Future options for searching axion-like particles through light-shining-through-a-wall experiments

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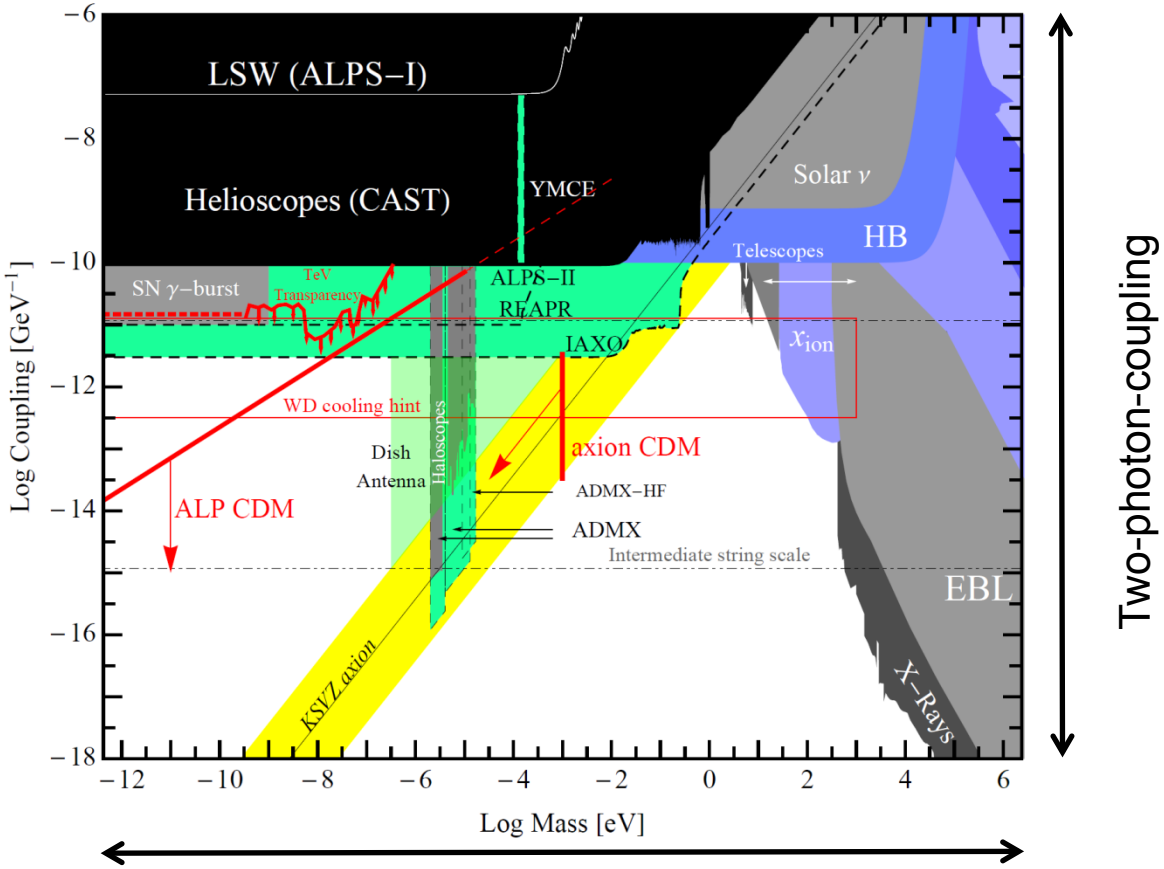
Benno Willke (AEI Hanover)
Herman Ten Kate (CERN)

HELMHOLTZ
ASSOCIATION

DESY

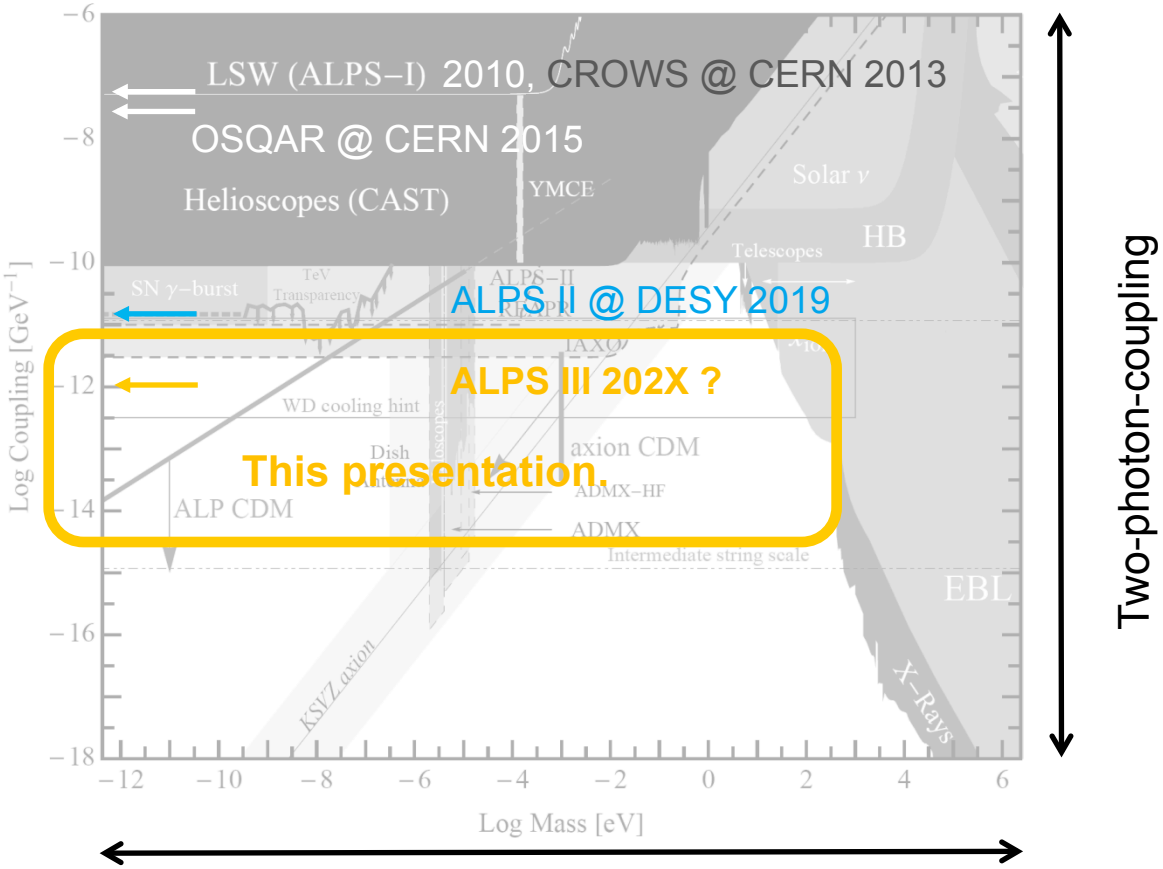
A LSW roadmap



Two-photon-coupling

axion-like particle mass

A LSW roadmap



Two-photon-coupling

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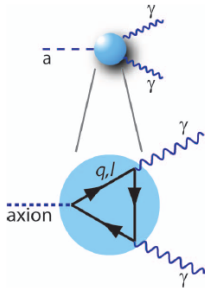
Outline

- Basics
  - Motivation
  - Challenges
  - Fundamentals of Light-Shining-through-a-Wall
- A future LSW experiment (“ALPS III”)
  - Pros and cons
  - Design criteria
  - Magnets, optics, detectors
  - Expected performance
- Summary

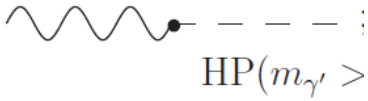
Introduction to WeaklyInteractingSlimParticles

- WISPs are hypothetical bosons with masses below 1eV (< 0,000002 m_e).
- 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: $\Omega_a / \Omega_c \sim (f_a / 10^{12}\text{GeV})^{7/6}$



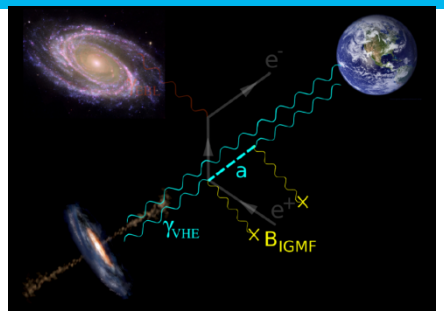
- Axion-like particles (ALPs):
  Coupling strength and mass are not related by one f_a.

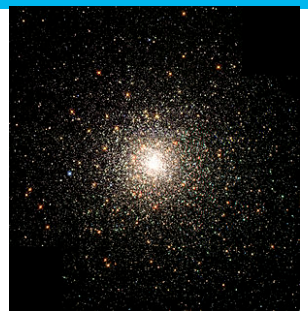
- Hidden photons: neutral vector bosons.

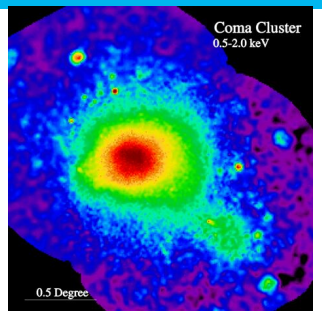


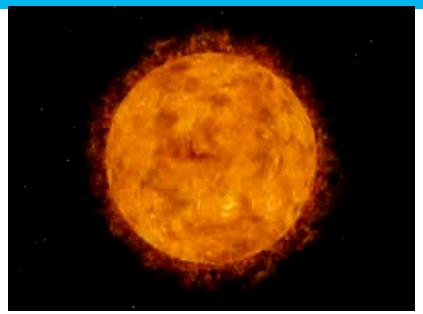
- Mini-charged particles, Chameleons, massive gravity scalars, …
  (some of these might be related to dark energy).

(Vague) hints for WISPs in the sky?





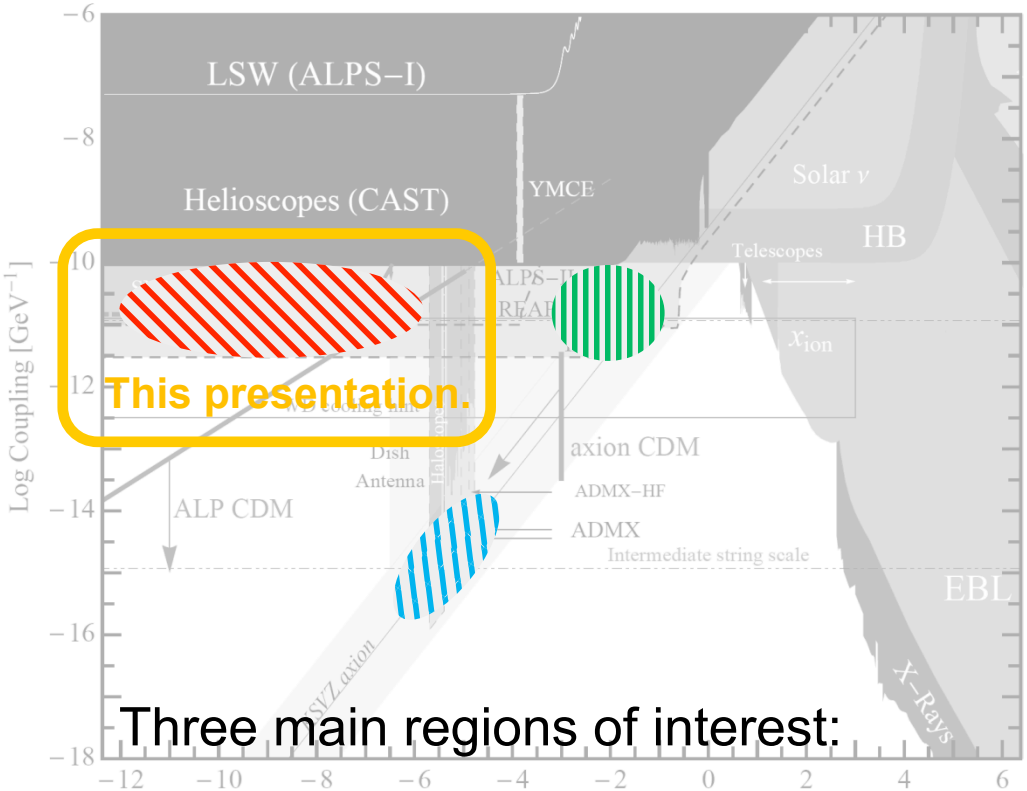


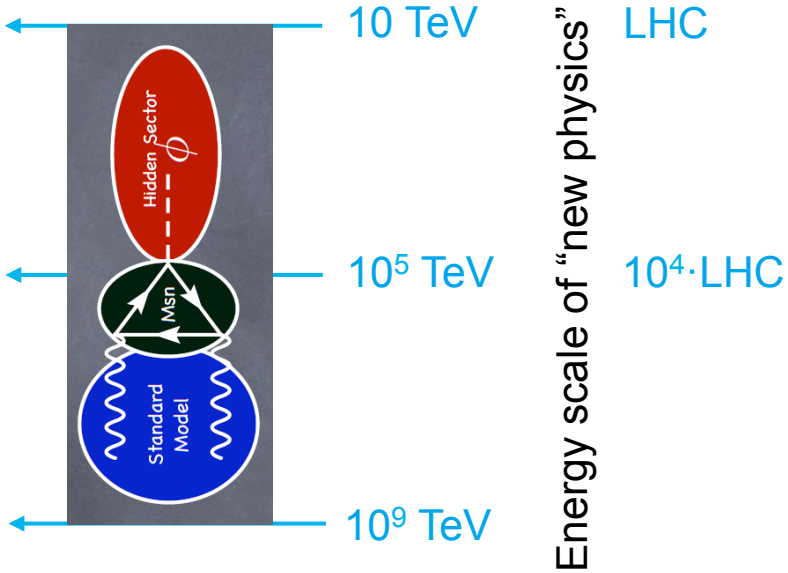


Phenomenon	ALP mass [eV]	ALP-γ coupl. [GeV^{-1}]	Reference
TeV transparency	$< 10^{-7}$	$> 10^{-12}$	arXiv:1302.1208 [astro-ph.HE]
Star developments	$< 10^{3}$	$\approx 3 \cdot 10^{-11}$	arXiv:1512.08108 [astro-ph.HE] arXiv:1605:06458 [astro-ph.SR]
CAB (Coma Cluster)	$< 10^{-13}$	10^{-12} to 10^{-13}	arXiv:1406.5188 [hep-ph]

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

The big picture: ALPs





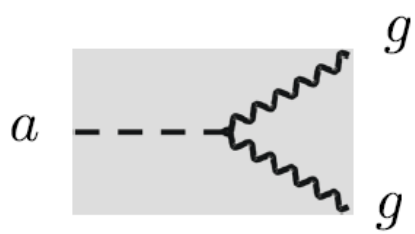
Three main regions of interest:

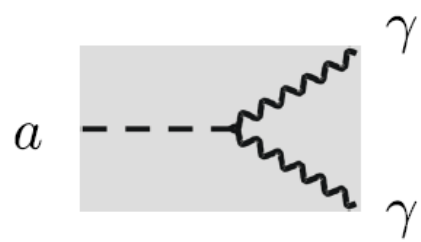
- Axion-like particles: "new physics" around 10^5 TeV.
- QCD axions: "new physics" around 10^5 TeV.
- QCD axions as dark matter: "new physics" around 10^9 TeV.

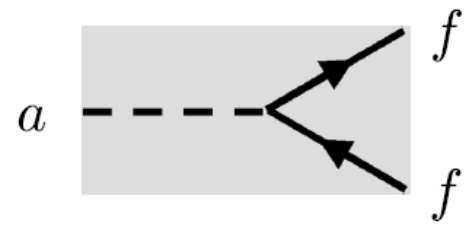
Axion and axion-like-particle (ALP) couplings

- 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.

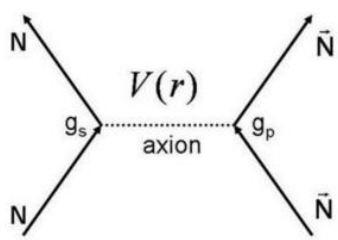
$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C_{ag}}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\partial_\mu a\, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

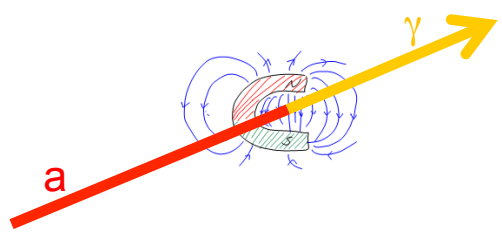


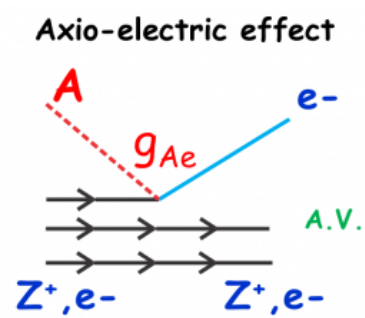




Courtesy A. Ringwald







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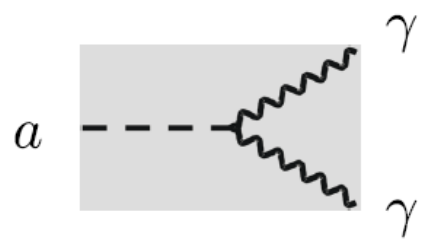
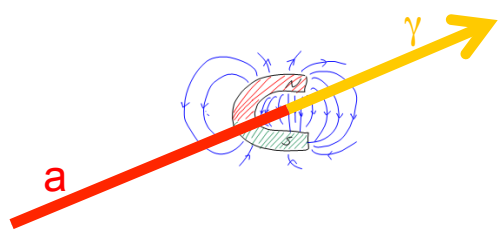




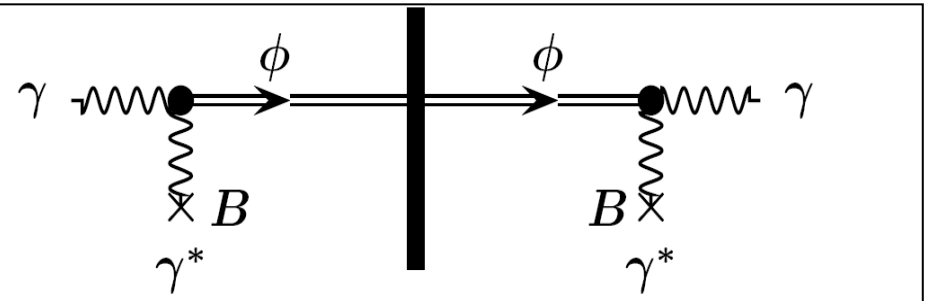
Courtesy A. Ringwald

How to look for ALPs …

… by exploiting their coupling to photons:

> WISPs pass any barrier and could make

light-shining-through-a-wall.



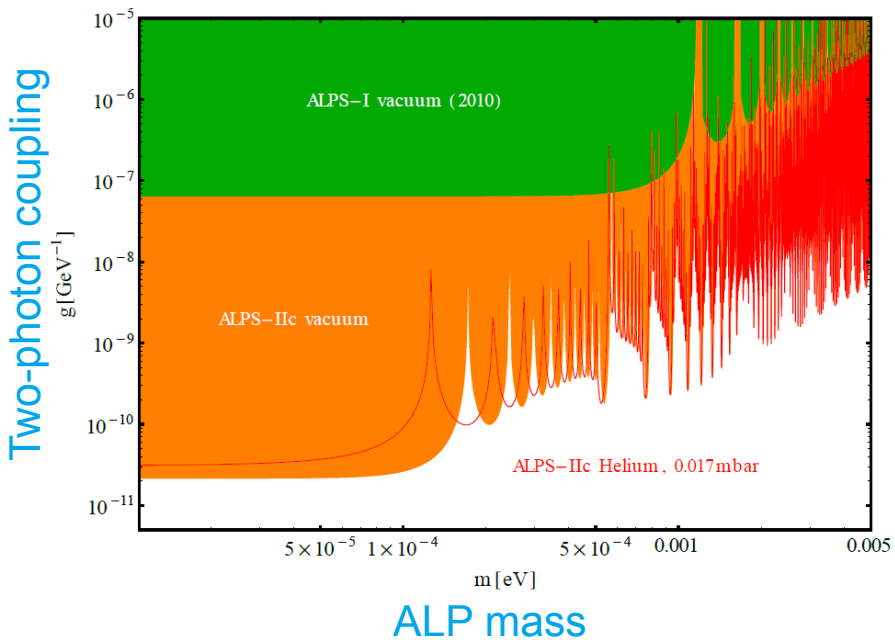
Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

Axions, axion-like particles

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

$q = p_\gamma - p_\Phi$
l: length of B field

Exemplary plot on sensitivity (ALPS II)



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TECHNICAL REPORT

Any light particle search II — Technical Design Report

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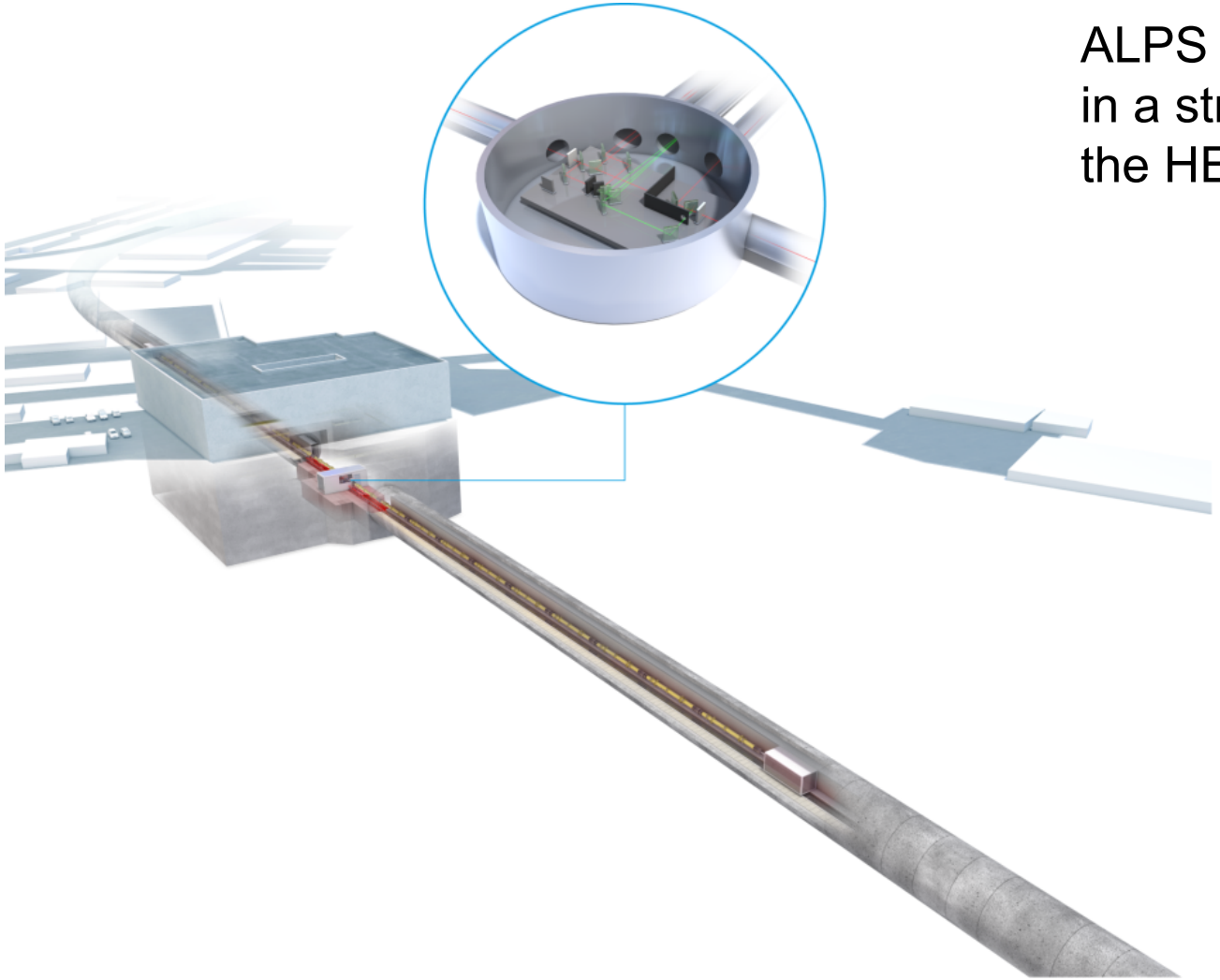
http://iopscience.iop.org/article/10.1088/1748-0221/8/09/T09001/meta;jsessionid=1674E7ACB2293DB65394D34574F3AF ED.c3.iopscience.cld.iop.org

LSW experiments working with optical photons (around 1 eV) provide high sensitivities for very low mass ALPs (below 0.1 meV).

- The mass reach follows from a phase shift developing between the light and ALP fields due to the non-zero ALP mass.

ALPS II at DESY in 2019



ALPS II will be installed in a straight section of the HERA tunnel.

How to look for ALPs …

… by exploiting their coupling to photons:

> WISPs pass any barrier and could make

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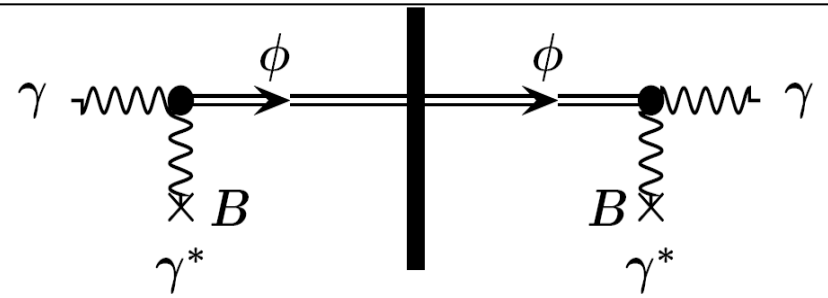

Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

Axions, axion-like particles

ql << 1; conversion and re-conversion:

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

Outline

- Basics
  - Motivation
  - Challenges
  - Fundamentals of Light-Shining-through-a-Wall
- A future LSW experiment (“ALPS III”)
  - Pros and cons
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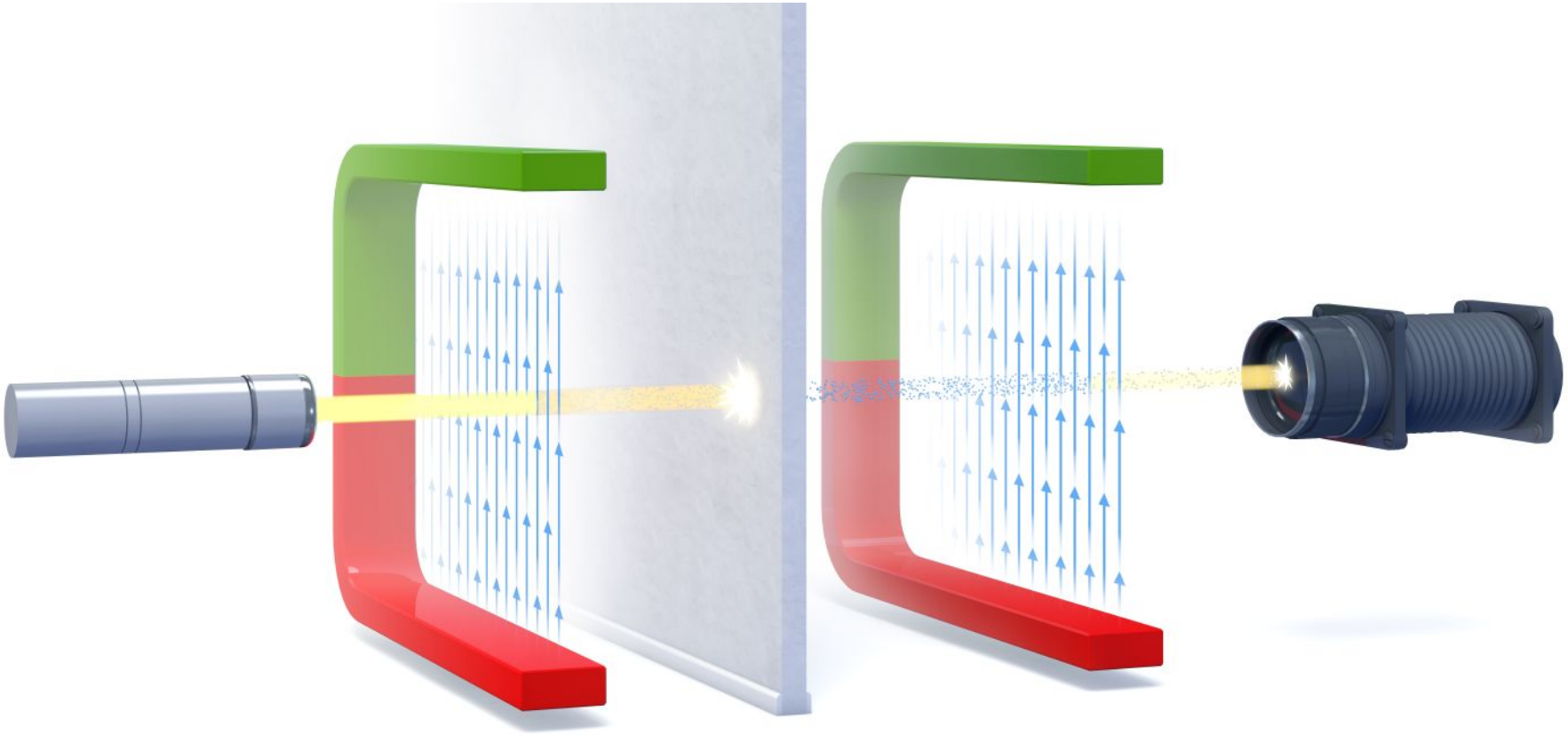
Light-shining-through-a-wall in the laboratory



Pros and cons for LSW in the laboratory

ALP parameter	LSW (laboratory)	Helioscopes	Dark matter searches

Pros and cons for LSW in the laboratory

ALP parameter	LSW (laboratory)	Helioscopes	Dark matter searches
Parity and spin	yes	perhaps	yes
Coupling $g_{a\gamma}$	yes	no	no
Coupling · flux	(does not apply)	yes	yes

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Rely on astrophysical assumptions	no	yes	yes

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Coupling $g_{a\gamma}$	yes	no	no
Coupling · flux	(does not apply)	yes	yes
Mass	perhaps	perhaps	yes
Rely on astrophysical assumptions	no	yes	yes
QCD axion	no	yes	yes

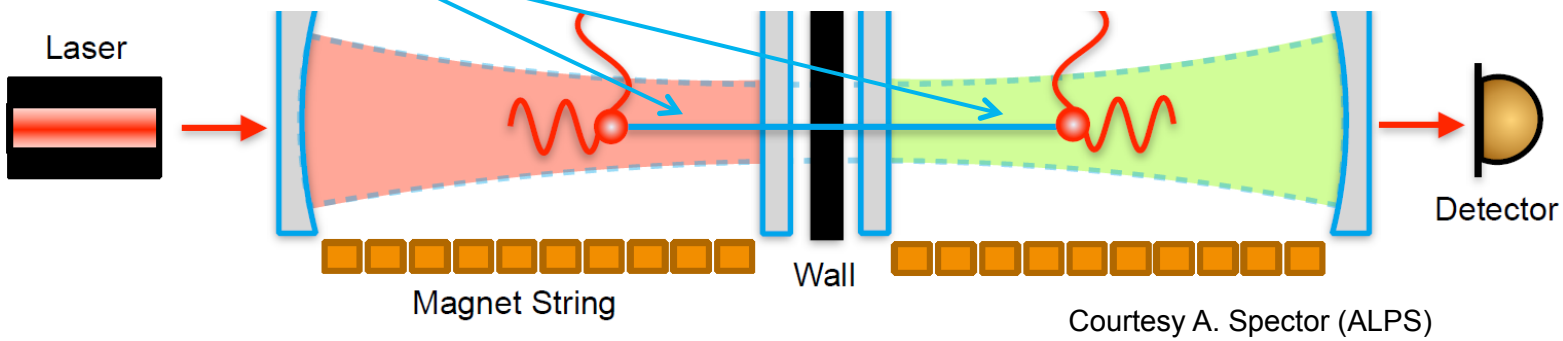
LSW in the laboratory is very well suited to look for axion-like particles.

Design criteria for LSW experiments

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

Design criteria for LSW experiments with optical resonators

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

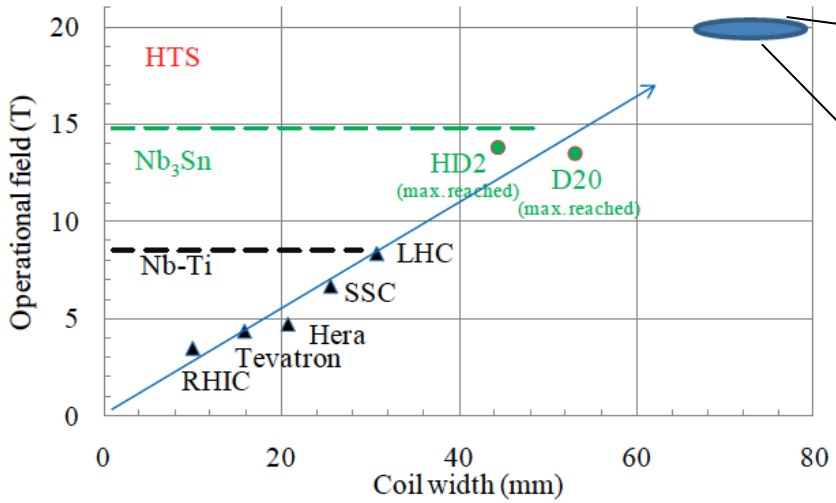


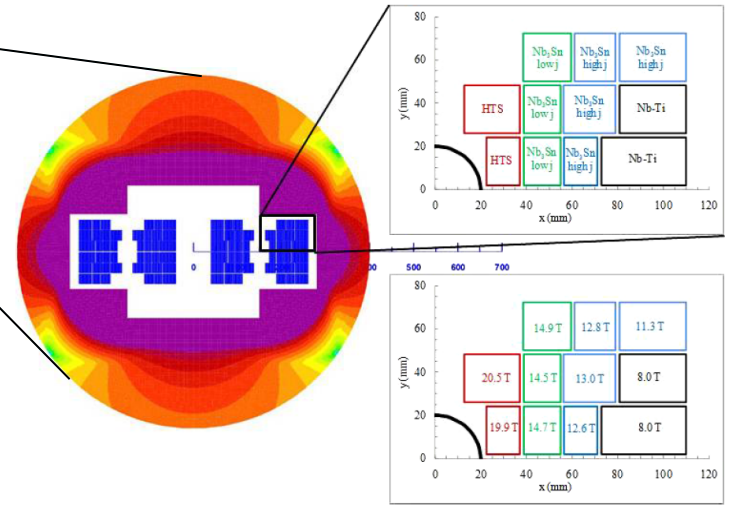
- Use long strings of strong dipole magnets.
- Implement optical resonators to recycle the light before the wall and to boost the re-conversion of ALPs to photons behind the wall.
- The maximal length is given by the aperture of the magnets and the beam shape of the resonating mode in the optical resonators.
- The maximal circulating light power before the wall is given by the damage threshold of the mirrors and the beam spot size.

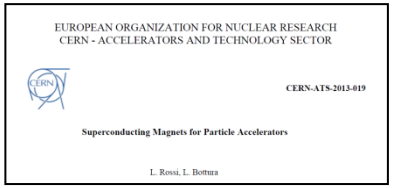
Present and future dipole magnets for LSW experiments

LSW experiments use dipoles developed for particle accelerators (and might use in future dipole magnets presently under development).

https://fcc.web.cern.ch/Pages/Magnets.aspx



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CERN-ATS-2013-019

Superconducting Magnets for Particle Accelerators

L. Rossi, L. Bottura

https://fcc.web.cern.ch/Documents/Publications/Magnets/CERN-ATS-2013-019.pdf

New demonstration dipole magnets under study for HE-LHC or FCC might provide

- a magnetic field of 13 T (or later even up to 15 or 16 T)
- in an aperture of 100 mm.

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LSW experiments use dipoles developed for particle accelerators (and might use in future dipole magnets presently under development).

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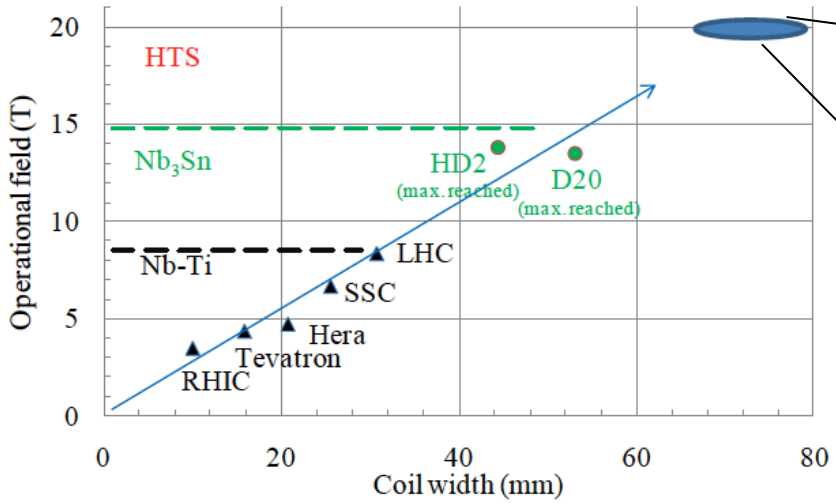

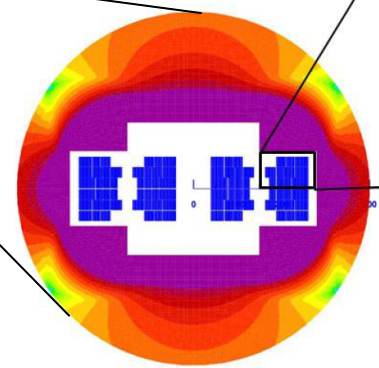

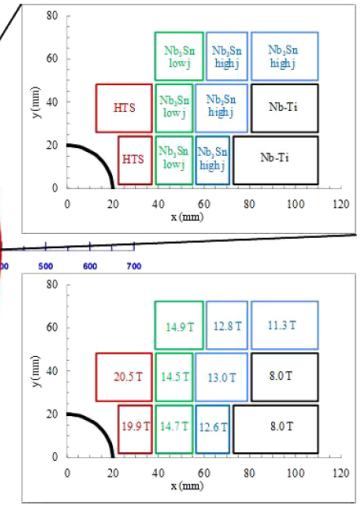

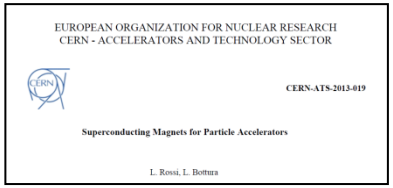
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CERN-ATS-2013-019

Superconducting Magnets for Particle Accelerators

L. Rossi, L. Bottura

https://fcc.web.cern.ch/Documents/Publications/Magnets/CERN-ATS-2013-019.pdf

- Thereafter one (or more) of these magnet designs may be produced in small series and become available for LSW experiments.
- Depending of unit length, some 30-40 units may be needed for a 500 m long magnet string.

Present and future dipole magnets for LSW experiments

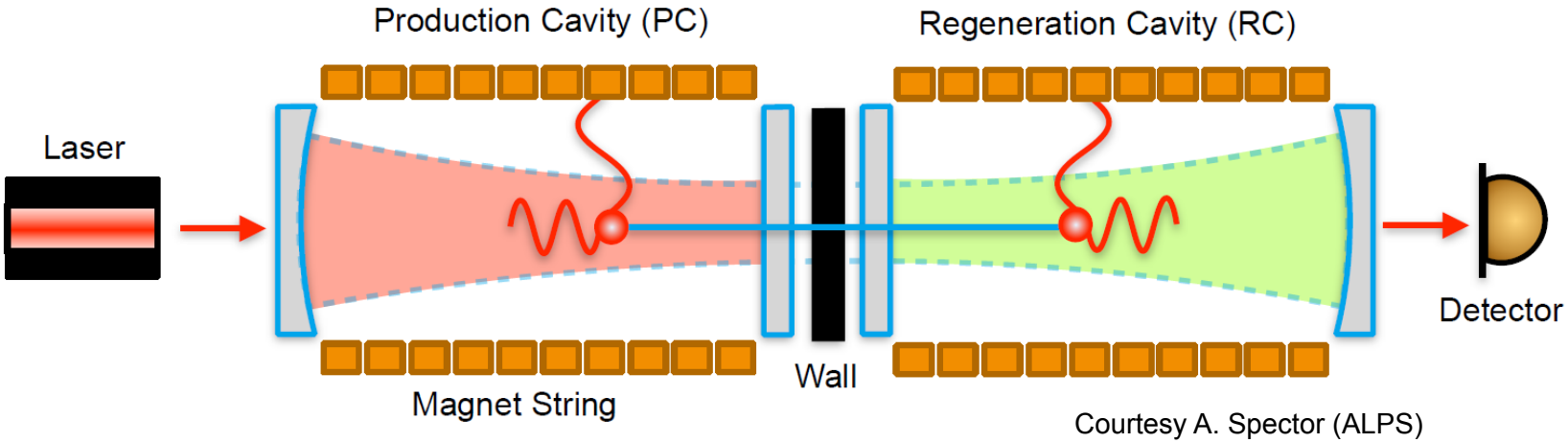
LSW experiments use dipoles developed for particle accelerators (and might use in future dipole magnets presently under development).

Dipole	Aperture [mm]	Field strength [T]	LSW experiment	Number of used dipoles
HERA (straightened)	50	5.3	ALPS II (DESY)	20
LHC	40	9.0	OSQAR (CERN)	2
"FCC"	100	13	"ALPS III"	

For the "FCC" dipole parameters see for example:

- Bottura L, de Rijk G, Rossi L, Todesco E., IEEE Trans. Appl. Supercond. 22:4002008 (2012), http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6656892
- Todesco E, Bottura L, de Rijk G, Rossi L., IEEE Trans. Appl. Supercond. 24:4004306 (2014), http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6172724

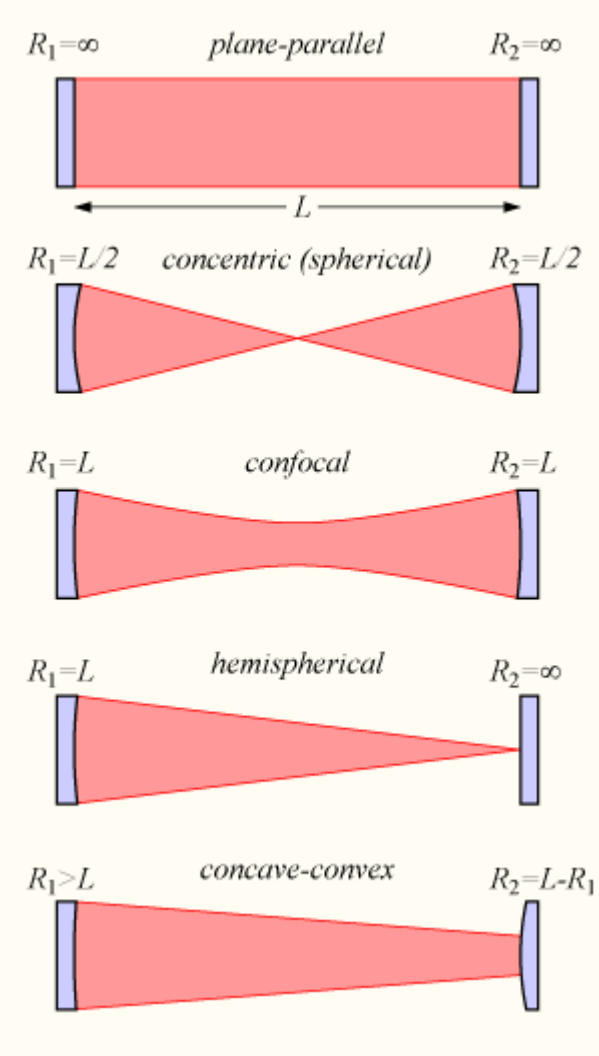
Optical resonators in LSW experiments



The resonators before and after the wall have to resonate to the same mode.

- Flat mirrors are placed in the center of the experiment around the wall.
- The light power density is highest on the flat mirror before the wall (mirror damage threshold)!

Optics for LSW experiments I: resonator configuration



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

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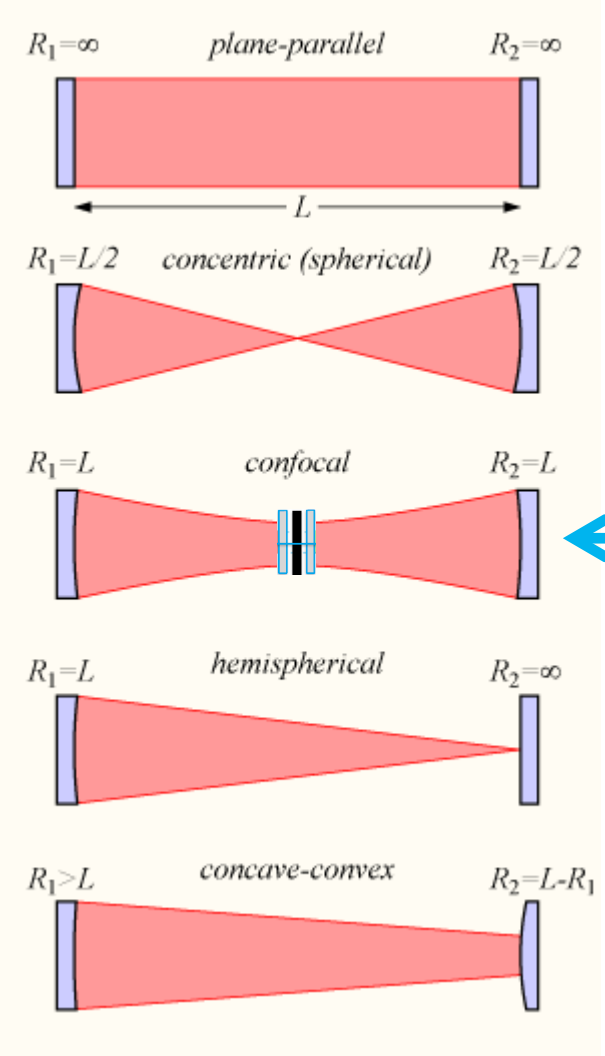

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A confocal cavity:

- longest resonator for a given aperture,
- largest beamspot in the center and hence lowest power density on central mirror, therefore highest circulating power in the resonator before the wall.

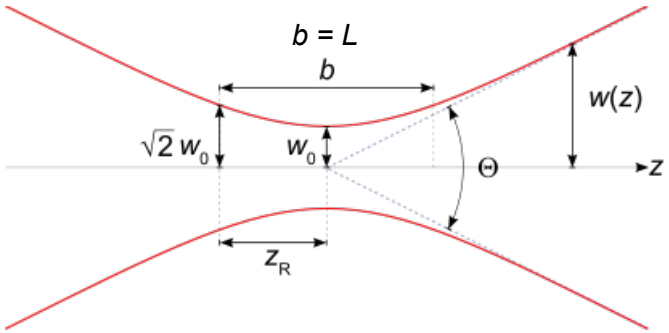
Gaussian beam in a confocal resonator

Using:

- L: length of the optical system, length of each resonator L/2.
- λ: wavelength of light

> Beam waist: $(\omega_0)^2 = (L \cdot \lambda) / 2\pi$

> Beam profile development:
$\omega^2(z) = (\omega_0)^2 \cdot (1+(z/z_R)^2)$,
$z_R = \pi(\omega_0)^2 / \lambda$
$\omega(L/2) = \text{sqrt}(2) \cdot \omega_0$



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

> Clear aperture required for a cavity with a power built-up ≈ 100,000:
$r_5 = 2.5 \cdot \omega(z)$

Optics for LSW experiments II: resonator examples

Aperture [mm]	Safety margin [mm]	Eff. aperture [mm]	ω (L/2) [mm]	ω_0 [mm]
40 (LHC)	10	30	6.0	4.2
50 (HERA)	10	40	8.0	5.7
100 (FCC)	10	90	18.0	12.7

Optics for LSW experiments II: resonator examples

Aperture [mm]	Safety margin [mm]	Eff. aperture [mm]	ω (L/2) [mm]	ω_0 [mm]	λ [nm]	L [m]
40 (LHC)	10	30	6.0	4.2	1064	106
50 (HERA)	10	40	8.0	5.7	1064	189
100 (FCC)	10	90	18.0	12.7	1064	957

- λ = 1064 nm is assumed following LIGO experience:
  mirror coatings for this wavelength can stand high power densities for long times.

Optics for LSW experiments II: resonator examples

Aperture [mm]	Safety margin [mm]	Eff. aperture [mm]	ω (L/2) [mm]	ω_0 [mm]	λ [nm]	L [m]	Maximal power [kW]	Magnetic length, one string [m]
40 (LHC)	10	30	6.0	4.2	1064	106	280	43
50 (HERA)	10	40	8.0	5.7	1064	189	500	81
100 (FCC)	10	90	18.0	12.7	1064	957	2500	426

- λ = 1064 nm is assumed following LIGO experiences: mirror coatings for this wavelength can stand high power densities for long times.
- For the maximal power assume a damage threshold of 500 kW/cm^2.
- For the magnetic length
  - subtract 10 m for the optical system outside the magnets and
  - assume a “filling factor” for the magnetic field of 90%.

Optics for LSW experiments IV: 532 nm options

Aperture [mm]	Safety margin [mm]	Eff. aperture [mm]	ω (L/2) [mm]	ω_0 [mm]	λ [nm]	L [m]	Maximal power [kW]	Magnetic length, one string [m]
50 (HERA)	10	40	8.0	5.7	1064	189	500	81
100 (FCC)	10	90	18.0	12.7	1064	957	2500	426
50 (HERA)	10	40	8.0	5.7	532	378	?	166
100 (FCC)	10	90	18.0	12.7	532	1913	? · 5	856

- If high power, high quality mirror coatings for λ = 532 nm were available, LSW experiments could be doubled in length compared to λ = 1064 nm.
- R&D is required to improve the power density damage threshold of coatings for 532 nm light.

Long optical resonators in real life

The stable operation of an optical resonator becomes difficult, if both mirrors cannot be placed on one optical bench anymore.

> The influence of seismic noise increases strongly.

LIGO has impressively proven that one can deal with such challenges.

By exploiting the LIGO expertise (AEI Hanover & Uni. of Gainesville, Florida) ALPS II has succeeded to install and operate a 20 m long resonator.

Characterization of optical systems for the ALPS II experiment

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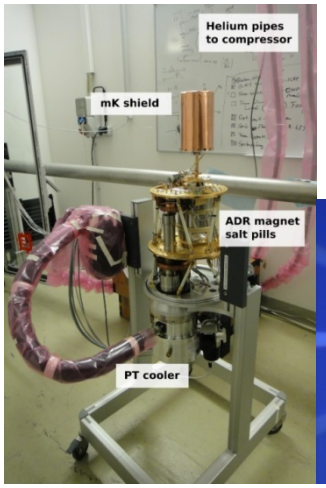
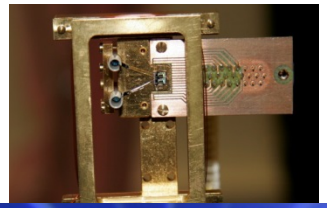
Publication in preparation

A detector for LSW experiments

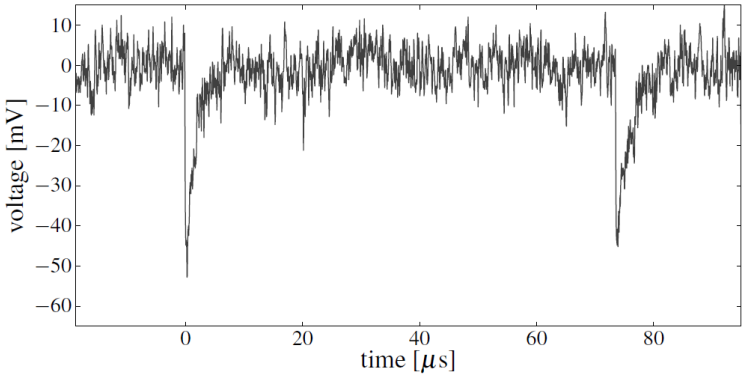
- ALPS II uses a Transition Edge Sensor
  - 20 nm thin Tungsten film.
  - Operated at 80 mK.
  - Single 1064 nm photon detection.
  - Single photon energy resolution < 8%.
  - Intrinsic background around 10^{-4} 1/s.





20 nm x 25 x 25 μm²

- A heterodyne detection scheme is being developed as an alternative for the ALPS II experiment.



Conservative assumption:
LSW experiments could detect a photon flux of 10^{-4} 1/s.

Ingredients for an “ALPS III” experiment

“ALPS III” sketch based on the following assumptions:

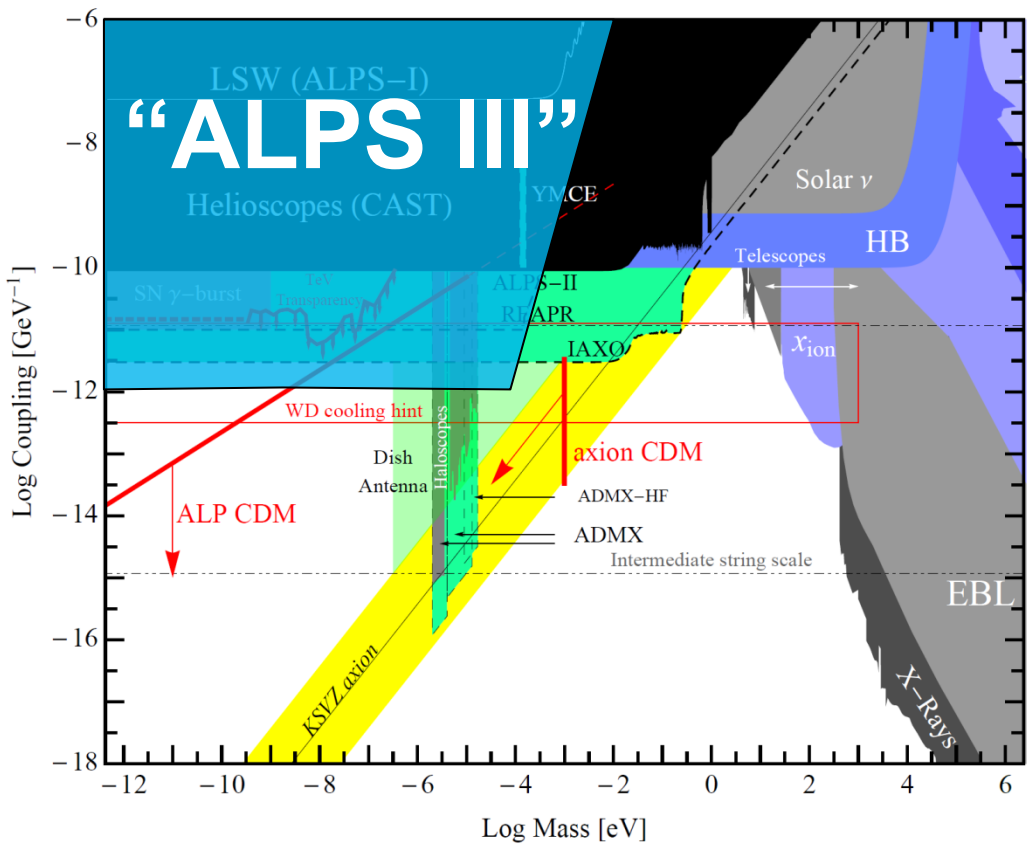
- Magnetic field strength: 13 T
- Magnetic length: 426 m
- Light wavelength: 1064 nm
- Circulating light power: 2.5 MW
  Photons against the wall: $1.4 \cdot 10^{25}$ s^{-1}
- Power built-up behind the wall: 10^5
- Detector sensitivity: 10^{-4} s^{-1}

- **Resulting sensitivity for $g_{a\gamma}$:**
  $1 \cdot 10^{-12}$ GeV^{-1} for m < 0.06 meV

“ALPS III” in context

“ALPS III”

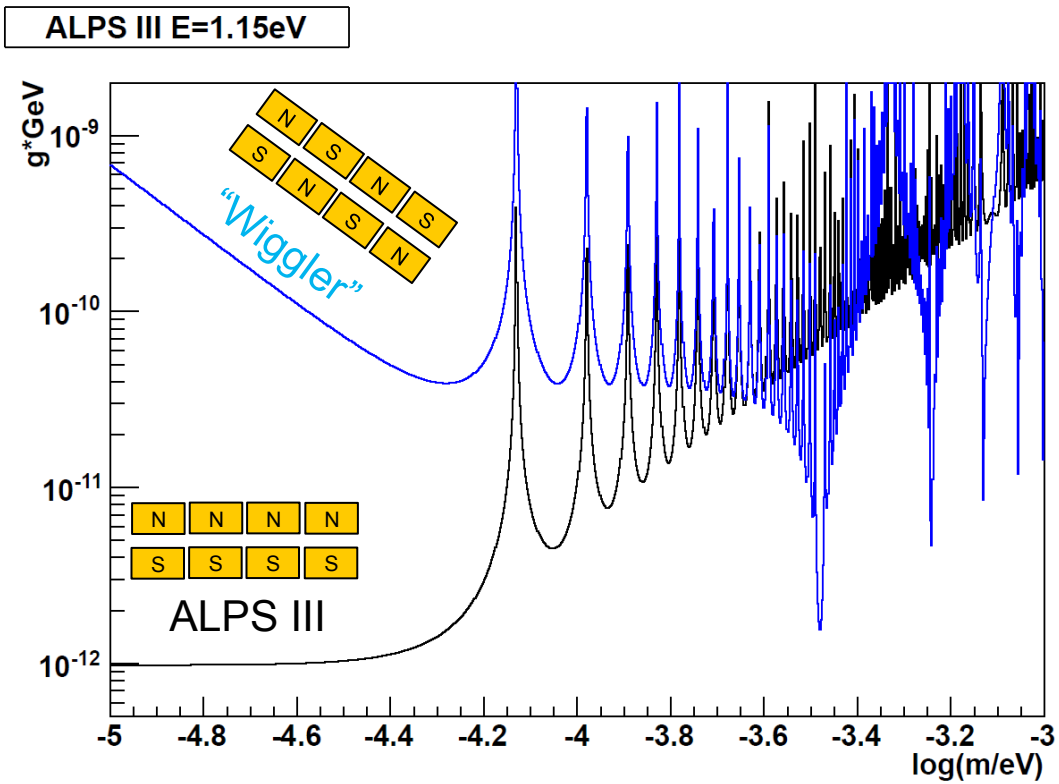
- would dramatically increase the sensitivity for purely laboratory based experiments searching for axion-like particles.
- would surpass even IAXO for very low mass ALPs.
- would definitely probe astrophysics hints for ALPs.
- would probe “dark matter” ALPs.
- would perfectly complement IAXO!



A little bonus

Assume to realize both magnet strings out of 40 dipoles each and

- switch polarity between each dipole ("wiggler configuration"):



The full sensitivity is restored at a specific mass!

Just for the fun of it: a little QCD axion bonus …

"ALPS III"

- would dramatically increase the sensitivity for purely laboratory based experiments searching for axion-like particles.
- would surpass even IAXO for very low mass ALPs.
- would definitely probe astrophysics hints for ALPs.
- would probe "dark matter" ALPs.
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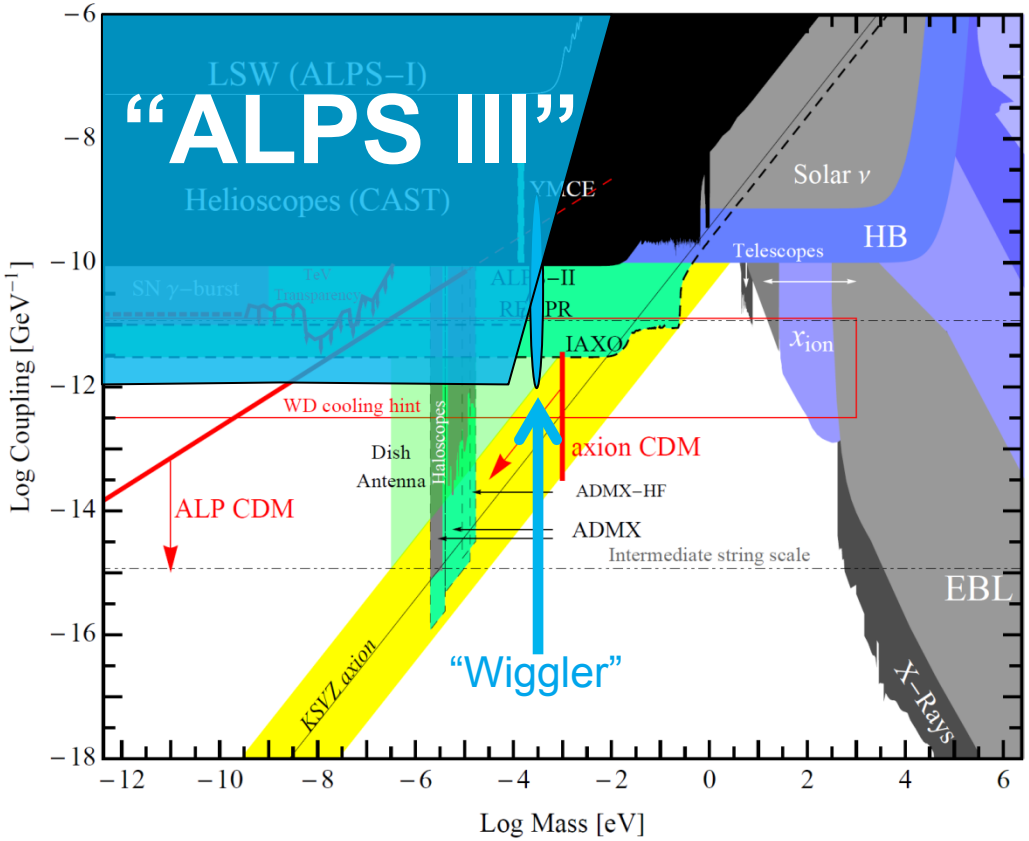

Summing up

By combining

> present day expertise in optics (ALPS II lessons learned from LIGO)

and

> present day expertise in detectors for very low photon fluxes (ALPS II)

with

> new dipole magnets under development for future accelerators

purely laboratory based searches for axion-like particles will be possible well beyond the sensitivities of experiments under preparation.

The sensitivity might be increased even more by pushing for R&D on mirror coatings for 532 nm light.

To-take-home

- Accelerator dipole magnets under development at CERN could be the basis of an “ultimate” light-shining-through-a-wall experiment mainly searching for axion-like particles.

- The costs of such an experiment would be dominated by the costs of the magnet strings.
  - The costs probably strongly correlate with decisions on future accelerator projects.

- Considering the development of the physics case for axion-like particles in the recent years, experiments have to move from the niche *“make best use of existing equipment built for something else”* to more dedicated installations:
  - IAXO and “ALPS III”.