QI

LIDA:
Laser-**I**nterferometric **D**etector for **A**xions

Alex Gill (speaker),
Joscha Heinze, Artemiy Dmitriev, Jiri Smetana, Tiangliang Yan, Vincent Boyer, and Denis Martynov

EPS-HEP Hamburg
24th August 2023

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UKRI Science and Technology Facilities Council
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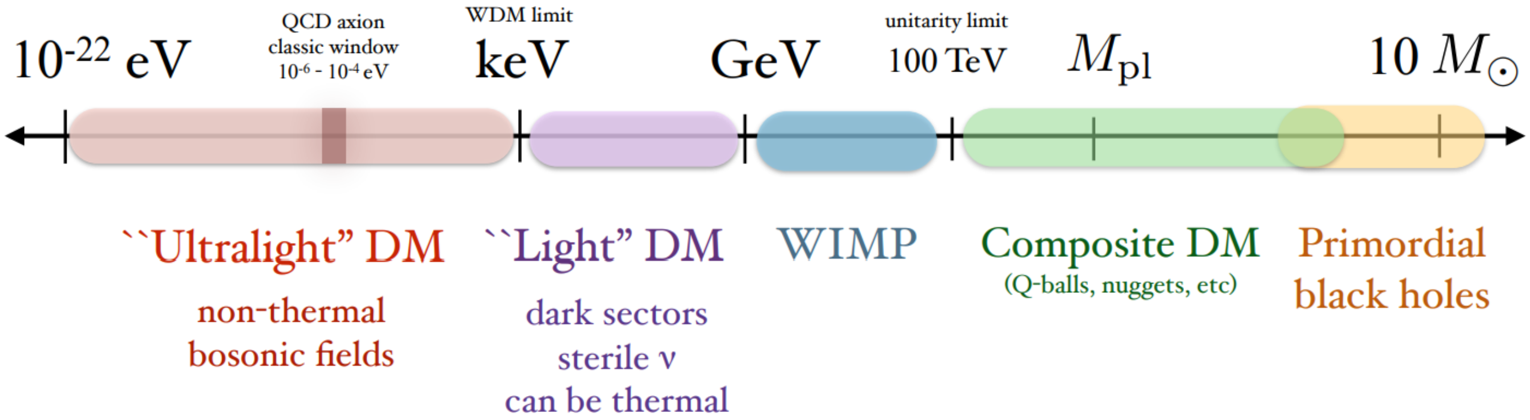
Mass range



T. Lin, arXiv:1904.07915 (2019)

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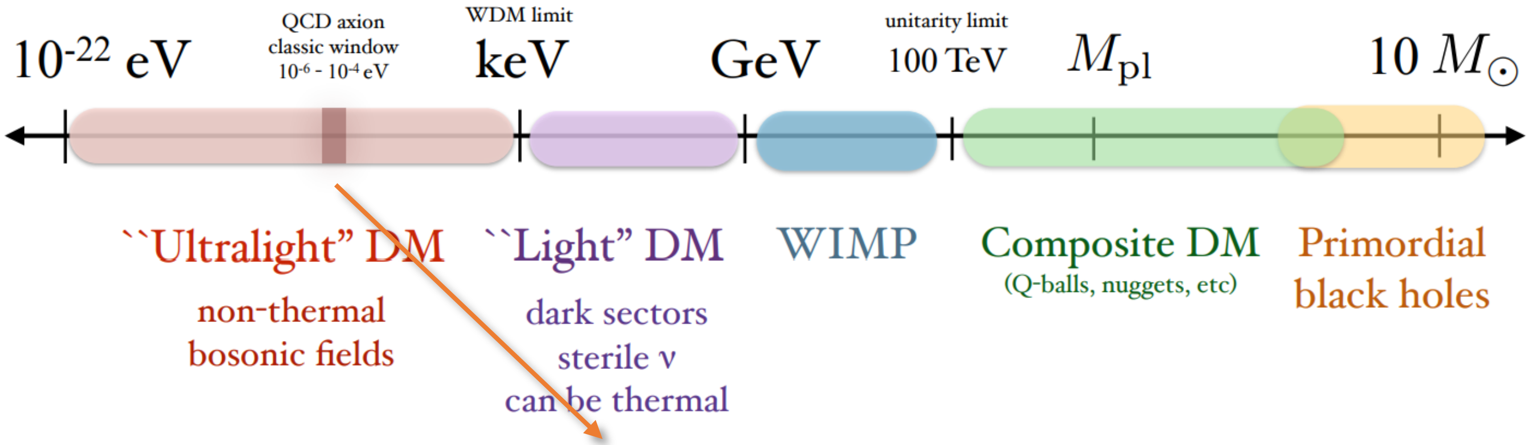

Wave-like: $a(t) = a_0 \sin(\Omega_a t)$

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Motivation

- Directly detect dark matter candidates: axions and axion-like particles.

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$$\mathcal{L} = \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Lagrangian $\mathcal{L}$
a: axion field
$g_{a\gamma}$: coupling coefficient
F: electromagnetic field-strength tensor

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$\Longrightarrow$

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wave equation for electric field $\boldsymbol{E}$

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phase difference $\Delta\phi$ between left- and right-handed circular polarisation

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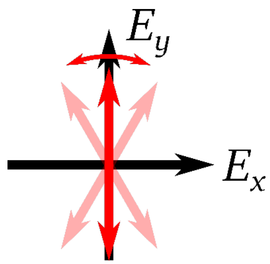
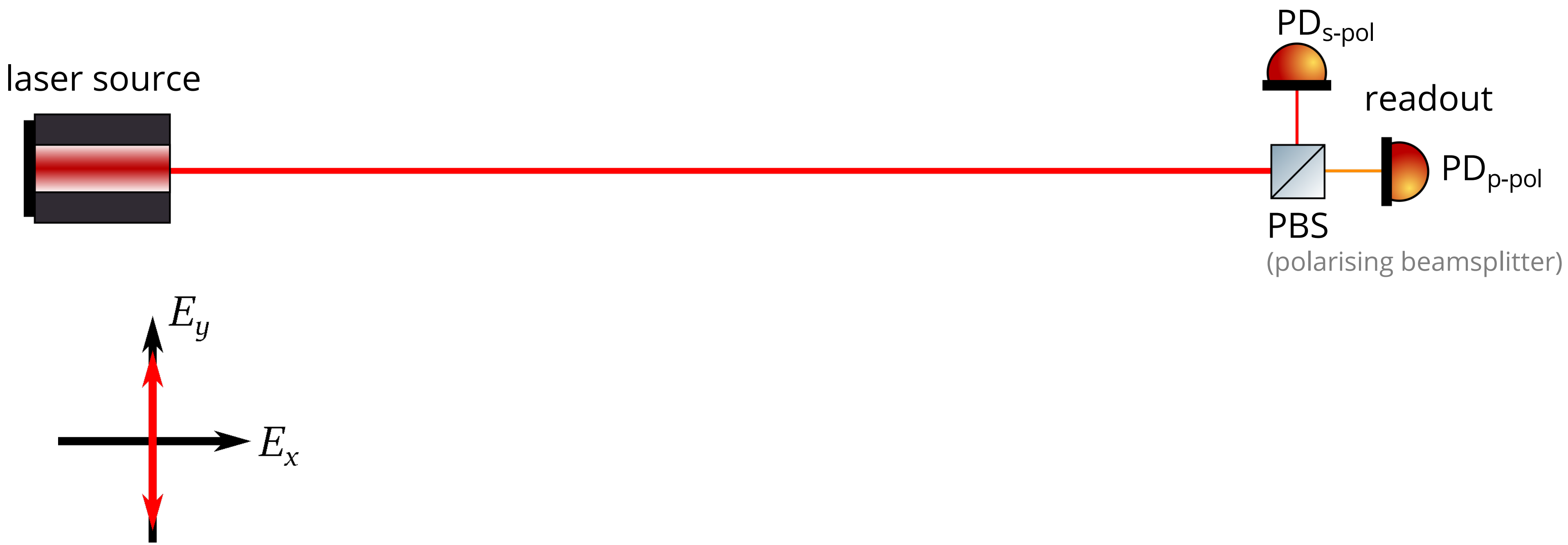
Observable effect:
Rotation of linear polarisation!

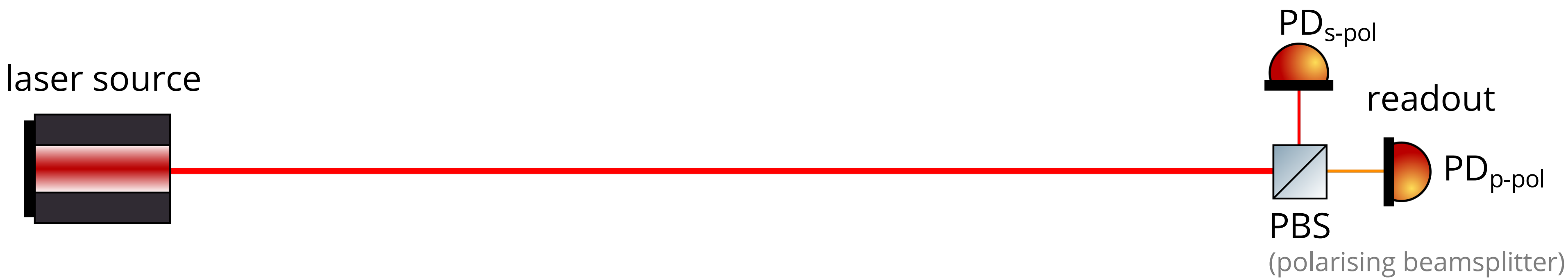


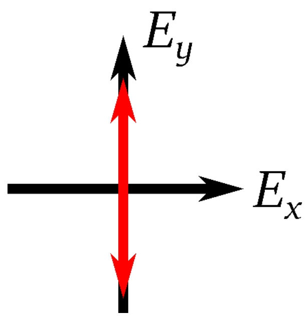
Signal generation



Input: linear s-polarisation.

Signal generation





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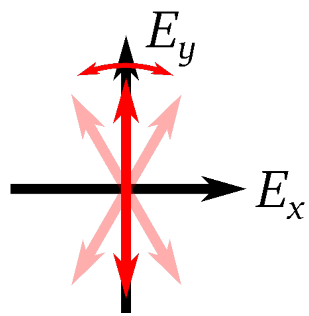
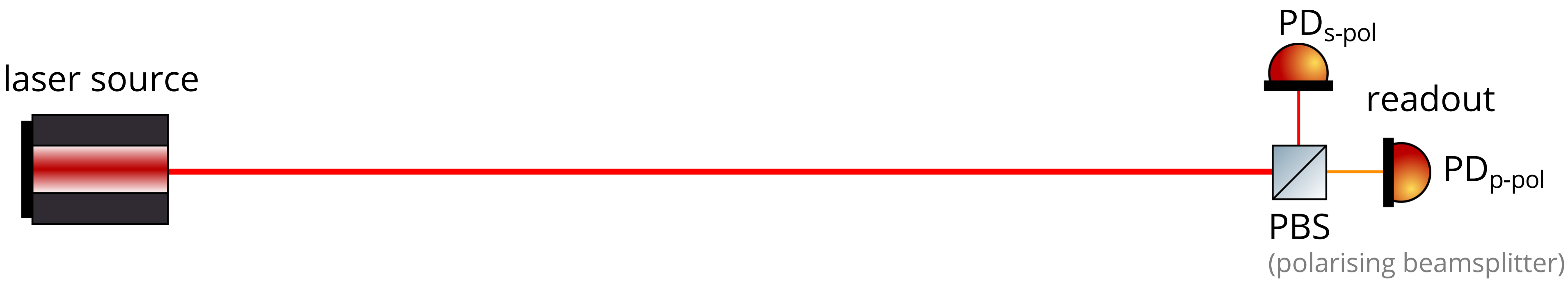
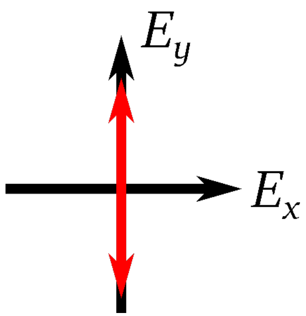


Effect: polarisation rotation.

Signal generation





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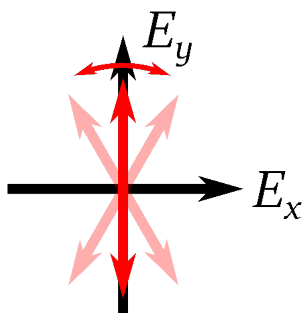

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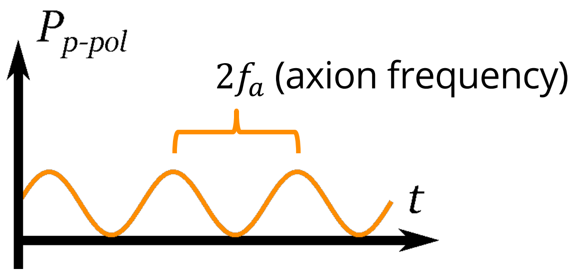
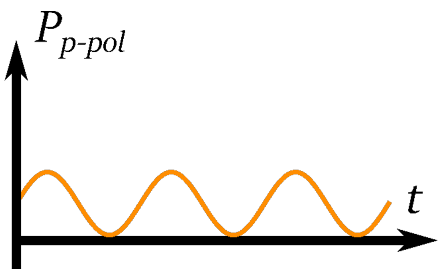
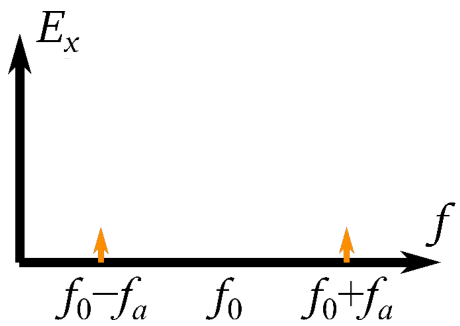


Output: signal in p-polarisation.

Signal generation



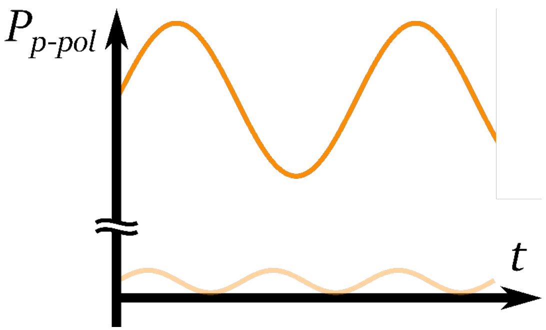
p-pol power
at readout



sideband picture
for p-pol readout

Signal enhancement

generate p-pol carrier
from s-pol pump field,
enhance signal via beat
of sidebands and carrier



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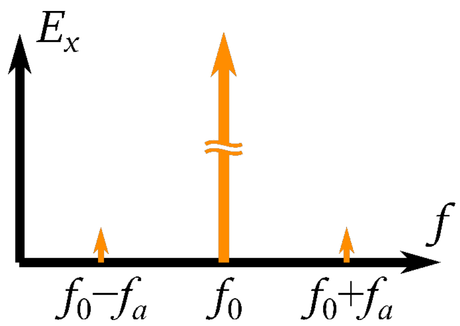

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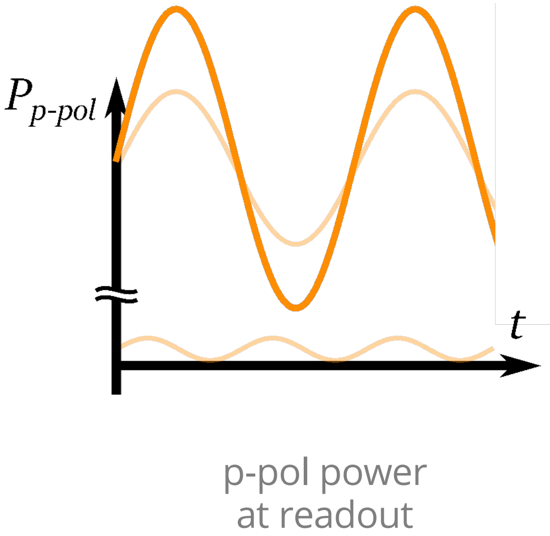
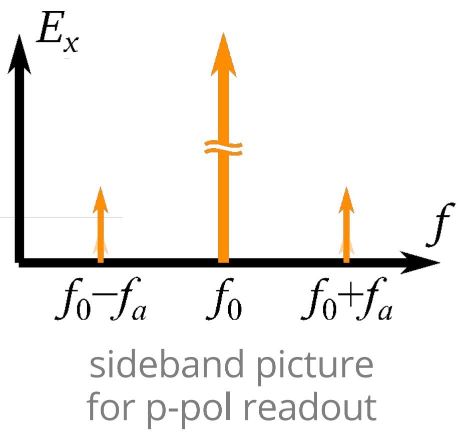
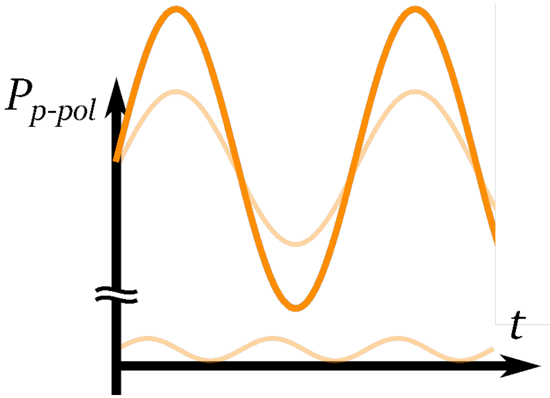


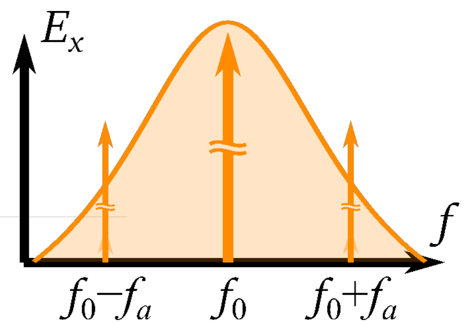


S-pol carrier is kept on resonance inside cavity.
⟹ Pump field buildup!
⟹ Larger sidebands!

Co-resonance



p-pol power
at readout



sideband picture
for p-pol readout

S-pol carrier is kept on resonance inside cavity.
⟹ Pump field buildup!
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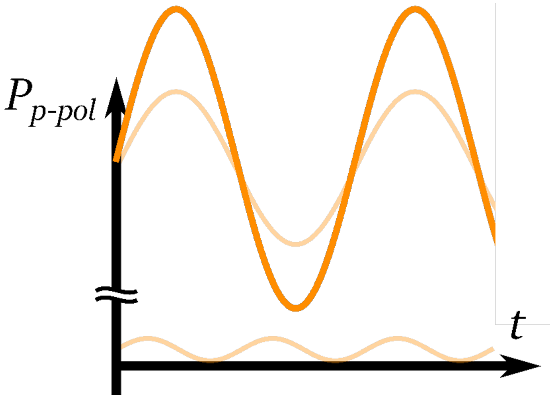
P-pol signal sidebands are co-resonant with s-pol pump carrier.
⟹ Sideband buildup!

Detuning



p-pol power
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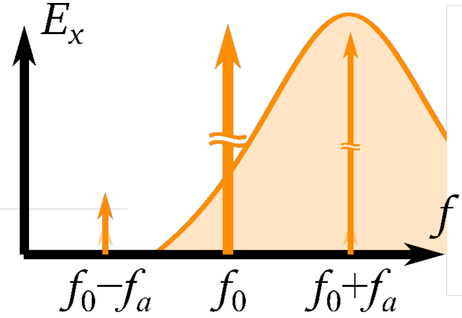


sideband picture
for p-pol readout

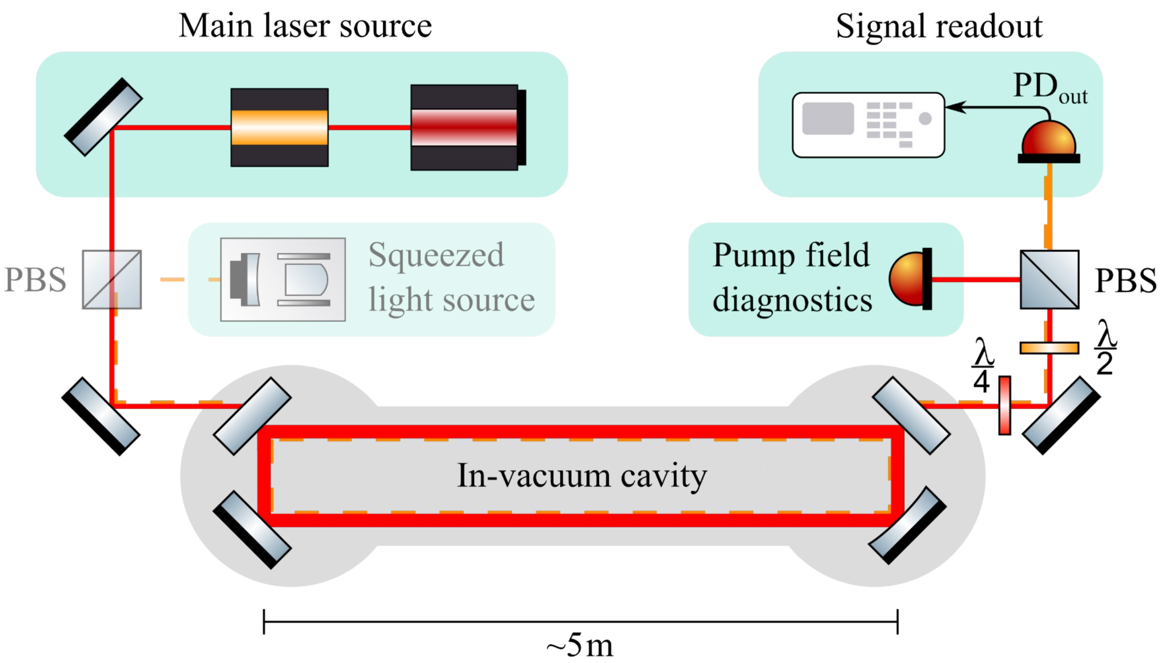
P-pol resonance of signal field is detuned from s-pol resonance of pump field.

$\Longrightarrow$ Asymmetric sideband buildup!

$\Longrightarrow$ Smaller low-frequency sensitivity!

$\Longrightarrow$ Sensitivity peak at a higher signal frequency!

Detector design



<u>Tabletop demonstration:</u>

– **200 kW** intra-cavity power to enhance signal
– **5 m** baseline to increase interaction time
– vacuum system
– **6 months** integration time for larger signal-to-noise ratio
– **squeezed light** to reduce quantum noise by up to 10 dB

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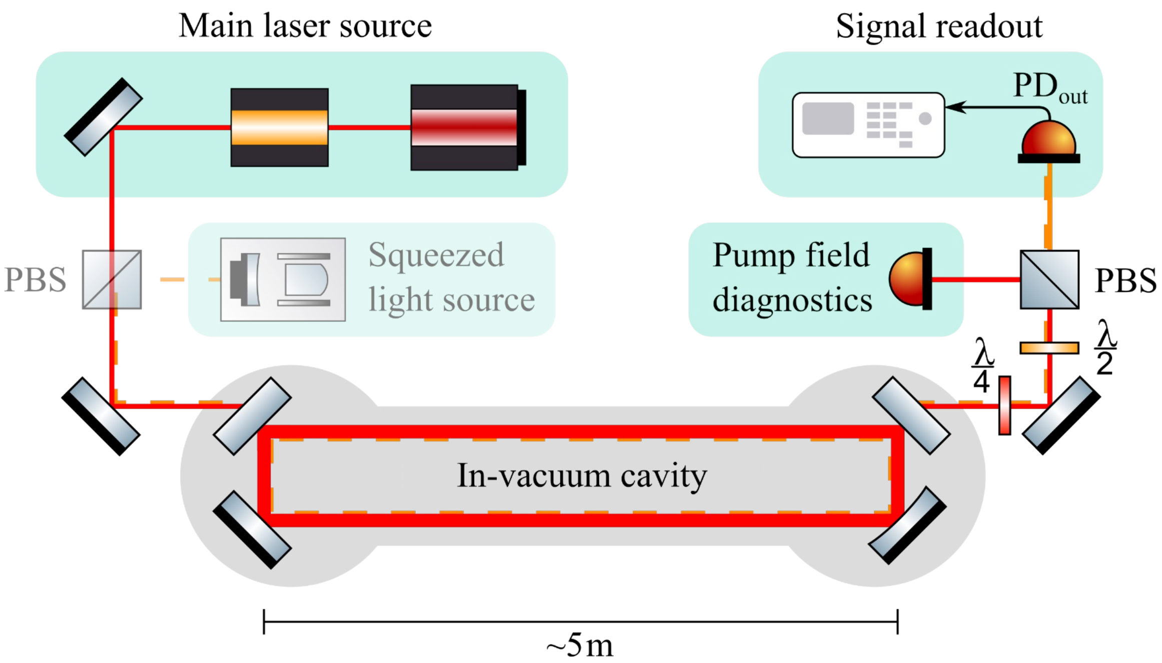

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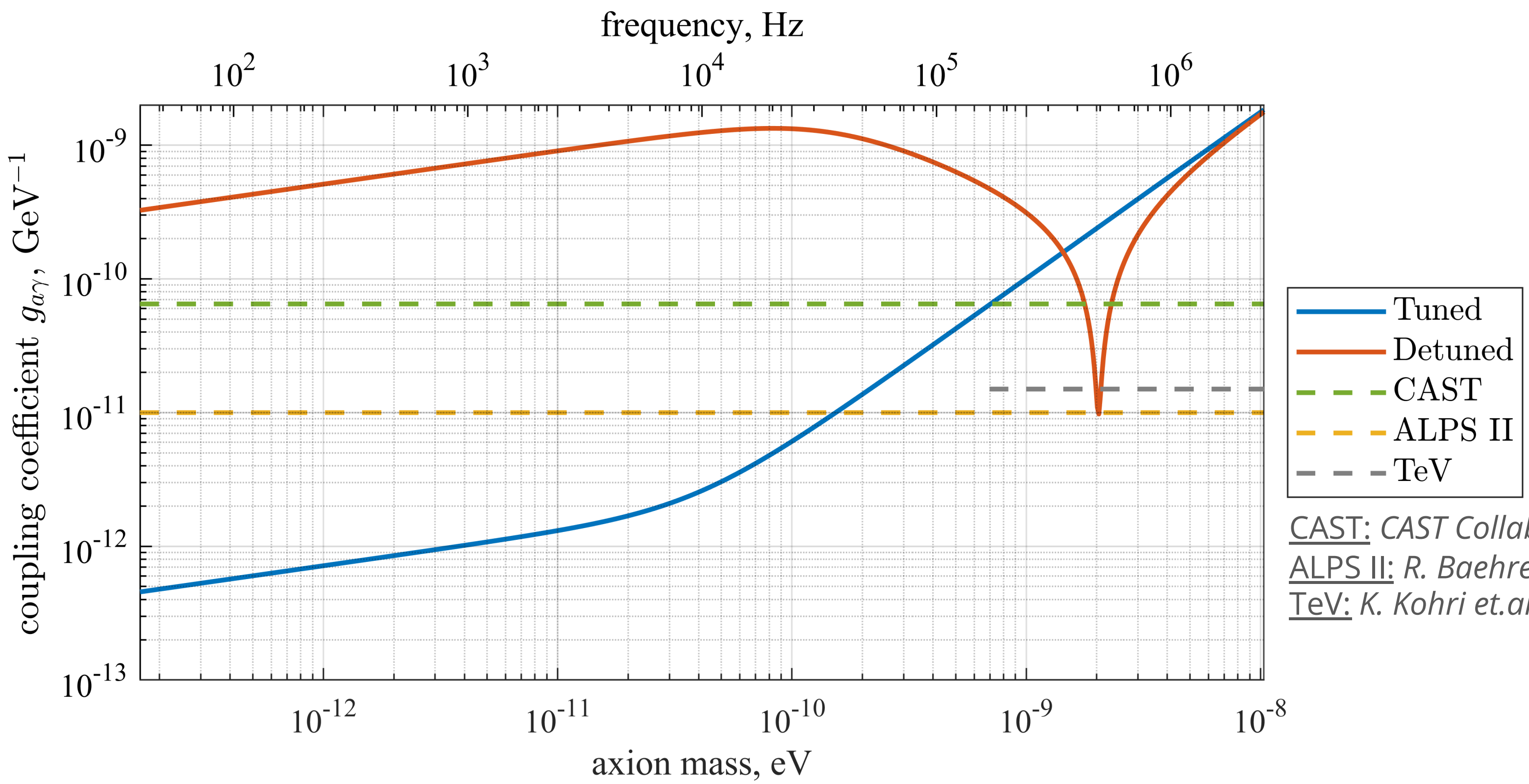
Large-scale detector:

- 1 MW intra-cavity power
- 4 km baseline
- use existing facilities of gravitational-wave detectors

Shot-noise limited design sensitivity

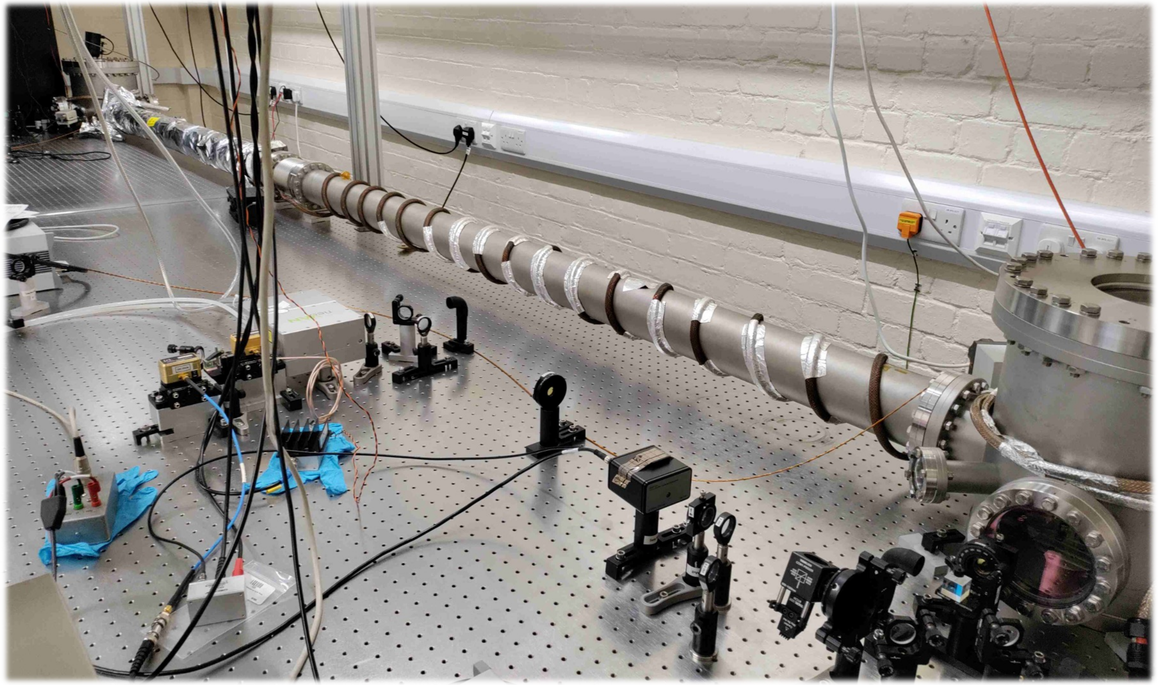


CAST: *CAST Collab., Nature Phys.* ***13****, 2017*
ALPS II: *R. Baehre et.al., JINST* ***8****, 2013*
TeV: *K. Kohri et.al., Phys. Rev. D* ***96****, 2017*

Status

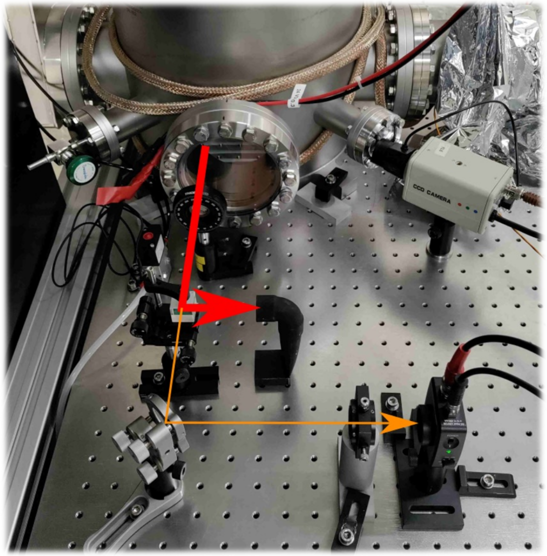
QI

✅ Vacuum system is set up!

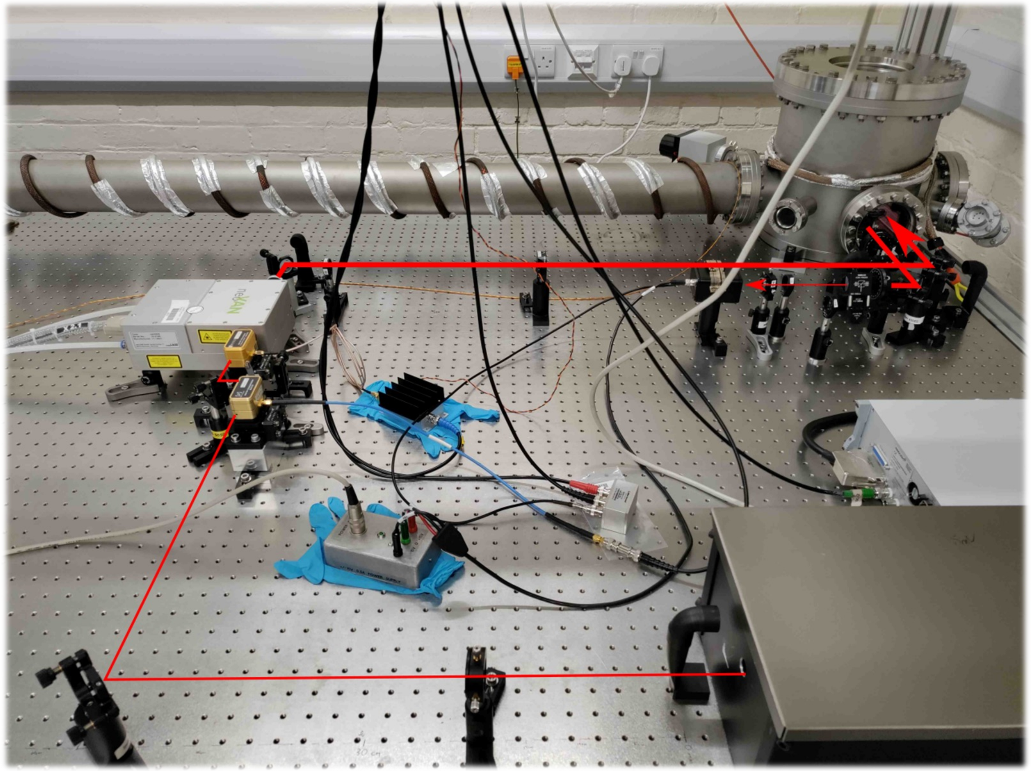


Status

- Vacuum system is set up!
- Basic optical setup is done!



Readout



Input

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- Vacuum system is set up!
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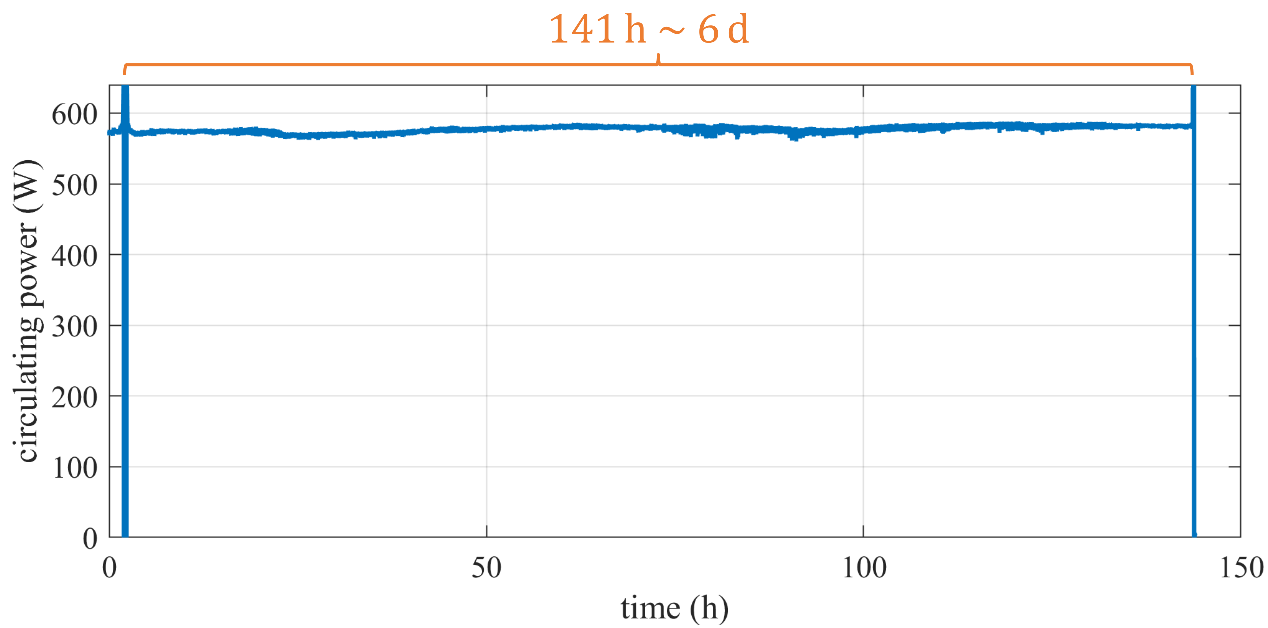
- Stable lock with injected light in P- and S-polarisation over days!



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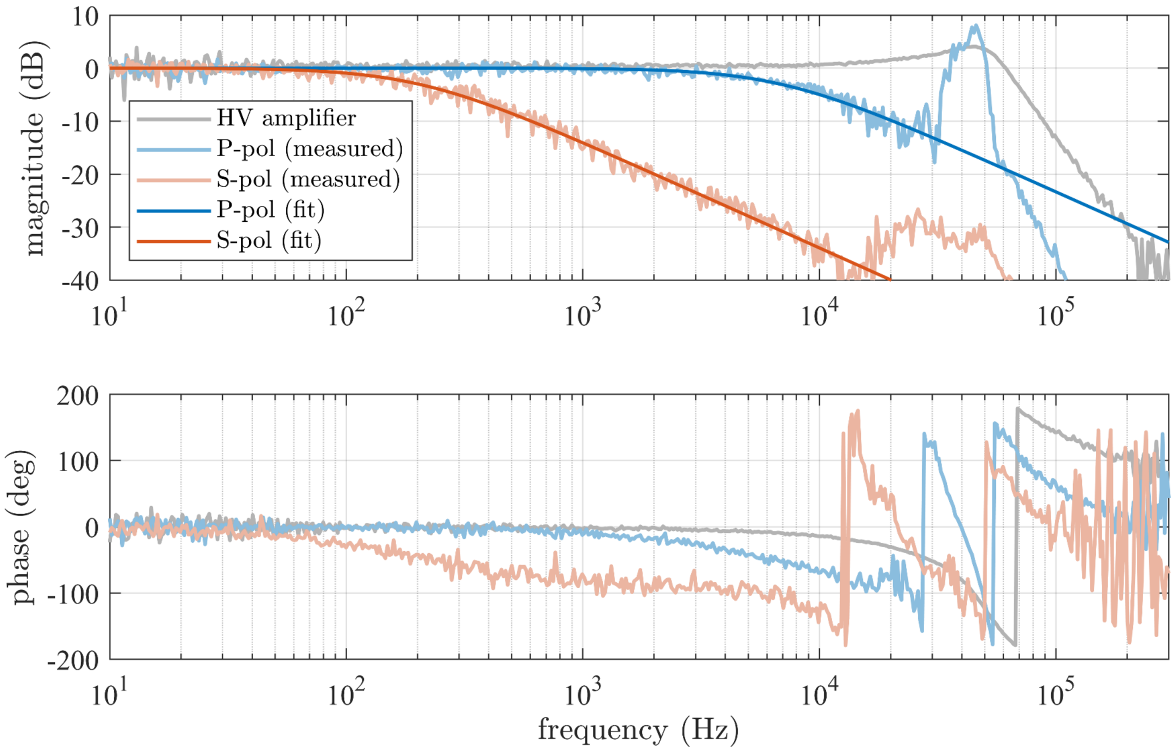
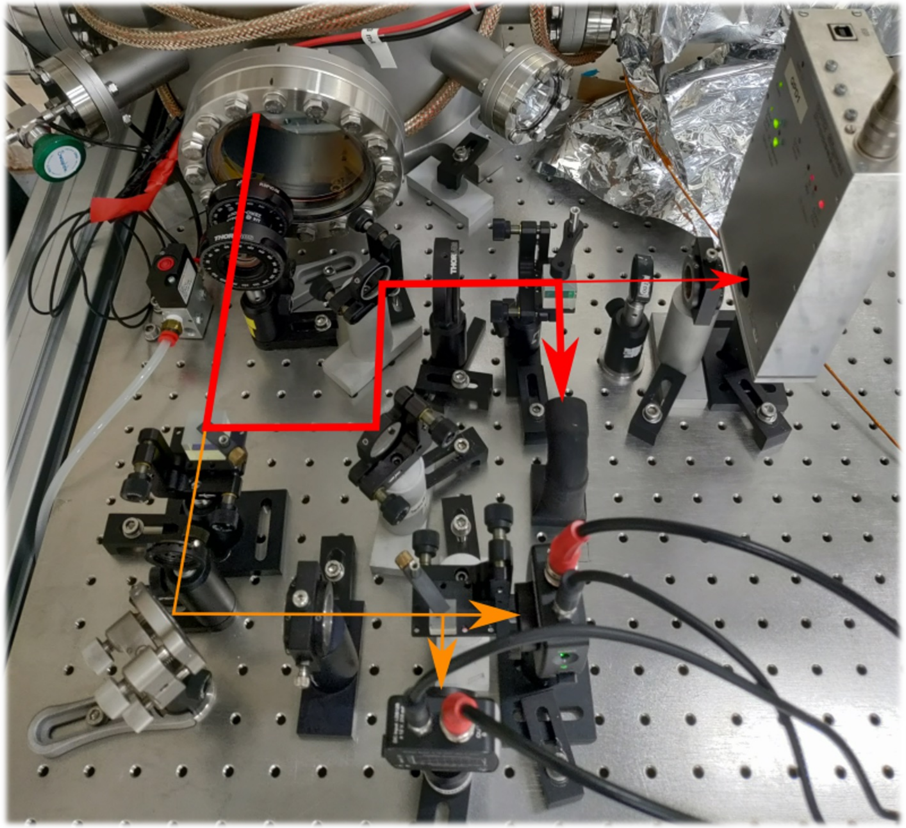
Status

- Vacuum system is set up!
- Basic optical setup is done!
- Stable lock with injected light in P- and S-polarisation over days!
- Default detuning: **~476 kHz** / **2 neV**
  P-pol. finesse: **2220**
  S-pol. finesse: **74220**
  Roundtrip loss: **51 ppm**



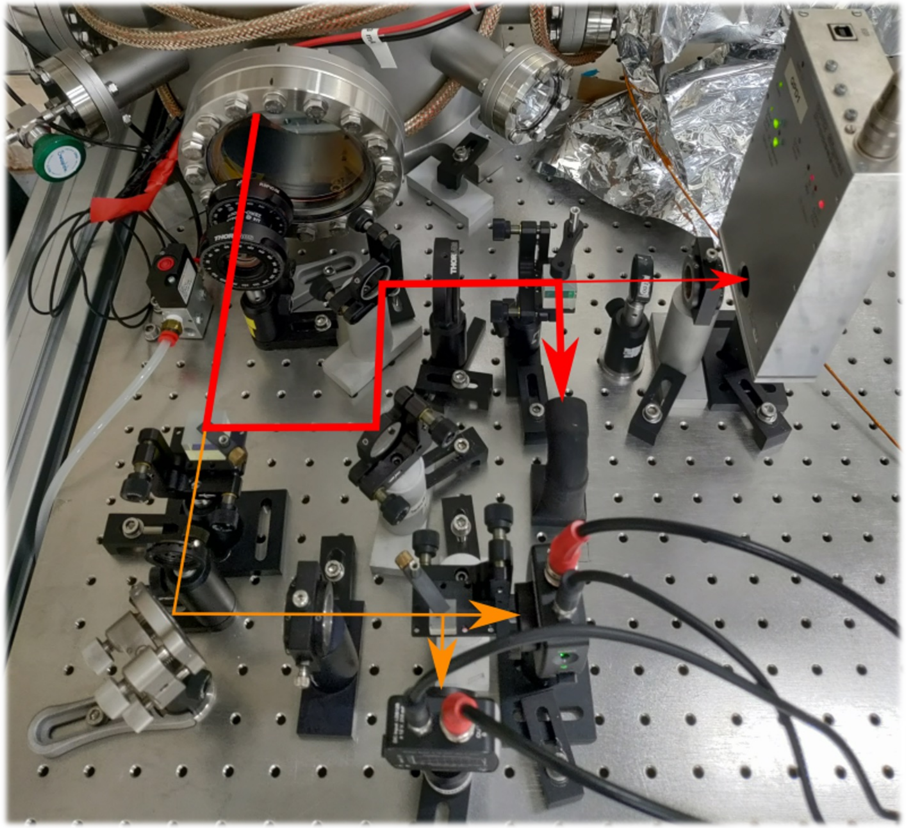
Altered readout

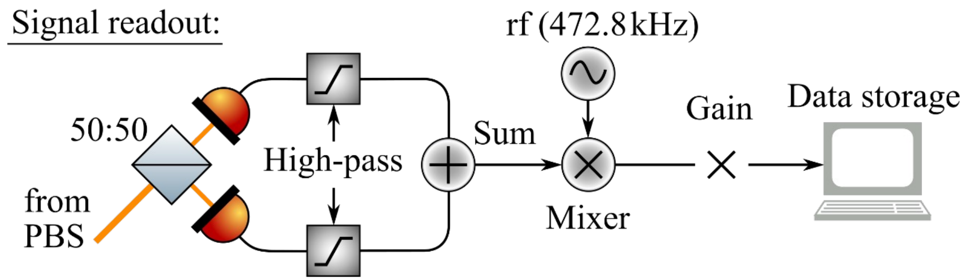


tracking the
circulating power

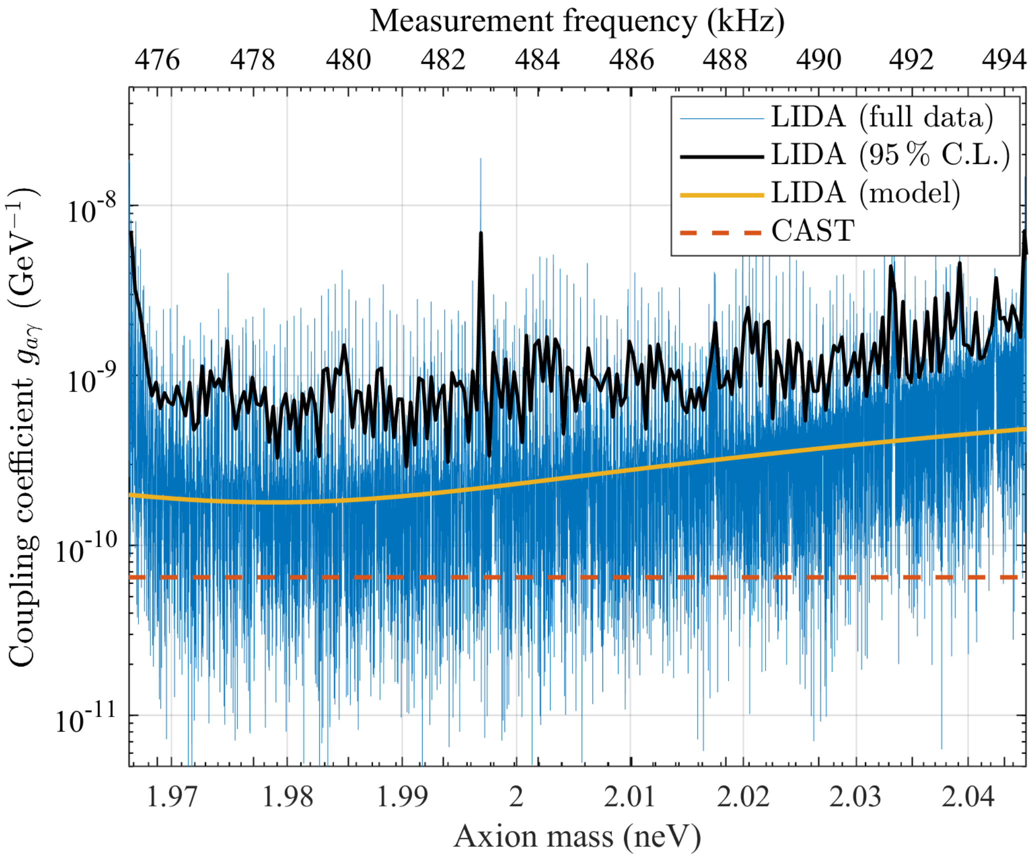
readout signal

Altered readout





Current sensitivity



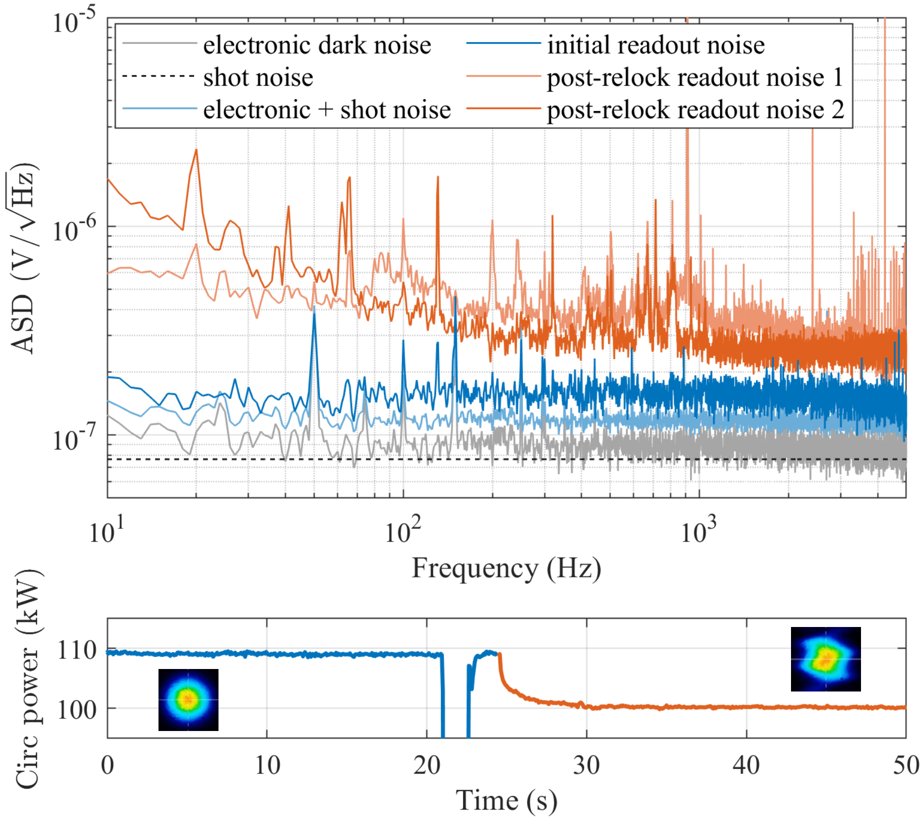
85 hours measurement time

Sensitivity of 2×10^{-10} GeV^{-1} at 1.989 neV at the 95% confidence level

Approaching CAST sensitivity

Squeezing → improved sensitivity

High-power effects



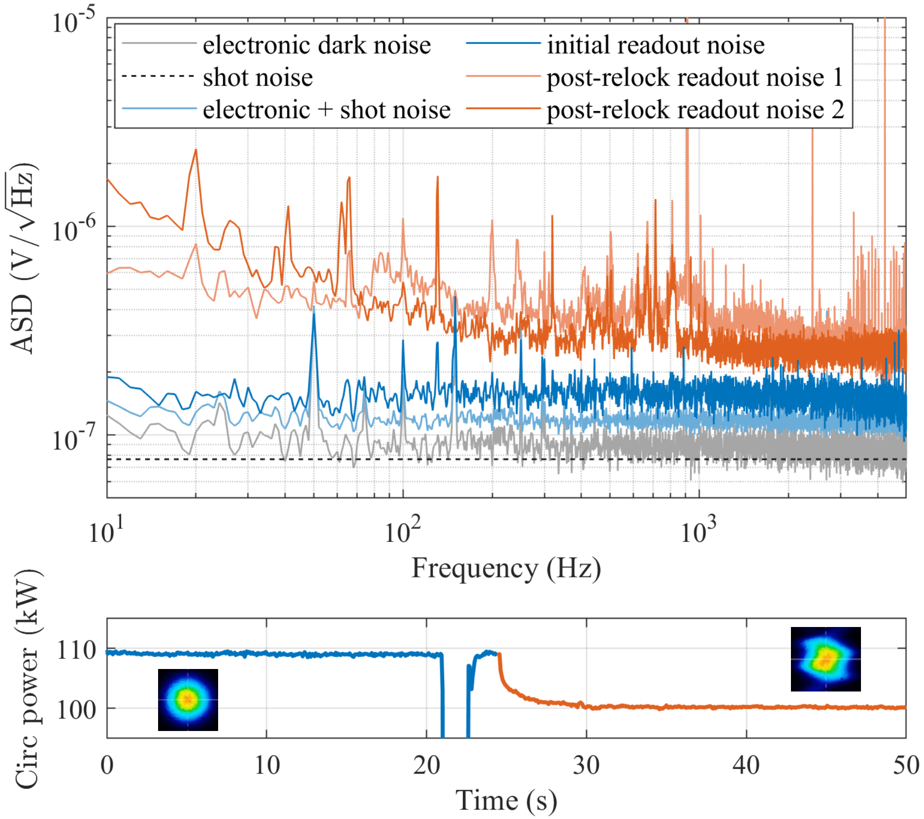
$124\ \mathrm{kW} \leftrightarrow 4.7\ \mathrm{MW/cm^2}$

<u>At high circulating power:</u>

A few seconds after lock, the cavity often changes "state" correlating with

- a reduction in circulating power,
- a distortion of the transmitted field,
- higher readout noise.

High-power effects



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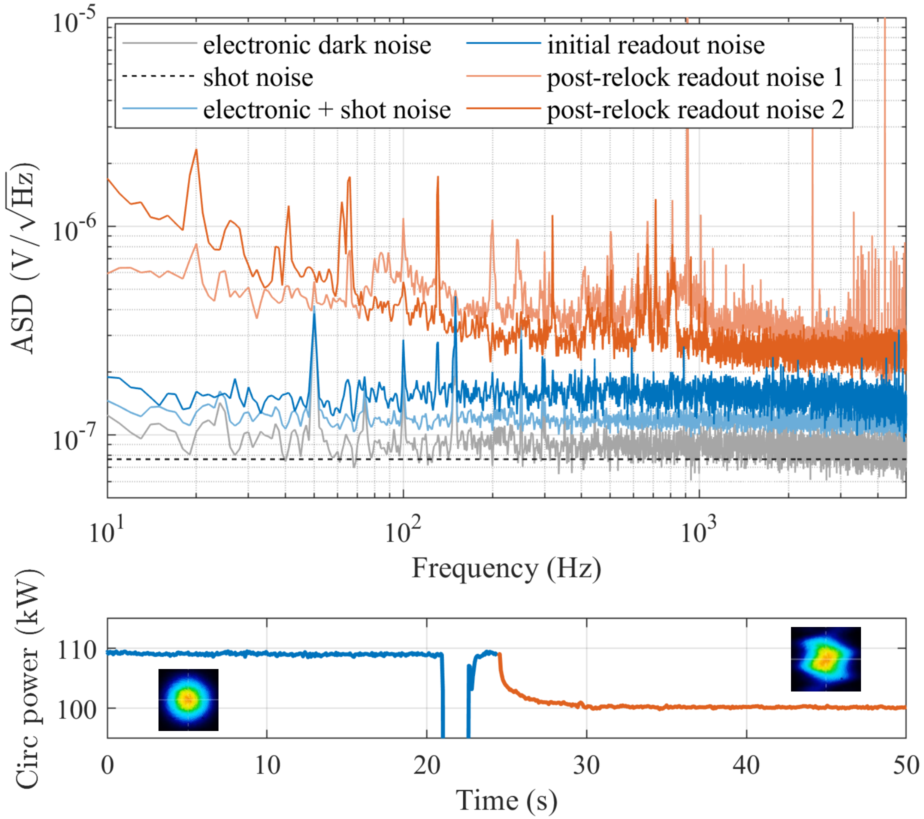

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<u>At high circulating power:</u>

If disturbed, the cavity often changes “state” correlating with

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Next steps

QI

Before next opening of vacuum tank. →

- **Optimise sensitivity** in current configuration!
  → Add input mode cleaner to filter out technical laser noise.
  → Add a squeezed light source.

- **Understand** (and possibly prevent) thermal effects, readout noise fluctuations and modes in the output field!

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After next opening of vacuum tank.

- Reduce **the detuning** of the P- and S-cavity eigenmodes!
- Optimise plane **cavity geometry**!

Conclusion

– Axions are highly motivated Dark Matter candidates

– **LIDA** is an interferometric detector currently operating at 2 neV axion mass

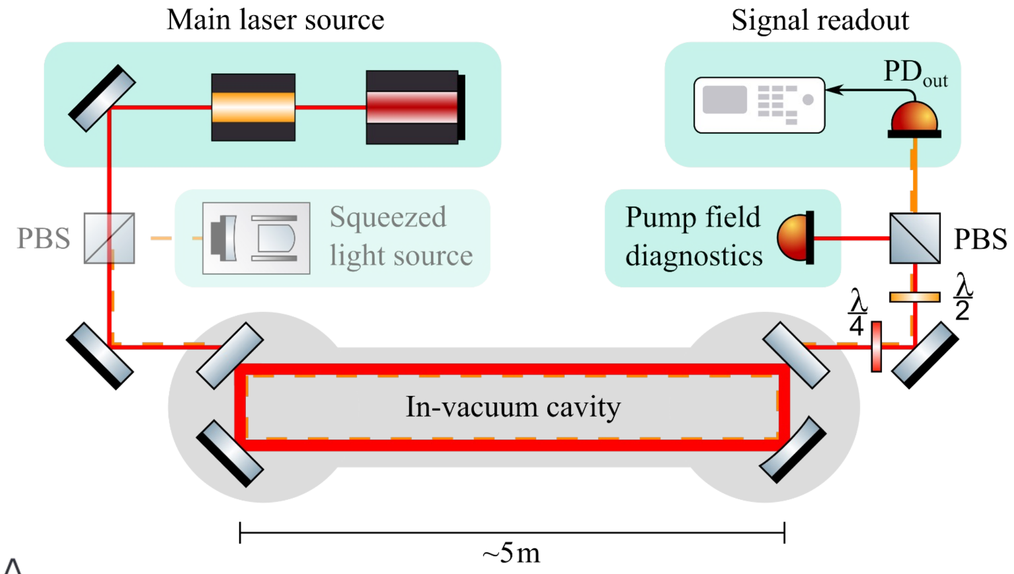
– Reaching **sensitivities of $\mathbf{2\times10^{-10}}$ $\boldsymbol{GeV^{-1}}$** at the 95% confidence level. This puts LIDA a factor of 8 above the CAST sensitivity level

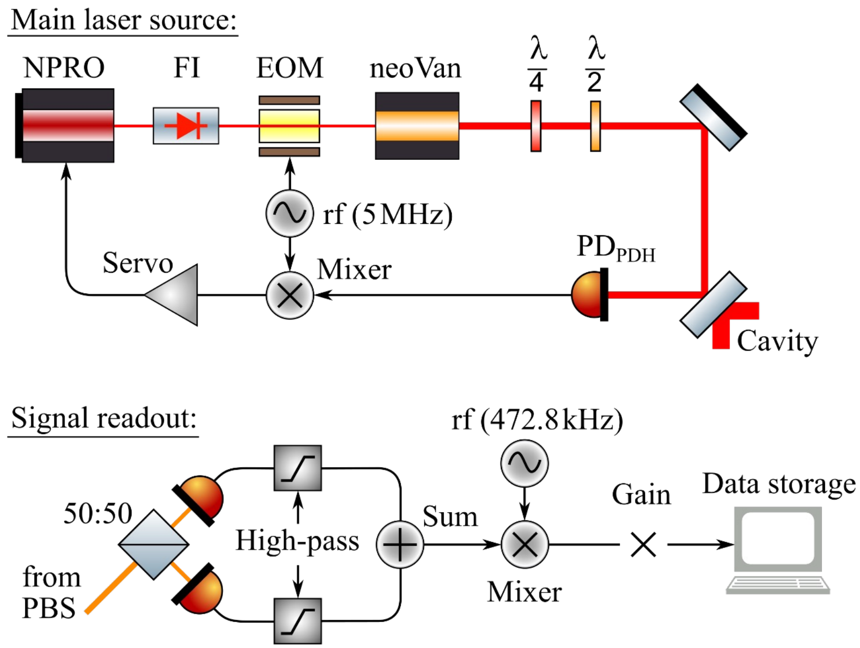
– We resonate high optical intensities of $\mathbf{4.7}$ $\boldsymbol{MW/cm^2}$

– At high powers, we see changes in a distorted mode, a decrease in circulating power and higher readout noise

Thank you!

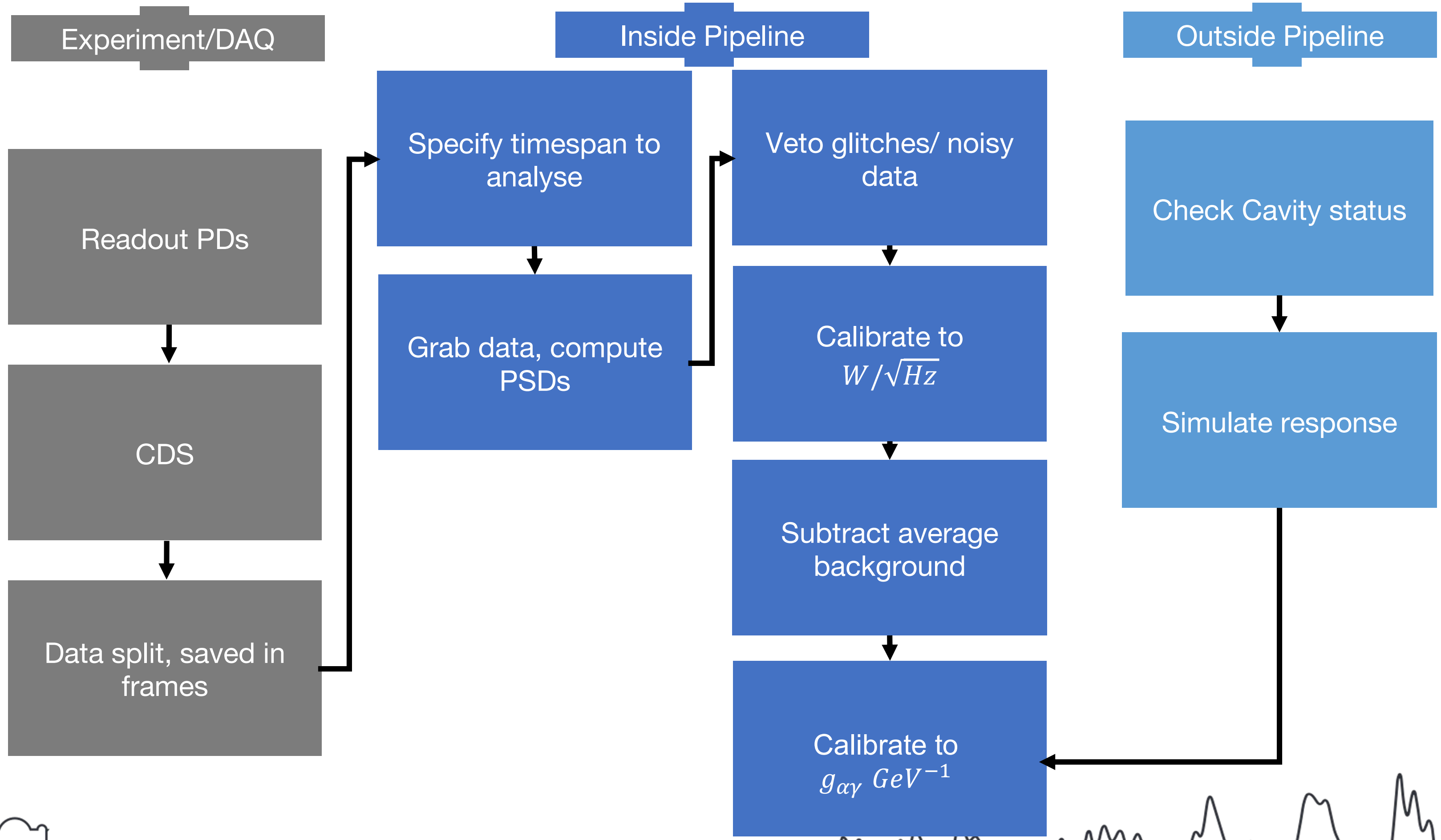
More detailed setup





EOM: electro-optic modulator, NPRO: non-planar ring oscillator, PBS: polarising beamsplitter, PD: photodetector, PDH: Pound-Drever-Hall, rf: radio-frequency generator

Current Data Analysis Pipeline



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