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RAL Space

Quantum Technologies for Applied and Fundamental Physics

Tristan Valenzuela
Quantum Sensors and Technology Programme Lead

Outline

- Intro to Quantum Technologies 2.0
- Applications of QT
- Intro to Cold Atoms and Atom Interferometry
- Applications I : Gravity mapping and Atmospheric Science
- Applications II: Gravitational Waves and Ultralight Dark Matter

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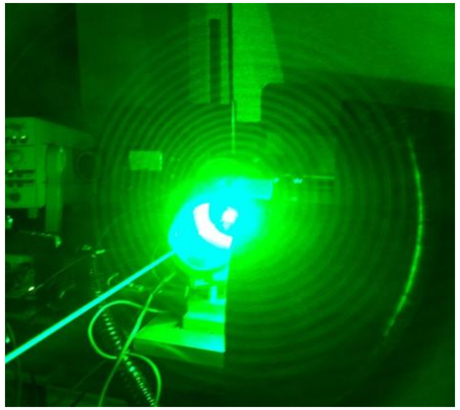
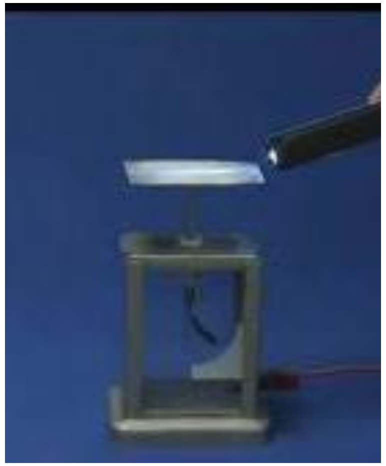
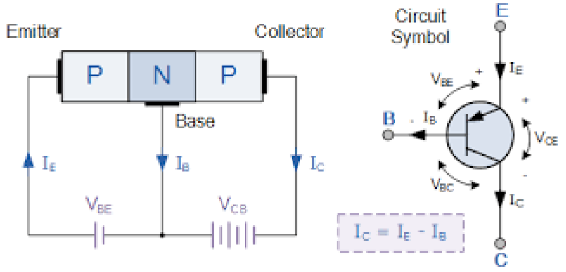
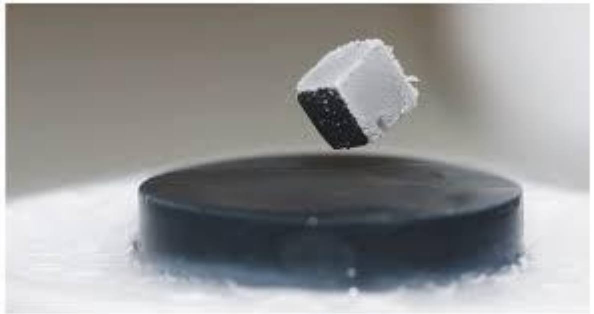
Quantum Technologies









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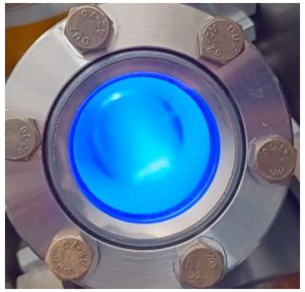
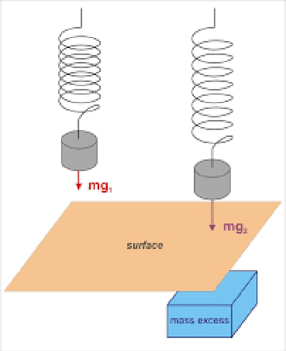
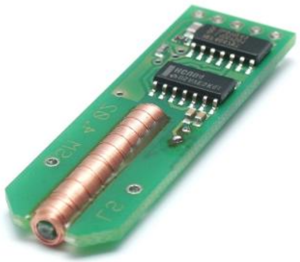
Quantum Technologies 2.0

Exploit quantum **superposition** and/or **entanglement**

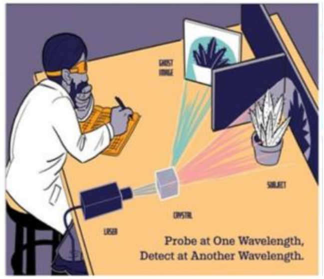
Sensing



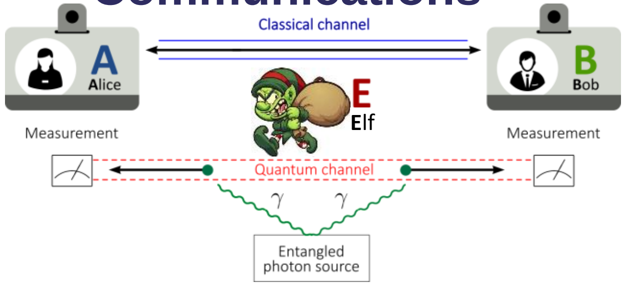


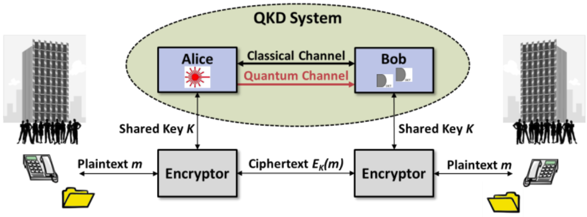


Imaging

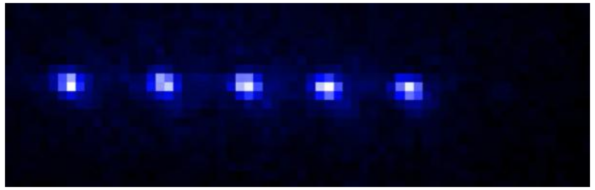


Communications



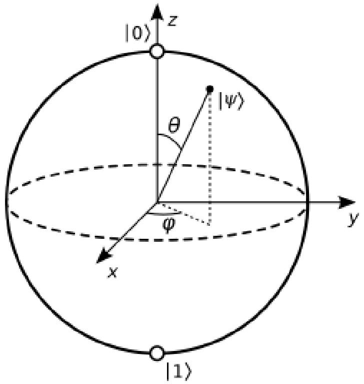


Computing



$|1\rangle$ and $|0\rangle$

$$\Psi = \alpha|0\rangle + \beta|1\rangle$$



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Applications of Quantum Technologies

From now on, in this talk

QT = QT-QC

Applications of Quantum Technologies

Earth Observation/Planetary Science/Space Weather

Atom Interferometers (Accelerometers)
& Magnetometers & Radiometers

- Geodesy
  - Earth & planetary interiors
- Climatic Effects
  - Ocean circulation & Water cycle
  - Glacial movements
- Earthquake monitoring
- Atmospheric Science

Fundamental Physics

Atomic clocks & Atom Interferometers:

- Tests of the Equivalence Principle
- Tests of General & Special Relativity
- Gravitational Red Shift
- Gravity Wave detection in the mid-frequency band
- Dark Mater detection

Telecommunications

Atomic clocks:

- Global time reference,
- High accuracy satellite navigation,
- Internet synchronisation.

Optical links and Quantum Memories

- Deep space ranging & communications
- Increased spectral efficiency and data rates
- Secure communications via QKD
- Entanglement Distribution

Applications of Quantum Technologies

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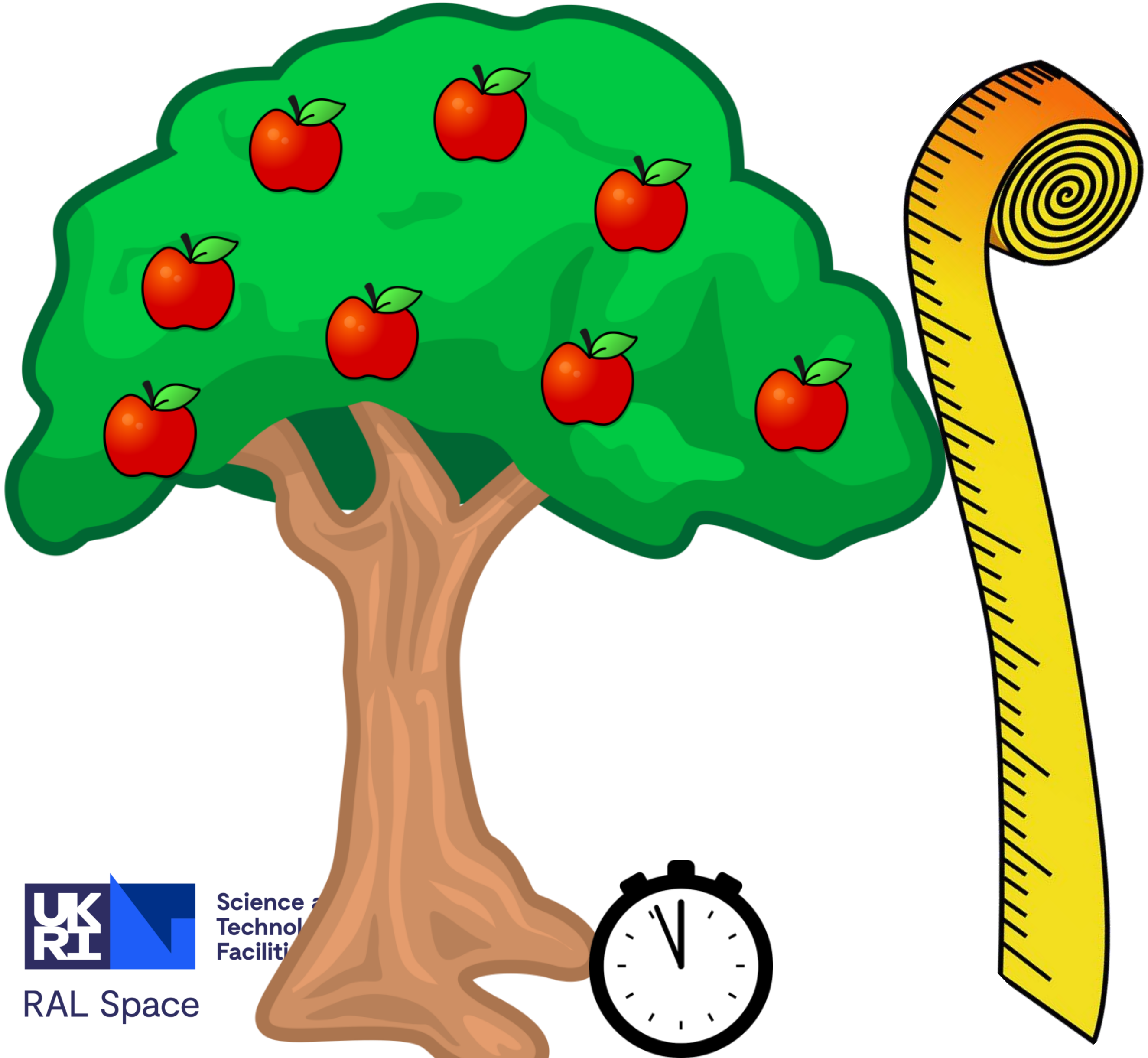
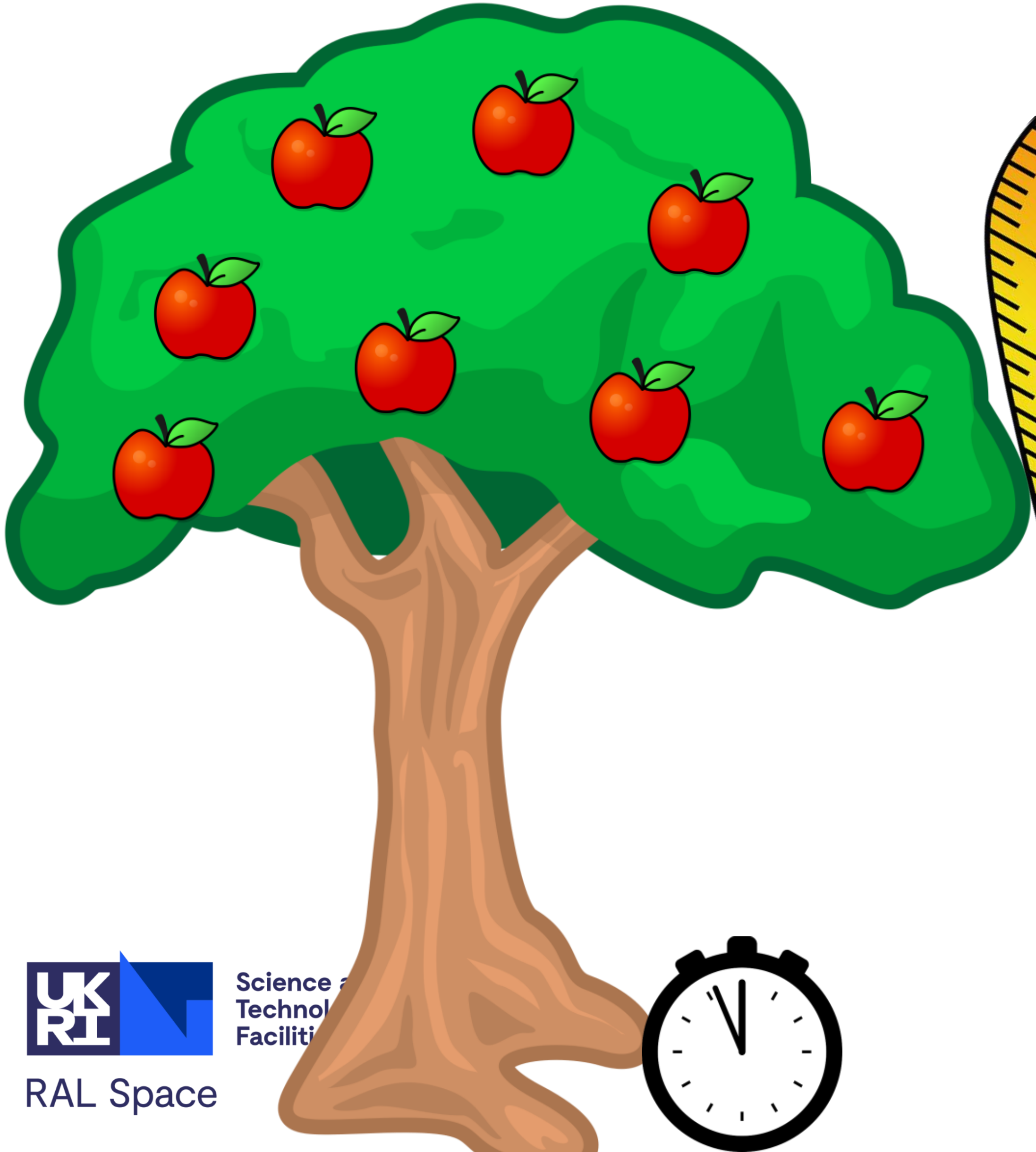
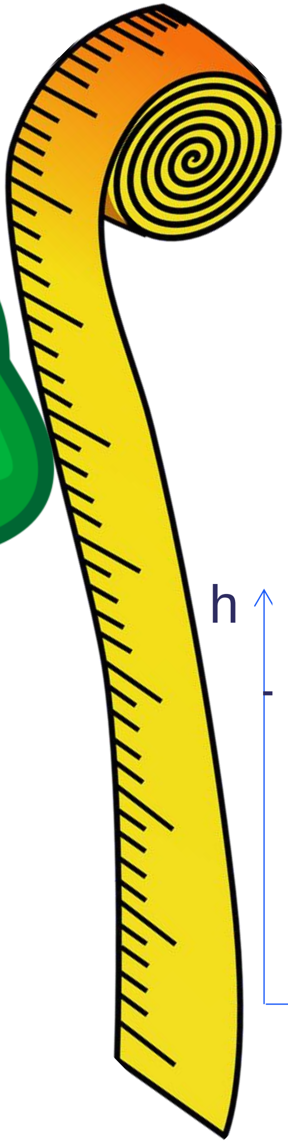
Space Based
Ground Based

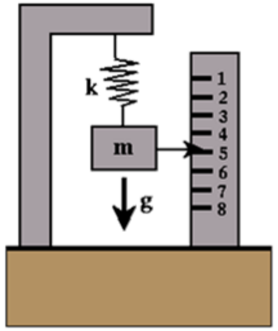
Classical accelerometry/gravimetry

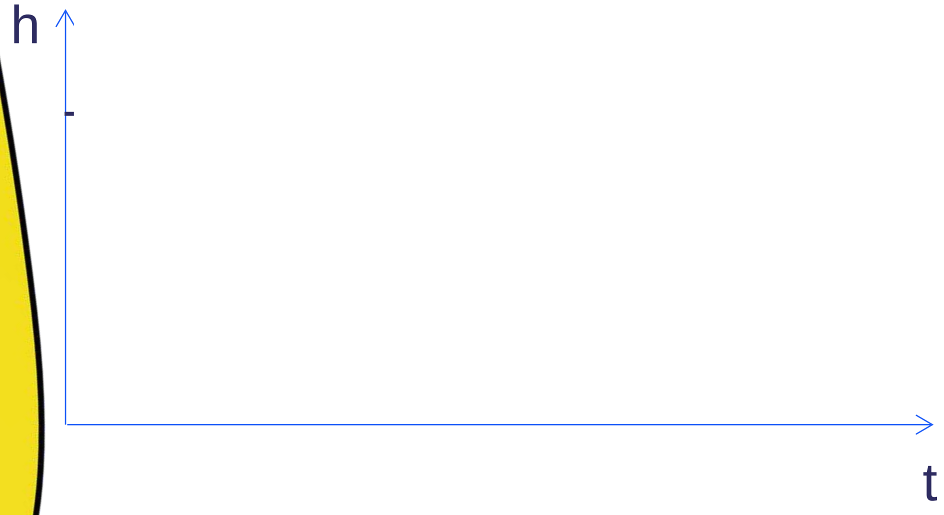


Classical accelerometry/gravimetry









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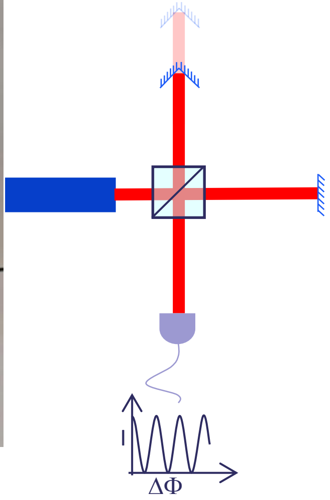
Classical accelerometry/gravimetry

Falling Corner Cube

Microg-LaCoste FG5

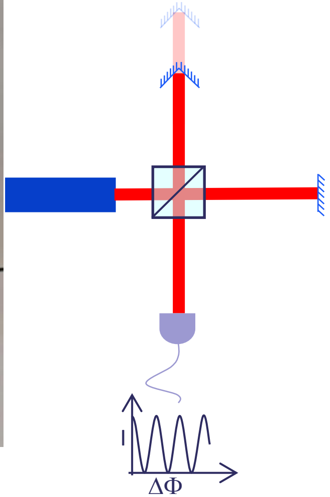


Spring elongation

Scintrex CG5

Classical accelerometry/gravimetry

Falling Corner Cube



Microg-LaCoste FG5

Spring elongation

Scintrex CG5

Limitations:

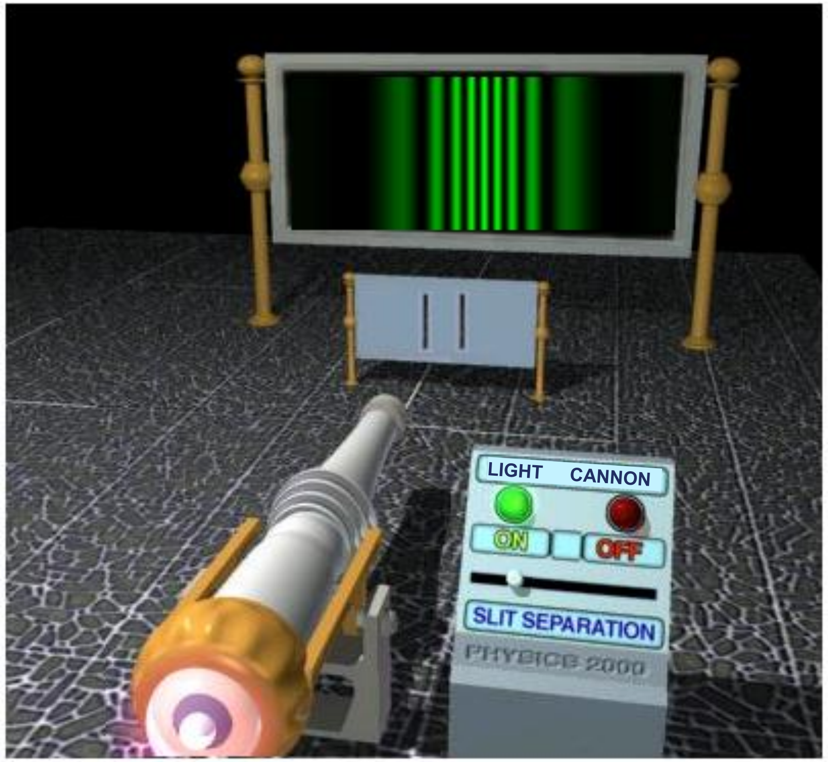
Free fall	Spring
Macroscopic mass	Ageing → Drift
Low rep rate	Readout noise
Residual vibrations	
Ground rebound	

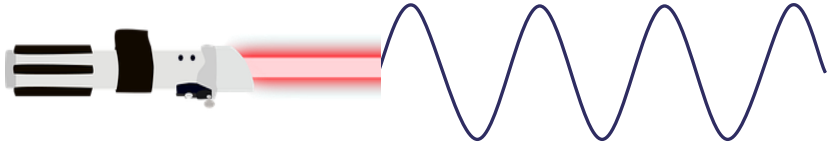
EM Wave Interferometry

- Young's double slit

  Phil. Trans. Roy. Soc. 92, 387 (1802)

  DOI:10.1098/rstl.1802.0016





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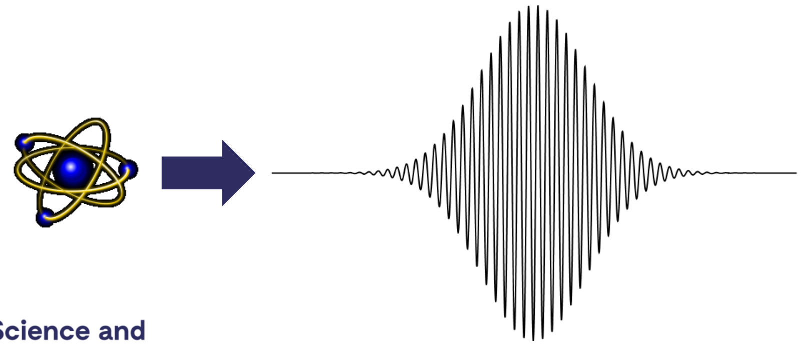
Matter Wave Interferometry

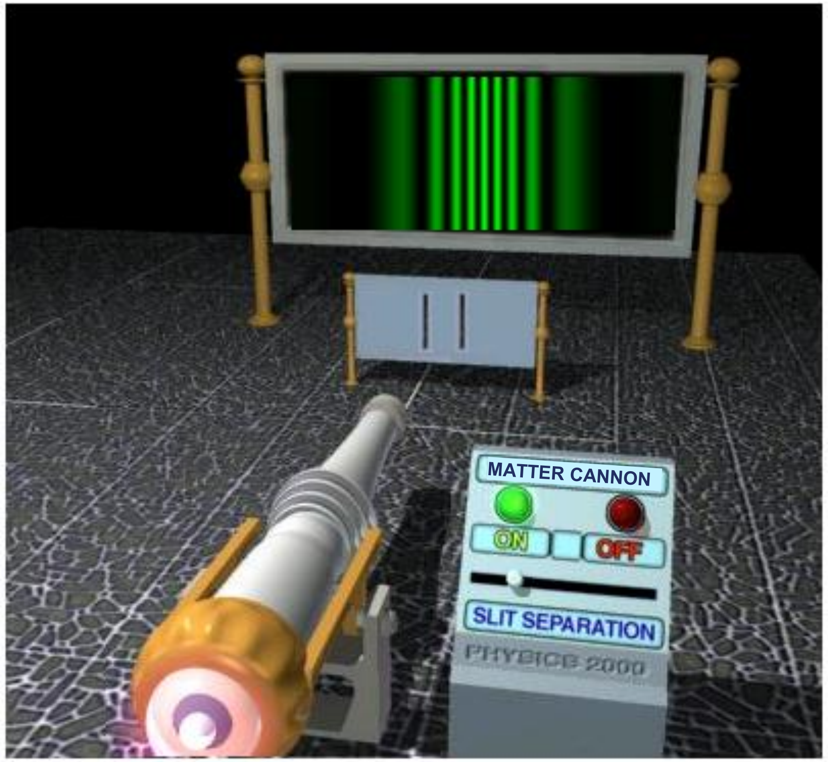
- de Broglie, wavelength of matter $\Rightarrow \boldsymbol{\lambda = \frac{h}{p} = \frac{h}{mv}}$

  Ann. Phys., Vol. 10, N°3 (1925), pp. 22–128
  DOI: 10.1051/anphys/192510030022

- Electron diffraction by GP Thomson and Reid, and Davisson and Germer

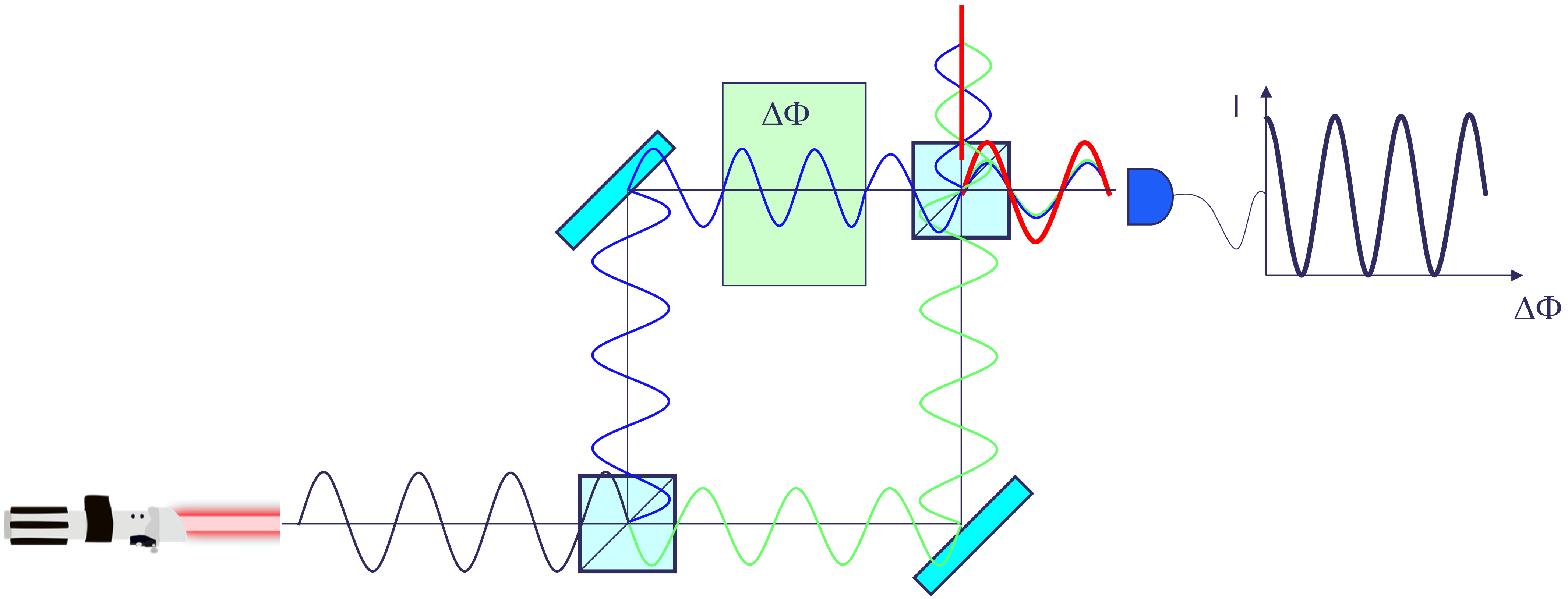
  T&R: Nature **119**, 890 (1927) DOI: 10.1038/119890a0
  D&G: Phys. Rev. **30**, 705 (1927) DOI: 10.1103/PhysRev.30.705





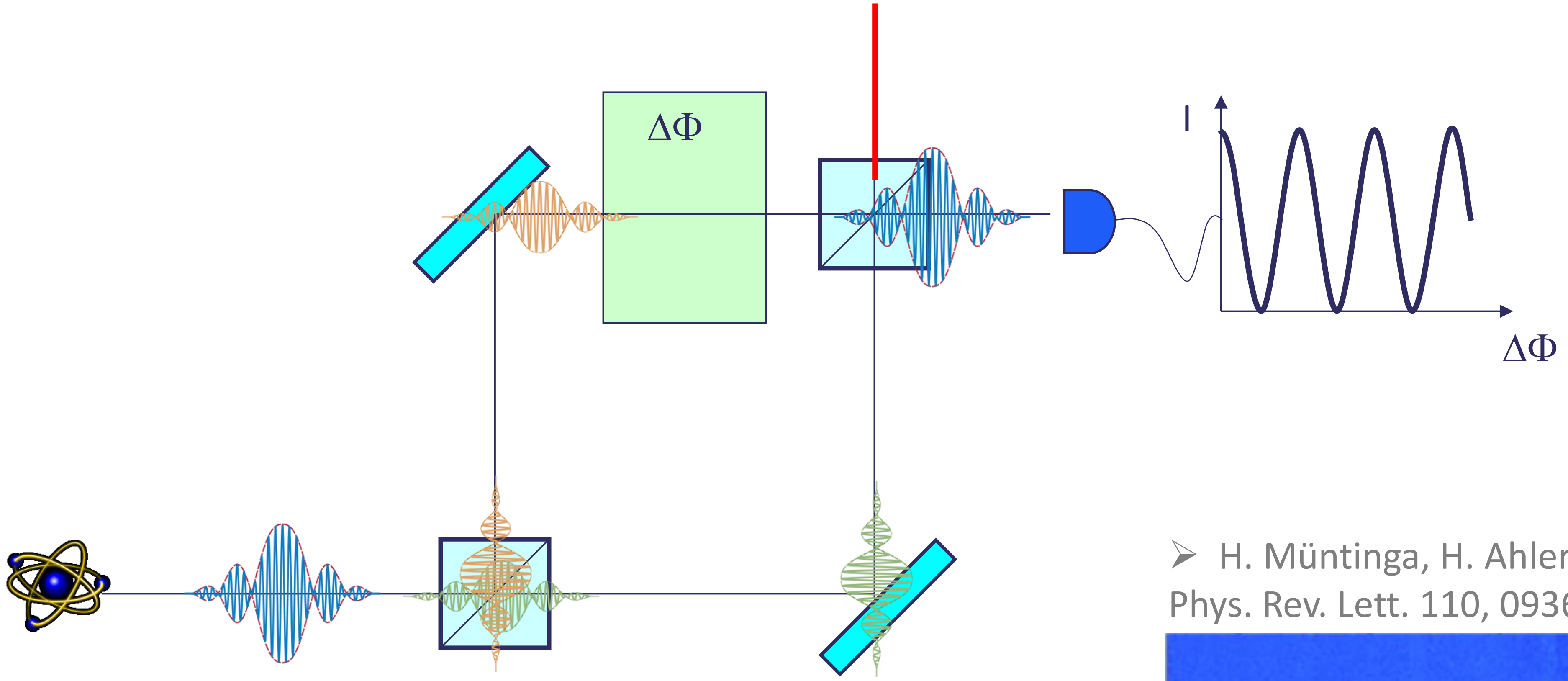
EM Wave Interferometry

Mach-Zehnder Interferometer

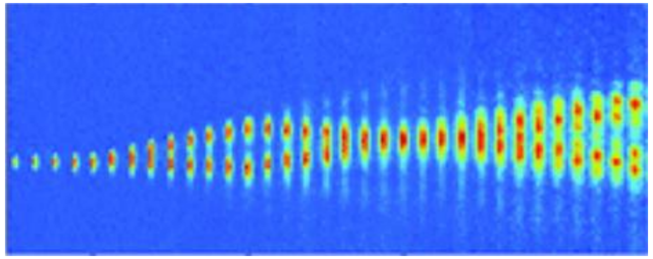


Matter Wave Interferometry

Mach-Zehnder Interferometer



➢ H. Müntinga, H. Ahlers, et al. Phys. Rev. Lett. 110, 093602



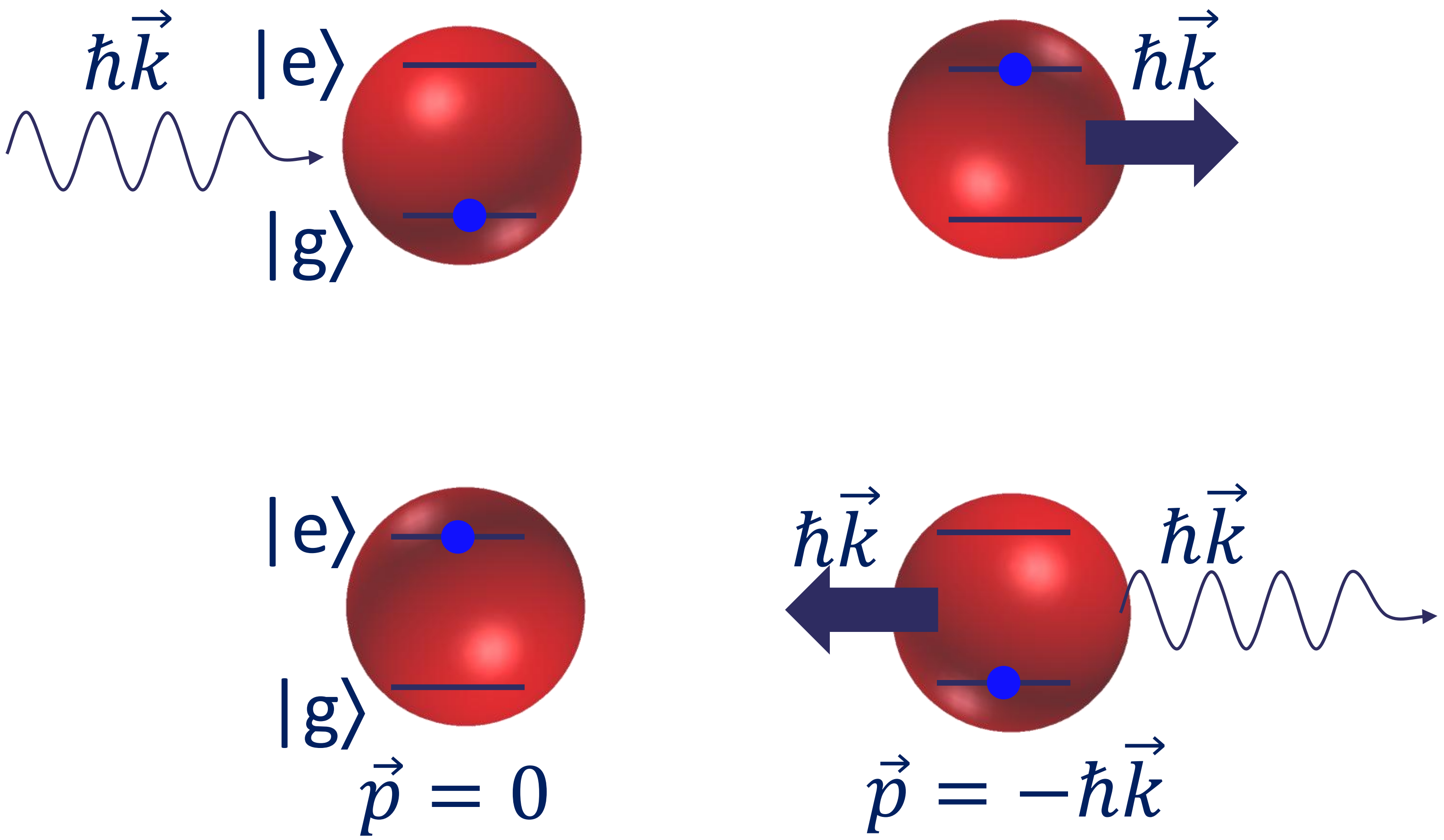
Intro to Cold Atom Interferometry

Some concepts: Energy-Momentum Conservation

$$\gamma \rightarrow \begin{cases} E = \hbar\omega \\ \vec{p} = \hbar\,\vec{k} \end{cases}$$

$$|\vec{p}| = \frac{E}{c}$$

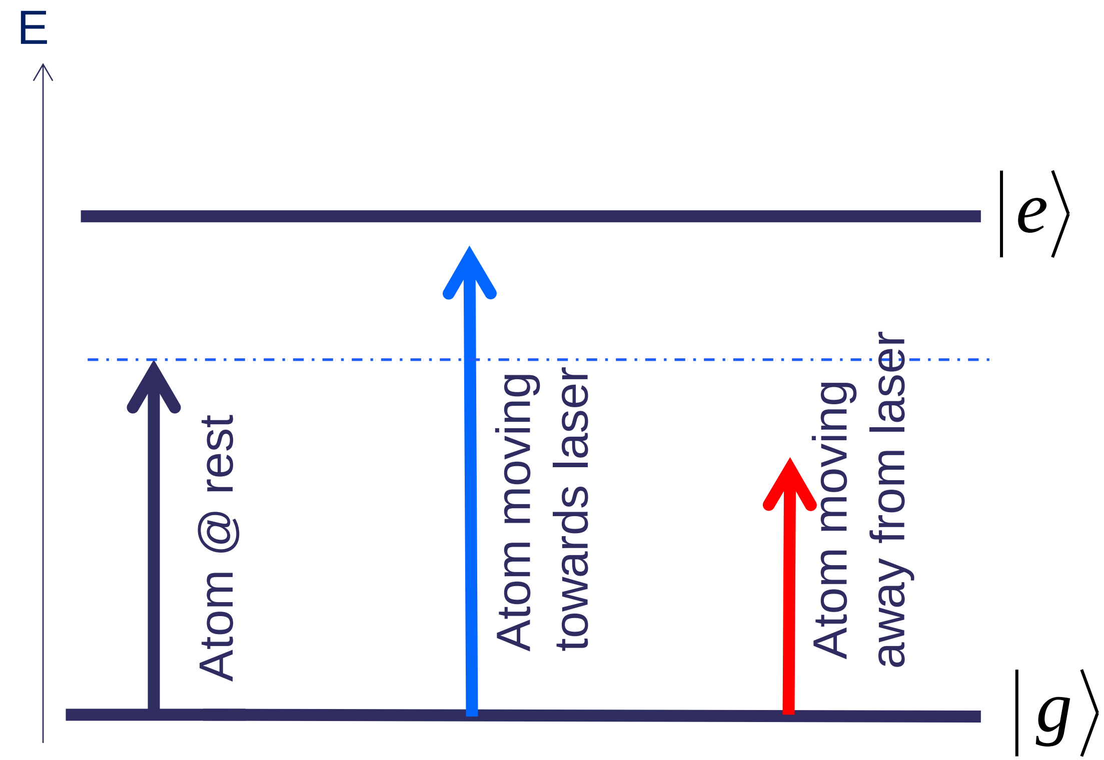
$$|\vec{k}| = \frac{\omega}{c} = \frac{2\pi}{\lambda}$$



Intro to Cold Atom Interferometry

Some concepts: Laser Cooling and Trapping

Doppler Effect



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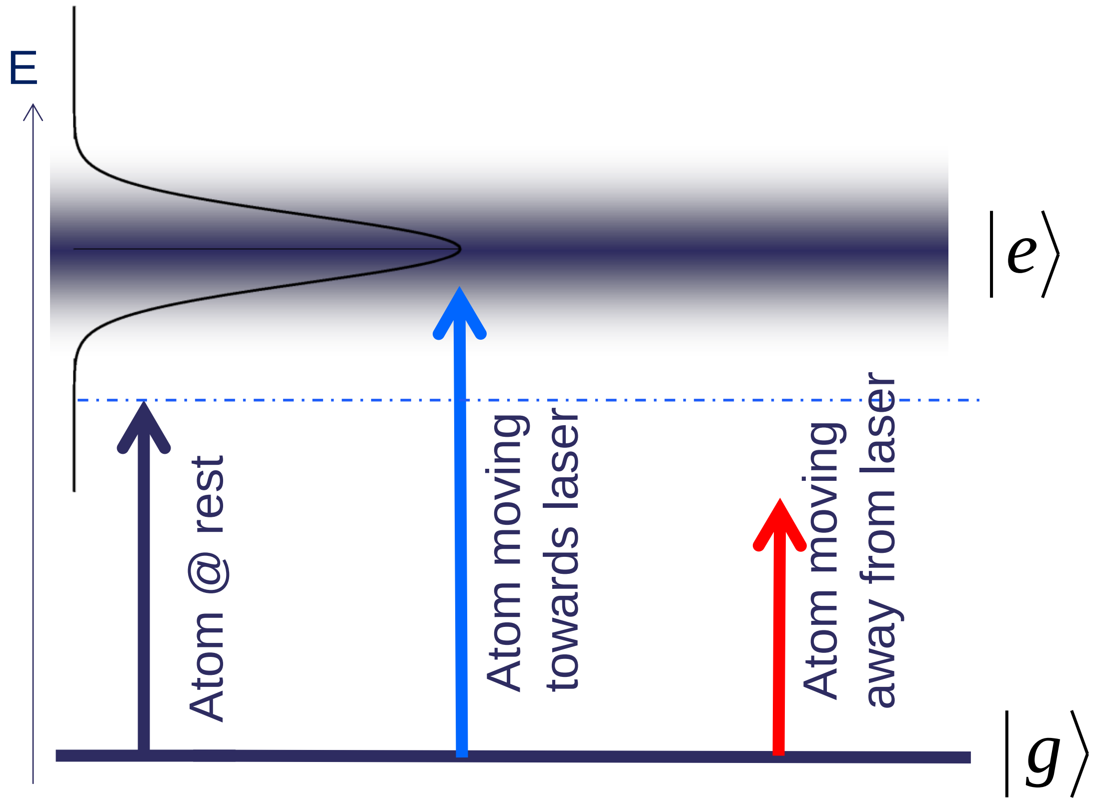

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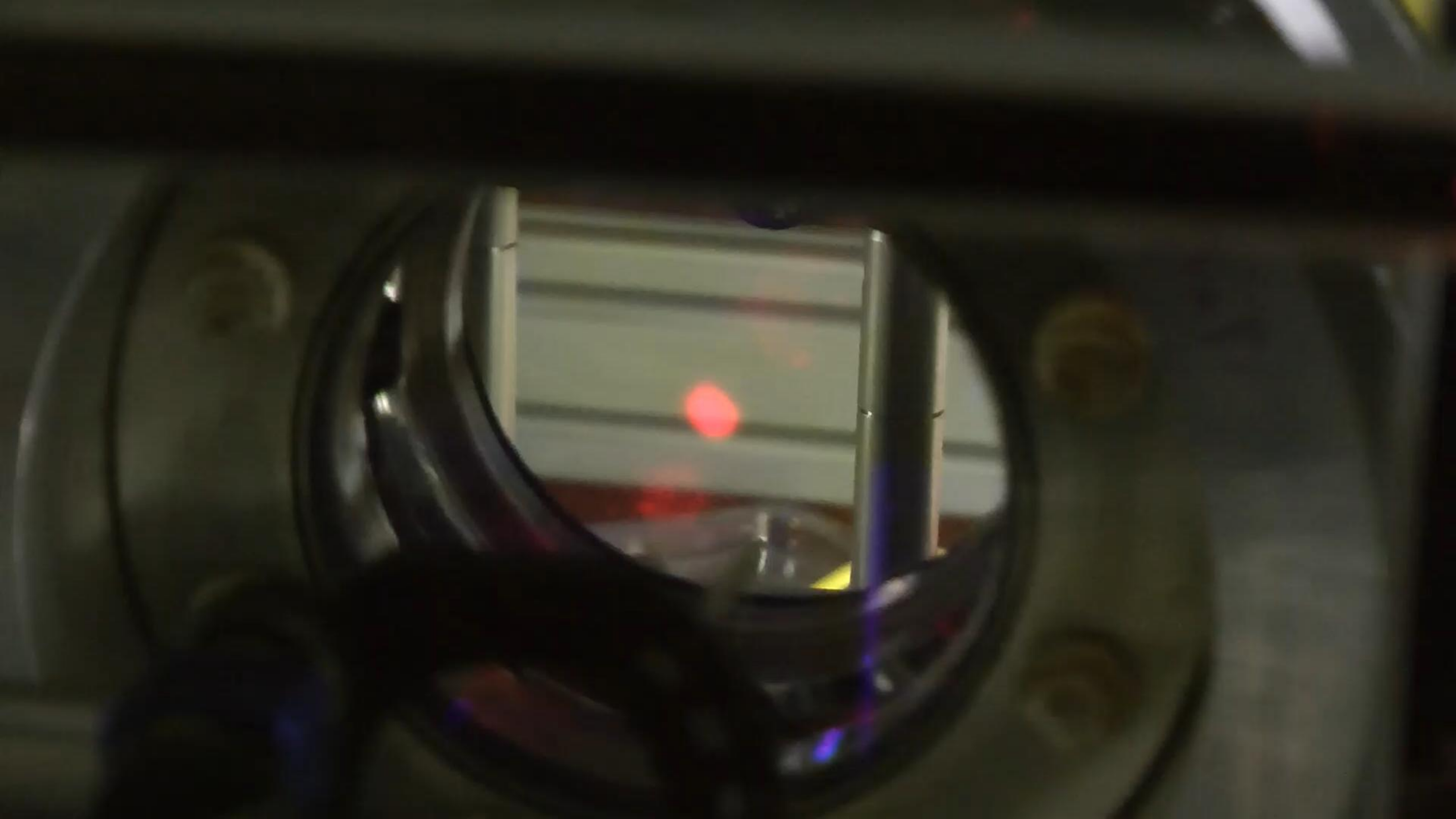
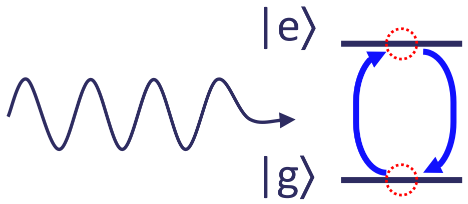


Intro to Cold Atom Interferometry

Some concepts: Rabi Oscillations

Continuous excitation of a two level atom

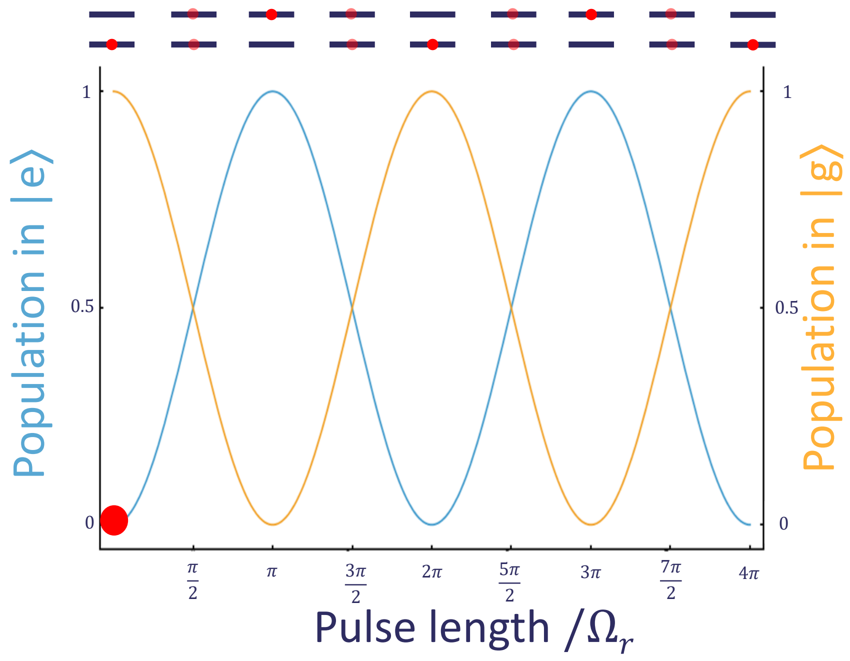


Rabi frequency $\rightarrow \Omega_r = \sqrt{{\Omega_{eg}}^2 + \delta^2}$

$$\Omega_{eg} = \frac{\langle e|\vec{d}\cdot\overrightarrow{E_0}|g\rangle}{\hbar}$$

$$\delta = \omega_L - \omega_{eg}$$
$$\omega_{eg} = E_{eg}/\hbar$$

Population in |e⟩ $\propto \sin^2\left(\frac{\Omega_r \cdot t}{2}\right)$



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Intro to Cold Atom Interferometry

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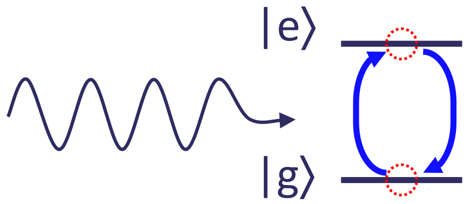

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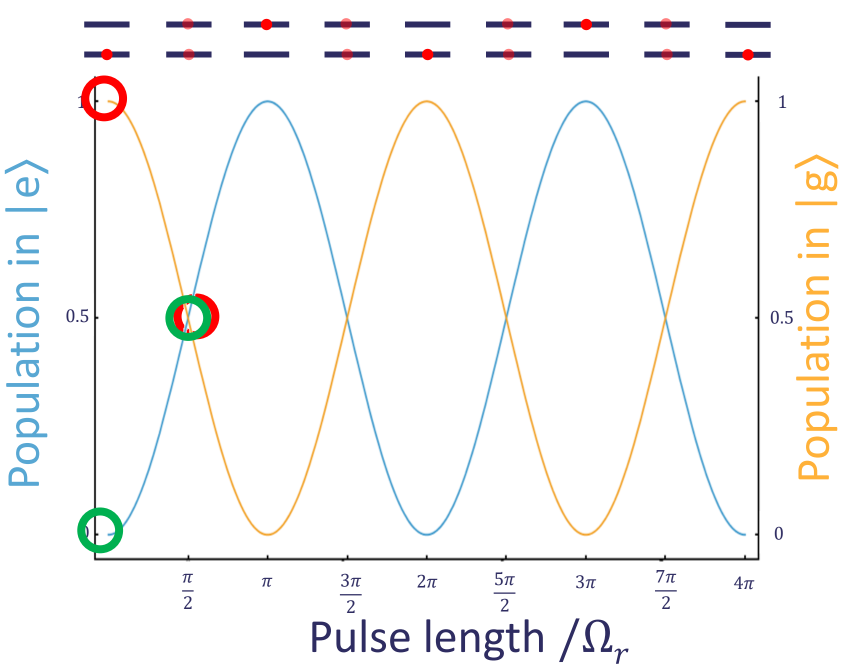

$$P_{ex} = \frac{1}{2}$$

$$|\psi_0\rangle = |g\rangle$$

⇓

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$$

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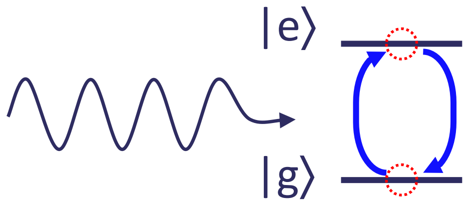
Intro to Cold Atom Interferometry

Some concepts: Rabi Oscillations

Continuous excitation of a two level atom



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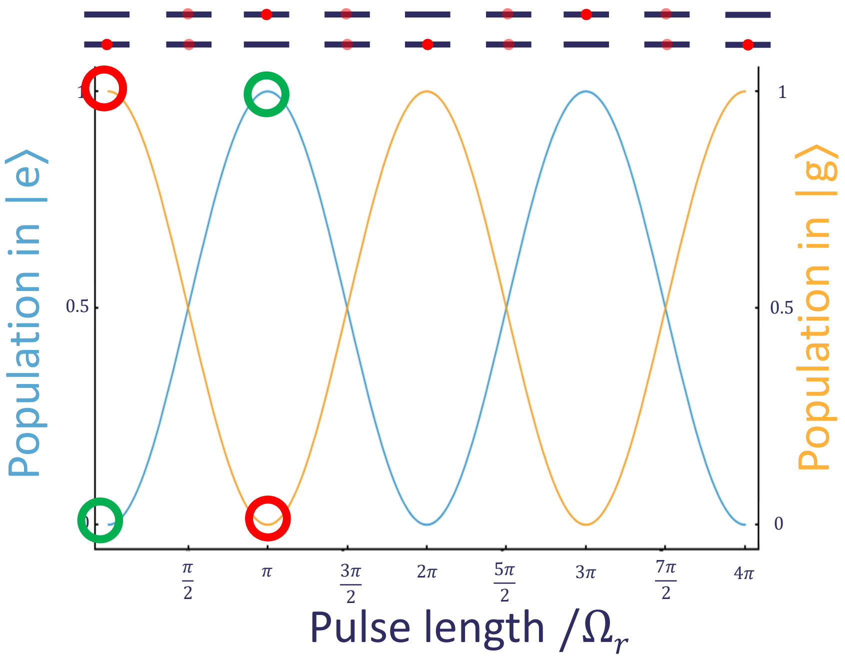

$P_{ex} = 1$

$|\psi_0\rangle = |g\rangle$

⇕

$|\psi_0\rangle = |e\rangle$

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Intro to Cold Atom Interferometry

Experimental sequence

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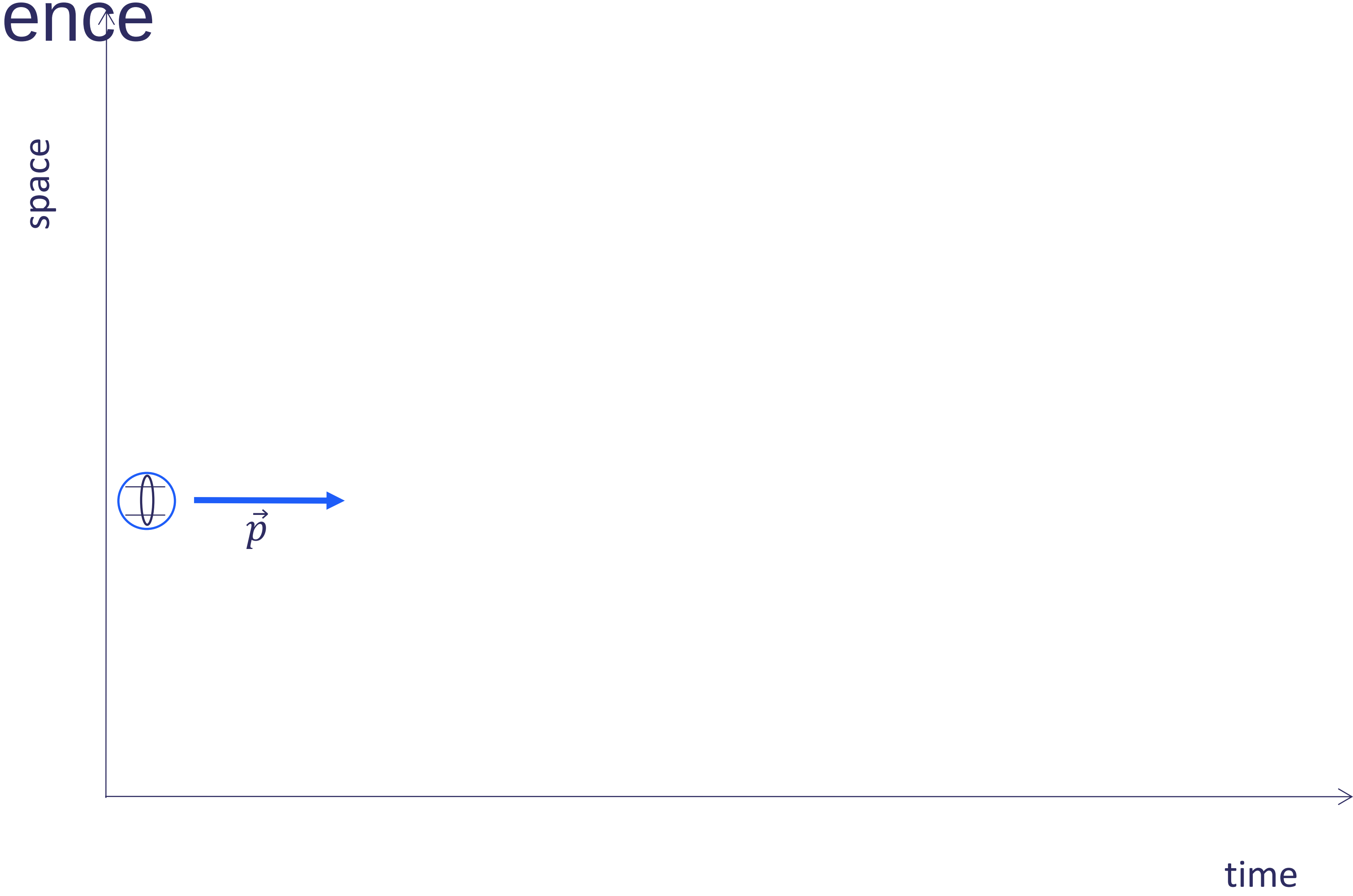
Intro to Cold Atom Interferometry

Experimental sequence

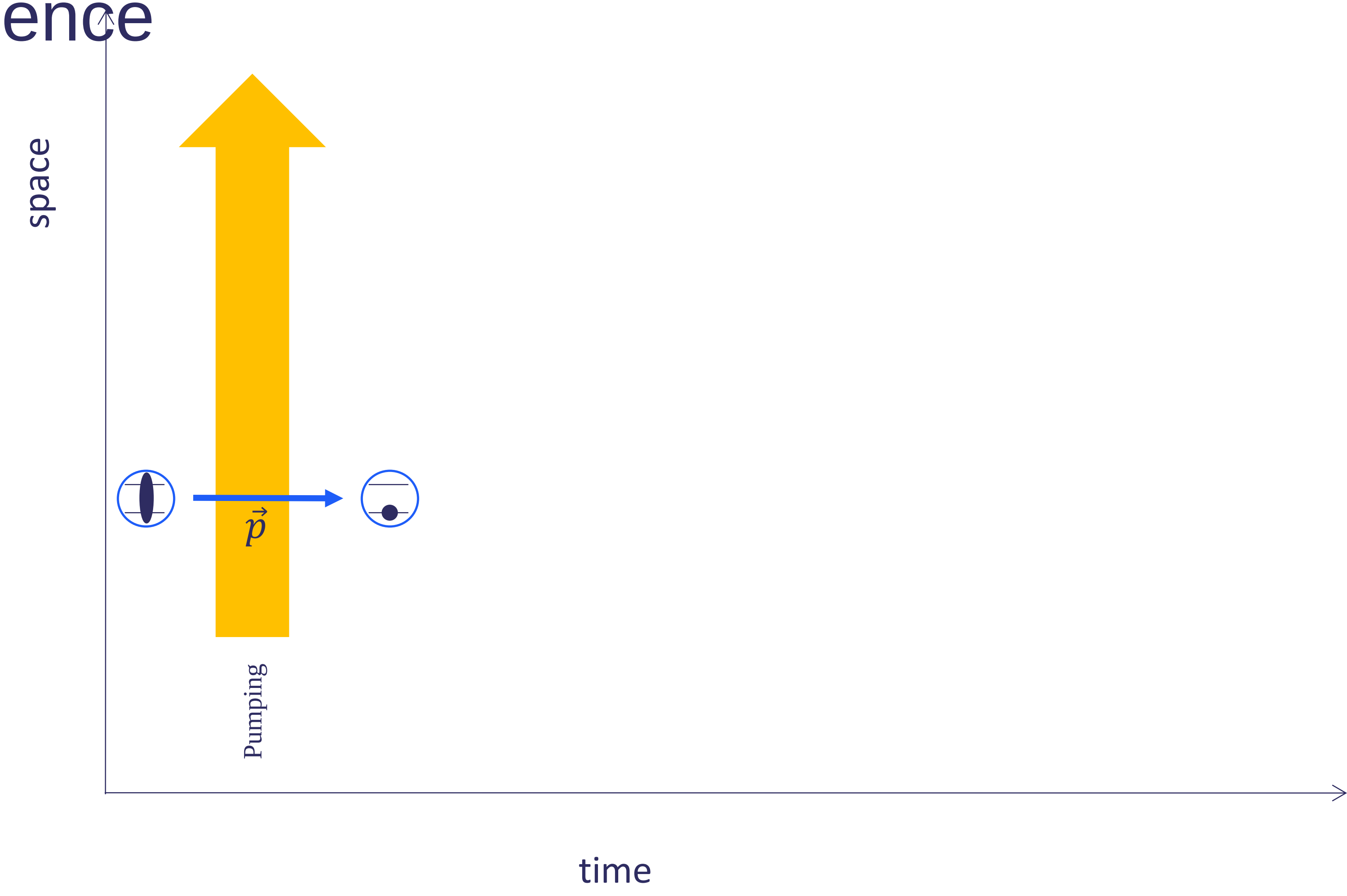


Intro to Cold Atom Interferometry

Experimental sequence

State preparation and release

$$|\psi\rangle = |g, \overrightarrow{p_0}\rangle$$

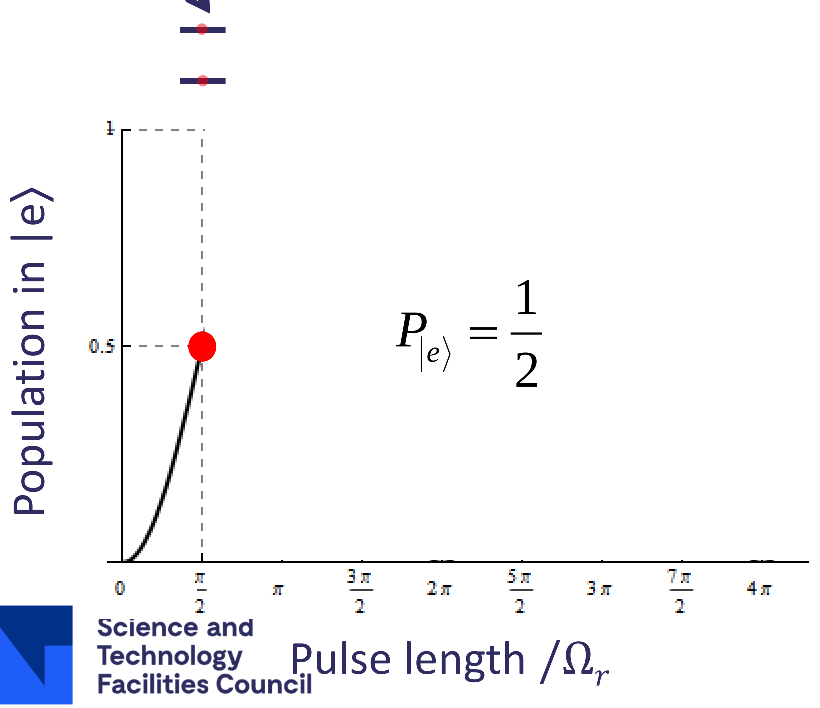


Intro to Cold Atom Interferometry

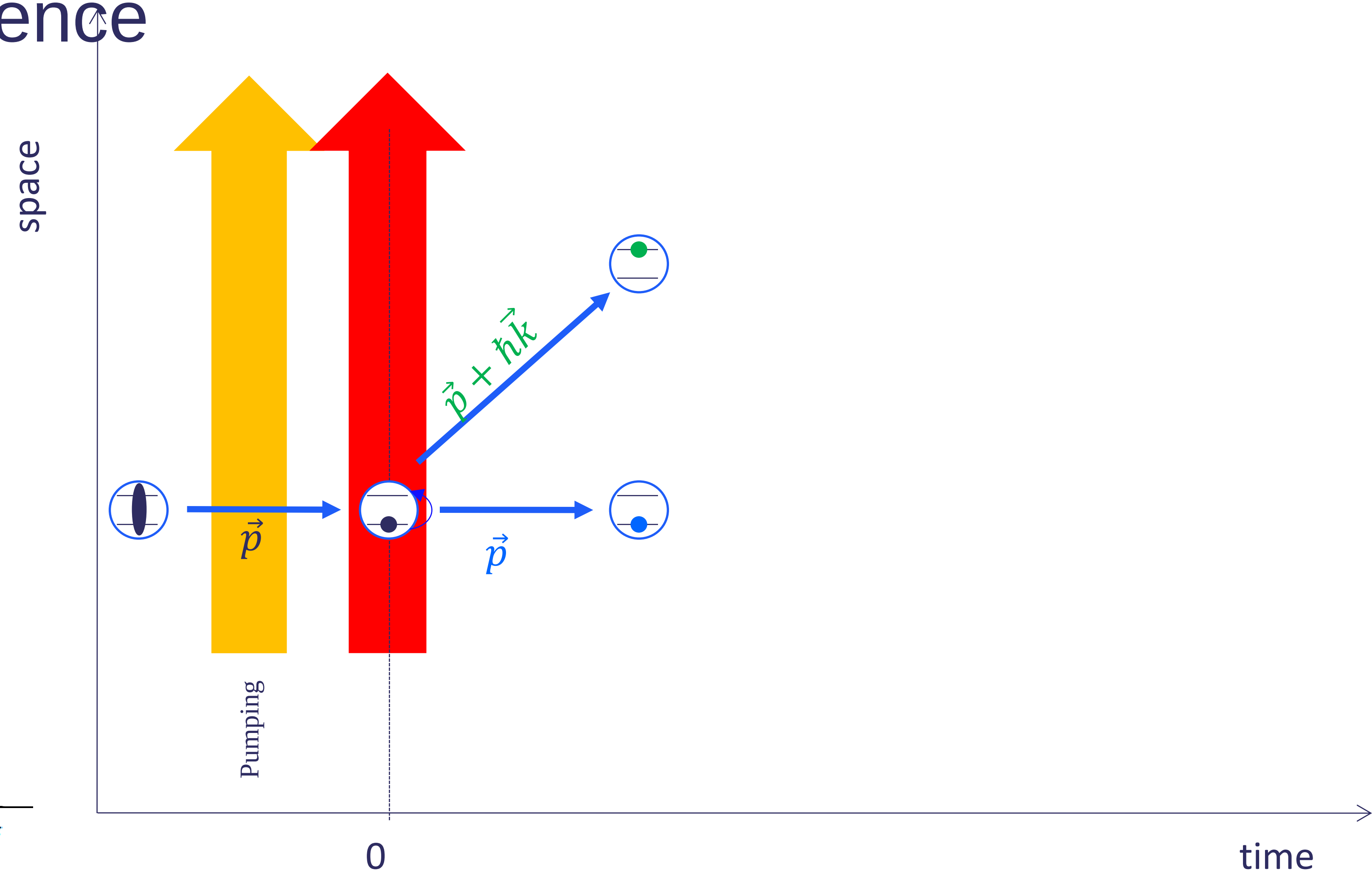
Experimental sequence

Pulse length = $^{\pi}/_{2}\,/\Omega_r$

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g, \overrightarrow{p_0}\rangle + |e, \overrightarrow{p_0} + \hbar\vec{k}\rangle\right)$$



$$P_{|e\rangle} = \frac{1}{2}$$



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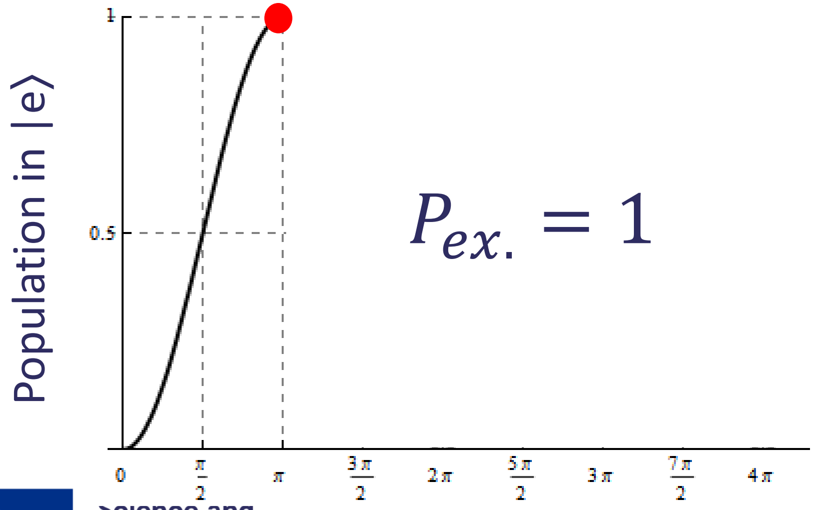
Intro to Cold Atom Interferometry

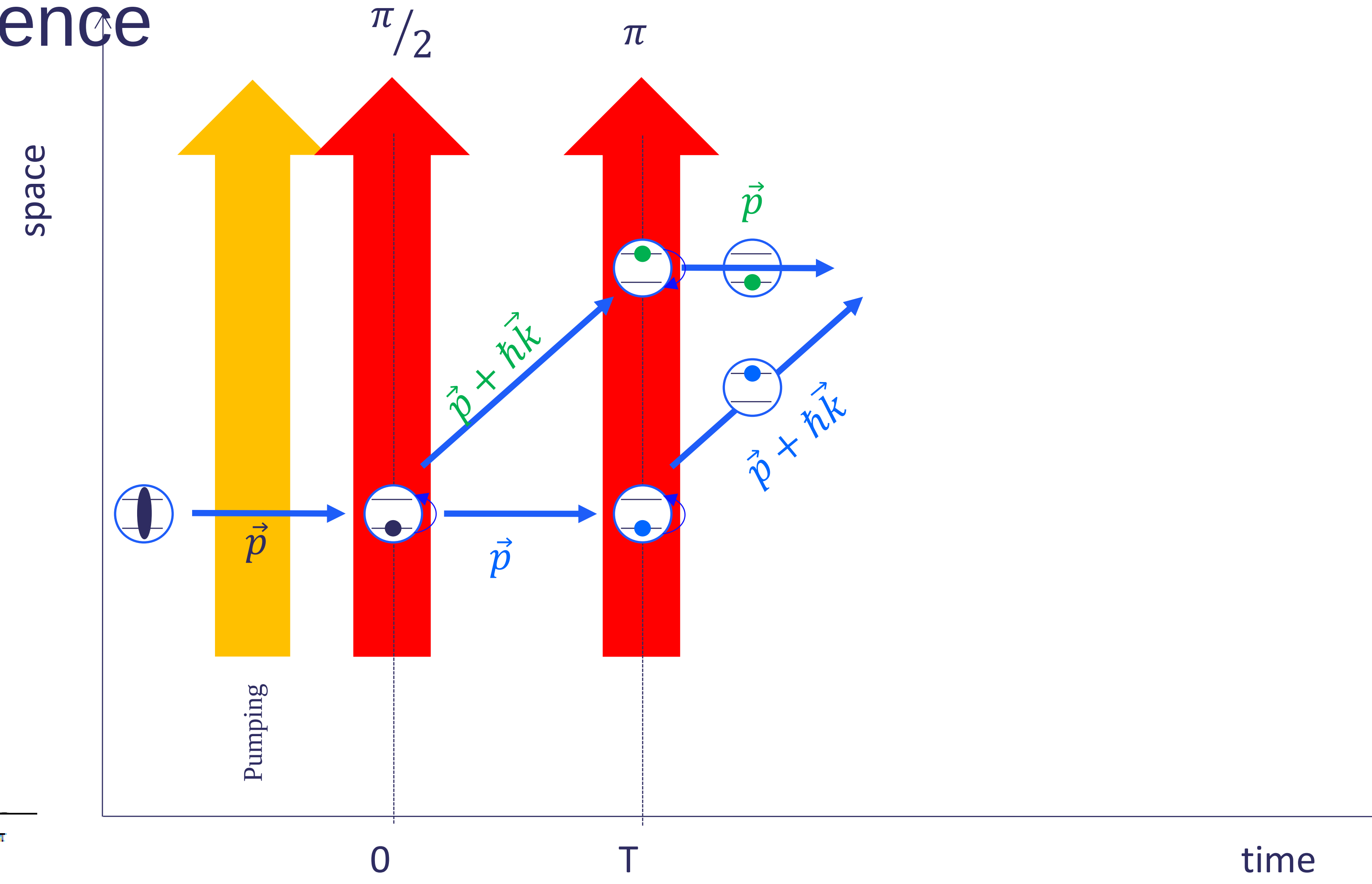
Experimental sequence

Pulse length $=\pi \cdot \Omega_r$

$$|g\rangle \Longrightarrow |e, \overrightarrow{p_0} + \hbar\vec{k}\rangle$$
$$|e\rangle \Longrightarrow |g, \overrightarrow{p_0}\rangle$$



$$P_{ex.} = 1$$



Intro to Cold Atom Interferometry

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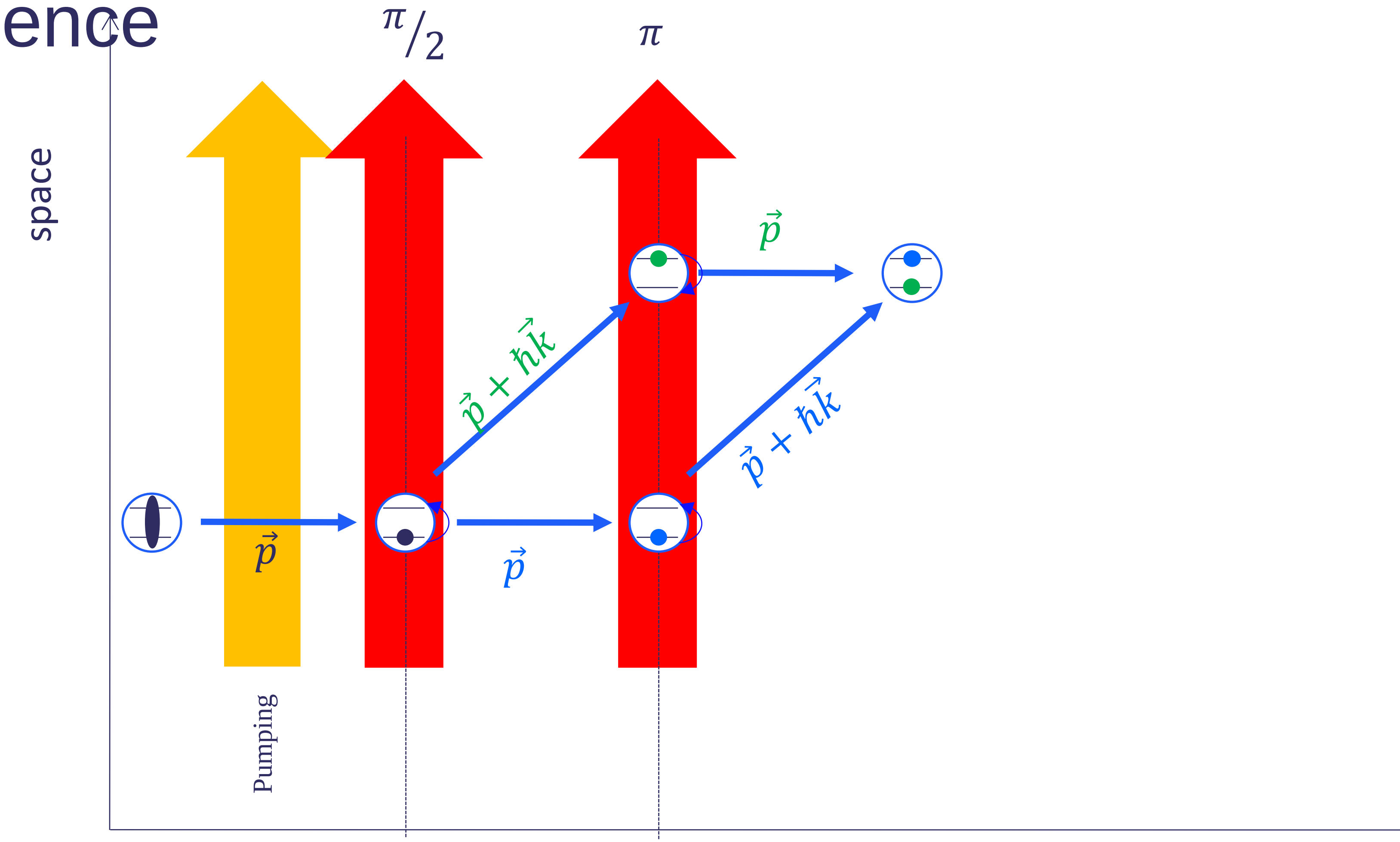

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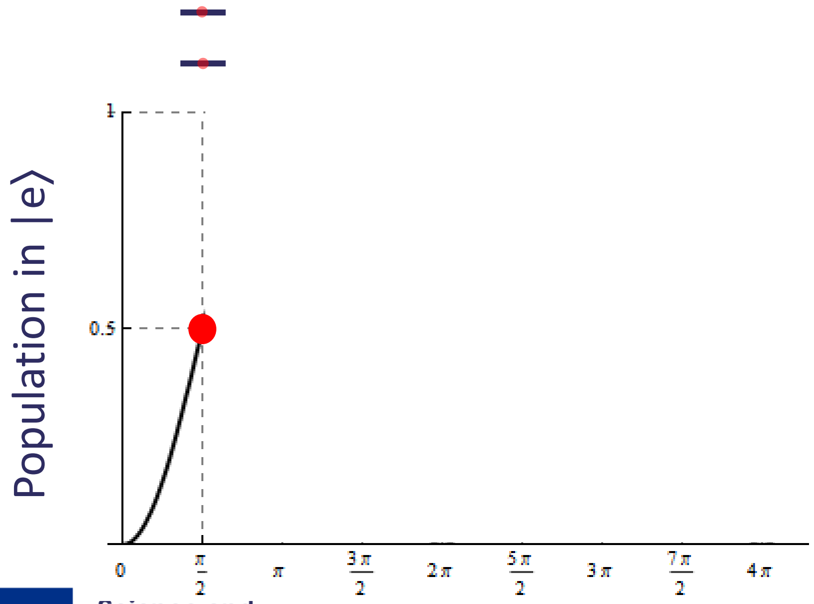
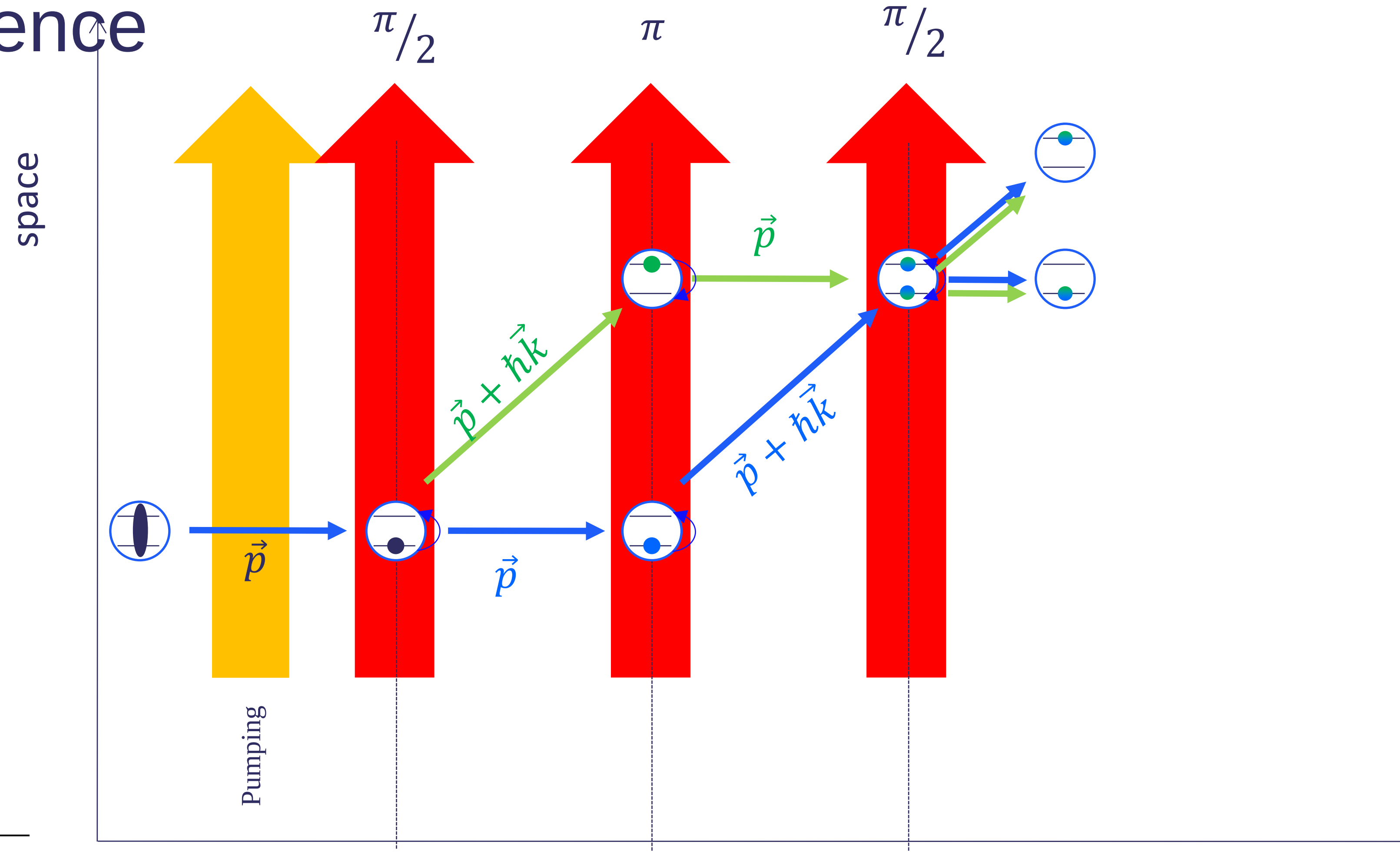
$$|e\rangle \Rightarrow \frac{1}{\sqrt{2}}\left(|e,\overrightarrow{p_0} + \hbar\vec{k}\rangle + |g,\overrightarrow{p_0}\rangle\right)$$



Pulse length $/\Omega_r$



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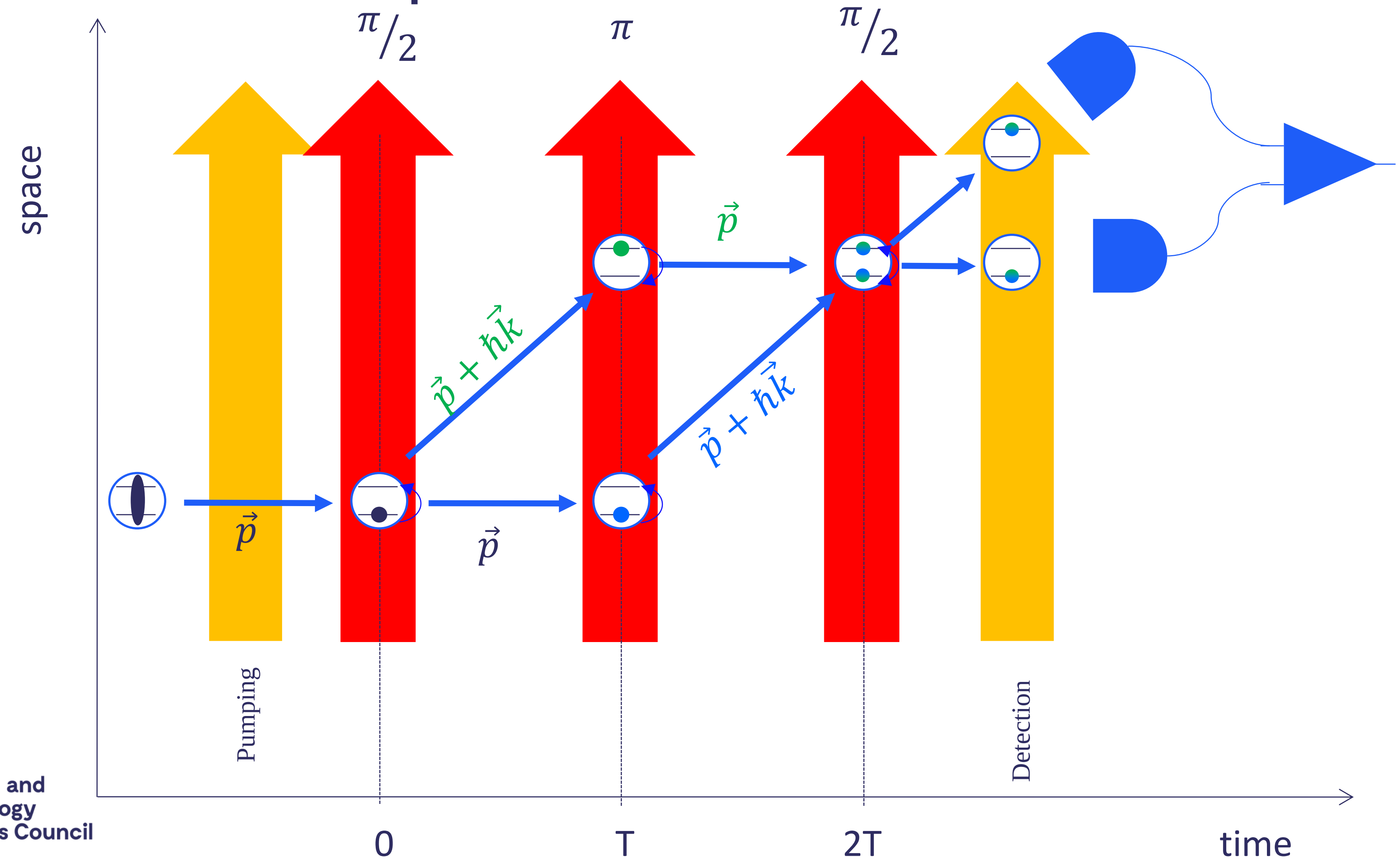

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Intro to Cold Atom Interferometry

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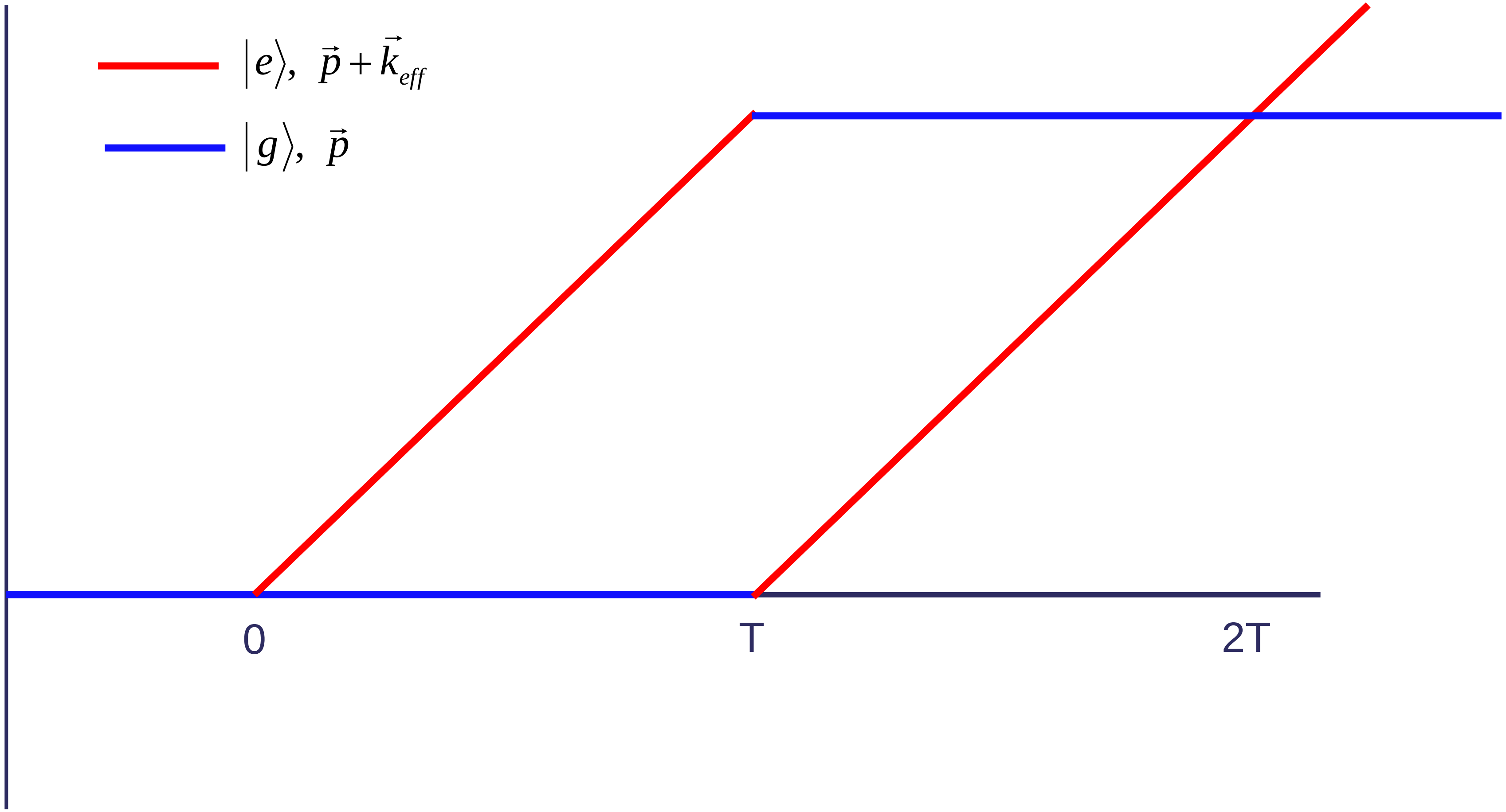

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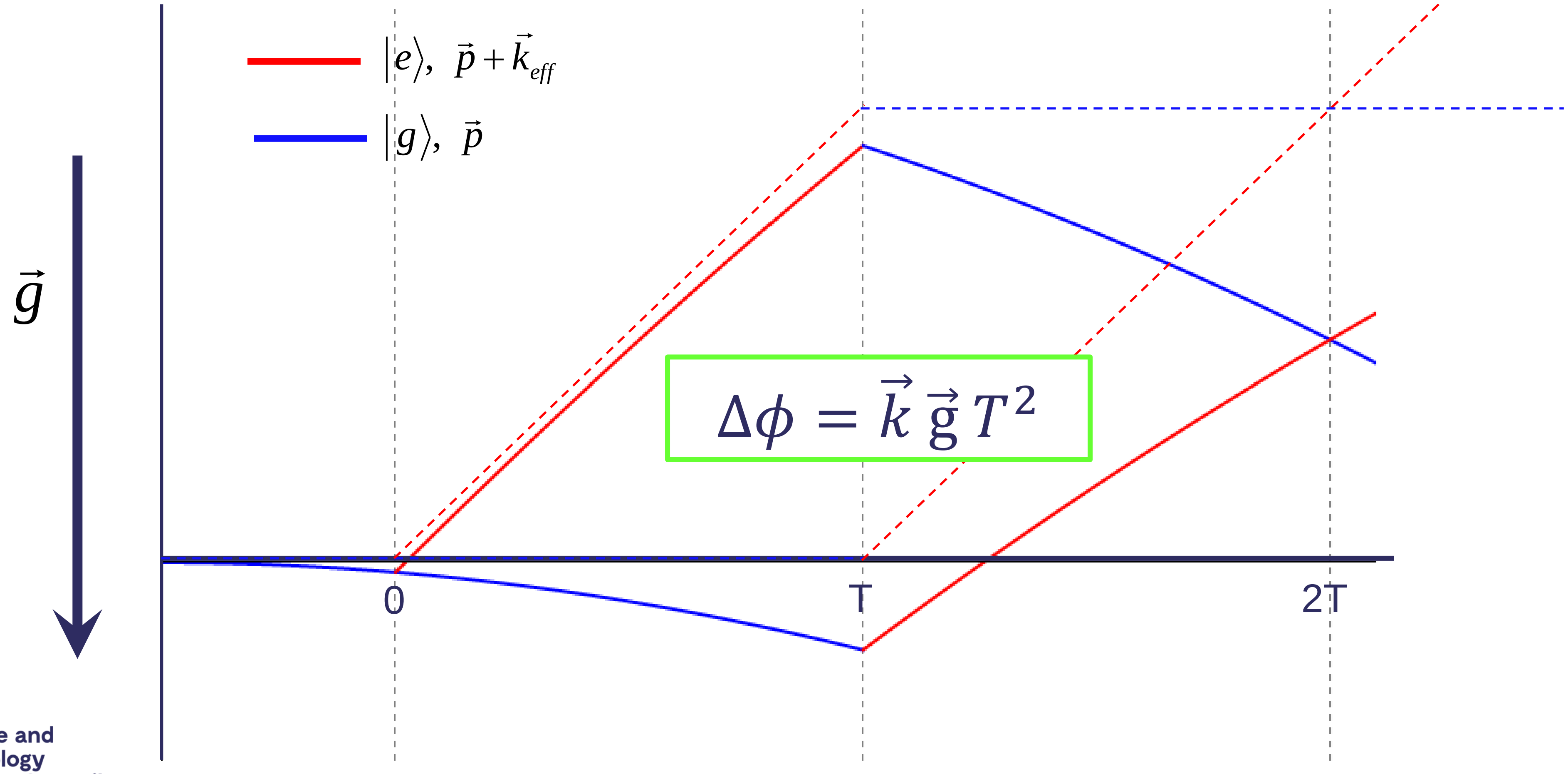
Experimental sequence



Intro to Cold Atom Interferometry

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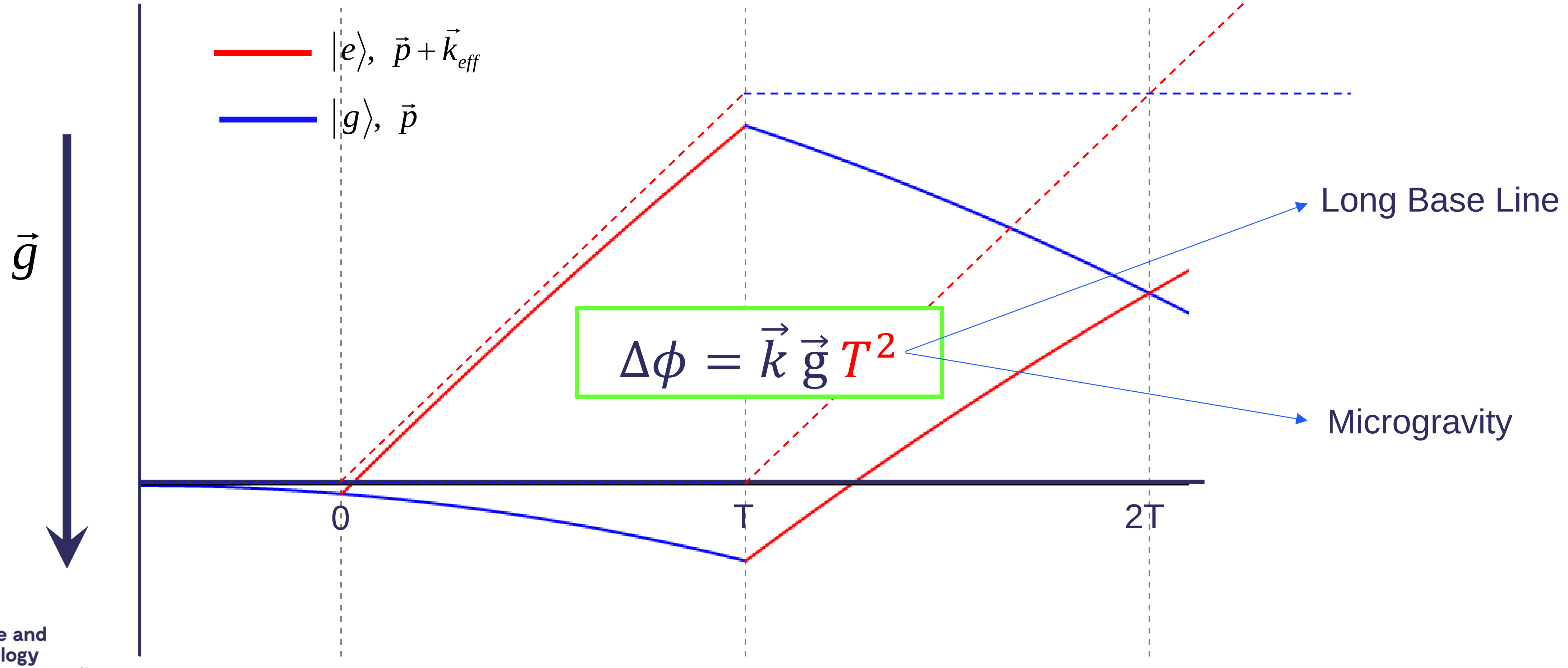

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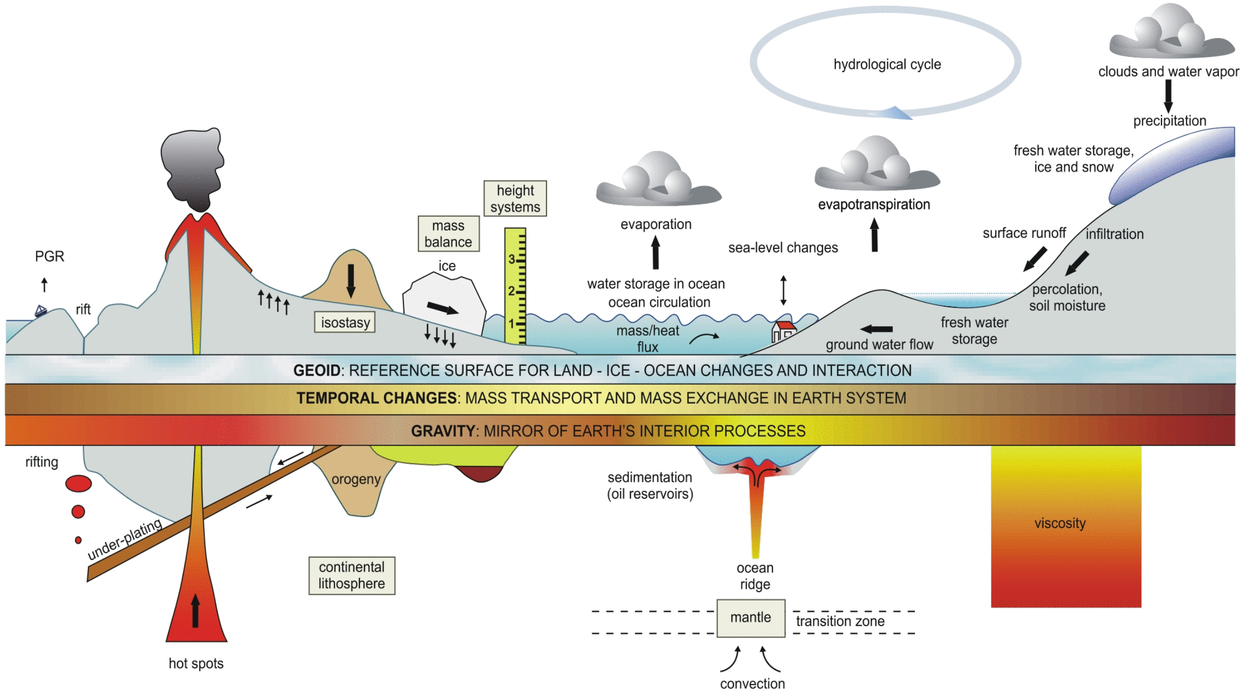
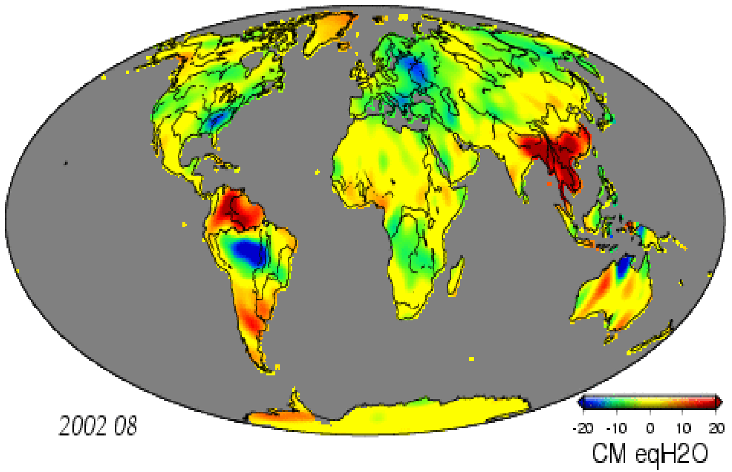
Gravity Mapping and …





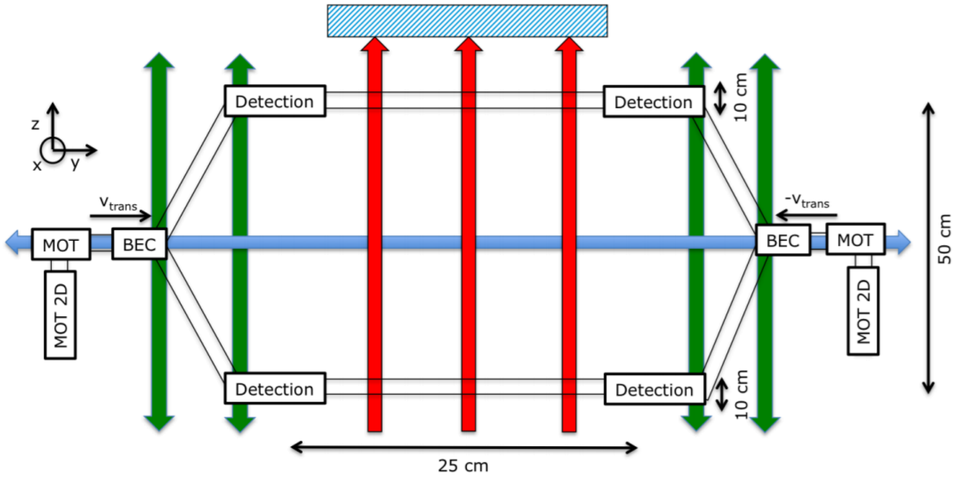
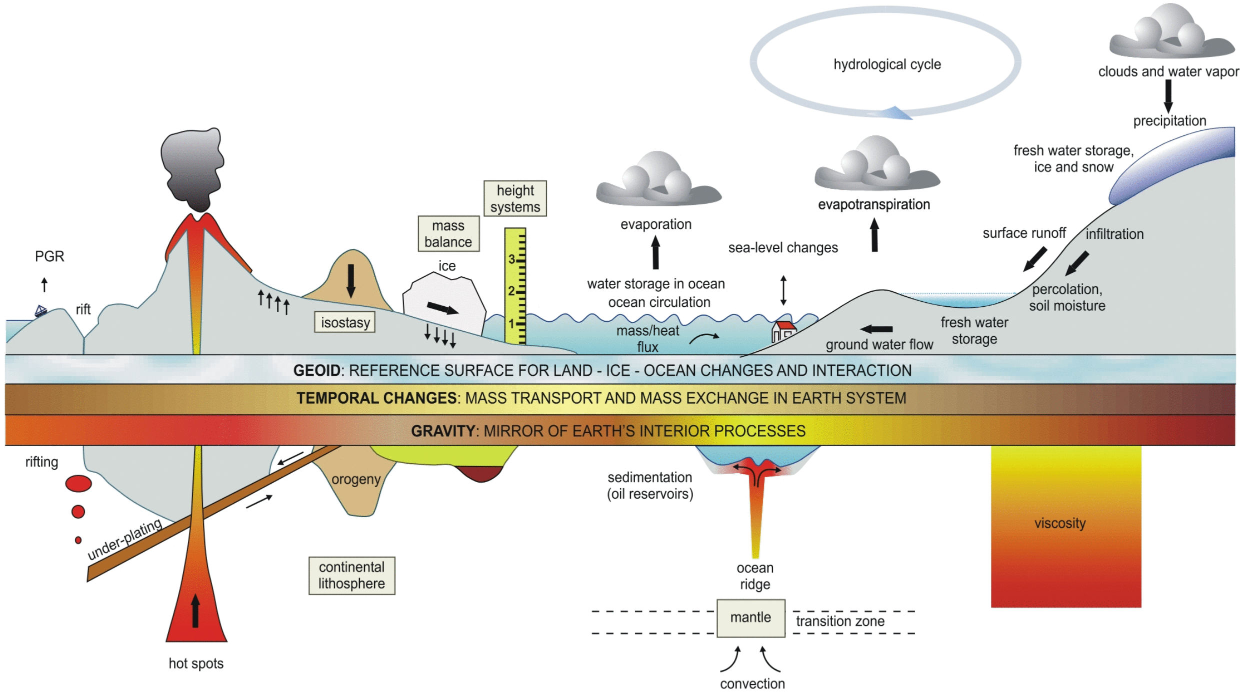
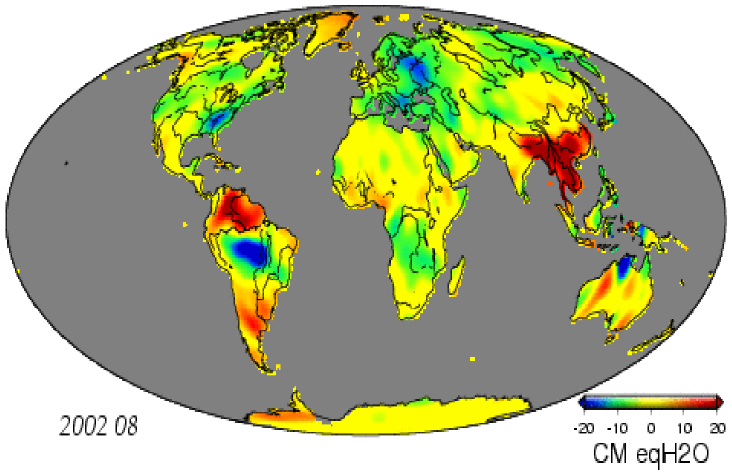


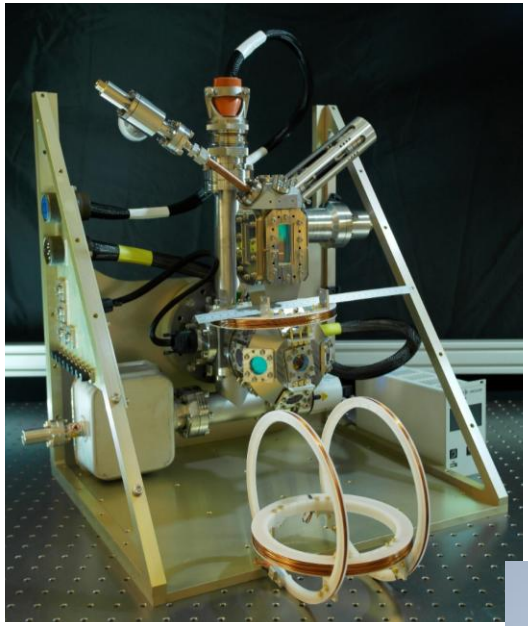
FIG. 3: (Color online) Scheme of the vacuum chamber (not drawn to scale; orientative sizing). The red arrows represent the Raman lasers for the interferometry part; the blue arrows represent the light pulse giving the transverse velocity v_{trans}; the green arrows represent the light pulses guiding the atoms from the cooling room to the interferometer room; the blue rectangle is the mirror, which will be the inertial reference.

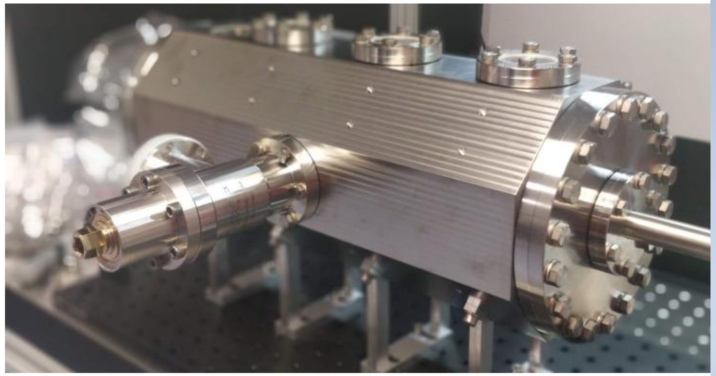
Based on O. Carraz et al, Microgravity Science and Technology v26, pp 139-145 (2014)

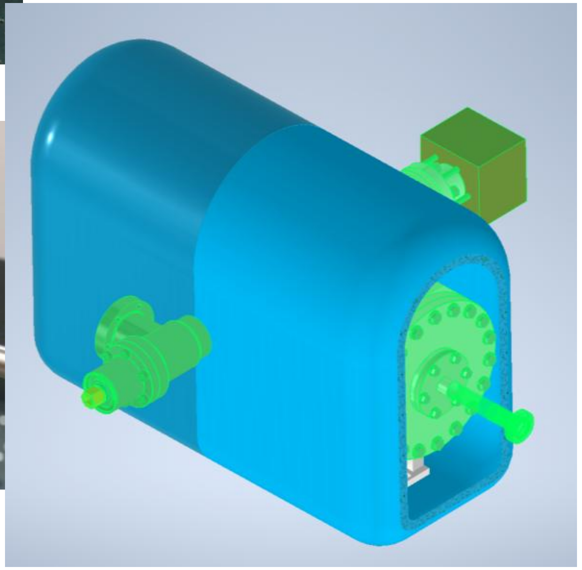
Gravity Mapping and …











… Atmospheric Science

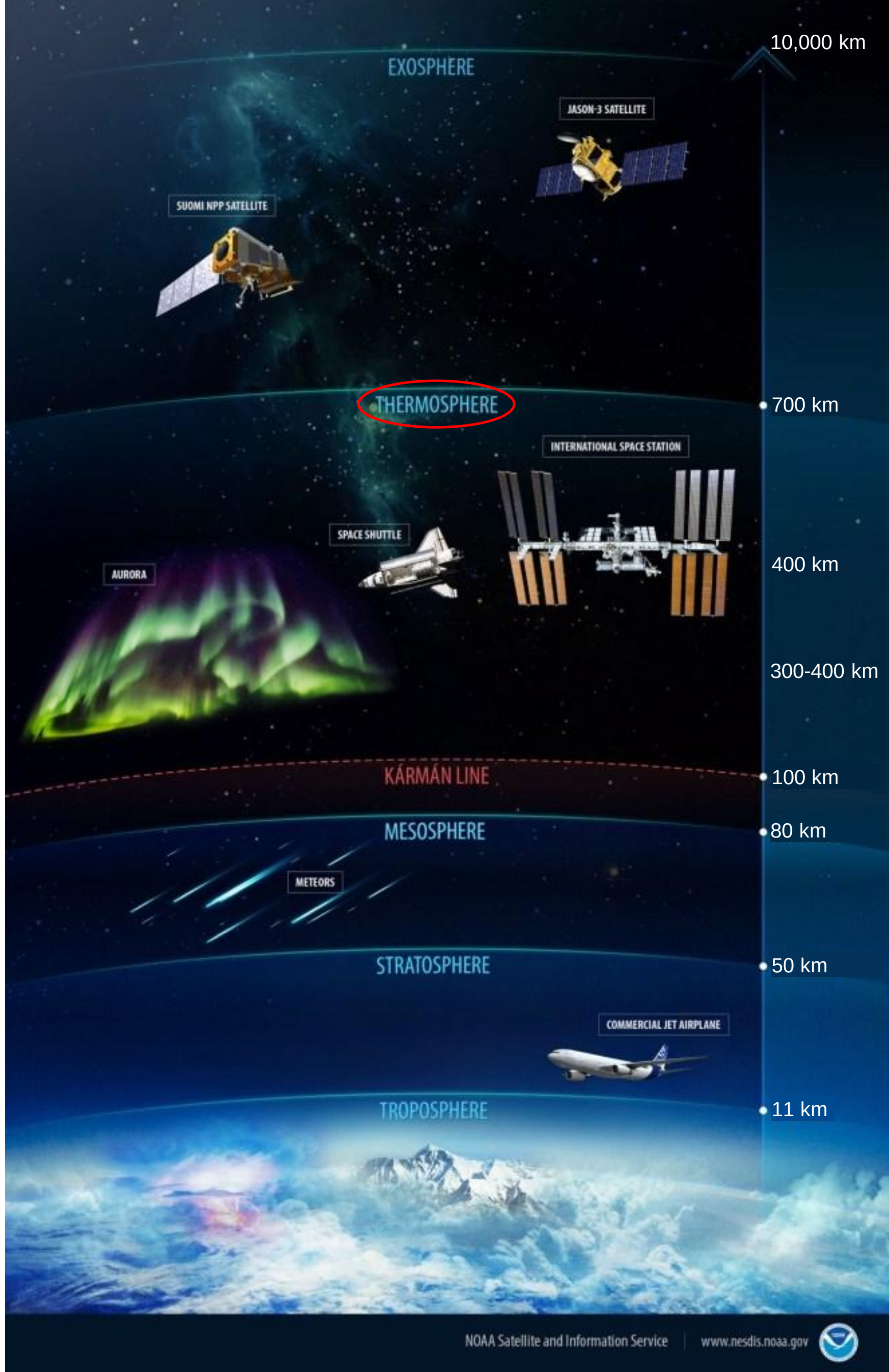
The Thermosphere

….is the interface between Earth and outer space

- important in the Earth system energy balance
- very limited knowledge → energy transport models impacted
- improved data sets → improved Climate modelling

….is where most of the New Space satellites fly

commercial interest on density data to improve predictions on orbit decay



… Atmospheric Science

CAITDM Cold Atom Interferometric Thermosphere Drag Measurement

Lasers + PL Electronics

Physics Package

Bus +Avionics

Science and Technology Facilities Council

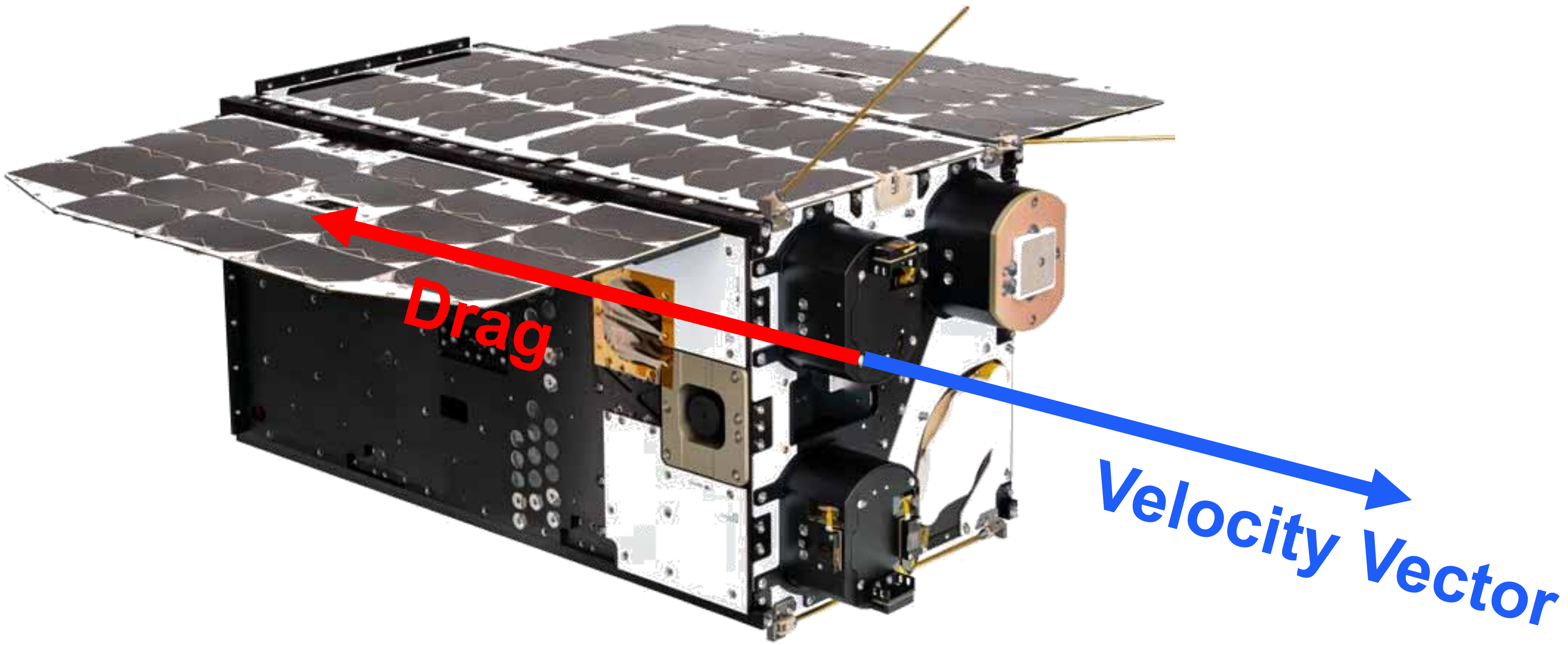
RAL Space

CAITDM

Lasers + PL Electronics

Physics Package

Bus +Avionics

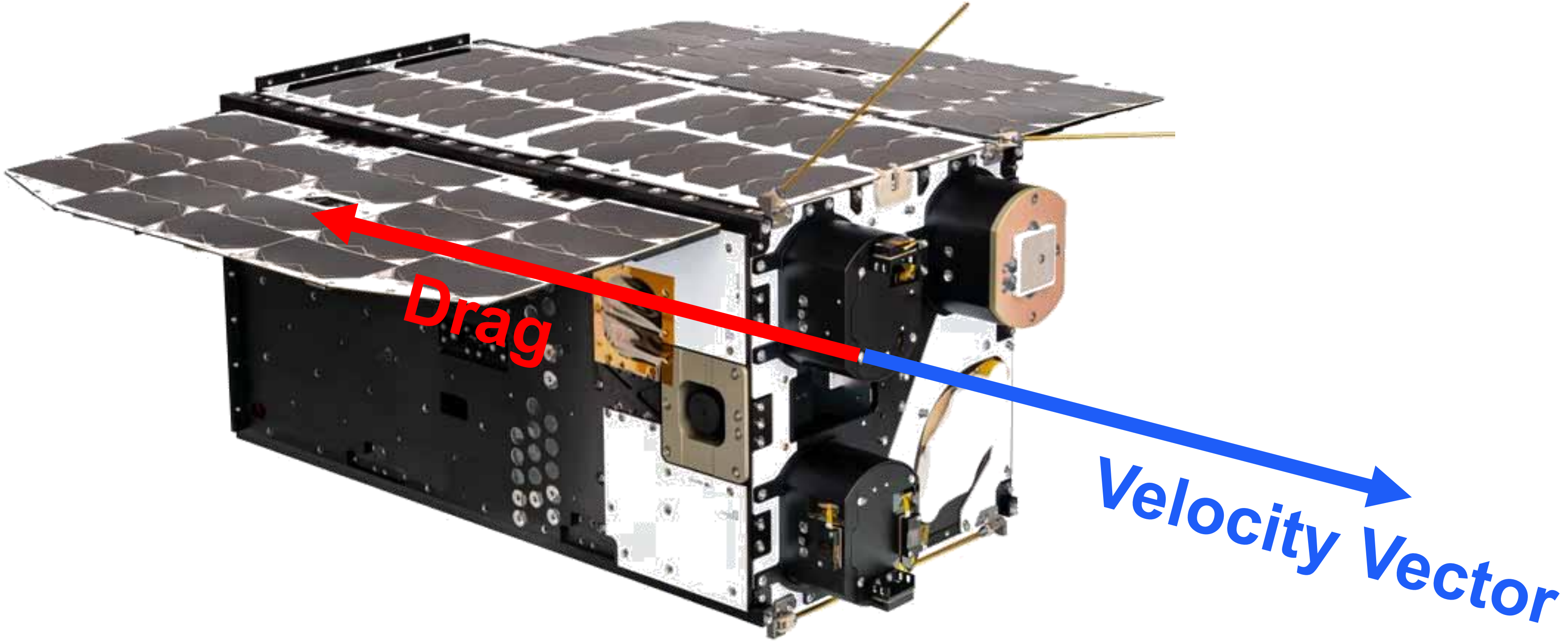


CAITDM

Lasers + PL Electronics

Physics Package

Bus +Avionics



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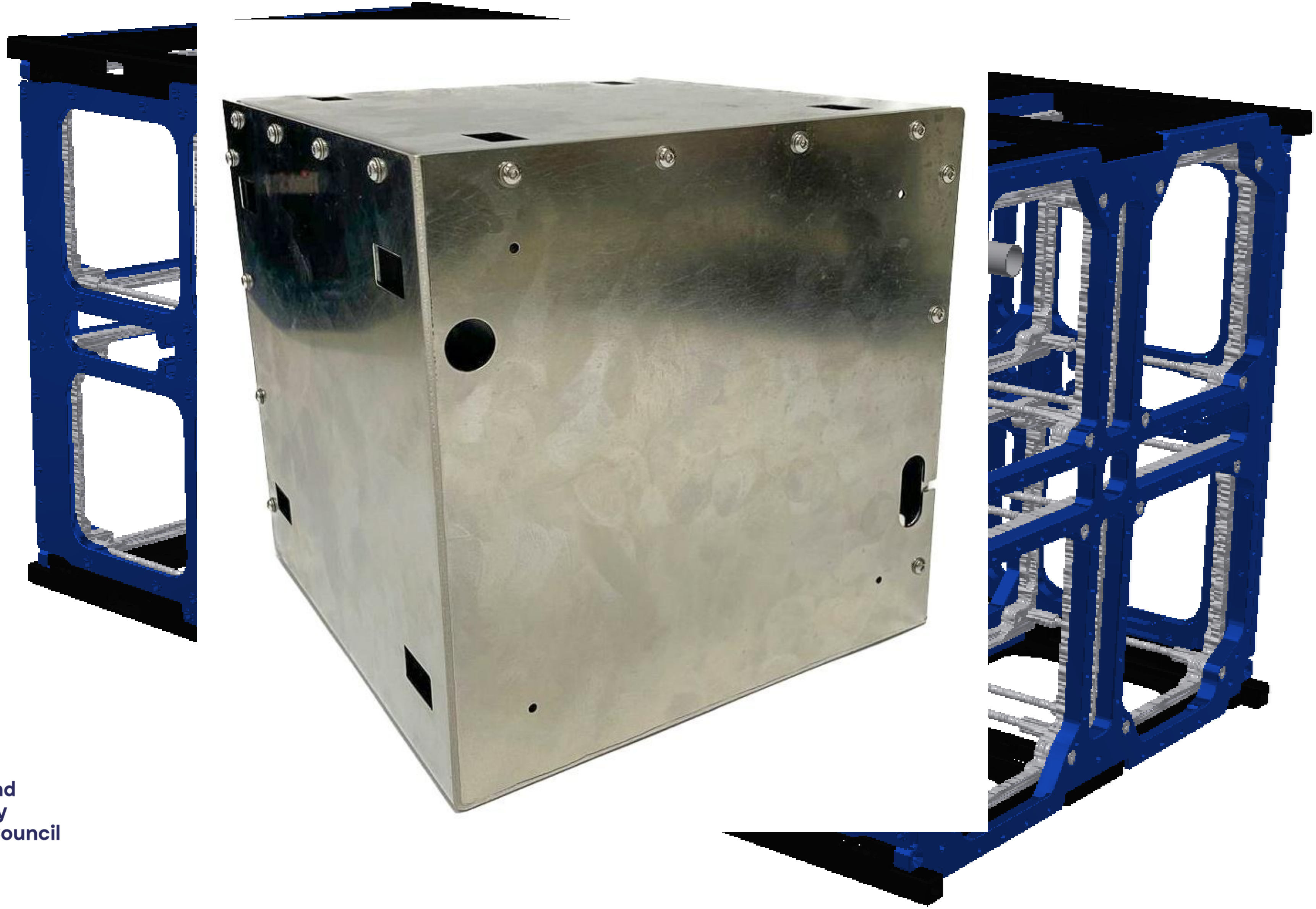
Physics Package



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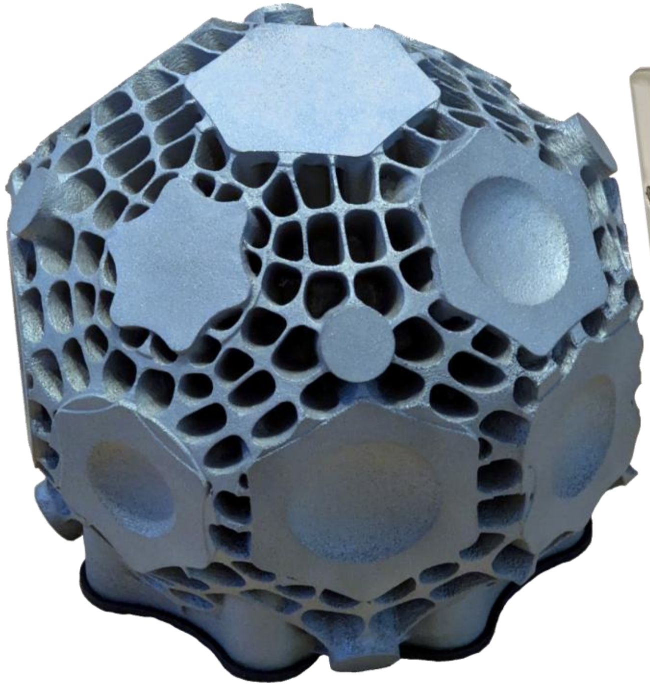

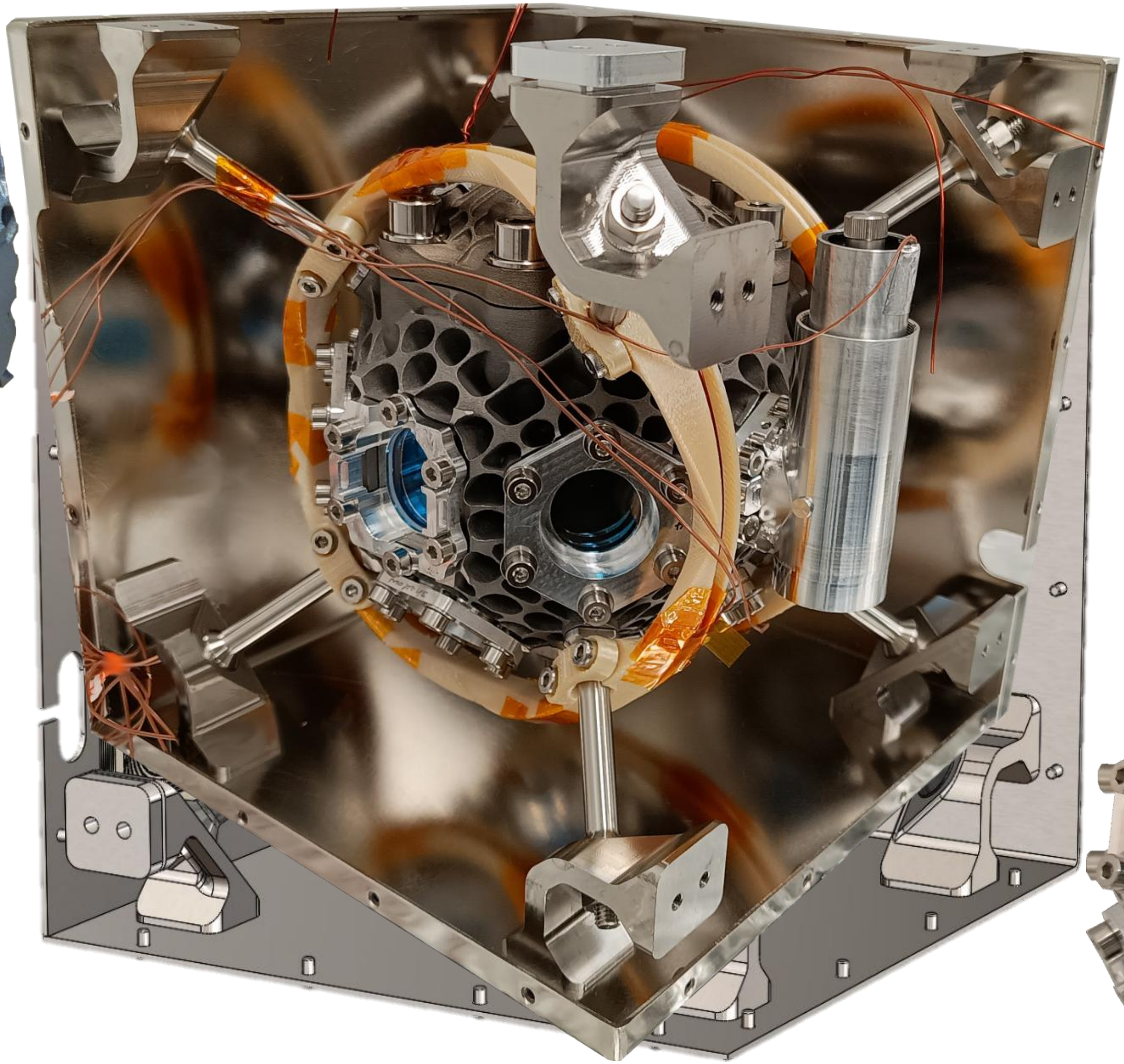

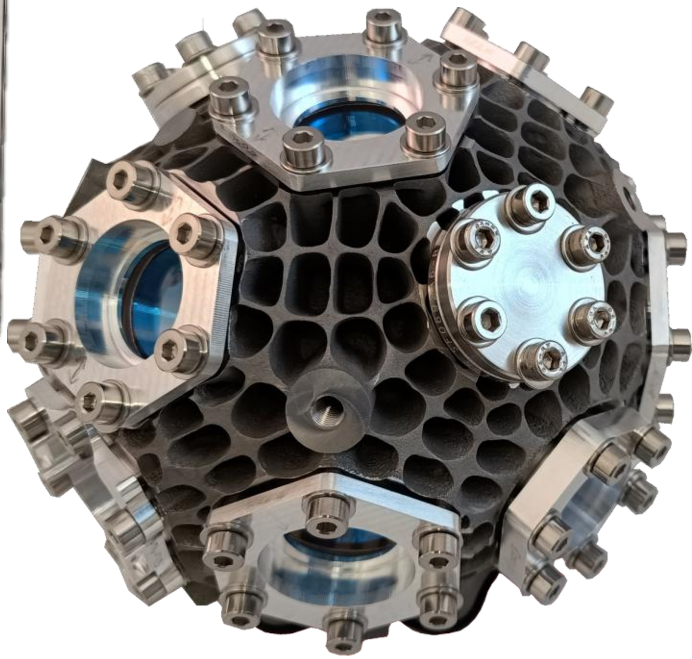

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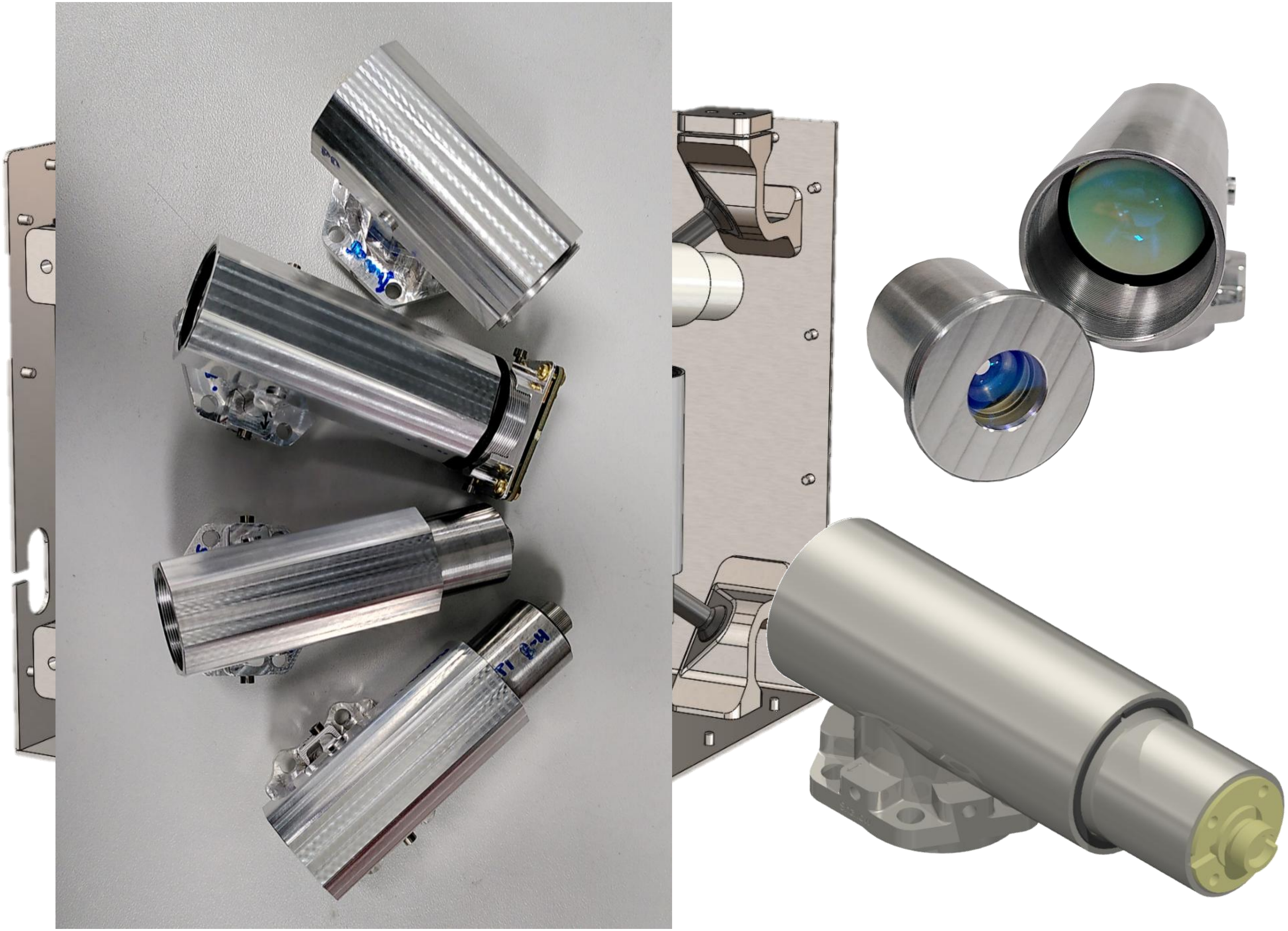

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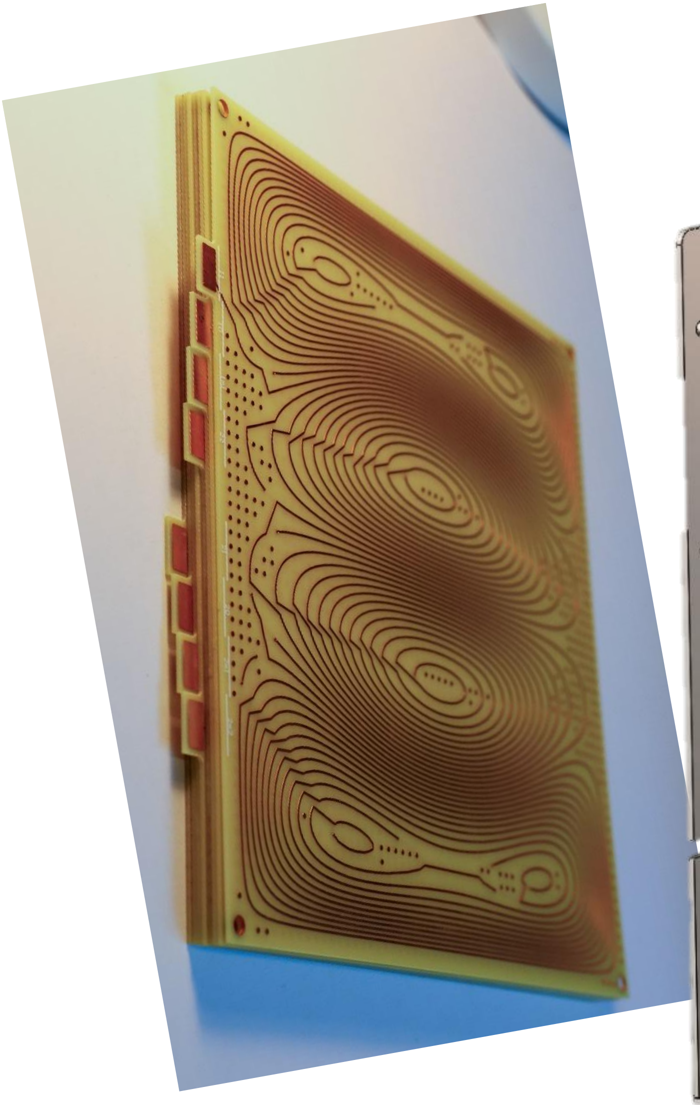

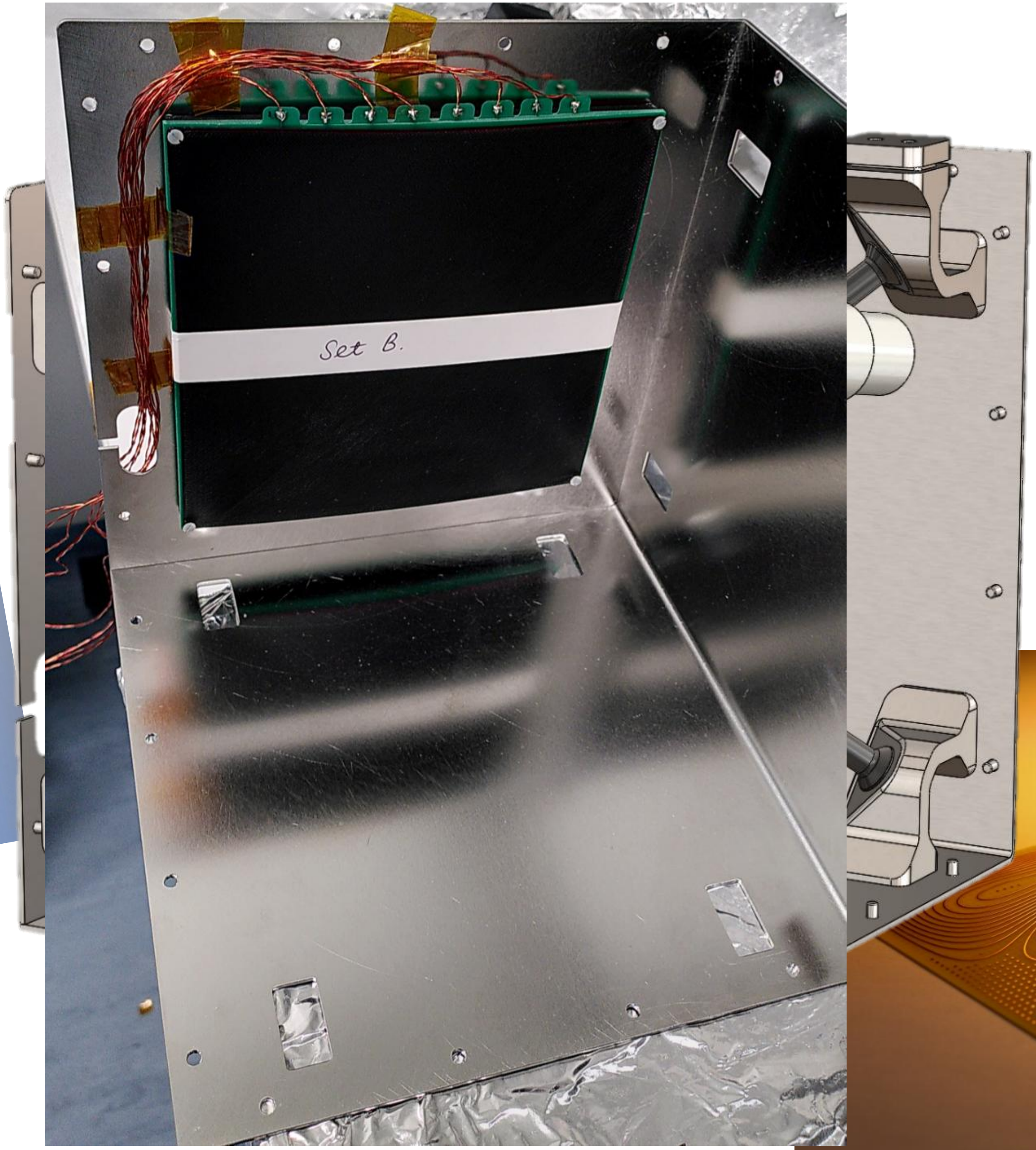

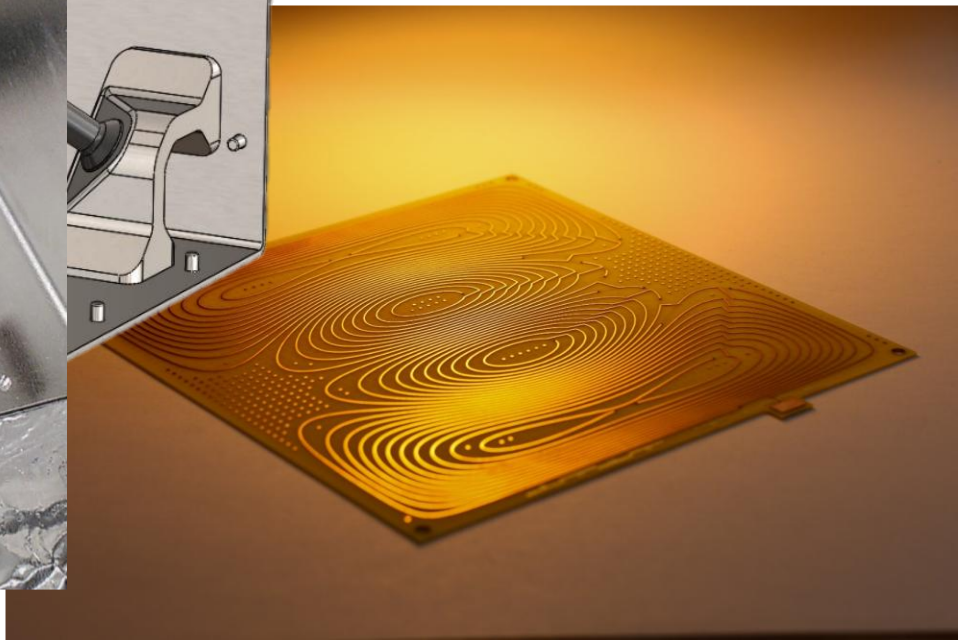

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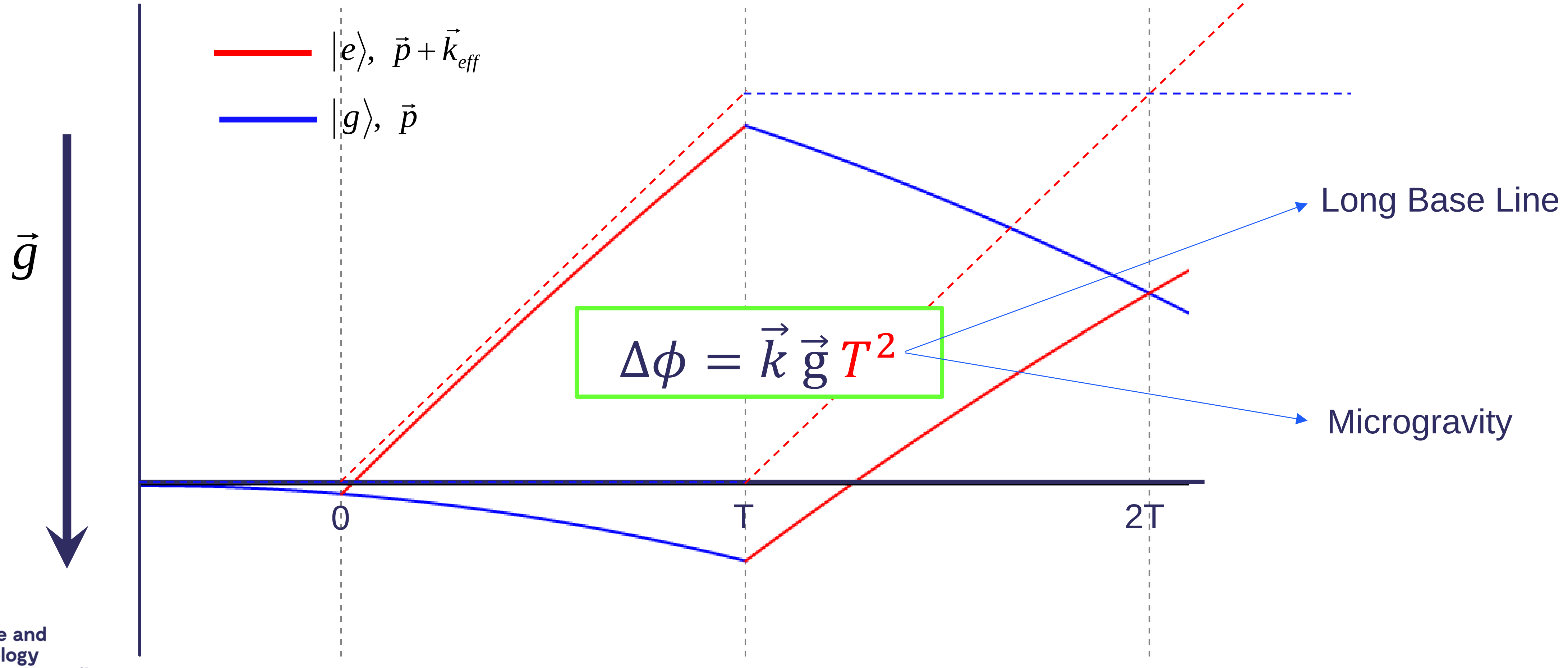
Environmental Testing

Thermal Cycling: 4 cycles -30℃ to +60℃

Vibration to NASA GEVS levels

Intro to Cold Atom Interferometry

Experimental sequence



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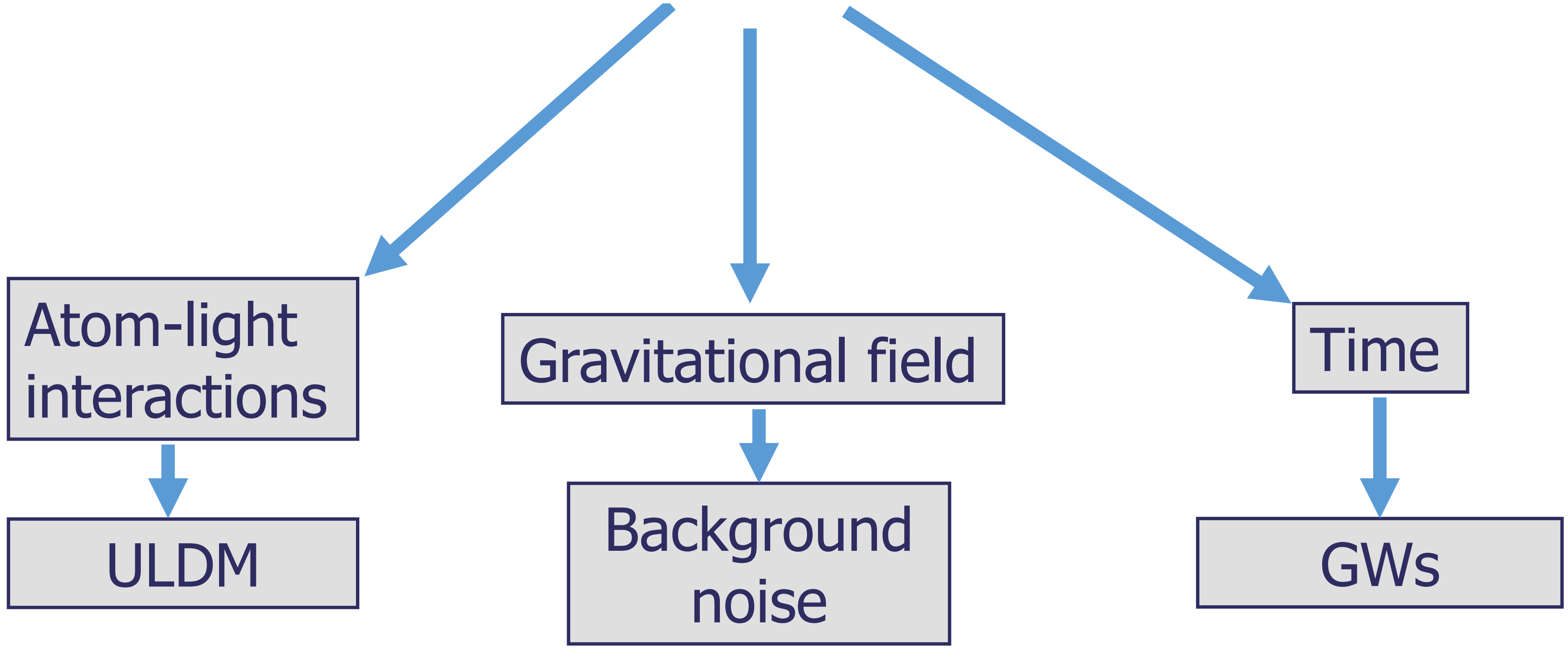
Gravitational Waves and UL Dark Matter

What we measure: $\Delta\phi = \vec{k}\,\vec{g}\,T^2$



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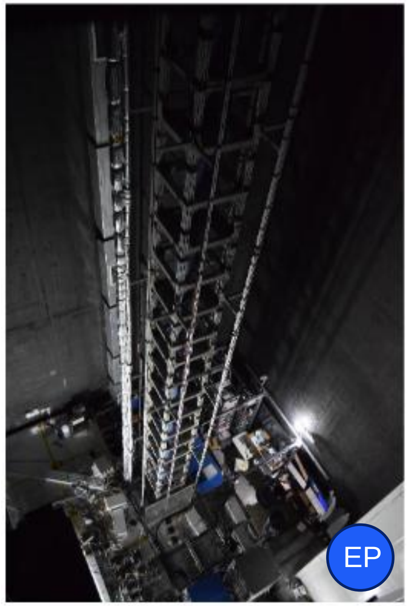
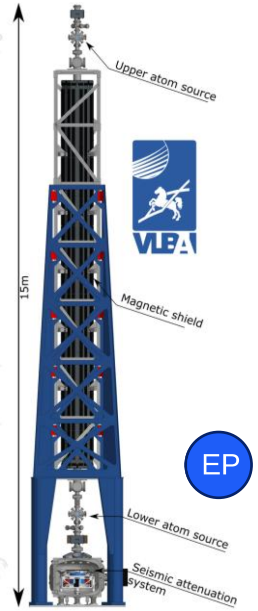
Fundamental Physics: Worldwide

10m fountain, Stanford, US

10m AI, Wuhan, CN

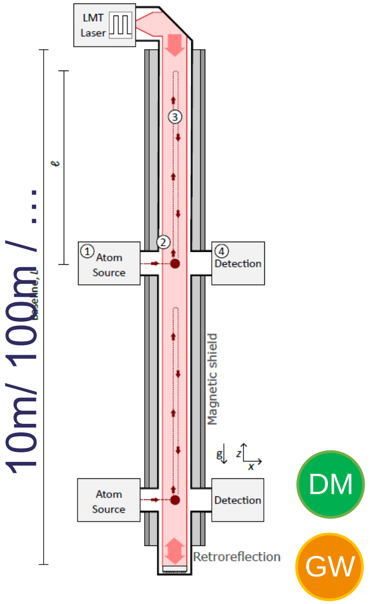


15m VLBAI, Hannover, DE



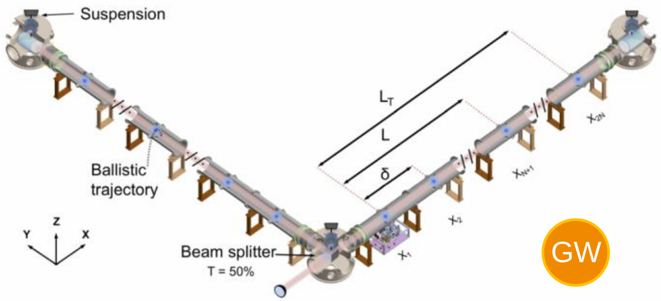
MAGIS, Stanford/Fermilab, US
10m / 100m /…

AION, UK
10m/ 100m / …

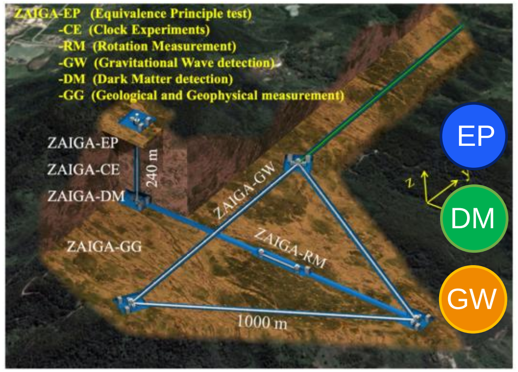


MIGA, FR

ELGAR, FR



ZAIGA, Wuhan, CN



EP Equivalence Principle

GW Gravitational Waves

DM UL Dark Matter

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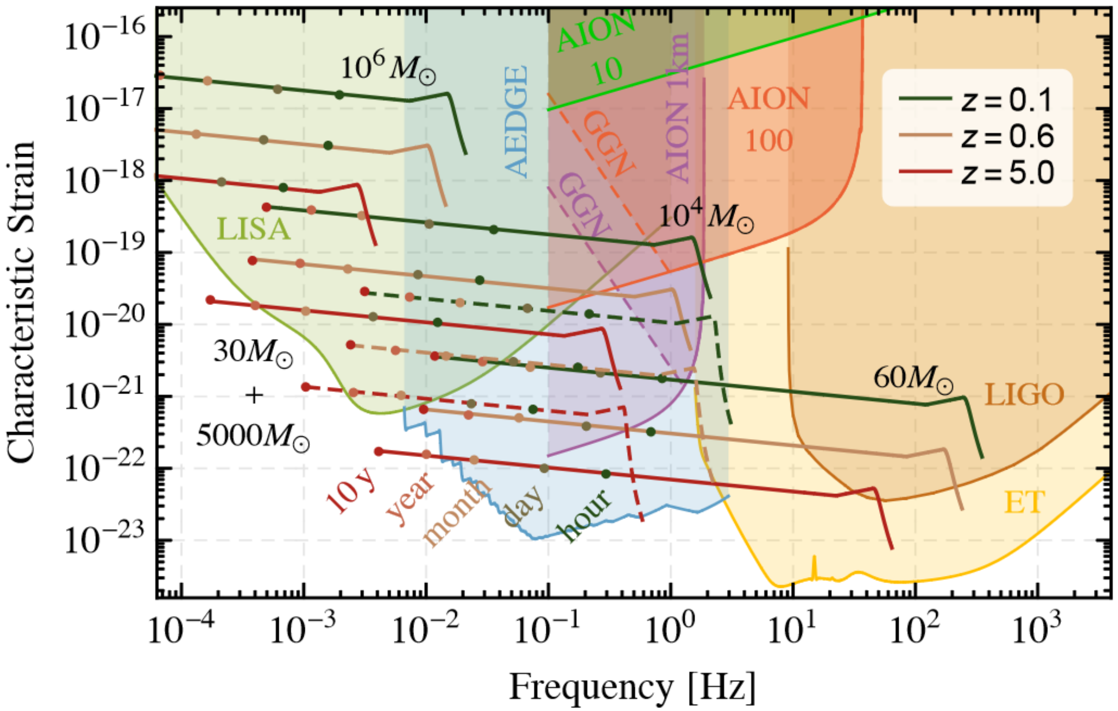
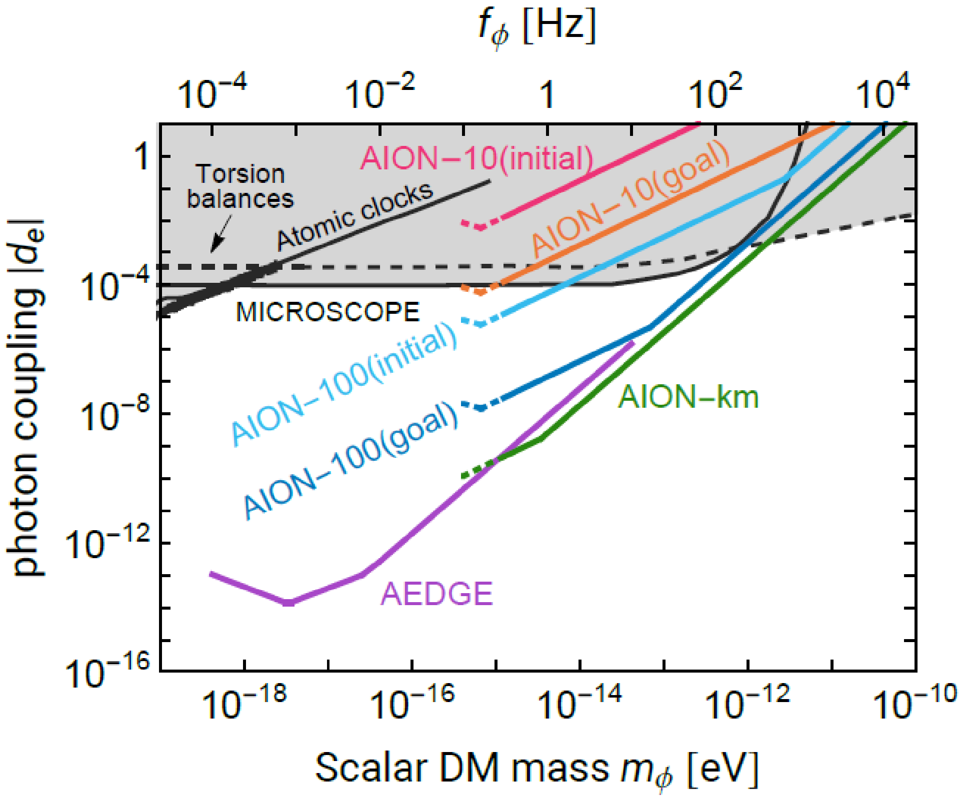
Gravitational Waves and UL Dark Matter





- Explore mid-frequency band GW
- Precision sensor for ultra-light DM

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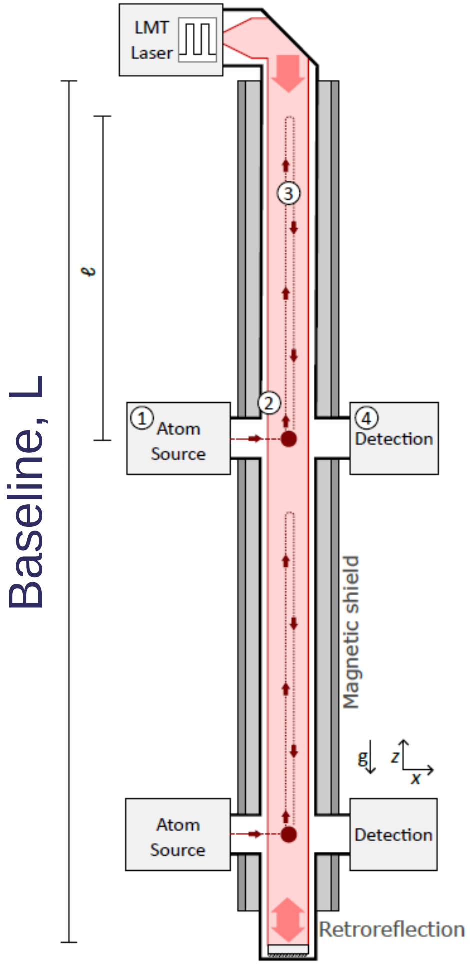
Atom Interferometry Observatory & Network



Model Philosophy

AION-10 – testing and characterisation

AION-100 – 10^4 solar-mass black hole mergers

AION-km – neutron star binaries or black hole mergers, multi-messenger astronomy

L. Badurina *et al.*, AION: an atom interferometer observatory and network, JCAP05(2020)011

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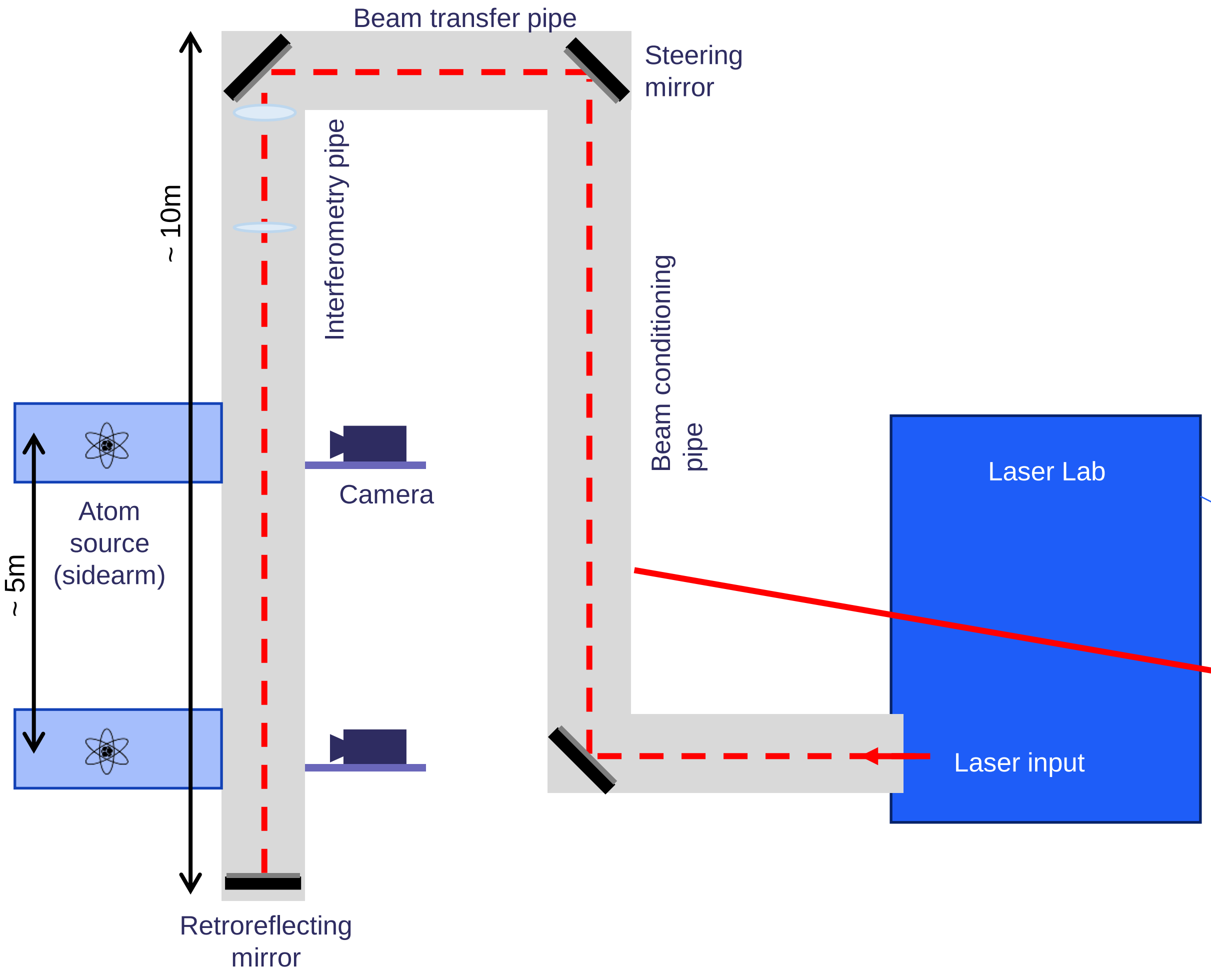

Beecroft building, Oxford

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Gravitational Waves

Phase shift accumulated consists of:

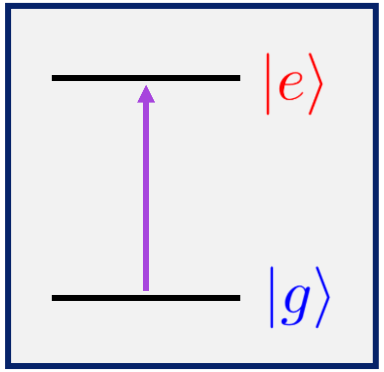
- **Propagation** phase along each path
- **Separation** phase at the end of the interferometer
- **Laser** phase at each node

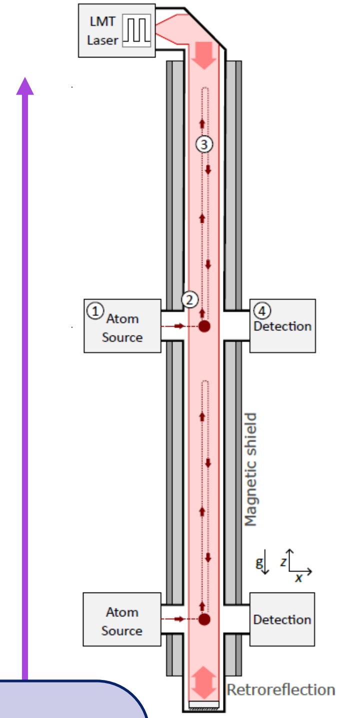
$$\Delta\phi_{\text{total}} = \Delta\phi_{\text{propagation}} + \phi_{\text{separation}} + \phi_{\text{laser}}$$

- Each laser pulse imprints phase on the wavefunction
- Position of the atom (at the time of the pulse) in encoded in its wavefunction

$$\phi_{\text{laser}} = k \cdot x(t_0) - \omega t_0 + \phi$$

Atom position





For a differential measurement:

Use the same laser pulse for both clouds… cancel the laser noise

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Hogan, Johnson, & Kasevich (2008). Light-pulse atom interferometry. Proc. Int. School Phys. Enrico Fermi.

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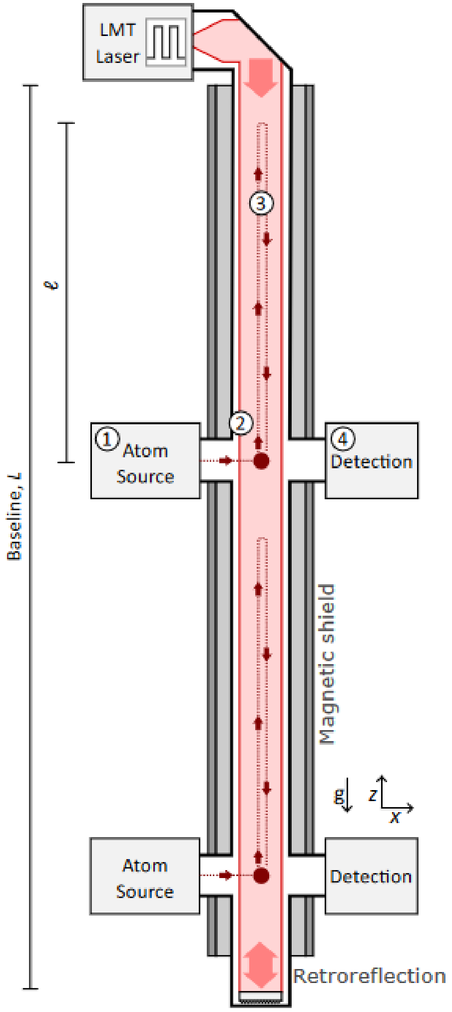
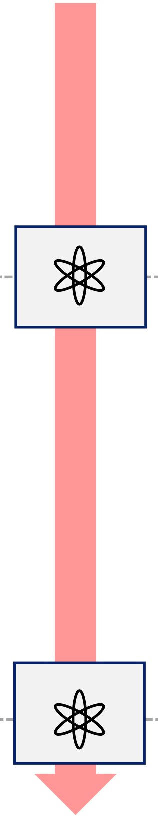
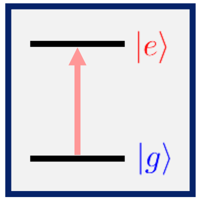
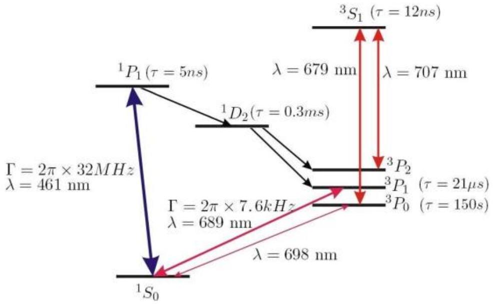
Gravitational Waves









Sr atoms have a long-lived excited state or '*clock transition*'

✓ Can use single colour photons

✓ Using a common laser beam for both interferometers allows noise rejection

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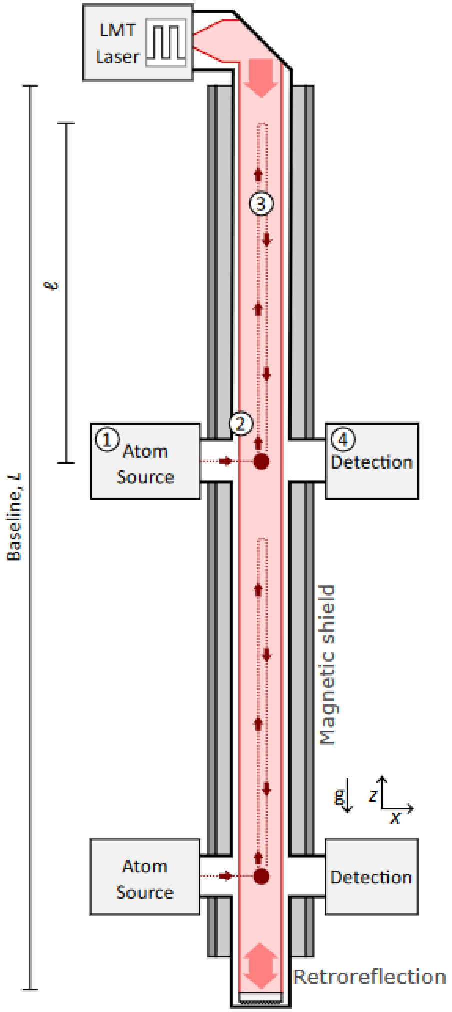
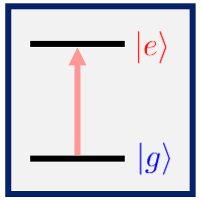
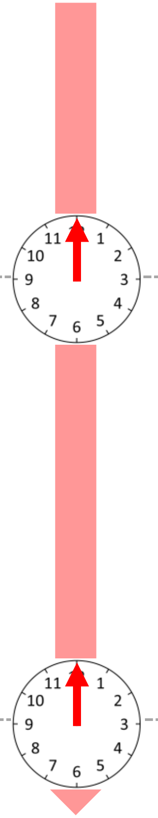
Gravitational Waves

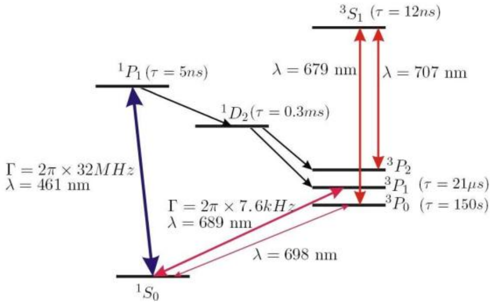






$\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$

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



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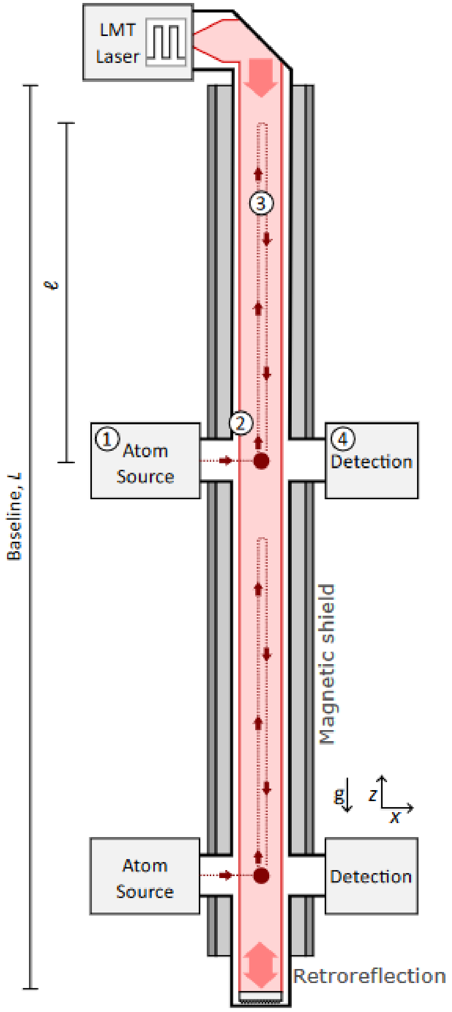

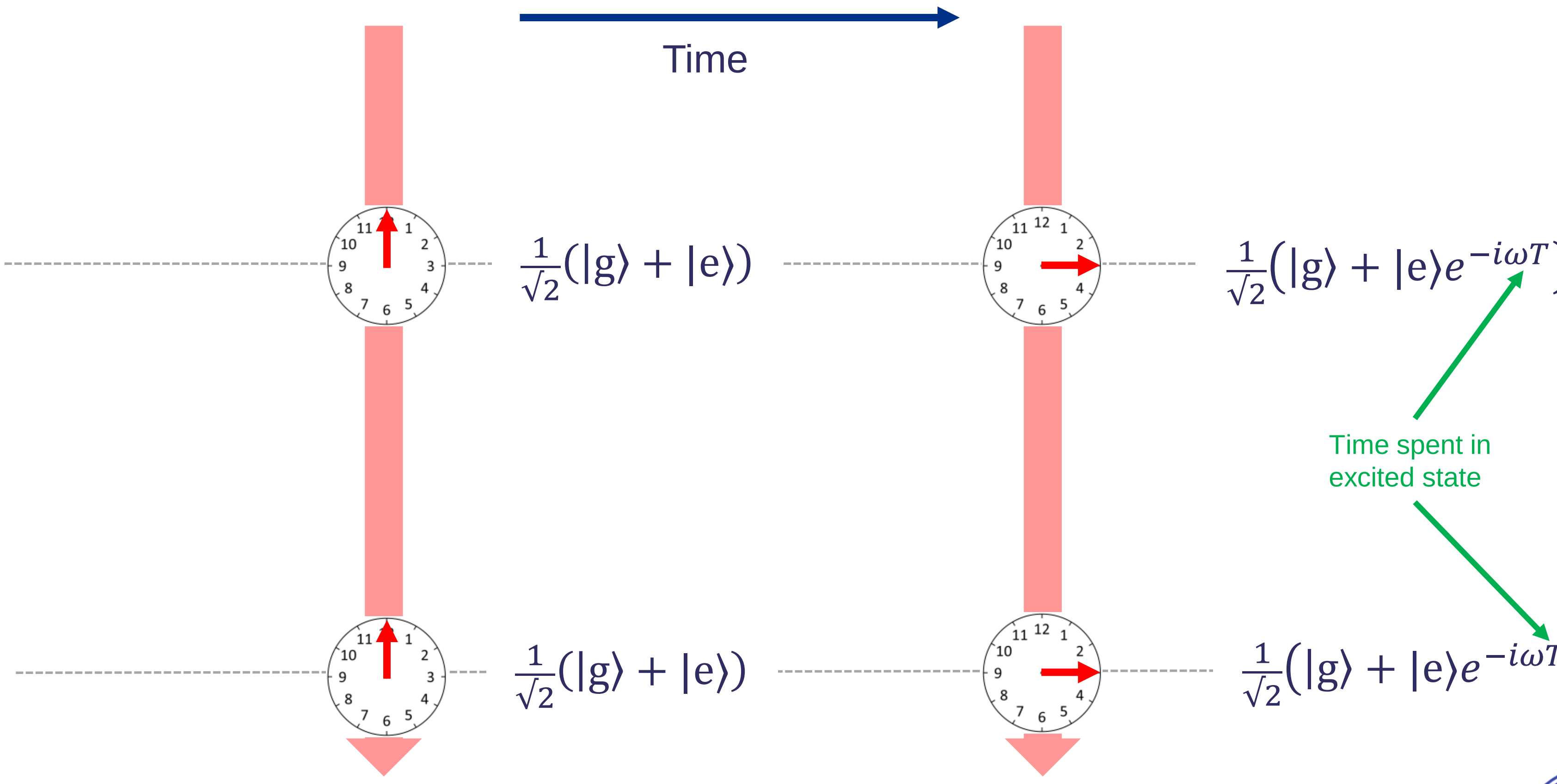

$\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$ $\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle e^{-i\omega T})$

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

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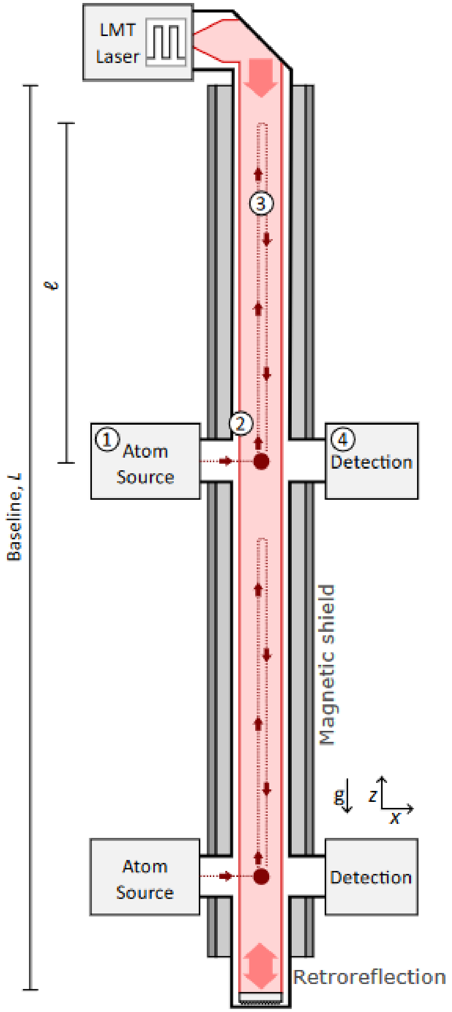
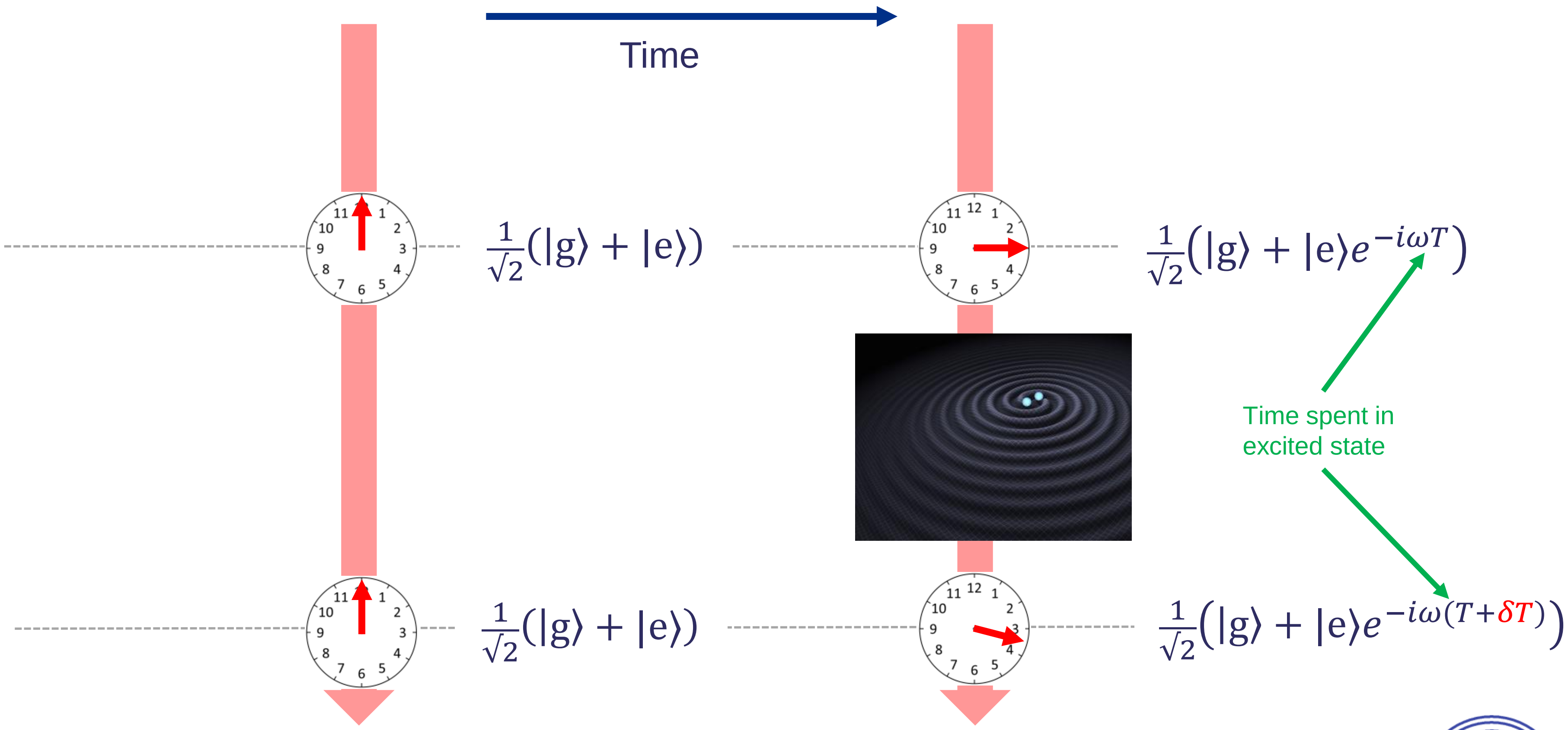
Gravitational Waves





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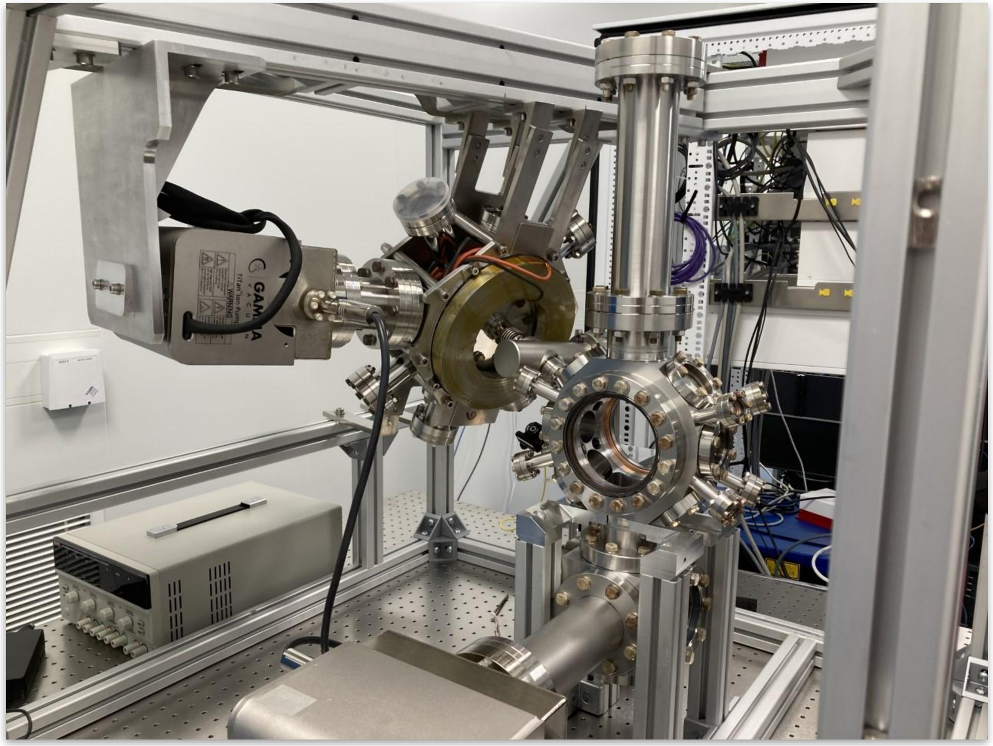
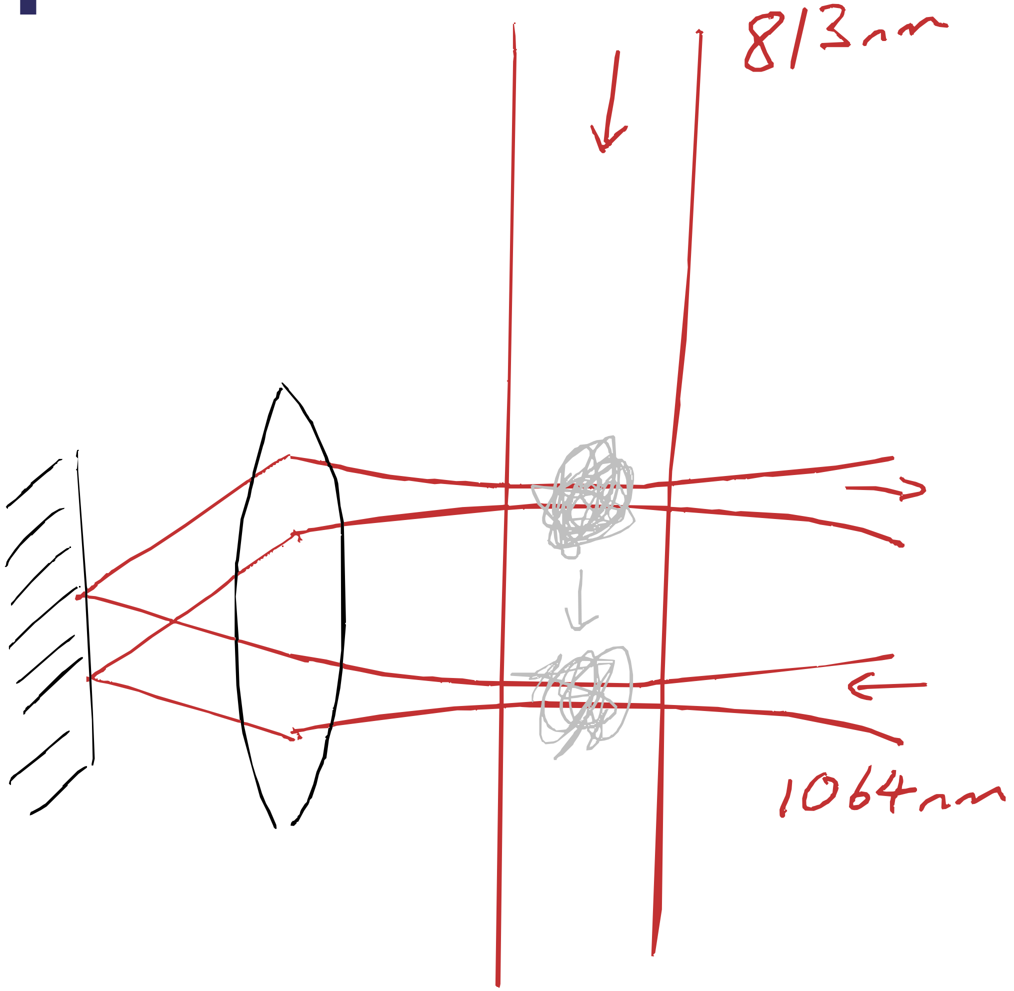
Concept Demonstration



B. Stray et al., AVS Quantum Sci. 6, 014409 (2024)



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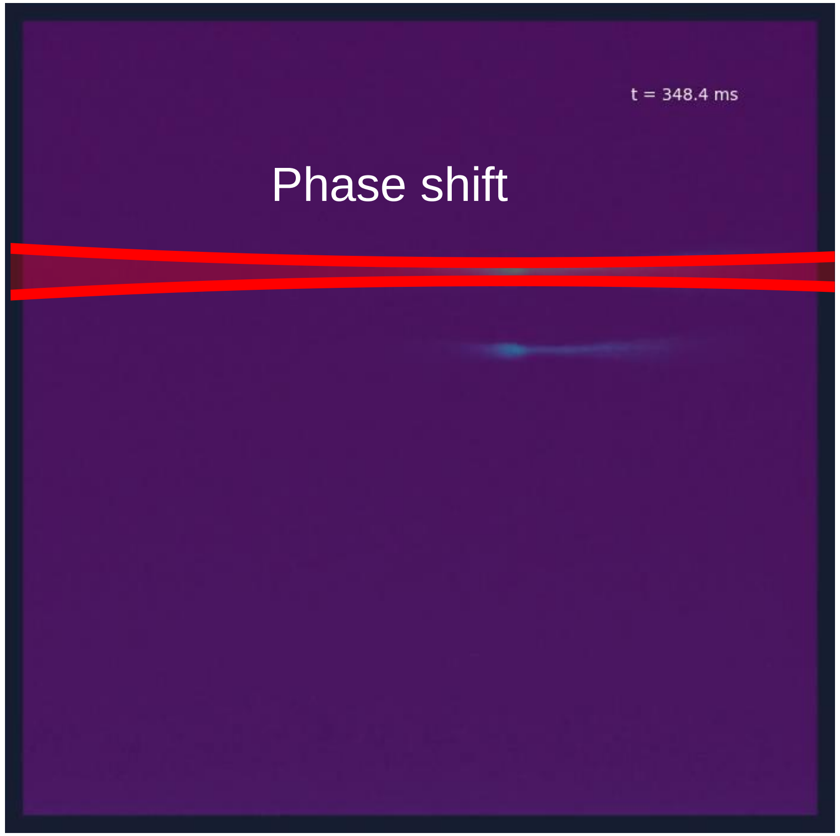

- 689nm Stark shifting pulse
- -80 MHz detuned from F=9/2 -> F=11/2
- 1mW in a 500um beam
- 30 us pulse creates a phase shift
  $\Delta\phi \approx 62°$

http://arxiv.org/abs/2504.09158

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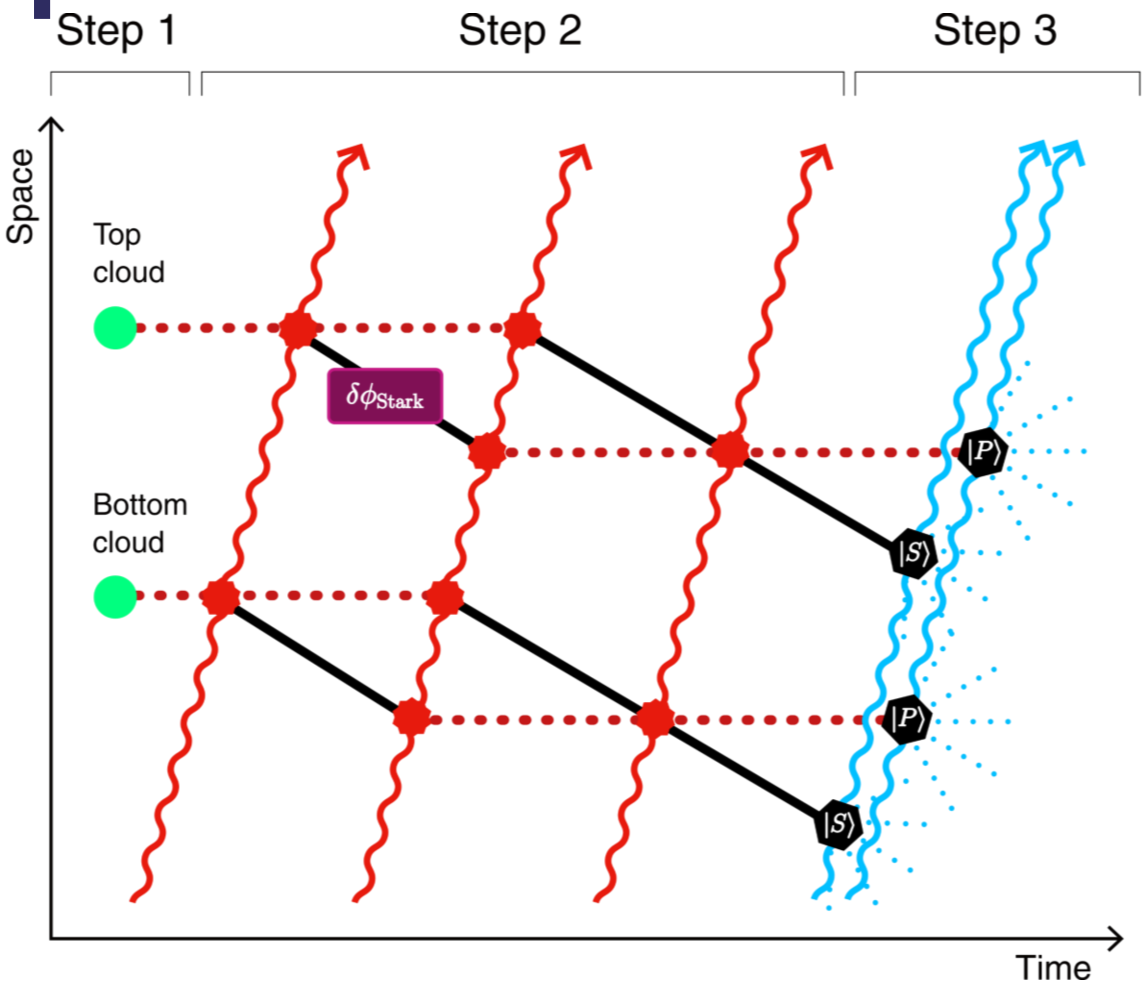

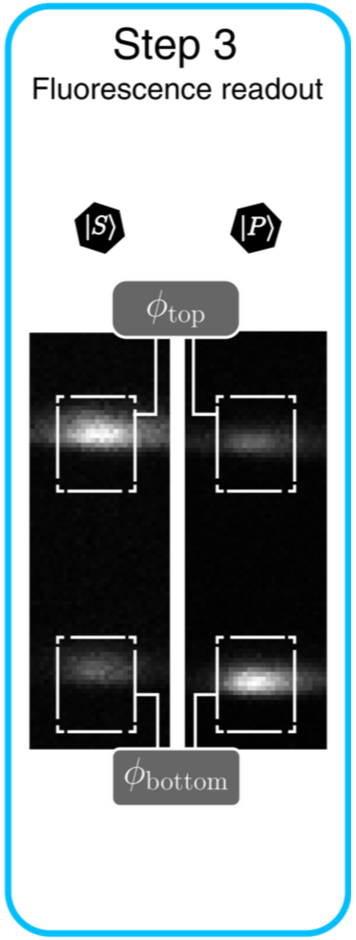

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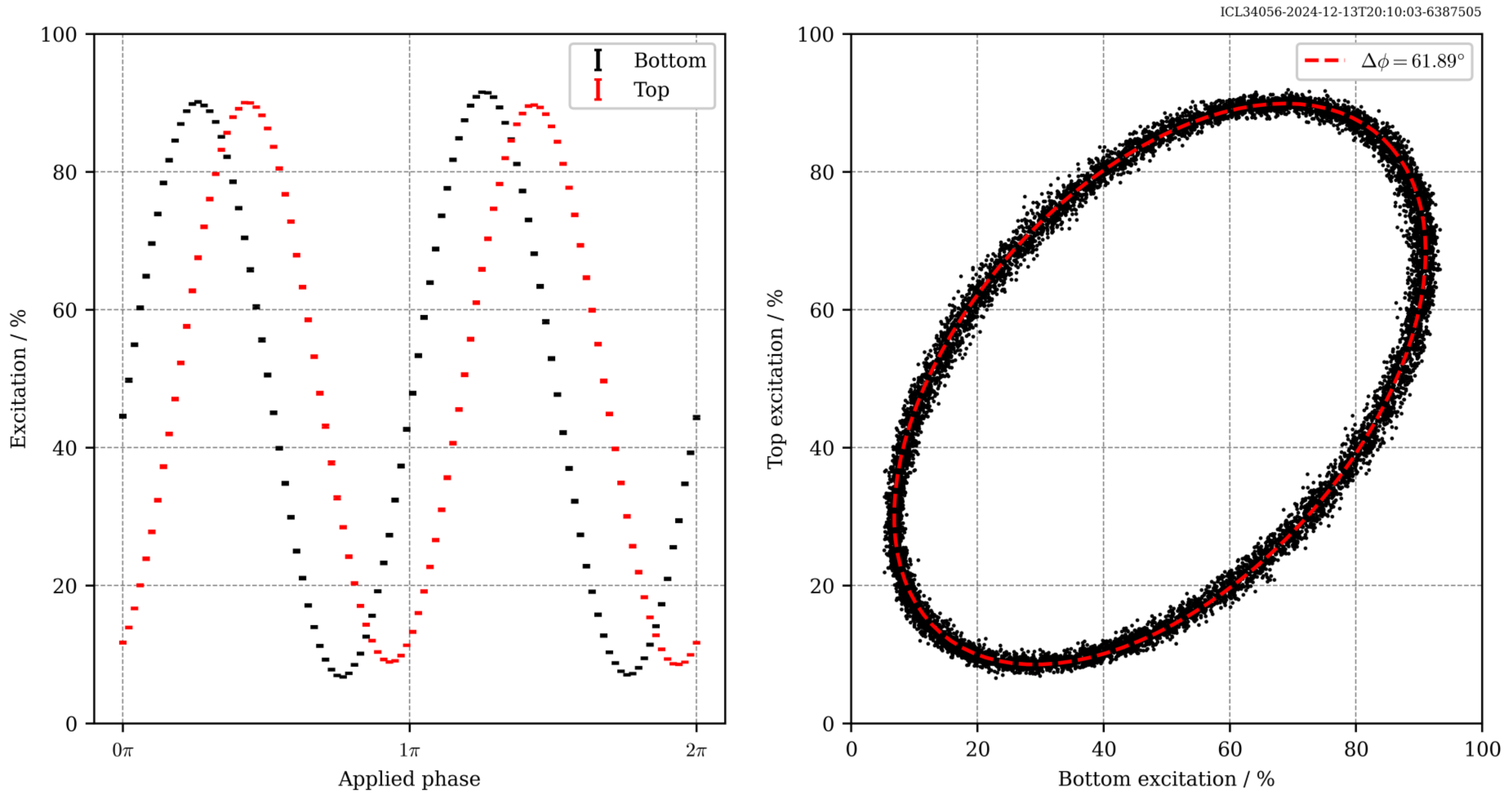

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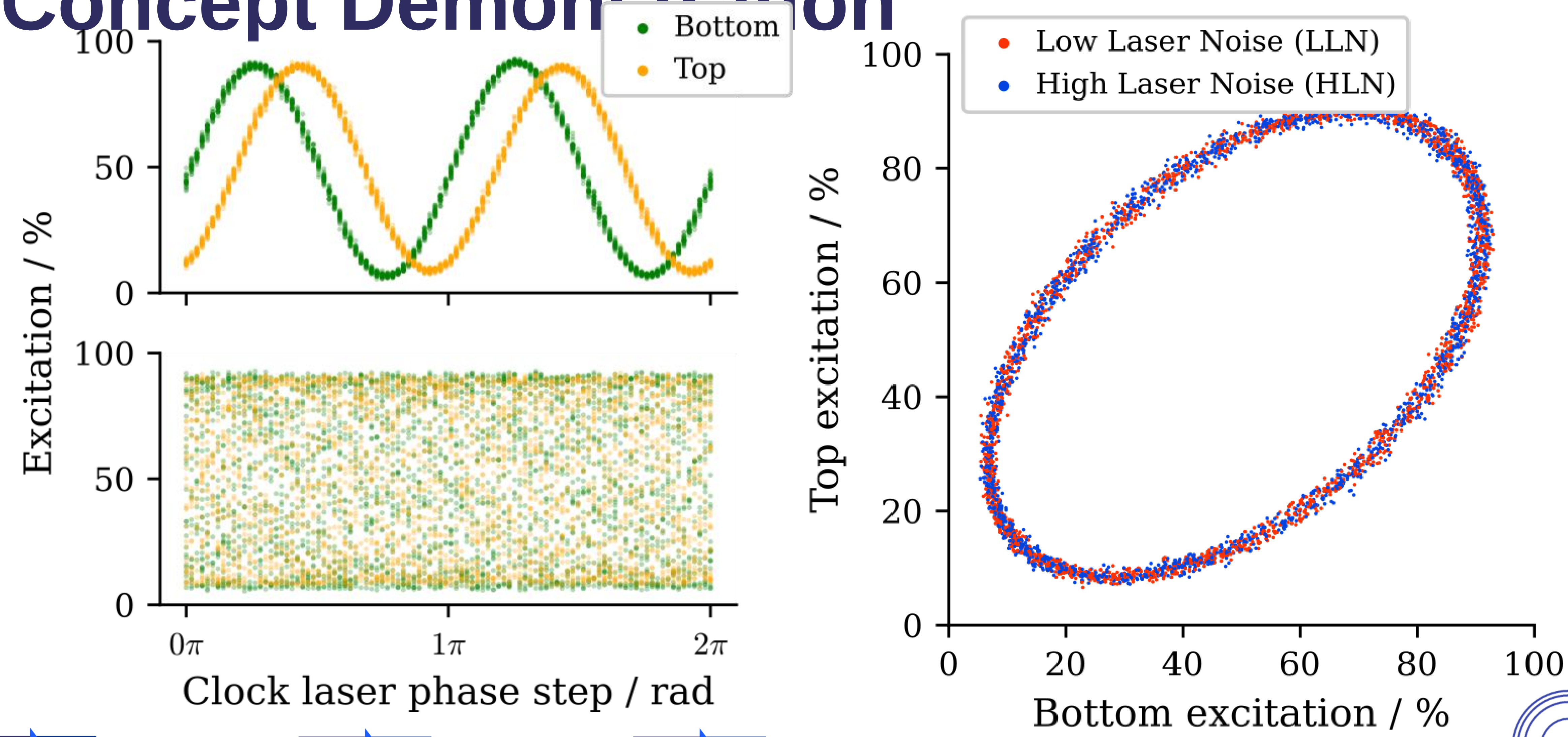

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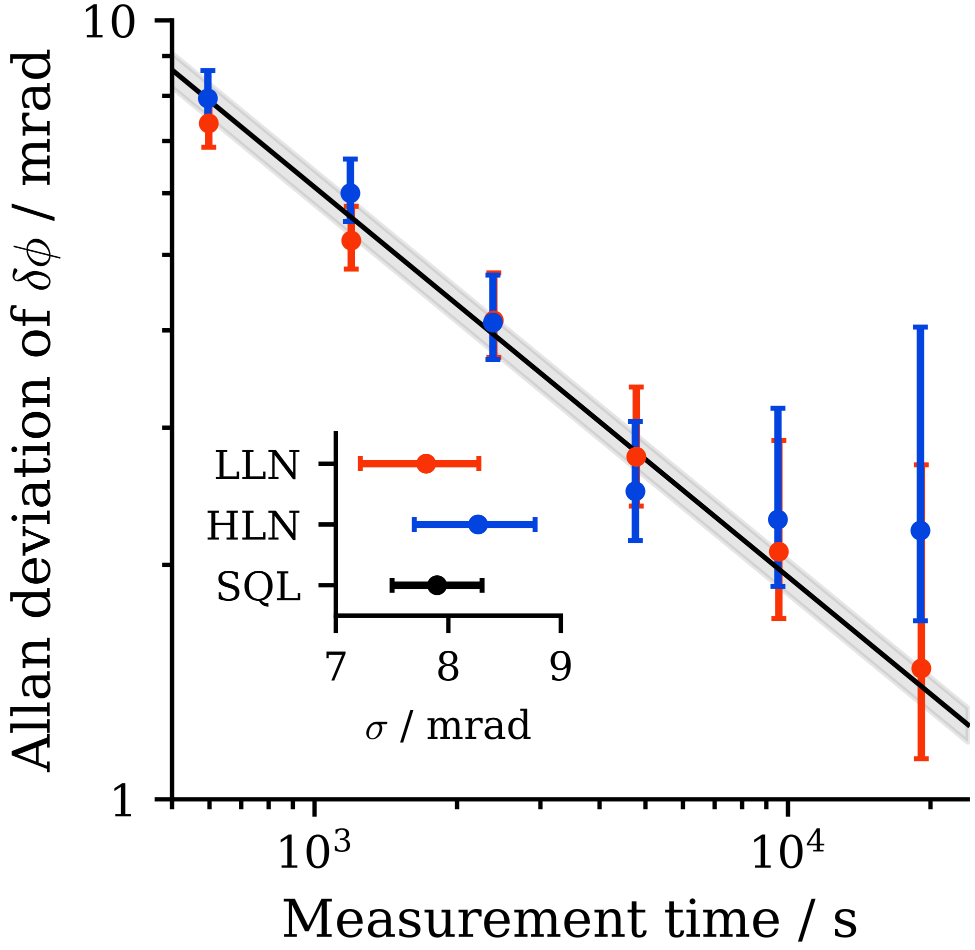

- 11200 samples
- Binned to 100 shots each
- Allan deviation
- ~1500 atoms/trap

- Standard deviations of δϕ are consistent with the standard quantum limit in both the LLN and the HLN dataset:
  - $\sigma_{LLN} - \sigma_{SQL} = 0.10^{+0.55}_{-0.66}$ mrad
  - $\sigma_{HLN} - \sigma_{SQL} = 0.57^{+0.54}_{-0.70}$ mrad

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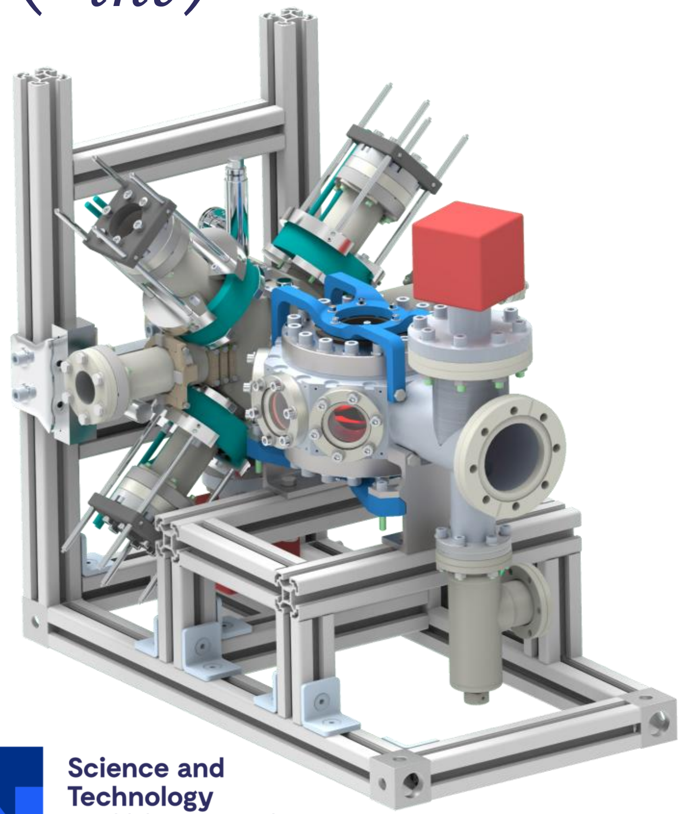
Improving Sensitivity

$$d^{best} \sim \left(\frac{1}{T}\right)^{\frac{5}{4}} \frac{1}{Cn\Delta r} \left(\frac{\Delta t}{N_{atom}}\right)^{\frac{1}{2}} \left(\frac{1}{T_{int}}\right)^{\frac{1}{4}}$$

Badurina, Blas, McCabe, PRD 105, 023006 (2022)

T	Interferometer duration
C	Contrast
n	Number of LMT
Δr	Separation between interferometers
Δt	Time between interferometer sequences
N_{atom}	Number of atoms
T_{int}	Total integration time



- More atoms
- Colder atoms
- Large momentum transfer
- Reliability

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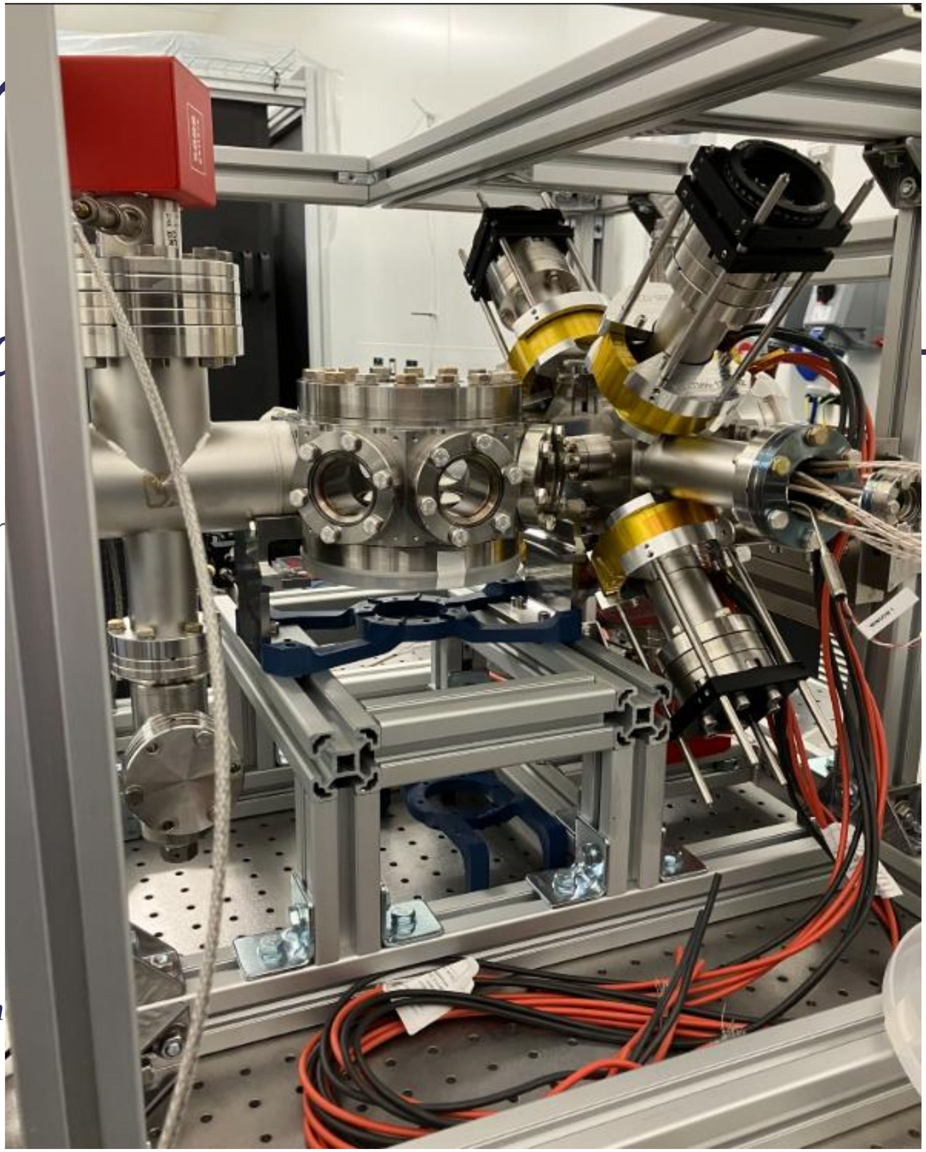
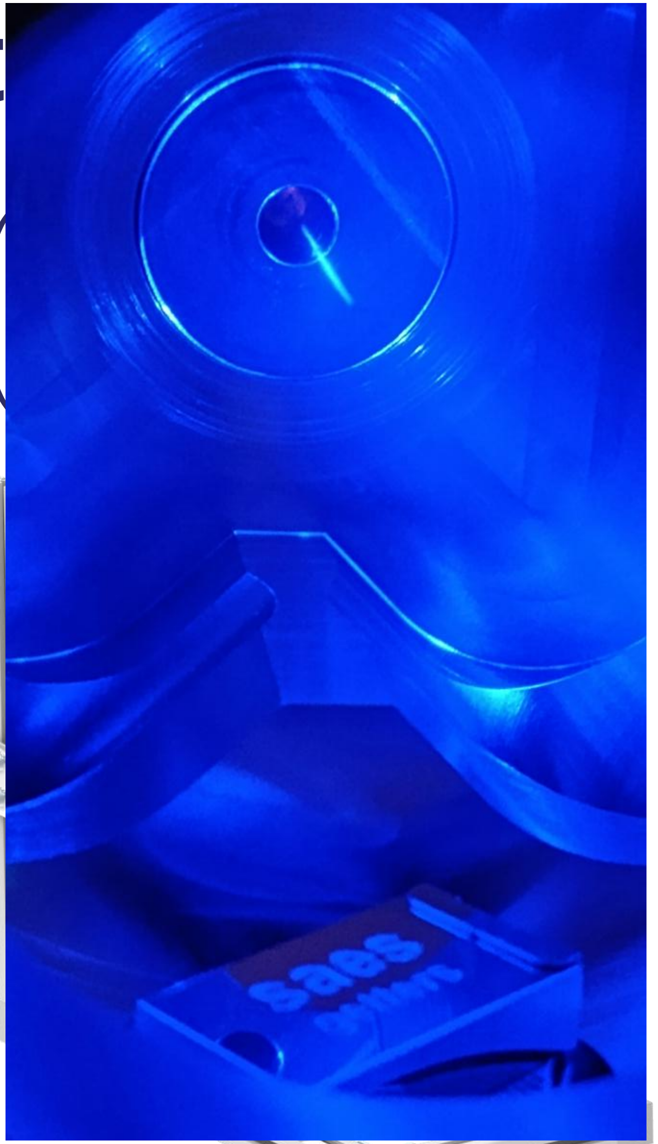
Ir … vit

$\left(\right)^{\frac{1}{2}}$

Badurin





T

C

n

Δr

Δt

N_{atom}

T_{int}

More atoms

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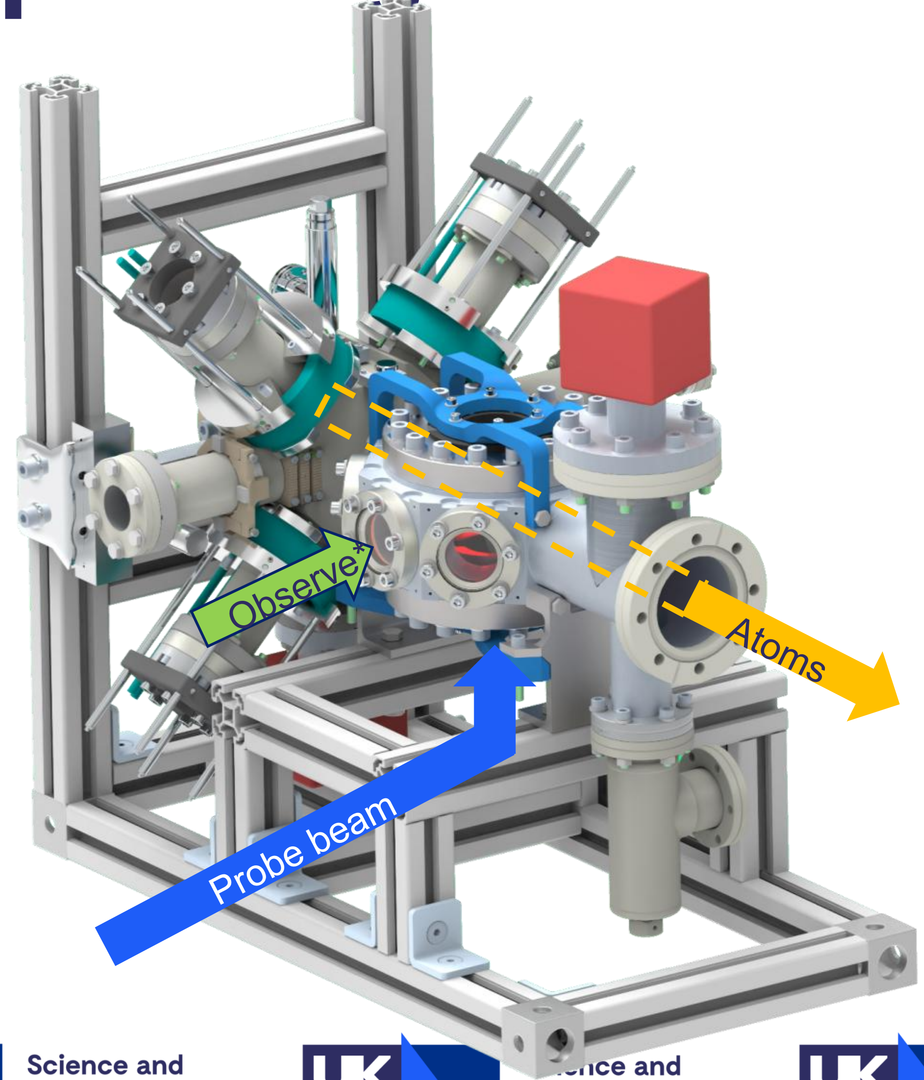
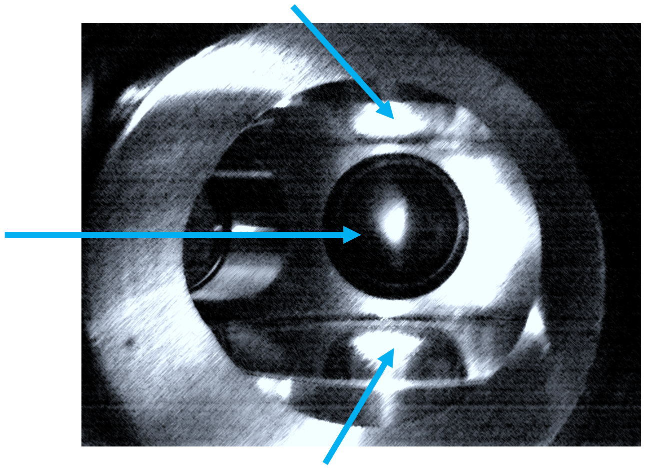
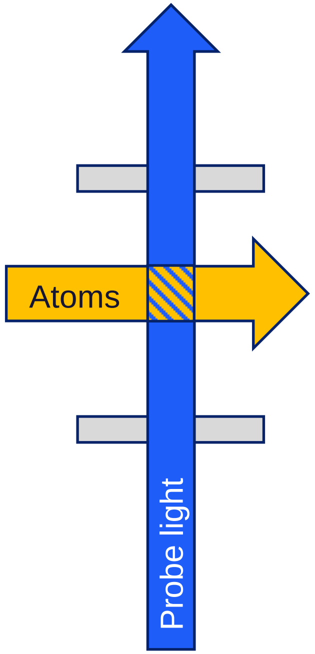
Improving Sensitivity

More atoms







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Technology

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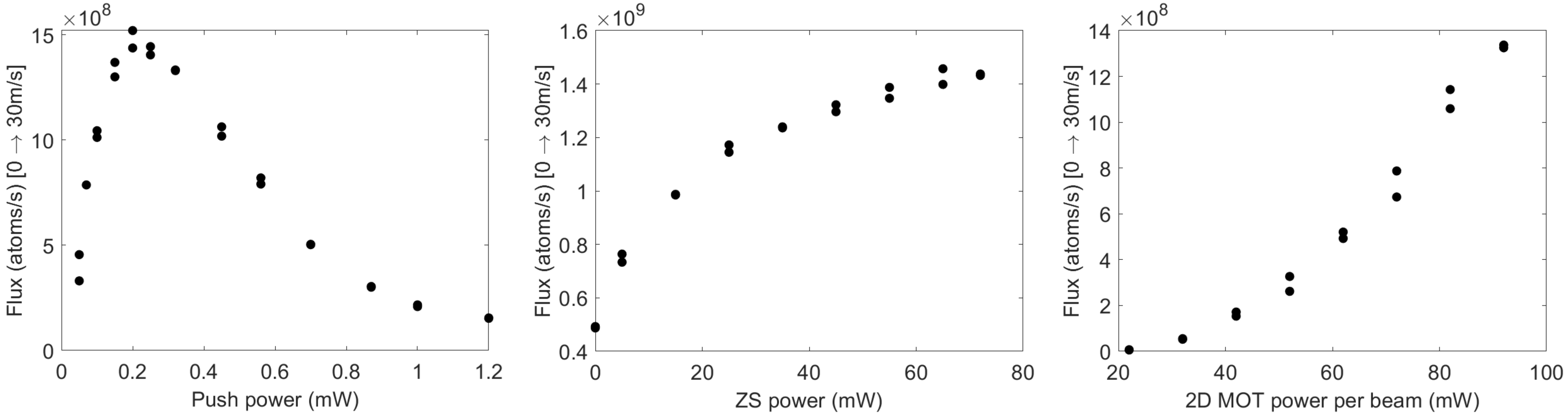
Improving Sensitivity

More atoms



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Thank you

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