ALPS & JURA

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for the ALPS collaboration

Axion Experiments in Germany
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Outline

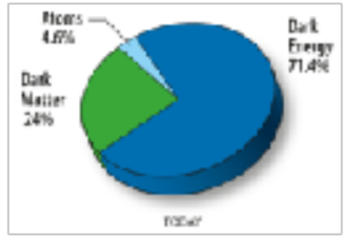
- ALPS II physics case
- Light shining through a wall approach
- ALPS I
- ALPS II
- JURA

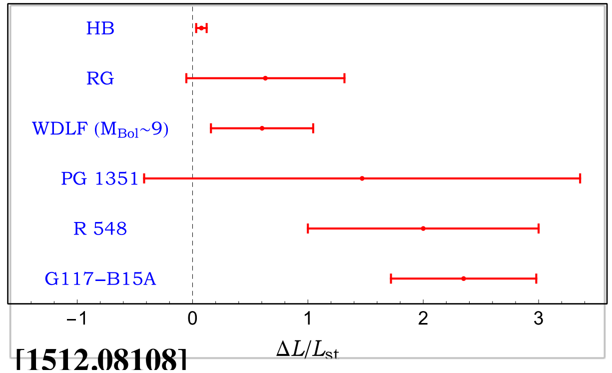
Physics beyond the standard model

Experimental results hint at

- dark matter
- dark energy
- strong CP-problem
  - no electric dipole moment of neutron observed
- excess cooling in stellar evolution
- TeV transparency

These observations are not explained by the standard model of particle physics.





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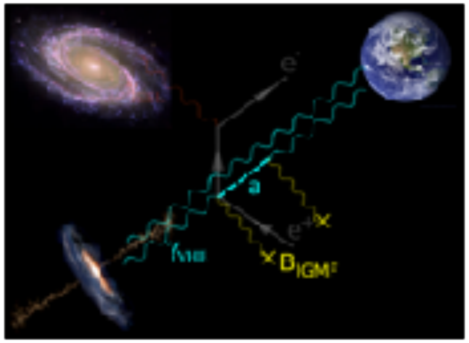

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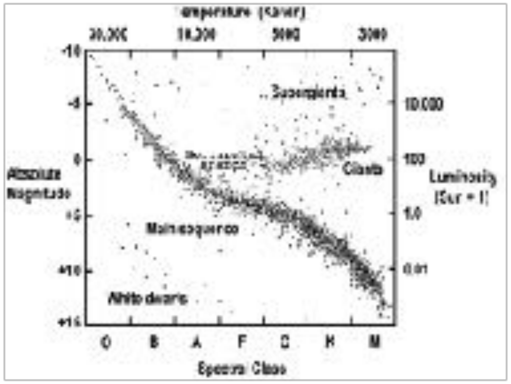


New ultra light particles

Weakly Interacting Slim Particles (WISPs)

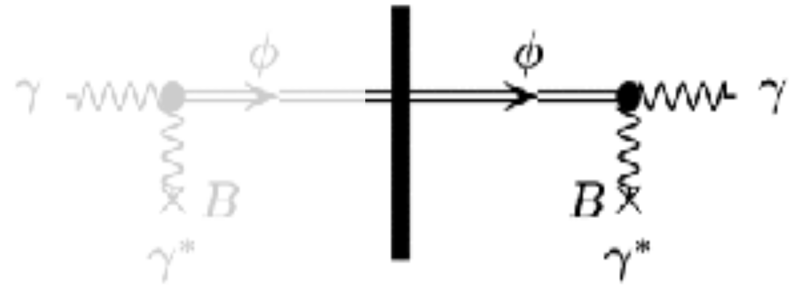
- masses below the eV-scale and very tiny couplings to SM particles (only photon couplings considered in this talk)
- occur naturally in string theory inspired extensions of the standard model as components of a “dark sector”

WISP include

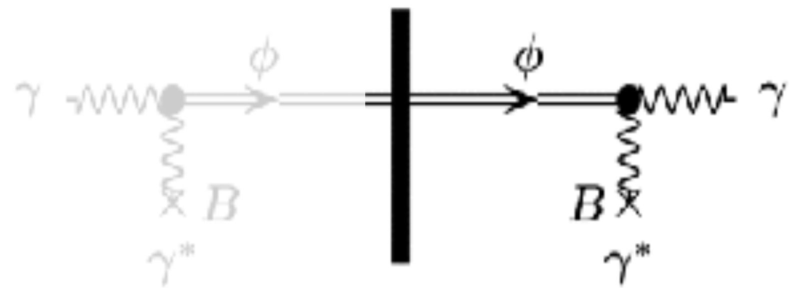
- QCD-Axion: predicted to solve the strong CP-problem
- Axion-like-particles (ALPs)
- Dark photons
- mini-charged particles, Chameleons,…

Experimental schemes searching for ALPs

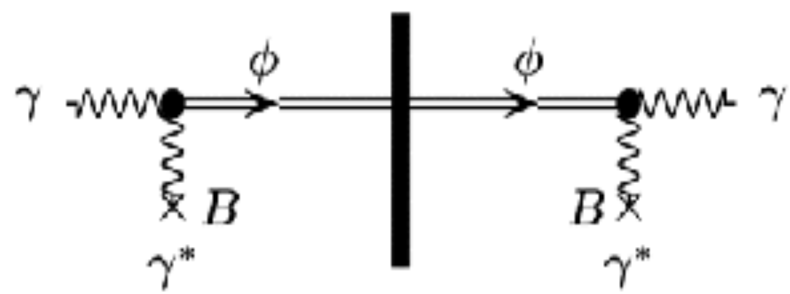
- Haloscopes: Dark Matter WISP candidates
  - microwave cavities



- Helioscopes: WISPs from the sun
  - magnet pointing at the sun
  - X-Ray photon search

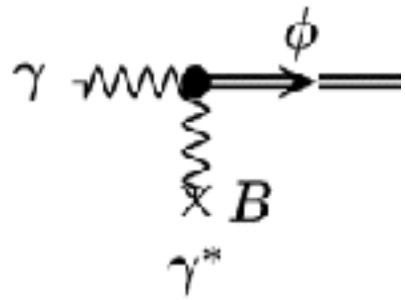


- Light-shining-through-a-wall
  - laboratory based
  - control of source



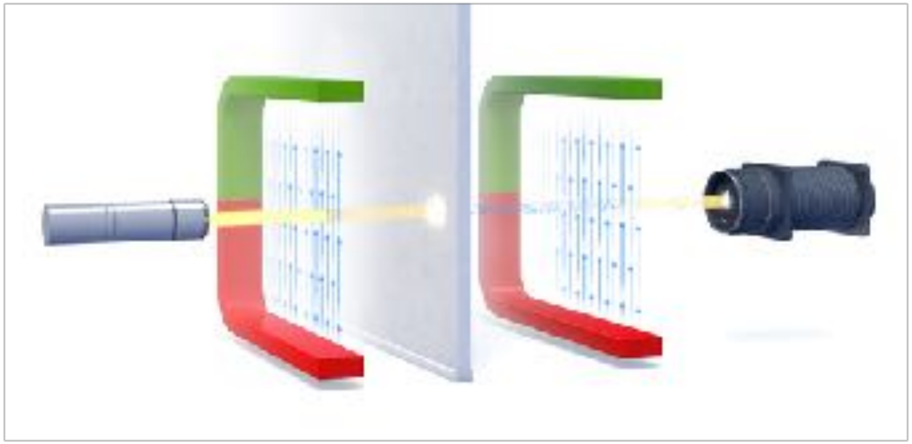
Light-shining-through-a-wall approach

- Lab based production, regeneration and detection of WISPs
- strong **magnets**, high power **source** and very sensitive **detection system** required



Primakoff effect

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}\, g_{a\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\, a\, \vec{E}\cdot\vec{B}$$



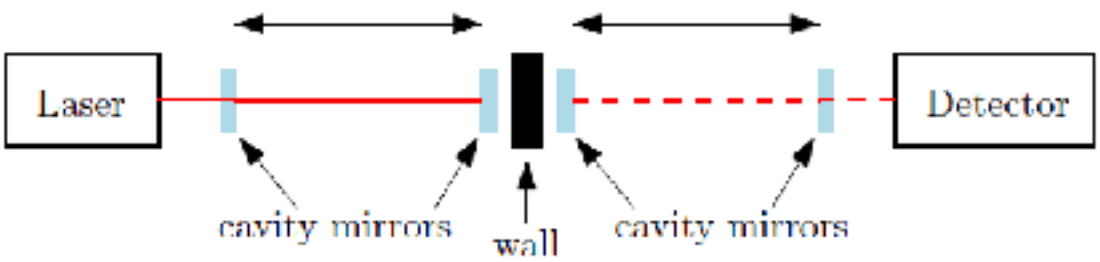
LSW detection capabilities

- Parameter accessibility of LSW experiments:

ALP parameter	LSW
Parity and spin	yes
Coupling $g_{a\gamma\gamma}$	yes
Mass	perhaps
Electron coupling	no
Astrophysical assumptions required	no
QCD axion	most likely not

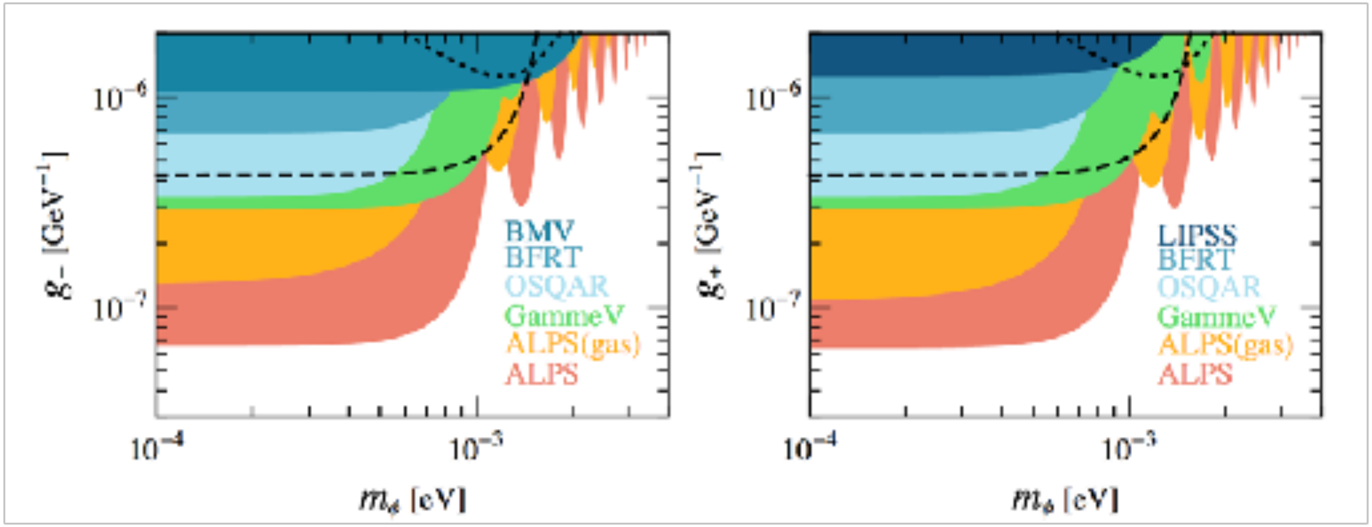
Optical Resonators in LSW experiments

- a single mode source (e.g. laser) allows for use of resonant enhancement techniques
- the light bounces forth and back in the optical resonator
- cavity in front of the wall increases the ALP production
- cavity behind the wall increases the probability of photon regeneration
- optical resonators need to be matched (one of the most complicated tasks in advanced LSW experiments like ALPS II)



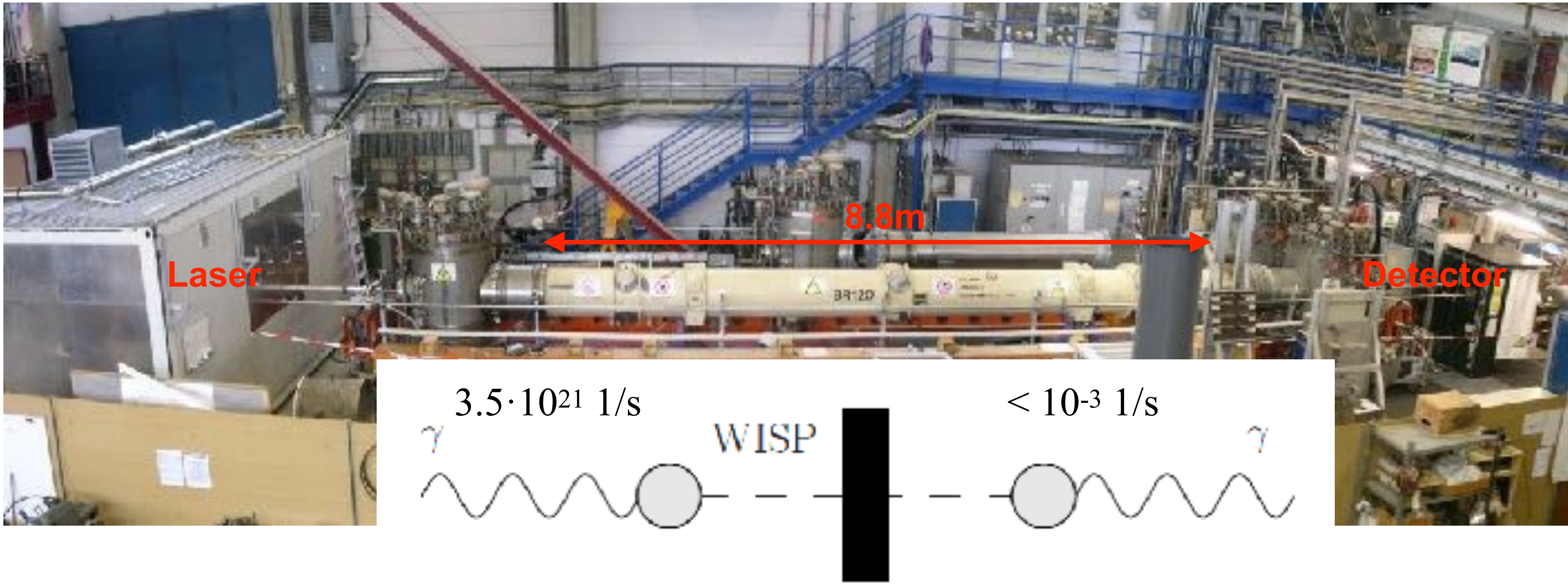
ALPS I

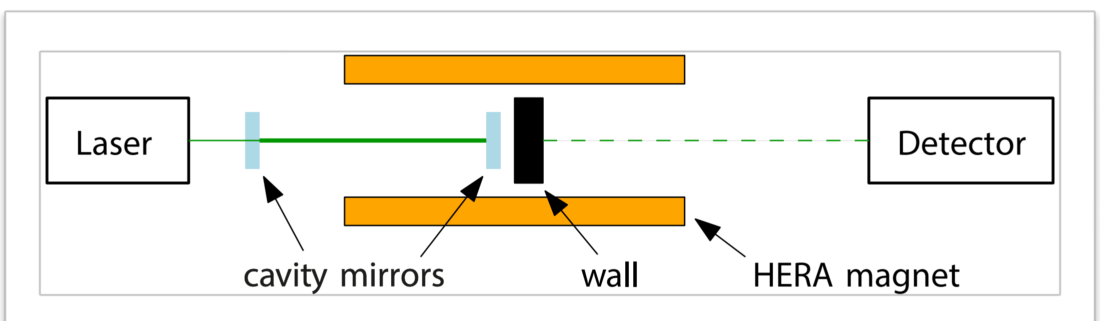
PLB Vol. 689 (2010), 149, or http://arxiv.org/abs/1004.1313



- LSW experiment at DESY (2007-2010)
- most sensitive LSW experiment at its time (in 2015 surpassed by OSQAR at CERN)
- first experiment of its kind using a cavity before the optical barrier
- used frequency doubled 1064nm laser with a power of 5W at 532nm
- CCD camera as detector

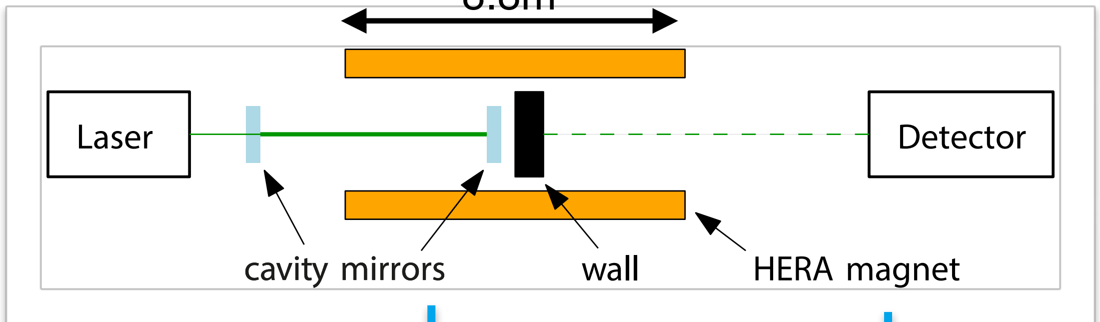
ALPS I - experimental setup





Advanced Light-shining-through-a-wall

> **ALPS I**

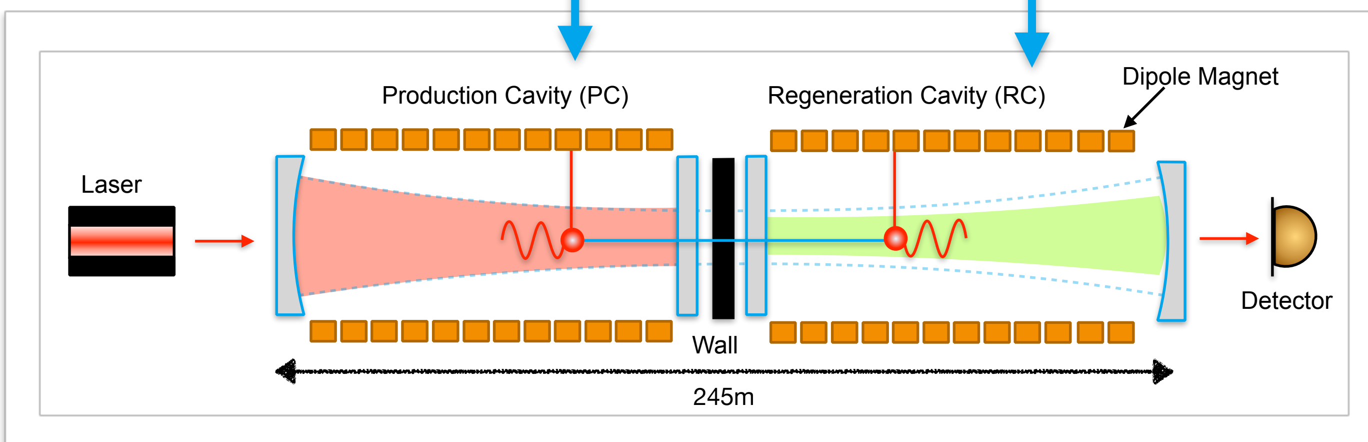


increase of resonator length, more magnets
➔ **sensitivity x24**

higher circulating power in first resonator
➔ **sensitivity x3.5**

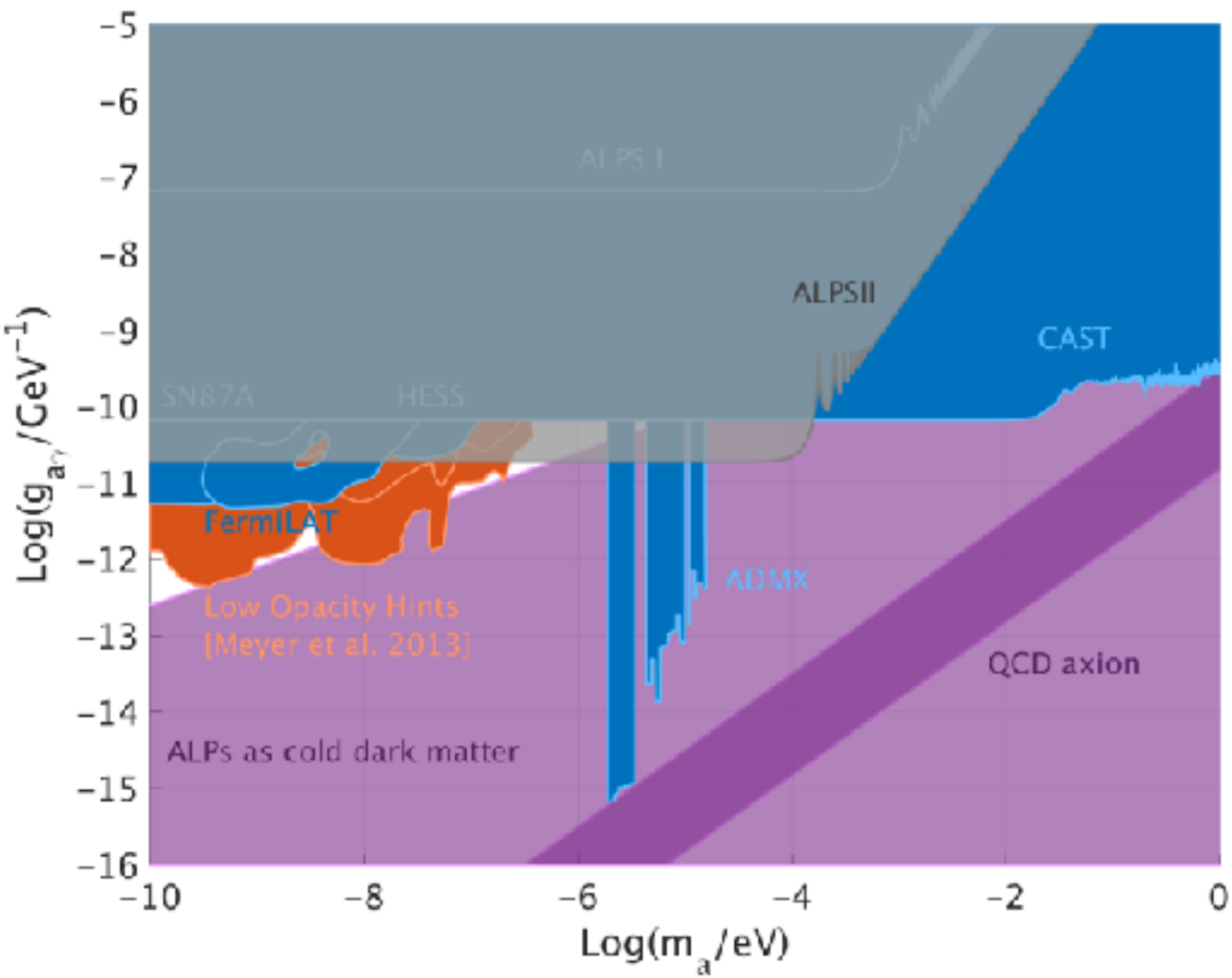
second resonator behind the wall
➔ **sensitivity x14**

> **ALPS II**



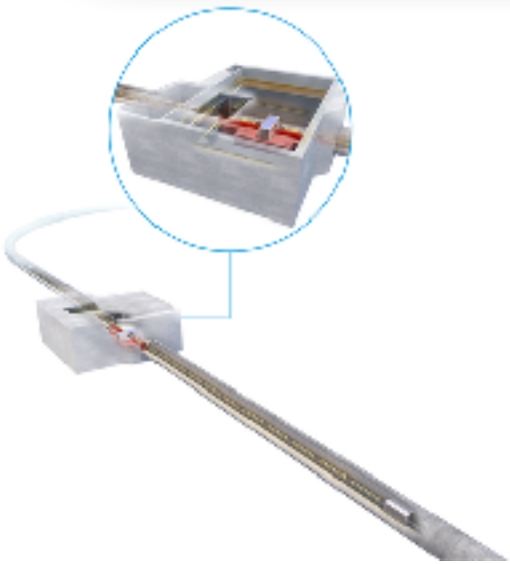
$$P_{\gamma\to\Phi\to\gamma} \propto P_{\mathrm{in}} \cdot PB_{\mathrm{PC}} \cdot PB_{\mathrm{RC}} \cdot (g_{\alpha\gamma} \cdot B \cdot l)^4$$

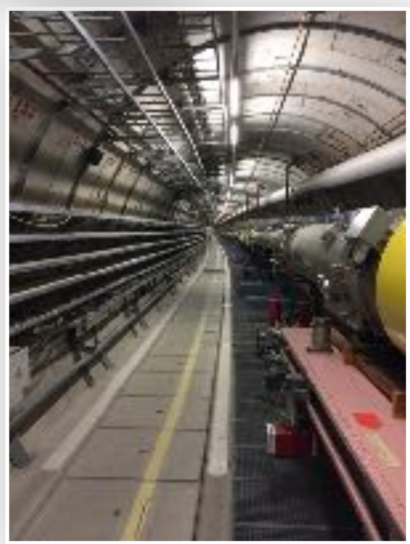
ALPS II design sensitivity

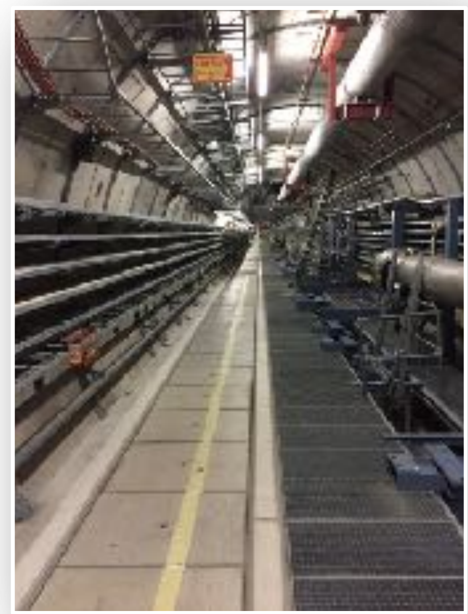


- A sensitivity of experiment for scalar and pseudo-scalar particles with 95 % confidence level at $g_{a\gamma\gamma} = 2 \times 10^{-11}$/GeV for masses below 0.1 meV and an integration time of 20 days.

Location: DESY Hamburg

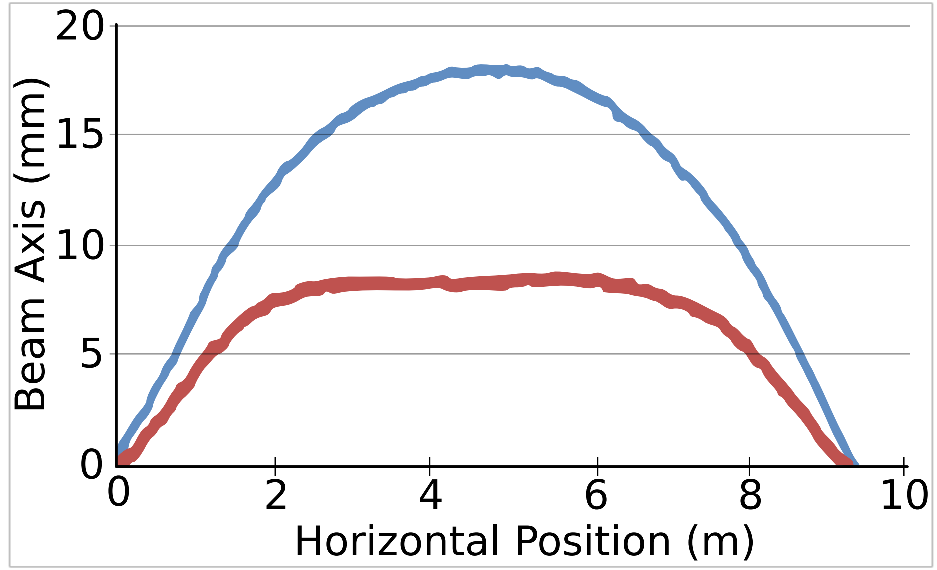




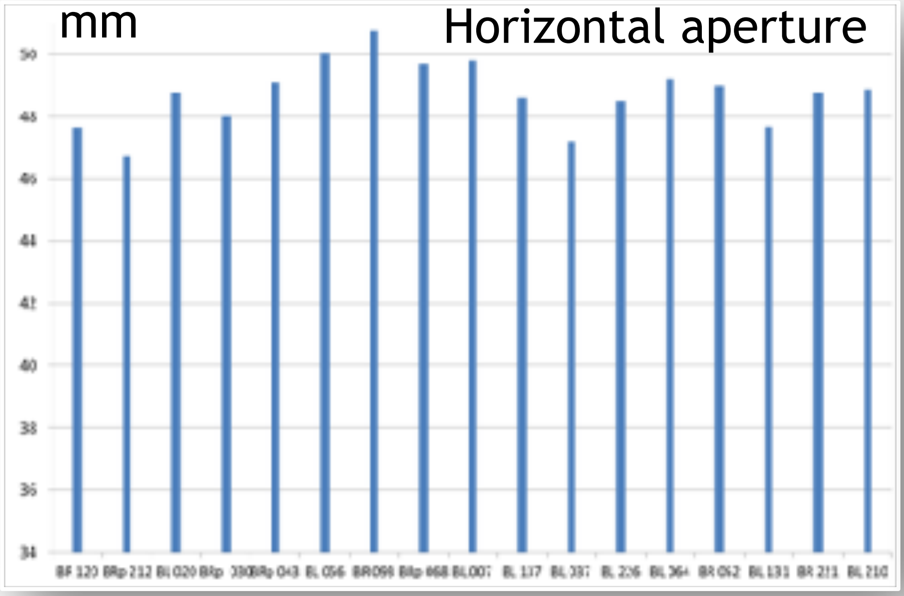


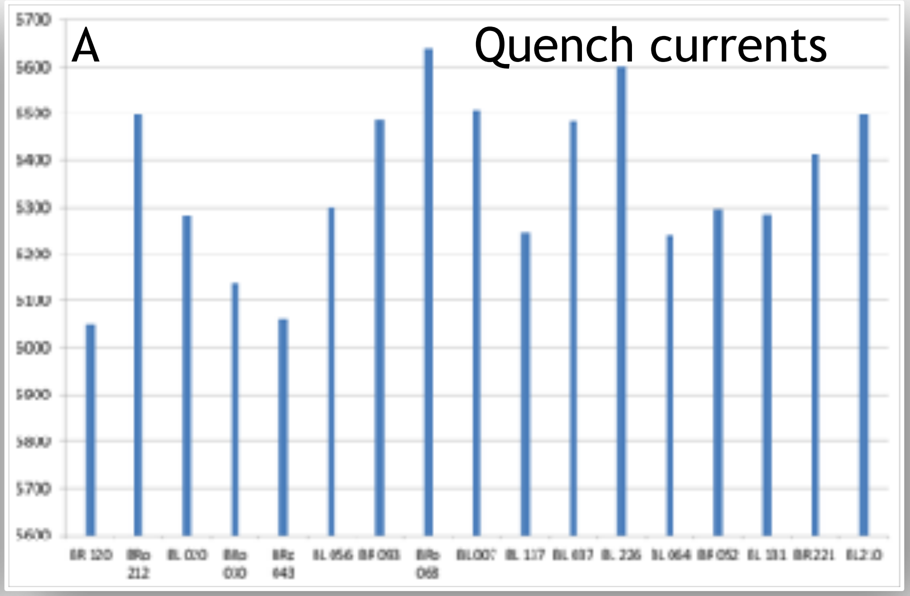
Superconducting Dipole Magnets I

- 5.3 T superconducting dipole magnets
- 600 m radius of curvature for HERA with 35mm free aperture
- unbending required for successful operation of ALPS II cavities
- 48mm free aperture after straightening on average
- 22 magnets successfully straightened

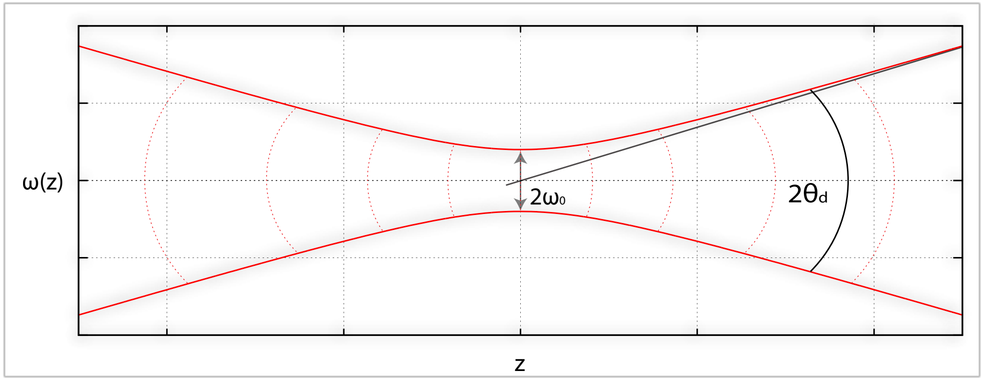


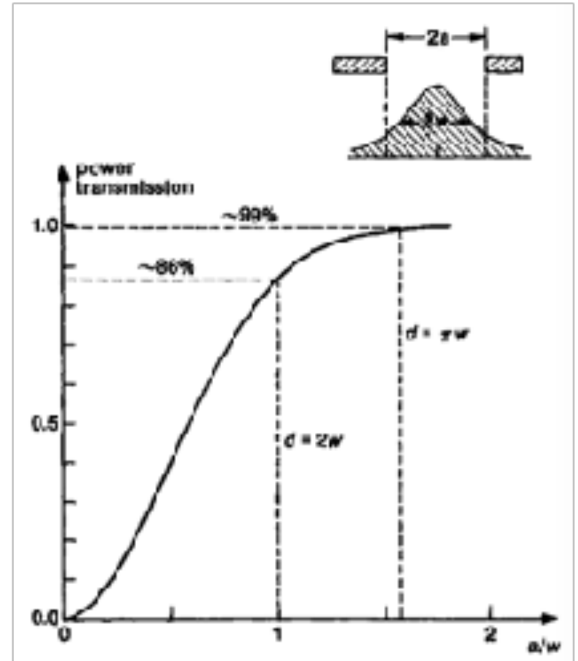
Superconducting Dipole Magnets II





Optics related constraints from Magnets



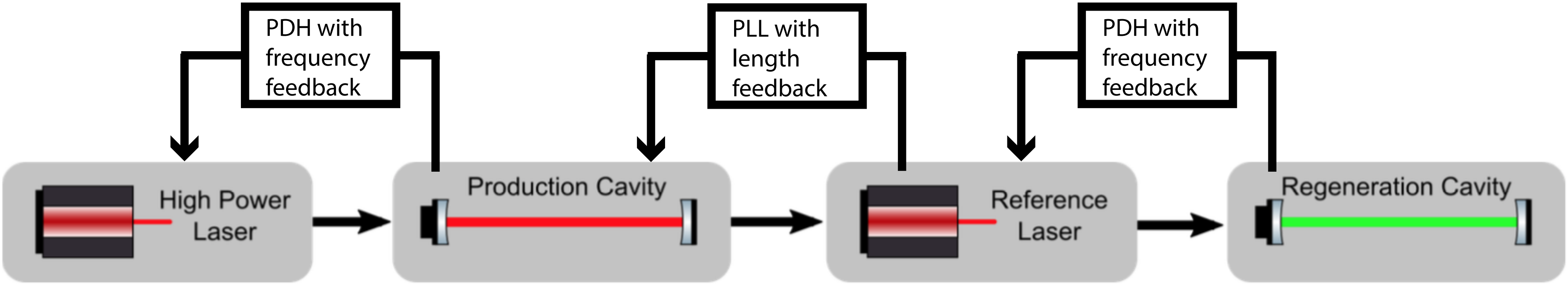


from Siegman, Lasers

- diffraction limited Gaussian beam
- clipping in magnet aperture (for high finesse resonators power in the tails of the Gaussian have to be considered as well)
- facility constraints: only straight section of HERA usable for ALPS II
- proposed 10+10 magnet configuration in TDR
- recently changed to 12+12 magnet configuration based on risk assessment and very positive results from magnet straightening

Cavity control scheme

- matching of the two cavity fields
  - tracking of cavity resonance frequency
  - spatial overlap
  - nested feedback control electronics required
- regeneration cavity control scheme depends on the detection system

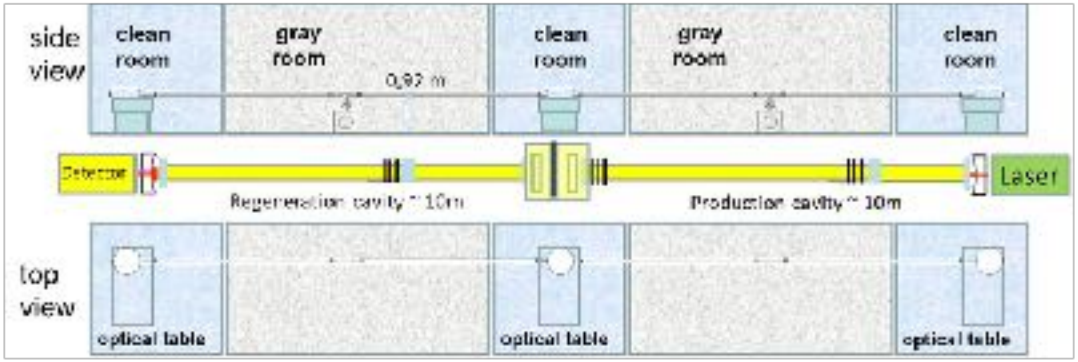


PDH: Pound-Drever-Hall (locking technique)

PLL: Phase-locked-loop

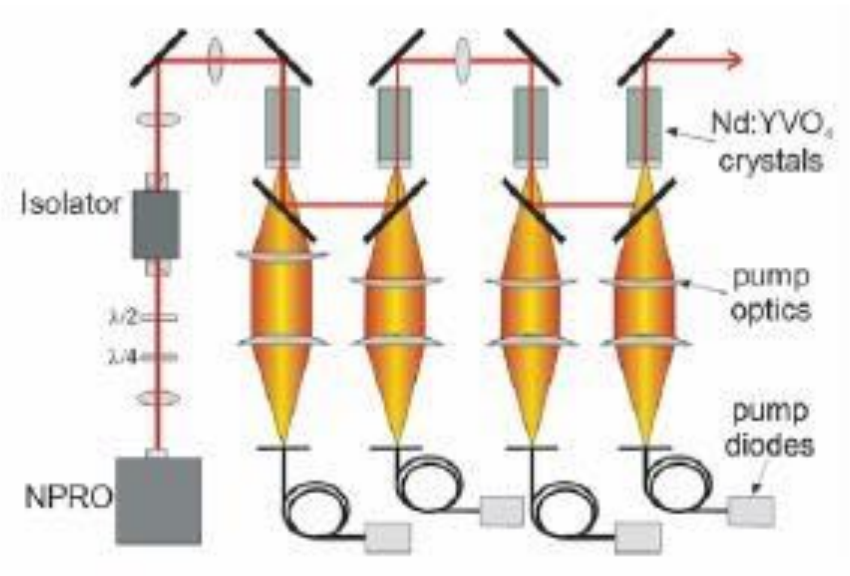
ALPS II optics challenges

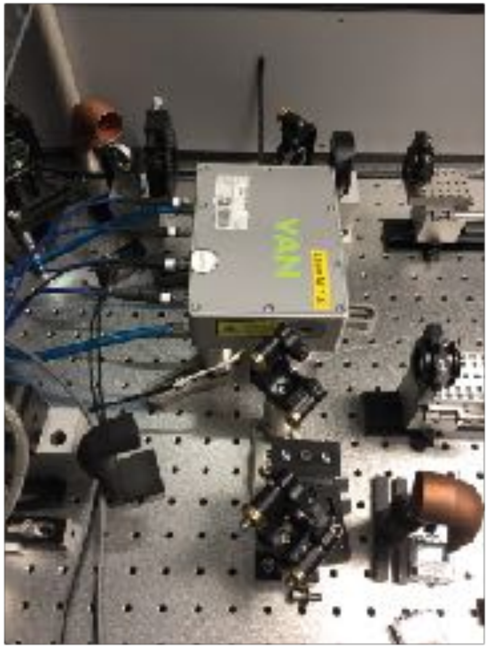
- high power operation in production cavity
- high finesse cavity for photon regeneration
- dual cavity lock
- high spatial overlap over long times
- light tightness and shutter

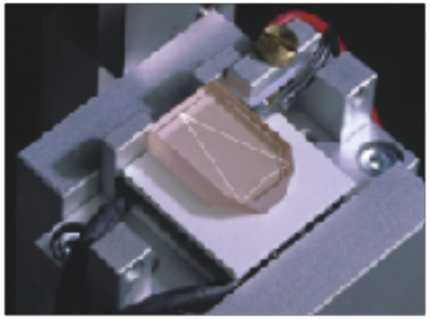


tests conducted in a 20m test facility located on the DESY campus which is operated without magnets

High Power Laser System



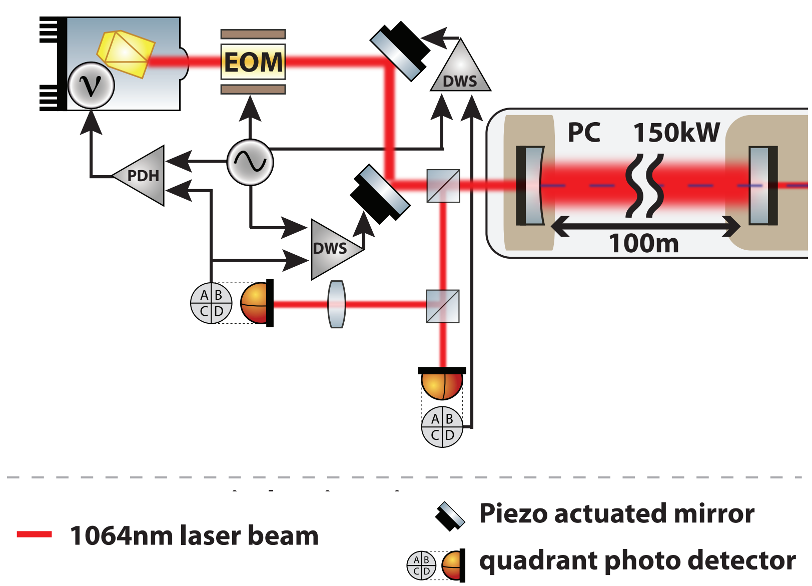


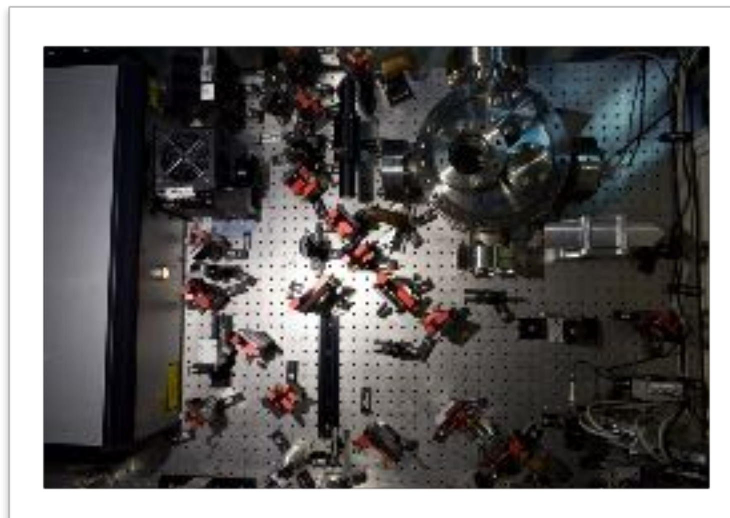


- ALPS II laser provides up to 70W output power at 1064nm
- high fundamental mode content
- 2W non-planar-ring-oscillator (NPRO) and four stage $Nd:YVO_4$ amplifier
- low frequency noise due to NPRO
- very reliable (used in gravitational wave detectors for many years)

ALP production

- increase number of photons in front of the wall
- power buildup factor of 5000 (Finesse 8000)
- 150kW circulating power limited by damage threshold of mirrors and free magnet aperture
- mirrors on separate optical tables
- feedback control systems to stabilize the laser frequency with respect to the cavity and the alignment to the cavity





ALP production - status

- length and alignment control systems were successfully tested and characterized with a confocal 20m cavity

- high power test were conducted with a 10m long production cavity
  - frequency stabilization control loop with 50kHz unity gain frequency
  - 50 kW circulating power
  - instabilities due to resonant higher order modes observed
  - further characterization of thermal effects ongoing

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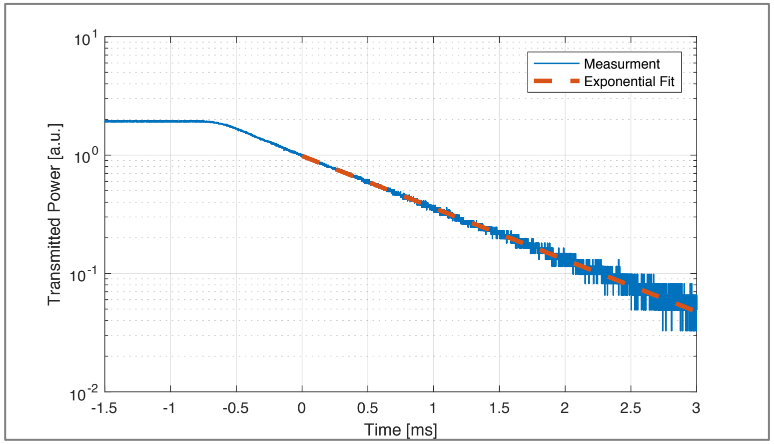
Optics EXPRESS

Characterization of optical systems for the ALPS II experiment

AARON D. SPECTOR,[1,*] JAN H. PÕLD,[2] ROBIN BÄHRE,[3,4] AXEL LINDNER,[2] AND BENNO WILLKE [3,4]

ALP regeneration

- 120m cavity with power buildup factor of 40,000 anticipated (Finesse 120,000, round trip losses <25ppm)
  - requires super polished mirrors with <2Å rms surface roughness and very few surface defects (beam diameter on end mirrors: 18mm)
  - very low transmission of 2ppm

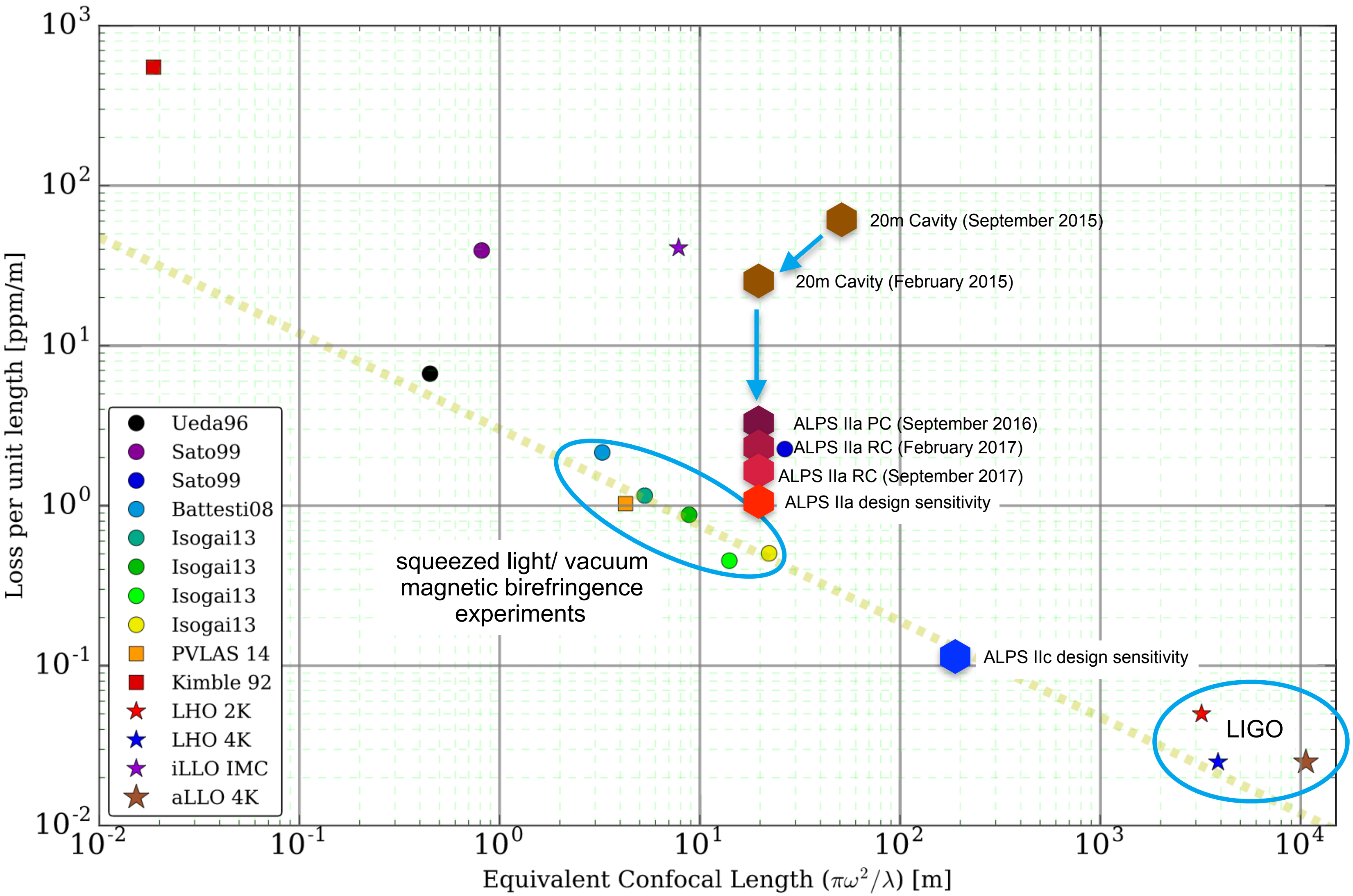


Demonstration of the length stability requirements for ALPS II with a high finesse 9.2 m cavity

Jan H. Põld,[1,2*] and Aaron D. Spector[2]

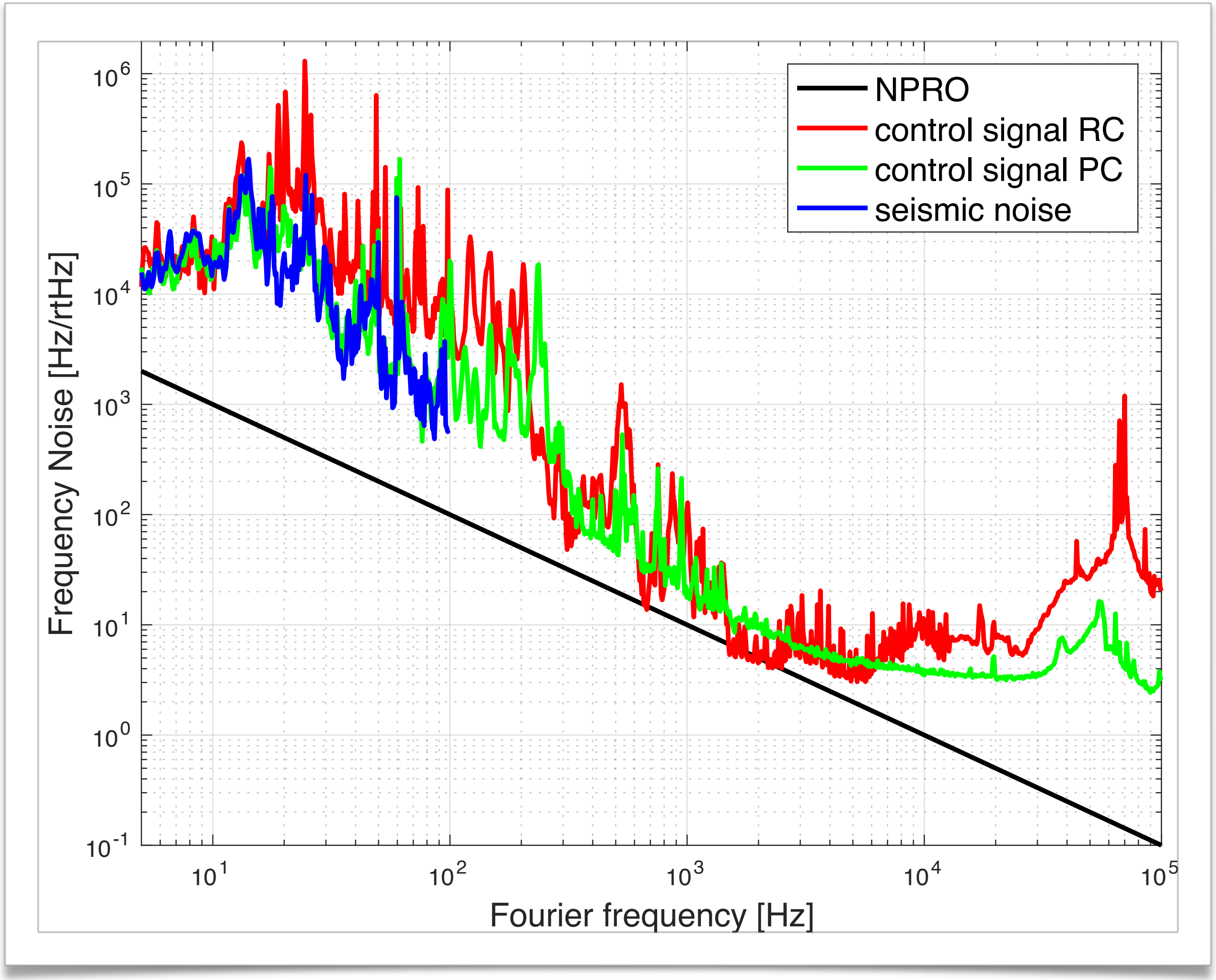
- experimental results
  - power buildup factor of 26,000 achieved in the 9.2m cavity configuration (corresponds to 36ppm round trip losses)
  - excess losses possibly due to mirror surface quality

Performance of ALPS II resonator in context of other cavity experiments



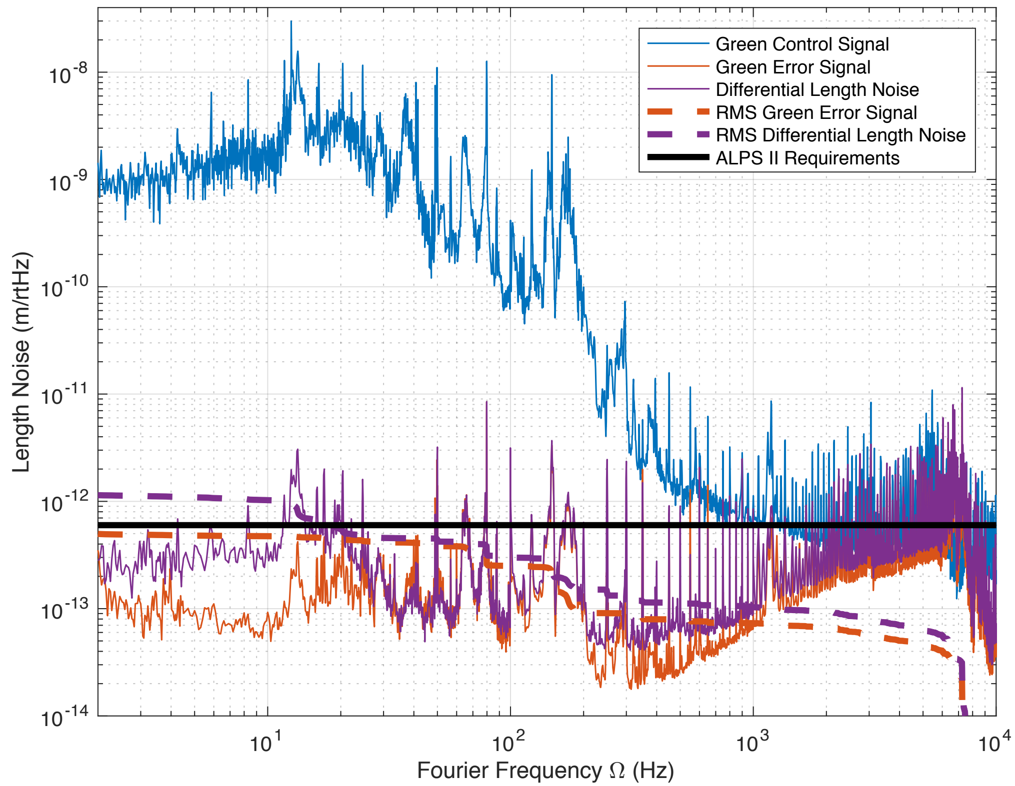
Noise budget for cavity locking

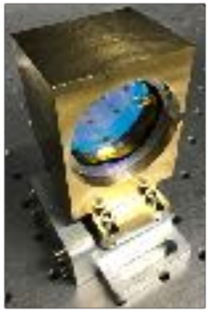
- mostly dominated by seismic noise below 1kHz
- common movement of optical tables at frequencies below 1Hz
- integrated rms noise needs to be suppressed well below the regeneration cavity linewidth (12Hz)



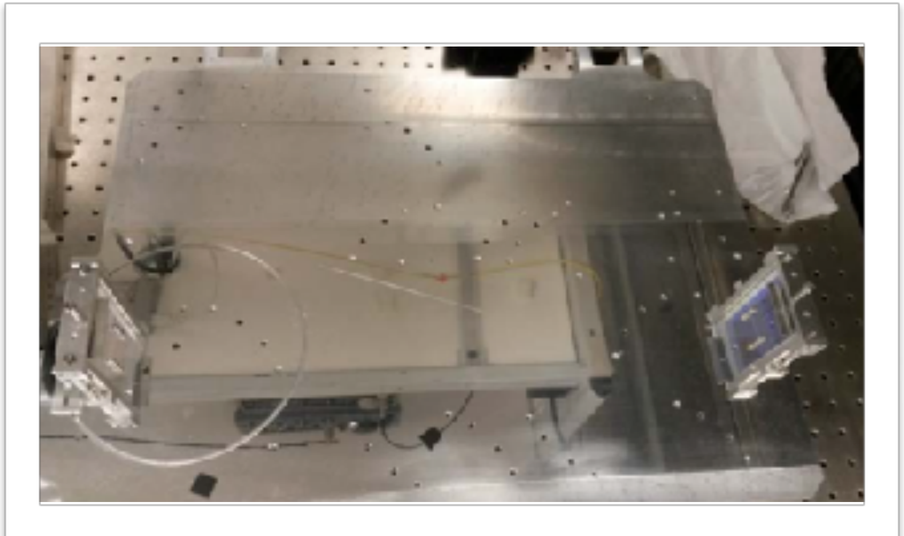
Fast length actuator

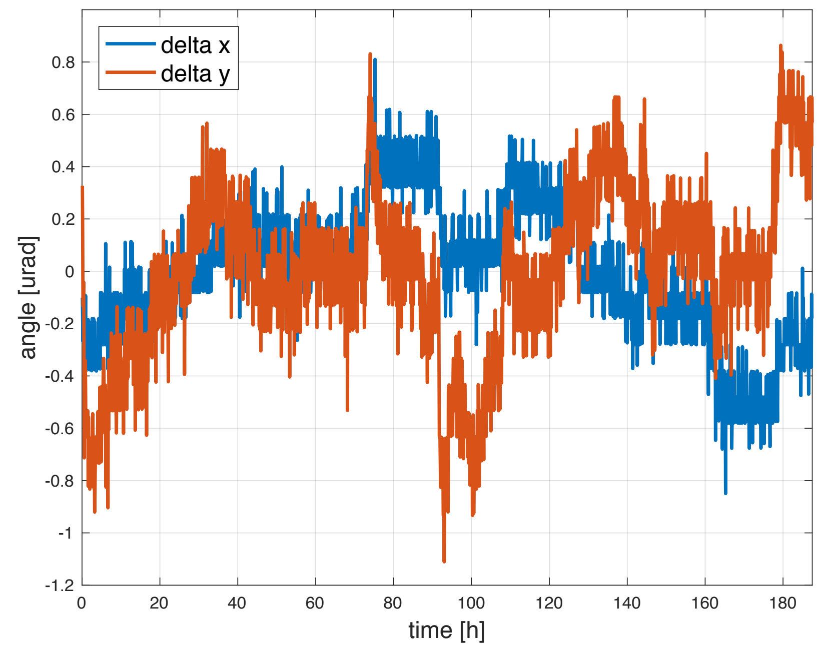
- projection of regeneration cavity length noise
- indication that we will meet the ALPS II dual resonance requirements with an actuator bandwidth of ~5kHz
- piezo actuated 2” mirror mount design



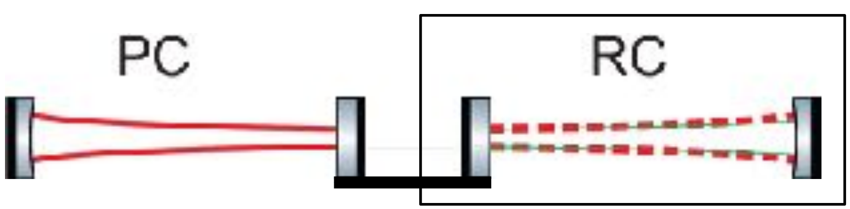


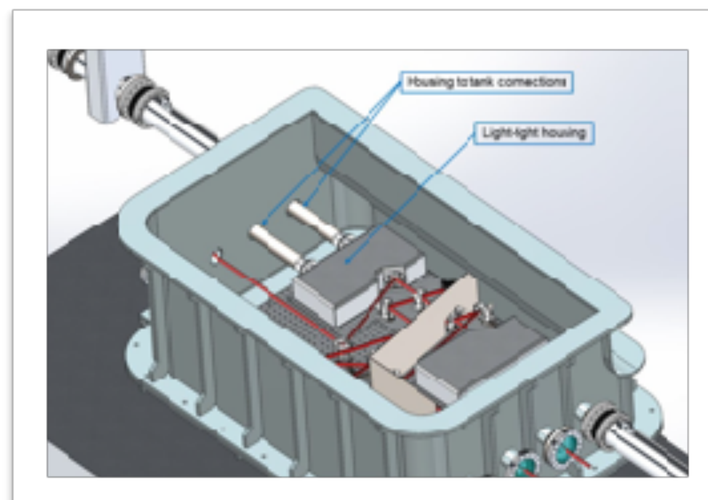
Alignment stability





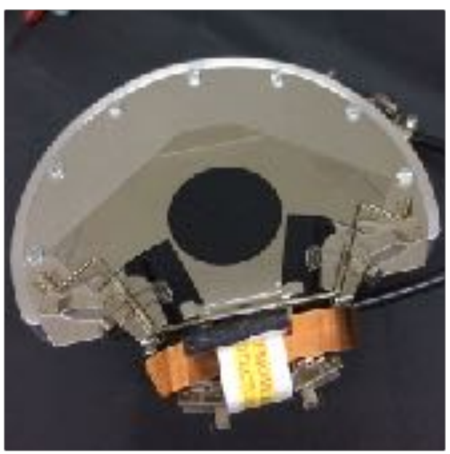
- Positions of cavity eigenmodes defined by central optics
- Positioning optics with autocollimator
- RMS drift <1µrad
- Pointing stability test in HERA north

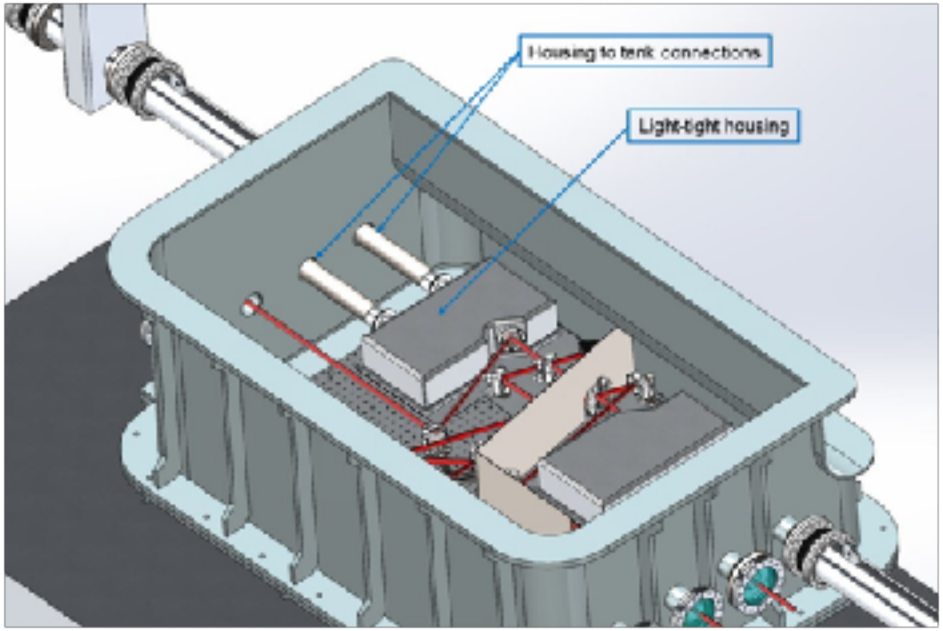




Shutter and light tightness

- “light tightness” for light at the signal frequency in the regeneration area
  - dichroic mirrors to block all light at signal frequency
- box to shield stray light from the production cavity
- shutter
  - to check resonant condition
  - blade shutter





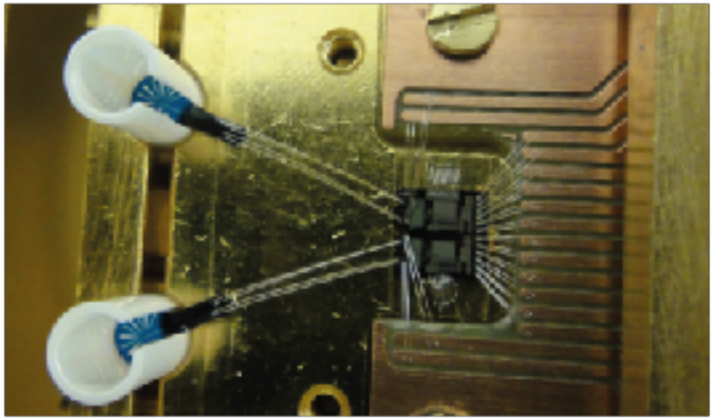
Summary: Challenges

- high power operation
  - thermal effects
  - cavity stability
- low losses in regeneration cavity
- dual cavity lock (with control signal in different color for TES detector)
  - differential length stabilization with sub-picometer accuracy
- high spatial overlap over long times
- “light tightness” for light at the signal frequency in the regeneration area

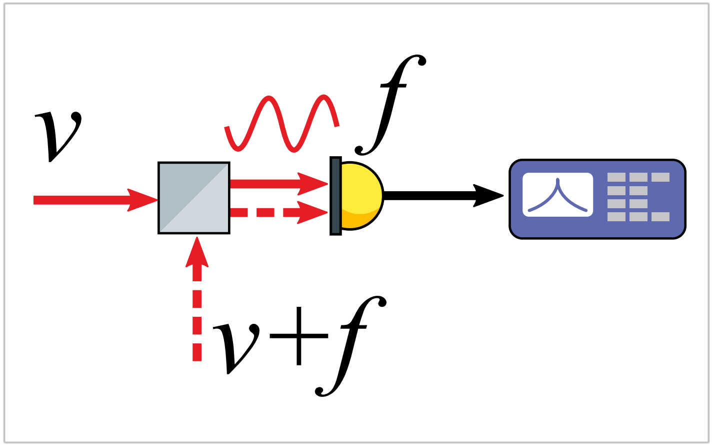
Detection Systems

- two detection schemes with very different systematics (required as there is no competing LSW experiment)
- expected signal rates of a few photons per hour to a few photons per month
- both schemes require a different setup, such that they will be implemented subsequently starting with Heterodyne Detection

- Transition edge sensor
  - photon counting

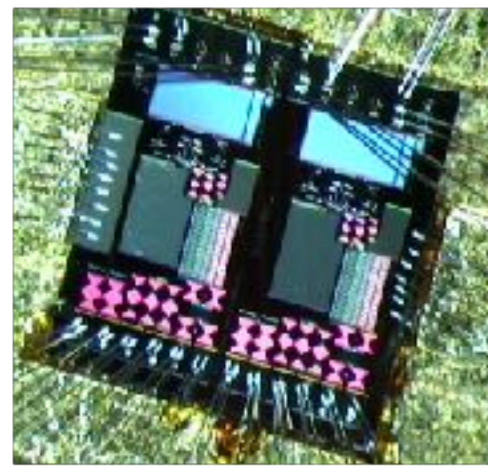


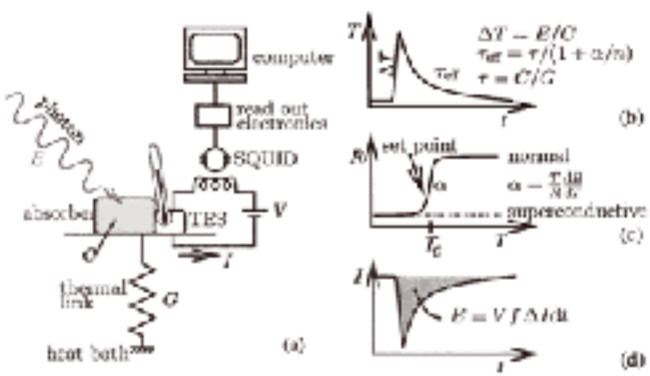
- Heterodyne Detection
  - field detection



Transition edge sensor (TES) - concept

- micro-calorimeter operating at 80mK
- single photon detector
- Tungsten film kept at the transition to superconductivity
  - sensor size 25µm x 25µm x 20nm
- SQUID readout
- >95% quantum efficiency demonstrated by NIST [Lita, 2008]





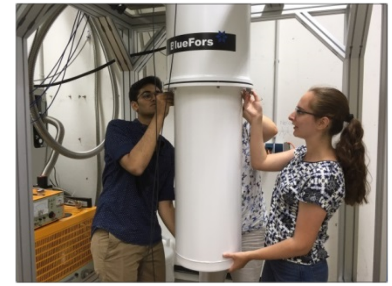
$\Delta T \approx 100\ \mu K$

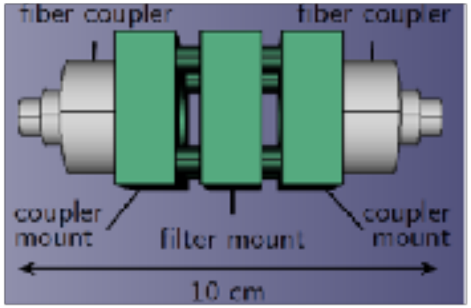
$\Delta R \approx 1\ \Omega$

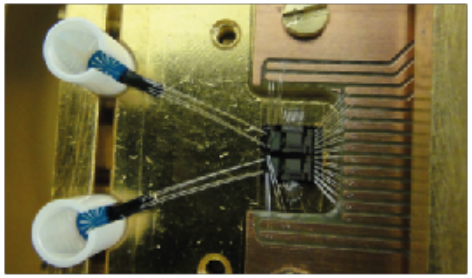
$\Delta I \approx 70\ nA$

Transition edge sensor (TES) - status

- after our adiabatic demagnetization refrigerator (ADR) failed, a new dilution refrigerator was installed in 2018
- TES detector dark count rate measured ~$1x10^{-2}$/s
  - arXiv:1502.07878
  - optical fiber guides the light towards the detector
  - black-body pile up events limit sensitivity
  - cryogenic filter unit under development
- dark count rate without fiber attached: $1x10^{-4}$/s
  - likely limited by ambient radioactivity and cosmic radiation
  - further improvement possible

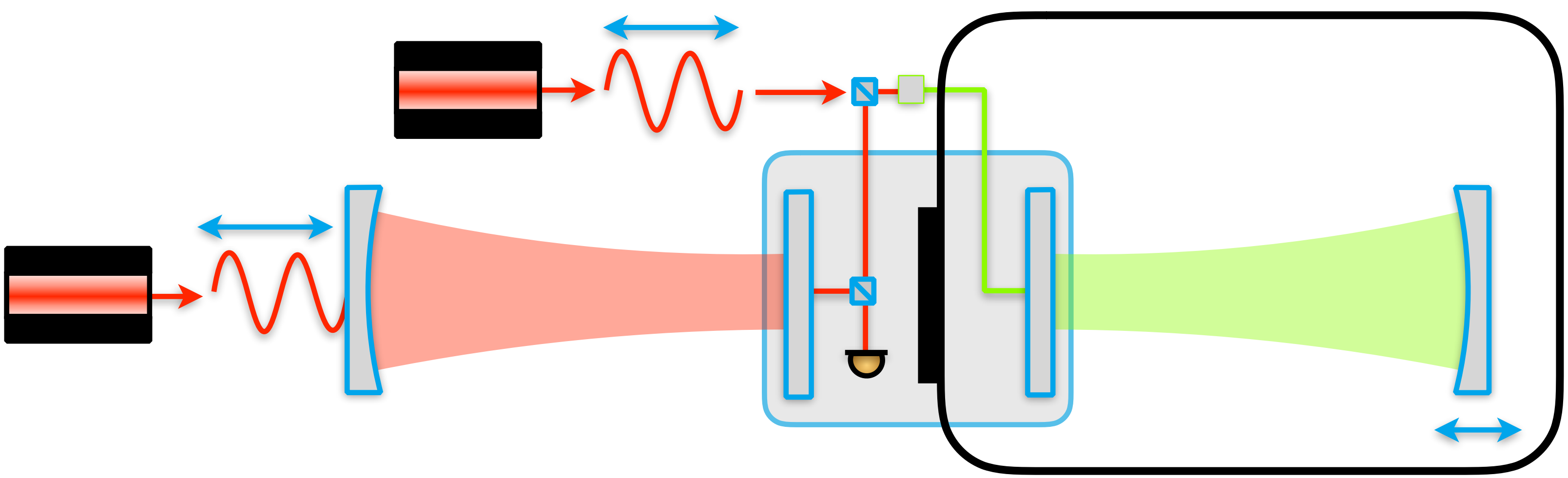






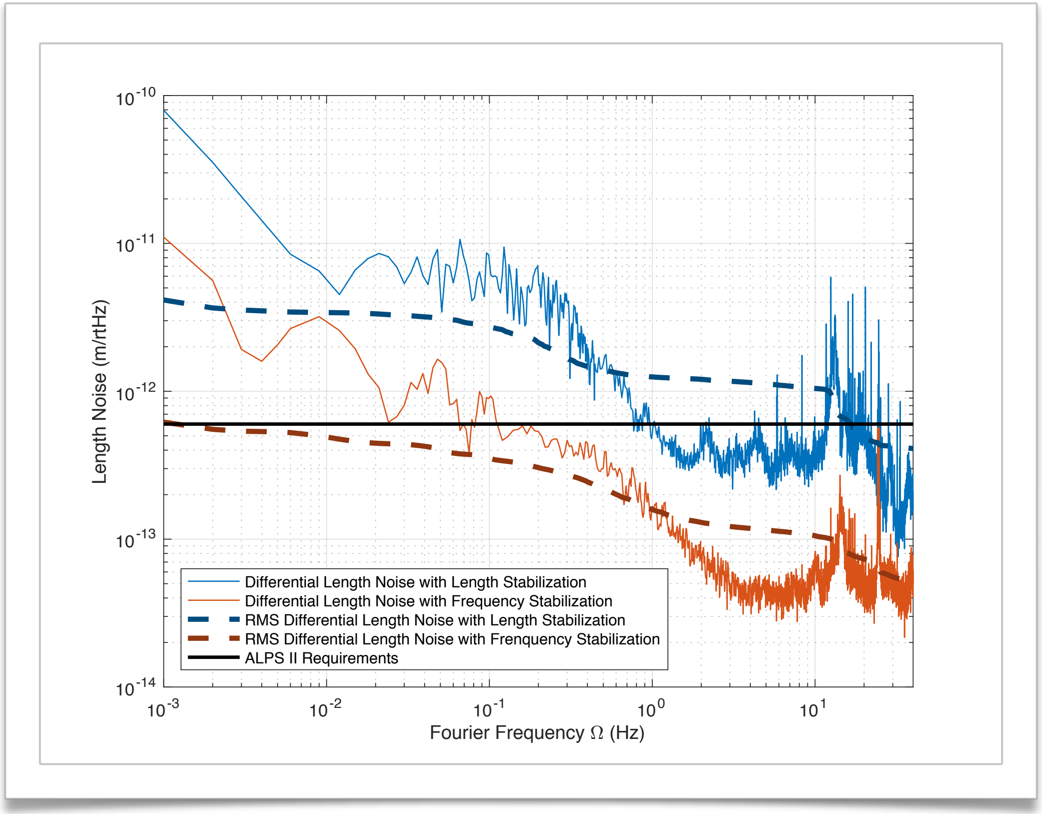
ALPS II control scheme - TES

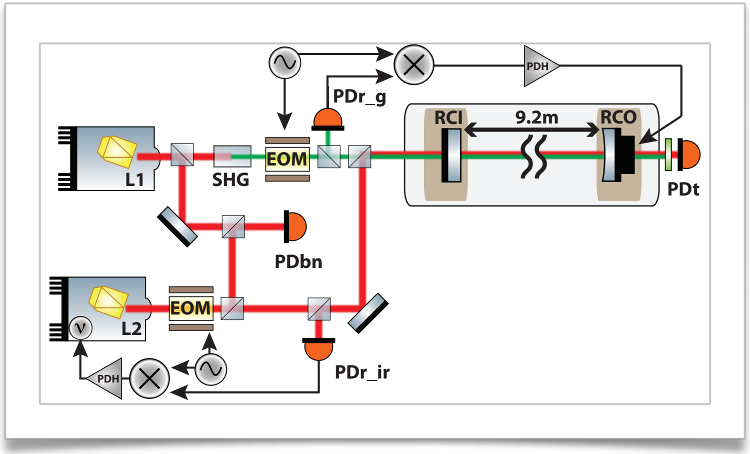
- Regeneration cavity locking with green light
- Actuation on the length of one cavity required
- Light is injected to Regeneration cavity via fiber
- Green light produced in second harmonic generation process



Out-of-loop noise - measurement

- out-of-loop length noise exceeds in-loop performance
- differential length noise between green and IR suspected
- required stability can be achieved over ~1000s





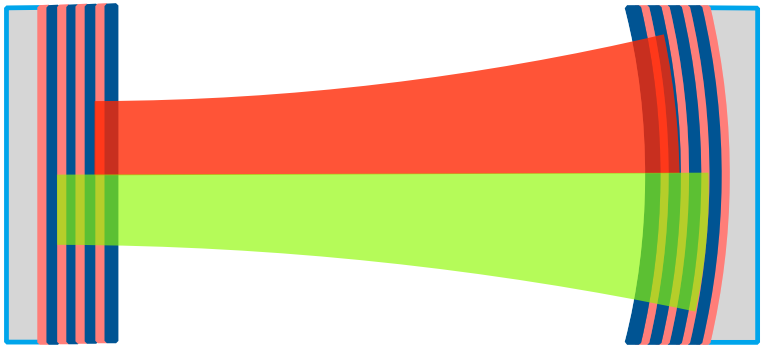
Out-of-loop noise - possible reasons

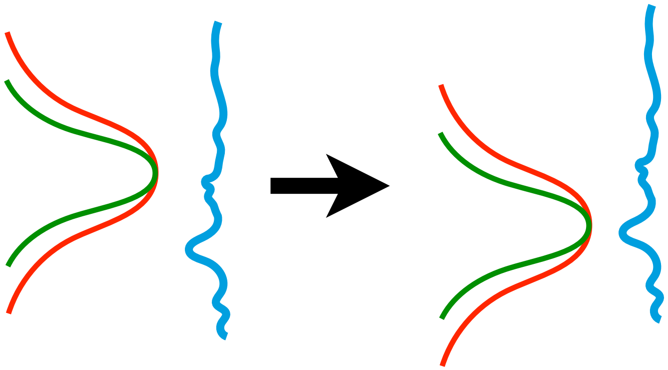
Path length changes in coating

- CTE and dn/dT of coating layers
- Temperature changes:
  - Change in reflected phase
  - Diff. changes for Green vs IR

Modes probing rough features

- Different eigenmode sizes
- Imperfections couple differently
  - Differential reflection plane
- Alignment noise ➜ position noise
  - Diff. dichroic length noise

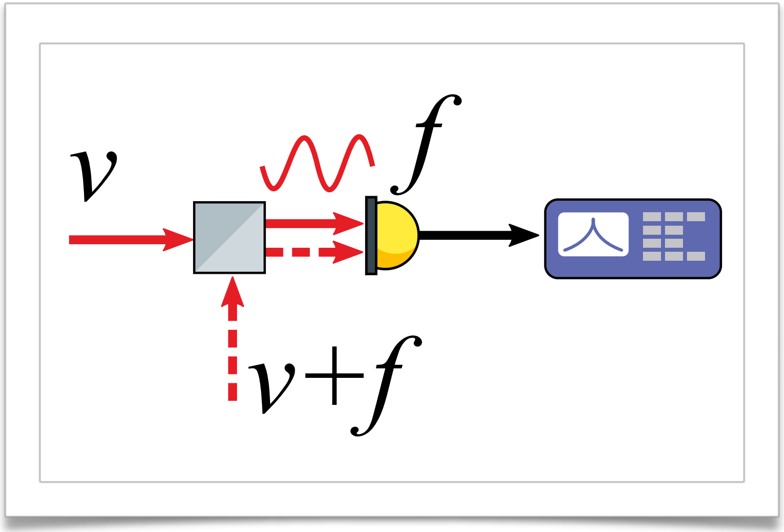




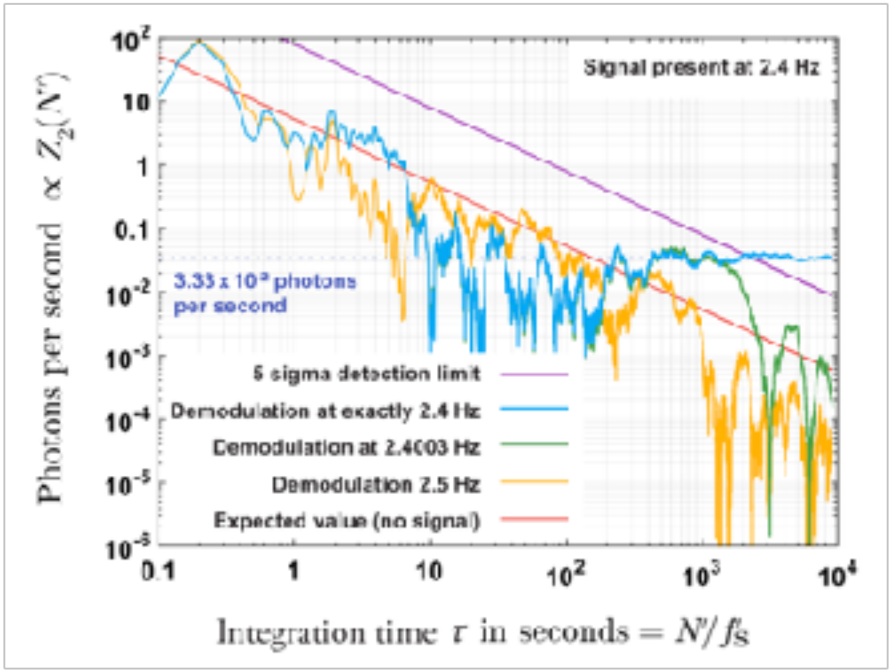
slide courtesy of A. Spector

Heterodyne detection scheme

- Heterodyne detector being developed at the University of Florida
- Interference beat note between measurement (very weak) signal and (strong) local oscillator (LO)
  - Phase relation between measurement signal and LO fixed
  - Coherently sum by demodulating at difference frequency
  - FPGA readout
  - third laser (LO) required



Heterodyne detection scheme - sensitivity



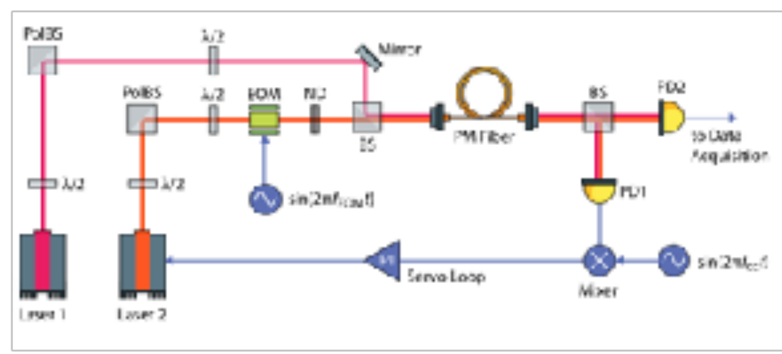
PHYSICAL REVIEW D 99, 022001 (2019)

Coherent detection of ultraweak electromagnetic fields

Zachary R. Bush,[1] Simon Barke,[1] Harold Hollis,[1] Aaron D. Spector,[2] Ayman Hallal,[1] Giuseppe Messineo,[1] D. B. Tanner,[1] and Guido Mueller[1]

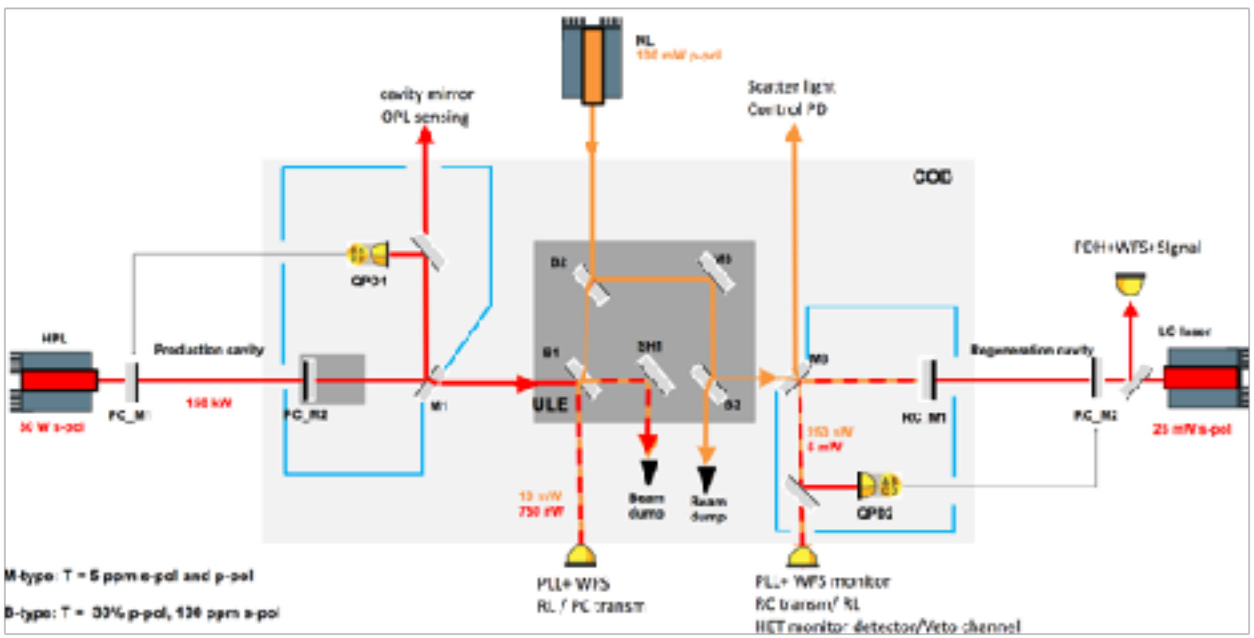
- results from table top experiment
- summing quadrature terms
- noise decreases linearly with time

$$S = |E_{SO}e^{i(\omega_1 t+\phi)} + E_{LO}e^{i\omega_2 t}|^2$$
$$= E_{LO}^2 + 2E_{LO}E_{SO}\cos(\Omega t + \phi)$$



ALPS II control scheme - Heterodyne

- three lasers required
- no green light involved
- avoid sources of scattered light
- minimize path length changes on central optical bench to preserve phase stability



Comparison: Detection Schemes

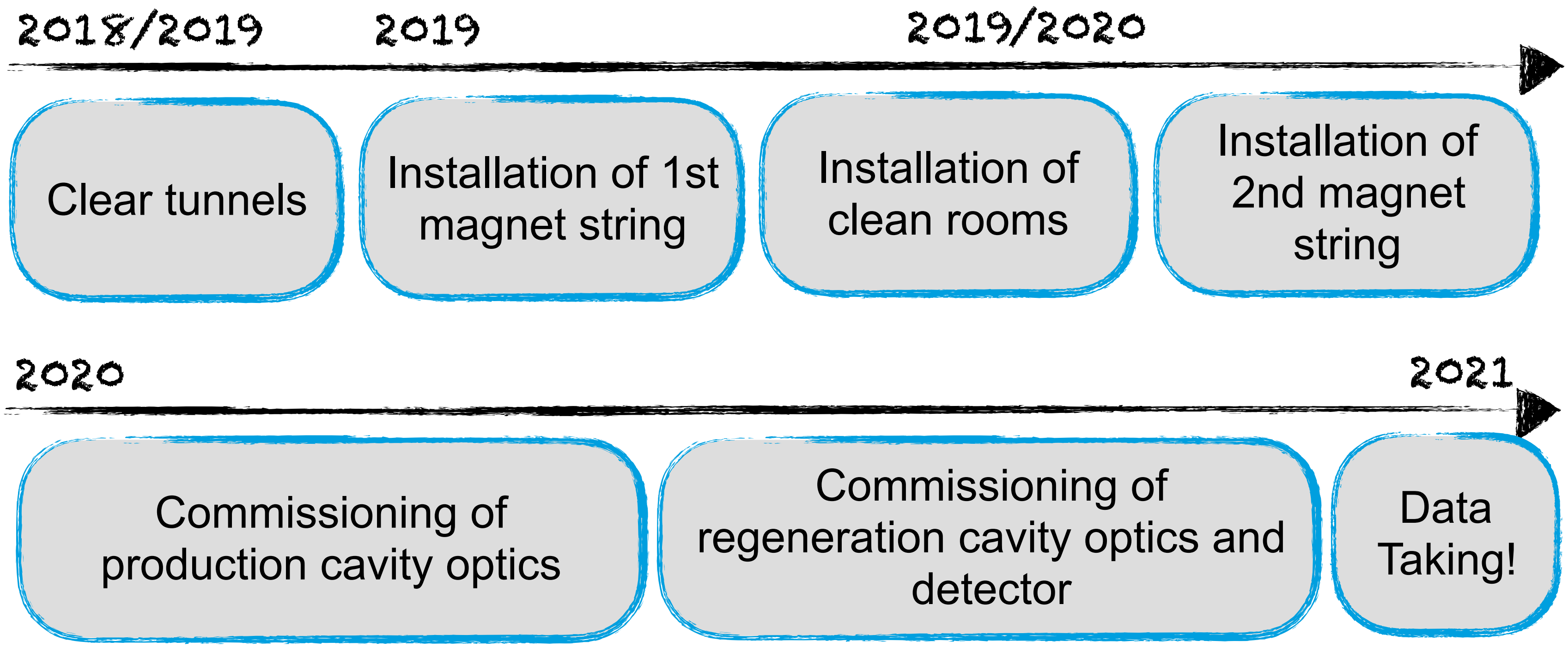
TES	Heterodyne detection
photon counting	field detection
energy resolution (<6%)	insensitive to incoherent background photons
cryogenic environment required	long term phase coherence of signal required
regeneration cavity has to be locked with green light, which has to be attenuated before reaching the detector	can be done when regeneration cavity is locked with IR light (at a slightly different frequency)

- heterodyne scheme more sensitive if signal photon rate << dark count rate

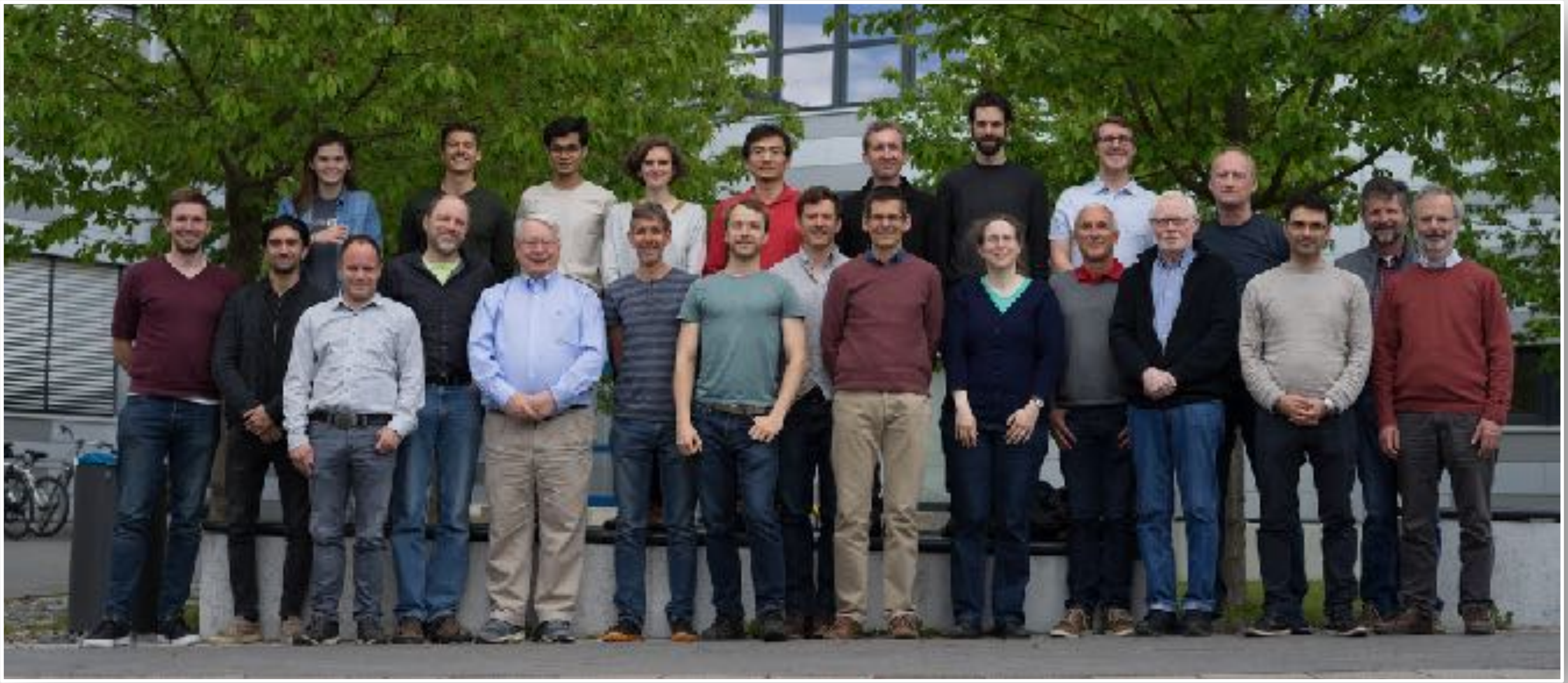
ALPS II status in a nutshell

	Goal	Status
Injected Power	30 W	32 W
PC circulating power	150 kW	50 kW
RC power buildup factor	40,000	26,000
CBB mirror alignement	< 5 µrad	< 1 µrad
Spatial overlap	> 95%	work ongoing (results from 1m prototype in Hannover promising)
RC length stabilization	< 0.6 pm	< 0.6 pm
TES Detector commissioning	$<1x10^{-4}/s$	$1.0x10^{-2}/s$ (expecting new results soon)
HET Detector commissioning	$<1x10^{-4}/s$	$3.3x10^{-2}/s$

ALPS II timeline



Collaboration



ALPS II is a joint effort of

- DESY, AEI Hannover, University of Florida, Mainz University & Cardiff University

with strong support from:

- NSF, neoLASE, PTB Berlin, NIST (US), Heising-Simons Foundation

Future LSW Experiments

Axion-like particles in the laboratory

Future LSW

- ALPS II optics and detectors will be
  "state of the art".
- The HERA dipole magnets are limited in field strength and aperture (defining the maximal length).
- JURA (*Joint Undertaking in Research on ALPs*) could combine ALPS II optics and detector developments with modern magnets being developed for future hadron colliders.

A physics case for a prototype series of Nb_3SN dipoles?

Axel Lindner, ESPP Symposium Granada, 14 May 2019

Challenges for JURA

> bigger magnet bore required
  > for more power in the generation part of the experiment
  > to not introduce clipping loss in a longer baseline experiment

> better optics required
  > to allow for higher power buildup in the regeneration area

Magnets for JURA

Dipole	Aperture [mm]	Field strength [T]	LSW experiment	Number of used dipoles
HERA (straightened)	50	5.3	ALPS II (DESY)	24
LHC	40	9.0	OSQAR (CERN)	2
"FCC"	100	13	JURA	~2x 500m strings

For the "FCC" dipole parameters see for example:

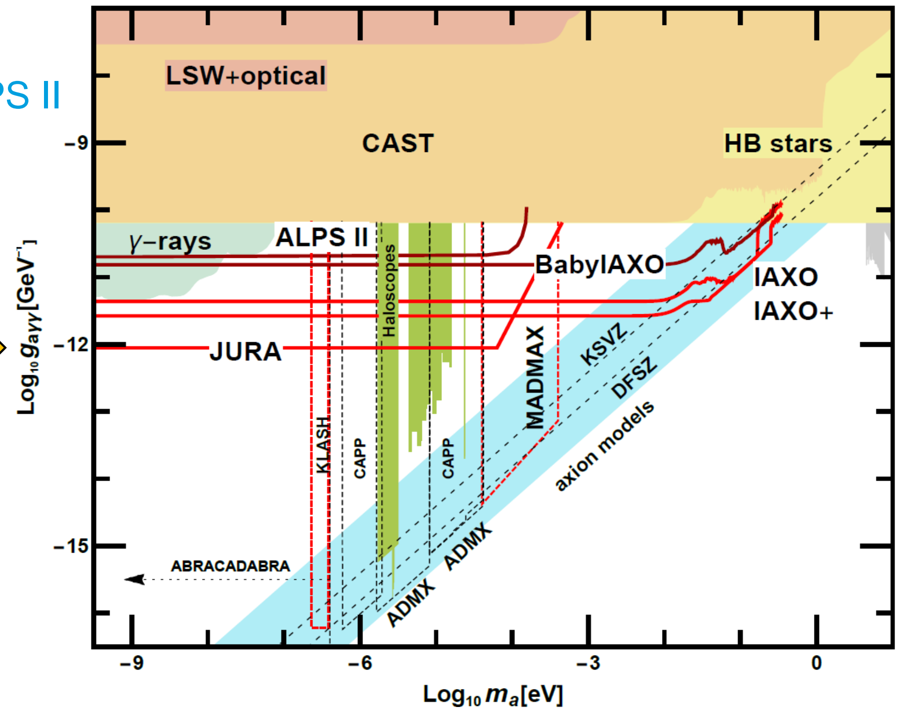
- Bottura L, de Rijk G, Rossi L, Todesco E., IEEE Trans. Appl. Supercond. 22:4002008 (2012), http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6656892
- Todesco E, Bottura L, de Rijk G, Rossi L., IEEE Trans. Appl. Supercond. 24:4004306 (2014), http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6172724

Axion-like particles in the laboratory

JURA

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

(13 T and 426 m: 10 · ALPS II)



JURA could allow to probe for very lightweight ALPs in the laboratory even beyond the IAXO reach.

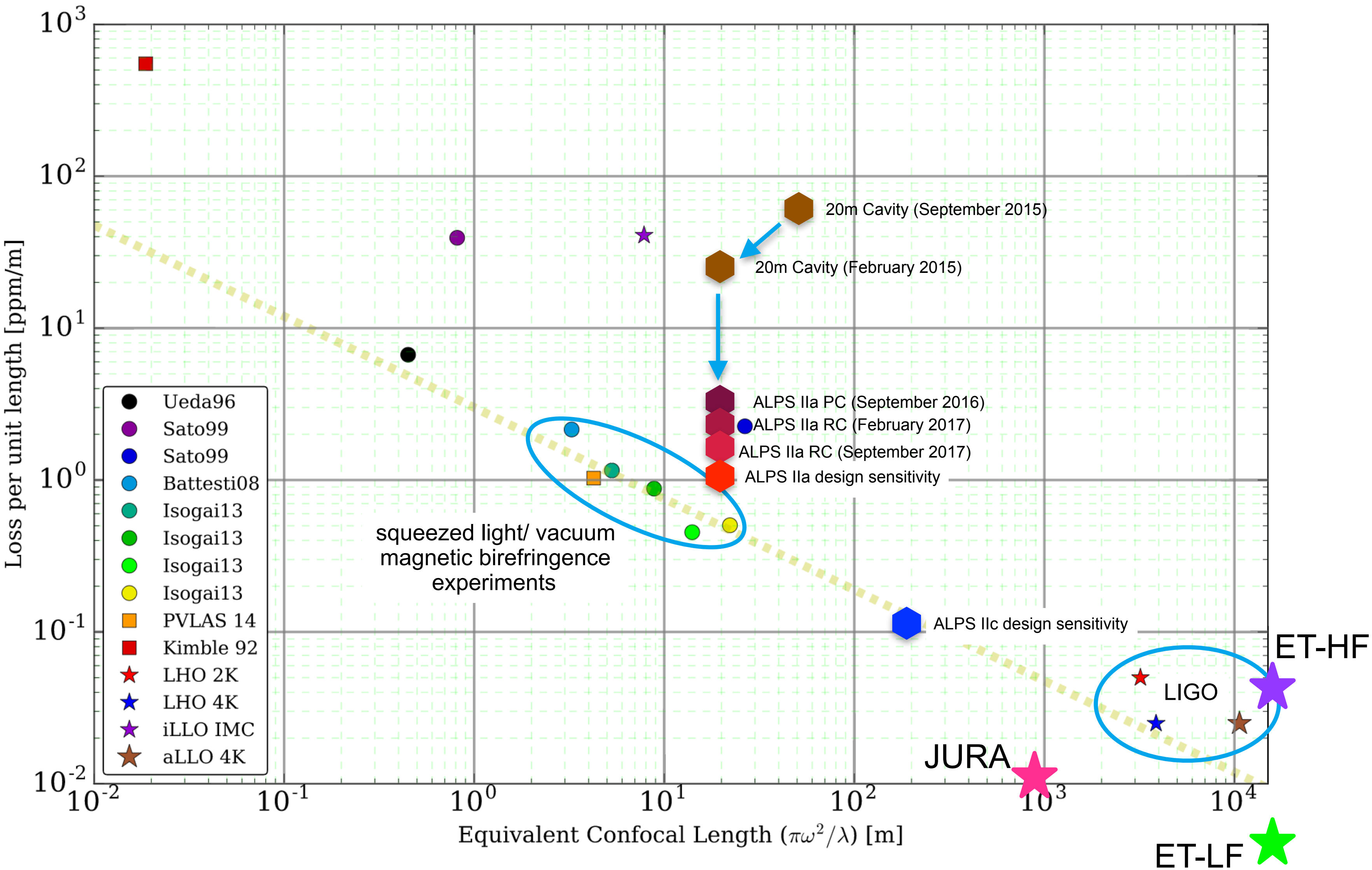
It would be a (costly) about 1km long apparatus.

If ALPS II fulfills expectations, JURA should be feasible.
Dipole magnet R&D is essential.

slide courtesy of A. Lindner

$$P_{\gamma\rightarrow\Phi\rightarrow\gamma} \propto P_{in} \cdot PB_{PC} \cdot PB_{RC} \cdot (g_{\alpha\gamma} \cdot B \cdot l)^4$$

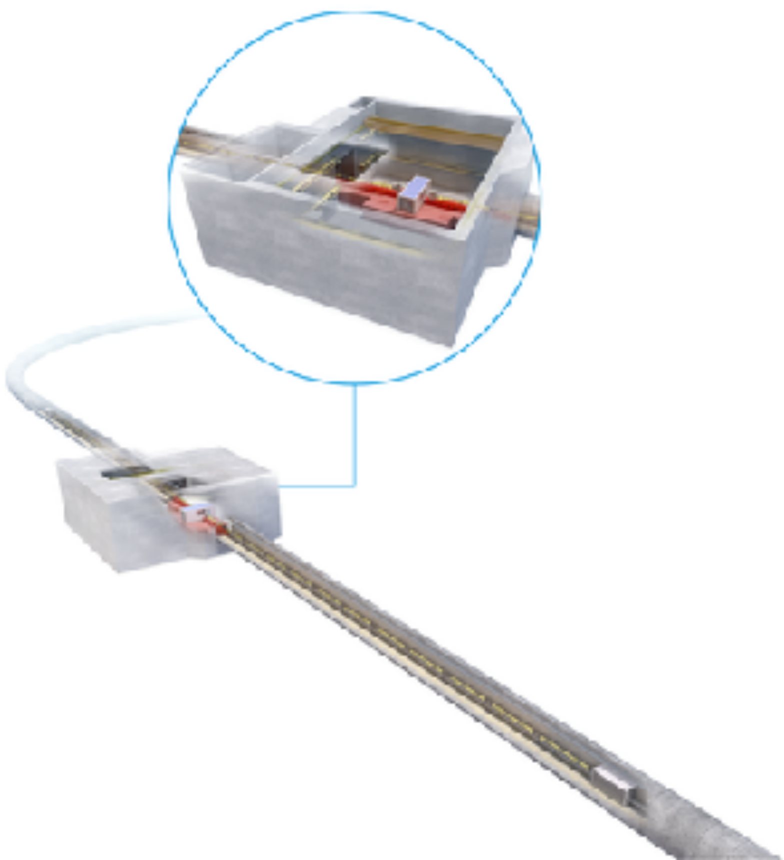
Performance of ALPS II resonator in context of other cavity experiments



Conclusion

- ALPS II is a light-shining-through-a-wall experiment at DESY in Hamburg comprising superconducting magnets and state-of-the-art optics
- ALPS II data taking is anticipated in the beginning of 2021 with two independent detection concepts
- JURA is a proposal for a 1km long light-shining-through-a-wall experiment that can exceed the sensitivity of ALPS II by a factor of 50
  - Strong physics case could emerge from ALPS II or babyIAXO results
  - Dedicated magnet development required

Thank you



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