Status of the ALPS II Experiment

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

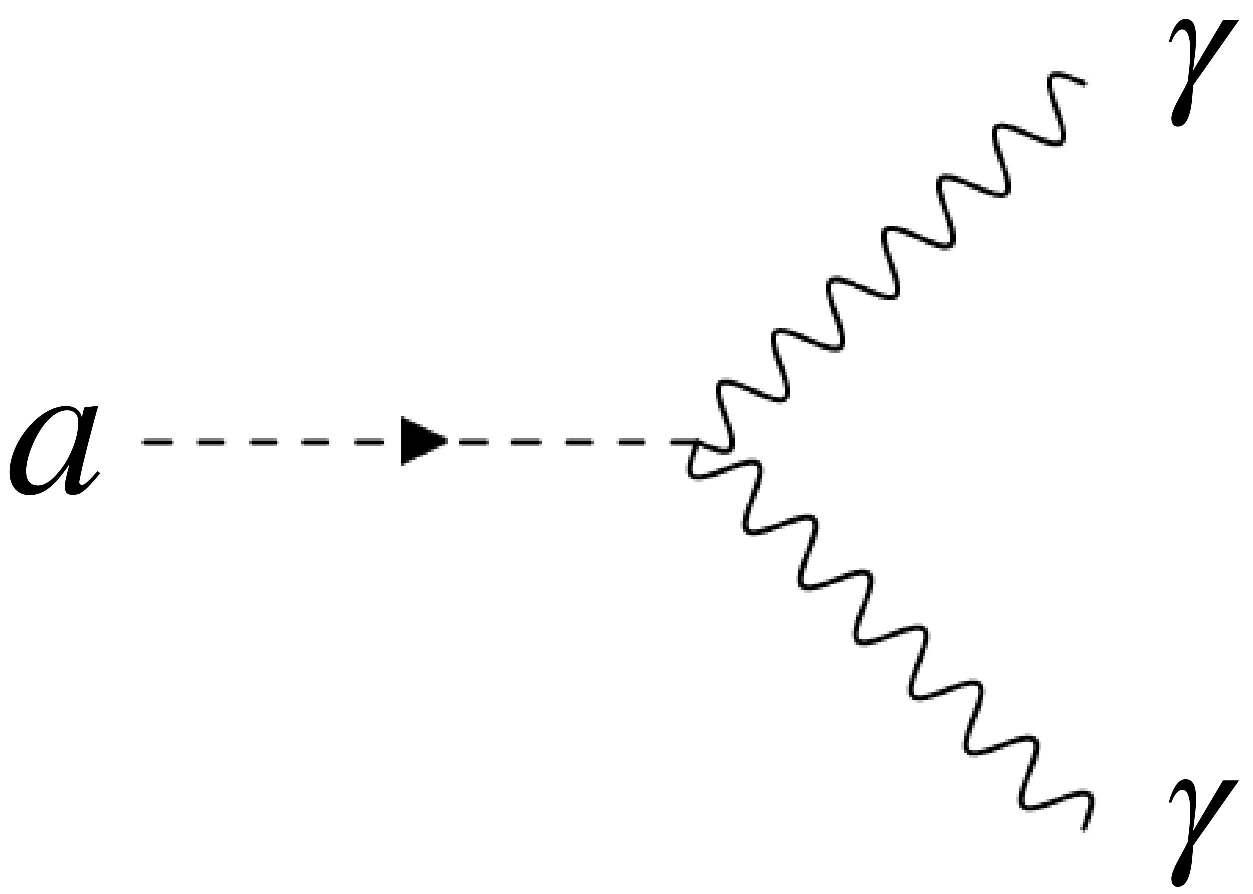
17th PATRAS Workshop 2022, Mainz

Motivation for Light Shining through Walls (LSW) Experiments

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

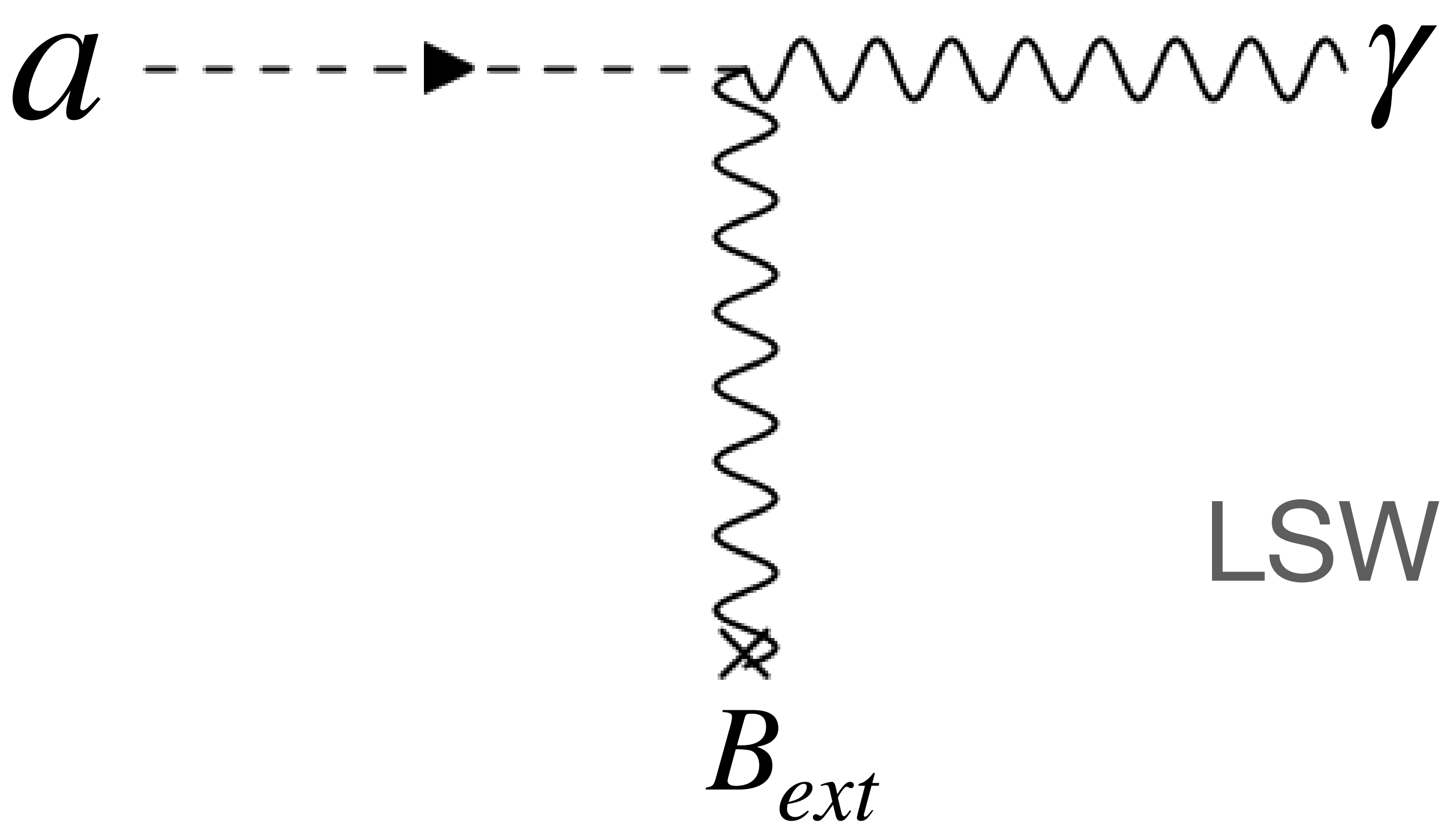
ALP coupling to photons

ALP decay



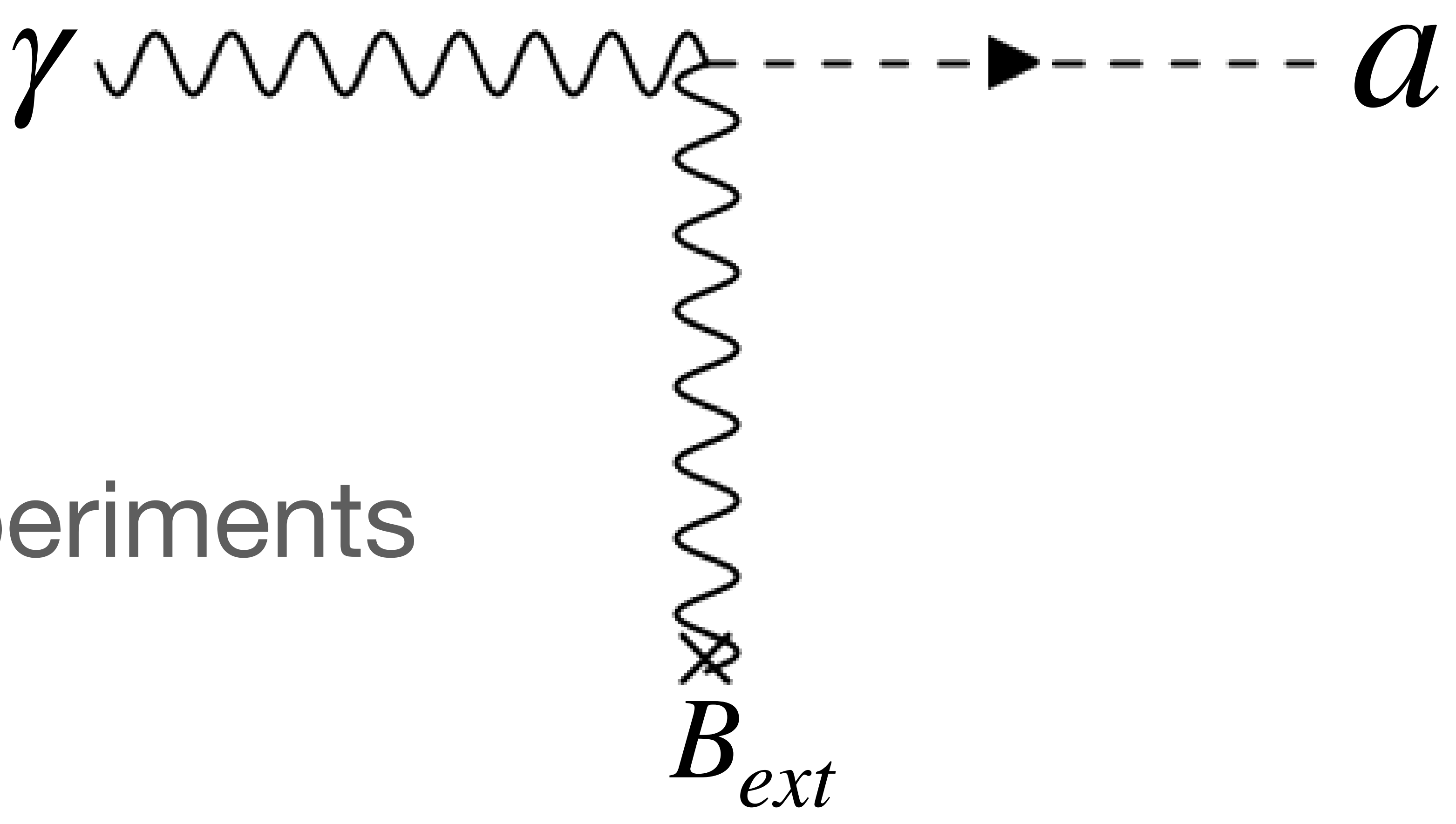
Astrophysics and cosmology

Sikivie effect



Haloscopes
Helioscopes

Inverse Sikivie effect



LSW Experiments

ALP coupling to photons

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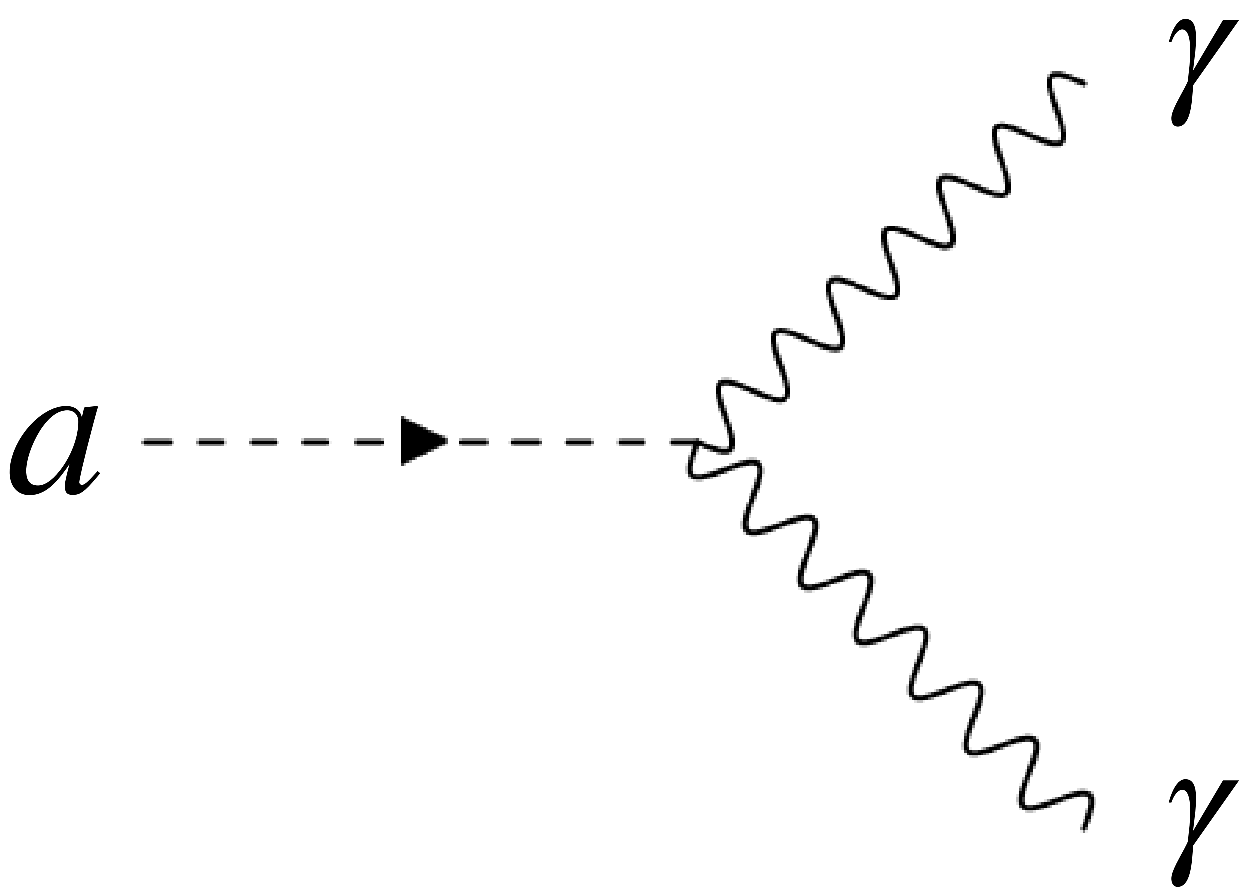
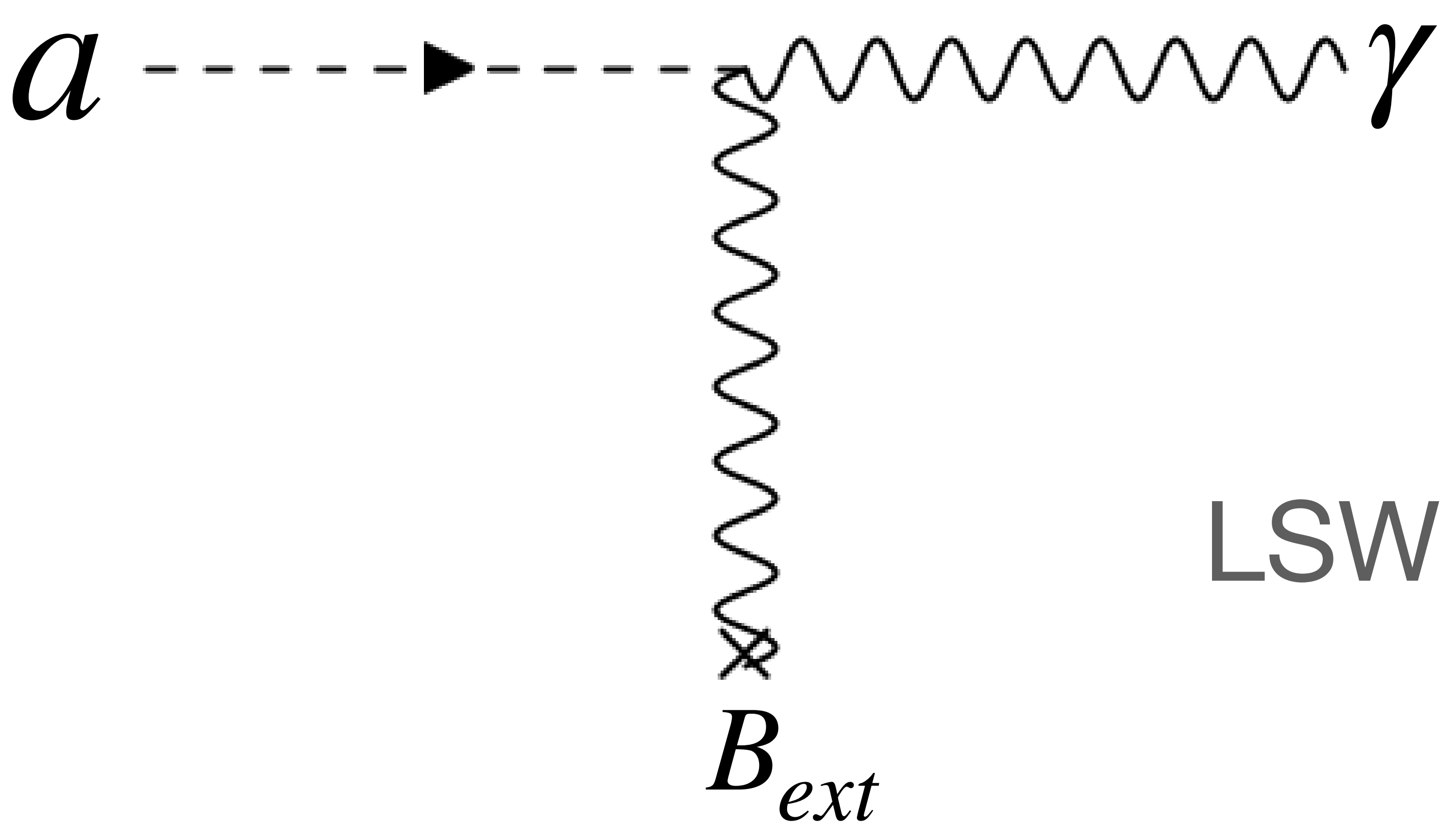


Sikivie effect



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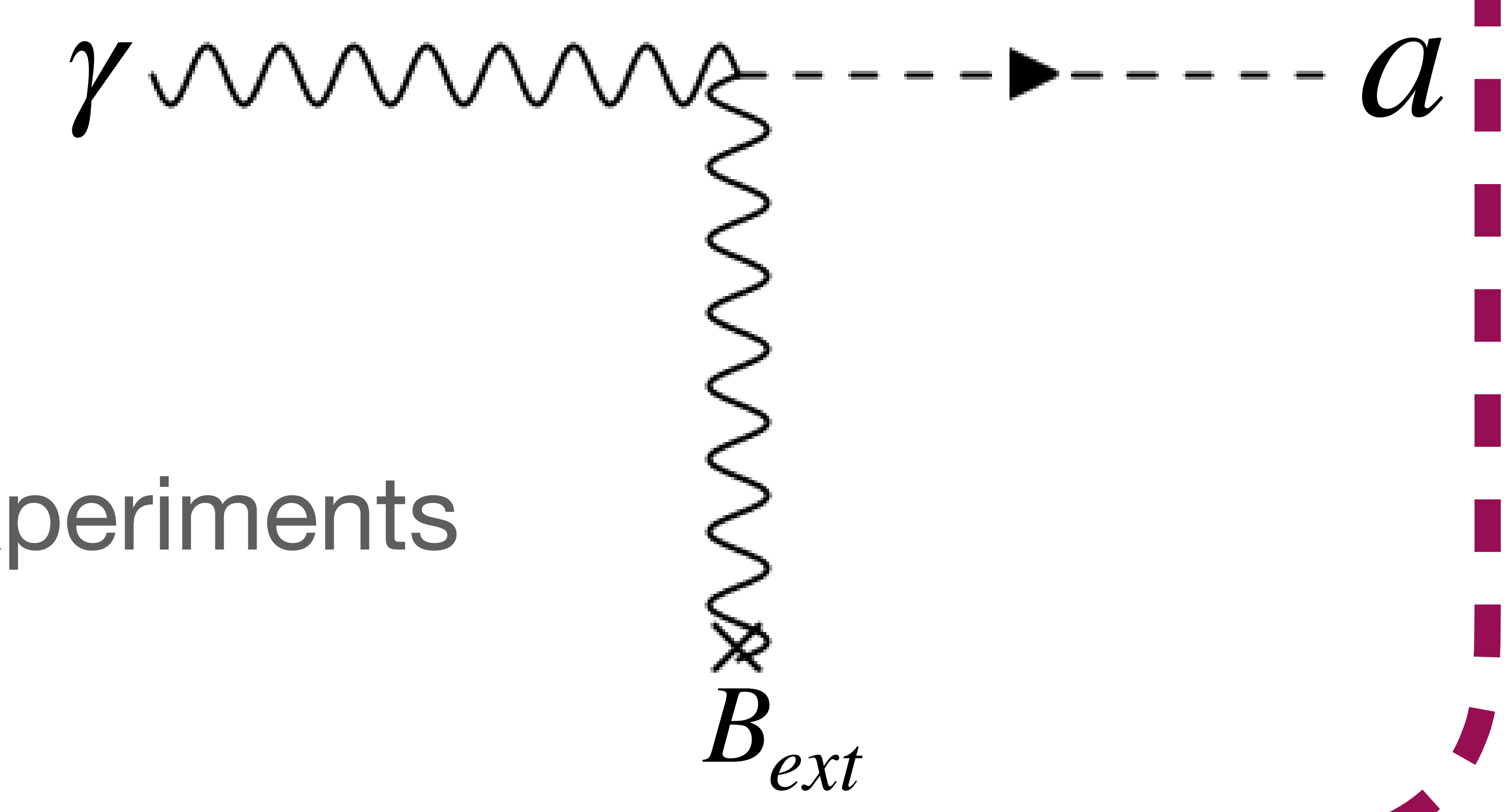
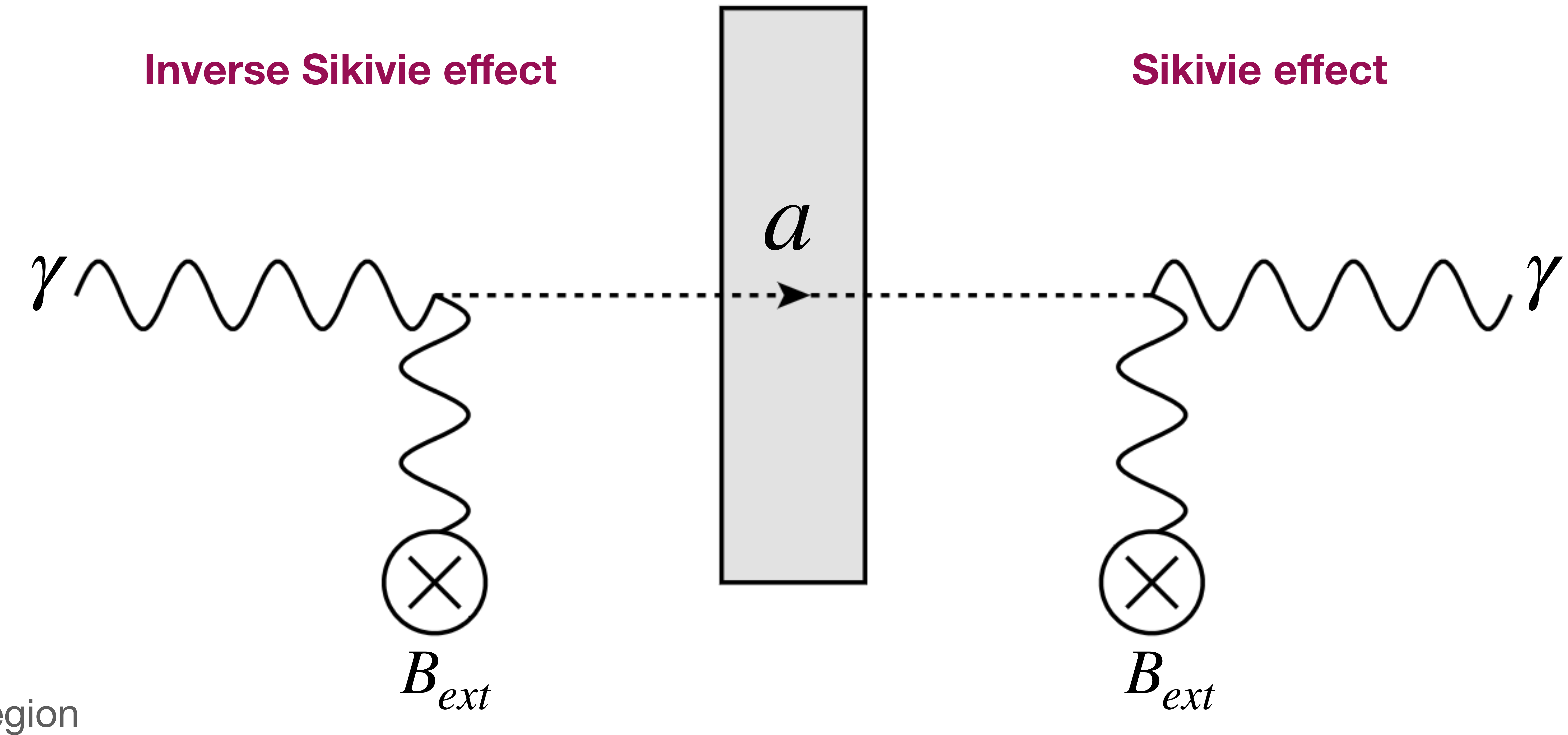


LSW Experiments

Astrophysics and cosmology

Haloscopes
Helioscopes

Light Shining Through Walls

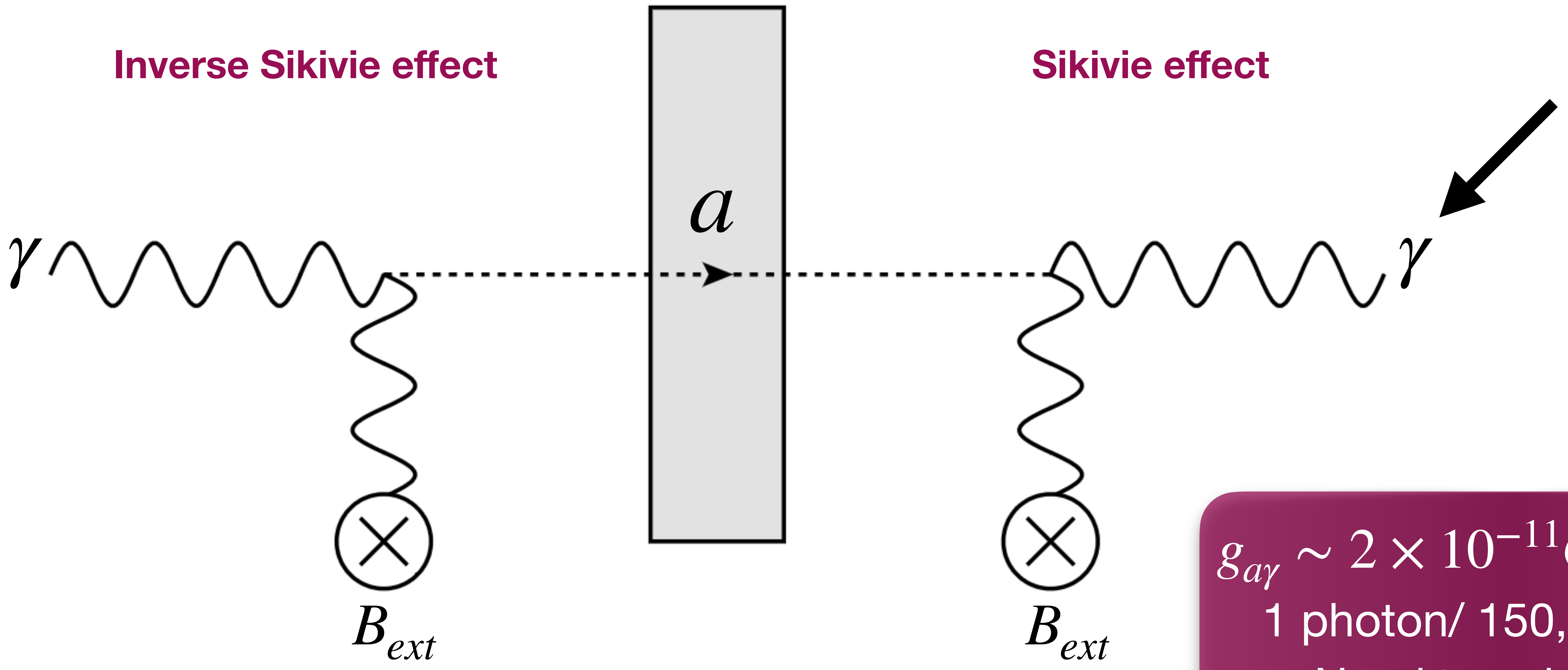


B → Magnetic field strength
L → Length in magnetic field region

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

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

Light Shining Through Walls



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

1 photon/ 150,000 years!

→Need to enhance signal!

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

$\omega \rightarrow$ laser energy

$\tau \rightarrow$ measurement time

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

$B \sim 5.3\ T$

$L \sim 2 \times 100\ m$

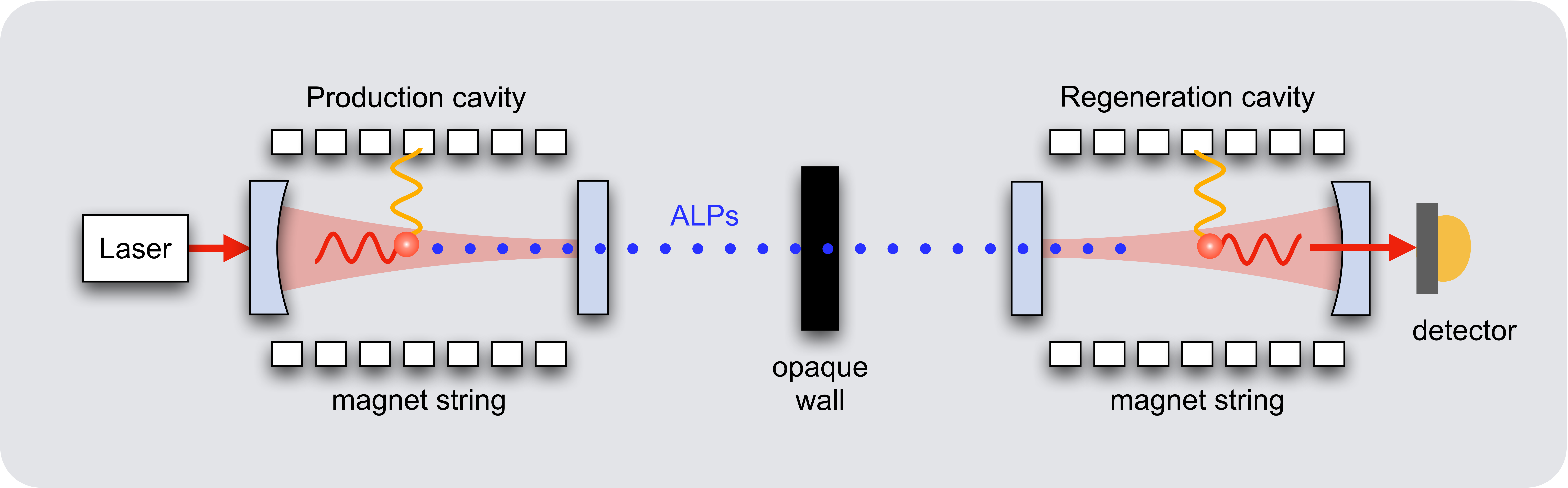
$P \sim 30\ W$

Any Light Particle Search (ALPS) II

Any Light Particle Search (ALPS) II

DESY, Hamburg | 6 institutions, ~30 members | Germany, US, UK

Any Light Particle Search (ALPS) II



Graphic from Katharina-Sophie Isleif

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

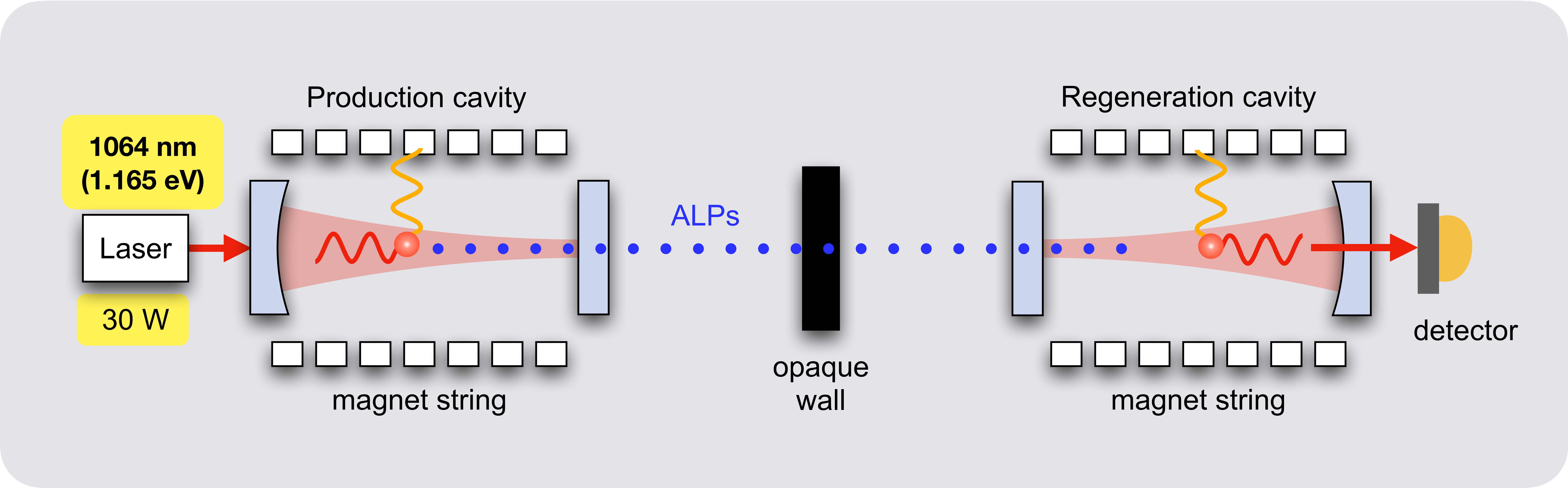
$\mathscr{P}_i \rightarrow$ laser power

$\omega \rightarrow$ 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



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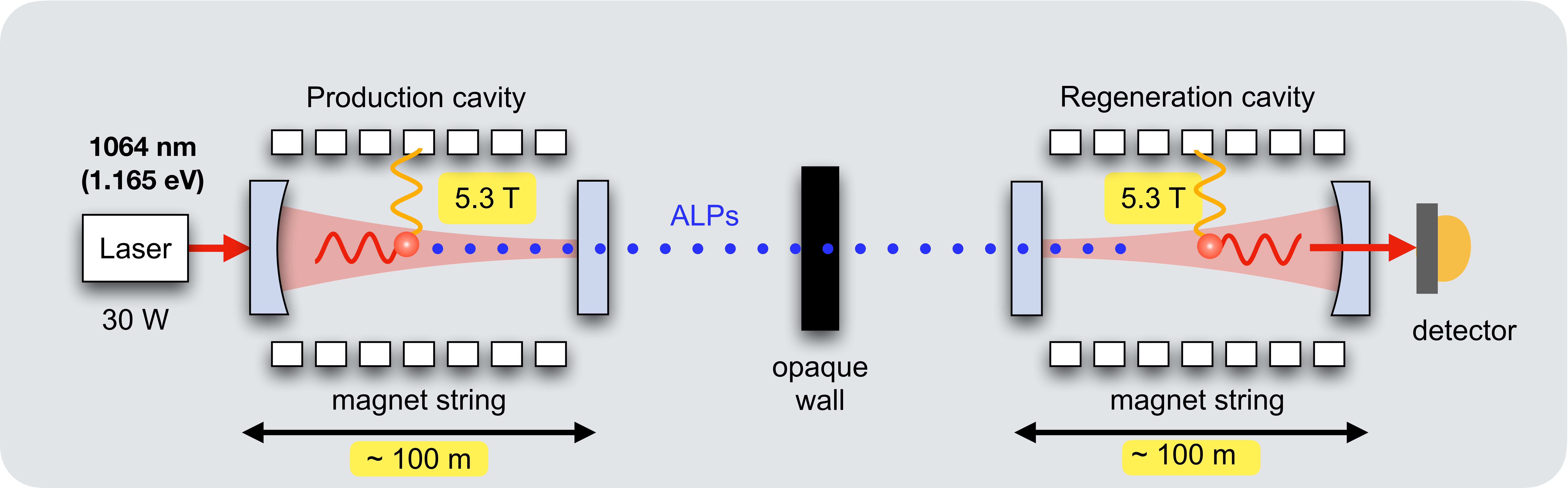
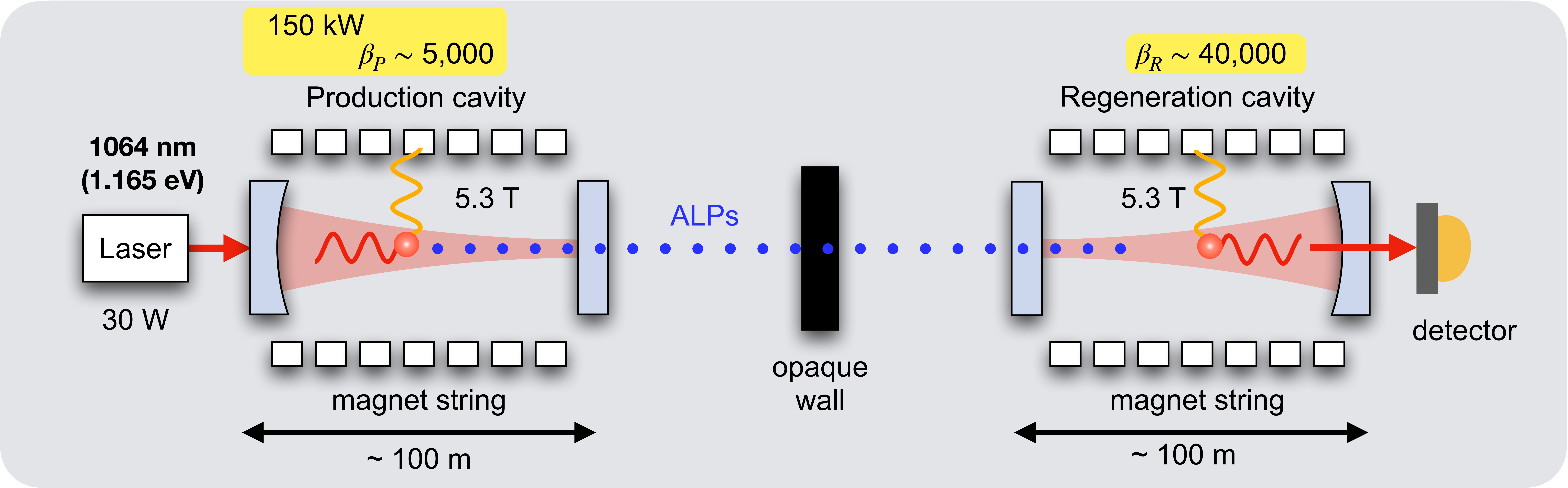


Graphic from Katharina-Sophie Isleif

- Using 24 straightened HERA magnets

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

Any Light Particle Search (ALPS) II



Graphic from Katharina-Sophie Isleif

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

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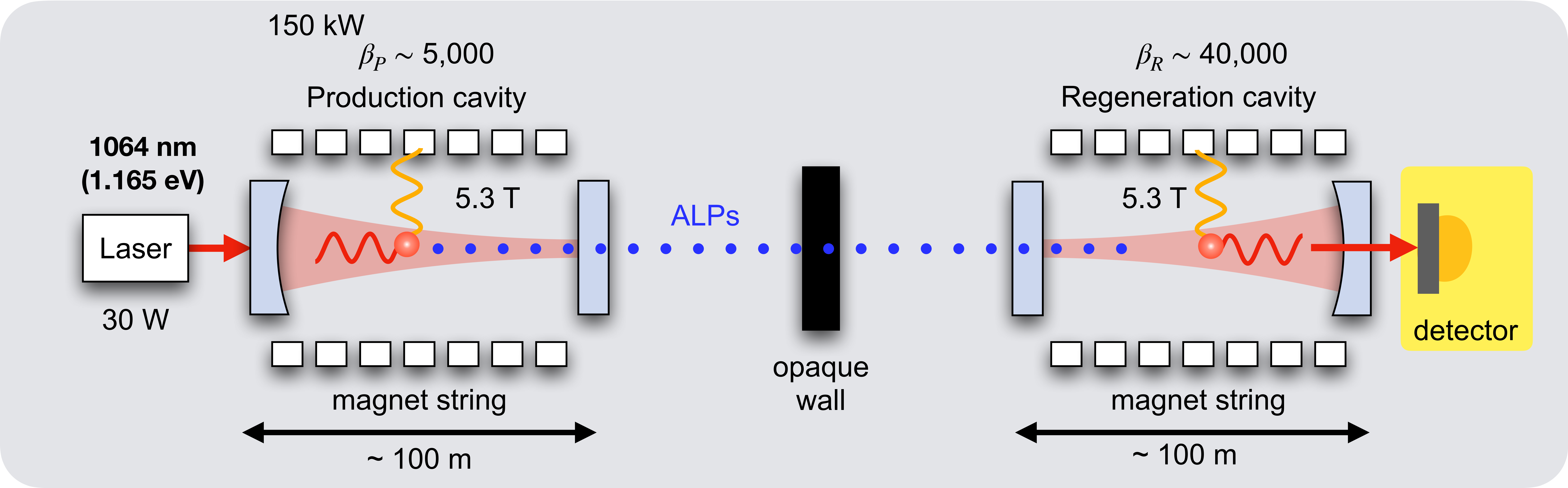
Any Light Particle Search (ALPS) II



Graphic from Katharina-Sophie Isleif

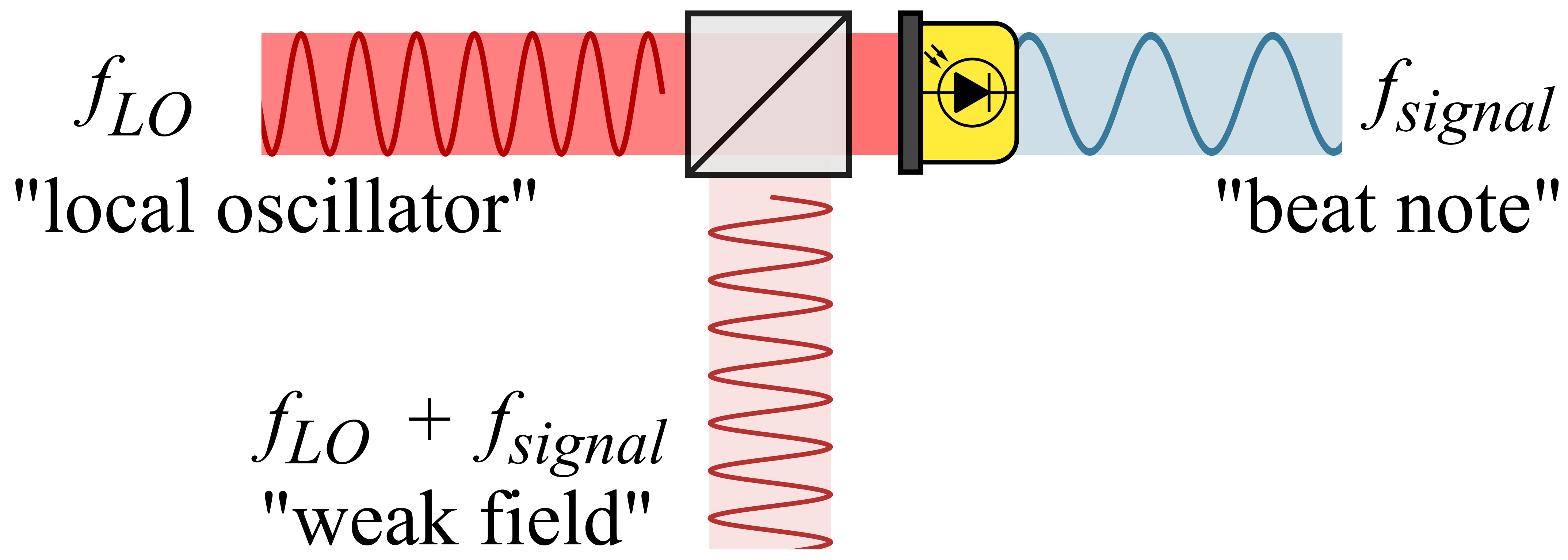
- Using 24 straightened HERA magnets
- Fabry-Perot resonators in production *and* regeneration region
- 150 kW → 10^{-24} W (~1 photon/day)

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

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

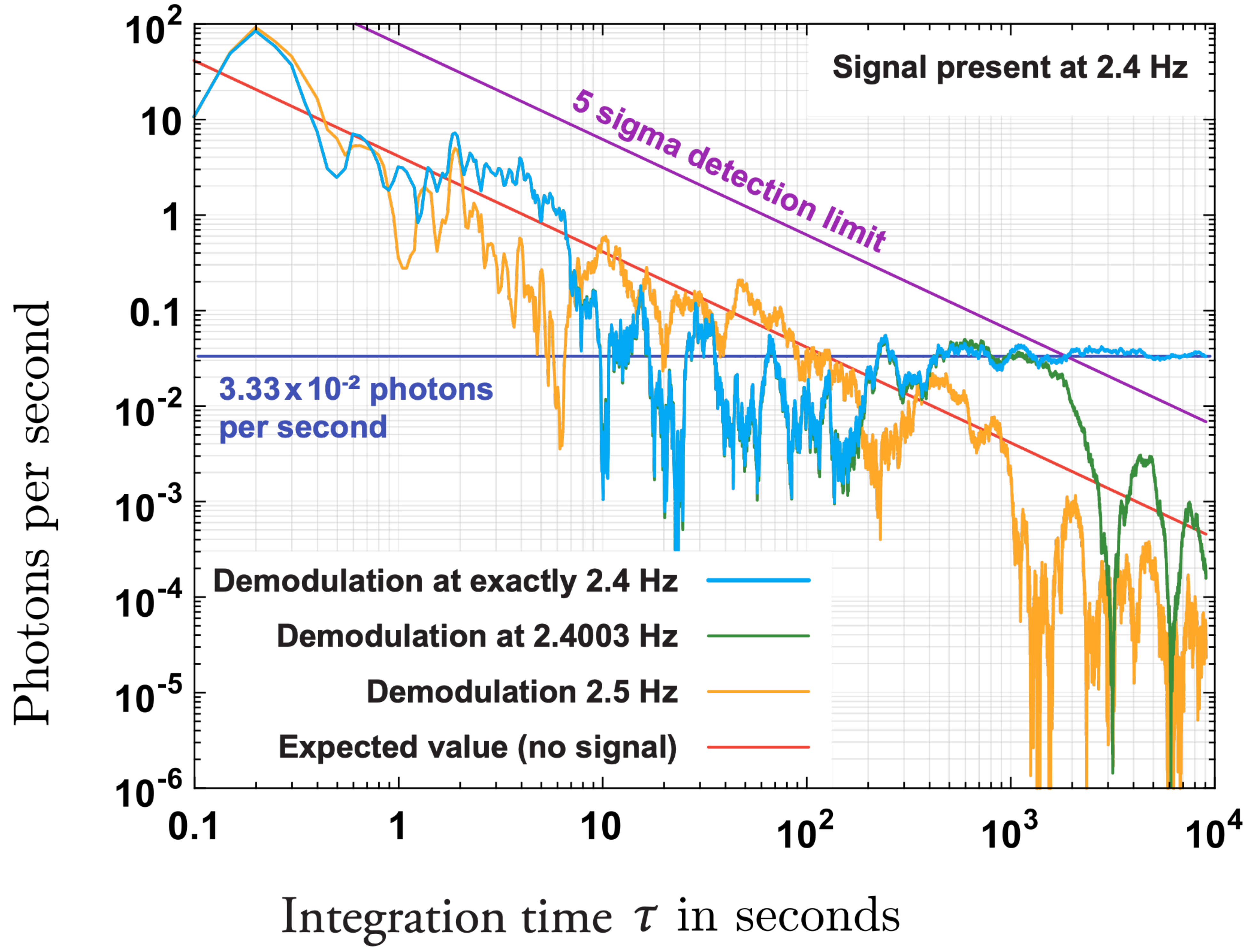
ALPS II- Heterodyne

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



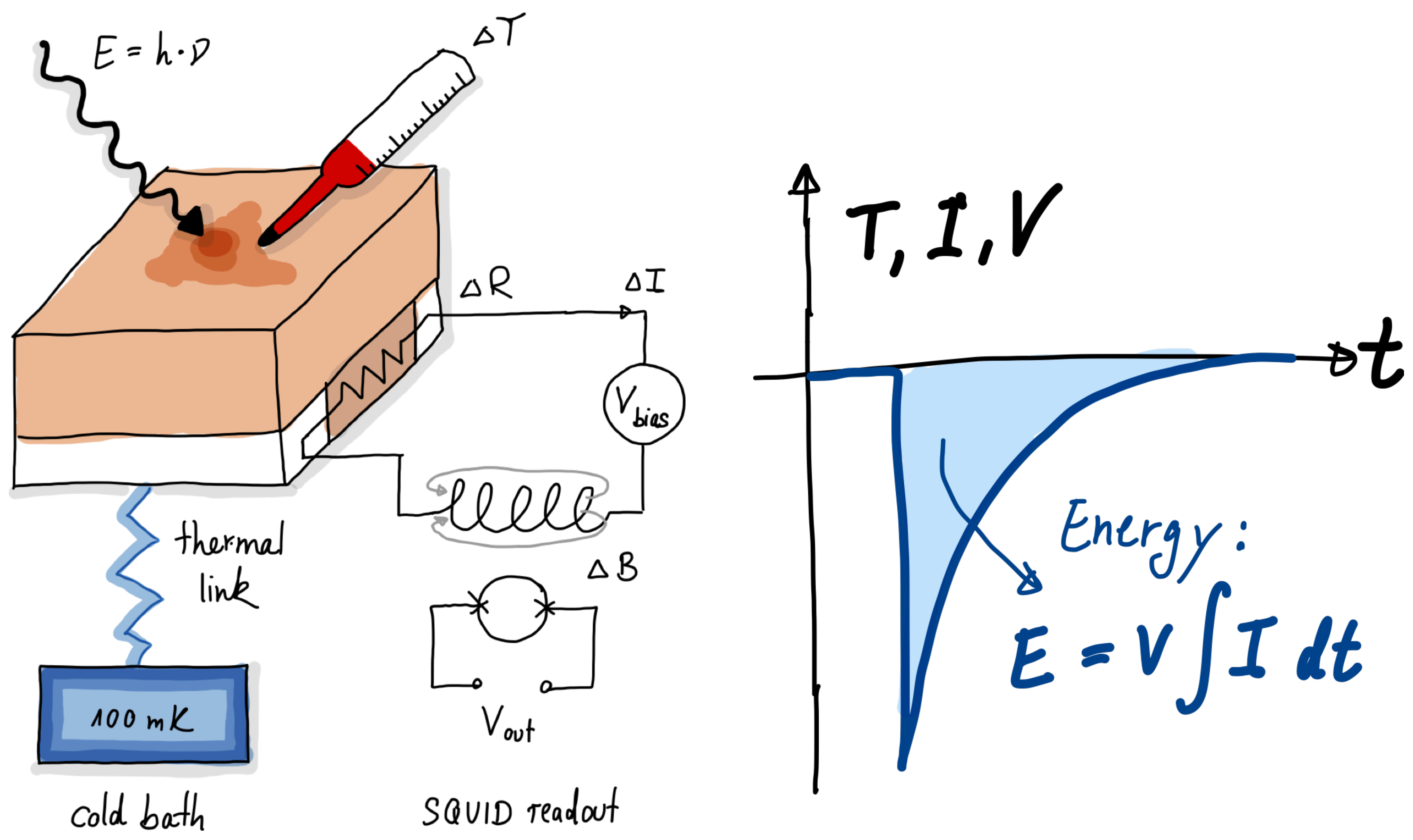
"Coherent detection of ultraweak electromagnetic fields",
Z. Bush et al., Phys. Rev. D 99, 022001 (2019)

ALPS II- Transition Edge Sensor

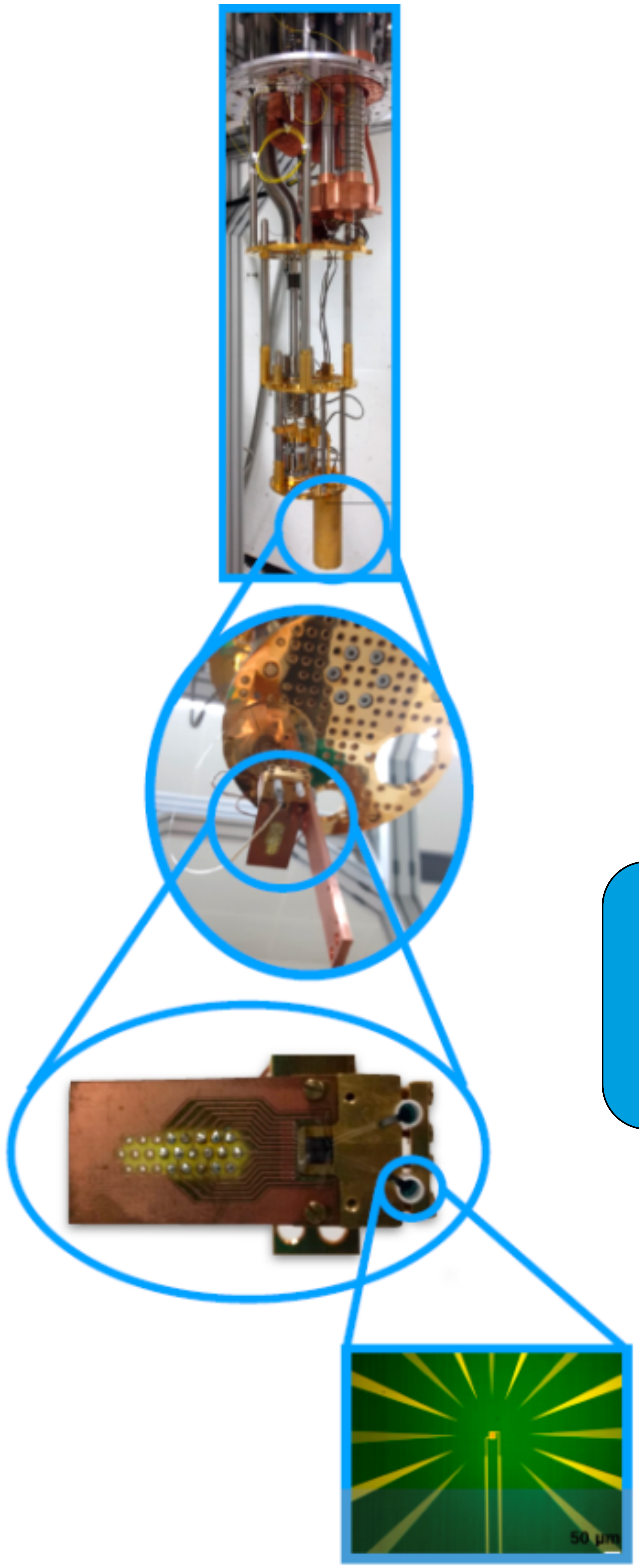
Looking for $5\cdot10^{-24}$ W @ 1064 nm

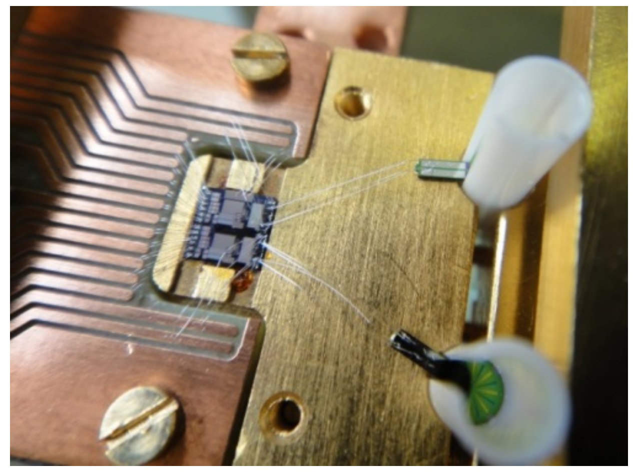
Option 2: photon counting

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



Low dark counts ($6.9^{+5.18}_{-2.93}\cdot10^{-6}$Hz, 95% CL) shown





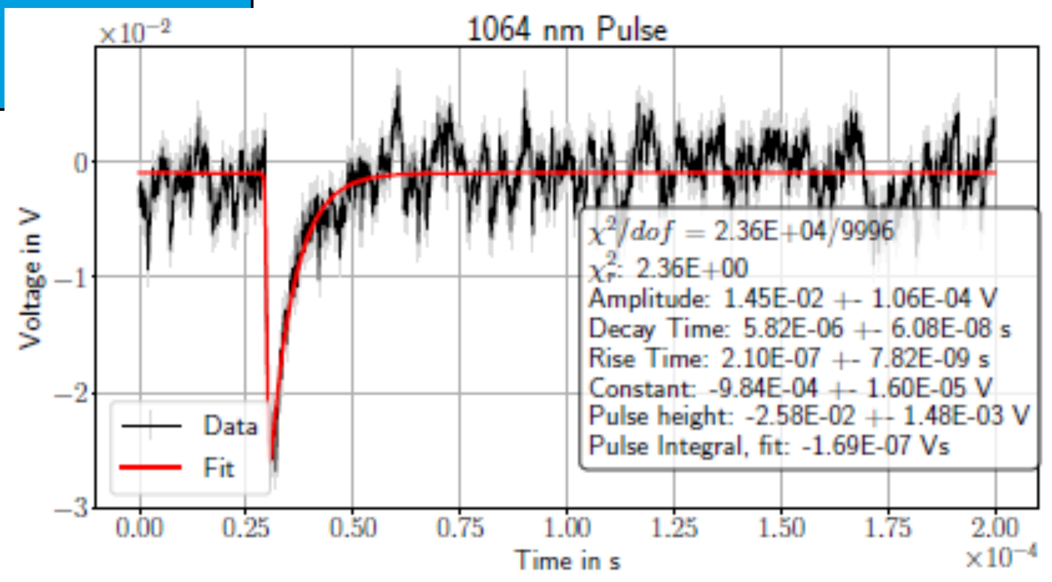
TES chip within the transition region at critical temperature

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

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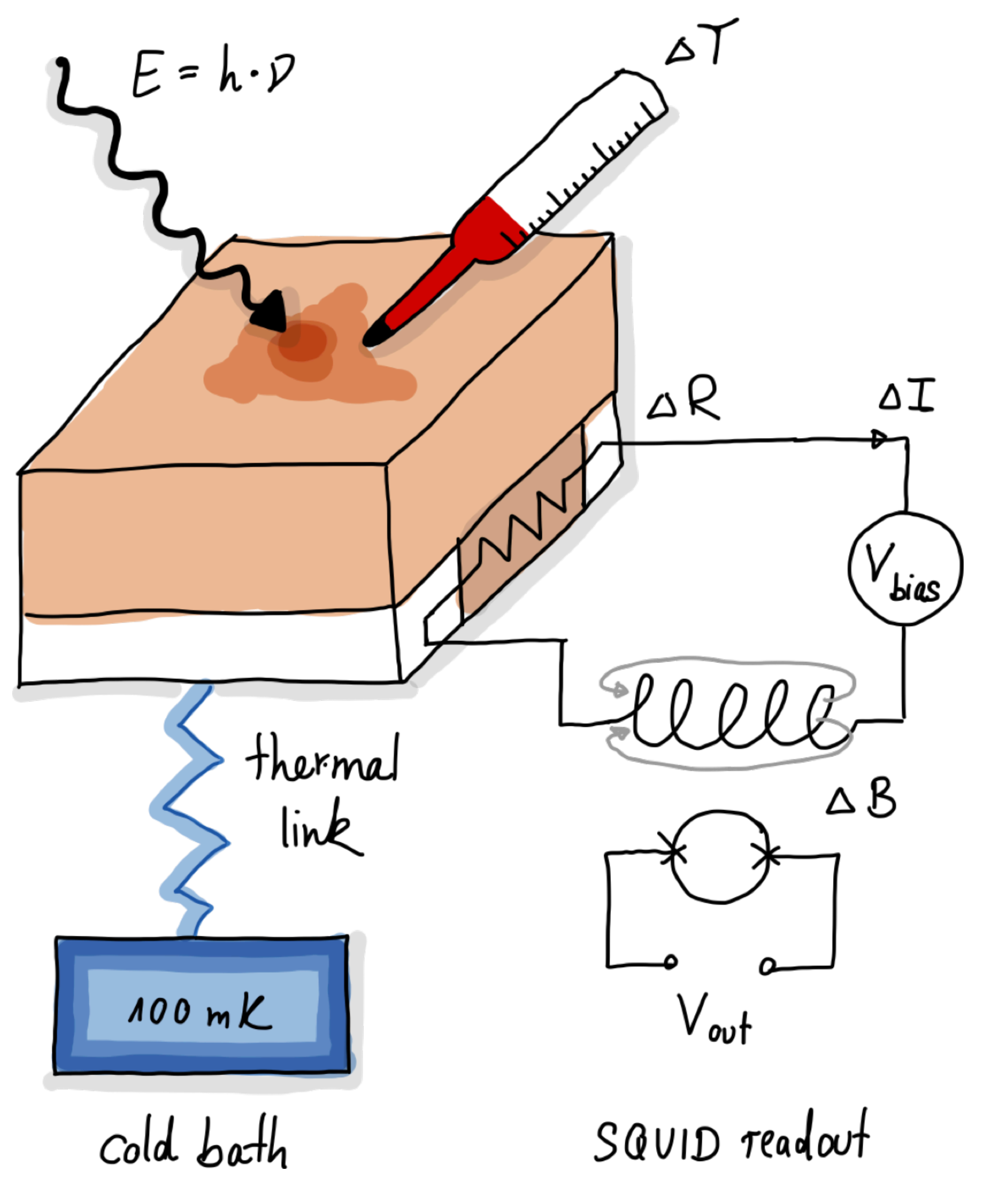
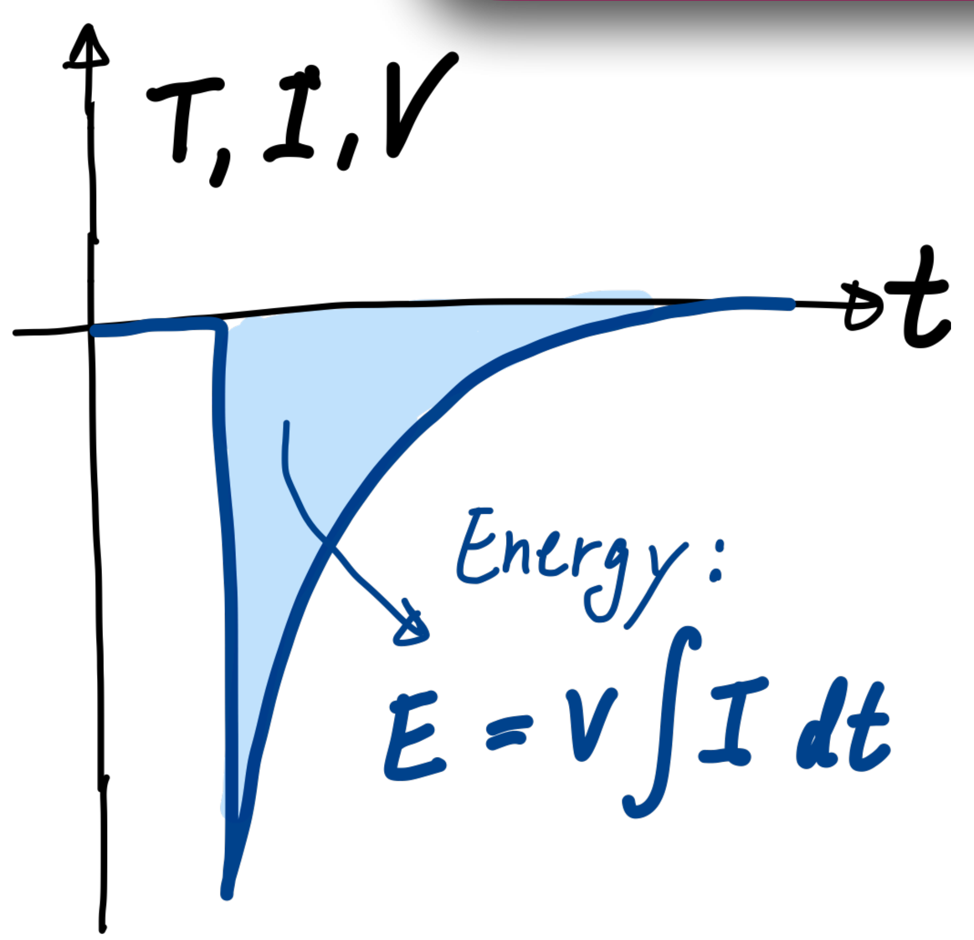
Poster session 1:
Manuel Meyer
Machine Learning with TES pulses

Poster session 2:
Rikhav Shah
TES for ALPS II





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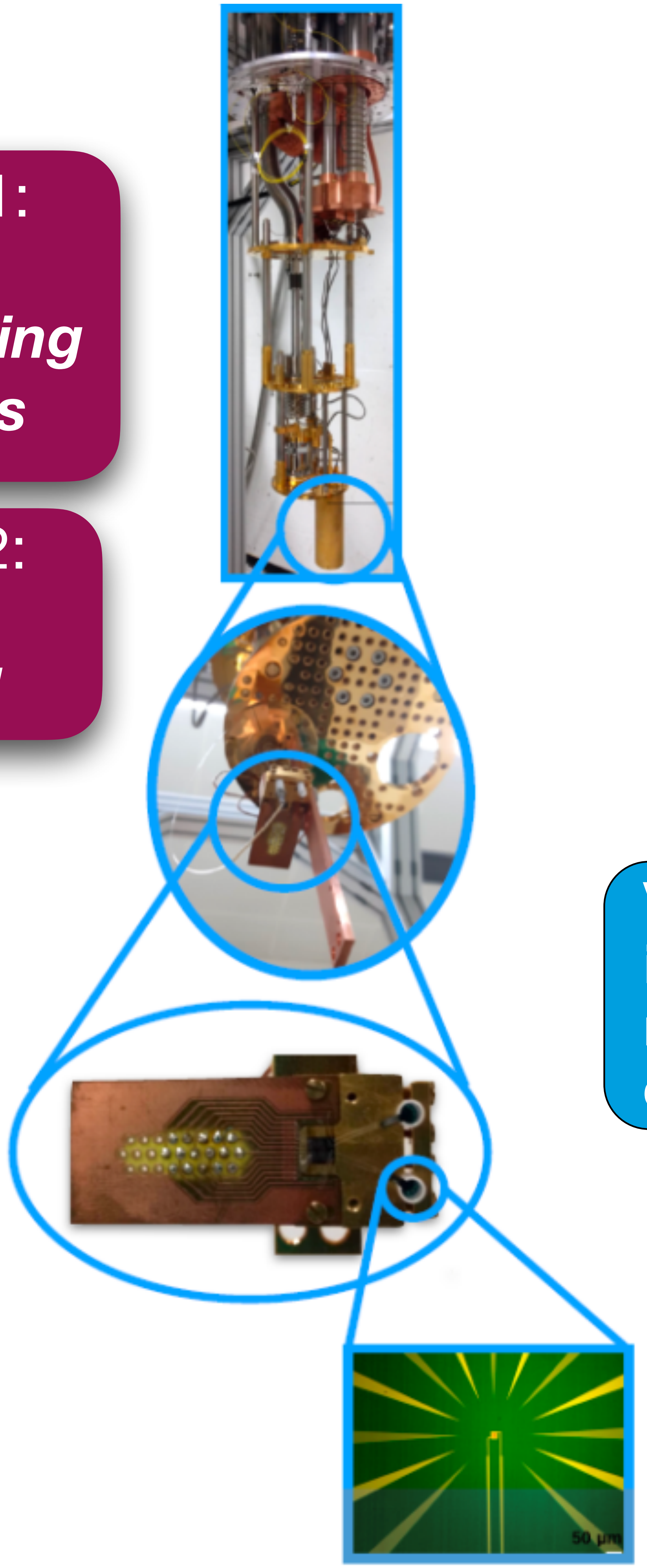

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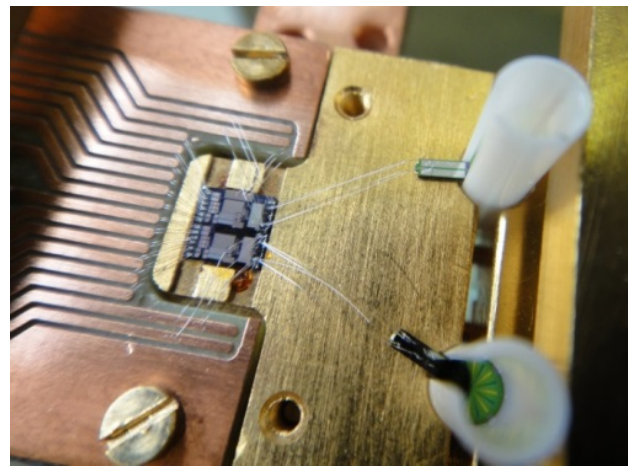

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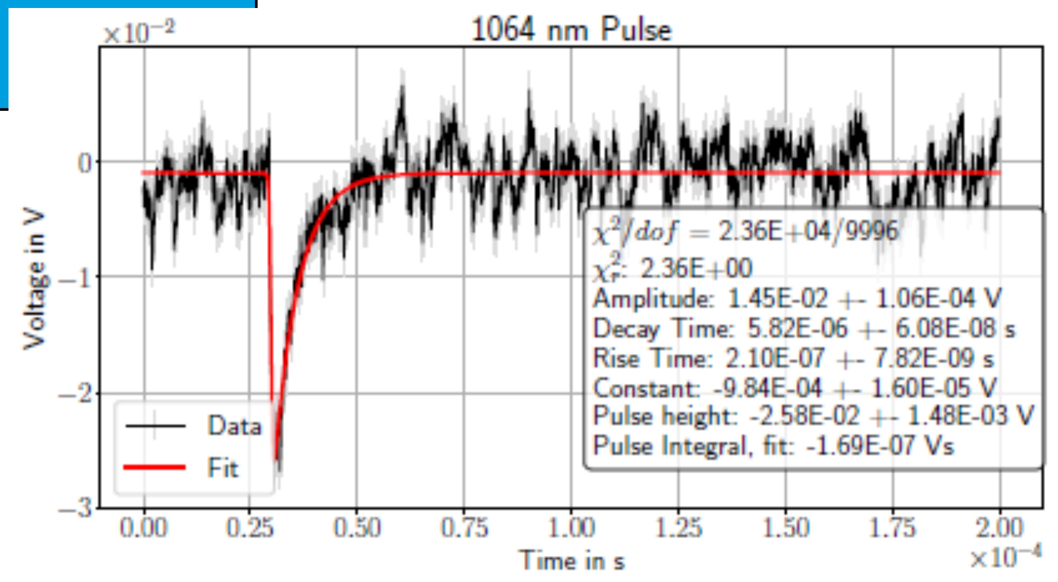
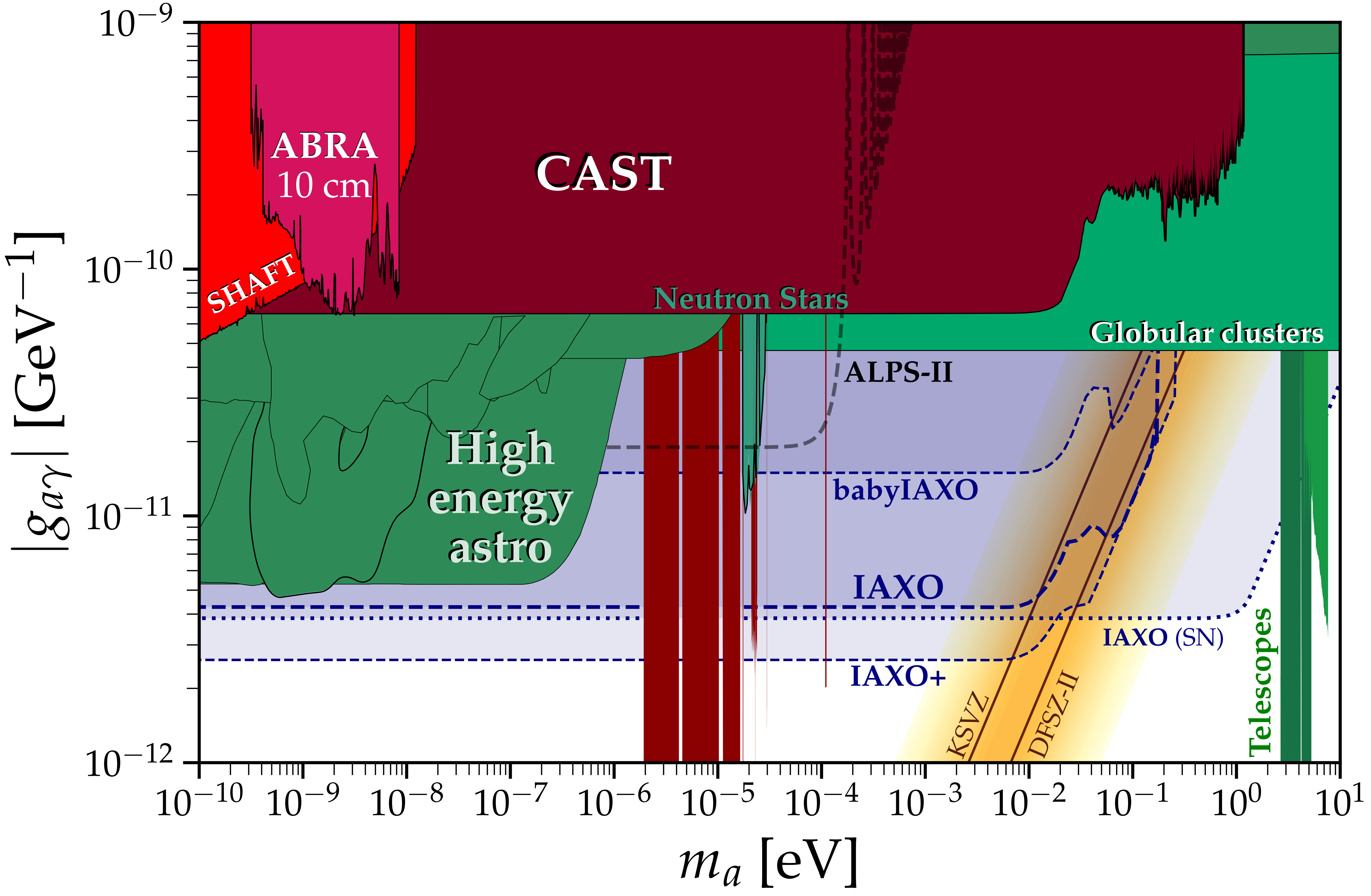


Slide from Friederike Januschek

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 year

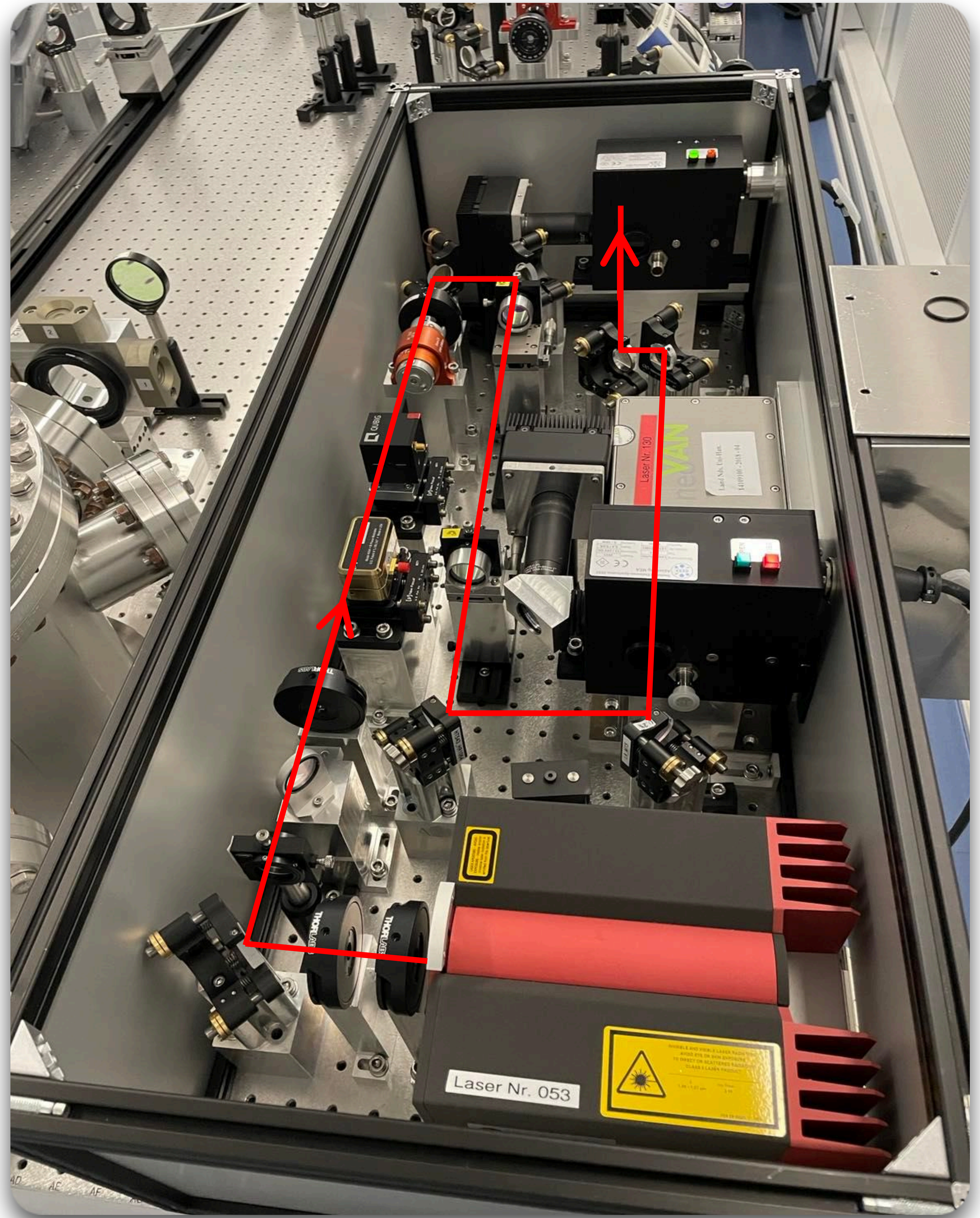
github.com/cajohare/AxionLimits/



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

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

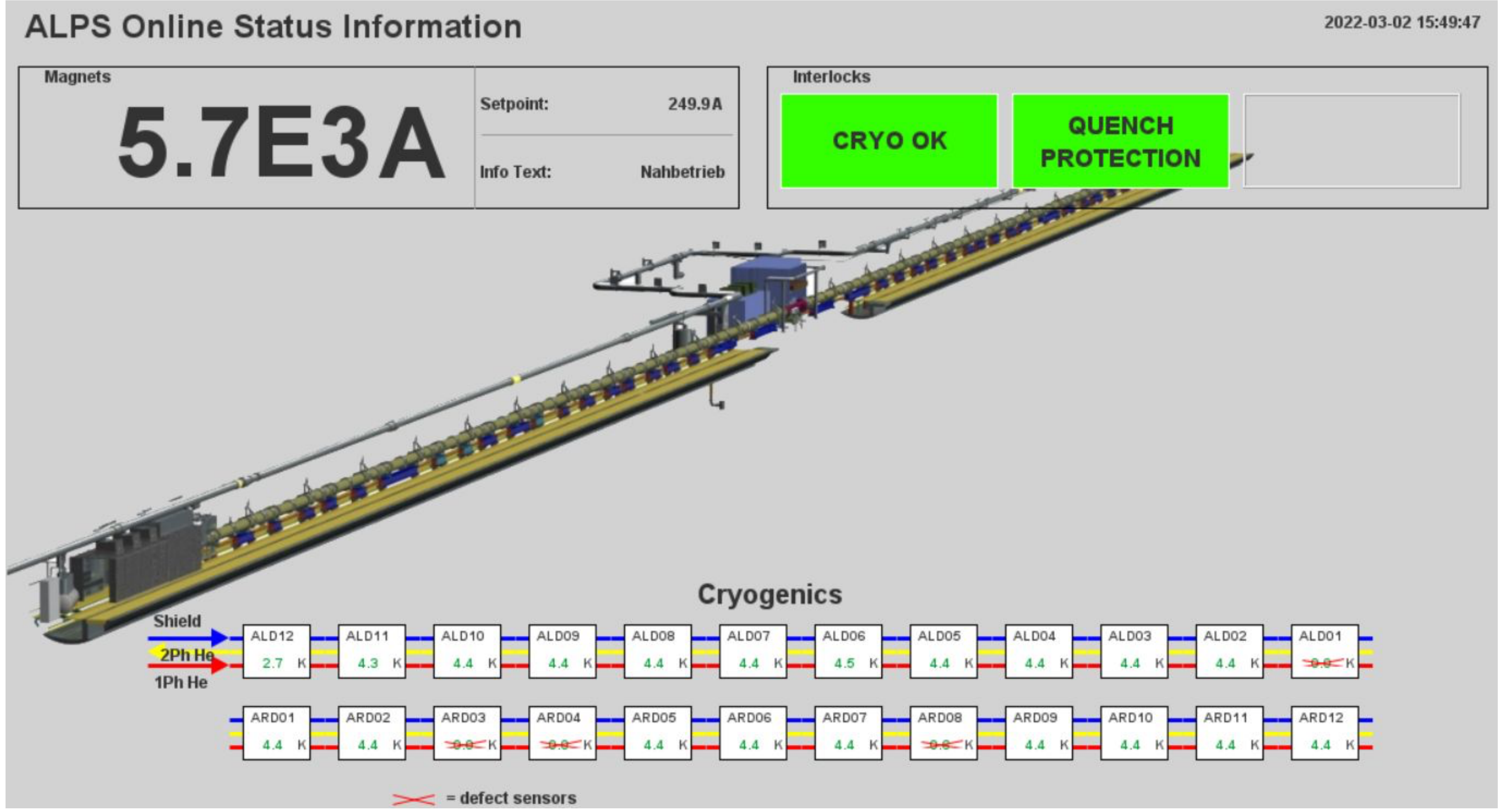


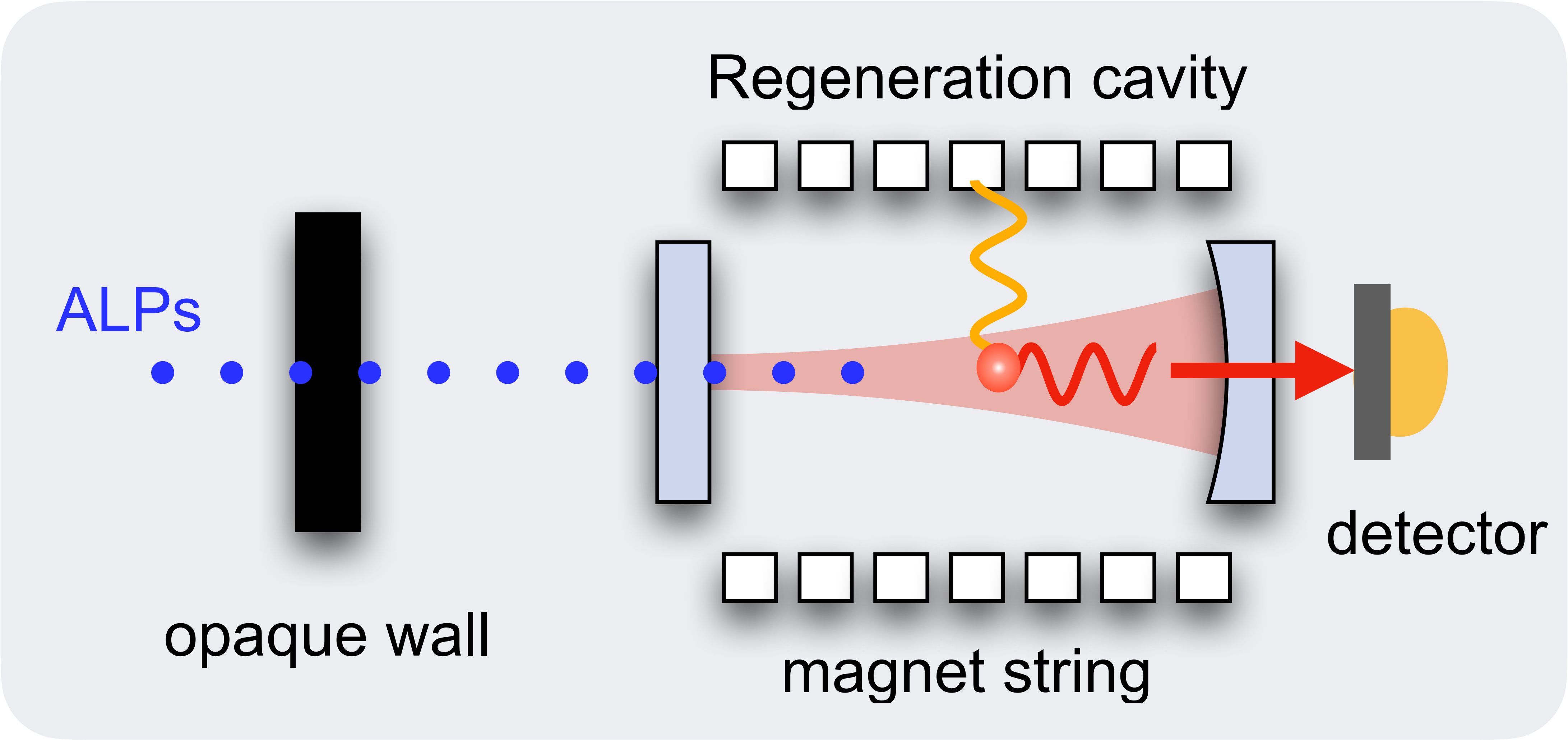
Photo by Heiner Müller-Elsner

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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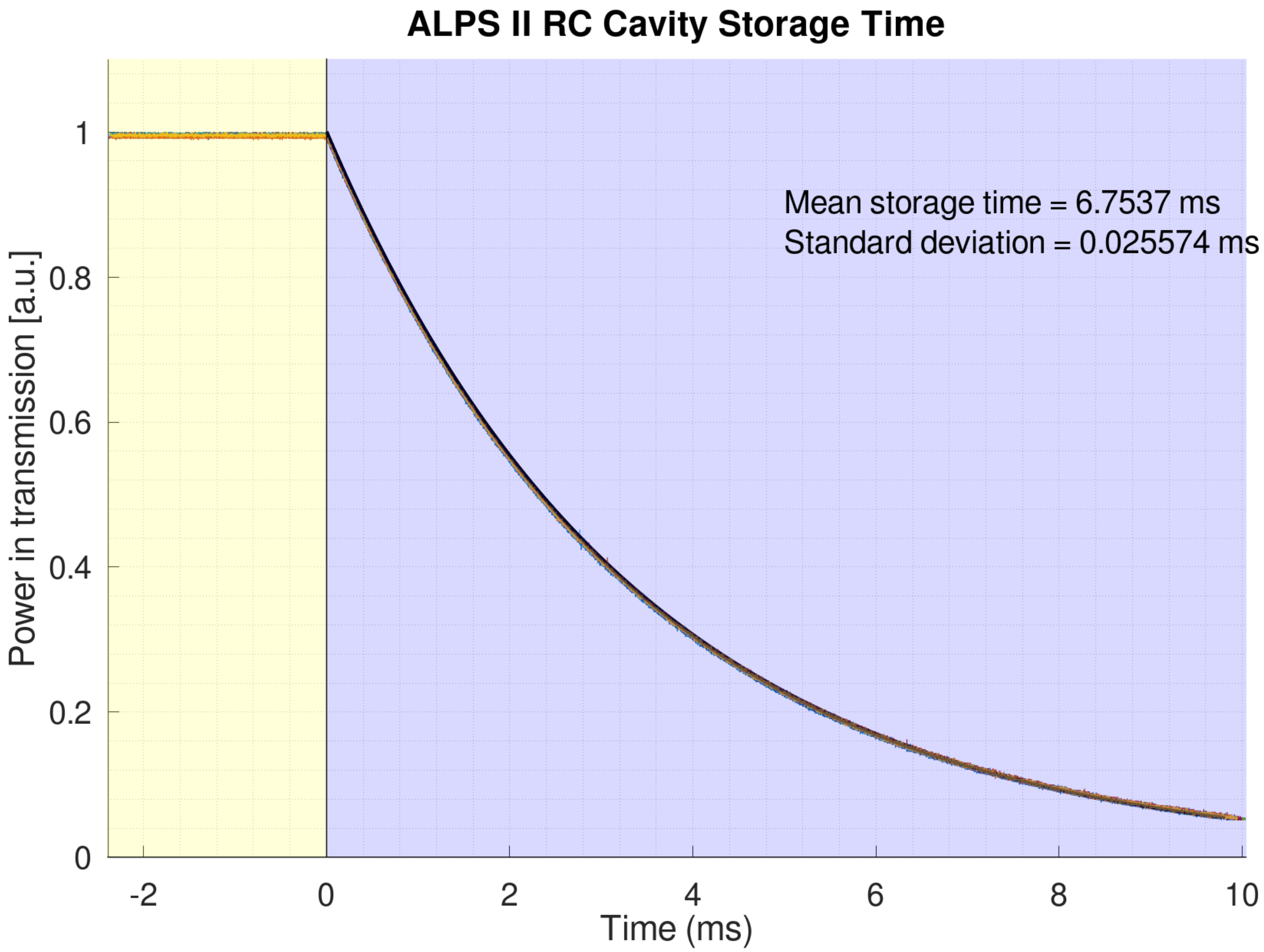


First Science Run **Before the end of the year!**

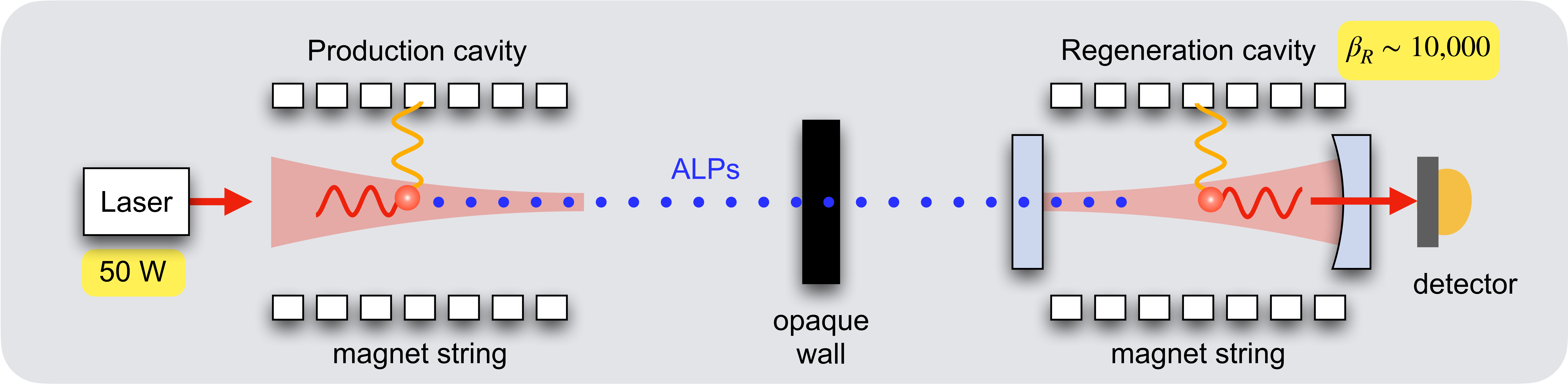
Commissioning optical setup without production cavity

- Simpler control scheme
- Stronger signals for stray light hunting

- Input 50 W laser power
- Regeneration cavity in place
  - Factor of ~350 improvement over ALPS I sensitivity

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

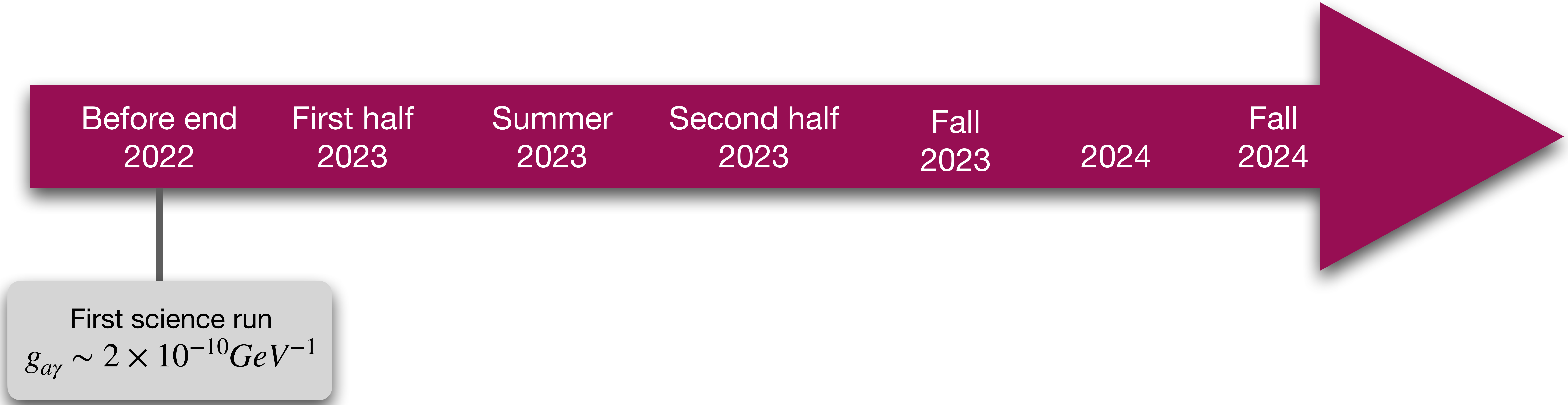
Graphic from Katharina-Sophie Isleif



Preliminary ALPS II Schedule

Before end 2022 | First half 2023 | Summer 2023 | Second half 2023 | Fall 2023 | 2024 | Fall 2024

Preliminary ALPS II Schedule



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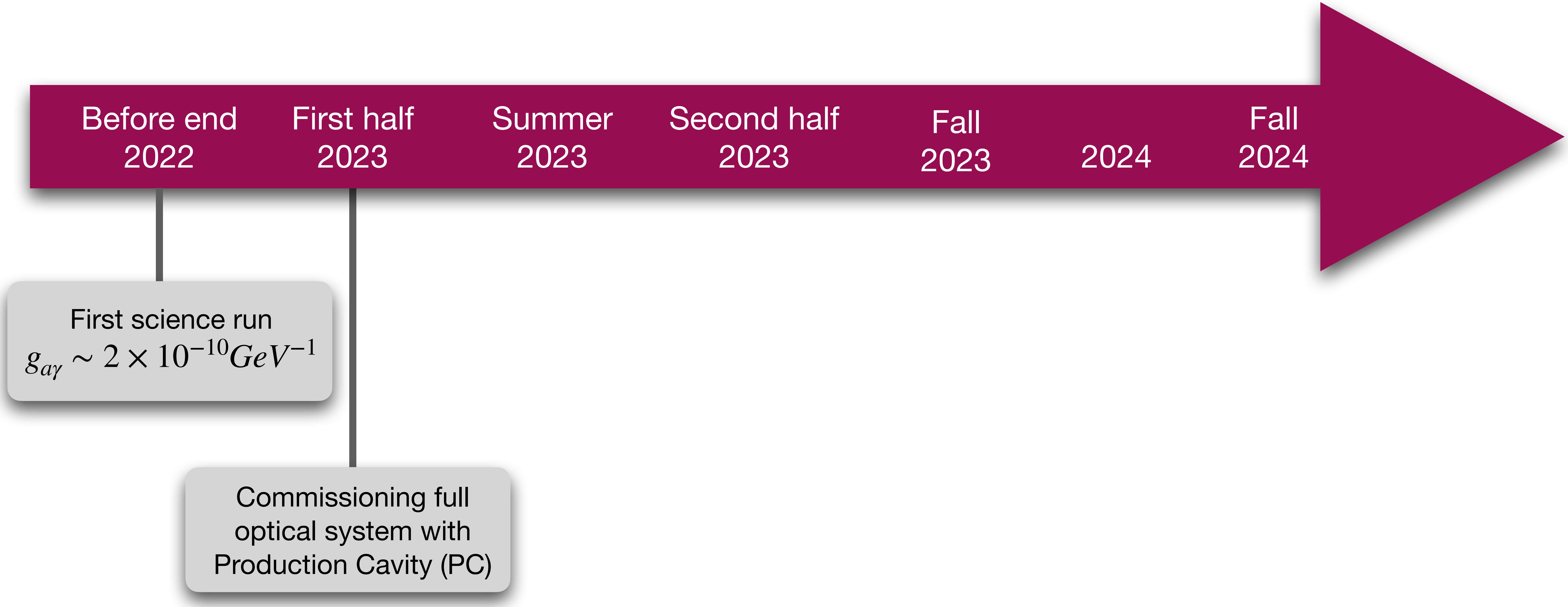

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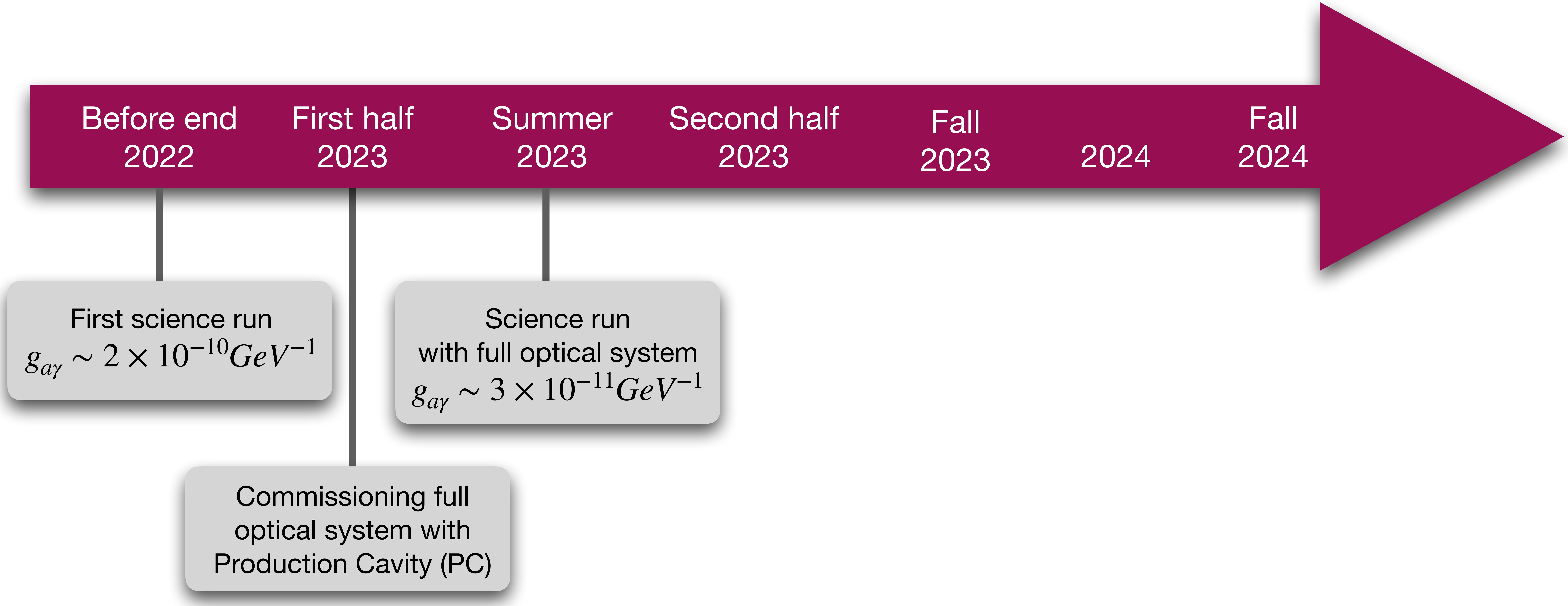

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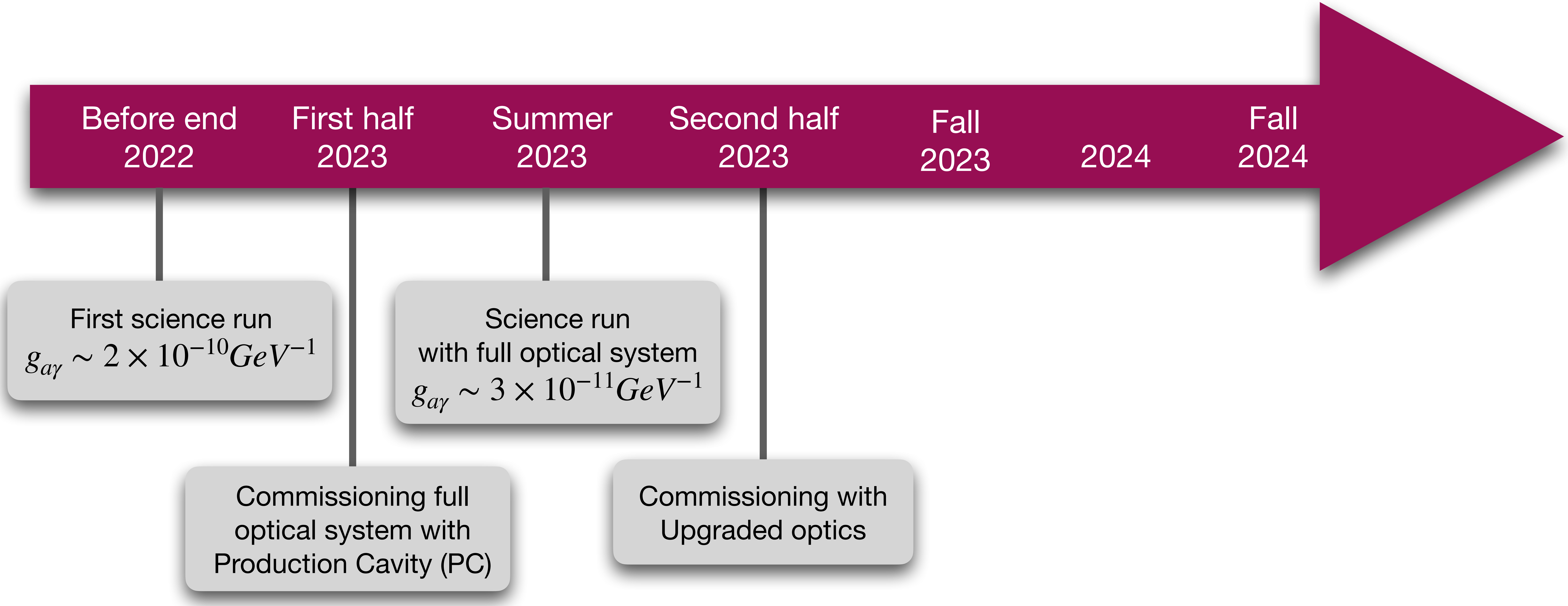

Preliminary ALPS II Schedule

- **Before end 2022** — First science run: $g_{a\gamma} \sim 2 \times 10^{-10} GeV^{-1}$
- **First half 2023** — Commissioning full optical system with Production Cavity (PC)
- **Summer 2023** — Science run with full optical system: $g_{a\gamma} \sim 3 \times 10^{-11} GeV^{-1}$
- **Second half 2023** — Commissioning with Upgraded optics
- **Fall 2023** — Science run with upgraded optics: $g_{a\gamma} \sim 2 \times 10^{-11} GeV^{-1}$
- **2024**
- **Fall 2024**

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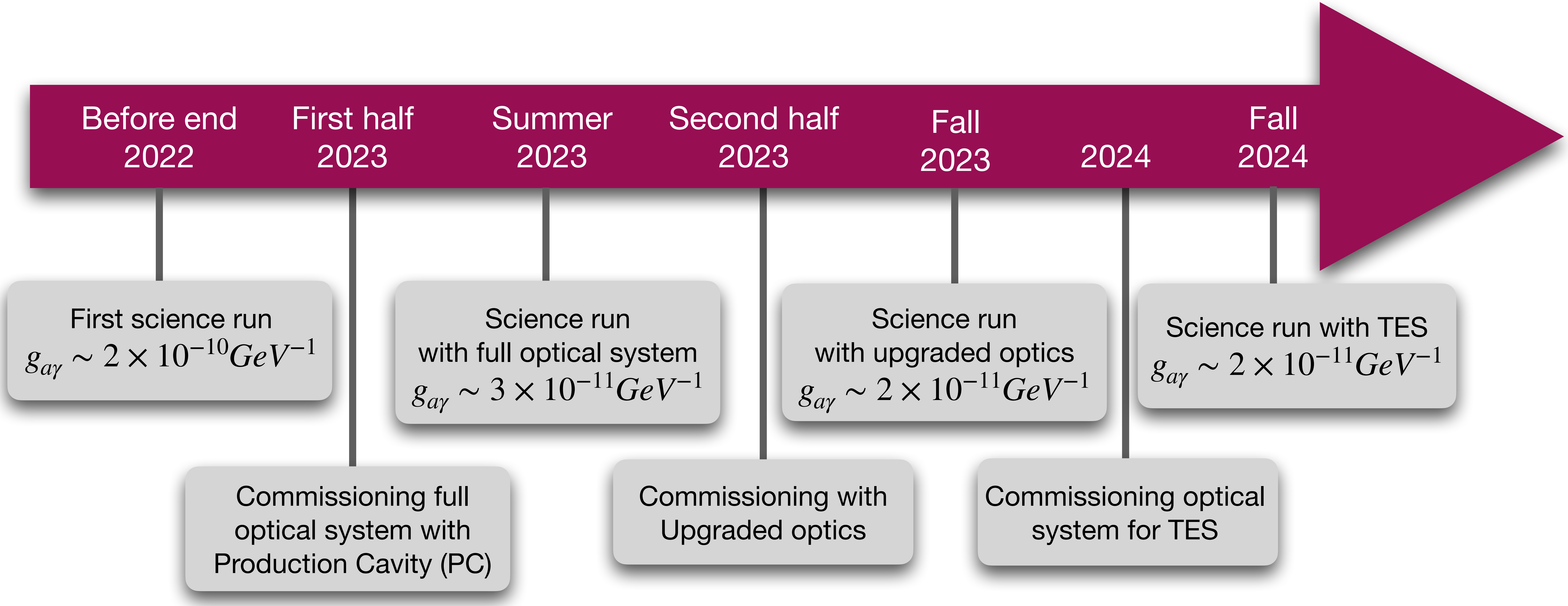
- **Fall 2023** — Science run with upgraded optics: $g_{a\gamma} \sim 2 \times 10^{-11} GeV^{-1}$
- **2024** — Commissioning optical system for TES
- **Fall 2024**

Preliminary ALPS II Schedule



Summary and Outlook

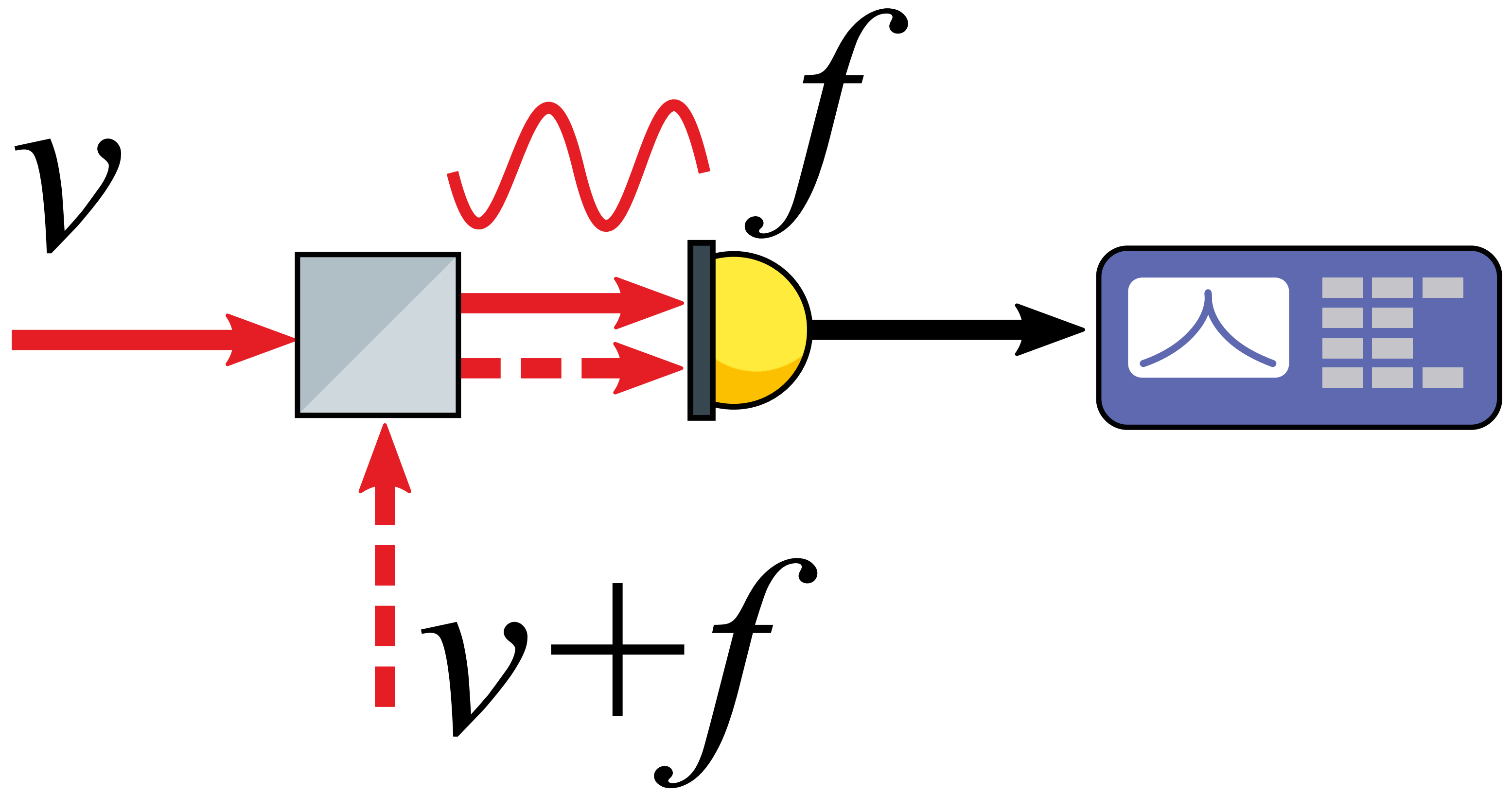
- ALPS II is a LSW experiment that will improve the limits for $g_{a\gamma}$ by over 3 orders of magnitude over OSQAR, ALPS I
- Begin checking astrophysical observations in a model-independent way
- First science run before the end of this year $\rightarrow g_{a\gamma} \sim 2 \times 10^{-10}\ GeV^{-1}$
- Full sensitivity run after upgrades around Fall 2023 $\rightarrow g_{a\gamma} \sim 2 \times 10^{-11}\ GeV^{-1}$

Thank you!

Backup slides

Heterodyne Interferometry

Measuring single photon power levels



Measuring the interference beatnote

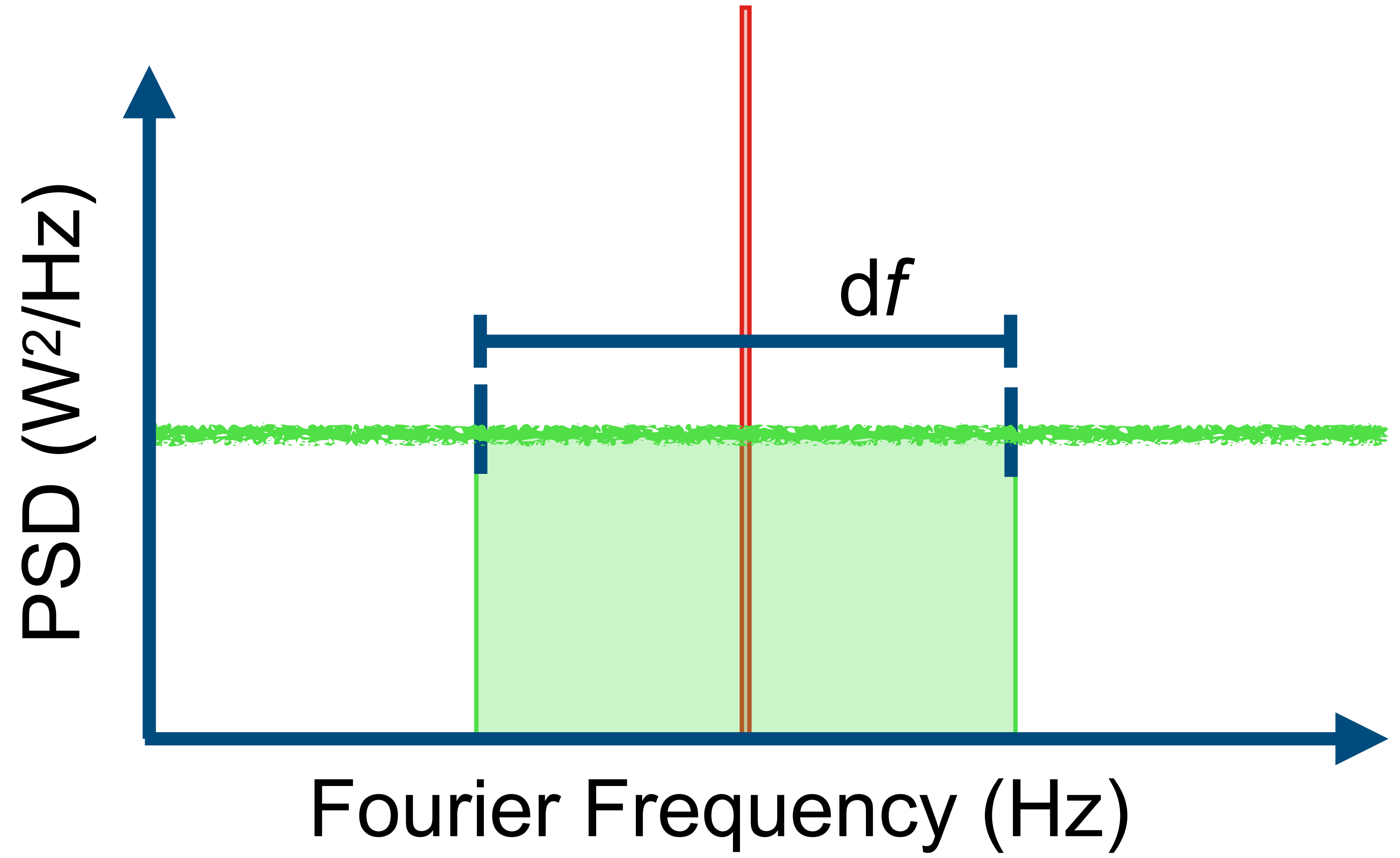
- Signal field optically mixed with Local Oscillator (LO) laser
  - Interference beatnote in power at the difference frequency
  - Photon counting stats -> Shot noise
- Demodulate power measurement at difference frequency

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

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

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

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



Heterodyne Interferometry

Measuring single photon power levels

Measuring the interference beatnote

- Signal field optically mixed with Local O
  - Interference beatnote in power at the
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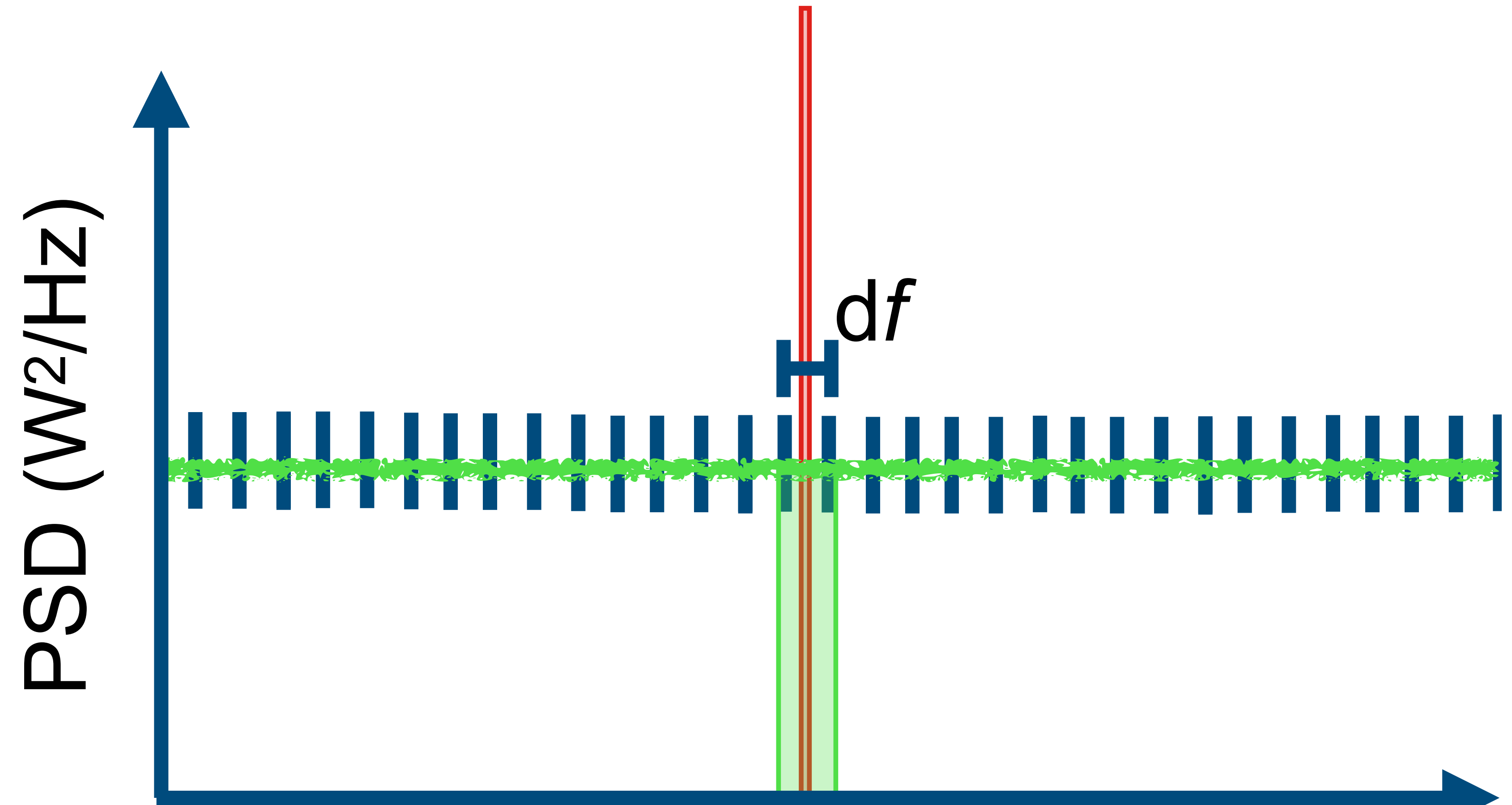
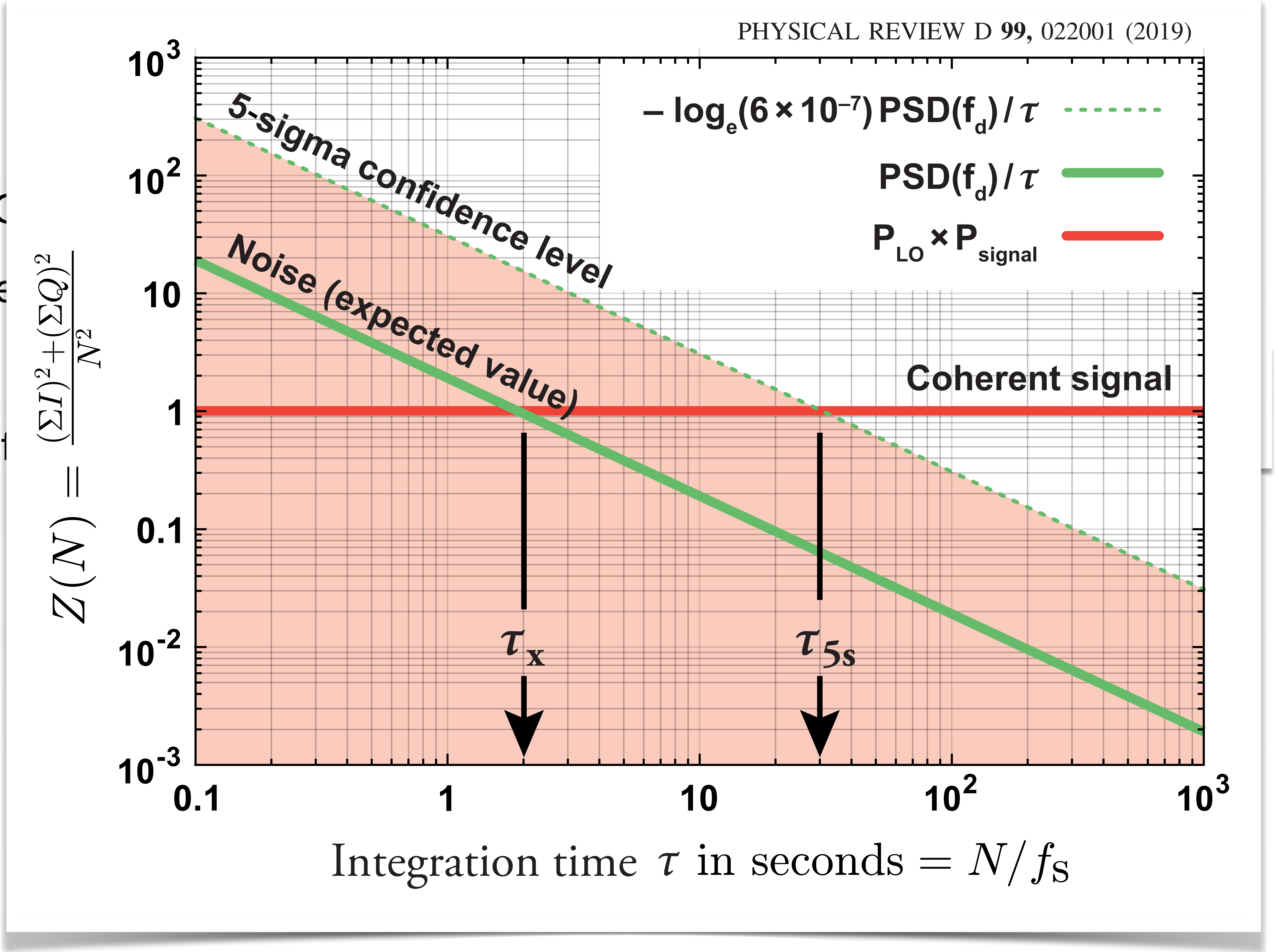
- Demodulate power measurement at di



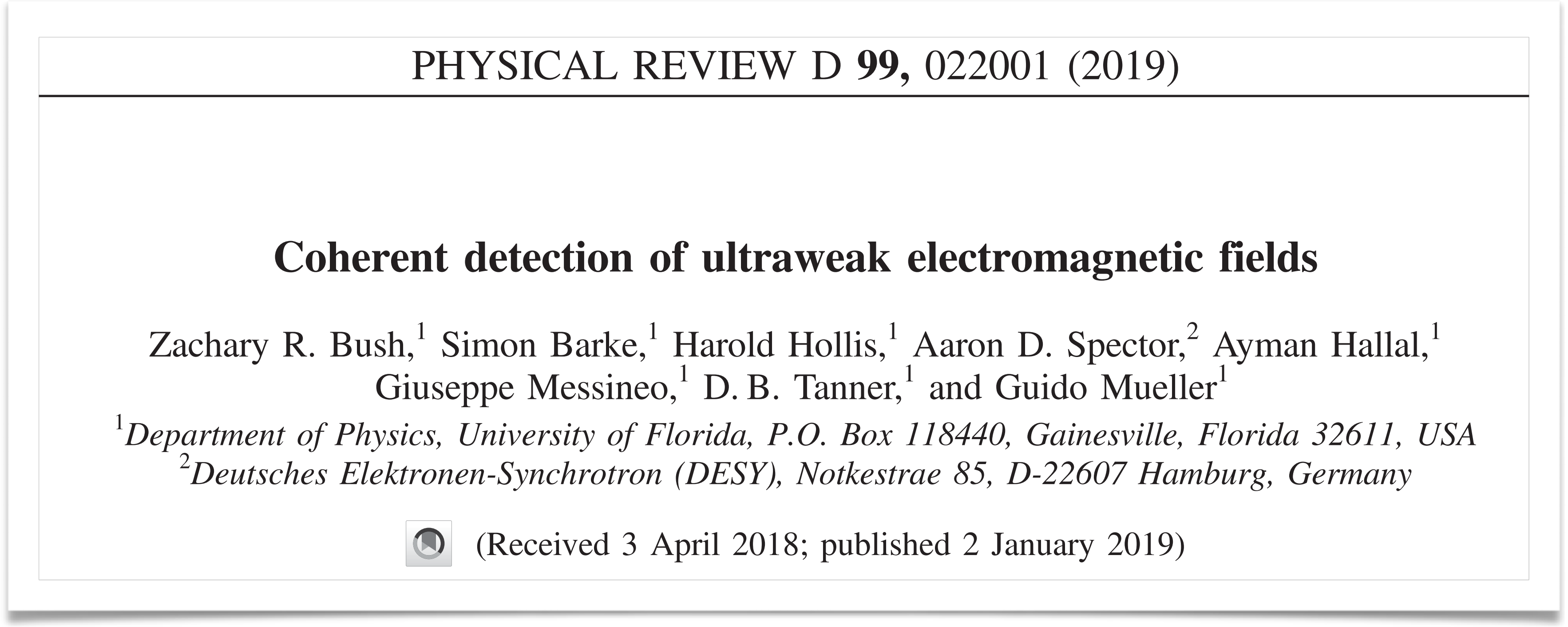


Heterodyne Signal

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

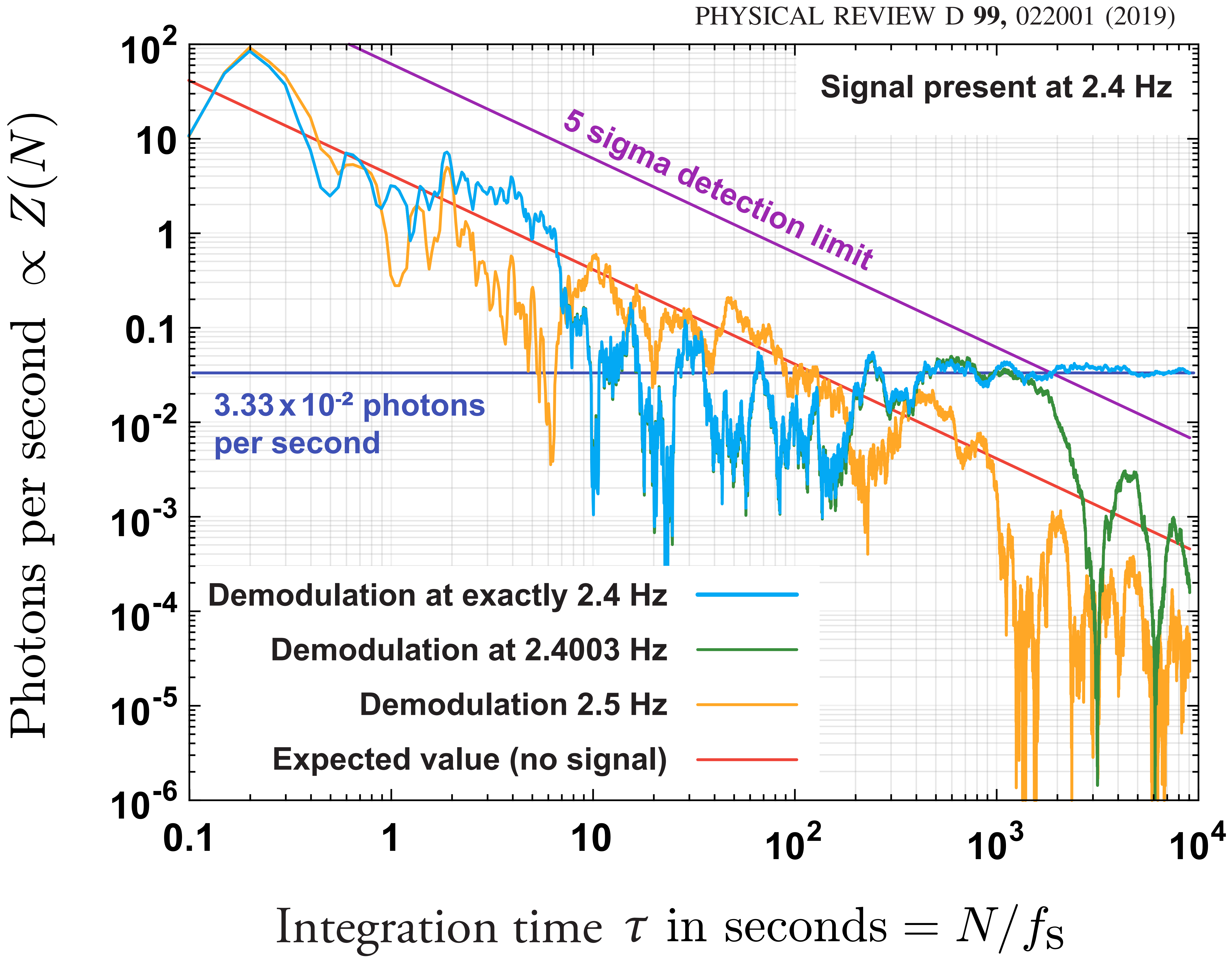

PHYSICAL REVIEW D **99,** 022001 (2019)

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]

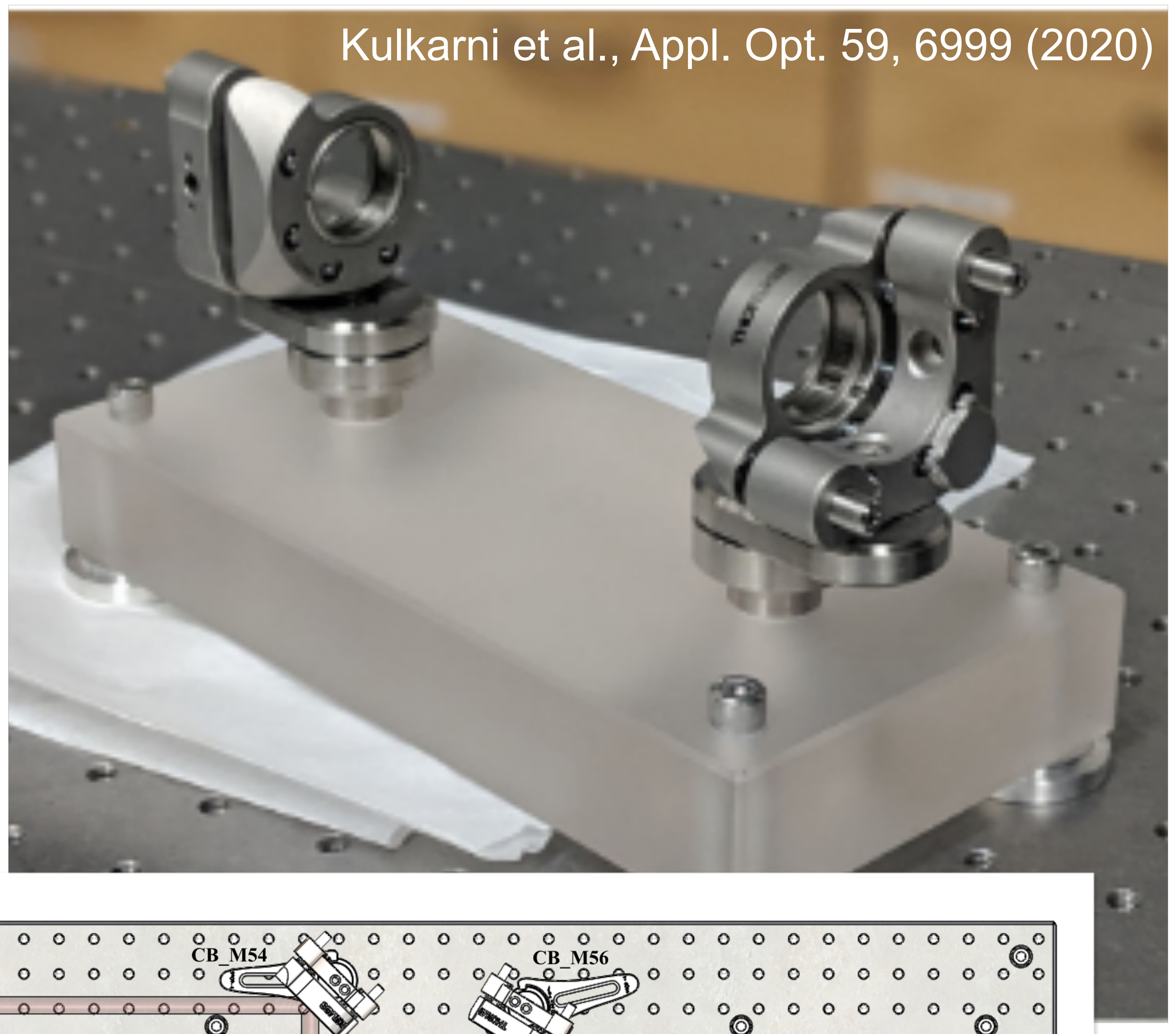
[1]*Department of Physics, University of Florida, P.O. Box 118440, Gainesville, Florida 32611, USA*
[2]*Deutsches Elektronen-Synchrotron (DESY), Notkestrae 85, D-22607 Hamburg, Germany*

(Received 3 April 2018; published 2 January 2019)



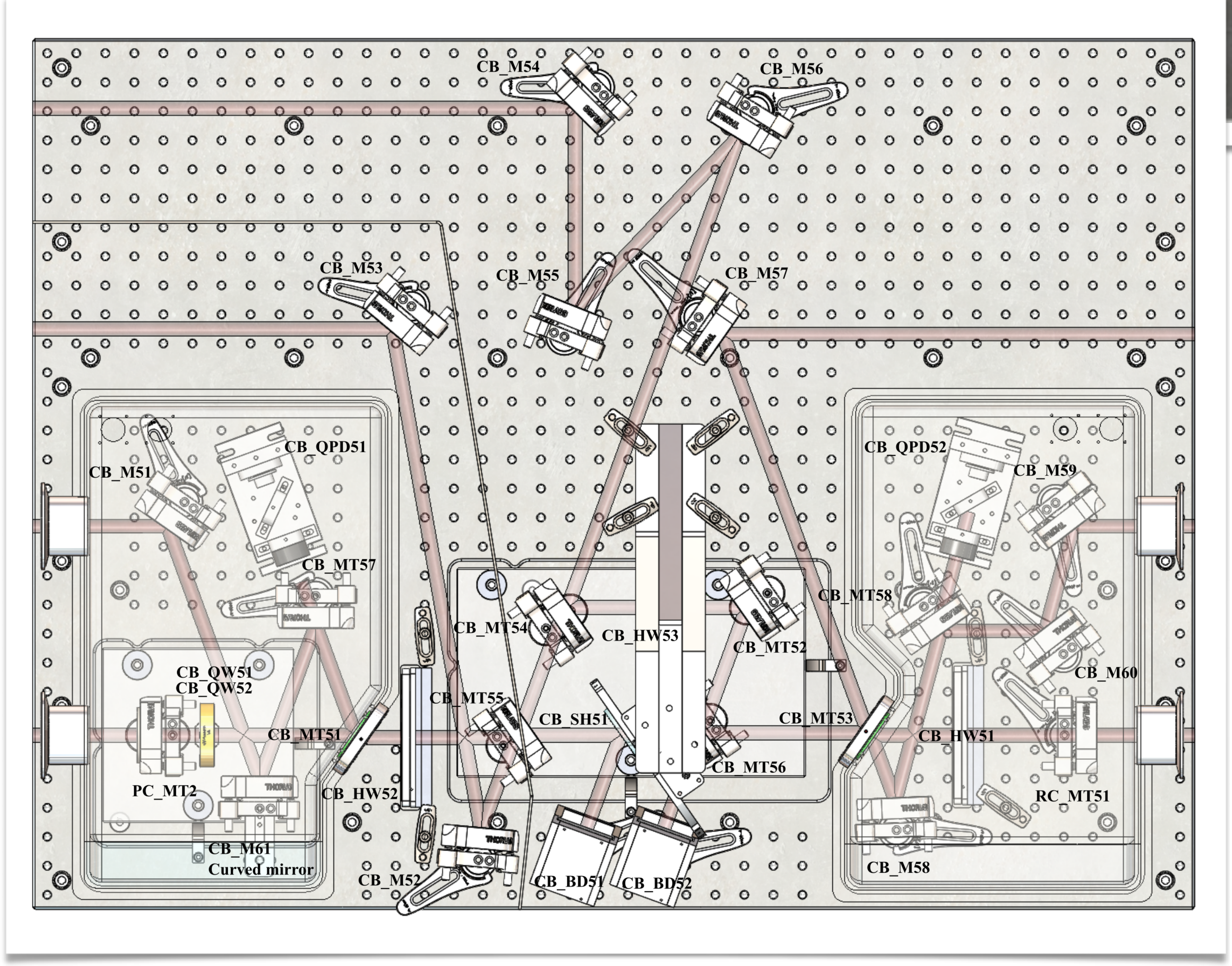
Heterodyne Detection

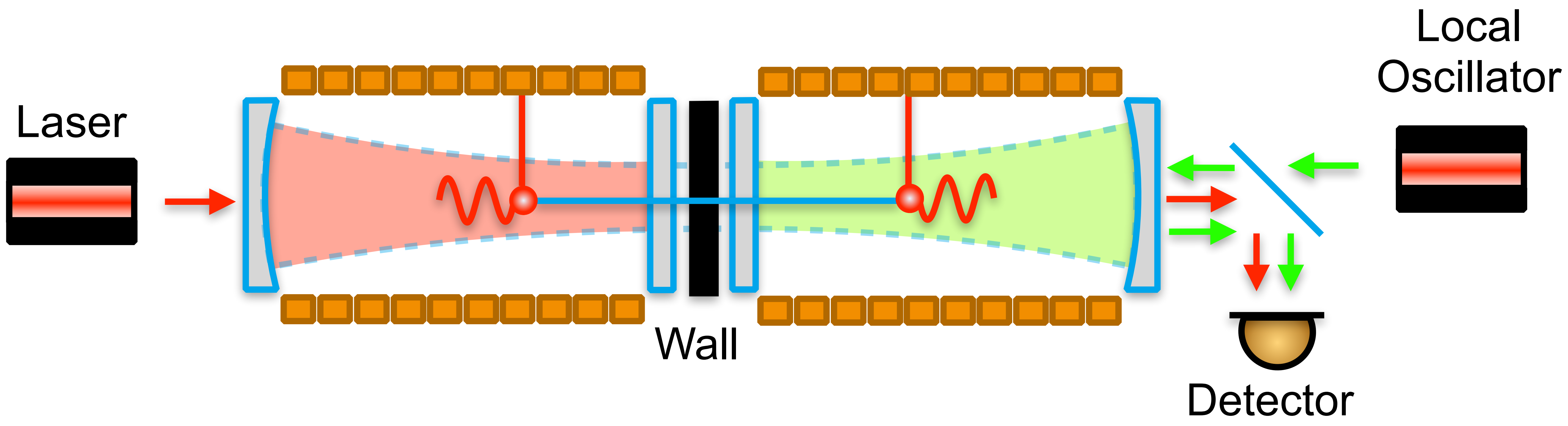
Measuring single photon power levels



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



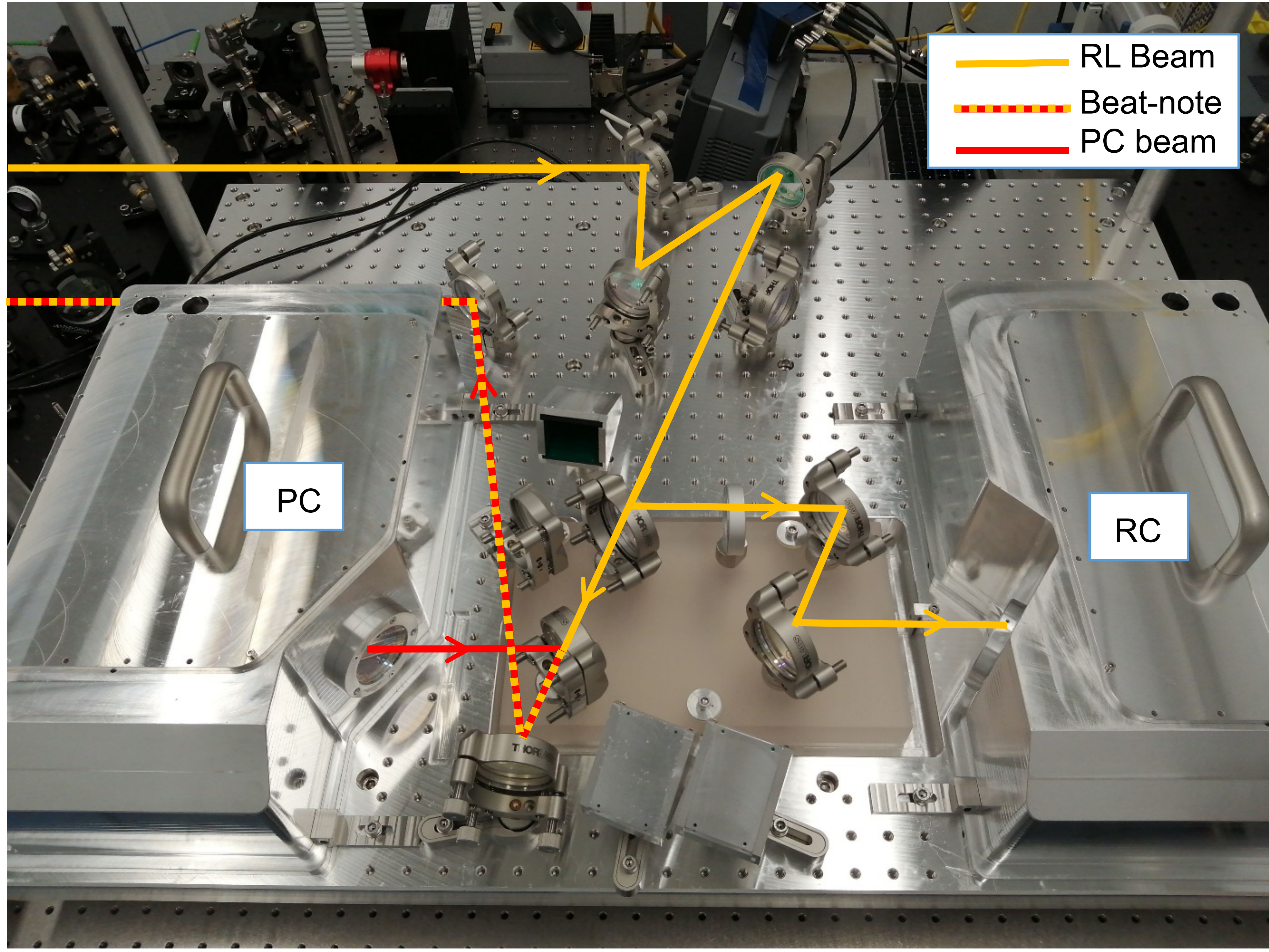


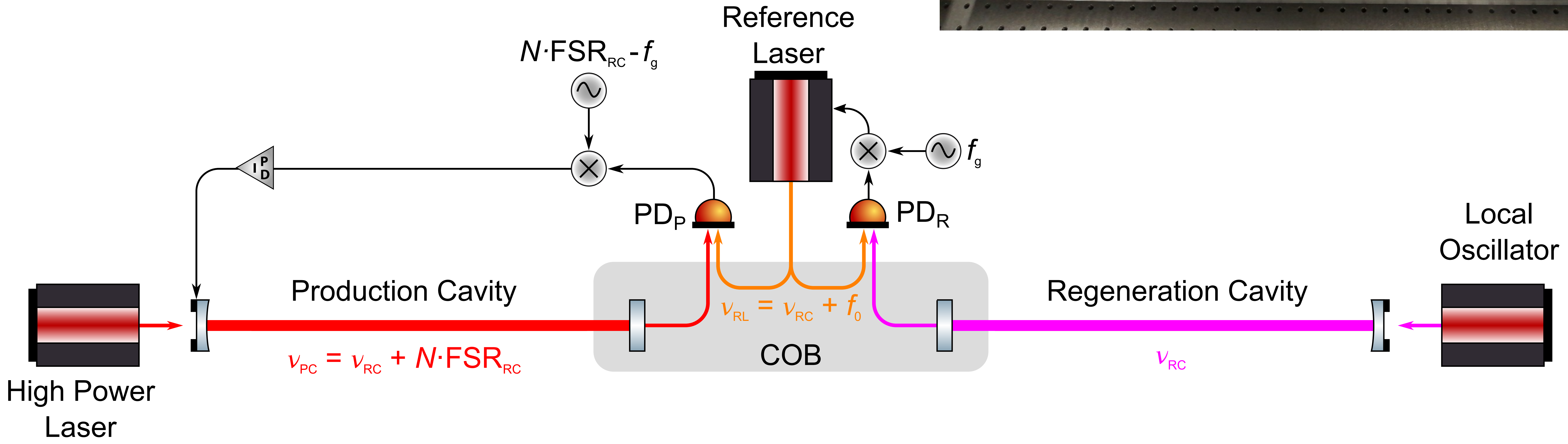
Central Optical Bench (COB)

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

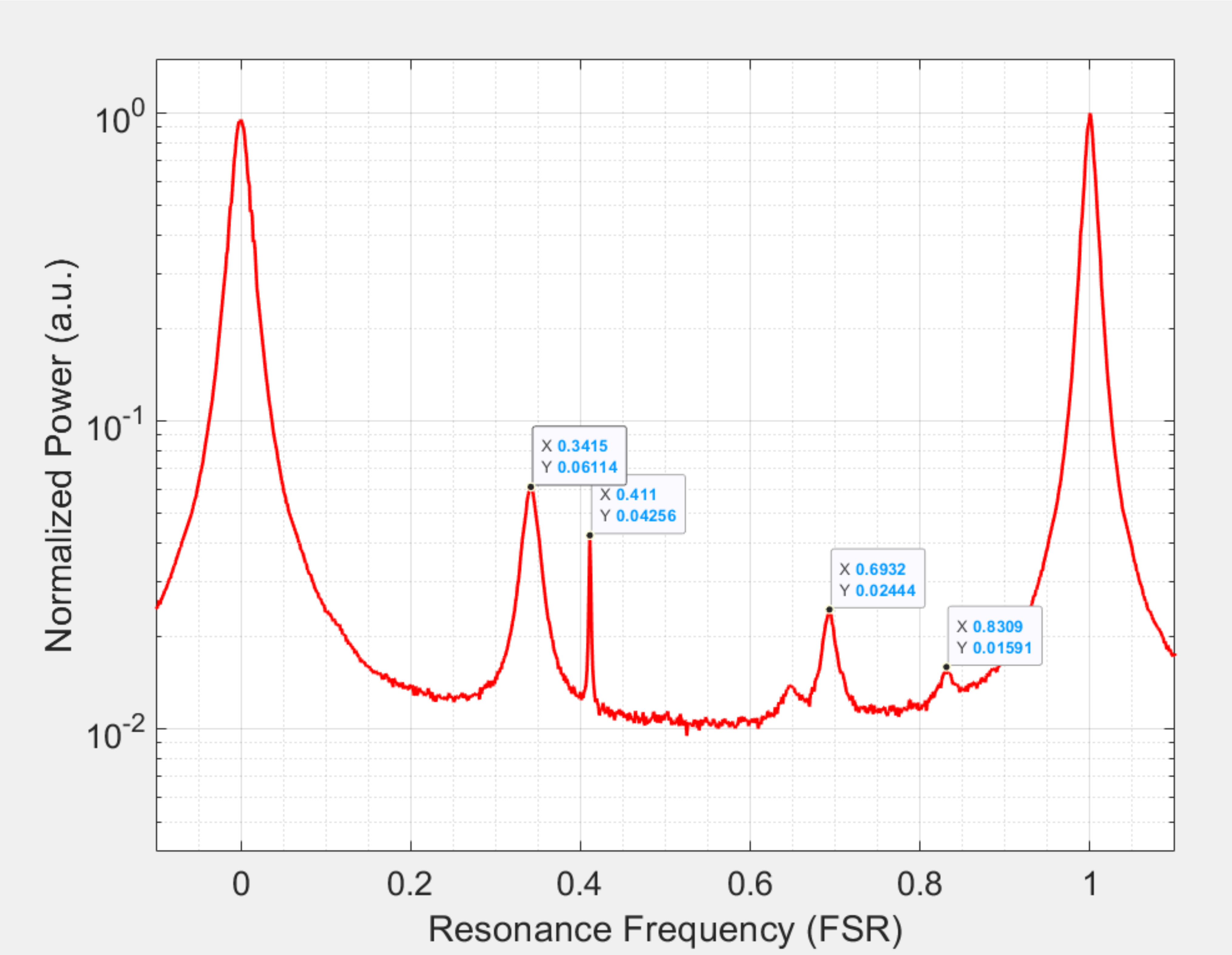
frequency offset < 1.5 Hz

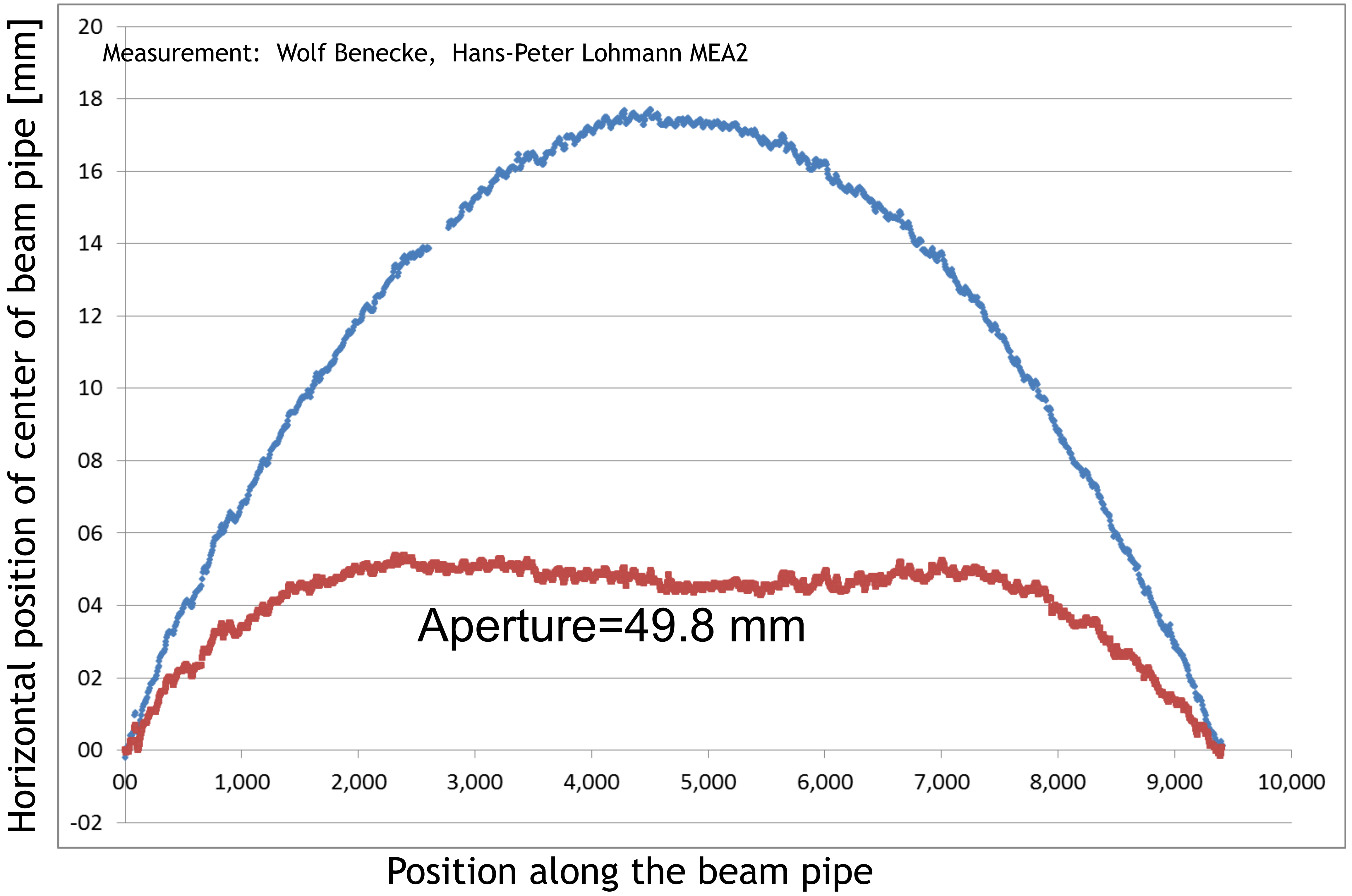
differential length noise < 0.6pm

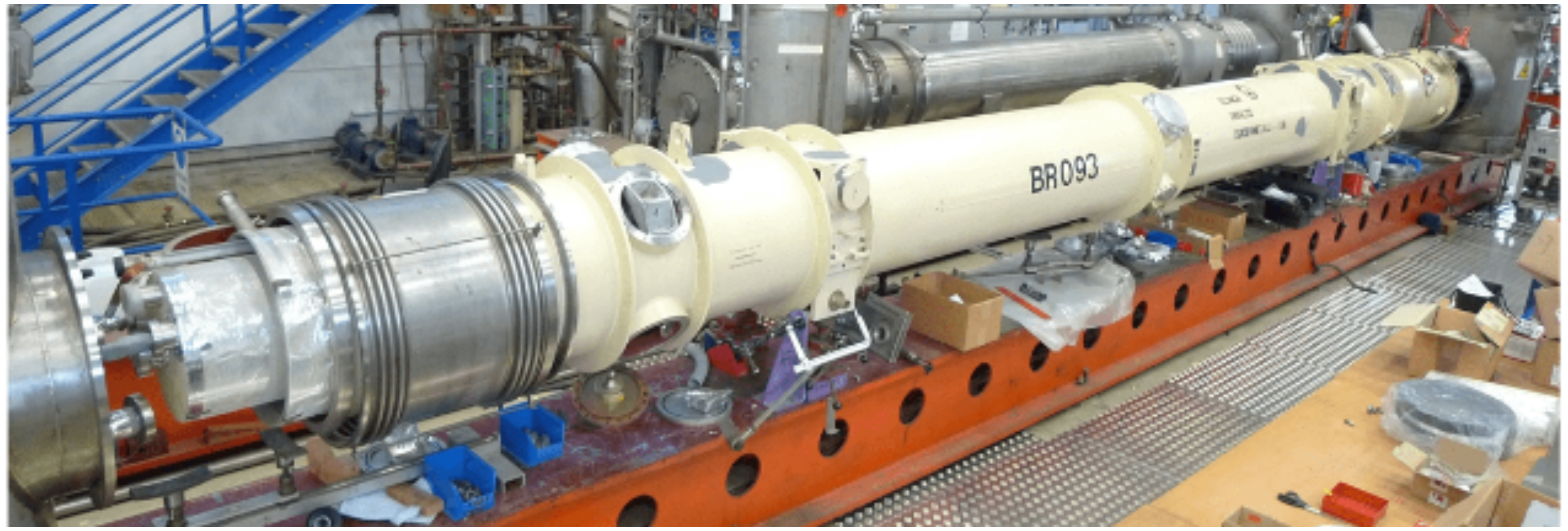
Unbending the HERA Magnets

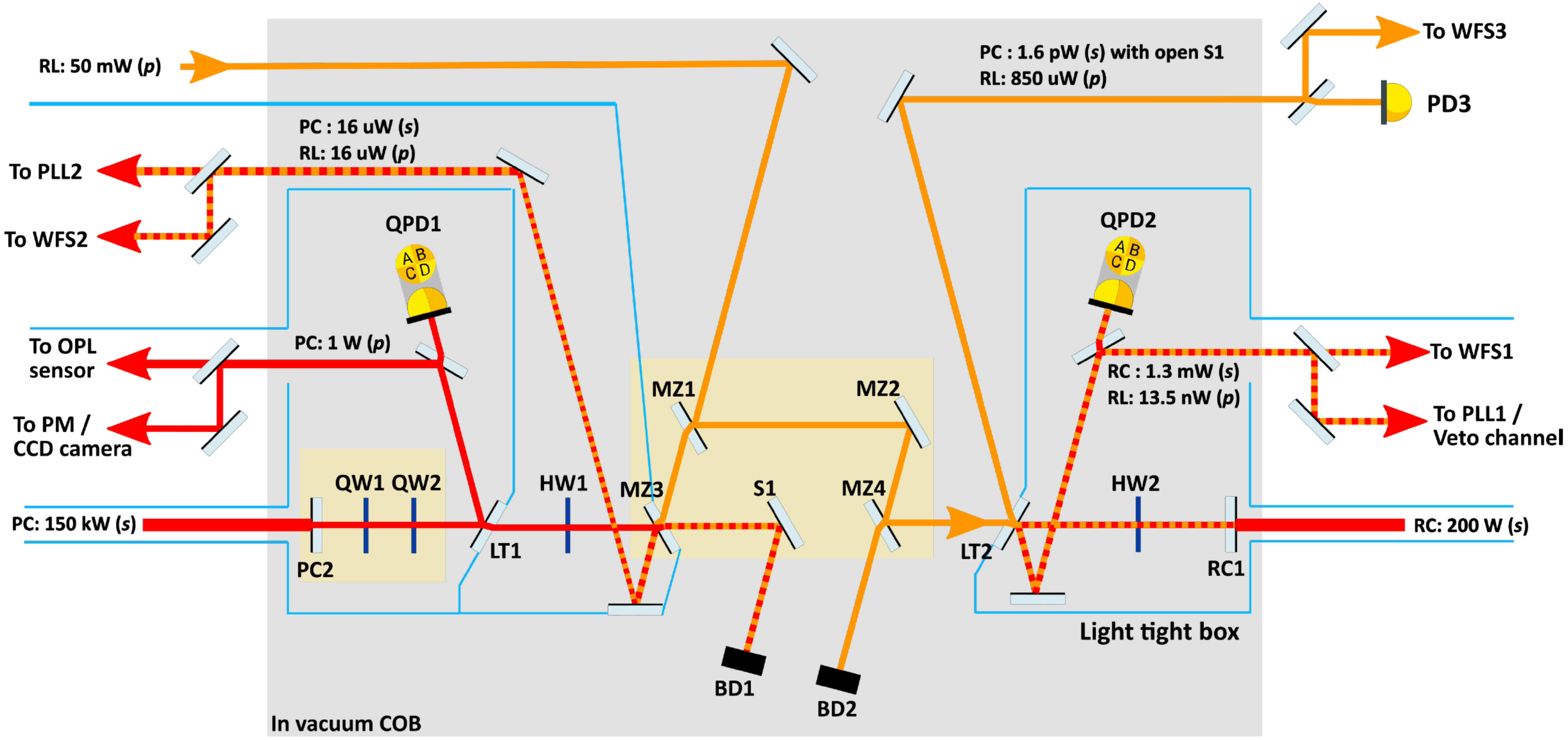
Preparing HERA dipoles for ALPS II

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
QPD2
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