# Status of the ALPS II Experiment

## PRC Open Session

Todd Kozlowski (University of Florida)

Hamburg, 03.11.2021

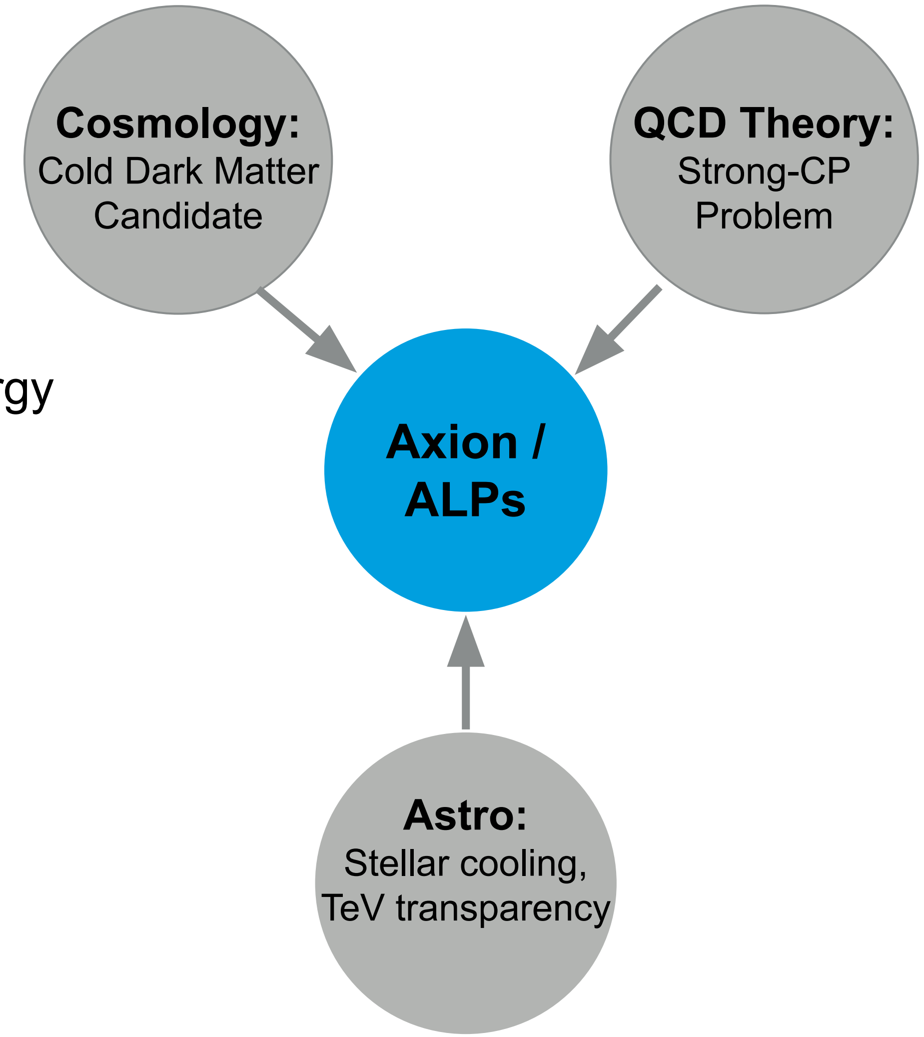
# Axions and Axion-like Particles

## Axions

- first introduced to solve the **Strong-CP problem** in QCD
- Lagrangian contains a feeble coupling to EM
- mass and coupling both defined by single symmetry-breaking energy
- **dark matter** particle candidate
    - feeble interaction strength with SM particles

## Axion-like Particles (ALPs)

- family of hypothetical sub-eV particles
- astrophysical motivations
    - excess stellar cooling observations
    - transparency of the universe to TeV light



# Axions and Axion-like Particles

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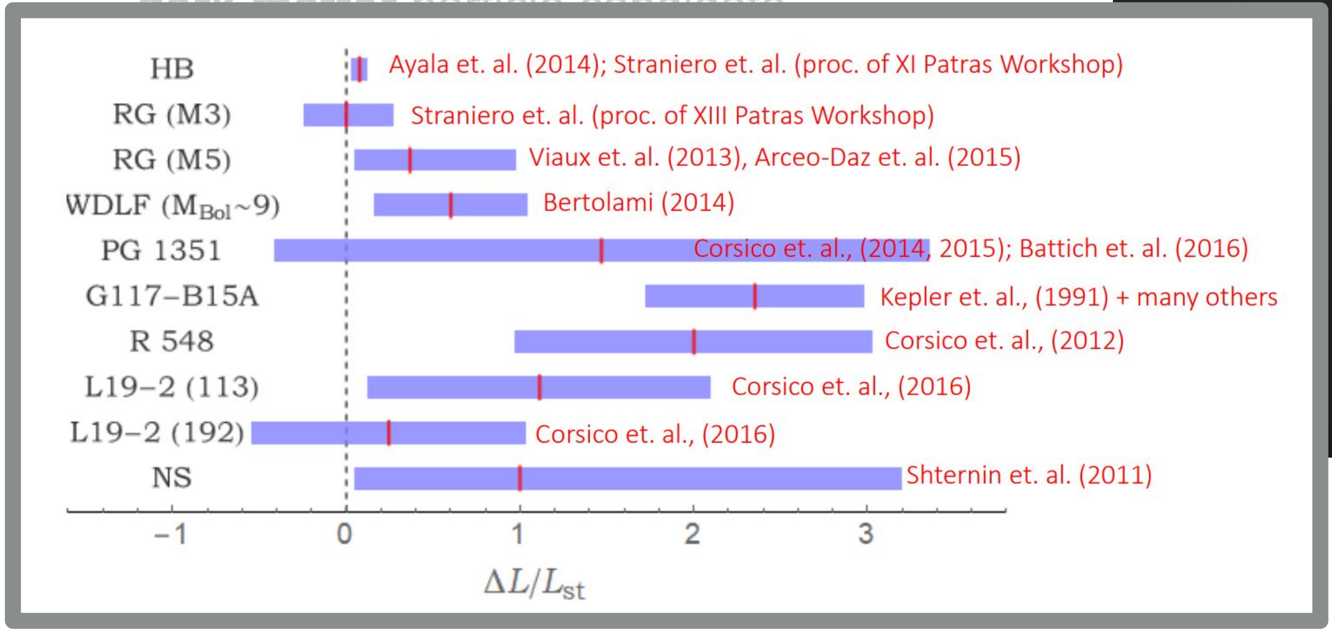
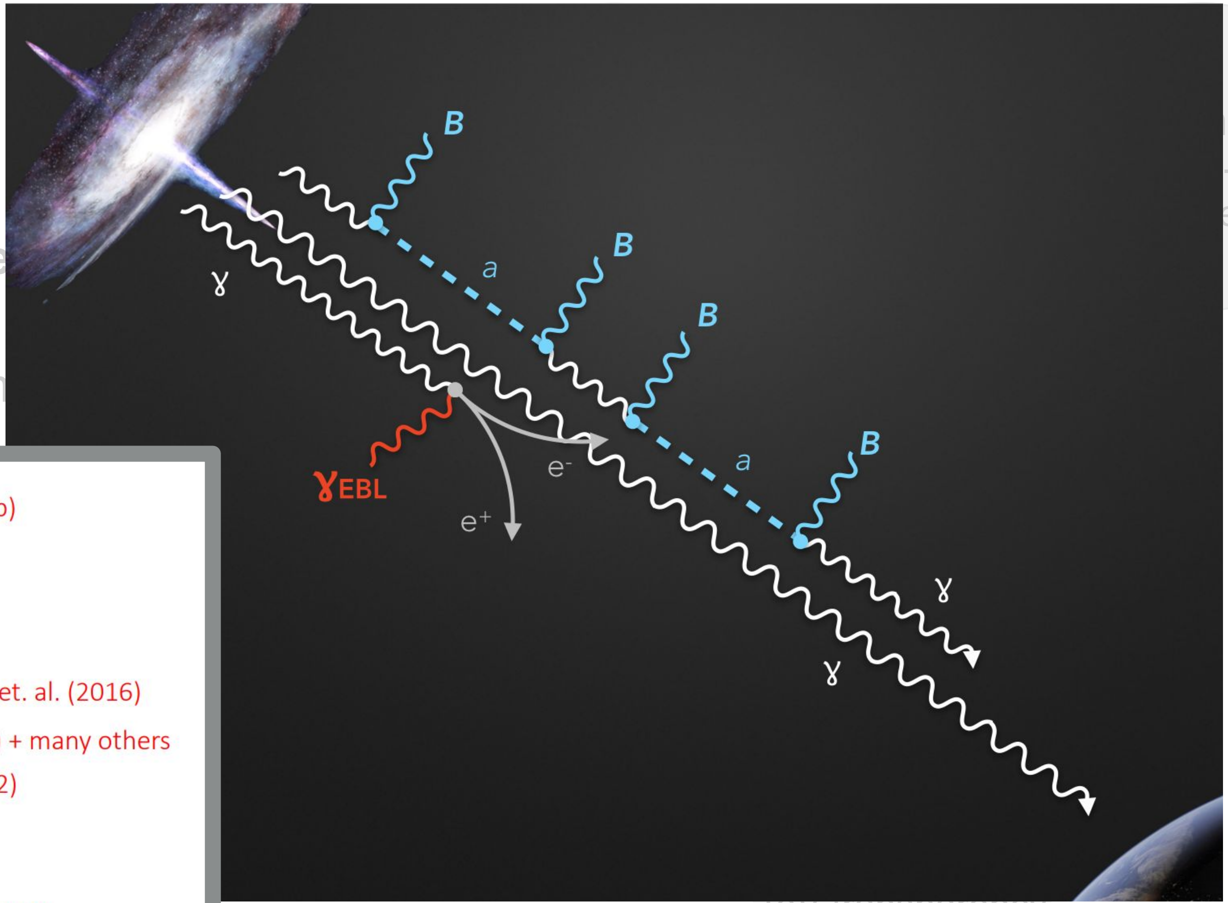



Excess cooling from a diverse sample of stellar populations. Giannotti 2019

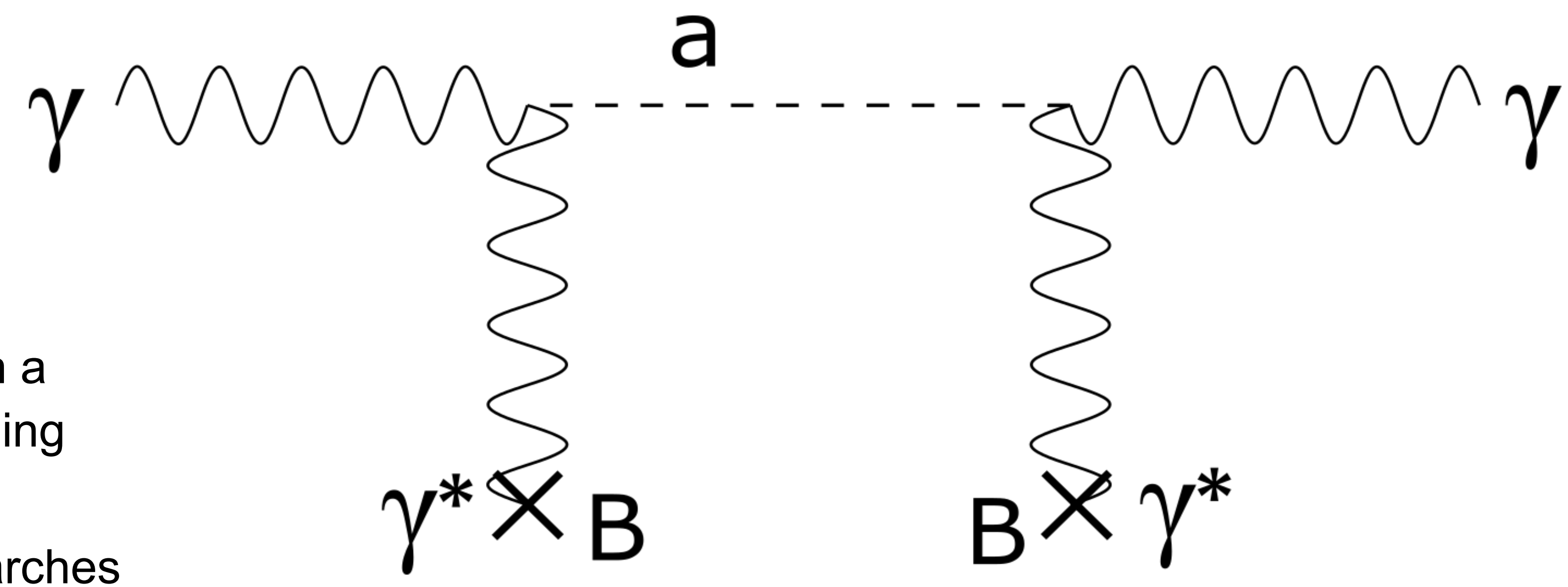



Depiction of ALP production from distant sources. Meyer 2019

# Axions and Axion-like Particles

## Sikivie Process

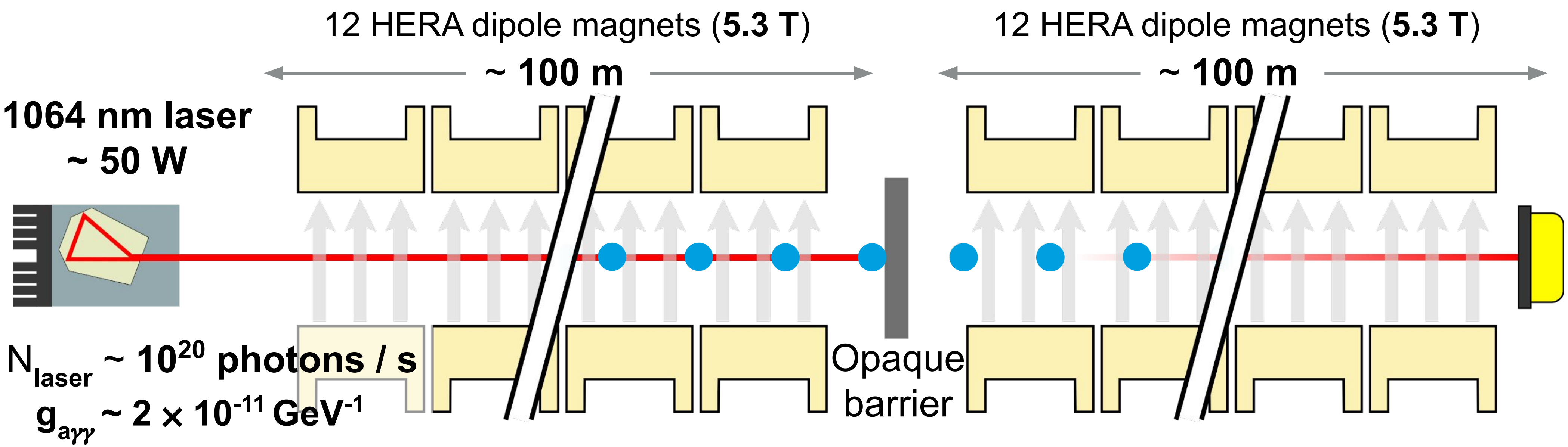
- Axion / ALP Lagrangian contains an interaction term with the EM field
- axion - photon oscillations possible in a background magnetic field with coupling strength ($g_{a\gamma\gamma}$)
- process exploited by some direct searches




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

Astrophysical hints (e.g. stellar cooling) motivate our search parameters:
**$g_{a\gamma\gamma}$ ~ $2 \times 10^{-11}$ GeV$^{-1}$**
**for masses < 0.1 meV**

# ALPS II: Cavity-Enhanced LSW




**without** optical cavities:

$$N_s = N_{laser} \frac{1}{16} \left(g_{\alpha\gamma\gamma} BL\right)^4$$

**~photon / 150,000 yrs**

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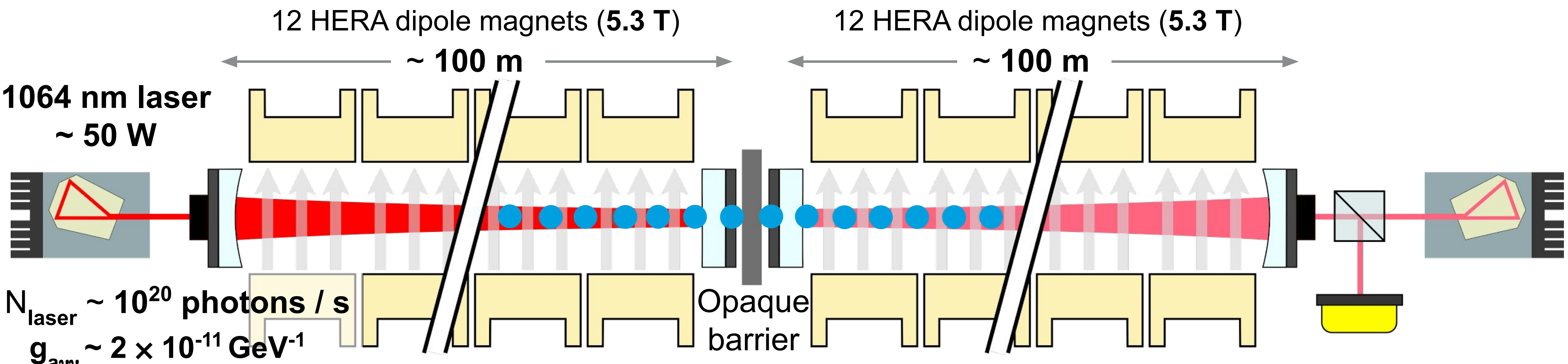



$N_{laser}$ **~ $10^{20}$ photons / s**

$g_{a\gamma\gamma}$ **~ $2 \times 10^{-11}$ GeV$^{-1}$**

**without** optical cavities:

$$N_s = N_{laser} \frac{1}{16} \left( g_{\alpha\gamma\gamma} BL \right)^4$$

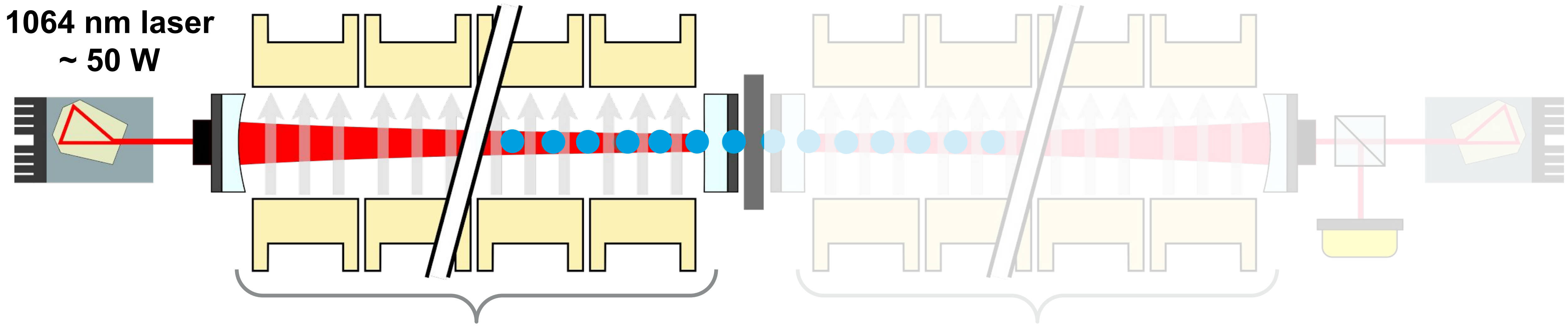
**~photon / 150,000 yrs**

**with** optical cavities:

$$N_s = \eta^2 N_{PC} \beta_{RC} \frac{1}{16} \left( g_{\alpha\gamma\gamma} BL \right)^4$$

**~photon / day!**

# ALPS II: Cavity-Enhanced LSW




## Production Cavity (PC)

- Builds up the power of stored light circulating in the magnetic field
- Increases axion-like particle flux
- Planned **150kW** of infrared light

## Regeneration Cavity (RC)

- Improves the reconversion probability of axion-like particles
- High resonant enhancement β > **14,000**, record-setting light storage time
- Part of the heterodyne detector

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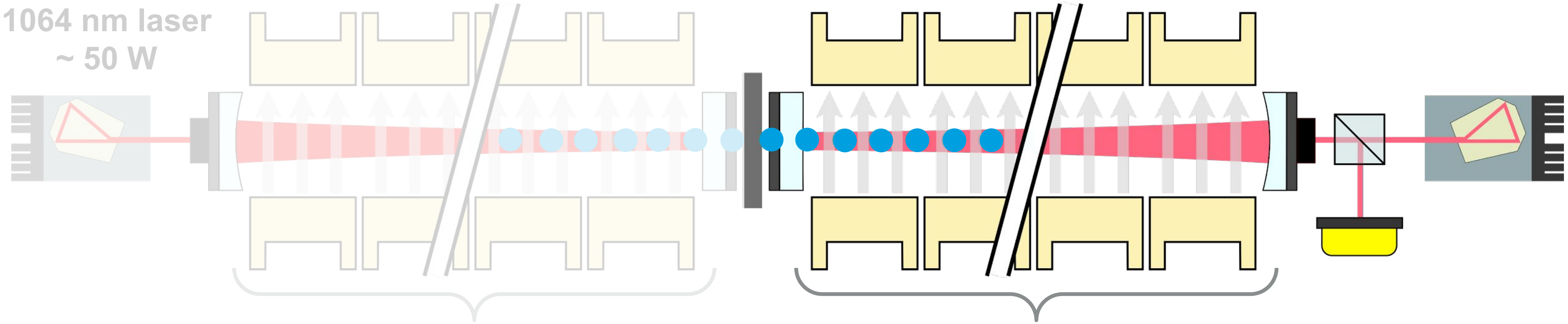


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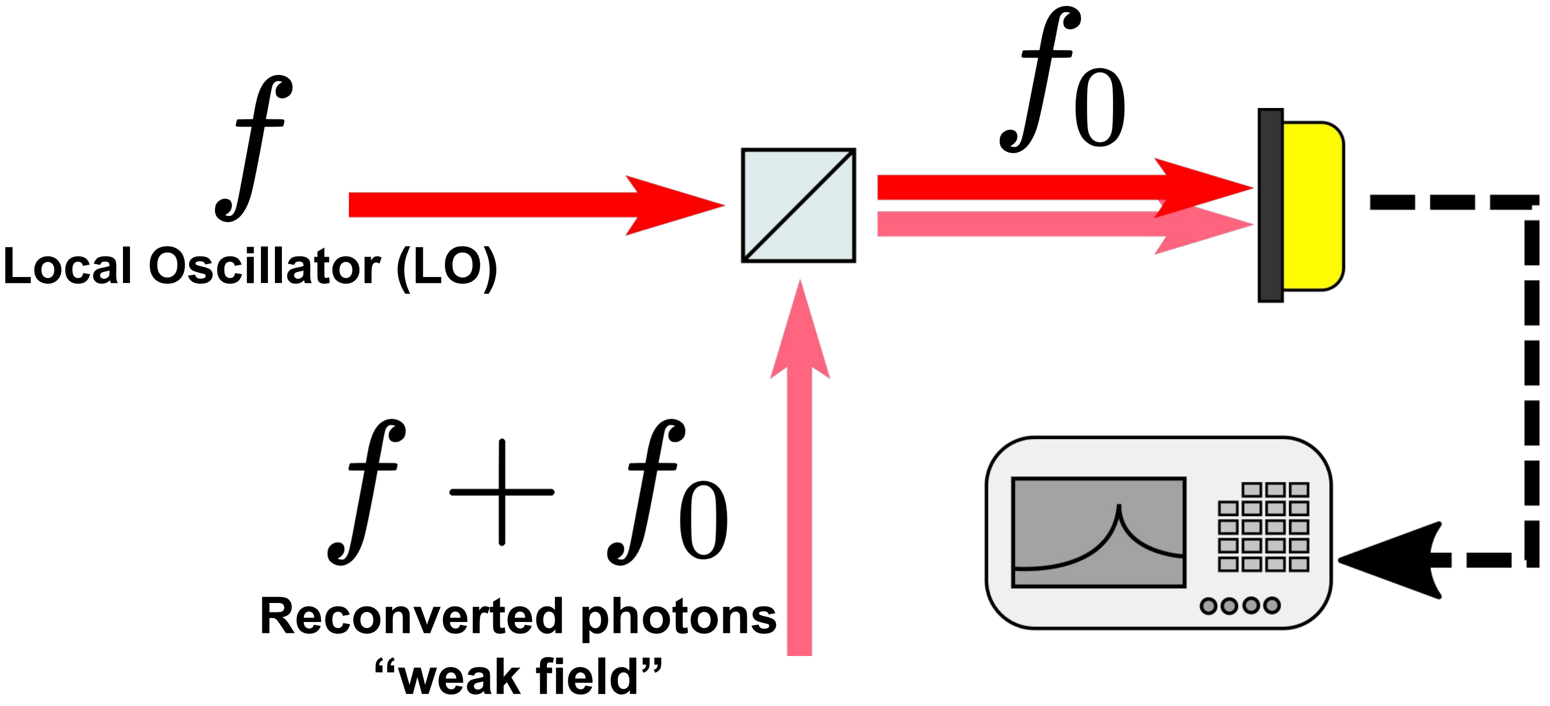
# ALPS II Detectors: Heterodyne




- Signal sums coherently
- Noise averages out
- Demonstrated noise floor below $10^{-5}$ photons / second

$$\left|\sqrt{\bar{P}_{\mathrm{LO}}}e^{i(2\pi f t+\phi_1)} + \sqrt{\bar{P}_{\mathrm{weak}}}e^{i[2\pi(f+f_0)t+\phi_2]}\right|^2 =$$

$$\bar{P}_{\mathrm{LO}} + \bar{P}_{\mathrm{weak}} + 2\sqrt{\bar{P}_{\mathrm{LO}}\bar{P}_{\mathrm{weak}}}\cos\left(2\pi f_0 t + \Delta\phi\right)$$

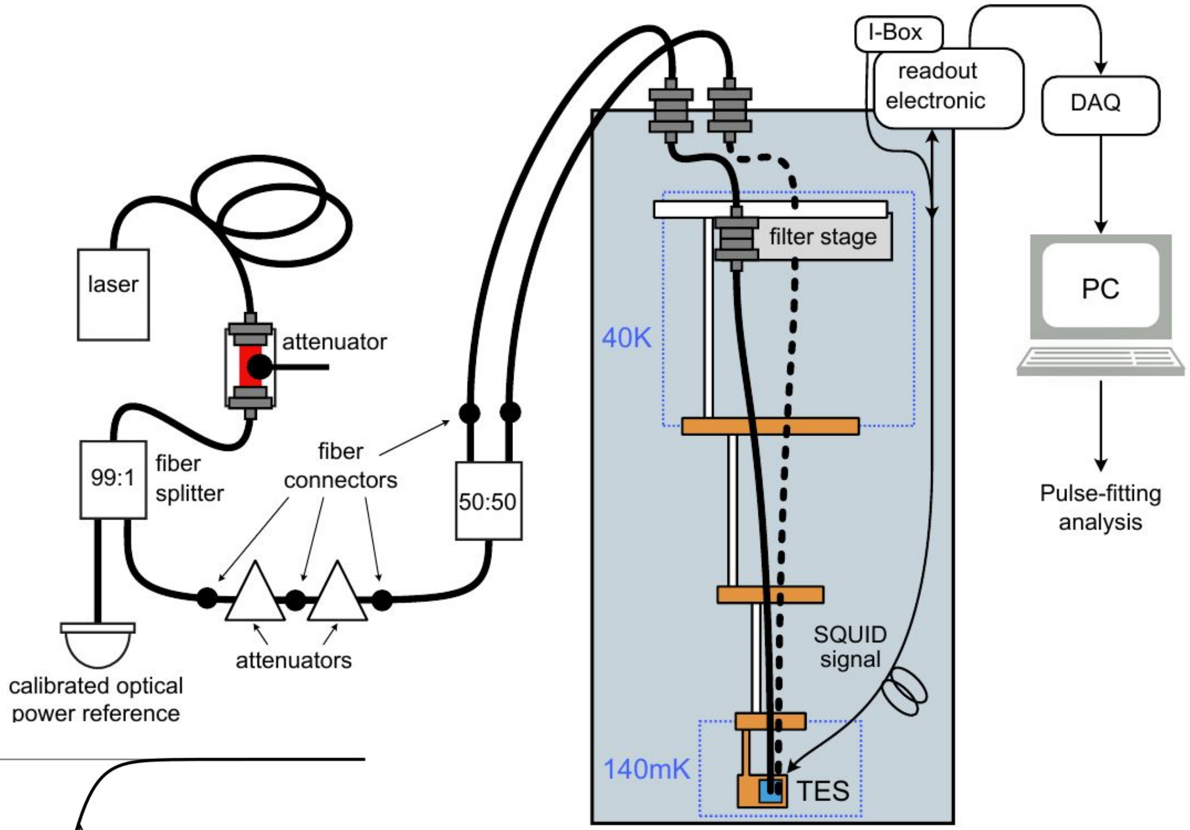
# ALPS II Detectors: TES

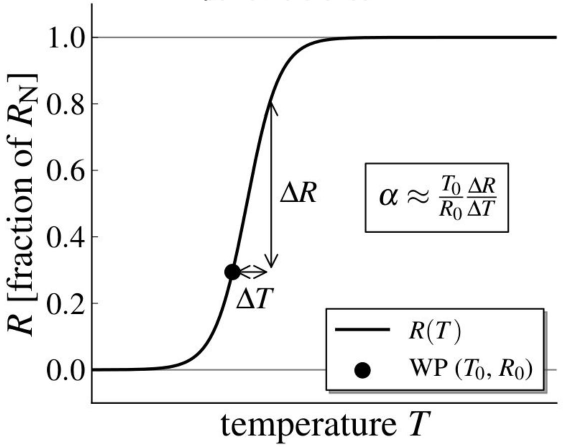
## Transition Edge Sensor

- Cryogenic single-photon detector
- Measures the change in the resistivity of a tungsten film held at the edge of superconductivity
- Efficiency and background rate characterization ongoing, will continue in parallel with installation of a second cryostat in HERA N
- Energy resolution **10%**
- Intrinsic dark count rate:

$$6.9(^{+2.62}_{-1.47}) \cdot 10^{-6}\,\mathrm{cps}$$

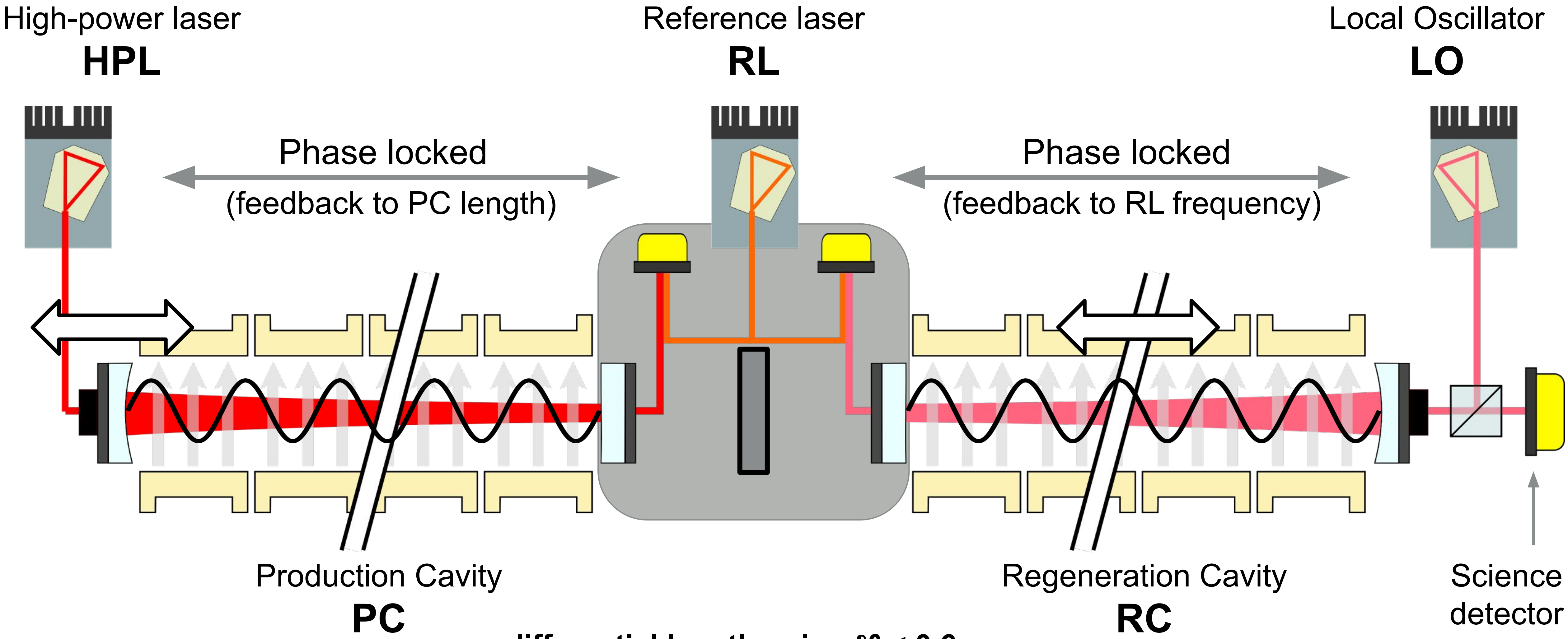
TES Detector for ALPS II. Shah, et.al. 2021



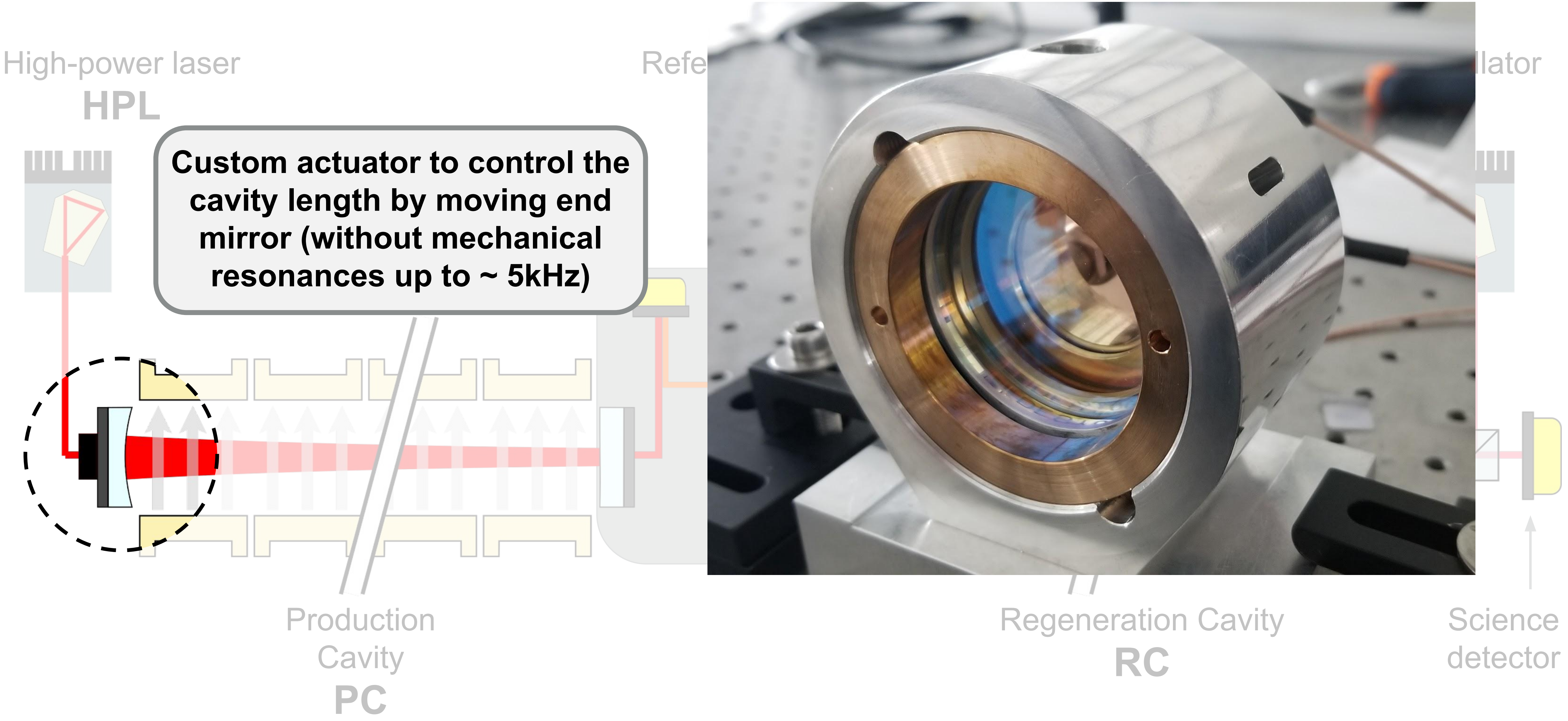

Experimental design for measuring detector efficiency.

# ALPS II: Double Phase-locked Loop



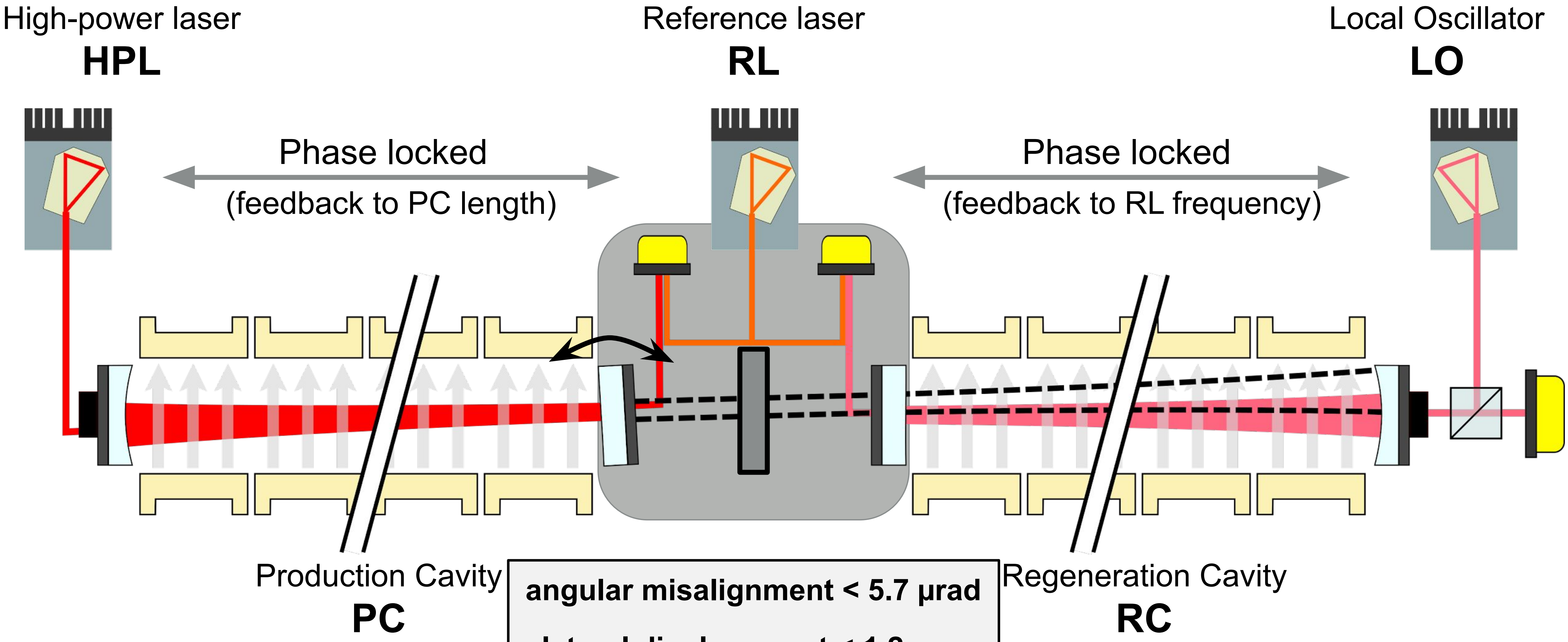

**differential length noise $\delta\ell$ < 0.6pm**

# ALPS II: Optics Challenges




Custom actuator to control the cavity length by moving end mirror (without mechanical resonances up to ~ 5kHz)

# ALPS II: Optics Challenges




**angular misalignment < 5.7 µrad**

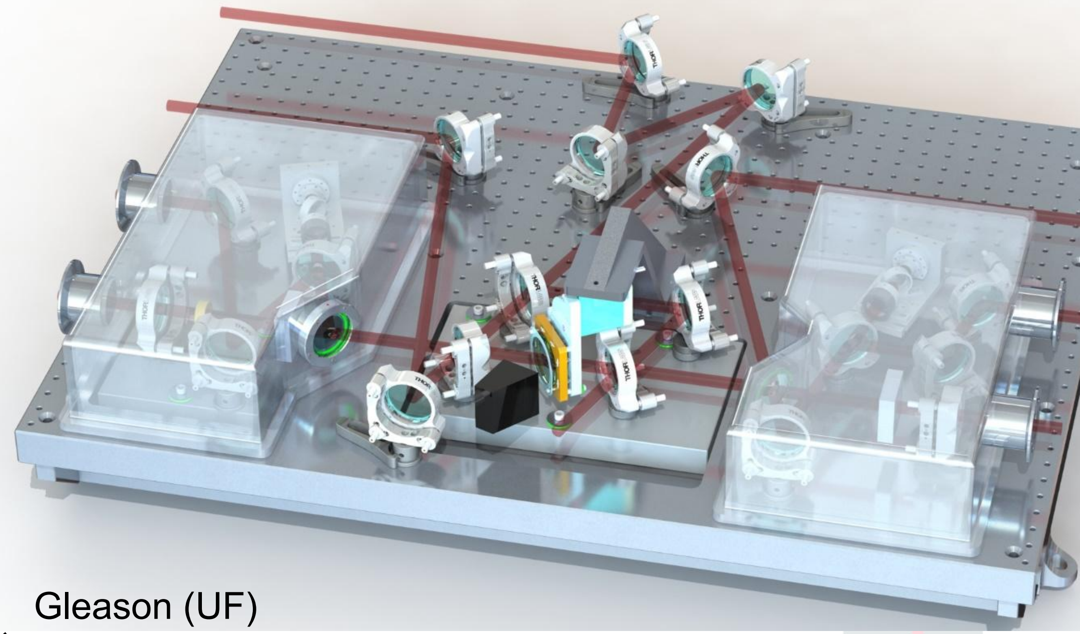
**lateral displacement < 1.2 mm**

# ALPS II: Optics Challenges

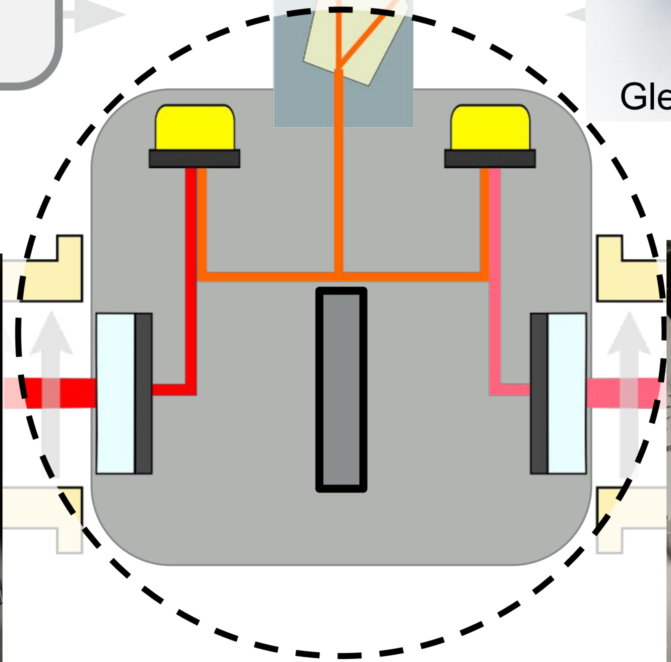
High-power laser
HPL

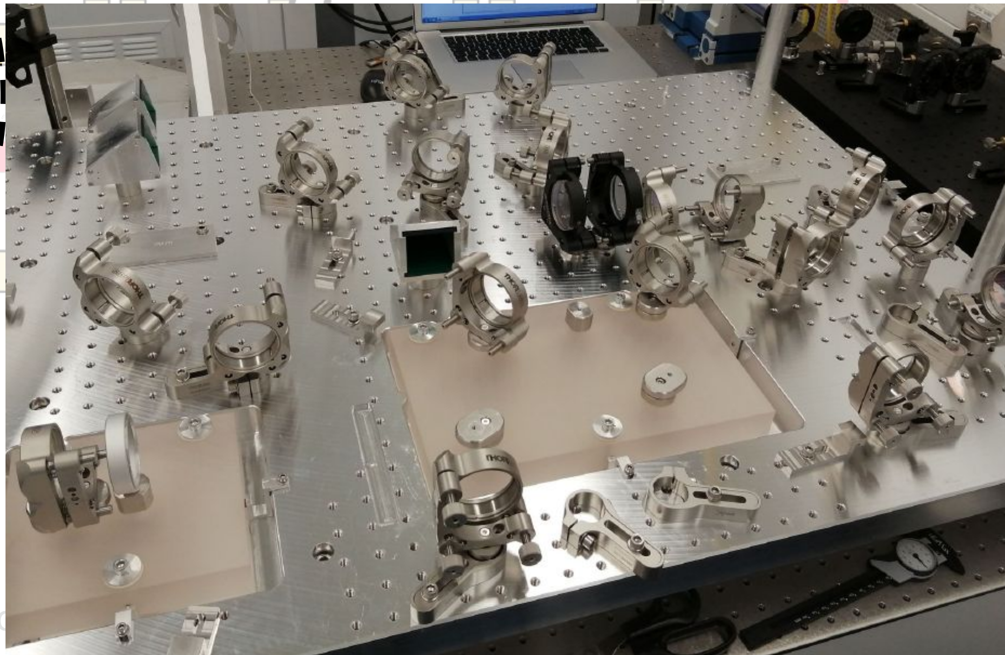
**Stable breadboard to ensure cavity eigenmode overlap and minimize phase noise.**

Reference laser
RL



Gleason (UF)

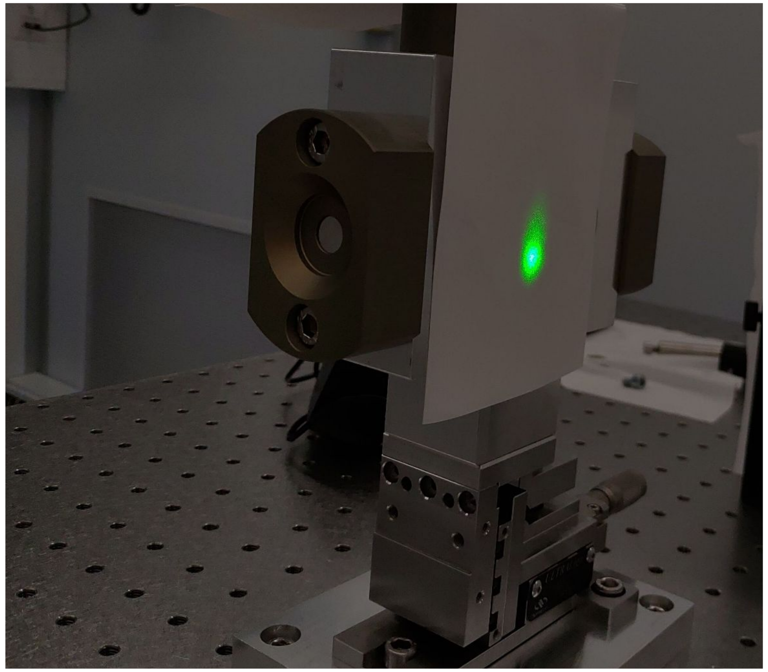


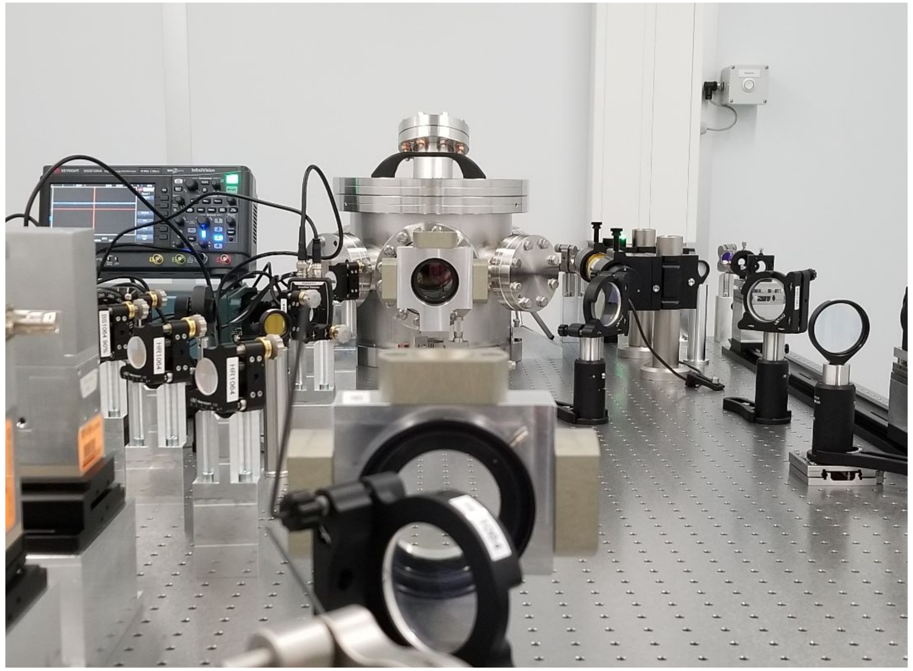


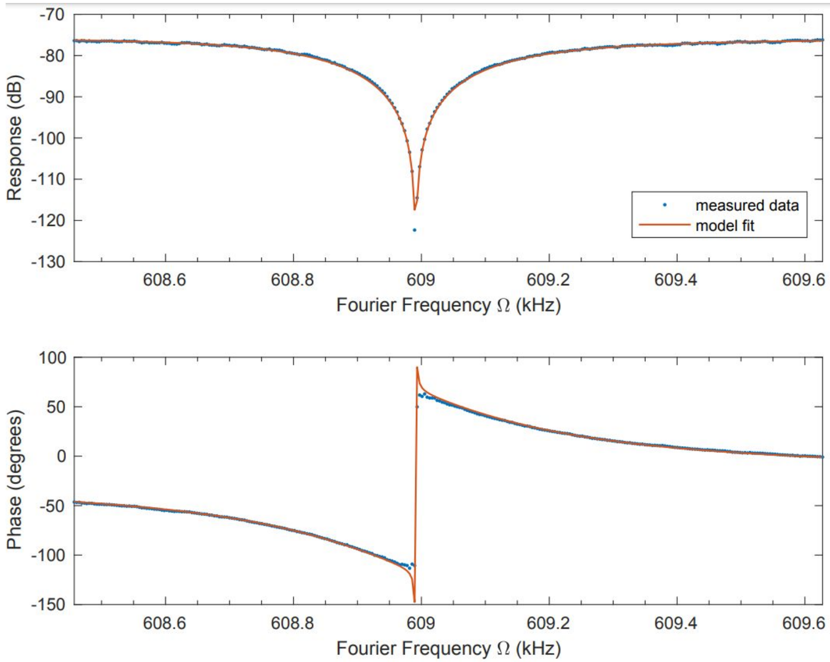
# ALPS II Update: Central Optical Breadboard Tests

- Successful test of COB installation procedure
- COB and tank both pass residual gas analysis vacuum tests

# ALPS II: 250-meter Cavity Commissioning



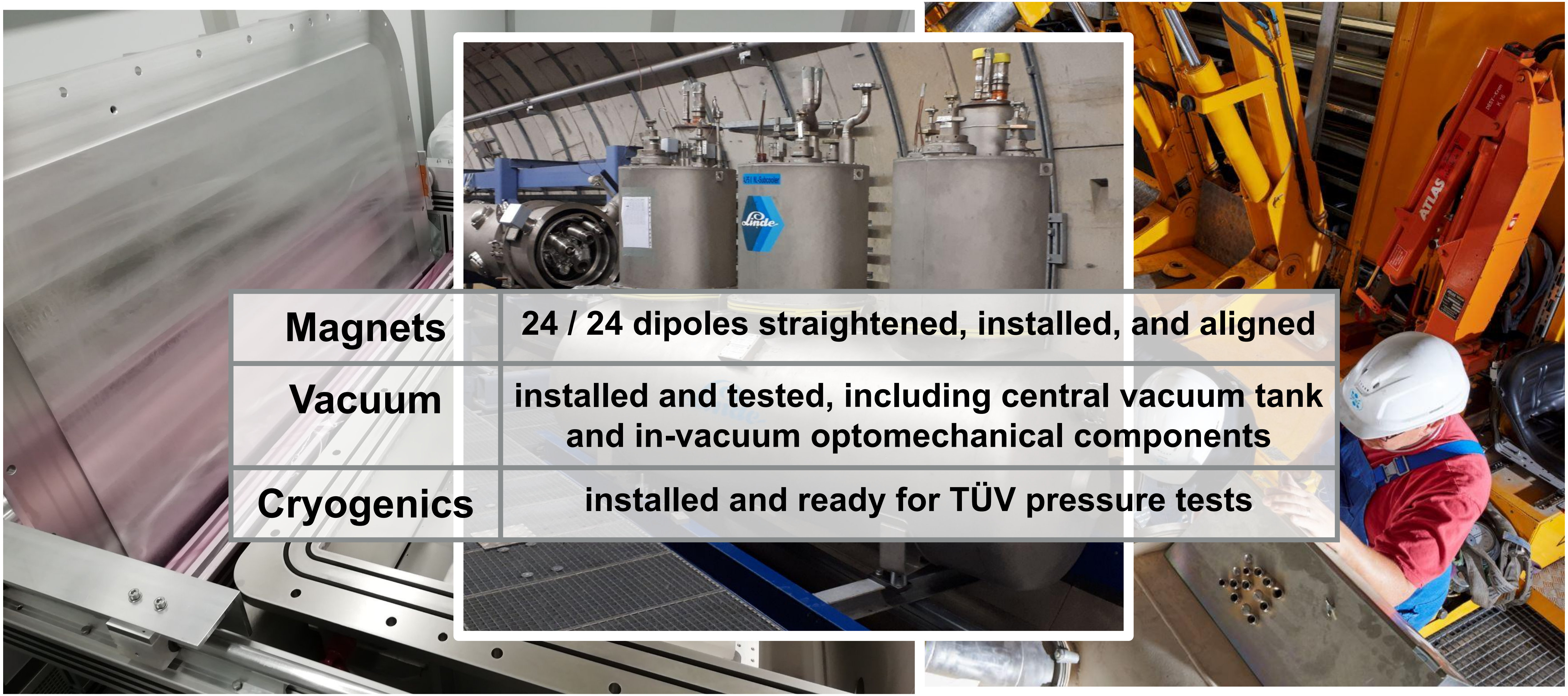





## 250m Commissioning Objectives

| | |
|---|---|
| Verify magnet string alignment and clear aperture by transmitting a laser from one end station to another | ✔ |
| Construct a 250 meter optical cavity and show ‘flashes’ of light in transmission, requiring precise alignment of 3” cavity mirrors | ✔ |
| Bring the Local Oscillator laser on resonance to characterize optics and environmental noise | ✔ |

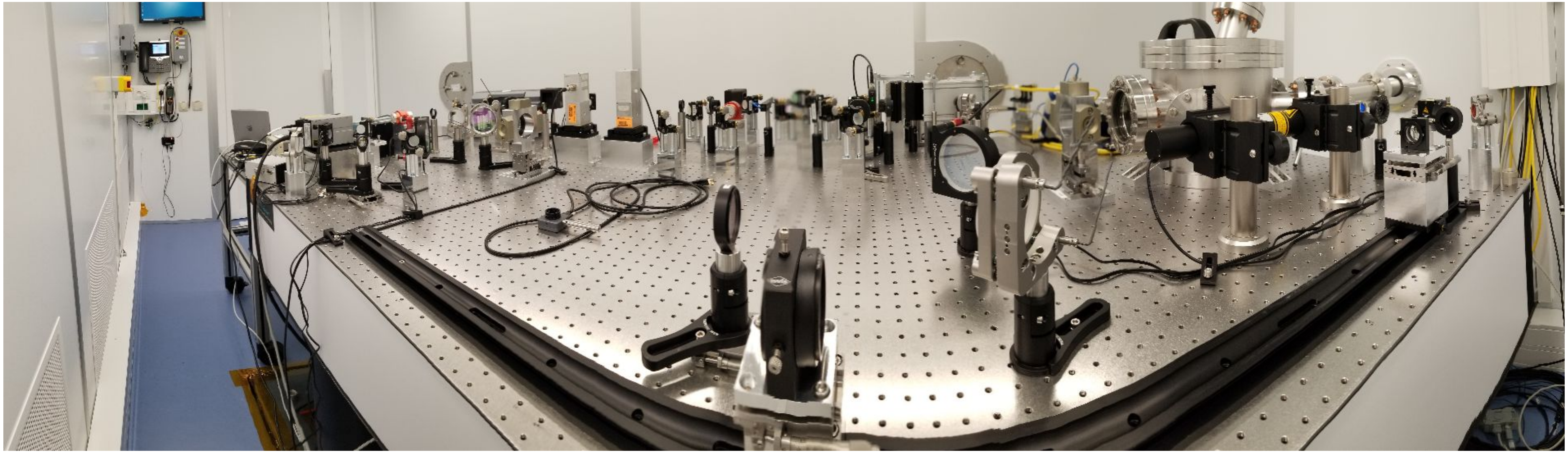
# ALPS II Update: Infrastructure Progress




| | |
|---|---|
| **Magnets** | **24 / 24 dipoles straightened, installed, and aligned** |
| **Vacuum** | **installed and tested, including central vacuum tank and in-vacuum optomechanical components** |
| **Cryogenics** | **installed and ready for TÜV pressure tests** |

# ALPS II Update: Infrastructure Progress

**All cleanrooms constructed and operational**



# ALPS II Optics Commissioning Roadmap

## Initial Alignment

- ➔ Use apertures to align green HeNe beam through the magnets.
- ➔ Measure long-term misalignments and magnet string clear aperture.

**Finished 2021**

## 250m Cavity Commissioning

- ➔ Measure test cavity and laser noise.
- ➔ Use as a platform to commission electronics e.g. auto-alignment and data acquisition hardware and software.

**In Progress 2021**

## COB Commissioning

- ➔ Install optical components on the central optical breadboard.
- ➔ Perform handling tests to confirm the flat cavity mirrors maintain parallelism during installation.

**In Progress 2021**

## Cavity Dual Resonance

- ➔ With all optics installed, test of dual resonance using double phase-locked control loop.
- ➔ Requires commissioning the digital length control system of the PC.

**First half 2022**

## Detector Integration

- ➔ Install and optimize heterodyne interferometer for detection.
- ➔ Continue development of the TES in parallel.
- ➔ Test runs with magnets, full optical systems.

**2022**

**Science Runs**

# Thank you

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**Collaboration members**

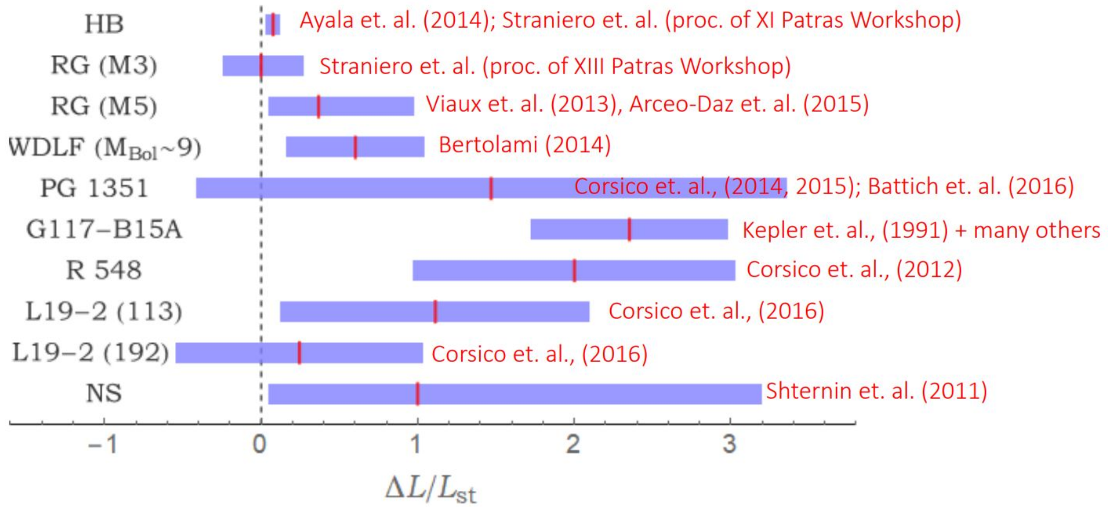
**Supported by**

Science and Technology Facilities Council

# SUPPLEMENT: Astrophysics Motivations for ALPs

## Stellar Cooling

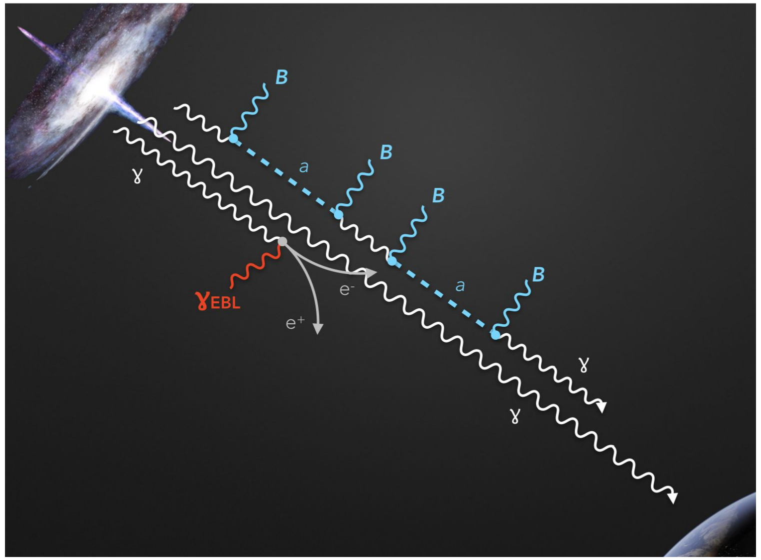
- ALP production in dense stellar cores would facilitate very efficient energy transfer out of the star
- Excess cooling rates compared to standard models have been observed in various star classes, from white dwarfs to red giants




Excess cooling from a diverse sample of stellar populations. Giannotti 2019

## TeV Transparency

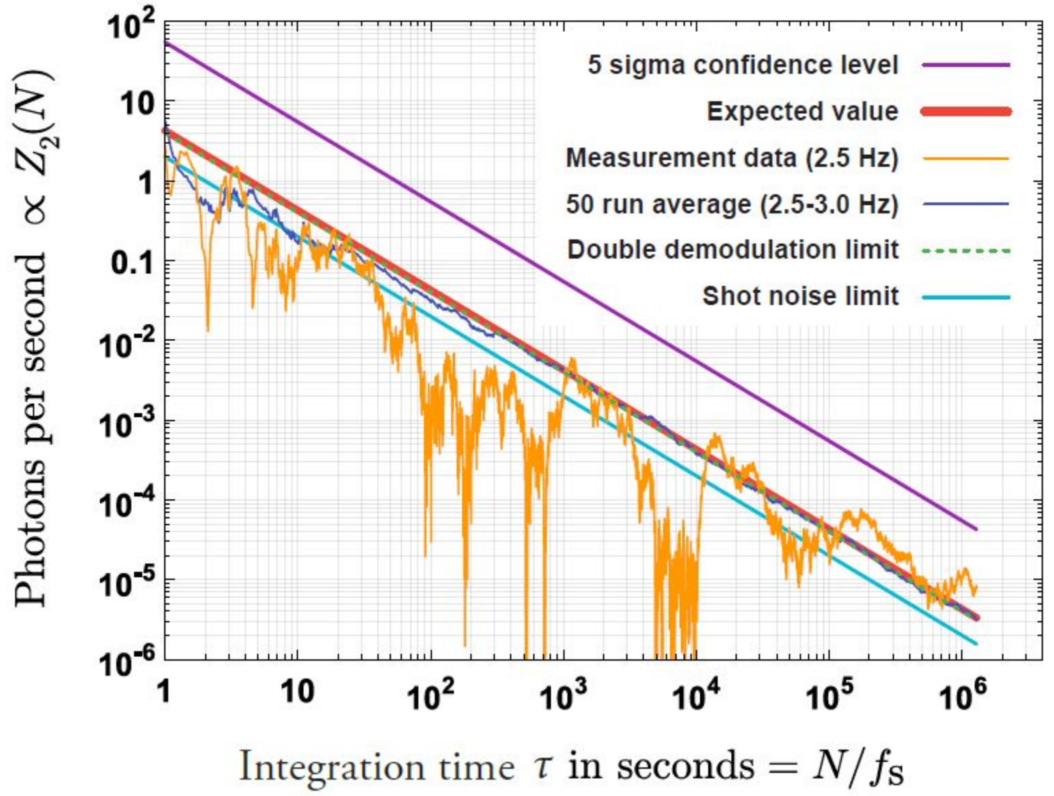
- the Universe is opaque to ultra high-energy photons from cosmic sources due to pair production
- potential TeV excess can be explained by photon-axion oscillations




Depiction of ALP production from distant sources. Meyer 2019

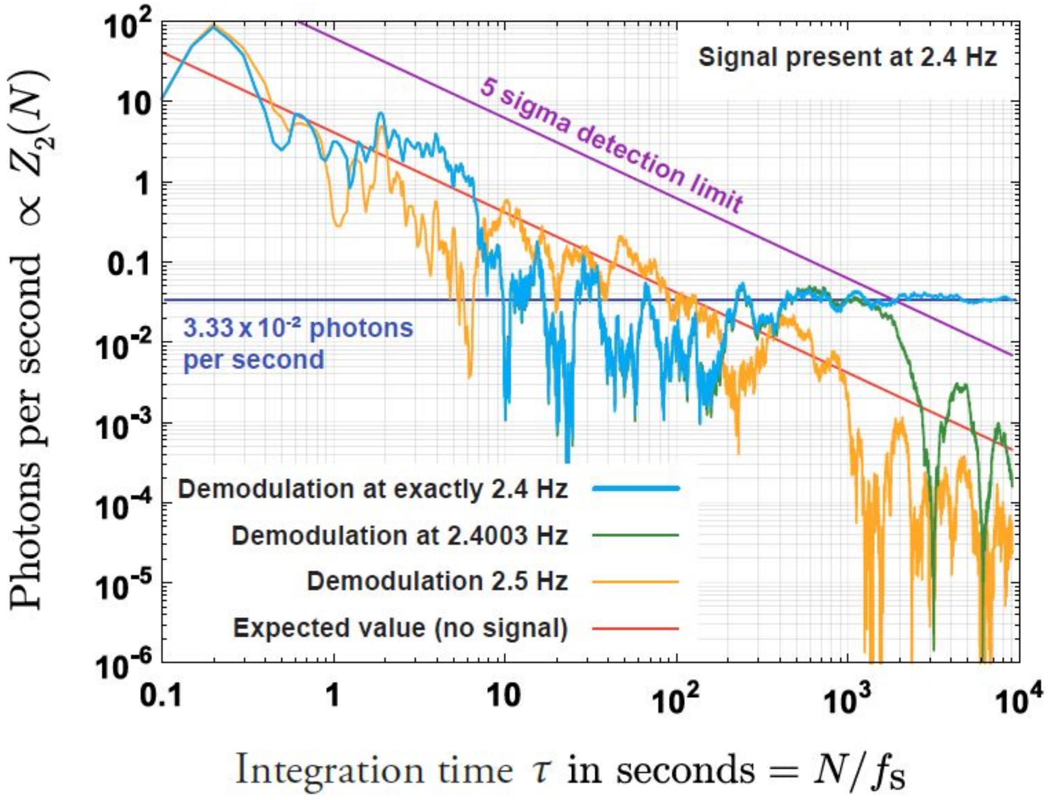
# SUPPLEMENT: Heterodyne Detection Method

## Detector noise floor




- Demonstrated integration noise floor below $2 \times 10^{-24}$ W (**$10^{-5}$ photons/s**)

## Ultra-weak signal detection




- Capable of detecting $6.4 \times 10^{-21}$ W (**3.33e-2 photons/s**) after 3 days integration to 5σ confidence

[Z. Bush et al., **PRD 99** 022001 (2019)]

# SUPPLEMENT: Experimental Challenges: Detection-side