New detection techniques for axion like particles

Terzo Pomeriggio di discussione su materia oscura
INFN, Roma I, Dip. di Fisica

26 May 2015

Axel Lindner, DESY

HELMHOLTZ
ASSOCIATION

DESY

Not so new detection techniques for axion like particles to be applied in new experiments

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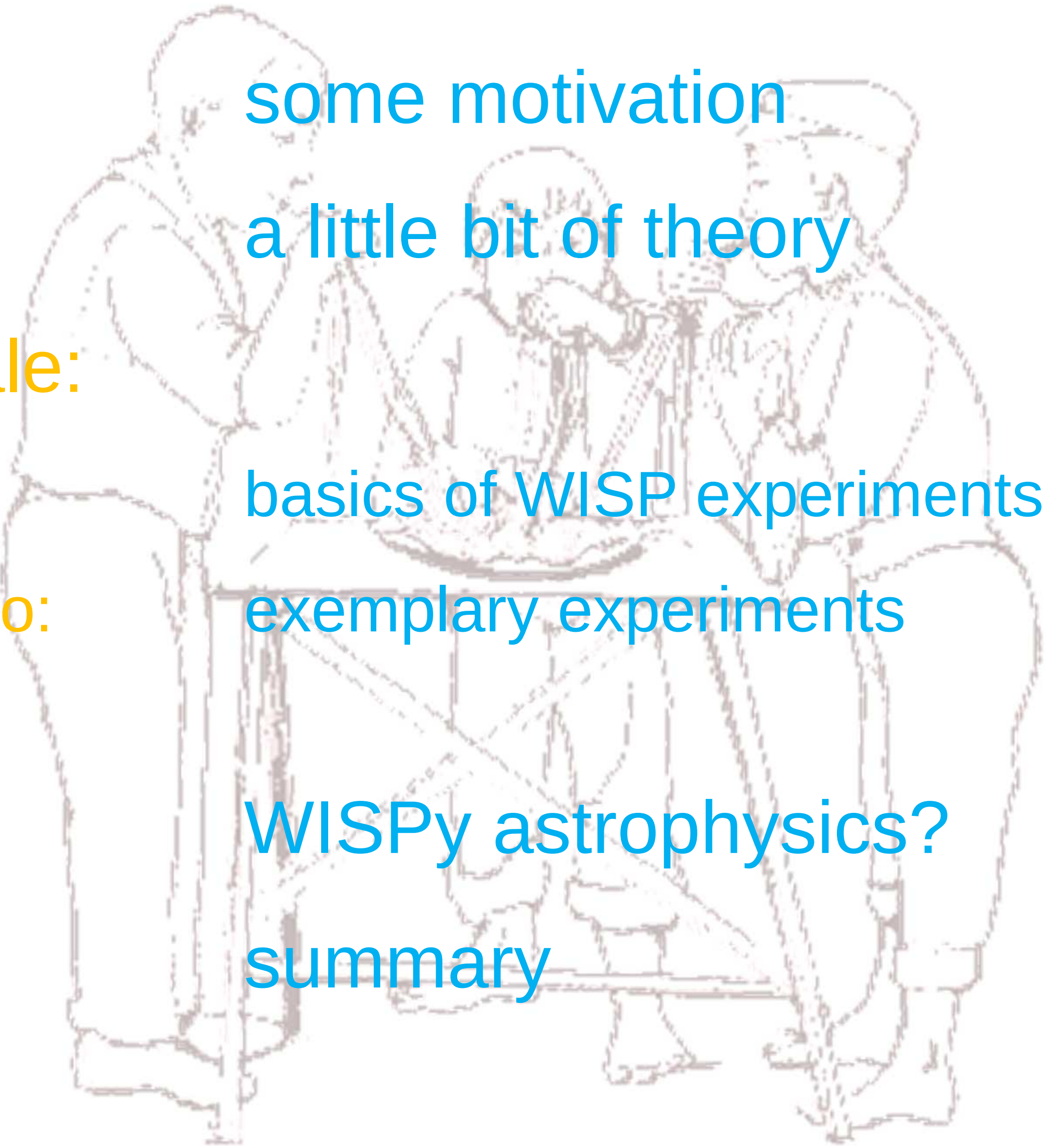
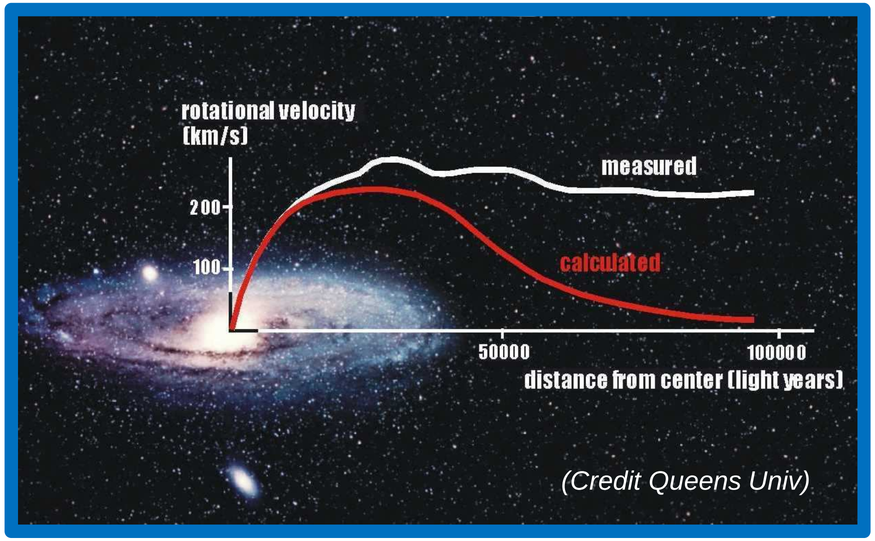
Outline

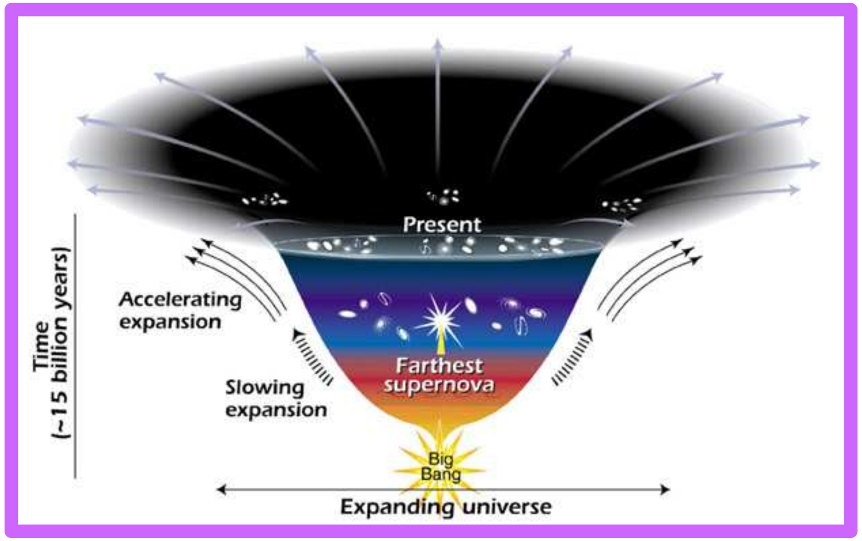


- Aperitivo: some motivation
- Antipasto: a little bit of theory
- Piatto principale:
  - Prima piatto: basics of WISP experiments
  - Seconda piatto: exemplary experiments
- Dolce: WISPy astrophysics?
- Caffè corretto: summary

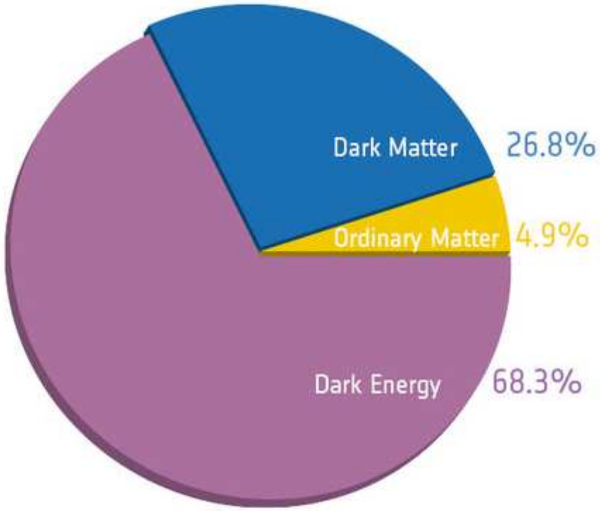
There is physics beyond the SM

- Dark matter and dark energy:





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

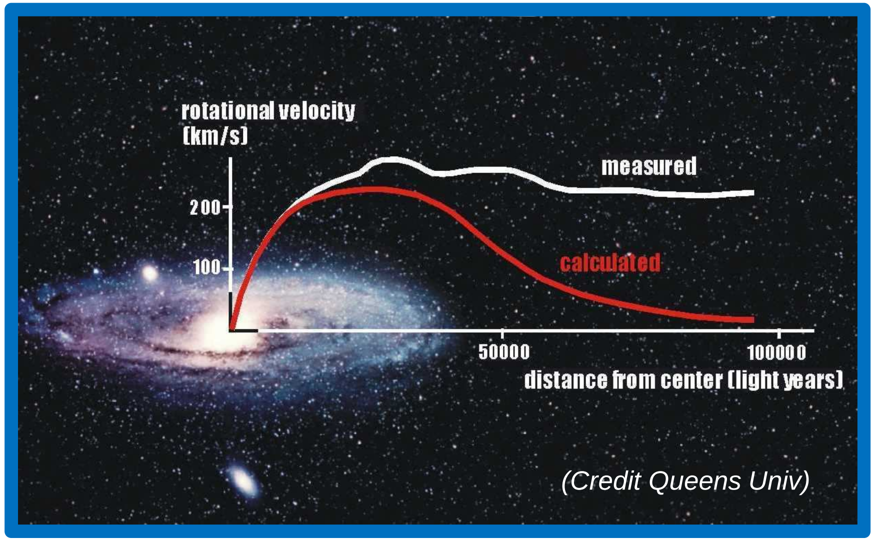


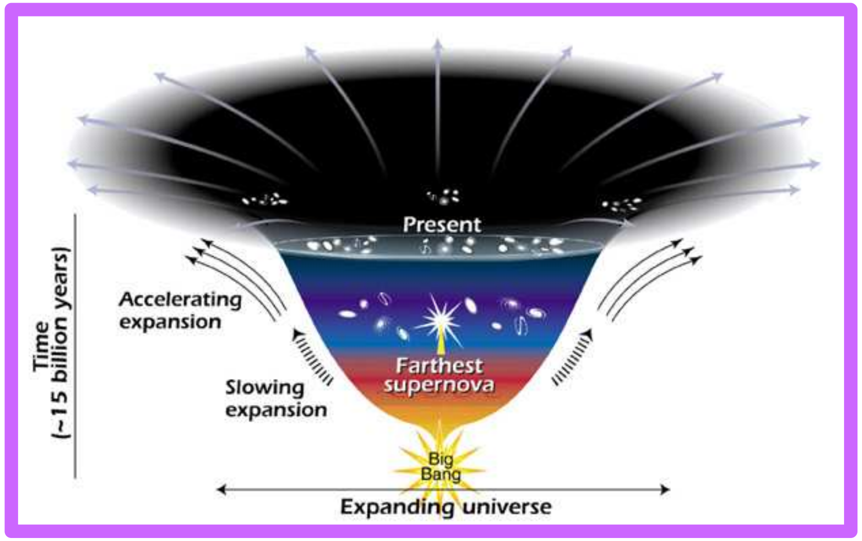
http://www.esa.int/For_Media/Photos/Highlights/Planck

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:





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

- 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

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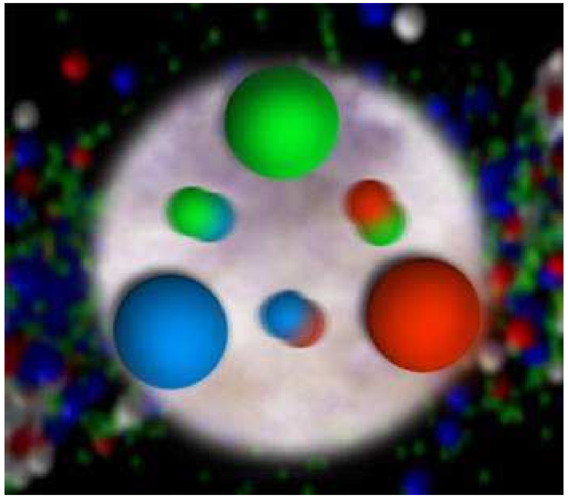
There might be physics beyond the SM

- 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 Θ could have any value between 0 and 2π.

  Experimentally, $\Theta < 10^{-9}$.

- A “fine-tuning” problem?

Physics beyond the standard model

> STRONG EVIDENCE FROM COSMOLOGY

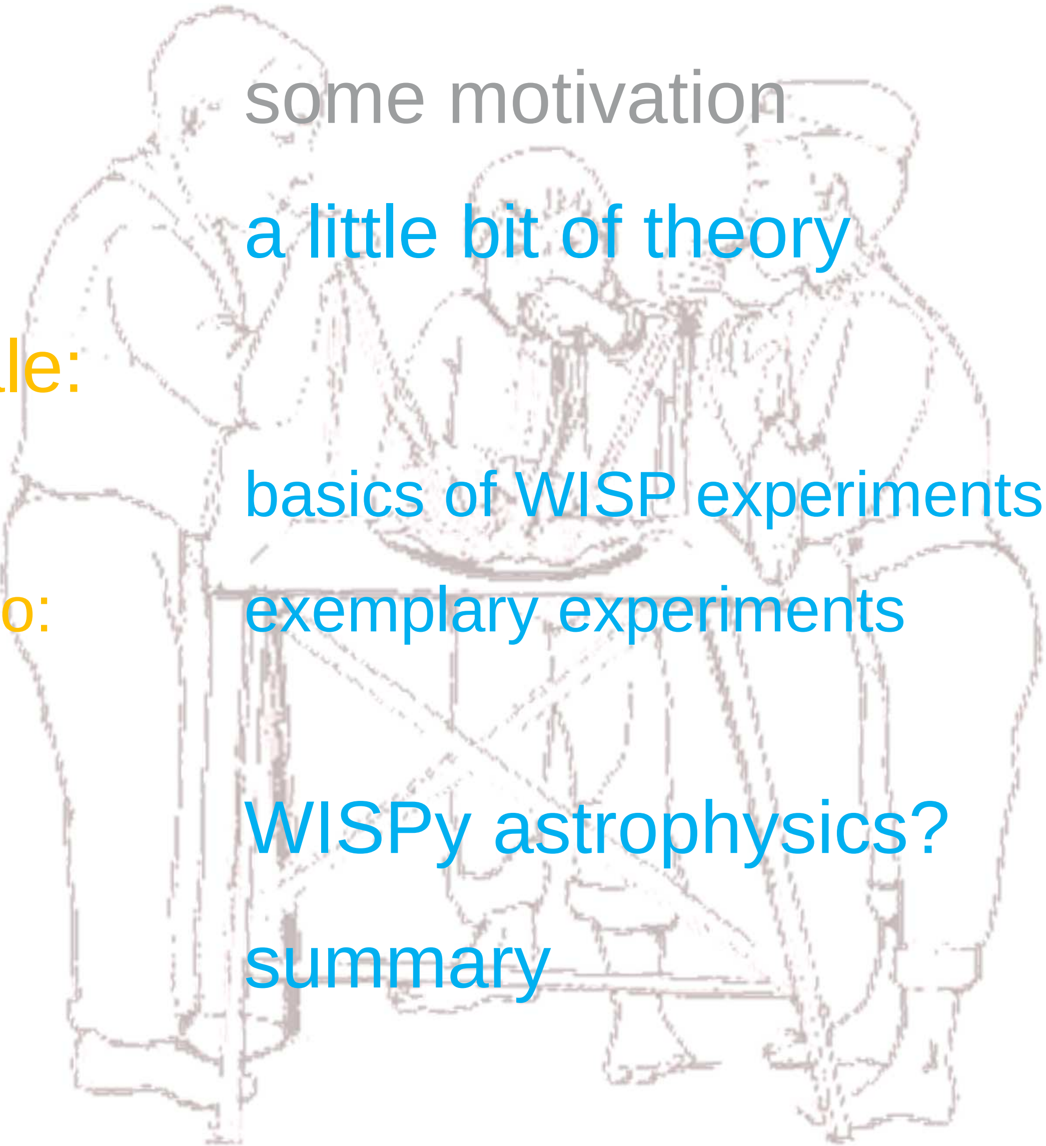
- No clue on energy scale of BSM physics from DM.

> 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

Outline



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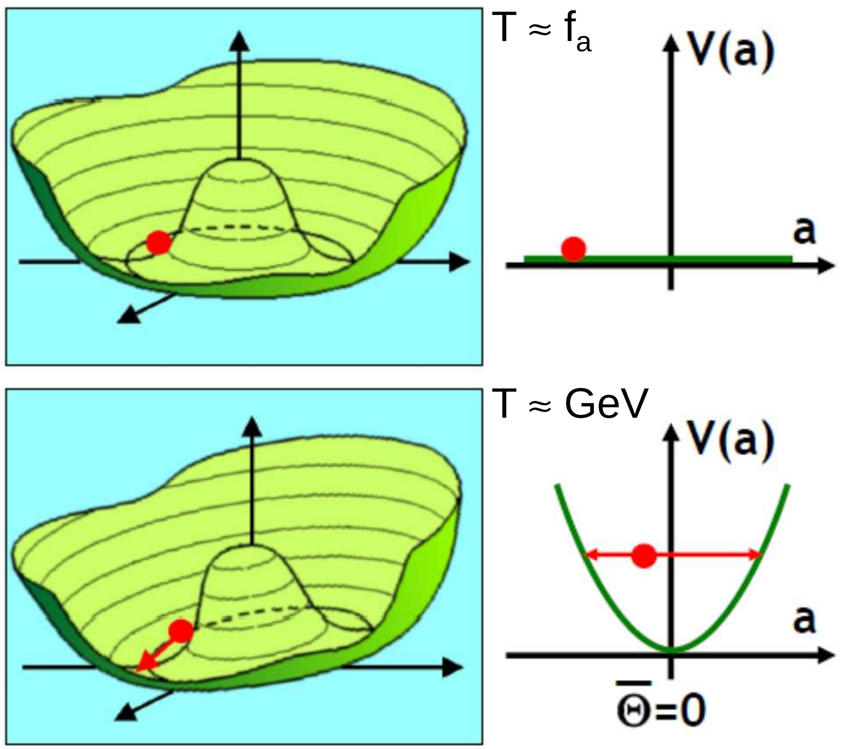
Introducing the axion

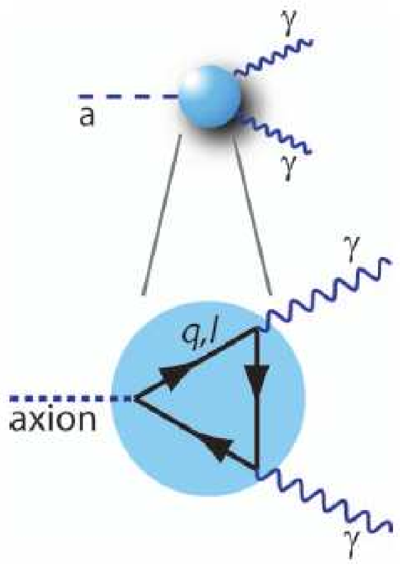
> CP-conservation in QCD:

A dynamic explanation for $\Theta < 10^{-9}$ 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

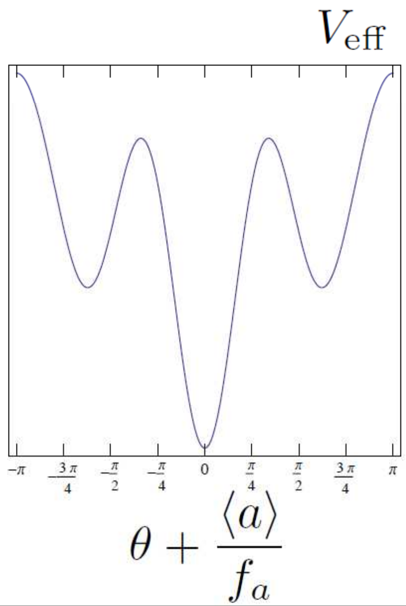
→ Massless Goldstone Boson: the axion

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

Free parameter → f_a

The QCD induced potential is minimized for ...

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



Tuesday, February 28, 2012

Introducing the axion

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Peccei-Quinn symmetry and the axion

Introduce a new axial global color-anomalous symmetry, which is spontaneously broken at a hig

The axions adjusts its v.e.v. to cancel the effects of any theta!

n

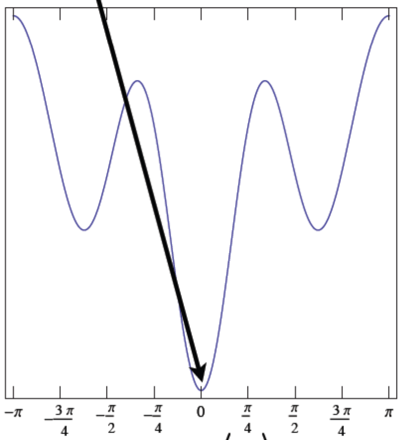
$V_{\rm eff}$

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

Just one → Free parameter

The QCD induced potential is minimized for ...

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



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

Tuesday, February 28, 2012

Searching for axions and ALPs (I)

Couplings to Standard Model constituents: how to look for WISPs

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

- QCD:

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

(dipole moment of the neutron)

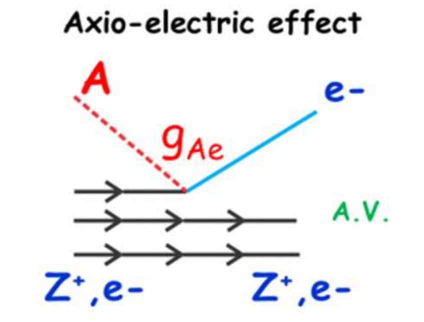
- QED:

two photon coupling

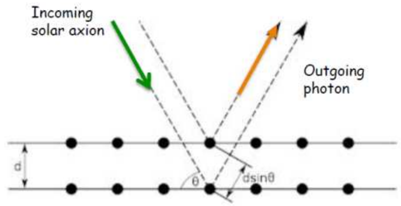
$$\mathscr{L} \supset \frac{1}{2}\partial_\mu A\,\partial^\mu A - \frac{1}{2}m_A^2 A^2 - \frac{g_{A\gamma}}{4}\,A\,F_{\mu\nu}\tilde{F}^{\mu\nu}\,.$$

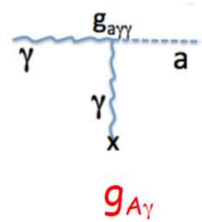
(photon appearance experiments)

Searching for axions and ALPs (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).





C. Nones, presentation at PATRAS 2013

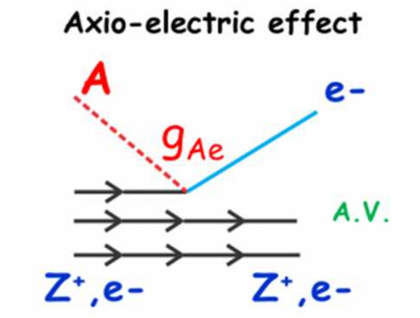
- Axions emitted in nuclear transitions (exploited in M1 transition of ^{57}Fe) with the axion converting into a photon or electron: $g_{Ae} \times g_{AN}^{eff}$

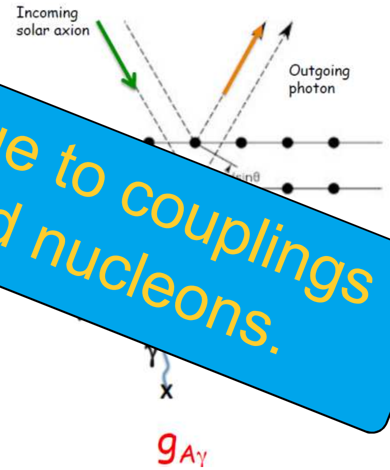
Searching for axions and ALPs (II)

- Axioelectric effect (for example exploited by XENON100, arXiv:1404.1455)
- Yu… interactions due to the exchange of A… s of 1s hyperfine splitting.
- Bragg diffra… (for example exploit…

Results often model-dependent due to couplings of axions and ALPs to electrons and nucleons.

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



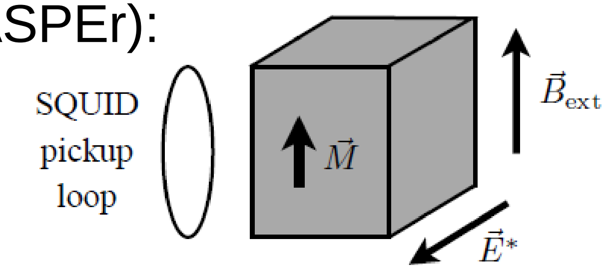


C. Nones, pres… tion at PATRAS 2013

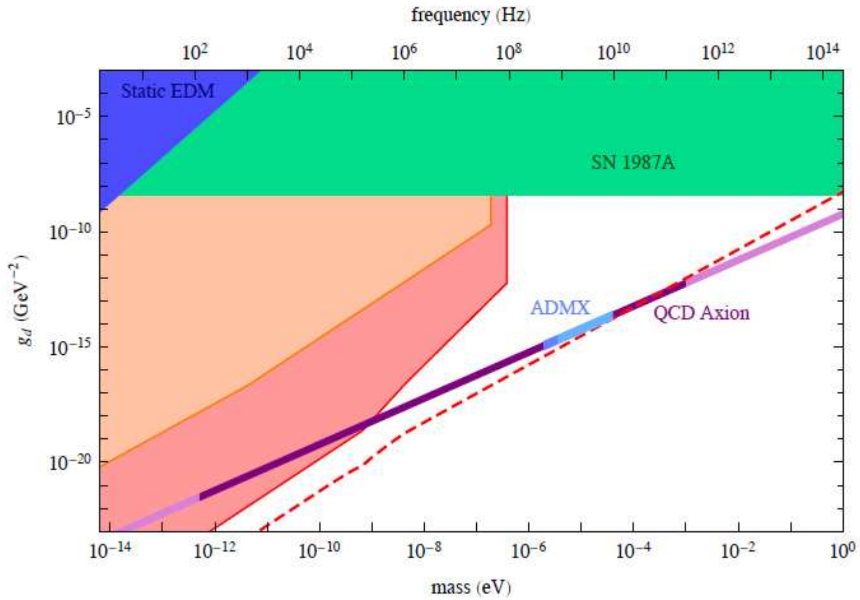
Searching for axions and ALPs (III)

- 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!

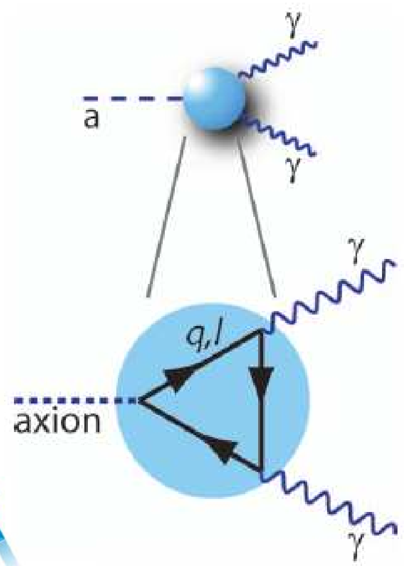


Properties of the axion

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

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

NON-THERMAL ORIGIN FROM VACUUM RE-ALIGNMENT



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

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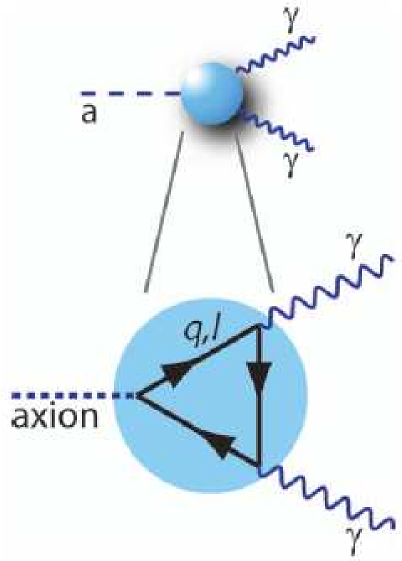
VERY LIGHTWEIGHT COLD DARK MATTER!

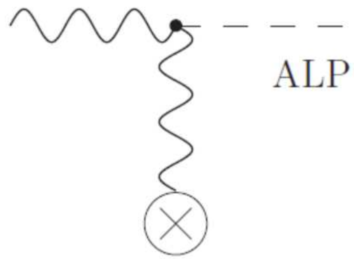


The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008

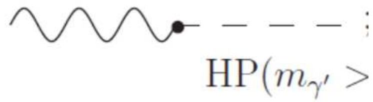
More general: WISPy particles

Weakly Interacting Slim Particles (WISPs):

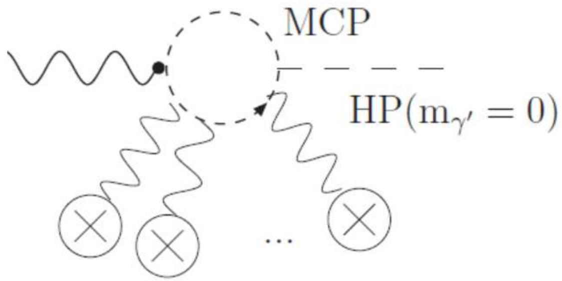
- Axions and
  axion-like particles
  ALPs, pseudoscalar or scalar bosons,
  m and g are not related by an f.



- 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*
ACCEPTED: *September 17, 2012*
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

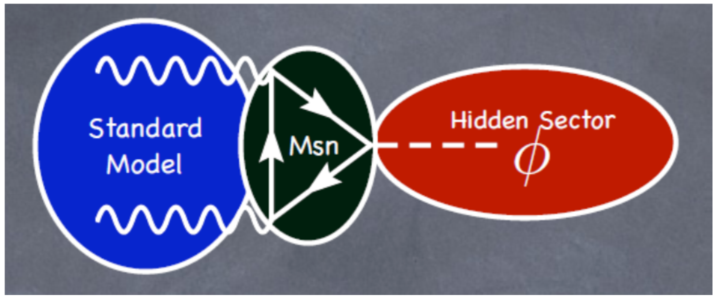
DESY 14-020

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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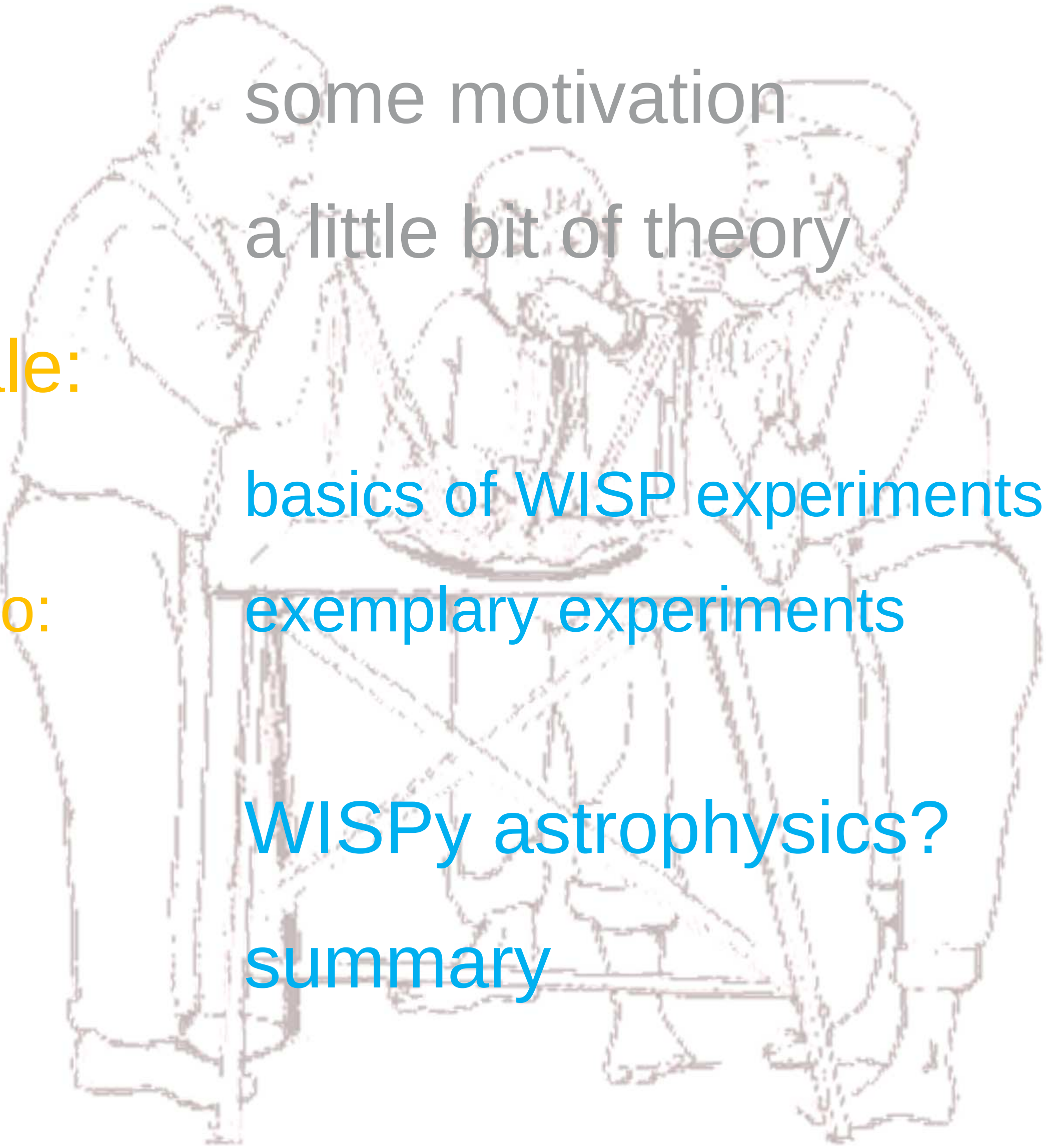

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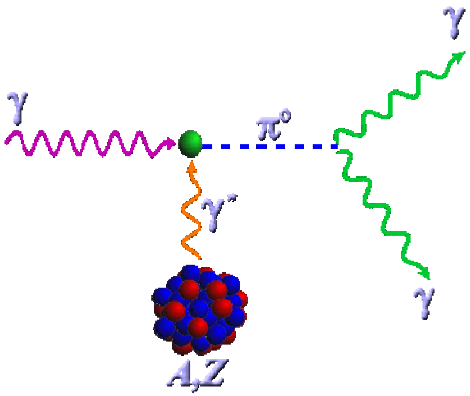
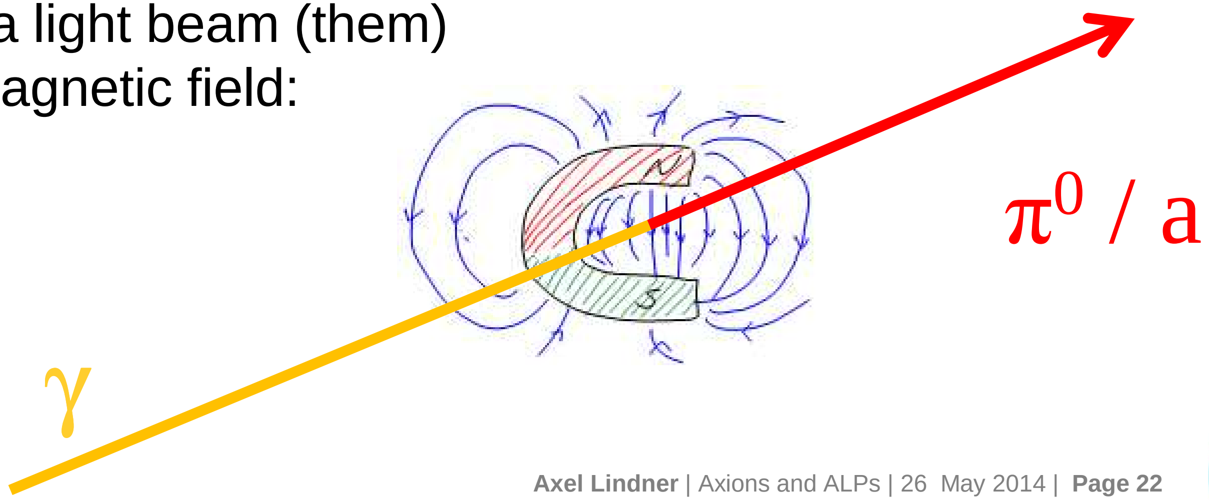
- Therefore the Primakoff effect will also work for the axion!



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



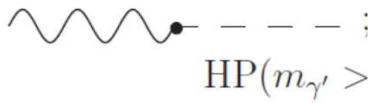
Basics of WISP experiments (I)

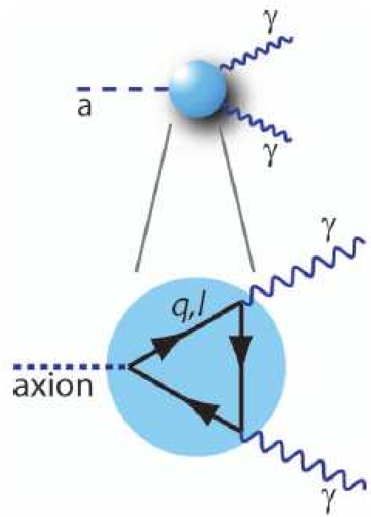
Weakly Interacting Slim Particles (WISPs) can be searched for by

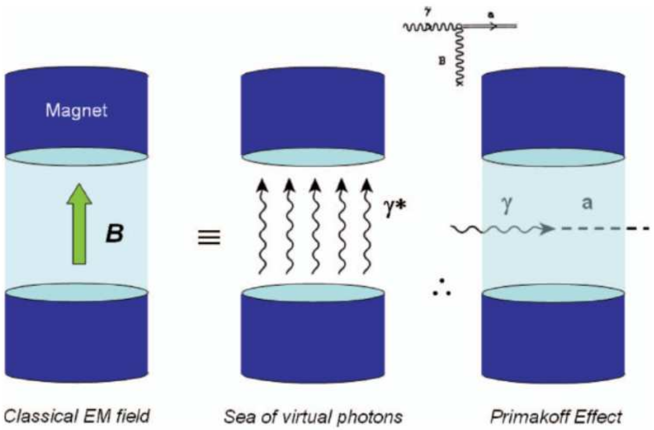
converting WISPs to photons (and vice versa) via

- 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.





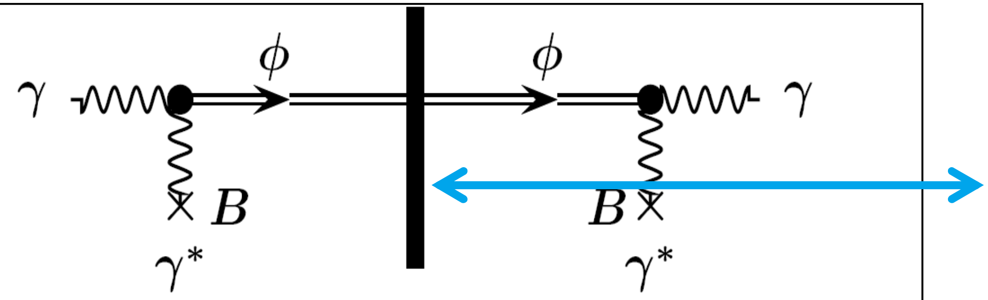


The Search for Axions,
Carosi, van Bibber, Pivovaroff,
Contemp. Phys. 49, No. 4, 2008

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.

- “Shining-through-a-wall”



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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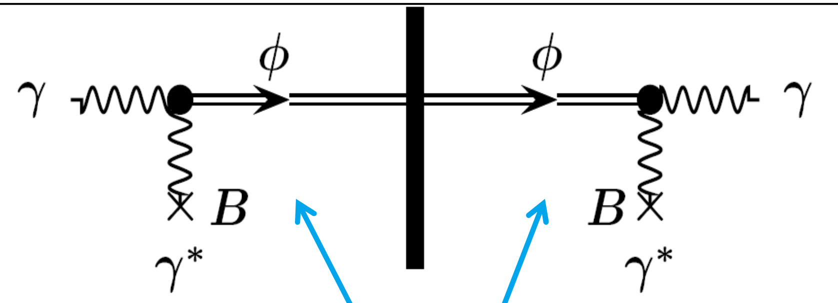

Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

Real WISPs are produced!

Basics of WISP experiments (IV)

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

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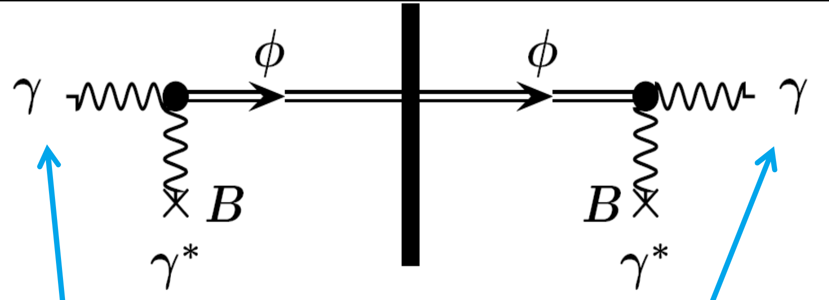

Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

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
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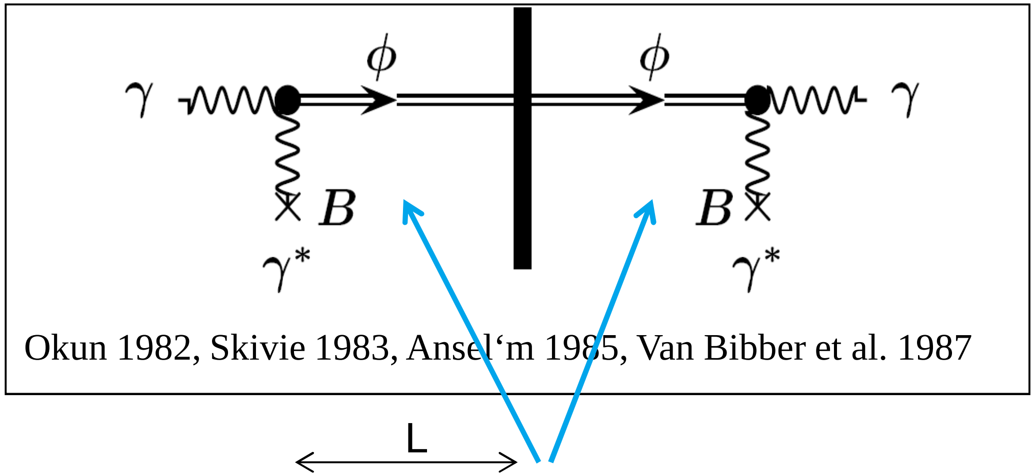
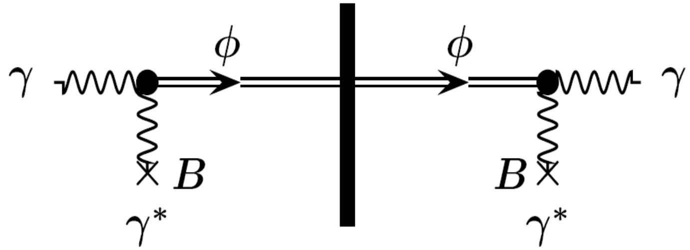
"Shining-through-a-wall"



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

ALPs in LSW experiments

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



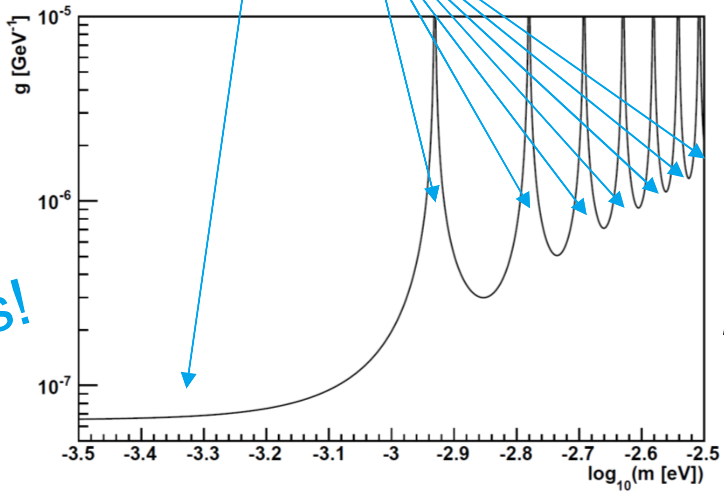
With: $q = p_\gamma - p_\Phi \approx ½ \cdot m^2/\omega$
l: length of B field

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

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)

Relativistic ALPs / axions!

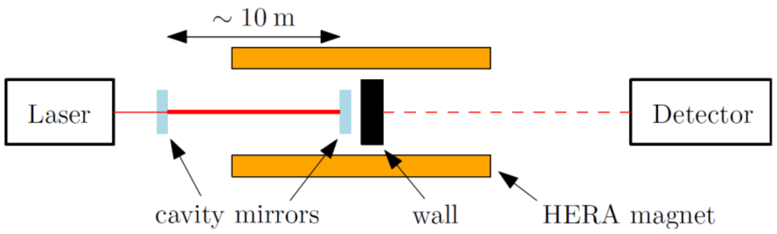


Example: the ALPS I experiment with 2.3 eV photons.

Three kinds of WISP searches

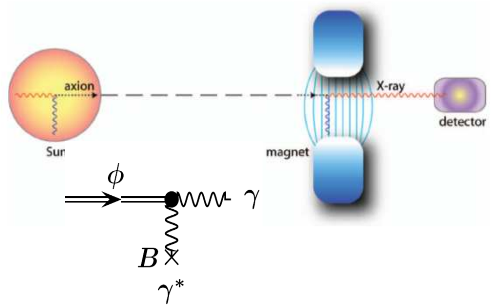
Weakly Interacting Slim Particles (WISPs) are searched for by

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



(a) ALPS-I

- Helioscopes (WISPs emitted by the sun), X-rays,



- Haloscopes (looking for dark matter constituents), microwaves.

Three kinds of WISP searches

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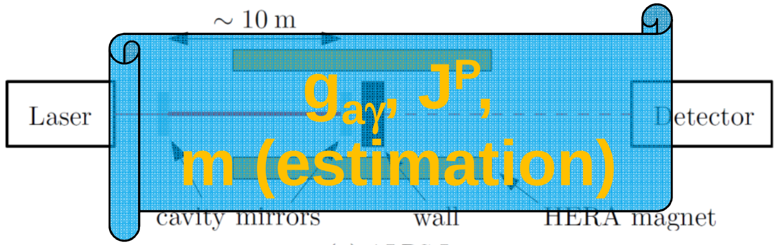

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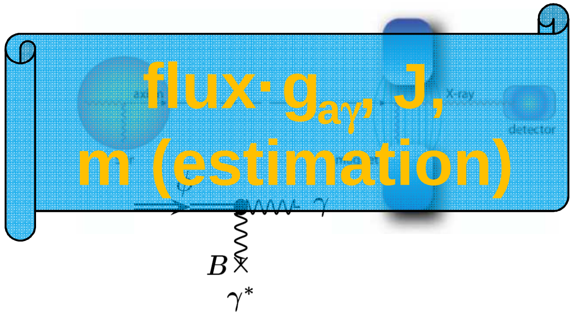

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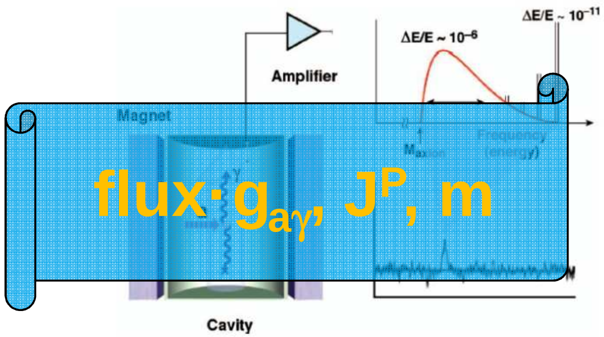

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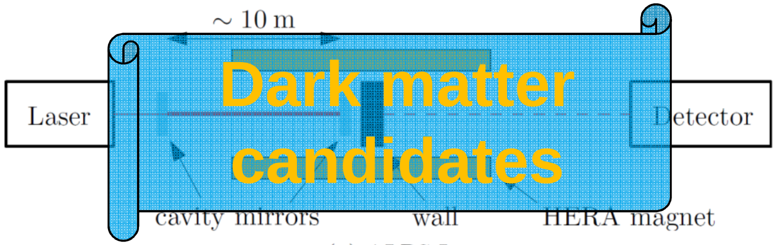

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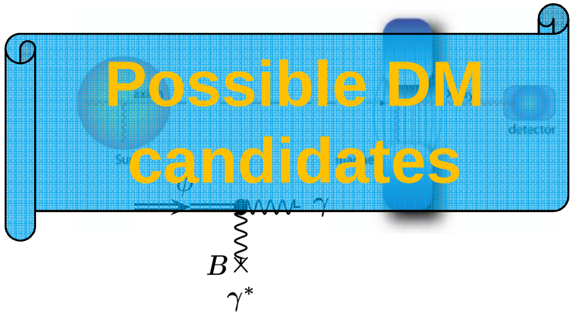

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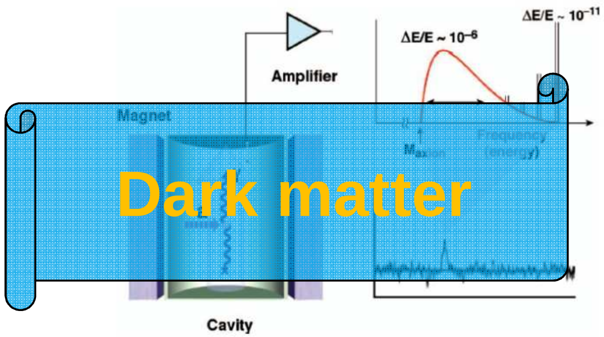

DESY

Three kinds of WISP searches

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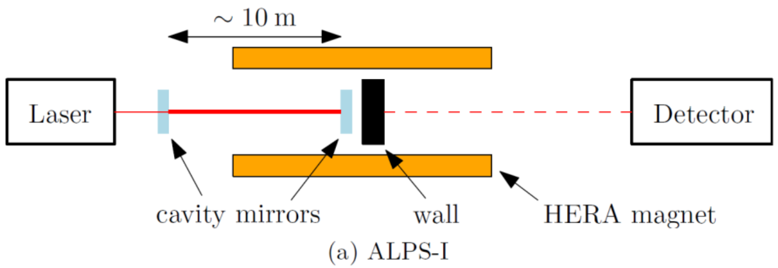

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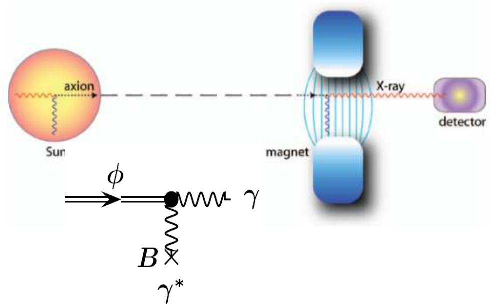

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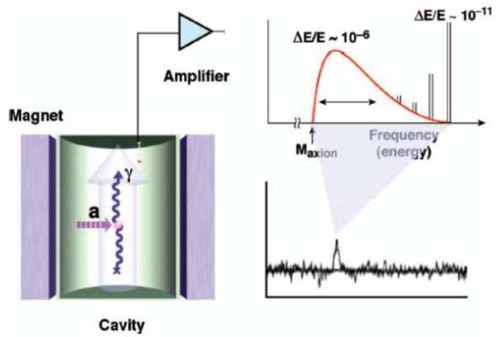

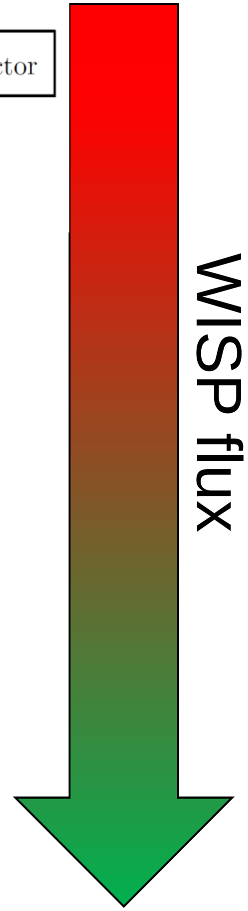

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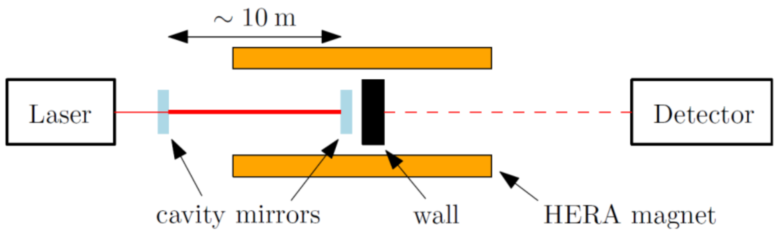

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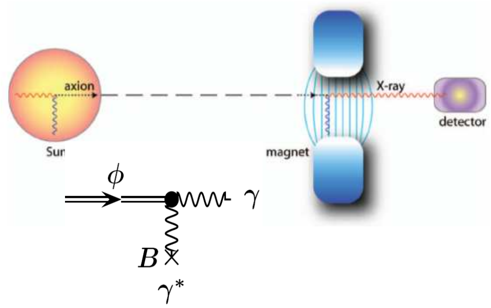

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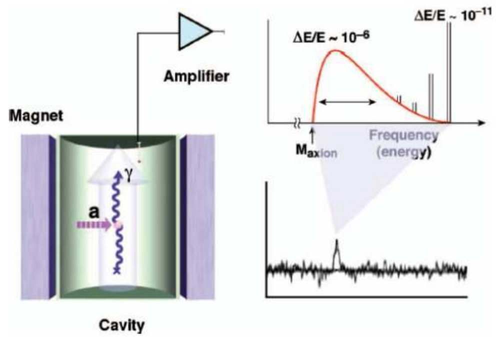

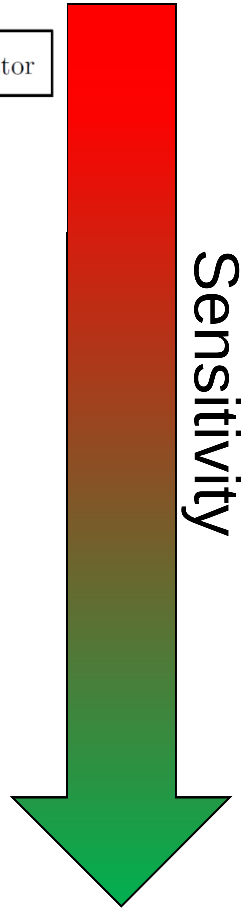

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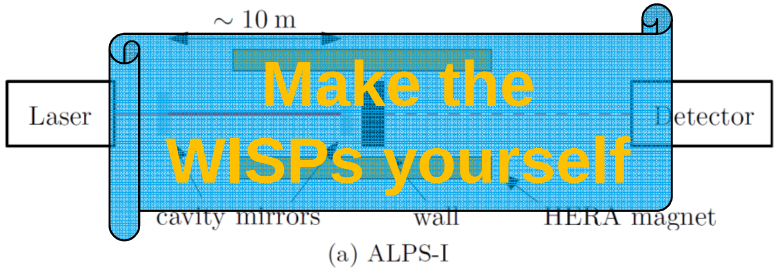

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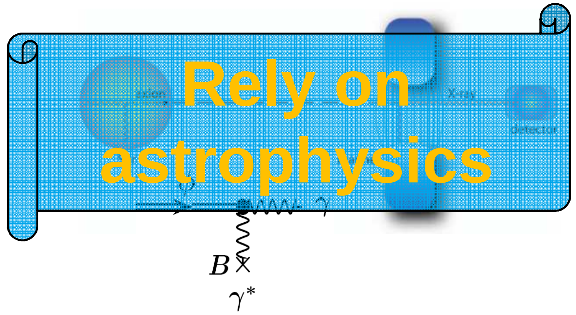

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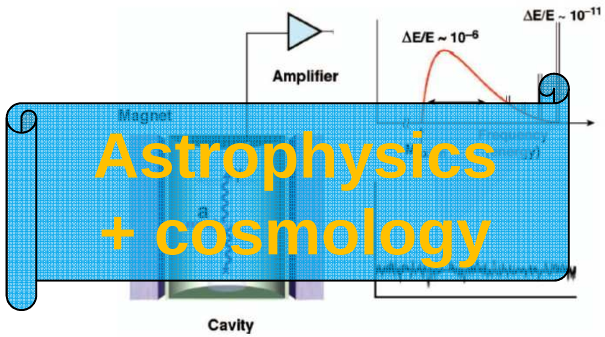

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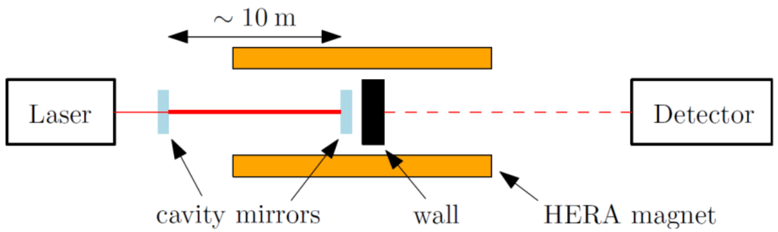

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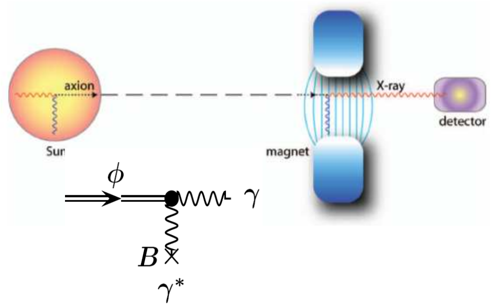

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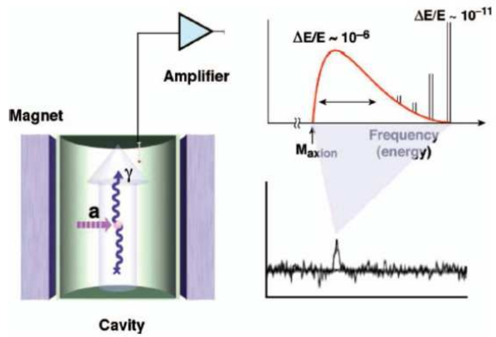

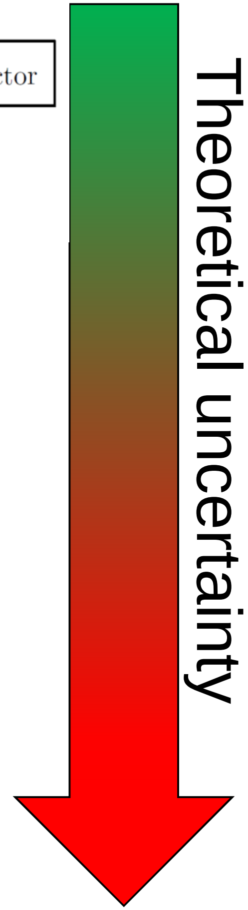

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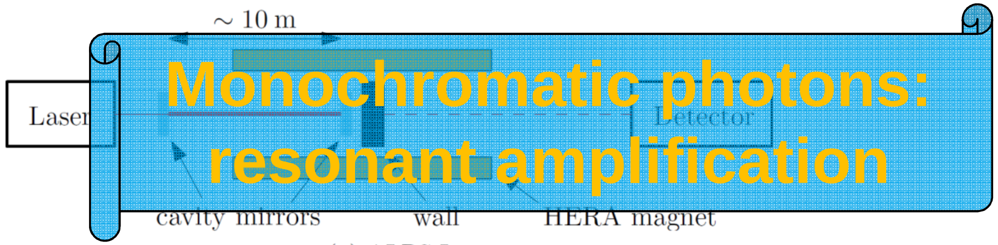

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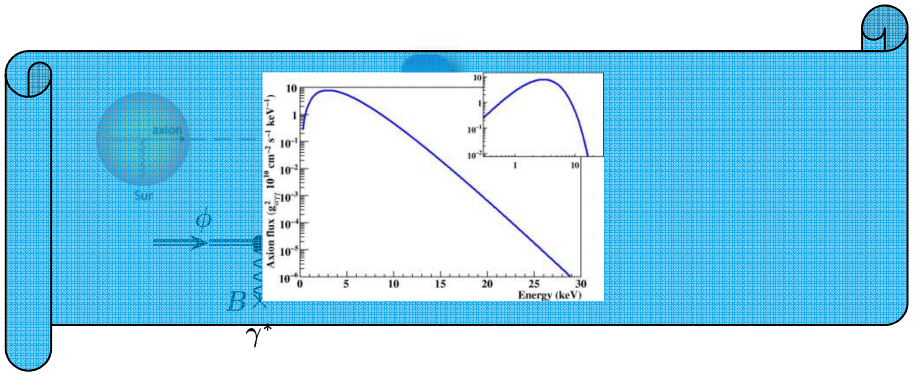

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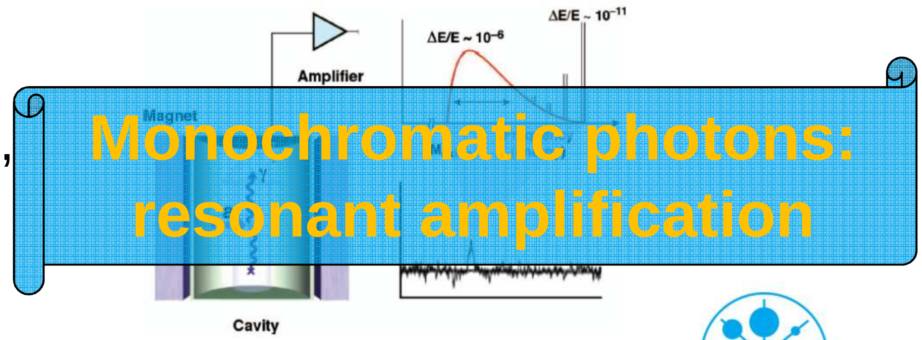
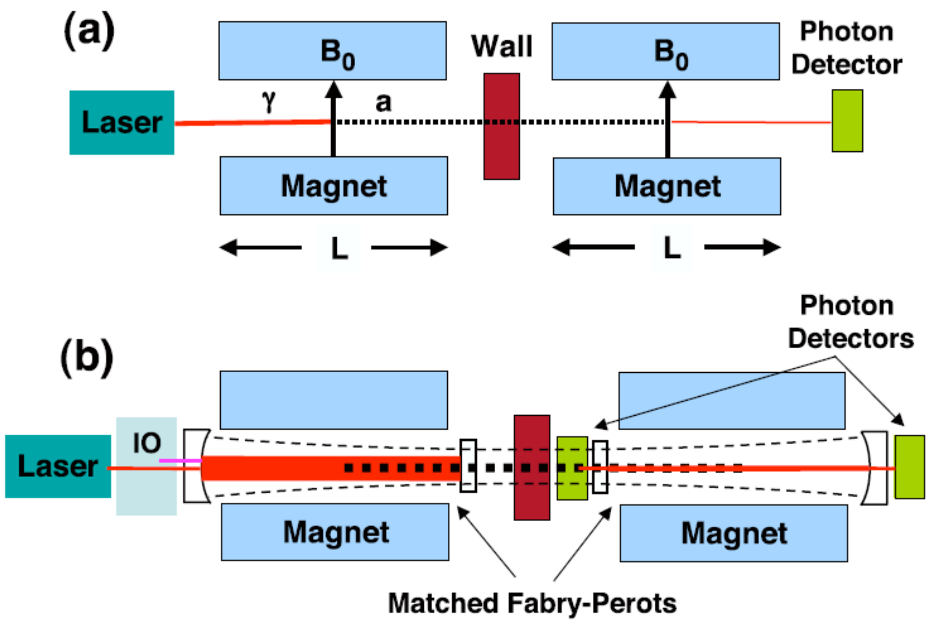


Resonant regeneration

- 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.

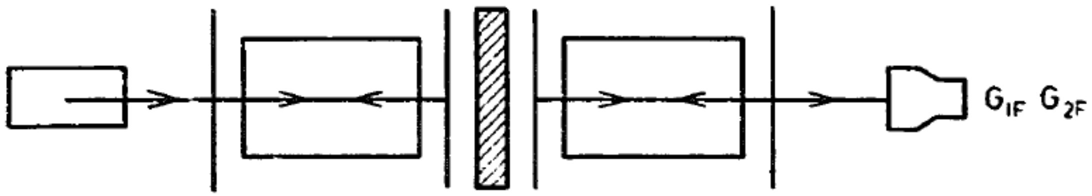
Regeneration in a cavity behind the wall: Increase back-conversion probability of WISPs into photons.

Resonant regeneration

- Already proposed in 1991!

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

F. Hoogeveen, T. Ziegenhagen / Light bosons



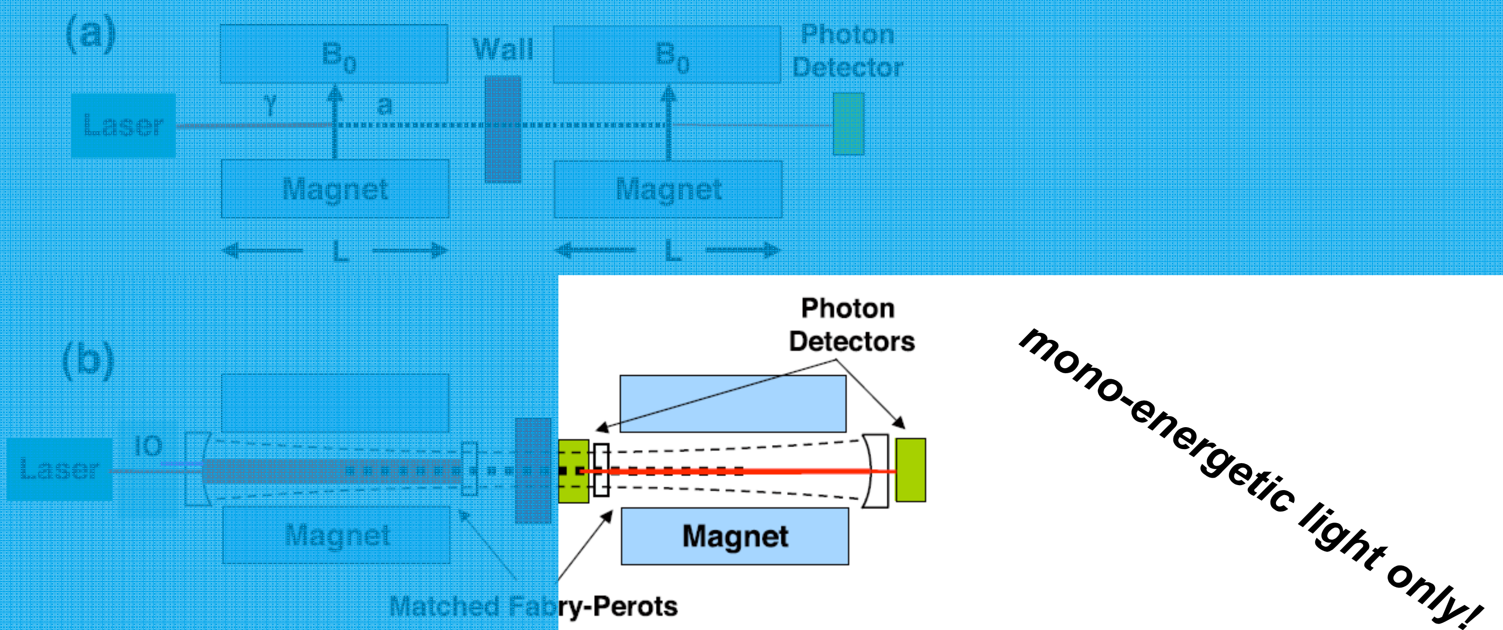
$$\frac{N_{\gamma\,\mathrm{out}}}{N_{\gamma\,\mathrm{in}}} = \frac{\Omega^2}{\Omega^2 - m_a^2}\left(\frac{g^2 B_1 B_2 L_1 L_2}{4}\right)^2 |F_1(q)|^2 F_2(q)|^2 |G_1|^2 |G_2|^2$$

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:



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

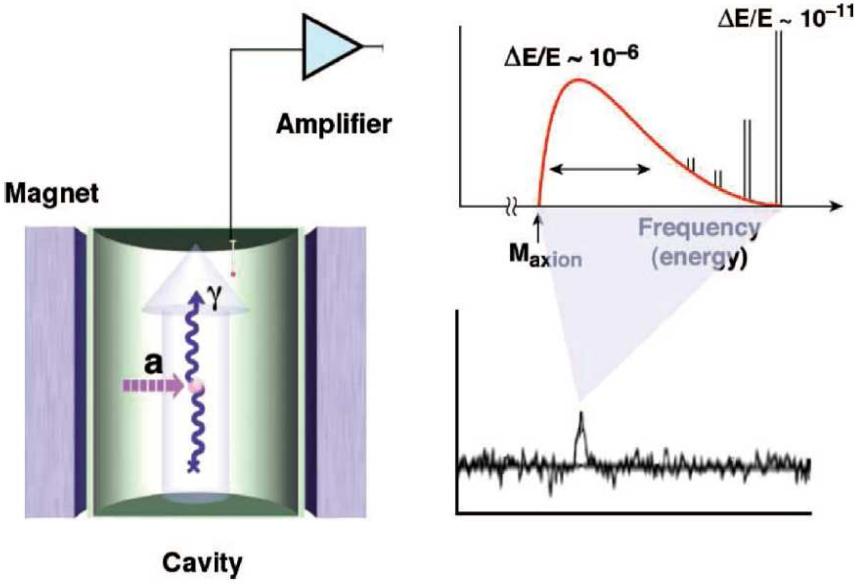
Regeneration in a cavity behind the wall: Increase back-conversion probability of WISPs into photons.

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):

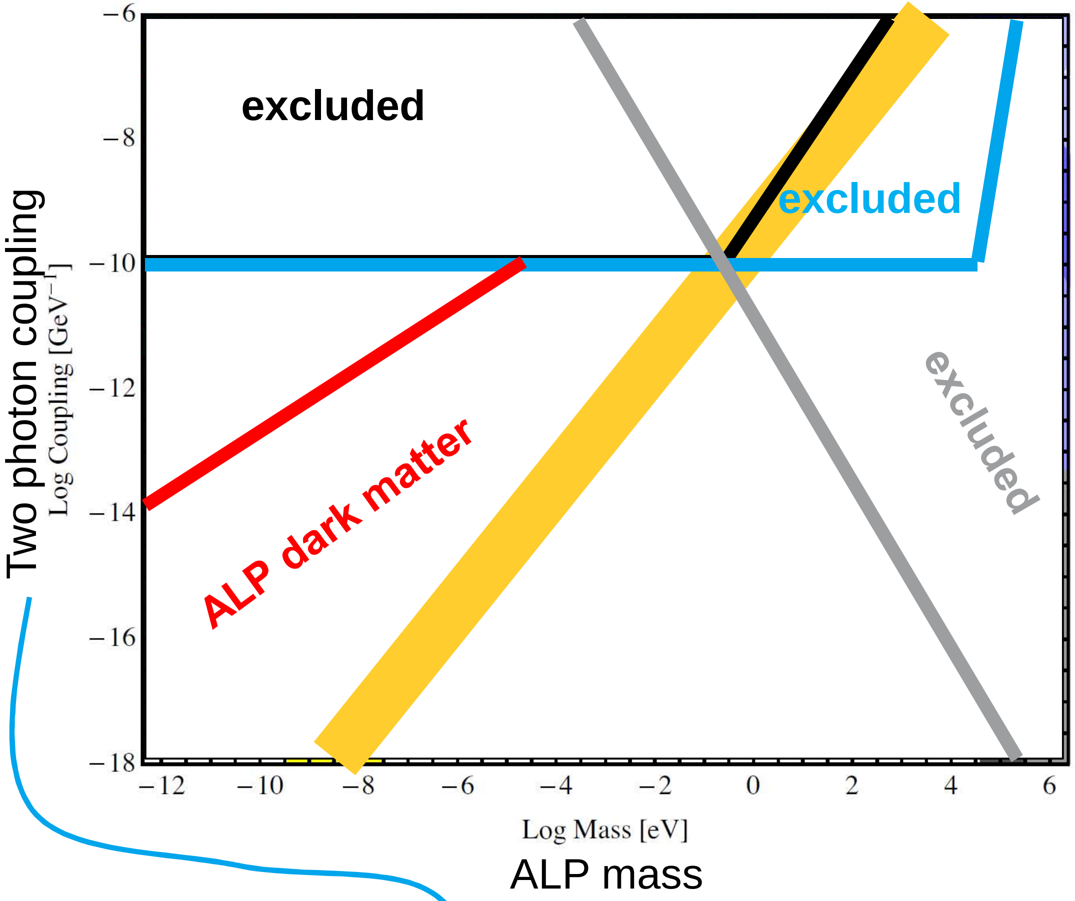
- When converting to photons, the photon energy is given by the WISP rest mass + an O(10^{-6}) correction.



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

Cavity volume; Cavity power build-up; Axion number density

The big picture: ALPs



QCD axion range

Excluded by WISP experiments

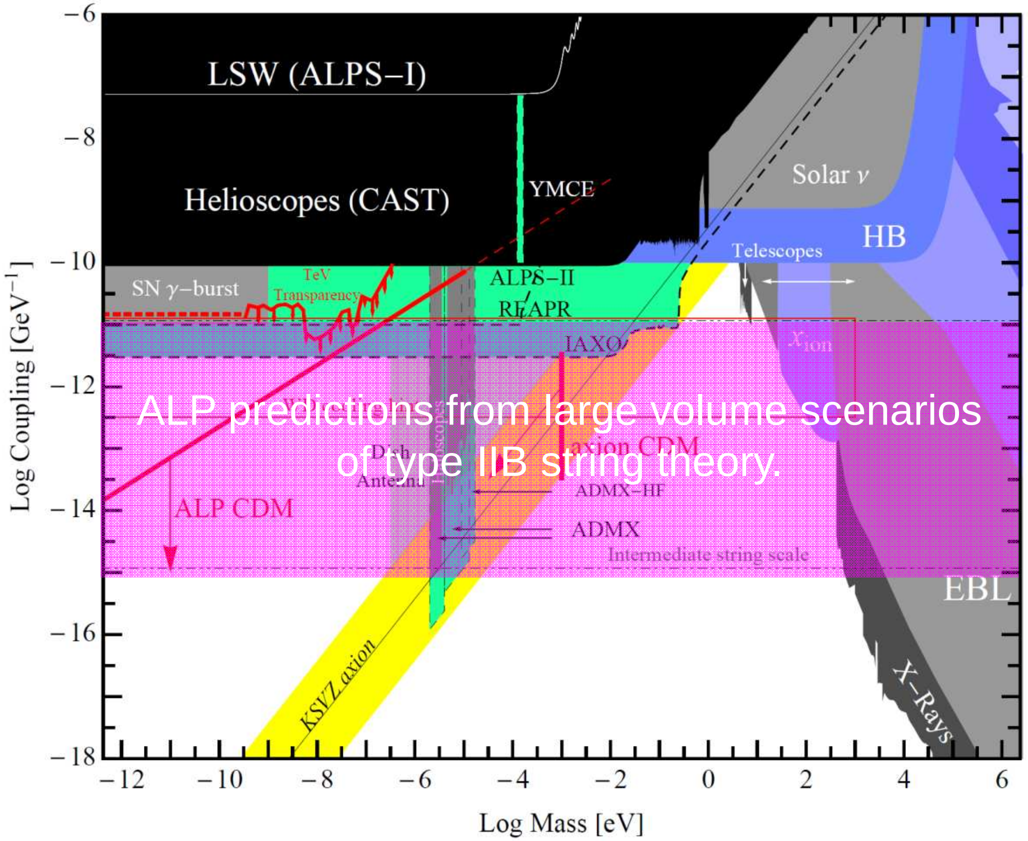
Excluded by astronomy (ass. ALP DM)

Excluded by astrophysics / cosmology

Axions or ALPs being cold dark matter

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

The big picture: ALPs




Dark Universe 1 (2012) 116–135

Contents lists available at SciVerse ScienceDirect

Dark Universe

ELSEVIER

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]**

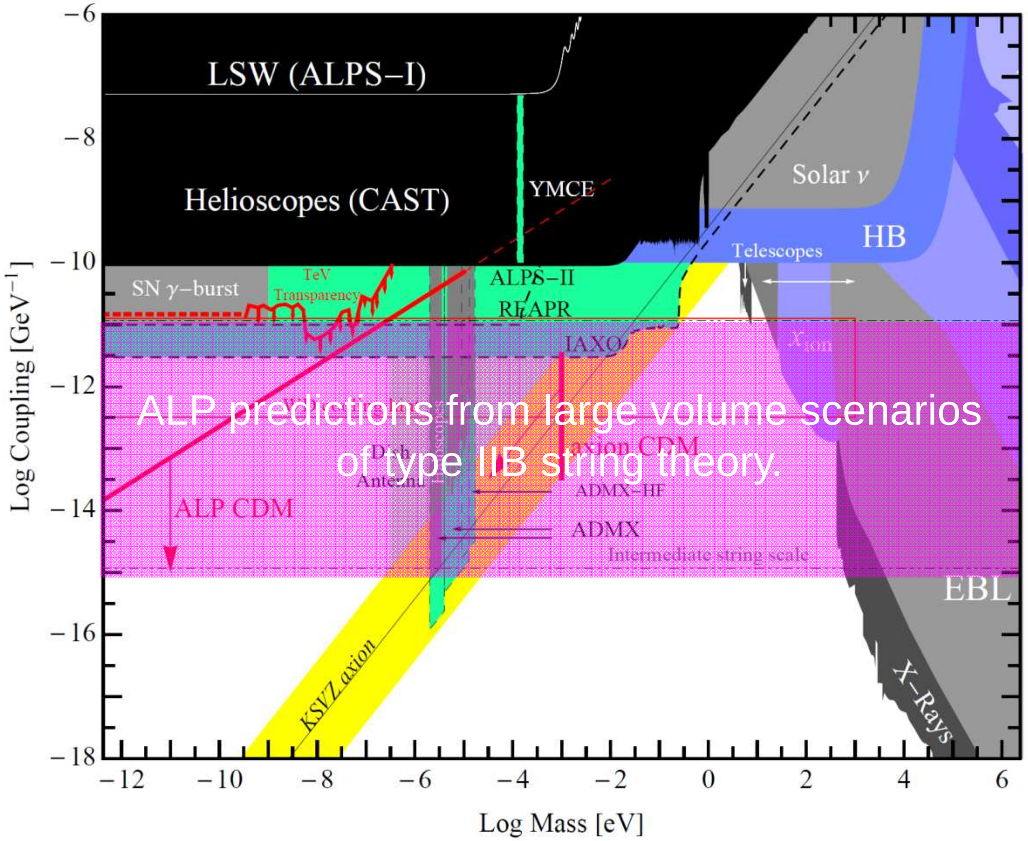
QCD axion range
Excluded by WISP experiments
Excluded by astronomy (ass. ALP DM)
Excluded by astrophysics / cosmology
Axions or ALPs being cold dark matter

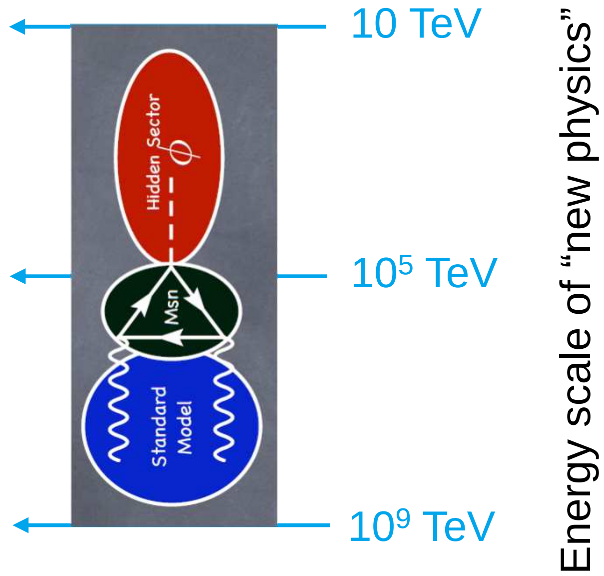
Sensitivity of next generation WISP exp.

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

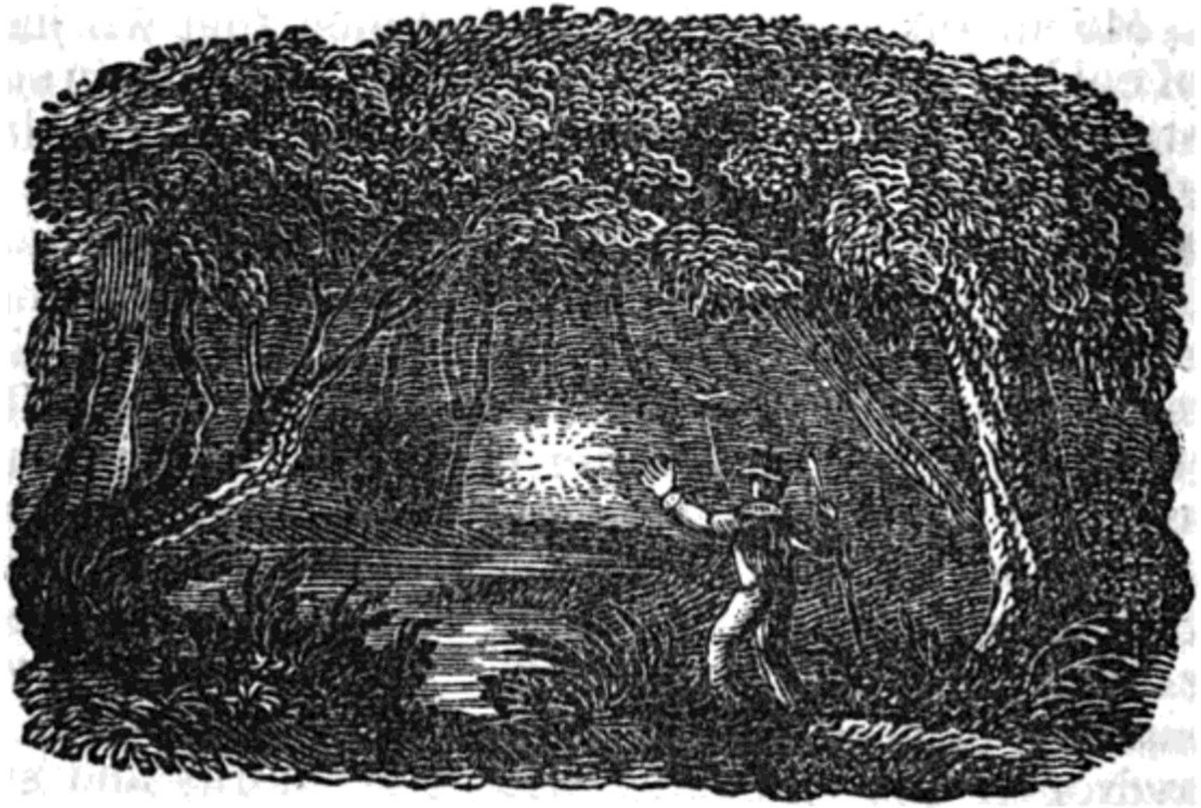




Particular interesting:

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

Looking for WISPs



Mudie, *A Popular Guide to the Observation of Nature* (1836, p.144).
http://books.google.de/books?id=kdknAAAAMAAJ&pg=PP1#v=onepage&q&f=false

WISP experiments worldwide

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

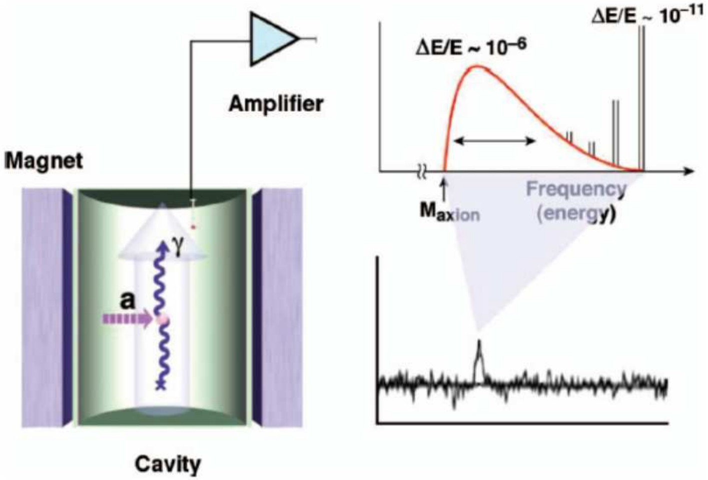
Experiment	Type	Location	Status
ALPS II	Laboratory experiments, light-shining-through-a-wall	DESY	construction
CERN microwave cavity experiment		CERN	finished
OSQAR		CERN	running
REAPR		FNAL	proposed
CAST	Helioscopes	CERN	running
IAXO		?	proposed
SUMICO		Tokyo	running
TSHIPS		Hamburg	running
ADMX	Haloscope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

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

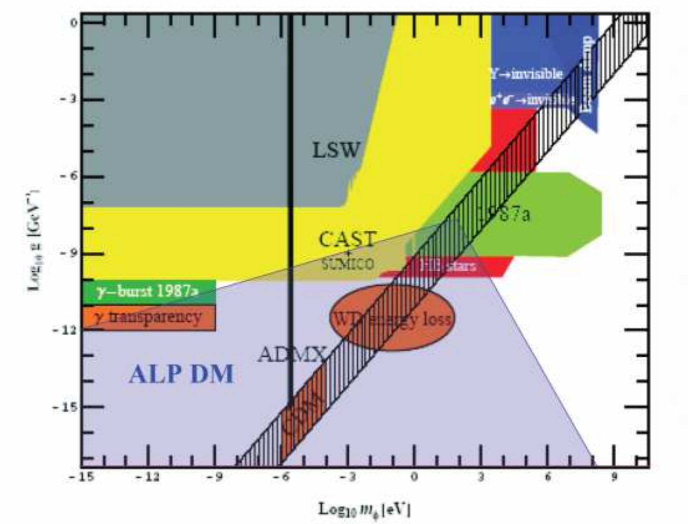
- Due to their low mass WISPy cold dark matter can not be detected by recoil techniques.
- WISPy dark matter particles have to convert into photons in a thoroughly shielded environment.
- The mass of the dark matter particle determines the energy to be detected. For axions it is in the microwave range.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

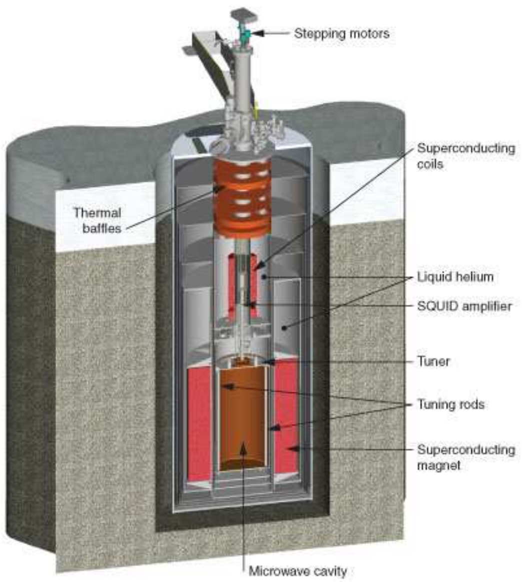


The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008

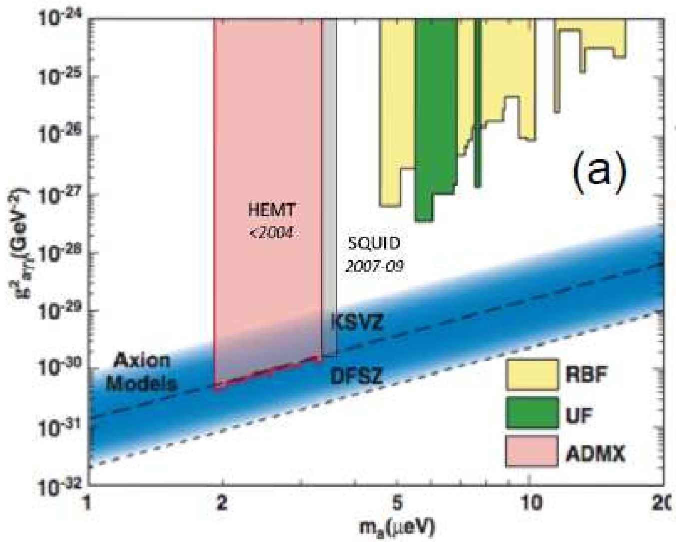
ADMX

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





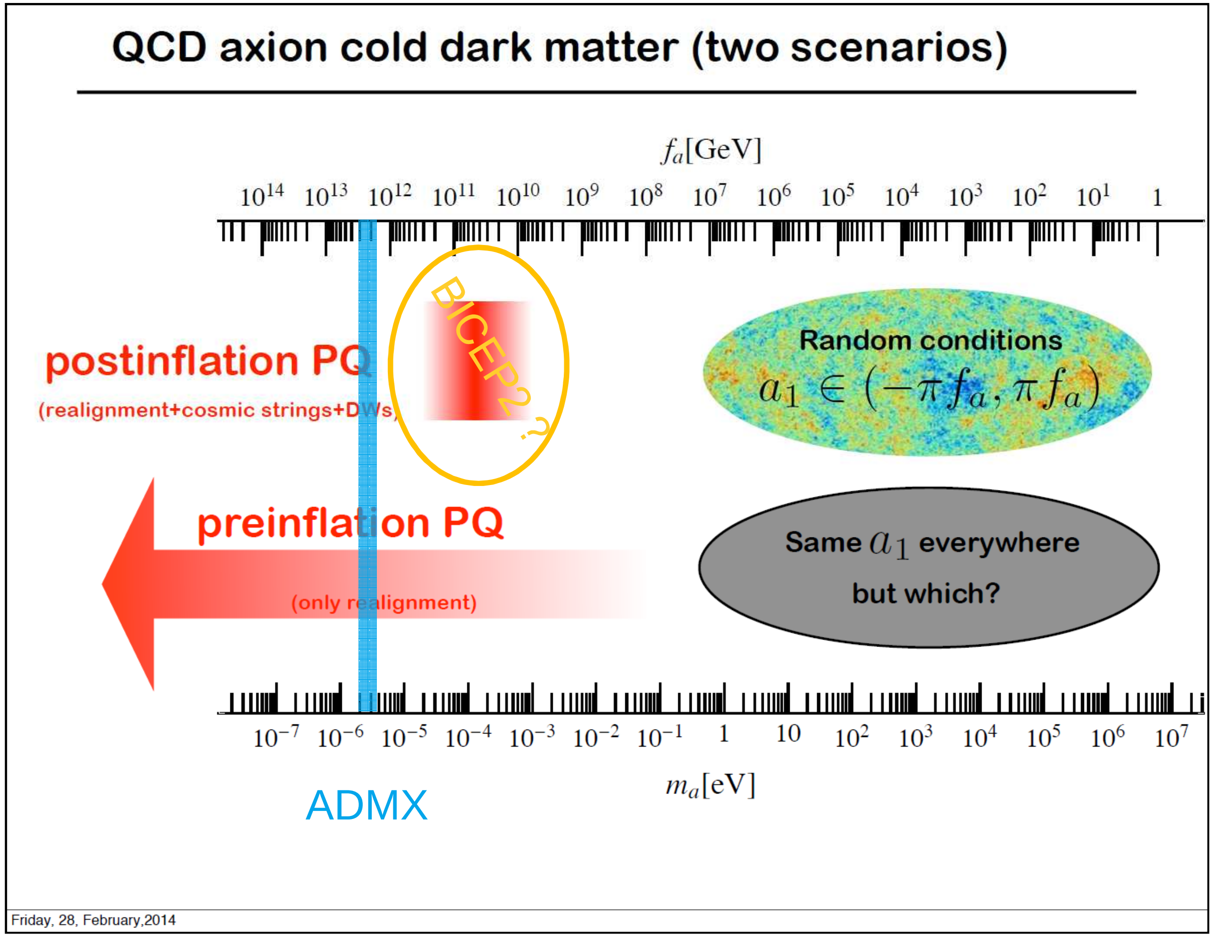
The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008



arXiv:1405.3685 [physics.ins-det]

Extending the DM search mass range

DM axions might hide in a large mass region:



Courtesy of Javier Redondo

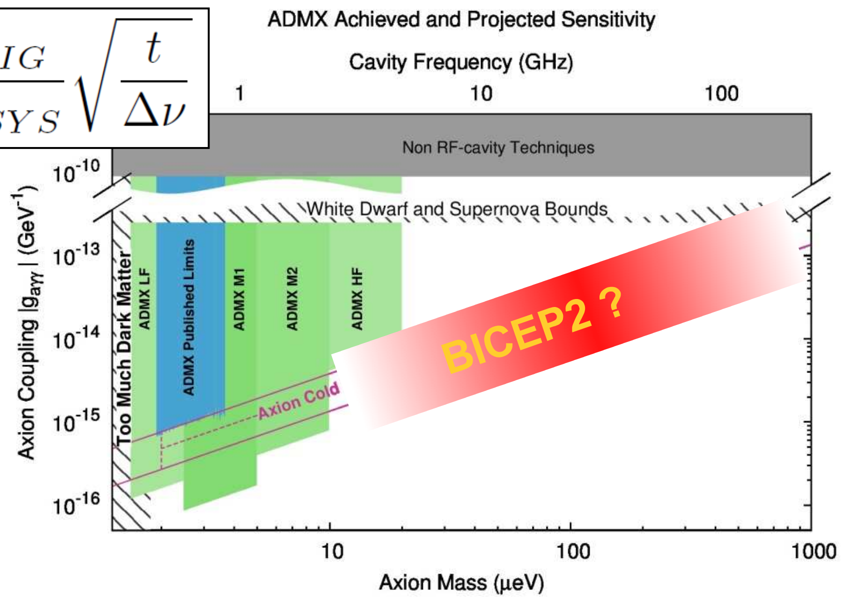
Extending the DM search mass range

- 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.

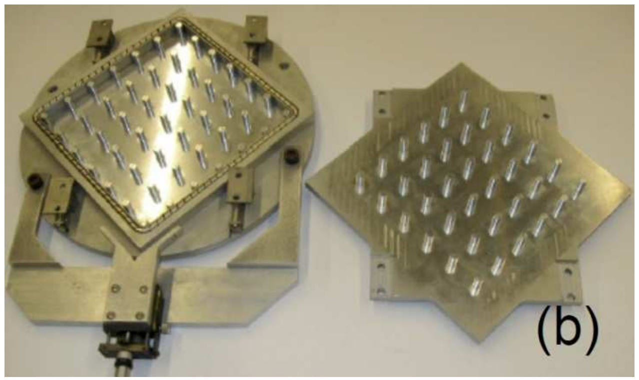
$$\frac{S}{N} = \frac{P_{SIG}}{kT_{SYS}}\sqrt{\frac{t}{\Delta\nu}}$$



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

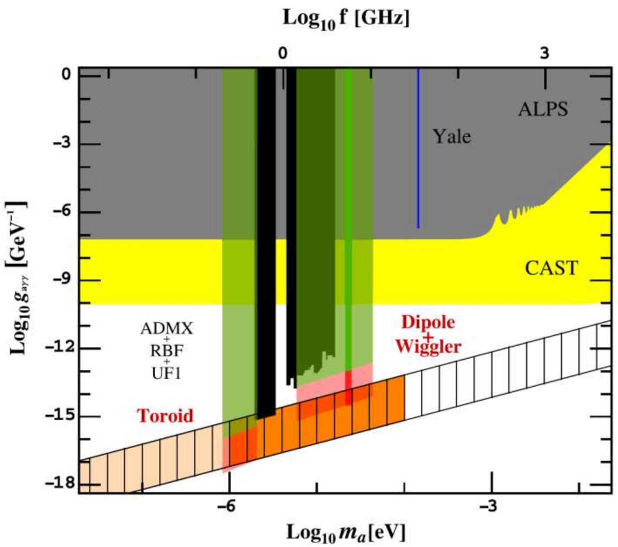
> Option 1: improve on cavity experiments

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.



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

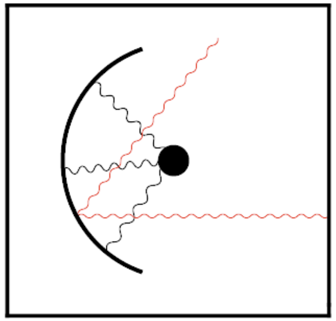
Joerg Jaeckel[1] and Javier Redondo[2,3]

[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)

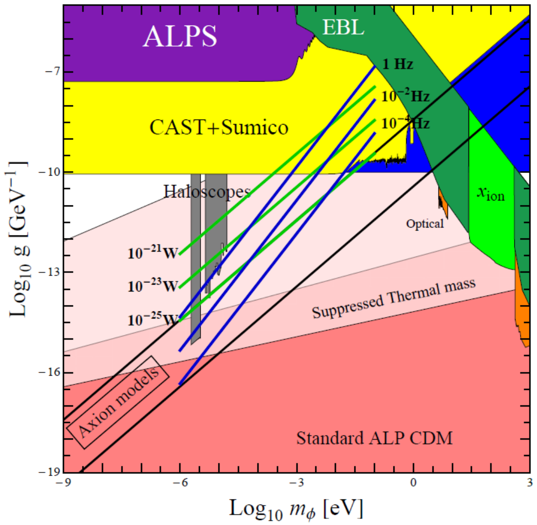
Extending the DM search mass range

> 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 1m² 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

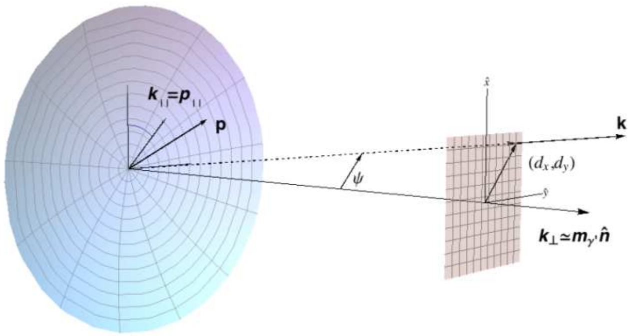
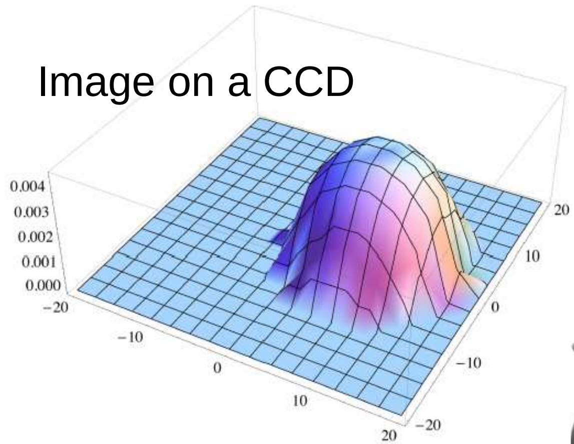


Image on a CCD



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, Föhringer Ring 6, 80805 Munich, Germany*

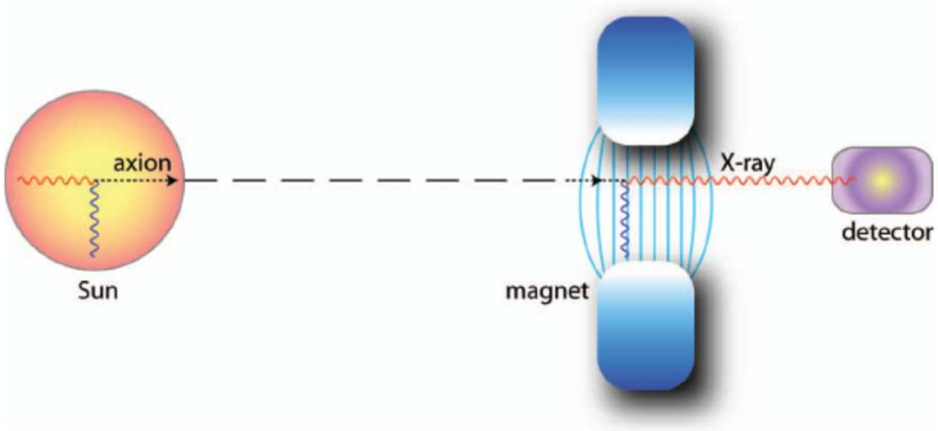
(Received 6 September 2013; published 2 December 2013)

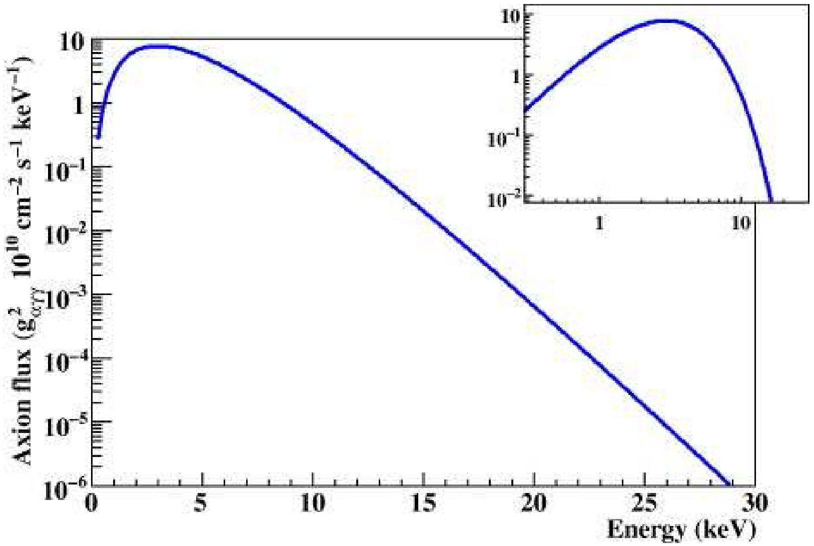
Helioscopes

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

CAST: the dominating helioscope

> LHC prototype magnet pointing to the sun.





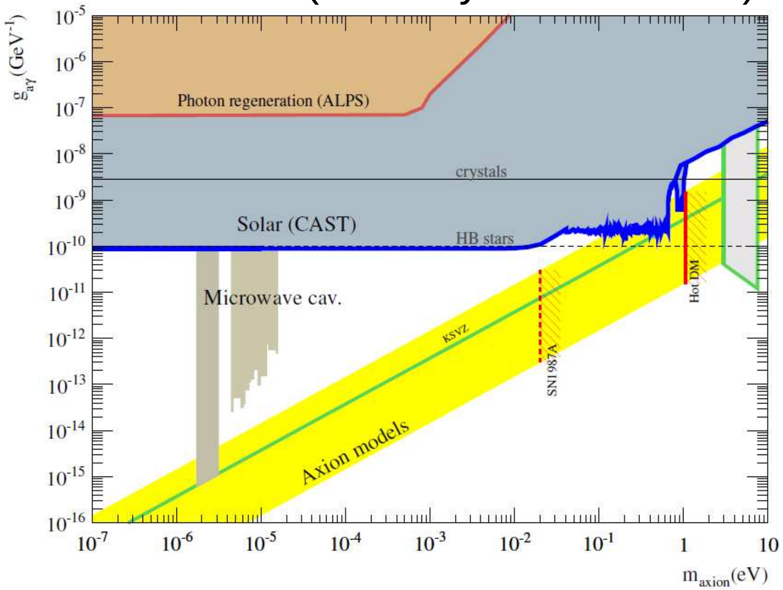
New J. Phys. **11** (2009) 105020

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

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!

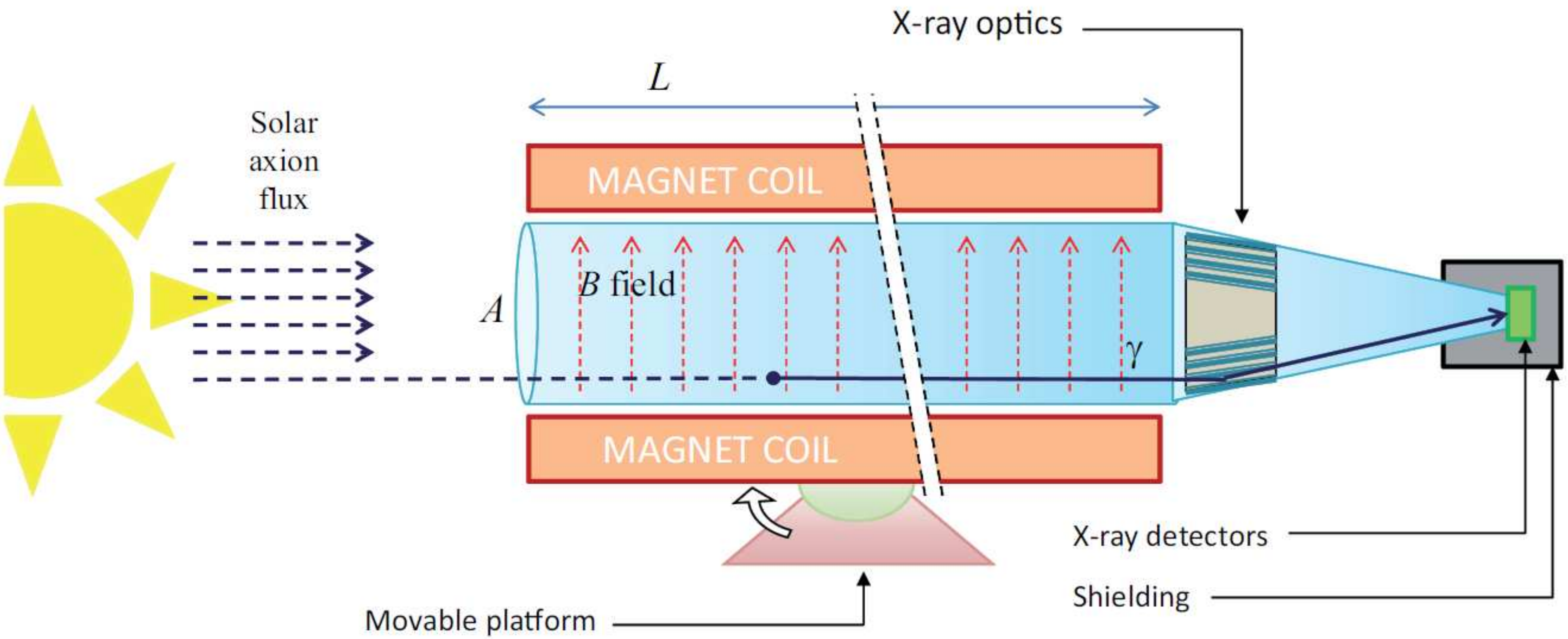
> However, CAST relies on astrophysics:

- CAST has to assume ALP production in the sun.

IAXO proposal

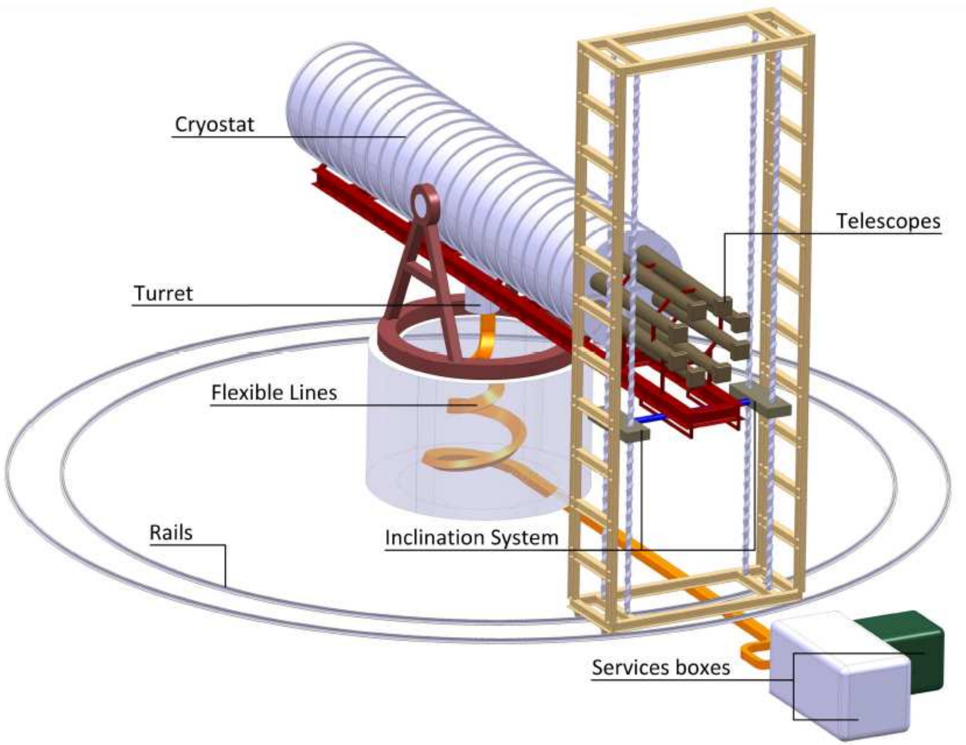
> The International Axion Observatory

- CAST principle with dramatically enlarged aperture



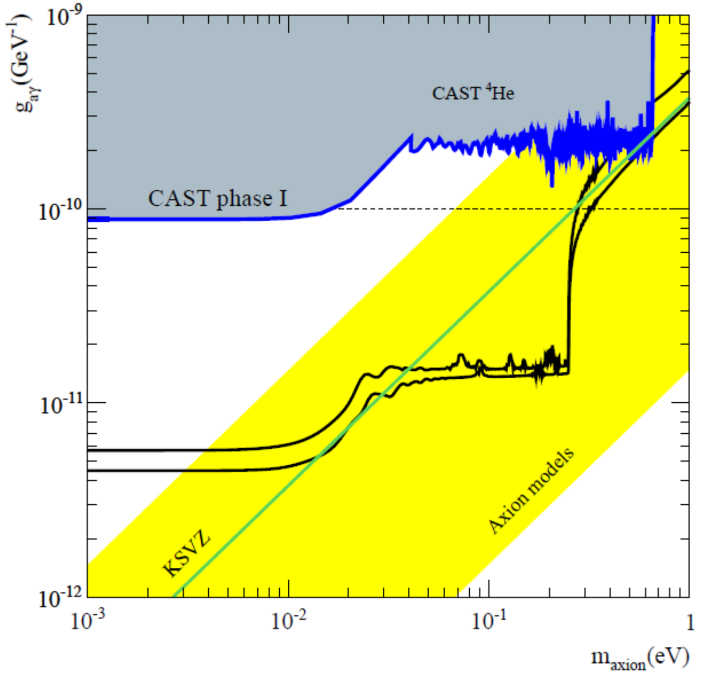
IAXO proposal

- 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

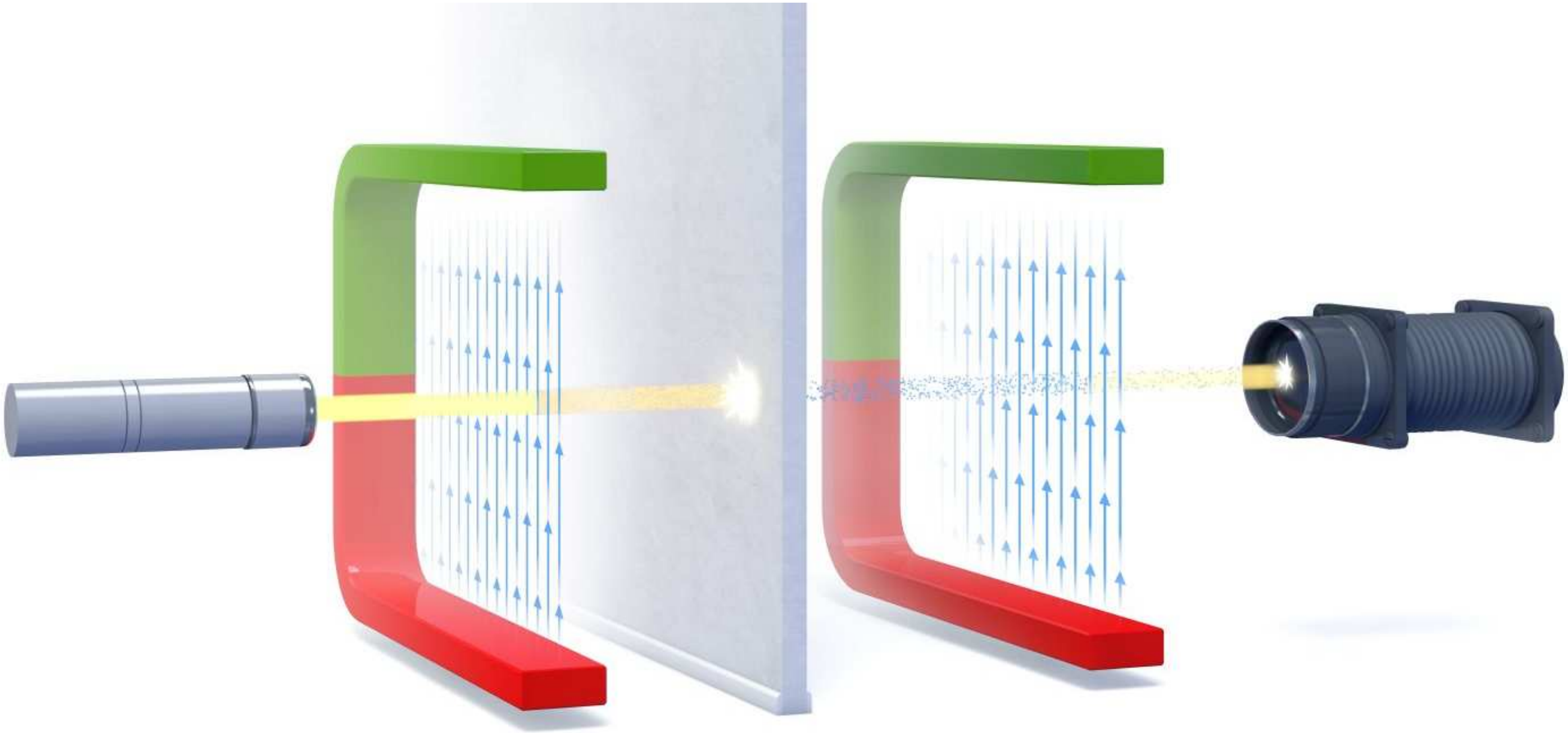
- The International Axion Observatory
  - Could be constructed within about six years.
- IAXO could probe QCD axions!



- However, DM axions are out of reach.

BICEP2 ?

Laboratory experiments



ALPS @ DESY in Hamburg

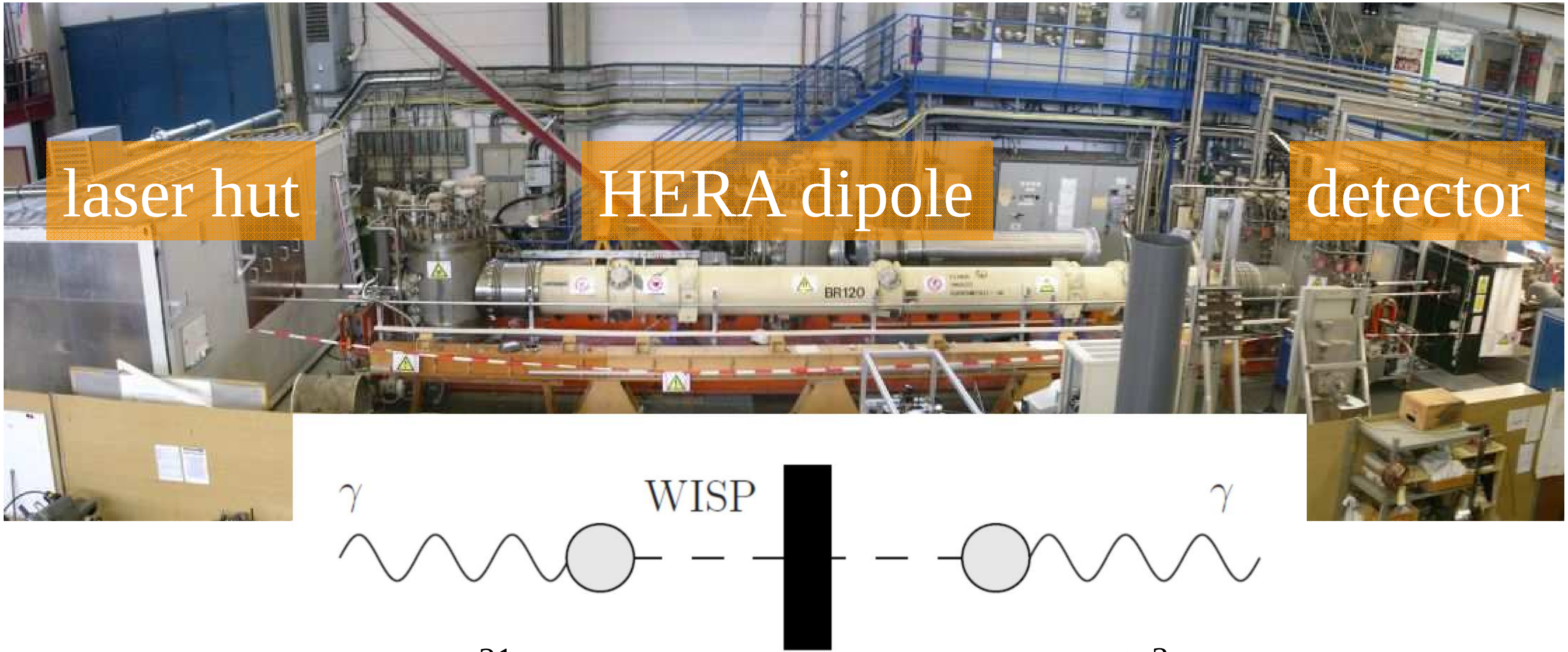
ALPS I at DESY in Hamburg

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!



$3.5 \cdot 10^{21}$ 1/s $\qquad$ $< 10^{-3}$ 1/s

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!

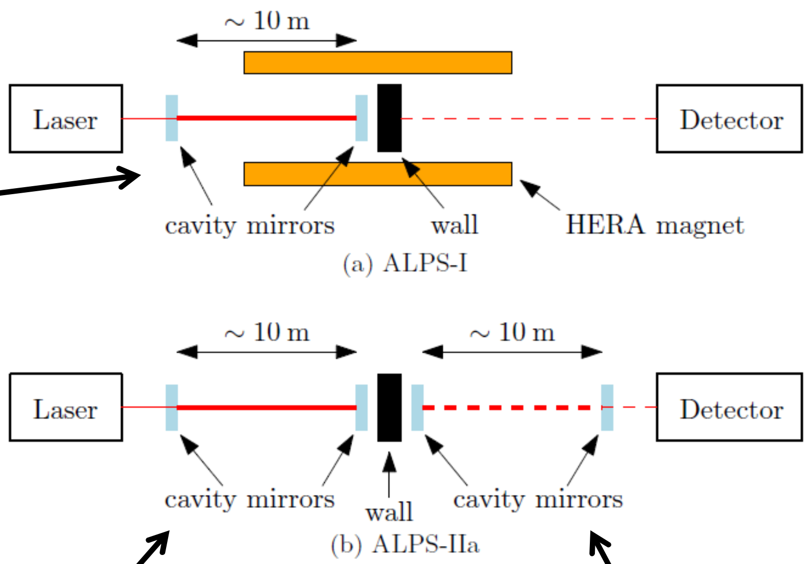
The ALPS II reach

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

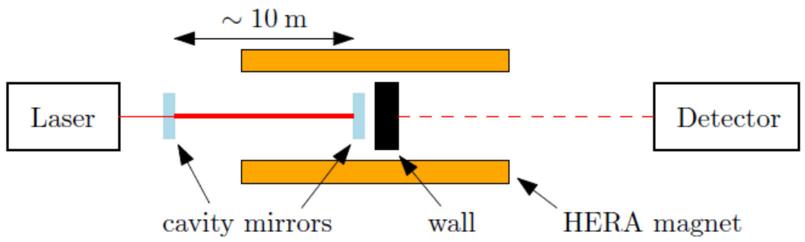
Optical resonator to increase the conversion probability

WISP→γ

First realization of a 23 year old proposal!

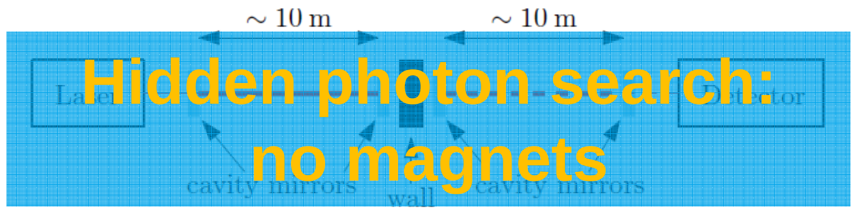
ALPS II will be realized in stages

ALPS I



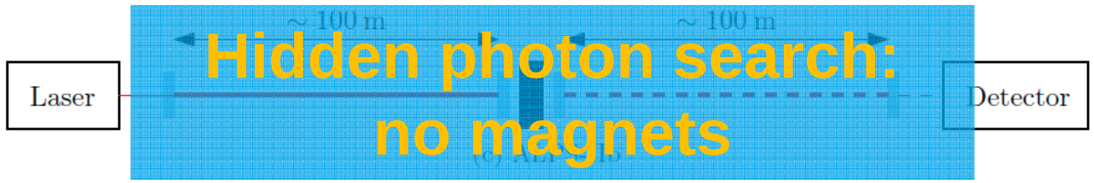
(a) ALPS-I

> **ALPS IIa**

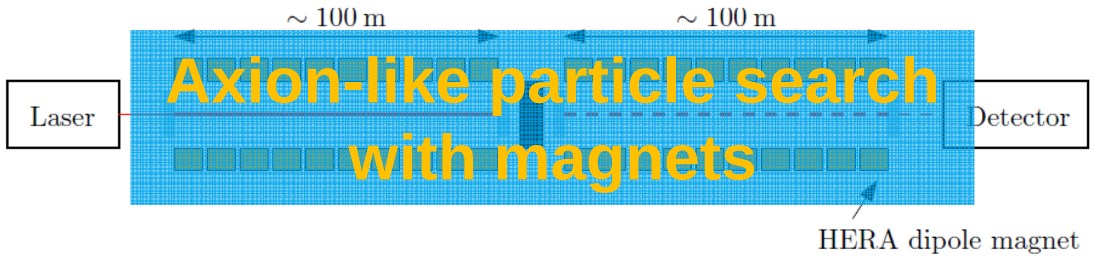


(b) ALPS-IIa

> **ALPS IIb**



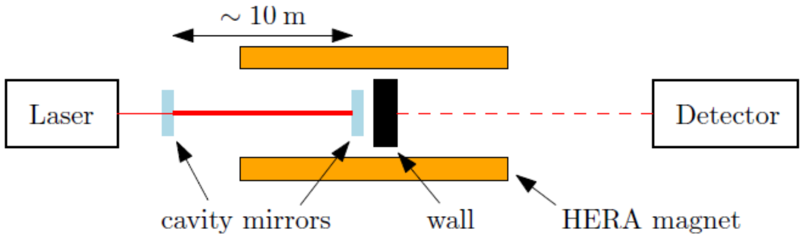
> **ALPS IIc**



(d) ALPS-IIc

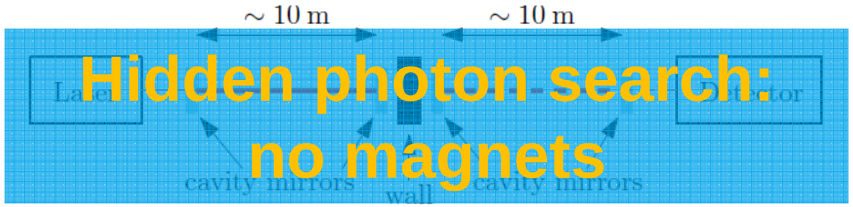
ALPS II will be realized in stages

ALPS I



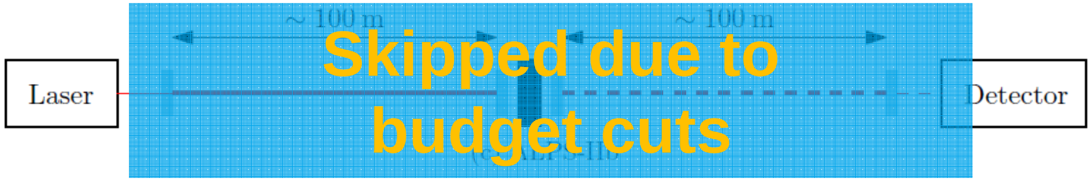
(a) ALPS-I

> **ALPS IIa**

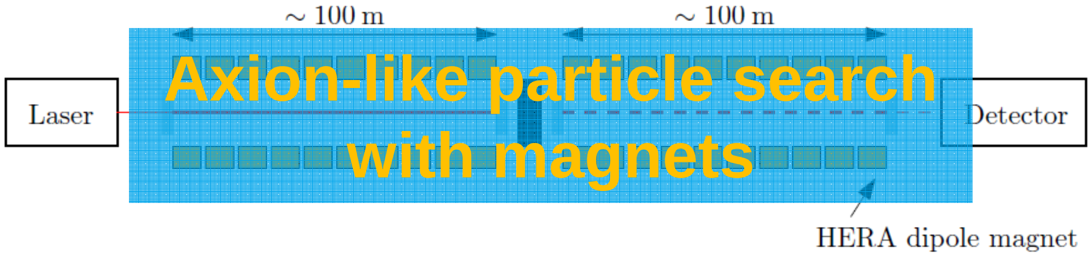


(b) ALPS-IIa

> **ALPS IIb**



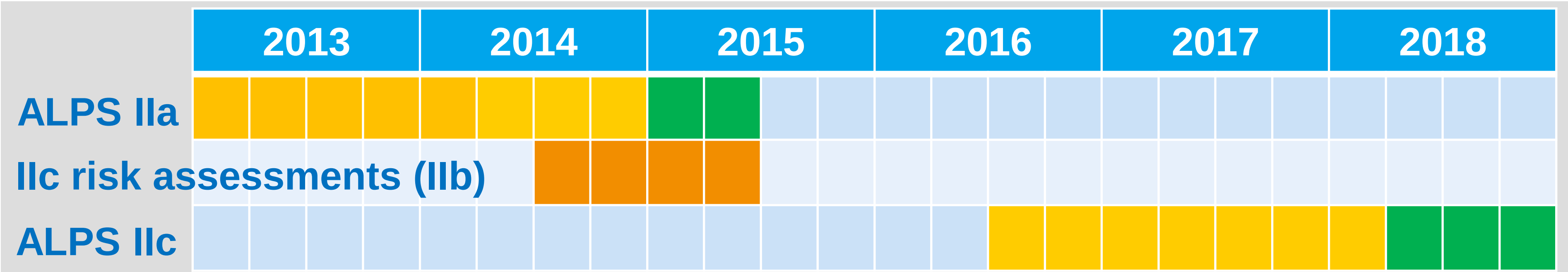
> **ALPS IIc**



(d) ALPS-IIc

DESY

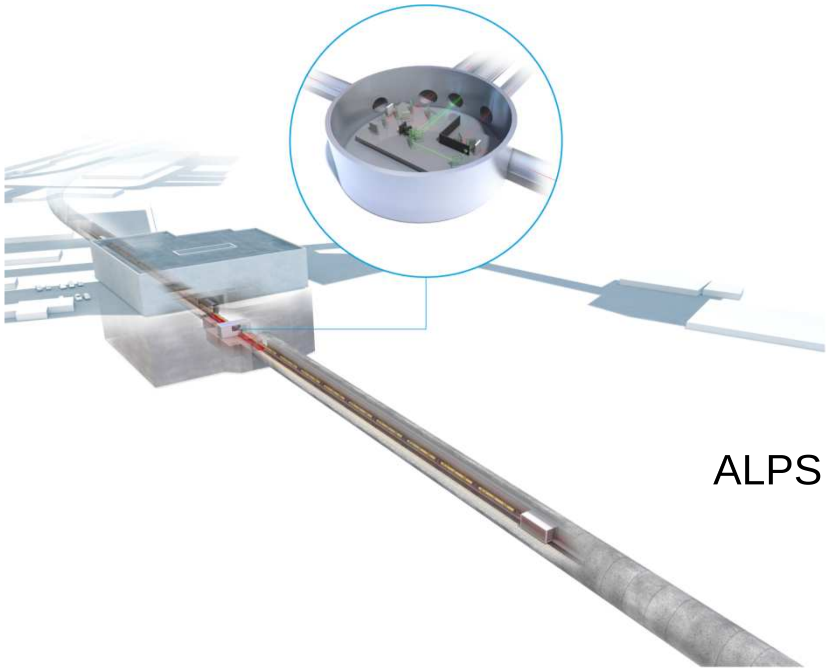
ALPS II schedule (rough)



installation

data runs

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

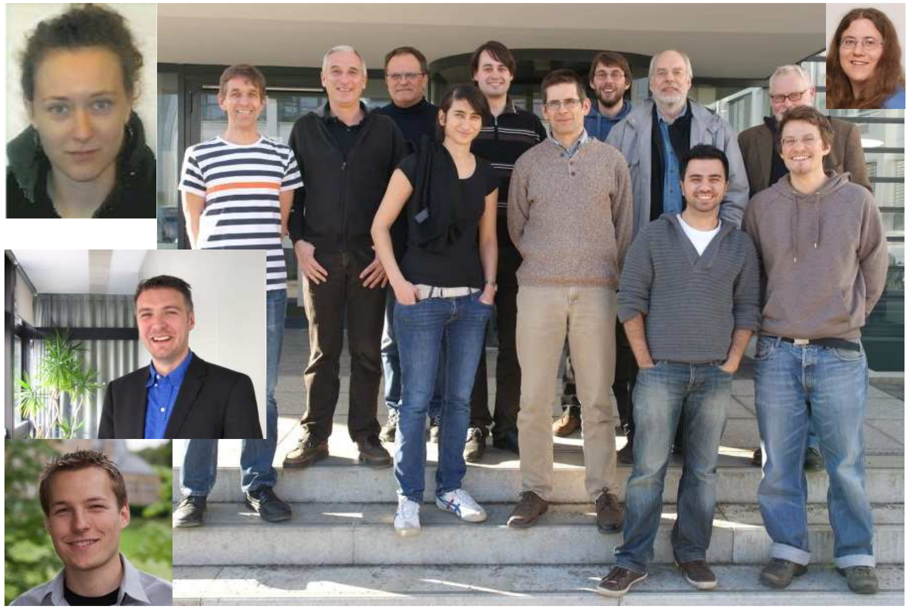


ALPS IIc in 2018 in the HERA tunnel

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

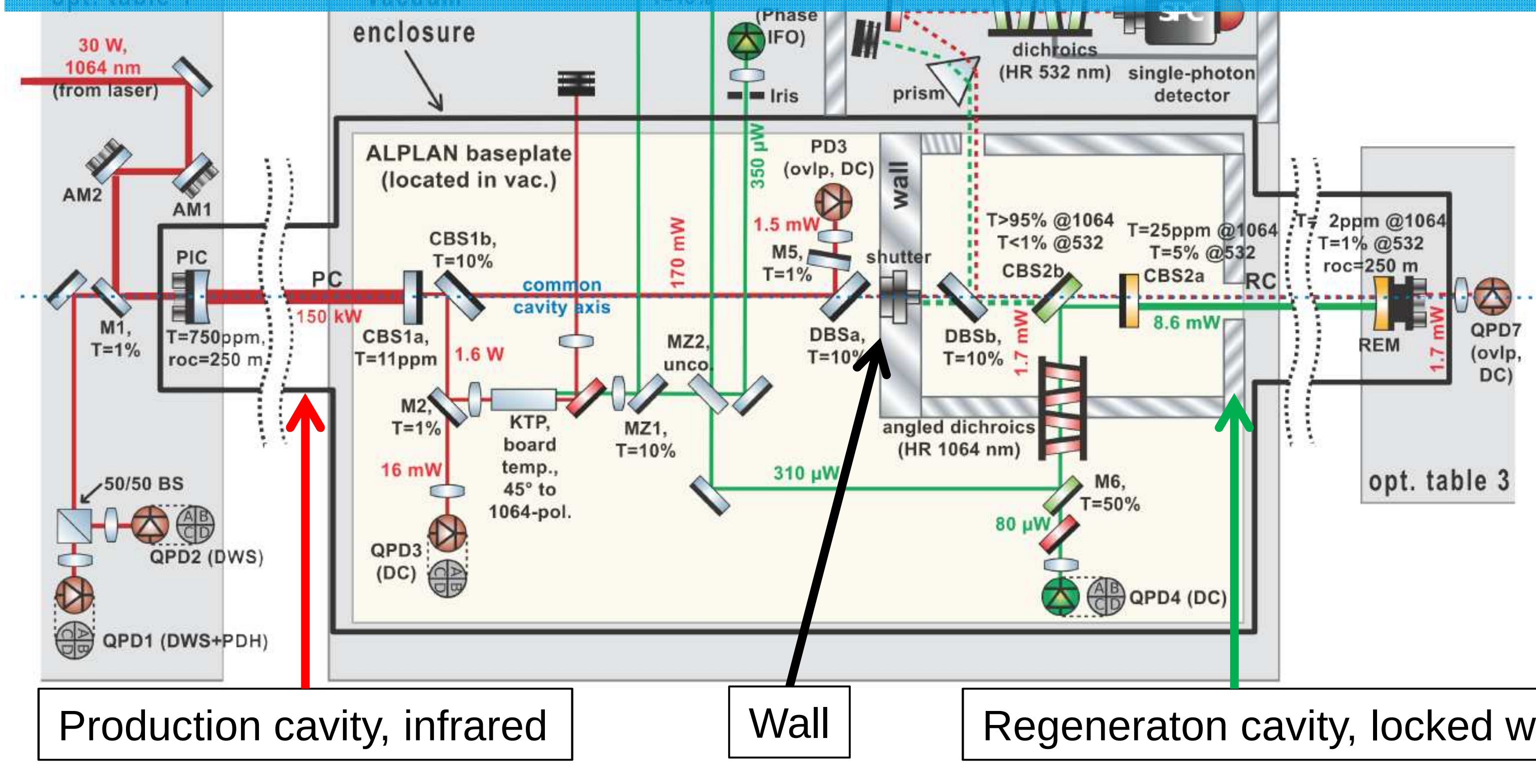


with strong support from

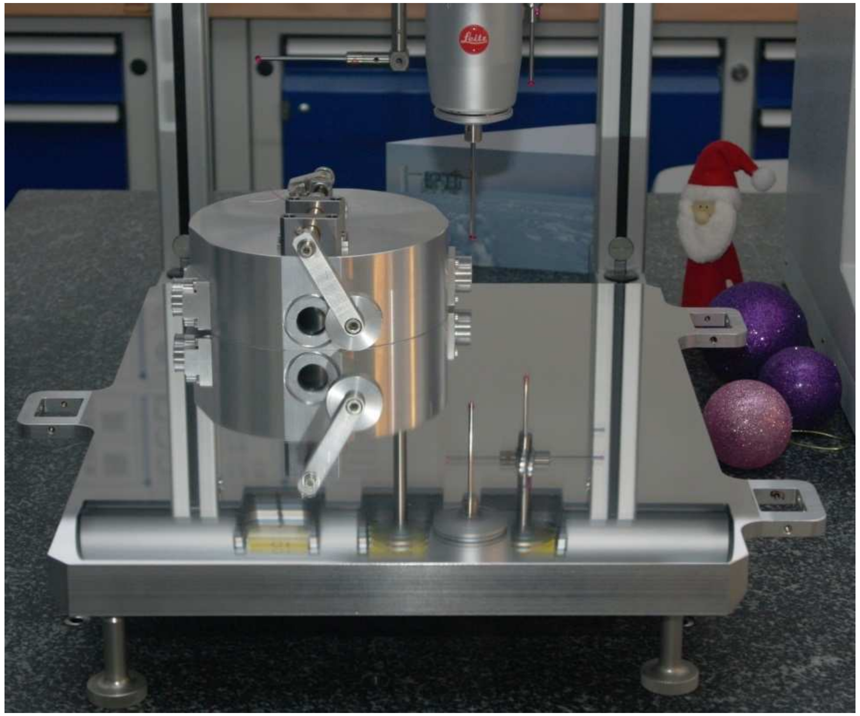
- neoLASE:
  Maik Frede, Bastian Schulz

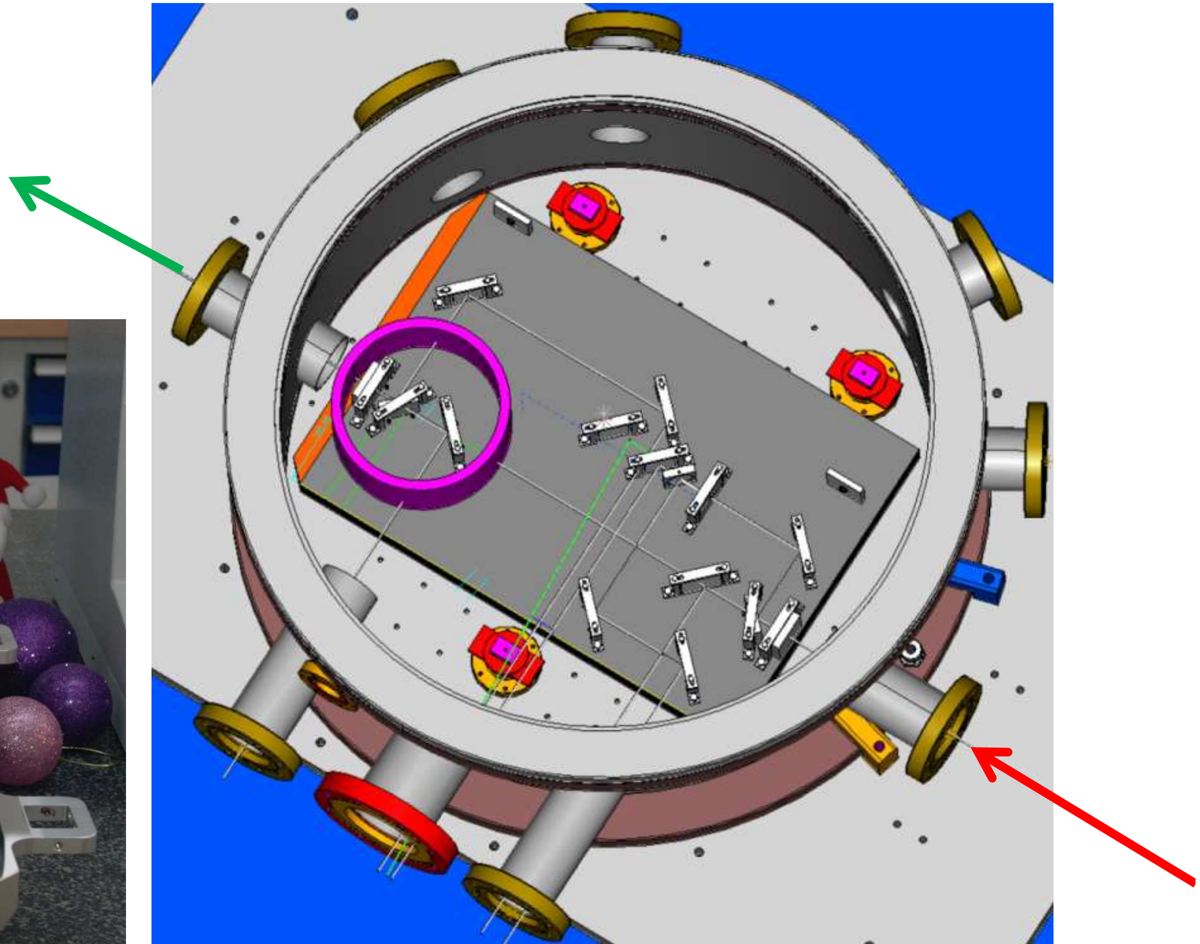
ALPS II essentials: laser & optics

- 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!

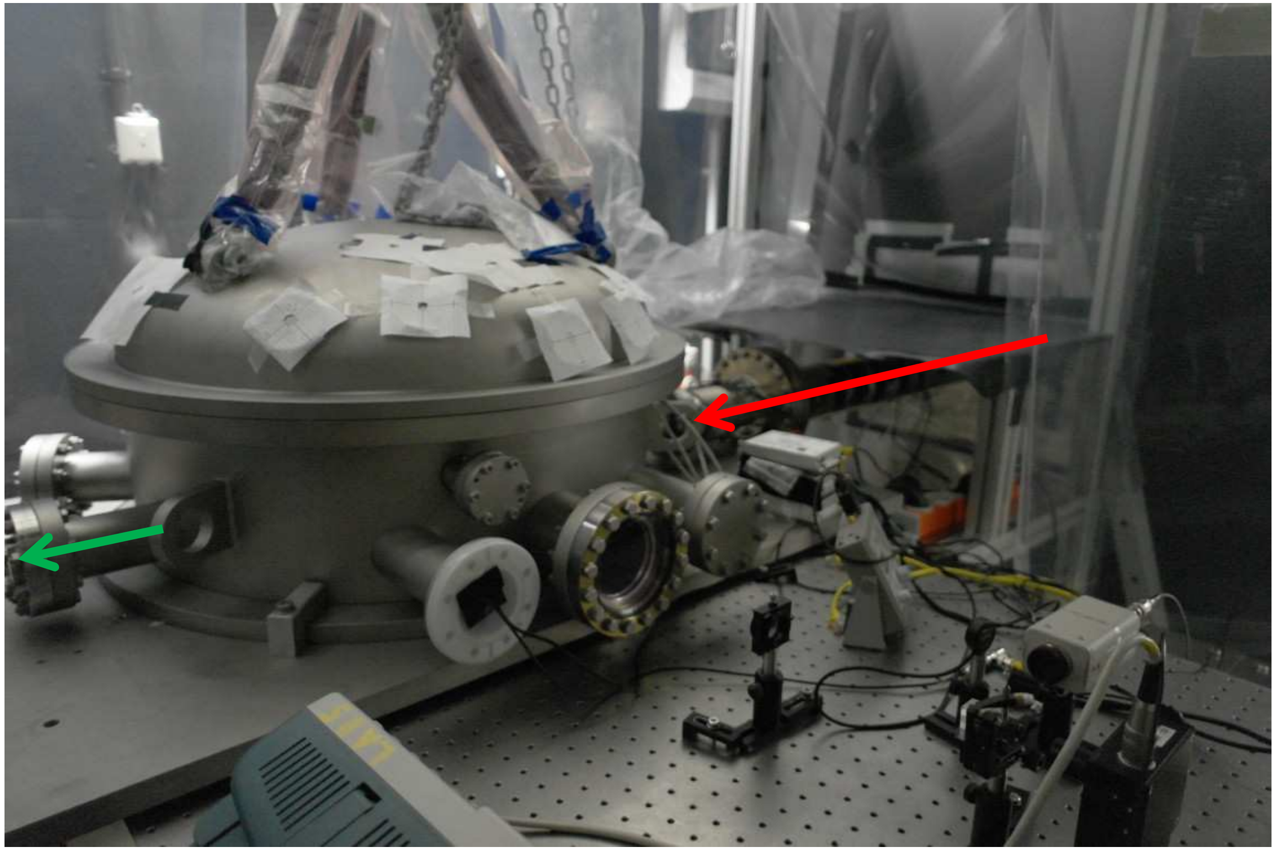


The central optics breadboard



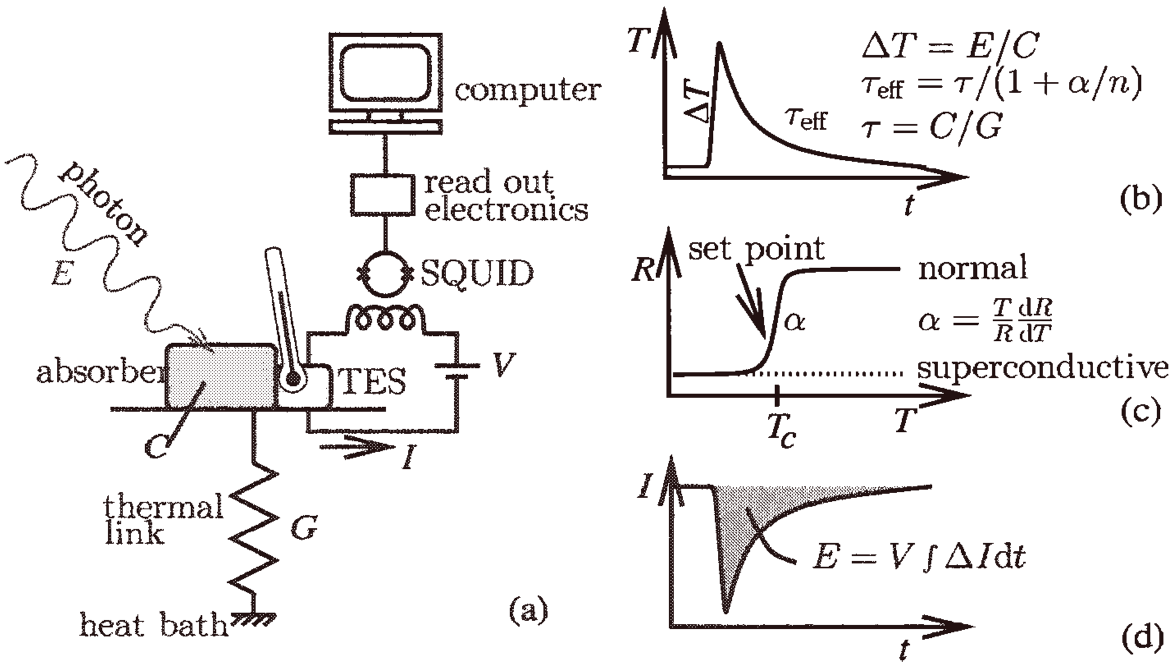


The big vacuum tank



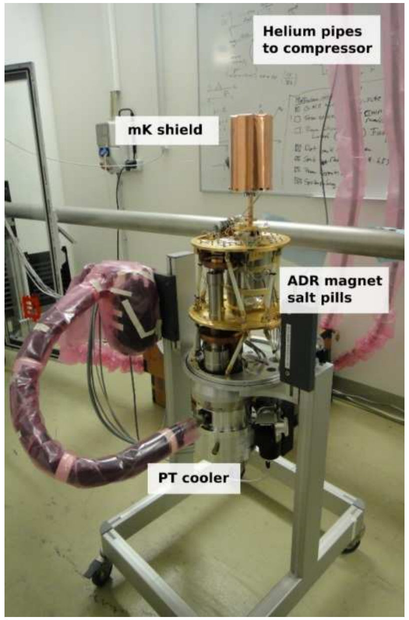
ALPS II detector

Transition Edge Sensor (TES)

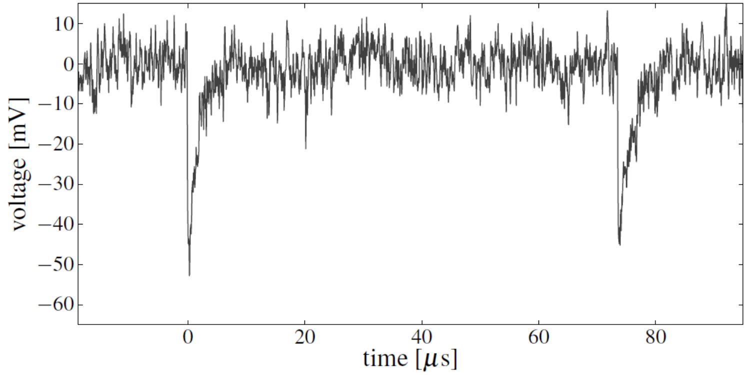


- Very high quantum efficiency, also at 1064 nm, very low noise.
- Tungsten film.
- Sensor size 25µm x 25µm x 20nm.
- To be operate around 100 mK.

ALPS II detector

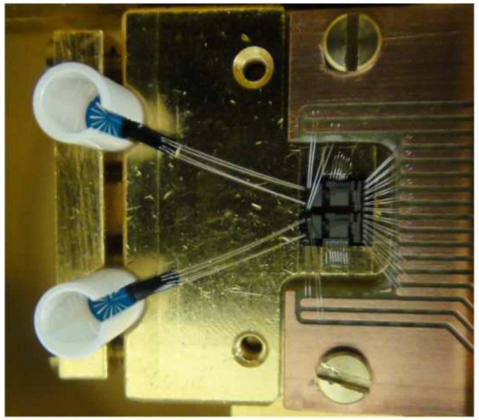


- Measure single 1066 nm photons!



- Energy resolution about 8%.
- Background 10^{-4} counts/second.
- Pulse shape well understood.

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

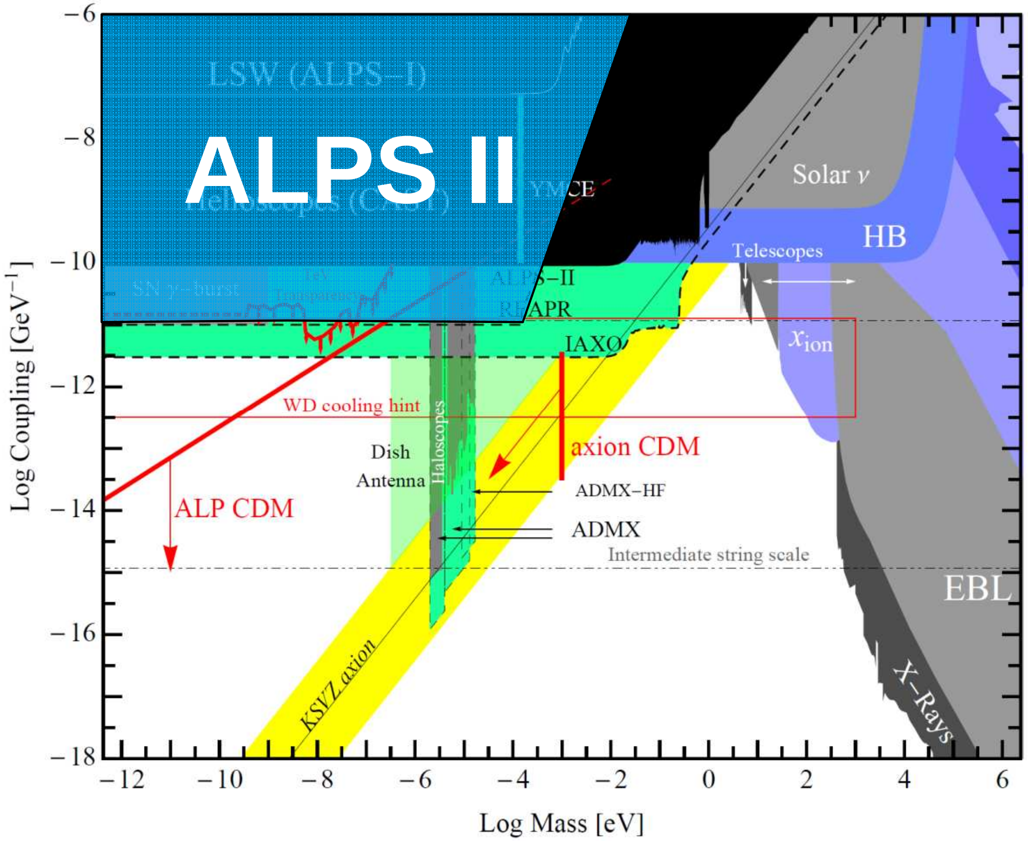


- Continue background studies, optimize fibers.
- Try to minimize background from ambient thermal photons.

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.

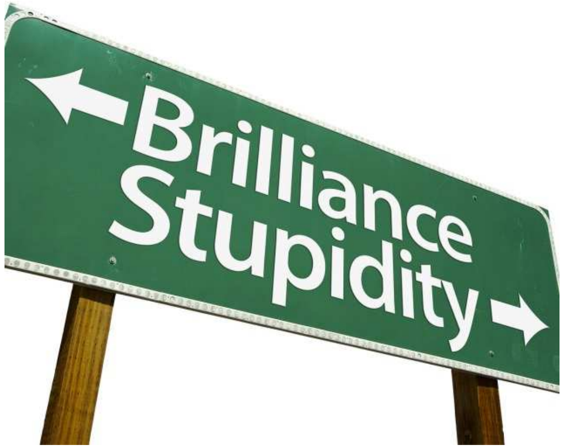


In-between-summary

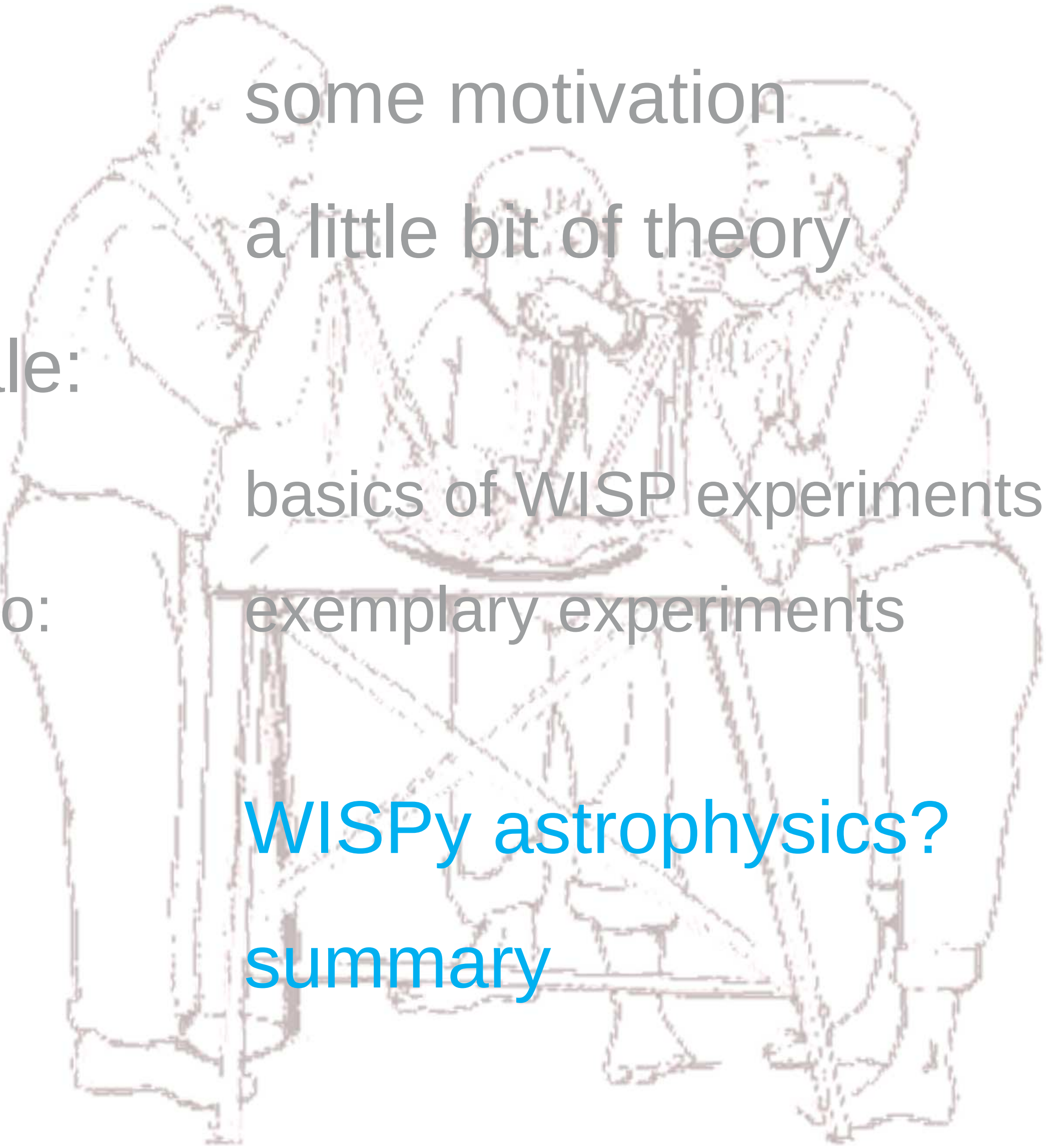
> Axion / ALP / WISP searches are performed by small scale experiments.

- Direct Dark Matter searches (haloscopes):
  technologies with sufficient sensitivity to probe for the QCD axion exist,
  but it is unclear how to cover the most promising mass region.
- Search for solar WISPs (helioscopes):
  A jump in sensitivity will take place with the next IAXO generation. Part of the QCD axion phase space will be probed.
- Purely laboratory based searches:
  The sensitivity will be increased by 3 orders of magnitude surpassing present day helioscopes and indirect limits from astrophysics.
  QCD axions are out of reach.

> So why should one invest to probe uncharted territory with IAXO, ALPS II and others?



Outline

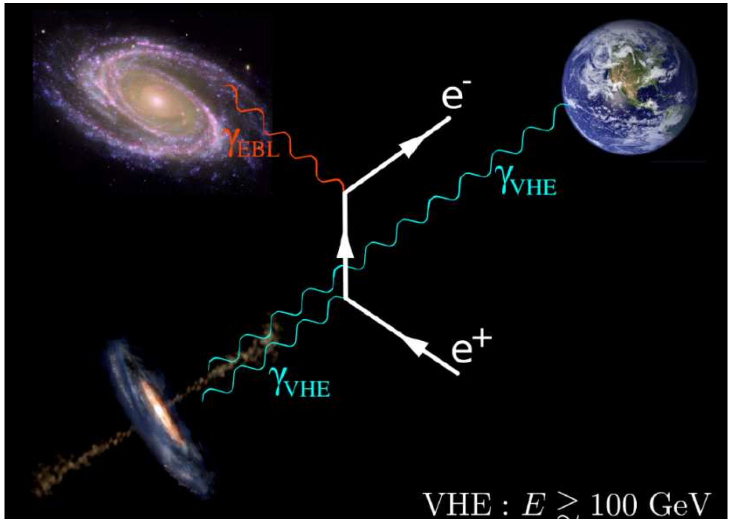


- Aperitivo: some motivation
- Antipasto: a little bit of theory
- Piatto principale:
  - Prima piatto: basics of WISP experiments
  - Seconda piatto: exemplary experiments
- Dolce: WISPy astrophysics?
- Caffè corretto: summary

Indications for a WISP world?

> Puzzles from astrophysics:

Example: TeV photons should be absorbed in the intergalactic space, …



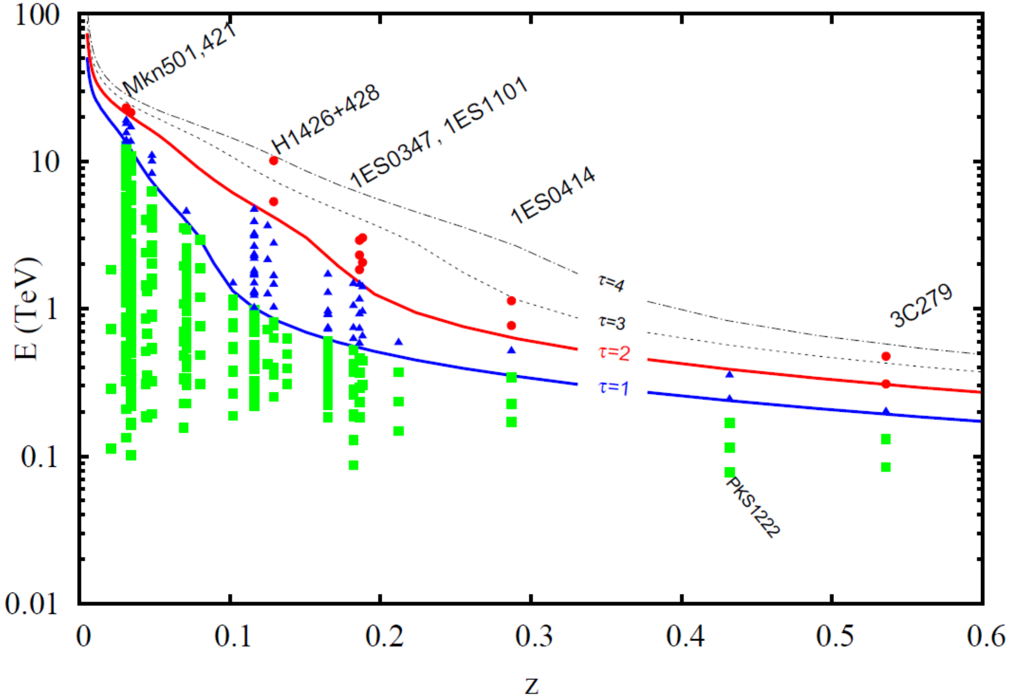
Center of mass energy about 1 MeV!

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

Indications for a WISP world?

> Puzzles from astrophysics:

… but this seems to be in conflict with observations.

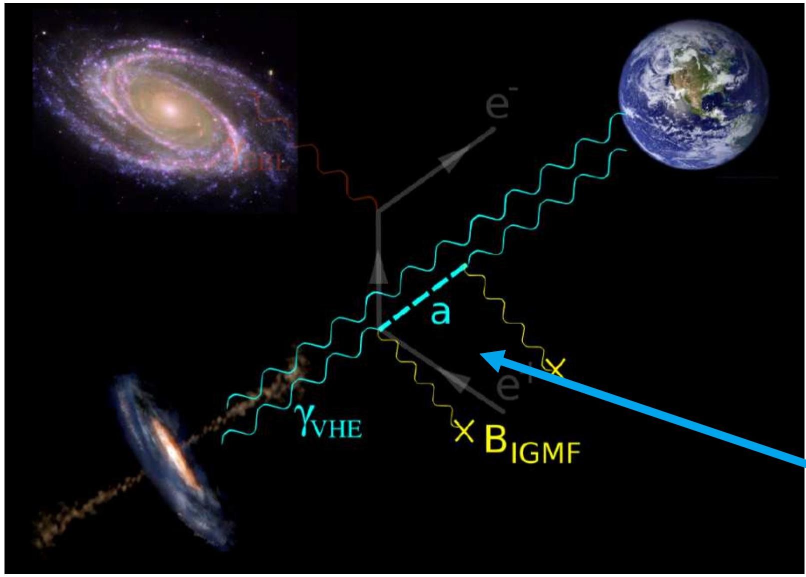


D. Horns, M. Meyer, JCAP 1202 (2012) 033

> 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:

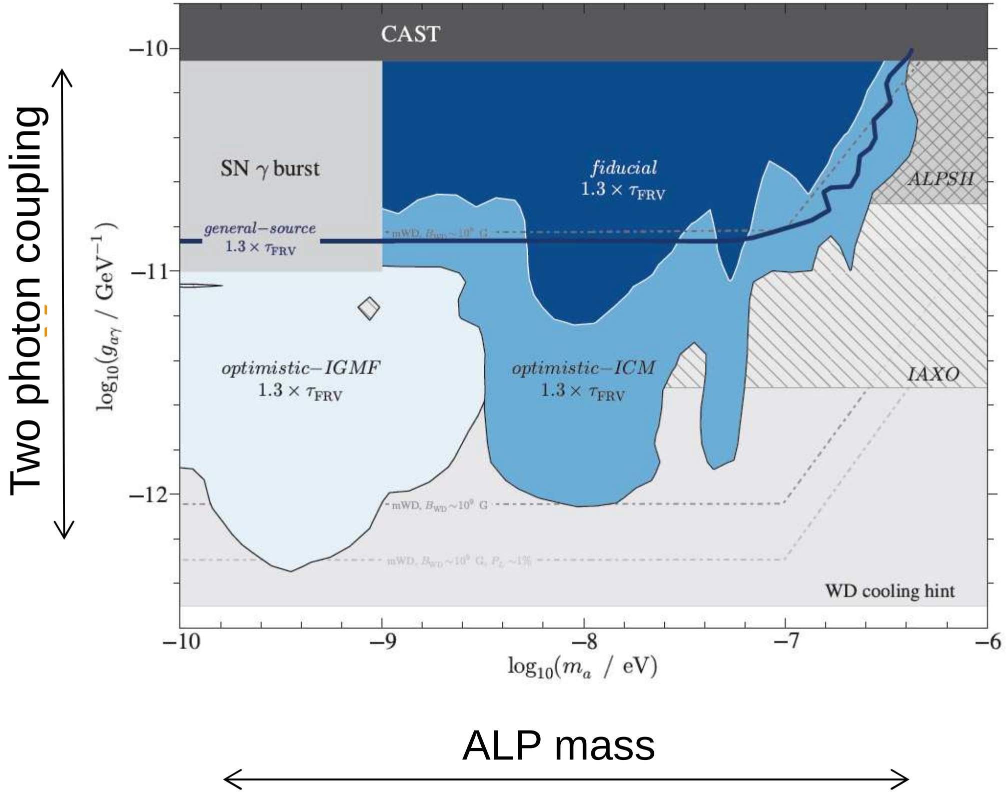


M. Meyer, 7th Patras Workshop on Axions, WIMPs and WISPs, 2011

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

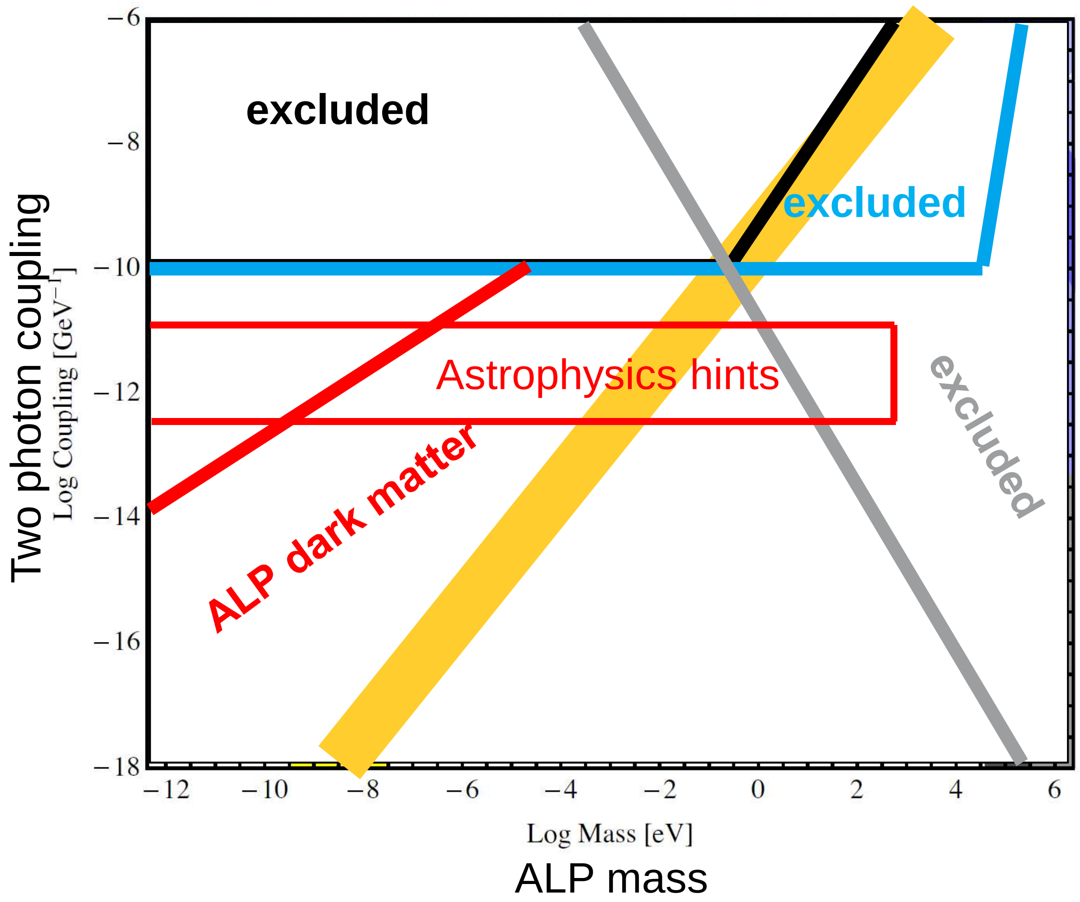
might hint at Weakly Interacting Slim Particles (WISPs).

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

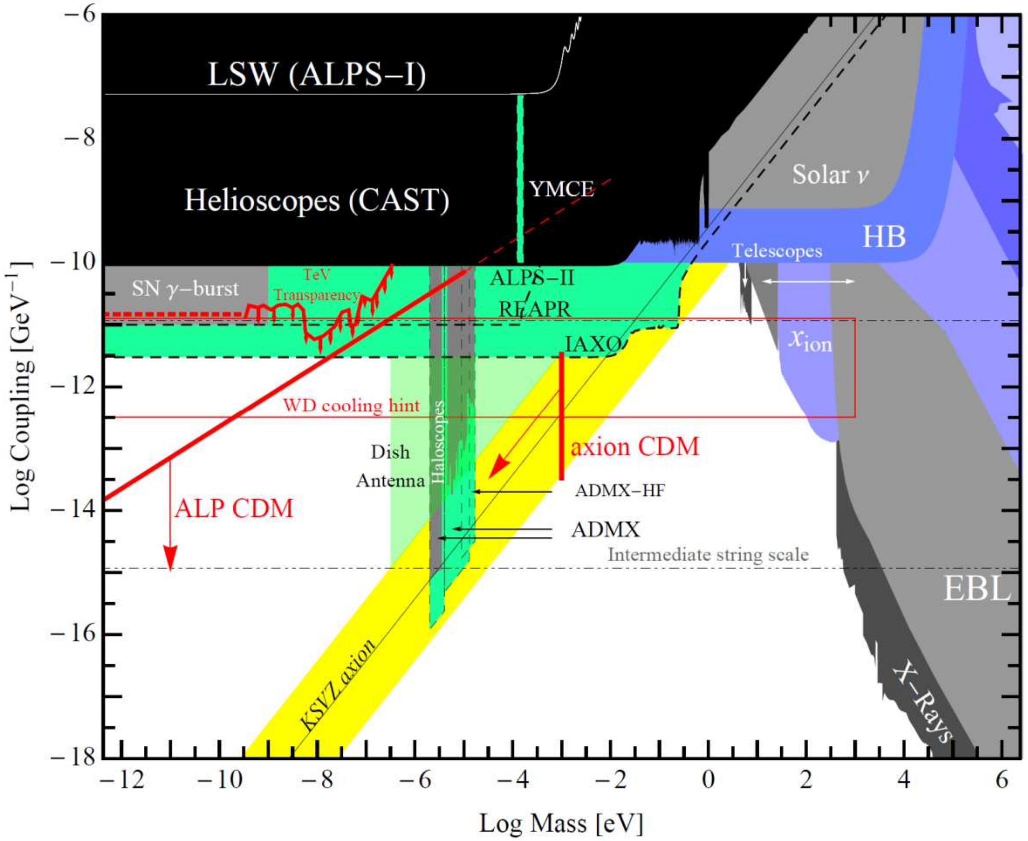
★ to be confirmed!

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
Contents lists available at SciVerse ScienceDirect
Dark Universe
journal homepage: www.elsevier.com/locate/agee
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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]**

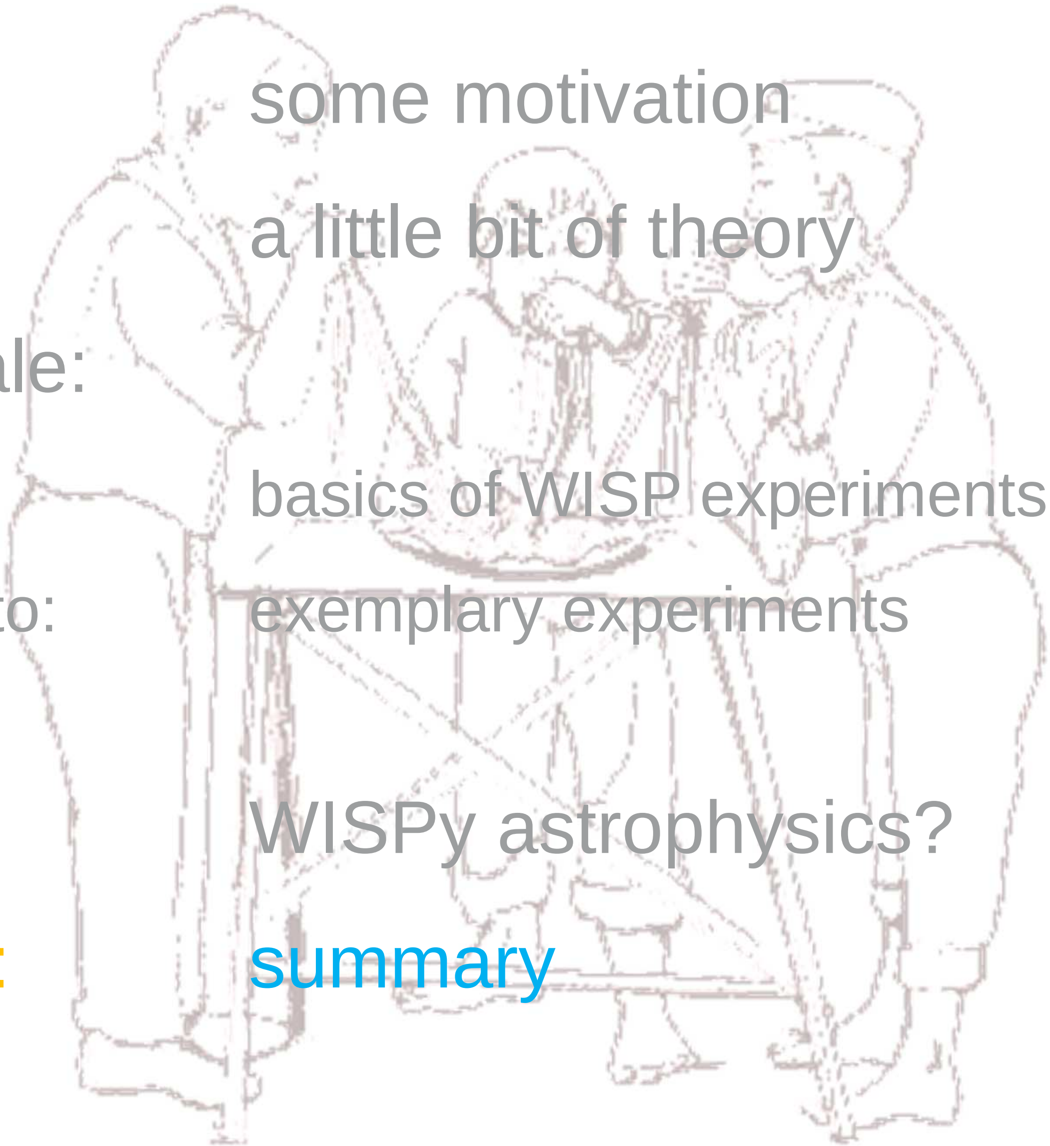
QCD axion range
Excluded by WISP experiments
Excluded by astronomy (ass. ALP DM)
Excluded by astrophysics / cosmology
Axions or ALPs being cold dark matter
WISP hints from astrophysics

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.

Outline



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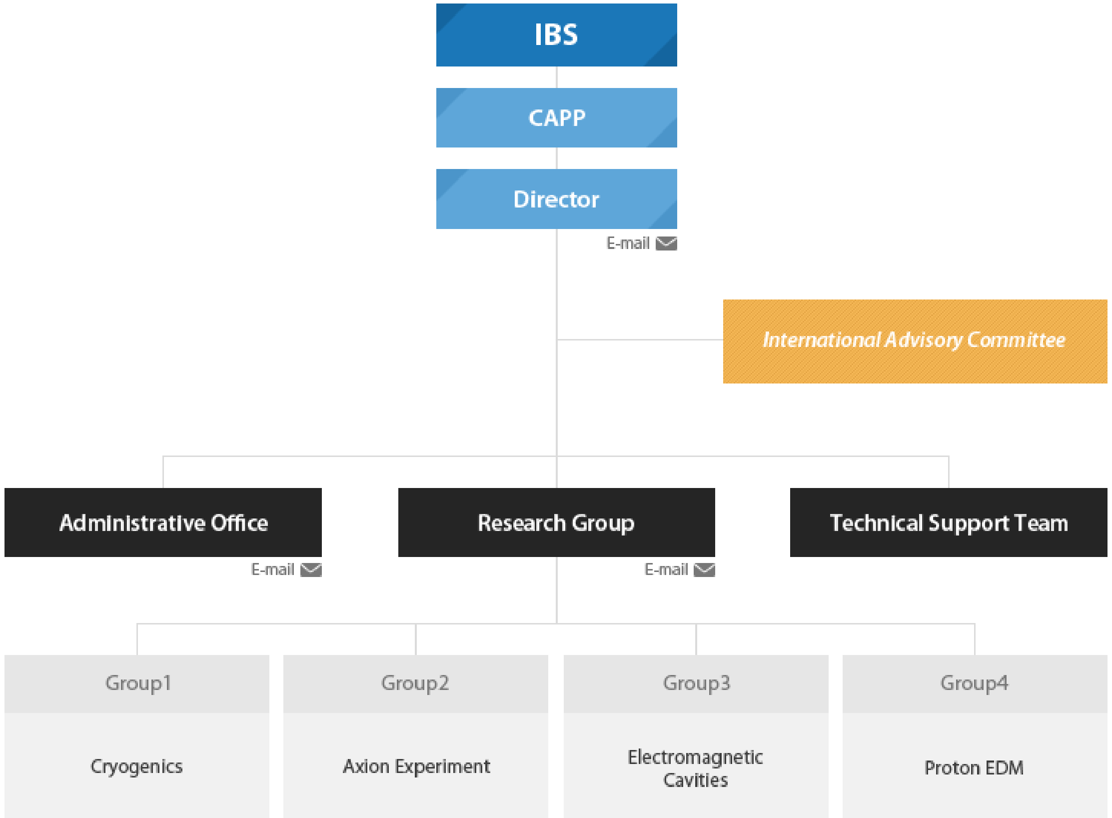
- Caffè corretto: summary

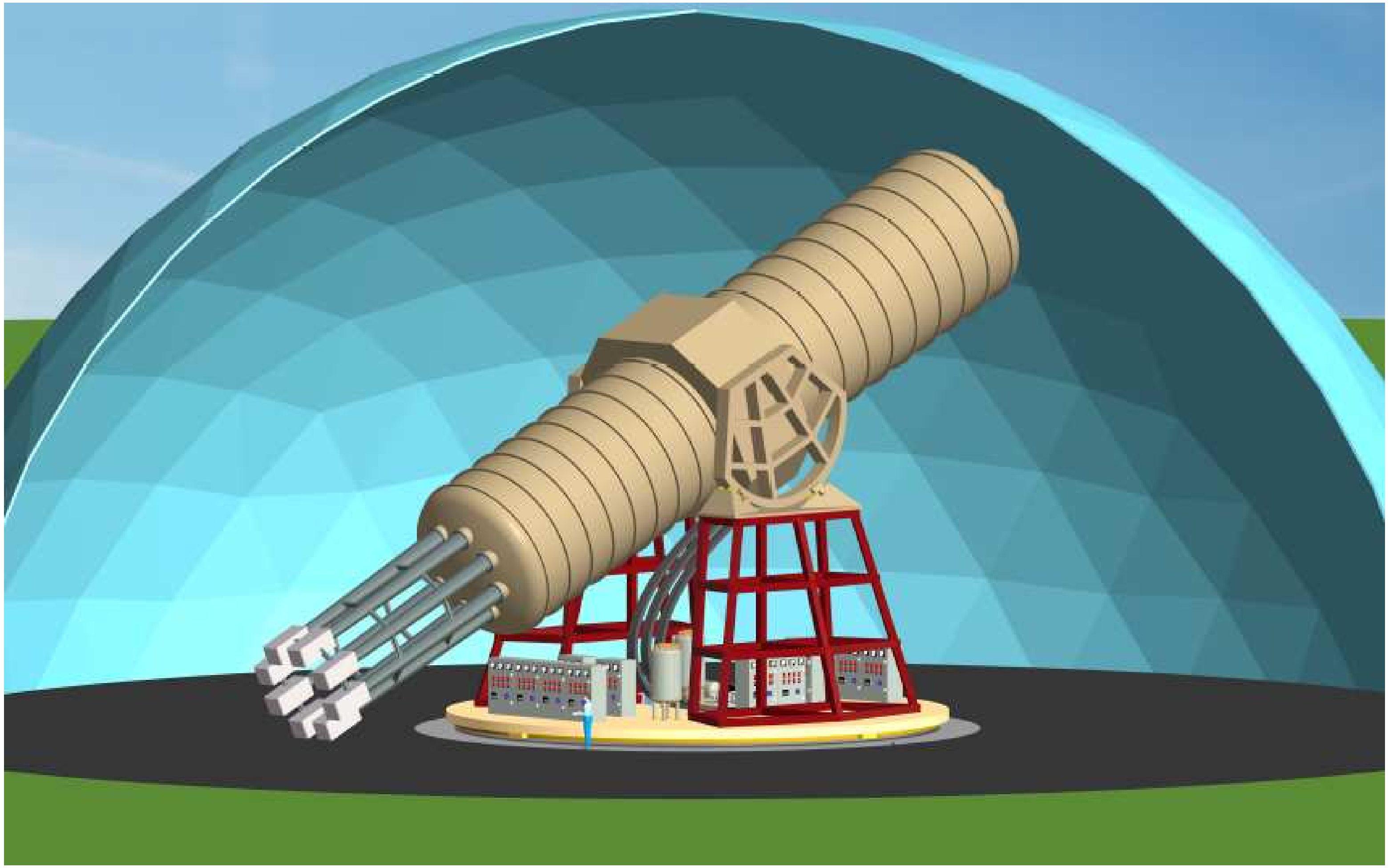
The first axion institute!

- 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

- Weakly Interacting Slim Particles might explain puzzles from cosmology, astrophysics and particle physics.
- With the recent developments in theory and astrophysics phenomena we know where to go
  - for axion-like particles and hidden photons.
- Next generation experiments are being constructed or prepared with sensitivities allowing to probe these predictions.
- One should exploit carefully new options provided by high power pulsed laser systems, large existing magnets or new approaches for dark matter searches for example.
- Relatively small scale and short term WISP experiments offer a fascinating complement to accelerator based "big science".
- **There is plenty of room for new ideas and quick experiments having the potential to change the (particle physicist's) world!**

BSM physics might hide anywhere!