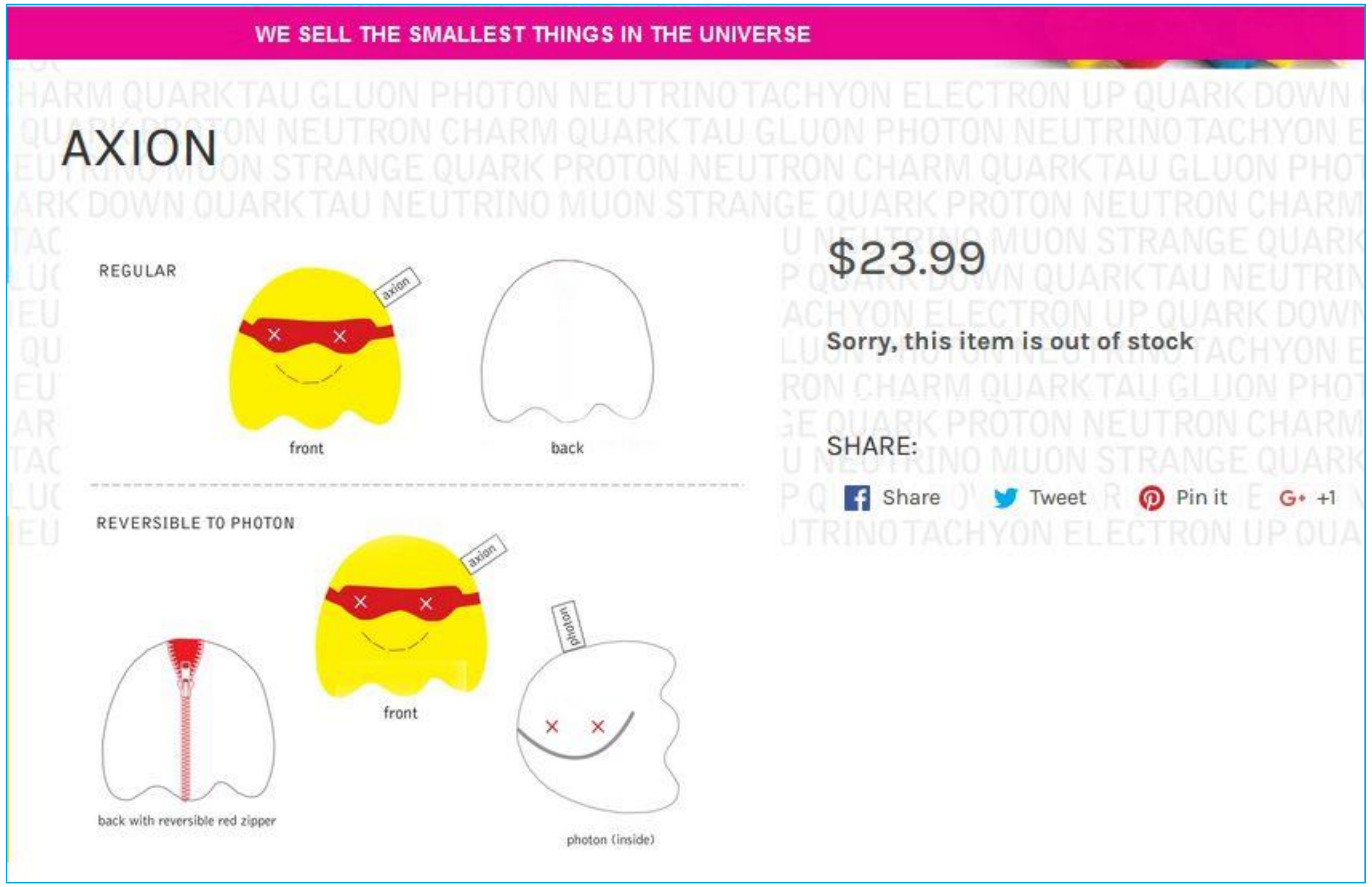
New experiments to identify dark matter and solve particle physics riddles

Part 2: finding the axion

DESY
Summerstudent Lecture 2025

Axel Lindner
Aaron Spector

DESY

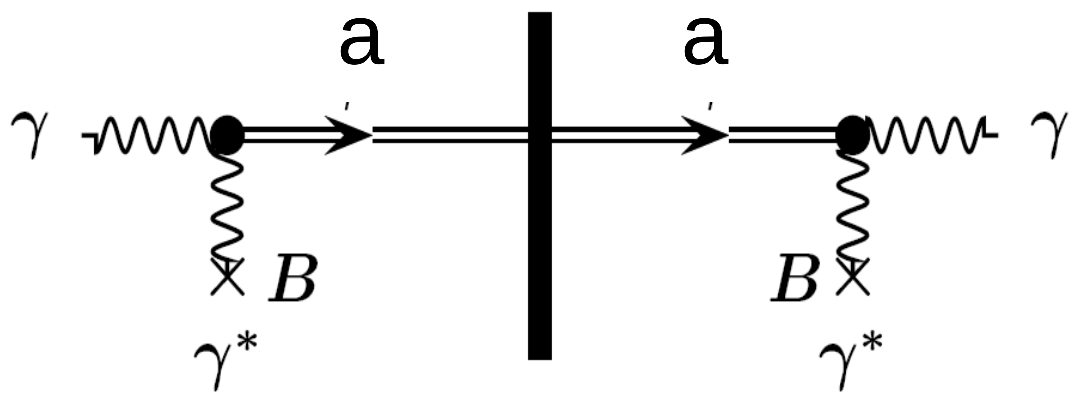


https://www.particlezoo.net

The DESY strategy

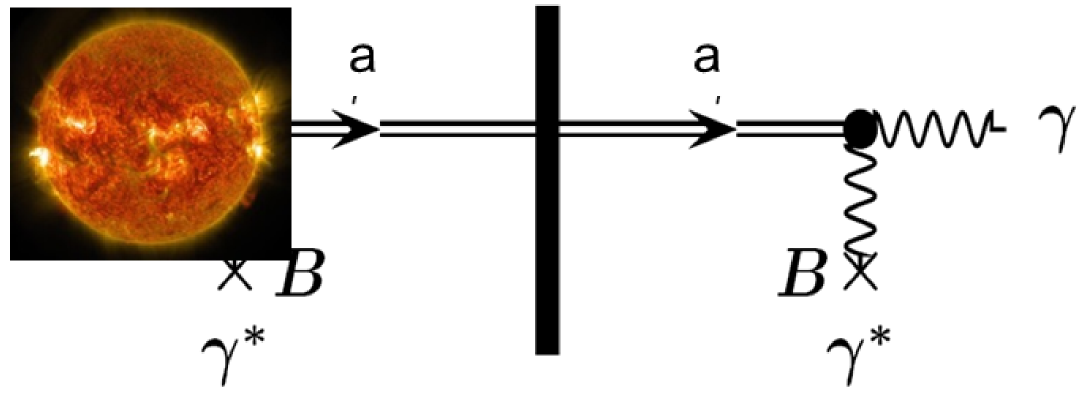
Complementary on-site experiments

1. Probe for axions / ALPs without additional assumptions:

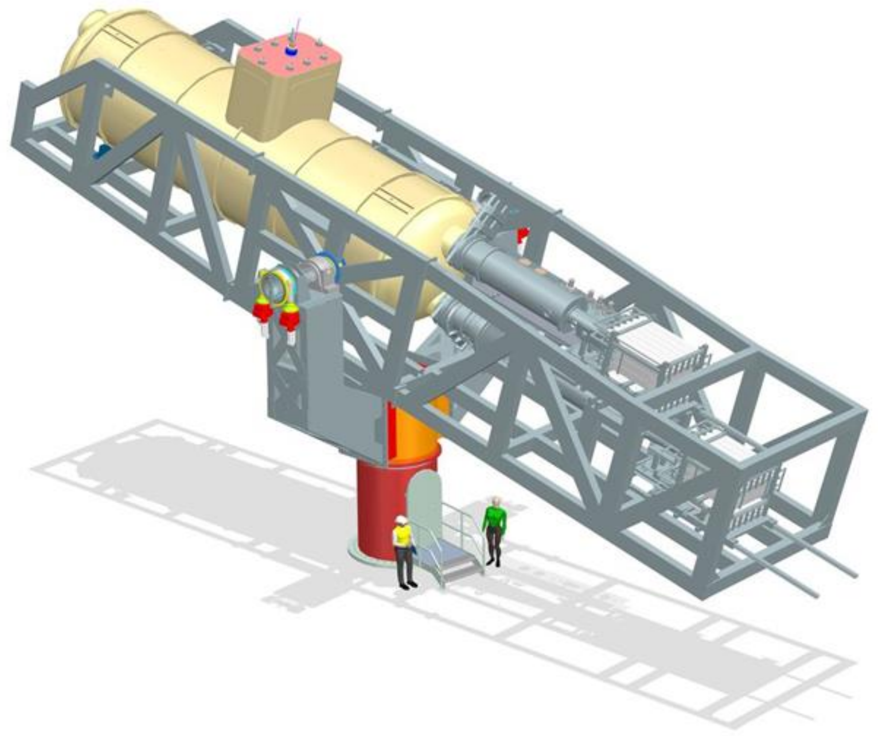


ALPS II
taking data

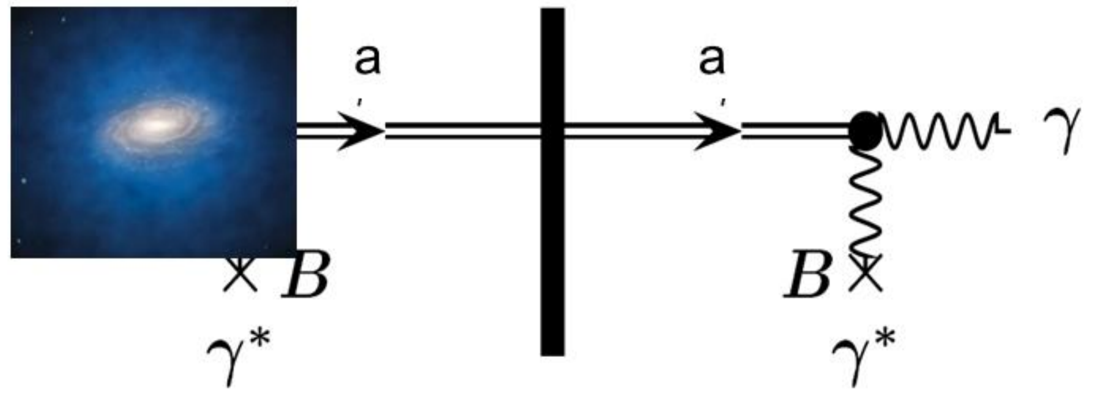
2. Probe for axions with minimal additional assumptions, increase the reach:



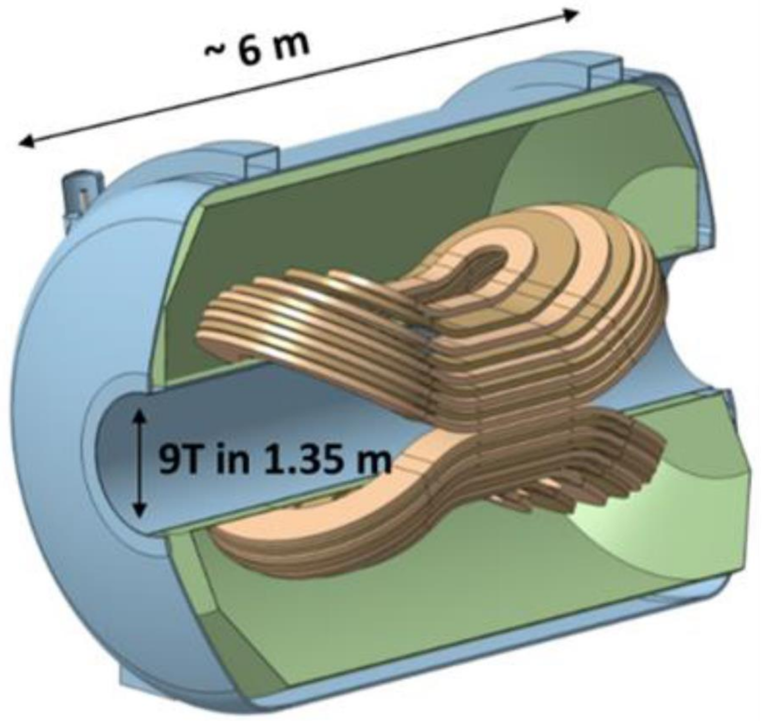
BabyIAXO
(nearly) ready to start construction



3. Probe for axions as dark matter constituents in a mass range not accessible by current experiments.



MADMAX
physics results from prototypes



The DESY strategy

Complementary on-site experiments

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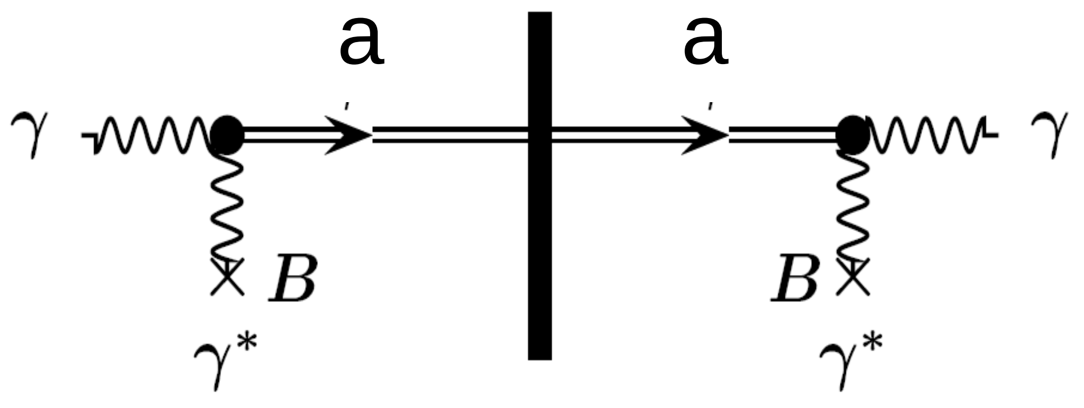

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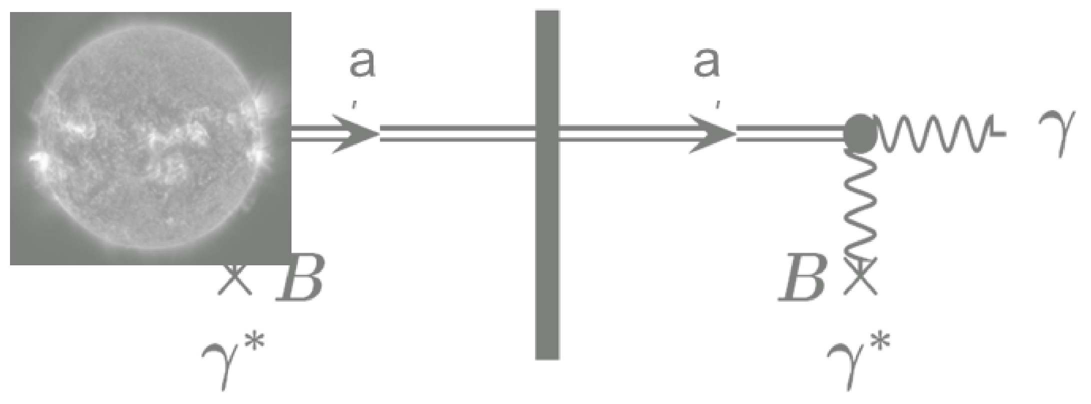

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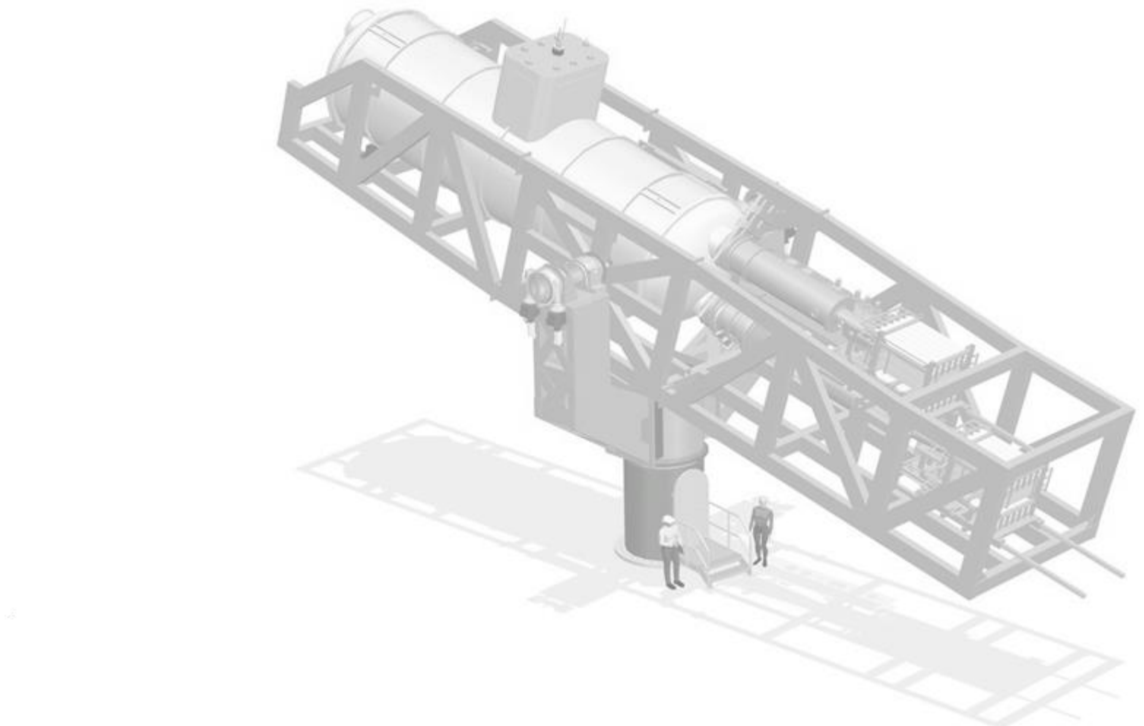

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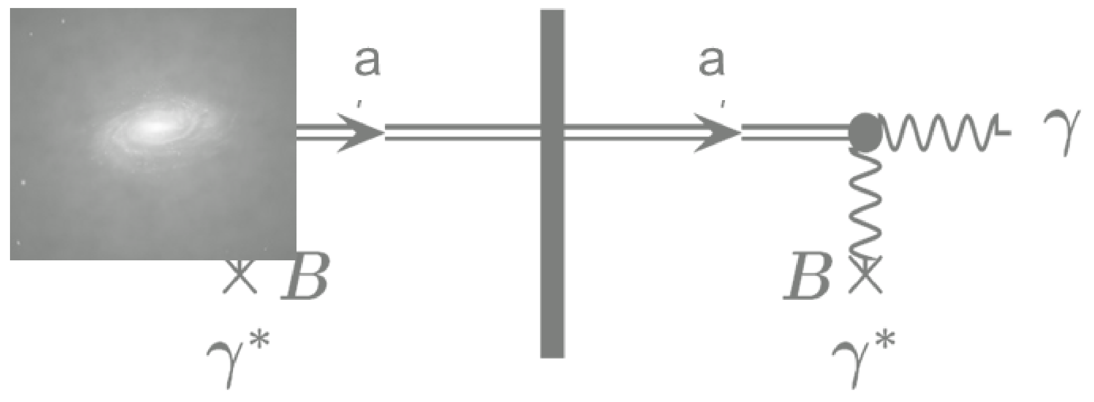

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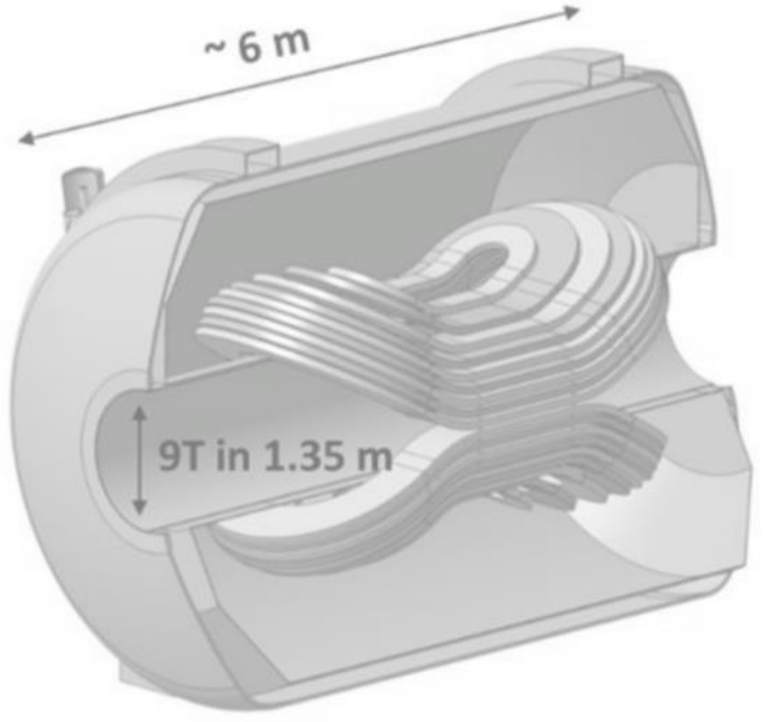
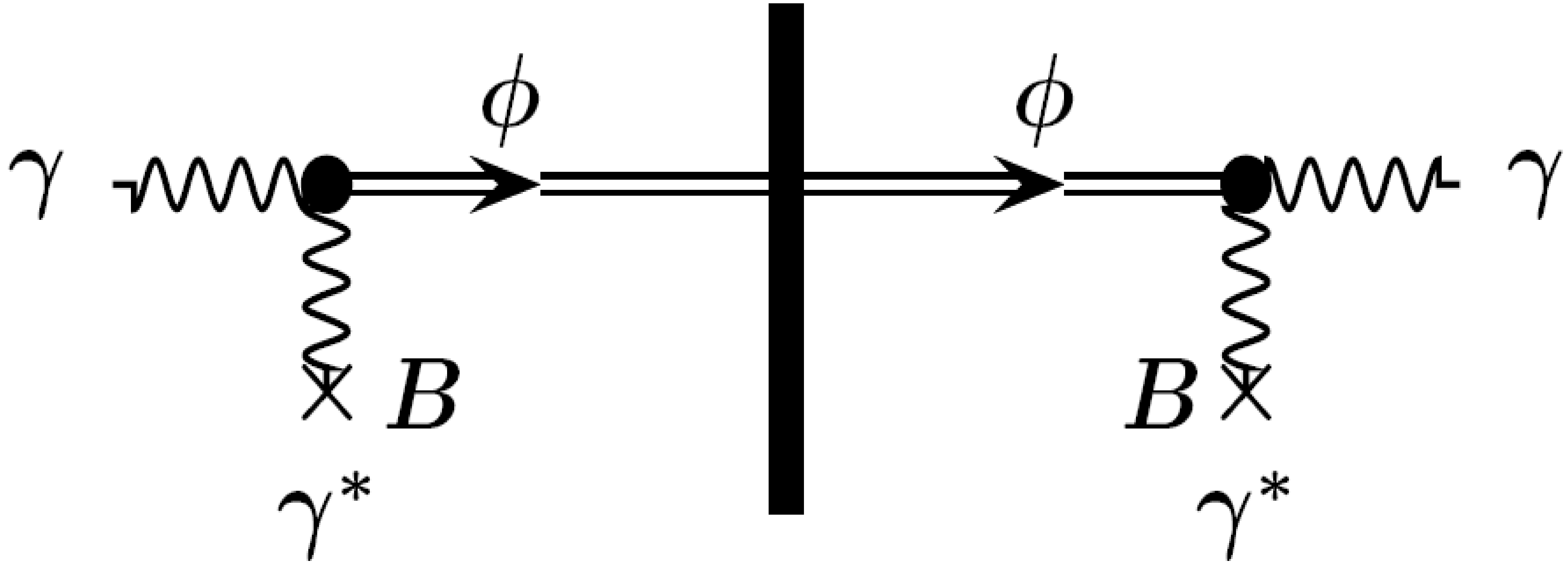


Light-Shinning-through-a-Wall Experiments and ALPS II

ALPS II: Light-shinning-through-walls

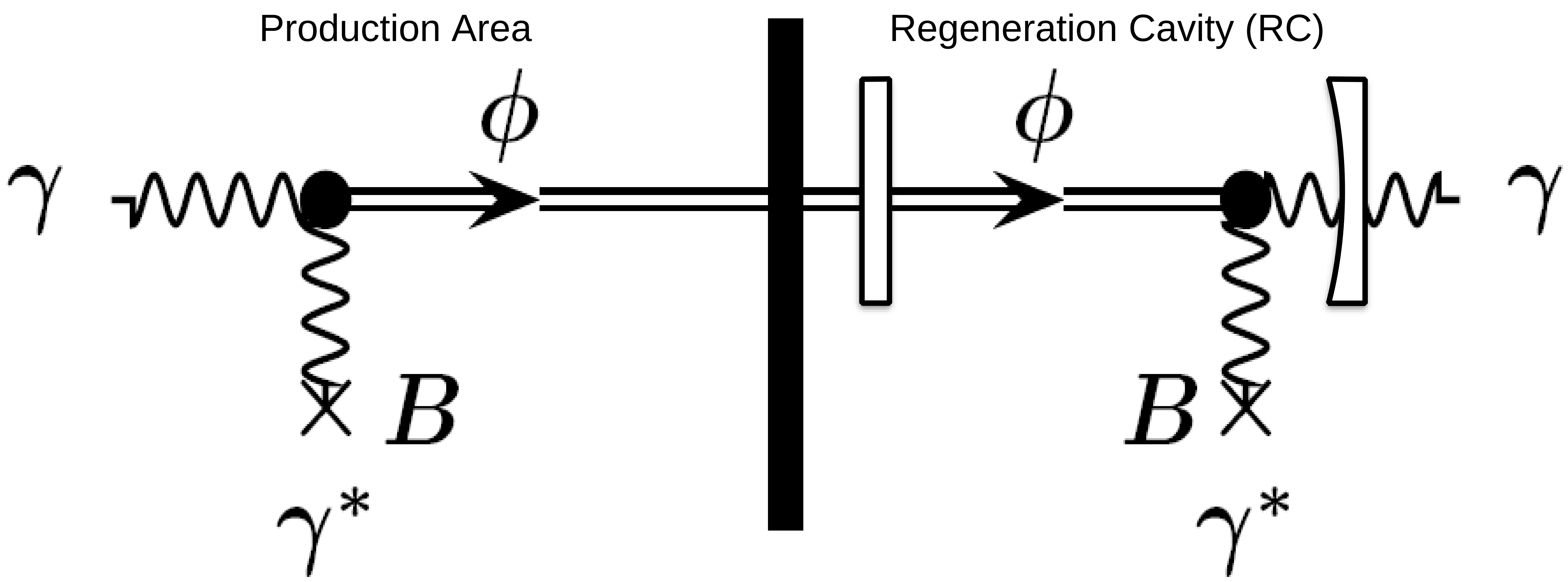
Using the axions coupling to two photons



$$P_\gamma = \left(\frac{g_{a\gamma\gamma} BL}{2}\right)^4 P_i$$

ALPS II first science campaign

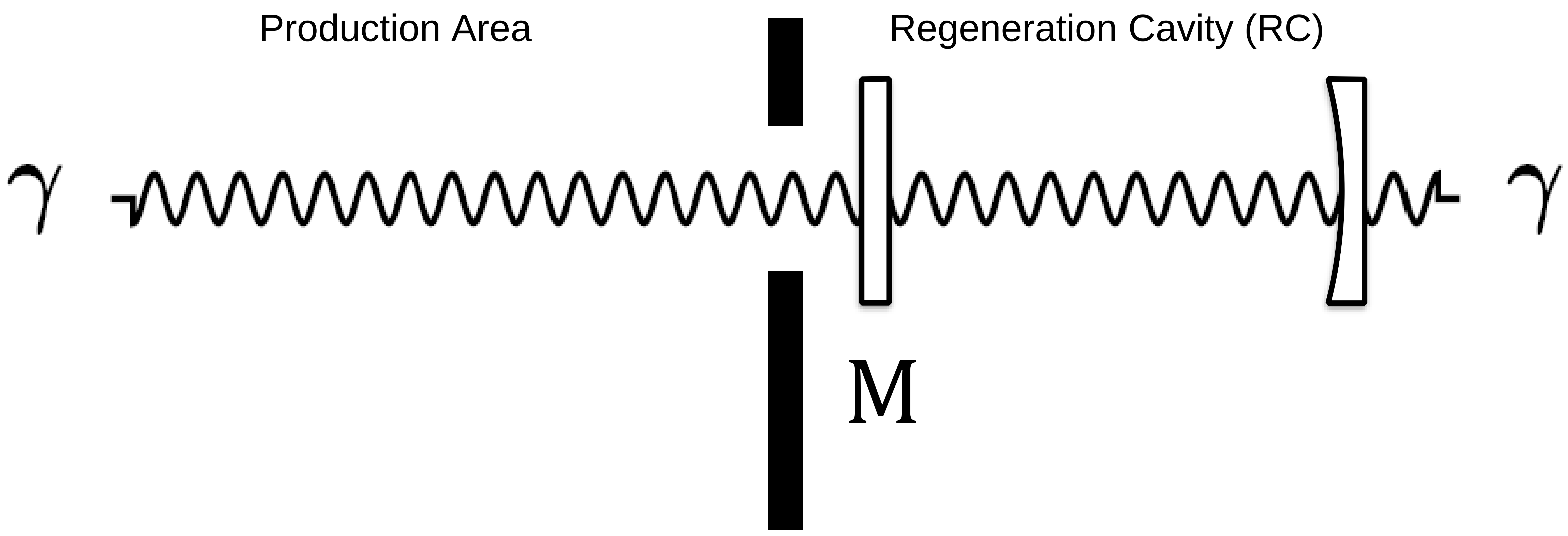
Amplifying the signal with an optical cavity



$$P_\gamma = \left(\frac{g_{a\gamma\gamma} B L}{2}\right)^4 \eta \beta_\mathrm{R} P_i$$

Open Shutter Runs

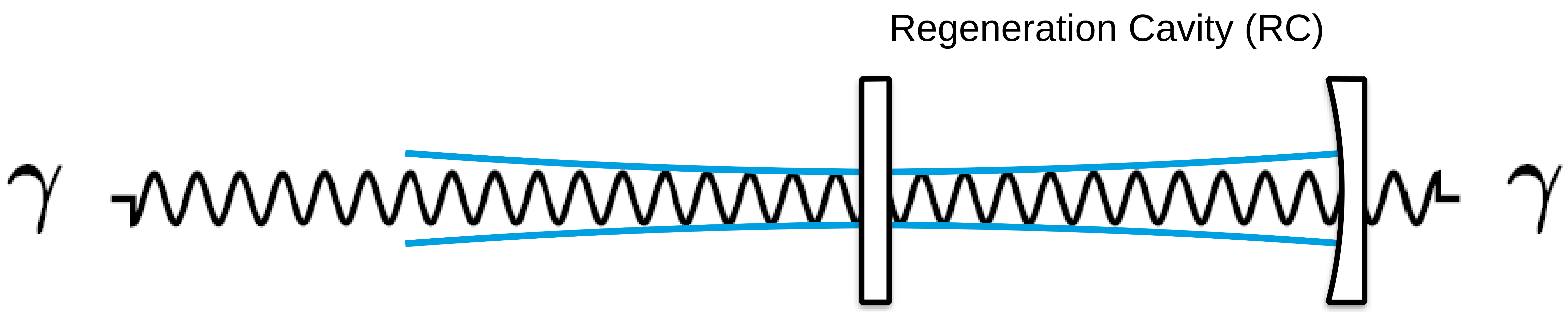
Checking the laser-cavity coupling



$$P_{\mathrm{open}} = T_{\mathrm{M}} \eta \beta_{\mathrm{R}} P_i$$

Power Overlap

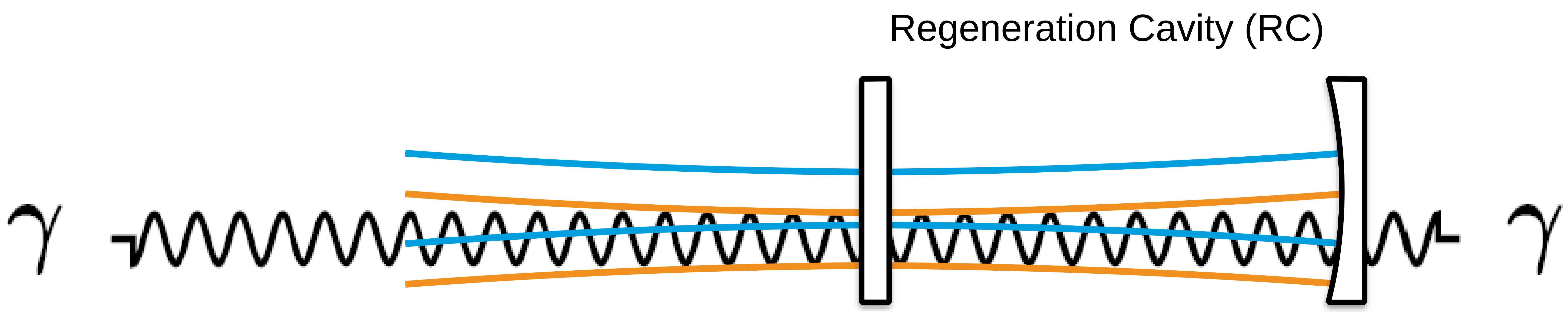
Checking the laser-cavity coupling



$$\eta = \eta_{\mathrm{spatial}} \times \eta_{\mathrm{longitudinal}}$$

Power Overlap

Checking the laser-cavity coupling



$$\eta = \eta_{\text{spatial}} \times \eta_{\text{longitudinal}}$$

η_{spatial} has 4 alignment degrees of freedom

- Vertical and horizontal lateral position of the waist
- Vertical and horizontal tilt

$$\eta_{\text{spatial}} = \frac{\left| \int E_1^* E_2 \mathrm{d}A \right|^2}{\int |E_1|^2 \mathrm{d}A \int |E_2|^2 \mathrm{d}A}$$

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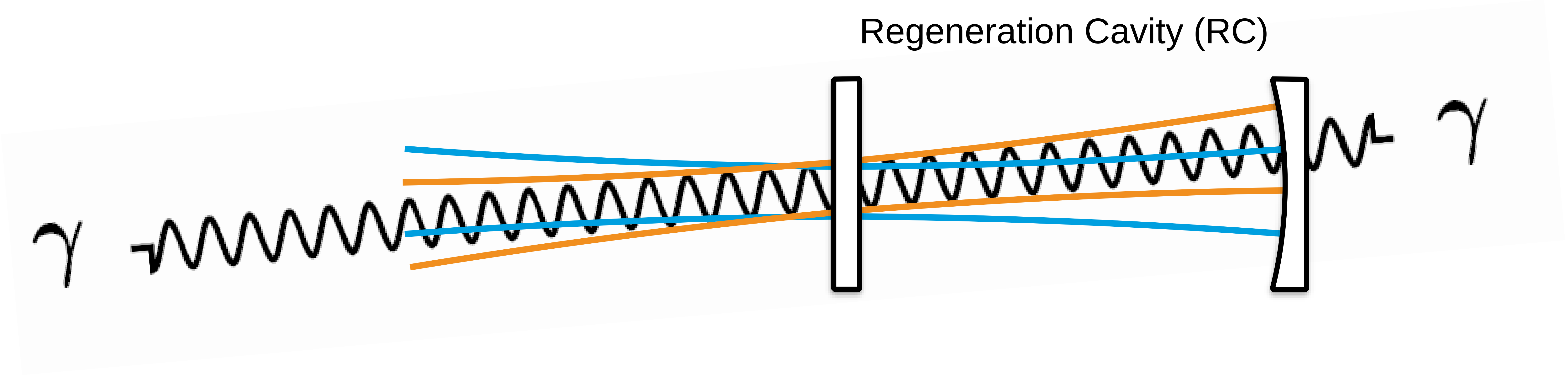

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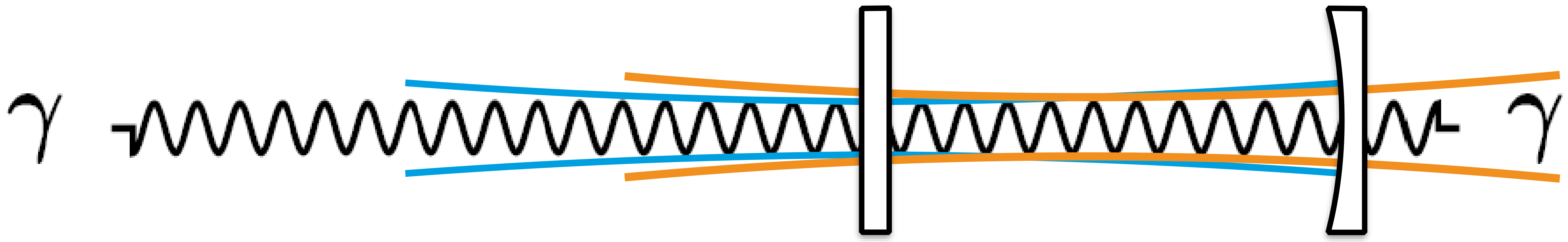

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η_{spatial} has 2 degrees of freedom related to the ‘mode shape’

- Longitudinal position of the waist
- Waist radius
- (Assuming there’s no astigmatism)

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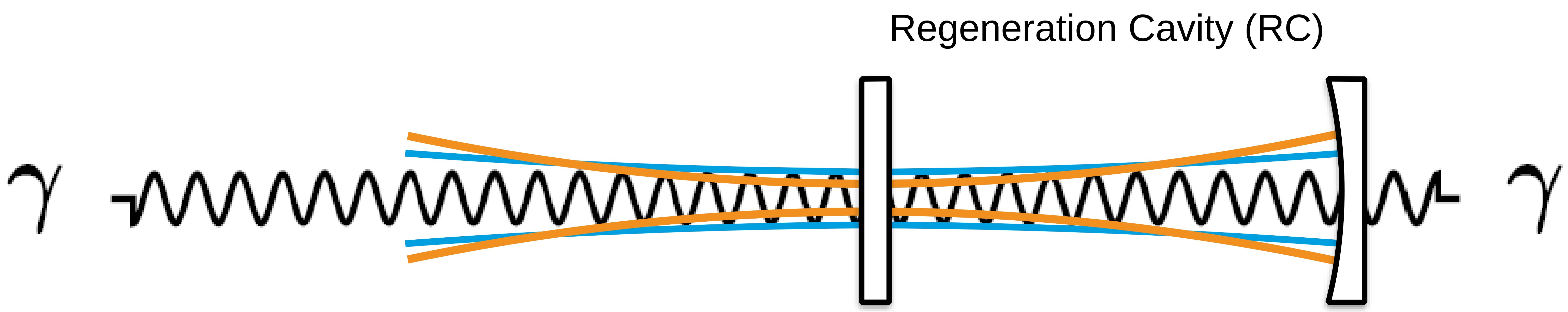

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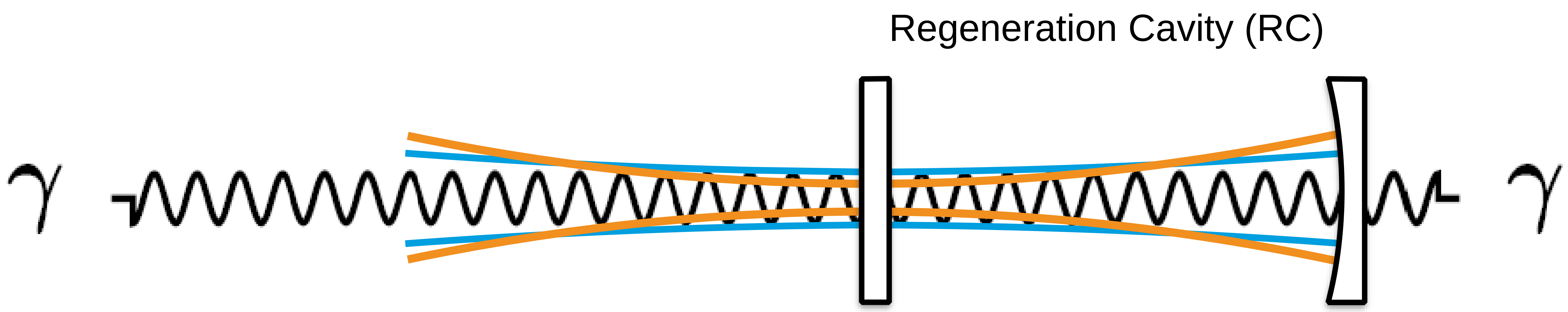


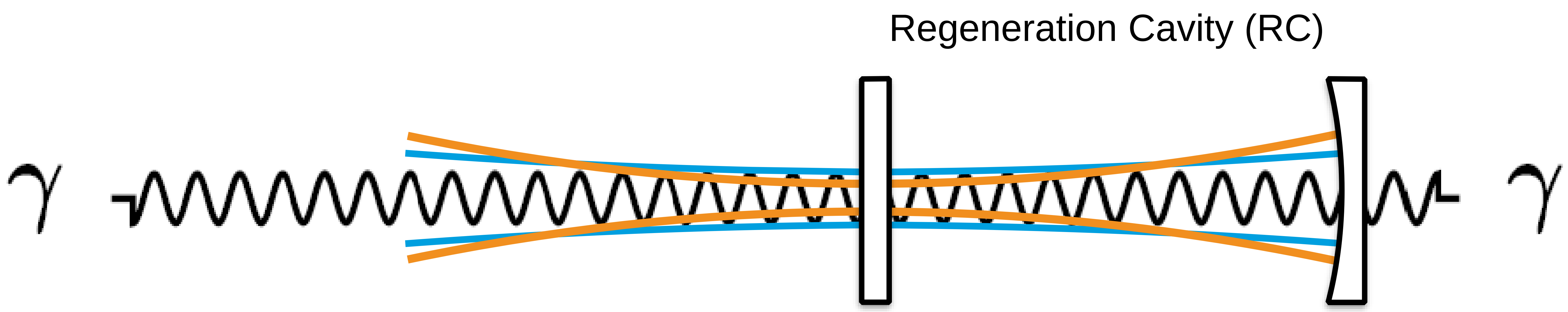
$$\eta = \eta_{\text{spatial}} \times \eta_{\text{longitudinal}}$$

$$E(r,z) = E_0 \frac{w_0}{w(z)} \exp\left(\frac{-r^2}{2w(z)^2}\right) \exp\left(i\left[kz - \arctan\frac{z}{z_{\mathrm{R}}} + \frac{kr^2}{2R(z)}\right]\right)$$

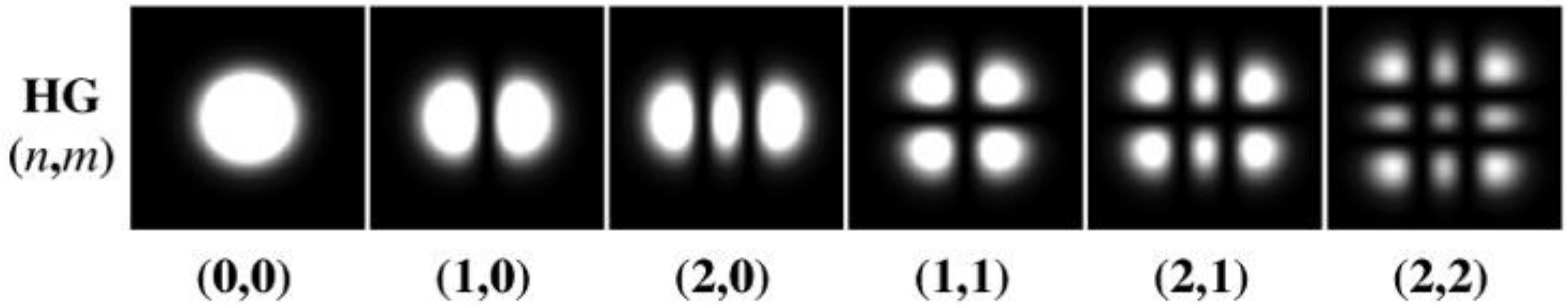
$$\eta_{\text{spatial}} = \frac{\left|\int E_1^* E_2 \mathrm{d}A\right|^2}{\int |E_1|^2 \mathrm{d}A \int |E_2|^2 \mathrm{d}A}$$

Power Overlap

Checking the laser-cavity coupling

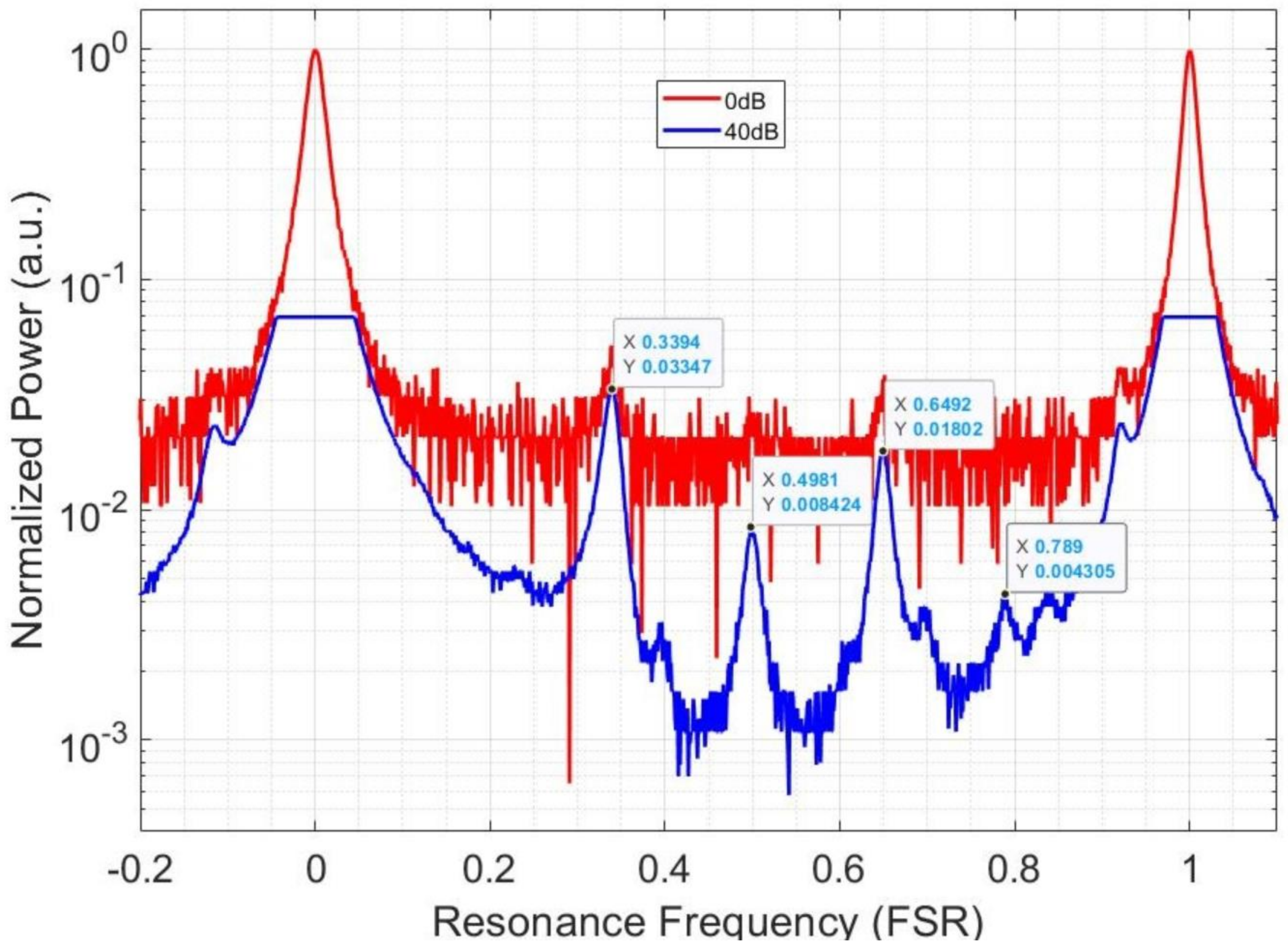


$$\Psi_{\mathrm{RC,lat}} \approx \Psi_{00} + \left(\frac{\delta x}{\omega_0} + i\frac{\delta\theta_{\mathrm{x}}}{\theta_d}\right)\Psi_{10} + \left(\frac{\delta y}{\omega_0} + i\frac{\delta\theta_{\mathrm{y}}}{\theta_d}\right)\Psi_{01} + \frac{1}{\sqrt{2}}\left(\frac{\delta\omega_0}{\omega_0} + i\frac{\delta z}{2z_{\mathrm{R}}}\right)(\Psi_{20} + \Psi_{02})$$



Power Overlap

Checking the laser-cavity coupling



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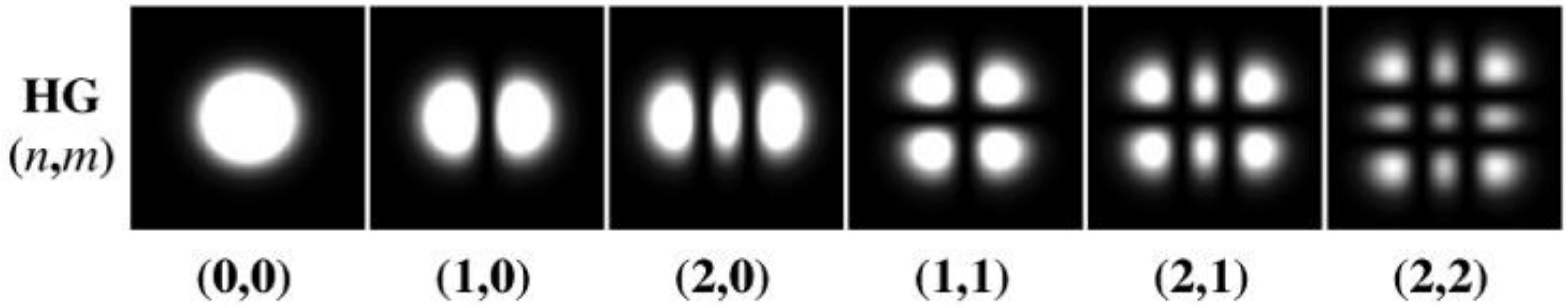

Power Overlap

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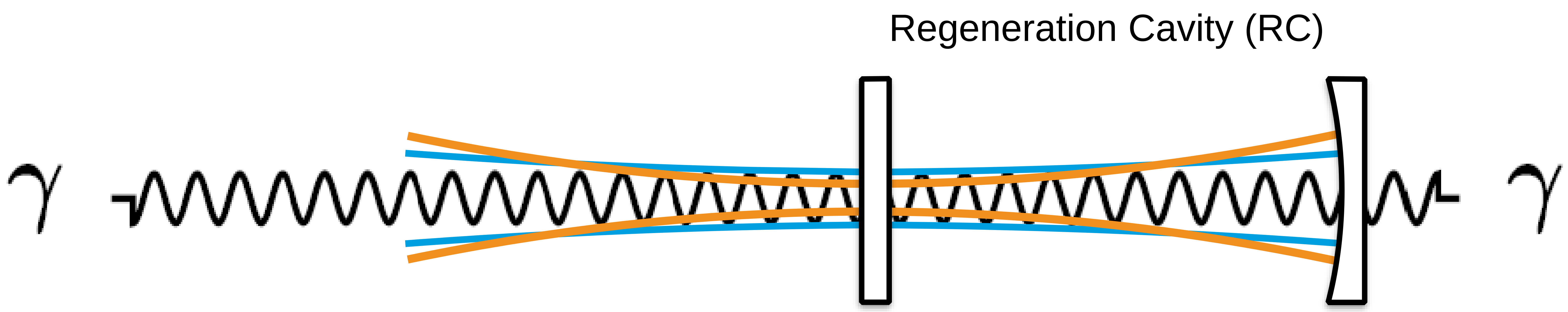

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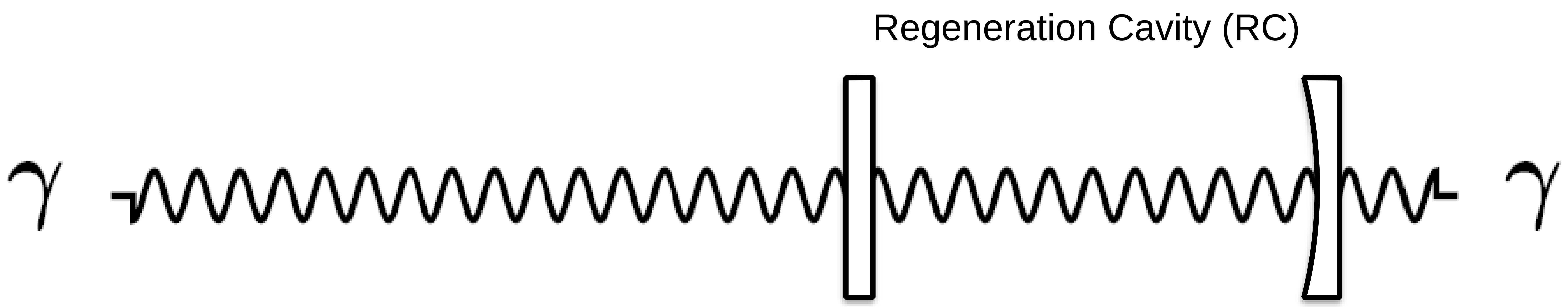
$$\eta_{\mathrm{spatial}} \approx 1 - \left|\frac{\delta x}{w_0} + i\,\frac{\delta\theta_x}{\theta_d}\right|^2 - \left|\frac{\delta y}{w_0} + i\,\frac{\delta\theta_y}{\theta_d}\right|^2 - \left|\frac{\delta w}{w_0} + i\,\frac{\delta z}{2z_{\mathrm{R}}}\right|^2$$

Power Overlap

Checking the laser-cavity coupling



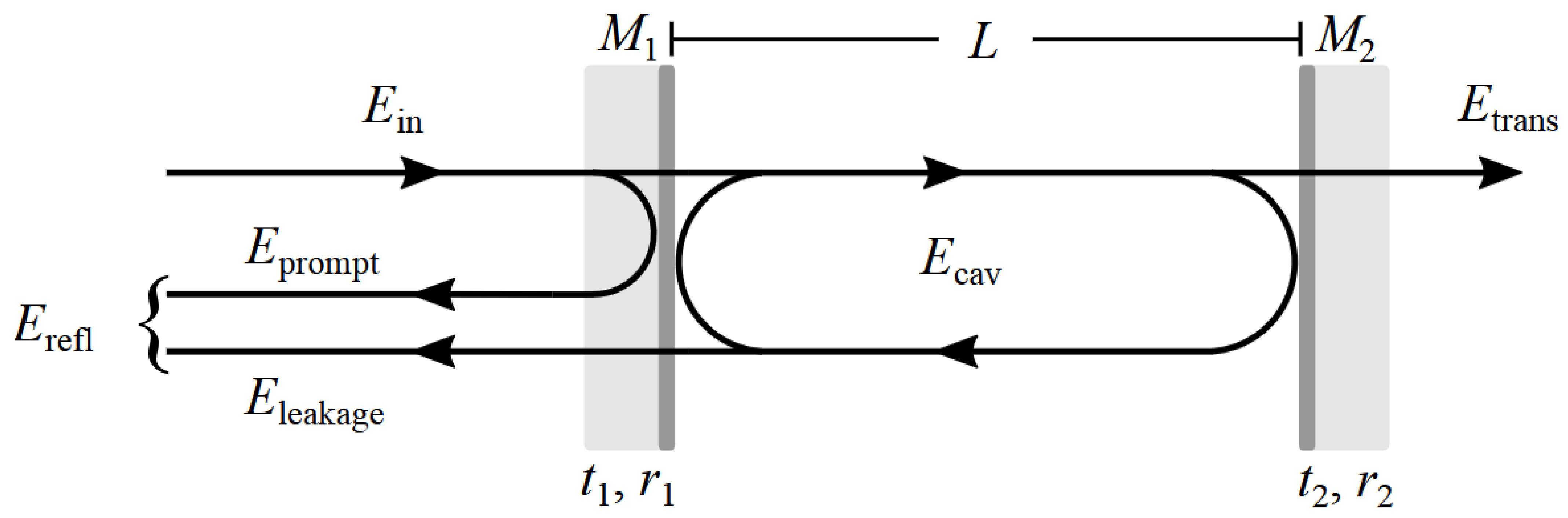
$$\eta = \eta_{\text{spatial}} \times \eta_{\text{longitudinal}}$$

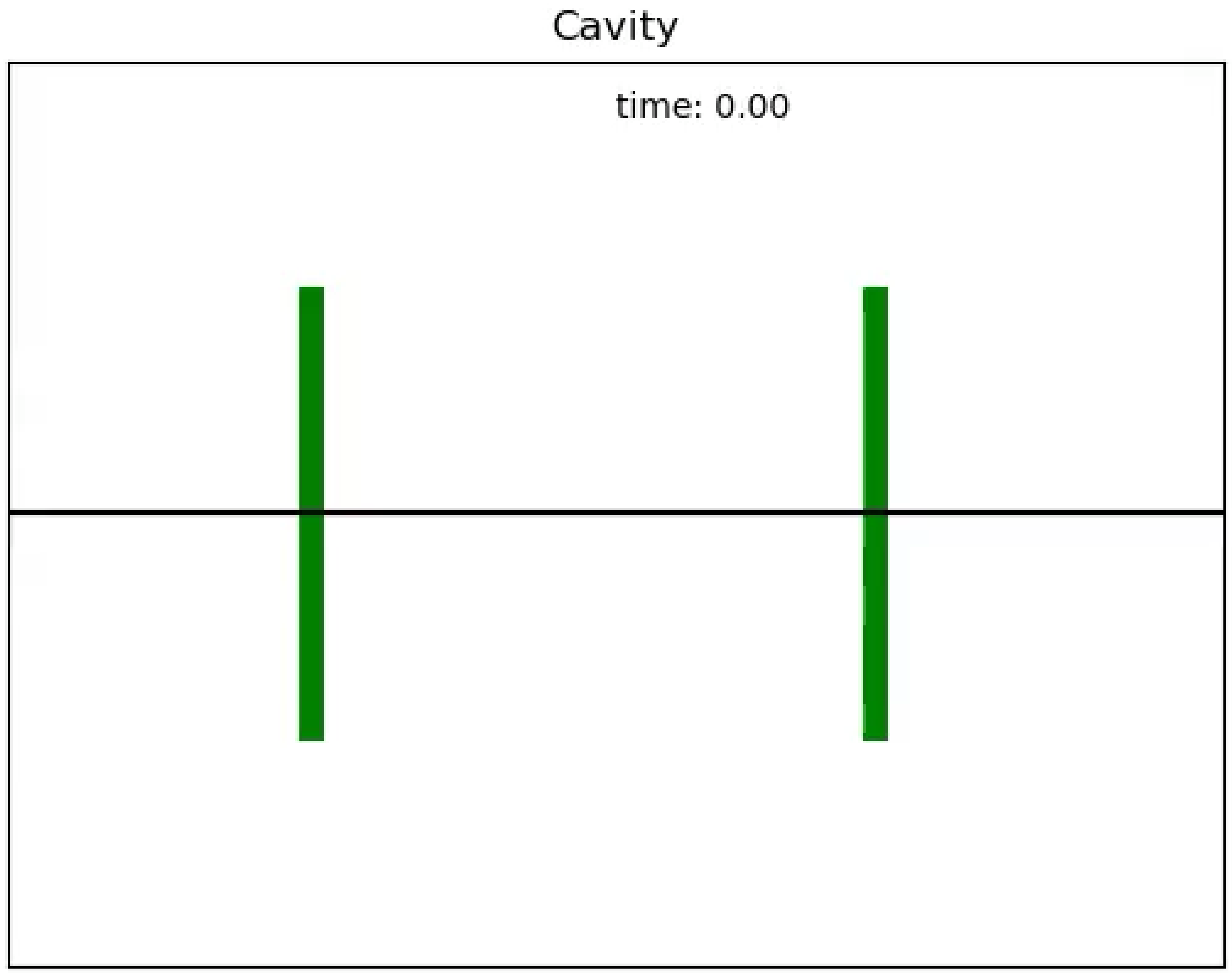
$\eta_{\text{longitudinal}}$ is the cavity resonance condition

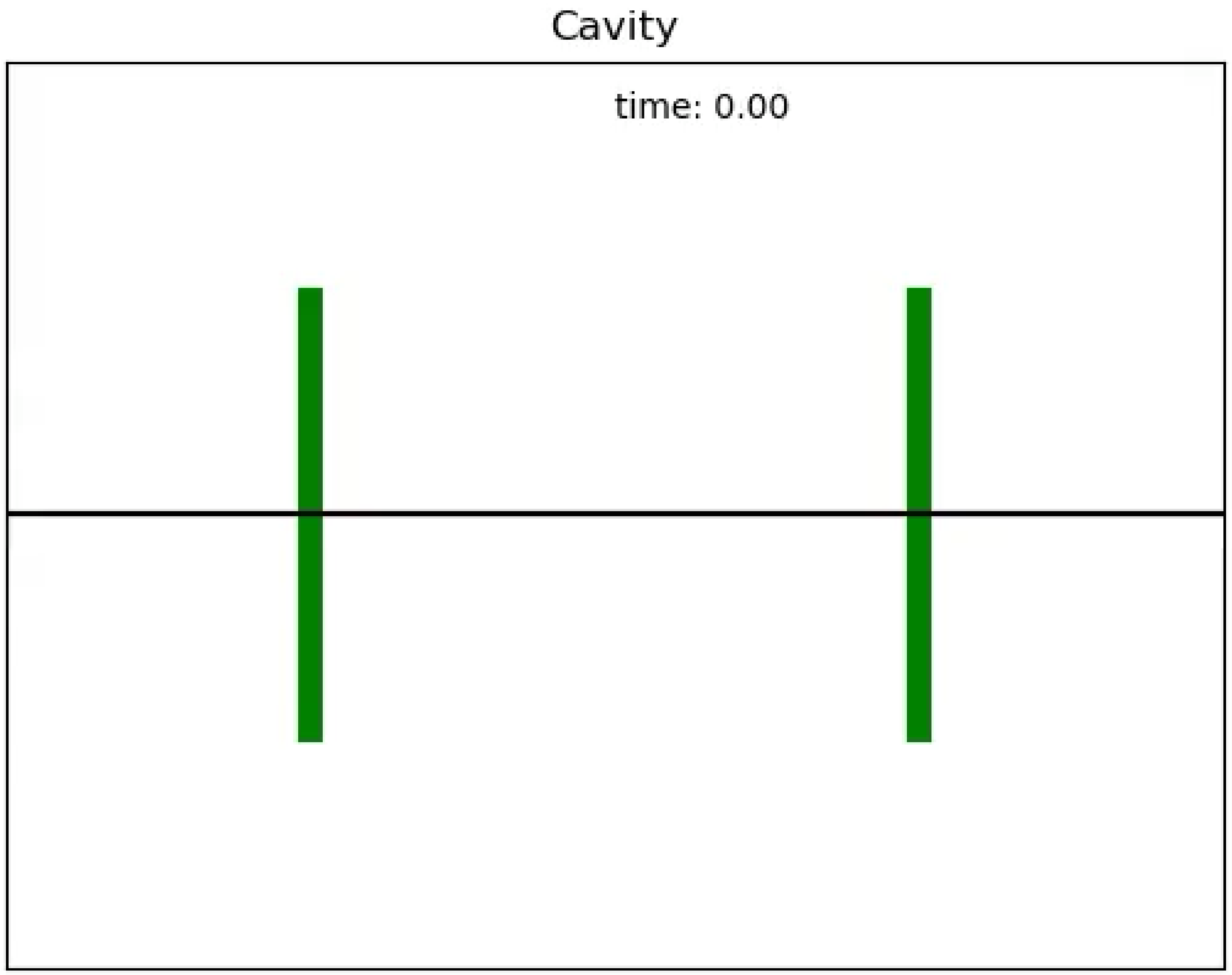
- Does the effective path length of the cavity correspond to some integer number of wavelengths of the laser?
- Can be expressed with the cavity Lorentzian

Cavity Resonance Condition

Amplifying the signal field

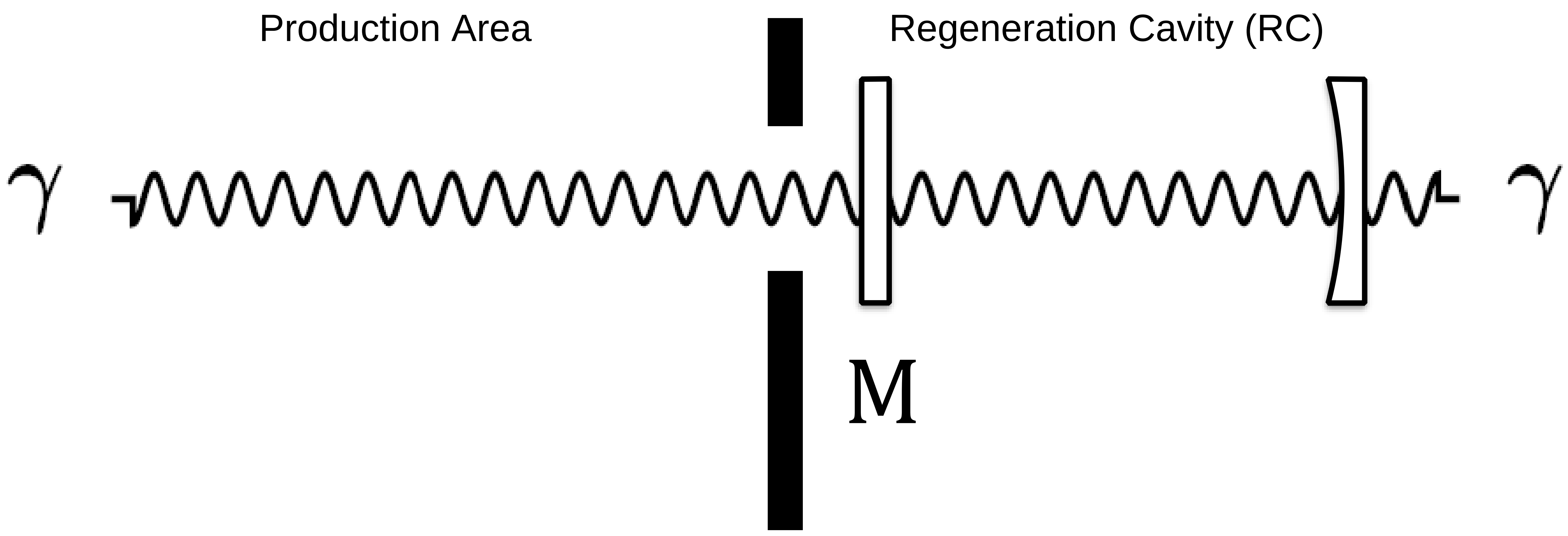






ALPS II first science campaign

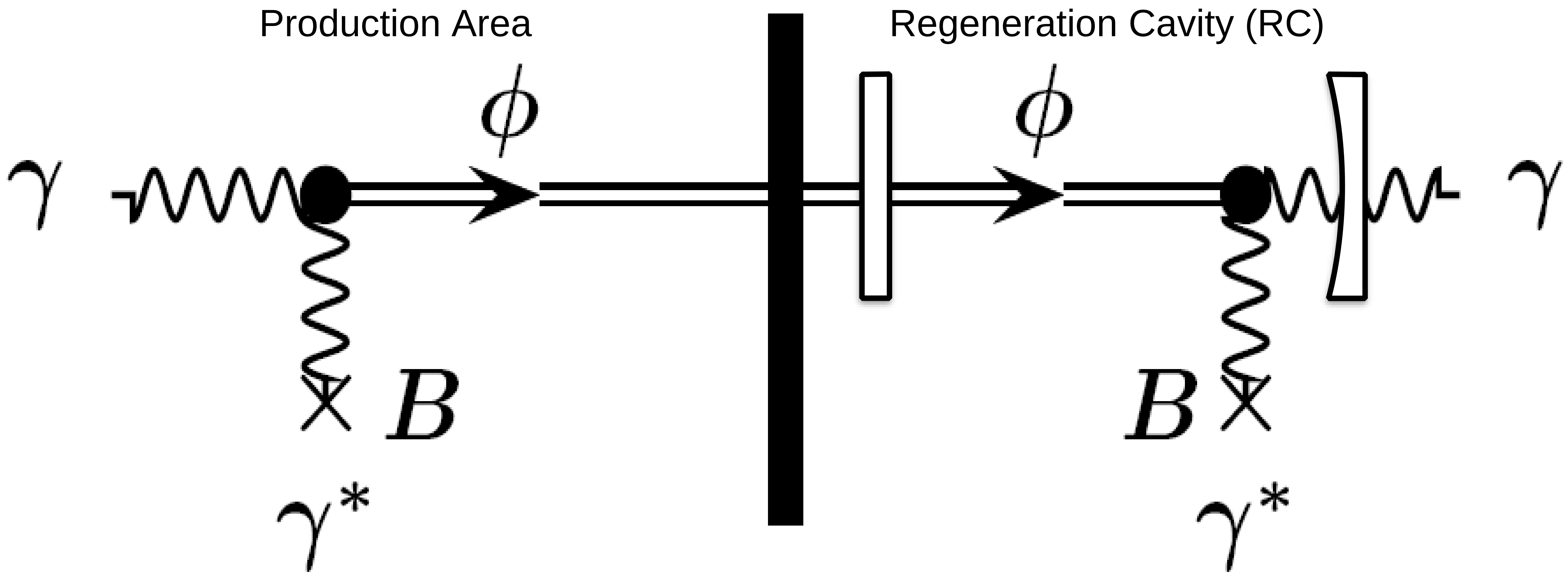
Checking the laser-cavity coupling



$$P_{\mathrm{open}} = T_{\mathrm{M}} \eta \beta_{\mathrm{R}} P_i$$

ALPS II first science campaign

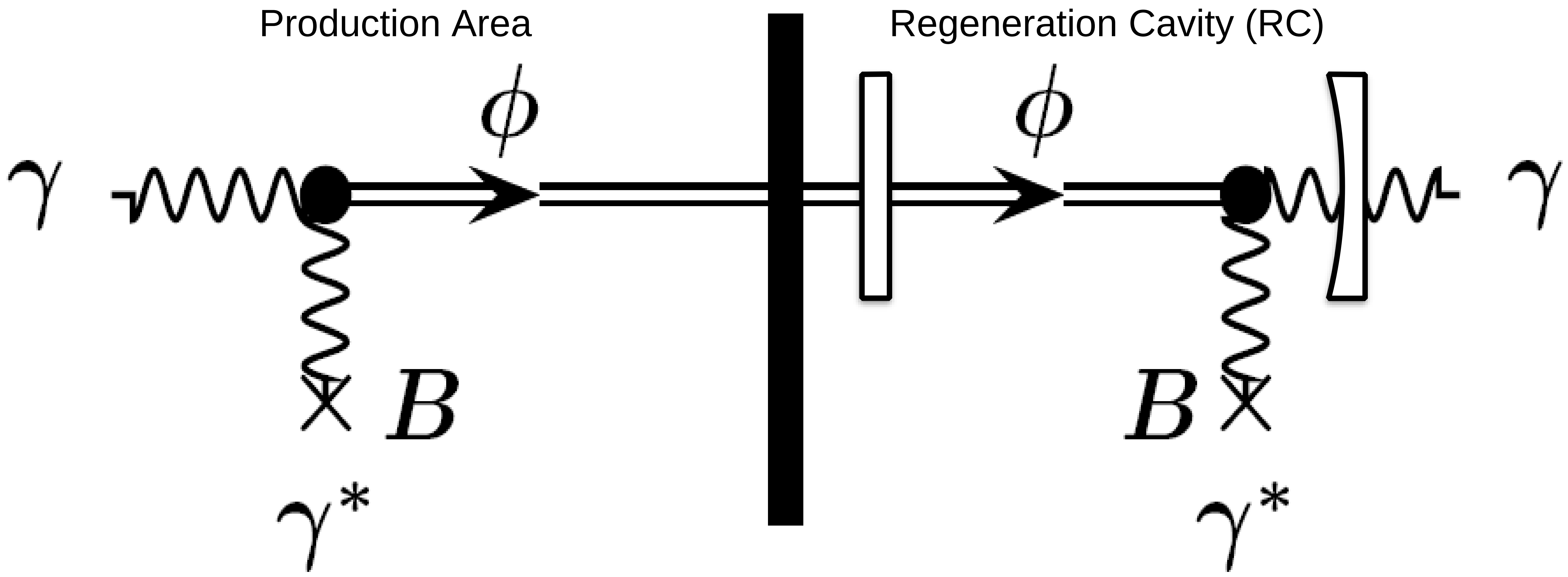
Critical parameters



$$P_\gamma = \left(\frac{g_{a\gamma\gamma} B L}{2}\right)^4 \eta \beta_\mathrm{R} P_i$$

ALPS II first science campaign

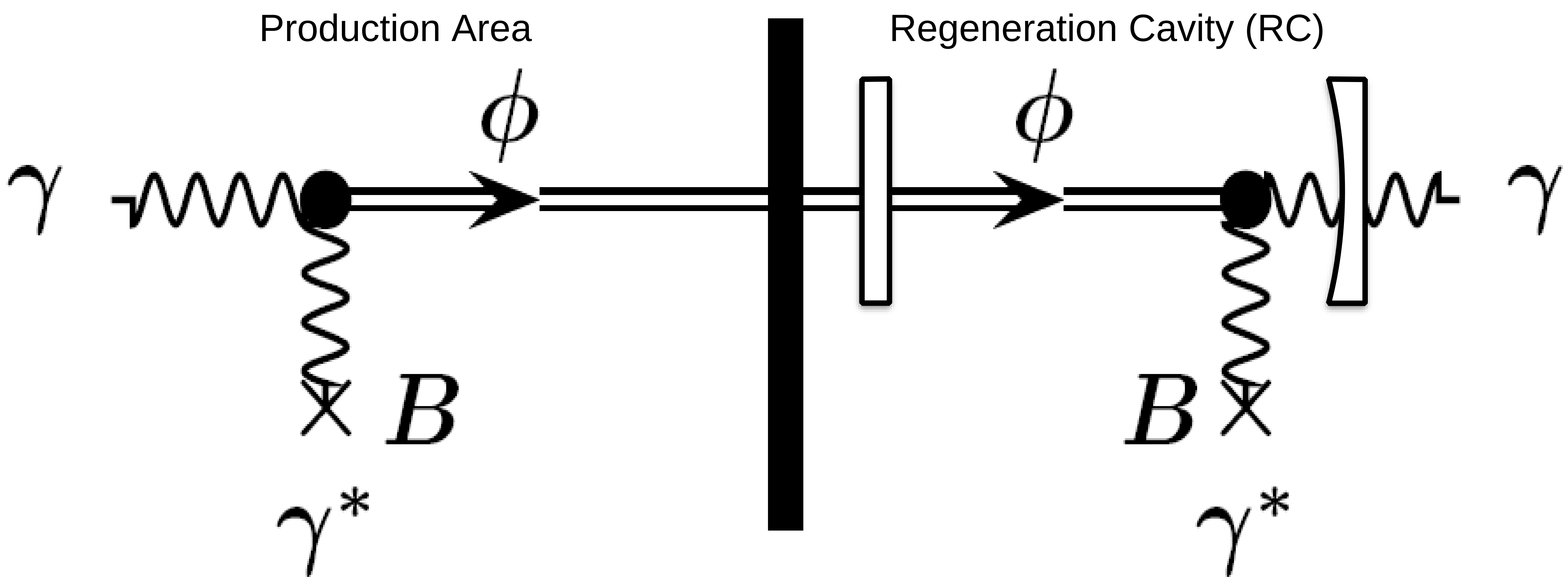
Cancelling measured parameter



$$\frac{P_\gamma}{P_{\text{open}}} = \left(\frac{g_{a\gamma\gamma} BL}{2}\right)^4 \frac{1}{T_{\text{M}}}$$

ALPS II first science campaign

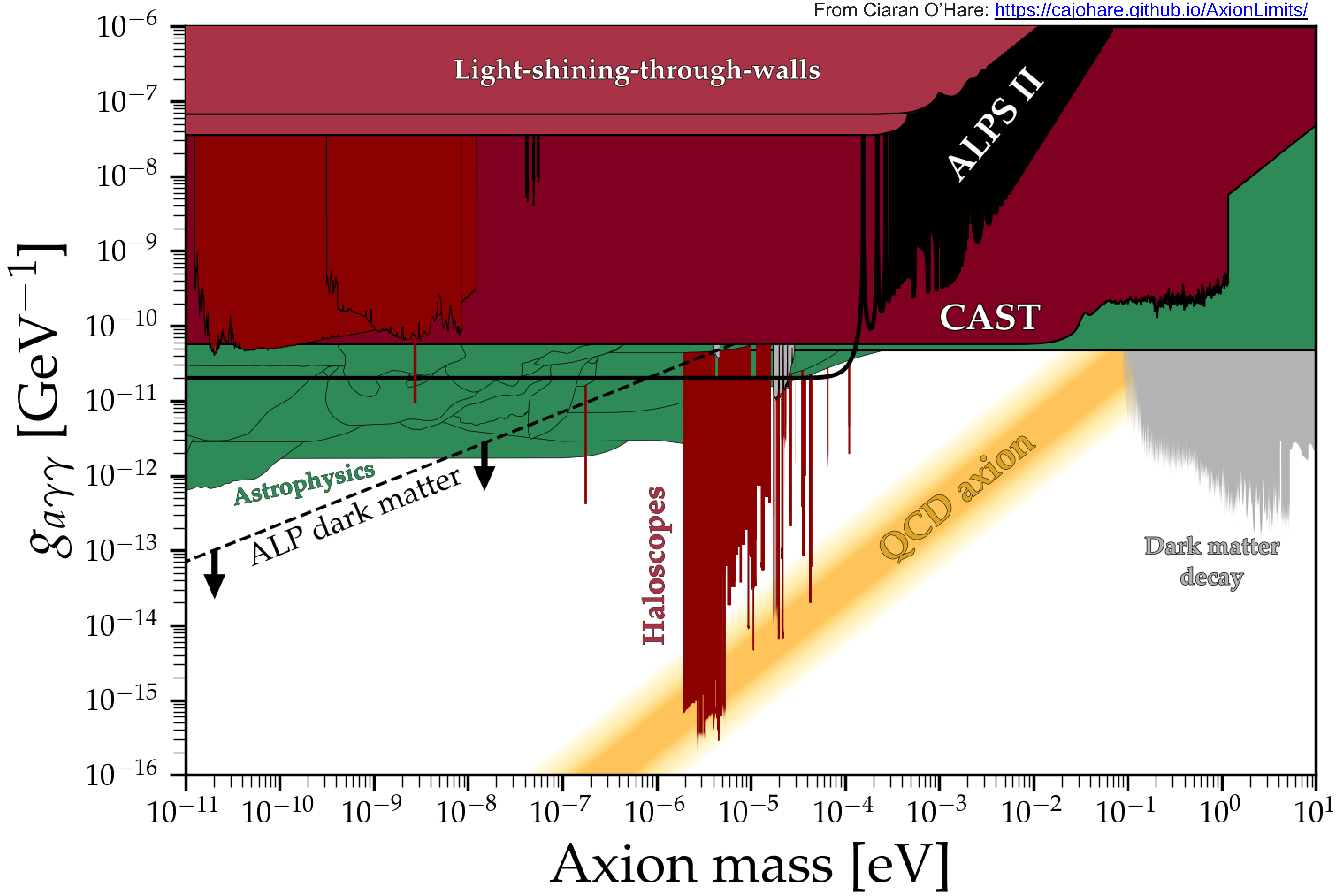
Calibrating the axion-photon coupling



$$g_{a\gamma\gamma} = \frac{2}{BL}\left(\frac{T_{\mathrm{M}} P_{\gamma}}{P_{\mathrm{open}}}\right)^{1/4}$$

Current Axion Limits vs ALPS II Design Sensitivity

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



What's the deal with the gaps at higher masses??

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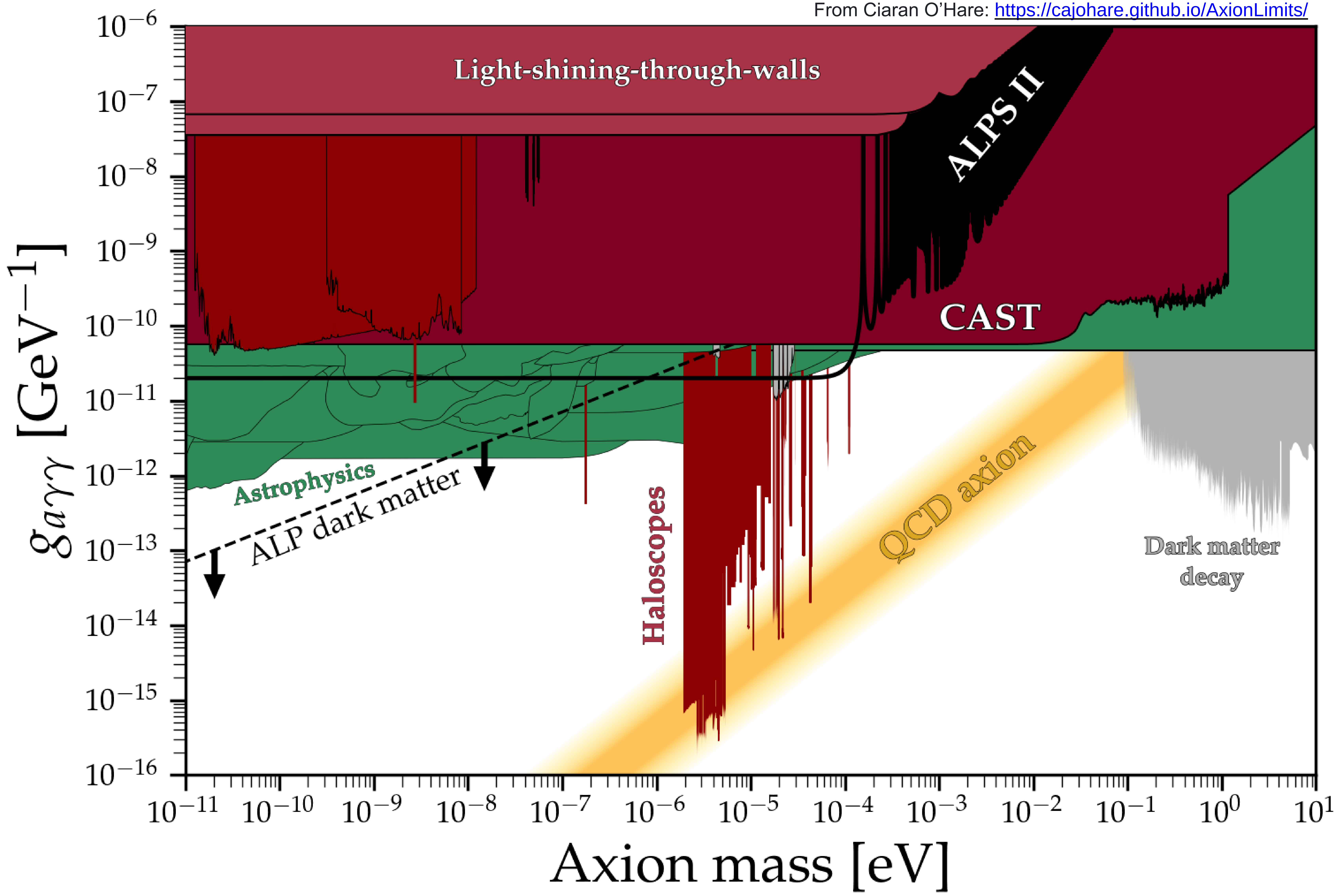


What’s the deal with the gaps at higher masses??

$$\varphi_p(x,t) = e^{-i(\omega t - k_\varphi x)} \frac{ig}{2k_\varphi} \int dx' \boldsymbol{E}(x') \cdot \boldsymbol{B}(x') e^{-ik_\varphi x'}$$

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

What's the deal with the gaps at higher masses??

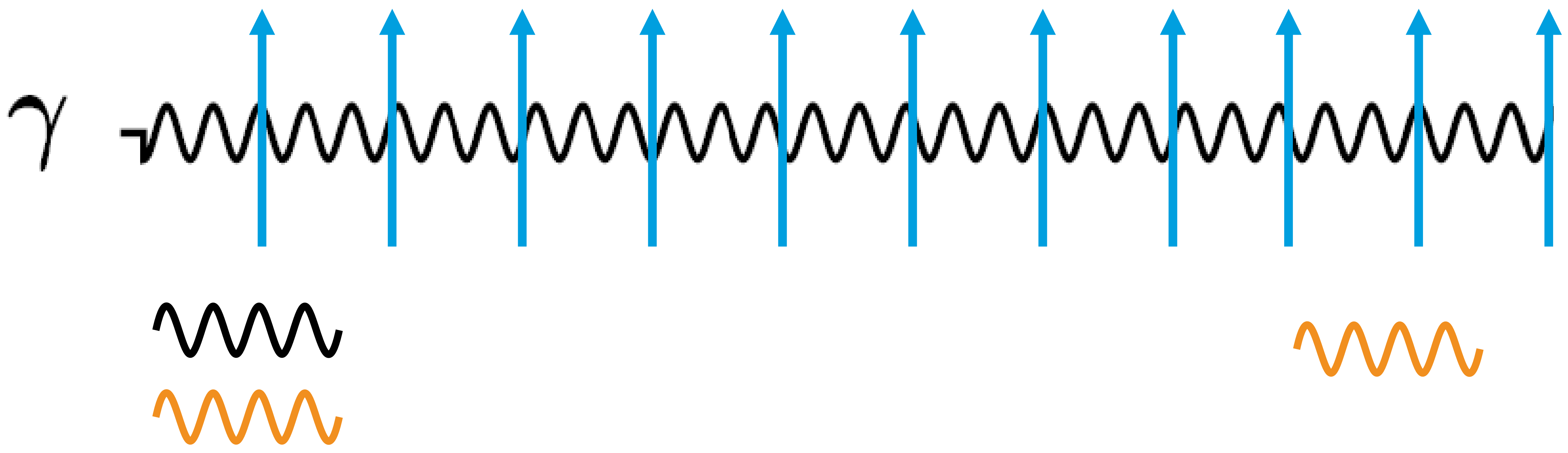
At higher masses the axion field has lower kinetic energy causing a phase lag between the components of the axion field generated along different positions within the magnet string.

This causes them to destructively interfere leading to null points in the sensitivity curve.

The integral also includes gaps between each of the individual magnets leading to a complicated structure of the sensitivity curve.

$$\varphi(x,t) = \frac{ig}{2k_\varphi} B E_0 e^{-i(\omega t - k_\varphi x)} \int dx' e^{iqx'}$$

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



ALPS II Experimental System

ALPS II Experimental System

Critical pieces

What do we need?

- Tunnel/hall with a long string of magnets that provide a strong dipole field
- High-power laser
- Long-baseline high-finesse cavity
- Optical system capable of maintaining coupling of input laser to cavity while suppressing background
- Detection system capable of measuring a few photons over weeks

$$P_\gamma = \frac{1}{16}\left(g_{a\gamma\gamma} B L\right)^4 \eta \beta_{\mathrm{R}} P_i$$

HERA Tunnel and Magnets

Providing the basis for ALPS II

HERA Tunnel and Magnets

Providing the basis for ALPS II

Magnets, tunnel, and infrastructure are the foundation of the experiment

- 2x strings of 12 HERA dipole magnets: 5.3 T, 106 m
  - Cryogenic infrastructure
- 3 clean rooms at the different stations of the experiment

Infrastructure at DESY

Providing the basis for ALPS II

Magnets, tunnel, and infrastructure are the foundation of the experiment

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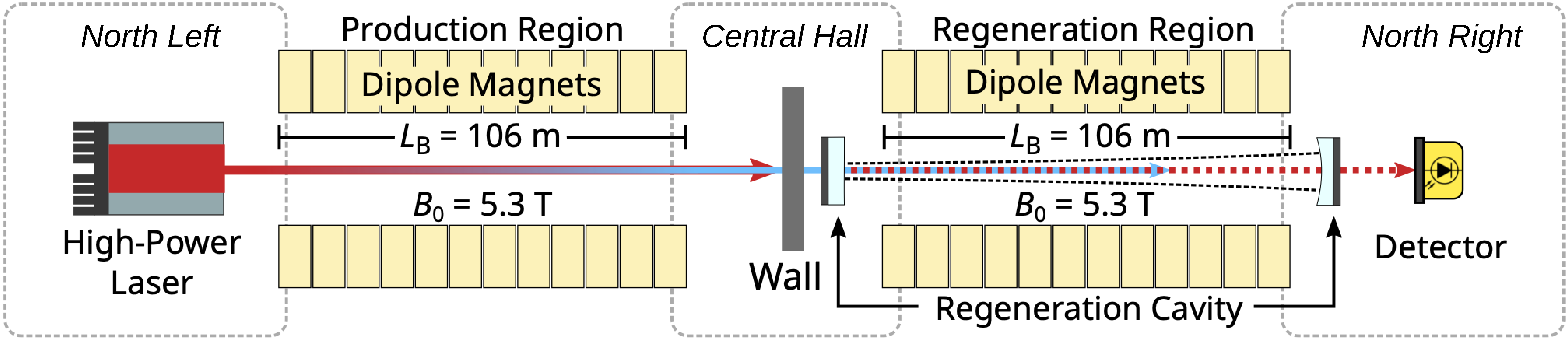
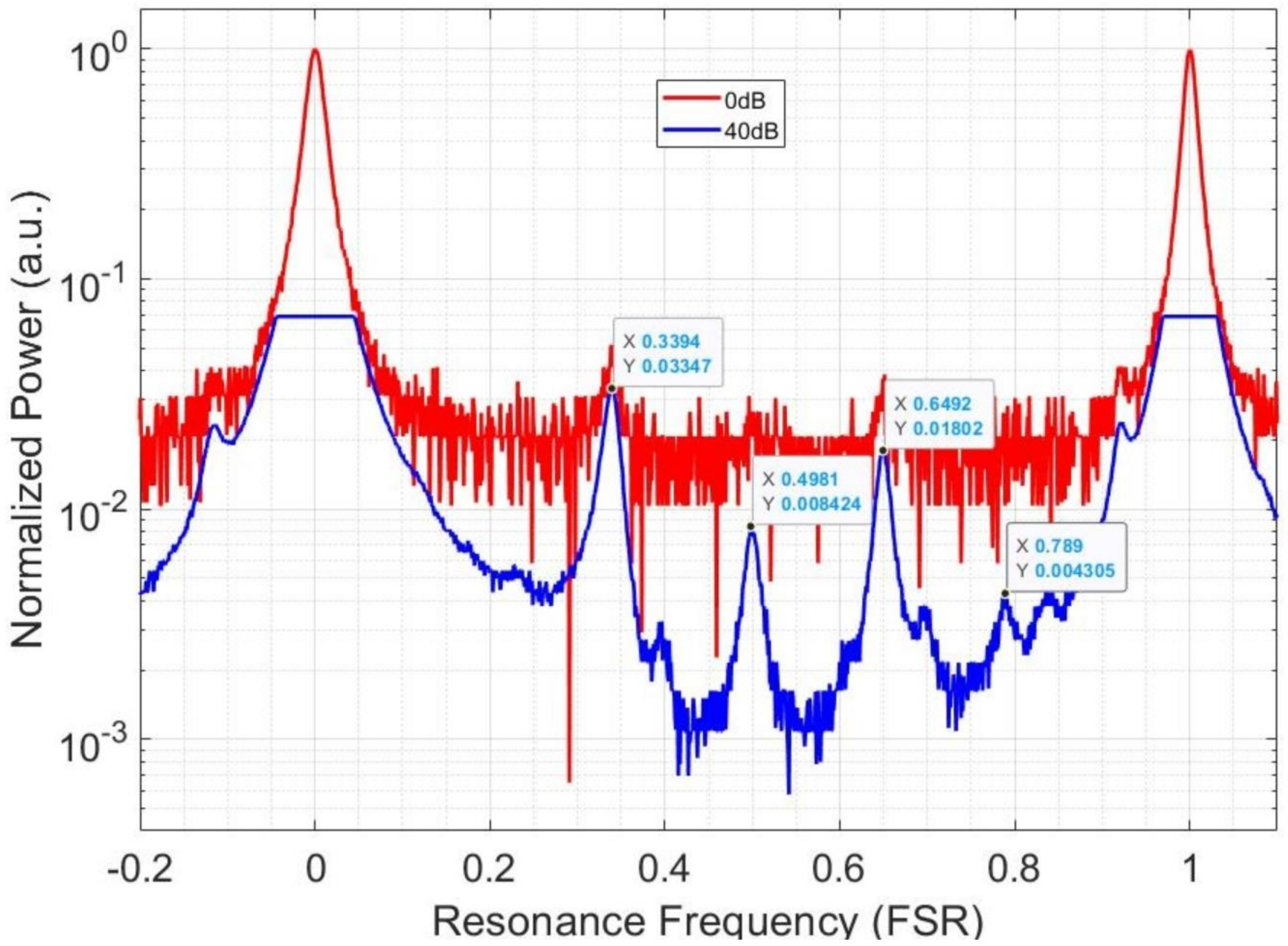


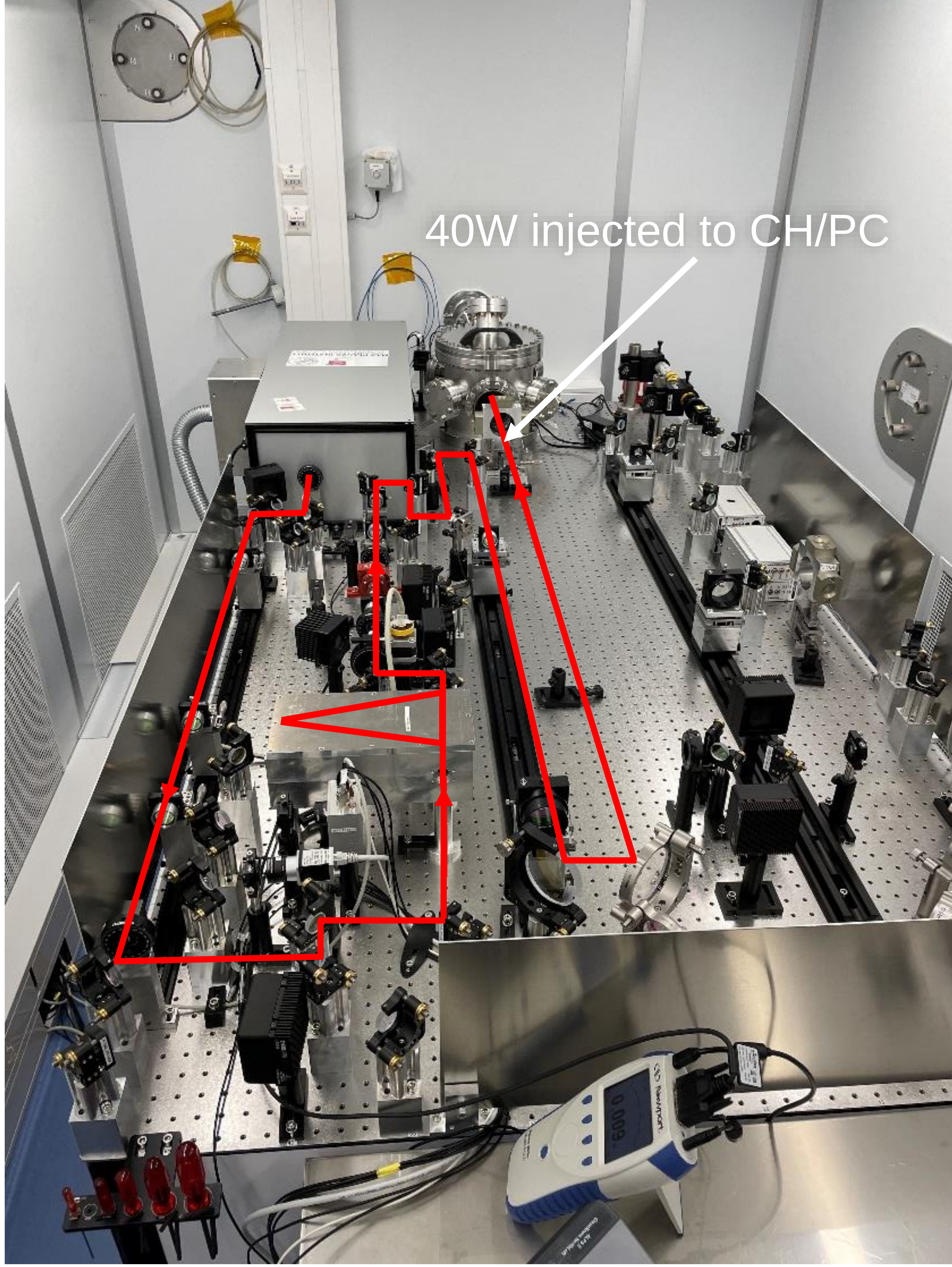
High Power Laser

Generating axion-like particles

Enhanced LIGO pre-stabilized laser

- 60 W of power at 1064 nm
- Can scan the resonances of a triangular cavity to check the mode content





ALPS II Regeneration Cavity

Amplifying the signal field

World record optical cavity

- Length: 122.4 m
- Storage time > 7 ms
  - (Plot to the right)
- Power buildup > 7600
  - Can calculate this with storage time

- Robust control system maintains cavity lock for days

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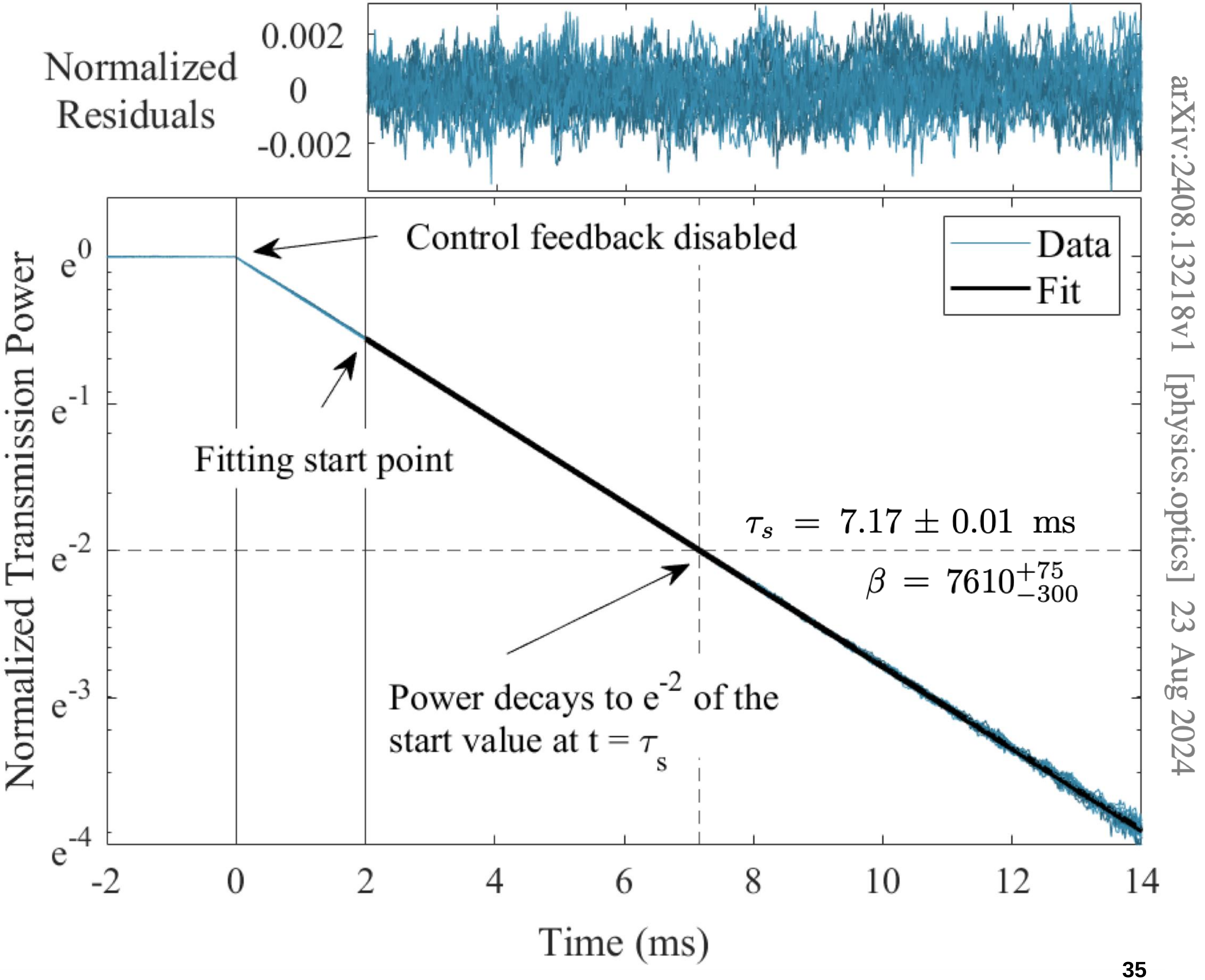
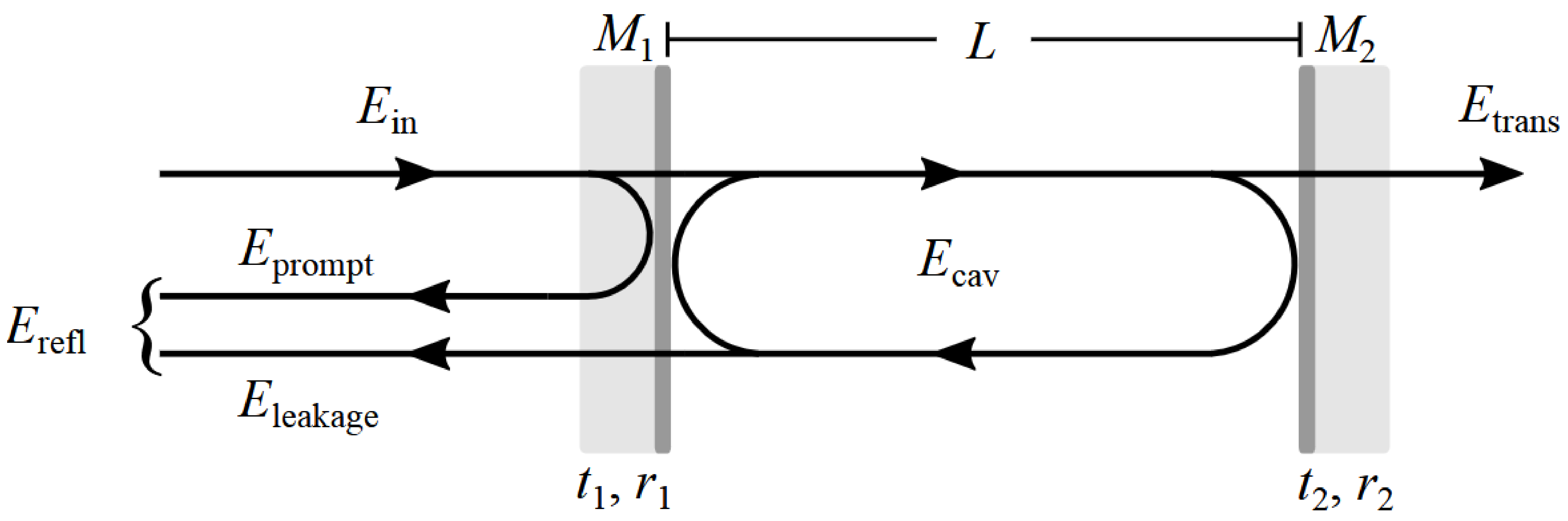


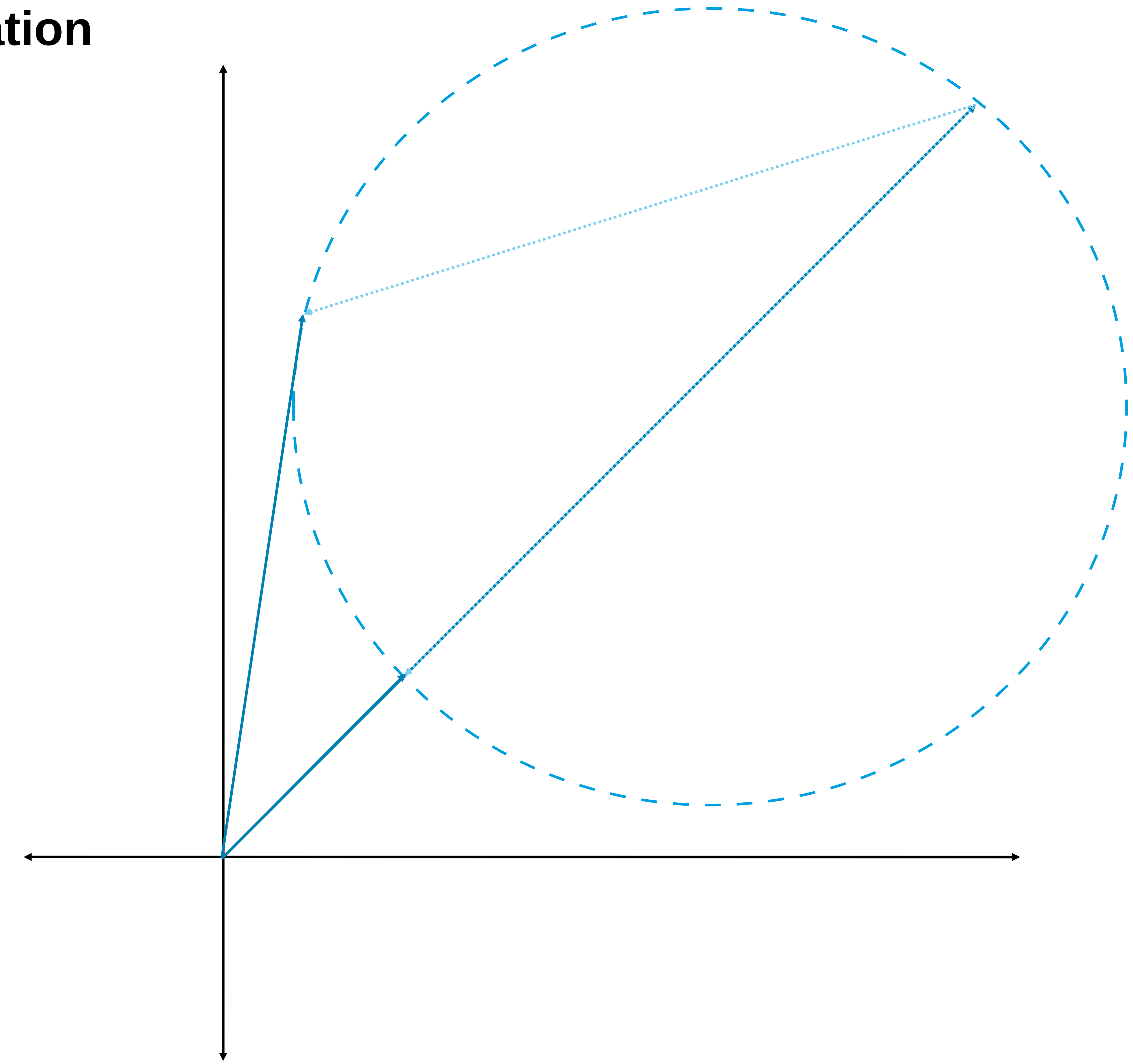
Laser frequency stabilization

Maintaining the resonance condition

Pound-Drever-Hall (PDH) Laser Frequency Stabilization

- Uses phase modulation to sense the resonance condition of the sidebands



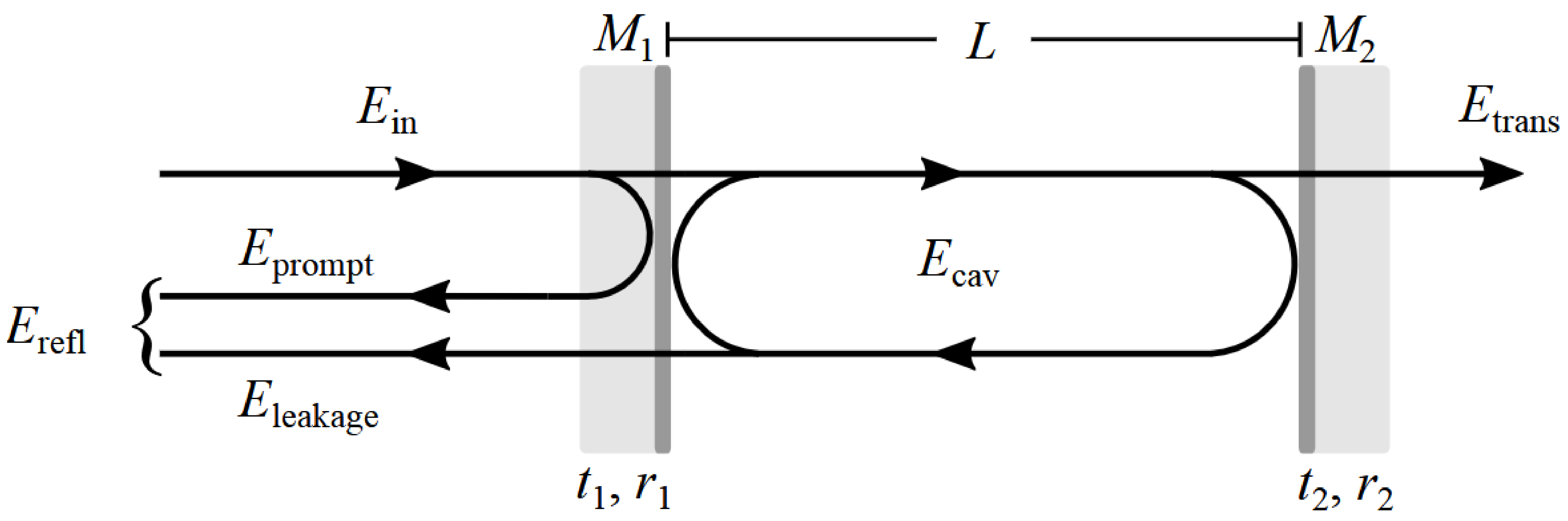


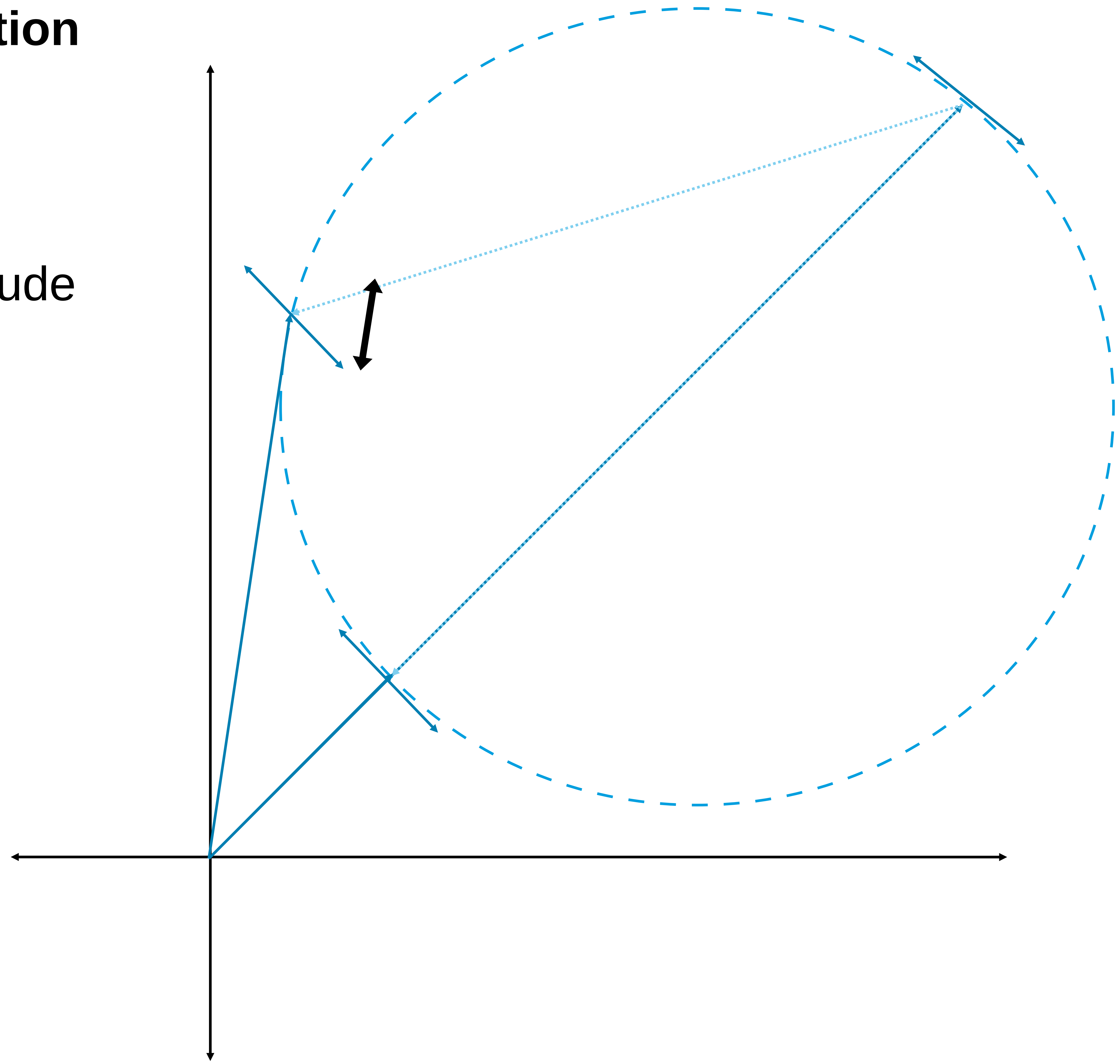
Laser frequency stabilization

Maintaining the resonance condition

Pound-Drever-Hall (PDH) Laser Frequency Stabilization

- Uses phase modulation to sense the resonance condition of the sidebands
- Sense the conversion of phase modulation to amplitude modulation



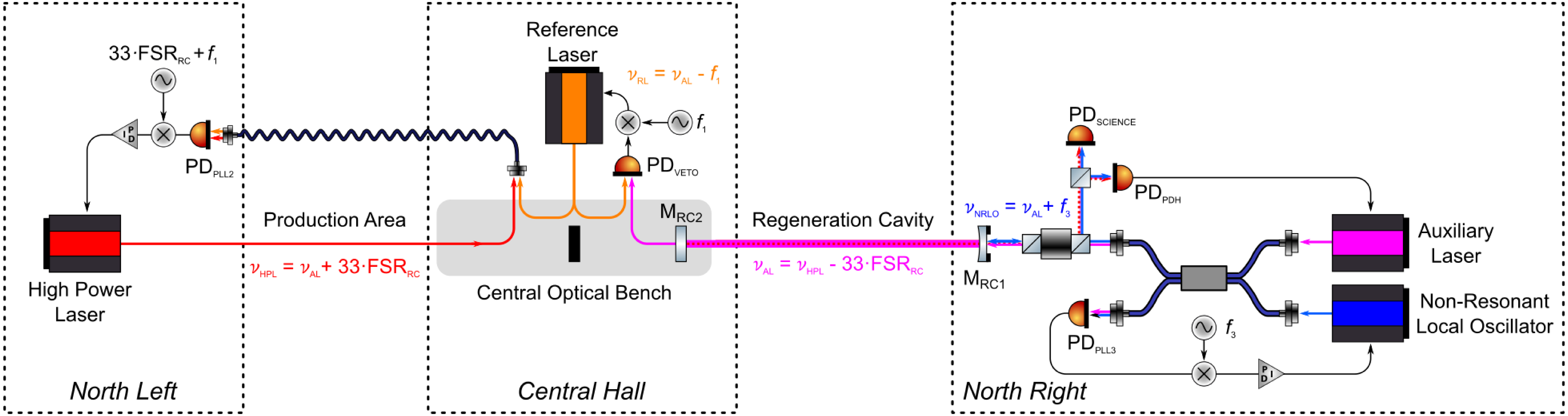


Optical System

Enhancing the sensitivity with precision interferometry

We can't just directly frequency stabilize the High-Power Laser to the Regeneration Cavity though!

- Any High-Power laser light inside the cavity will look exactly like the signal we are looking for
- Use Auxiliary and Reference lasers to sense frequency of High power laser with respect to the cavity



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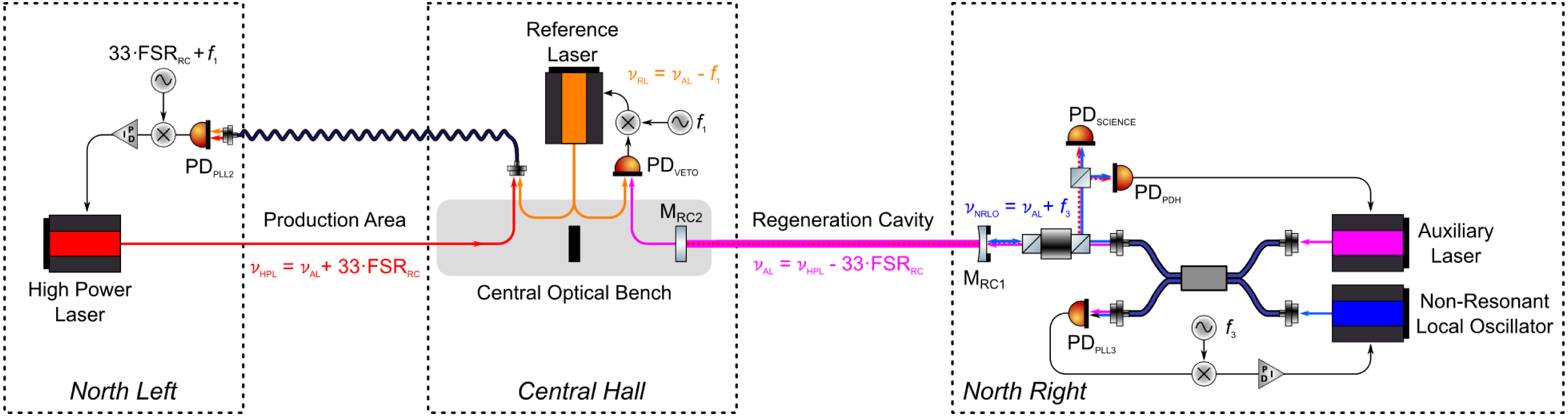

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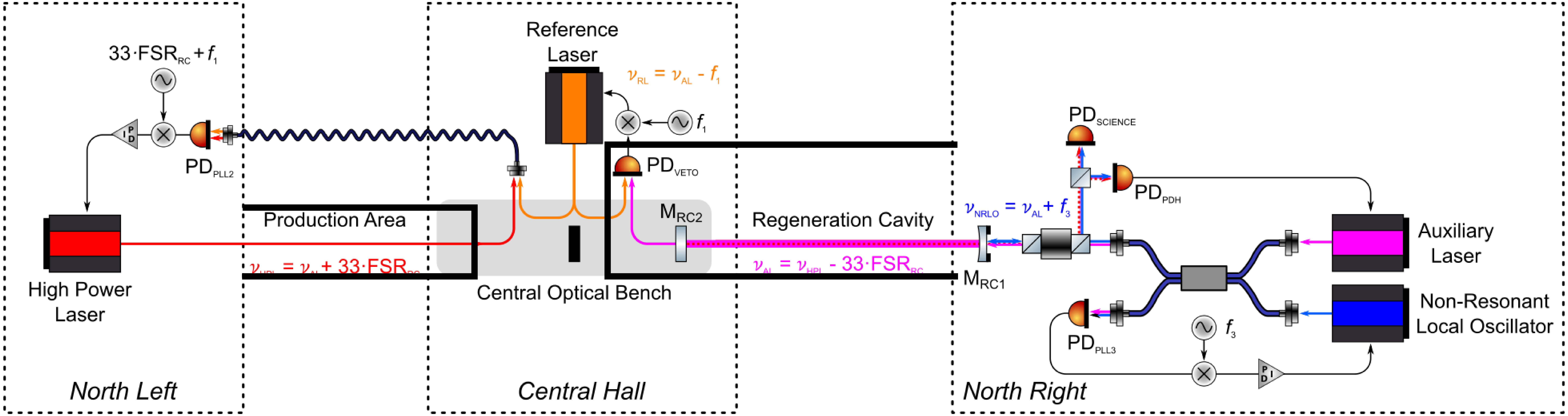
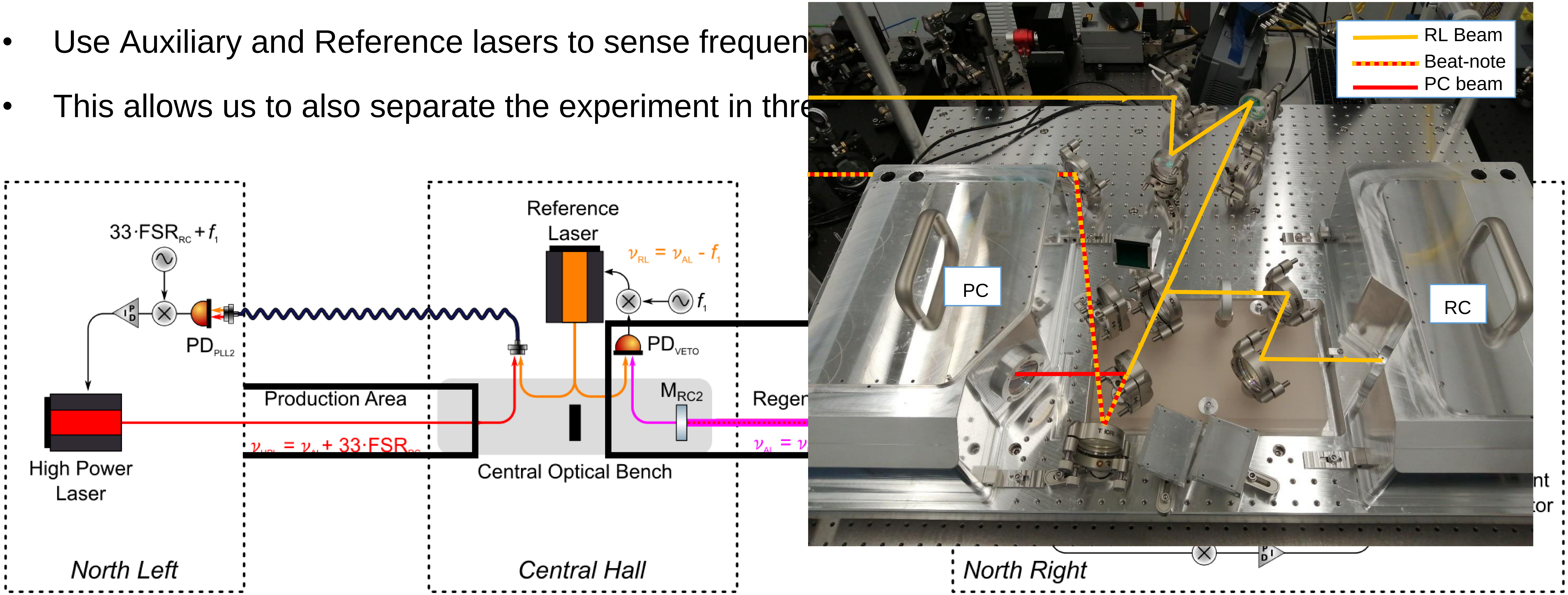


Optical System

Enhancing the sensitivity with precision interferometry

We can’t just directly frequency stabilize the High-Power Laser to the Regeneration Cavity though!

- Any High-Power laser light inside the cavity will look exactly like the signal we are looking for
- Use Auxiliary and Reference lasers to sense frequen
- This allows us to also separate the experiment in thre



Optical System

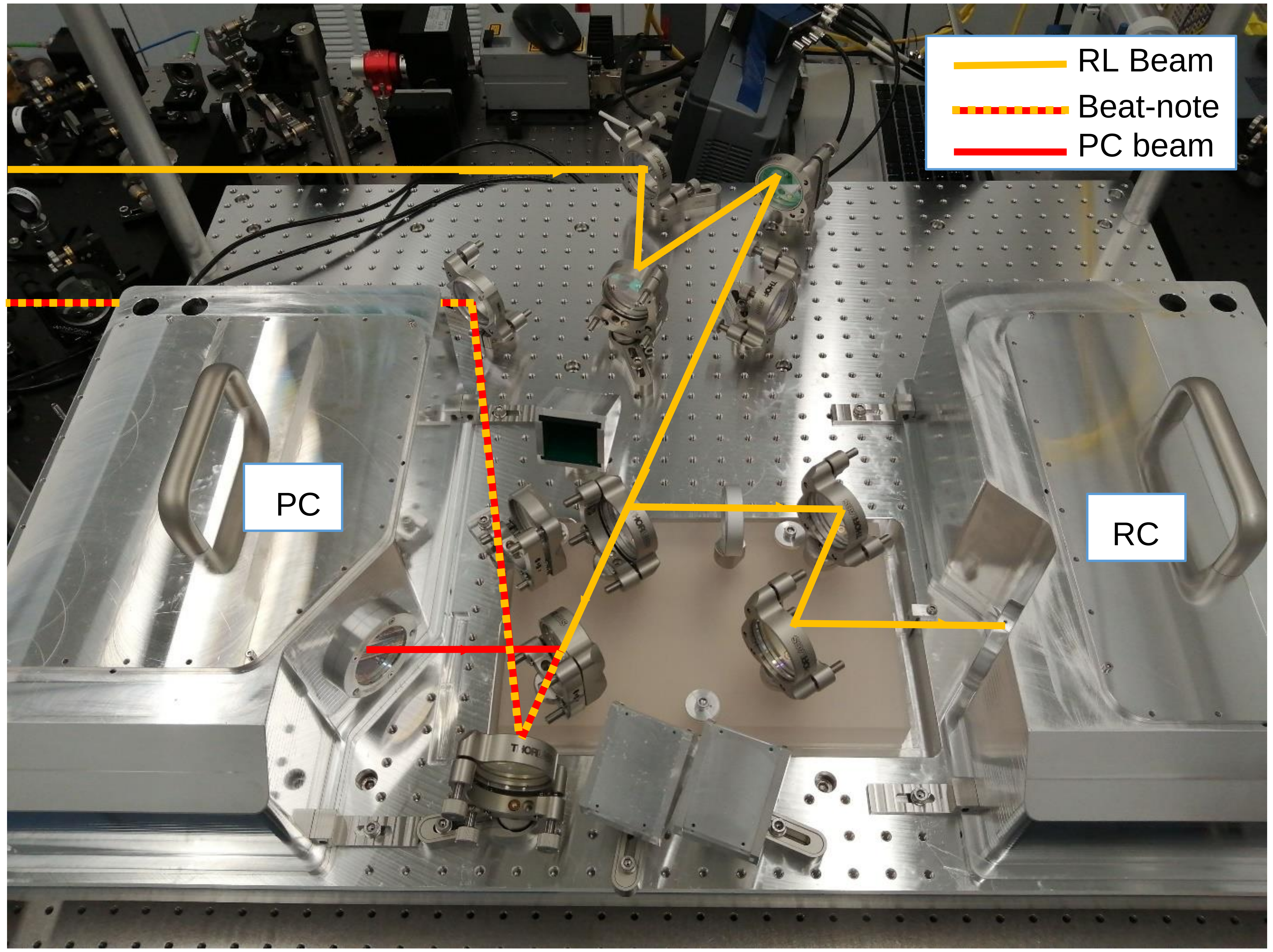
Enhancing the sensitivity with precision interferometry

Central Optical Bench

$$P_{\text{open}} = T_{\text{COB}} \eta \beta_{\text{R}} P_i$$

$$g_{a\gamma\gamma} = \frac{2}{BL} \left(\frac{T_{\text{COB}} P_\gamma}{P_{\text{open}}} \right)^{1/4}$$

$$T_{\text{COB}} = 9 \times 10^{-23}$$

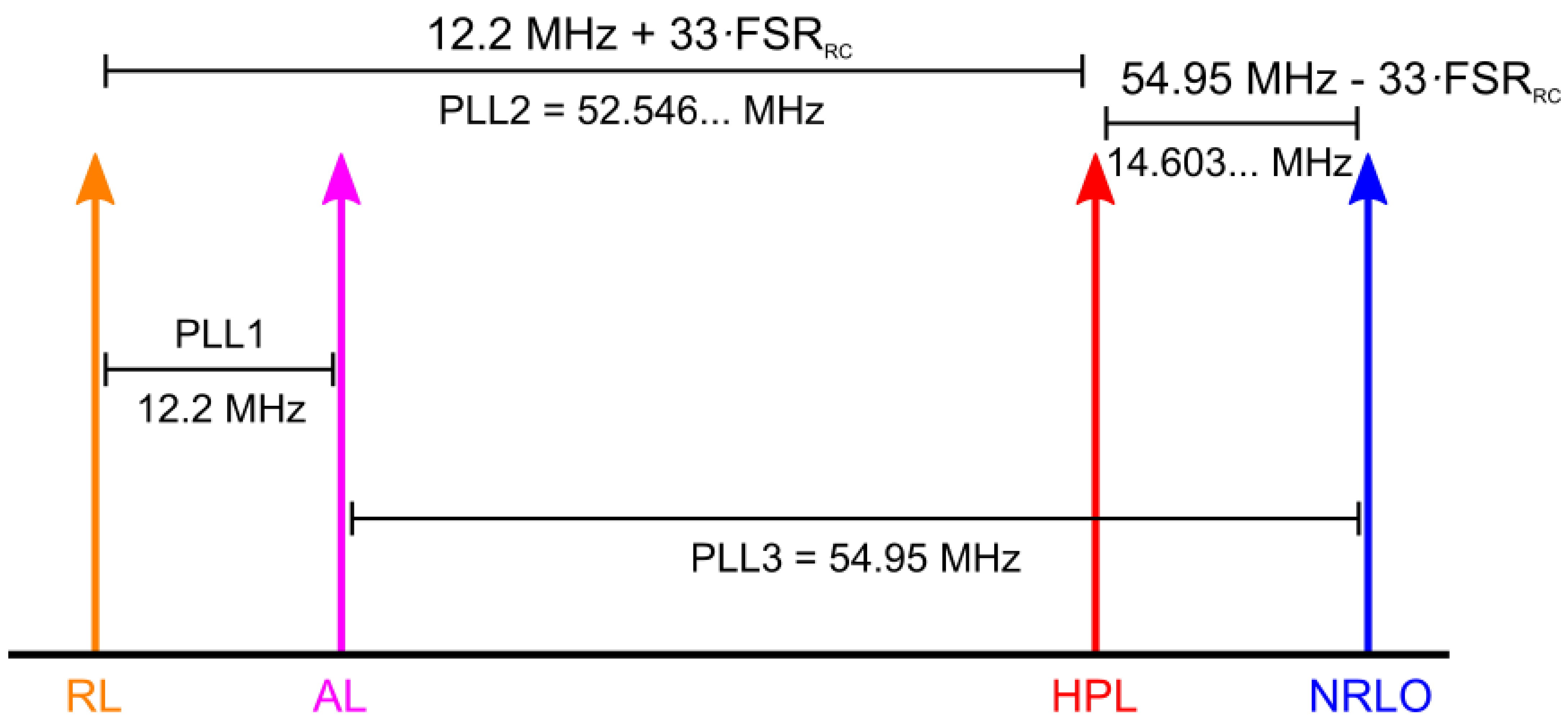


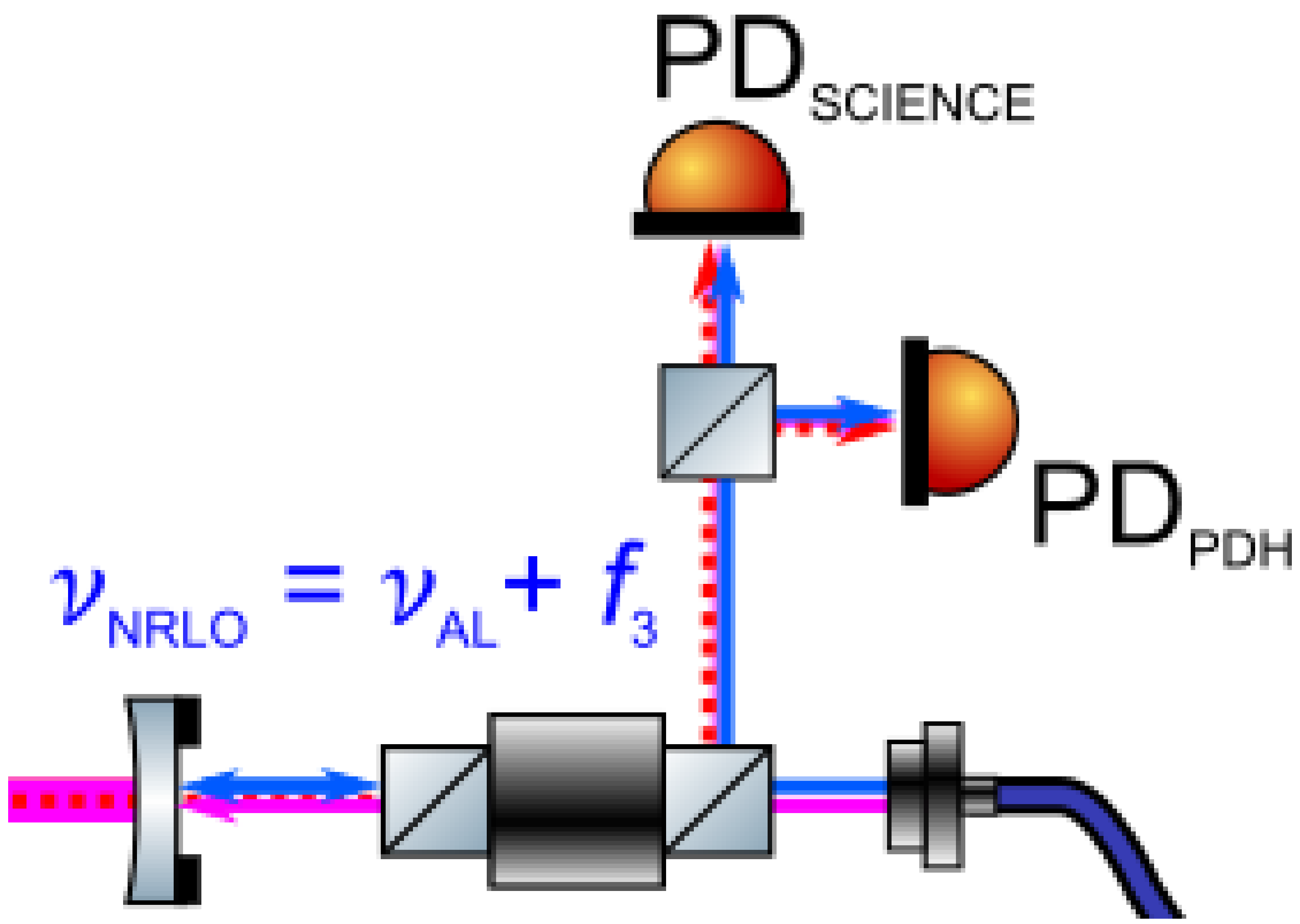
Heterodyne Detection

Detecting single photon power levels

We have three fields at our photodetector

- The fields have power noise
- The photodetector has voltage noise
- HOW DO WE SEE THIS VERY WEAK SIGNAL???





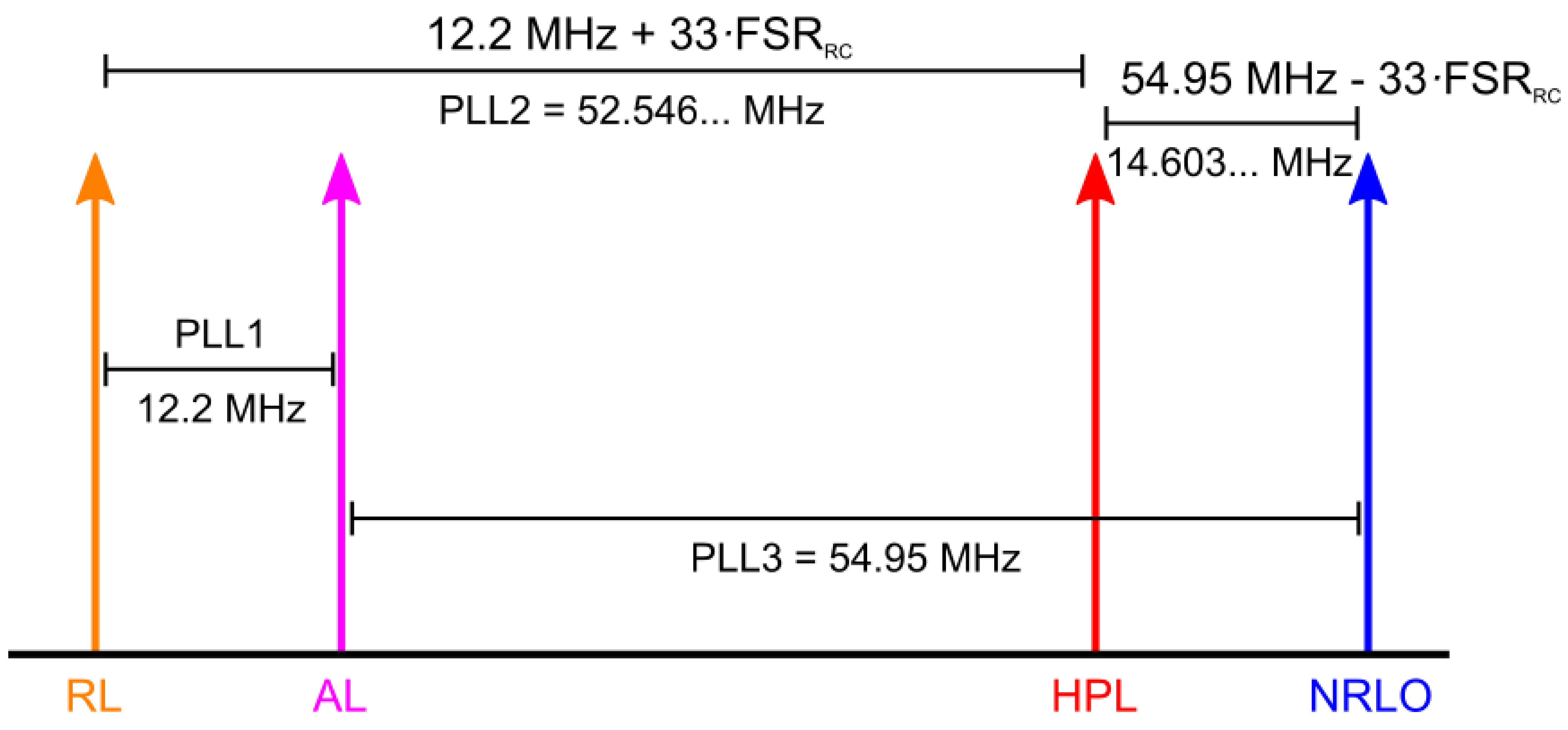
$$P_{\mathrm{SCI}}(t) = (R_{\mathrm{cav}} + 1 - \eta_{\mathrm{aux}})P_{\mathrm{aux}} + P_{\mathrm{lo}} + P_{\mathrm{sci}} + \cdots$$

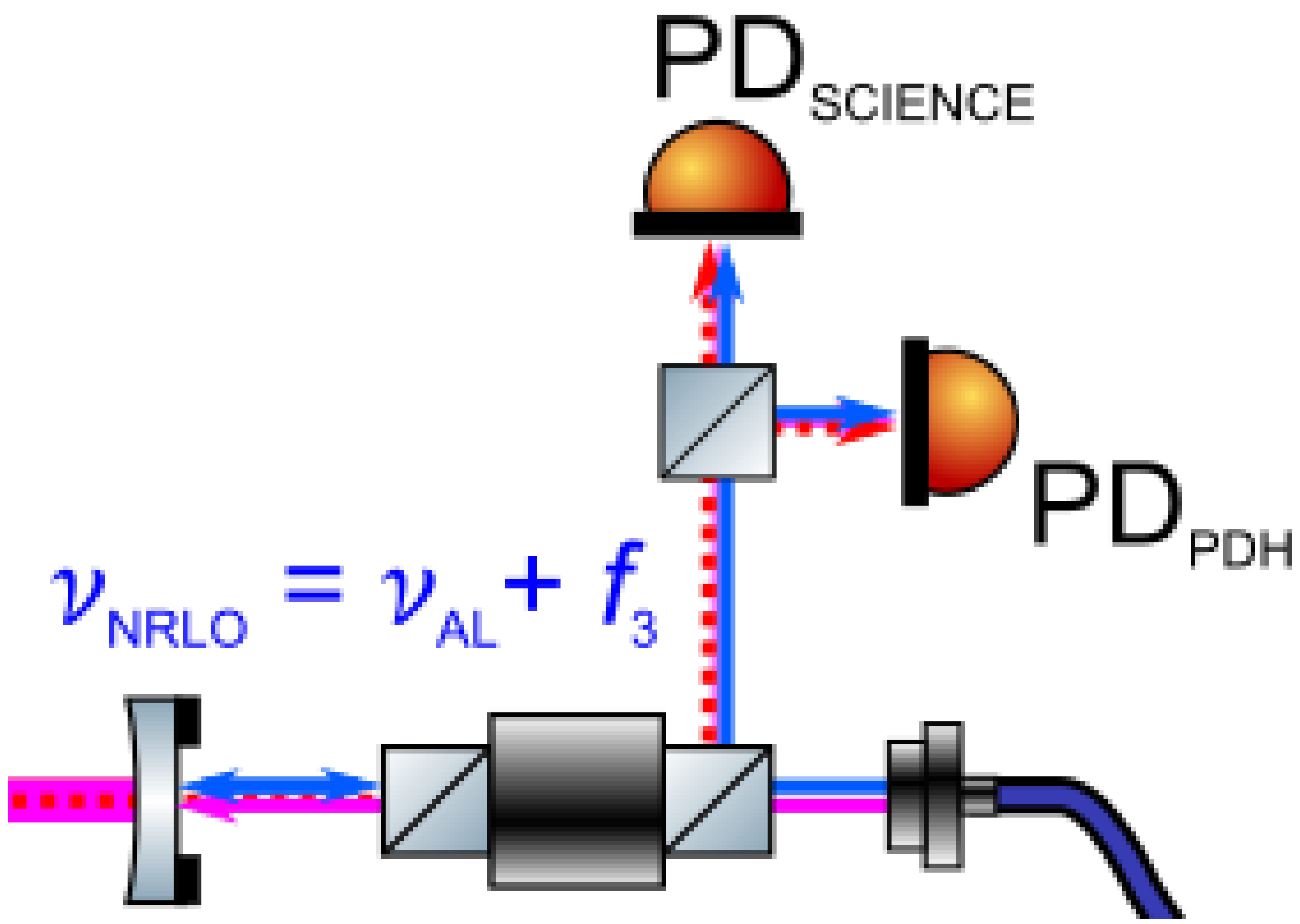
Heterodyne Detection

Detecting single photon power levels

Intereference beatnote between HPL and LO Laser

- Three fields present at $PD_{science}$
  - Local oscillator laser, auxillary laser, science field
  - Science field DC power too small to measure
- We are interested in the interference beat note between the local oscillator laser and science field





$$P_{SCI}(t) = (R_{cav} + 1 - \eta_{aux})P_{aux} + P_{lo} + P_{sci} + \cdots$$
$$+2\eta_{lo}\sqrt{P_{lo}P_{sci}}\sin(2\pi(\nu_{HPL} - \nu_{lo})t + \phi) + \cdots$$

Heterodyne Detection

Detecting single photon power levels

Intereference beatnote between HPL and LO Laser

- Three fields present at $PD_{science}$
  - Local oscillator laser, auxillary laser, science field
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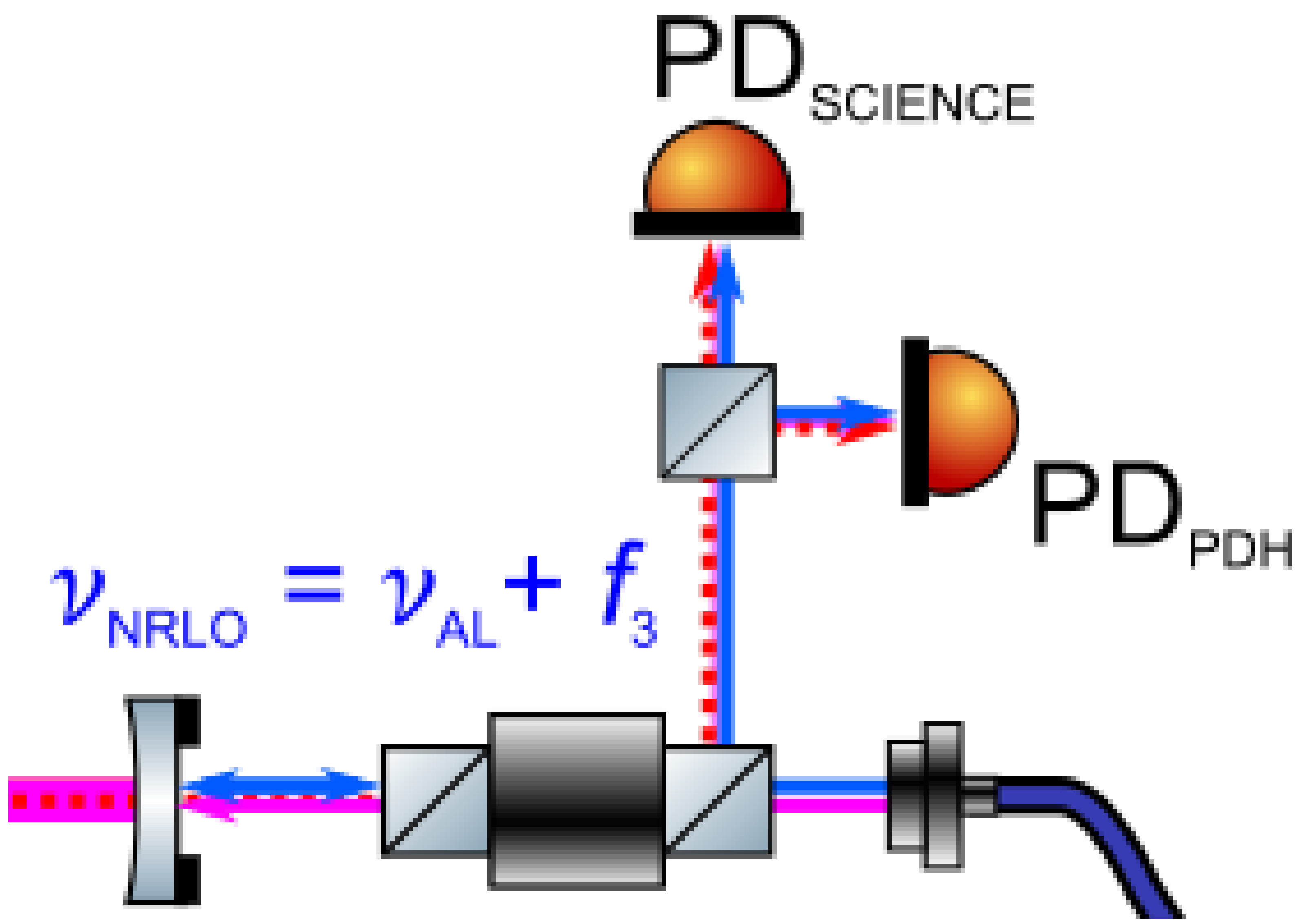

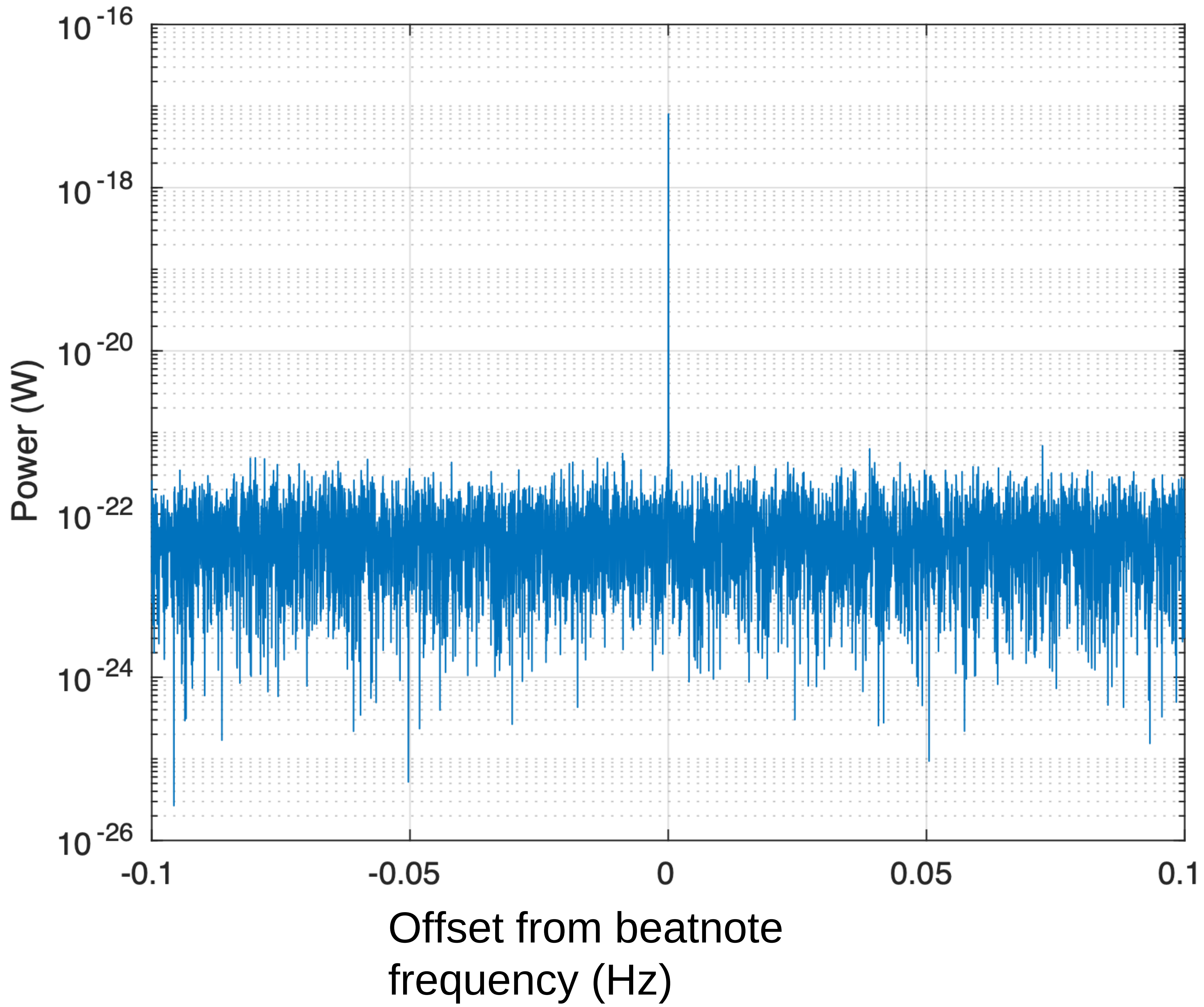

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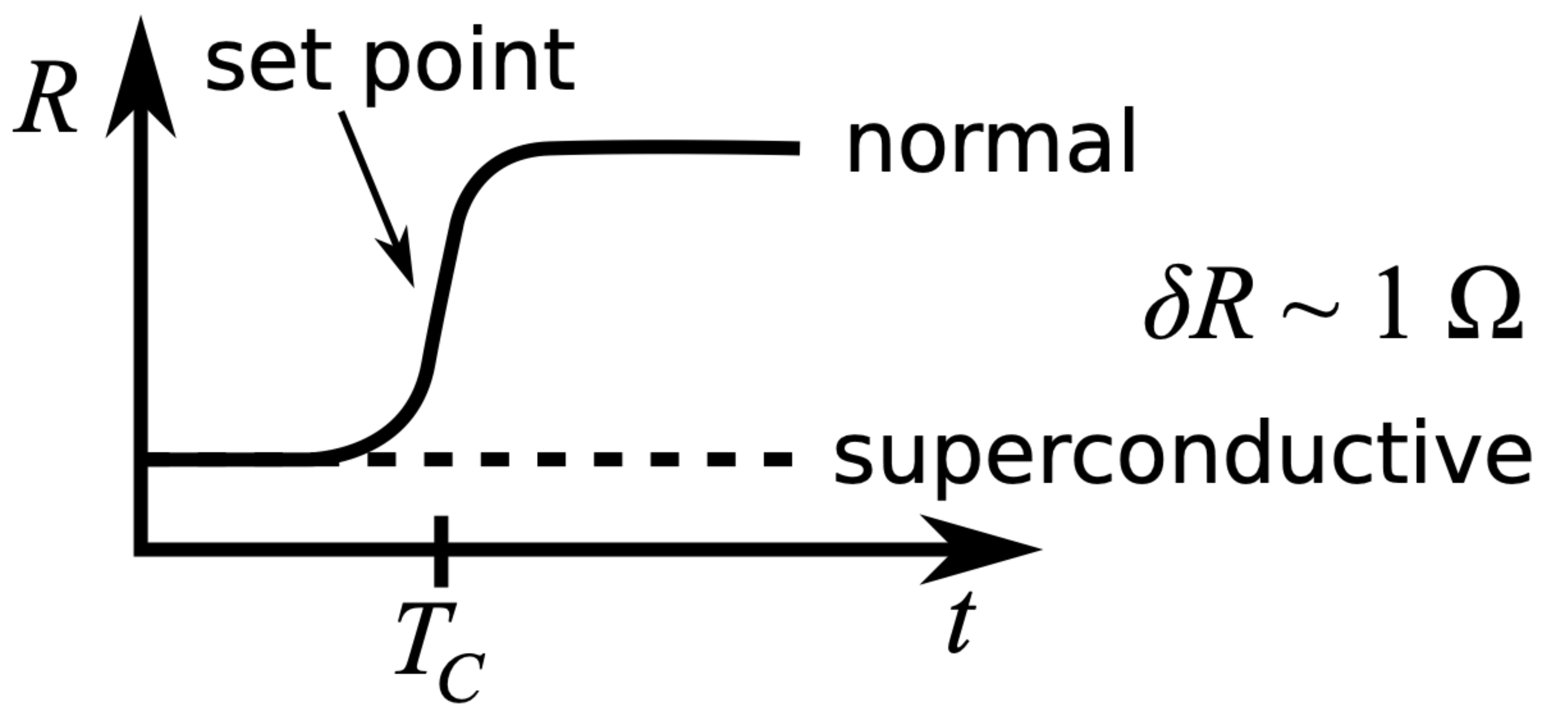
$$+ 2\eta_{lo}\sqrt{P_{lo}P_{sci}}\sin(2\pi(\nu_{HPL} - \nu_{lo})t + \phi) + \cdots$$

Transition Edge Sensor

Counting individual photons

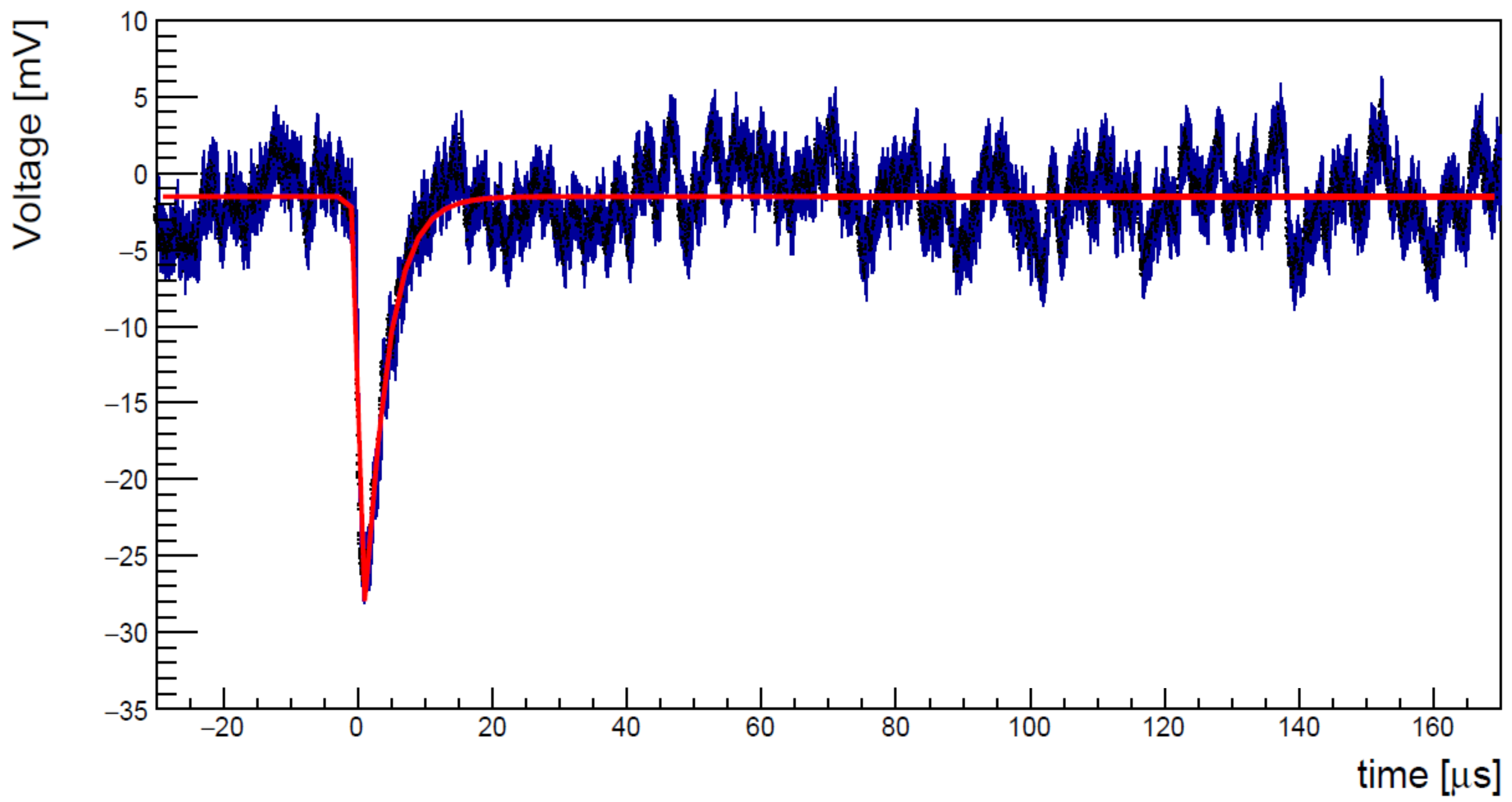
Concept

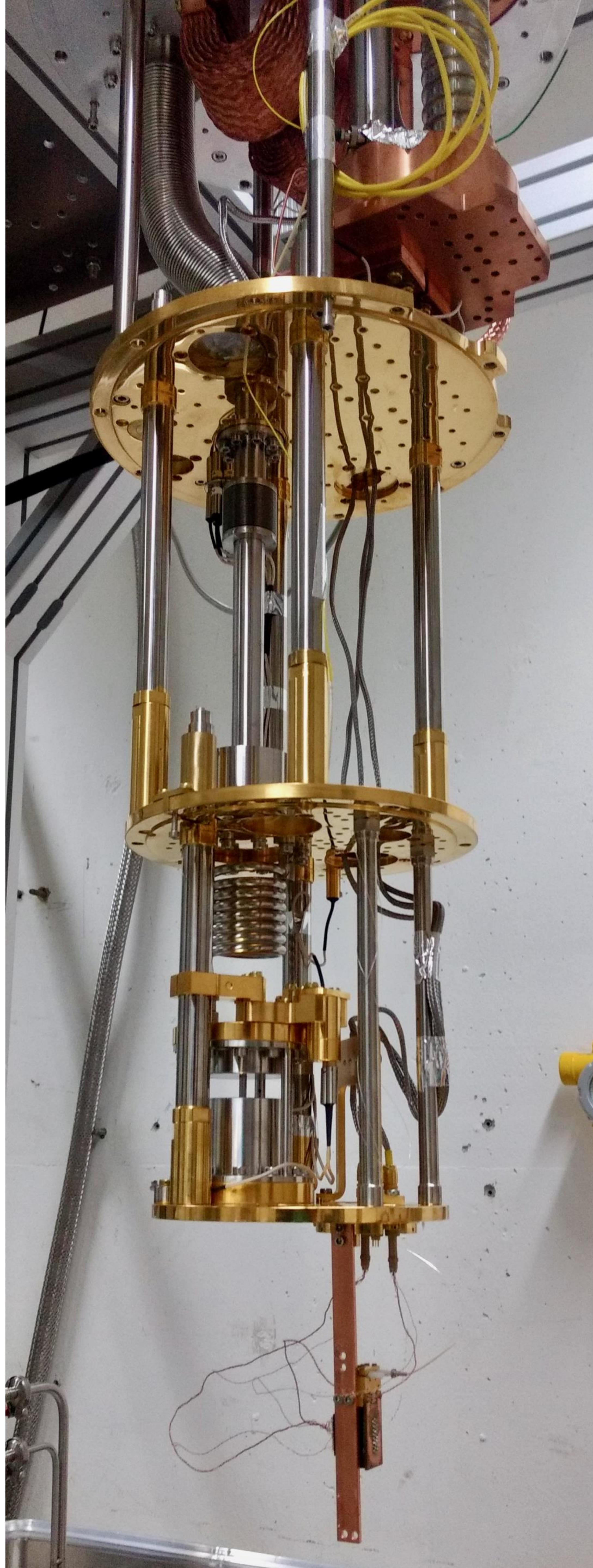
- Chip held at temperature threshold between normal conductivity and superconductivity
- Photon incident on chip transfers heat
- Temperature increase ➜ current pulse
- Squid readout of current via coil



Advantages

- High efficiency and low intrinsic background
- Very different detection method from heterodyne with very different systematics





Commissioning

Building the optical system

Commissioning

Building the optical system

Commissioning

Building the optical system

Commissioning

Building the optical system

ALPS II First Science Run

First science campaign performance

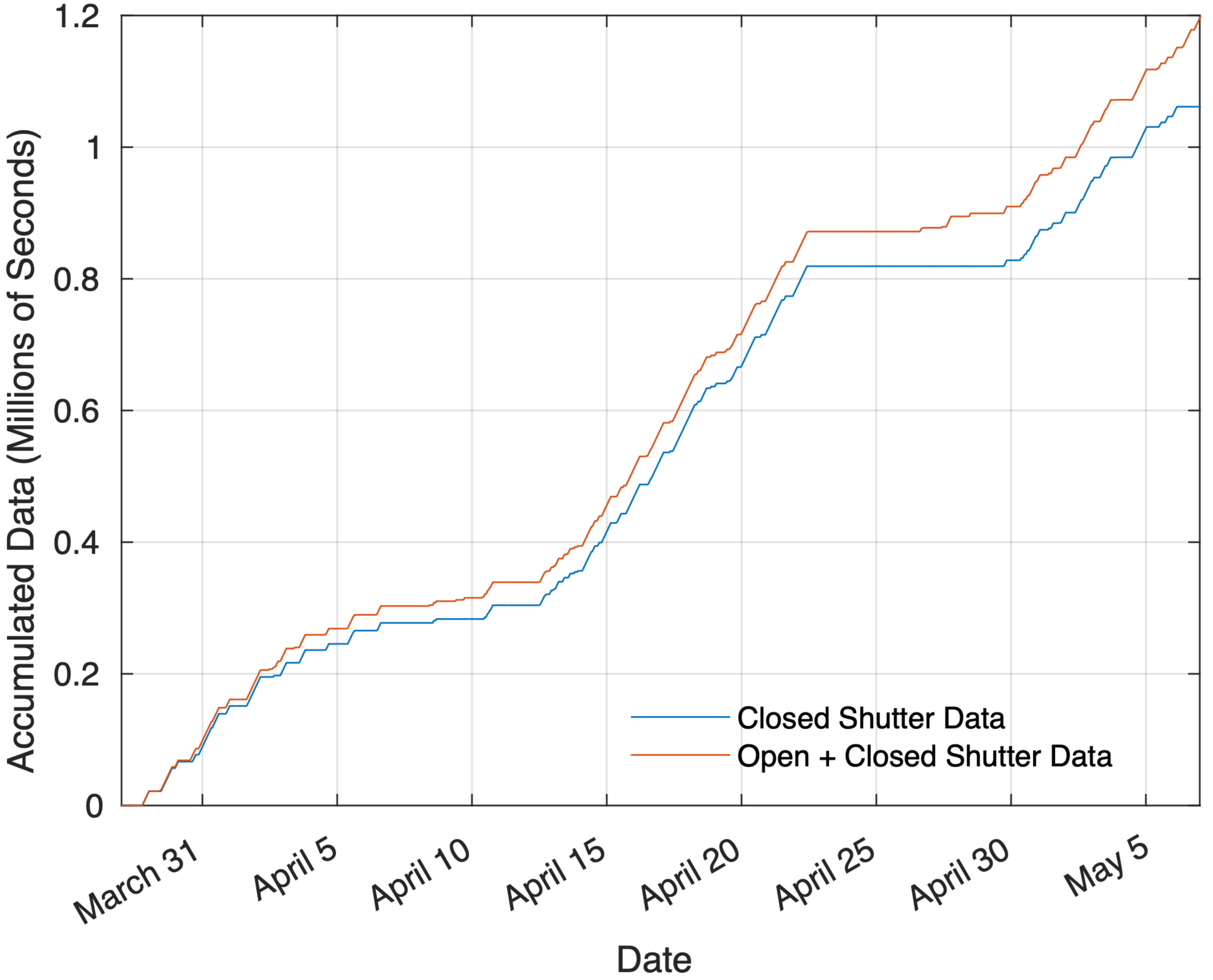
Taking a first look

Scalar Run from February 2-16, 2024

- Laser polarization orthogonal to magnetic field
- Acquired > 620,000 s of closed shutter data
- Average $|\eta|^2$: 0.54

Pseudo Scalar Run from March 30-May 6, 2024

- Laser polarization parallel to magnetic field
- Acquired > 1,060,000 s of closed shutter data
- Average $|\eta|^2$: 0.49

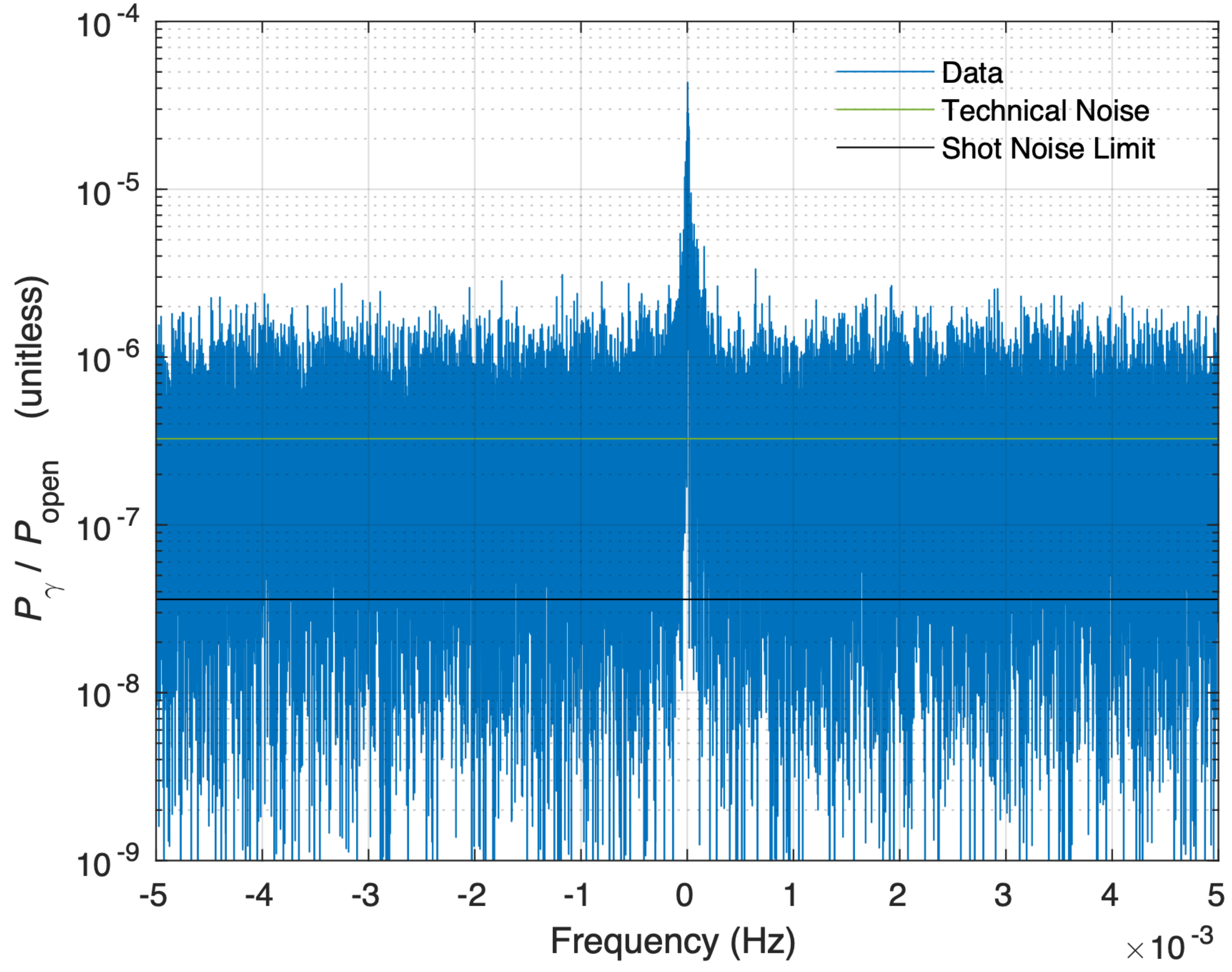


Results

Taking a first look

$$g_{a\gamma\gamma} = \frac{2}{BL}\left(\frac{T_{\text{COB}}P_{\gamma}}{P_{\text{open}}}\right)^{1/4}$$

Limited by stray-light



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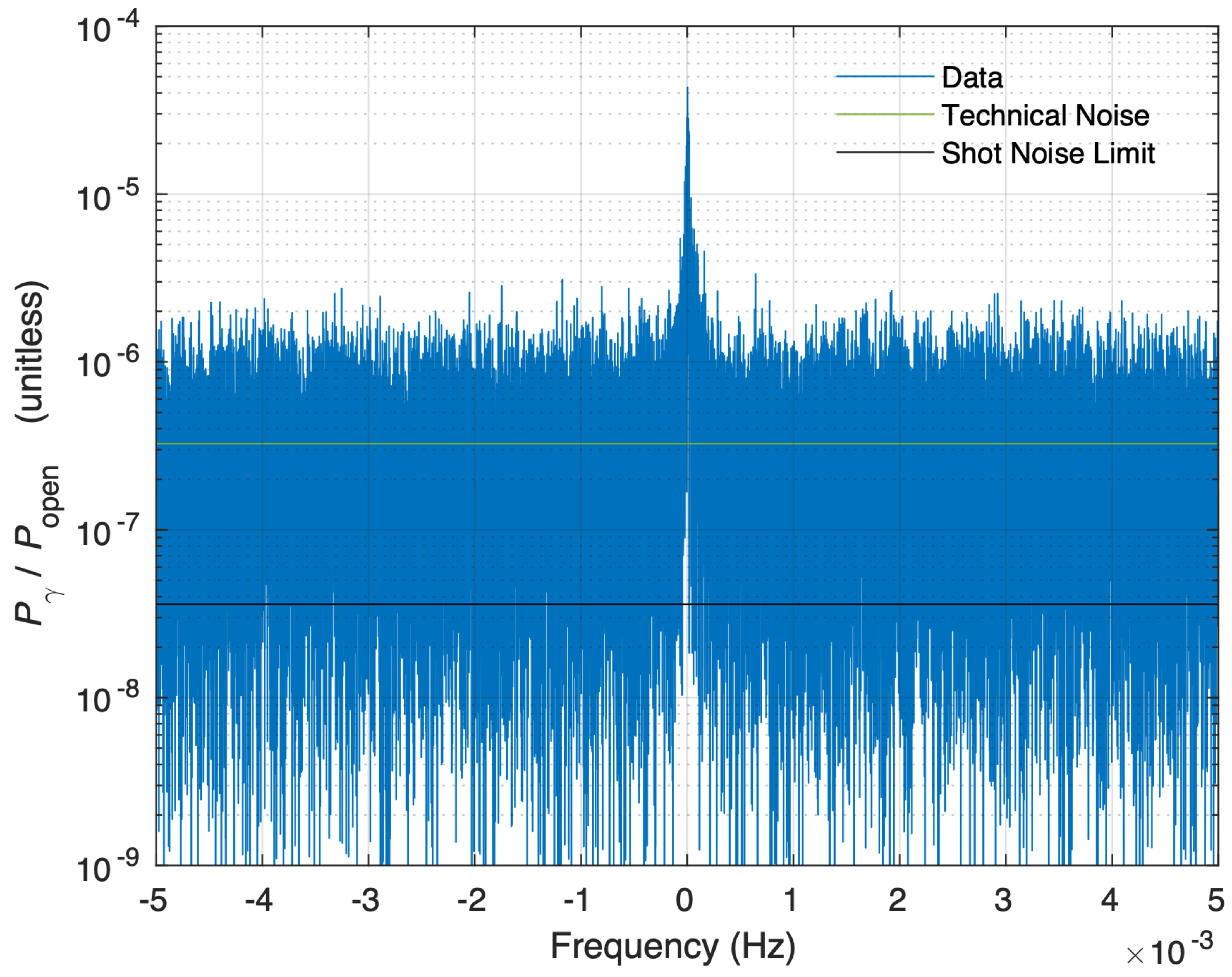
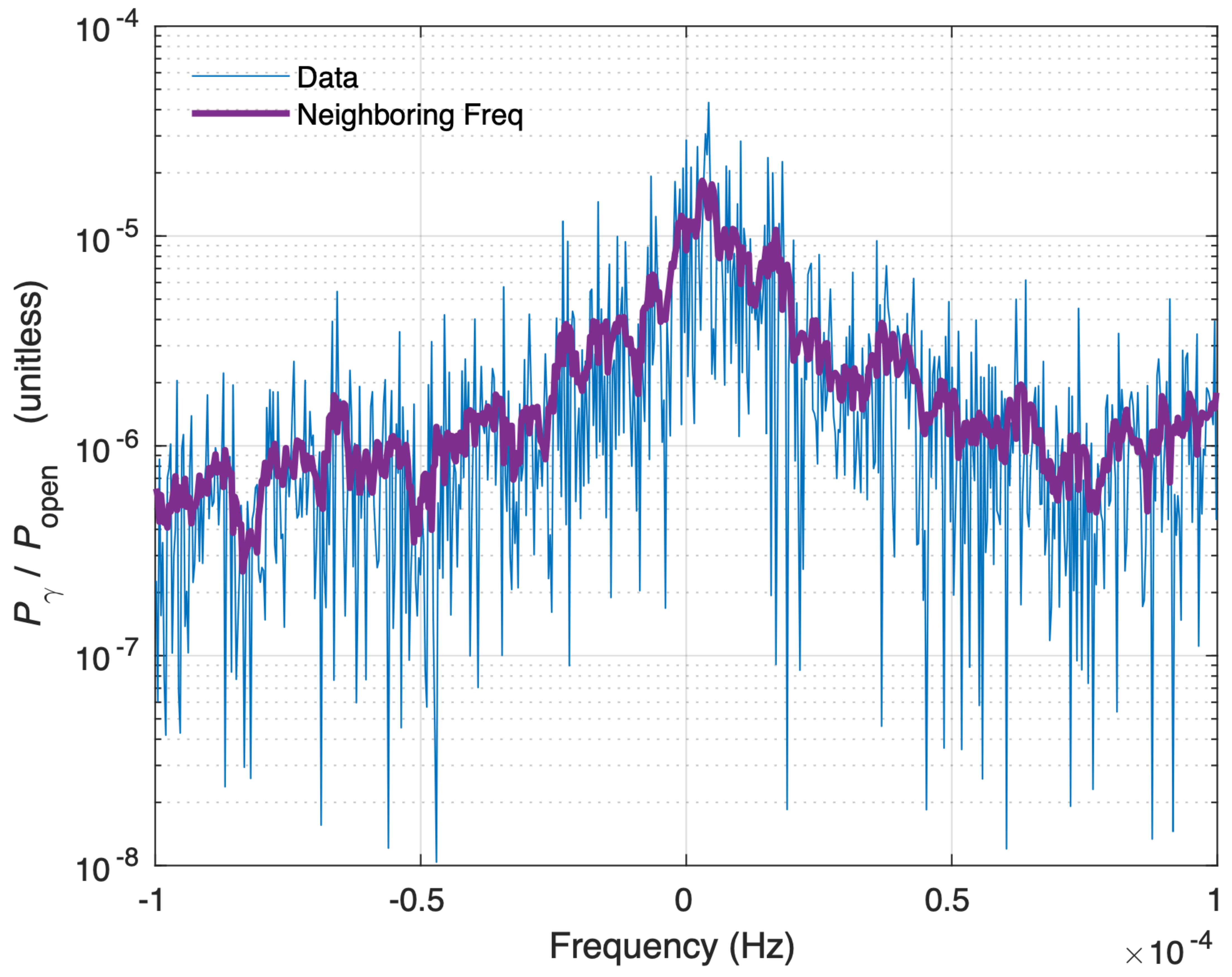
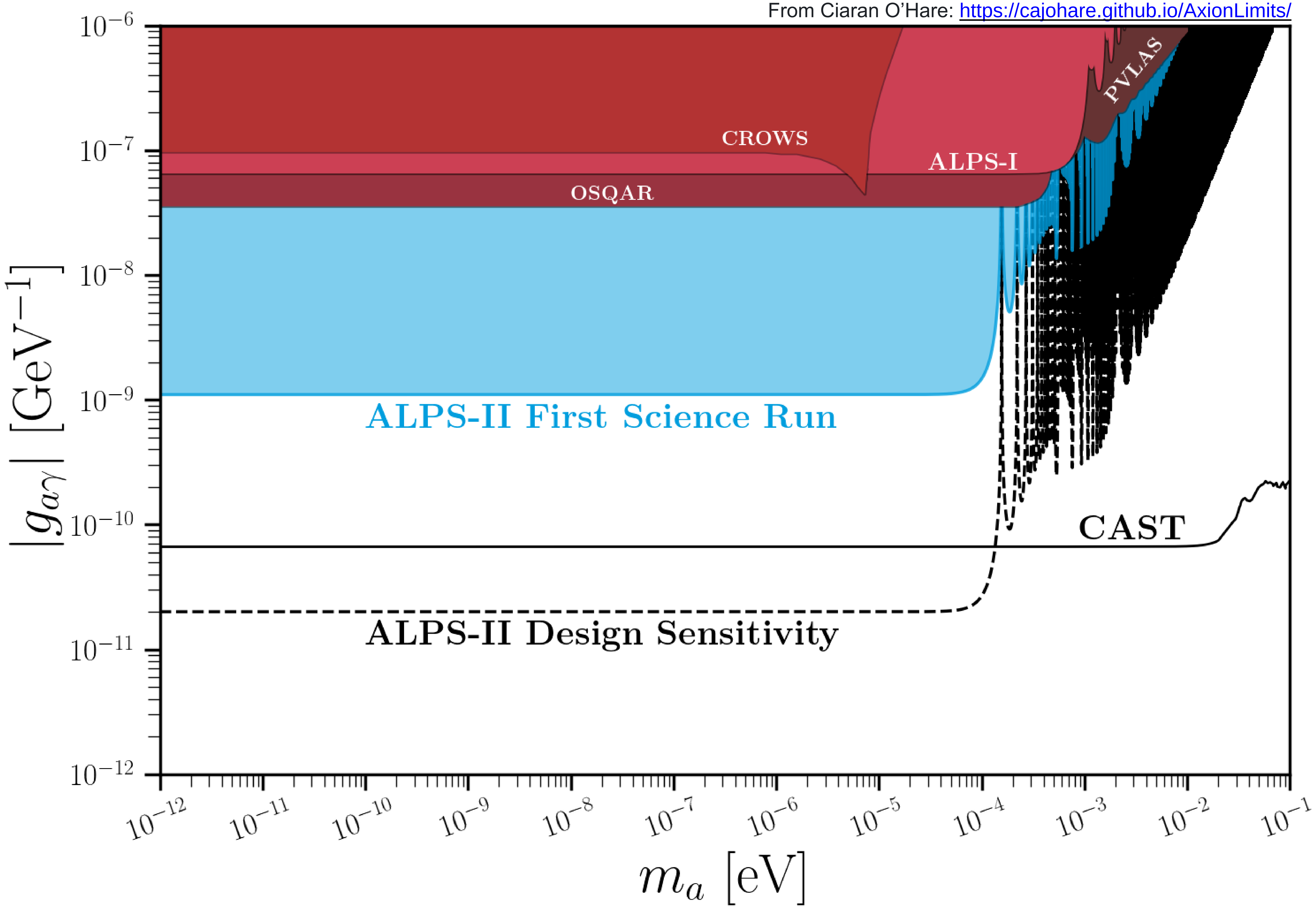




Exclusion limits

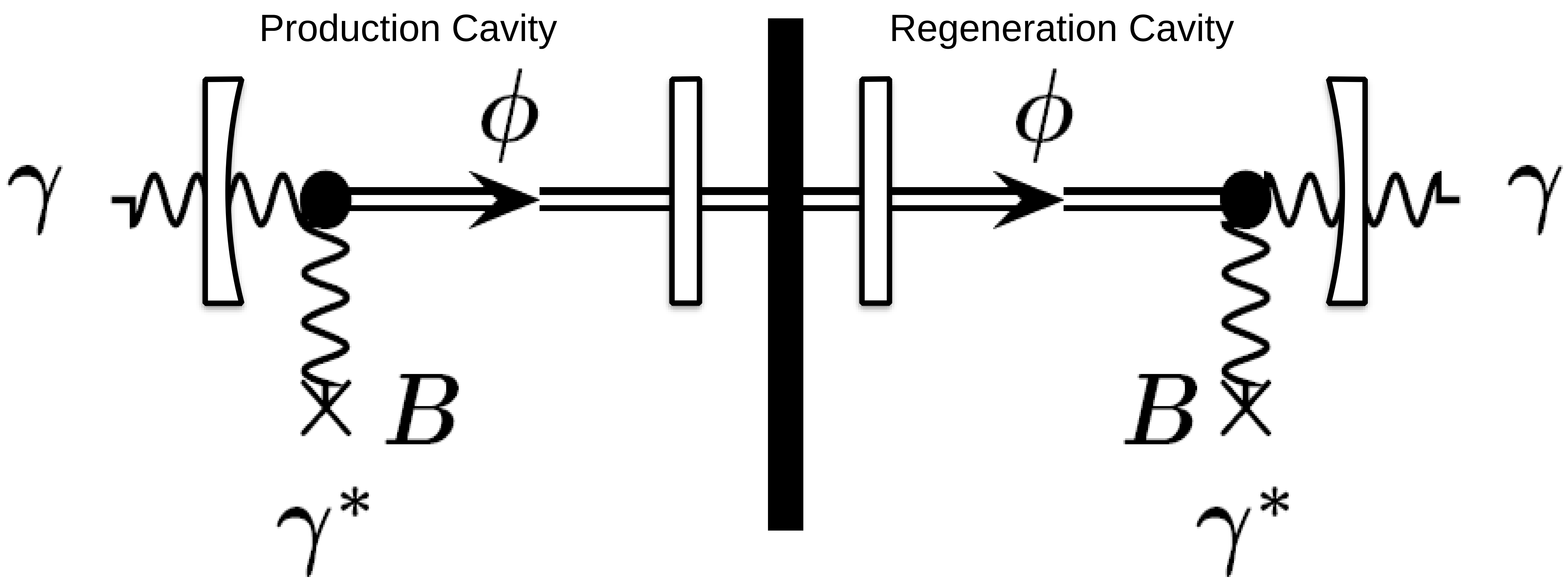
A factor of ~30 improvement from OSQAR

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



ALPS II Full System

Adding the production cavity



$$P_{\gamma} = \left(\frac{g_{a\gamma\gamma}BL}{2}\right)^{4} \eta\beta_{\mathrm{R}}\beta_{\mathrm{C}}P_{i}$$

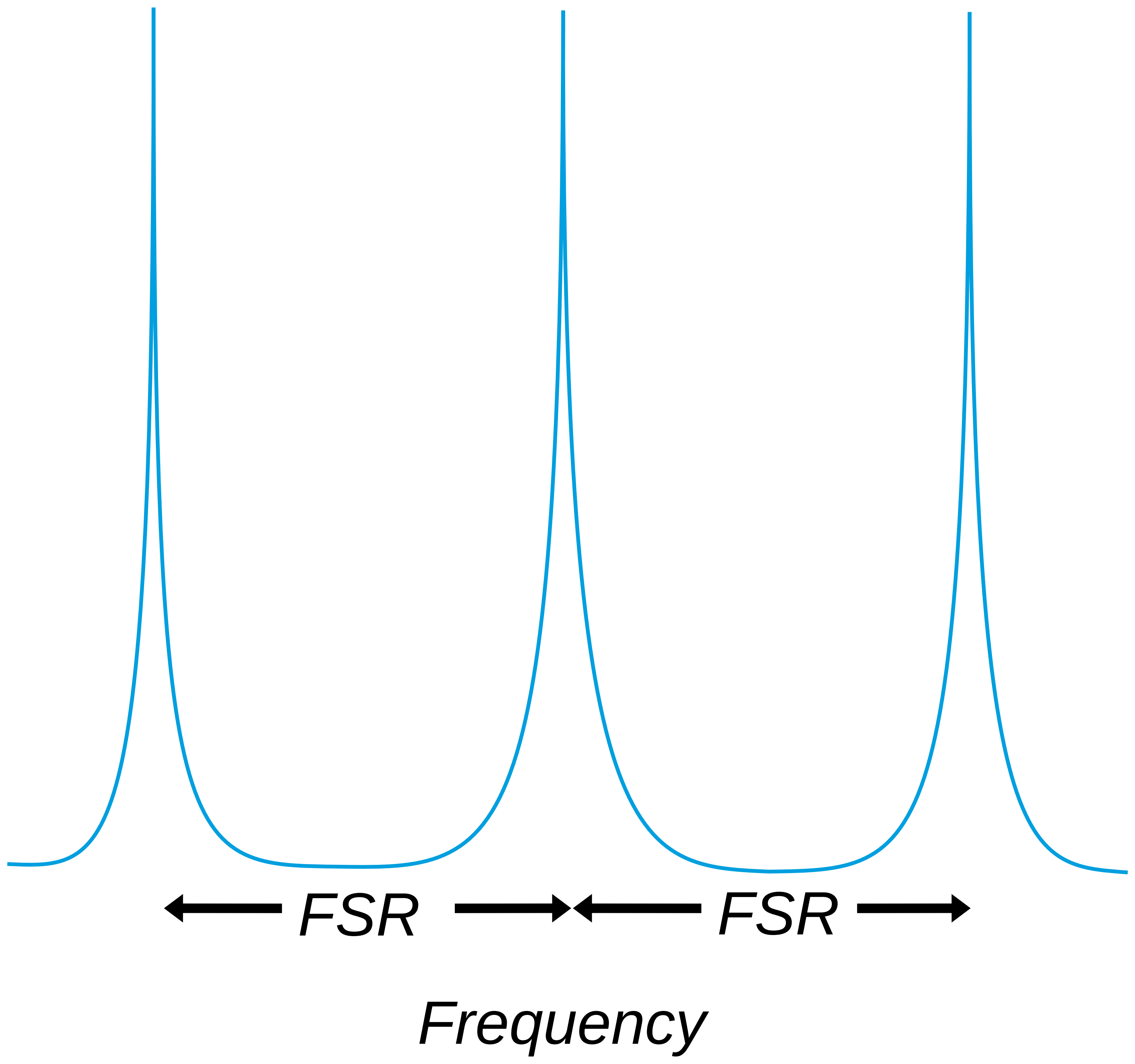
Sensing Length Noise with an Optical Cavity

Testing our Environment

Cavities are sensitive to length noise

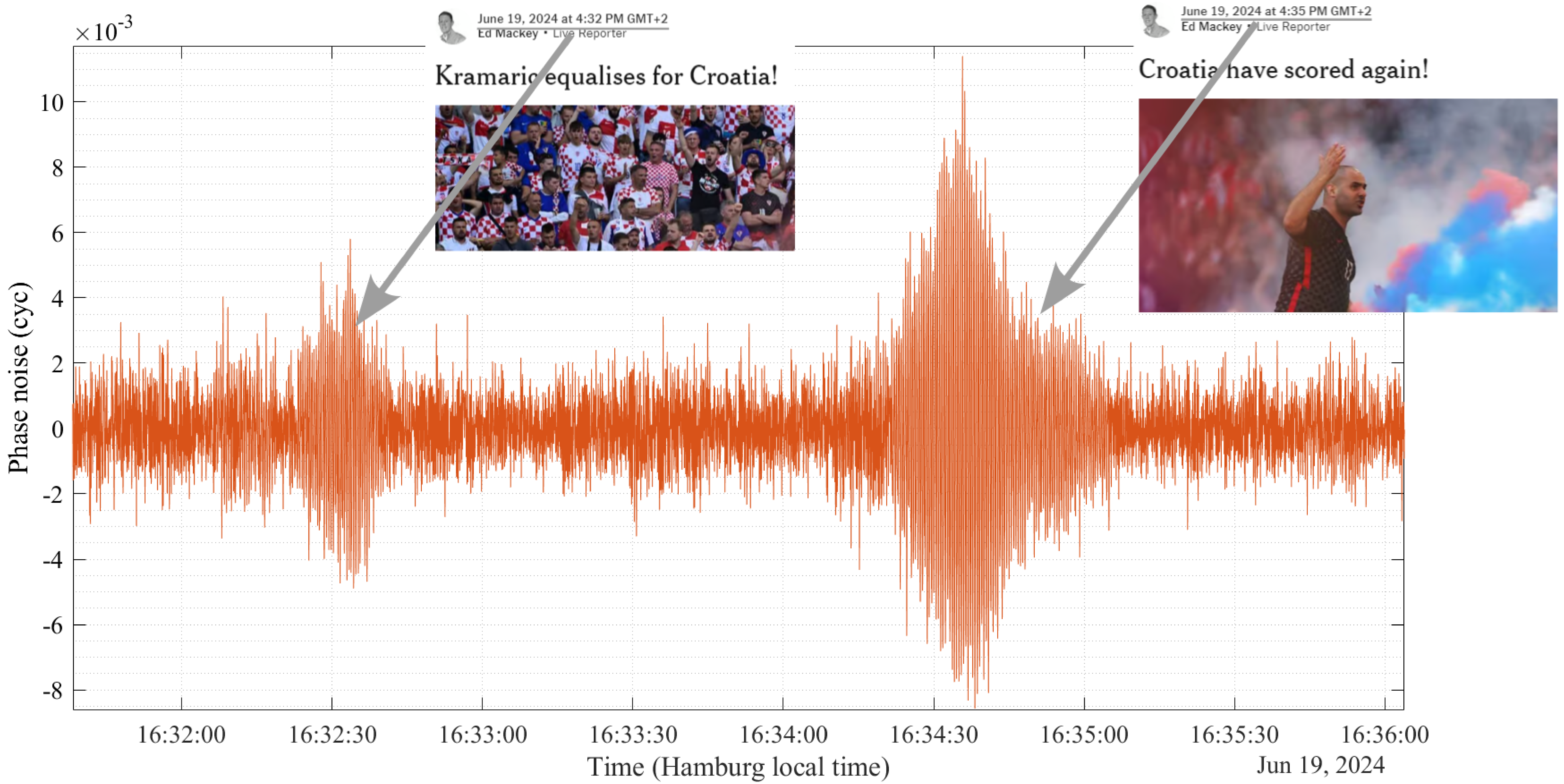
- Risk, but also an opportunity as we can use the cavity to sense ground motion
- Cavity length is encoded on the frequency spacing of the resonances
- Can measure changes in this frequency spacing

$$FSR = \frac{c}{2L}$$



Sensing Length Noise with an Optical Cavity

Testing our Environment



Sensing Length Noise with an Optical Cavity

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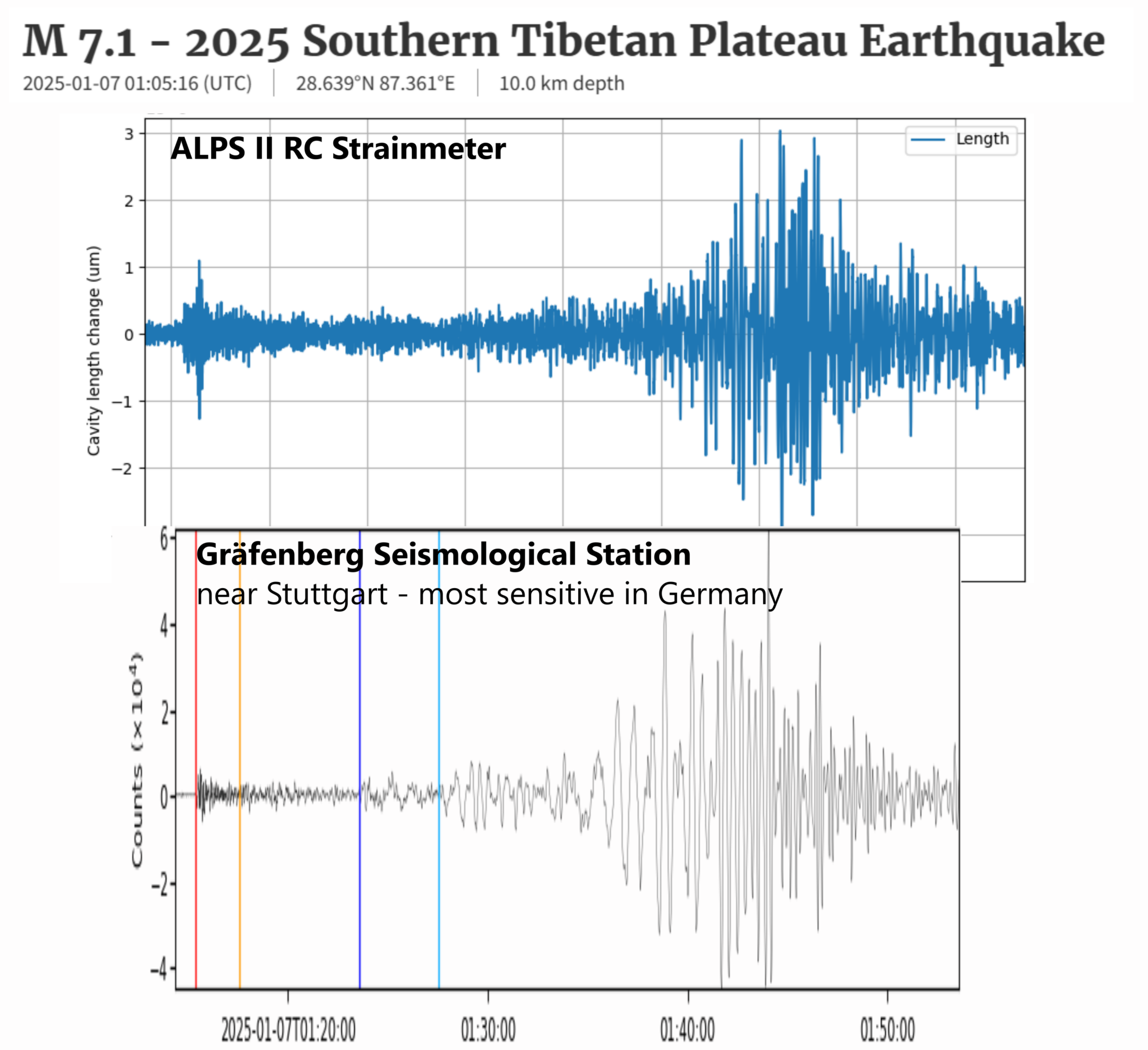


P-Wave Arrival @ Grafenberg Seismology Station
2025-01-07 01:15:21 +10m 5s

SWIFT QUAKE.

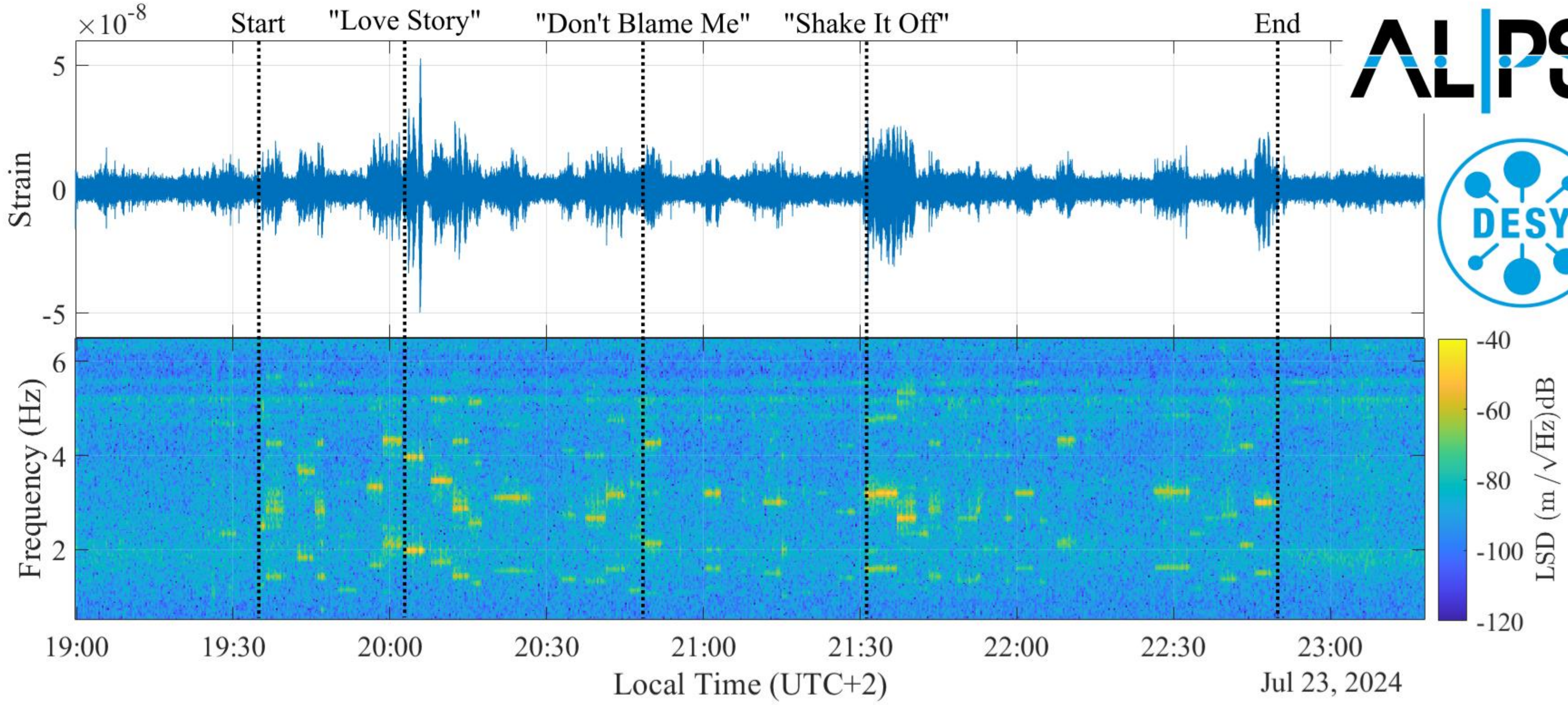

tagesschau • Follow
Taylor-Swift-Konzert in Hamburg
Mehr Vibrationen als bei der Fußball-EM
Sie waren noch in vier Kilo-
meter Entfernung messbar.
tagesschau


tagesschau • Follow
Konzert von Swift bringt Boden zum vibrieren
Forschende der Uni Hamburg untersuchten mit einem Netzwerk aus Glasfaserkabeln als seismische Sensoren, welche Vibrationen die Konzerte der Sängerin auslösen
Erste Auswertungen ergaben, dass die Vibrationen vier Kilometer entfernt messbar waren – es seien aber Bodenvibrationen, keine Erdbeben
Laut dem Deutschen Elektronen-Synchrotron (DESY) war das Signal doppelt so groß wie bei den EM-Spielen


tagesschau • Follow
Das waren für uns die größten Störungen, die wir jeweils in unserem Messapparat gesehen haben.
Axel Lindner
Deutsches Elektronen-Synchrotron (DESY)
tagesschau
Quelle: ndr.de
225K
1,913
Liked by robnroll21 and others

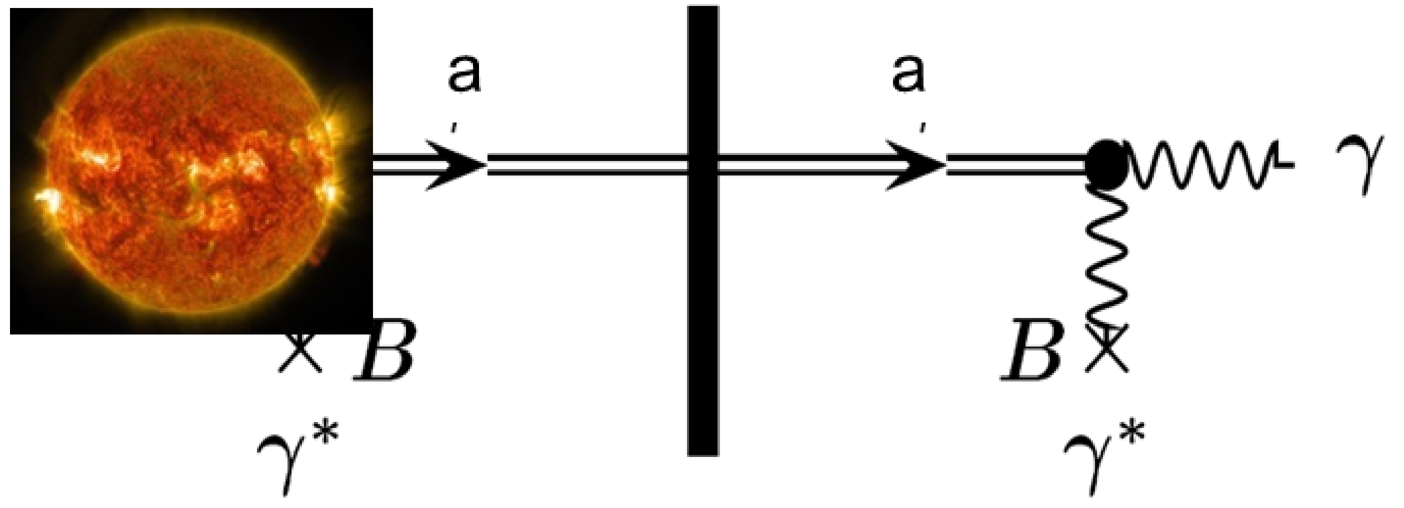
Sensing Length Noise with an Optical Cavity

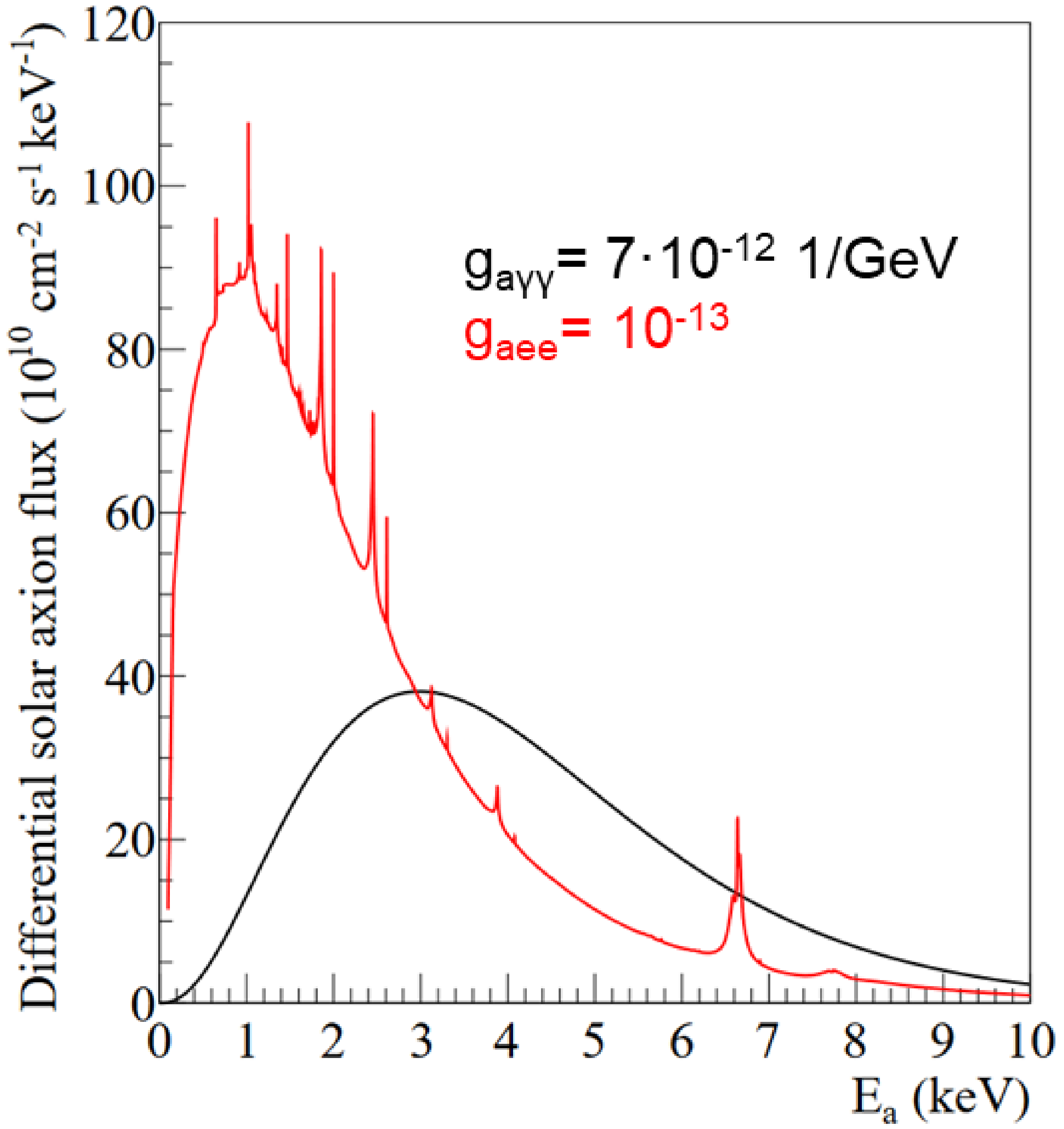
Testing our Environment



Measure the Sun's dark luminosity

International AXion Observatory IAXO



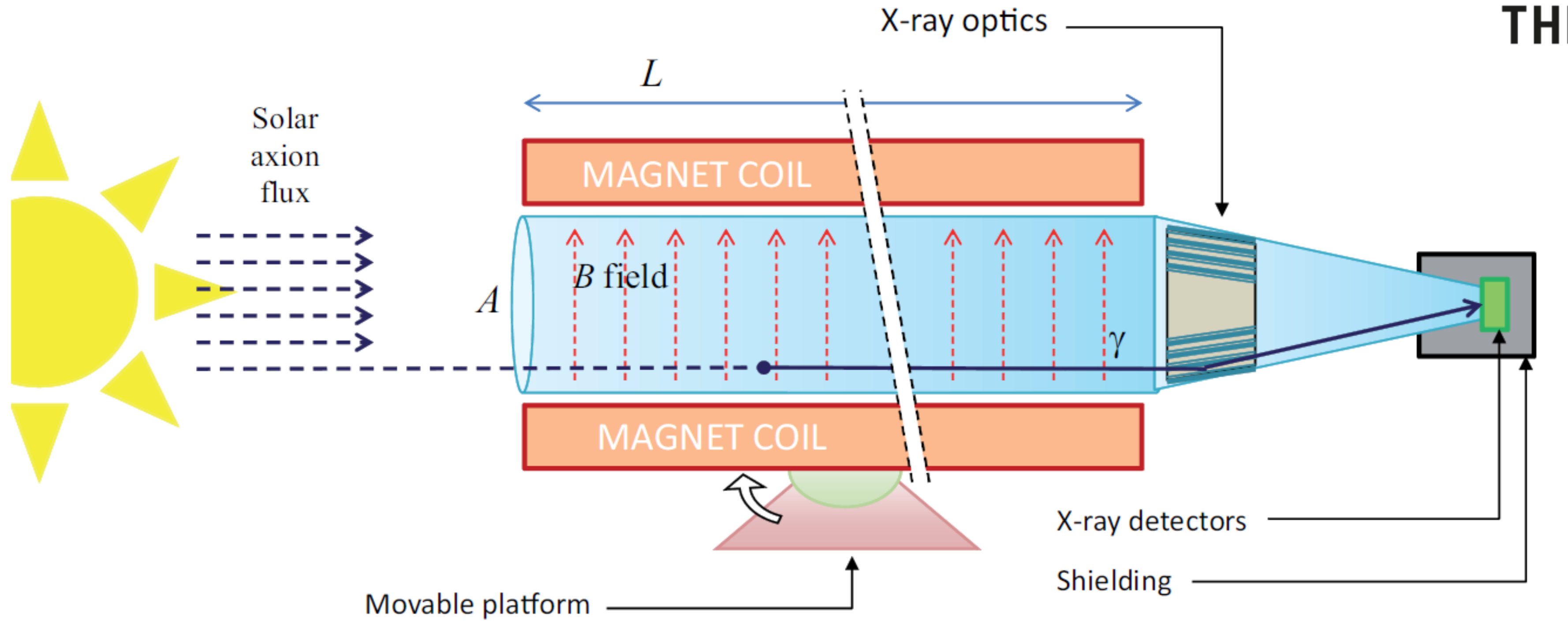


Solar axions generated via couplings to photons, electrons and nuclear transitions (i.e. 14.4 keV).

JCAP01(2016)034

BabyIAXO located in the hall HERA South (option).

Annual Review of Nuclear and Particle Science, Vol. 65: 485-514 (2015)



MATTER AND THE UNIVERSE MU

Full members: Kirchhoff Institute for Physics, Heidelberg U. (Germany) | Siegen University (Germany) | University of Bonn (Germany) | DESY (Germany) | University of Mainz (Germany) | Technical University Munich (TUM) (Germany) | University of Hamburg (Germany) | MPE/PANTER (Germany) | MPP Munich (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | INAF-Brera (Italy) | CERN (Switzerland) | ICCUB-Barcelona (Spain) | Barry University (USA) | MIT (USA) | LLNL (USA) | University of Cape Town (S. Africa) | CEFCA-Teruel (Spain) | U. Polytechnical of Cartagena (Spain)

Associate members: DTU (Denmark) | U. Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

BabyIAXO achievements and goals

Ready to start construction - reach sensitivity beyond ALPS II

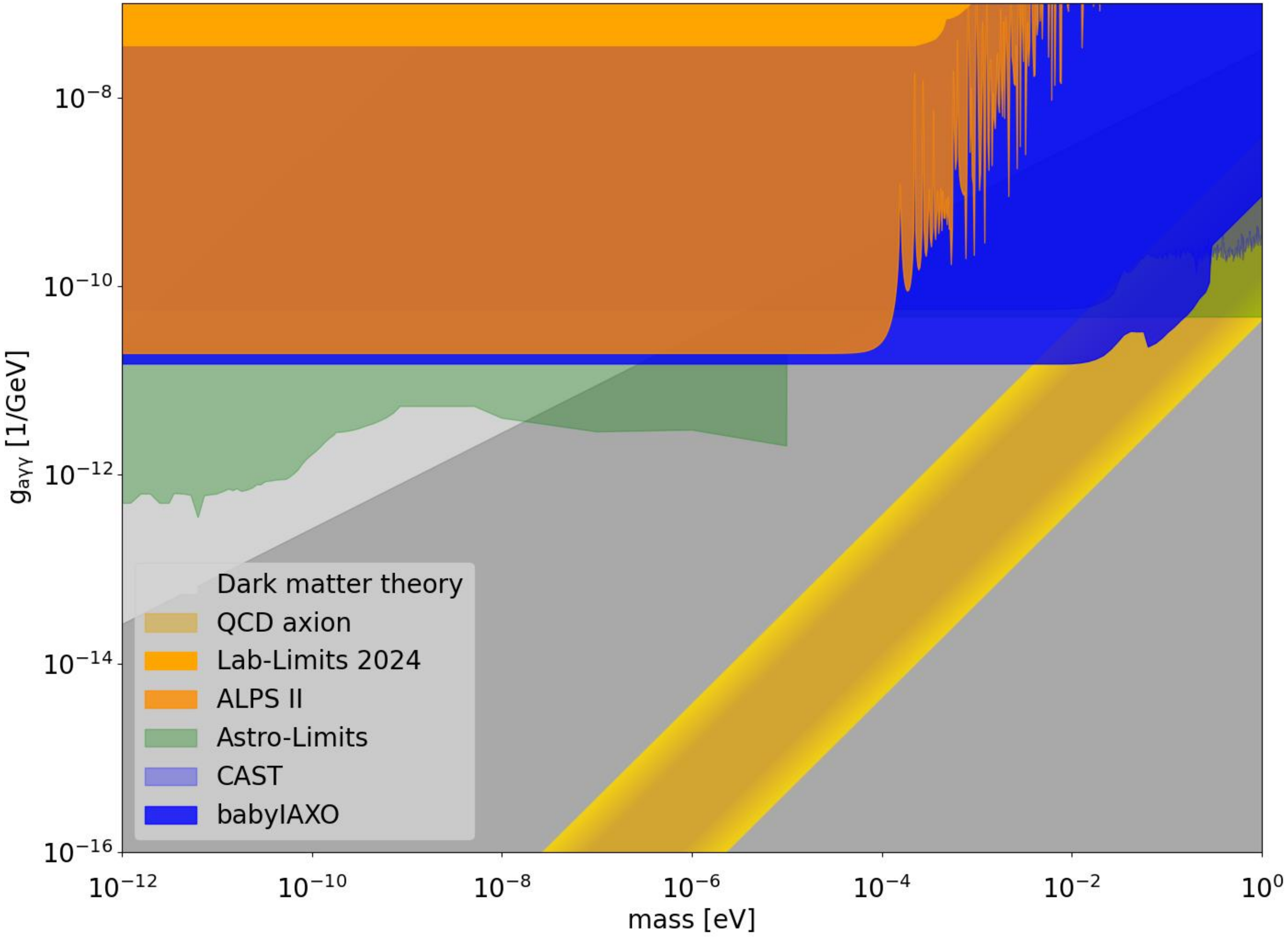
Key achievements:

- Magnet CDR and TDR (2025), recovered from suspension of Russia in February 2022.
- Promising funding scenario.

- Extensions of the science case:
  - Direct dark matter searches with RADES.
  - Supernova axions.

Component / Status	Technical	Funding
Structure & Drive system	(✓)	(✓)
Vacuum & Gas System	✓	✓
Magnet	(✓)	(?)
X-ray Telescopes	✓	✓
Detectors	✓	✓

Laboratory experiments and astrophysics 2035



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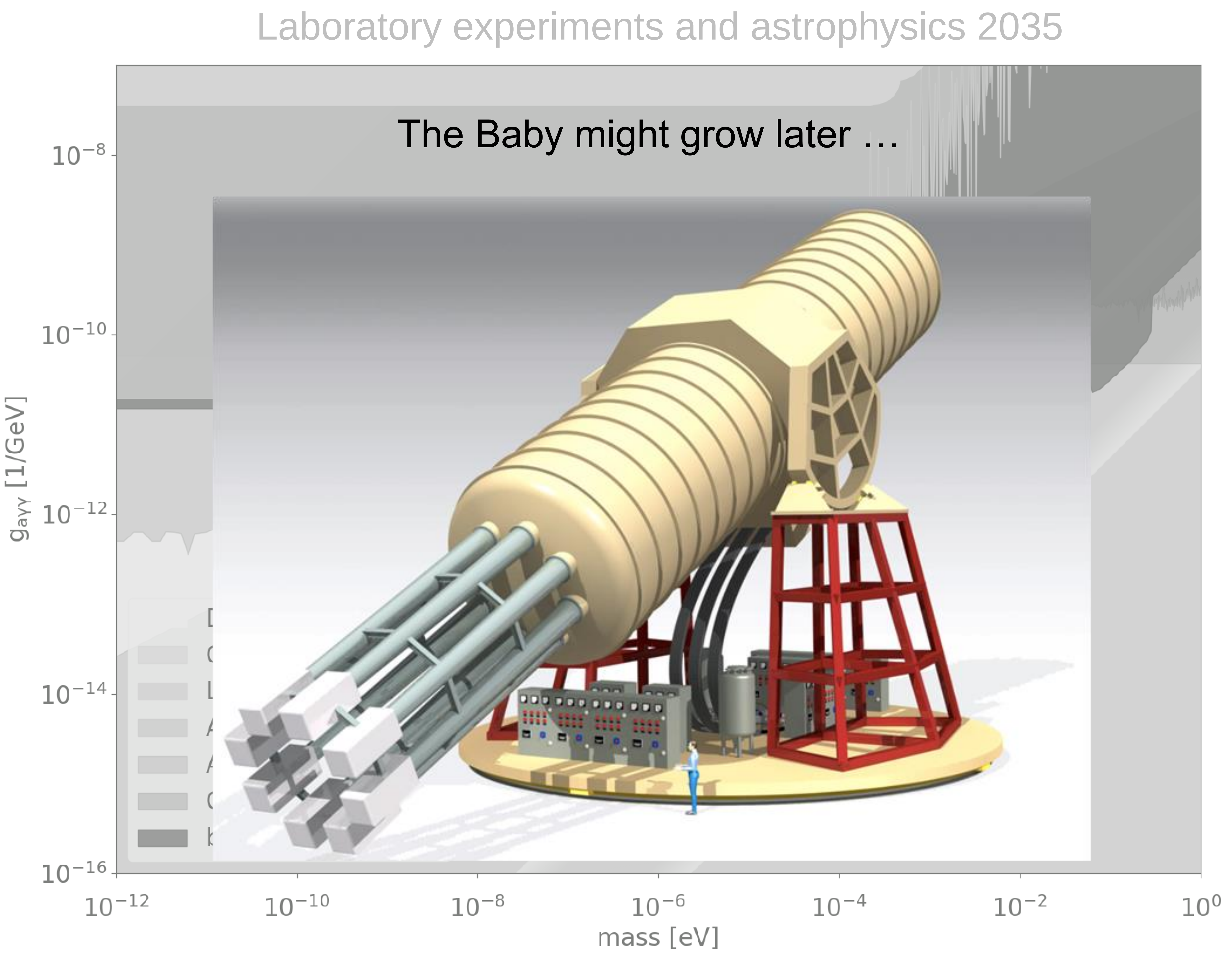
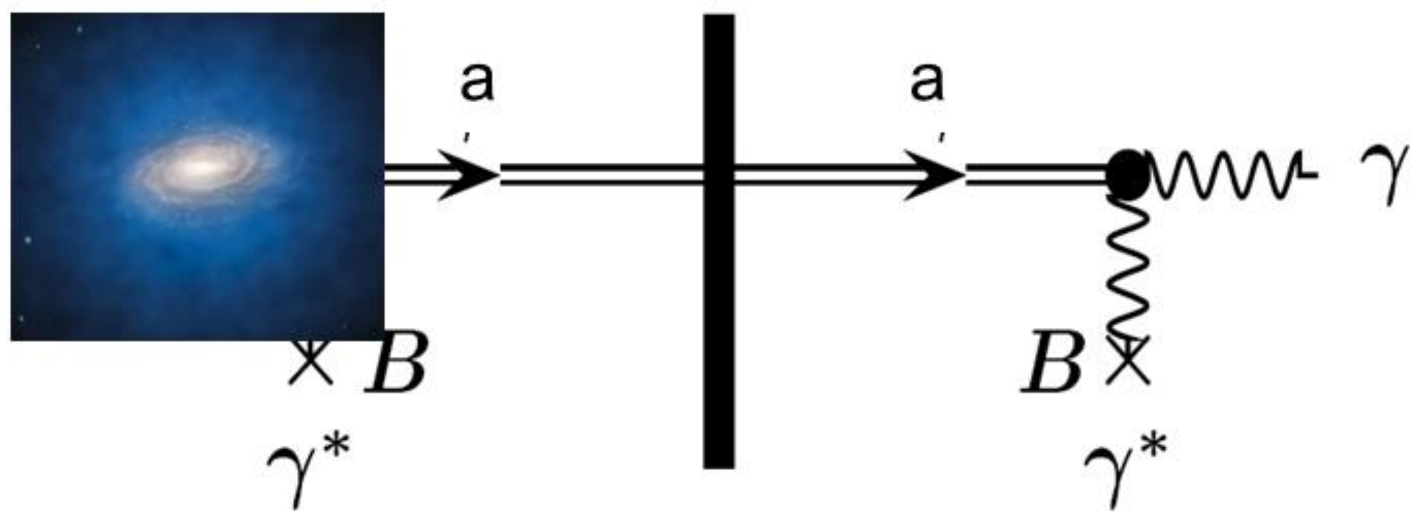


Finding ambient dark matter

MAgnetized Disc and Mirror Axion eXperiment

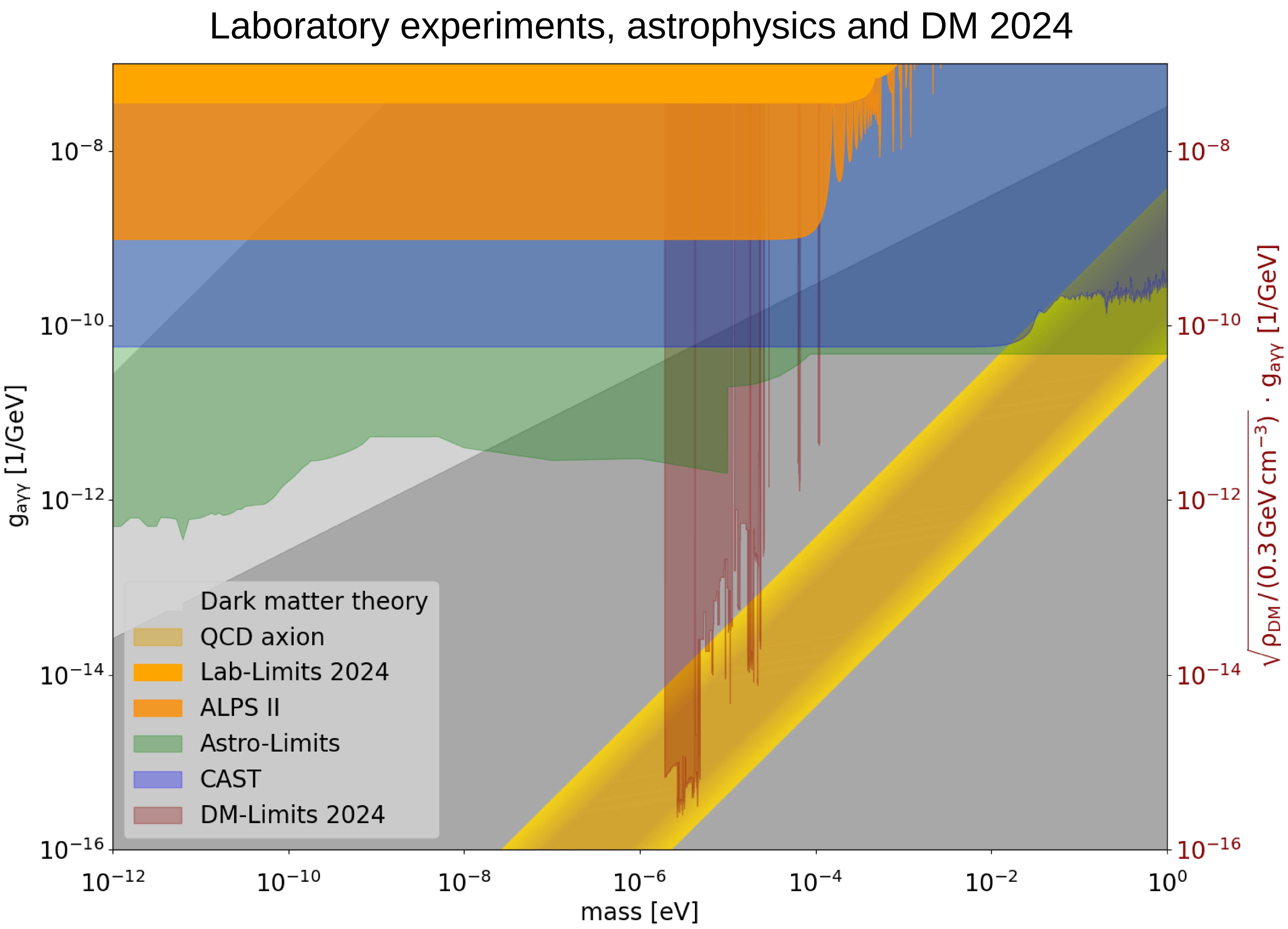


Purely laboratory based searches

Solar axion searches (CAST@CERN)

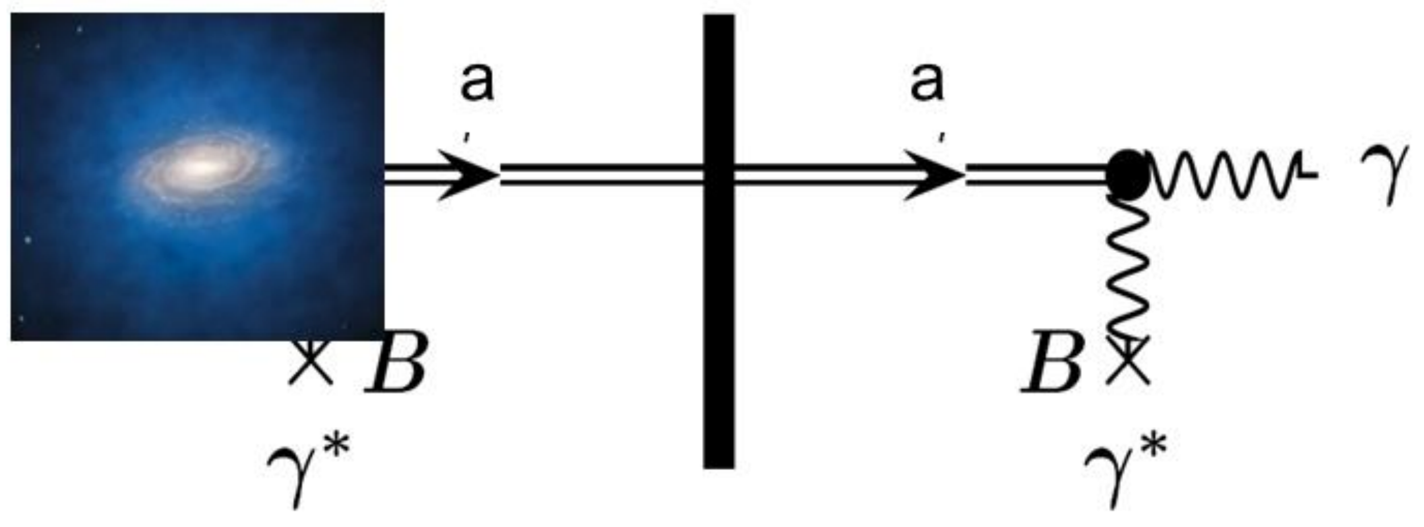
Astrophysical searches

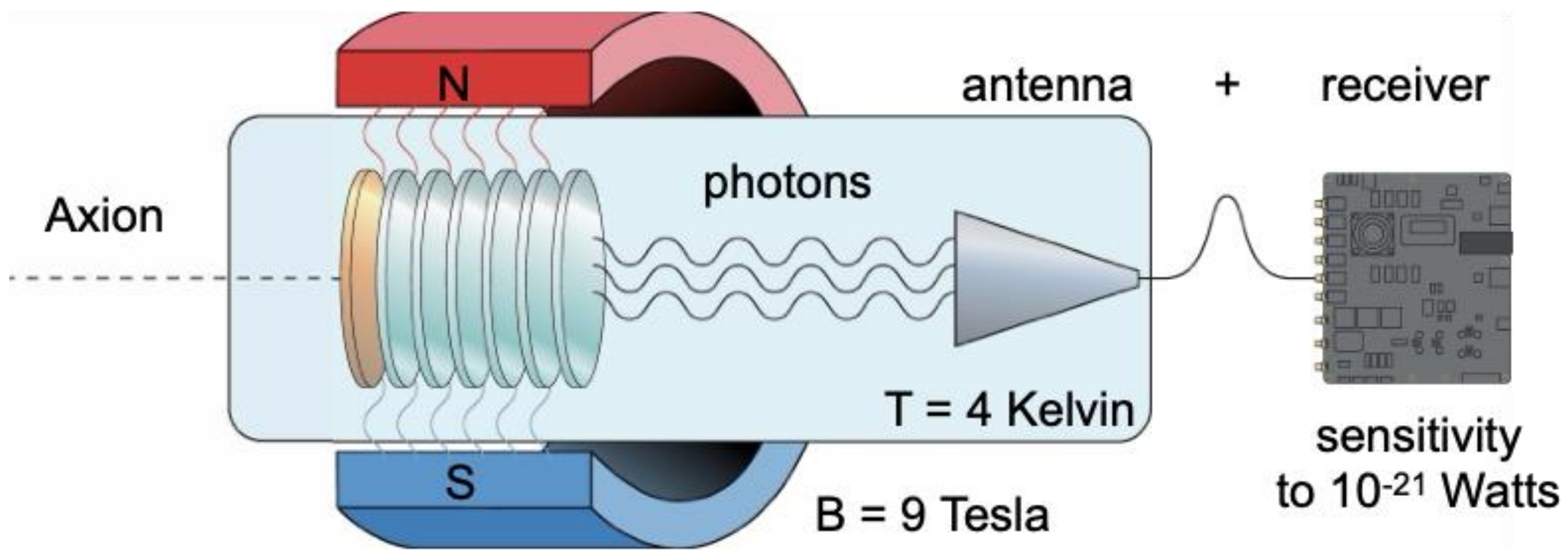
Direct dark matter searches (ADMX@FNAL)

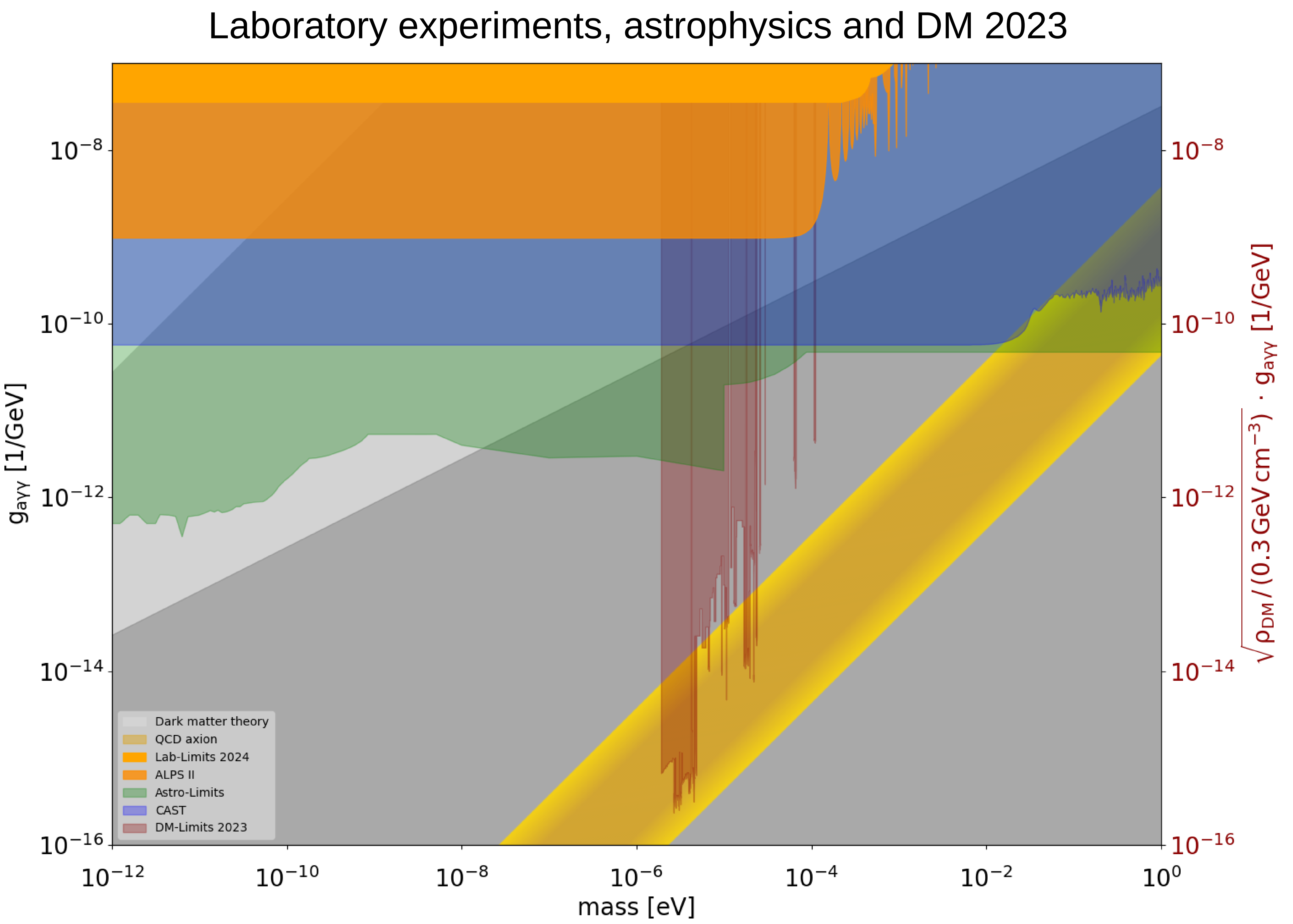


Finding ambient dark matter

MADMAX: new technologies to search for 10-100 μeV axions







MAgnetized Disc and Mirror Axion eXperiment

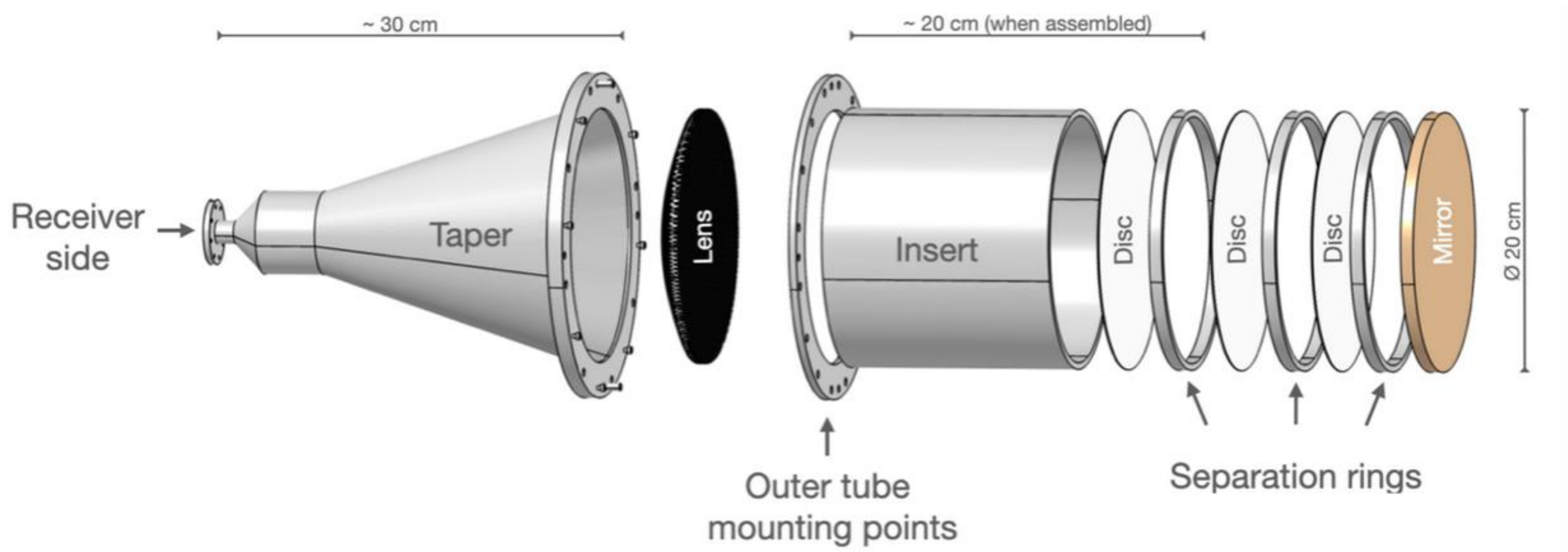
https://madmax.mpp.mpg.de/

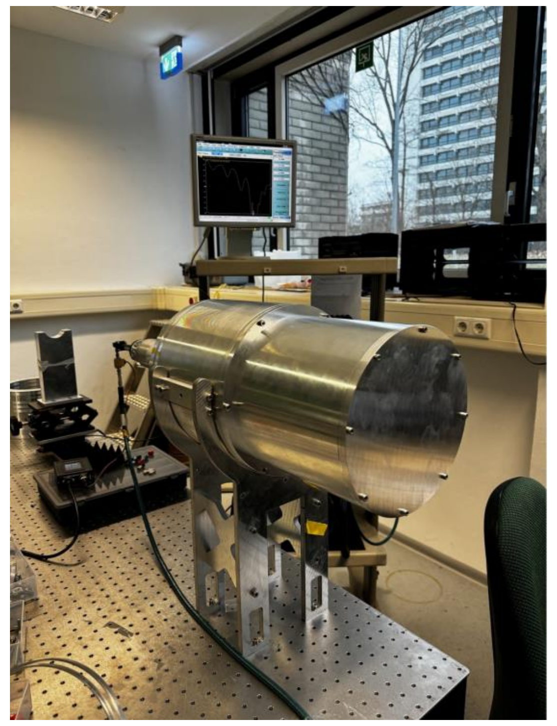
- CPPM, France
- DESY Hamburg, Germany
- Néel Institute, Grenoble, France
- **MPI für Physik, Munich, Germany**
- MPI für Radioastronomie, Bonn, Germany
- RWTH Aachen, Germany
- University of Hamburg, Germany
- University of Tübingen, Germany
- University of Zaragoza, Spain

MADMAX achievements

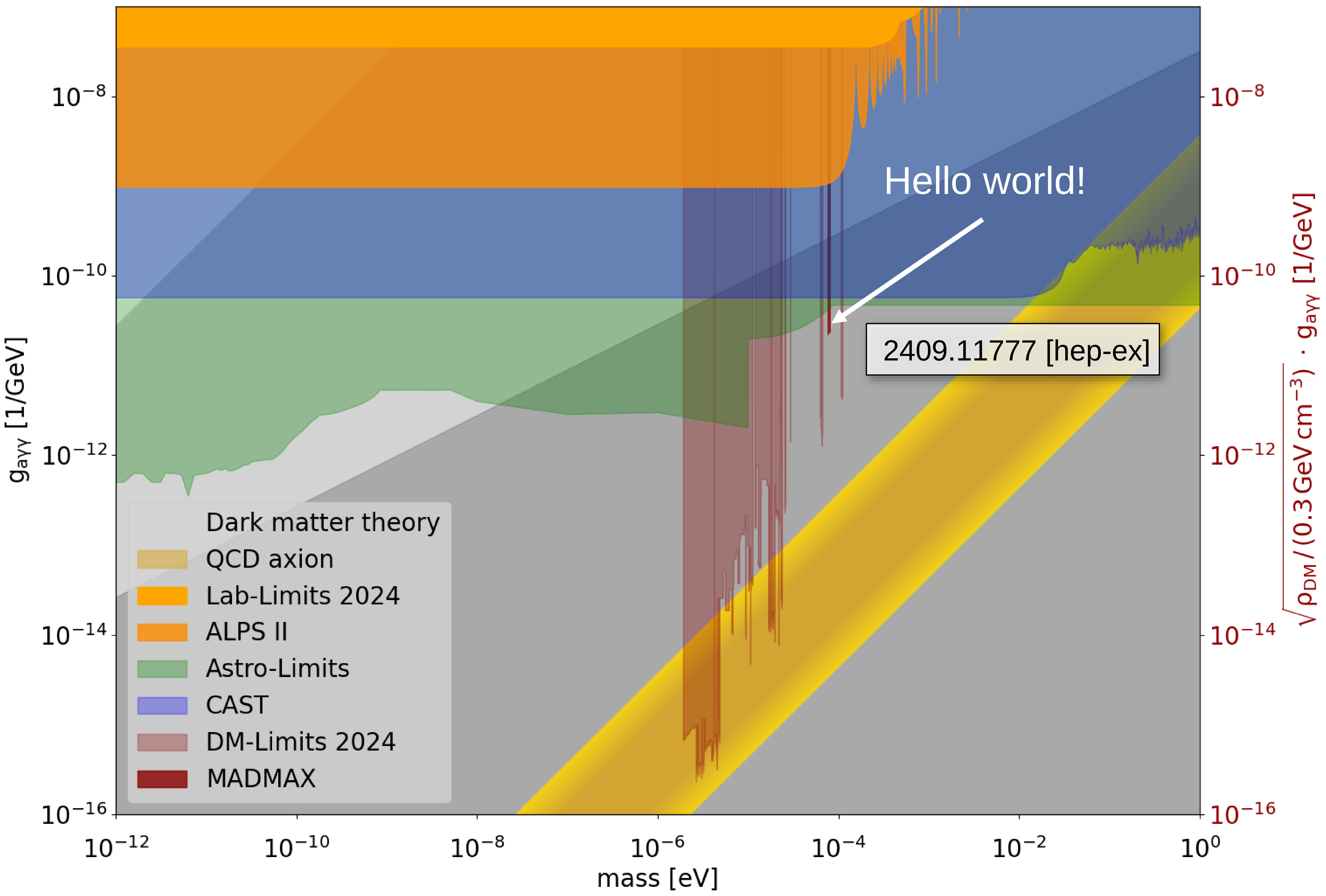
Science results on axion and dark photon searches

Technical feasibility demonstrated!





Laboratory experiments, astrophysics and DM 2024

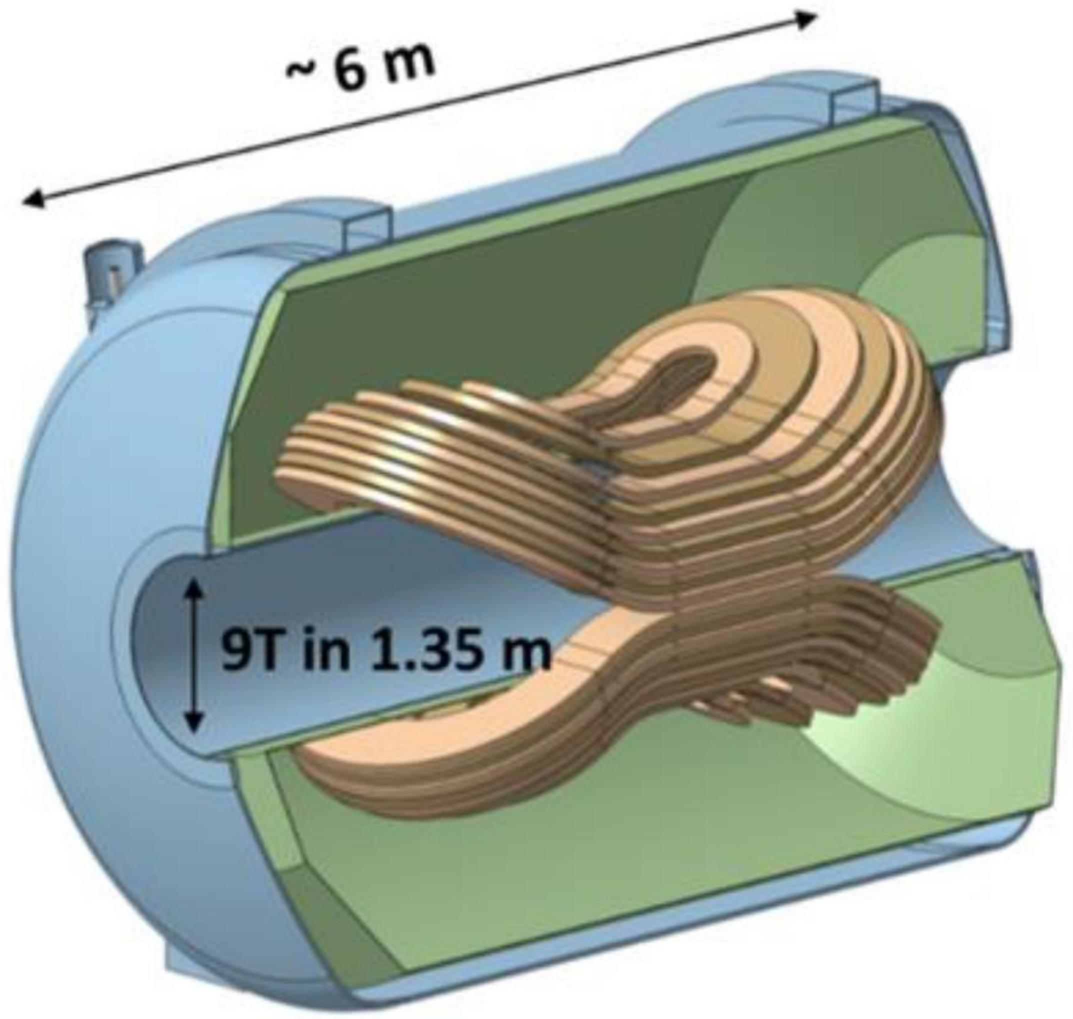


MADMAX goals

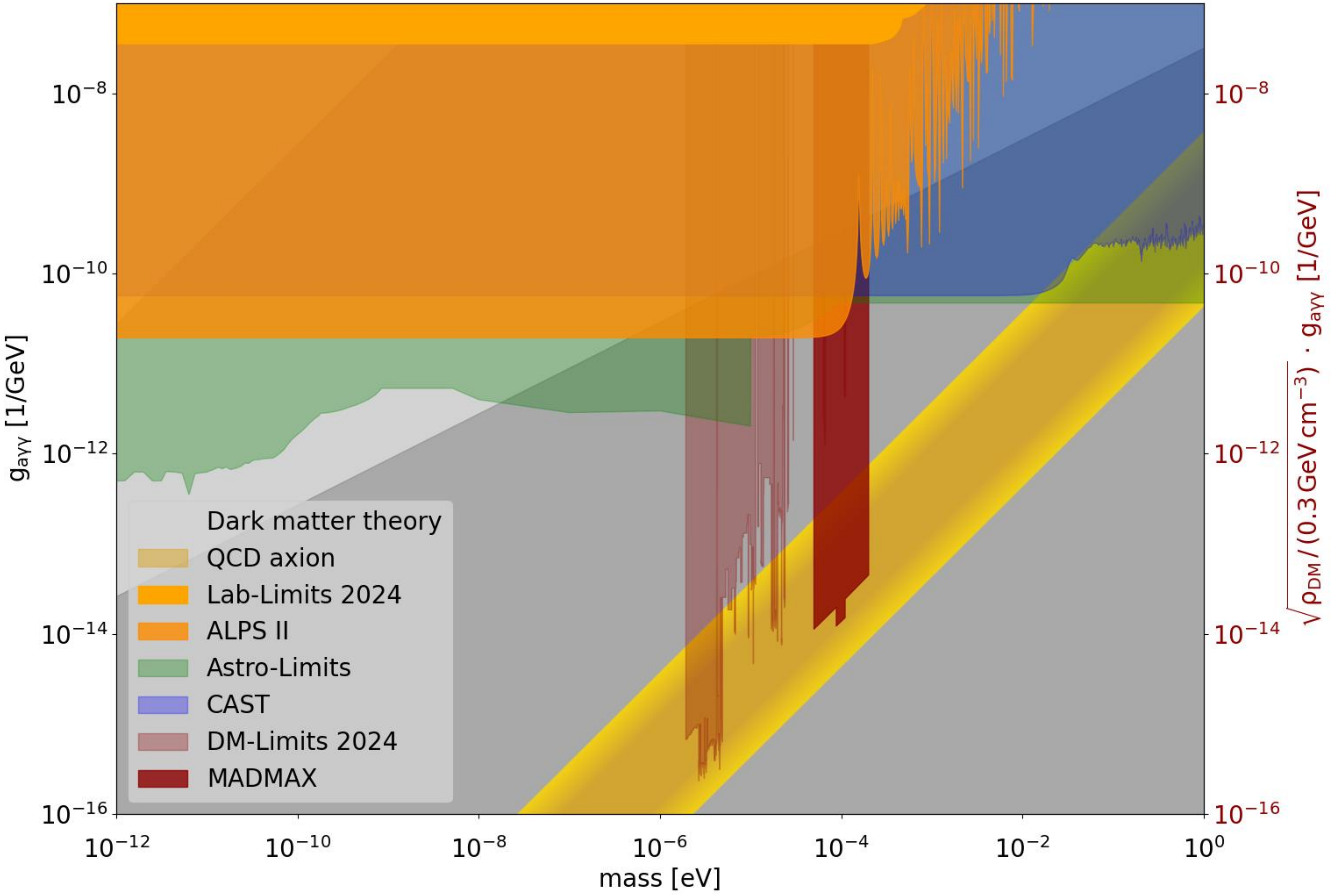
Reach out for vanilla QCD axions

Key activities:

- Scaling up the “booster”, cryogenic: further prototype measurements @ CERN.
- 10^{-24} W RF sensing.
- Building a huge dipole magnet.



Laboratory experiments, astrophysics, MADMAX 2035/40



Hypothetical light bosons for BSM physics

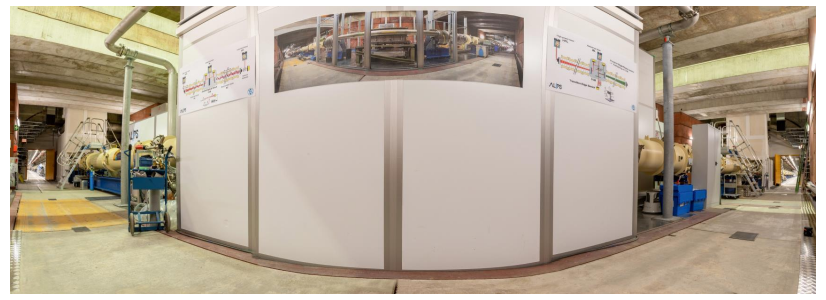
DESY ambition: a world-leading axion site

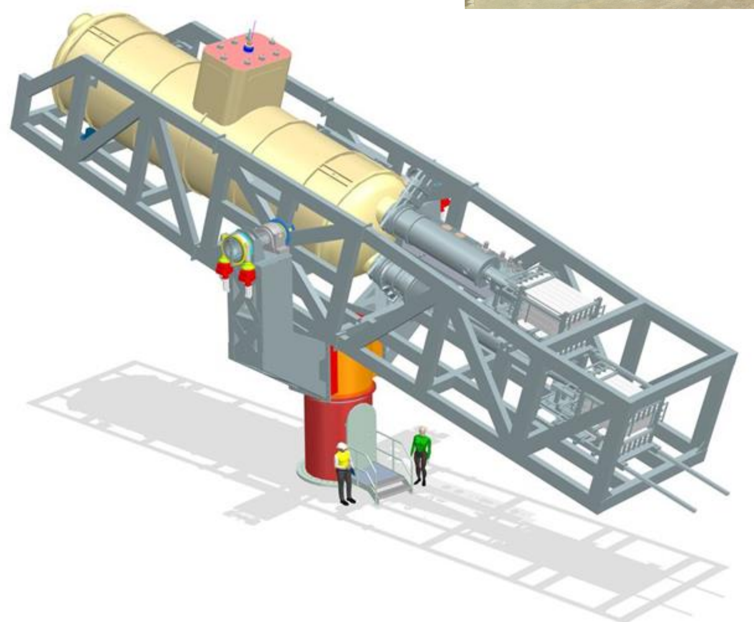
ALPS II target sensitivity

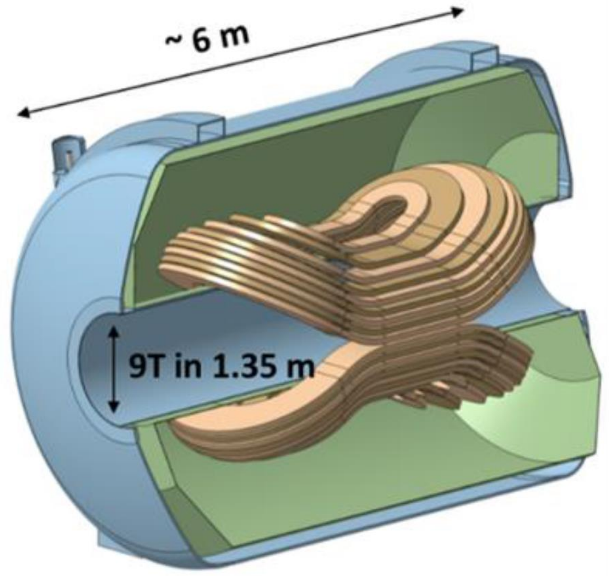
MADMAX target sensitivity

RADES target sensitivity (using the BabyIAXO magnet)

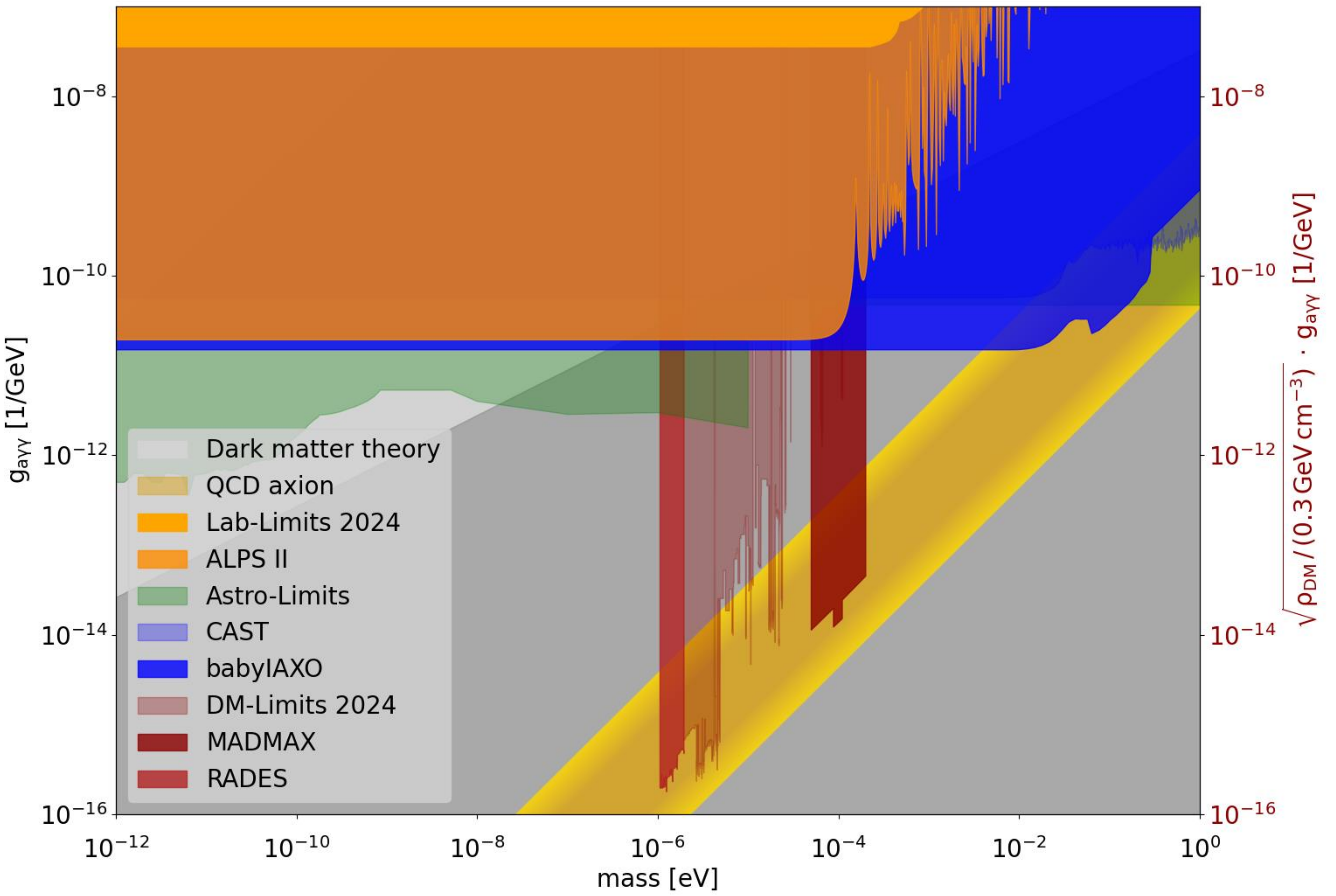
BabyIAXO target sensitivity







Laboratory experiments, astrophysics and DM 2035/40



Axion technologies for more physics

Beyond hypothetical boson searches

$\Delta n = 4 \cdot 10^{-24} \cdot B\,[T]$

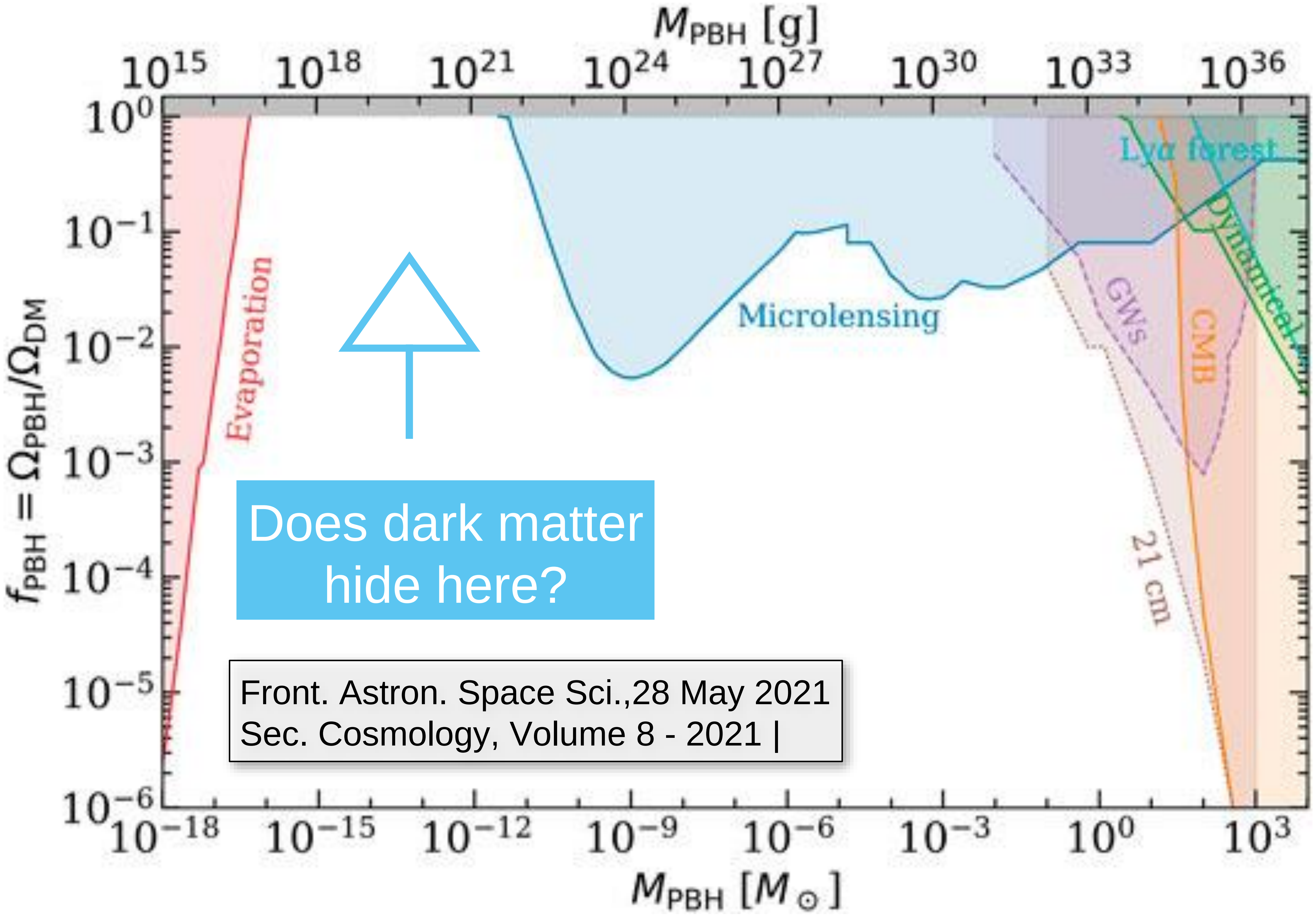
Vacuum magnetic birefringence:
- High-precision long-baseline interferometry
- ALPS II magnet string

Sub-MeV dark matter searches:
- Quantum sensing

Axion dark matter searches without magnets:
- High-precision long-baseline interferometry

High-frequency gravitational waves:
- High-precision long-baseline interferometry
- Magnets of ALPS II, BabyIAXO, MADMAX
- Quantum sensing.

…



ECRs and media attention

Successes beyond physics and technologies

Early careers at ALPS II

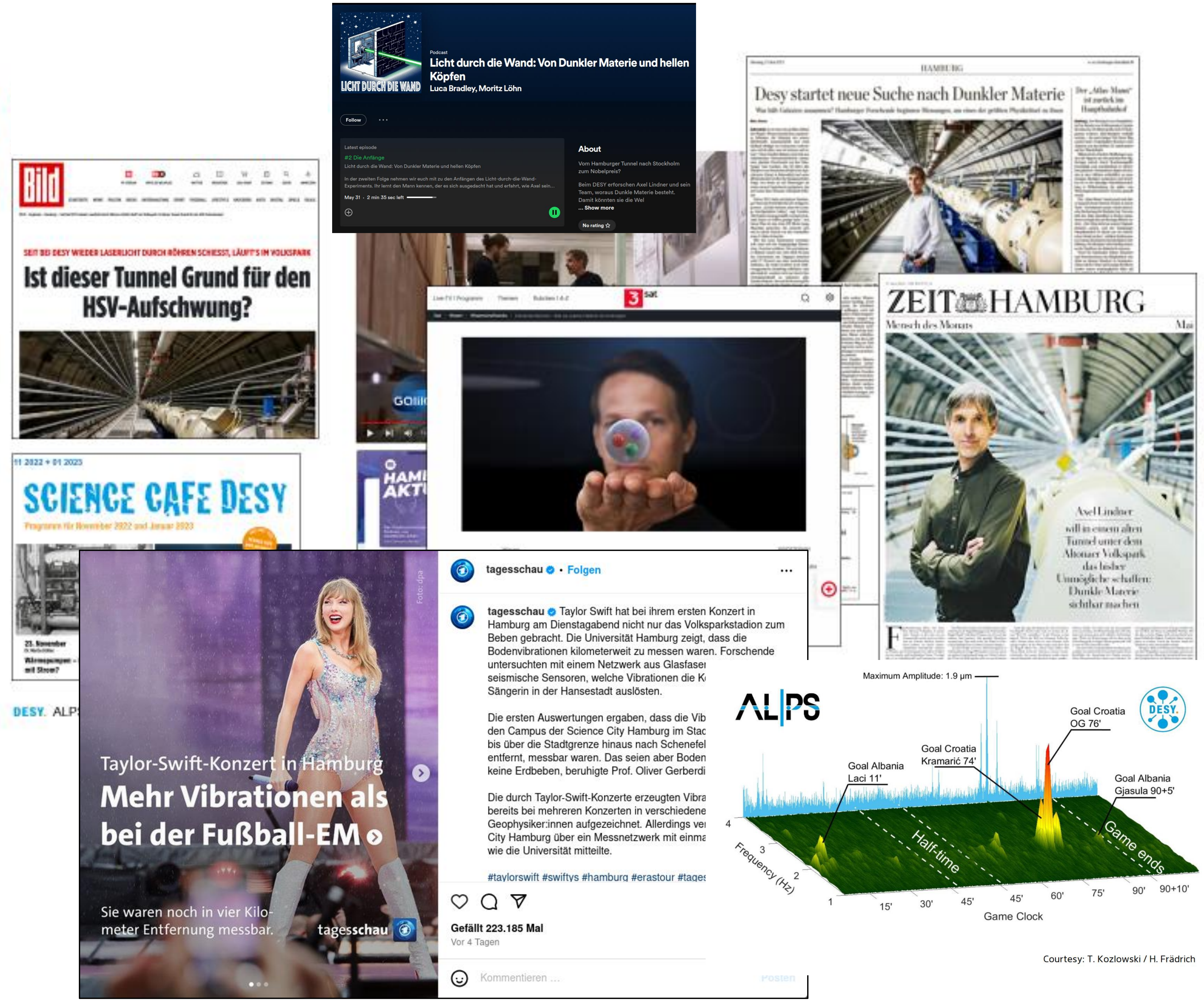
ALPS II doctoral researchers:

- 14 dissertations in experimental physics.
- 1 dissertation in engineering.
- At least 4 theses still to come.

Former ALPS II DESY fellows:

- 5 permanent positions in academia.
- 1 junior professorship.
- 3 left for other postdoc positions.
- 2 left to industry.

Media on the ALPS II

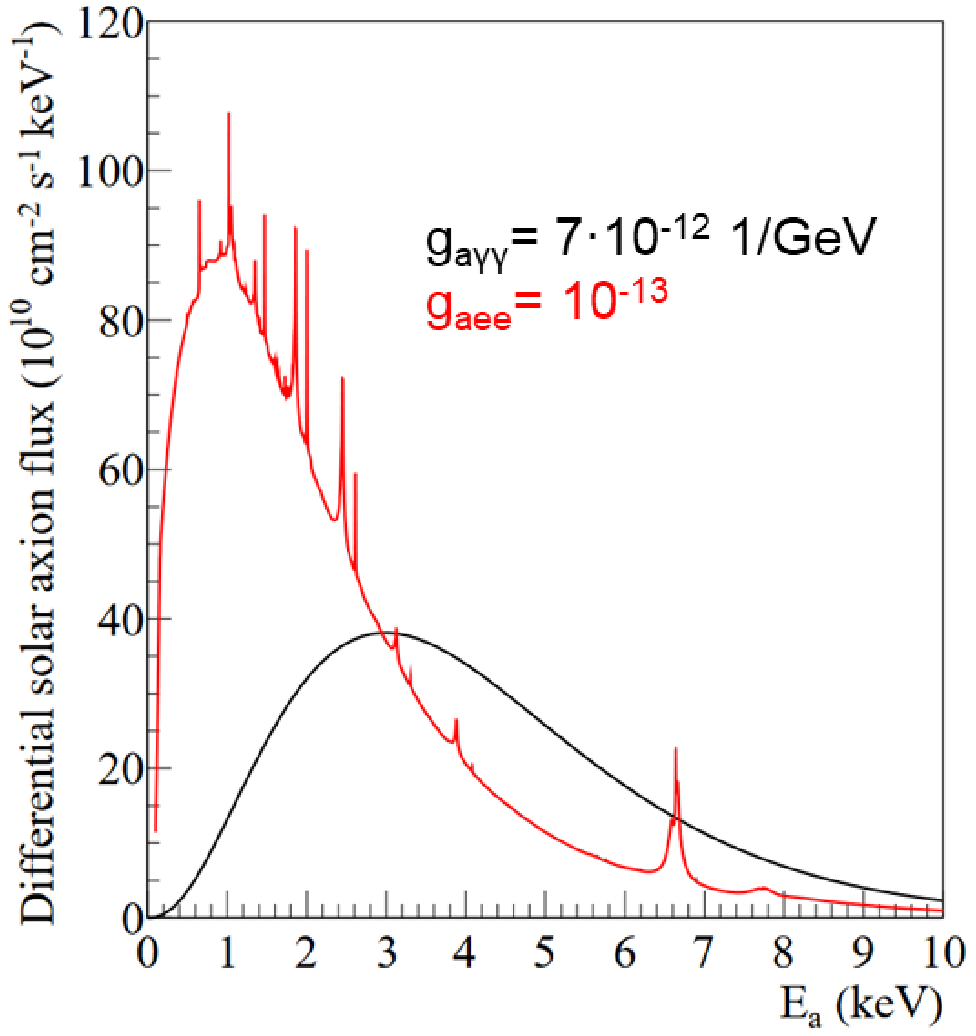


A step beyond axion discovery

Examples for more physics

Particle physics:

- Did we find the (QCD) axion or an axion?
- Probe different axion couplings.
- Does the axion hint at string theories?

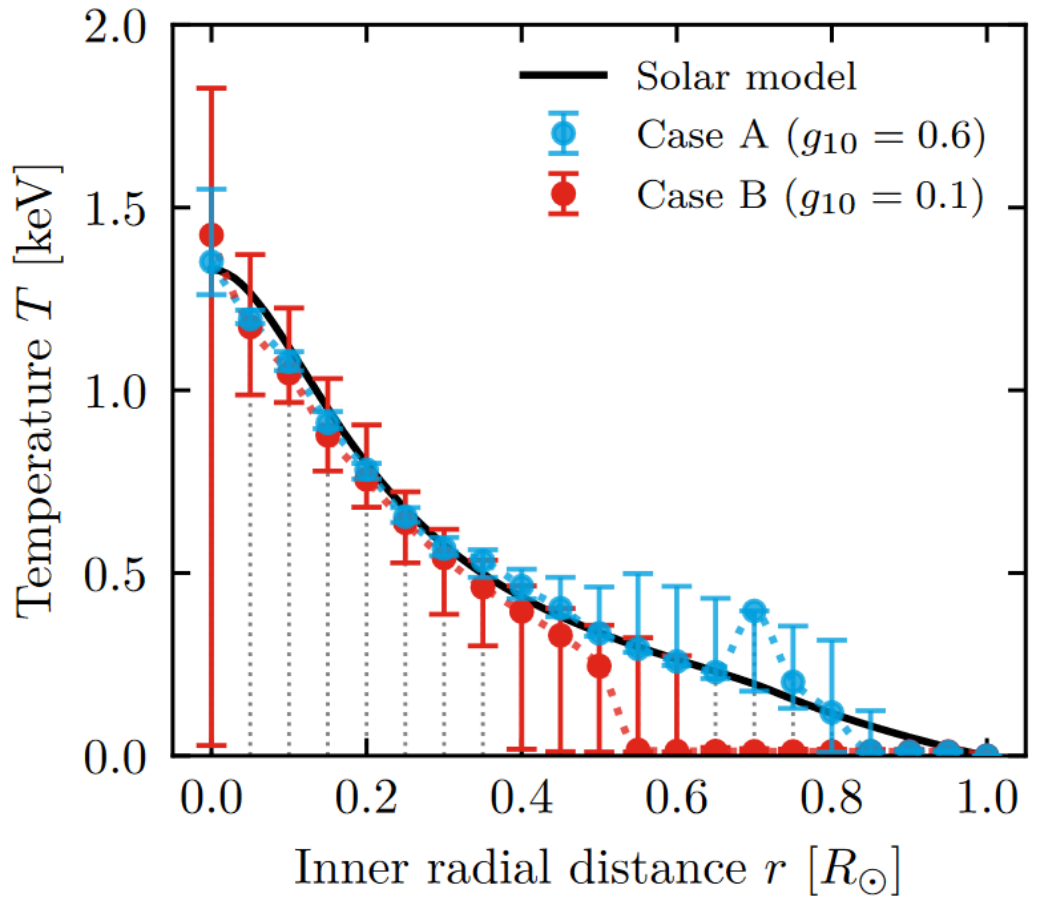


Solar axions generated via couplings to photons, electrons and nuclear transitions (i.e. 14.4 keV).

https://inspirehep.net/literature/1967014

Astrophysics:

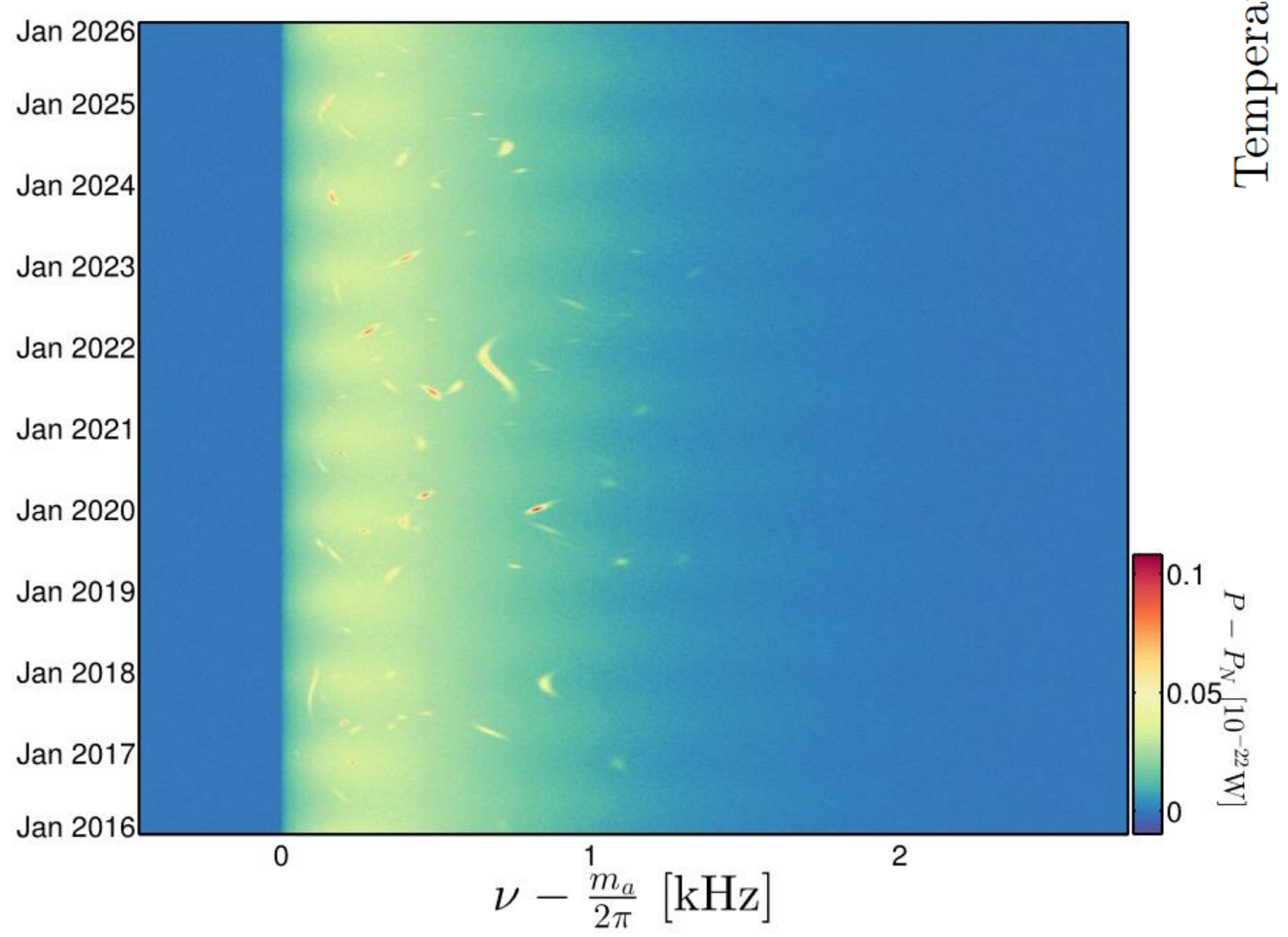
- Map solar temperatures and magnetic fields.
- Can we also see axions from supernovae?



JCAP 10 (2023) 024

Cosmology:

- Decipher the history of the milky way.



https://inspirehep.net/literature/1508820

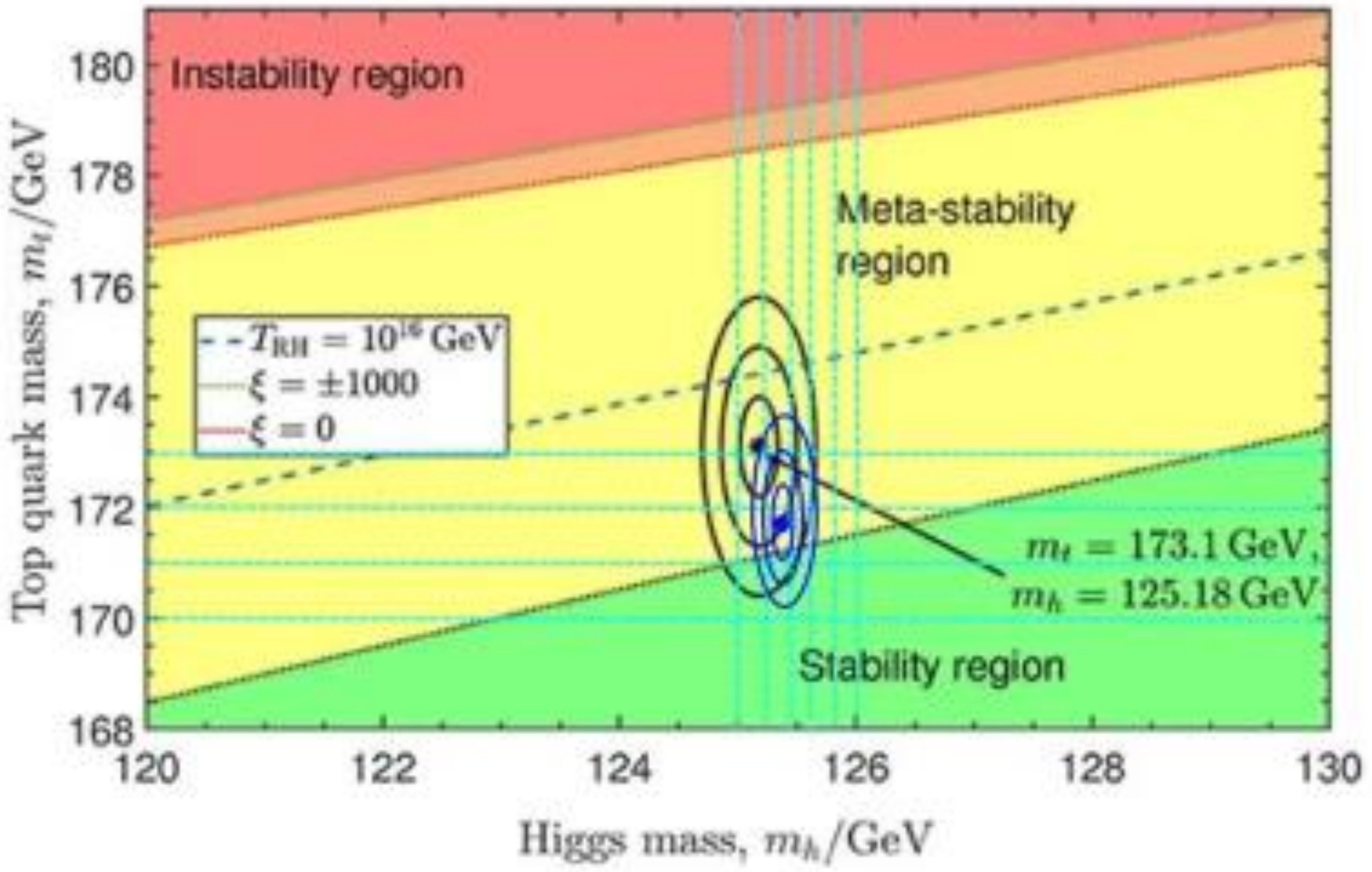
Reminder from the first lecture

The status of particle physics

What do we know (I)

The next relevant energy scale might be out of reach at accelerators

QCD (1 GeV) ⟶ Electroweak (246 GeV, LHC) ⟶ Planck 10^{19} GeV (10^{15}·LHC)



https://bigthink.com/starts-with-a-bang/universe-fundamentally-unstable/
https://arxiv.org/pdf/1809.06923

There is no hint for a "new physics energy scale".

A next relevant energy scale might be out of reach for any "thinkable" future accelerator.

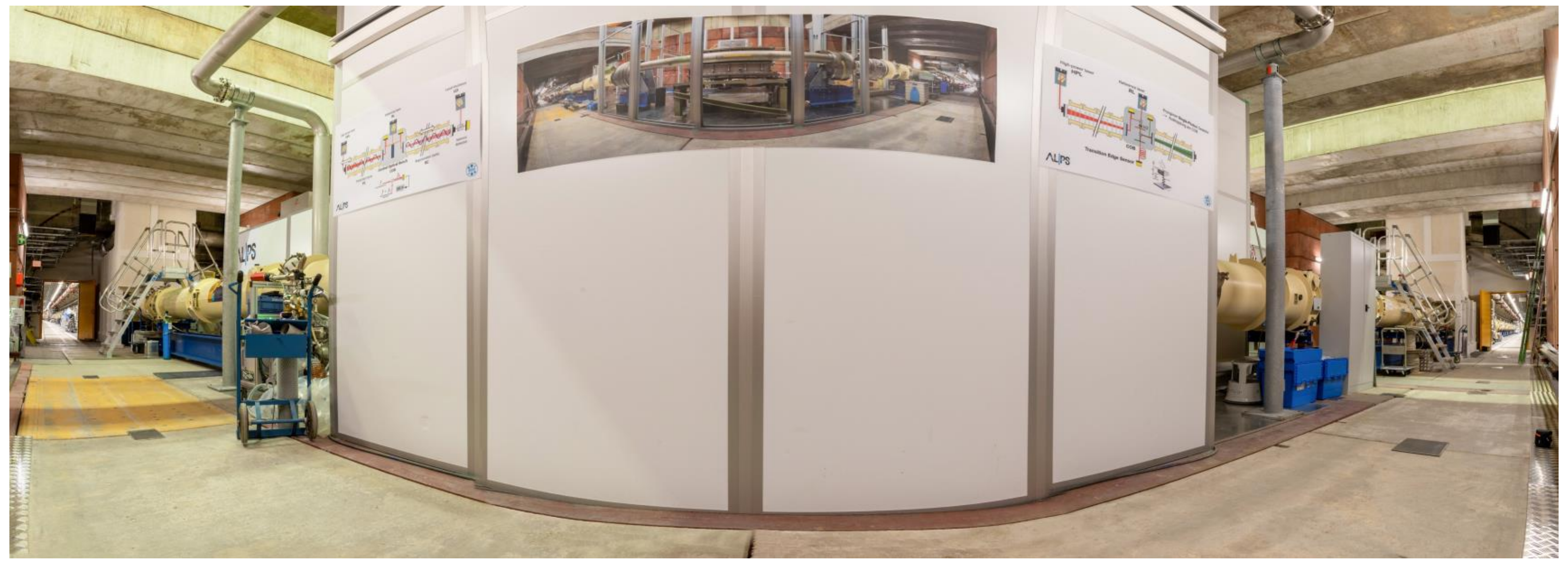
An experimental loophole:
Look for (pseudo) Goldstone bosons originating from spontaneous breaking of continuous symmetries.

- Such symmetries are predicted by many theories.
- Goldstones would be very lightweight,
- but interact extremely weakly with the SM: usually not detectable at colliders.

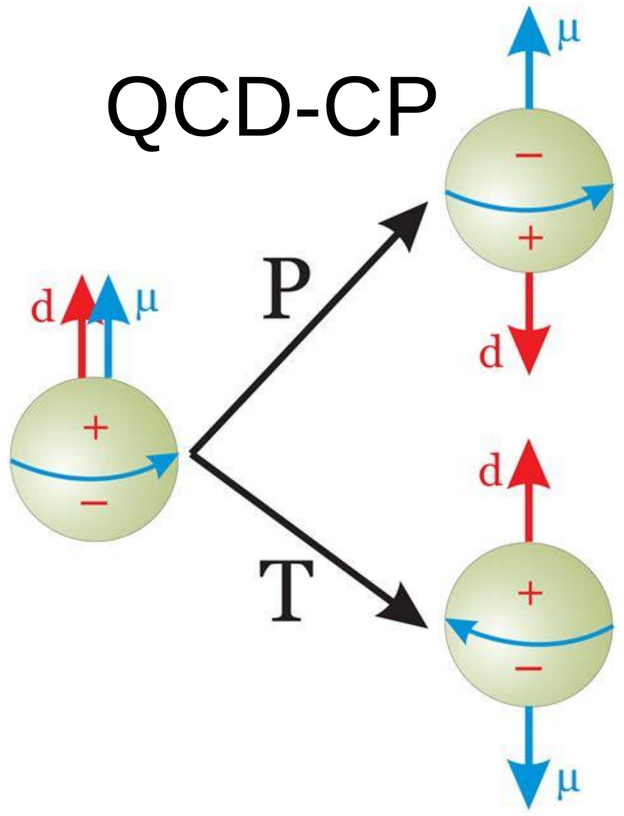
A prime example is the axion.

Axions might provide the key to understand “everything”

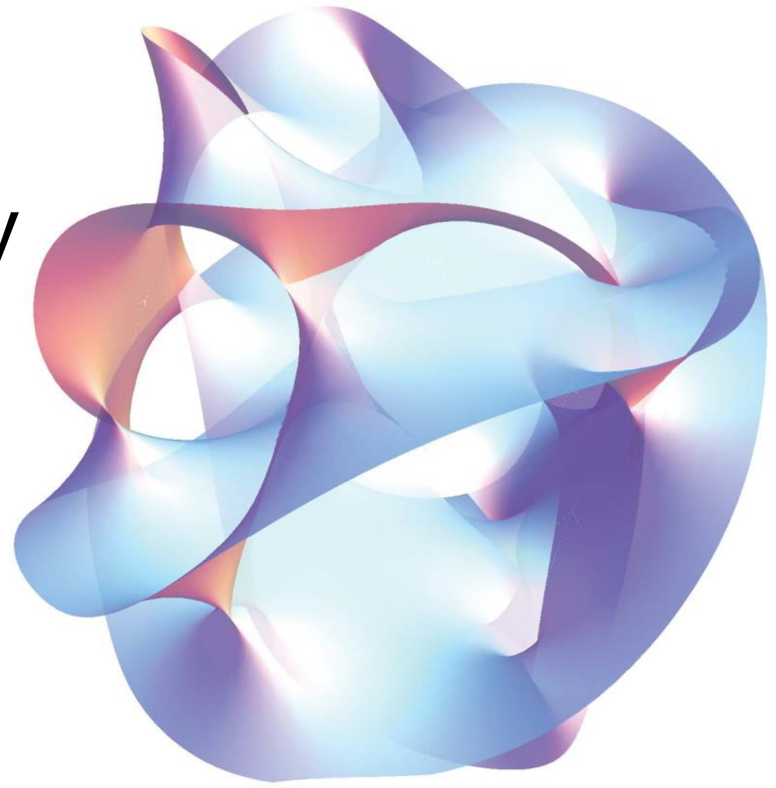
Cosmology, particle physics, unification of quantum mechanics and general relativity

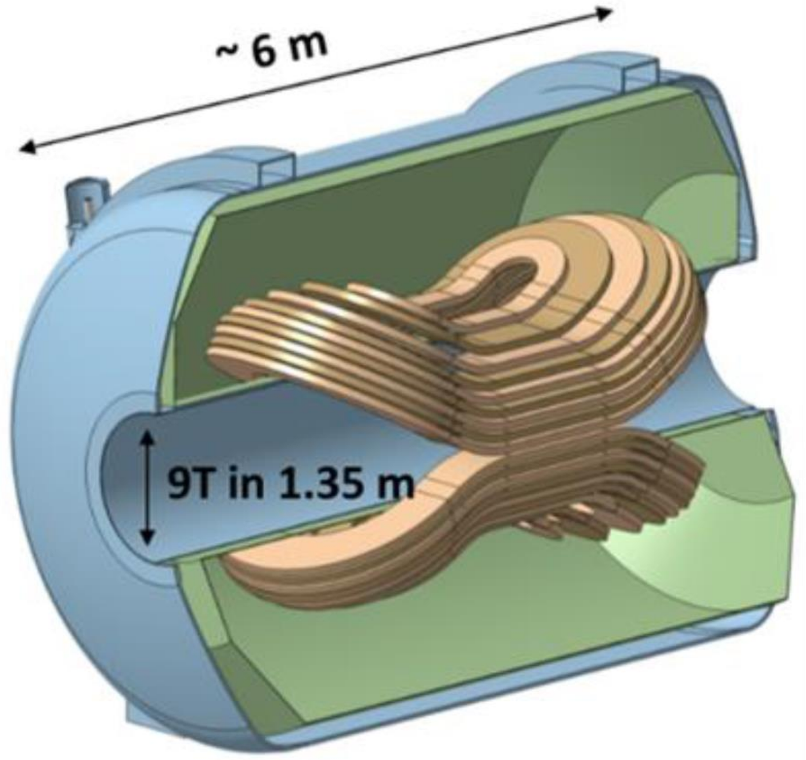


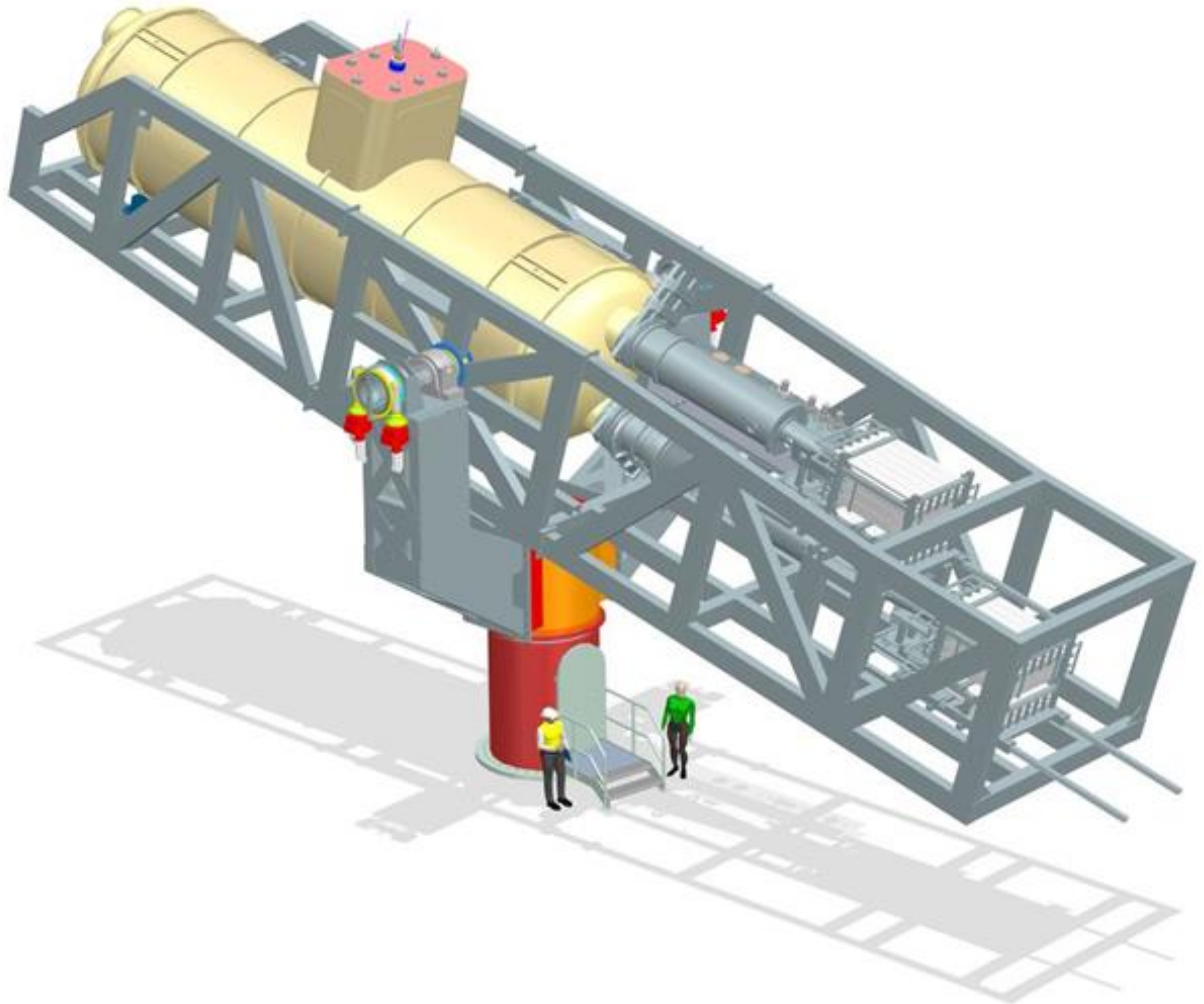
QCD-CP



String
theory







Experiments will tell!

Thank you

…. any our many colleagues for their engagement in trying to make the invisible visible ….

Contact

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