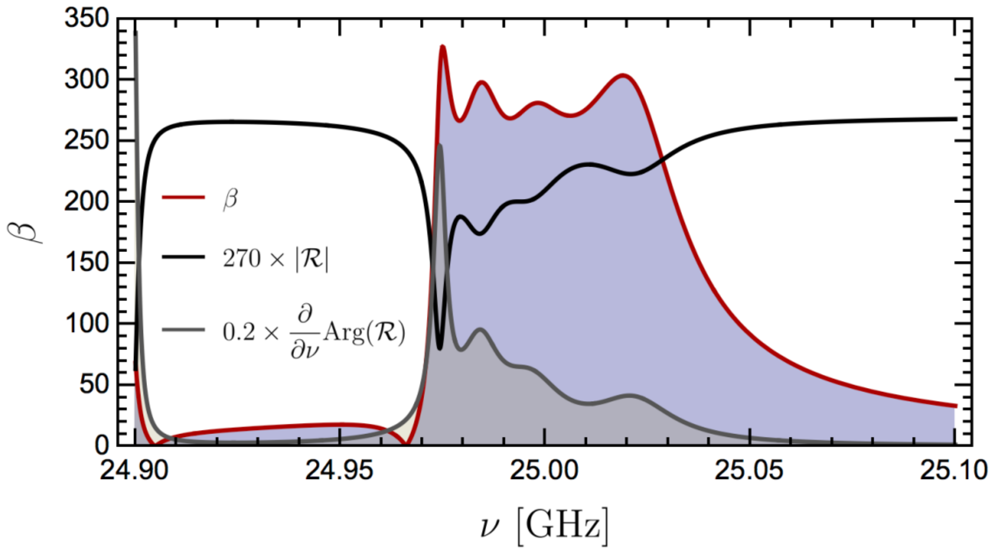
IAXO: Projected Sensitivity



MADMAX: Concept



- **80 adjustable $LaAlO_3$ ~1m² diameter discs in front of mirror**
- **Magnet FoM: 100 T^2m^2 (dipole)**
- **Focal mirror pointed towards antenna**
- **Radiometer 10-100GHz, $P_{sens}=10^{-23}W$**



Simulations:

Power boost of

$>10^4$ seems achievable

with 80 discs

Can be tested using transmissivity and reflectivity

Main challenges:

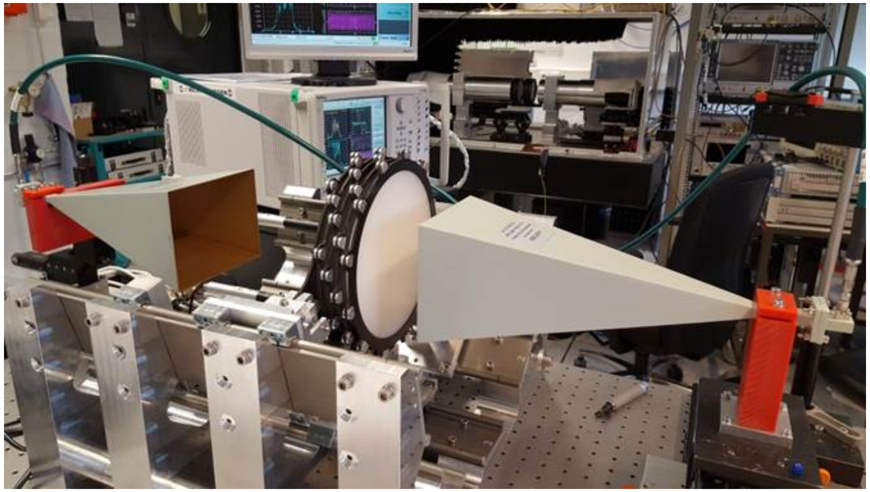
Magnet, reach 100 T²m²

Detector: Sensitivity $P \sim 10^{-23}W$ in 1week

Precision: ~10µm for positioning

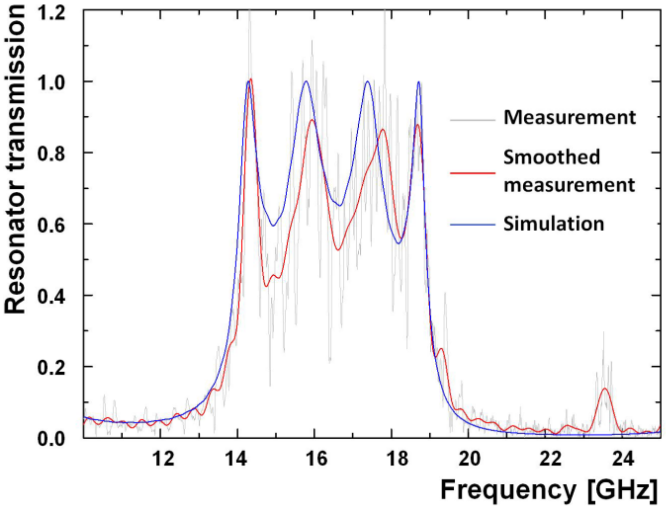
Tiling: Availability of large discs

MADMAX: Prototype setup



Excellence Cluster Universe

Prototype setup partly funded as seed project by:



Tests performed with prototype setup at **MPP Munich**:

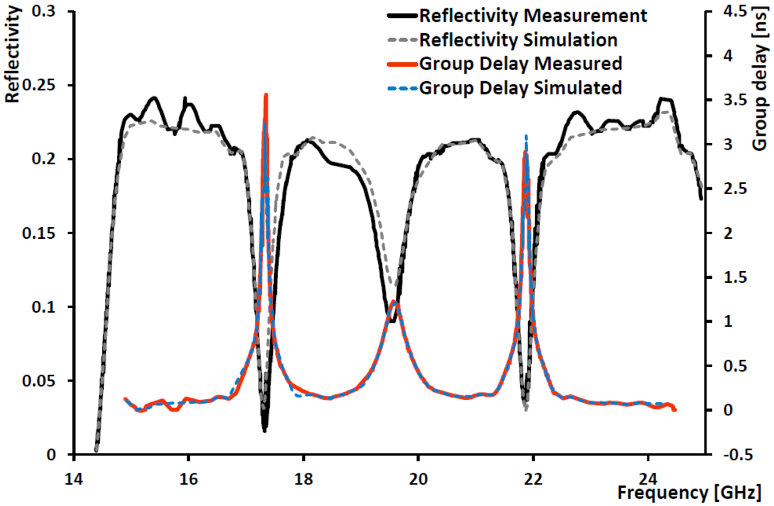
Comparison of simulation with measurement: transmissivity and reflectivity

→ Good reproducibility with 5 discs

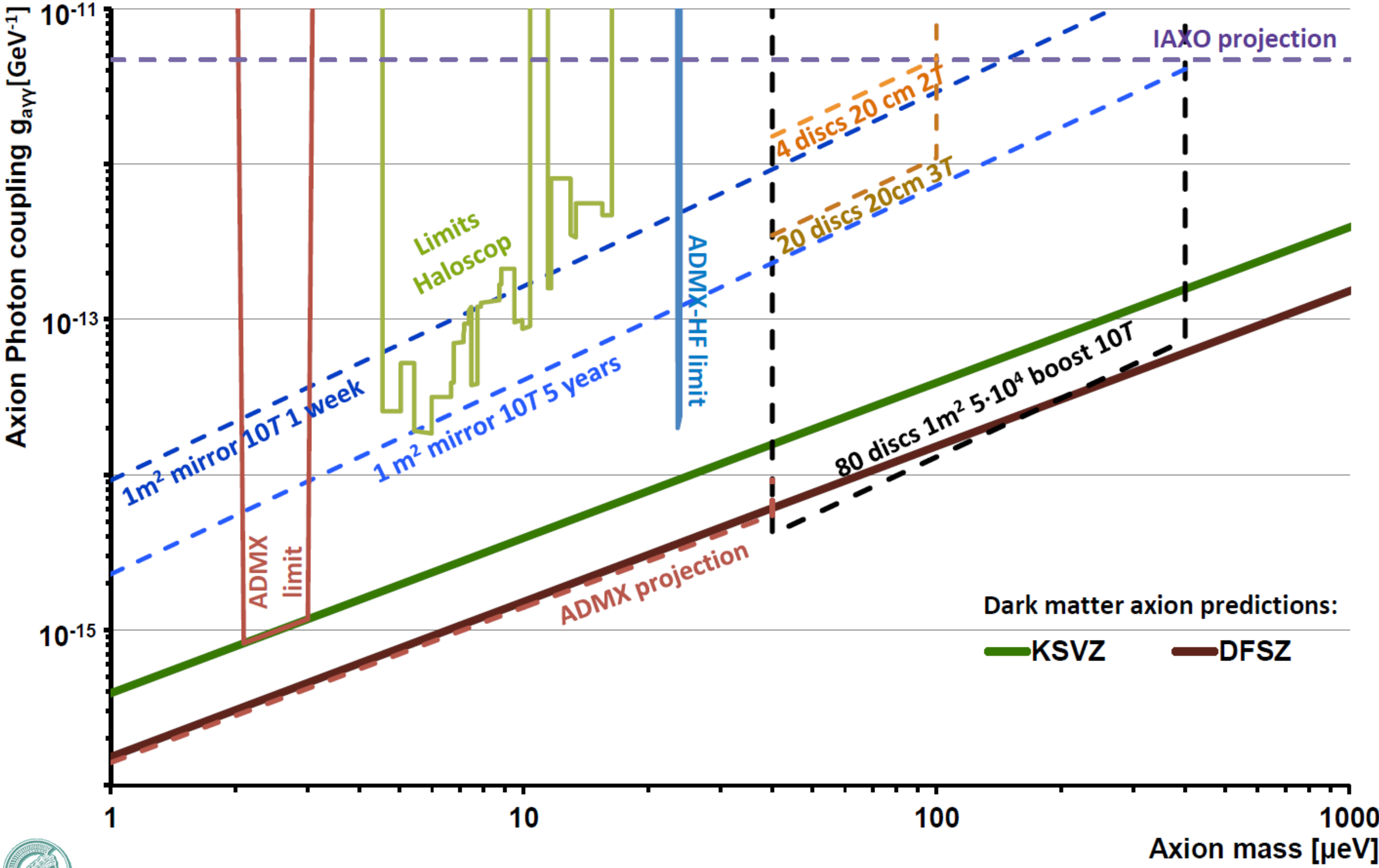
→ Positioning precision ~ µm

Setup radiometer: could detect 10^{-23}W signal @17GHz within ~ week

The principle works!

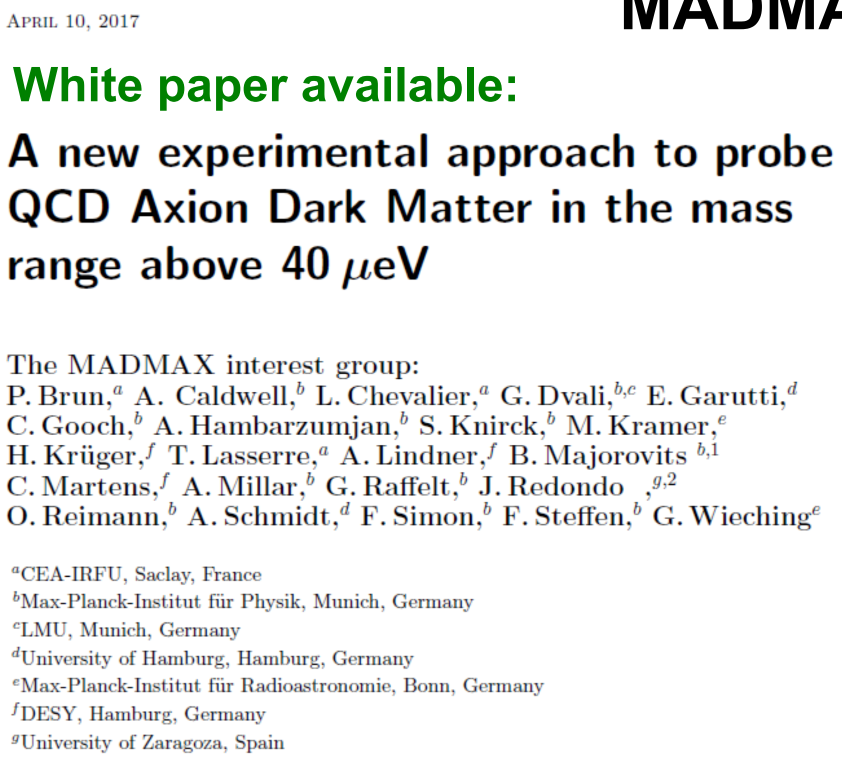


MADMAX sensitivity projection



MADMAX: Plans

White paper available:



APRIL 10, 2017

A new experimental approach to probe QCD Axion Dark Matter in the mass range above 40 μeV

The MADMAX interest group:
P. Brun,[a] A. Caldwell,[b] L. Chevalier,[a] G. Dvali,[b,c] E. Garutti,[d]
C. Gooch,[b] A. Hambarzumjan,[b] S. Knirck,[b] M. Kramer,[e]
H. Krüger,[f] T. Lasserre,[a] A. Lindner,[f] B. Majorovits [b,1]
C. Martens,[f] A. Millar,[b] G. Raffelt,[b] J. Redondo ,[g,2]
O. Reimann,[b] A. Schmidt,[d] F. Simon,[b] F. Steffen,[b] G. Wieching[e]

[a]CEA-IRFU, Saclay, France
[b]Max-Planck-Institut für Physik, Munich, Germany
[c]LMU, Munich, Germany
[d]University of Hamburg, Hamburg, Germany
[e]Max-Planck-Institut für Radioastronomie, Bonn, Germany
[f]DESY, Hamburg, Germany
[g]University of Zaragoza, Spain

Further plans:

- Form collaboration (2017)
  (next meeting 10-11 May 2017
  in Paris/Saclay)
- Magnet feasibiltiy studies (by 2018)
- Build prototype setup (~2020)
- Build full scale experiment

MADMAX interest group:
MPIfR Bonn: RF
DESY Hamburg: tbd (site evaluation)
Uni Hamburg: Cryogenics of booster, dis
tiling
MPP Munich: Radiometer, booster, magnet
CEA-IRFU Saclay: magnet
Uni Zaragoza: Phenomenology

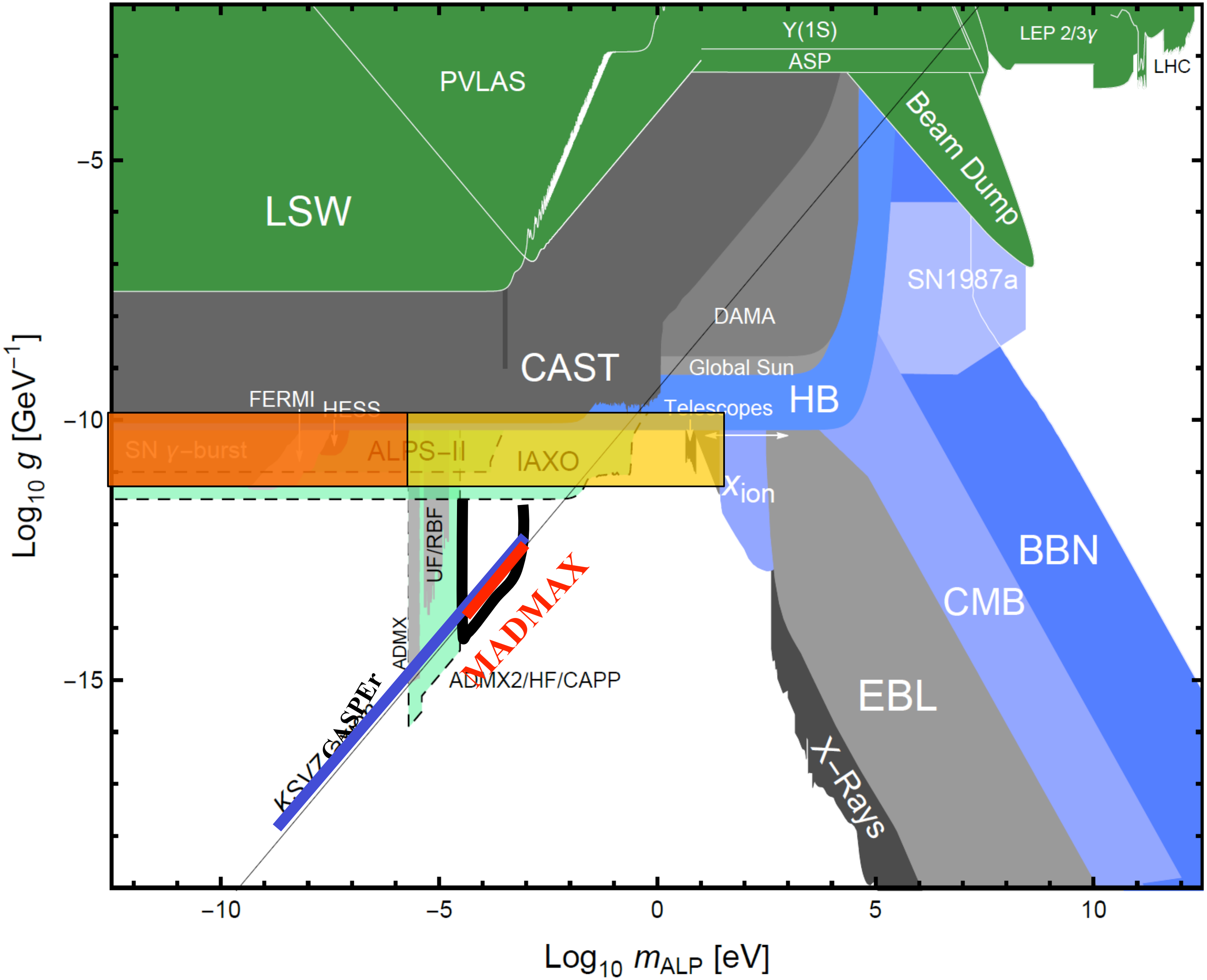
Budget needs:

- Magnet cost driver (5-15 M€).
  more solid numbers in 2018
- Additional costs few M€
- So far: MPG, EU Infradev proposal

Site:

- Constructive discussions with DESY

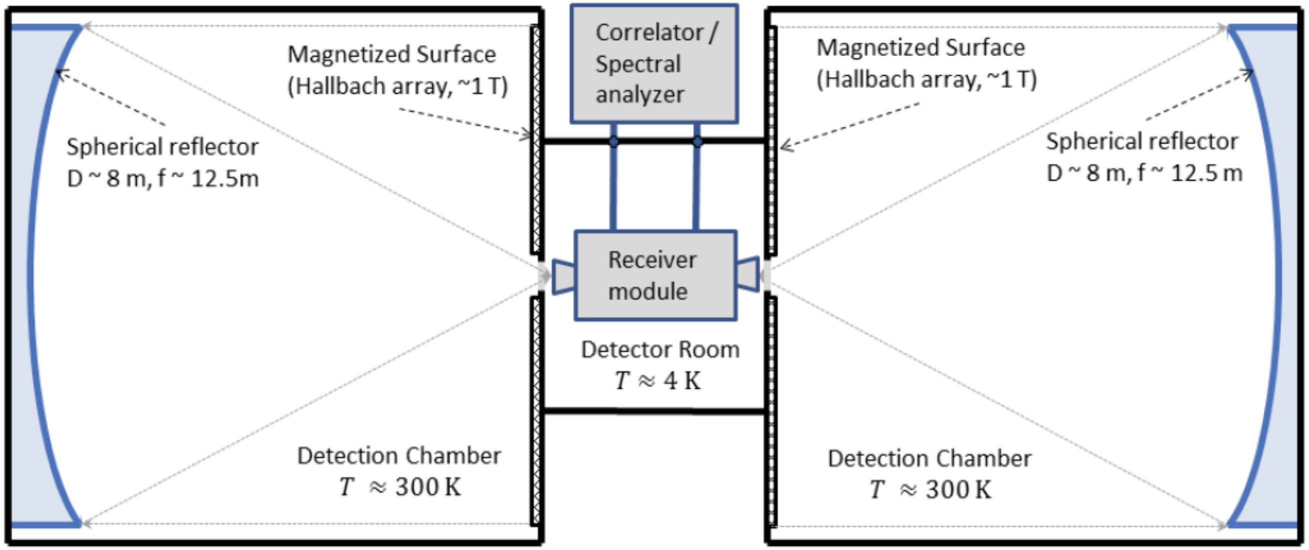
MADMAX sensitivity projection



BRASS: Dish antenna + magn. Surface:

Broadband Radiometric Axion SearcheS

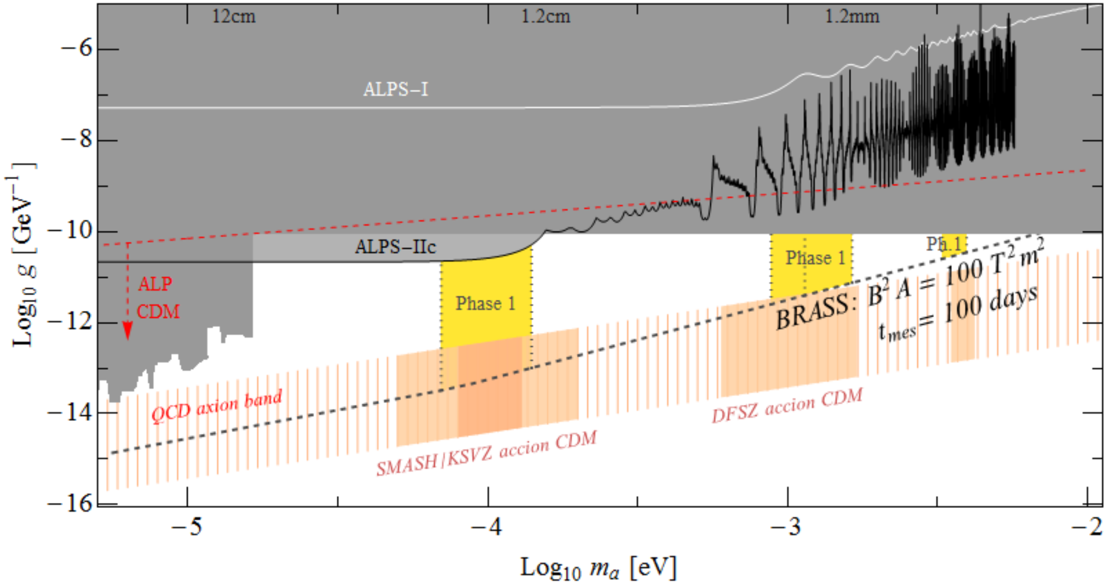
Initiative of University of Hamburg (D. Horns) and MPIfR Bonn (A. Lobanov)



- **Sesnitive in 20-8000 µeV axion- ALP-mass range**
- **Combination of dish approach with permanently magnetized flat surface for a→γ conversion**
- **Benchmark sensitivity for FOM of 100 T^2m^2 & optimistic photon detection efficiency and system noise temperature 0.3 K**
- **Multiple chambers for directional sensitivity**

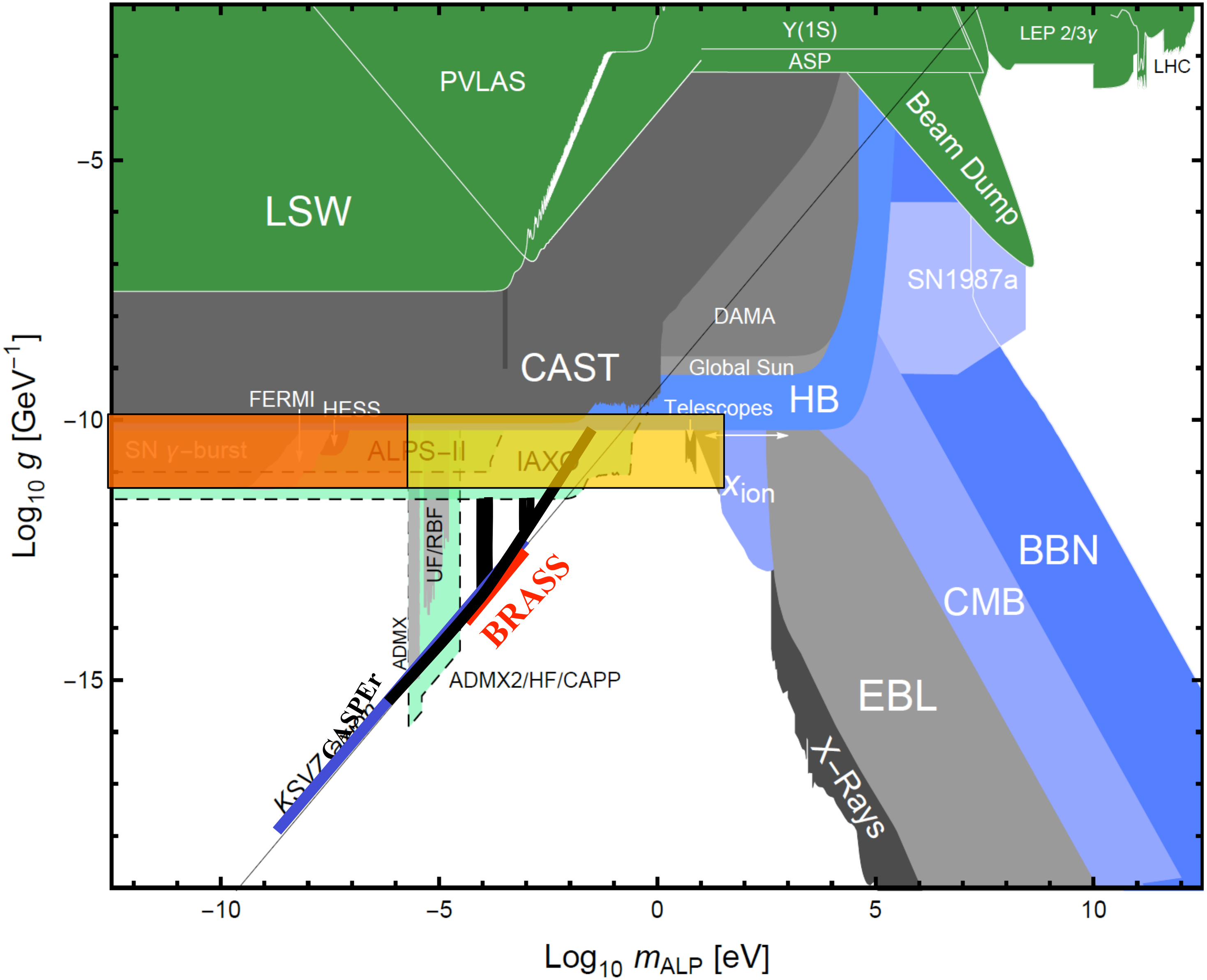
BRASS: Dish antenna + magn. surface

- Reach axion DM sensitivity with measurements of ~100 days per recording band (16 GHz).
- Phase 1 could cover 4 bands within next 3-5 years (0.07-0.14, 0.88-1.14, 1.14-54, 3.27-3.95 meV), corresponding to K/Ka, APEX 1, APEX 2, and ALMA 10 radio bands.

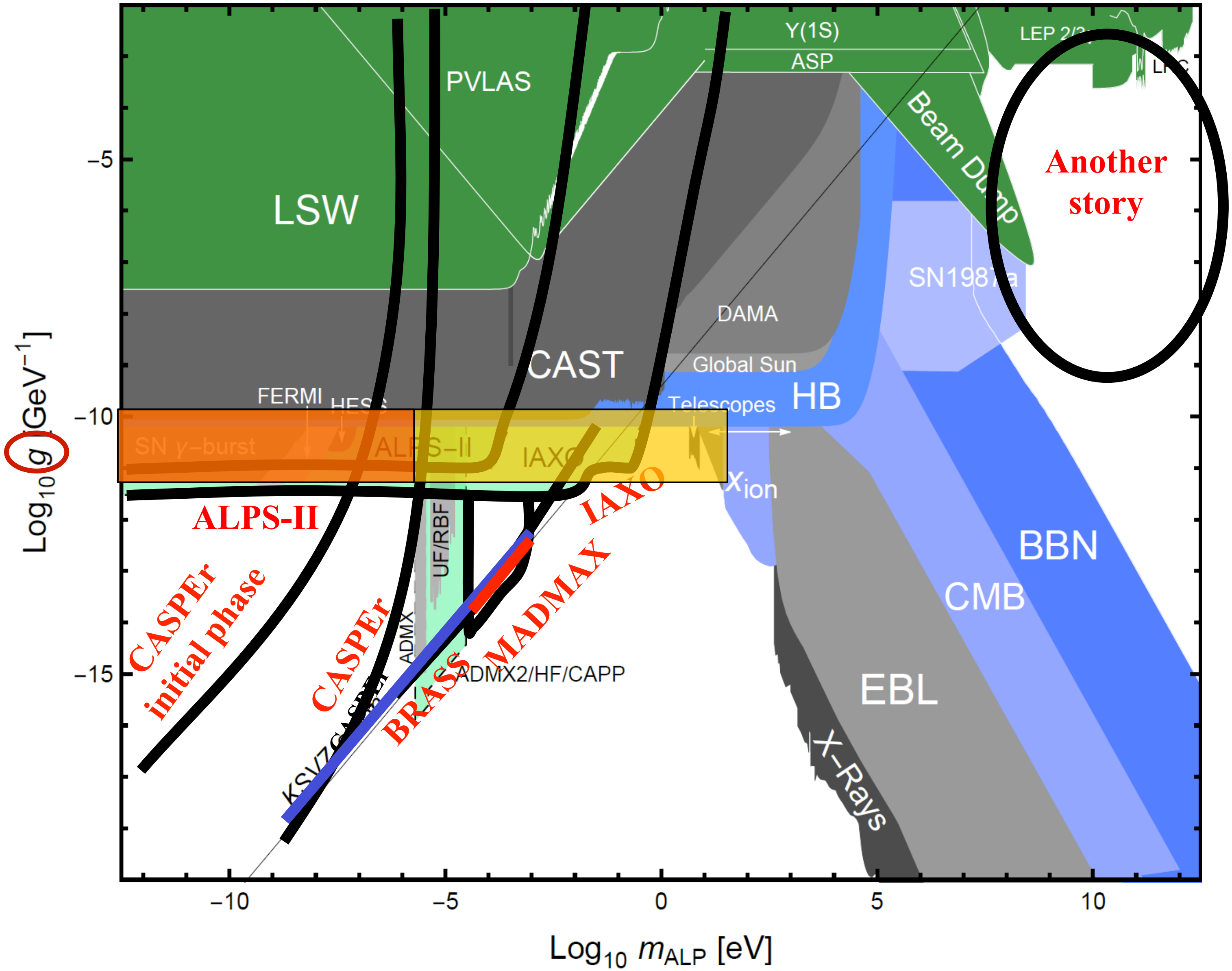


- Synergy with frontline detection and signal processing technology from radio astronomy.
- Proposal to fund a DFG Forschergruppe: University of Hamburg, MPIfR Bonn (DESY)

The Axion and ALPs landscape



The German Axion and ALPs landscape



CONCLUSIONS on Axions and ALPs

Could solve one or two mysteries?

DM & strong CP problems

QCD axion (neV-1μeV)

solar QCD axions

ALPs

Could find new fields:

Stringy axions, new scalar fields, dark photons:

Possible experimentally not yet excluded interaction terms

High Discovery Potential:

- **– explore the unexplored**
- **– expect the unexpected**

Even for non-observation:

still very insightfull!

CONCLUSIONS on German efforts

Could solve one or two mysteries?

DM & strong CP problems

QCD axion (neV-1μeV)

solar QCD axions

ALPs

Could find new fields:

Stringy axions, new scalar fields, dark photons:

Possible experimentally not yet excluded interaction terms

- **Very complementary approaches in time and sensitivity**
- **Very synergetic: technologies from particle- and astroparticle-phsics are applicable!**
- **Price/(potential output) ratio seems very favorable (my view)**
- **Timelines until ~2030**
- **Very exciting decade ahead!**