ALPS II Initial Science Run

Shining a Light on Axion-like Dark Matter

Image credit: DESY PR

Invisibles'23

Todd Kozlowski (DESY)

Göttingen, 29.08.2023

ALPS II

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Outline

1 Introduction and Theoretical Motivation

- Axions and axion-like particles
- Basic operating principle of LSW experiments

2 ALPS II Experimental Technology

- Leveraging techniques in optics, control, and detection
- Resonantly-enhanced LSW

3 Results of the ALPS II Initial Science Run

- Calibration of the two-week heterodyne detector data
- Preliminary achievable exclusion limits

Axions and Axion-like Particles

Axions:

- hypothetical BSM particle, pseudo-Nambu-Goldstone boson of new U(1) symmetry
- favored solution to the strong charge-parity symmetry (CP) problem in QCD
- axion-photon interactions described by axion-extended QCD lagrangian:

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

a → axion field

g → coupling strength

E → electric field (i.e. light)

B → background magnetic field

Axions and Axion-like Particles

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

pseudo-scalar:

$$\vec{E} \parallel \vec{B}$$

Axion-like particles (ALPs):

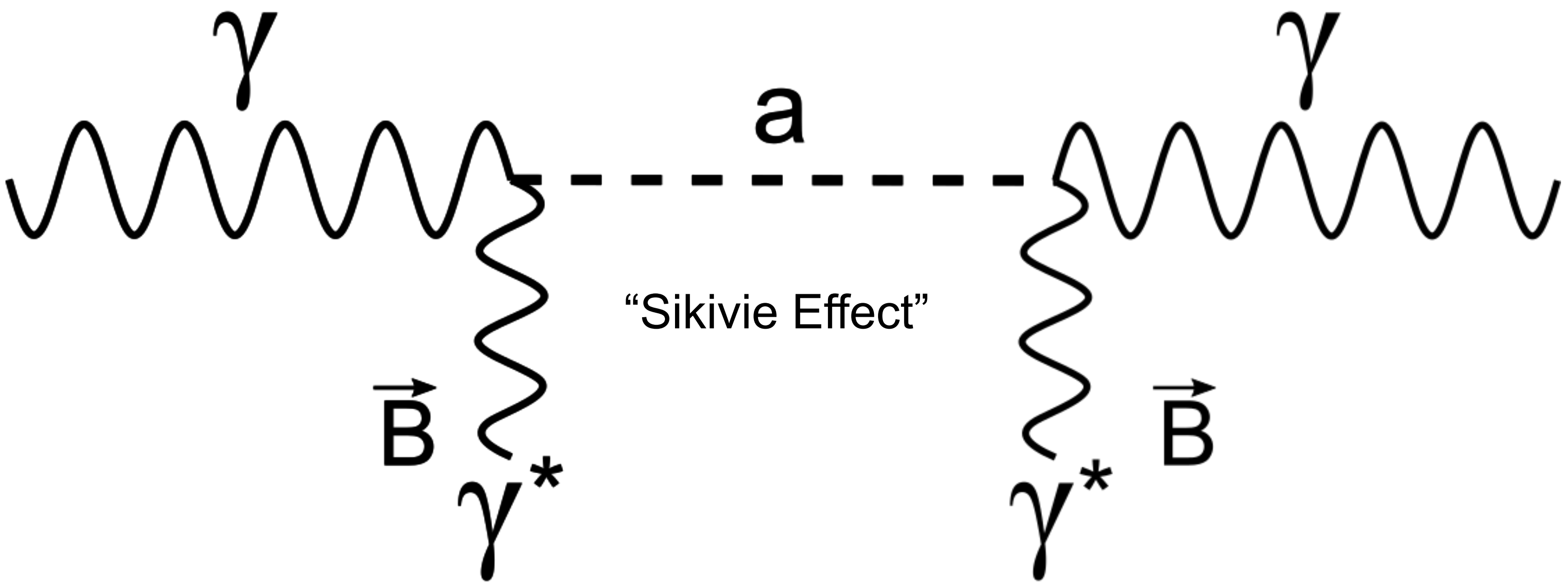
- a family of so-called "Weakly-Interacting Sub-eV Particles" (WISPs)
- properties similar to the classical axion
  - scalar or pseudo-scalar bosons
- motivated by ***astrophysical hints***
- excellent ***dark matter candidate***

$$\mathcal{L}_{a\gamma}^{sc} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \left(\vec{E}^2 - \vec{B}^2 \right)$$

scalar:

$$\vec{E} \perp \vec{B}$$

Axions and Axion-like Particles

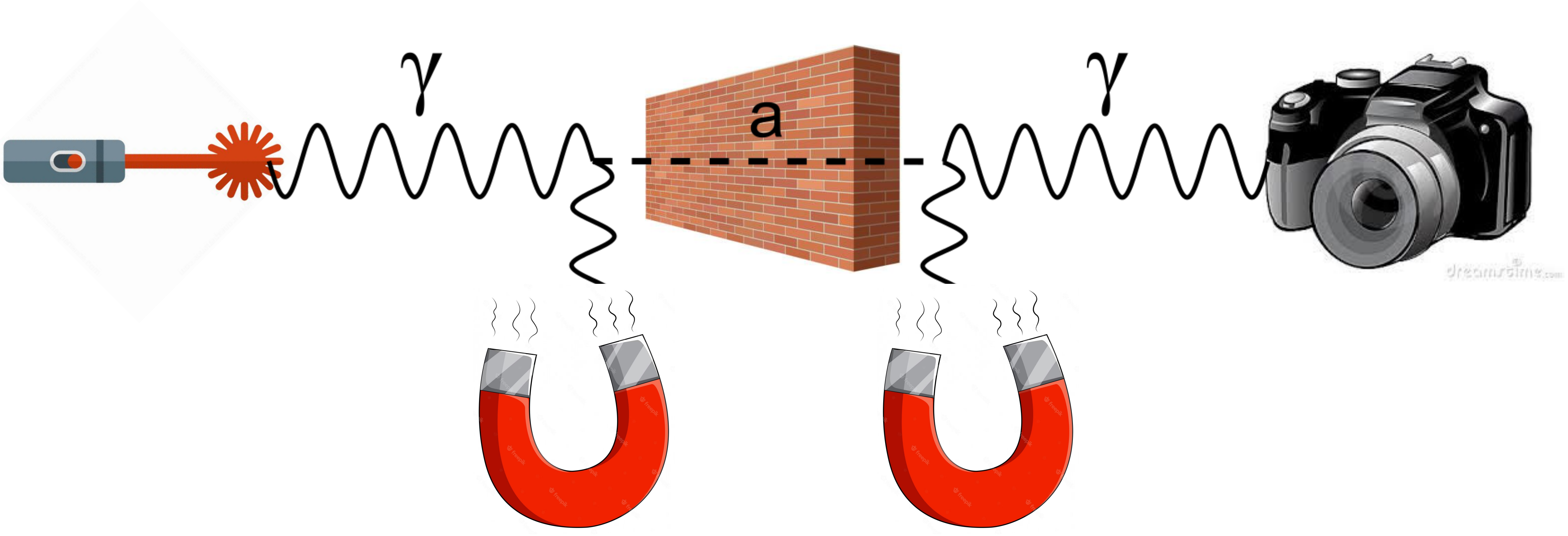


P. Sikivie
Phys. Rev. Lett. **51**, 1415 (1983)

$$P_{\gamma\to a} \approx \frac{1}{4}(g_{a\gamma\gamma}BL)^2 \qquad P_{a\to\gamma} \approx \frac{1}{4}(g_{a\gamma\gamma}BL)^2$$

$$P_{\gamma\to a\to\gamma} \approx \frac{1}{16}(g_{a\gamma\gamma}BL)^4$$

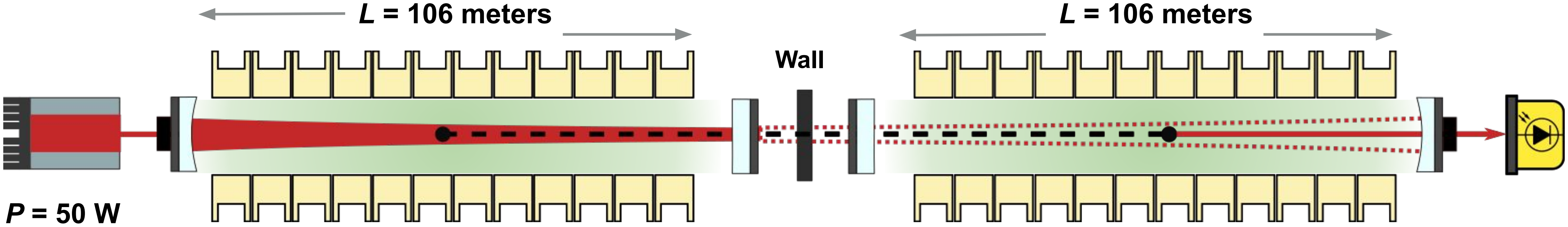
Basic Principles of LSW



$$P_{\gamma\to a\to\gamma} \approx \frac{1}{16}(g_{a\gamma\gamma}BL)^4$$

$$n_{\text{signal}} \approx n_{\text{laser}}\frac{1}{16}(g_{a\gamma\gamma}BL)^4$$

ALPS II: a Resonantly Enhanced LSW Design



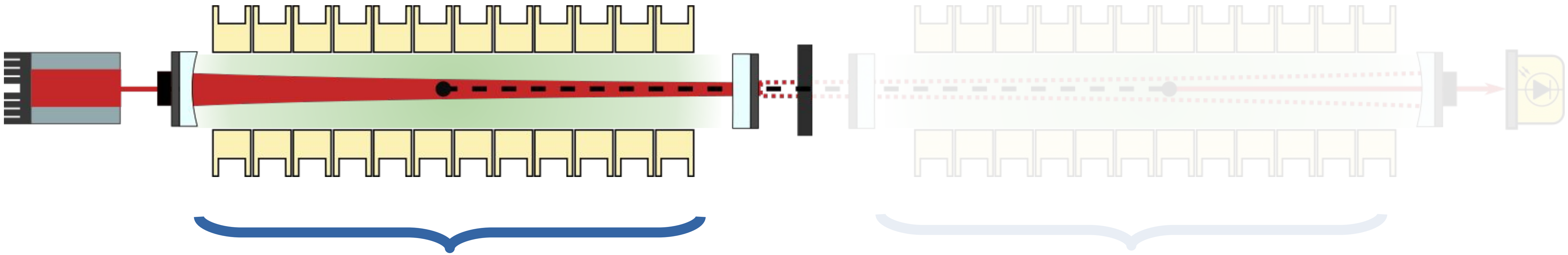
$$P_{\gamma\to a\to\gamma} \approx \frac{1}{16}(g_{a\gamma\gamma}BL)^4$$

$$n_{\rm signal} \approx n_{\rm laser}\frac{1}{16}(g_{a\gamma\gamma}BL)^4$$

$$n_{\rm signal} \approx \frac{1\ \rm photon}{115{,}000\ \rm yr}\cdot\left(\frac{P_{\rm laser}}{50\ \rm W}\right)\left(\frac{g_{a\gamma\gamma}}{2{\times}10^{-11}\ \rm GeV^{-1}}\right)^4\left(\frac{B}{5.3\ \rm T}\right)^4\left(\frac{L}{106\ \rm m}\right)^4$$

Design of the ALPS II Optical System (2022). *Physics of the Dark Universe, 35*: 100968. doi:10.1016/j.dark.2022.100968

ALPS II: a Resonantly Enhanced LSW Design



Production Cavity (PC)

- Builds up the power of the light circulating in the magnetic field
- Increases the flux of axion-like particles flowing through the wall

$$n_{\mathrm{laser}} \rightarrow n_{\mathrm{PC}}$$

Design objective: **150 kW circulating power (n_{PC} ~ 10^{24} /s)**

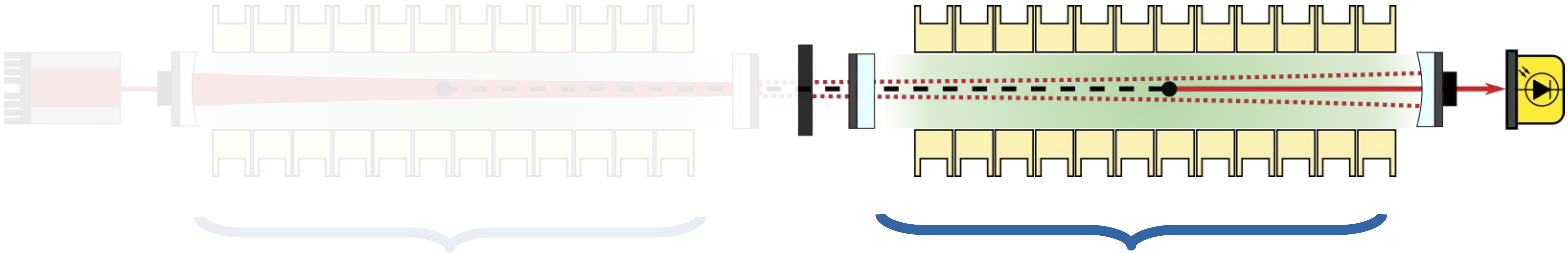
Regeneration Cavity (RC)

- Electromagnetic component of the ALP field is resonantly enhanced
- Improves the ALP-photon reconversion signal rate

$$n_{\mathrm{signal}} \rightarrow n_{\mathrm{signal}} \times \beta_{\mathrm{RC}}$$

Design objective: **β_{RC} > 10,000 power build-up**

ALPS II: a Resonantly Enhanced LSW Design



Production Cavity (PC)

- Builds up the power of the light circulating in the magnetic field
- Increases the flux of axion-like particles flowing through the wall

$$n_{\text{laser}} \rightarrow n_{\text{PC}}$$

Design objective: **150 kW circulating power (n_{PC} ~ 10^{24} /s)**

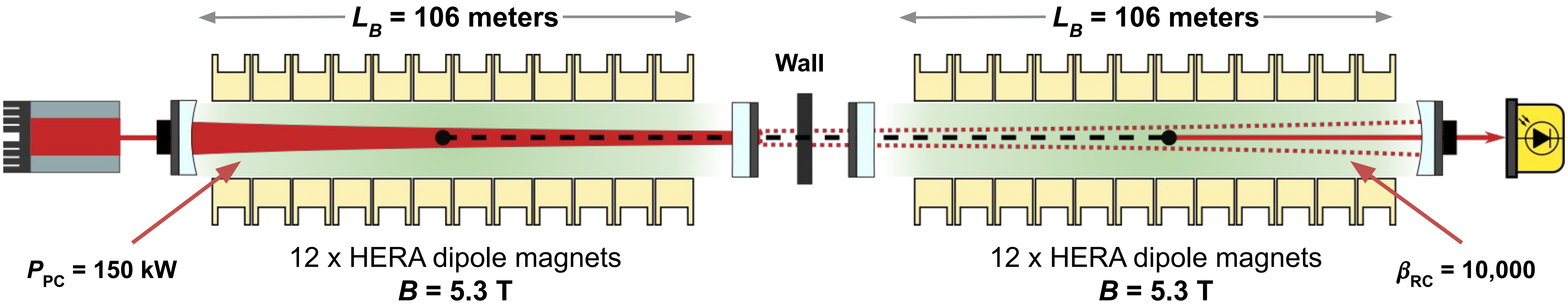
Regeneration Cavity (RC)

- Electromagnetic component of the ALP field is resonantly enhanced
- Improves the ALP-photon reconversion signal rate

$$n_{\text{signal}} \rightarrow n_{\text{signal}} \times \beta_{\text{RC}}$$

Design objective: **β_{RC} > 10,000 power build-up**

ALPS II: a Resonantly Enhanced LSW Design



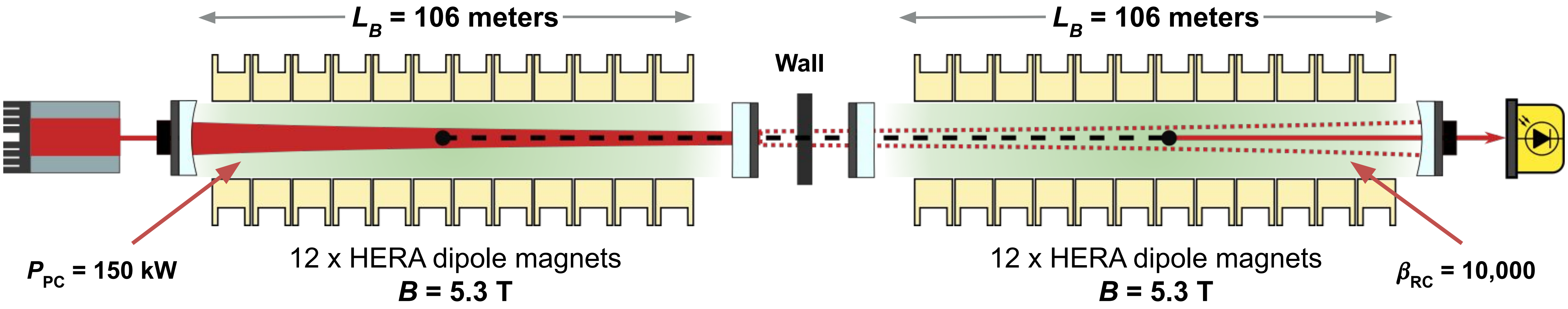
$$n_{\text{signal}} \approx n_{\text{PC}} \beta_{\text{RC}} \frac{\eta}{16} (g_{a\gamma\gamma} BL)^4$$

For the ALPS II design parameters:

$$n_{\text{signal}} \approx \frac{1 \text{ photon}}{37 \text{ hours}} \cdot \left(\frac{P_{\text{PC}}}{150 \text{ kW}}\right)\left(\frac{\beta_{\text{RC}}}{10{,}000}\right)\left(\frac{\eta}{0.9}\right)\left(\frac{g_{a\gamma\gamma}}{2\times 10^{-11} \text{ GeV}^{-1}}\right)^4 \left(\frac{B}{5.3 \text{ T}}\right)^4 \left(\frac{L}{106 \text{ m}}\right)^4$$

Design of the ALPS II Optical System (2022). *Physics of the Dark Universe, 35*: 100968. doi:10.1016/j.dark.2022.100968

ALPS II: a Resonantly Enhanced LSW Design



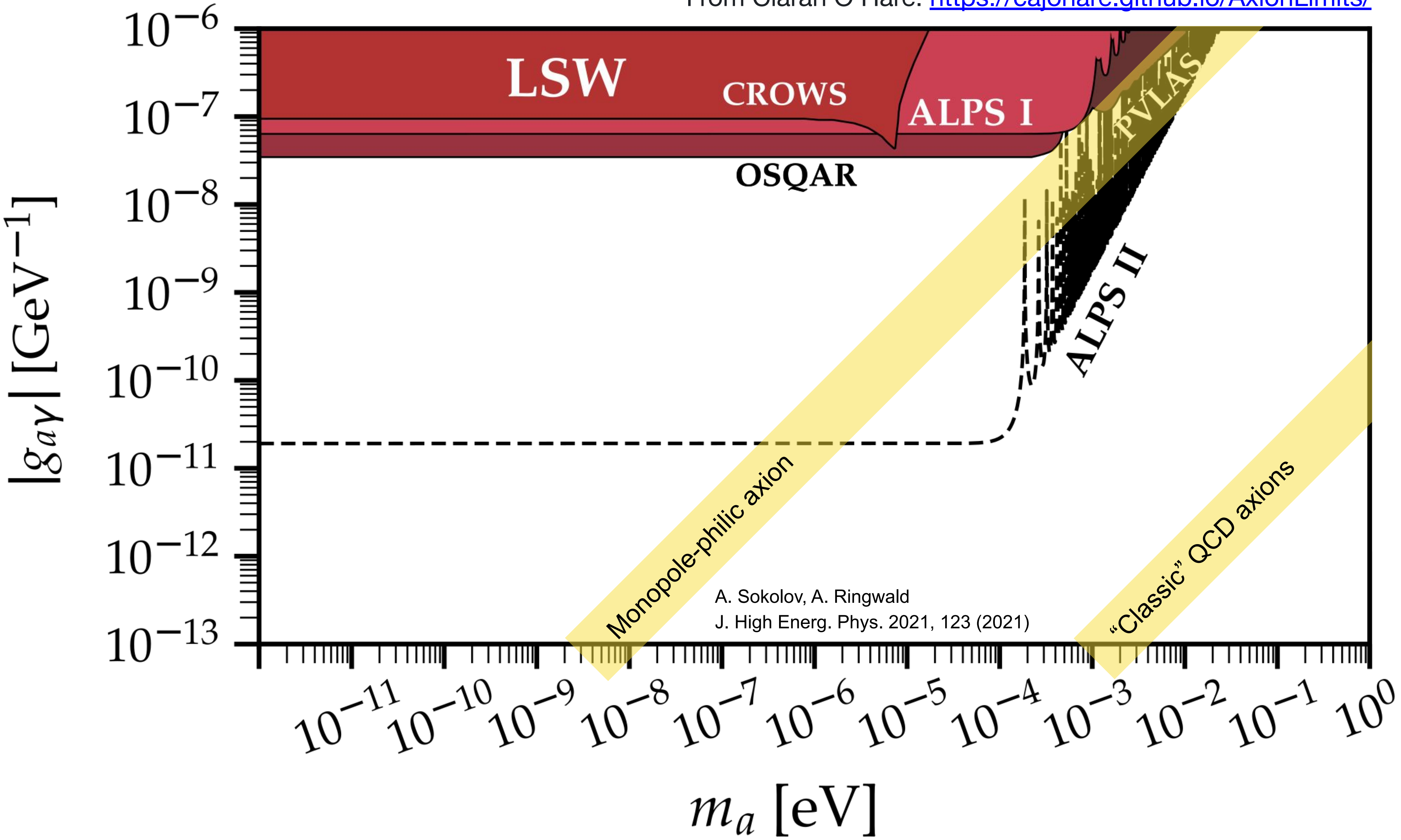
ALPS II Technology

1. Magnets and Infrastructure
2. Optical Systems
3. Control Systems
4. Ultra-low power Detector

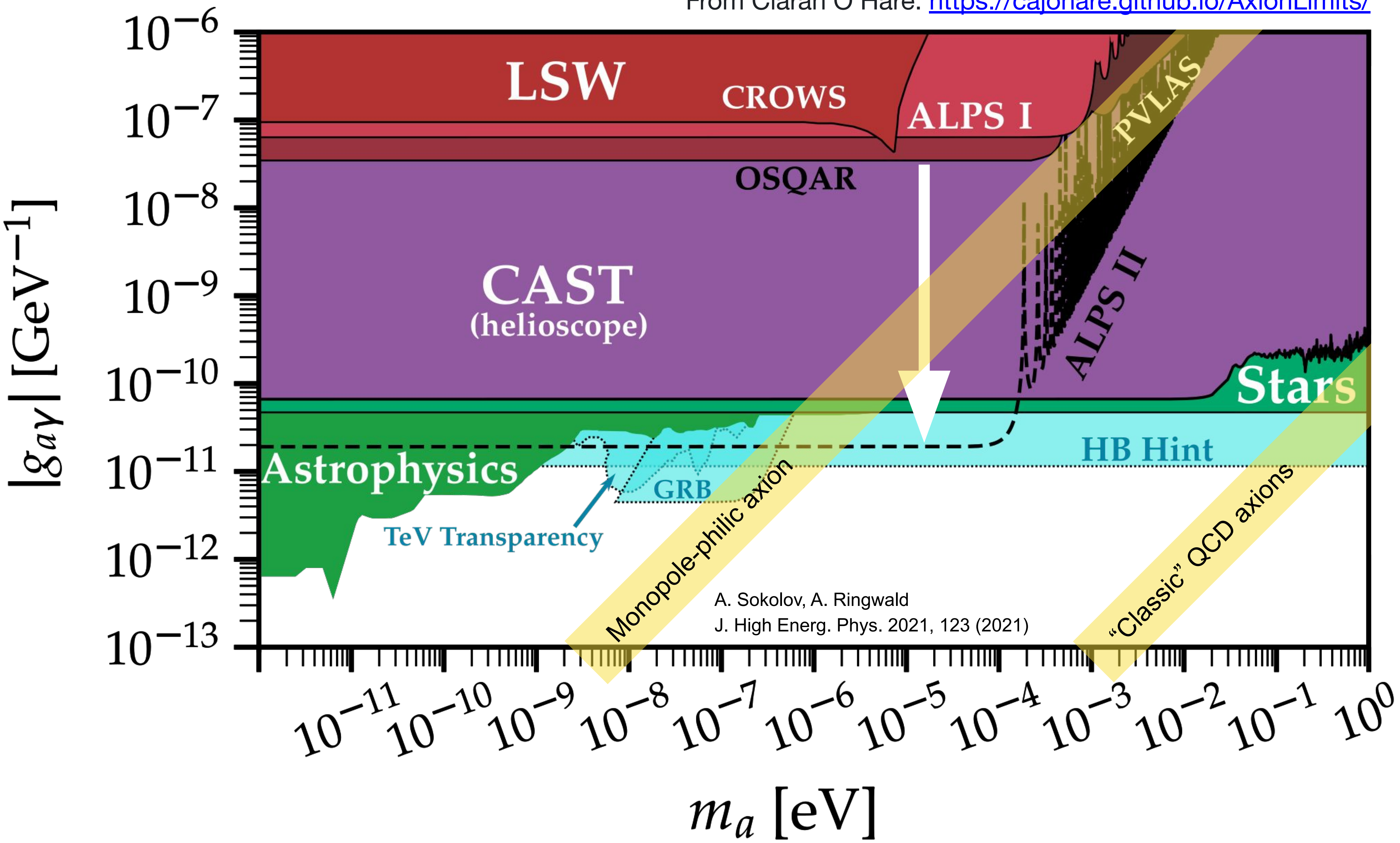
$$n_{\text{signal}} \approx \frac{1\ \text{photon}}{37\ \text{hours}} \cdot \left(\frac{P_{\text{PC}}}{150\ \text{kW}}\right)\left(\frac{\beta_{\text{RC}}}{10{,}000}\right)\left(\frac{\eta}{0.9}\right)\left(\frac{g_{a\gamma\gamma}}{2\times10^{-11}\ \text{GeV}^{-1}}\right)^4\left(\frac{B}{5.3\ \text{T}}\right)^4\left(\frac{L}{106\ \text{m}}\right)^4$$

Design of the ALPS II Optical System (2022). *Physics of the Dark Universe, 35*: 100968. doi:10.1016/j.dark.2022.100968

From Ciaran O'Hare: https://cajohare.github.io/AxionLimits/

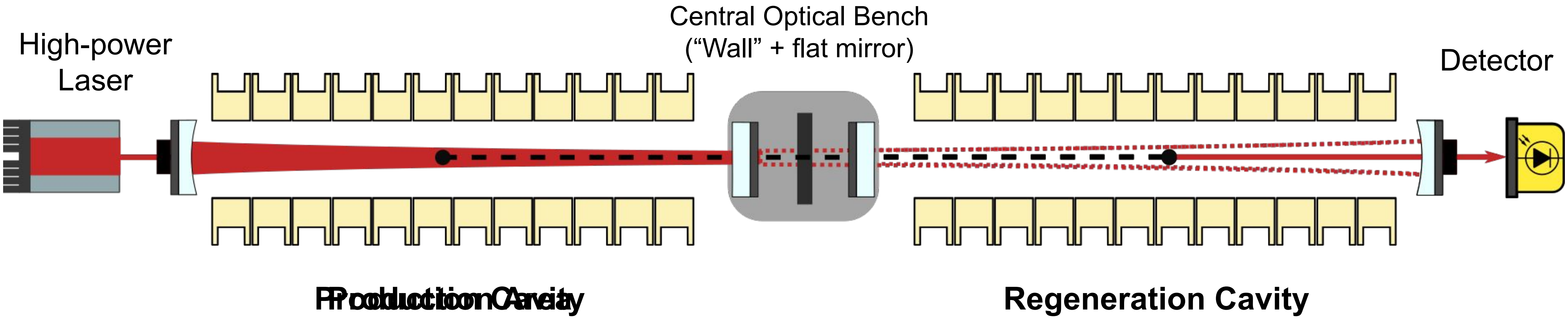


From Ciaran O'Hare: https://cajohare.github.io/AxionLimits/




ALPS II
HERA North
HERA South
MADMAX
IAXO

ALPS II Design for the First Science Run

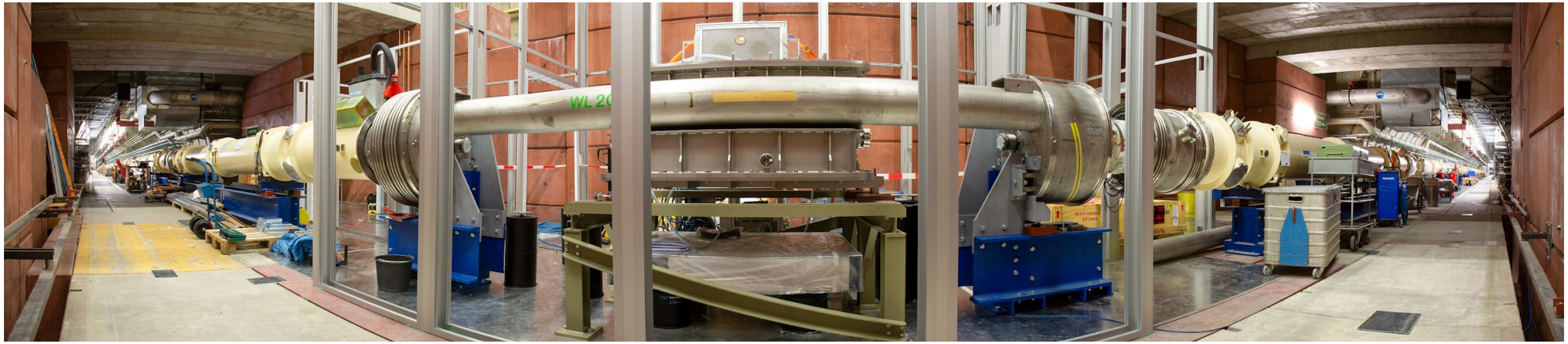


- simplified one-cavity design makes frequency and alignment control simpler for the first science run
- 40x more incident HPL light on the COB to better identify stray light sources
- will nevertheless produce the most sensitive model-independent / laboratory-based ALP search

ALPS II Technology: Magnets and Infrastructure

Photo credit: D. Reuther, M. Mayer, A. Spector

October 202

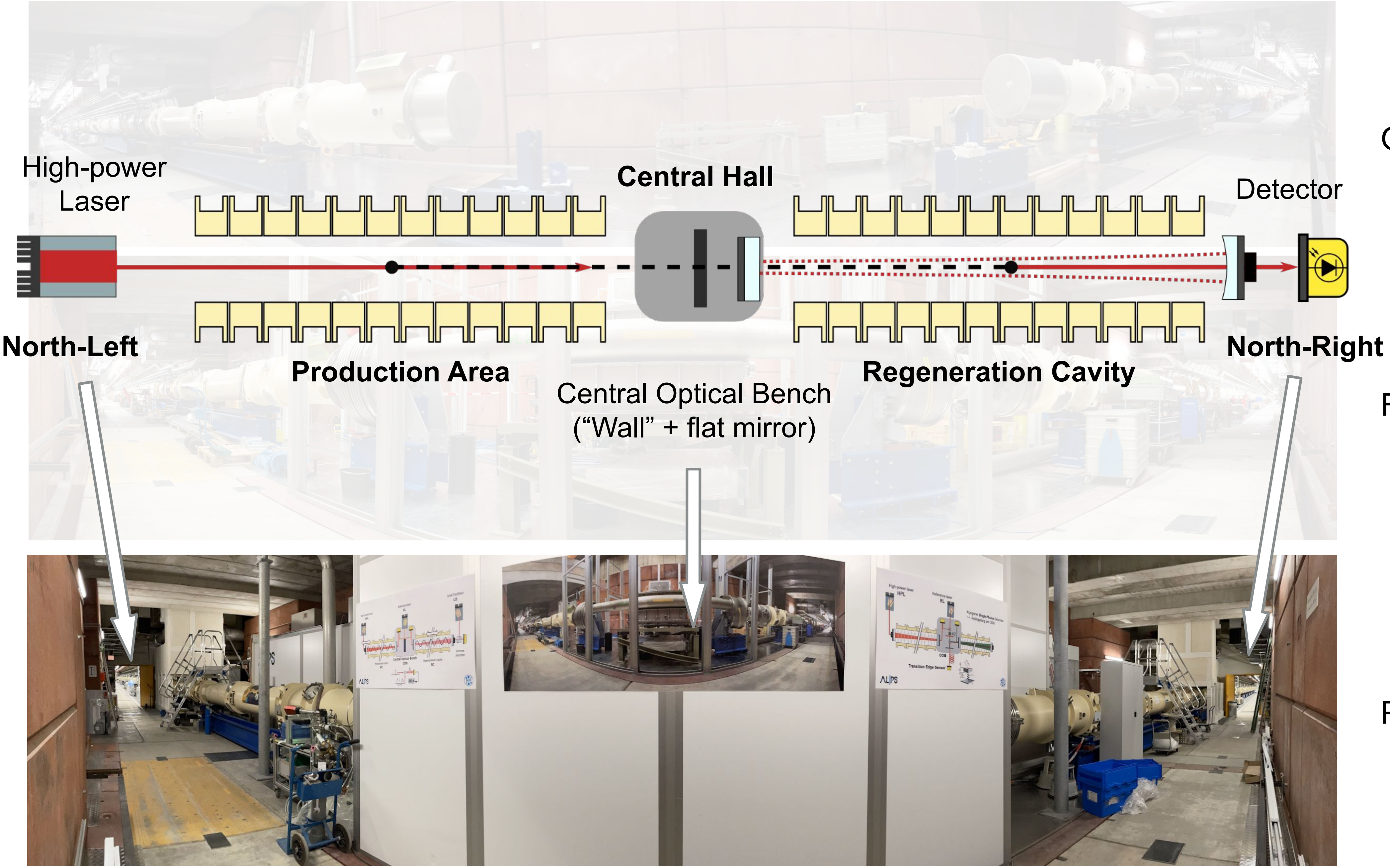


February 20

Present

ALPS II Technology: Magnets and Infrastructure

Photo credit: D. Reuther, M. Mayer, A. Spector



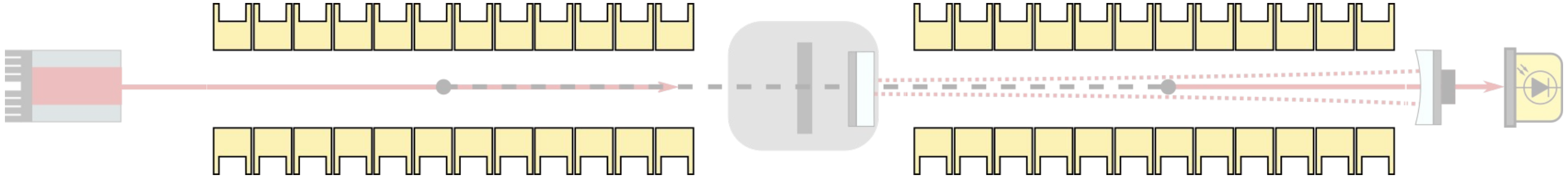
October 202

February 20

Present

Image credits: D. Reuther, L. Wei, DESY MVS

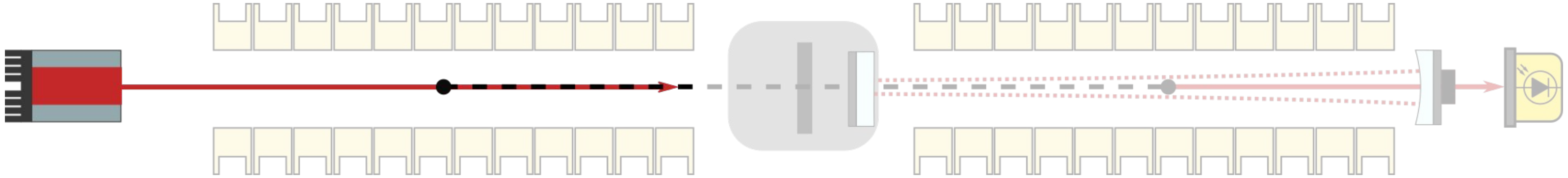
Magnets



- 24 (2 x 12) repurposed HERA dipole magnets successfully straightened, current- and quench-tested, aligned and operational
  - 5.3 T field strength at nominal 5700 A
  - Expanded beam tube aperture allows for longer optical cavities → improved sensitivity

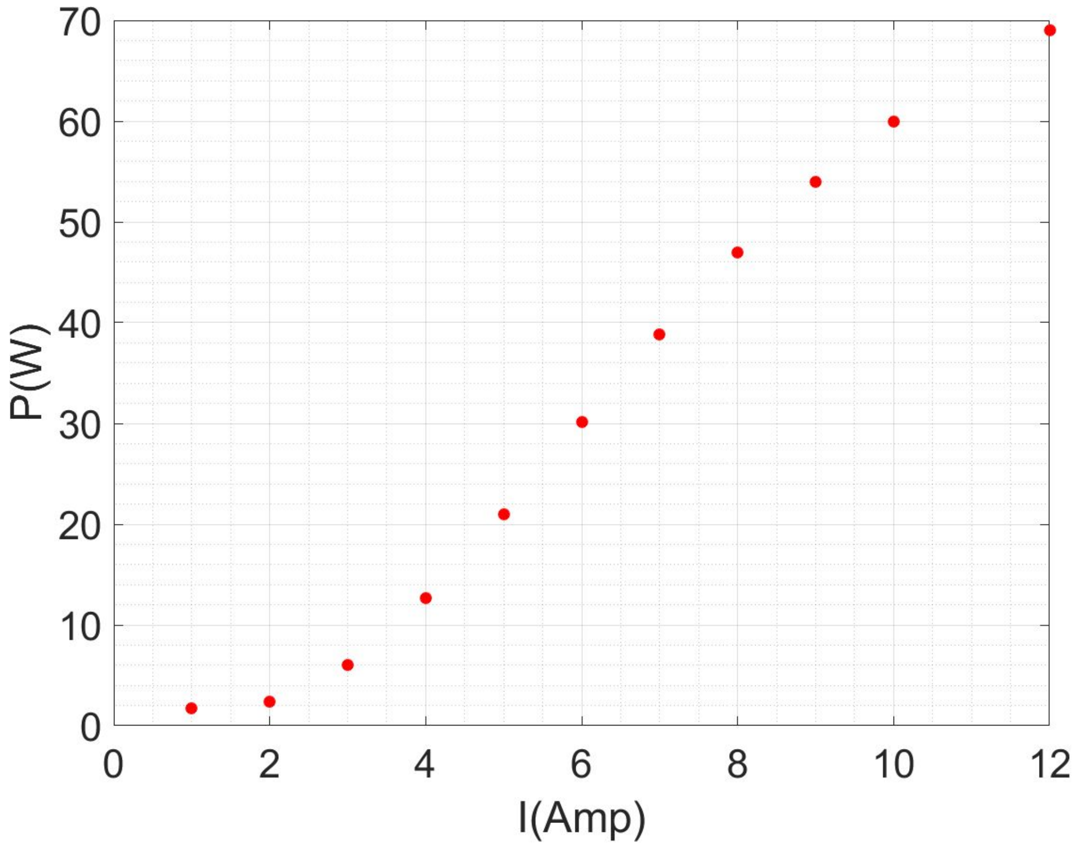
Albrecht, C., Barbanotti, S., Hintz, H. *et al.* Straightening of superconducting HERA dipoles for the any-light-particle-search experiment ALPS II. *EPJ Techn Instrum* 8, 5 (2021).

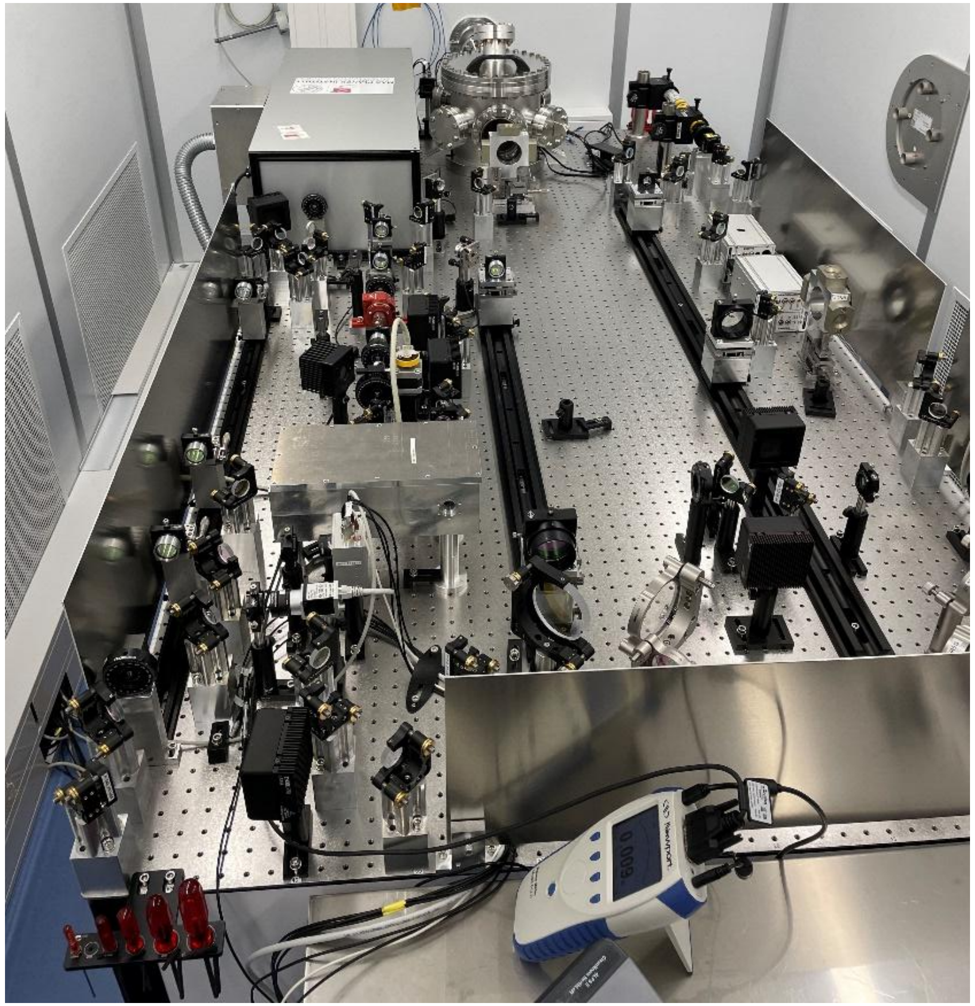
Optics



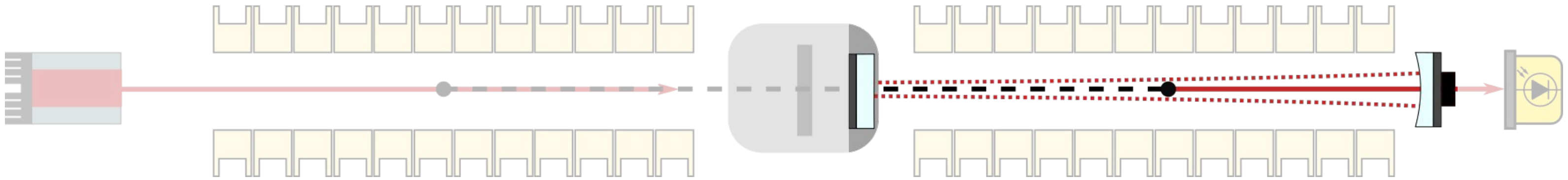
High Power Laser (HPL) System

- stable operation at 40 W of 1064 nm light





Optics

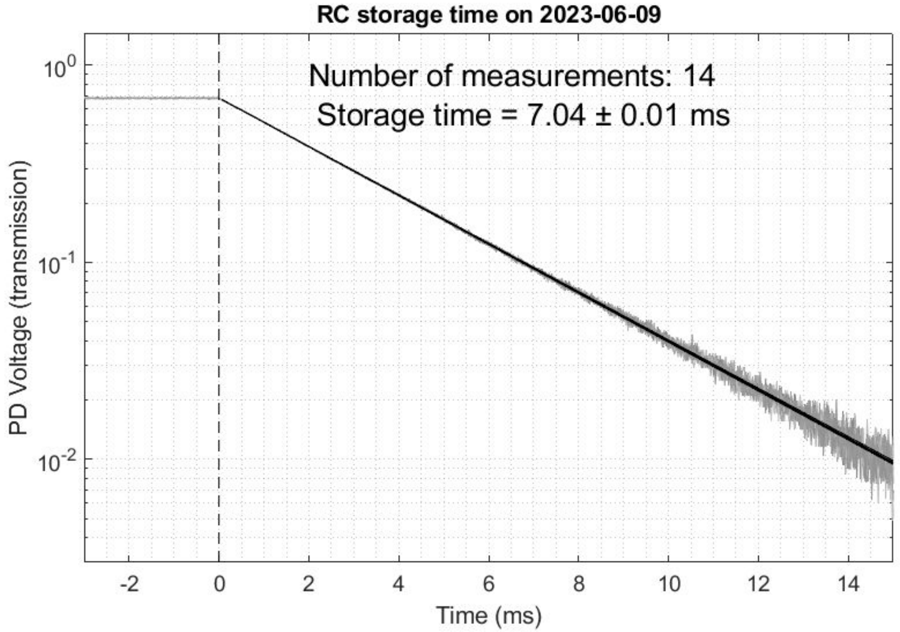


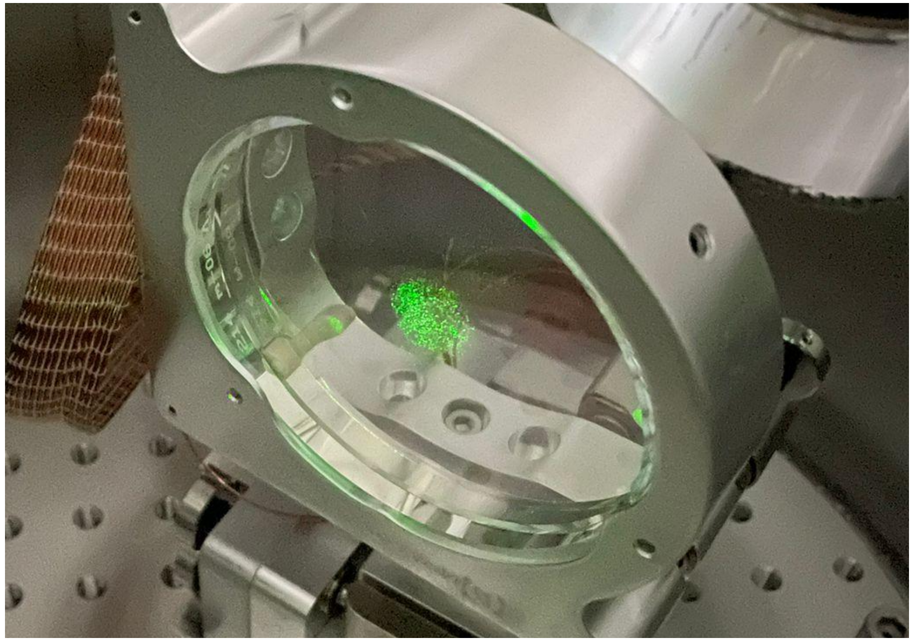
High Power Laser (HPL) System

- stable operation at 40 W of 1064 nm light

Regeneration Cavity

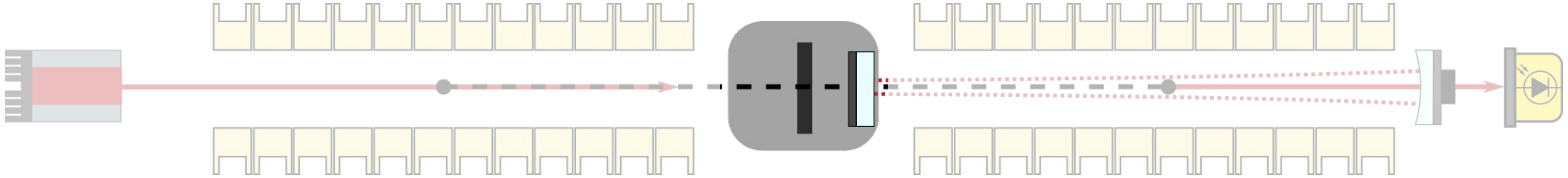
- Half-confocal, 122 meters long
- Cavity light storage time: **7.04 ms (world record)**
  - **power build-up: 7,700**





RC 3” curved mirror in vacuum tank

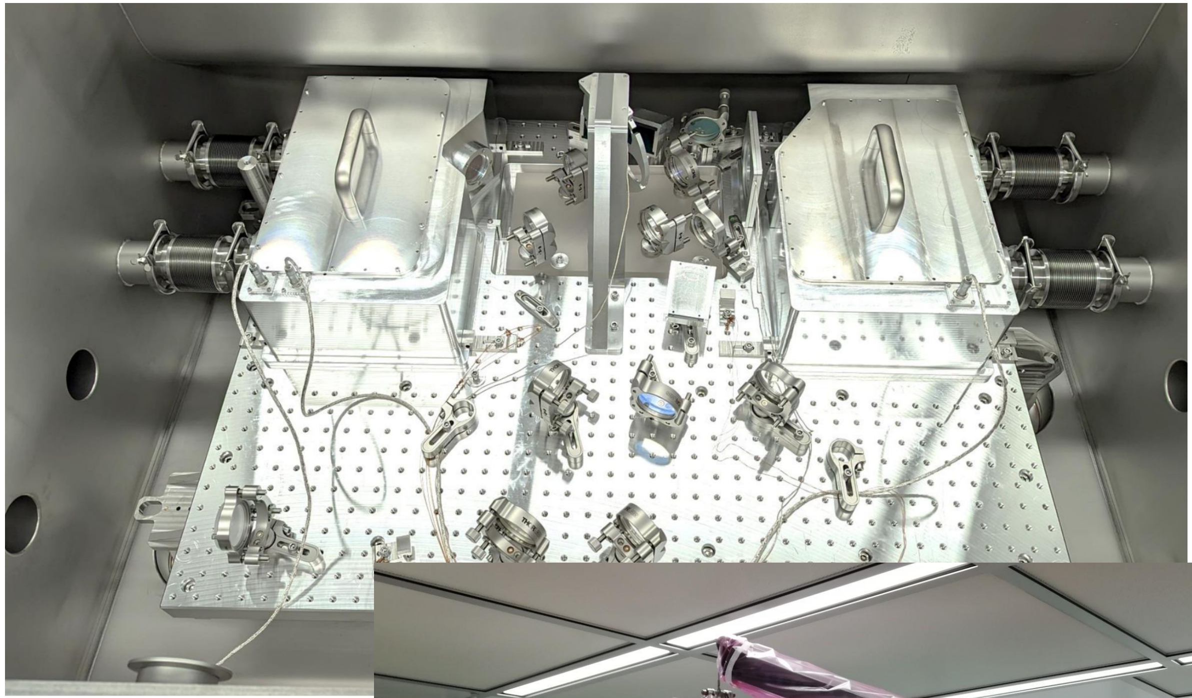
Optics



High Power Laser (HPL) System
- stable operation at 40 W of 1064 nm light

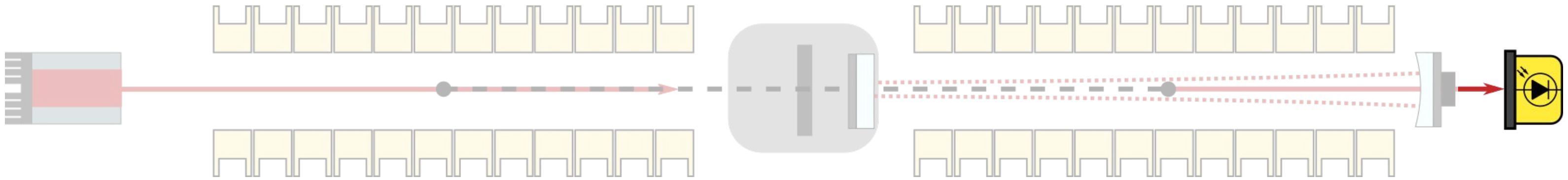
Regeneration Cavity
- Half-confocal, 122 meters long
- Cavity storage time: **7.04 ms (world record)**
  - **power build-up: 7,700**

Central Optical Bench
- Ensures passive alignment between PC and RC
- Light-tight housings to reduce stray light
- Remotely operable shutter serving as the “wall”



Central Optical Bench in-situ in central vacuum chamber

Optics



High Power Laser (HPL) System

- stable operation at 40 W of 1064 nm light

Regeneration Cavity

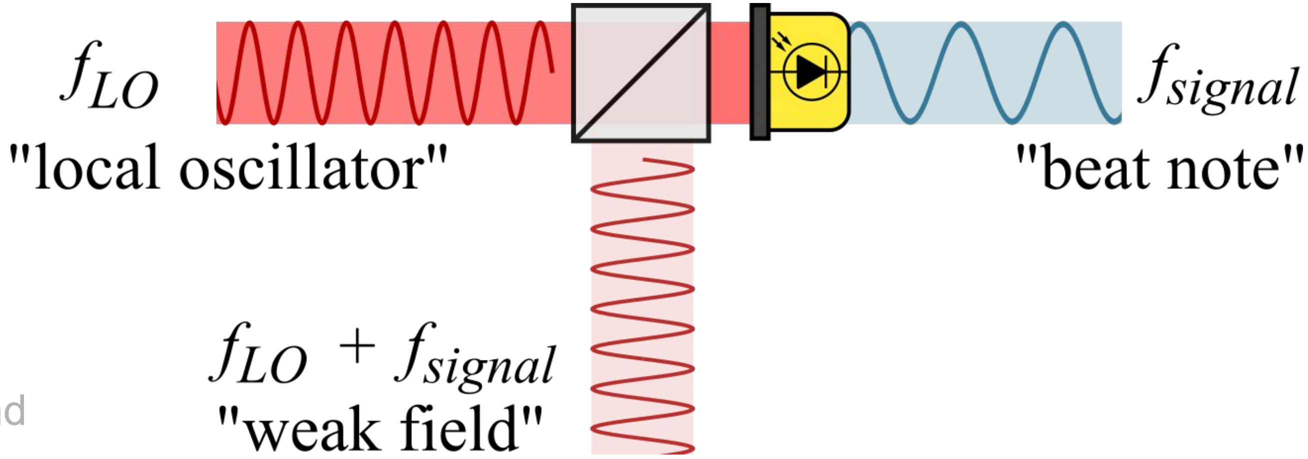
- Half-confocal, 122 meters long
- Cavity storage time: **7.04 ms (world record)**
  - **power build-up: 7,700** (design goal 10,000)

Central Optical Bench

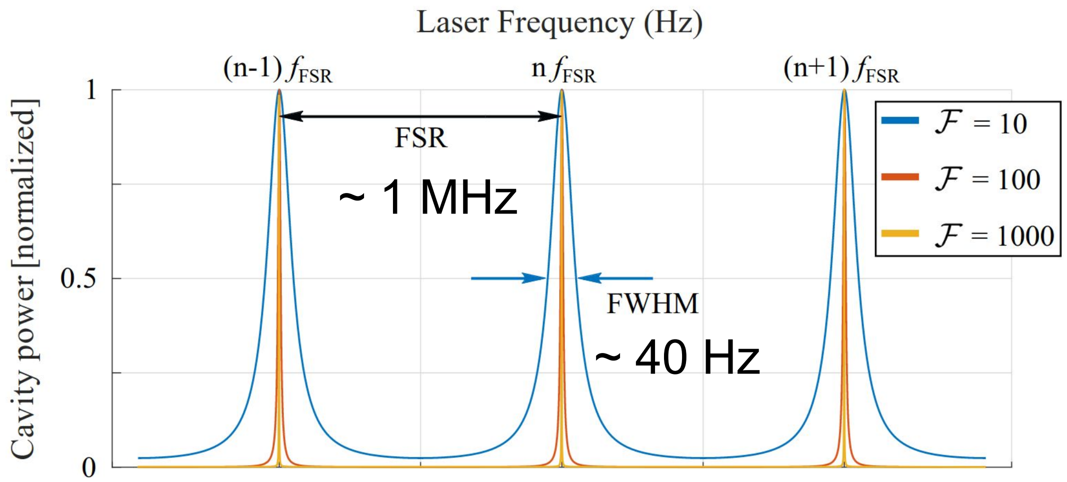
- Ensures passive alignment between PC and RC
- Light-tight housing to reduce stray light background
- Remotely operable shutter serving as the “wall”

Heterodyne Interferometric Detector

- Coherent detection of extremely weak fields
- Relies on high relative phase stability between two different frequency fields over long periods



Frequency and Phase Control



Resonant Enhancement

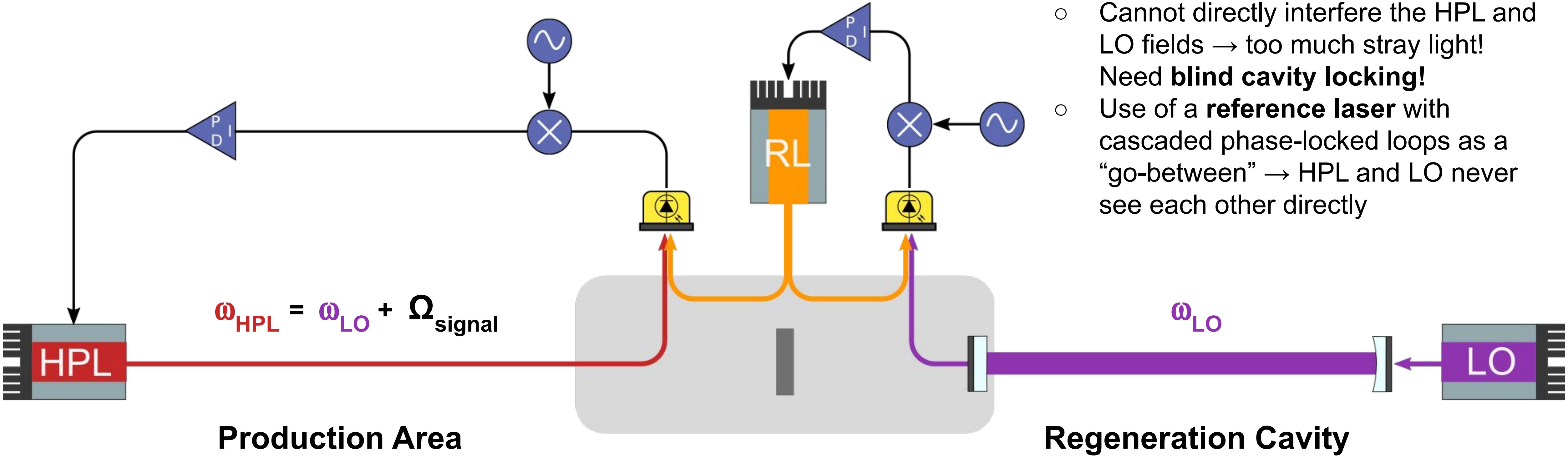
- Power build-up only when the HPL frequency is resonant within the RC
- Cannot directly interfere the HPL and LO fields → too much stray light! Need **blind cavity locking!**

$$\Omega_{signal} = n \times FSR$$

Frequency and Phase Control

Resonant Enhancement

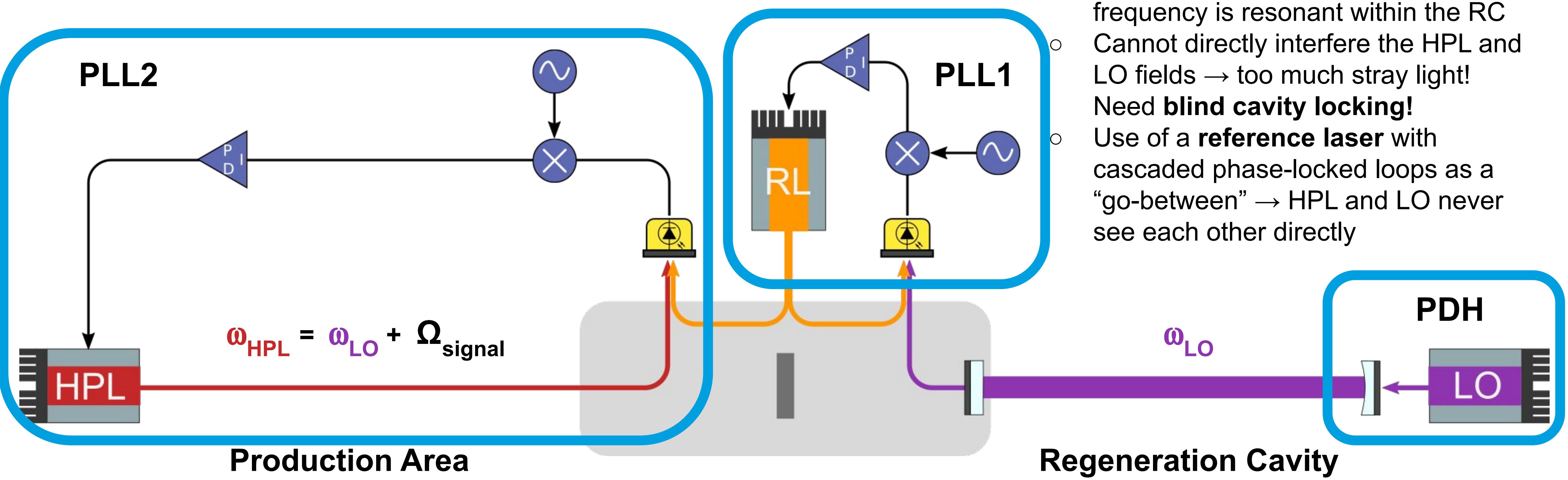
- Power build-up only when the HPL frequency is resonant within the RC
- Cannot directly interfere the HPL and LO fields → too much stray light! Need **blind cavity locking!**
- Use of a **reference laser** with cascaded phase-locked loops as a “go-between” → HPL and LO never see each other directly



Frequency and Phase Control

Resonant Enhancement

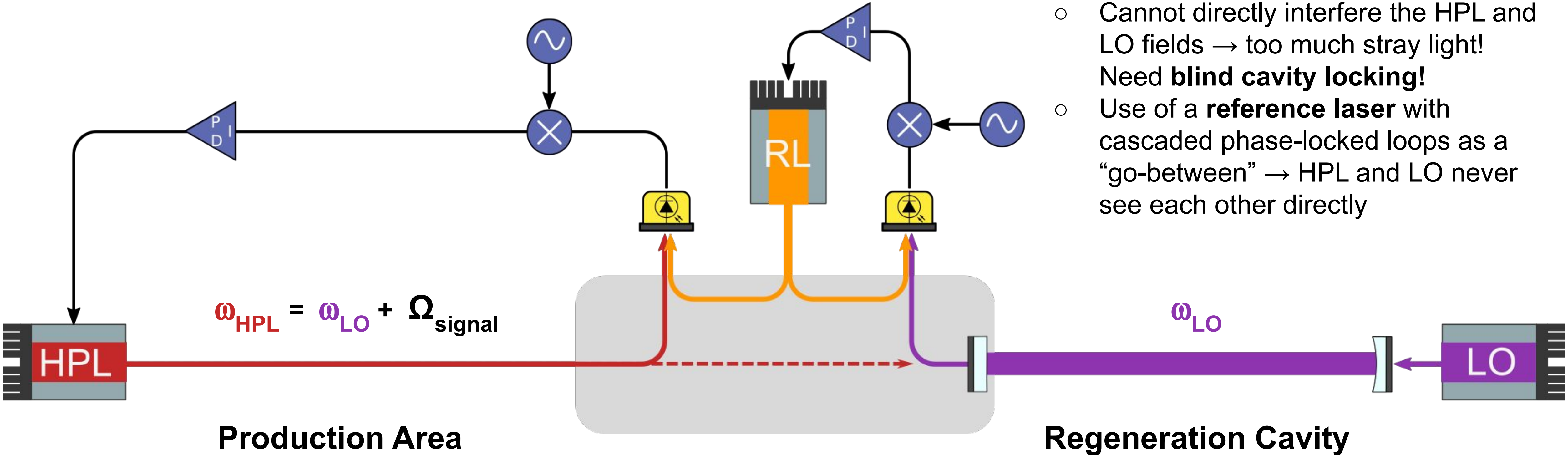
- Power build-up only when the HPL frequency is resonant within the RC
- Cannot directly interfere the HPL and LO fields → too much stray light! Need **blind cavity locking!**
- Use of a **reference laser** with cascaded phase-locked loops as a "go-between" → HPL and LO never see each other directly



Frequency and Phase Control

Resonant Enhancement

- Power build-up only when the HPL frequency is resonant within the RC
- Cannot directly interfere the HPL and LO fields → too much stray light! Need **blind cavity locking!**
- Use of a **reference laser** with cascaded phase-locked loops as a "go-between" → HPL and LO never see each other directly



Open-Shutter Measurements

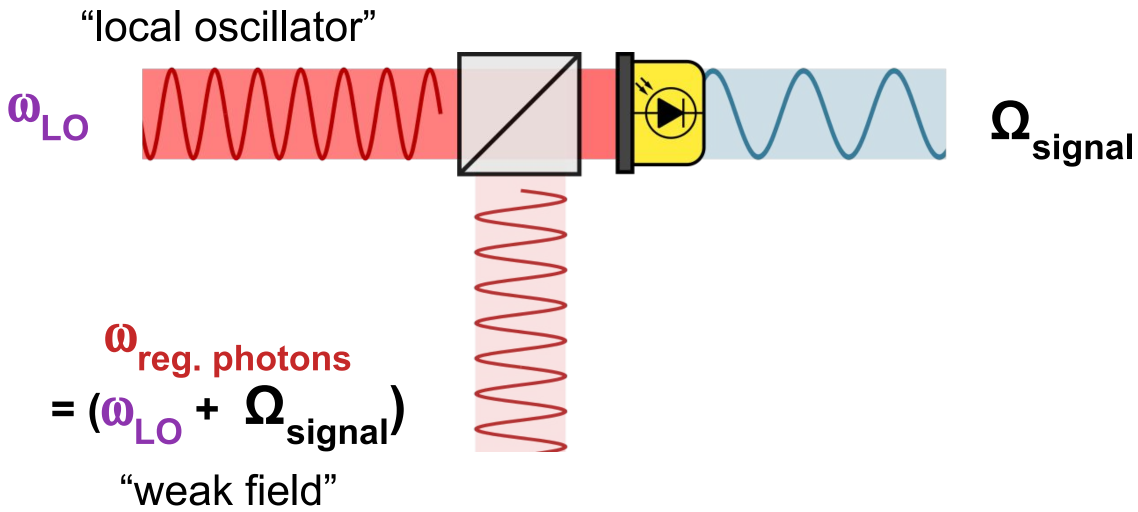
- by opening the "wall", we are able to **verify the resonance condition of the HPL**, as well as assess the system alignment and **long-term phase evolution**

Heterodyne Interferometric Detection

Heterodyne Interferometry

- interference beat-note between:
    1. *weak field* (regenerated photons from axions)
    2. strong *local oscillator* (additional laser)

  on a photodetector



$$\left|\sqrt{P_{LO}}e^{i\omega_{LO}t} + \sqrt{P_{reg.\ photons}}e^{i[(\omega_{LO}+\Omega_{signal})t+\phi]}\right|^2$$

$$= \underbrace{P_{LO} + P_{reg.\ photons}}_{\text{D.C. terms}} + \underbrace{2\sqrt{P_{LO}P_{reg.\ photons}}\cos(\Omega_{signal}t + \phi)}_{\text{RF beatnote}}$$

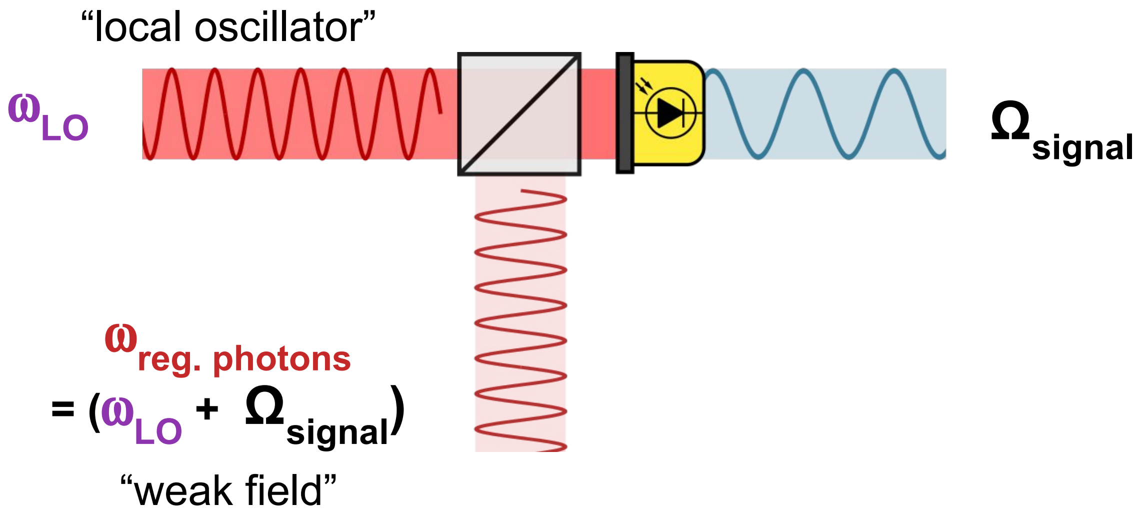
Heterodyne Interferometric Detection

Heterodyne Interferometry

- interference beat-note between:
    1. *weak field* (regenerated photons from axions)
    2. strong *local oscillator* (additional laser)

  on a photodetector

- with *fixed frequency and phase offset*, detection is **coherent** and **noise integrates away**
    - only stray light is present as a background
        - even stray light demonstrates (slow) phase evolution



$$\left|\sqrt{P_{LO}}e^{i\omega_{LO}t} + \sqrt{P_{reg.\ photons}}e^{i[(\omega_{LO}+\Omega_{signal})t+\phi]}\right|^2$$

$$= \underbrace{P_{LO} + P_{reg.\ photons}}_{\text{D.C. terms}} + \underbrace{2\sqrt{P_{LO}P_{reg.\ photons}}\cos(\Omega_{signal}t + \phi)}_{\text{RF beatnote}}$$

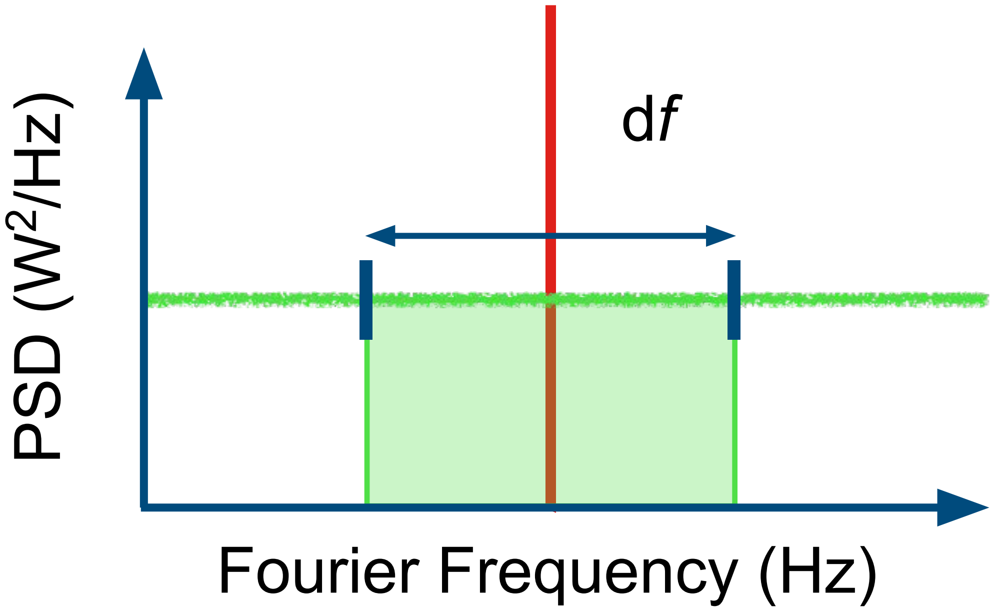
Heterodyne Interferometric Detection

Heterodyne Interferometry

- interference beat-note between:
  1. *weak field* (regenerated photons from axions)
  2. strong *local oscillator* (additional laser)

  on a photodetector

- with *fixed frequency and phase offset*, detection is **coherent** and **noise integrates away**
  - only stray light is present as a background
    - even stray light demonstrates (slow) phase evolution



Graphic courtesy of Aaron Spector

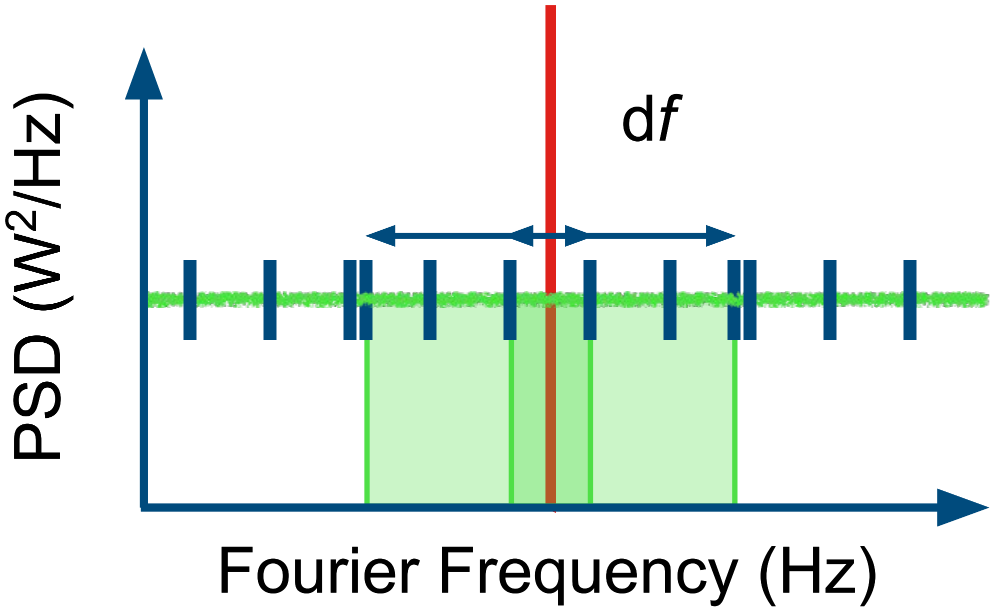
Heterodyne Interferometric Detection

Heterodyne Interferometry

- interference beat-note between:
    1. *weak field* (regenerated photons from axions)
    2. strong *local oscillator* (additional laser)

  on a photodetector

- with *fixed frequency and phase offset*, detection is **coherent** and **noise integrates away**
    - only stray light is present as a background
        - even stray light demonstrates (slow) phase evolution



Graphic courtesy of Aaron Spector

Heterodyne Interferometric Detection

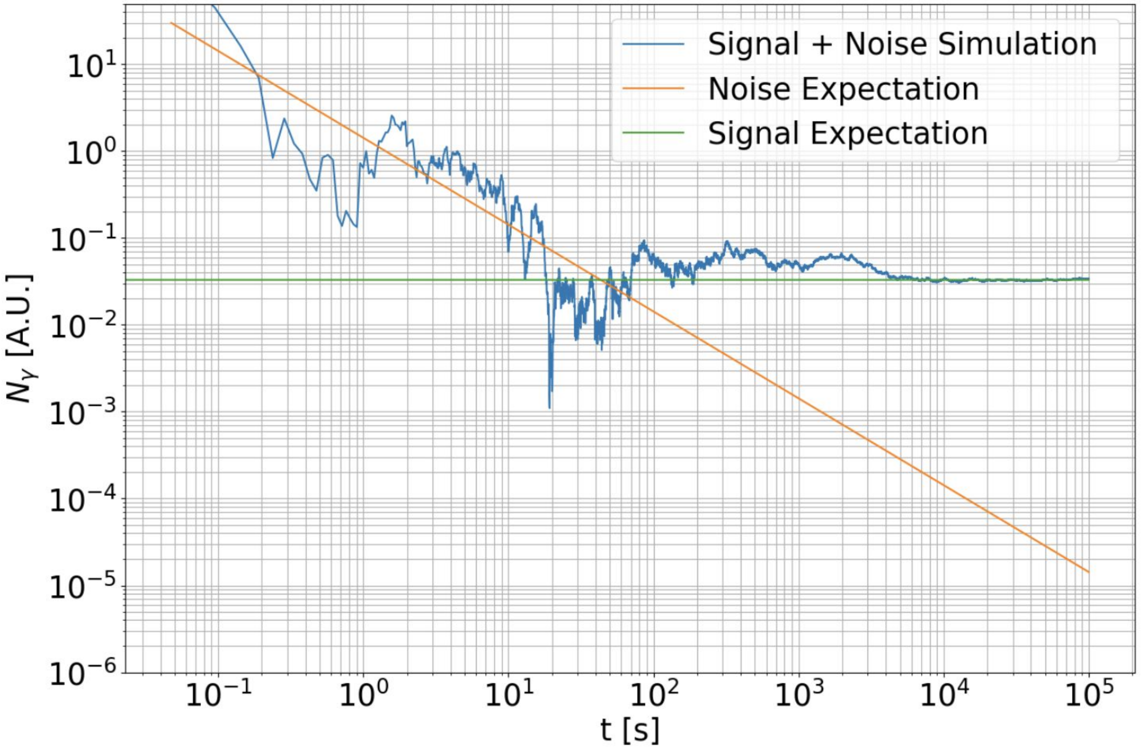
Heterodyne Interferometry

- interference beat-note between:
  - a *weak field* (regenerated photons from axions)
  - a strong *local oscillator* (additional laser)

  on a photodetector

- with *fixed frequency and phase offset*, detection is **coherent** and **noise integrates away**
  - only stray light is present as a background
    - even stray light demonstrates (slow) phase evolution

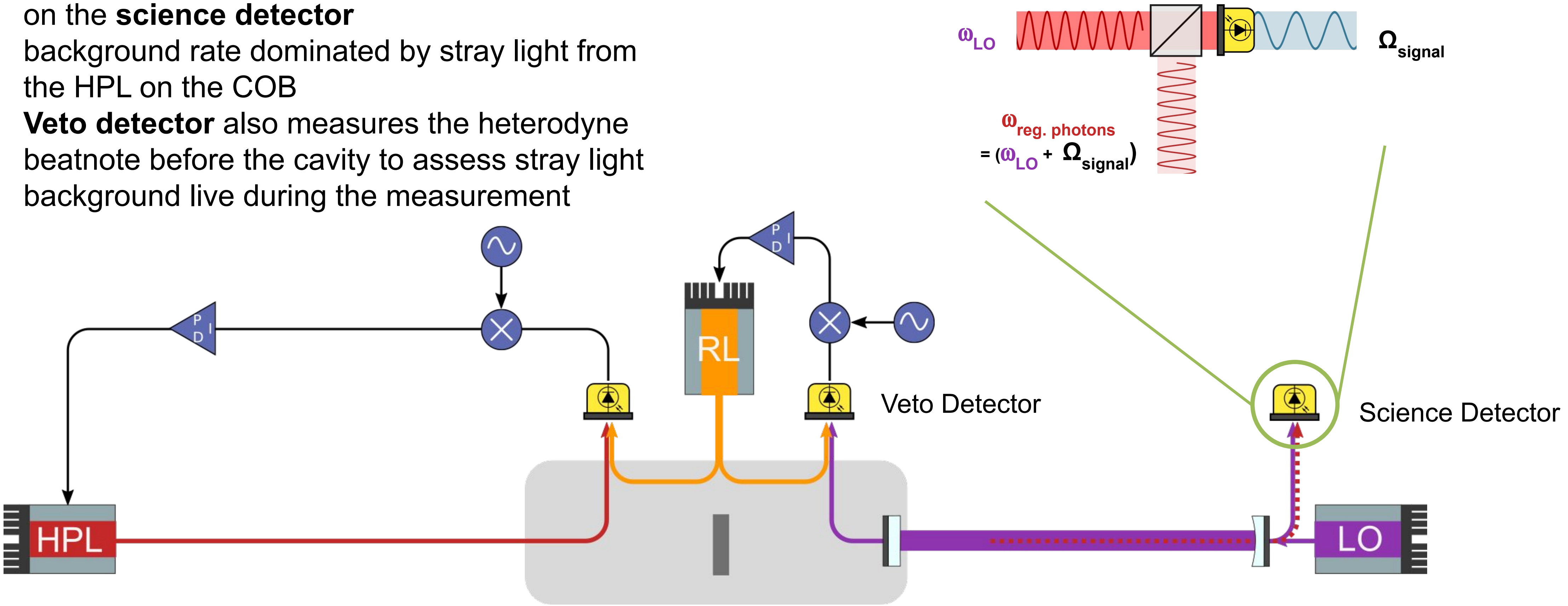
SIMULATION



Heterodyne Interferometric Detection

Heterodyne detection in ALPS II

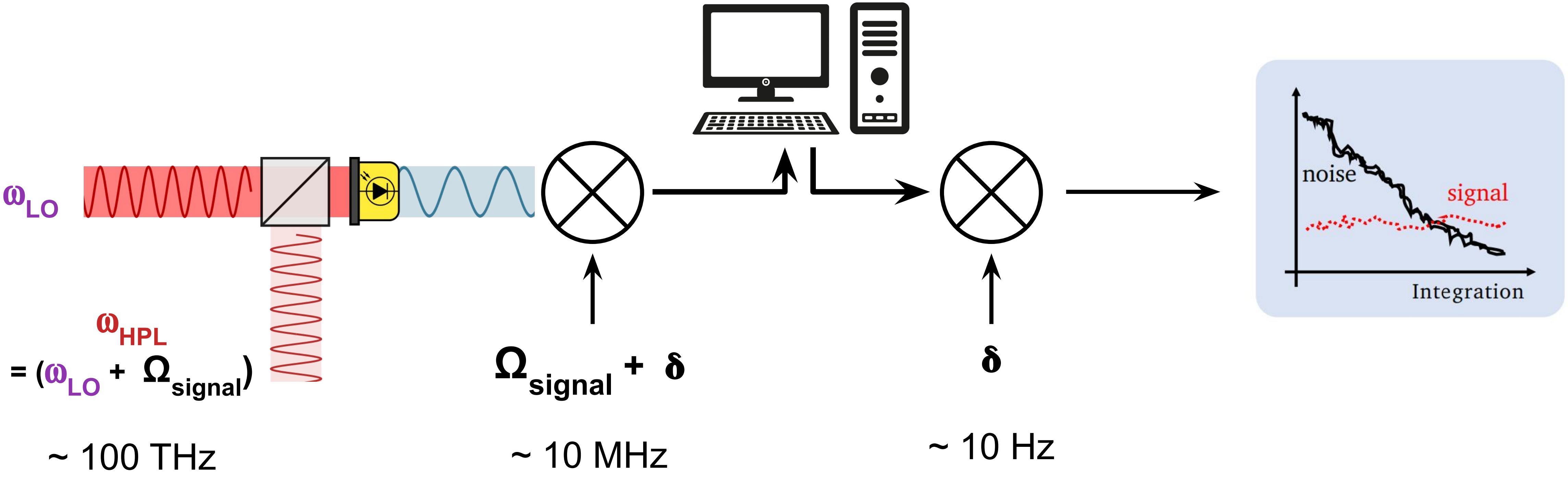
- MHz beat-note formed between the LO (~mW) and regenerated photons in reflection of the RC on the **science detector**
- background rate dominated by stray light from the HPL on the COB
- **Veto detector** also measures the heterodyne beatnote before the cavity to assess stray light background live during the measurement



Heterodyne Interferometric Detection

Two-stage Digital Demodulation Signal Extraction

- local oscillator and regenerated photon fields form signal at frequency: $\boldsymbol{\Omega}_{\mathbf{signal}}$
- first demodulation on-board FPGA lock-in amplifier instrument to an intermediate frequency: $\boldsymbol{\delta}$
- second demodulation performed "offline"



A First Look with ALPS II

First measurement performed from 23. to 31. May

- ○ good overall stability and alignment performance
- ○ ~ 45 hours of "system locked" science data acquired with magnets on
- ○ operated with laser light polarization oriented for a "scalar" ALP search

- Open-shutter periods:
  - reconstruct the long term phase evolution of the system
  - monitor the alignment and calibration mid-measurement for calibration
- Closed-shutter periods:
  - the "science" data

Evaluating "Open Shutter" Periods

A. Spector, PATRAS 2023

Step 1: demodulate recorded signal to generate in-phase and quadrature components of the raw heterodyne function

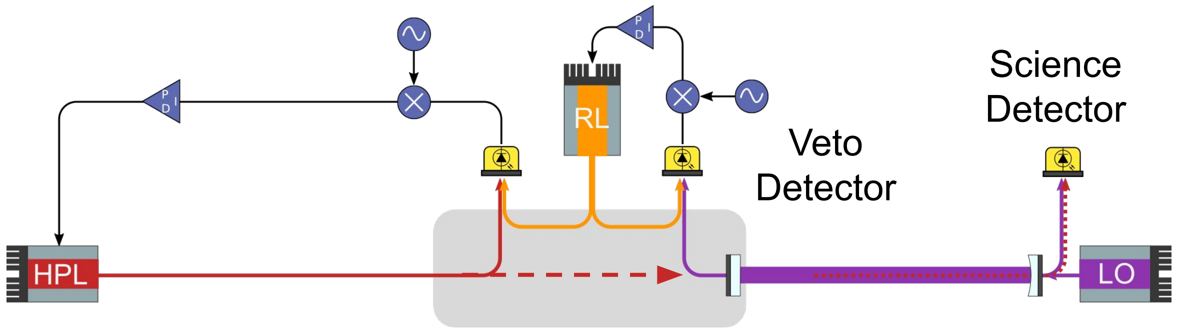
Step 2: calibrate raw heterodyne data in terms of photon rate

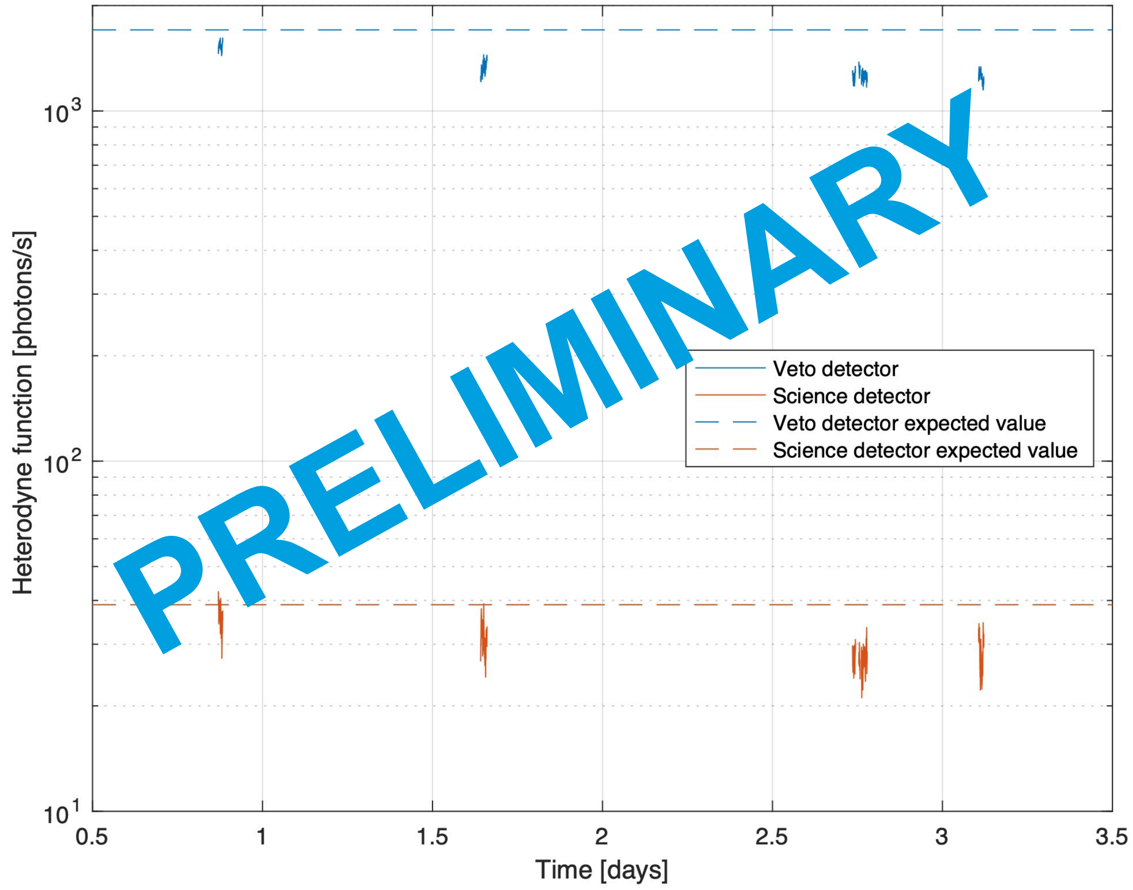
From I[n] and Q[n]

$$z[N] = \frac{(\sum_i^N I[n])^2 + (\sum_i^N Q[n])^2}{N^2}$$

Number of photons

$$N_\gamma = \frac{z[N]}{G^2 P_{LO} h\nu}$$





Evaluating "Closed Shutter" Periods

Generate the Heterodyne function

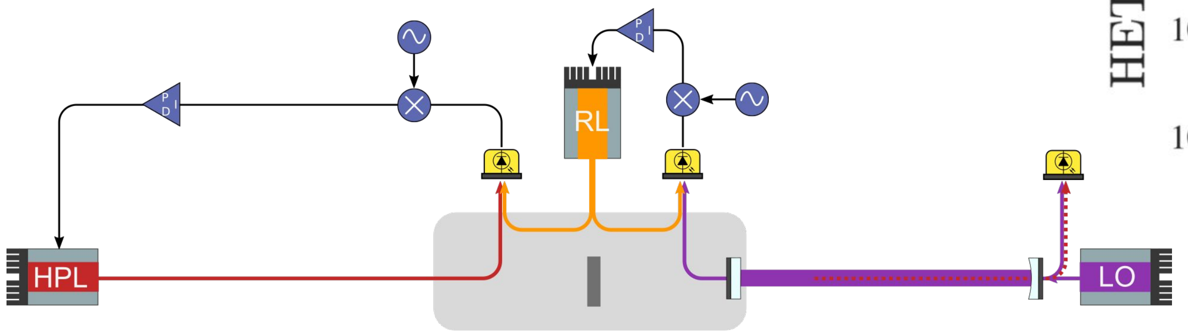
- combine closed shutter data sets

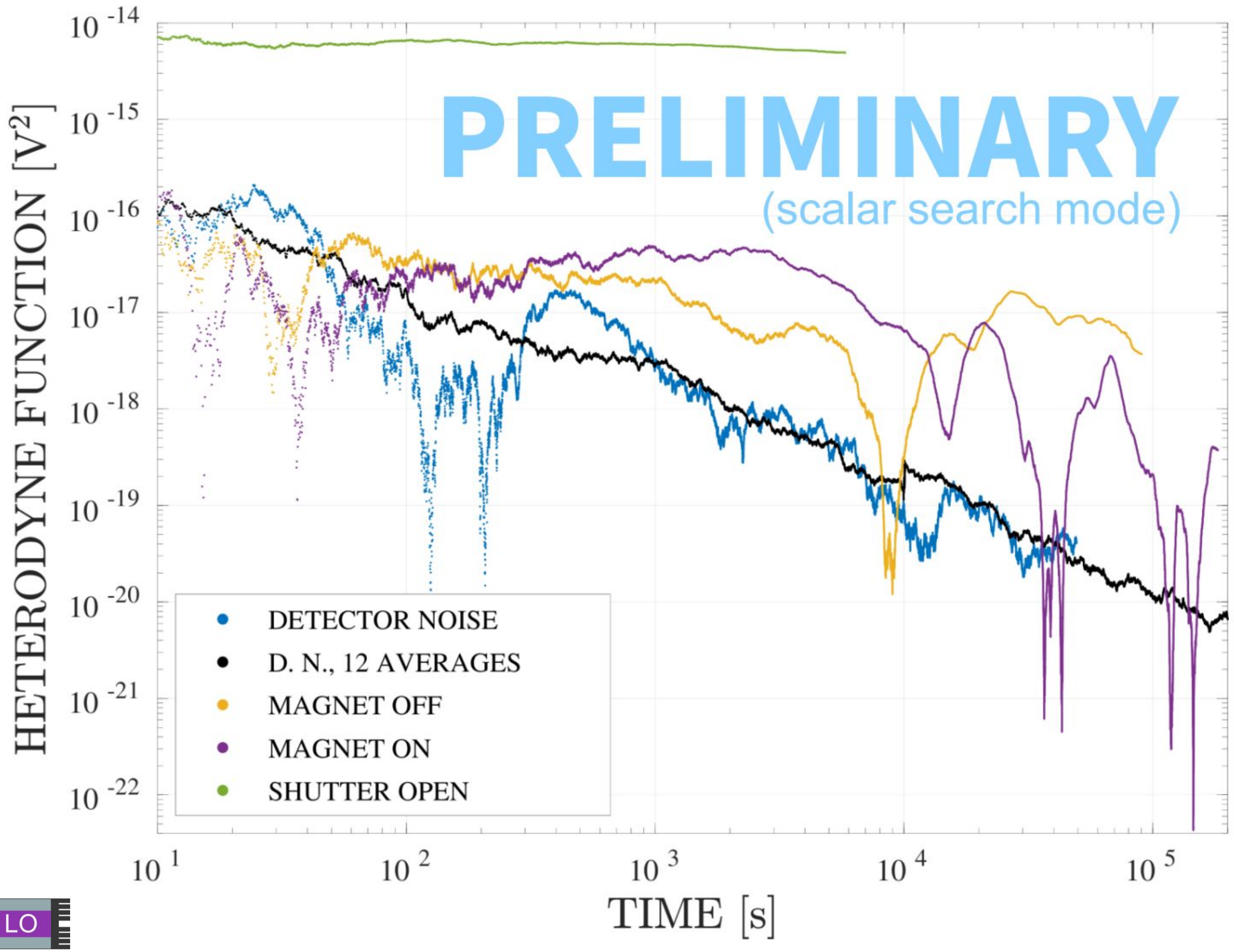
$$n_{\text{signal}} \approx n_{\text{HPL}} \beta_{\text{RC}} \frac{1}{16} (g_{a\gamma\gamma} \cdot B \cdot L)^4$$

Calibrate to a sensitivity in $g_{a\gamma\gamma}$ (GeV^{-1}):

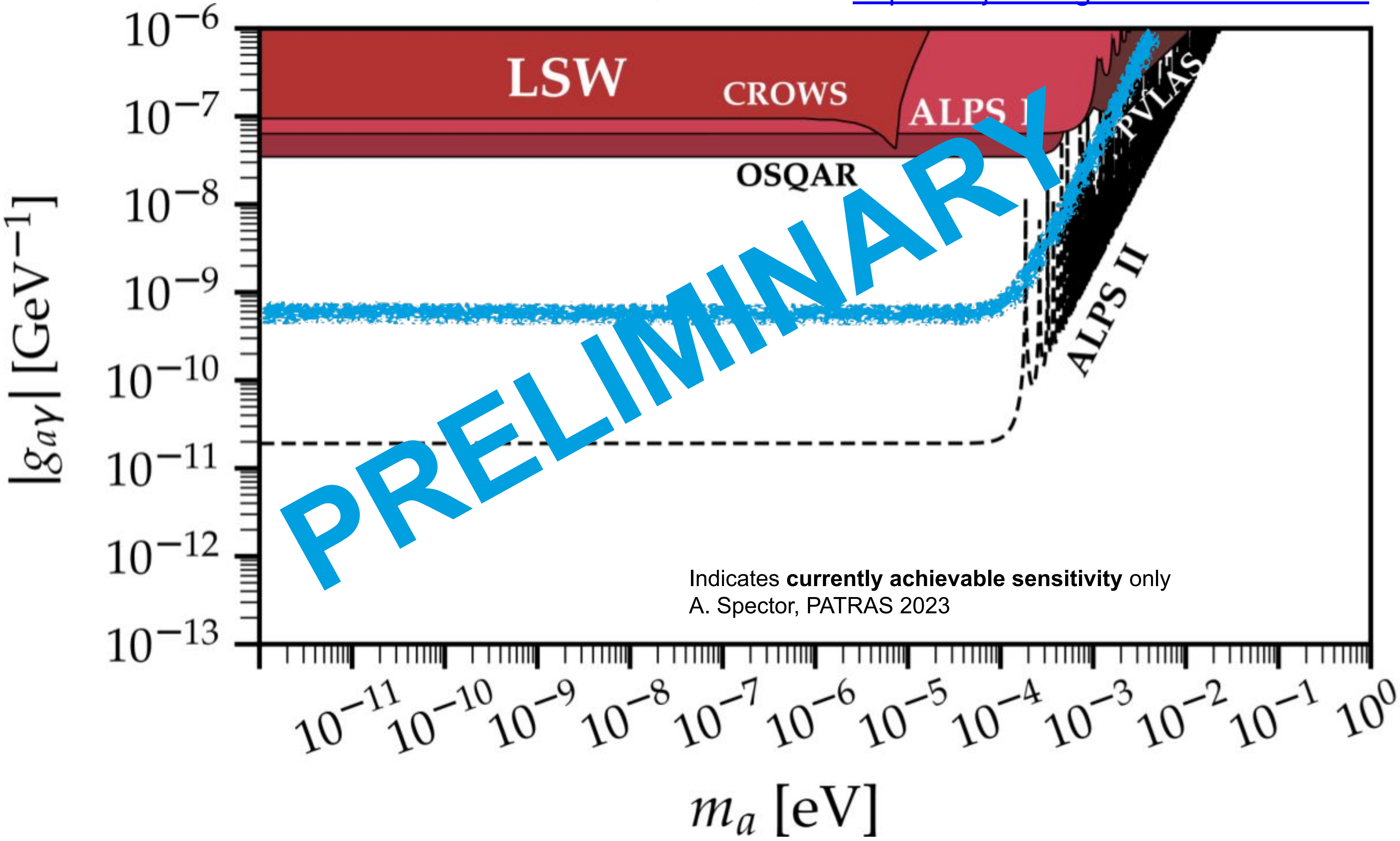
Using measured values for:

- cavity power build-up (β_{RC})
- high power laser power (n_{HPL})
- magnetic field ($B \times L$)





From Ciaran O'Hare: https://cajohare.github.io/AxionLimits/



On the horizon …

Preparations for full Initial Science Run

- full system automation for improved duty cycle
- 1 million seconds of magnets-on data
  - initial assessments indicate stray light has slow phase evolution → longer measurements lower backgrounds

End 2023

Upgraded cavity optics

Early 2024

Production Cavity commissioning

2024

SDU
University of Southern Denmark

UHH

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

JG|U

DESY.

UF
UNIVERSITY of FLORIDA

Collaboration members

ALPS II

Todd Kozlowski
todd.kozlowski@desy.de

Supported by

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DFG

HEISING-SIMONS FOUNDATION

NSF

UKRI
Science and Technology Facilities Council

PRISMA+