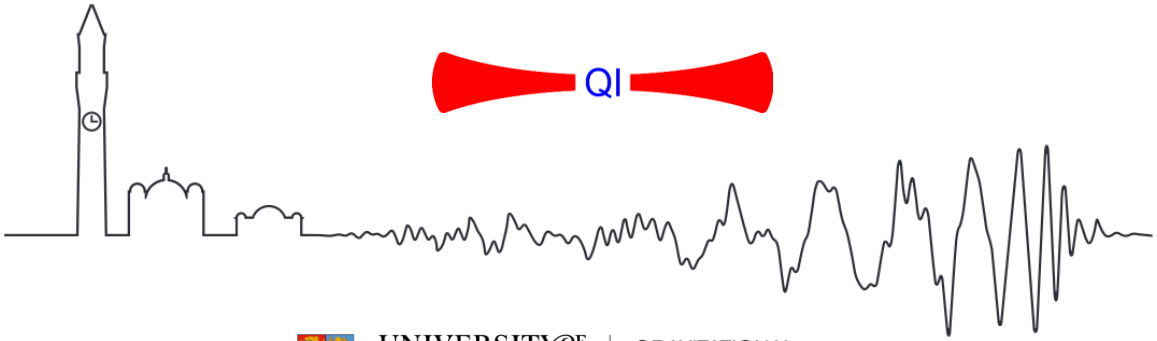
# LIDA:
# First results and future prospects

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

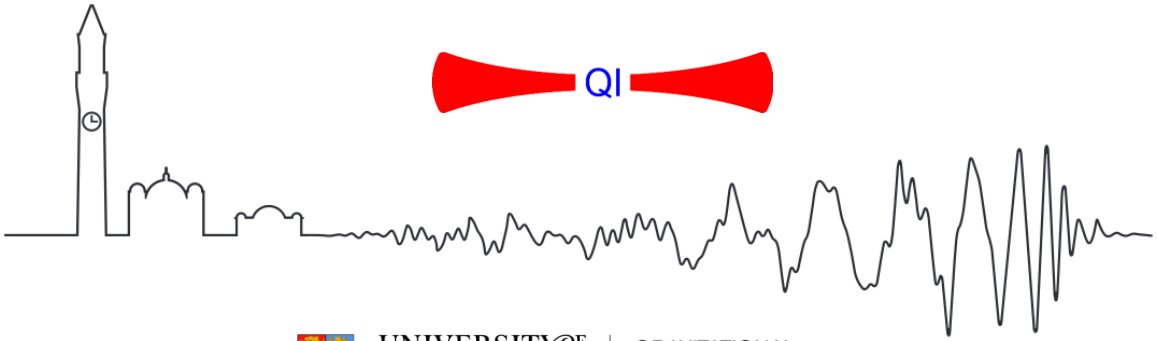

UNIVERSITY OF BIRMINGHAM | GRAVITATIONAL WAVE ASTRONOMY

Science and Technology Facilities Council

Engineering and Physical Sciences Research Council

# **L**aser-**I**nterferometric **D**etector for **A**xions**:** First results and future prospects

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

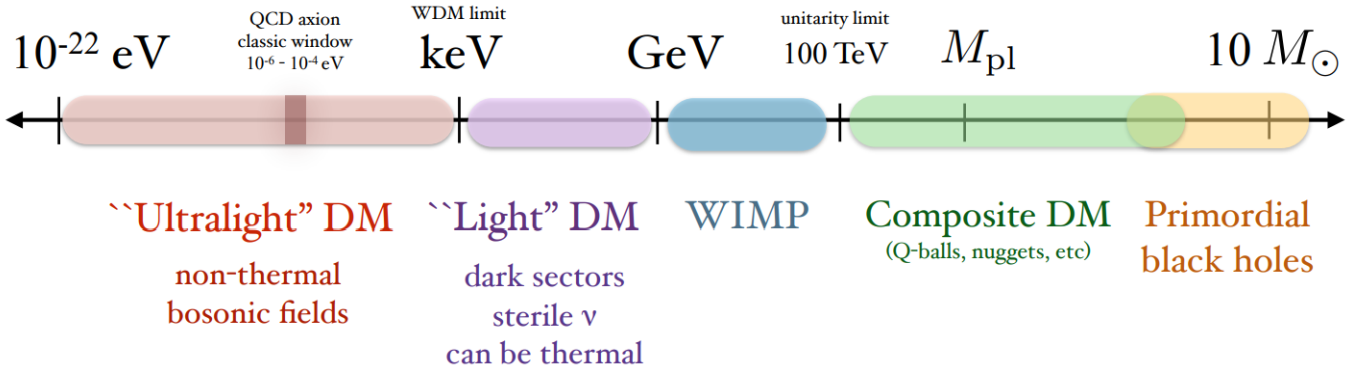




UNIVERSITY OF BIRMINGHAM | GRAVITATIONAL WAVE ASTRONOMY

UKRI Science and Technology Facilities Council

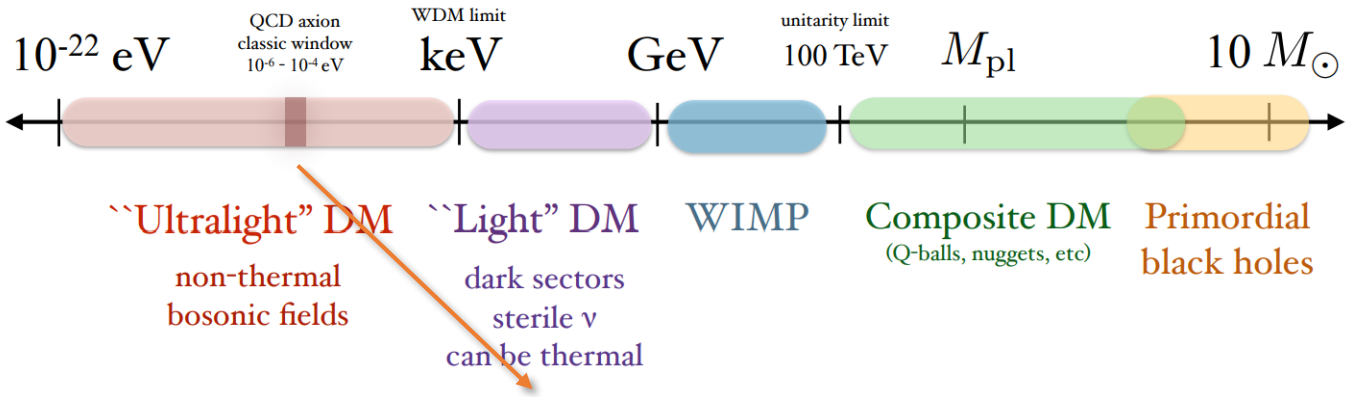
UKRI Engineering and Physical Sciences Research Council

# Mass range




T. Lin, arXiv:1904.07915 (2019)

# Mass range




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

T. Lin, arXiv:1904.07915 (2019)

# Operating principle

# Operating principle

- Directly detect axions and axion-like particles ($10^{-16} - 10^{-8}$ eV).

# Operating principle

- Directly detect axions and axion-like particles ($10^{-16} - 10^{-8}$ eV).
- Use coupling of **axions to photons**:

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

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

# Operating principle

- Directly detect axions and axion-like particles ($10^{-16} - 10^{-8}$ eV).
- Use coupling of **axions to photons**:

$$\mathcal{L} = \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \Longrightarrow \quad \frac{\partial^2 \boldsymbol{E}}{\partial t^2} - \nabla^2 \boldsymbol{E} = g_{a\gamma} \dot{a} (\nabla \times \boldsymbol{E})$$

Lagrangian $\mathcal{L}$

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

$a$: axion field

$g_{a\gamma}$: coupling coefficient

$F$: electromagnetic field-strength tensor

# Operating principle

- Directly detect axions and axion-like particles ($10^{-16} - 10^{-8}$ eV).
- Use coupling of **axions to photons**:

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

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

$$\Rightarrow \quad \frac{\partial^2 \boldsymbol{E}}{\partial t^2} - \nabla^2 \boldsymbol{E} = g_{a\gamma} \dot{a} (\nabla \times \boldsymbol{E})$$

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

$$\Rightarrow \quad \Delta\phi = g_{a\gamma}[a(t) - a(t-\tau)]$$

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

# Operating principle

- Directly detect axions and axion-like particles ($10^{-16} - 10^{-8}$ eV).
- Use coupling of **axions to photons**:

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

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

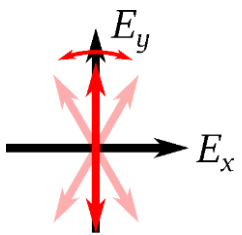
$$\frac{\partial^2 \boldsymbol{E}}{\partial t^2} - \nabla^2 \boldsymbol{E} = g_{a\gamma} \dot{a} (\nabla \times \boldsymbol{E})$$

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

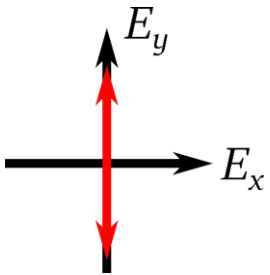
$$\Delta\phi = g_{a\gamma}[a(t) - a(t-\tau)]$$

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

Observable effect:
Rotation of linear polarisation!

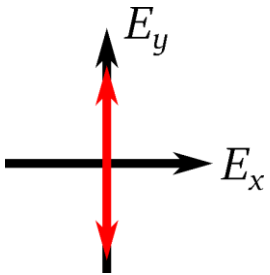


# Signal generation

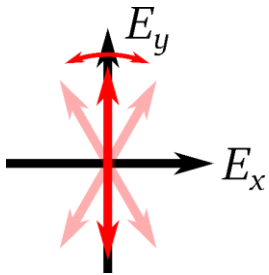




Input: linear s-polarisation.

# Signal generation

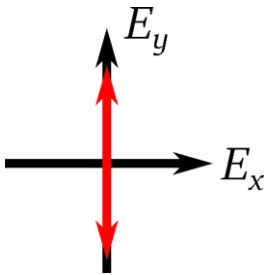




Input: linear s-polarisation.

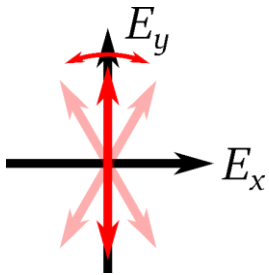



Effect: polarisation rotation.

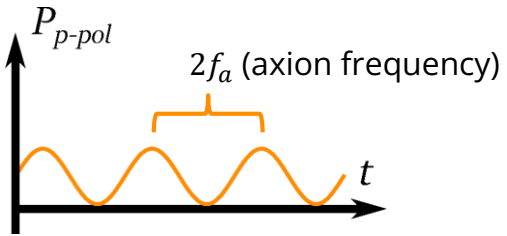
# Signal generation


Input: linear s-polarisation.

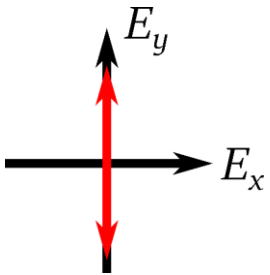



Effect: polarisation rotation.

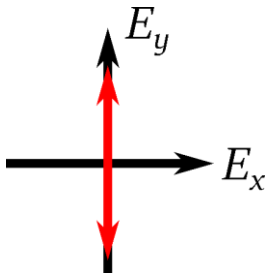



Output: signal in p-polarisation.

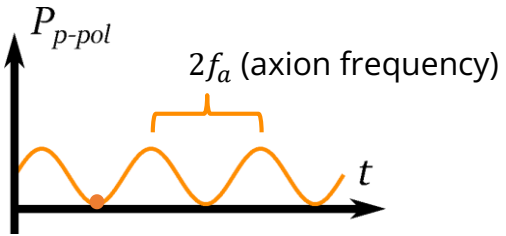
# Signal generation


Input: linear s-polarisation.

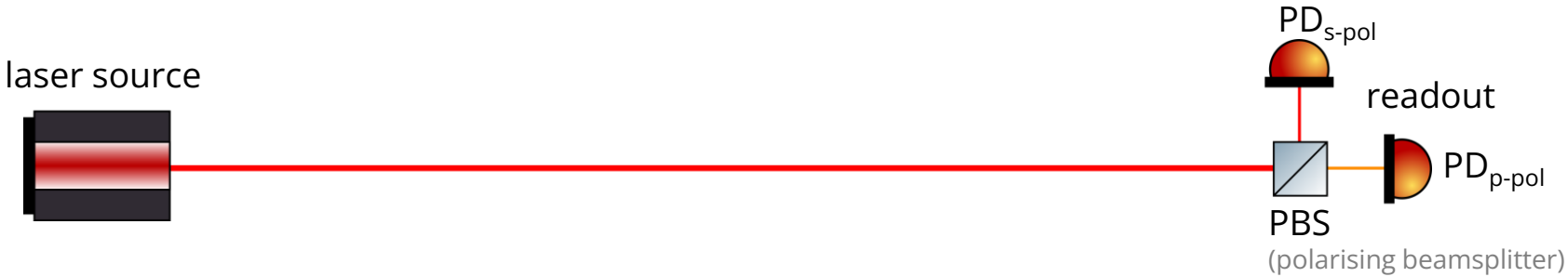


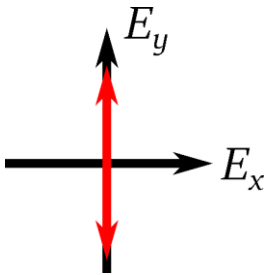

Effect: polarisation rotation.



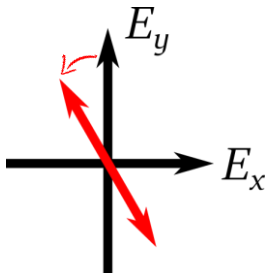

Output: signal in p-polarisation.

# Signal generation

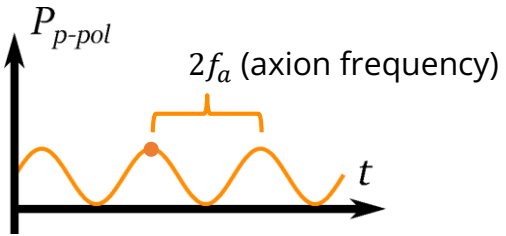



Input: linear s-polarisation.

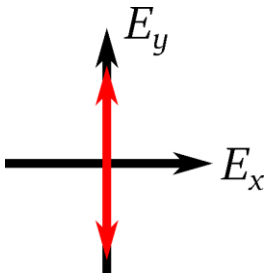



Effect: polarisation rotation.

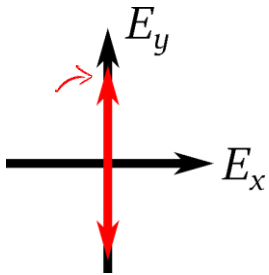



Output: signal in p-polarisation.

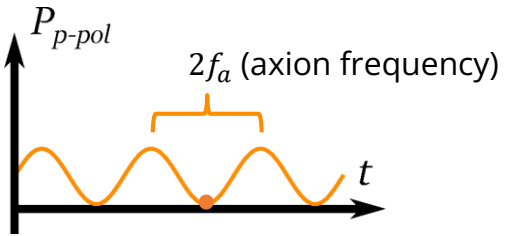
# Signal generation


Input: linear s-polarisation.

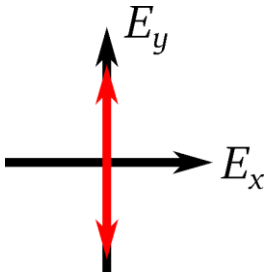



Effect: polarisation rotation.

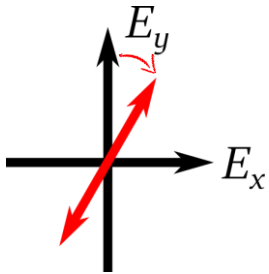



Output: signal in p-polarisation.

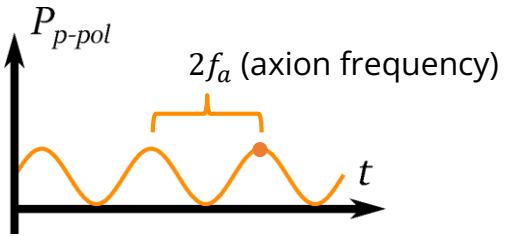
# Signal generation


Input: linear s-polarisation.

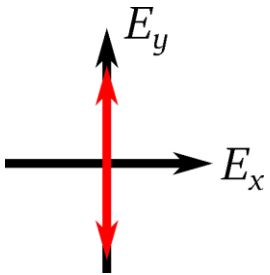



Effect: polarisation rotation.

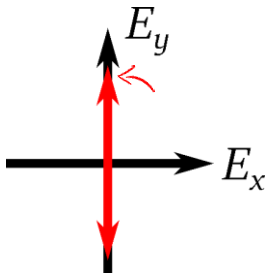



Output: signal in p-polarisation.

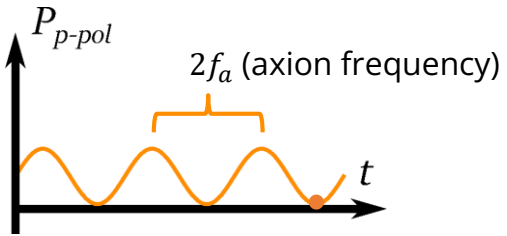
# Signal generation


Input: linear s-polarisation.

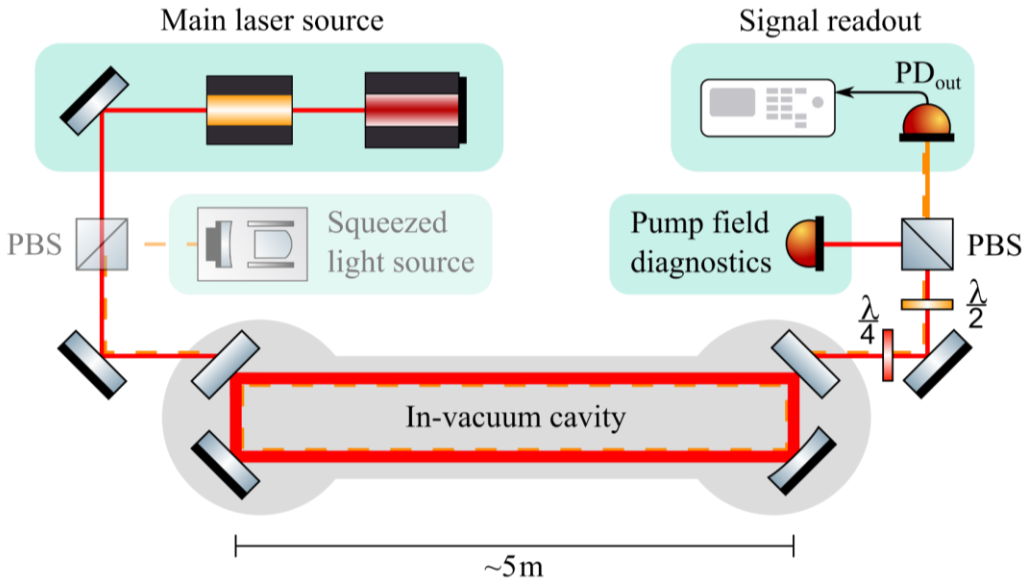



Effect: polarisation rotation.




Output: signal in p-polarisation.

# Detector design



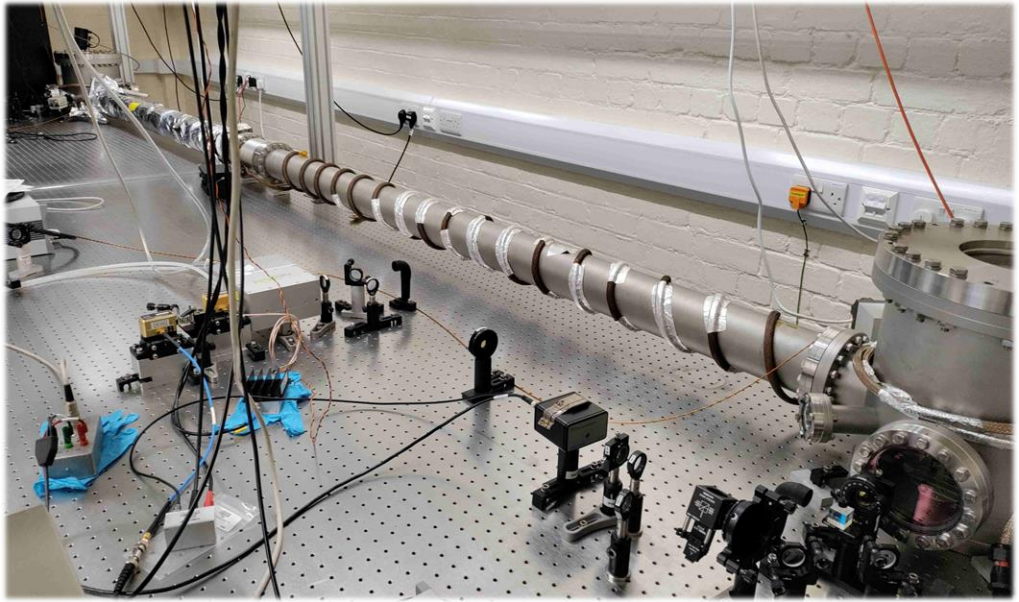

Tabletop demonstration:

- **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

# Status and first results

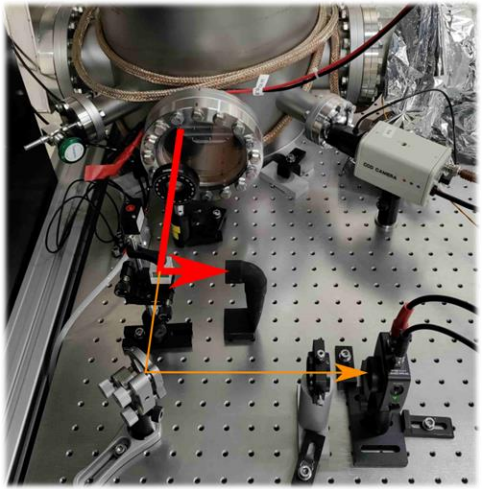
# LIDA in the lab

- 5 m long vacuum system!

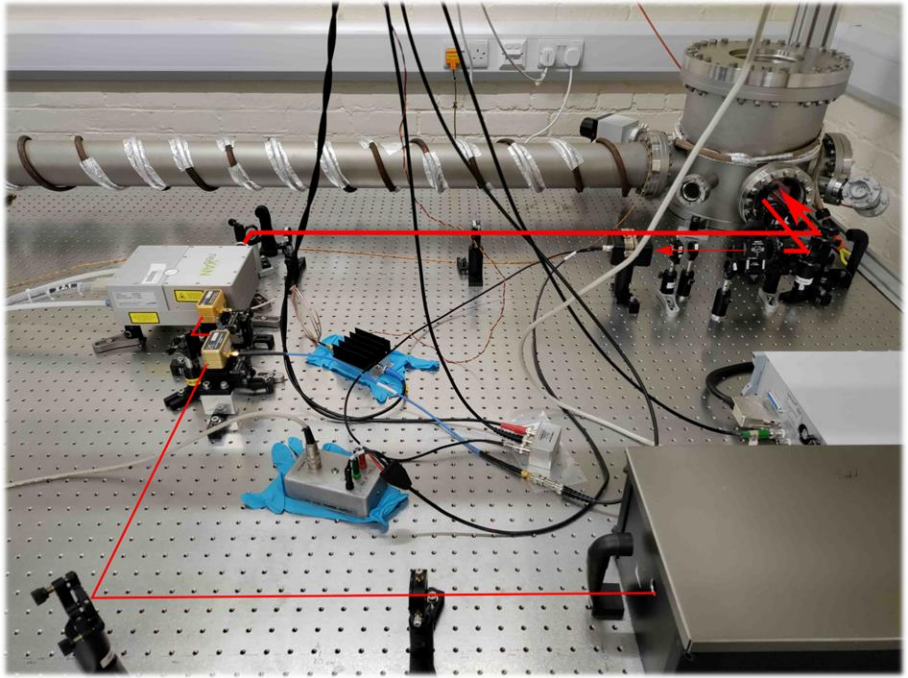


# LIDA in the lab

- 5 m long vacuum system!
- Input and readout setup!



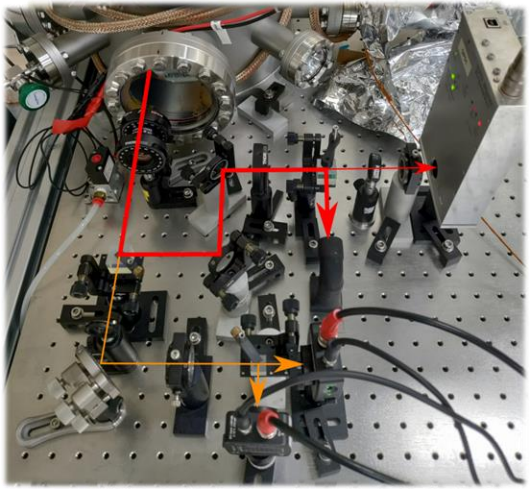
Readout



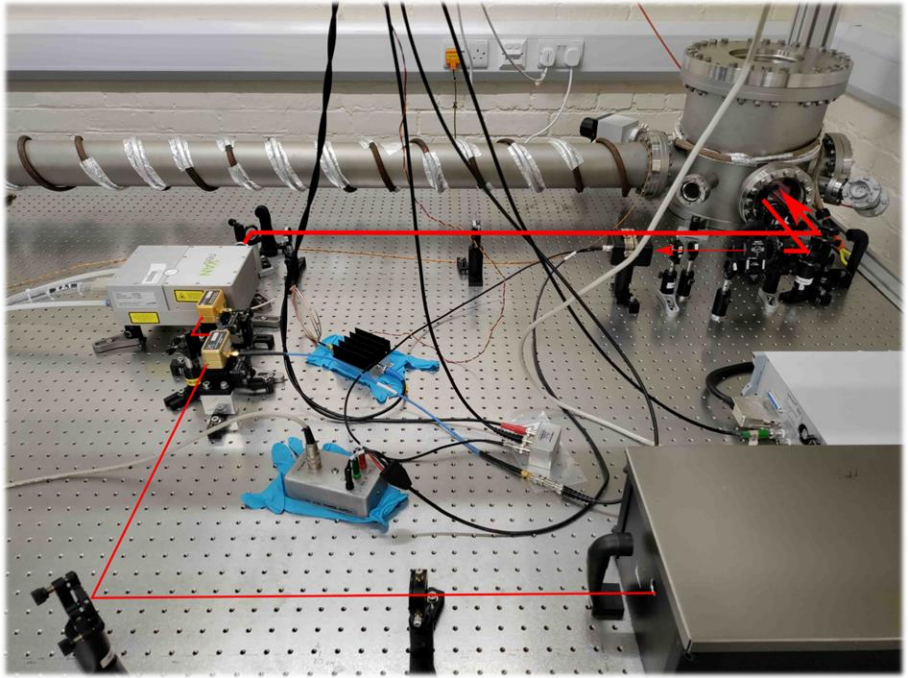
Input

# LIDA in the lab

- 5 m long vacuum system!
- Input and readout setup!



Readout



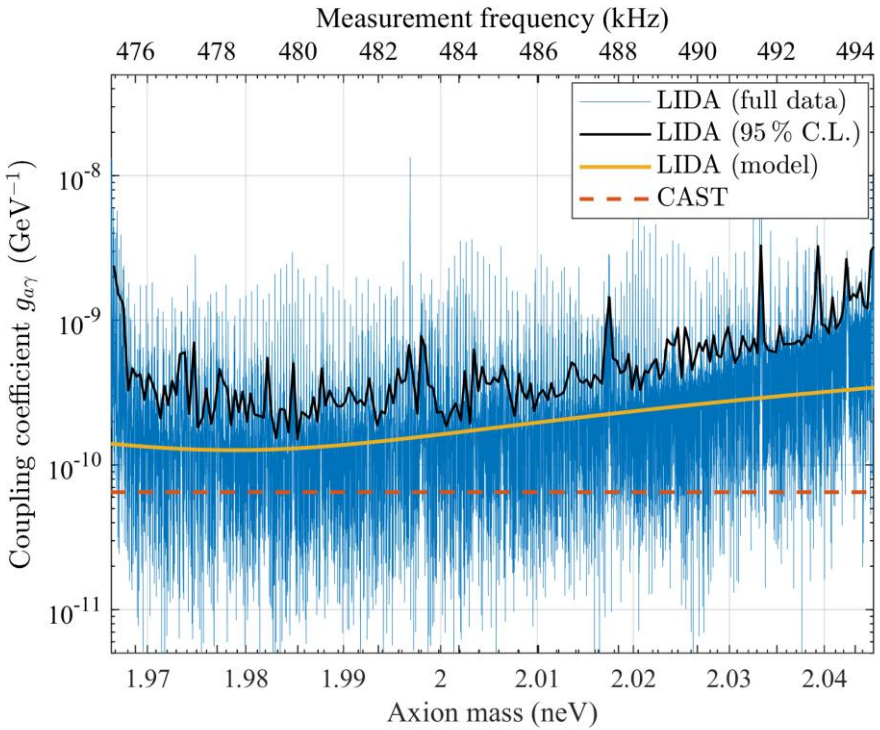
Input

# 1st science run

| | First run |
|---|---|
| Input pump power | 12 W |
| Intra-cavity power | 118 kW |
| Measurement time | 85 h |
| Squeezing level | – |
| Detuning | 478 kHz |

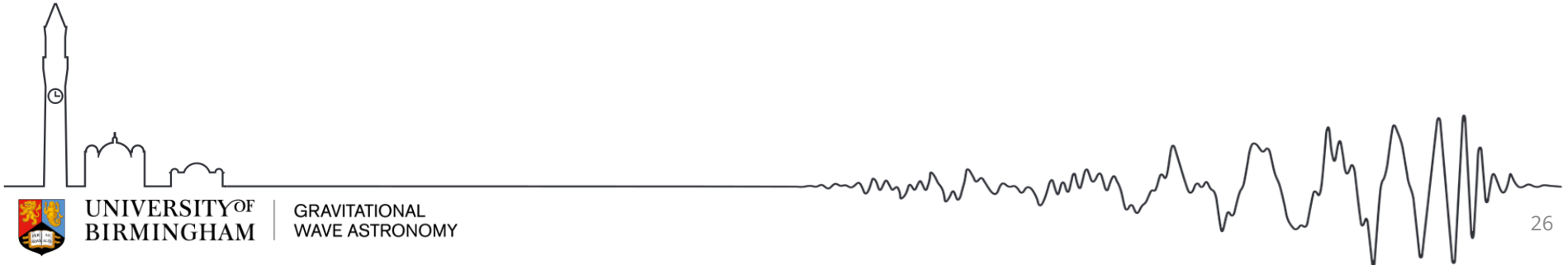
Peak sensitivity: $\mathbf{1.51 \times 10^{-10}\,GeV^{-1}}$

Avg sensitivity: $\mathbf{3.2 \times 10^{-10}\,GeV^{-1}}$



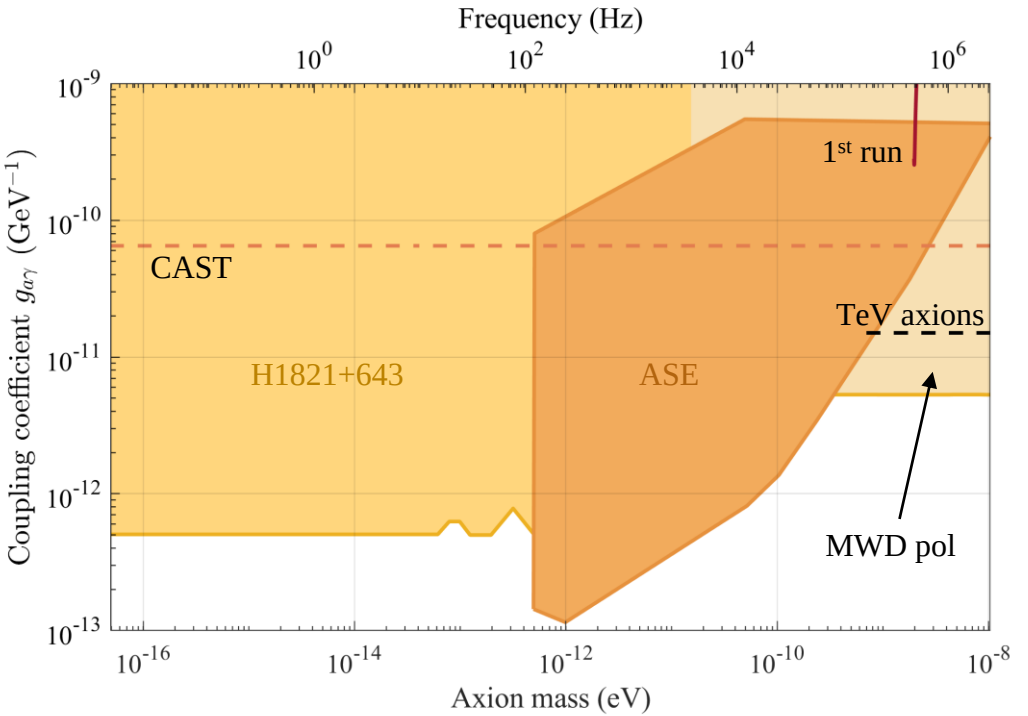

Published: J Heinze, et. al., PRL 123 (2024)

# Prospects for LIDA



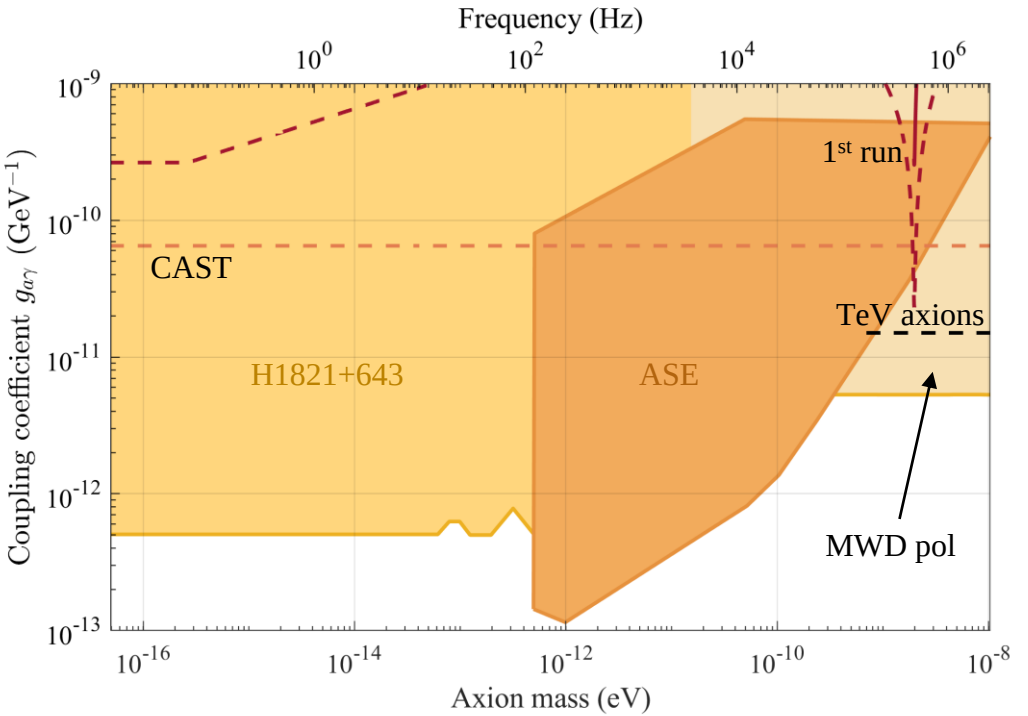
# Prospects for LIDA

| | First run | Next run |
|---|---|---|
| Intra-cavity power (kW) | 118 | ? |
| Measurement time | 85 h | ? |
| Squeezing level (dB) | – | ? |
| Detuning | 478 kHz | ? |



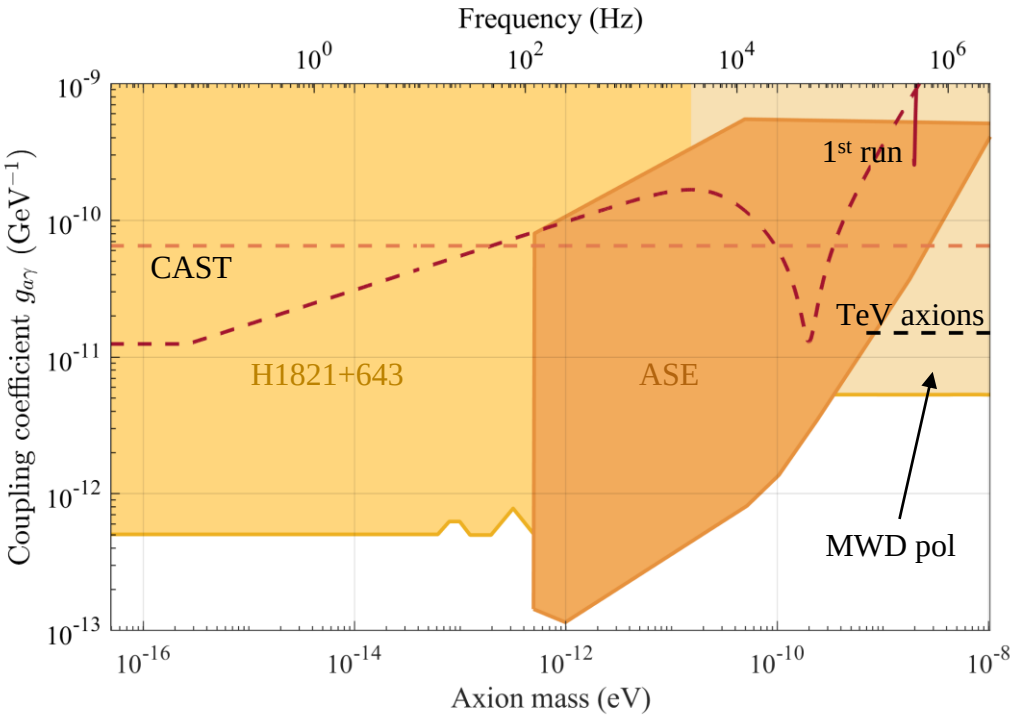
# Prospects for LIDA

| | First run | Next run |
|---|---|---|
| Intra-cavity power (kW) | 118 | 200 |
| Measurement time | 85 h | 6 months |
| Squeezing level (dB) | – | 10 dB |
| Detuning | 478 kHz | 478 kHz |



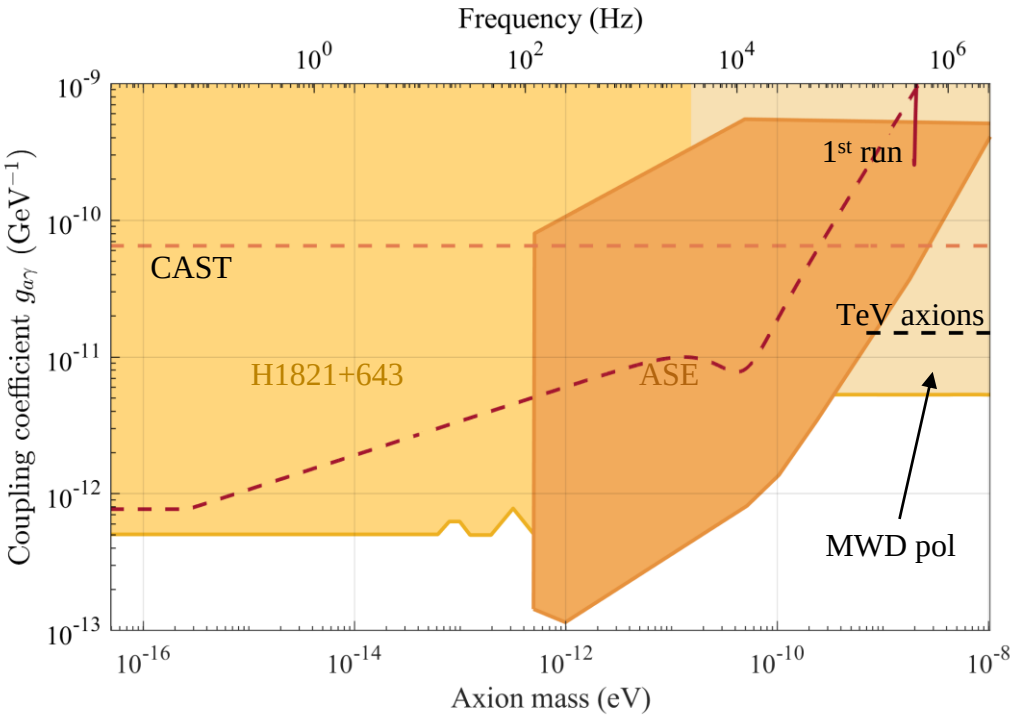
# Prospects for LIDA

| | First run | Next run |
|---|---|---|
| Intra-cavity power (kW) | 118 | 200 |
| Measurement time | 85 h | 6 months |
| Squeezing level (dB) | – | 10 dB |
| Detuning | 478 kHz | 48 kHz |



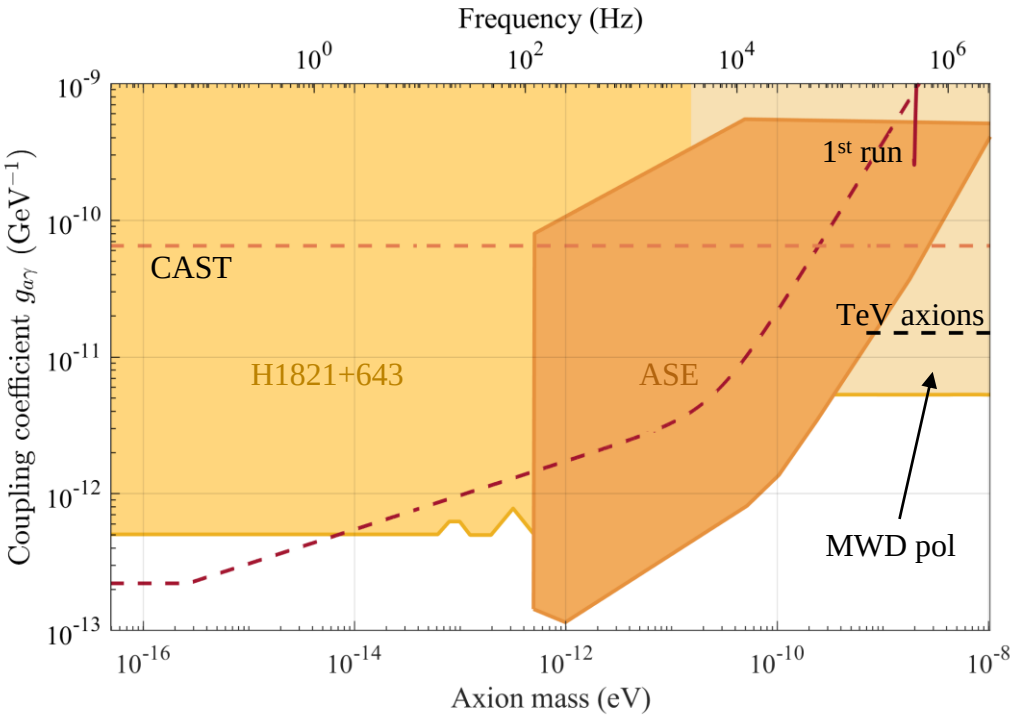
# Prospects for LIDA

| | First run | Next run |
|---|---|---|
| Intra-cavity power (kW) | 118 | 200 |
| Measurement time | 85 h | 6 months |
| Squeezing level (dB) | – | 10 dB |
| Detuning | 478 kHz | 10 kHz |



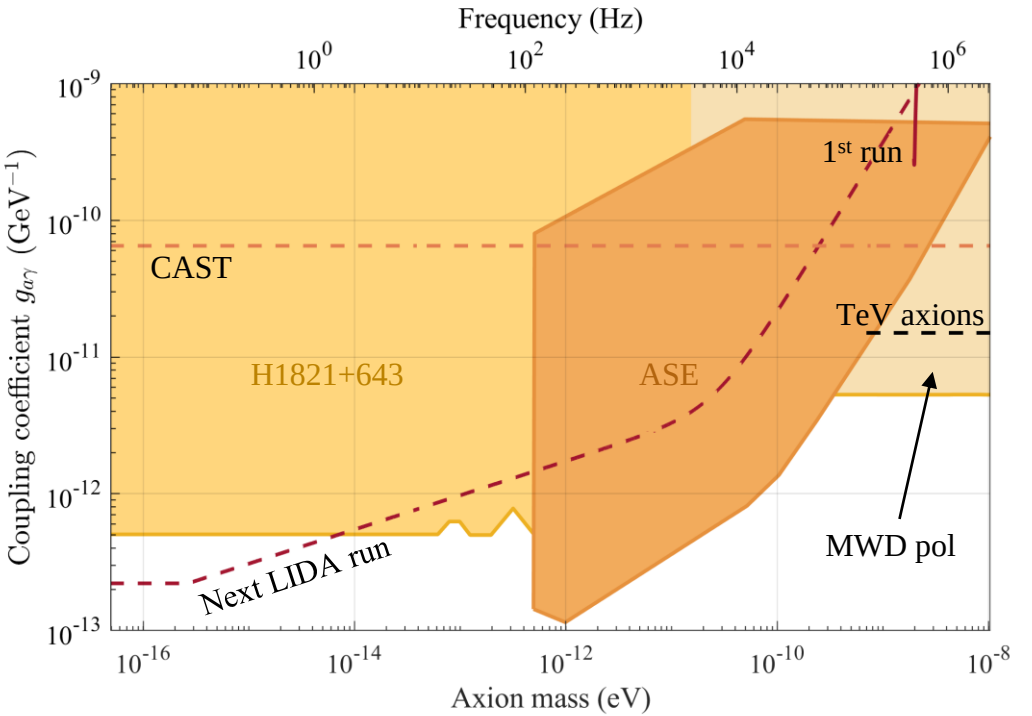
# Prospects for LIDA

| | First run | Next run |
|---|---|---|
| Intra-cavity power (kW) | 118 | 200 |
| Measurement time | 85 h | 6 months |
| Squeezing level (dB) | – | 10 dB |
| Detuning | 478 kHz | 0 kHz |



# Prospects for LIDA

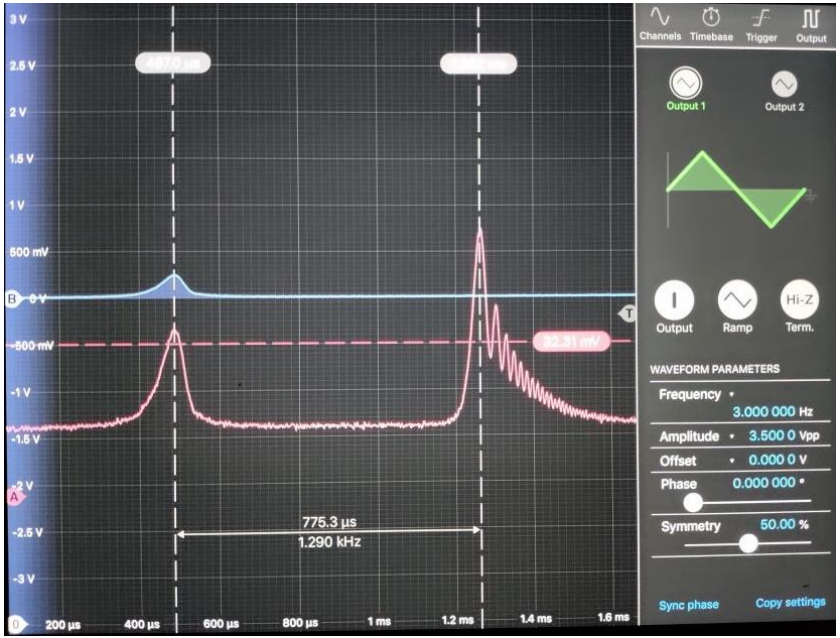
| | First run | Next run |
|---|---|---|
| Intra-cavity power (kW) | 118 | 200 |
| Measurement time | 85 h | 6 months |
| Squeezing level (dB) | – | 10 dB |
| Detuning | 478 kHz | 0 kHz |



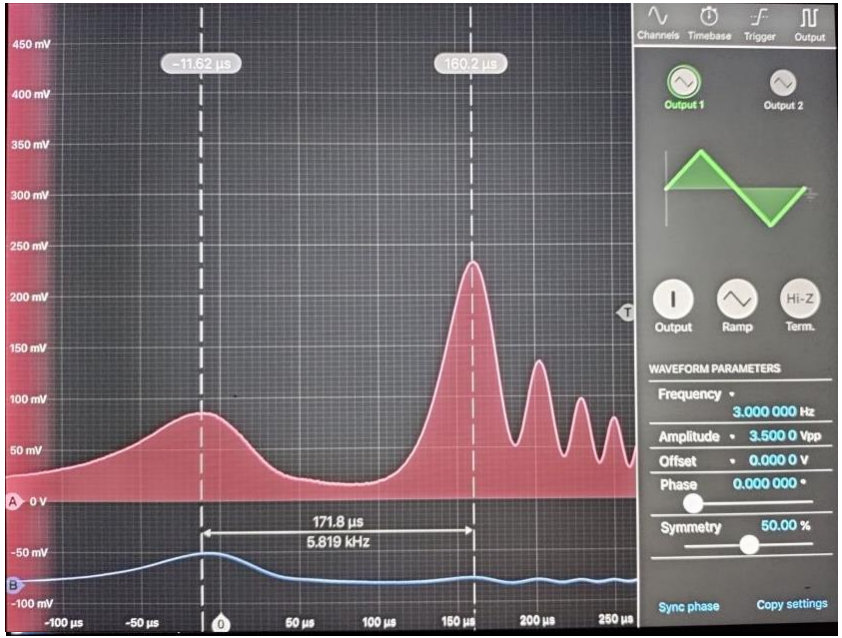
# Adjusting the detuning

# Adjusting the detuning

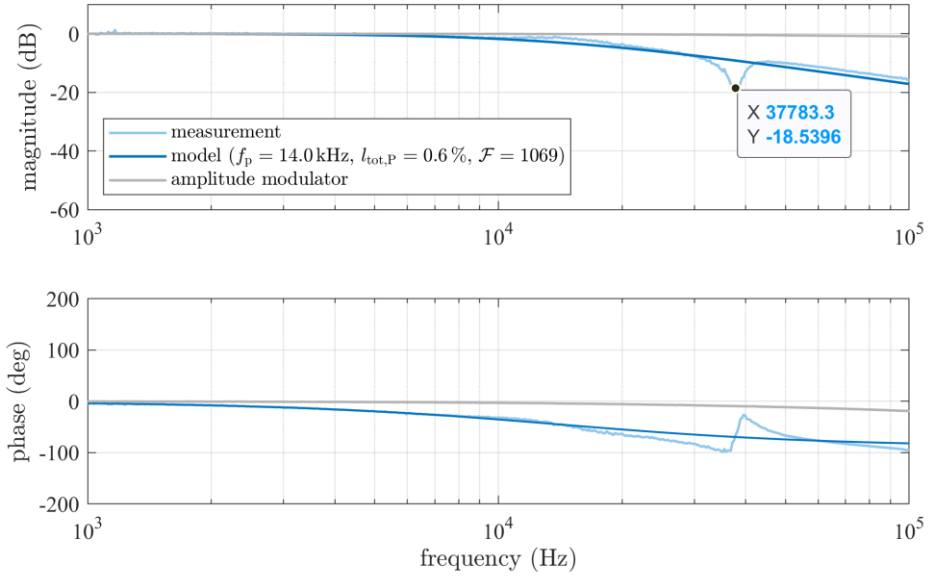
# Adjusting the detuning



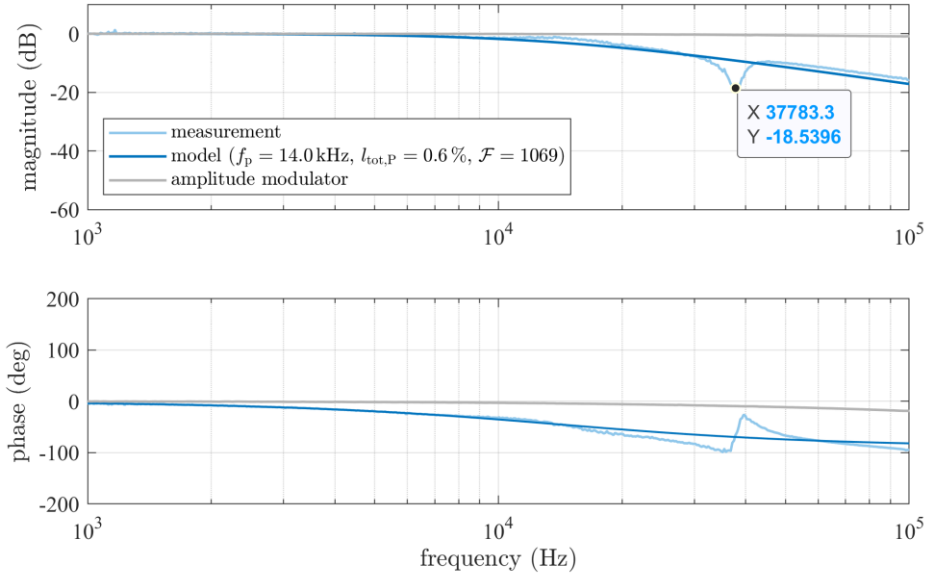
# Adjusting the detuning



# Adjusting the detuning

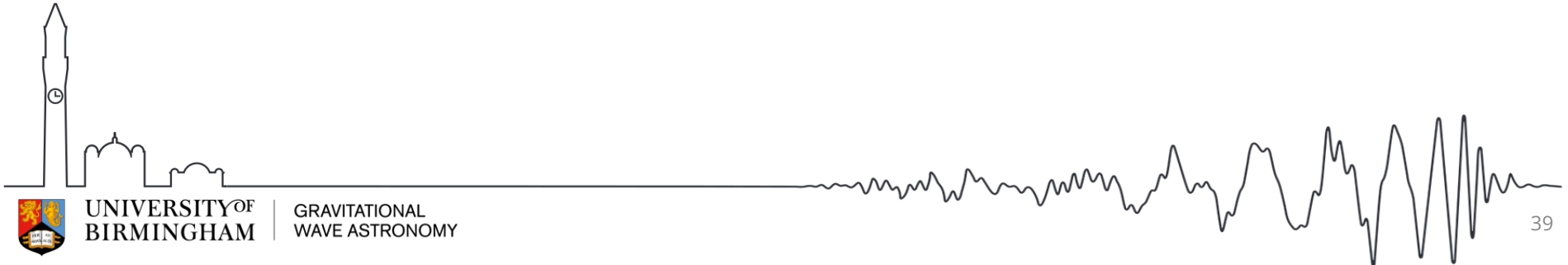


# Adjusting the detuning



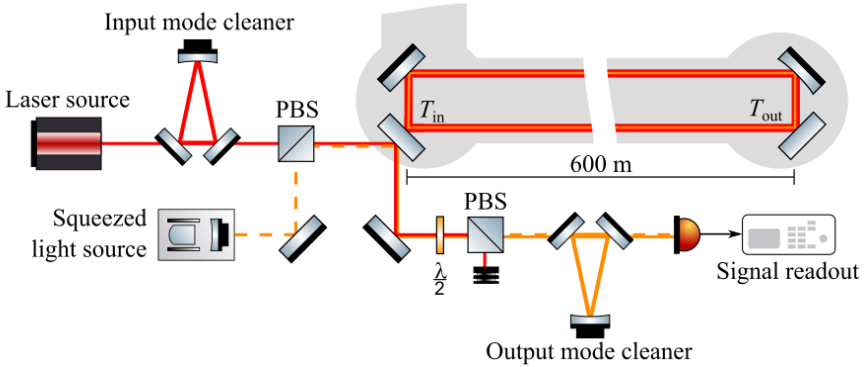

Looks very promising!
Install picomotors for fine-tuning!

# Proposal for GEO600



# GEO600 → DarkGEO

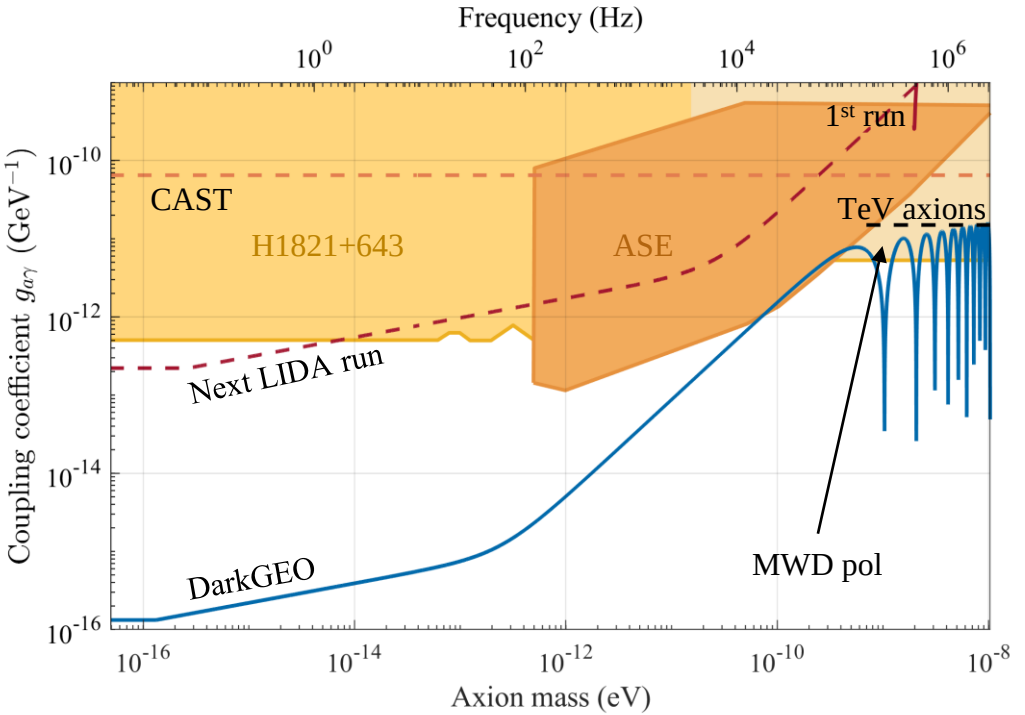
GEO600: close to Hanover, Germany (credit: geo600.org)




Published: J Heinze, et. al., NJP 26 (2024)

# DarkGEO prospects

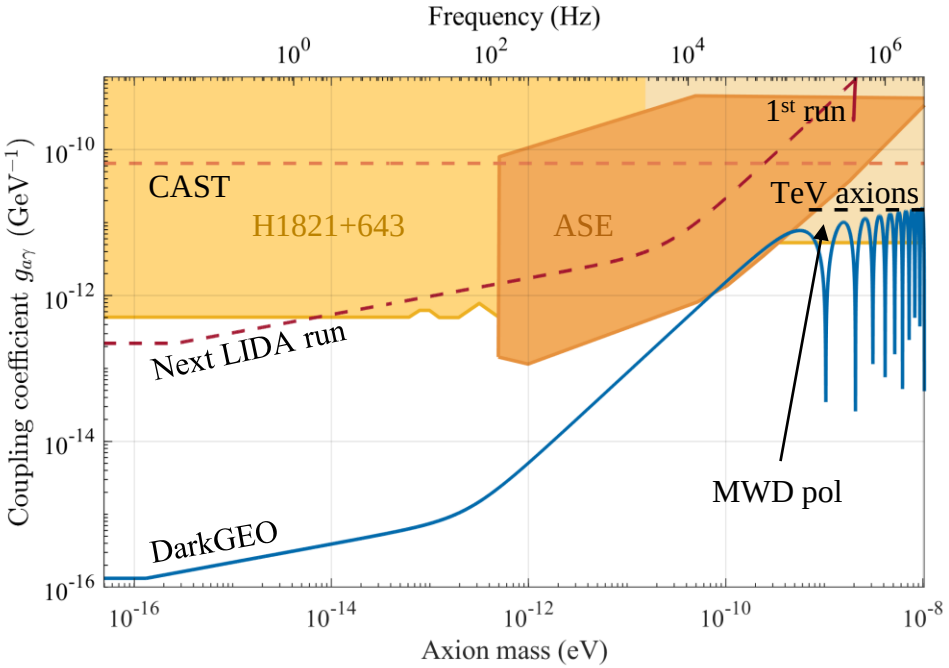
| | First LIDA | Next LIDA | DarkGEO |
|---|---|---|---|
| Power (kW) | 118 | 200 | 10,000 |
| Meas time | 85 h | 6 months | 1 year |
| Squeezing (dB) | – | 10 dB | 10 dB |
| Detuning | 478 kHz | 0 kHz | 0 kHz |



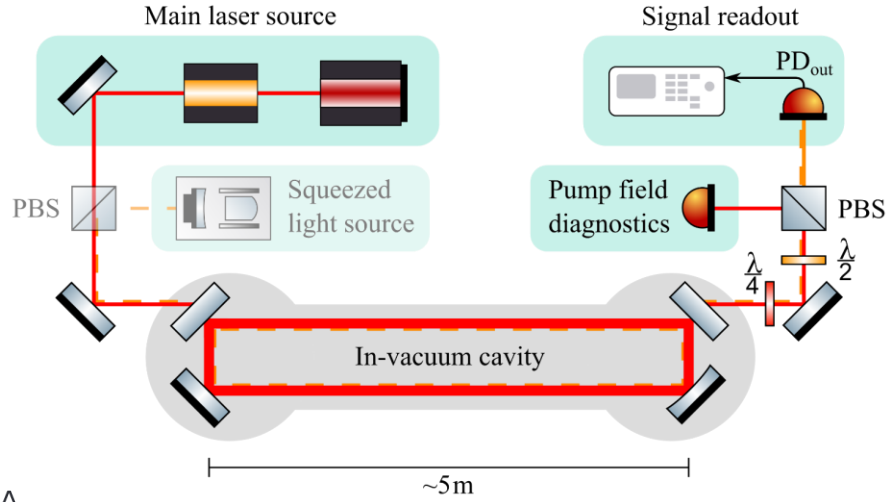

Published: J Heinze, et. al., NJP 26 (2024)

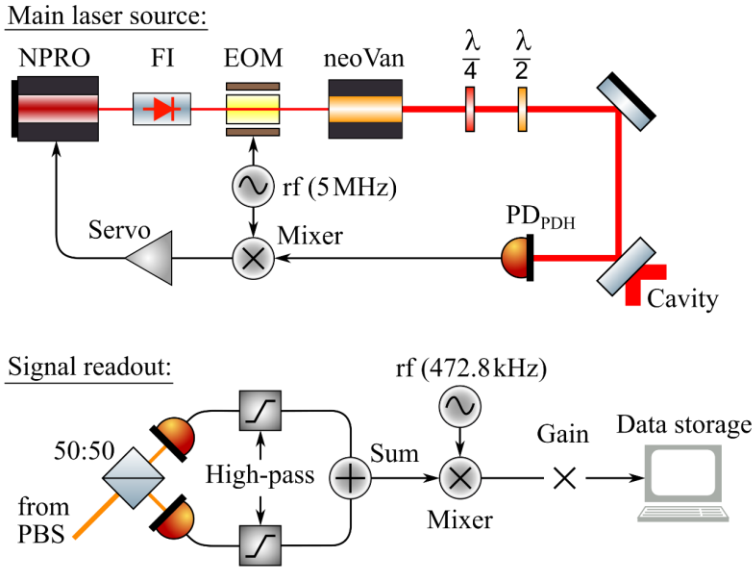
# Summary

- **LIDA** is a **laser-interferometric detector for axions** sensitive to a rotation of linear polarisation!
- First science run yielded very **promising results**, paper submitted!
- **Prospects** to even probe unexplored regions in the next observing run at lower axion masses!
- **Challenge** to reduce detuning shows first success!
- **DarkGEO** could further boost the sensitivity by several orders of magnitude, paper in preparation!



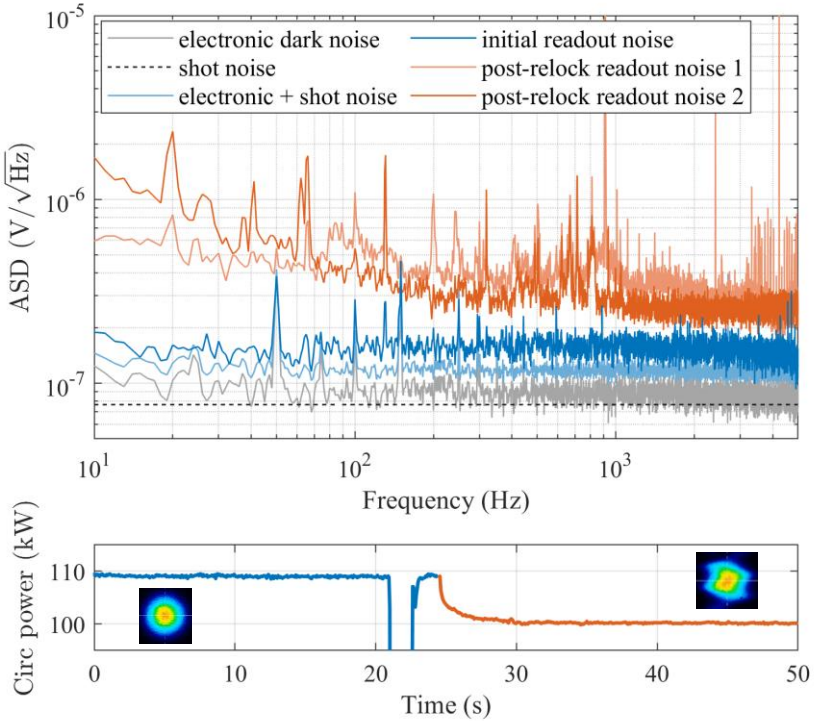
# More detailed setup




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

# High-power effects




At high circulating power:

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

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

# GEO600 → DarkGEO

GEO600: close to Hanover, Germany (credit: geo600.org)

| Parameter (DarkGEO-I) | Value | Unit |
|---|---|---|
| Wavelength | 1064 | nm |
| Cavity roundtrip length | 1.2 | km |
| Input coupler transmissivity, $T_{\mathrm{in}}$ | 20 | ppm |
| Output coupler transmissivity, $T_{\mathrm{out}}$ | 1 | ppm |
| Cavity roundtrip loss, $l_{\mathrm{rt}}$ | 20 | ppm |
| Laser input power | 210 | W |
| Intra-cavity power, $P_{\mathrm{m,cav}}$ | 10 | MW |
| Measurement time, $T_{\mathrm{meas}}$ | 1 | year |
| Main laser field polarisation | vertical | |
| Signal field polarisation | horizontal | |

| Parameter (DarkGEO-II/III) | Value | Unit |
|---|---|---|
| Wavelength | 1064 | nm |
| Cavity roundtrip length | 1.2 | km |
| Input coupler transmissivity, $T_{\mathrm{m,in}}$ | 45 | ppm |
| Output coupler transmissivity, $T_{\mathrm{m,out}}$ | 1 | ppb |
| Input coupler transmissivity, $T_{\mathrm{sig,in}}$ | 3000 | ppm |
| Output coupler transmissivity, $T_{\mathrm{sig,out}}$ | 2.5 | ppm |
| Cavity roundtrip loss, $l_{\mathrm{rt}}$ | 45 | ppm |
| Laser input power | 460 | W |
| Intra-cavity power, $P_{\mathrm{m,cav}}$ | 10 | MW |
| Effective squeezing level | 10 | dB |
| Measurement time, $T_{\mathrm{meas}}$ | 1 | year |
| Detuning, $\beta$ | 0.13 (scanned) | |
| Main laser field polarisation | vertical | |
| Signal field polarisation | horizontal | |

Published: J Heinze, et. al., arXiv:2401.11907 (2024)