Experimental WISP searches

Dark matter and dark matter candidate searches for Axions, ALPs and other WISPs

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DESY

Challenges in the Dark Sector, Laboratori Nazionali di Frascati, 16 December 2015

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Disclaimer

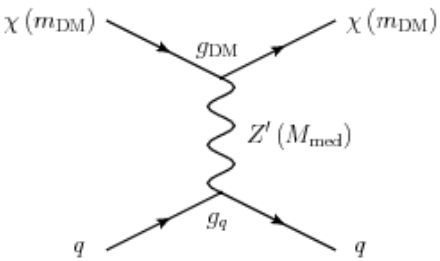
This presentation focuses mainly on hypothetical

very *Weakly Interacting and very lightweight Sub-eV Particles (WISPs),*

which are viable dark matter constituents.

Searches for hypothetical

dark mediators,



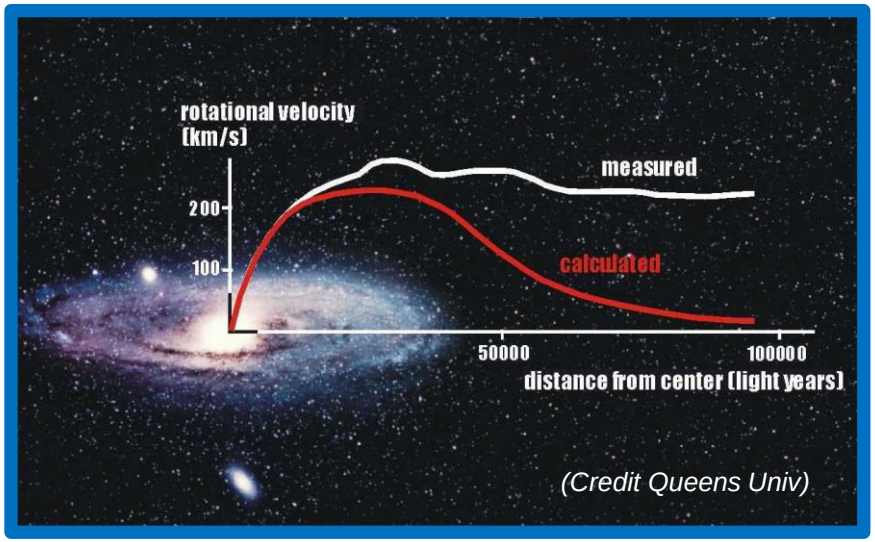
which care for self-interacting dark matter and/or dark matter couplings to SM constituents, will be covered by Felix Kalhöfer on Thursday.

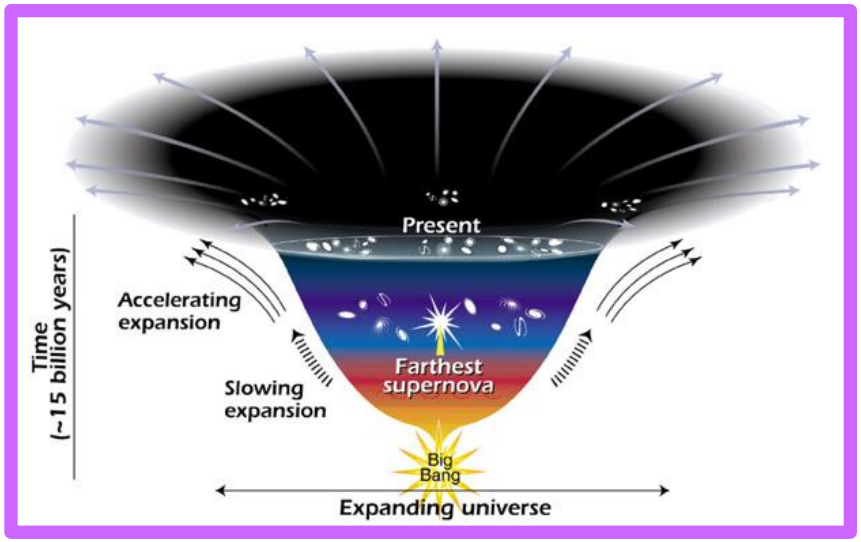
The WISP program of this session

- Dark matter and dark matter candidates
- Axions and other WISPs
- Dark matter search options
- Dark matter candidate search options
- Summary

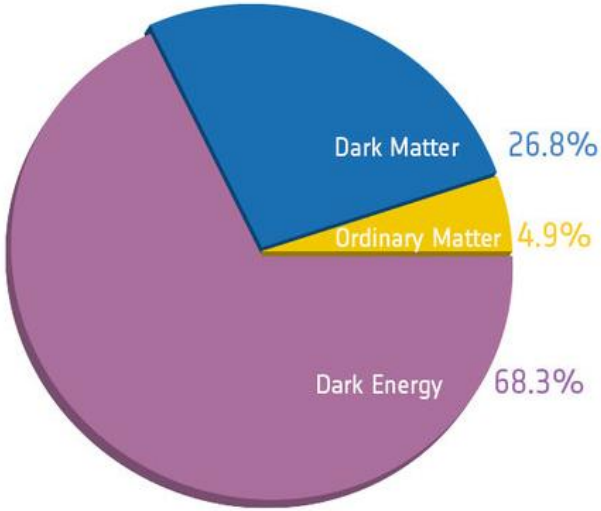
There is physics beyond the SM

- Dark matter and dark energy:





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

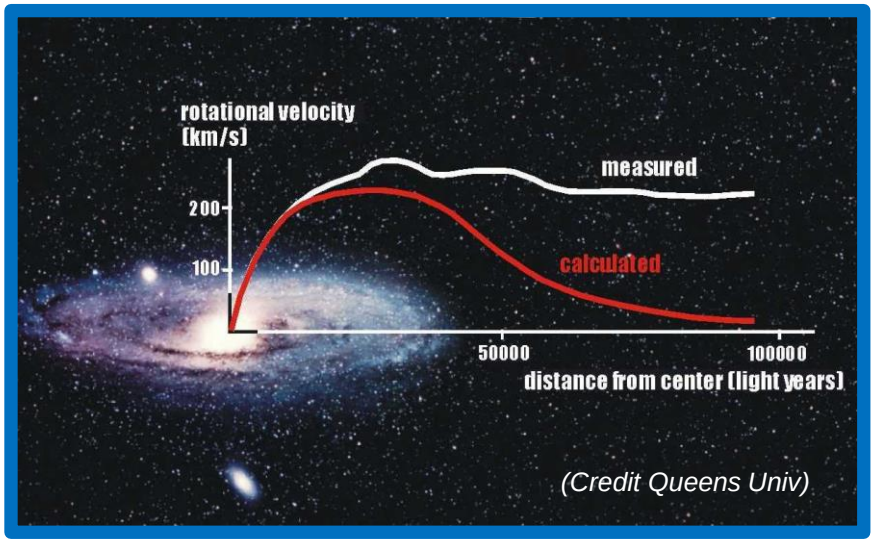


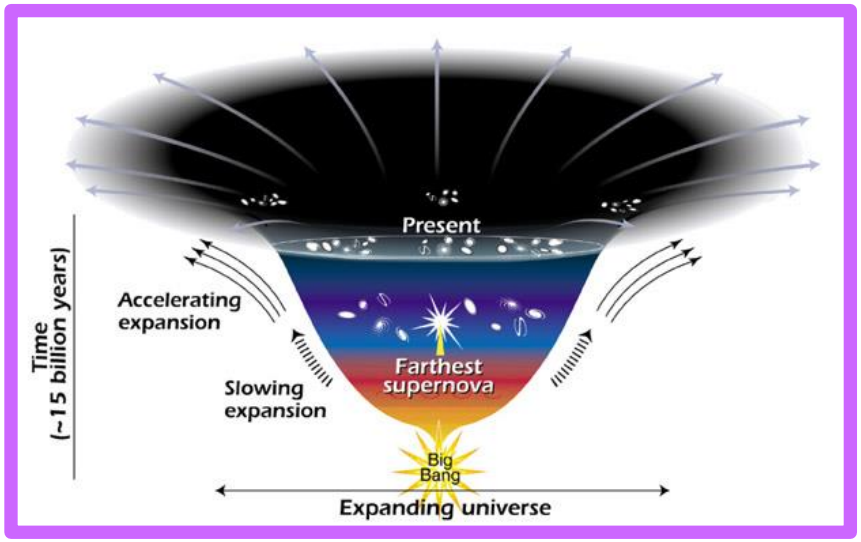
http://www.esa.int/For_Media/Photos/Highlights/Planck

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

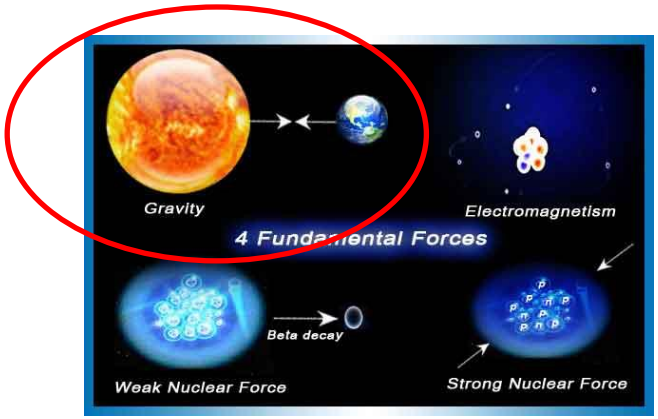
NO HINT ON MASS OF DM CONSTITUENTS!

- Extremely lightweight scalar particle

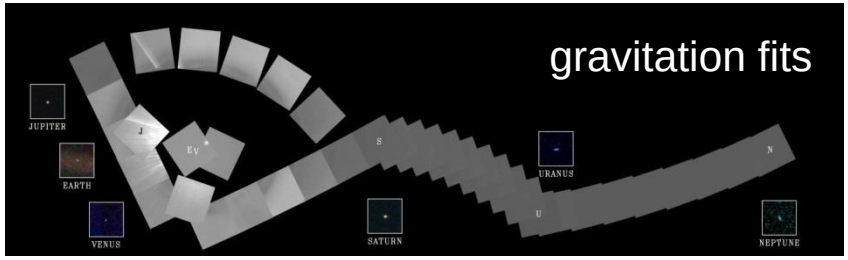
Evidence for dark matter in the universe

Dark matter

- shows up in gravitation only, which is the only interaction not embedded in the standard model.



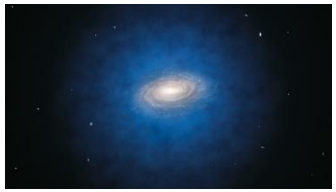
- only shows up in large systems much beyond the scale of the solar system!

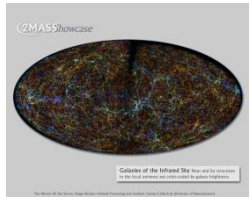


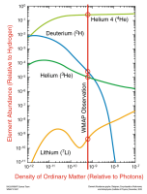
Dark matter properties

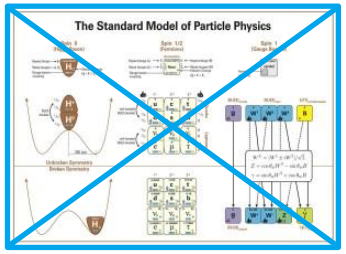
- The dark matter density around us is of about $0.3\ \mathrm{GeV/cm^3} = 5\cdot10^{-25}\ \mathrm{g/cm^3}$
- It has negligible interactions with our "visible" world and negligible self-interaction. The couplings is "weakly" at maximum.
- It is "cold", moving at non-relativistic speeds only.
- It is non-baryonic.
- The dark matter constituents must have a lifetime much longer than the age of the universe.

None of the known particles within the Standard Model fulfills all these requirements!





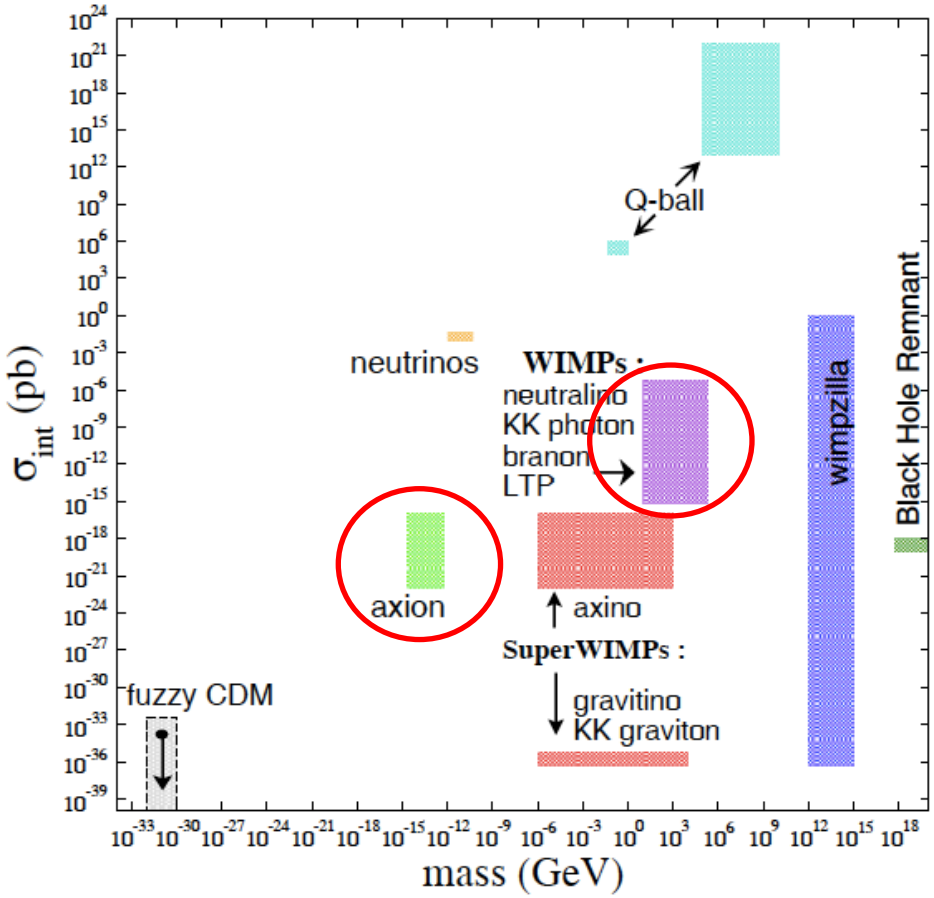




Dark matter candidates: where to focus experimentally?

Selection criteria:

- Are experimental options in reach to either
  - identify dark matter candidates in laboratory experiments,
  - find directly of indirectly the particles composing the dark matter halo we are living in?
- Does the theory explain "just" dark matter or is it embedded in a more general extension of the standard model of particle physics?



Prog.Part.Nucl.Phys. 71 (2013) 167-184 arXiv:1303.4758 [hep-ph]

The WISP program of this session

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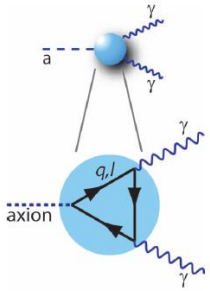
Intoduction to WeaklyInteractingSlimParticles

- In this presentation: WISPs are hypothetical bosons with m < 1eV.
- Axion: a neutral pseudoscalar predicted to explain the CP conservation in QCD. Its physics is determined just by a symmetry breaking scale f_a:
  - Mass: $m_a = 0.6\text{eV} \cdot (10^7\text{GeV} / f_a)$
  - Coupling to two photons: $g_{a\gamma\gamma} = \alpha \cdot g_\gamma / (2\pi \cdot f_a)$
  - Abundancy in the universe: $\Omega_a / \Omega_c \sim (f_a / 10^{12}\text{GeV})^{7/6}$



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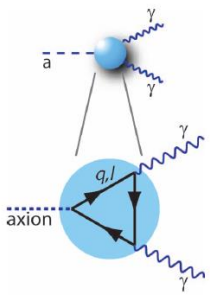

Cold Dark Matter!

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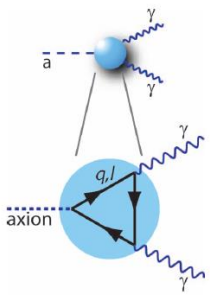
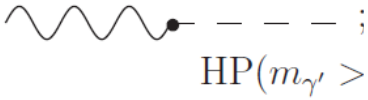


- Axion-like particles (ALPs):
  Coupling strength and mass are not related by one f_a.
- Hidden photons: neutral vector bosons.

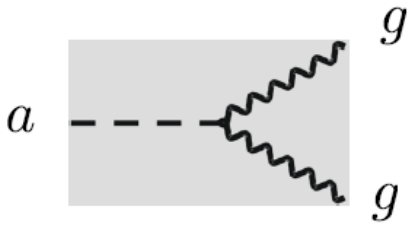


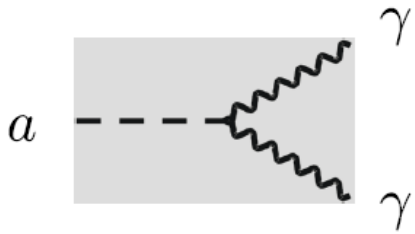
- Mini-charged particles, Chameleons, massive gravity scalars, …
  (some of these might be related to dark energy).

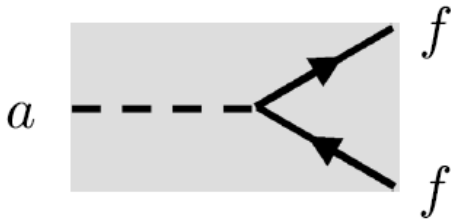
Axion and axion-like-particle (ALP) couplings

- 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.

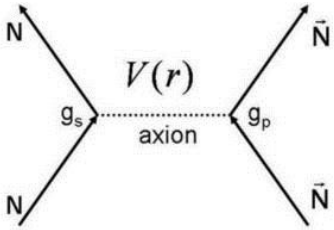
$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C_{ag}}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\partial_\mu a\, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

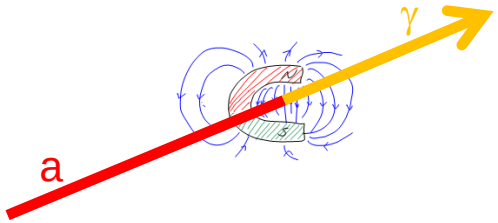


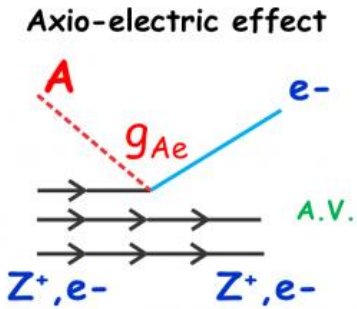




Courtesy A. Ringwald







Recent developments in WISP theory

- Axion cosmology: arXiv:1508.06917 [hep-lat]
  lattice QCD calculations are used to determine the amount of axion Dark Matter today via the temperature dependence of the axion mass.
- Baryon genesis from the axion: Phys.Rev.Lett. 113 (2014) 17, 171803
  this cold genesis requires a coupling of the Higgs to a new scalar with O(100 GeV) mass (to be tested at LHC!).
- A naturally small electroweak scale: arXiv:1506.09217 [hep-ph]
  could be explained by a cosmological Higgs-axion interplay.
  The symmetry breaking scale f_a may be at the same time the see-saw scale explaining the active neutrino masses,
  $m_A \sim m_\nu \sim 1/f_a$, JHEP 1406 (2014) 037

There are viable theoretical models addressing fundamental problems in cosmology and particle physics without predicting any new physics around the electroweak energy scale.

Just WISPs could show up!

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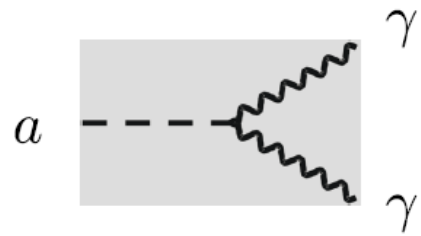
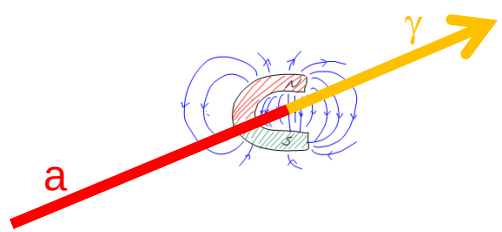




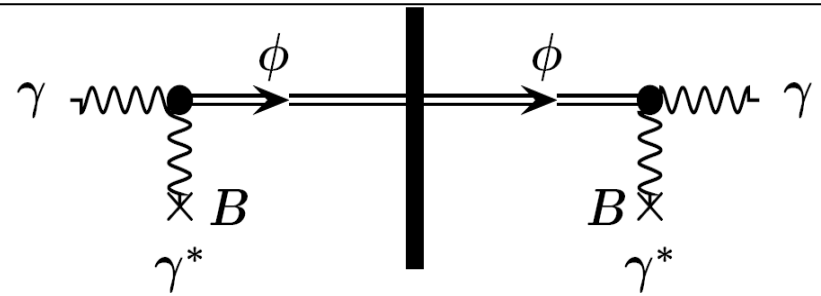
Courtesy A. Ringwald

How to look for WISPs …

… by exploiting their coupling to photons:

> WISPs pass any barrier and could make

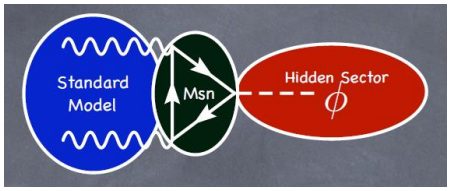
light-shining-through-a-wall.

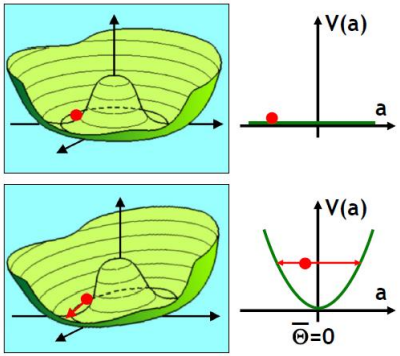


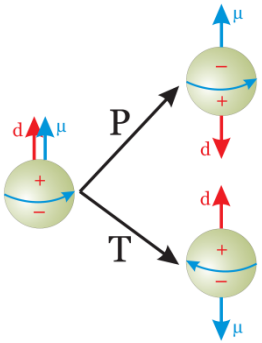
Okun 1982, Skivie 1983, Ansel‘m 1985, Van Bibber et al. 1987

Introducing this session'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.

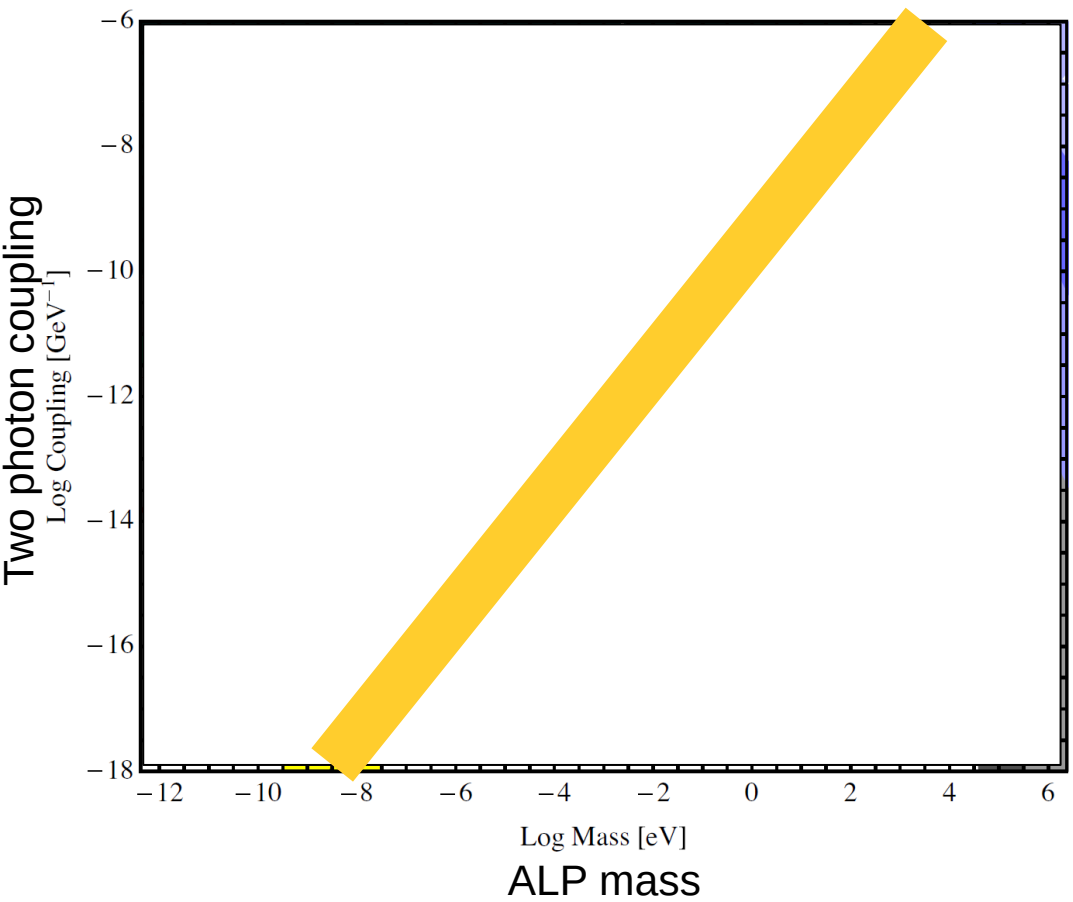






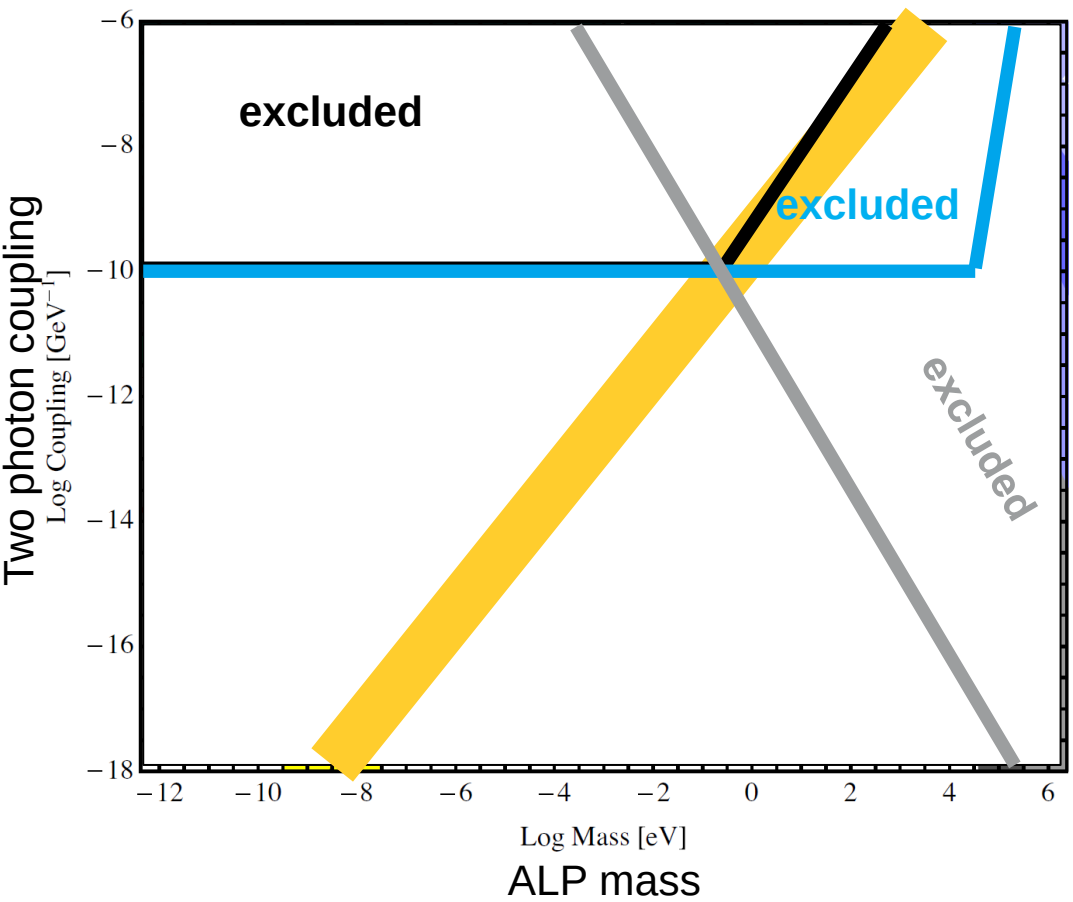
- Prediction:
  Dark matter is composed out of elementary particles with masses below 1 meV. Its number density is larger than 10^{12} 1/cm^3.

The big picture: ALPs (axion & axion-like)



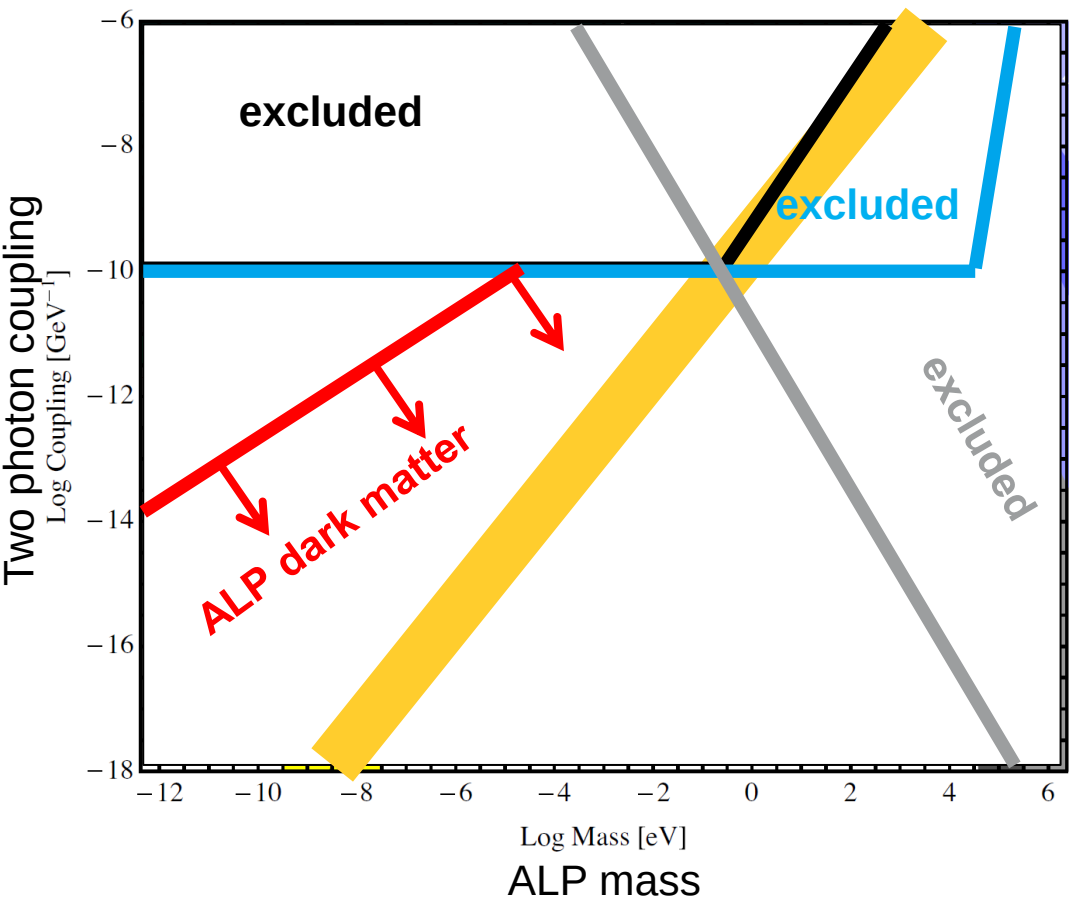
QCD axion range

The big picture: ALPs exclusions



QCD axion range
Excluded by WISP experiments
Excluded by astronomy (ass. ALP DM)
Excluded by astrophysics / cosmology

The big picture: ALPs



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Axions or ALPs being cold dark matter

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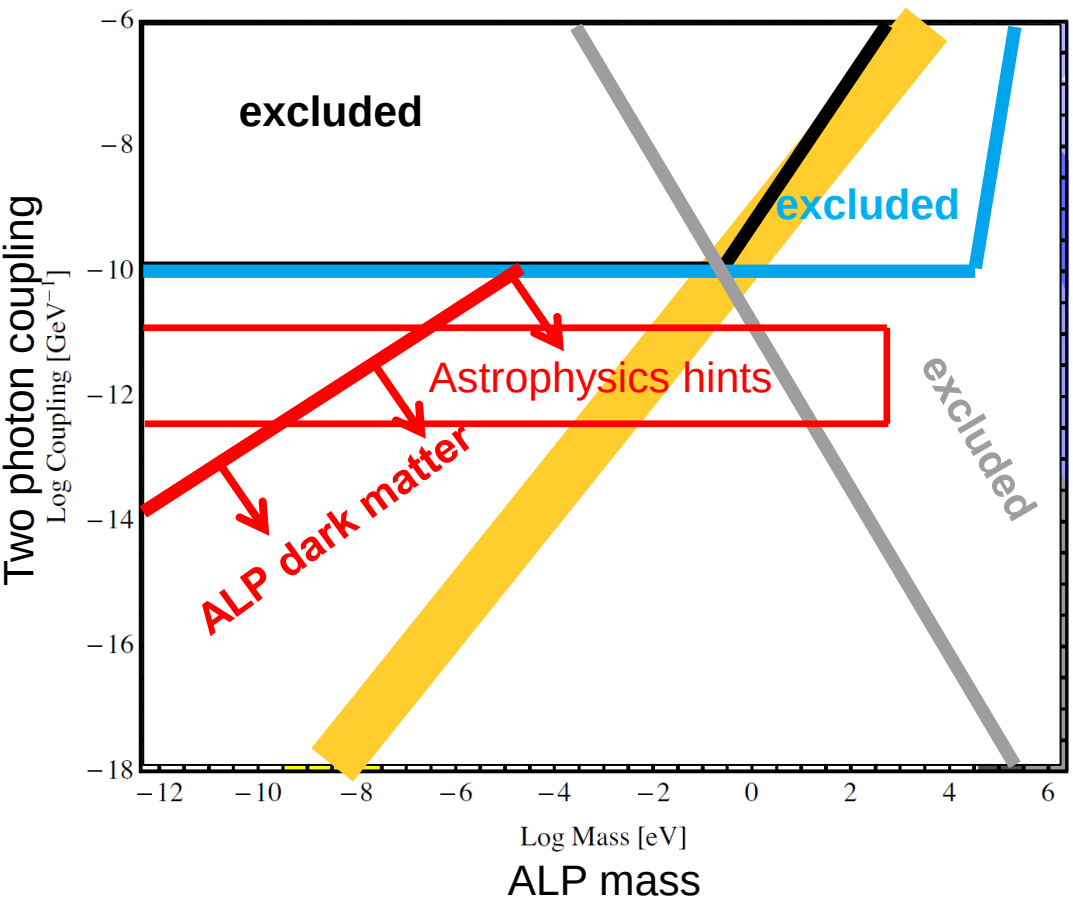

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WISP hints from astrophysics

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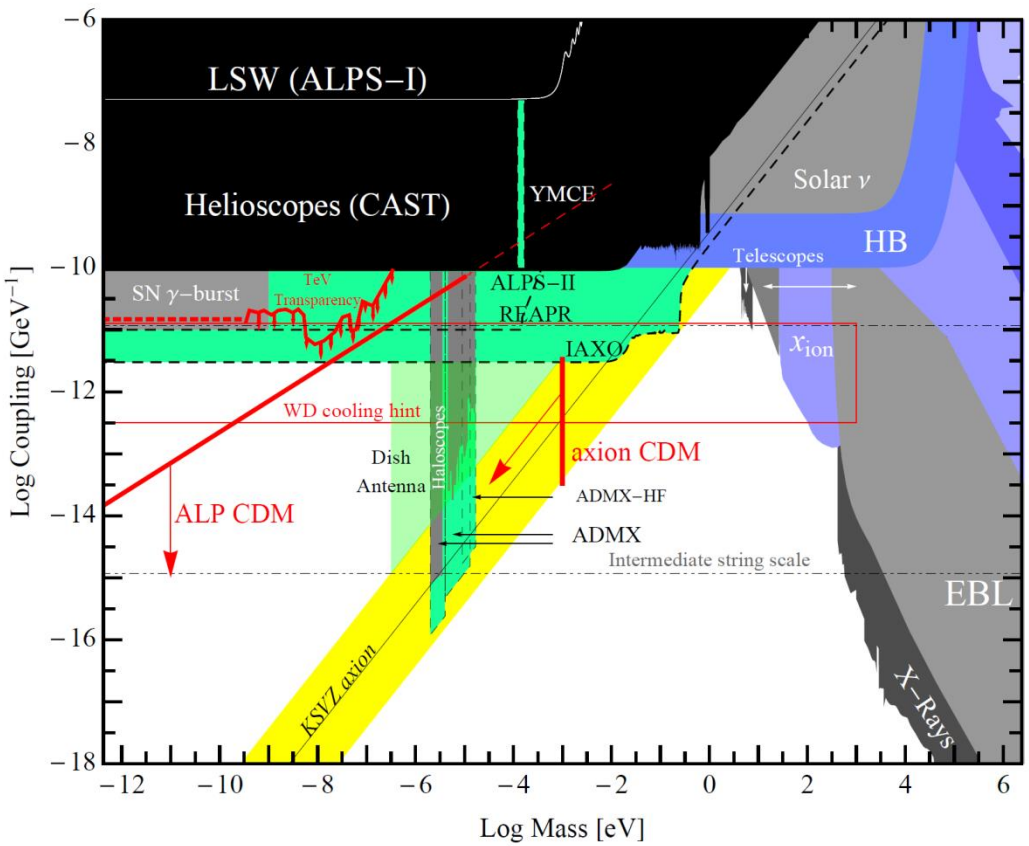

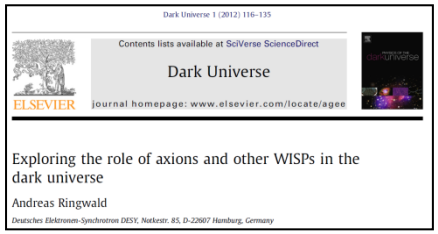

DOI: 10.1016/j.dark.2012.10.008
e-Print: **arXiv:1210.5081 [hep-ph]**

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Axions or ALPs being cold dark matter
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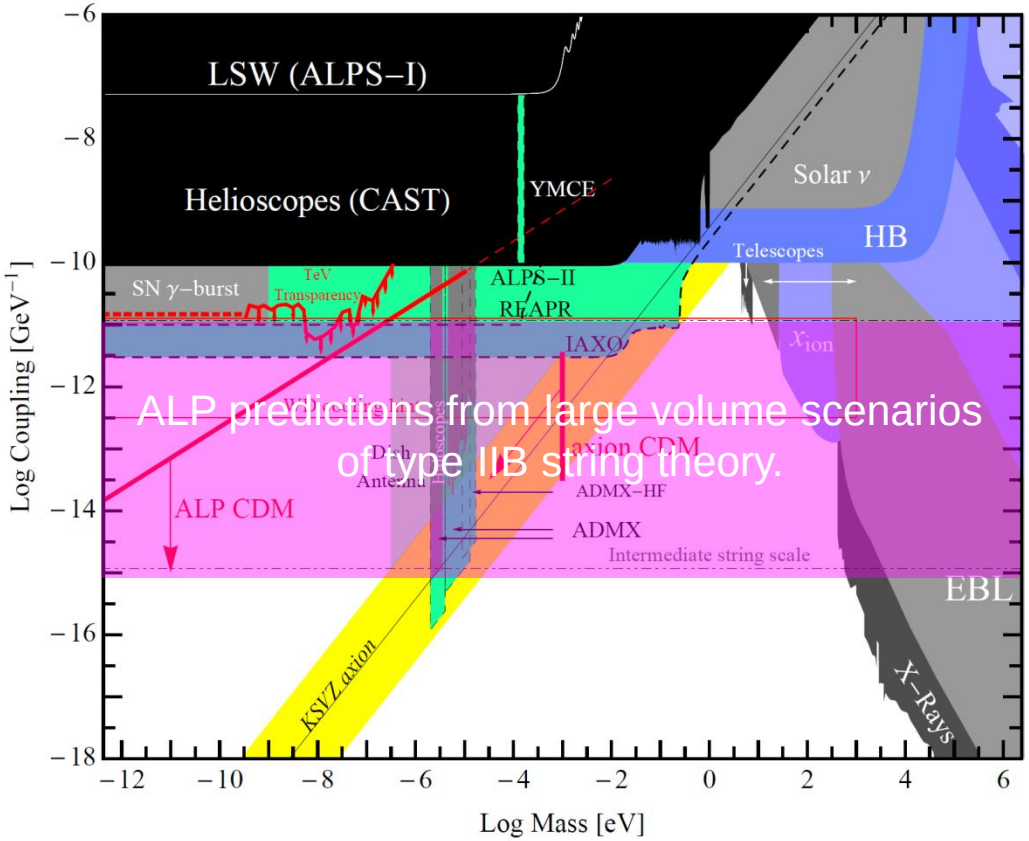
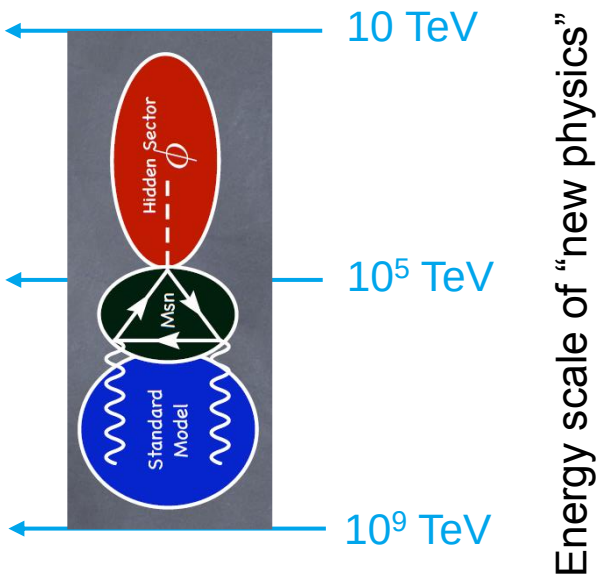
Sensitivity of next generation WISP exp.

Particular interesting:

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

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.

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http://thisdarkmatter.com/reviews/lockwood-co-just-dark-enough/

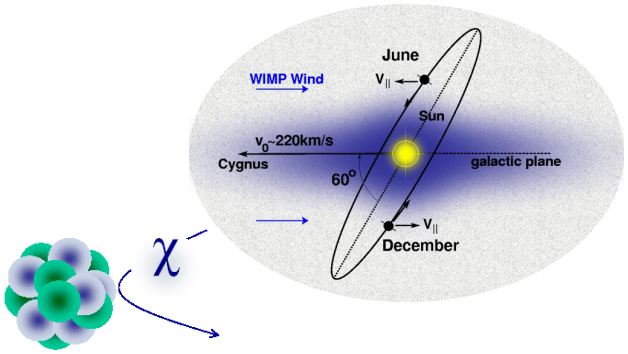
Dark matter search strategies:

- Direct:
  detecting particles of the DM halo

- Indirect:
  finding astrophysical signatures
  of the DM halo constituents.

Dark matter search strategies: WIMPs

- Direct:
  detecting particles of the DM halo



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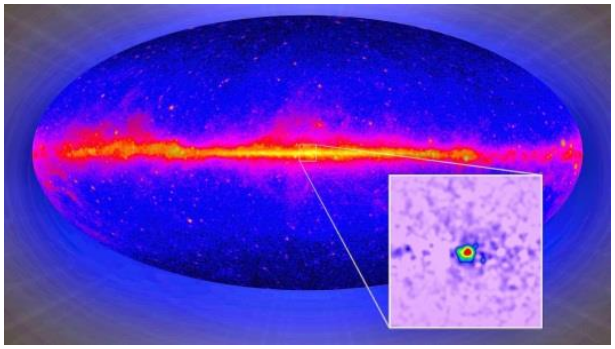

Dark matter search strategies: WISPs

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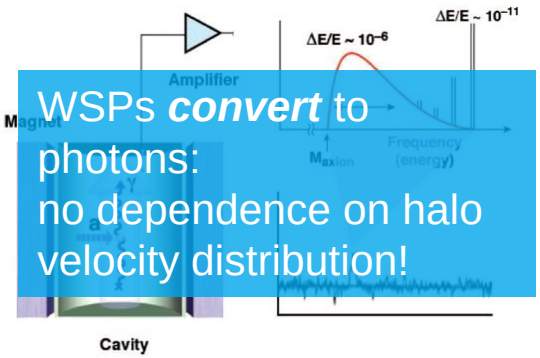

WSPs ***convert*** to photons:
no dependence on halo velocity distribution!

- Indirect:
  finding astrophysical signatures of the DM halo constituents.

Dark matter search strategies: WISPs

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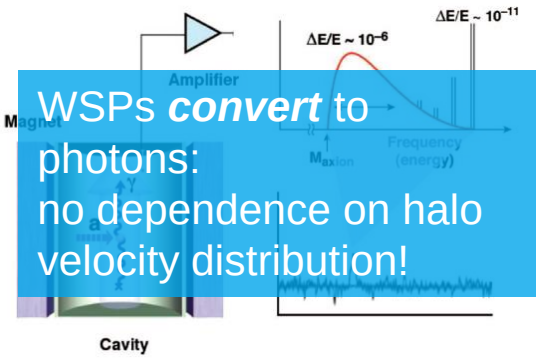
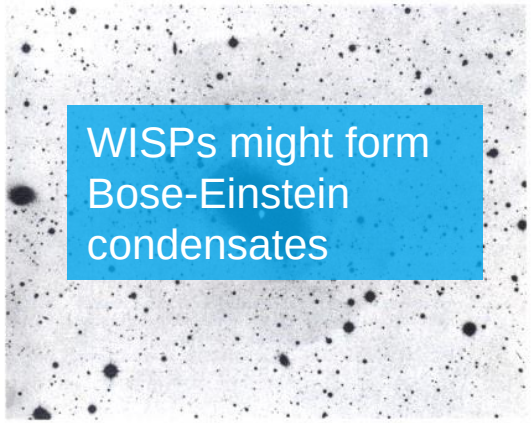


WSPs ***convert*** to photons:
no dependence on halo velocity distribution!

- Indirect:
  finding astrophysical signatures of the DM halo constituents.



WISPs might form Bose-Einstein condensates

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.

WISPy dark matter: option I – exploit microwave cavities

- Make dark matter WISPs convert to photons in an otherwise dark environment.

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

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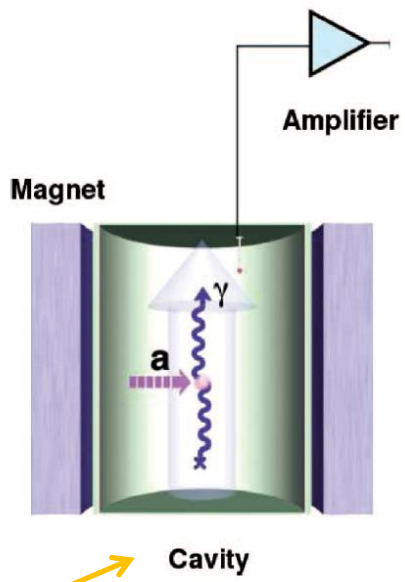
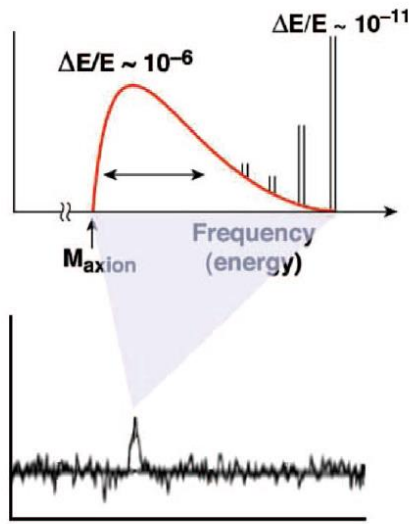
- When converting to photons, the photon energy is given by the WISP rest mass + an O(10^{-6}) correction (WISPs move non-relativistic).



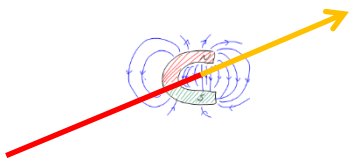


$$P_{a\to\gamma} \propto \left(B_0^2 V Q\right)\left(g_\gamma^2 \frac{\rho_a}{m_a}\right)$$

Cavity volume

Cavity power build-up

Axion number density



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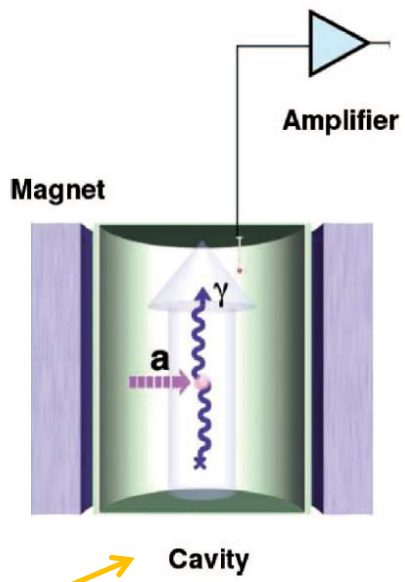
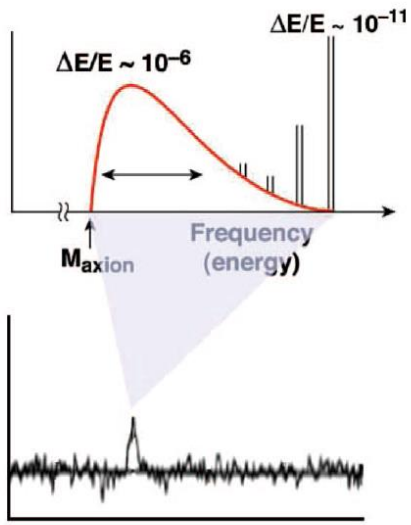


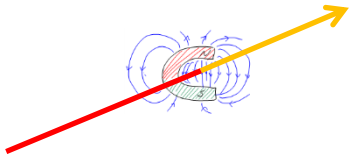


$$P_{a\to\gamma} \propto \left(B_0^2 V Q\right)\left(g_\gamma^2 \frac{\rho_a}{m_a}\right)$$

Cavity volume

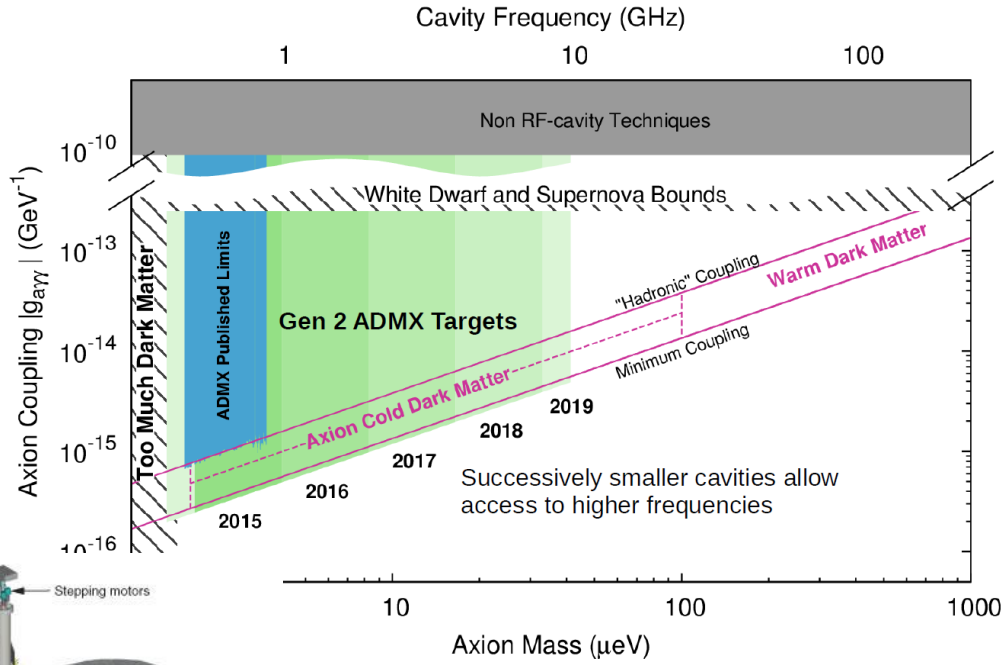
Cavity power build-up: the cavity frequency has to match m_a!

Axion number density

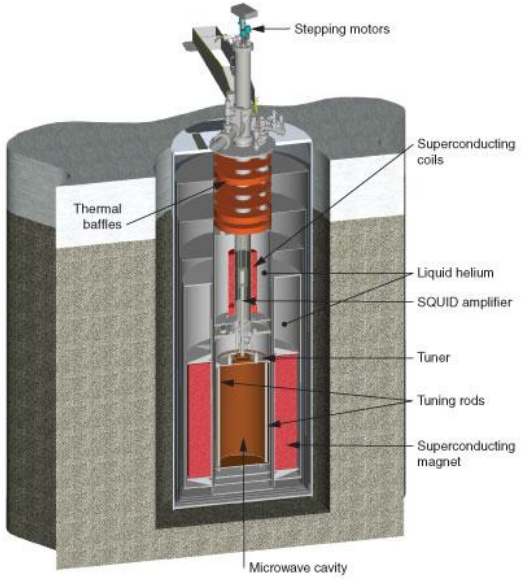


The Axion Dark Matter eXperiment

- ADMX at Washington Univ., Seattle.
- Sufficient sensitivity to detect DM axions,
  - **<u>if axions happen to have the right mass.</u>**



G. Rybka, PATRAS 2015

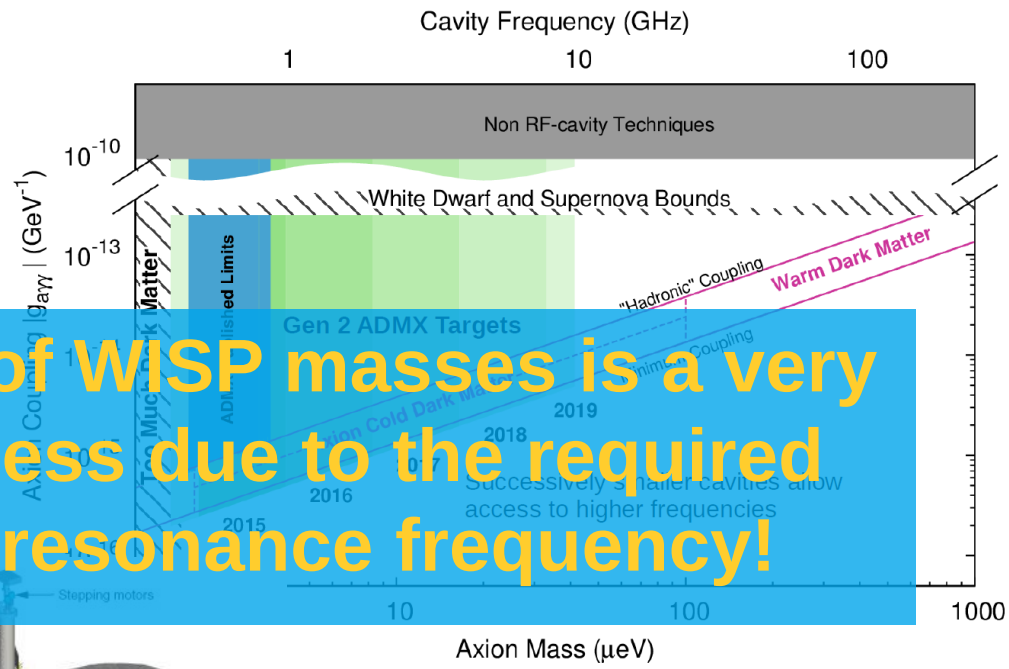


The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008

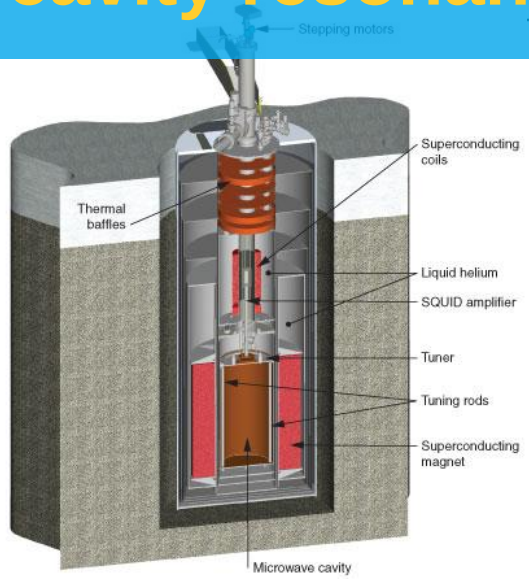
The Axion Dark Matter eXperiment

- ADMX at Washington Univ., Seattle.
- Sufficient sensitivity to detect DM axions,
  - If axions happen to have the right mass

Probing a large range of WISP masses is a very time consuming process due to the required tuning of the cavity resonance frequency!



G. Rybka, PATRAS 2015

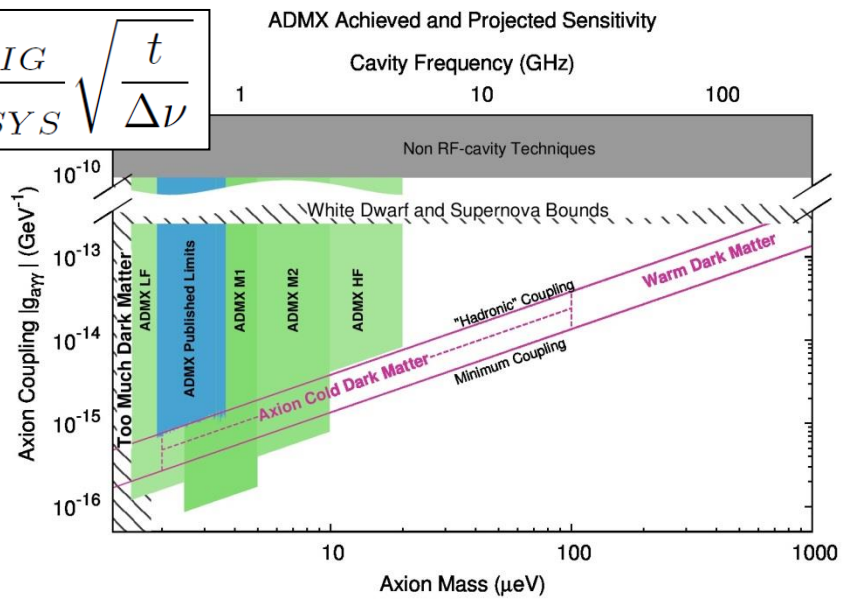


The Search for Axions, Carosi, van Bibber, Pivovaroff, Contemp. Phys. 49, No. 4, 2008

Extending the DM search mass range

- 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.

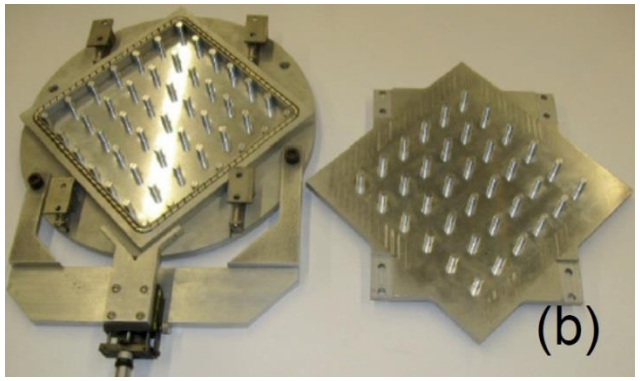
$$\frac{S}{N} = \frac{P_{SIG}}{kT_{SYS}}\sqrt{\frac{t}{\Delta\nu}}$$



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

Get smaller!

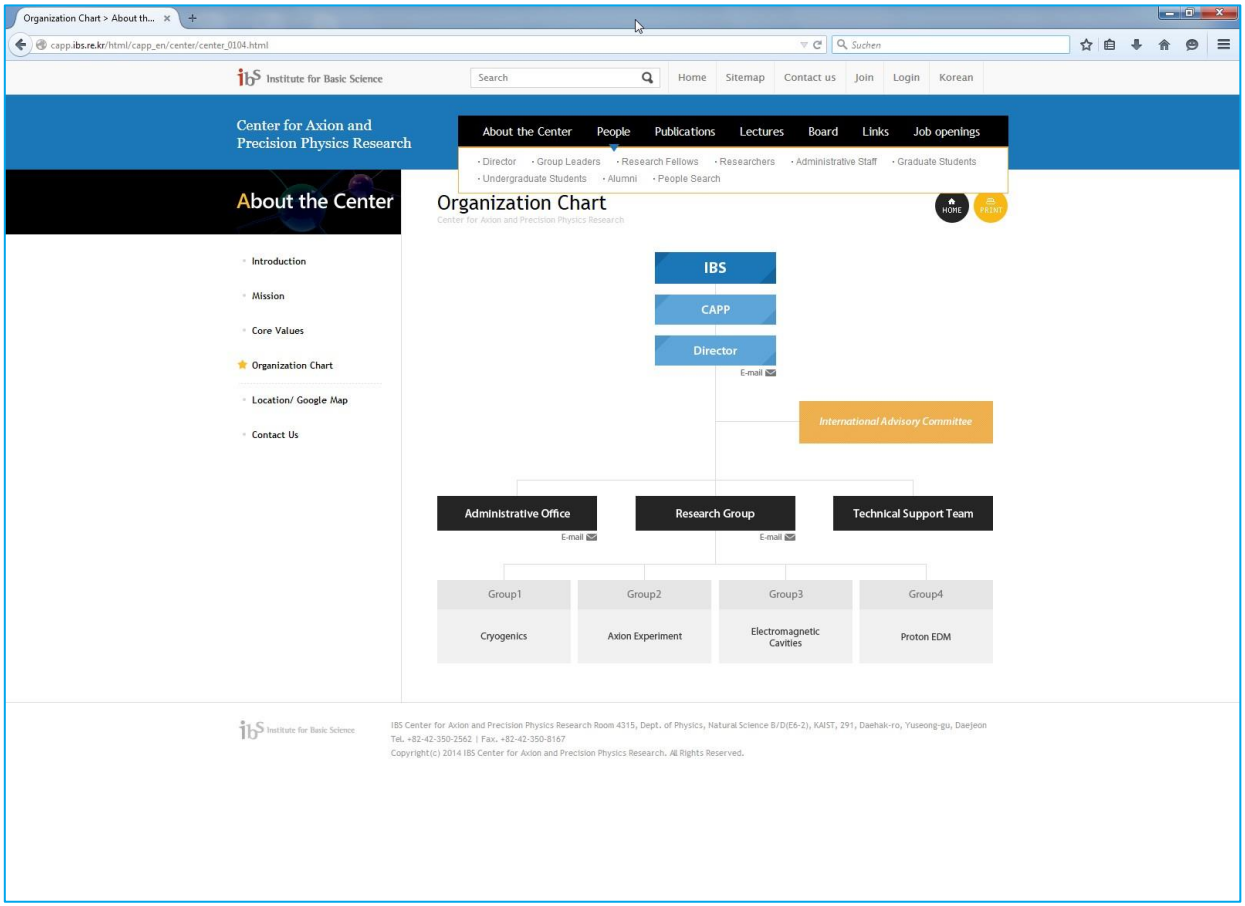
$$P_{a\to\gamma} \propto \left(B_0^2 V Q\right)\left(g_\gamma^2 \frac{\rho_a}{m_a}\right)$$



arXiv:1405.3685 [physics.ins-det]

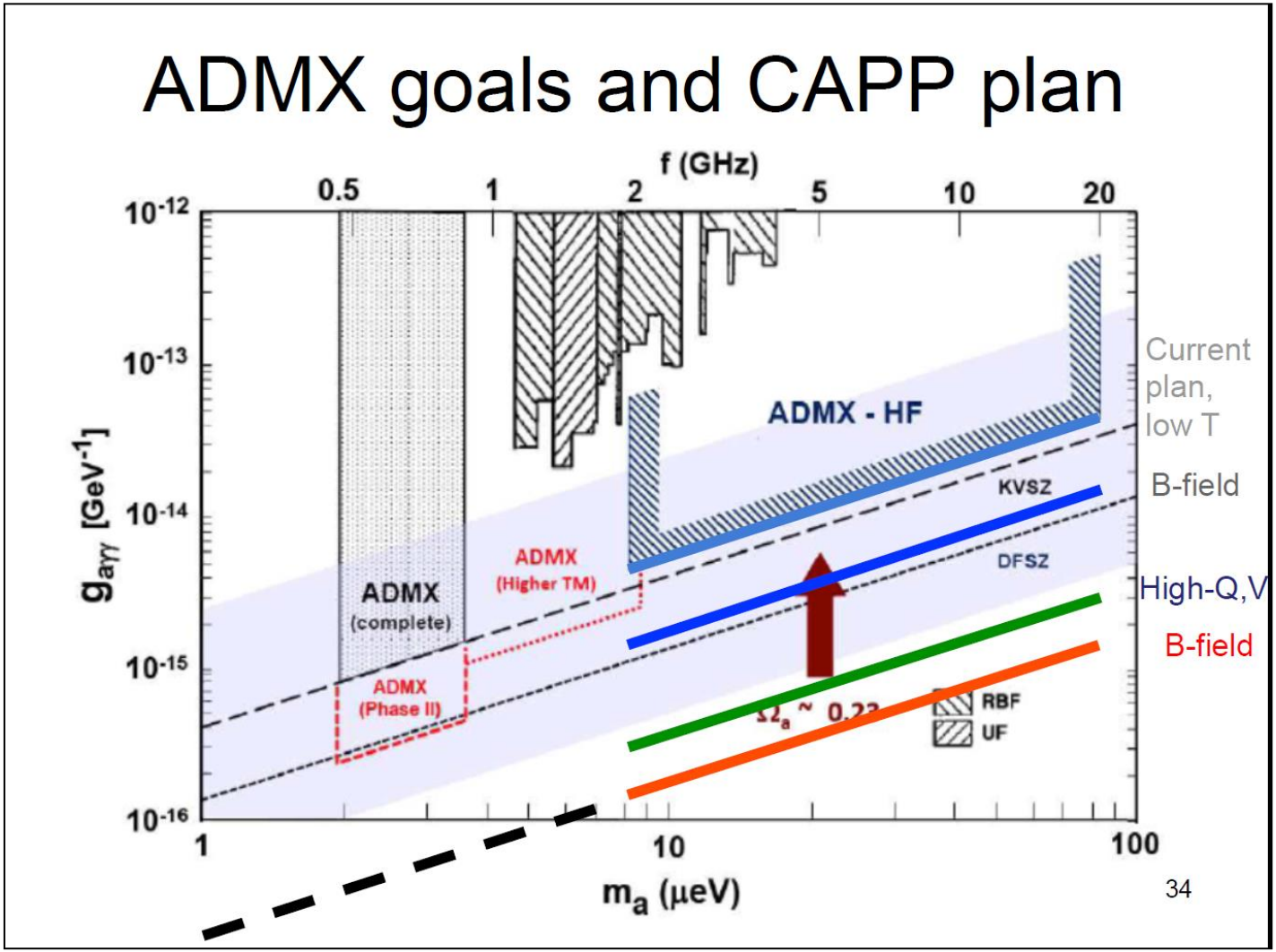
WISP searches at CAPP

There will be more experiments soon: in South Korea a dedicated "Center for Axion and Precision Physics Research" has been founded.



Director: Y. K. Semertzidis

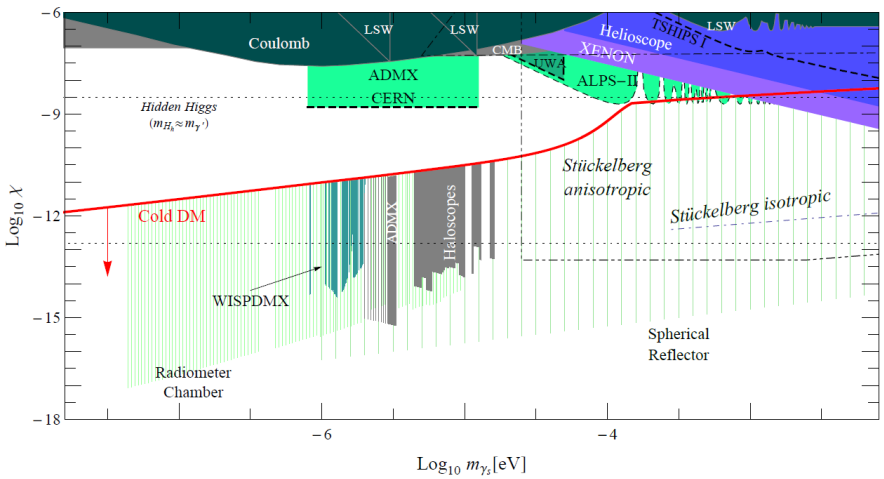
WISP searches at CAPP

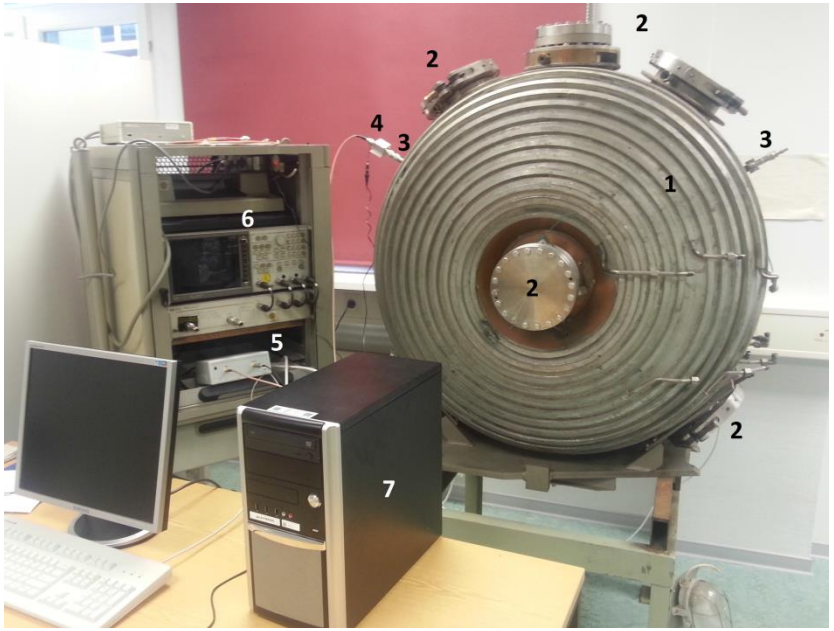


(courtesy Y. Semertzidis)

WISPDMX in Hamburg

- A 208 MHz cavity from the HERA accelerator is used to search for hidden photons below the ADMX mass range.





http://arxiv.org/abs/1410.6302

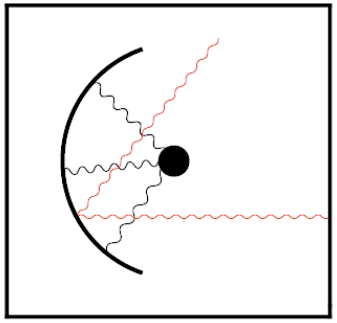
- If a suitable magnet is found, axions and ALPs can be searched for.

WISPy dark matter: option II - broad band mass searches

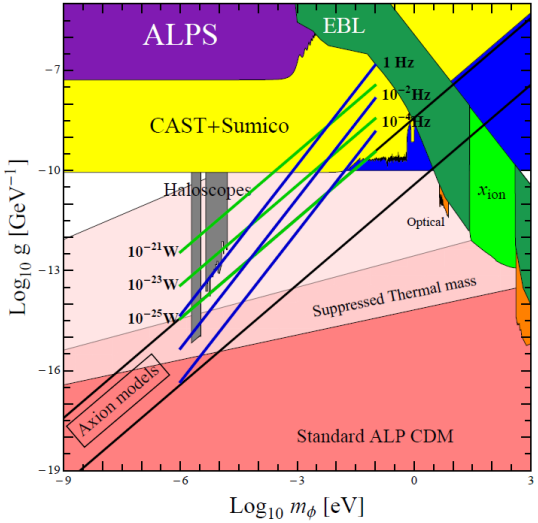
- Convert dark matter to photons, but do not exploit resonance effects to achieve a broad acceptance in mass.

WISPy dark matter: option II - broad band mass searches

- Convert dark matter to photons, but do not exploit resonance effects to achieve a broad acceptance in mass.
  - If the WISP wave function encounters a sharp reflecting surface a (tiny) electromagnetic wave is reflected.
  - This wave is emitted perpendicular to a reflecting surface (assuming cold dark matter).
  - This emission can be concentrated onto a photon detector.
  - Axions/ALPs: with dish sizes of 1m^2 in a 5T field competitive sensitivities can be reached.



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

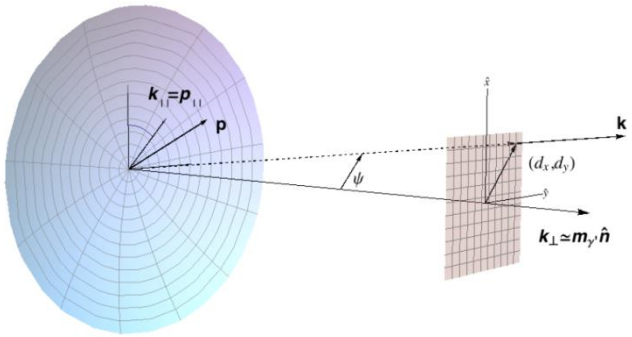


D. Horns et al., JCAP04 (2013) 016

Seeing the dark matter halo!

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

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



For some theory:

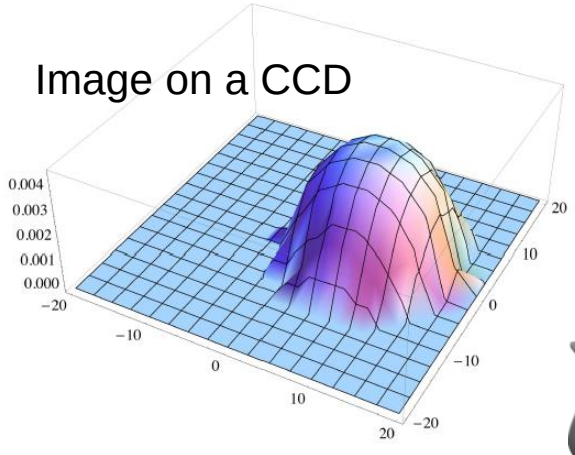
PHYSICAL REVIEW D **88,** 115002 (2013)

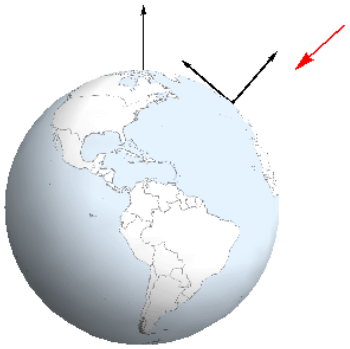
Resonant to broadband searches for cold dark matter consisting of weakly interacting slim particles

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, Fohringer Ring 6, 80805 Munich, Germany*
(Received 6 September 2013; published 2 December 2013)

Image on a CCD

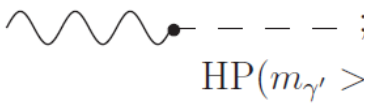


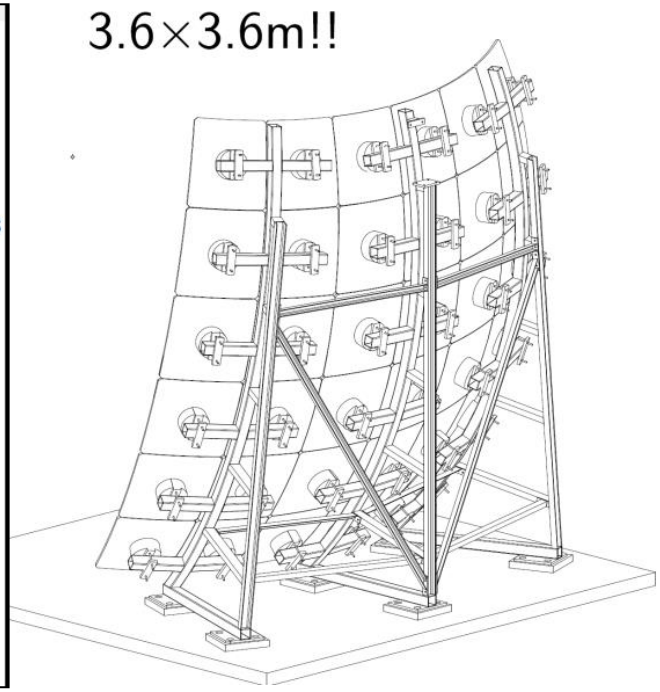


Thanks to J. Redondo

FUNK: a KIT- DESY study

- Pilot “dish” experiment searching for hidden photons: **F**inding **U**(1)s of a **N**ovel **K**ind.

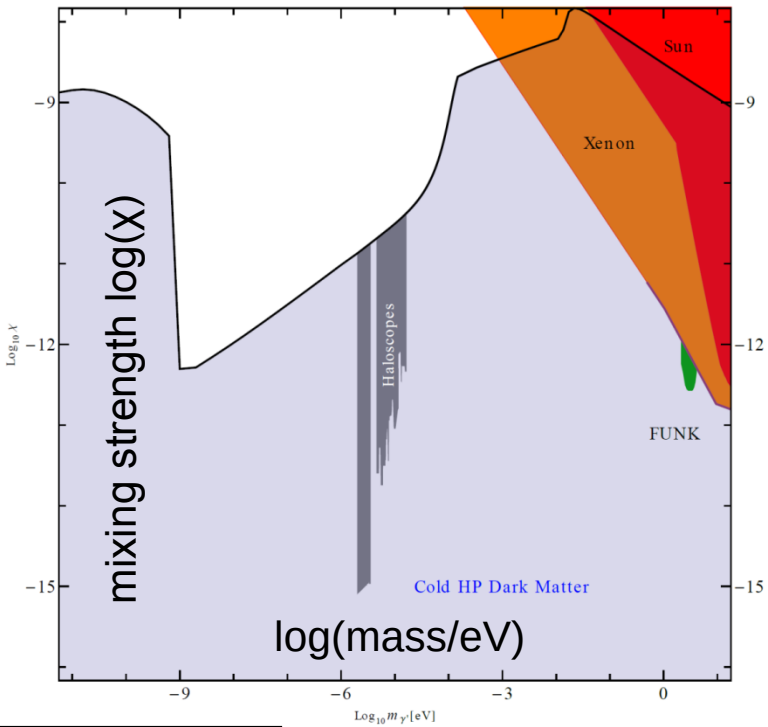




Hidden photons convert to light at a spare mirror system of the AUGER fluorescence telescopes, which is focused onto a photomultiplier.

FUNK: a KIT- DESY study

- However, to find dark matter soon a little luck is required.
- Most important:
  getting started with a new experimental approach!
- More info at:
  arXiv:1501.03274



Hidden Photon Dark Matter Search with a Large Metallic Mirror

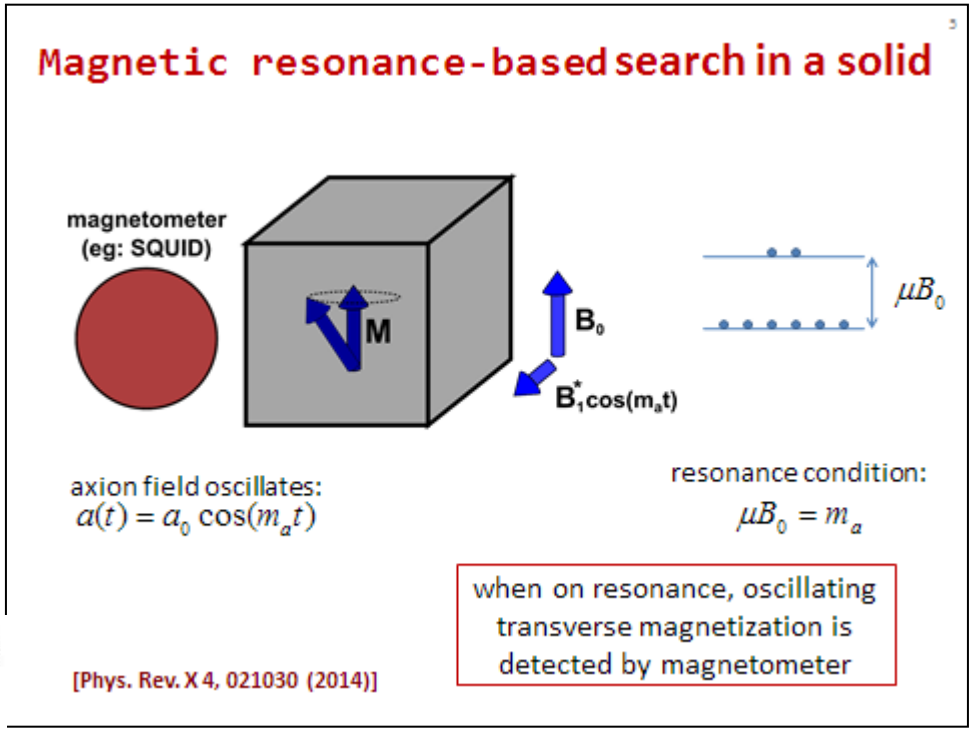
Babette Döbrich[1], *Kai Daumiller*[2], *Ralph Engel*[2], *Marek Kowalski*[1,3], *Axel Lindner*[1], *Javier Redondo*[4], *Markus Roth*[2]

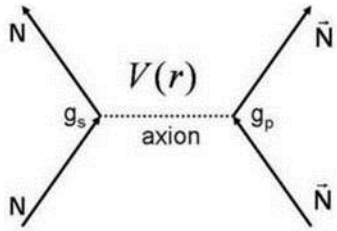
[1]Deutsches Elektronen-Synchrotron (DESY), 22607 Hamburg and 15738 Zeuthen, Germany
[2]Karlsruher Institut für Technologie (KIT), IKP, 76021 Karlsruhe, Germany
[2]Humboldt Universität, Institut für Physik, 12489 Berlin, Germany
[4]Zaragoza University, Pedro Cerbuna 12, E-50009 Zaragoza, Spain

WISPy dark matter: option III - time-dependent effects

Exploit time-dependent effects:

- Axions (and other dark matter WISPs) are the quanta of an oscillating field in the universe: $a(t) = a_0 \cdot \cos(ma \cdot t)$
- This oscillating field induces an oscillating electric dipole moment:
  $d \approx 3\times10^{-16}(a/f_a)\, e\cdot cm$
- This can be searched for in NMR-like experiments.





A. Sushkov, PATRAS 2015

WISPy dark matter: option III - time-dependent effects

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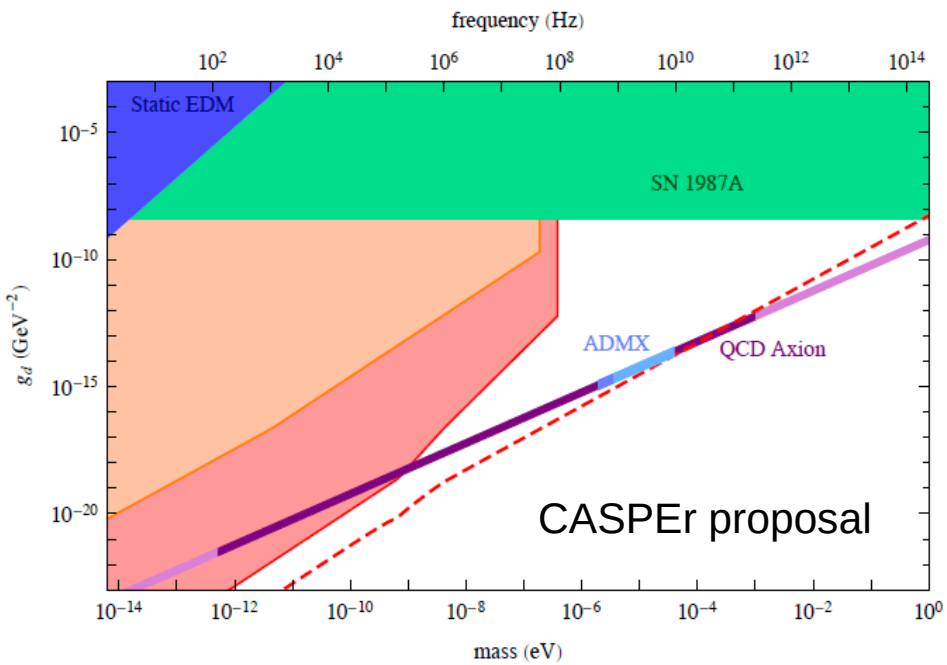
- This oscillating field induces an oscillating electric dipole moment:
  $d \approx 3\times10^{-16}(a/f_a)\, e\cdot cm$
- This can be searched for in NMR-like experiments.
  - Axion coupling to the nucleon spin (CASPEr wind)
  - Time varying nucleon EDM induced by axions (CASPEr electric)



WISPy dark matter: option III - time-dependent effects

PHYSICAL REVIEW X **4,** 021030 (2014)

Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)

Dmitry Budker,[1,5] Peter W. Graham,[2] Micah Ledbetter,[3] Surjeet Rajendran,[2] and Alexander O. Sushkov[4]
[1]*Department of Physics, University of California, Berkeley, California 94720, USA and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*
[3]*AOSense, 767 North Mary Avenue, Sunnyvale, California 94085-2909, USA*
[4]*Department of Physics and Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts 02138, USA*
[5]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*
(Received 9 July 2013; published 19 May 2014)

The QUAX proposal: a search of galactic axion with magnetic materials

G Ruoso[1], A Lombardi[1], A Ortolan[1], R Pengo[1], C Braggio[2], G Carugno[2], C S Gallo[2], C C Speake[3]
[1] Laboratori Nazionali di Legnaro, Viale dell'Università 2, 35020 Legnaro (Italy)
[2] INFN and Dipartimento di Fisica e Astronomia, Via Marzolo 8, 35131 Padova (Italy)
[3] School of Physics and Astronomy, University of Birmingham, West Midlands B15 2TT (UK)
E-mail: `Giuseppe.Ruoso@lnl.infn.it`

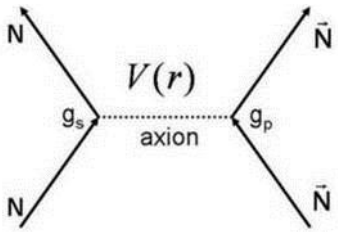
arXiv:1511.09461v1 [hep-ph]

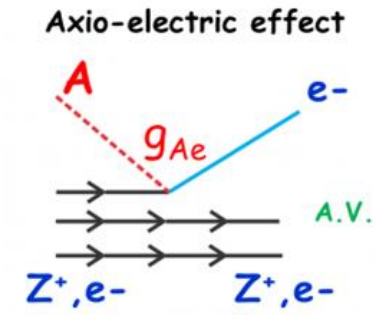
WISPy dark matter: option IV - spectroscopy

Axion dark matter detection by laser spectroscopy of ultracold molecular oxygen: a proposal

L. Santamaria[1], C. Braggio[2], G. Carugno[2], V. Di Sarno[1], P. Maddaloni[1,3]‡, G. Ruoso[4]

[1]CNR-INO, Istituto Nazionale di Ottica, Via Campi Flegrei 34, 80078 Pozzuoli, Italy
[2]Dipartimento di Fisica "G. Galilei", Università di Padova, Via F. Marzolo 8, 35131 Padova, Italy
[3]INFN, Istituto Nazionale di Fisica Nucleare, Sez. di Firenze, Via G. Sansone 1, 50019 Sesto Fiorentino, Italy
[4]INFN, Laboratori Nazionali di Legnaro, Viale dell'Università 2, 35020 Legnaro, Italy

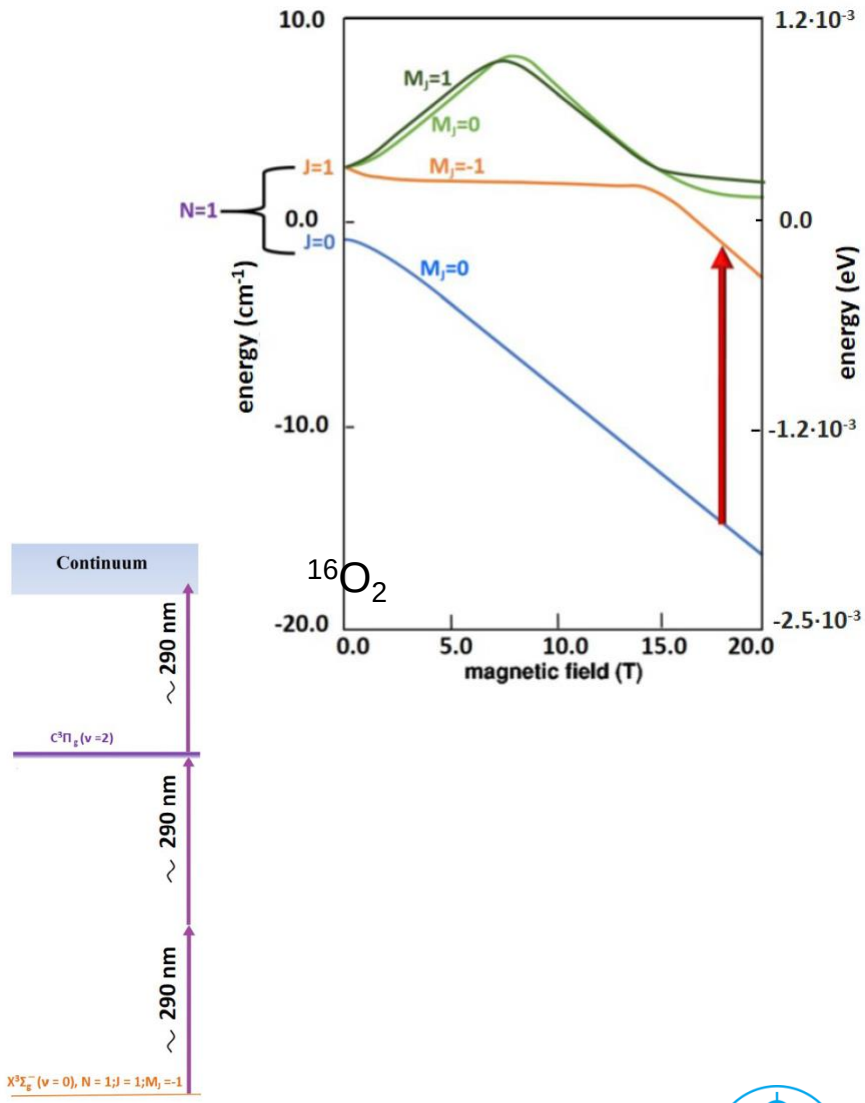




Accepted for publication by NJP

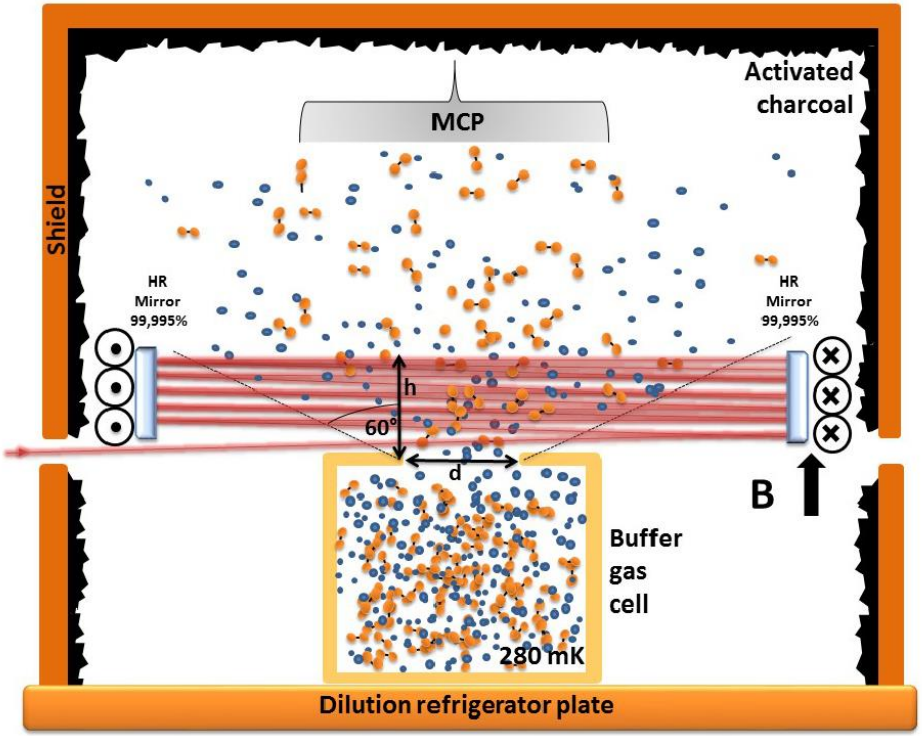
WISPy dark matter: option IV - spectroscopy

- Dark matter axions could introduce atomic transitions which could not happen otherwise, if the axion mass corresponds to the energy difference of the transition.
- Use the Zeeman effect to tune the energy difference between two states to the axion mass.
- Use resonance-enhanced multi-photon ionization to detect the few molecules excited by axion absorption.



WISPy dark matter: option IV - spectroscopy

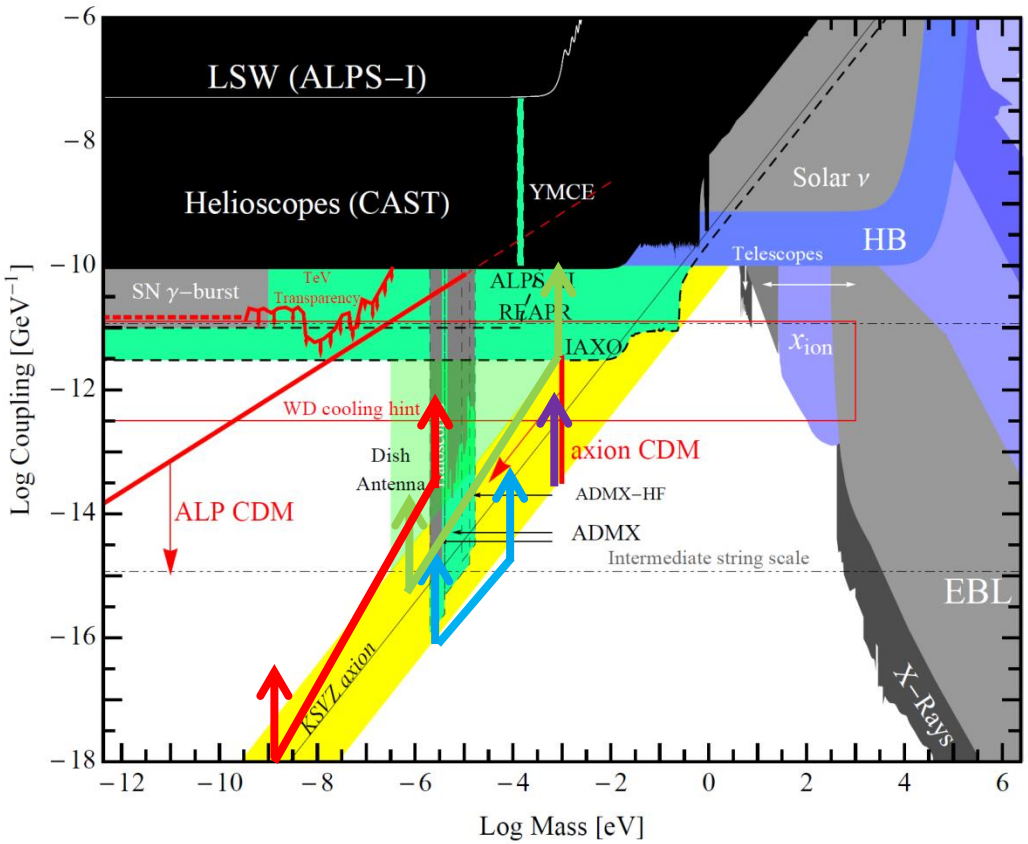
- Such an apparatus could probe rather heavy dark matter axions of 1.4 to 1.9 meV.
- The signal depends also on the kinetic energy of the DM axion with respect to the detector. Hence, one could measure the DM velocity distribution and its daily/seasonal changes.
- However, the experimental techniques are challenging!



Summary on direct axion / ALP dark matter searches

Warning: this is just to guide the eye! Not all experiments will measure the coupling to photons!

- Resonating cavity experiments
- Dish antenna
- NMR
- Spectroscopy



Many experiments, many different tools, very different expertise required.

Indirect WISPy dark matter searches

- Dark matter WISPs, which do not originate from a thermal freeze-out process, but have been produced by a phase transition, are extremely cold and might even form Bose-Einstein condensates (BECs).
- Ultralight WISPy ($m<10^{-20}$ eV, $\lambda_c>10^{13}$ m) dark matter would suppress small scale structure formation.
- Very lightweight WISPs might mimic dark energy.

PHYSICAL REVIEW D **78,** 063508 (2008)

Caustic ring model of the Milky Way halo

L. D. Duffy[1,*] and P. Sikivie[2,+]
[1]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*University of Florida, Gainesville, Florida 32611, USA*
(Received 30 May 2008; published 5 September 2008)

A search for ultralight axions using precision cosmological data

Renée Hlozek,[1] Daniel Grin,[2] David J. E. Marsh,[3,*] and Pedro G. Ferreira[4]
[1]*Department of Astronomy, Princeton University, Princeton, NJ 08544, USA*
[2]*Kavli Institute for Cosmological Physics, Department of Astronomy and Astrophysics, University of Chicago, Chicago, Illinois, 60637, U.S.A.*
[3]*Perimeter Institute, 31 Caroline Street N, Waterloo, ON, N2L 6B9, Canada*
[4]*Astrophysics, University of Oxford, DWB, Keble Road, Oxford, OX1 3RH, UK*
(Dated: May 22, 2015)

Phys. Rev. D 91, 103512 (2015)

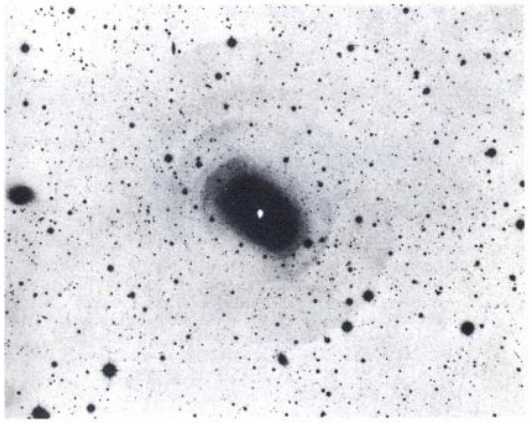


Figure 7-22. The giant elliptical galaxy NGC 3923 is surrounded by faint ripples of brightness. Courtesy of D. F. Malin and the Anglo-Australian Telescope Board.

Cosmological implications of WISPy dark matter: work in progress, very interesting!

The WISP program of this session

> Dark matter and dark matter candidates

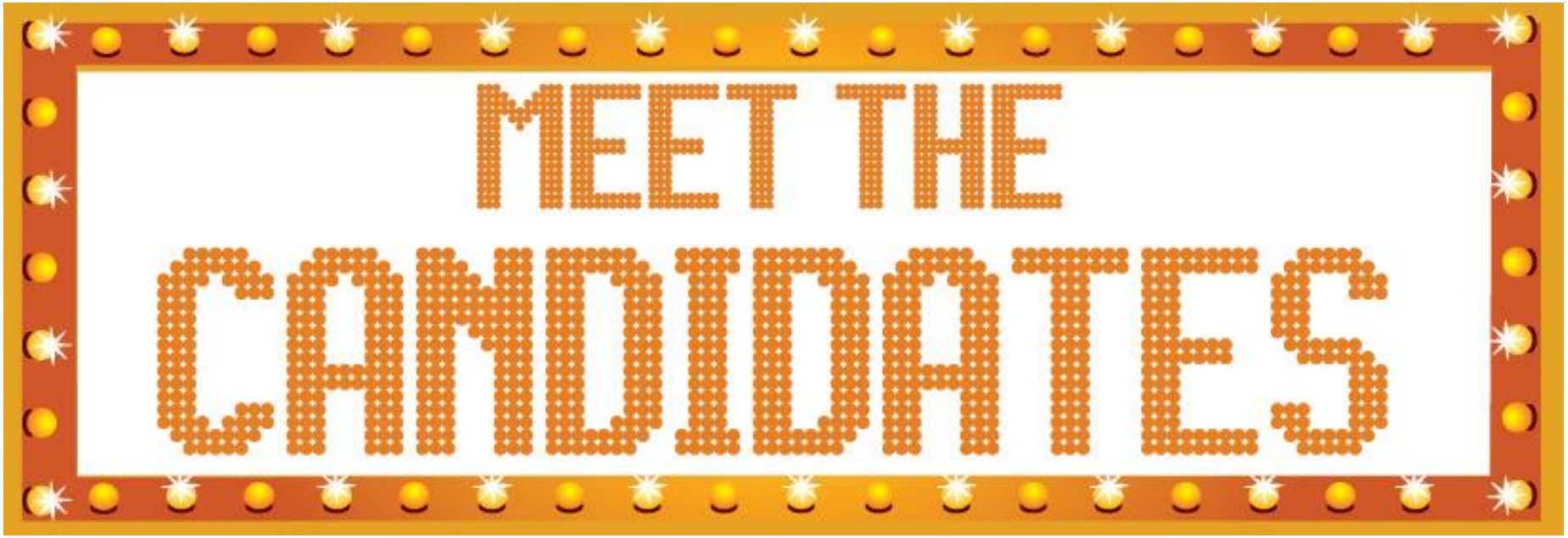
> Axions and other WISPs

> Dark matter search options

> Dark matter candidate search options

> Summary

WISPy dark matter candidates



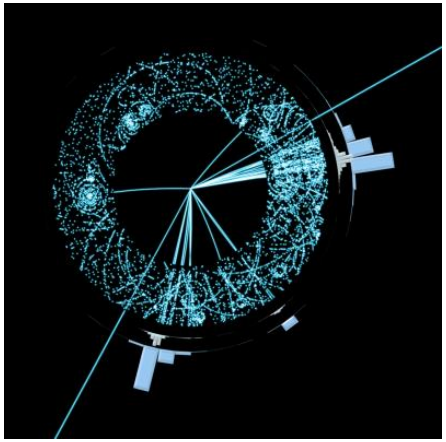
Dark matter candidate search strategies:

- Laboratory experiments:
  finding (possible) candidates

- Astrophysics:
  identifying phenomena hinting at new particles which could be the dark matter constituents

Dark matter candidate search strategies: WIMPs

- Laboratory experiments:
  finding (possible) candidates

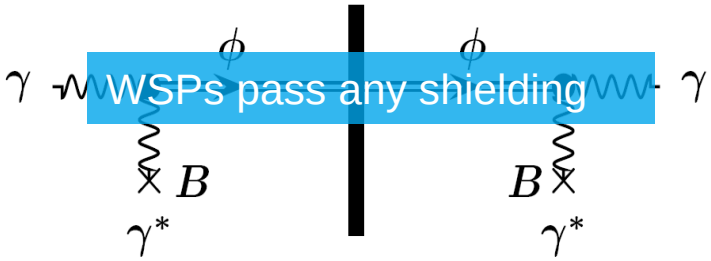


- Astrophysics:
  identifying phenomena hinting at new particles which could be the dark matter constituents

In general: the high WIMP mass prohibits significant influence in present day's astrophysics.

Dark matter candidate search strategies: WISPs

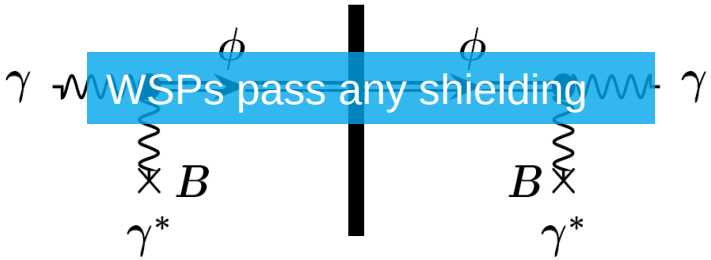
- Laboratory experiments:
  finding (possible) candidates



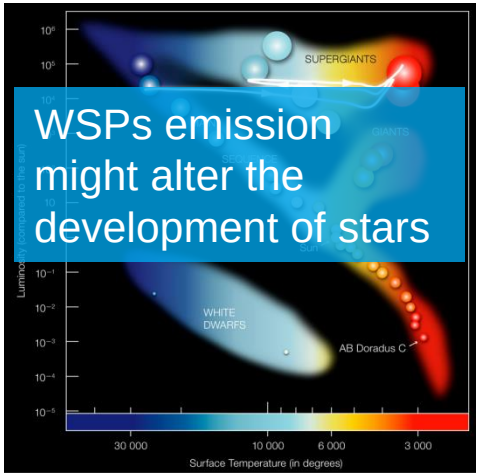
- Astrophysics:
  identifying phenomena hinting at new particles which could be the dark matter constituents

Dark matter candidate search strategies: WISPs

- Laboratory experiments:
  finding (possible) candidates



- Astrophysics:
  identifying phenomena hinting at new particles which could be the dark matter constituents



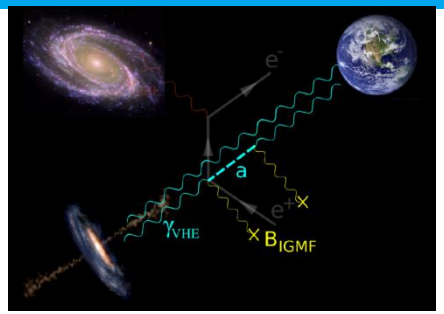
https://physics.aps.org/assets/d3e15240-0e17-4941-9195-f9fb739a1058/e14_1.png

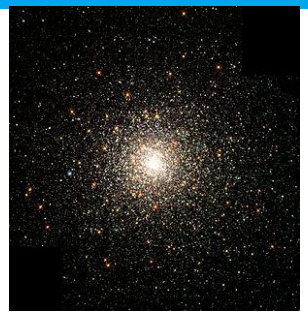
Hints for WISPs in the sky?

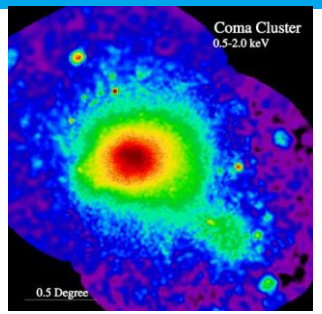
WISPy effects could show up in astrophysics due to the low WISP masses.

- WISP could change the propagation of TeV photons in the universe.
- WISP could change the development of stars.
- There could be a Cosmic Axion Background (CAB).

(Vague) hints for WISPs in the sky?







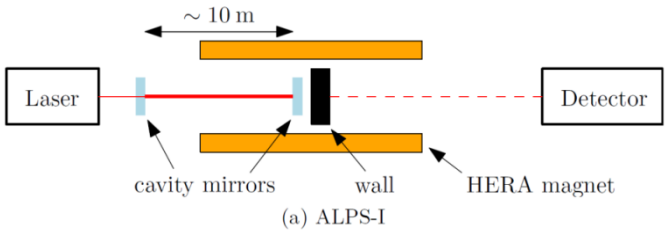
Phenomenon	ALP mass [eV]	ALP-γ coupl. [GeV^{-1}]	Reference
TeV transparency	$< 10^{-7}$	$> 10^{-11}$	arXiv:1302.1208 [astro-ph.HE]
Globular cluster stars (HB)	$< 10^{-4}$	$5 \cdot 10^{-11}$	arXiv:1406.6053 [astro-ph.SR]
CAB (Coma Cluster)	$< 10^{-13}$	10^{-12} to 10^{-13}	arXiv:1406.5188 [hep-ph]
White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

See talks by M. Roncadelli and J. Redondo!

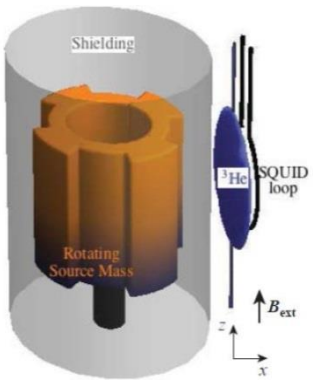
- There are allowed regions in parameter space where an ALP can simultaneously explain the gamma ray transparency, the cooling of HB stars, and the soft X-ray excess from Coma and be a subdominant contribution to CDM.

Direct searches for WISPs as dark matter candidates

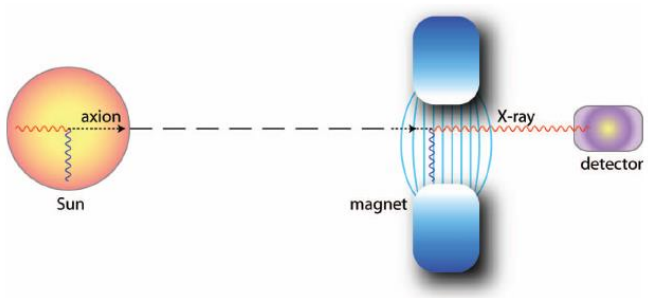
- Experiments in the laboratory

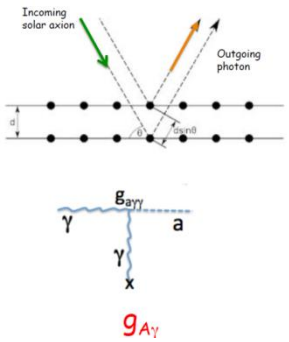


(a) ALPS-I



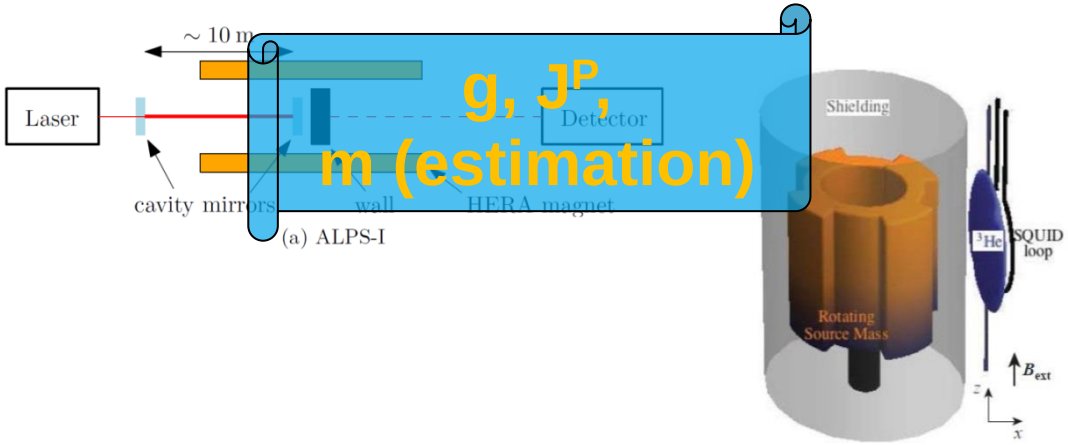
- Helioscopes





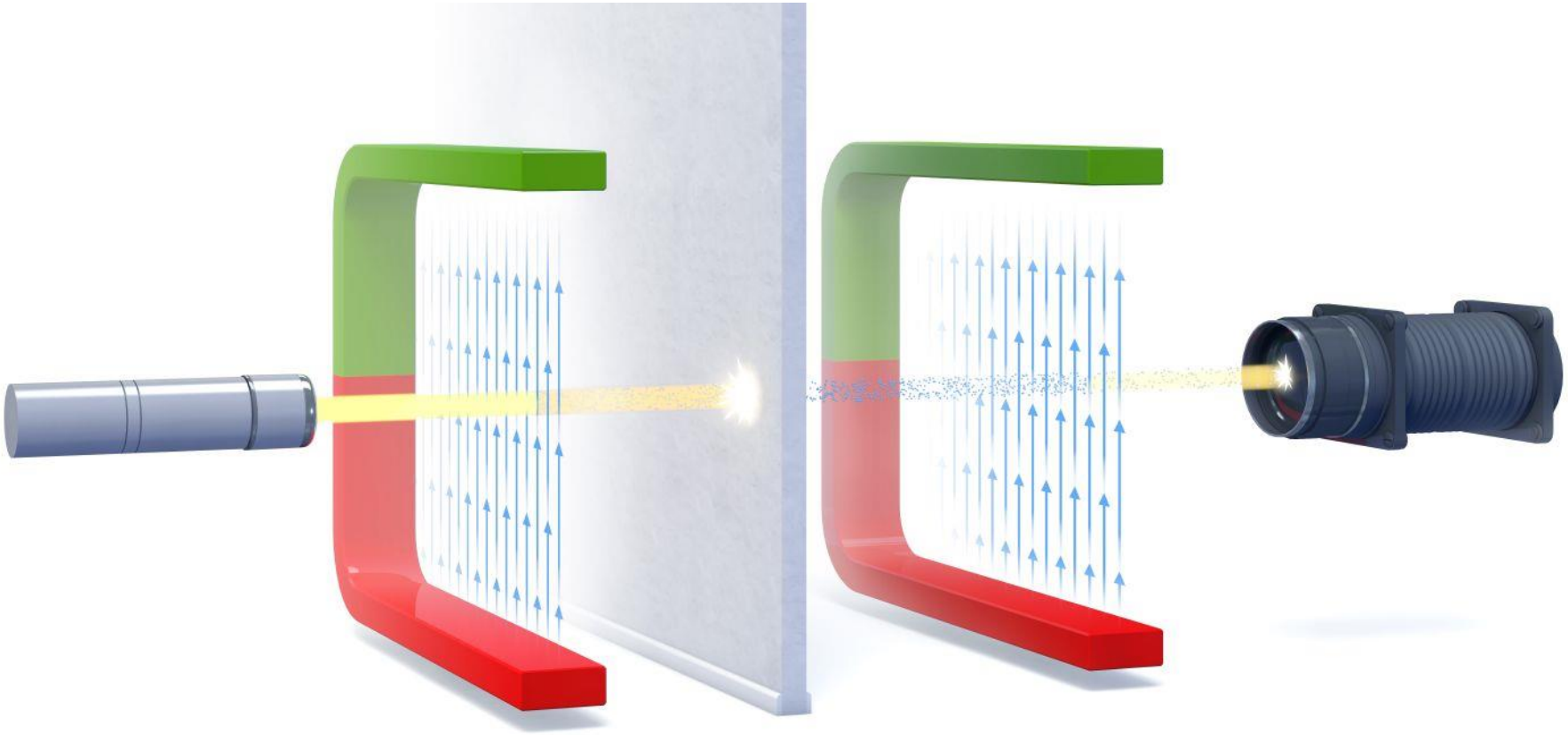
Direct searches for WISPs as dark matter candidates

- Experiments in the laboratory



- Helioscopes

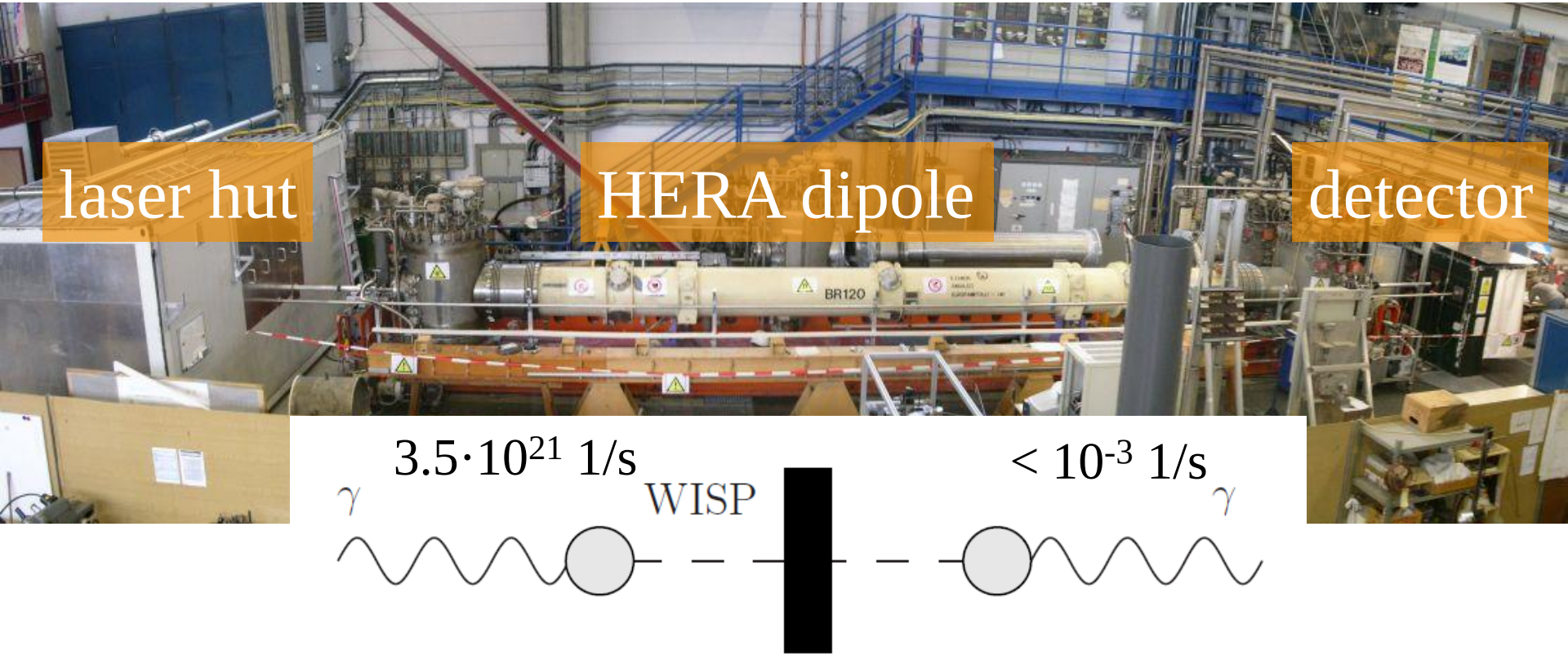
Laboratory experiments



ALPS I 2007-2010

(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 (nearly).

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.

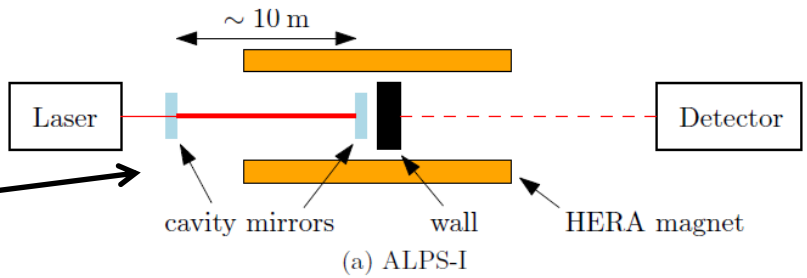
- Magnet: upgrade to 10+10 straightened HERA dipoles instead of ½+½ used for ALPS I.

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

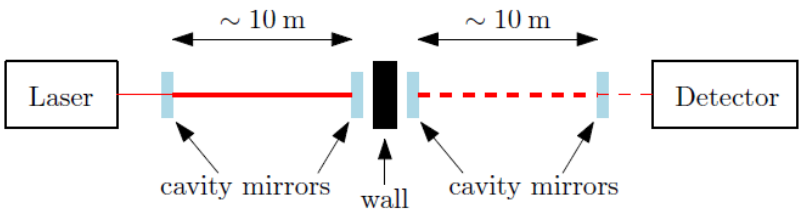
All set up in a clean environment!

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

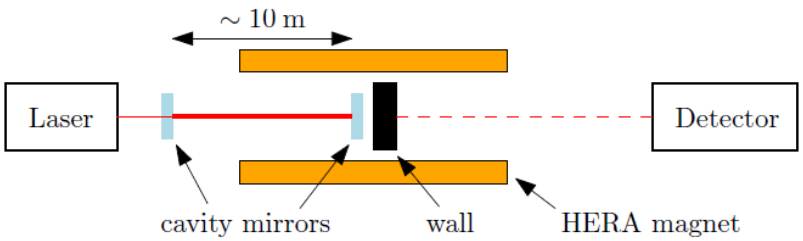
Optical resonator to increase the conversion probability

WISP→γ

First realization of a 24 year old proposal :
F. Hoogeveen, T. Ziegenhagen,
Nucl.Phys. B358 (1991) 3-26

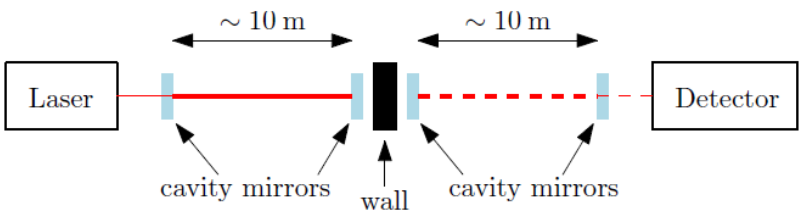
ALPS II is realized in stages

ALPS I



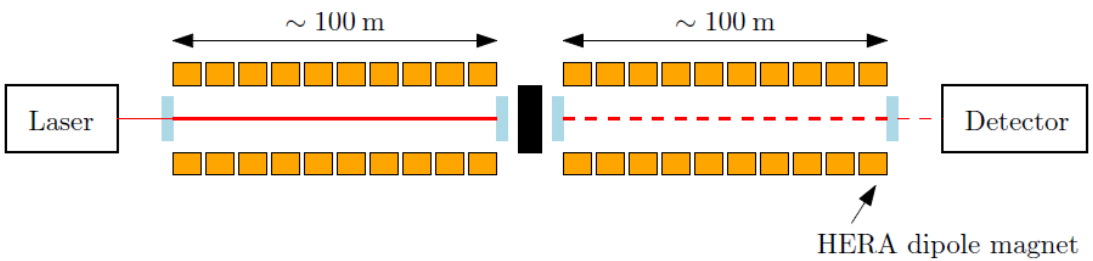
(a) ALPS-I

> **ALPS IIa**



(b) ALPS-IIa

> **ALPS IIc**



(d) ALPS-IIc

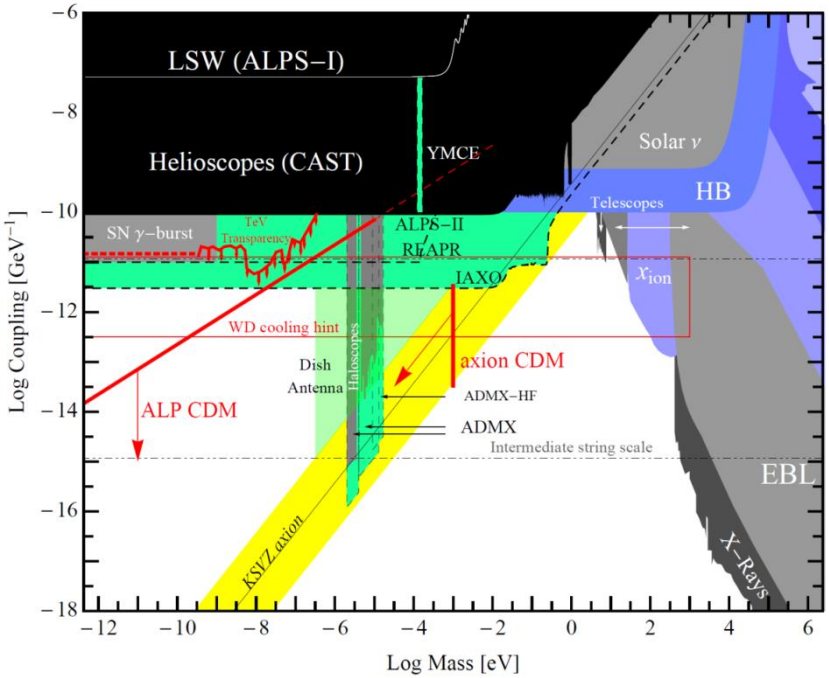
20 HERA dipoles, 200 m long

The ALPS II challenge

- Photon regeneration probability:

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

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

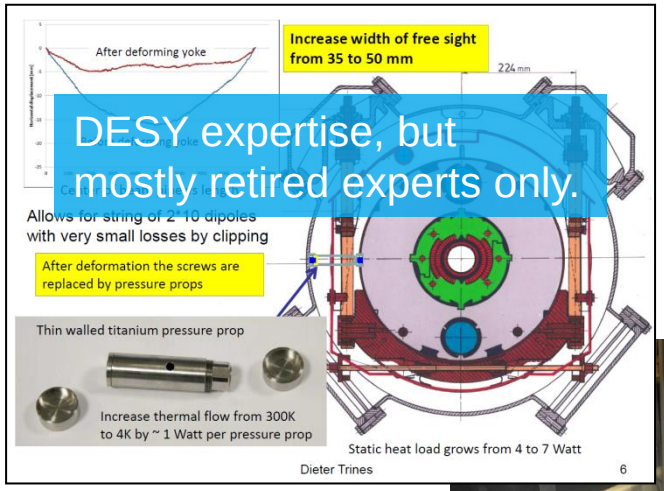


$P_{\gamma\to\phi\to\gamma} = 6\cdot10^{-23}$, 30 photons per hour

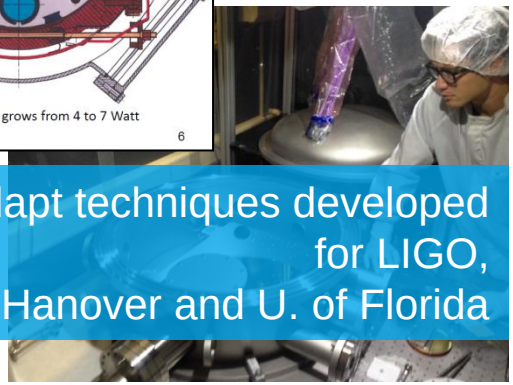
$P_{\gamma\to\phi\to\gamma} = 6\cdot10^{-27}$, 2 photons per month

ALPS II: main experimental challenges

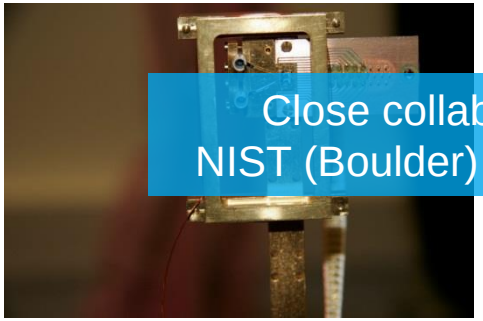
- HERA dipole magnets:
  straighten the cold mass cheap and reliably to increase the 35 mm aperture to 50 mm.
- Optics:
  construct and operate two 100 m long optical resonators of high quality which are mode matched and aligned to better than 10 µrad.
- Detector:
  characterize and operate a superconducting Transition Edge Sensor (25µm·25µm·20nm) at 80 mK to count single 1064 nm photons.



DESY expertise, but mostly retired experts only.

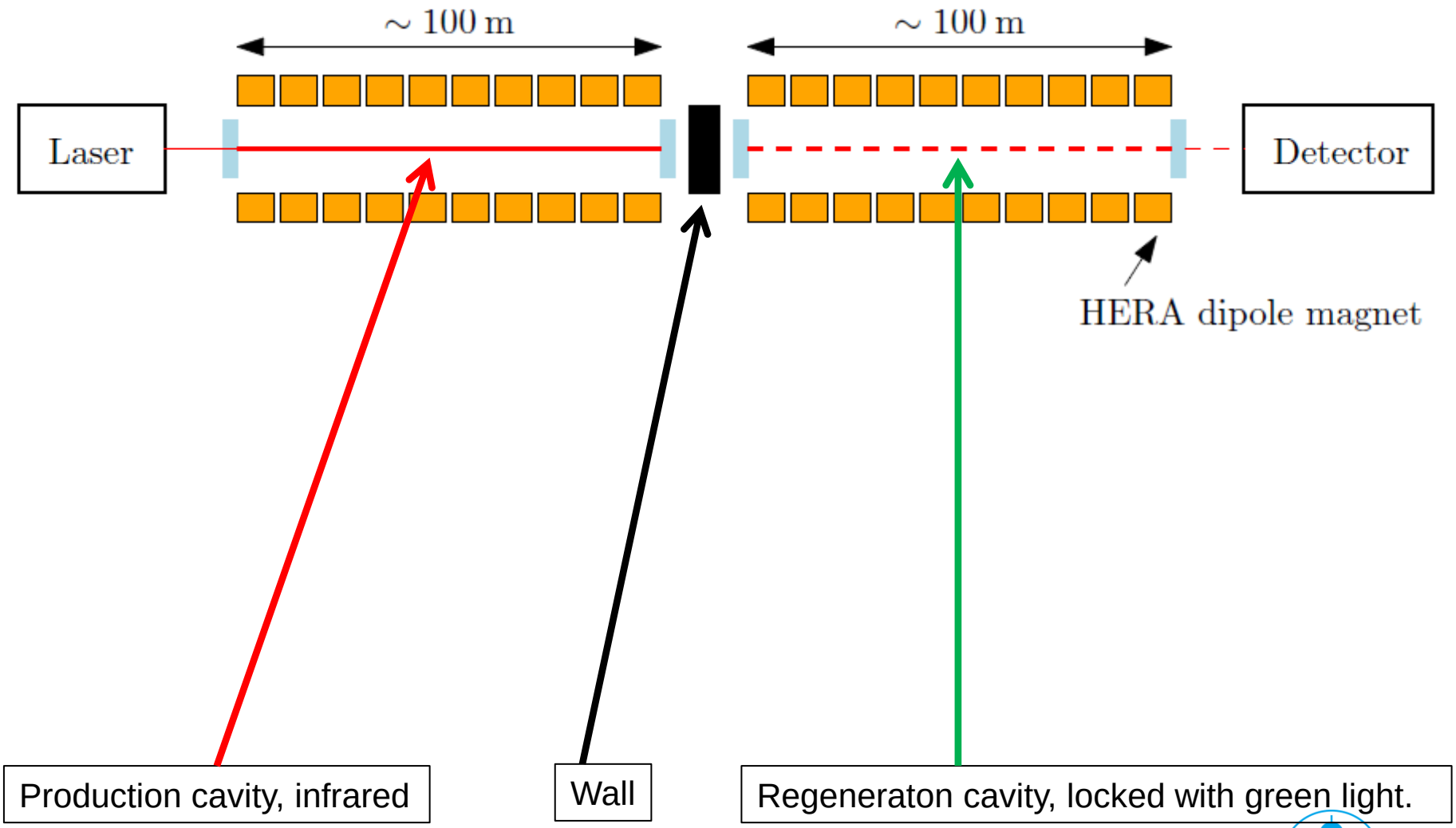


Adapt techniques developed for LIGO, AEI Hanover and U. of Florida

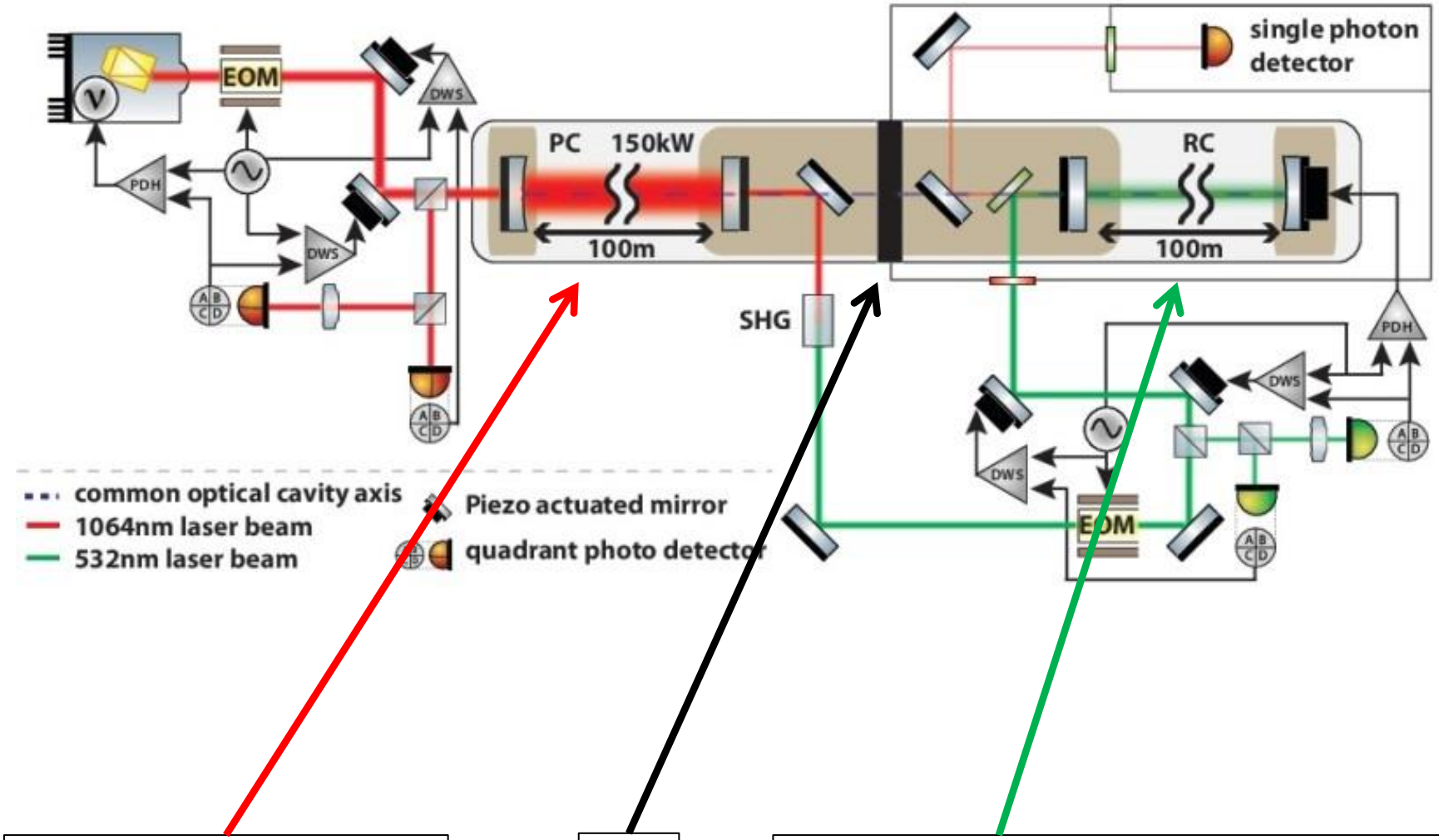


Close collaboration with NIST (Boulder) and PTB Berlin

ALPS II optics



ALPS II optics

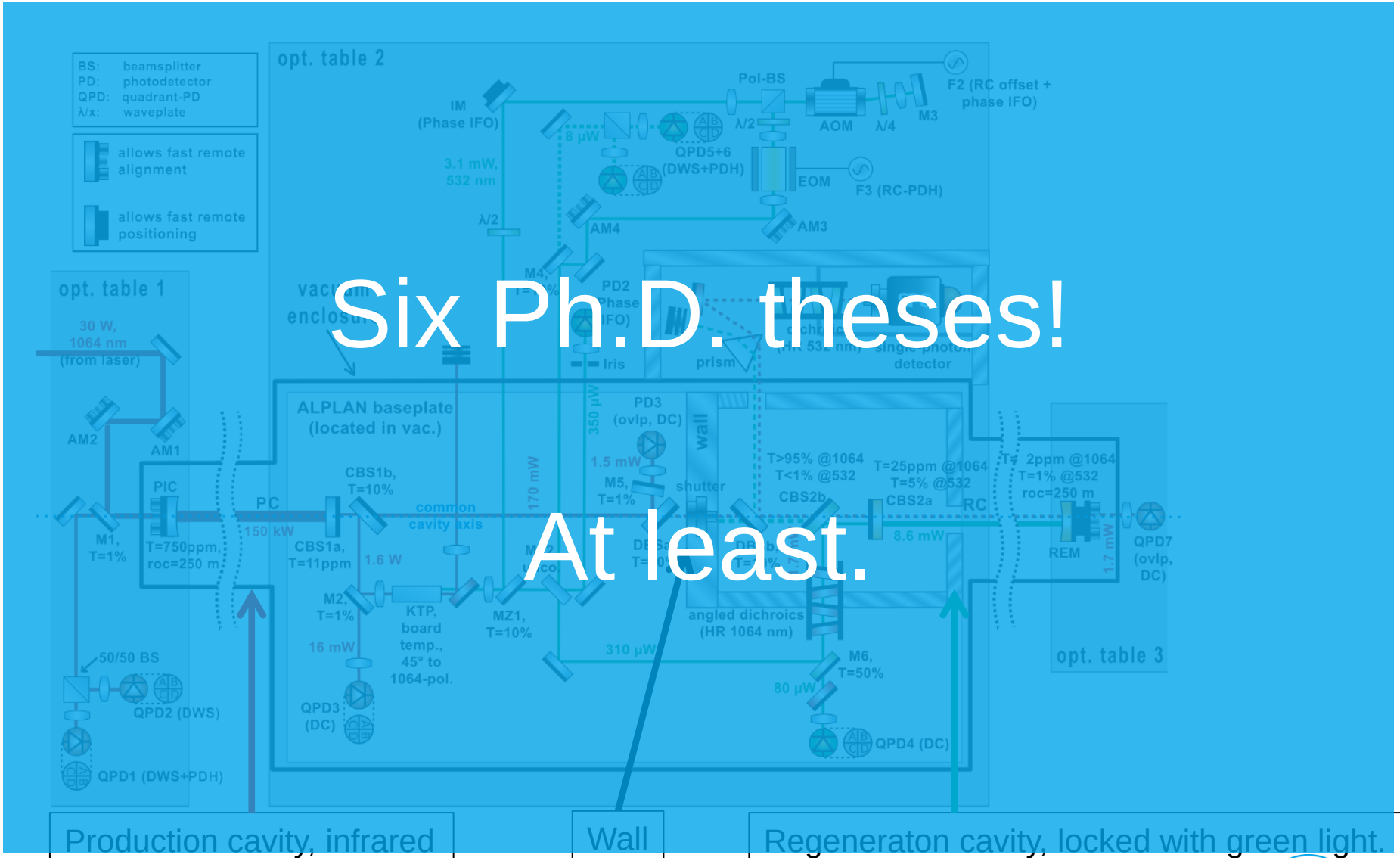


Production cavity, infrared

Wall

Regeneraton cavity, locked with green light.

ALPS II optics



Six Ph.D. theses!

At least.

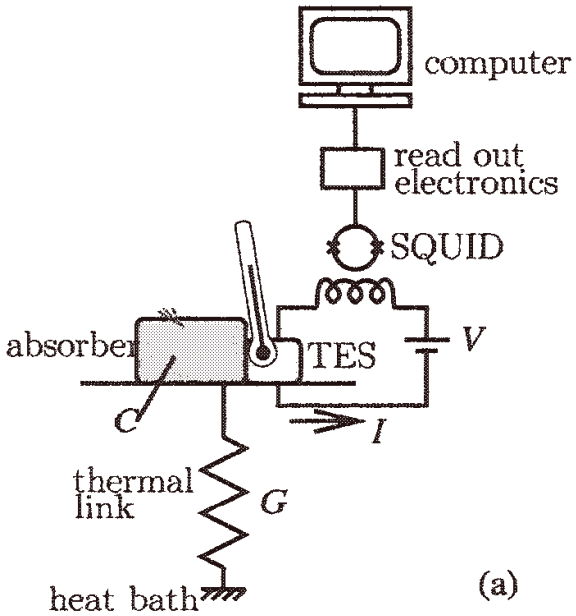
Production cavity, infrared

Wall

Regeneraton cavity, locked with green light.

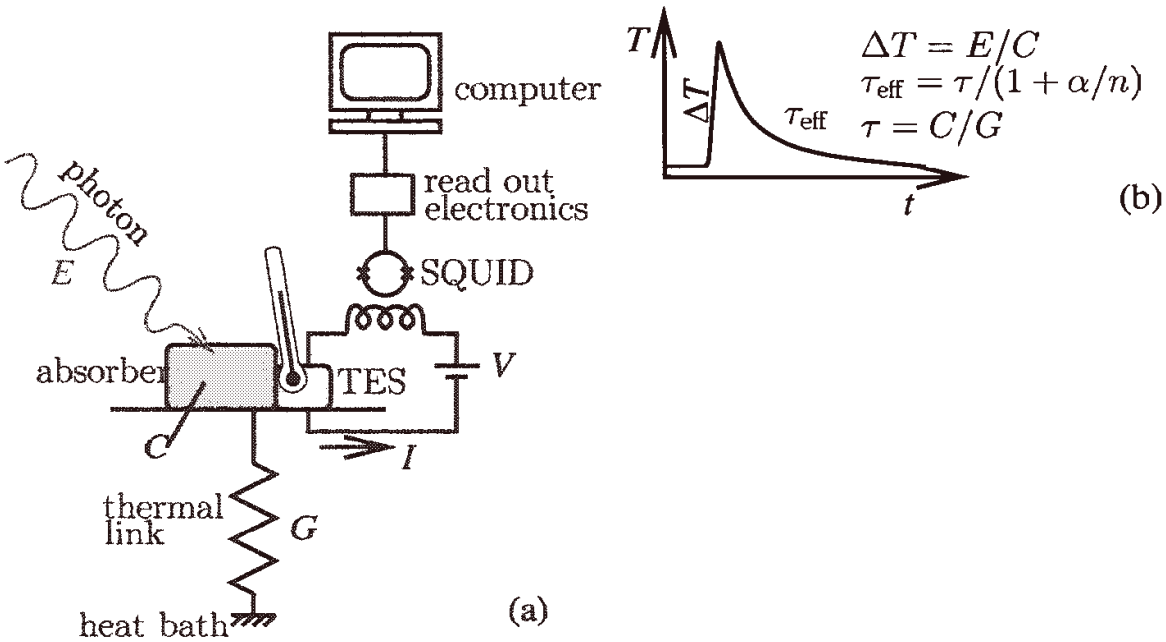
ALPS II detector

Transition Edge Sensor (TES)



ALPS II detector

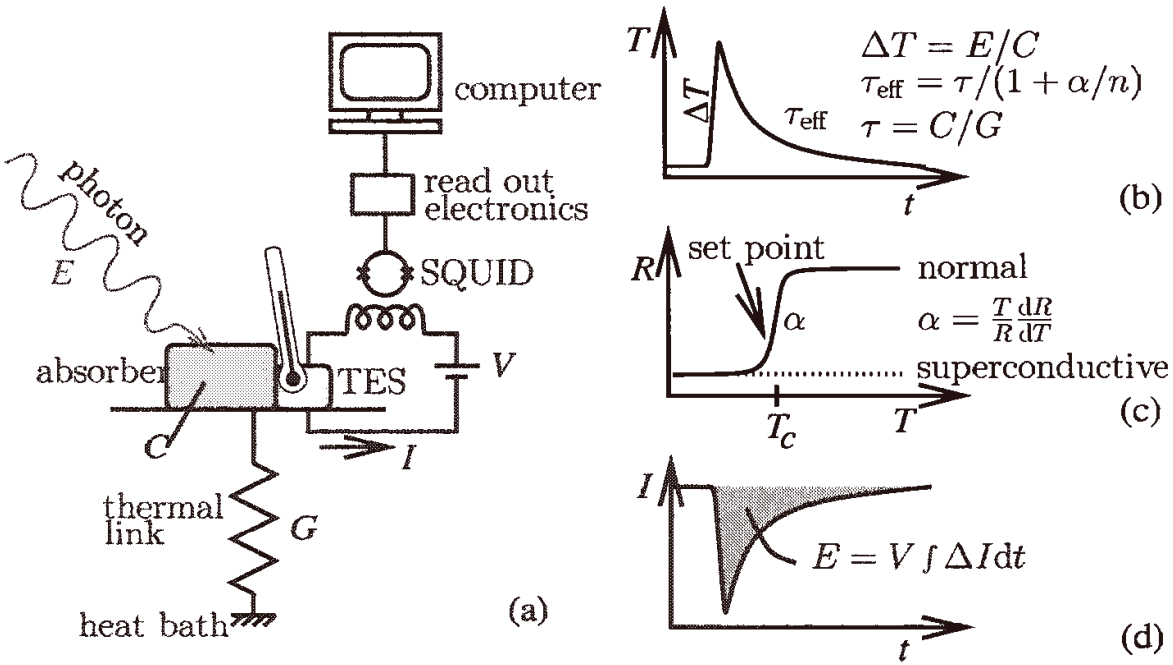
Transition Edge Sensor (TES)



ΔT = 100 μK

ALPS II detector

Transition Edge Sensor (TES)



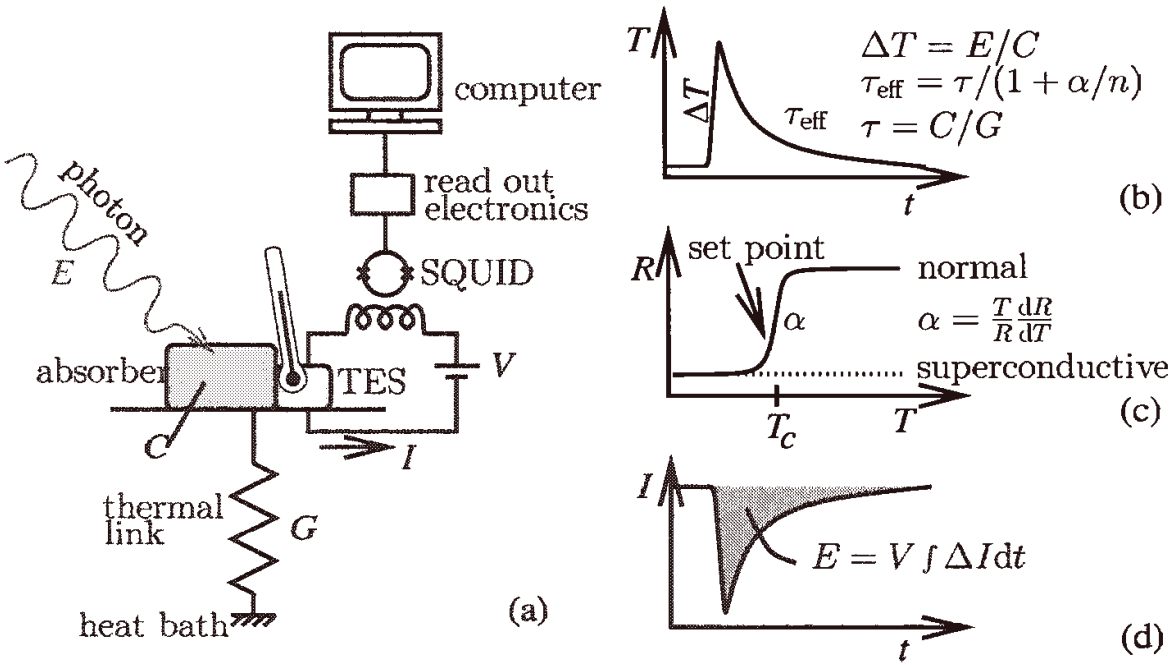
ΔT ≈ 100 μK

ΔR ≈ 1 Ω

ΔI ≈ 70 nA

ALPS II detector

Transition Edge Sensor (TES)



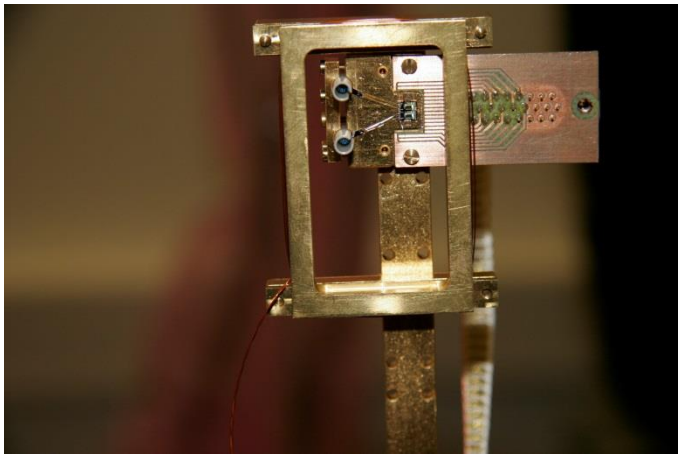
ΔT ≈ 100 μK

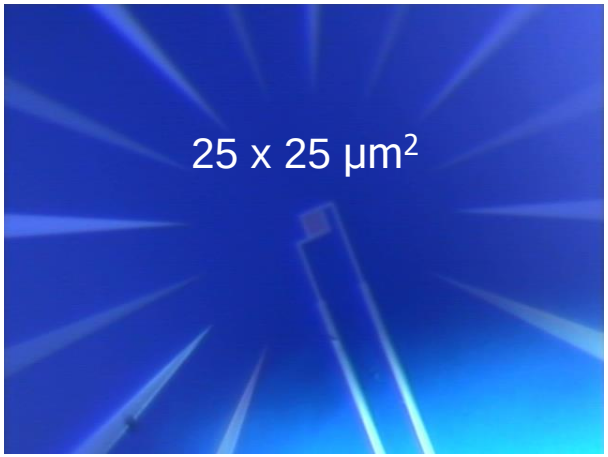
ΔR ≈ 1 Ω

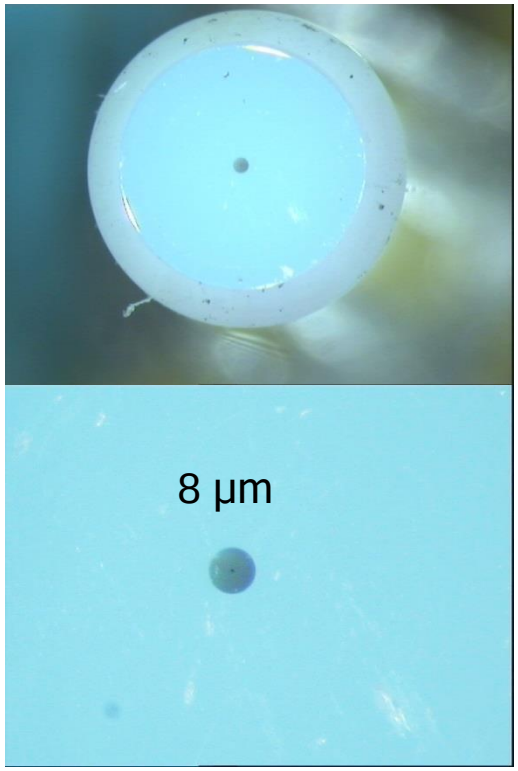
ΔI ≈ 70 nA

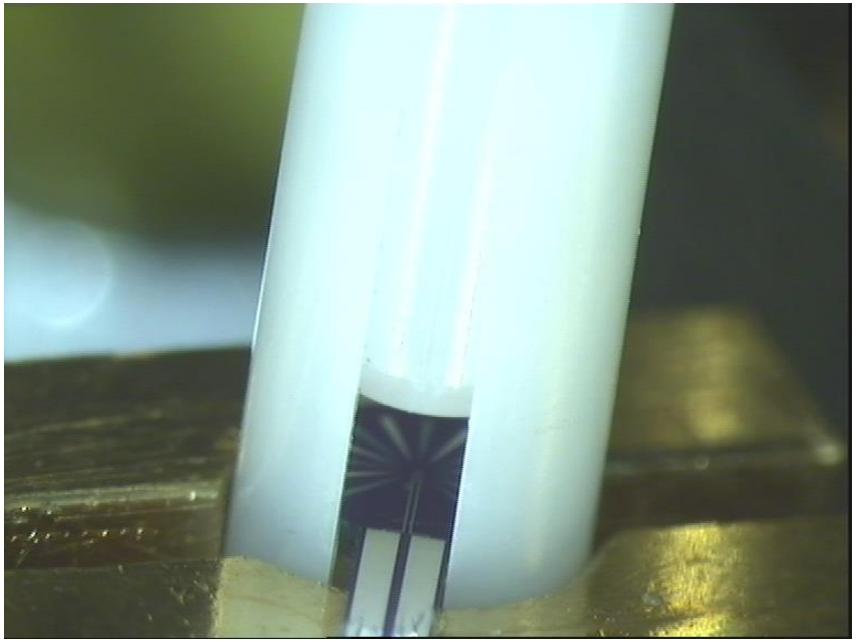
- Expectation:
  very high quantum efficiency, also at 1064 nm,
  very low noise.

ALPS II: Transition Edge Sensor (TES)

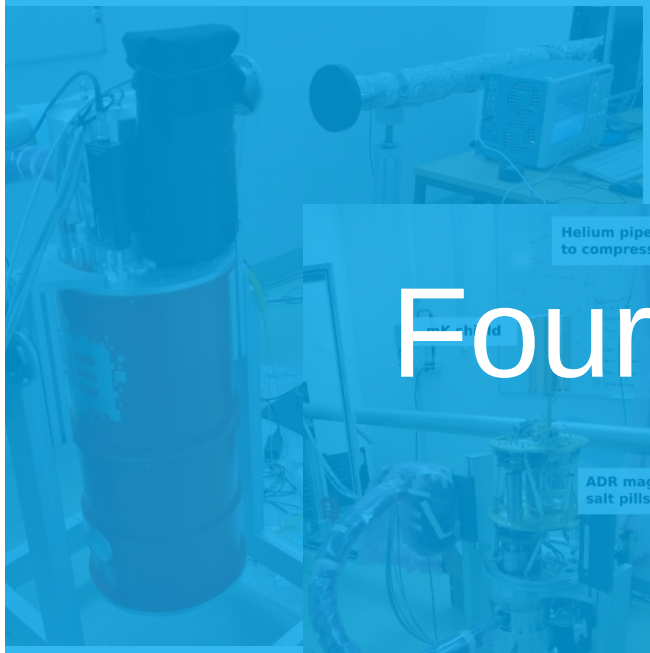




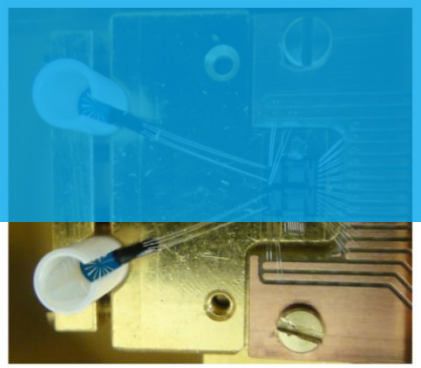




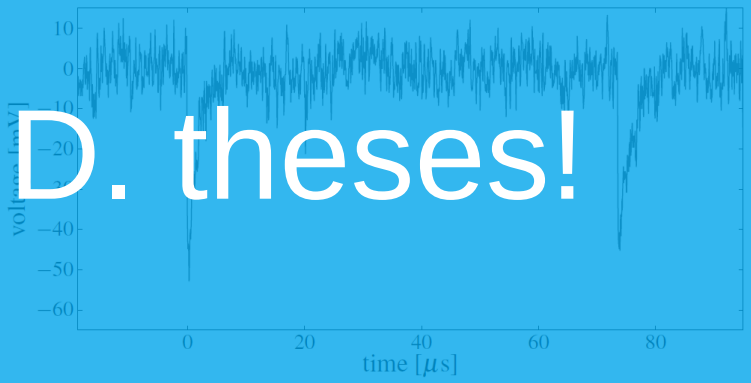
ALPS II: Transition Edge Sensor (TES)



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.

Four Ph.D. theses!

At least.

First ALPS II results

- WISP measurements:

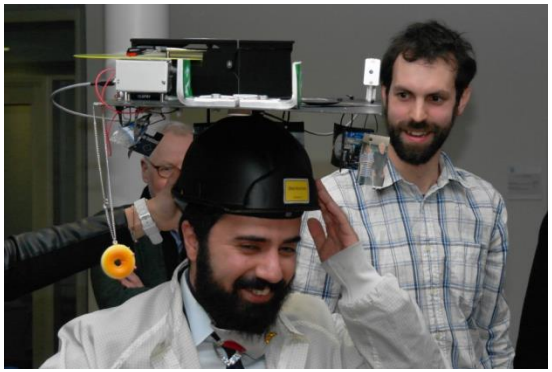
First ALPS II results

- WISP measurements: none

First ALPS II results

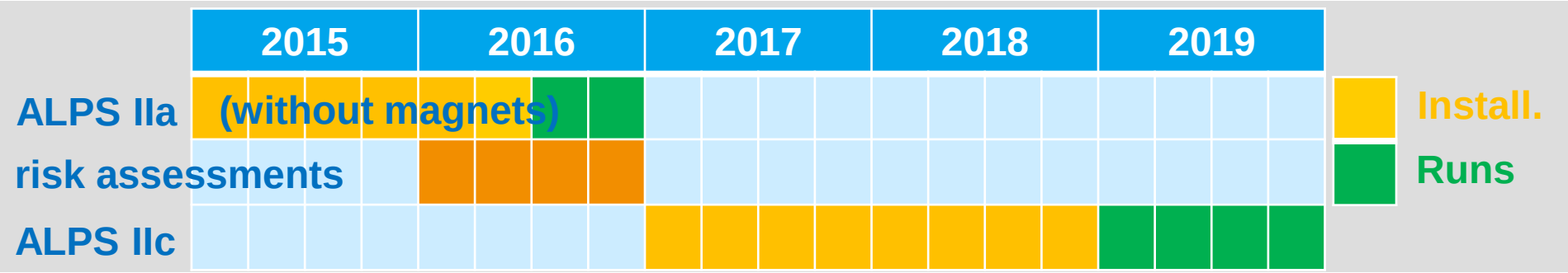
- WISP measurements: none
- But starting careers with ALPS seems to work:
  The three (male) DESY PhD students have finished 2014 and 2015.



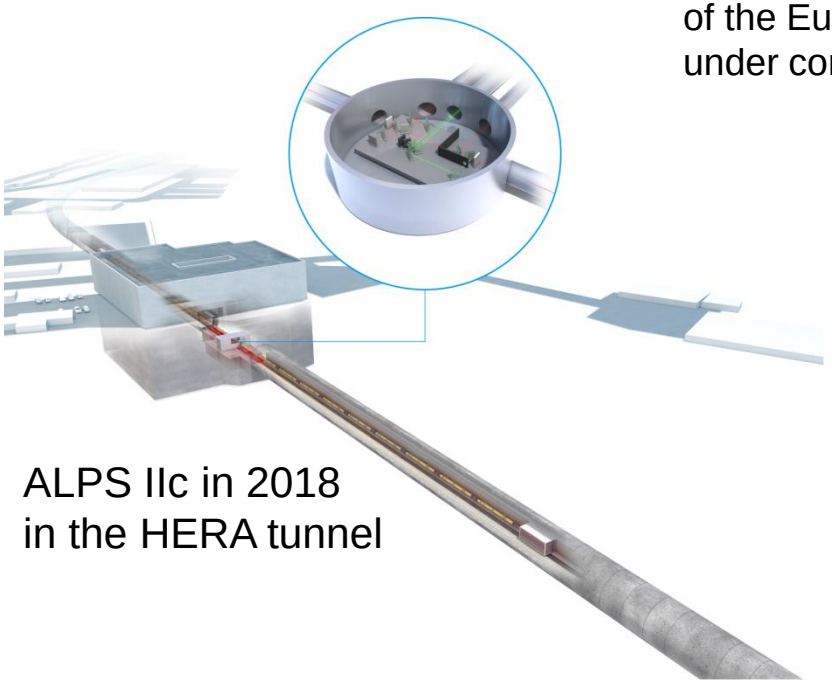


- The two (female) postdocs got nice positions:
  - Tenure track at XFEL (much too early from the ALPS point of view),
  - CERN fellowship.

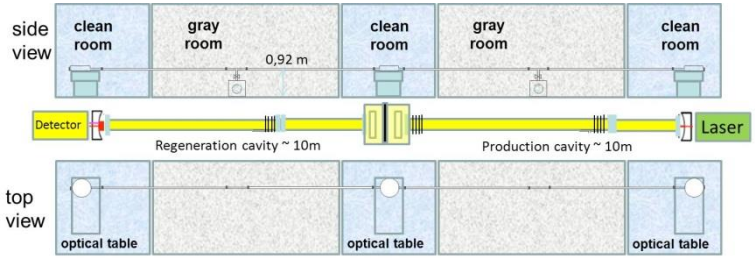
ALPS II schedule (rough)



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



ALPS IIc in 2018
in the HERA tunnel



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

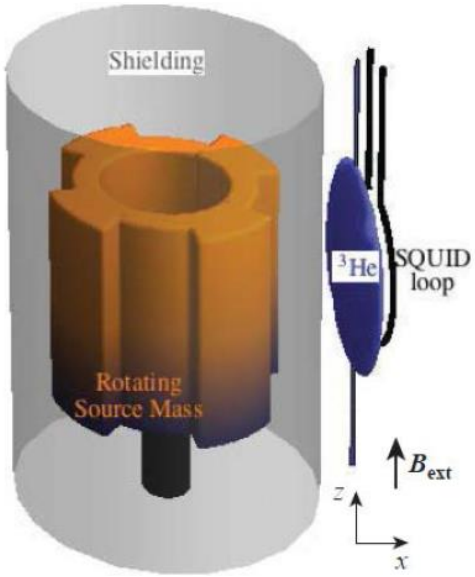
- neoLASE, PTB Berlin, NIST (Boulder).

Exploiting WISP-nucleon couplings in the lab

Search for long range forces mediated by axions / ALPs:

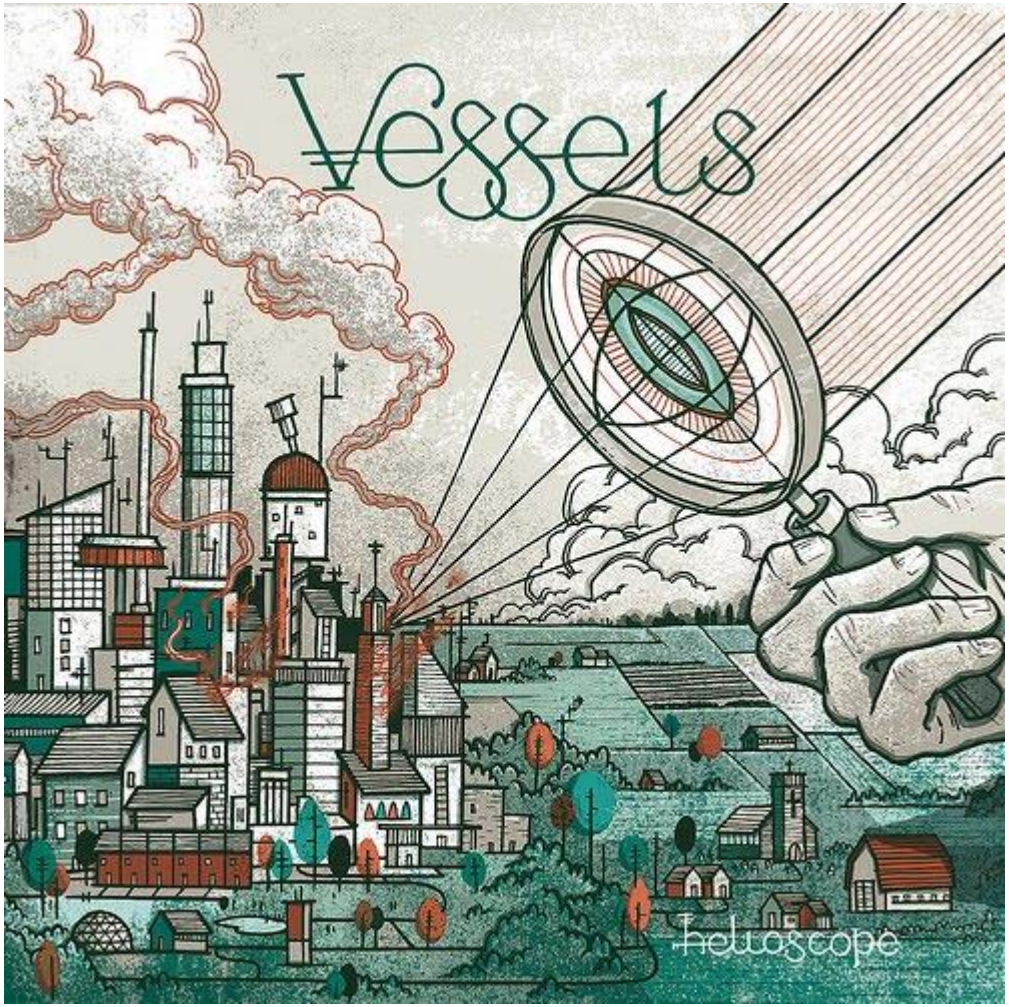
Axion **R**esonant **I**nter**A**ction **D**etectioN **E**xperiment (ARIADNE)

- A rotating mass induces a periodic axion-mediated force on a polarized target.
- An external B-field and NMR techniques are used to measure this force.
- ARIADNE will be sensitive mainly to spin-dependent forces and could bridge the gap between astrophysical bounds and dark matter axion searches.



A.Arvanitaki and A.Geraci, Phys. Rev. Lett. 113,161801 (2014).

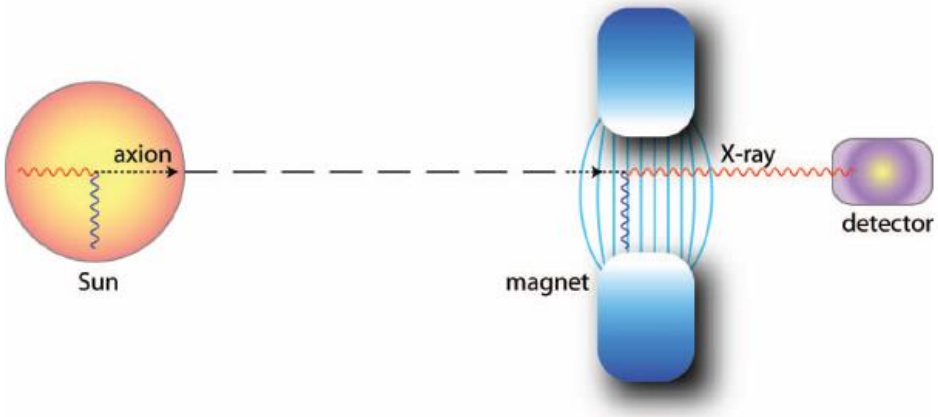
Helioscopes

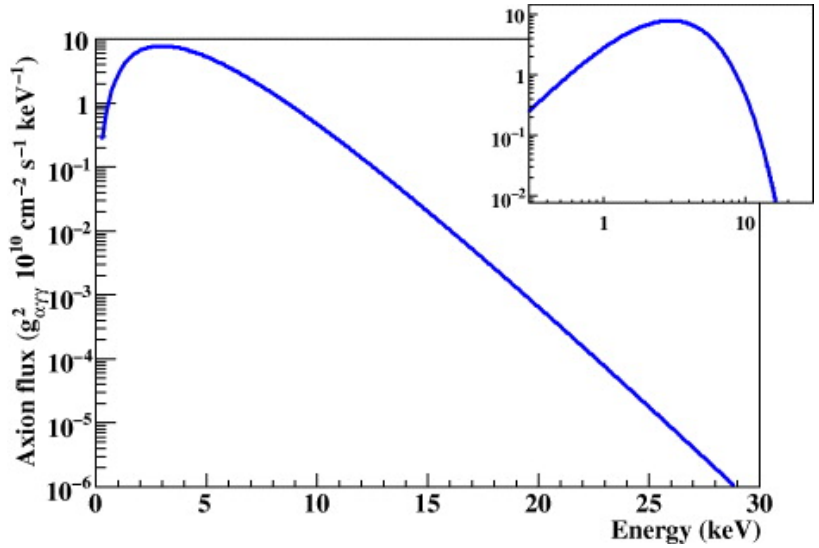


http://middleboop.blogspot.de/2011/02/vessels-helioscope.html

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.

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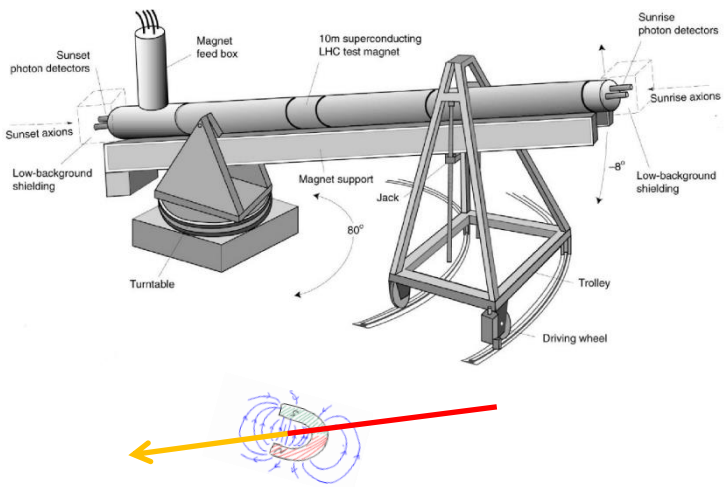
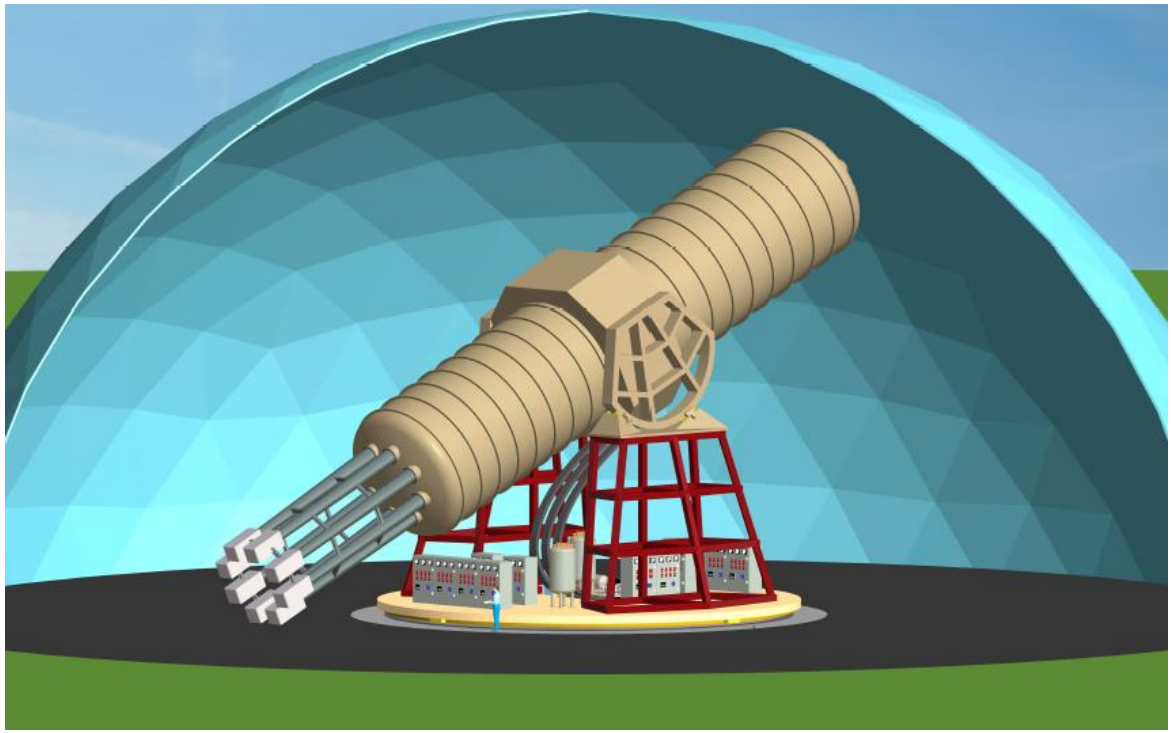


- Most sensitive experiment searching for axion-like particles.
  - Unfortunately no hints for WISPs yet.
  - If a WISP is found, it would be compatible with known solar physics!

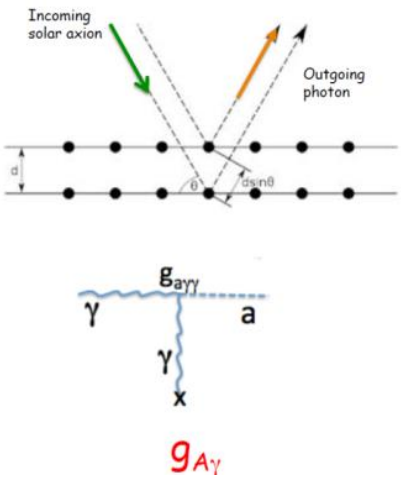
IAXO proposal

- 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.



Solar axions in EDELWEISS

- Axions / ALPs produced in the sun might convert into photons via coherent Bragg diffraction in the crystals of EDELWEISS.



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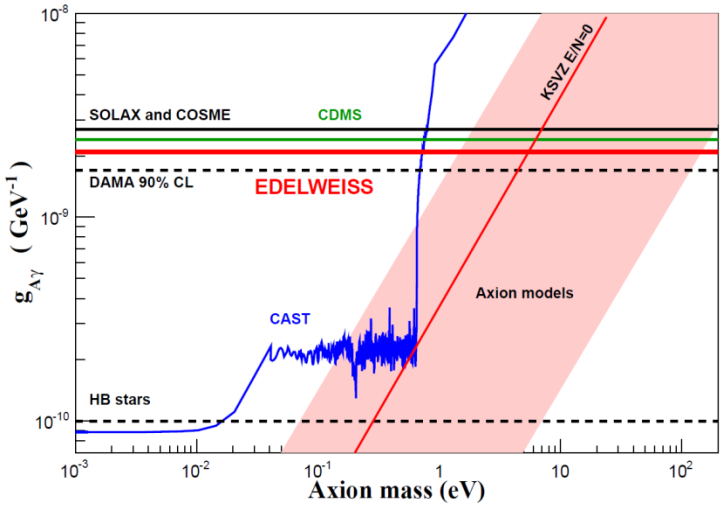
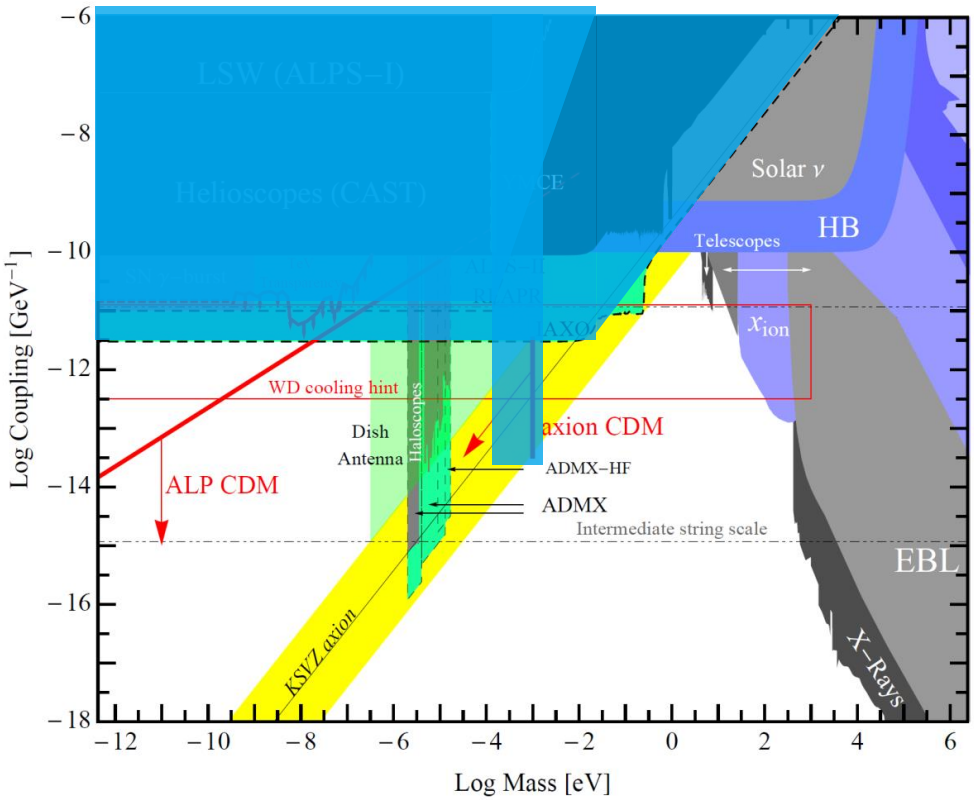


- Such experiments probe parameter region higher masses not accessible in other experiments.
- Nice opportunities to search for WISPs in experiments designed for WIMPs!

Summary on axion / ALP candidate searches

Warning: this is just to guide the eye! Not all experiments will measure the coupling to photons!

- ALPS II can reach the parameter region indicated by hints from astrophysics.
- Helioscopes reach QCD axion parameter space.
- However:
  IAXO is of O(50 M€),
  ALPS II is of O(2 M€).
- ARIADNE might probe the QCD axion around 0.1 meV.



More on axions

- The University of Bonn is organizing a "Bethe Forum" on "Axions and the Low Energy Frontier", 7-18 March 2016.

Summing up

Maturity of selected WISP searches

A very coarse and very subjective exemplary classification scheme:

WISP search	Quick experiment just with stuff sitting around	Do the best with available equipment	Dedicated tools for dedicated experiments

Maturity of selected WISP searches

A very coarse and very subjective exemplary classification scheme:

WISP search	Quick experiment just with stuff sitting around	Do the best with available equipment	Dedicated tools for dedicated experiments
Direct DM search	FUNK		ADMX
Indirect DM search	Analysis of archive data		
Candidates in the laboratory	ALPS I	ALPS II	
Candidates in astrophysics		CAST	IAXO
	Analysis of archive data		

Many WISP experiments are just starting!

To-take-home

- Axion, ALPs and other WISPs are strongly motivated by theory and could provide the dark matter in the universe.
- WISPs provide a window to particle physics beyond 10^5 TeV.
- Perhaps we already start seeing WISPy phenomena in astrophysics.
- WISPy experiments are not always mature yet and a plenty of new concepts are waiting for realization.
  WISP experiments are realized in time and resource domains very different from accelerator based particle physics.
- Experimental and theoretical WISP physics is (still) an emerging physics field with lots of options for young (and even not so young) scientists.
- In order to get a clue on dark matter, one has to exploit all experimental possibilities.

The fun of it: WISP experiments with German participation

Thank you very much for your attention!