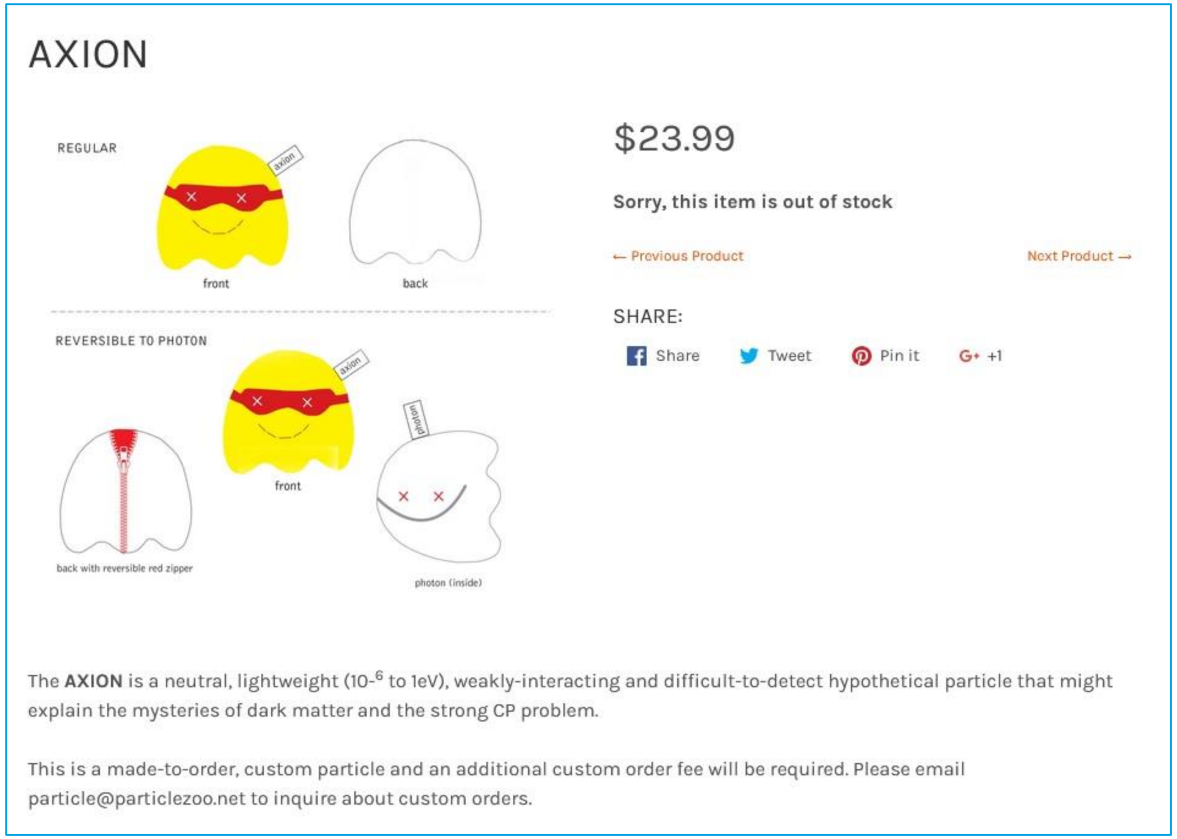
Catching a glimpse of the invisible axion and other WISPs

Experiments @ DESY in Hamburg

Colloquium
2 July 2021

Axel Lindner
DESY

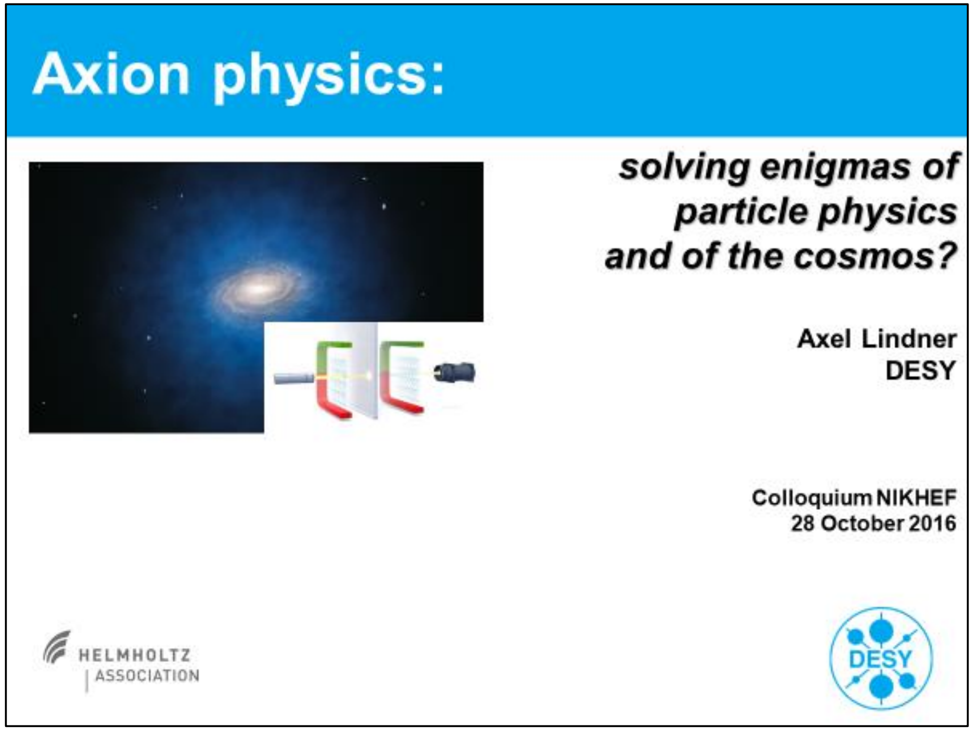


https://www.particlezoo.net

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

A quick summary

Compared to the status in 2016



- Presentations are now in 16:9.

- The enigmas of particle physics and cosmology remain unchanged.
- The parameter region for the QCD axion has expanded.
- Astrophysical hints for axions are still disputed.

- ALPS II at DESY is nearly ready to start data taking.
- BabyIAXO at DESY will probably start construction this year.
- MADMAX has entered the prototyping phase.

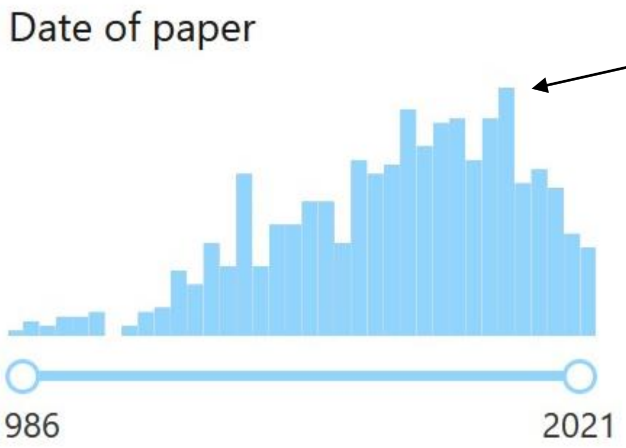
- DESY is strongly committed to axion experiments and is setting up infrastructures for more on-site particle physics experiments.

- The excitement on axion physics is increasing.

Axions are becoming mainstream

inspirehep.net (29 June 2021)

- "title WIMP"



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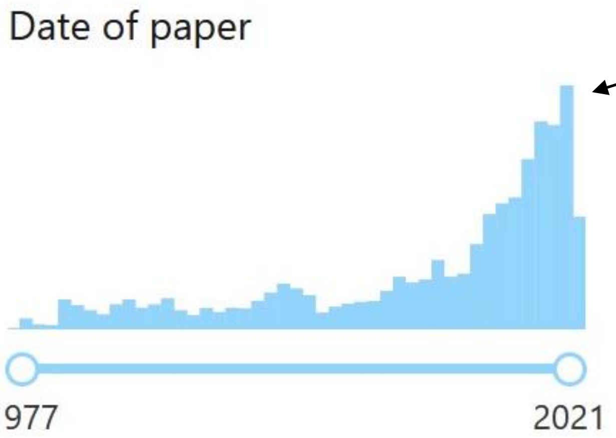
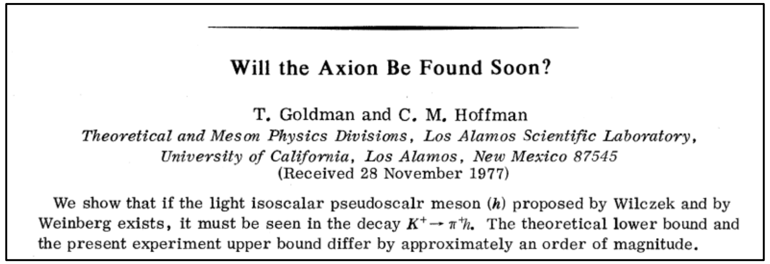
- "title axion"



293

Phys.Rev.Lett. 40 (1978) 220



Will the Axion Be Found Soon?

T. Goldman and C. M. Hoffman
Theoretical and Meson Physics Divisions, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545
(Received 28 November 1977)

We show that if the light isoscalar pseudoscalr meson (h) proposed by Wilczek and by Weinberg exists, it must be seen in the decay $K^+ \to \pi^+ h$. The theoretical lower bound and the present experiment upper bound differ by approximately an order of magnitude.

Axions are becoming mainstream

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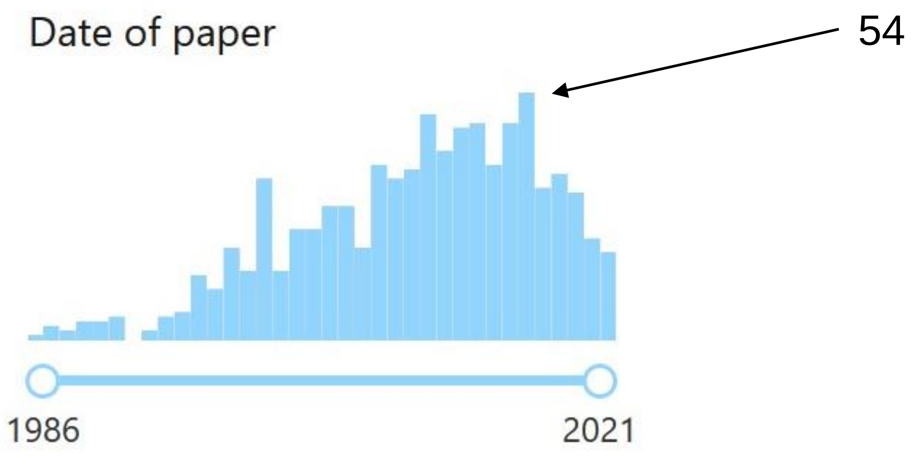
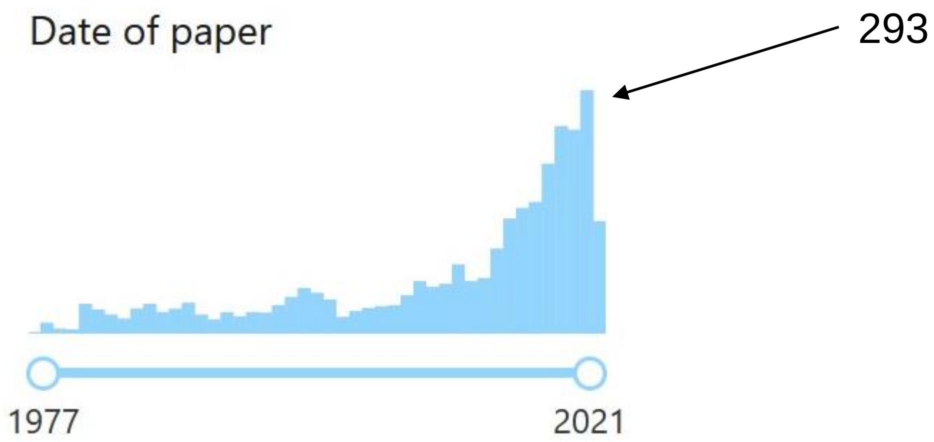


- "title axion"

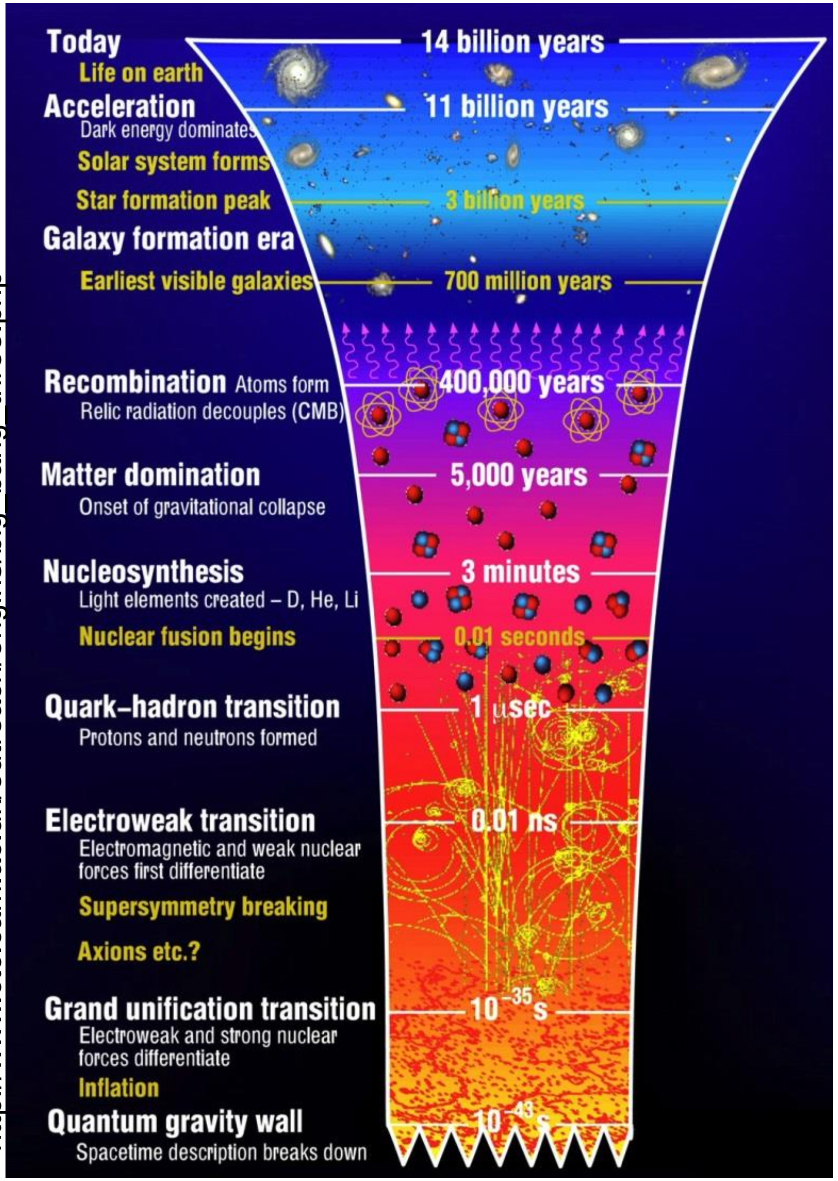


Disclaimer:

In the following I will focus mainly on selected examples and will not even try to cover all aspects of axion physics.

Why?

To understand our universe!



http://www.ctc.cam.ac.uk/outreach/origins/big_bang_three.php

3,000,000,000 years after the Big Bang

400,000 years after BB

3 minutes after BB

0.000001 seconds after BB

0.00000000001 seconds after BB

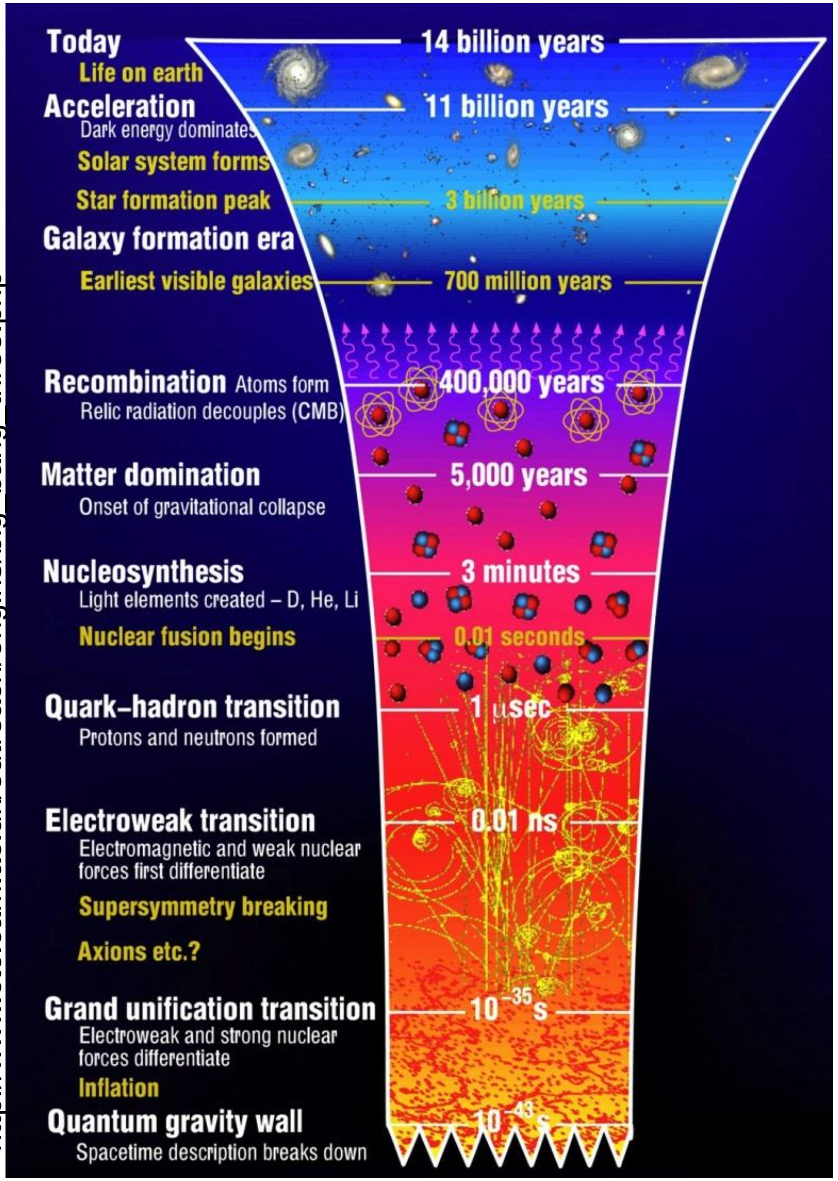
Astronomy

BB in the laboratory:

Elementary particle physics

Why?

To understand our universe!



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3,000,000,000 years after the Big Bang

400,000 years after BB

3 minutes after BB

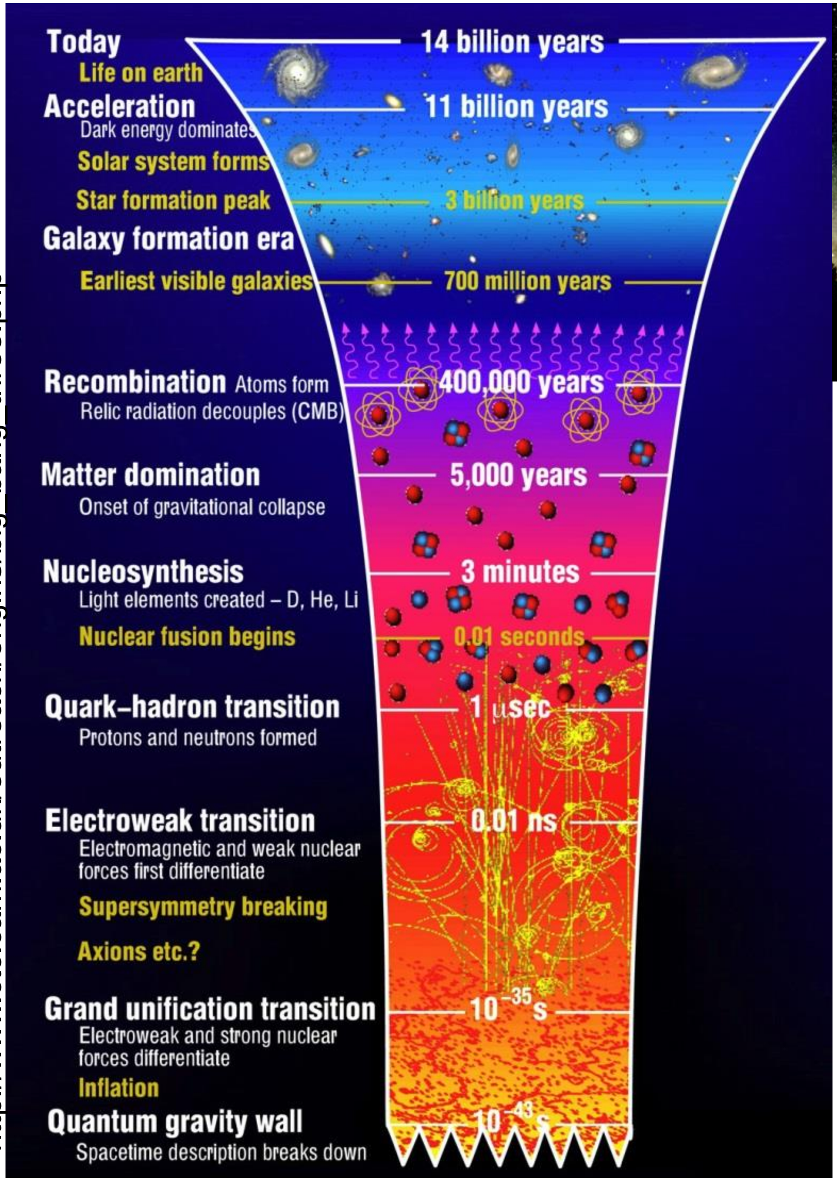
0.000001 seconds after BB

0.00000000001 seconds after BB

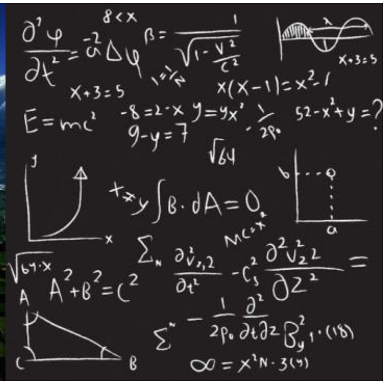
Gravitational waves?

What do we know

A very brief status report



http://www.ctc.cam.ac.uk/outreach/origins/big_bang_three.php



Astronomy, particle physics theory

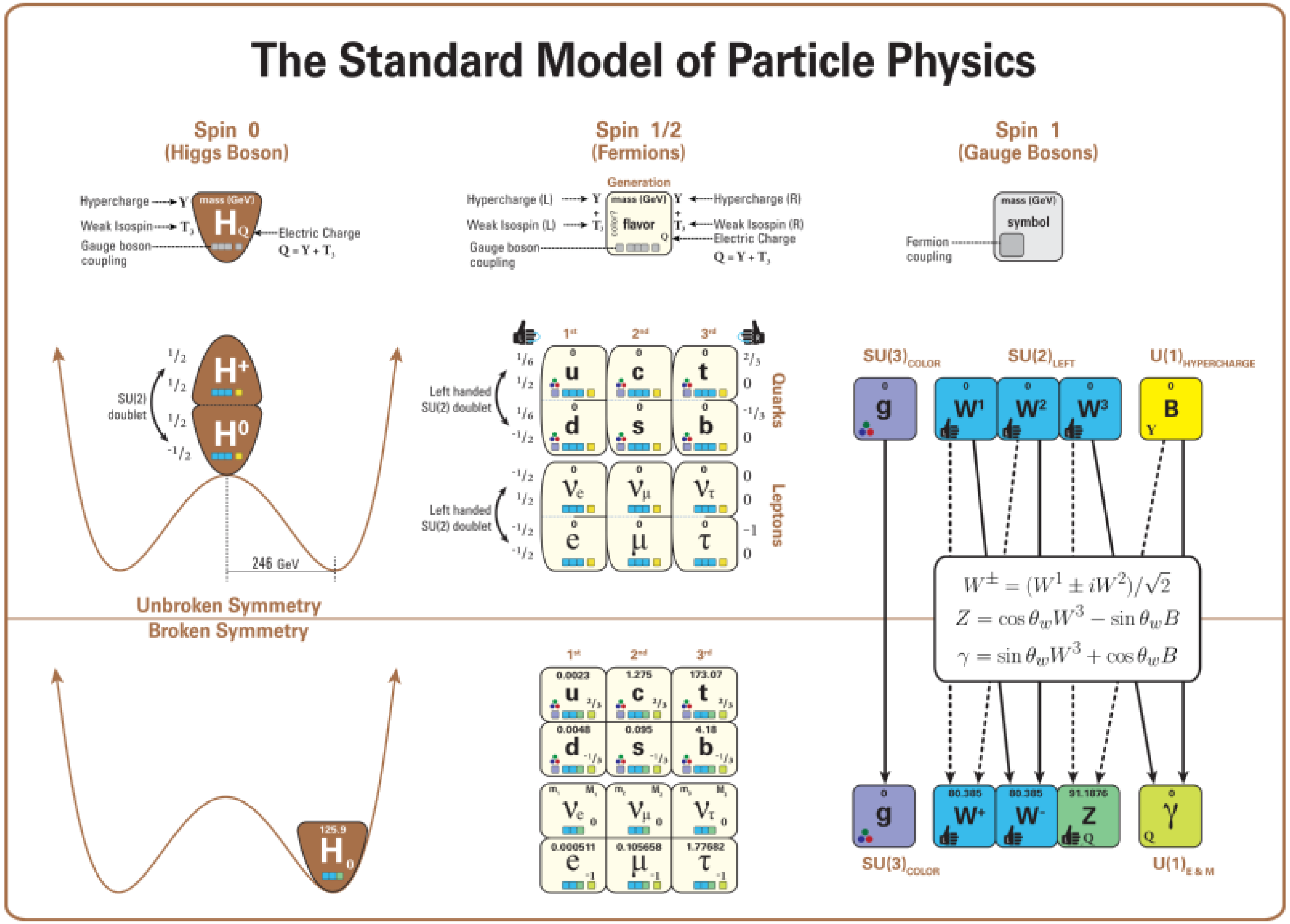
seem to fit perfectly!

We seem to understand how the universe evolved precisely.

Example:
Age of the universe = 13.799 ± 0.021 billion years (0.15% accuracy!)

What do we know

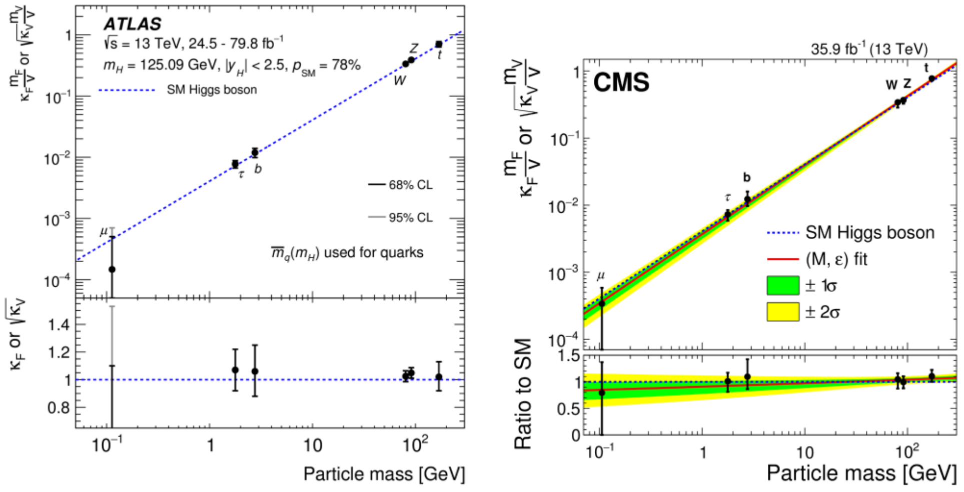
A very brief status report



https://en.wikipedia.org/wiki/Standard_Model

All experiments probing the smallest constituents of matter and its interactions perfectly fit to the standard model,
apart from non-zero neutrino masses.

Example: properties of the Higgs.



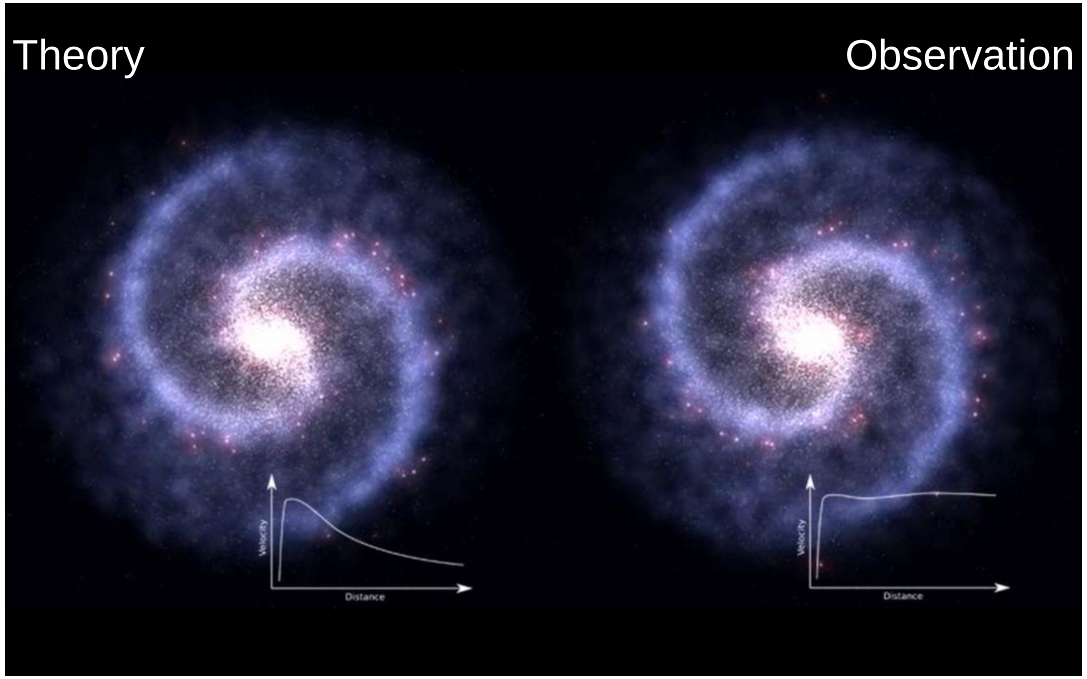
Precision Measurements in the Higgs Sector at ATLAS and CMS, A. Sopczak, arXiv:2001.05927 [hep-ex]

What do we know

Flaw(s) ?

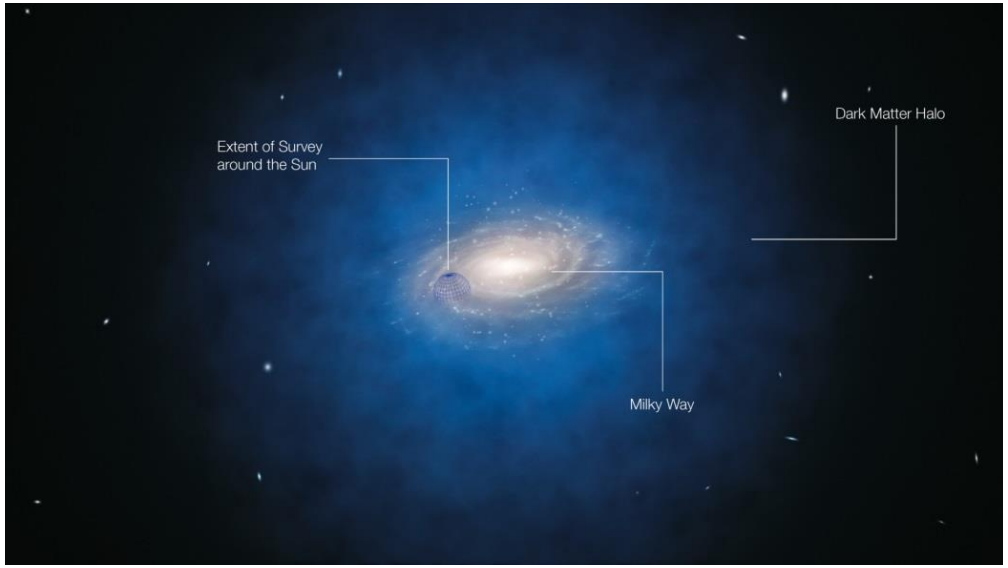
Particle physics and cosmology only fit if a large amount of mass and energy of unknown constituents exist.

Example: rotation of galaxies.



http://beltoforion.de/article.php?a=spiral_galaxy_renderer

Dark matter ≈ 10 · visible matter



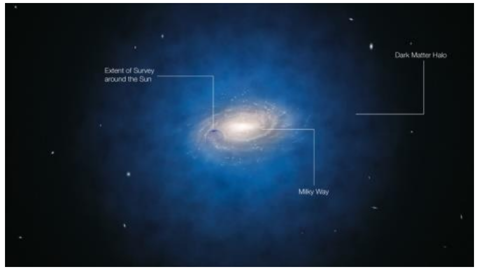
https://www.eso.org/public/news/eso1217/

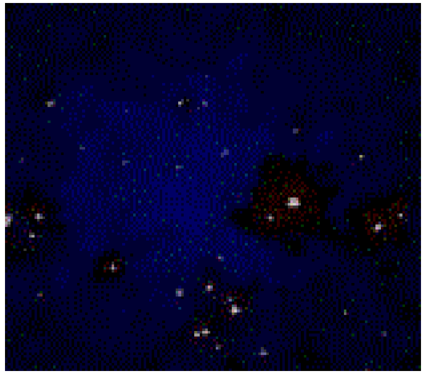
What do we know

Flaw(s) ?

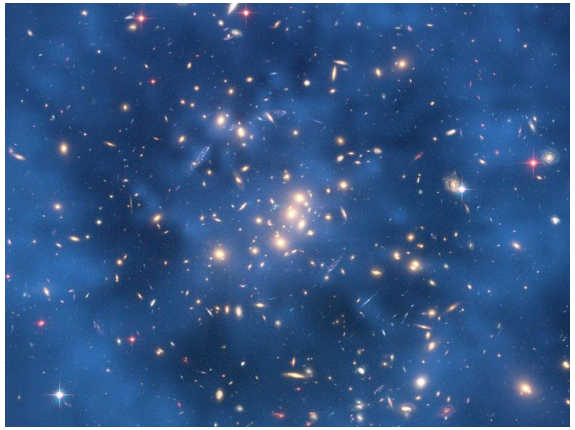
Particle physics and cosmology only fit if a large amount of mass and energy of unknown constituents exist.

Many evidences for dark matter on length scales of galaxies and beyond.



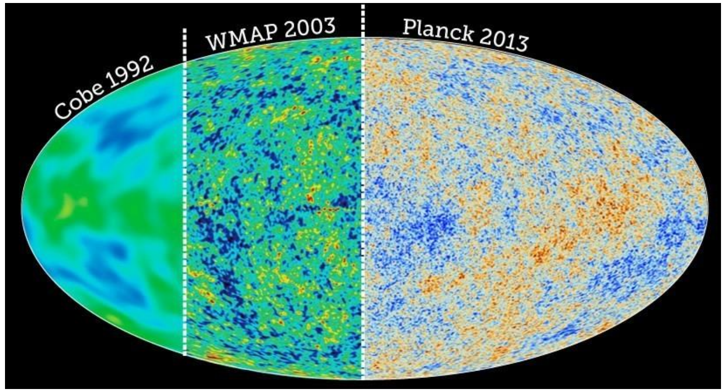


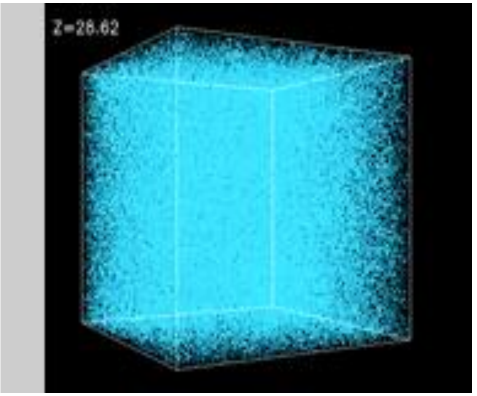
http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/galaxydist.htm



https://www.esa.int/Science_Exploration/Space_Science/Hubble_sees_dark_matter_ring_in_a_galaxy_cluster

https://www.researchgate.net/figure/Temperature-fluctuations-observed-in-the-CMB-using-COBE-WMAP-Planck-data-Gold-et-al_fig1_328474806



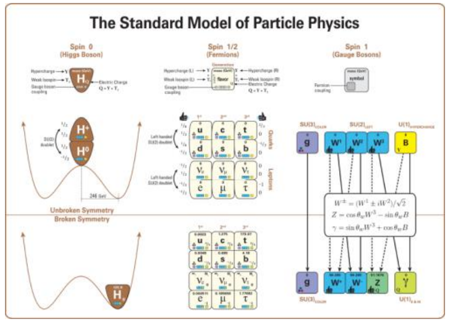


http://cosmicweb.uchicago.edu/filaments.html

What do we know

Composition of the universe

stars	gas / dust	dark matter	dark energy
0.5%	4.5%	26%	69%



additional gravitation (galaxies & beyond)

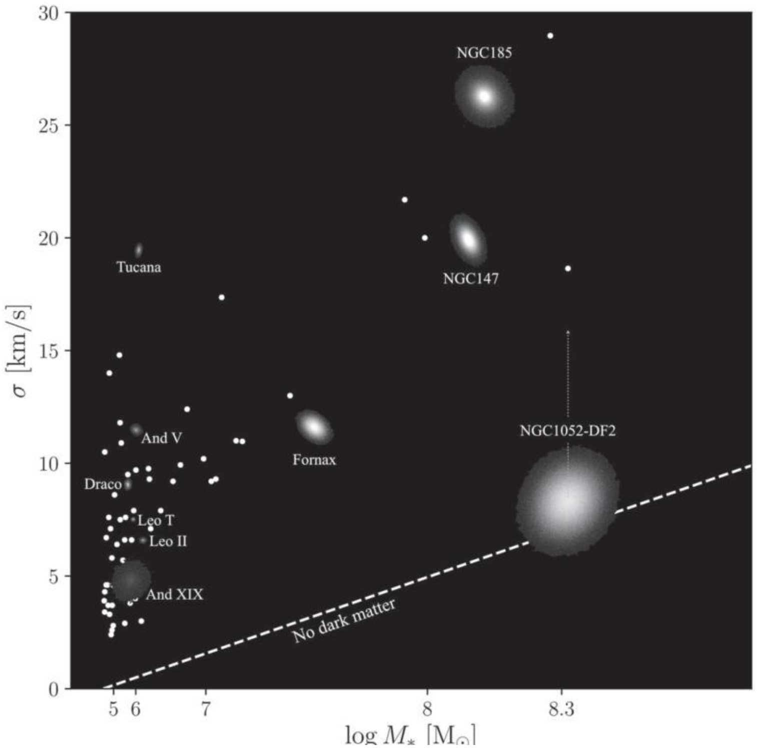
anti-gravitation on largest scales

NGC 1052–DF2 and NGC 1052–DF4

No dark matter as strong evidence for dark matter

van Dokkum *et al.*, *Nature* **555,** 629–632 (2018)

The Astrophysical Journal Letters, 874:L12 (8pp), 2019 April 1



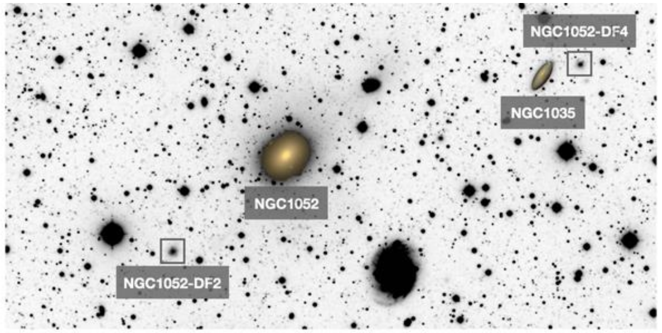
Shany Danieli *et al* 2019 *ApJL* **874** L12

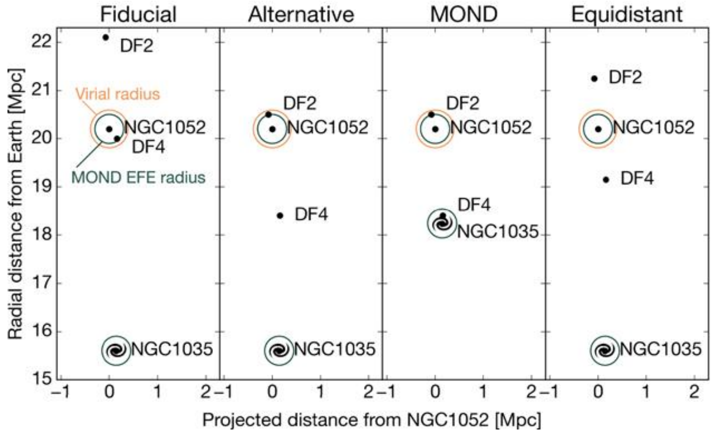
The dynamics in both galaxies does not require any dark matter component.

This strongly excludes MOND as an alternative to dark matter.

Both galaxies show more unusual properties hinting at special evolutions.

A MOND external field effect seems to be excluded after recent new distance measurements.





Zili Shen *et al* 2021 *ApJL* **914**

Particle Physics beyond the Standard Model ?

For sure!

The standard model (SM) of particle physics is

- extremely successful, but
- does not provide answers to crucial questions (a selection):
  - How to integrate non-zero neutrino masses?
  - What are dark matter and dark energy?
  - How to explain the baryon-antibaryon asymmetry of the universe?
  - Why is the Higgs so light?
  - Why is CP conserved in QCD?
  - Why is the vacuum energy so tiny?

Here the SM fails!

Cosmology

Fine tuning

Where to look for beyond-SM-Physics?

Wherever you can!

An exemplary selection:	energy reach
• Laboratory experiments	
• Energy frontier	10 TeV (LHC)
• Precision frontier	10^3 TeV (eEDM, model dependent)
• Rare decays	10^3 TeV (Mu3e, model dependent)
• Light-through-walls (lab, solar)	10^5 TeV (axions, model dependent)
• Astrophysics	
• Stellar evolutions, light propagation	10^5 TeV (axions, model dependent)
• Dark matter searches	10^9 TeV (axions, model dependent)
• Cosmology	
• CMB, gravitational waves	10^{12} TeV (inflation, model dependent)

Outline

- Brief motivation for axions and the likes
- The axion landscape and astrophysics hints
- Direct dark matter searches with MADMAX
- The IAXO helioscope
- Light-shining-through-walls with ALPS II
- Summary

A brief motivation for the axion

Missing: a CP violation of QCD

The QCD Lagrangian includes a CP violating term:

$$L_\theta = -\theta(\alpha_s/8\pi)\,\tilde{G}^a_{\mu\nu}G^a_{\mu\nu}$$

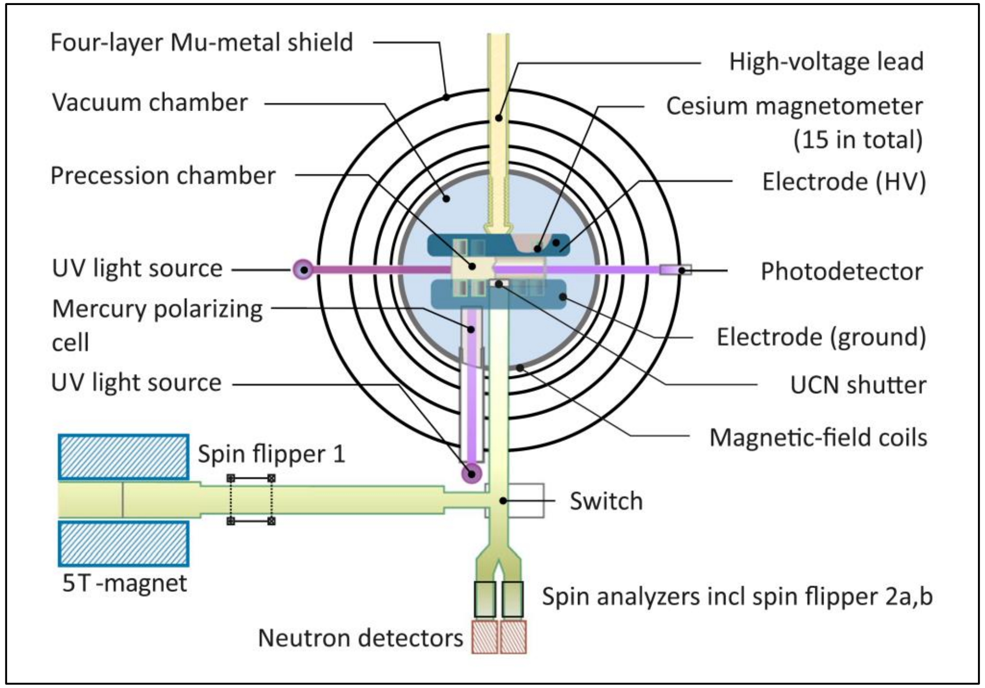
This imposes a neutron electric dipole moment: $d_n = \theta \cdot 2{\cdot}10^{-16}$ e·cm.

Any permanent EDM of the neutron would violate CP.

Measurements (example):

$$d_n = (0.0 \pm 1.1_{\rm stat} \pm 0.2_{\rm sys}) \times 10^{-26}\ e.\mathrm{cm}$$

C. Abel *et al.*, Phys. Rev. Lett. 124, 081803



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Any permanent EDM of the neutron would violate CP.

Experimentally, $\theta < 10^{-10}$.

Suspicion: perhaps θ = 0 ?

If yes, how to get θ = 0 ? Alternatives:

- The u or d quark is massless: experimentally excluded.
- It is “just” so. Nature is “fine-tuned”.
- Does a special mechanism drive θ to zero?
  Such a mechanism is not known in the standard model of particle physics.

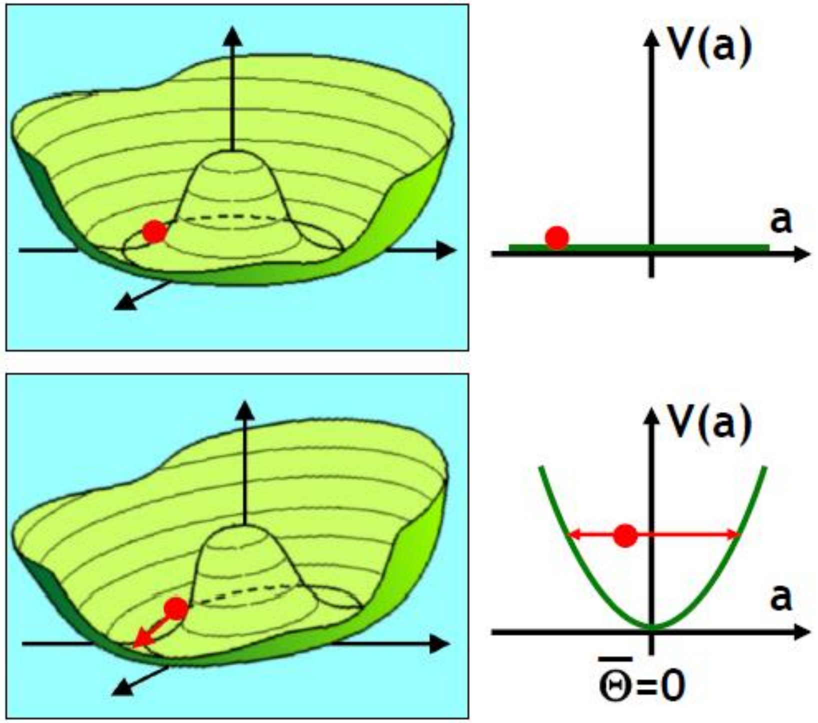
A brief motivation for the axion

The Peccei-Quinn mechanism of 1977

Idea: if θ is not a fixed value, but an evolving field, it relaxes to zero by QCD instanton effects.

Peccei-Quinn symmetry:

- Global U(1), complex scalar field.
- Spontaneously broken at very high energies: a massless Goldestone boson should exist. This is the axion.
- QCD instanton effects explicitly break the axion (a) symmetry, so that it becomes inexact at QCD energies. The axion acquires mass.



S. Hannestad, presentation at 5th Patras Workshop 2009

If θ = 0 by the Peccei-Quinn mechanism,
an axion should exist!

And vice versa.

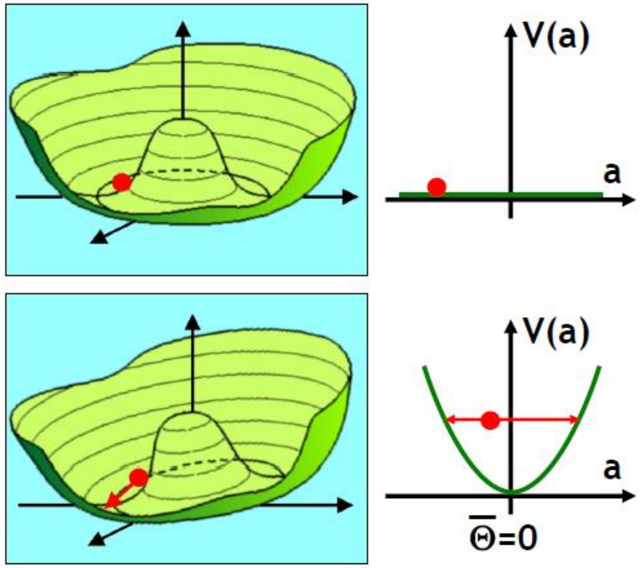
Axion properties (1)

Feeble interactions

- Mass: $m_a = 0.6 \text{ eV} \cdot (10^7 \text{GeV} / f_a)$
  Couplings ~ $1/ f_a$ (hence ~ m_a)

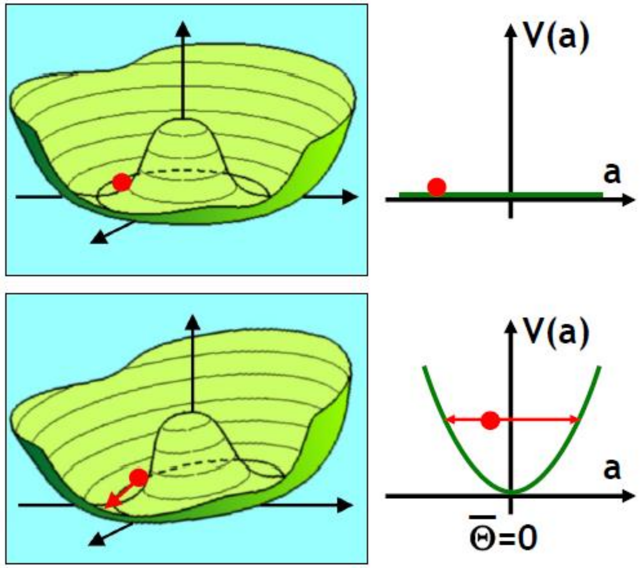
  f_a is the energy at which the "Mexican hat" appears.

  At QCD energies the "hat" gets tilted.



Axion properties (2)

Feeble interactions and ideal dark matter candidates



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  f_a is the energy at which the "Mexican hat" appears.

- The PQ symmetry breaking happened also in the early universe.
  Thus, axions contribute to dark matter (simplified picture):

  $\Omega_a / \Omega_c \sim (f_a / 10^{12}\mathrm{GeV})^{7/6} = (6\ \mu\mathrm{eV} / m_a)^{7/6}$

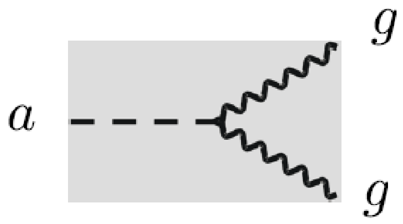
  For $f_a \approx 10^{12}$GeV ($10^8 \cdot$LHC) and m_a around 10 μeV the axion could make up all of the dark matter!

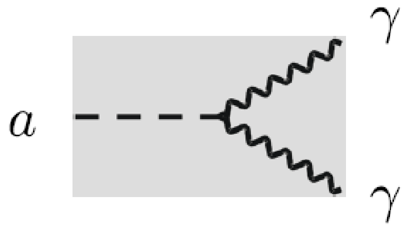
  Such axions originate from the symmetry breaking and not from any thermal process (like WIMPs).
  Thus they are very cold.

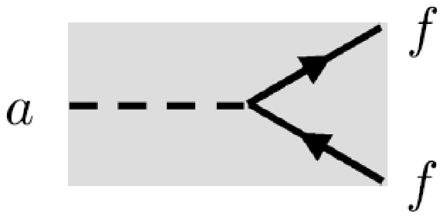
Axion properties (3)

Making them visible

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C_{ag}}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\partial_\mu a\; \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$







Courtesy A. Ringwald

CP conservation in QCD

Exploited in most experiments

The factors *C* depend on details of the axion model. Benchmark models are:

- KSVZ (Kim 1979 / Shifman, Vainshtein, Zakharov 1980):
  Only BSM fermions carry PQ charges, only direct “hadronic” coupling via gluons to SM.
- DFSZ (Zhitnitsky 1980 / Dine, Fischler, Srednicki 1981):
  SM fermions carry PQ charges, additional Higgs, additional SM singlet.
  Direct coupling to electrons!

ALP – photon couplings

Exploited by most experiments for lightweight ALPs / axions

Axion decay to two photons

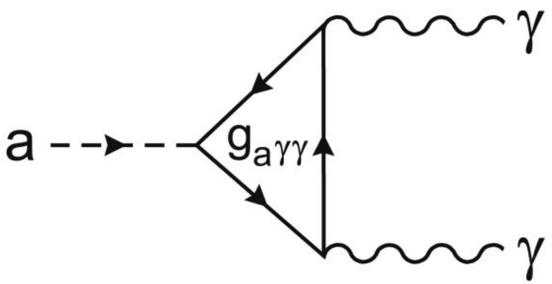
https://pdg.lbl.gov/2021/reviews/contents_sports.html

$$m_A = 5.691(51)\left(\frac{10^9\,\mathrm{GeV}}{f_A}\right)\mathrm{meV}$$

$$\Gamma_{A\to\gamma\gamma} = \frac{g_{A\gamma\gamma}^2 m_A^3}{64\,\pi}$$

$$g_{A\gamma\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - 1.92(4)\right)$$

Axion model   Axion-Pion mixing

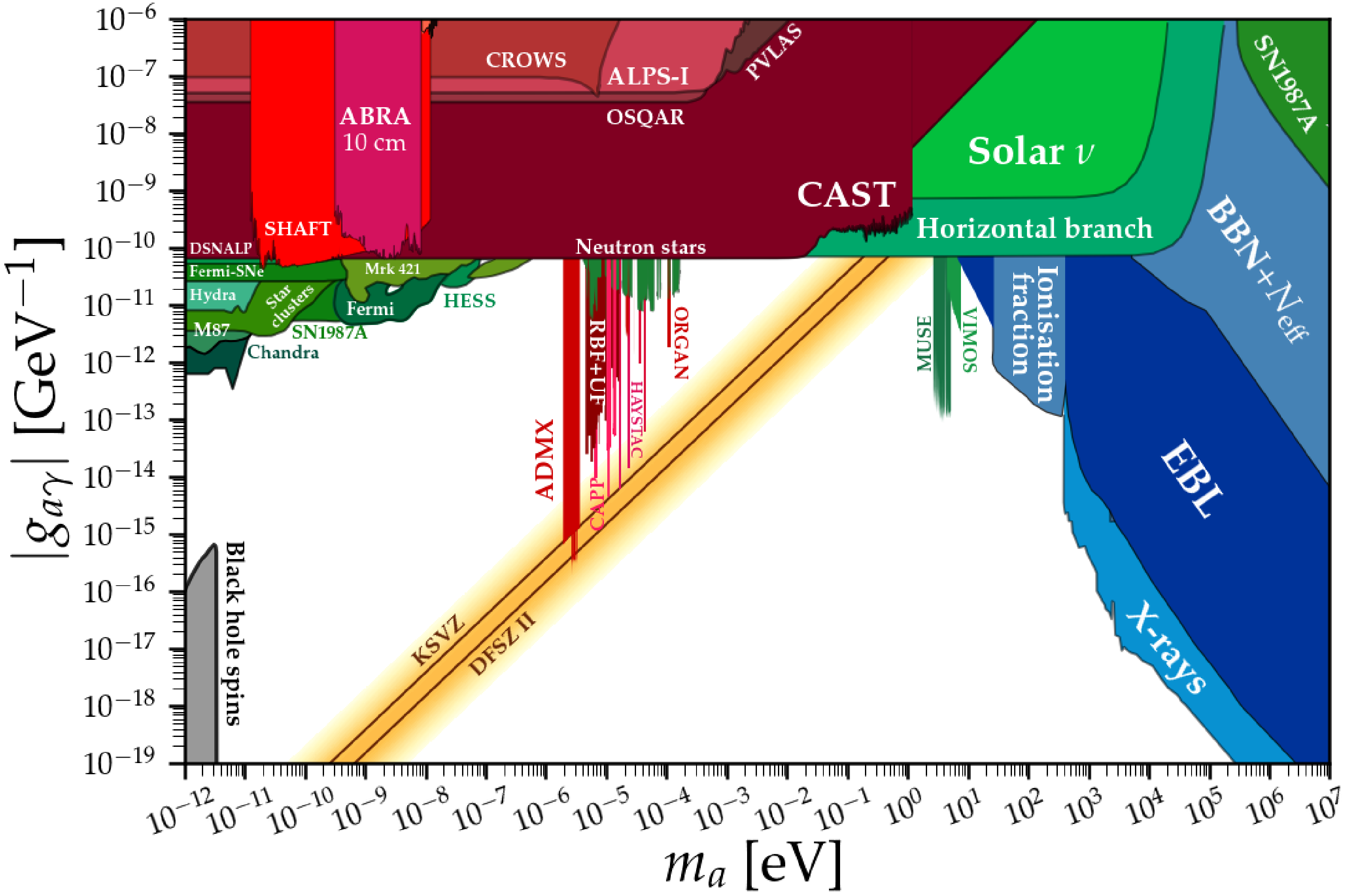


KSVZ:	E/N = 0	(new BSM quark without electric charge)
DFSZ:	E/N = 8/3	(GUT theories)

Roughly: $\tau_{ma=1eV} \approx 10^{16}$ years

The axion landscape

Making them visible



Ciaran O'Hare,

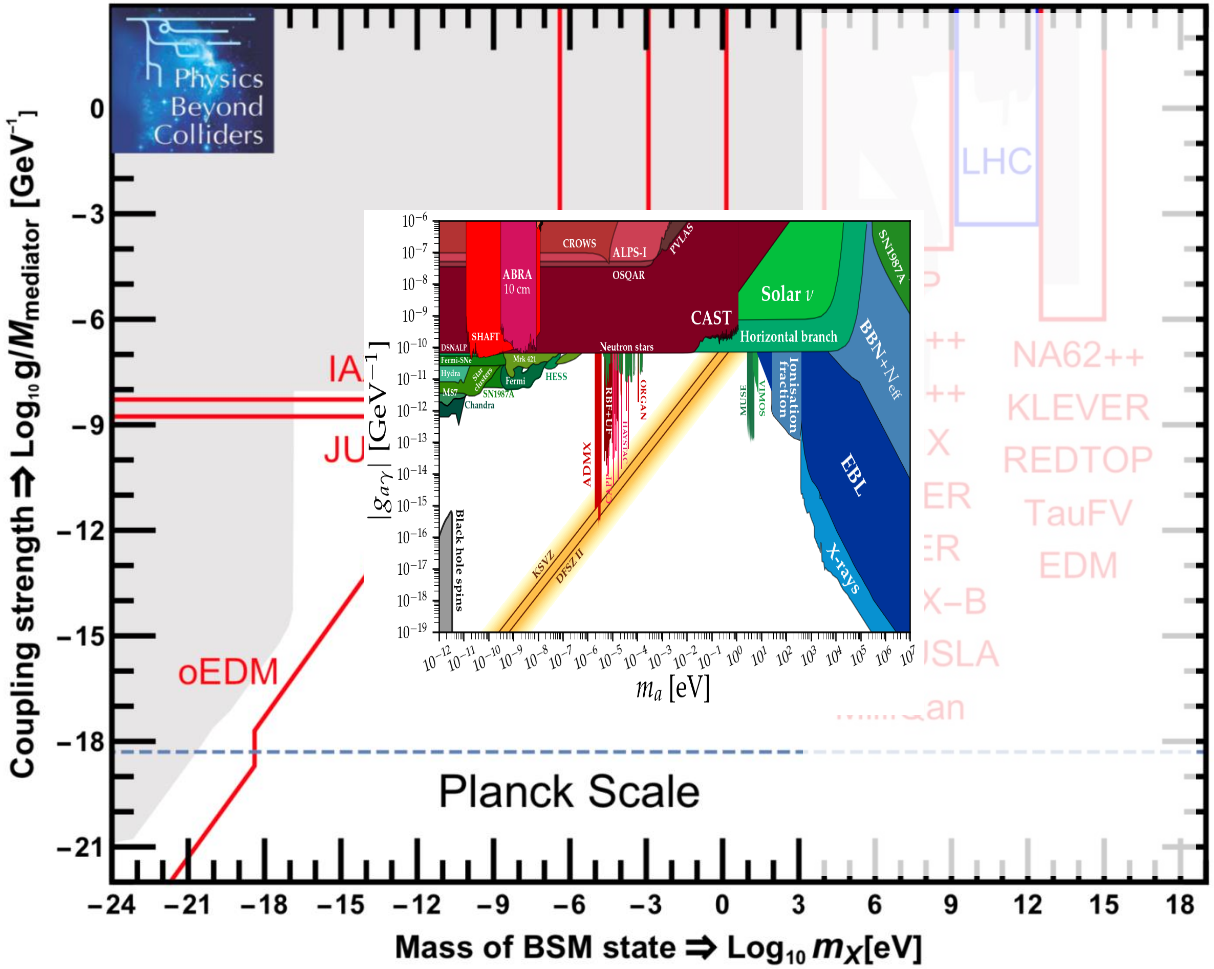
https://cajohare.github.io/AxionLimits/

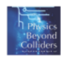
Many orders of magnitude in mass and coupling strength to be probed by different experiments:

- On earth
- Astrophysics
- Cosmology
- Gravitational waves

The axion landscape extended

37 orders of magnitude in mass!





EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PBC-REPORT-2018-007

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

This plot:

- no new proposals for direct dark matter searches included.

This talk:

- masses roughly < 1 eV,
- non-accelerator searches.

Non-accelerator experiments might probe energy scales > 10^4·LHC.

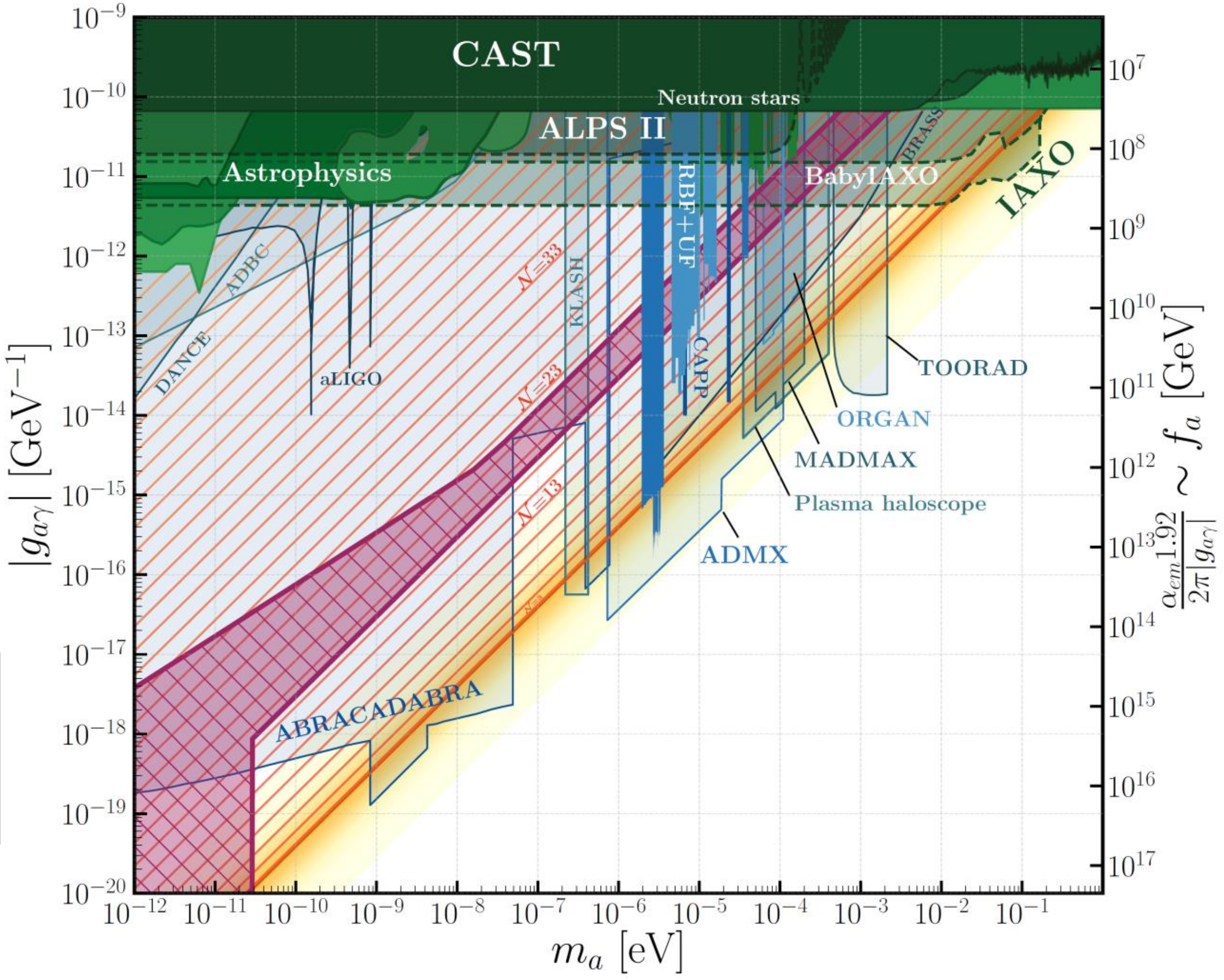
More axions (1)

Beyond benchmark models

“An even lighter QCD axion” (L. Di Luzio, B. Gavela, P. Quilez and A. Ringwald, arXiv:2102.00012 [hep-ph]):

In nature many copies of the standard model exist and are linked by the QCD axion.

Purple: axions can make up 100% dark matter



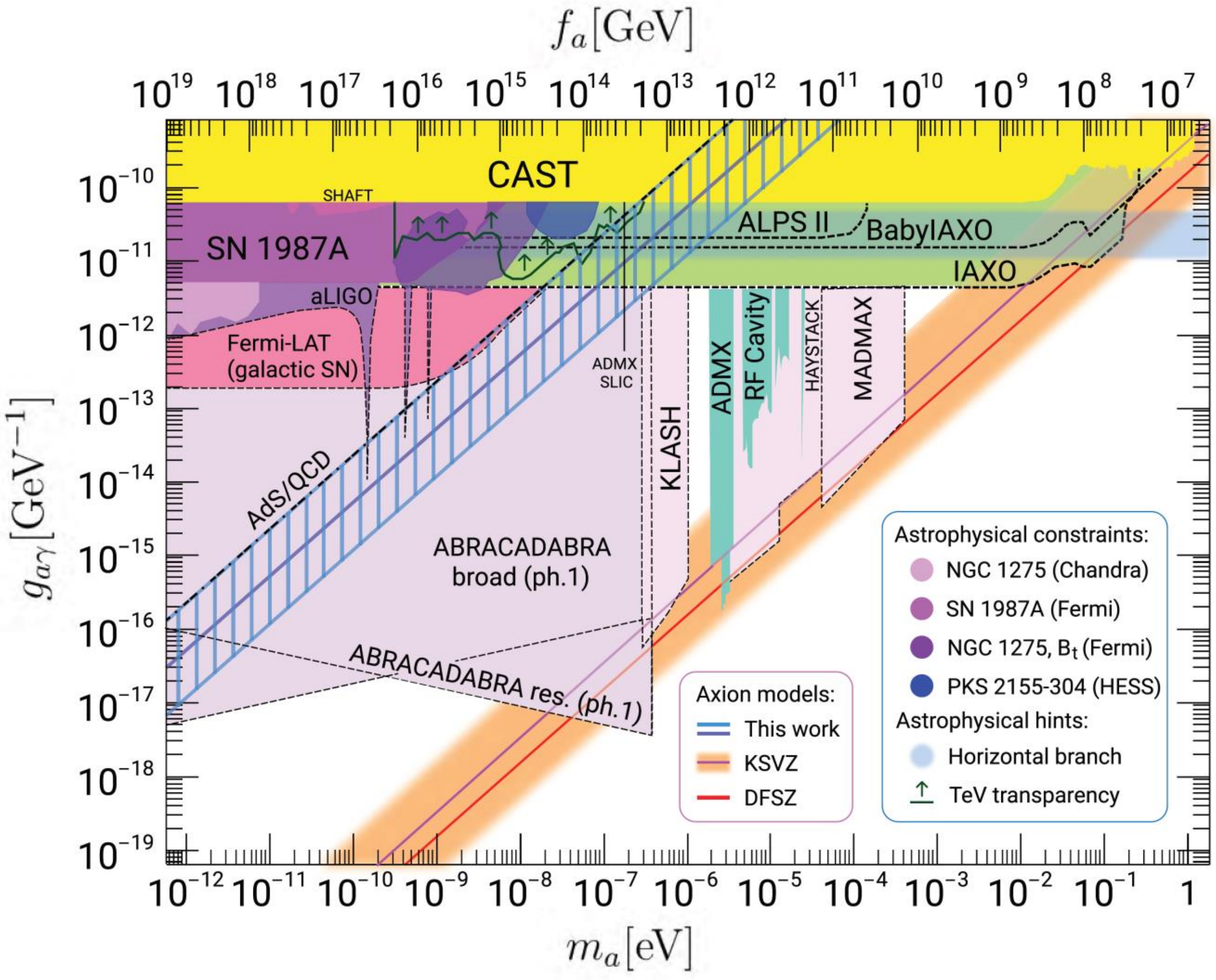
More axions (2)

Beyond benchmark models

“Photophilic hadronic axion from heavy magnetic monopoles“
(A. V. Sokolov and A. Ringwald, arXiv:2104.02574 [hep-ph]) :

The QCD axion is realized through a Yukawa coupling of the Peccei-Quinn (PQ) scalar field to magnetically charged fermions.

The photon coupling of this axion is drastically enhanced, by a factor $10/\alpha^2 \approx 10^5$.



More axions (3)

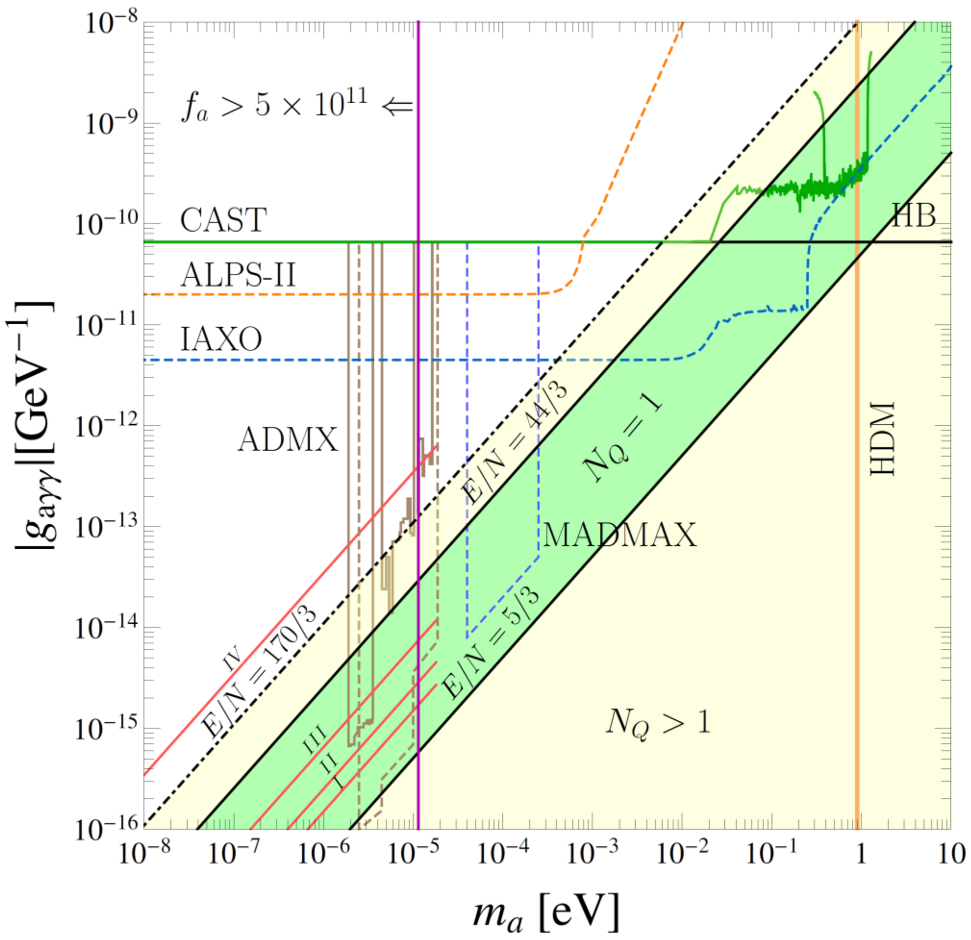
Beyond benchmark models

"Window for preferred axion models”
(Luca Di Luzio, Federico Mescia, and Enrico Nardi, Phys. Rev. D 96, 075003)

The axion might be photophobic:
KSVZ-like new heavy quarks might diminish axion-photon couplings.

Reminder: $g_{A\gamma\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - 1.92(4)\right)$

„Such a cancellation is immoral,
but not unnatural“.
(“Opening the Axion Window”, D. B.Kaplan, Nucl. Phys. B 260 (1985))



Weakly Interacting Slim Particles (WISPs)

More than the axion

There may be a complex hidden sector of sub-eV mass particles:

- Pseudoscalars: axion-like partcles (ALPs): couplings ~ 1/ f_a, mass independend from f_a.
- Vector bosons: hidden photons
- Scalars: dilaton fields
- Minicharged particles

Such particles are expected in theories of quantum gravity (lot’s of global symmetry breakings).

In general WISPs with masses below 1eV are dark matter candidates

- if they are bosonic,
- if they are of non-thermal origin.

Disclaimer:

In the following I will not distinguish anymore between the QCD-axion and ALPs, but use both as synonyms.

Unless stated otherwise.

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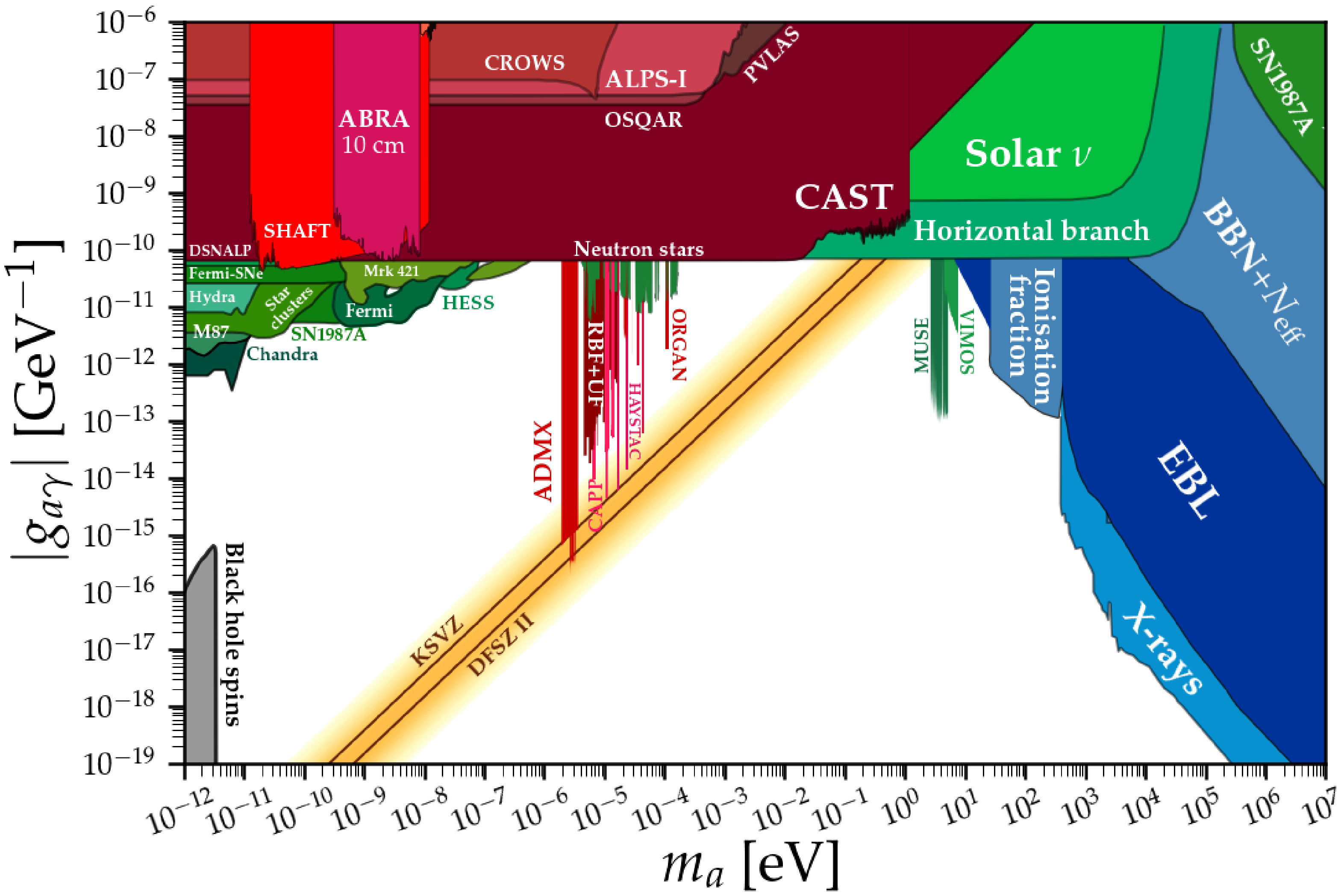
The axion landscape

Making them visible



Ciaran O'Hare,

https://cajohare.github.io/AxionLimits/

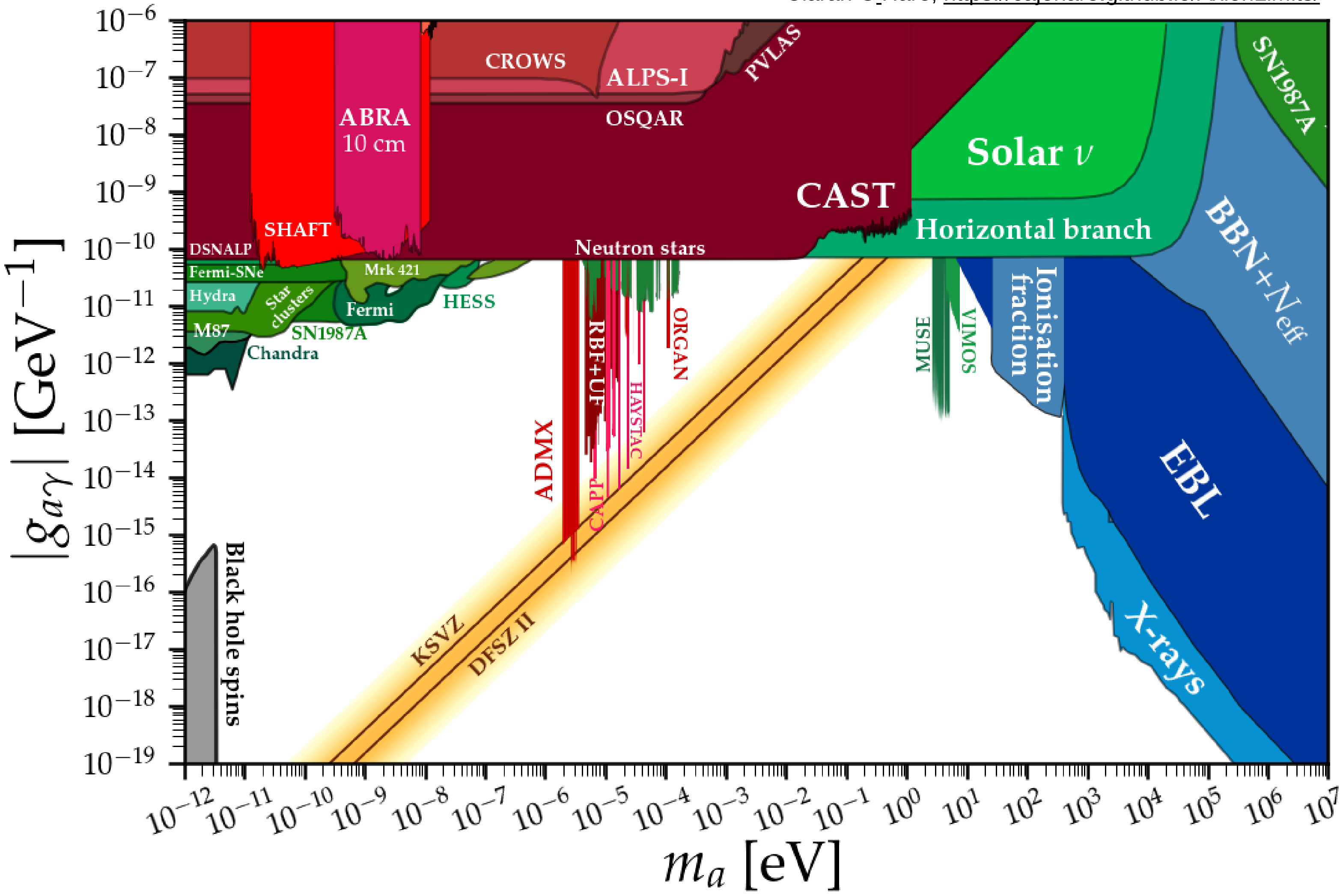
Many orders of magnitude in mass and coupling strength to be probed by different experiments:

- On earth
- Astrophysics
- Cosmology
- Gravitational waves

Axion searches

Making them visible

Ciaran O'Hare, https://cajohare.github.io/AxionLimits/

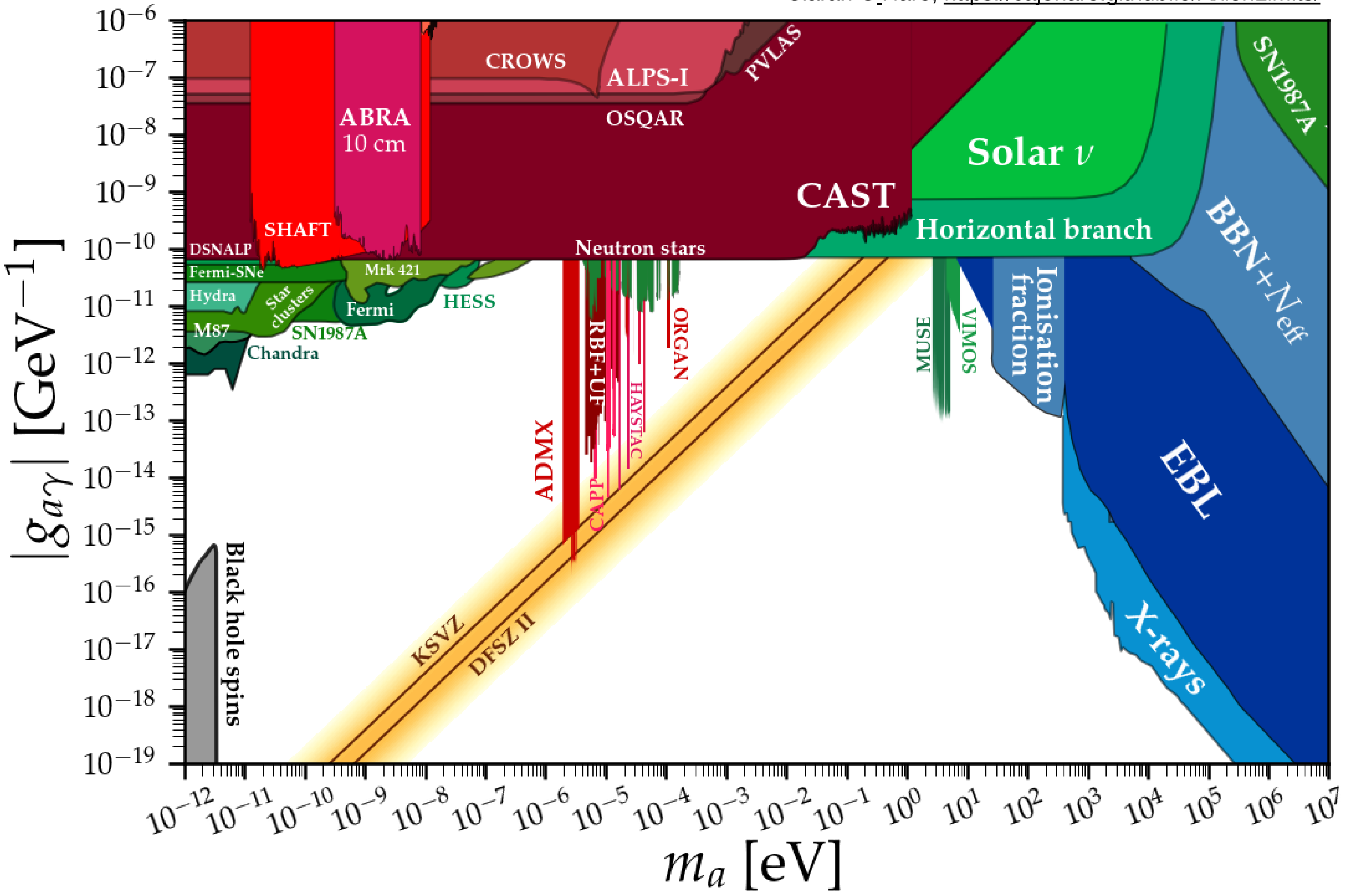


- On earth
- Astrophysics
- Cosmology
  - Looking for signatures of dark matter axions.
- Gravitational waves
  - Superradiance: axions might extract energy from spinning black holes.

Axion searches

Making them visible

Ciaran O'Hare, https://cajohare.github.io/AxionLimits/

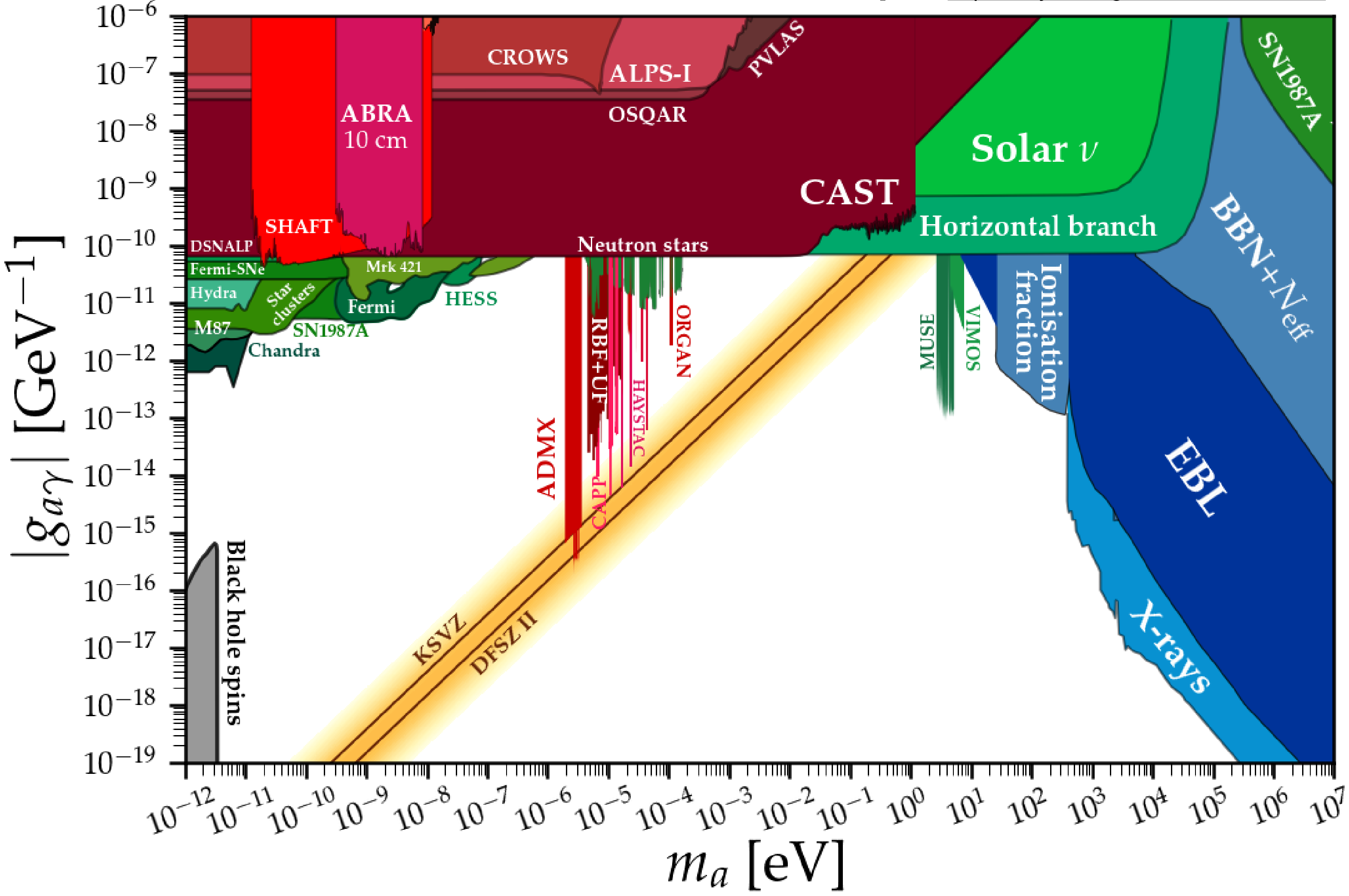


- On earth
- Astrophysics
  - General: Axions as very light particles might be generated in today's universe.
  - Some examples later ...
- Cosmology
- Gravitational waves

Axion searches

Making them visible

Ciaran O'Hare, https://cajohare.github.io/AxionLimits/



- On earth
  - Direct detection of dark matter axions.
  - Direct detection of solar axions.
  - Purely laboratory-based experiments.
- Astrophysics
- Cosmology
- Gravitational waves

Axion searches

Without and with the dark matter paradigm

Axion (m_a<1eV) searches target BSM energy scales larger than $f_a = 10^5$ TeV.

- Couplings to SM constituents are suppressed by 1/ f_a and hence extremely weak.
  - Flux of solar axions: $\text{flux}_{\text{Primakoff}} \approx 1.8 \cdot 10^{13} \cdot (10^5 \text{ TeV} / f_a)^2 \text{ s}^{-1} \cdot \text{m}^{-2} \approx 0.02 \cdot (10^5 \text{ TeV} / f_a)^2 \cdot$ [solar neutrino flux] corresponding roughly to $0.1 \cdot (10^5 \text{ TeV} / f_a)^2 \text{ W} \cdot \text{m}^{-2}$.

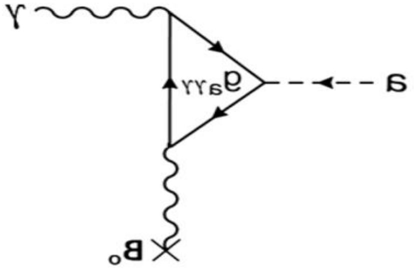
- If axions are dark matter, their number density at earth would be extremely large:
  - $n_a \approx 3 \cdot 10^{13} \cdot (10 \mu\text{eV} / m_a) \text{ cm}^{-3}$.
  - Dark matter axions originate from a phase transition and have never been in thermal equilibrium with other constituents in our universe.
  - In general, searches for dark matter axions are significantly more sensitive than other approaches.

However, upper limits from searches for dark matter axions tell: $\neg$ [(axions exist) $\wedge$ (axions are dark matter)]

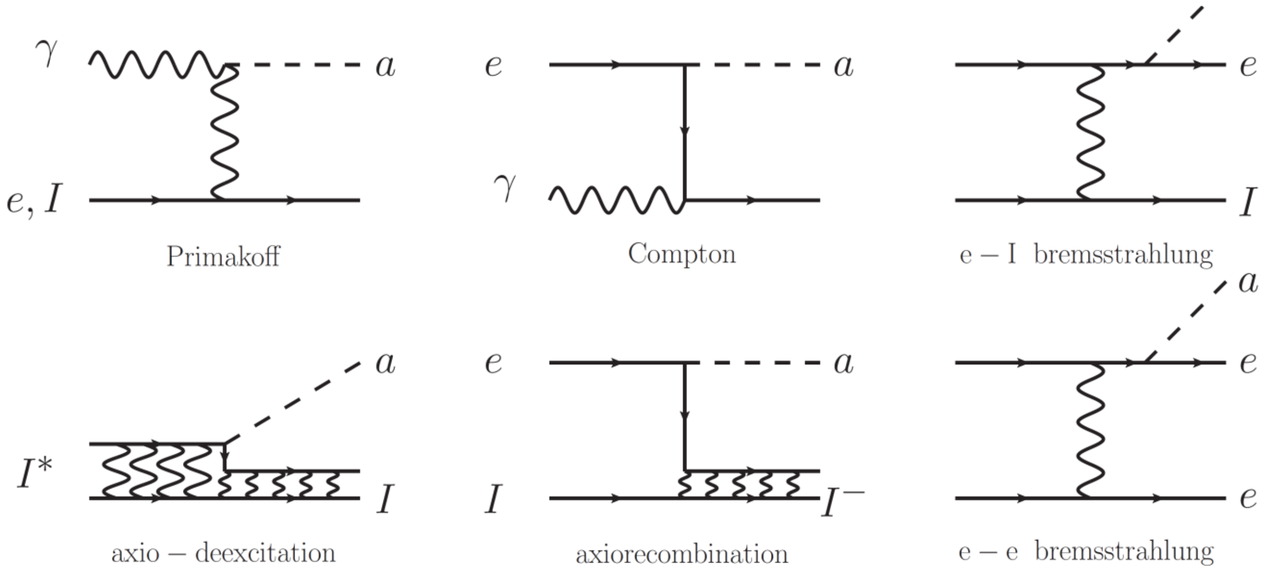
- One cannot strictly conclude on the existence of axions from such experiments.
  "Two Nobel prizes or none".

Astrophysics hints for WISPs?

sub-eV particles may affect processes in today‘s universe



Axions / ALPs might be produced in e.m. fields and might change the propagation of photons in the universe.



Axions / ALPs might be produced in stellar plasmas also via coupling to electrons.

“Solar axion flux from the axion-electron coupling”, J. Redondo JCAP12(2013)008

Astrophysics hints for ALPs: GeV photon propagation

Missing photons?

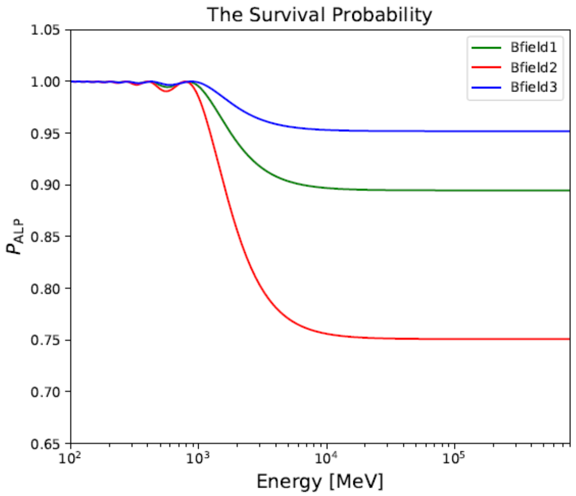
Photon spectra from SNRs might be changed due to photon-ALP conversion in magnetic fields (10.1103/PhysRevD.97.063003, Zi-Qing Xia et al.):

$$P_{\mathrm{ALP}} = 1 - P_{\gamma \to a}$$

$$= 1 - \frac{1}{1 + E_{\mathrm{c}}^2 / E_\gamma^2} \sin^2 \left[\frac{g_{a\gamma} B_{\mathrm{T}} l}{2} \sqrt{1 + \frac{E_{\mathrm{c}}^2}{E_\gamma^2}} \right]$$

where the characteristic energy E_{c} is defined as

$$E_{\mathrm{c}} = \frac{\left| m_a^2 - w_{\mathrm{pl}}^2 \right|}{2 g_{a\gamma} B_{\mathrm{T}}},$$



Spectral modulations might hint at the existence of ALPs!

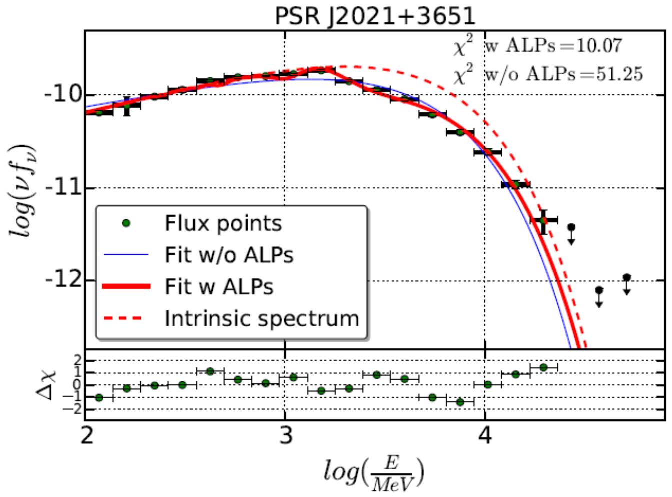
Astrophysics hints for ALPs: GeV photon propagation

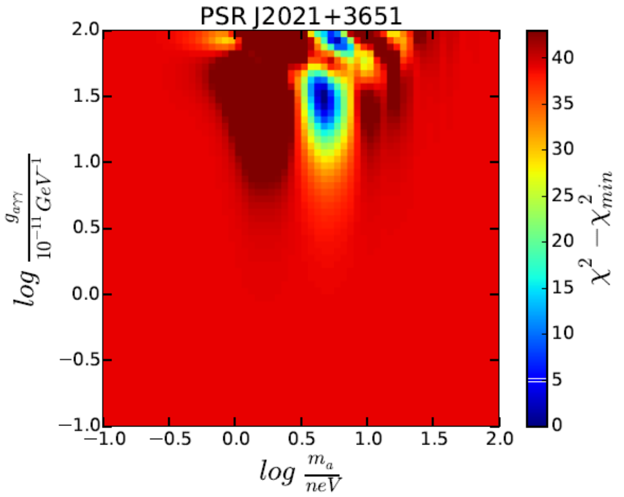
Missing photons from galactic pulsars?

Galactic pulsars (J. Majumdar *et al* JCAP04(2018)048):

Pulsars selected according to the magnetic field strength along the line of sight.

Method checked with close pulsar.





Pulsar name	N_0 [10^{-9}MeV^{-1} cm^{-2} s^{-1}]	Γ_1	E_{cut} [GeV]	$g_{a\gamma\gamma}$ [10^{-10} GeV^{-1}]	m_a [neV]
J1420-6048	0.0016(2)	1.74(4)	5.4(6)	1.7(3)	3.6(1)
J1648-4611	0.0028(2)	0.88(3)	3.4(2)	5.3(9)	4.3(1)
J1702-4128	0.13(3)	0.9(1)	1.0(2)	4.4(2)	8.1(5)
J1718-3825	0.024(2)	1.48(4)	2.1(1)	2.4(3)	8.9(2)
J2021+3651	0.18(1)	1.45(3)	3.5(1)	3.5(3)	4.4(1)
J2240+5832	0.005(1)	1.5(1)	2.4(6)	2.1(4)	3.7(3)

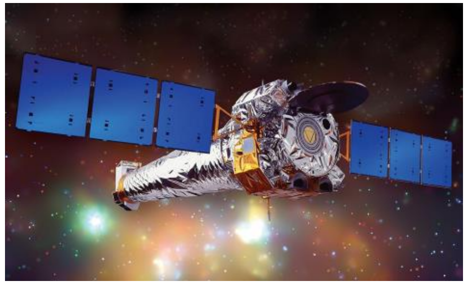
Data analyses prefer fits including axion-like particles.

ALPs propagation in the Universe

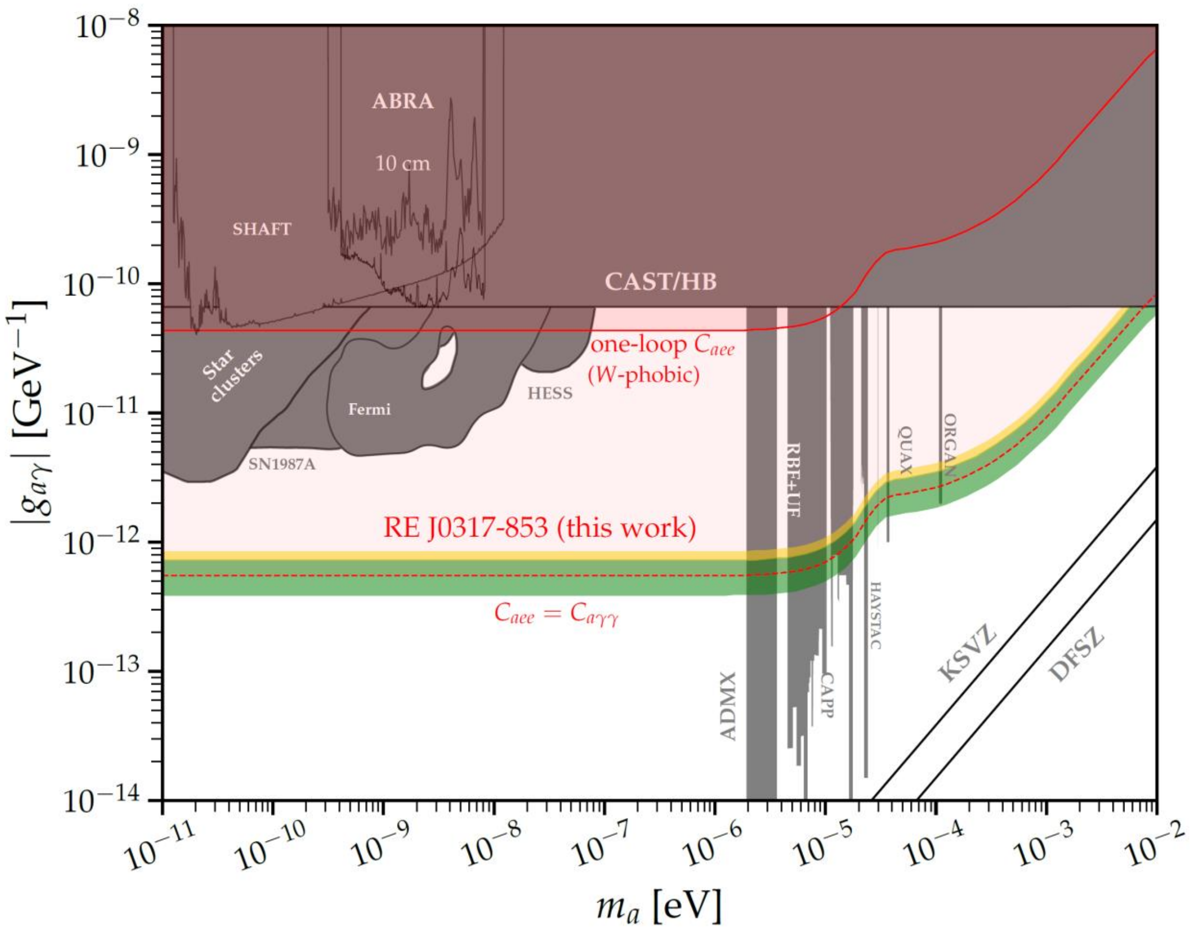
Axions from white dwarfs?

"No evidence for axions from Chandra observation of magnetic white dwarf", C. Dessert, A.J. Long, B.R. Safdi, arXiv:2104.12772 [hep-ph]

- Axions are produced in white dwarfs via their coupling to electrons.
- In the strong magnetic fields of the white dwarfs some axions are converted to X-ray photons.



Chandra:
no such photons from
RE J0317-853.



- Axions do not exist in this phase space?
- Axions do not couple to electrons?
- RE J0317-853 is "special"?
- …

Another axion presentation today

Friday 2 July, 16:00 CET

B.R. Safdi

White dwarfs and neutron stars as axion laboratories

The quantum chromodynamics axion and axion-like particles are some of the most sought-after beyond the Standard Model particles at present because of their possible connections with the strong-CP problem, dark matter, and ultraviolet physics such as Grand Unification and String Theory. Laboratory searches are underway around the world to search for these hypothetical particles, but certain regions of axion parameter space -- such as ultralight axions with weak couplings to matter – are notoriously difficult to probe with terrestrial experiments, despite their theoretical motivations. However, axions in this part of the parameter space may be produced in abundance within compact stars such as white dwarfs and neutron stars. It has long been recognized that axion production in compact stars opens up a new pathway for them to cool. I will point out, however, that axions may also lead to novel X-ray signatures around these stars, whereby the axions are produced within the stellar cores and then convert to photons in the strong magnetic fields surrounding the stars. I will discuss recent data taken by the XMM-Newton and Chandra telescopes from nearby neutron stars and white dwarfs that provide some of the strongest probes to-date of axions by searching for these processes.

https://desy.zoom.us/j/97654094397

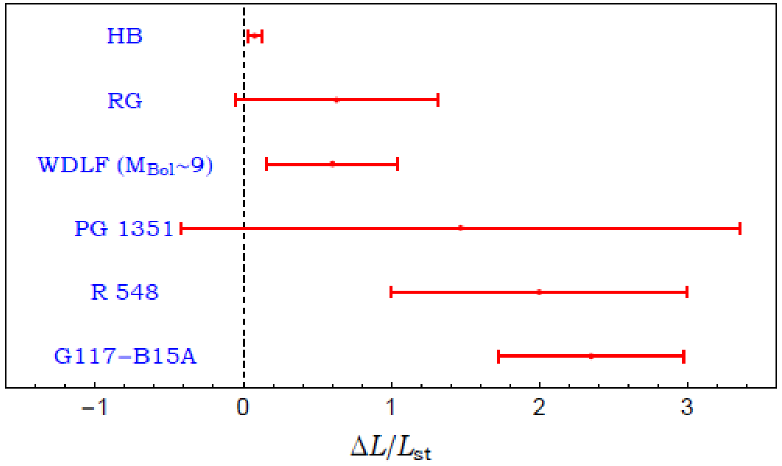
Meeting-ID: 976 5409 4397

Code: 685571

Astrophysics hints for ALPs: stellar evolutions

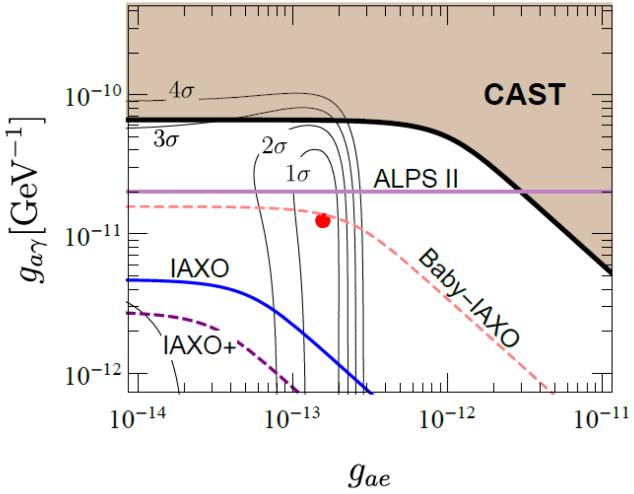
Preference for an additional neutrino-like radiation

- Extra energy loss beyond SM expectations is indicated by stellar developments.
- Such losses can be explained consistently by the emission of axions coupling to photons and electrons.
  Light ALPs would also work.



M. Giannotti, I. Irastorza,
J. Redondo, A. Ringwald,
http://arxiv.org/abs/1512.08108

M. Giannotti, I. Irastorza,
J. Redondo, A. Ringwald, K. Saikawa
https://arxiv.org/abs/1708.02111



P. Di Vecchia, M. Giannotti,
M. Lattanzi, A. Lindner
https://arxiv.org/abs/1708.02111

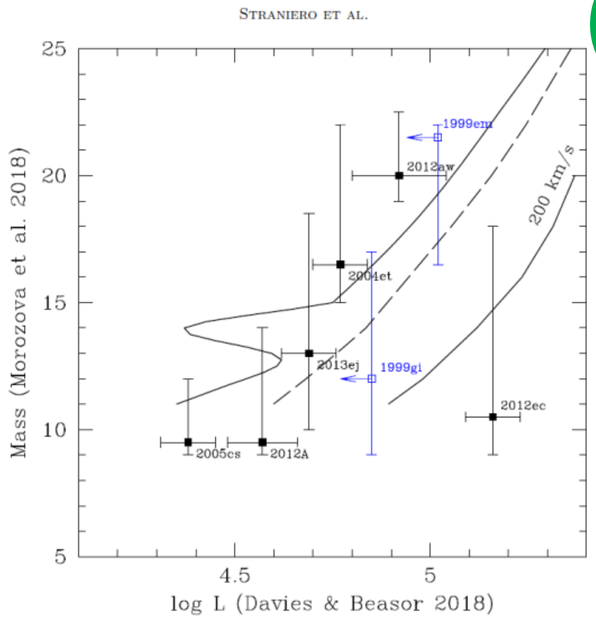
At least an interesting parameter region for experiments!

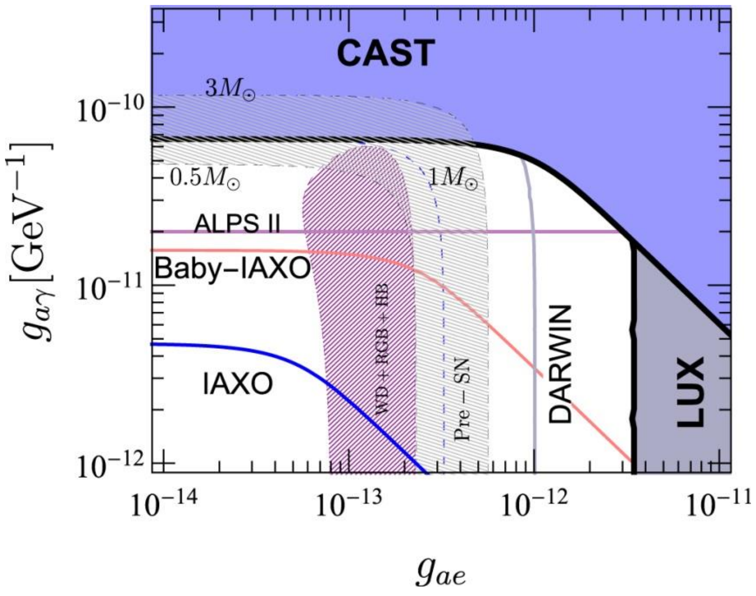
ALPs from stellar evolutions: example

Supernovae and their progenitors

Oscar Straniero *et al* 2019 *ApJ* **881** 158:

- Supernovae seem to be a bit too dim as inferred from their progenitors.
- Axion / ALP emission by the progenitors is the only known process to potentially resolve this hint fort a discrepancy: a more efficient cooling of the stellar core freezes the development of the envelope at lower luminosities.
- The required coupling strengths of about $g_{a\gamma} \approx 6{\cdot}10^{-11}\mathrm{GeV}^{-1}$ and $g_{ae} \approx 4{\cdot}10^{-13}$ are also derived from
  - stellar evolutions,
  - propagation of gamma rays in magnetic fields,
  - the transparency of the universe to TeV photons.





At least an interesting parameter region for experiments!

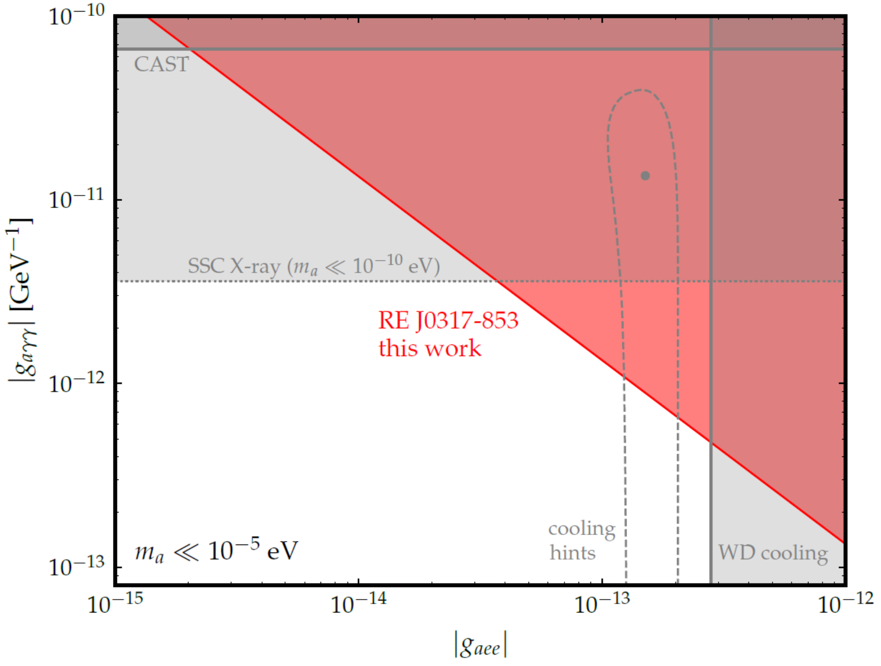
ALPs from stellar evolutions: example

Supernovae and their progenitors

Coming back to RE J0317-853.

"No evidence for axions from Chandra observation of magnetic white dwarf",
C. Dessert, A.J. Long, B.R. Safdi, arXiv:2104.12772 [hep-ph]

"Lastly, we note that our results are especially relevant for the upcoming ALPS II light-shining-through-walls experiment …"



Axion hints from the Universe

The need of dedicated experiments

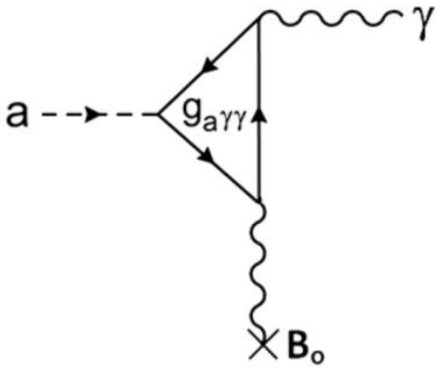
“Reconciling hints on axion-like-particles from high-energy gamma rays with stellar bounds“, G.A. Pallathadka et al, arXiv:2008.08100 [hep-ph].

Notably, it has been claimed that the spectral modulation observed in gamma rays from Galactic PSRs and supernova remnants can be due to conversions of photons into ultra-light ALPs in large scale Galactic magnetic fields. ***These hints appear to be in tension with the stellar bounds****. Here, we have shown how they can be reconciled with the known experimental and astrophysical bounds, assuming that the ALP-photon coupling has* ***an environmental dependence that suppresses it in the dense stellar plasma, leaving it unaffected in the low-density Galactic environment****. We have discussed the phenomenological implications of this scenario, and shown how the CAST bound and the constraints from helium burning stars and SN 1987A would be relaxed under this assumption, relieving the tension with the PSR claim. Furthermore,* ***this scenario is directly testable in the light-shining-through-the-wall experiment ALPS II****, which is expected to be operative in a year or so.*

ALP – photon coupling

Two axion photon mixings

Sikivie conversion



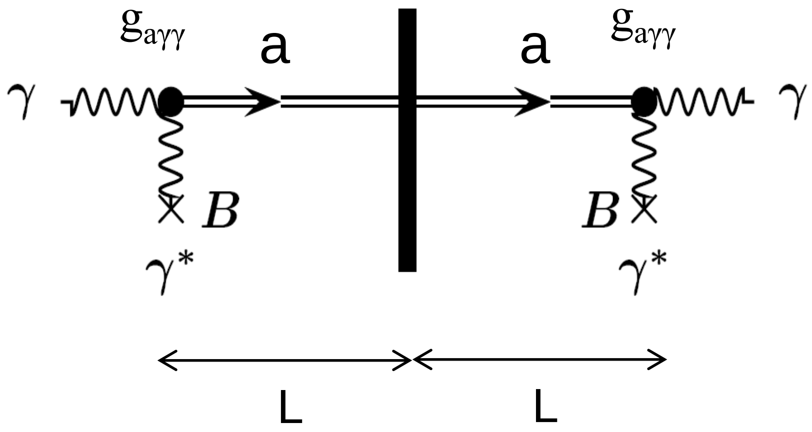
and light-shining-through-walls.

$P(\gamma \rightarrow a \rightarrow \gamma)$

$= 6 \cdot 10^{-38} \cdot (g_{a\gamma\gamma}[10^{-10}\mathrm{GeV}^{-1}] \cdot B[1T] \cdot L[10m])^4$

$= 9 \cdot 10^{-34}$ (ALPS II at DESY)

$g_{a\gamma\gamma} = 0.2 \cdot 0^{-10}\mathrm{GeV}^{-1}$, B =5.3 T, L = 106 m



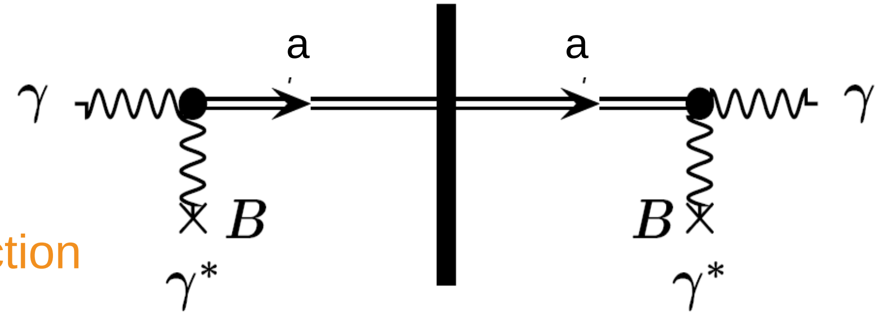
How to look: three kinds of light-shining-through-walls

Axion/ALP photon mixing in magnetic fields

Target sensitivity

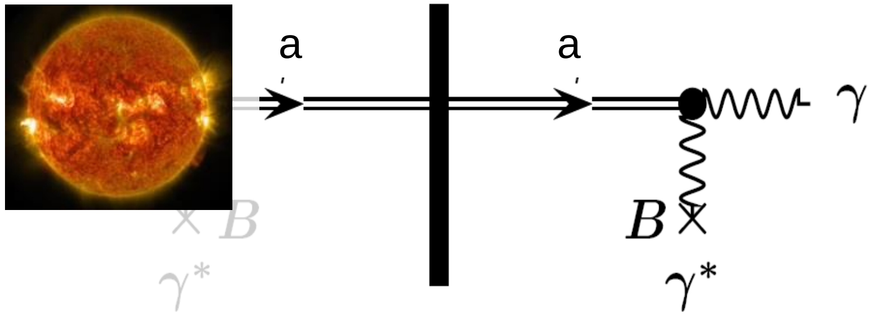
- Purely laboratory experiments
  "light-shining-through-walls",
  microwaves, optical photons

1 photon/day
exploit resonant detection



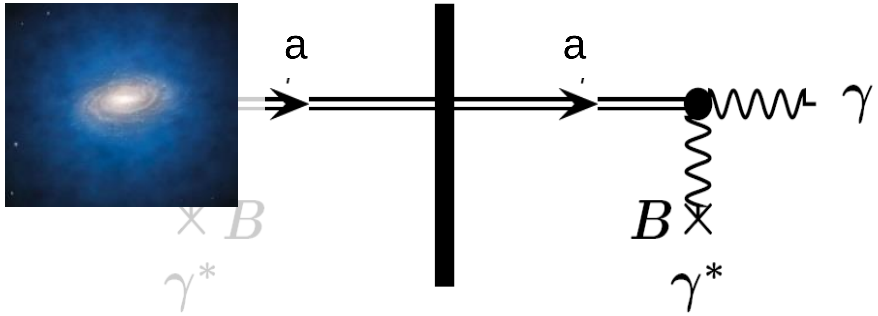
- Helioscopes
  ALPs emitted by the sun,
  X-rays

1 photon/year



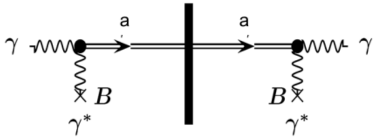
- Haloscopes
  looking for dark matter constituents,
  microwaves.

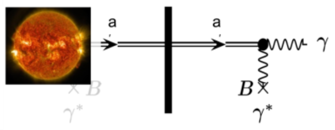
10^{-23} W
exploit resonant
detection

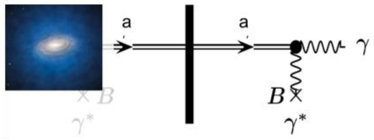


How to look: three kinds of light-shining-through-walls

Pros and cons





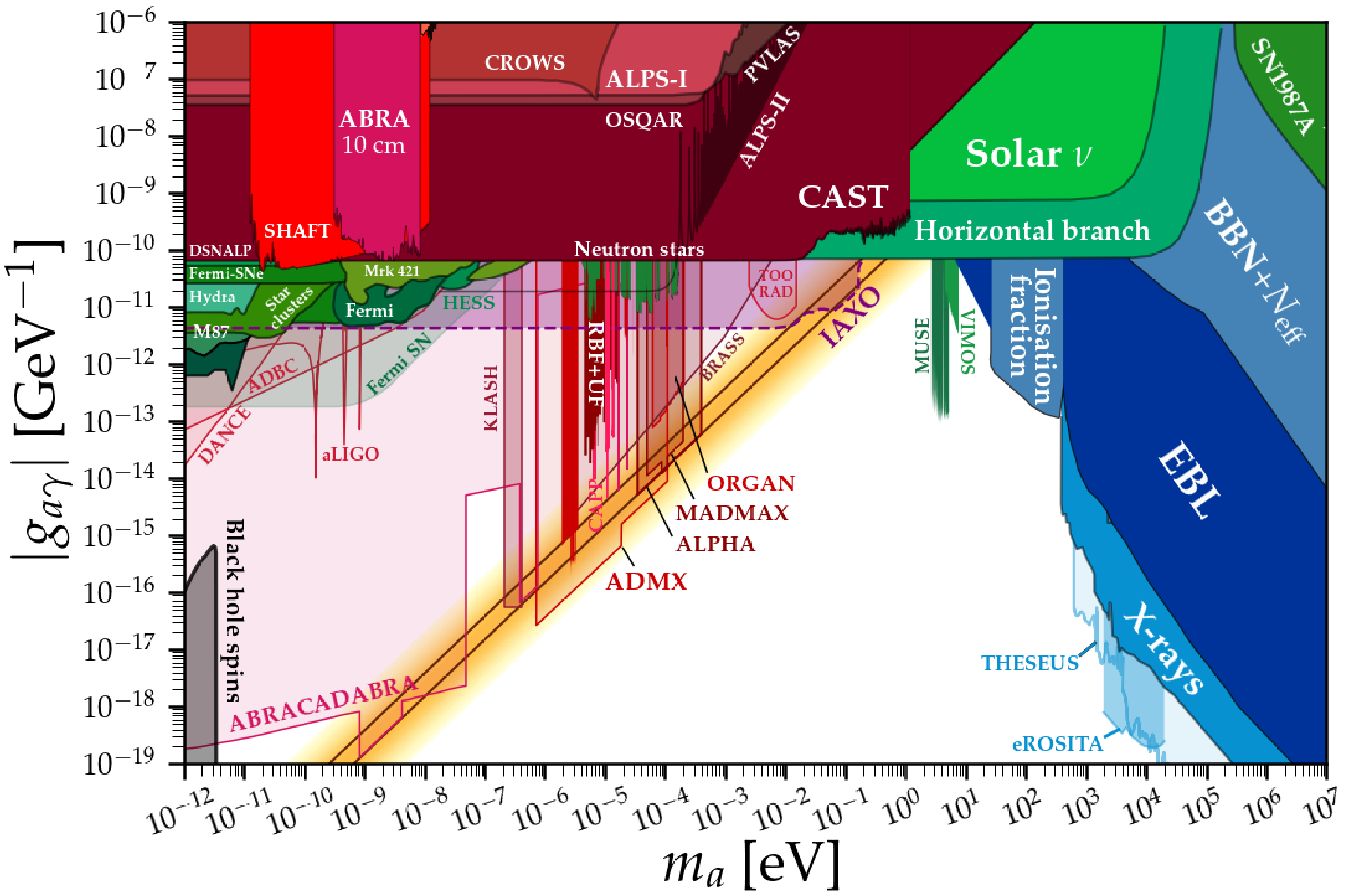


ALP parameter	LSW (laboratory)	Helioscopes	Haloscopes
Source region	Lab (vacuum)	Dense plasma	Cosmology
Rely on astrophysical assumptions	no	yes	yes
Parity and spin	yes	perhaps	yes
Coupling $g_{a\gamma\gamma}$	yes	no	no
Coupling · flux	(does not apply)	yes	yes
Mass	perhaps	perhaps	yes
Electron coupling	no	yes	no
QCD axion	no (?)	yes	yes

The three approaches complement each other:
combination of results may enable to distinguish between models!

The axion landscape

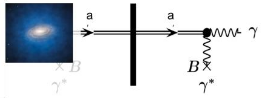
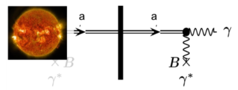
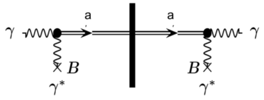
Tomorrow



Ciaran O‘Hare,

https://cajohare.github.io/AxionLimits/

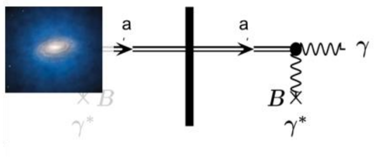
Potential to probe large part of the phase space within the next decade. Some focus on experiments at DESY:

- MADMAX 
- IAXO 
- ALPS II 

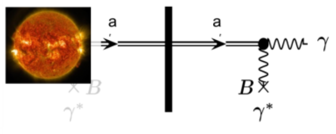
Search strategies

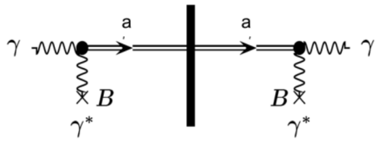
For axions and other WISPs

1. Look for axions as the constituents of the local dark matter.



2. Look for axions independent of the dark matter paradigm.





3. Look for an axion-mediated 5th force (not covered here).

Outline

- Brief motivation for axions and the likes
- The axion landscape and astrophysics hints
- Direct dark matter searches with MADMAX
- The IAXO helioscope
- Light-shining-through-walls with ALPS II
- Summary

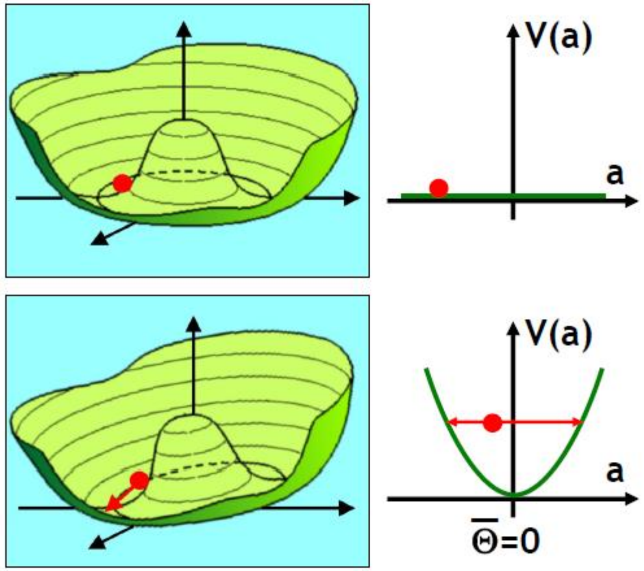
Axion cosmology in brief

Two different cosmological scenarios

PQ symmetry breaking before inflation:

Our universe is covered by one “patch” of PQ symmetry breaking with random initial conditions:

Initial misalignment angle θ_i.



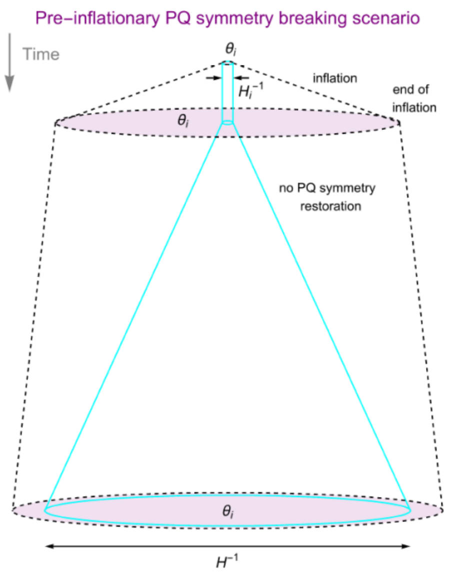
S. Hannestad, presentation at
5th Patras Workshop 2009

Axion cosmology in brief

Two different cosmological scenarios

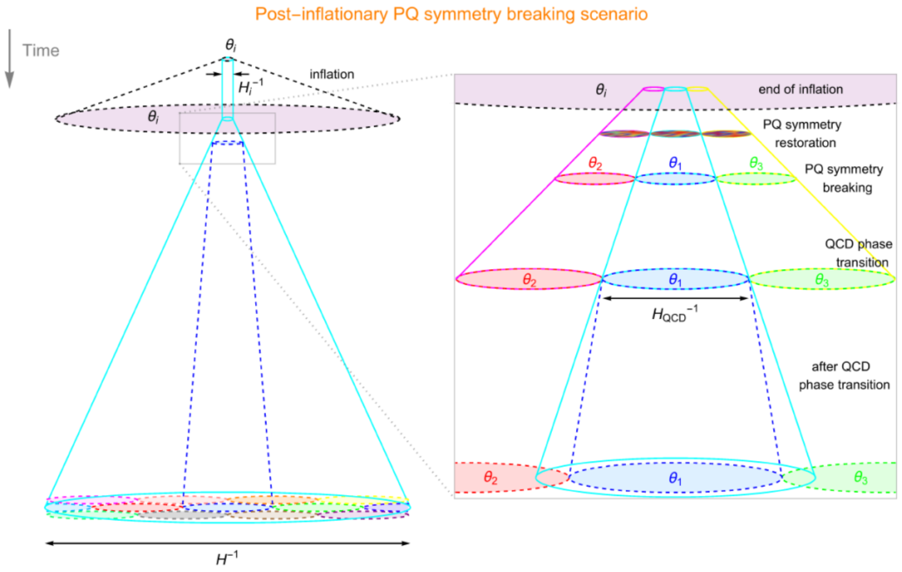
PQ symmetry breaking before inflation:

Our universe is covered by one “patch” of PQ symmetry breaking with random initial conditions.



PQ symmetry breaking after inflation:

Axions in our universe are given by averaging over many PQ symmetry breaking “patches” with random initial conditions.



Physics potential of the International Axion Observatory (IAXO), JCAP 1906 (2019) 047

Axion cosmology in brief

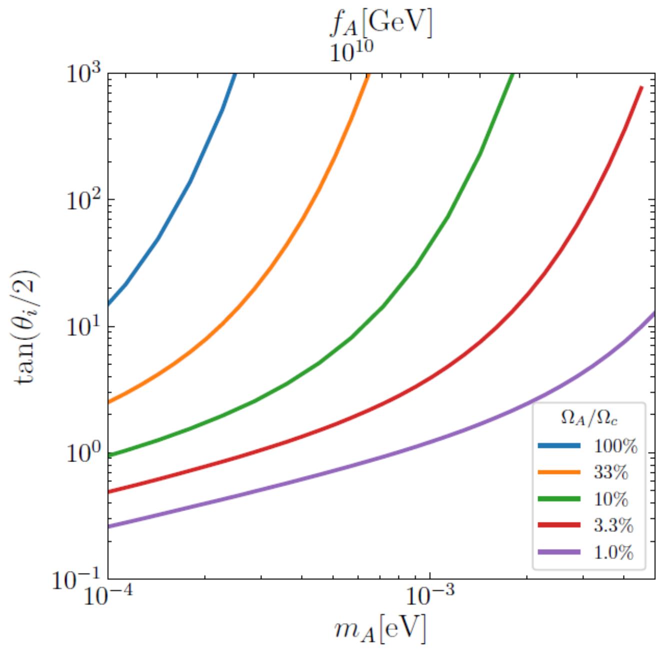
Two different cosmological scenarios

PQ symmetry breaking before inflation:

Our universe is covered by one “patch” of PQ symmetry breaking with random initial conditions:

Initial misalignment angle θ_i.

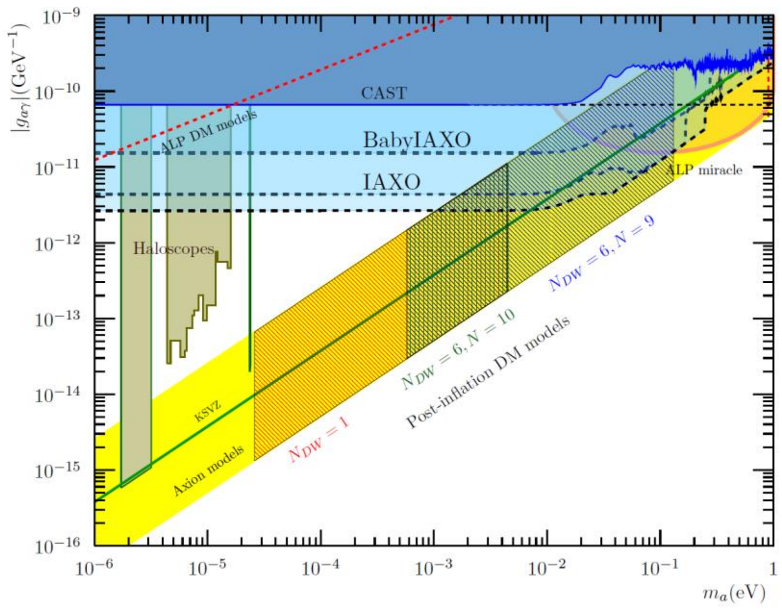
$$\Omega_{A,\mathrm{real}}h^2 \approx 0.35\left(\frac{\theta_i}{0.001}\right)^2 \times \begin{cases} \left(\frac{f_A}{3\times10^{17}\,\mathrm{GeV}}\right)^{1.17} & \text{for} \quad f_A \lesssim 3\times10^{17}\,\mathrm{GeV}, \\ \left(\frac{f_A}{3\times10^{17}\,\mathrm{GeV}}\right)^{1.54} & \text{for} \quad f_A \gtrsim 3\times10^{17}\,\mathrm{GeV}. \end{cases}$$



PQ symmetry breaking after inflation:

$$\Omega_{A,\mathrm{real}}h^2 \approx (3.8\pm0.6)\times10^{-3}\times\left(\frac{f_A}{10^{10}\,\mathrm{GeV}}\right)^{1.165}$$

plus contributions from string and domain wall decays.



Physics potential of the International Axion Observatory (IAXO), JCAP 1906 (2019) 047

Axion cosmology in brief

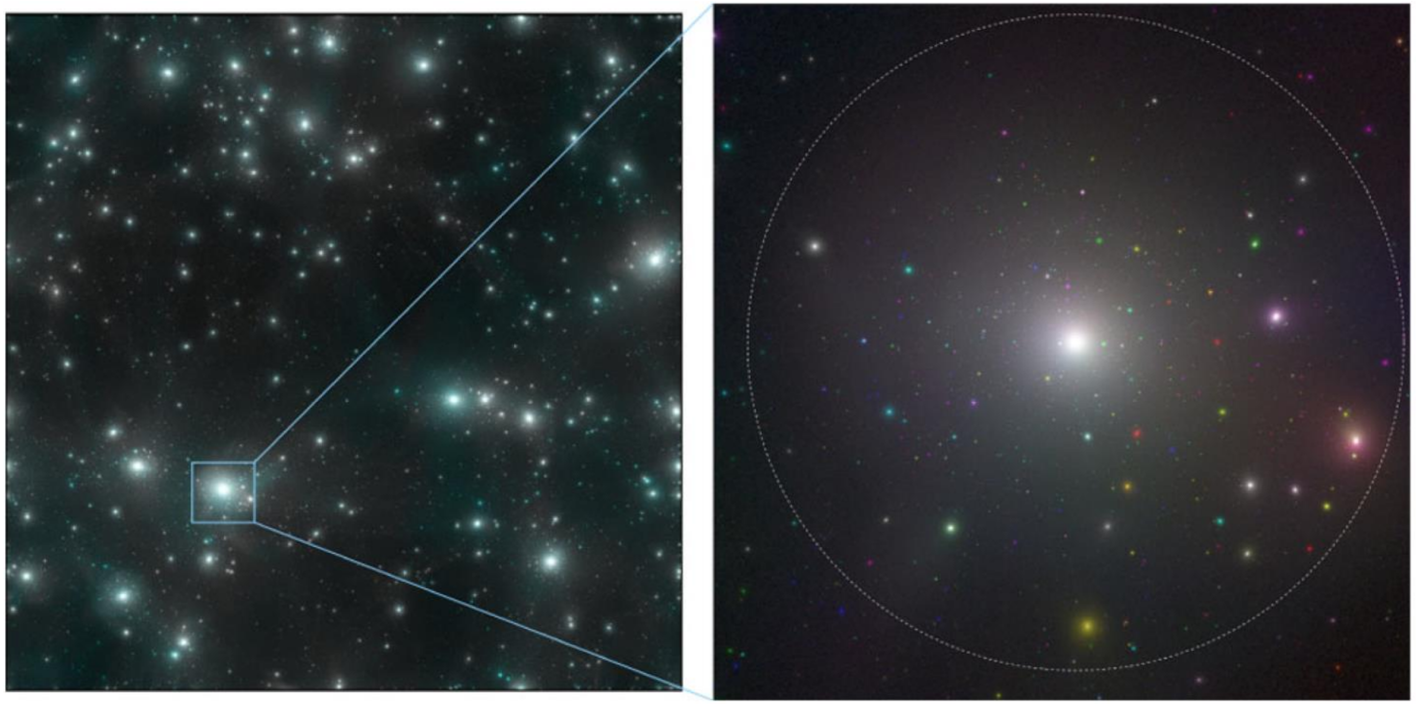
More unknowns

Axion dark matter might collapse gravitationally into clusters

- $\approx 10^{-12}$ solar masses,
- $\approx 10^{12}$ cm radius.

This depends on cosmological assumptions before BBN.

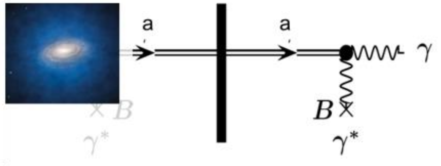
The probability of tidal disruption when encountering stars is still to be determined.



“First Simulations of Axion Minicluster Halos”, B. Eggemeier et al., Phys. Rev. Lett. 125, 041301

Axion dark matter might be clumped
and not evenly distributed like assumed when interpreting experimental data.

Strategy 1: Axion dark matter searches



Many experiments world-wide

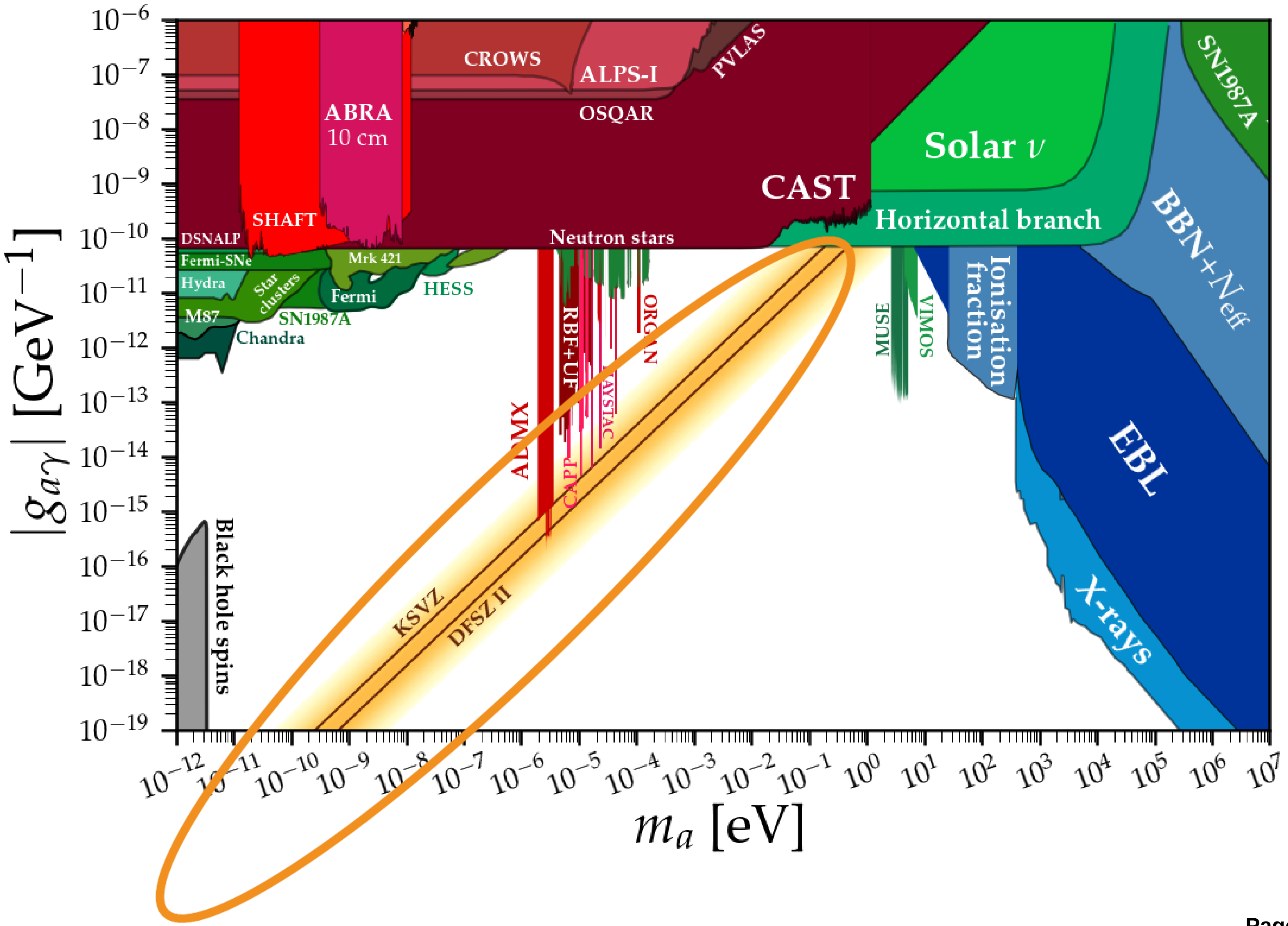
Large mass range for different cosmological scenarios.

- DM = non-relativistic particles: photon energy from axion conversion given by m_a, need to tune resonant experiments to m_a.

Experiments have to span a huge mass range!

Particle physics uncertainties:

- Axion-photon coupling might be much larger than in benchmark models.
- Mass-coupling relation differs in more complex axion models.



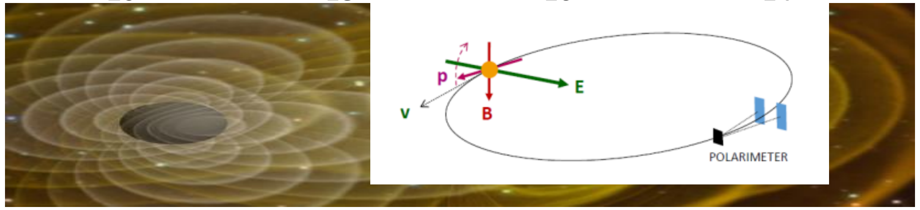
Strategy 1: Axion dark matter searches in brief

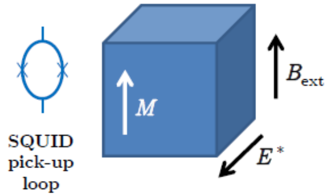
Experiments at DESY in Hamburg

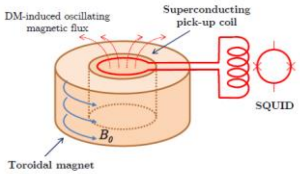
DESY in Hamburg

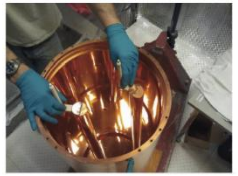
$\log_{10}(m/eV)$

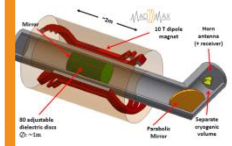
-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0

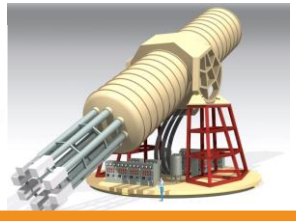












Bosonic clouds (at BH),.oEDM searches

NMR

Toroidal magnets

Microwave cavities: ADMX

Dielectric booster: MADMAX

IAXO (solar axions)

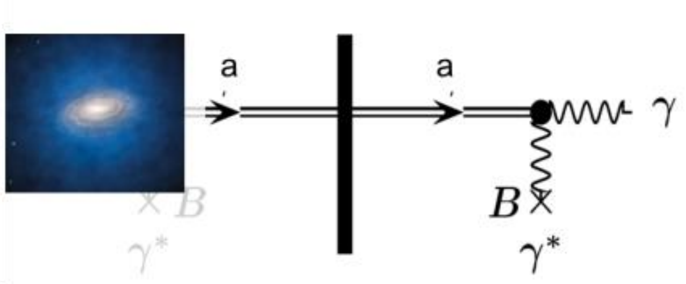
Rely on axions making up the local dark matter

Many ideas, lot’s of R&D ongoing.

ADMX is the only experiment taking data at benchmark axion sensitivities.

Dark matter axion searches

Necessity of resonant amplification



The axion dark matter number density is very large:

- $n_a = (\rho_a/m_a) = 3 \cdot 10^{13}/\text{cm}^3$ for 10 μeV axions.

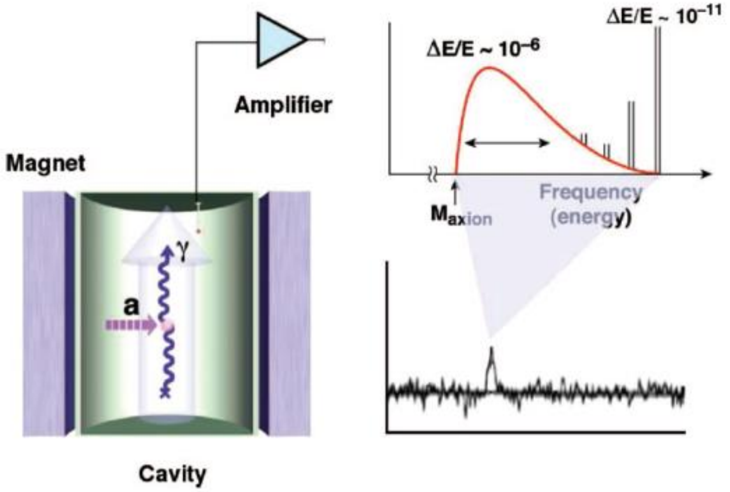
However, the power emitted by axion-photon conversion is very low:

- "Benchmark models": $P/V \approx 10^{-26}$ W/100l for B = 10T and 10 μeV axions.

This is impossible to measure!

Idea: exploit a resonant amplification of the axion-photon conversion.

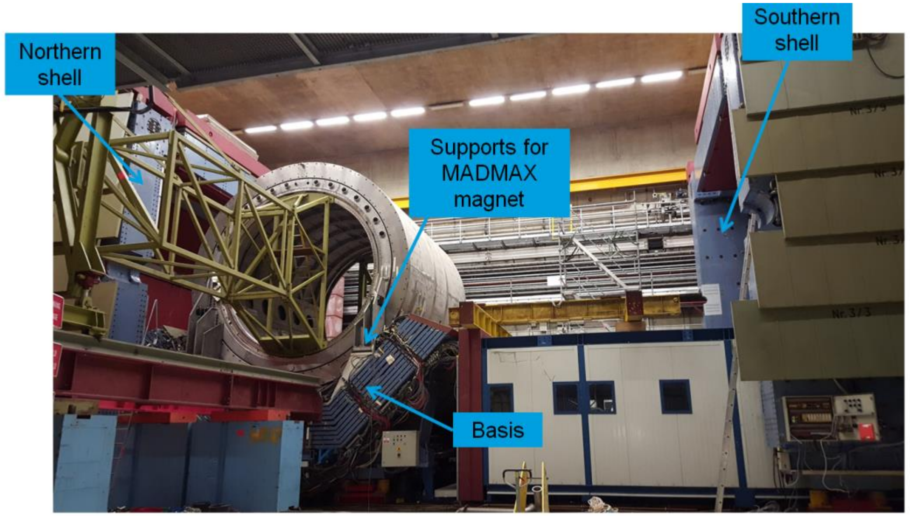
- The photon energy is given by the axion mass: $E_\gamma = m_a \cdot c^2$
- Example ADMX: tune a microwave cavity to this photon energy.
- The power P is boosted by Q_{cavity} ("easily" 10^5).
- Disadvantage:
  the resonating structure is to be tuned to all possible axion masses.

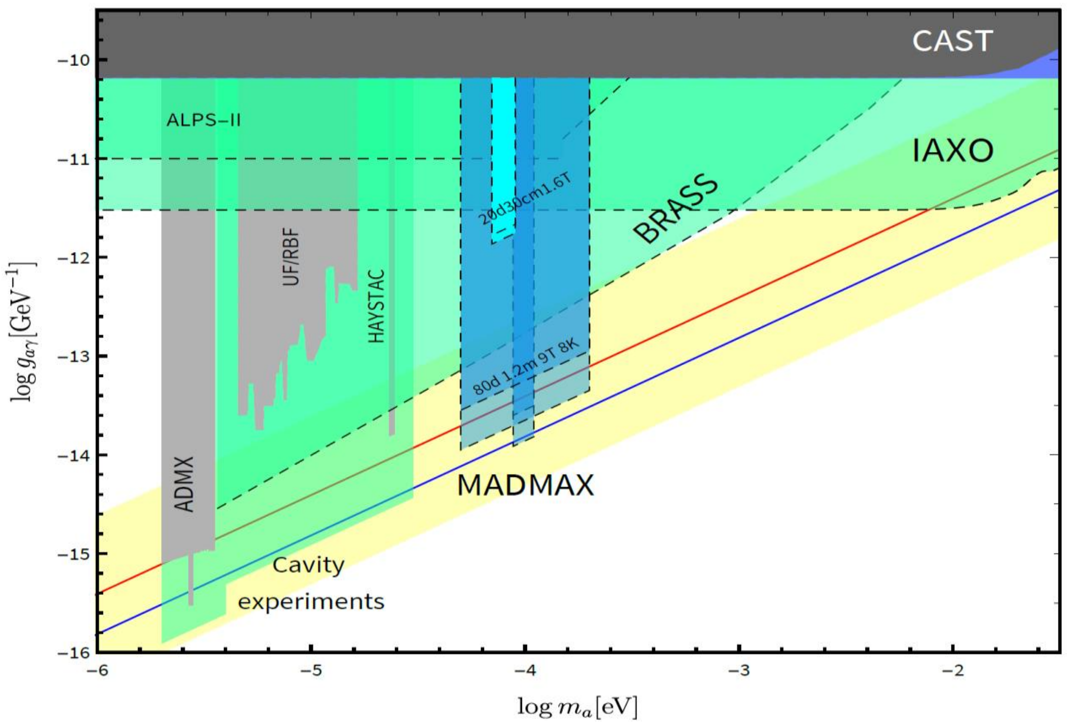


P. Sikivie, Experimental Tests ofthe "Invisible" Axion, Phys. Rev. Lett. 51, 1415 (1983):

MAgnetized Disc and Mirror Axion eXperiment MADMAX

Who, what, where





MADMAX targets dark matter axions 40 to 400 µeV predicted by

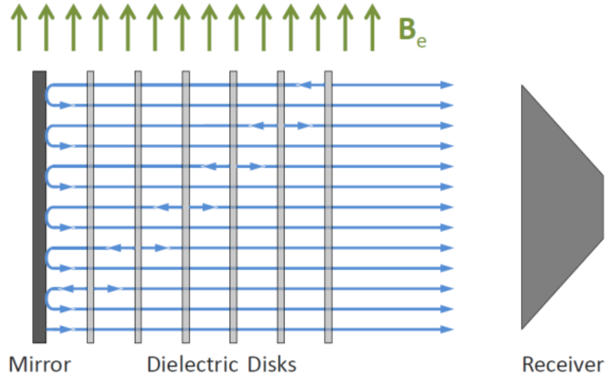
- post-inflation scenarios (PQ symmetry breaking after inflation),
- high mass region of pre-inflation scenarios.

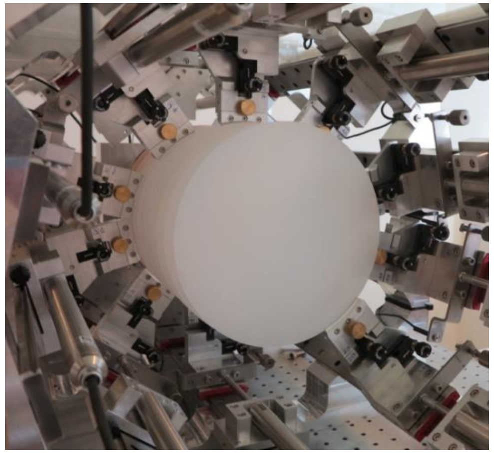
MADMAX technology

Dielectric booster …

The axion field generates a (tiny) electromagnetic field at dielectric discontinuities embedded in a magnetic field.

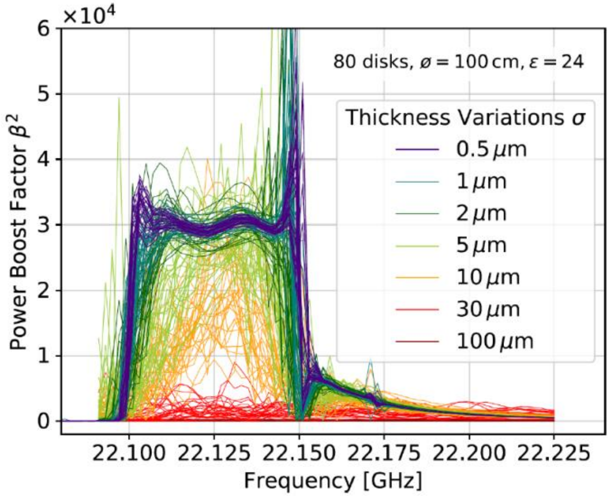
- Coherent generation of electromagnetic radiation at all surfaces as L(MADMAX) < λ (axion).
- Constructive interference results in a power boost factor β^2.
- The booster can be tuned to frequency and bandwidth by changing the disc positions.





Required figures of merit:

- 80 sapphire or $LaAlO_3$ discs of 1.2m² each.
- 10 T magnetic field of about 1.3 m length.

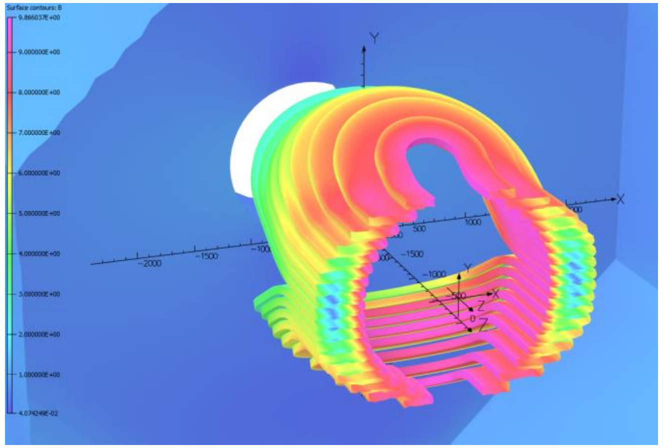


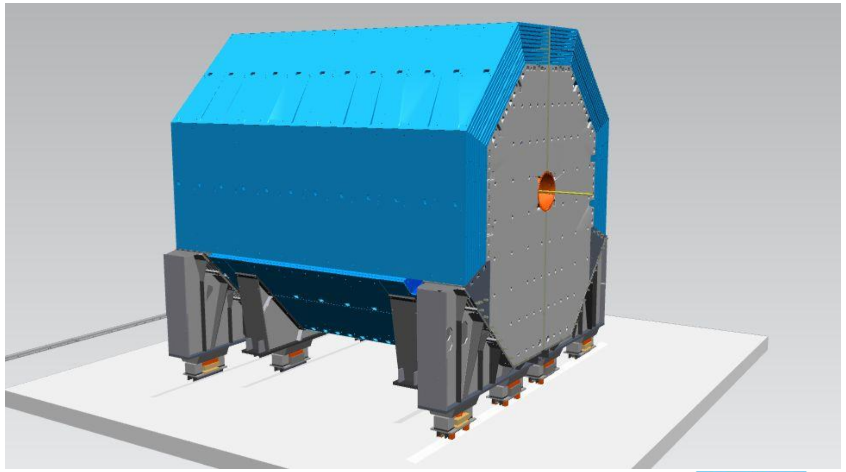
MADMAX technology

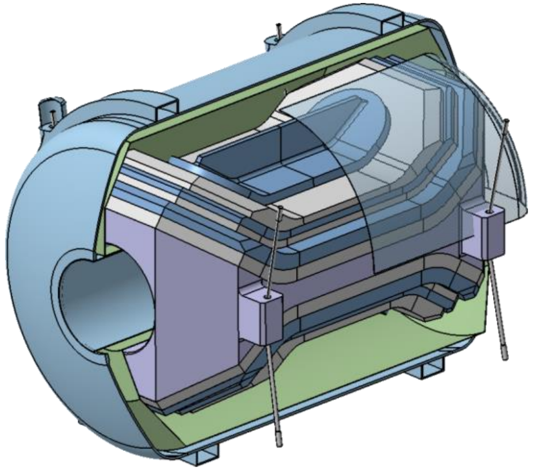
Dielectric booster in a strong magnetic field

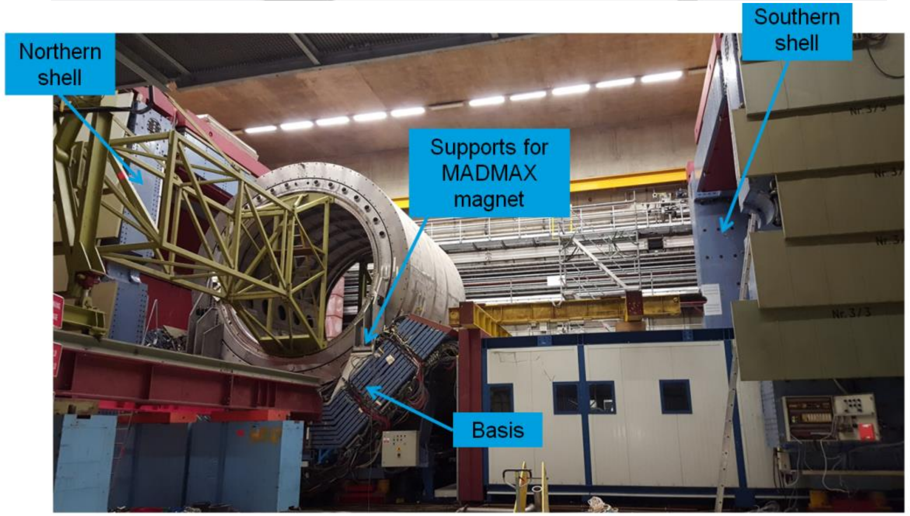
A huge dipole magnet is required to be placed in the iron yoke of the former H1 experiment in the HERA North hall.

Parameter	Results
J_E	50 A/mm²
By (0,0,0)	-8.82 T
Bpeak (x,y,0)	9.85 T
Bpeak	**9.87 T**
Overfield (B_{peak}/B_0)	11.8 %
FoM	**94.4 T²m²**
H+ / H- (Z = 0.0 m)	-0.9 % / 5.0 %
Energy	**482 MJ**
Volume	**4.435 m³**
Length	**5.0 m**







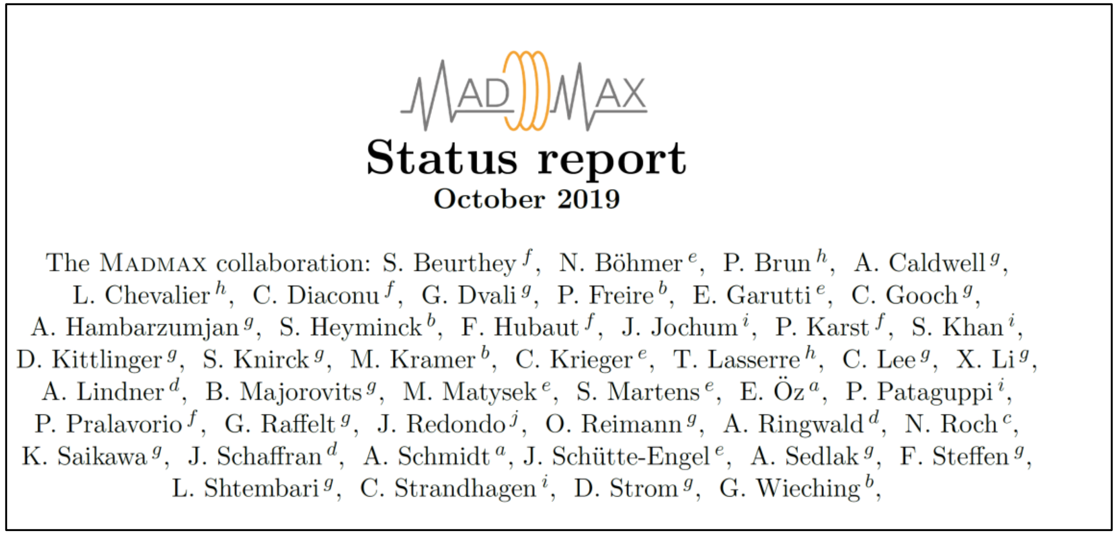


MADMAX

Summary

Status:

- R&D phase successfully concluded.
- Phase 2 (prototype, magnet) just started.
- Prototype runs at CERN (MORPURGO) approved.



MADMAX

Status report

October 2019

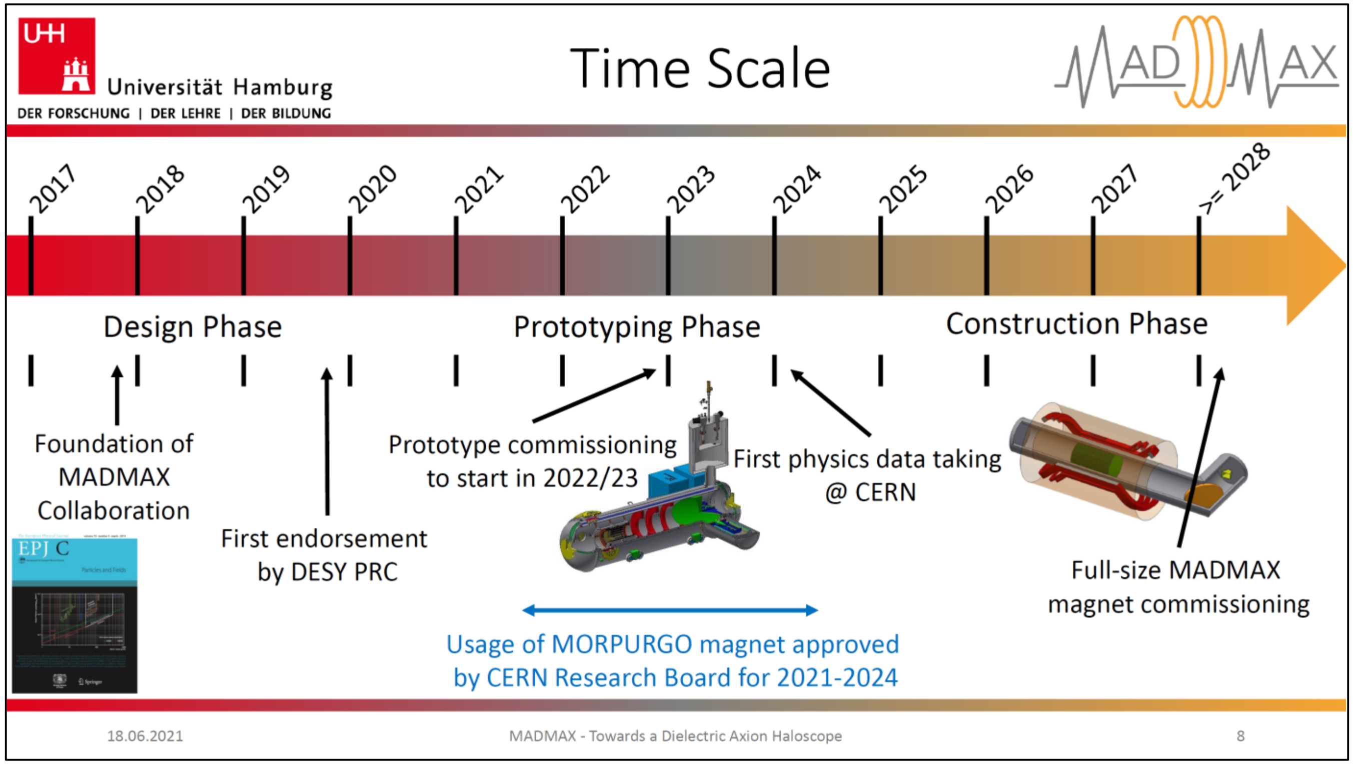
The MADMAX collaboration: S. Beurthey[f], N. Böhmer[e], P. Brun[h], A. Caldwell[g], L. Chevalier[h], C. Diaconu[f], G. Dvali[g], P. Freire[b], E. Garutti[e], C. Gooch[g], A. Hambarzumjan[g], S. Heyminck[b], F. Hubaut[f], J. Jochum[i], P. Karst[f], S. Khan[i], D. Kittlinger[g], S. Knirck[g], M. Kramer[b], C. Krieger[e], T. Lasserre[h], C. Lee[g], X. Li[g], A. Lindner[d], B. Majorovits[g], M. Matysek[e], S. Martens[e], E. Öz[a], P. Pataguppi[i], P. Pralavorio[f], G. Raffelt[g], J. Redondo[j], O. Reimann[g], A. Ringwald[d], N. Roch[c], K. Saikawa[g], J. Schaffran[d], A. Schmidt[a], J. Schütte-Engel[e], A. Sedlak[g], F. Steffen[g], L. Shtembari[g], C. Strandhagen[i], D. Strom[g], G. Wieching[b],

arXiv:2003.10894 [physics.ins-det]

Site:

- Cryoplatform in the DESY HERA North hall (next to ALPS II).

Data taking could start in 2028.



C- Krieger, PATRAS 2021

Outline

- Brief motivation for axions and the likes
- The axion landscape and astrophysics hints
- Direct dark matter searches with MADMAX
- The IAXO helioscope
- Light-shining-through-walls with ALPS II
- Summary

Strategy 2: ALP / axion searches independent of dark matter

Motivated by astrophysics and theory

Probe astrophysics anomalies and close axion mass window ≈ 1eV.

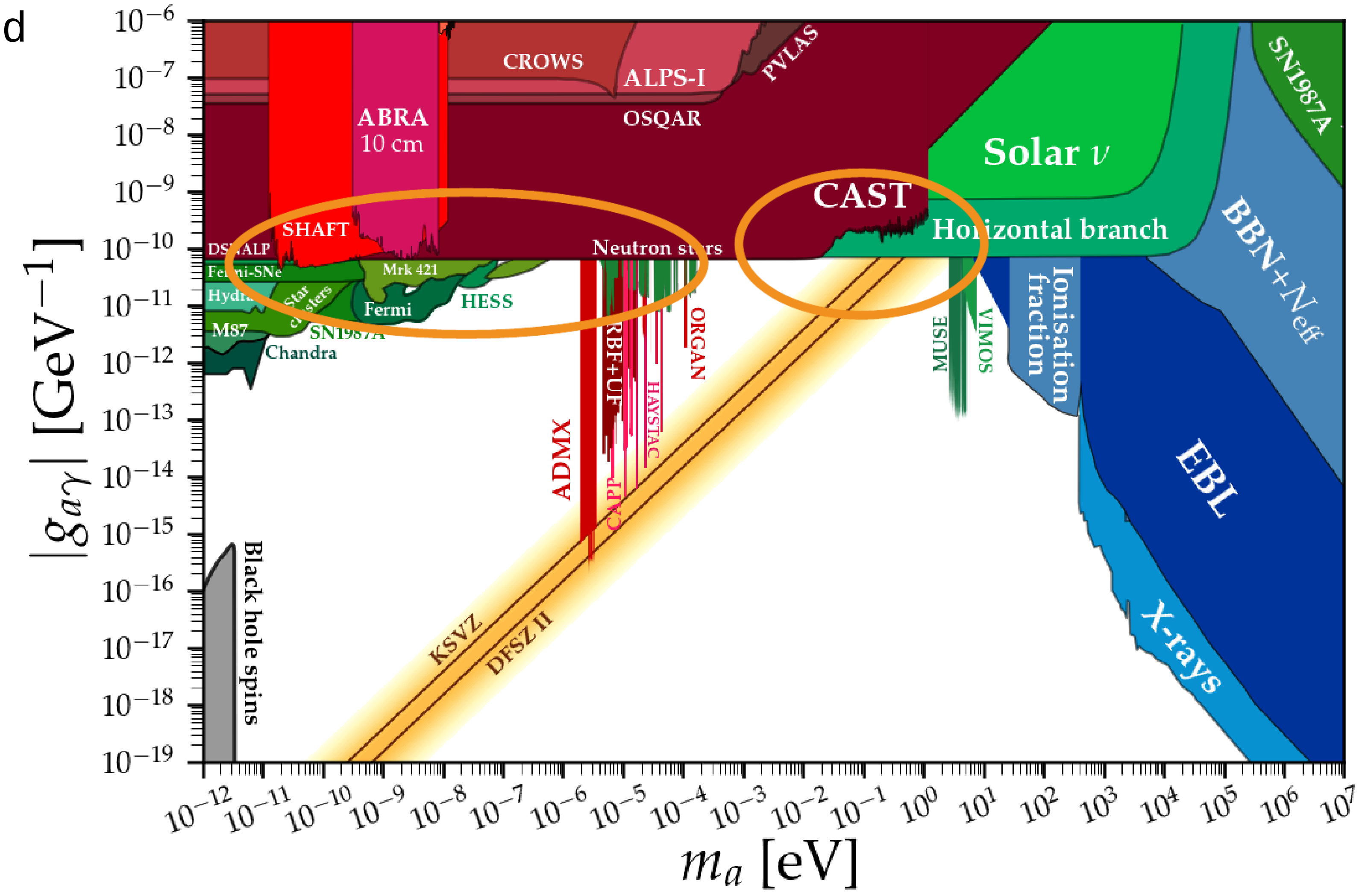
Generate axions / ALPs in the laboratory or rely on solar emission:

- results independent of cosmological assumptions,
- but less sensitive than dark matter searches.

Approach:
Relativistic ALP / axions:

- E_γ is given by E_a, m_a not relevant.
- Sensitive to broad mass range!

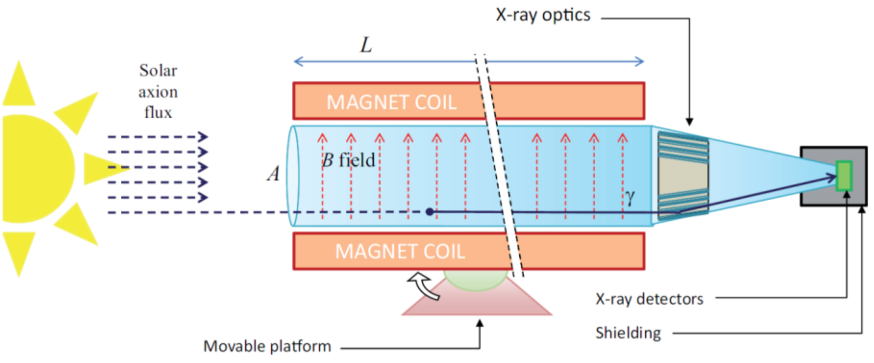
Find dark matter candidates!



International Axion Observatory

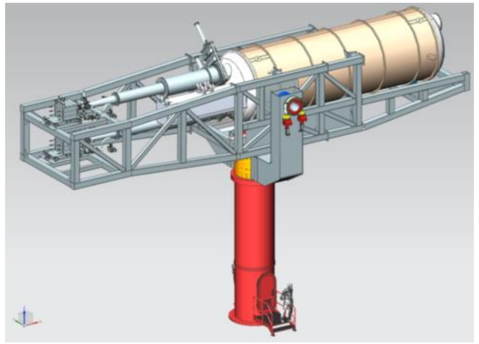
Solar axions up to 1eV mass

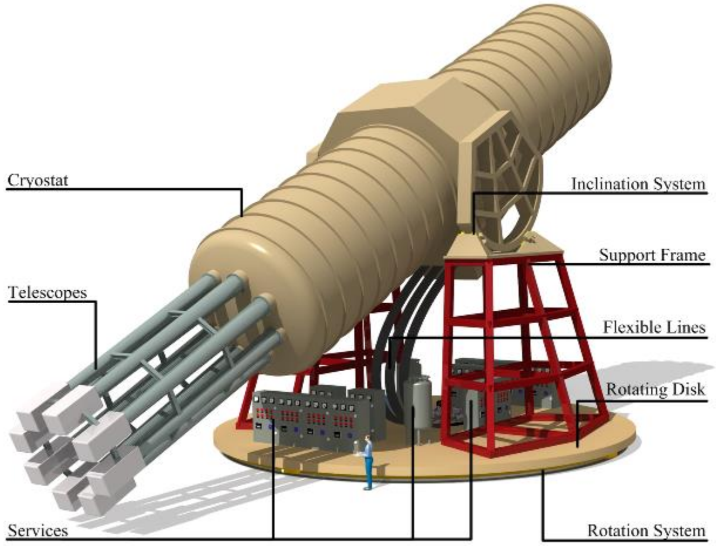
Technology:
20 m long toroidal magnet with eight 60 cm bores tracking the sun, X-ray optics to focus signal onto very low background detectors.



Status and schedule:
- R&D finished.
- BabyIAXO (nearly) approved and could be ready for a 1st physics run in 2024 / 2025.
- IAXO could be ready in 2028.

Site:
BabyIAXO: HERA South hall.
IAXO: options on DESY campus earmarked.

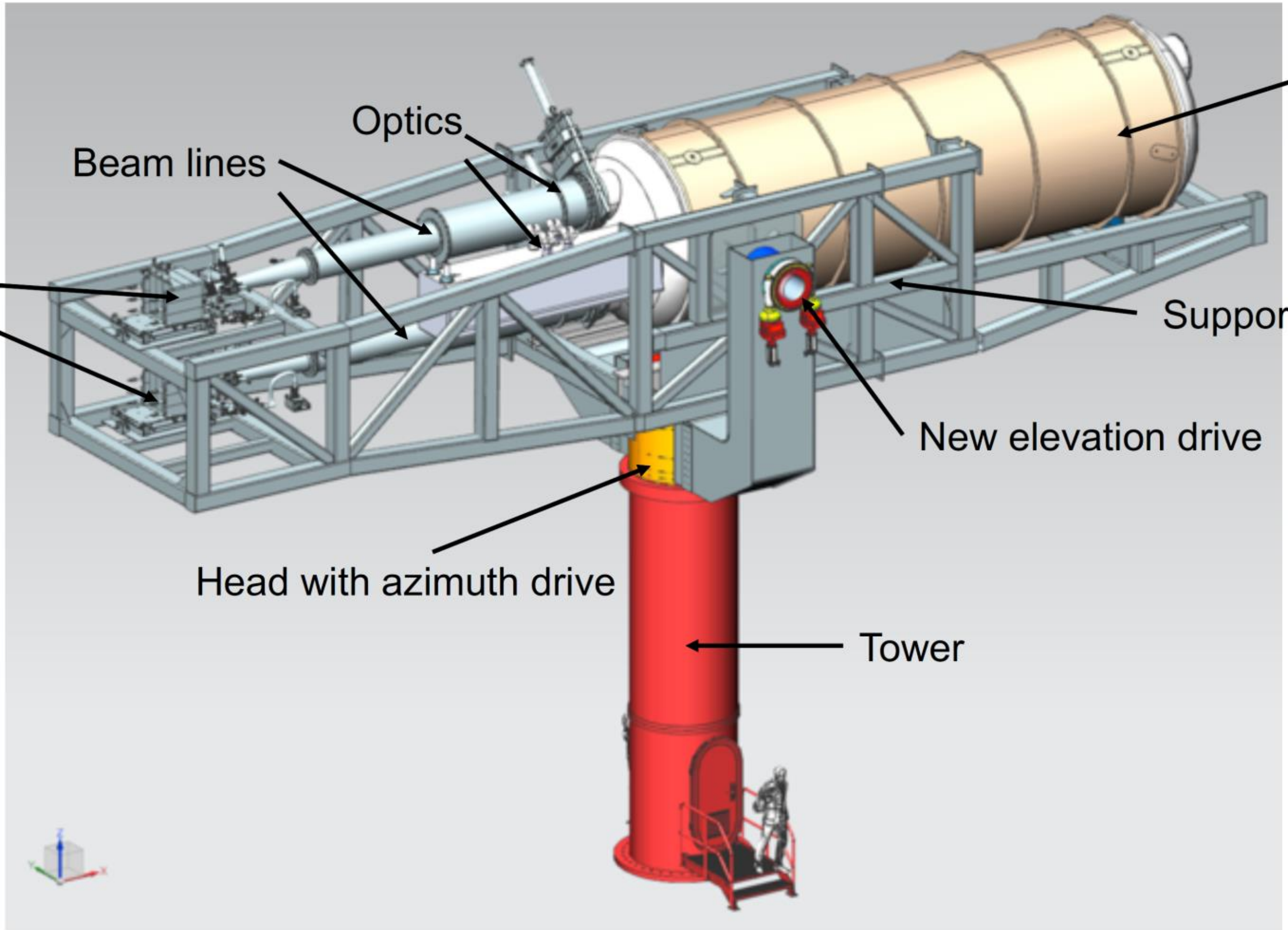




BabyIAXO

Components

- Magnet:
  provided by CERN.
- Optics:
  Technology derived from X-ray satellites; one telescope from ESA (XMM Newton).
- Detectors:
  micromegas, kryogenic detctors or CCDs.
- Tower and drive:
  see next pages.



International Axion Observatory

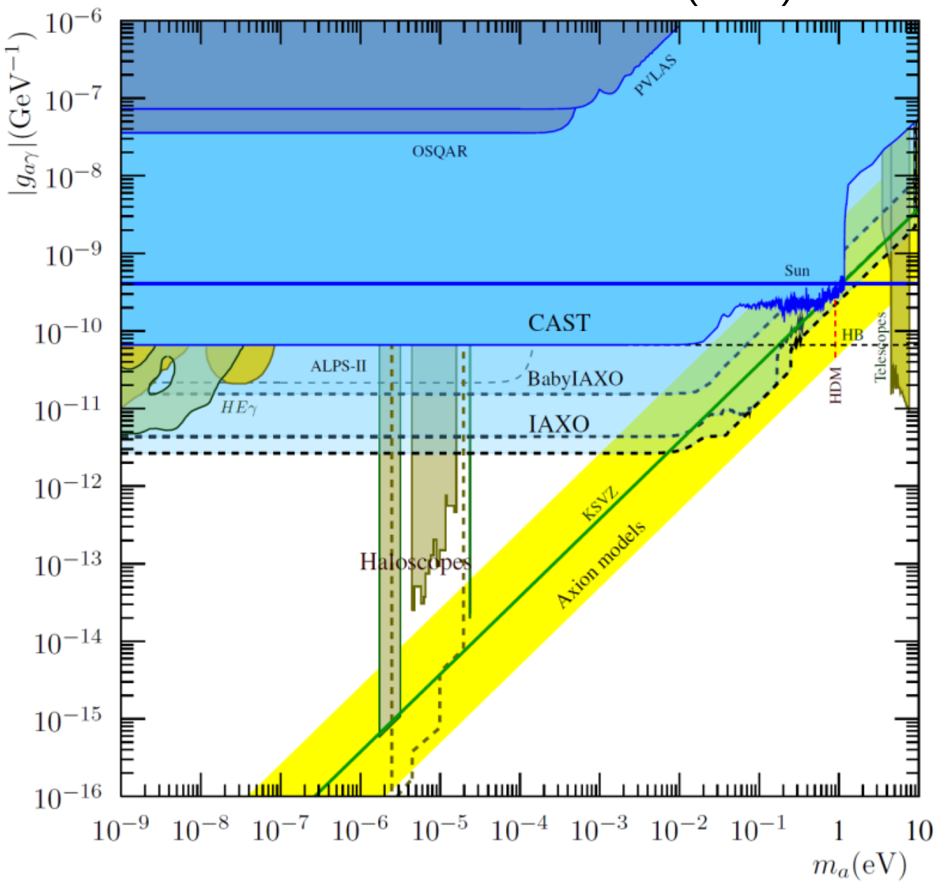
Figures of merit

Parameter	Units	BabyIAXO	IAXO baseline	IAXO upgraded
B	T	~ 2	~ 2.5	~ 3.5
L	m	10	20	22
A	m^2	0.77	2.3	3.9
f_M	$T^2 m^4$	~ 230	~ 6000	~ 24000
b	$keV^{-1}\,cm^{-2}\,s^{-1}$	1×10^{-7}	10^{-8}	10^{-9}
ϵ_d		0.7	0.8	0.8
ϵ_o		0.35	0.7	0.7
a	cm^2	2×0.3	8×0.15	8×0.15
ϵ_t		0.5	0.5	0.5
t	year	1.5	3	5

CAST: 11 T^2m^4

E. Armengaud *et al* JCAP06(2019)047

JCAP (2019) 06 047



Signal / noise:

- BabyIAXO / CAST ≈ 100
- IAXO / BabyIAXO ≈ 100 to 1000.

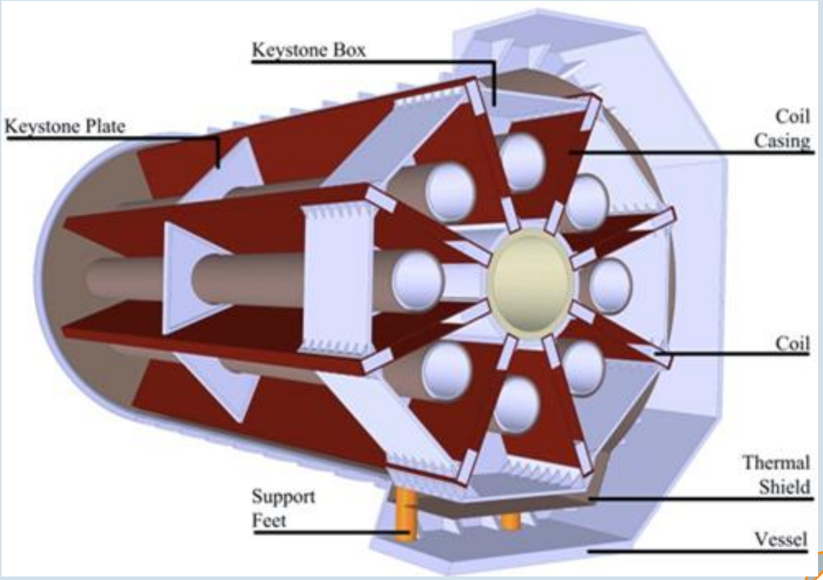
The BabyIAXO and ALPS II sensitivities are similar.

International Axion Observatory

Magnets

IAXO magnet

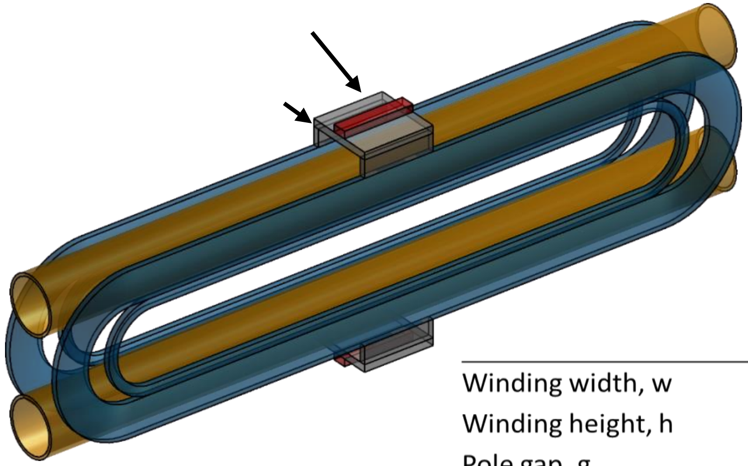
- Superconducting "detector" magnet.
- Toriodal geometry (8 coils)
- Based on ATLAS toroid technical solutions.
- CERN+CEA expertise
- 8 bores / 20 m long / 60 cm Ø per bore

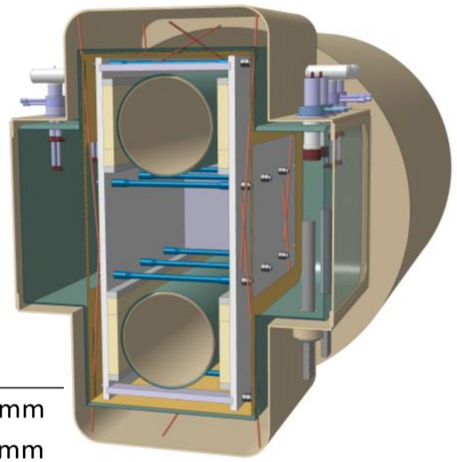


Baseline developed at:
IAXO Conceptual Design: JINST 9 (2014) T05002 (arXiv:1401.3233)

BabyIAXO magnet:

- 10m long magnet for the experiment and prototype for the IAXO magnet.
- Detailed design worked out by CERN (H. ten Kate).





Winding width, w	595 mm
Winding height, h	82 mm
Pole gap, g	1000 mm
Magnet energy	50 MJ
Inductance	1.0 H
Peak magnetic field	**3.2 T**
Current density	56 A/mm^2
Operating current	**9.8 kA**
Conductor length	**11.4 km**
MFOM 3-D	232 T^2 m^4
MFOM 2-D	**326 T^2 m^4**

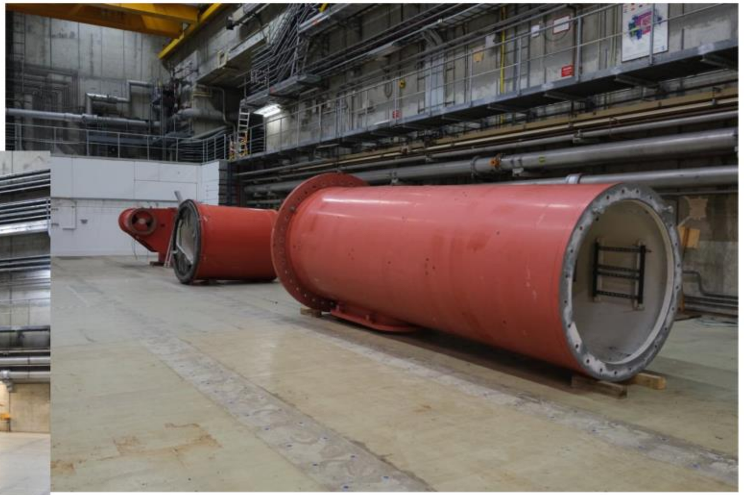
International Axion Observatory

BabyIAXO tower from CTA-MST

Accidentally, the specifications for the BabyIAXO and the CTA-MST towers are nearly identical.

Accidentally, the prototype MST in Berlin-Adlershof will be dismantled in spring 2020.

We got the tower for BabyIAXO free of charge.



International Axion Observatory

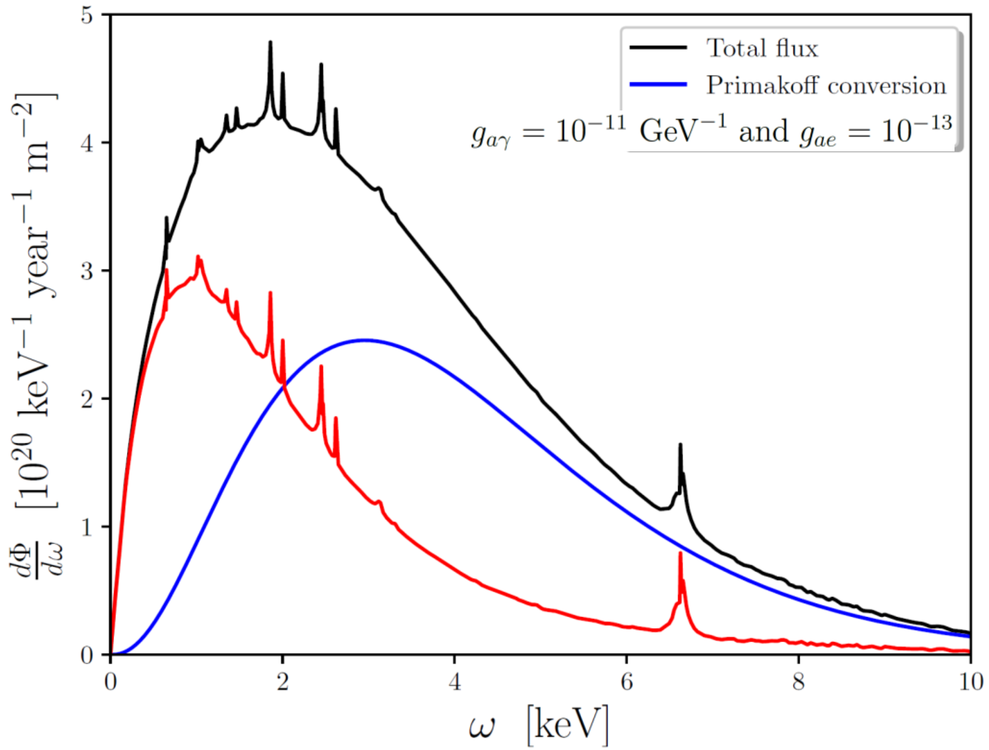
Physics reach

Solar axions produced via

- the Primakoff effect (axion-photon coupling),
- axion-electron coupling,
- axion-nucleon coupling
  (14.4 keV from ^{57}Fe).

IAXO results may allow to distinguish between different axion models!

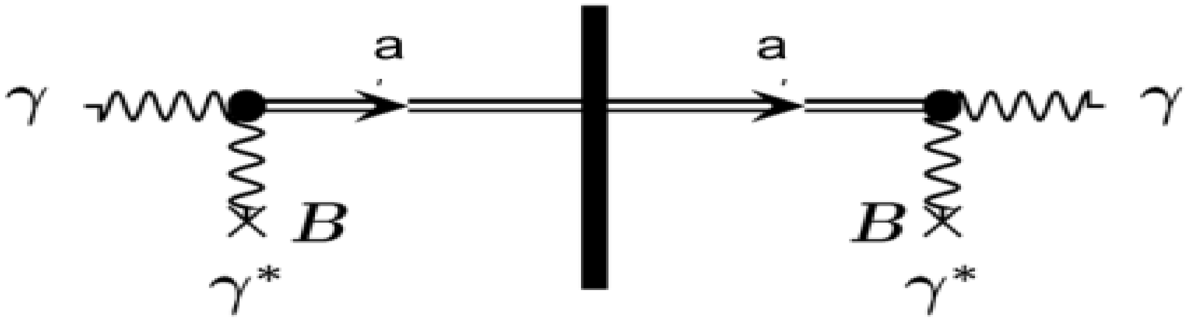
In an ideal scenario $g_{a\gamma}$ is known from ALPS II model-independently.



"Distinguishing Axion Models with IAXO"
J. Jaeckel, L.J. Thormaehlen, JCAP 03 (2019), 039

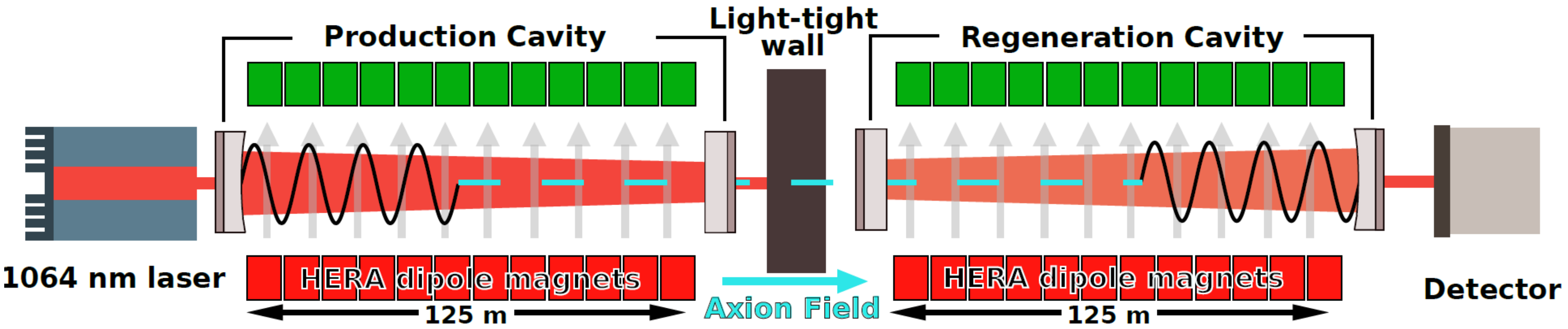
Any Light Particle Search ALPS II

Model independent search: light-shining-through-walls



Any Light Particle Search ALPS II

Model independent search: light-shining-through-walls



$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot10^{-38}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\frac{B}{1\,T}\frac{l}{10m}\right)^4$$

$= 10^{-25}$

5.000 40.000 0.2 5.3 10.56

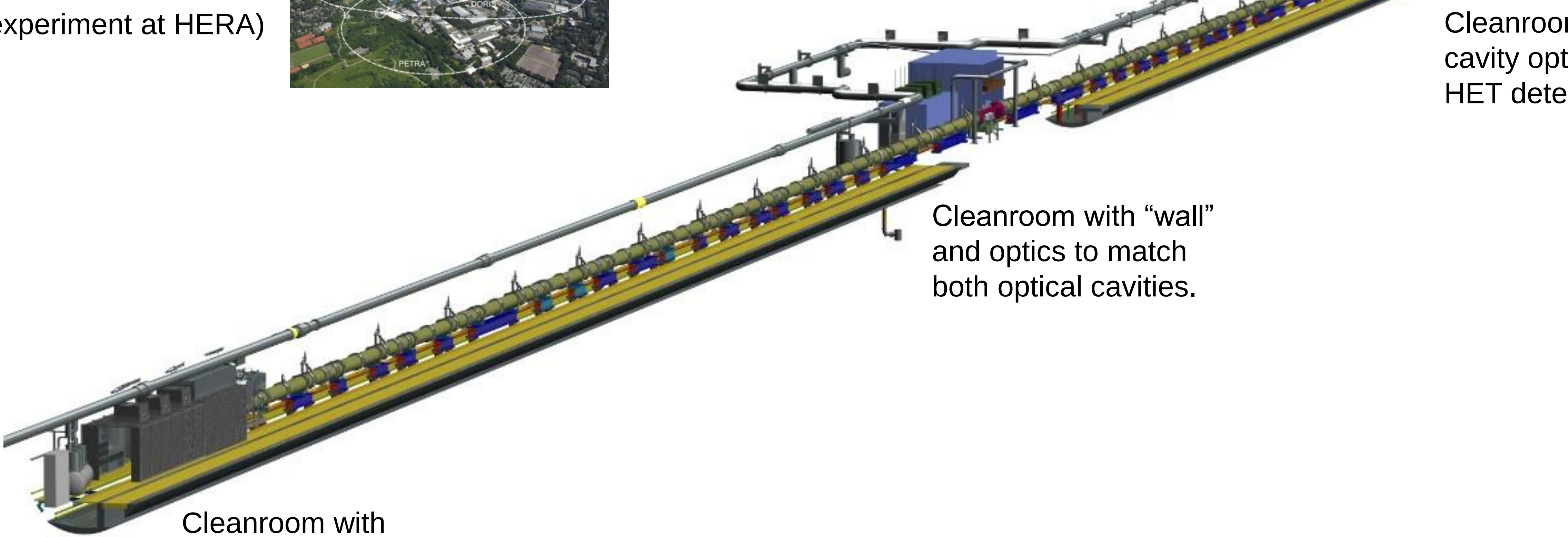
astrophysics
ALP motivation

30 W cw laser at 1064 nm: $3\cdot10^{-5}$ photon/s ($5\cdot10^{-24}$ W).

ALPS II in the HERA tunnel

250m installation in a straight HERA section

HERA hall North
(former H1
experiment at HERA)



Cleanroom with
cavity optics and
HET detection.

Cleanroom with “wall”
and optics to match
both optical cavities.

Cleanroom with
high power laser.

Any Light Particle Search ALPS II

Collaboration

Albert Einstein Institute Hannover

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

ALPS II main contributions				
Partner	Magnets	Optics	Detectors	Infrastructure
DESY	X	X	X	X
AEI Hannover		X		
U. Cardiff		X		
U. Florida		X	X	X
U. Mainz			X	

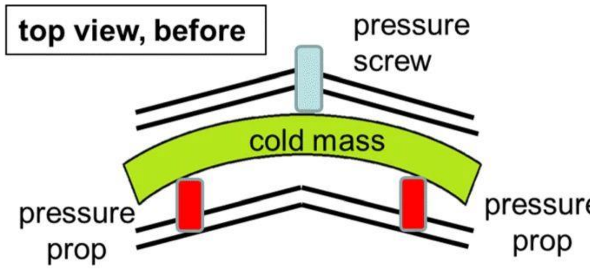
Significant funding from HEISING-SIMONS FOUNDATION

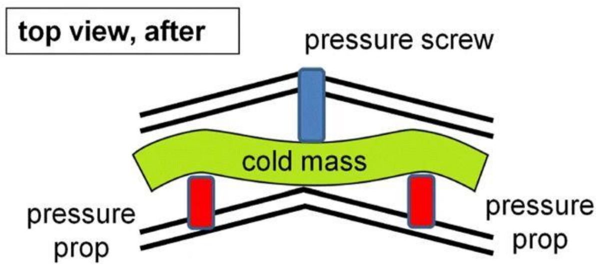
Strong support by PTB, TU Berlin, Magnicon, NIST for detector development.

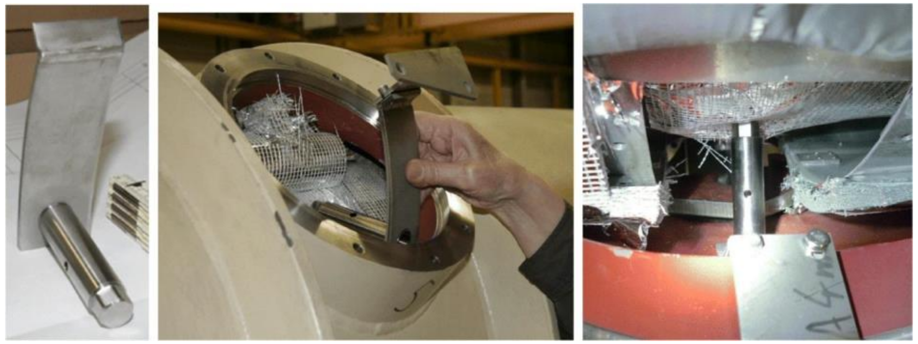
ALPS II: dipole magnets

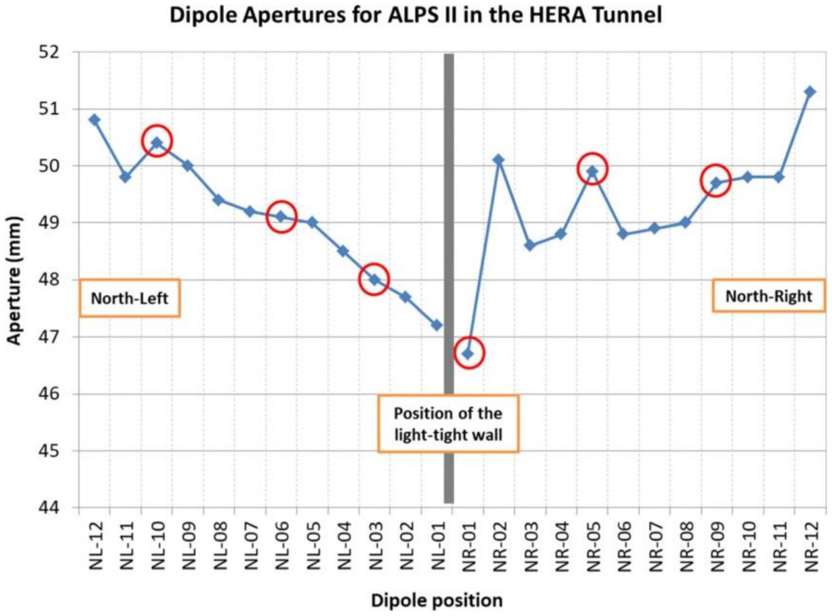
Re-using superconducting HERA dipoles

- 12+12 superconducting dipoles from HERA, each 5.3 T on 8.8 m.
- Straightened to achieve
  ≈ 50 mm aperture
  from 35 mm (600 m bending radius).
- 26 magnets modified and tested successfully (out of 27).
- All magnets are installed and aligned.









"Straightening of superconducting HERA dipoles for the any-light-particle-search experiment ALPS II",
C. Albrecht *et al., EPJ Techn Instrum* 8, 5 (2021).

ALPS II magnet string construction

HERA North area before ALPS II

ALPS II magnet string construction

Disassemble HERA mid 2018 to mid 2019

ALPS II magnet string construction

Foundations

ALPS II magnet string construction

Magnets going underground

First Magnet Fest 28 October 2019

ALPS II magnet string construction

Magnet installation

ALPS II magnet string construction

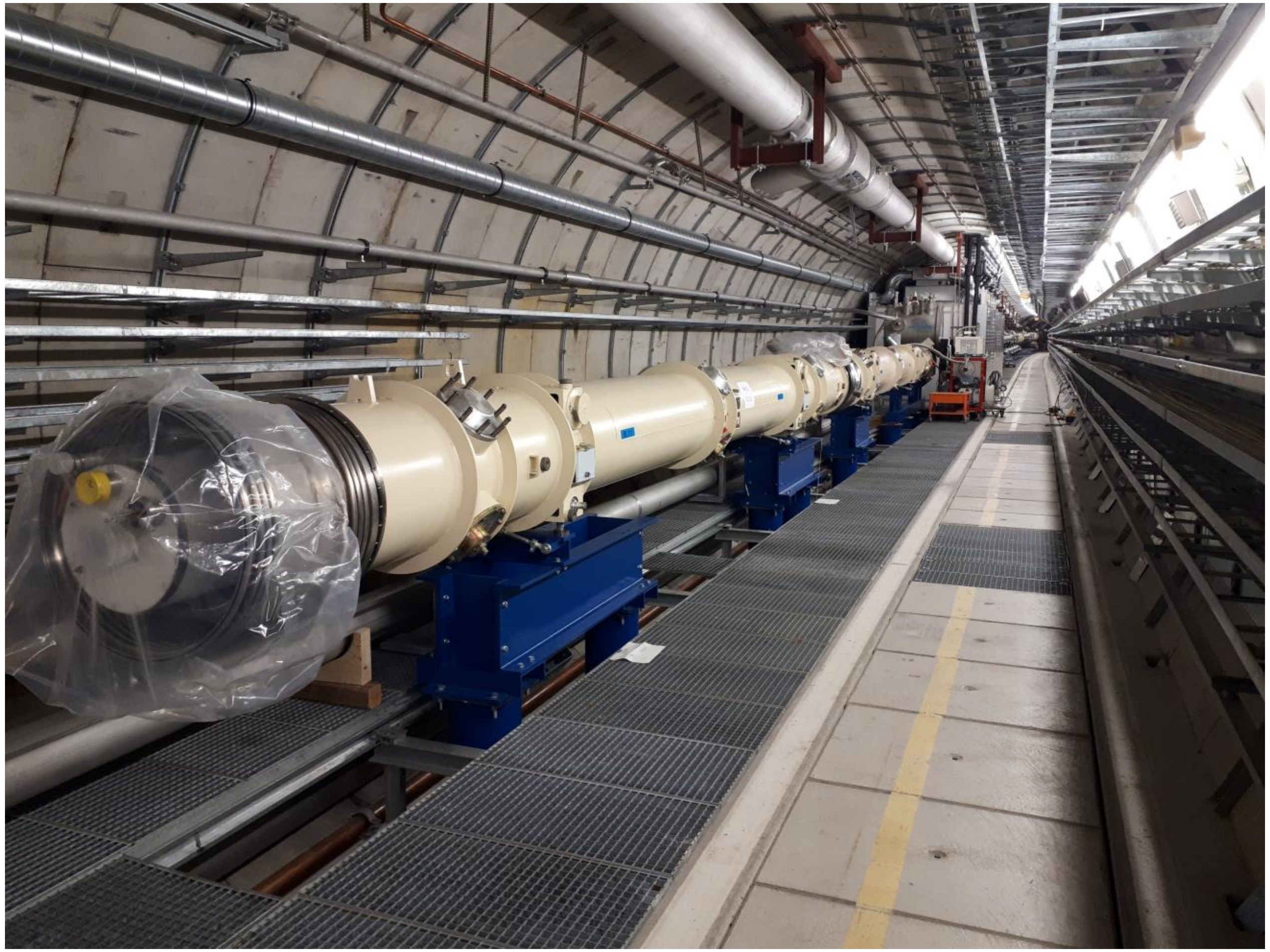
Magnet installation

ALPS II magnet string construction

More magnets

ALPS II magnet string construction

More magnets

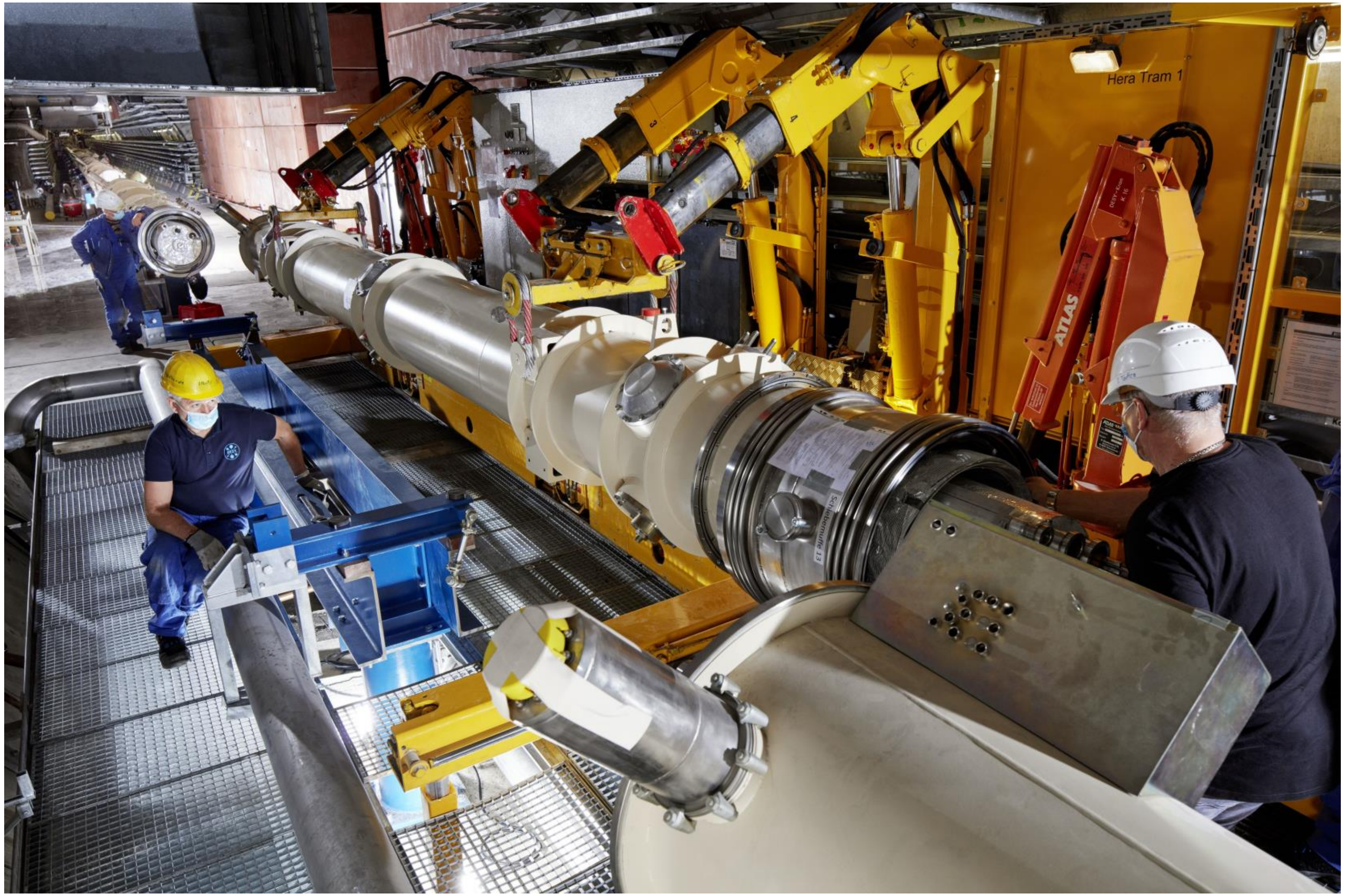


ALPS II magnet string construction

More magnets

ALPS II magnet string construction

22 October 2020: the last magnets are installed



ALPS II magnet string construction

22 October 2020: the last magnets are installed

Joachim Mnich, director in charge of particle physics (now at CERN)

Wim Leemans, director of the accelerator division

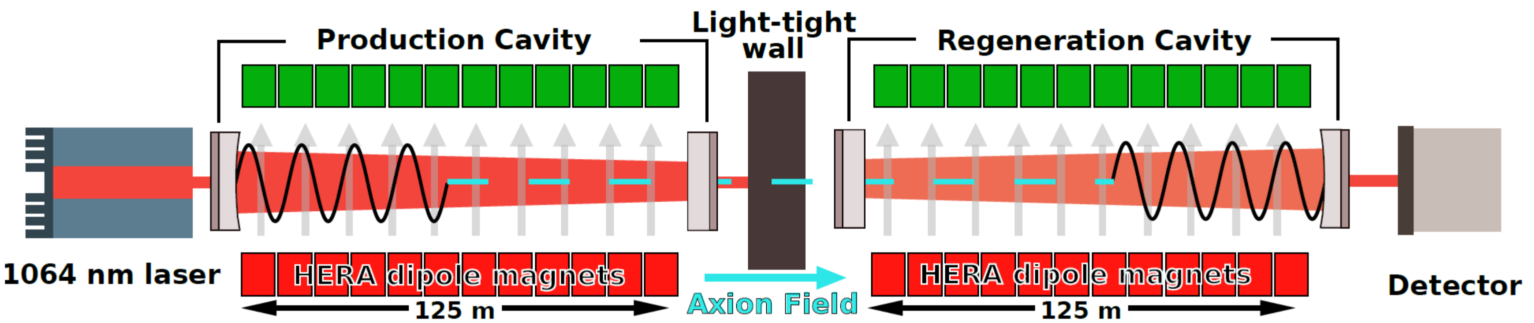
ALPS II: the site

December 2020

ALPS II: optics

Adapting technologies from aLIGO, GEO 600

“Design of the ALPS II Optical System”, arXiv:2009.14294 [physics.optics]



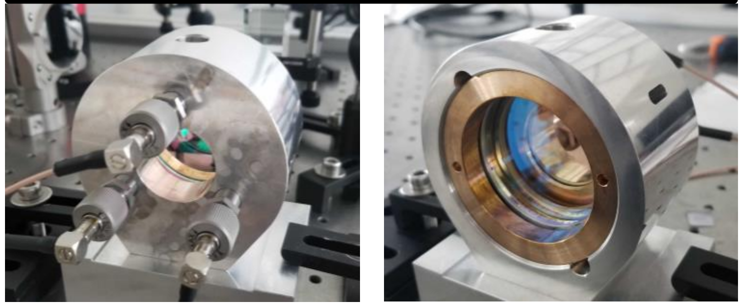
- Mode-matched optical resonators before (“PC”) and behind (“RC”) the wall.
- Relative angle between PC and RC less than 0.5 µrad.
- Each 124 m long, need to compensate seismic noise.
- Circulating power PC: 150 kW.
- Power built-up RC: 16,000 (aim for 40,000 later).
- PC and RC relative length stabilized to pm accuracy.
- Light-tightness PC to RC: less than 10^{-30}.

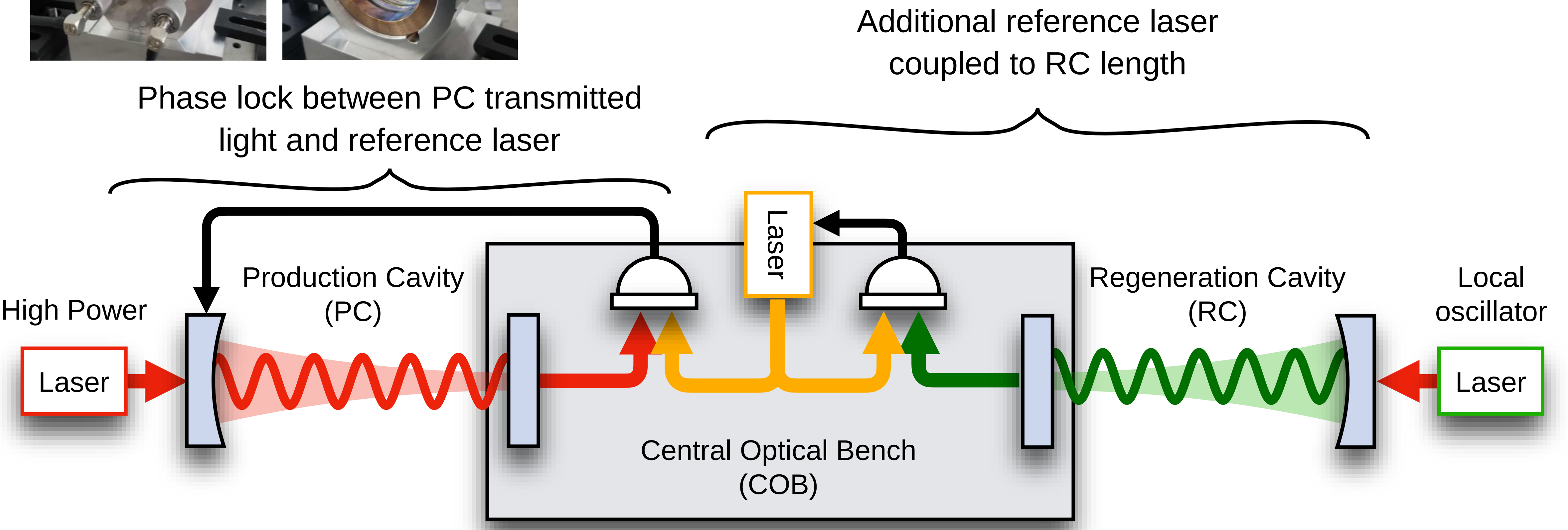
Light storage time: 5.4 ms
(2 x world-record;
aLIGO 1.0 ms)

Optics challenges

Example: dual resonance; field in PC resonant in RC

Actuators: *picometer* position accuracy required



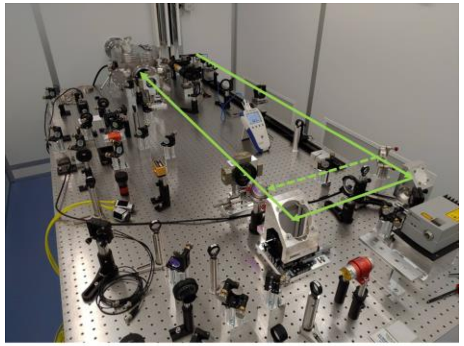


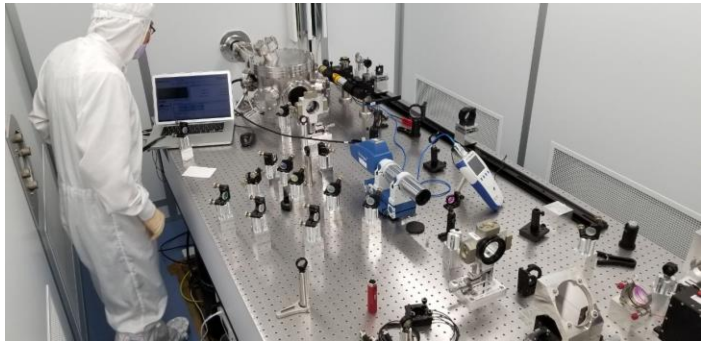
Optics status

From R&D to installation

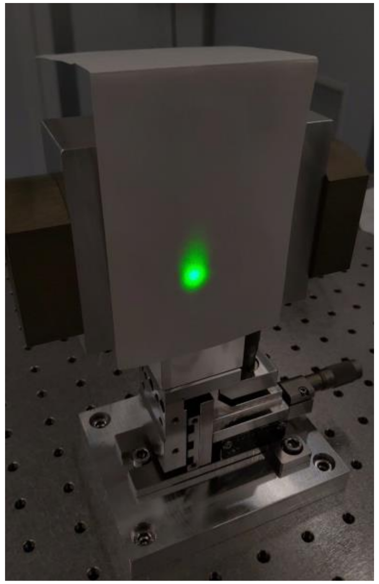
- R&D started 2012 in a dedicated laserlab at DESY as well as at AEI Hanover and (a bit later) at University of Florida.

- March 2021:
  installation of optics at ALPS II started.





- April 2021:
  Initial alignment laser through the magnet string.

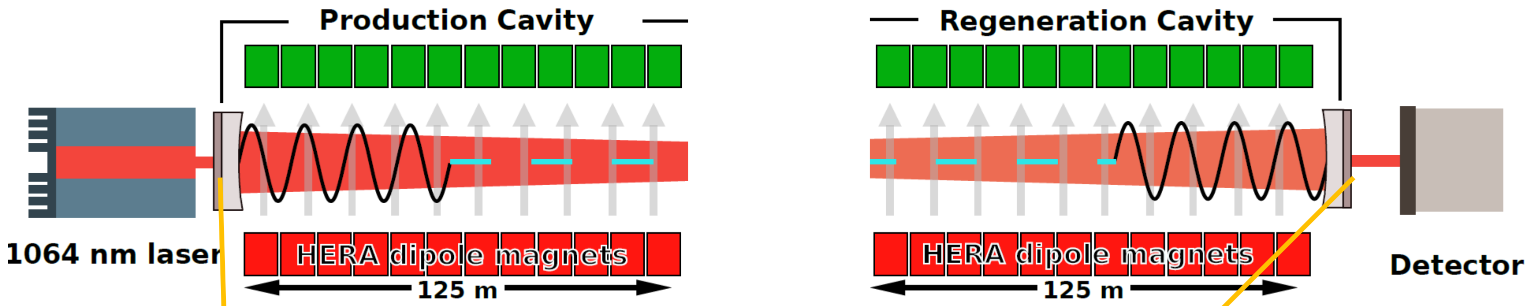


- May 2021:
  infrared laser through the magnet string.

50 mm aperture on 250 m lenght!

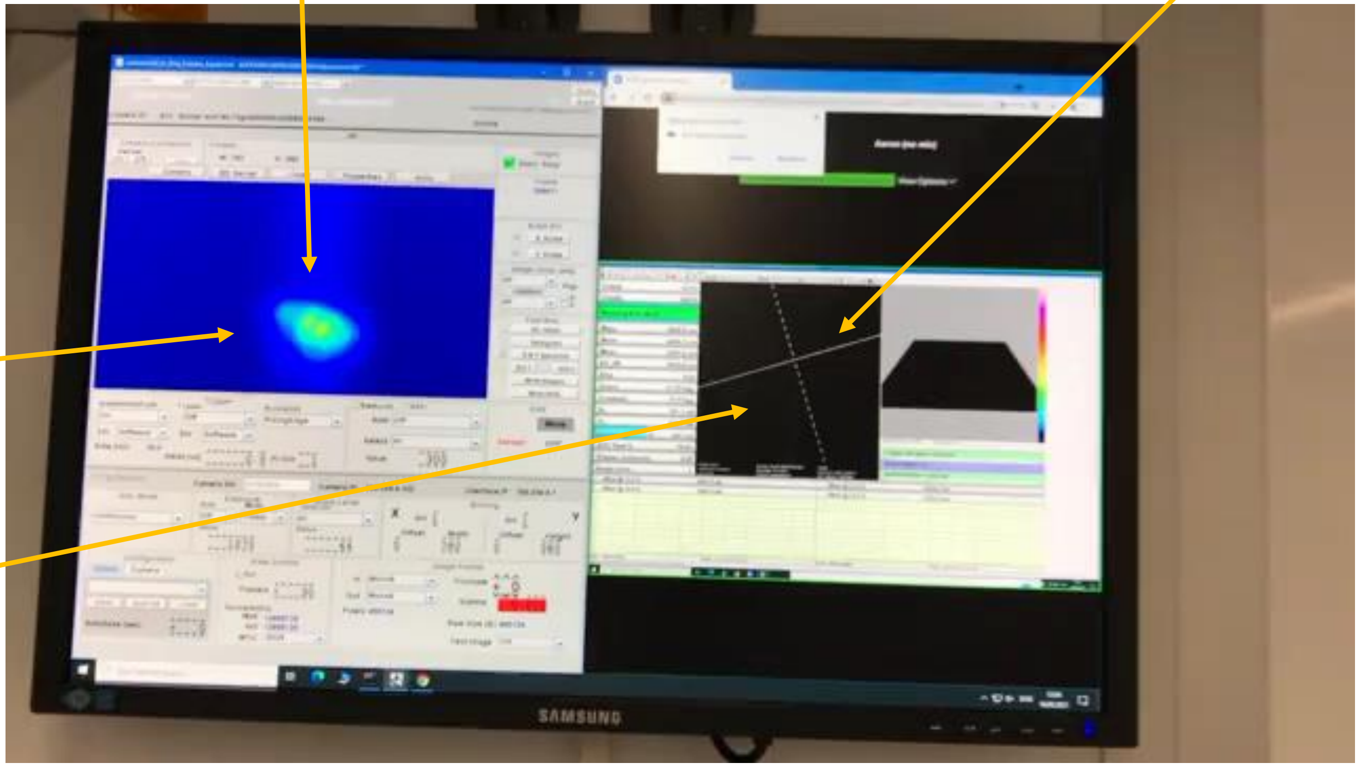
Optics status

First cavity lock!



- Start with 250 m cavity
  to understand seismic noise and
  check aperture constrains.

- 21 June 2021:
  Robust cavity "lock"!



Reflection of
in-coupling mirror.

Transmission of
cavity end mirror

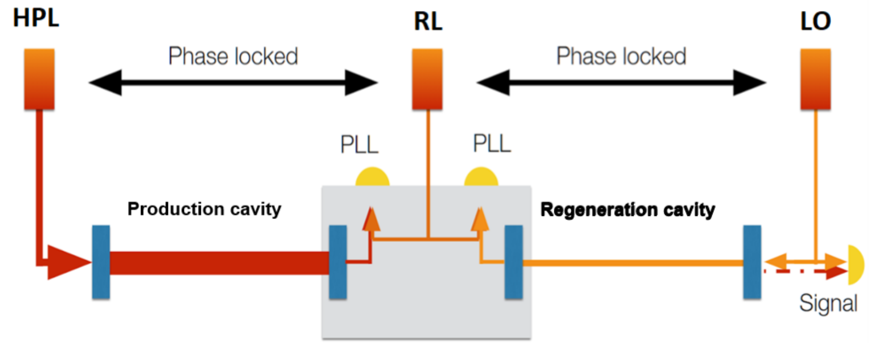
ALPS II: detectors

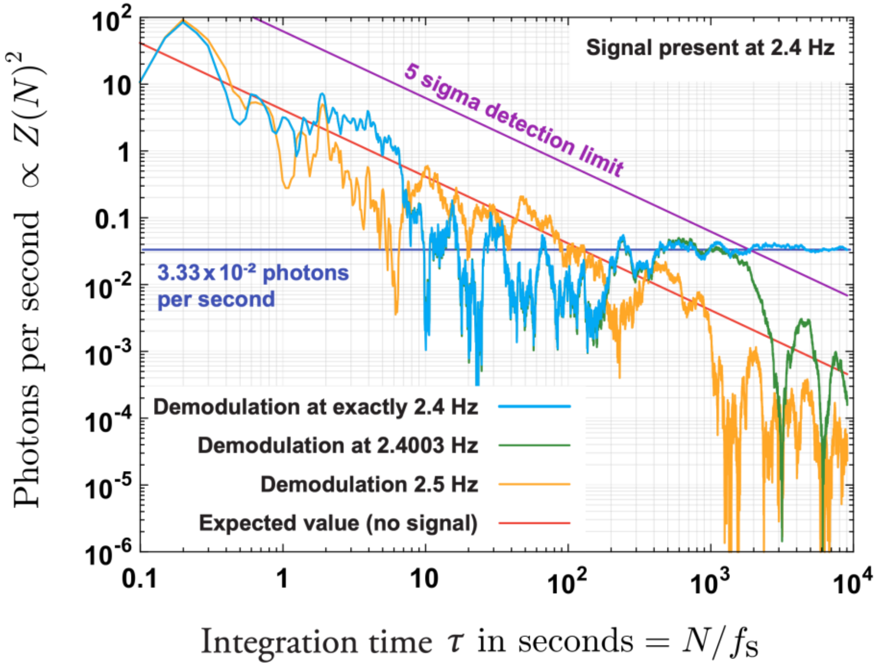
“Coherent detection of ultraweak electromagnetic fields”,
Z. Bush et al., Phys. Rev. D 99, 022001 (2019)

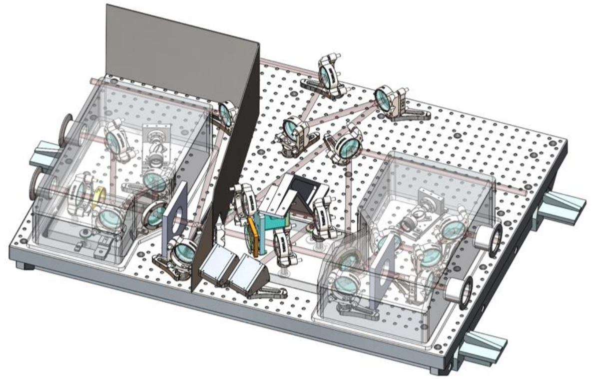
Looking for $5 \cdot 10^{-24}$ W @ 1064 nm

Option 1: heterodyne sensing

- Mix weak signal with a frequency f shifted local oscillator and demodulate at f.
- Detection of a photon flux corresponding to $5 \cdot 10^{-21}$ W demonstrated.
- Sensitivity of 10^{-24} W demonstrated.







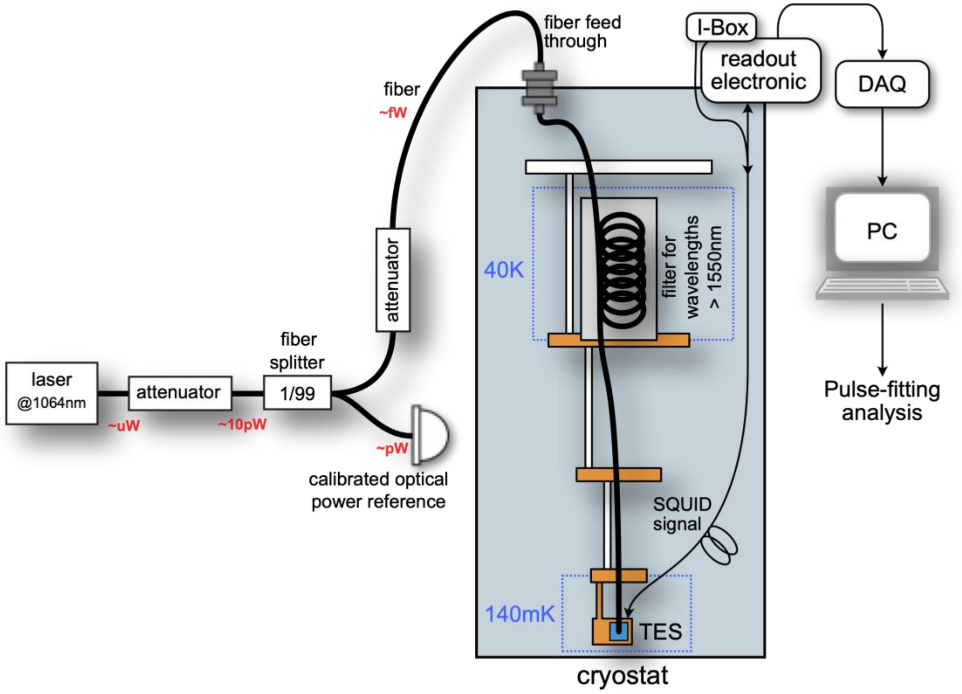
The first science runs of ALPS II will use heterodyne sensing.

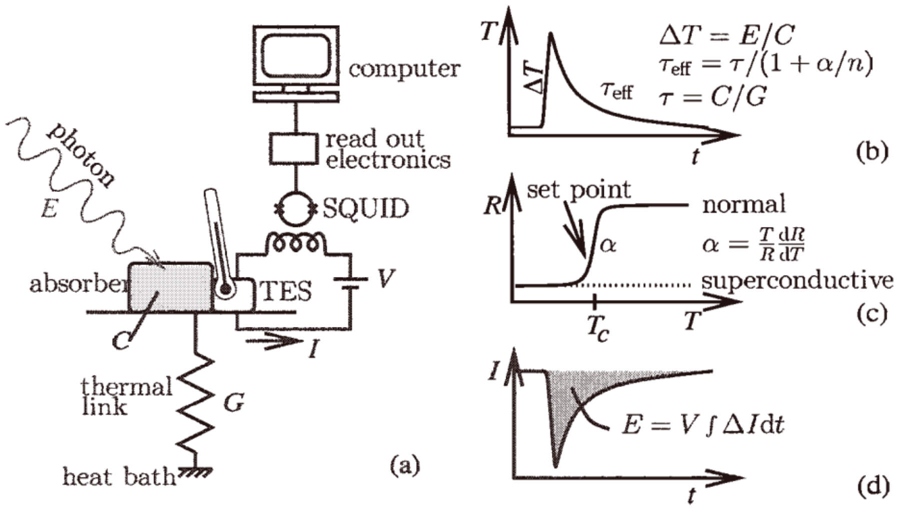
ALPS II: detectors

Looking for $5 \cdot 10^{-24}$ W @ 1064 nm

Option 2: photon counting

- Using a superconducting transition edge sensor (TES) operated at about 100 mK.





$\Delta T \approx 300$ μK

$\Delta R \approx 1\ \Omega$

$\Delta I \approx 70$ nA

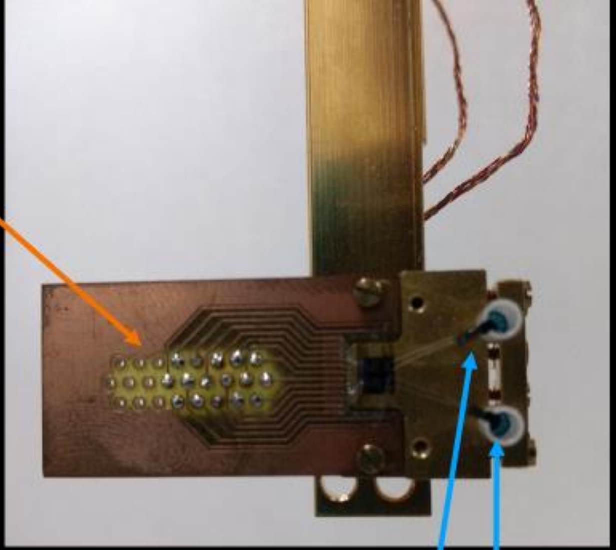
"Characterization, 1064 nm photon signals and background events of a tungsten TES detector for the ALPS experiment", J. Dreyling-Eschweiler et al., Journal of Modern Optics, 62:14, 1132-1140

Cryostat

- Bluefors Dilution refrigerator (mixing He3/4) achieving 21mK
- Control from Bluefors (manually and remote software)
- Remote control (Windows PC)
- DOOCS Panel for remote view

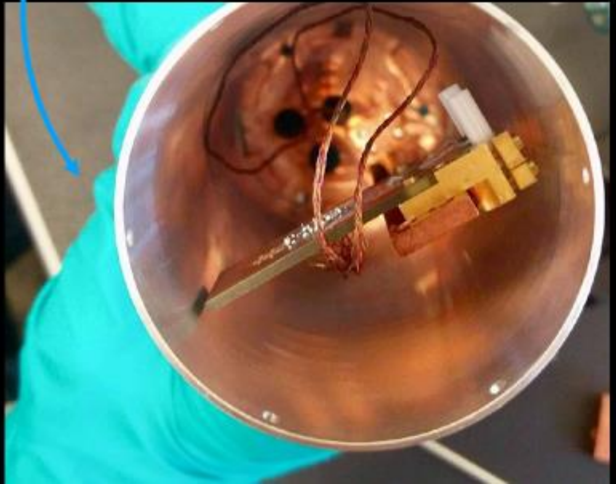
SQUID (PTB, Magnicon)

- I-Box
- Electronics from Magnicon
- IV curve measurement via Oscilloscope



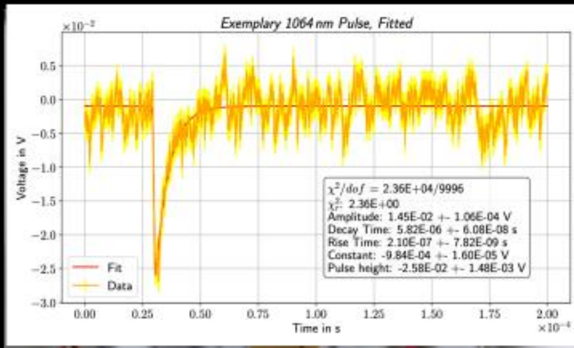
TES

- 2 Tungsten sensors (NIST)
- High-efficient layers (>99% transmission for 1064 nm)
- Fiber coupled
- Coupled to the bath via copper
- aluminium can for shielding against magnetic, EM, BB… ?



DAQ

- Alazar ATS9626 250Ms/s via PCI on a Linux system
- GUI programmed in-house
- Triggering for different working points of TES resistance
- Different analysis lines

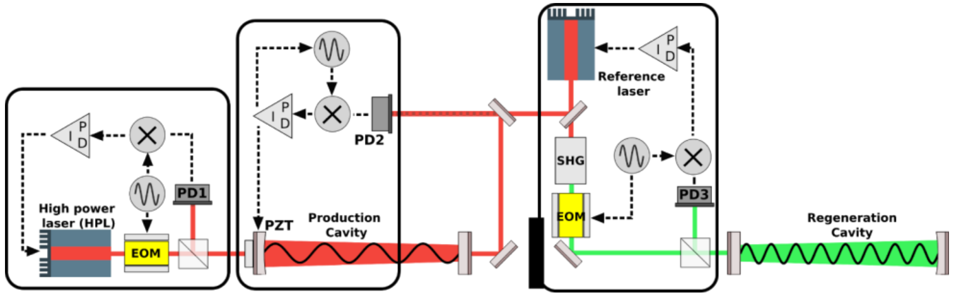


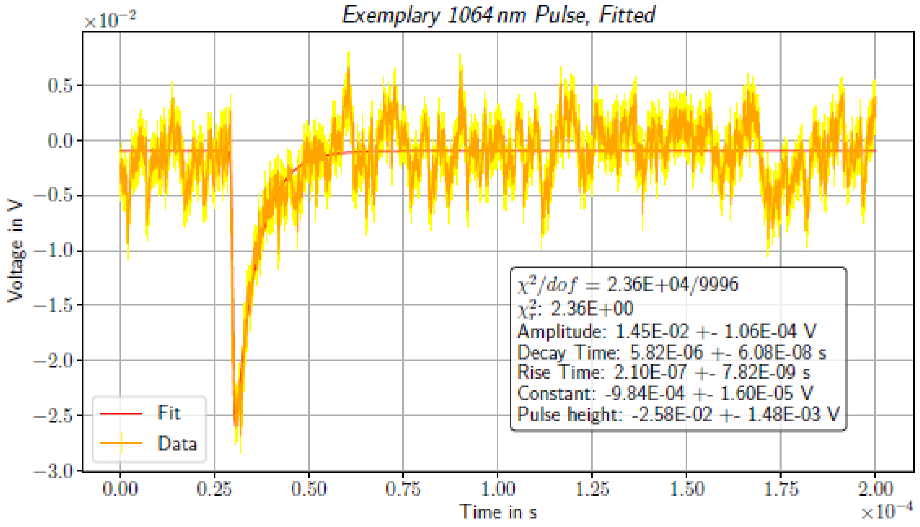
ALPS II: detectors

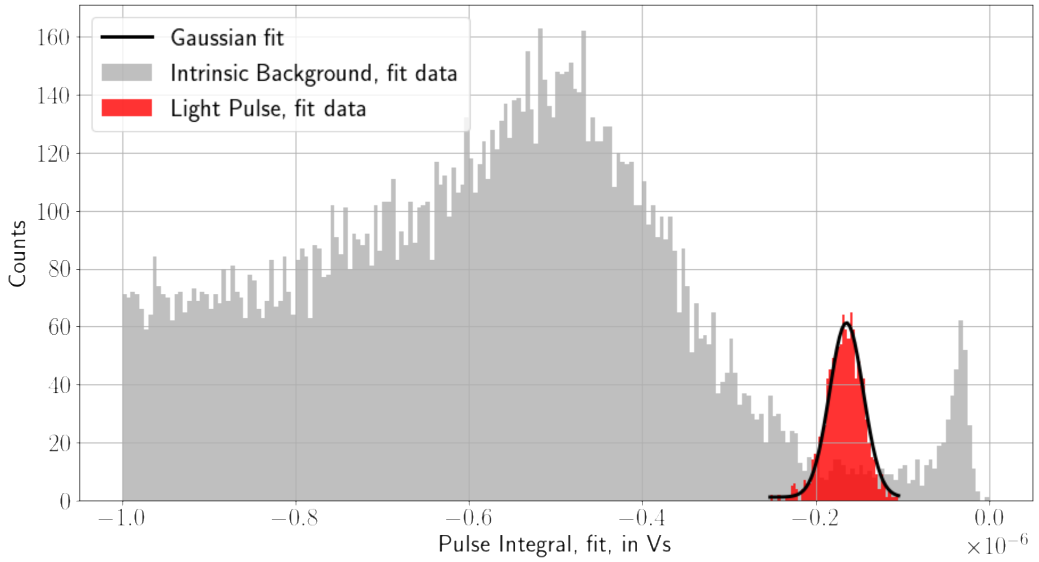
Looking for 5·10^{-24} W @ 1064 nm

Option 2: photon counting

- Using a superconducting transition edge sensor (TES) operated at about 100 mK.
- Energy resolution of 10% demonstrated.
- Background rate below 10^{-5} s^{-1} demonstrated (no fiber coupled to the TES).
- TES data taking requires a different optics setup.







A daydream …

- ALPS II discovers an axion and determines its coupling to photons.
- BabyIAXO determines the flux of solar axions using the coupling from ALPS II.
- IAXO allows for precision axion physics
  - addressing also axion-electron and axion-nucleon couplings,
  - addressing solar physics.
- MADMAX detects the dark matter axion allowing to
  - address the history of the milky way,
  - provide new input to cosmology.

"Quantifying uncertainties in the solar axion flux and their impact on determining axion model parameters"
S. Hoof, J. Jaeckel, L.J. Thormaehlen, arXiv:2101.08789 [hep-ph]

More realistic …

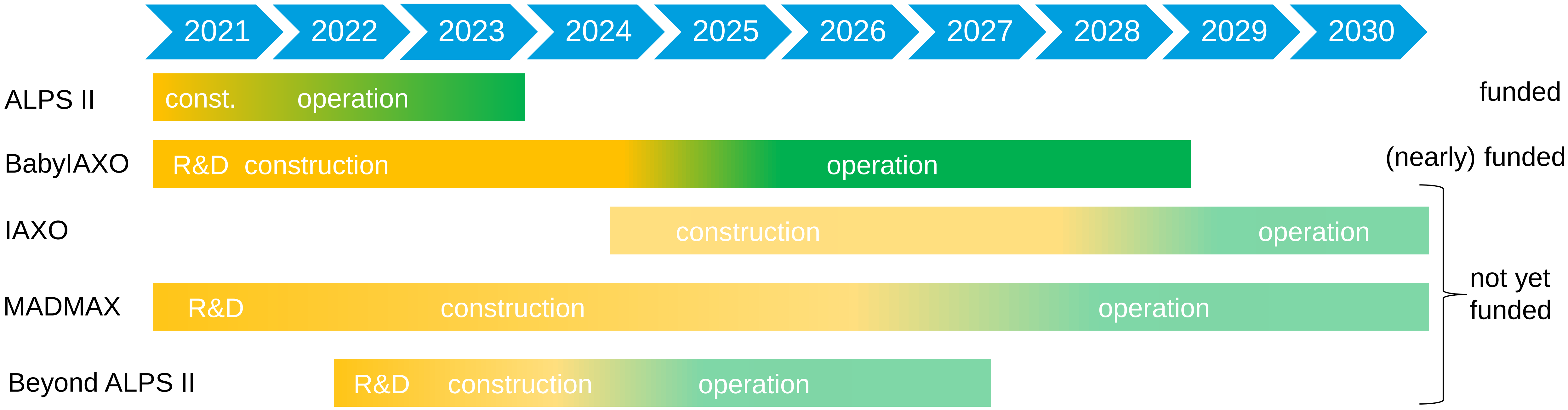
- The ALPS II infrastructure and the cryoplatform at DESY provide a unique infrastructure for
  - upgrading ALPS II in sensitivity and mass reach?
  - measuring the vacuum magnetic birefringence?
  - looking for high frequency gravitational waves?
  - …

"beyond ALPS II"
https://indico.desy.de/event/28588/

Timelines

ALPS II and beyond, BabyIAXO, IAXO, MADMAX

Some optimistic view (funding), assuming no surprises (axion discovery).

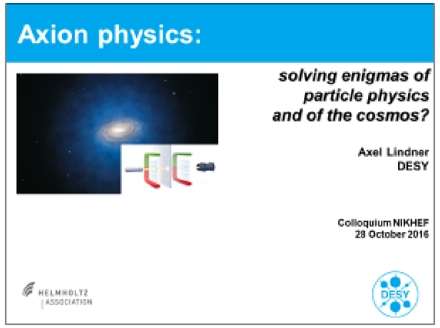


DESY: also a center for experimental axion physics in this decade?
Program well aligned with other international axion searches.

Summary

A quick summary

Compared to the status in 2016

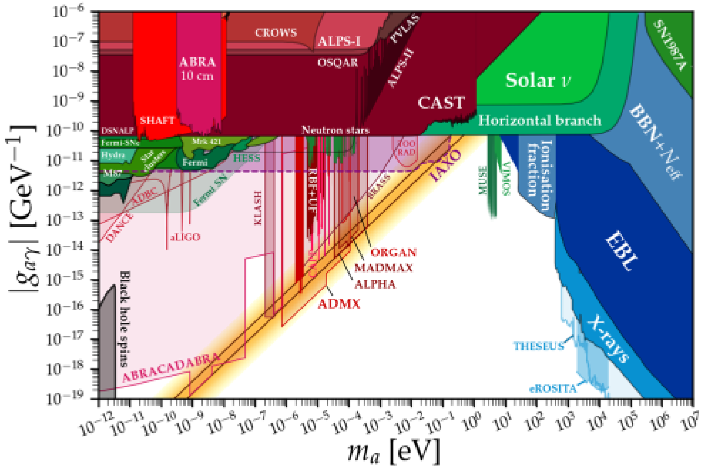


- Presentations are now in 16:9.
- The enigmas of particle physics and cosmology remain unchanged.
- The parameter region for the QCD axion has expanded.
- Astrophysical hints for axions are still disputed.
- ALPS II at DESY is nearly ready to start data taking.
- BabyIAXO at DESY will probably start construction this year.
- MADMAX has entered the prototyping phase.
- DESY is strongly committed to axion experiments and is setting up infrastructures for more on-site particle physics experiments.
- The excitement on axion physics is increasing.

DESY. Axions | NIKHEF Colloq., 2 July 2021 | Axel Lindner Page 2

The axion landscape

Tomorrow



Ciaran O'Hare,
https://cajohare.github.io/AxionLimits/

Potential to probe large part of the phase space within the next decade.
Some focus on experiments at DESY:

- MADMAX
- IAXO
- ALPS II

DESY. Axions | NIKHEF Colloq., 2 July 2021 | Axel Lindner Page 56

The next decade will see results of many axion experiments probing a large part of the most compelling phase space.

If the axion or ALPs exist, there is a fair chance for a discovery in Hamburg.

Thank you

… and all my colleagues for the slides I‘ve stolen ….

Contact

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