Status of ALPS II @ DESY

Searching for Weakly-Interacting-Slim Particles by shining light-through-a-wall

Axel Lindner
DESY

CERN, 17 September 2015

A brief primer on

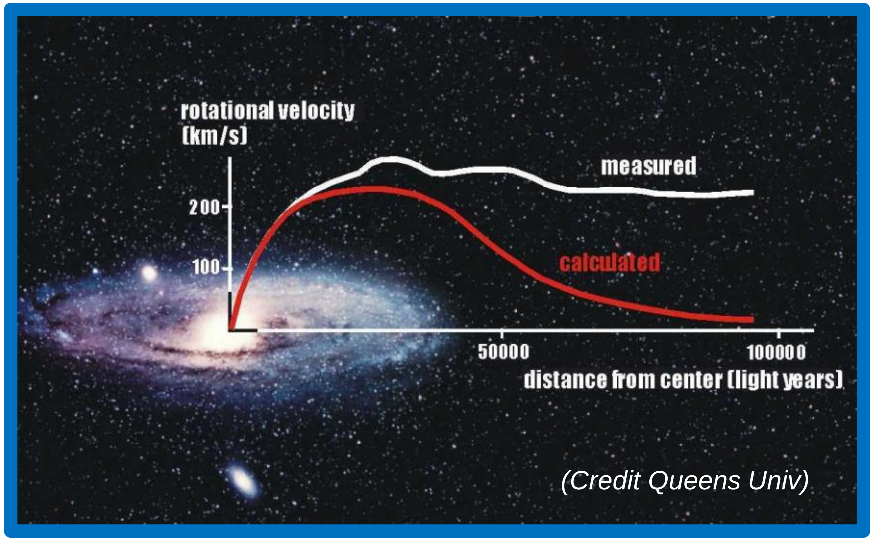
- W
- I
- S
- P
- S

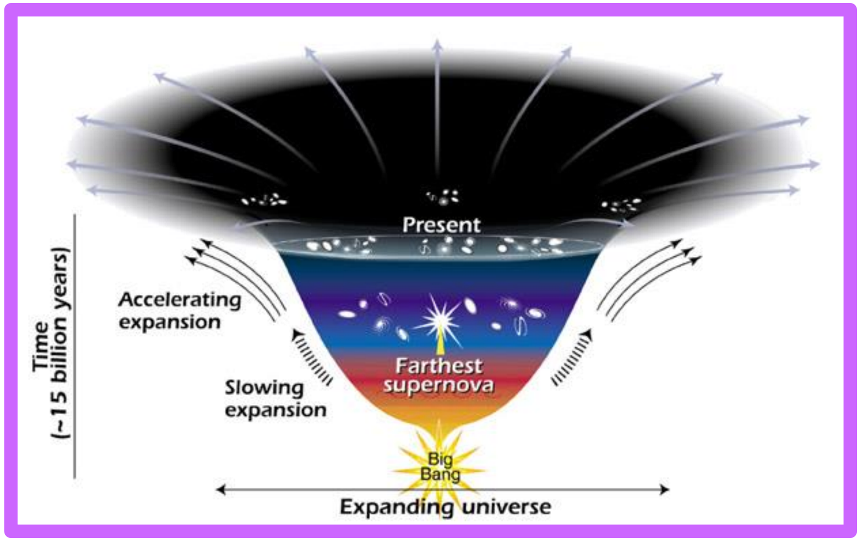
A brief primer on

- Why are we looking for WISPs
- Indications for WISPs?
- Searches for WISPs
- Plans for WISPs at DESY: ALPS II
- Summary

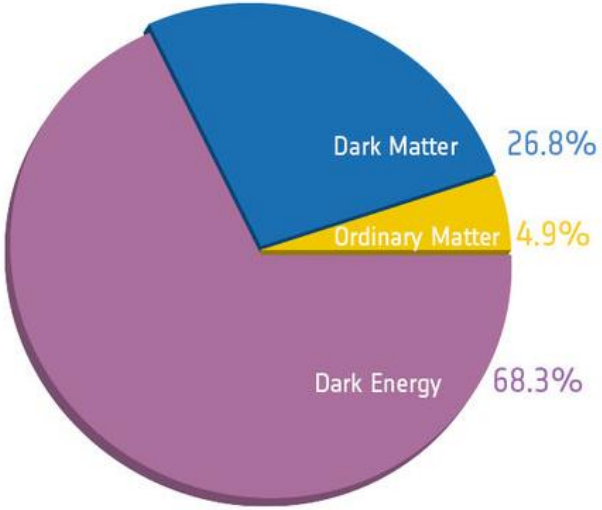
There is physics beyond the SM

- Dark matter and dark energy:





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

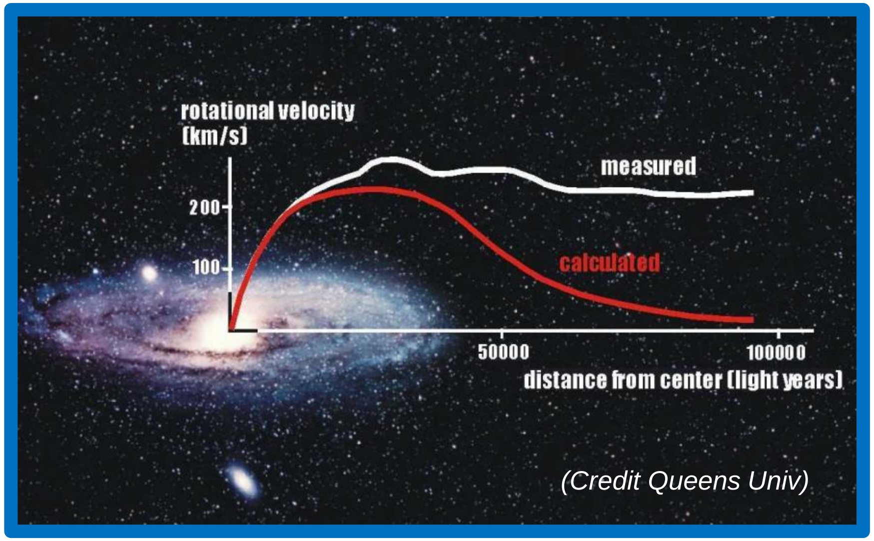


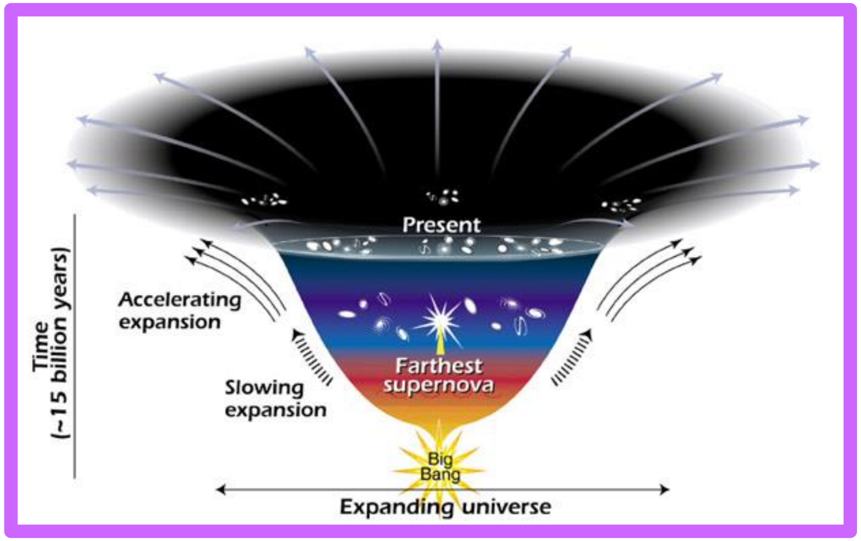
http://www.esa.int/For_Media/Photos/Highlights/Planck

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

NO HINT ON MASS OF DM CONSTITUENTS!

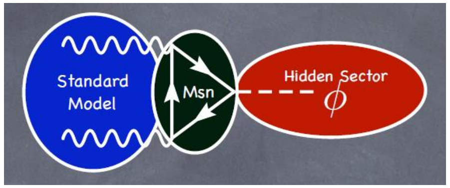
- Extremely lightweight scalar particle

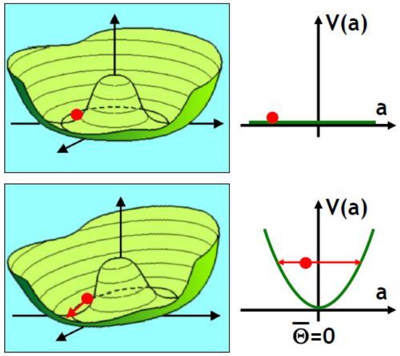
DESY

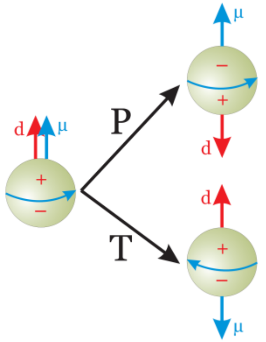
Introducing today's dark matter candidates: WISPs

> Weakly Interacting Slim Particles (WISPs)

- Theory: WISPs might arise as (pseudo) Goldstone bosons related to extra dimensions in theoretical extensions (like string theory) of the standard model.
- Dark matter: in the early universe WISPs are produced in phase transitions and would compose very cold dark matter in spite of their low mass.
- Additional benefit: with axions (the longest known WISP) the CP conservation of QCD could be explained, axion-like particles could explain different astrophysical phenomena.





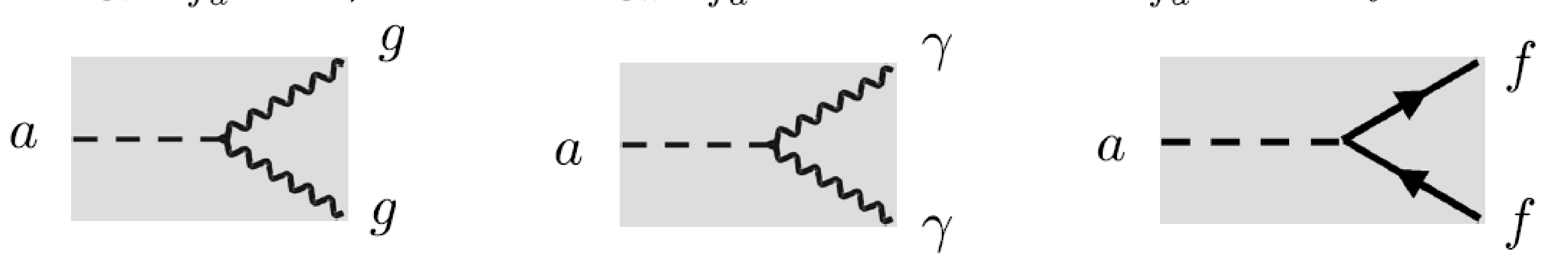


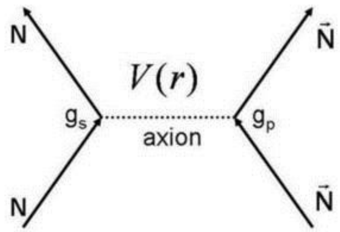
> Prediction:
> Dark matter is composed out of elementary particles with masses below 1 meV. Its number density is larger than 10^{12} 1/cm^3.

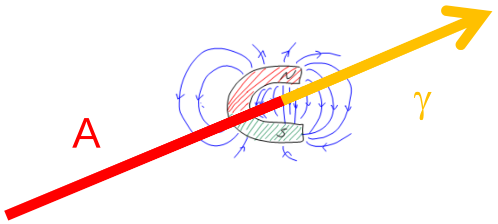
Axions and other WISPs in theory

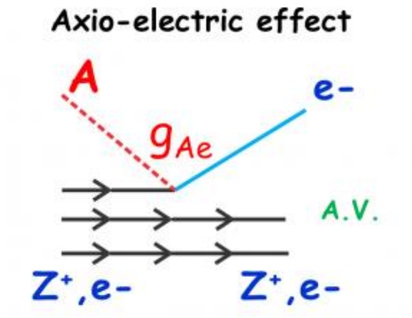
- Axion and other Nambu-Goldstone bosons arising from spontaneous breakdown of global symmetries are theoretically well-motivated very weakly interacting slim (ultra-light) particles.
  The coefficients are determined by specific ultraviolet extension of SM.

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









Courtesy A. Ringwald

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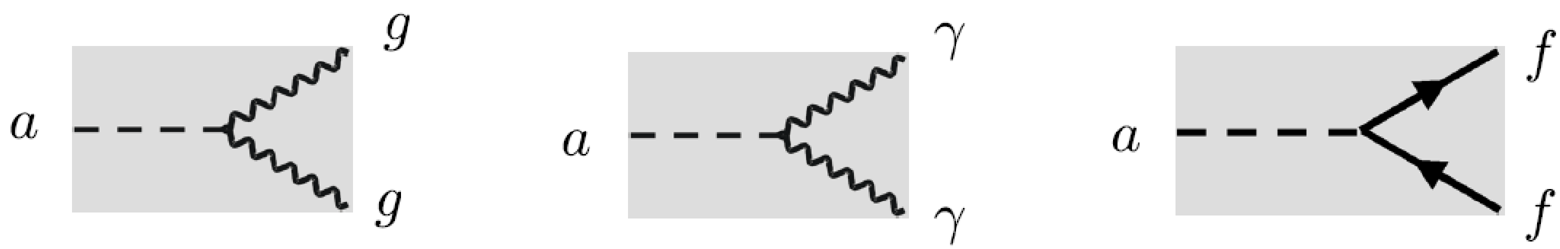
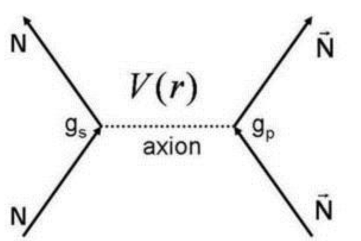
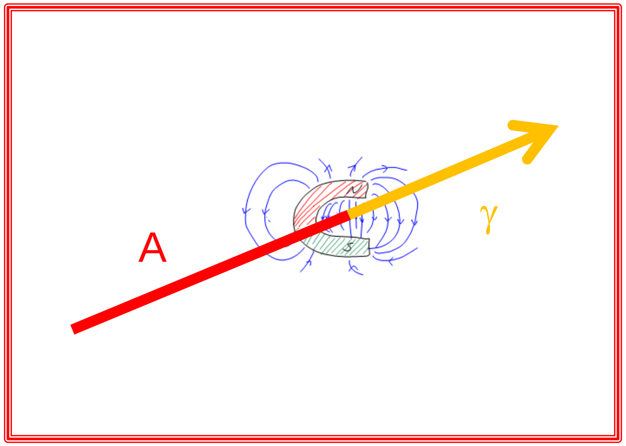
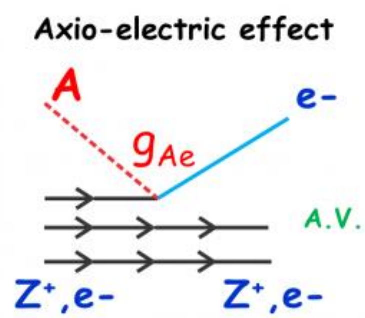








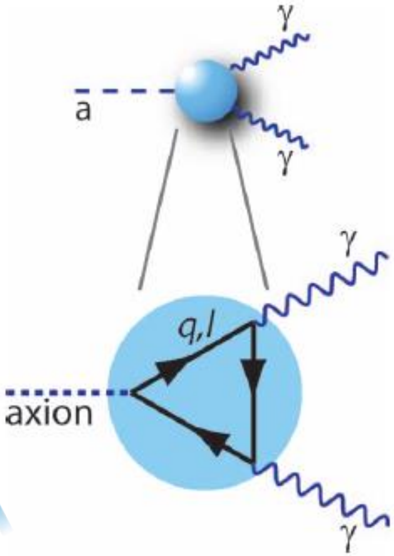
Courtesy A. Ringwald

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

    $f_a < 10^{12}$GeV
    $m_a > \mu$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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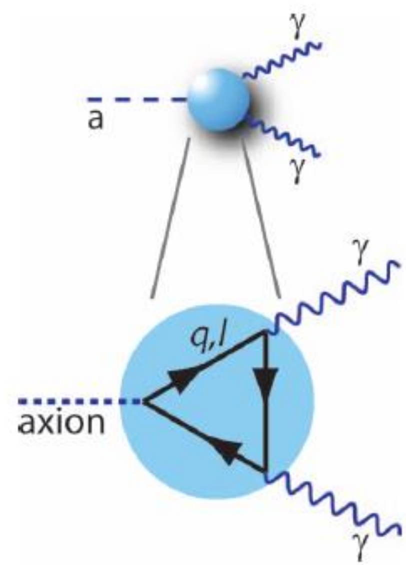
VERY LIGHTWEIGHT COLD DARK MATTER!



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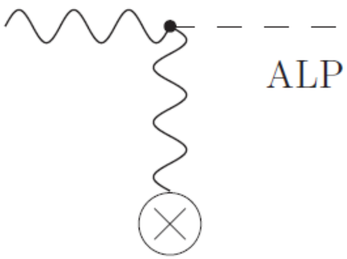
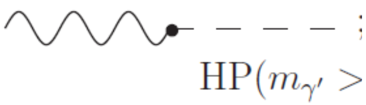
Other WISPy particles as predicted by theory

Weakly Interacting Slim Particles (WISPs):

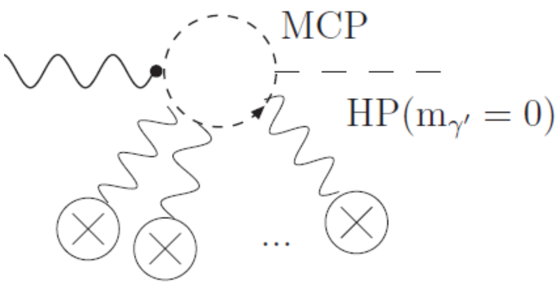
- Axions and
  axion-like particles
  ALPs, pseudoscalar or scalar bosons,
  m and g are not related by an f.



- Hidden photons (neutral vector bosons)



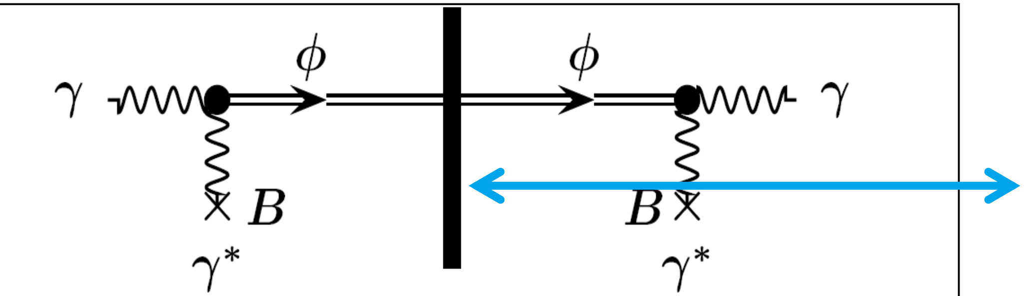
- Mini-charged particles



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

Basics of many WISP experiments

- 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,
….

- > Why are we looking for WISPs
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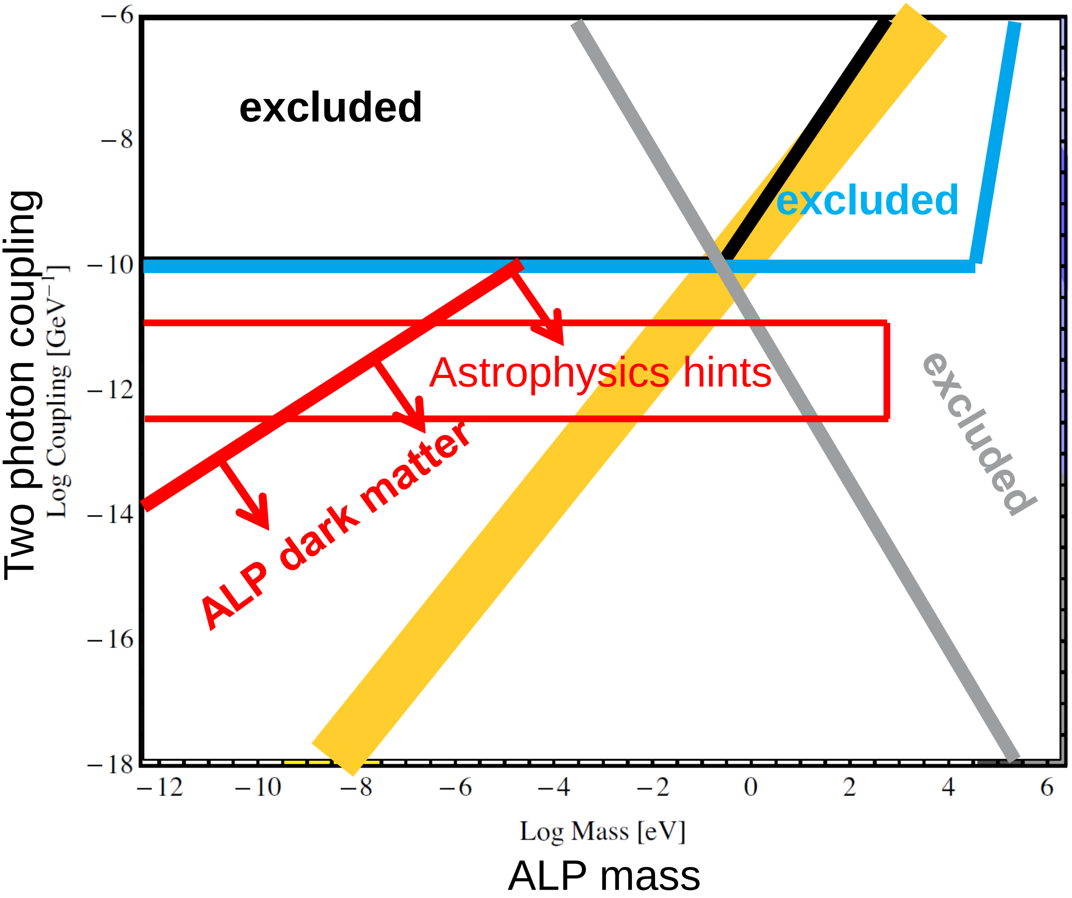
Hints for WISPs / ALPs?

- Is the universe more transparent to TeV photons than predicted?
- Do stars cool down too fast?
- Is there a Cosmic Axion-like-particle Background (CAB)?

Phenomenon	ALP mass [eV]	ALP-γ coupl. [GeV^{-1}]	Reference
TeV transparency	$< 10^{-7}$	$> 10^{-11}$	arXiv:1302.1208 [astro-ph.HE]
Globular cluster stars (HB)	$< 10^{4}$	$\approx 5 \cdot 10^{-11}$	arXiv:1406.6053 [astro-ph.SR]
CAB (Coma Cluster)	$< 10^{-13}$	10^{-12} to 10^{-13}	arXiv:1406.5188 [hep-ph]
White dwarfs	$< 10^{-2}$	($g_{ae} \approx 5 \cdot 10^{-13}$)	arXiv:1304.7652 [astro-ph.SR]

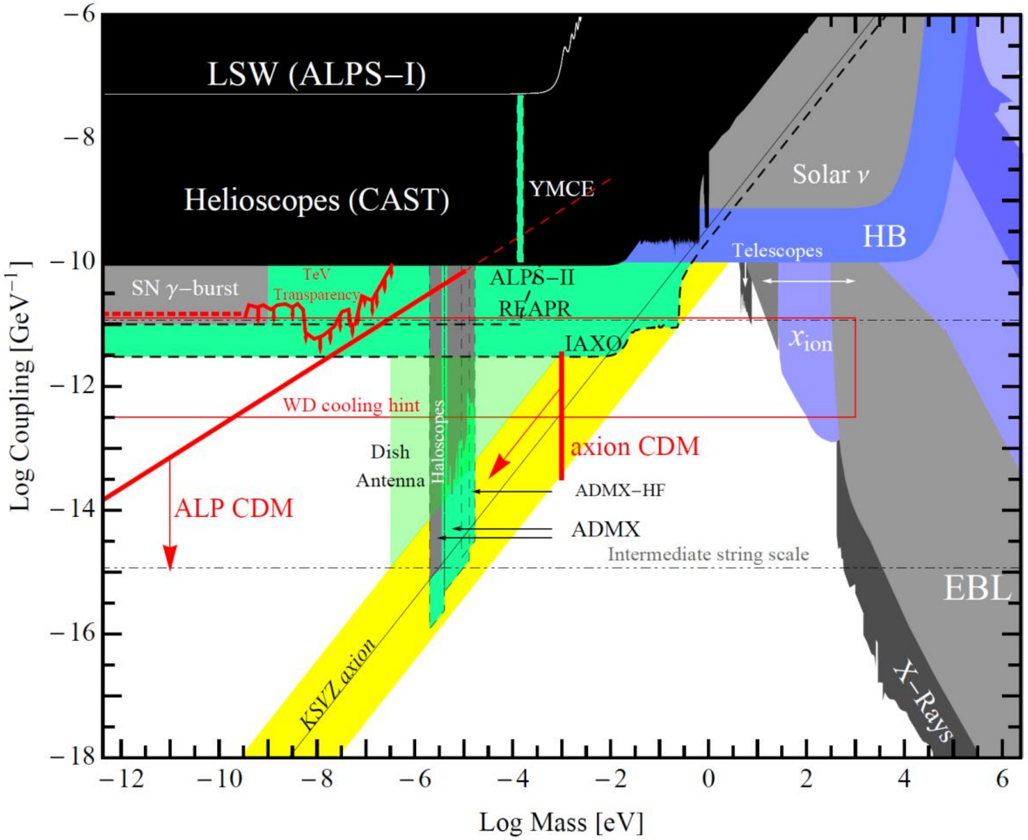
- There are allowed regions in parameter space where an ALP can simultaneously explain the gamma ray transparency, the cooling of HB stars, and the soft X-ray excess from Coma and be a subdominant contribution to CDM.

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

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

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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.

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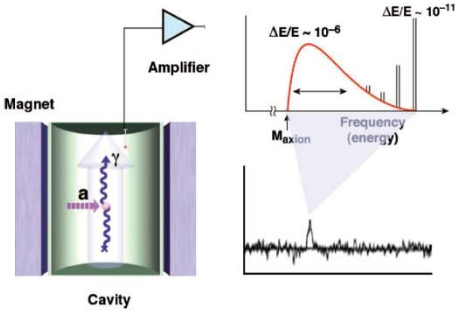
Dark matter (DM) search strategies: WISPs

- Direct:
  an experiment detects particles of the DM halo all around us.

- Indirect:
  an experiment finds astrophysical signatures (next to gravitation) of the DM halo particles.

- Candidates:
  an experiment identifies new particles which are candidates for the constituents of the DM halo.



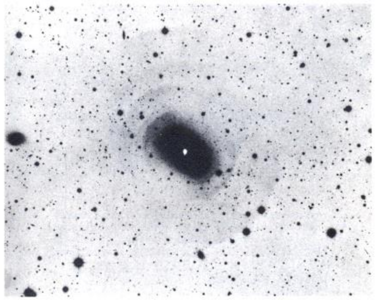
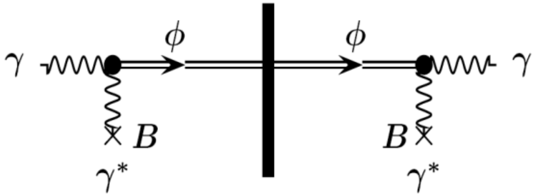


Figure 7-22. The giant elliptical galaxy NGC 3923 is surrounded by faint ripples of brightness. Courtesy of D. F. Malin and the Anglo-Australian Telescope Board.



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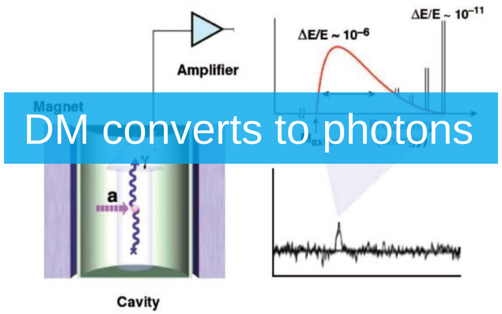

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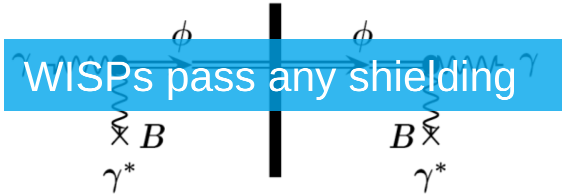

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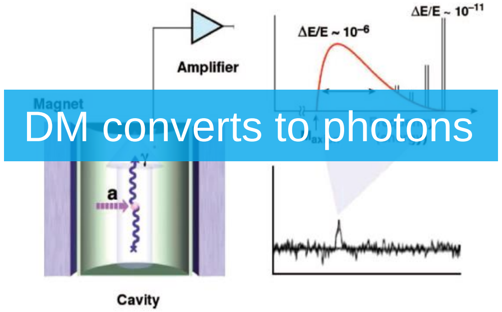

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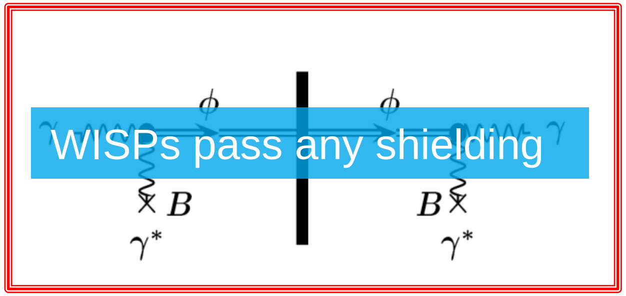
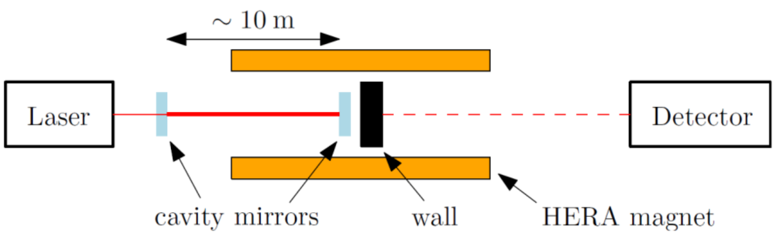


Searching for WISPs

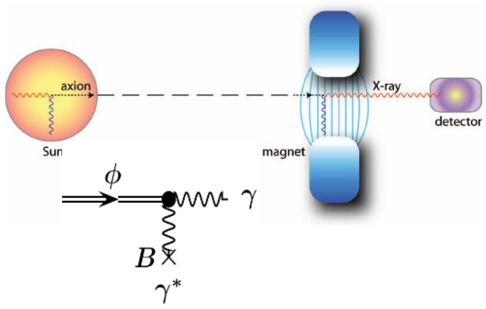
Weakly Interacting Slim Particles (WISPs) are searched for by

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



(a) ALPS-I

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



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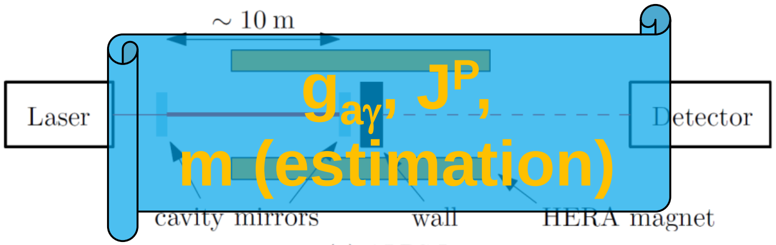

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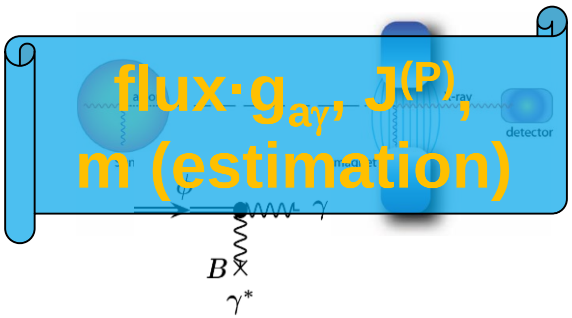
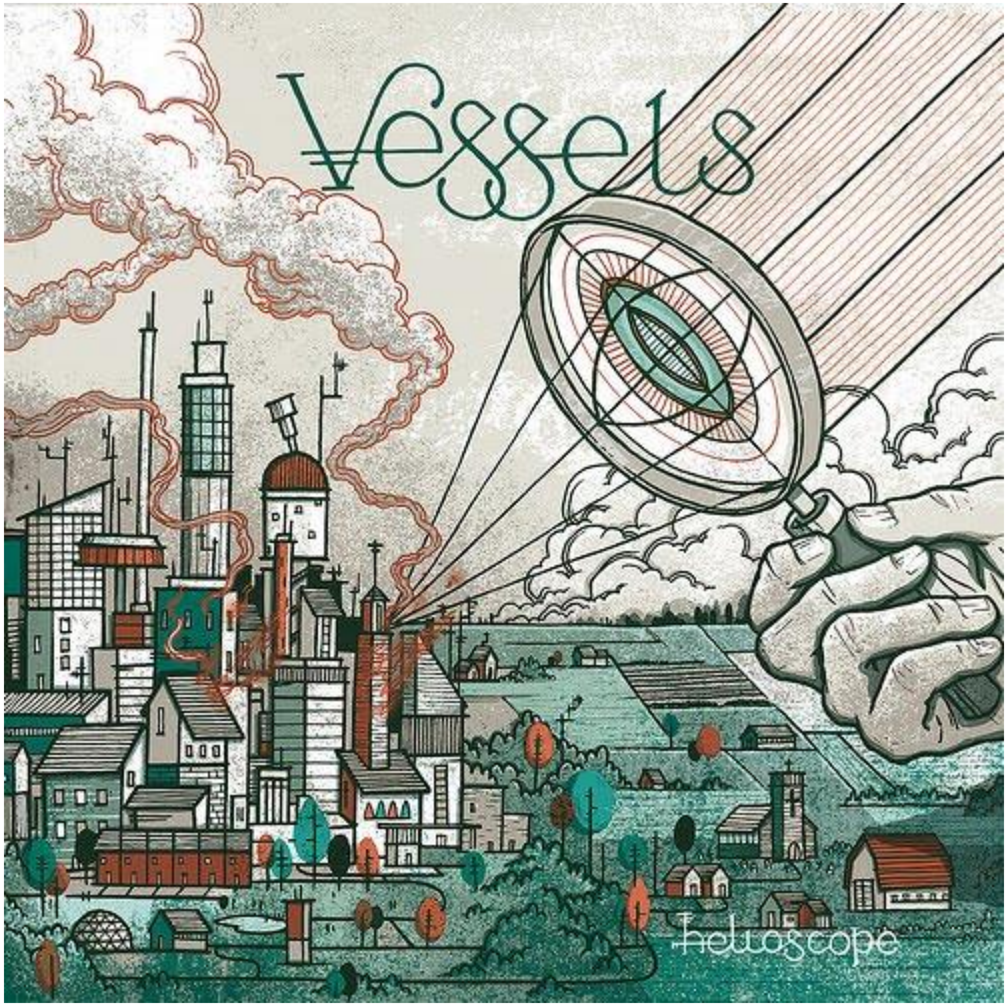


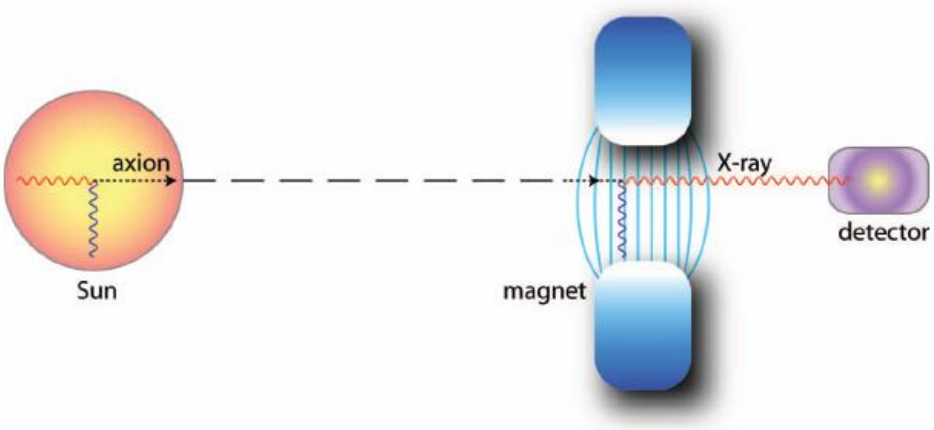
Helioscopes

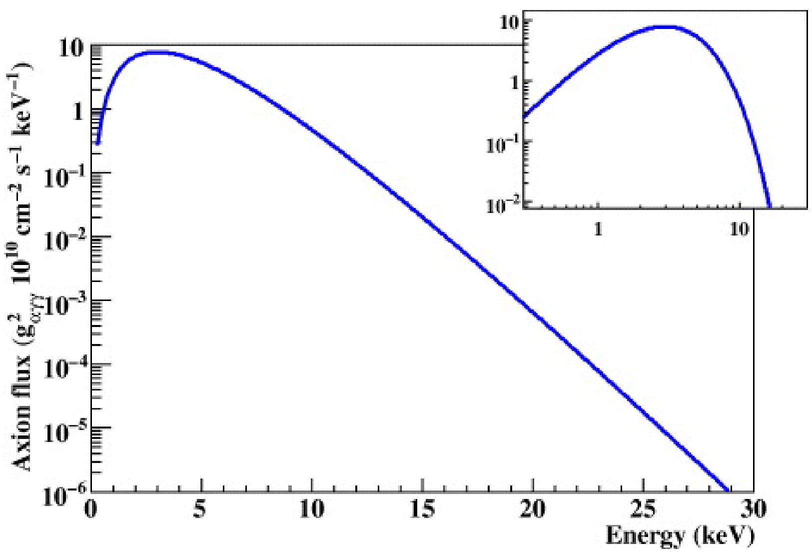


http://middleboop.blogspot.de/2011/02/vessels-helioscope.html

CAST: the dominating helioscope

- “Just” point a magnet to the sun!



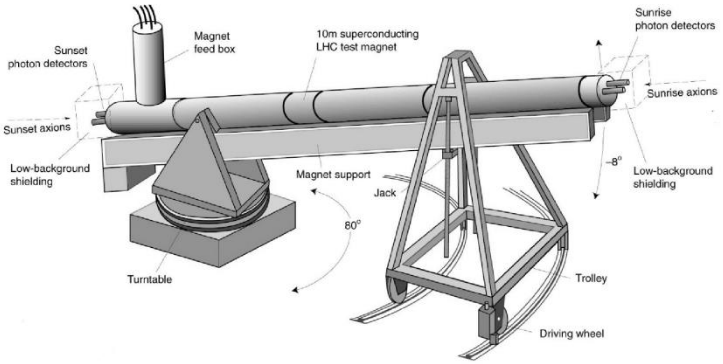


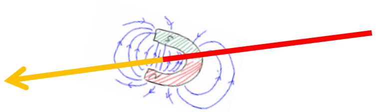
Axions or ALPs from the center of the sun would come with X-ray energies.

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

CAST: the dominating helioscope

> LHC prototype magnet pointing to the sun.





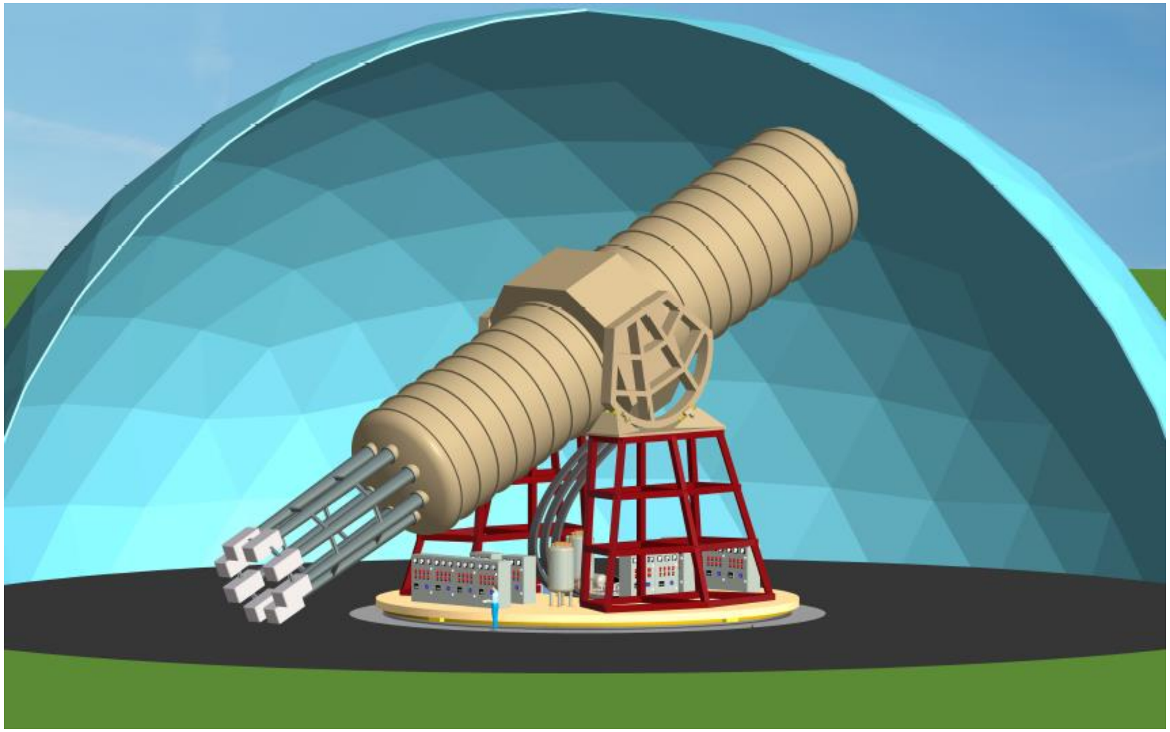
> Most sensitive experiment searching for axion-like particles.

- Unfortunately no hints for WISPs yet.
- If a WISP is found, it would be compatible with known solar physics!

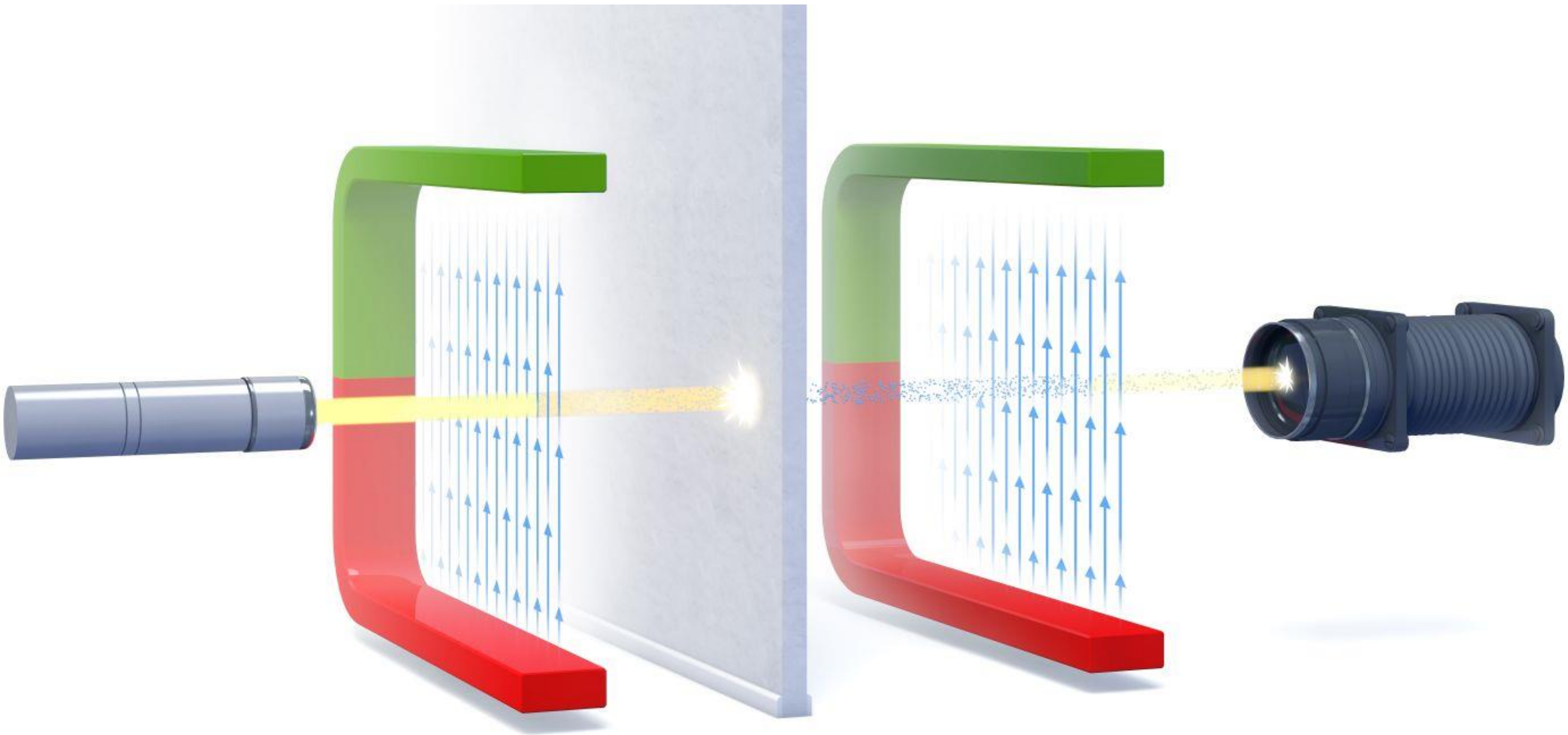
IAXO proposal

> The International Axion Observatory

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



Laboratory experiments



A brief primer on

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- > Searches for WISPs
- > **Plans for WISPs at DESY: ALPS II**
- > **Summary**

ALPS @ DESY in Hamburg

ALPS I at DESY in Hamburg

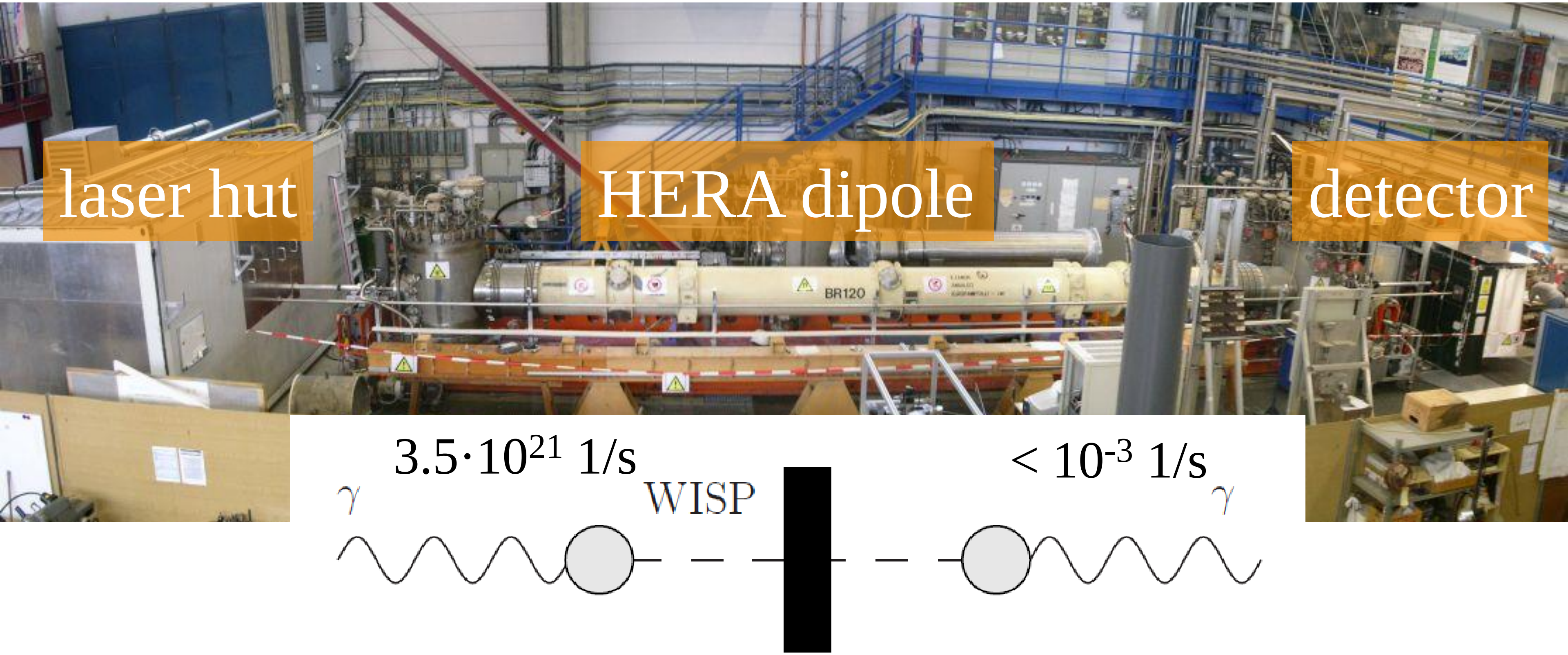
Any Light Particle Search @ DESY: ALPS I

Approved in 2007, concluded in 2010

ALPS I results

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

- Unfortunately, no light was shining through the wall!



- The most sensitive WISP search experiment in the laboratory (up to 2014).

Prospects for ALPS II @ DESY

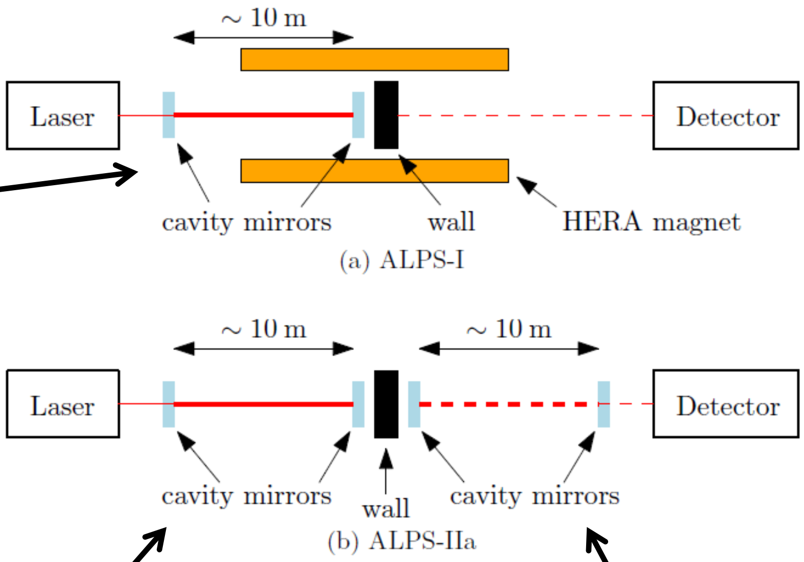
- Laser with optical cavity to recycle laser power, switch from 532 nm to 1064 nm, increase effective power from 1 to 150 kW.
- Magnet:
  upgrade to 10+10 straightened HERA dipoles instead of ½+½ used for ALPS I.
- Regeneration cavity to increase WISP-photon conversions, single photon counter (superconducting transition edge sensor).

All set up in a clean environment!

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

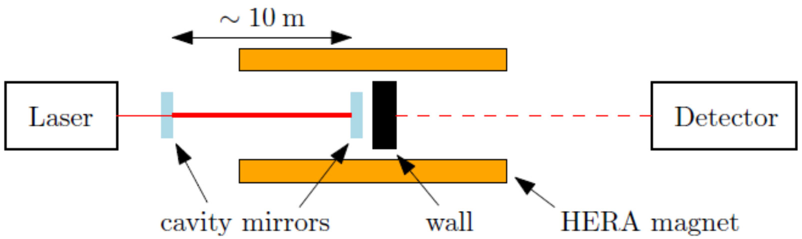
Optical resonator to increase the conversion probability

WISP→γ

First realization of a 24 year old proposal!

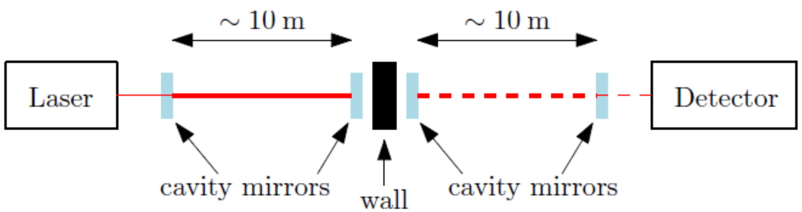
ALPS II is realized in stages

ALPS I



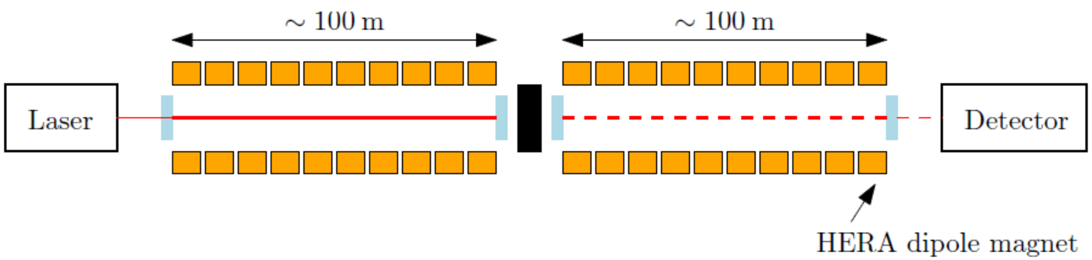
(a) ALPS-I

> **ALPS IIa**



(b) ALPS-IIa

> **ALPS IIc**



(d) ALPS-IIc

The ALPS II challenge

- Photon regeneration probability:

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

- ALPS II:
  - F_{PC} = 5000, F_{RC} = 40000 (power build-up in the optical resonators)
  - B = 5.3 T, l = 88 m

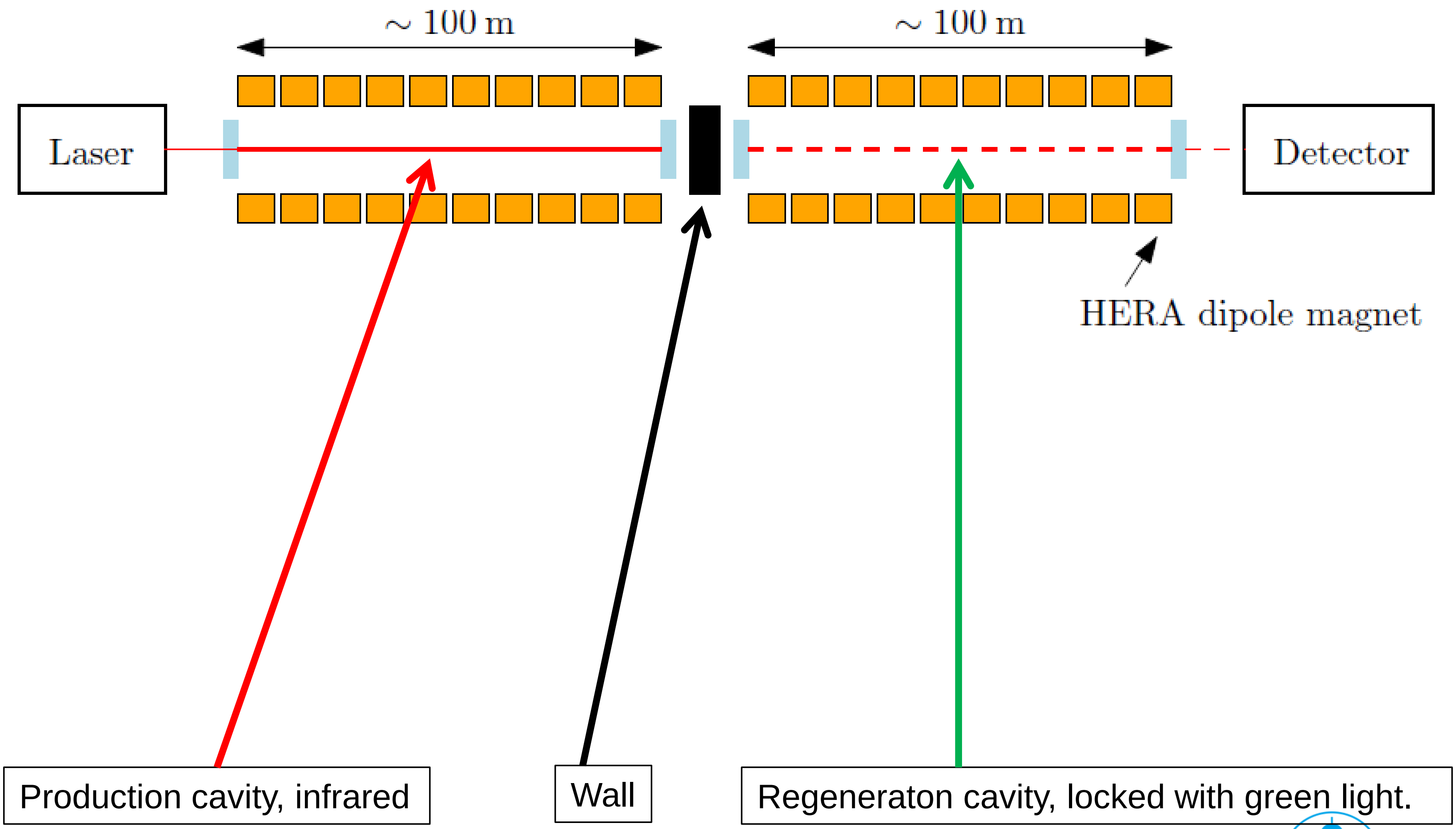
  $P_{\gamma\to\phi\to\gamma}$ = $6\cdot10^{-23}$ for g=10^{-10}GeV^{-1} resp. $6\cdot10^{-27}$ for g=10^{-11}GeV^{-1}

  - With a laser power of 35 W (1064 nm):

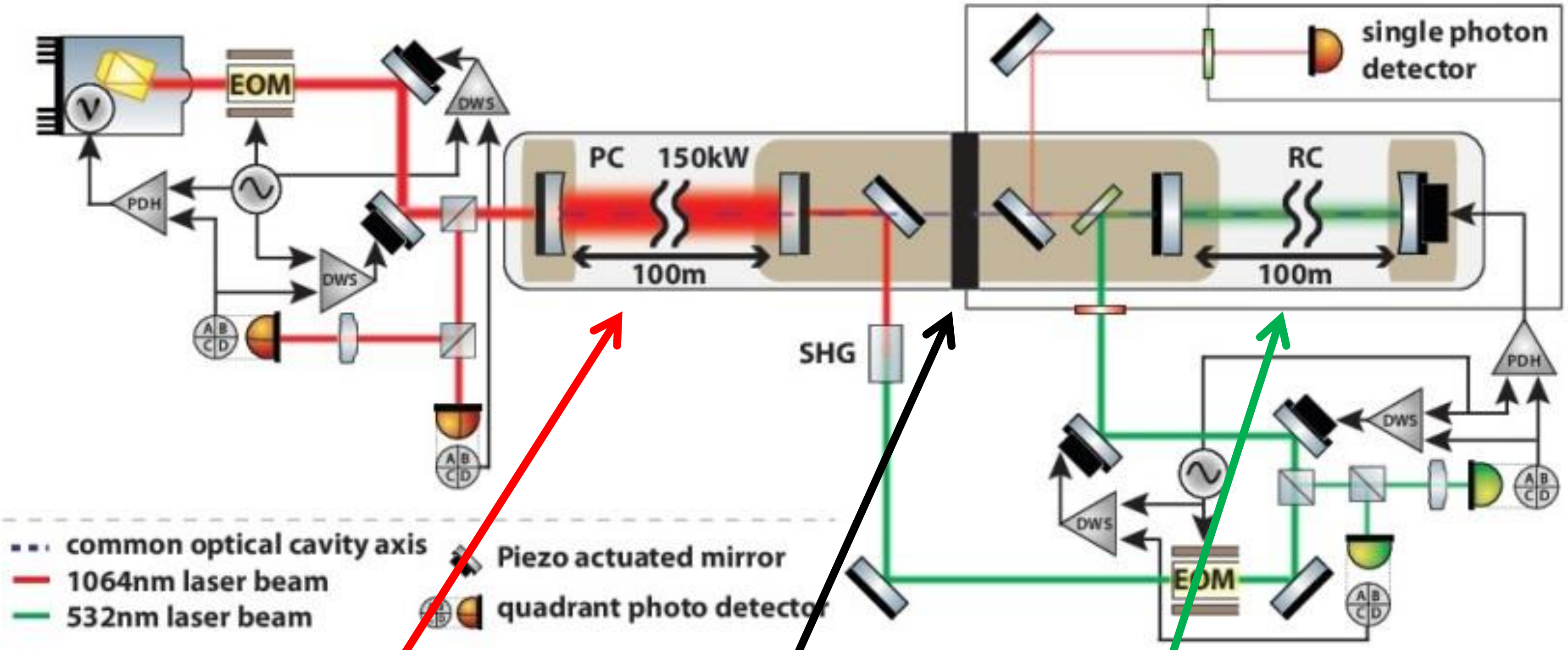
  expected photon rates:
  dn/dt = 30 h^{-1} for g=10^{-10}GeV^{-1} resp. 3 month^{-1} for g=10^{-11}GeV^{-1}

- ALPS II will probe the ALP region indicated by astrophysics phenomena.

ALPS II optics



ALPS II optics

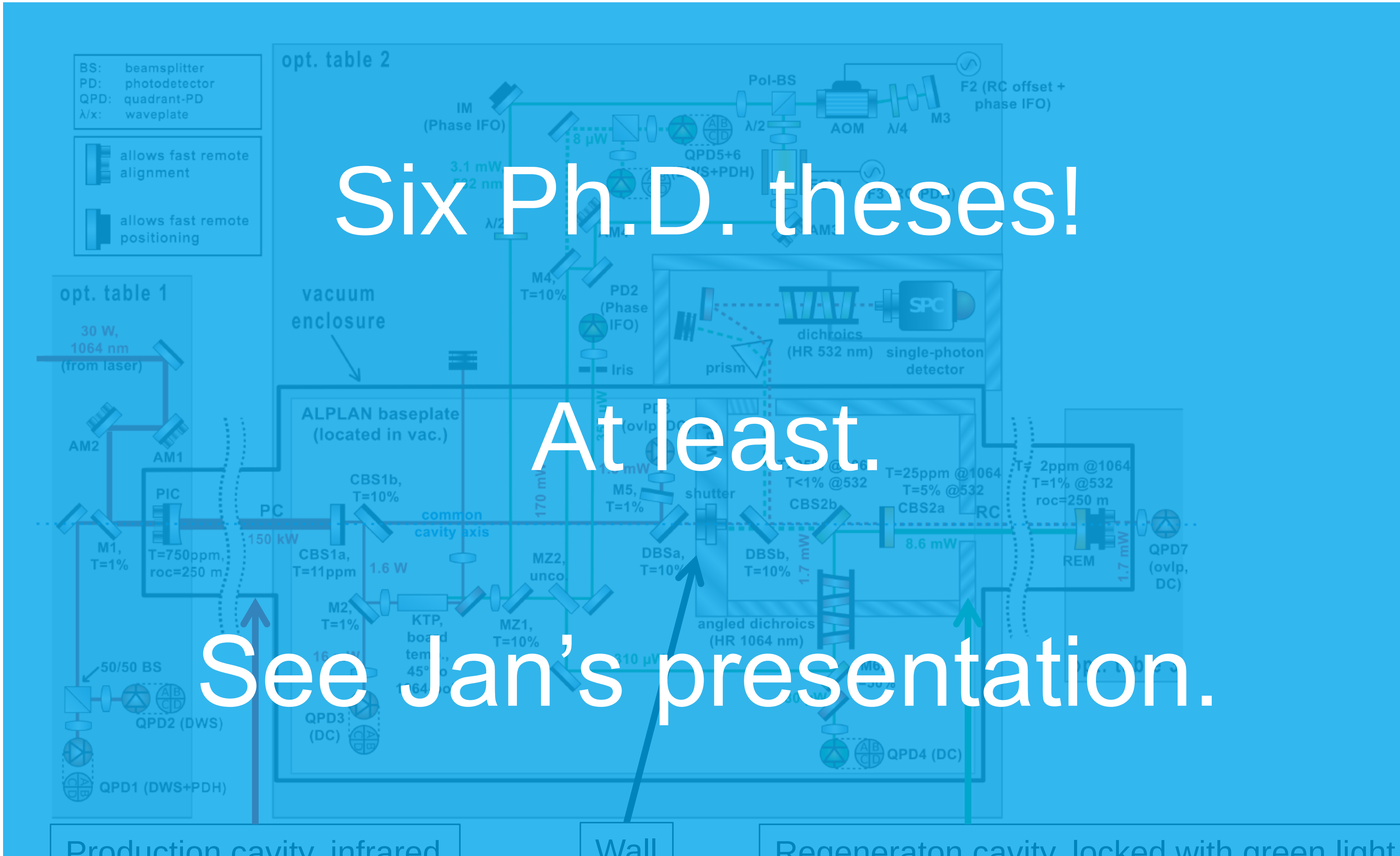


Production cavity, infrared

Wall

Regeneraton cavity, locked with green light.

ALPS II optics



Six Ph.D. theses!

At least.

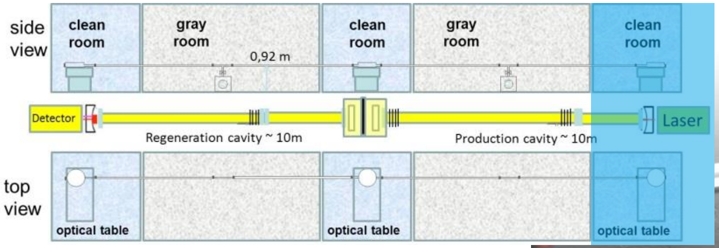
See Jan's presentation.

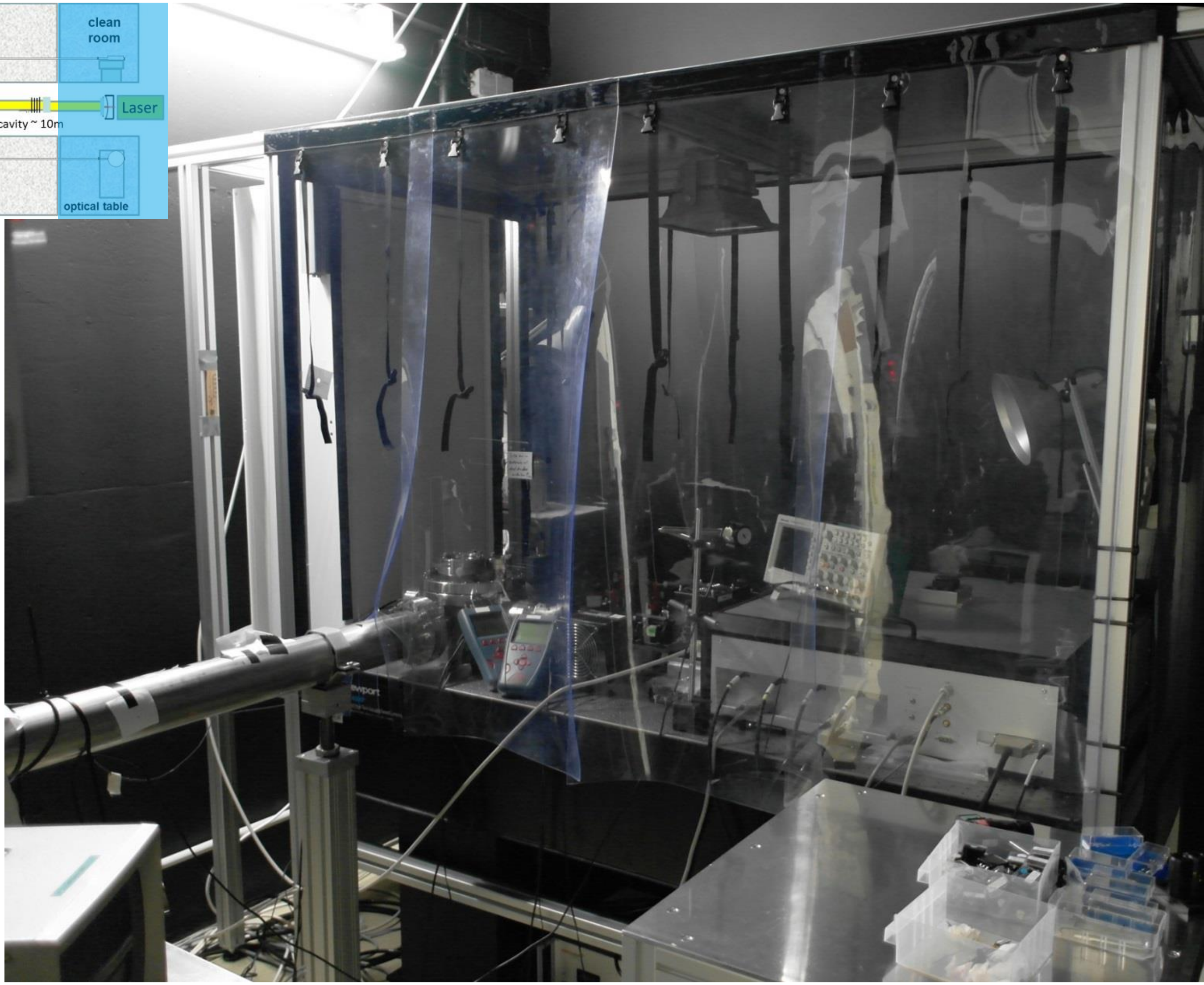
Production cavity, infrared

Wall

Regeneraton cavity, locked with green light.

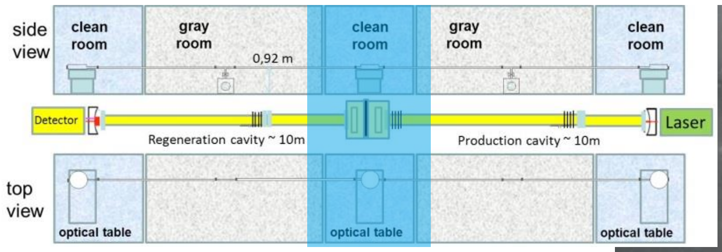
The photon source

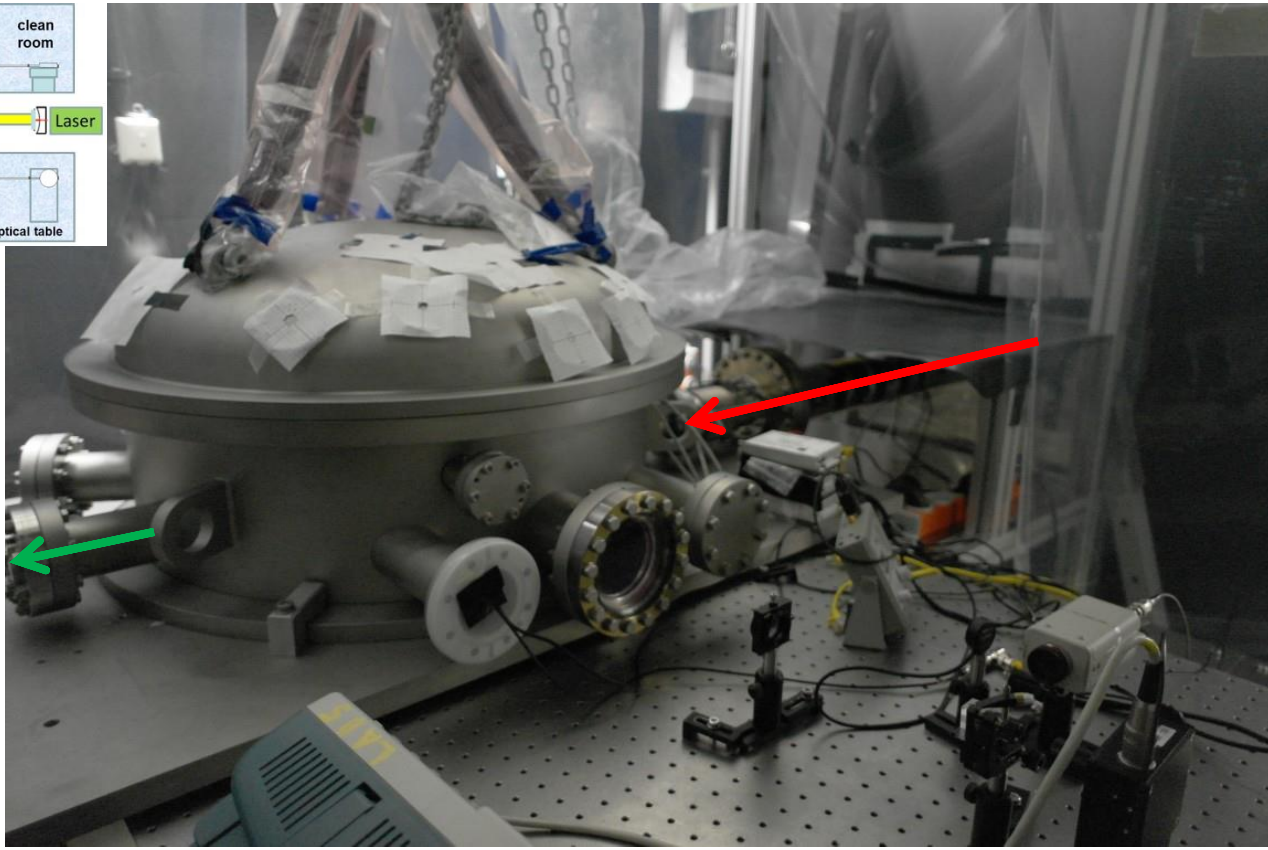




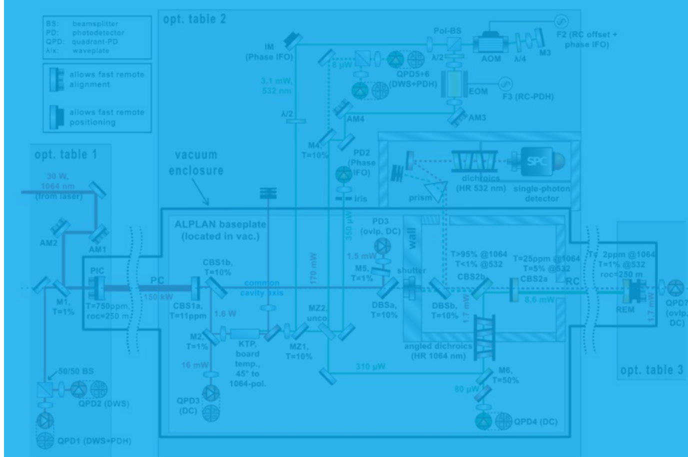
The laser has been developed for LIGO:
35 W, 1064 nm, M^2<1.1
based on
2 W NPRO by Innolight/Mephisto (Nd:YAG (neodymium-doped yttrium aluminium garnet)

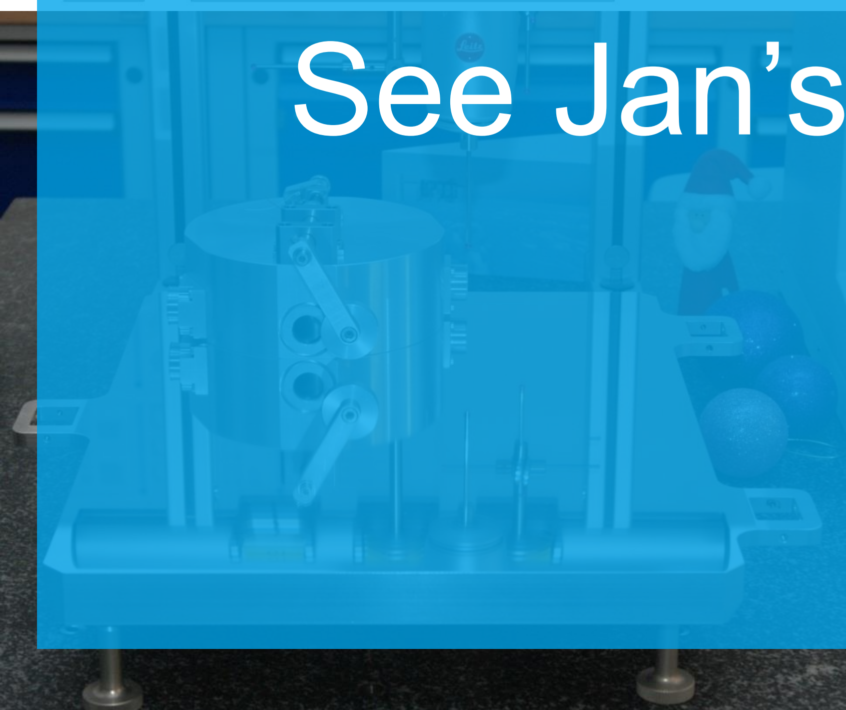
The central optics





The central optics breadboard

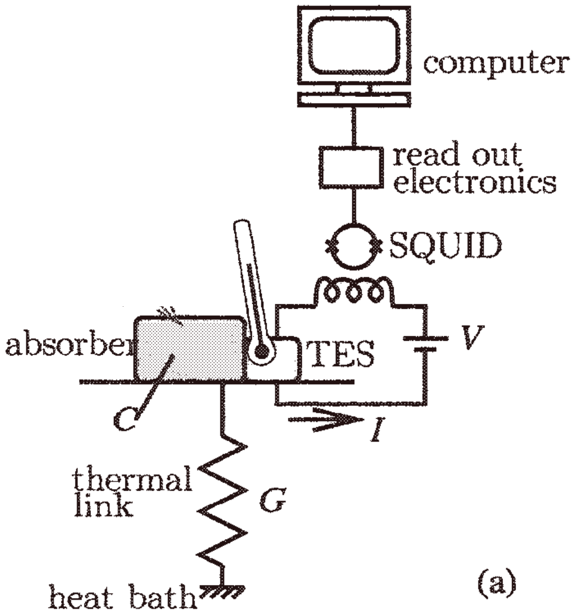




See Jan’s presentation.

ALPS II detector

Transition Edge Sensor (TES)



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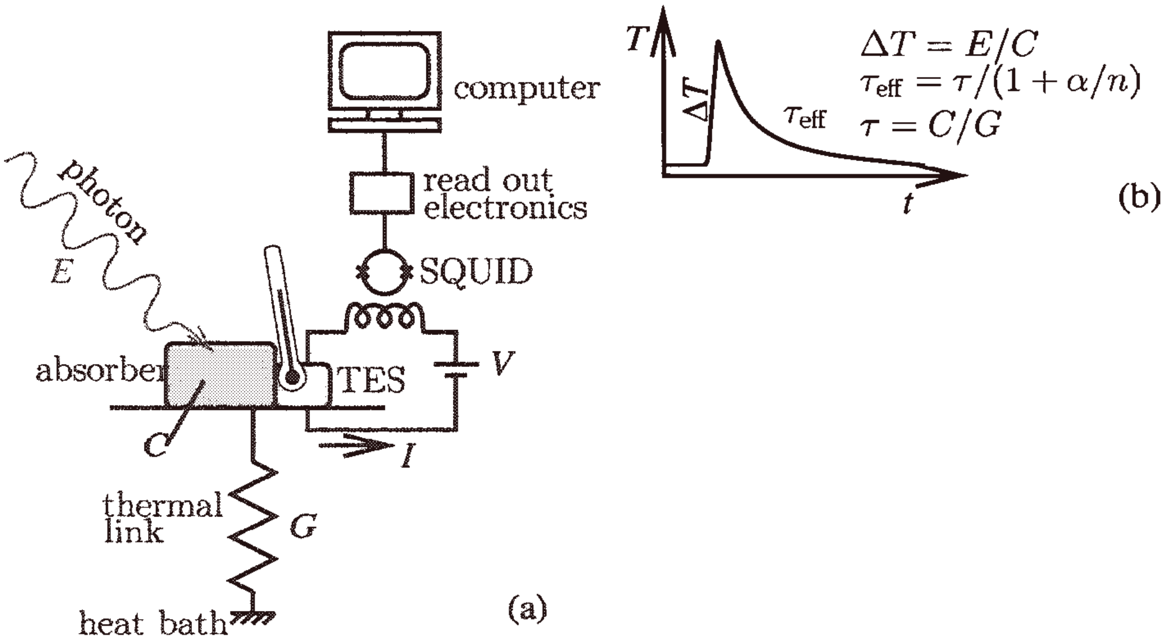

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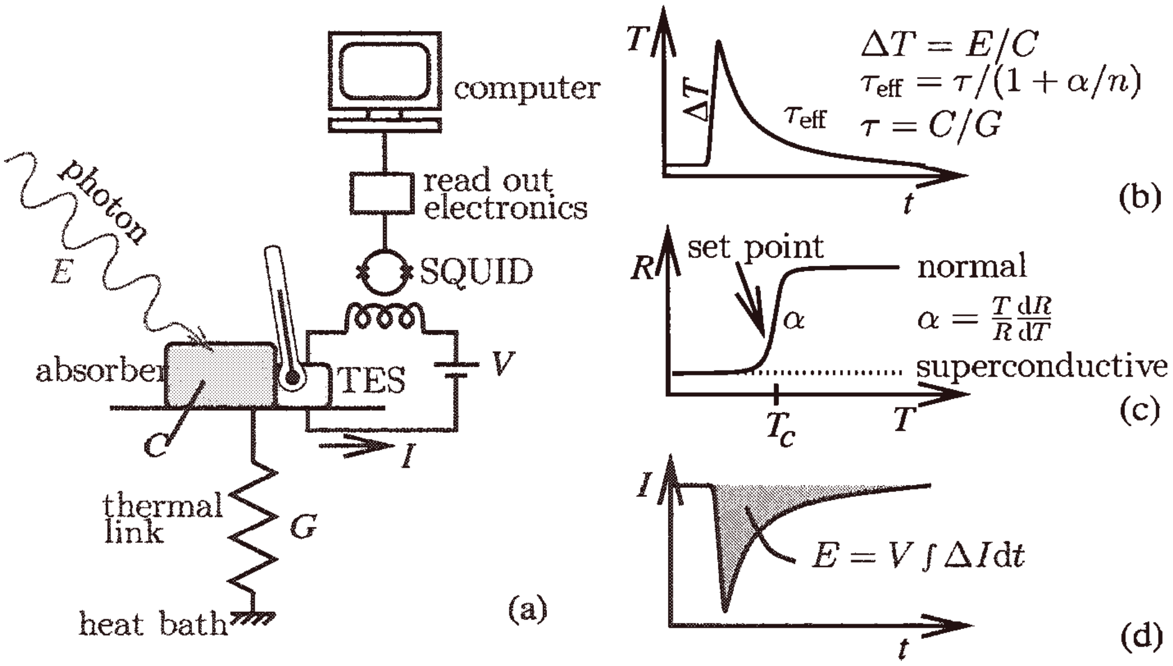

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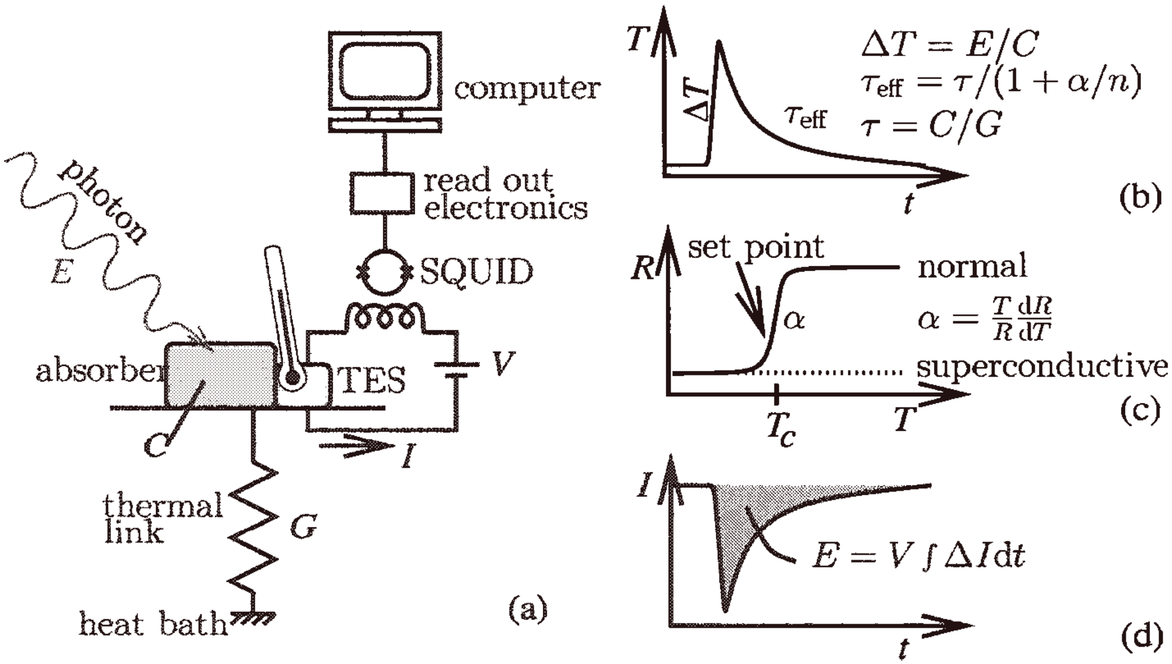
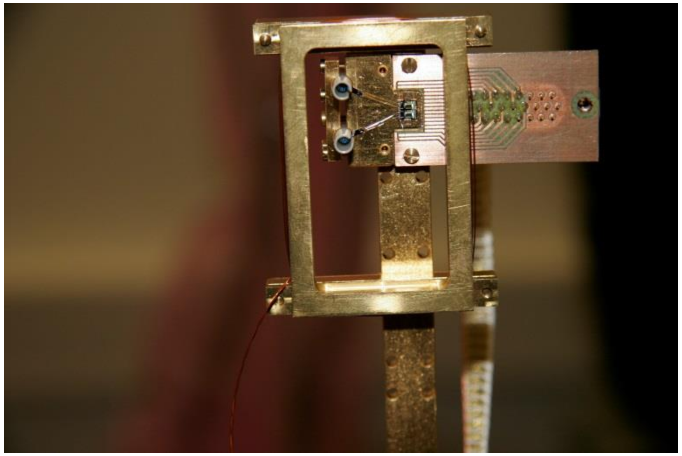
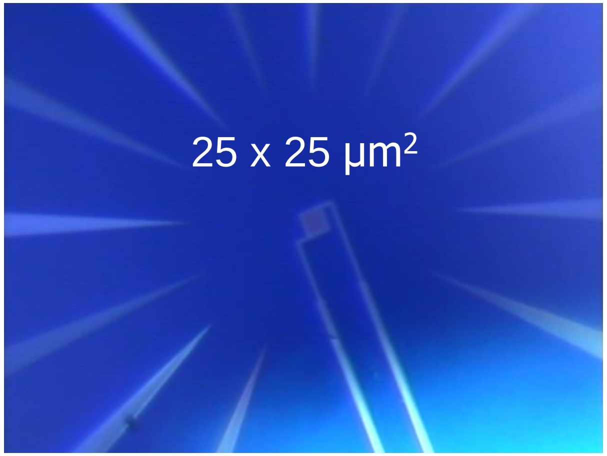
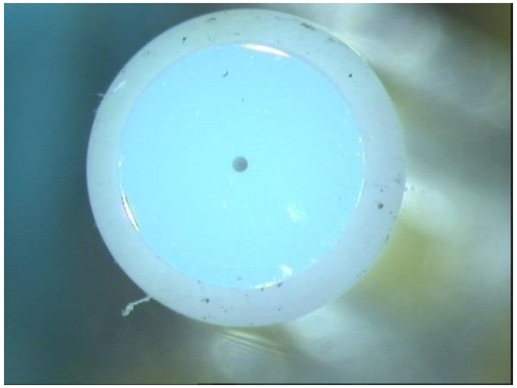


> Expectation:
very high quantum efficiency, also at 1064 nm,
very low noise.

ALPS II: Transition Edge Sensor (TES)







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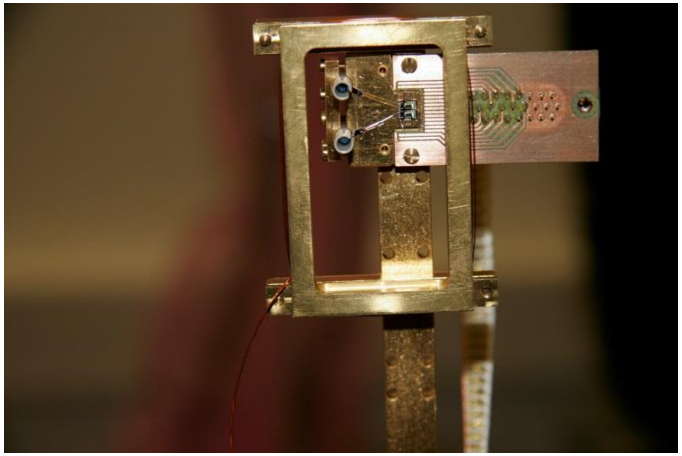
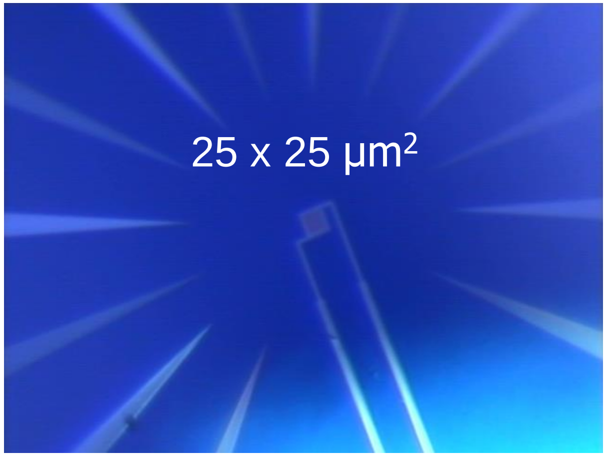
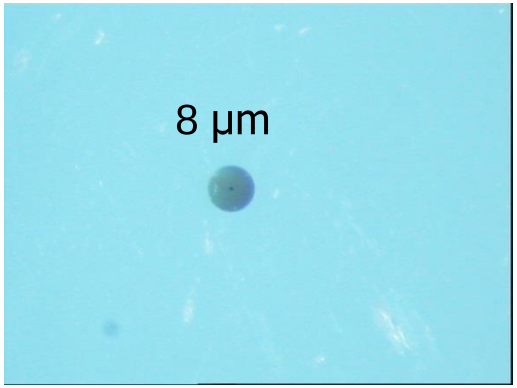
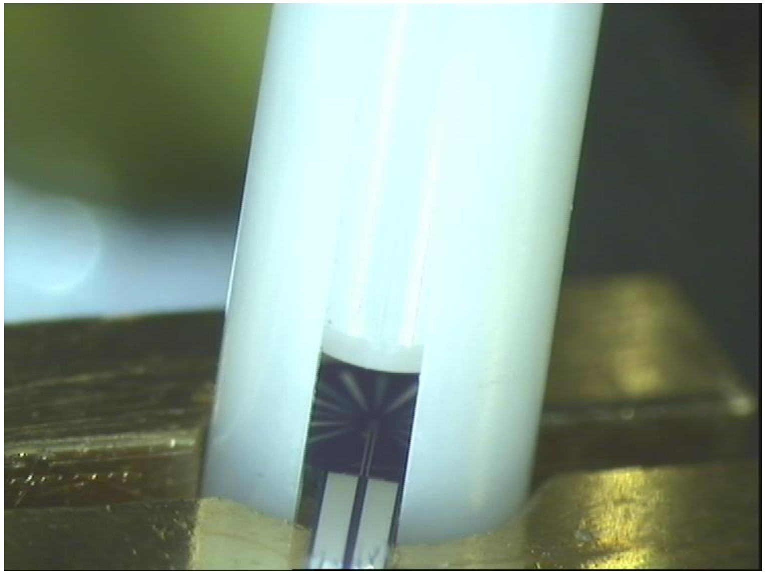
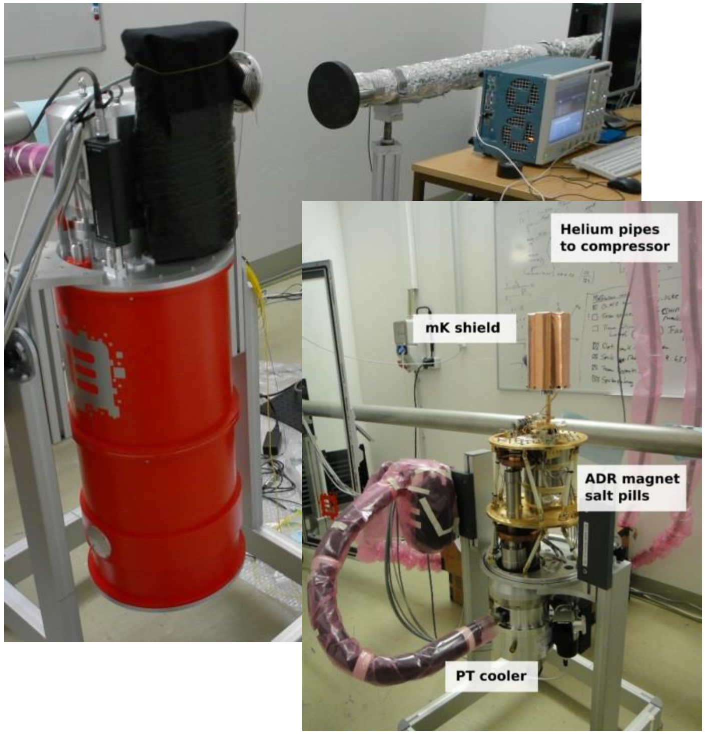




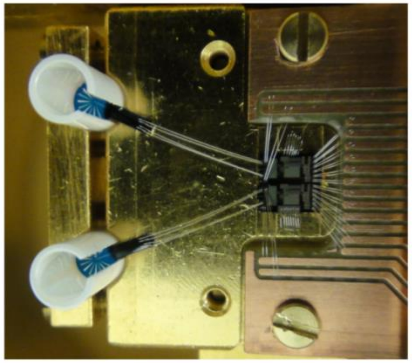




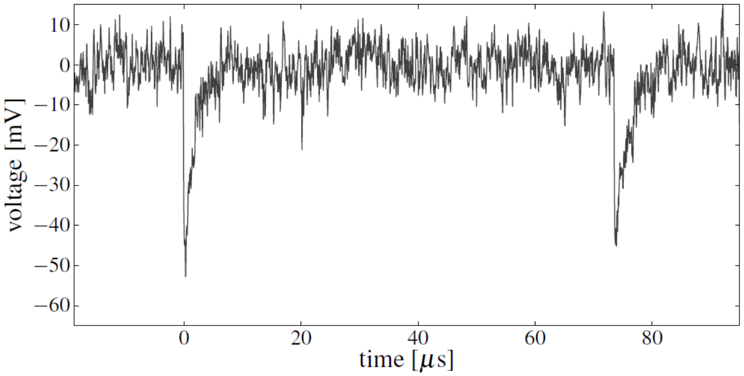
ALPS II: Transition Edge Sensor (TES)



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



- Tungsten film kept at the transition to superconductivity at 80 mK.
- Sensor size 25µm x 25µm x 20nm.



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

ALPS II: Transition Edge Sensor (TES)

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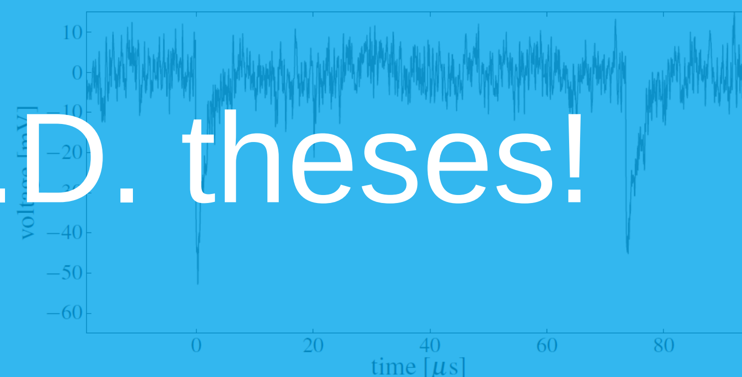

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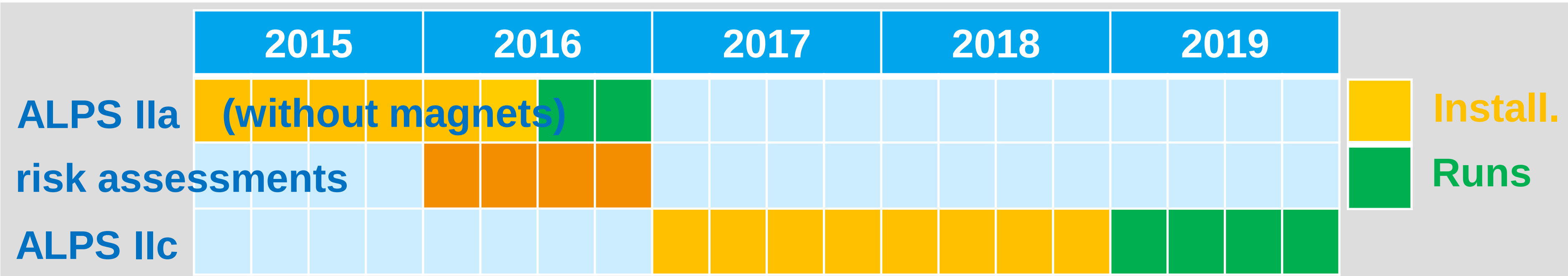
Four Ph.D. theses!

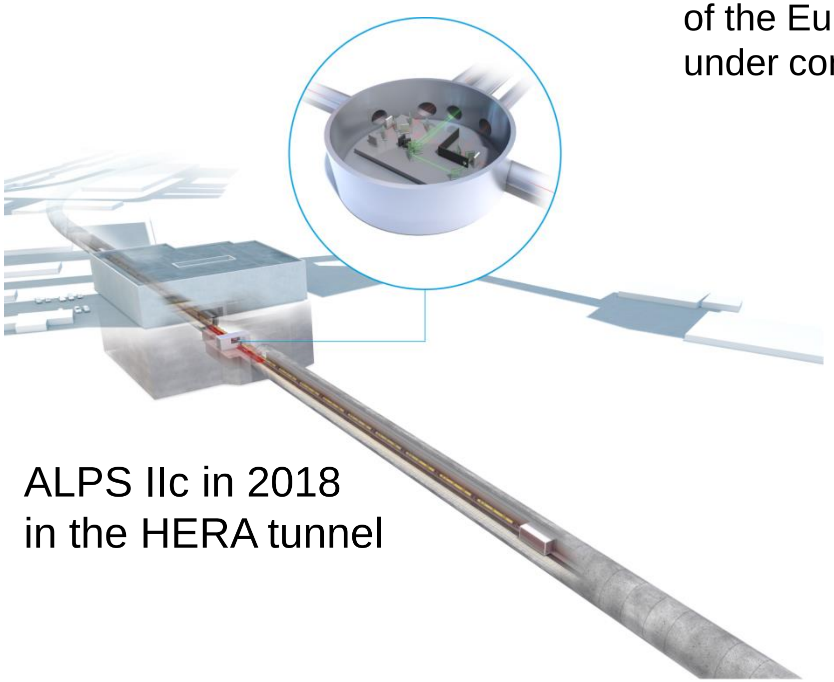
At least.

DESY

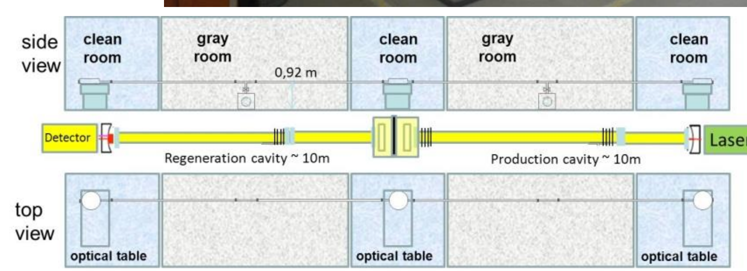
ALPS II schedule (rough)



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



ALPS IIc in 2018 in the HERA tunnel



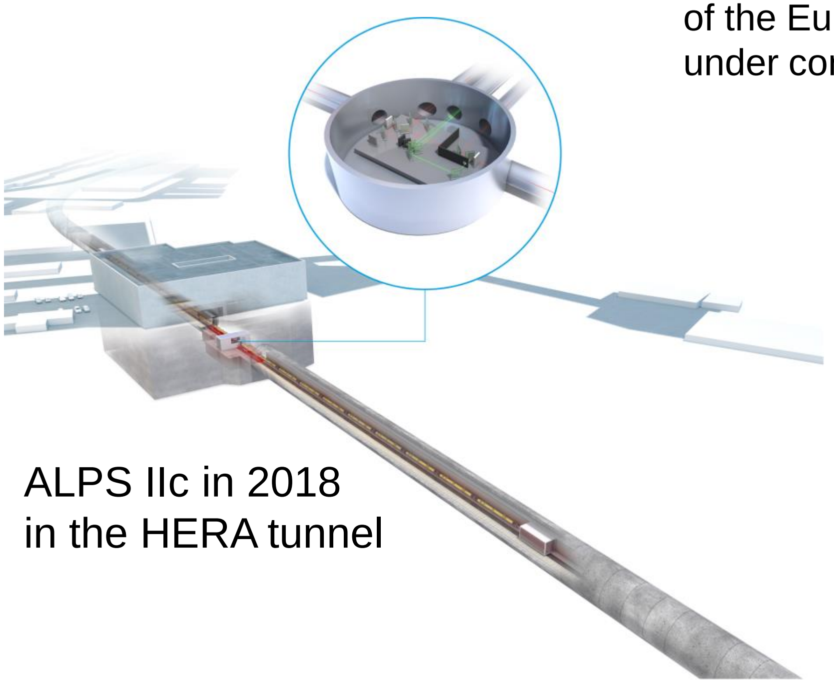
ALPS II schedule (rough)

	2015	2016	2017	2018	2019
ALPS IIa	(without magnets)				
risk assessments					
ALPS IIc					

Install.
Runs

Option for an intermediate stage at CERN?

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



ALPS IIc in 2018
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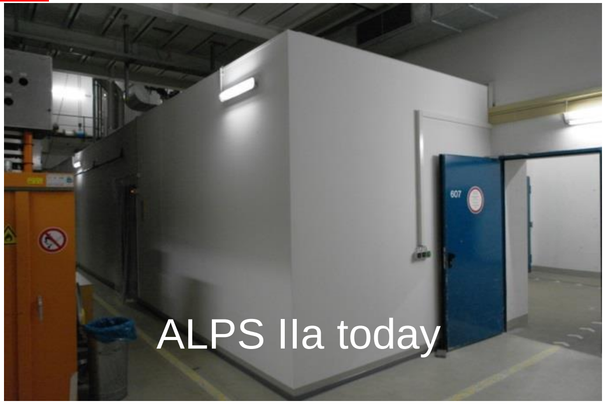
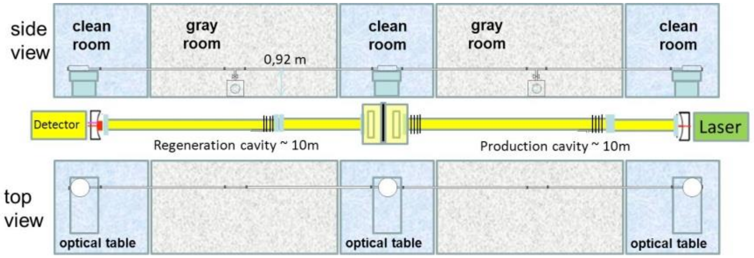
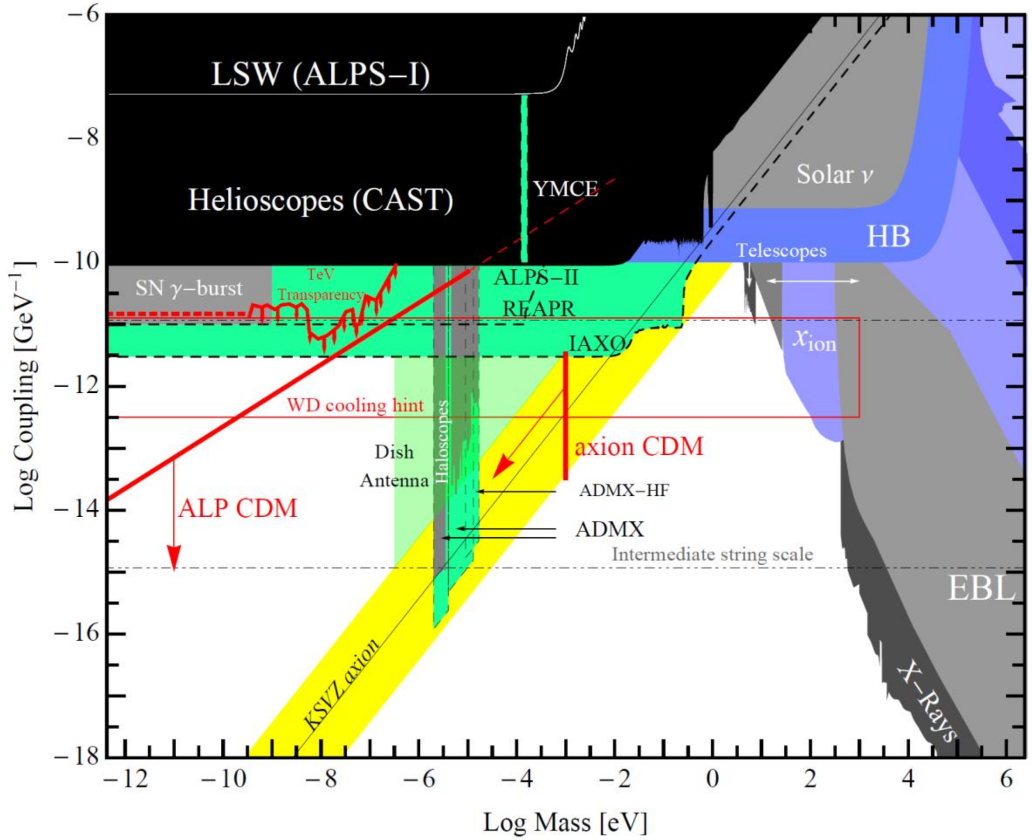


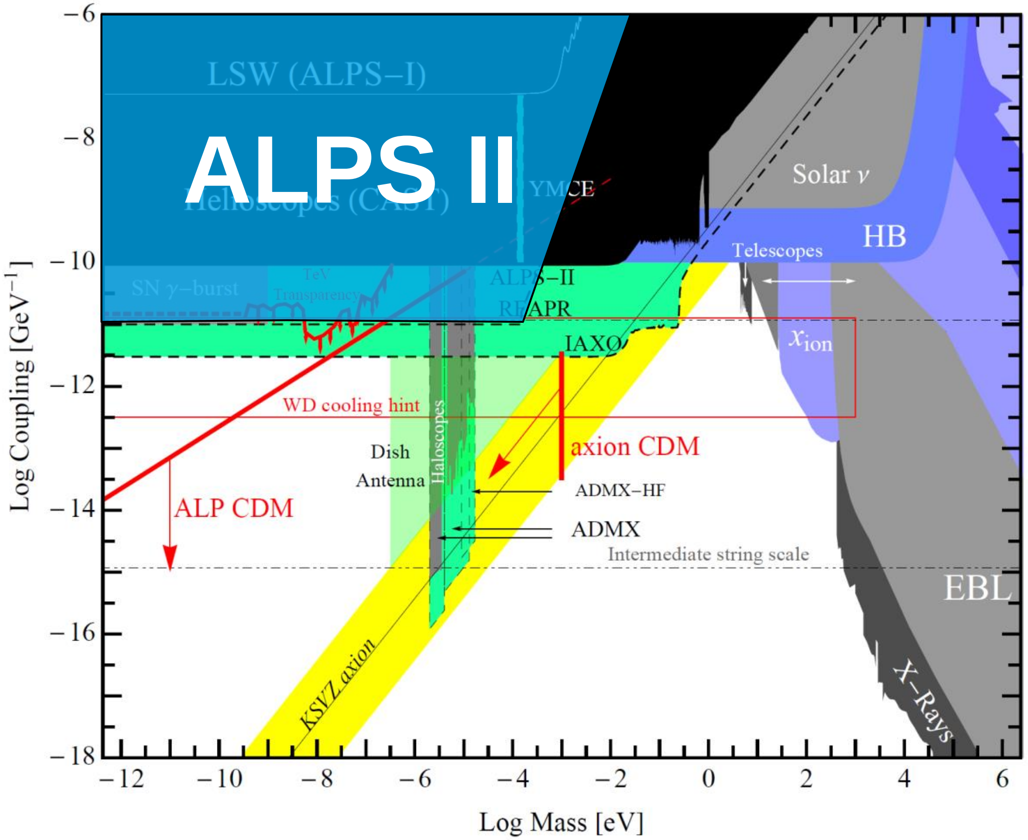


The axion-like particle landscape



ALPS II sensitivity

- Well beyond current limits.
- Aim for data taking in 2019.
- QCD axions not in reach.
- Able to probe hints from astrophysics.
- The ALPS optics+detector combined with two LHC-dipoles could reach (9T·14.3m) / (10·5.3T·8.8m) = 30% of the ALPS II sensitivity allowing to just surpass CAST (if we are lucky).



The ALPS collaboration

ALPS II is a joint effort of

- DESY,
- Hamburg University,
- AEI Hannover
(MPG & Hannover Uni.),
- Mainz University,
- University of Florida
(Gainesville)

with strong support from

- neoLASE, PTB Berlin, NIST (Boulder).

Summary

- The axion "invented" to explain the CP-conservation in QCD is also a perfect and extremely lightweight cold dark matter candidate.
- 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.
  - Astrophysics phenomena might point at the existence of WISPs.
- Experiments like ALPS II have sufficient sensitivity to discover axion-like particles or other WISPs.
- New ideas for dark matter experiments are being tested.
- 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!

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Ann. Phys. (Berlin), 1–7 (2013) / DOI 10.1002/andp.201300727

annalen der physik

The quest for axions and other new light particles

K. Baker[1], G. Cantatore[2], S. A. Cetin[3], M. Davenport[4], K. Desch[5], B. Döbrich[6,], H. Gies[7], I. Irastorza[8], J. Jaeckel[9], A. Lindner[6], T. Papaevangelou[10], M. Pivovaroff[11], G. Raffelt[12], J. Redondo[12], A. Ringwald[6], Y. Semertzidis[13], A. Siemko[4], M. Sulc[13], A. Upadhye[14], and K. Zioutas[15]*

DESY