Recent Updates on the ALPS II Experiment

Gulden (Joule) Othman for the ALPS II collaboration
University of Hamburg

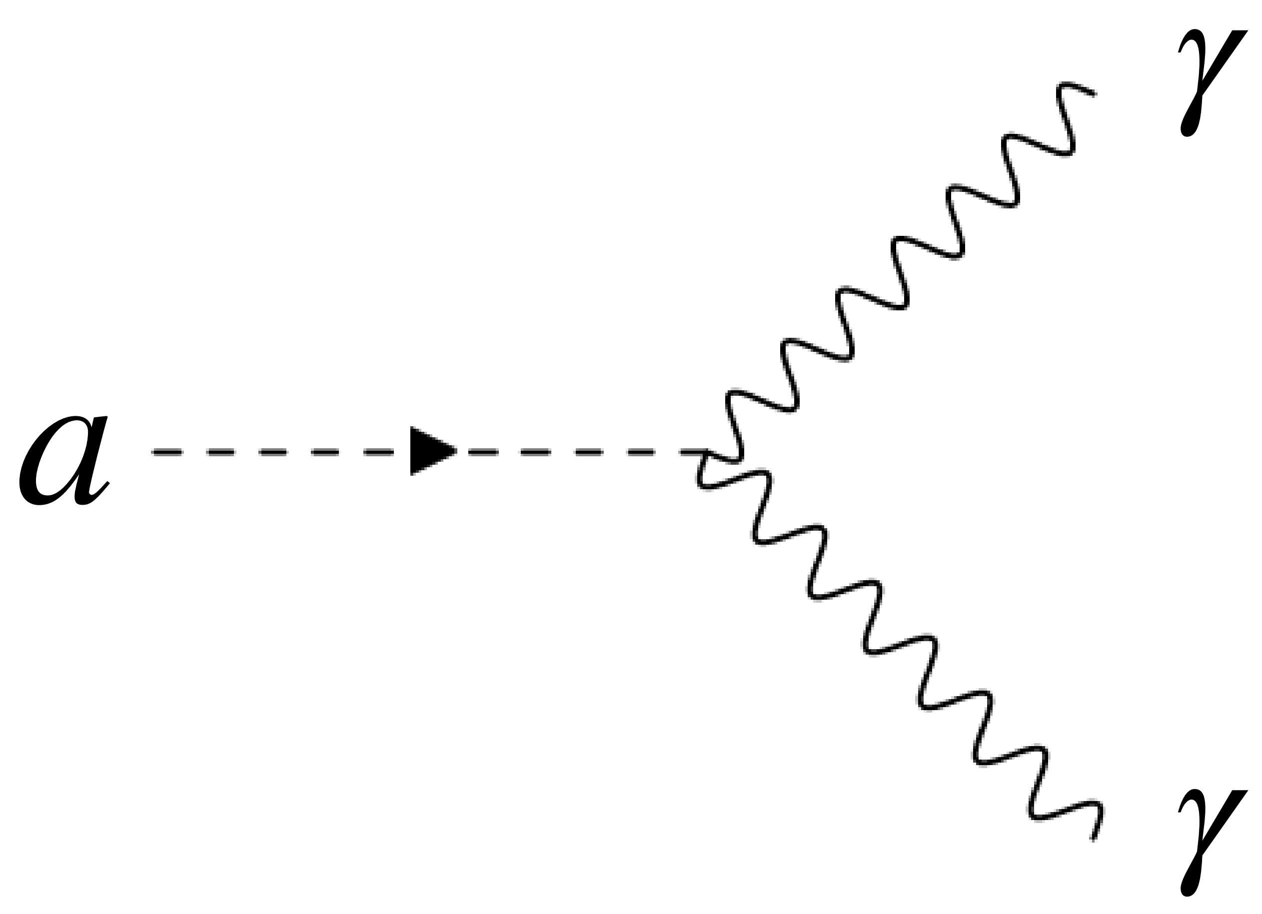
20 March, 2023. DPG Spring Meeting, Dresden

Motivation for Light Shining through Walls (LSW) Experiments

- Extensive observational evidence for the existence of dark matter
  - Axions and Axion-like particles (ALPs) can be dark matter candidates
- LSW experiments can search for axions and ALPs in a model-independent way
- Test astrophysical observations
  - Stellar cooling
  - TeV transparency

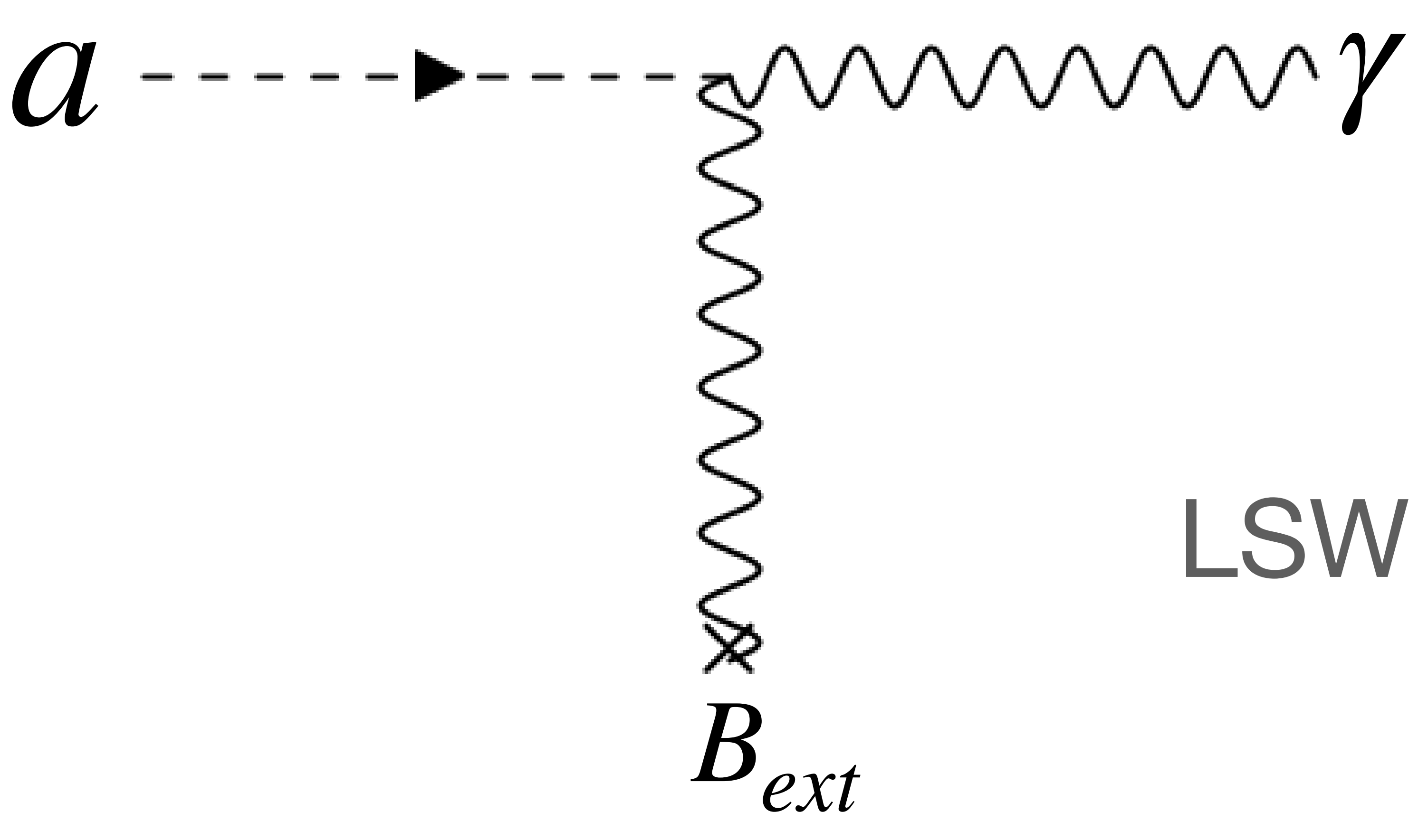
Axion coupling to photons

Axion decay



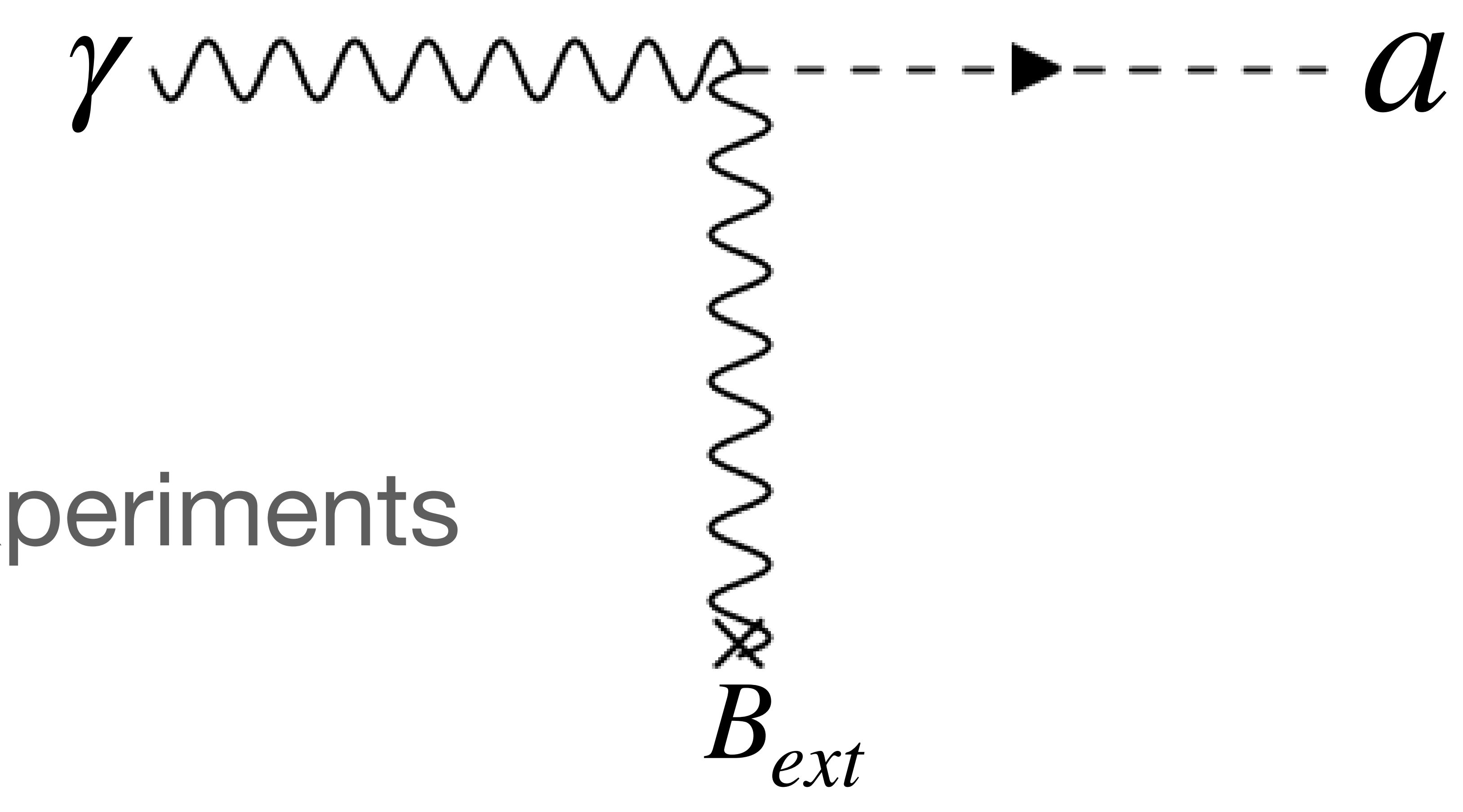
Astrophysics and cosmology

Sikivie effect



Haloscopes
Helioscopes

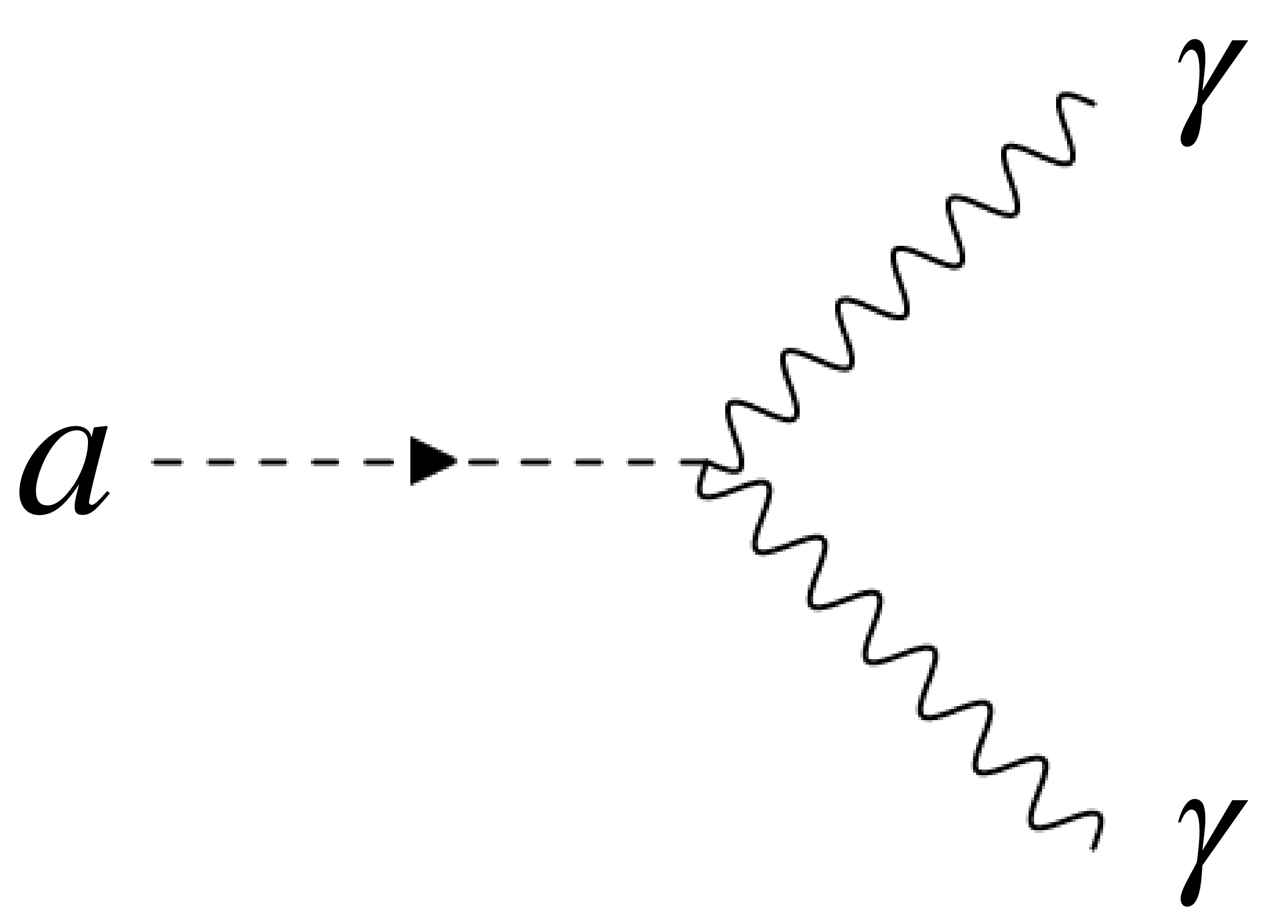
Inverse Sikivie effect



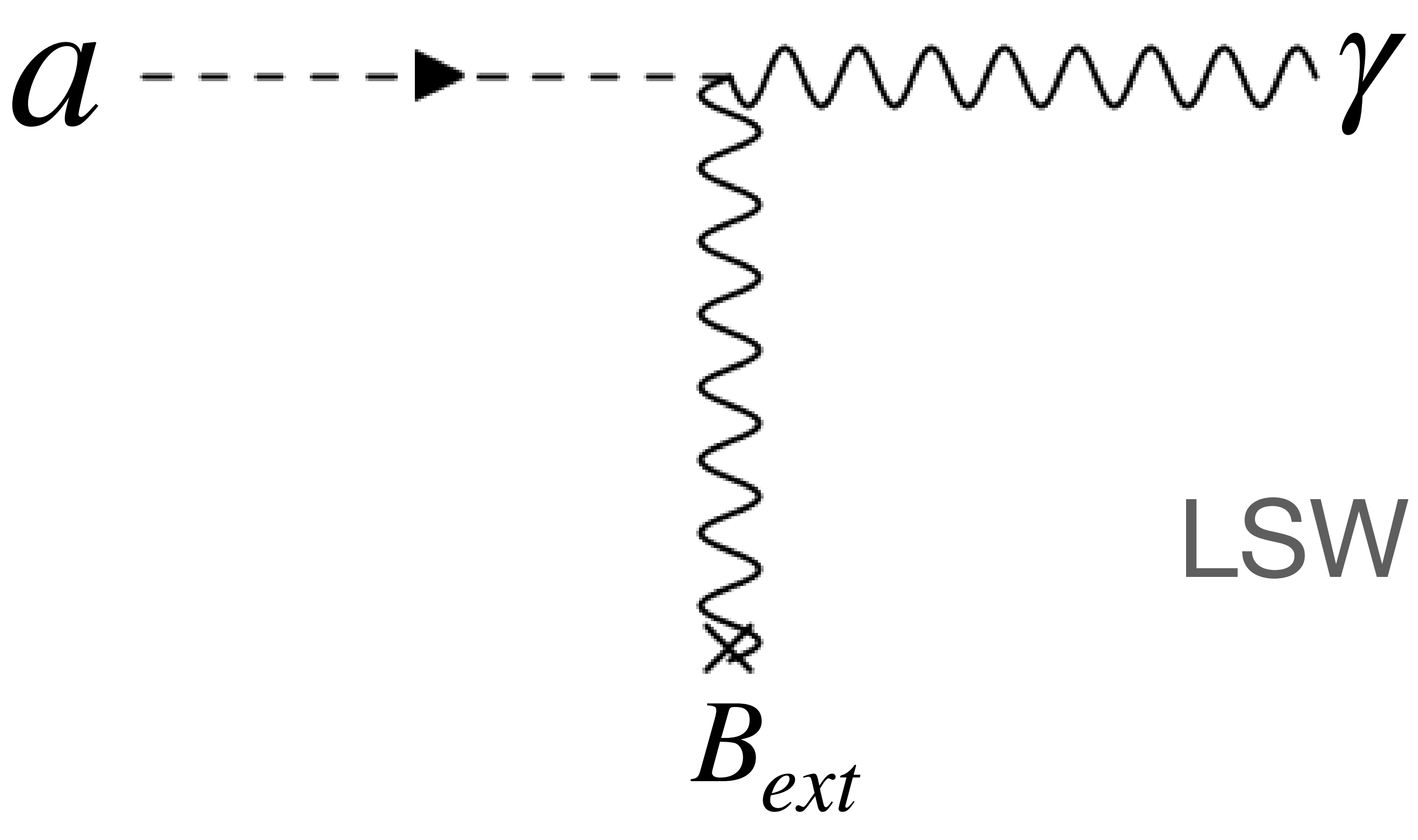
LSW Experiments

Axion coupling to photons

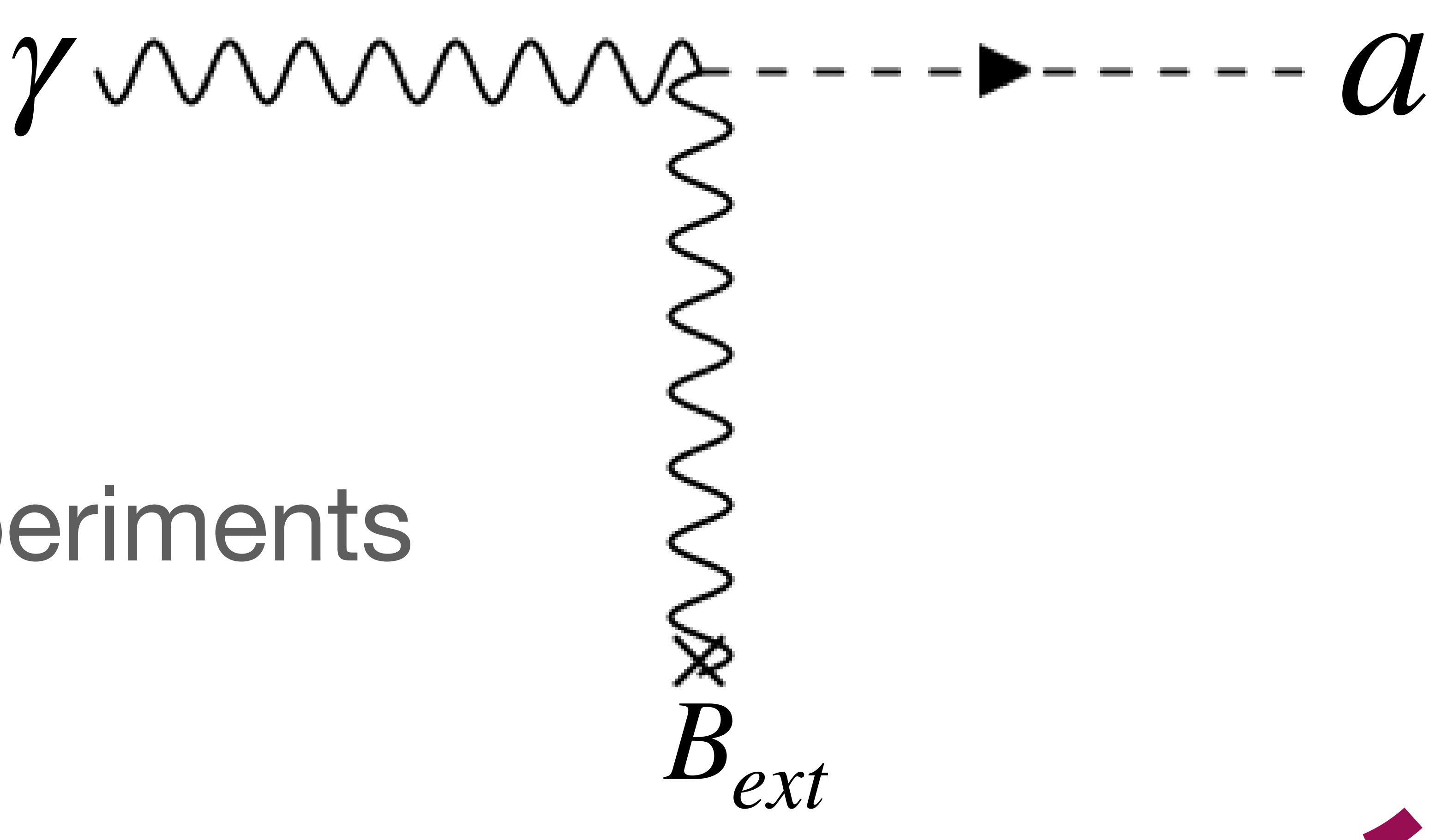
Axion decay



Sikivie effect



Inverse Sikivie effect

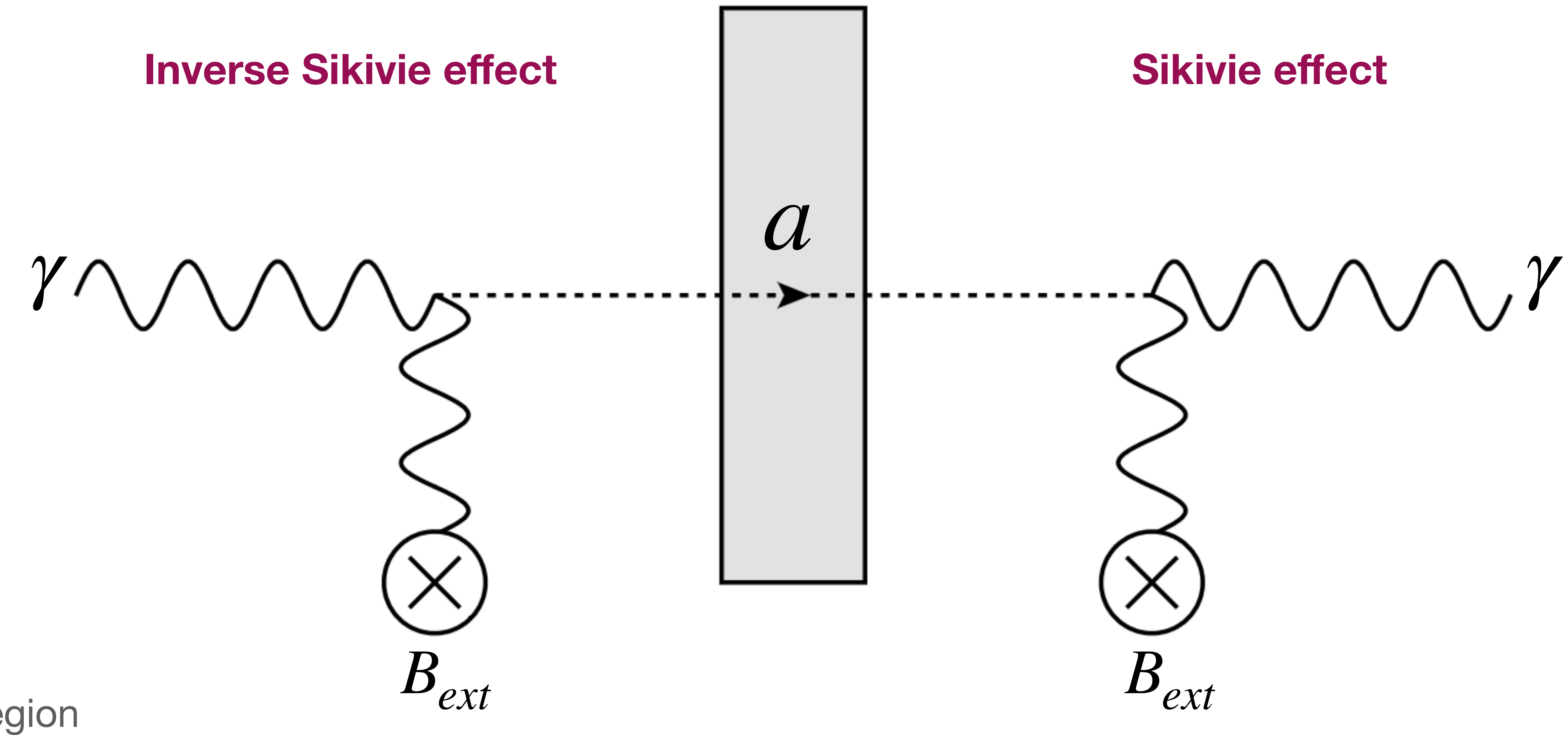


LSW Experiments

Astrophysics and cosmology

Haloscopes
Helioscopes

Light Shining Through Walls

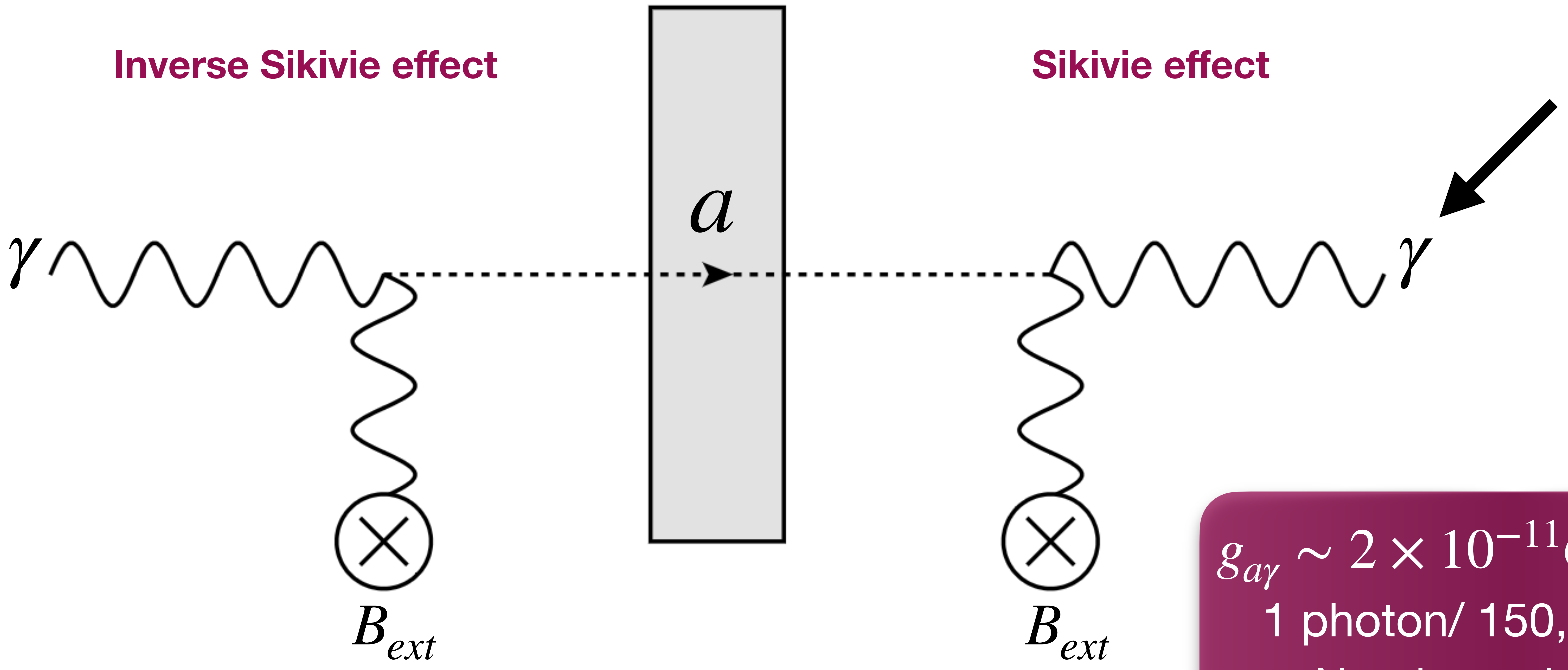


B → Magnetic field strength
L → Length in magnetic field region

$$P(\gamma \rightarrow a \rightarrow \gamma) \sim \left(\frac{g_{a\gamma}BL}{2}\right)^4$$

Because you have to convert twice, take an extra hit in $g_{a\gamma}$

Light Shining Through Walls



$\mathscr{P}_i \rightarrow$ laser power
$\omega \rightarrow$ laser energy
$\tau \rightarrow$ measurement time

$$N_\gamma = \frac{1}{16}(g_{a\gamma}BL)^4\frac{\mathscr{P}_i}{\omega}\tau$$

$g_{a\gamma} \sim 2 \times 10^{-11} GeV^{-1}$
1 photon/ 150,000 years!
$\rightarrow$Need to enhance signal!

$B \sim 5.3\ T$
$L \sim 2 \times 100\ m$
$P \sim 30\ W$

Any Light Particle Search (ALPS) II

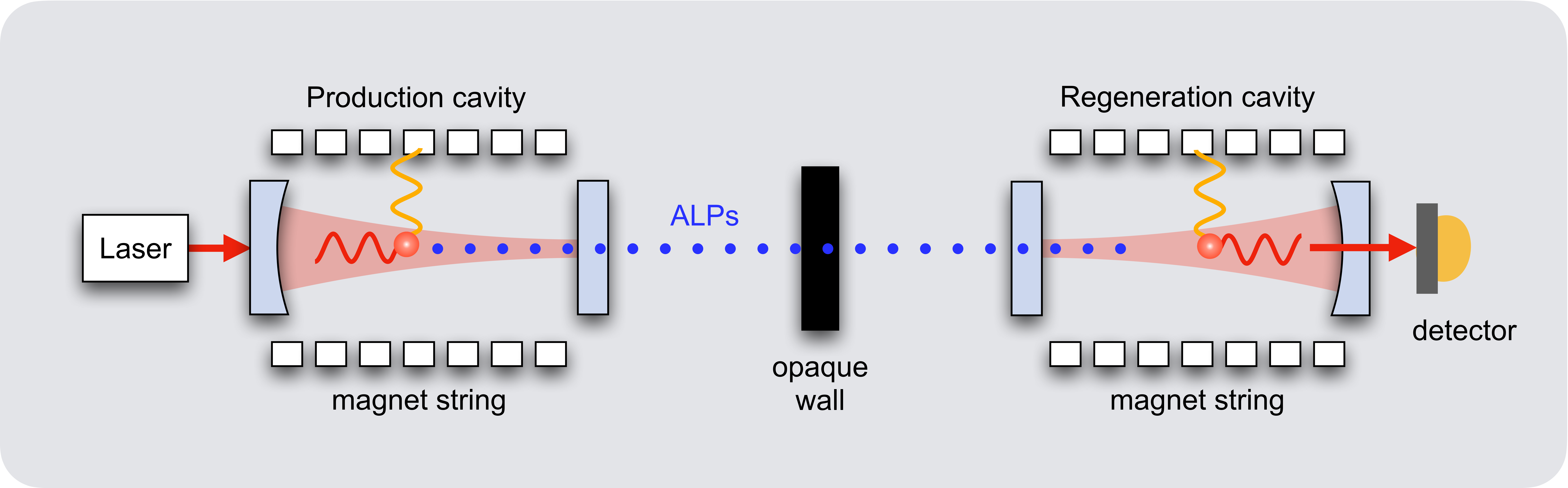
Any Light Particle Search (ALPS) II

DESY, Hamburg

7 institutions, ~30 members

Germany, US, UK, Denmark

Any Light Particle Search (ALPS) II



Graphic from Katharina-Sophie Isleif

$\beta_{P(R)} \rightarrow$ Power buildup in production (regeneration)

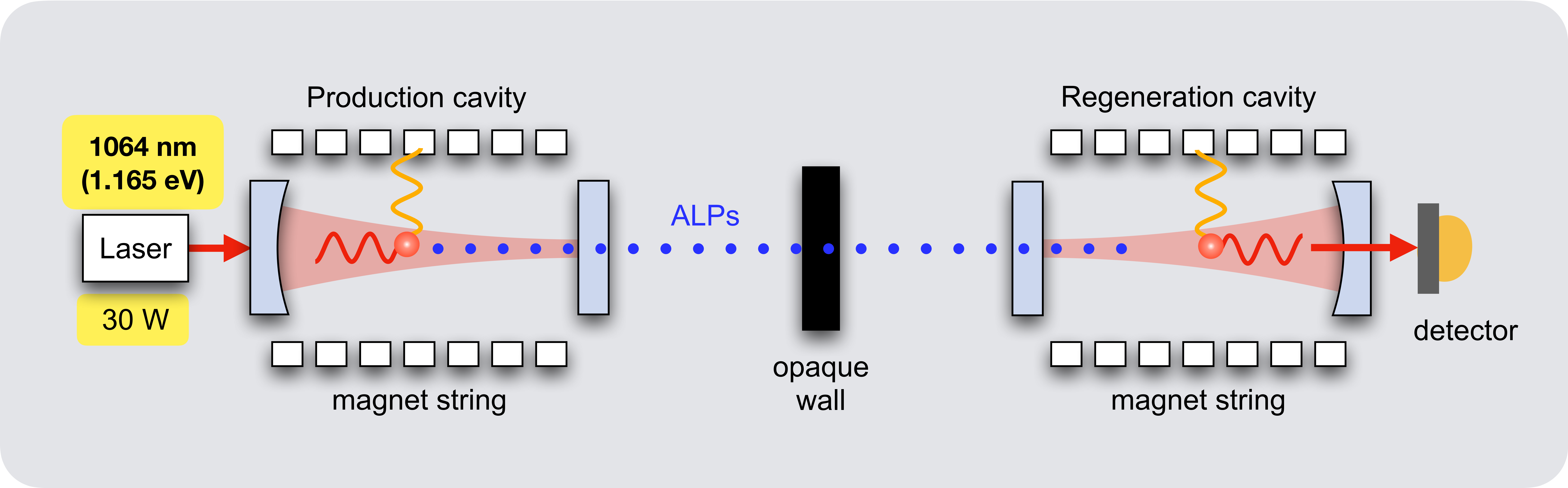
$\mathscr{P}_i \rightarrow$ laser power

$\omega \rightarrow$ laser energy

$\tau \rightarrow$ measurement time

$$N_\gamma = \frac{1}{16}(g_{a\gamma}BL)^4 \frac{\mathscr{P}_i}{\omega} \beta_P \beta_R \tau$$

Any Light Particle Search (ALPS) II



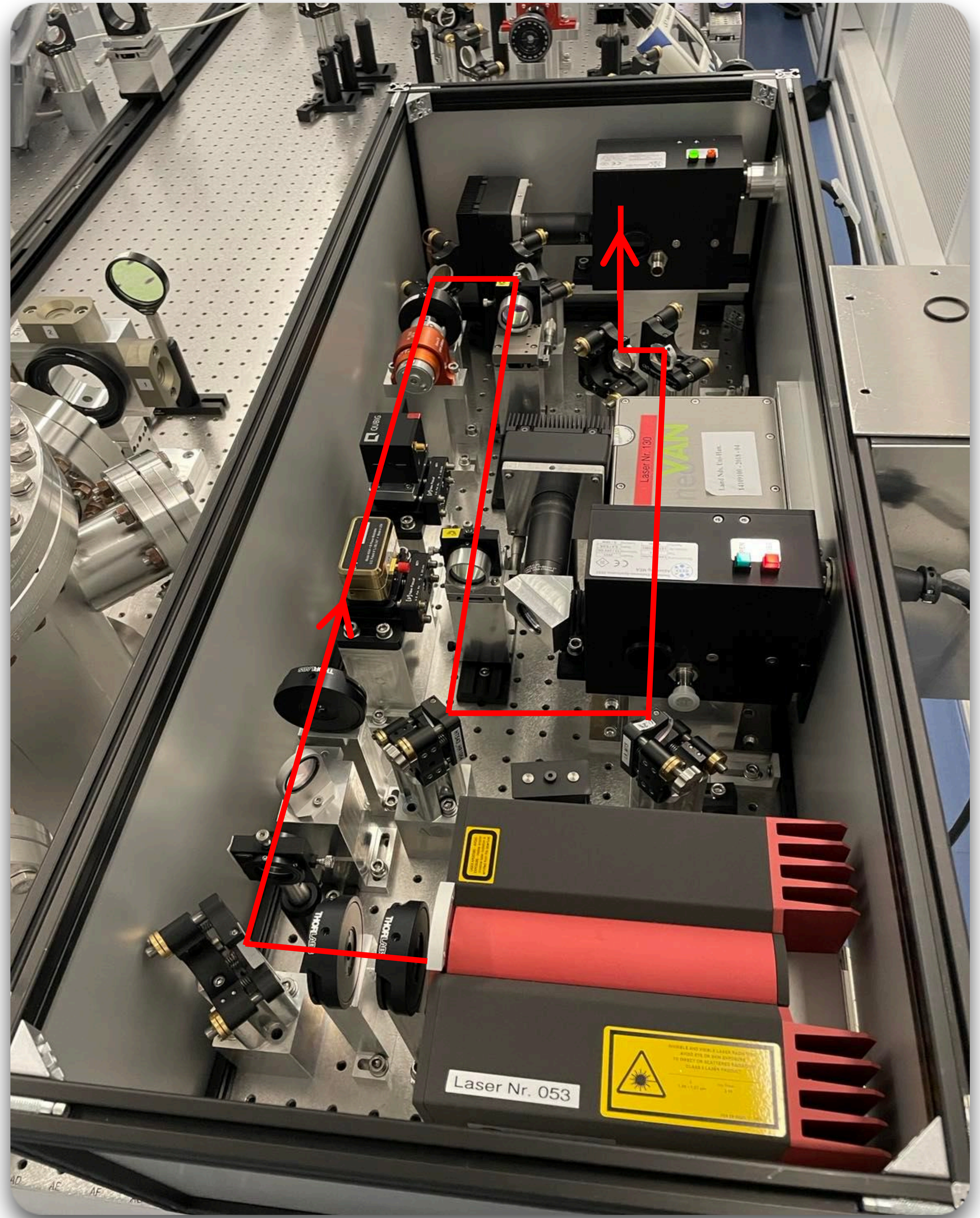
Graphic from Katharina-Sophie Isleif

$$N_\gamma = \frac{1}{16}(g_{a\gamma}BL)^4 \frac{\mathscr{P}_i}{\omega}\beta_P\beta_R\tau$$

High-Powered Laser

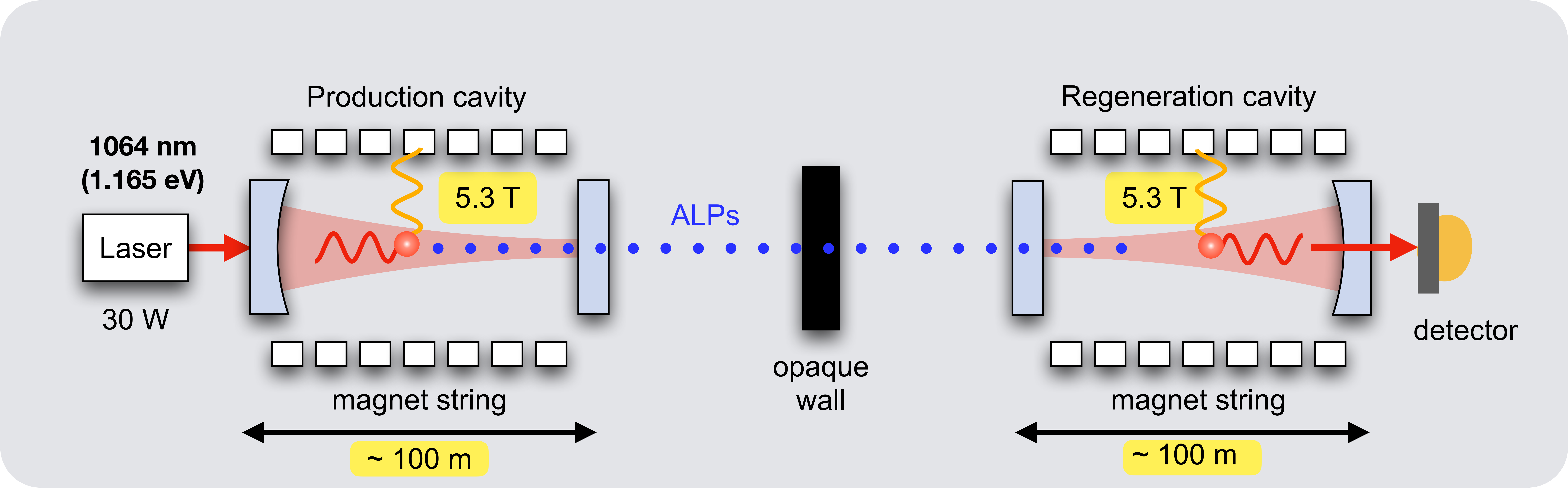
Amplified Non Planar Ring Oscillator (NPRO)

- Demonstrated over 60 W of power at 1064 nm
- > 90% of power in fundamental mode



Slide from Aaron Spector

Any Light Particle Search (ALPS) II



Graphic from Katharina-Sophie Isleif

- Using 24 straightened HERA magnets

$$N_\gamma = \frac{1}{16}(g_{a\gamma}BL)^4 \frac{\mathscr{P}_i}{\omega} \beta_P \beta_R \tau$$

Magnet Strings

- 24 HERA dipole magnets
- October 2020: Magnets installed and aligned
- March 2022: Magnet strings run successfully at full current
    - 5.7 kA, 5.3 T

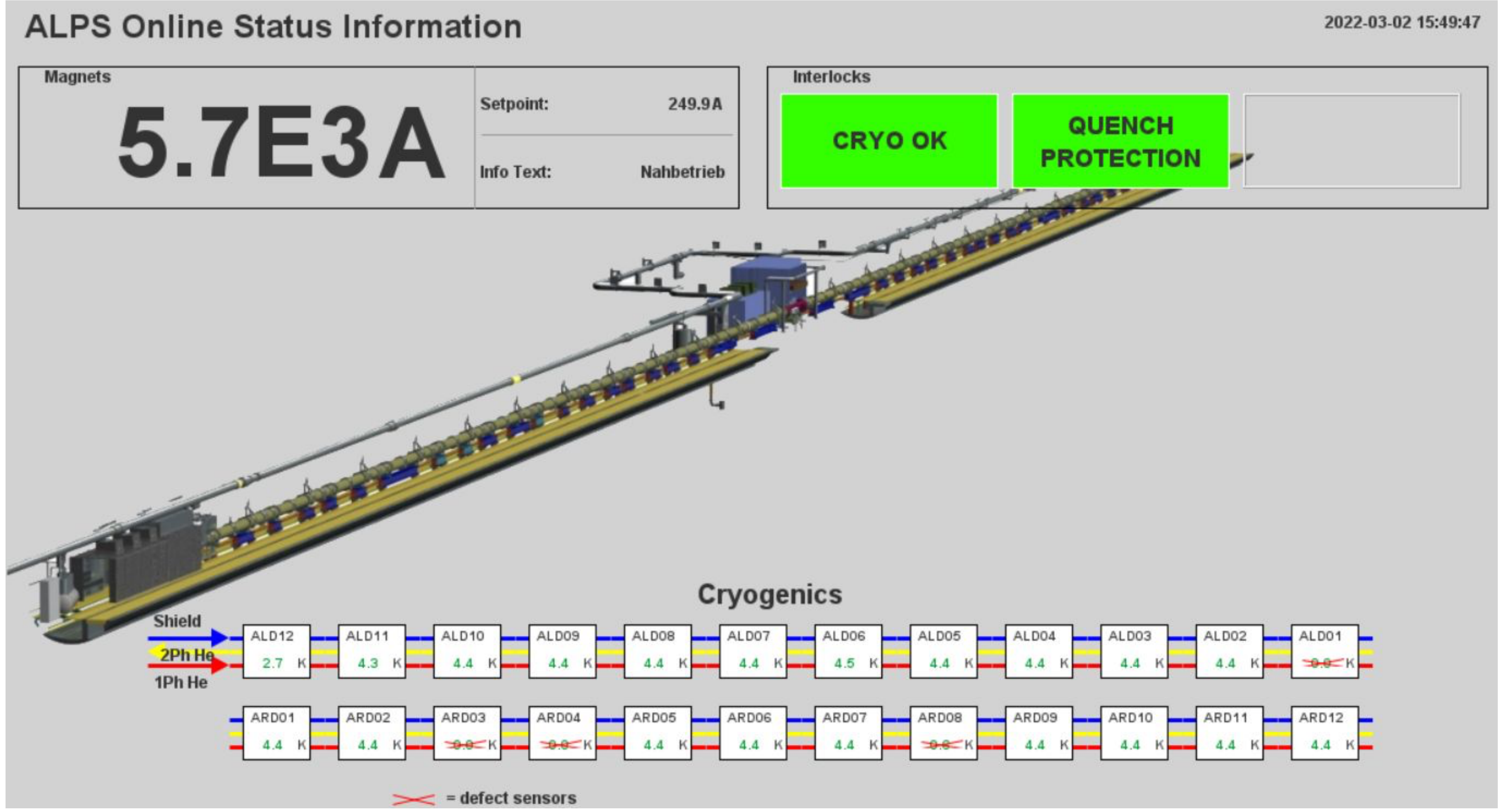
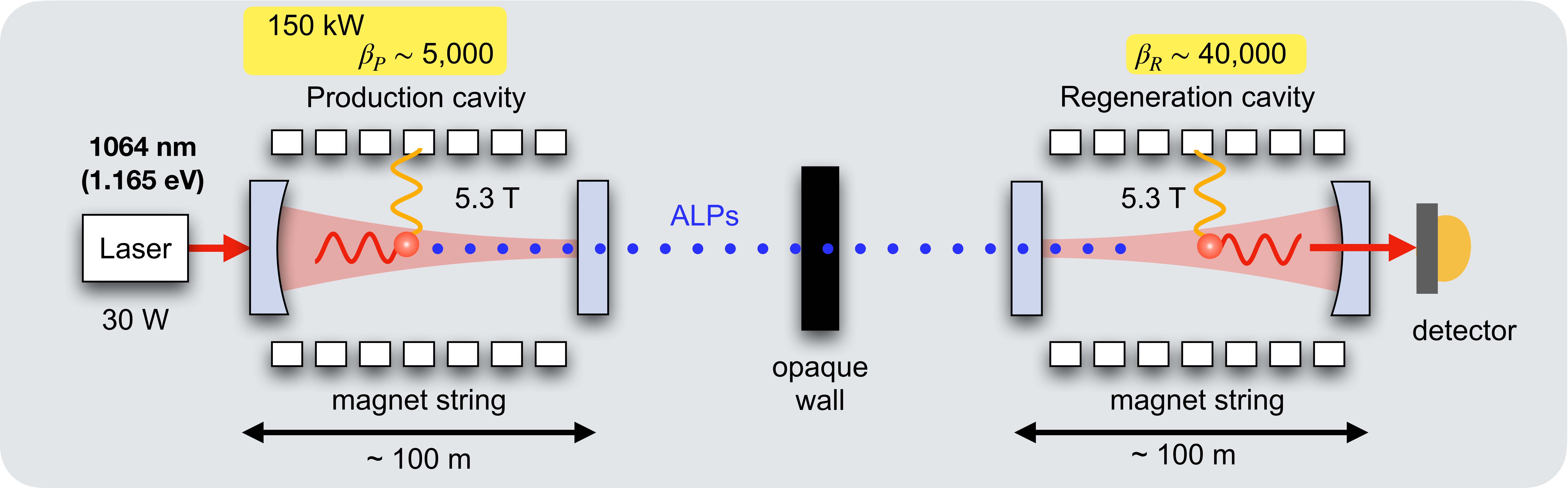


Photo by Heiner Müller-Elsner

Any Light Particle Search (ALPS) II



Graphic from Katharina-Sophie Isleif

- Using 24 straightened HERA magnets
- Fabry-Perot resonators in production *and* regeneration region

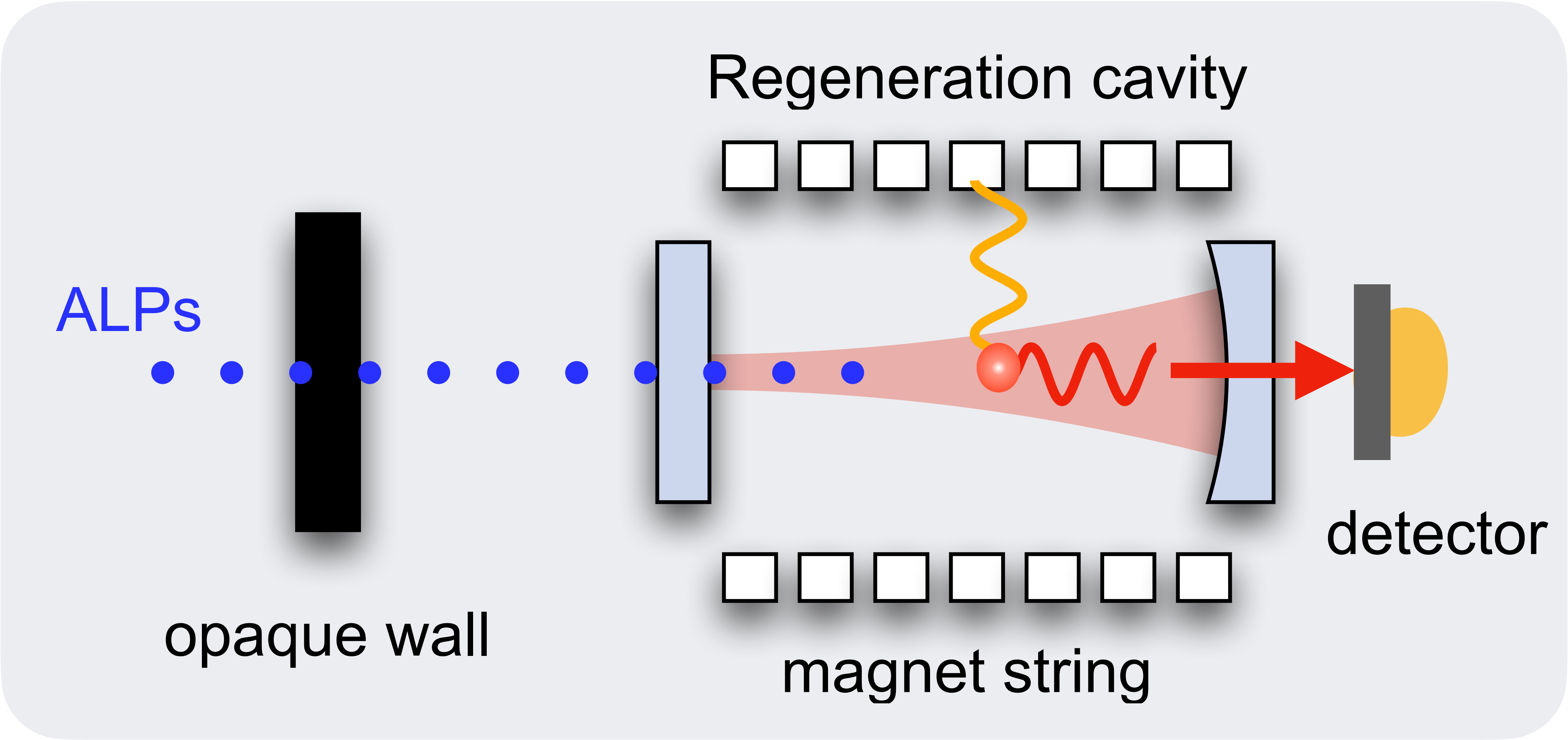
$$N_\gamma = \frac{1}{16}(g_{a\gamma}BL)^4 \frac{\mathscr{P}_i}{\omega} \beta_P \beta_R \tau$$

Regeneration Cavity (RC)

Talk by Aaron Spector
IDM 2022

Longest storage time Fabry Perot cavity ever!

- Length: 124.6m, FSR: 1.22 MHz
- Storage time: 6.75 ms (*world record*)
- Power build up factor: β ~ 7000



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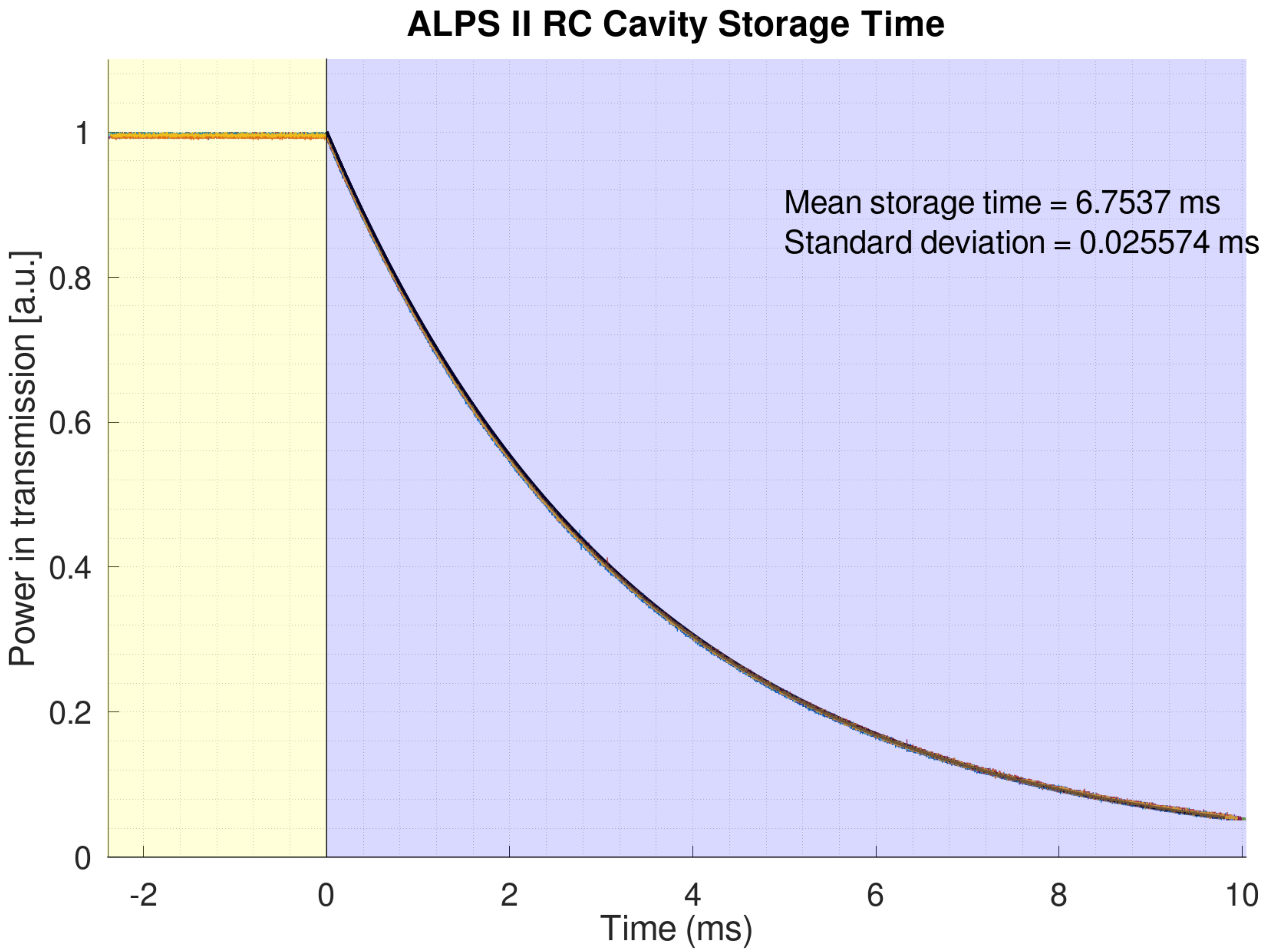

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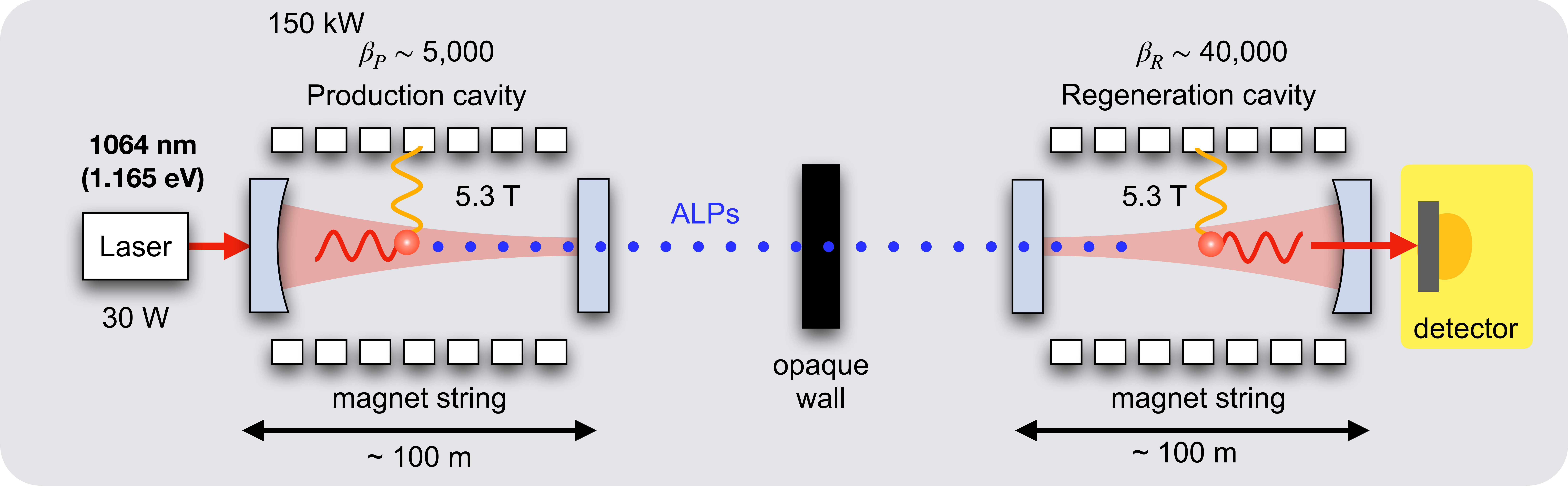


Graphic from Katharina-Sophie Isleif

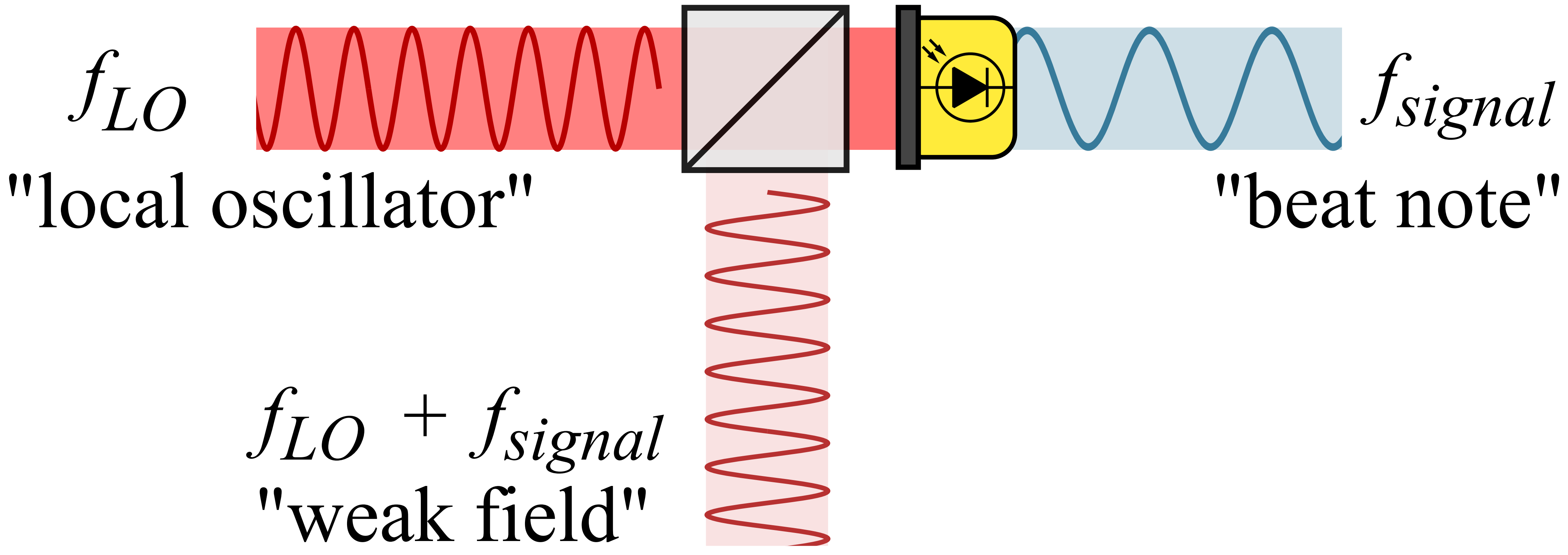
- Using 24 straightened HERA magnets
- Fabry-Perot resonators in production *and* regeneration region
- 150 kW → 10^{-24} W (~1 photon/day)

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

$$N_\gamma = \frac{1}{16}(g_{a\gamma}BL)^4 \frac{\mathscr{P}_i}{\omega} \beta_P \beta_R \tau$$

ALPS II- Heterodyne

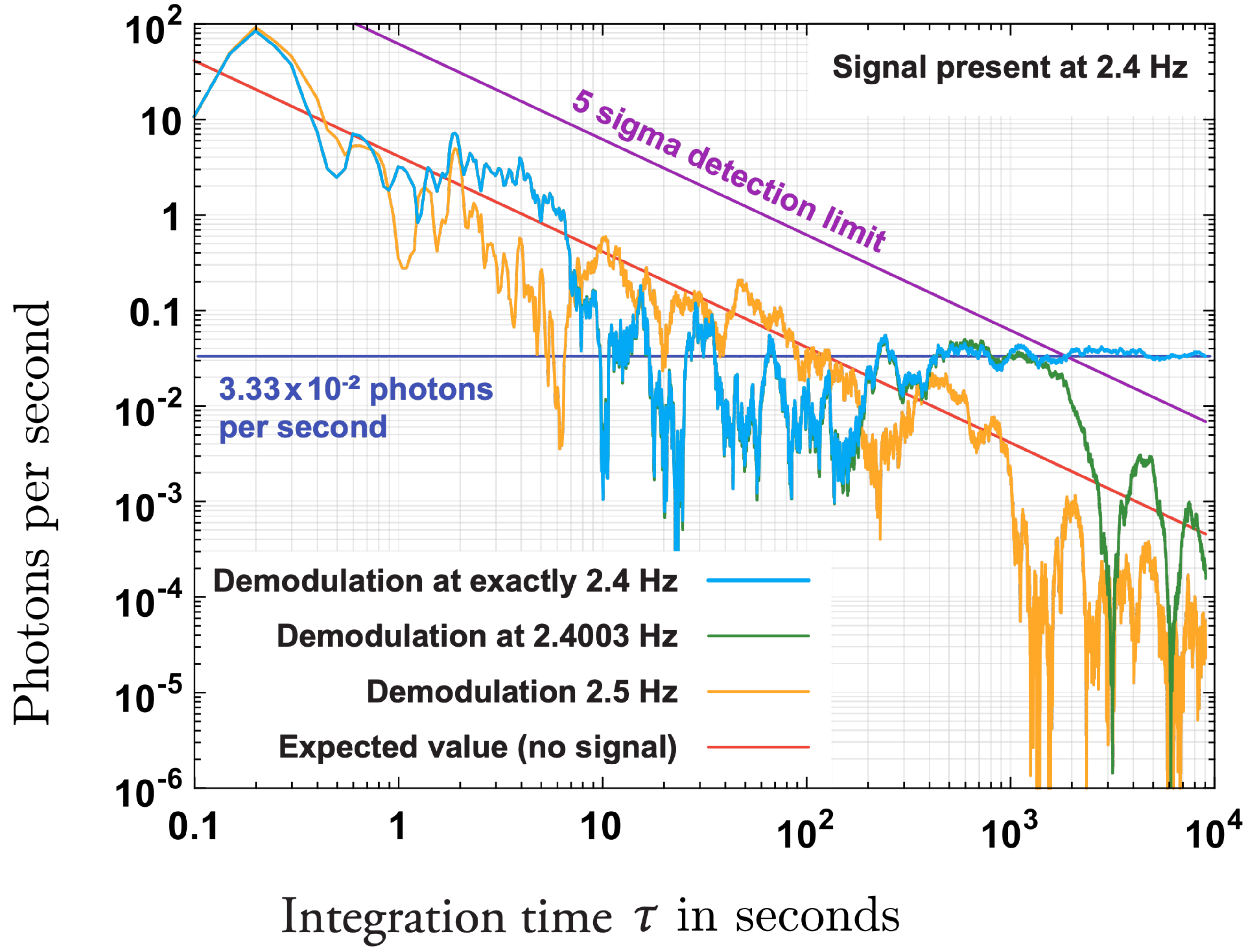
Looking for 5·10^{-24} W @ 1064 nm



Option 1: heterodyne sensing

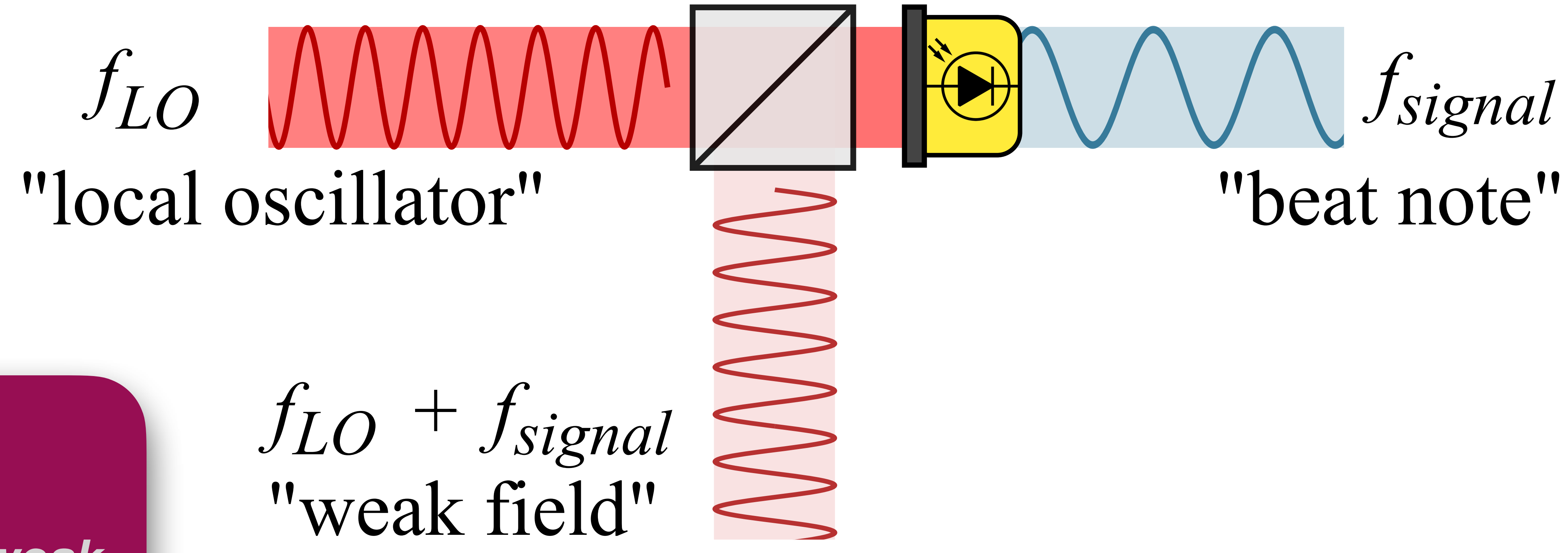
- Mix weak signal with a frequency f shifted local oscillator ➔ beat note signal
- Detection of a photon flux corresponding to 5·10^{-21} W demonstrated.
- Sensitivity of 10^{-24} W demonstrated.
- First detecting scheme to be used in ALPS II

"Coherent detection of ultraweak electromagnetic fields", Z. Bush et al., Phys. Rev. D 99, 022001 (2019)



ALPS II- Heterodyne

Looking for $5 \cdot 10^{-24}$ W @ 1064 nm



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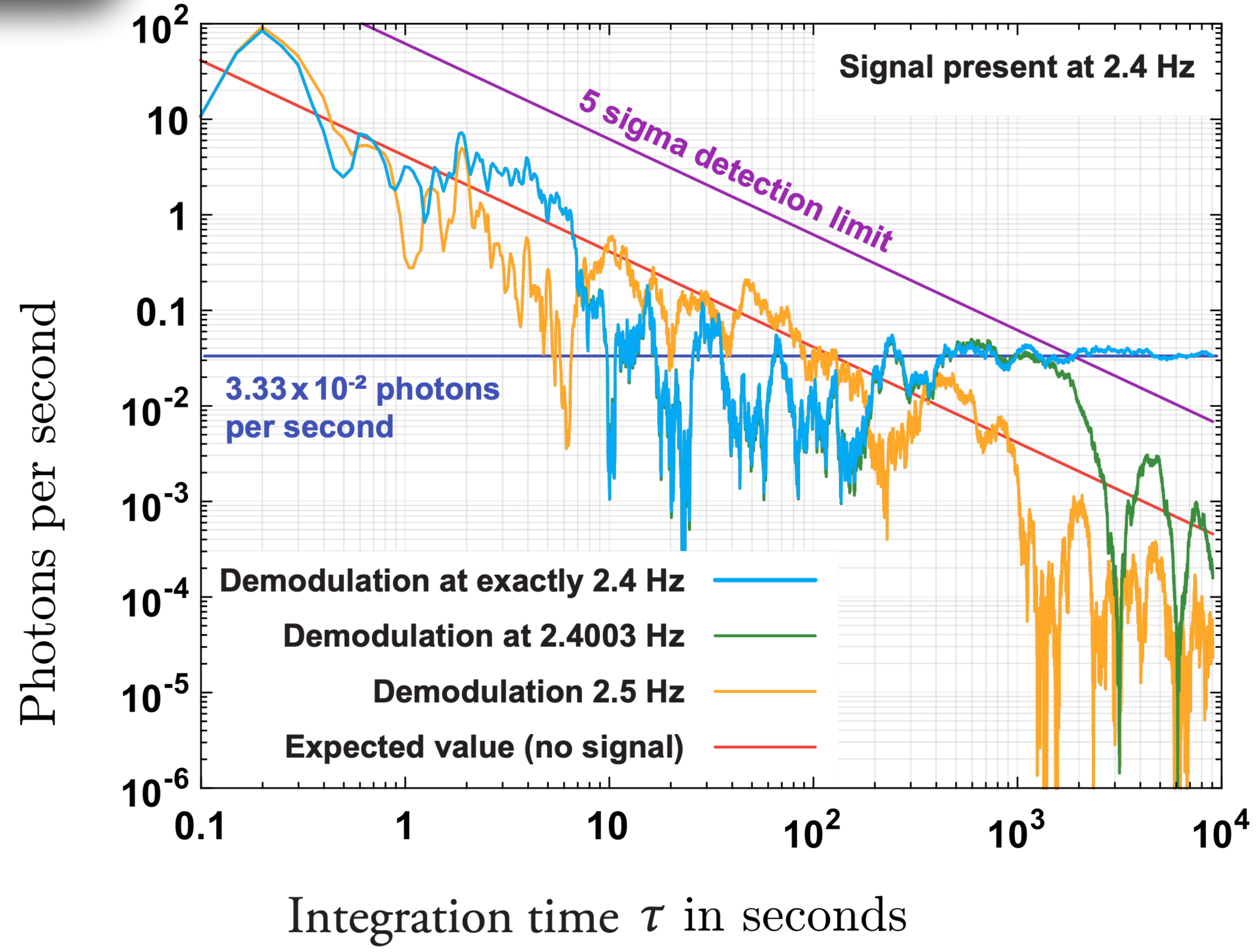
Thursday: T 117.5
Isabella Oceano
Heterodyne detection of weak fields in ALPS II



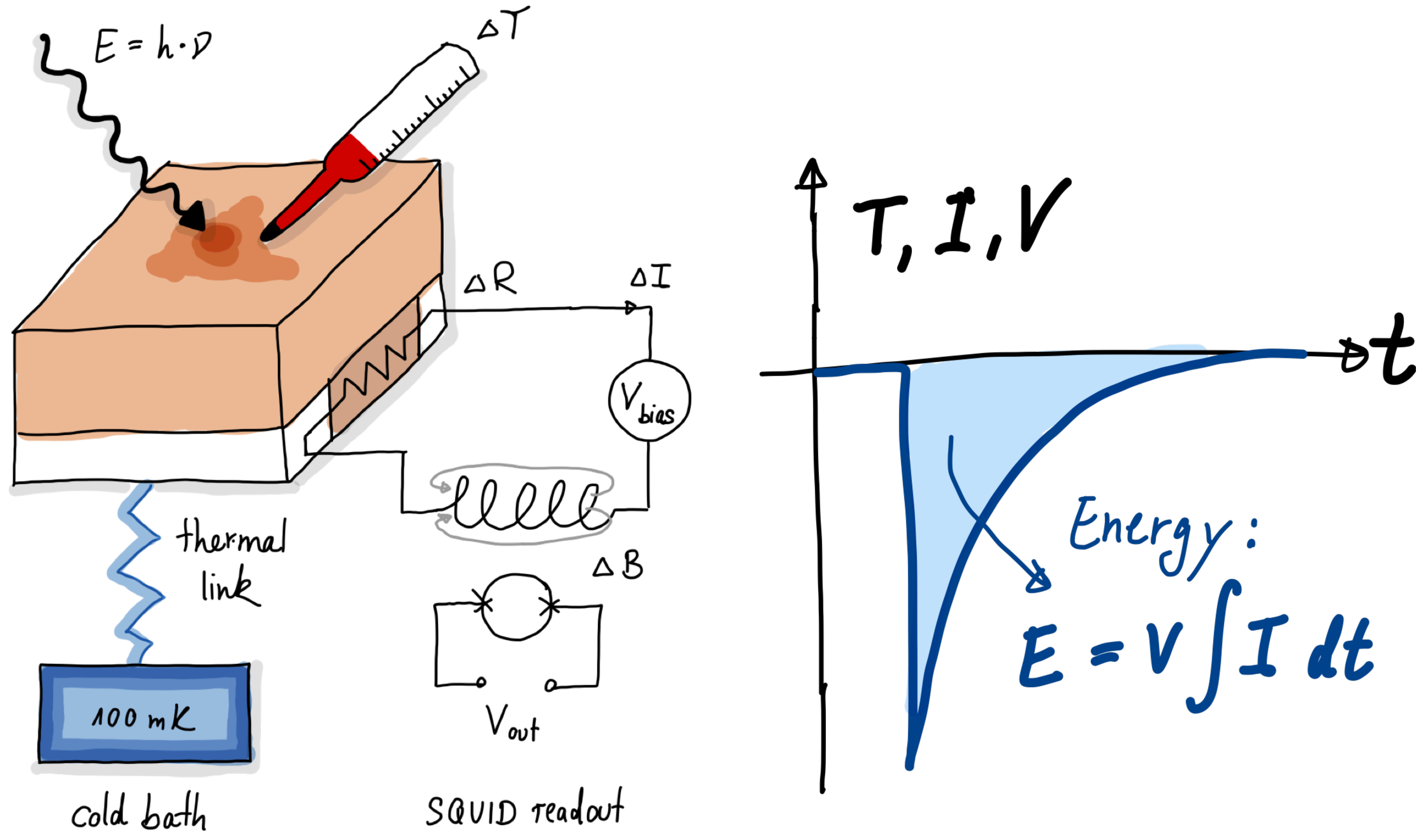
"Coherent detection of ultraweak electromagnetic fields", Z. Bush et al., Phys. Rev. D 99, 022001 (2019)

ALPS II- Transition Edge Sensor

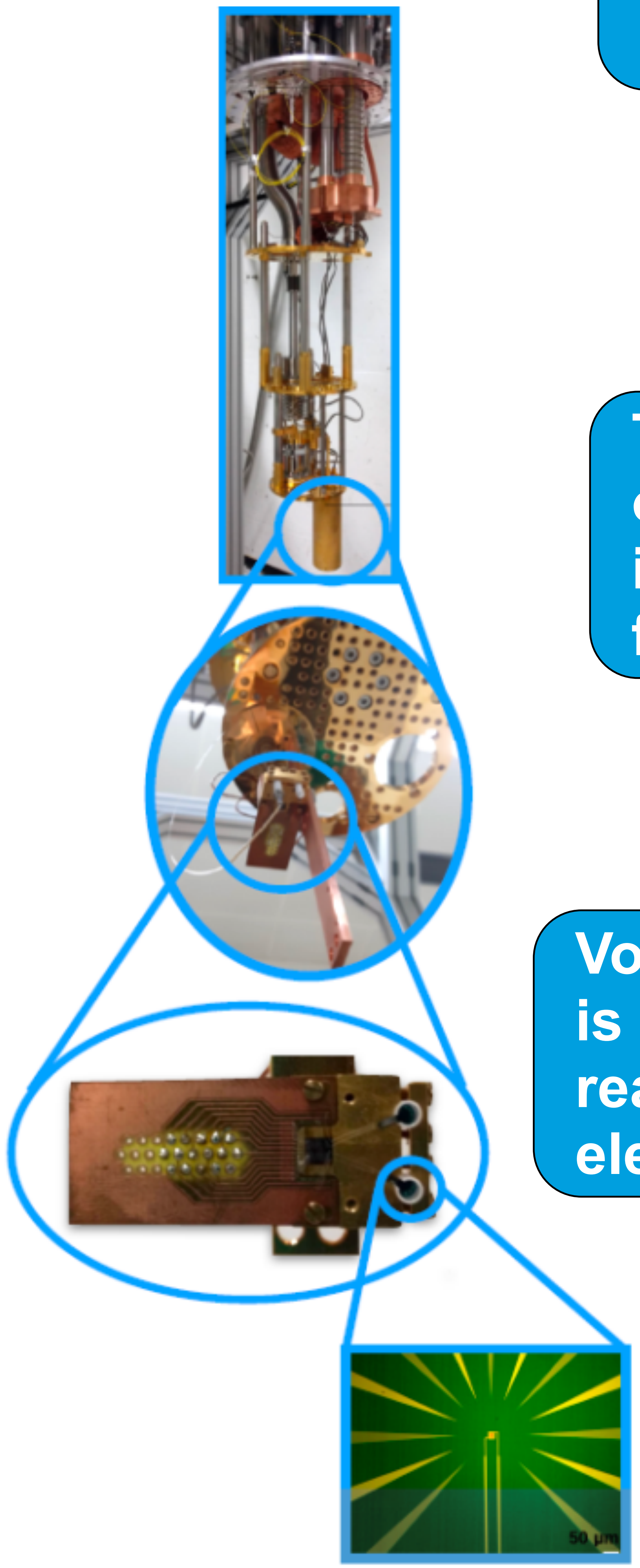
Looking for $5 \cdot 10^{-24}$ W @ 1064 nm

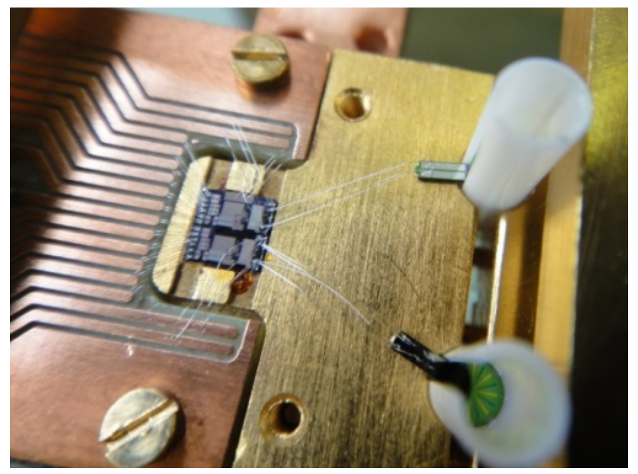
Option 2: photon counting

- Using a superconducting transition edge sensor (TES) operated at about 100 mK.



Low dark counts ($6.9^{+5.18}_{-2.93} \cdot 10^{-6}$Hz, 95% CL) shown





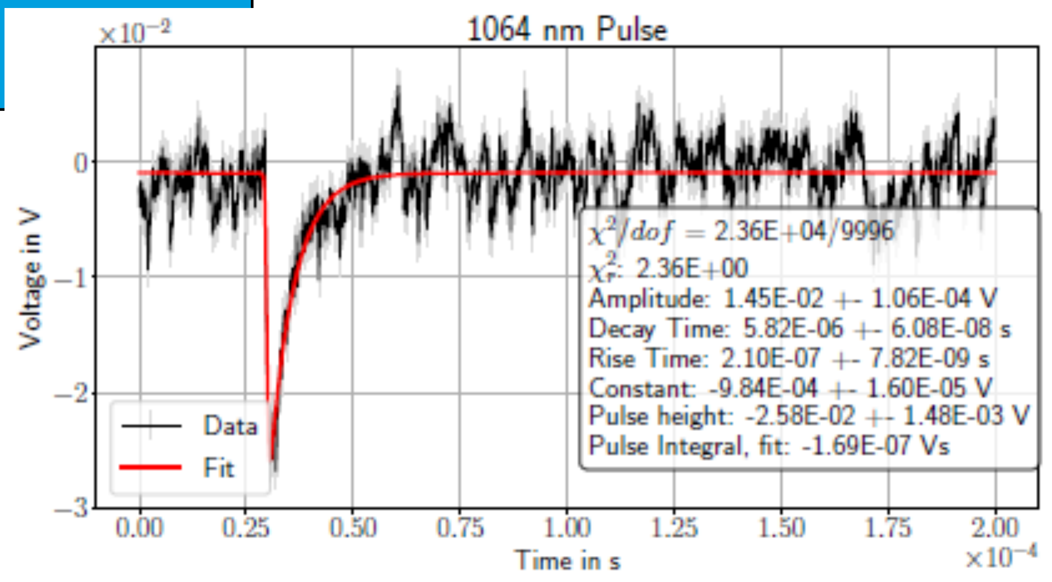
TES chip within the transition region at critical temperature

Single 1064 nm photon heats TES by ~100μK

The resistance of the TES chip increases by a few Ohm

The current changes by about 100 nA and is read out by SQUIDS

Voltage change is measured by readout electronics



Slide from Friederike Januschek

ALPS II- Transition Edge Sensor

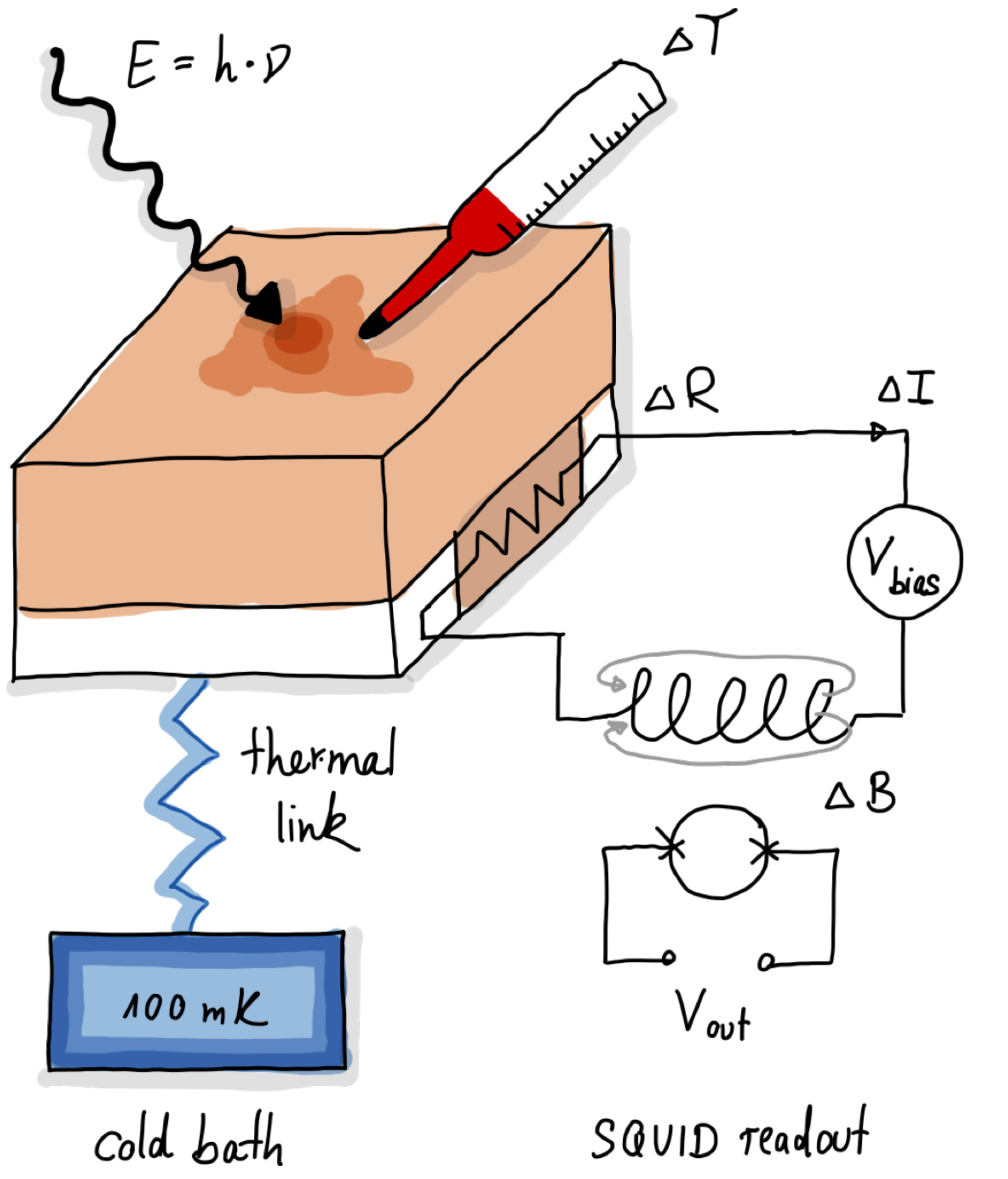
Looking for $5 \cdot 10^{-24}$ W @ 1064 nm

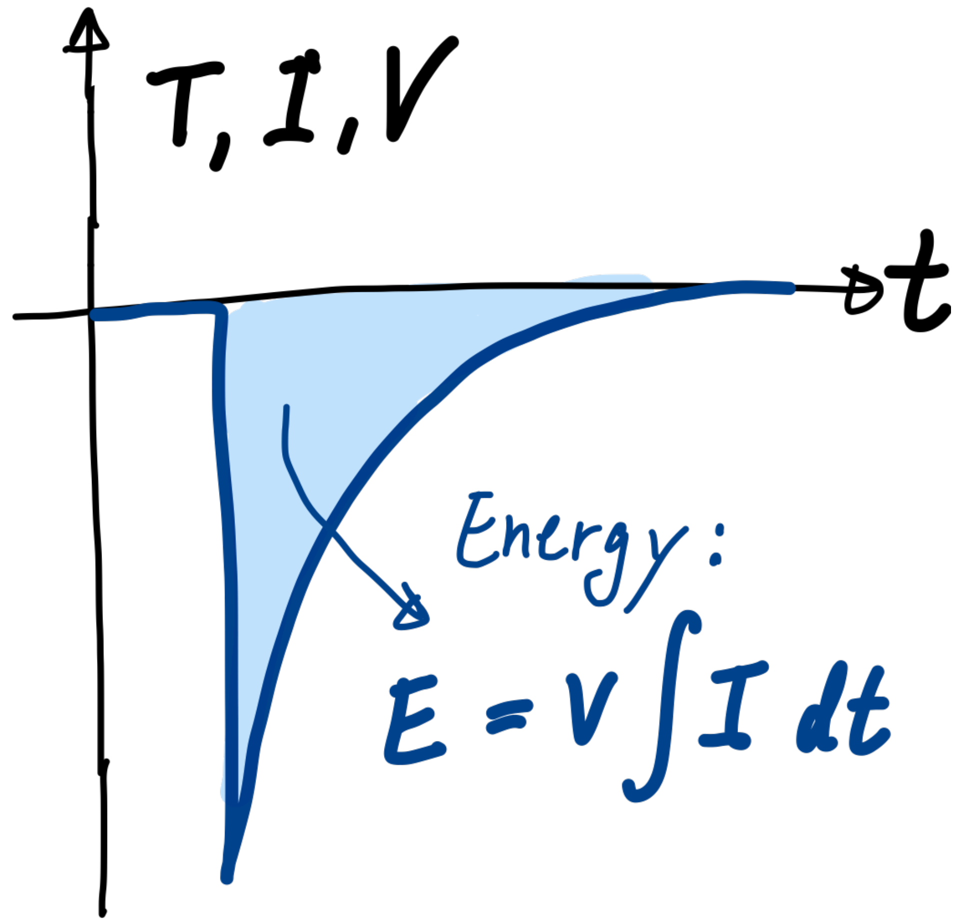
Option 2: photon counting

- Using a superconducting transition edge sensor (TES) operated at about 100 mK.

Tuesday: T 27.5
José Alejandro Rubiera Gimeno
A TES for ALPS II - Status and Prospects

Thursday: T 117.4
Christina Schwemmbauer
Further dark matter searches using ALPS II's TES detector





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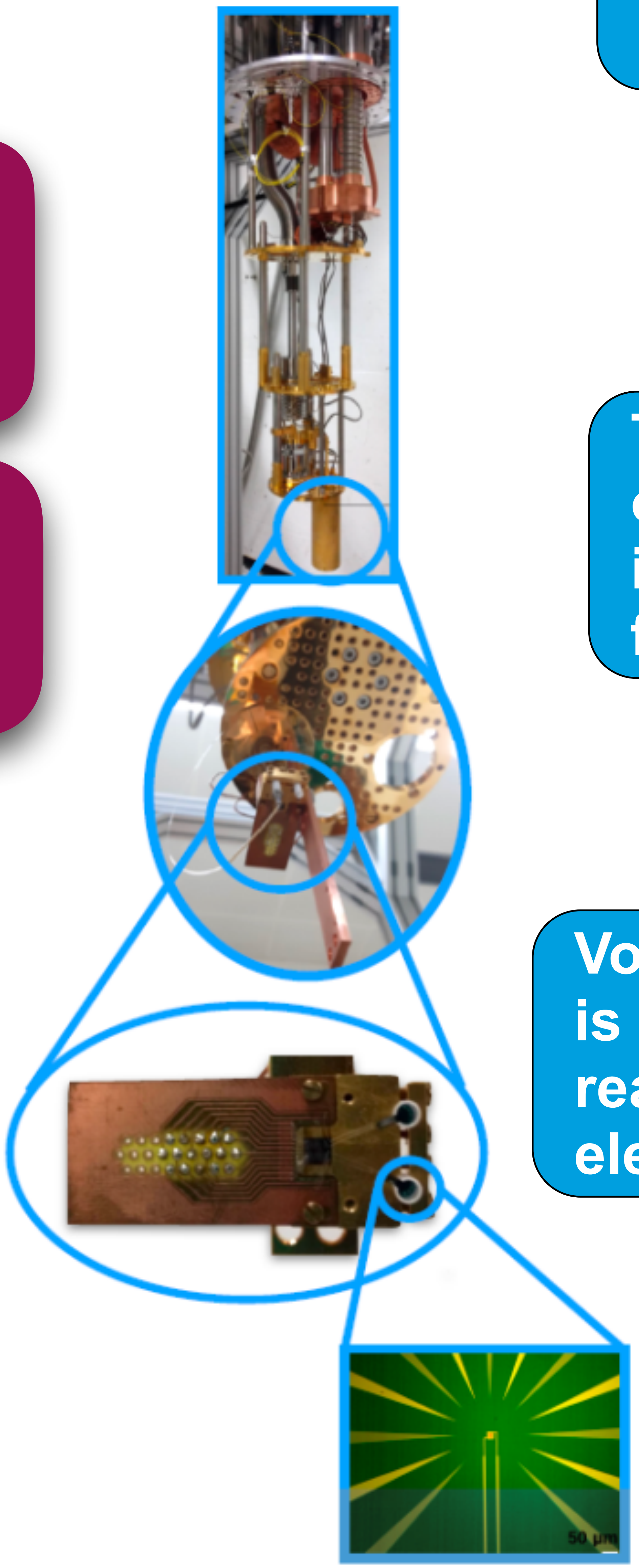

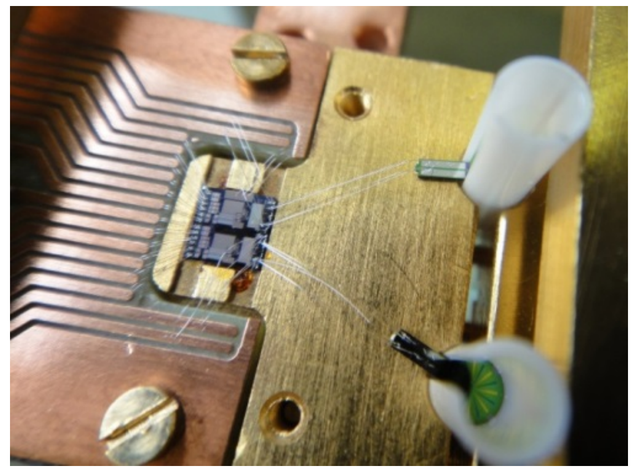

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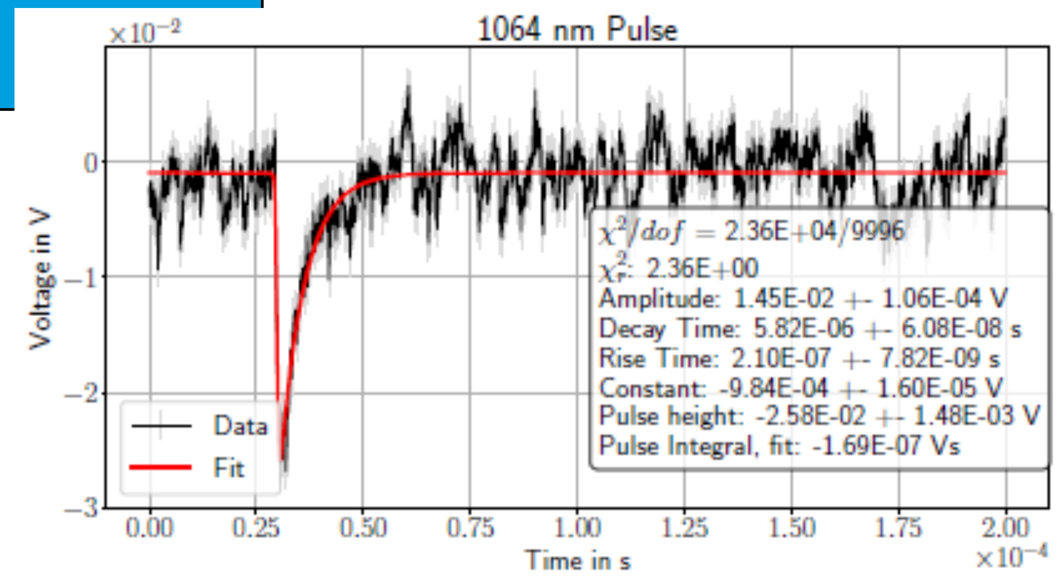
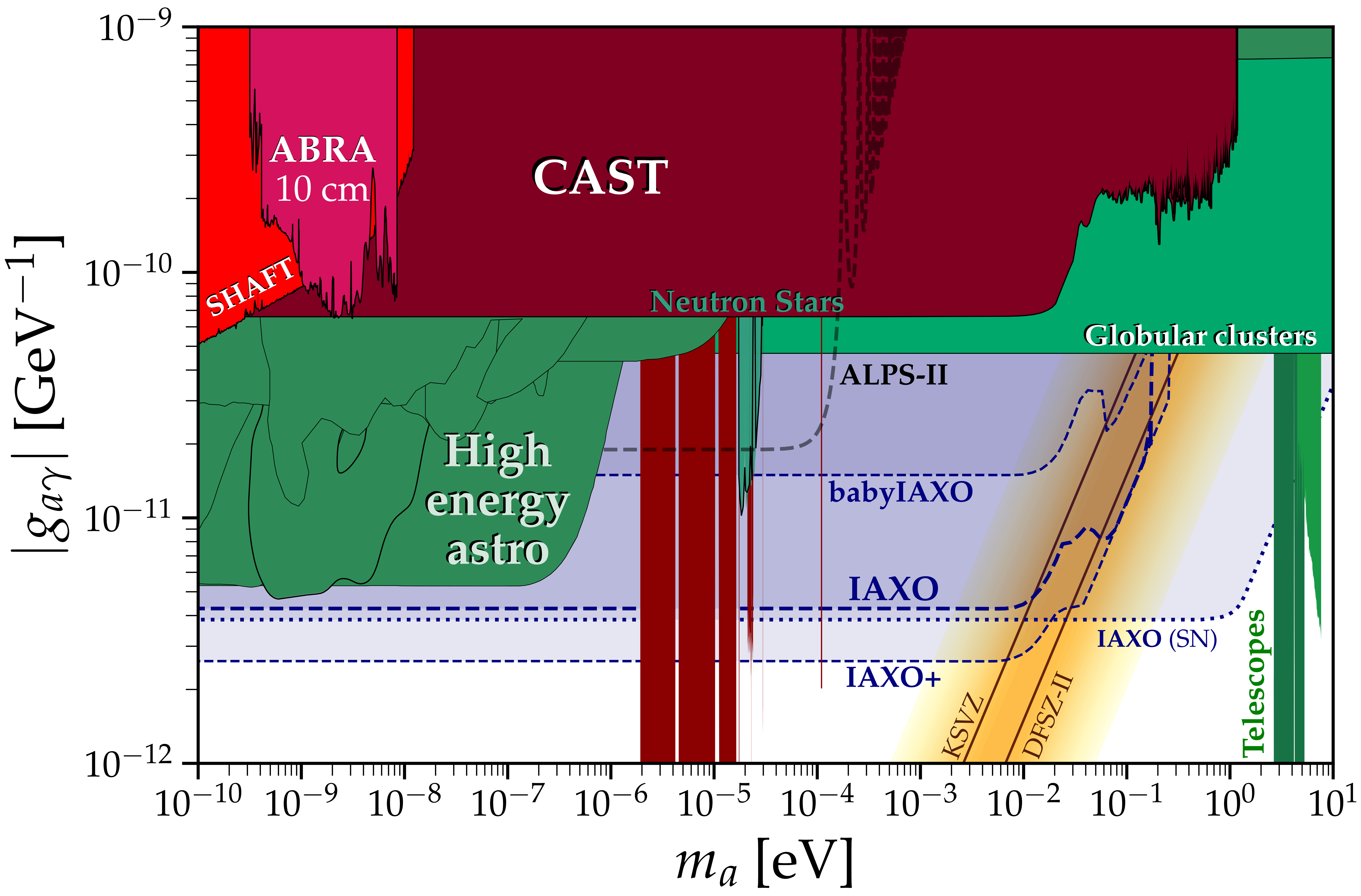


Slide from Friederike Januschek

ALPS II Sensitivity

- $g_{a\gamma} > 2 \times 10^{-11} GeV^{-1}$
  - $m_a < 0.1$ meV
  - Increase sensitivity > 3 orders of magnitude over OSQAR, ALPS I
  - Factor of 3 over CAST
- Begin to probe astrophysical phenomena in model-independent way
  - Stellar cooling
  - TeV transparency
- Early science run with limited sensitivity later this summer

github.com/cajohare/AxionLimits/



First Science Run This Summer

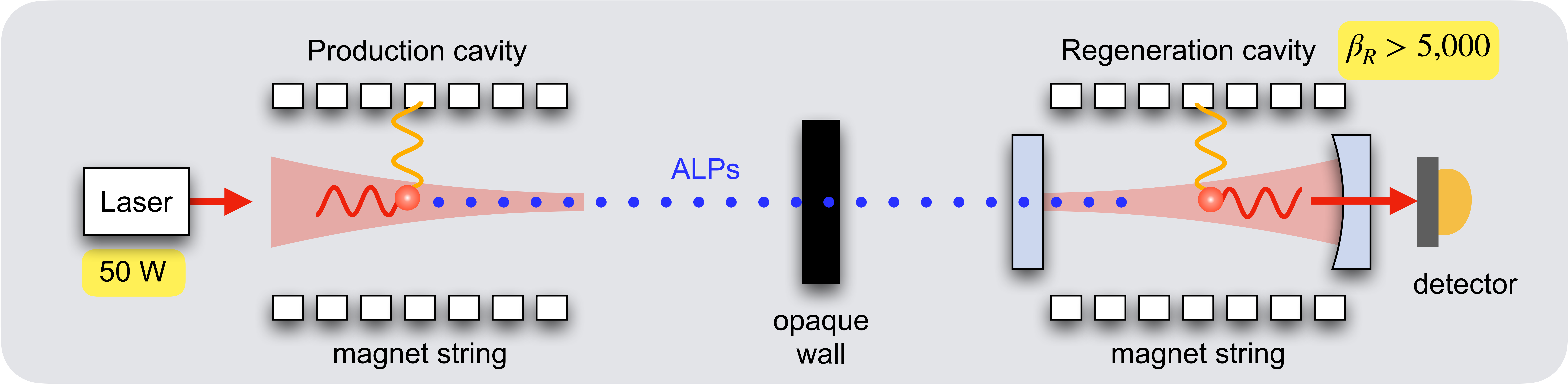
Commissioning optical setup without production cavity

- Simpler control scheme
- Stronger signals for stray light hunting

- Input 50 W laser power
- Regeneration cavity in place
  - Factor of ~210 improvement over ALPS I sensitivity

$$\rightarrow g_{a\gamma} \sim 2 \times 10^{-10} GeV^{-1}$$

Graphic from Katharina-Sophie Isleif



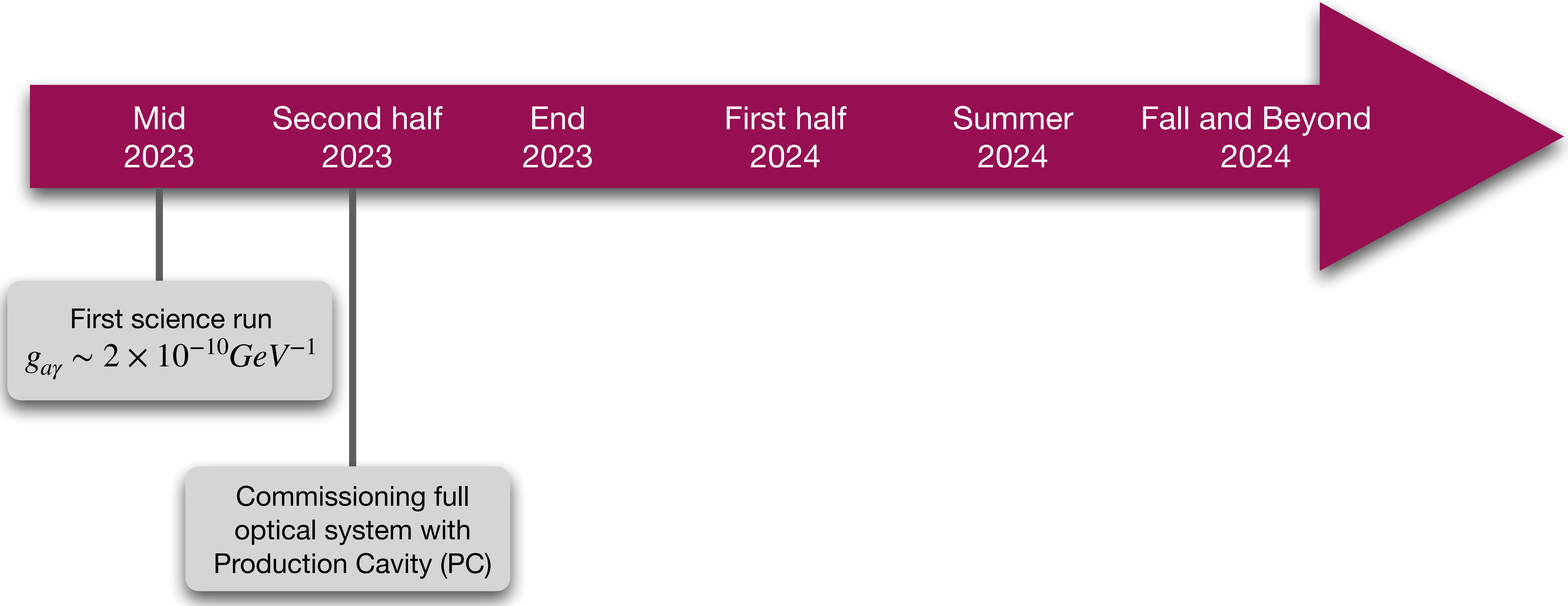
Preliminary ALPS II Schedule

Preliminary ALPS II Schedule

Mid 2023 | Second half 2023 | End 2023 | First half 2024 | Summer 2024 | Fall and Beyond 2024

Mid 2023: First science run
$g_{a\gamma} \sim 2 \times 10^{-10} GeV^{-1}$

Preliminary ALPS II Schedule

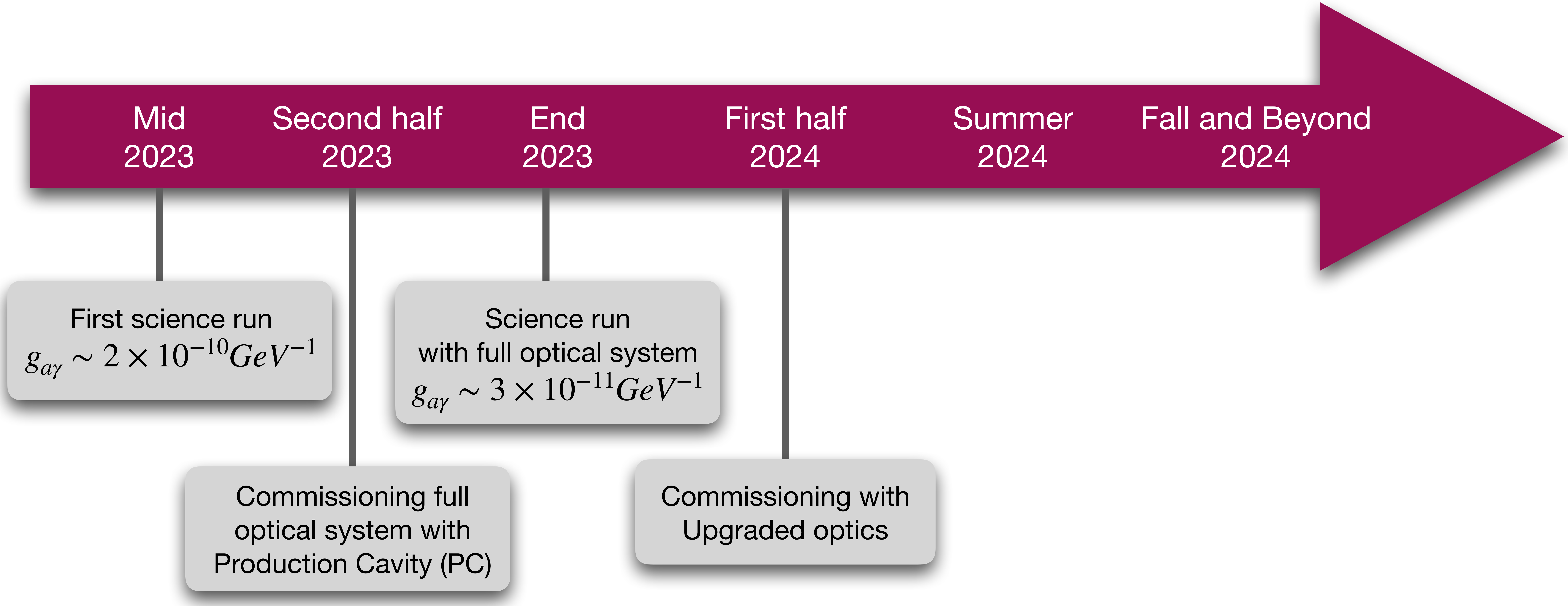


Preliminary ALPS II Schedule

Mid 2023 | Second half 2023 | End 2023 | First half 2024 | Summer 2024 | Fall and Beyond 2024

- **Mid 2023**: First science run $g_{a\gamma} \sim 2 \times 10^{-10} GeV^{-1}$
- **Second half 2023**: Commissioning full optical system with Production Cavity (PC)
- **End 2023**: Science run with full optical system $g_{a\gamma} \sim 3 \times 10^{-11} GeV^{-1}$

Preliminary ALPS II Schedule



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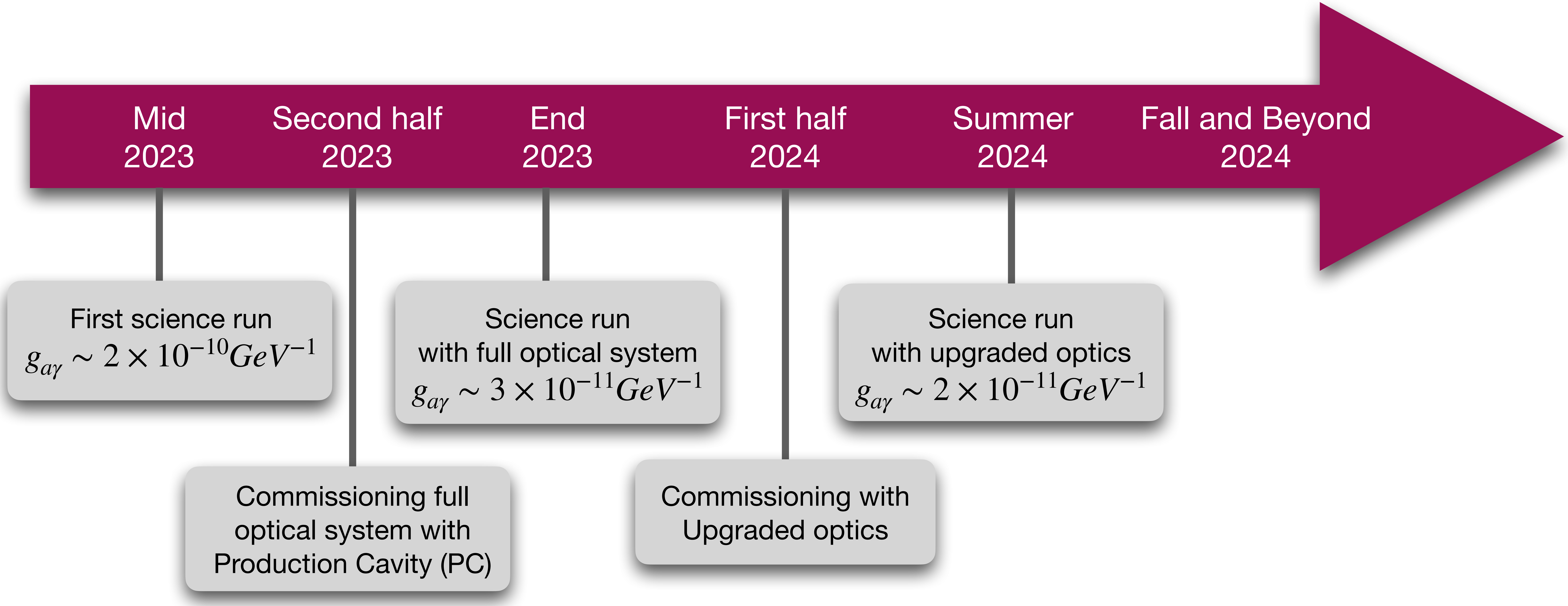


Preliminary ALPS II Schedule

Mid 2023
First science run
$g_{a\gamma} \sim 2 \times 10^{-10} GeV^{-1}$

Second half 2023
Commissioning full optical system with Production Cavity (PC)

End 2023
Science run with full optical system
$g_{a\gamma} \sim 3 \times 10^{-11} GeV^{-1}$

First half 2024
Commissioning with Upgraded optics

Summer 2024
Science run with upgraded optics
$g_{a\gamma} \sim 2 \times 10^{-11} GeV^{-1}$

Fall and Beyond 2024
TBD based on full science run results
- Commissioning optical system for TES
- Vacuum Magnetic Birefringence (VMB) search
- High-Frequency gravitational wave search

Summary and Outlook

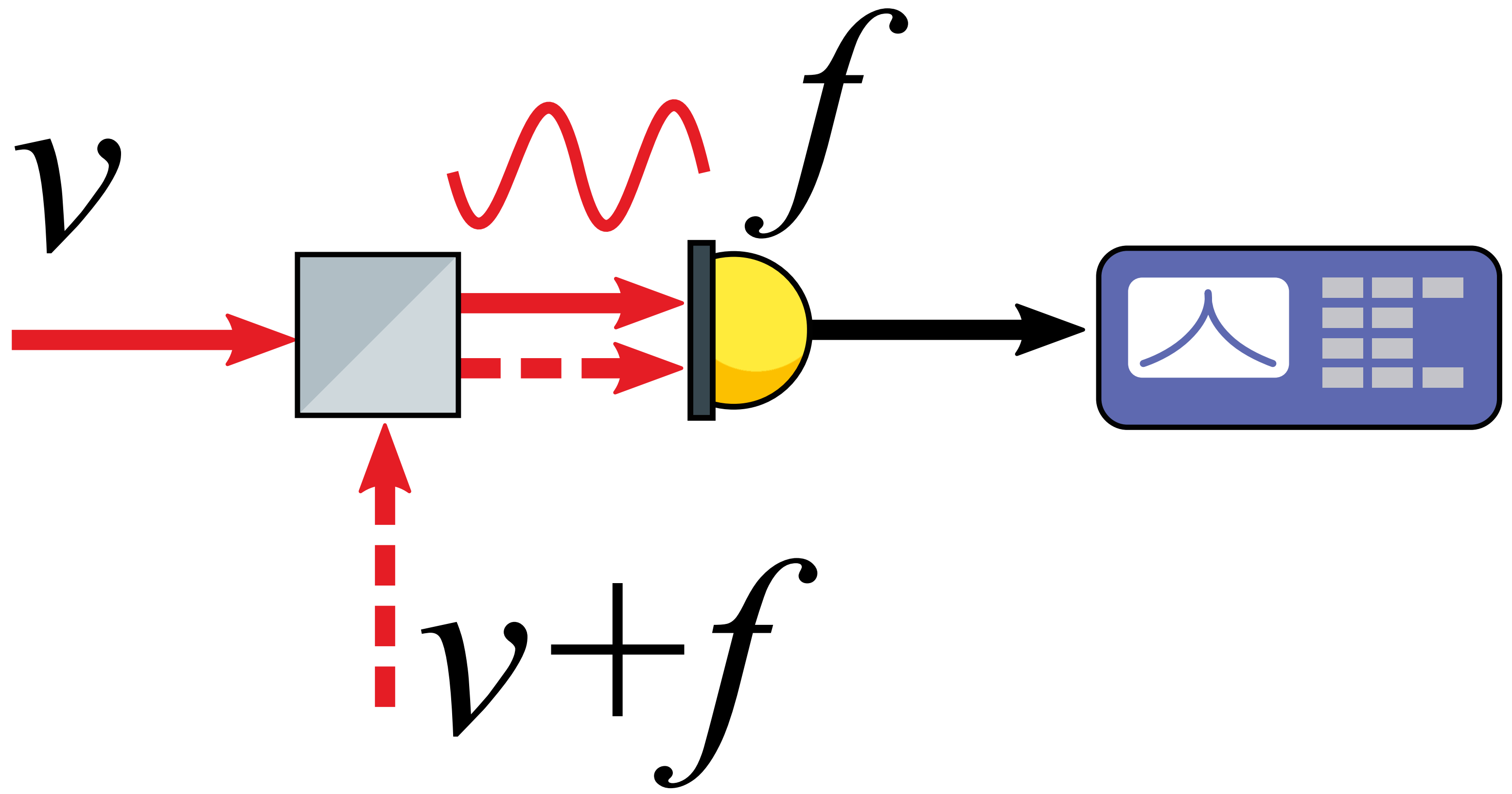
- ALPS II is a LSW experiment that will improve the limits for $g_{a\gamma}$ by over 3 orders of magnitude over OSQAR, ALPS I
- Begin checking astrophysical observations in a model-independent way
- First science run this summer $\rightarrow g_{a\gamma} \sim 2 \times 10^{-10}\ GeV^{-1}$
- Full sensitivity run after upgrades around Summer 2024 $\rightarrow g_{a\gamma} \sim 2 \times 10^{-11}\ GeV^{-1}$

Thank you!

Backup slides

Heterodyne Interferometry

Measuring single photon power levels



Measuring the interference beatnote

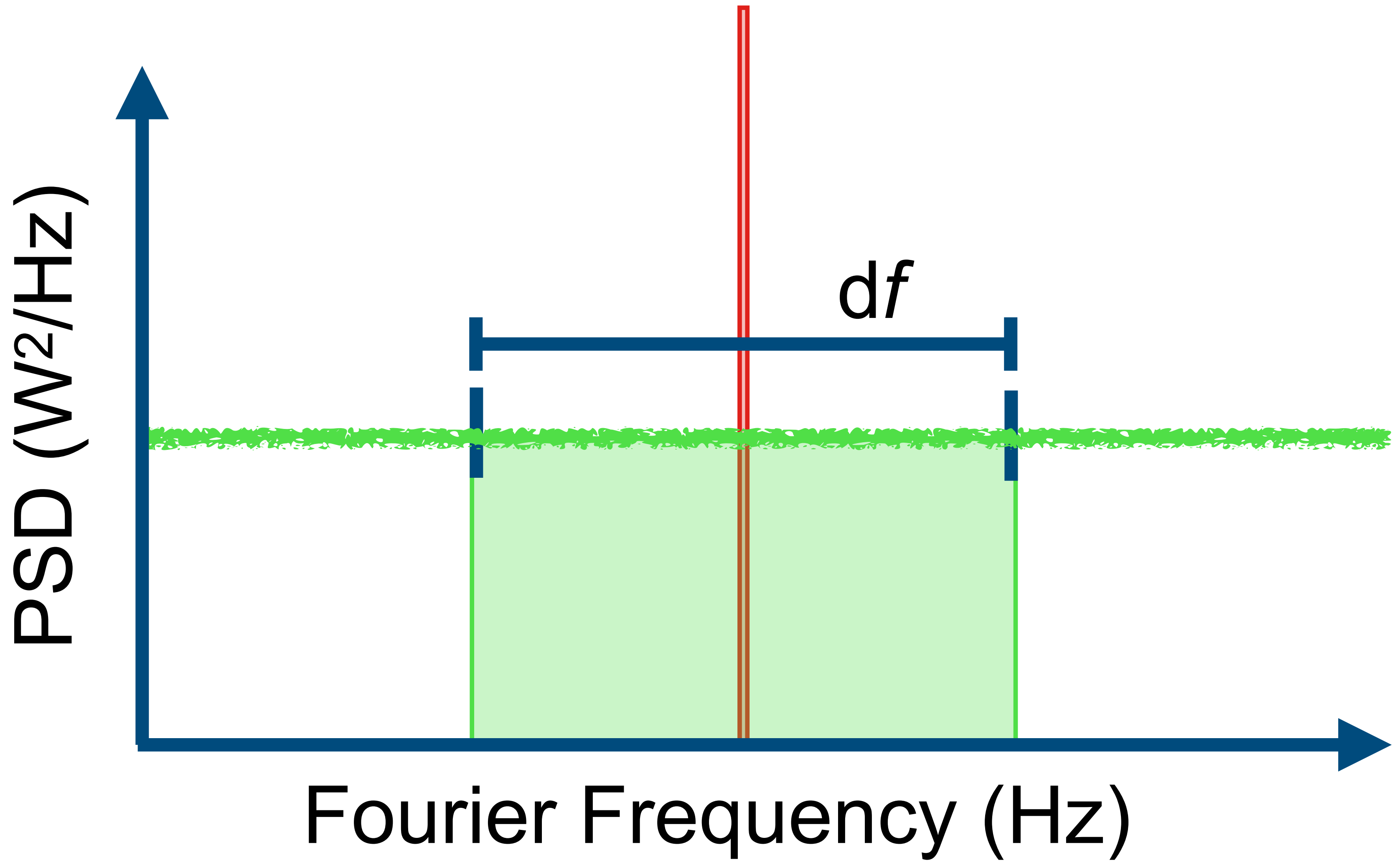
- Signal field optically mixed with Local Oscillator (LO) laser
  - Interference beatnote in power at the difference frequency
  - Photon counting stats -> Shot noise
- Demodulate power measurement at difference frequency

$$P(t) = P_{LO} + P_S + 2\sqrt{P_{LO}P_S}\cos(\Delta\omega t - \phi)$$

$$Z(N) = \frac{\left(\sum_{n=1}^{N} I[n]\right)^2 + \left(\sum_{n=1}^{N} Q[n]\right)^2}{N^2}$$

$$I[n] = x_{\text{sig}}[n] \times \cos\left(2\pi\frac{f_d}{f_s}n\right)$$

$$Q[n] = x_{\text{sig}}[n] \times \sin\left(2\pi\frac{f_d}{f_s}n\right)$$

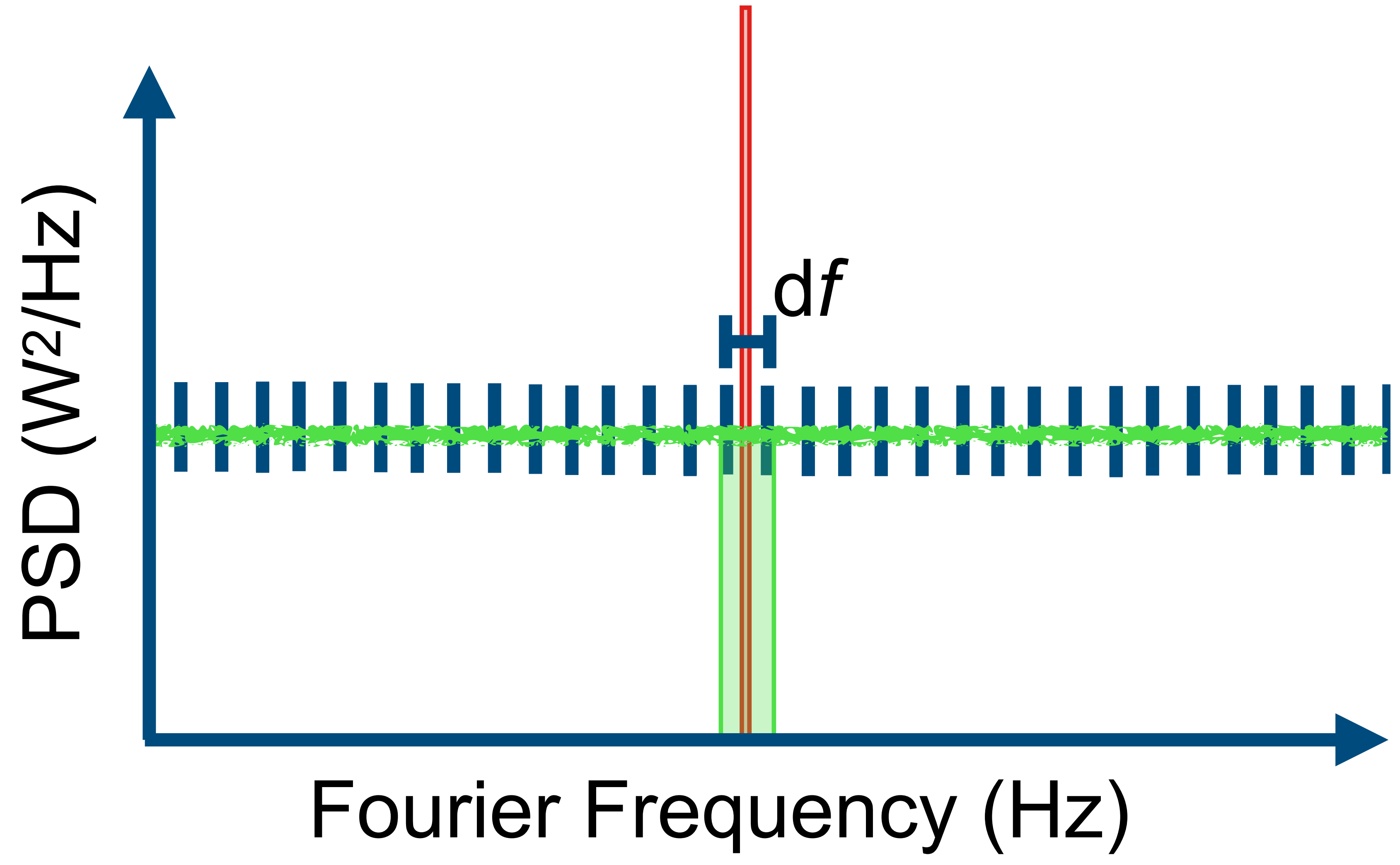


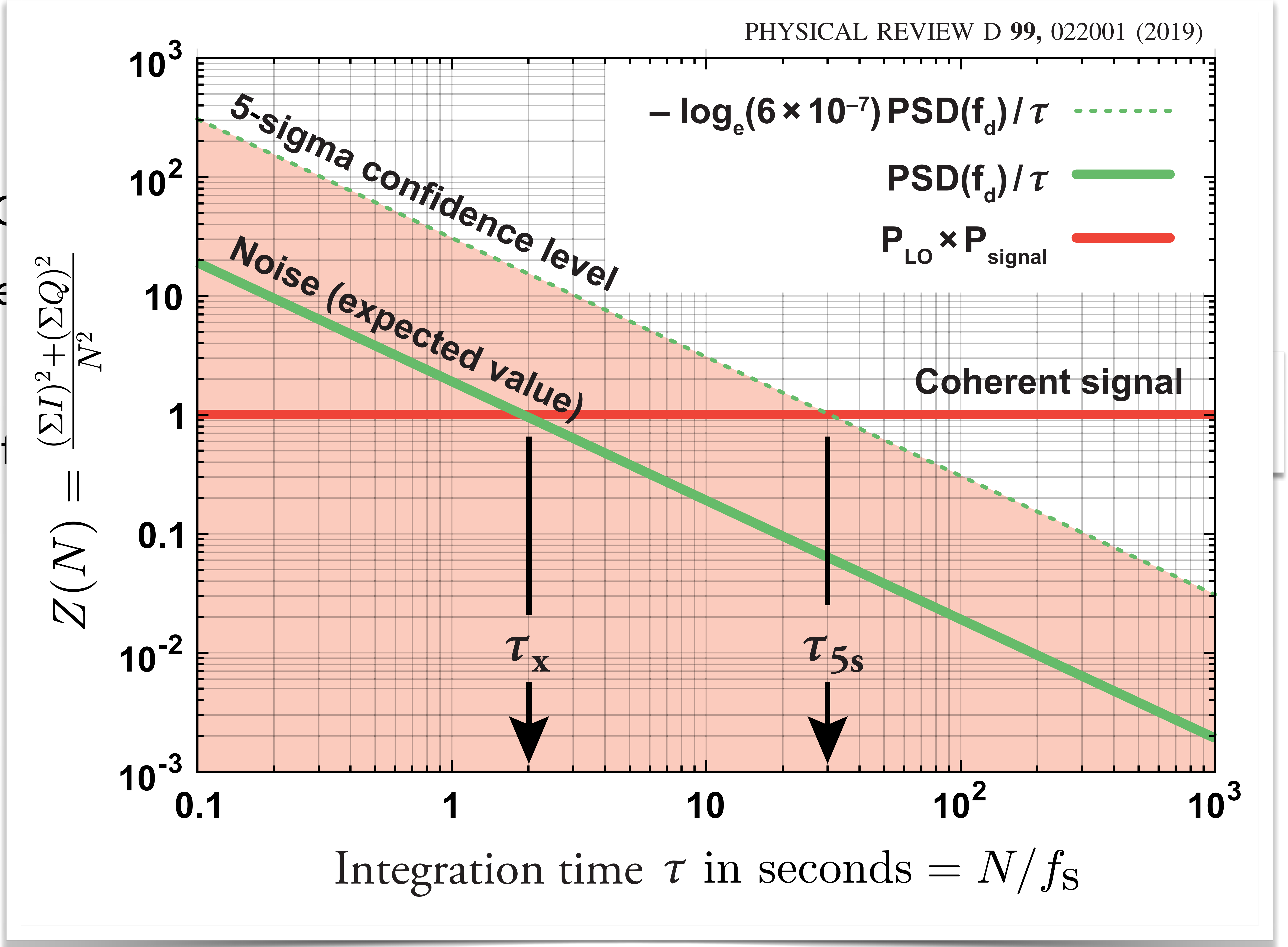
Heterodyne Interferometry

Measuring single photon power levels

Measuring the interference beatnote

- Signal field optically mixed with Local O
  - Interference beatnote in power at the
  - Photon counting stats -> Shot noise
- Demodulate power measurement at di



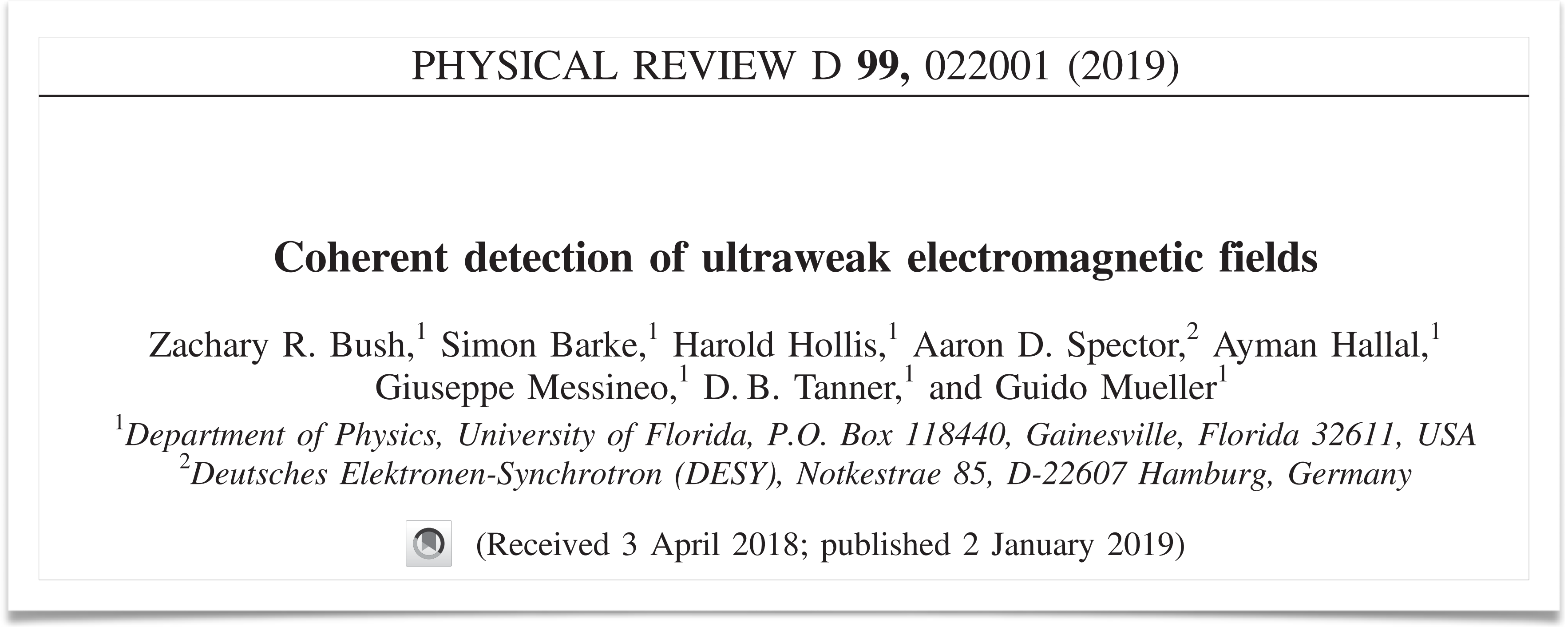


Heterodyne Signal

Measuring single photon power levels

SNR increases with integration time

- Expectation value from shot noise decreases with integration time
- Expectation value from signal is constant in time



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]

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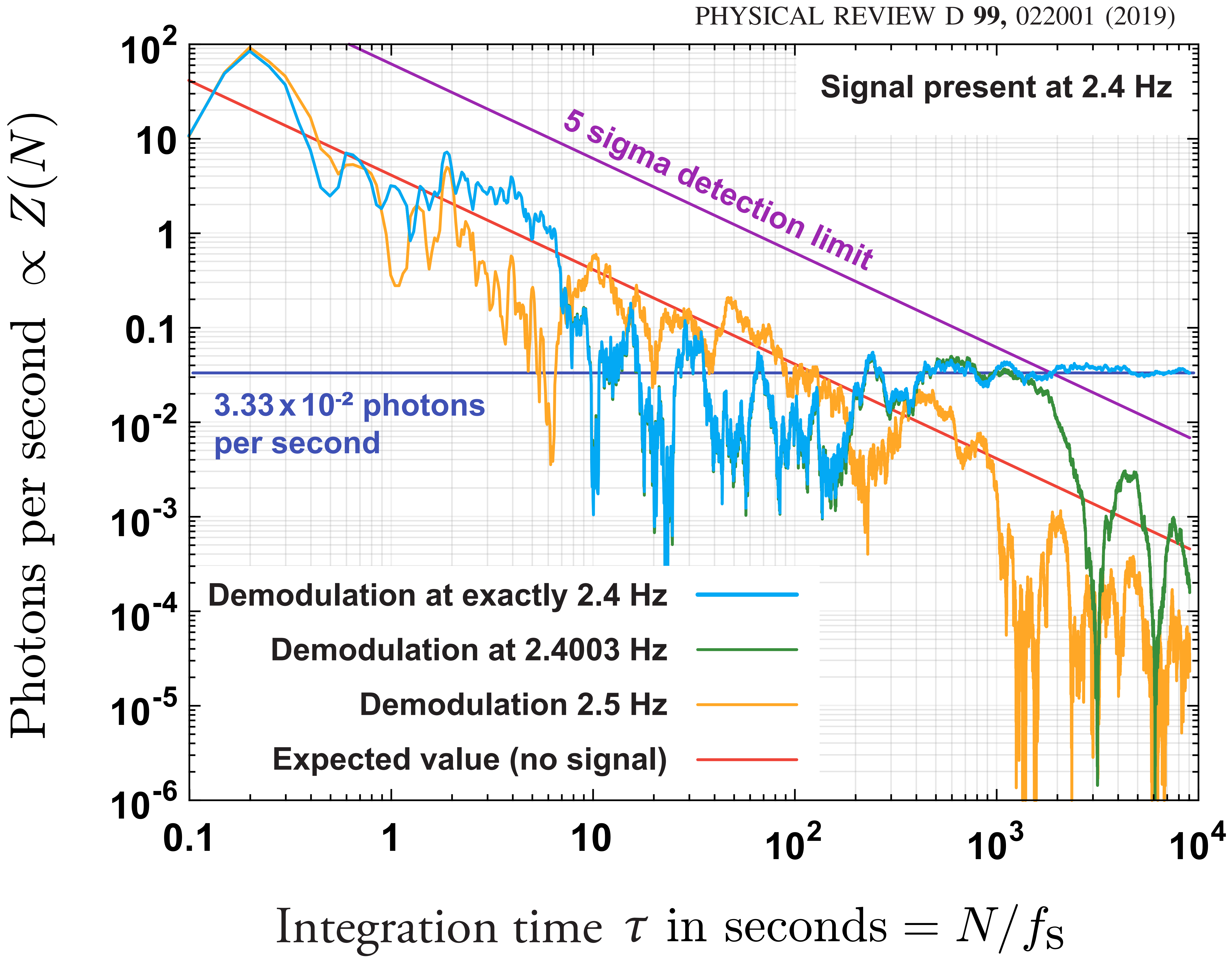
[2]*Deutsches Elektronen-Synchrotron (DESY), Notkestrae 85, D-22607 Hamburg, Germany*

(Received 3 April 2018; published 2 January 2019)

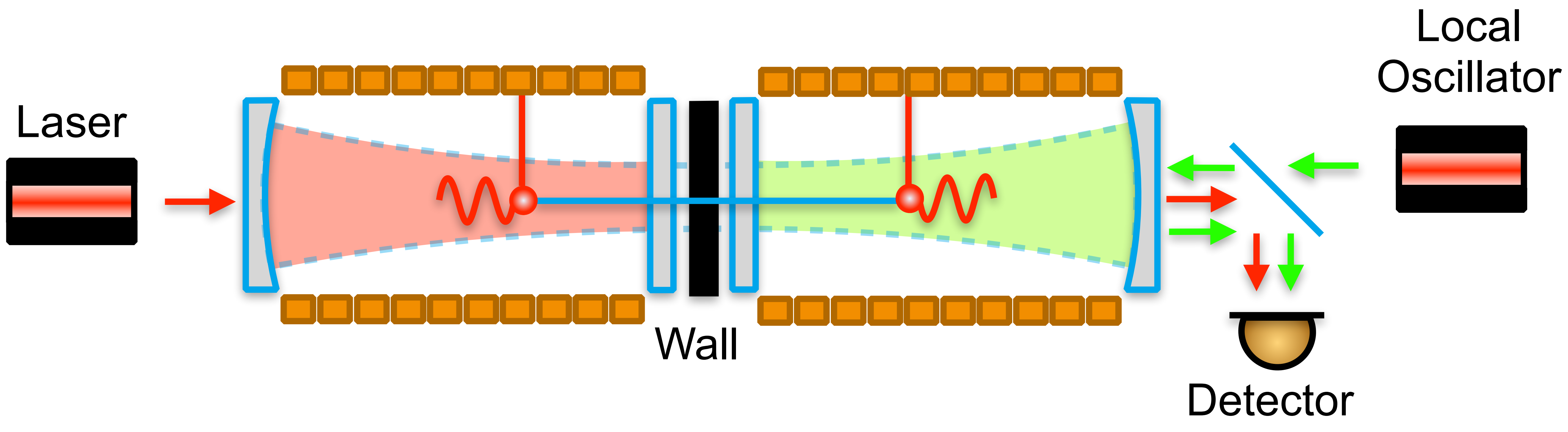


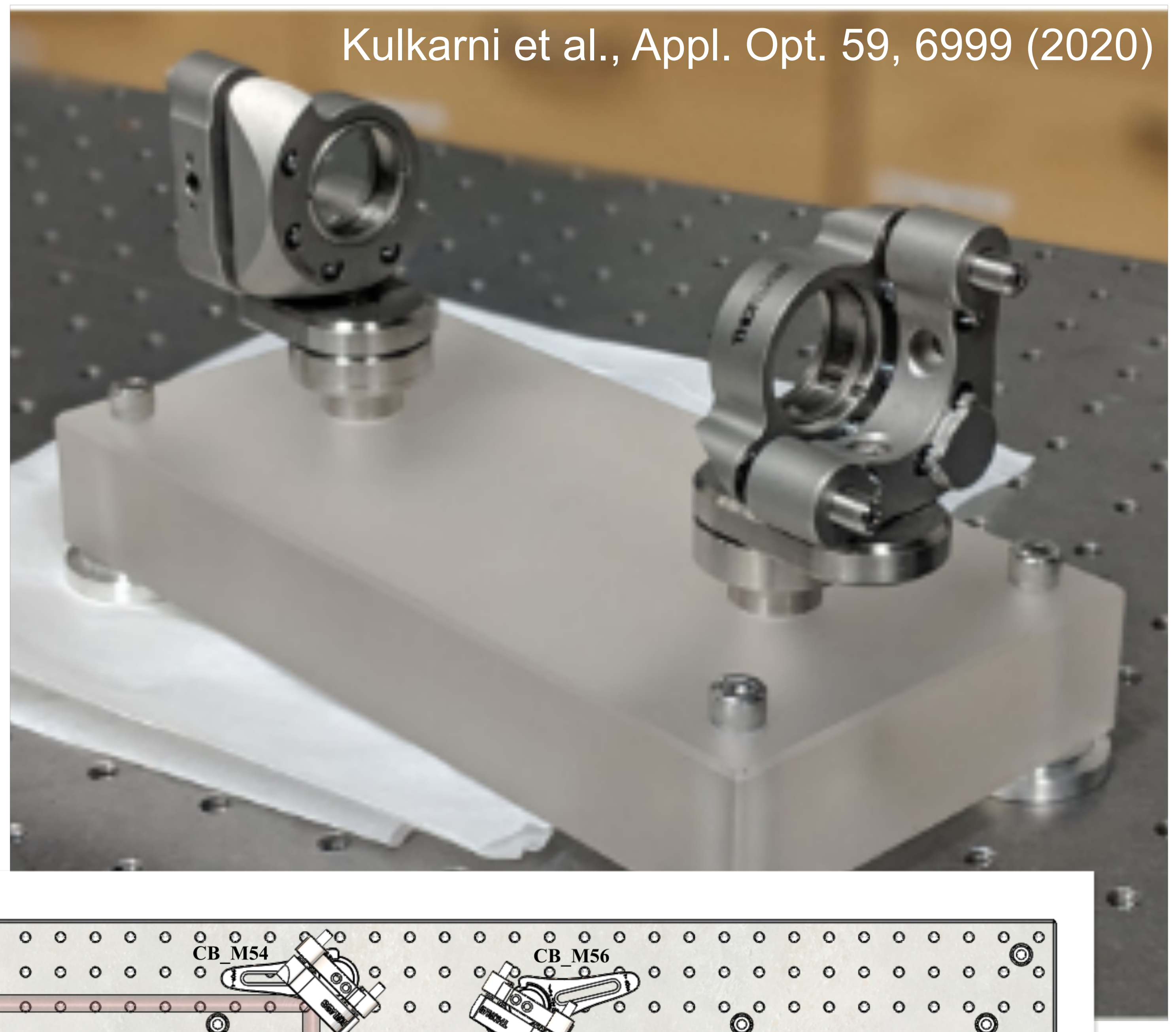
Heterodyne Detection

Measuring single photon power levels

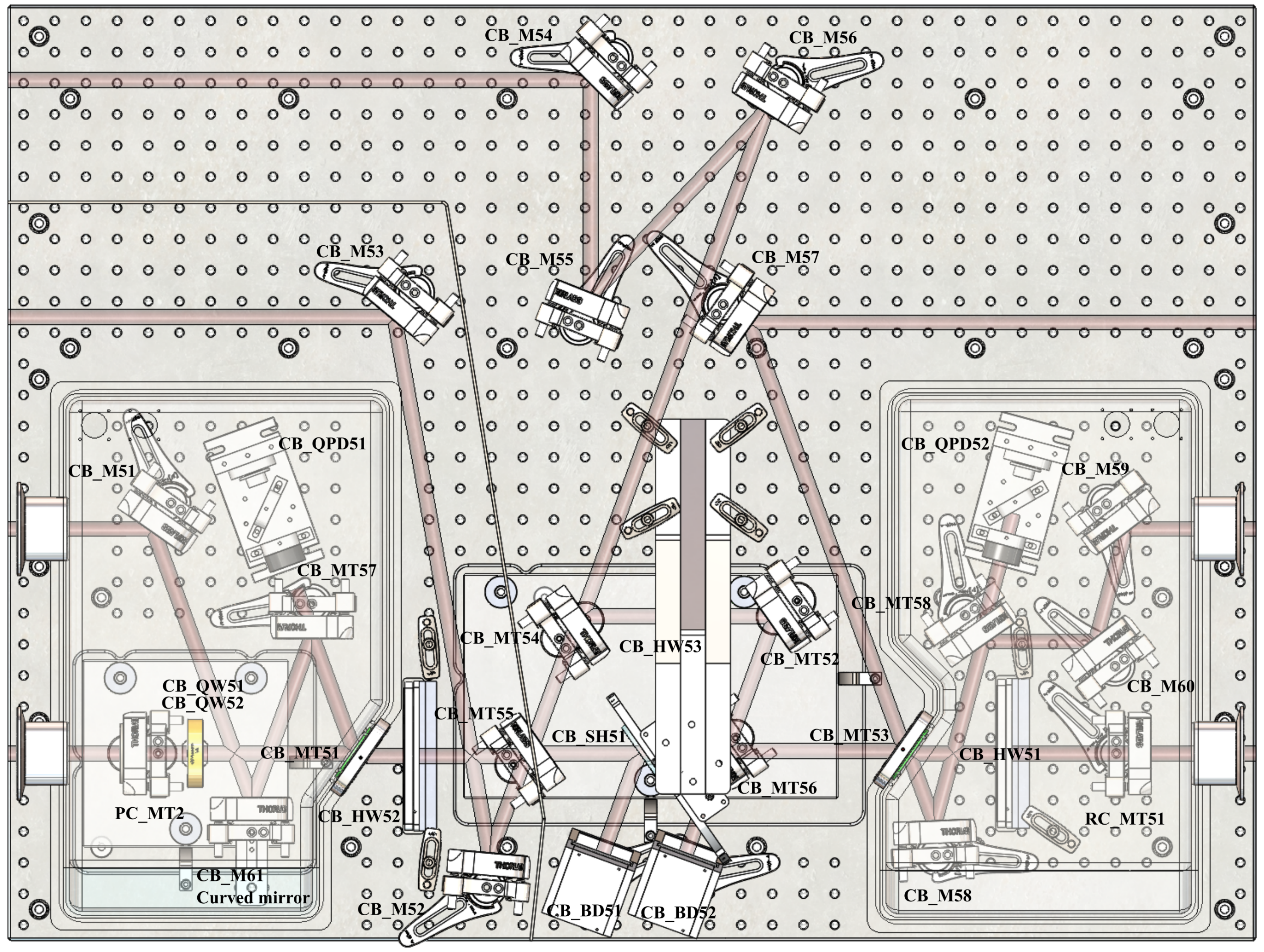
Regenerated Field Mixed with Local Oscillator Laser (LO)

- LO must be phase coherent with regenerated field
  - Information transfer via COB
    - Tracks OPL changes between cavity mirrors
    - Suppress stray light from PC
- Interference beatnote measured by photodetector





Kulkarni et al., Appl. Opt. 59, 6999 (2020)

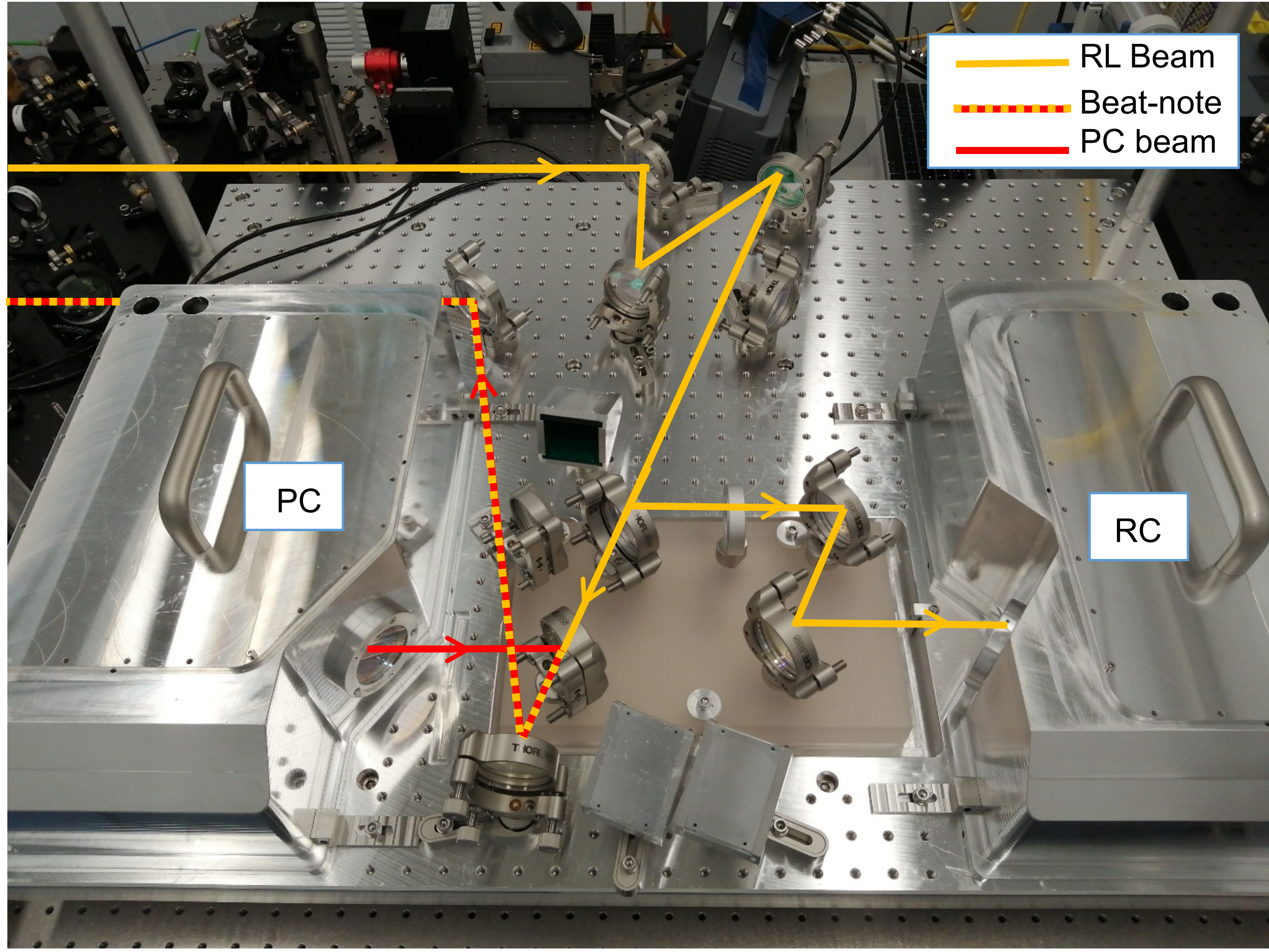


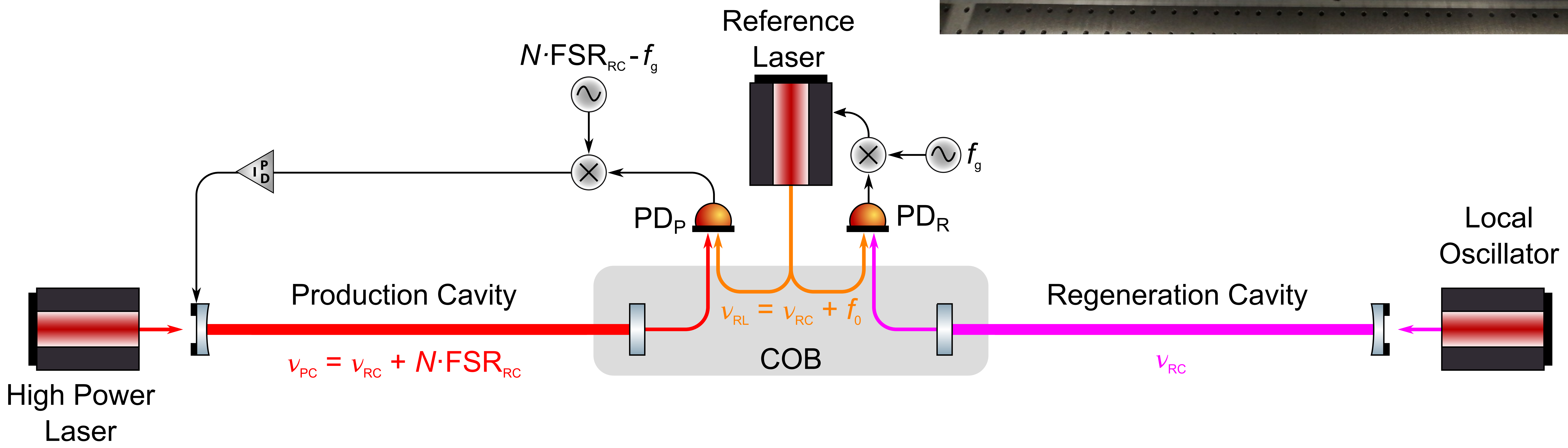
Central Optical Bench (COB)

Maintaining dual resonance and spatial overlap

Ensure PC light is resonant with RC

- Interference beatnotes transfer phase information between PC and RC
- System cannot allow 'light leaks'





ALPS II Optics: Current Work

frequency offset < 1.5 Hz

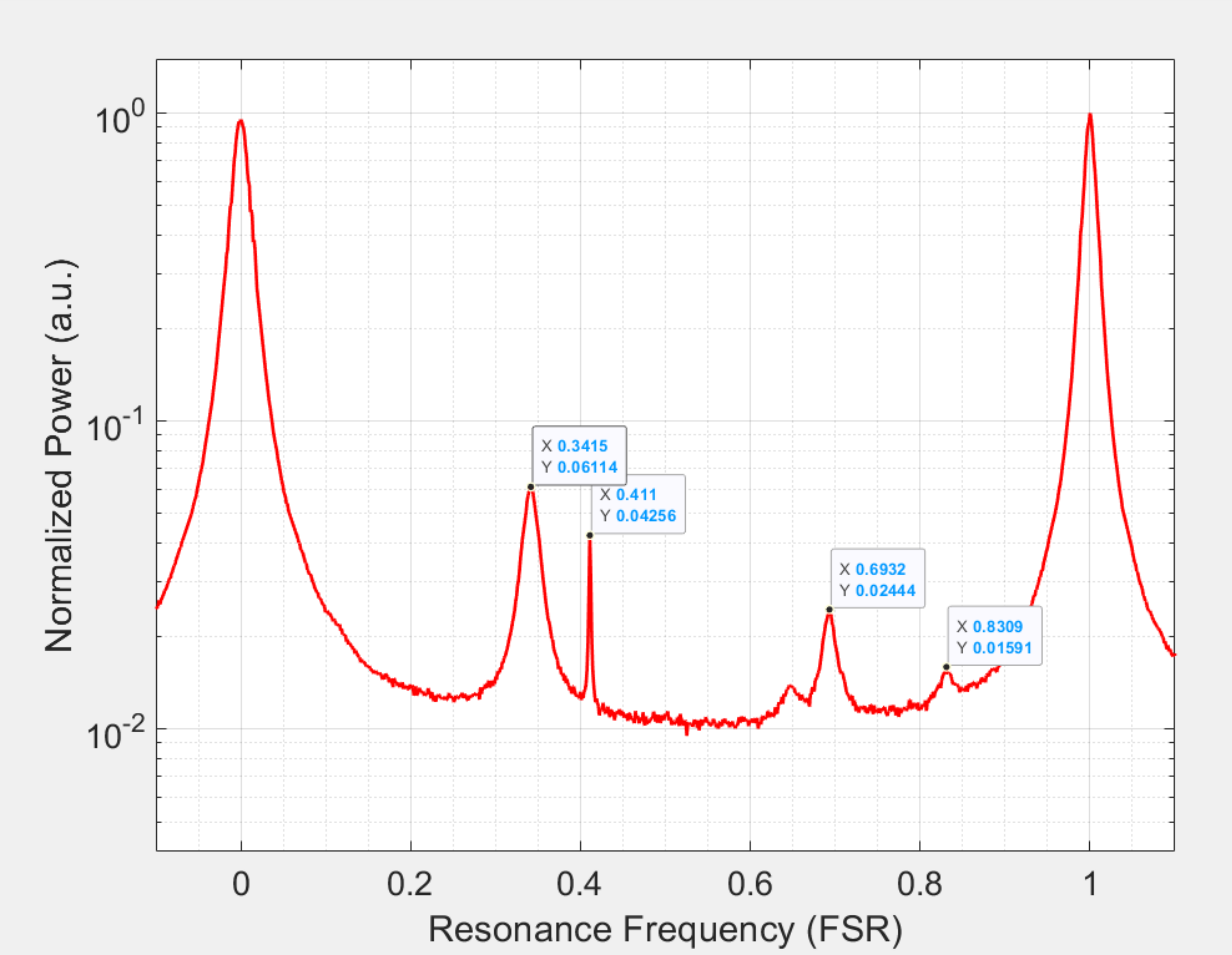
differential length noise < 0.6pm

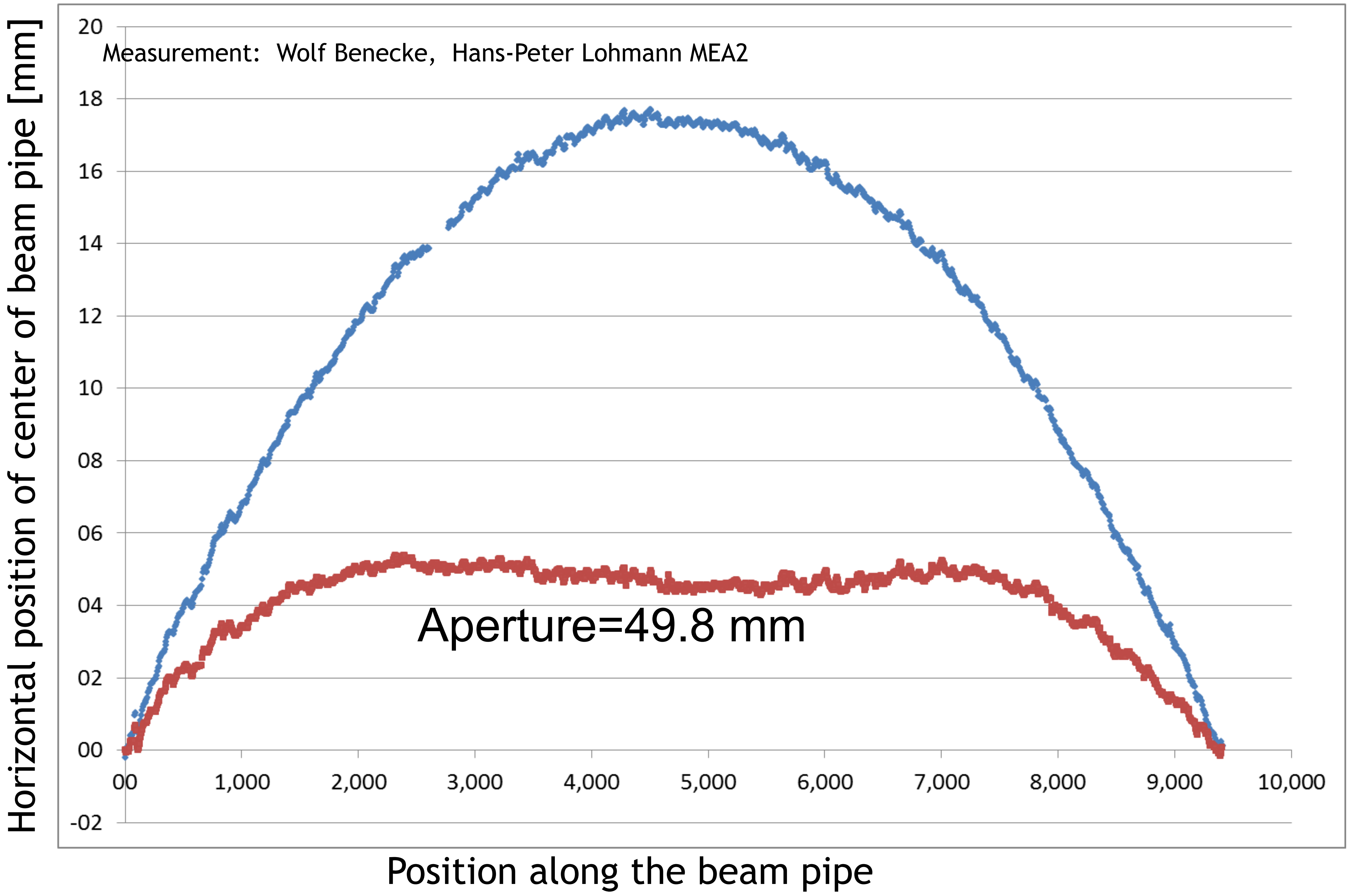
Unbending the HERA Magnets

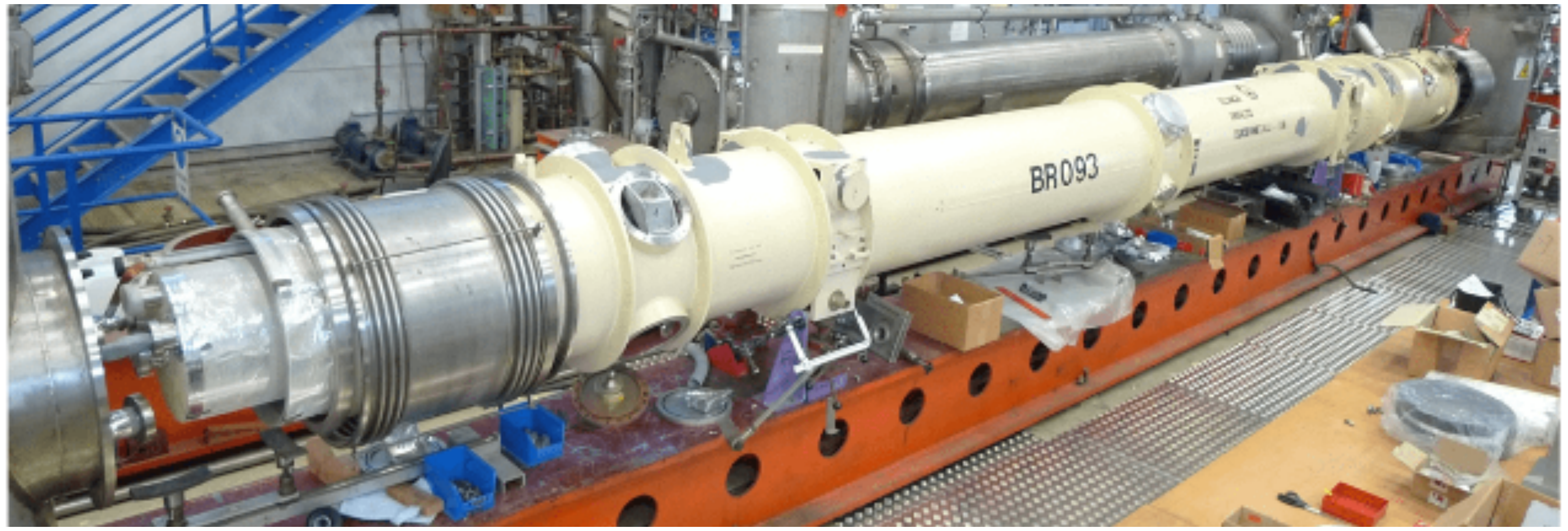
Preparing HERA dipoles for ALPS II

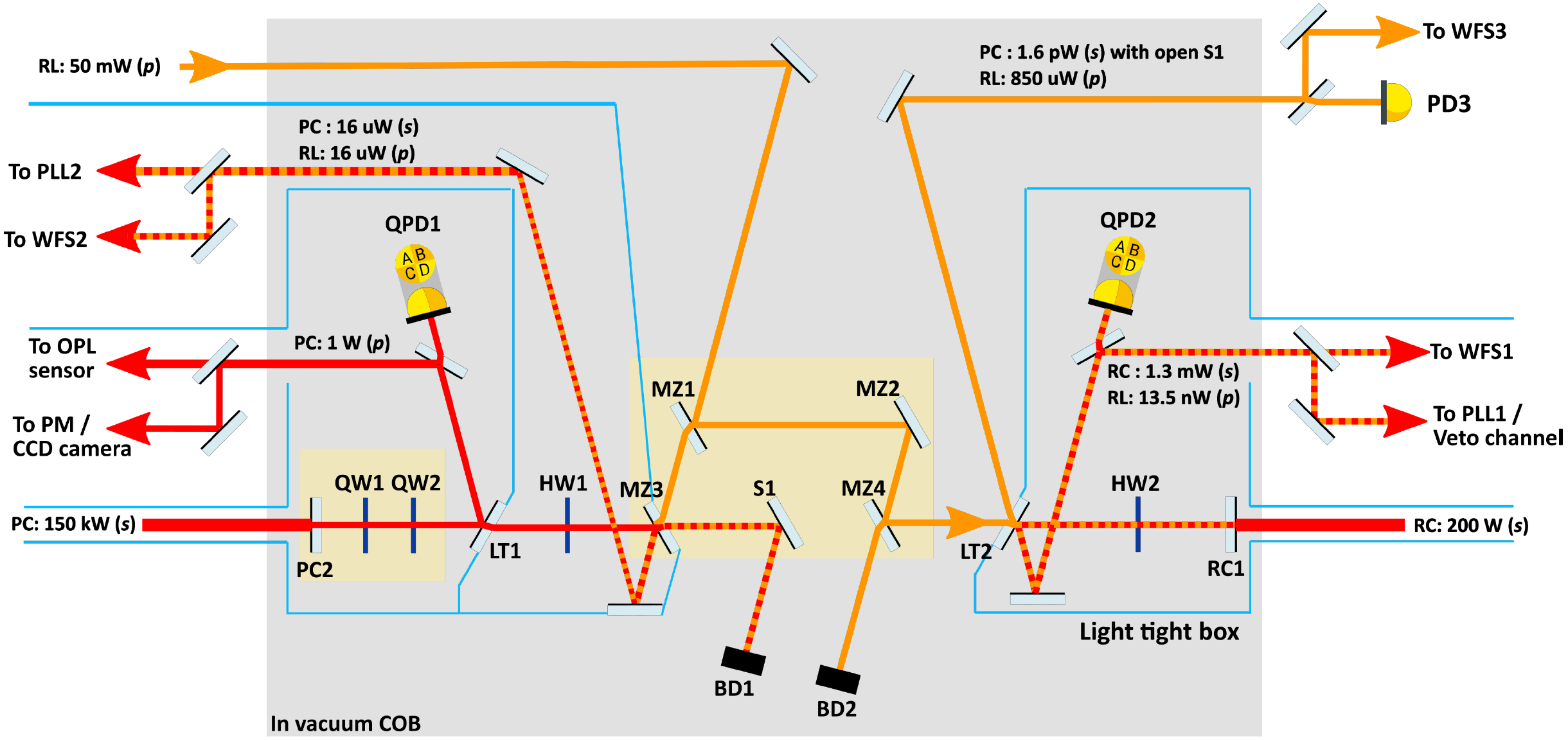
Magnets must be unbent

- Formerly used in HERA arcs
- Straightened for sufficient aperture
-








RL: 50 mW (*p*)
PC : 1.6 pW (*s*) with open S1
RL: 850 uW (*p*)
To WFS3
PD3
PC : 16 uW (*s*)
RL: 16 uW (*p*)
To PLL2
To WFS2
QPD1
A B
C D
QPD2
A B
C D
To OPL sensor
PC: 1 W (*p*)
To PM / CCD camera
MZ1
MZ2
To WFS1
RC : 1.3 mW (*s*)
RL: 13.5 nW (*p*)
To PLL1 / Veto channel
QW1 QW2
HW1
MZ3
S1
MZ4
HW2
PC: 150 kW (*s*)
RC: 200 W (*s*)
PC2
LT1
LT2
RC1
Light tight box
BD1
BD2
In vacuum COB