Introduction to
and
laboratory-based searches for axions and axion-like particles

10th Workshop on
Science with the New Generation of High-Energy Gamma-ray experiments

Lisbon, Portugal

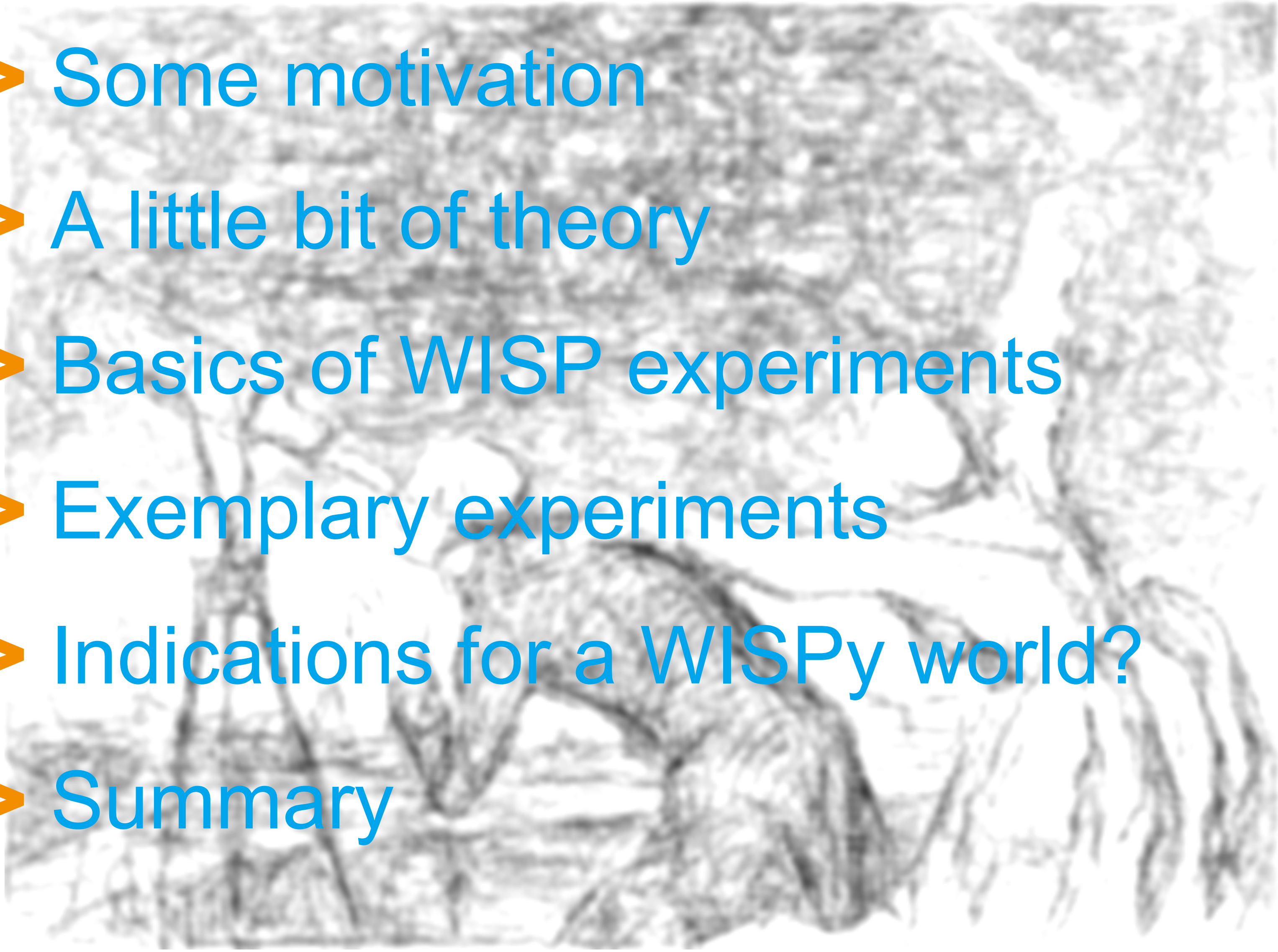
04 June 2014

Axel Lindner, DESY

HELMHOLTZ
ASSOCIATION

DESY

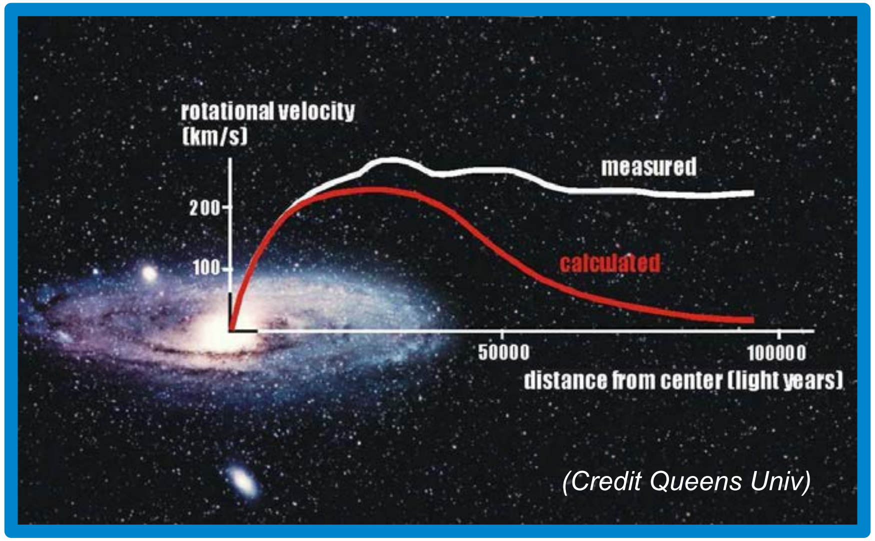
Outline

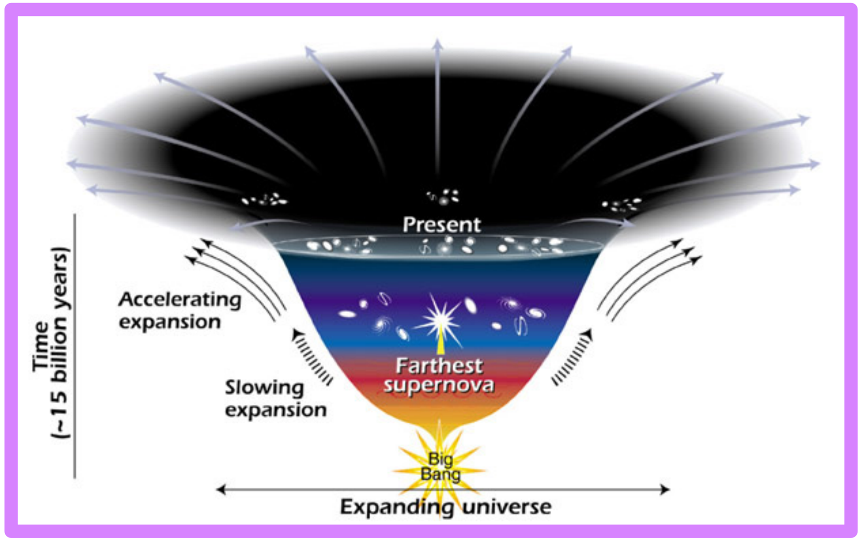


- Some motivation
- A little bit of theory
- Basics of WISP experiments
- Exemplary experiments
- Indications for a WISPy world?
- Summary

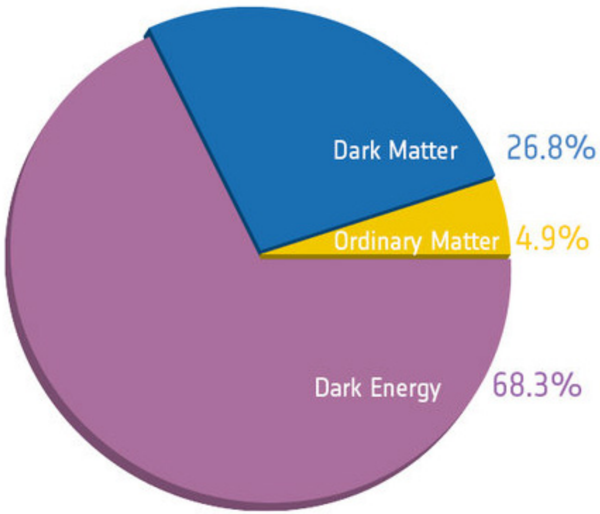
There is physics beyond the SM

> Dark matter and dark energy:





http://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy/

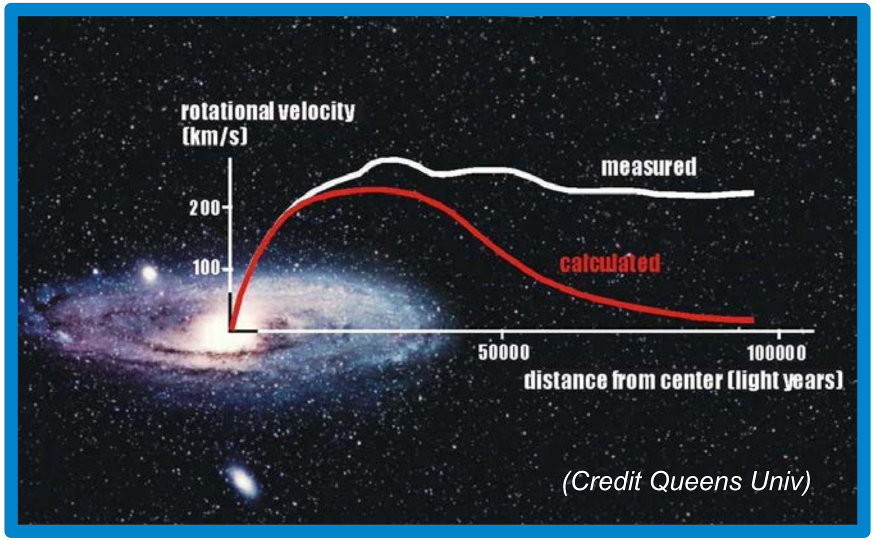


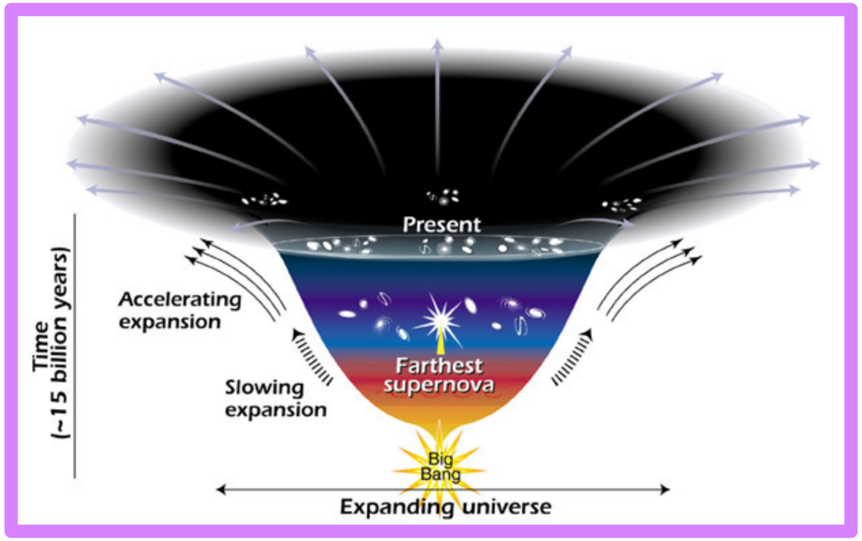
http://www.esa.int/For_Media/Photos/Highlights/Planck

Even if one neglects dark energy:
85% of the matter is of unknown constituents.

There is physics beyond the SM

> Dark matter and dark energy candidate constituents:





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> Very weak interaction with SM matter

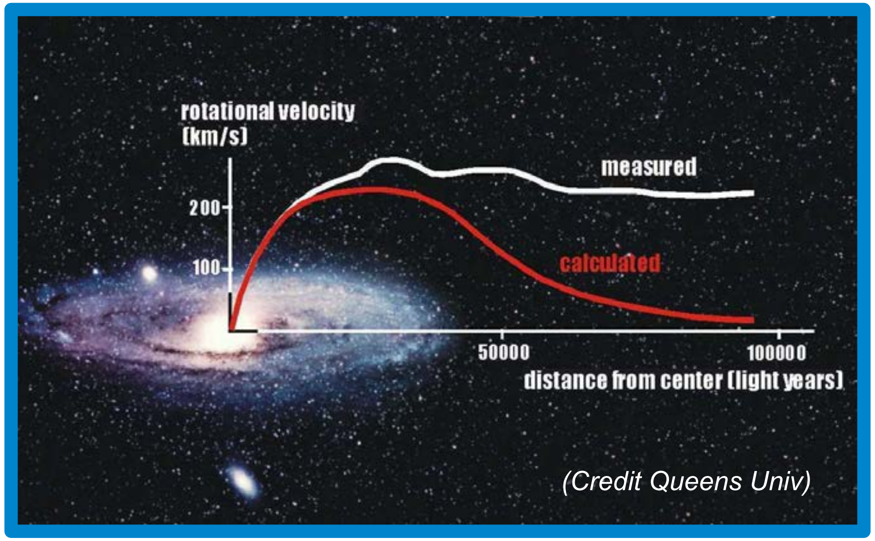
> Very weak interaction among themselves

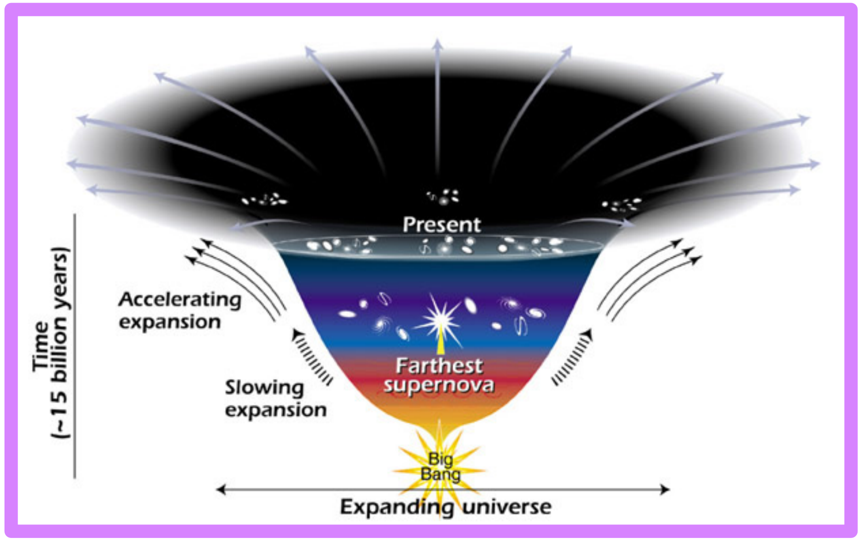
> Stable on cosmological times

> Non-relativistic

There is physics beyond the SM

- Dark matter and dark energy candidate constituents:





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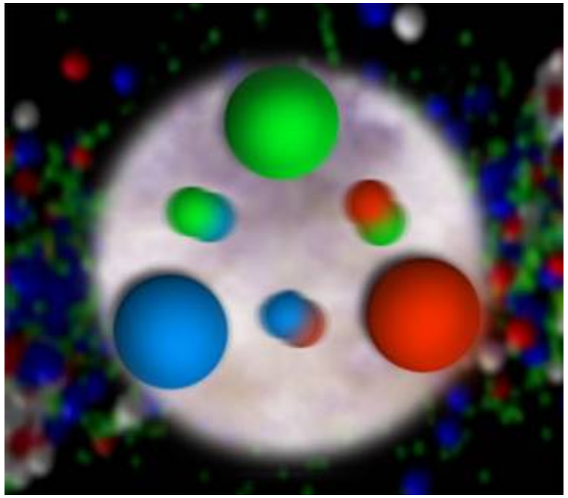
- Very weak interaction with SM matter
- Very weak interaction among themselves
- Stable on cosmological times
- Non-relativistic

NO HINT ON MASS OF DM CONSTITUENTS!

- Extremely lightweight scalar particle

There might be physics beyond the SM

- CP-conservation in QCD:
  why does the static electromagnetic dipole moment of the neutron vanish?



http://www.lbl.gov/Science-Articles/Archive/sabl/2006/Oct/3.html

Why do the wave functions of the three quarks *exactly* cancel out any observable static charge distribution in the neutron?

Why does QCD conserve CP?

In principle QCD would allow for CP violation parameterized by an overall phase θ of the quark mass matrix.

There might be physics beyond the SM

- CP-conservation in QCD:

F. Wilczek at “Vistas in Axion Physics”, Seattle, 26 April 2012
(see http://www.int.washington.edu/talks/WorkShops/int_12_50W/People/Wilczek_F/Wilczek.pdf)

The overall phase of the quark mass matrix is physically meaningful.
In the minimal standard model, this phase is a free parameter, theoretically.
Experimentally it is very small.
This is the most striking unnaturality of the standard model, aside from the cosmological term.
It does not seem susceptible of anthropic “explanation”.

In QCD a free parameter [illegible] could have any value between 0 and 2π.

Experimentally, [illegible] $< 10^{-9}$.

- A “fine-tuning” problem!

Physics beyond the standard model

> STRONG EVIDENCE FROM COSMOLOGY

- No clue on energy scale of BSM physics from DM.

> HINTS FROM PARTICLE PHYSICS

- Fine-tuning issues not only at the TeV-scale!

http://wp.patheos.com.s3.amazonaws.com/blogs/crossexamined/files/2014/04/Balancing-Chairs-2.jpg

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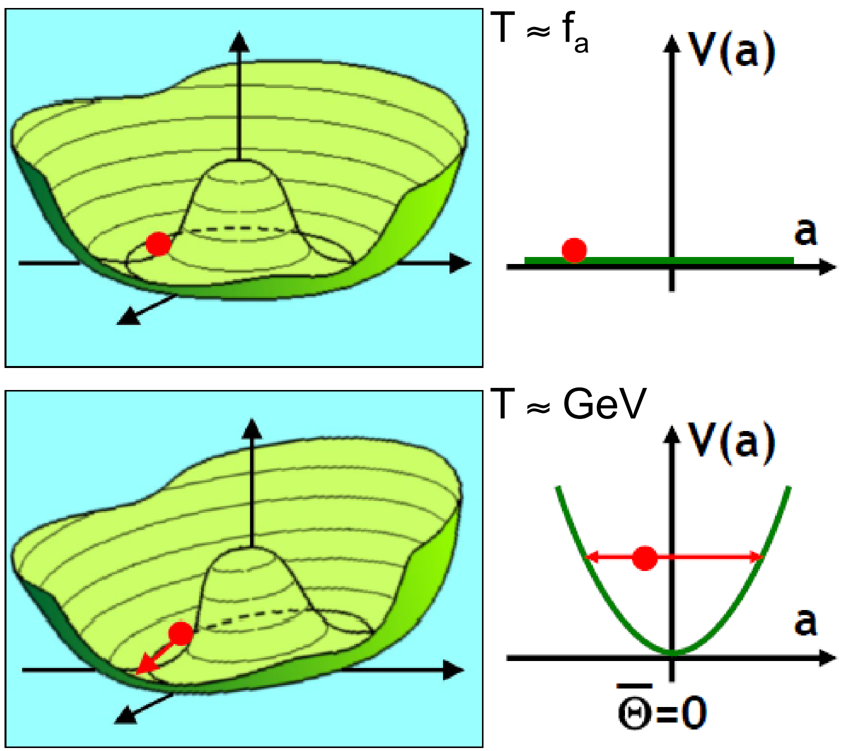
Introducing the axion

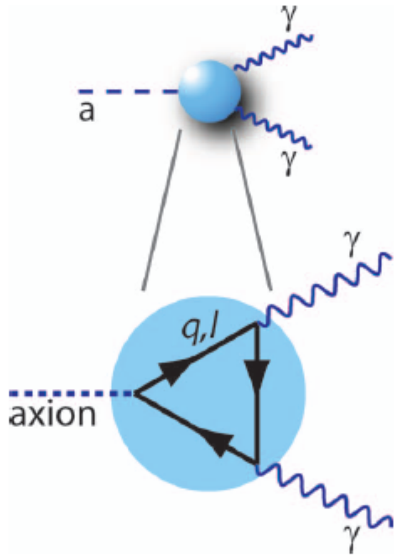
> CP-conservation in QCD:

A dynamic explanation for $\bar{\Theta} < 10^{-9}$ predicts the axion, which couples very weakly to two photons.

Peccei-Quinn 1977



Wilczek and Weinberg 1978



S. Hannestaad, presentation at 5th Patras Workshop on Axions, WIMPs and WISPs, 2009

The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008

Introducing the axion

Javier Redondo's talk at the 2012 DPG spring meeting:

Peccei-Quinn symmetry and the axion

Introduce a new axial global color-anomalous symmetry, which is spontaneously broken at a high energy scale, >>> TeV

➡ Massless Goldstone Boson: the axion

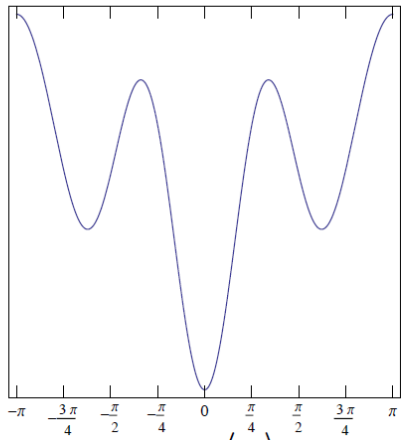
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\mathrm{tr}\left\{G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}\right\}\left(\theta + \frac{a}{f_a}\right)$$

Free parameter → f_a

The QCD induced potential is minimized for ...

$$\theta_{\rm eff} = \theta + \frac{\langle a \rangle}{f_a} = 0$$

$V_{\rm eff}$



$\theta + \frac{\langle a \rangle}{f_a}$

Tuesday, February 28, 2012

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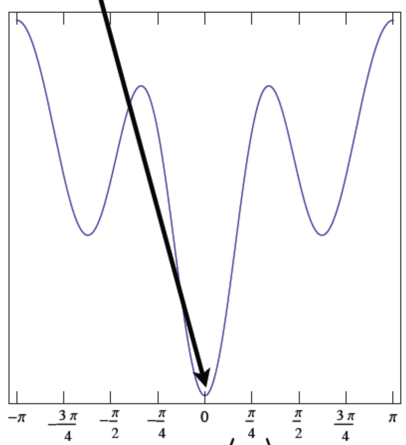

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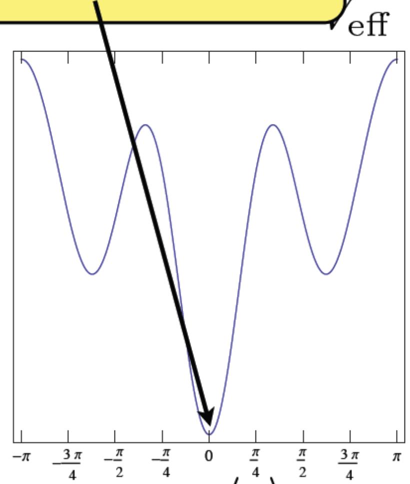
Just one → Free parameter

The QCD induced potential is minimized for ...

$$\theta_{\mathrm{eff}} = \theta + \frac{\langle a \rangle}{f_a} = 0$$



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Searching for axions (I)

Couplings to Standard Model constituents: how to look for WISPs

A. G. Dias et al., arXiv:1403.5760 [hep-ph]

- QCD:

$$\mathscr{L} \supset -\frac{\alpha_s}{8\pi}\frac{A}{f_A} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

(coupling to nucleons)

- QED:

two photon coupling

$$\mathscr{L} \supset \frac{1}{2}\partial_\mu A\,\partial^\mu A - \frac{1}{2}m_A^2 A^2 - \frac{g_{A\gamma}}{4} A\,F_{\mu\nu}\tilde{F}^{\mu\nu} .$$

(photon appearance experiments)

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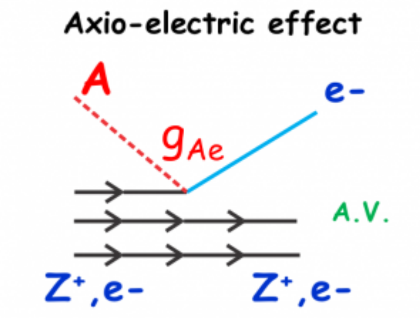
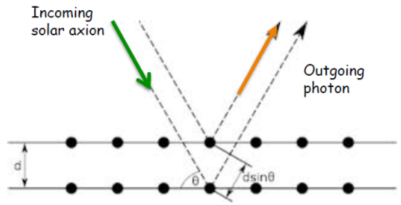
Searching for axions (II)

> Axioelectric effect
(for example exploited by XENON100, arXiv:1404.1455)

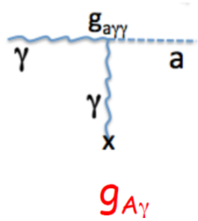


> Yukawa type interactions due to the exchange of ALPs lead to corrections of 1s hyperfine splitting.

> Bragg diffraction
(for example exploited by EDELWEISS).



> Axions emitted in nuclear transitions
(exploited in M1 transition of ^{57}Fe)
with the axion converting into a
photon or electron: $g_{Ae} \times g_{AN}^{eff}$



C. Nones, presentation at PATRAS 2013

Searching for axions (II)

- Axioelectric effect
  (for example exploited by XENON100, arXiv:1404.1455)
- Y… …teractions due to the exchange of A… …s of 1s hyperfine splitting.
- Bragg diffrac…
  (for example exploit… …)
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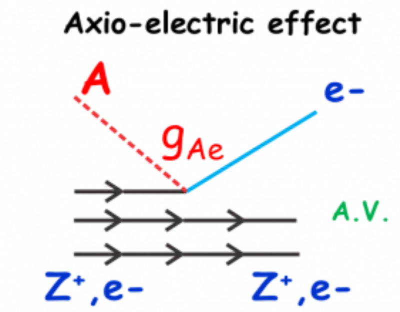
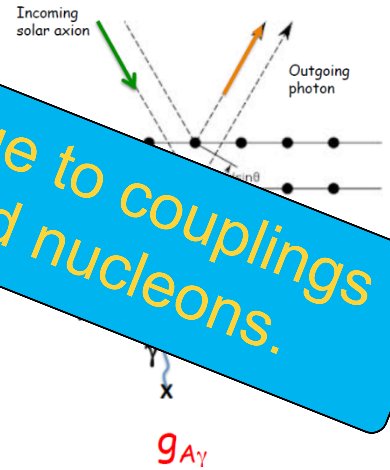
Results often model-dependent due to couplings of axions and ALPs to electrons and nucleons.



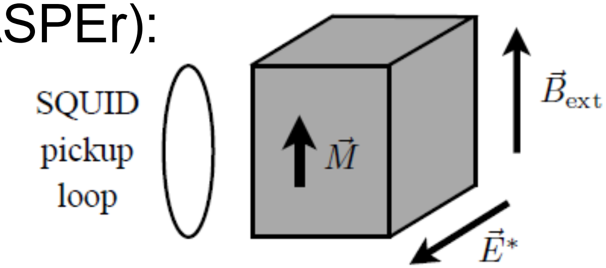


C. Nones, pres… …tion at PATRAS 2013

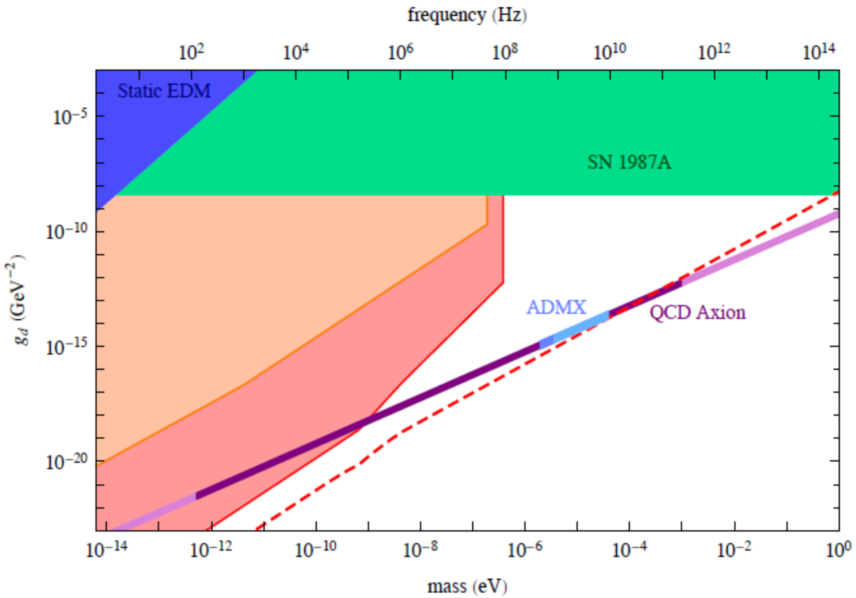
Searching for axions (III)

> Axion-induced effects in atoms, molecules, and nuclei:
Y. V. Stadnik and V. V. Flambaum, PHYSICAL REVIEW D 89, 043522 (2014)

> Cosmic Axion Spin Precession Experiment (CASPEr):
arXiv:1306.6089v1 [hep-ph]



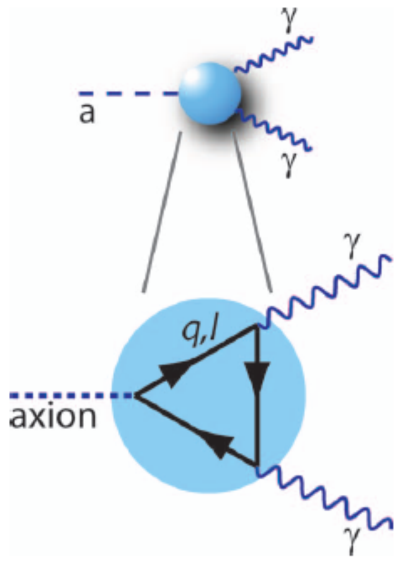
- Dark Matter axions induce a nucleon EDM of 10^{-34} e·cm oscillating at $m_a c^2/h$.
- This oscillation is brought into resonance with oscillating moments induced by B and E fields in the laboratory.



- Pathfinder experiment needed!

Properties of the axion

- The QCD axion: light, neutral pseudoscalar boson.
- The QCD axion: the light cousin of the π^0.
  - Mass and the symmetry breaking scale f_a are related:
    $m_a = 0.6\text{eV} \cdot (10^7\text{GeV} / f_a)$
  - The coupling strength to photons is
    $g_{a\gamma\gamma} = \alpha \cdot g_\gamma / (\pi \cdot f_a)$,
    where g_γ is model dependent and O(1).
    Note: $g_{a\gamma\gamma} = \alpha \cdot g_\gamma / (\pi \cdot 6 \cdot 10^6\text{GeV}) \cdot m_a$



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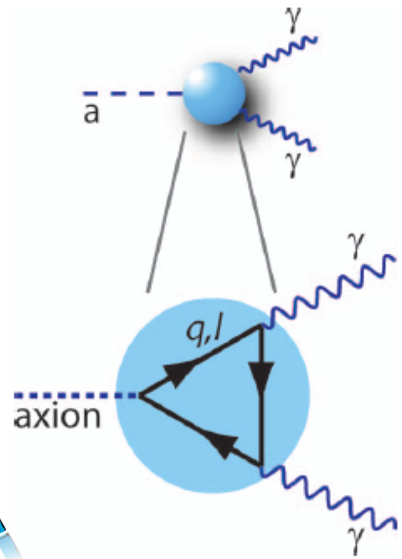
    Note: $g_{a\gamma\gamma} = \alpha \cdot g_\gamma / (\pi \cdot 6 \cdot 10^6\text{GeV}) \cdot m_a$
  - The axion abundance in the universe:
    $\Omega_a / \Omega_c \sim (f_a / 10^{12}\text{GeV})^{7/6}$.

    $f_a < 10^{12}$GeV
    $m_a > \mu$eV

NON-THERMAL ORIGIN FROM VACUUM RE-ALIGNMENT



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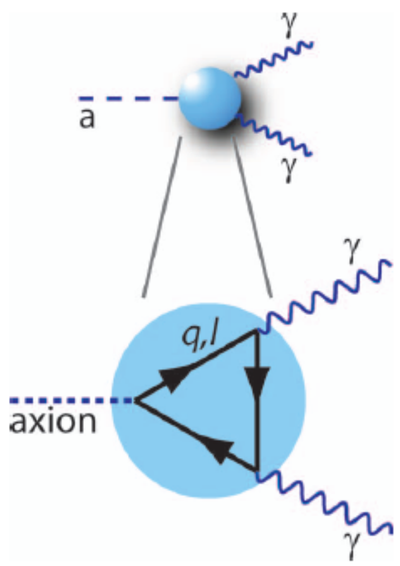
VERY LIGHTWEIGHT COLD DARK MATTER!



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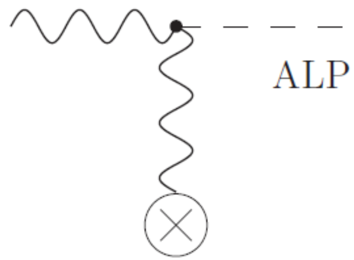
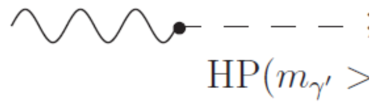
More general: WISPy particles

Weakly Interacting Slim Particles (WISPs):

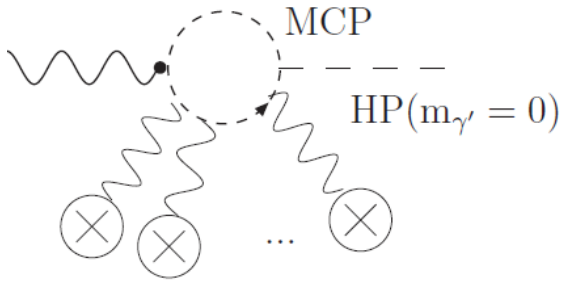
- Axions and
  axion-like particles
  ALPs, pseudoscalar or scalar bosons,
  m and g are not related by an f.



- Hidden photons (neutral vector bosons)



- Mini-charged particles



- Chameleons (self-shielding scalars), massive gravity scalars

Such WISPs are expected by theory

- Axions, ALPs and other WISPs occur naturally in string theory inspired extensions of the standard model as components of a “hidden sector”.

JHEP — Published for SISSA by Springer

Received: *July 13, 2012*
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Published: *October 22, 2012*

The type IIB string axiverse and its low-energy phenomenology

Michele Cicoli,[a,b] Mark D. Goodsell[c] and Andreas Ringwald[d]

DOI: 10.1007/JHEP10(2012)146
http://www.arxiv.org/abs/1206.0819v1

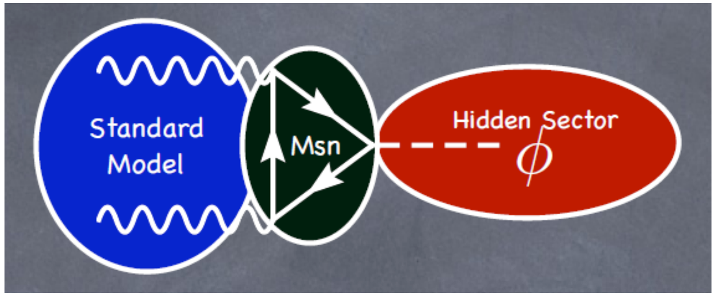
DESY 14-020

The Quest for an Intermediate-Scale Accidental Axion and Further ALPs

A. G. Dias[1,*] A. C. B. Machado[2,†] C. C. Nishi[1,‡] A. Ringwald[3,§] and P. Vaudrevange[4¶]

http://arxiv.org/abs/arXiv:1403.5760

- Their weak interaction might be related to very heavy messenger particles.
  Thus WISPs may open up a window to particle physics at highest energies.



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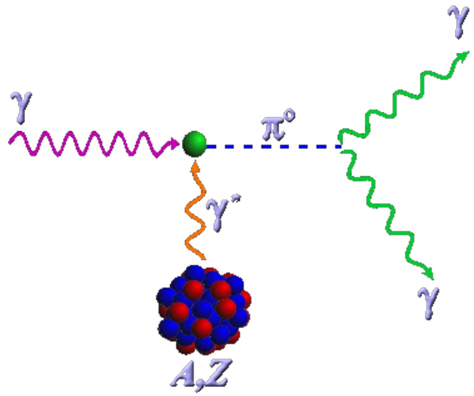
- Therefore the Primakoff effect will also work for the axion!



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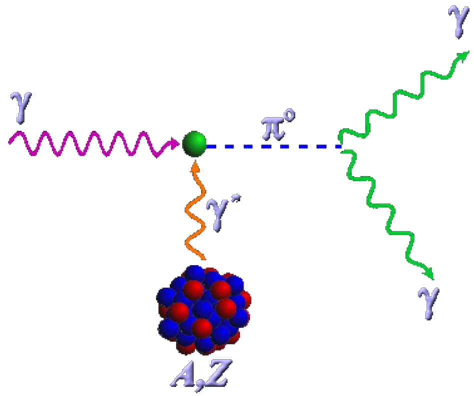
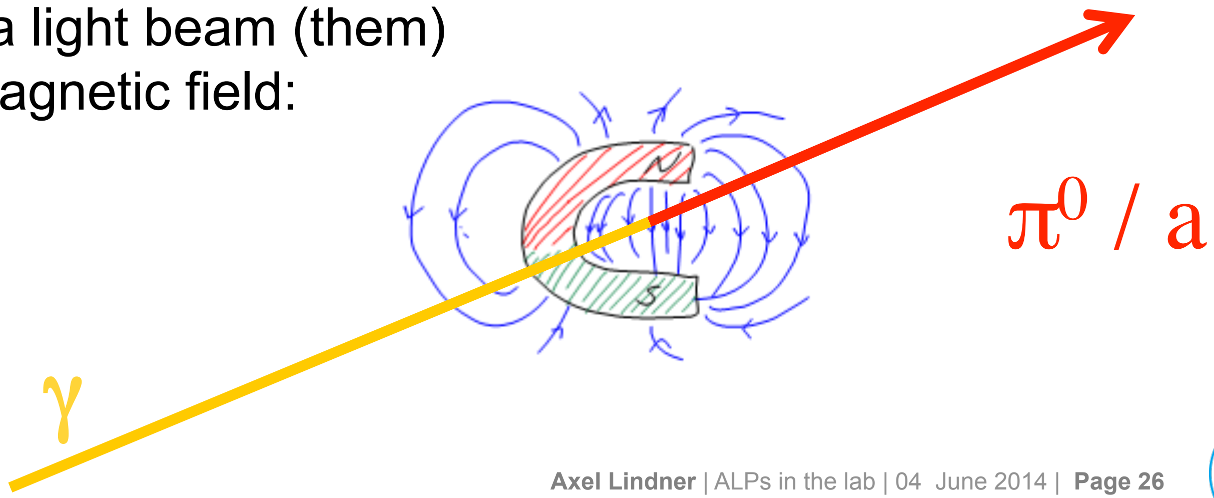


- Axions could be produced (detected) by sending a light beam (them) through a magnetic field:



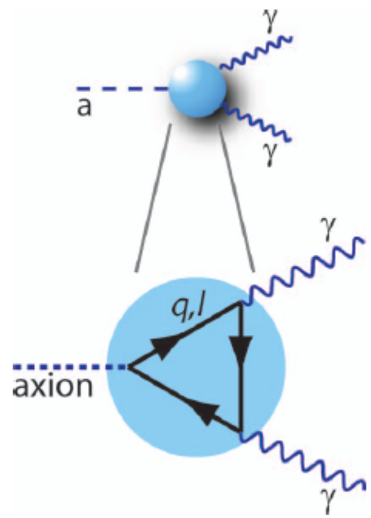
Basics of WISP experiments (I)

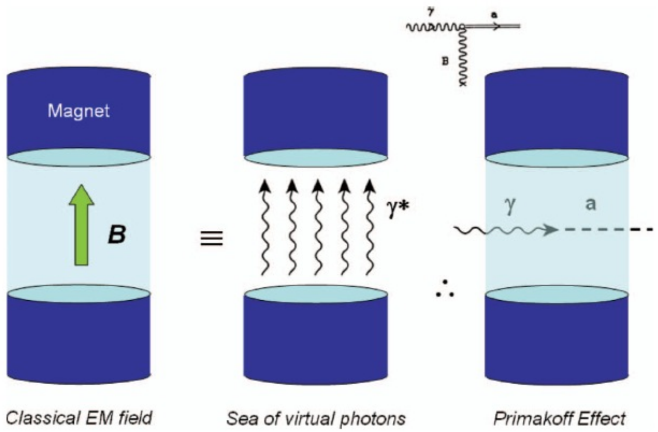
Weakly Interacting Slim Particles (WISPs) can be searched for by

converting WISPs to photons (and vice versa) via

- kinetic mixing (hidden photons)
- the Primakoff effect (axion-like particles)
  - photon + (virtual) photon → ALP
    ALP + (virtual) photon → photon

    A virtual photon can be provided by
    an electromagnetic field.



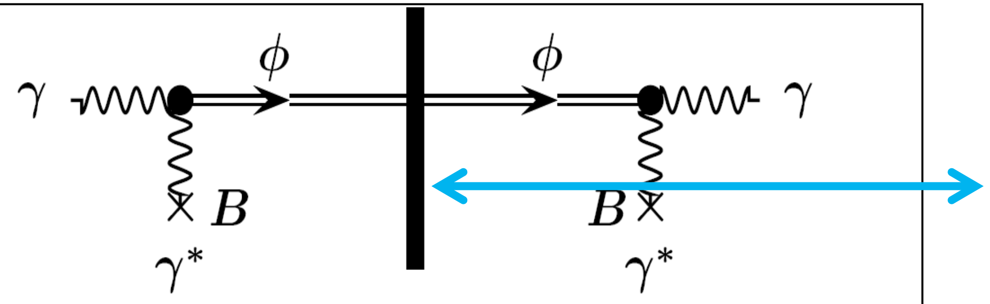


The Search for Axions,
Carosi, van Bibber, Pivovaroff,
Contemp. Phys. 49, No. 4, 2008

Basics of WISP experiments (II)

- Basic idea: due to their very weak interaction WISPs may traverse any wall opaque to Standard Model constituents (except ν and gravitons).
  - WISP could transfer energy out of a shielded environment
  - WISP could convert back into detectable photons behind a shielding.

- "Light-shining-through-a-wall" (LSW)



Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

steel wall, cryostat,
earth's atmosphere,
stellar body,
intergalactic background light,
….

Basics of WISP experiments (III)

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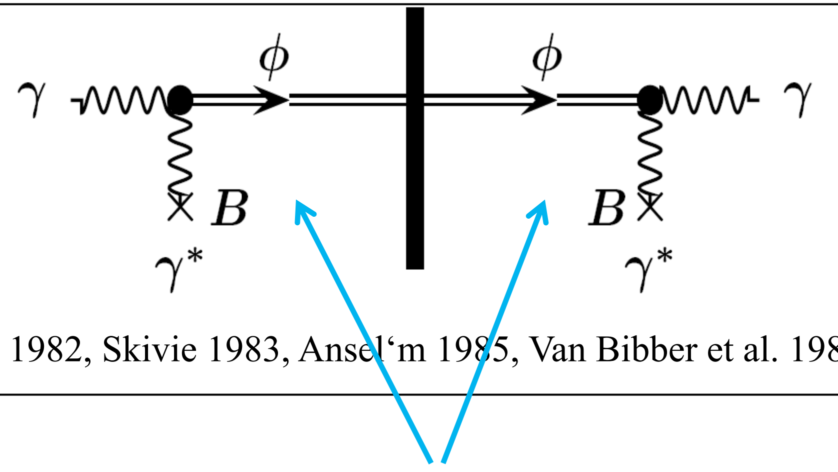

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Real WISPs are produced!

Basics of WISP experiments (IV)

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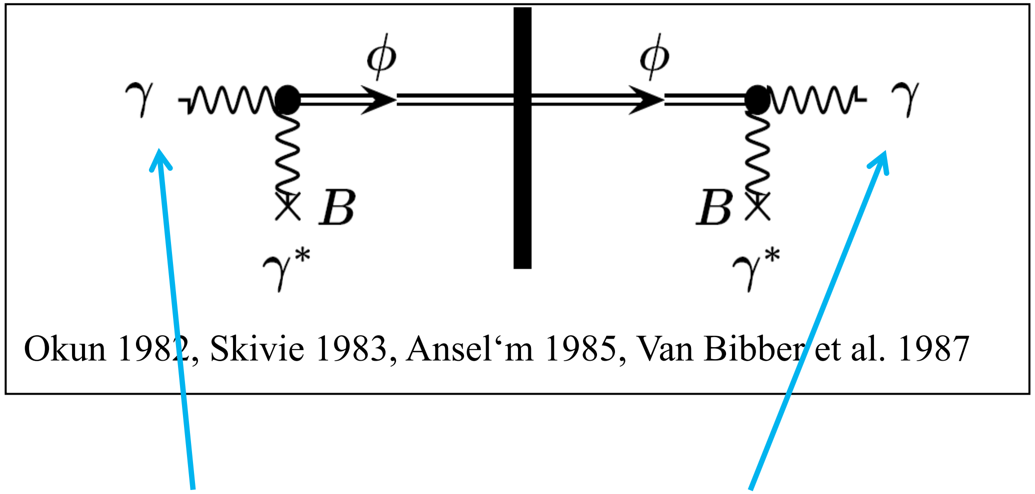
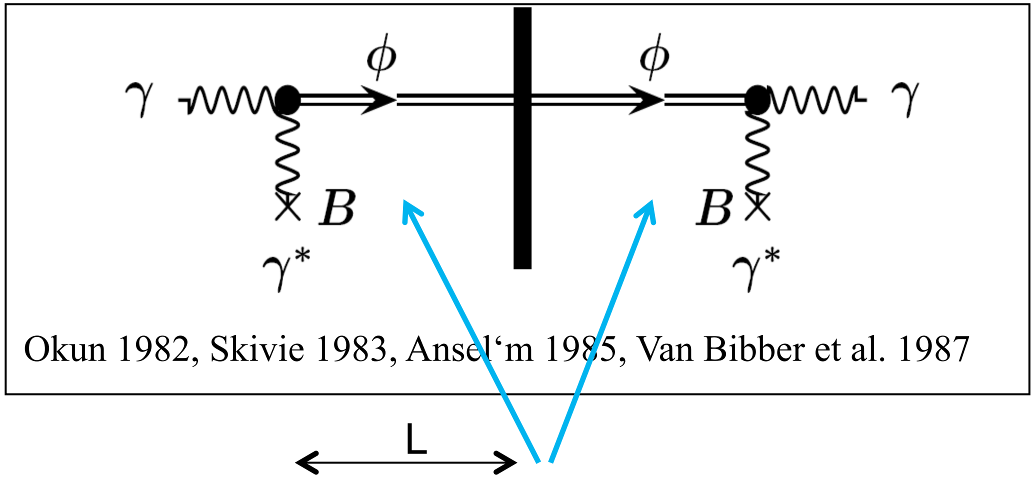


The primary and the regenerated photons have exactly the same properties (energy, polarization).

Basics of WISP experiments (V)

- Basic idea: due to their very weak interaction WISPs may traverse any wall opaque to Standard Model constituents (except ν and gravitons).
  - WISP could transfer energy out of a shielded environment
  - WISP could convert back into detectable photons behind a shielding.

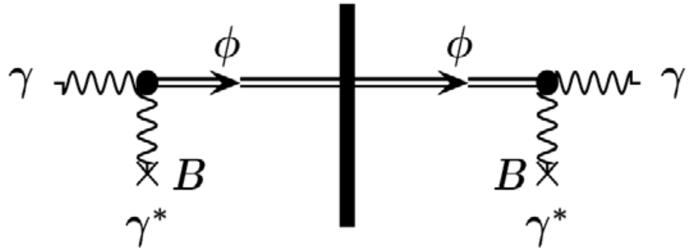
"Light-shining-through-a-wall" (LSW)



Coherent production and regeneration: $P_{\gamma\rightarrow\Phi} \propto (B\cdot L)^2$

ALPs in LSW experiments

- The production (and re-conversion) of WISPs takes place in a coherent fashion.

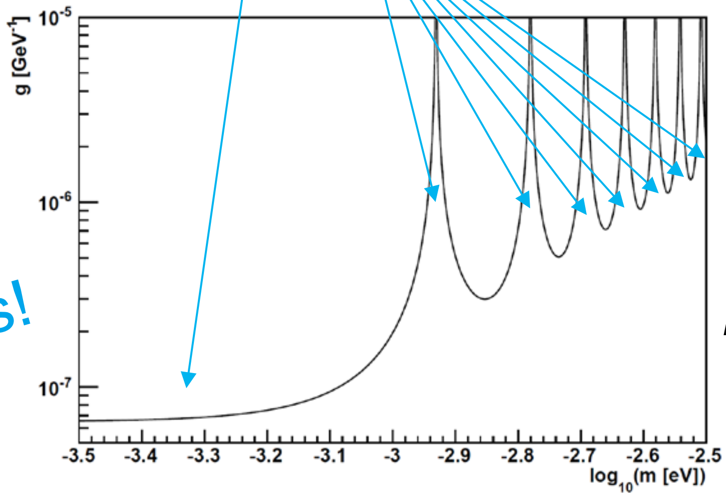


With: *$q = p_\gamma - p_\Phi \approx ½ \cdot m^2/\omega$*
l: length of B field

$$P_{\gamma\to\phi}(B,\ell,q) = \frac{1}{4}\,(g\,B\,\ell)^2\;F(q\ell) \qquad F(q\ell) = \left[\frac{\sin\left(\frac{1}{2}q\ell\right)}{\frac{1}{2}q\ell}\right]^2$$

With $P_{\gamma\to\Phi}=P_{\Phi\to\gamma}= P^{1/2}$: $g = (P)^{1/4} \cdot 2 \cdot / (L\cdot B) / F^{1/2}$

P =
(photon flux behind wall) /
(flux before wall)



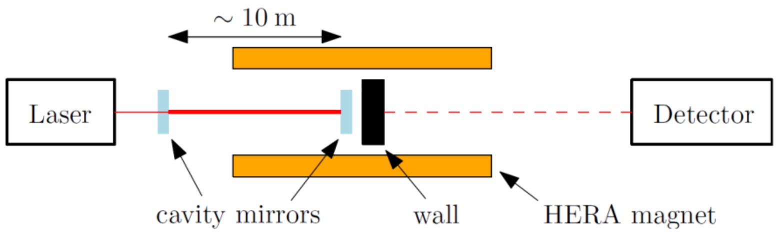
Example: the ALPS I experiment with 2.3 eV photons.

Relativistic ALPs / axions!

Three kinds of WISP searches

Weakly Interacting Slim Particles (WISPs) are searched for by

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



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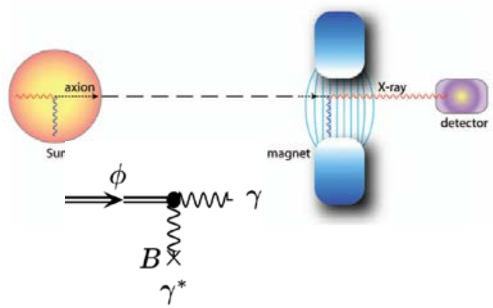

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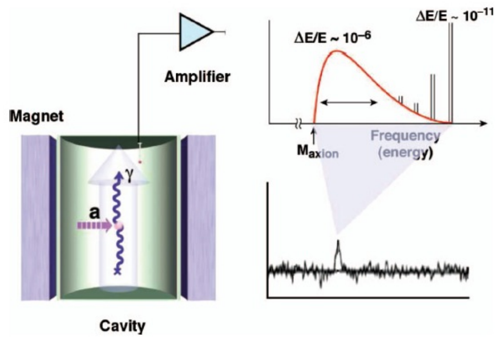

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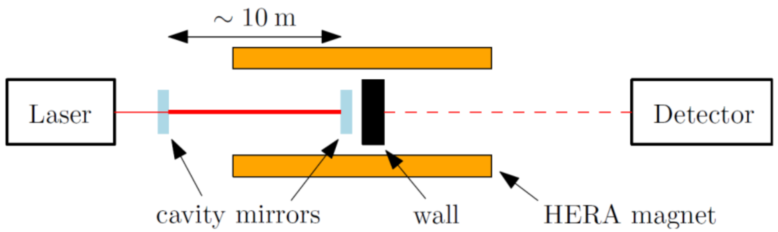

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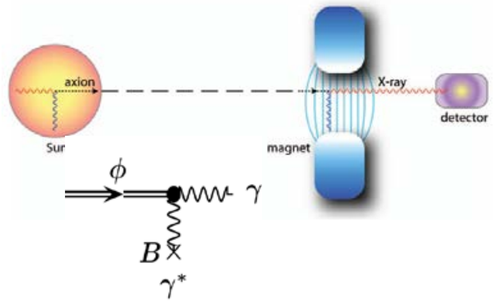

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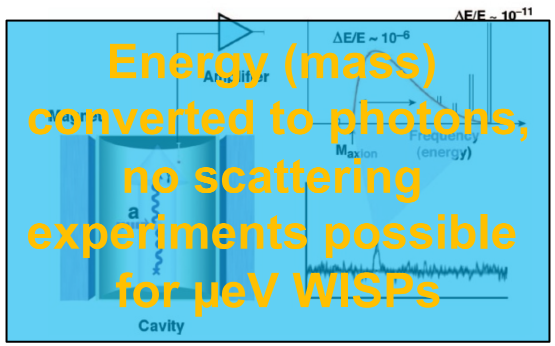

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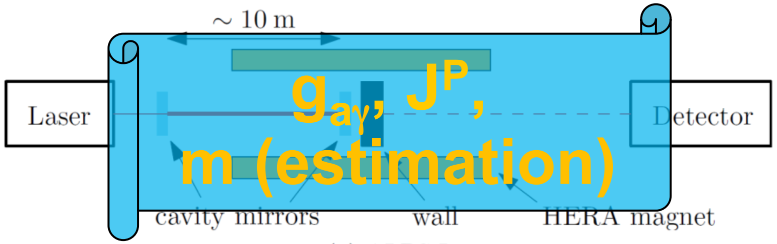

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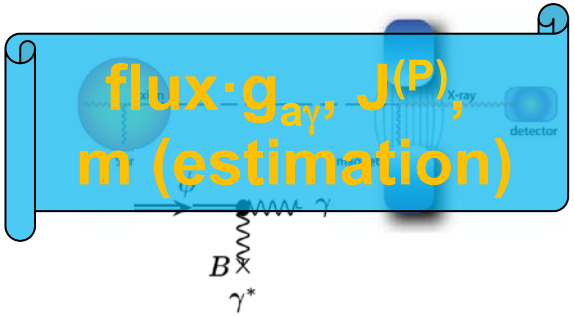

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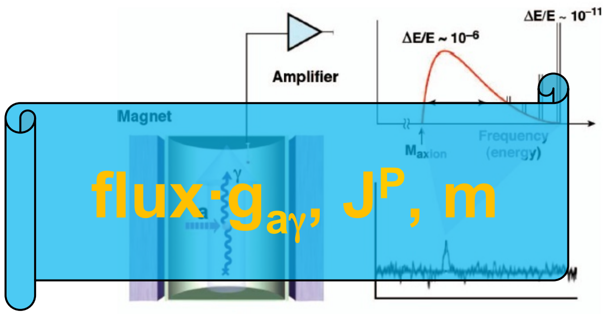

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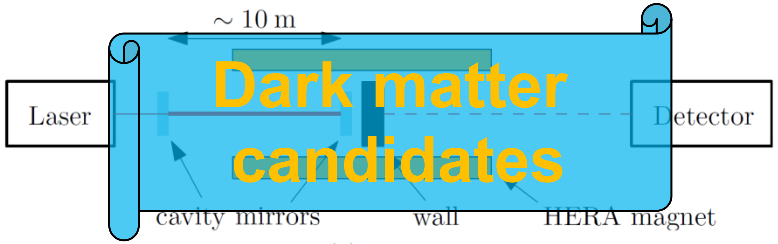

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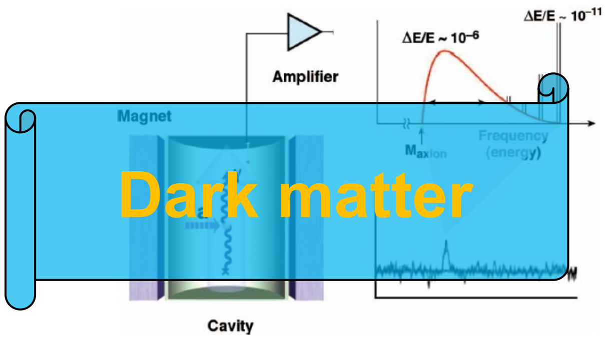

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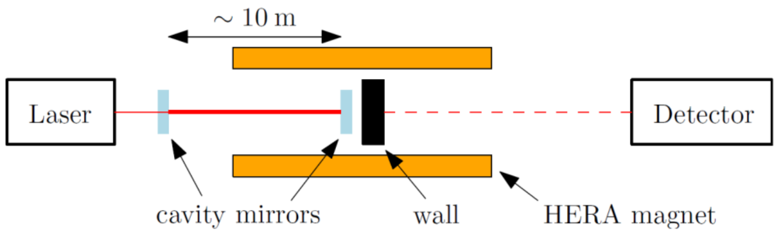

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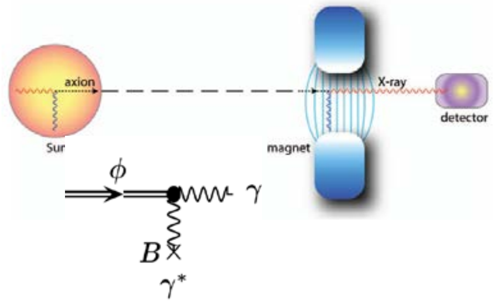

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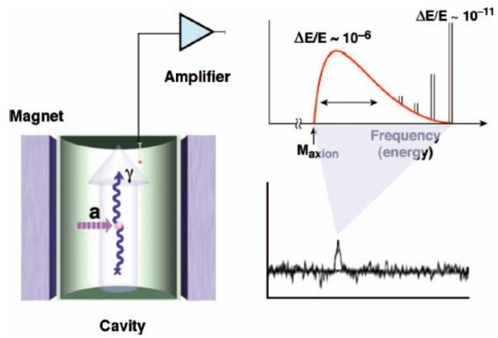

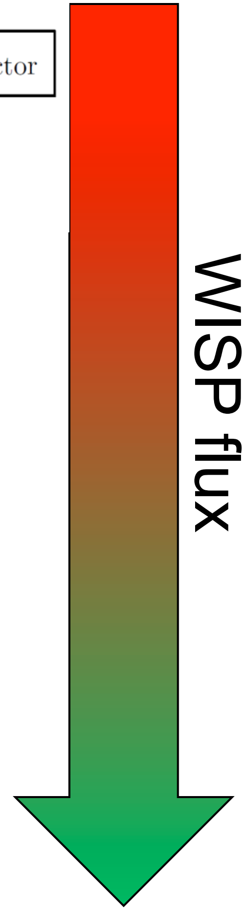

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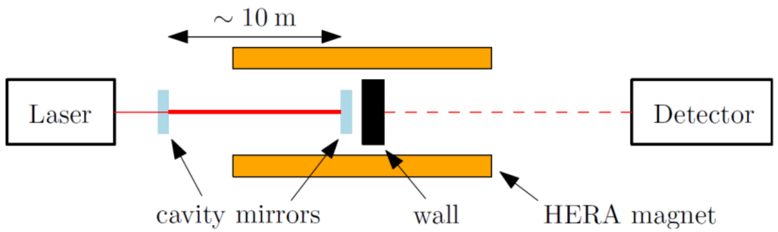

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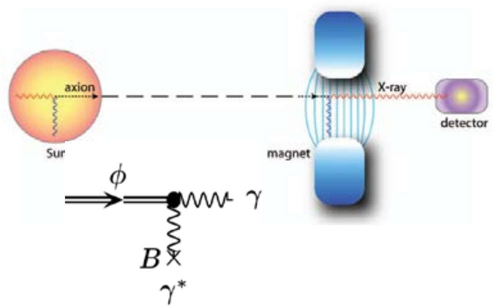

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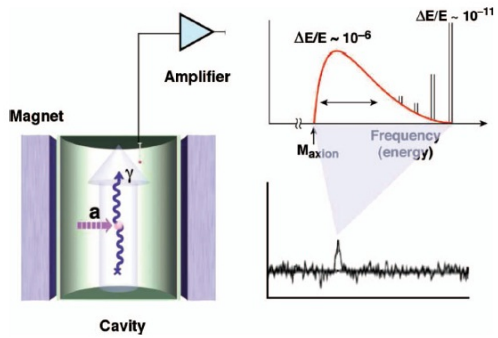

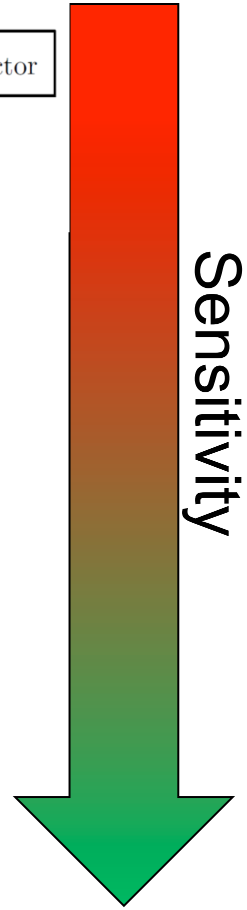

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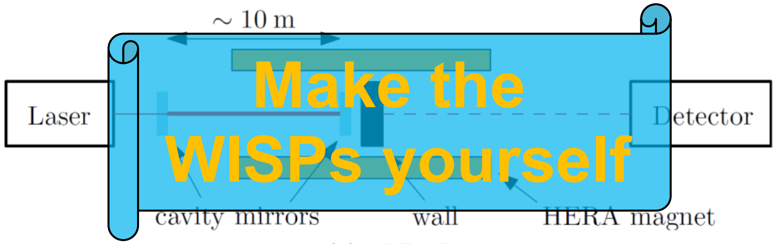

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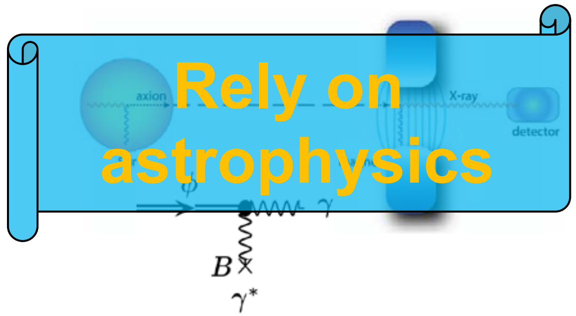

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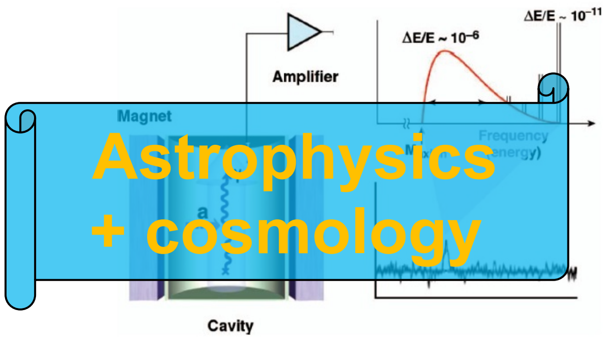

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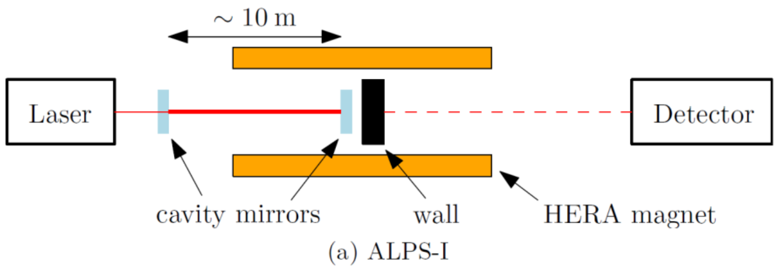

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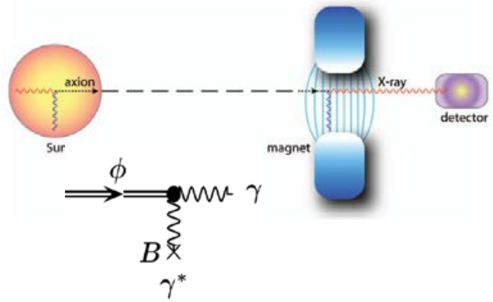

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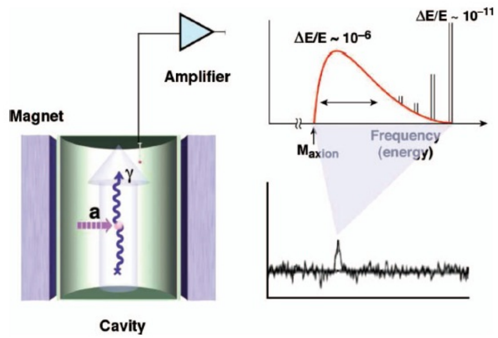

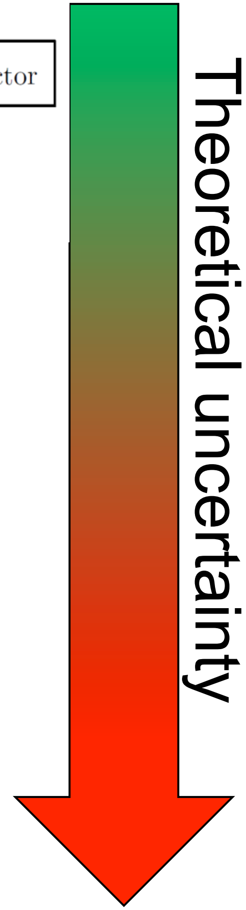

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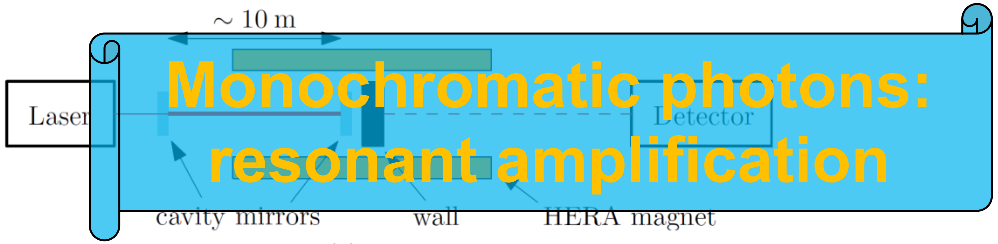

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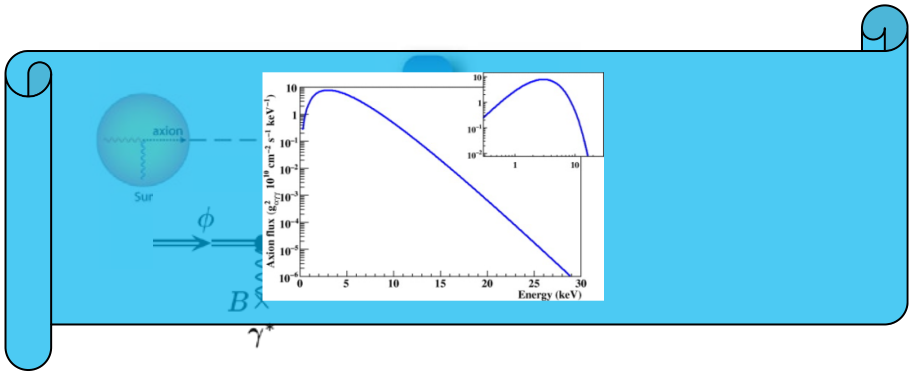

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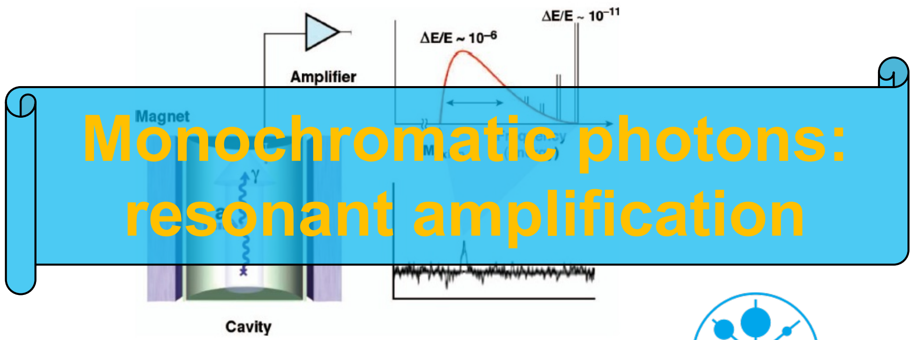
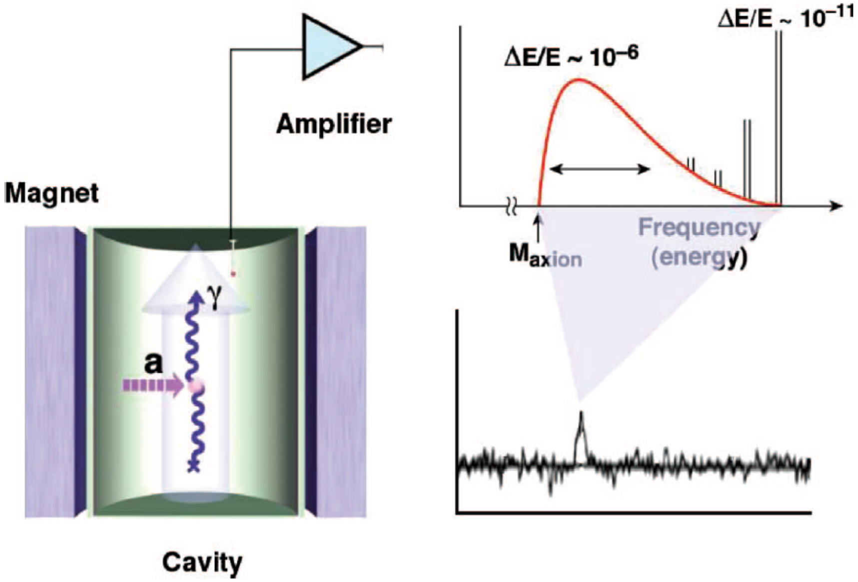


The Dark Matter case: ALPs at rest

- Cold Dark Matter: ALPs / axions move at non-relativistic speeds.

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

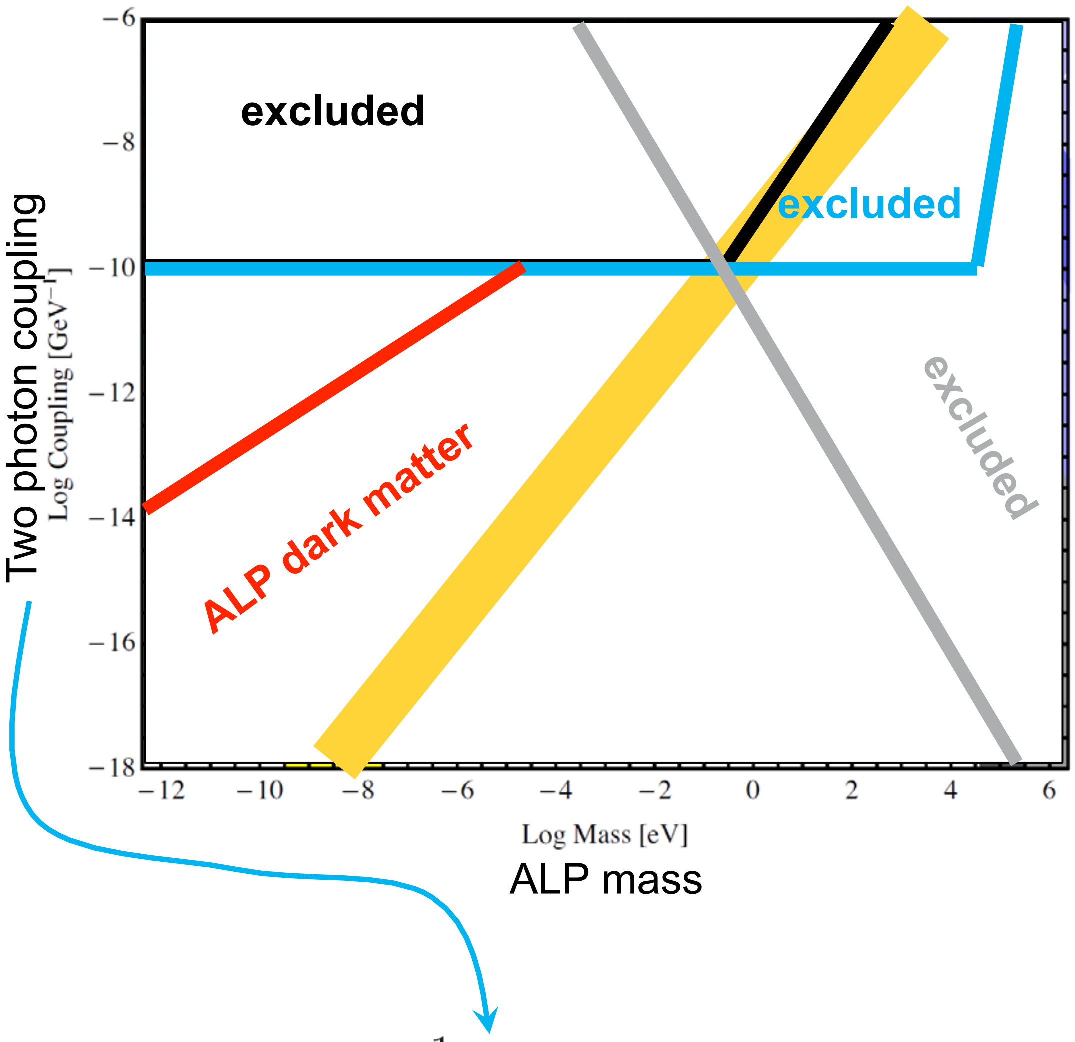
- When converting to photons, the photon energy is given by the WISP rest mass + an $O(10^{-6})$ correction.



$$P_{a\to\gamma} \propto \left(B_0^2 V Q\right)\left(g_\gamma^2 \frac{\rho_a}{m_a}\right)$$

Cavity volume (B_0^2) — Cavity power build-up (Q) — Axion number density (ρ_a)

The big picture: ALPs



QCD axion range

Excluded by WISP experiments

Excluded by astronomy (ass. ALP DM)

Excluded by astrophysics / cosmology

Axions or ALPs being cold dark matter

$$P_{\gamma\to\phi}(B,\ell,q) = \frac{1}{4}\,(g\,B\,\ell)^2\;F(q\ell)$$

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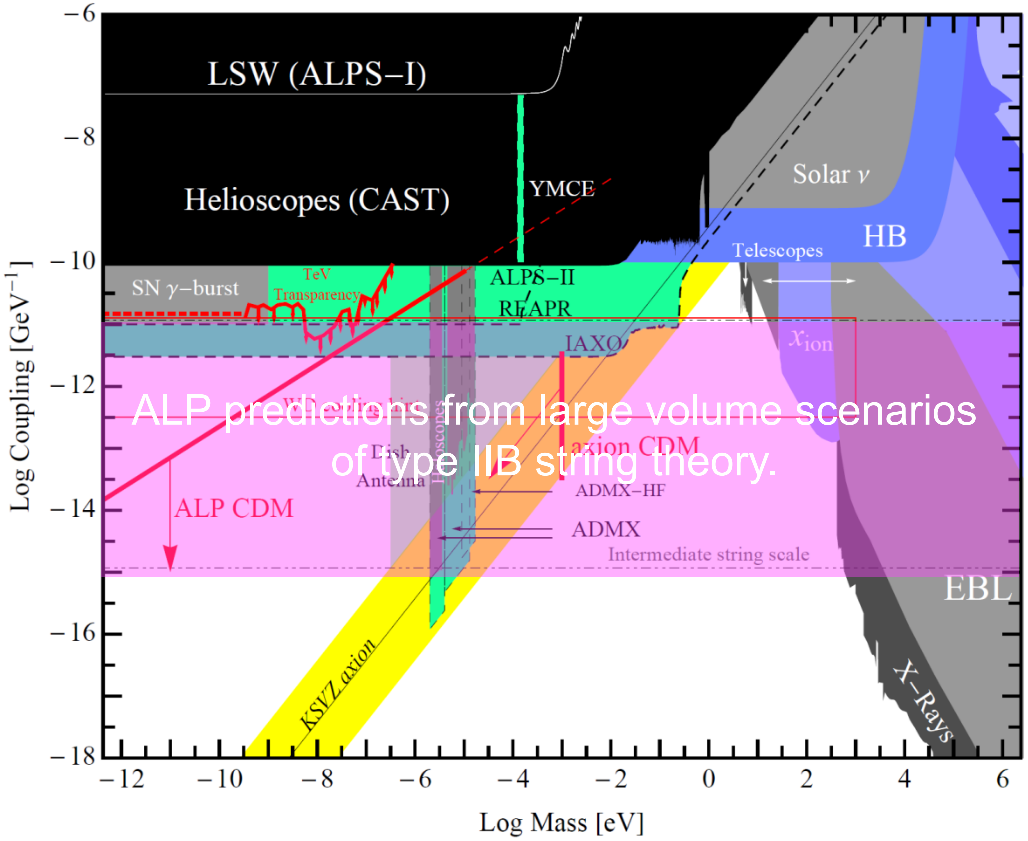

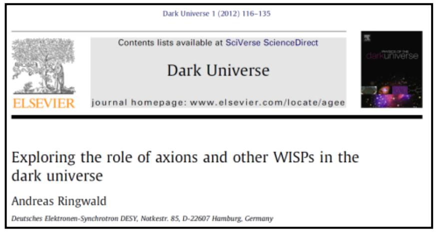

DOI: 10.1016/j.dark.2012.10.008
e-Print: **arXiv:1210.5081 [hep-ph]**

QCD axion range
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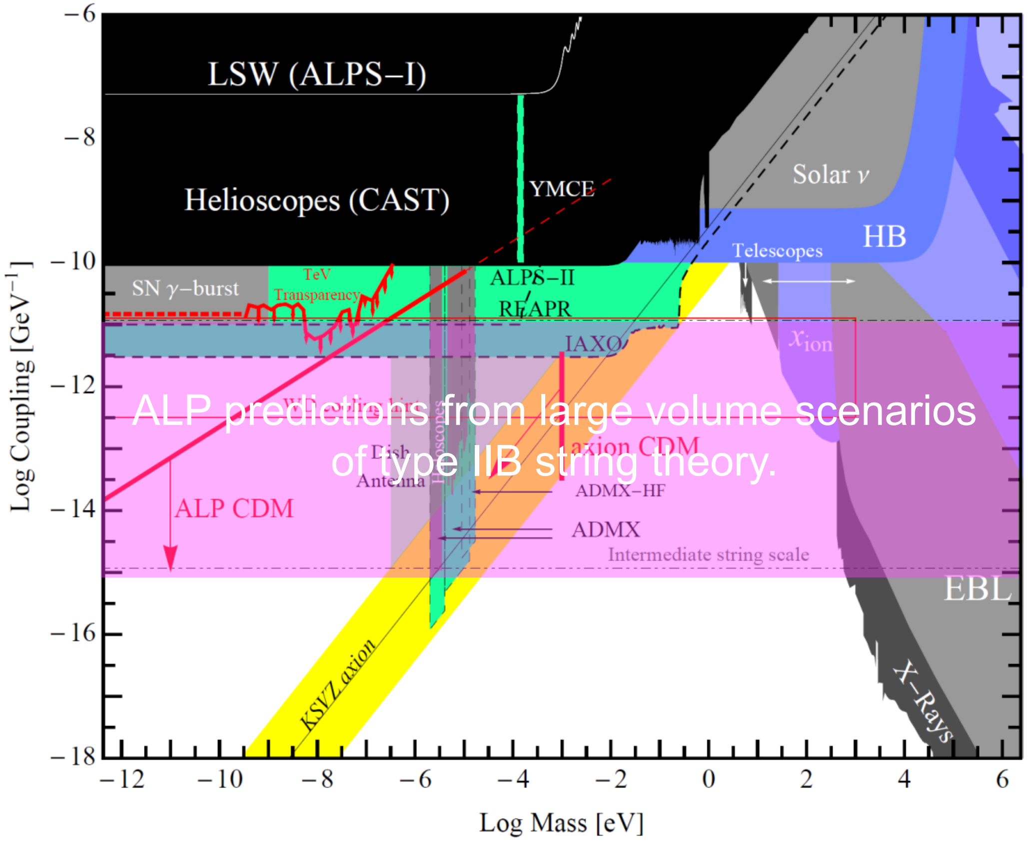
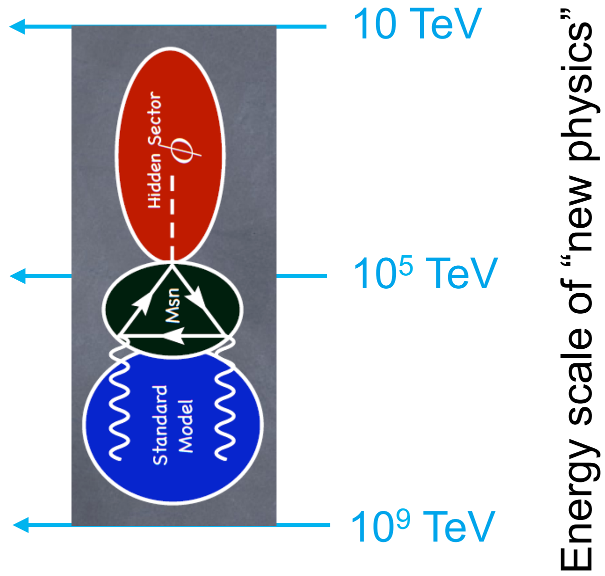
Sensitivity of next generation WISP exp.

Particular interesting:

> ALP-photon couplings around 10^{-11}GeV^{-1}, masses below 1 meV. Such ALPs are predicted by string theory.

The big picture: ALPs





Particular interesting:

- ALP-photon couplings around $10^{-11}GeV^{-1}$, masses below 1 meV. Physics at a scale of 10^5 TeV will be probed.

Outline

- Some motivation
- A little bit of theory
- Basics of WISP experiments
- Exemplary experiments
- Indications for a WISPy world?
- Summary

WISP experiments worldwide

An incomplete selection of (mostly) small-scale experiments:

Experiment	Type	Location	Status
ALPS II	Laboratory experiments, light-shining-through-a-wall	DESY	construction
CERN microwave cavity experiment		CERN	finished
OSQAR		CERN	running
REAPR		FNAL	proposed
CAST	Helioscopes	CERN	running
IAXO		?	proposed
SUMICO		Tokyo	running
TSHIPS		Hamburg	running
ADMX	Haloscope	Seattle, NH	running
WISPDMX		DESY in HH	studies

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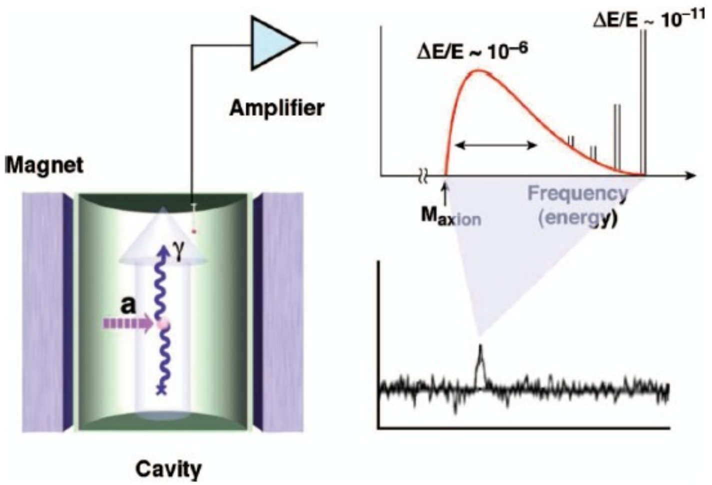
DESY

Haloscopes


MHP
MAXIMUM HUMAN PERFORMANCE
High Velocity
Nano - Physics
DARK MATTER™
The Ultimate Post Workout Muscle Growth Accelerator*
Absorbs Faster Than Whey Isolate*
600% Increase in Protein Synthesis–Equal to 40 Grams of Protein*
Dramatically Spikes Insulin with WaxiMAX-C3G™*
Multi-Phase HydroSIZE™ Creatine Transport*
Replenishes Glycogen and Increases Cell Volume*
2.6lbs (1200g)
Dietary Supplement
Blue Raspberry

Searches for WISPy cold dark matter

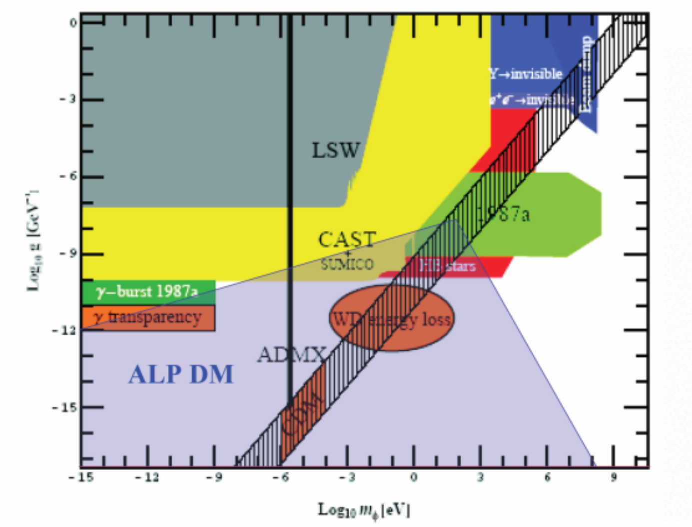
- Due to their low mass WISPy cold dark matter can not be detected by recoil techniques.
- WISPy dark matter particles have to convert into photons in a thoroughly shielded environment.
- The mass of the dark matter particle determines the energy to be detected. For axions it is in the microwave range.
- The resonance frequency of the cavity is to be tuned to the WISP mass to be probed.
This is a very time consuming process!

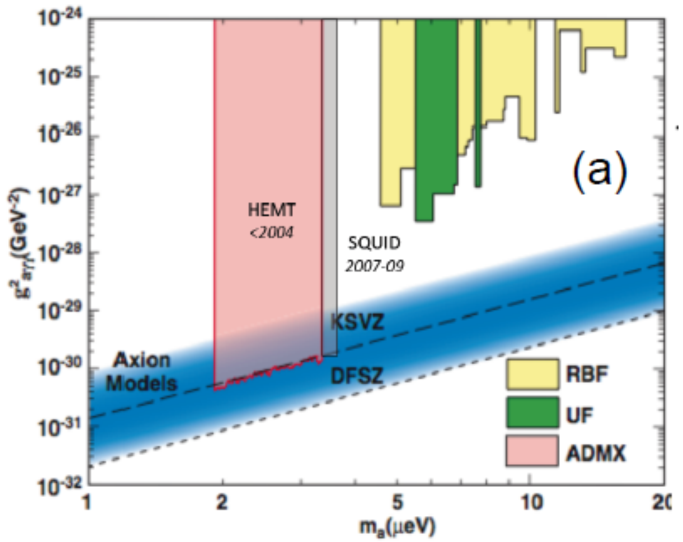


The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008

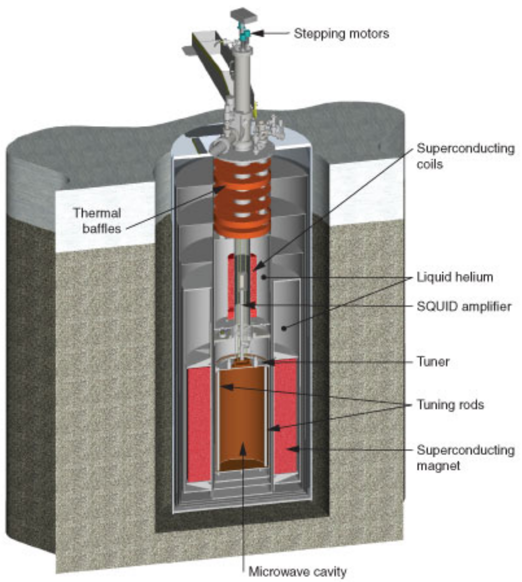
ADMX

- ADMX at Washington university, Seattle.
- Sufficient sensitivity to detect DM axions,
  - if they constitute all of the DM,
  - if the KSVZ model is right,
  - if axions happen to have the right mass.





arXiv:1405.3685 [physics.ins-det]



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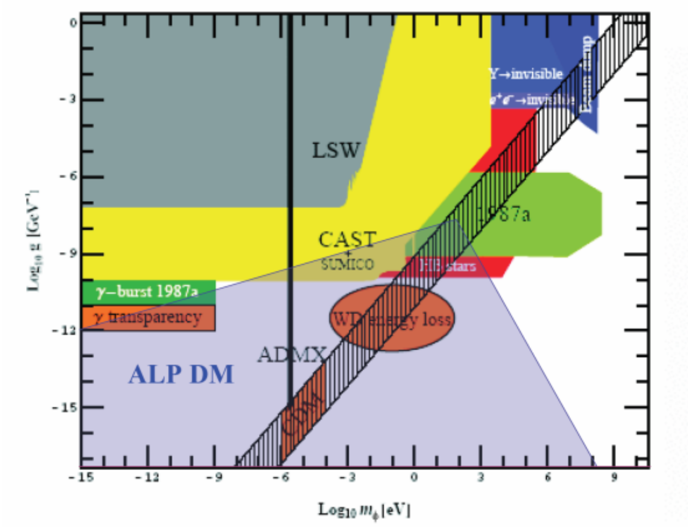

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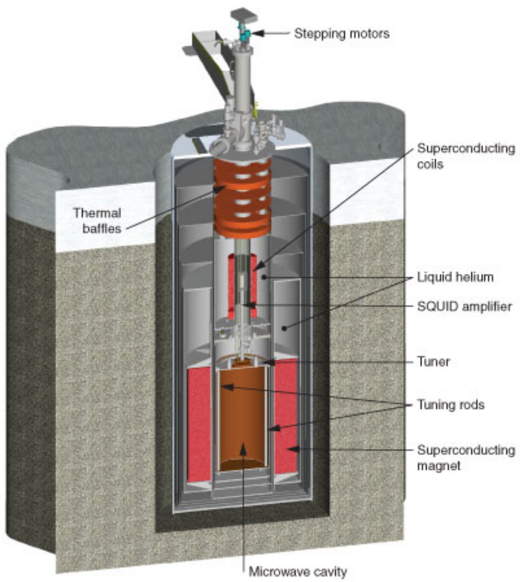

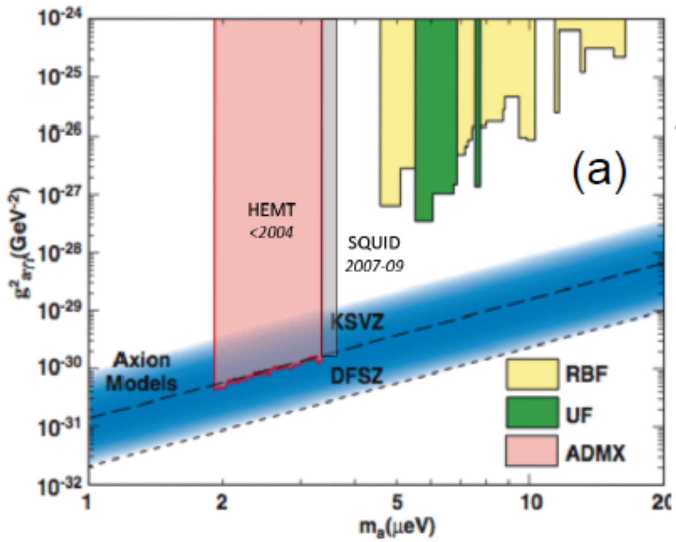

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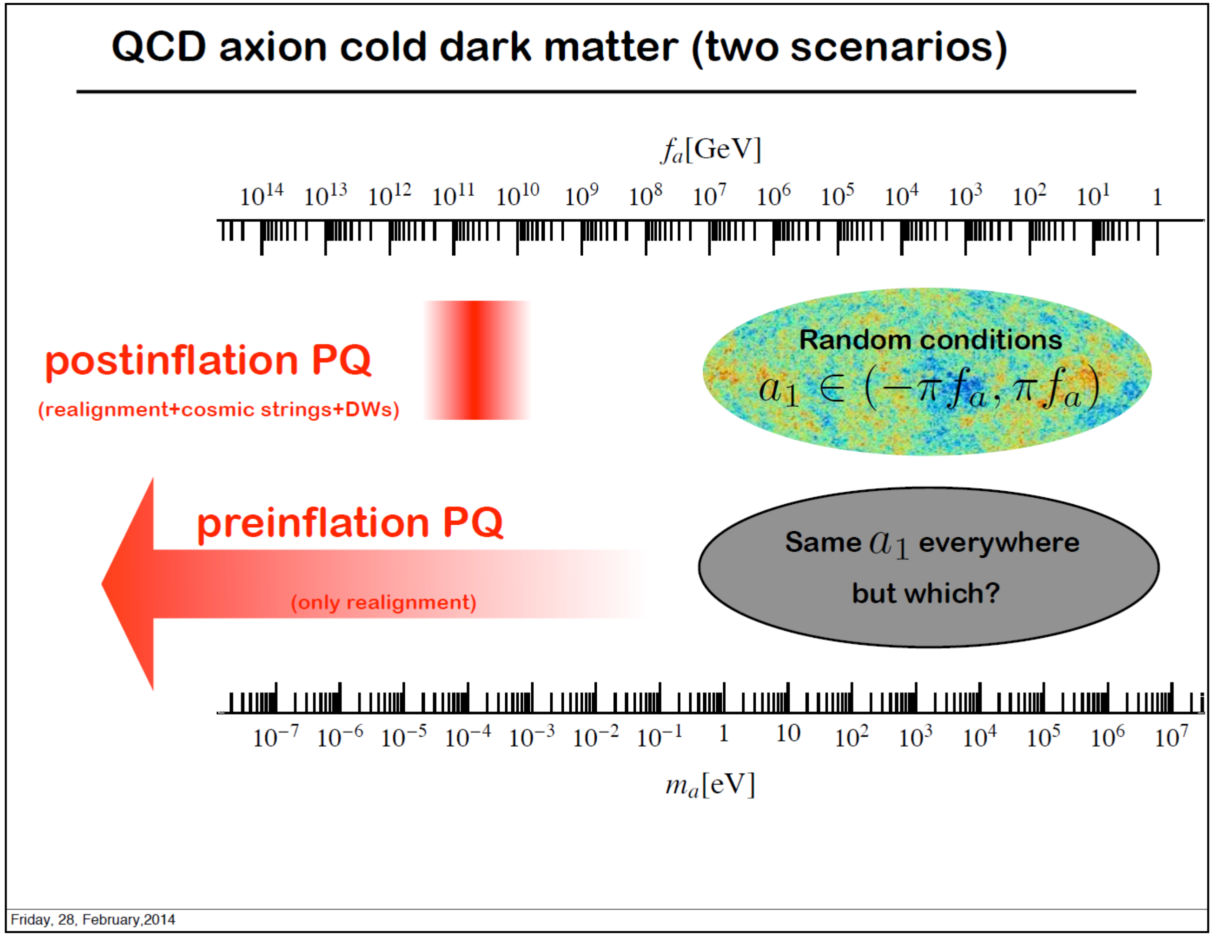
Extending the DM search mass range

DM axions might hide in a large mass region:



Courtesy of Javier Redondo

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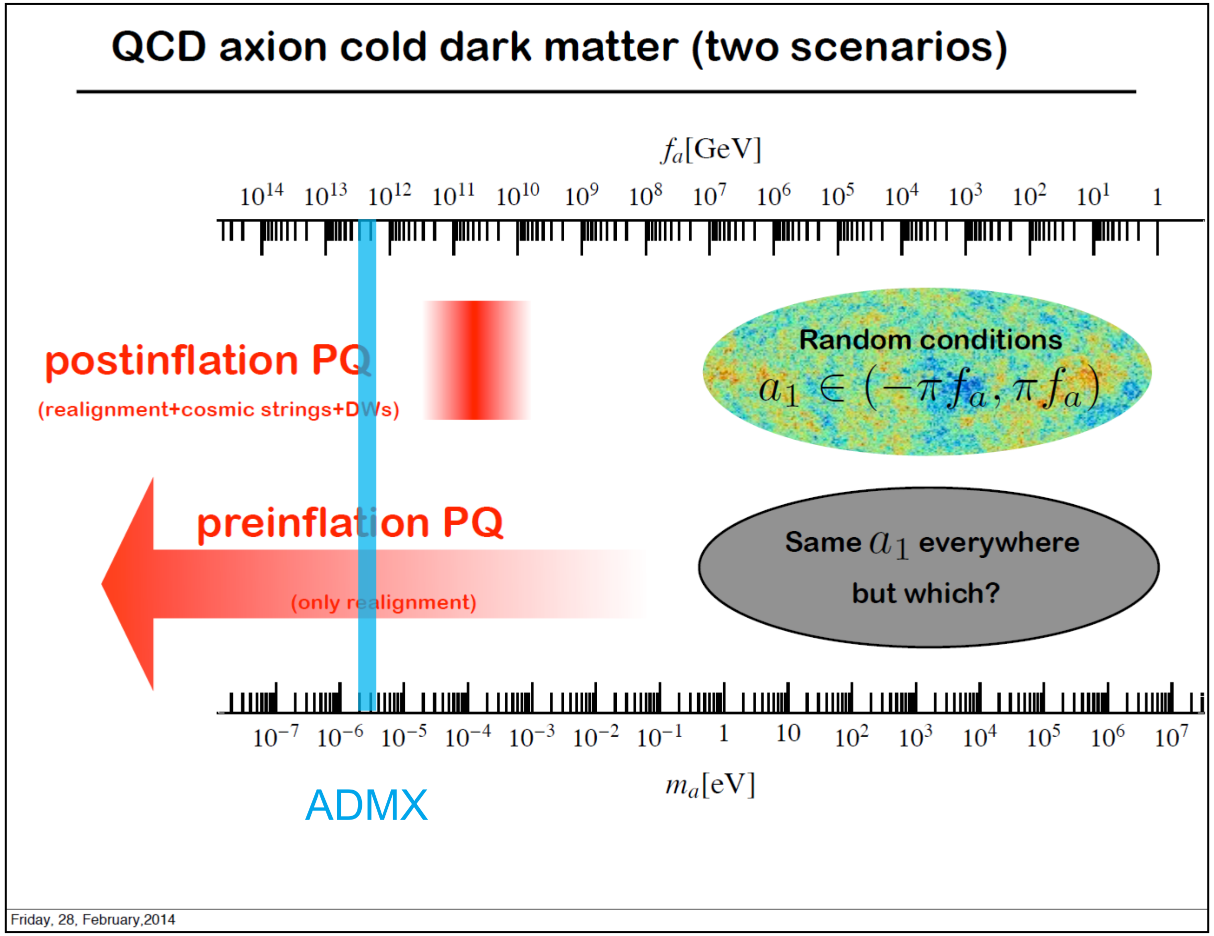

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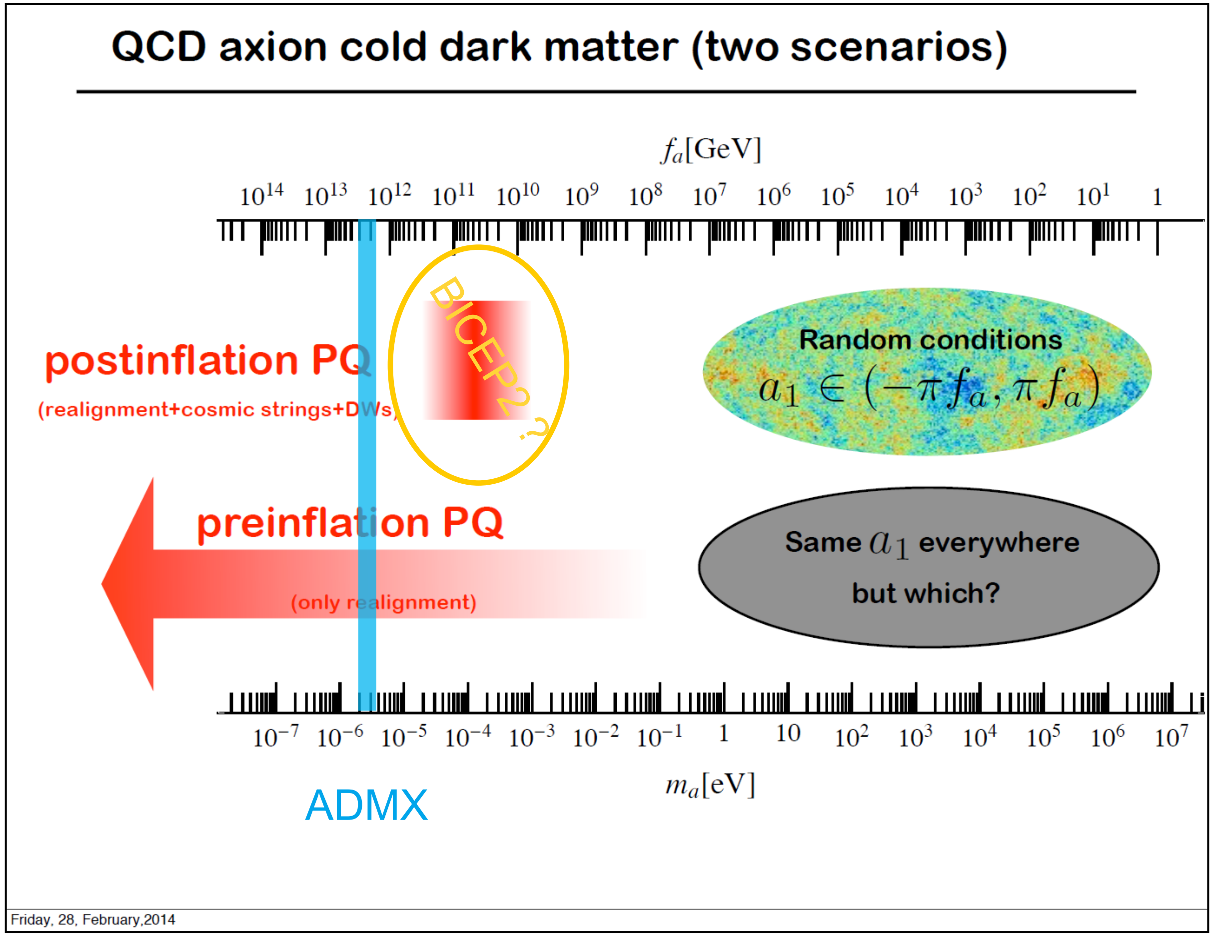


Courtesy of Javier Redondo

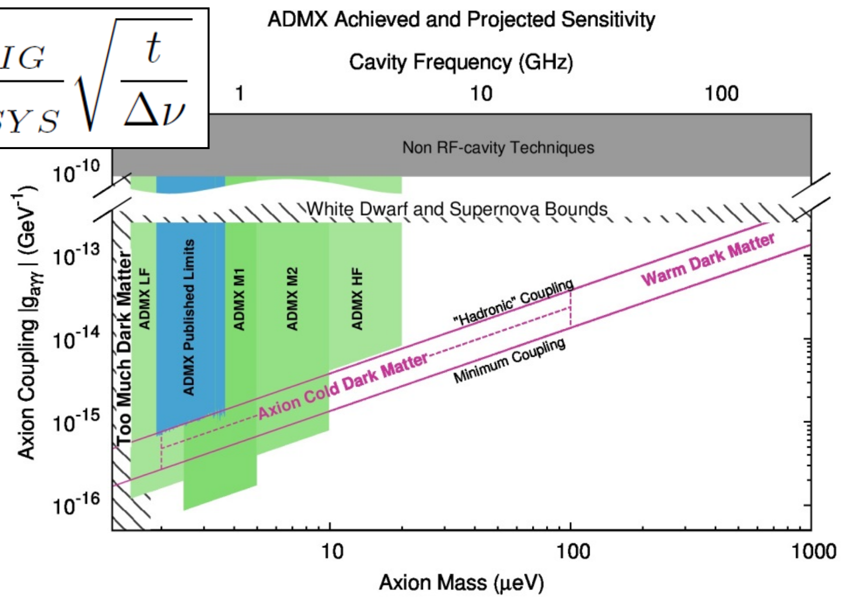
Extending the DM search mass range

- Option 1: improve on cavity experiments
- Option 2: approaches to new broad-band searches

Extending the DM search mass range

- Option 1: improve on cavity experiments
  - ADMX will be upgraded with a new SQUID amplifier and dilution refrigerator to cover a mass region up to 10 µeV.
  - ADMX-HF will be a pathfinder for higher masses and test-bed for hybrid superconducting cavities (to be placed in a 10 T field). Up to a few 10 µeV?
  - For searches above 10 GHz photonic-band-gap cavities are evaluated.

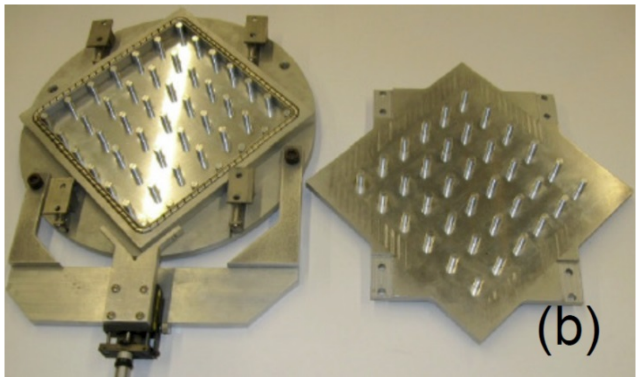
$$\frac{S}{N} = \frac{P_{SIG}}{kT_{SYS}}\sqrt{\frac{t}{\Delta\nu}}$$



http://www.phys.washington.edu/groups/admx/home.html

Get smaller!

$$P_{a\to\gamma} \propto \left(B_0^2 V Q\right)\left(g_\gamma^2 \frac{\rho_a}{m_a}\right)$$



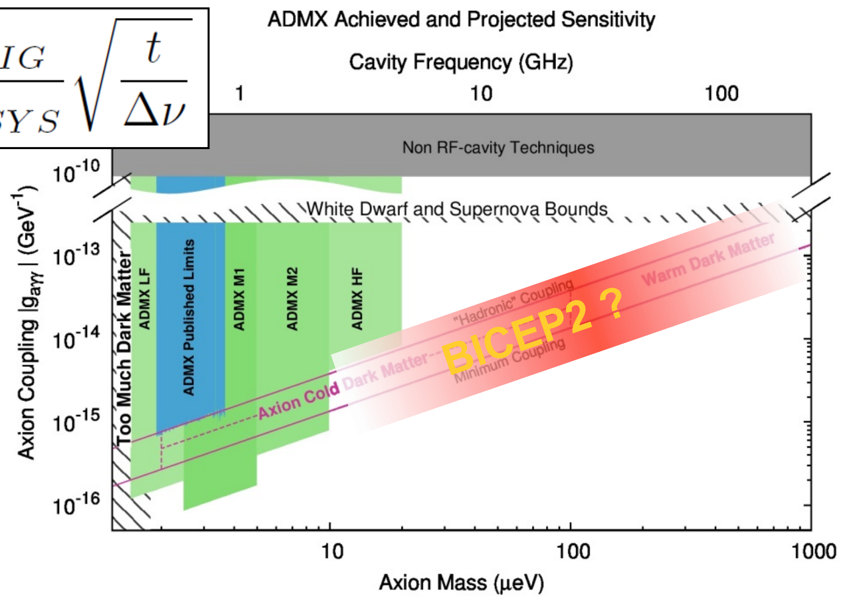
arXiv:1405.3685 [physics.ins-det]

Extending the DM search mass range

> Option 1: improve on cavity experiments

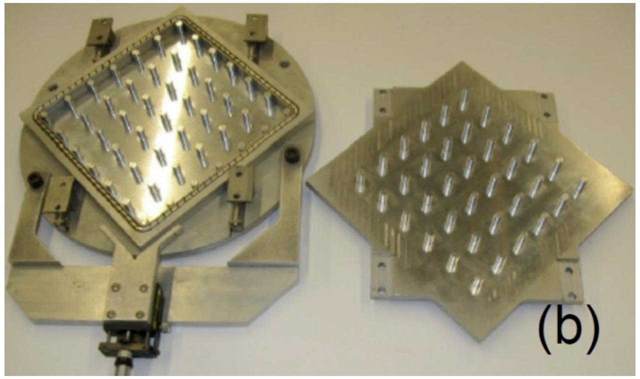
- ADMX will be upgraded with a new SQUID amplifier and dilution refrigerator to cover a mass region up to 10 µeV.
- ADMX-HF will be a pathfinder for higher masses and test-bed for hybrid superconducting cavities (to be placed in a 10 T field). Up to a few 10 µeV?
- For searches above 10 GHz photonic-band-gap cavities are evaluated.

$$\frac{S}{N} = \frac{P_{SIG}}{kT_{SYS}} \sqrt{\frac{t}{\Delta \nu}}$$



Get smaller!

$$P_{a\rightarrow\gamma} \propto \left(B_0^2 V Q\right)\left(g_\gamma^2 \frac{\rho_a}{m_a}\right)$$



arXiv:1405.3685 [physics.ins-det]

http://www.phys.washington.edu/groups/admx/home.html

Extending the DM search mass range

> Option 1: improve on cavity experiments

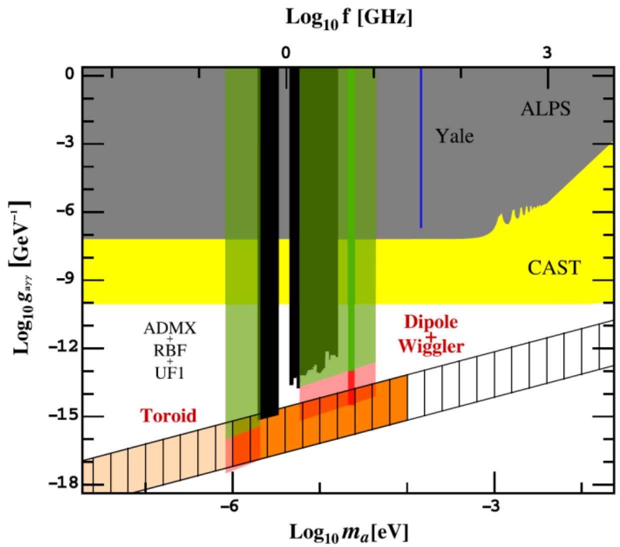
PHYSICAL REVIEW D **85**, 035018 (2012)

Prospects for searching axionlike particle dark matter with dipole, toroidal, and wiggler magnets

Oliver K. Baker,[1] Michael Betz,[2] Fritz Caspers,[2] Joerg Jaeckel,[3] Axel Lindner,[4] Andreas Ringwald,[4]
Yannis Semertzidis,[5] Pierre Sikivie,[6] and Konstantin Zioutas[7]
[1]*Department of Physics, Yale University, New Haven, Connecticut 06520-8120, United States, USA*
[2]*CERN, CH-1211 Geneva, Switzerland*
[3]*Institute for Particle Physics Phenomenology, Durham DH1 3LE, United Kingdom*
[4]*Deutsches Elektronen Synchrotron DESY, Notkestrasse 85, D-22607 Hamburg, Germany*
[5]*Brookhaven National Laboratory, New York-USA*
[6]*Department of Physics, University of Florida, Gainesville, Florida 32611, USA*
[7]*University of Patras, Patras, Greece*
(Received 10 November 2011; published 17 February 2012)

> No really promising ideas on how to reach a sensitivity to probe DM axions,

> but ALP DM could be found!



Extending the DM search mass range

> Option 2: approaches to new broad-band searches

PHYSICAL REVIEW D **88**, 115002 (2013)

Resonant to broadband searches for cold dark matter consisting of weakly interacting slim particles

Joerg Jaeckel[1] and Javier Redondo[2,3]

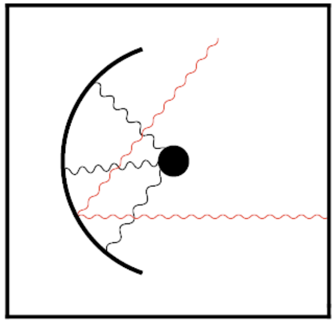
[1]*Institut für theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*
[2]*Arnold Sommerfeld Center, Ludwig-Maximilians-Universität, Theresienstrasse 37, 80333 Munich, Germany*
[3]*Max-Planck-Institut für Physik, Fohringer Ring 6, 80805 Munich, Germany*

(Received 6 September 2013; published 2 December 2013)

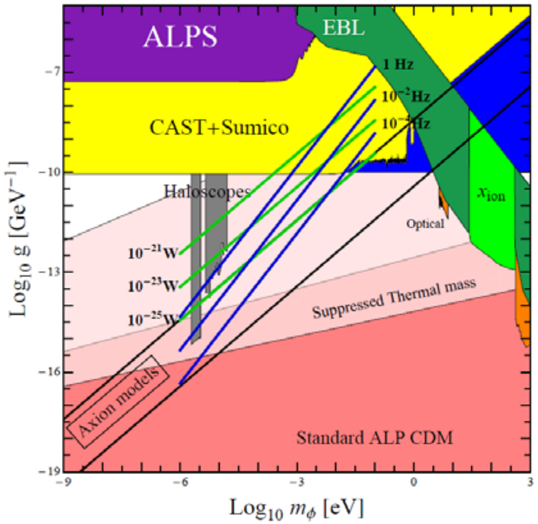
Extending the DM search mass range

> Option 2: approaches to new broad-band searches

- If the axion wave function encounters a sharp magnetic boundary, a (tiny) electromagnetic wave is reflected.
- This wave is emitted perpendicular to a reflecting surface (assuming a very slow moving axion).
- This emission can be concentrated onto a photon detector.
- With dish sizes of $1\,\mathrm{m}^2$ in a 5T field competitive sensitivities can be reached.



$$g_{\phi\gamma\gamma,\,\mathrm{sens}} = \frac{4.6\times10^{-6}}{\mathrm{GeV}}\left(\frac{5\,\mathrm{T}}{\sqrt{\langle|\mathbf{B}_{||}|^2\rangle}}\right)\left(\frac{R_{\gamma,\mathrm{det}}}{1\,\mathrm{Hz}}\right)^{\frac{1}{2}}\left(\frac{m_\phi}{\mathrm{eV}}\right)^{\frac{3}{2}}\left(\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_{\mathrm{DM,halo}}}\right)^{\frac{1}{2}}\left(\frac{1\,\mathrm{m}^2}{A_{\mathrm{dish}}}\right)^{\frac{1}{2}}$$



D. Horns et al., JCAP04 (2013) 016

> A tuning of cavities to a specific axion mass is not required!

Extending the DM search mass range

> Option 2: approaches to new broad-band searches

- This “dish antenna” approach even allows to measure the axion DM velocity distribution with respect to the dish.

J. Jaeckel, J. Redondo, JCAP11 (2013) 016

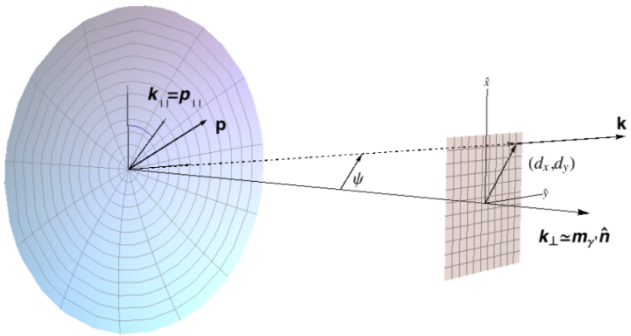
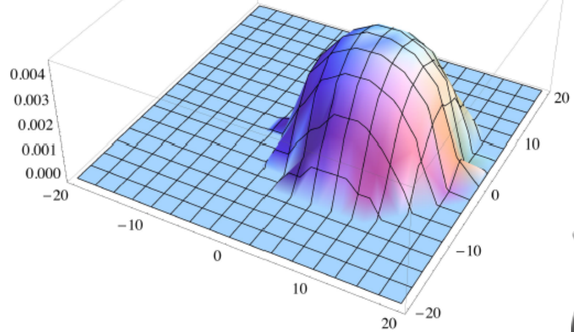


Image on a CCD



For some theory:

PHYSICAL REVIEW D **88**, 115002 (2013)

Resonant to broadband searches for cold dark matter consisting of weakly interacting slim particles

Joerg Jaeckel[1] and Javier Redondo[2,3]

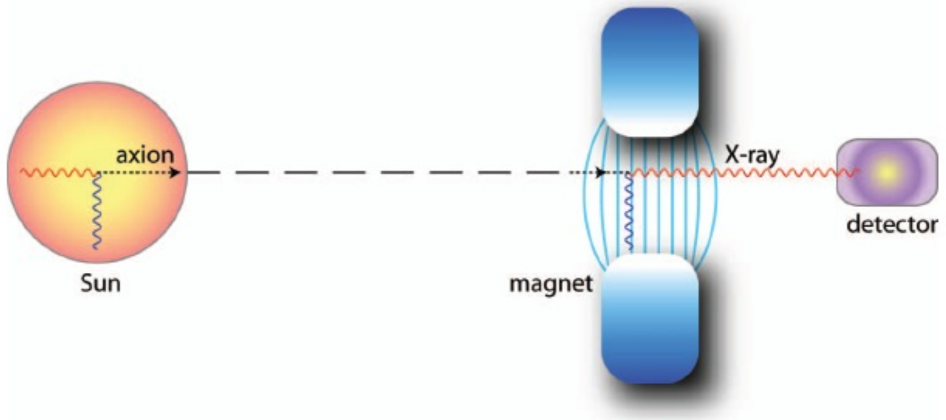
[1]*Institut für theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*
[2]*Arnold Sommerfeld Center, Ludwig-Maximilians-Universität, Theresienstrasse 37, 80333 Munich, Germany*
[3]*Max-Planck-Institut für Physik, Føhringer Ring 6, 80805 Munich, Germany*
(Received 6 September 2013; published 2 December 2013)

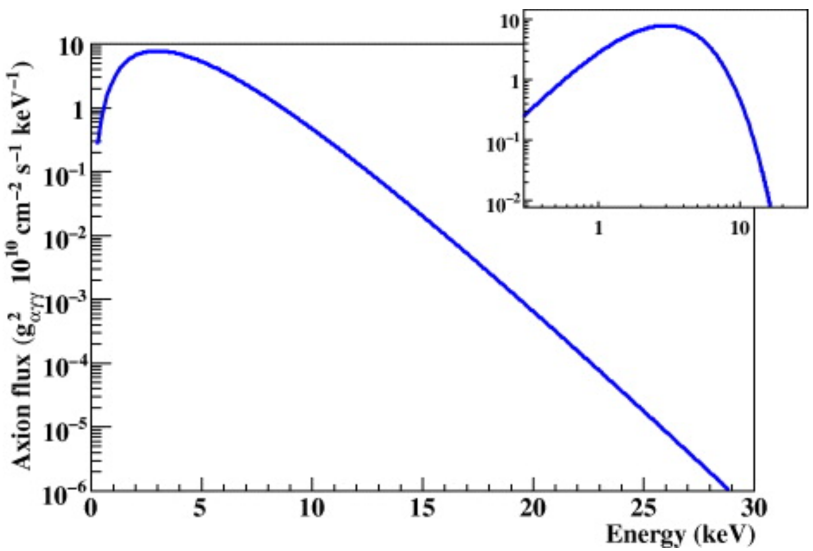
Helioscopes

http://middleboop.blogspot.de/2011/02/vessels-helioscope.html

CAST: the dominating helioscope

> LHC prototype magnet pointing to the sun.





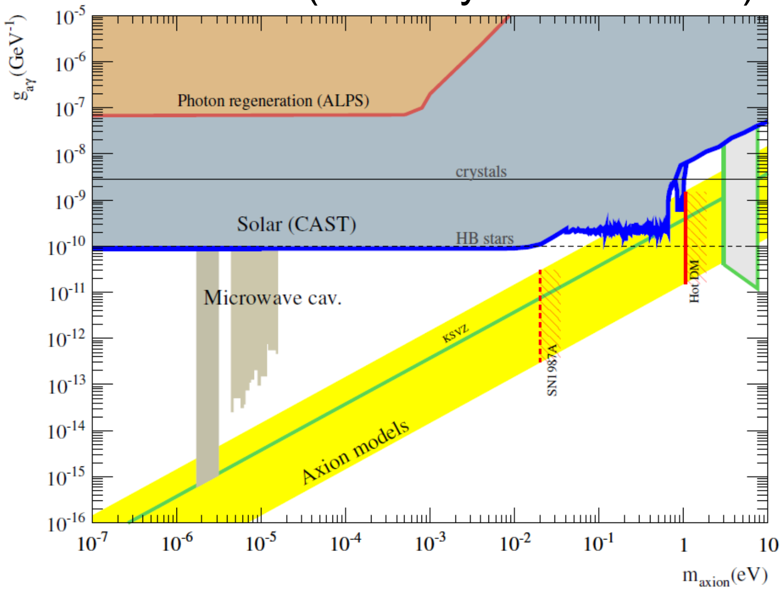
Axions or ALPs from the center of the sun would come with X-ray energies.

New J. Phys. **11** (2009) 105020

CAST: the dominating helioscope

- LHC prototype magnet pointing to the sun.

(courtesy of I. Irastorza)

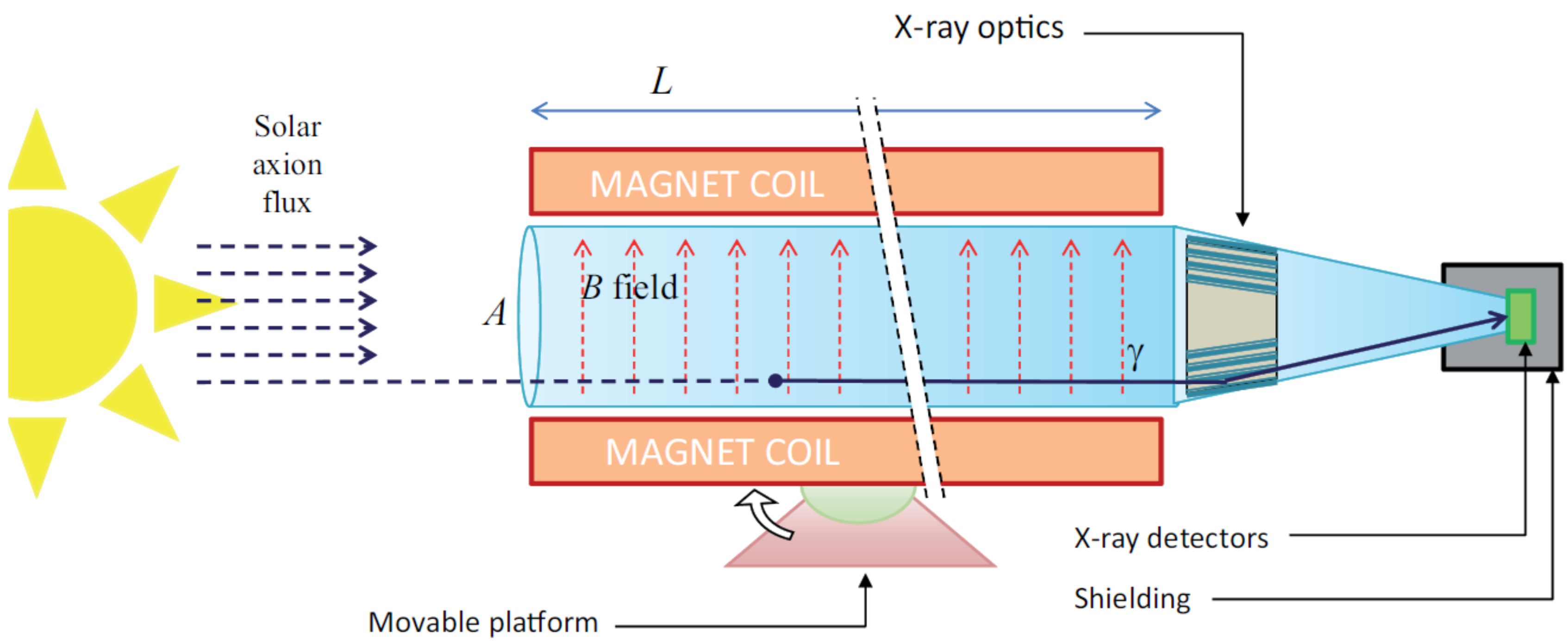


- Most sensitive experiment searching for axion-like particles.
  - Unfortunately no hints for WISPs yet.
  - If an ALP is found, it would be compatible with known solar physics!

- However, CAST relies on astrophysics:
  - CAST has to assume ALP production in the sun.

IAXO proposal

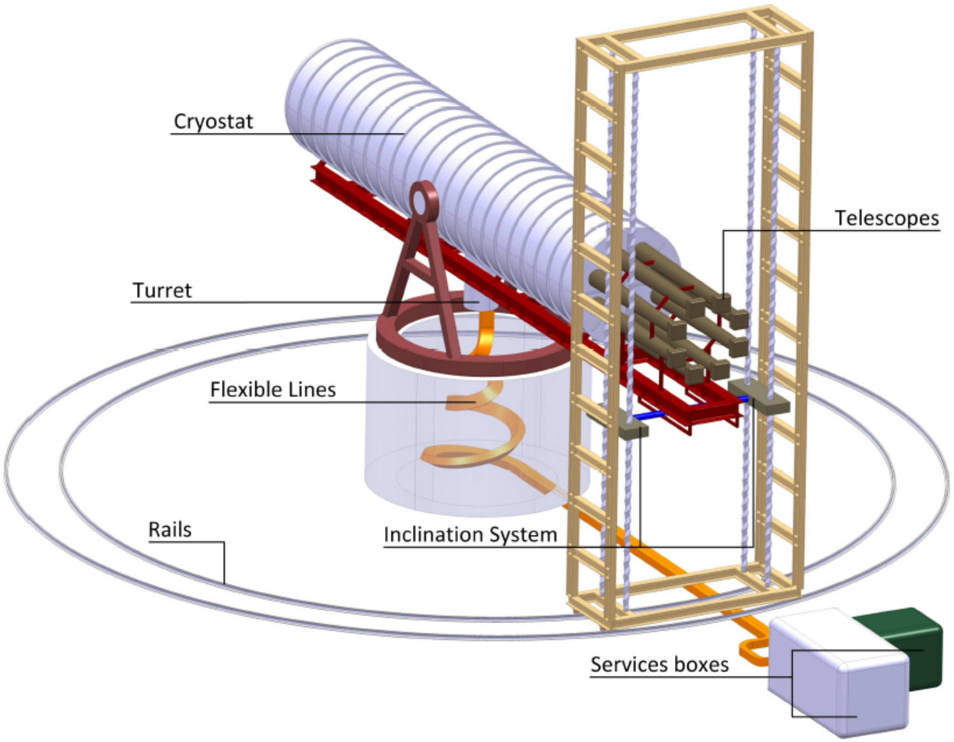
> The International Axion Observatory
  - CAST principle with dramatically enlarged aperture



IAXO proposal

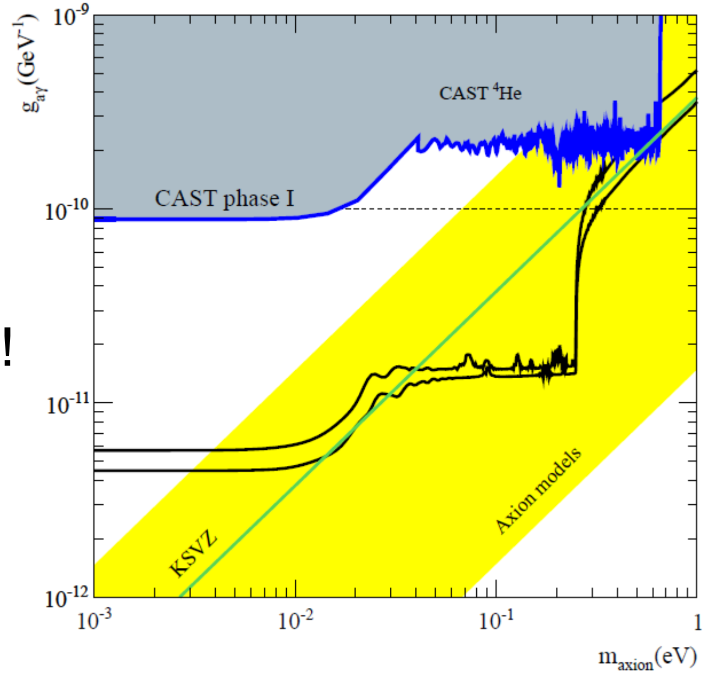
> The International Axion Observatory

- CAST principle with dramatically enlarging the aperture
- Use of toroid magnet similar to ATLAS
- X-ray optics similar to satellite experiments.



IAXO proposal

- The International Axion Observatory
  - Could be constructed within about six years.
- IAXO could probe QCD axions
  as well as ALPs
  (even in their Dark Matter parameter space)!



IAXO proposal

- The International Axion Observatory
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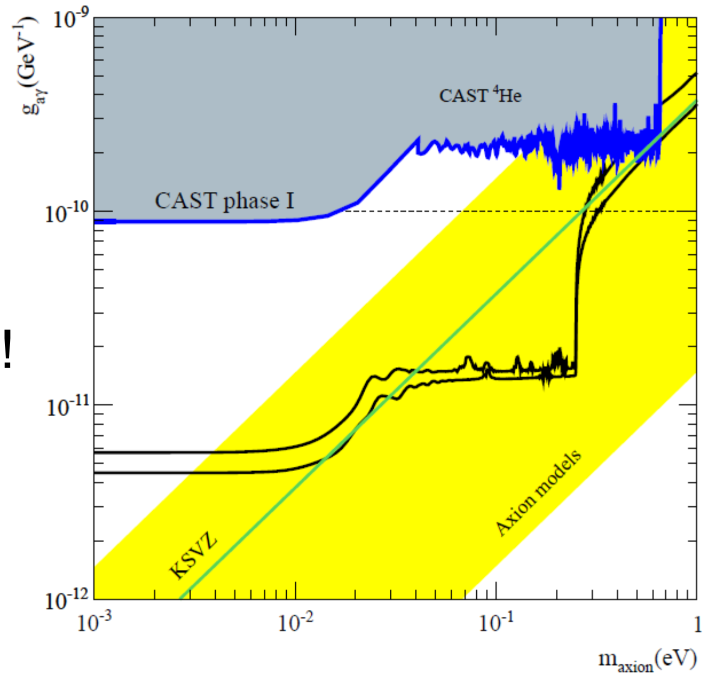
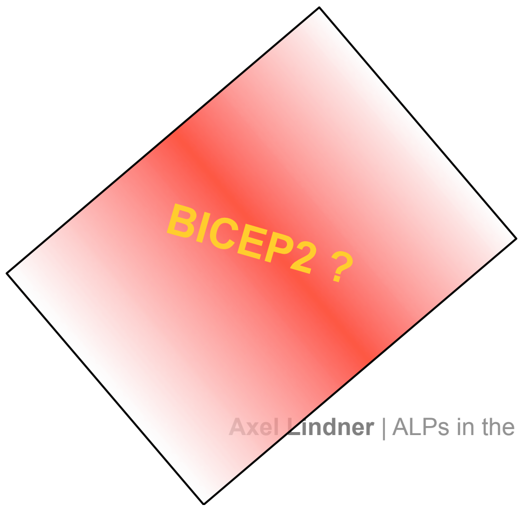
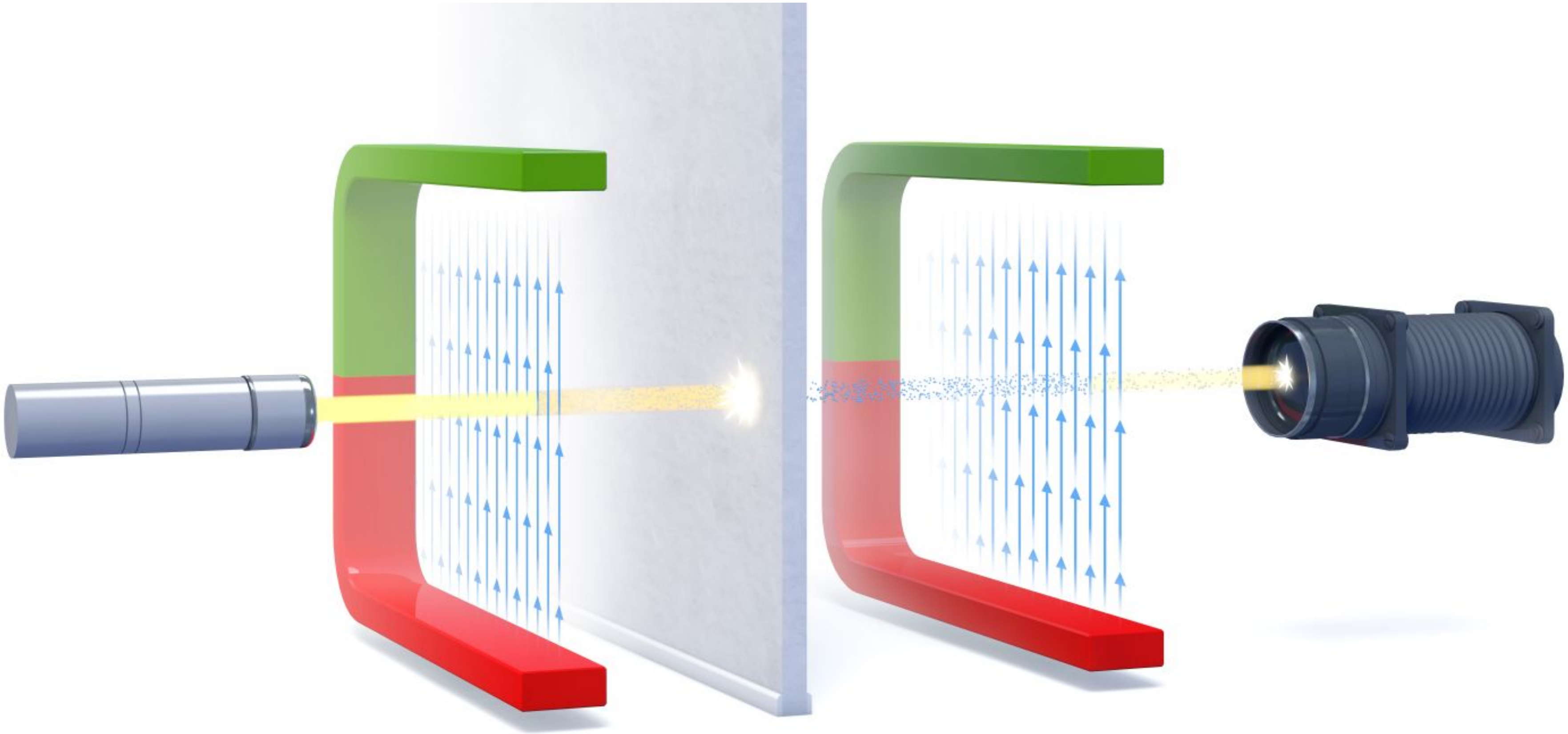


- However, DM axions are out of reach.



Laboratory experiments



ALPS @ DESY in Hamburg

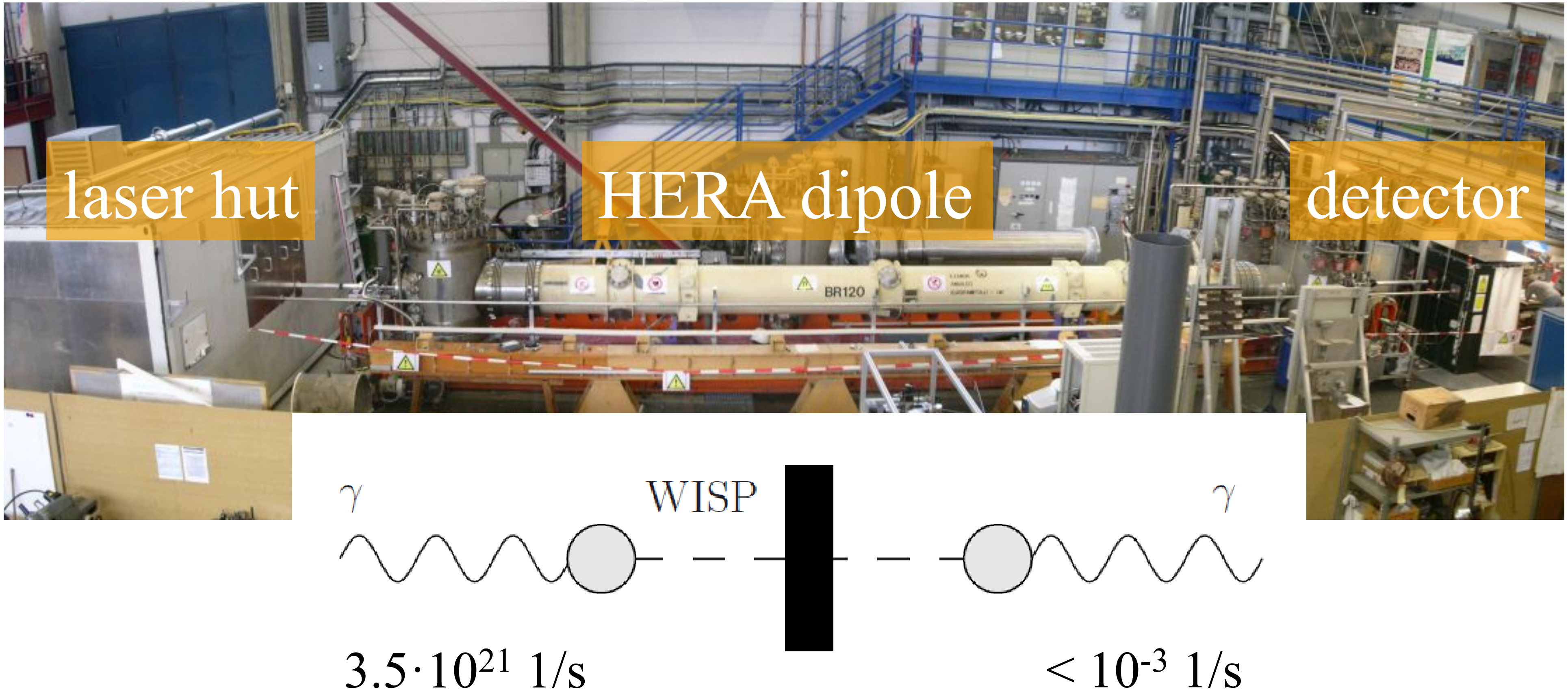
ALPS I at DESY in Hamburg

Any Light Particle Search @ DESY: ALPS I concluded in 2010

ALPS I results

(PLB Vol. 689 (2010), 149, or http://arxiv.org/abs/1004.1313)

- The most sensitivity WISP search experiment in the laboratory (still).
- Unfortunately, no light was shining through the wall!



Prospects for ALPS II @ DESY

- Laser with optical cavity to recycle laser power,
  switch from 532 nm to 1064 nm,
  increase effective power from 1 to 150 kW.

- Magnet:
  upgrade to 10+10 straightened HERA dipoles
  instead of ½+½ used for ALPS I.

- Regeneration cavity to increase WISP-photon conversions, single photon counter (superconducting transition edge sensor?).

All set up in a clean environment!

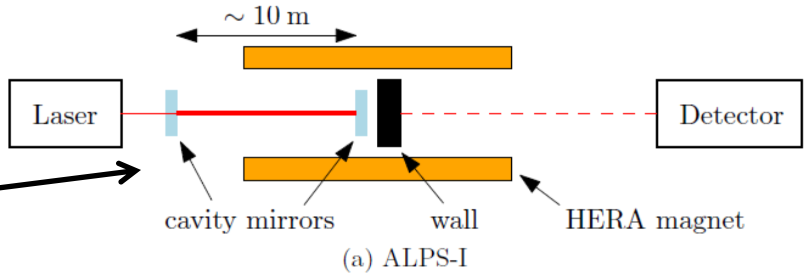
The ALPS II reach

Parameter	Scaling	ALPS-I	ALPS-IIc	Sens. gain
Effective laser power P_{laser}	$g_{a\gamma} \propto P_{\text{laser}}^{-1/4}$	$1\,\text{kW}$	$150\,\text{kW}$	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC P_{RC}	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	14
BL (before& after the wall)	$g_{a\gamma} \propto (BL)^{-1}$	$22\,\text{Tm}$	$468\,\text{Tm}$	21
Detector efficiency QE	$g_{a\gamma} \propto QE^{-1/4}$	0.9	0.75	0.96
Detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	$0.0018\,\text{s}^{-1}$	$0.000001\,\text{s}^{-1}$	2.6
Combined improvements				3082

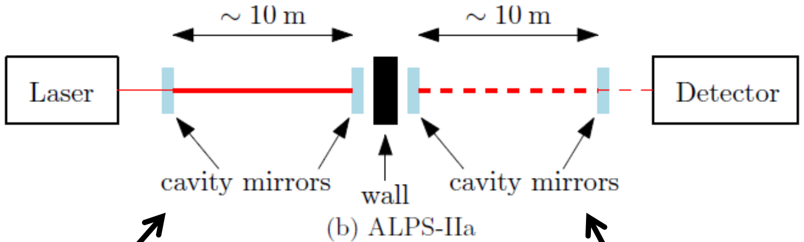
Three orders of magnitude gain in ALP coupling and two orders of magnitude in HP mixing!

ALPS II essentials: laser & optics

ALPS I:
basis of success was the optical resonator in front of the wall.



> **ALPS IIa**



Optical resonator to increase effective light flux by recycling the laser power

Optical resonator to increase the conversion probability

WISP→γ

First realization of a 23 year old proposal!

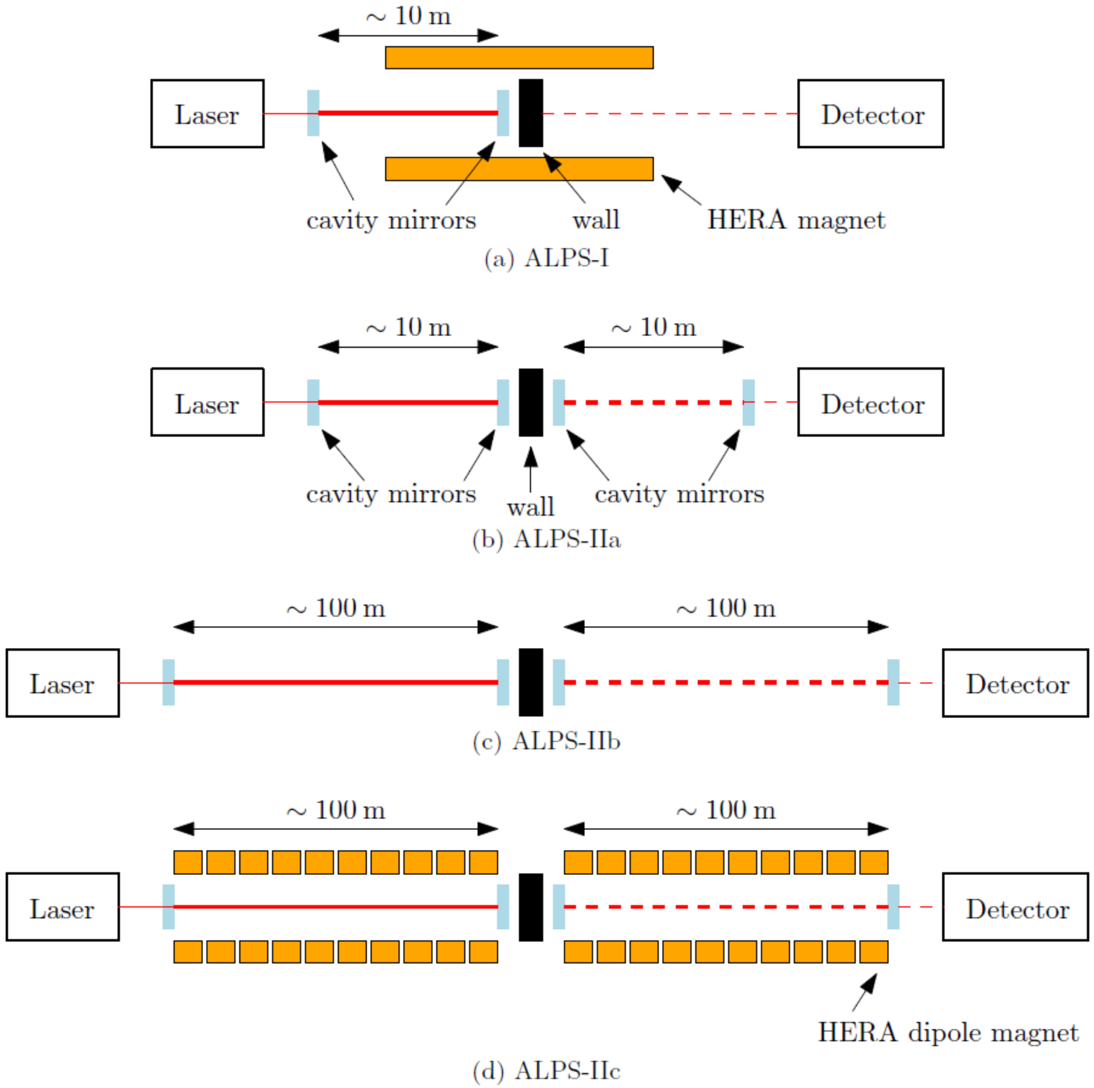
ALPS II will be realized in stages

ALPS I

> **ALPS IIa**

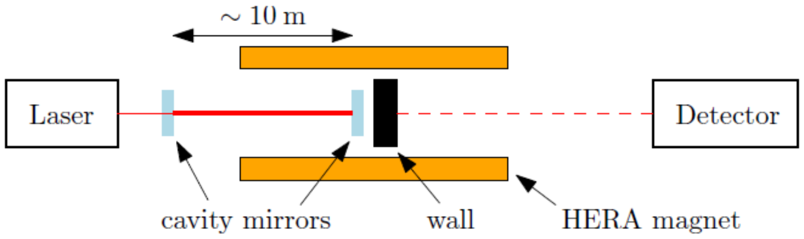
> **ALPS IIb**

> **ALPS IIc**



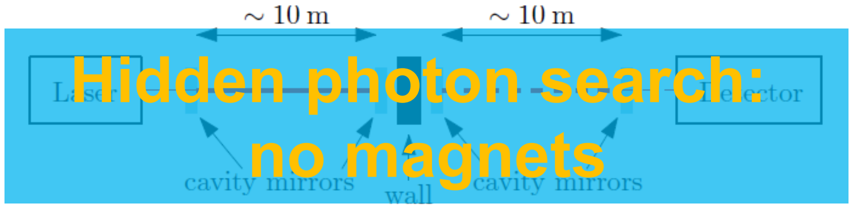
ALPS II will be realized in stages

ALPS I



(a) ALPS-I

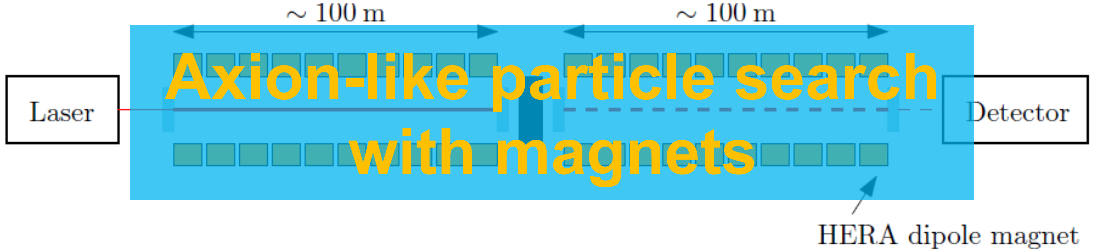
- **ALPS IIa**



(b) ALPS-IIa

- **ALPS IIb**

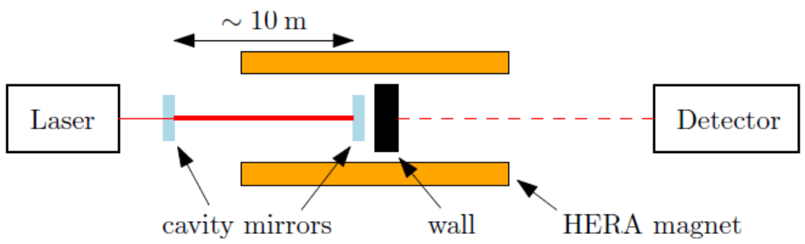
- **ALPS IIc**



(d) ALPS-IIc

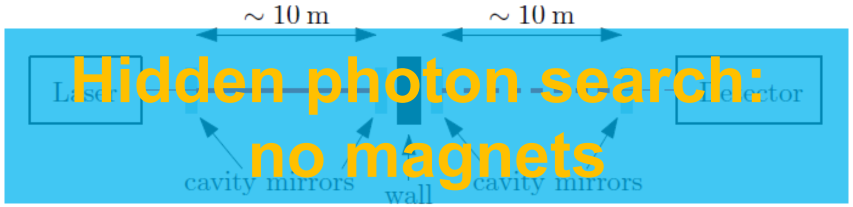
ALPS II will be realized in stages

ALPS I



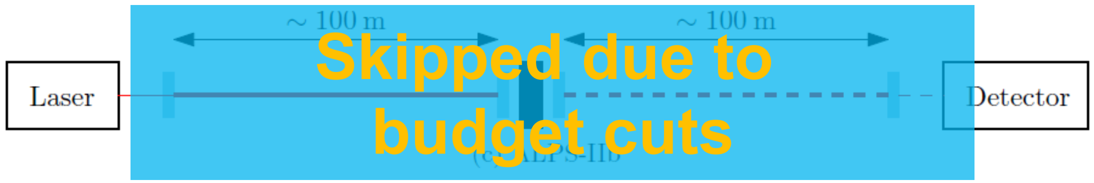
(a) ALPS-I

> **ALPS IIa**

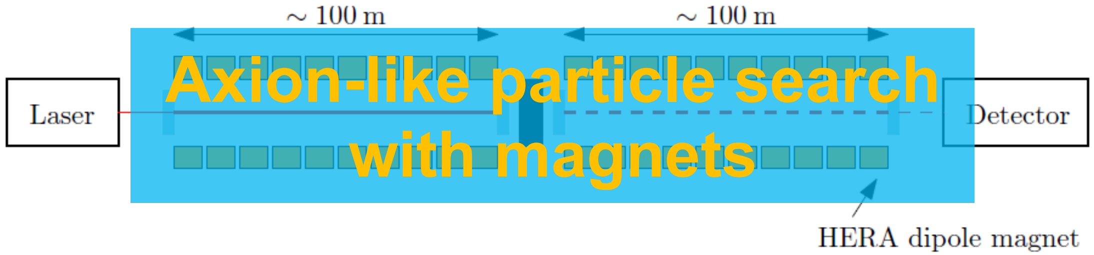


(b) ALPS-IIa

> **ALPS IIb**

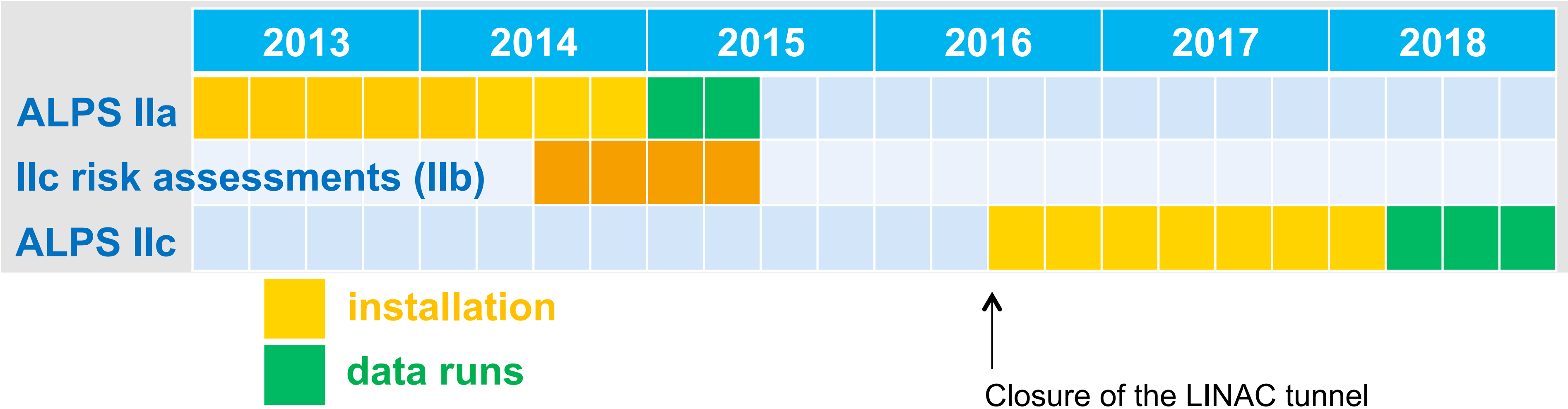


> **ALPS IIc**

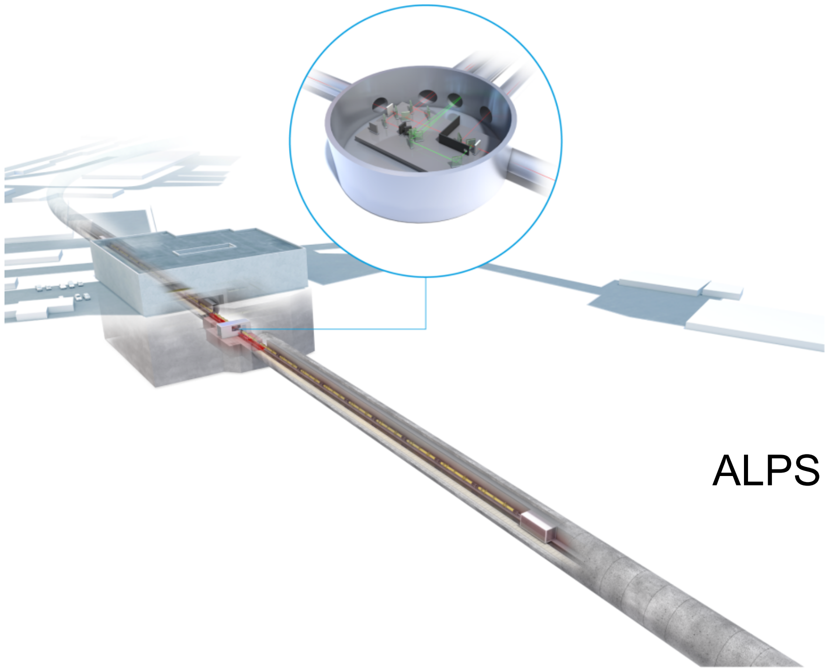


(d) ALPS-IIc

ALPS II schedule (rough)



Closure of the LINAC tunnel of the European XFEL project under construction at DESY.

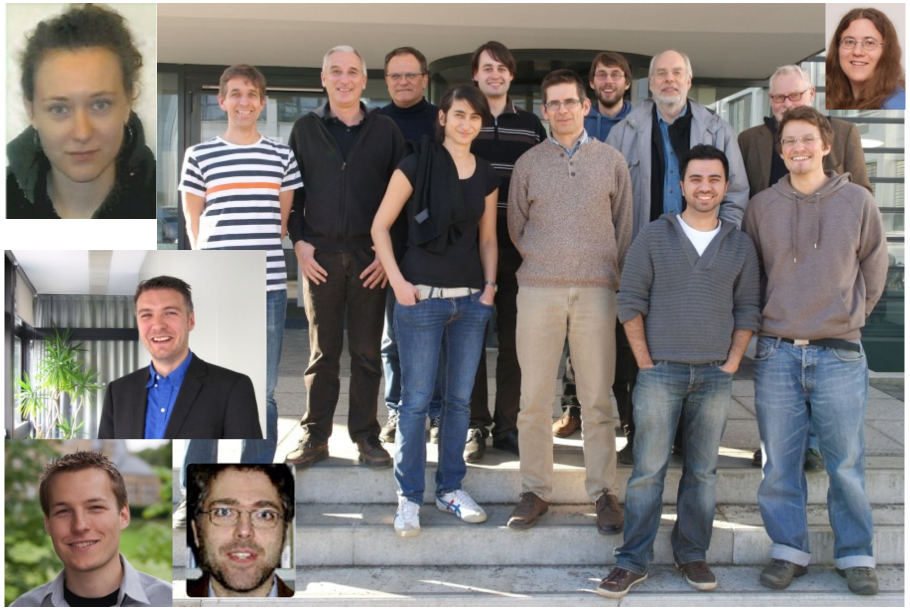


ALPS IIc in 2018 in the HERA tunnel

The collaboration: PhDs and postdocs

ALPS II is a joint effort of

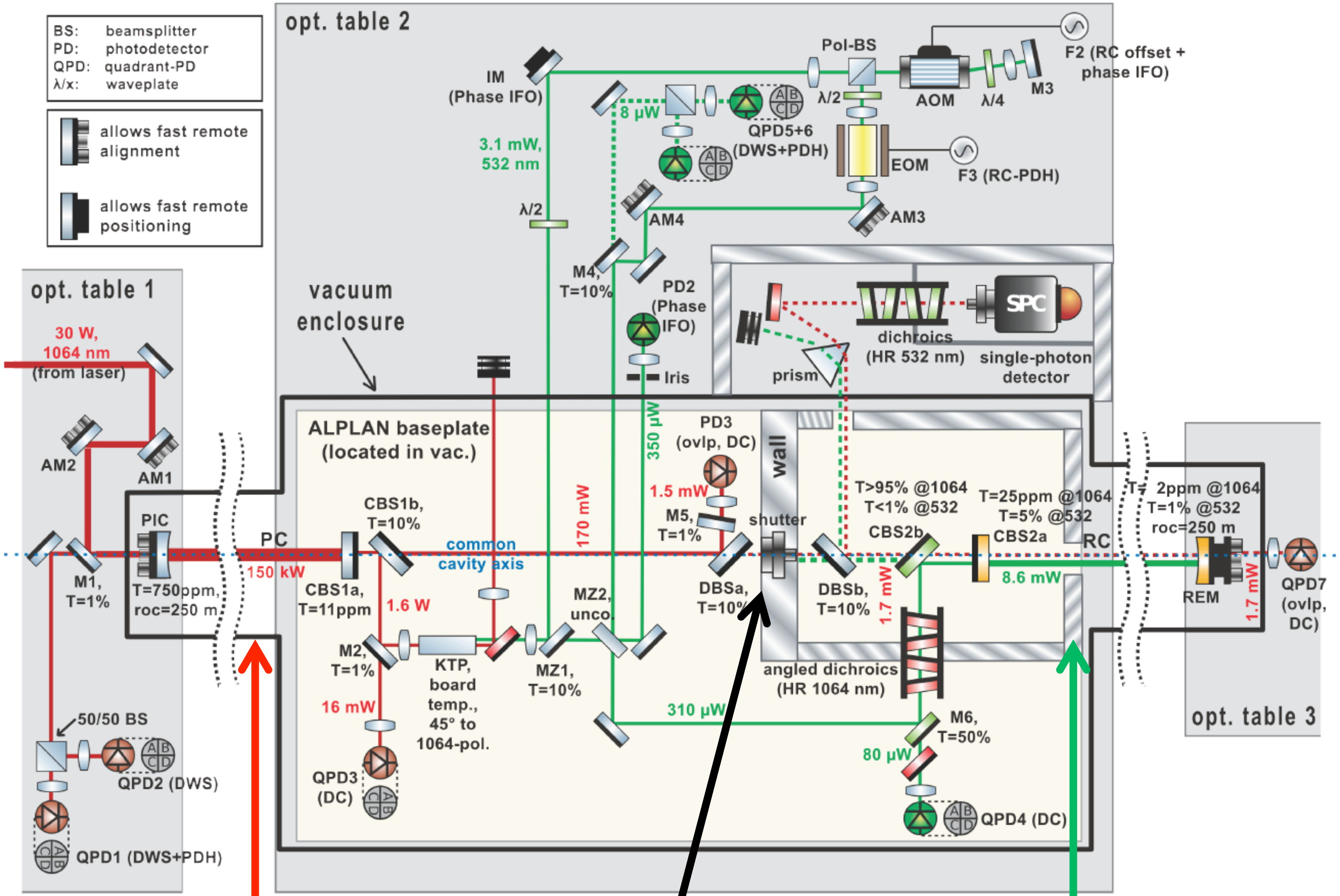
- DESY:
  Babette Döbrich, Jan Dreyling-Eschweiler, Samvel Ghazaryan,
  Reza Hodajerdi, Friederike Januschek, Ernst-Axel Knabbe, Axel Lindner,
  Andreas Ringwald, Jan Eike von Seggern, Richard Stromhagen, Dieter Trines
- Hamburg University:
  Noemie Bastidon, Dieter Horns
- AEI Hannover
  (MPG & Hannover Uni.):
  Robin Bähre, Benno Willke
- Mainz University:
  Matthias Schott, Christoph Weinsheimer



with strong support from

- neoLASE:
  Maik Frede, Bastian Schulz

ALPS II essentials: laser & optics



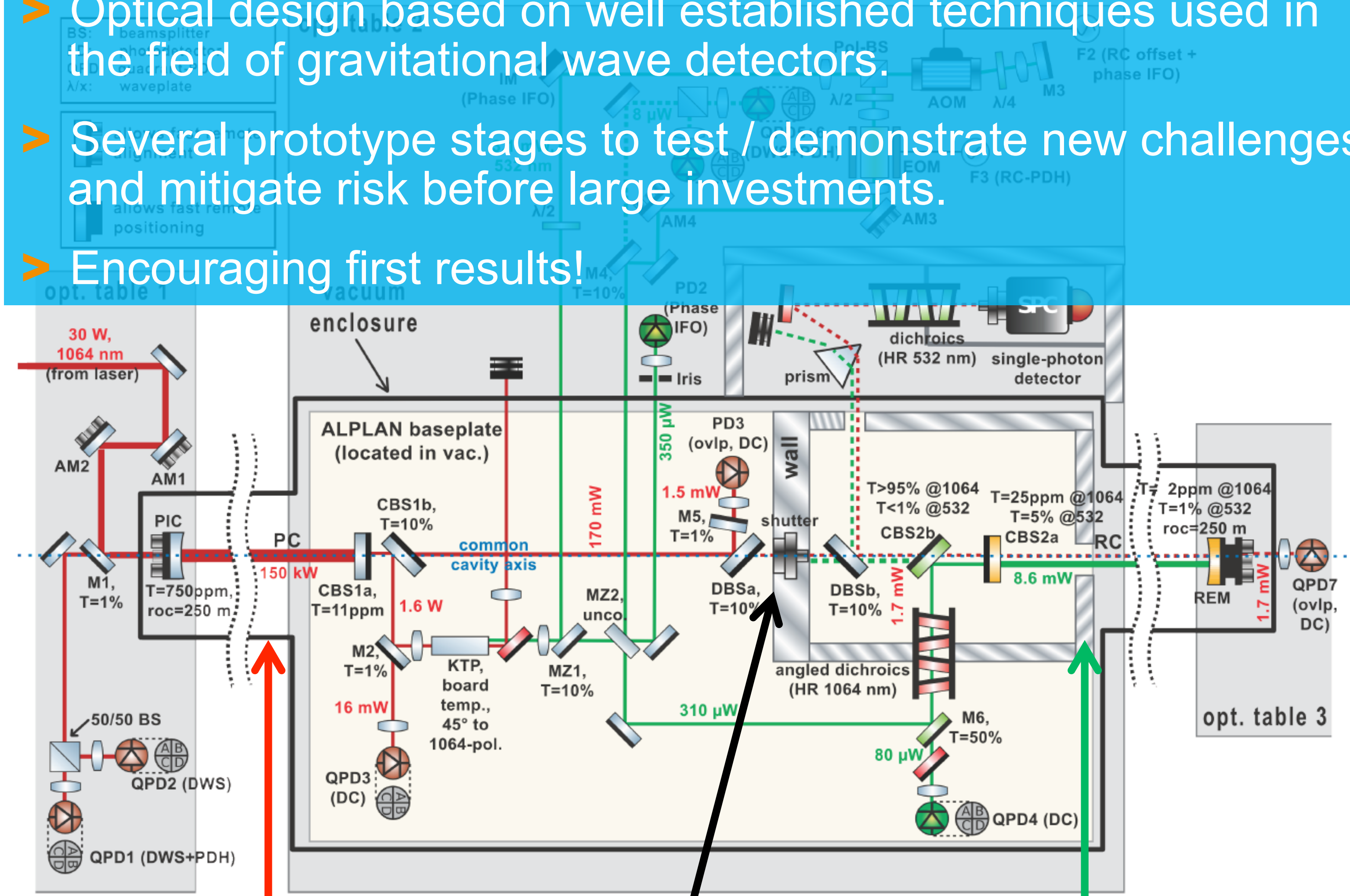
Production cavity, infrared

Wall

Regeneraton cavity, locked with green light.

ALPS II essentials: laser & optics

- Optical design based on well established techniques used in the field of gravitational wave detectors.
- Several prototype stages to test / demonstrate new challenges and mitigate risk before large investments.
- Encouraging first results!

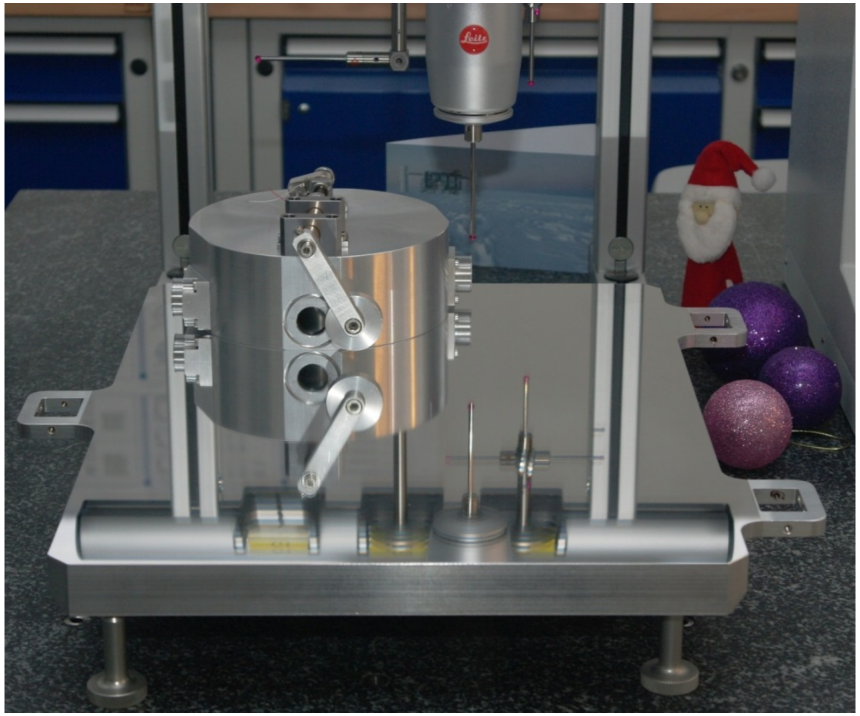


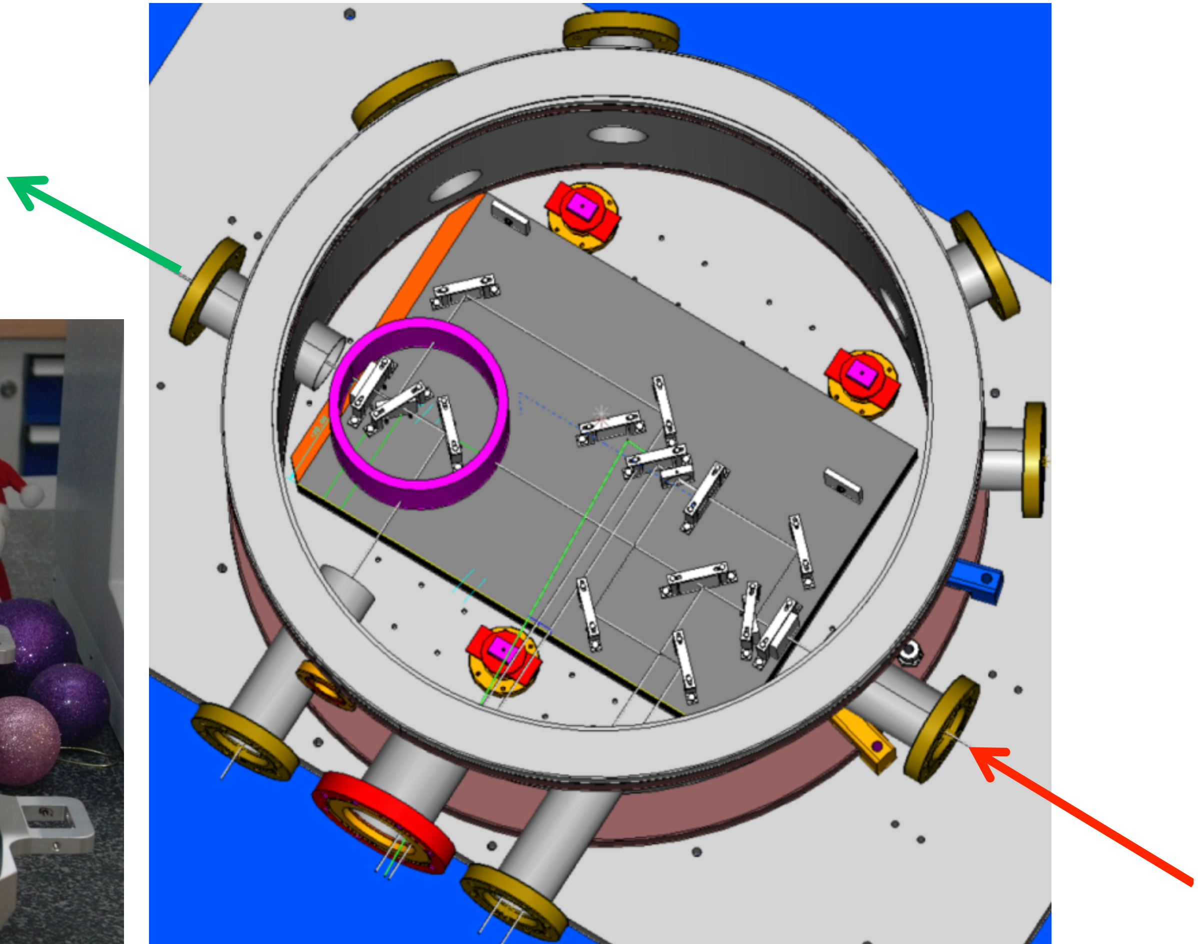
Production cavity, infrared

Wall

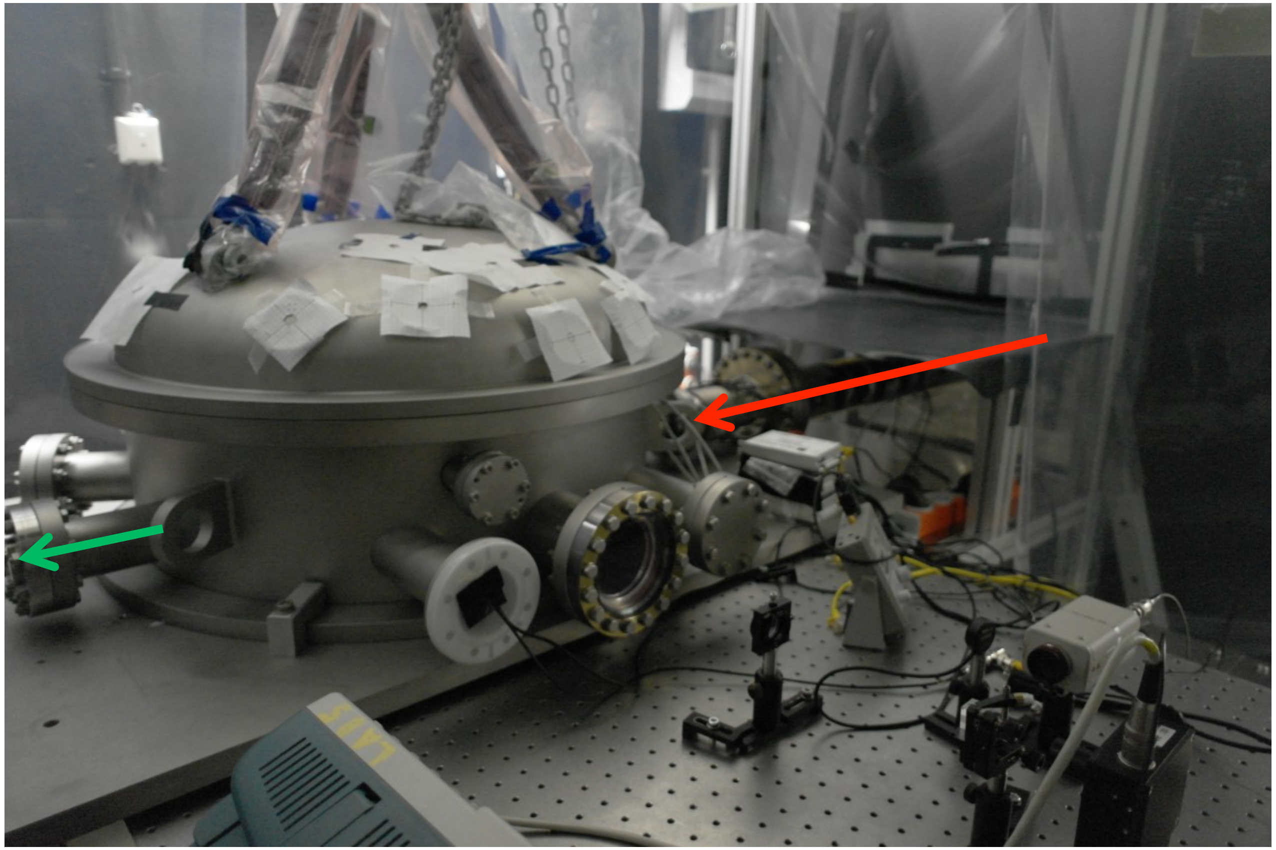
Regeneraton cavity, locked with green light.

The central optics breadboard

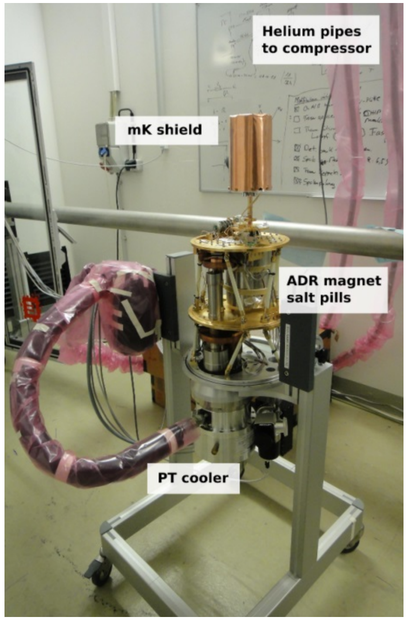




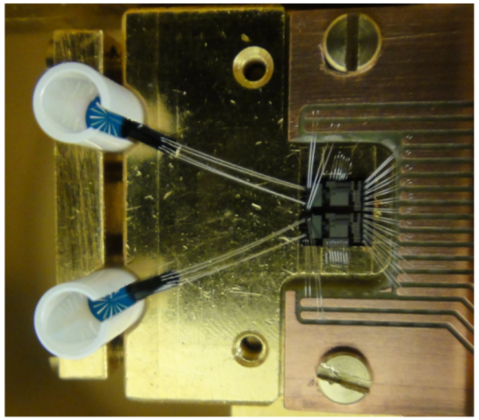
The big vacuum tank



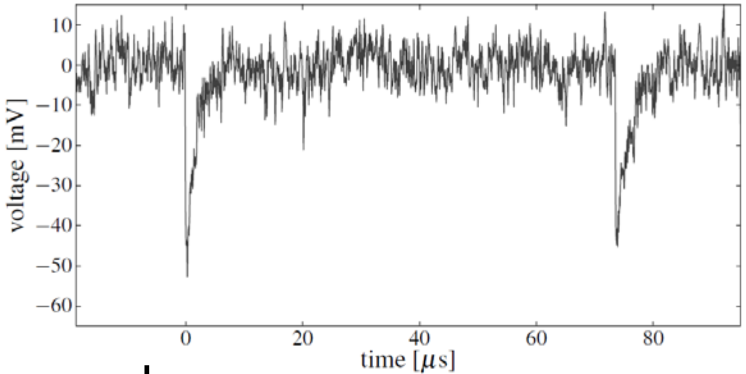
ALPS II: Transition Edge Sensor (TES)



module with two channels
(scale ~ 3cm x 3cm)



- High quantum efficiency at 1064 nm, very low noise.
- Tungsten film kept at the transition to superconductivity.
- Sensor size 25µm x 25µm x 20nm.
- To be operate around 100 mK.

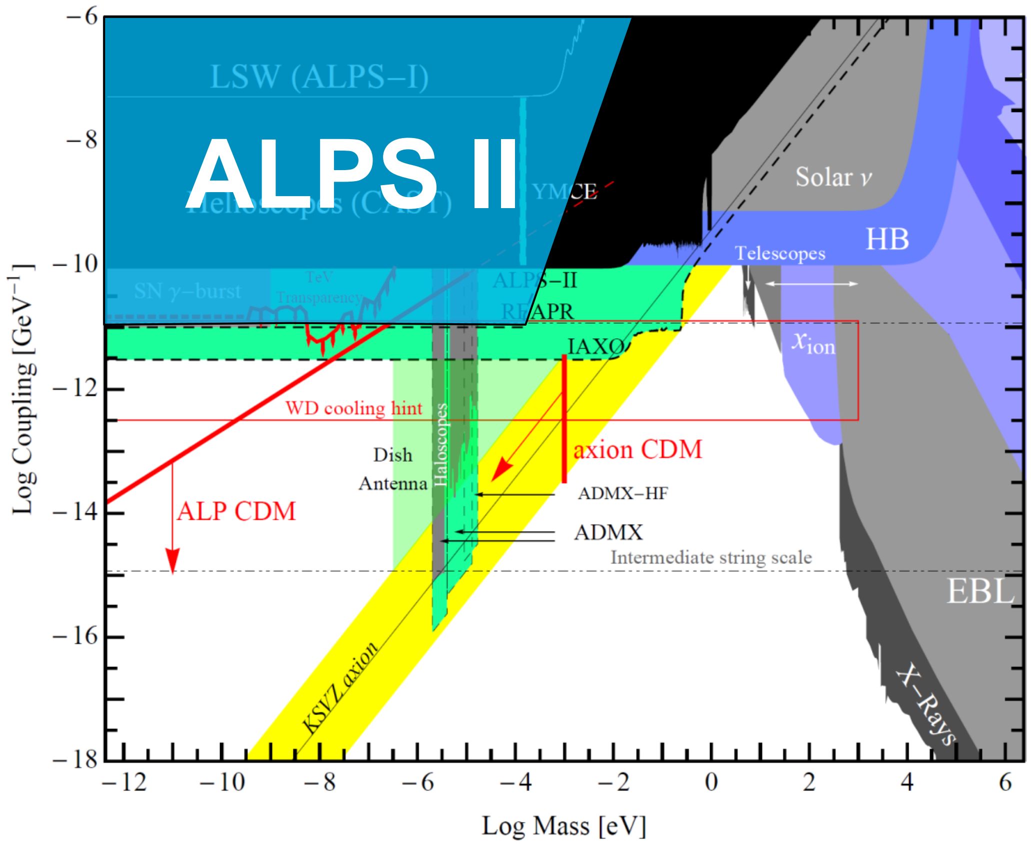


- Single 1066 nm photon pulses!
- Energy resolution ≈8%.
- Background 10^{-4} counts/second.
- Pulse shape well understood.
- Ongoing: background studies, optimize fibers.
  Try to minimize background from ambient thermal photons.

ALPS II sensitivity

- Well beyond current limits.
- Less sensitive than IAXO (but much cheaper).
- Aim for data taking in 2018.

- QCD axions not in reach.
- Sensitive to Dark Matter axion-like particles.



Beyond ALPS II

- Rough estimation with some crucial parameters:

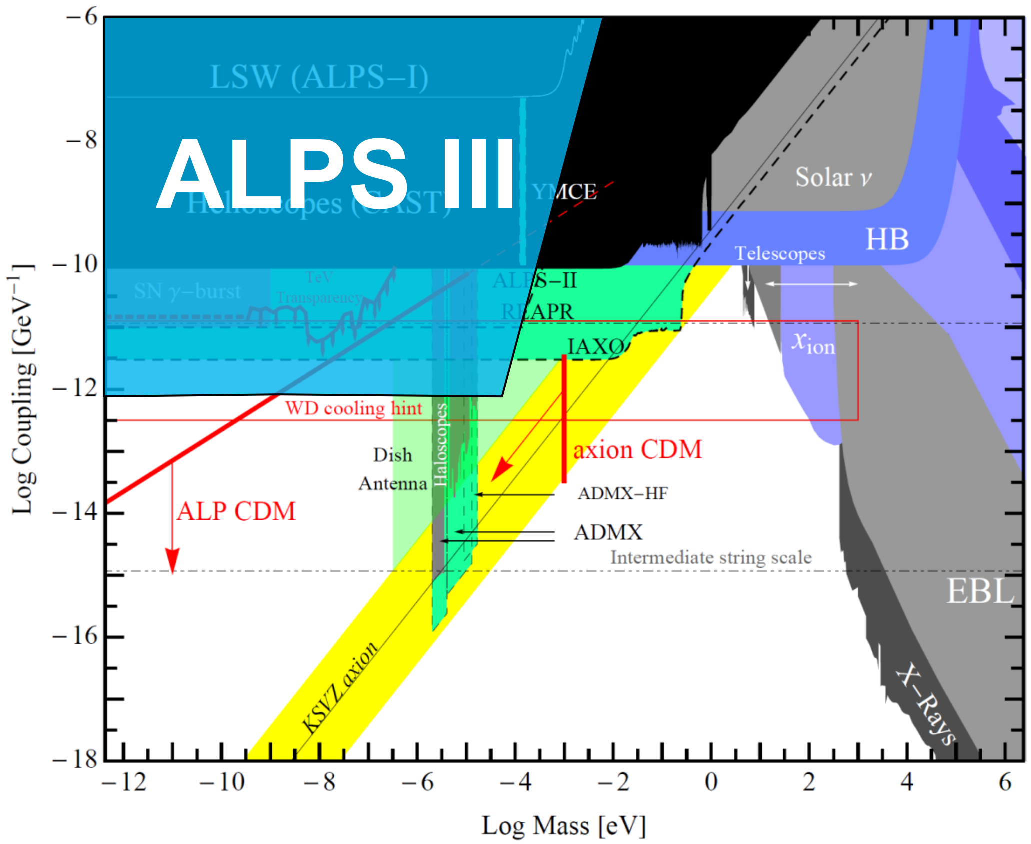
Exp.	Photon flux (1/s)	Photon E (eV)	B (T)	L (m)	B·L (Tm)	PB reg.cav.	Sens. (rel.)	Mass reach (eV)
ALPS I	$3.5 \cdot 10^{21}$	2.3	5.0	4.4	22	1	0.0003	0.001
ALPS II	$1 \cdot 10^{24}$	1.2	5.3	106	468	40,000	1	0.0002
"ALPS III"	$3 \cdot 10^{25}$	1.2	13	400	5200	100,000	27	0.0001
European XFEL	$< 10^{18}$	$1 \cdot 10^{4}$	5.3	106	562	1	0.001	0.01
PW laser	10^{20} 1/pulse	2.3	10^{6}	10^{-5}	10	1	0.0003	0.5

"ALPS III" sensitivity

- With a multi - 10 M€ project one could even probe well beyond the IAXO reach.

However:

- It is to be shown first that ALPS II can be realized.
- Magnets as being developed for the LHC energy upgrade are essential.
- "ALPS III" not before 2025.



DESY

Outline

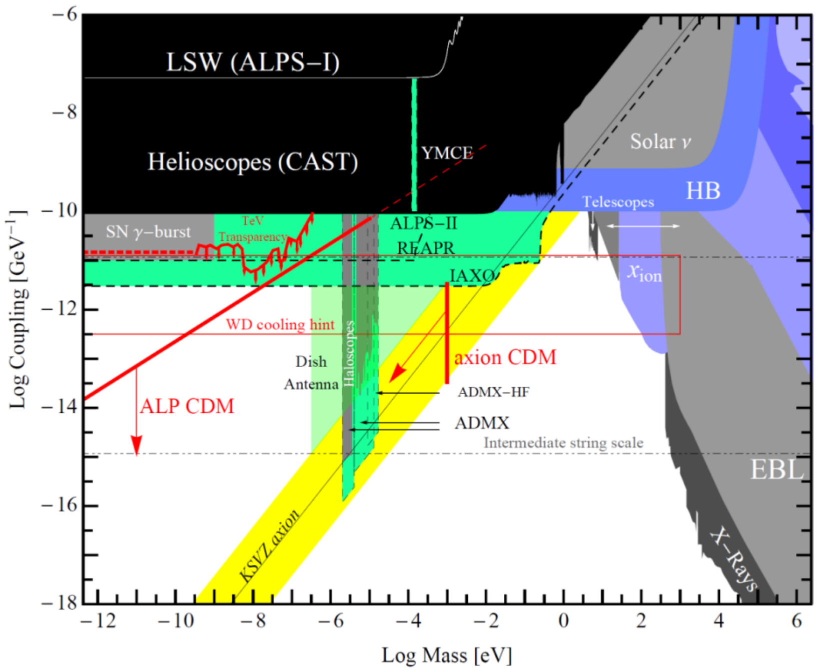
- Some motivation
- A little bit of theory
- Basics of WISP experiments
- Exemplary experiments
- Indications for a WISPy world?
- Summary

Indications for a WISP world?

Do white dwarfs (WDs) cool too fast?

- The luminosity distribution of WDs as well as http://arxiv.org/abs/1304.7652
- the pulsation changes in individual WDs suggest http://arxiv.org/abs/1205.6180
- and extra cooling mechanism.

This could be the emission of axions or ALPs coupling to electrons.



Indications for a WISP world?

Is there a cosmic axion background radiation (CABR)?

PREPARED FOR SUBMISSION TO JCAP

http://arxiv.org/abs/1312.3947

Soft X-ray Excess in the Coma Cluster from a Cosmic Axion Background

Stephen Angus,[a] Joseph P. Conlon,[a] M.C. David Marsh,[a] Andrew J. Powell[a] and Lukas T. Witkowski[a,b]

[a]Rudolf Peierls Centre for Theoretical Physics, University of Oxford,
1 Keble Road, Oxford OX1 3NP, United Kingdom
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Philosophenweg 19, 69120 Heidelberg, Germany

Indications for a WISP world?

Is there a cosmic axion (or ALP) background radiation (CABR)?

- A relativistic CAB is well motivated from compactifications of string theory to four dimensions.
- A CAB is compatible with CMBR measurements (ΔN_{eff}).
- Such ALPs may convert into soft X-ray photons in the magnetic fields of clusters of galaxies and explain the observed soft X-ray excess.
- It is difficult to explain the excess with conventional astrophysics (warm gas, inverse Compton scattering of the CMB).

- In the CABR scenario:

$$m_a \lesssim 10^{-12}\,\mathrm{eV}$$

$$10^{11}\,\mathrm{GeV} \lesssim M \lesssim 7 \times 10^{12} \sqrt{\frac{\Delta N_{\mathrm{eff}}^{(a)}}{0.5}}\,\mathrm{GeV}$$ (with M = 1/g)

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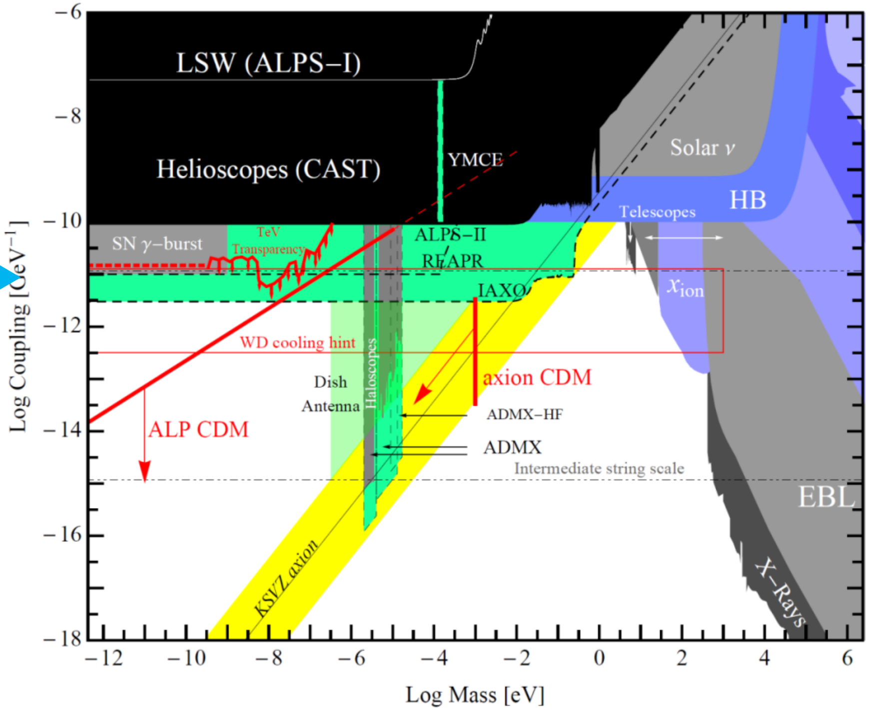

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DESY

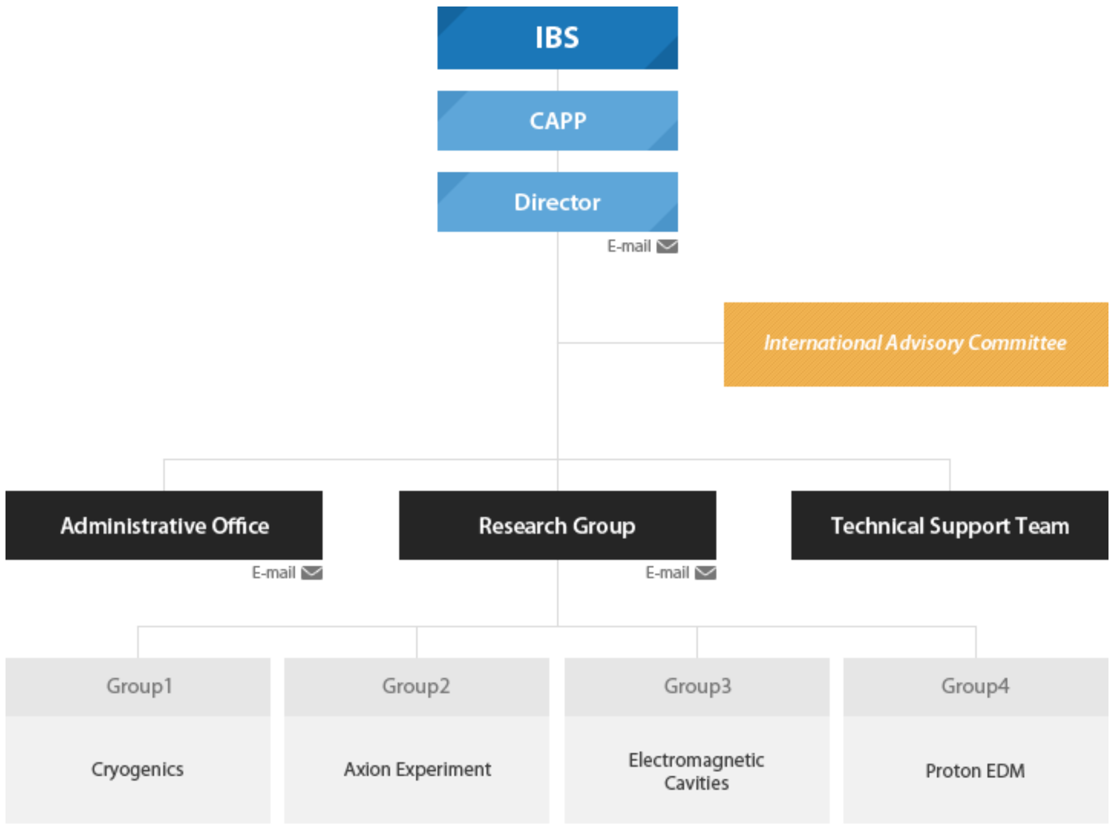
Indications for a WISP world?

More to come in the next talks!

DESY

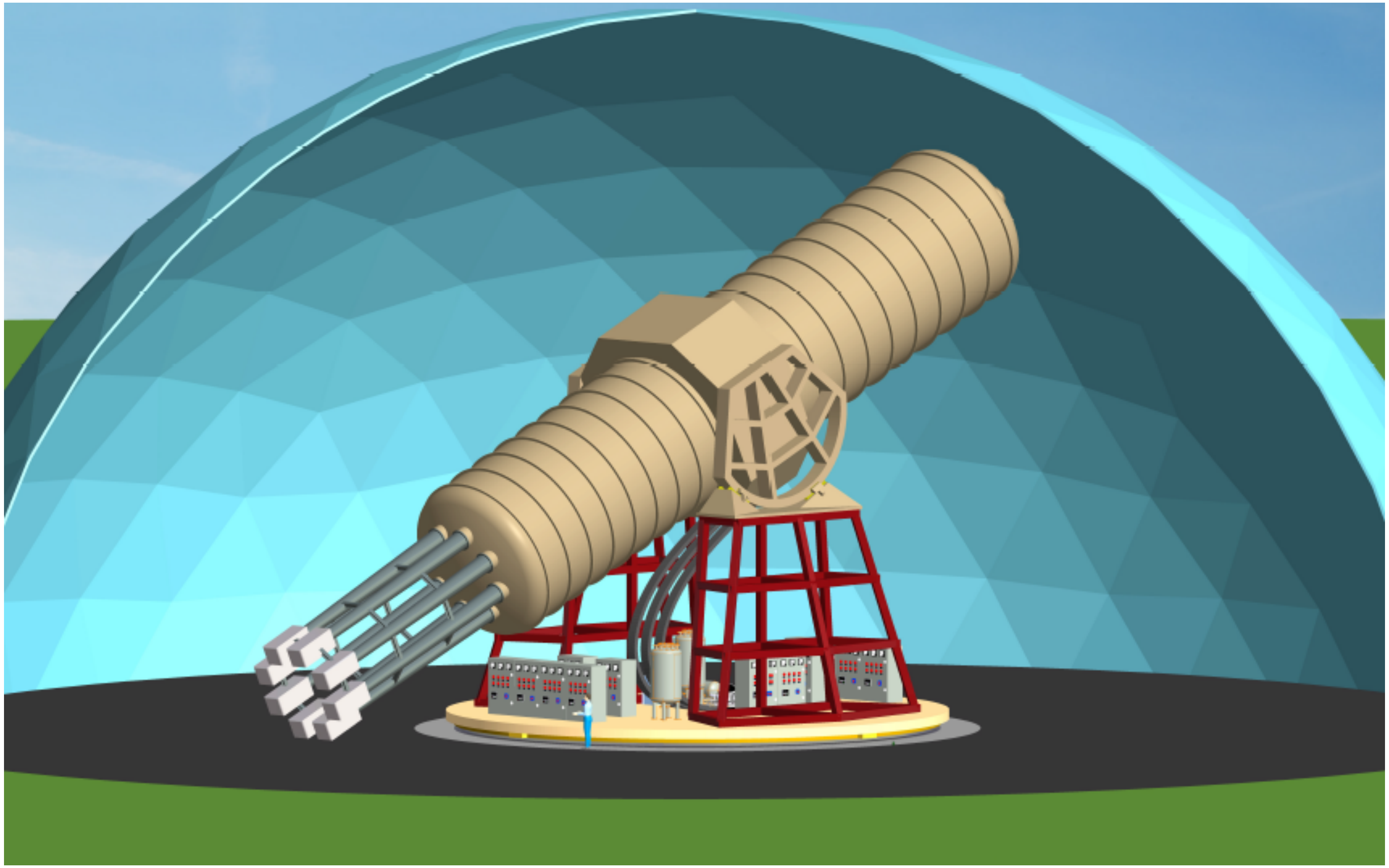
The first axion institute!

- The Center for Axion and Precision Physics Research (CAPP) is funded by the Institute for Basic Science in Korea. http://capp.ibs.re.kr/html/capp_en/
- Director: Y. Semertzidis
- Resources dedicated to axion searches!
- CAPP is very open to new ideas and proposals for experiments!



The first "global" axion effort?

- The **I**nternation **AX**ion **O**berservatory



"Patras" workshop series http://axion-wimp.desy.de/

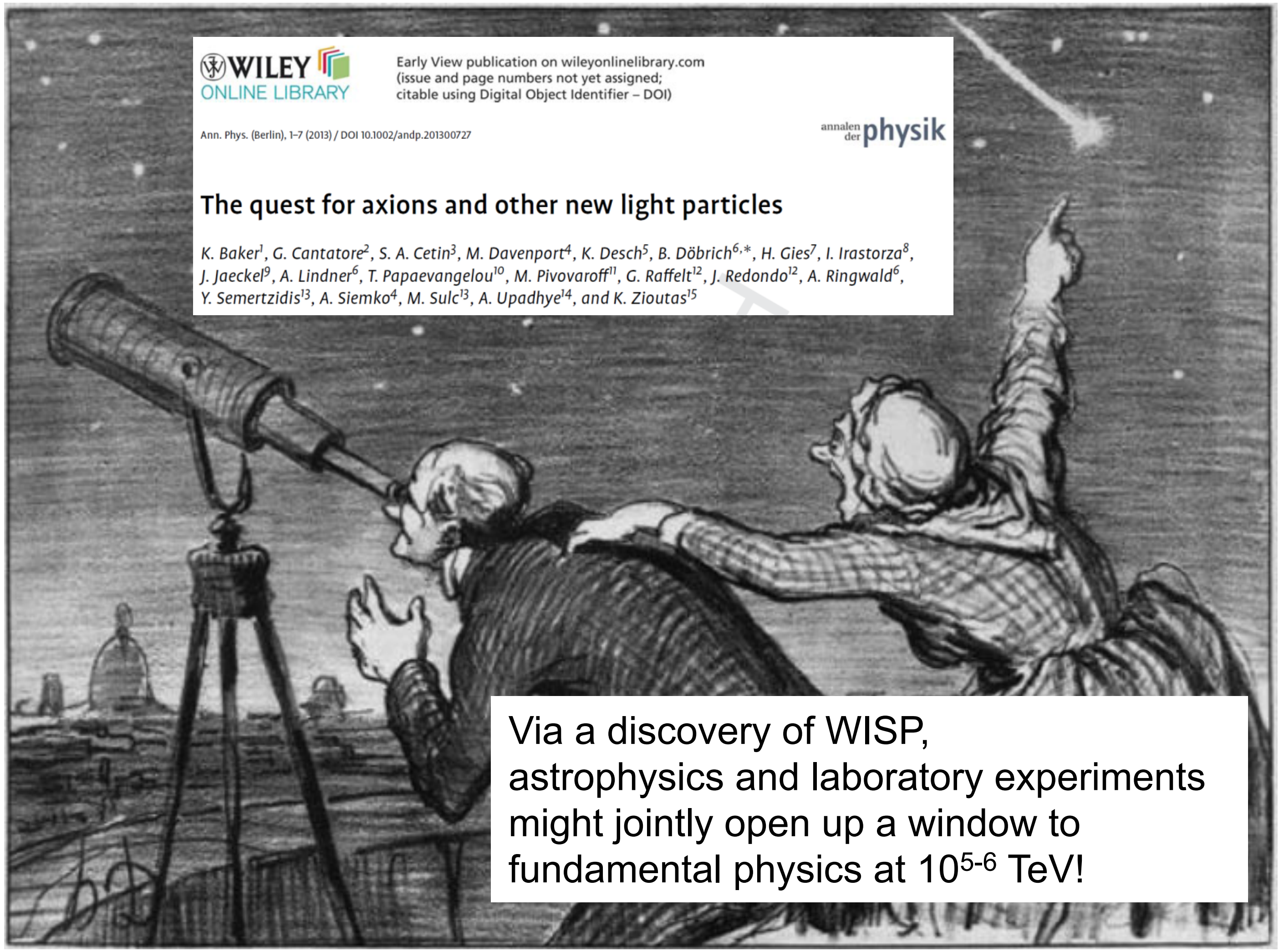
> Workshop on WIMPs and WISPs!

Summary

- The axion "invented" to explain the CP-conservation in QCD is also a perfect and extremely lightweight cold dark matter candidate.
  - It can be searched for in dedicated dark matter experiments.
  - Helioscopes as well as purely laboratory experiments will – in the foreseeable future – not provide sufficient sensitivities to probe the parameter region of dark matter axions.
- In addition to axions theory predicts axion-like particles (ALPs) as well as other Weakly Interacting Slim Particles (WISPs).
  - Such ALPs and other WISPs might also constitute the dark matter.
- There may be hints for ALPs from astrophysics with couplings $5 \cdot 10^{-13}\mathrm{GeV}^{-1} < g\gamma\gamma < 5 \cdot 10^{-11}\mathrm{GeV}^{-1}$.
- Couplings down to $2 \cdot 10^{-11}\mathrm{GeV}^{-1}$ will be probed by ALPS II in ≈2018.
- IAXO or a possible ALPS III might in future go down to $10^{-12}\mathrm{GeV}^{-1}$.
- **The next decade could see "low energy BSM physics" jointly discovered by astro(particle)physics and in the laboratory!**

BSM physics might hide anywhere!

BSM physics might hide anywhere!

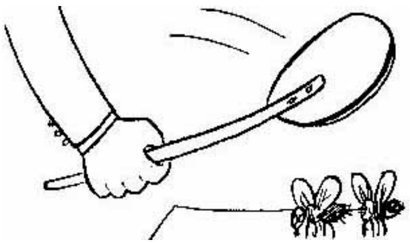


Via a discovery of WISP, astrophysics and laboratory experiments might jointly open up a window to fundamental physics at 10^{5-6} TeV!

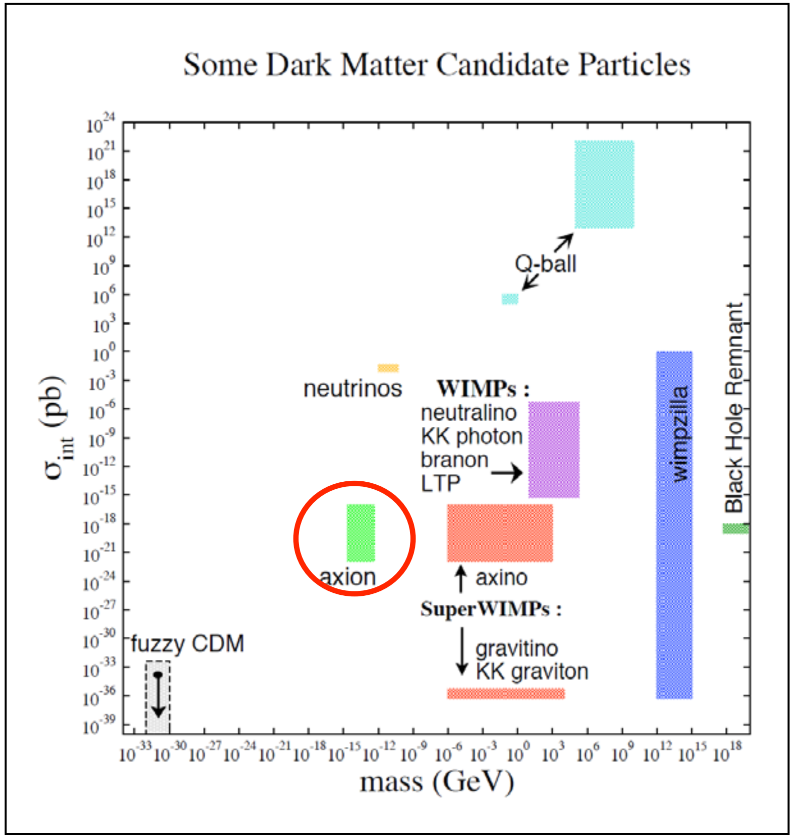
Backup slides

Axions are perfect cold DM candidates

- Axions with µeV mass are perfect cold dark matter candidates.
- They would interact extremely weakly with SM constituents.
- Similar to SUSY-WIMPs axions would solve two puzzles in one go:
  - Dark matter
  - CP conservation in QCD.



52 orders of magnitude

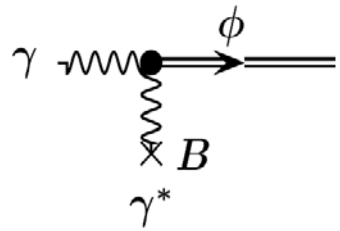


52 orders of magnitude

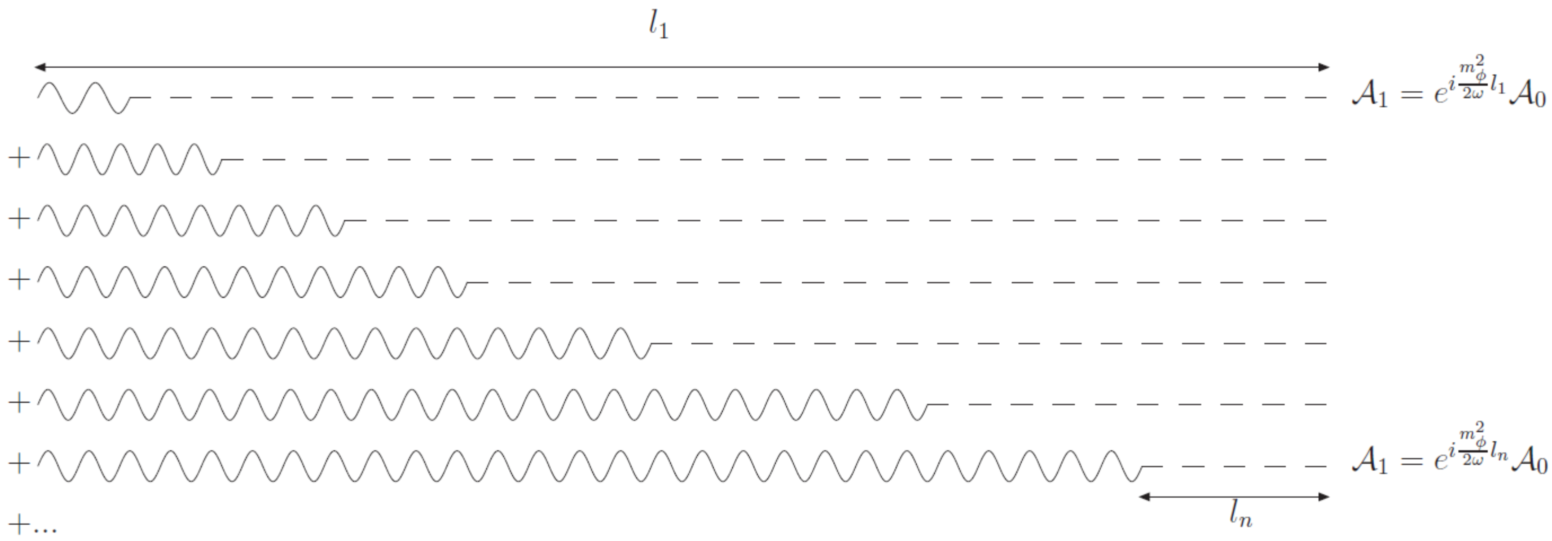
H. Baer, presentation at 5th Patras Workshop on Axions, WIMPs and WISPs, 2009

ALPs in LSW experiments arXiv:1011.3741 [hep-ph]

A plane e.m. wave propagating in an external magnetic field:



- ALPs may be produced via $\mathcal{L} \supset \frac{g}{4}\,\phi\, F_{\mu\nu}\tilde{F}^{\mu\nu} = -g\,\phi\,\vec{E}\cdot\vec{B}$.
- At each position on the e.m. wave's path through the magnetic field an ALP may be produced.
- The final state does not depend on the origin of the ALP production.
- Hence one has to sum the amplitudes over the path through the B-field:



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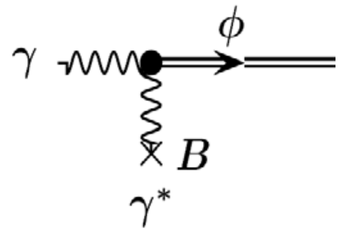

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- The final state does not depend on the origin of the ALP production.
- Hence one has to sum the amplitudes over the path through the B-field:

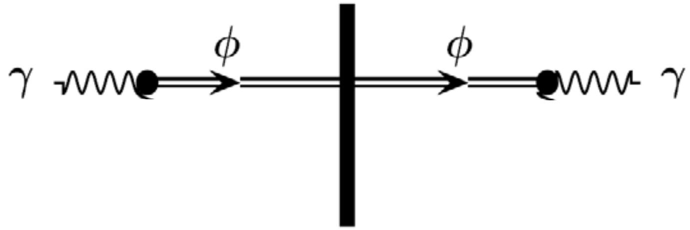
$$\mathcal{A}(\gamma \to \phi) = i\int_0^L \frac{gB_{\mathrm{ext}}}{2} e^{i\frac{m_\phi^2}{2\omega}l}\,dl = i\frac{gB_{\mathrm{ext}}\omega}{m_\phi^2}\left(1 - e^{i\frac{m_\phi^2}{2\omega}L}\right)$$

- There are interference effects! The probability to produce an ALP is:

$$P(\gamma \to \phi) = |\mathcal{A}|^2 = 4\frac{g^2 B_{\mathrm{ext}}^2 \omega^2}{m_\phi^4}\sin^2\left(\frac{m_\phi^2 L}{4\omega}\right).$$

Hidden photons in LSW experiments

- The production (and re-conversion) of WISPs takes place in a coherent fashion.

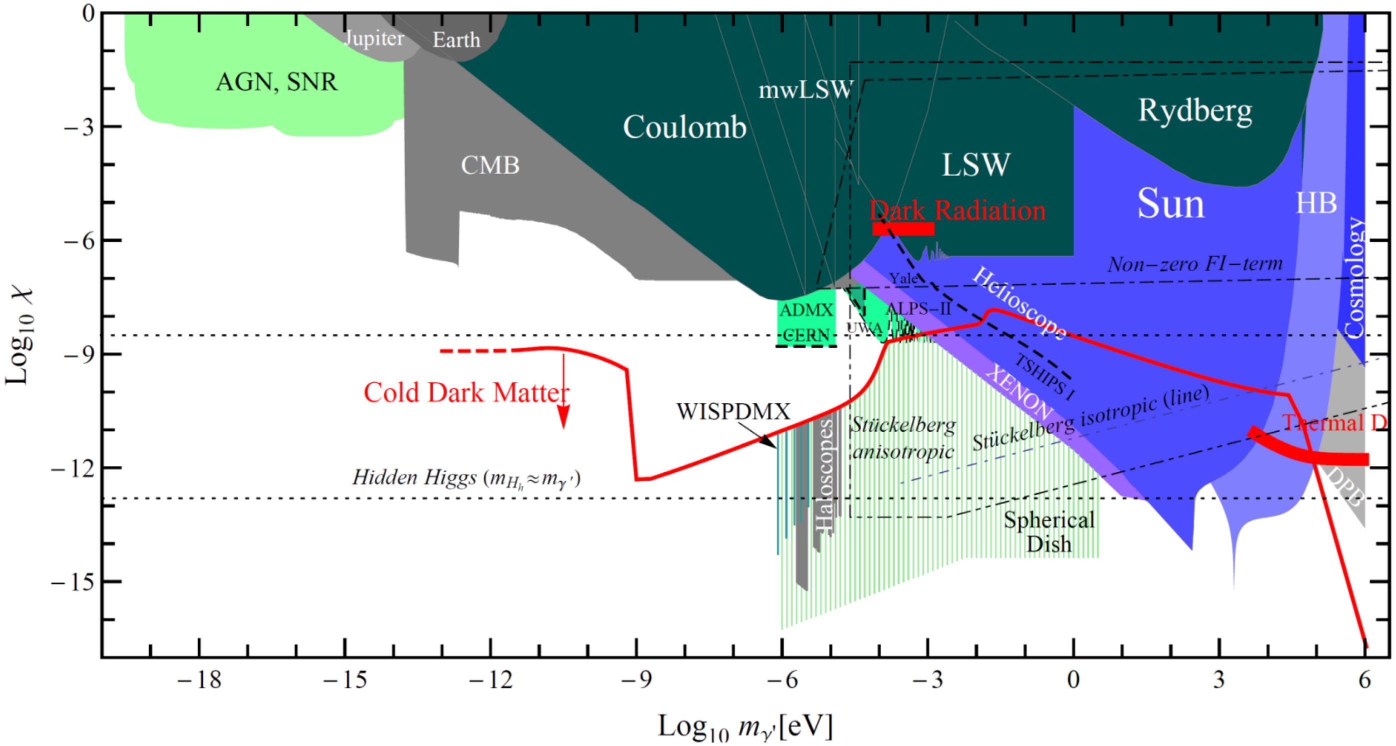


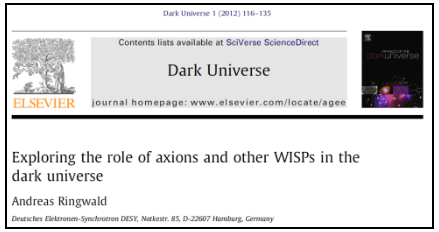
$$P(\gamma \leftrightarrow \gamma') \simeq 4\chi^2 \frac{m_{\gamma'}^4}{\left(m_{\gamma'}^2 + 2\omega^2(n-1)\right)^2} \sin^2\left(\frac{m_{\gamma'}^2 + 2\omega^2(n-1)}{4\omega} L\right)$$

With $P_{\gamma\to\gamma'} = P_{\gamma'\to\gamma} = P^{1/2}$: $\chi = (P)^{1/4}$

P =
(photon flux behind wall) /
(flux before wall)

The big picture: hidden photons





Dark Universe 1 (2012) 116–135

Contents lists available at SciVerse ScienceDirect

Dark Universe

ELSEVIER journal homepage: www.elsevier.com/locate/agee

Exploring the role of axions and other WISPs in the dark universe

Andreas Ringwald

Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, D-22607 Hamburg, Germany

DOI: 10.1016/j.dark.2012.10.008
e-Print: **arXiv:1210.5081 [hep-ph]**

Excluded by WISP experiments, helioscopes and WIMP dark matter search
Excluded by astronomy
Excluded by astrophysics and cosmology
Dark radiation in the CMB epoch
Hidden photons as dark matter

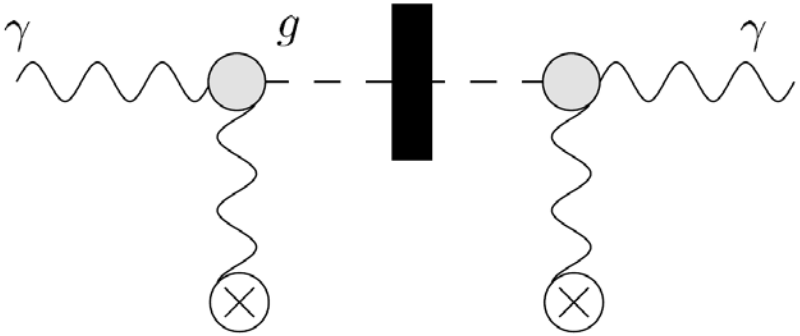
Sensitivity of next generation WISP exp.

Standard model background

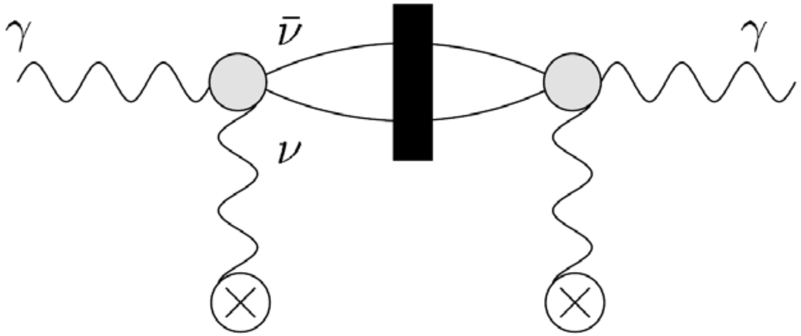
arXiv:1011.3741 [hep-ph] (J. Redondo, A. Ringwald):

> Light-shining-through a wall mediated by

gravitons



neutrinos

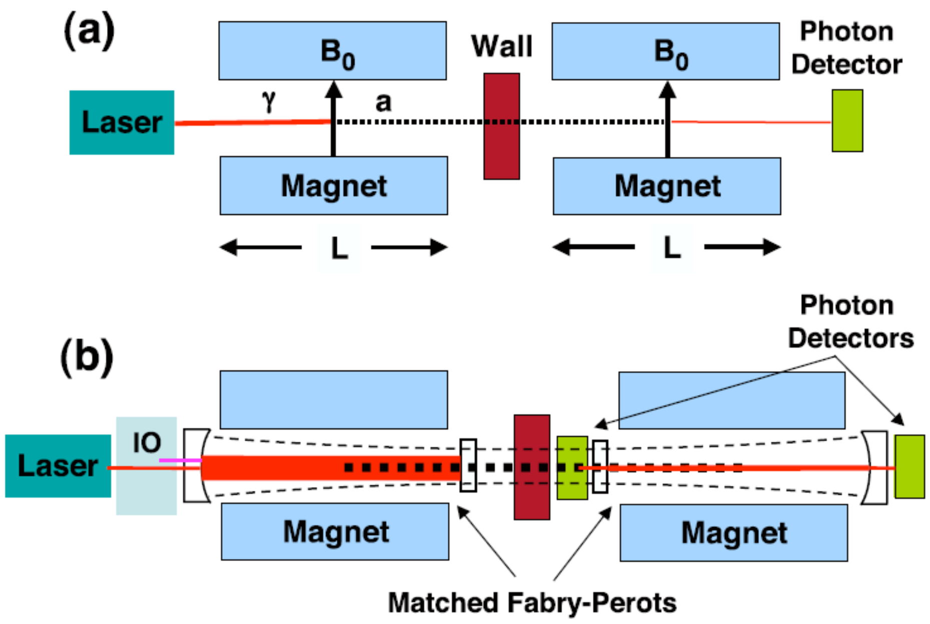


$$P(\gamma \to g \to \gamma) \simeq 10^{-83} \left(\frac{B}{\mathrm{T}}\right)^4 \left(\frac{L}{\mathrm{m}}\right)^4$$

> Negligible!

Resonant regeneration

> From one-way experiments to resonant set-ups:



2007: http://link.aps.org/doi/10.1103/PhysRevLett.98.172002

mono-energetic light only!

> Generation in a cavity before the wall: "recycle photons" to enhance the effective photon flux.

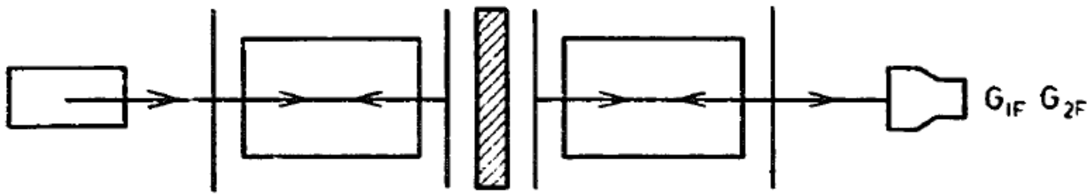
Regeneration in a cavity behind the wall: Increase back-conversion probability of WISPs into photons.

Resonant regeneration

- Already proposed in 1991!

http://dx.doi.org/10.1016/0550-3213(91)90528-6

F. Hoogeveen, T. Ziegenhagen / Light bosons



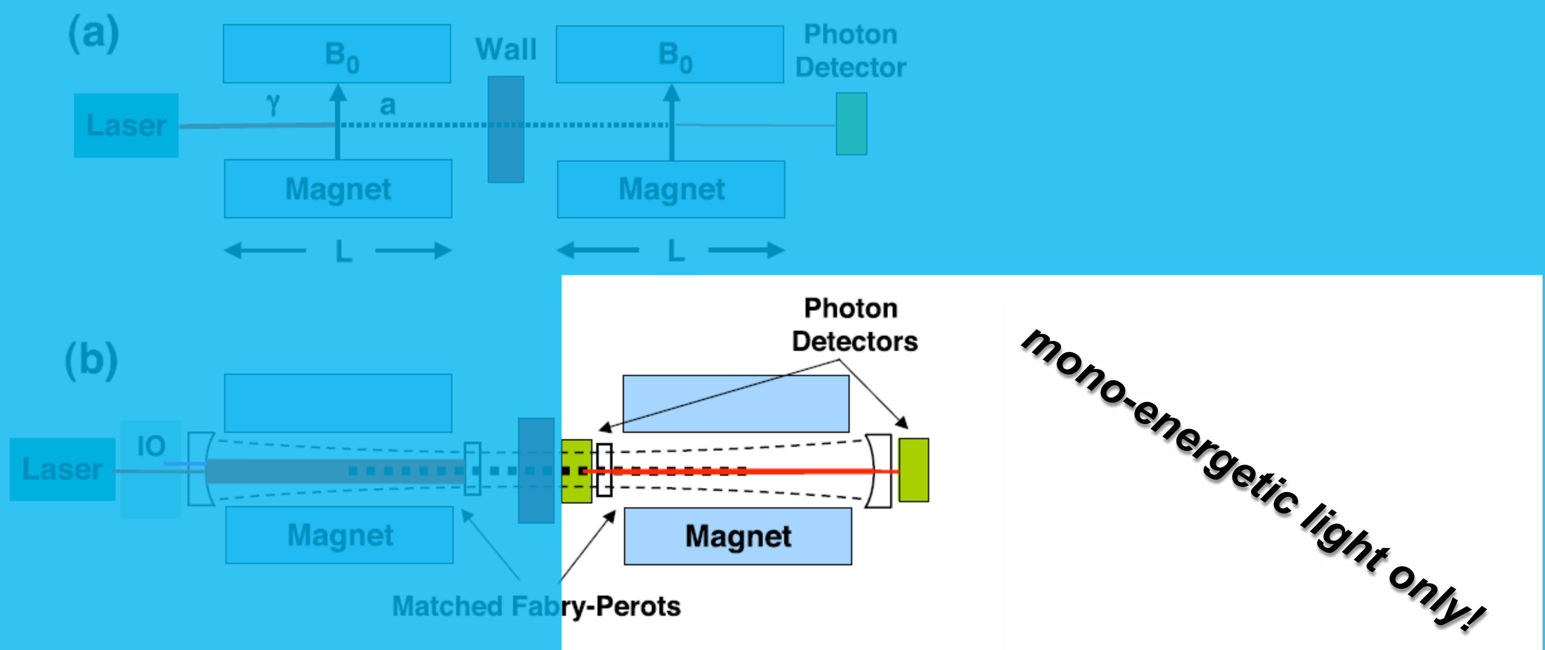
$$\frac{N_{\gamma\,\mathrm{out}}}{N_{\gamma\,\mathrm{in}}} = \frac{\Omega^2}{\Omega^2 - m_a^2}\left(\frac{g^2 B_1 B_2 L_1 L_2}{4}\right)^2 |F_1(q)|^2 F_2(q)|^2 |G_1|^2 |G_2|^2$$

with $|G|^2$ = power build-up Q in a cavity

- With Q up to 10^5: very large sensitivity improvements possible.

Resonant regeneration in haloscopes

- From one-way experiments to resonant set-ups:



2007: http://link.aps.org/doi/10.1103/PhysRevLett.98.172002

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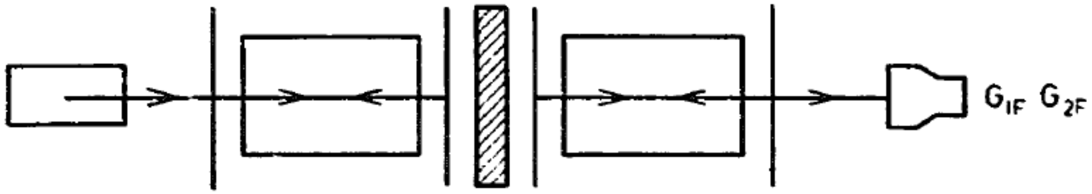


The number of photons produced is extremely small. One might therefore wonder whether it is allowed to make this calculation using classical fields, surpassing a proper quantum-mechanical treatment. In such a treatment however, the proper states to use are not the eigenstates of particle number, but coherent states. The amplitude of coherent states is a solution to the classical equations of motion, whether or not the particle number is macroscopically large. In this sense it is allowed to consider here classical fields only.

> Purcell effect (1940-ties):
> spontaneous emission rates change inside a resonating cavity.

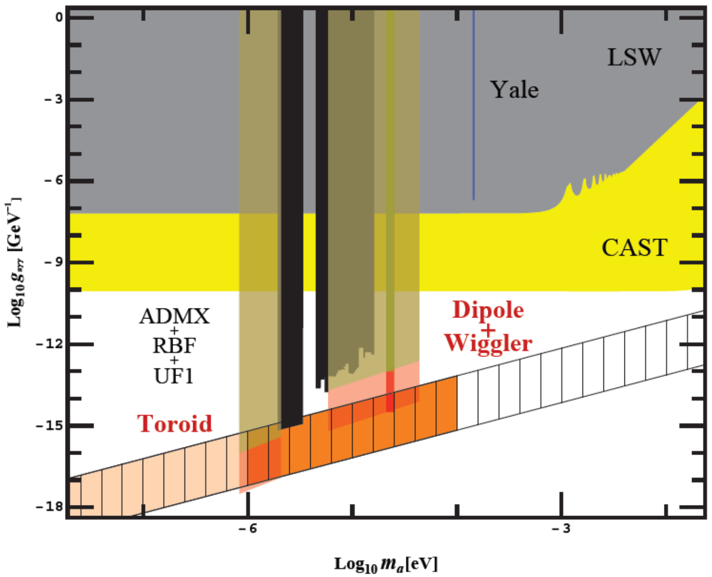
Exploit the possibilties of other magnets

PHYSICAL REVIEW D **85**, 035018 (2012)

Prospects for searching axionlike particle dark matter with dipole, toroidal, and wiggler magnets

Oliver K. Baker,[1] Michael Betz,[2] Fritz Caspers,[2] Joerg Jaeckel,[3] Axel Lindner,[4] Andreas Ringwald,[4]
Yannis Semertzidis,[5] Pierre Sikivie,[6] and Konstantin Zioutas[7]

DOI: 10.1103/PhysRevD.85.035018, arXiv:1110.2180v1 [physics.ins-det]



Experiments with toroid (IAXO),dipole and wiggler magnets could complement ADMX (using a solenoid).

Options with Tore Supra

- Use large magnetic volume equipped with microwave cavities to search for dark matter ALPs and axions.

Experiment	B (T)	V (m^3)	$B^2 \cdot V$ ($T^2 m^3$)
ADMX	8	1	64
Tore Supra	4	35	560

- However, Tore Supra cannot be (easily) cooled down to a few K.

- Questions
  - Is the electromagnetic noise within the magnet tolerable?
  - Is it possible to use the magnet as a cavity at its fundamental resonance at about 145 MHz (0.6 µeV)? What is the Q value here?
  - Is it possible to assemble a number of smaller cavities inside the magnet?
  - Does a broad spectral range search for dark matter make sense (Q=1)?

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08 Jul - 12 Jul, 2012
39th IEEE Int'l Conference on Plasma Science (ICOPS2012)
Edinburgh, U.K.

27 Aug - 31 Aug, 2012
TOFE 2012 - Realizing new technologies for the age of fusion energy
Nashville, US

03 Sep - 14 Sep, 2012
6th International School on Fusion Technologies
Karlsruhe, Germany

17 Sep - 21 Sep, 2012
IPP Summer University on Plasma Physics and Fusion Research
Garching, Germany

24 Sep - 28 Sep, 2012
27th Symposium on Fusion Technology (SOFT) Conference
Liège, Belgium

08 Oct - 13 Oct, 2012
24th IAEA Fusion Energy Conference
San Diego, USA

18 Mar - 21 Mar, 2013
6th I'ntl Workshop on

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15 Jun, 2012 - #227

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Focus On

Will tokamaks unveil the #1 mystery of the Universe?

-Robert Arnoux

Because of their large magnetized volume, tokamaks could be used to detect the elusive particles that are postulated to constitute dark matter/dark energy.

The more astronomers observe the Universe, the more matter they need to find to explain it all. Do "exotic particles" hold the key to the mystery? © A. Schaller (STScI)

A huge chunk of mass appears to be missing from the Universe. The billions and billions of galaxies that telescopes observe, the giant gas and dust clouds that float in the immensity of intergalactic space account for only a fraction of what is really there. The rest is invisible and remains undetectable.

The existence of a "dark matter" permeating the Universe and accounting for such gravitational phenomena as the rotational speed of galaxies or the "bending" of light around massive astronomical objects was inferred by cosmologists as early as the 1930s. Theories were established that remain unconfirmed to this day.

Decades later, observations of the accelerating expansion of the Universe led cosmologists to postulate the existence of another mysterious entity, a force whose nature can only be surmised— the so-called "dark energy".

It is generally estimated that the mass-energy content of the Universe is made up of approximately 74 percent dark energy, 22 percent dark matter and only 4 percent ordinary matter such as stars, planets, dust and intergalactic gas.

Dark matter and dark energy hold the answers to our ultimate destiny. Will the Universe expand forever in all directions or will it eventually retract and end in a Big Crunch? The question is definitely worth pondering ...

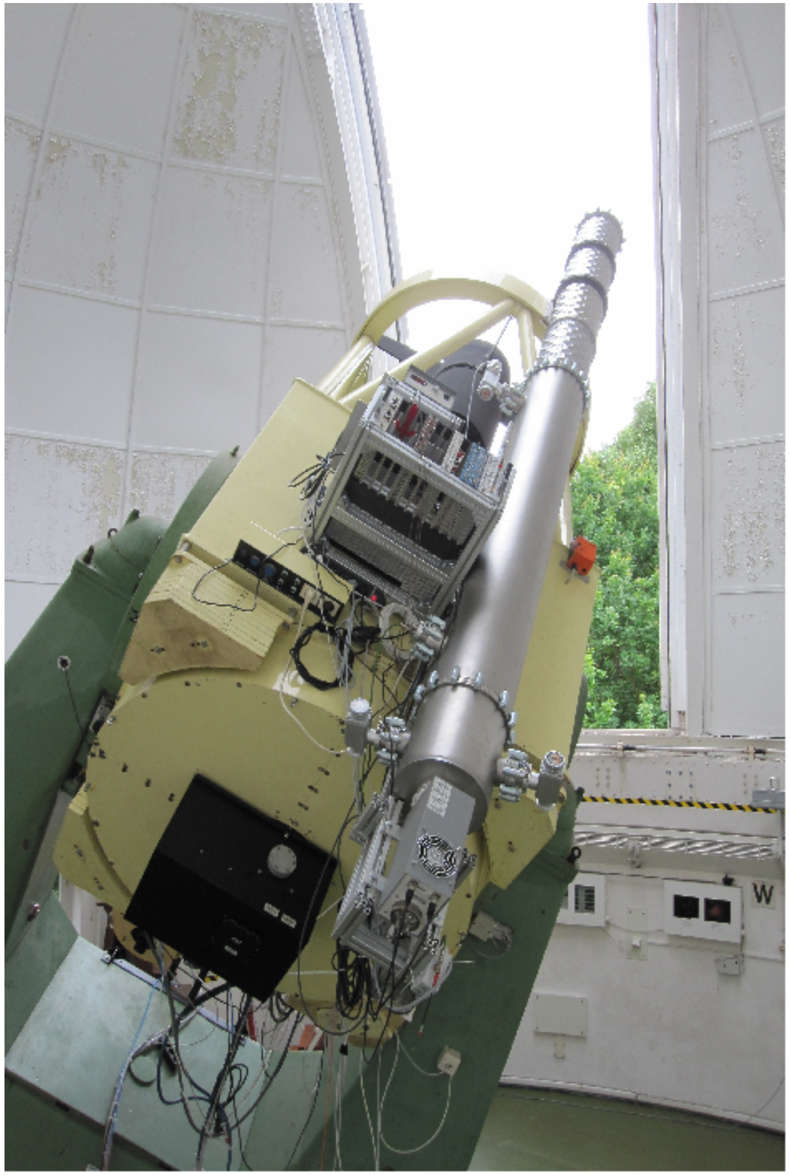
Dr Jean-Claude Vallet, of CEA's Institut de Recherche sur la Fusion Magnétique (IRFM), is participating in the preliminary discussions with CERN and ESA on turning Tore Supra into a part-time dark matter detector.

There is a consensus among cosmologists and particle physicists that "exotic" particles are key to understanding dark energy and dark matter. Dubbed "chameleons" (they are able to change their own mass) and "axions" (in reference to the US detergent Axion because their existence may help to clean up some theory problems) these hypothetical particles have been assigned a set of properties that would explain the behaviour of the Universe. As of today, however, both chameleons and axions have escaped detection.

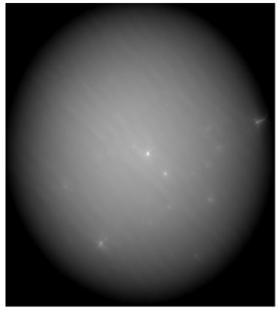
Now, there's big news on the cosmic front. Tokamaks—and specifically the CEA-Euratom machine Tore Supra in Cadarache, France—could play a decisive role in the detection of some of these elusive particles: the "solar chameleons" that may originate in the Sun, and the "relic axions" that were produced right after the Big Bang ...

Axions and chameleons are postulated to interact weakly with matter (they traverse it as if it didn't exist) and to change into photons via the "Primakoff effect" in the presence of an intense magnetic field. However, experiments aimed at confirming their existence, like the CERN Axion Solar Telescope (CAST) in Geneva, have failed, to this day, to detect either axions or chameleons.

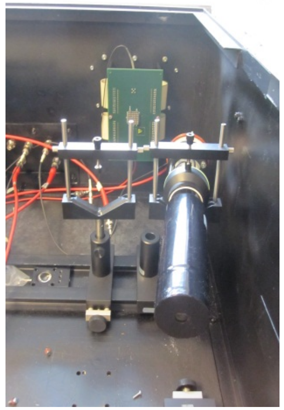
TSHIPS-I status



- Light collected via a 20 cm Fresnel lens:

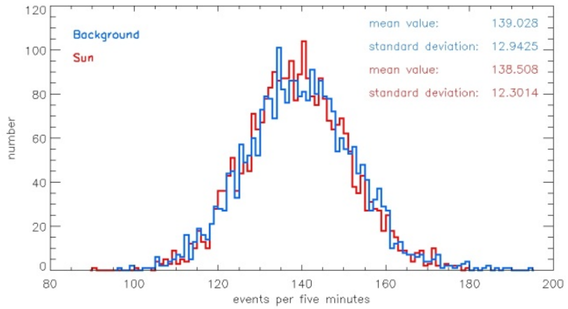


- Low noise PM:
  (ET Enterprises 9893/350B)



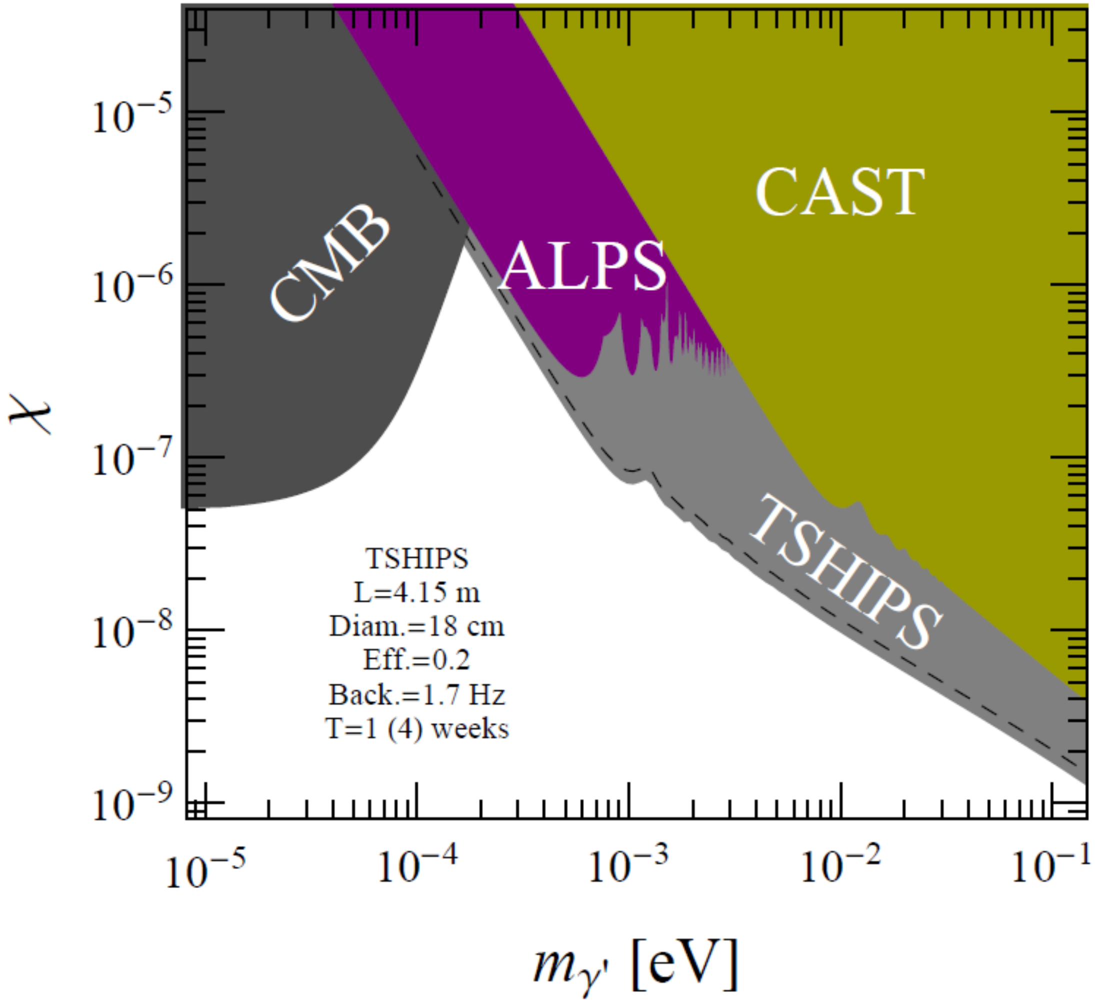
- Data taking since March 2013: 250 h of sun + background data each,

  but no hint for an excess (yet).



DESY

TSHIPS-I potential

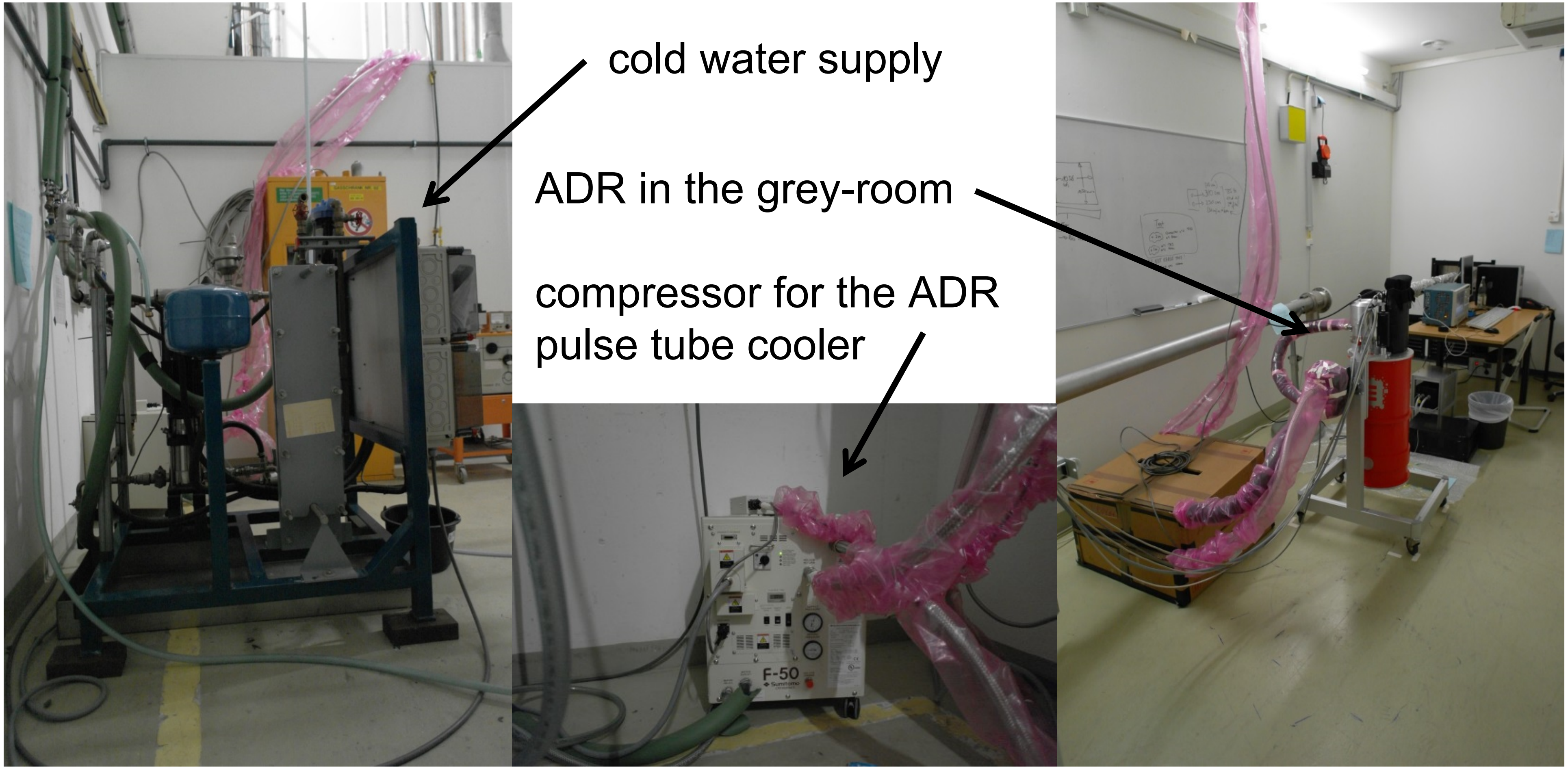


Significant improvement compared to present experimental sensitivities!

Search for hidden photons, hence no magnets required!

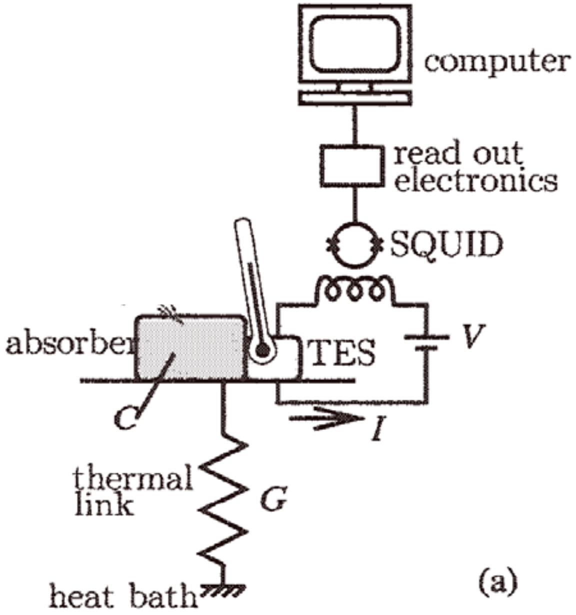
ALPS II detector

The studies of the Transition Edge Sensors proceed.



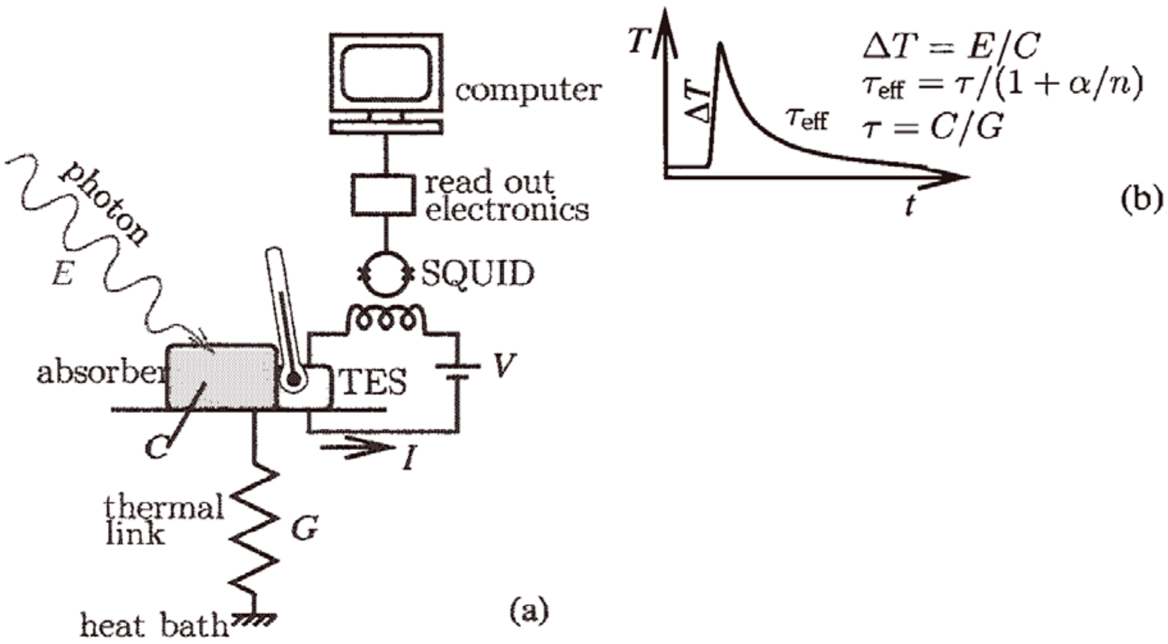
ALPS II detector

Transition Edge Sensor (TES)



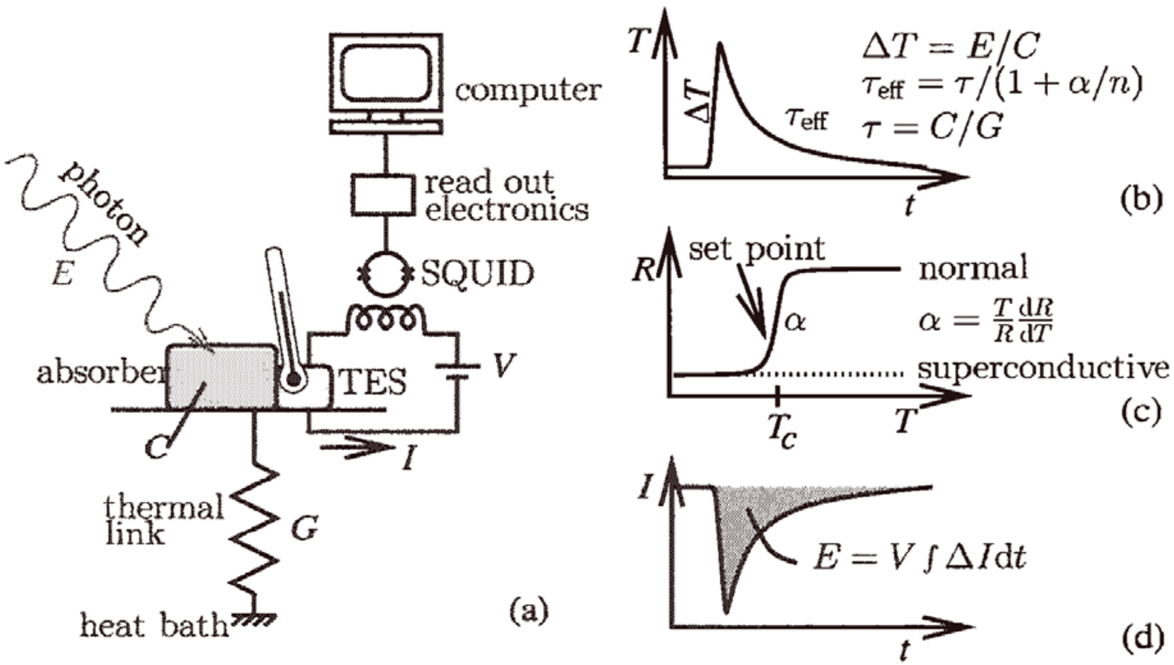
ALPS II detector

Transition Edge Sensor (TES)



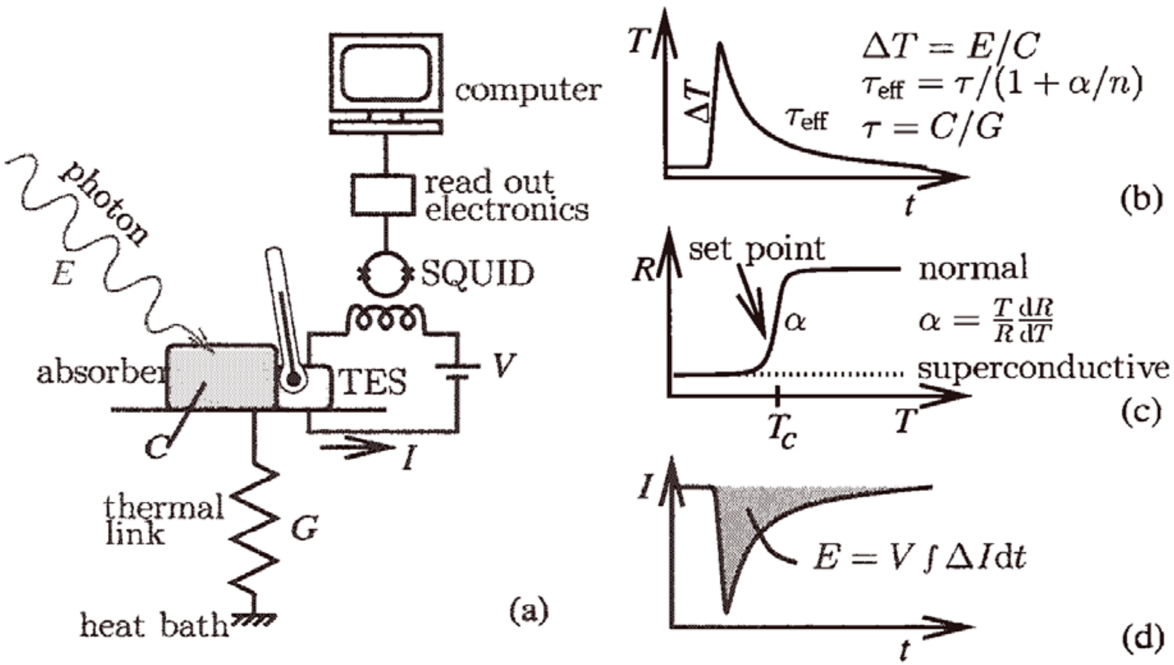
ALPS II detector

Transition Edge Sensor (TES)



ALPS II detector

Transition Edge Sensor (TES)



- > Very high quantum efficiency, also at 1064 nm, very low noise.
- > Tungsten film.
- > Sensor size 25µm x 25µm x 20nm.
- > To be operate around 100 mK.

ALPS II essentials: magnets

The aperture of the magnets determines the lenghts of the optical cavities:

> The laser beam diverges and clipping is to be avoided to not spoil the power built-up in the cavities.

Eff. dipole aperture		Max. # of dipoles		B·L (Tm)	
		HERA	LHC	HERA	LHC
35 mm	(HERA)	2·4		187	
40 mm	(LHC)	2·6	2·4	281	514
50 mm	(HERA almost straight)	2·10		468	
55 mm	(HERA straight)	2·12		562	

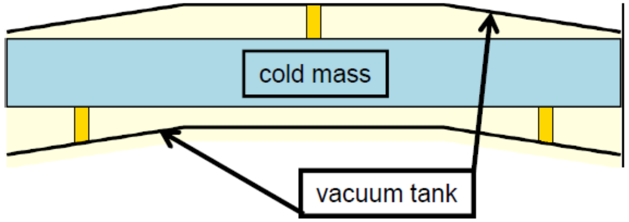
HERA dipoles are competitive with LHC dipoles, if one could get them straight!

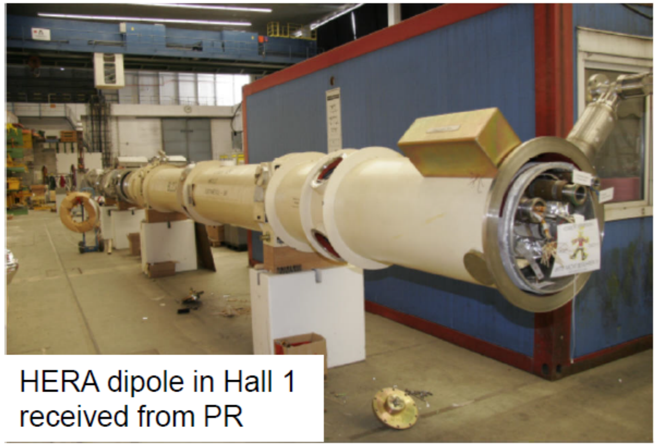
> Challenge:
> develop (cheap) straigthening procedure for HERA dipole magnets!

ALPS II essentials: magnets

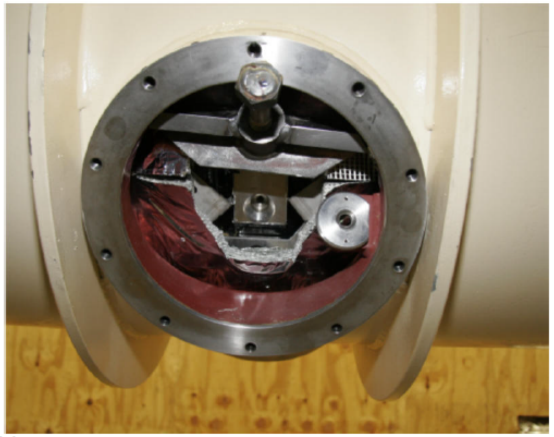
Inexpensive method to increase the aperture of the vacuum pipe in the HERA dipole

Force ends and middle of cold mass towards the center with simple deformation tools





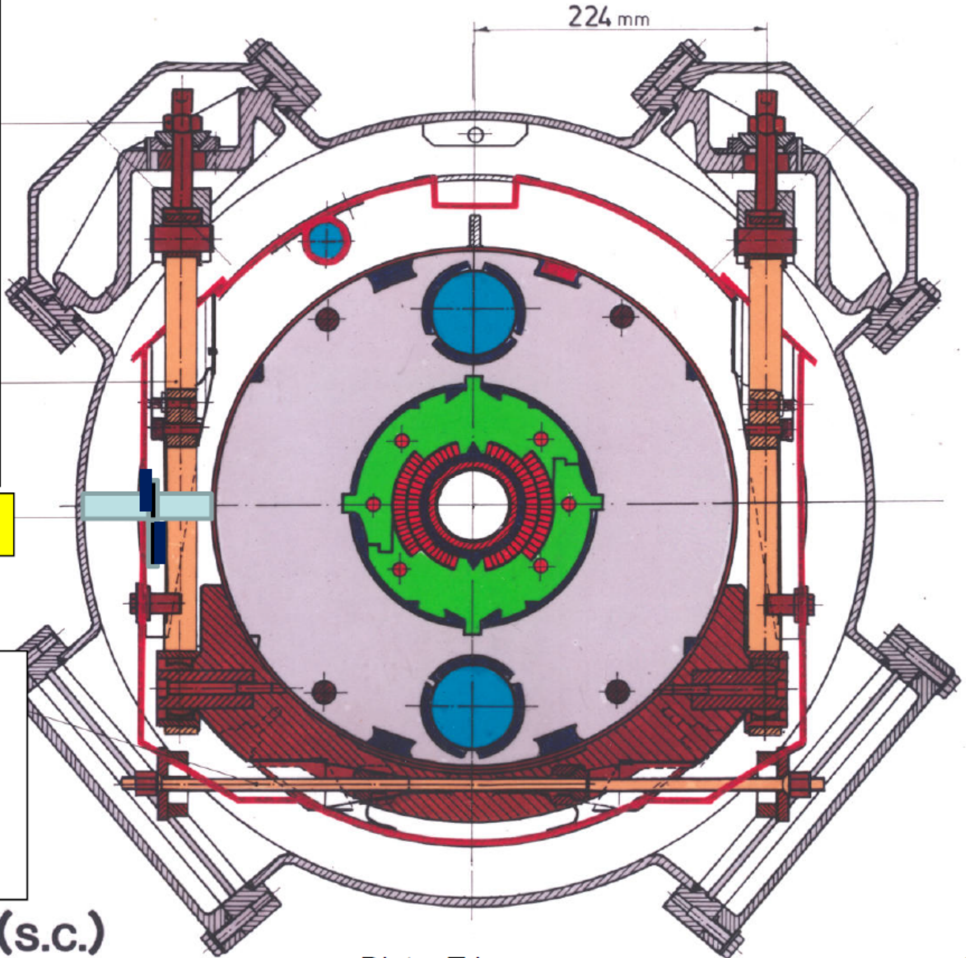
HERA dipole in Hall 1
received from PR



ALPS II essentials: magnets

The deformation of the yoke is elastic. Therefore the force must be maintained also during cryogenic operation of the dipole.
So, the deformation tools are replaced by **pressure props with a sufficiently low heat flow to the 4K helium vessel**.

pressure prop



The outer pressure props have to follow the length change of the helium vessel during cool down and warm-up.

Dipole Magnet (s.c.)

Dieter Trines
PRC Review Nov 7th 2012

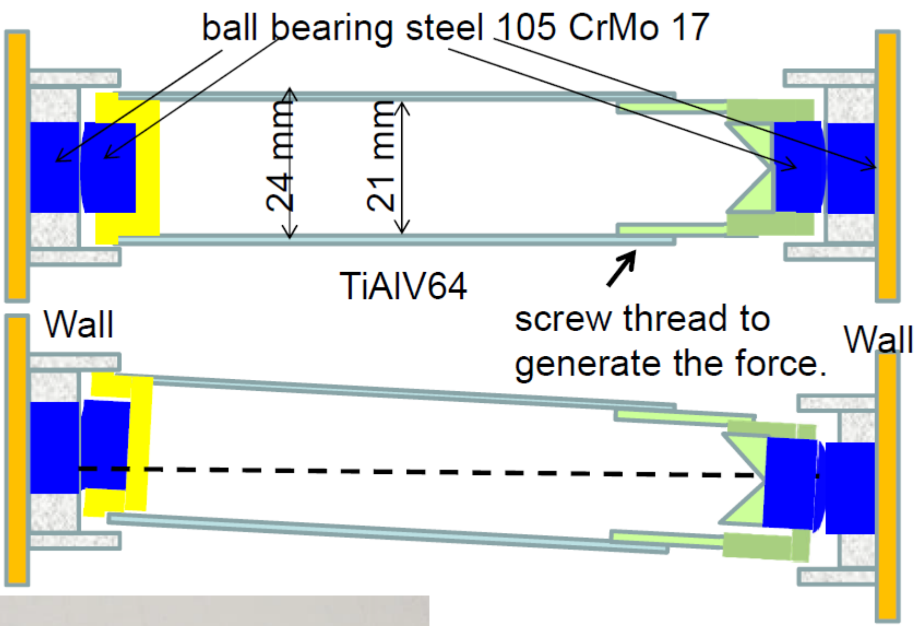
8

ALPS II essentials: magnets

The problem to follow the shrinkage of the cold mass was solved by using the section of a sphere, which rolls with the motion of the cold mass.

Low heat flow pressure prop

The distance between warm and cold wall does not change during roll except for a thermal shrinkage of the pressure prop



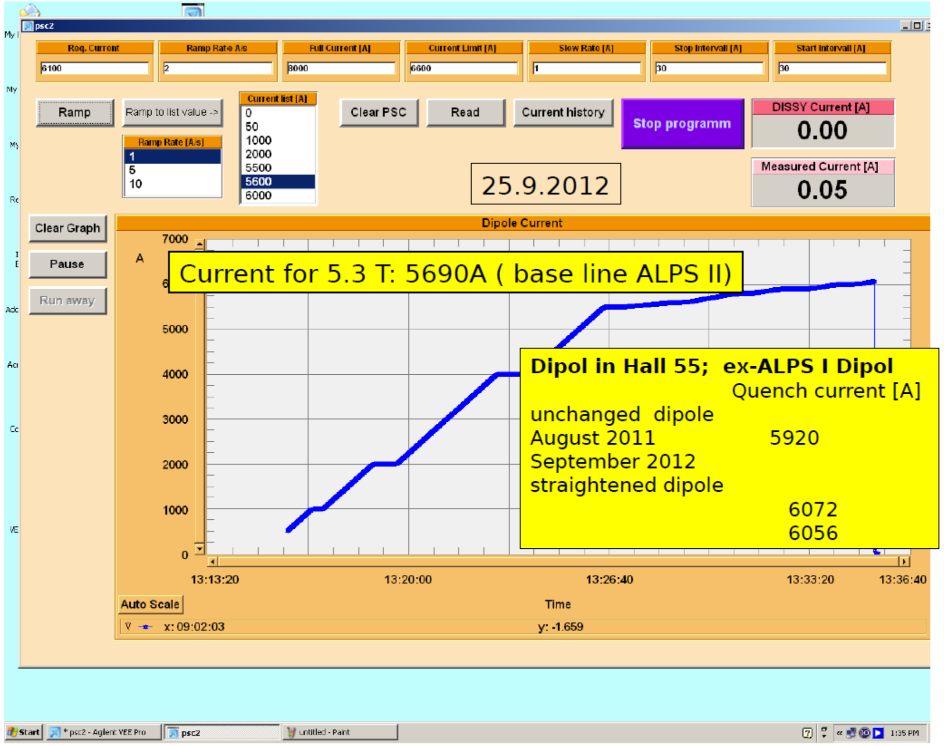
The prototype was tested at liquid nitrogen temperature in vacuum

Dieter Trines 9
PRC Review Nov 7th 2012

DESY

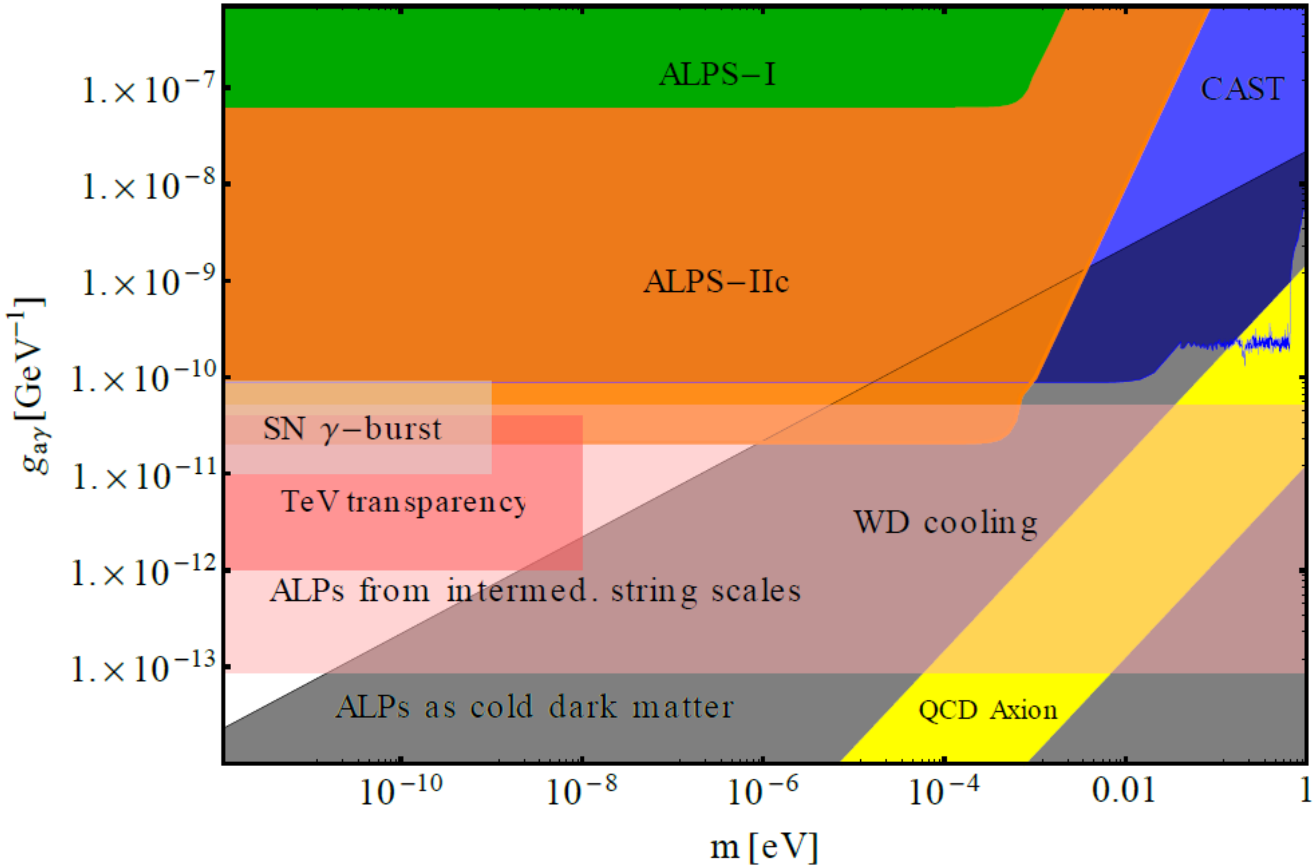
Status of magnets

> Already the first test of the straightening procedure in September 2012 was very successful!



> The straightening procedure for the HERA dipoles has been revised. A simpler and more robust method will be tested soon.

Sketch of the ALPS II sensitivity



- ALPS IIc will surpass present day direct and indirect limits.
- ALPS IIc will probe the parameter region proposed by astrophysics phenomena and theory (strings, dark matter).

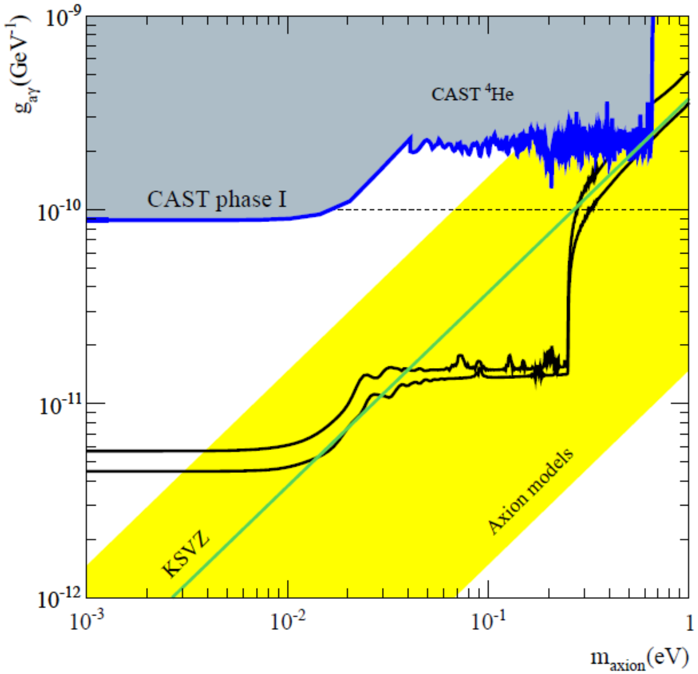
Beyond ALPS II

- On the longer run one could strive for an "ALPS III":
  - New dipoles based on developments for LHC energy upgrade: B = 13T, aperture 100 mm: gain in B·L by a factor of about 10.
  - Increasing the cw laser power to a few MW.
  - Reach for ALP couplings down to 10^{-12} GeV^{-1}!
  - However, only light ALPs with masses below 0.1 meV could be searched for!

$$P_{\gamma\to\phi}(B,\ell,q) = \frac{1}{4}\left(g\,B\,\ell\right)^2\,F(q\ell) \qquad F(q\ell) = \left[\frac{\sin\left(\frac{1}{2}q\ell\right)}{\frac{1}{2}q\ell}\right]^2$$

ALPS and IAXO

- The International Axion Observatory: could be ready in 2020.
- ALPS II aims for data taking in 2018.
- An “ALPS III” need considerable R&D and might be ready in 2025.

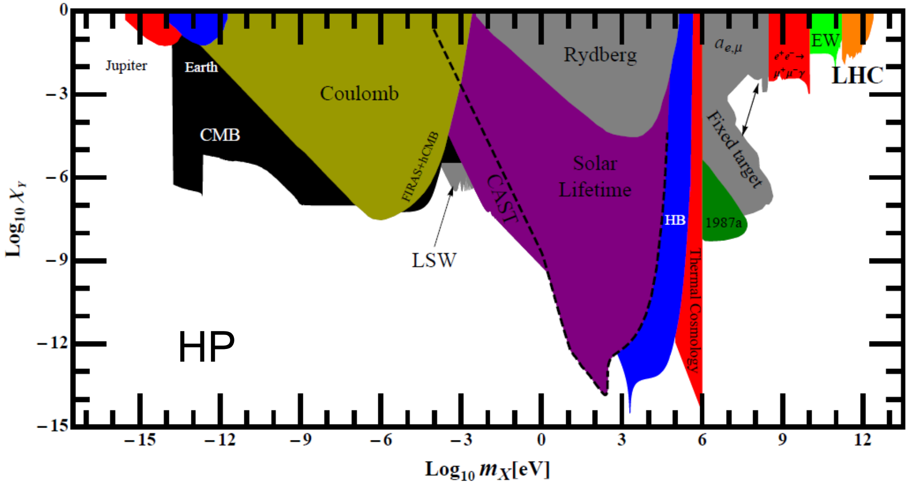


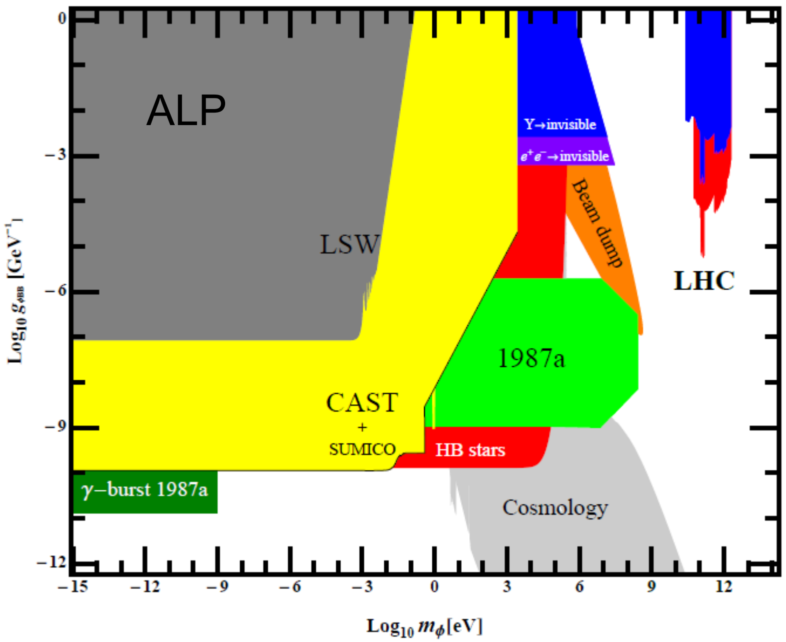
← ALPS I 2007-2010

← ALPS II (but m < 0.2meV) 2018

← “ALPS III” dream (but m < 0.1meV) 2025?

WI(S)P searches at LHC





IPPP/12/94; DCPT/12/188;

IPPP/12/94; DCPT/12/188
arXiv:1212.3620 [hep-ph]

LHC probes the hidden sector

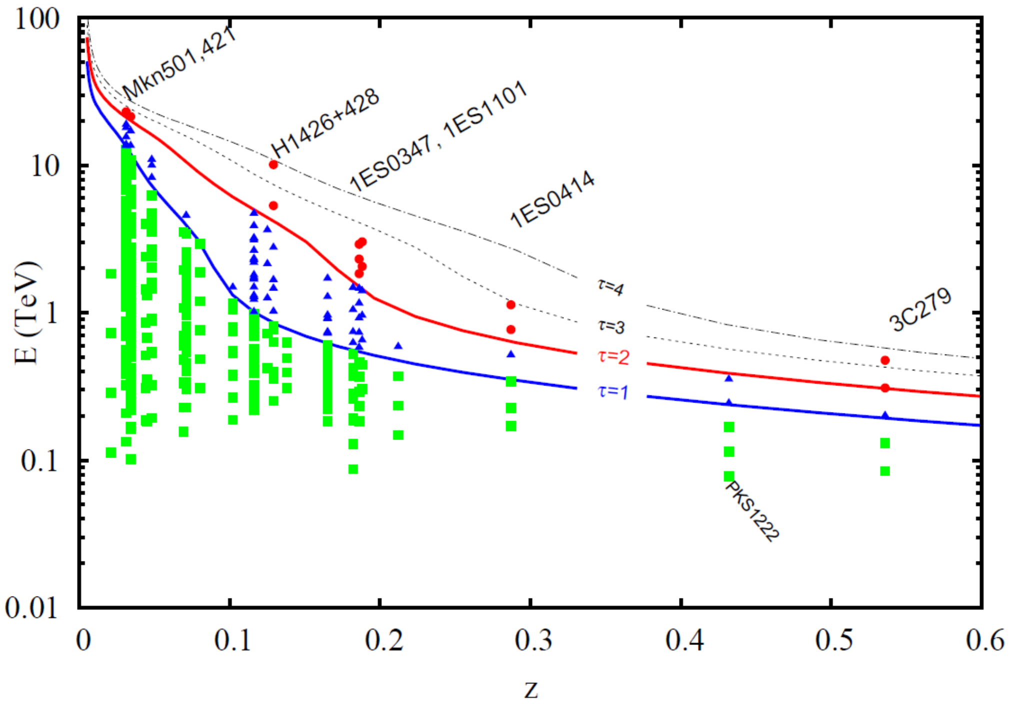
Joerg Jaeckel[1*], Martin Jankowiak[1†] and Michael Spannowsky[2‡]

- LHC can probe couplings much weaker than the typical values of the visible sector.
- However, there is hardly any sensitivity for lightweight particles, which are of cosmological relevance.

Indications for a WISP world?

> Puzzles from astrophysics:

… but this seems to be in conflict with observations.

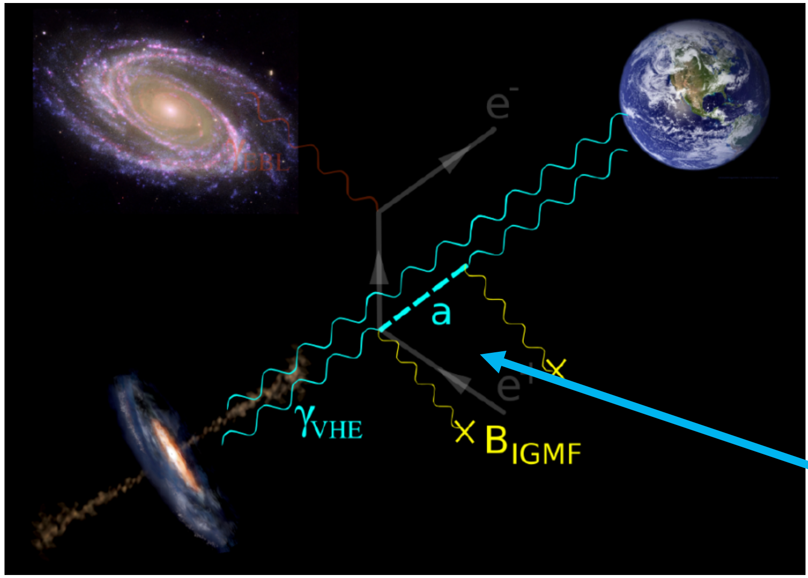


D. Horns, M. Meyer, JCAP 1202 (2012) 033

> If physics beyond the SM is involved, it happens below the MeV scale!

Indications for a WISP world?

- Axion-like particles might explain the apparent transparency of the Universe for TeV photons:

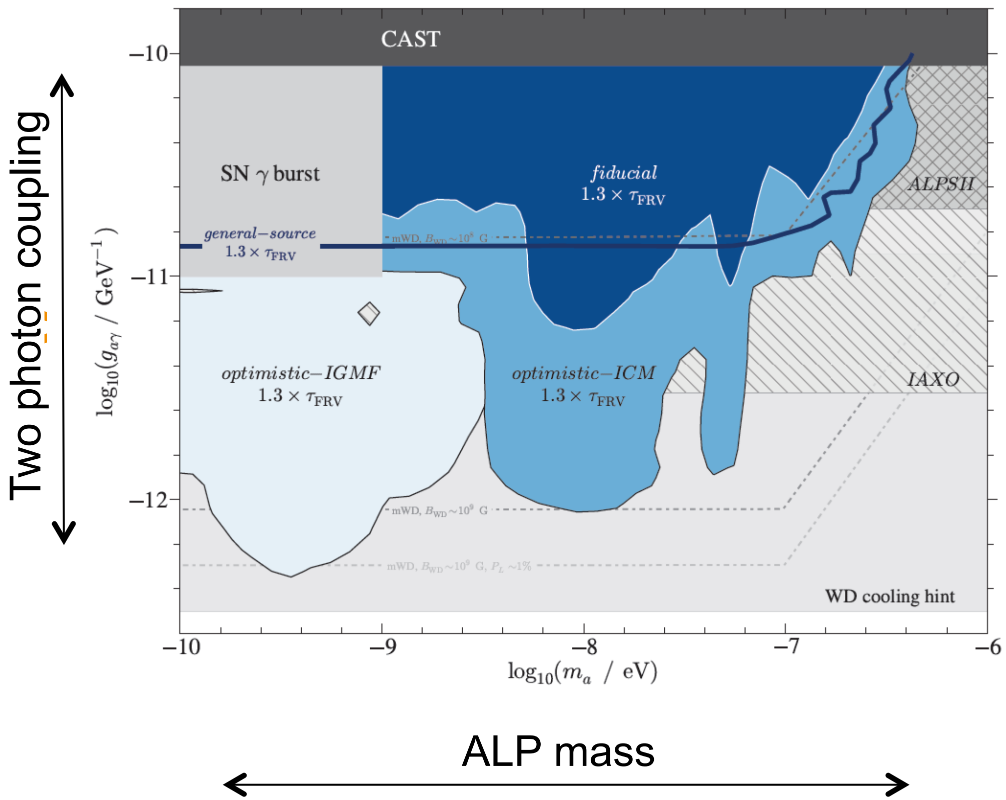


M. Meyer, 7th Patras Workshop on Axions, WIMPs and WISPs, 2011

TeV photons may “hide” as ALPs:
LSW in the Universe!

ALPs and cosmic TeV photons

> Axion-like particles might explain the apparent transparency of the Universe for TeV photons:



significance above 3.5 σ

$g_{a\gamma} \approx 10^{-11} GeV^{-1}$, $m_a < 10^{-7} eV$ have to be probed!

M. Meyer, D. Horns, M. Raue,
arXiv:1302.1208 [astro-ph.HE], Phys. Rev. D 87, 035027 (2013)

Unexplained physics phenomena

might hint at Weakly Interacting Slim Particles (WISPs).

- Axions and axion-like particles (ALPs, pseudoscalar or scalar bosons)
- Hidden photons (neutral vector bosons)
- Mini-charged particles
- Chameleons (self-shielding scalars)

Phenomenon	WISPy explanation
Solar phenomena ★	Chameleon, ALP
White dwarf cooling ★	Axion, ALP
TeV transparency ★	ALP
CMBR neutrino number ★	HP, Chameleon (?)
Dark matter	Axion, ALP, HP
Dark energy ★	Chameleon

★ to be confirmed!

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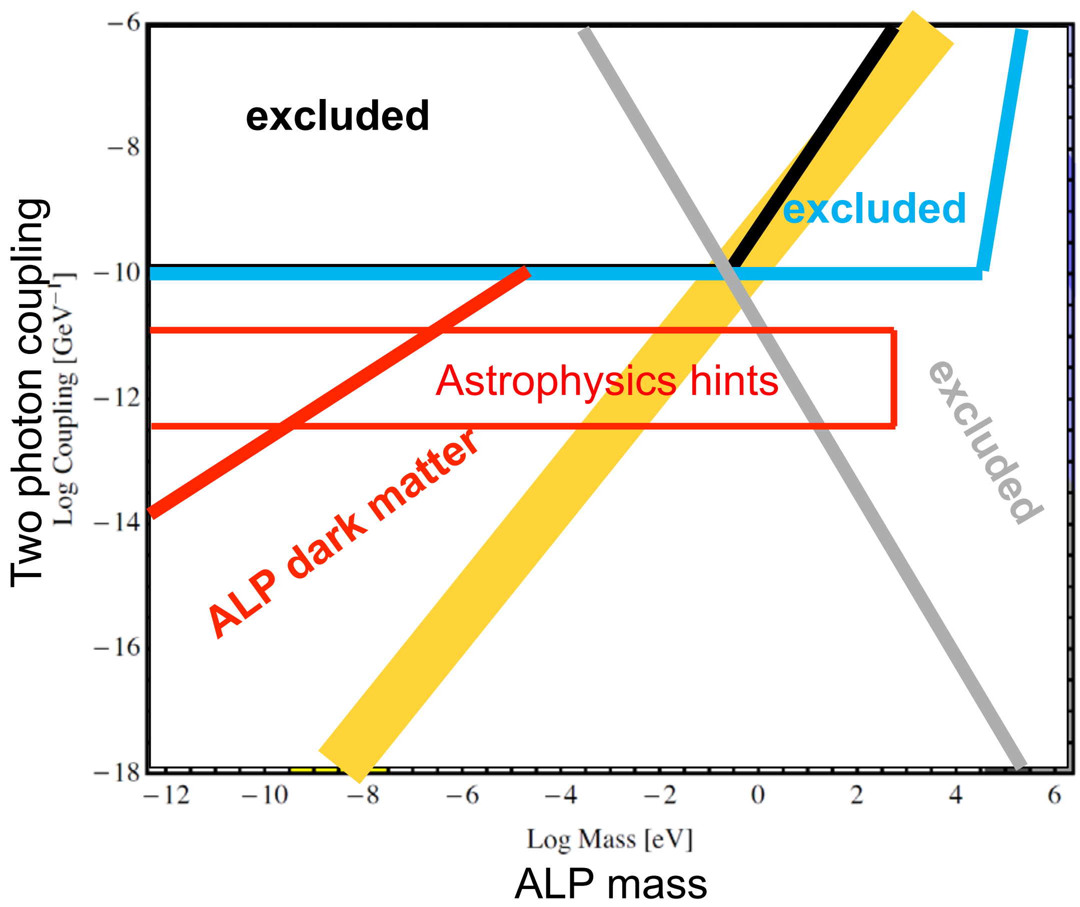
The big picture: ALPs



QCD axion range

Excluded by WISP experiments

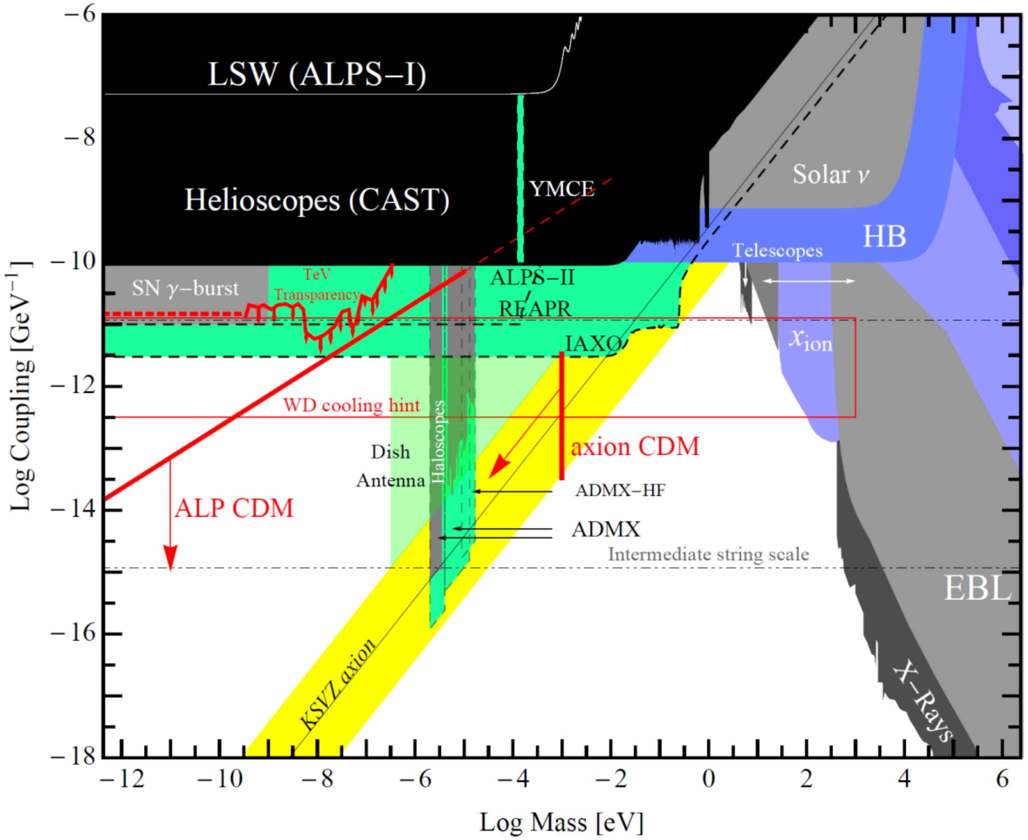
Excluded by astronomy (ass. ALP DM)

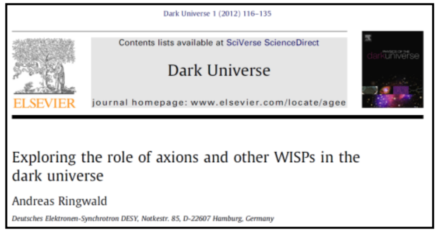
Excluded by astrophysics / cosmology

Axions or ALPs being cold dark matter

WISP hints from astrophysics

The big picture: ALPs




Dark Universe 1 (2012) 116–135

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Dark Universe

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Exploring the role of axions and other WISPs in the dark universe

Andreas Ringwald

Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, D-22607 Hamburg, Germany

DOI: 10.1016/j.dark.2012.10.008
e-Print: arXiv:1210.5081 [hep-ph]

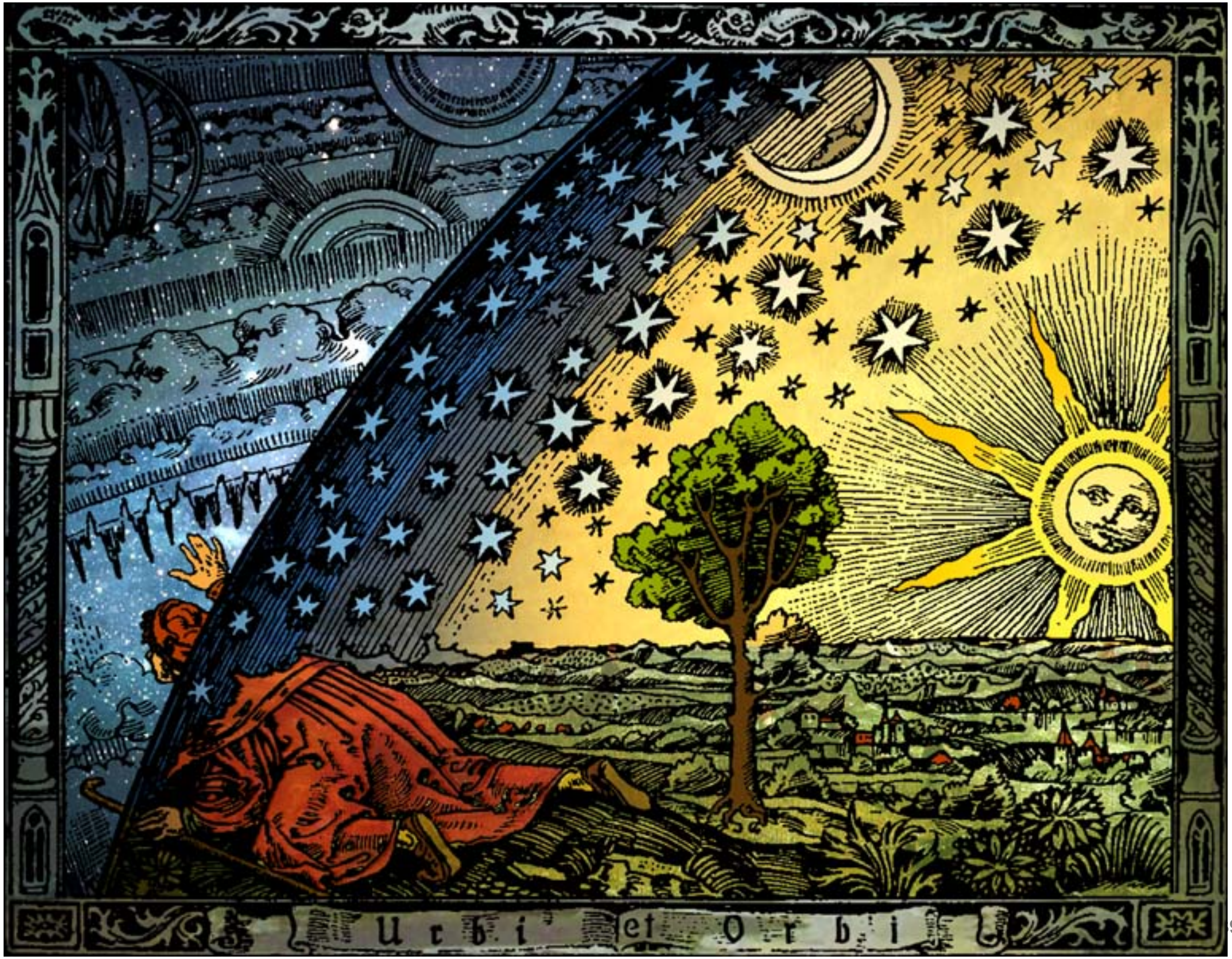
QCD axion range
Excluded by WISP experiments
Excluded by astronomy (ass. ALP DM)
Excluded by astrophysics / cosmology
Axions or ALPs being cold dark matter
WISP hints from astrophysics

Sensitivity of next generation WISP exp.

Particular interesting:

> ALP-photon couplings around 10^{-11}GeV^{-1}, masses below 1 meV.
This can be probed by the next generation of experiments.

Physics beyond the standard model



http://es.wikipedia.org/wiki/Archivo:Universum.jpg

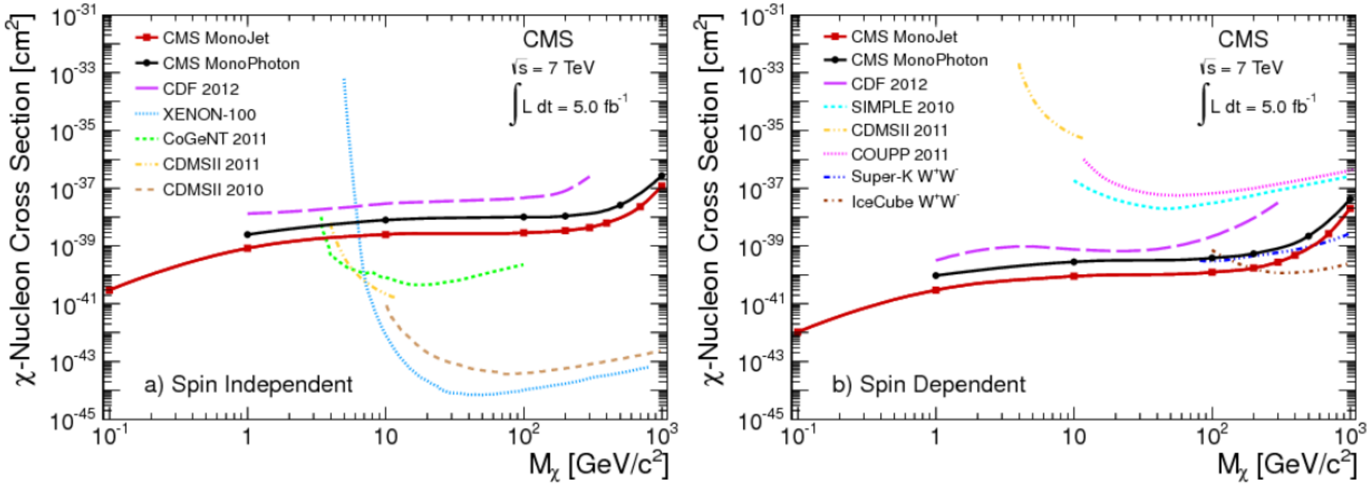
Input to the discussion on the future European strategy on particle physics:

- In searches for WISPs as a Dark Matter component a variety of new experimental approaches have recently emerged and deserve serious attention, as they may yield an experimental program complementary to and competitive with the leading US Axion Dark Matter search eXperiment (ADMX).
- In searches for WISPs emitted by the sun the proposal for an International AXion Observatory (IAXO) stands out as a larger scale follow-up of the successful CAST helioscope at CERN.
- In purely laboratory based WISP searches the proposal for Any Light Particle Search (ALPS II) at DESY offers leading prospects for this technique worldwide.

Although significant challenges remain, the rewards of exploring the low-energy frontier of particle physics could be enormous. Looking through the low-energy window may reveal fundamental insights on the underlying structure of nature and shed light on such important mysteries as the origin of Dark Matter and Dark Energy.

Dark Matter WIMPs

Model independent limits on the direct detection cross section



- LHC limits on SD and SI interactions are comparable
  SD, SI are properties of non-relativistic operators
  no enhancement of SI due to coherent scattering with nucleus
- strong limits on light dark matter as observable recoil energy does not depend on dark matter mass