Science and Technology Facilities Council

Imperial College London

AION: the Atom Interferometer Observatory and Network

Richard Hobson, Imperial College London, AION collaboration

DMUK 22/09/2022

This talk:

1. Introducing AION's goals:
    1. Dark Matter
    2. Gravitational Waves
2. How does the AION detector work?
3. Progress so far
4. Outlook

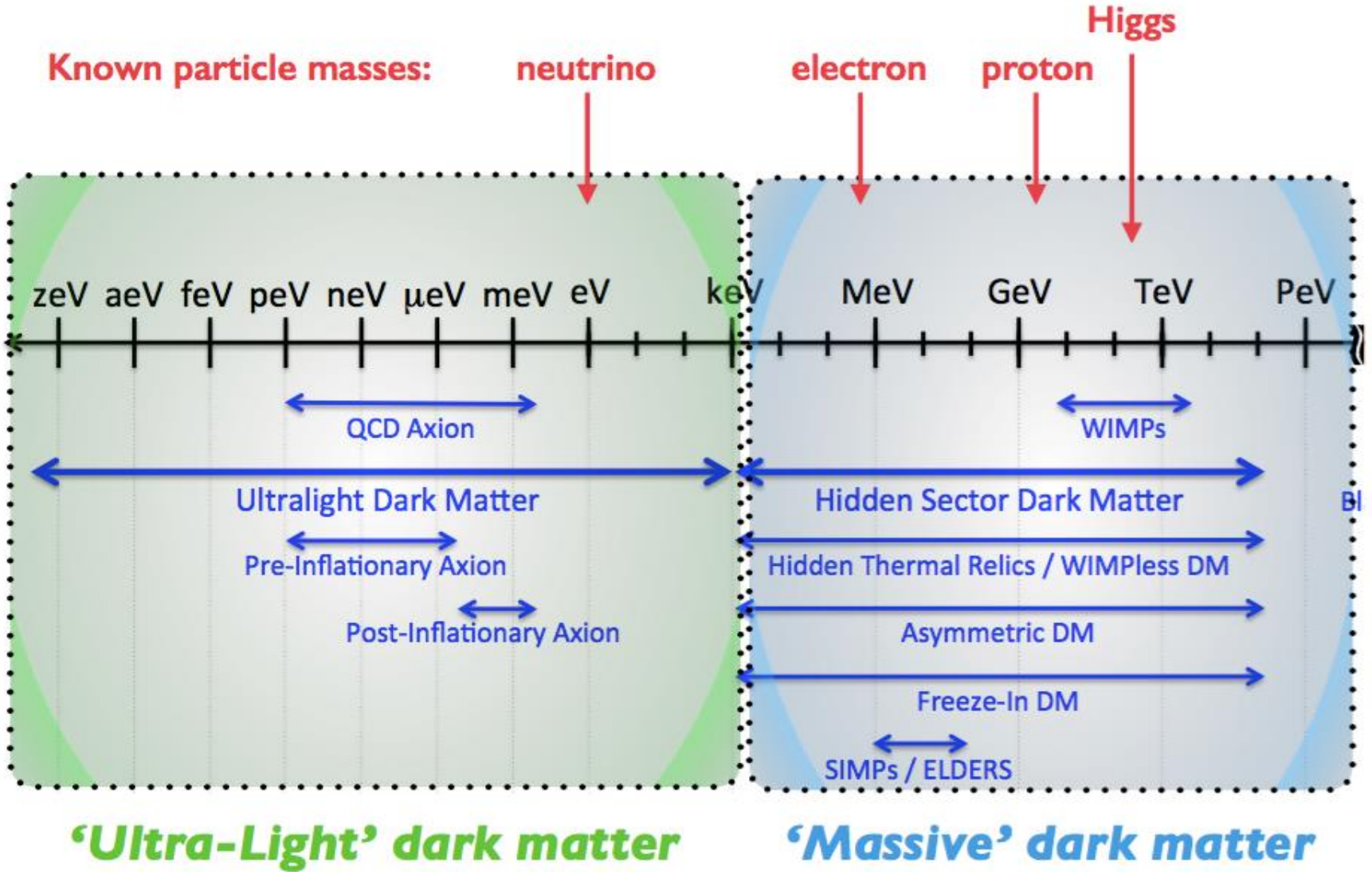
Dark matter

Bullet cluster: Gravitational lensing (blue) vs x-ray emissions (red)
From https://chandra.harvard.edu/photo/2006/1e0657/more.html

85% of the mass of the universe is dark matter

What is it?

Dark matter candidates



Ultra-light dark matter detectors

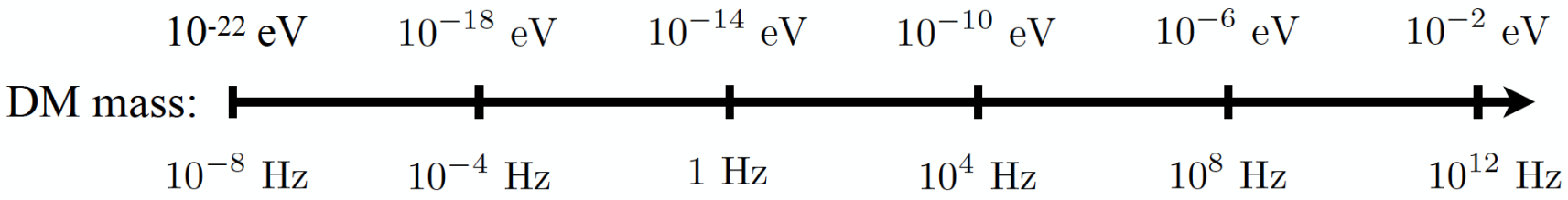
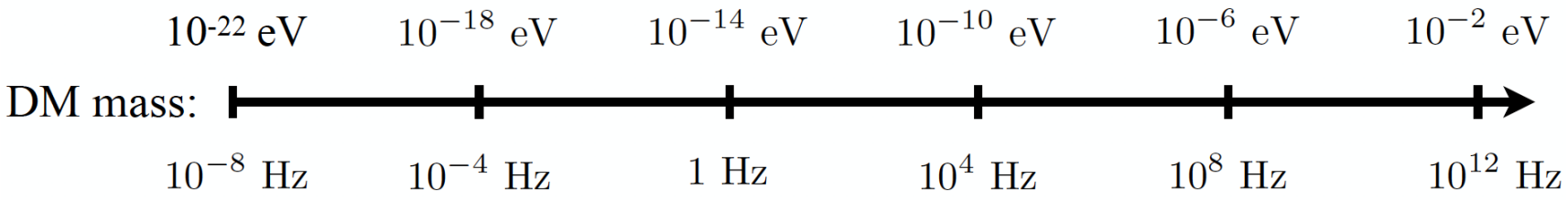


Diagram credit: P. Graham's talk at HEP Front 2018

Ultra-light dark matter detectors



← atom interferometry →

MAGIS /AION

Diagram credit: P. Graham's talk at HEP Front 2018

Ultra-light dark matter detectors

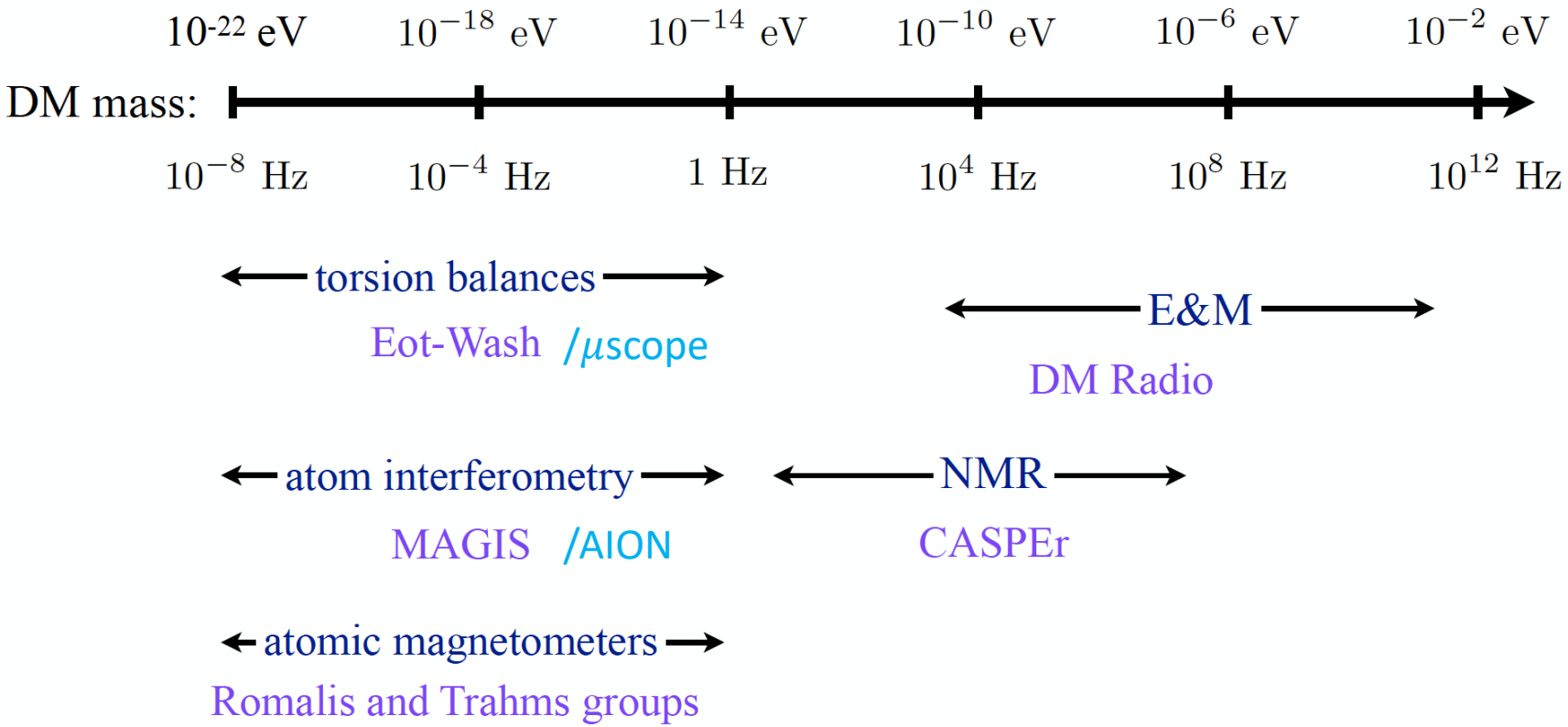


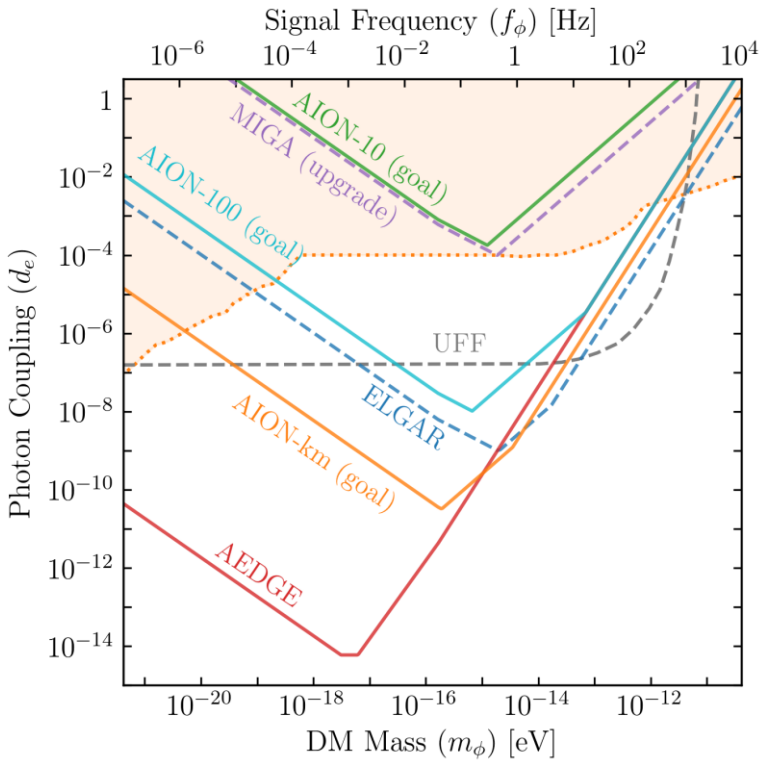
Diagram credit: P. Graham's talk at HEP Front 2018

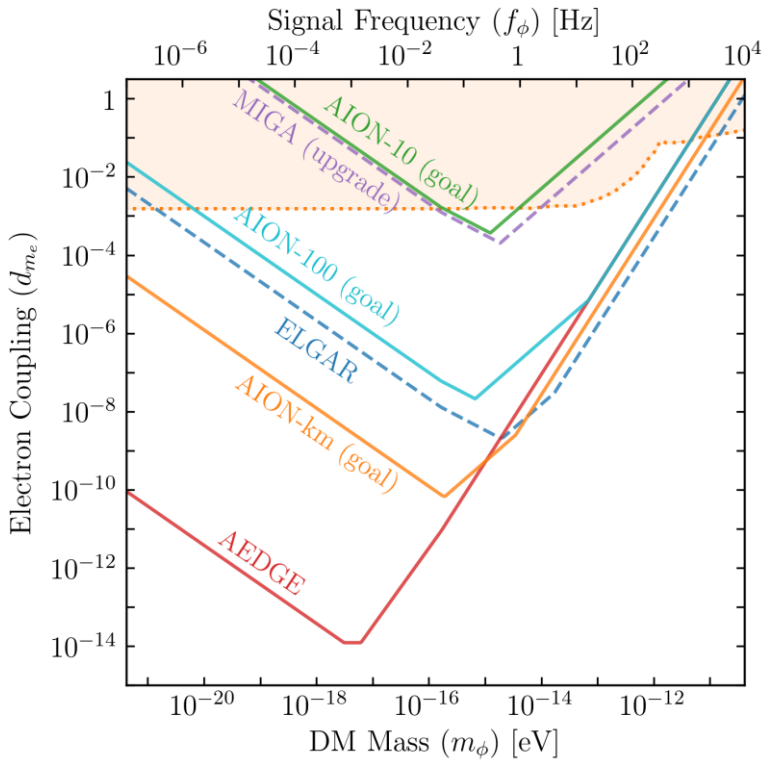
Dark matter: AION sensitivity

E.g. Postulate field ϕ with linear couplings to standard model fields:

$$\phi(\mathbf{x},t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi}\cos[m_\phi(t-\mathbf{v}_\phi\cdot\mathbf{x})+\cdots]$$

$$\mathcal{L}_{{\rm int}\phi} = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

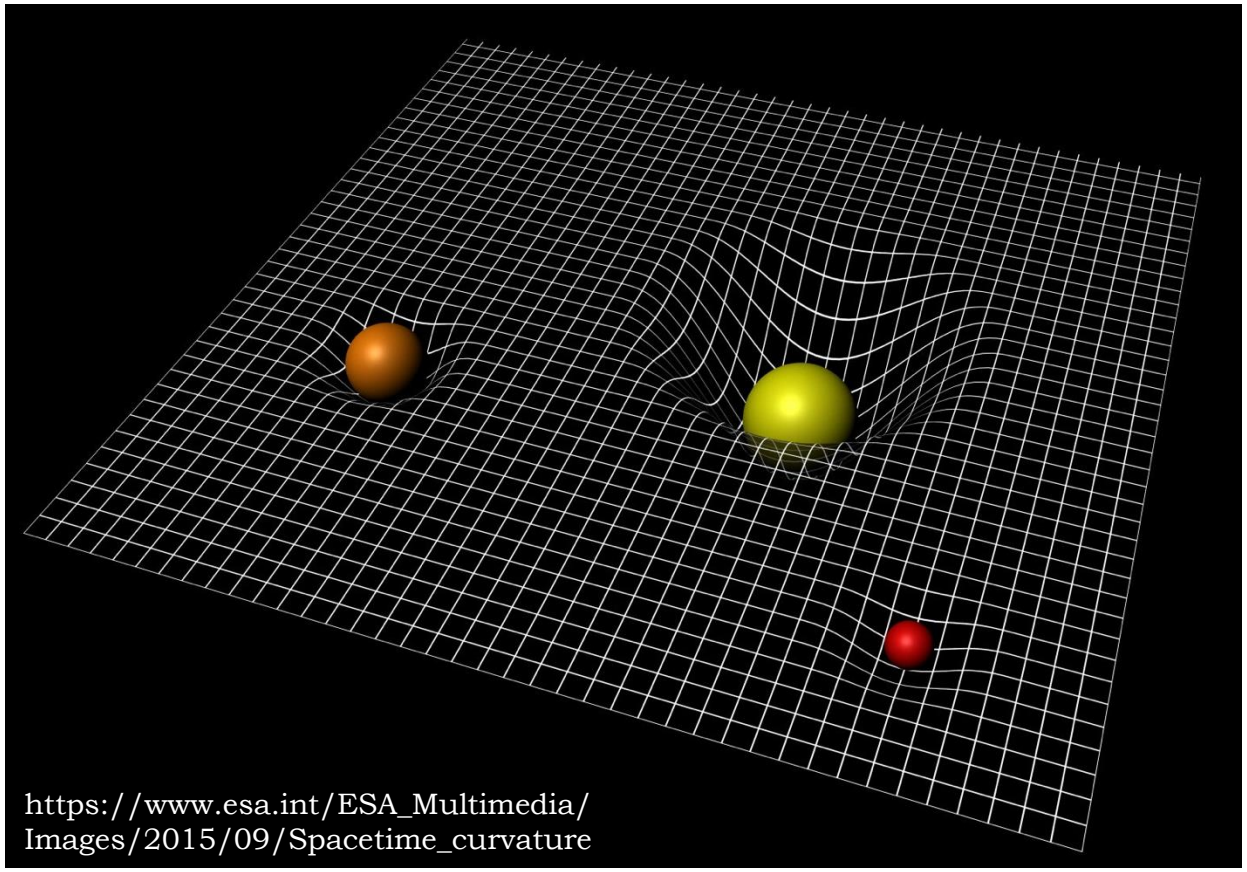




AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

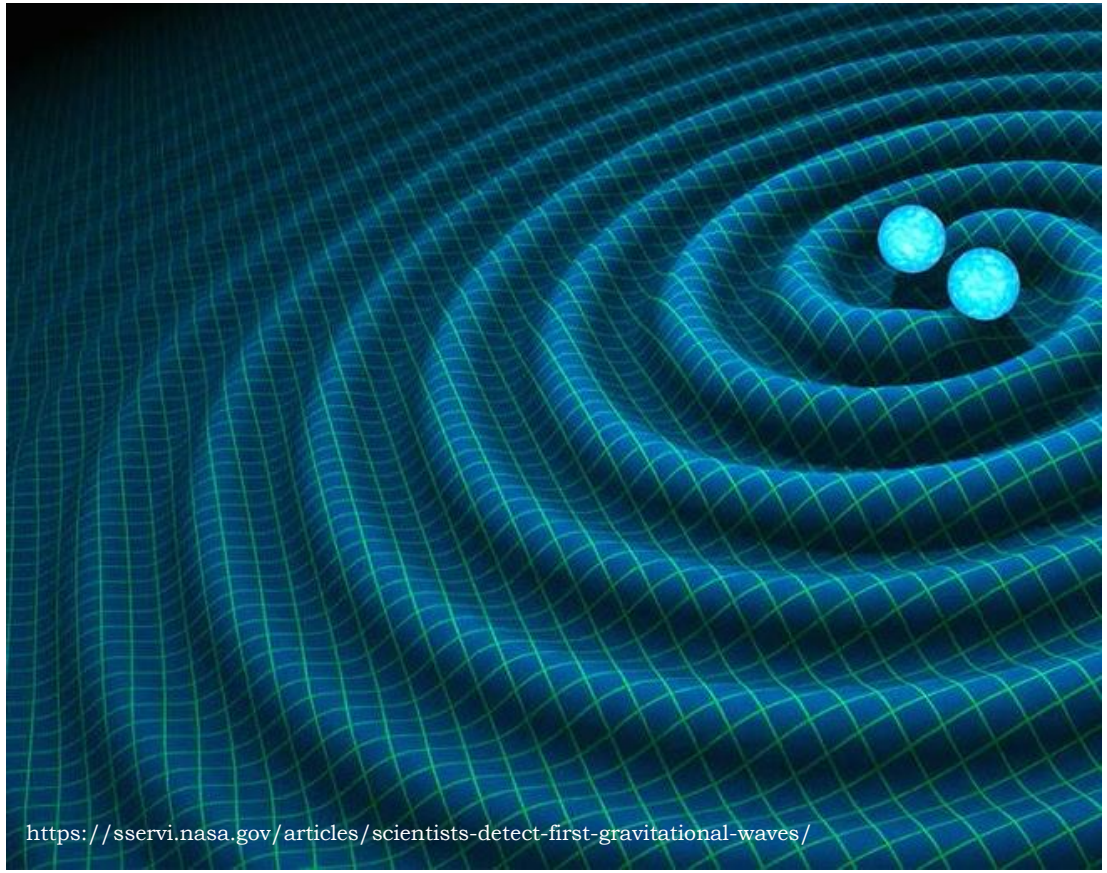
Gravitational waves

Massive objects distort space-time (gravity)



https://www.esa.int/ESA_Multimedia/Images/2015/09/Spacetime_curvature

Accelerating masses → strain waves



https://sservi.nasa.gov/articles/scientists-detect-first-gravitational-waves/

Gravitational wave detectors

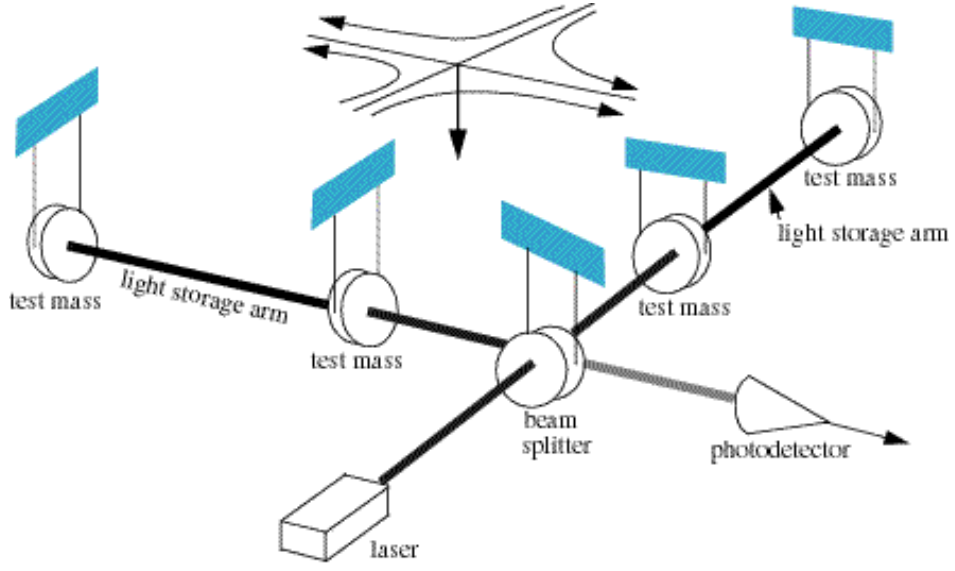


Image credit: LIGO Lab/Caltech/MIT

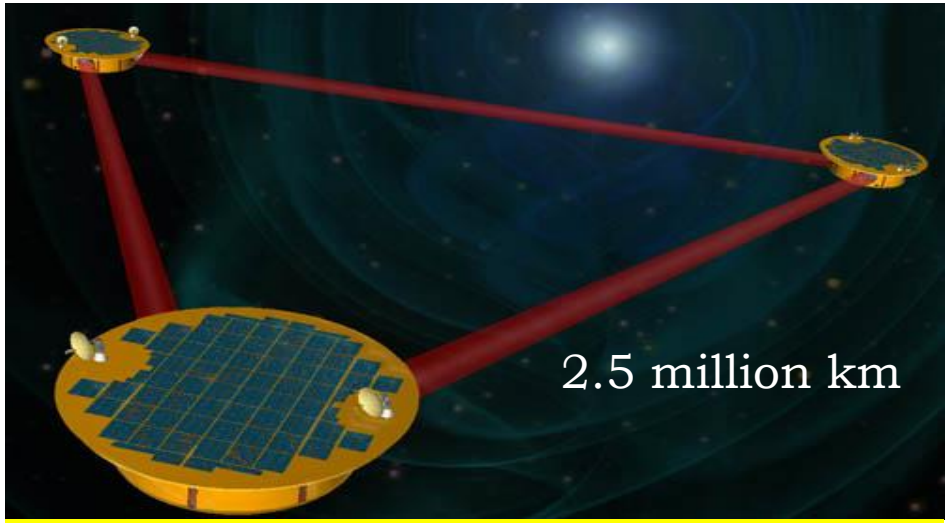
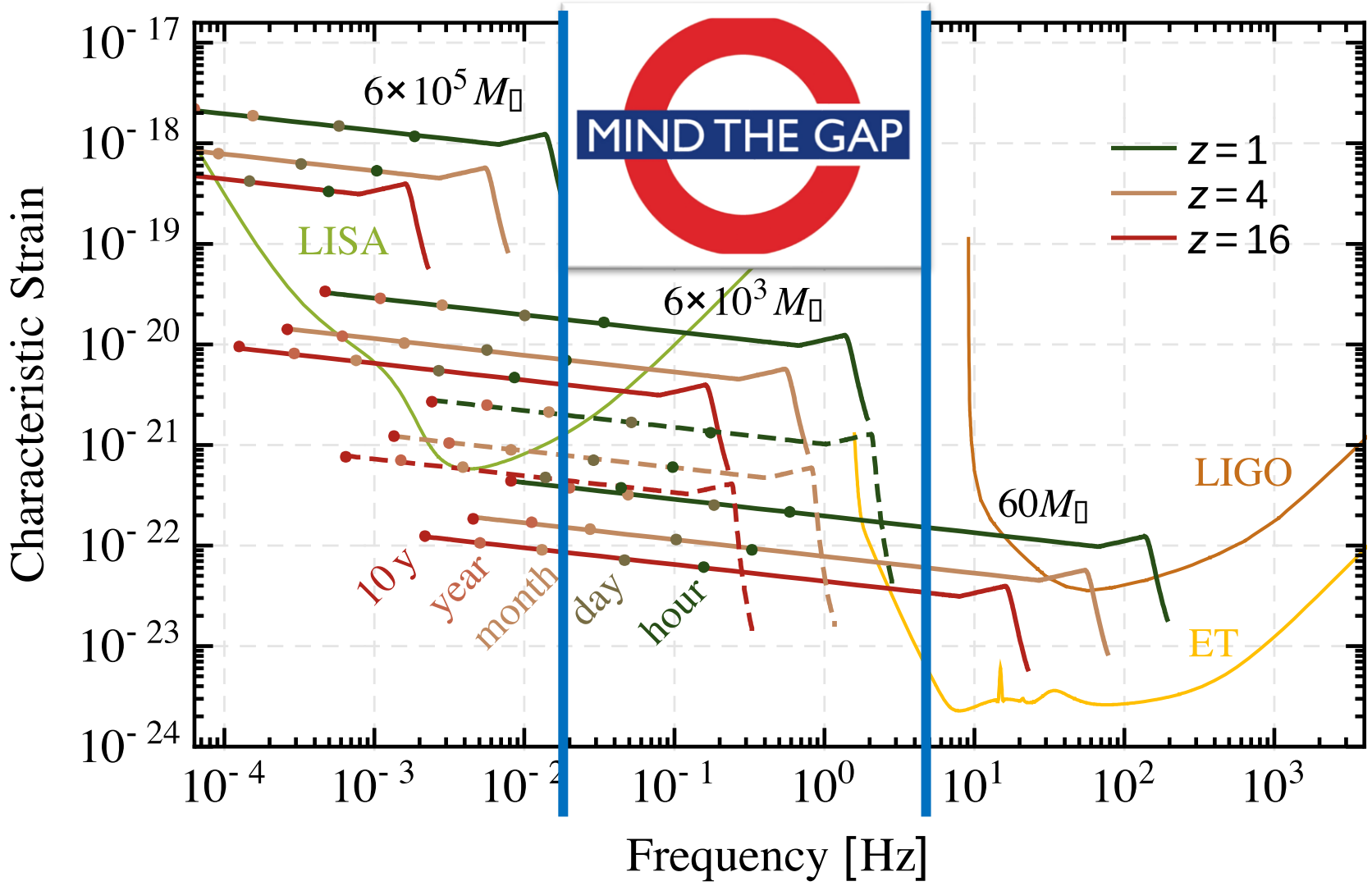


Image credit: NASA (LISA project)

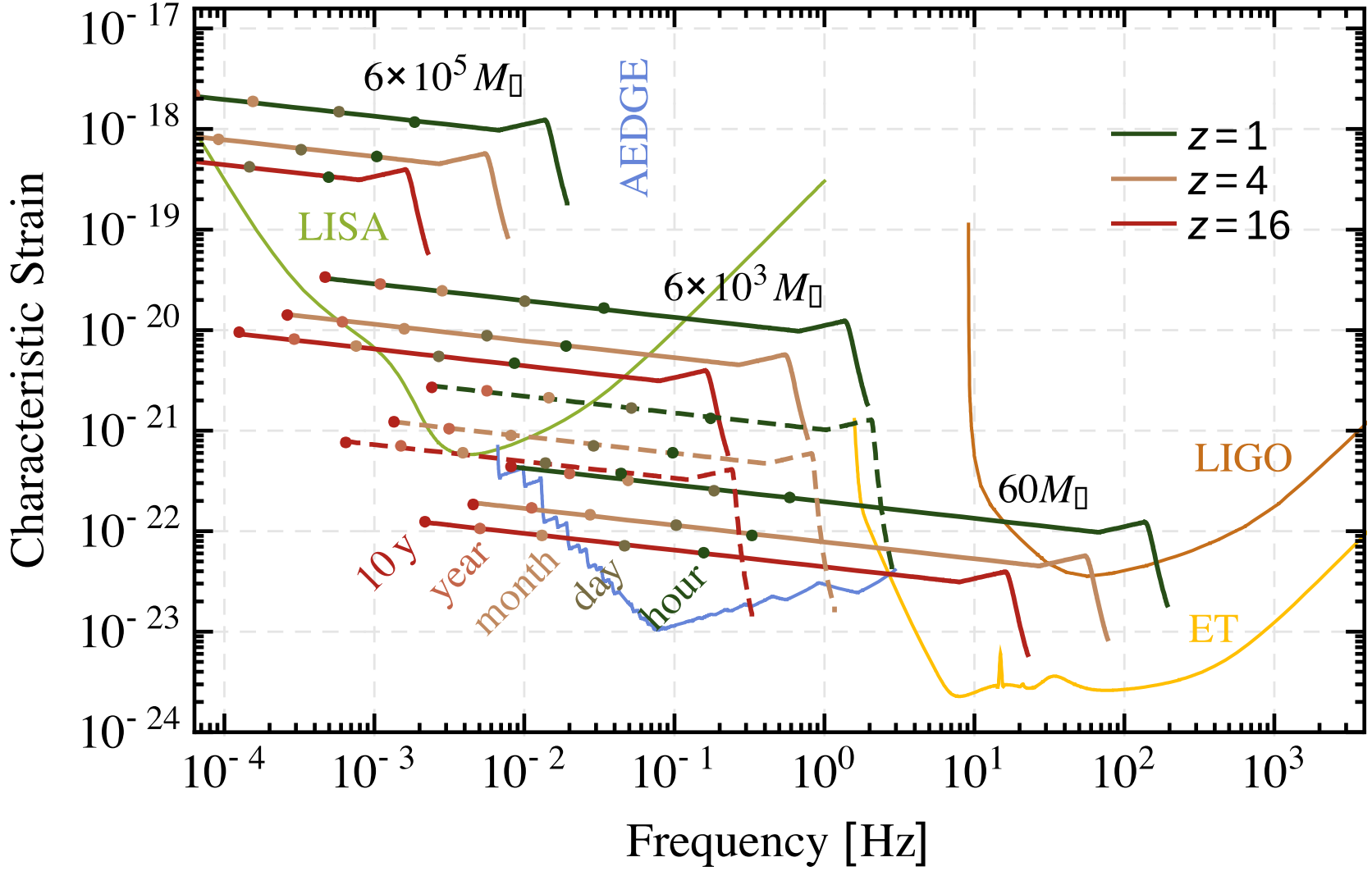
Change in arm length:

$$\Delta L = \delta L_x - \delta L_y = h(t)L$$

Gravitational waves: AION sensitivity



Gravitational waves: AION sensitivity



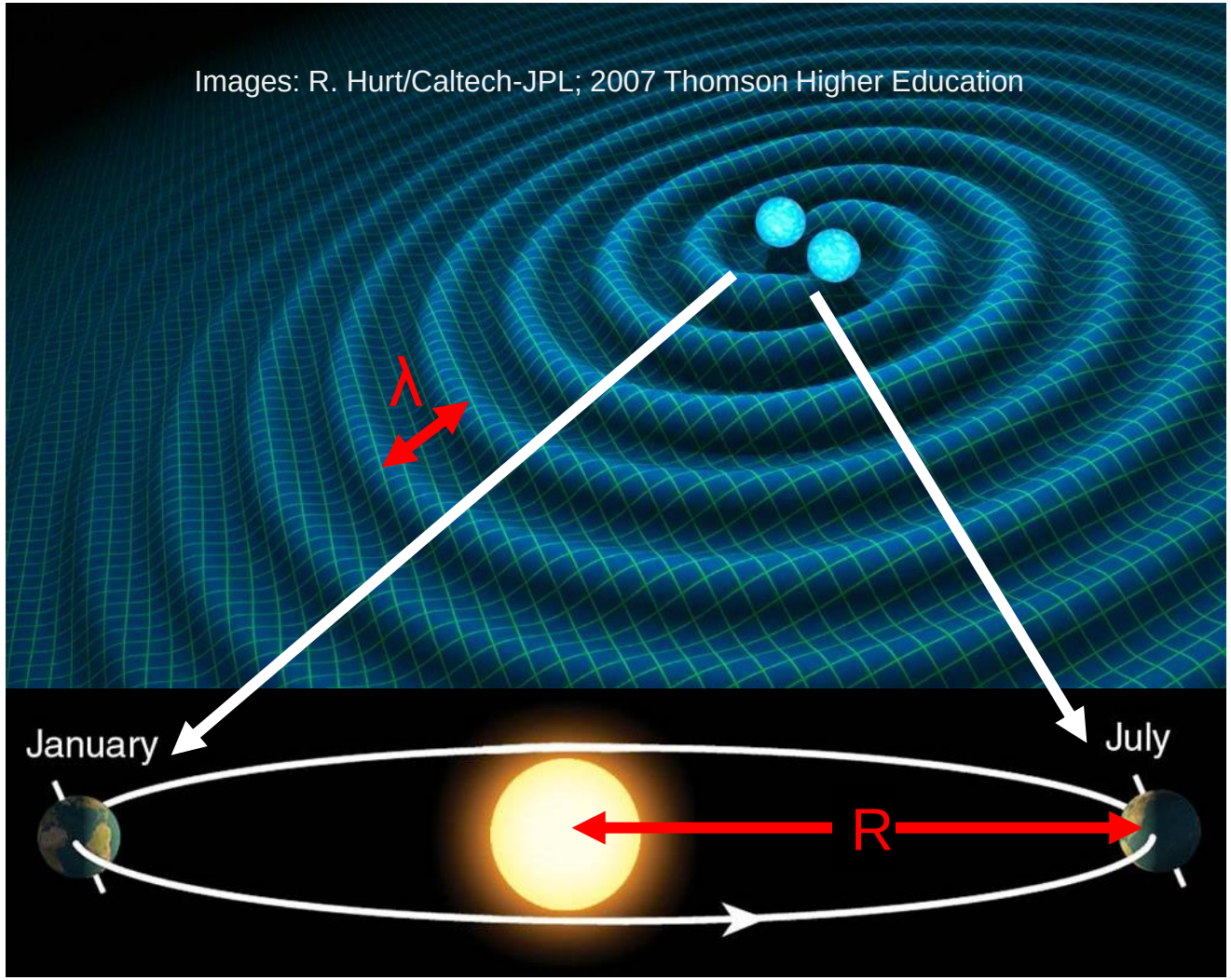
Gravitational waves: The mid-band

Signals last for ~ months

→ Multi-messenger astronomy

→ Triangulation of source location

Gravitational echoes from the very early universe: phase transitions?



Summary of physics goals

AION

1. Ultra-light dark matter

Peak sensitivity $m_\phi \lesssim 10^{-13}$ eV

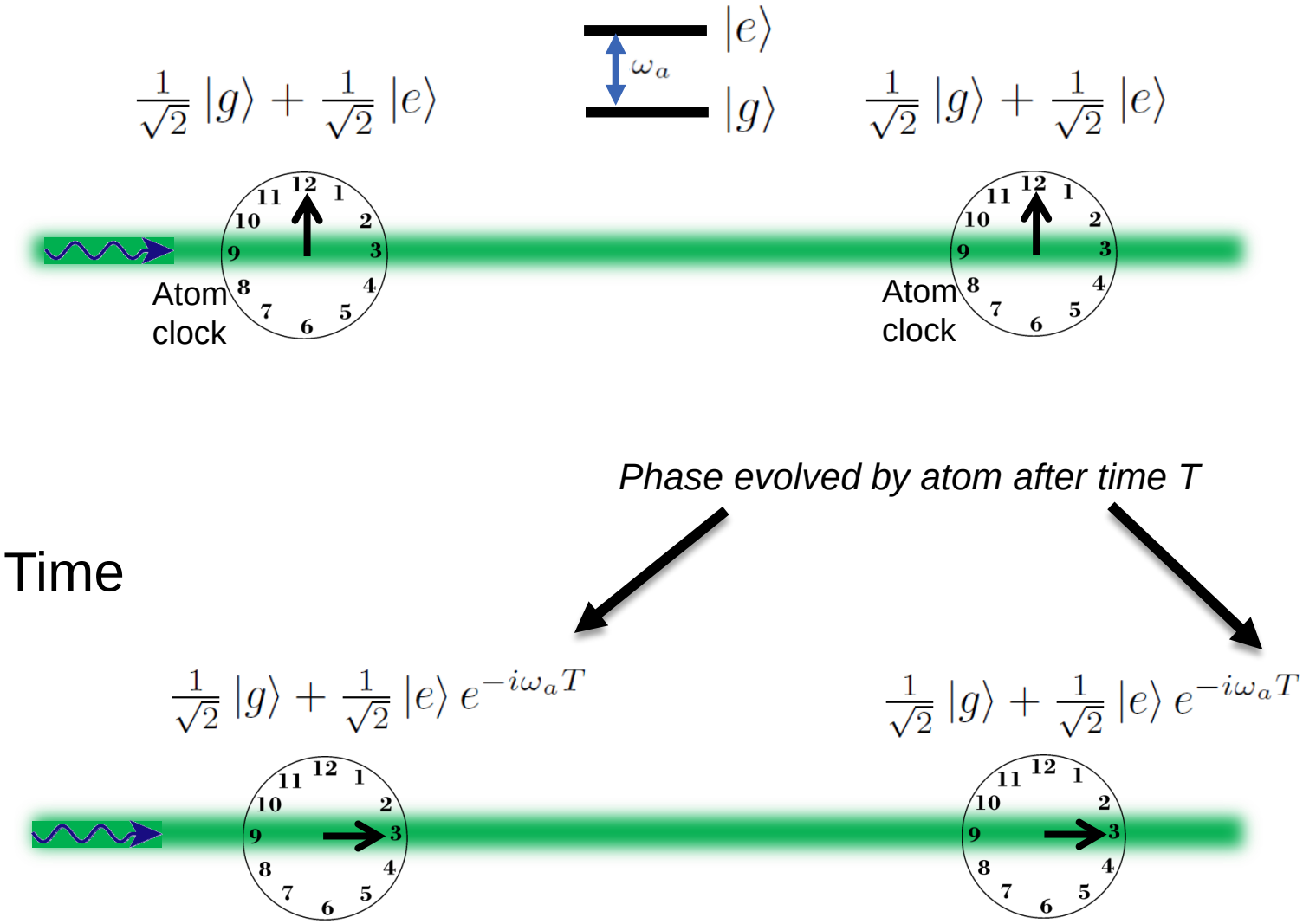
2. Mid-band gravitational waves

Peak sensitivity 10 mHz to 10 Hz (between LIGO and LISA)

But how are atom interferometers sensitive to these things?

Simple model: Two atomic clocks

Two-pulse clock
("Ramsey")



Simple model: Two atomic clocks

AION

$|e\rangle$

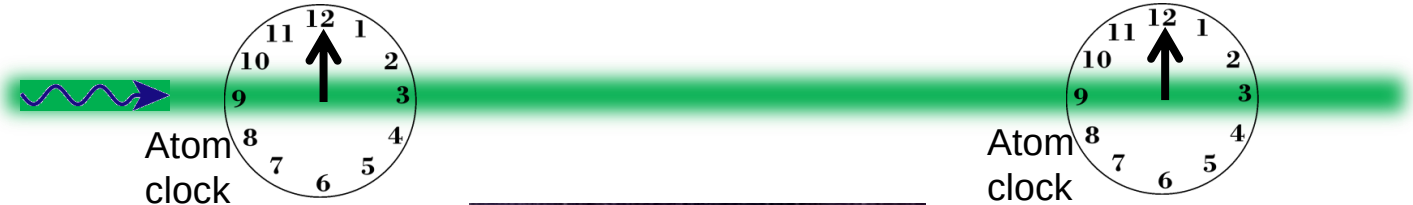
ω_a

$|g\rangle$

$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$

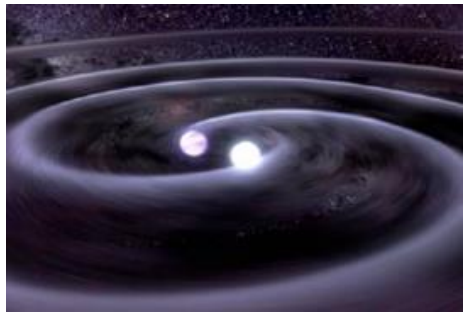
$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$

Pulse 1:



Atom clock

Atom clock



GW changes light travel time

$\Delta T \sim hL/c$

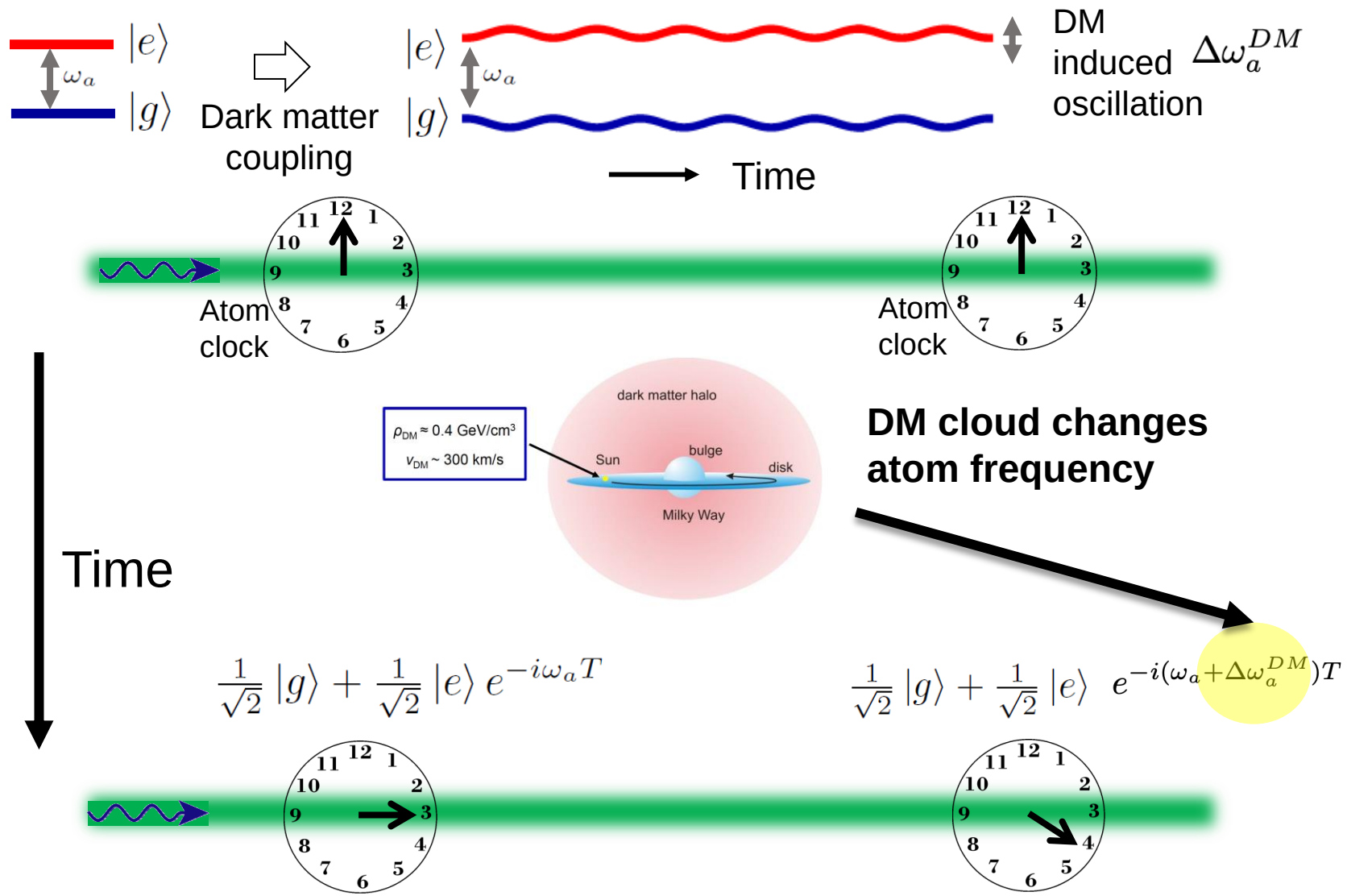
Time

$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T}$

$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a (T+\Delta T)}$

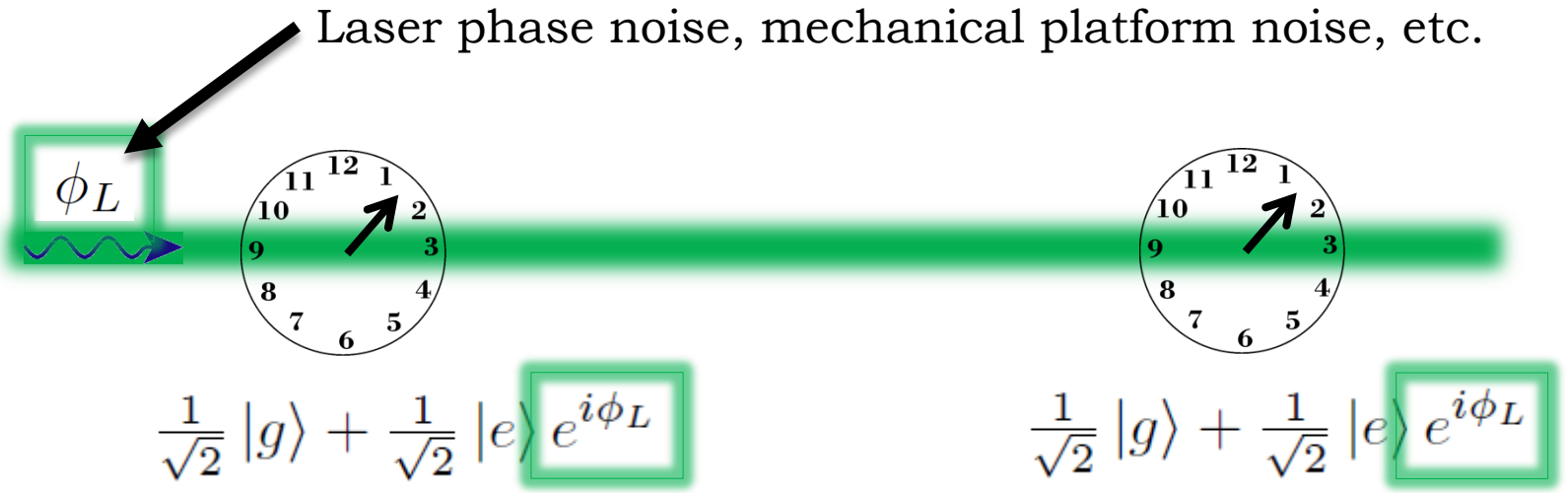
Pulse 2:

Simple model: Two atomic clocks



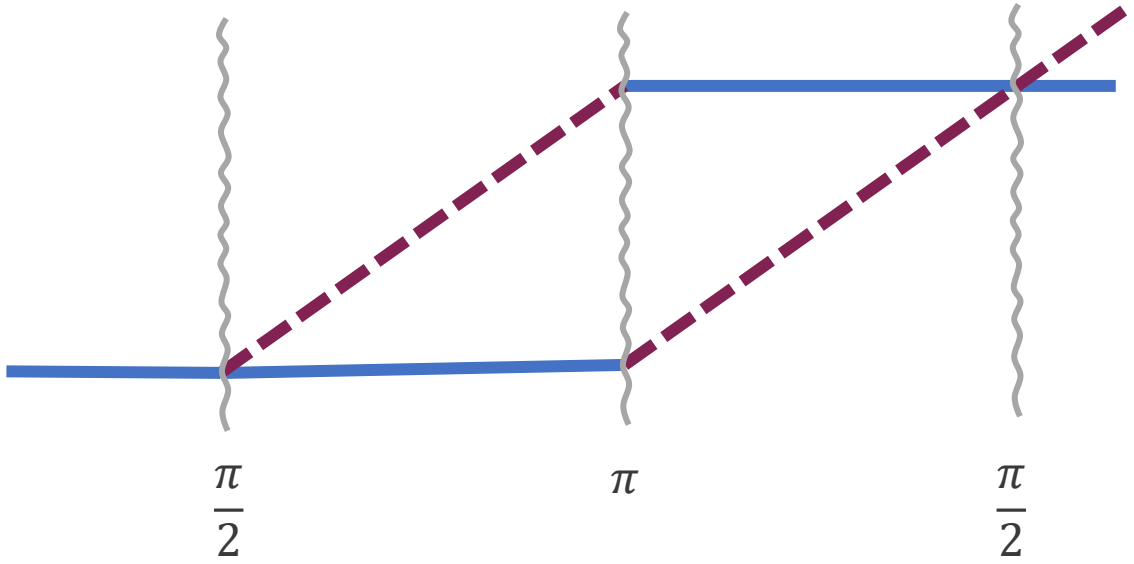
Simple model: Two atomic clocks

The phase of the laser is imprinted onto the atom.



Laser phase is **common** to both atoms → rejected in a differential measurement.

Full model: Atom interferometry



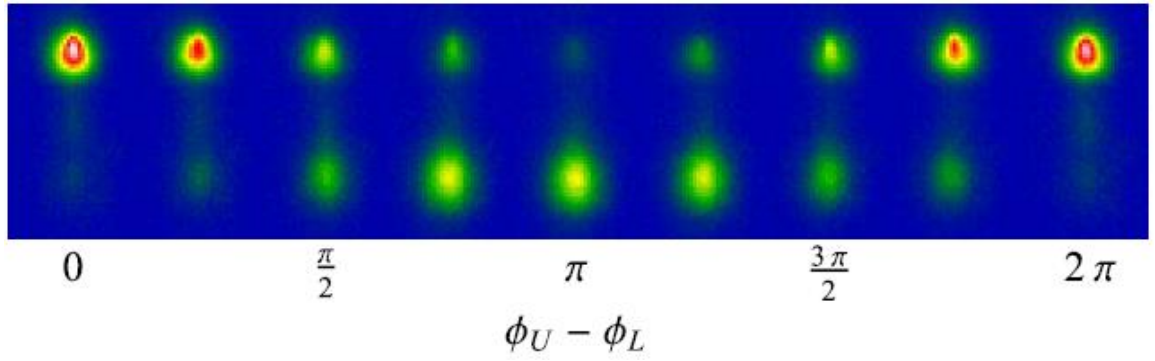
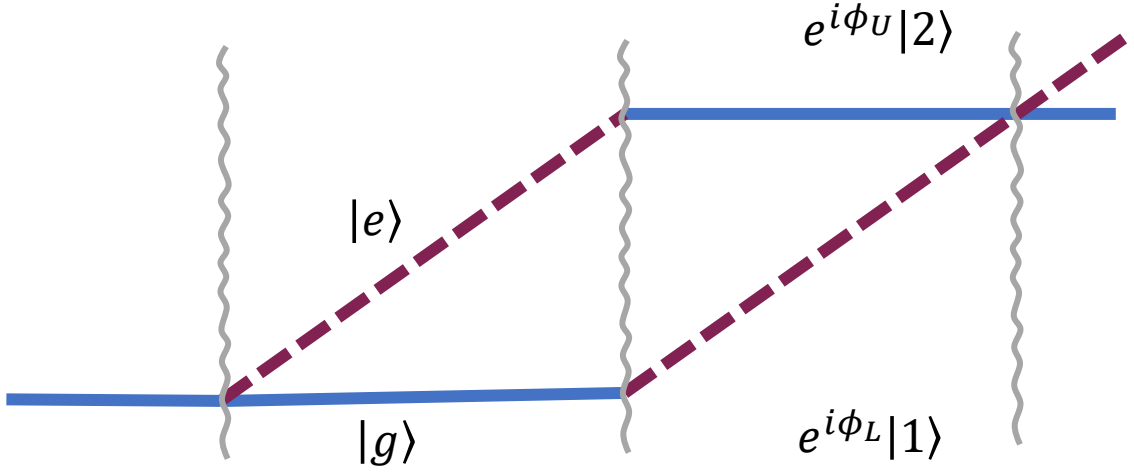
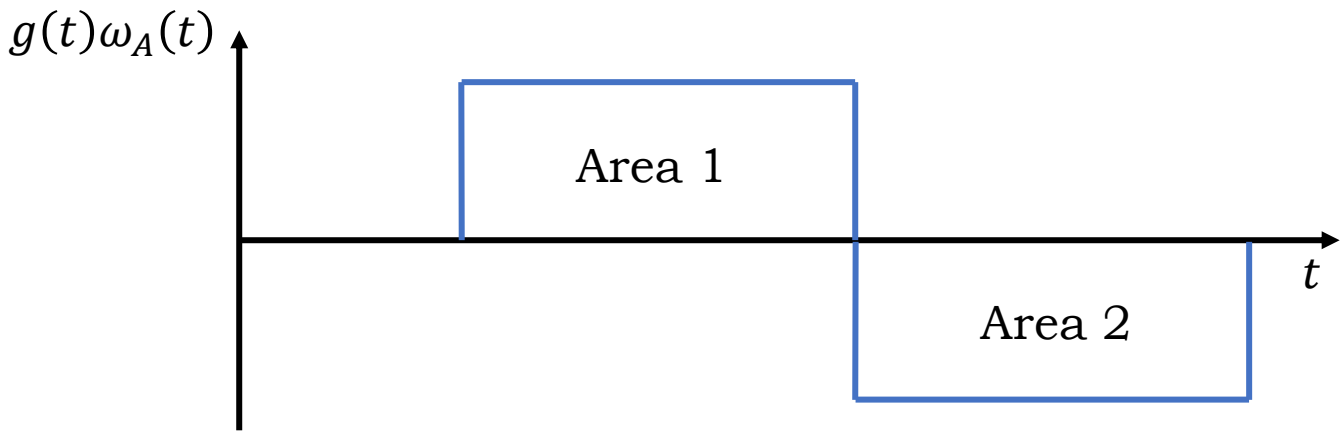


Image credit: Alex Sugarbaker PhD thesis, Kasevich group, Stanford

Sensitivity function





Interferometer signal ϕ:

$$\phi = \phi_U - \phi_L$$

"Clock" component of ϕ:

$$\phi_{clock} = \int g(t)\omega_A(t)dt$$

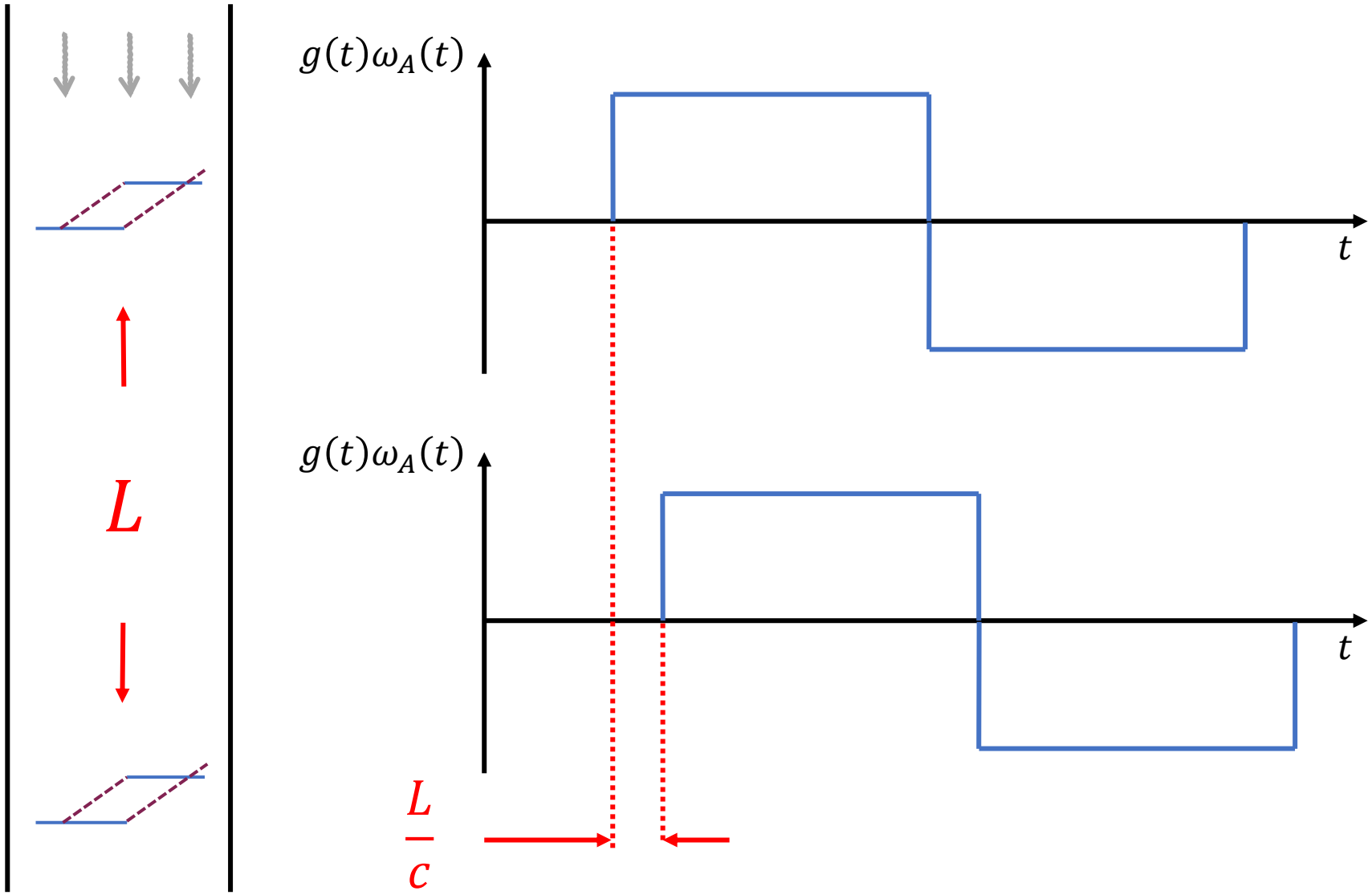
If

Area 1 = Area 2

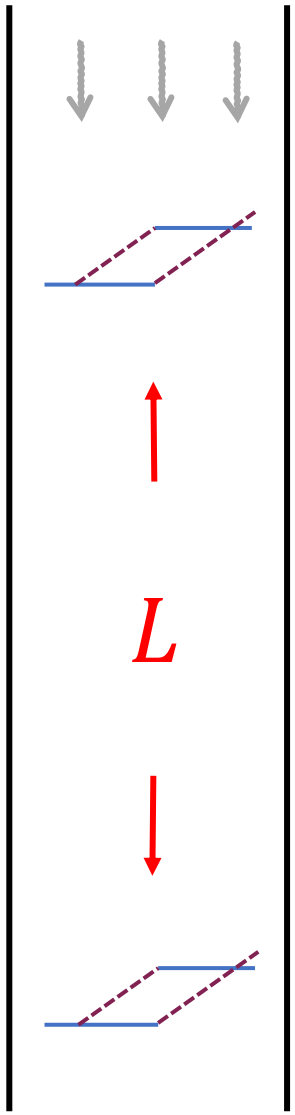
then

$$\phi_{clock} = 0$$

Two atom interferometers



Gravitational wave signal



$g(t)\omega_A(t)$

t

$\phi_{clock} = 0$

$g(t)\omega_A(t)$

t

Gravitational wave → fluctuating $\frac{L}{c}$

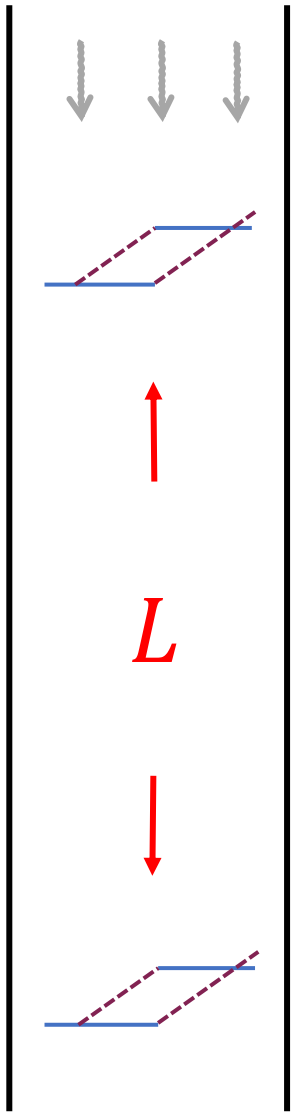
$\phi_{clock} \neq 0$

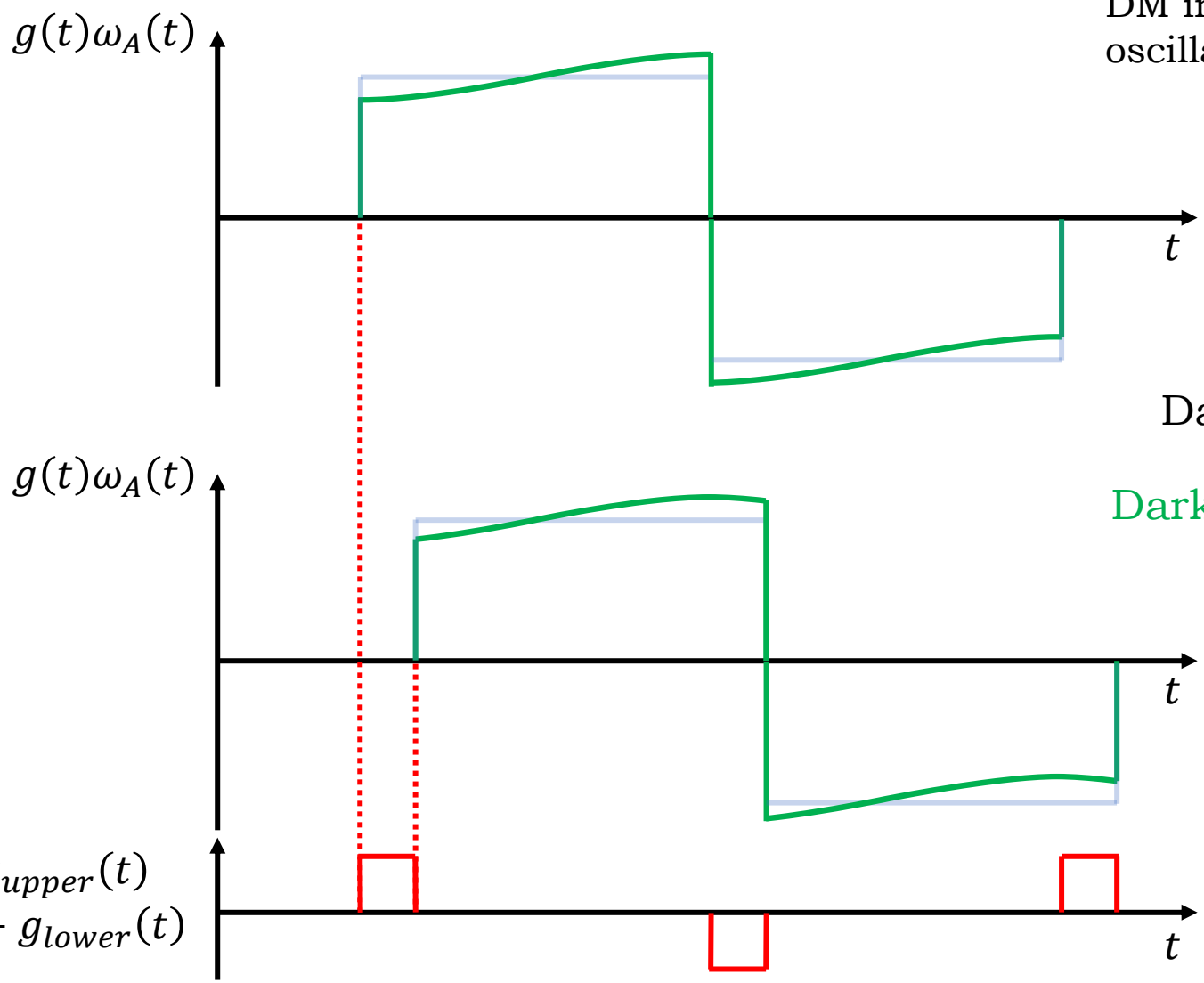
$\frac{L}{c}$

$\frac{\Delta L_1}{c}$

$\frac{\Delta L_2}{c}$

Dark matter signal





DM induced oscillation $|e\rangle$ $|g\rangle$

$\phi_{clock} = 0$

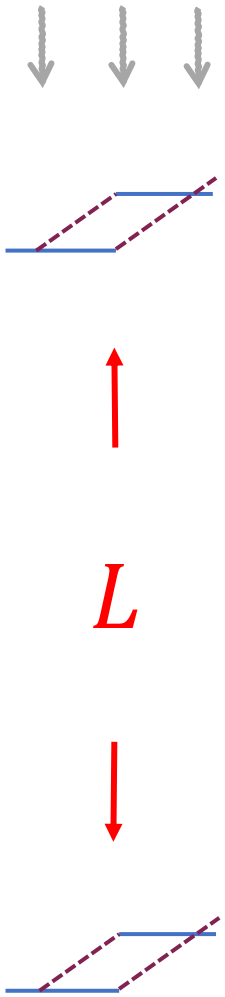
Dark matter → fluctuating ω_A

Dark matter is sampled differently because of L/c delay

$\phi_{clock} \neq 0$

Differential sensitivity

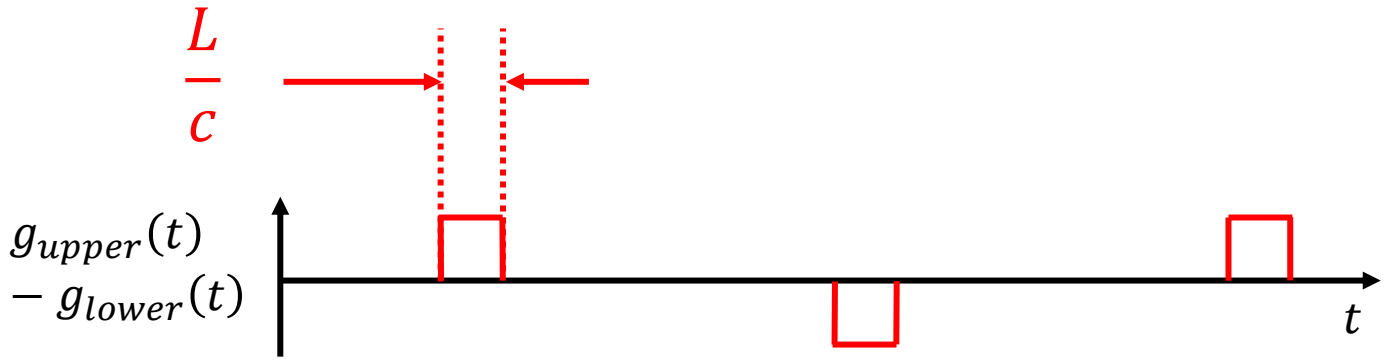
Sensitivity lever 1: Distance



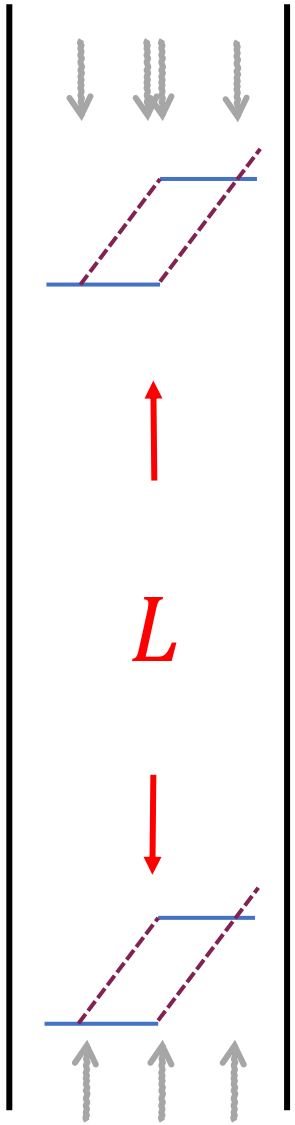
The gravitational wave signal increases with L because the length changes increase:

$$\Delta L = h(t)L$$

The dark matter signal increases with L because the **differential** sensitivity peaks get wider (i.e. there is more time L/c for the dark matter field to evolve):



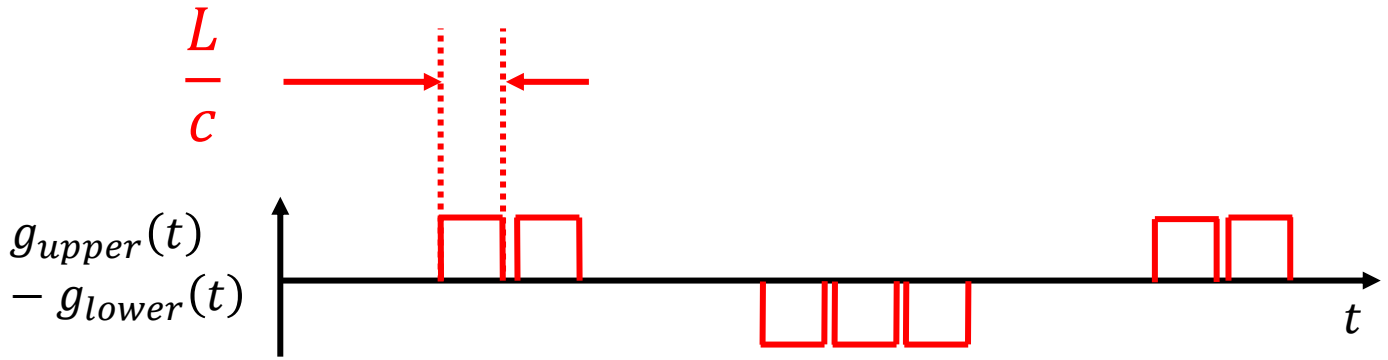
Sensitivity lever 2: More pulses



"Large momentum transfer": Send a train of n pulses from alternating directions

→ We sample the gravitational wave (or differential dark matter field) n times

Example: $n = 2$



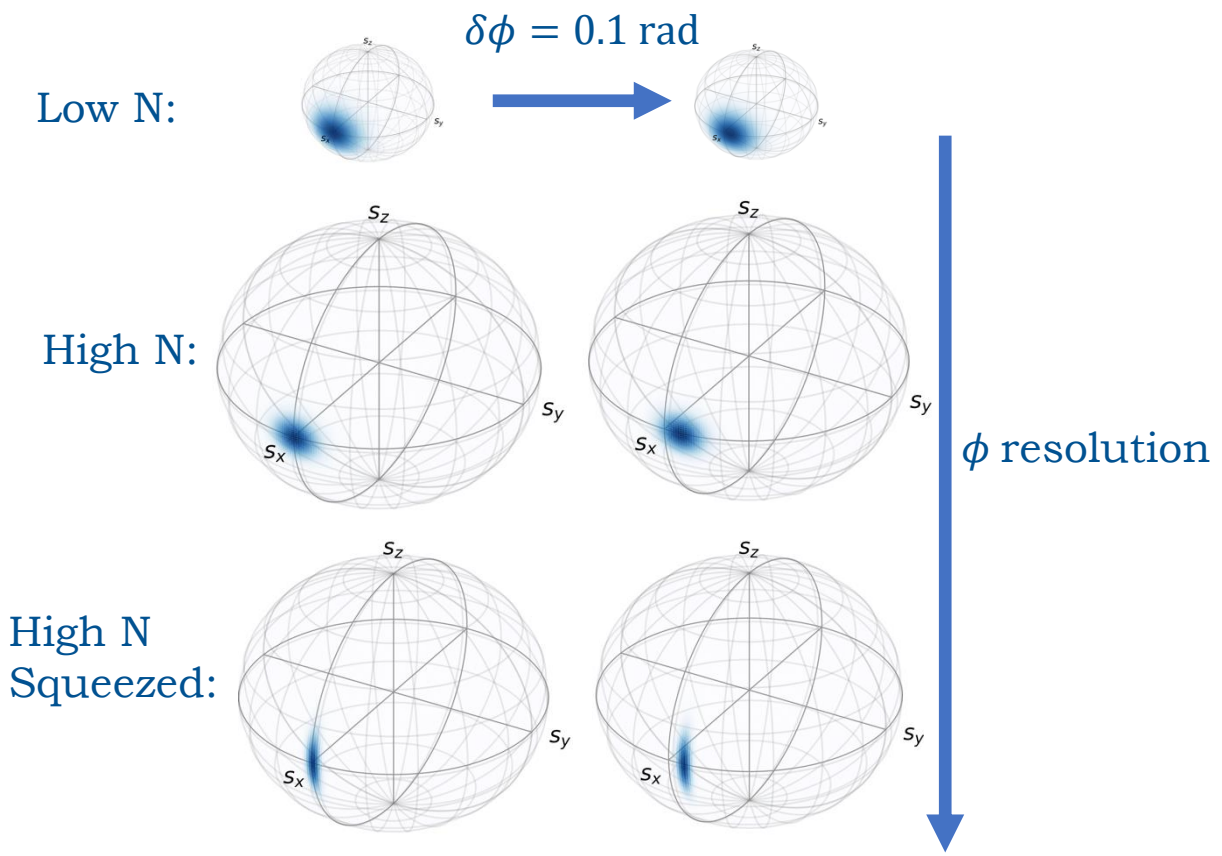
Sensitivity lever 3: Phase resolution

Atom shot noise limit:

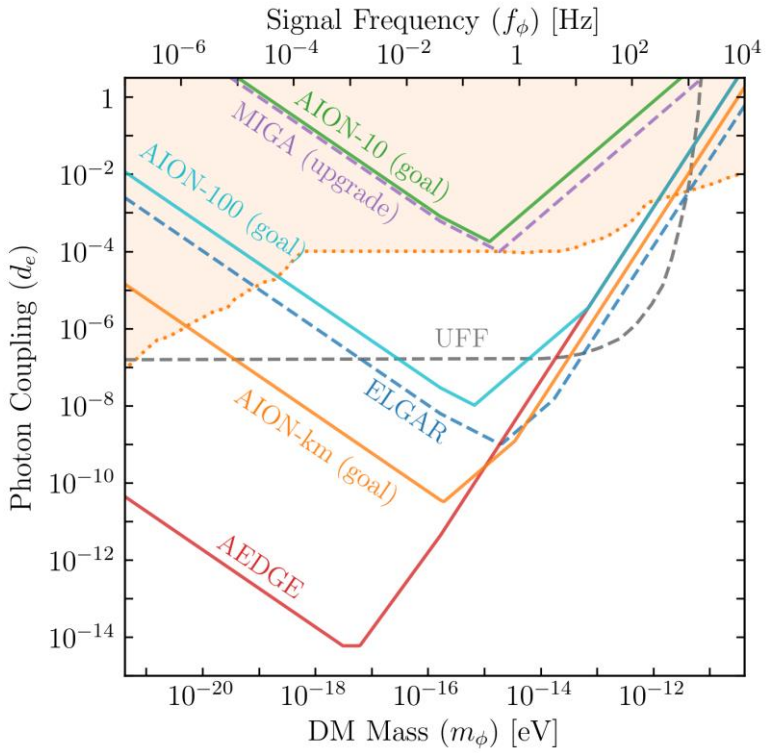
$$\delta\phi = \xi \times \frac{1}{\sqrt{N_{atoms}}}$$

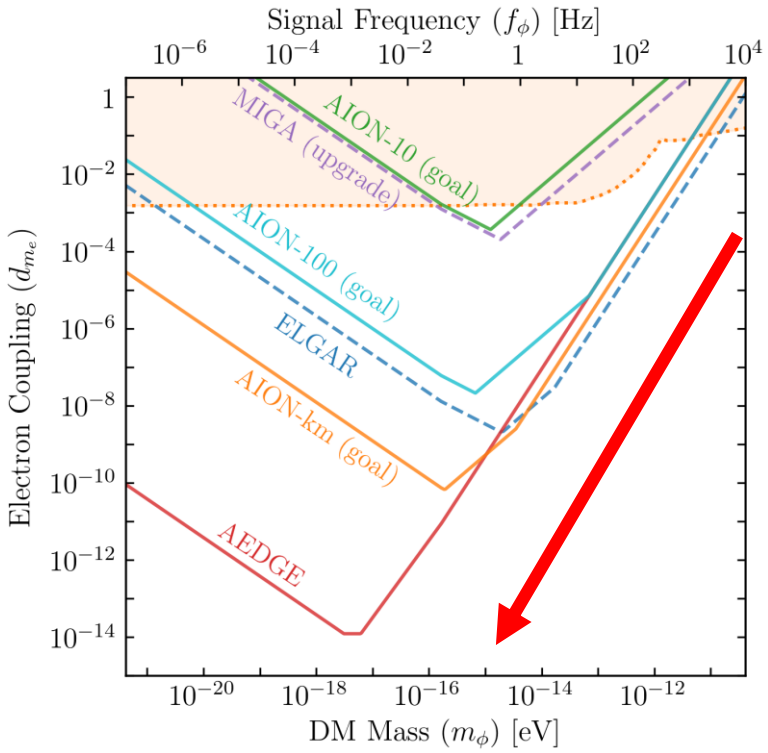
Quantum squeezing ($\xi < 1$)

More atoms



Project progression





Increasing sensitivity & Increasing cost

10 m

100 m

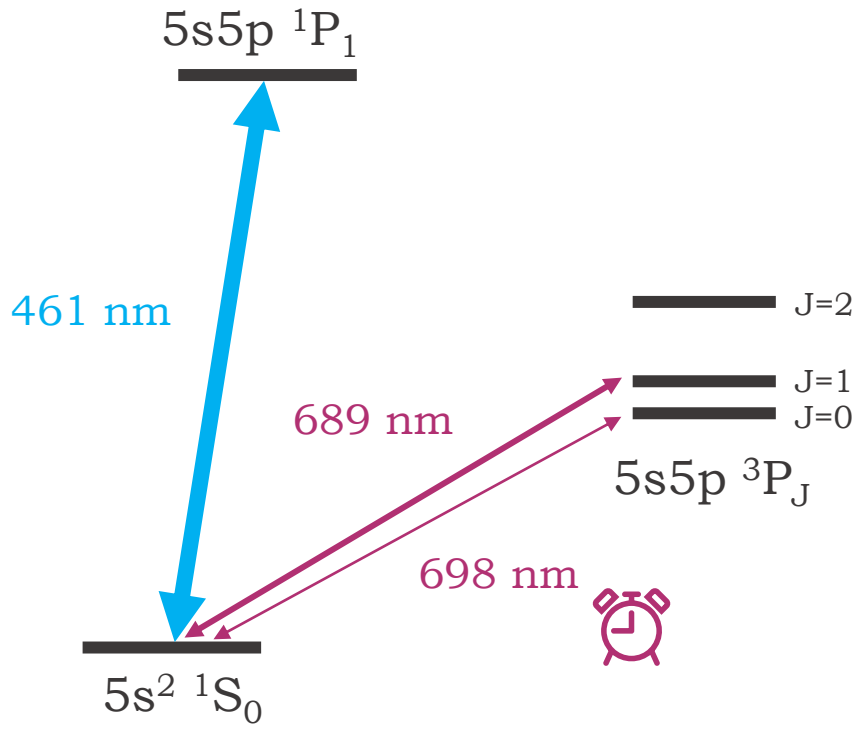
2 km

40,000 km

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

The AION experiment so far

- Sr
  - Clock transition
  - Single-photon interferometry [1,2]



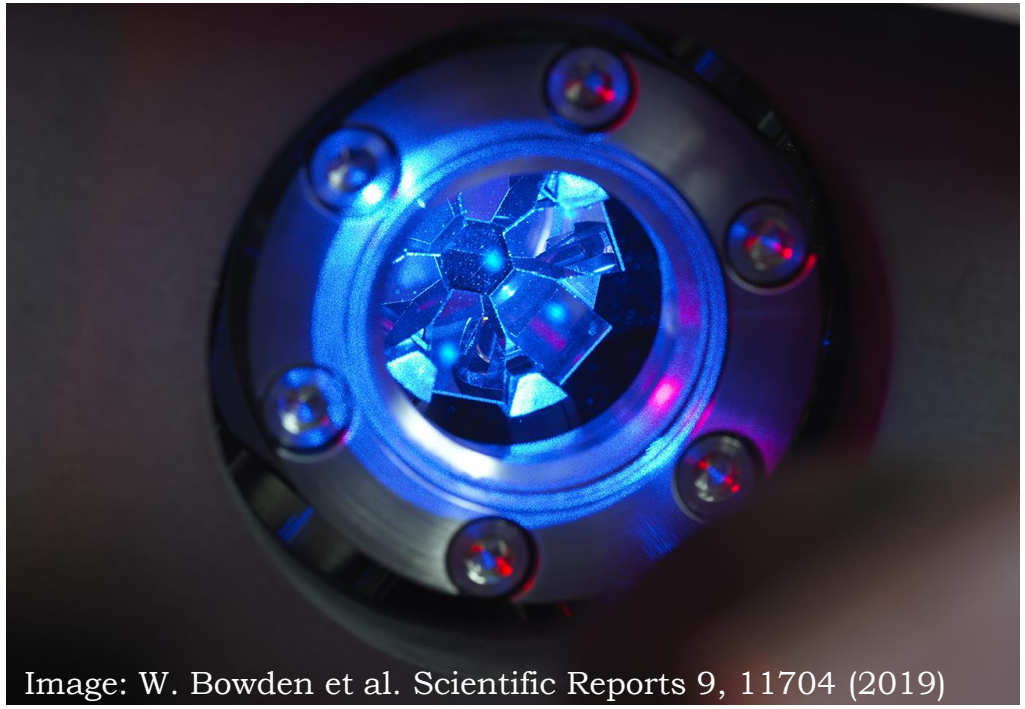
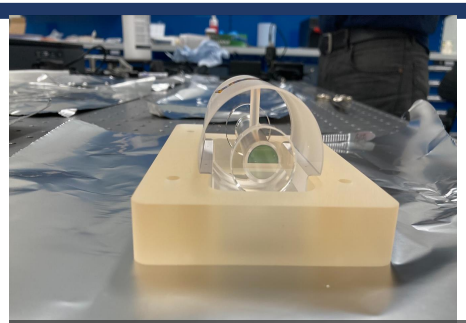


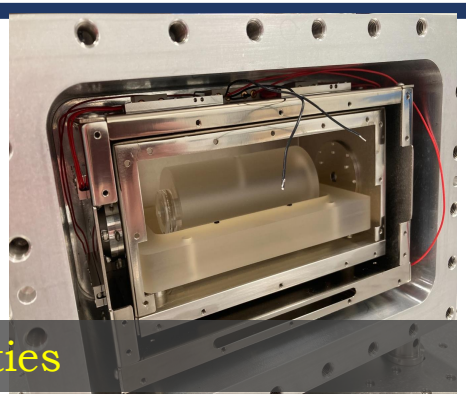
Image: W. Bowden et al. Scientific Reports 9, 11704 (2019)

Image:
Journal of Cosmology and Astroparticle Physics **5**, 011 (2020)

[1] P. Graham *et al.* PRL **110** 171102 (2013)
[2] L. Hu *et al.* PRL **119**, 263601 (2017)

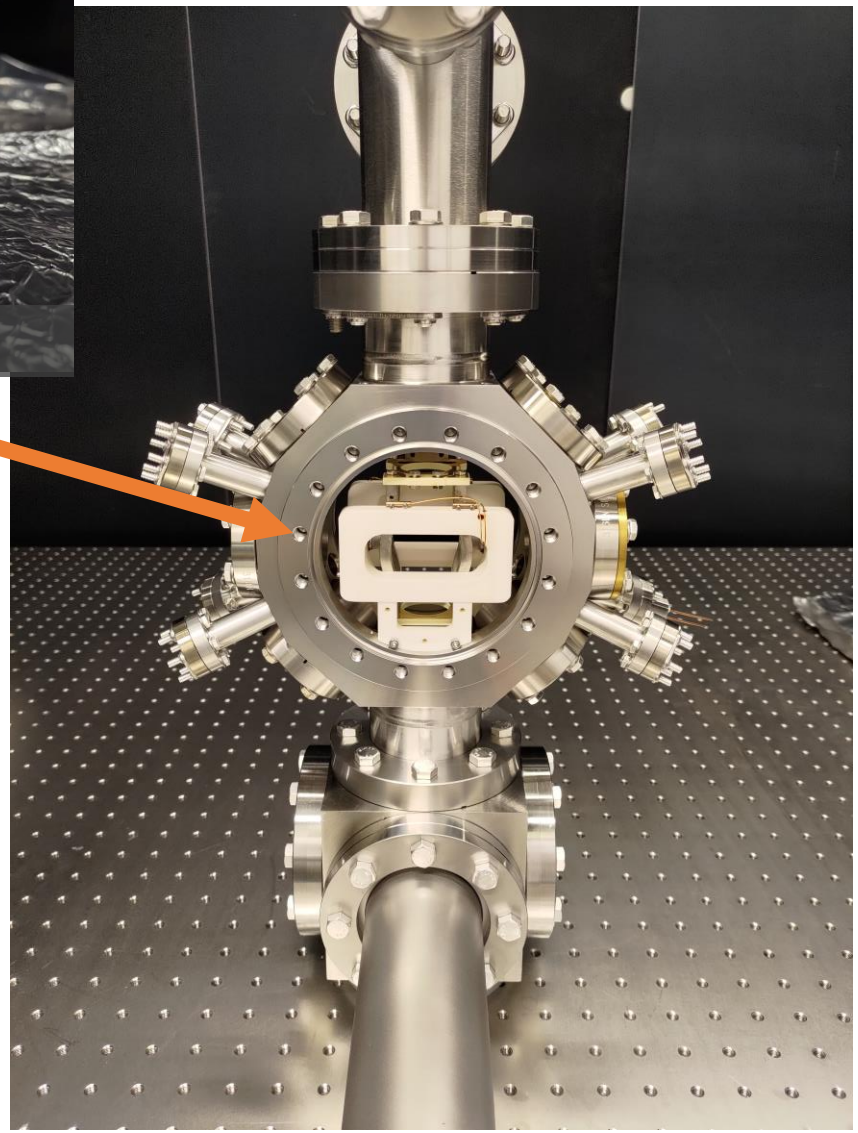
AION cold atom labs

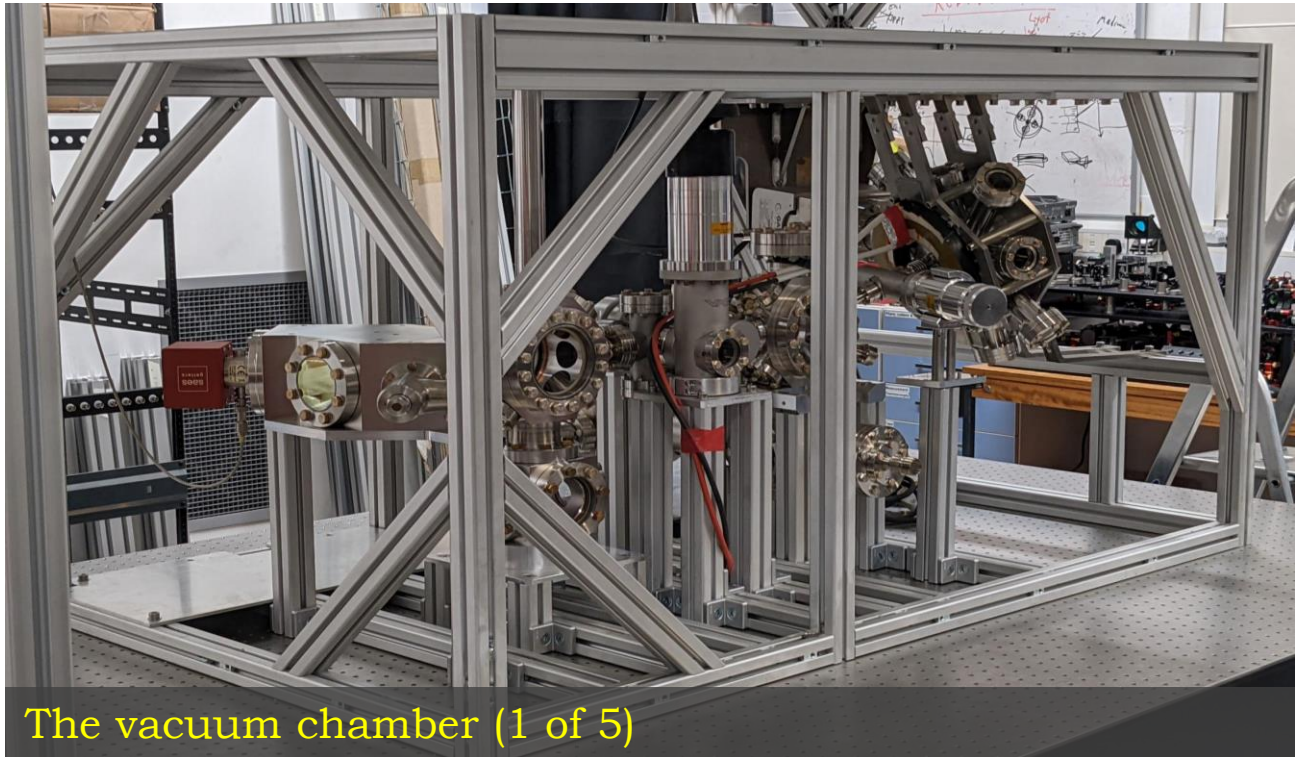




Laser stabilization cavities

Squeezing cavity

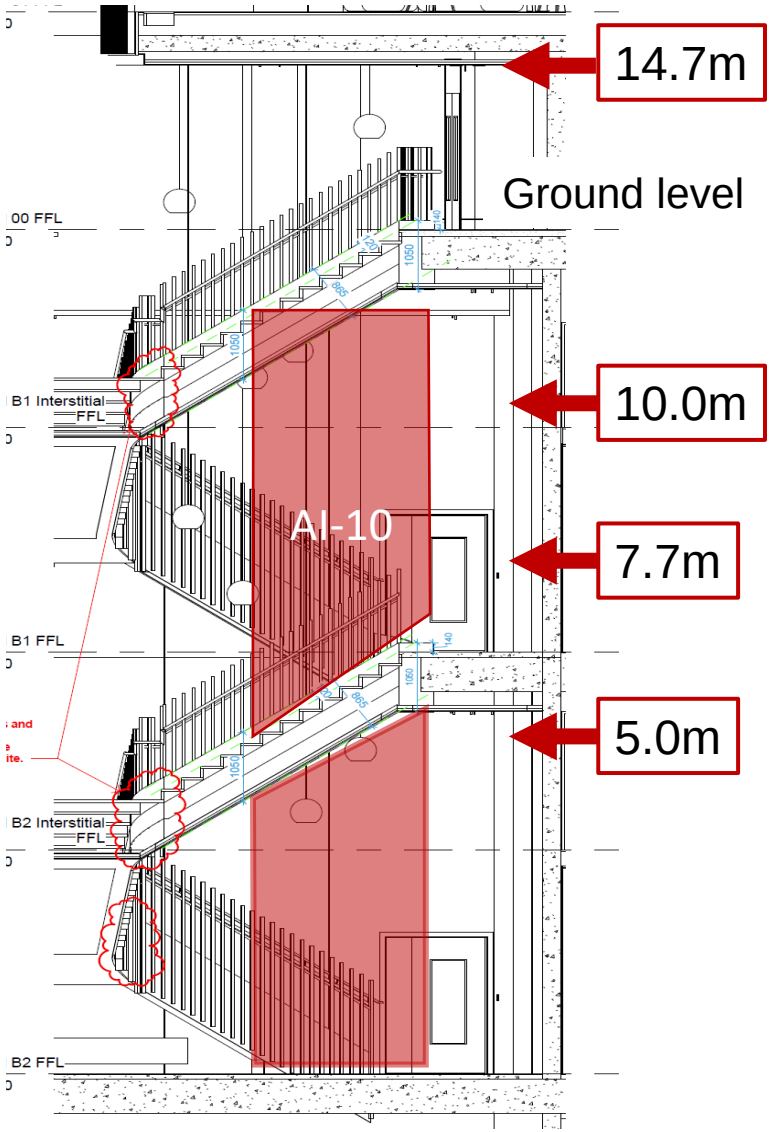


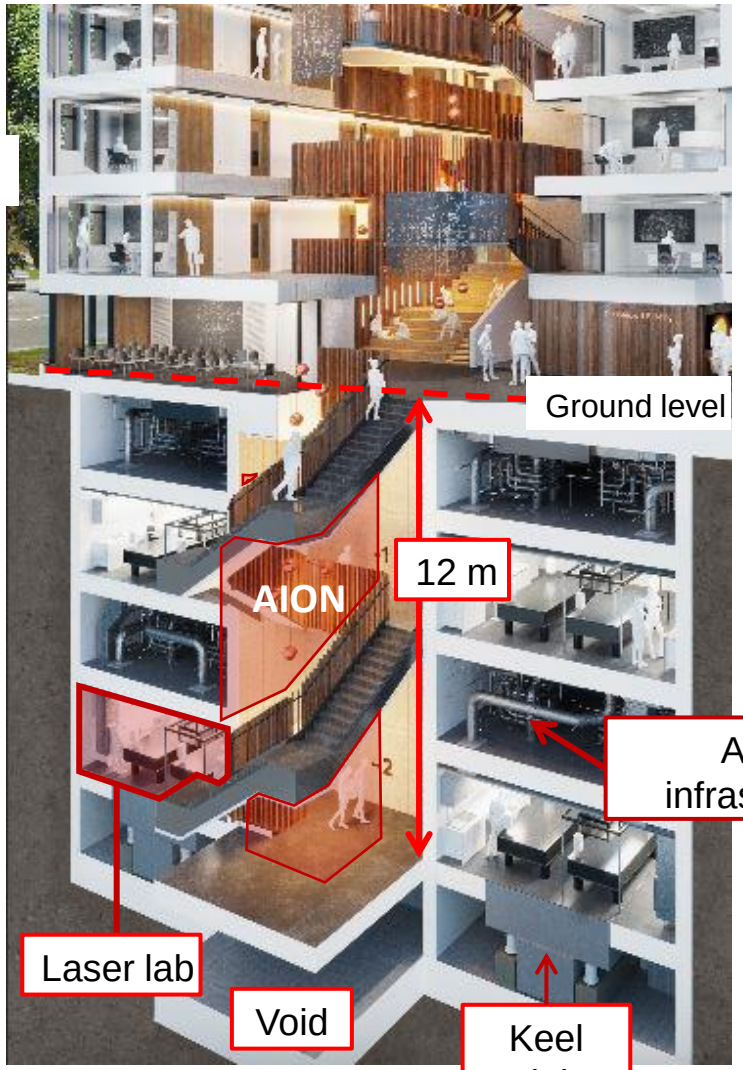


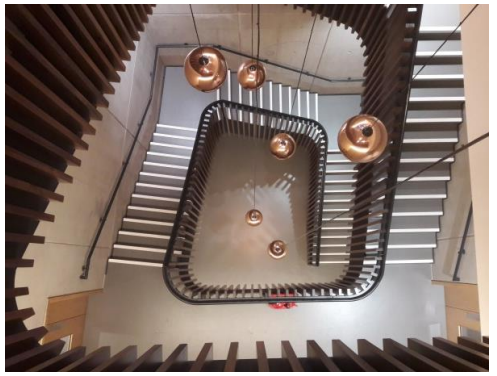
The vacuum chamber (1 of 5)

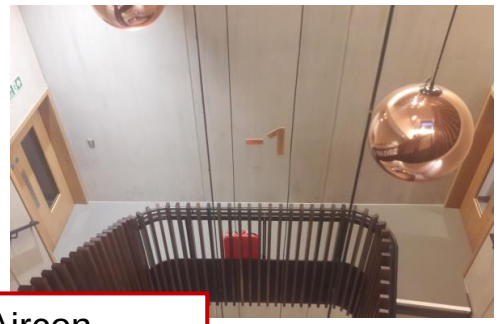
Cambridge July 2022
On the way:
Oxford September 2022
RAL October 2022
Imperial July 2022
Birmingham July 2022

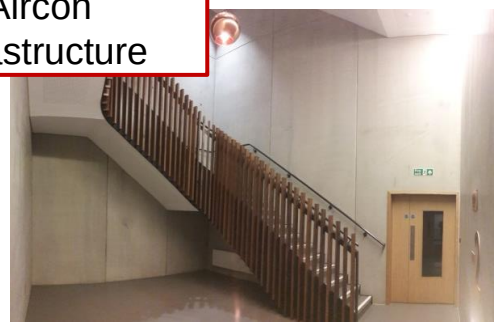
AION-10 prototype











Aircon infrastructure

Ultralow vibration

- All plant isolated
- Thick concrete walls

Adjacent laser lab reserved for AION use

- keel slabs
- $\pm 0.1^{\circ}C$ stability
- Isolated mains

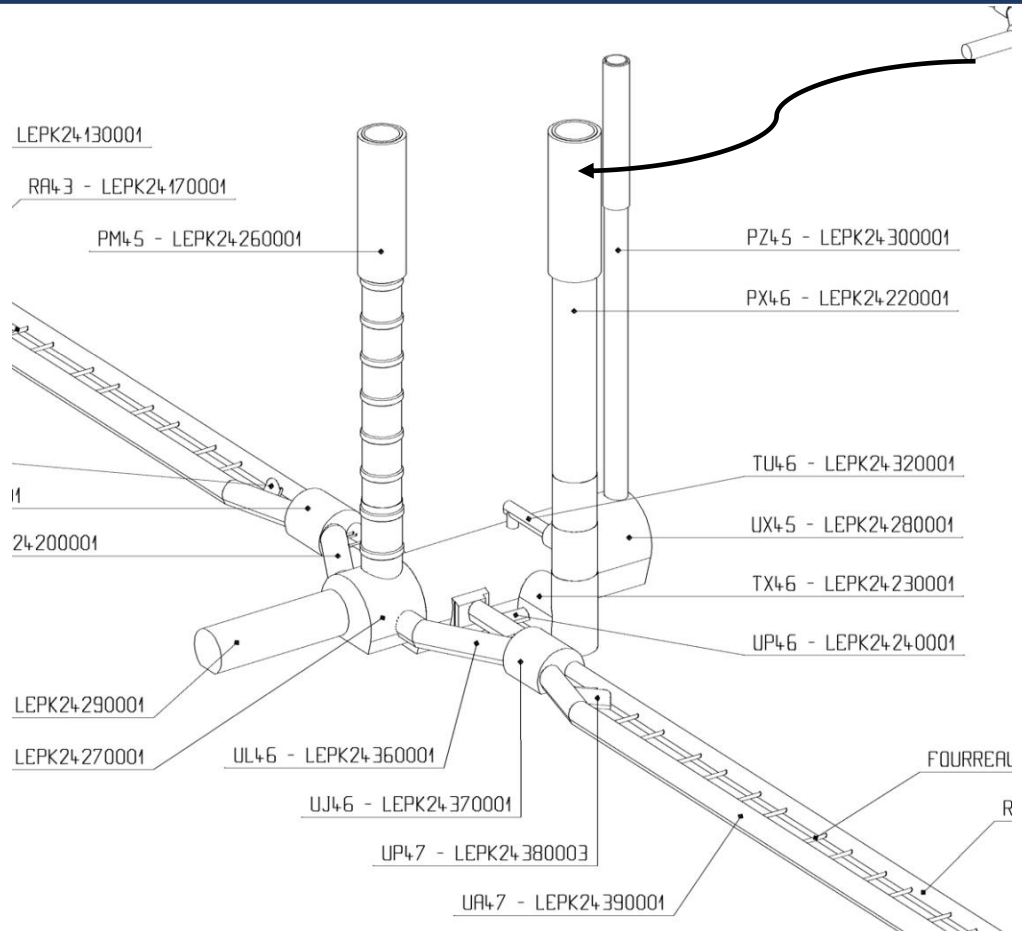
Vertical space

- 12m basement to ground floor
- 14.7m floor to ceiling

Stairwell is **not** a fire escape route.

Bakeout room and cleanroom nearby

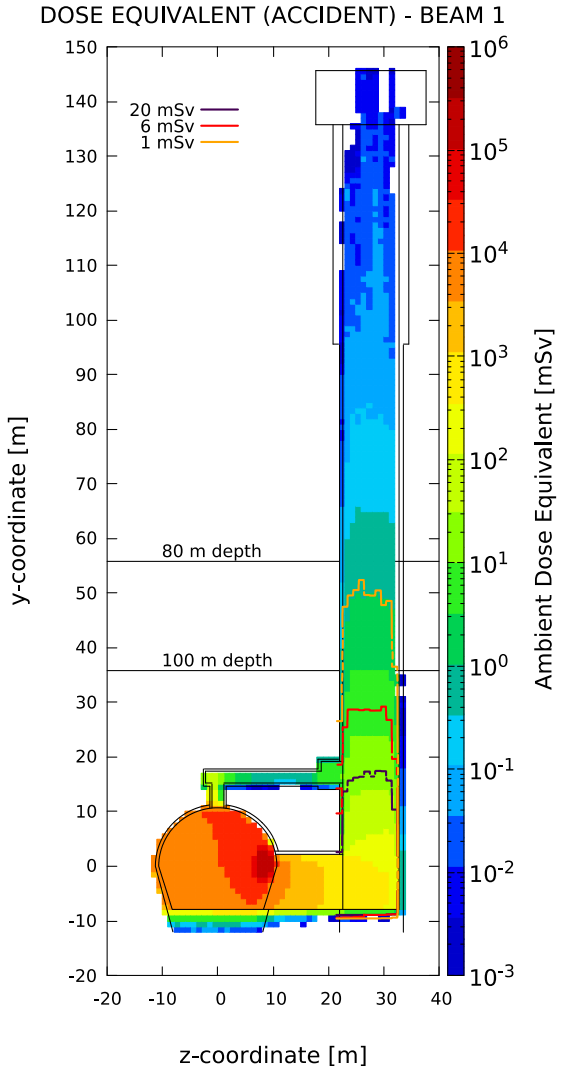
Outlook: 100-meter site at CERN



PX46 Support shaft
Length 143m
Diameter = 10.10m

Initial radiation and safety evaluations look promising, but more work is needed.

Feasibility study with CERN's Physics Beyond Colliders (PBC) team by ~ early 2023

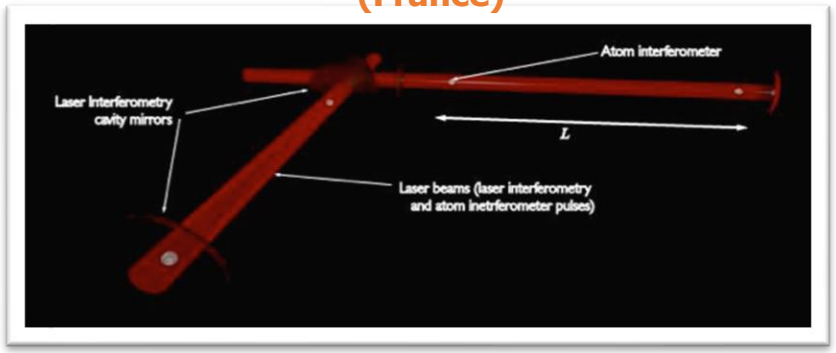


Alternative site options: the national facilities in Boulby (UK) or Daresbury (UK)

Outlook: Global efforts

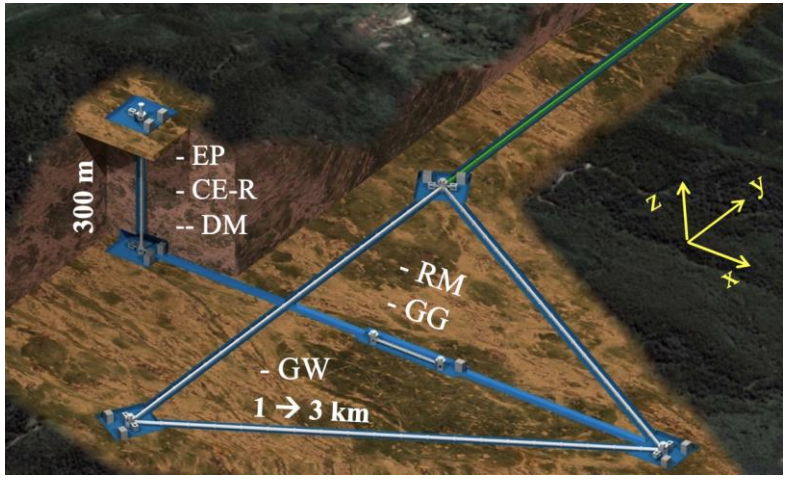
MIGA: Terrestrial detector using atom interferometer at O(100m)

(France)



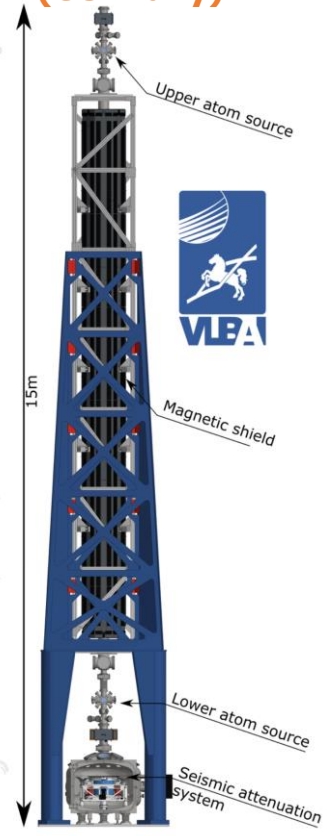
ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)

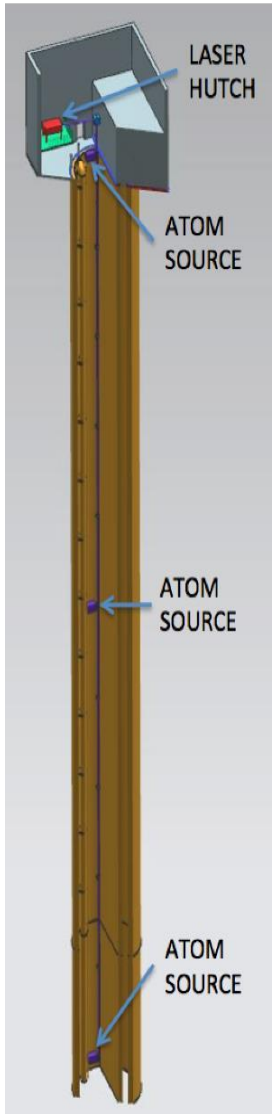
(China)



VLBAI: Terrestrial tower using atom interferometer O(10m)

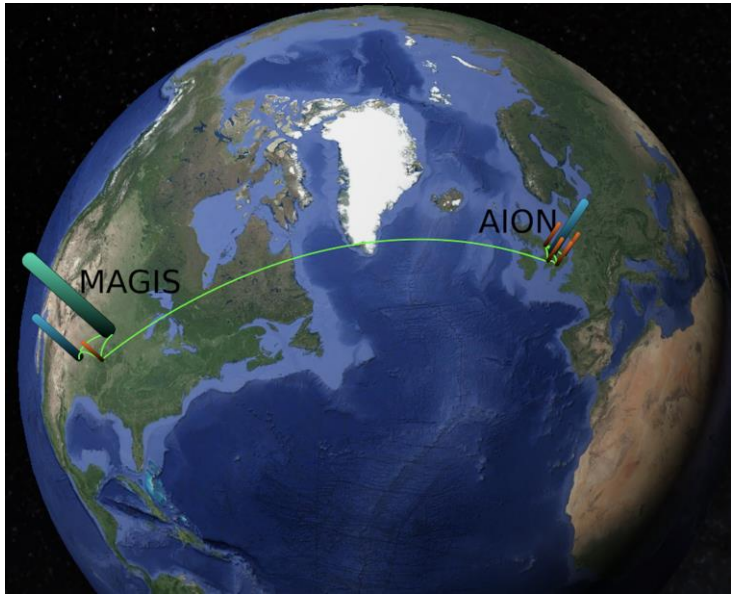
(Germany)





AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned

(UK)



MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)

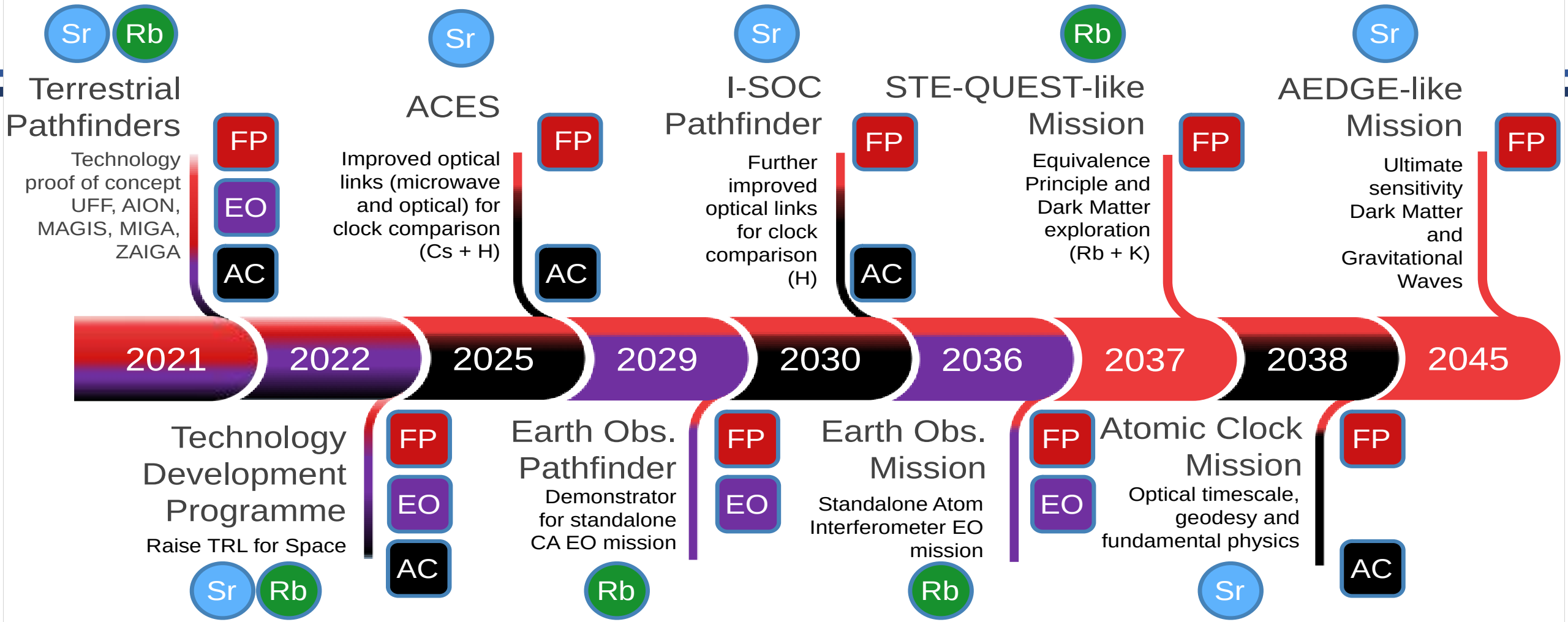
(US)

Planned network operation

The end

~ 1:1 ratio of Cold Atom Physicists : Particle/Fundamental Physicists

Community Proposal for an ESA Road-Map for Cold Atoms in Space



Legends:

Main Cold Atom Species

- Sr — Strontium
- Rb — Rubidium

Areas of Relevance

- EO — Earth Observation
- AC — Atomic Clocks
- FP — Fundamental Physics

Main Milestone Area (colour coded)

2045 — Example: Fundamental Physics

CERN AION100 Site Exploration with PBC

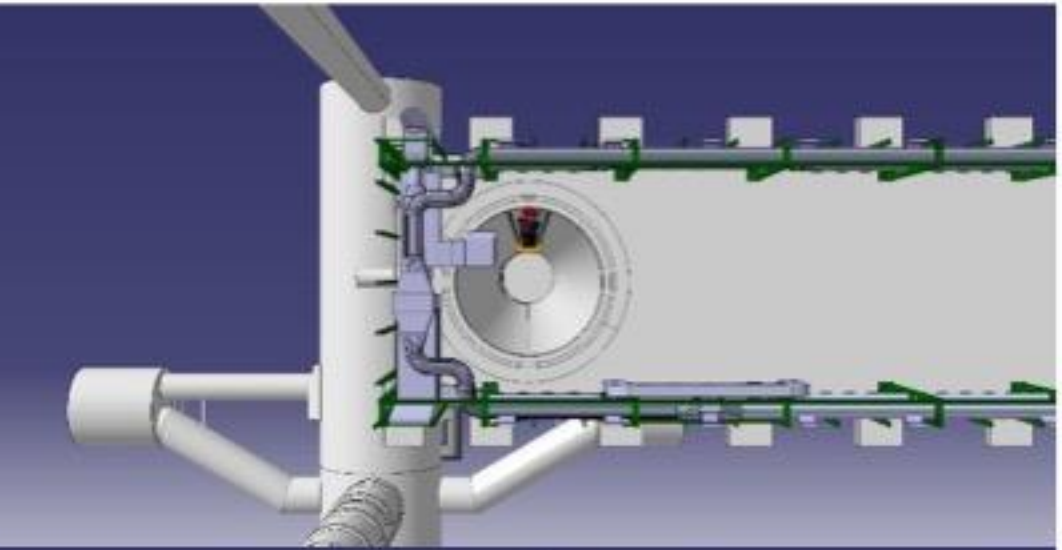
Introduction

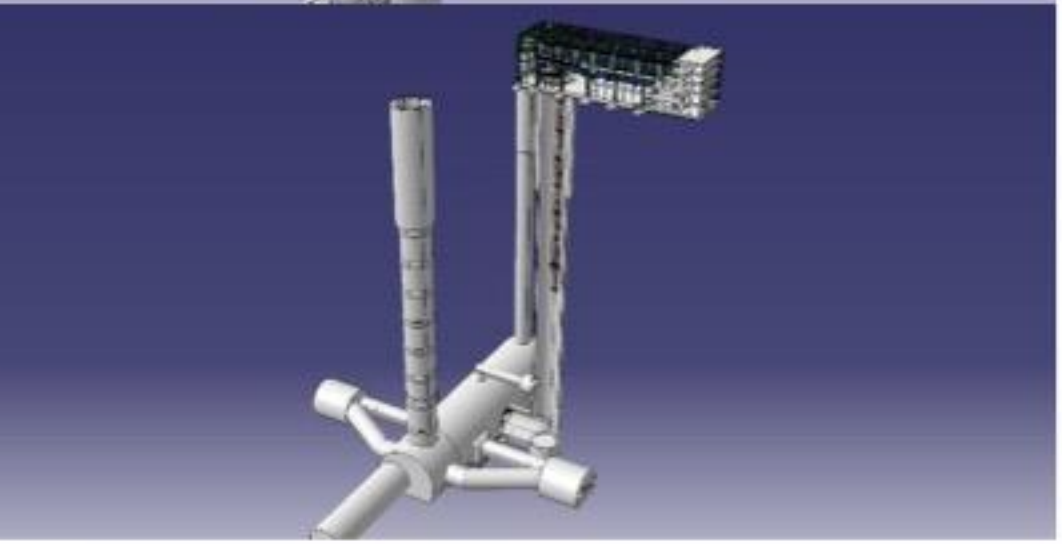
EM Noise Levels

Slides from Sergio Calatroni (TE-VSC and PBC)

- **AION-100 experiment is an ion interferometer, proposed to be installed in the PX46 pit**
- **Feasibility study under way, with the support of the Physics Beyond Collider study - Technology Working Group. Aiming for official letter of intent at the end of the year.**
- **For info of other feasibility studies under way for AION-100: https://indi.to/RkZdN**
- **Need to measure EM background noise (1 mHz – 100 kHz) at the top (few meters below the steel lid) and at the bottom of PX46 during machine operation, using fluxgates up to 1-3 kHz, and 3D pick-up coils for the high frequency spectrum**
- **Choice of a closed plastic tube installed in the lid, after drilling, for hosting the probes**
- **Installation procedure approved by LMC: https://edms.cern.ch/document/2710516/1.0**
- **Many thanks to all services and people involved for the support: everybody was fully motivated to help**

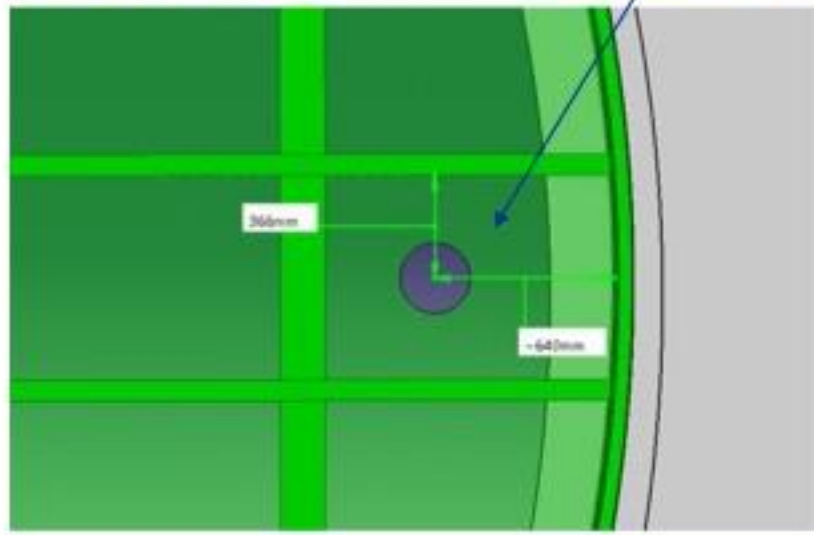
AION-100





Location of AION-100

Drilling location



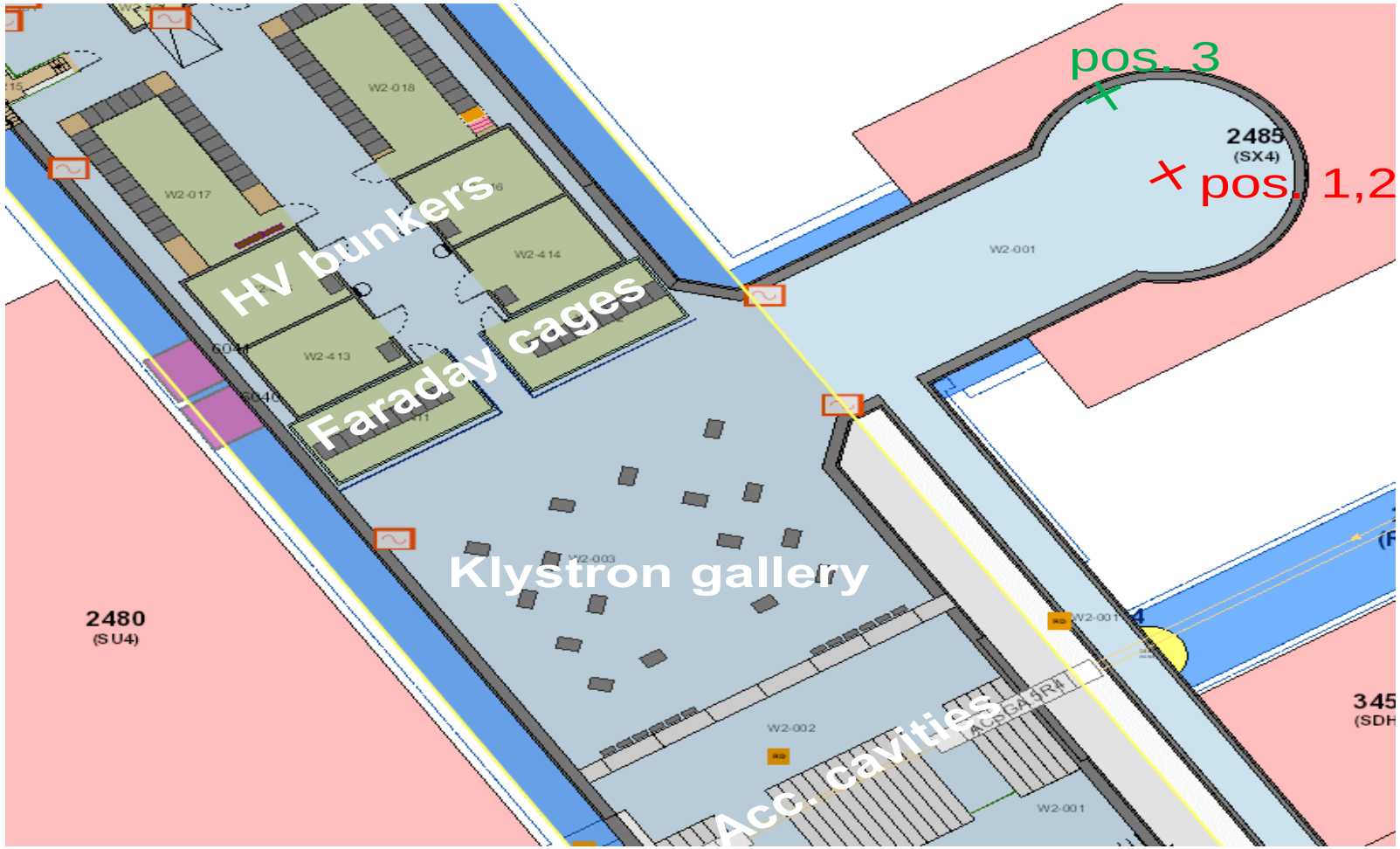
The tube (thanks to EN-MME)

PP plastic, closed at bottom
225 mm outer diameter
199,4 mm inner diameter
5000 mm length
Al flange for support

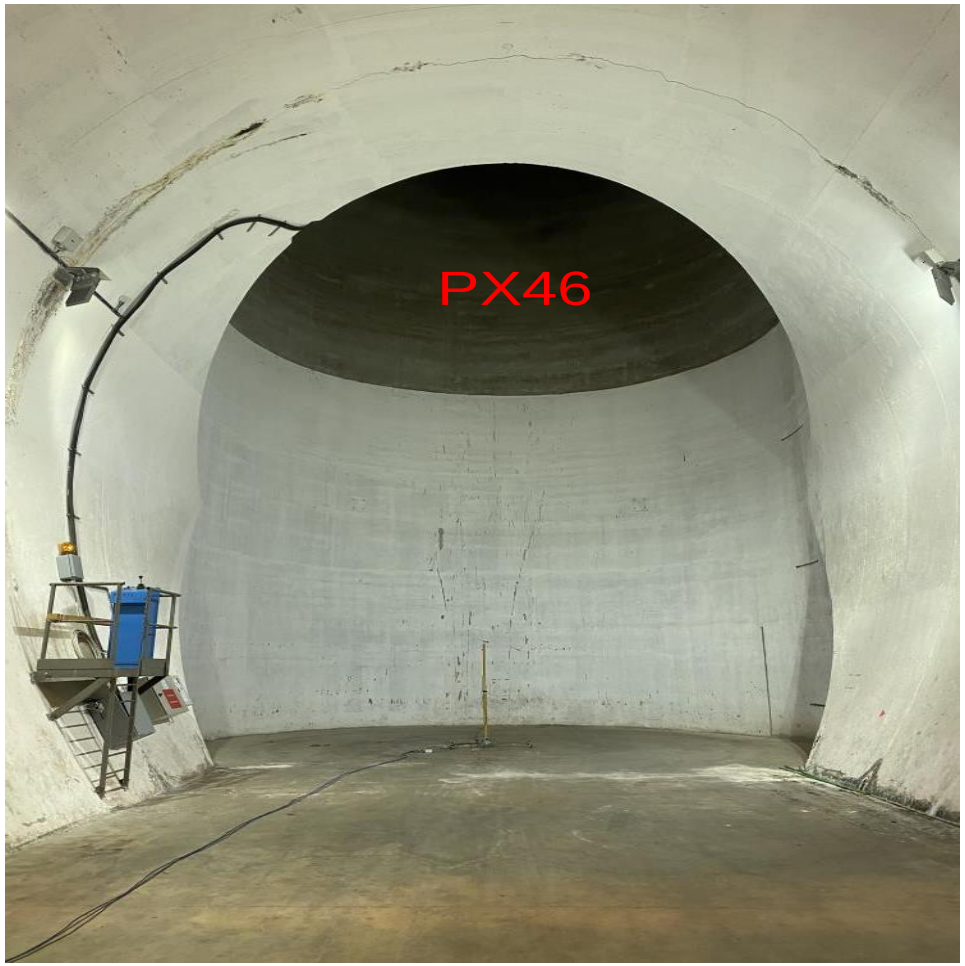
Installation (thanks to EN-ACE, EN-HE, EN-CV)

Measurement location at the bottom of the PX46 shaft, UX45 building

Slides from Marco Buzio, Mariano Pentella, Daniel Valuch



Measurement location at the bottom of the PX46 shaft, UX45 cavern

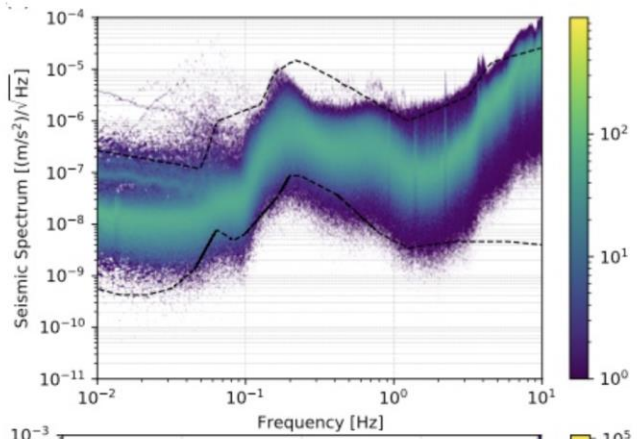


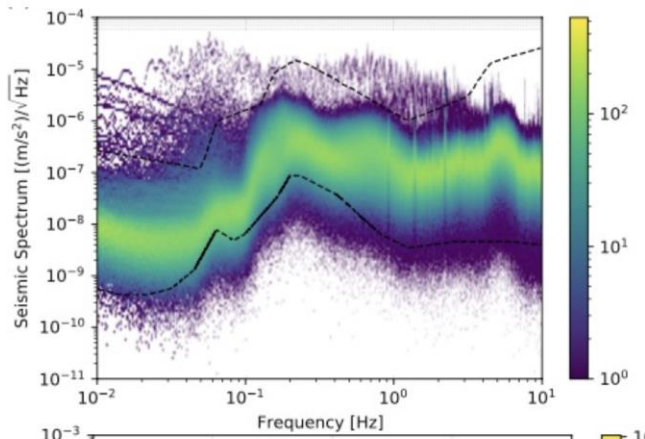
ATION-100 at CERN – Site Investigation

Surface

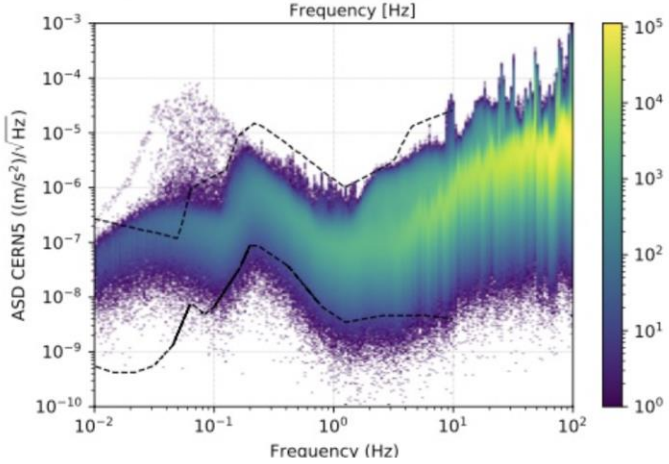
Underground

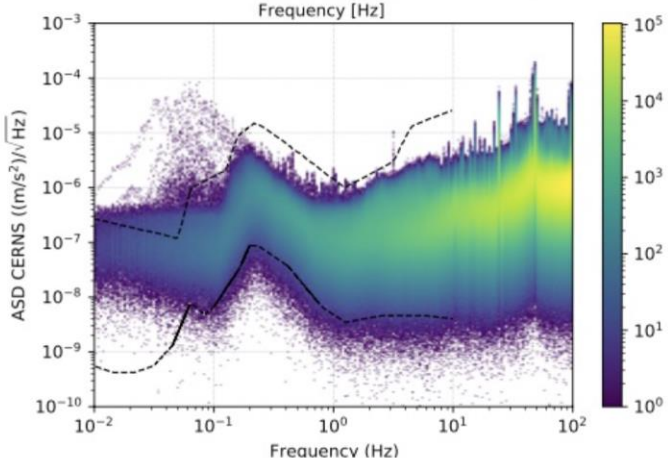
FNAL



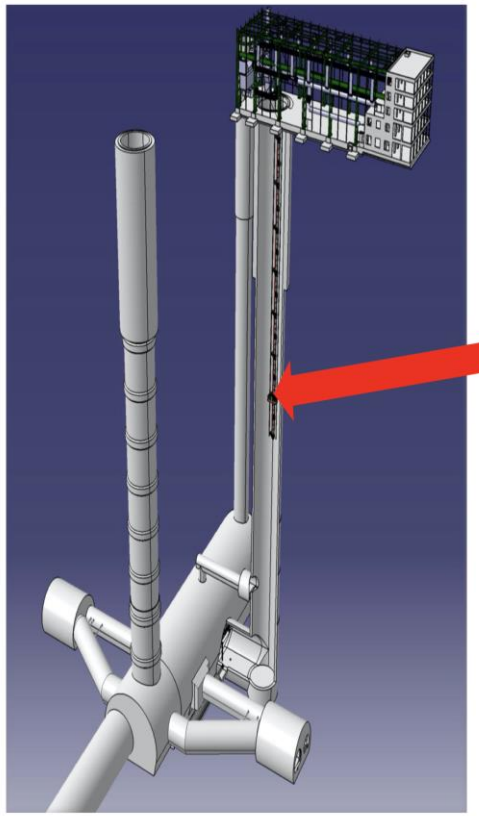


CERN

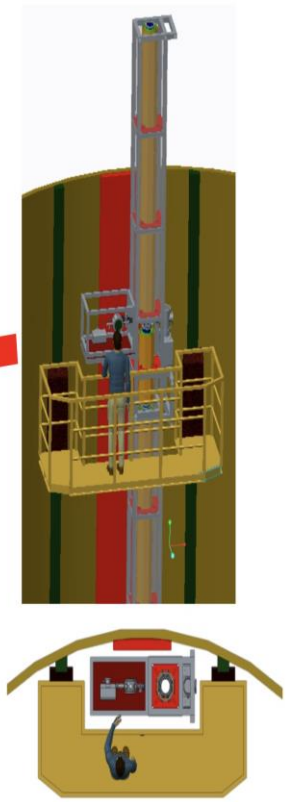




General view of LHC Point 4

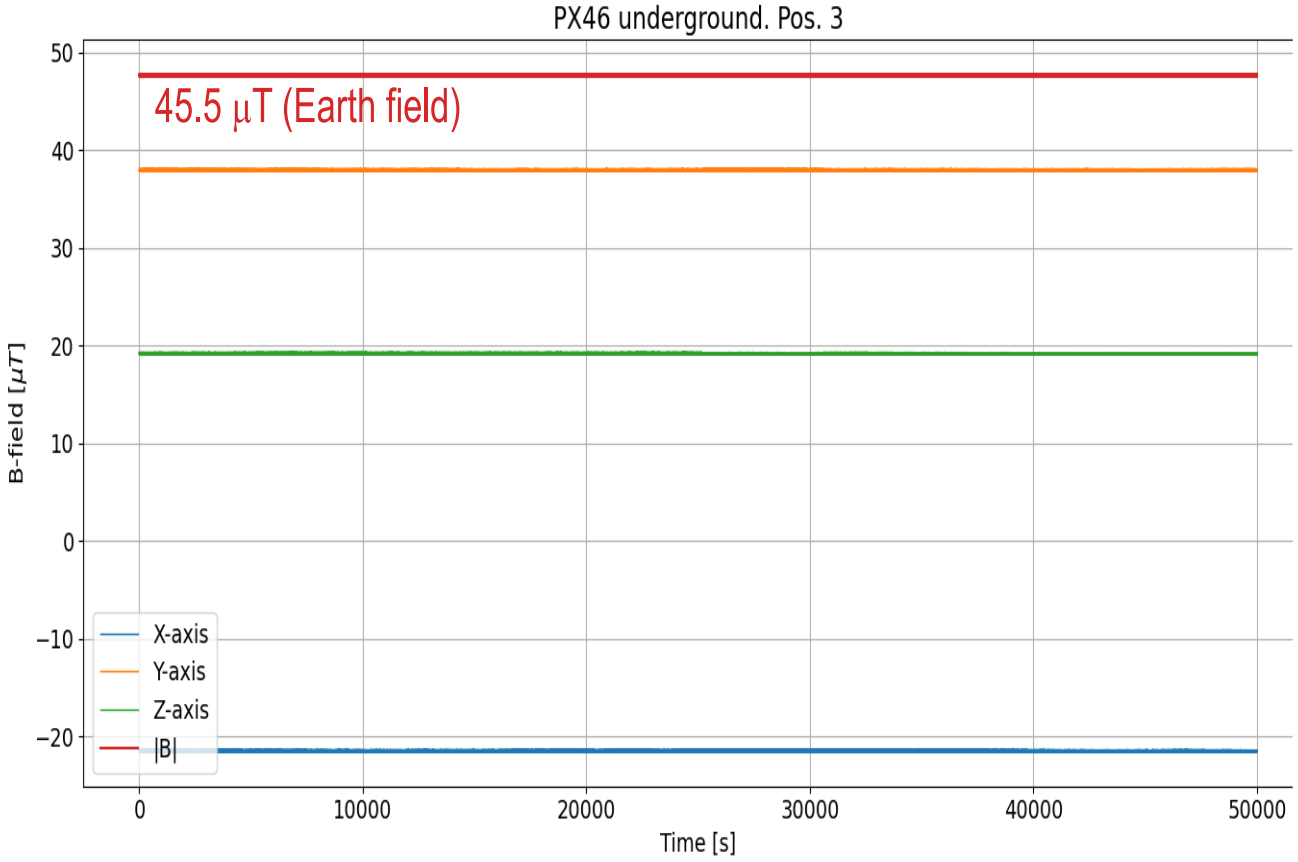


Possible layout in PX46 shaft



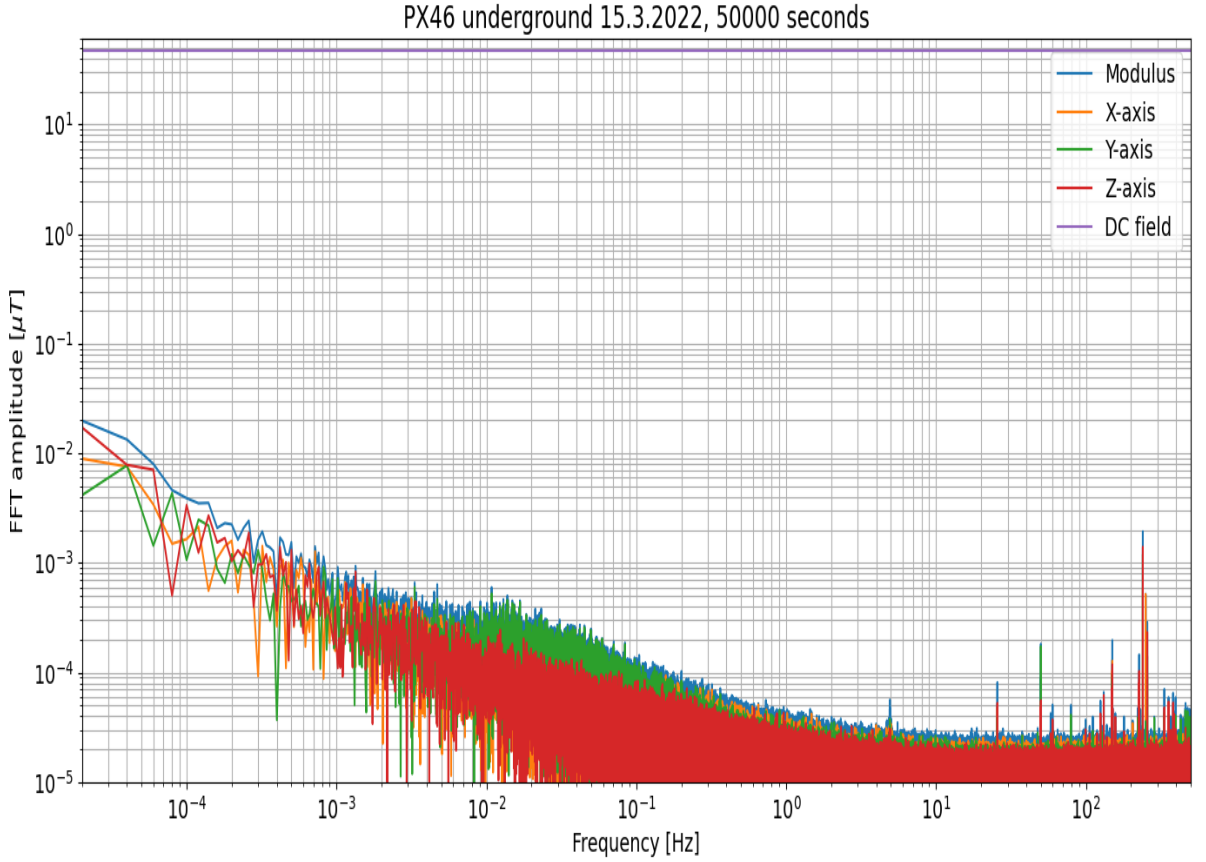
Spectrum similar to that measured at Fermilab for MAGIS

Location: bottom of the PX46 shaft. Systems in UX45 running



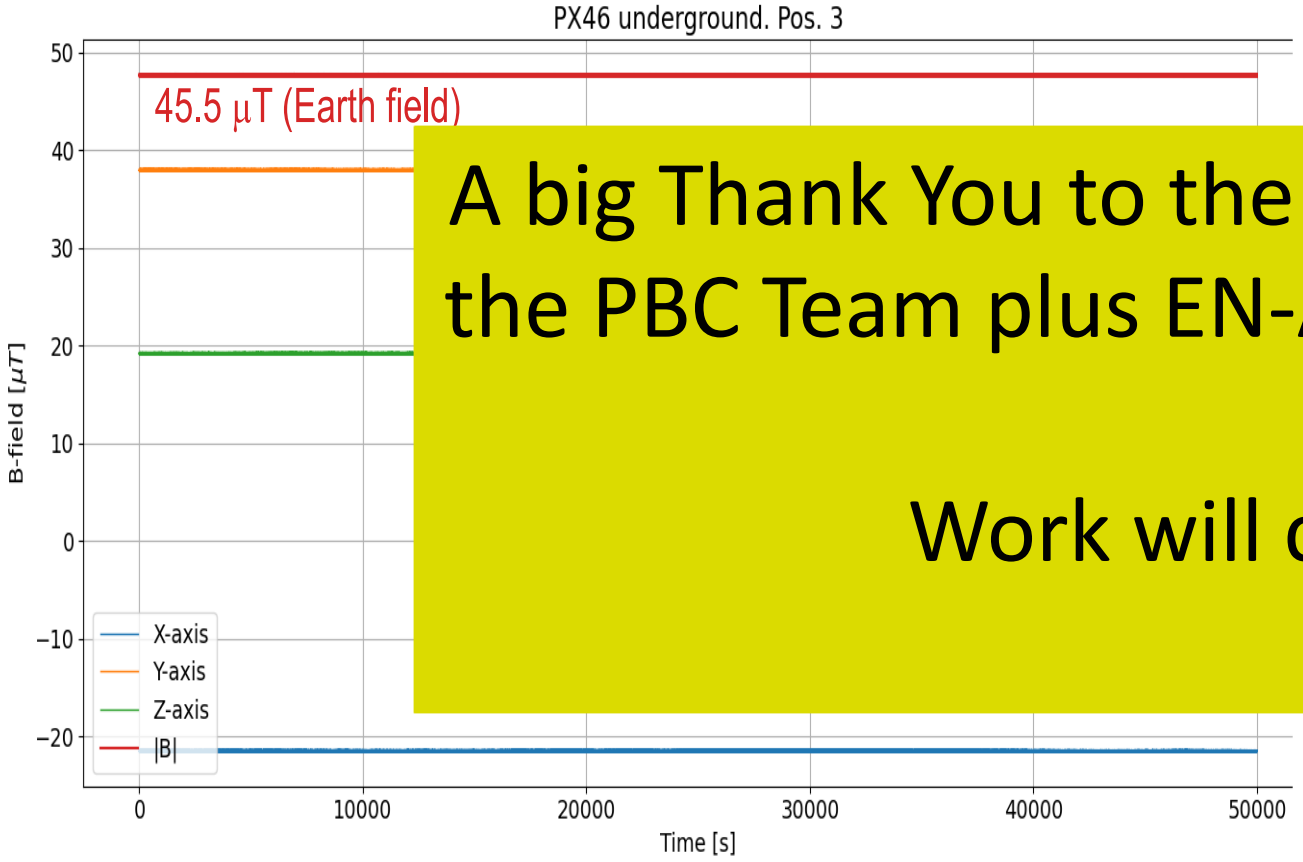
Location 3, wall of PX46. Quiet, Earth field for scale

Location: bottom of the PX46 shaft. Systems in UX45 running



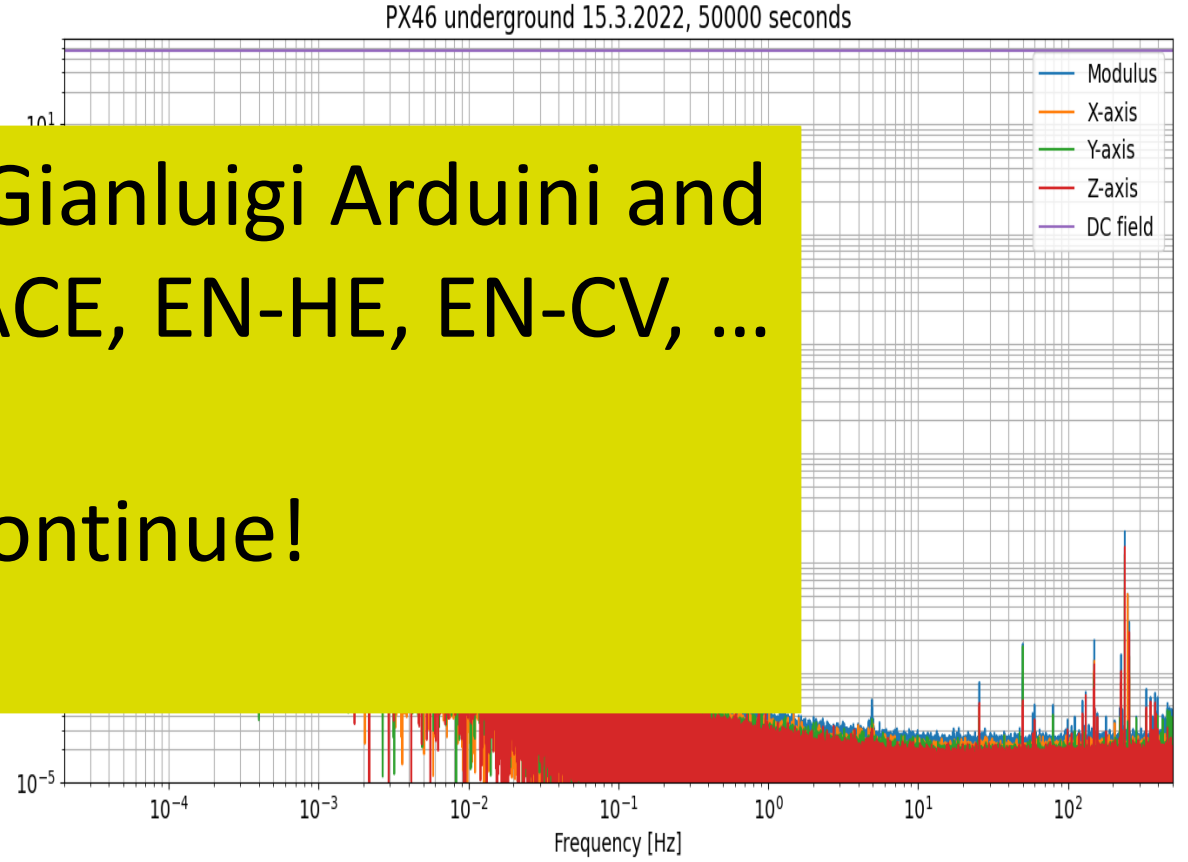
Location 3, wall of PX46. Earth (DC) field for scale

Location: bottom of the PX46 shaft. Systems in UX45 running



Location 3, wall of PX46. Quiet, Earth field for scale

Location: bottom of the PX46 shaft. Systems in UX45 running



A big Thank You to the Gianluigi Arduini and the PBC Team plus EN-ACE, EN-HE, EN-CV, …

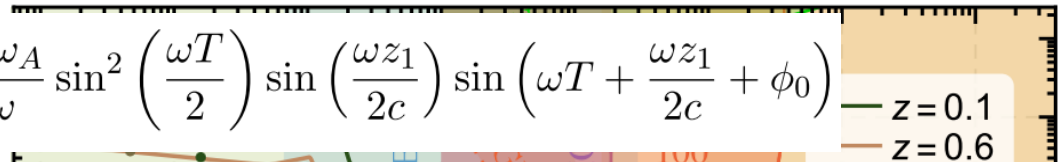
Work will continue!

Location 3, wall of PX46. Earth (DC) field for scale

Gravitational waves

Modulation of L – affects phase shift of each interferometer:

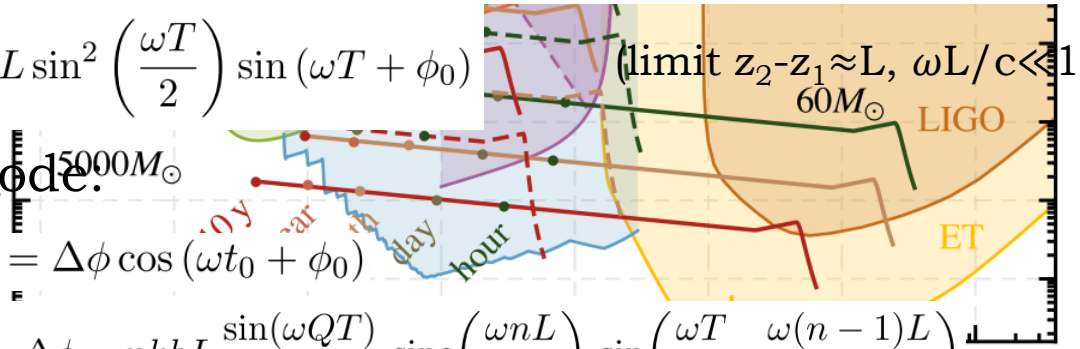
$$4\frac{h\,\omega_A}{\omega}\sin^2\left(\frac{\omega T}{2}\right)\sin\left(\frac{\omega z_1}{2c}\right)\sin\left(\omega T+\frac{\omega z_1}{2c}+\phi_0\right)$$



$$\Delta\phi_{\rm diff}=4\frac{h\,\omega_A}{\omega}\sin^2\left(\frac{\omega T}{2}\right)\sin\left(\frac{\omega\,(z_2-z_1)}{2c}\right)\sin\left(\omega T+\frac{\omega\,(z_1+z_2)}{2c}+\phi_0\right)$$

$$\Delta\phi_{\rm diff}\approx 2hkL\sin^2\left(\frac{\omega T}{2}\right)\sin\left(\omega T+\phi_0\right)$$

(limit z_2-z_1≈L, ωL/c≪1)



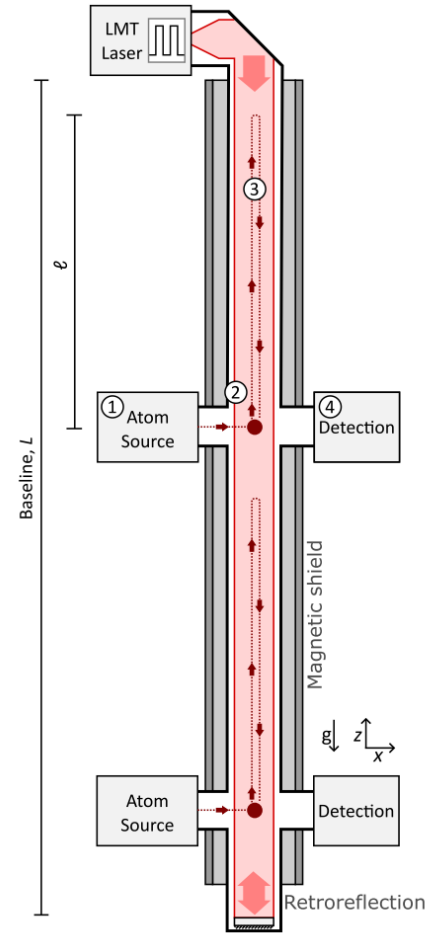
Resonant mode:

$$\Delta\Phi_{\rm grad}(t_0)=\Delta\phi\cos\left(\omega t_0+\phi_0\right)$$

$$\Delta\phi=nkhL\frac{\sin(\omega QT)}{\cos(\omega T/2)}\,\mathrm{sinc}\left(\frac{\omega nL}{2c}\right)\sin\left(\frac{\omega T}{2}-\frac{\omega(n-1)L}{2c}\right)$$

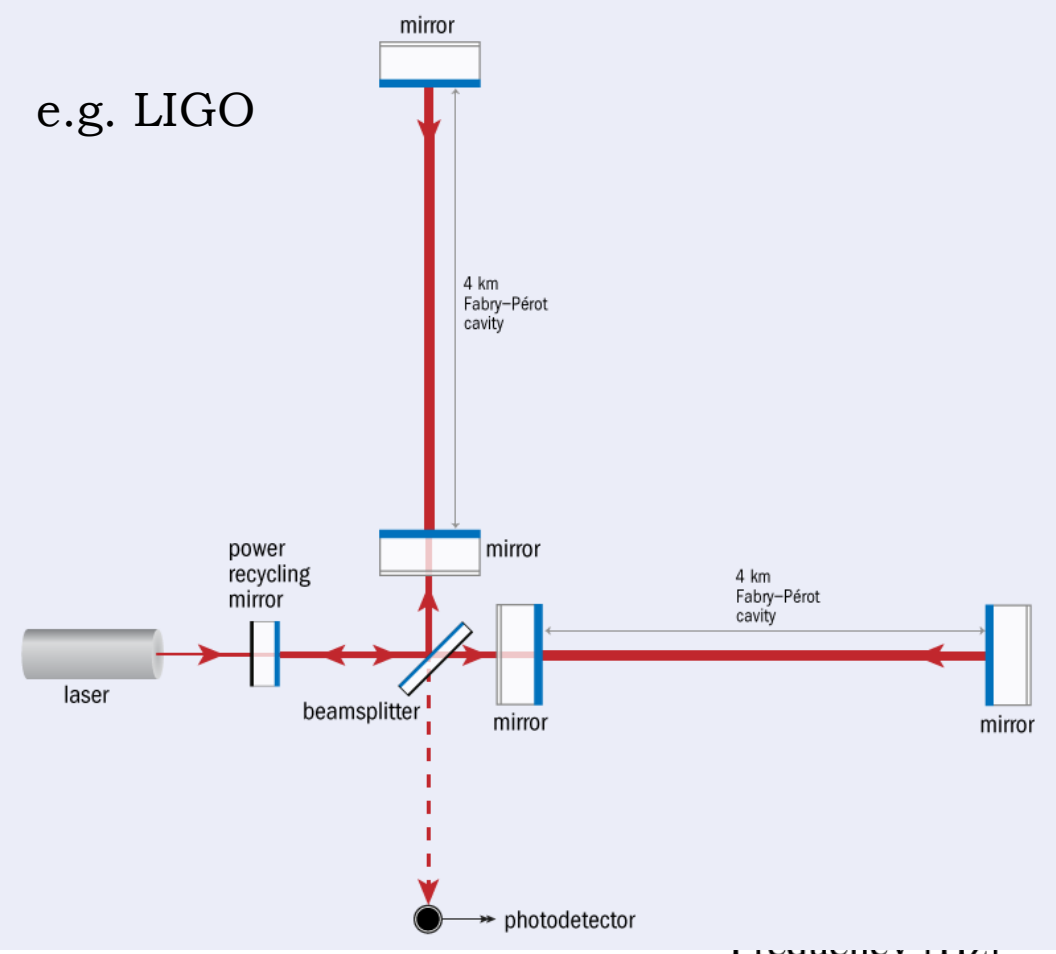
resonance:

$$\Delta\phi_{\rm res}=2QnkhL\,\mathrm{sinc}\left(\frac{\omega_r nL}{2c}\right)\cos\left(\frac{\omega_r(n-1)L}{2c}\right)\approx 2QnkhL \quad (\text{for } \omega_r \ll \frac{c}{nL})$$



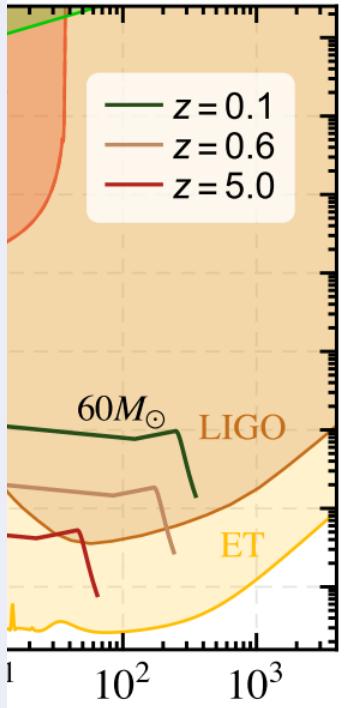
Images: Journal of Cosmology and Astroparticle Physics **5**, 011 (2020)

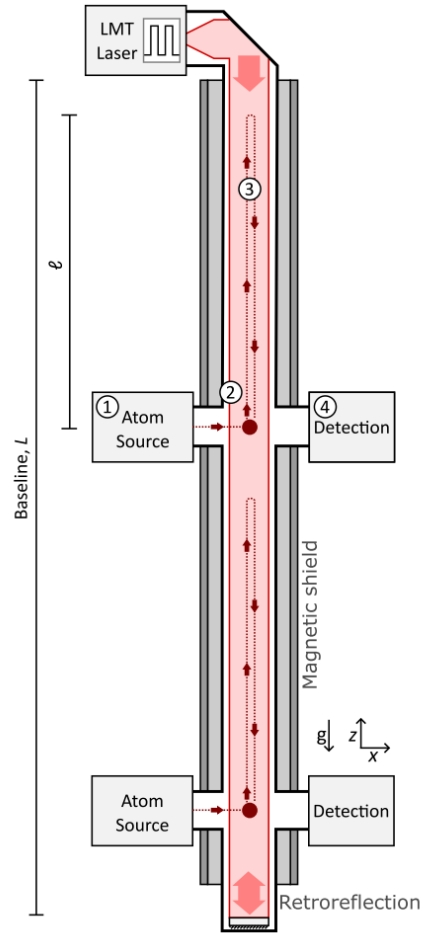
Gravitational wave detection



https://physicsworld.com/a/ligo-detects-first-ever-gravitational-waves-from-two-merging-black-holes/

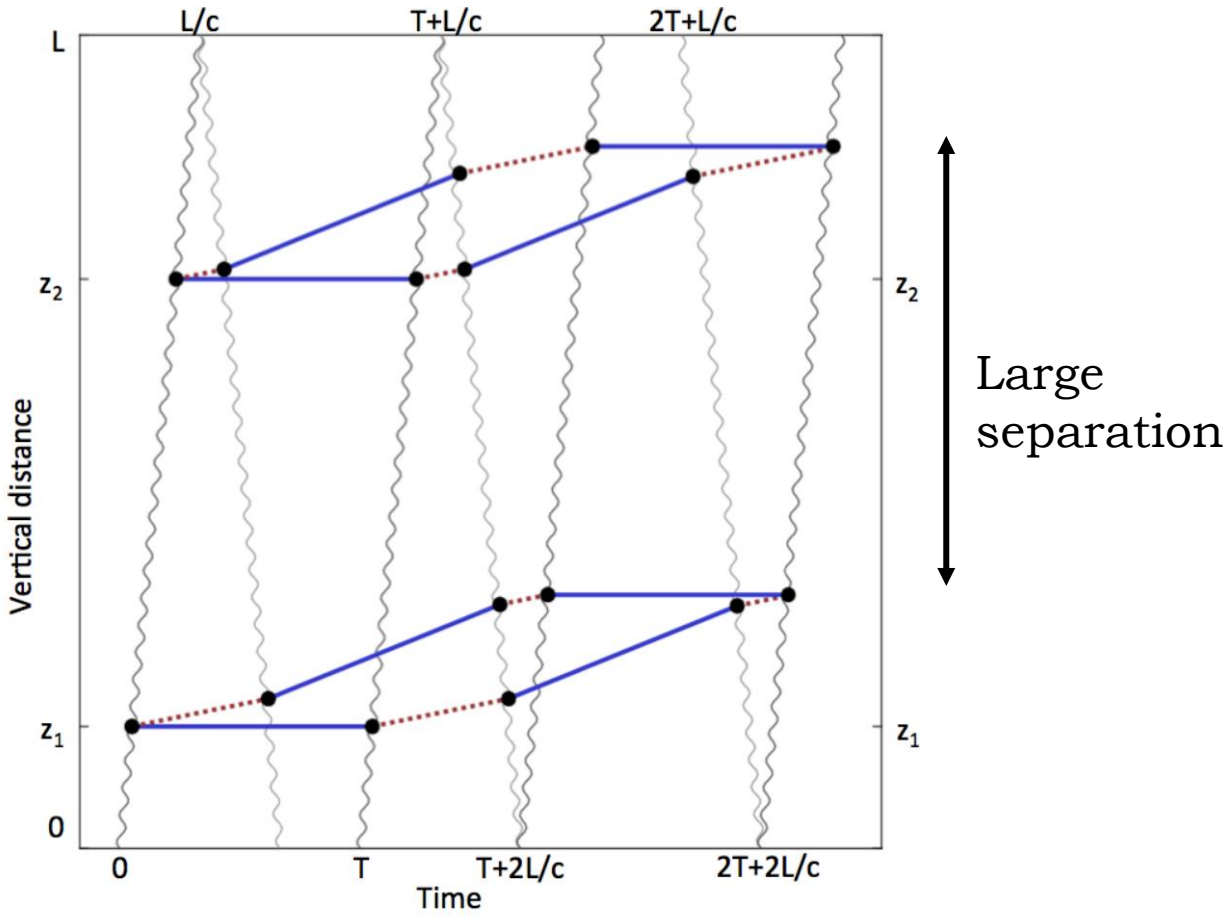
...each interferometer





Images: Journal of Cosmology and Astroparticle Physics **5**, 011 (2020)

Atom interferometry*



- Sr
  - Clock transition
  - Single-photon interferometry [1,2]
- Differential measurement: fluctuations in relative phase between AIs

[1] P. Graham *et al.* PRL **110** 171102 (2013)
[2] L. Hu *et al.* PRL **119**, 263601 (2017)

*AION – other interferometers for fundamental physics also exist! e.g. MAGIS, MIGA, ZAIGA, ELGAR

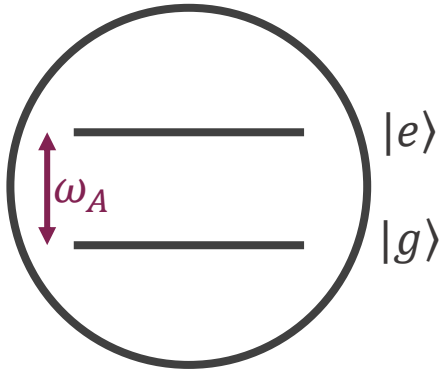
Image:
Journal of Cosmology and Astroparticle Physics **5**, 011 (2020)

Ultra-light scalar dark matter

AION

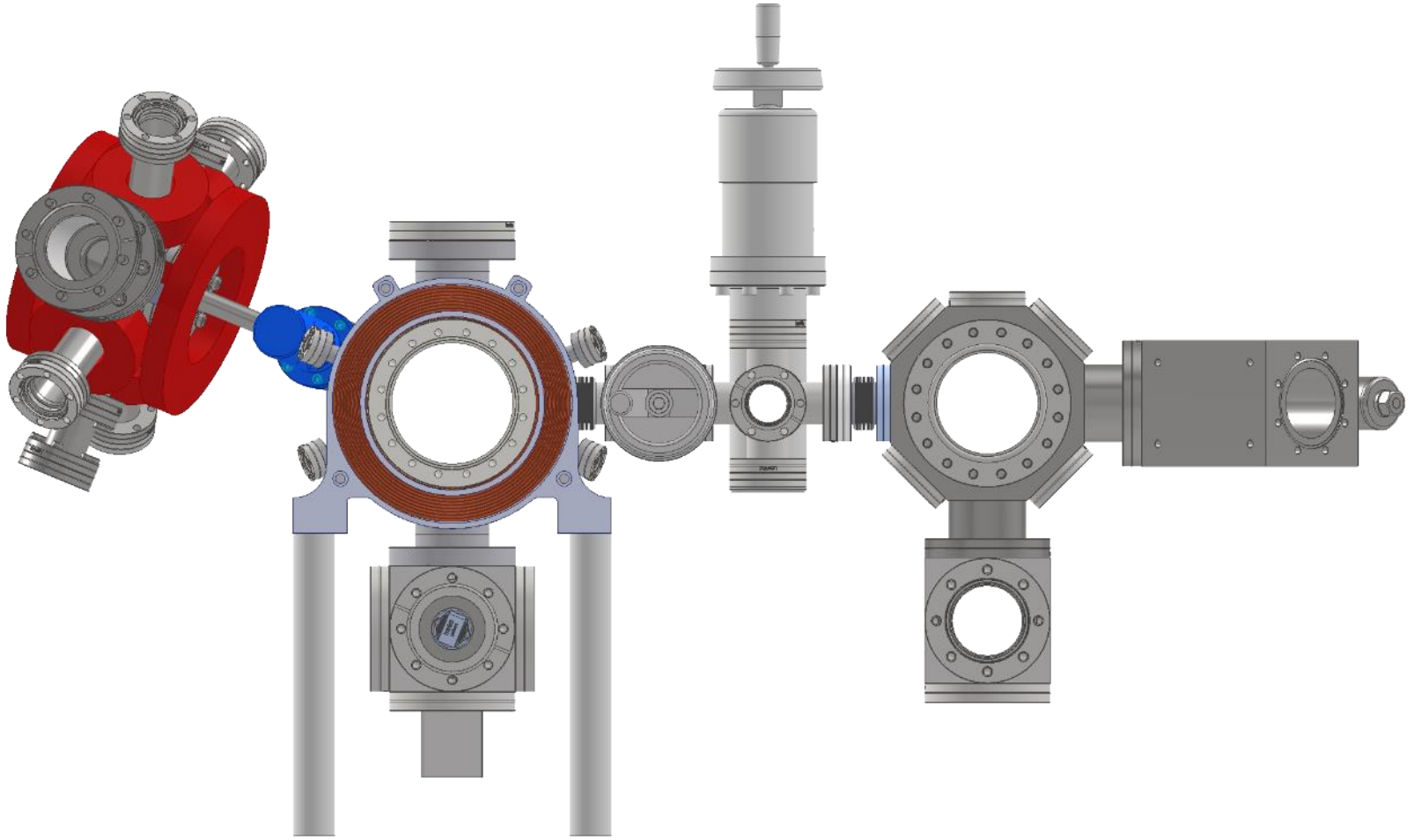
Coupling to standard model fields: time-varying m_e, α [1,2] changes transition frequency.

Oscillation frequency from dark matter mass m_ϕ, mid-frequency sensitivity [3, 4]

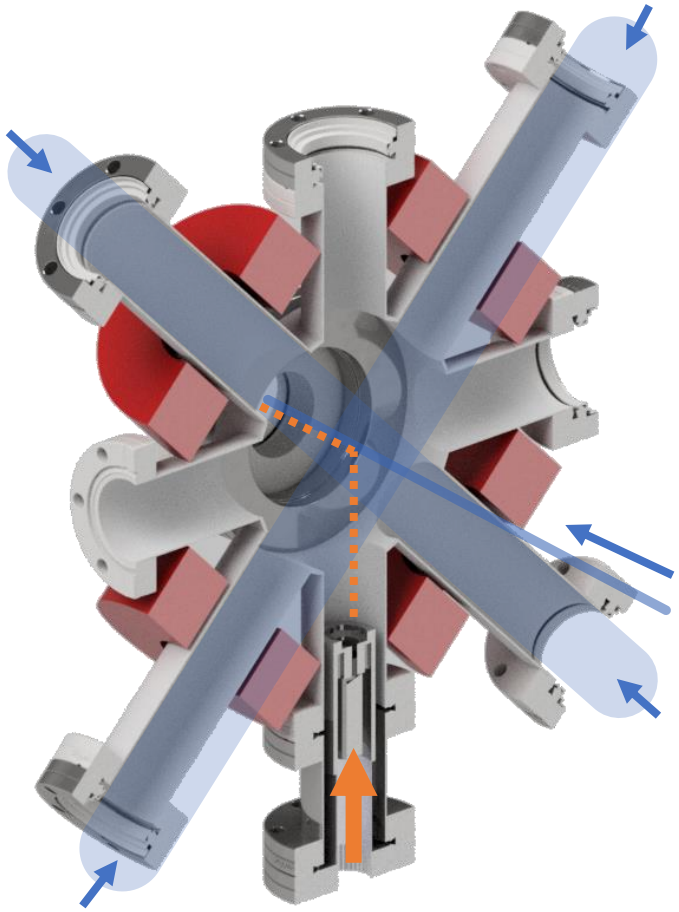


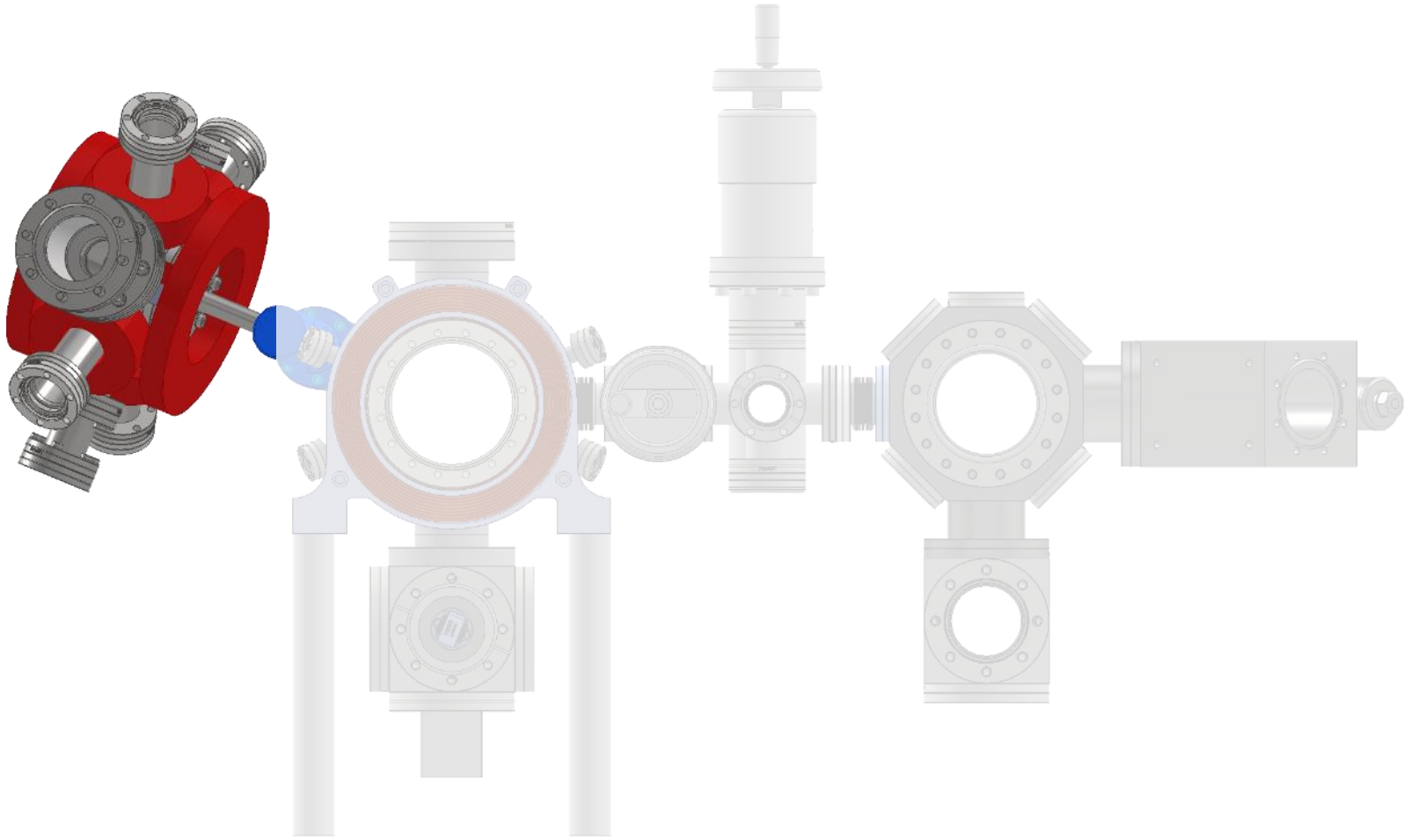
[1] Y. V. Stadnik and V. V. Flambaum, PRL **114** 161301 (2015)
[2] A. Arvanitaki *et al.* Phys. Rev. D **91** 015015 (2015)
[3] L. Badurina *et al.* arXiv:2108.02468 (2021)
[4] L. Badurina *et al.* J. Cosmol. Astropart. Phys. **5**, 011 (2020)

AION in the lab

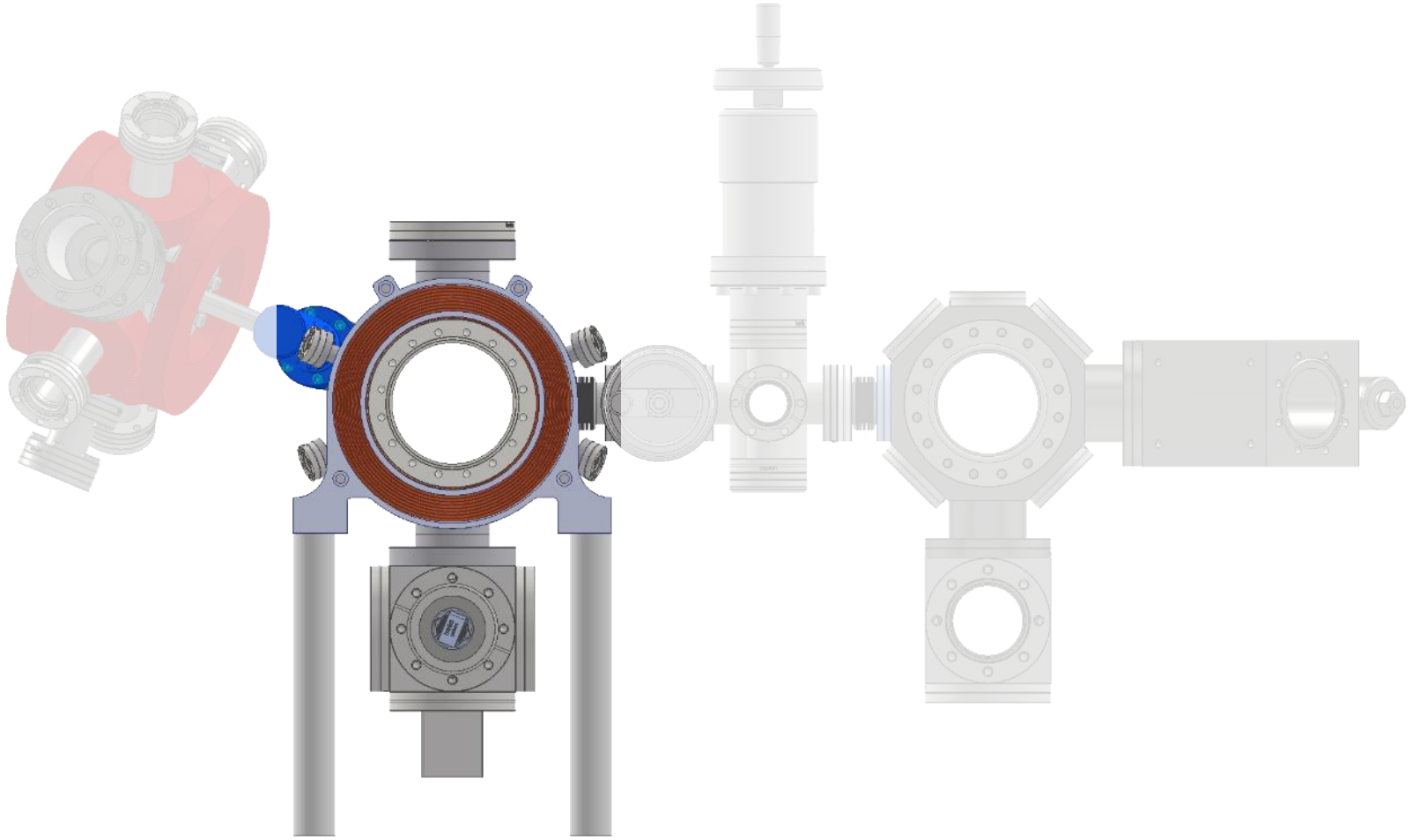


AION in the lab



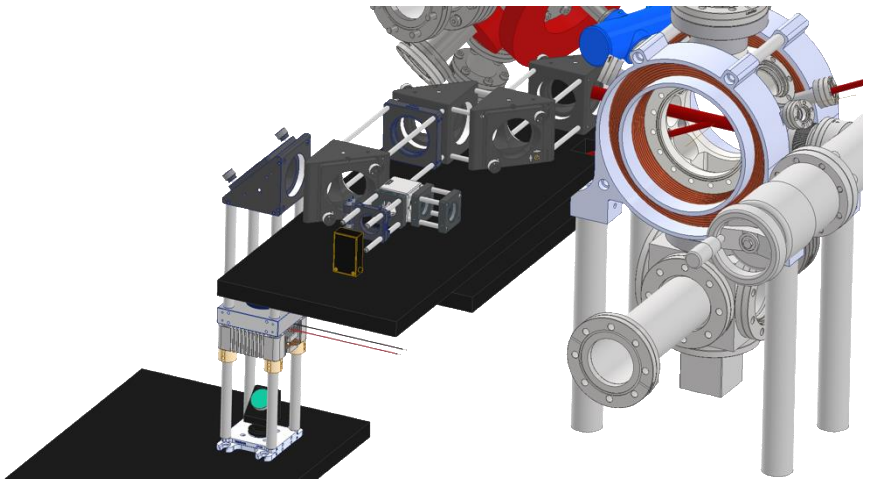


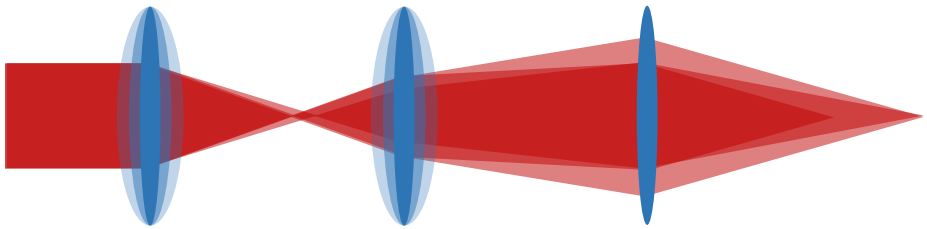
AION in the lab

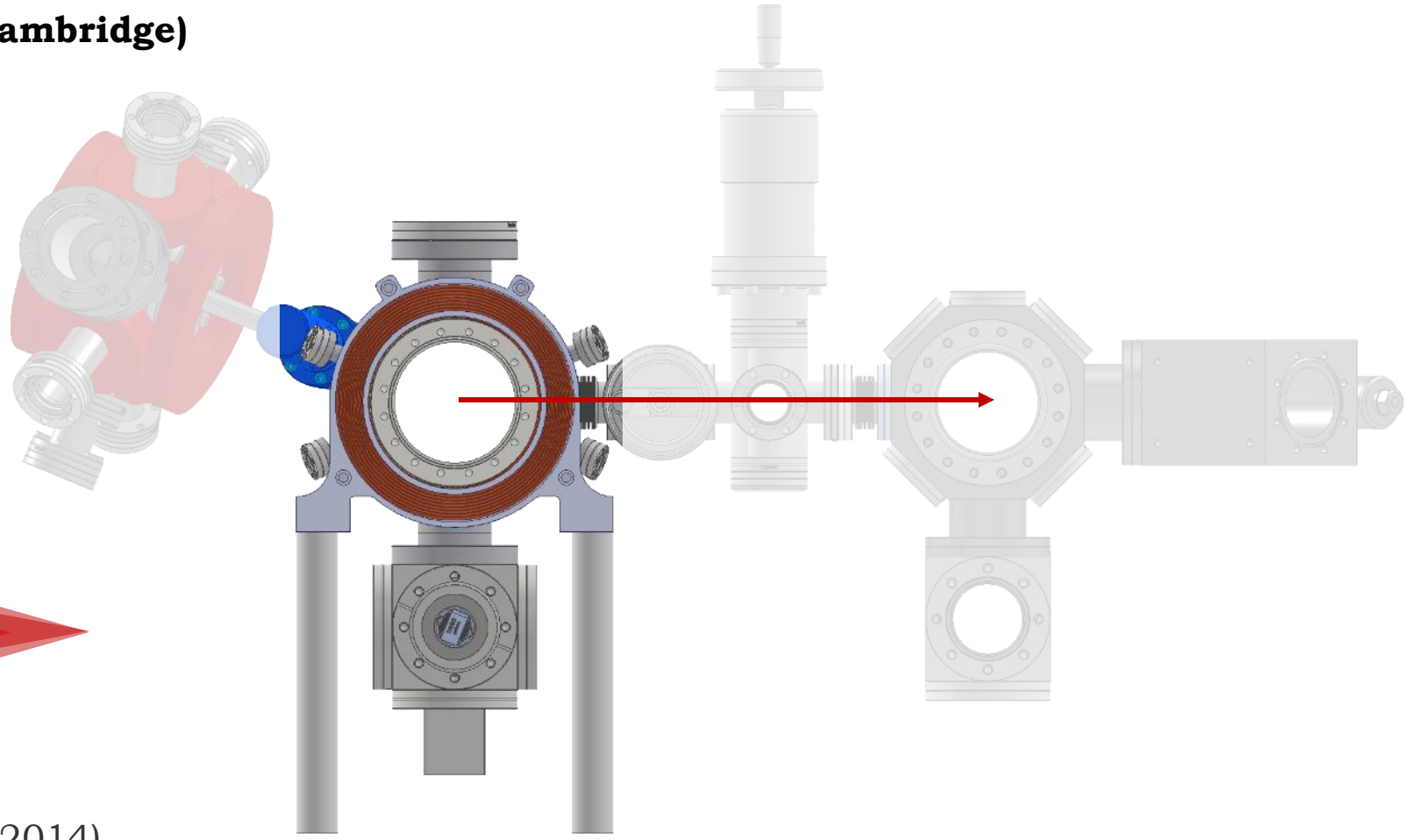


AION in the lab

Transport, cooling and atom optics (Cambridge)



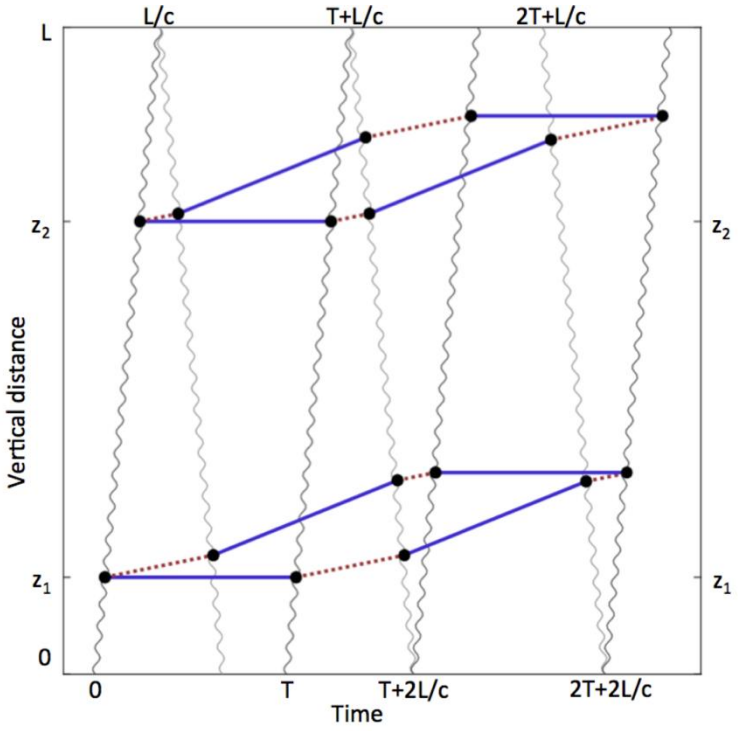


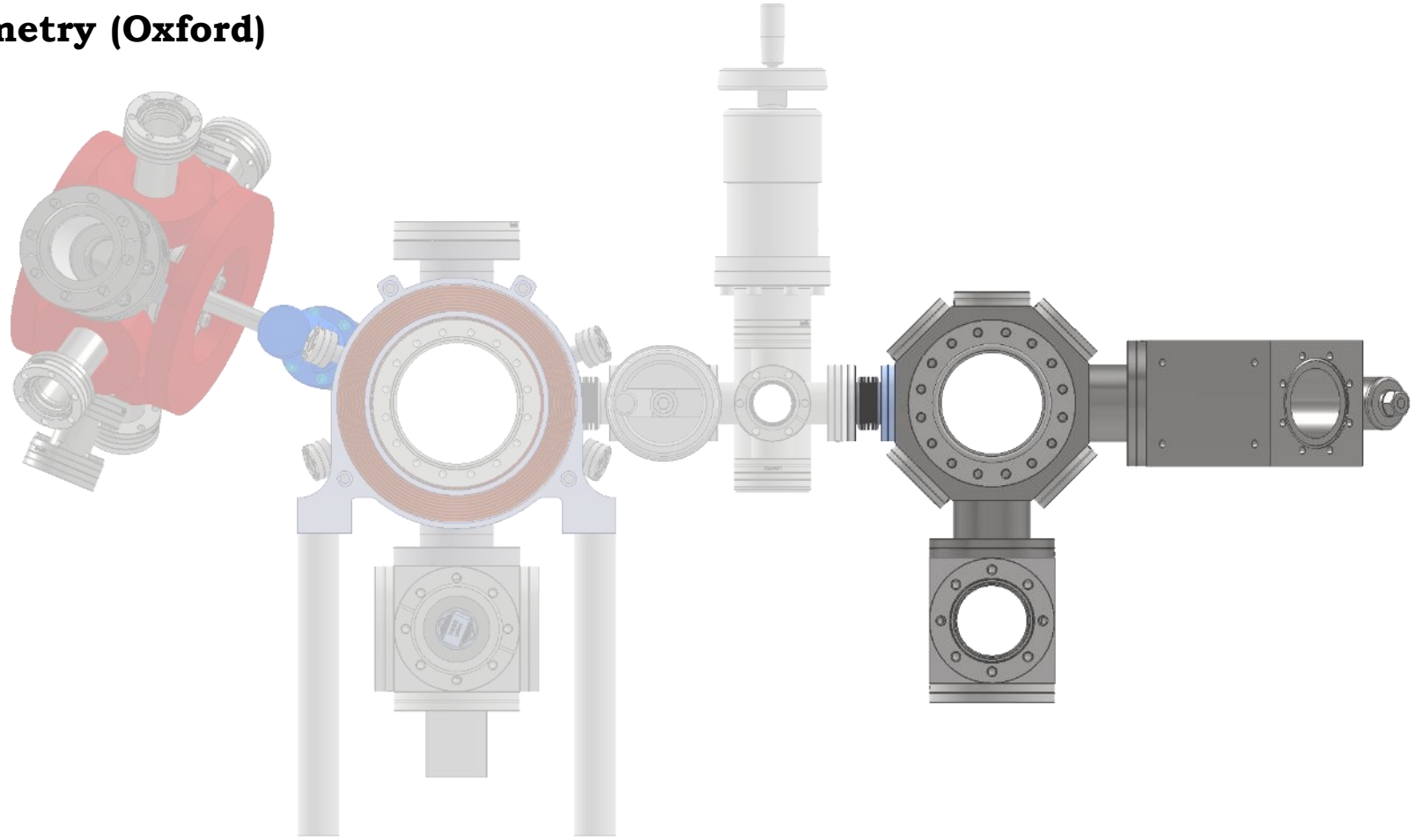


Optical transport:
J. Léonard *et al.* *New J. Phys.* **16** 093028 (2014)
G.Unnikrishnan *et al.* Rev. Sci. Instruments **92** 063205 (2021)
Poster session 1 - Luca Donini, University of Cambridge

AION in the lab

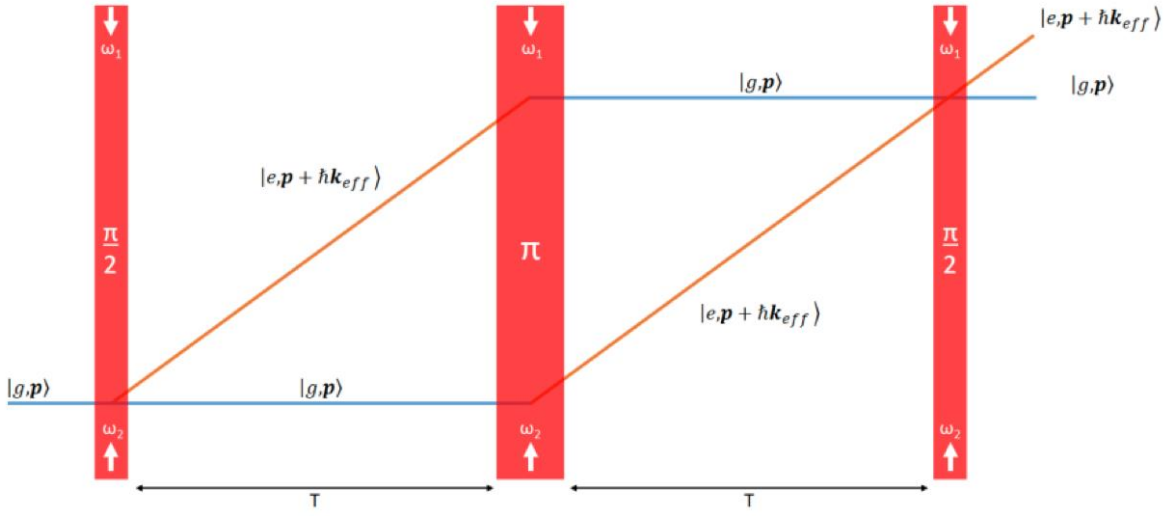
Technology integration and interferometry (Oxford)

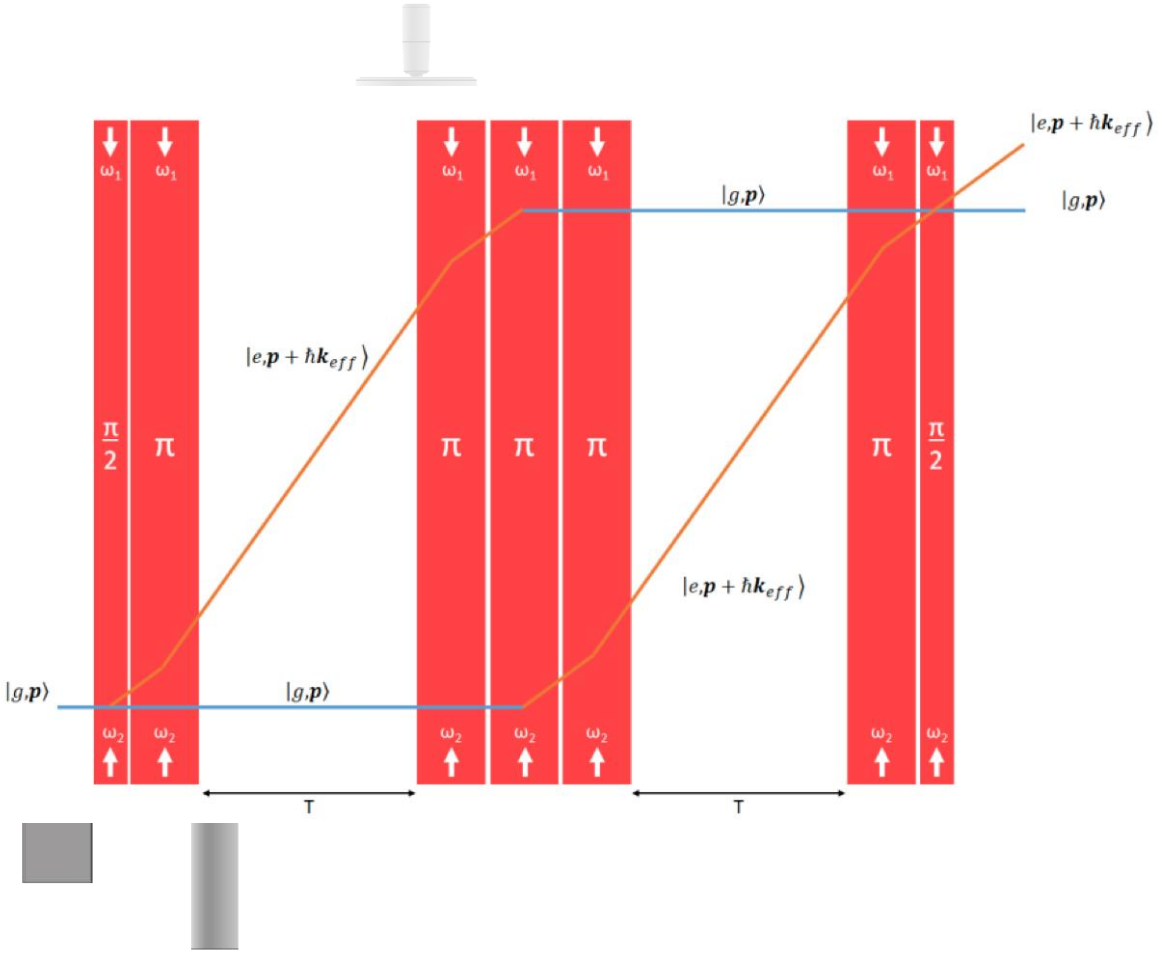




AION in the lab

Large momentum transfer (Birmingham)

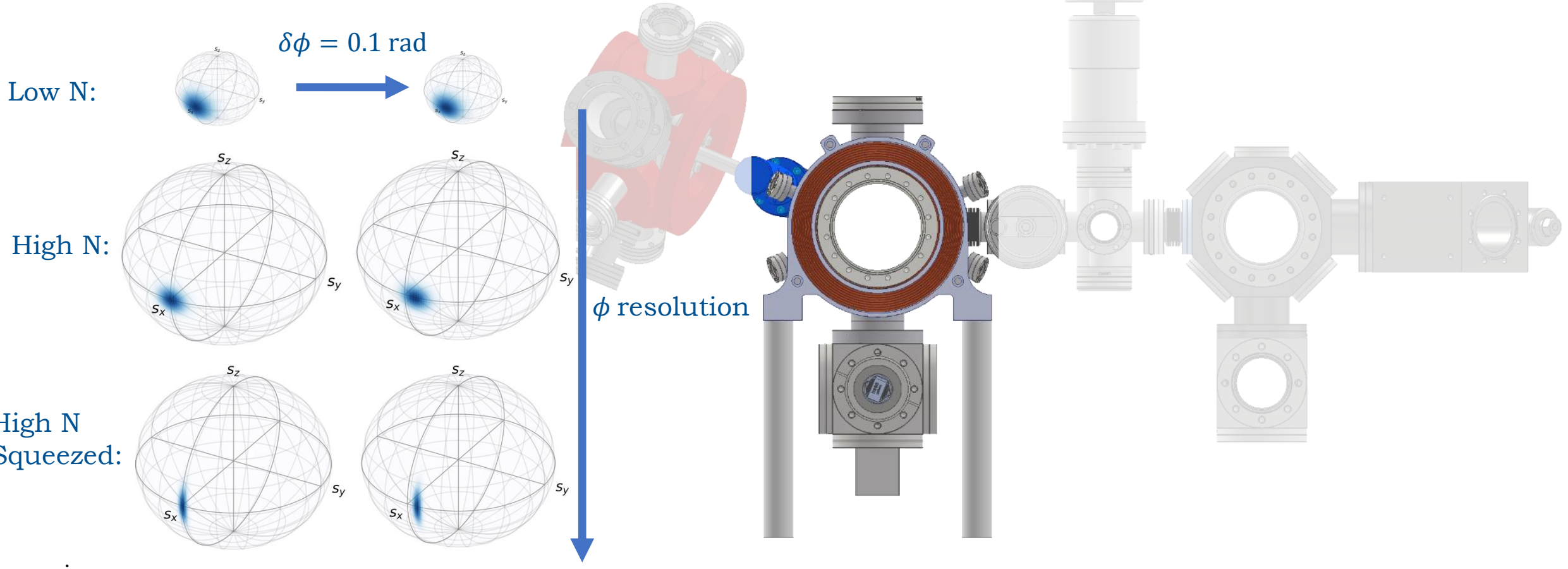




For large momentum transfer see e.g.:
J. Rudolph *et al.* PRL **124**, 083604 (2020)
J. M. McGuirk et al. PRL **85**, 4498 (2000)

AION in the lab

Squeezing (Imperial/RAL)



Squeezing:
Hosten *et al.* Nature **529**, 505–508 (2016)

Simulations: AtomECS

Data

- Las
- Mag
- Opt
- Coll
- … v

New c

https:

https:

elliot.l

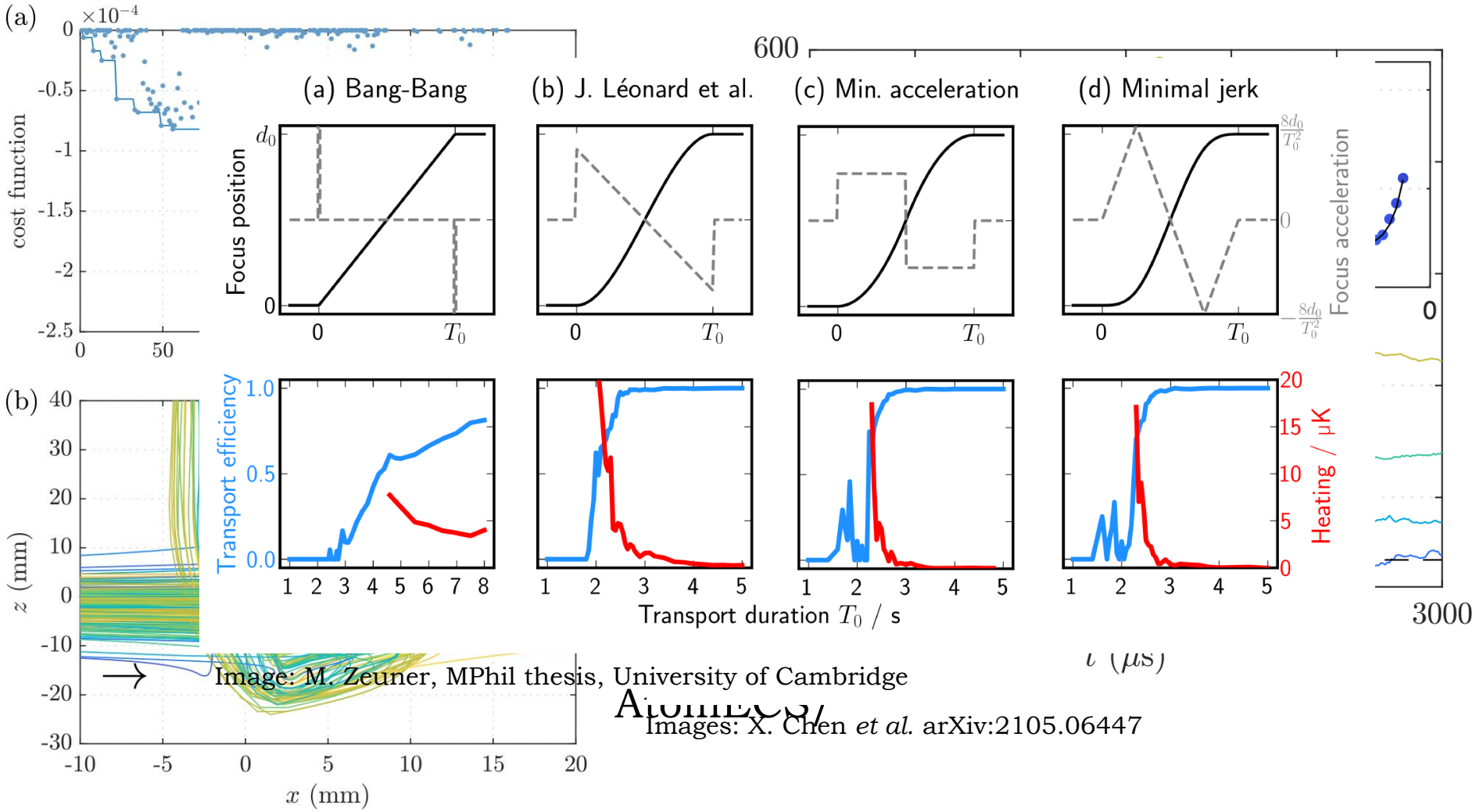
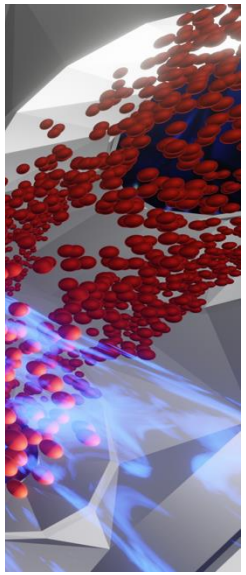


Image: M. Zeuner, MPhil thesis, University of Cambridge

AtomECS

Images: X. Chen *et al.* arXiv:2105.06447



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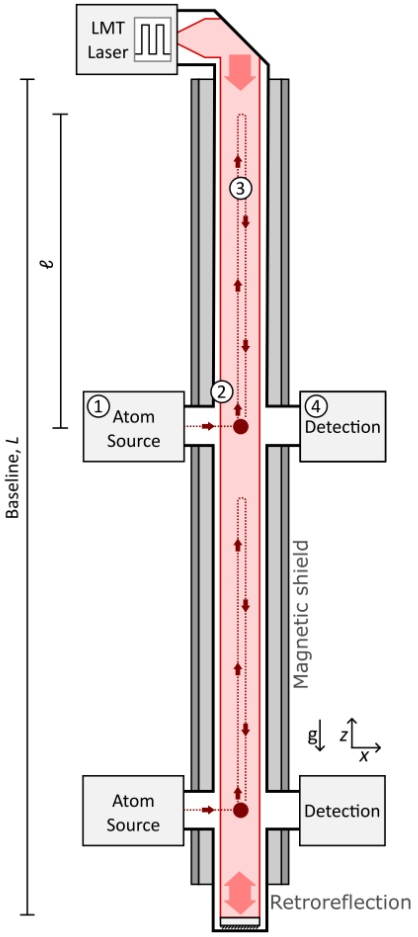
Differential Sr interferometry measurement to detect **gravitational waves** and **ultralight dark matter**, complementing existing detectors.



Paper: L. Badurina *et al.* Journal of Cosmology and Astroparticle Physics **5**, 011 (2020)

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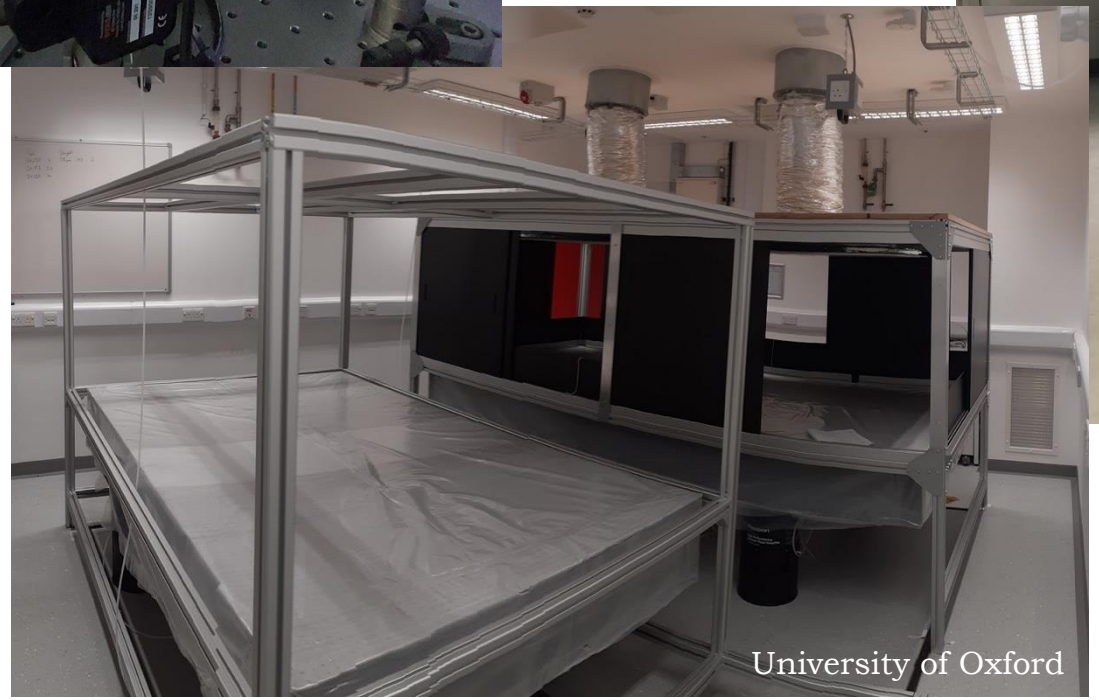

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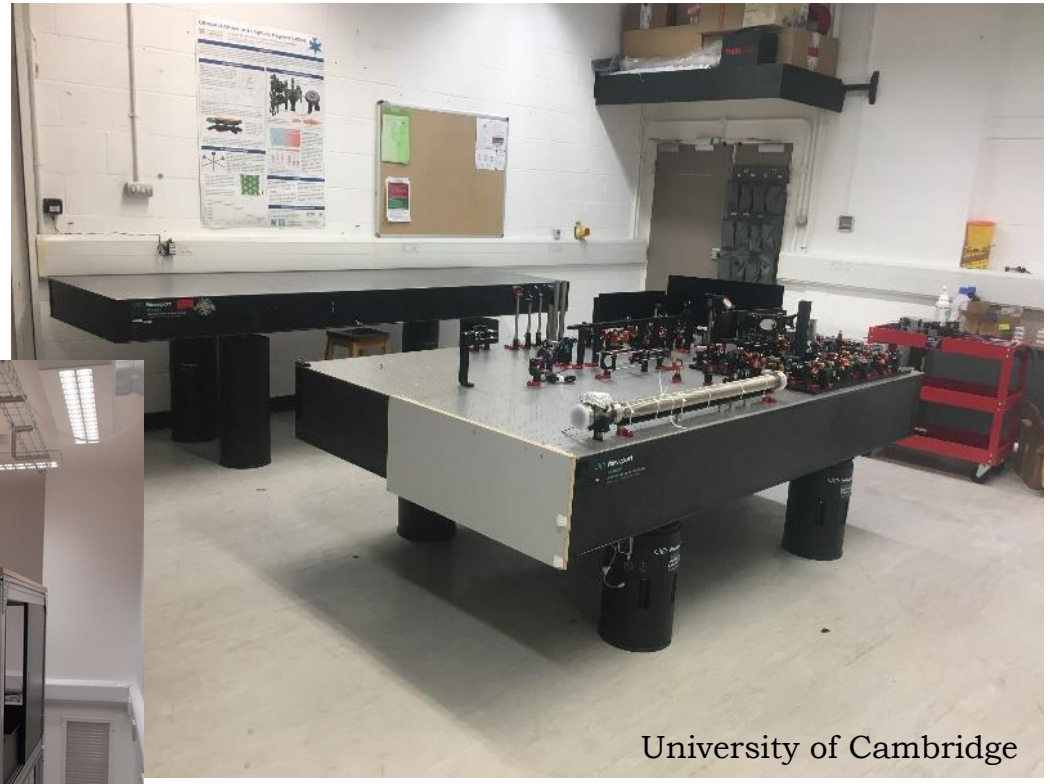

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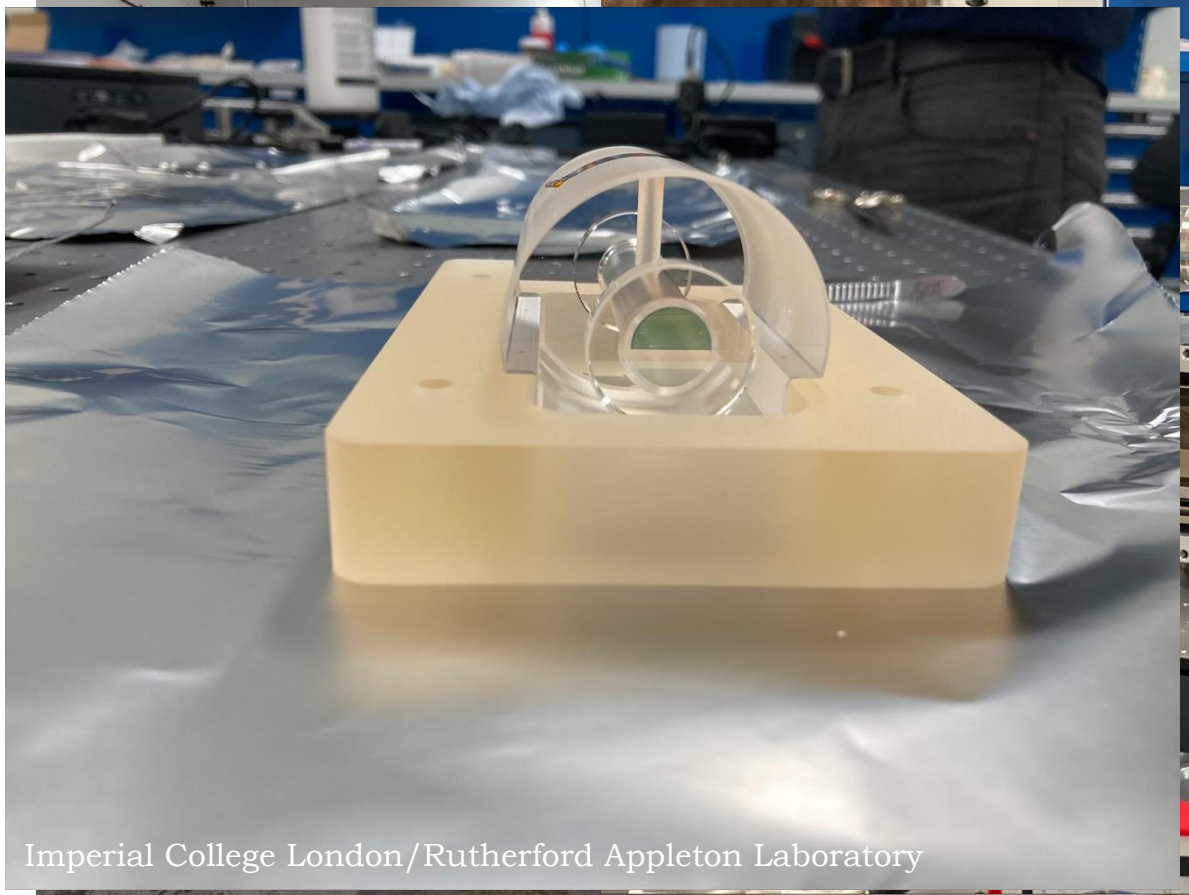

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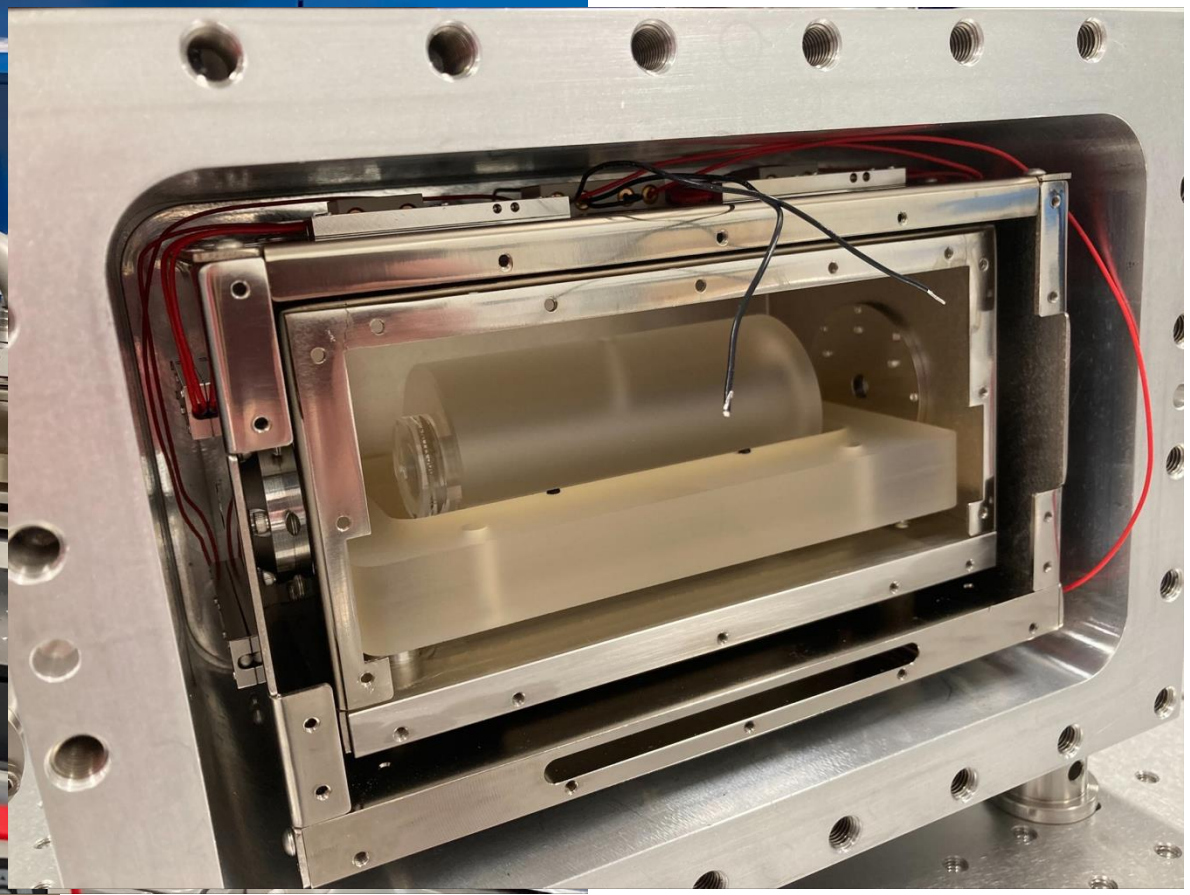


Imperial College London/Rutherford Appleton Laboratory
(Dr Richard Hobson)

Imperial College London

Ultra-light scalar dark matter

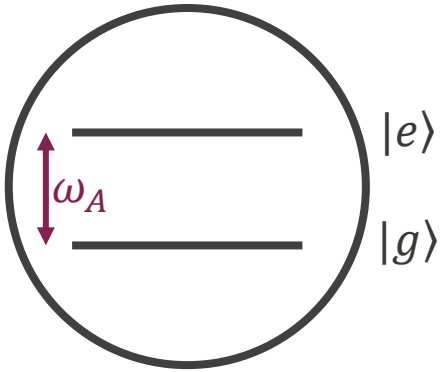
Coupling to standard model fields:

$$\mathcal{L}_{\text{int}}^{\text{lin}} \supset -\phi(\mathbf{x},t)\cdot\sqrt{4\pi G_{\text{N}}}\cdot\left[d_{m_e}m_e\bar{e}e-\frac{1}{4}d_e F_{\mu\nu}F^{\mu\nu}\right]+b\,\phi(\mathbf{x},t)|H|^2$$

$$\phi(\mathbf{x},t)=\frac{\sqrt{2\rho_{\text{DM}}}}{m_\phi}\cos[m_\phi(t-\mathbf{v}_\phi\cdot\mathbf{x})+\cdots]$$

Affects electron mass and fine structure constant [1,2]

$$\omega_A \propto m_e\alpha^{2+\xi_A}$$



$$\Delta\omega_A=\frac{\sqrt{8\pi G_{\text{N}}\rho_{\text{DM}}}}{m_\phi}\cdot\omega_A\cdot(d_{m_e}+\xi_A d_e)$$

Oscillation frequency from dark matter mass m_ϕ, highest in mid-frequency range [3, 4]

[1] Y. V. Stadnik and V. V. Flambaum, PRL **114** 161301 (2015)
[2] A. Arvanitaki *et al.* Phys. Rev. D **91** 015015 (2015)
[3] L. Badurina *et al.* arXiv:2108.02468 (2021)
[4] L. Badurina *et al.* J. Cosmol. Astropart. Phys. **5**, 011 (2020)

AION

Oxford

Technology integration, building the detector

MAGIS-UK

Imperial

High-resolution interferometry, laser locking

Cambridge

Transport, cooling and atom optics,

MAGIS-UK

Birmingham

Large momentum transfer

RAL

Engineering, AION-100 planning

KCL

Fundamental physics theory

Liverpool

MAGIS-UK

AION-10 (prototype detector)

University of Oxford: C. Foot, E. Bentine, T. Hird, A. Coughlan

High-resolution interferometry

Imperial College London: R. Hobson, C. Baynham, M. Tarbutt, B. Sauer

Rutherford Appleton Laboratory: T. Valenzuela Salazar, M. Bason, A. Marchant

Transport, Cooling and Atom-Optics

University of Cambridge: U. Schneider, T. Harte, K. Tkalčec, X. Su, M. Zeuner

Large momentum transfer

University of Birmingham: M. Holynski, M. Langlois, S. Lellouch, B. Stray, S. Hedges, O. Ennis, K. Bongs, Y. Singh, Y.-H. Lien

AION-physics (fundamental physics)

King's College London: J. Ellis, C. McCabe, L. Badurina

Universitat Autònoma de Barcelona: D. Blas, V. Vaskonen

University of Warsaw: M. Lewicki

MAGIS-UK:

University of Liverpool: J. Coleman, G. Elertas, L. Hawkins, S. Hindley, K. Bridges

University of Cambridge: V. Gibson, M. Uchida, J. Mitchell

University of Oxford: I. Shipsey, D. Bortoletto, C. Foot, J. March-Russell, D. Wood , D. Weatherill

AION-100

Rutherford Appleton Laboratory: D. Newbold, P. Majewski, I. Wilmut, M. Van der Grinten, S. Greenwood, P. Je M. Courthold, J. Boehm

Management

University of Oxford: A. Lowe, C. Gomez

Imperial College London: O. Buchmueller (PI)