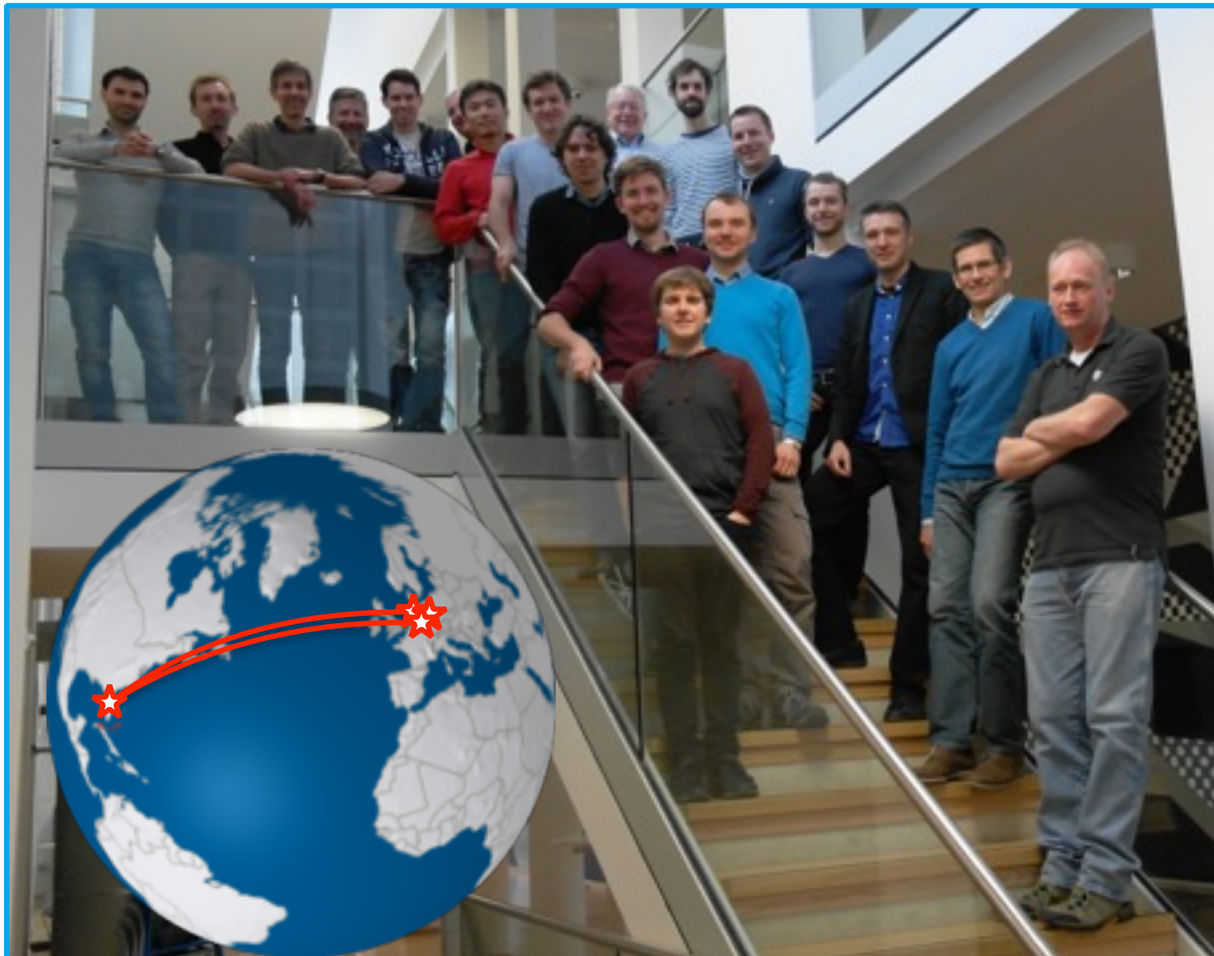
Any Light Particle Search II (ALPS II)

Searching for Axion-like Particles with Optical Cavities

Aaron Spector

International workshop on Axion physics and dark matter cosmology

Osaka University, Japan
December 20-21, 2017



Overview

- Three questions:

  - How can optical cavities help us search for Axion-like particles?

  - What challenges exist when using optical cavities?

  - Where do we currently stand in addressing these challenges?

Axions and Axion-like-particles

- Solution to the strong CP problem
  - Axion cancels terms that break CP symmetry in QCD Lagrangian

- Coupling between Axions and photons

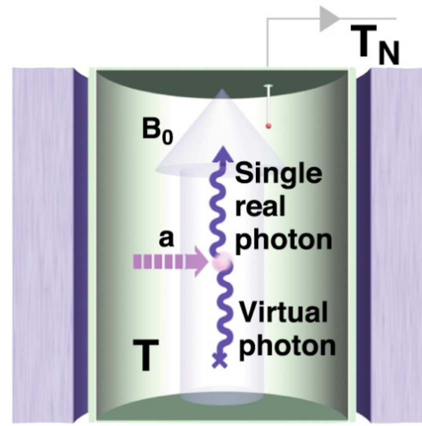
$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}\, g_{a\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\, a\, \vec{E}\cdot\vec{B}$$

- Axion would explain various astrophysical phenomena
  - Stellar cooling excesses
  - TeV transparency

- Axion-like particles

Experimental Axion Searches

- Haloscopes: ADMX
  - Axions in DM halo
  - Microwave cavities with B-fields

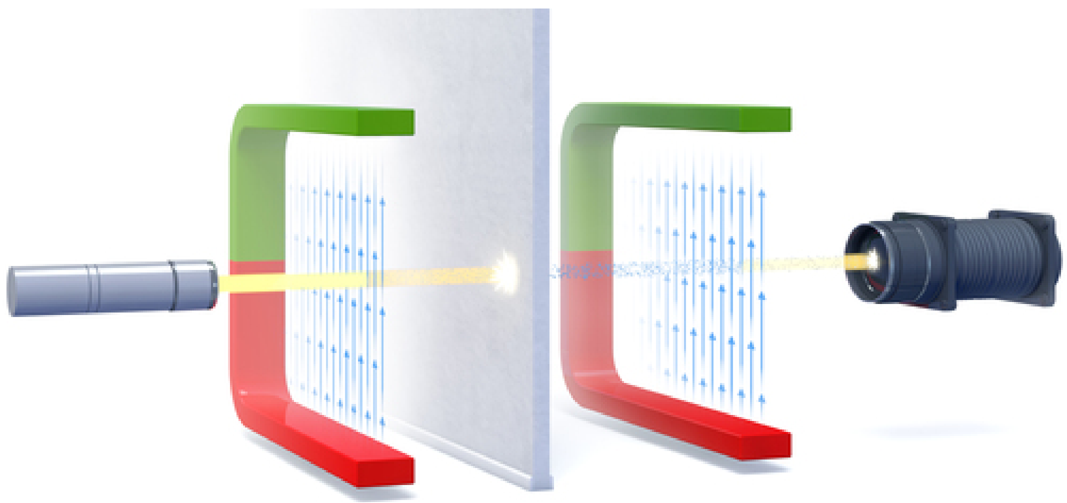


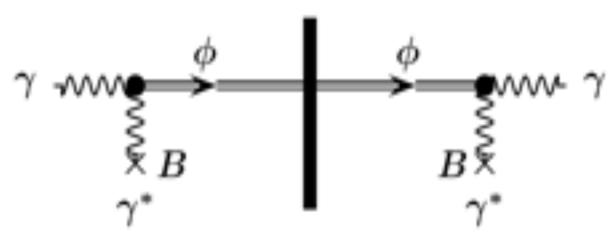
- Helioscopes: CAST, IAXO
  - Axions generated by the sun
  - Light tight X-ray telescopes in B-fields

- Light-shining-through-a-wall (LSW): ALPS I, ALPS II
  - Creating Axion-like-particles in lab with lasers and B-fields

LSW Experimental Concept

- Axion-like-particles generated by high power laser source in B-field
  - Propagates though region of strong B-field toward wall
- Axions-like-particles reconverted to photons behind wall
  - Region of strong B-field behind the wall
  - Light tight enclosure prevents light from entering regeneration area
  - Regenerated photons measured with a single photon detector

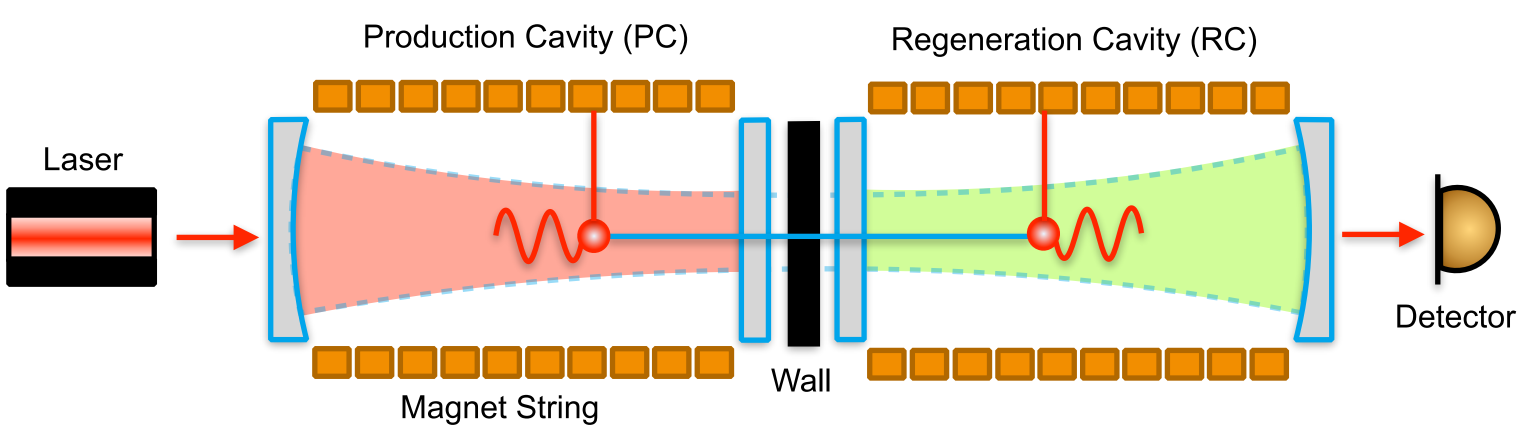




ALPS II Concept

- Production cavity increases circulating power before wall
  - Increases the flux of axion-like-particles through the wall
- Regeneration cavity resonantly enhances probability of $a \rightarrow \gamma$
  - Amplifies the electromagnetic component of the Axion-like field
- Number of regenerated photons:

$$\boxed{N_{\mathrm{S}} = \eta^2 N_{\mathrm{PC}} \frac{\mathcal{F}_{\mathrm{RC}}}{\pi} \frac{1}{16} (g_{a\gamma} B L)^4}$$

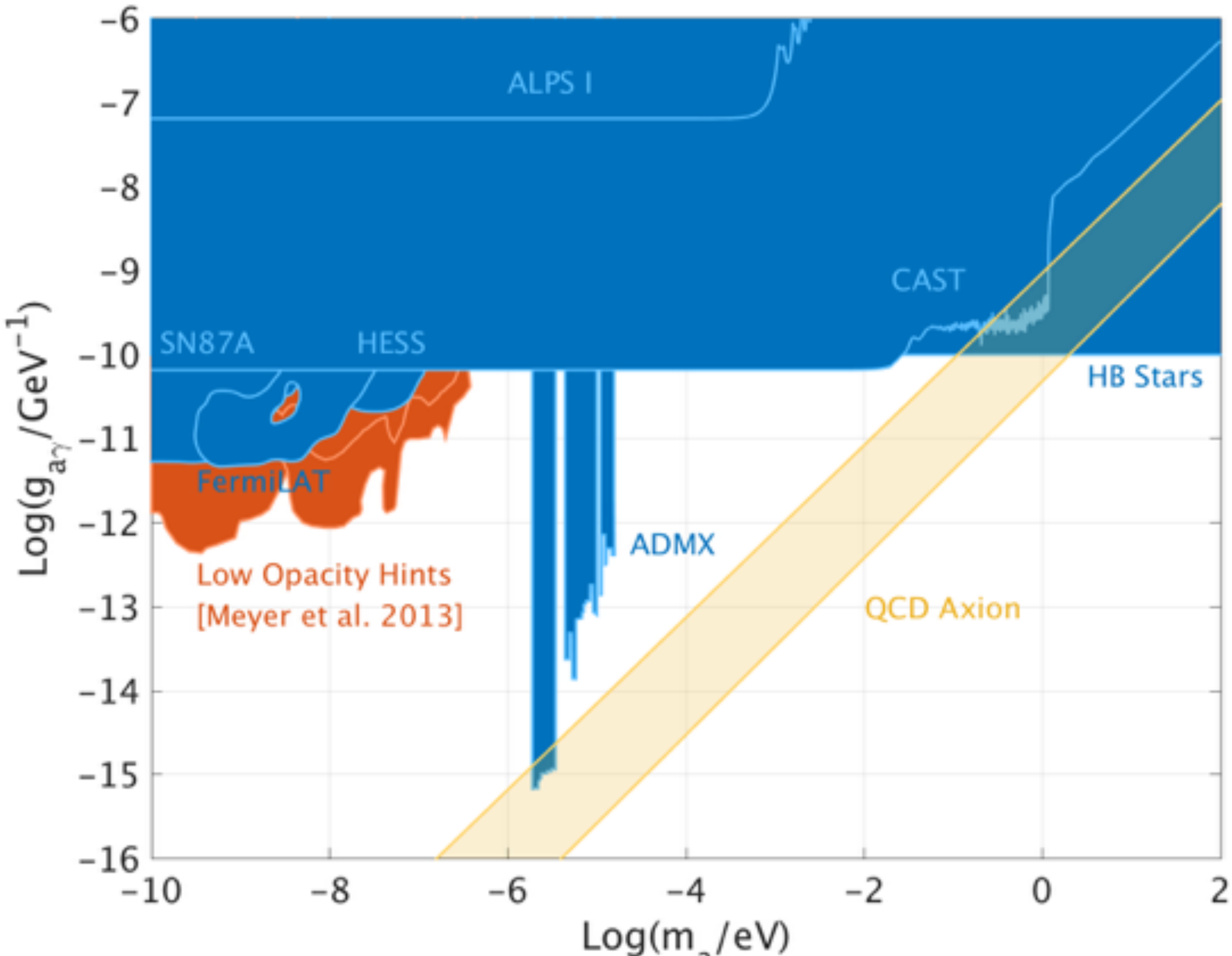


ALPS II Design Parameters

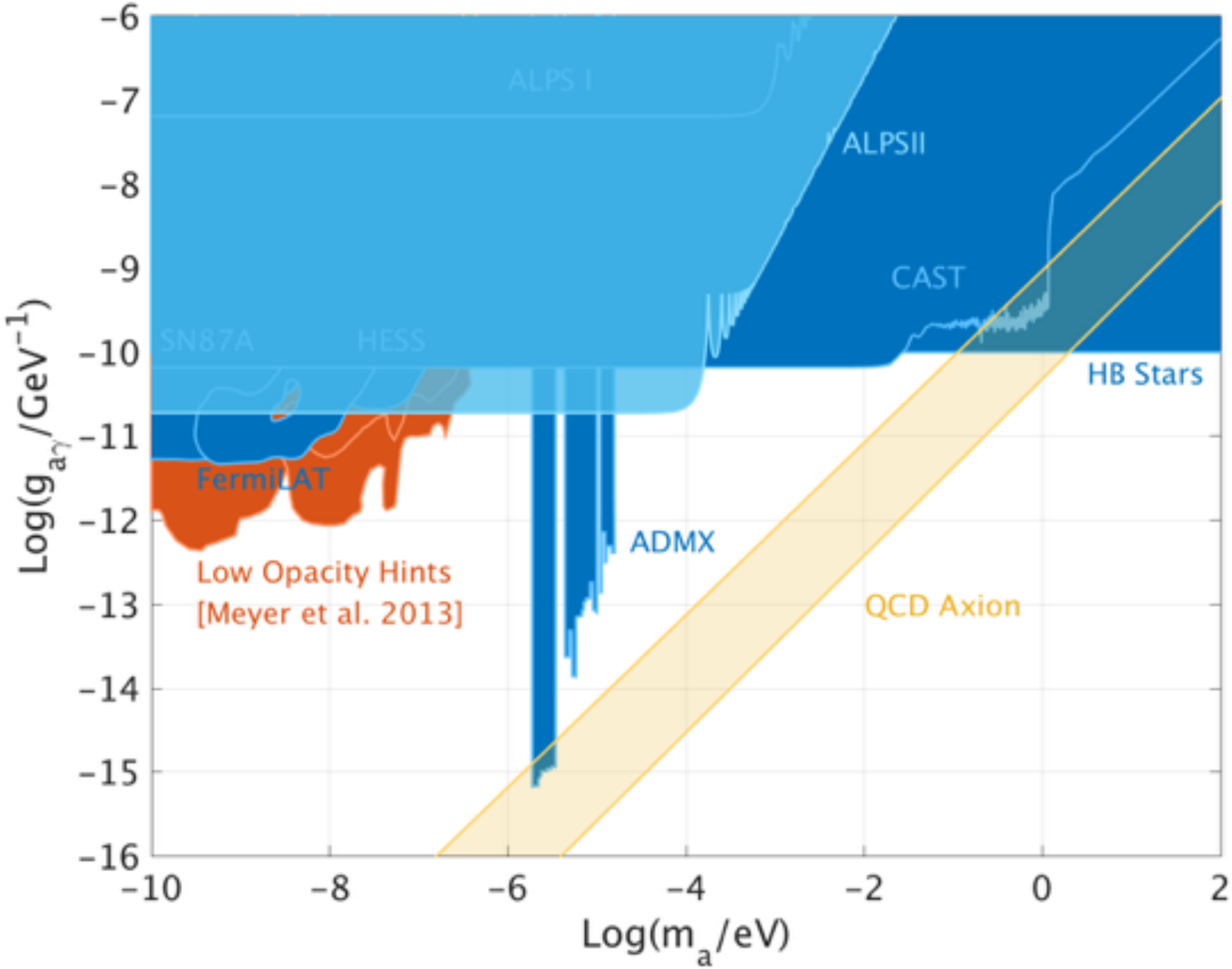
- Magnets: 5.3 T superconducting HERA dipoles, 10 per cavity
  - 468 Tm magnetic field length per cavity
- Production cavity: 100 m, 30 W input laser, 5000 power build up
  - 150 kW circulating power in the PC
- Regeneration cavity: 100m, 120,000 finesse
  - Current state of the art of mirrors for ~100 m cavities
- ALPSII factor ~3000 more sensitive than ALPSI
  - Factor of 14 from the RC, 21 from BL, 3.5 from PC power

$$\boxed{N_{\mathrm{S}} = \eta^2 N_{\mathrm{PC}} \frac{\mathcal{F}_{\mathrm{RC}}}{\pi} \frac{1}{16} (g_{\alpha\gamma} B L)^4}$$

ALPS II Sensitivity

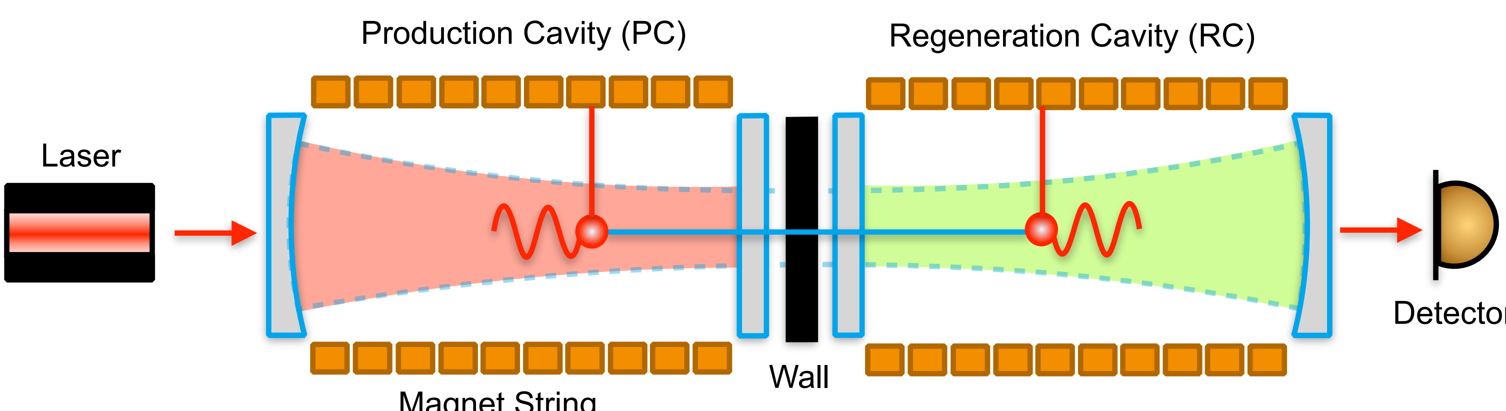


ALPS II Sensitivity



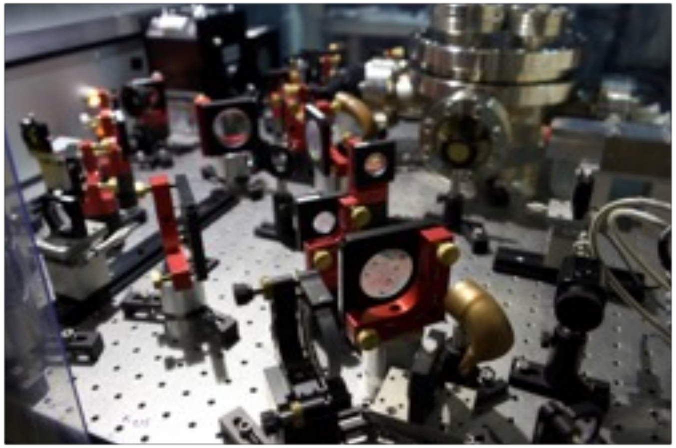
Experimental Challenges

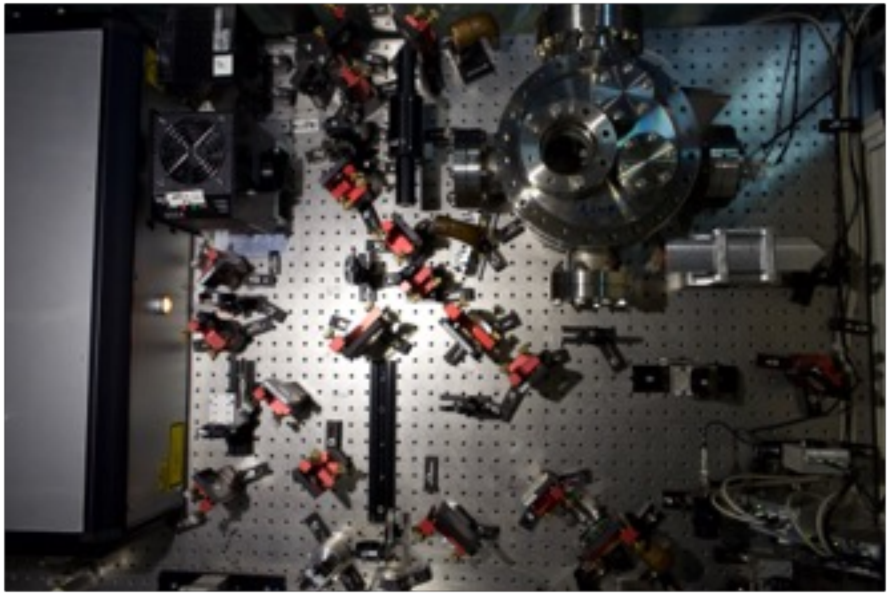
- Regeneration cavity introduces several challenges
  - Dual resonance
    - PC circulating field must be resonant with RC
  - Light Tightness
    - Can’t use IR light to maintain length stability
  - Spatial overlap
    - PC and RC spatial Eigenmodes must overlap



ALPSIIa Pathfinder Experiment

- Test optical systems for ALPSIIc
- 10m collinear cavities, no magnets
- Sensitive to Hidden Photons
- Full optics demonstration summer 2018





Cavity Status for ALPSIIa

- Production Cavity:
  - 35 W input power, power build factor of 4000 (low power operation)
  - PDH frequency stabilization, auto-alignment
  - 50 kW stable high power operation (requirement: 150 kW)
- Regeneration Cavity
  - Measured finesse of 93,000 (requirement: 120,000)
  - Implemented length control system

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Characterization of optical systems for the ALPS II experiment

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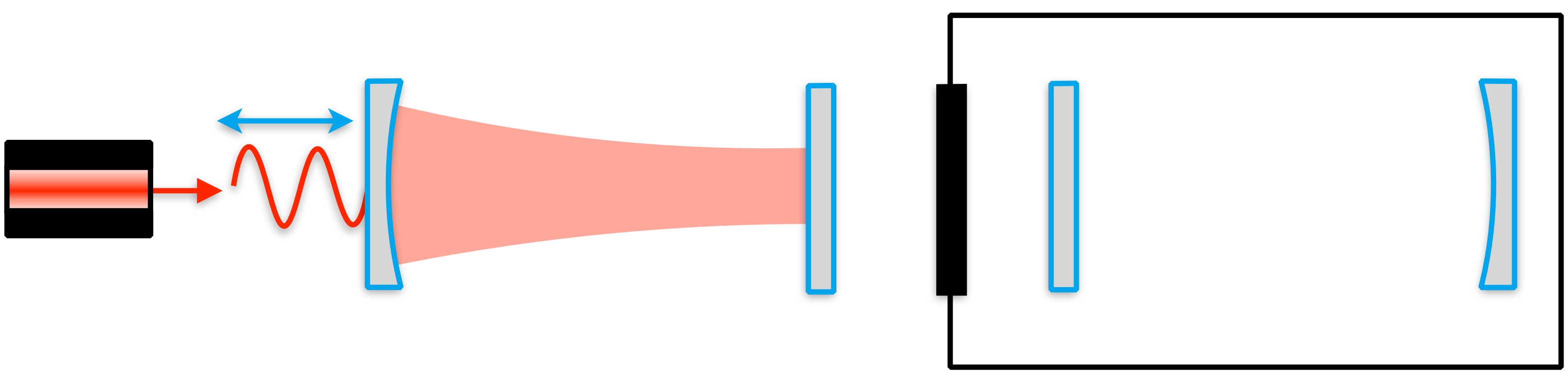
Demonstration of the length stability requirements for ALPS II with a high finesse 10 m cavity

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

[1]Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, D-22607 Hamburg, Germany

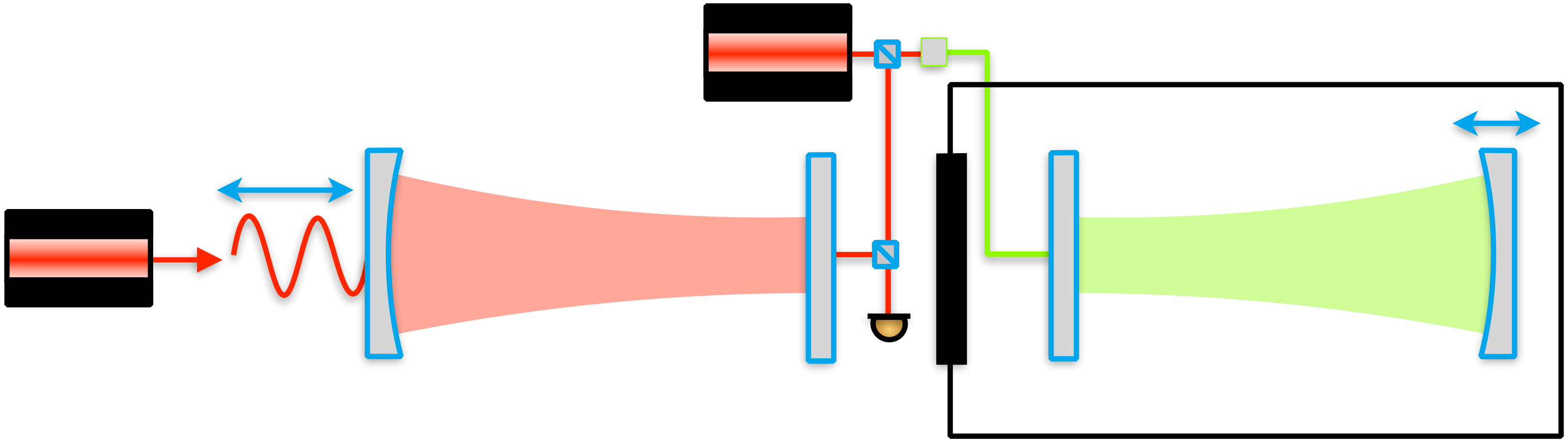
Dual Resonance Concept

- PC resonance condition maintained with PDH frequency control loop



Dual Resonance Concept

- PC resonance condition maintained with PDH frequency control loop
- RC length must be resonant with PC circulating field
  - RC RMS frequency noise must be < 10% RC IR line-width
  - RC RMS length noise must be < 0.5 pm (ALPS IIc)
- Light tightness: Frequency double 1064 nm to 532 nm (green)
  - RC must be stabilized to < 1/10,000 of a line-width for 532 nm



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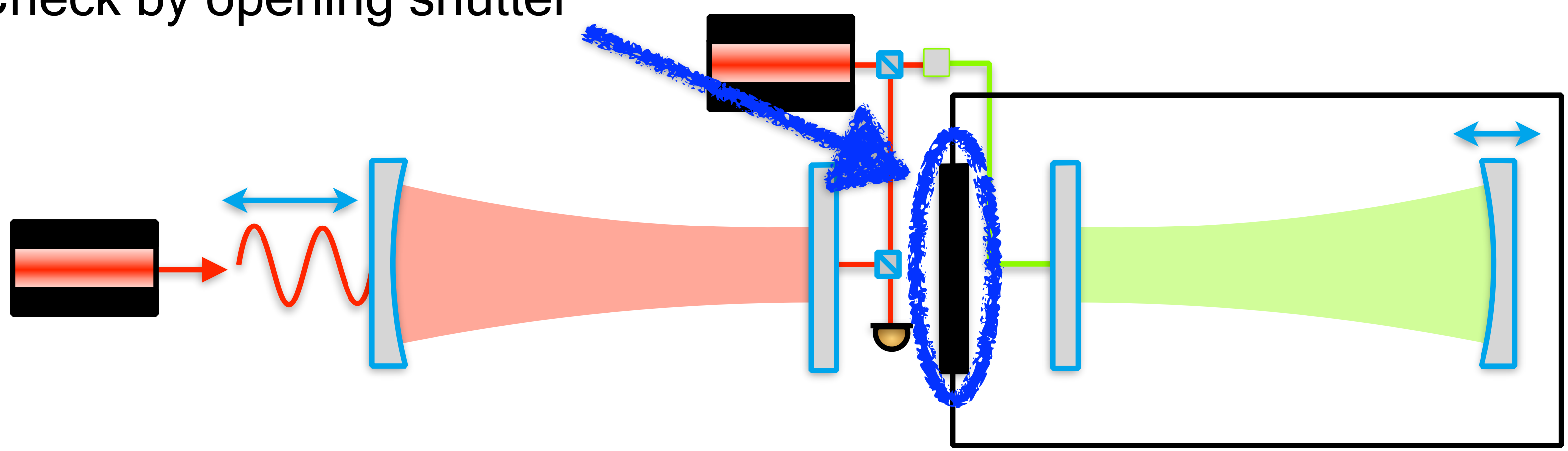
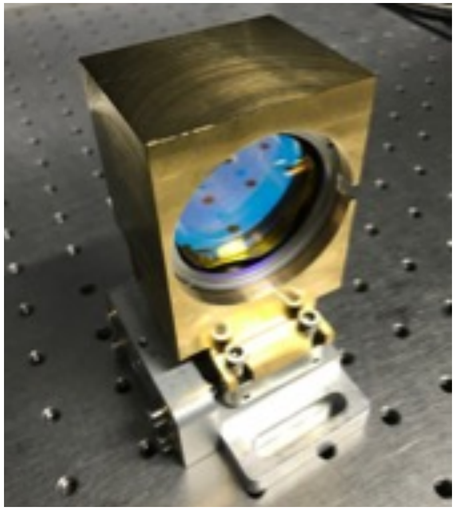
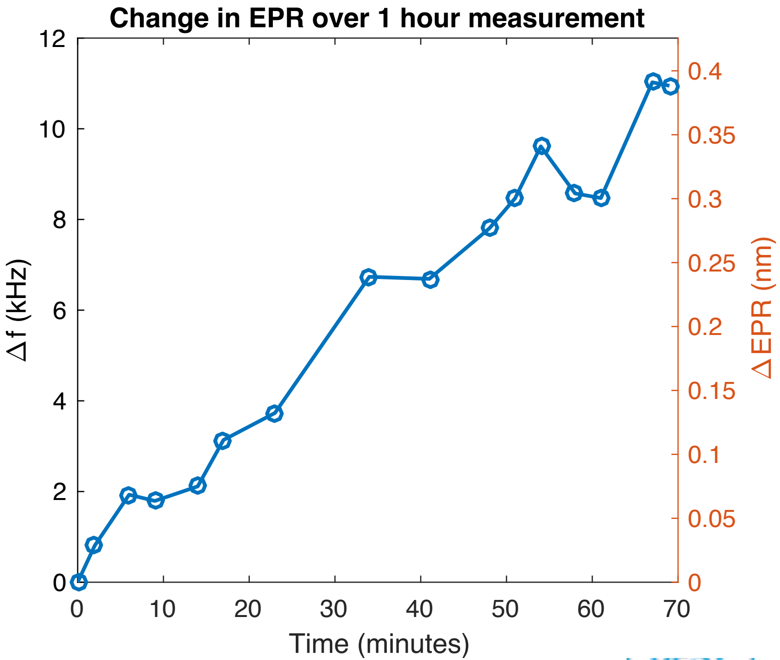
- Check by opening shutter

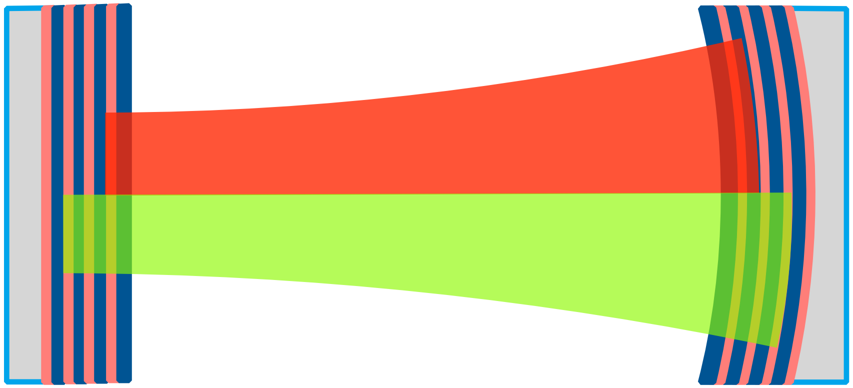


Dual Resonance Status

- Length actuator developed
  - Custom mount with Piezo
  - Suppressed in-loop length noise to < 0.3 pm
  - Next step: out-of-loop measurements
- Effective point of reflection changes
  - Must be suppressed < 0.5 pm
  - Measured 0.4 nm changes in 1 hour

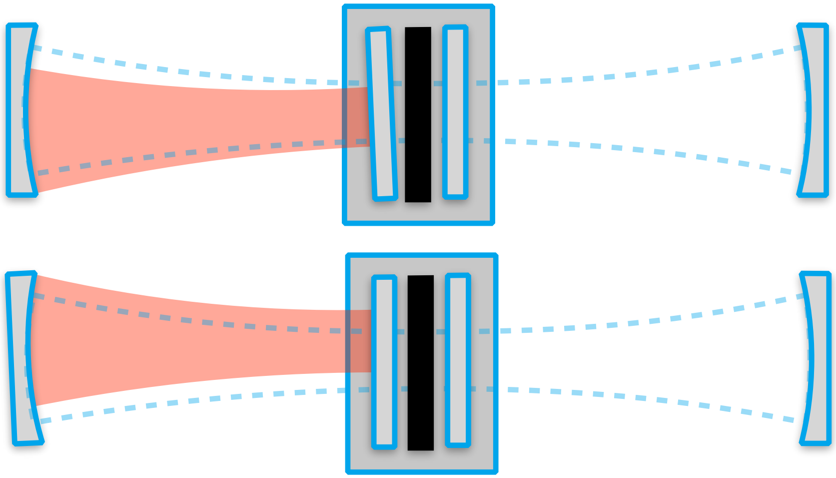


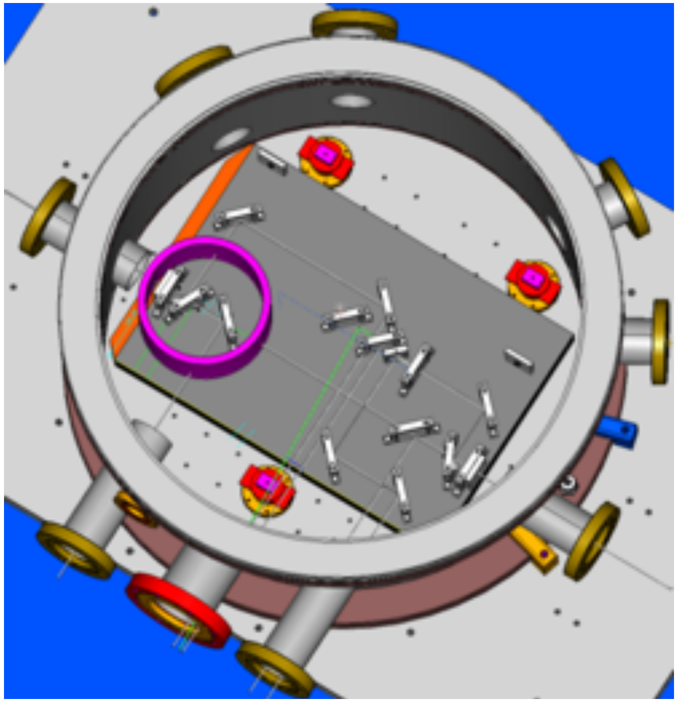




Spatial Overlap

- RC must maintain 95% spatial overlap with the PC
  - Cavity mirror alignment requirement: 5 µrad (ALPS IIc)
    - Central breadboard used to maintain alignment
    - Measured < 1 µrad drift in 1 week
  - Active alignment of end mirrors





Optics Status Summary

	Requirement	Status
PC circulating power	150 kW	50 kW
RC finesse	120,000	93,800
Spatial overlap	> 95%	• Breadboard mirror alignment meets requirements
RC length stabilization	< 0.5 pm	< 0.3 pm

ALPSII Detection Schemes

- Two independent detection schemes

  - Transition Edge Sensor (TES)
    - Microcalorimeter measures temperature change induced by photon on absorber
    - Dilution refrigerator purchased from BlueFors (April delivery)

  - Heterodyne detection scheme
    - Regenerated photons coherent with PC circulating field
    - Coherent summation of measurement signal over time
    - Incoherent summation of noise

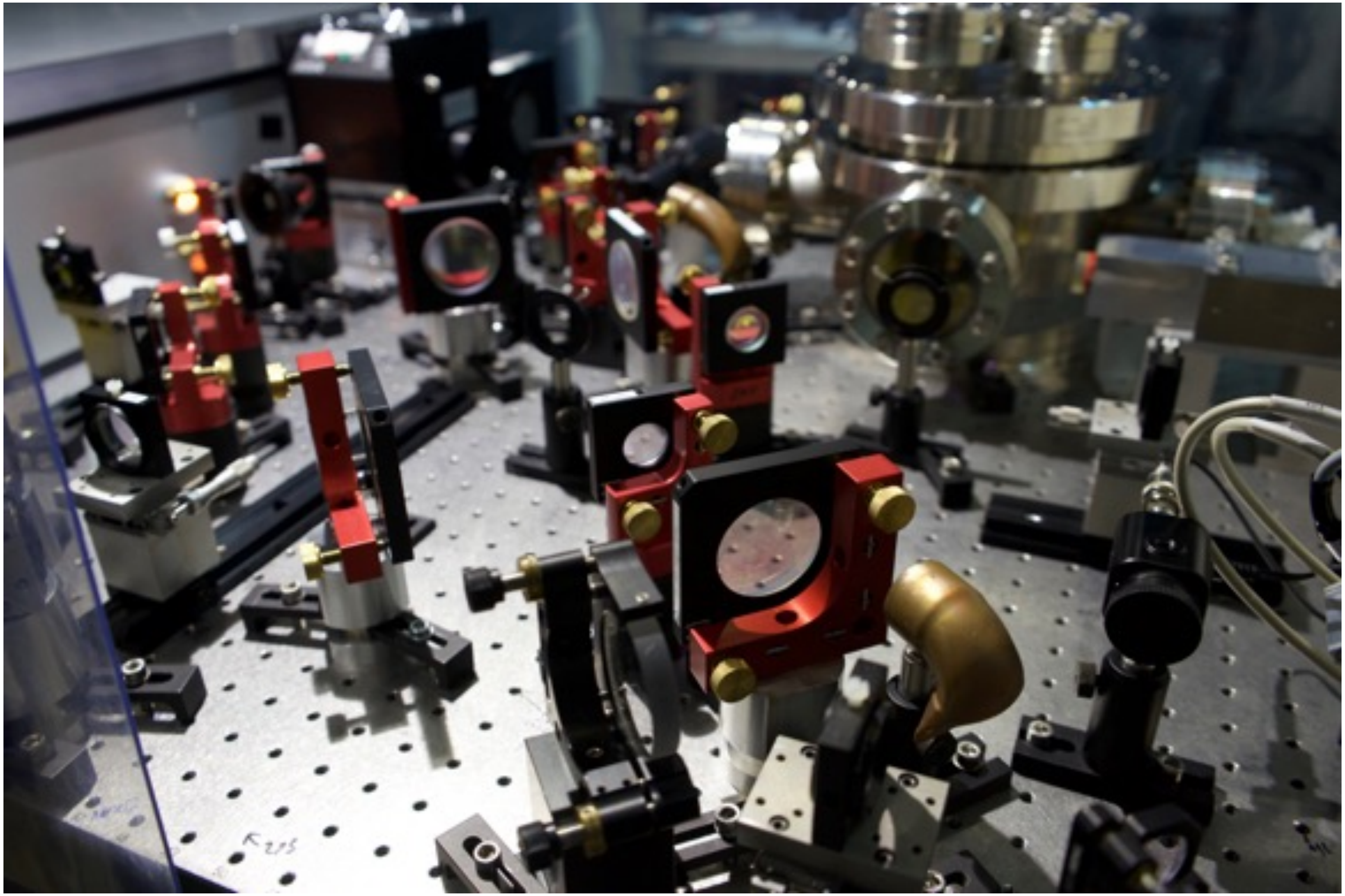
Future Challenges and Timeline

- Demonstration of dual resonance
  - Operate both cavities simultaneously, mitigate EPR changes
- Demonstration of spatial overlap
- Light tightness
- Detector development

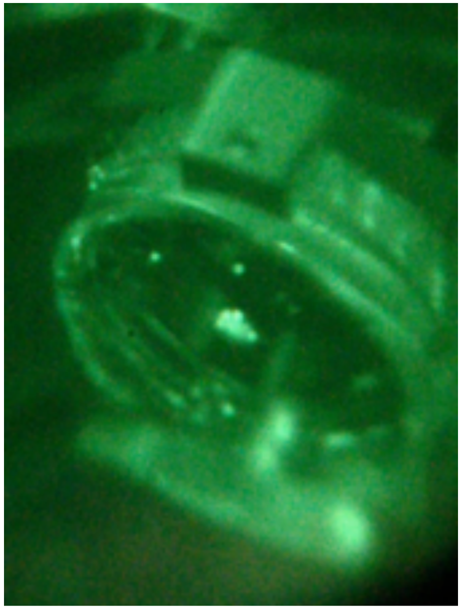
- Timeline
  - ALPS IIa full optics concept demonstration summer 2018
  - ALPS IIc optics commissioning beginning fall 2018
  - ALPS IIc data runs in 2020

Thanks for listening!

- Any questions



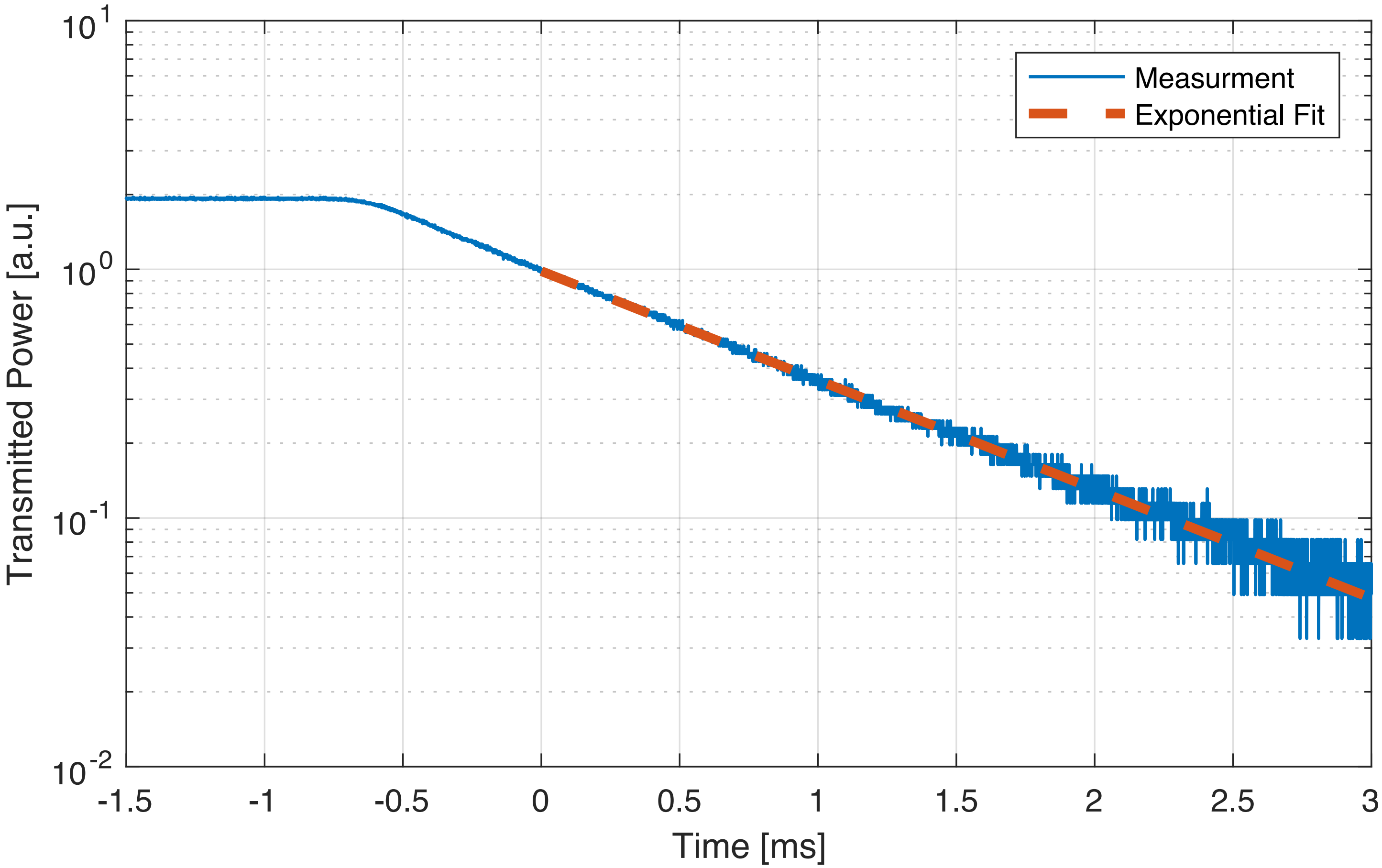
Production Cavity Status



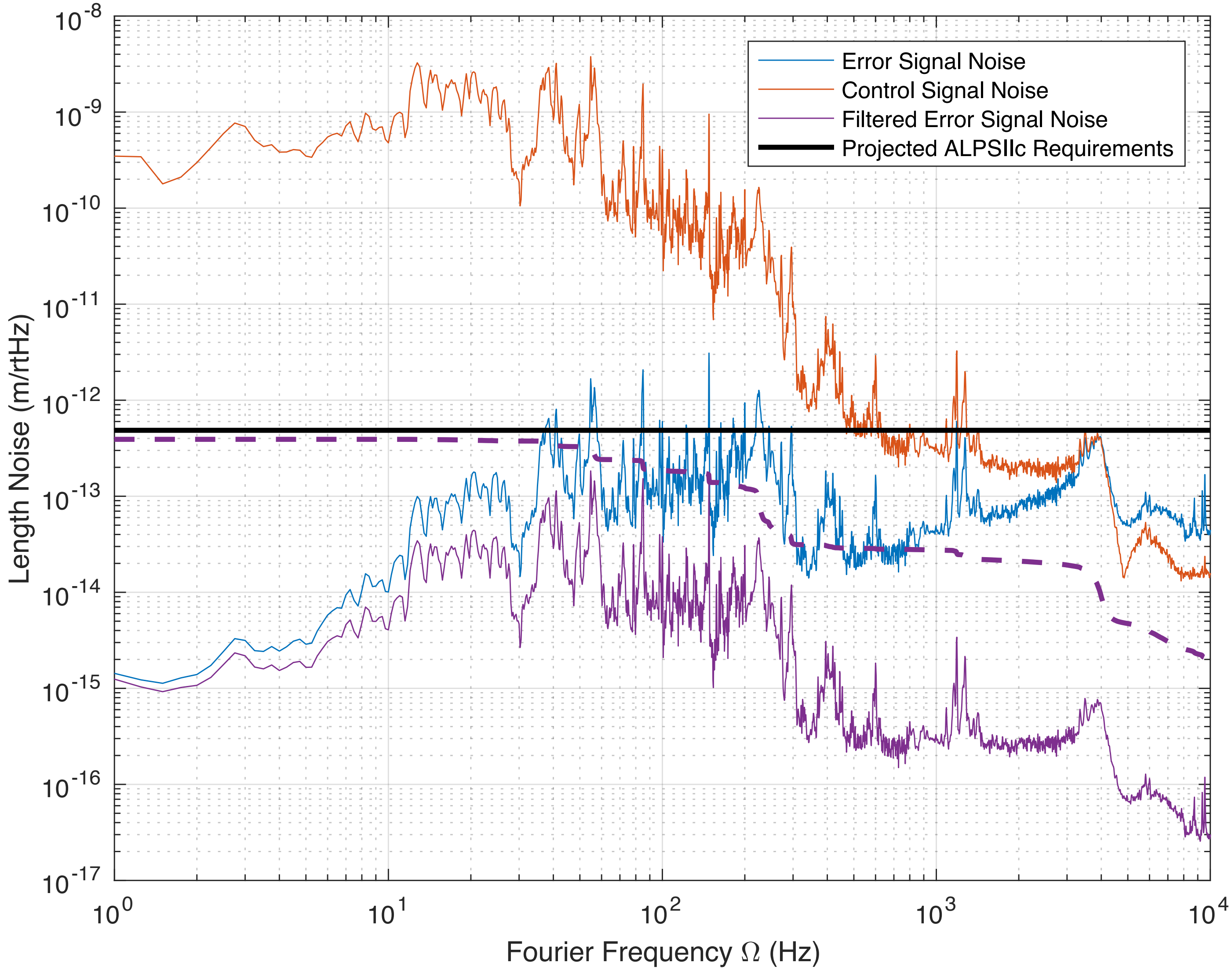
- Requirements: 150 kW of circulating power
  - 30 W input power
  - Design power build 5000
  - Automatic alignment system
- Measured power build up 4000 at 0.5 W
  - Losses of 115+-35 ppm (power build up factor without losses 4500)
- High Power operation with 30 W input power
  - Thermal effects ➜ reduced circulating power
  - 50 kW stable operation

Regeneration Cavity Status

- Measured finesse of 93,000 (design for 120,000)
  - 39 ppm losses (23 ppm design)

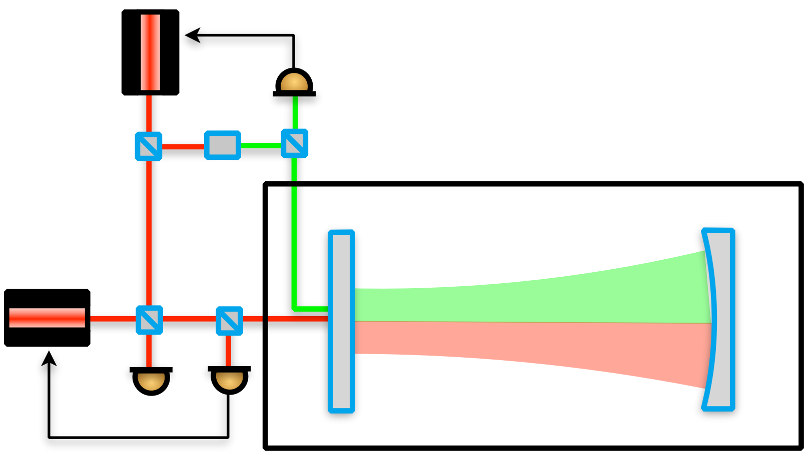


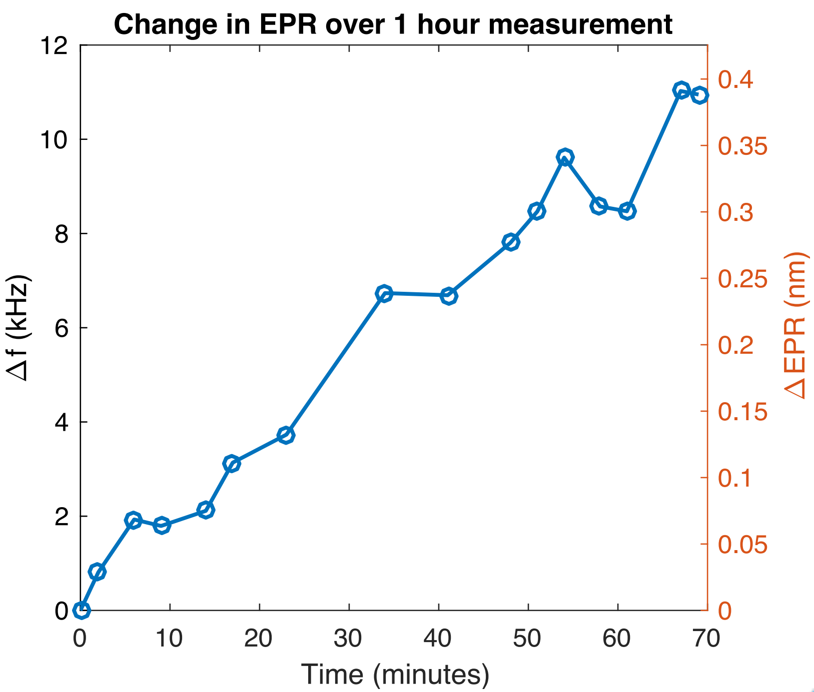
RC Length Stabilization results



Effective Point of Reflection Measurement

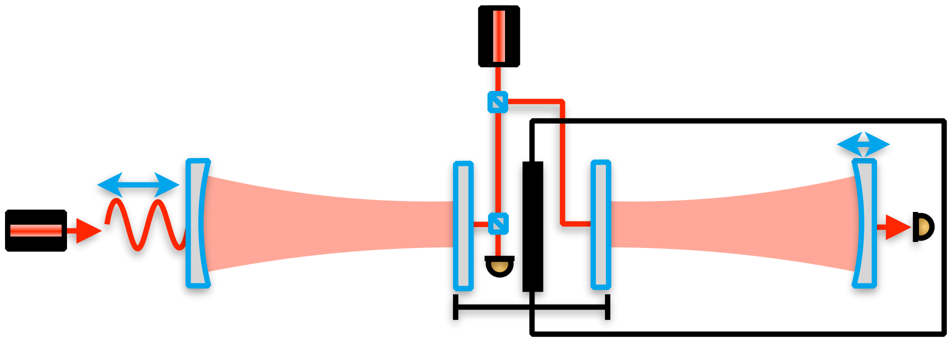
- Measured EPR changes
  - Simultaneously locked 532 nm and 1064 nm to RC
  - Measured relative drift of resonant frequencies
    - 11 kHz RMS over ~1 hour (0.4nm)

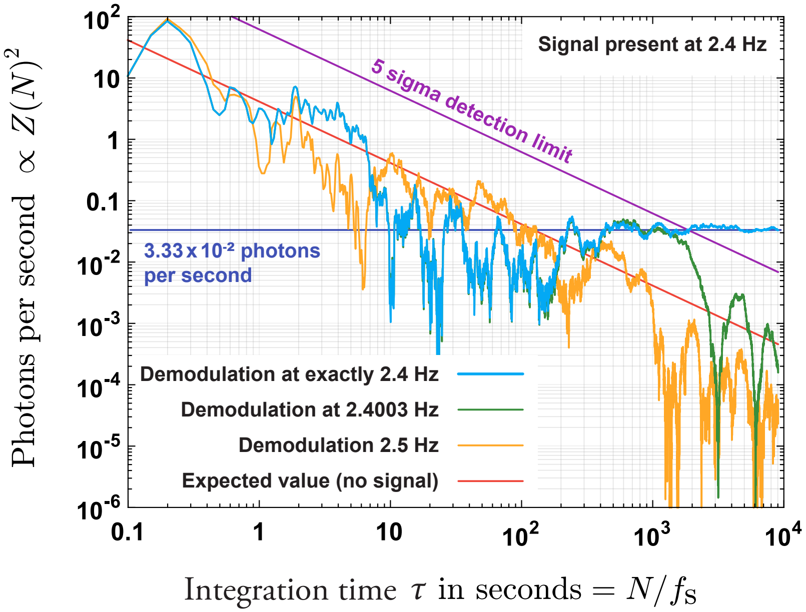




Heterodyne Detection

- Interference beat note between measurement signal and local oscillator
  - Phase relation between measurement signal and LO fixed
  - Coherently sum by demodulating at signal frequency
- Demonstrated 2 week data run with no spurious signals from ADC
- PC-RC distance fixed by ULE plate
  - Lasers in phase lock loop





Heterodyne Detection

- Interference beat note between measurement signal and local oscillator
  - Phase relation between measurement signal and LO fixed
  - Coherently sum by demodulating
    - SNR = square root of N_S
  - Demonstrated 2 week data run with no spurious signals from ADC

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

$$S_I = 2\sqrt{N_{LO}N_S}\cos\phi$$

$$S_Q = 2\sqrt{N_{LO}N_S}\sin\phi$$

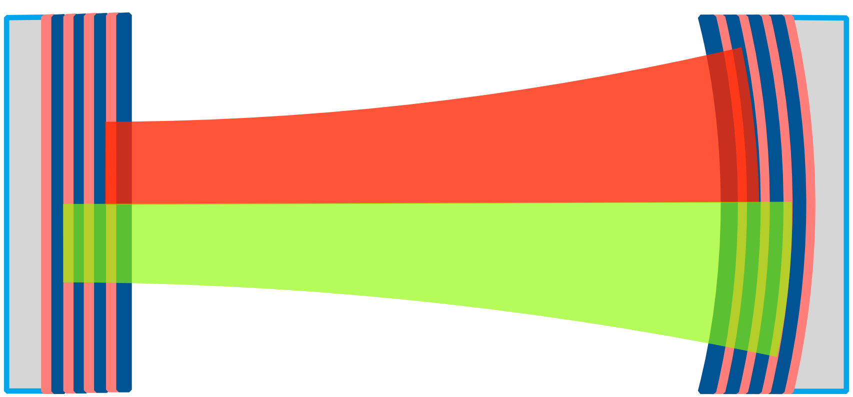
$$\frac{S_\Sigma}{\sigma_\Sigma} = \sqrt{N_S}$$

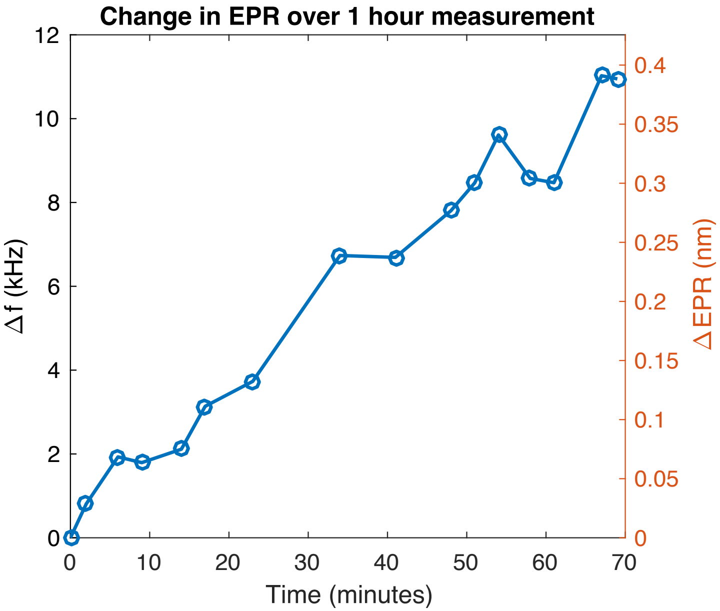
$$S_\Sigma = \sqrt{S_I^2 + S_Q^2} = 2\sqrt{N_{LO}N_S}$$

$$\sigma_\Sigma = \sqrt{\sigma_I^2 + \sigma_Q^2} = 2\sqrt{N_{LO}}$$

Effective Point of Reflection Changes

- RC mirrors will have different EPR for 532 nm and 1064 nm
  - EPR changes also subject to < 0.5 pm requirements
    - Layer thickness of coating stacks: CTE
    - Index of refraction of layers: dn/dT
  - Measured drift of resonant frequencies
    - 0.4nm RMS over ~1 hour

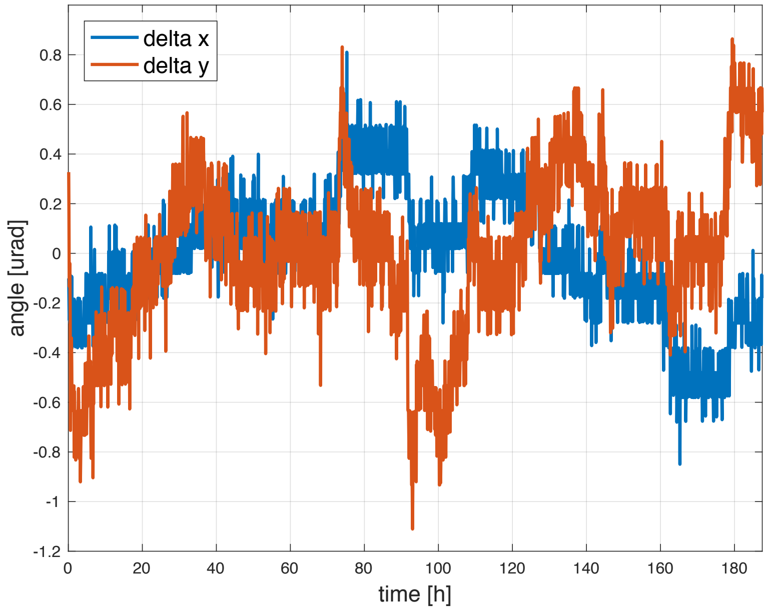




Spatial Overlap

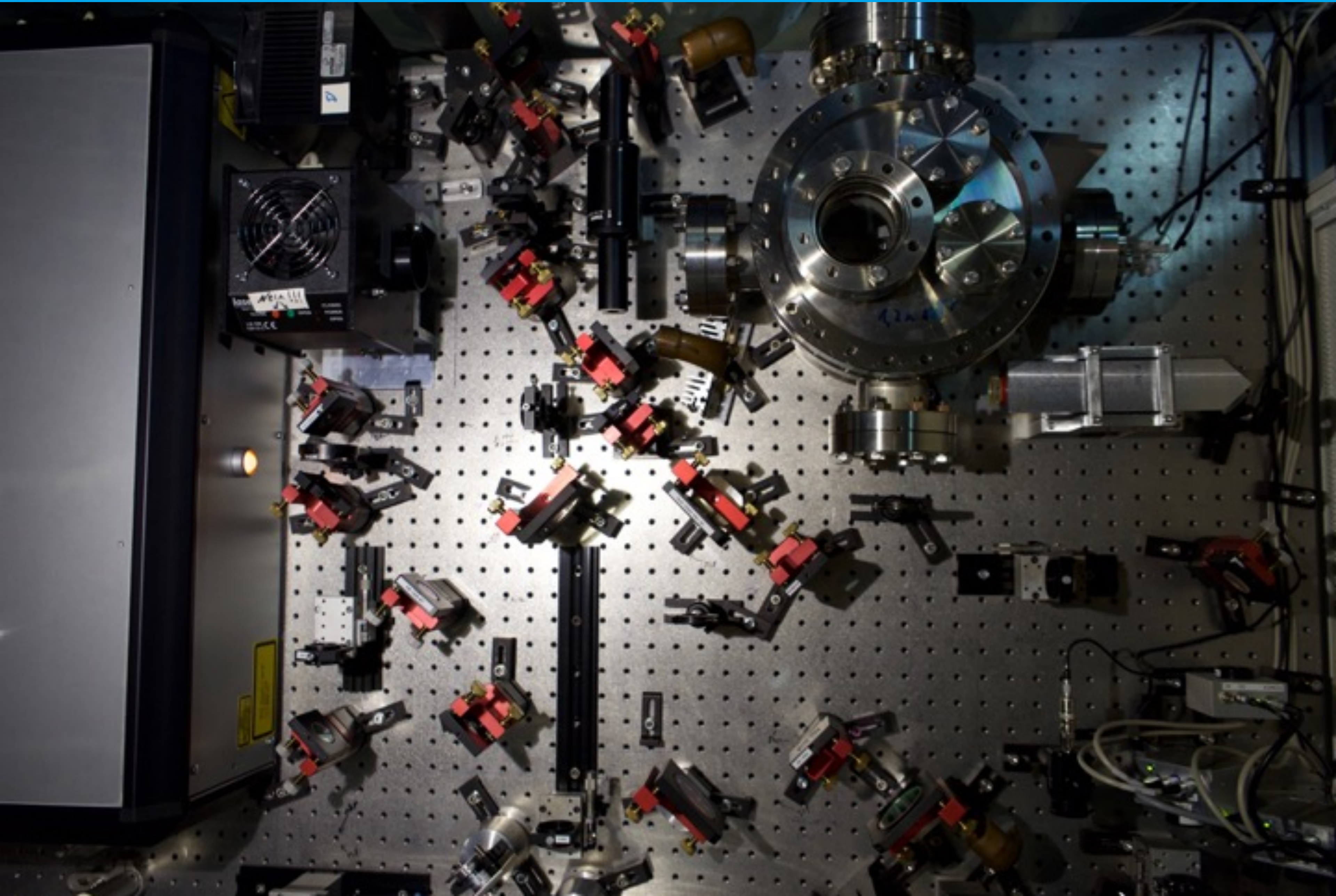
- RC must maintain 95% spatial overlap with the PC
  - Cavity mirror alignment requirement: 5 urad (ALPS IIc)
    - Monolithic aluminum breadboard used to maintain alignment

- Measured alignment drift of PC RC mirrors on aluminum breadboard
  - RMS < 1 urad



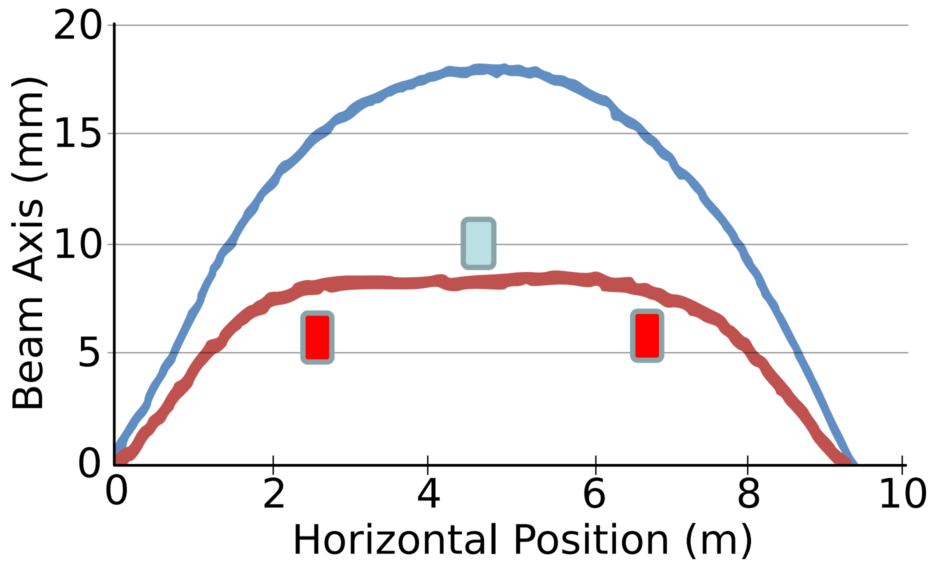
- Aligned RC with PC transmitted beam as alignment reference
  - Frequency stabilized PC
  - Observed flashes of fundamental mode in transmission of the RC

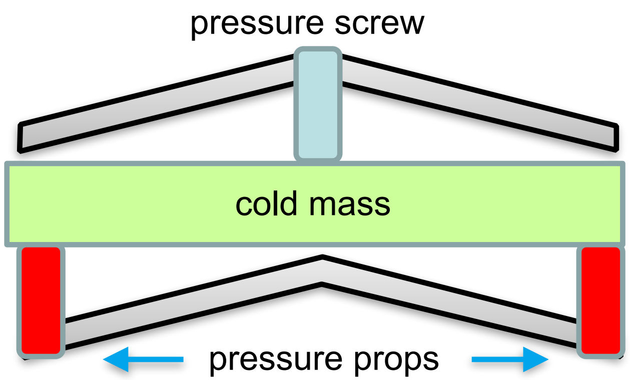
Optical Layout Table 1



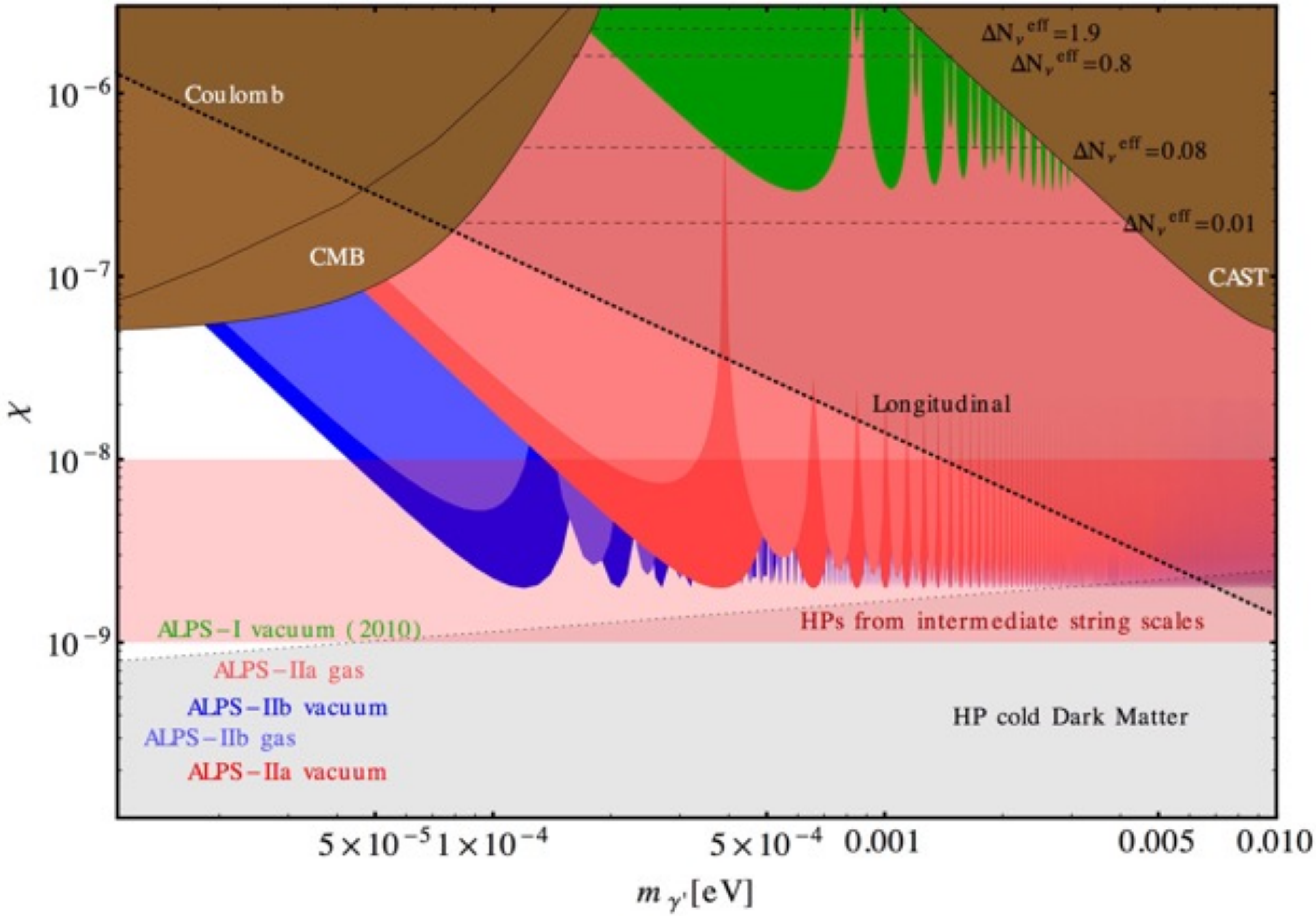
Magnets

- Using HERA dipole magnets
  - 5.3 T superconducting magnets
  - 600 m radius of curvature
    - Unbend cold mass
    - 4 have been unbent
    - Successfully operated
  - 48 mm free aperture (need 40 mm)

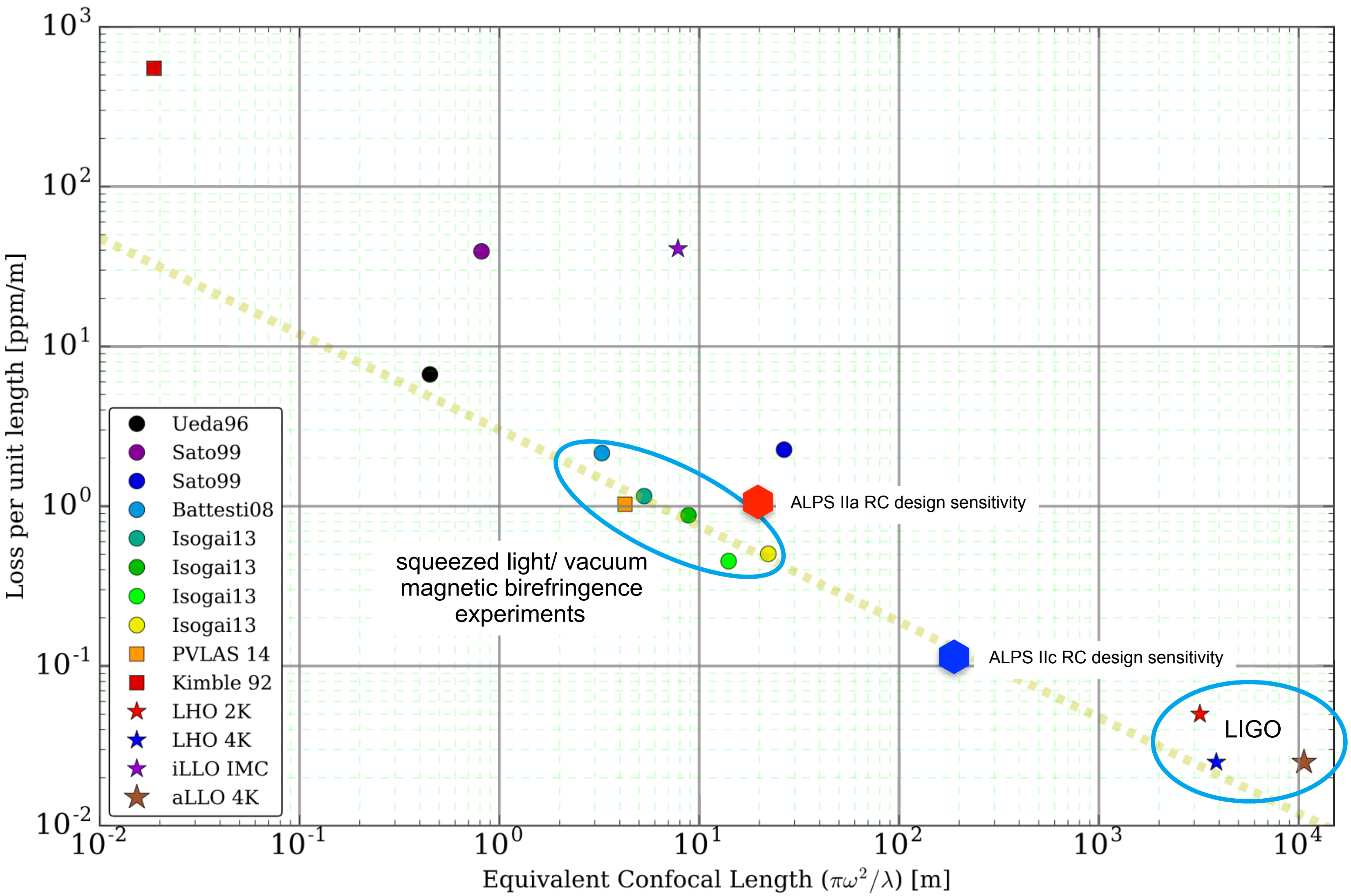




ALPS II Sensitivity to Hidden Sector Photons

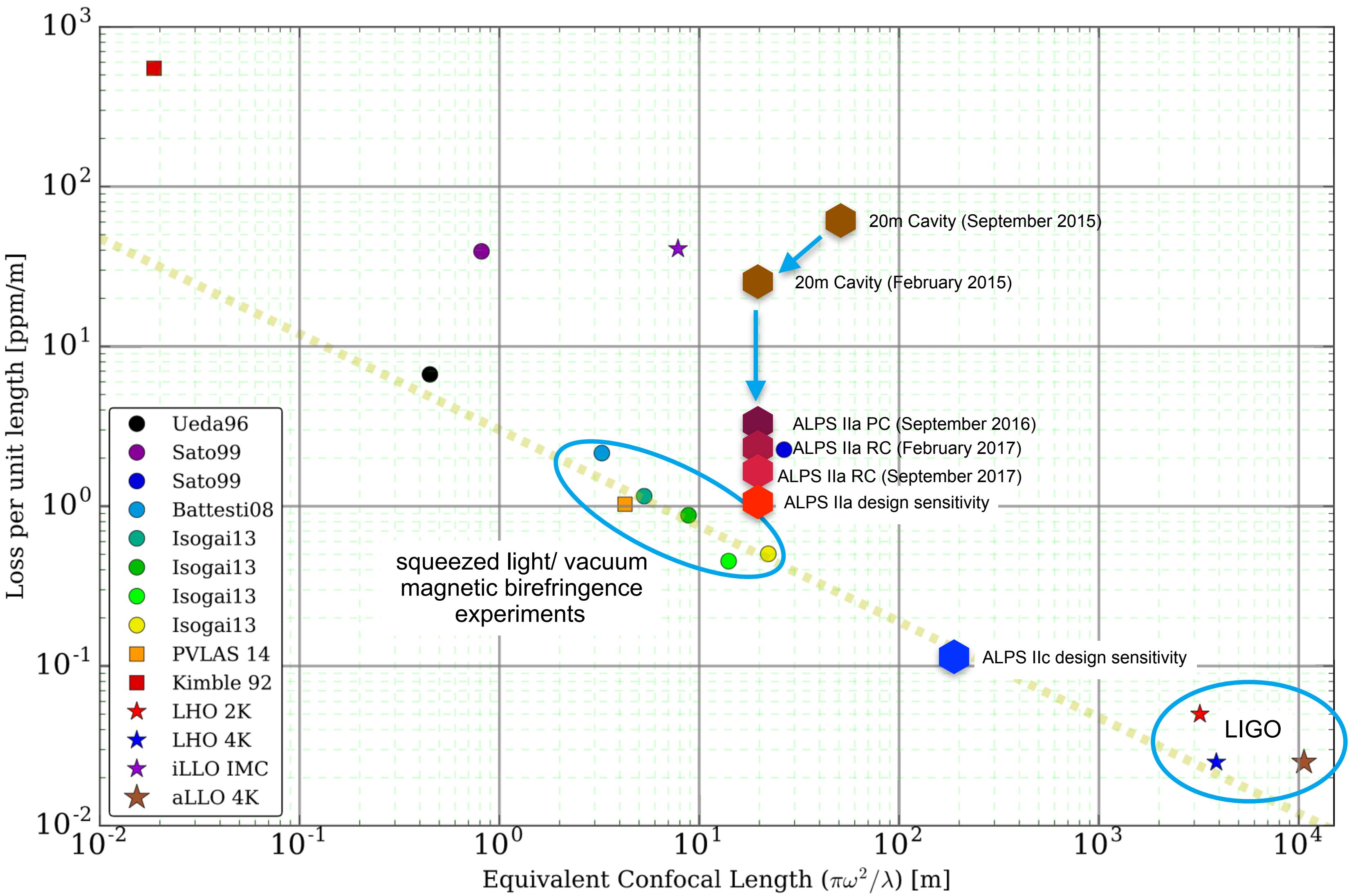


Long baseline optical resonators



plot from LIGO T-1400226-v6

Long baseline optical resonators

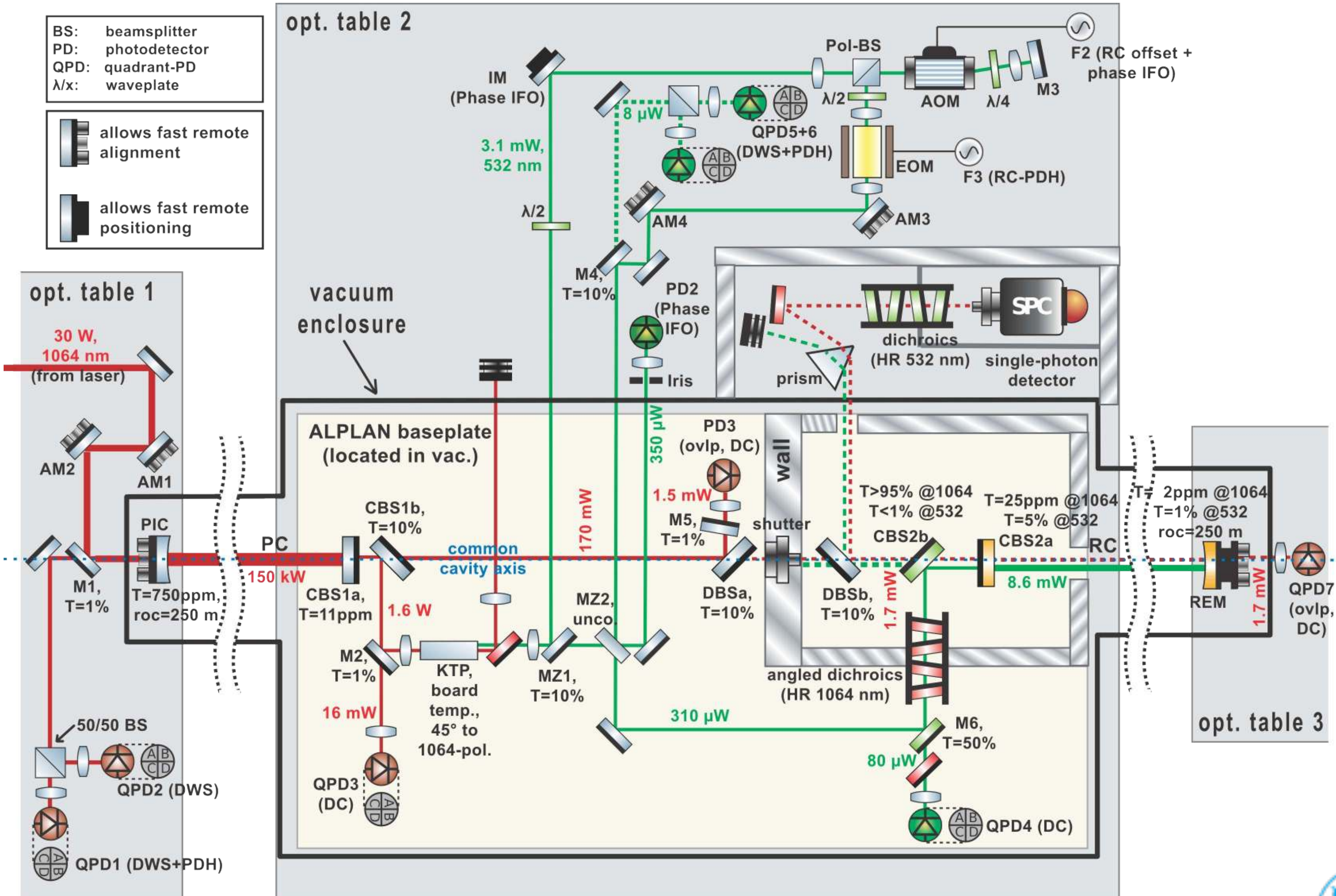


plot from LIGO T-1400226-v6

ALPS II Design Parameters and Sensitivity Gains

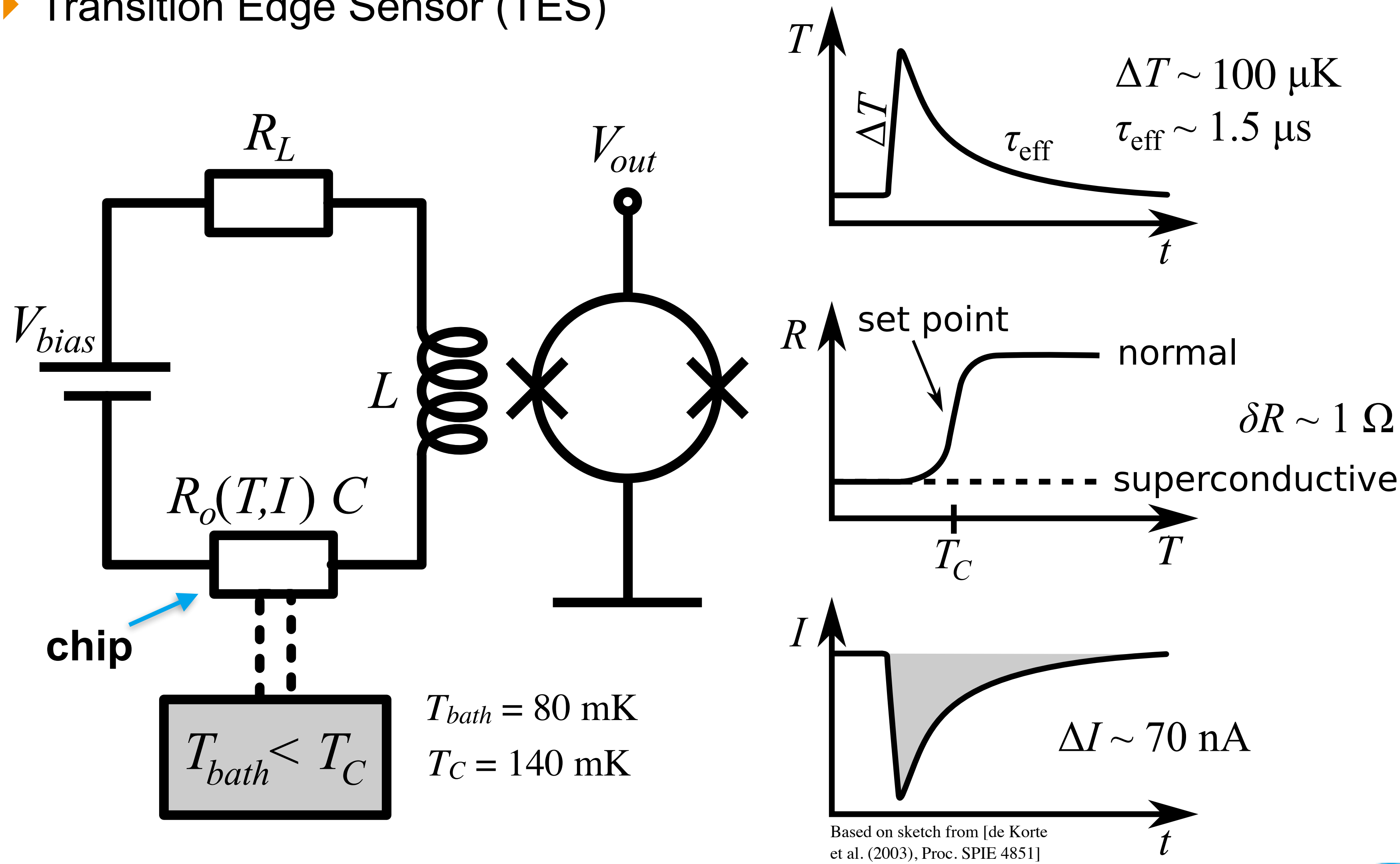
Parameter	Scaling	ALPS-I	ALPS-IIc	Sens. gain
Effective laser power P_{laser}	$g_{a\gamma} \propto P_{\text{laser}}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC P_{RC}	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	14
BL (before& after the wall)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
Detector efficiency QE	$g_{a\gamma} \propto QE^{-1/4}$	0.9	0.75	0.96
Detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	$0.0018\,\text{s}^{-1}$	$0.000001\,\text{s}^{-1}$	2.6
Combined improvements				3082

ALPS II Optical Layout



Detection Schemes

- Transition Edge Sensor (TES)



Based on sketch from [de Korte et al. (2003), Proc. SPIE 4851]

Heterodyne Detection

- Interference beat note between measurement signal and local oscillator
  - Phase relation between measurement signal and LO fixed
  - Coherently sum by demodulating
    - SNR = square root of N_S
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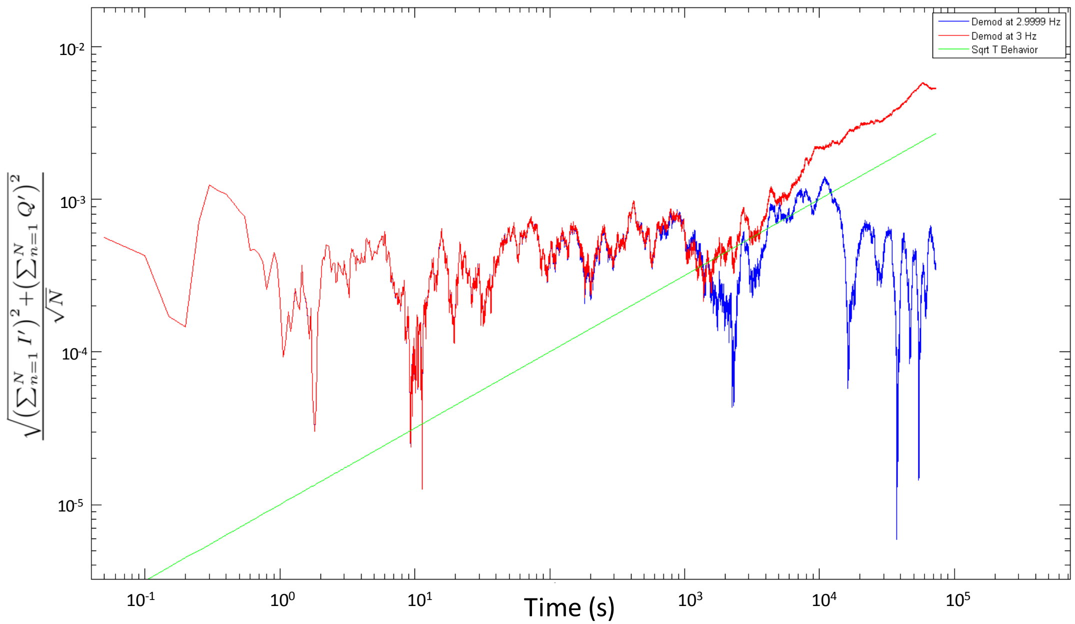
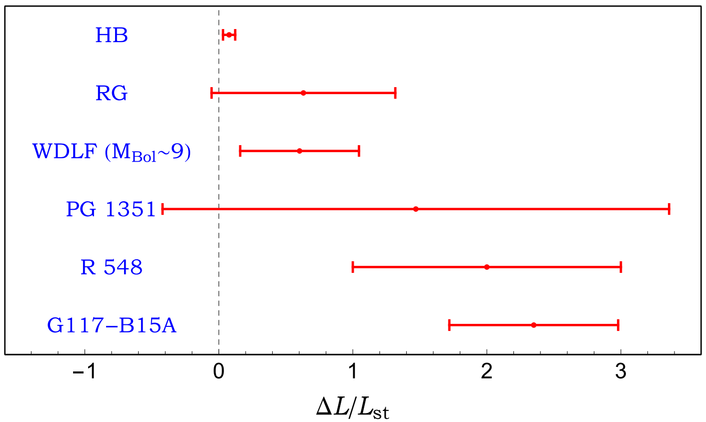


Stellar energy loss excess

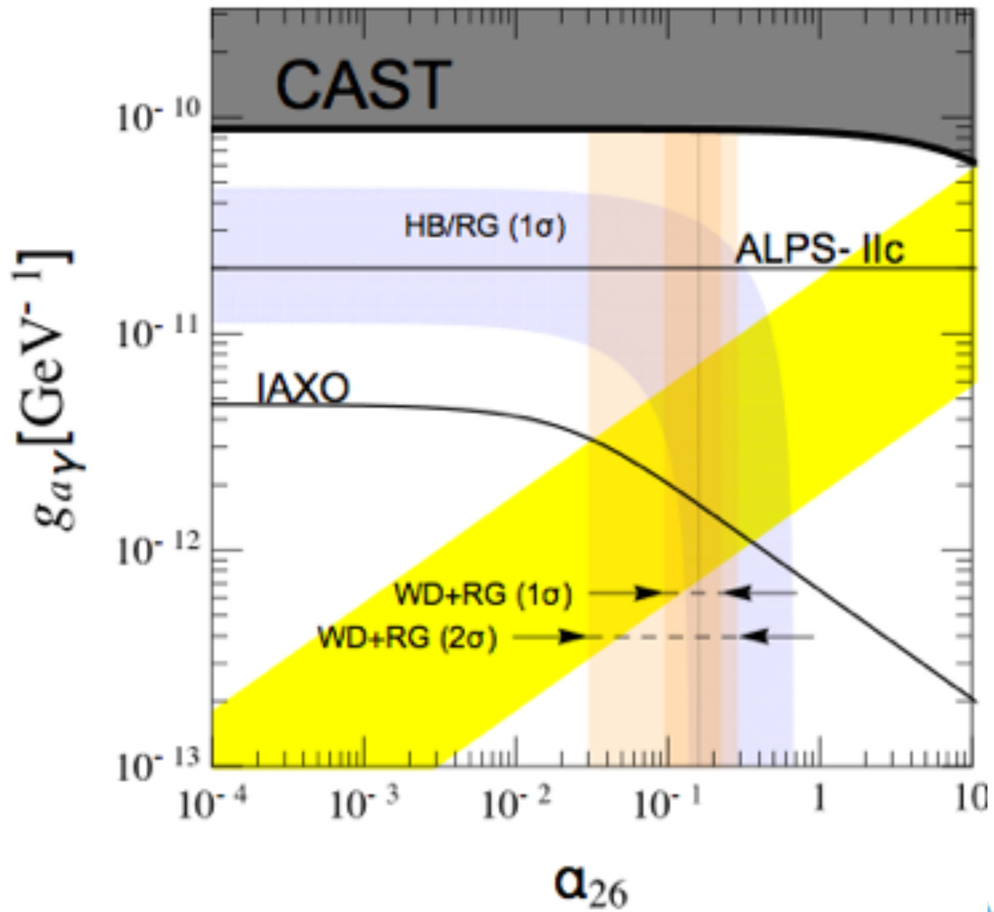
- WDs, RGs, and HB systematically cool more efficiently than expected
  - Axion or ALP coupling to photons and electrons best explains excesses



best fit:

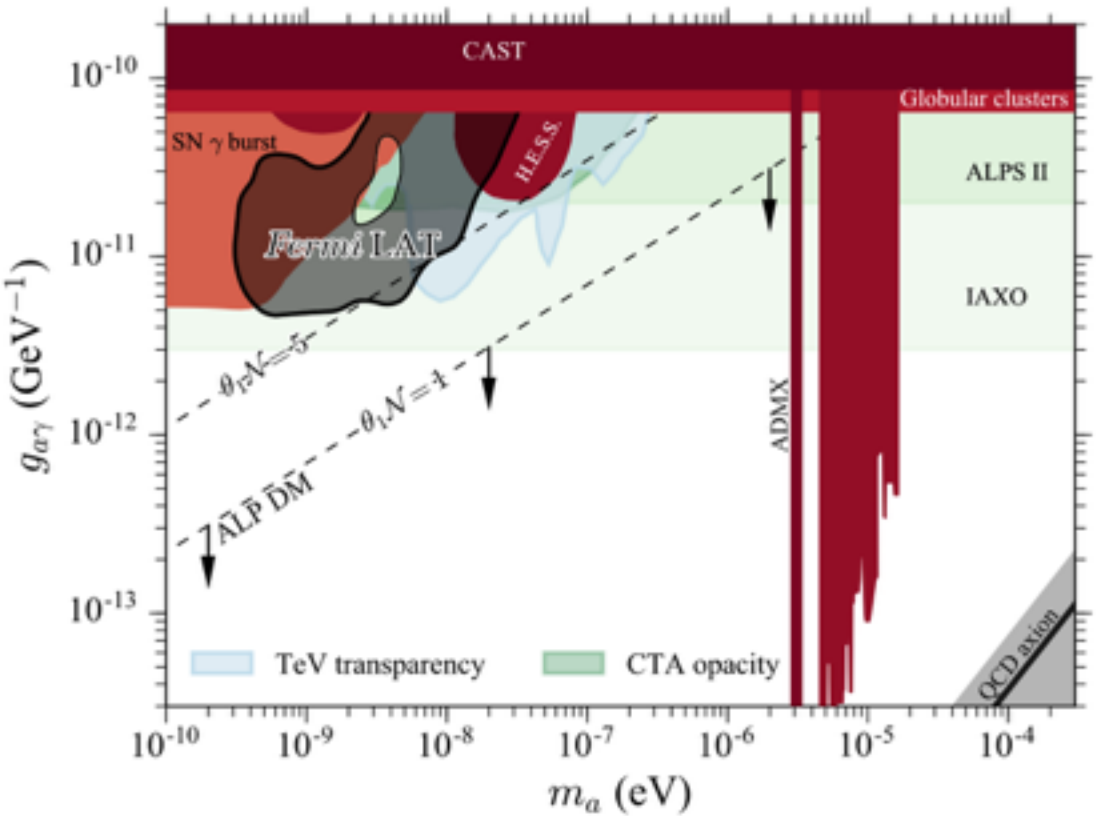
$$g_{ae} = 1.5\times10^{-13}$$
$$g_{a\gamma} = 0.14\times10^{-10}\,\mathrm{GeV}^{-1}$$
$$\chi^2_{min}/\mathrm{d.o.f.} = 1.14$$

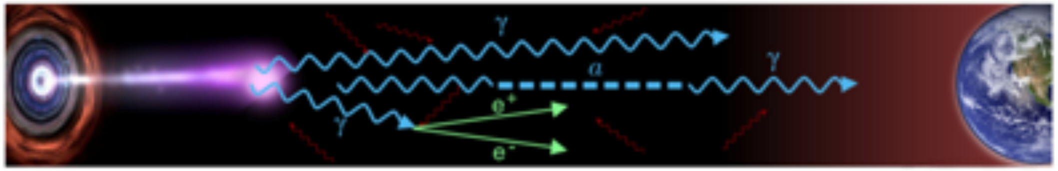
$$\alpha_{26} = g_{ae}^2/(4\pi)/10^{-26}$$



TeV Transparency

- Energetic photons undergo pair production
  - Expected to attenuate high energy photons from extra-galactic sources
  - Intergalactic space appears transparent for these photons
  - Coupling to axions of ALPs could explain this





DESY