

ALPS II



HELMHOLTZ RESEARCH FOR
GRAND CHALLENGES



SDU
University of
Southern Denmark

UF
UNIVERSITY of
FLORIDA



CARDIFF
UNIVERSITY

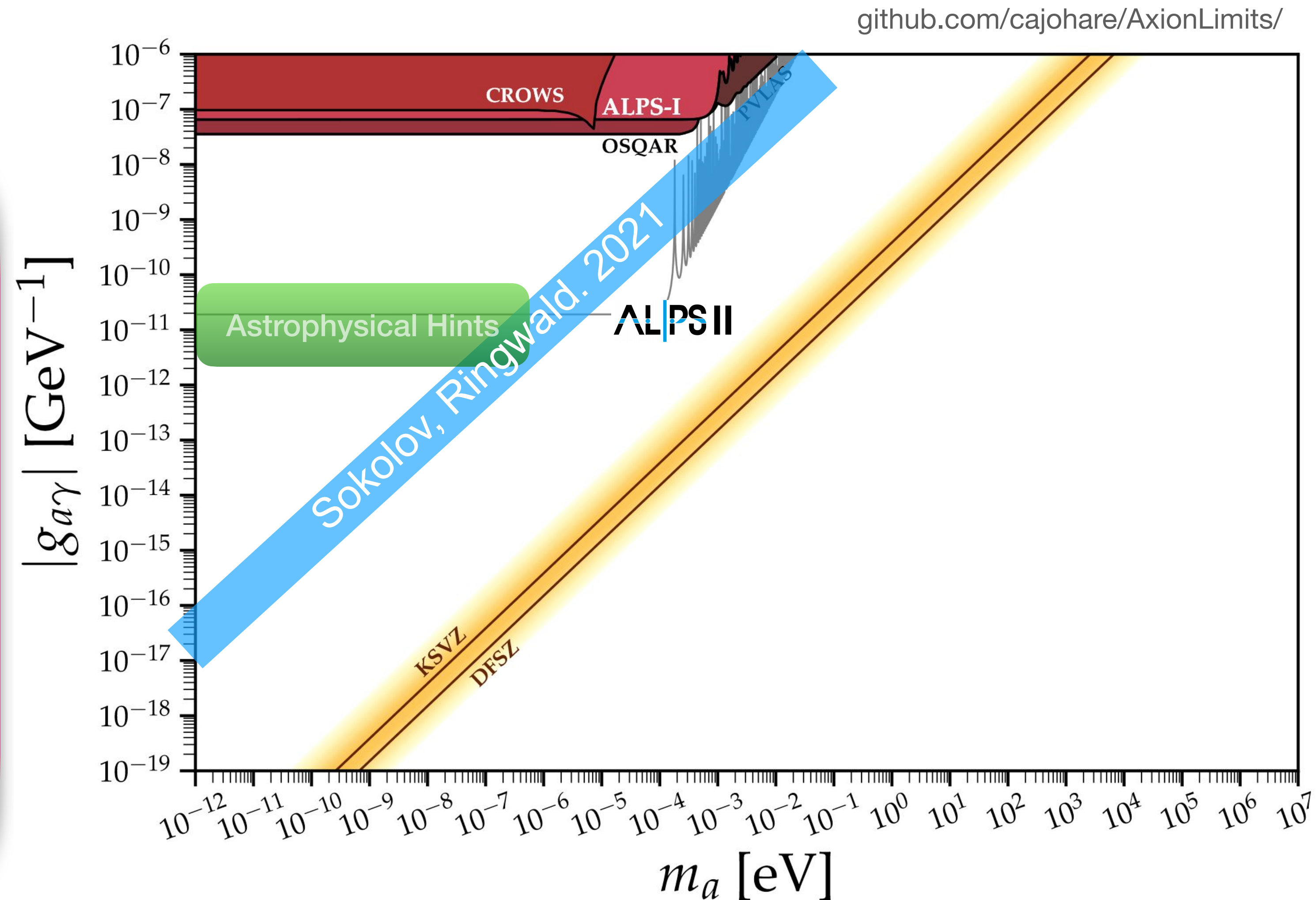
Recent Updates on the ALPS II Experiment

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

20 March, 2023. DPG Spring Meeting, Dresden

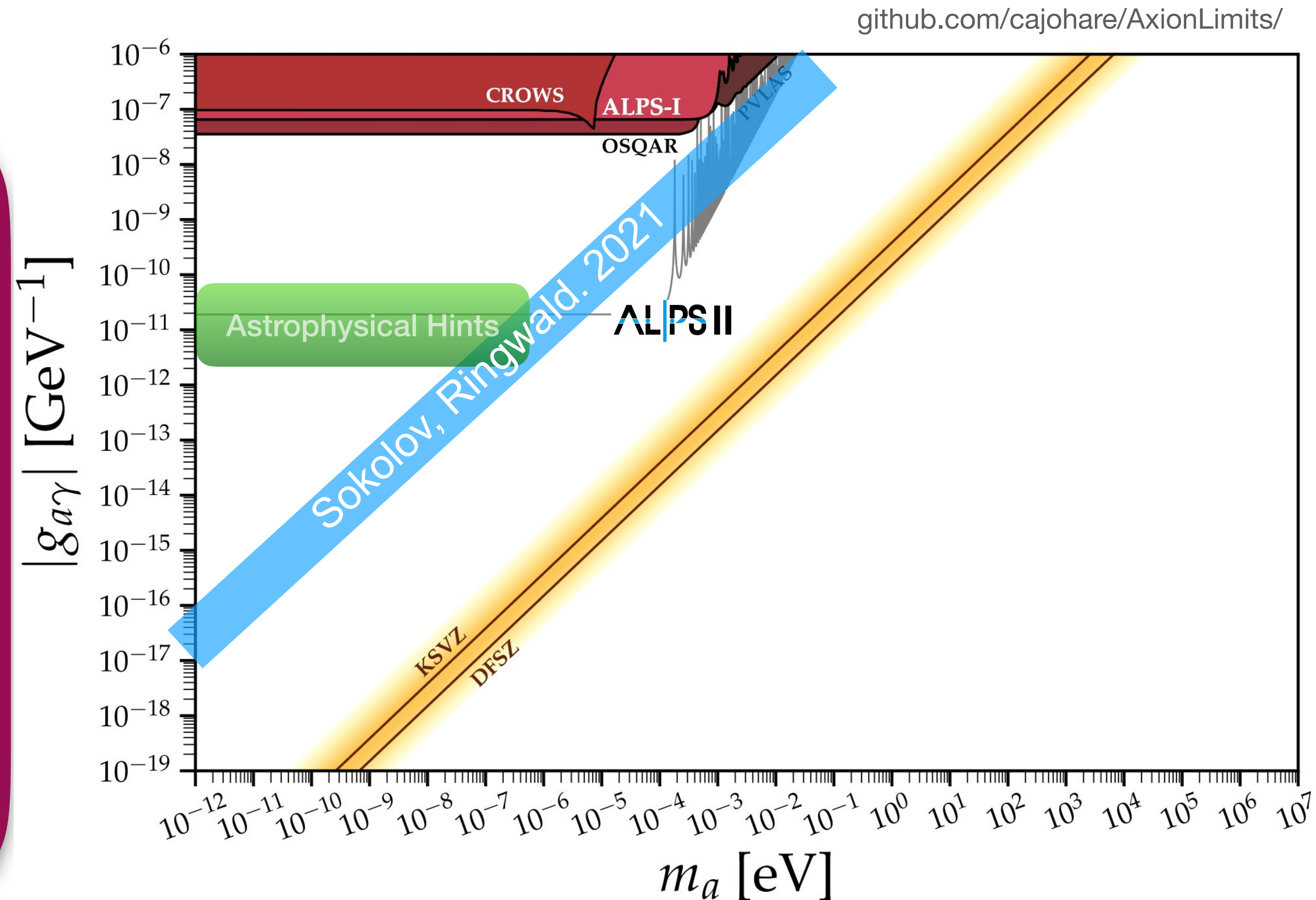
Motivation for **L**ight **S**hining through **W**alls (LSW) Experiments

- Extensive observational evidence for the existence of dark matter
 - Axions and Axion-like particles (ALPs) can be dark matter candidates
 - Axions can additionally be a solution to the Strong CP problem
- LSW experiments can search for axions and ALPs in a model-independent way
- Sensitivities out of reach of accelerator searches
- Test astrophysical observations
 - Stellar cooling
 - TeV transparency



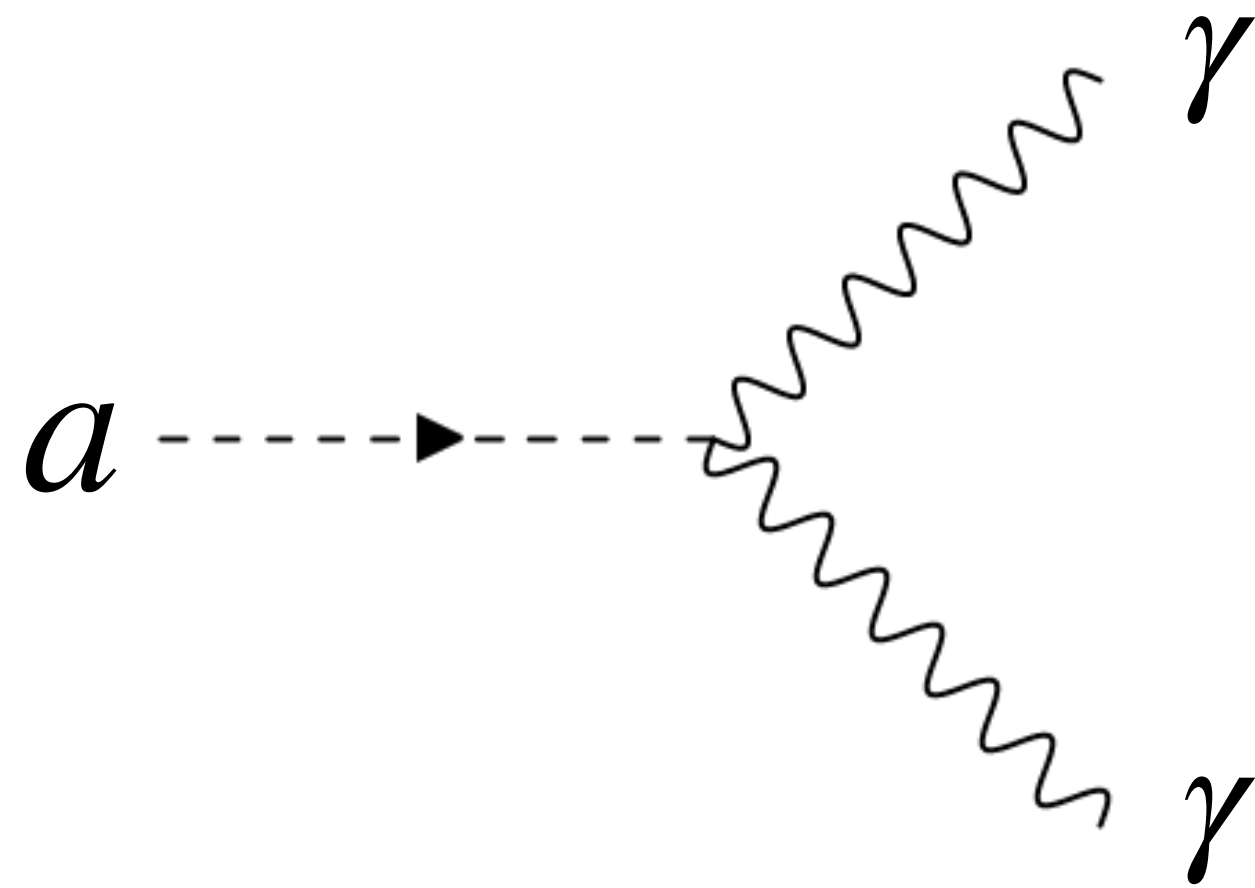
ALPS II Sensitivity

- $g_{a\gamma} > 2 \times 10^{-11} \text{GeV}^{-1}$
 - $m_a < 0.1 \text{ meV}$
 - 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



Axion coupling to photons

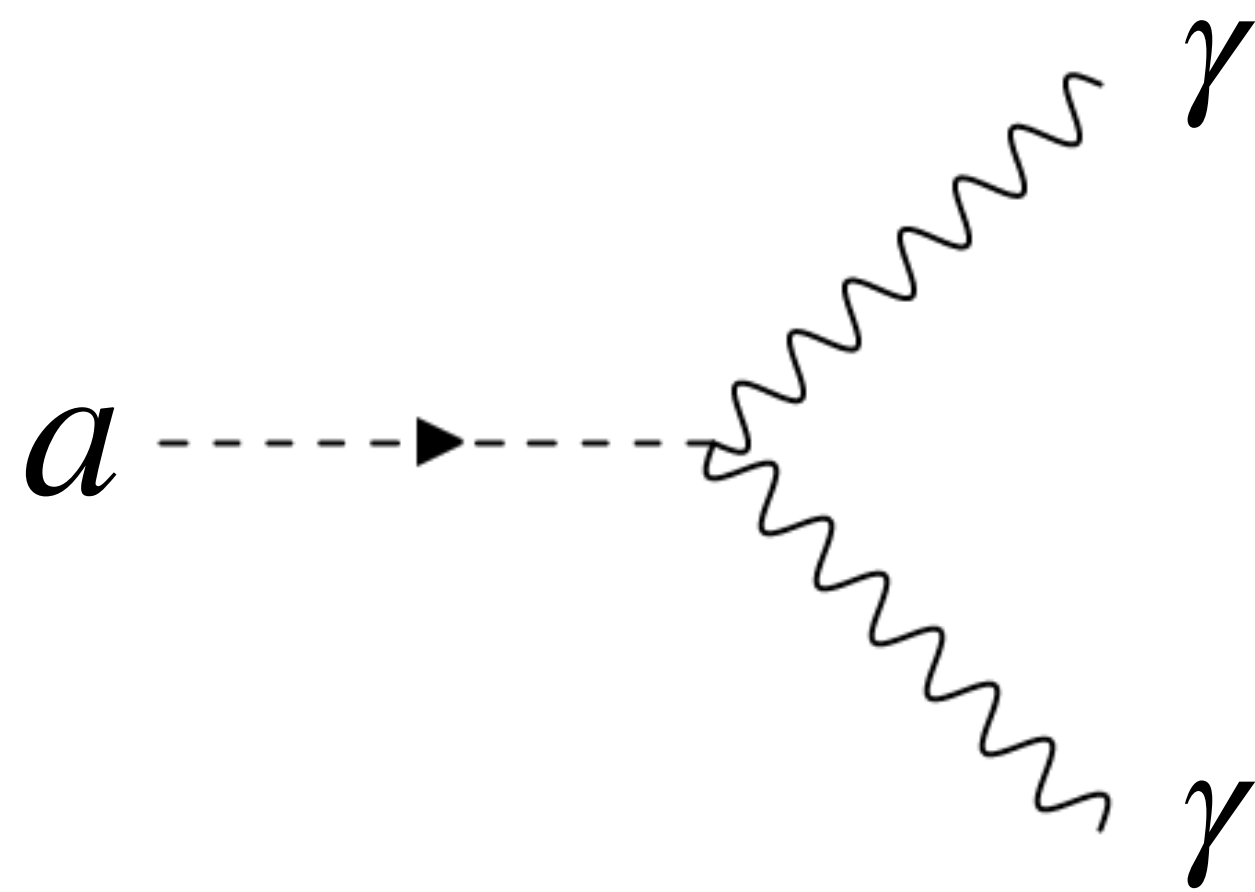
Axion decay



Astrophysics and
cosmology

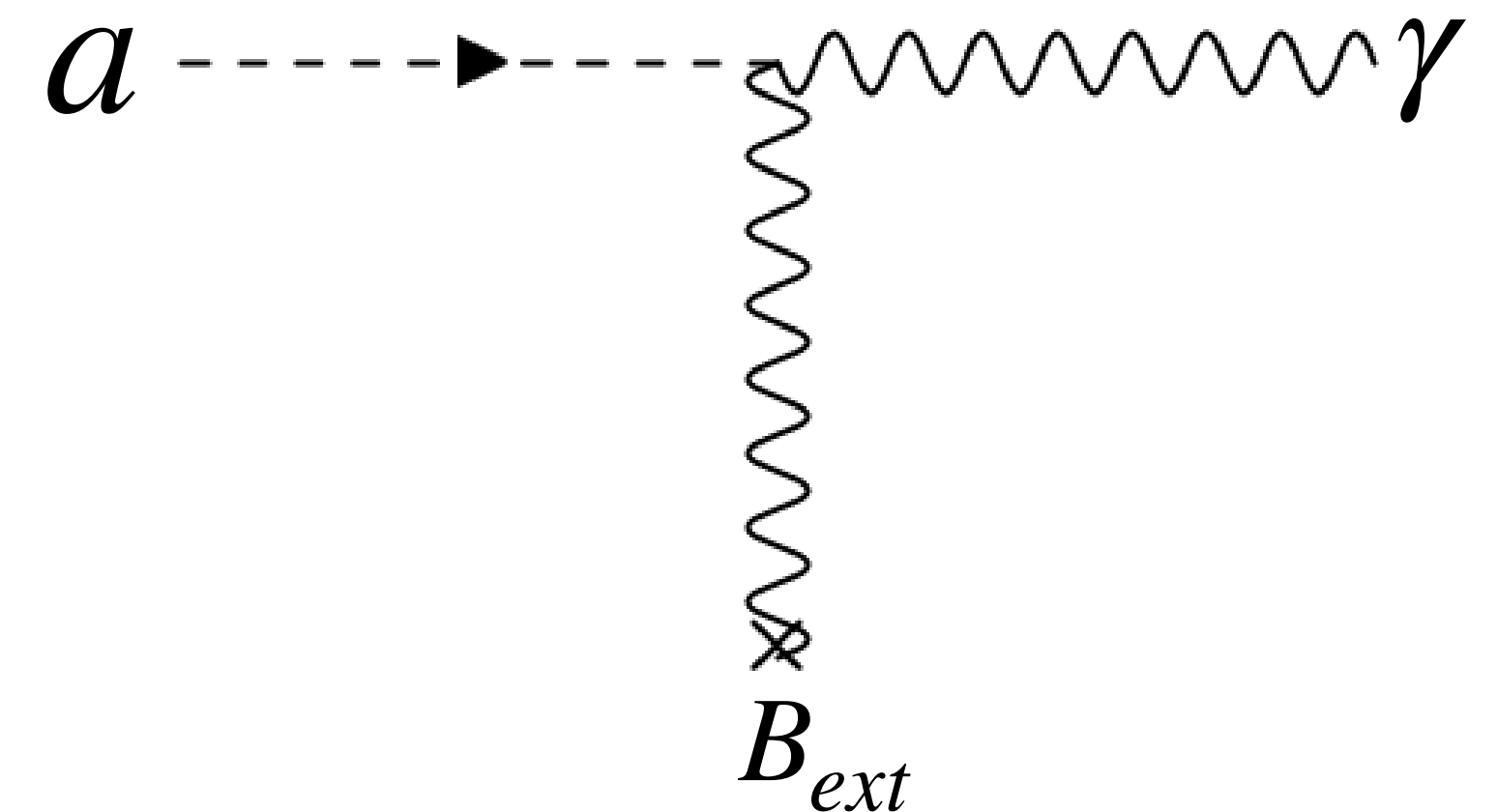
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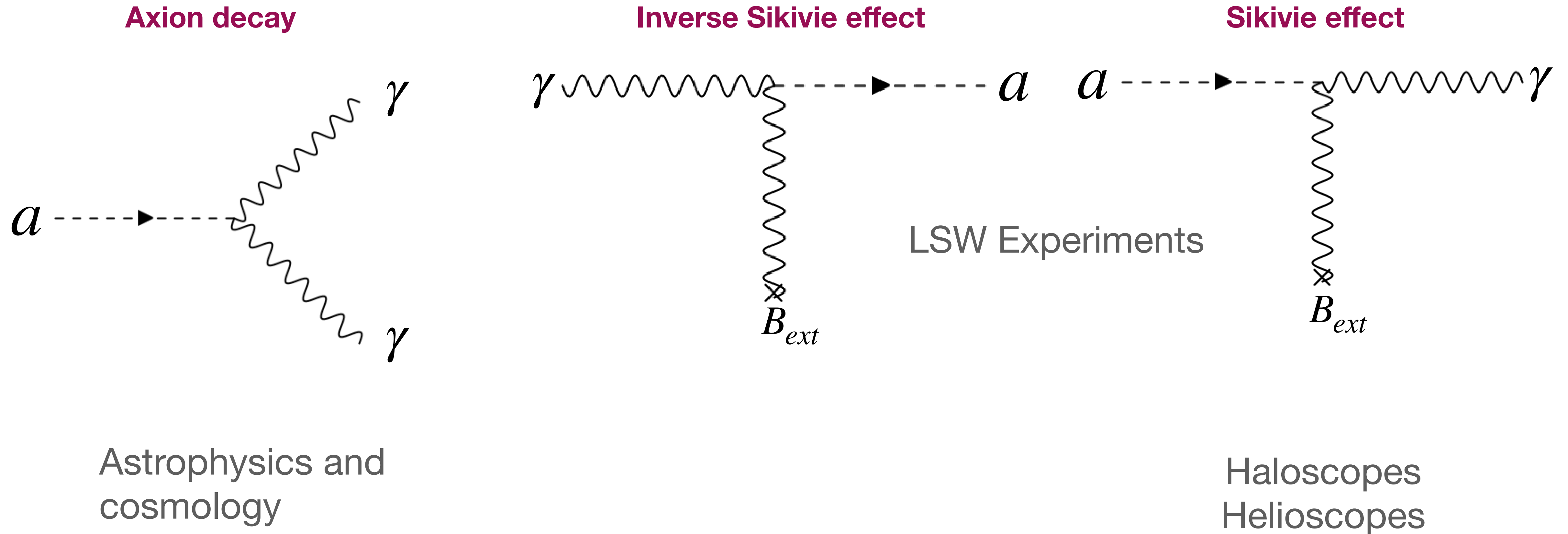
Astrophysics and
cosmology

Sikivie effect

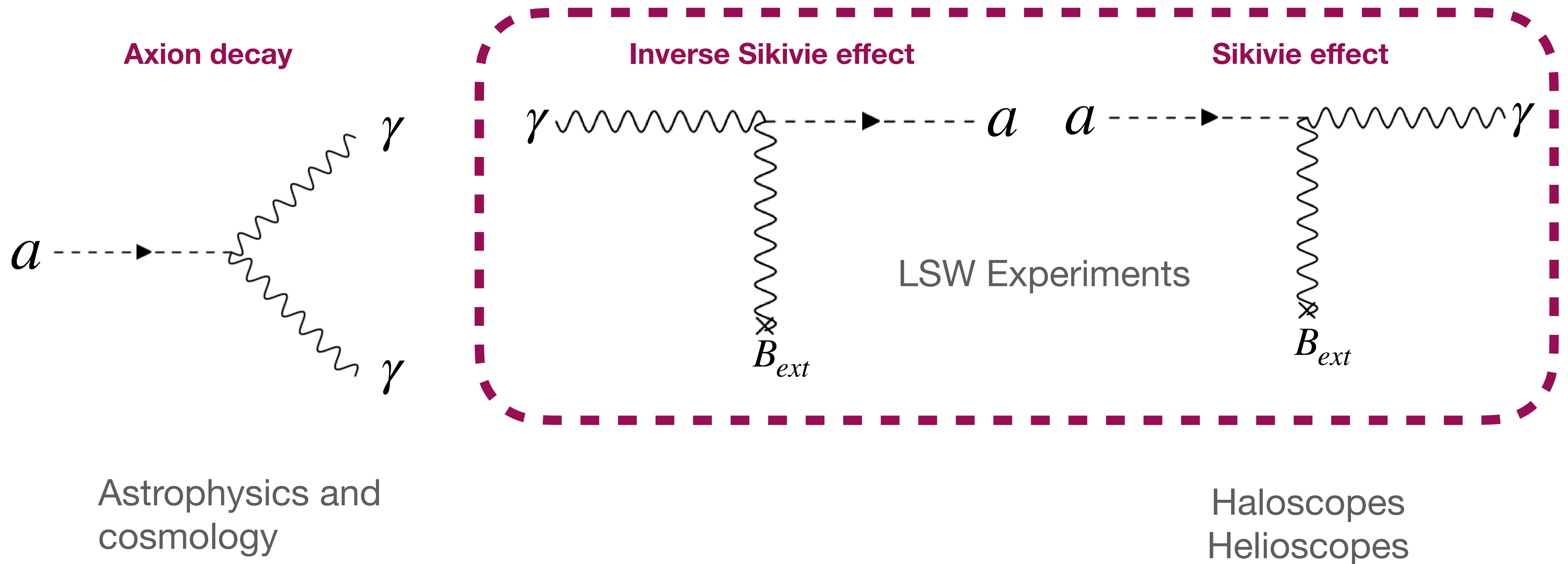


Haloscopes
Helioscopes

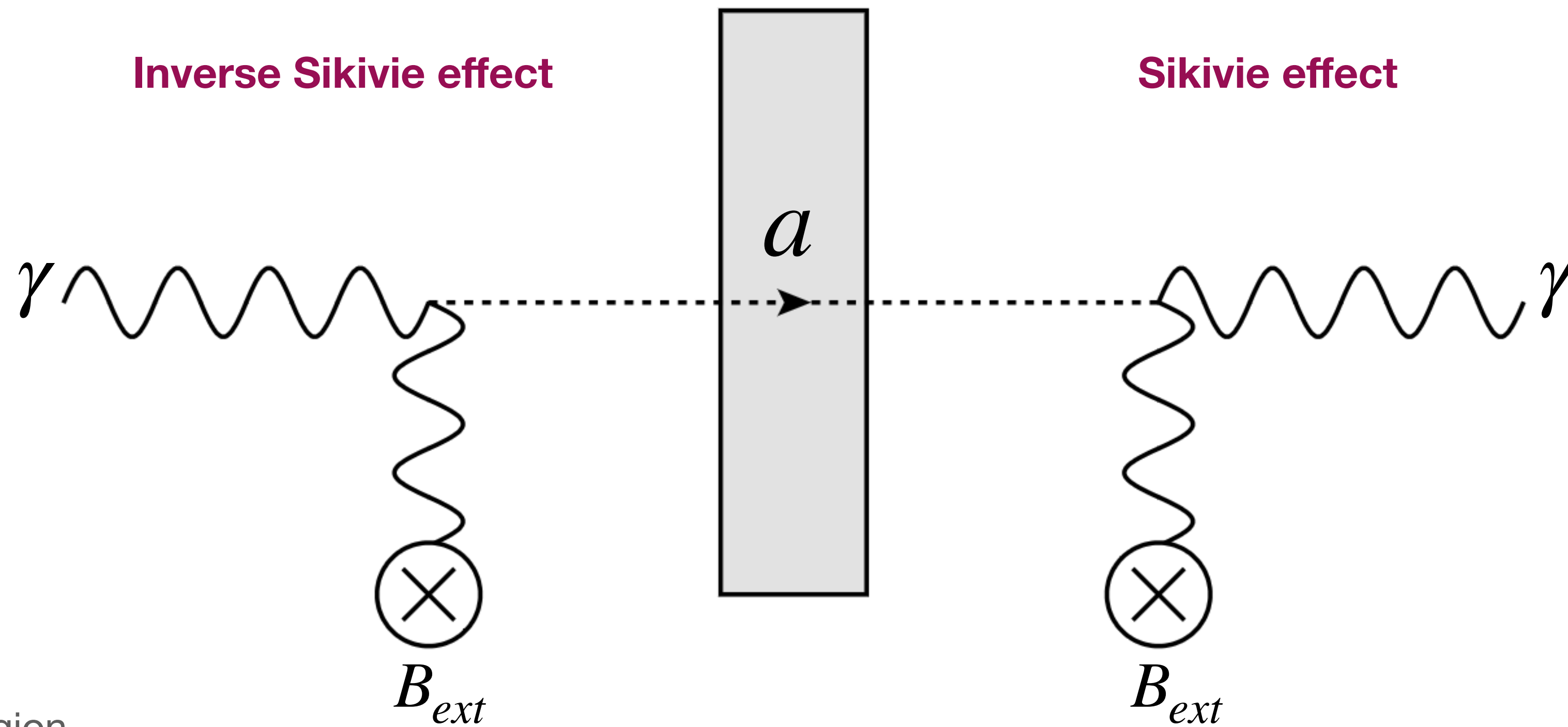
Axion coupling to photons



Axion coupling to photons



Light Shining Through Walls

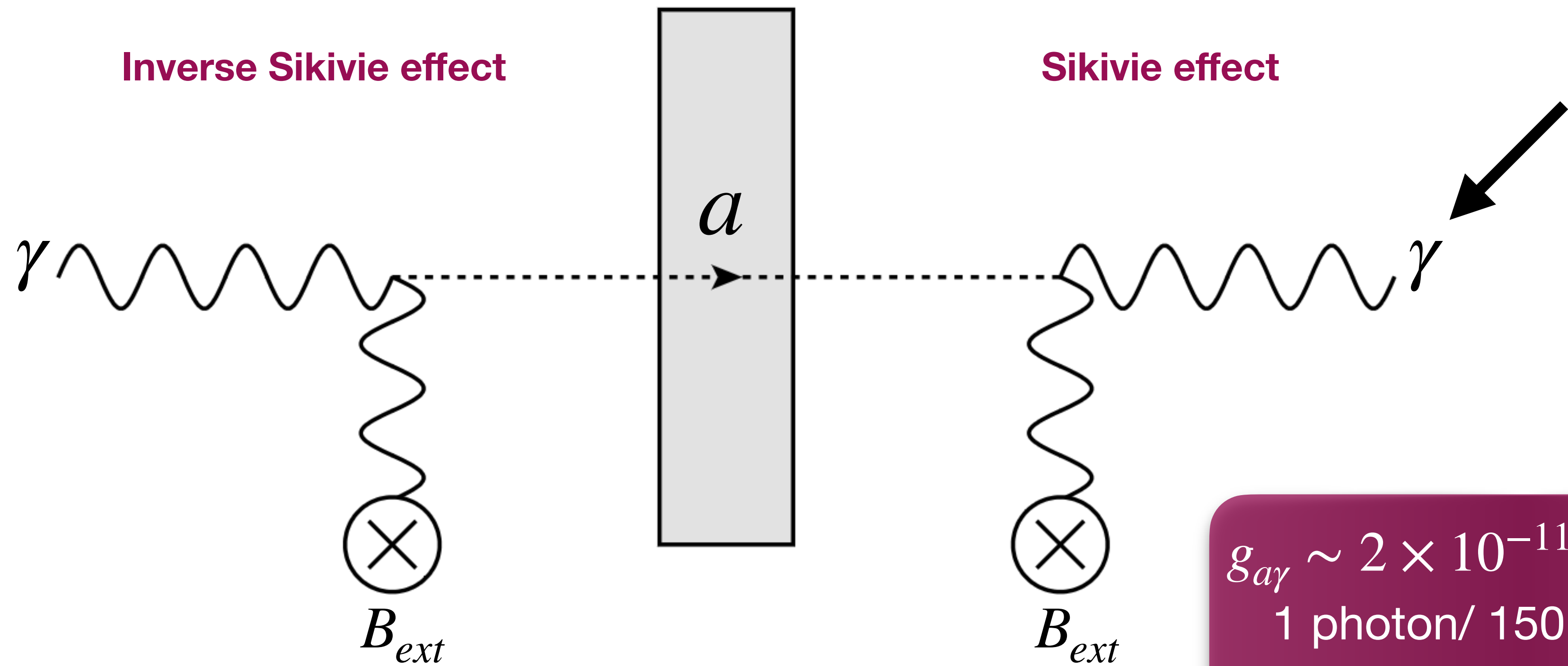


$B \rightarrow$ Magnetic field strength
 $L \rightarrow$ Length in magnetic field region

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

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

Light Shining Through Walls



$\mathcal{P}_i \rightarrow$ laser power
 $h\nu \rightarrow$ laser photon energy
 $\tau \rightarrow$ measurement time

$$N_\gamma = \frac{1}{16} (g_{a\gamma} B L)^4 \frac{\mathcal{P}_i}{h\nu} \tau$$

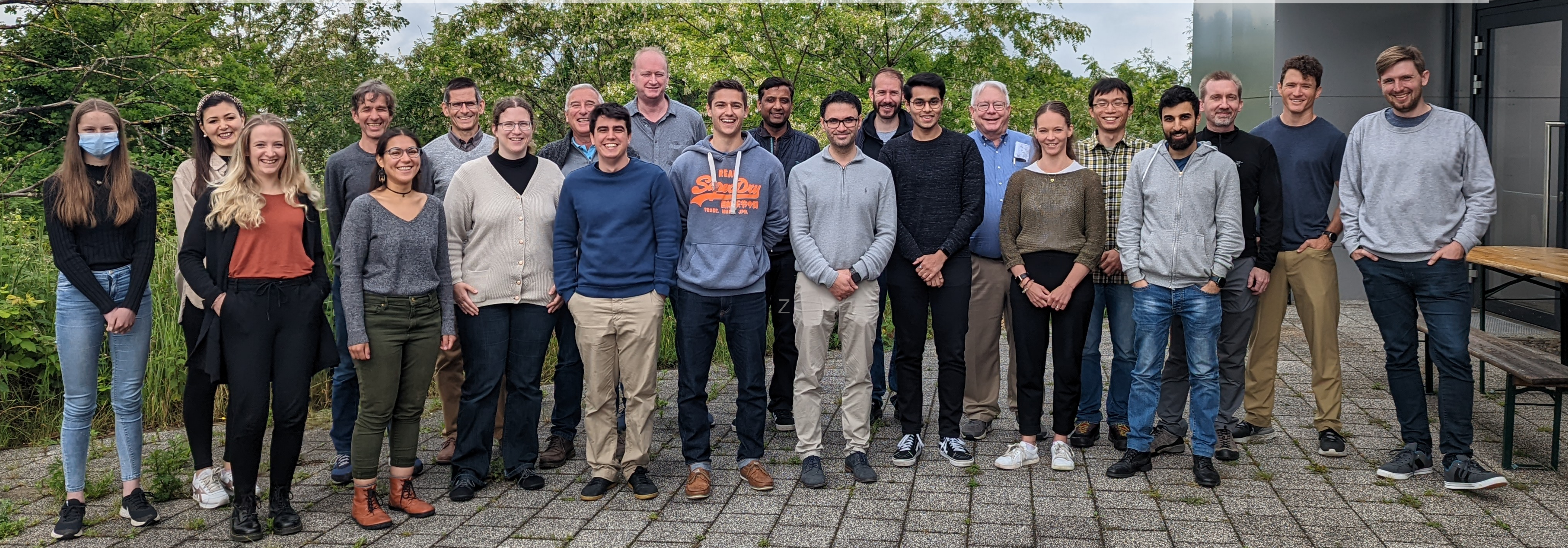
$g_{a\gamma} \sim 2 \times 10^{-11} \text{ GeV}^{-1}$
 1 photon/ 150,000 years!
 → Need to enhance signal!

$B \sim 5.3 \text{ T}$
 $L \sim 100 \text{ m}$
 $\mathcal{P} \sim 30 \text{ W}$

Any Light Particle Search (ALPS) II



Any Light Particle Search (ALPS) II



DESY, Hamburg

7 institutions, ~30 members

Germany, US, UK, Denmark

Gefördert durch



Deutsche
Forschungsgemeinschaft

HELMHOLTZ

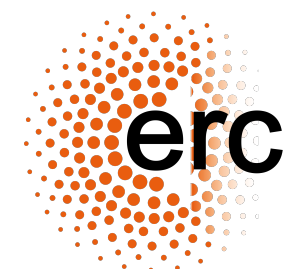
RESEARCH FOR
GRAND CHALLENGES



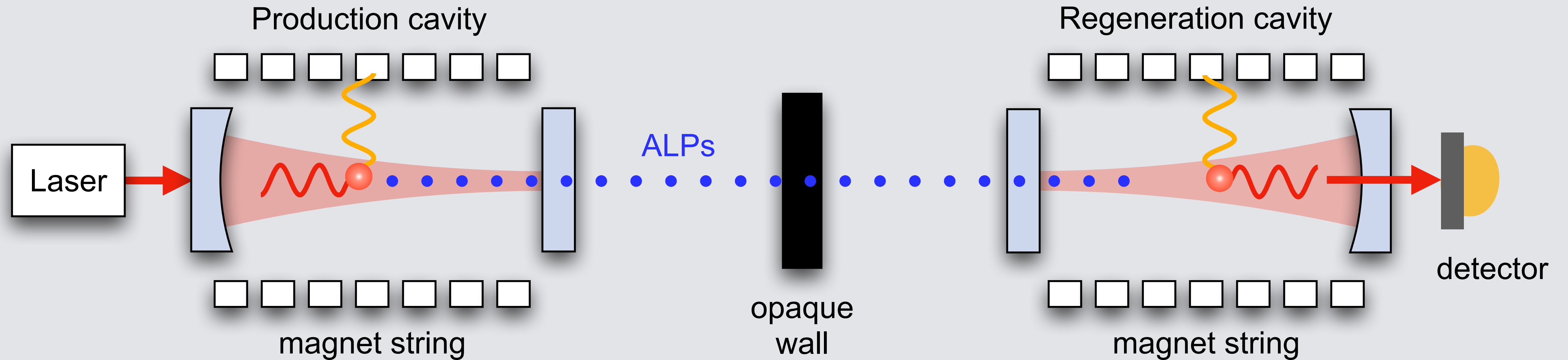
HEISING-SIMONS
FOUNDATION



Science & Technology
Facilities Council



Any Light Particle Search (ALPS) II



Graphic from Katharina-Sophie Isleif

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

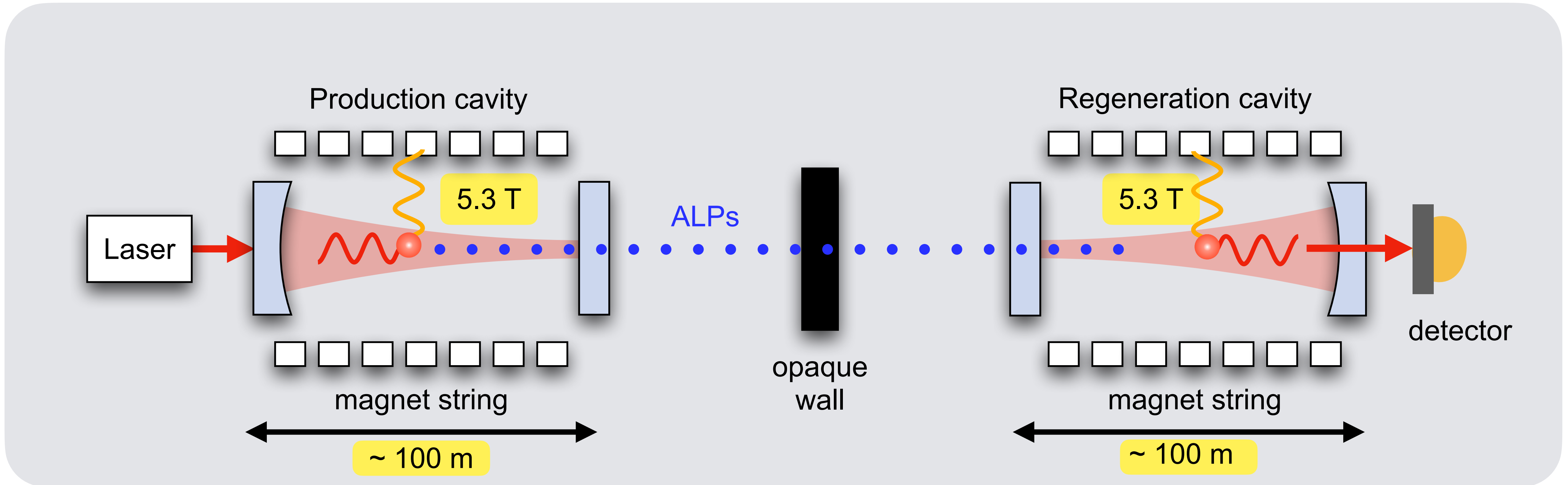
\mathcal{P}_i → laser power

$h\nu$ → laser photon energy

τ → measurement time

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

Any Light Particle Search (ALPS) II



Graphic from Katharina-Sophie Isleif

- Using 24 straightened HERA magnets

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

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

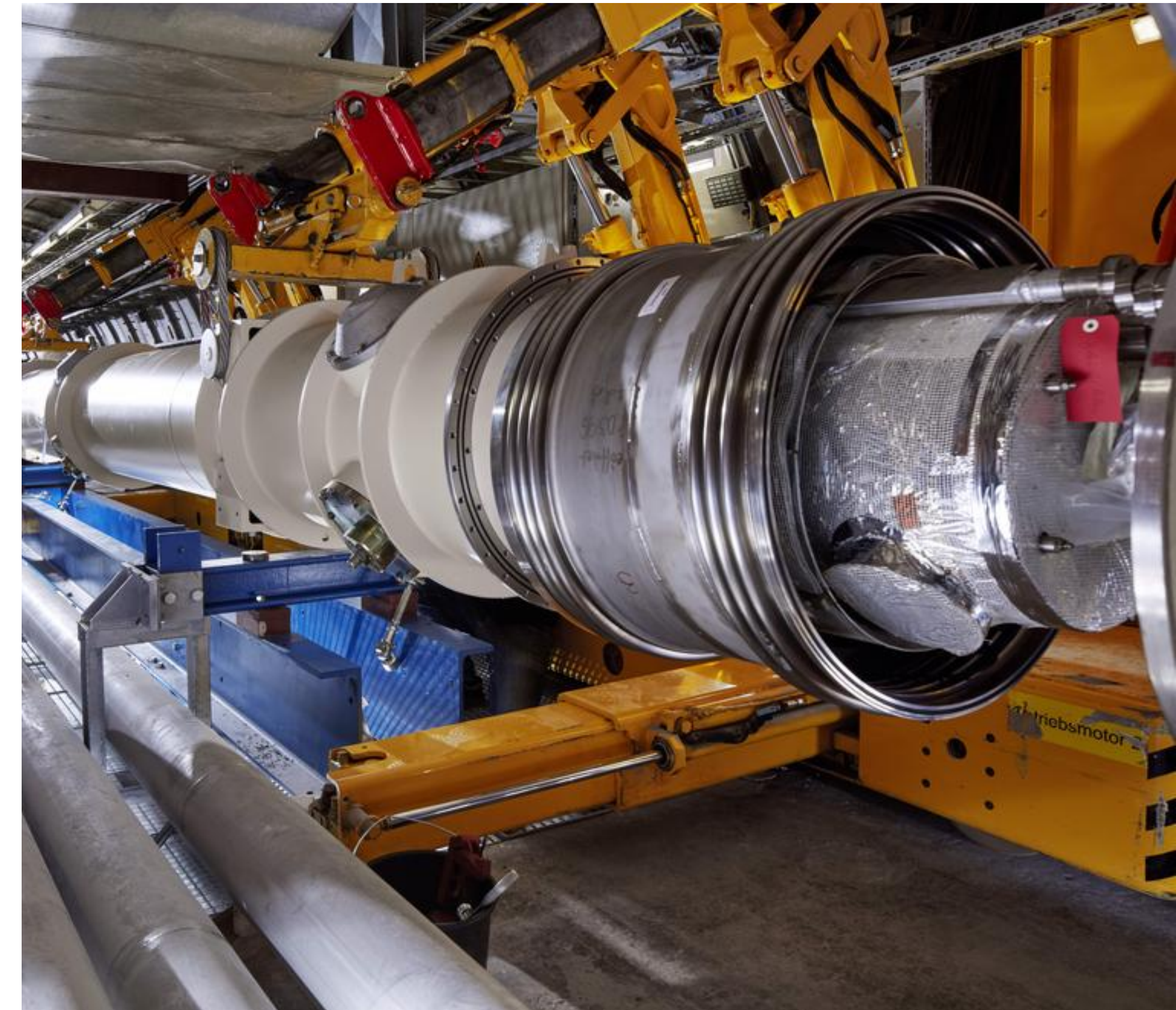
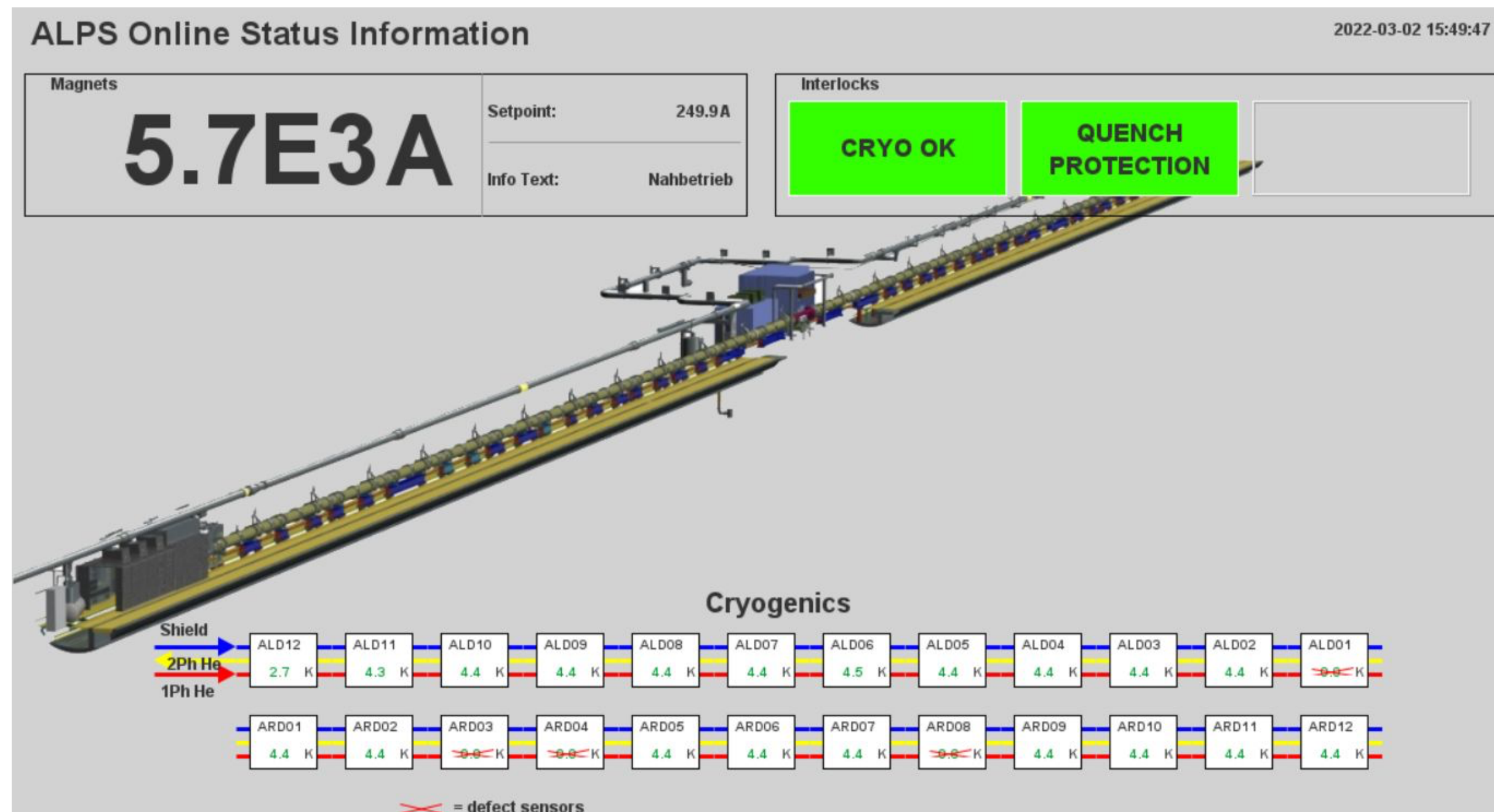
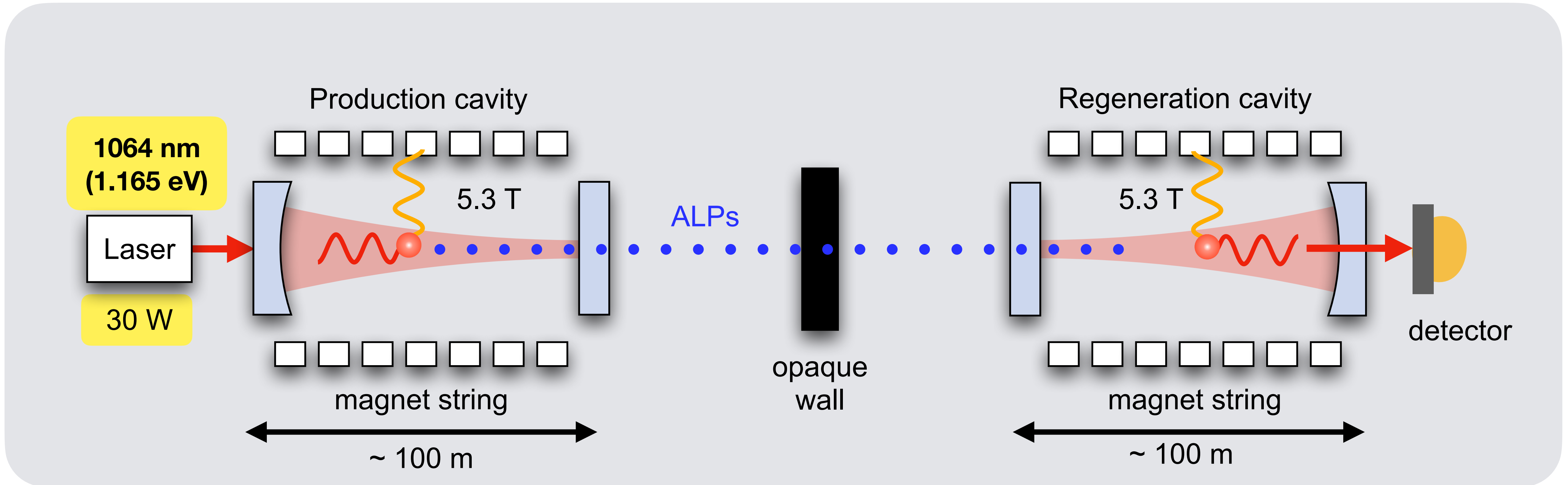


Photo by Heiner Müller-Elsner

Any Light Particle Search (ALPS II)

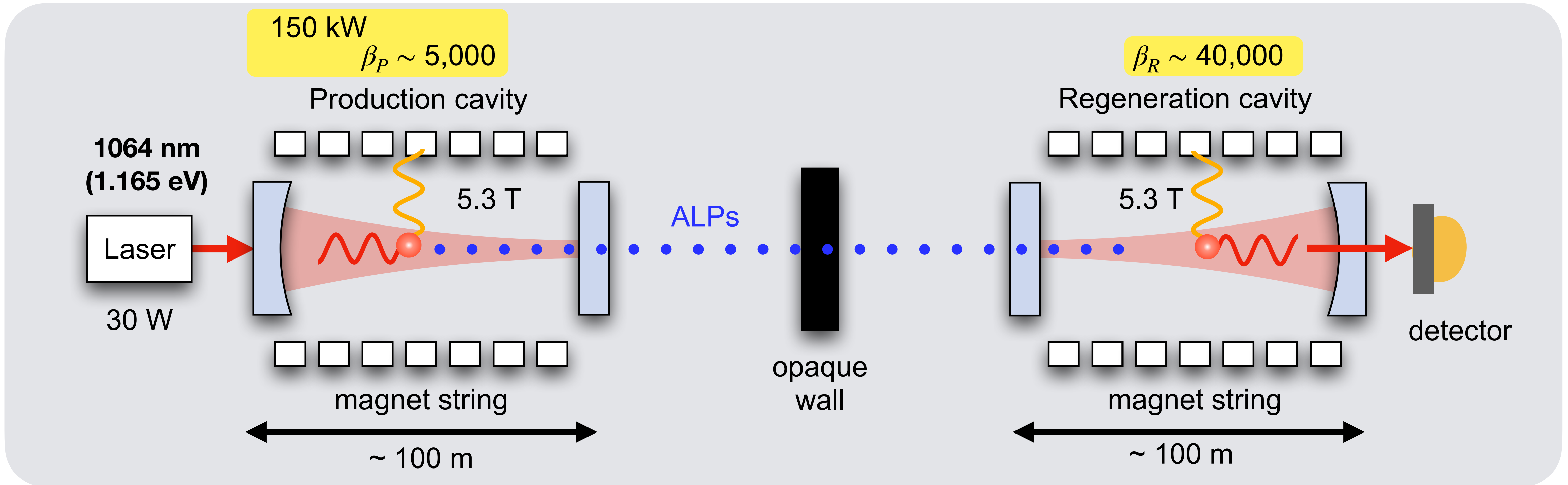


Graphic from Katharina-Sophie Isleif

- Using 24 straightened HERA magnets

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

Any Light Particle Search (ALPS II)



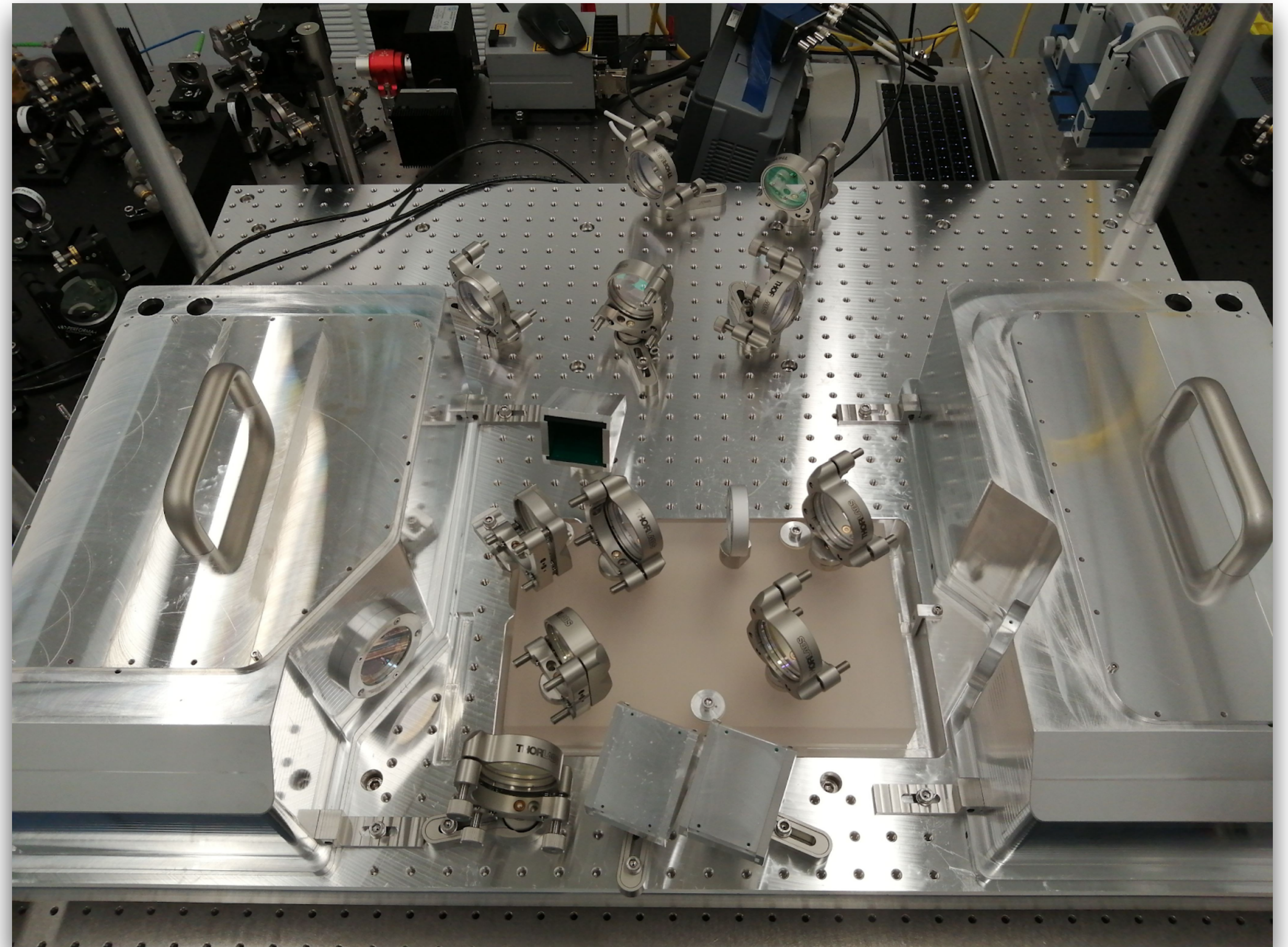
Graphic from Katharina-Sophie Isleif

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

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

Central Optical Breadboard (COB)

- Houses the optical shutter (wall)
- Maintains coherence between cavities
- Provide “beat notes” for Heterodyne detection

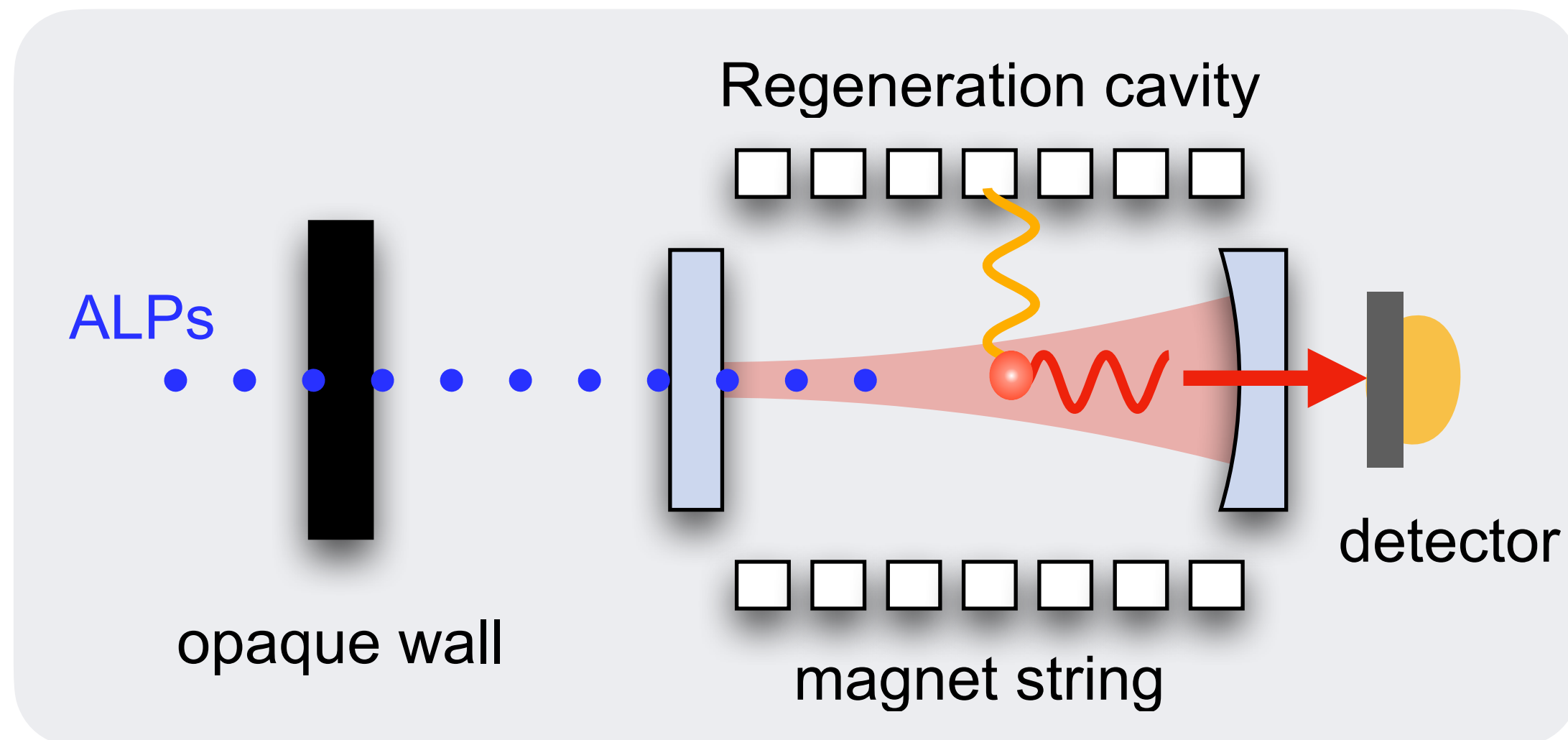


Regeneration Cavity (RC)

Talk by Aaron Spector
IDM 2022

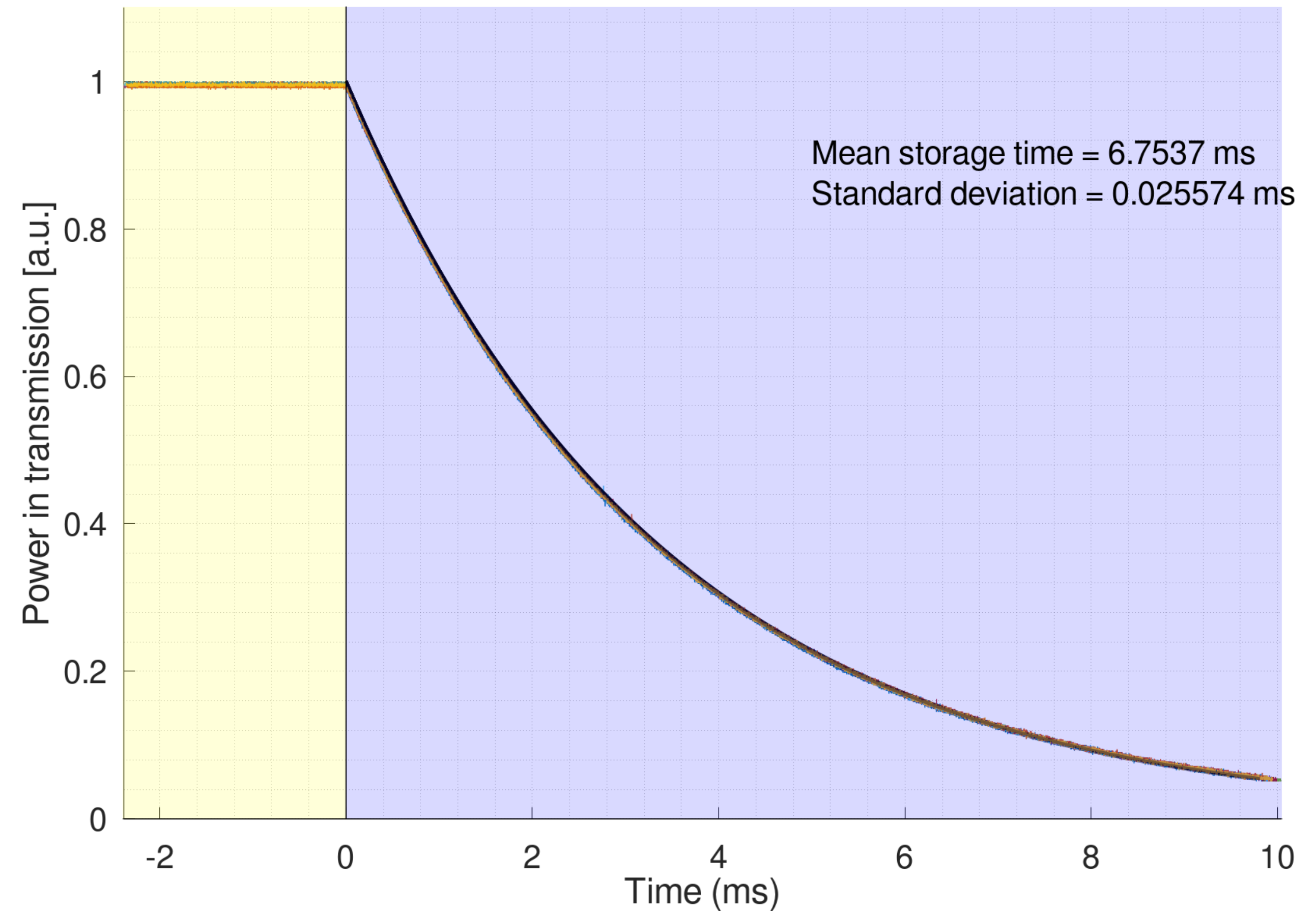
Longest storage time Fabry Perot cavity ever!

- Length: 124.6m, FSR: 1.22 MHz
- Storage time: 6.75 ms (*world record*)
- Power build up factor: $\beta \sim 7000$

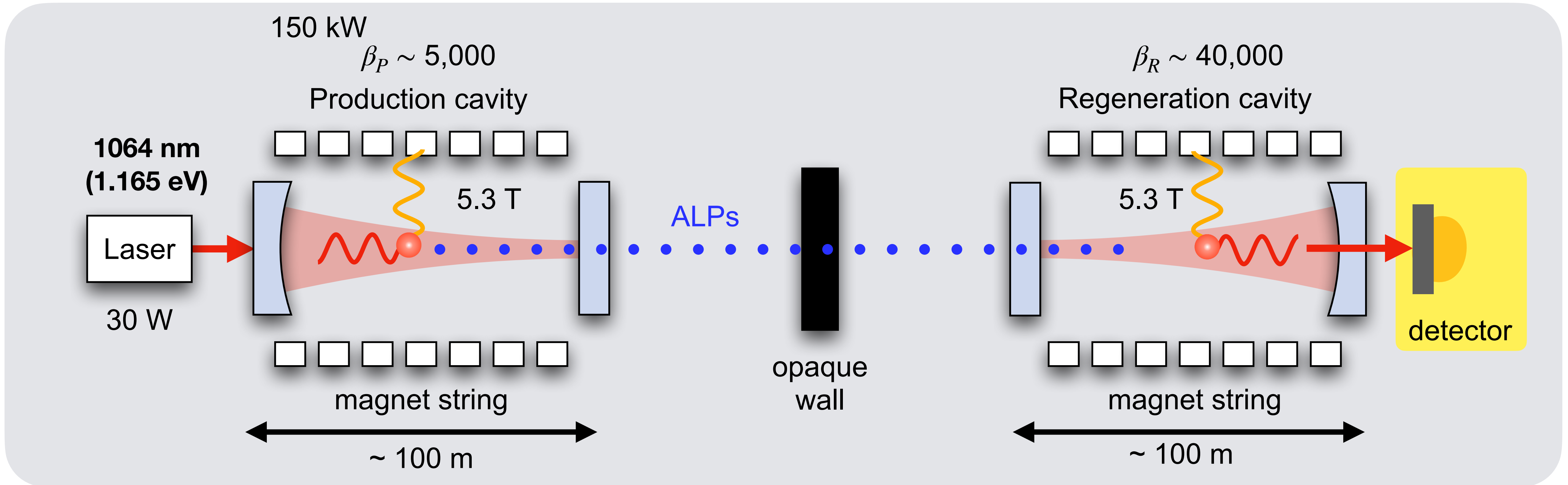


Graphic from Katharina-Sophie Isleif

ALPS II RC Cavity Storage Time



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 \rightarrow 10^{-24} W (~ 1 photon/day) $g_{a\gamma} \sim 2 \times 10^{-11} \text{ GeV}^{-1}$

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

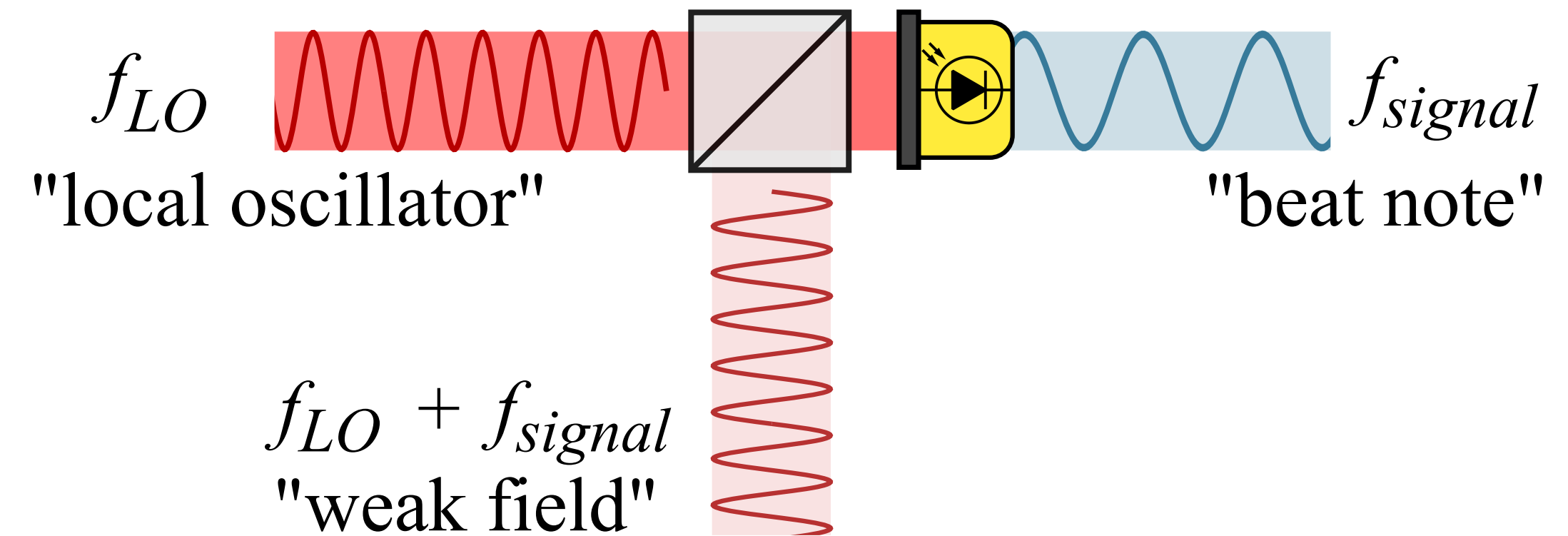
ALPS II- Heterodyne

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

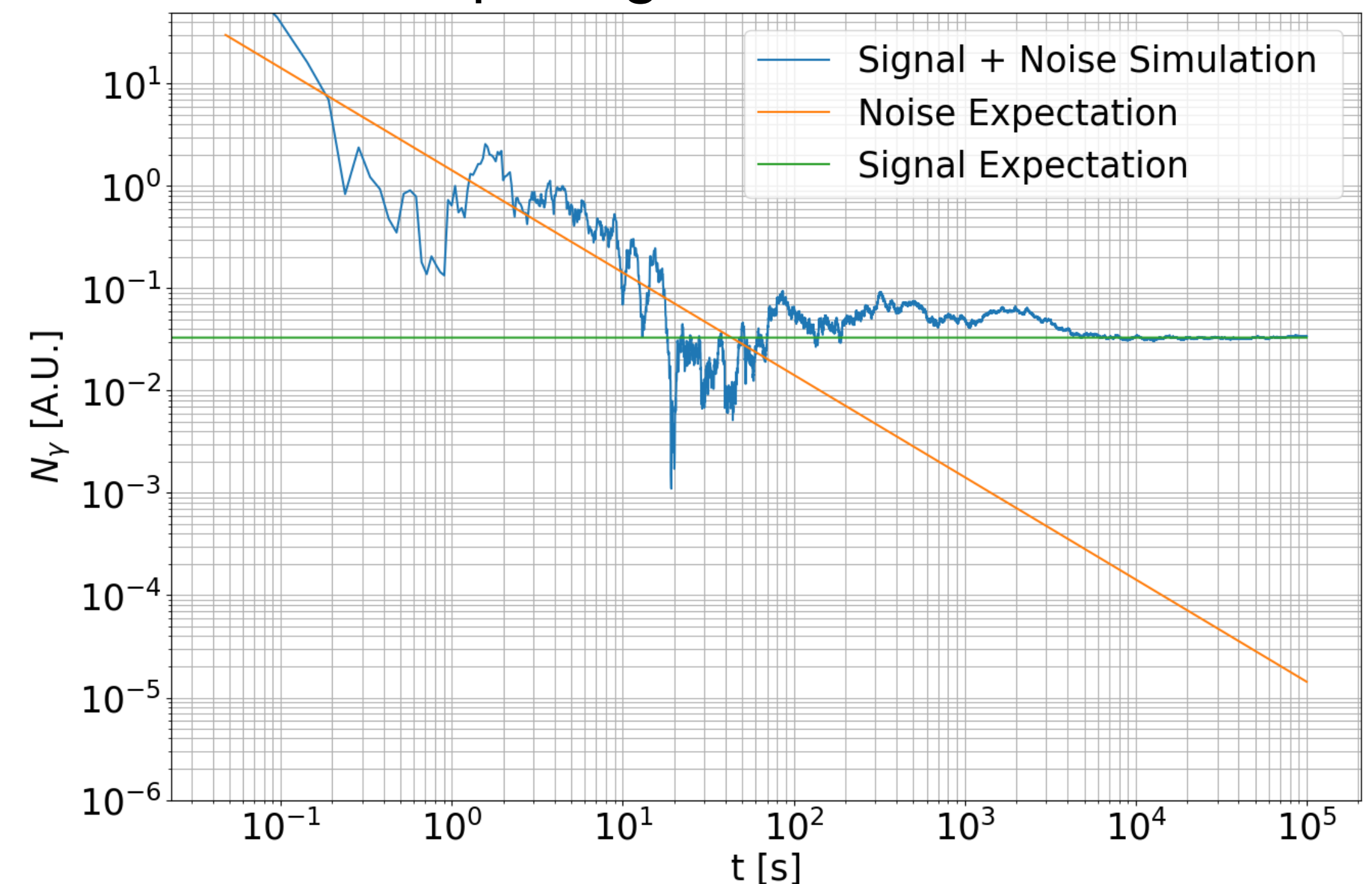
Option 1: heterodyne (HET) sensing

- Mix weak signal with a frequency-shifted local oscillator \rightarrow beat note signal
- Detection of a photon flux corresponding to $5 \cdot 10^{-21}$ W demonstrated.
- Sensitivity of 10^{-24} W demonstrated.
- Good prospects to being shot-noise limited
- 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)



Example signal from simulation



ALPS II- Heterodyne

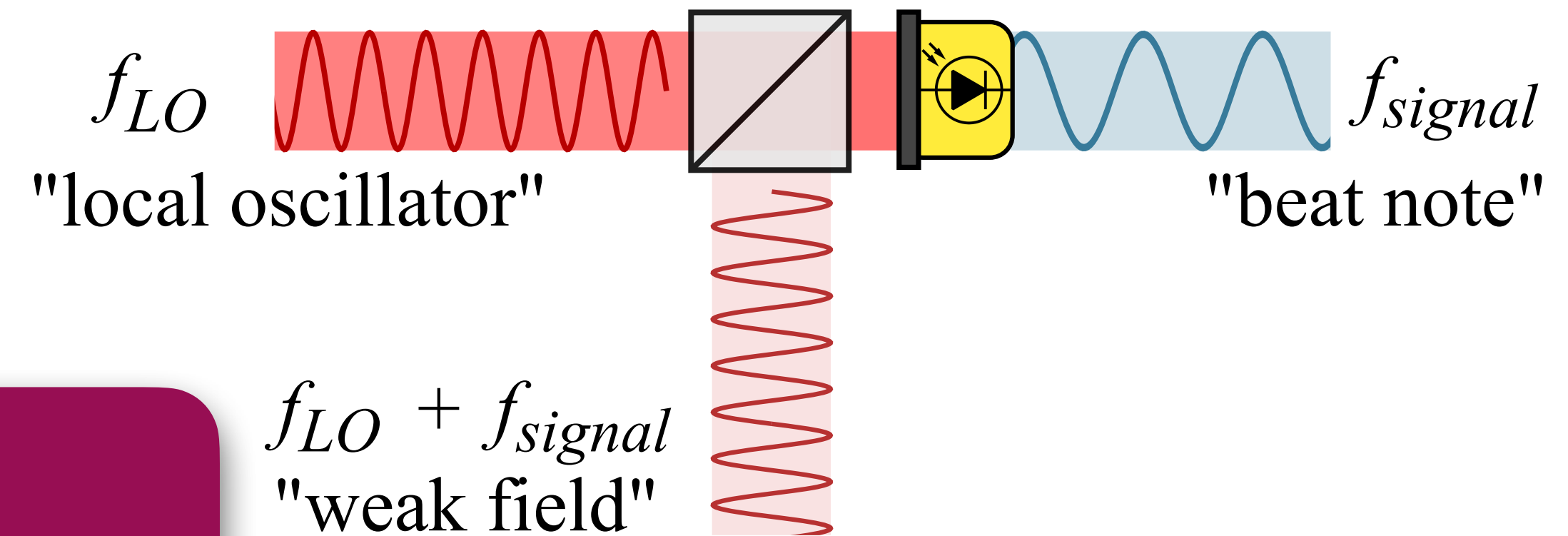
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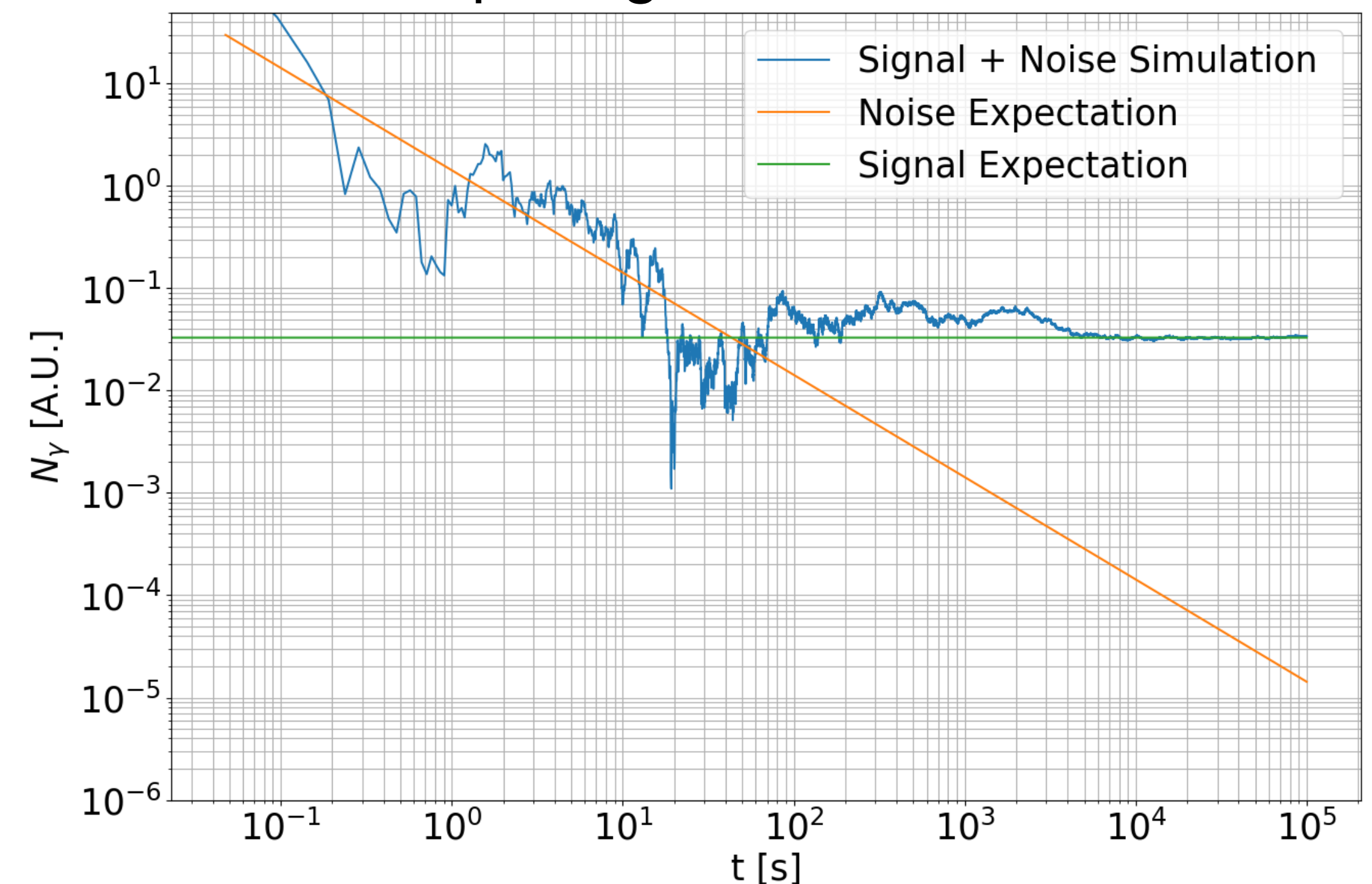
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Z. Bush et al., Phys. Rev. D 99, 022001 (2019)

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



Example signal from simulation

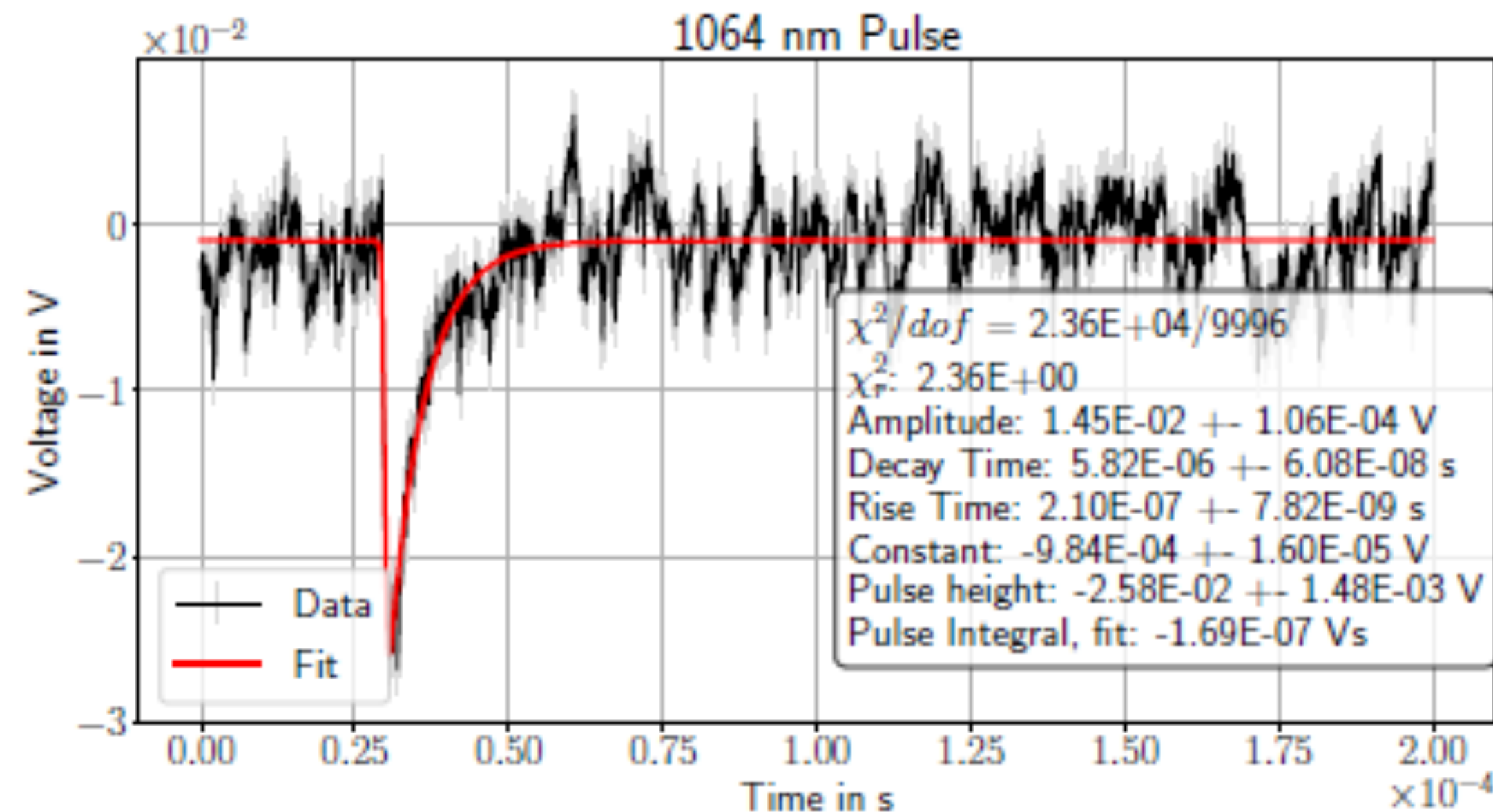
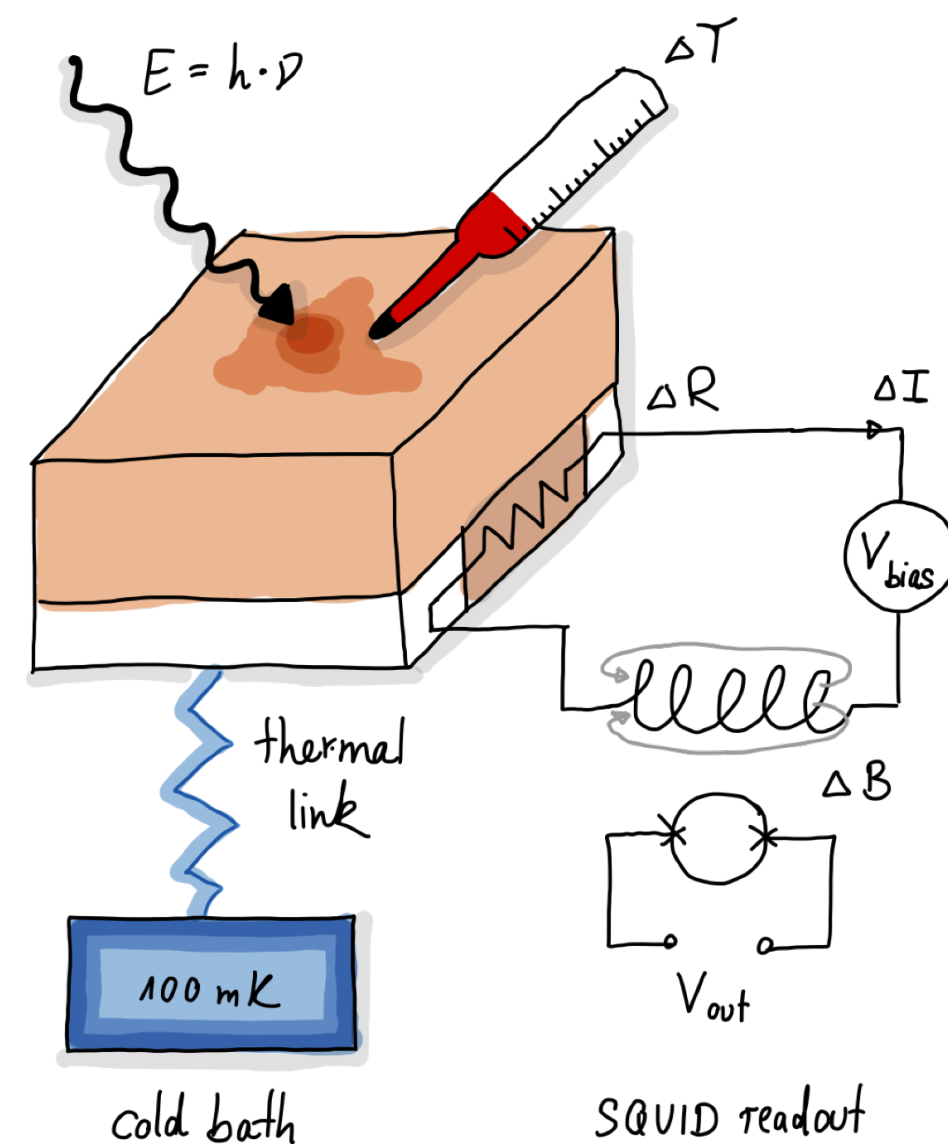


ALPS II- Transition Edge Sensor

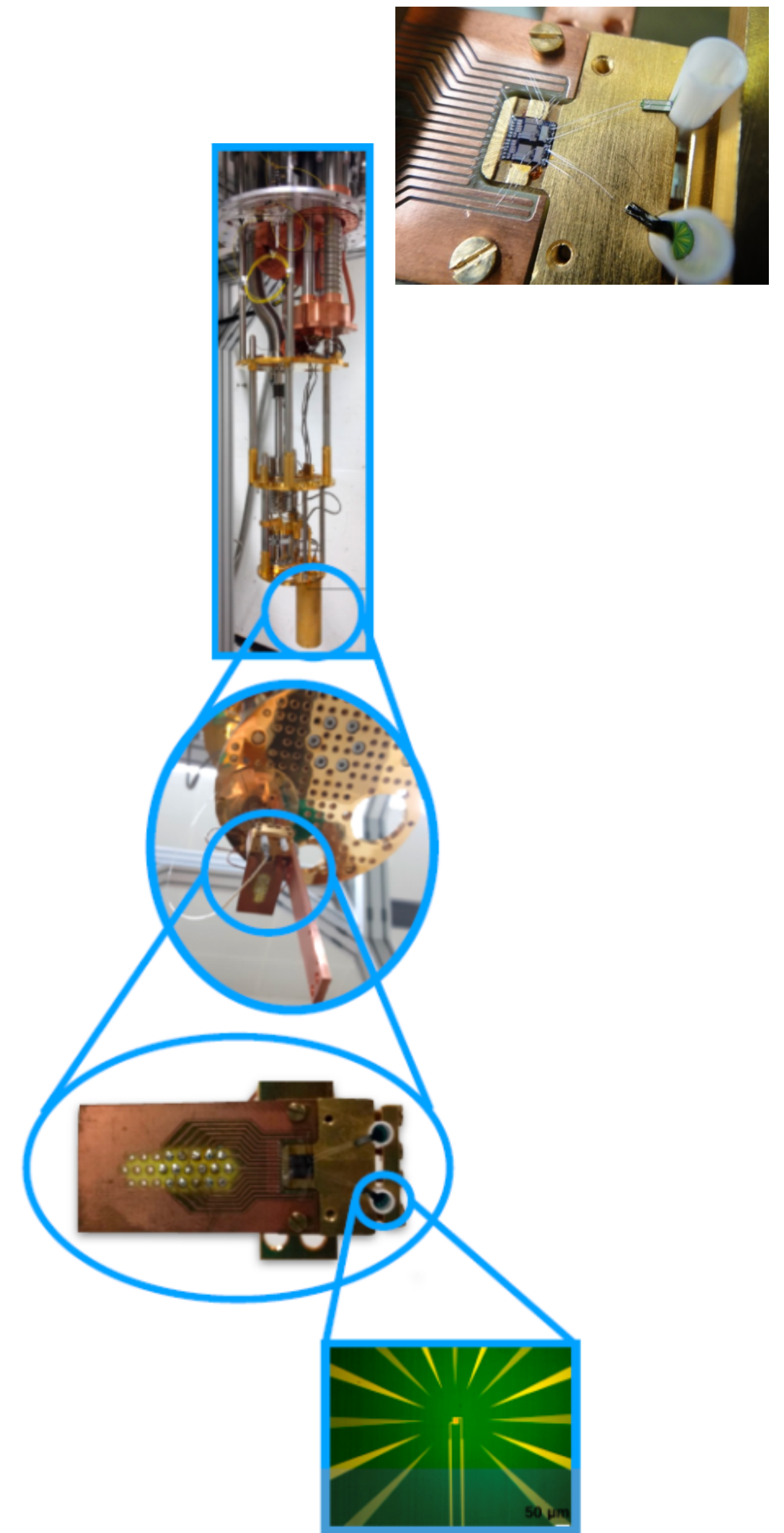
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Option 2: photon counting

- Second option to confirm HET signal
- 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



Graphic from Friederike Januschek

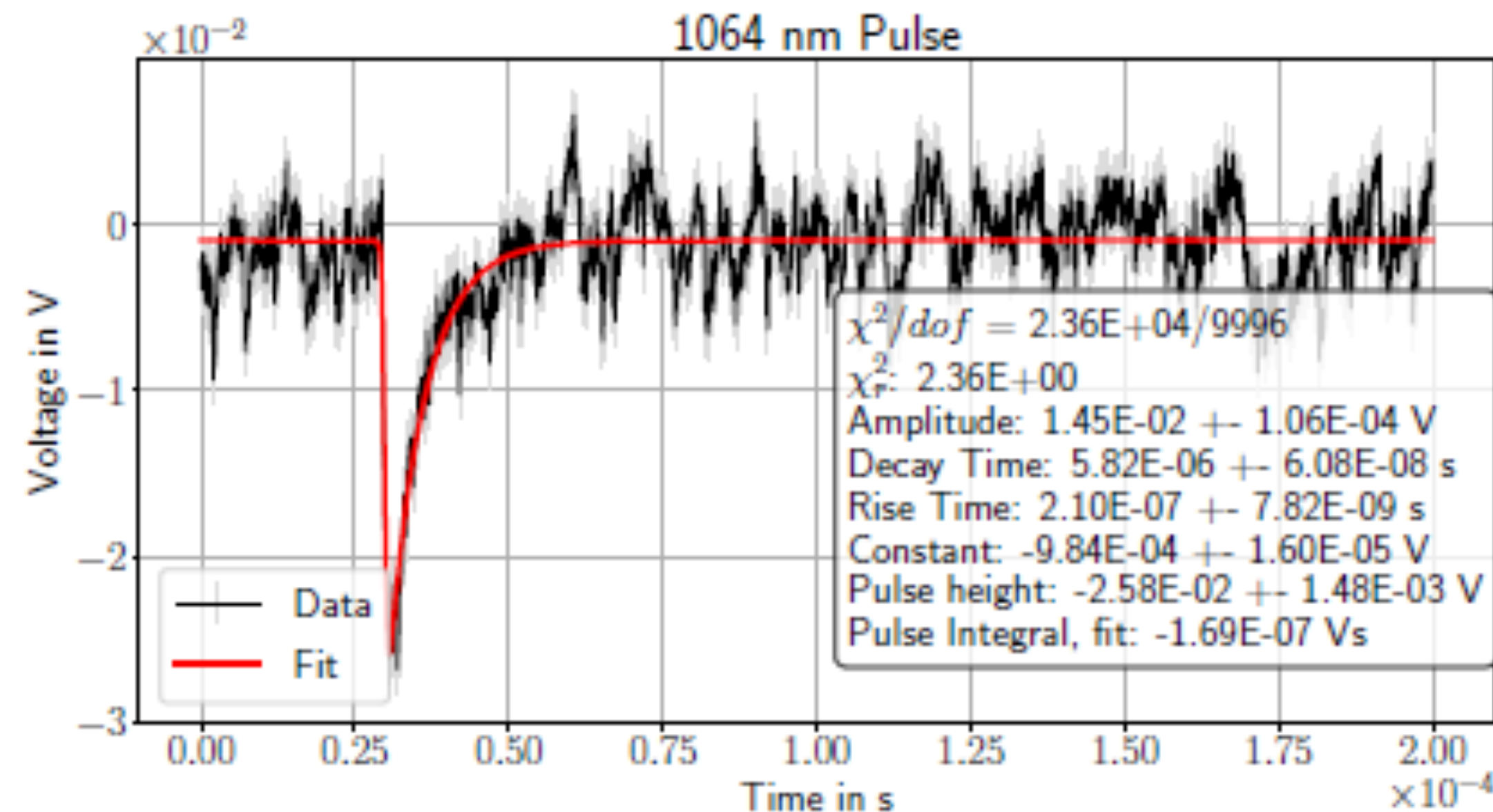
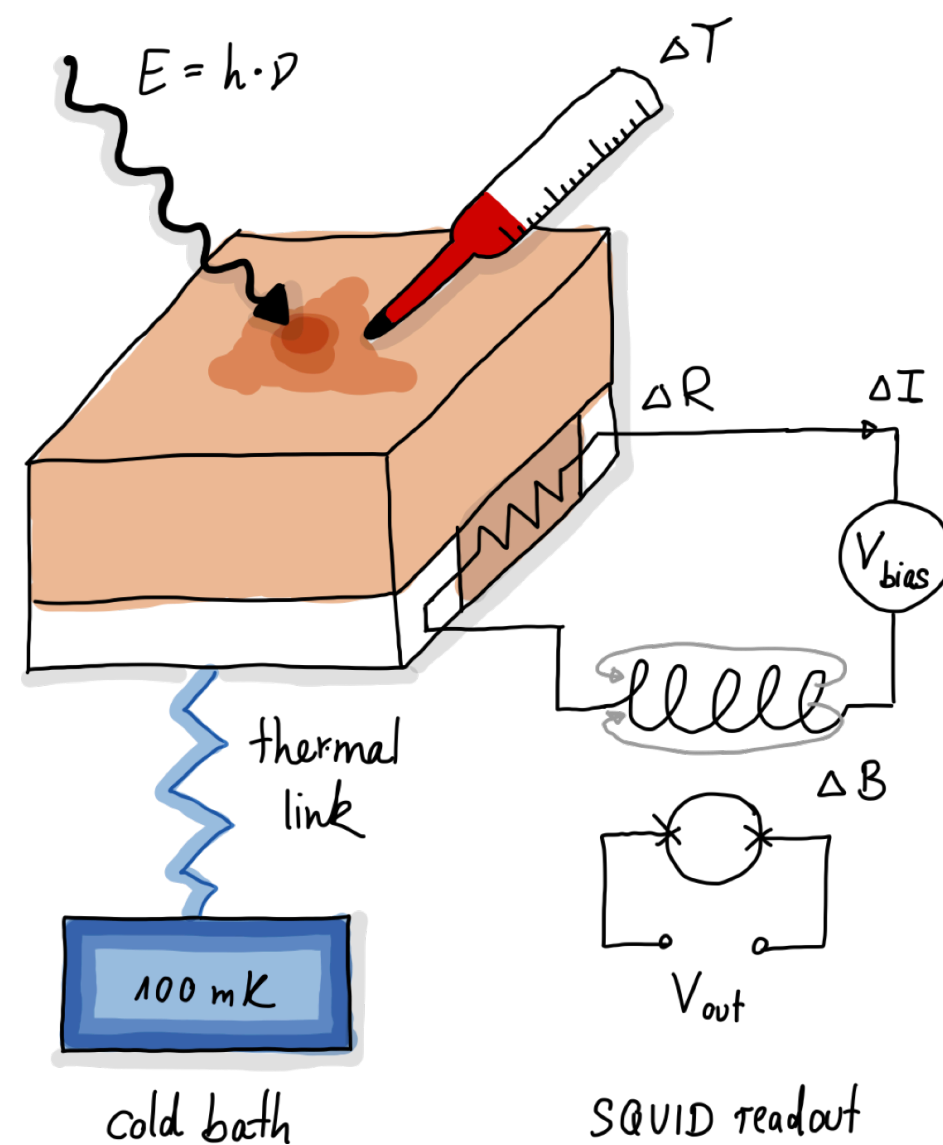
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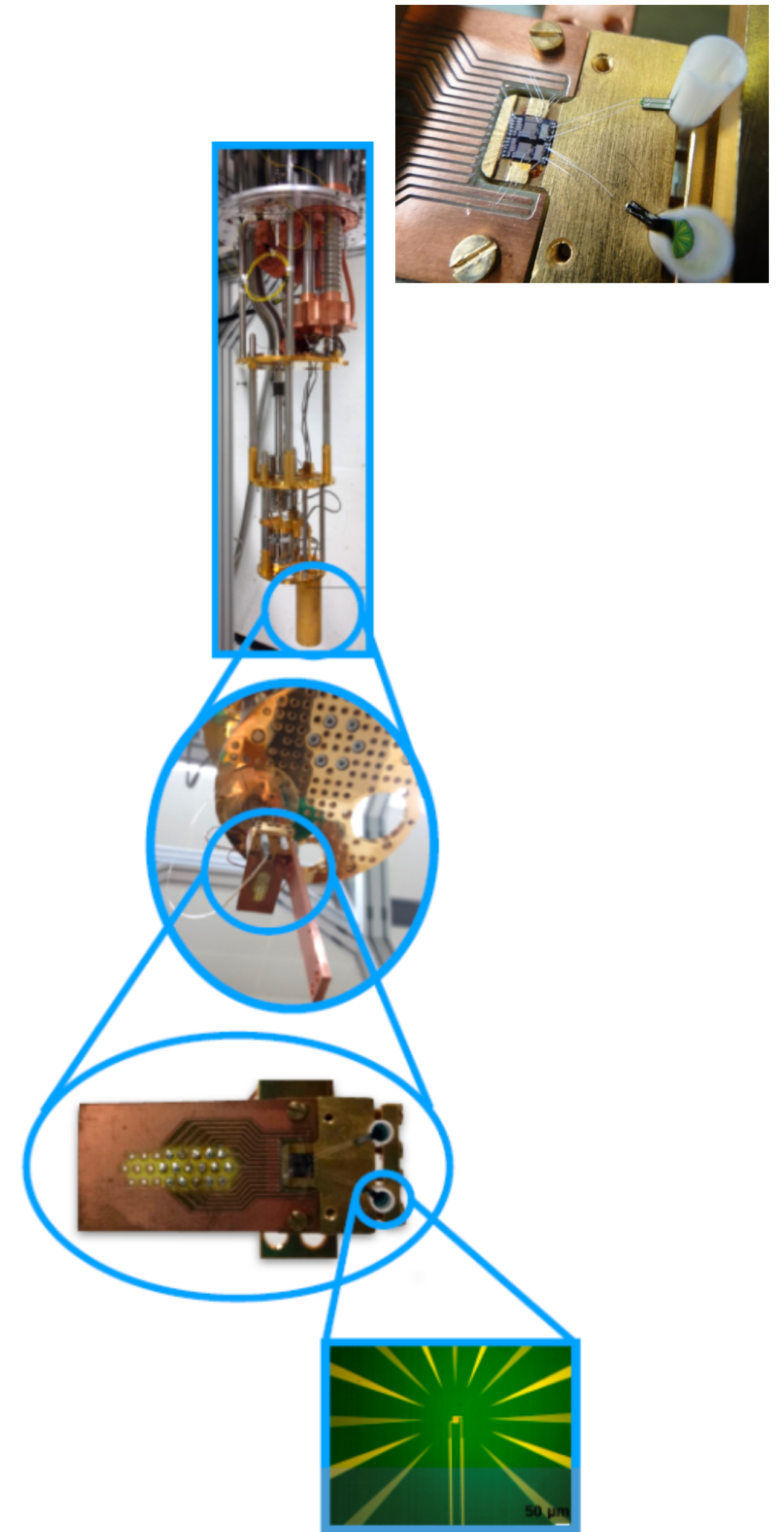
Option 2: photon counting

Already have demonstrated:

- Low-backgrounds (μHz)
- Good energy resolution ($\sim 10\%$)
- Long-term stability (~ 20 days)



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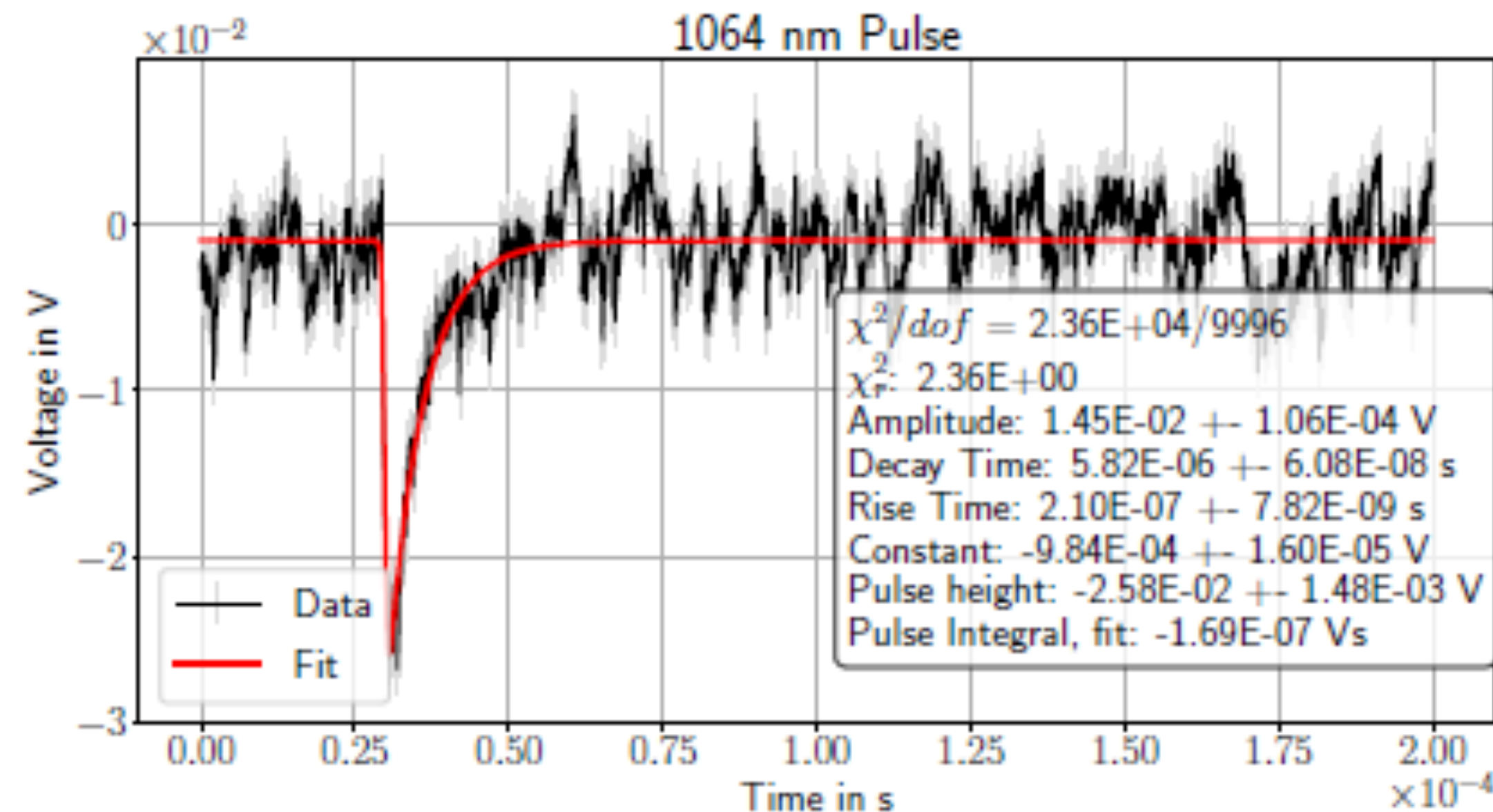
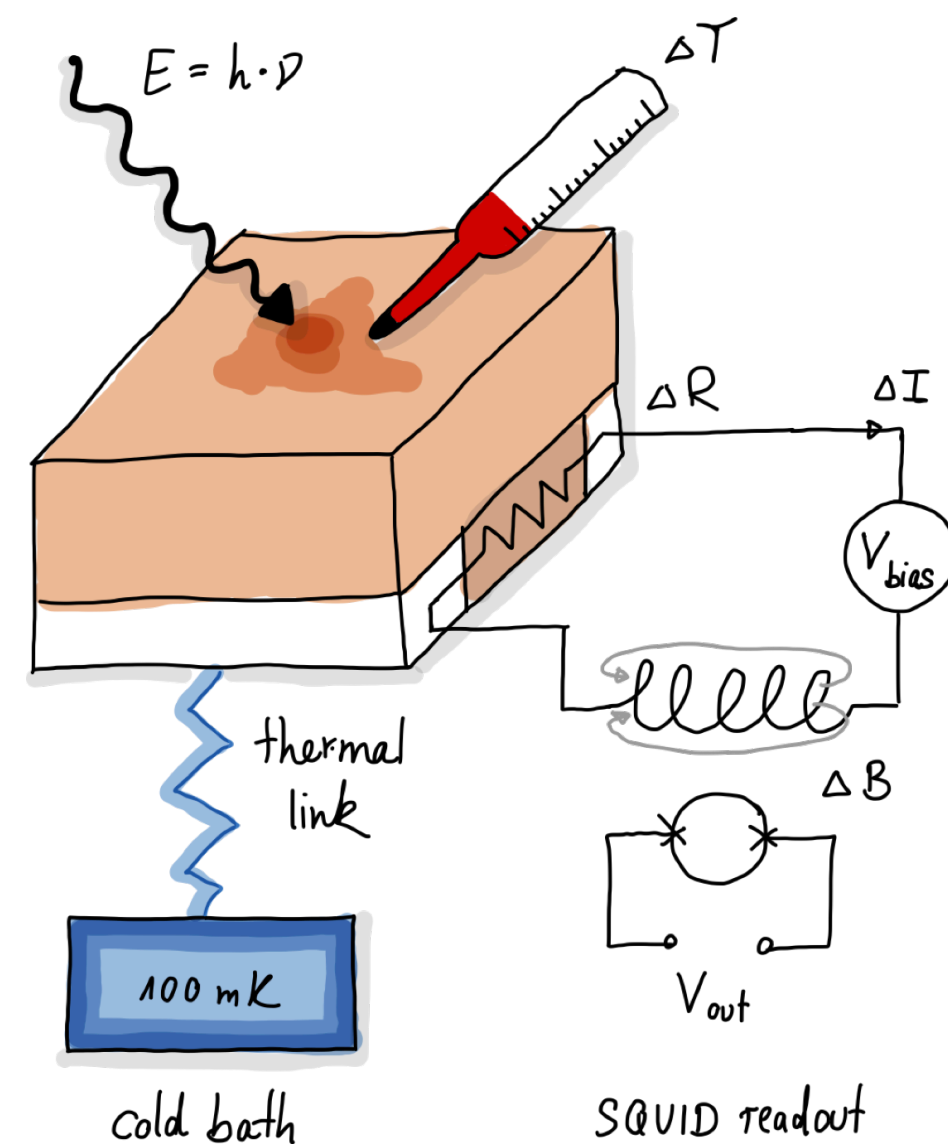
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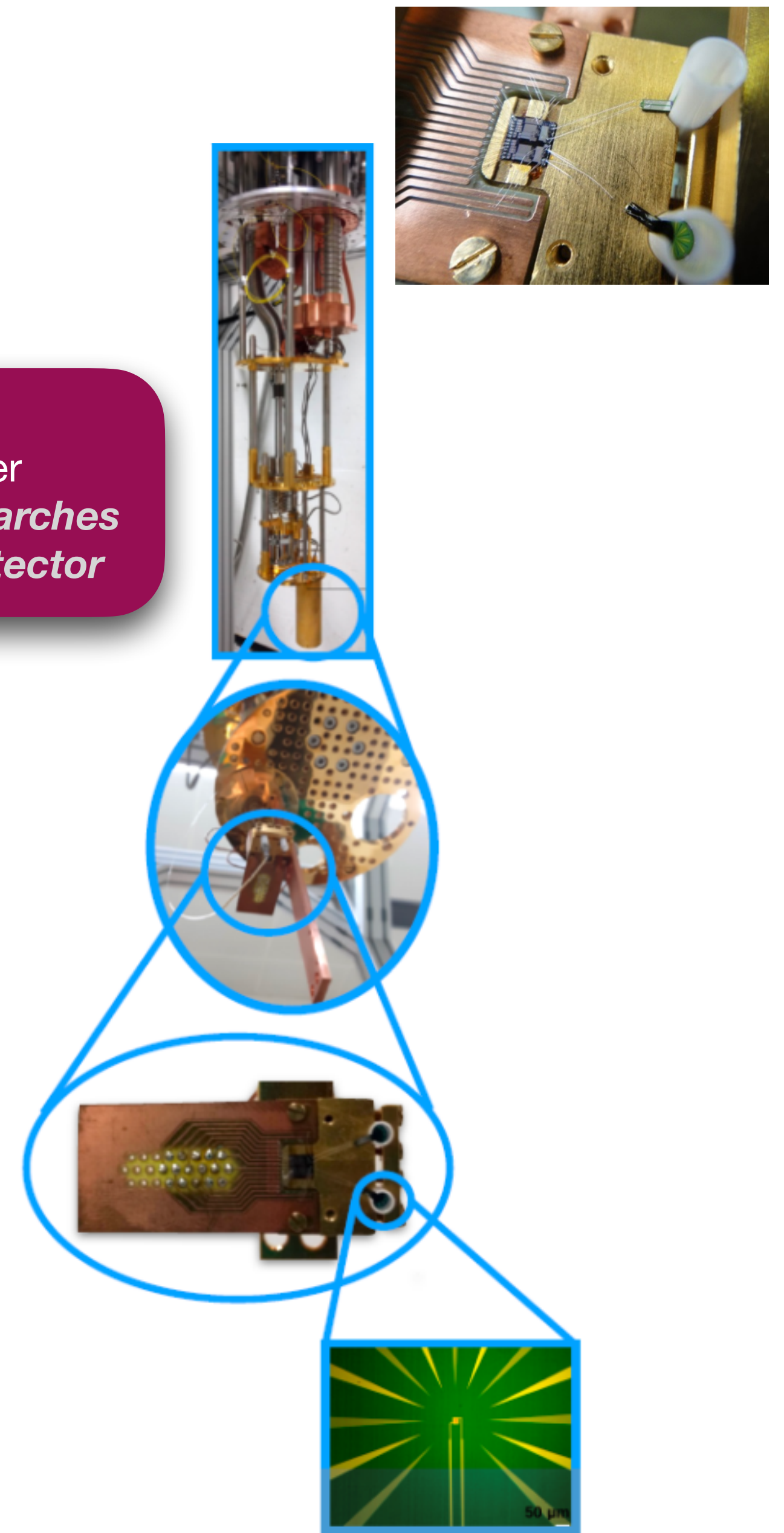
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Graphic from Friederike Januschek

First Science Run **This Summer**

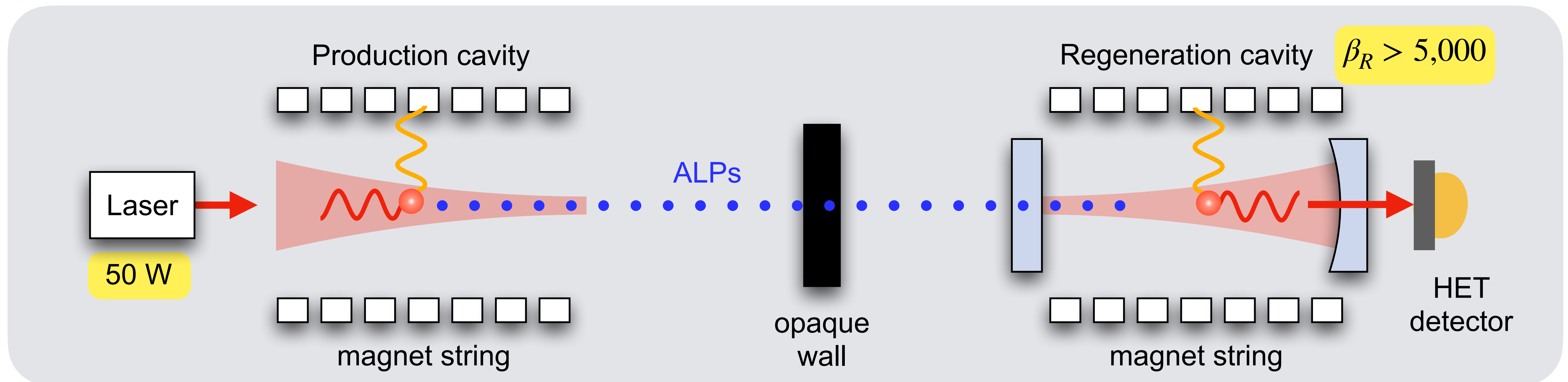
Commissioning optical setup without production cavity

- Simpler control scheme
- Stronger signals for stray light hunting
- HET Detector

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

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

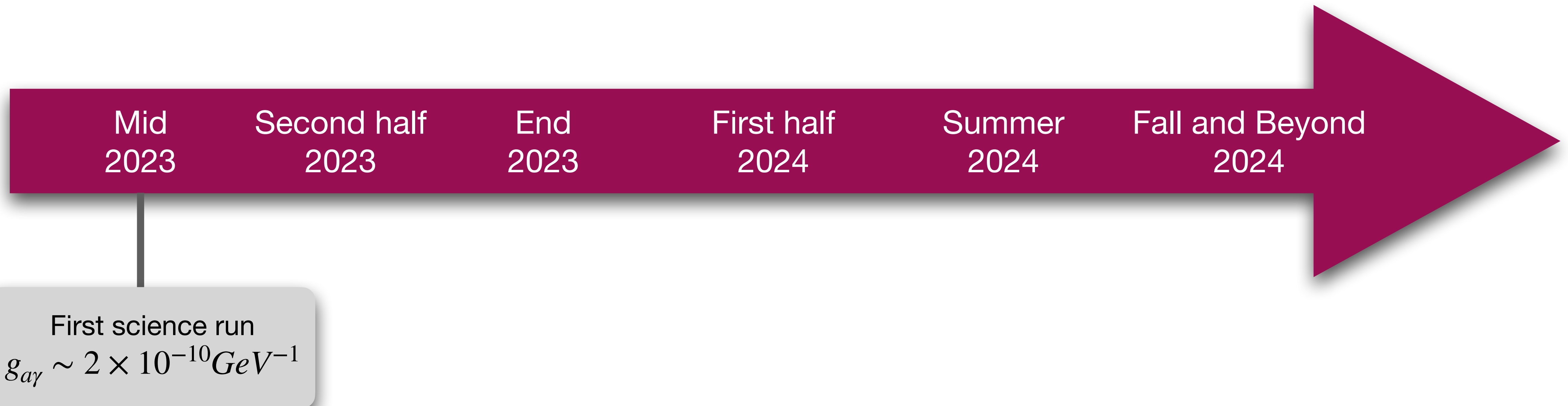
Graphic from Katharina-Sophie Isleif



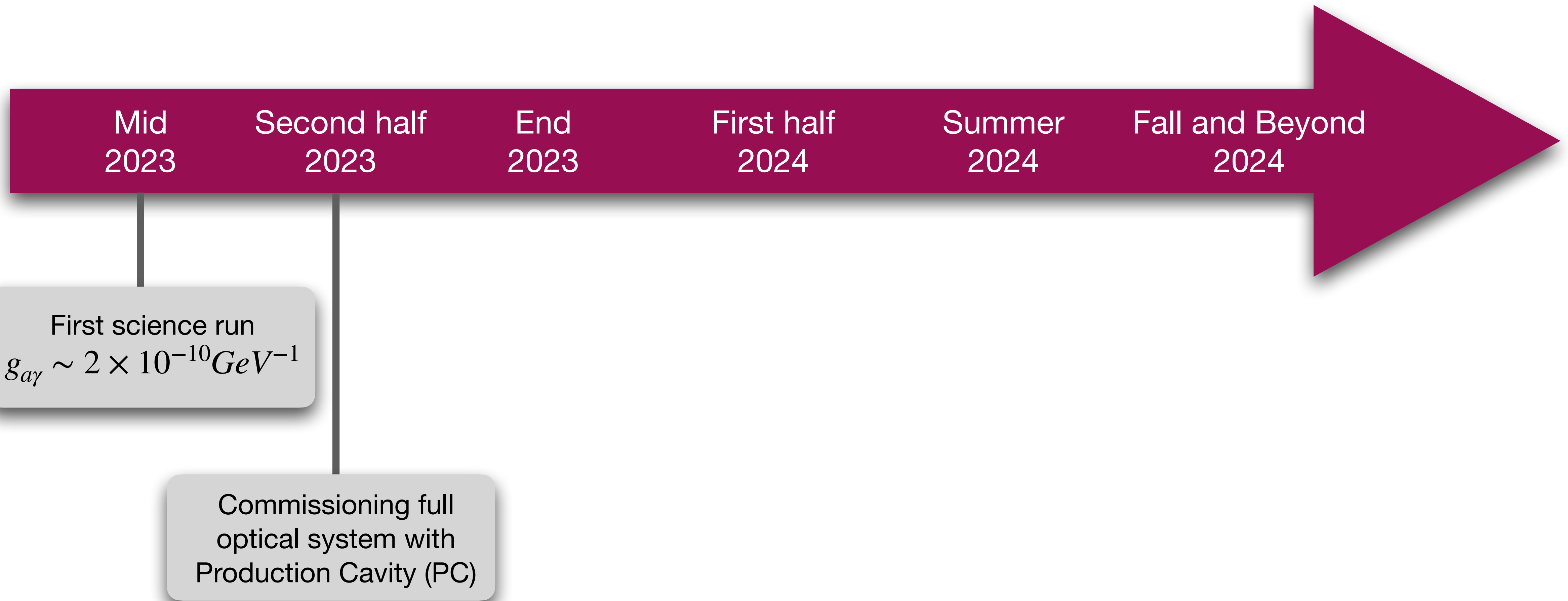
Preliminary ALPS II Schedule



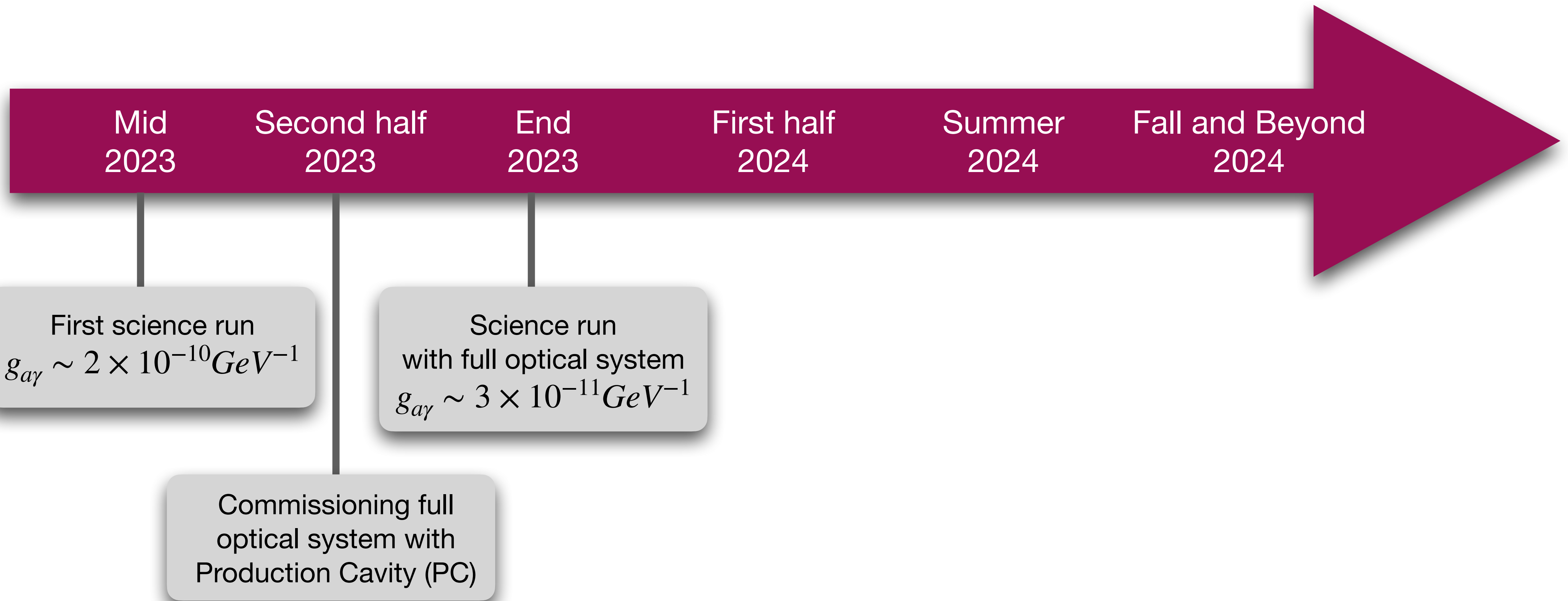
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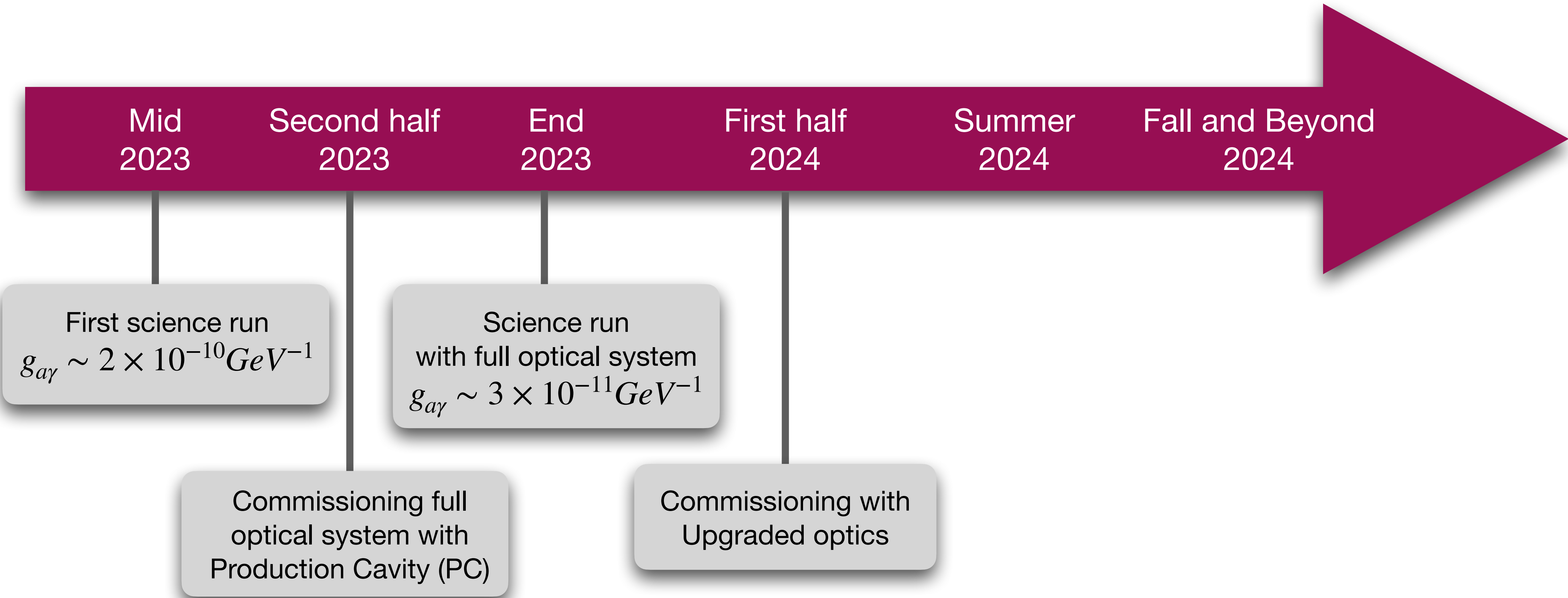
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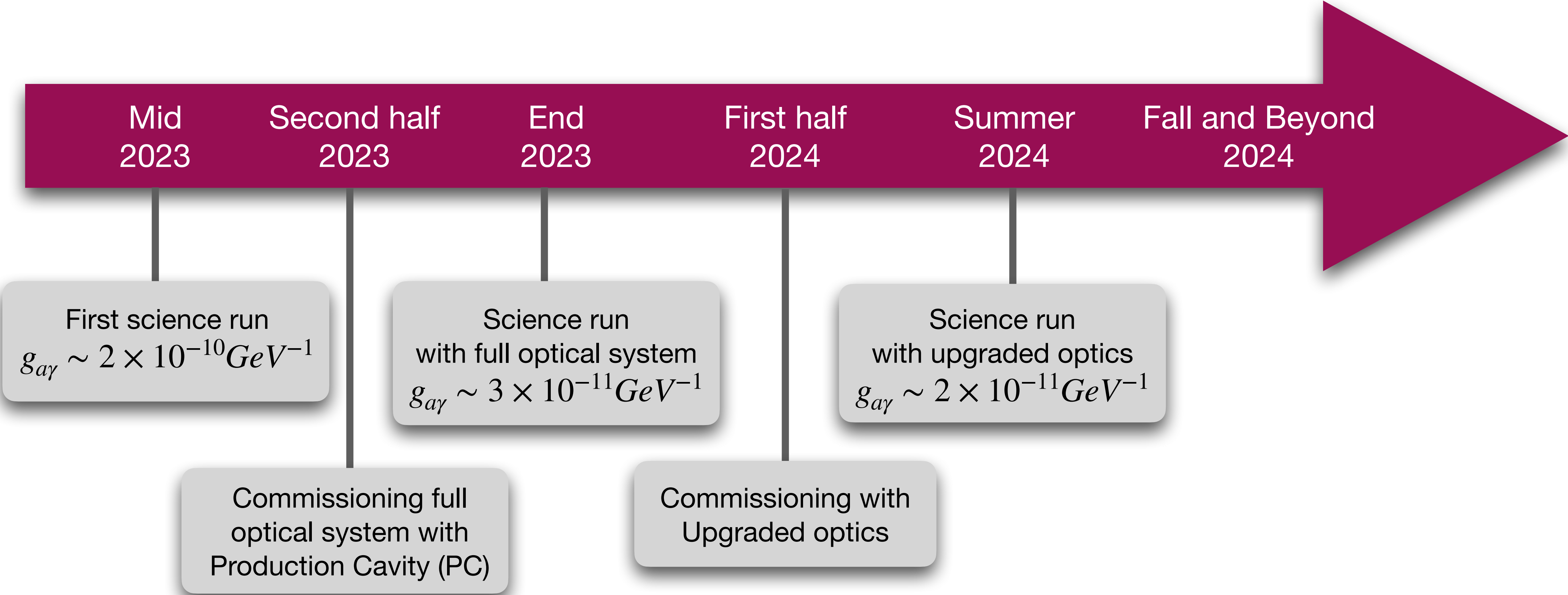
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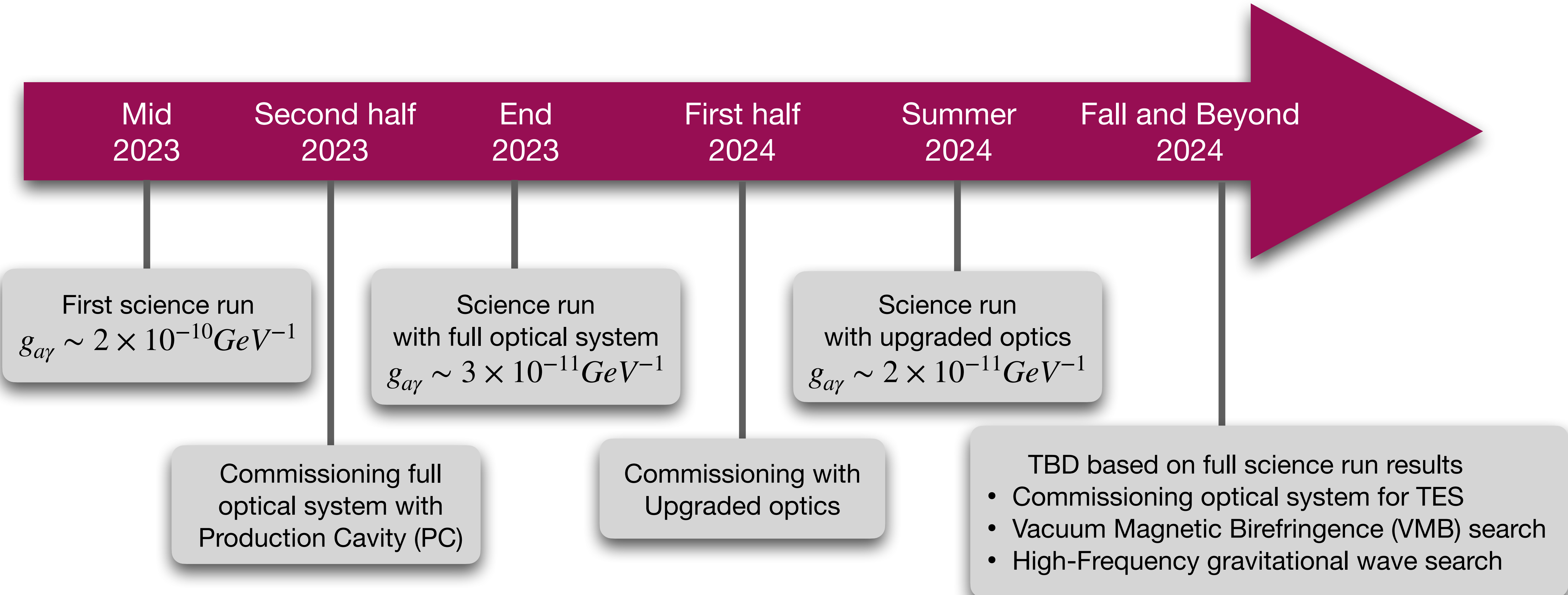
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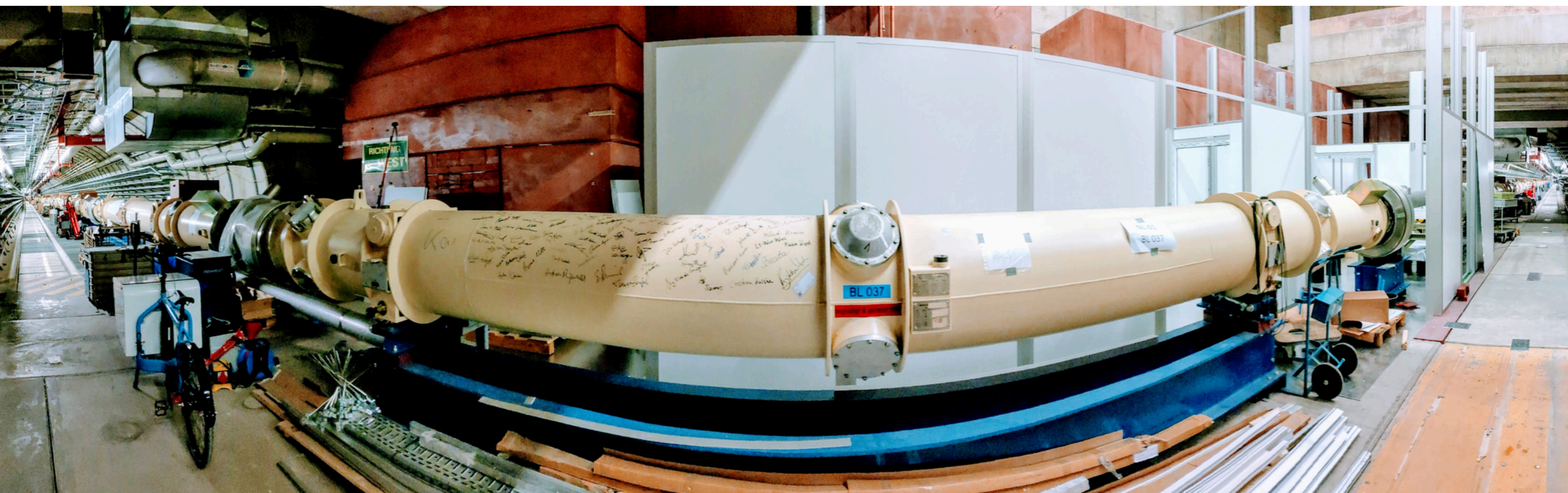
Preliminary ALPS II Schedule



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 this summer $\rightarrow g_{a\gamma} \sim 2 \times 10^{-10} \text{ GeV}^{-1}$
- Full sensitivity run after upgrades around Summer 2024 $\rightarrow g_{a\gamma} \sim 2 \times 10^{-11} \text{ GeV}^{-1}$

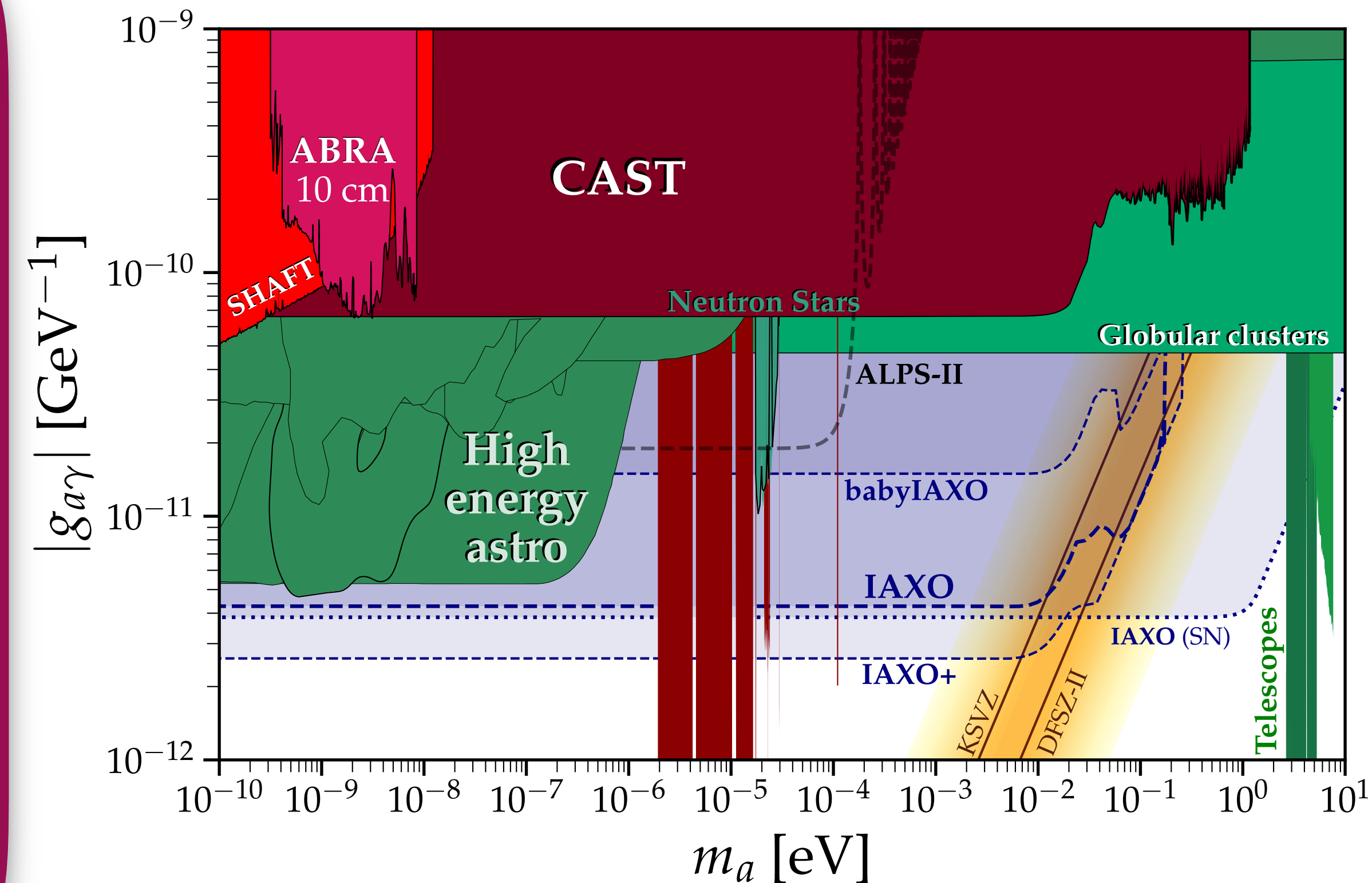
Thank you!



Backup slides

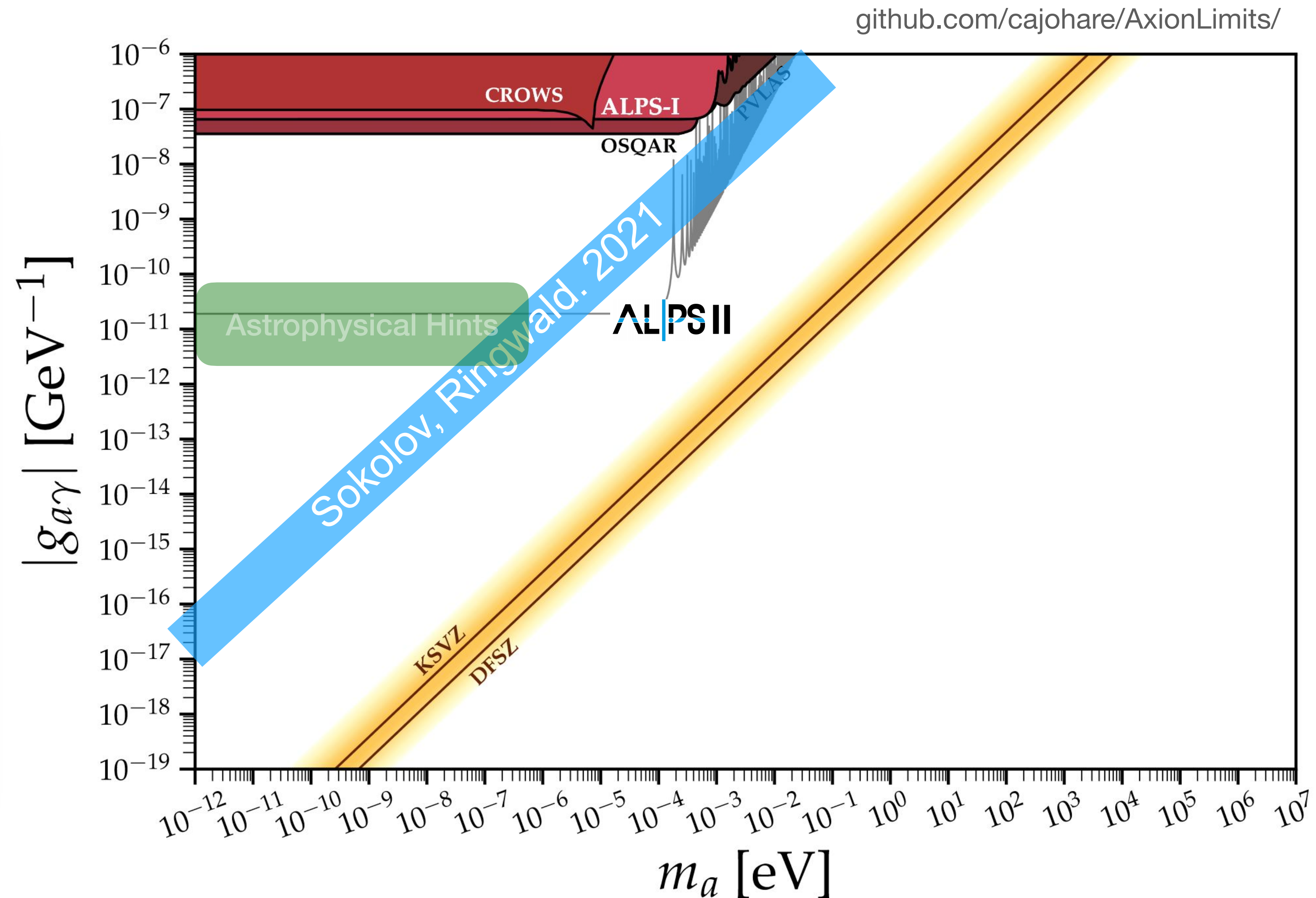
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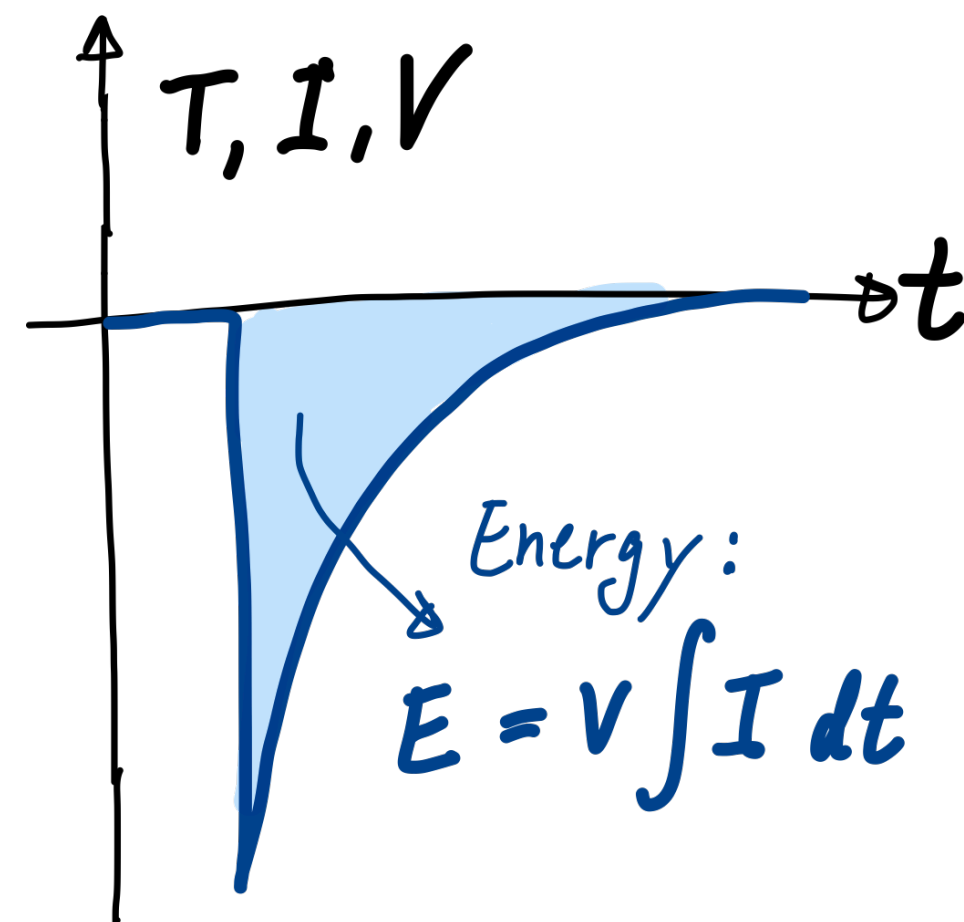
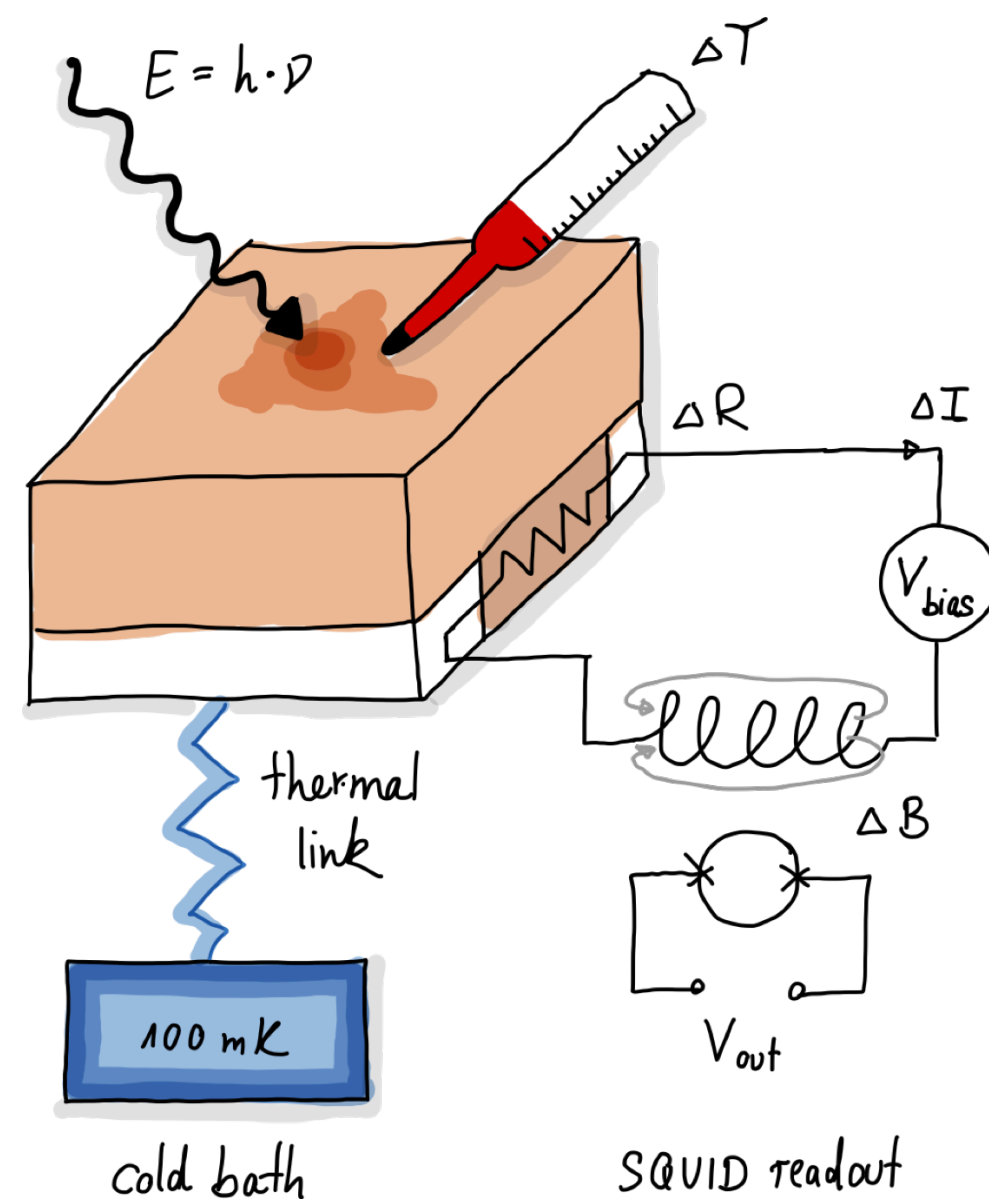


ALPS II- Transition Edge Sensor

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

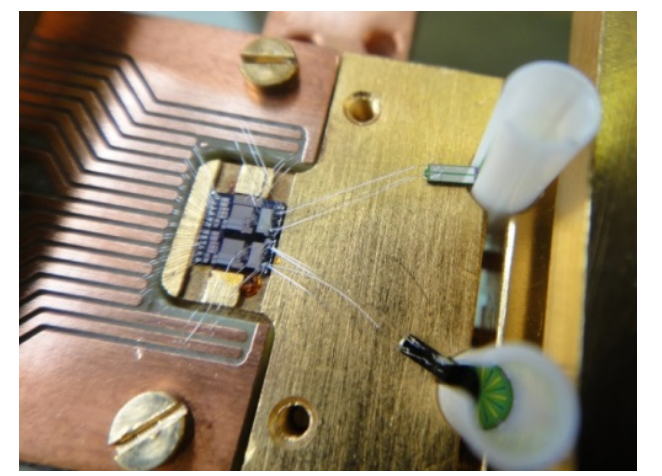
Option 2: photon counting

- 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

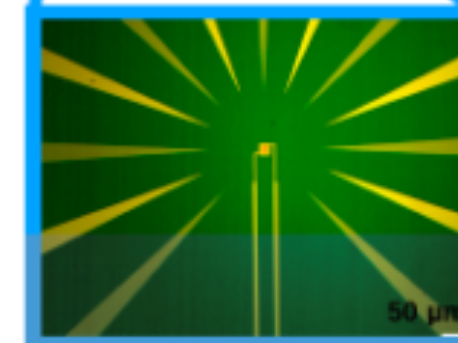
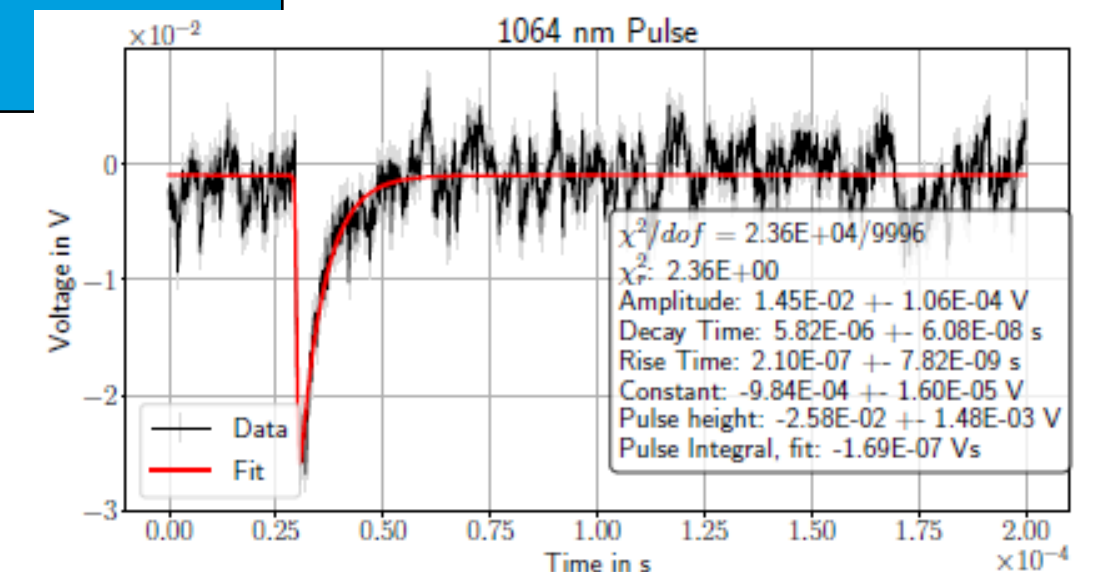


Single 1064 nm photon heats TES by $\sim 100 \mu\text{K}$

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



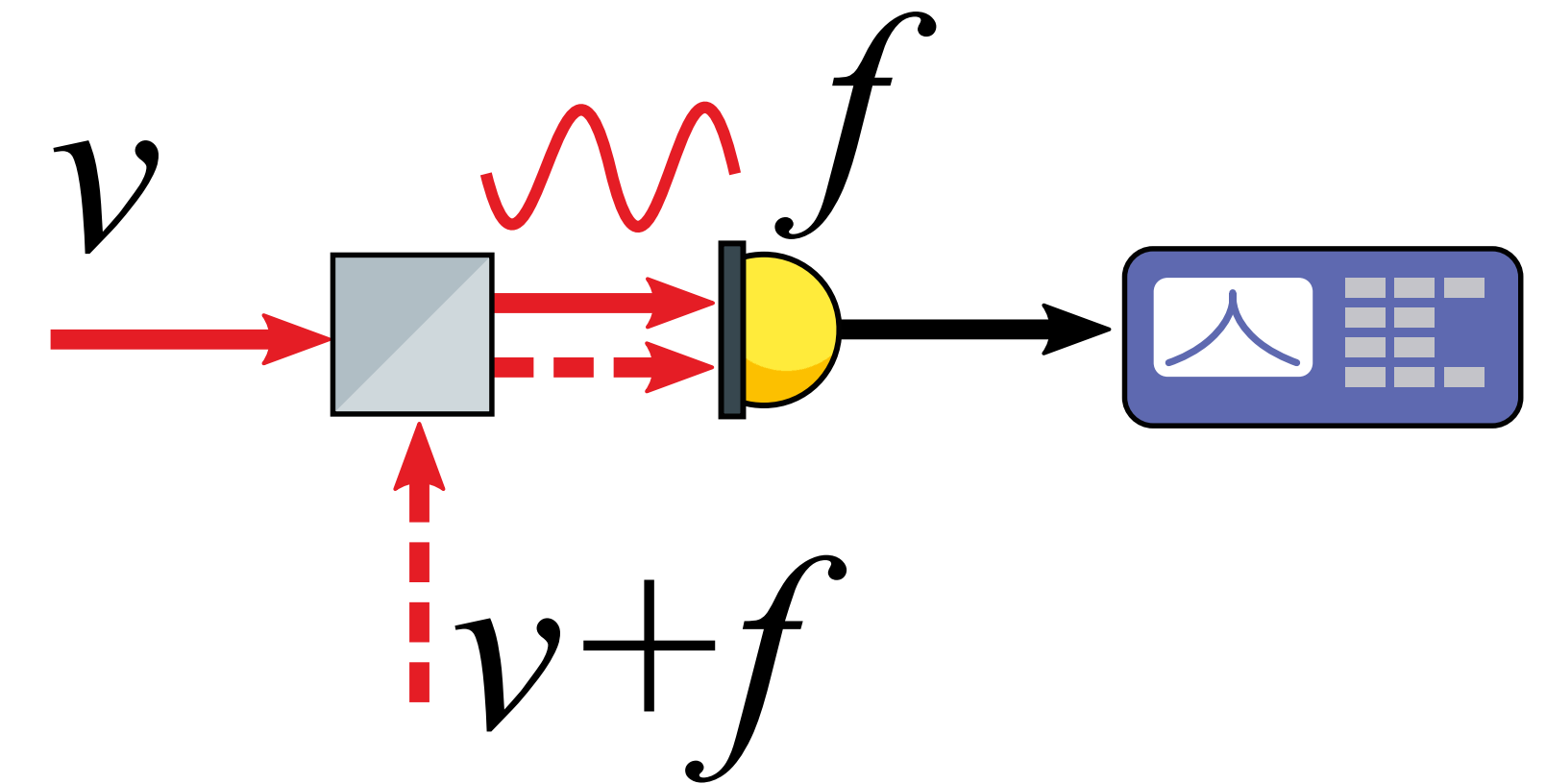
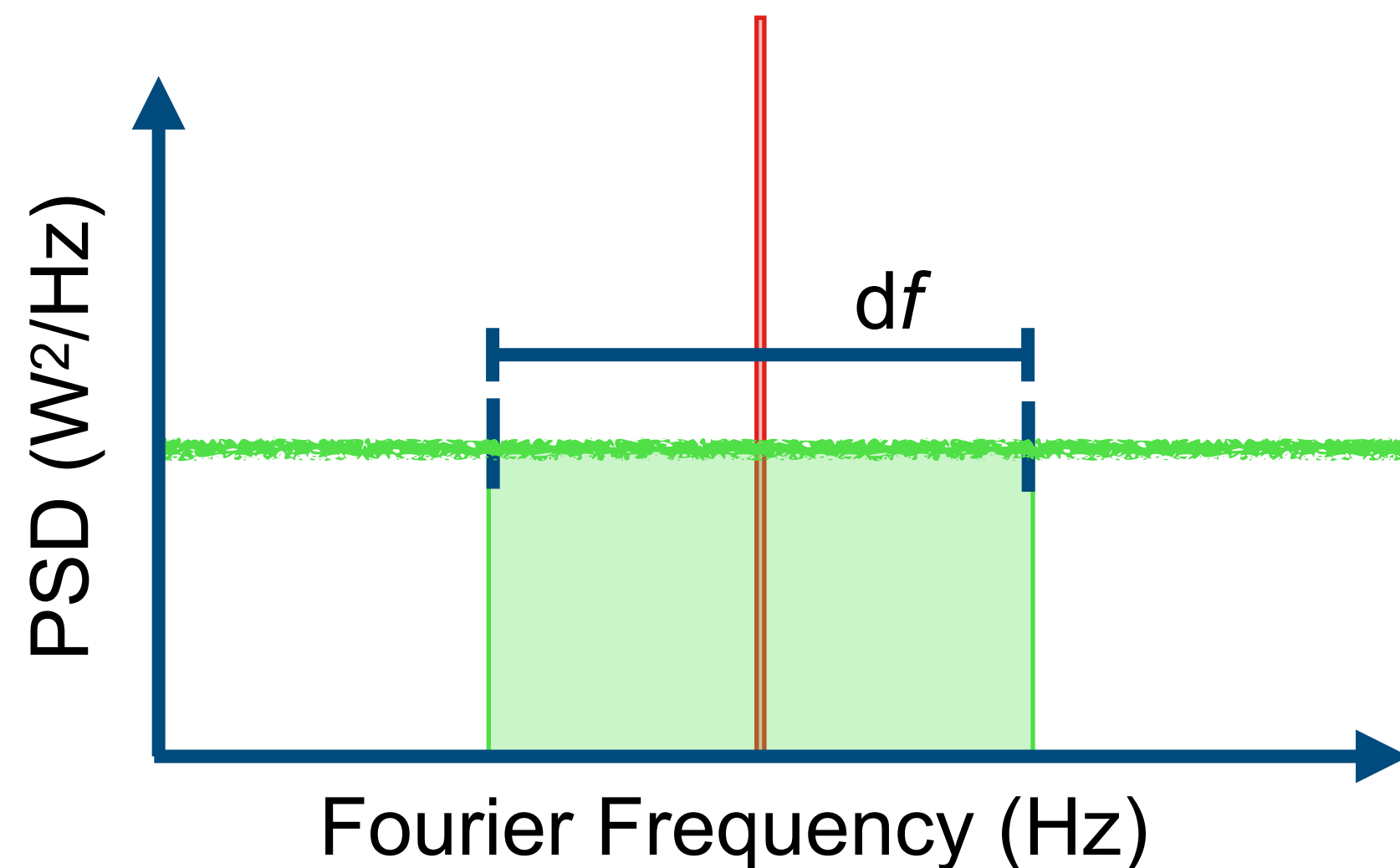
Slide from Friederike Januschek

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



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

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

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

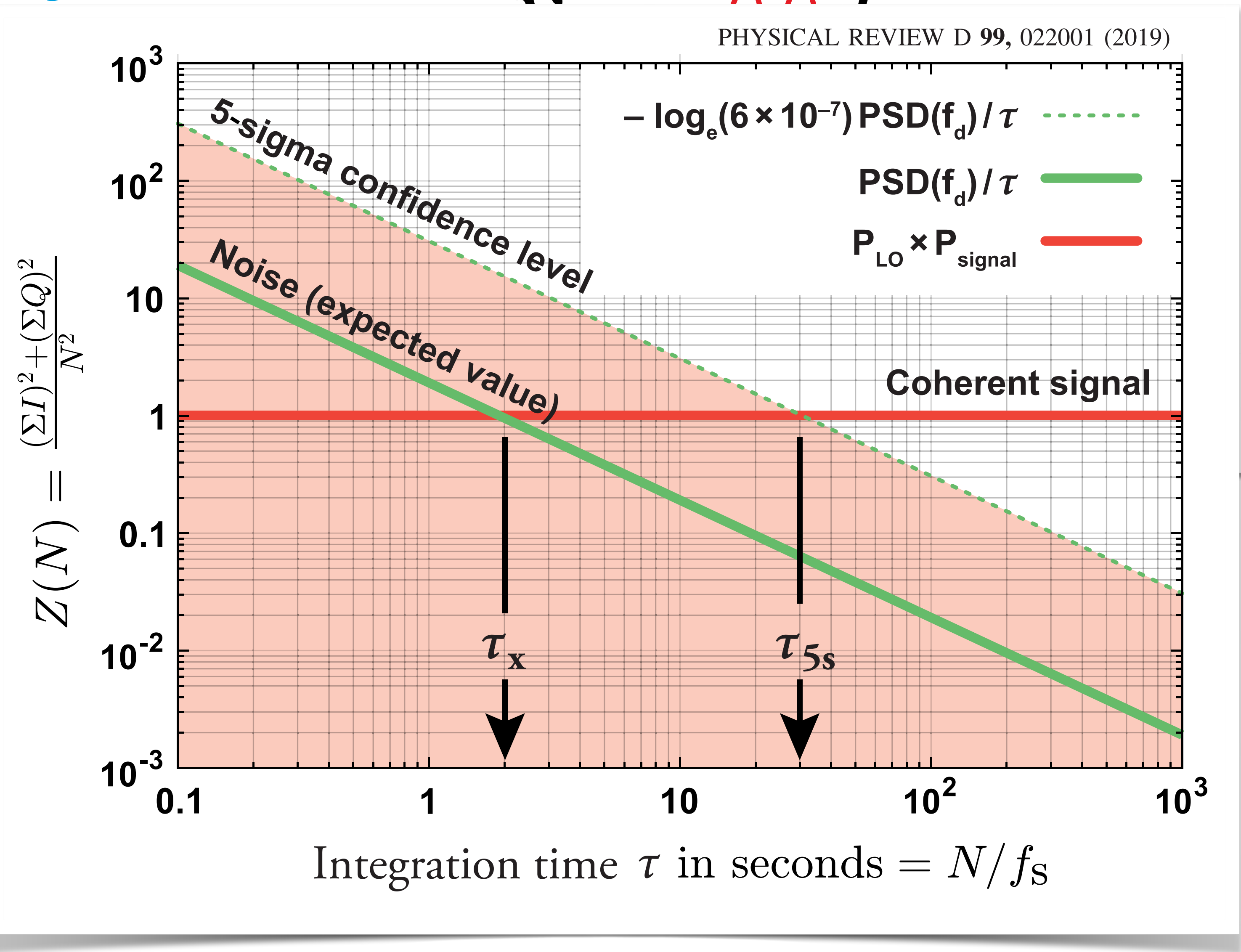
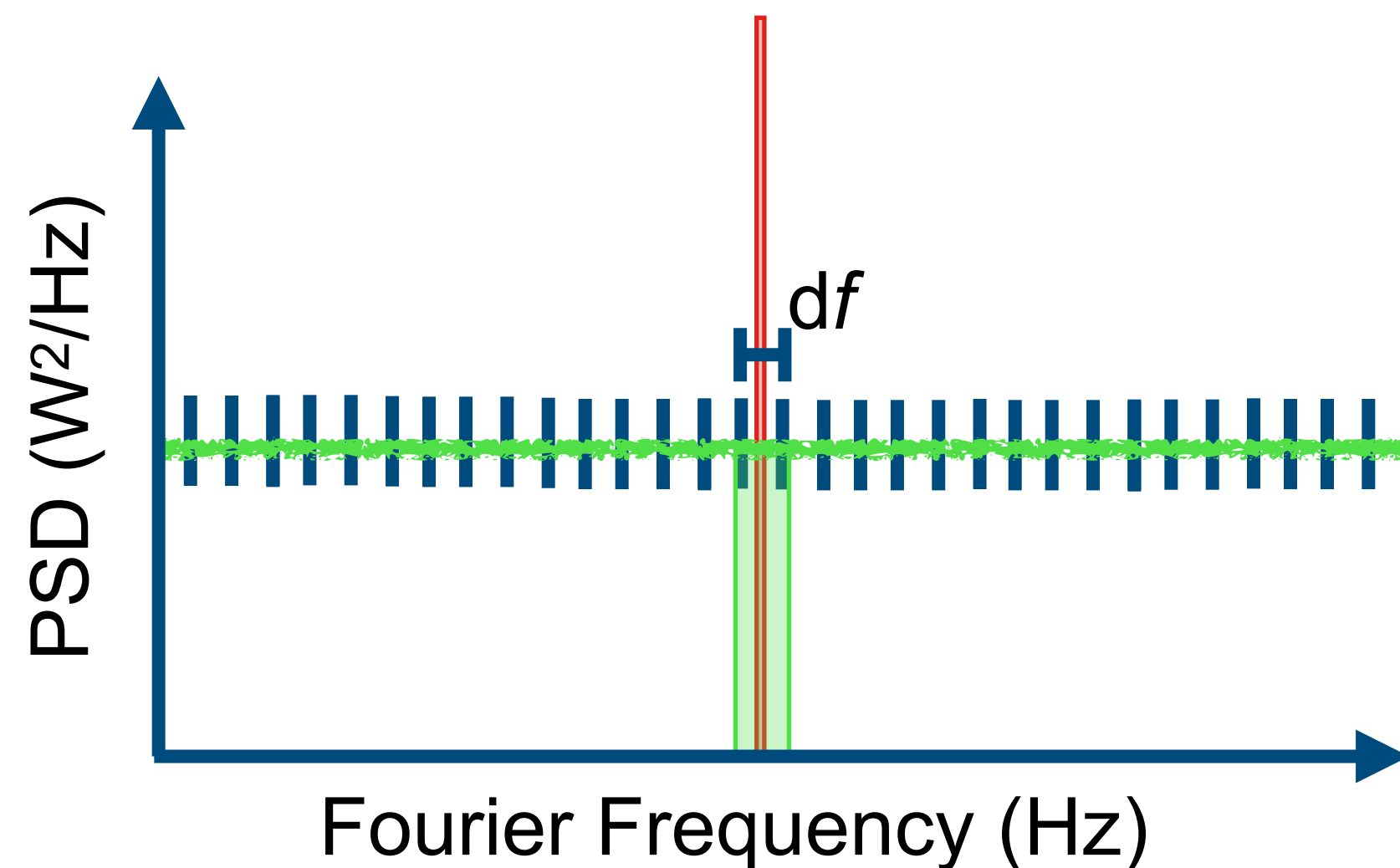
$$Q[n] = x_{\text{sig}}[n] \times \sin\left(2\pi \frac{f_d}{f_s} n\right)$$

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 dif



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

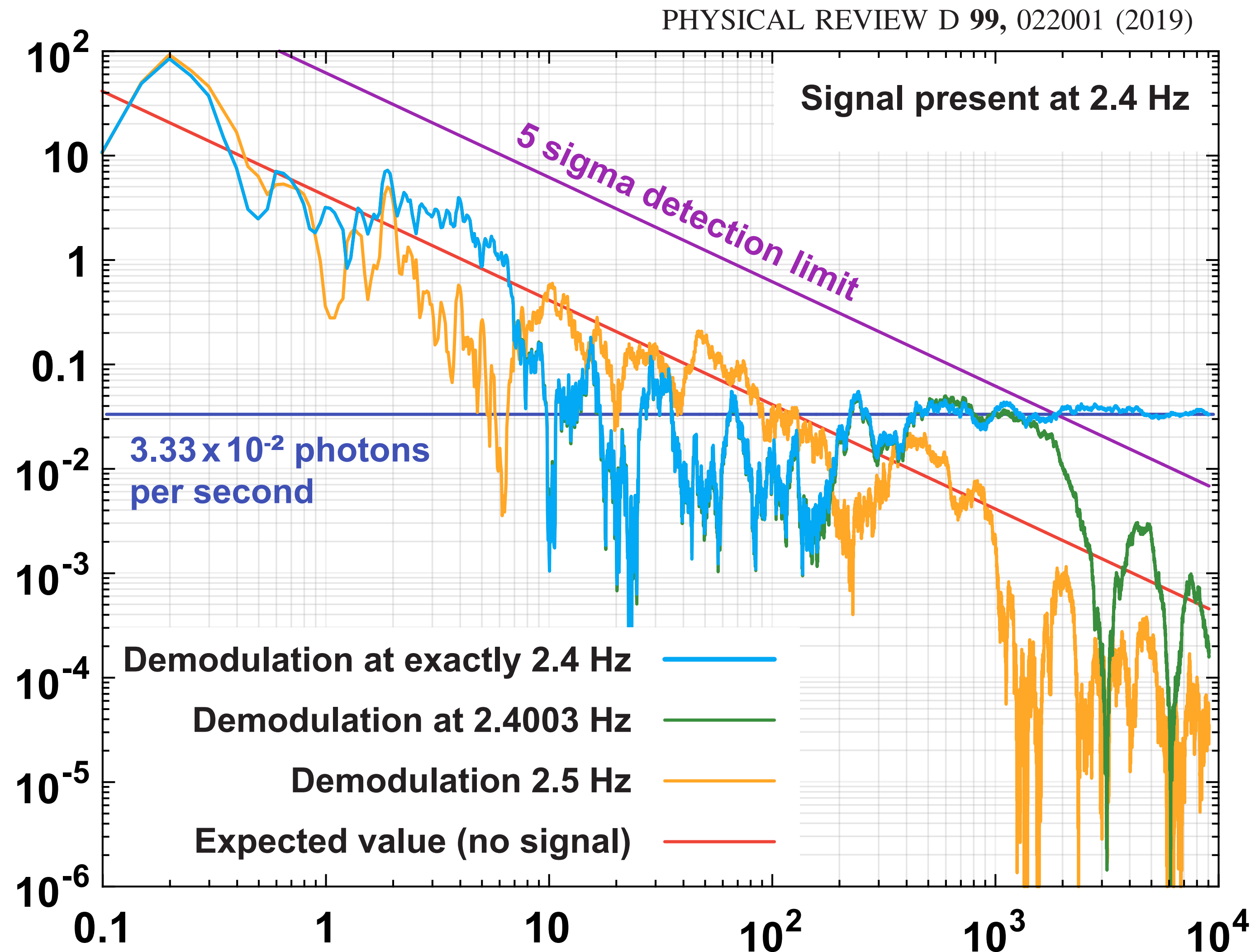
Zachary R. Bush,¹ Simon Barke,¹ Harold Hollis,¹ Aaron D. Spector,² Ayman Hallal,¹
Giuseppe Messineo,¹ D. B. Tanner,¹ and Guido Mueller¹

¹Department of Physics, University of Florida, P.O. Box 118440, Gainesville, Florida 32611, USA

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

(Received 3 April 2018; published 2 January 2019)

Photons per second $\propto Z(N)$

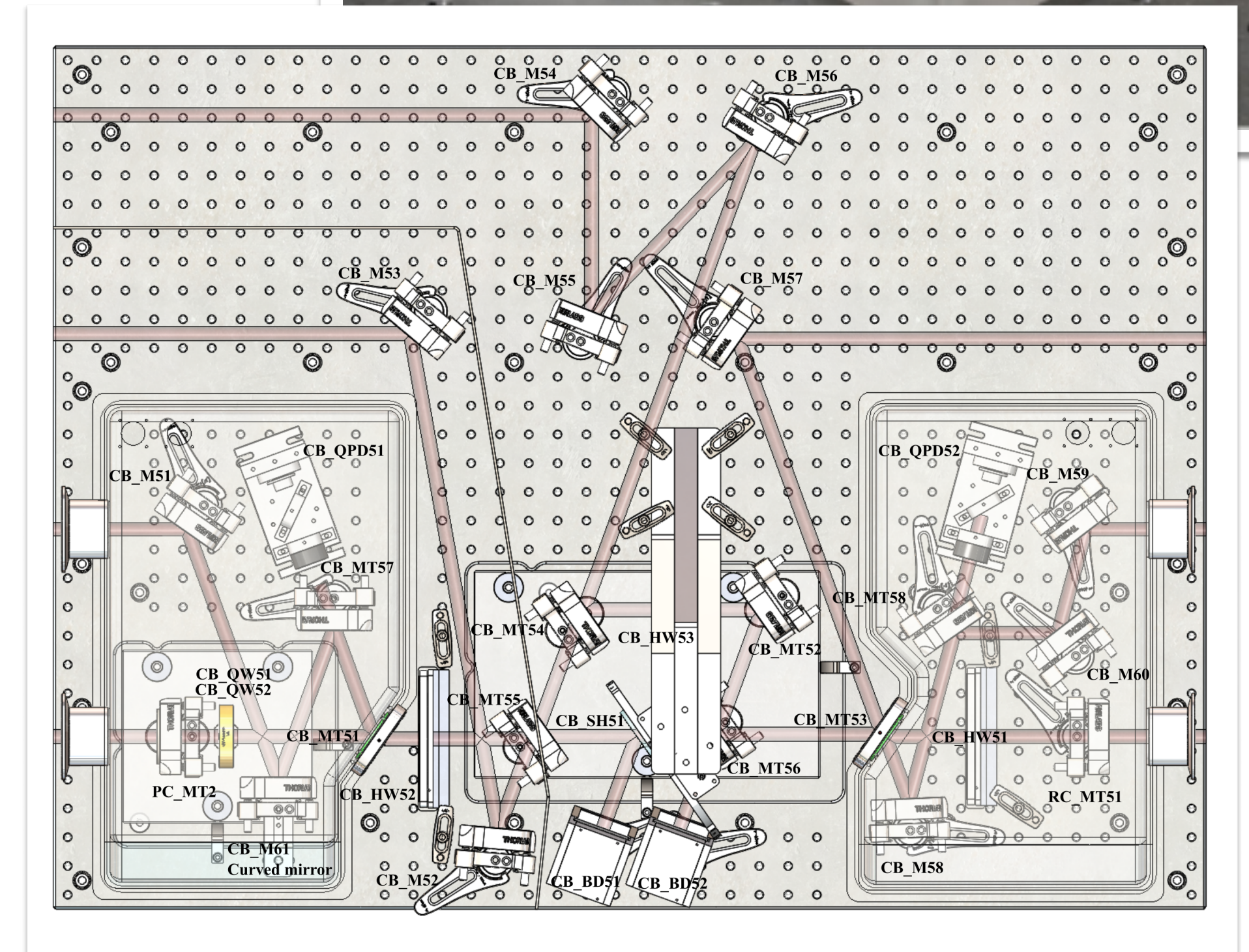
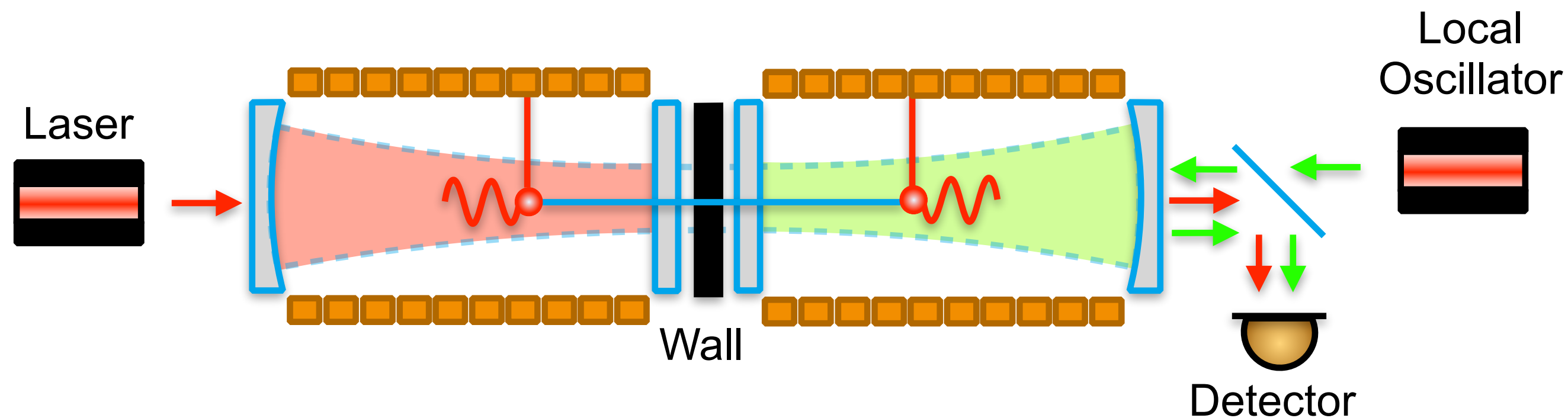


Heterodyne Detection

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

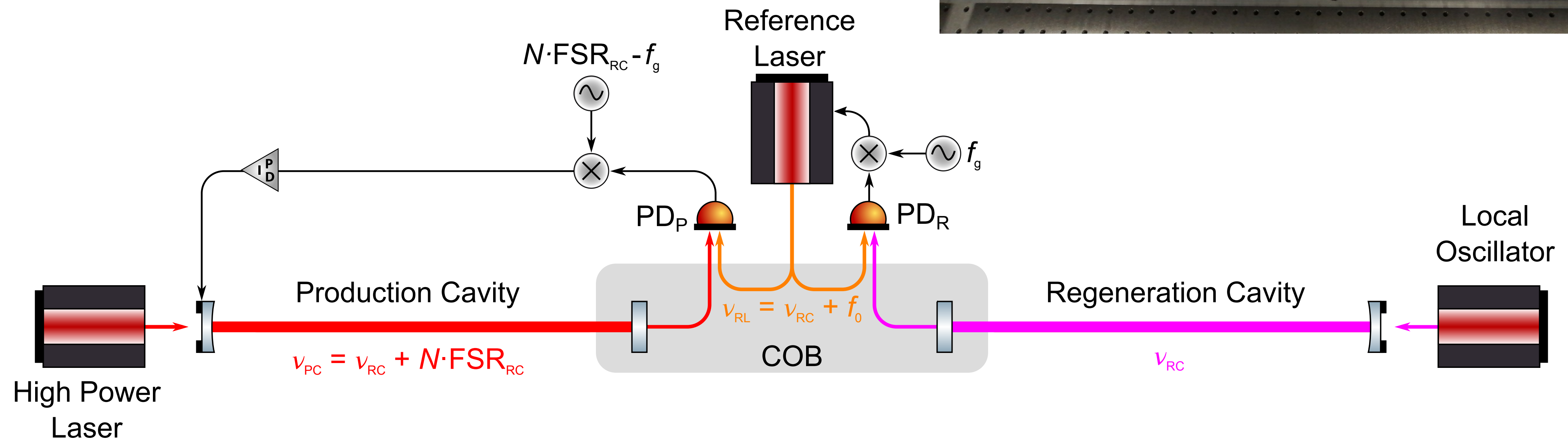
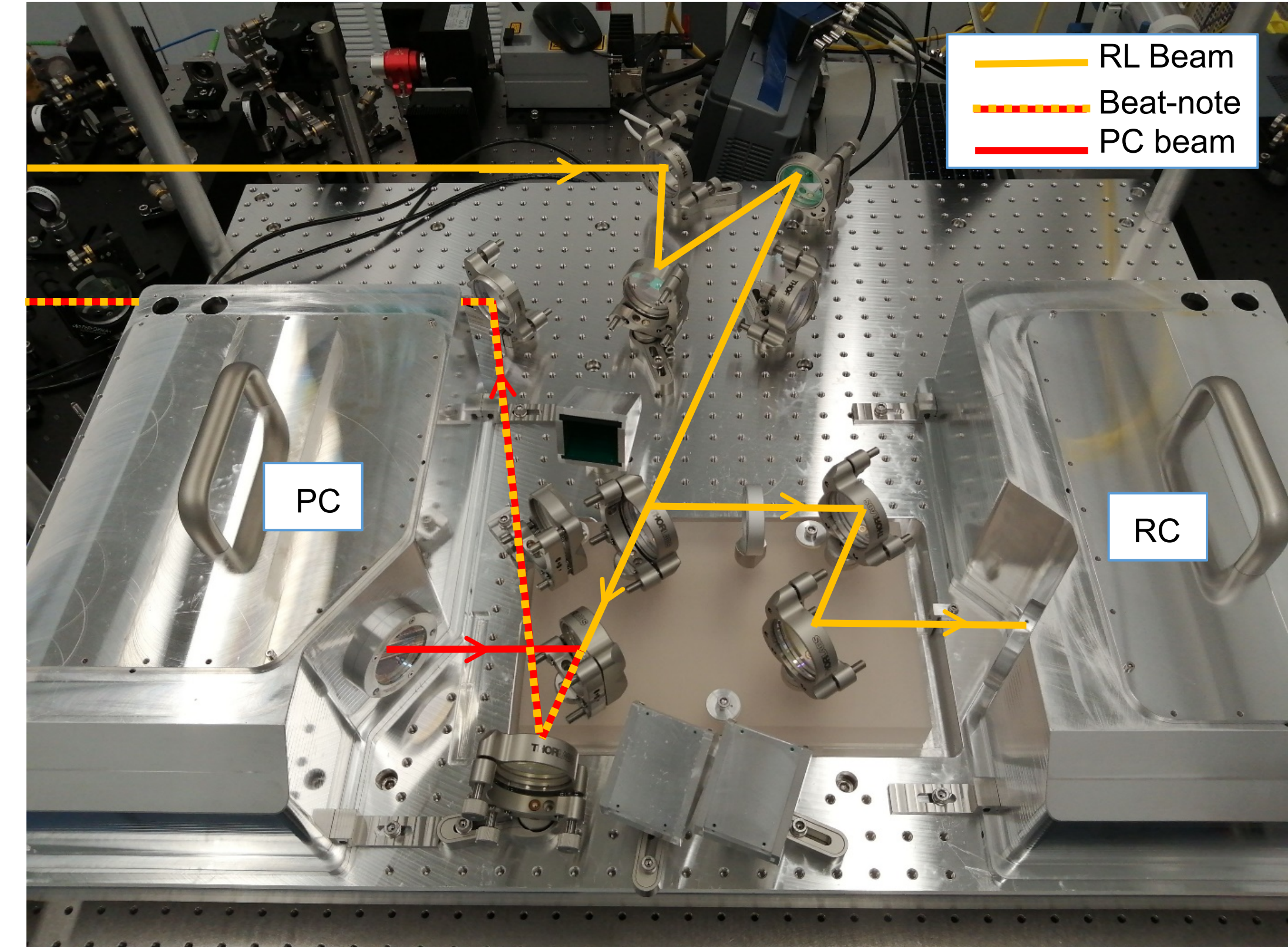


Central Optical Bench (COB)

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'

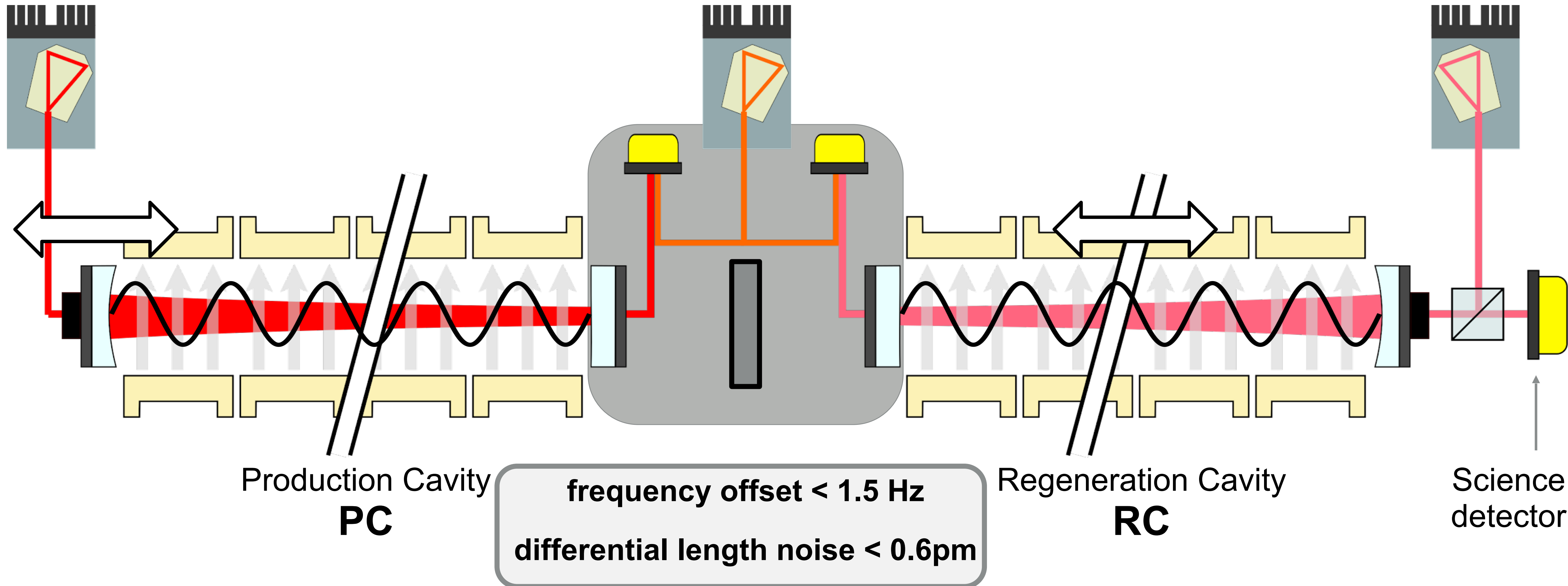


ALPS II Optics: Current Work

High-power laser
HPL

Reference laser
RL

Local Oscillator
LO



Unbending the HERA Magnets

Preparing HERA dipoles for ALPS II

Magnets must be unbent

- Formerly used in HERA arcs
- Straightened for sufficient aperture

