Stray Light challenges in LISA Interferometry

Sources, Dynamics, & Mitigation Strategies

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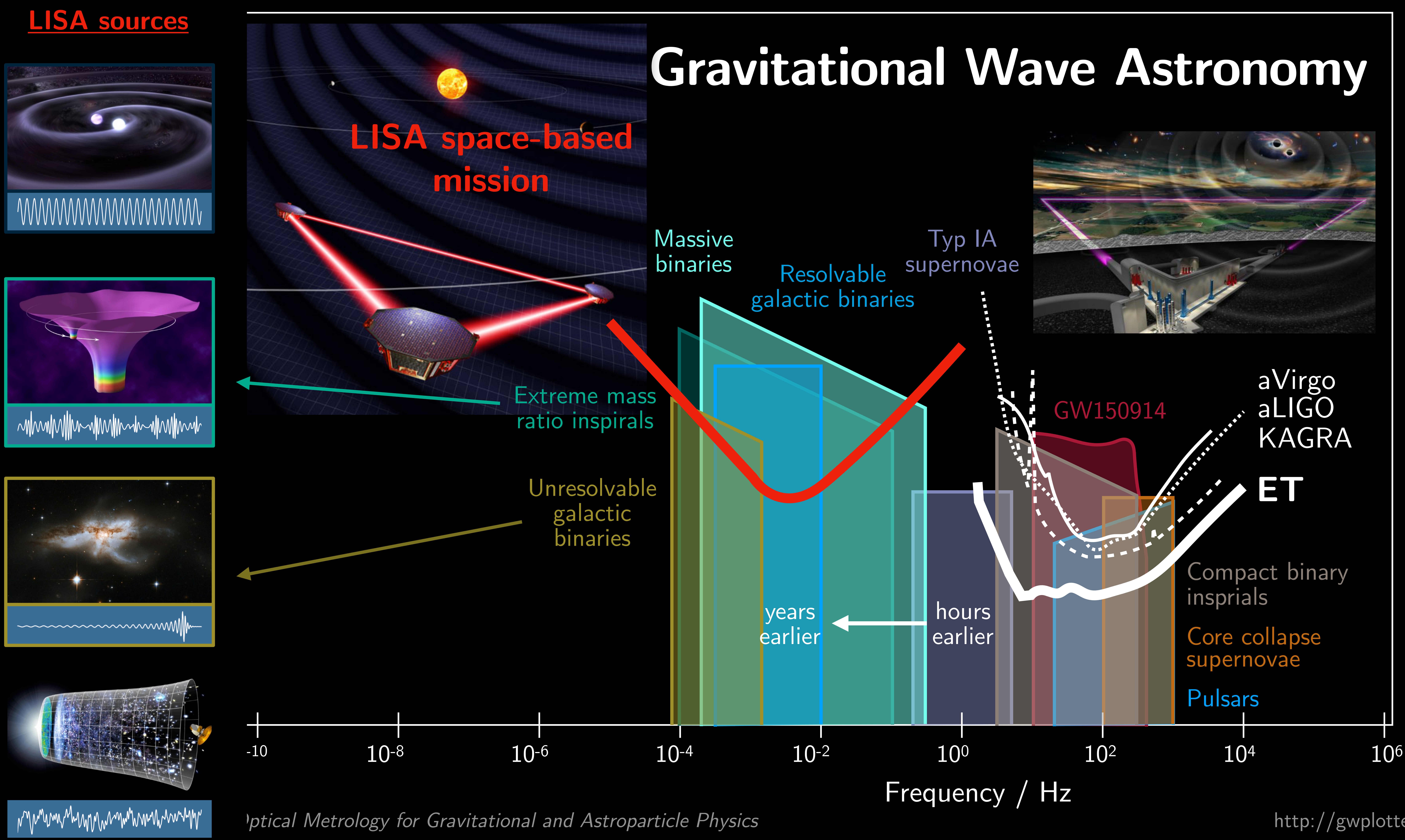
Helmut Schmidt University

Particle Physics Pizza Seminar DESY, 13.05.2024

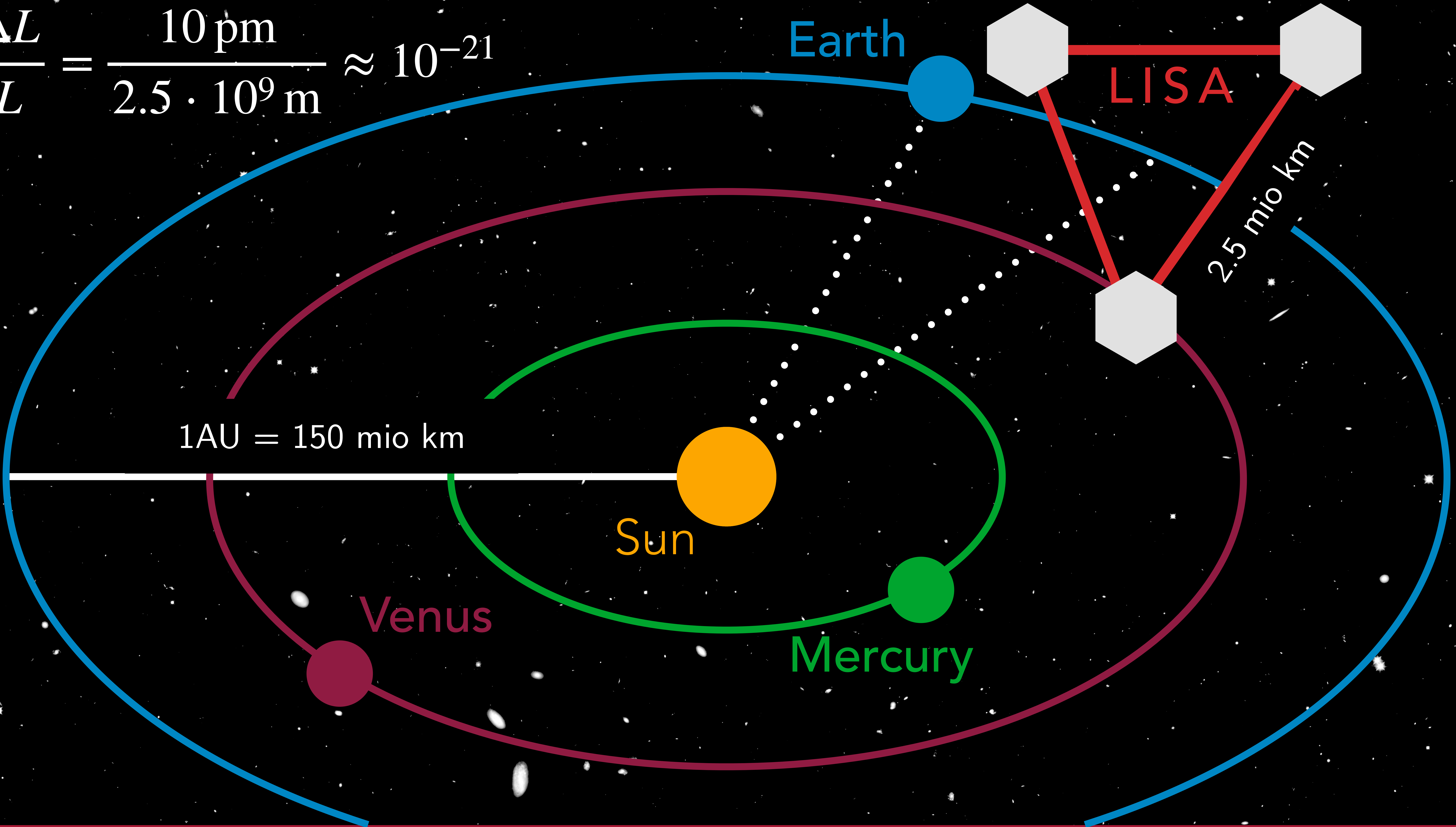
HELMUT SCHMIDT UNIVERSITÄT
Universität der Bundeswehr Hamburg

Gravitational Wave Astronomy



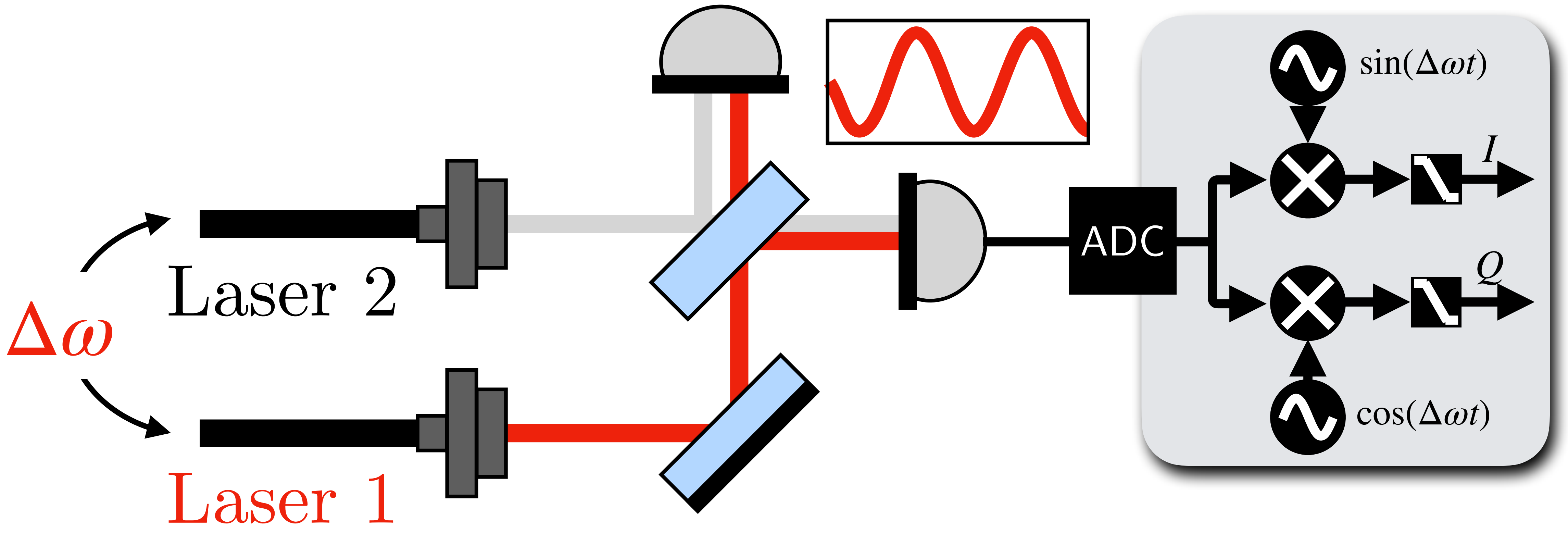
Laser Interferometer Space Antenna

$$h_{GW} = \frac{\Delta L}{L} = \frac{10\,\mathrm{pm}}{2.5 \cdot 10^9\,\mathrm{m}} \approx 10^{-21}$$



Heterodyne Interferometry

- Heterodyne interferometry:



Phase readout goal: $6\,\mu\mathrm{rad}/\sqrt{\mathrm{Hz}}$ @ 1mHz, λ=1064nm

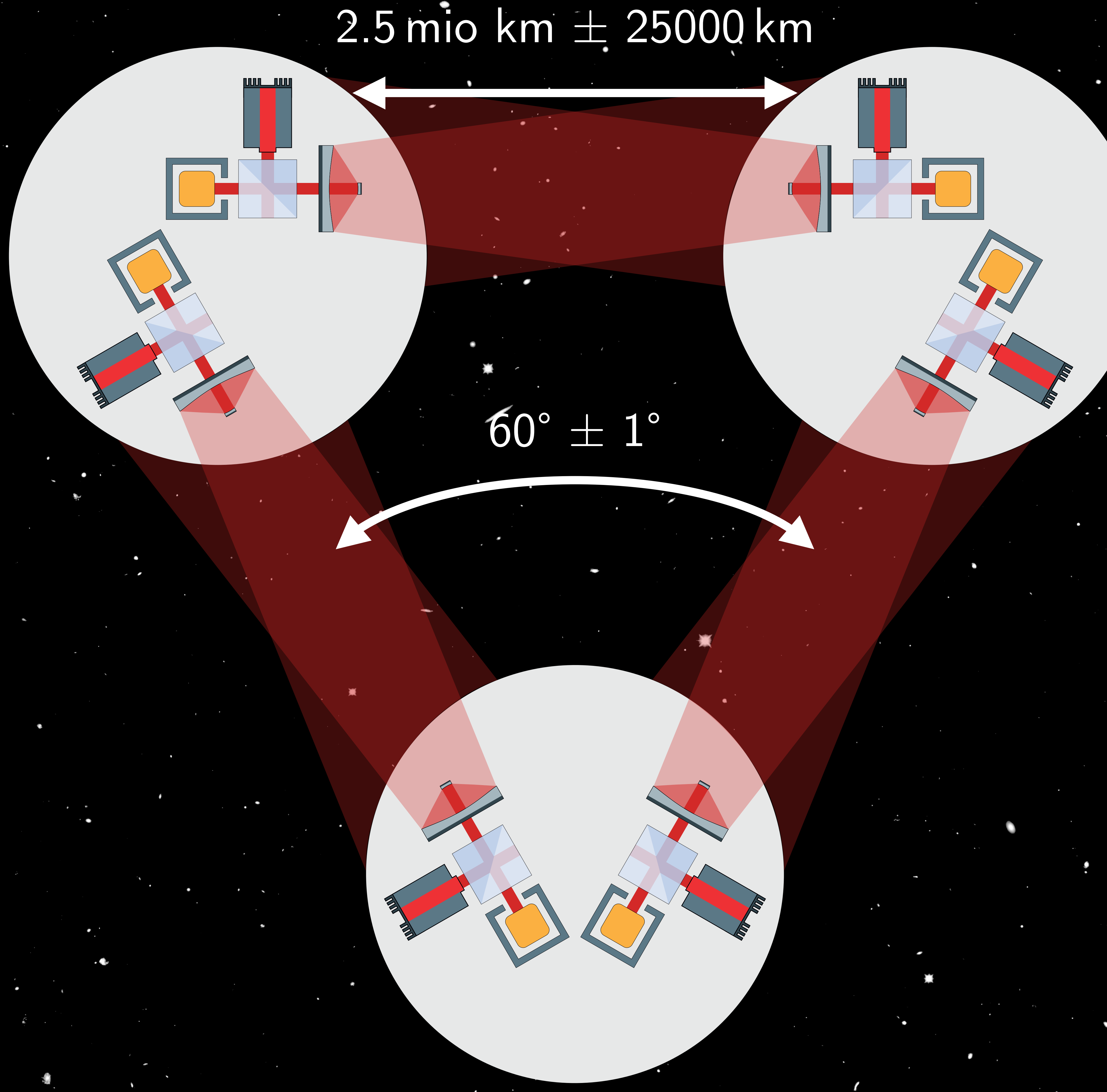
Orbital changes of 1% over the year:

1. Arm breathing: 25000km arm length mismatch

   Satellite max. velocity:

   $v_{\mathrm{max}} = 15\,\mathrm{m/s}$ (= MHz Doppler shift)

2. 60° Angular variations: Backlink fiber



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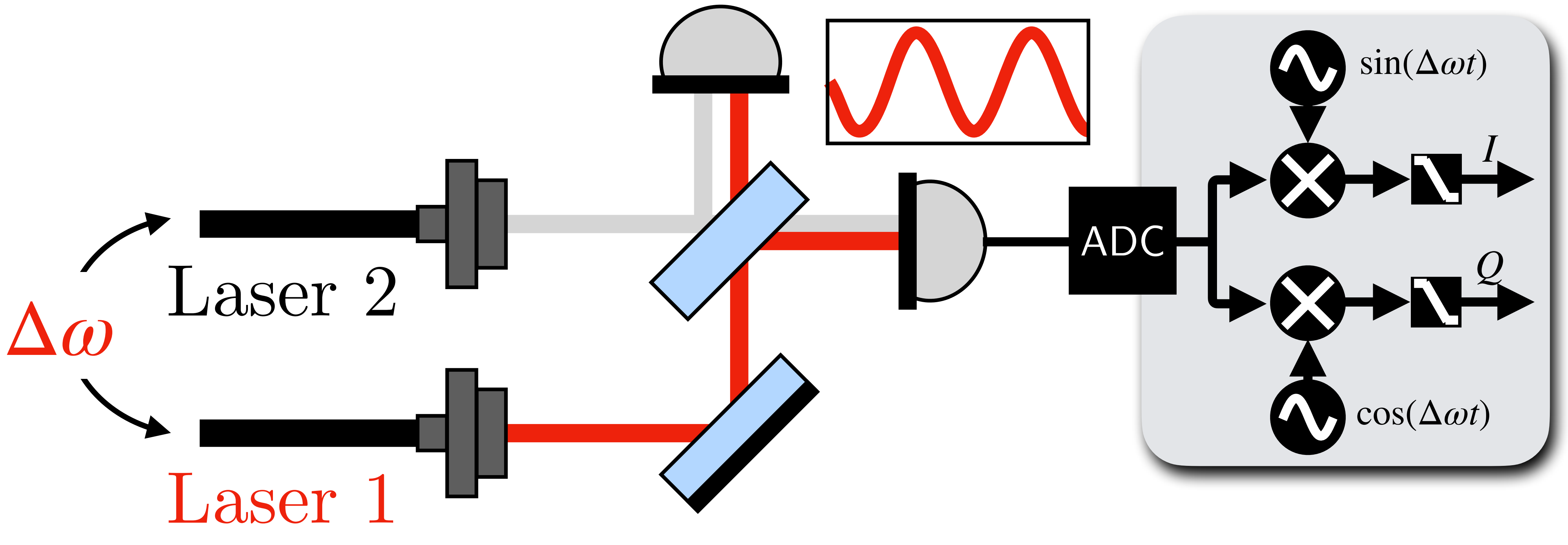

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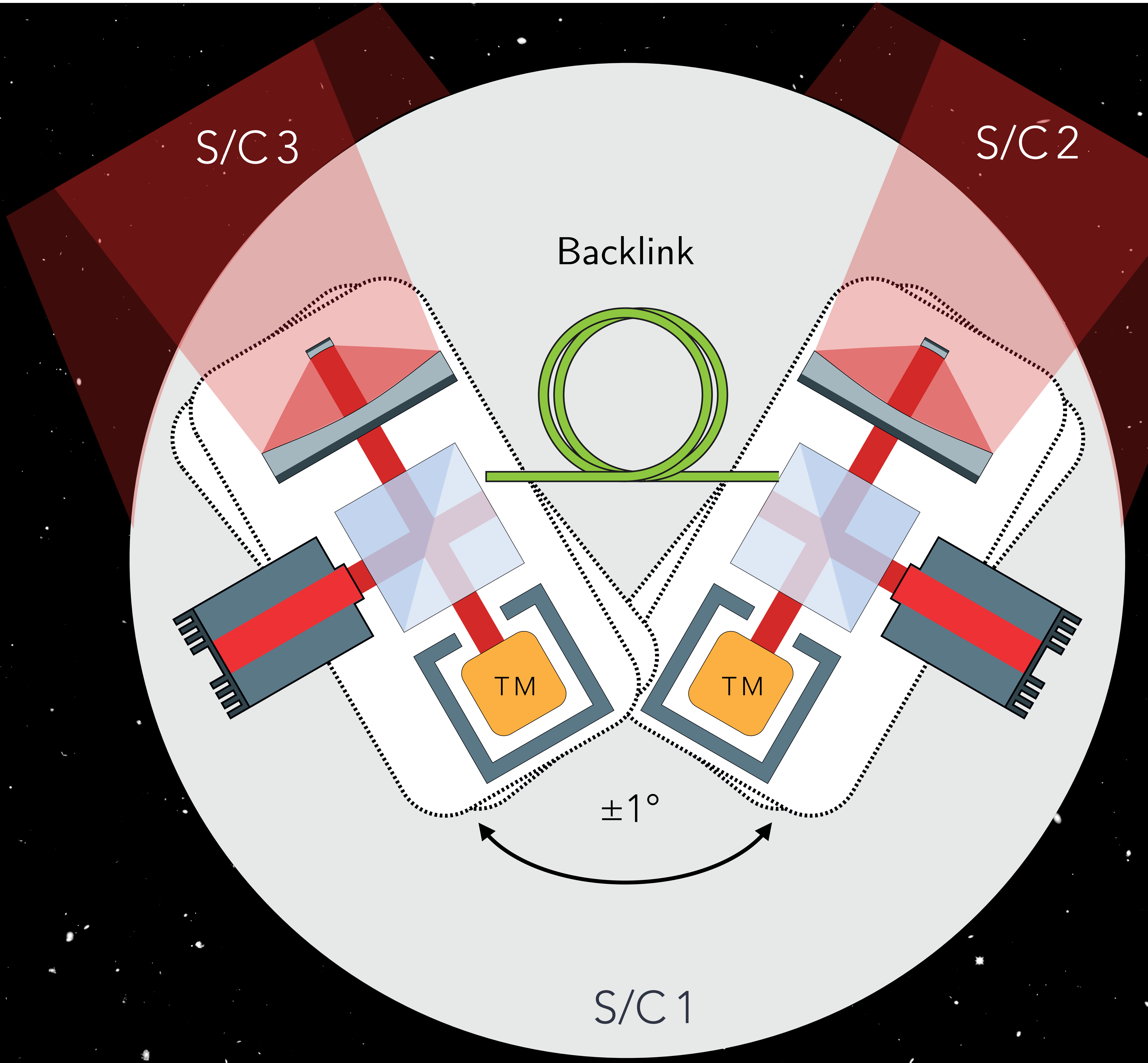
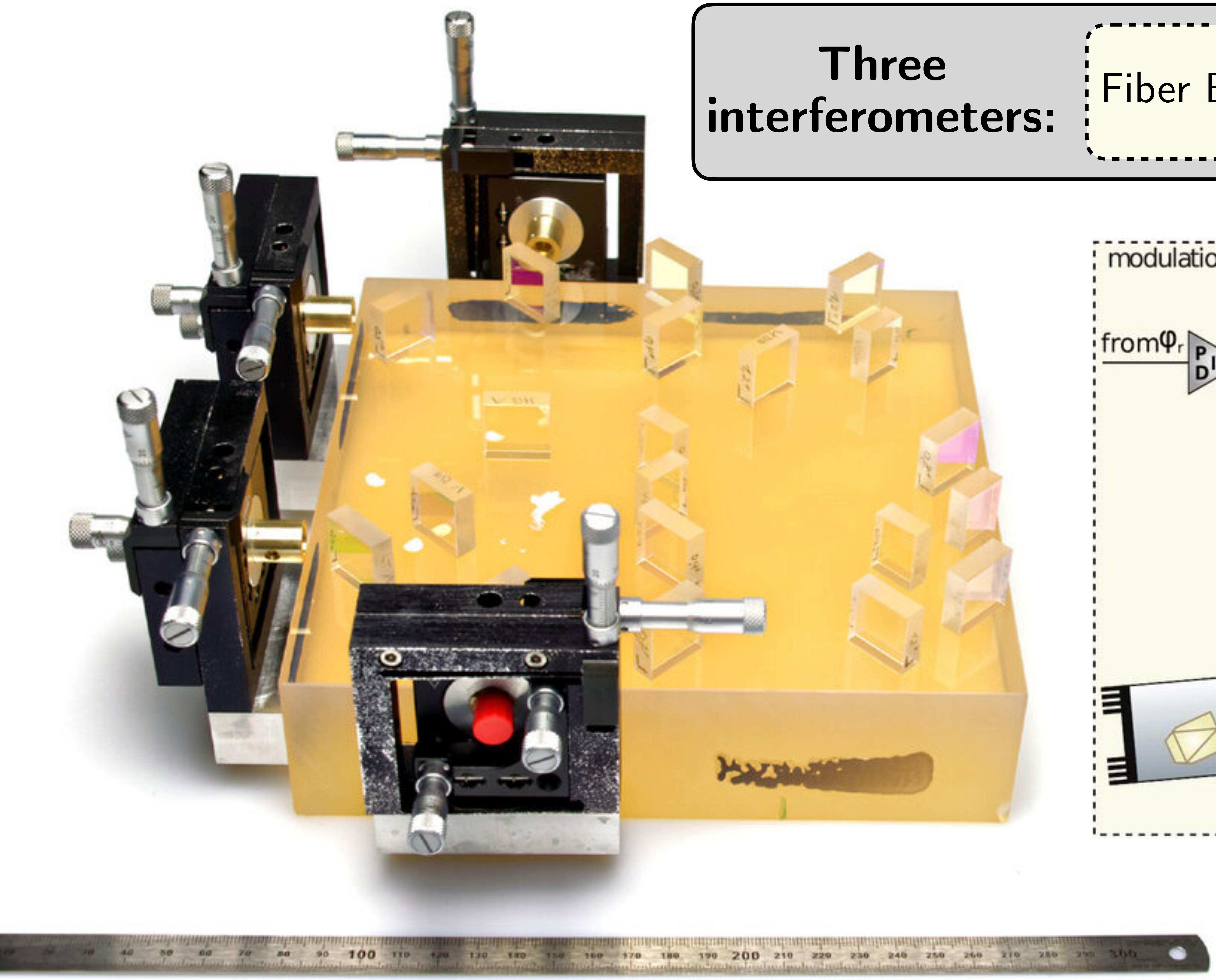
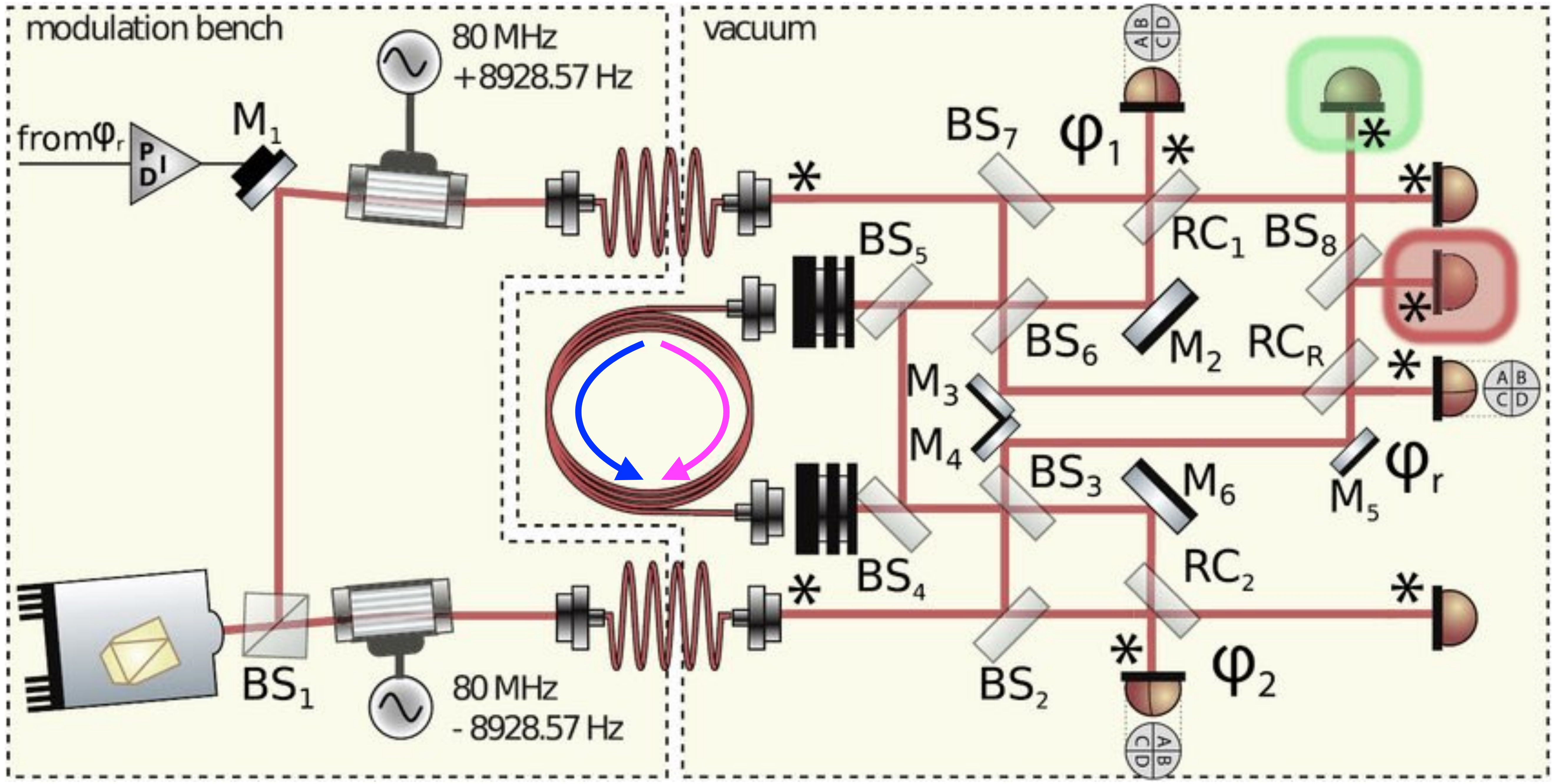


Fiber non-reciprocal measurements



Three interferometers: Fiber Backlink CW | Fiber Backlink CCW | Non-fiber reference



Fleddermann, *R., et. Al (2018). Sub-pm non-reciprocal noise in the LISA backlink fiber. Classical and Quantum Gravity, 35(7), 075007.*

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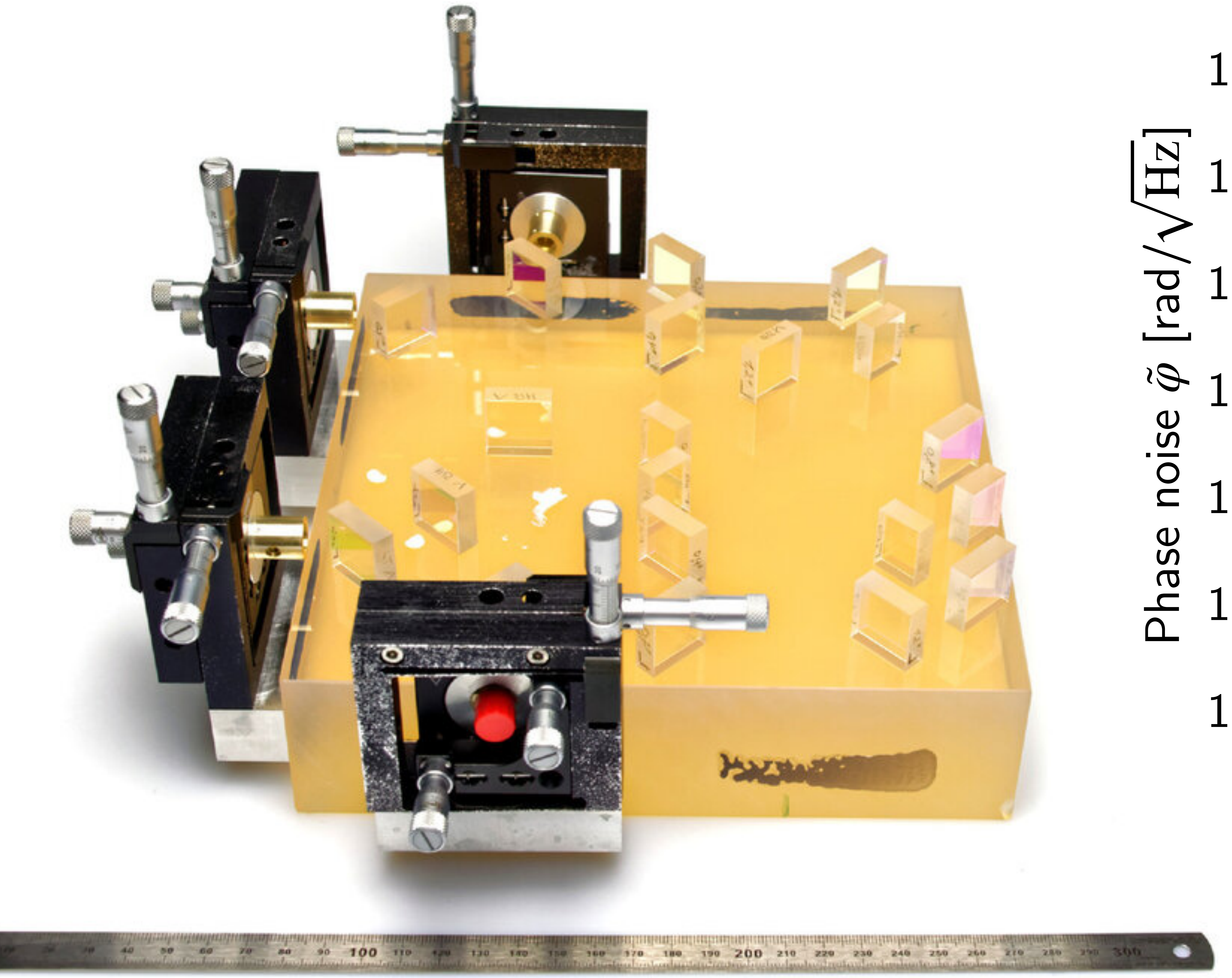
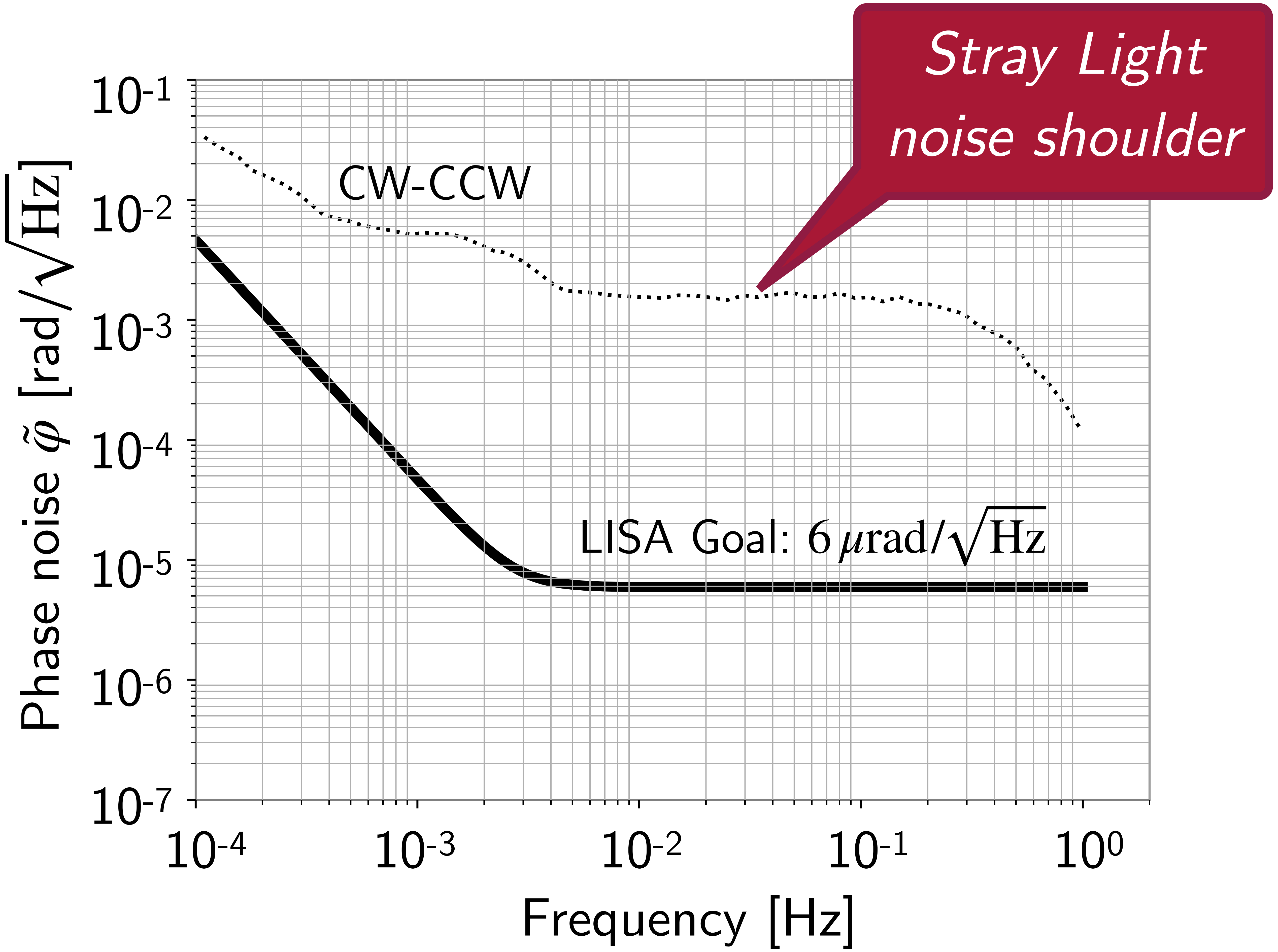
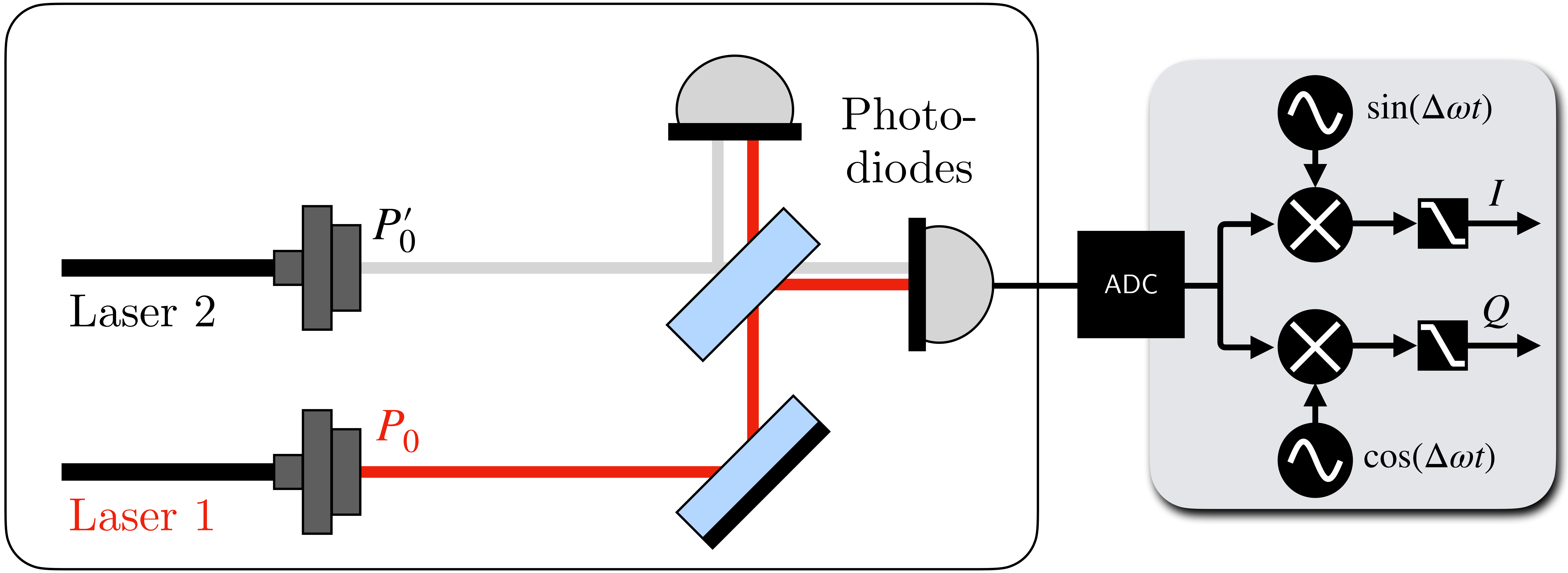




***Fleddermann**, R., et. Al (2018). Sub-pm non-reciprocal noise in the LISA backlink fiber. Classical and Quantum Gravity, 35(7), 075007.*

Heterodyne **phase readout**...

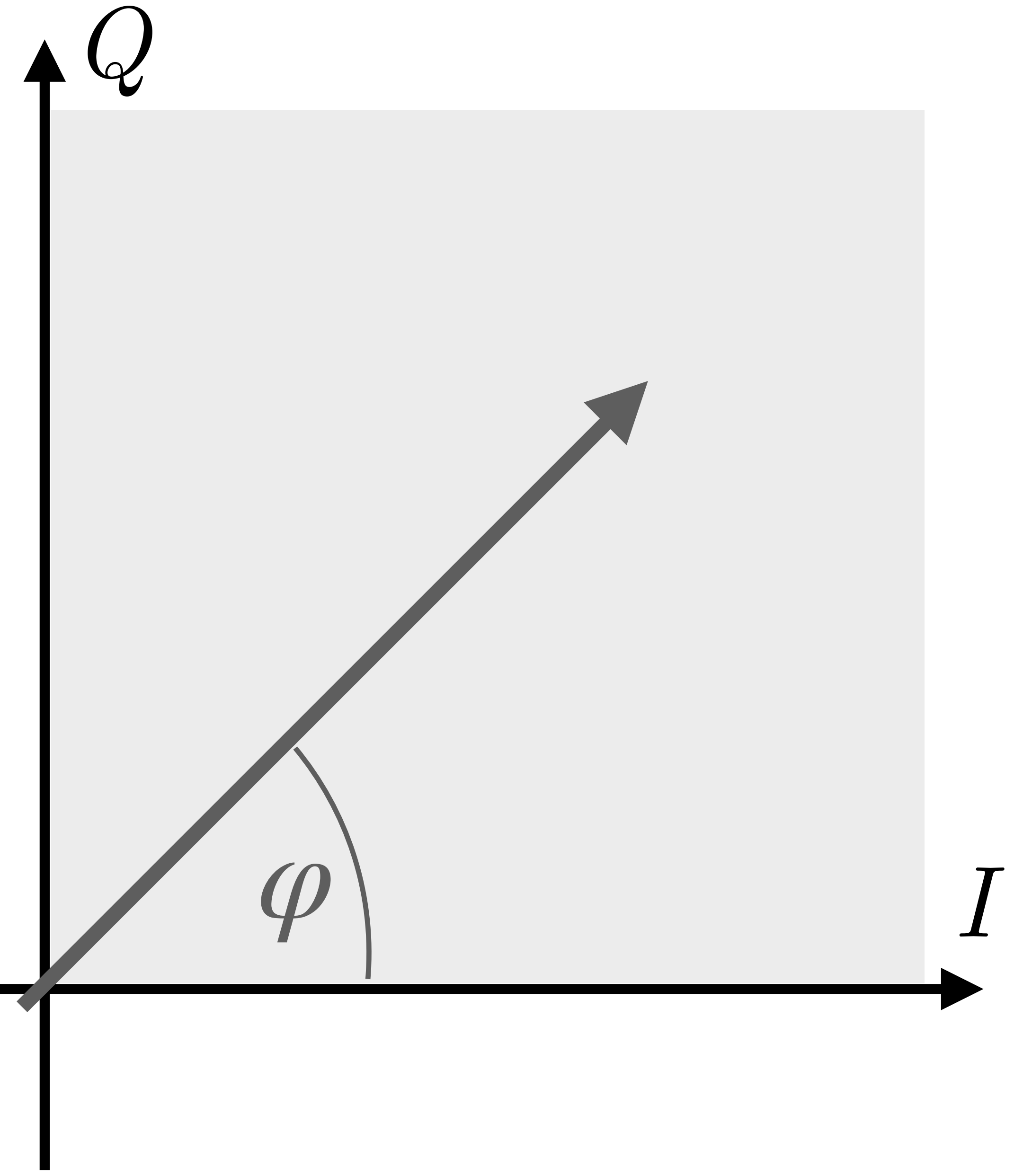


$$u_{ac} \propto \hat{E}_1 \hat{E}_2 \eta \cos(\Delta\omega t + \varphi)$$

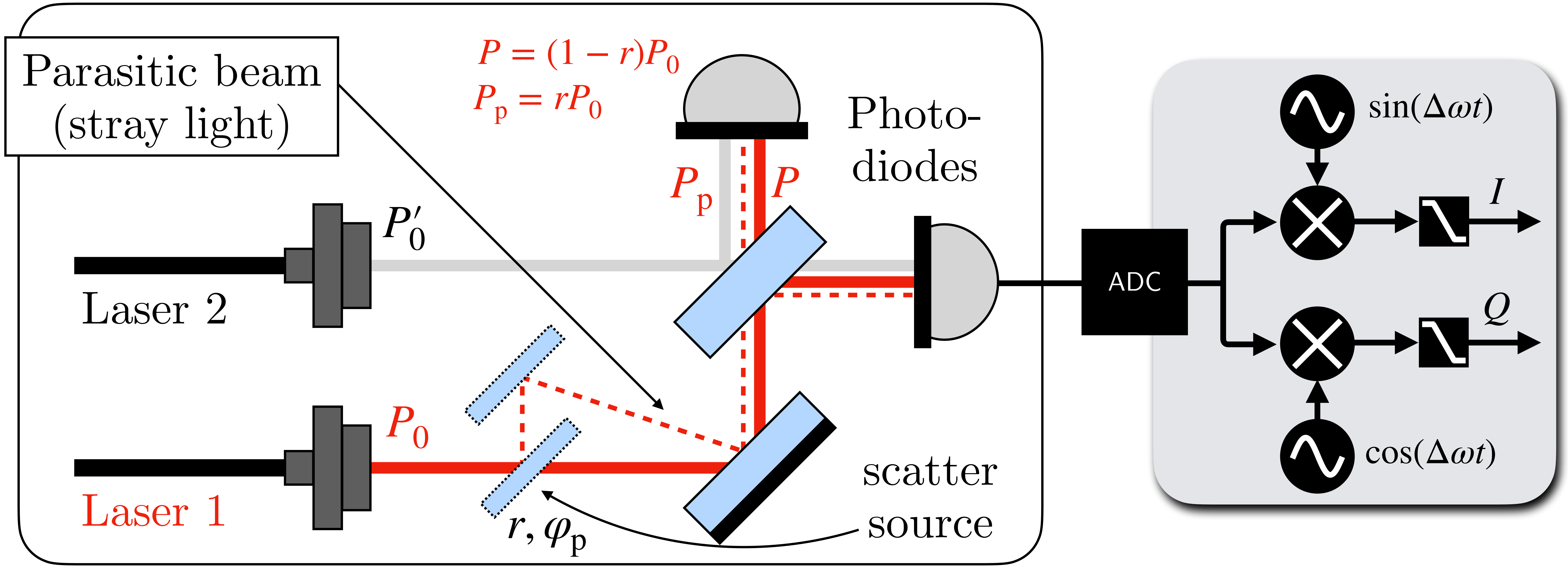
$$I = u_{ac} \cdot \cos([\omega_2 - \omega_1]t) = \hat{E}_1 \hat{E}_2 \cdot \cos\varphi$$

$$Q = u_{ac} \cdot \sin([\omega_2 - \omega_1]t) = \hat{E}_1 \hat{E}_2 \cdot \sin\varphi$$

$$\varphi = \arctan(Q/I)$$



… with **parasitic** beams (interferometers)



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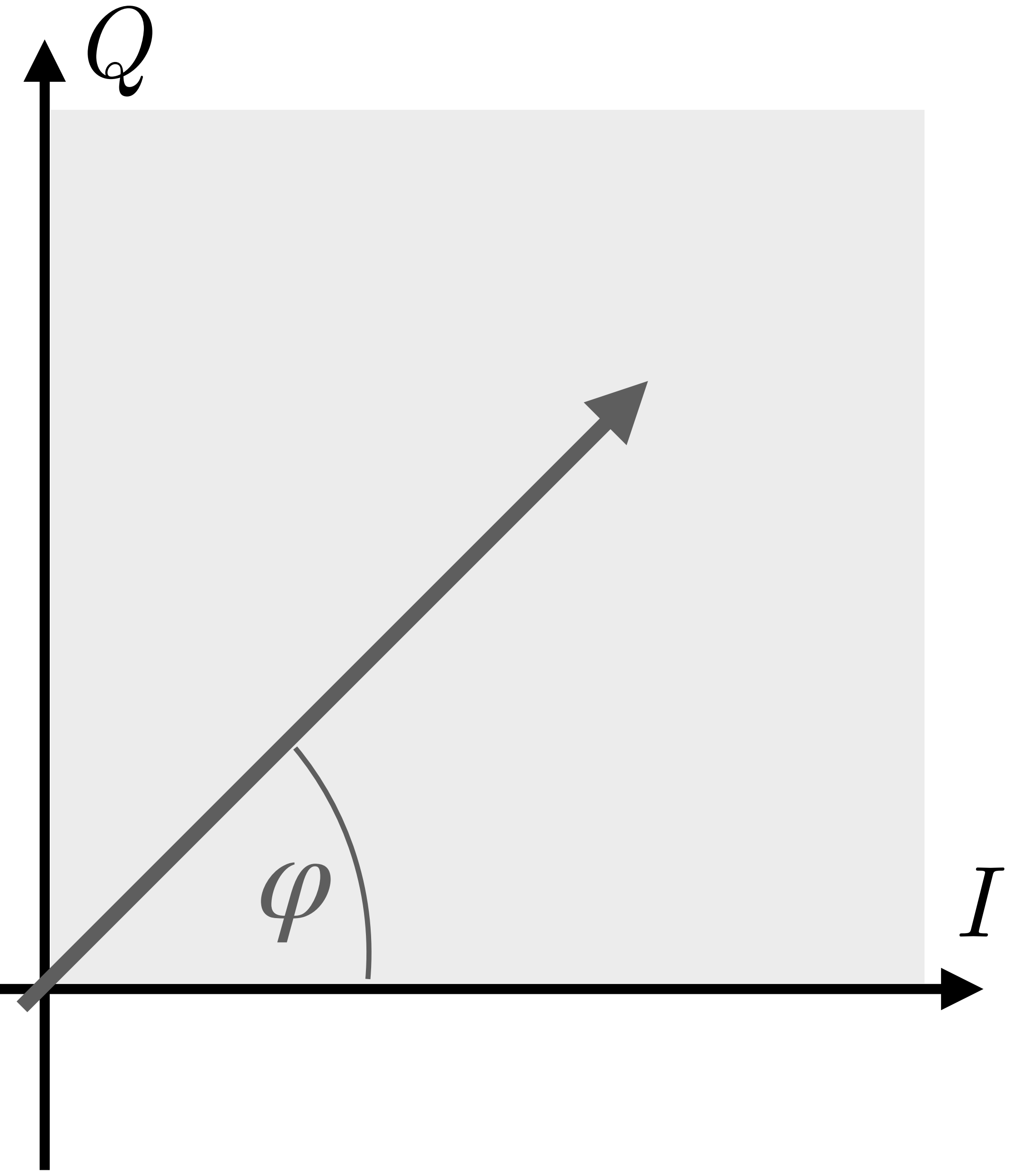

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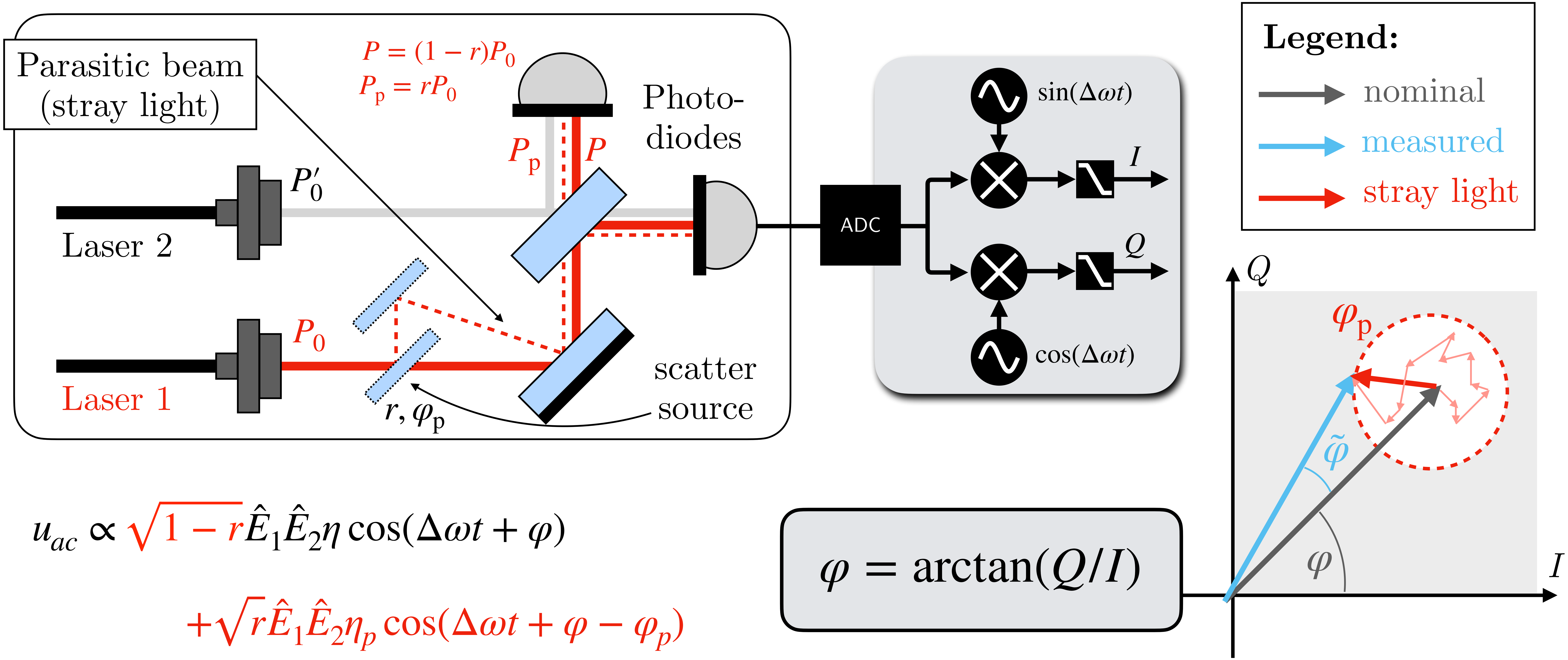
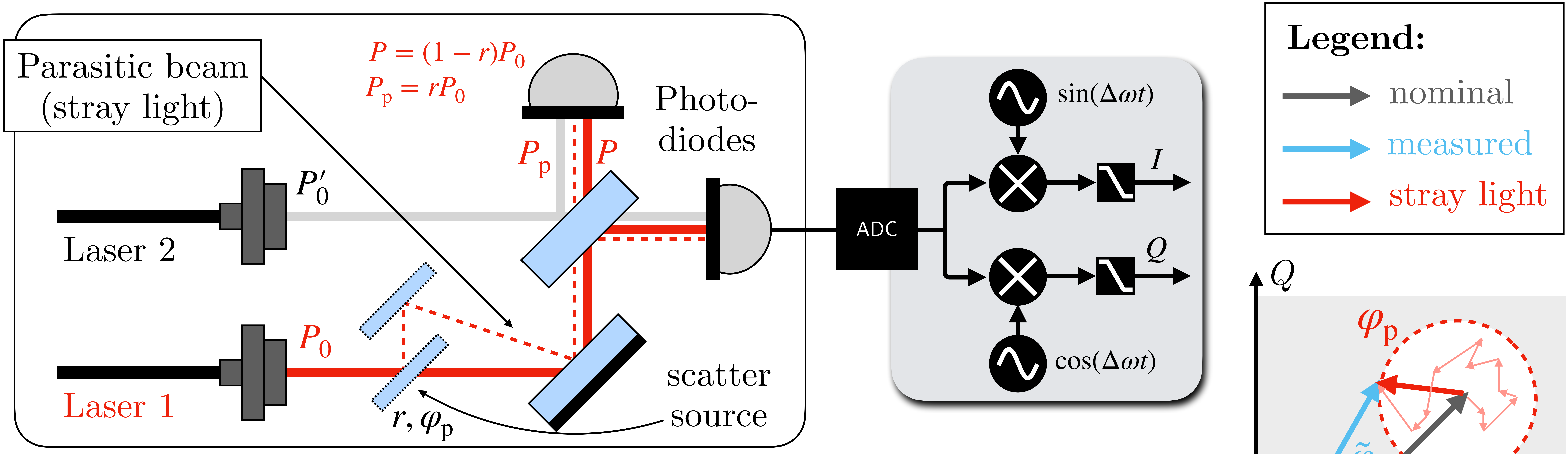


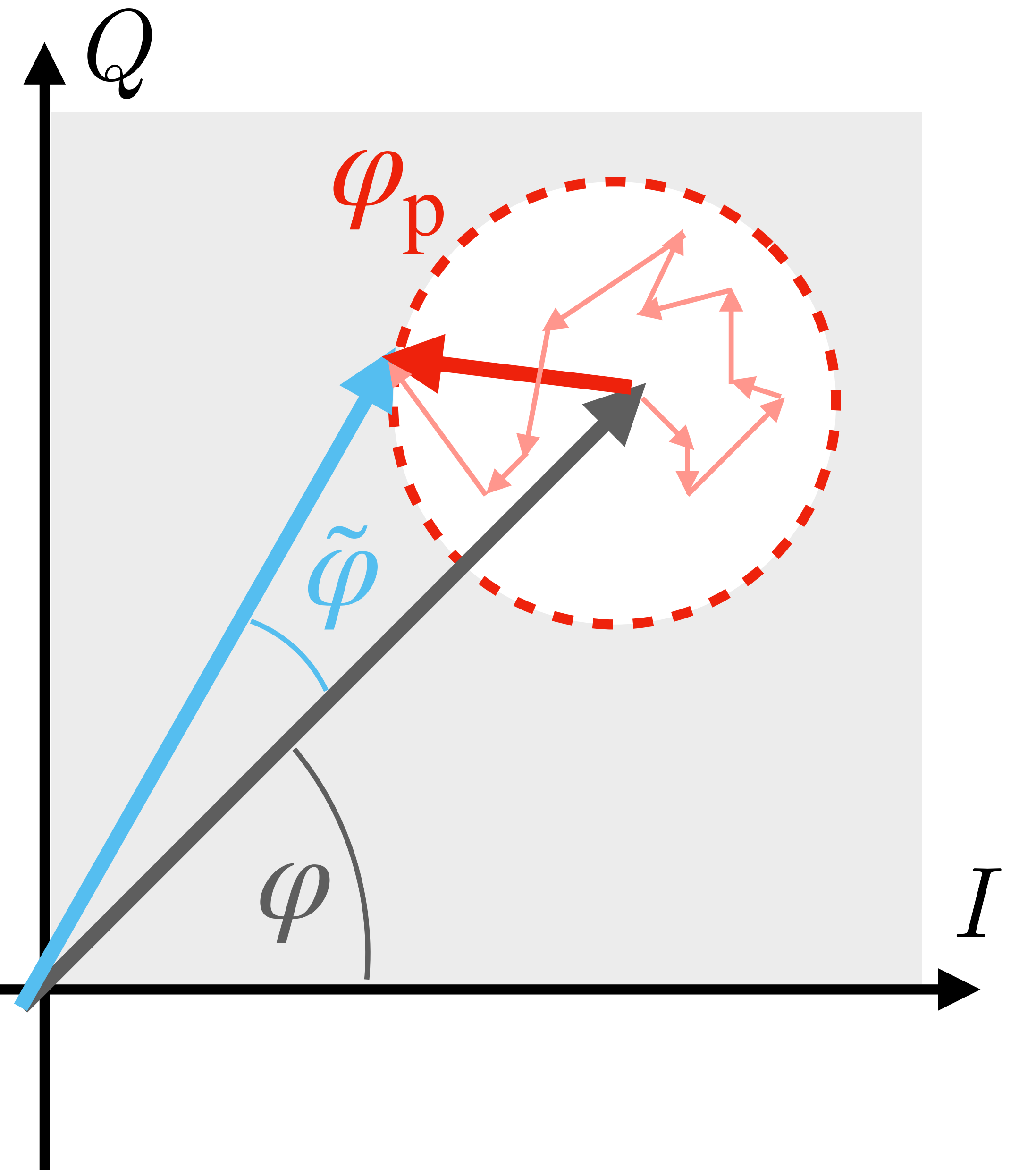
$$u_{ac} \propto \sqrt{1-r}\hat{E}_1\hat{E}_2\eta\cos(\Delta\omega t + \varphi)$$

$$+\sqrt{r}\hat{E}_1\hat{E}_2\eta_p\cos(\Delta\omega t + \varphi - \varphi_p)$$

$$\varphi = \arctan(Q/I)$$

… with **parasitic** beams (interferometers)



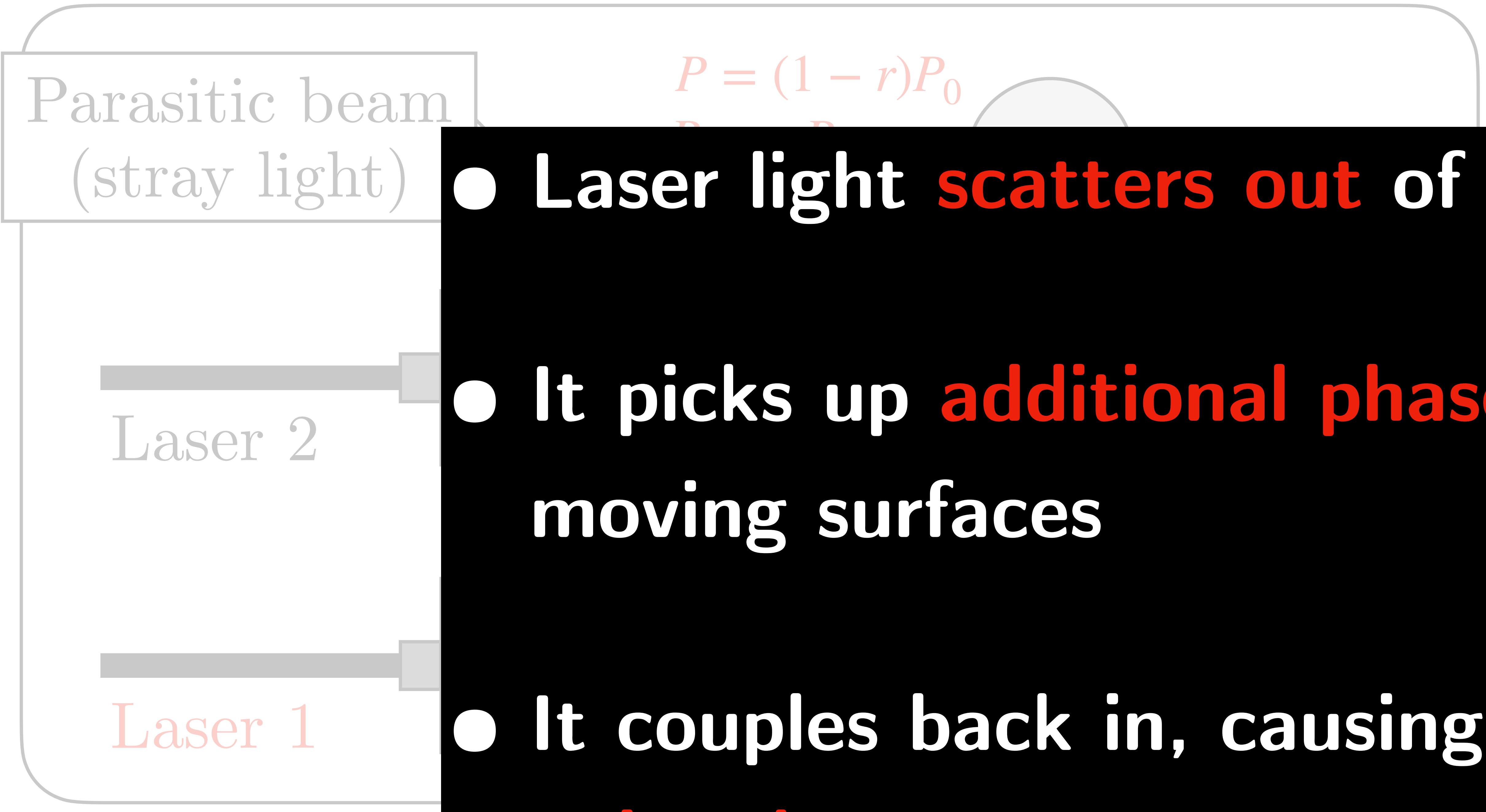


$$I_p^{\pm} = \pm\sqrt{1-r}\hat{E}_1\hat{E}_2 \cdot \cos\varphi + \sqrt{r}\hat{E}_1\hat{E}_2 \cos(\varphi - \varphi_p)$$

$$Q_p^{\pm} = \pm\sqrt{1-r}\hat{E}_1\hat{E}_2 \cdot \sin\varphi + \sqrt{r}\hat{E}_1\hat{E}_2 \sin(\varphi - \varphi_p)$$

$$\varphi = \arctan(Q/I)$$

… with parasitic beams (interferometers)



- Laser light **scatters out** of the main beam path
- It picks up **additional phase noise** by reflecting at moving surfaces
- It couples back in, causing a **non-linear readout noise that can up-convert to higher frequencies**

$$I_p^{\pm} = \pm\sqrt{1 - r}\hat{E}_1\hat{E}_2 \cdot \cos\varphi + \sqrt{r}\hat{E}_1\hat{E}_2 \cos(\varphi - \varphi_p)$$

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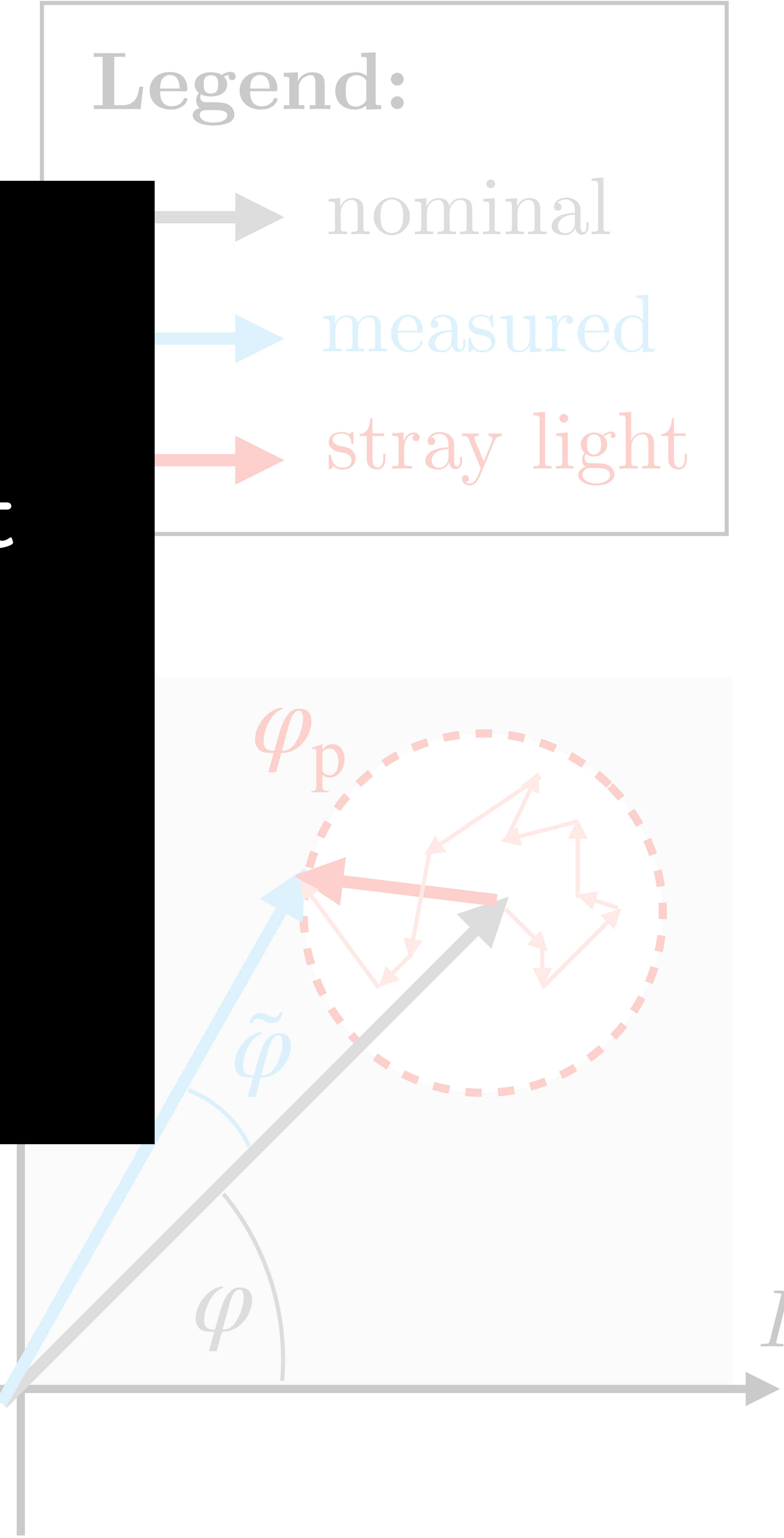
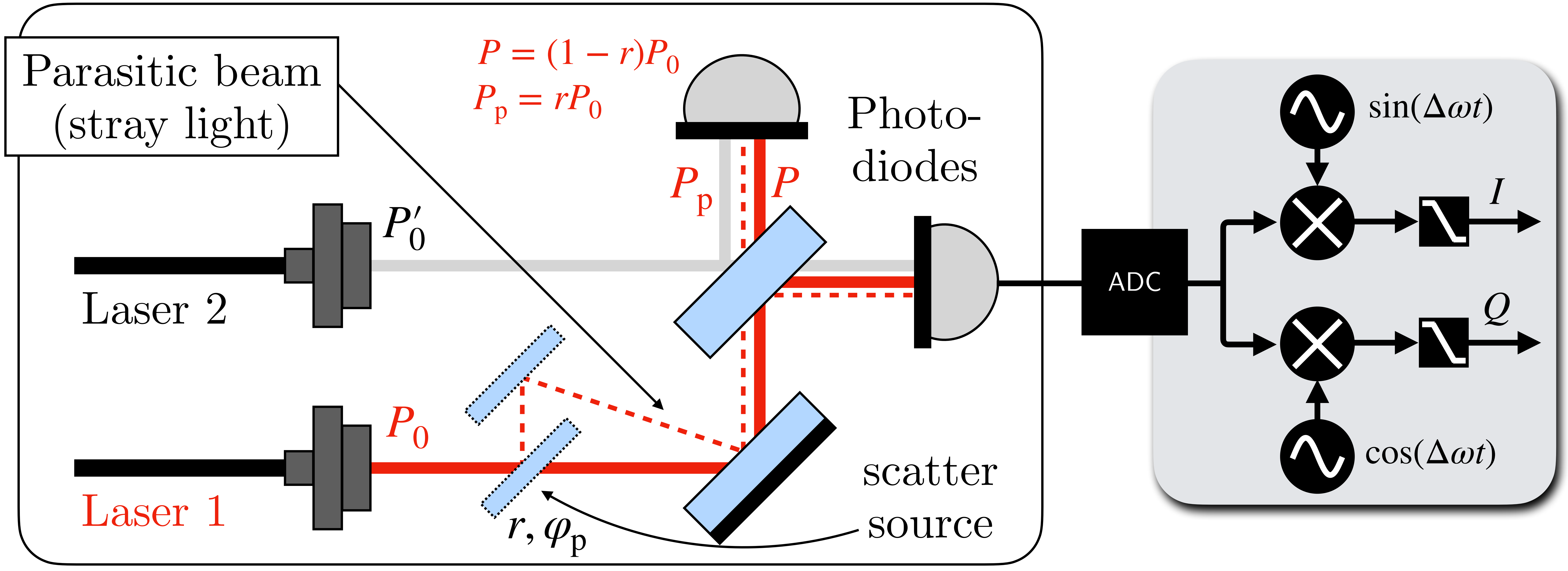
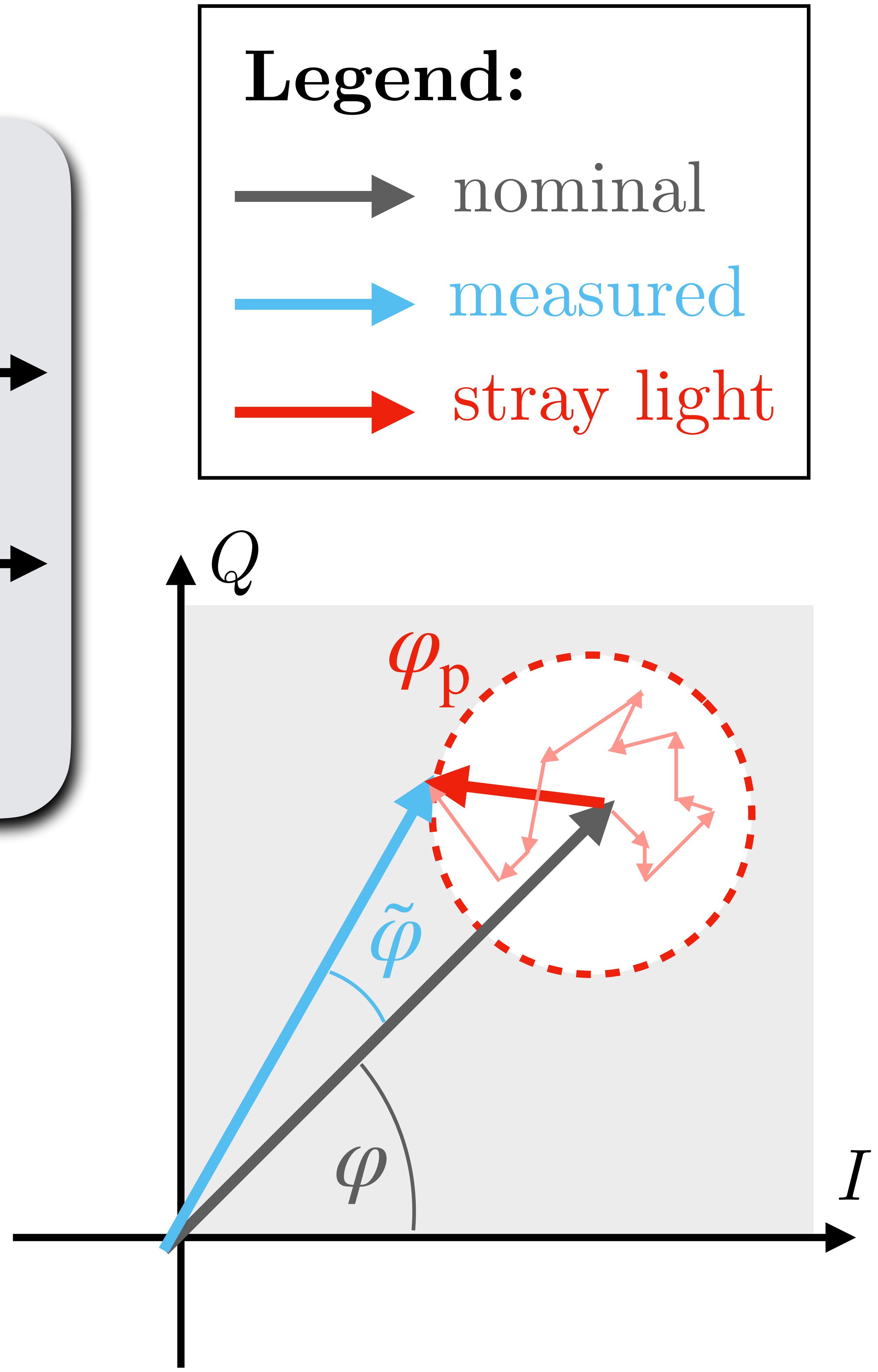


Phase error due to parasitic beams



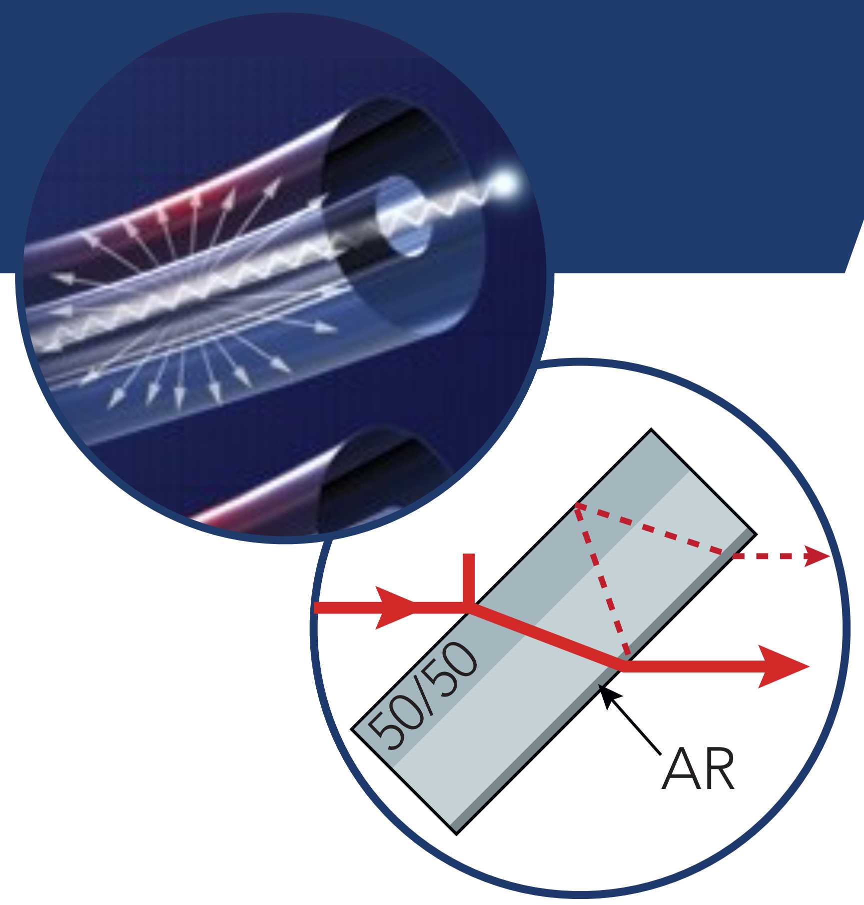


$$\tilde{\varphi}^{\pm} = \arctan\left(\frac{Q}{I}\right) = \frac{\pm\sqrt{r}\sin\varphi_{\mathrm{p}}}{\pm\sqrt{1-r}+\sqrt{r}\cos\varphi_{\mathrm{p}}} \approx \sqrt{\frac{P_{\mathrm{p}}}{P}}\cdot\sin\varphi_p$$

Coupling of parasitic beams

SOURCES

P_p

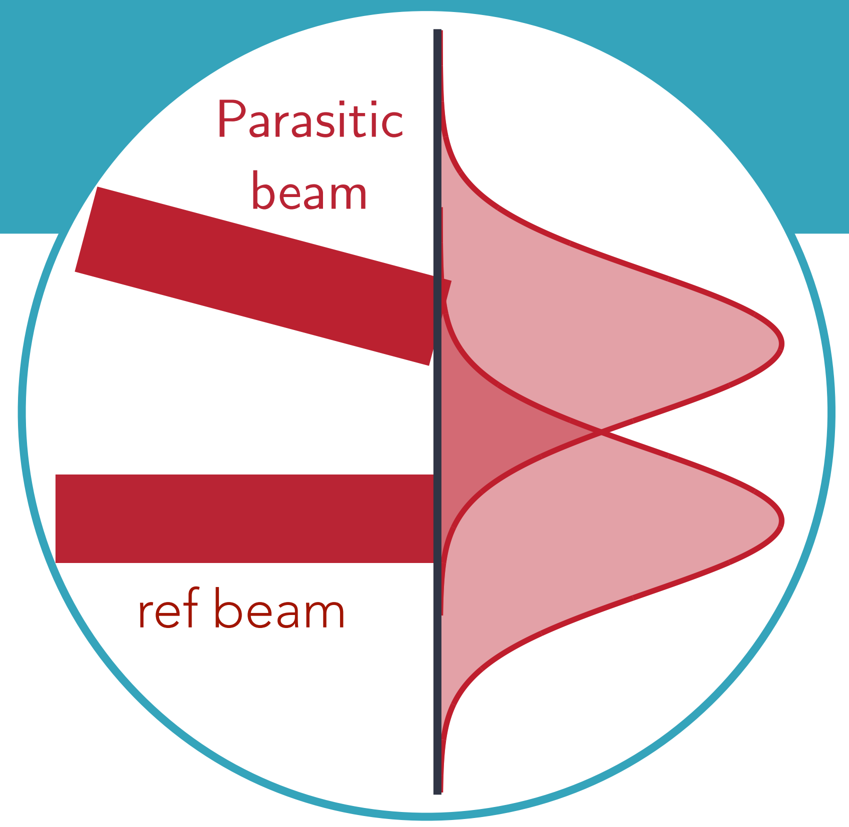


DYNAMICS

φ_p

OVERLAP

η_p

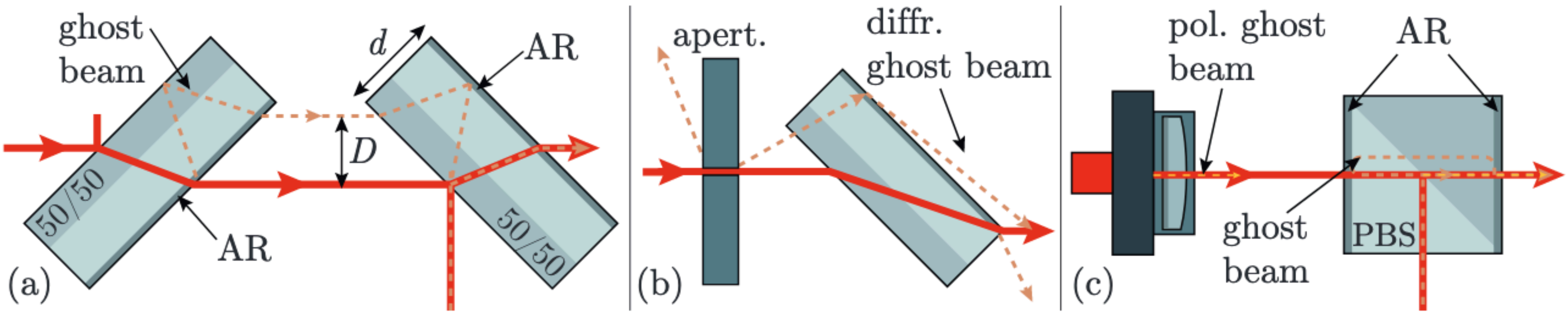


DETECTION

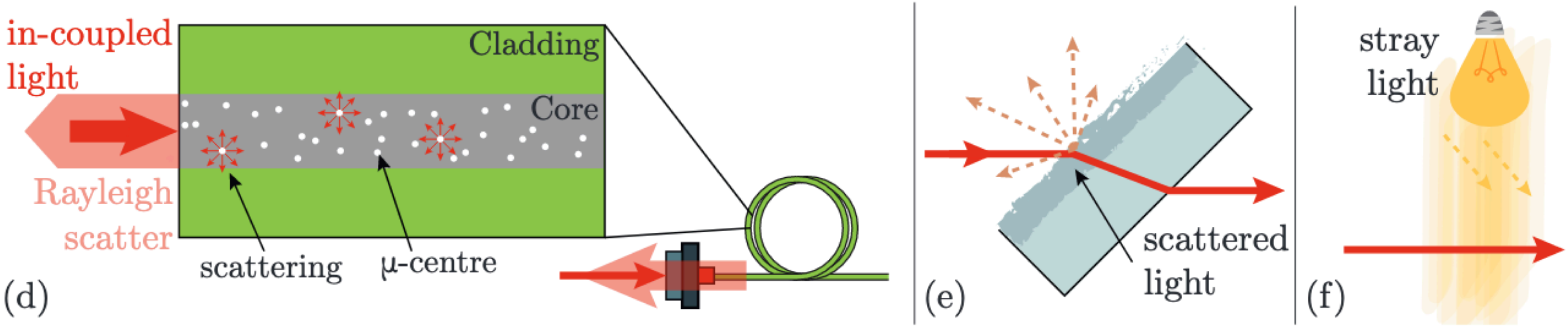
$$\tilde{\varphi} \approx \sqrt{\frac{\eta_p P_p}{\eta P_0}} \sin(\varphi_p)$$

Sources of parasitic beams

Ghost beams



Scattering



Sources of parasitic beams

Ghost beams

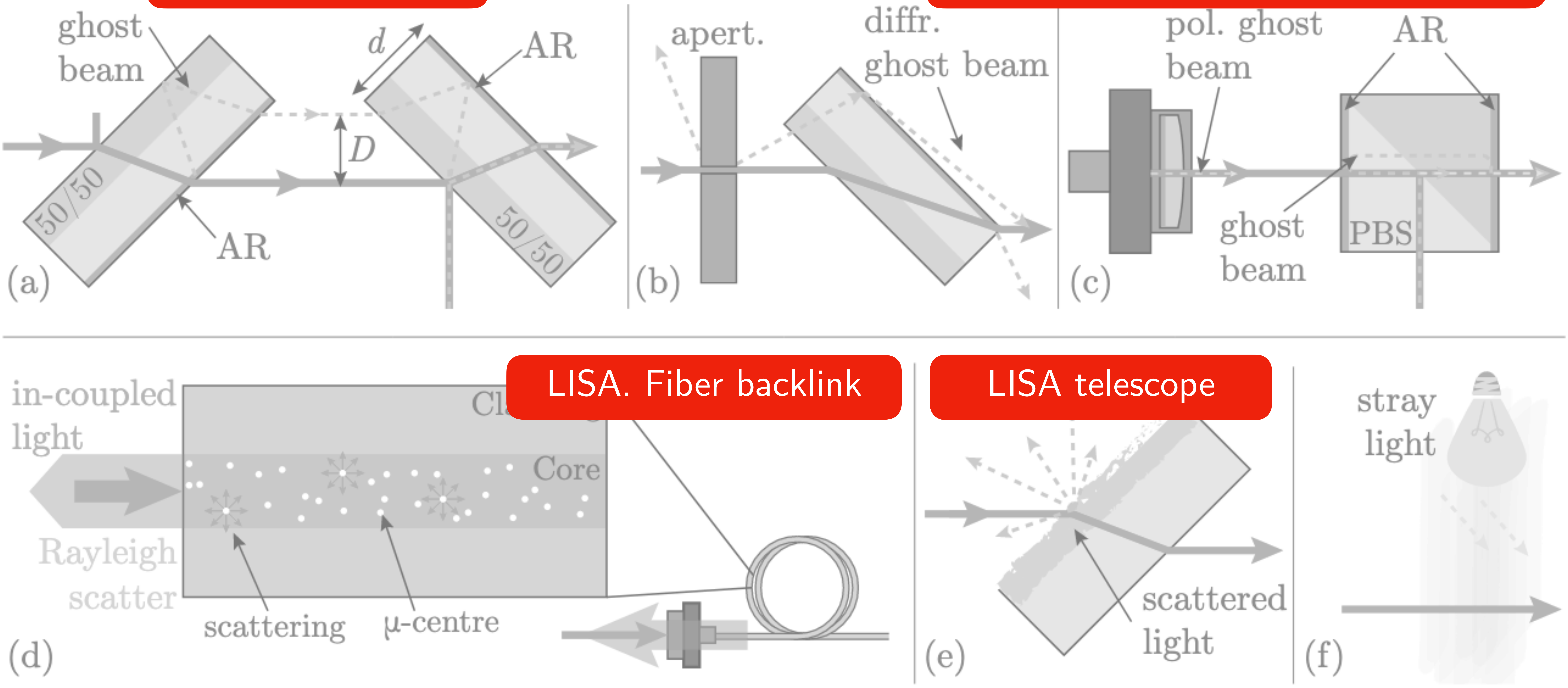
LISA optical bench

LISA optical bench + fiber backlink

Scattering

LISA. Fiber backlink

LISA telescope



Isleif (2018) https://doi.org/10.15488/3526

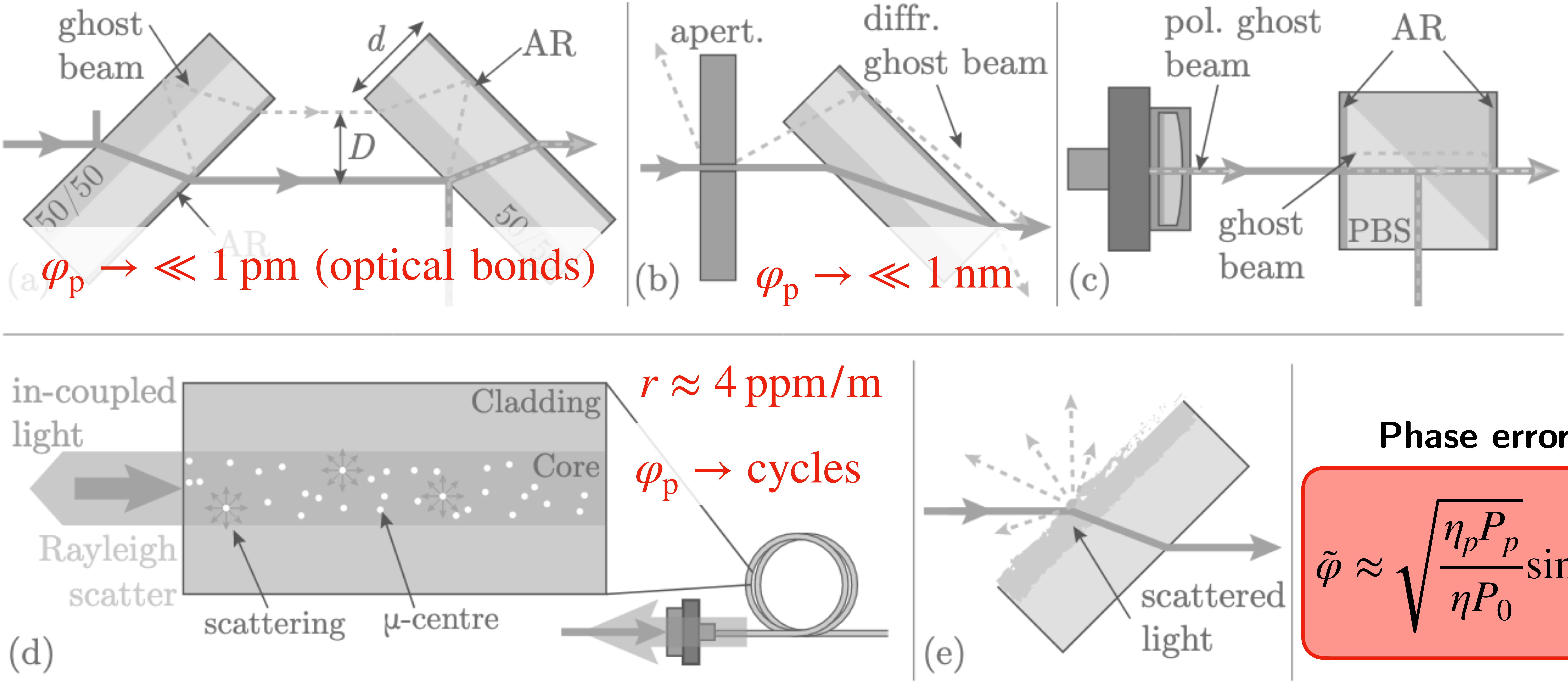
Dynamics & power of parasitic beams

Ghost beams

$r \approx 0.1\,\%$ $\qquad$ $r \approx 0.1\,\%$

$\varphi_\mathrm{p} \rightarrow \ll 1\,\mathrm{pm}$ (optical bonds)

$\varphi_\mathrm{p} \rightarrow \ll 1\,\mathrm{nm}$



Scattering

$r \approx 4\,\mathrm{ppm/m}$

$\varphi_\mathrm{p} \rightarrow$ cycles

Phase error:

$$\tilde{\varphi} \approx \sqrt{\frac{\eta_p P_p}{\eta P_0}} \sin(\varphi_p)$$

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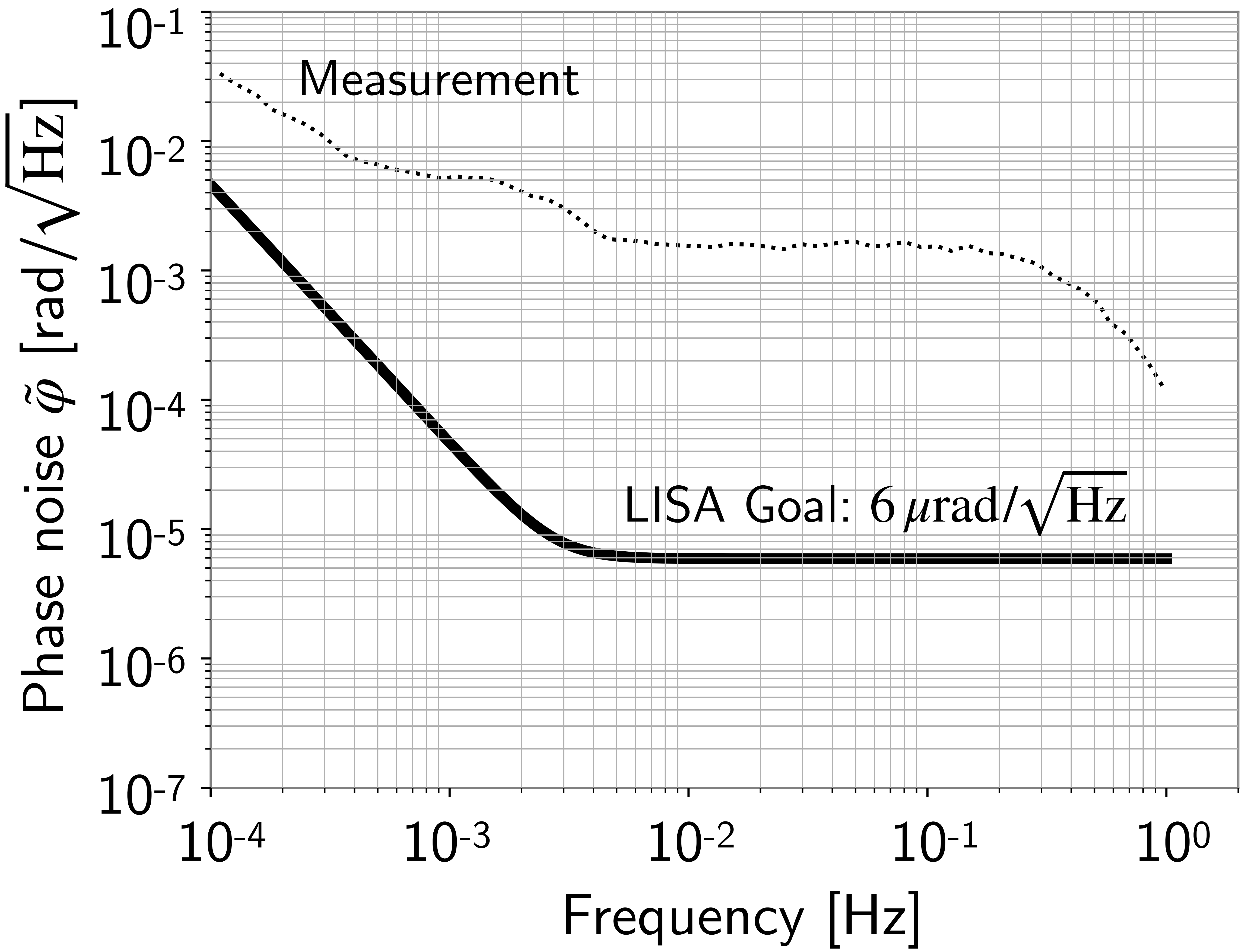
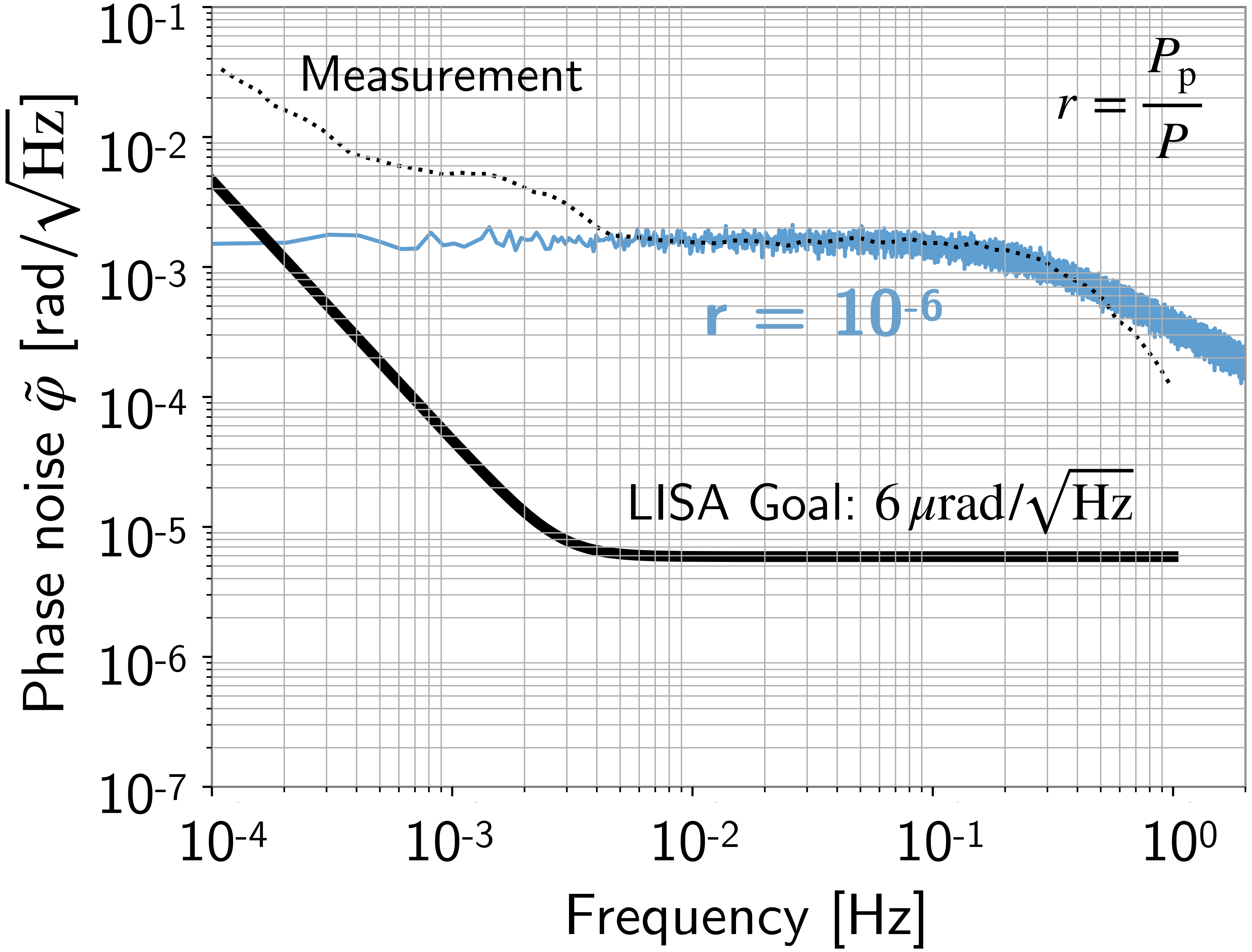
Phase measurement in LISA

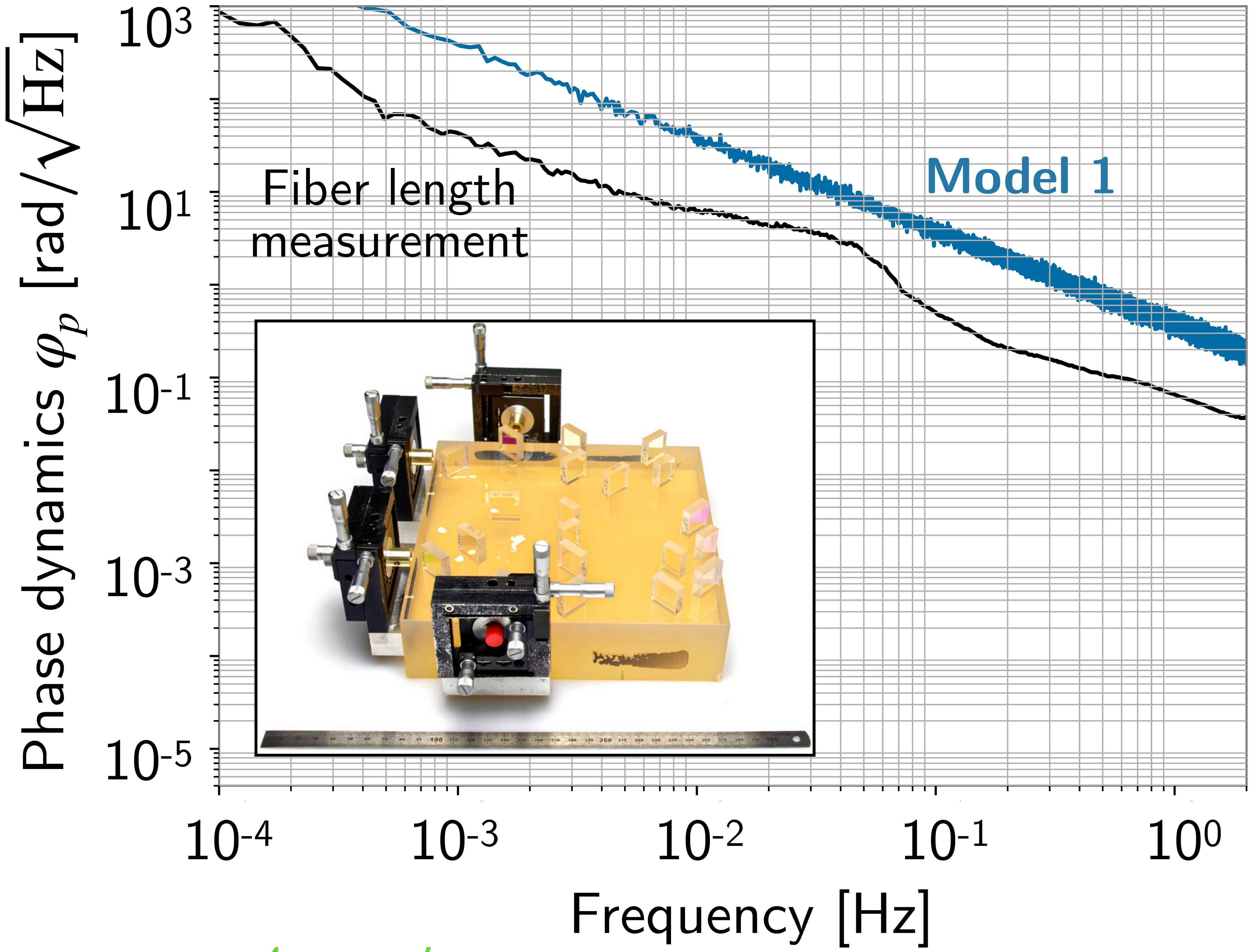


Simulations of induced phase errors

Phase error: $\tilde{\varphi} \approx \sqrt{r} \cdot \sin \varphi_p$



φ_p



Fiber backscatter: $r \approx 4\,\text{ppm/m}$

Simulations of induced phase errors

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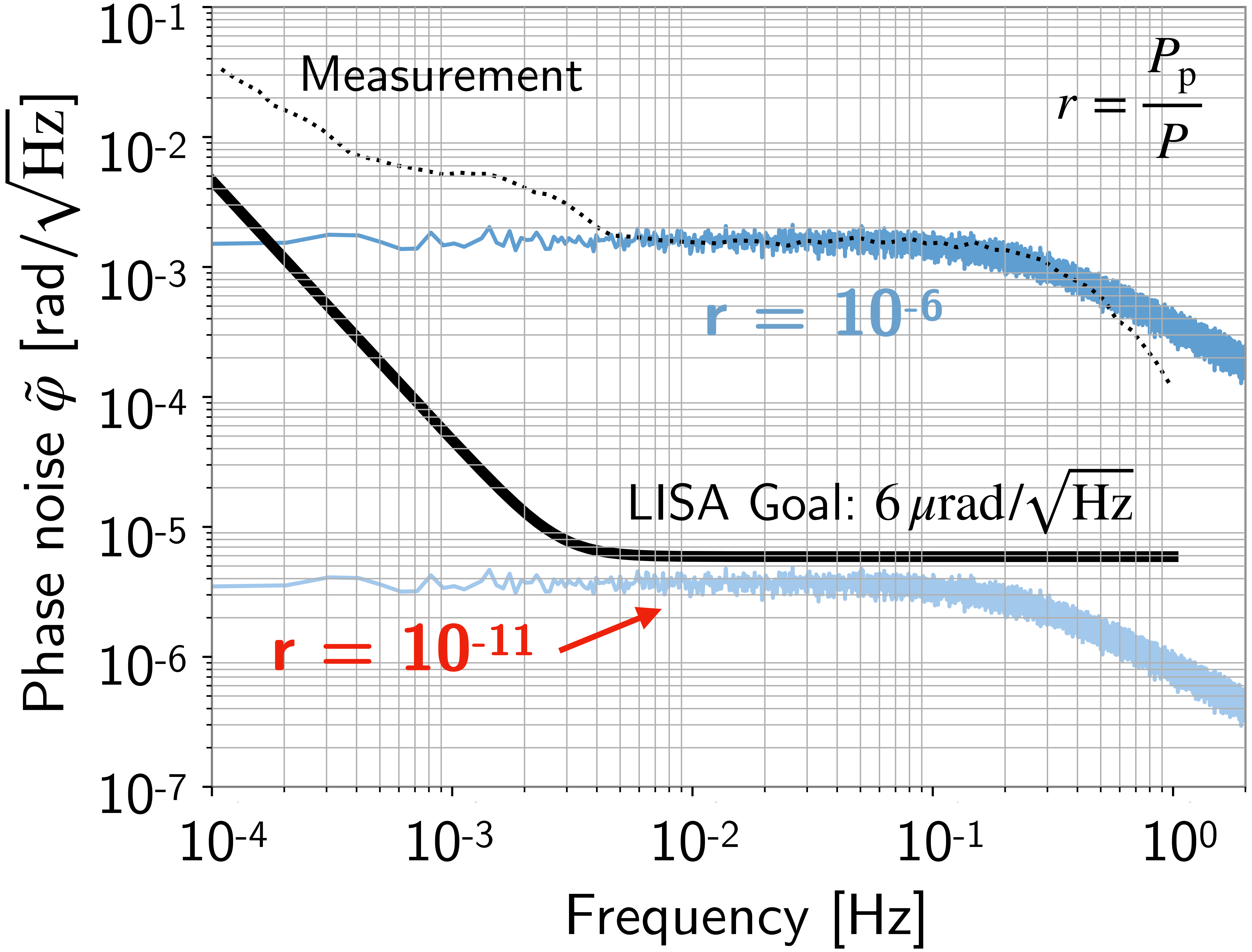
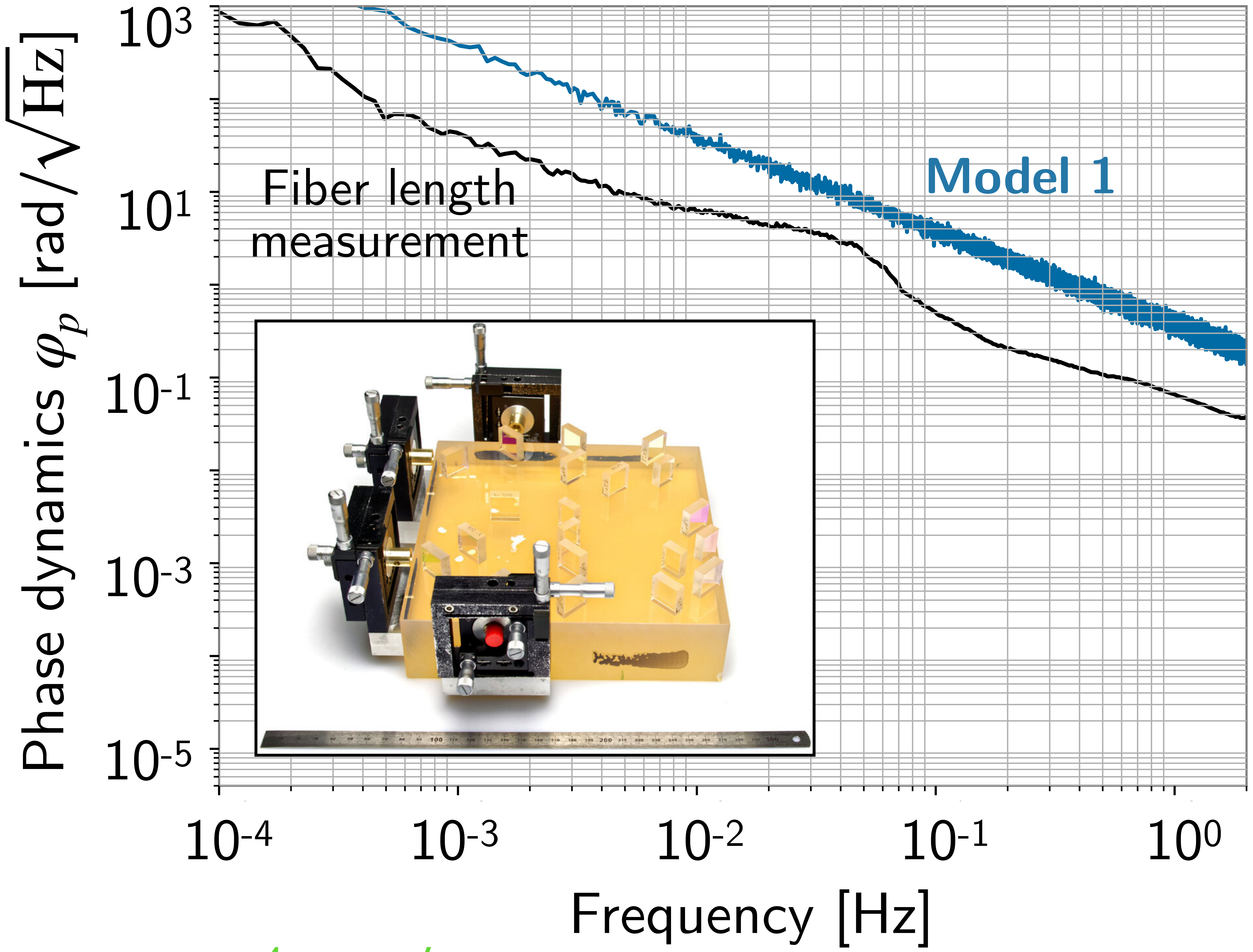


φ_p



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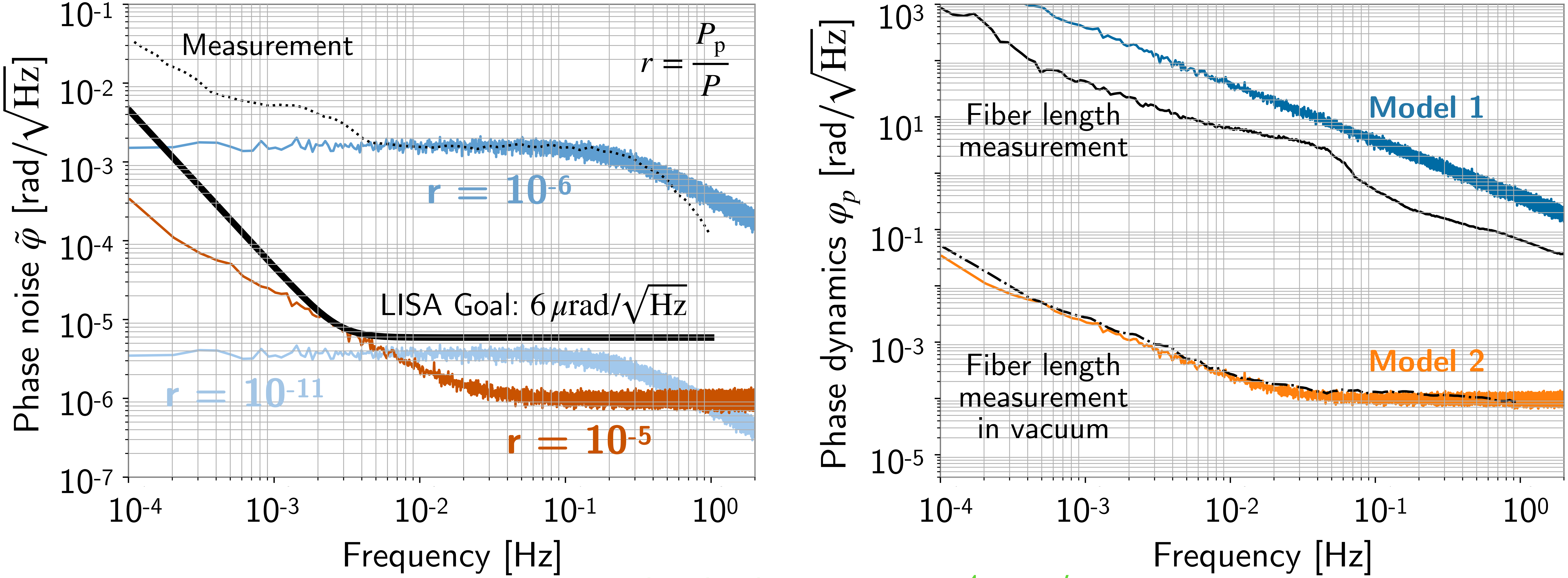

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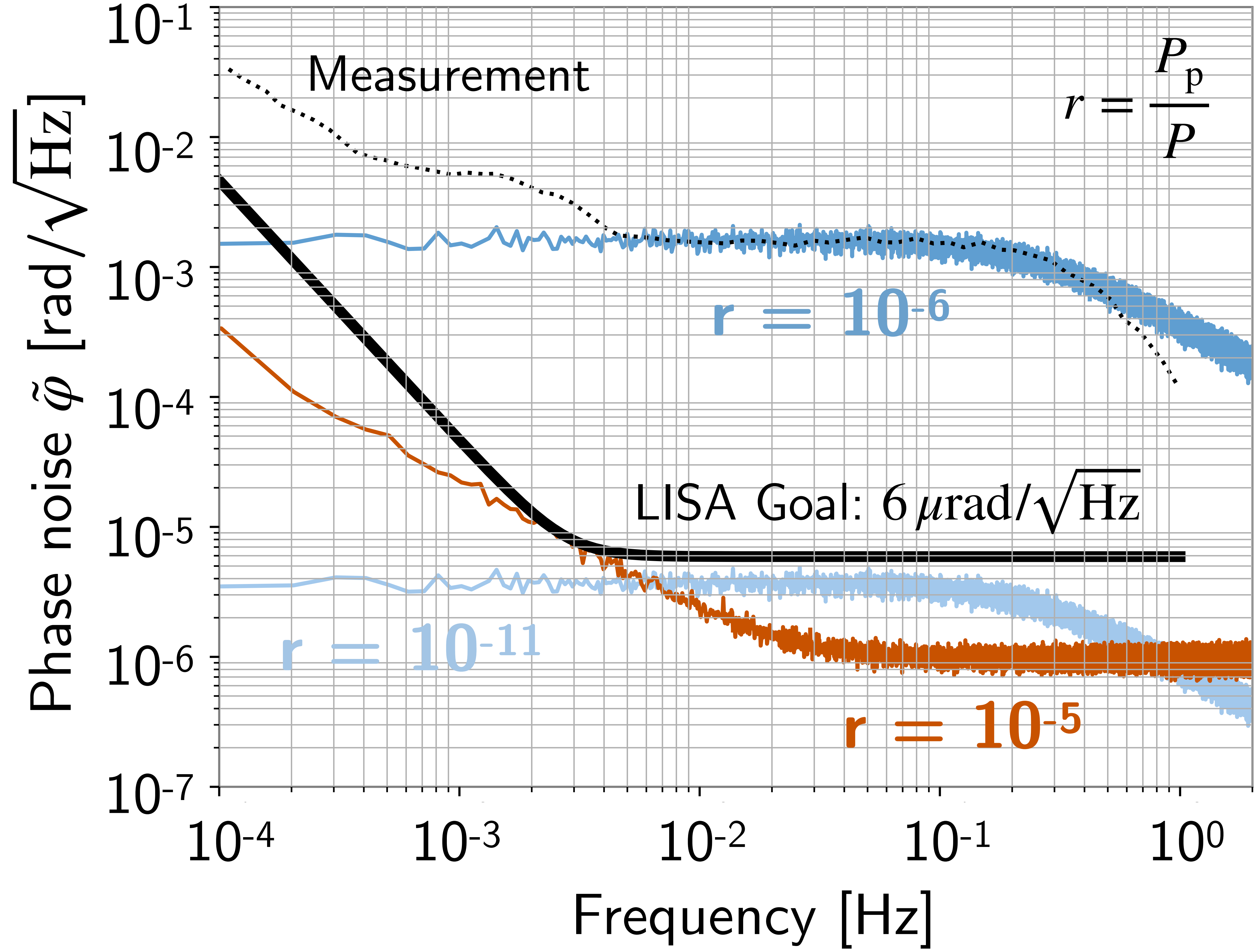
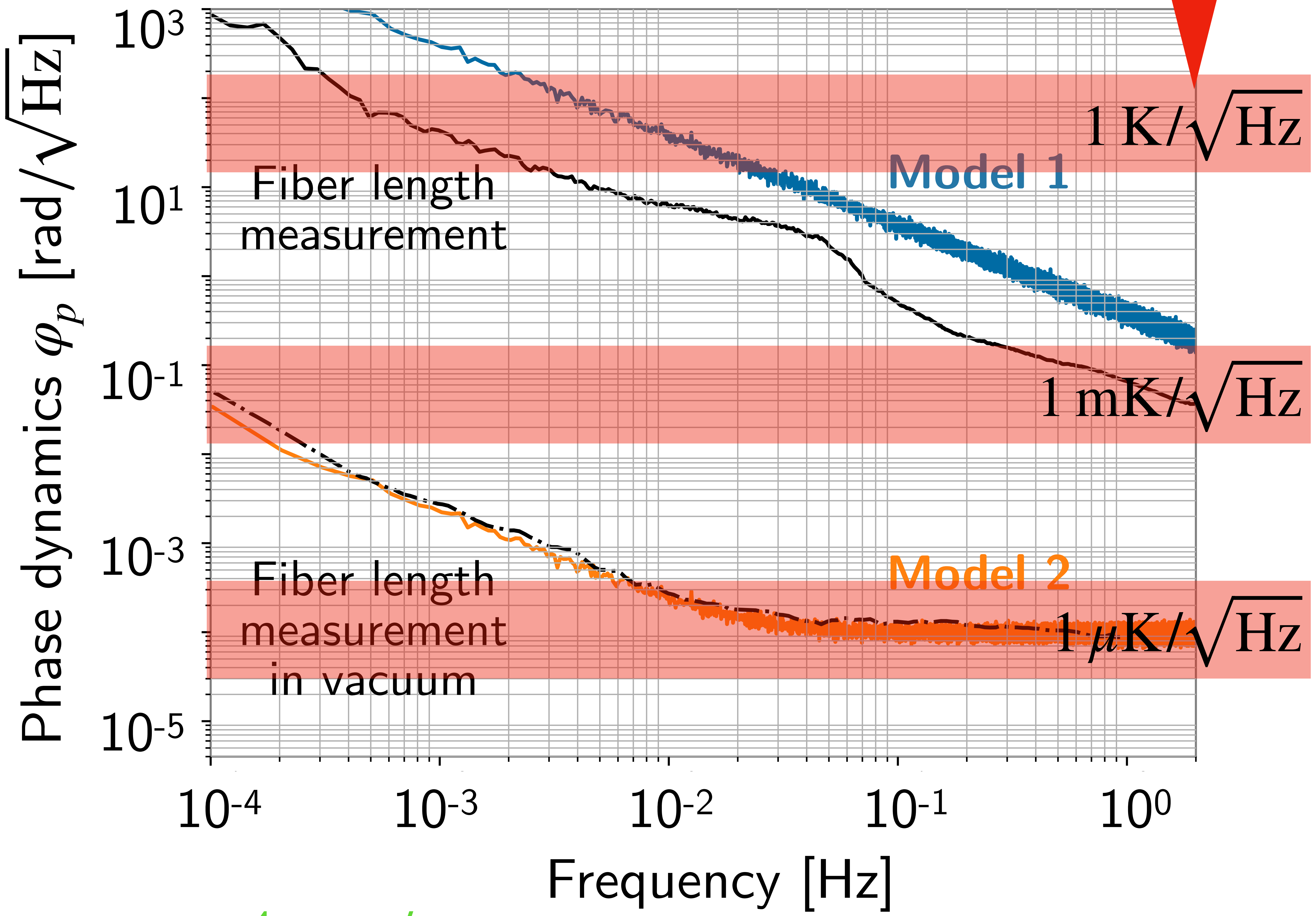


φ_p

Fiber: 100 rad/K/m



Fiber backscatter: $r \approx 4\,\mathrm{ppm/m}$

Mitigation strategies

11th International LISA Symposium — IOP Publishing

IOP Conf. Series: Journal of Physics: Conf. Series **840** (2017) 012016 doi:10.1088/1742-6596/840/1/012016

Suppressing ghost beams: Backlink options for LISA

K-S Isleif[1], O Gerberding[2], D Penkert[2], E Fitzsimons[3], H Ward[4], D Robertson[4], J Livas[5], G Mueller[6], J Reiche[2], G Heinzel[2] and K Danzmann[1,2]

[1] Leibniz Universität Hannover, Institute for Gravitational Physics, Callinstr. 38, 30167 Hannover, Germany
[2] Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Callinstr. 38, 30167 Hannover, Germany
[3] UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ
[4] University of Glasgow, R460 Level 4, IGR Physics & Astronomy, Kelvin Building, University Avenue Glasgow G12 8QQ
[5] NASA's Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA
[6] University of Florida, Department of Physics, Gainesville, Florida 32611, USA

Eliminate origin spurious beams ($P \rightarrow 0\,\mathrm{W}$)

- By optical design (not entering diodes)
  - Block ghost beams: baffles
  - Avoid 0° surfaces (use wedged 2ndary surface)

Reduce power of spurious beams ($P \rightarrow \mathrm{nW} - \mathrm{pW}$)

- Clean surfaces to avoid scattering
- Good Coatings (AR, polarization, …)
- Attenuation stages (reduce r, polarization, …)

Reduce dynamics ($\varphi_p \rightarrow 0\,\mathrm{rad}$)

- Stable interferometer (e.g. quasi-monolithic)
- Fiber length stabilization / OPL
- Stabilize environment (temperature, air, …)

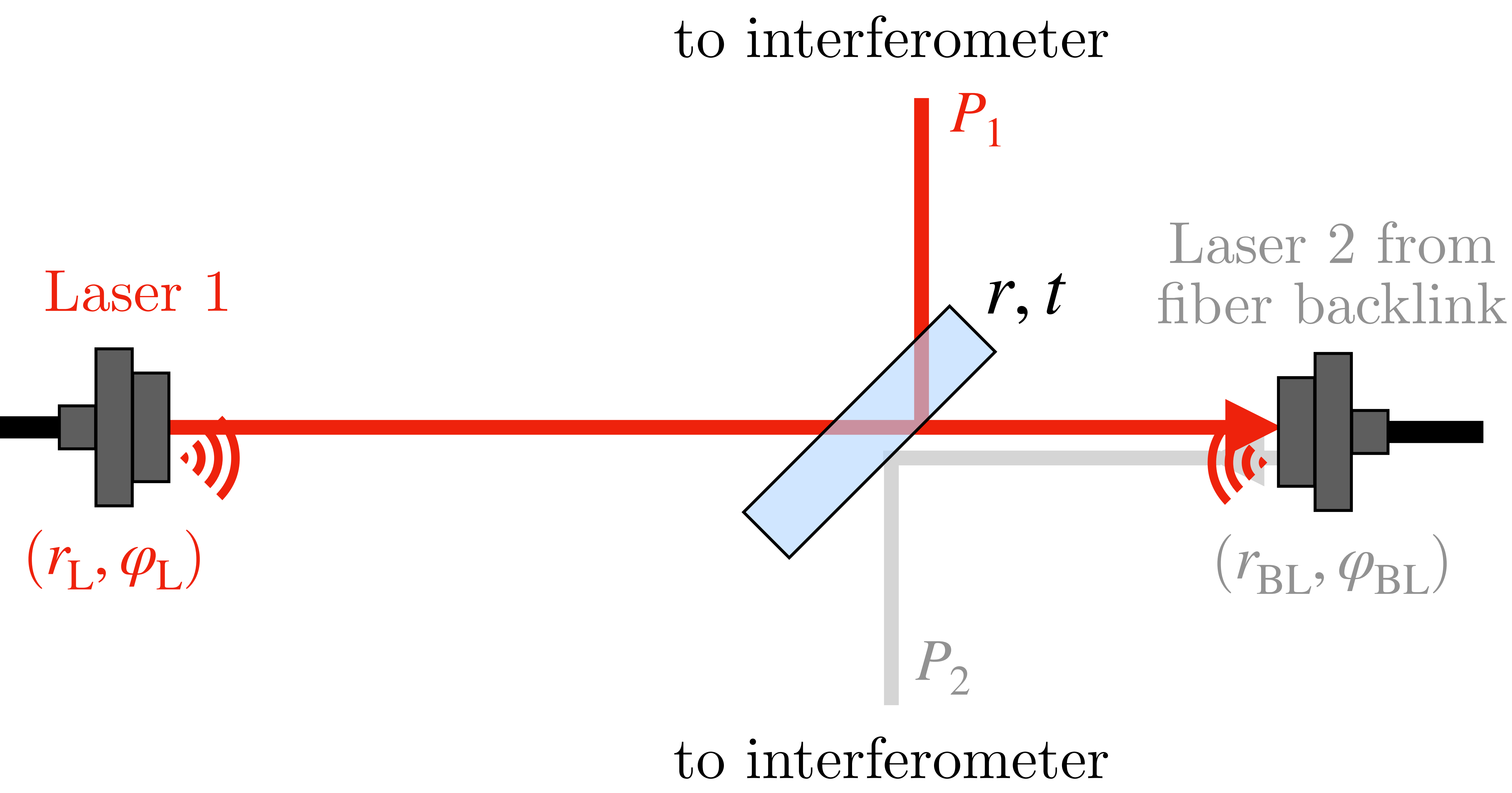
Auxiliary sensing

- Balanced detection
- Coherent noise cancellation

Distinguish ghost beams from main interferometer

- Frequency-shifted, AOM
- Polarization/Faraday Isolator
- Digitally-enhanced interferometry: destroy coherence

Mitigation strategies



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Isleif et. al (2017) doi:10.1088/1742-6596/840/1/012016

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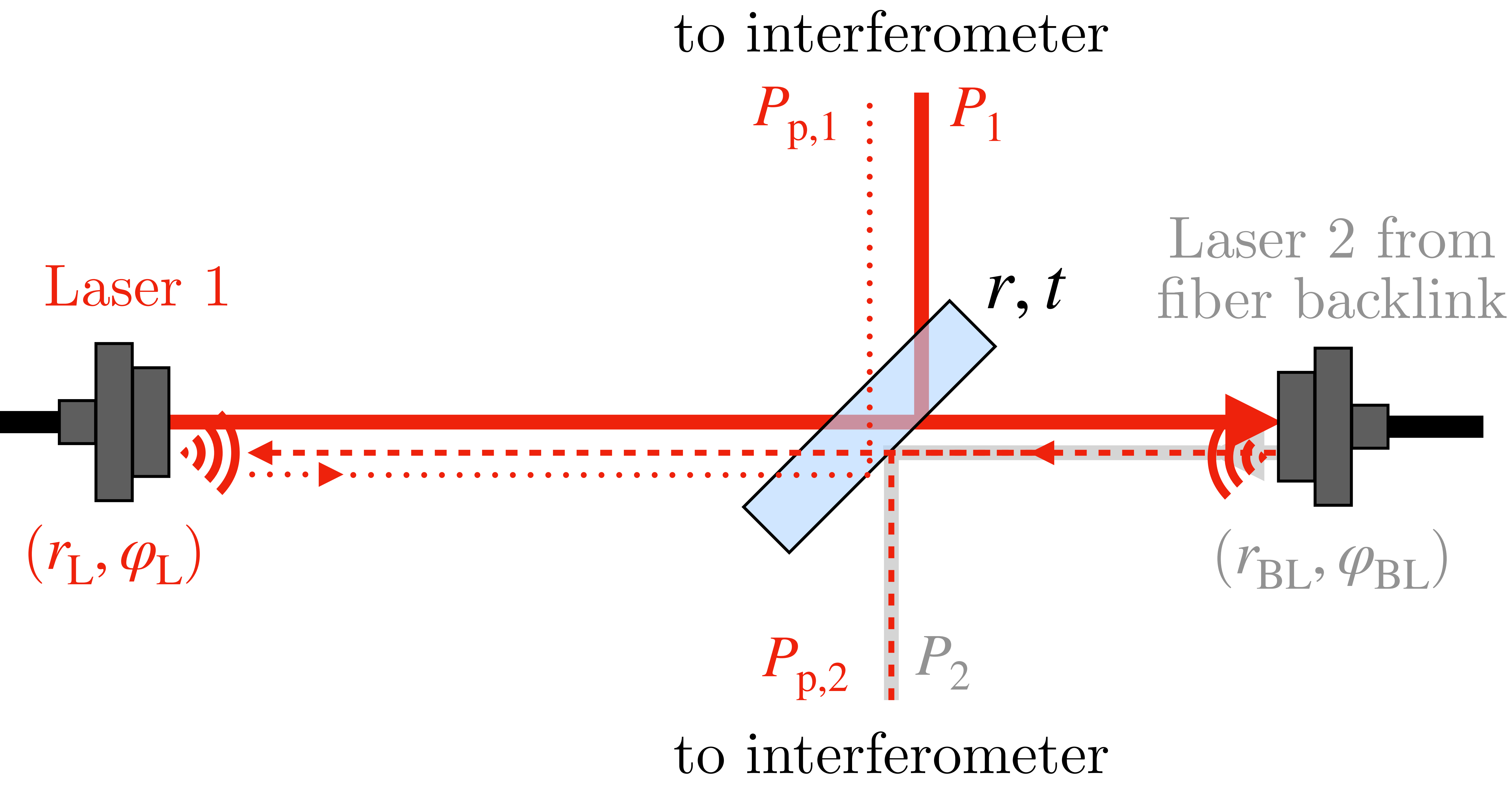

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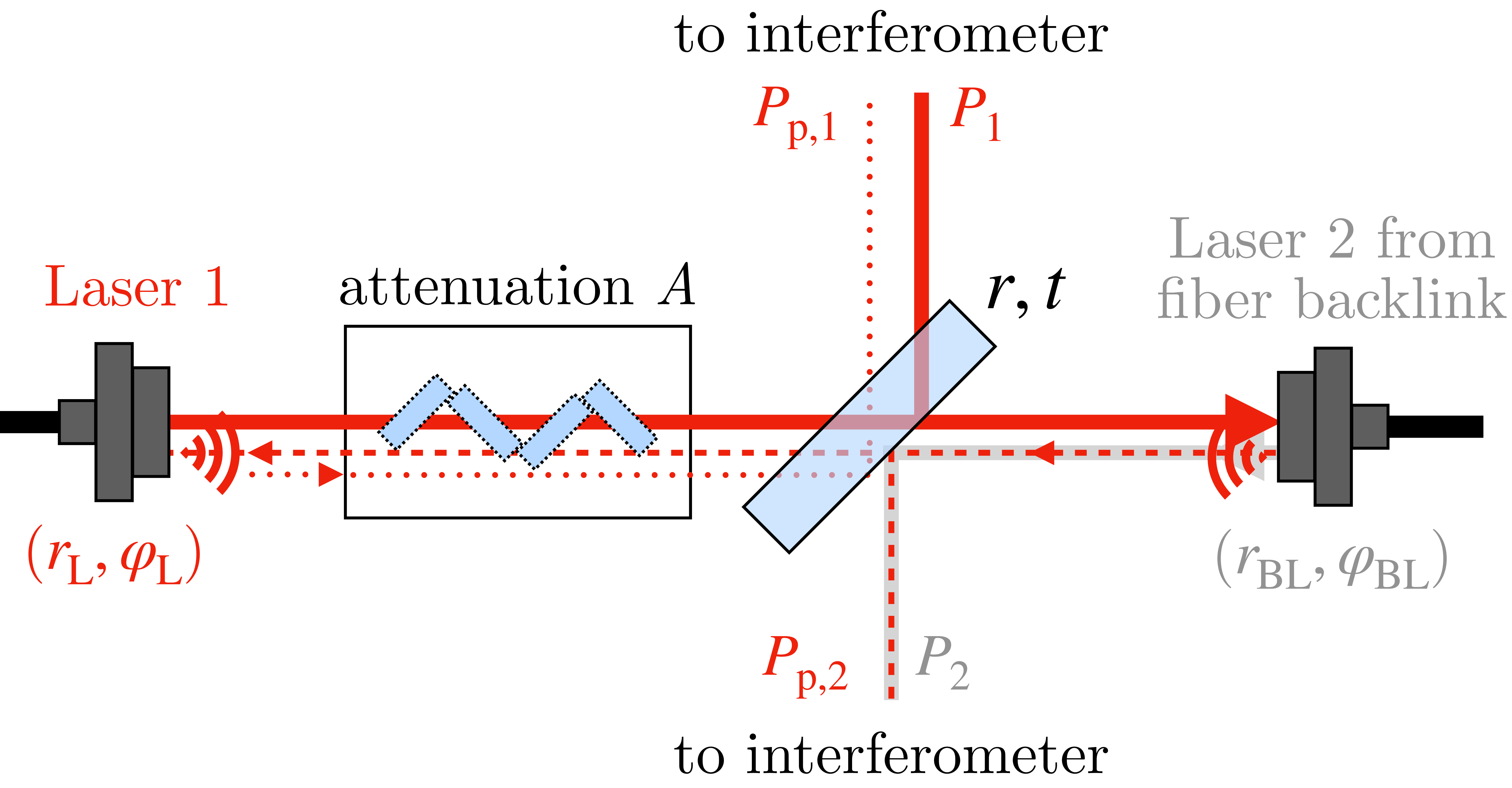

$$\tilde{\varphi} \approx \sqrt{\frac{rA^3 r_L t^2 r_{BL} P_0}{rAP_0}} \cdot \sin\varphi_p = A\sqrt{r_{tot}}\sin(\varphi_p)$$

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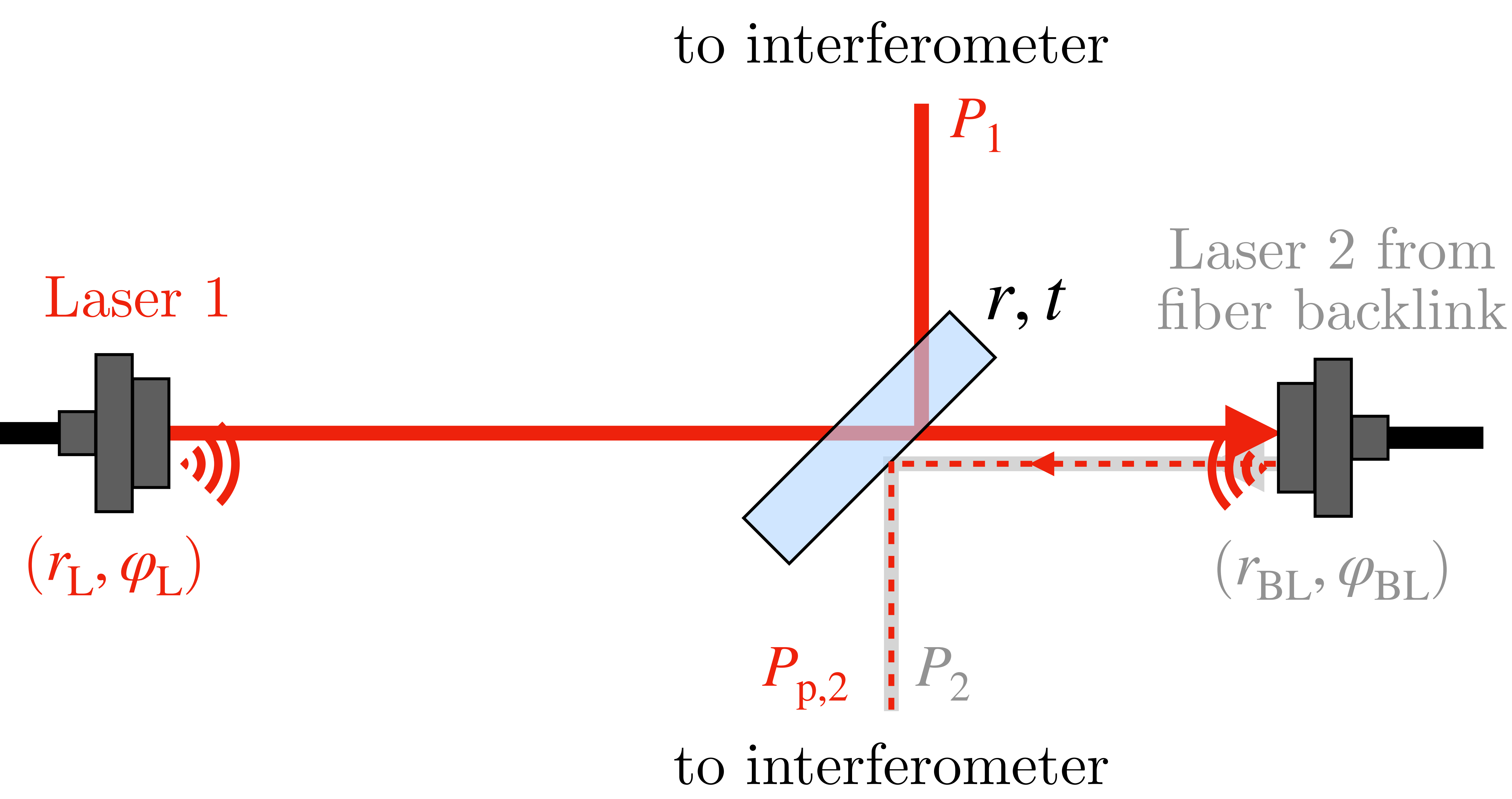

Balanced detection

10x suppression (2 photodiodes required per intereferometer)

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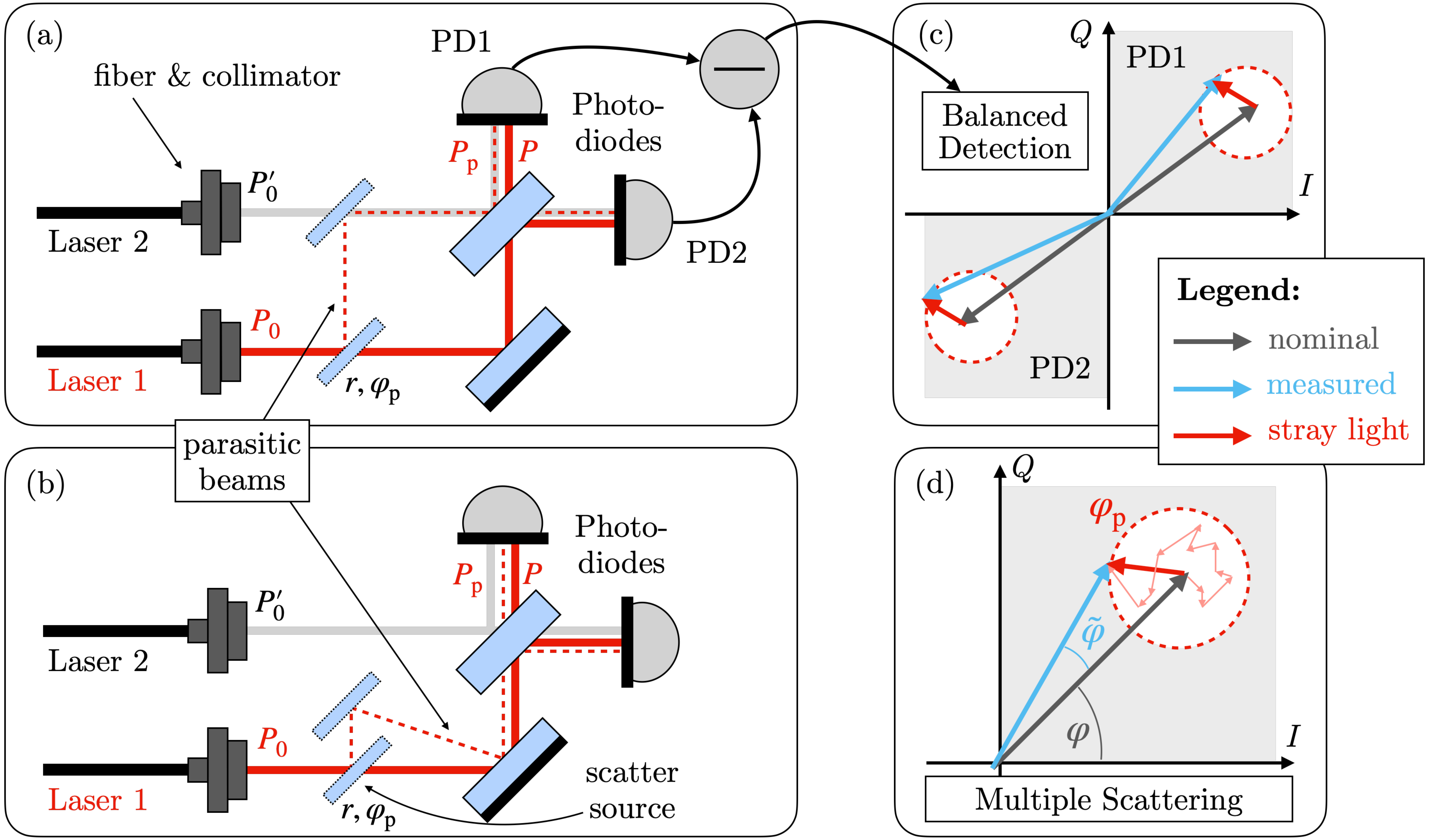
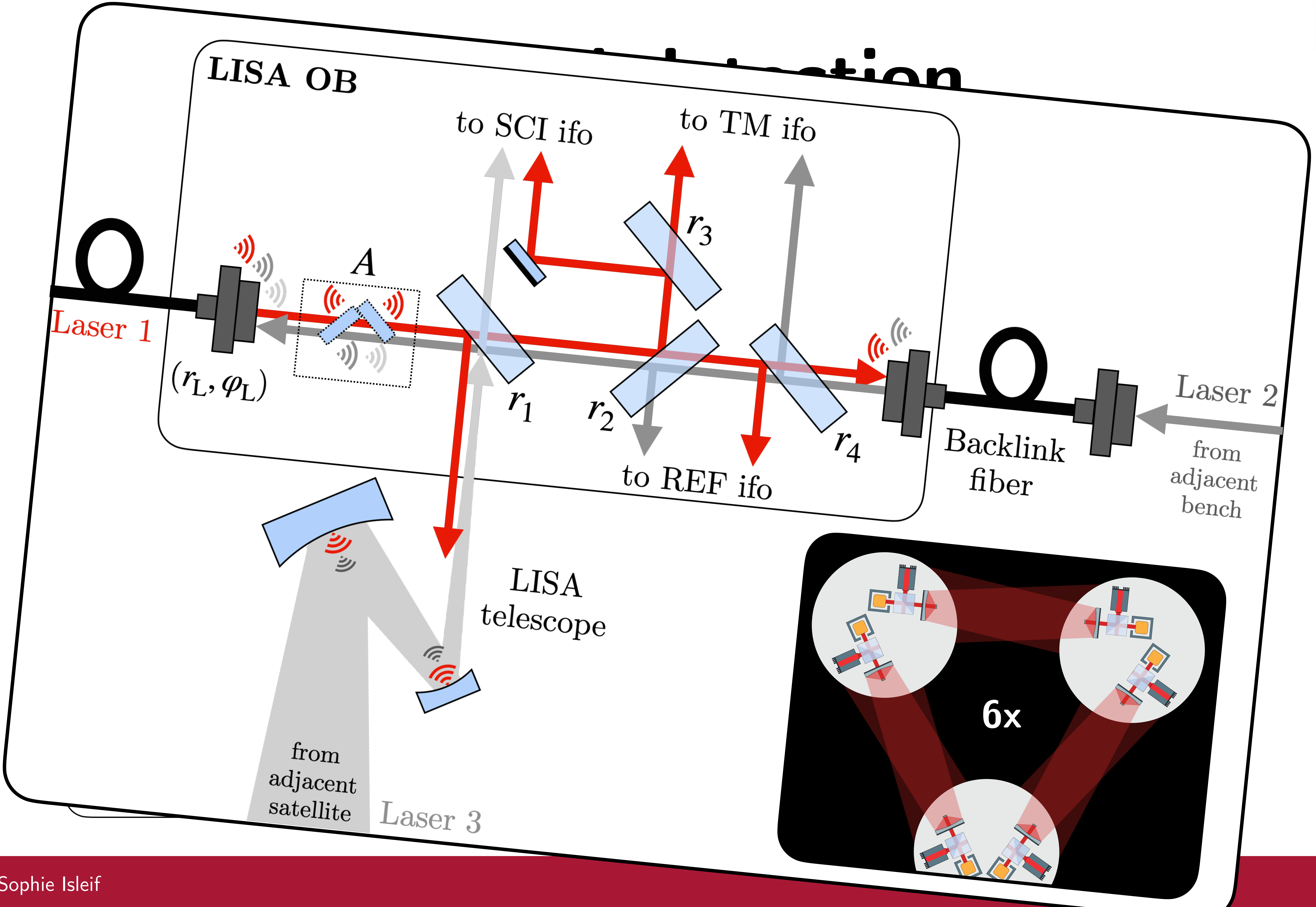
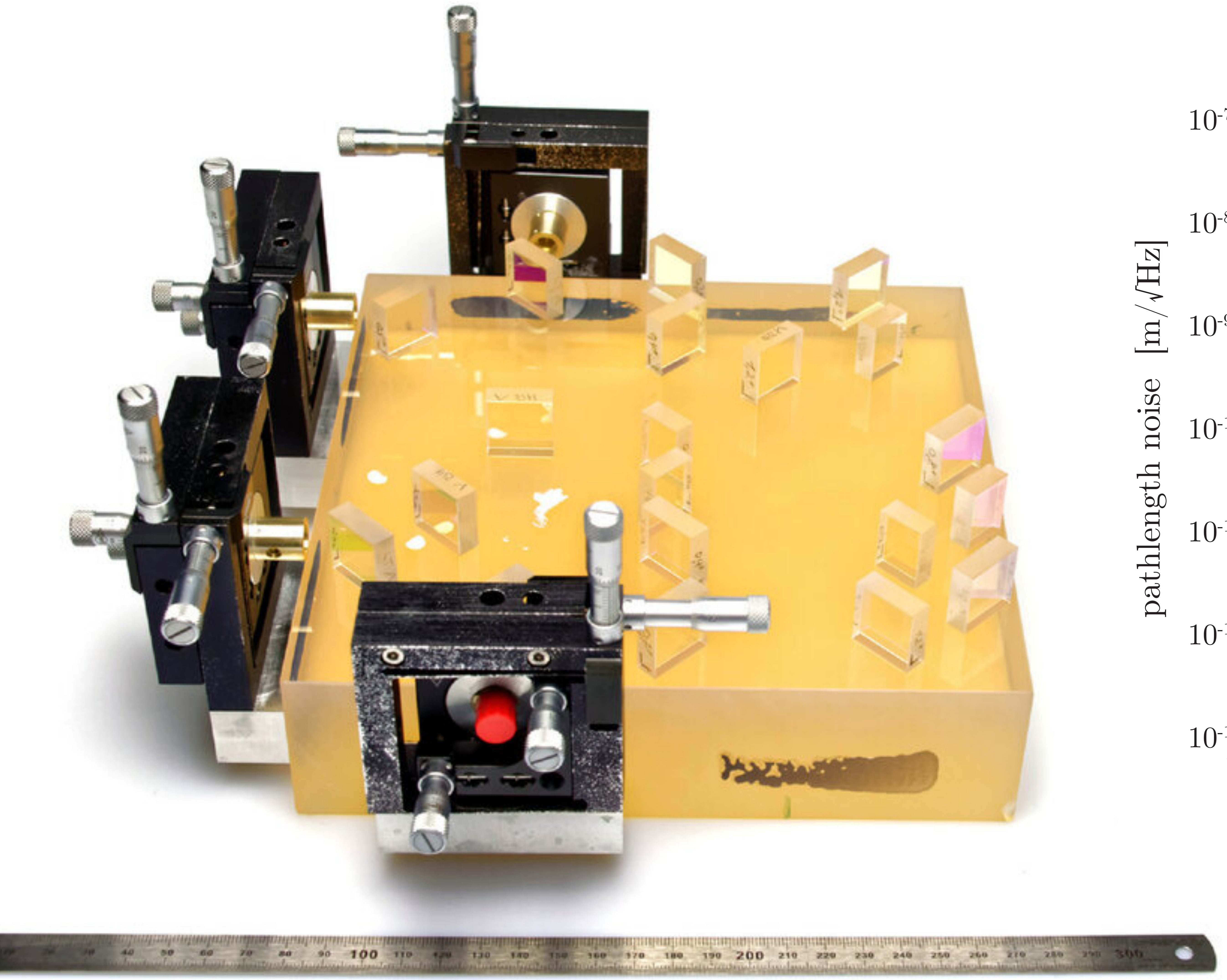
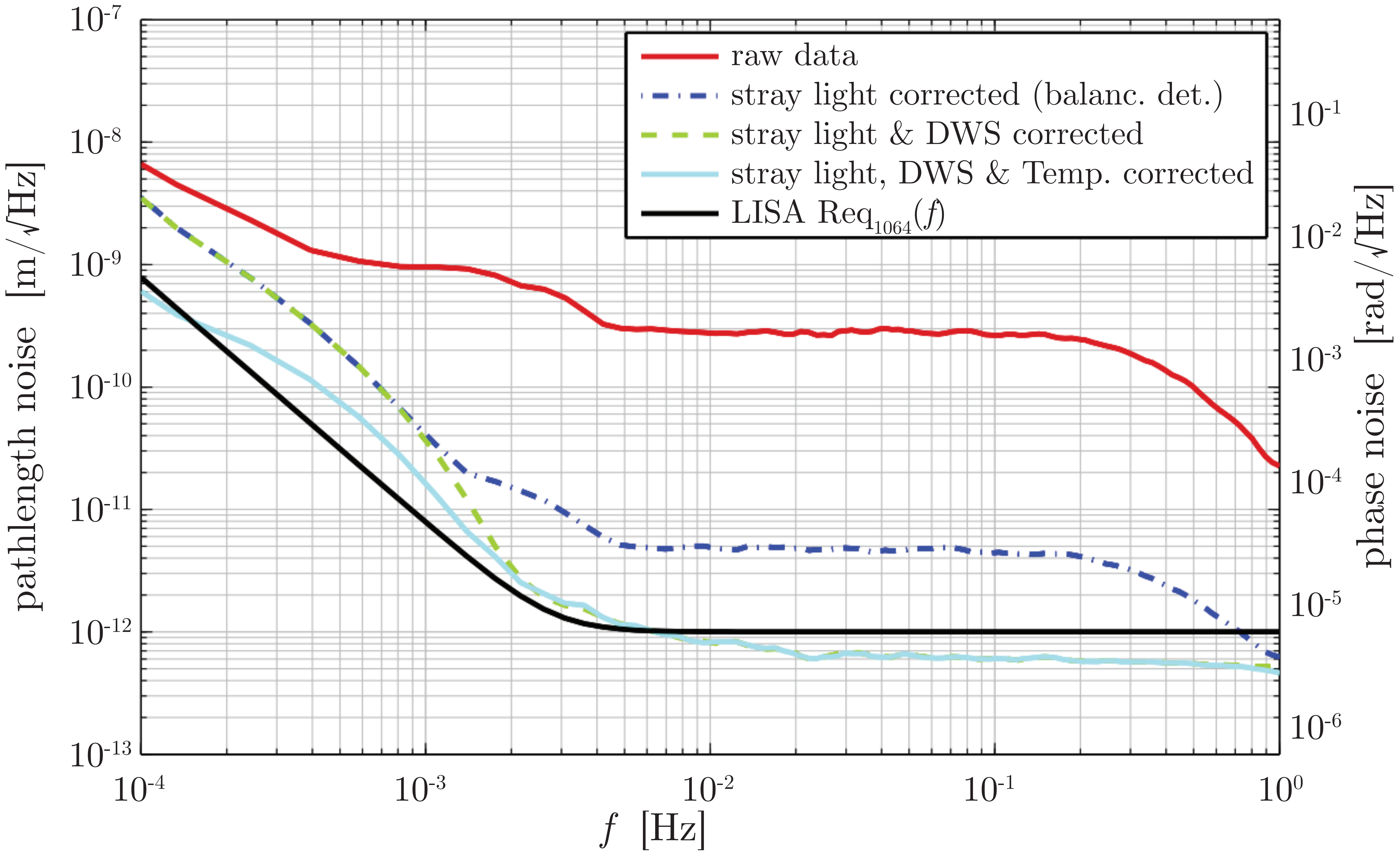
Balanced detection




LISA OB
to SCI ifo
to TM ifo
A
Laser 1
(r_L, φ_L)
r_1
r_2
r_3
r_4
to REF ifo
Backlink
fiber
Laser 2
from
adjacent
bench
LISA
telescope
from
adjacent
satellite
Laser 3
6x

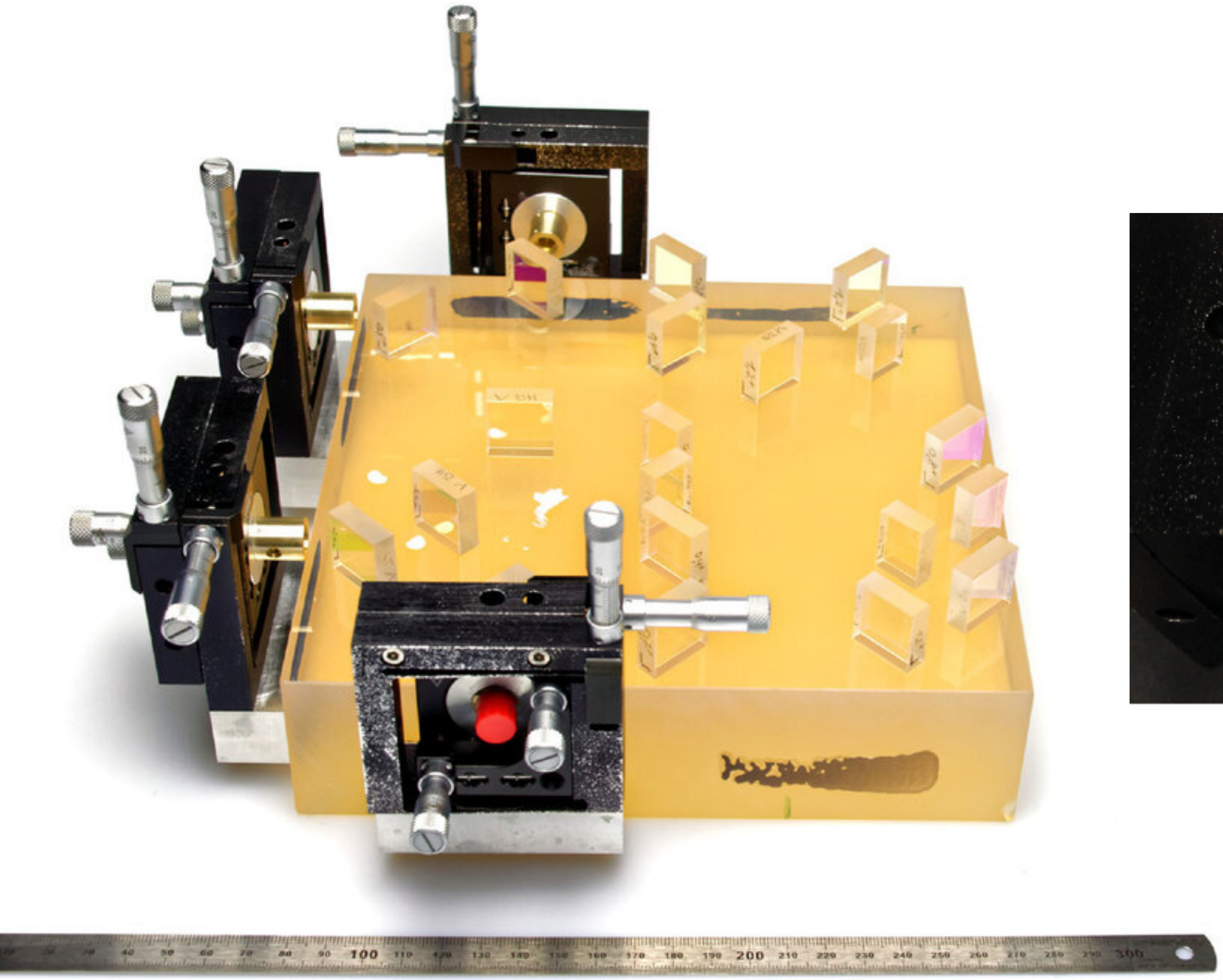
Fiber non-reciprocal measurements

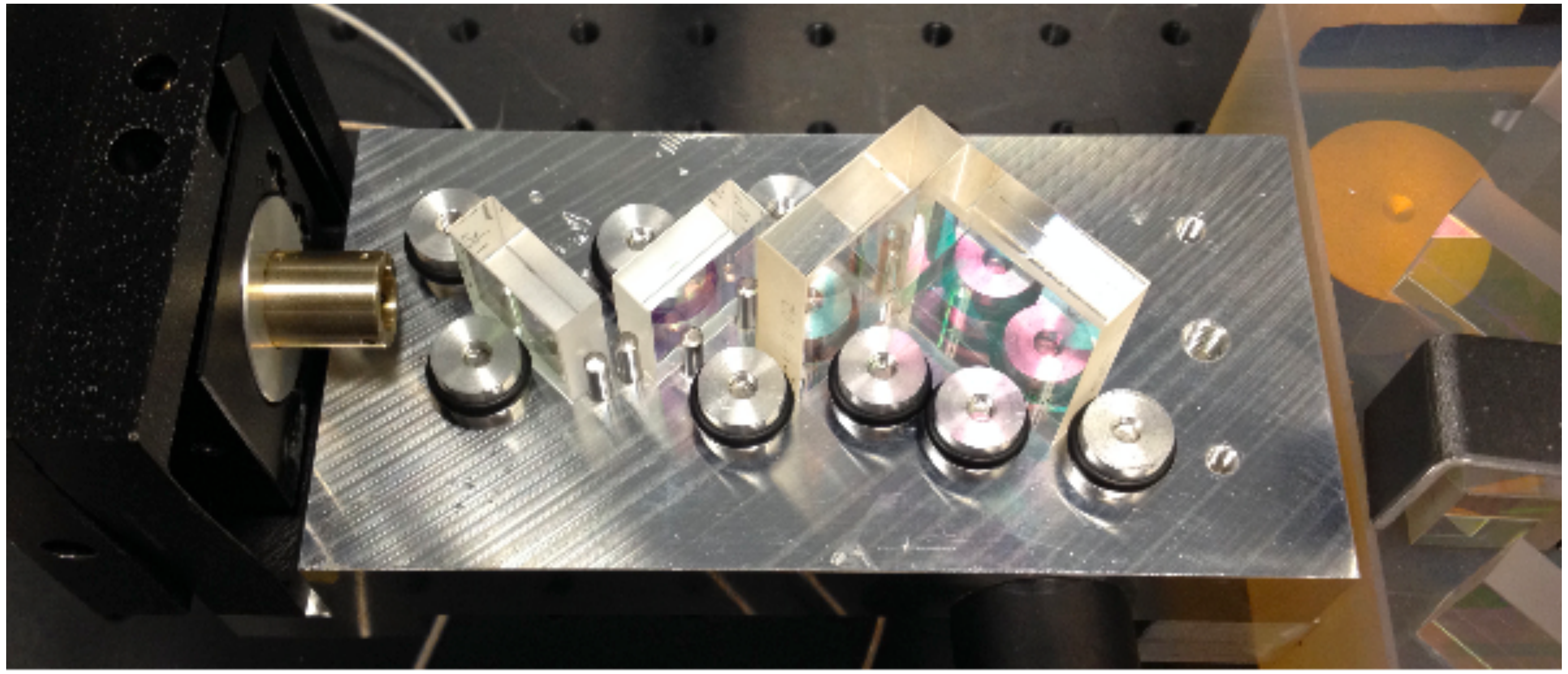




__Fleddermann__, R., et. Al (2018). Sub-pm non-reciprocal noise in the LISA backlink fiber. Classical and Quantum Gravity, 35(7), 075007.

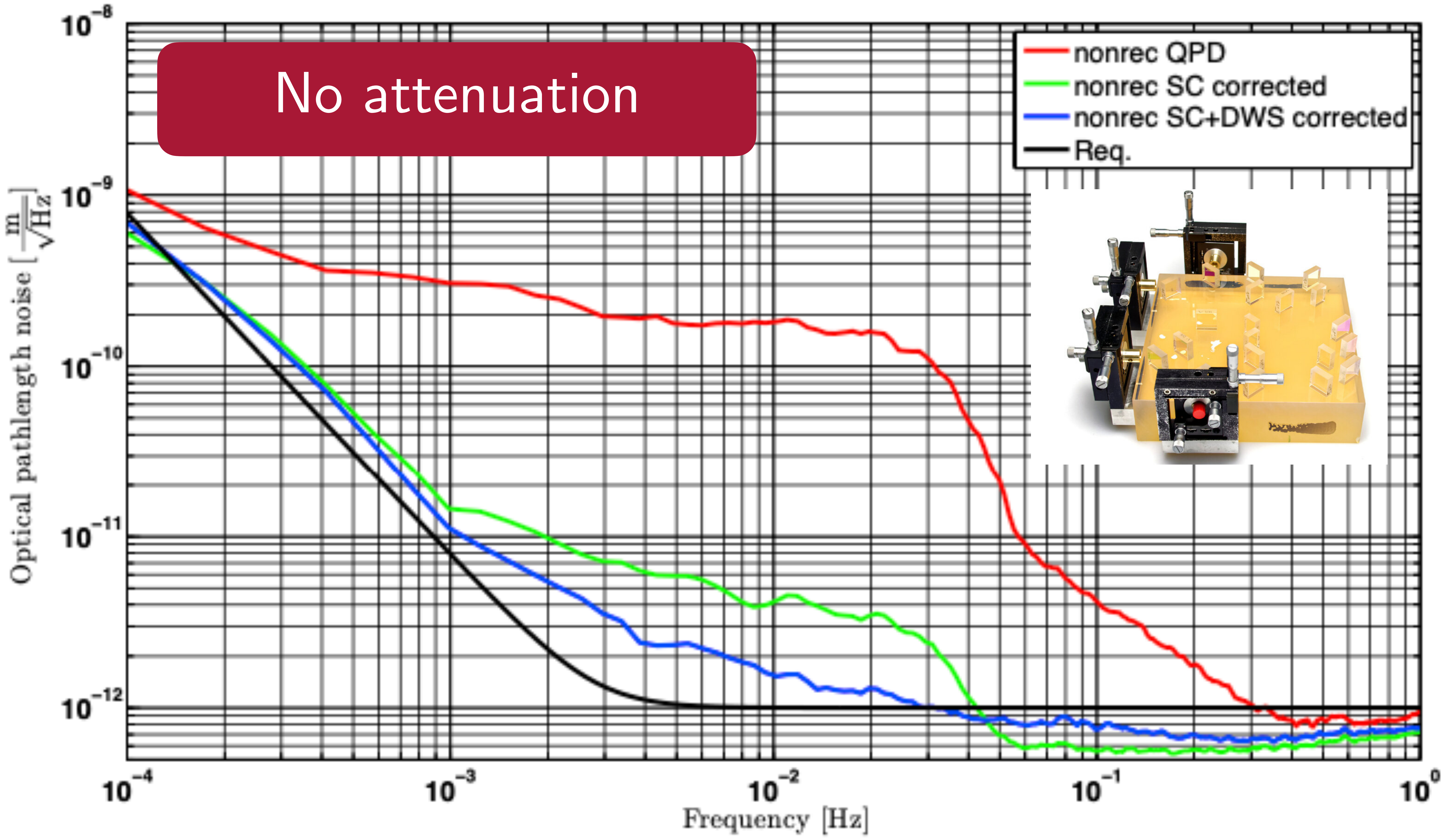
Attenuation stage

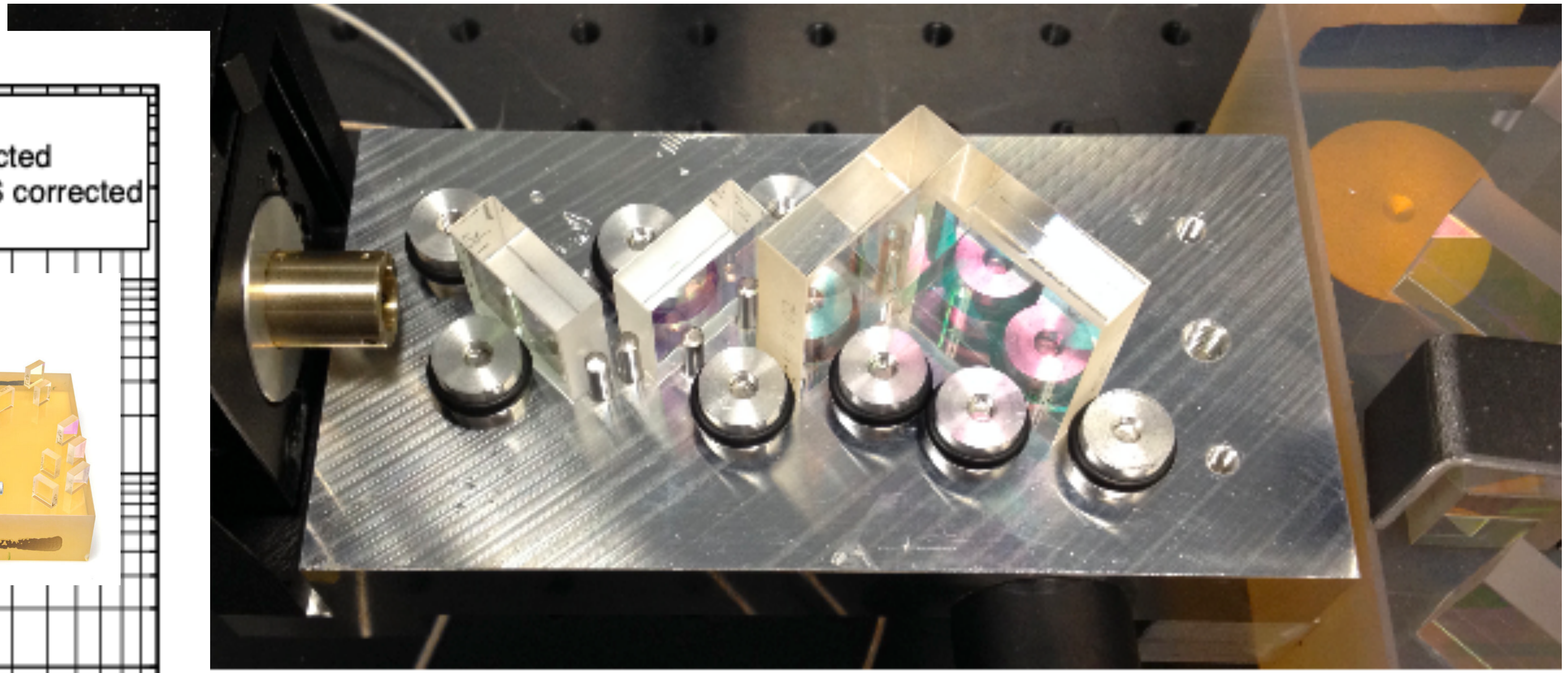




Hennig, J, Master thesis 2013, *Mitigation of stray light effects in the LISA Backlink*

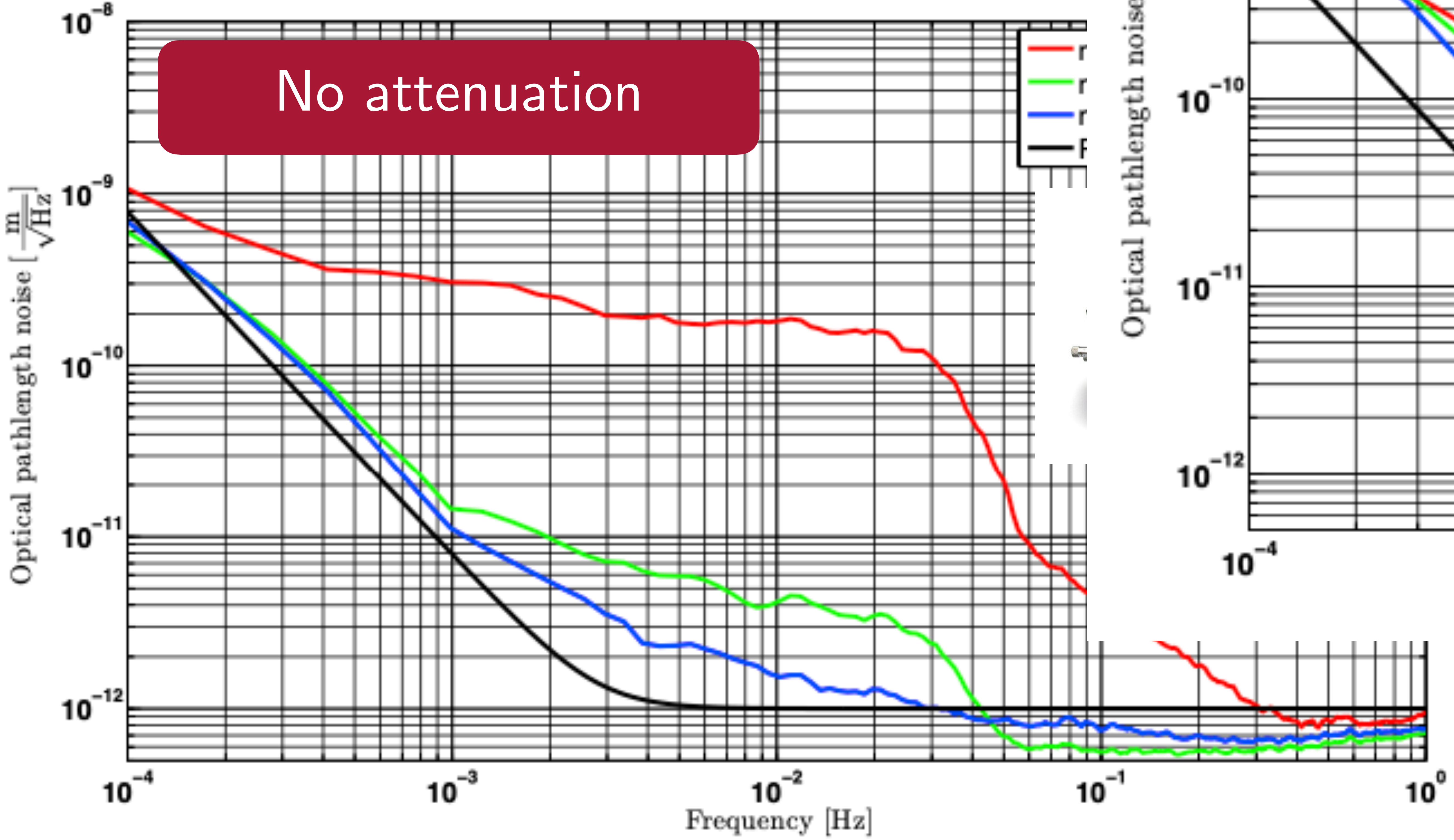
Attenuation stage

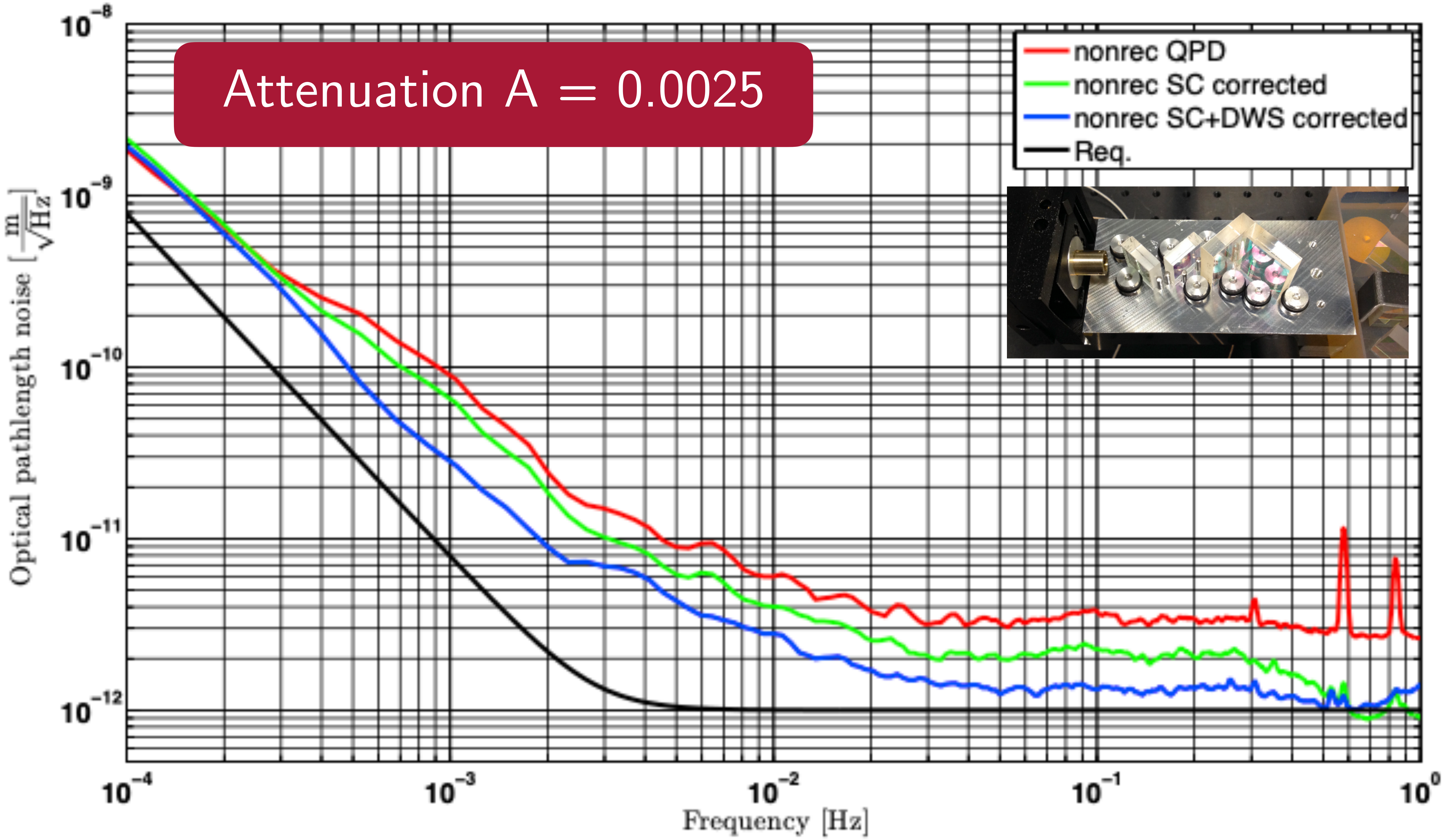




Hennig, J, Master thesis 2013, *Mitigation of stray light effects in the LISA Backlink*

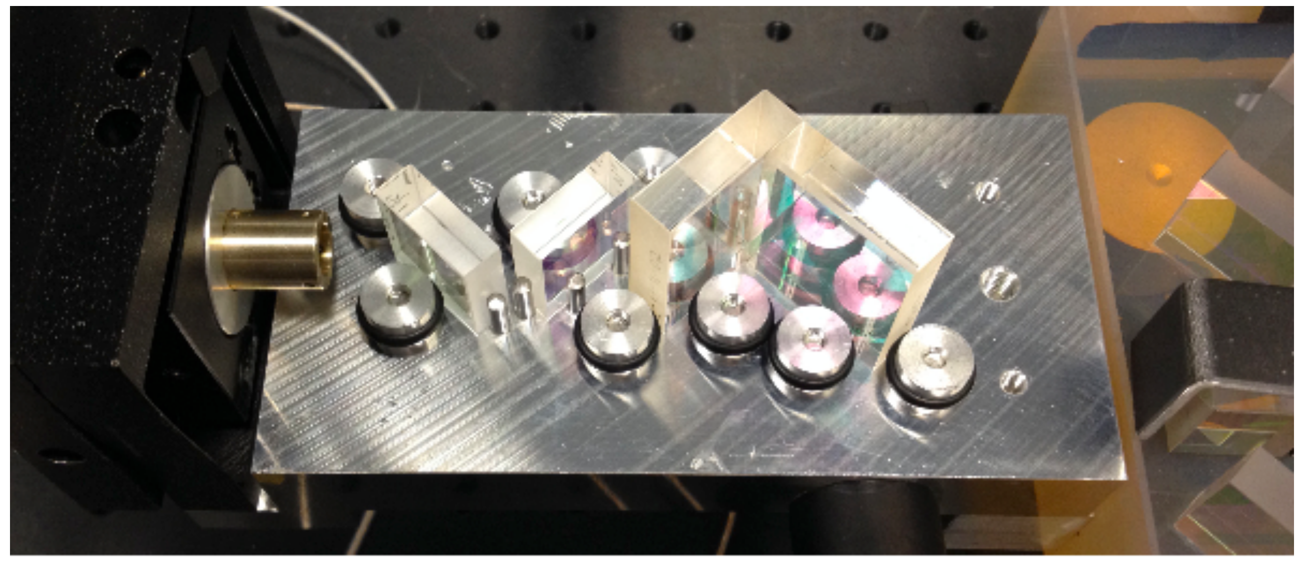
Attenuation stage



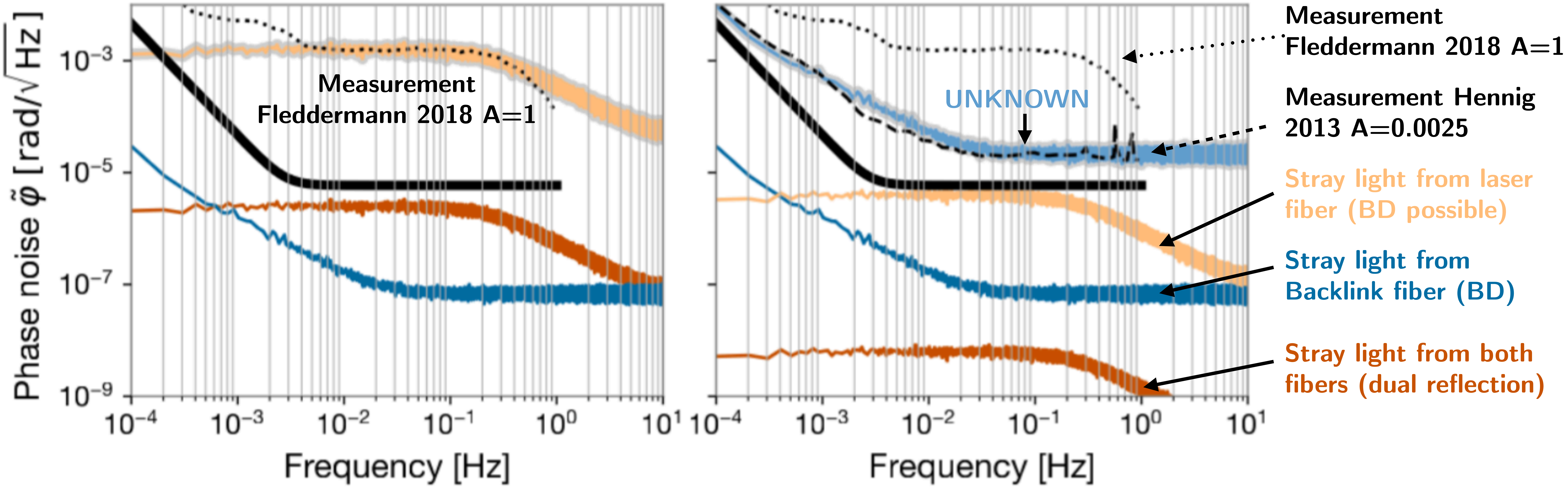


Hennig, J, Master thesis 2013, *Mitigation of stray light effects in the LISA Backlink*

Simulations with attenuation stage



No attenuation (A=1) | Attenuation A = 0.0025

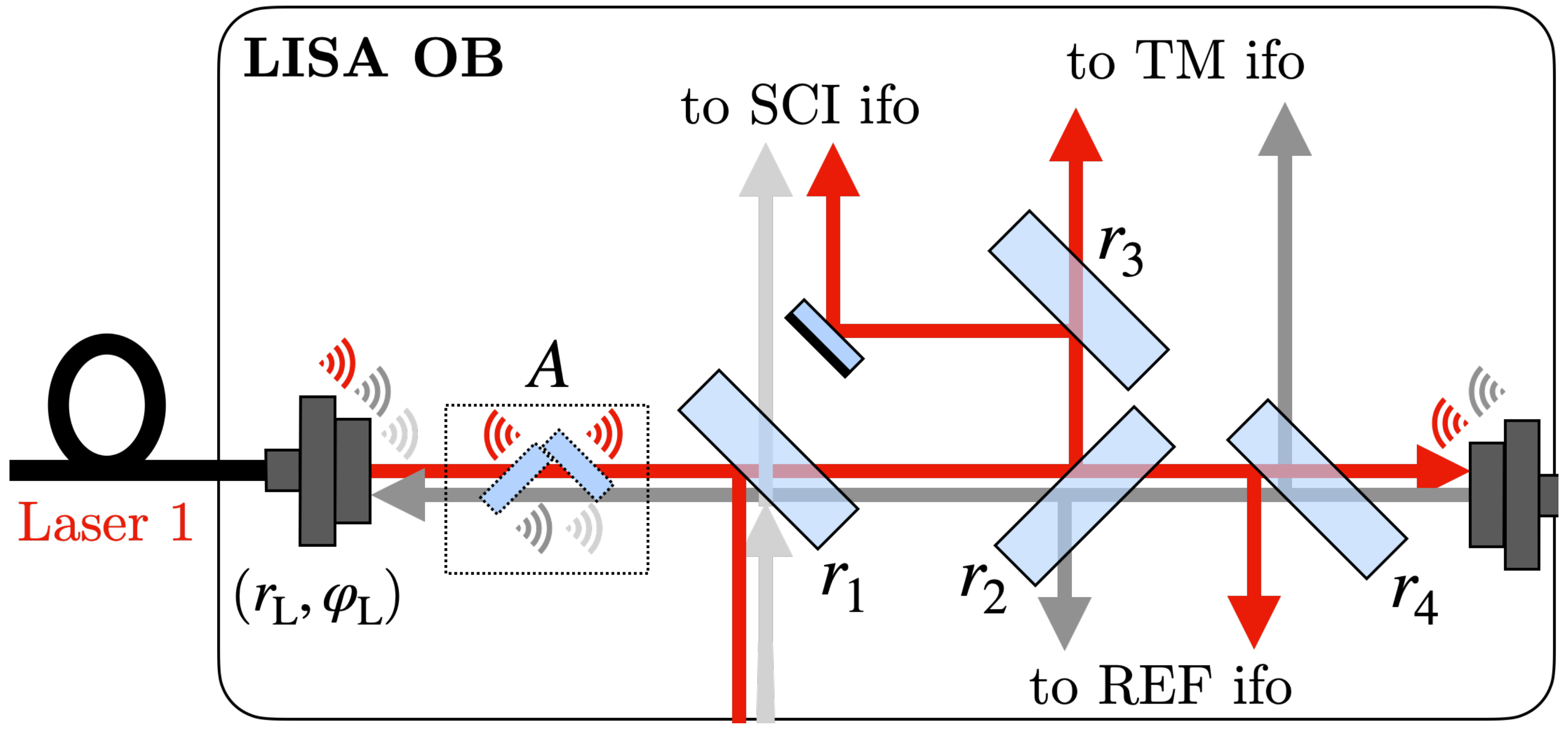


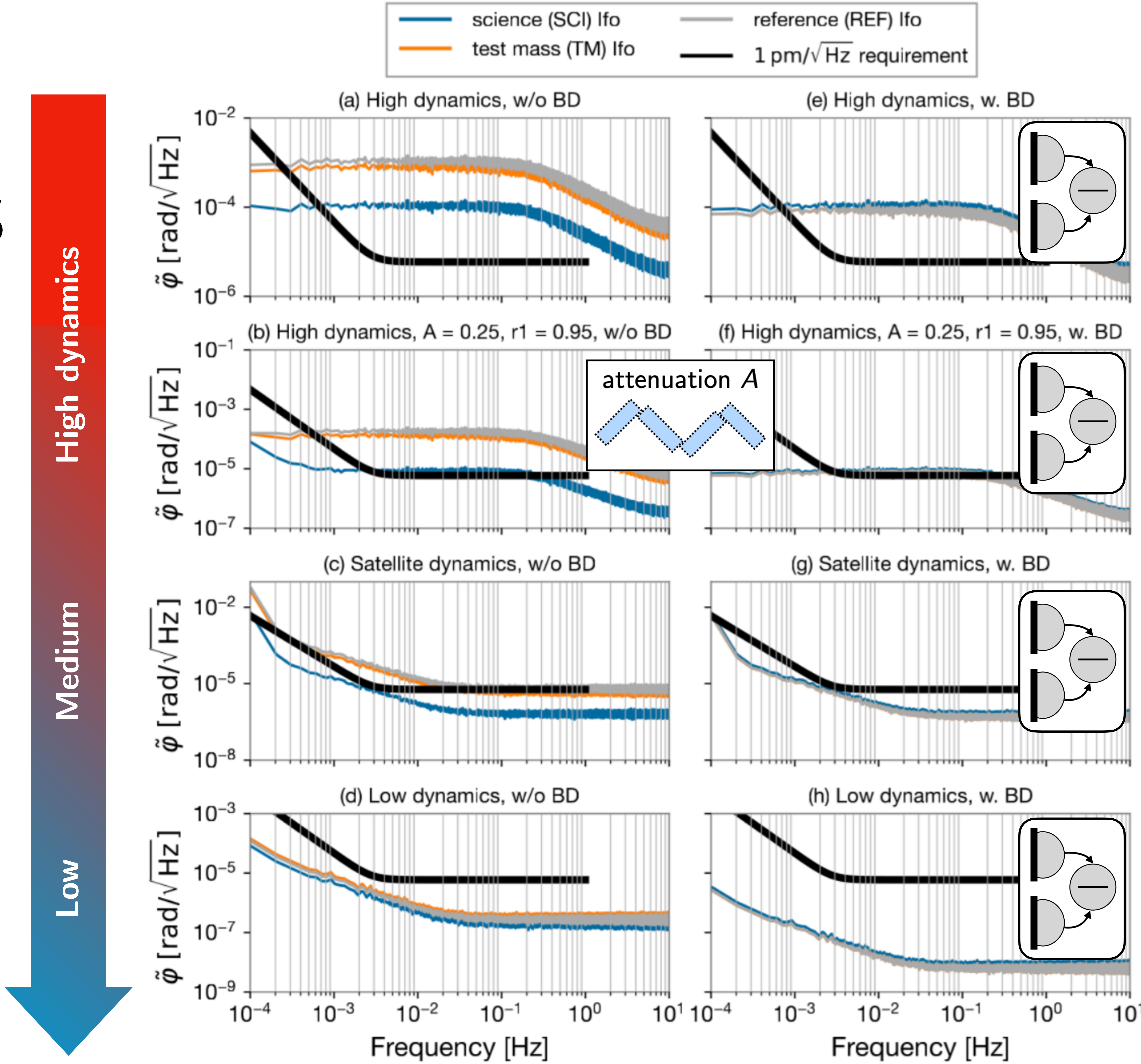
LISA interferometers

- Parasitic beams (from fiber backlink) contaminating all LISA interferometers

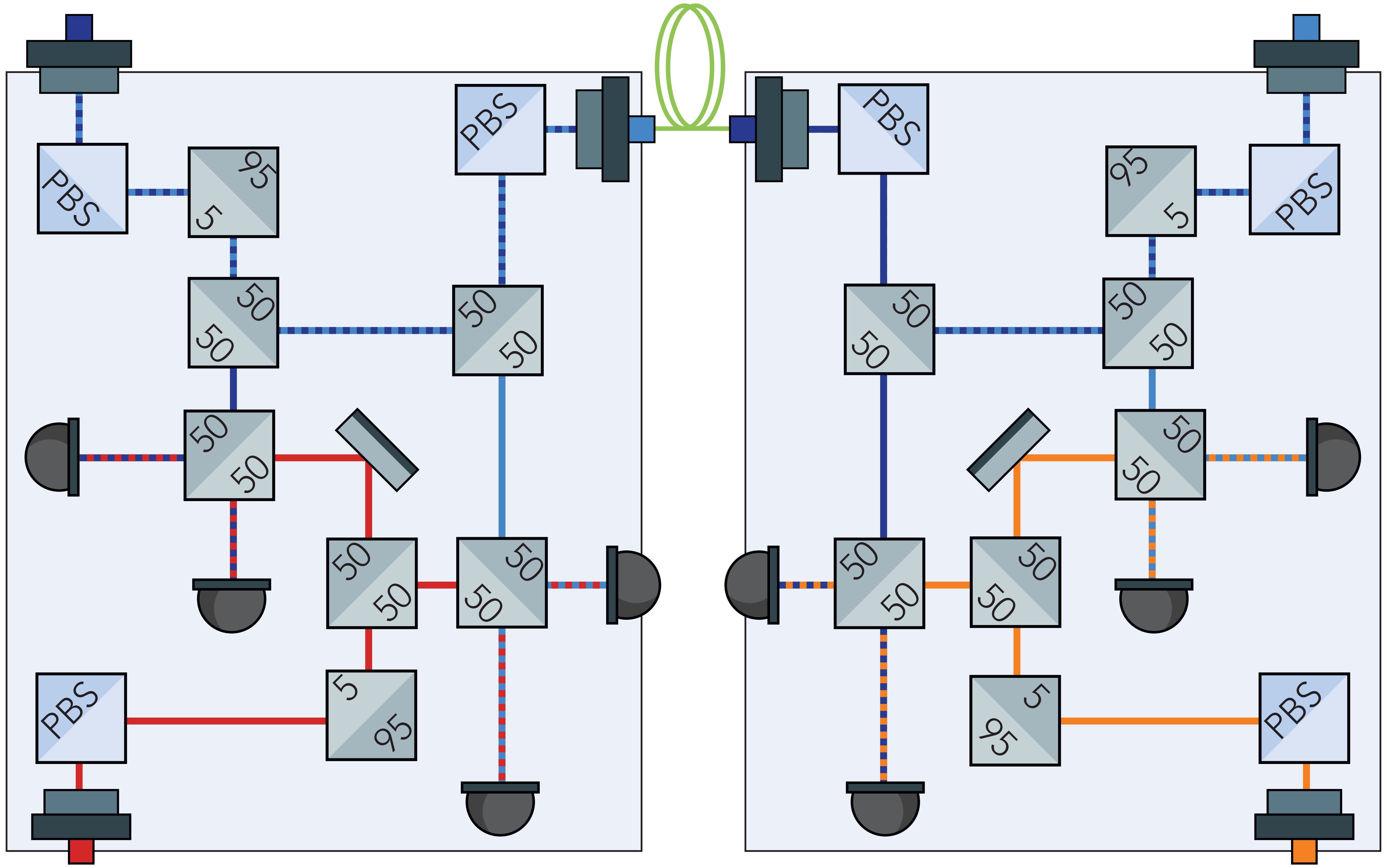
Simulations for:

- Different dynamics
- With and without balanced detection
- With and without attenuation stage





Mitigation strategies



Parasitic beams do not contaminate other LISA interferometers, they oscillator at different beat note

Eliminate origin spurious beams ($P \to 0\,\mathrm{W}$)

- By optical design (not entering diodes)
  - Block ghost beams: baffles
  - Avoid 0° surfaces (use wedged 2ndary surface)

Reduce power of spurious beams ($P \to \mathrm{nW} - \mathrm{pW}$)

- Clean surfaces to avoid scattering
- Good Coatings (AR, polarization, ...)
- Attenuation stages (reduce r, polarization, ...)

Reduce dynamics ($\varphi_p \to 0\,\mathrm{rad}$)

- Stable interferometer (e.g. quasi-monolithic)
- Fiber length stabilization / OPL
- Stabilize environment (temperature, air, ...)

Auxiliary sensing

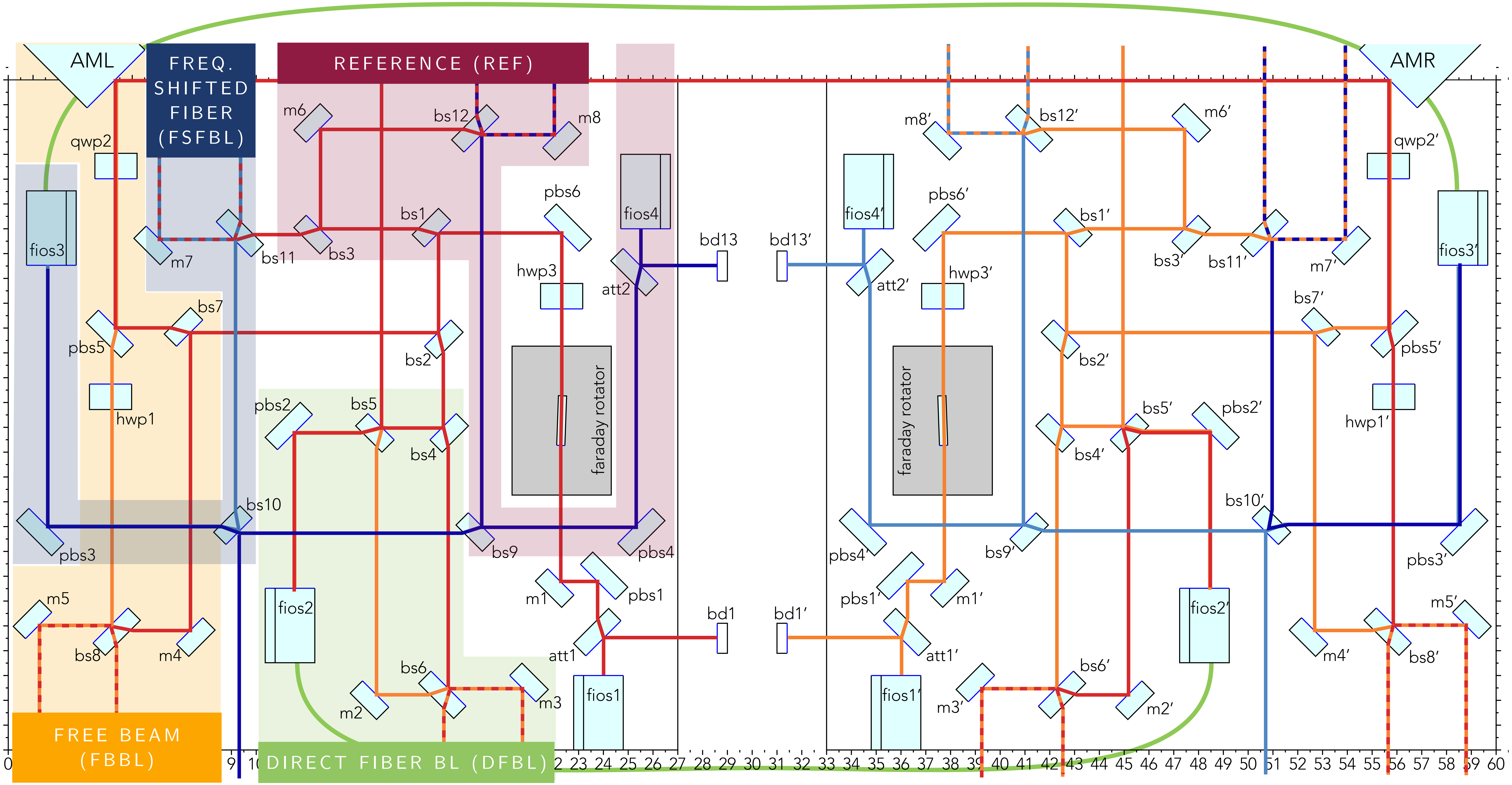
- Balanced detection
- Coherent noise cancellation

Distinguish ghost beams from main interferometer

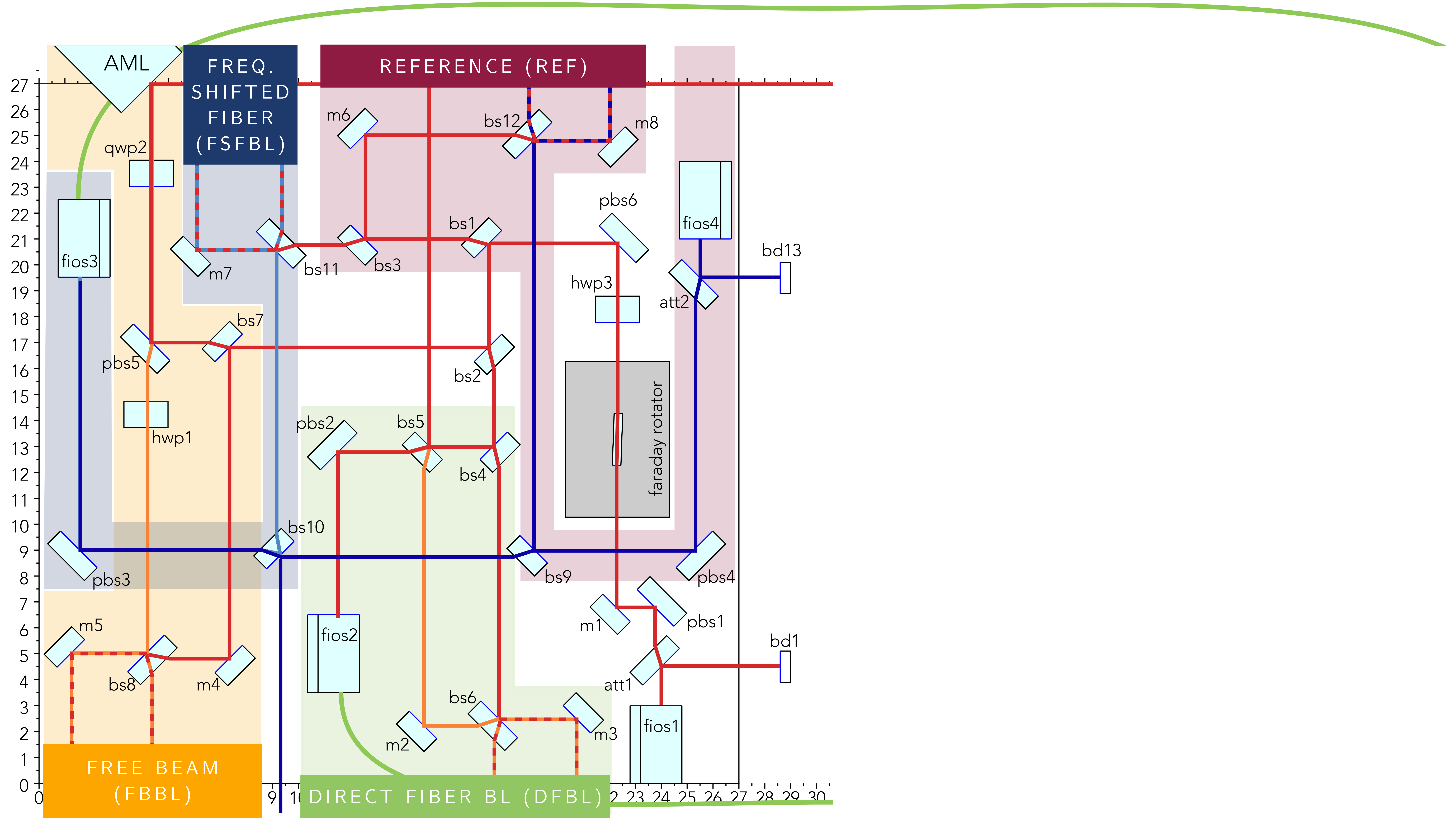
- Frequency-shifted: two additional lasers per bench
- Polarization/Faraday Isolator
- Digitally-enhanced interferometry: destroy coherence

Isleif et. al (2017) doi:10.1088/1742-6596/840/1/012016

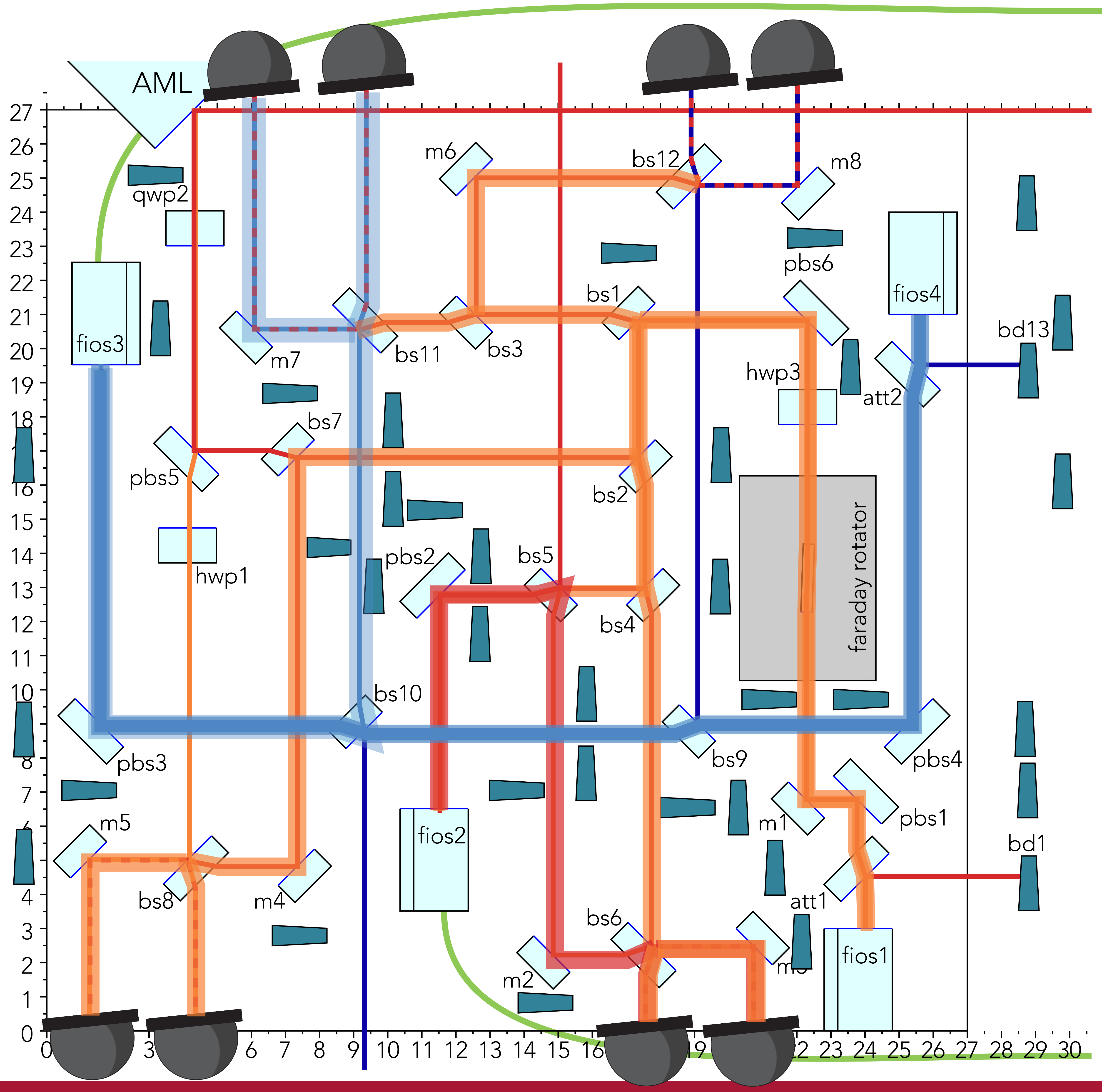
Three-Backlink Interferometer



Three-Backlink Interferometer



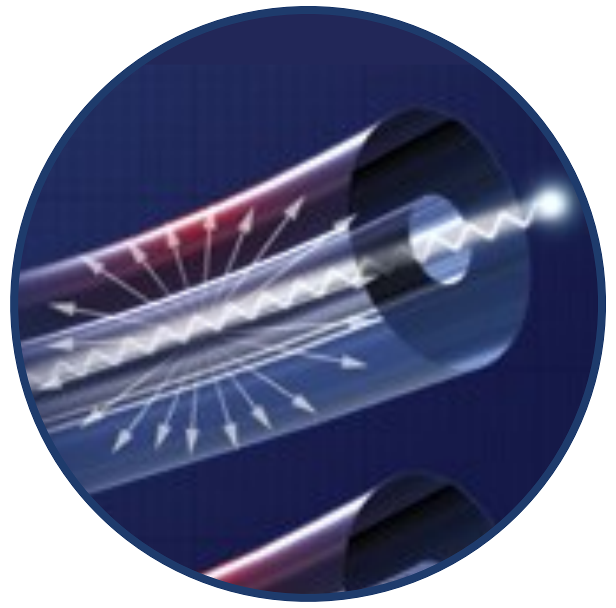
Three-Backlink Interferometer

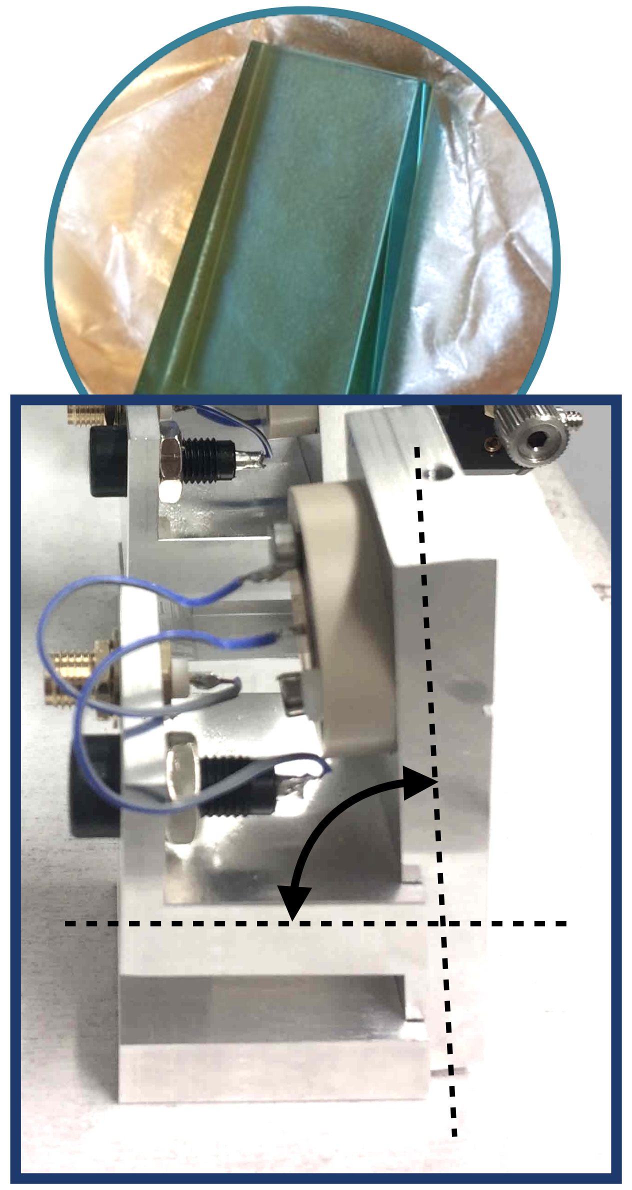


FIBER BACKSCATTER

- direct fiber BL contaminates all interferometers: Faraday
- balanced detection to suppress 100 pm fiber noise
- dual-cavity ghost beams: 0.02 pm

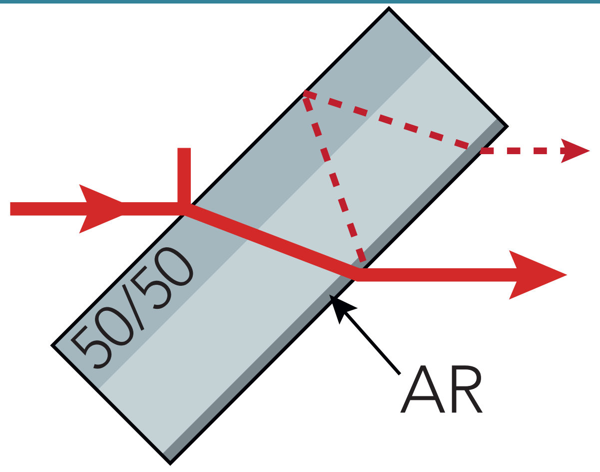
20 ppm





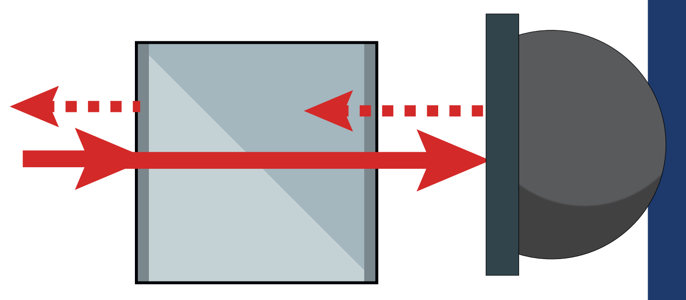
AR-COATING

- 40 beam dumps per bench

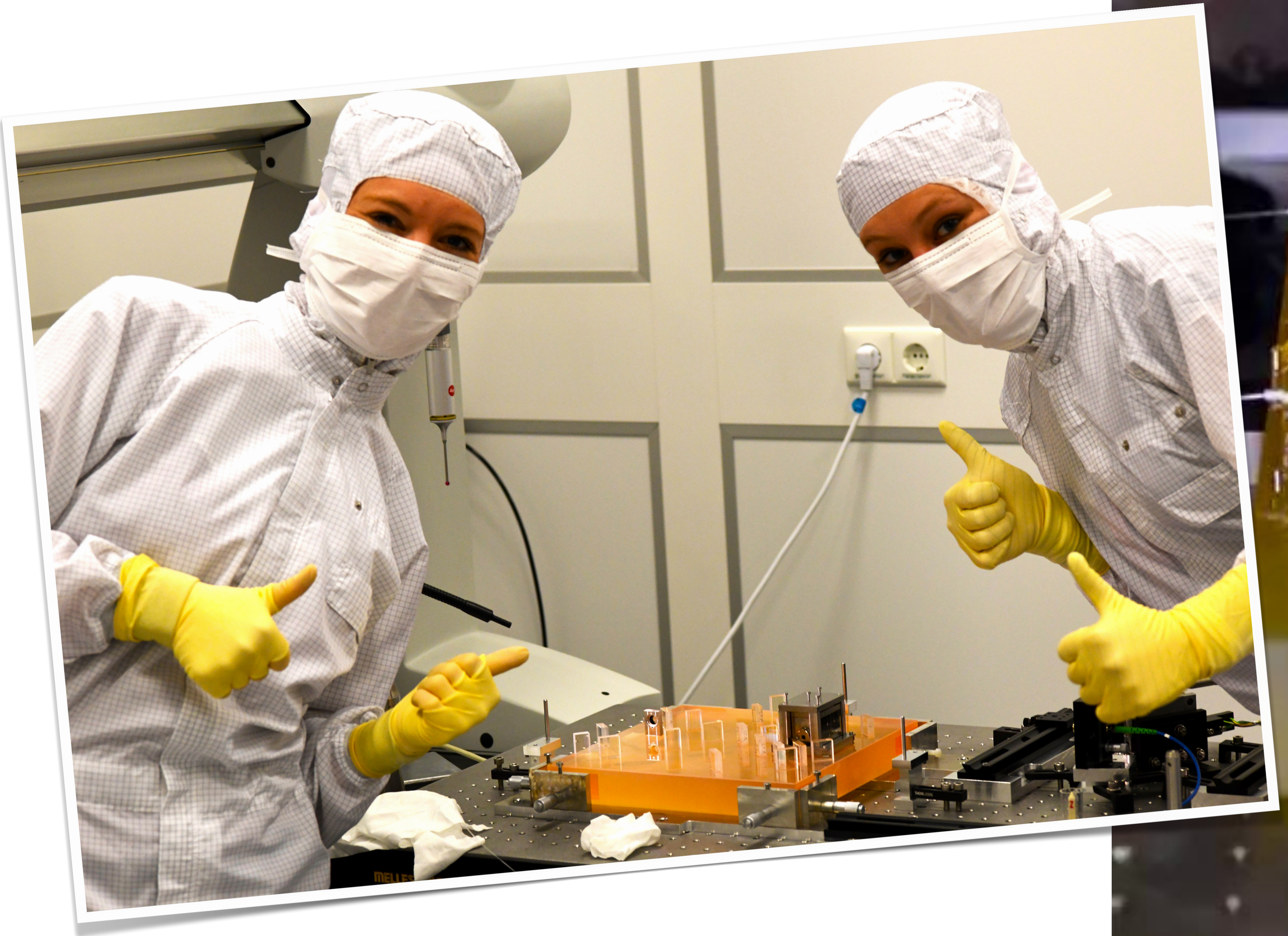


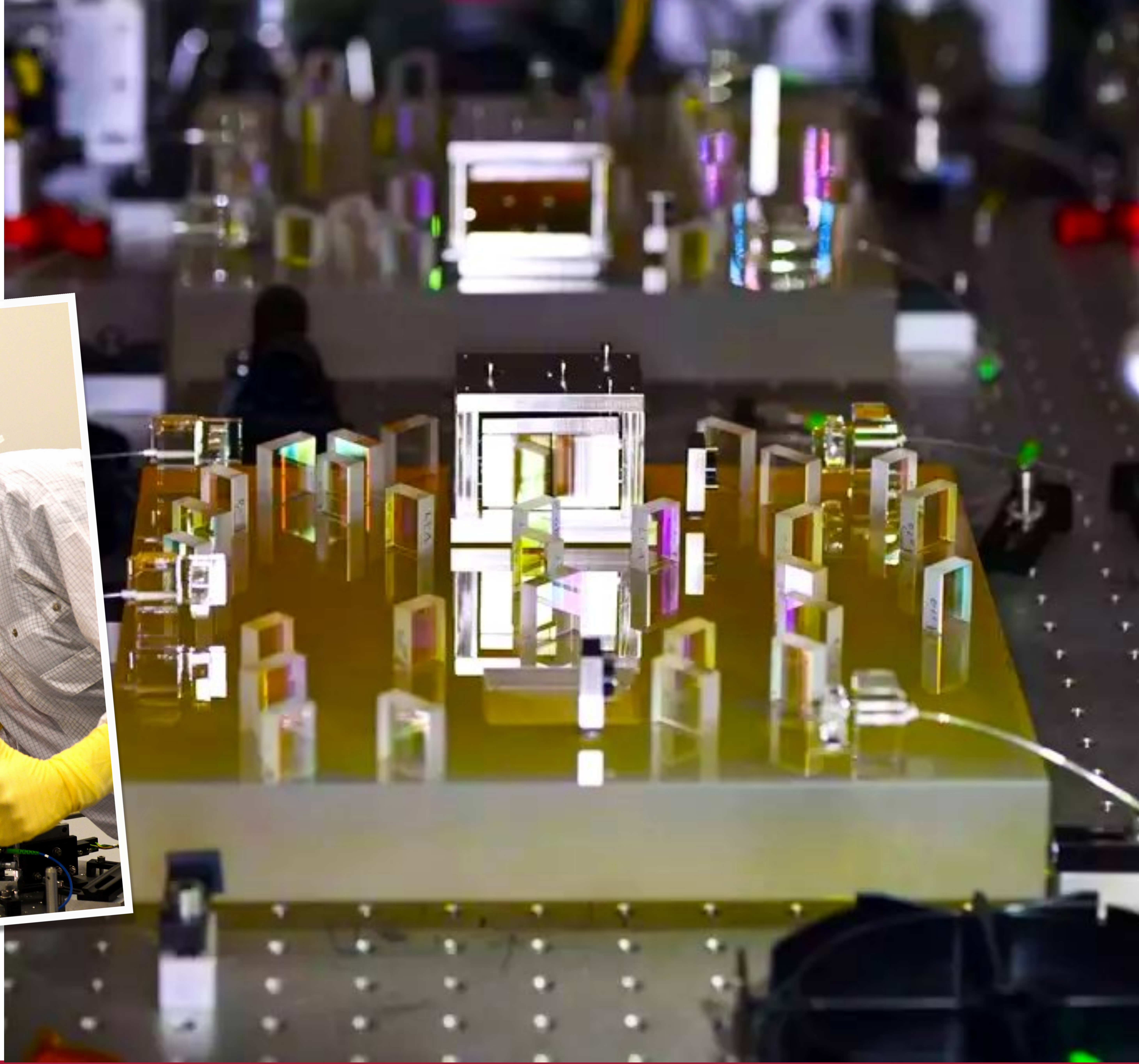
OTHER REFLECTION

- angled / wedged components



Three Backlink

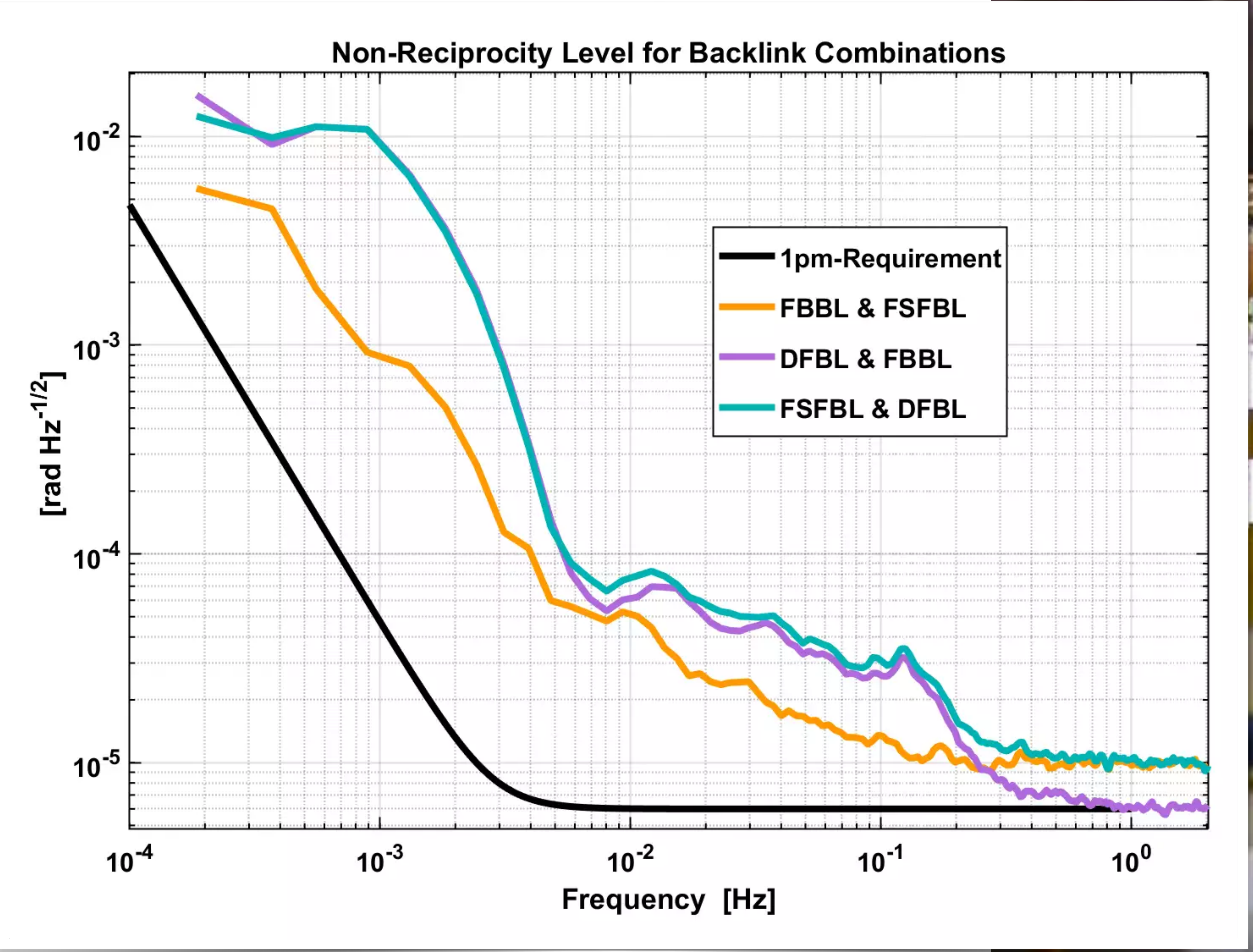


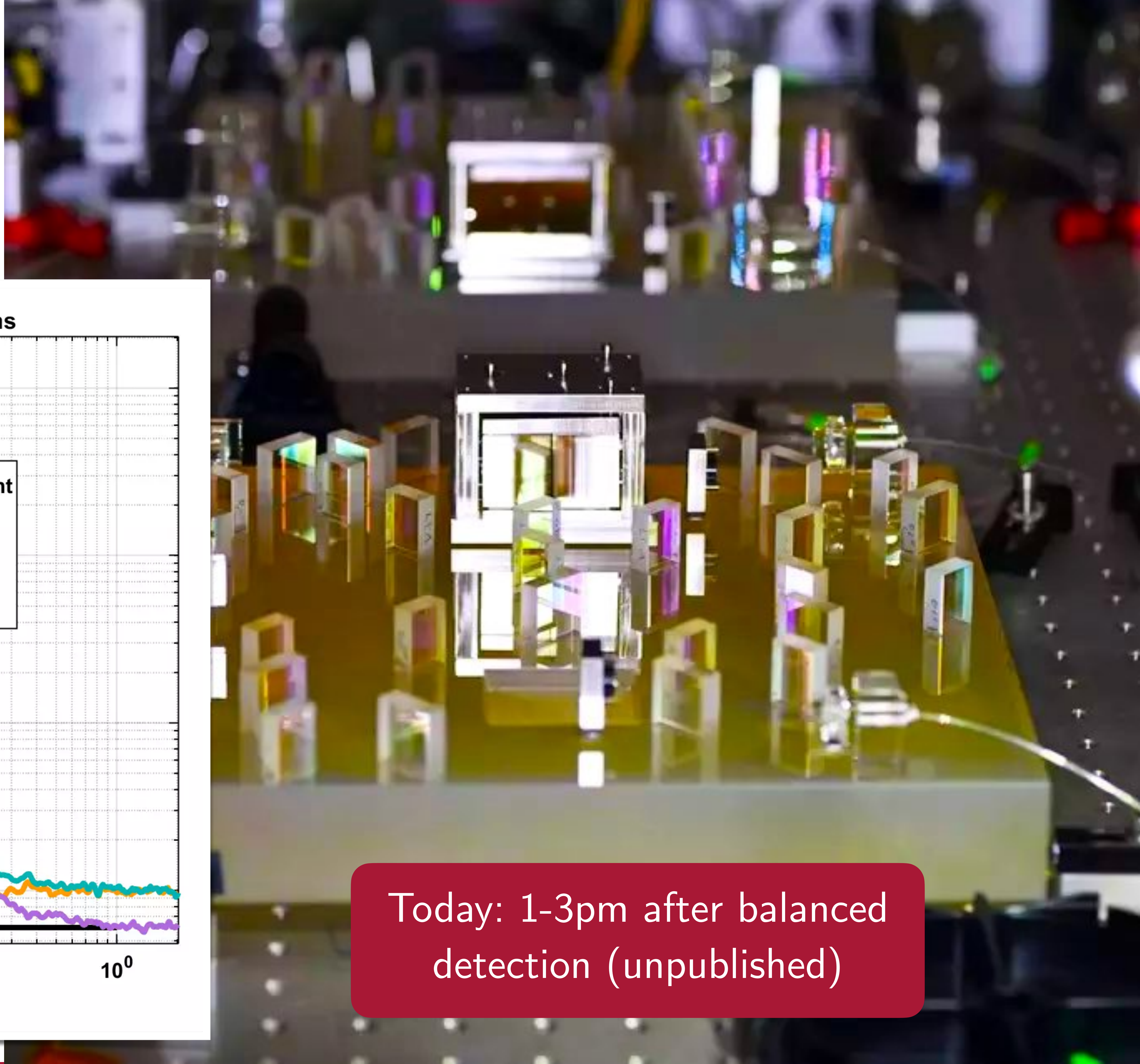


Isleif (2018) https://doi.org/10.15488/3526

Bischof (2023) https://doi.org/10.15488/3526

Three Backlink

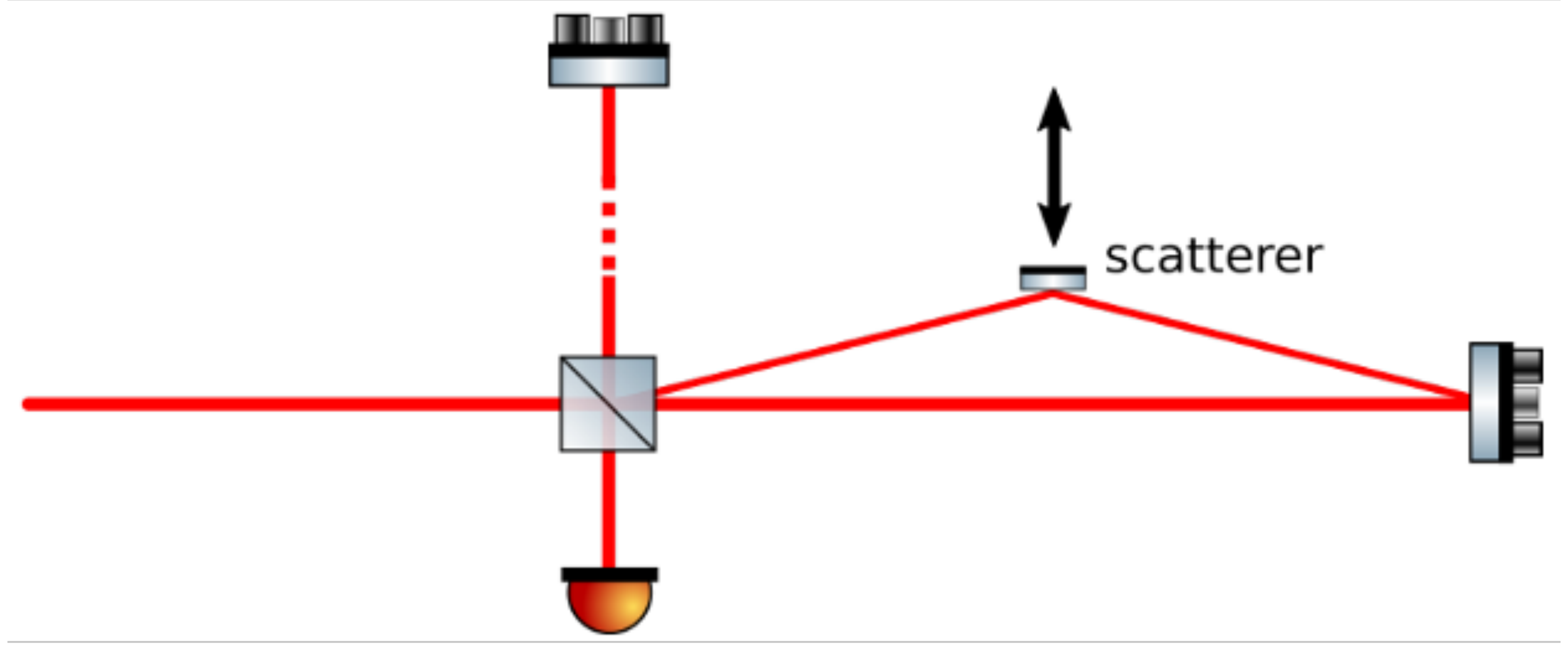


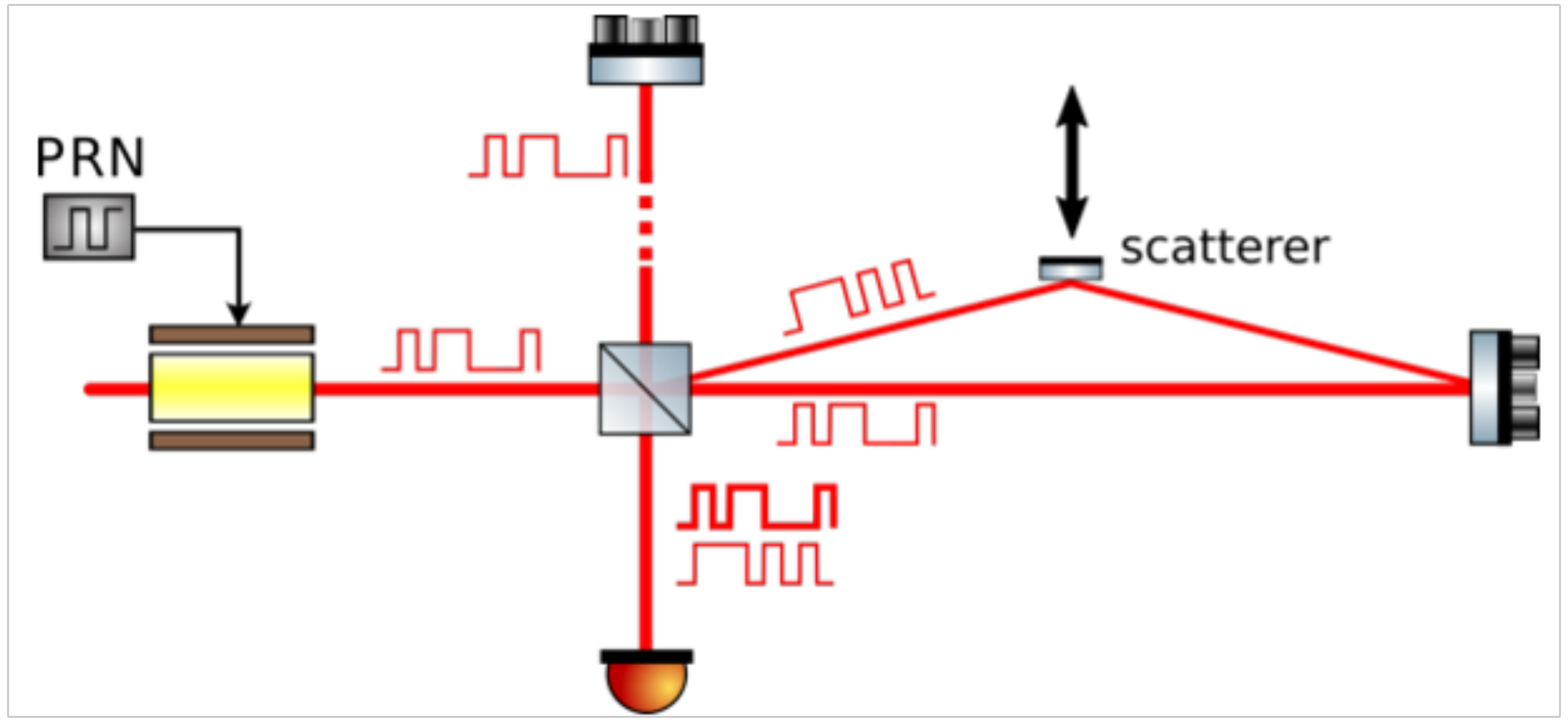


Today: 1-3pm after balanced detection (unpublished)

Bischof (2023) https://doi.org/10.15488/13195

Mitigation strategies





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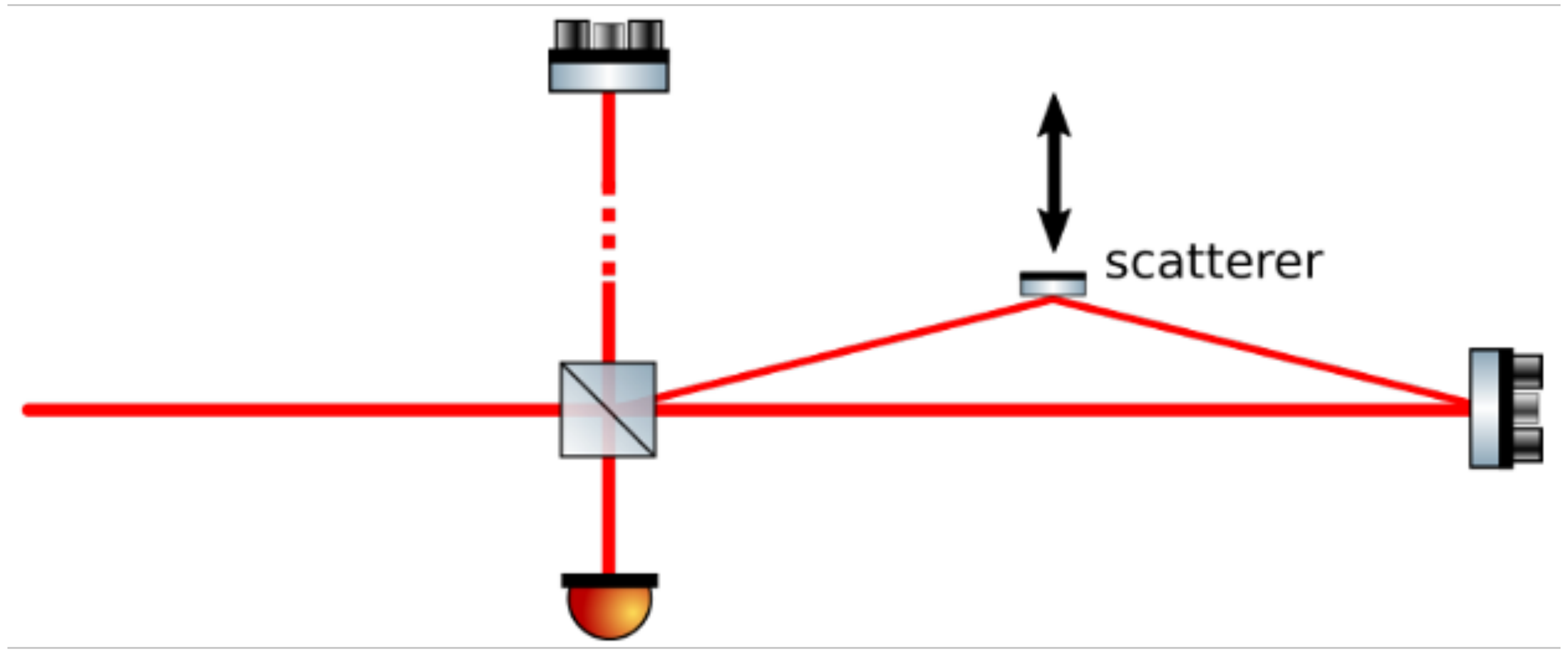
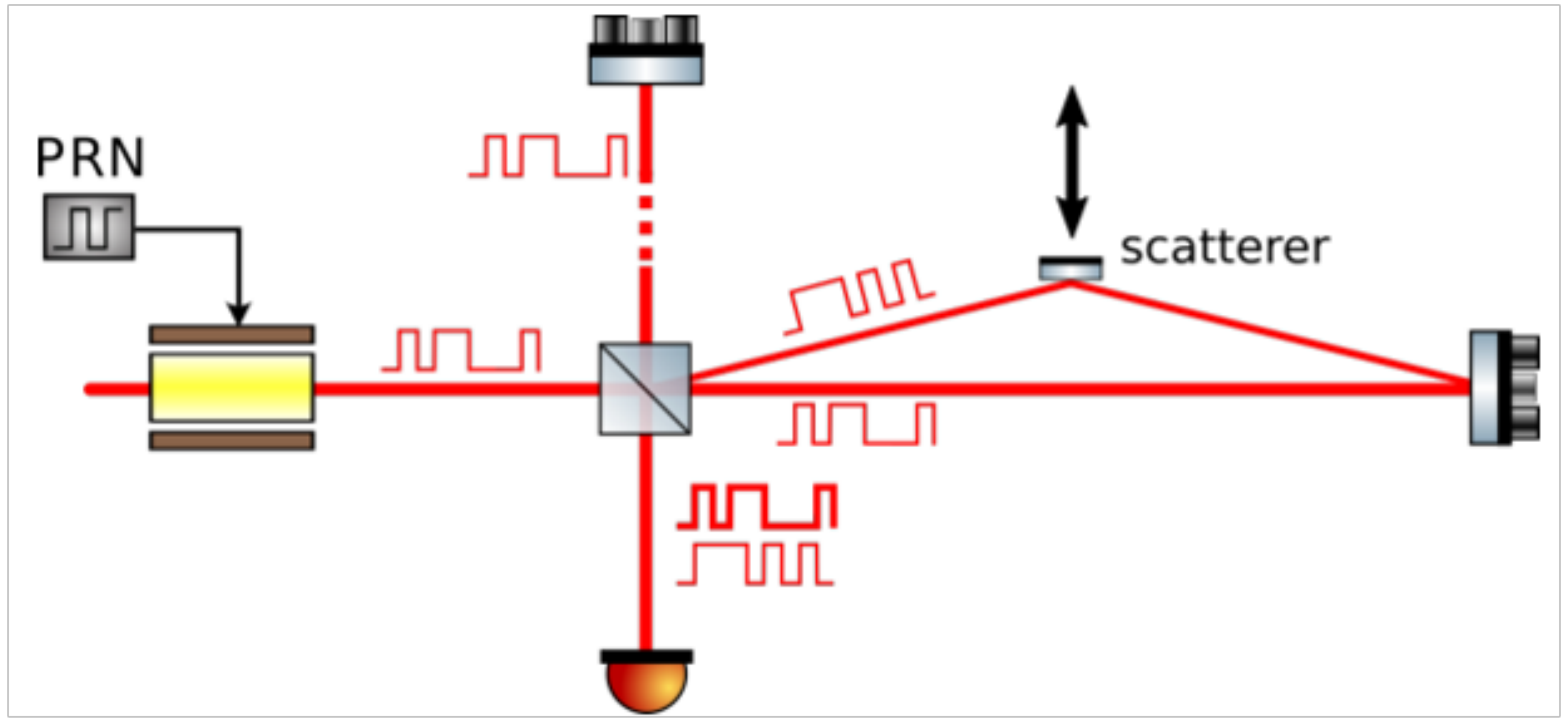
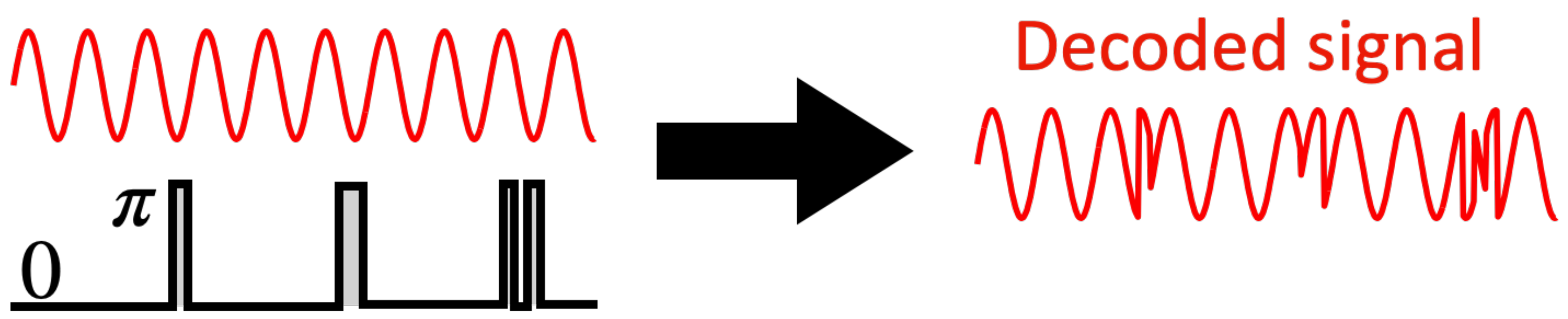
D. Voigt et al., Applied Physics Letters, 123(2) 2023 https://doi.org/10.1063/5.0176639

Tunable coherence for scattered light suppression

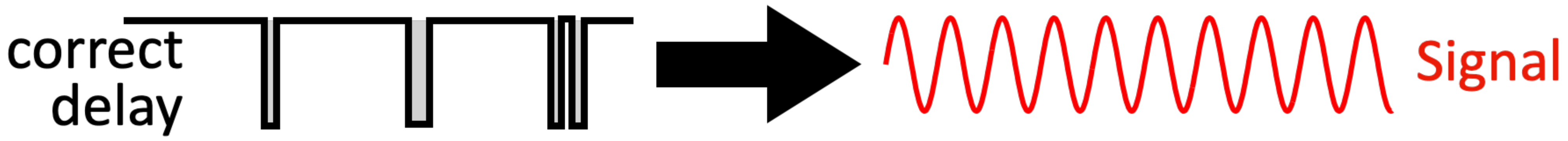




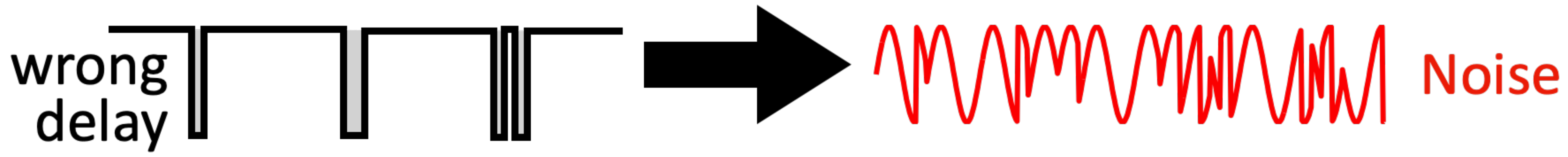
- Combines multiplexing with continuous wave interferometry
- **Pseudo-random noise (PRN) timestamps** are imprinted onto the laser phase:



- Digital **demodulation** recovers signal if delay is matched:



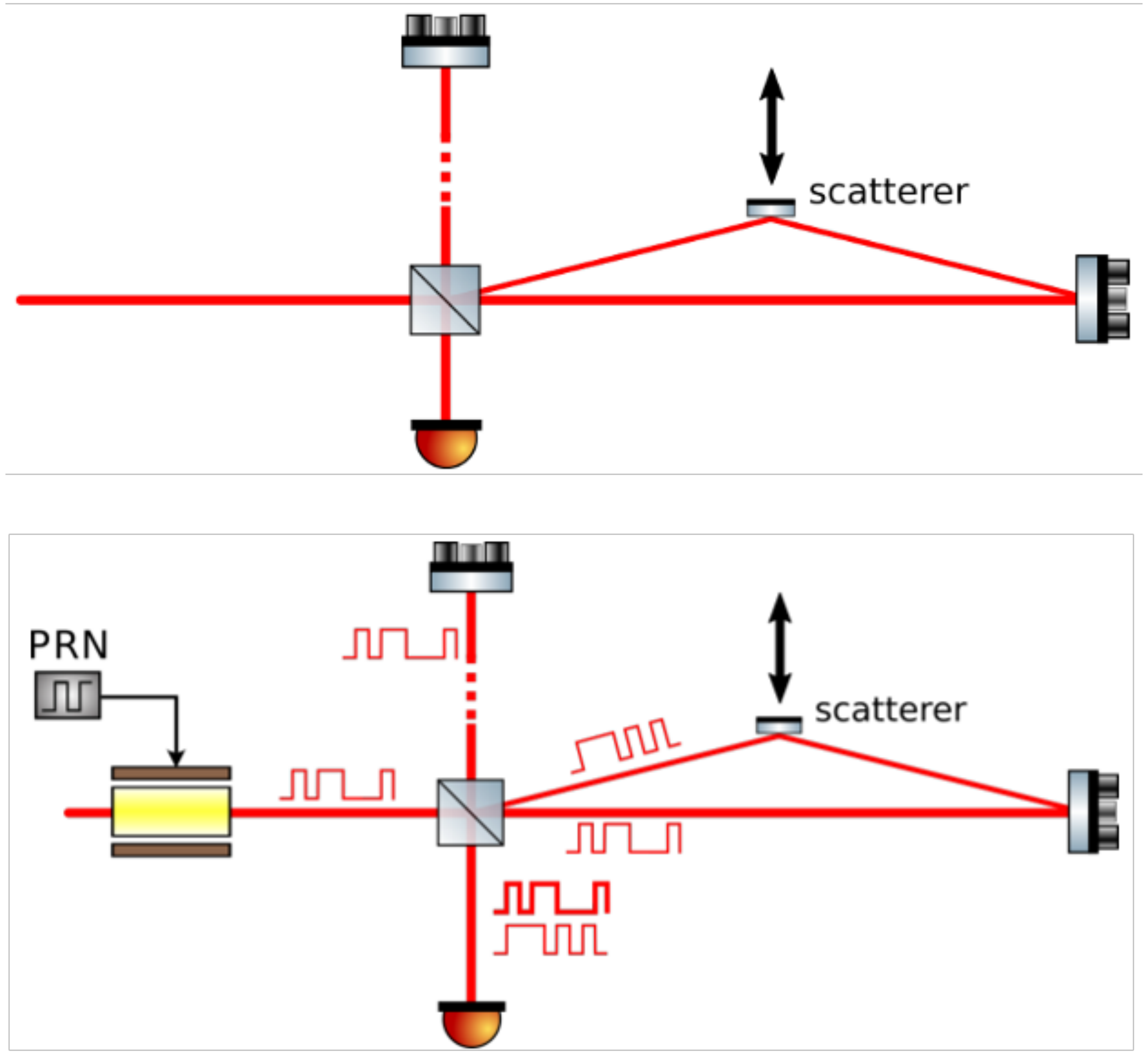
- sequences with strong **autocorrelation** properties allows isolation of signals based on time-of-flight:

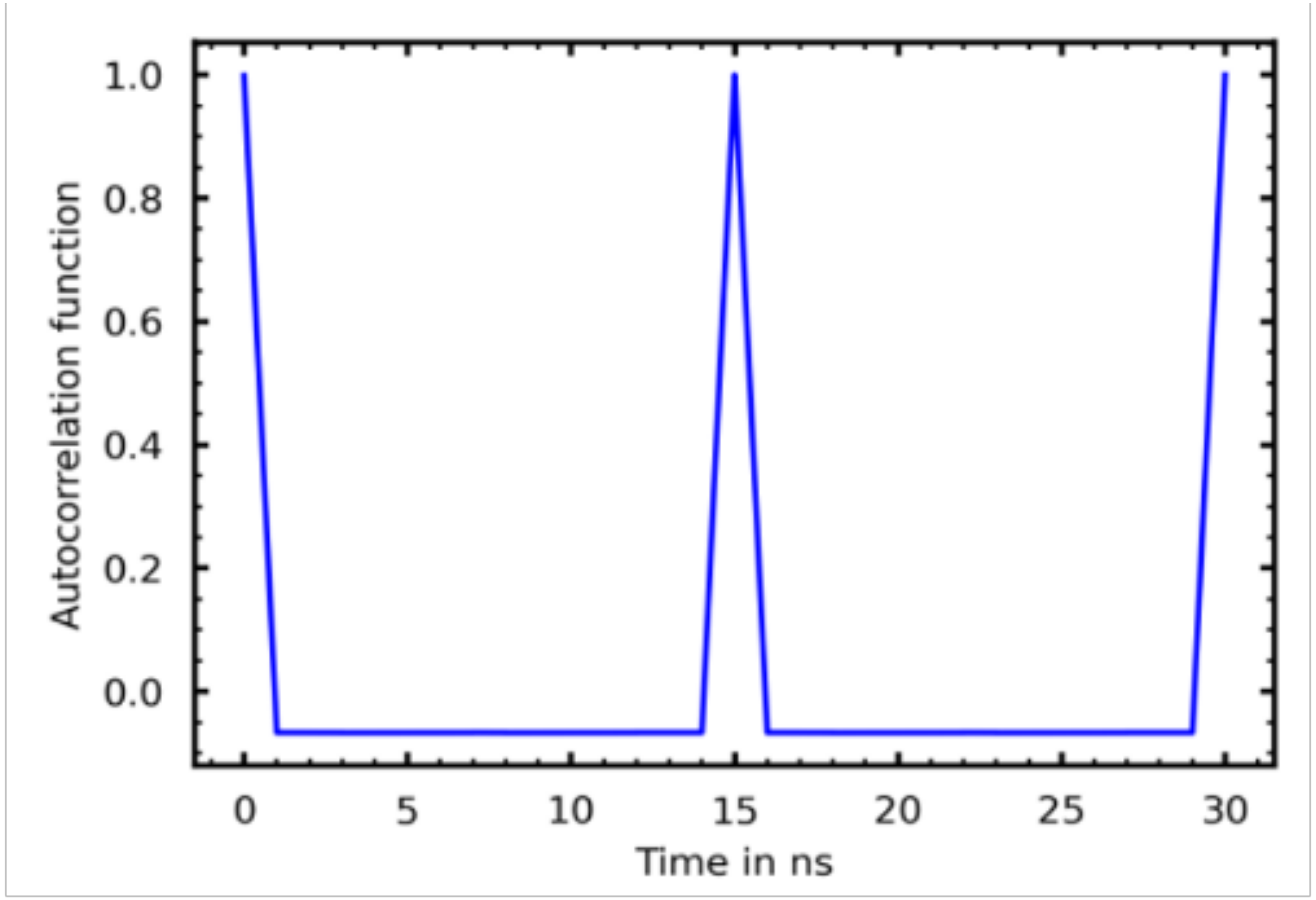


GHz phase modulations => cm scale coherence

D. Voigt et al., Applied Physics Letters, 123(2) 2023 https://doi.org/10.1063/5.0176639

Tunable coherence for scattered light suppression



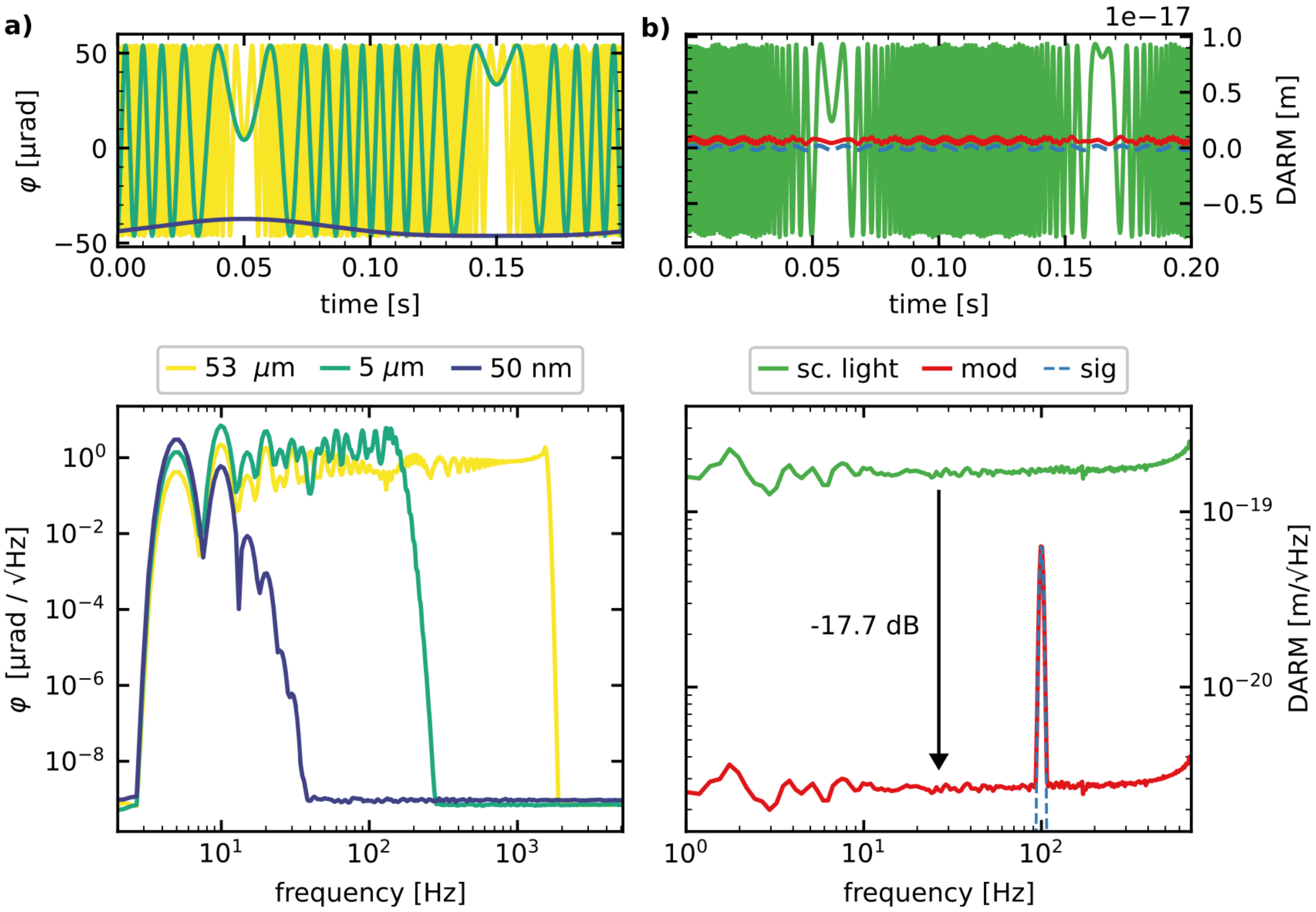


GHz phase modulations => cm scale coherence

D. Voigt et al., Applied Physics Letters, 123(2) 2023 https://doi.org/10.1063/5.0176639

Simulations

- Tunable coherence
- Simulation of scattered light in a Michelson interferometer
- Credit: Oliver Gerberding



Tunable coherence for scattered light suppression

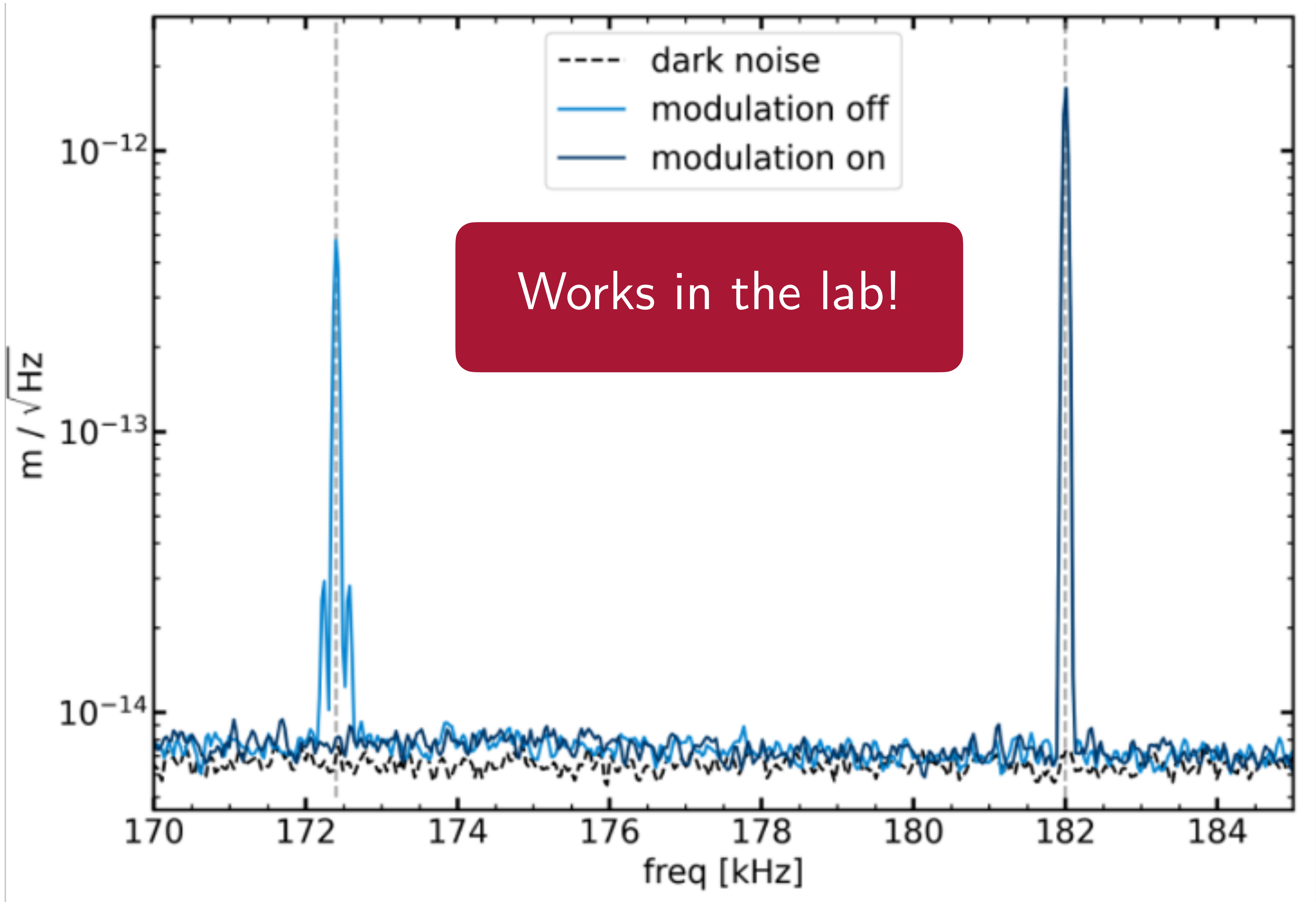
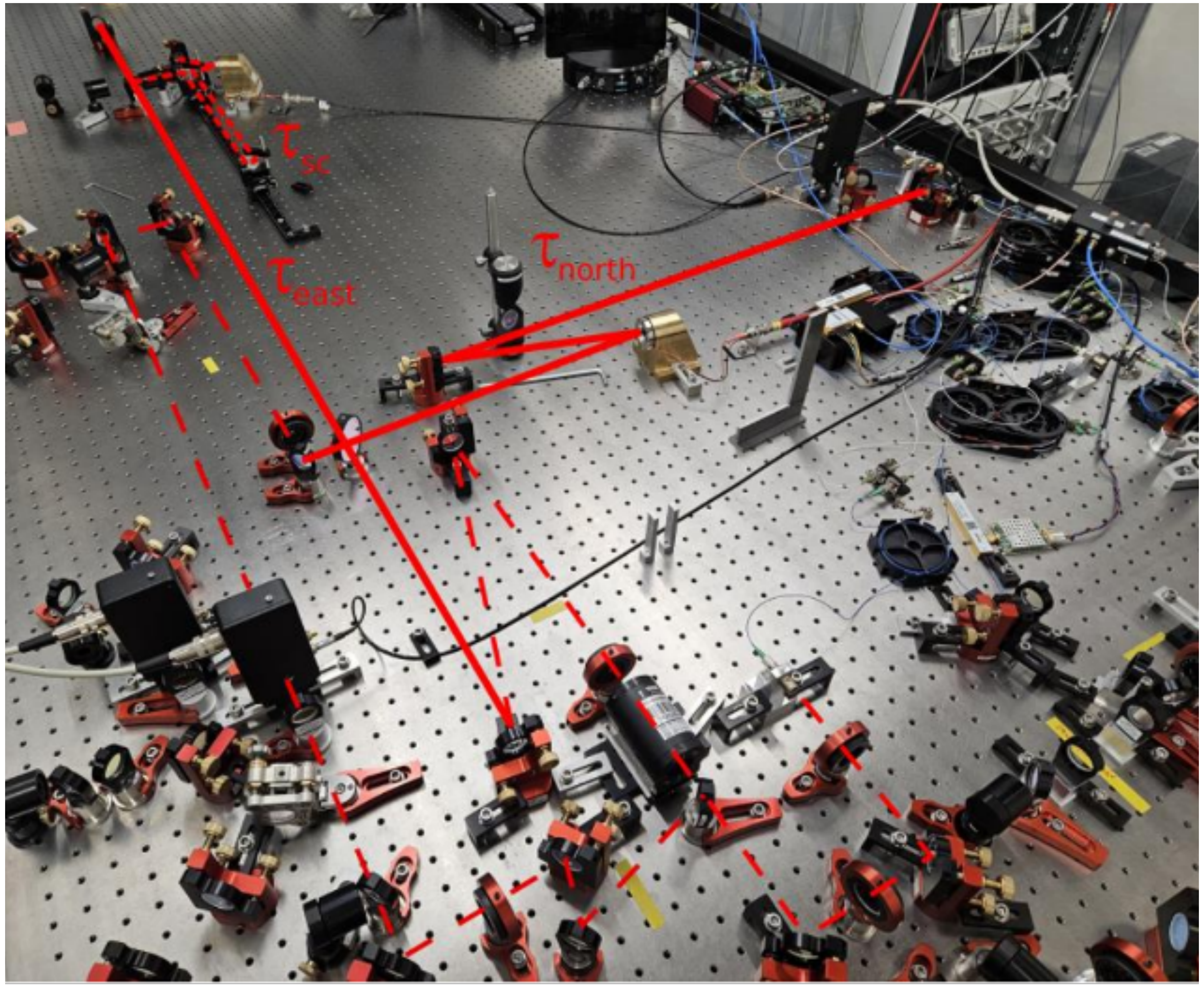


Figure: scatter suppression with 127 chips at 1 GHz



Tunable coherence for scattered light suppression

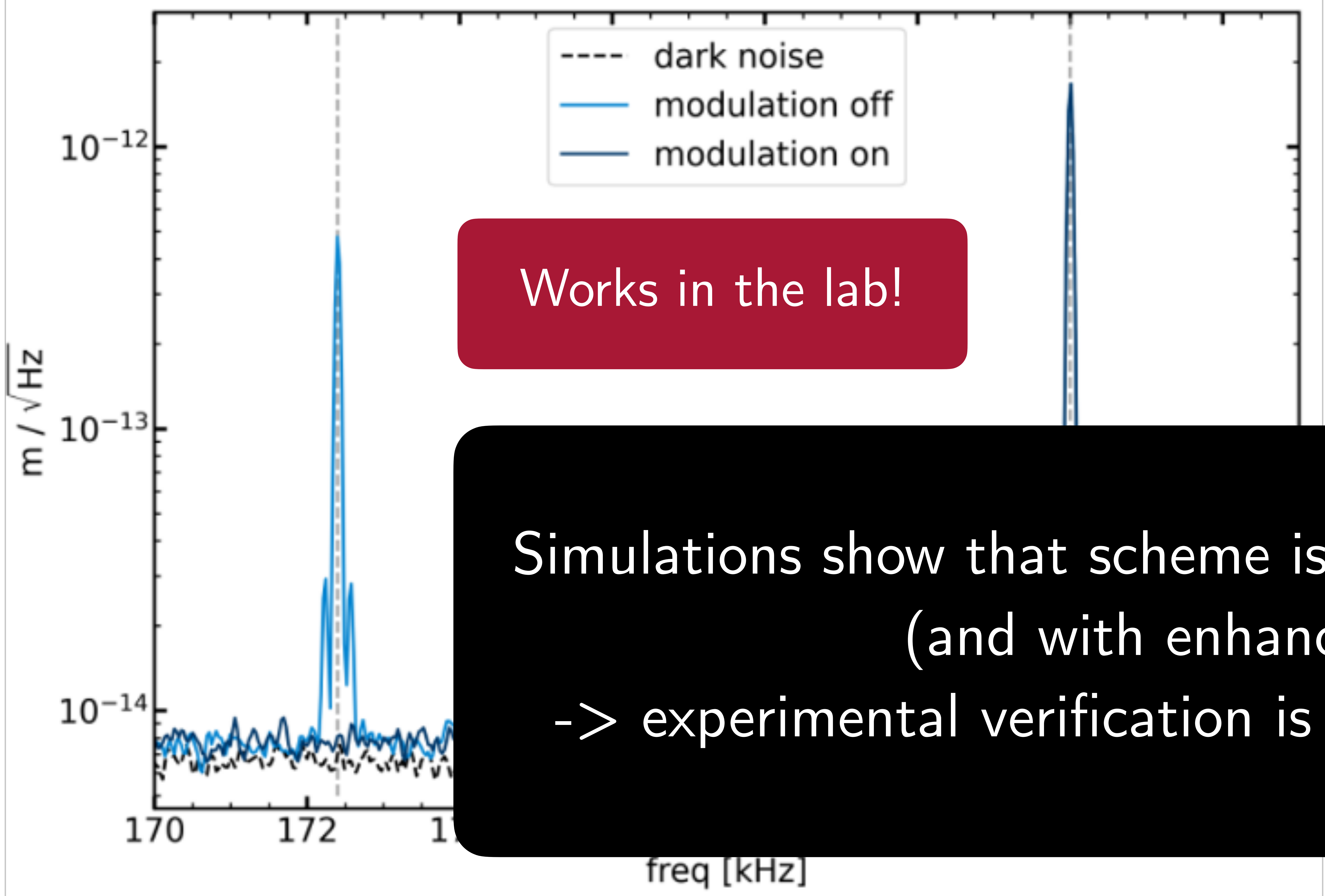
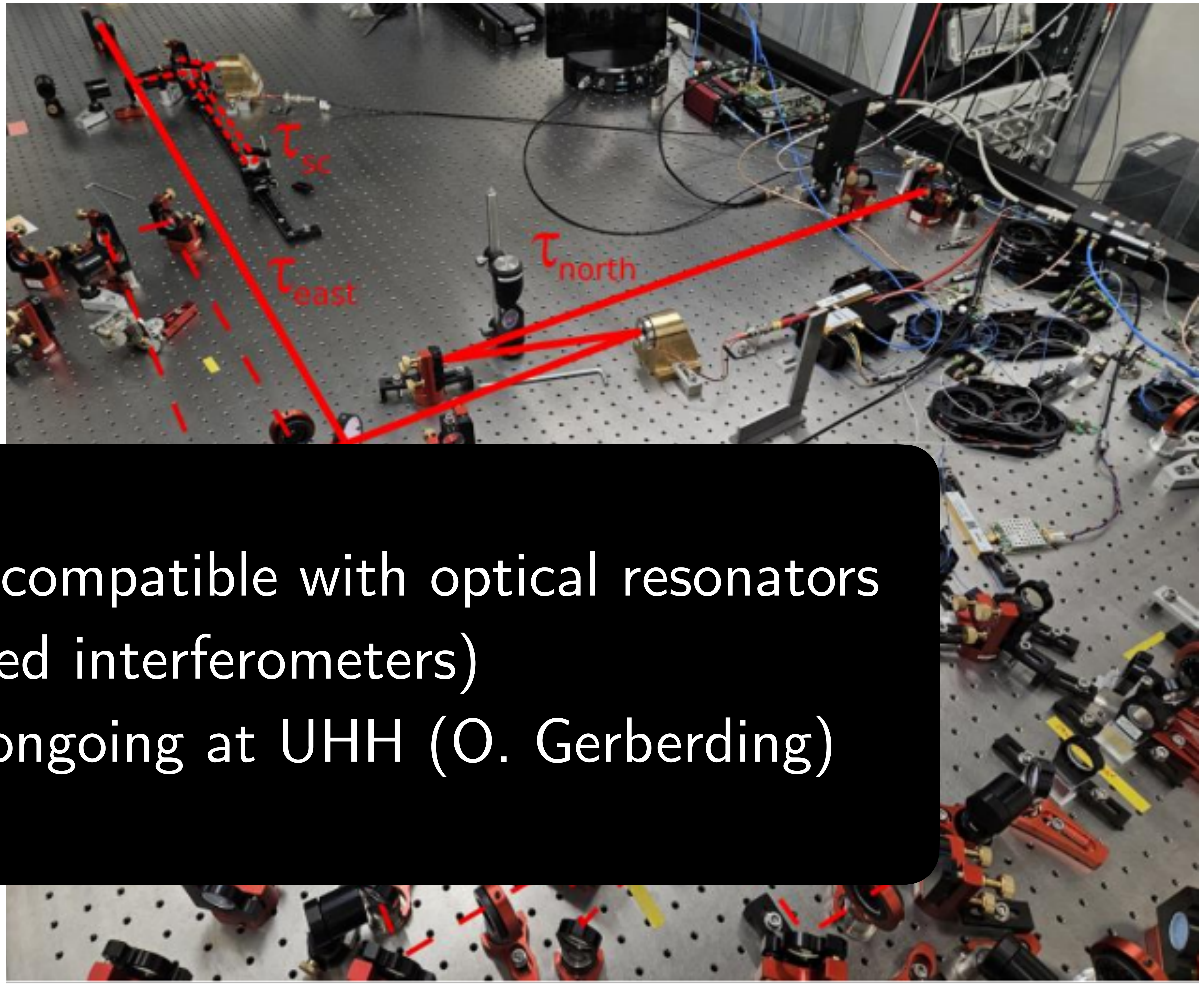


Figure: *scatter suppression with 127 chips at 1 GHz*

Works in the lab!

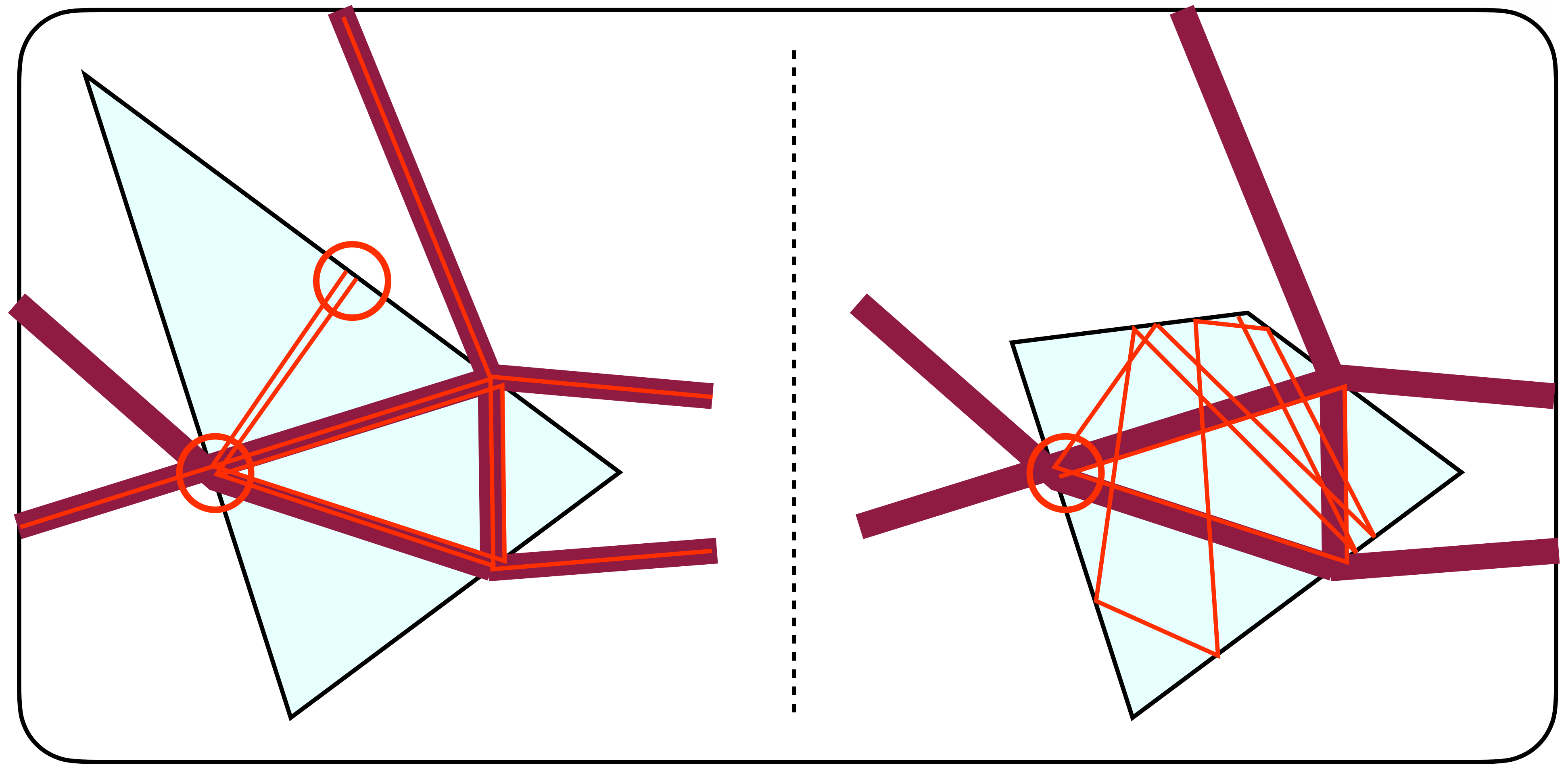


Simulations show that scheme is compatible with optical resonators (and with enhanced interferometers)

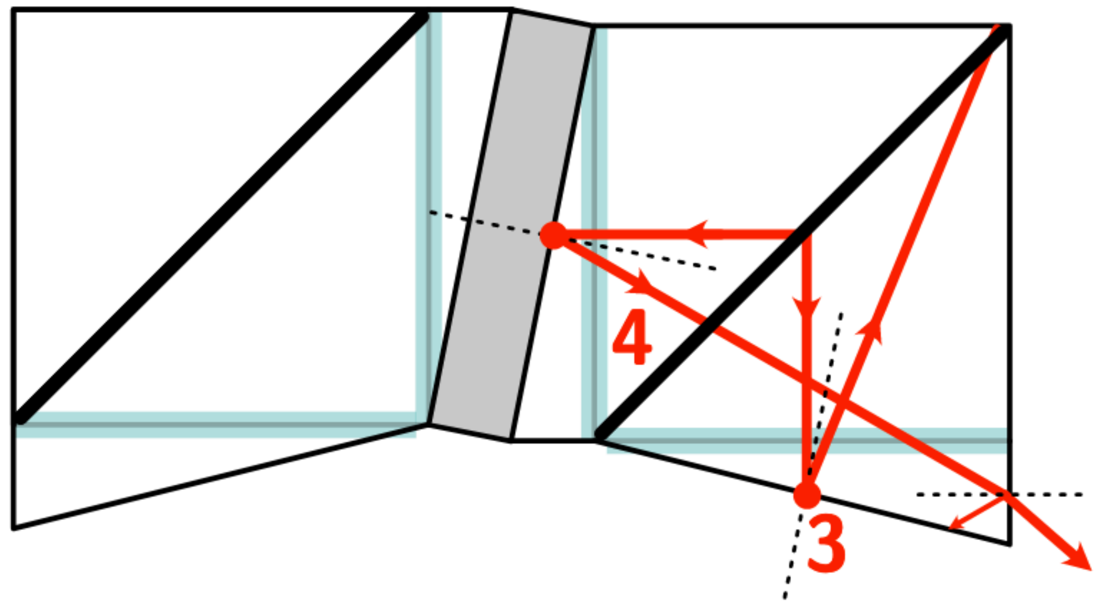
-> experimental verification is ongoing at UHH (O. Gerberding)

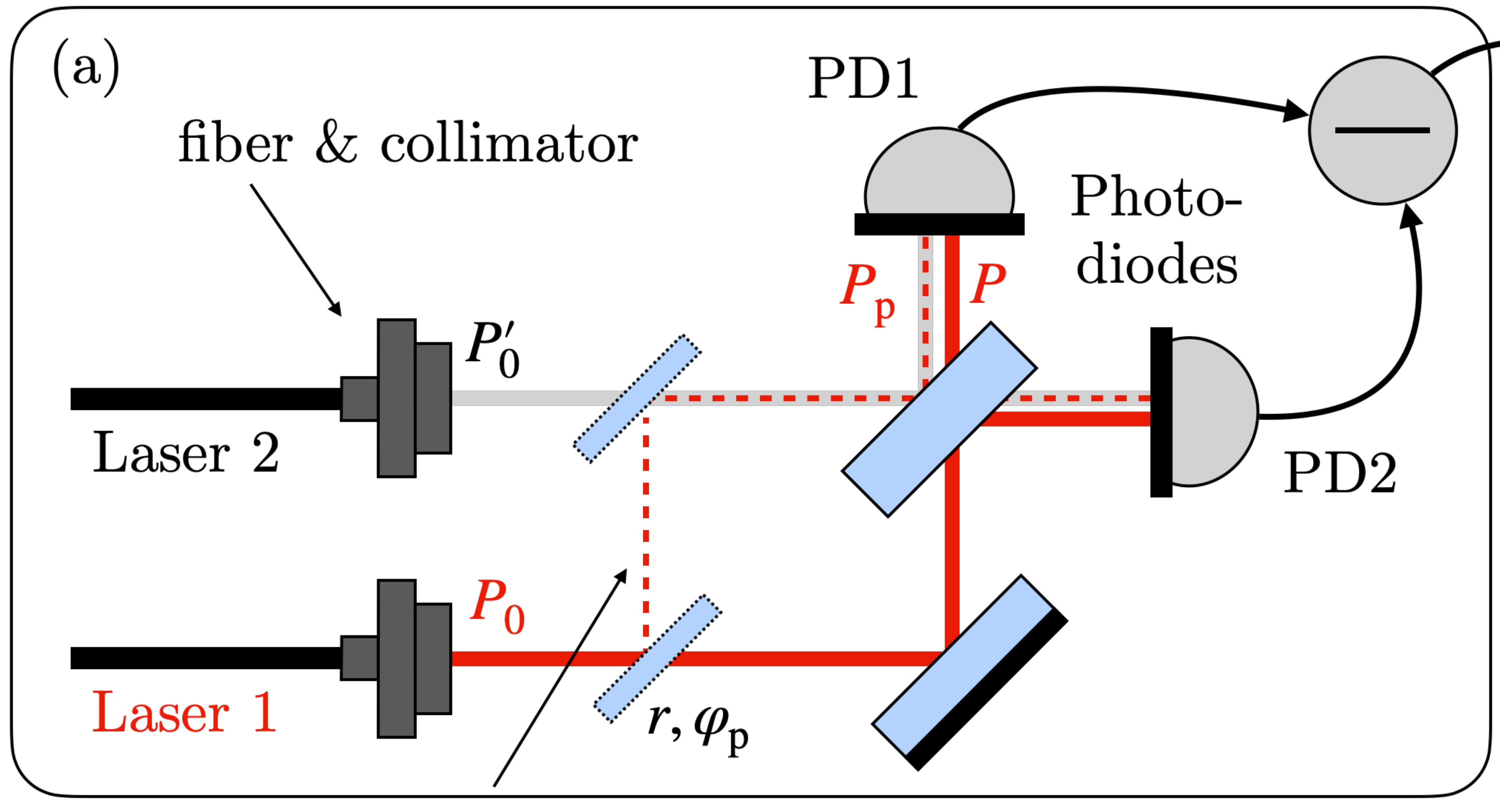
Summary and Conclusion

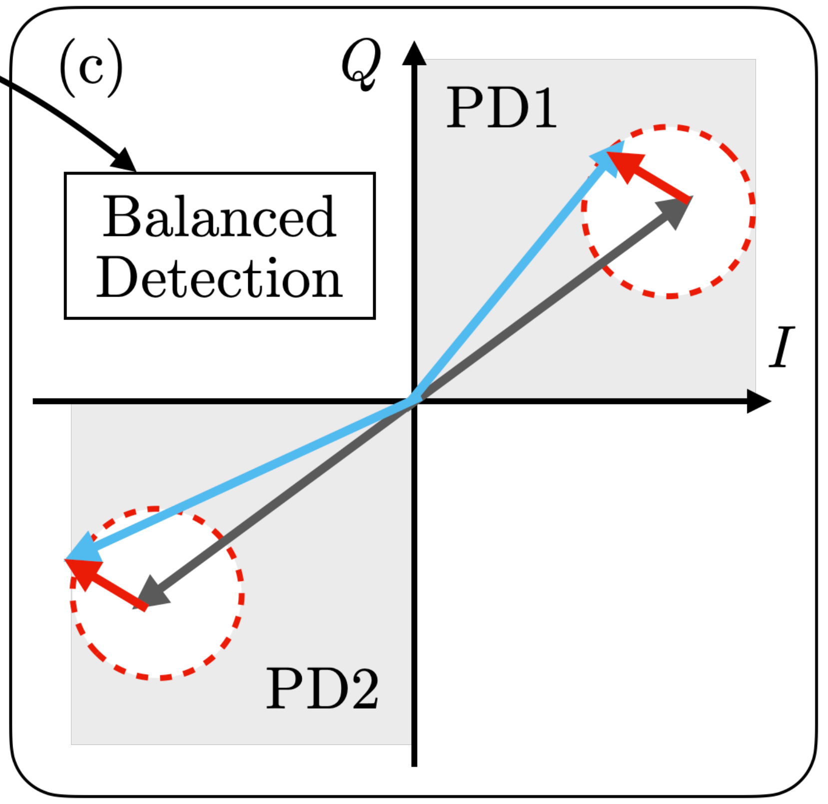
- Non-linear coupling from parasitic beams produce *noise shoulder*
- resulting phase error depends on power, mode overlap and dynamics
- **Mitigation** strategies involve
  - **Passive** reduction (baffled, by design,...)
  - **Active** reduction (Faraday isolator, frequency swap, tunable coherence, balanced detection)
  - **Environmental** reduction (reduce phase dynamics, stabilize temperature, air, vacuum)



$$\tilde{\varphi} \approx \sqrt{\frac{\eta_p P_p}{\eta P_0}} \sin(\varphi_p)$$







Stray Light challenges in **LISA Interferometry**

Sources, Dynamics, & Mitigation Strategies

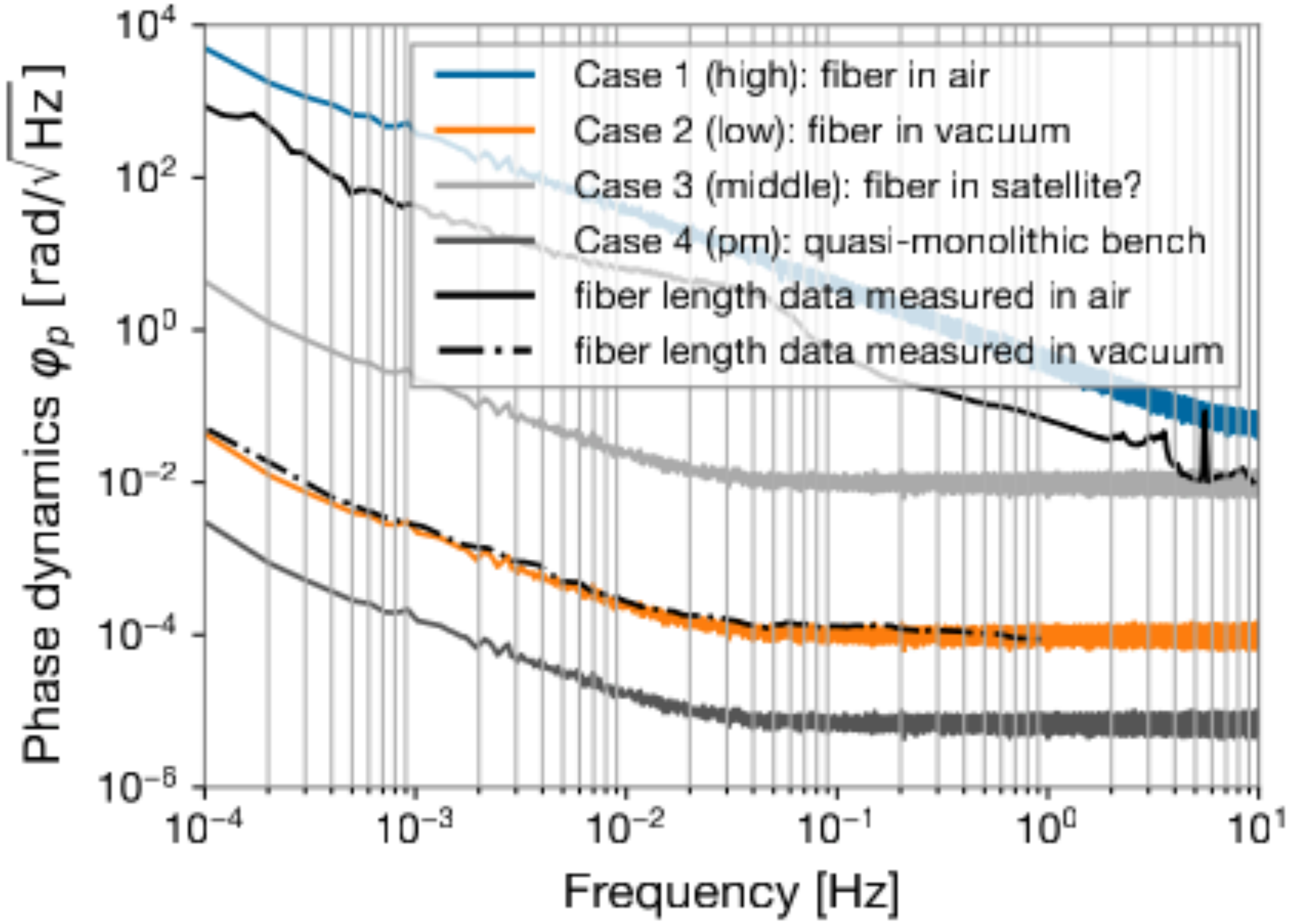
Katharina-Sophie Isleif
Helmut Schmidt University

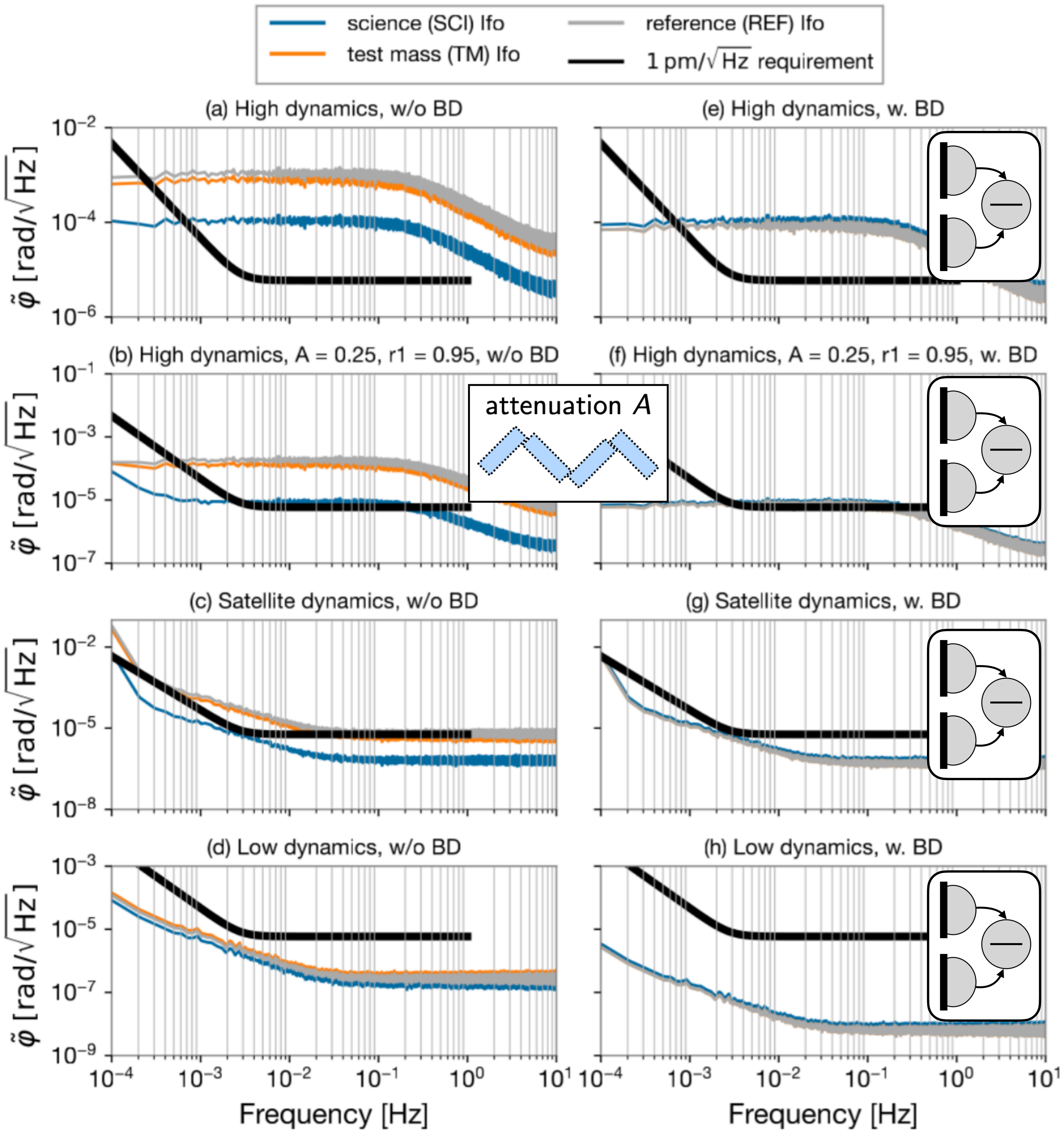
Particle Physics Pizza Seminar DESY, 13.05.2024

HELMUT SCHMIDT UNIVERSITÄT
Universität der Bundeswehr Hamburg

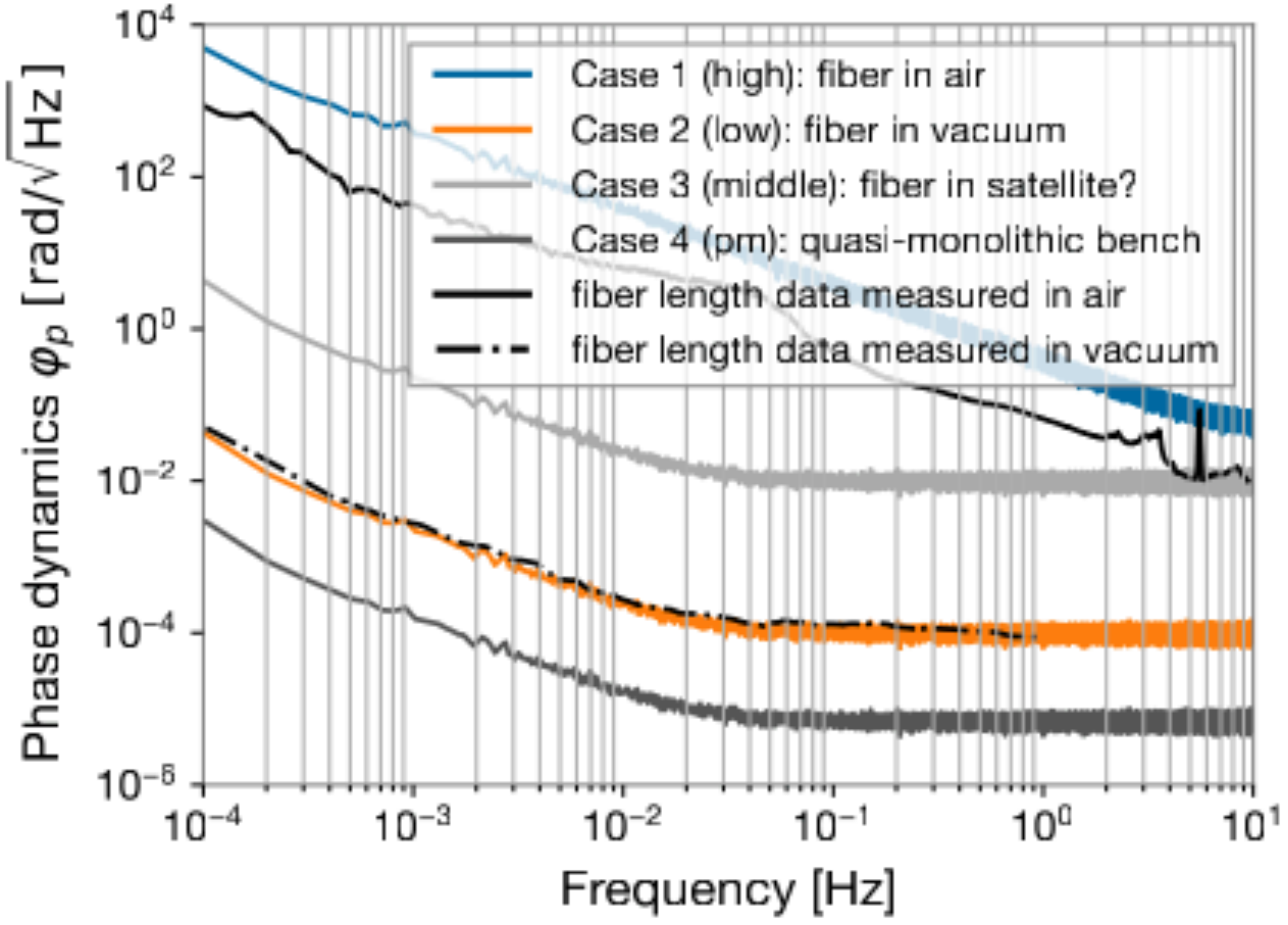
Additional slides

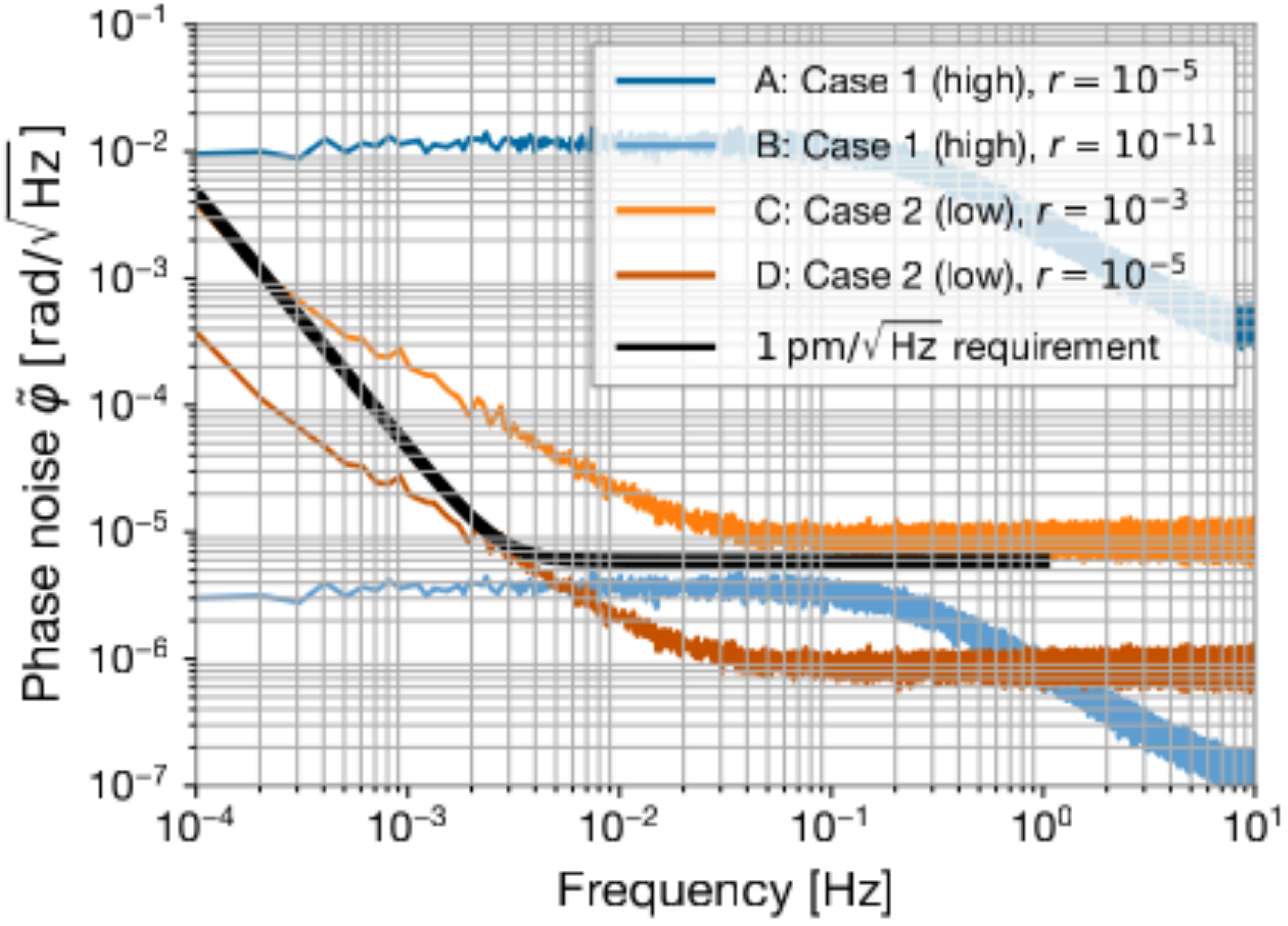
LISA interferometers



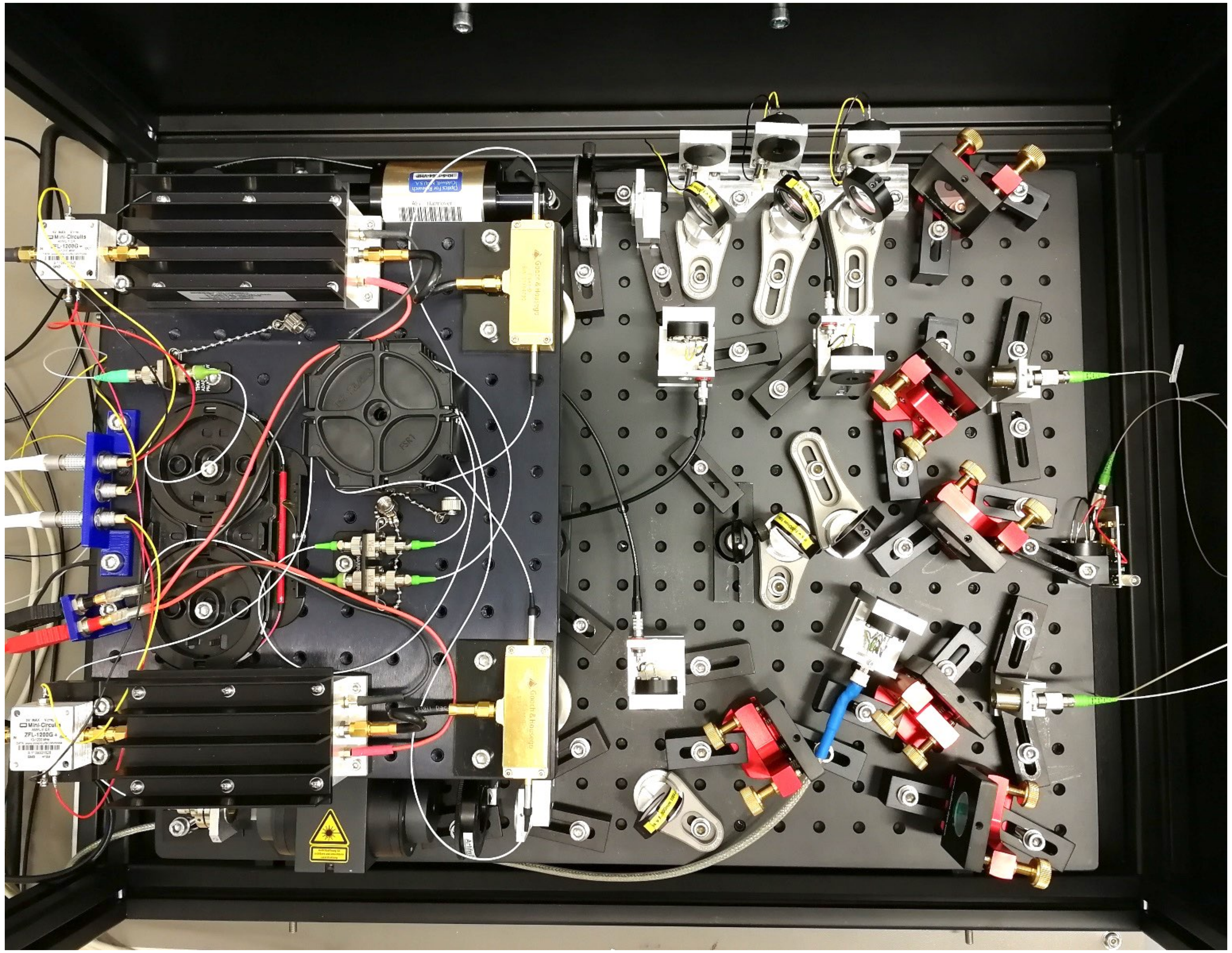


Dynamics in the LISA satellite

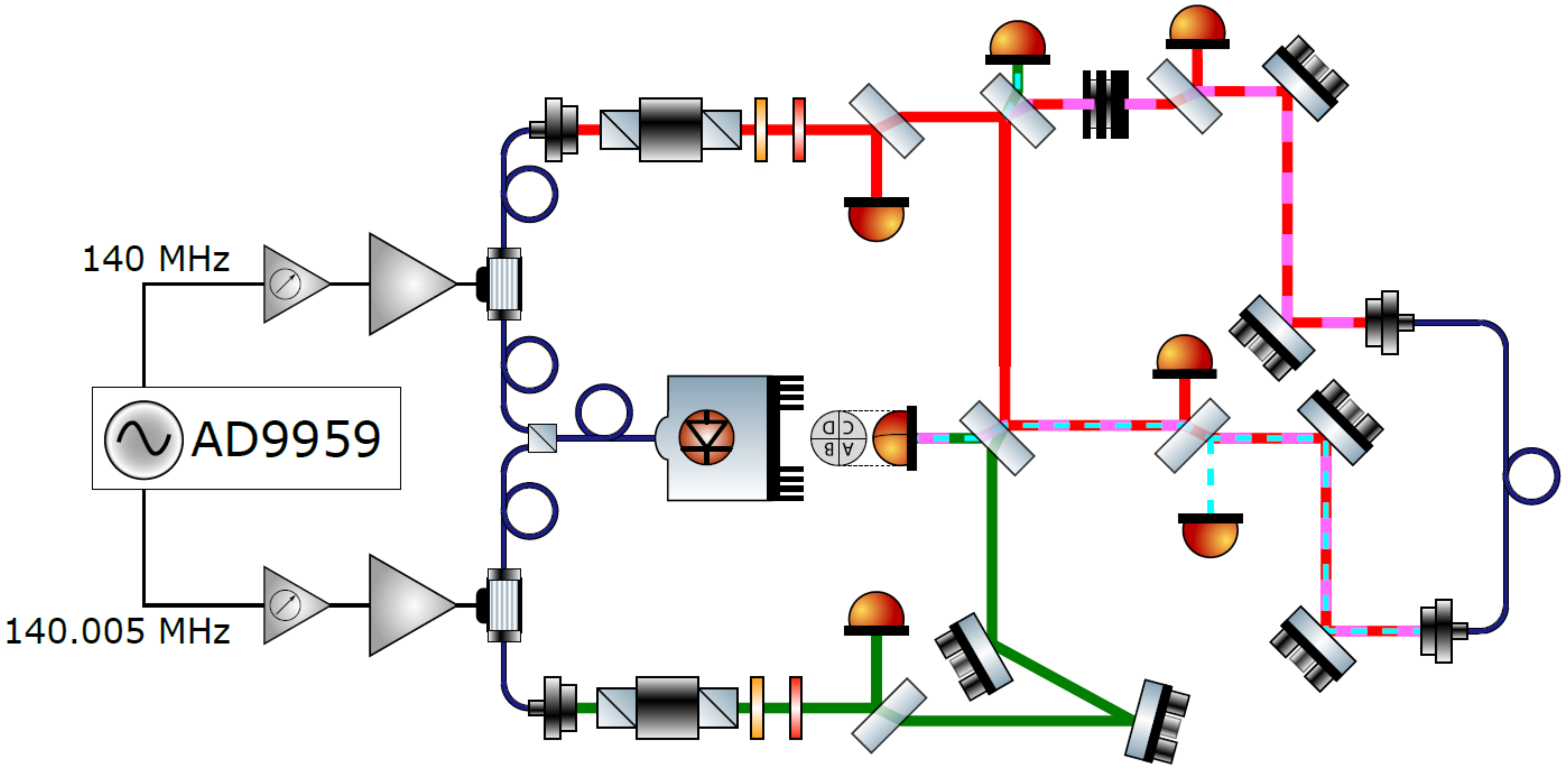




Fiber backscatter experiment

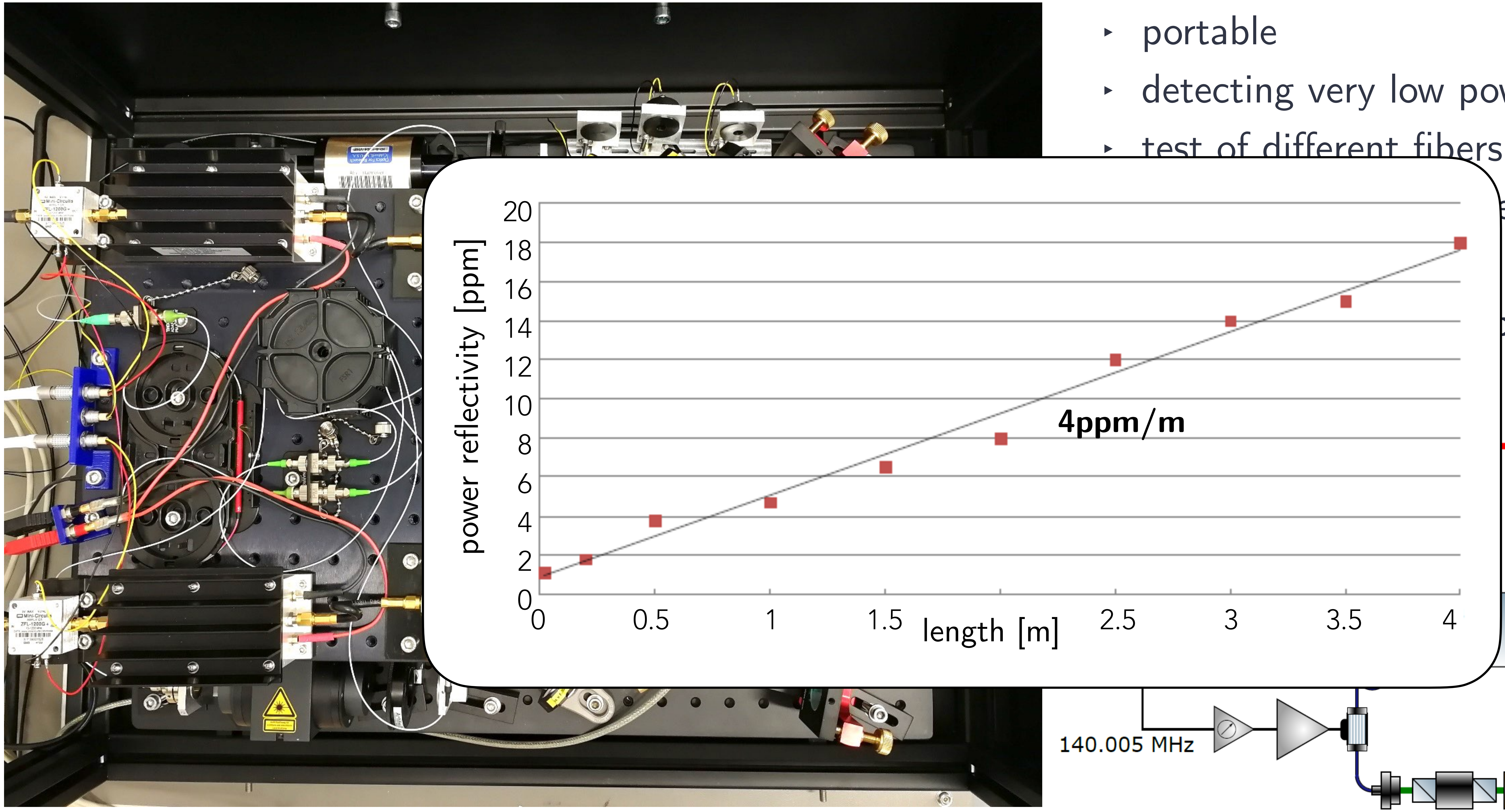


- portable
- detecting very low power levels of backscatter
- test of different fibers and fibers connectors
- calibration measurements
- test of radiated fibers
- backscatter over temperature



Rohr, 2022, https://doi.org/10.15488/12537
Rohr et. al, 2022, https://doi.org/10.1364/OE.404139

Fiber backscatter experiment



- portable
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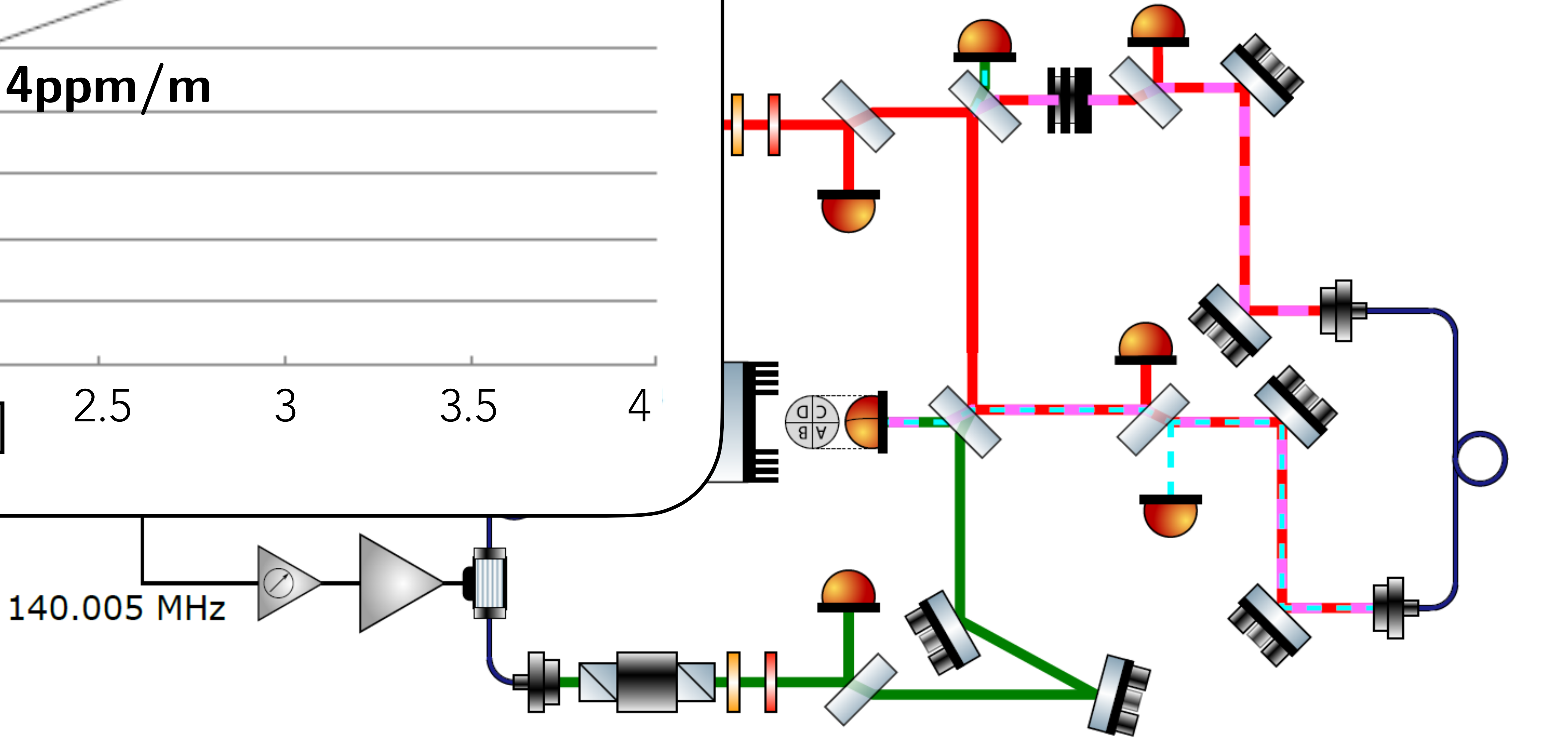
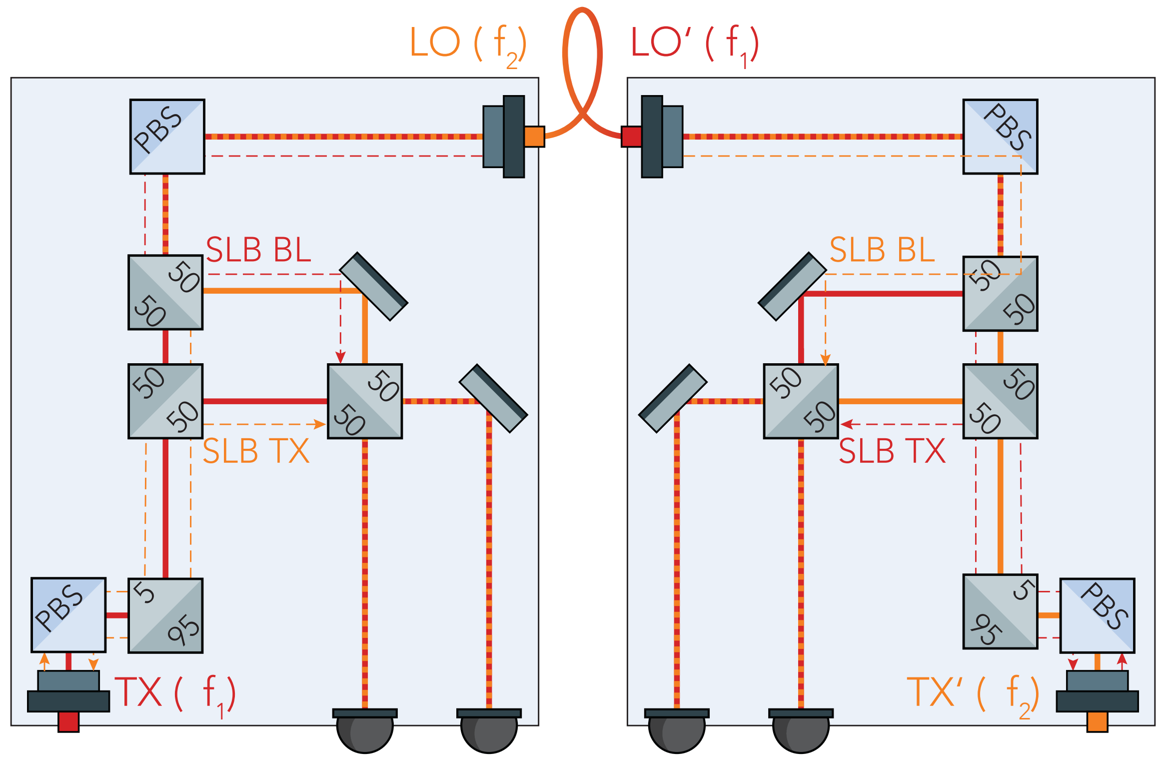
- ents
- perature

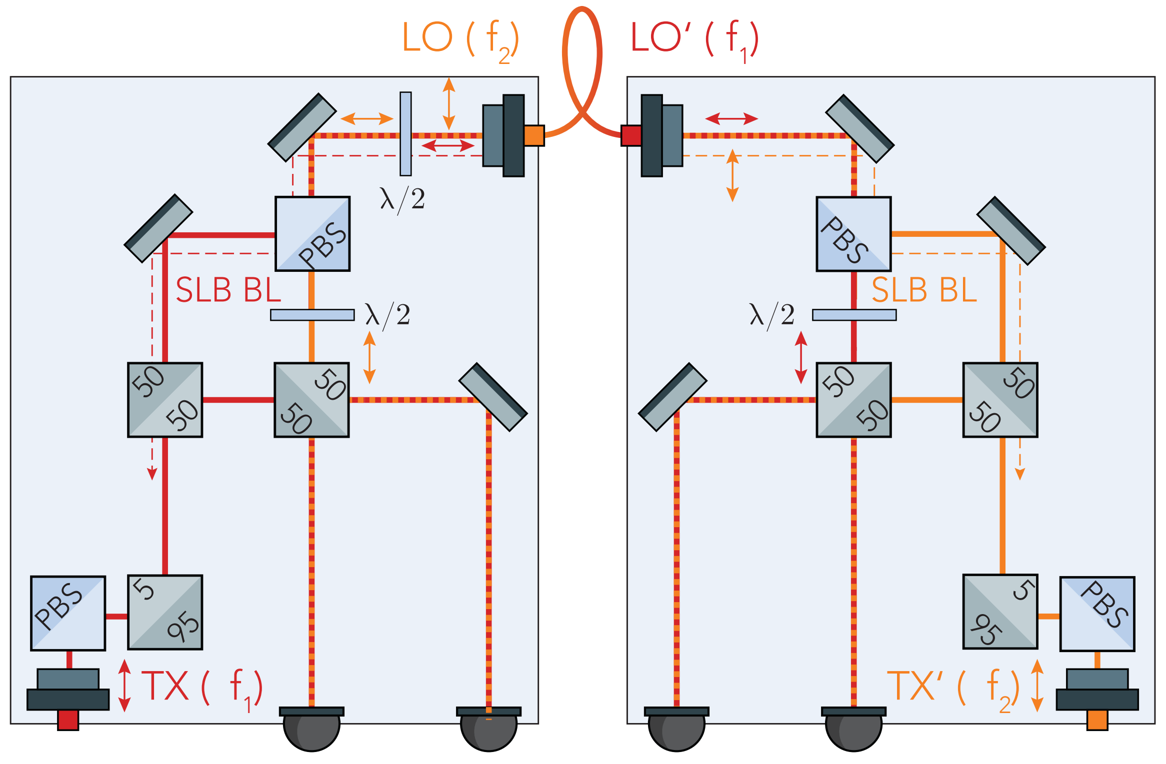


Backlink alternatives

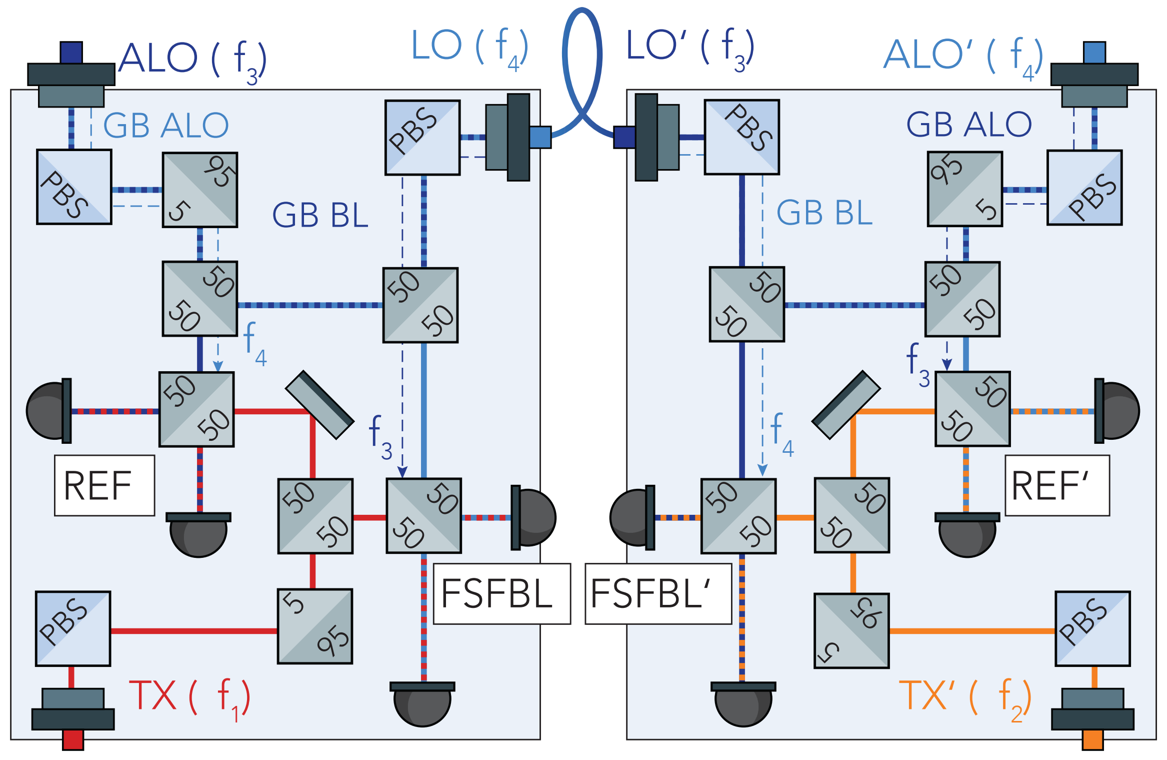
Direct fiber



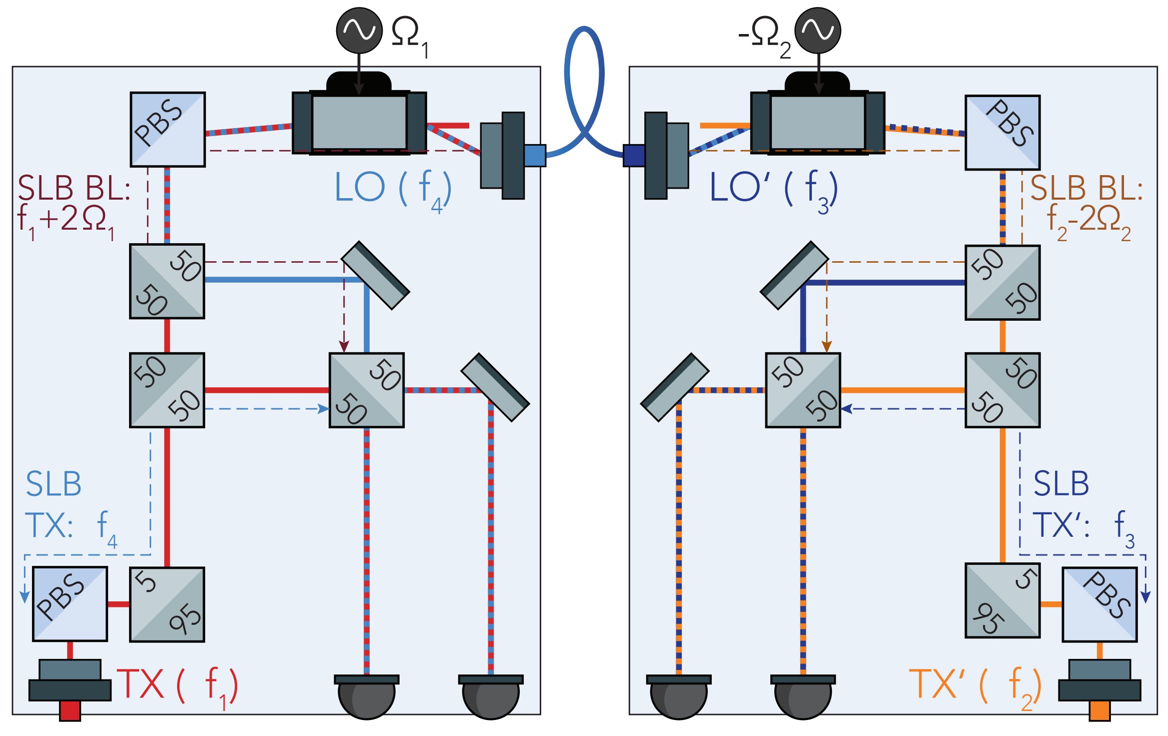
Polarisation fiber



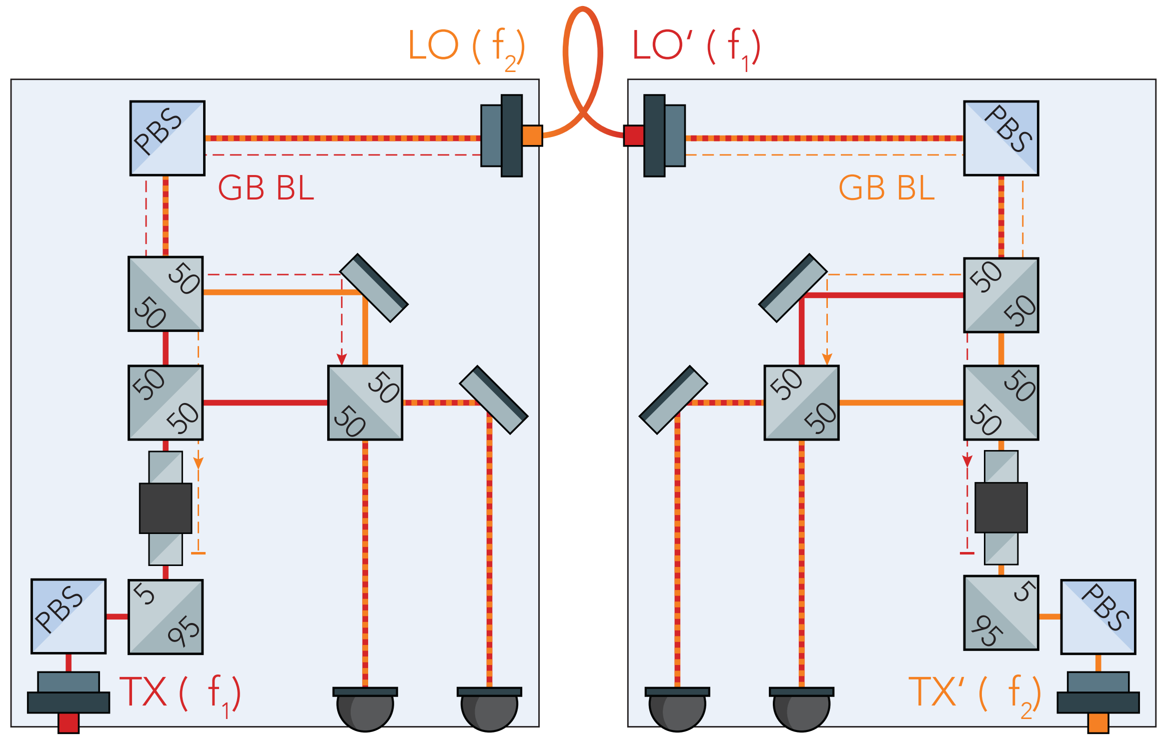
Frequency shifted fiber



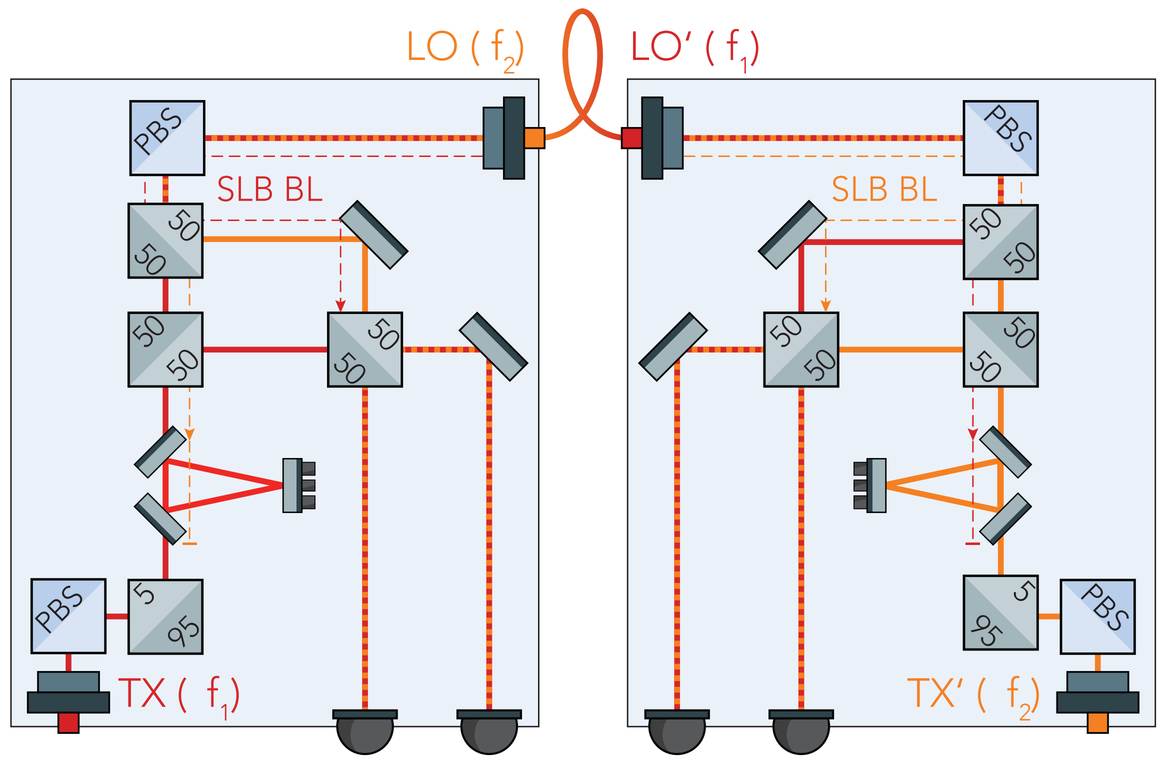
AOM fiber



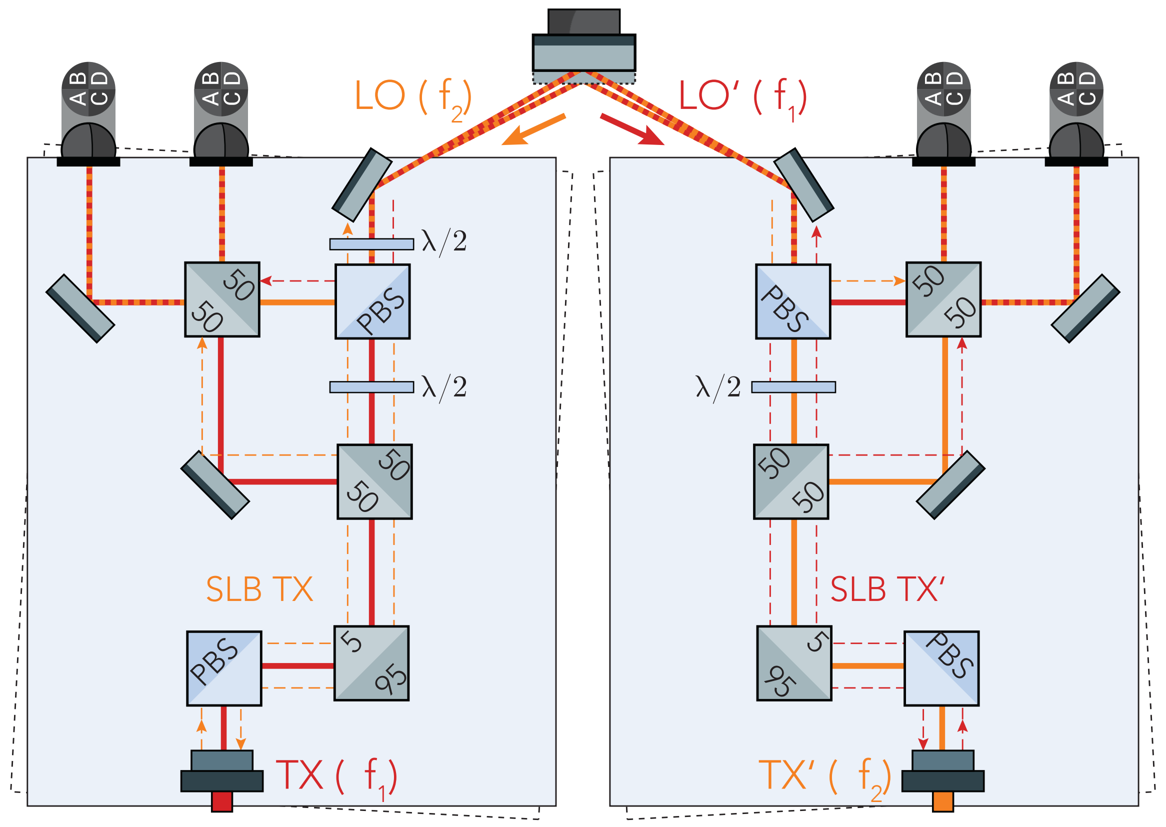
Faraday fiber



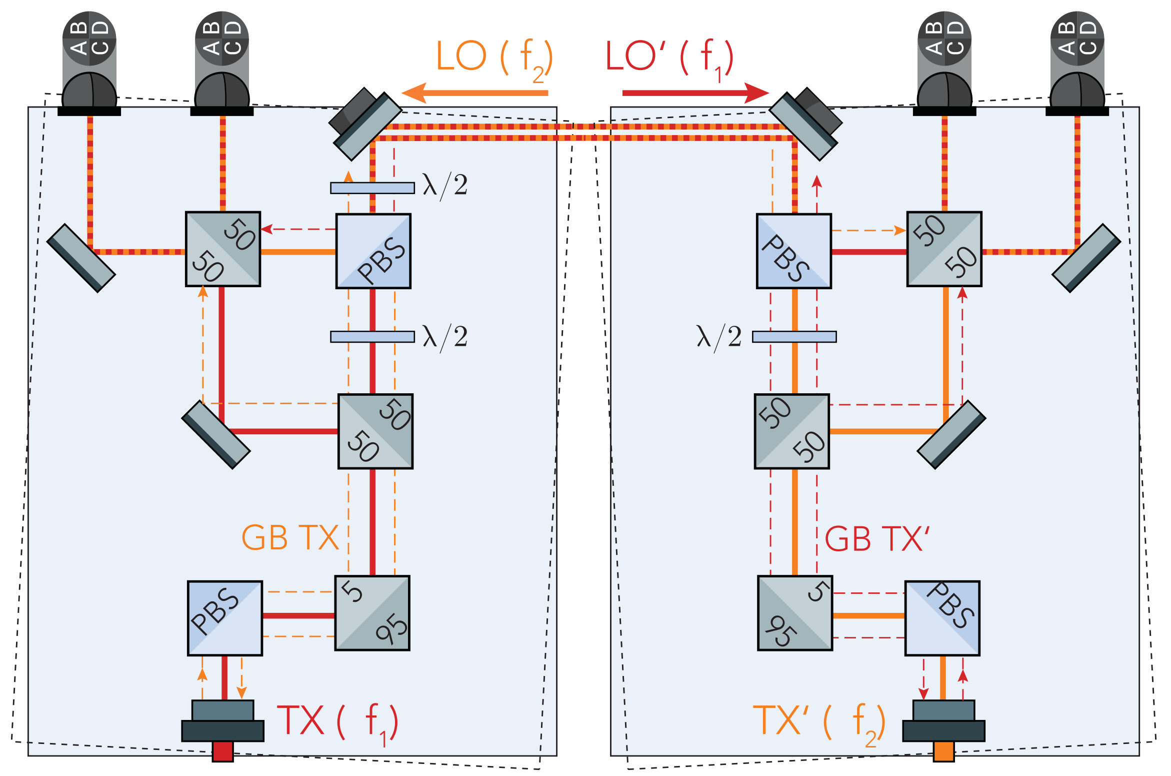
Cavity fiber



Reflector in the middle



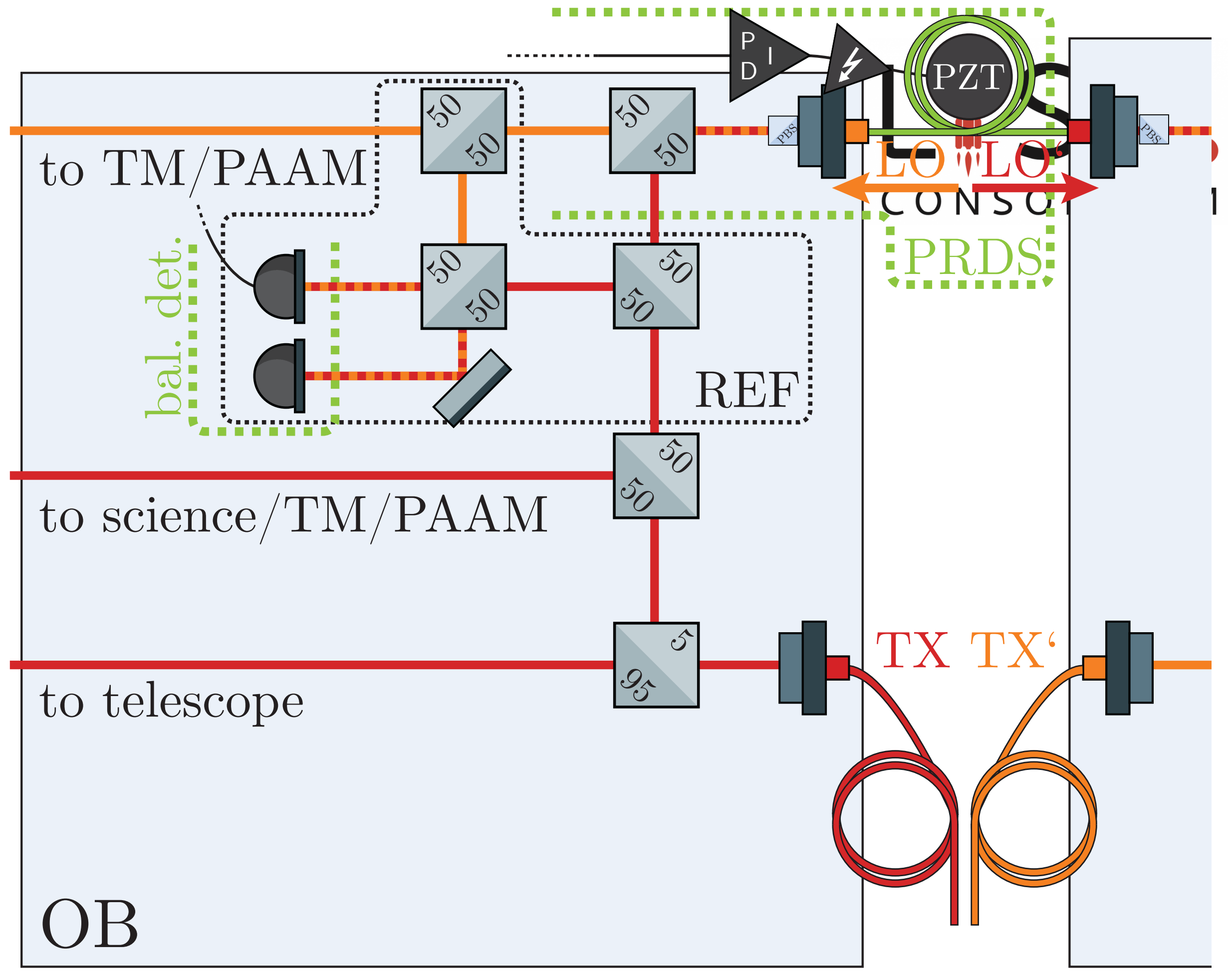
Free beam

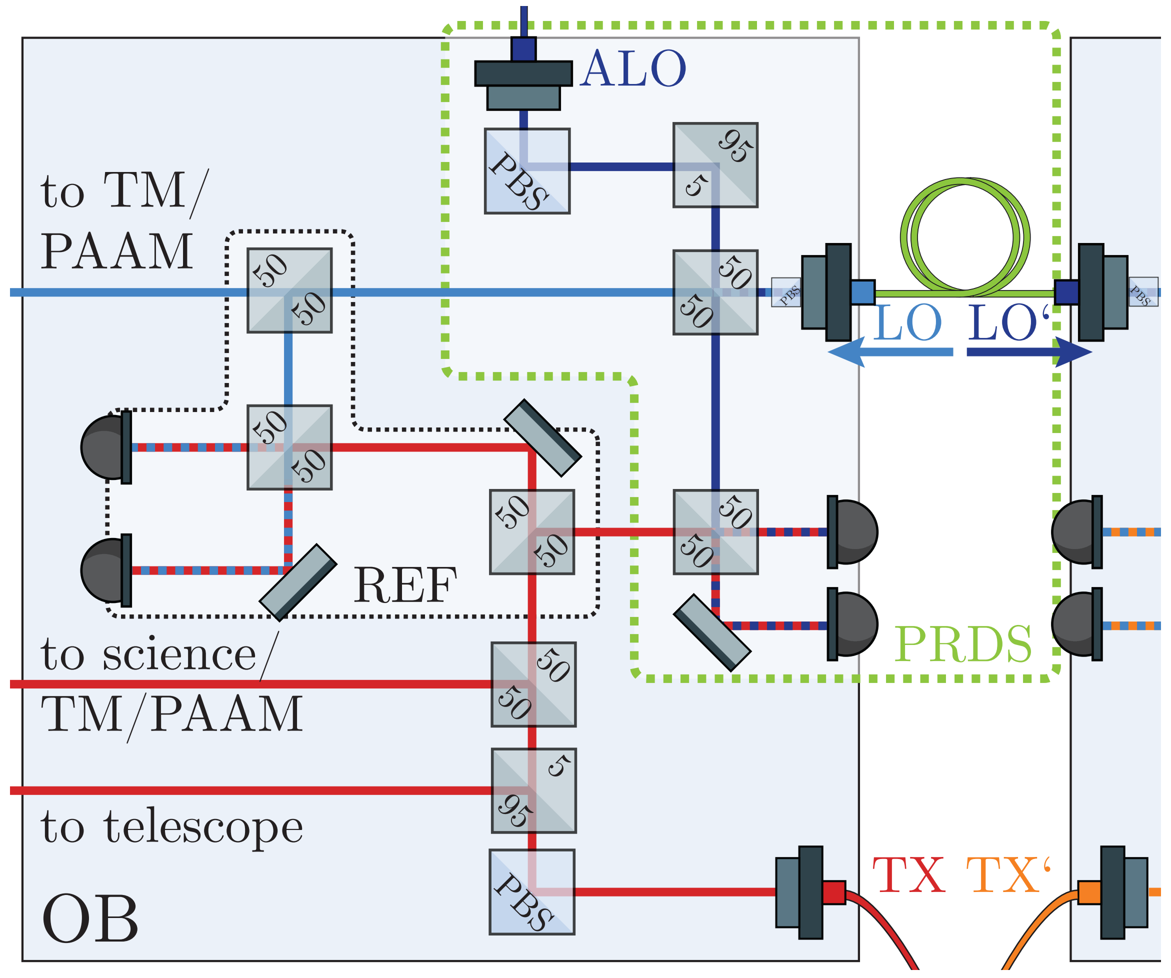


Backlink options

backlink	interfering beams		phase error [rad]
DFBL	SLB TX SLB BL SLB TX	TX LO SLB ALO	$1.1 \cdot 10^{-4}$ $2.2 \cdot 10^{-3}$ $0.25 \cdot 10^{-6}$
PFBL / RMBL / FBBL	SLB TX SLB BL SLB TX	TX LO SLB ALO	$\sqrt{\text{PBS}_{\text{extc}}} \cdot 1.1 \cdot 10^{-4}$ $\sqrt{\text{PBS}_{\text{extc}}} \cdot 4.4 \cdot 10^{-3}$ $\text{PBS}_{\text{extc}} \cdot 0.5 \cdot 10^{-6}$
FIFBL	SLB TX SLB BL SLB TX	TX LO SLB BL	$\sqrt{\text{ISO}_{\text{extc}}} \cdot 1.1 \cdot 10^{-4}$ $2.2 \cdot 10^{-3}$ $\sqrt{\text{ISO}_{\text{extc}}} \cdot 0.25 \cdot 10^{-6}$
CFBL	SLB TX SLB BL SLB TX	TX LO SLB BL	$\sqrt{\text{CAV}_{\text{extc}}} \cdot 1.1 \cdot 10^{-4}$ $2.2 \cdot 10^{-3}$ $\sqrt{\text{CAV}_{\text{extc}}} \cdot 0.25 \cdot 10^{-6}$
FSFBL REF	SLB BL SLB ALO –	LO ALO –	$0.25 \cdot 10^{-6}$ $0.25 \cdot 10^{-6}$
AOMFBL	SLB TX SLB BL SLB TX	TX LO SLB BL	$1.1 \cdot 10^{-4}$ – –

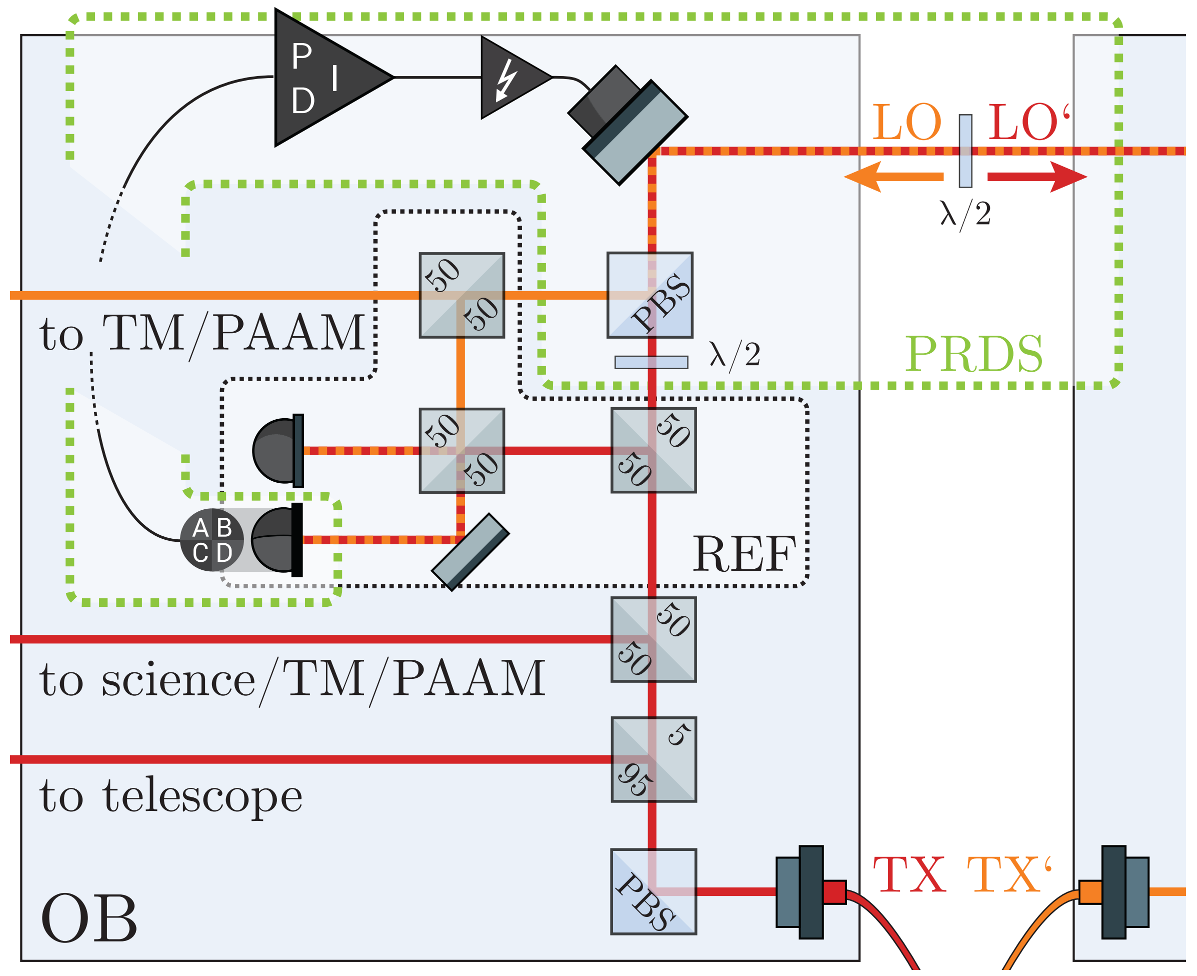
Direct fiber (DFBL)



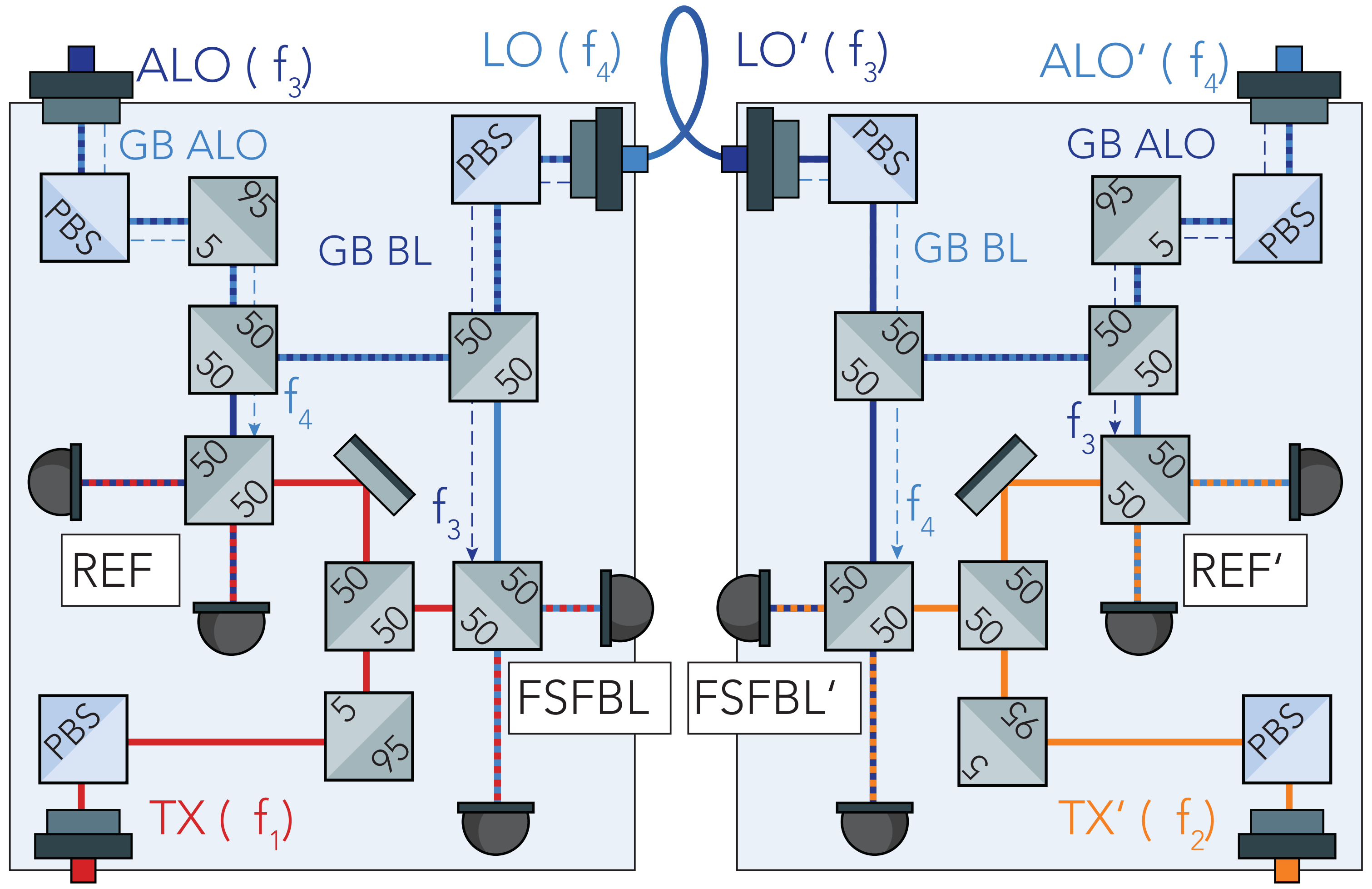


Frequency shifted fiber (FSFBL)

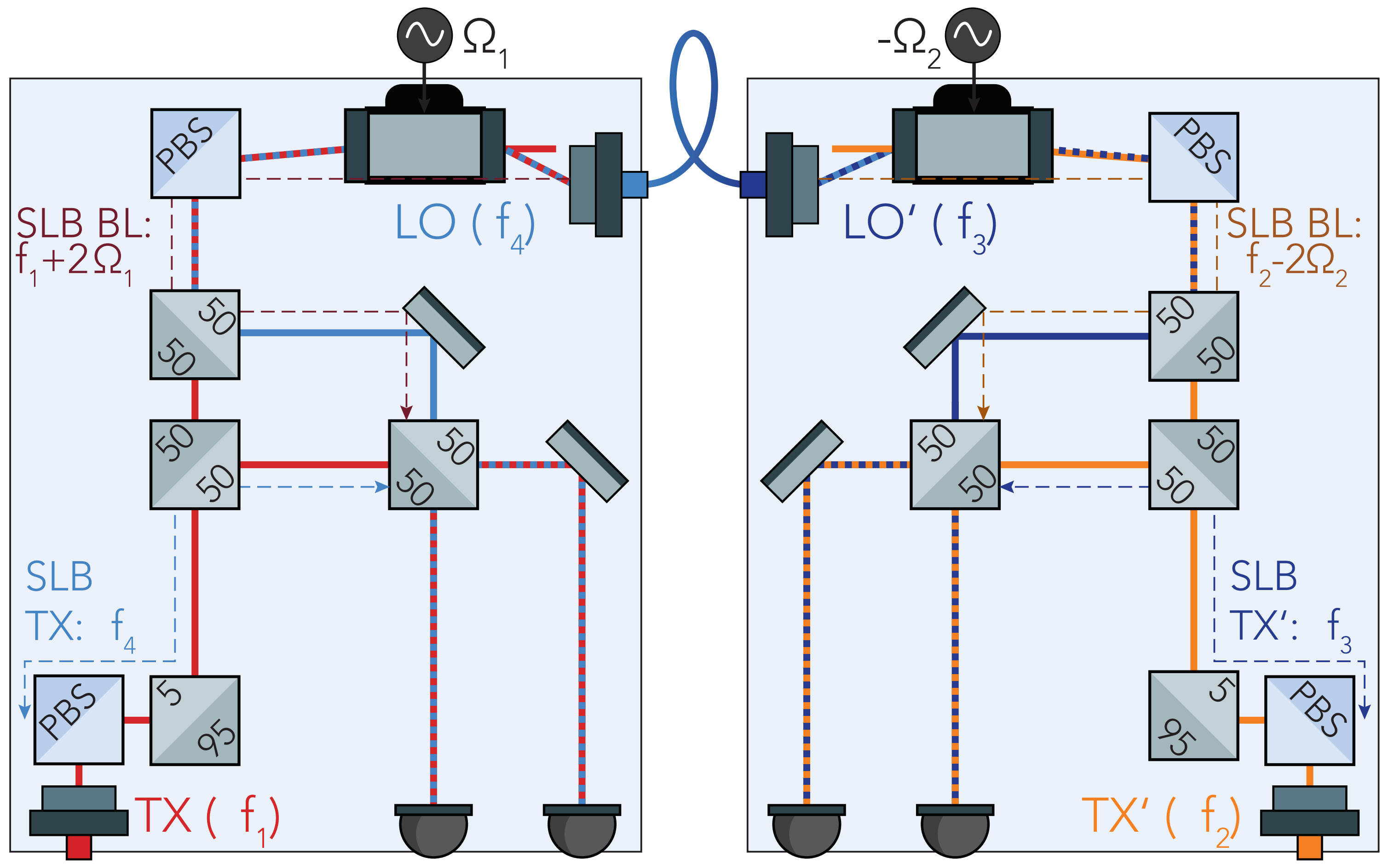
Free beam (FBBL)



Frequency shifted fiber backlinks

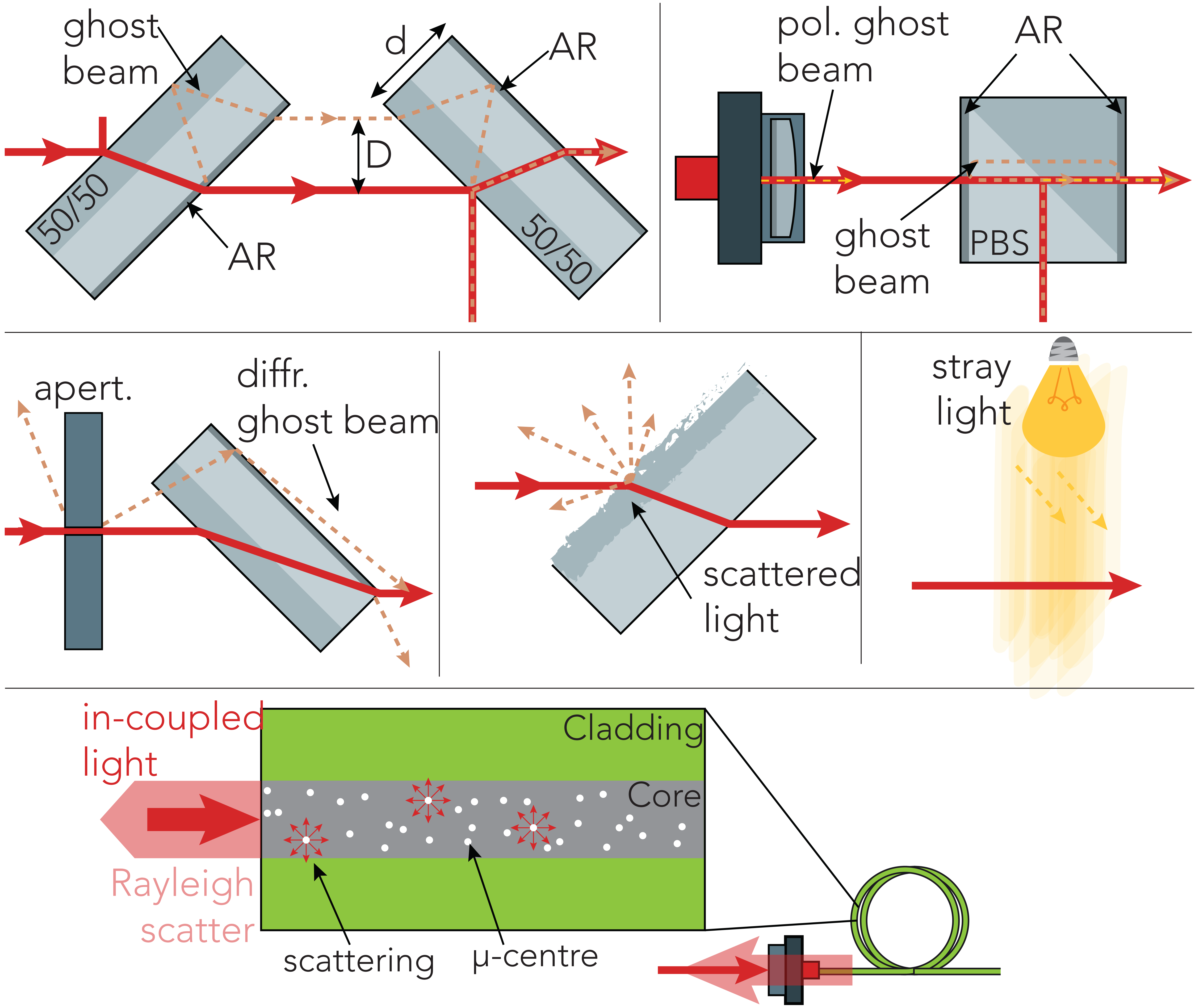


interferometer	$f_1 > f_2 > f_3 > f_4$ nominal beat	SLS beats		$f_1 = f_2$ nominal beat	SLS beats	
REF	$f_1 - f_3$	$f_3 - f_4$	$f_1 - f_4$	$f_1 - f_3$	$f_3 - f_4$	$f_1 - f_4$
REF'	$f_2 - f_4$	$f_3 - f_4$	$f_2 - f_3$	$f_1 - f_4$	$f_3 - f_4$	$f_1 - f_3$
FSFBL	$f_1 - f_4$	$f_3 - f_4$	$f_1 - f_3$	$f_1 - f_4$	$f_3 - f_4$	$f_1 - f_3$
FSFBL'	$f_2 - f_3$	$f_3 - f_4$	$f_2 - f_4$	$f_1 - f_3$	$f_3 - f_4$	$f_1 - f_4$



interferometer	$f_1 > f_2$ and $f_4 = f_2 - \Omega_2 + \Omega_1$ and $f_3 = (f_1 + \Omega_1 - \Omega_2)$ nominal beat	SLS beats		
AOMFBL	$f_1 - f_4$	$f_1 - f_4$	$f_1 - (f_1 + 2\Omega_1)$	$f_4 - (f_1 + 2\Omega_1)$
AOMFBL'	$f_2 - f_3$	$f_2 - f_3$	$f_2 - (f_2 - 2\Omega_2)$	$f_3 - (f_2 - 2\Omega_2)$

Sources of spurious beams

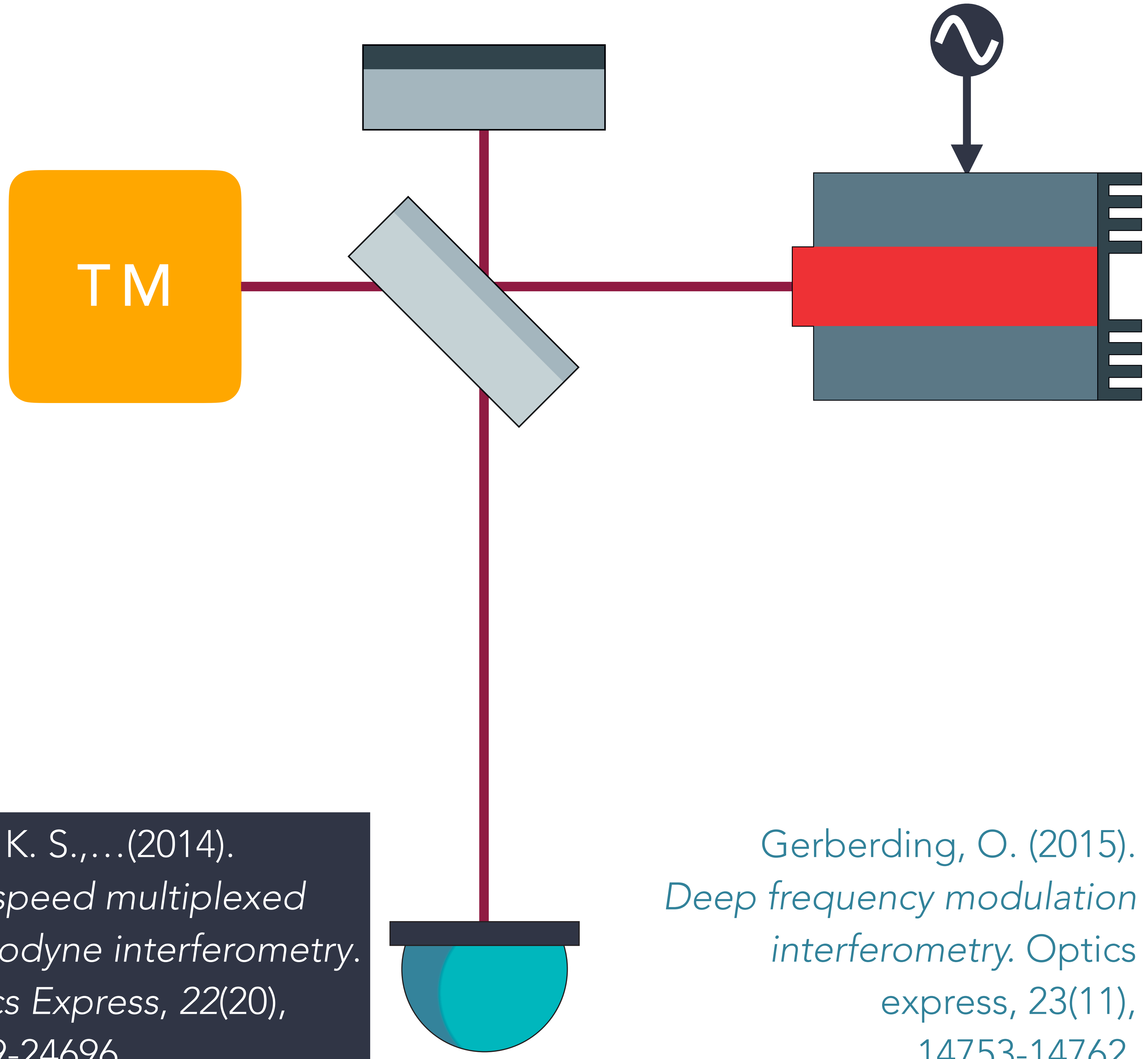


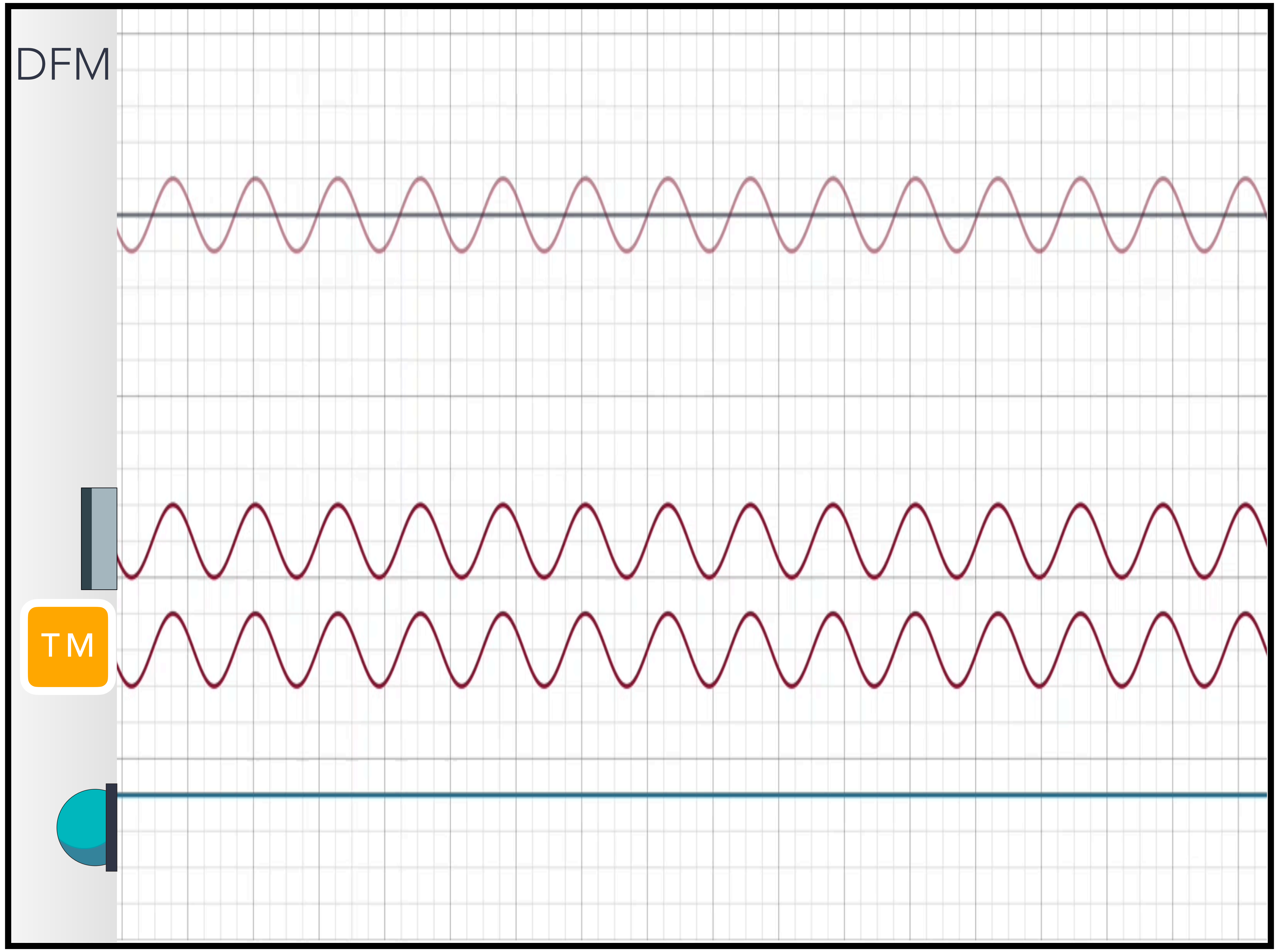
category		noise source: comp	origin	dynamic	model	phase error [rad]
ghost beams		bonded	2nd refl.	$\ll 1\,\mathrm{pm}$	P, rays	$\sqrt{\frac{P_{\mathrm{SLB}}}{P_{\mathrm{ref}}}}$
		metal mounted	2nd refl.	$\ll 1\,\mathrm{nm}$	P, rays, overlap, dynamics	$\sqrt{\frac{\eta_{\mathrm{SLS}} P_{\mathrm{SLB}}}{\eta P_{\mathrm{ref}}}} \varphi_{\mathrm{SLS}}$
		fibers	fiber scatter	thermal, angle jitter, stress		
	diffracted	Isolator, aperture	diffraction, clipping	$\ll 1\,\mathrm{nm}$	P, rays	$\sqrt{\frac{P_{\mathrm{SLB}}}{P_{\mathrm{ref}}}}$
	p-pol.	fiber	fast axis coupling	thermal, acoustic, coupling pointing	no model used	unknown
		FIOS	FIOS misalignm., birefringent lens			
scattered light		bonded	dust, surface roughness, scratches, coating quality	$\ll 1\,\mathrm{pm}$	P, rays	$\sqrt{\frac{P_{\mathrm{SLB}}}{P_{\mathrm{ref}}}}$
		metal mounted		$\ll 1\,\mathrm{nm}$	P, rays, overlap, dynamics	$\sqrt{\frac{\eta_{\mathrm{SLS}} P_{\mathrm{SLB}}}{\eta P_{\mathrm{ref}}}} \varphi_{\mathrm{SLS}}$
		steering mirrors		thermal, steering		
stray light		external	lamp			$\sqrt{\frac{P_{\mathrm{SLB}}}{P_{\mathrm{ref}}}} 10^{-6}$

Isleif (2018) https://doi.org/10.15488/3526

DFMI

Deep Frequency Modulation interferometry



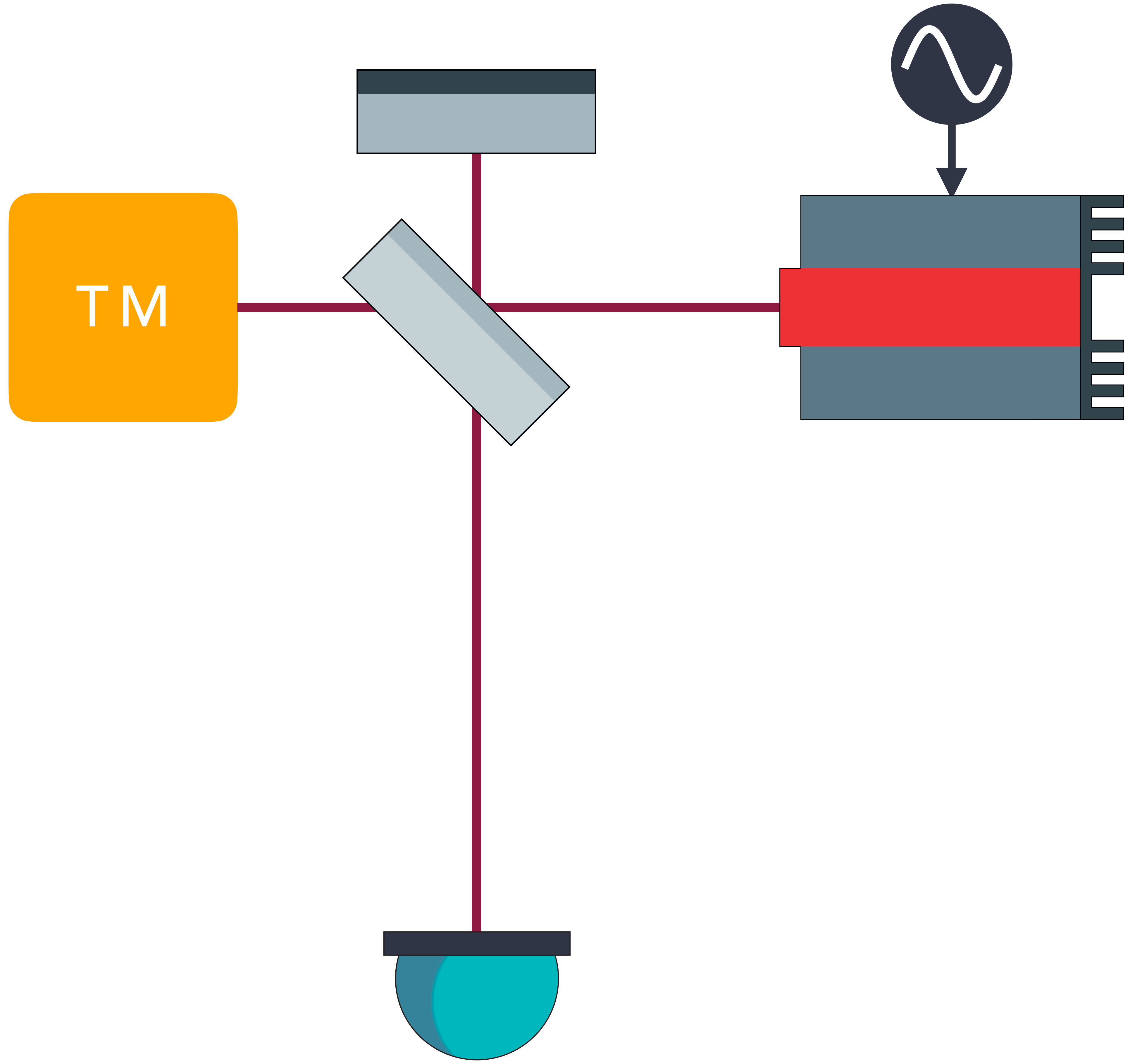


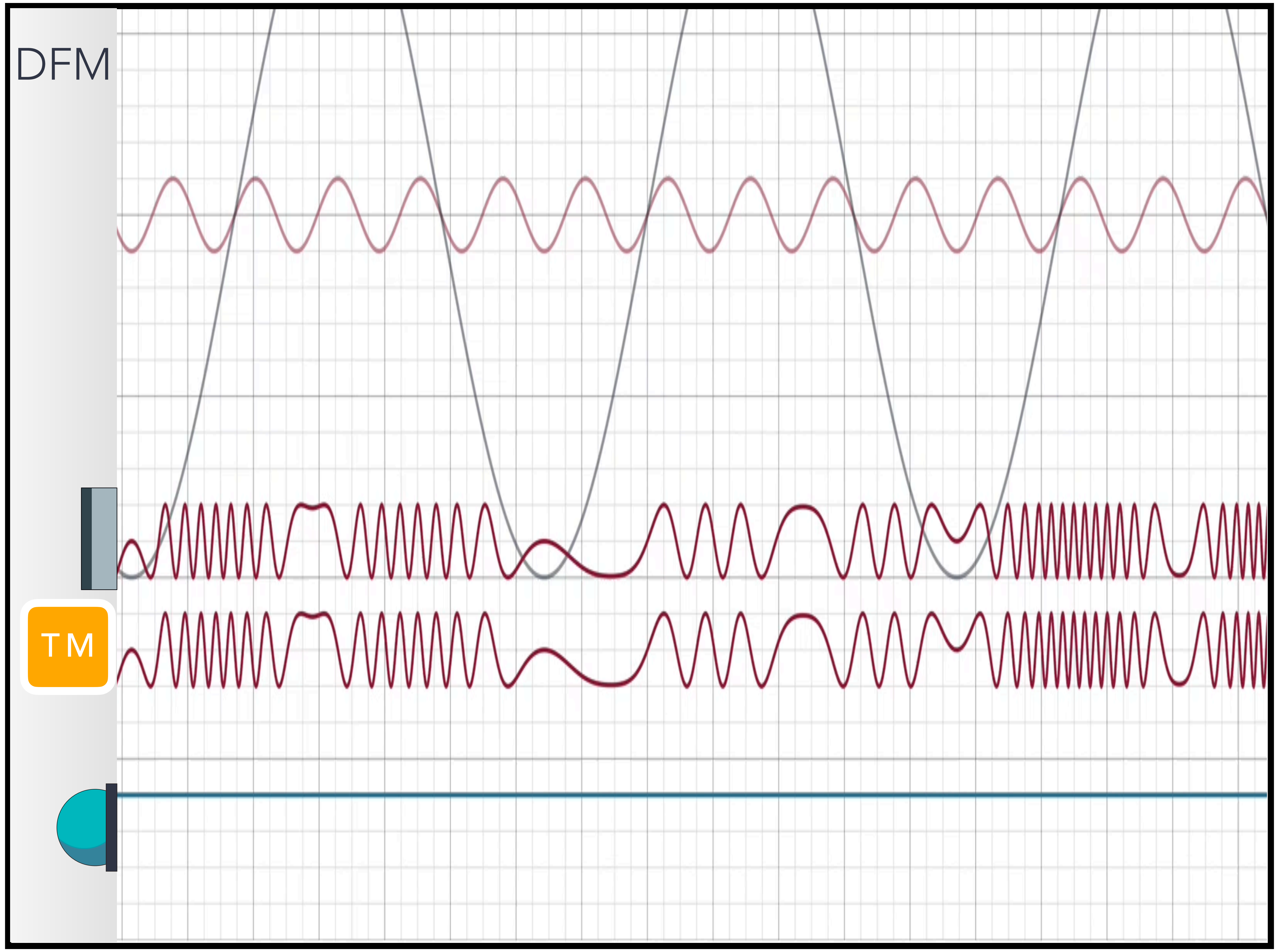
Isleif, K. S.,…(2014). *Highspeed multiplexed heterodyne interferometry. Optics Express, 22*(20), 24689-24696.

Gerberding, O. (2015). *Deep frequency modulation interferometry.* Optics express, 23(11), 14753-14762.

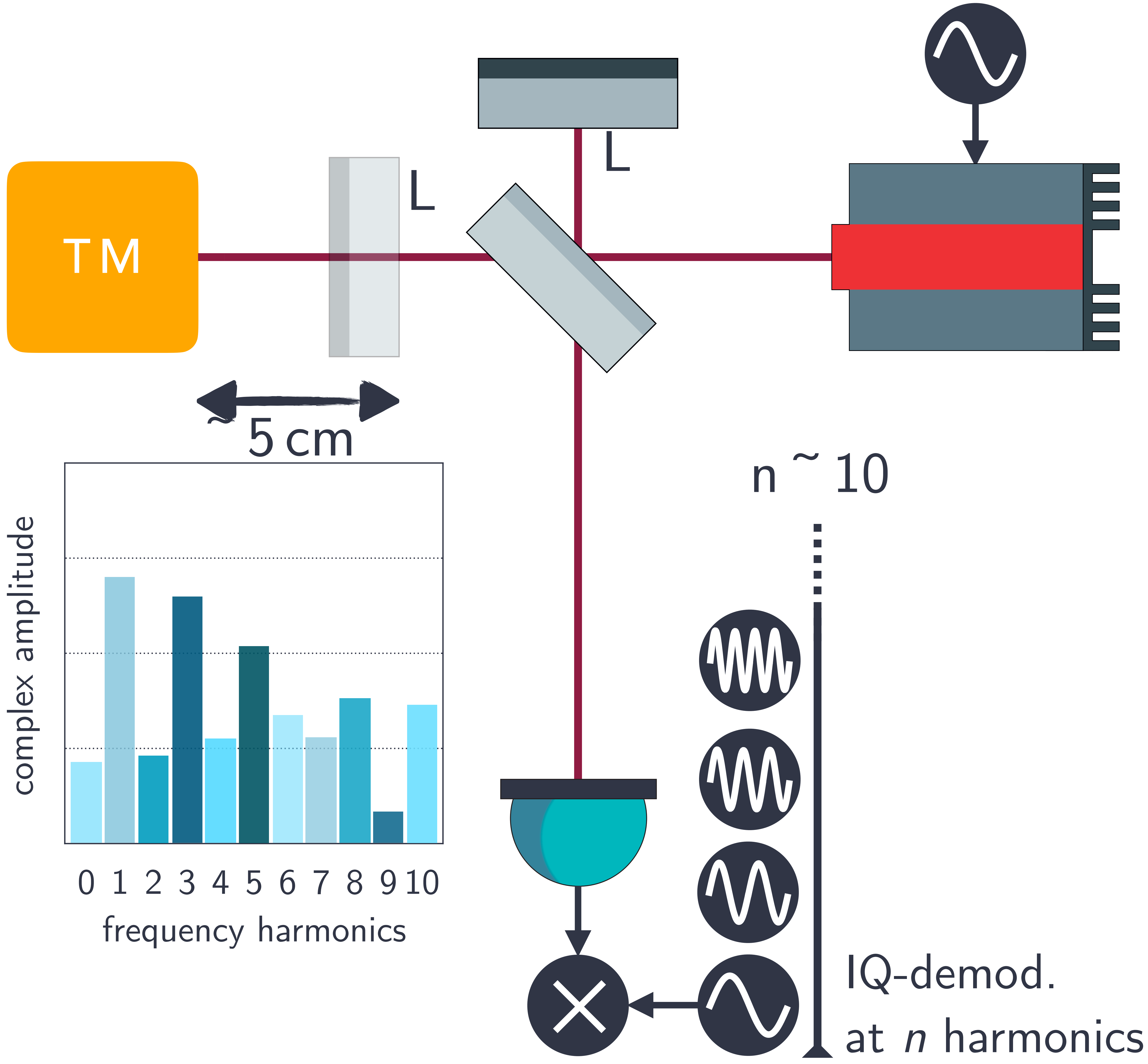
Isleif, K. S., Gerberding O.,…. (2016, May). *Comparing interferometry techniques for multi-degree of freedom test mass readout.* In *Journal of Physics: Conference Series* (Vol. 716, No. 1, p. 012008). IOP Publishing.

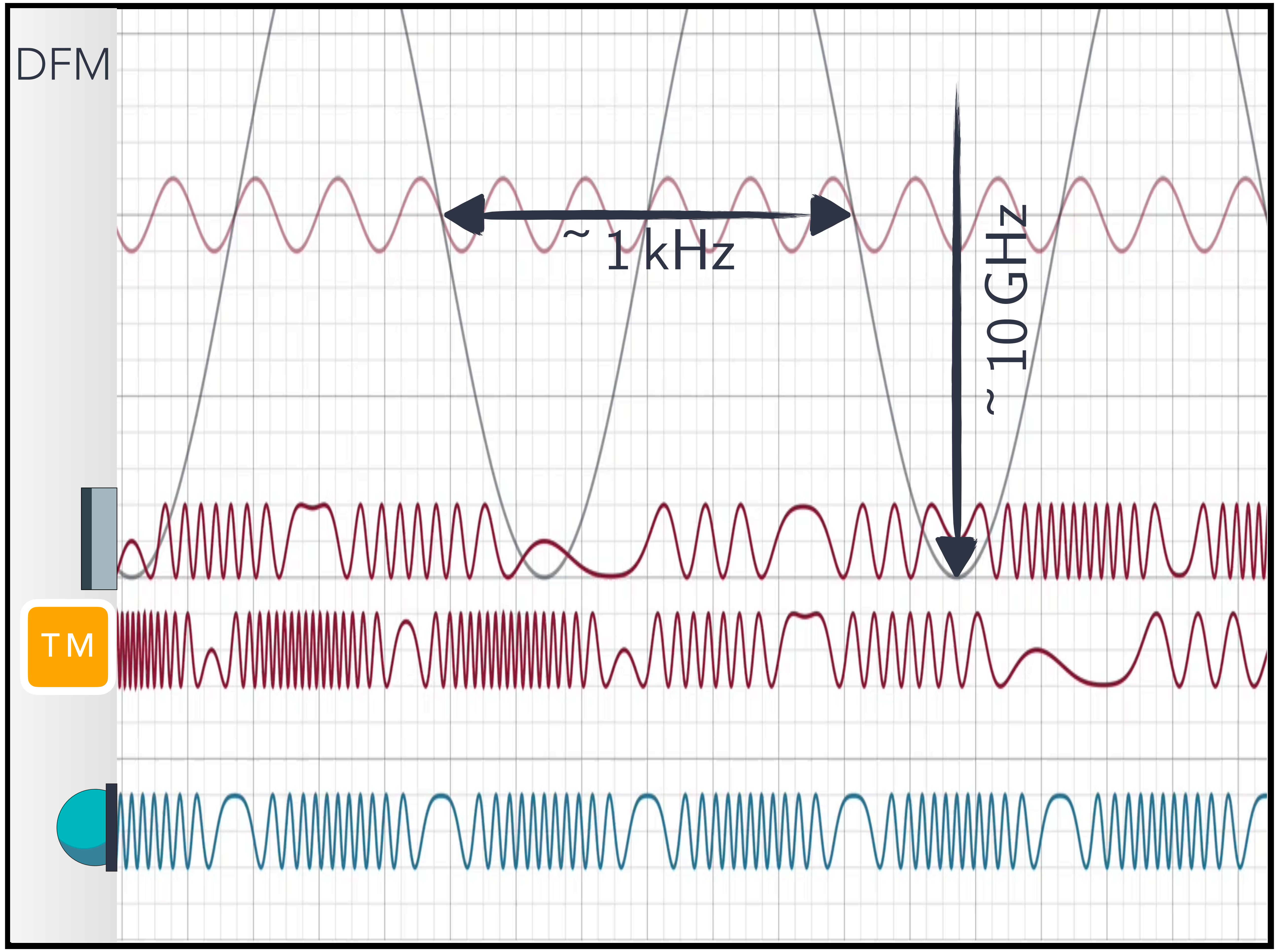
Deep Frequency Modulation interferometry





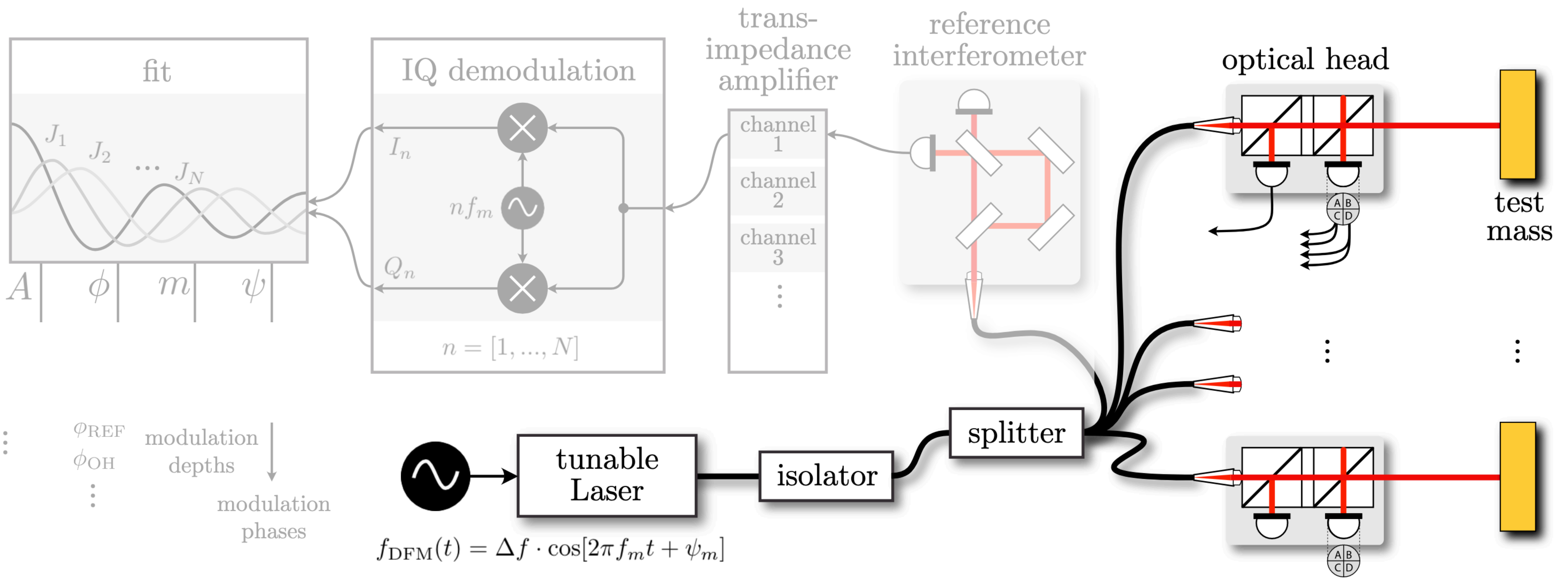
Deep Frequency Modulation interferometry



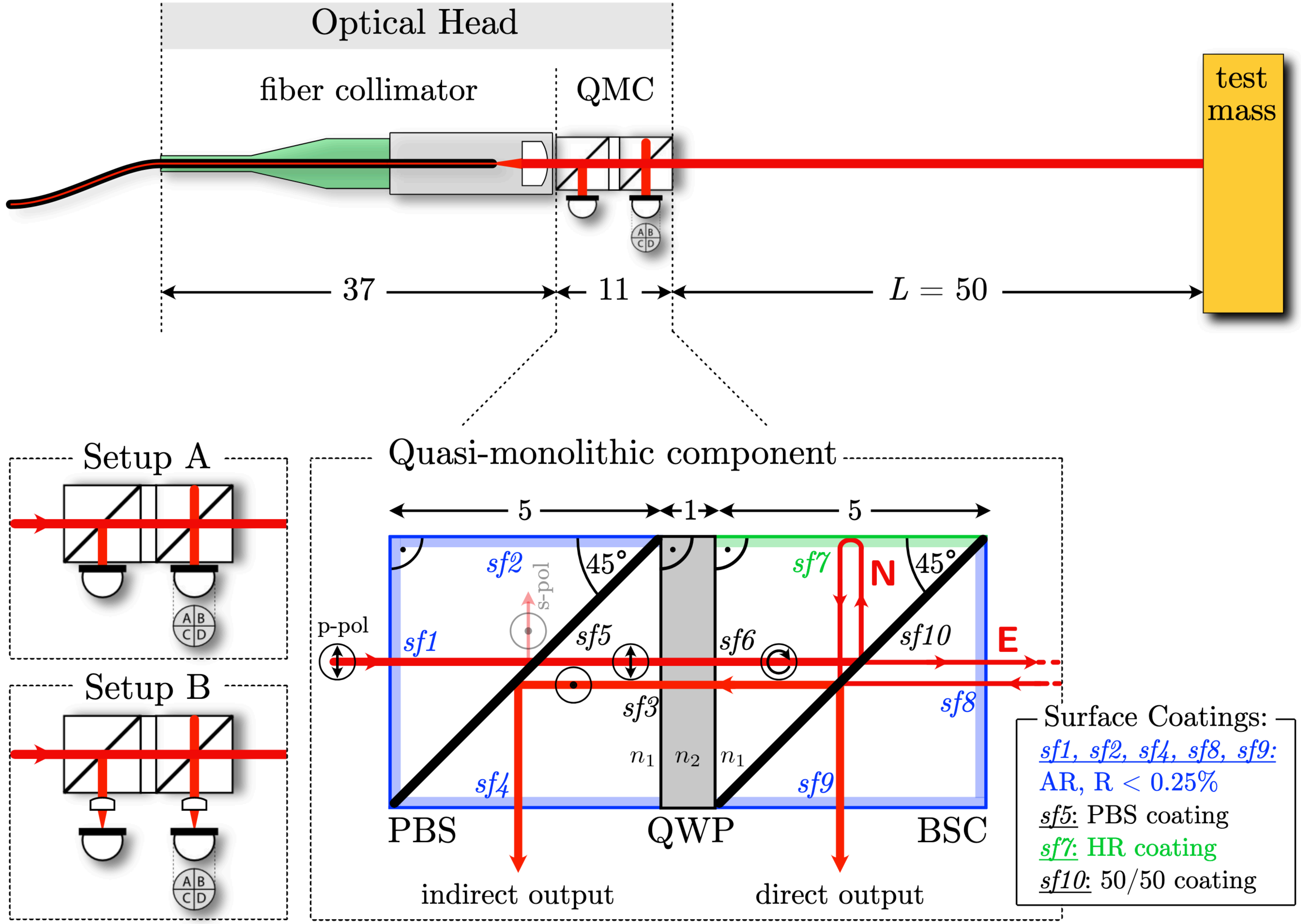


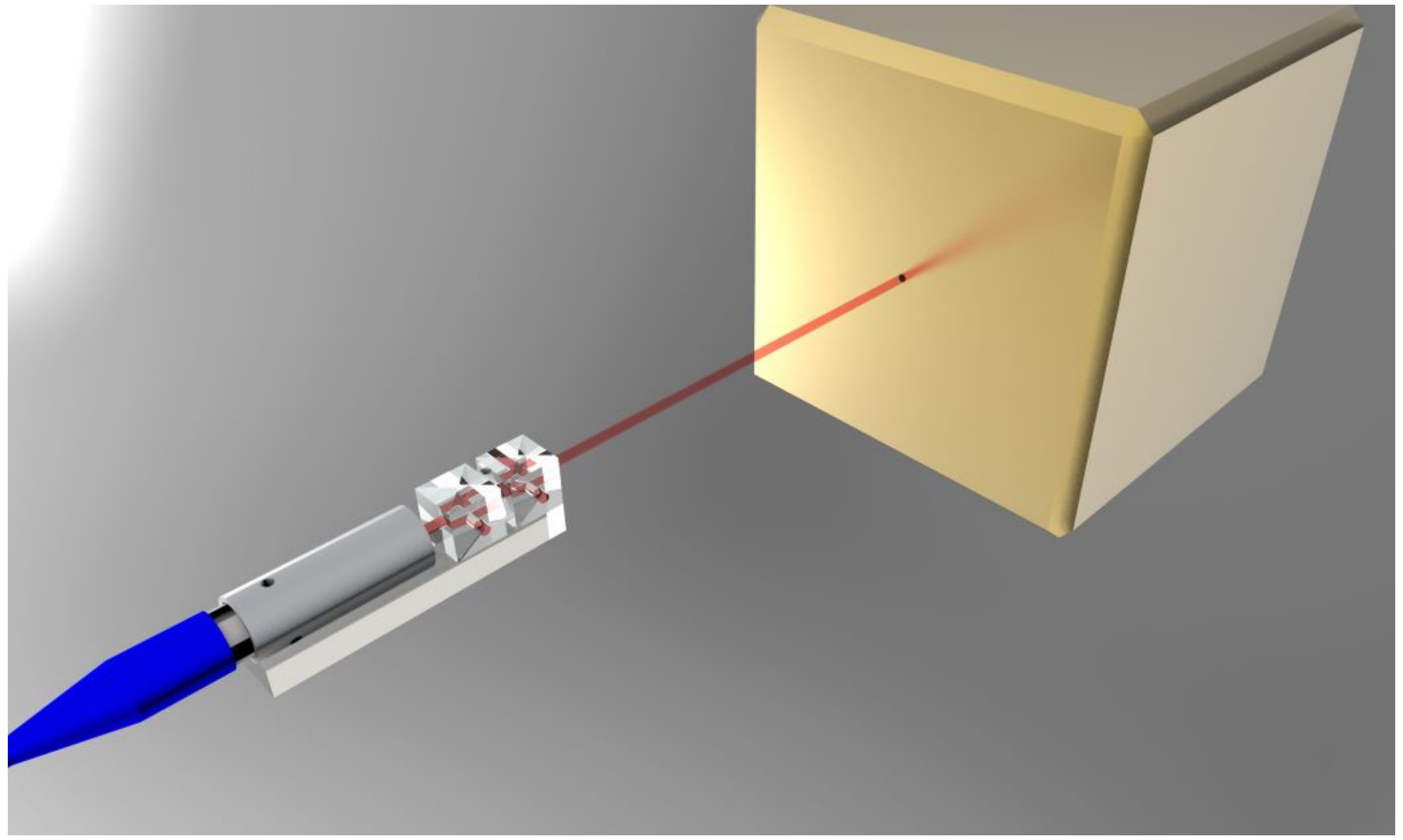
Ghost beam suppression in DFMI

$$P^{\pm} \propto \frac{E_S^2}{2} + \frac{E_L^2}{2} \pm E_L E_S \left[J_0(m)\cos(\phi) + 2\sum_{n=1}^{\infty} J_n(m)\cos\left(\phi + n\frac{\pi}{2}\right)\cos\left(n(\omega_m t + \psi)\right)\right] \quad (2)$$

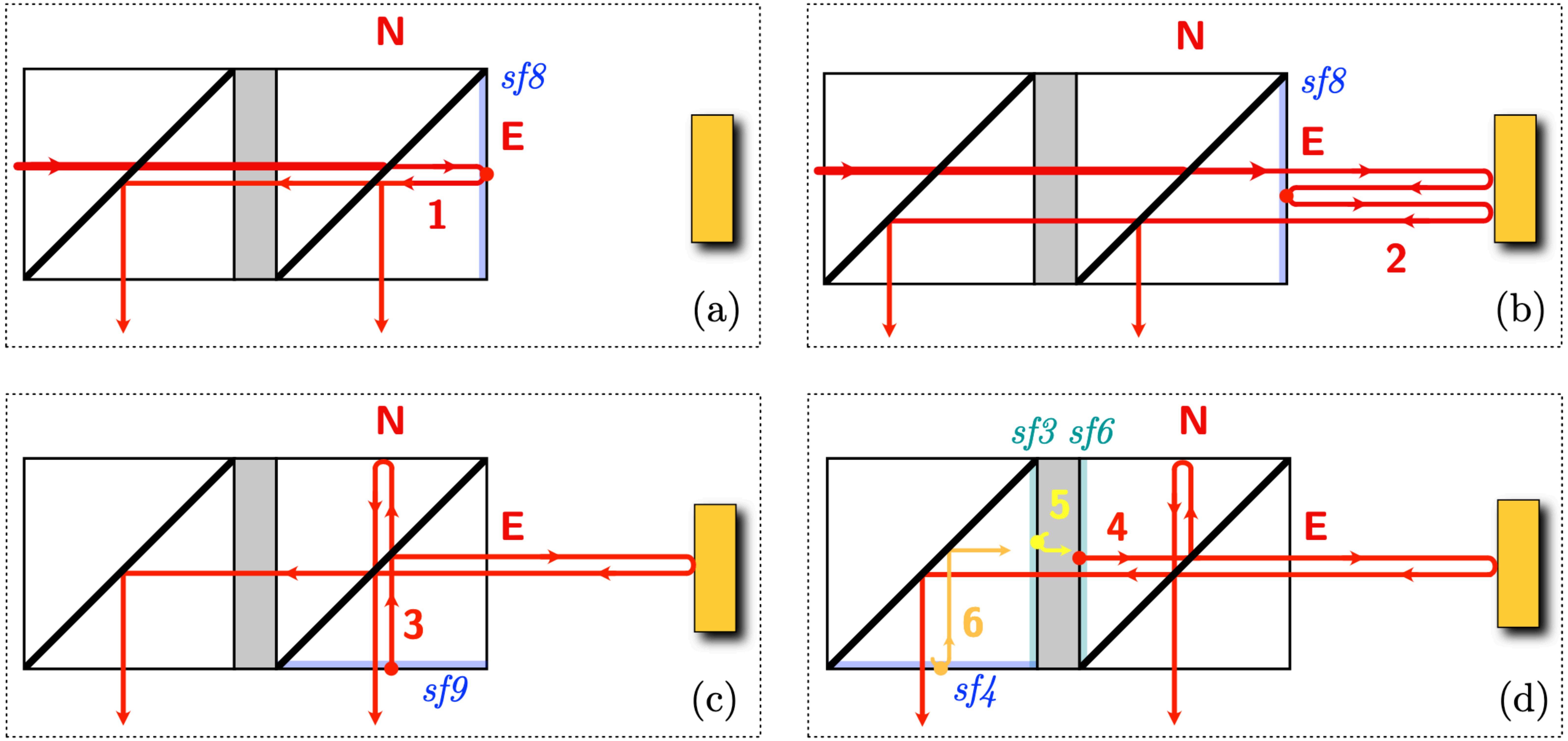


Ghost beam suppression in DFMI



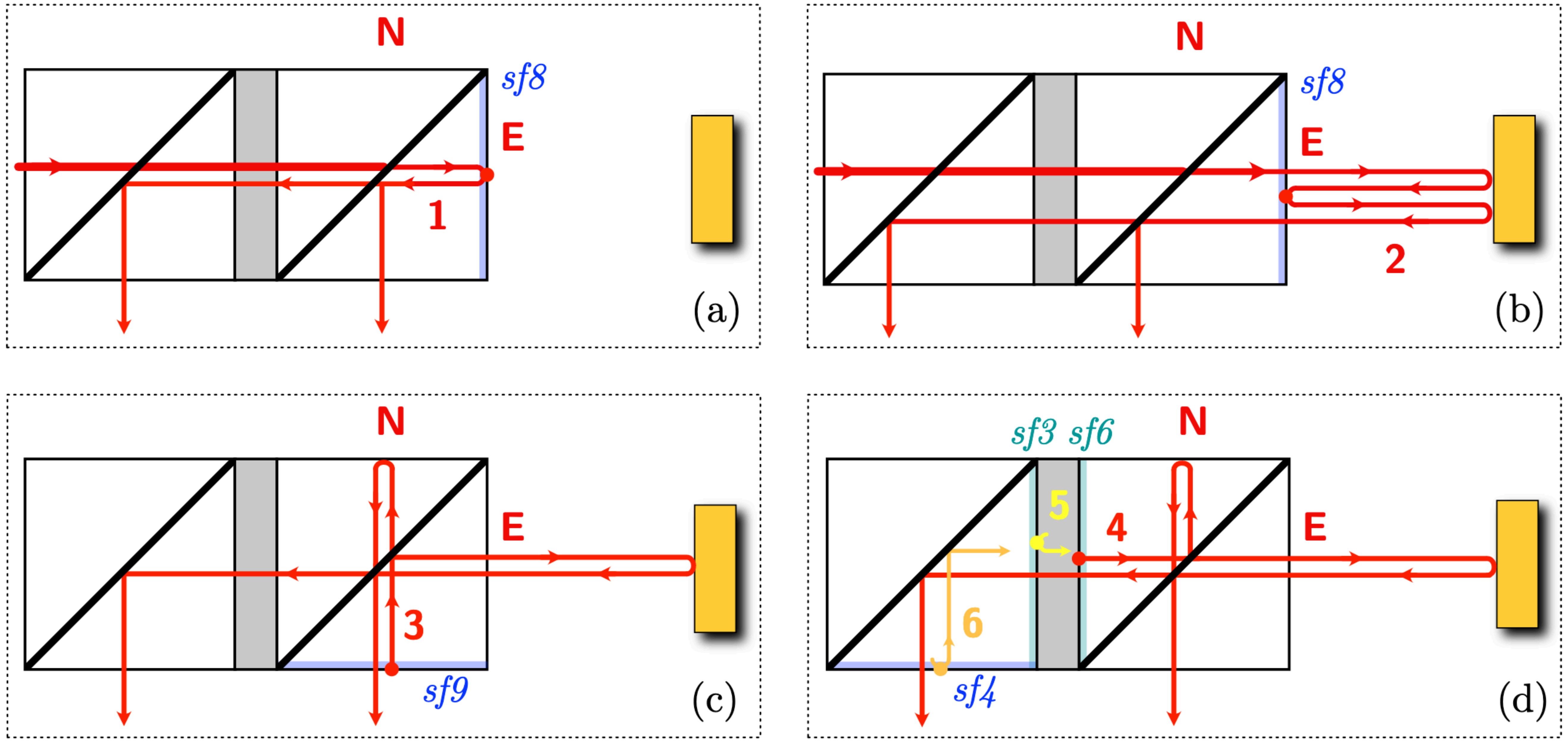


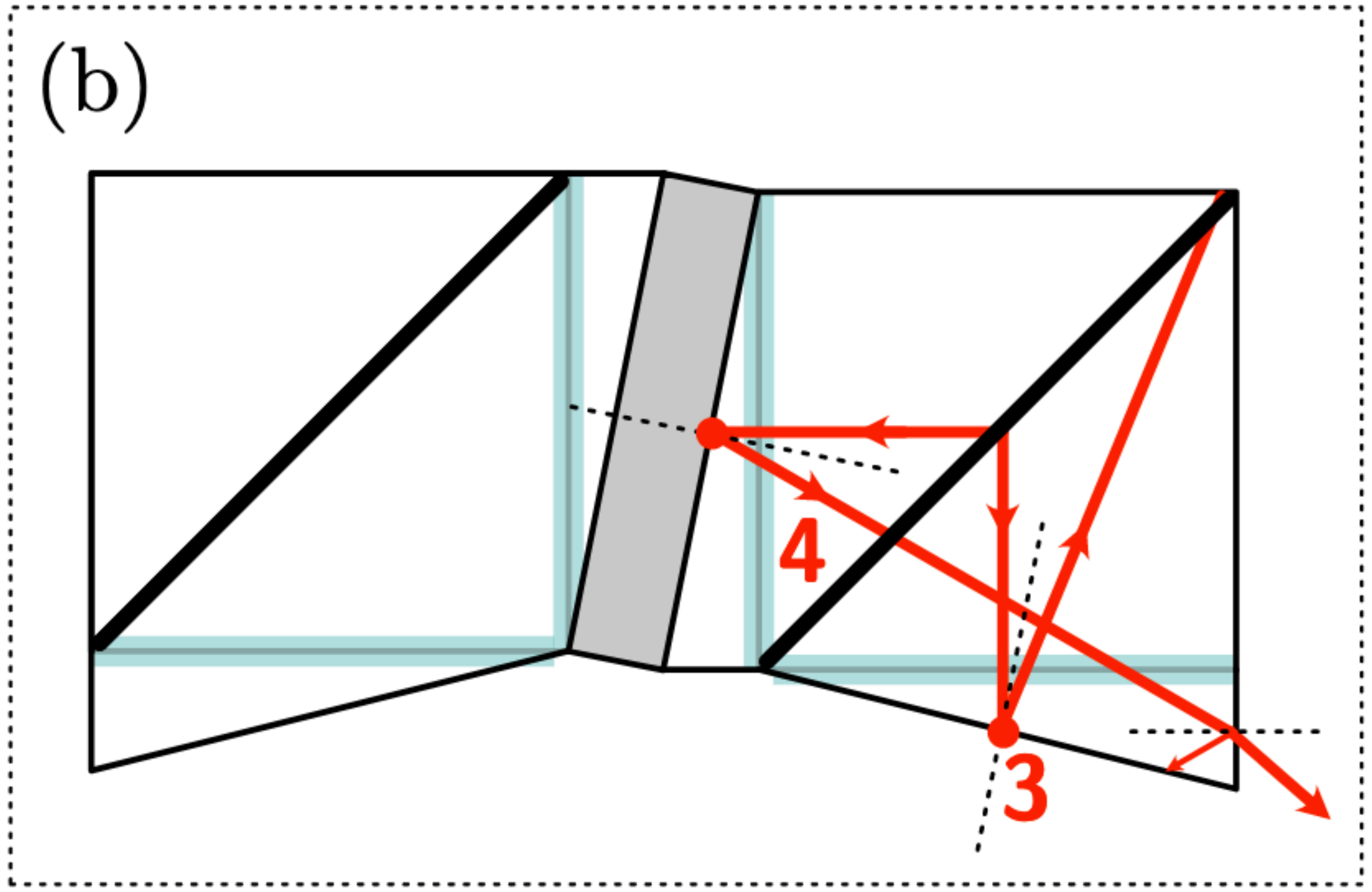
Ghost beams in DFMI



$$
\begin{aligned}
P^{\pm}_{\mathrm{N,E,1,2}} = & \pm E_{\mathrm{N}} E_{\mathrm{E}} \cos\left[\phi_{\mathrm{E}} + m_{\mathrm{E}} c(t)\right] \\
& \pm E_{\mathrm{N}} E_1 \cos\left[\phi_1 + m_1 c(t)\right] \\
& \pm E_{\mathrm{N}} E_2 \cos\left[2\phi_{\mathrm{L}} + \phi_1 + (2m_{\mathrm{L}} + m_1) c(t)\right] \\
& + E_{\mathrm{E}} E_1 \cos\left[\phi_{\mathrm{L}} + m_{\mathrm{L}} c(t)\right] \\
& + E_{\mathrm{E}} E_2 \cos\left[\phi_{\mathrm{L}} + m_{\mathrm{L}} c(t)\right] \\
& + E_1 E_2 \cos\left[2\phi_{\mathrm{L}} + 2m_{\mathrm{L}} c(t)\right] \\
= & \pm 1 \cos\left[\phi_{\mathrm{E}} + m_{\mathrm{E}} c(t)\right] \\
& \pm 0.05 \cos\left[\phi_1 + m_1 c(t)\right] \\
& \pm 0.05 \cos\left[2\phi_{\mathrm{E}} - \phi_1 + (2m_{\mathrm{L}} + m_1) c(t)\right] \\
& + 0.05 \cos\left[\phi_{\mathrm{E}} - \phi_1 + m_{\mathrm{L}} c(t)\right] \\
& + 0.05 \cos\left[\phi_{\mathrm{E}} - \phi_1 + m_{\mathrm{L}} c(t)\right] \\
& + 0.0025 \cos\left[2\phi_{\mathrm{E}} - 2\phi_1 + 2m_{\mathrm{L}} c(t)\right]
\end{aligned}
$$

Ghost beam suppression in DFMI





● origin of ghost beam reflectance

Ghost beam suppression in DFMI

sensors

MDPI

Article

Ghost Beam Suppression in Deep Frequency Modulation Interferometry for Compact On-Axis Optical Heads

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