Any Light Particle Search II (ALPS II)

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DESY
Hamburg, Germany

13th Terascale Detector Workshop
April 6-8, 2021

ALPS Collaboration

Combining the expertise of gravitational wave instrumentalists with particle physicists

Partnership between 5 institutions with ~30 members

ALPS II Main Contributors				
Partner	**Optics**	**Detector**	**Magnets**	**Infrastructure**
DESY	X	X	X	X
AEI / LUH	X			
U. Florida	X	X		X
Cardiff U.	X			
U. Mainz		X		

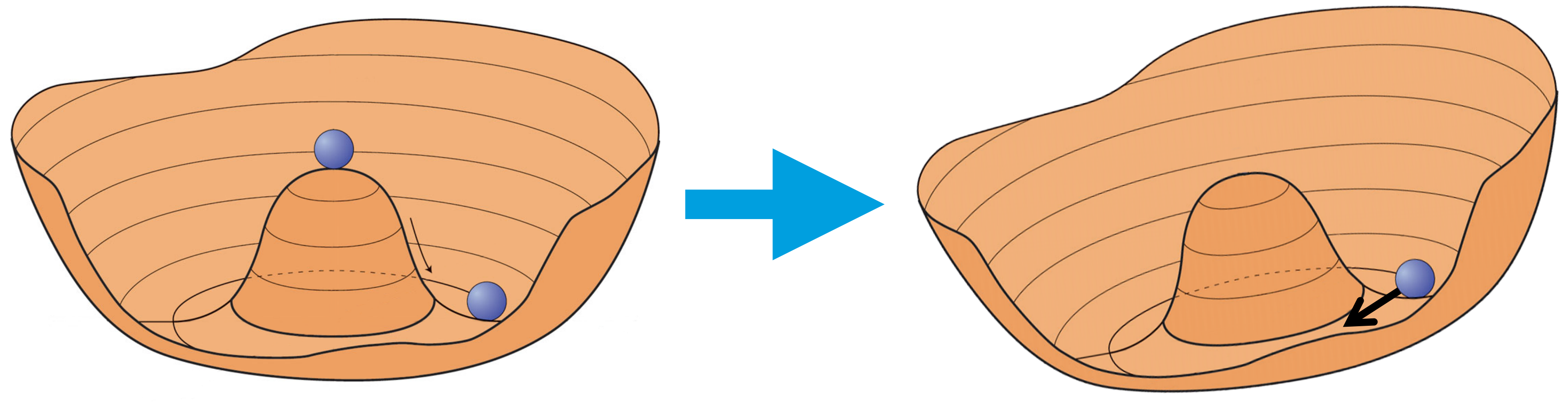
Axions

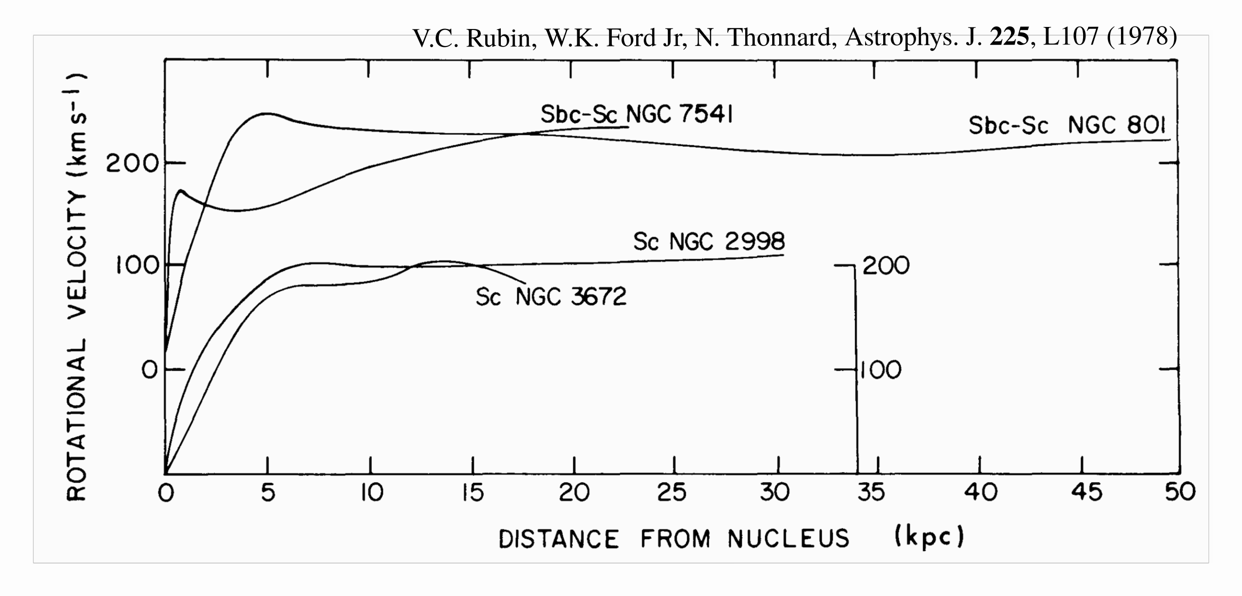
Hints of the unknown

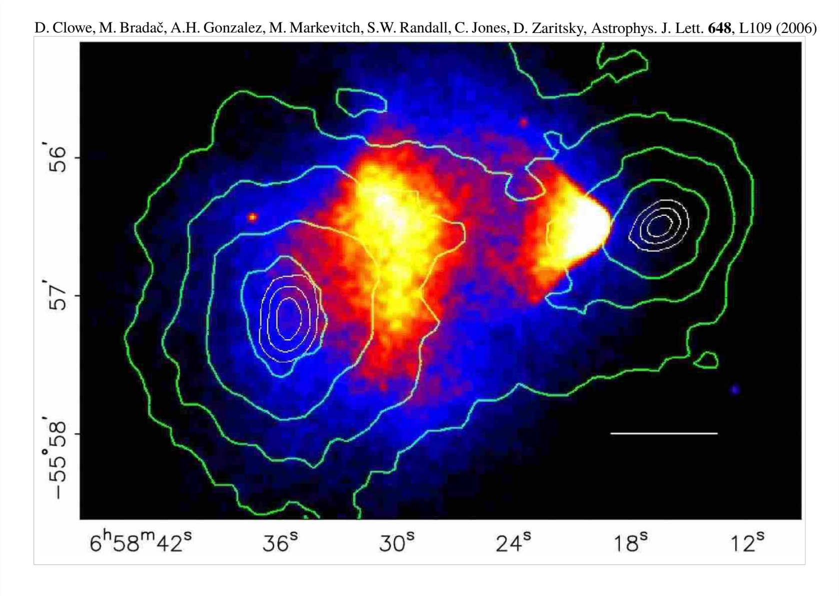
Mysterious unexplained phenomena

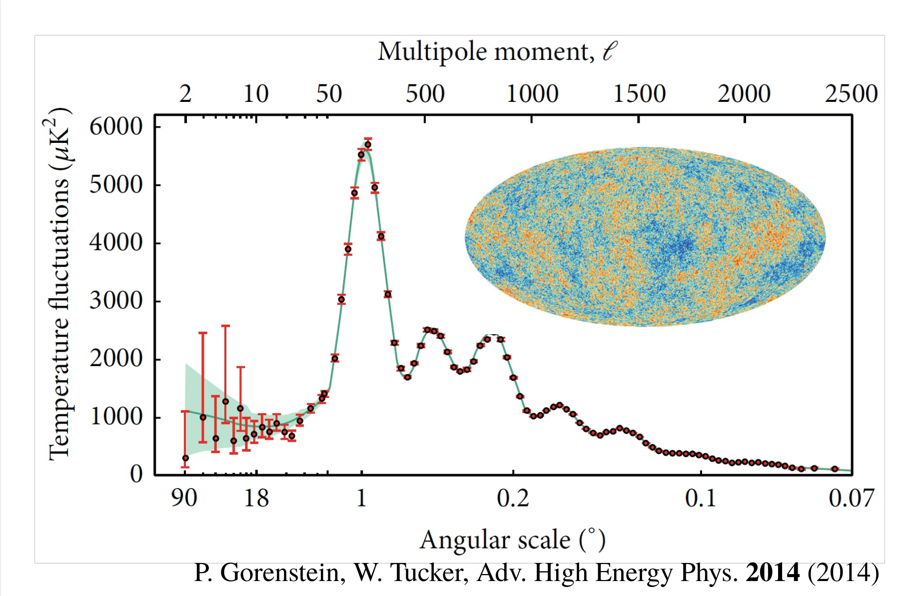
- Strong CP problem
  - Pecci-Quinn Solution
- Cold Dark matter
  - Galactic clusters/rotation rates
  - Gravitational lensing
  - CMB polarization
- Stellar cooling rates
- TeV transparency

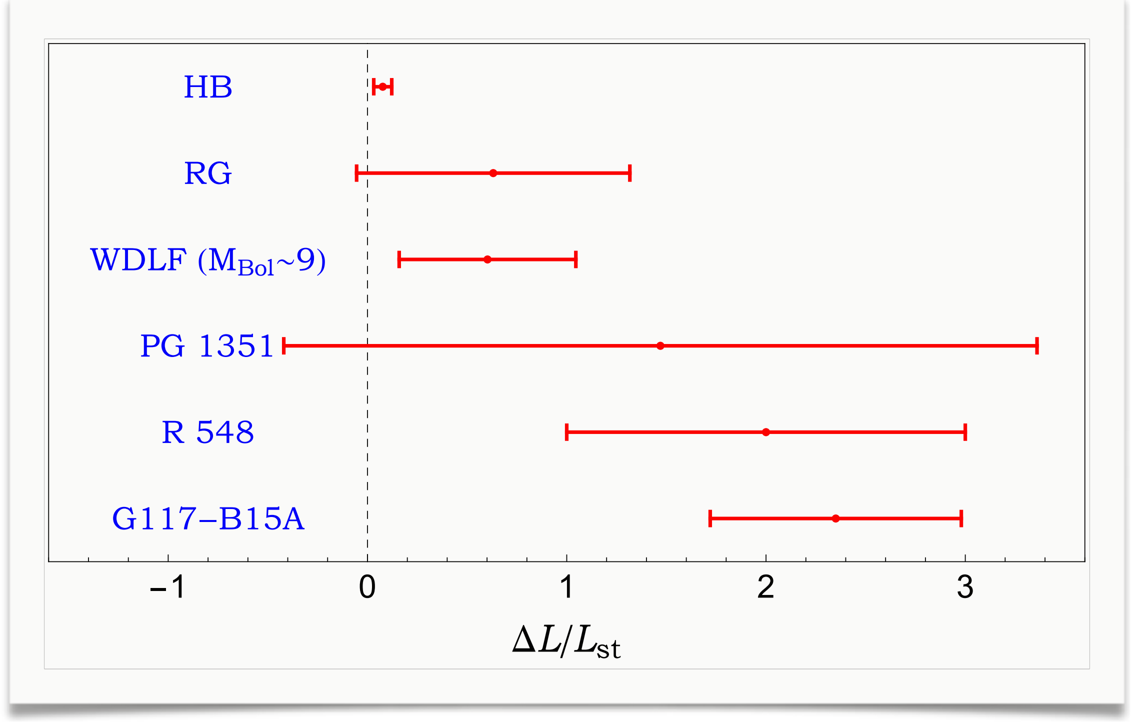
$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

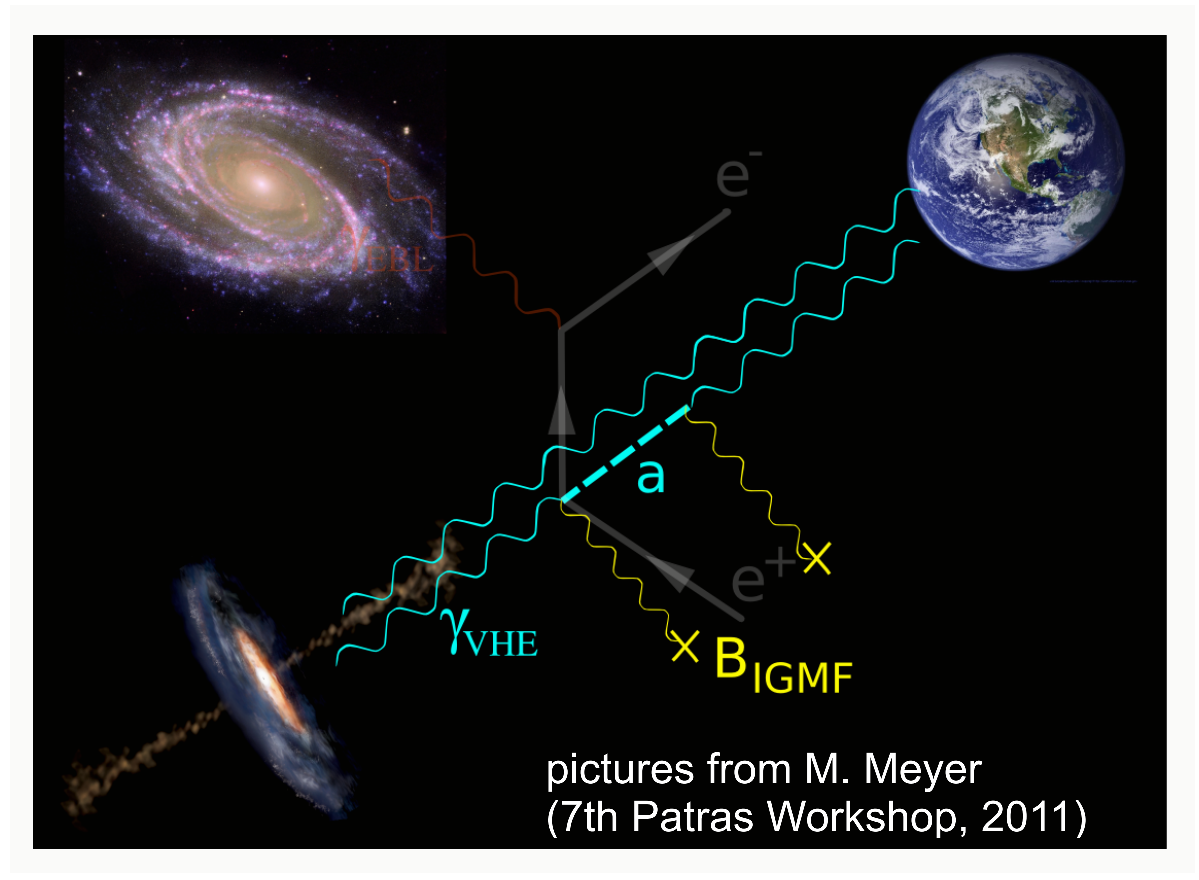










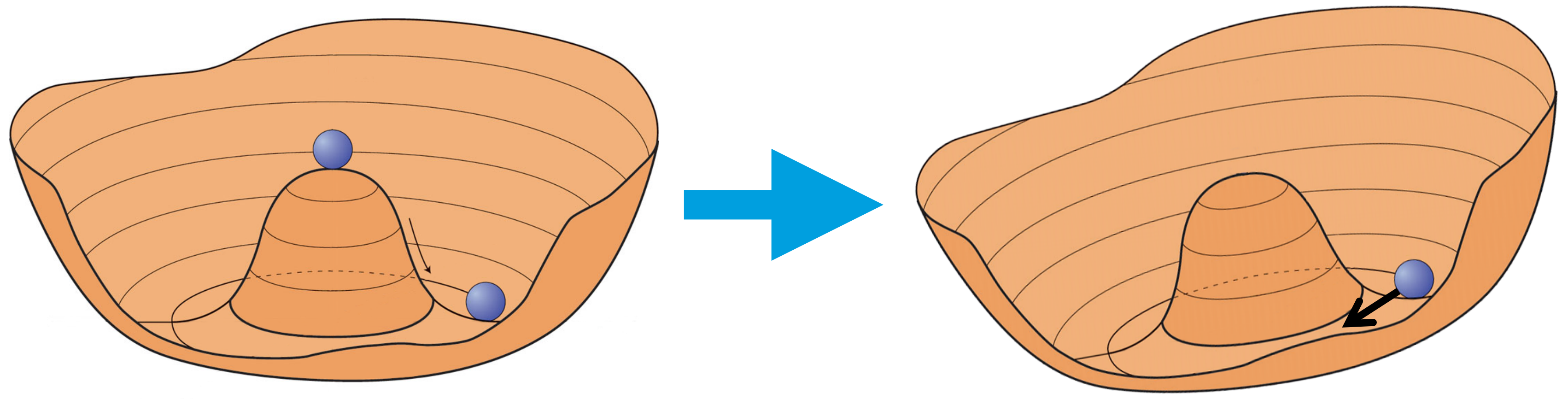


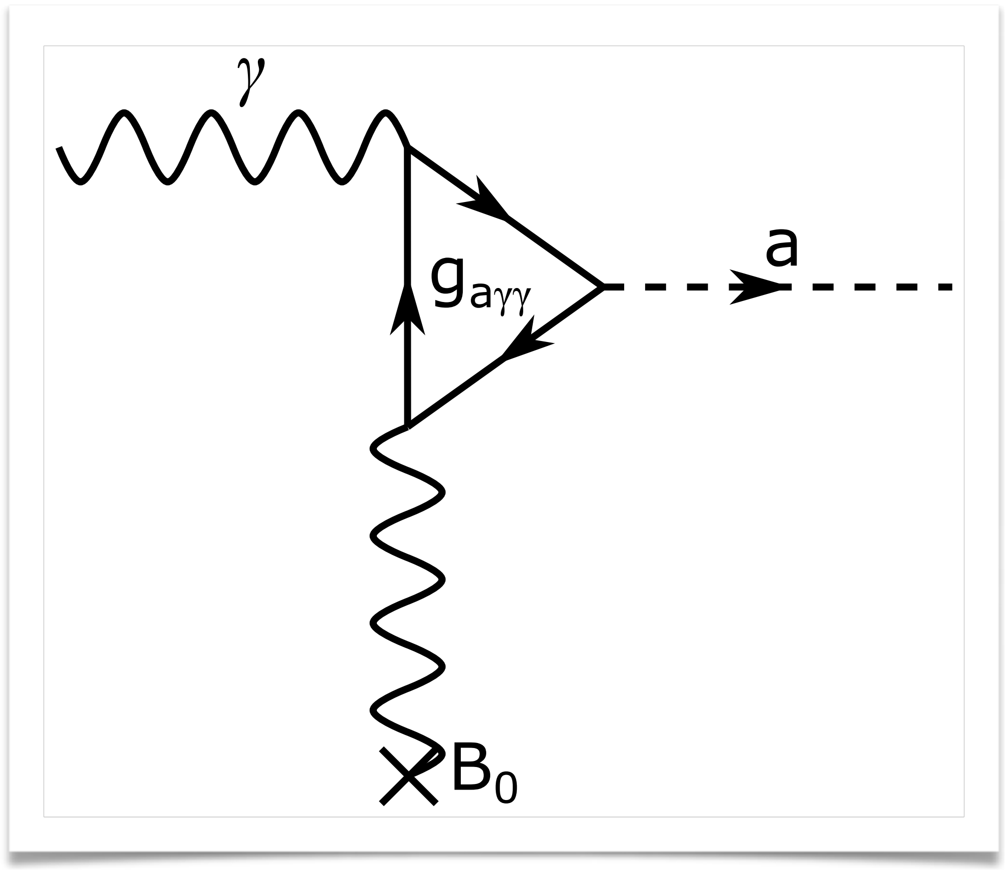
Axions

Hints of the unknown

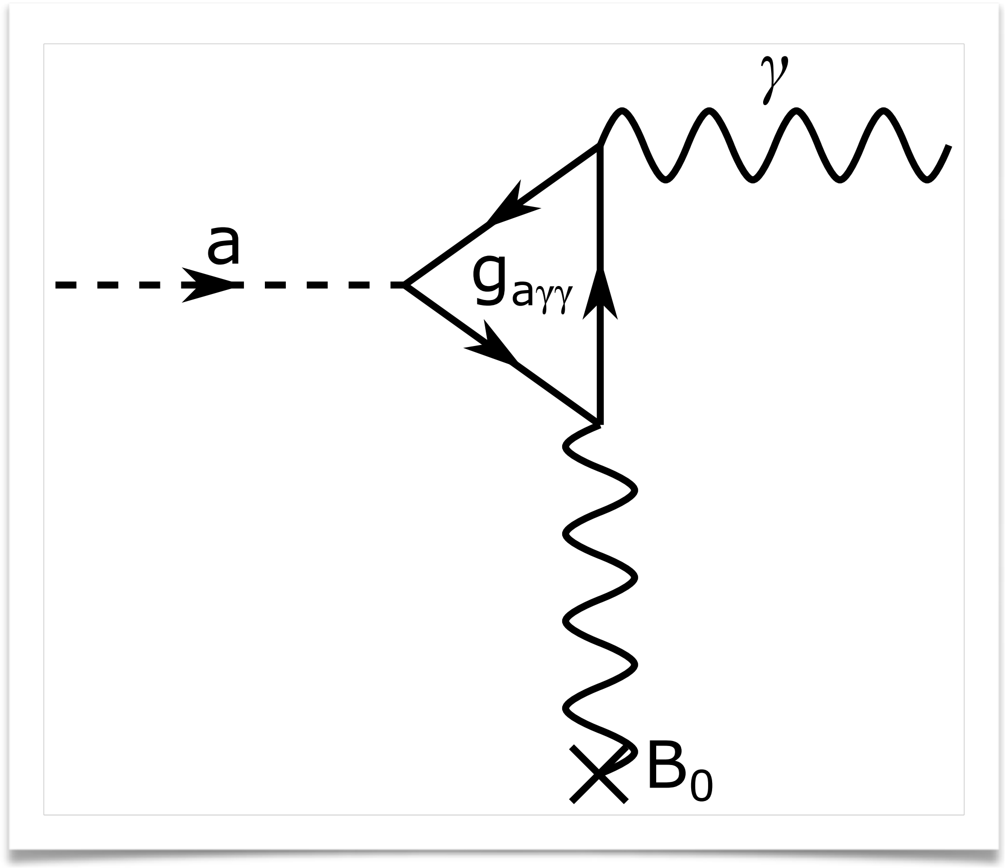
Potential explanation

- Axions
  - Low mass and weak coupling to SM particles
  - A single particle could explain:
    - Strong CP problem
    - Cold dark matter
    - Stellar cooling rates
- Axion-like particles
  - Mass and coupling unconstrained
  - Could explain CDM, stellar cooling, TeV transparency
    - Do not explain strong CP problem





Primakoff



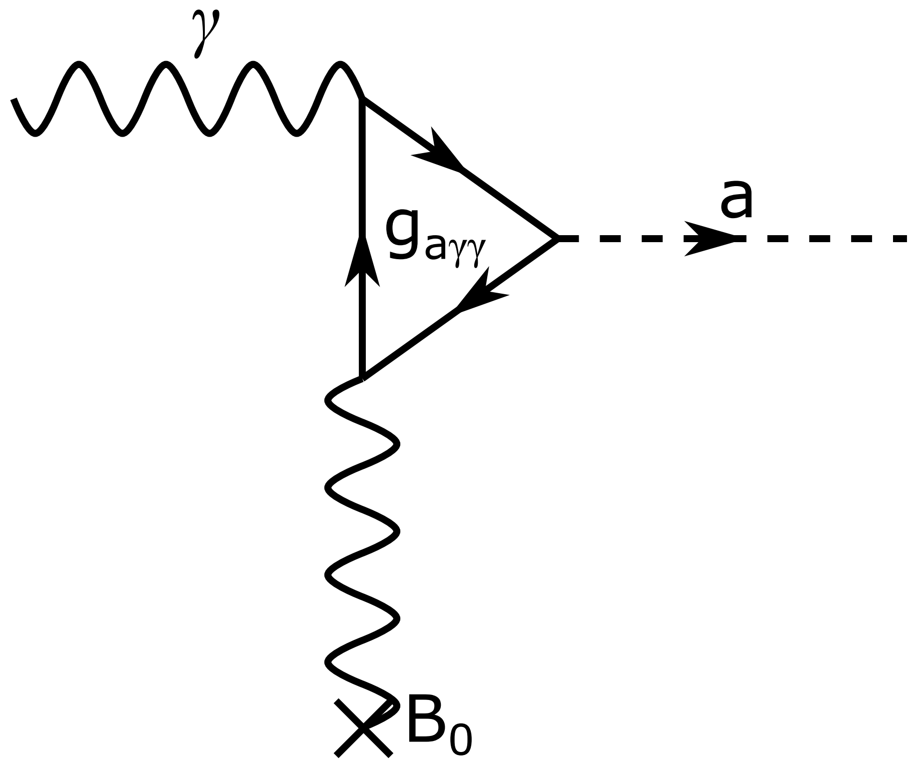
Sikivie

Searches for Axion-like Particles

Using the coupling to photons in magnetic field

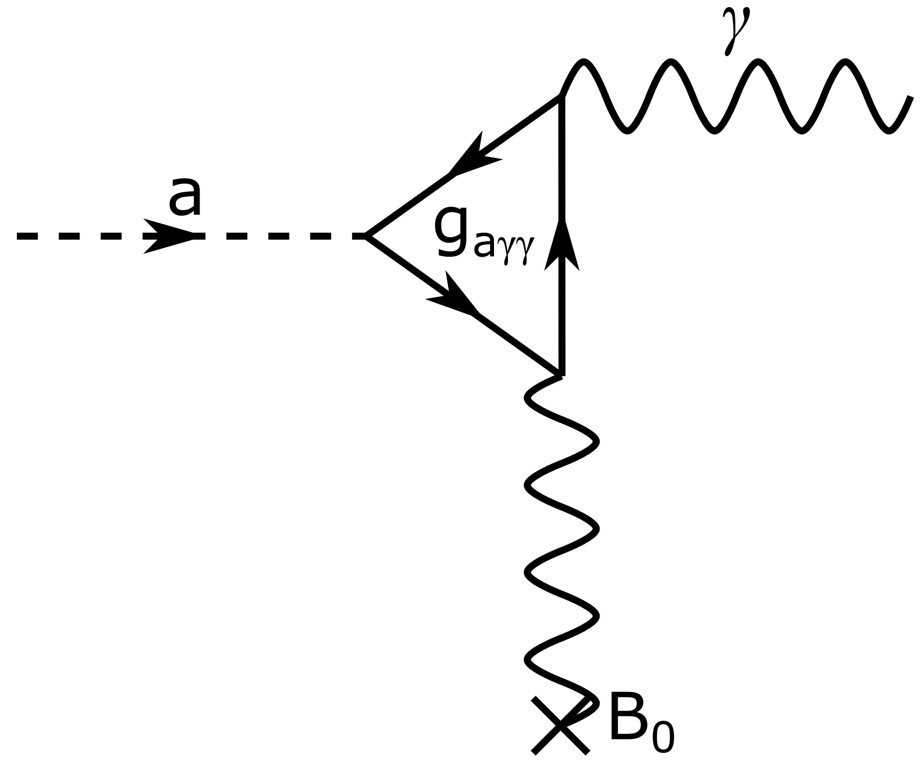
LSW Experiments

- Lasers in B fields:
  photon ➜ laboratory axions ➜ photons
- ALPS I, ALPS II, OSQAR



Helioscopes

- Magnets and X-ray telescopes:
  Solar axions ➜ photons
- CAST, IAXO, BabyIAXO



Haloscopes

- Volume of magnetic field:
  Axions from DM halo ➜ photons
- ADMX, HAYSTAC, MADMAX

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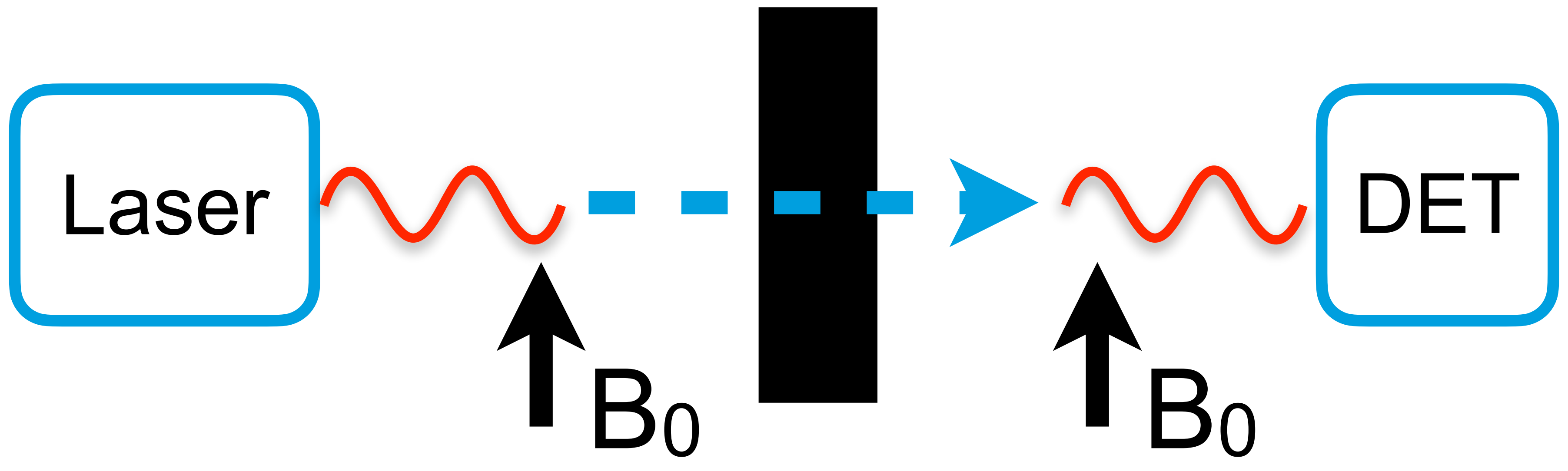

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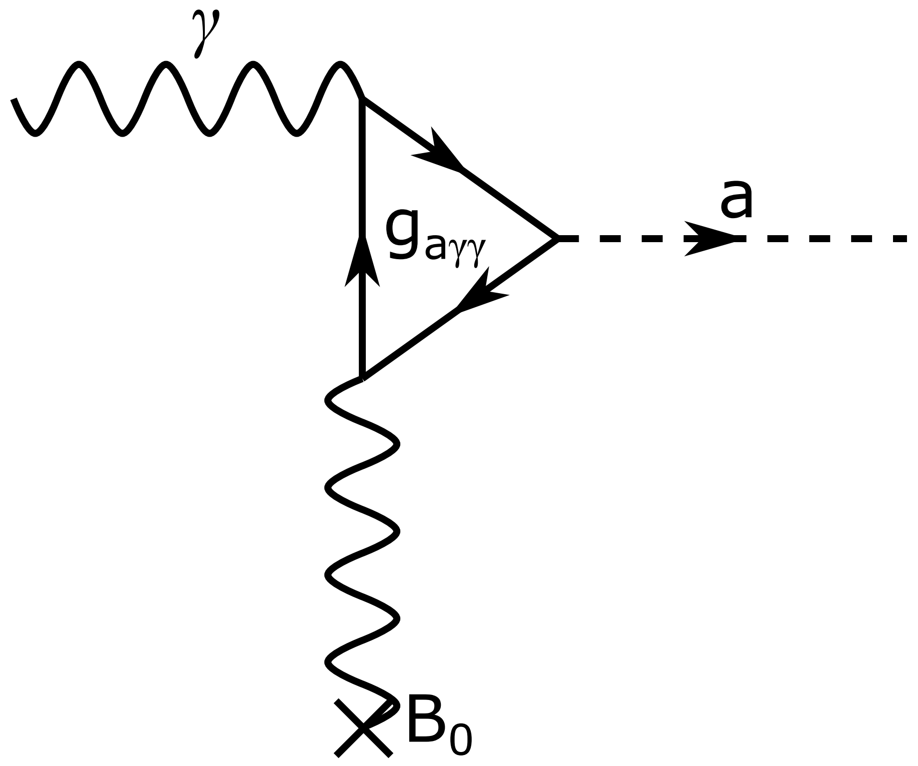

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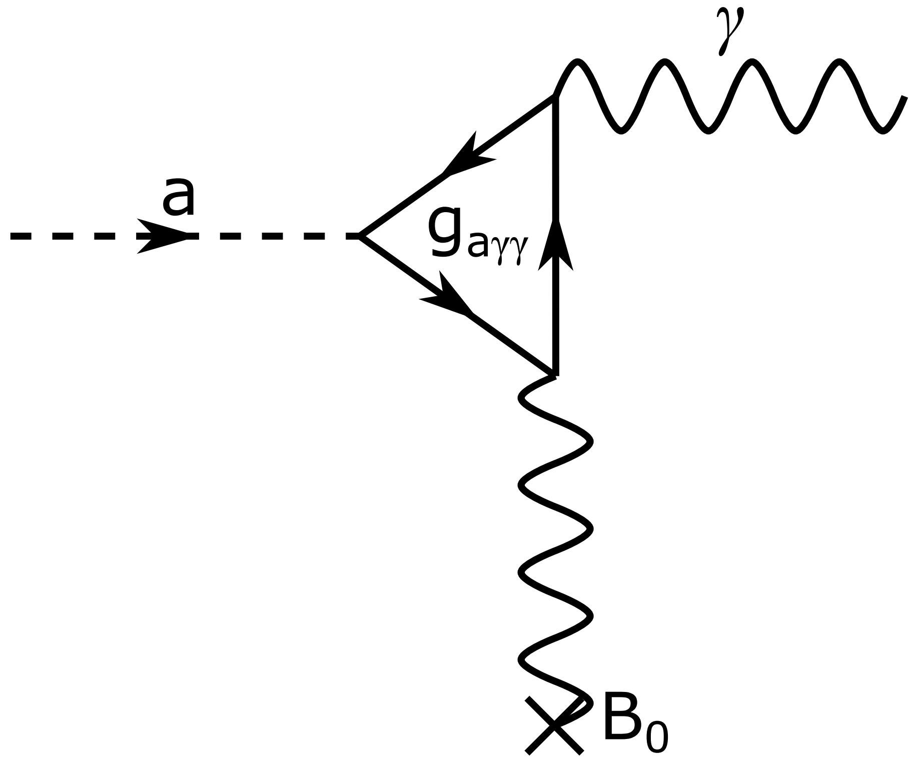

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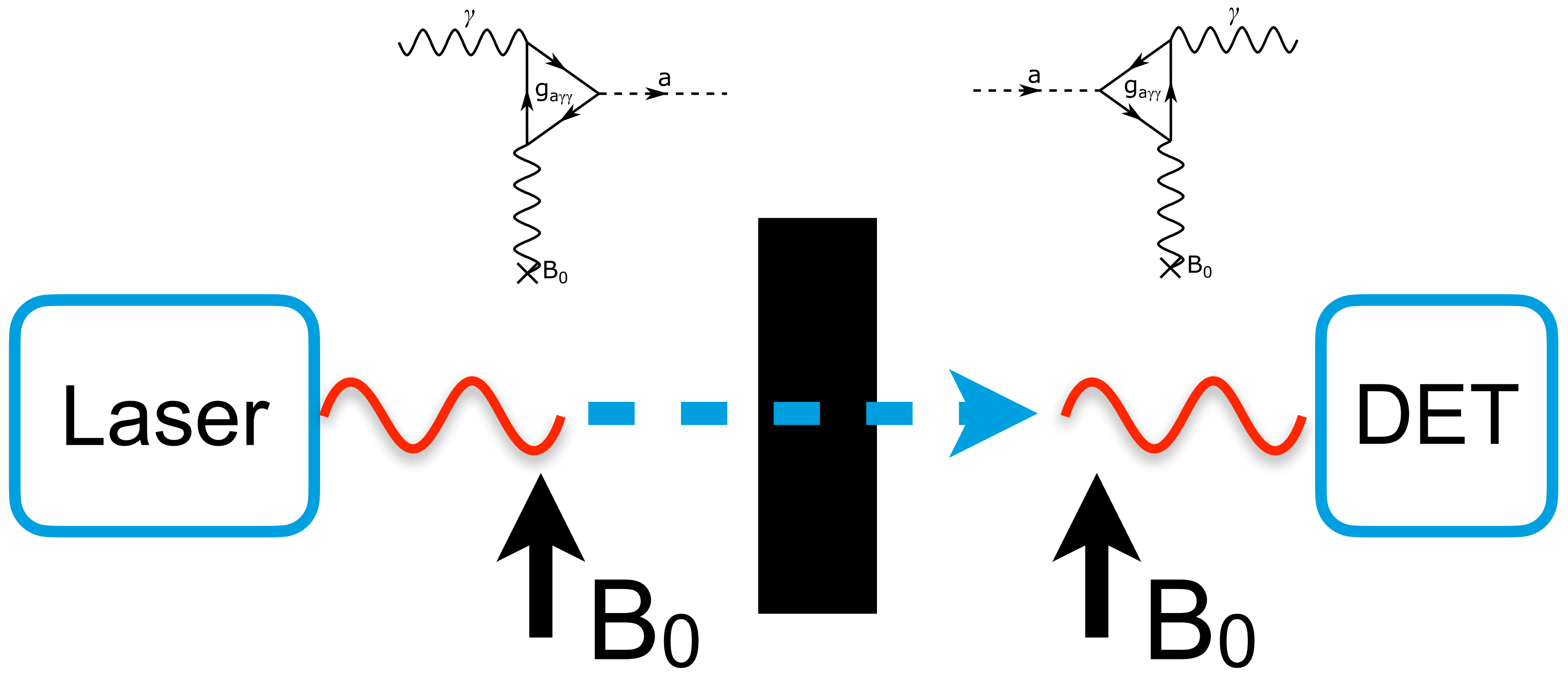

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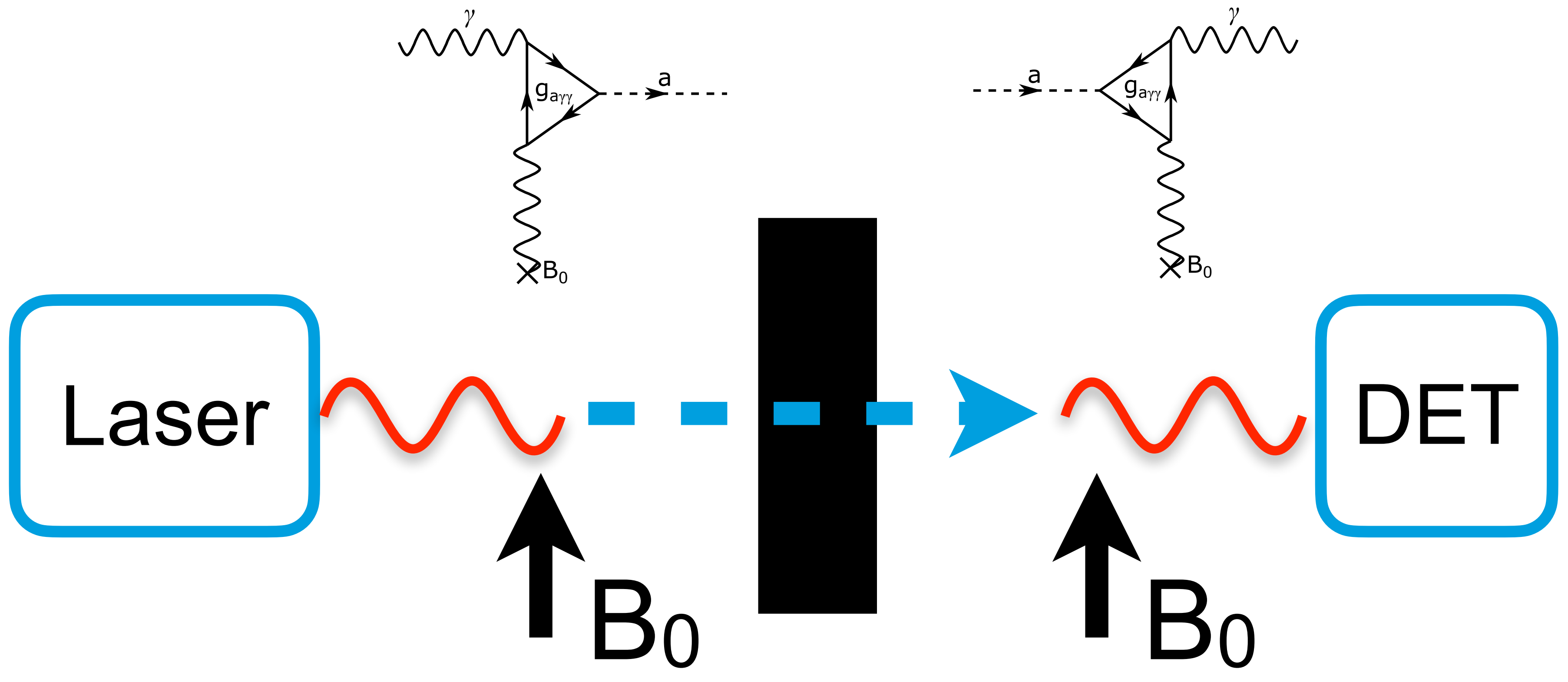

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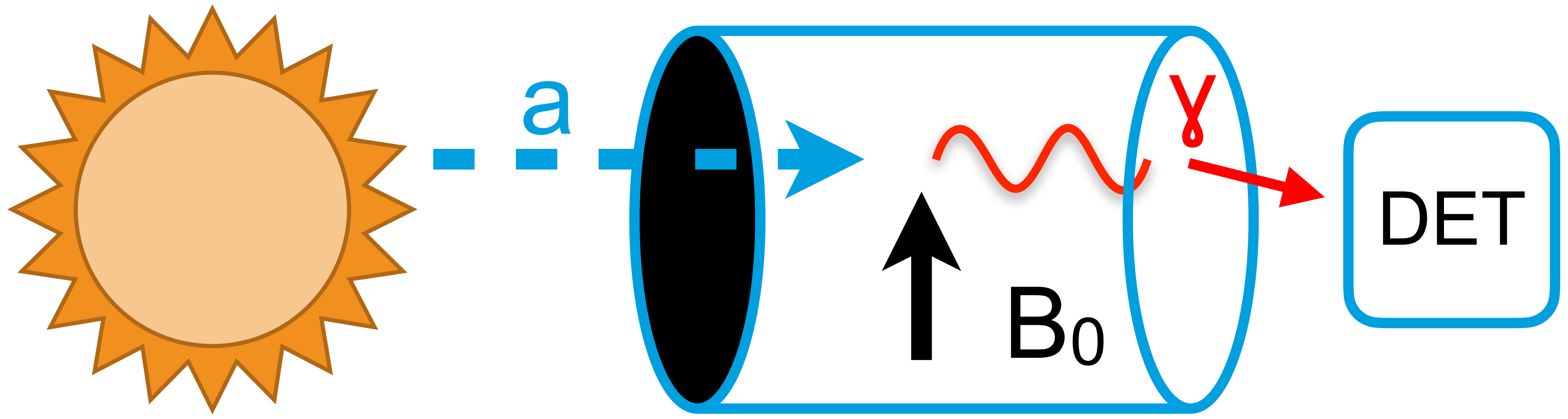

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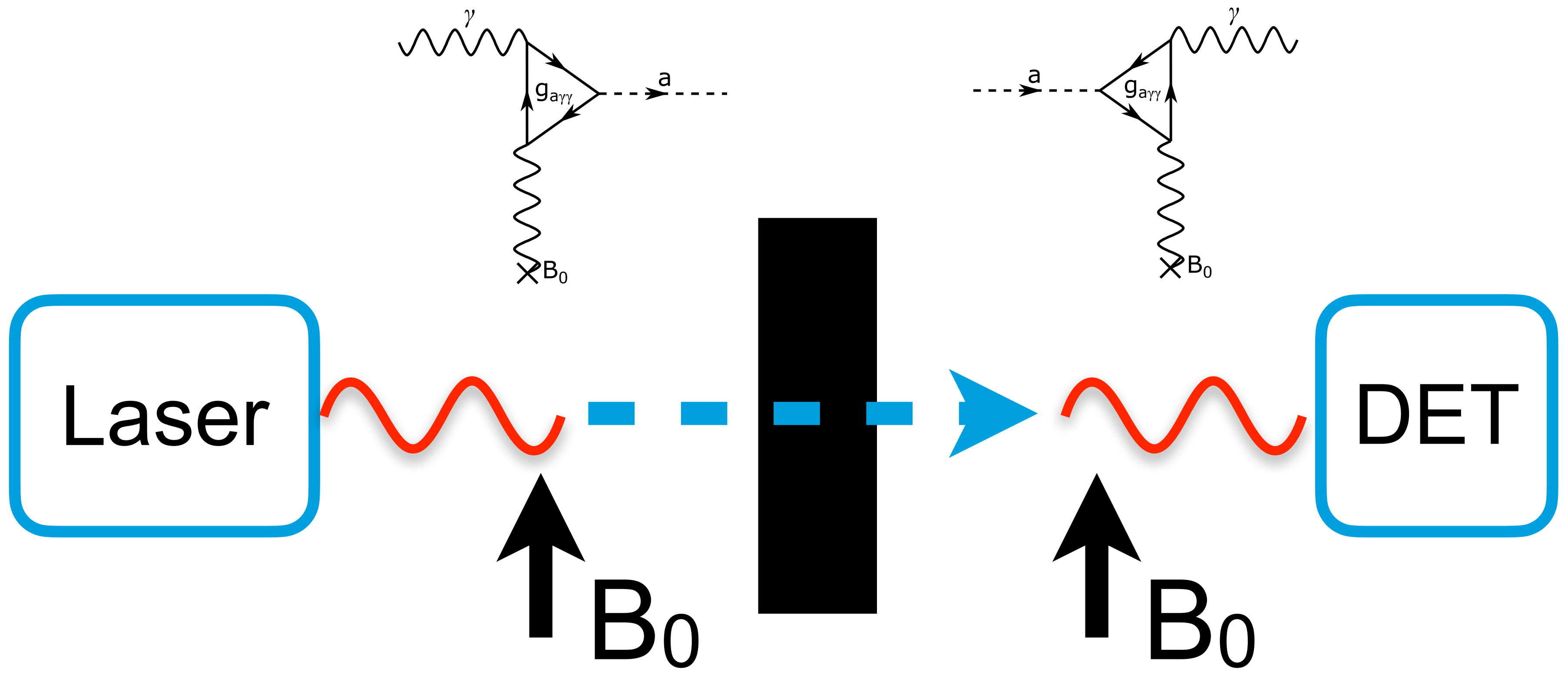

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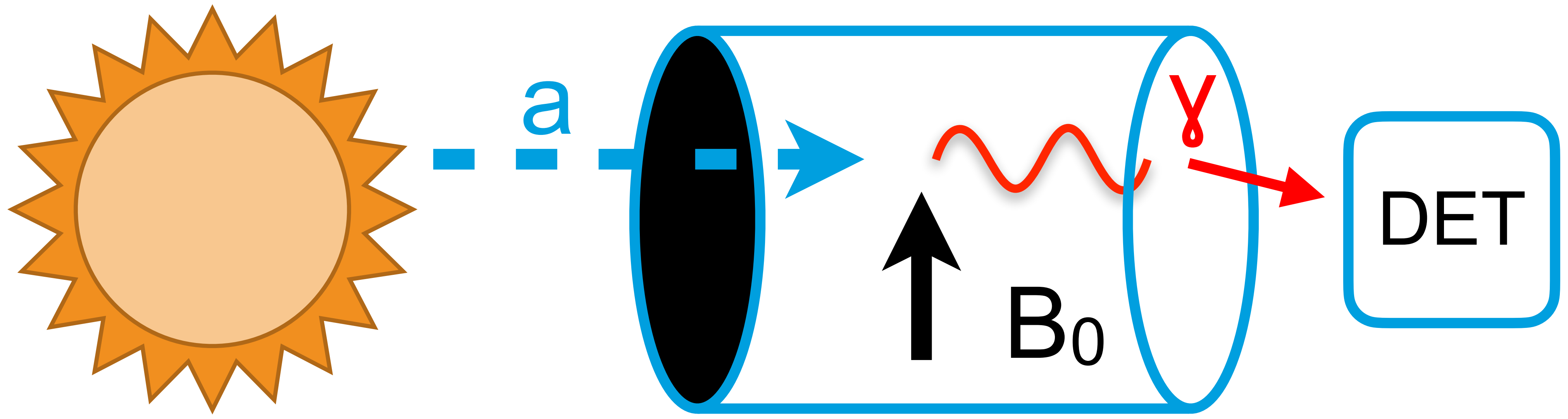

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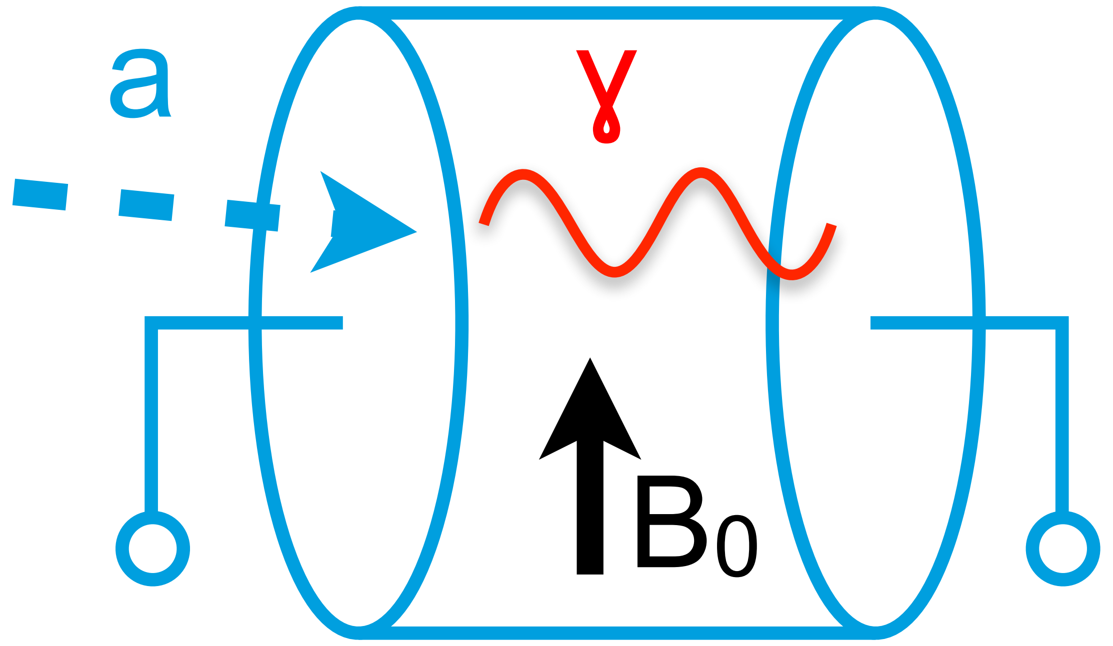


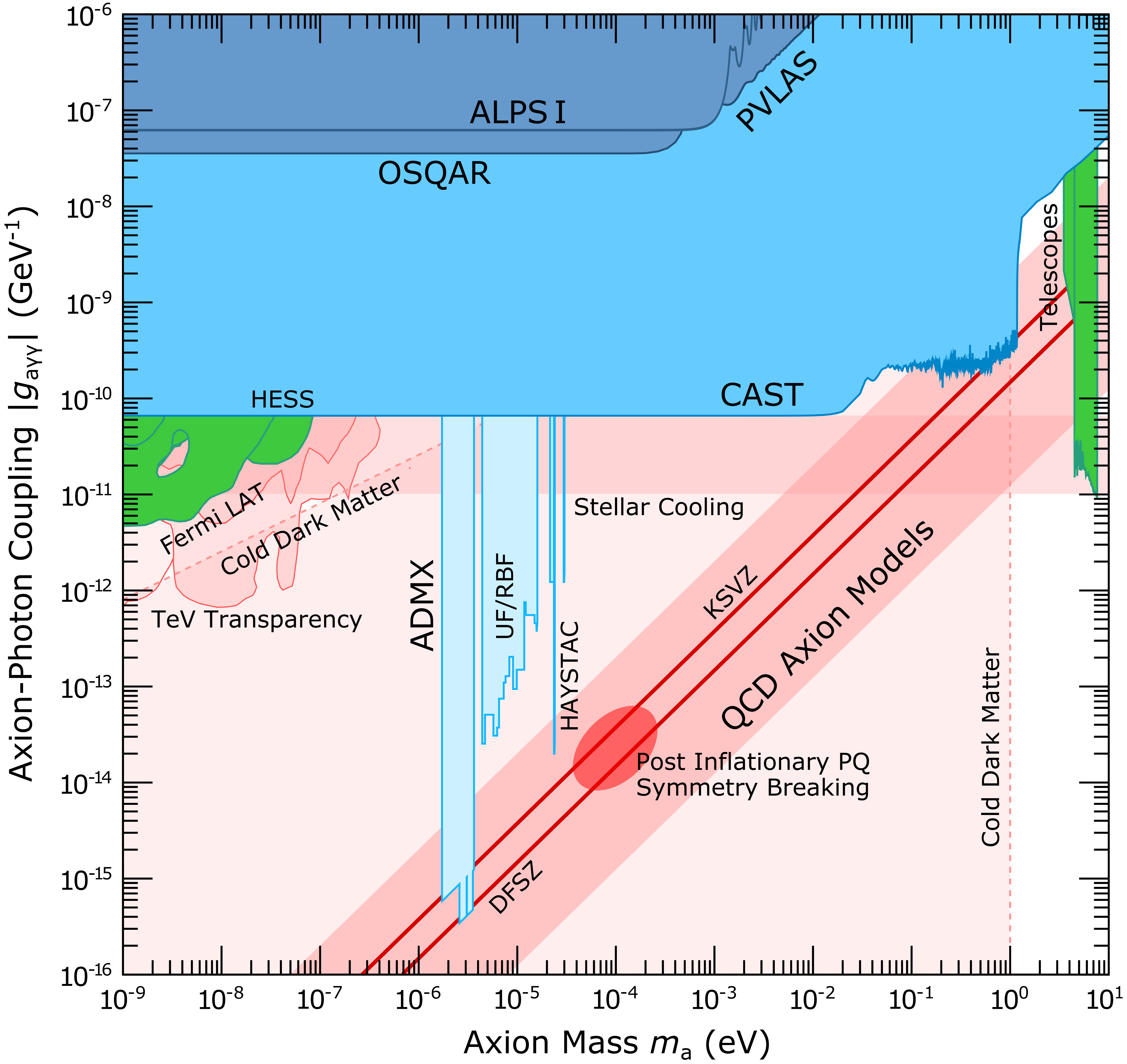
Parameter Space

Current experimental limits

- Haloscopes deep and narrow
- Helioscopes wide band
- LSW not quite there yet

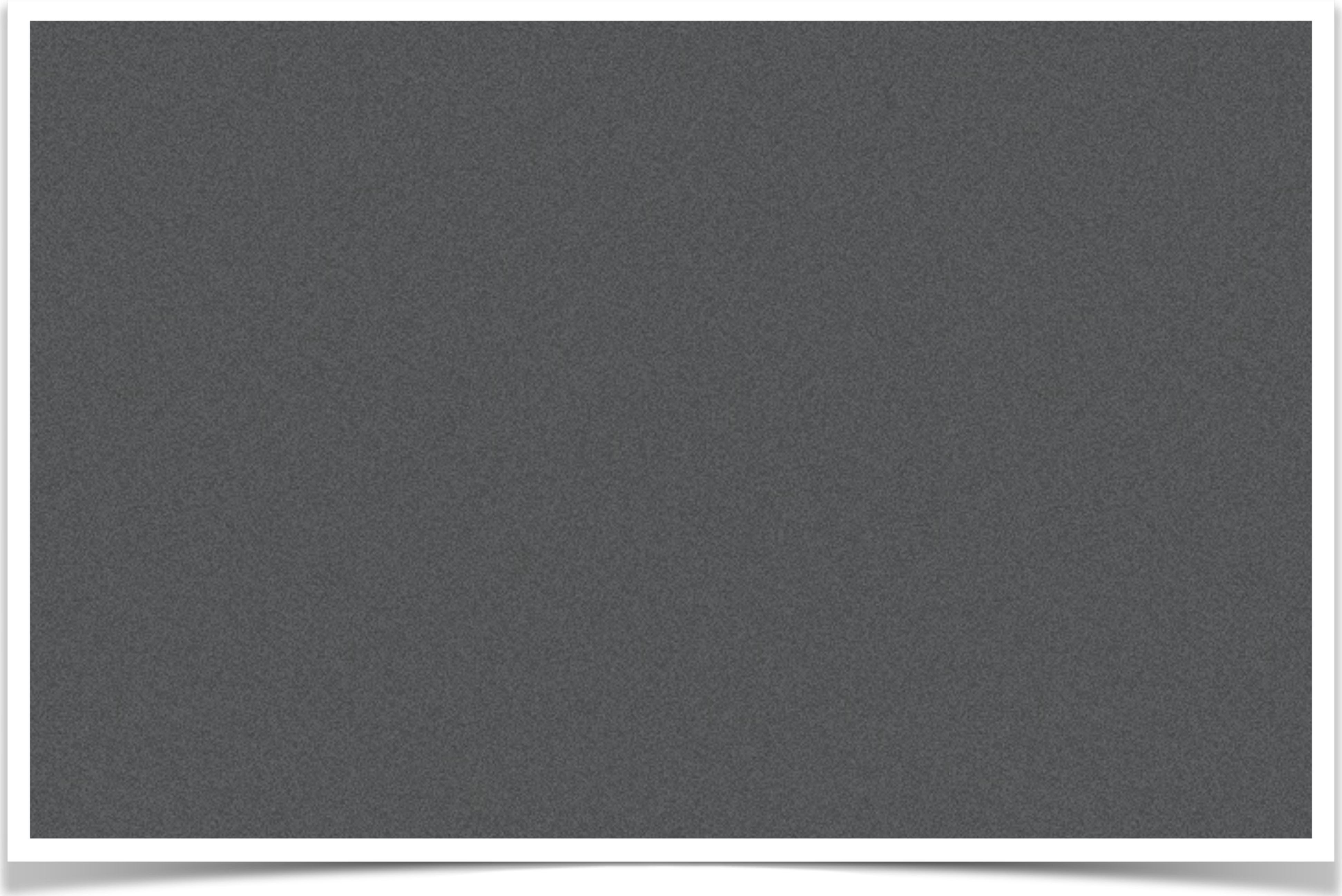
Hints

- QCD axion models
    - Post-inflation PQ symmetry breaking
- Cold dark matter
- TeV
- Stellar cooling



Light shining through a wall experiments

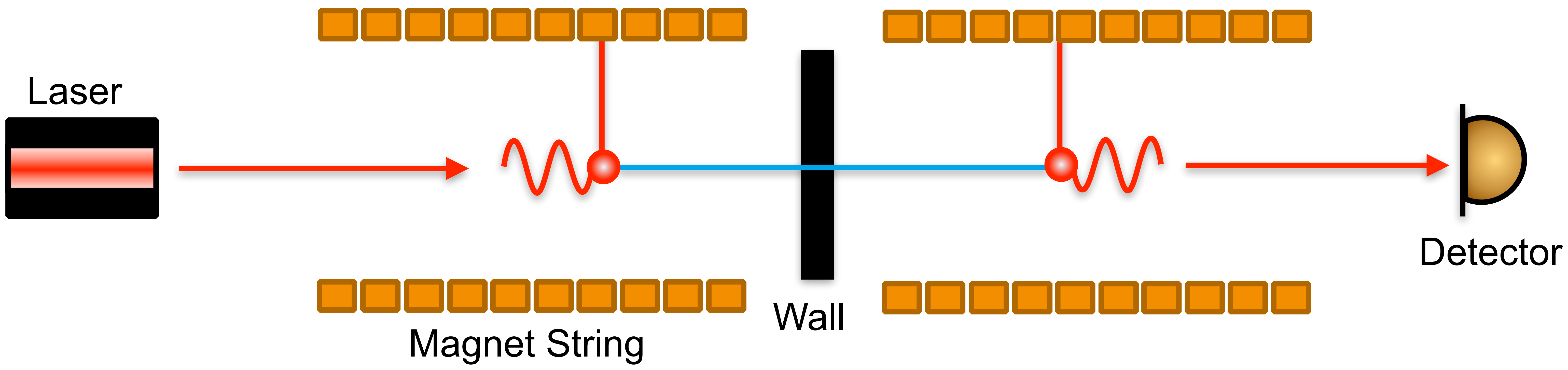
Measuring the conversion-reconversion of Axion-like particles



Light shining though a wall concept

- High power source directs light through magnetic field
  - Creates flux Axion-like particles through wall
- Magnetic field converts Axion-like particles back to photons

Conversion probability: $\mathcal{P}_{\gamma\to\varphi} = \mathcal{P}_{\varphi\to\gamma} = \frac{1}{4}\frac{\omega}{k_{\varphi}}(gBL)^2|F(qL)|^2$



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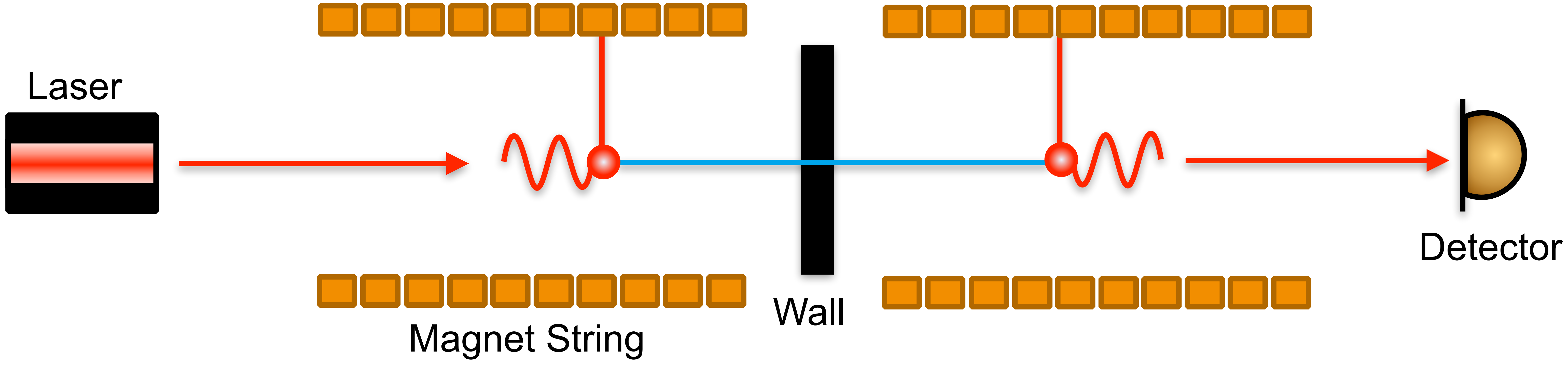
Photons at the detector: $N_\gamma = \frac{1}{16}\left(g_{a\gamma\gamma}BL\right)^4 P_\mathrm{i}\,\tau$

($m^2 << 2\omega/L$)



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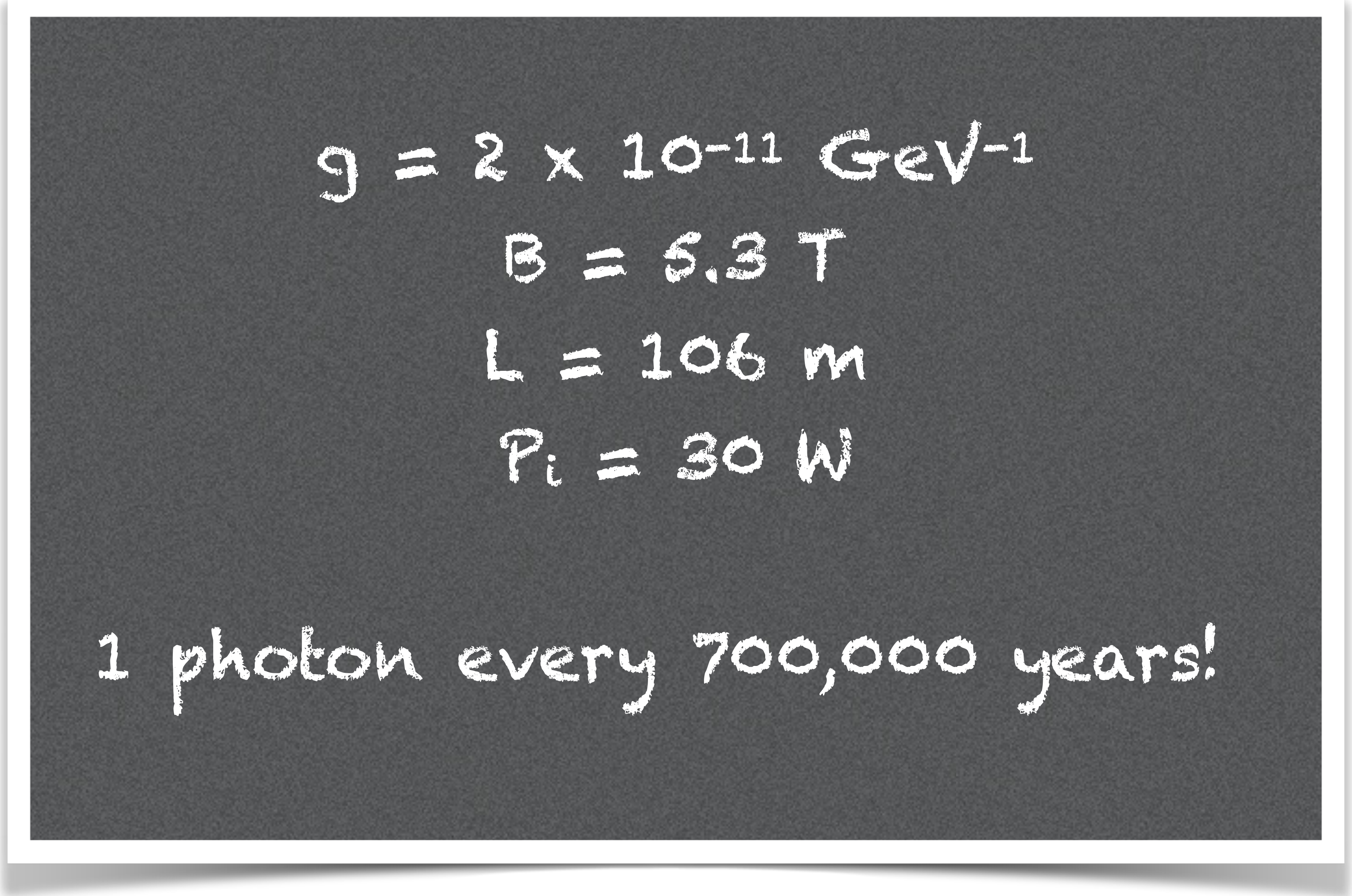

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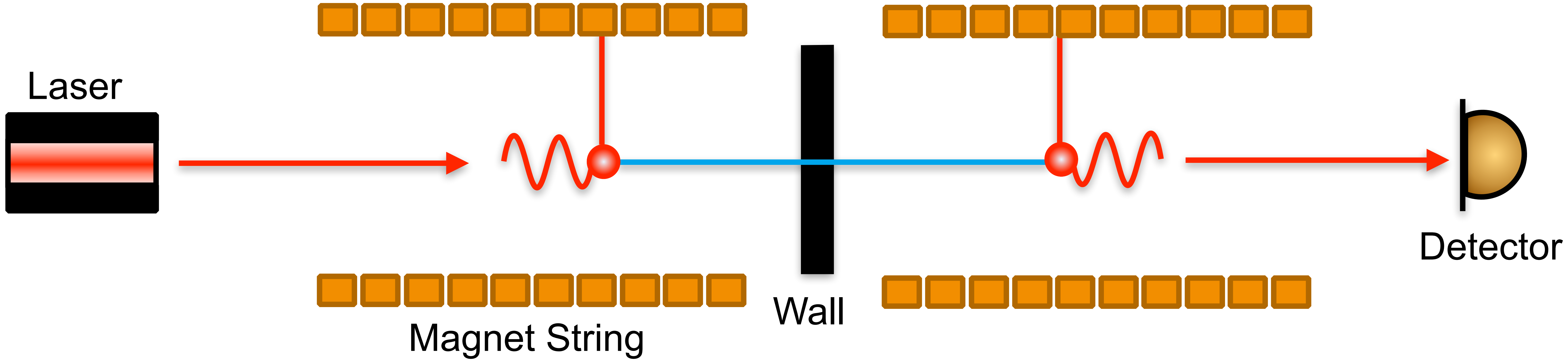

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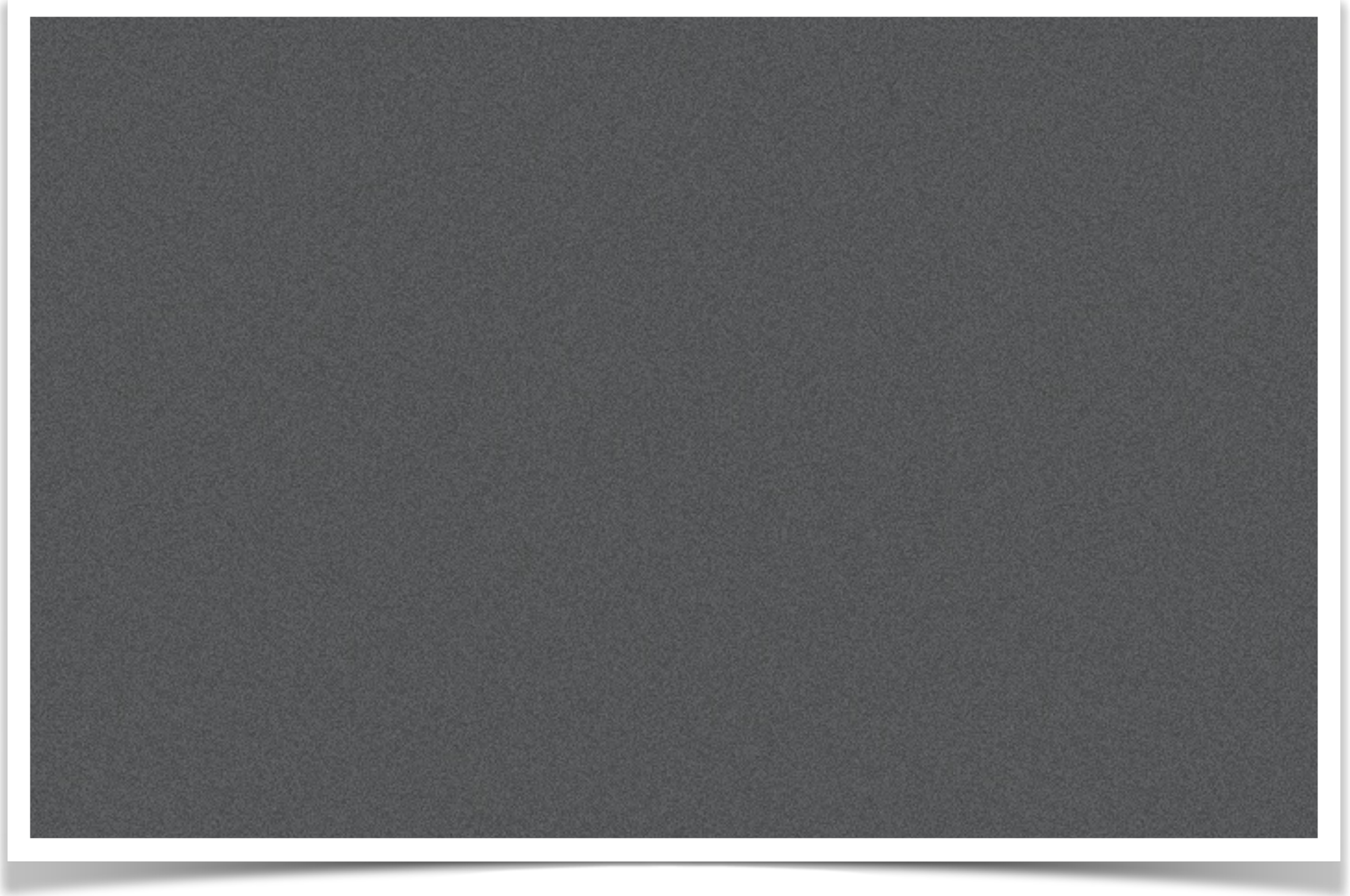

Production Cavity

- Amplifies circulating power before the wall
- Increases flux Axion-like particles through wall
- Boosts reconverted power by cavity power build up factor

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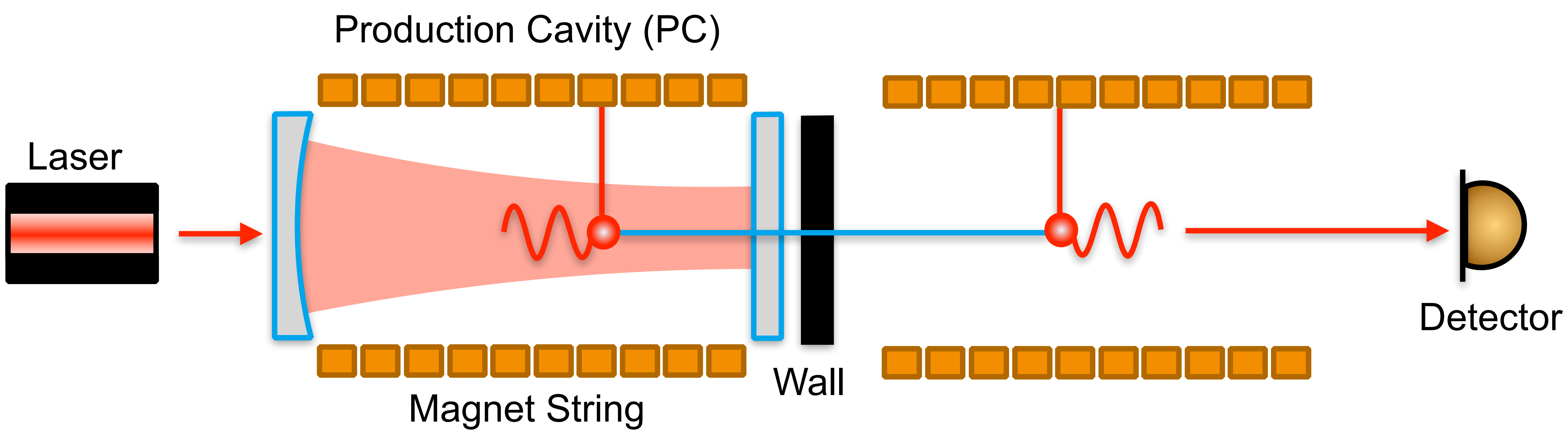

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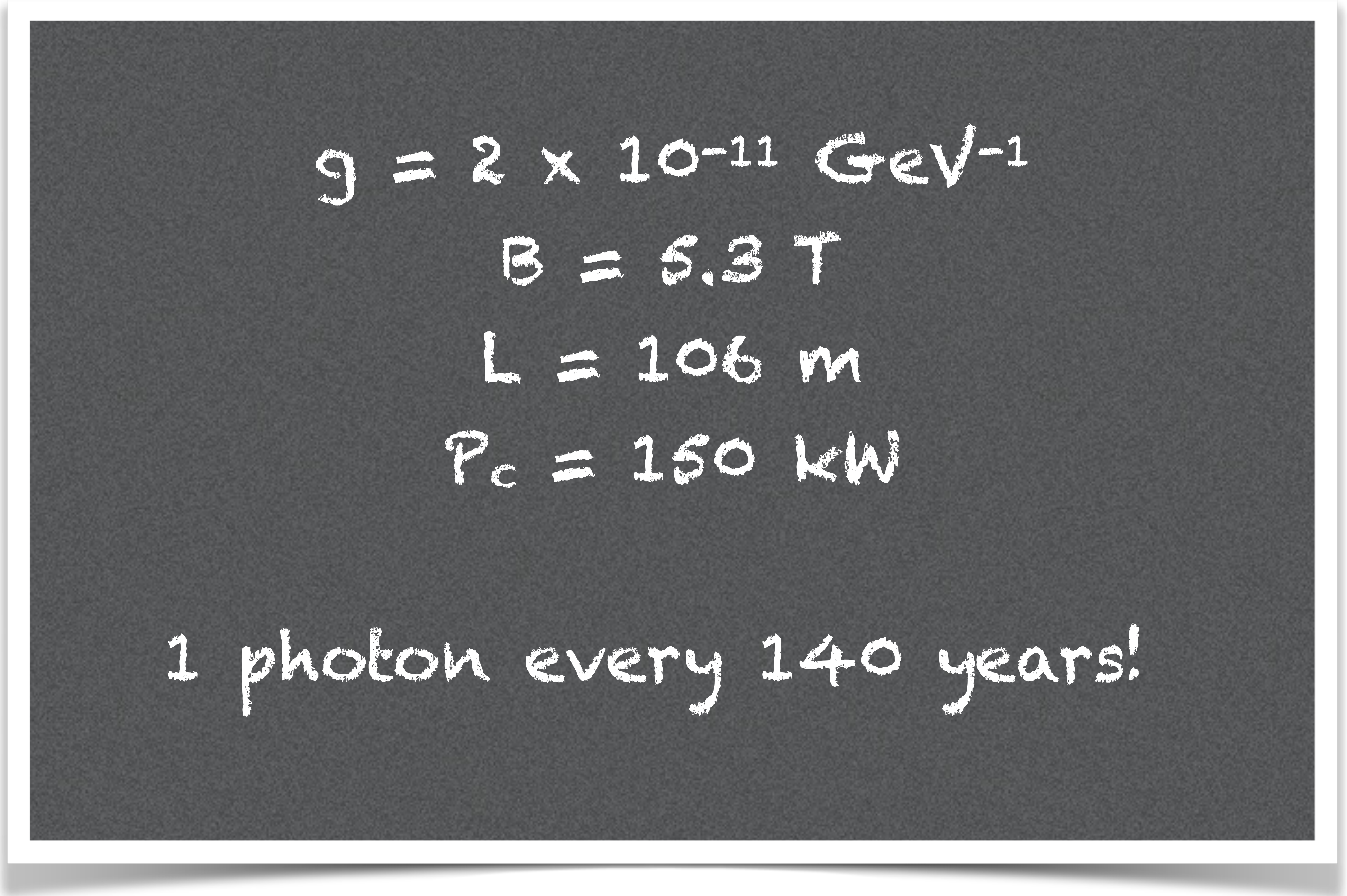

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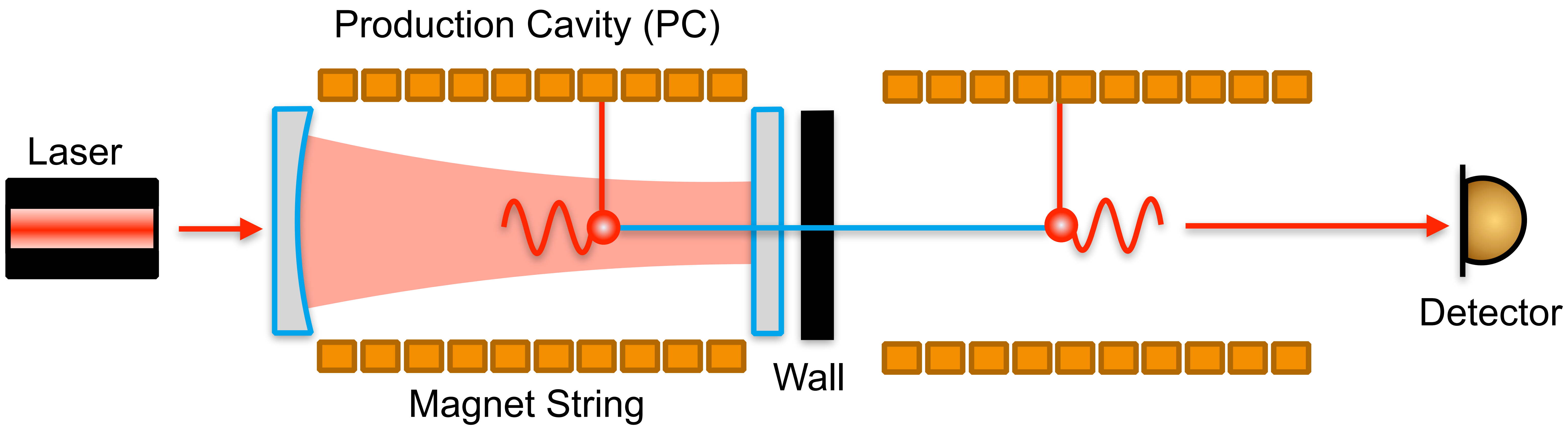

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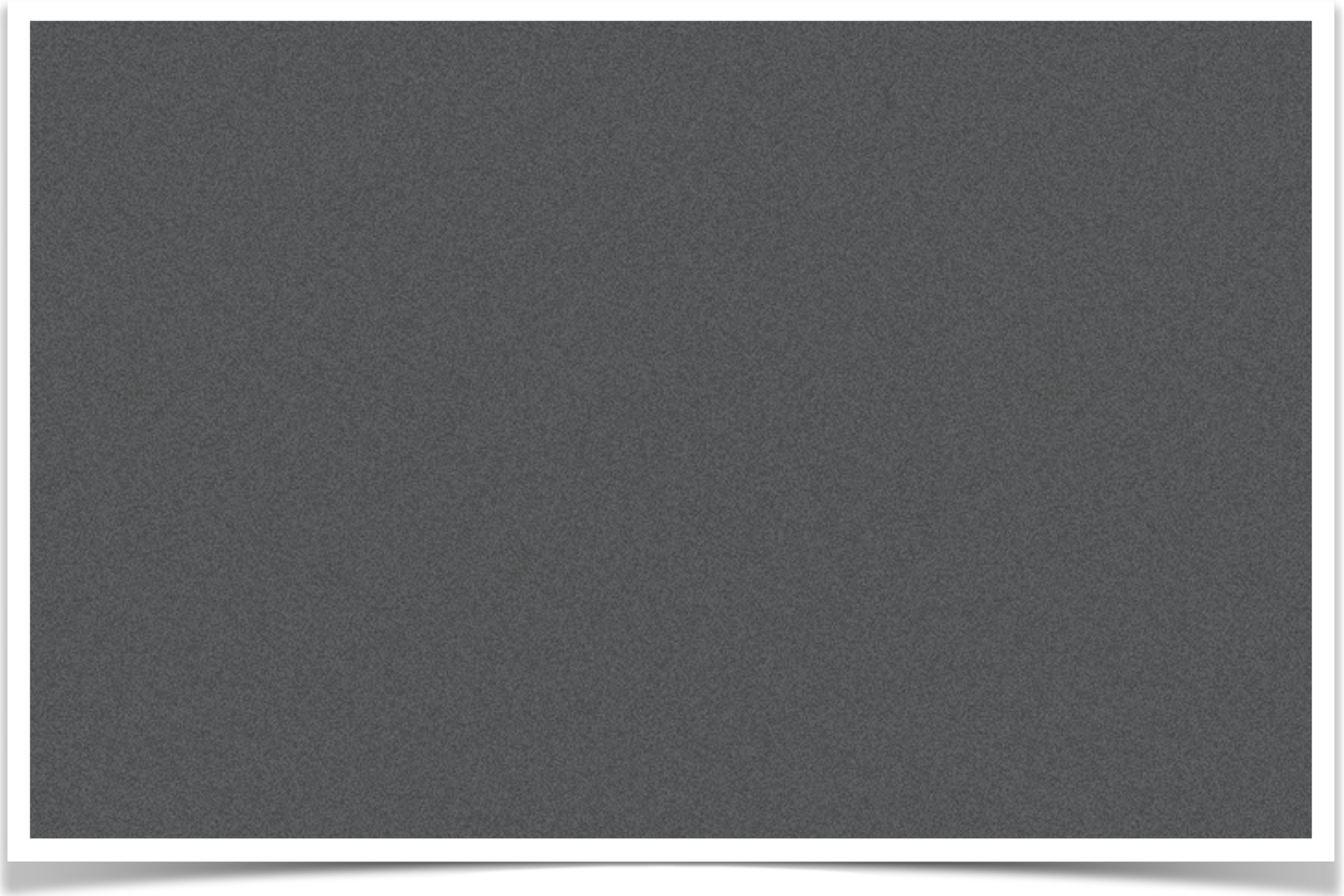

Regeneration Cavity

- Amplifies electromagnetic component of the axion field
- Increases reconversion probability after the wall
- Boosts reconverted power by resonant enhancement factor

Photons at the detector: $$N_\gamma = \frac{1}{16}\left(g_{a\gamma\gamma}BL\right)^4 \eta\beta_\mathrm{R} P_\mathrm{c}\tau,$$

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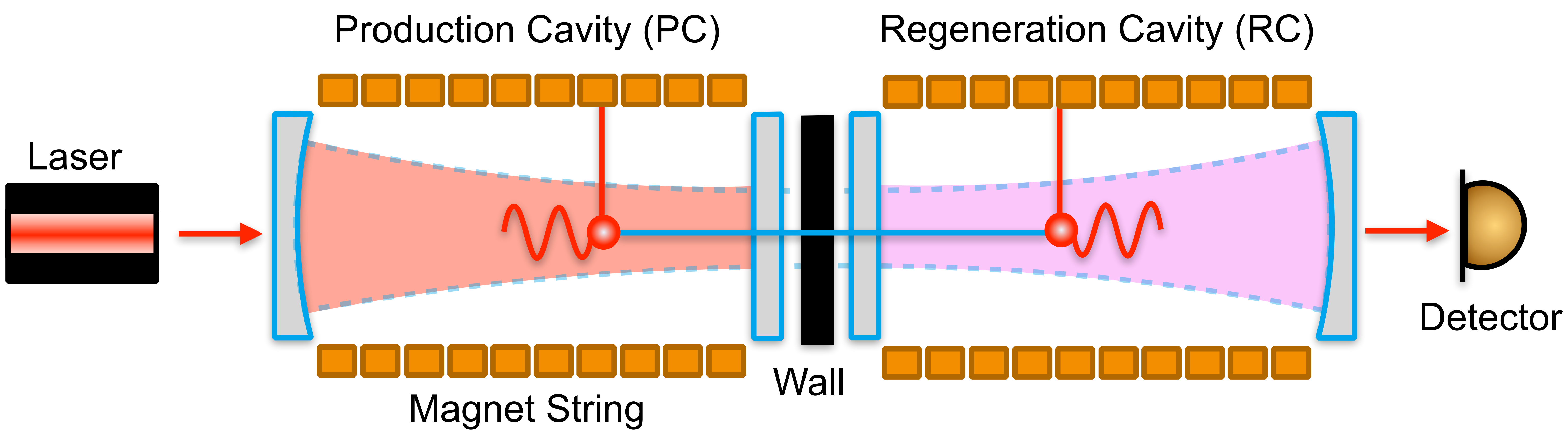

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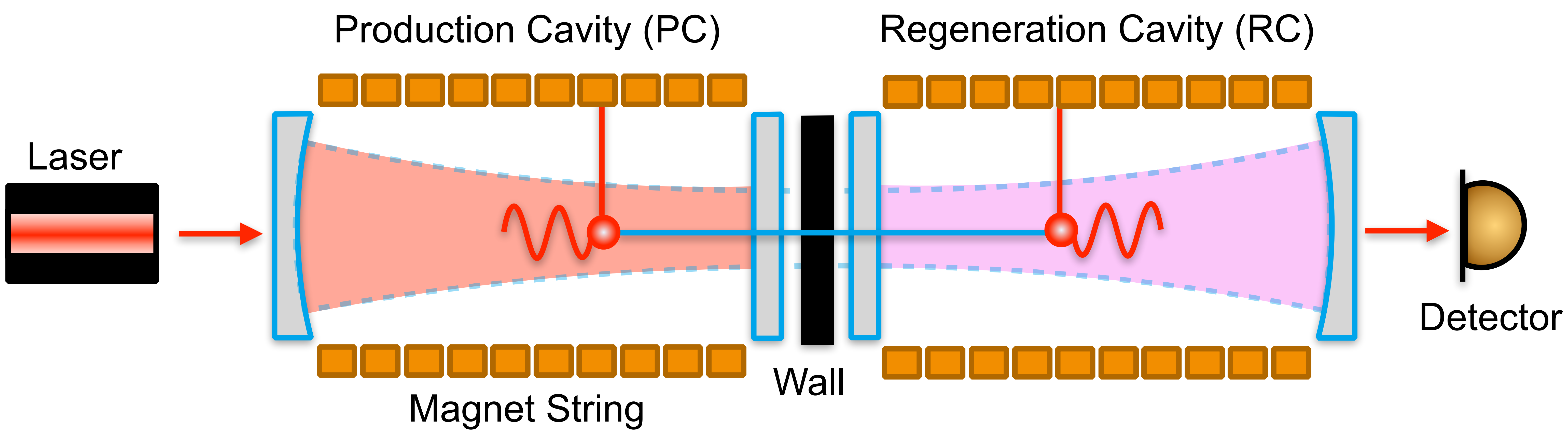
$g = 2 \times 10^{-11}$ GeV^{-1}
$B = 5.3$ T
$L = 106$ m
$P_c = 150$ kW
$\beta = 20{,}000$

1 photon per day!



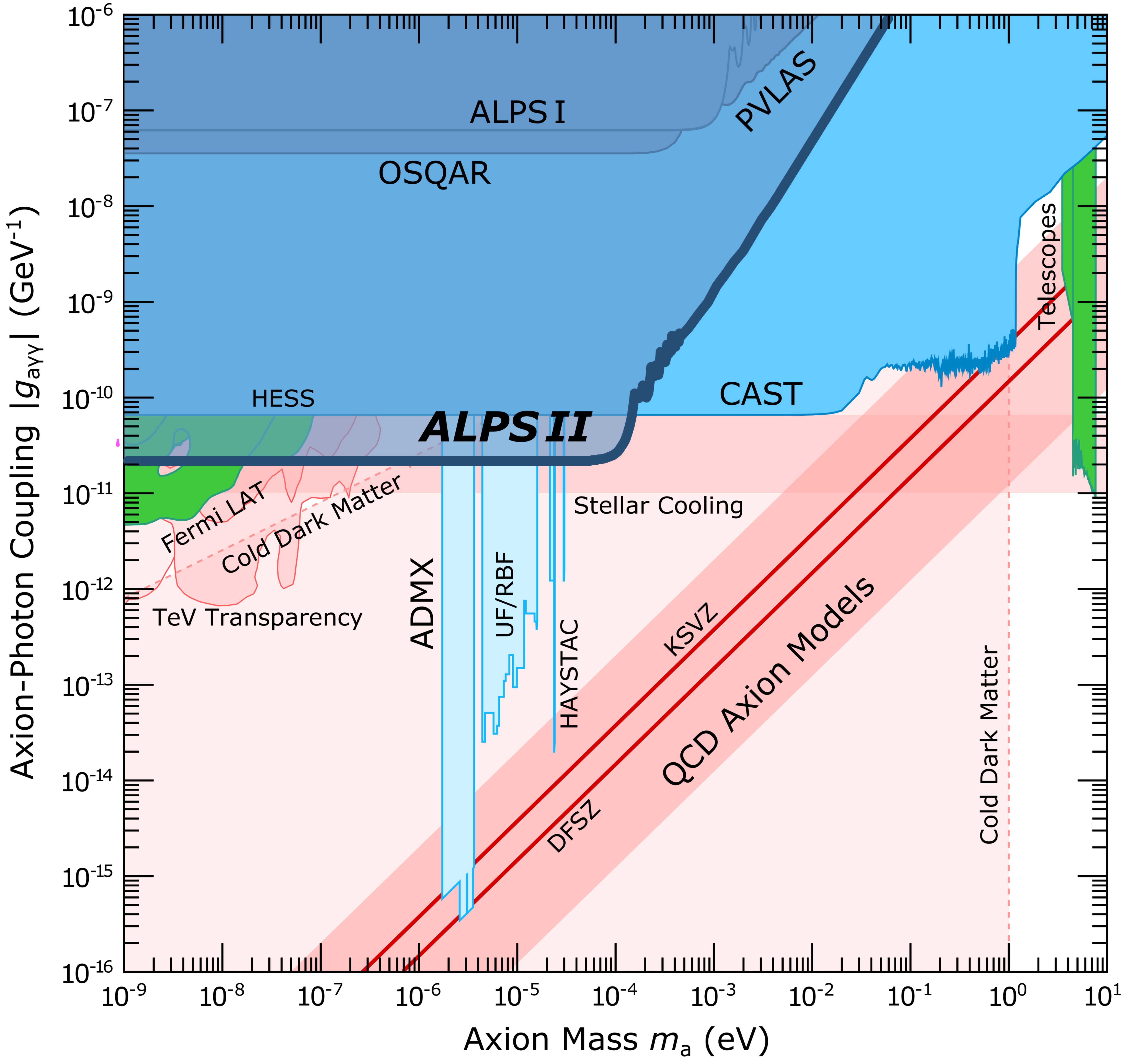
ALPS II Sensitivity

Target Sensitivity

- $g > 2 \times 10^{-11}$ GeV^{-1}
  - 3x beyond CAST limit
- m < 0.1 meV

Hints probed

- TeV transparency
- Stellar Cooling



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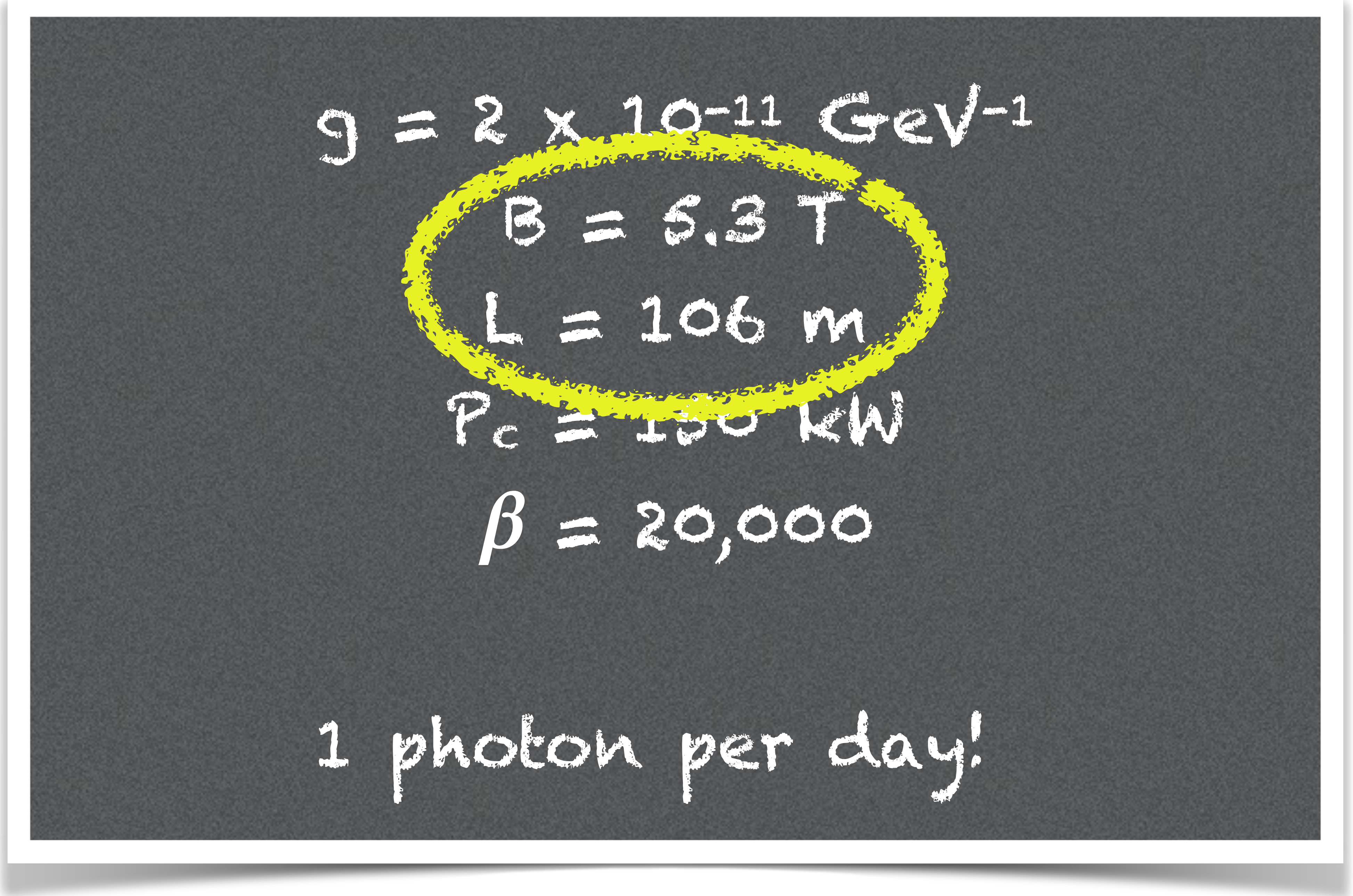

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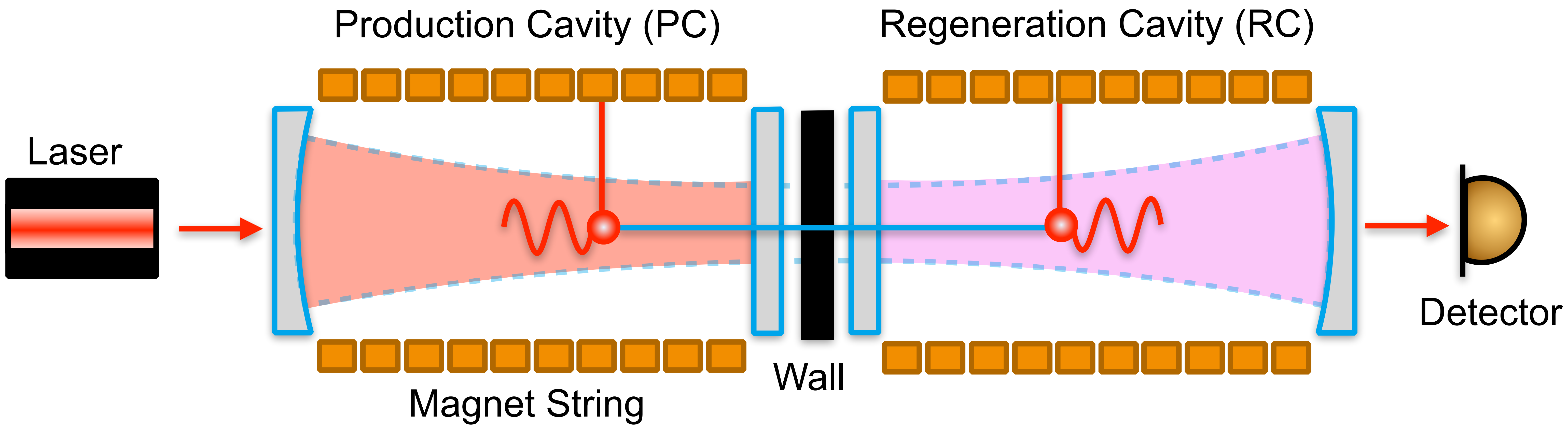
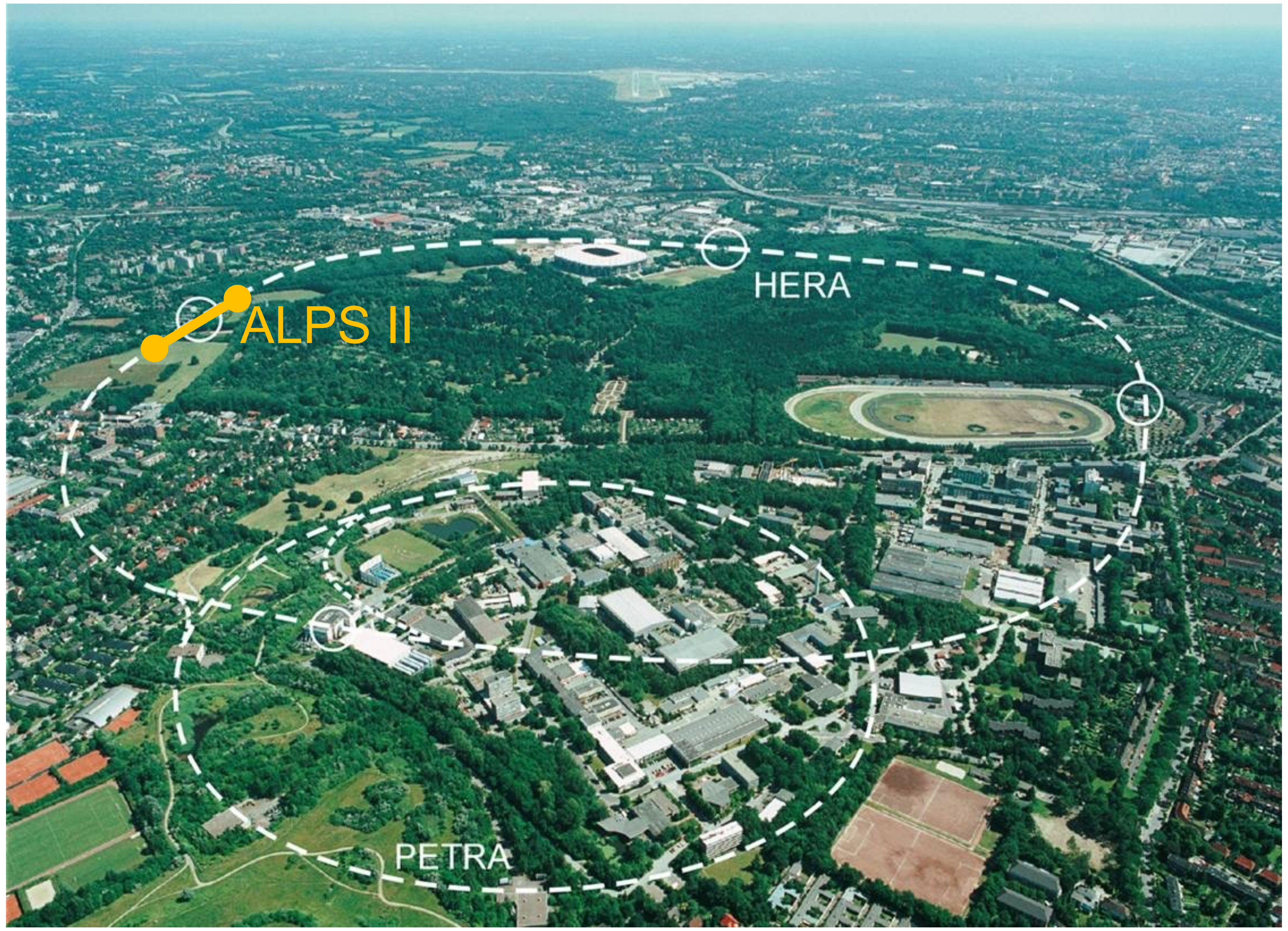


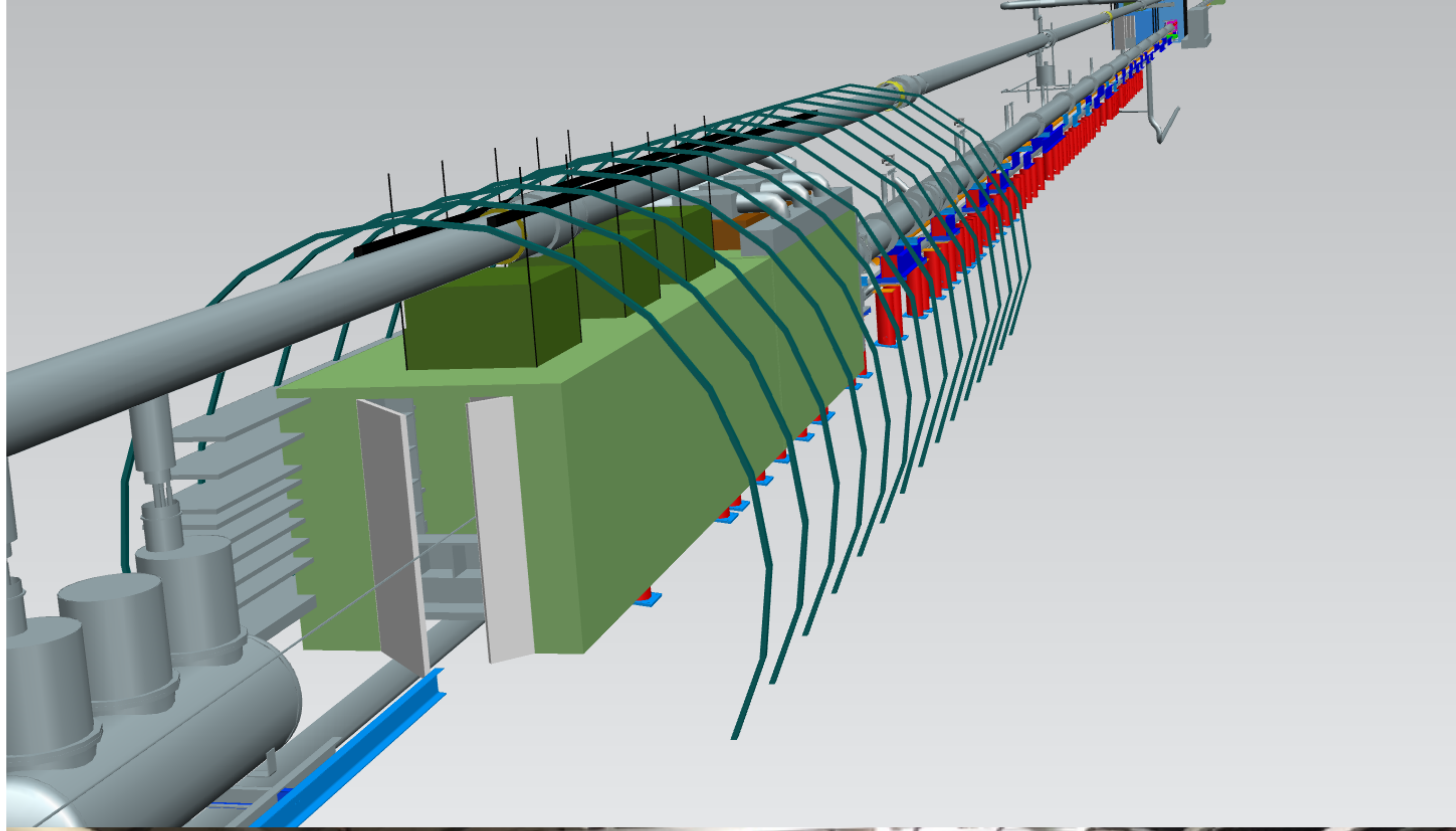
Infrastructure at DESY

Providing the foundation for ALPS II

Tunnels with 250 m straight sections

- Cryogenic infrastructure
- 12 x 12 HERA dipole magnets: 5.3 T, 106 m





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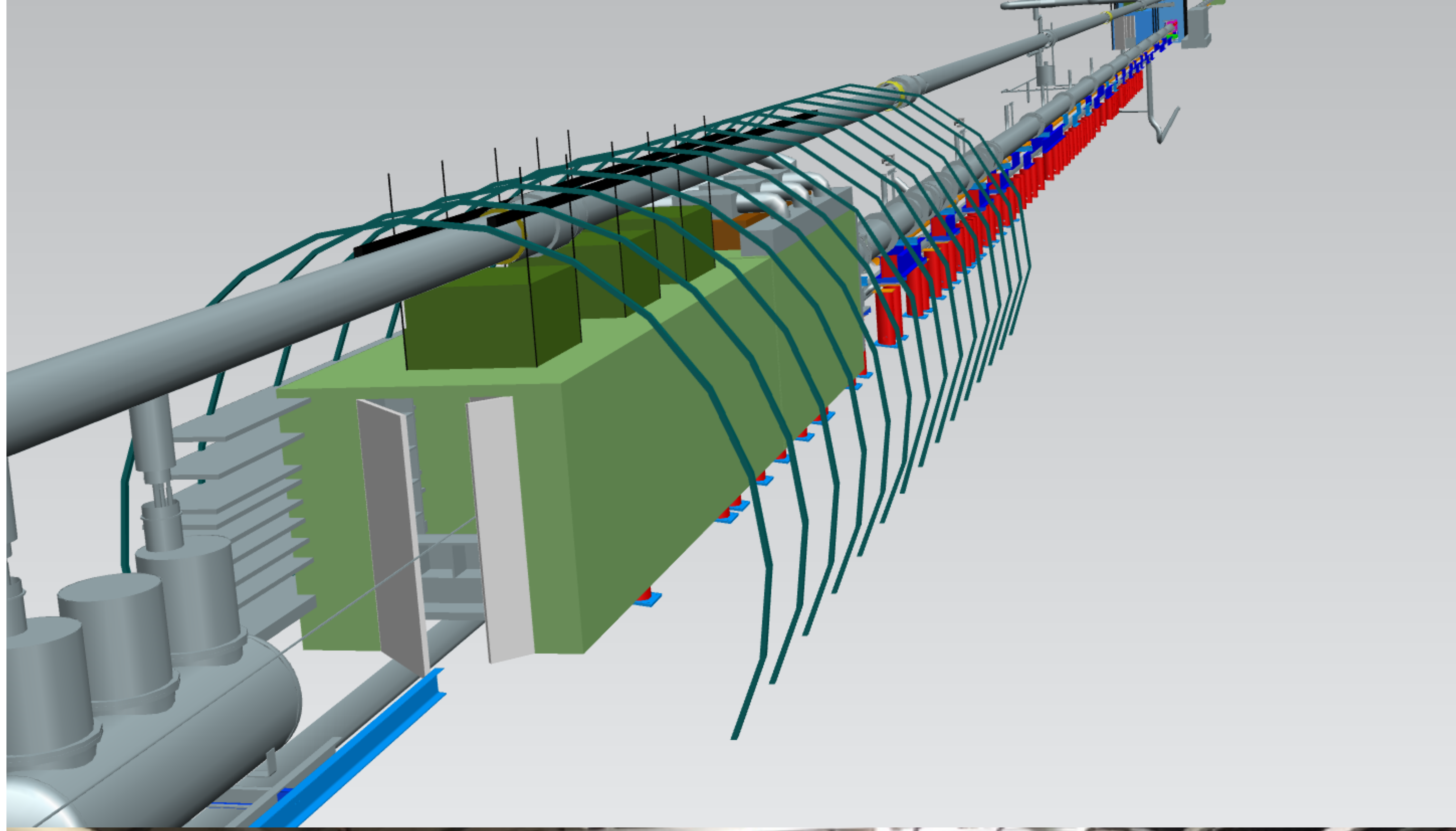

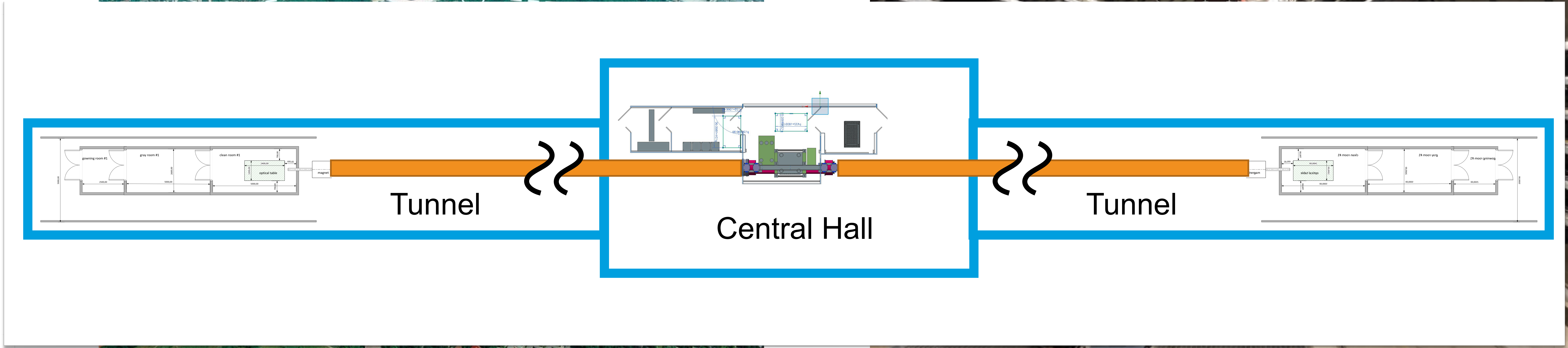

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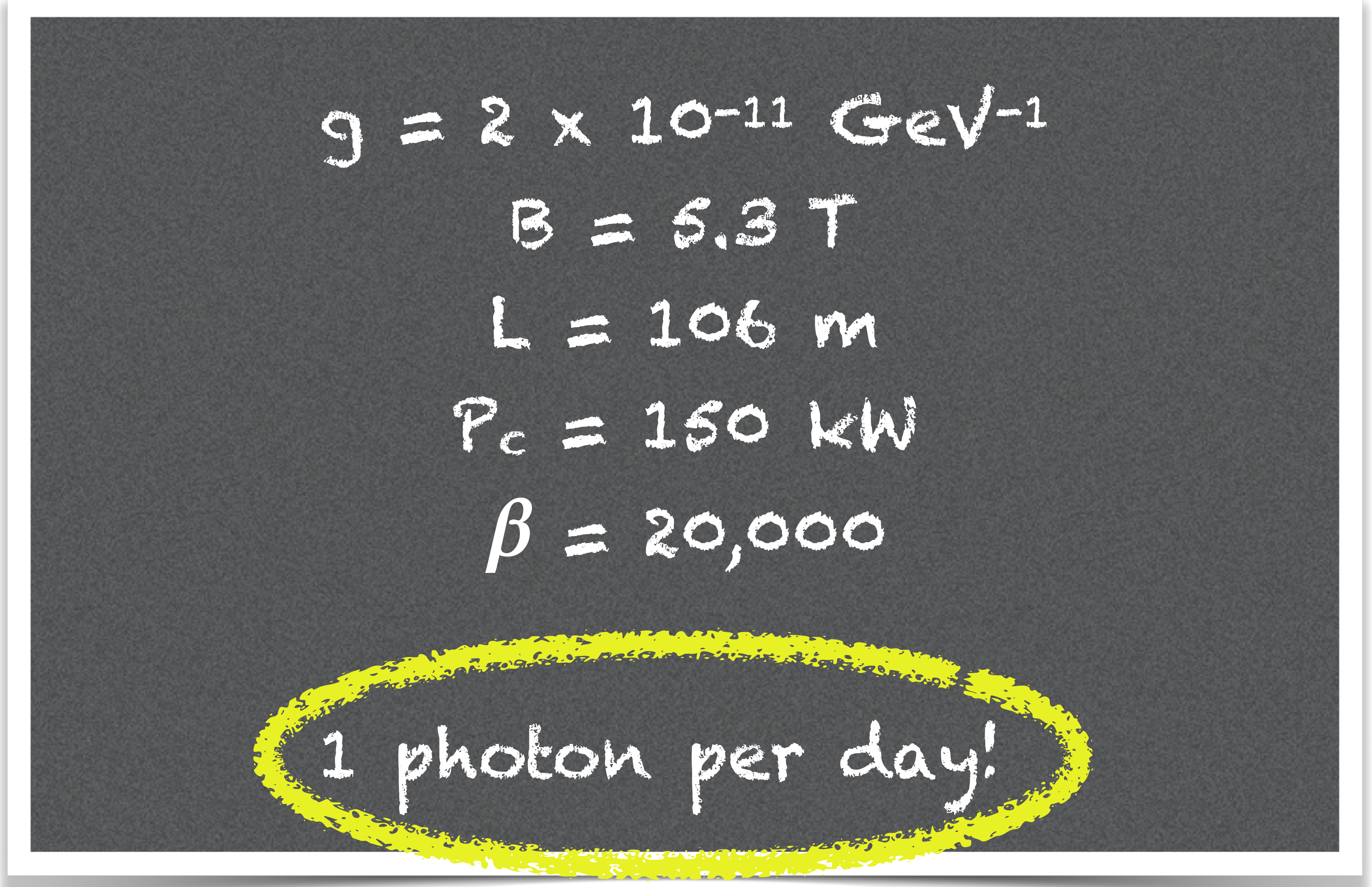

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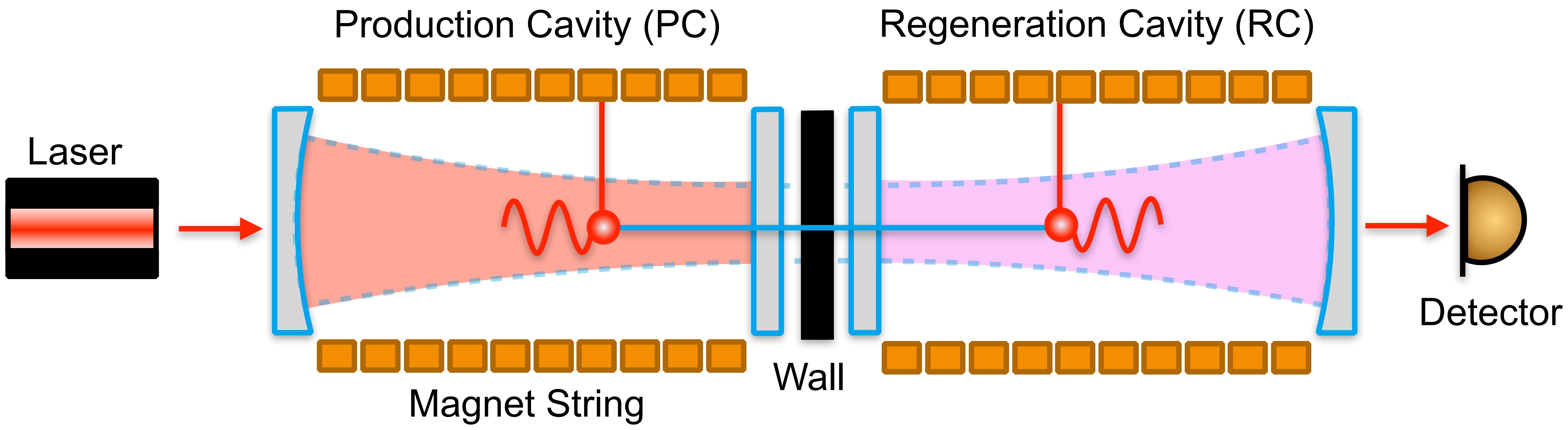


Detection schemes

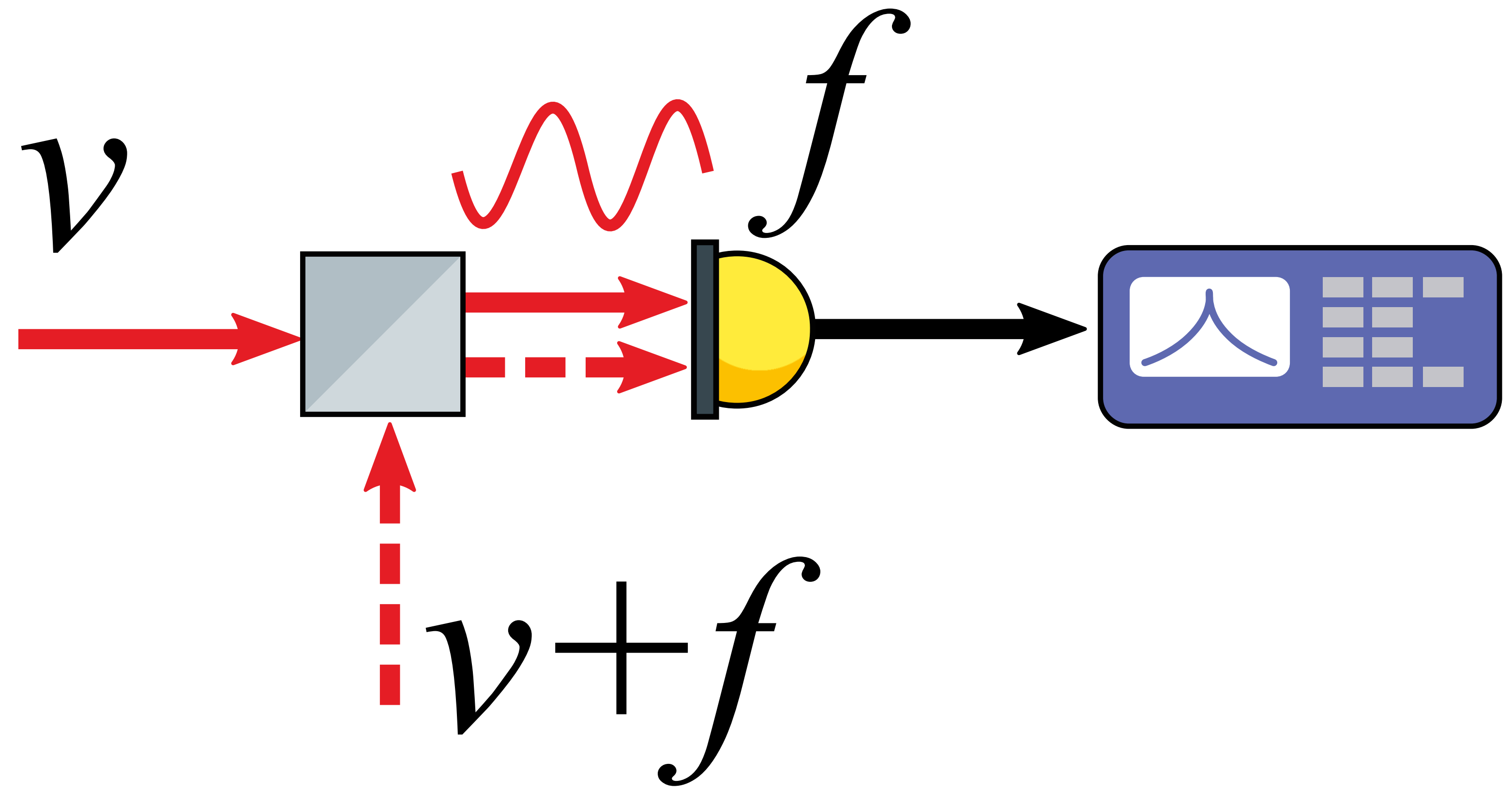
Measuring single photon power levels

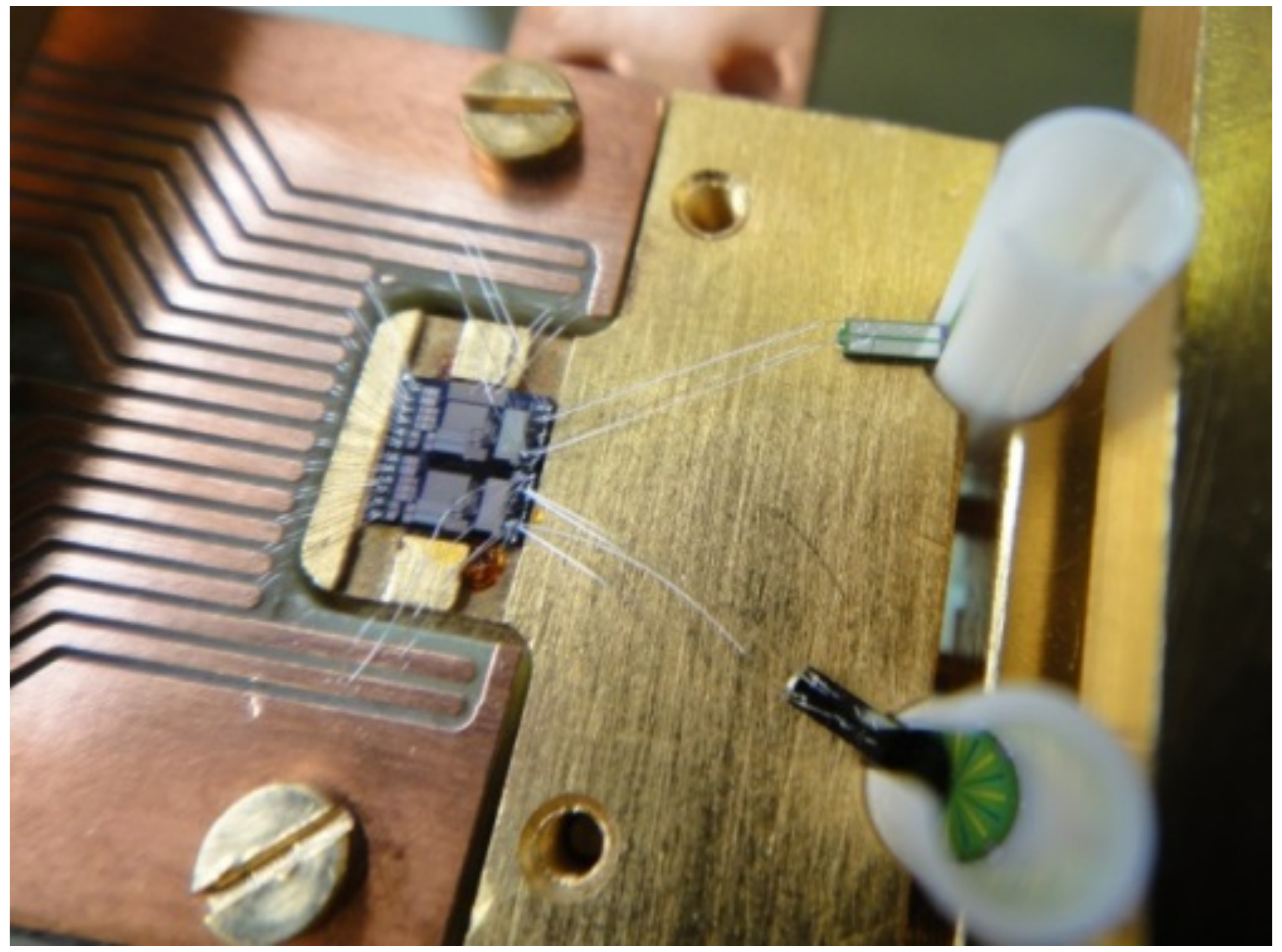
Heterodyne detection system

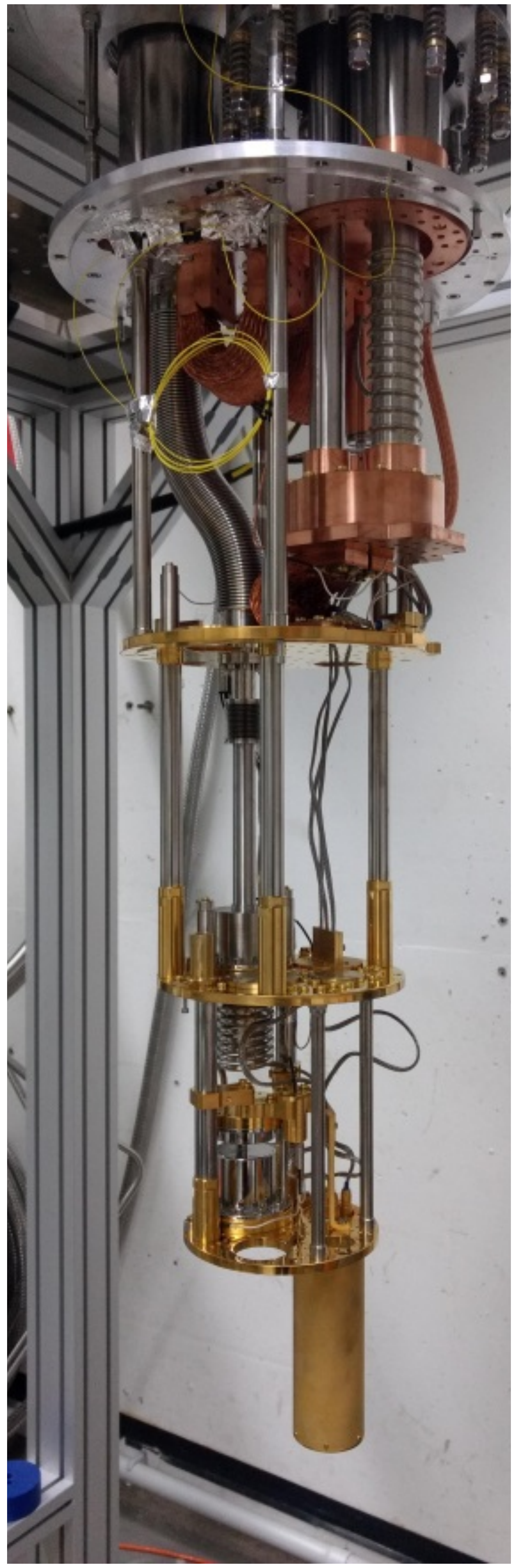
- AC measurement of interference of regenerated field with local oscillator
- Shot noise limited detection
- Demonstrated system at UF

Transition edge sensor

- A Microcalorimeter measures temp. change induced by absorbed photon
- Background characterization on-going
- Demonstrated system at DESY







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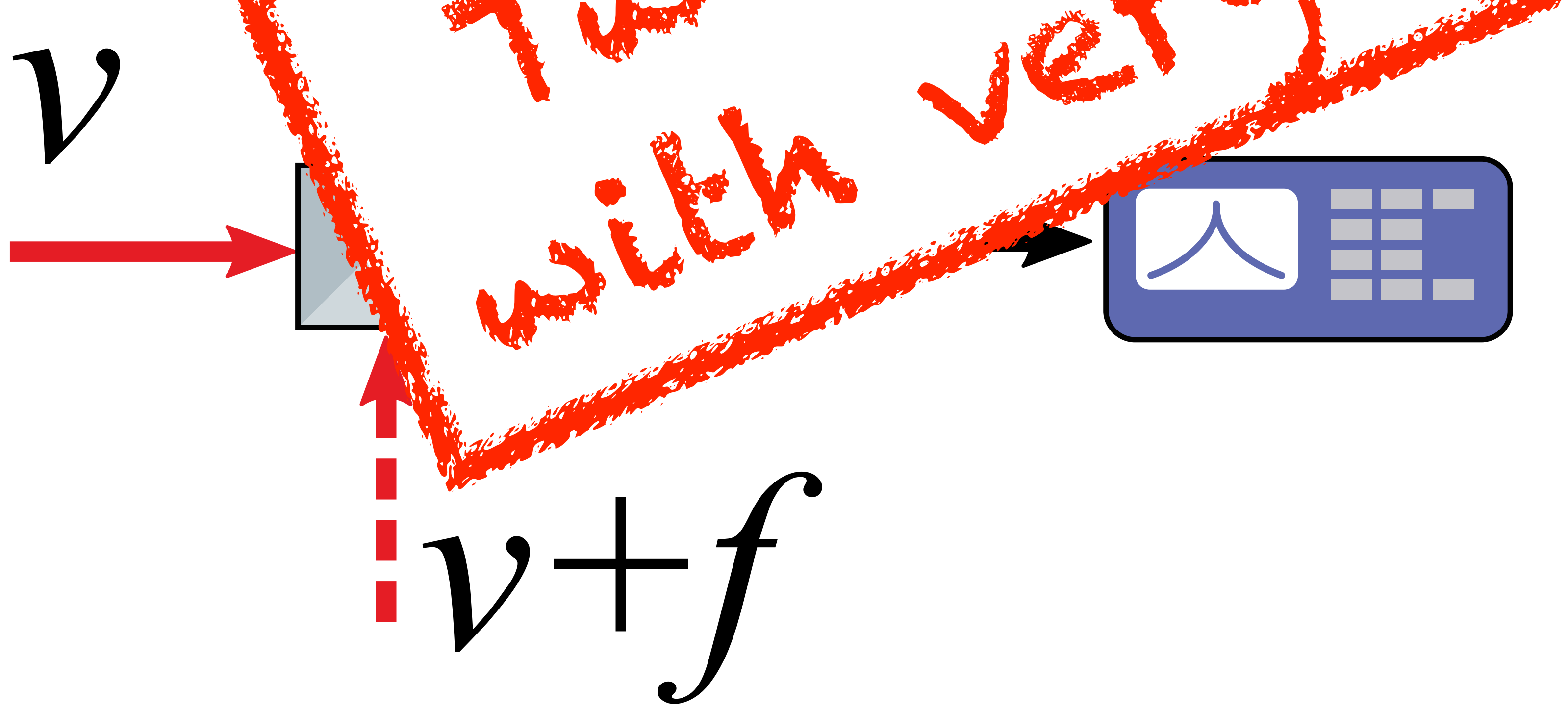
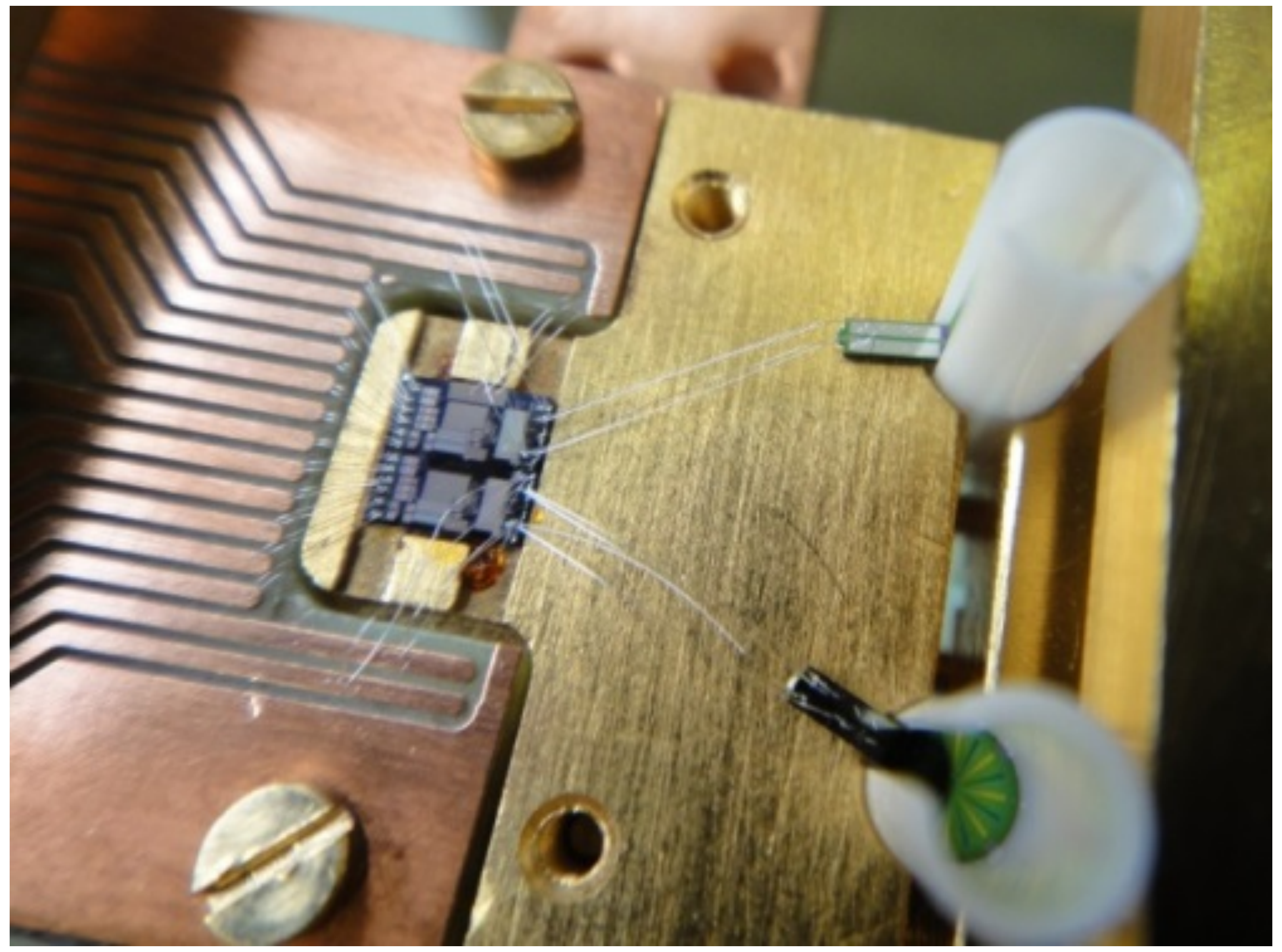
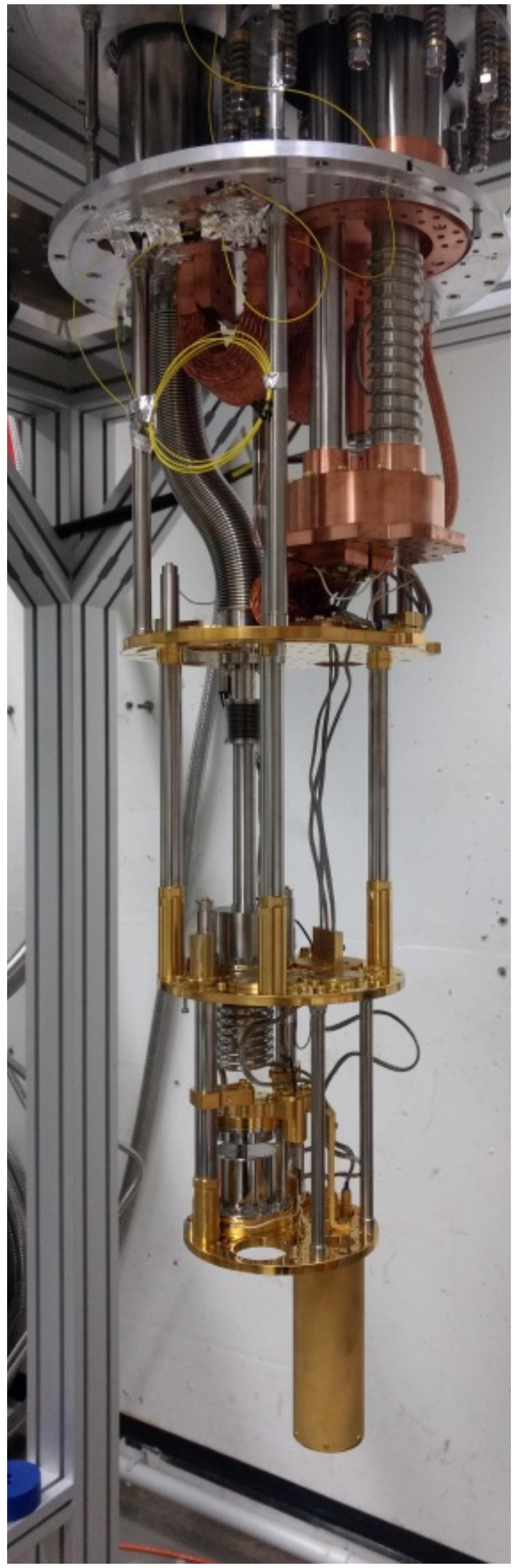


Transition edge sensor

- A Microcalor… mp. chan… ton
- …n on-going
- …ystem at DESY

Two measurement techniques with very different systematics





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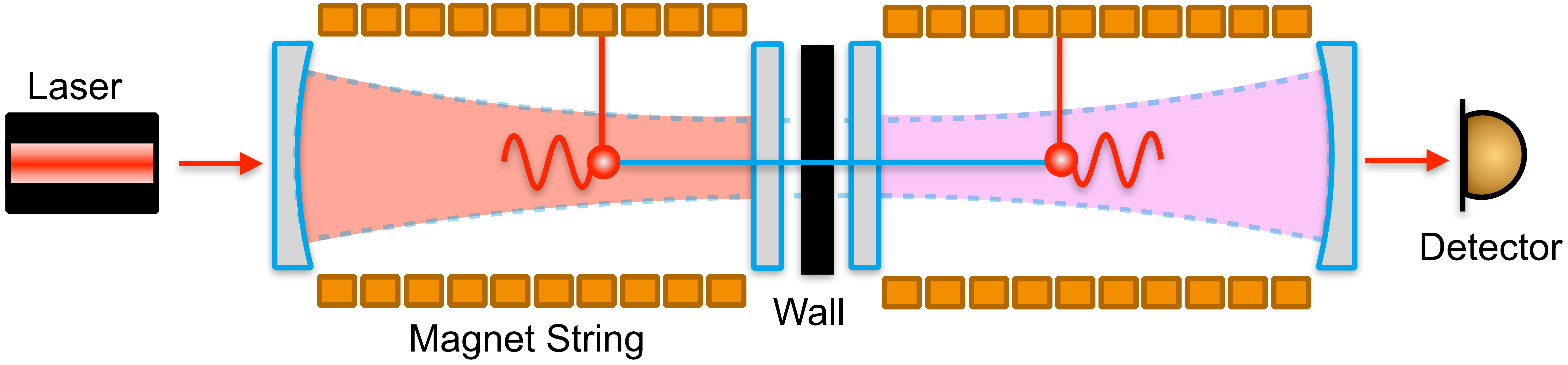


ALPS II Optical Cavities

Measuring the conversion-reconversion of Axion-like particles

Production Cavity

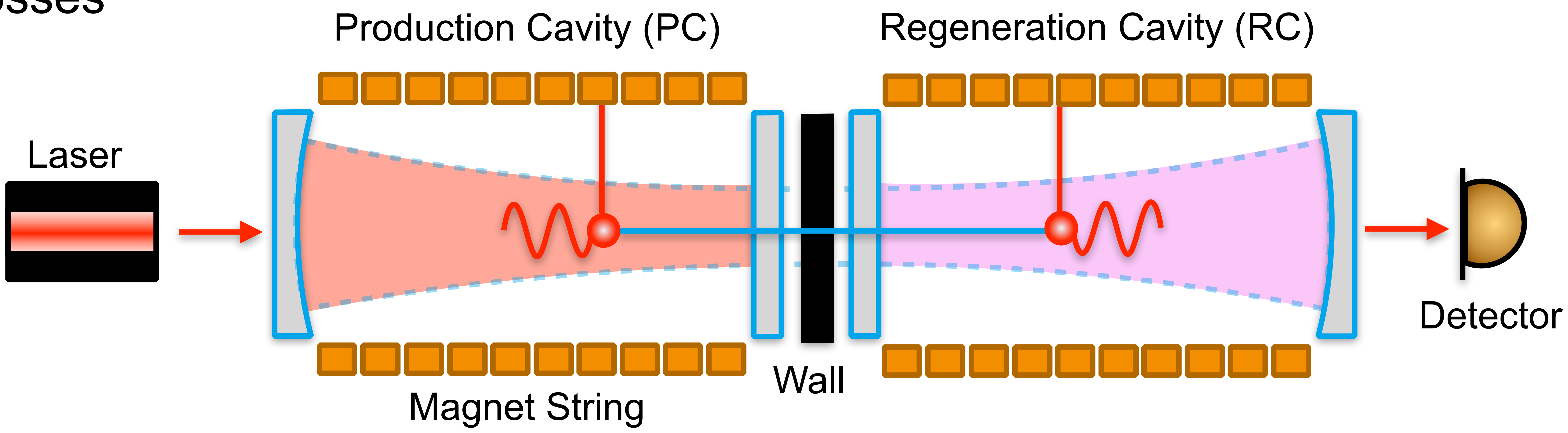
- Length: 124 m
- Input power: 70 W amplified NPRO (1064 nm)
- Circulating power: 150 kW

Regeneration Cavity

- Length: 124 m
- Power-build-up factor: 16,000
  - Optimized mirror coatings based on expected scattering losses

Technology Demonstrations on 10 m Cavity

- Circulating power ~ 50 kW
- Power build up factor ~ 33,000
- Laser frequency and cavity length stabilization
  - Techniques from gravitational wave detectors



ALPS II Optical Cavities

Measuring the conversion-reconversion of Axion-like particles

Research Article Vol. 24, No. 25 | 12 Dec 2016 | OPTICS EXPRESS 29237

Optics EXPRESS

Characterization of optical systems for the ALPS II experiment

AARON D. SPECTOR,[1,*] JAN H. PÕLD,[2] ROBIN BÄHRE,[3,4] AXEL LINDNER,[2] AND BENNO WILLKE [3,4]

Põld and Spector *EPJ Techniques and Instrumentation* (2020) 7:1
https://doi.org/10.1140/epjti/s40485-020-0054-8

EPJ.org

EPJ Techniques and Instrumentation

RESEARCH ARTICLE Open Access

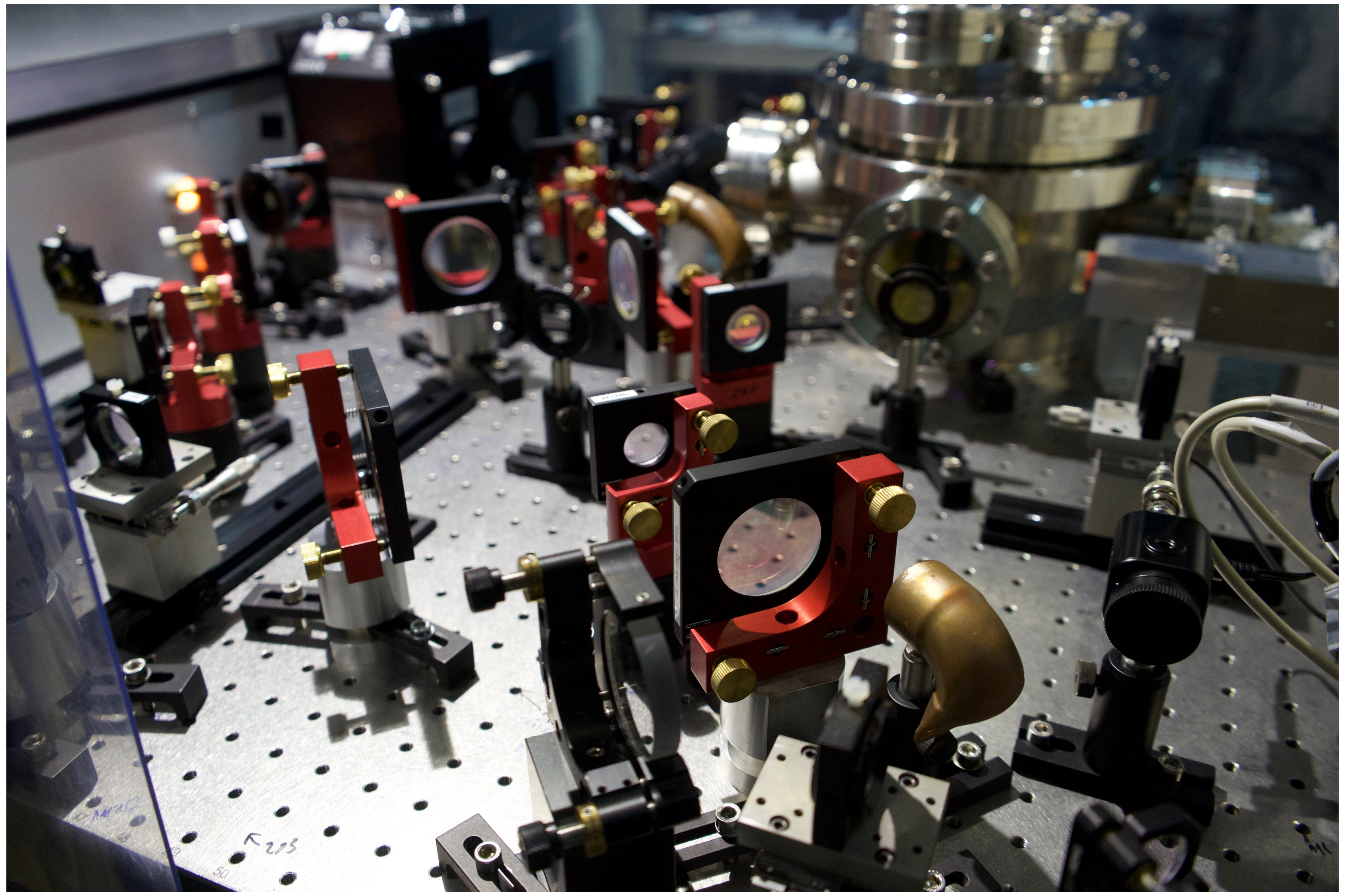
Demonstration of a length control system for ALPS II with a high finesse 9.2 m cavity

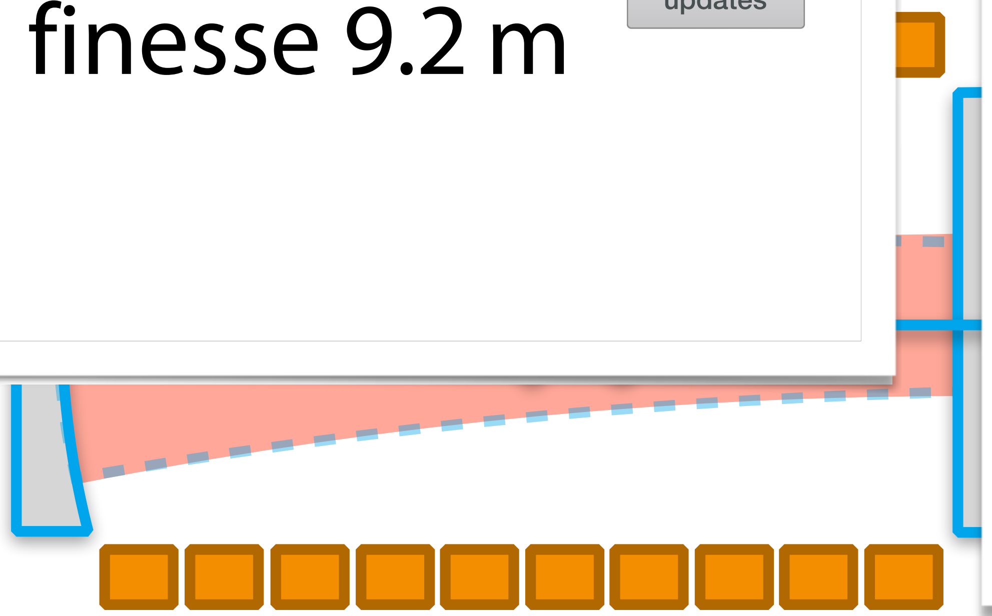
Check for updates

Jan H. Põld[1,2*] and Aaron D. Spector[3]

Technology I

- Circulatin
- Power bui





Field Overlap

Quantifying the coupling between the cavities

Dual Resonance

- PC circulating field must be resonant with length of the RC
- Coupling follows cavity Lorentzian

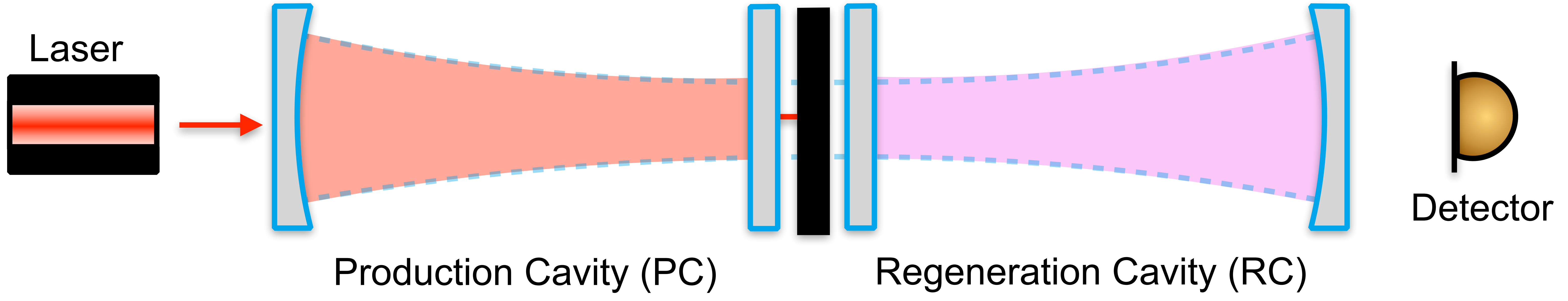
$$\eta_{\text{long}} \approx \frac{1}{\sqrt{1+\left(\frac{2\mathcal{F}\delta\nu}{\nu_{\text{FSR}}}\right)^2}}$$

Spatial overlap

- PC and RC must share same spatial eigenmode
- Can be expressed as an overlap integral that is simplified to the terms in following expression

$$\eta_{\text{lat}}(t) \approx \sqrt{1-\left|\frac{\delta x}{\omega_0}+i\frac{\delta\theta_{\text{x}}}{\theta_d}\right|^2-\left|\frac{\delta y}{\omega_0}+i\frac{\delta\theta_{\text{y}}}{\theta_d}\right|^2-\left|\frac{\delta \omega}{\omega_0}+i\frac{\delta z}{2z_R}\right|^2}$$

$$\eta_{total} > 0.9$$



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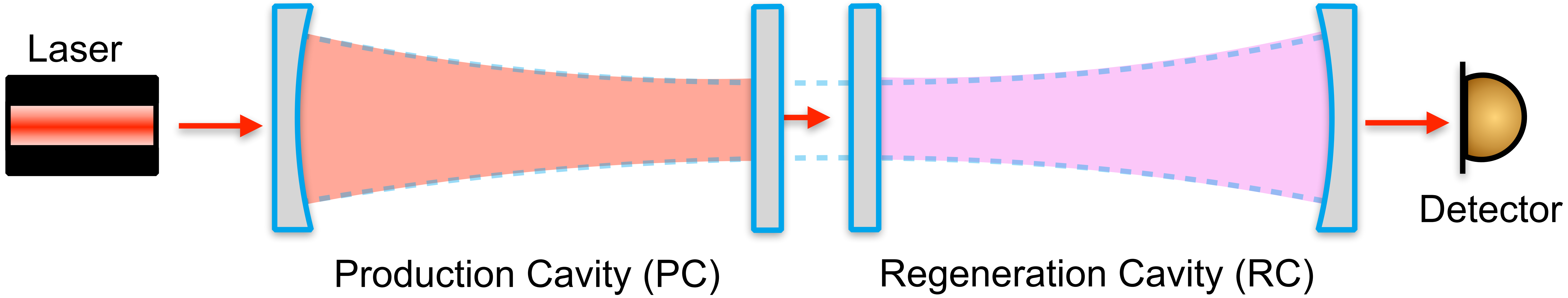
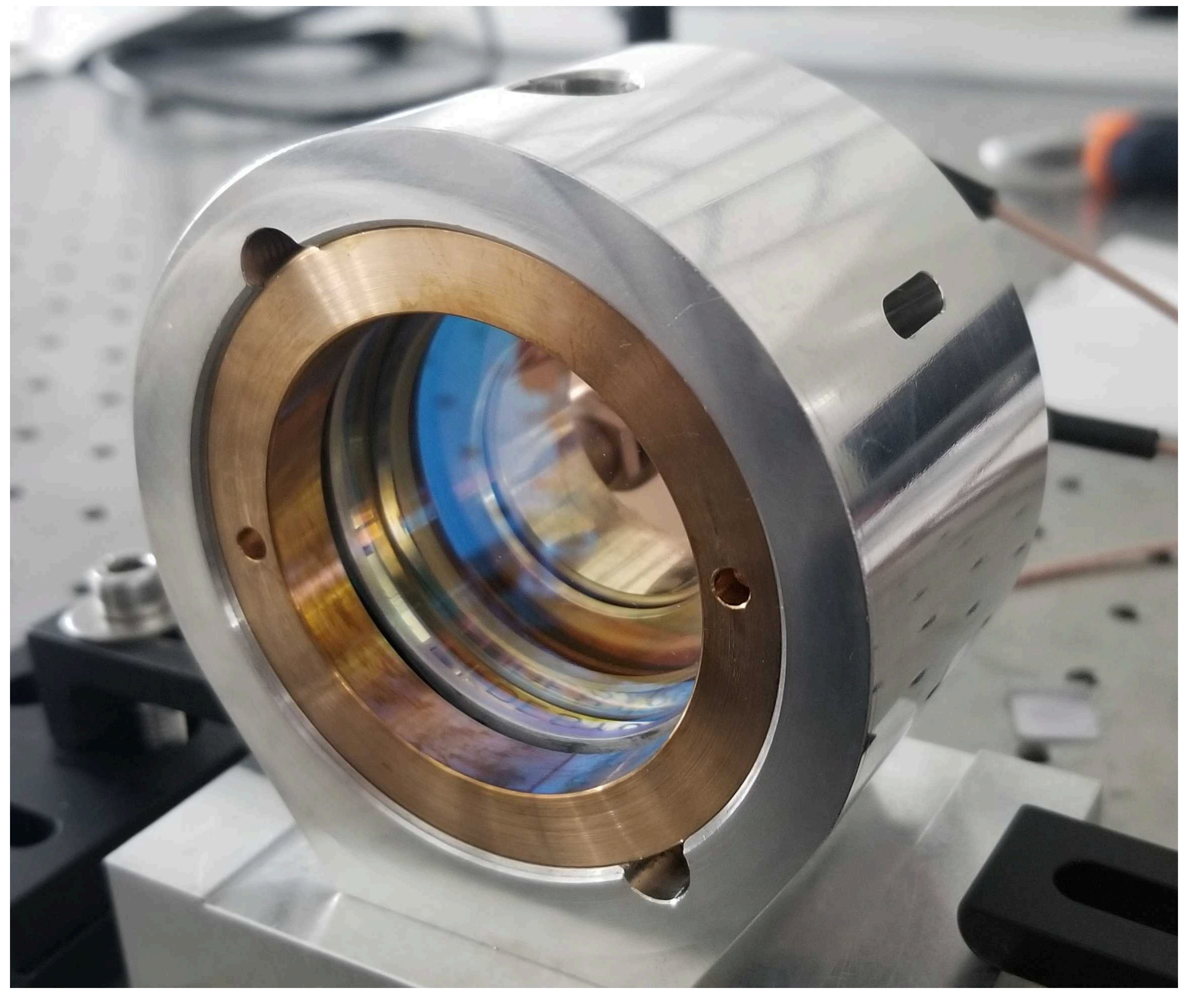
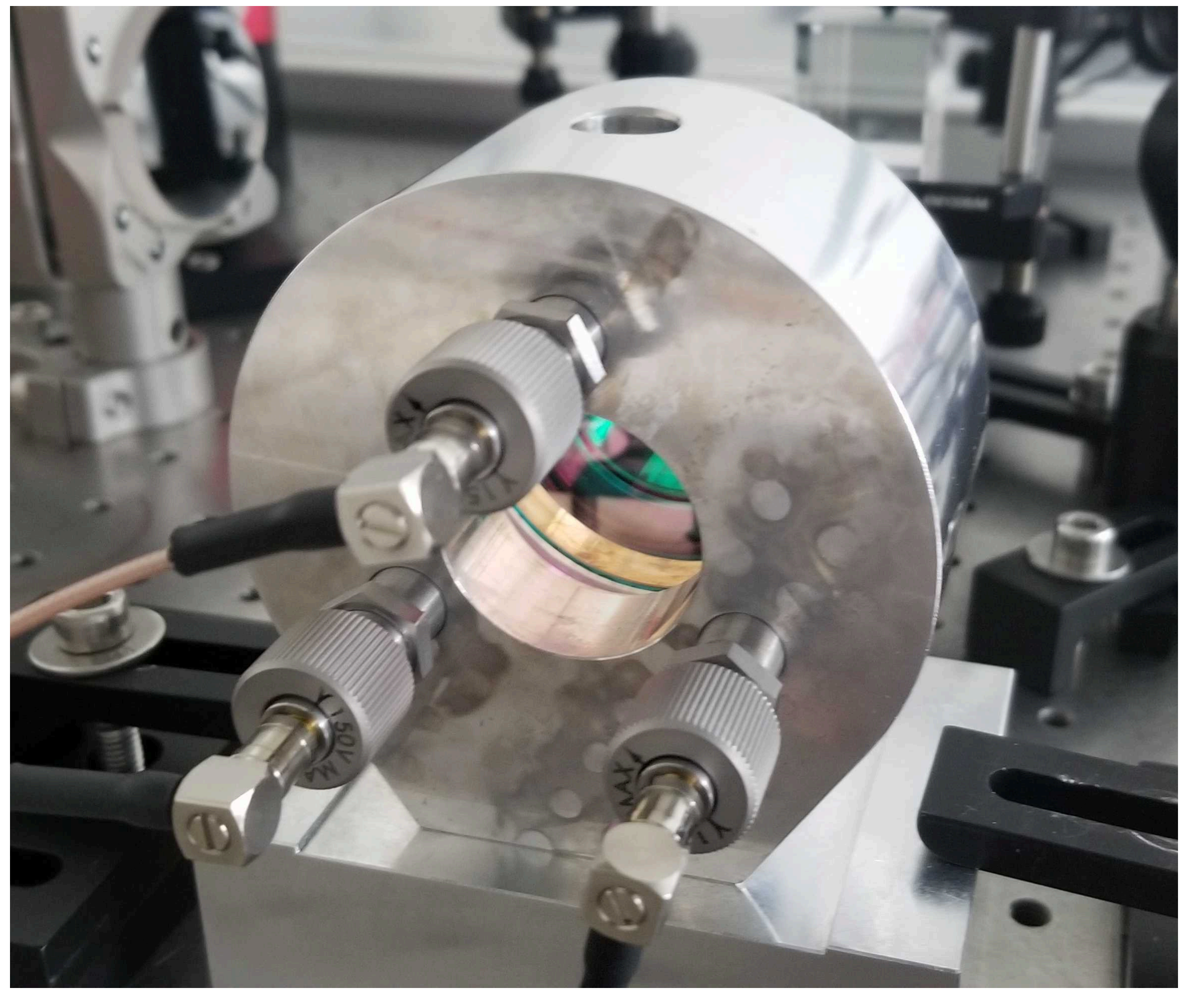


Dual Resonance

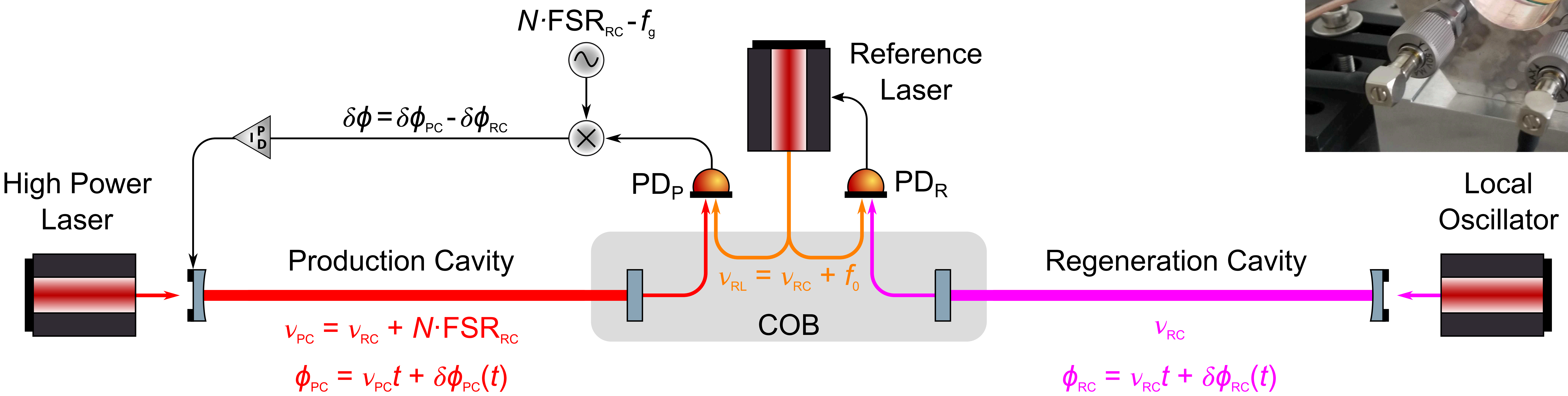
Maintaining the coupling between the cavities





PC circulating field must be resonant in RC

- Additional Reference Laser will be coupled to RC length
- Phase lock loop established by actuating on the length of the PC
  - Requires position accuracy on the order of pm
  - Environmental noise > 10 μm ➜ Length actuation with kHz bandwidths

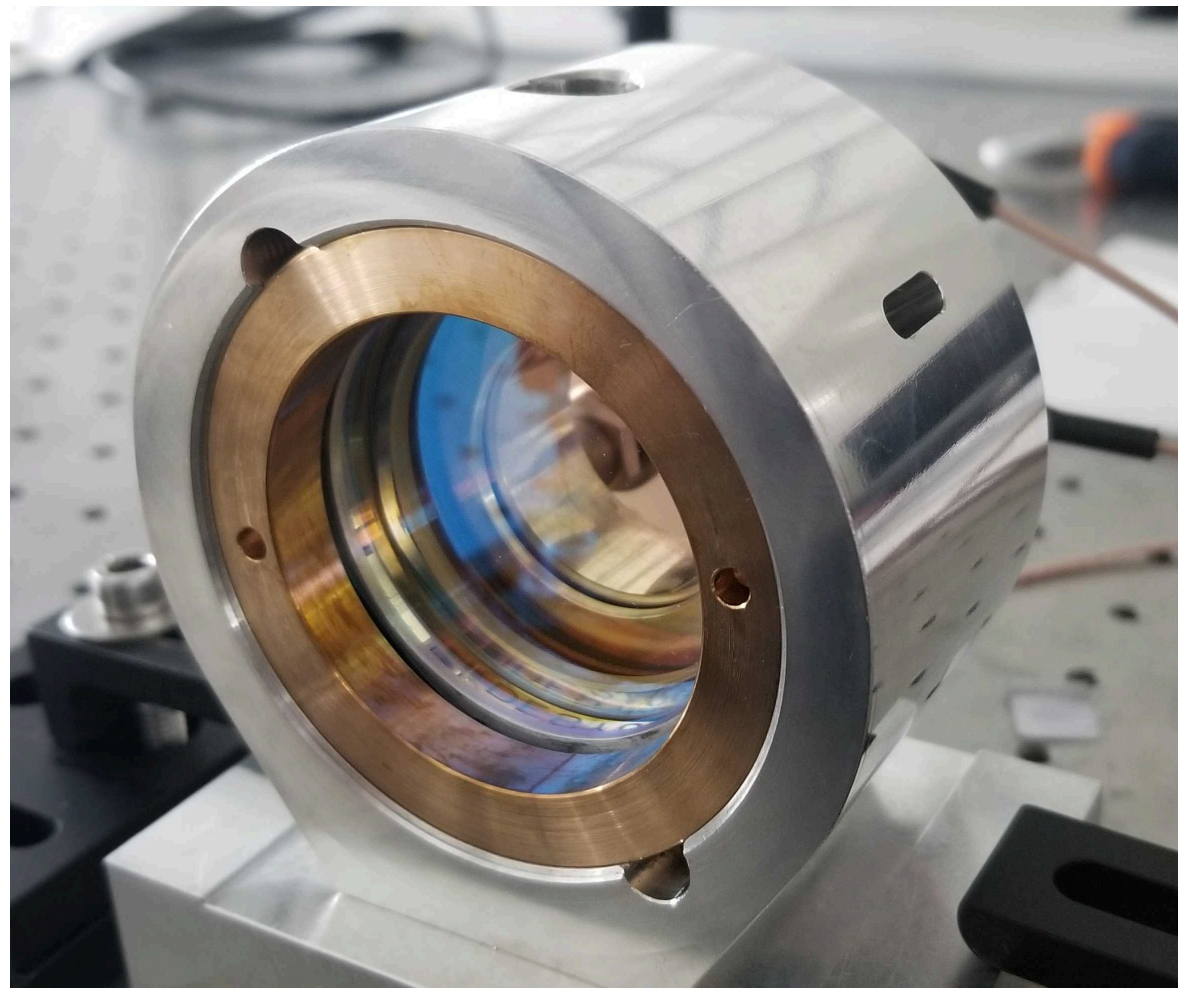


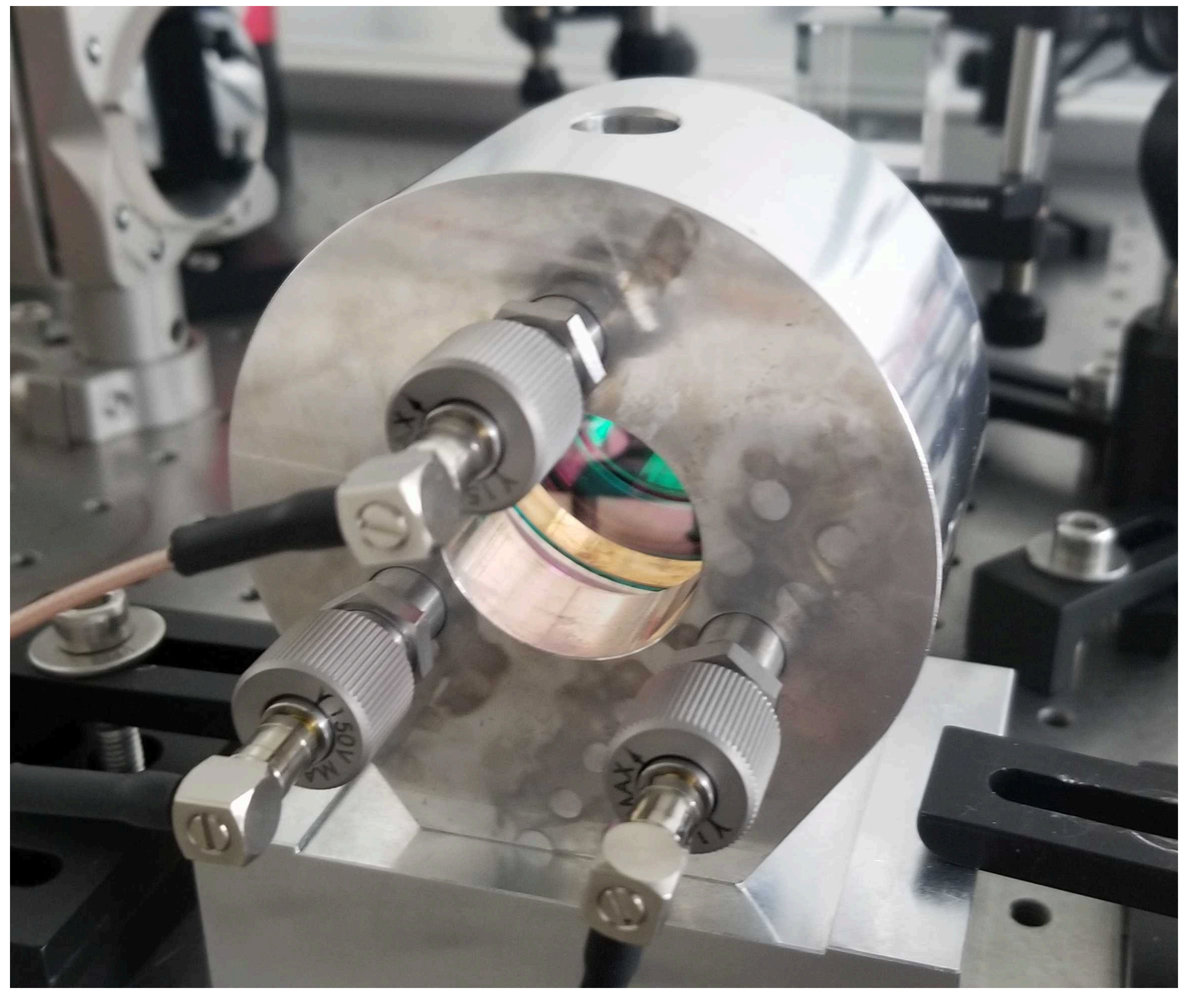
Spatial Overlap

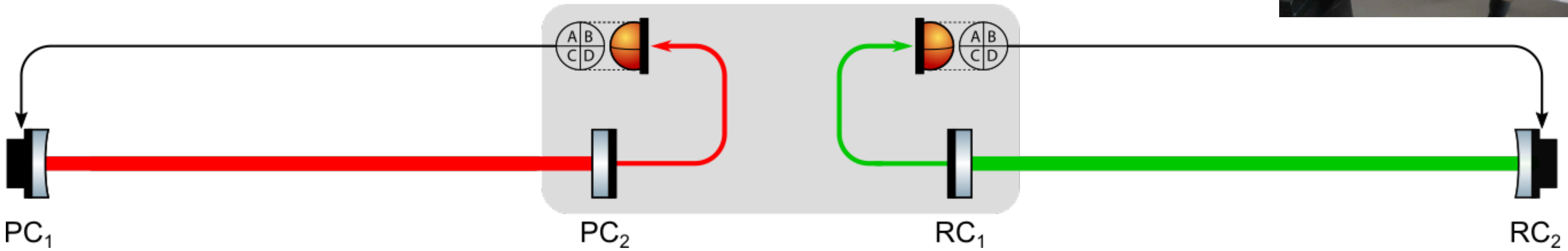
Maintaining the coupling between the cavities

PC circulating field must in nearly the same mode as the RC

- Central Optical Bench maintains alignment of the flat mirrors (< 5 μrad)
  - Passive stability of COB demonstrated with prototypes
- Eigenmode position sense with QPDs on the COB
  - Fed back to alignment actuators for the curved end mirrors



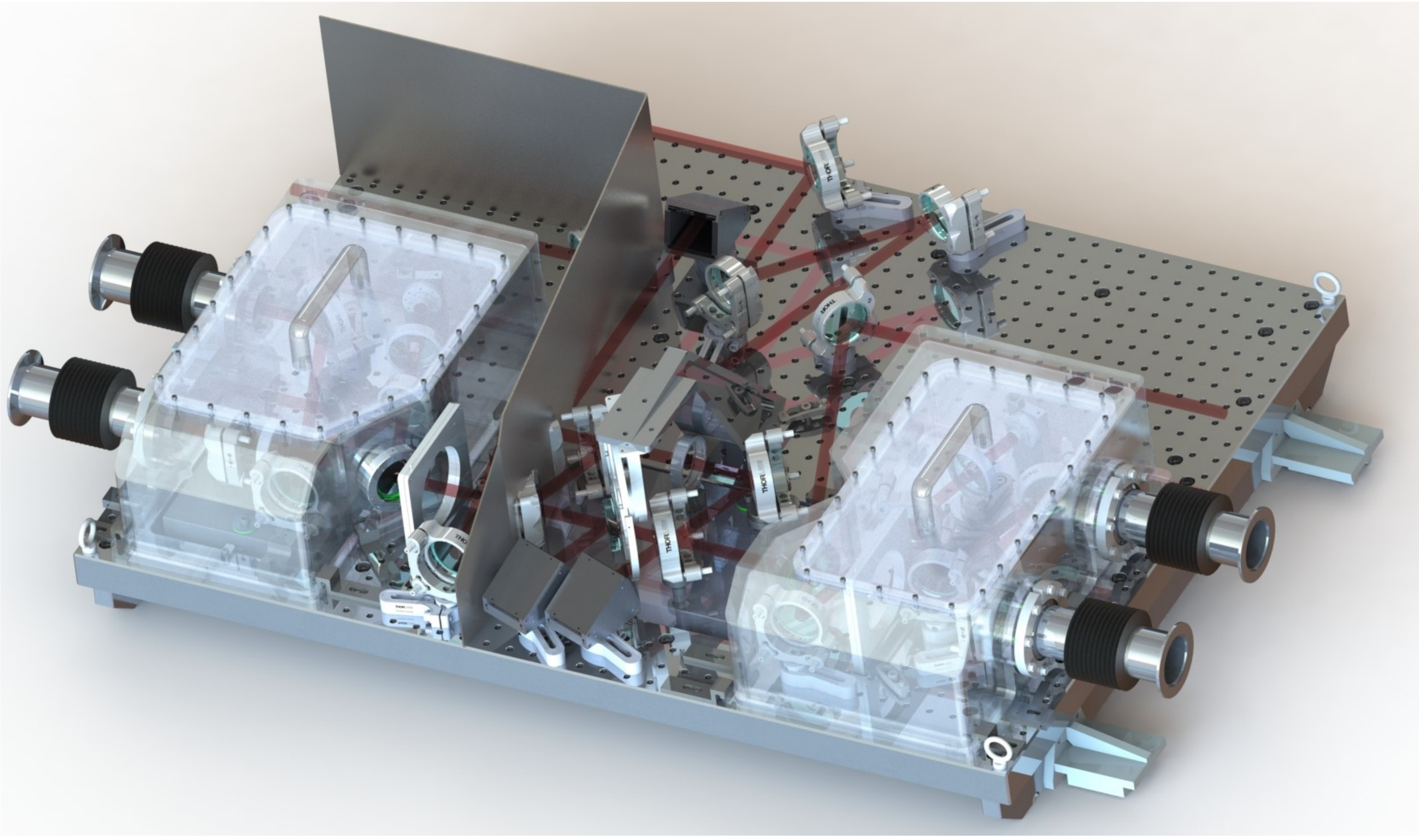


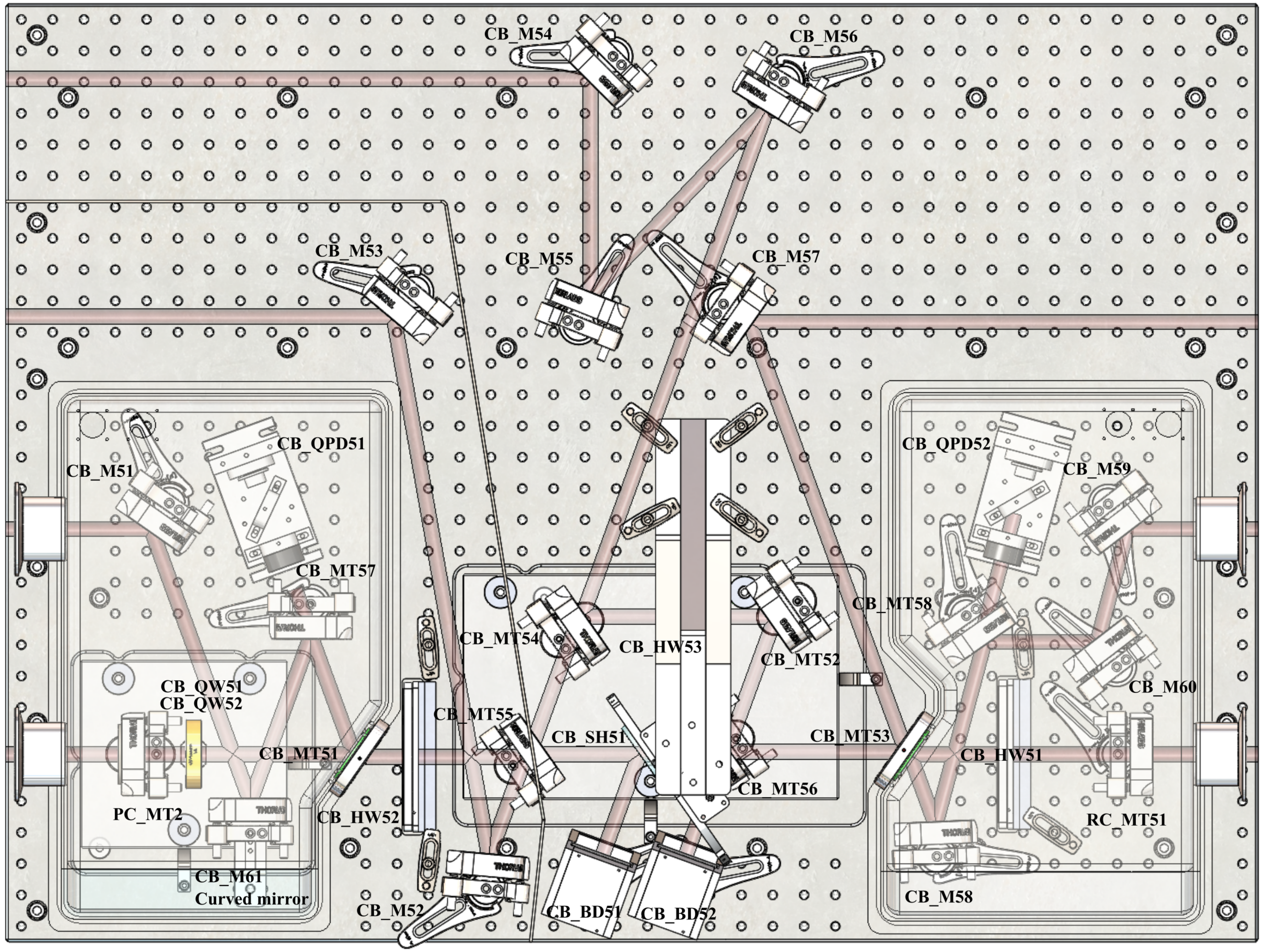


Central Optical Bench

Maintaining the coupling between the cavities

- Tracks path length changes
- Maintains cavity alignment
- Wall
- Stray light mitigation system





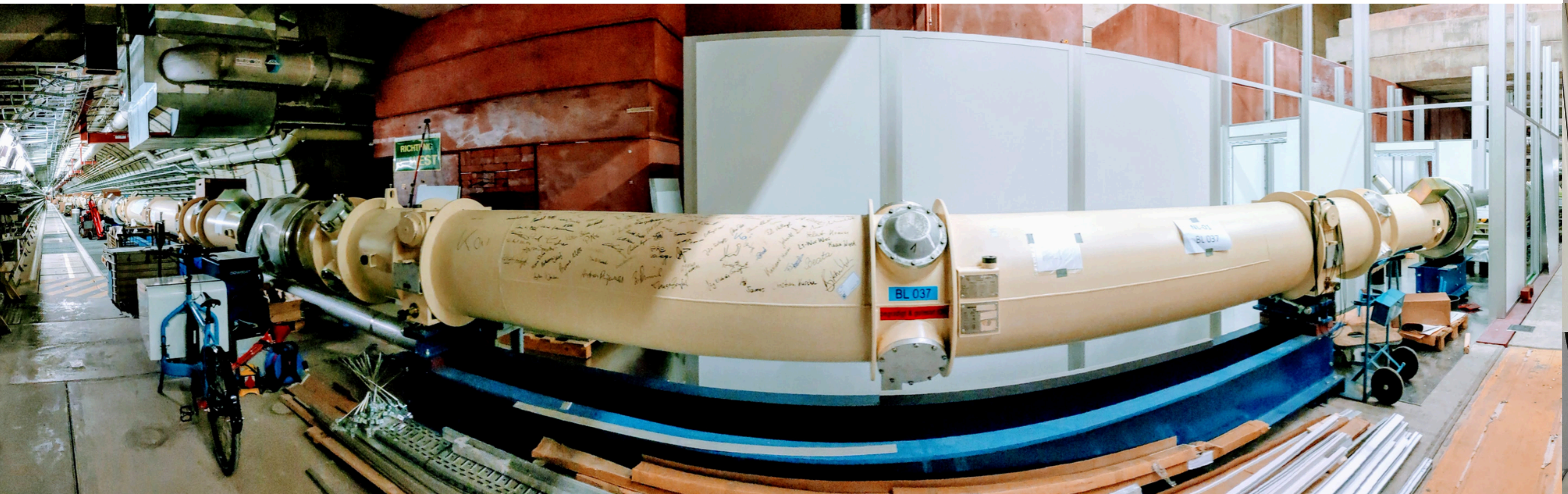
ALPS II Status

Nearly ready for science!

Construction progressing

- All 24 magnets are now installed and aligned
- Cleanrooms at end stations are now operational
- Commissioning of the optical system has begun
- Cryogenic operation of magnets July 2021

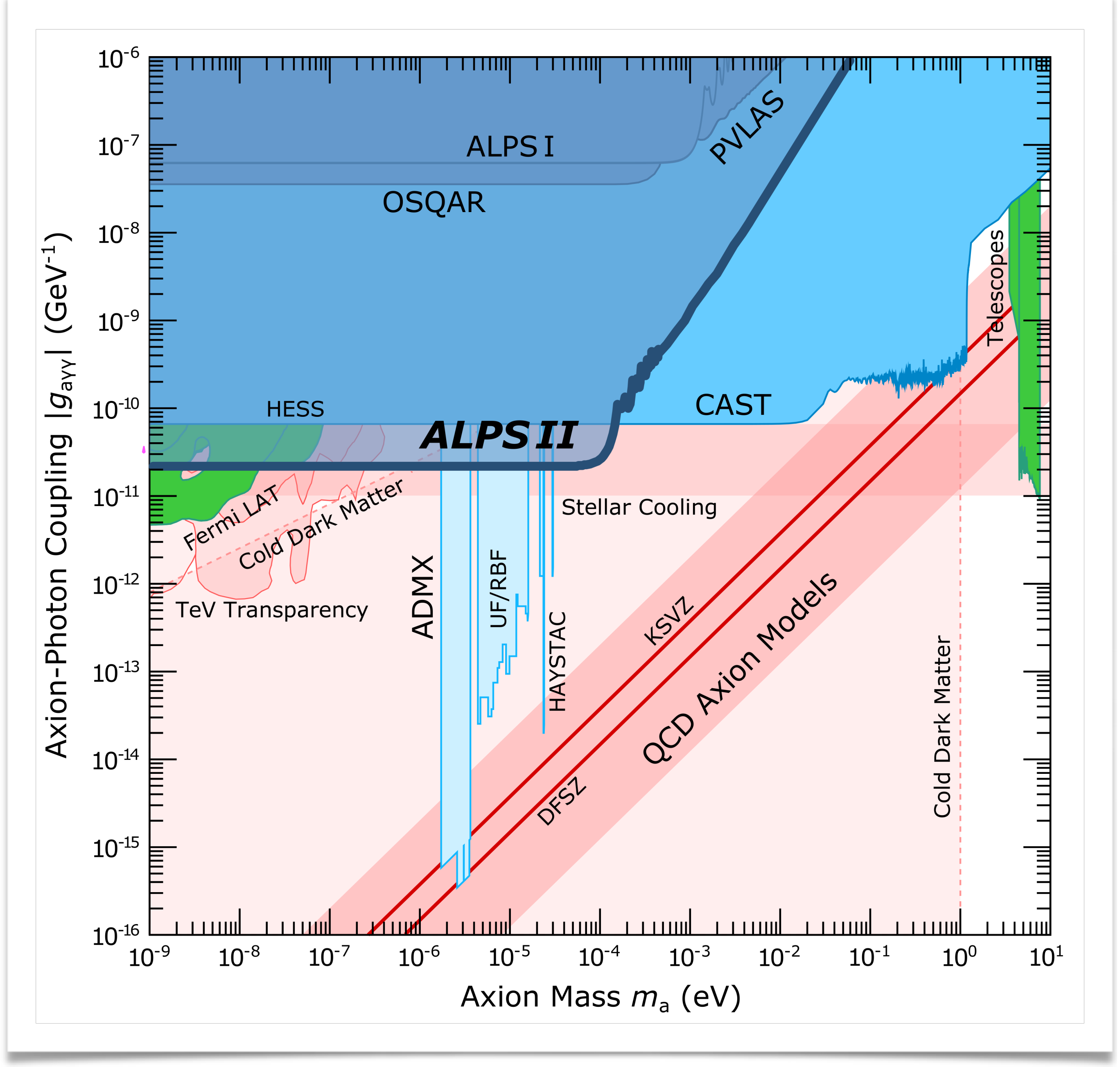
First science run at the end of 2021



Conclusion

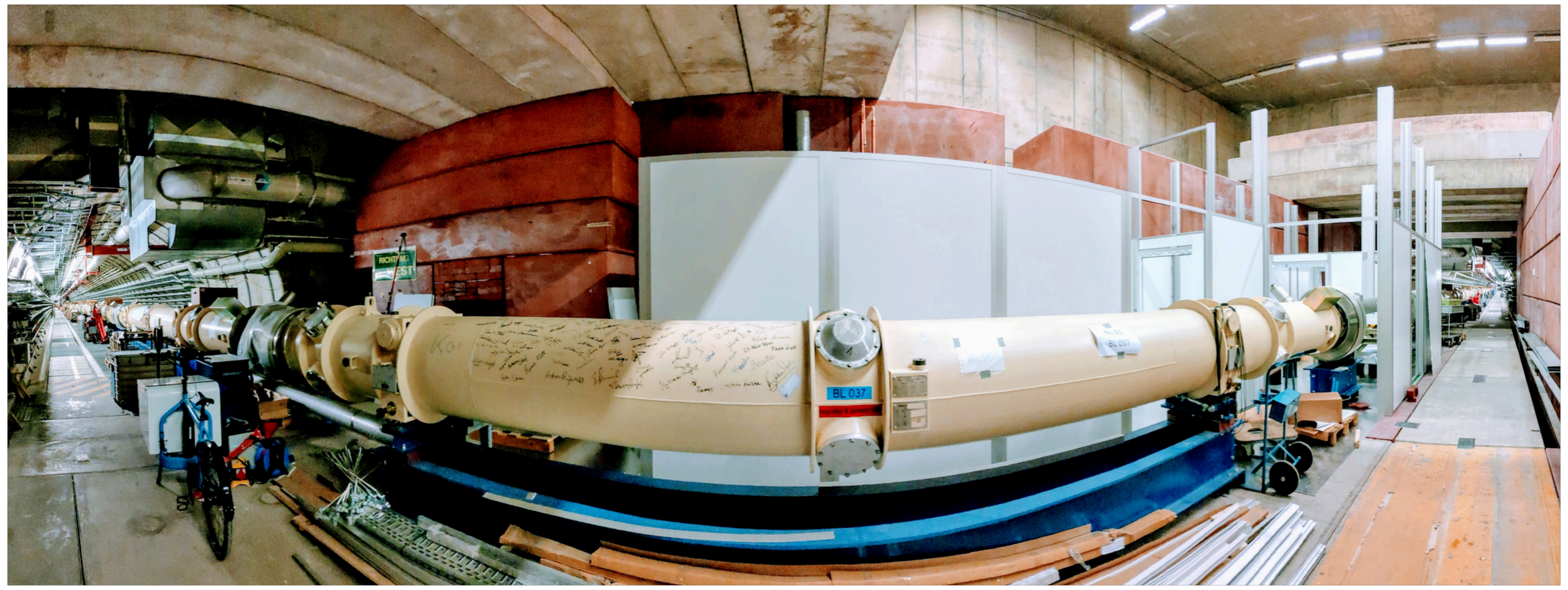
ALPS II will probe beyond the CAST limit (m < 0.1 meV)

- Probe of hints from stellar cooling and TeV transparency
- Requires sophisticated optical and detection systems
- Optical system approaching limits of conventional LSW



ALPS II is nearly ready to go

- First science run planned for this year!



Future

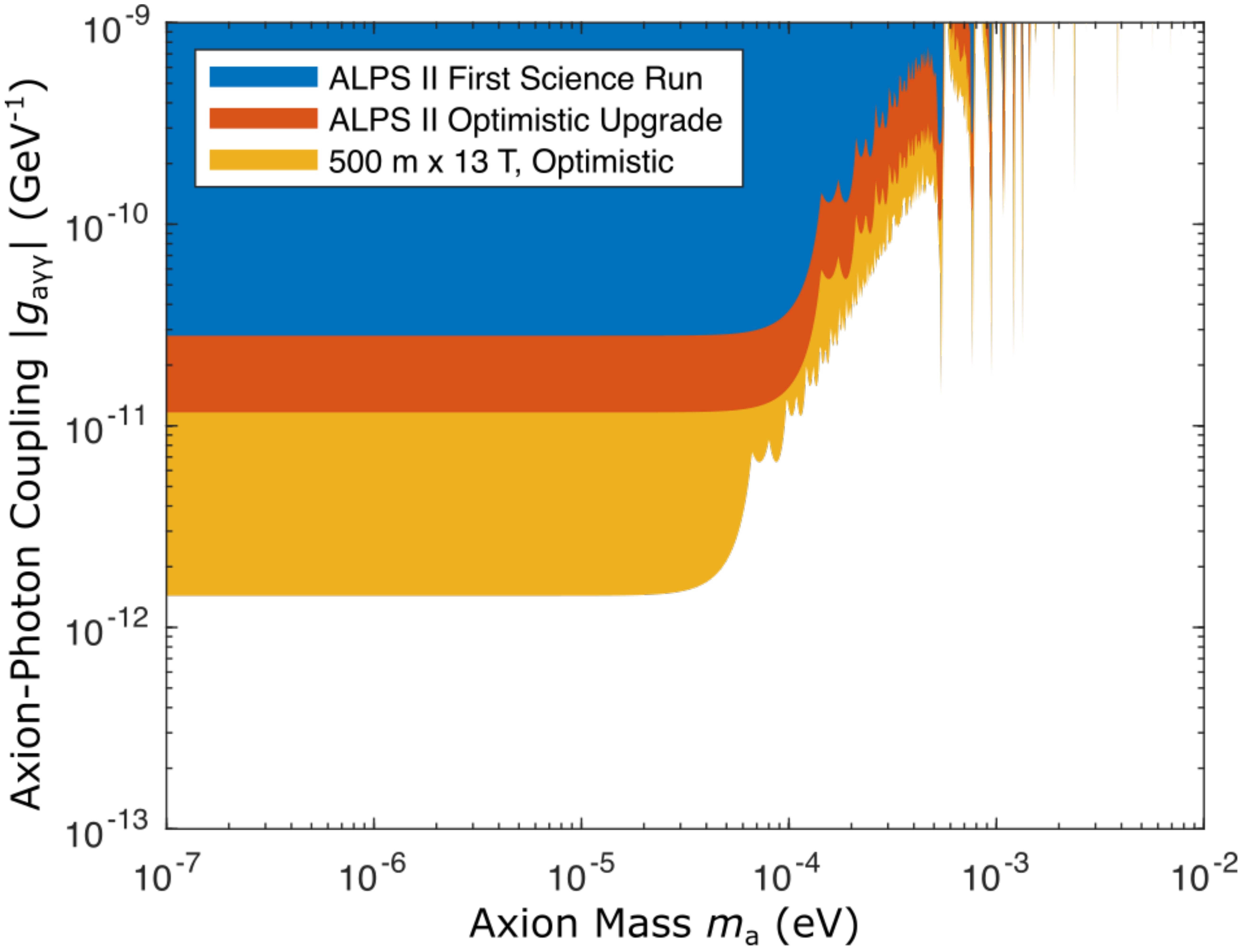
How far can ALPS II and LSW go?

ALPS II Optics upgrade

- What is ALPS II capable of?
- P_{PC}: 2 MW, β_{RC}: 40,000
- Sensitivity of g ~ 1.2 x 10^{-11} GeV^{-1}???

Future LSW

- Dipole magnets:
  - 13T w/ 100mm bore (~500 m strings)
- P_{PC}: 1 MW, β_{RC}: 20,000
- Sensitivity of g ~ 1.4 x 10^{-12} GeV^{-1}???
  - More advanced actuation/suspension required for larger mirrors



Magnets:

- Bottura L, de Rijk G, Rossi L, Todesco E., IEEE Trans. Appl. Supercond. 22:4002008 (2012), http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6656892
- Todesco E, Bottura L, de Rijk G, Rossi L., IEEE Trans. Appl. Supercond. 24:4004306 (2014), http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6172724

Searches for Axion-like Particles

Using the coupling to photons in magnetic field

Haloscopes

- Microwave cavities ➜ axions from DM halo
- ADMX, HAYSTAC, MADMAX

Helioscopes

- Dipole magnets and X-ray telescopes ➜ solar axions
- CAST, IAXO, babyIAXO

LSW Experiments

- Lasers in B fields ➜ axions in the laboratory
- ALPS I, ALPS II, OSQAR

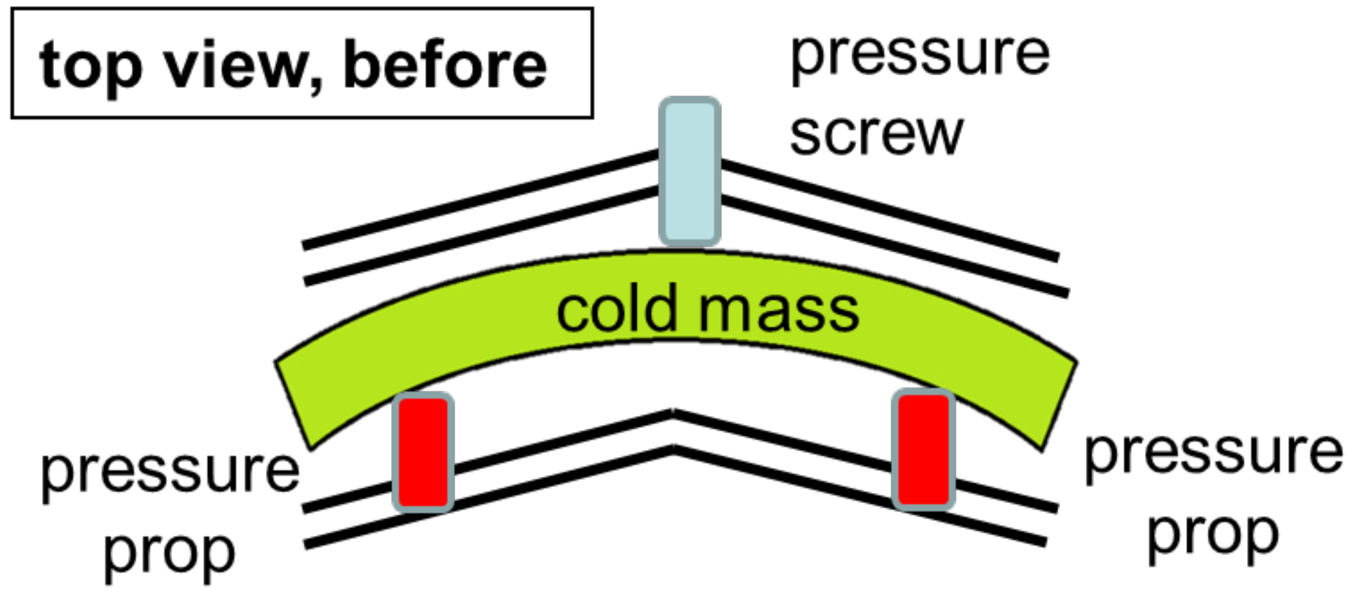
	Haloscopes	Helioscopes	LSW
Axion-flux	High	Medium	N/A
Coupling sensitivity	High	Medium	Medium
Mass Band	Narrow	Wide	Wide
Model Dependence	High	Medium	Low

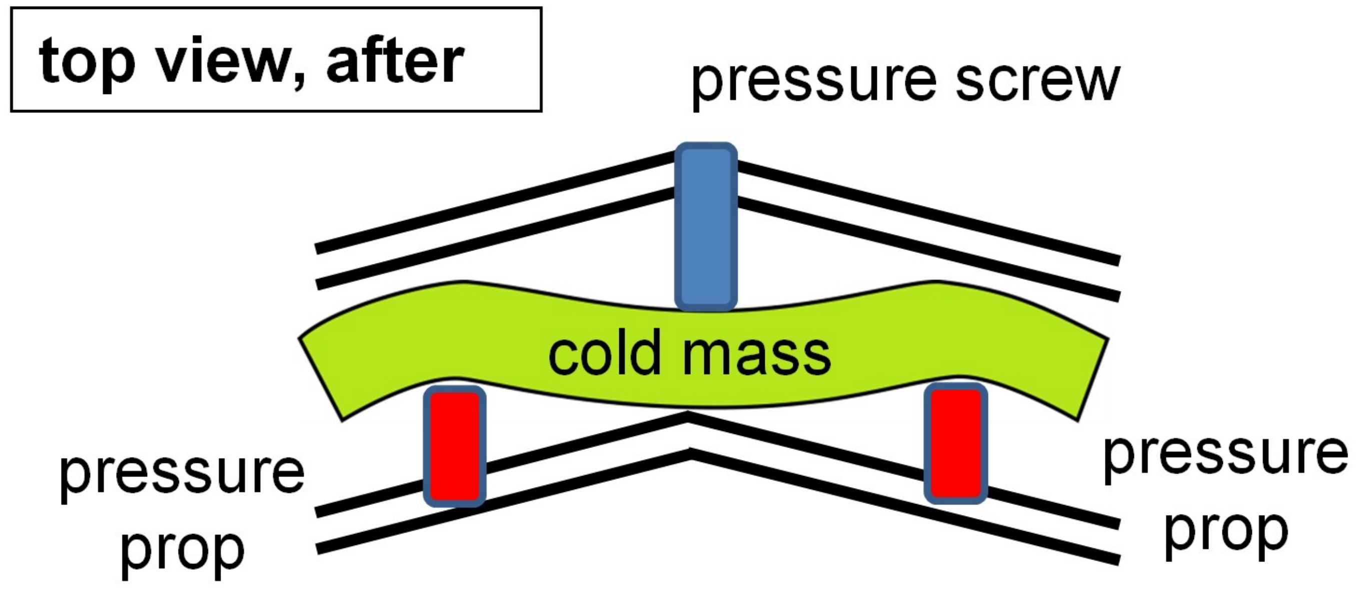
Unbending the HERA Magnets

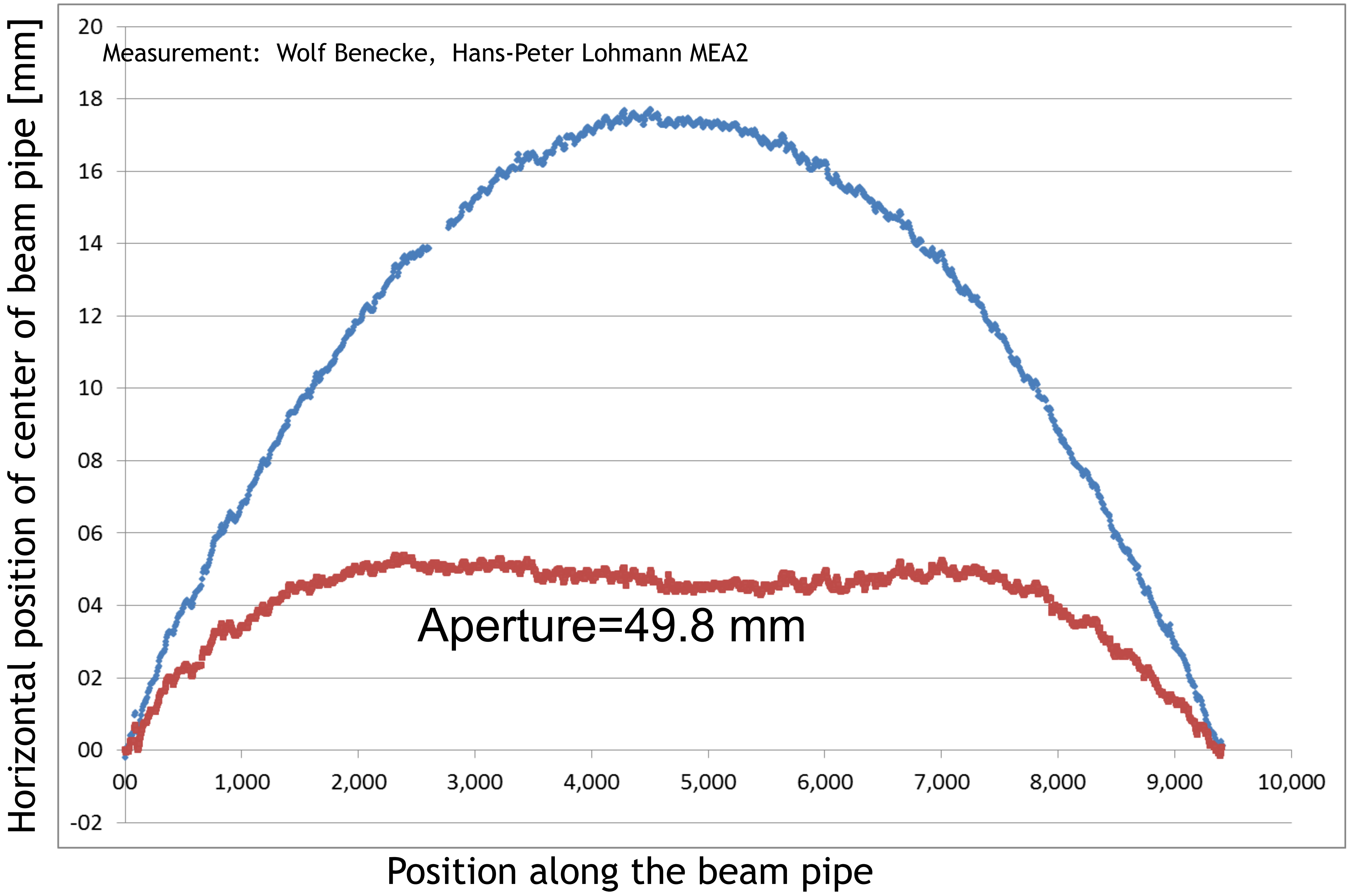
Preparing HERA dipoles for ALPS II

Magnets must be unbent

- Formerly used in HERA arcs
- Straightened for sufficient aperture
- 24 straightened and tested, all 24 worked







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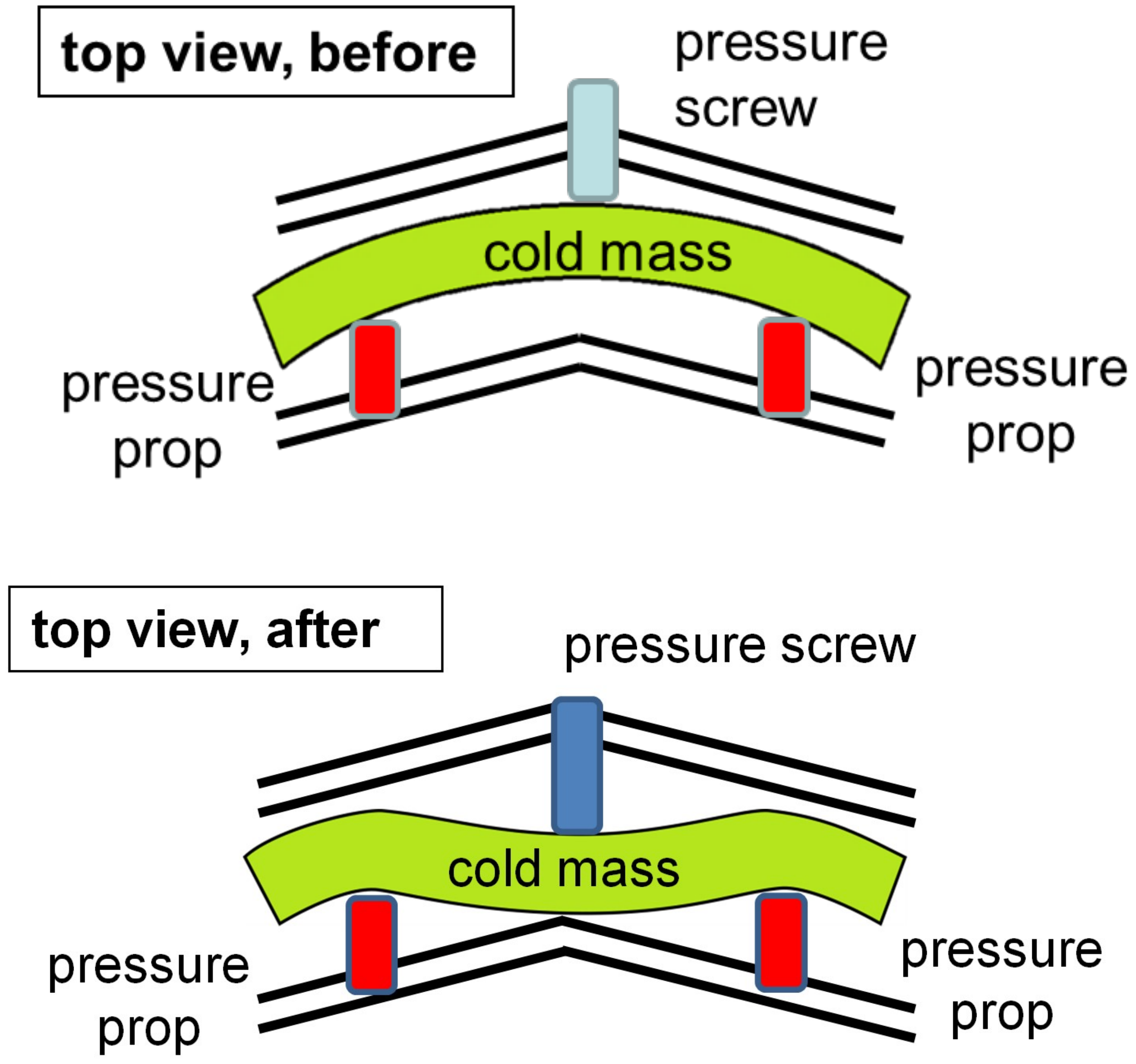
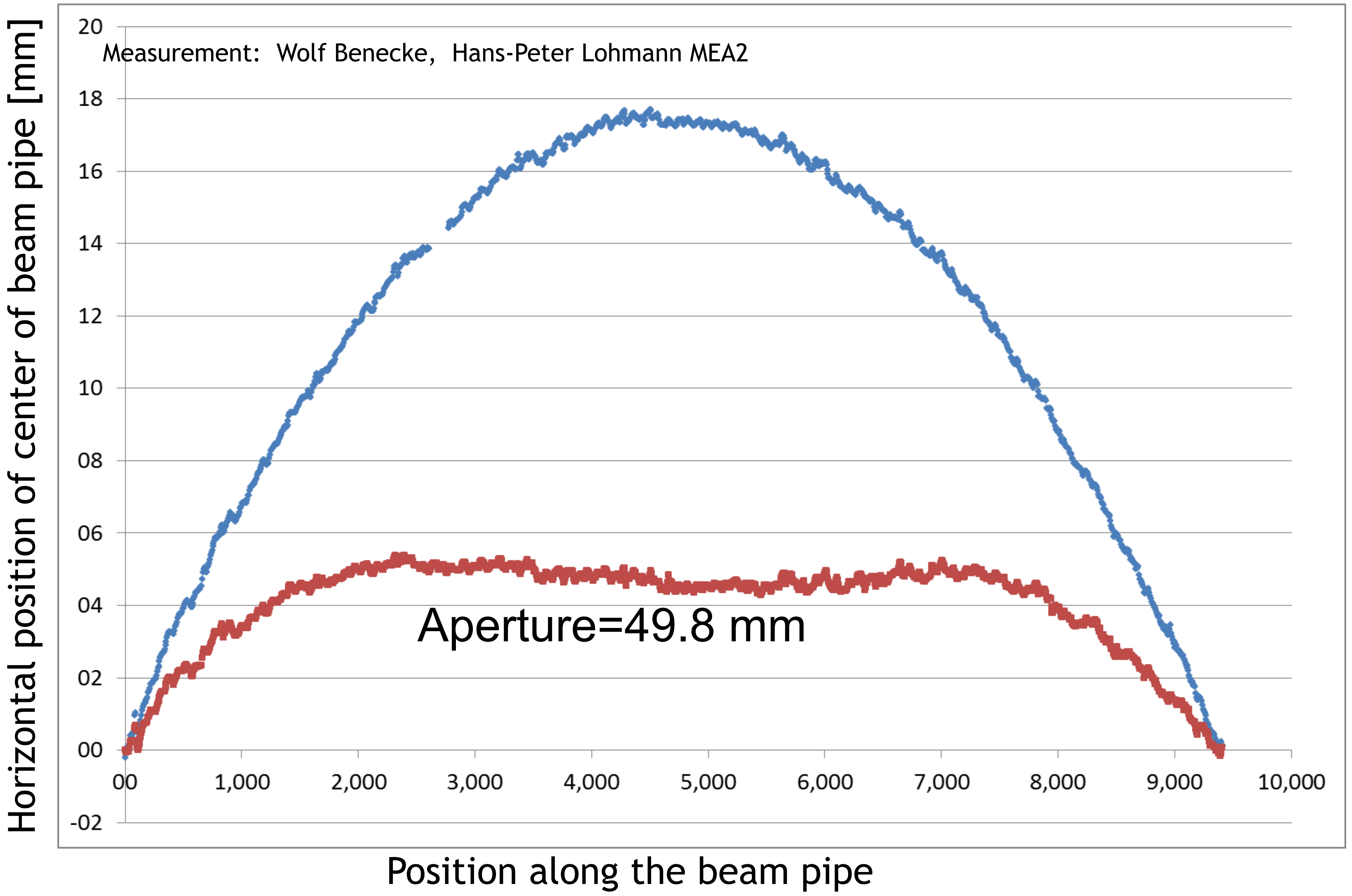
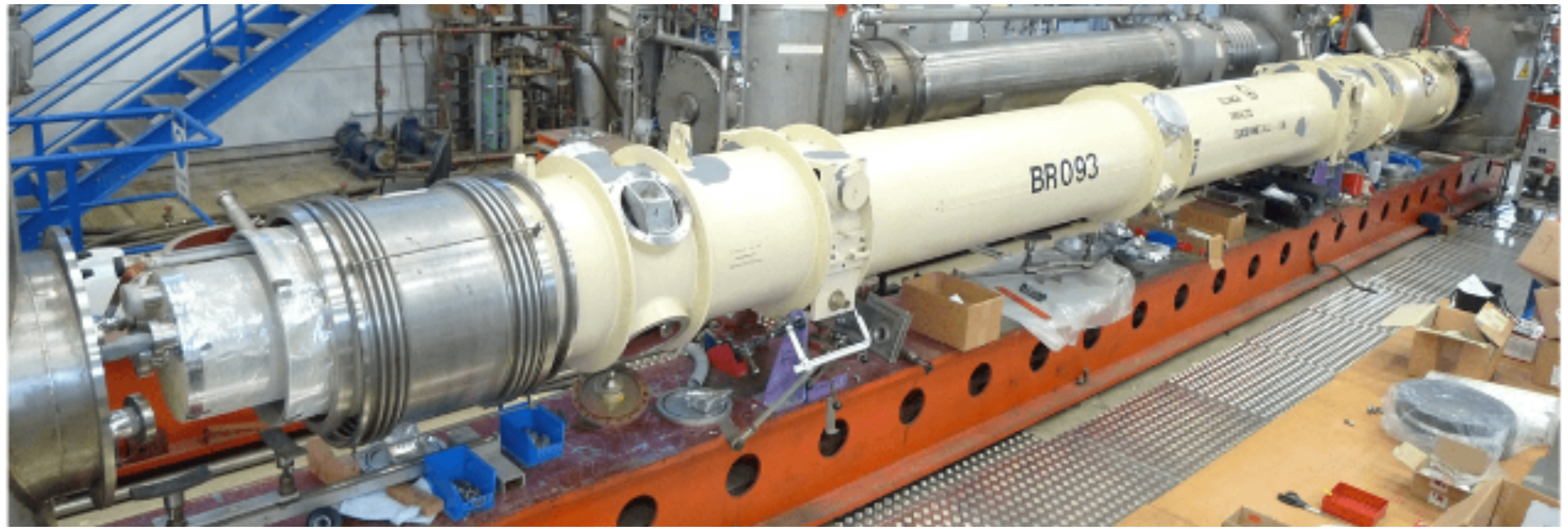
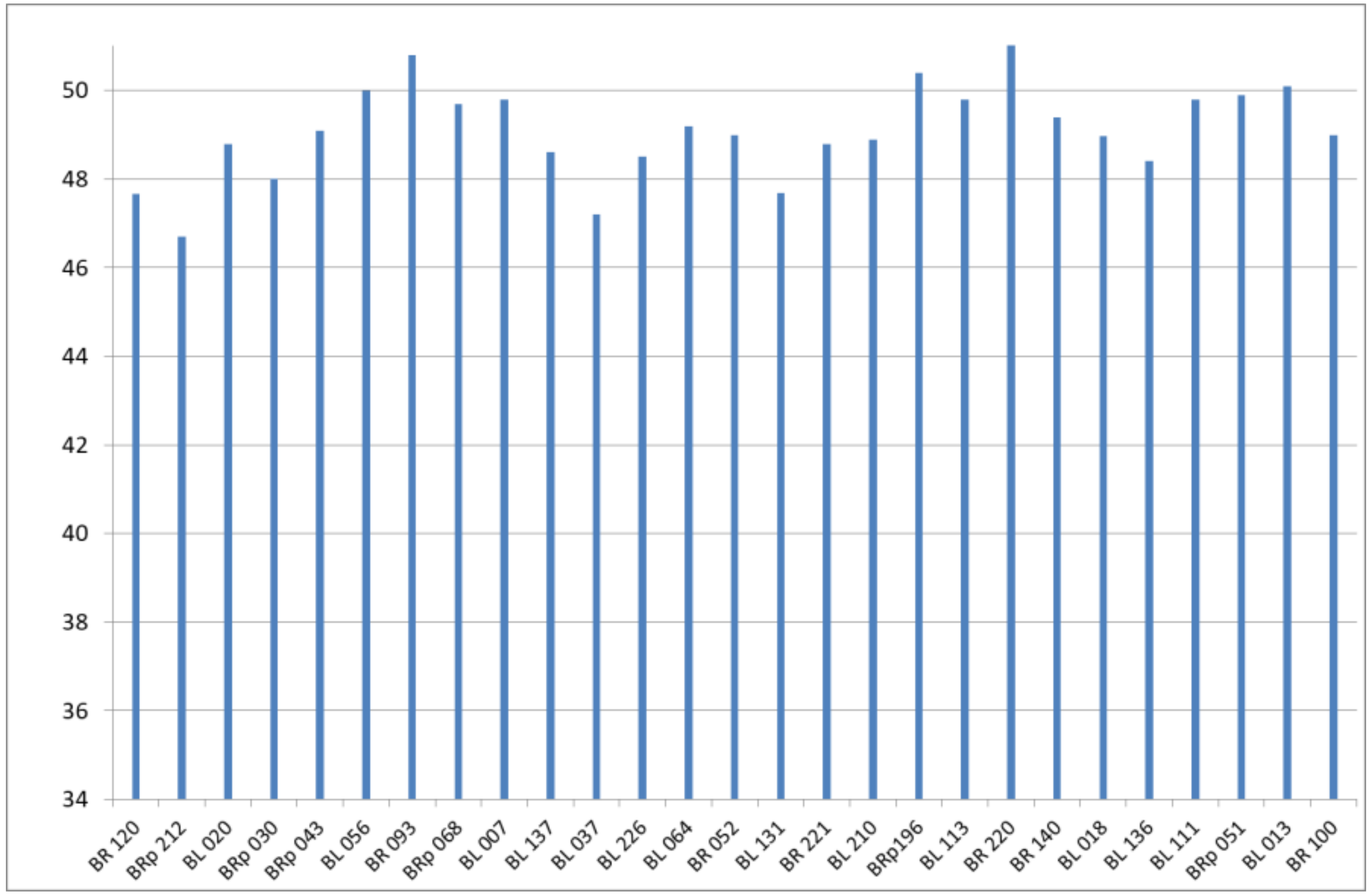






Configuration of the Magnets

Determining the order of the magnet string

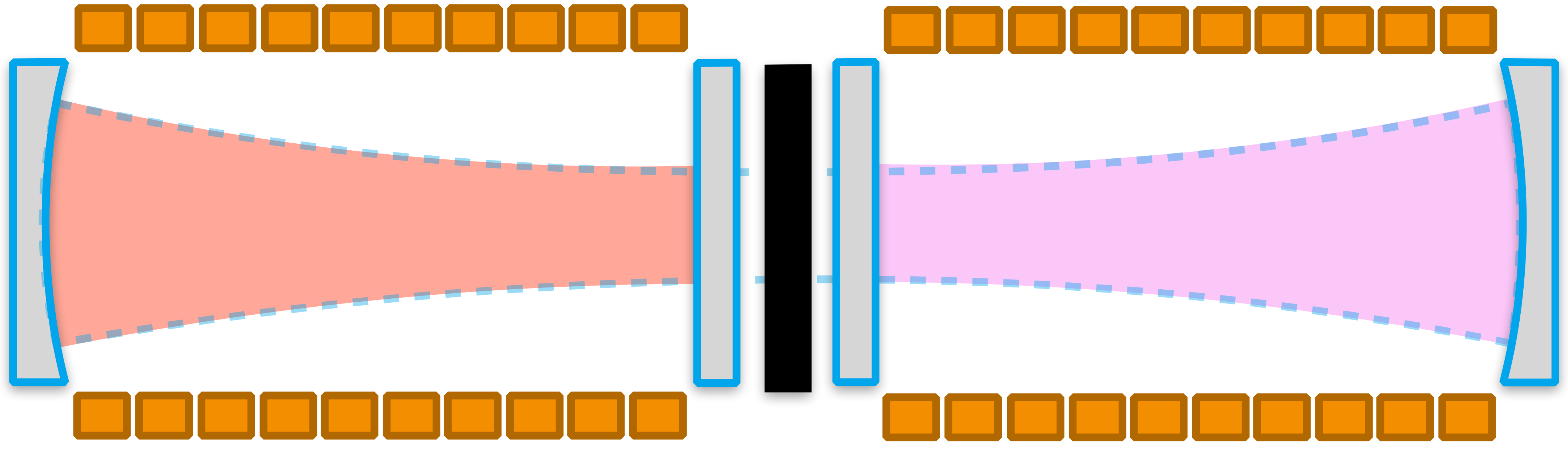


Magnet sequence based on free aperture

- Largest aperture magnets placed at ends
- Smallest aperture at center
- Allows for lowest cavity clipping losses

$$I(r,z) = \frac{2P}{\pi w(z)^2} \exp\left(-2\frac{r^2}{w(z)^2}\right) \qquad w(z) = w_0\sqrt{1+\left(\frac{z}{z_r}\right)^2}$$

- 500 m magnet strings: ~100 mm bore diameter



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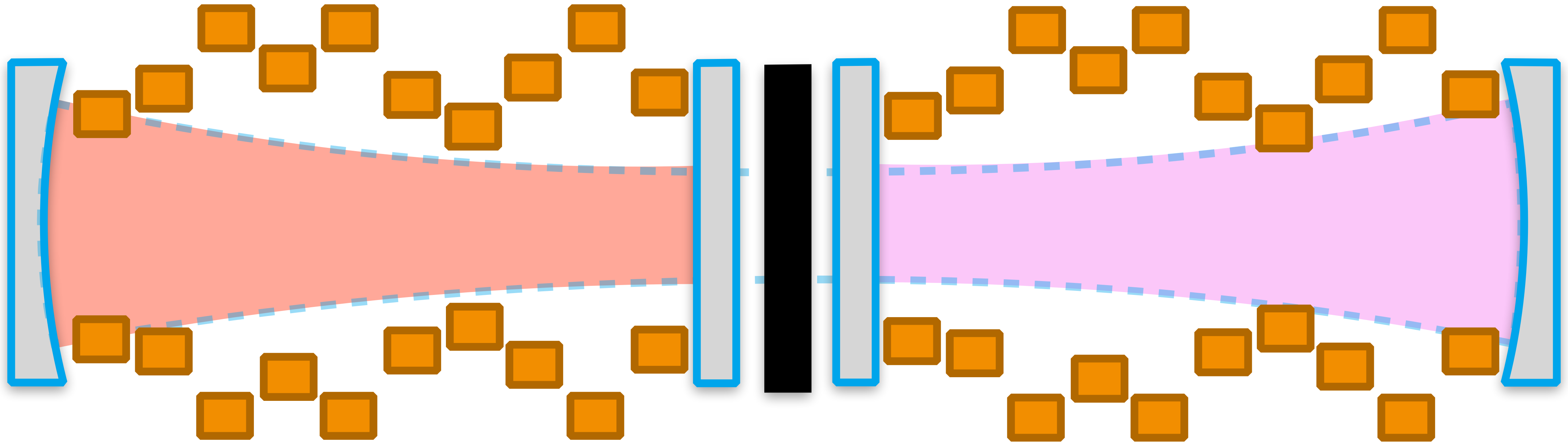

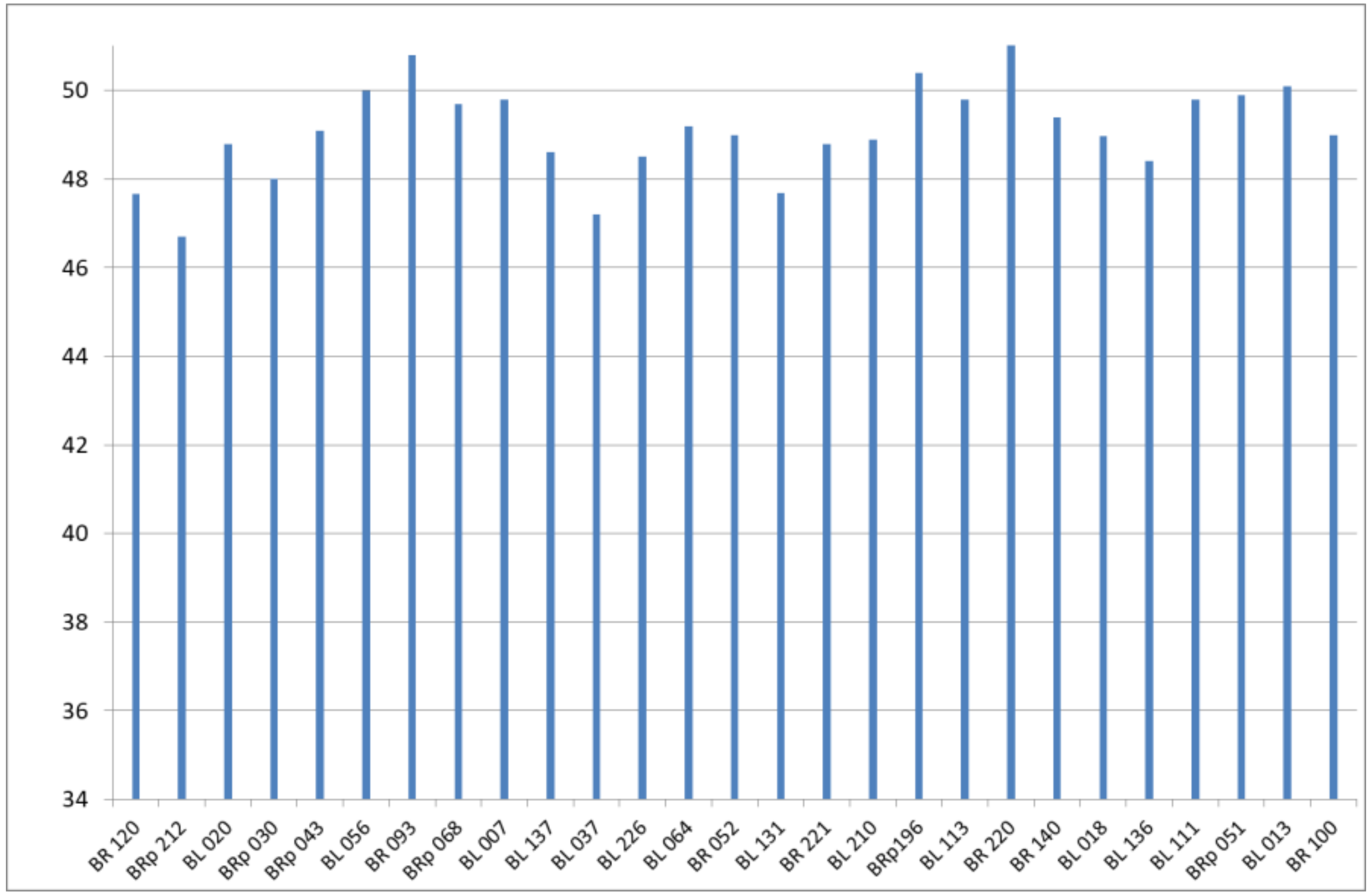

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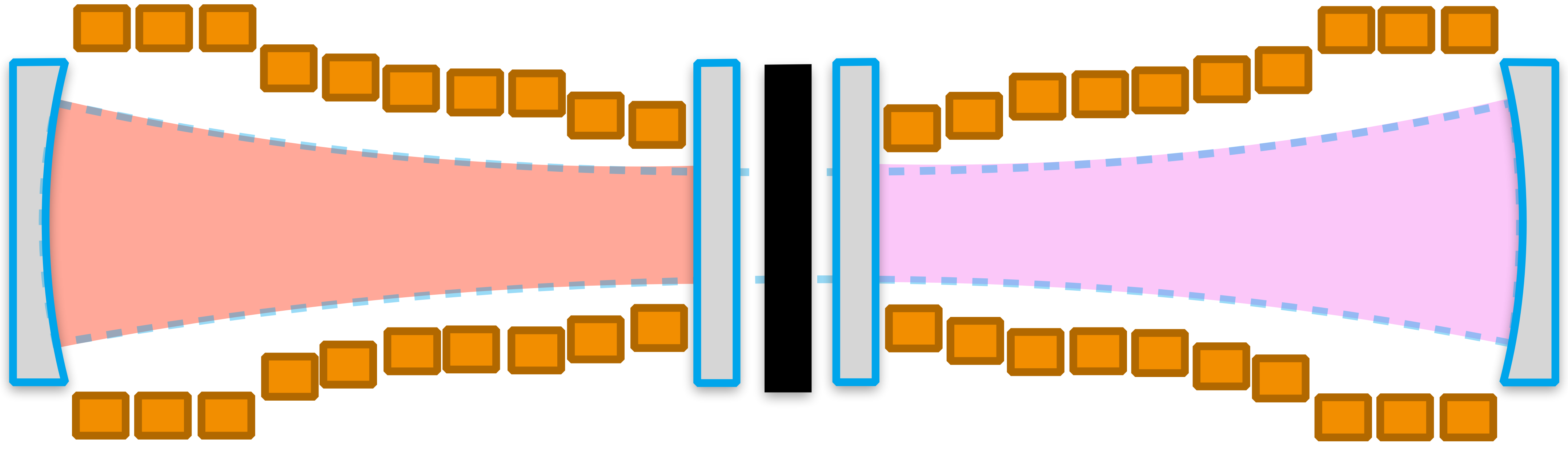

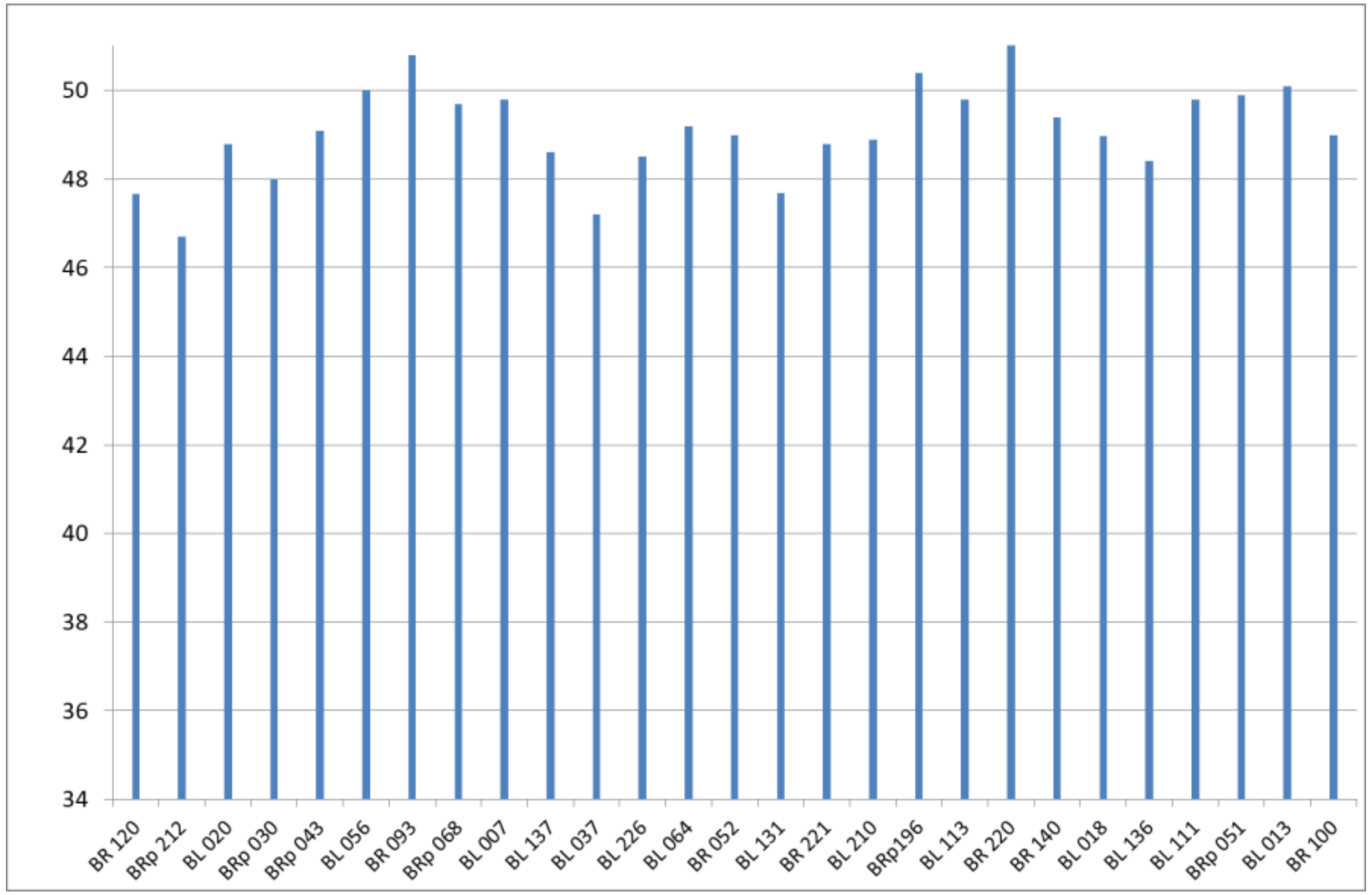

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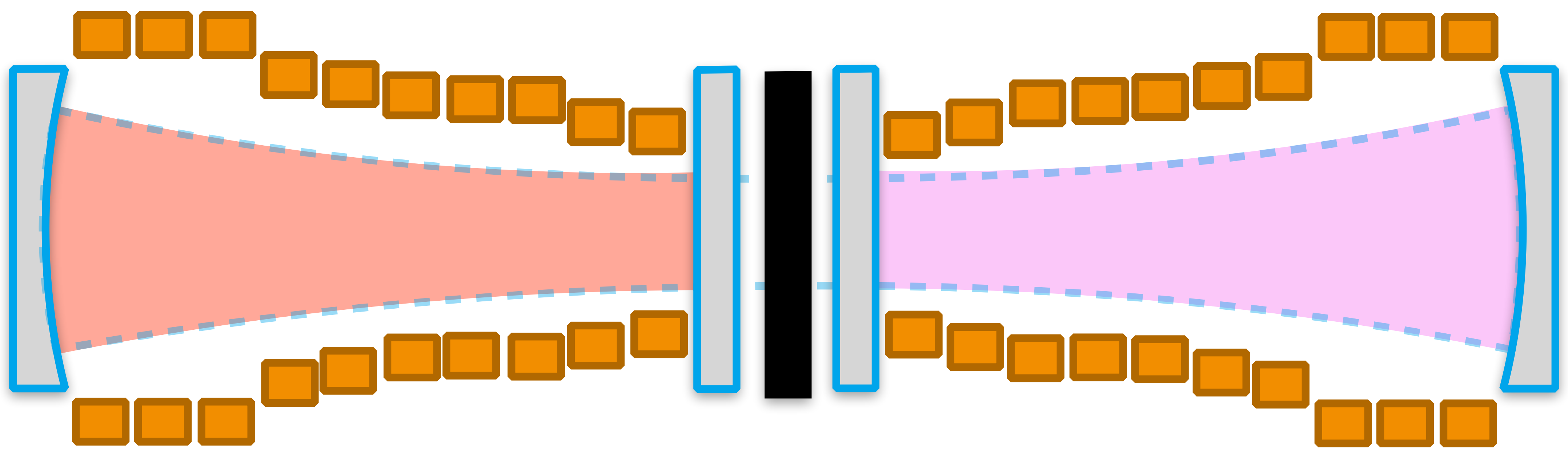

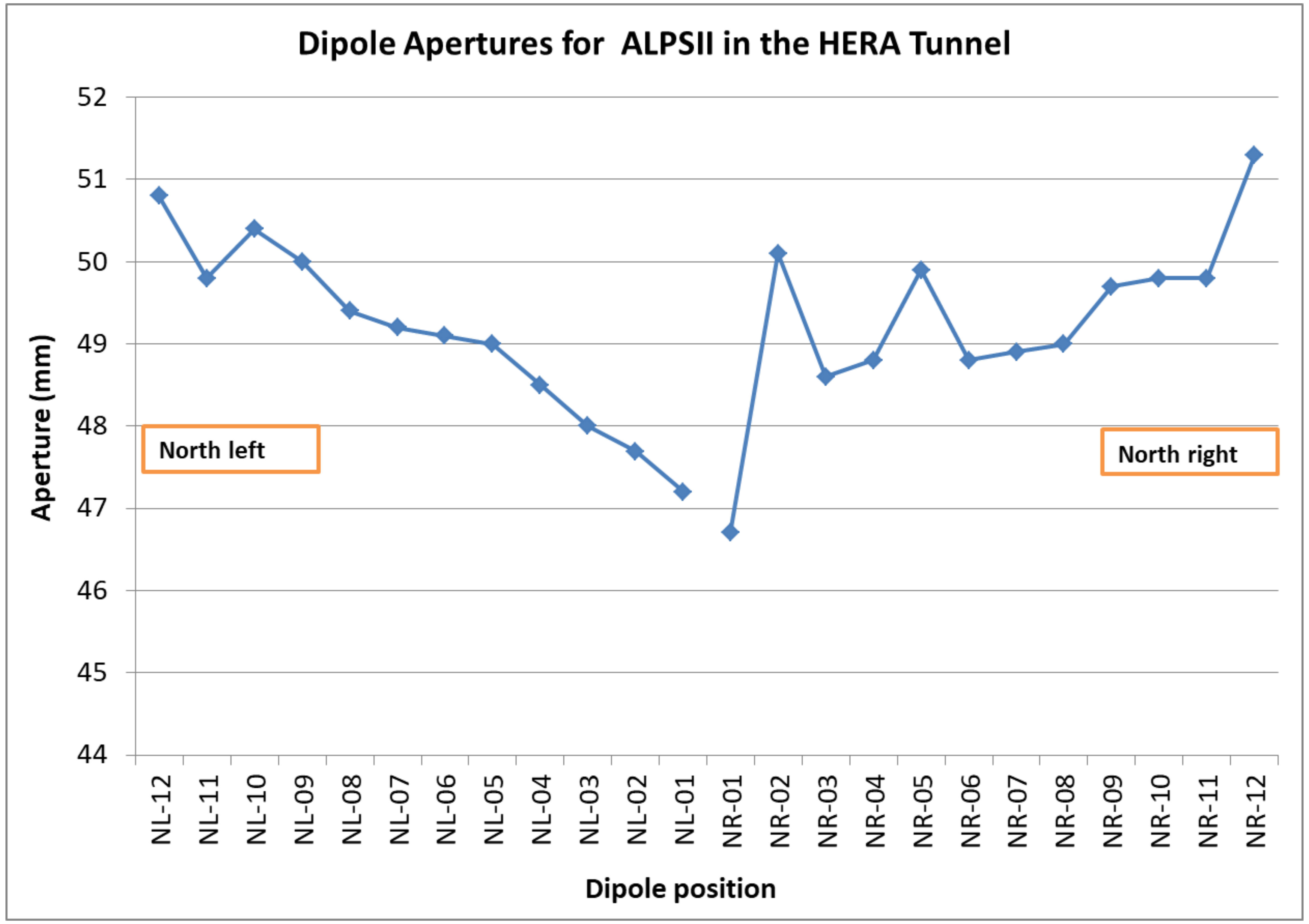

Axion-Photon Interaction in a Magnetic Field

Measuring the conversion-reconversion of Axion-like particles

Probability of photon converting to axion-like particle

- Probability of conversion: $\mathcal{P}_{\gamma\to\varphi} = \mathcal{P}_{\varphi\to\gamma} = \frac{1}{4}\frac{\omega}{k_\varphi}(gBL)^2|F(qL)|^2$

$$k_\varphi = \sqrt{\omega^2 - m_\varphi^2}$$

- Large enough mass will cause a loss in the coherence of the axion-like field

    - For low masses ($m^2 << 2\omega/L$) $F = 1$

$$\left|F_{\text{single}}(qL)\right| = \left|\frac{2}{qL}\sin\left(\frac{qL}{2}\right)\right|$$

$$q = n\omega - \sqrt{\omega^2 - m_\varphi^2} \approx \omega(n-1) + \frac{m_\varphi^2}{2\omega}$$