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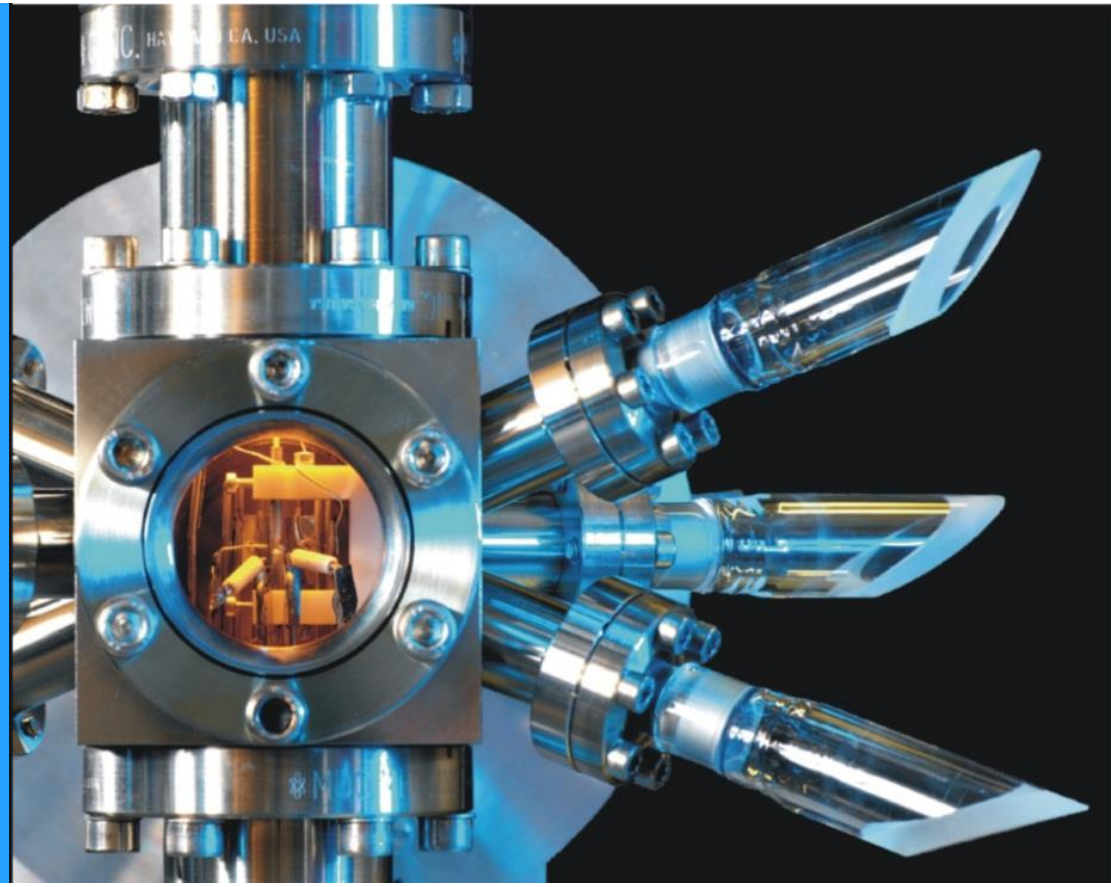
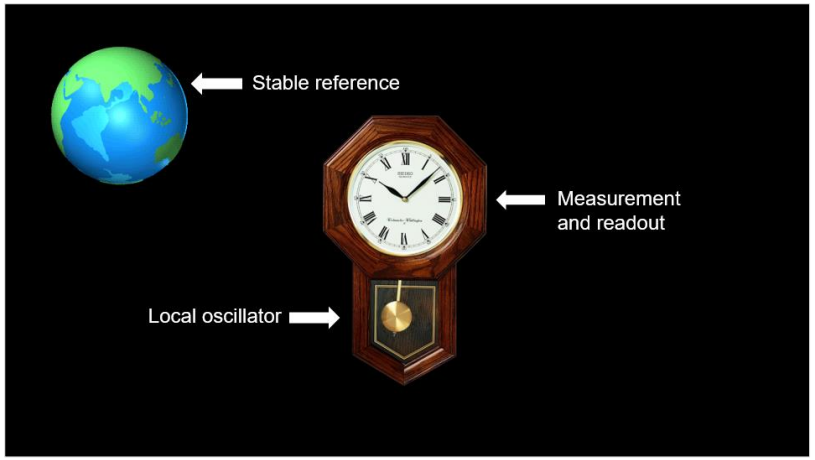
An ytterbium ion clock and its role in the search for dark matter

Dr. Charles Baynham

ECCTI, CERN (13th-17th January 2020)



Contents



Optical atomic clocks

The ytterbium ion

A search for dark matter

Why ^{171}Yb+ as a clock?

$$Q = \frac{\nu_0}{\Delta\nu}$$

- Presence of two accessible metastable states including long-lived octupole transition
- Low sensitivity to external fields
- $I = \frac{1}{2}$ so possibility of $\Delta m_F = 0 \rightarrow 0$ transition

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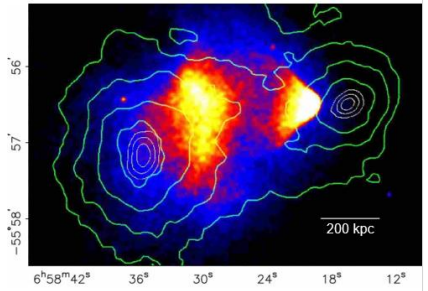
Dark matter – the motivation

- 6x more DM than SM matter
- …but WIMPs proving elusive
- Alternative explanations include light dark matter:
  $m_\phi \ll 1\text{eV}$
- Self interactions could lead to macroscopic structure: topological defects (TDs)

$$\alpha^{\text{eff}} = \alpha\left(1 - \frac{\phi^2}{\Lambda_\gamma^2}\right)^{-1}$$

Detectable by clocks!



[figure] 10.1086/508162 [theory] 10.1038/nphys3137

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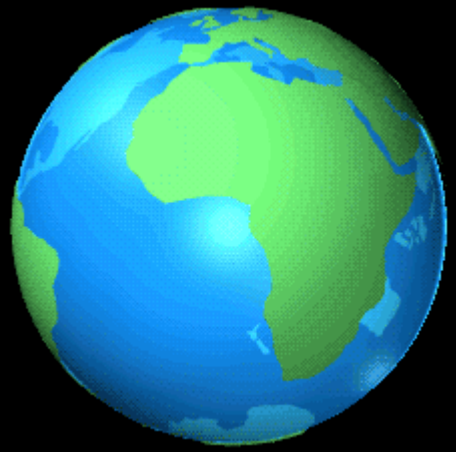


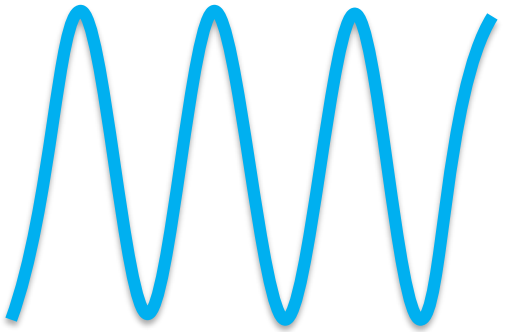
Stable reference

Measurement
and readout

Local oscillator

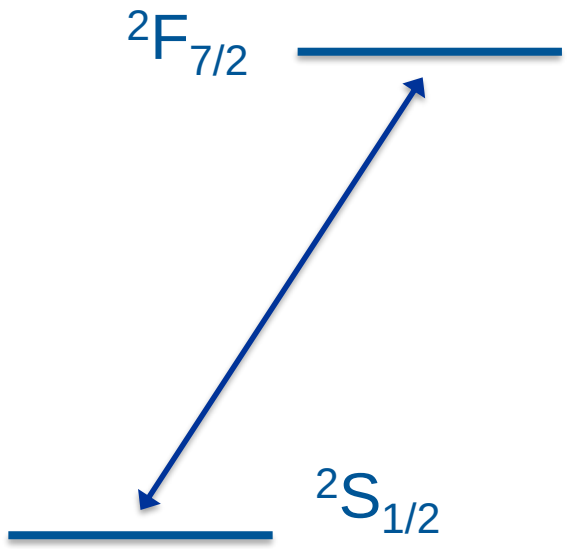
Components of an atomic clock

Local oscillator



Frequency-tuned laser

Stable reference

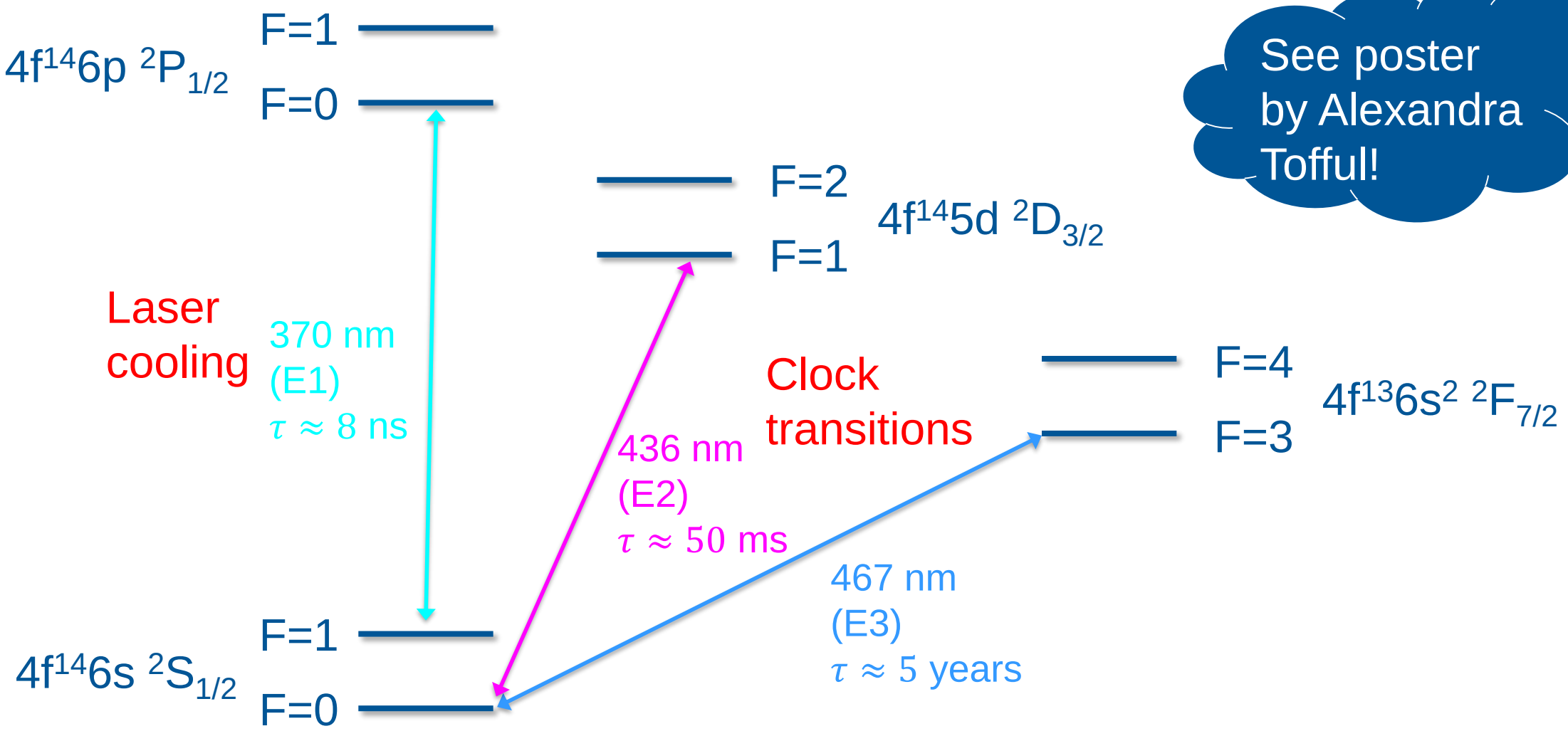


Forbidden atomic transition

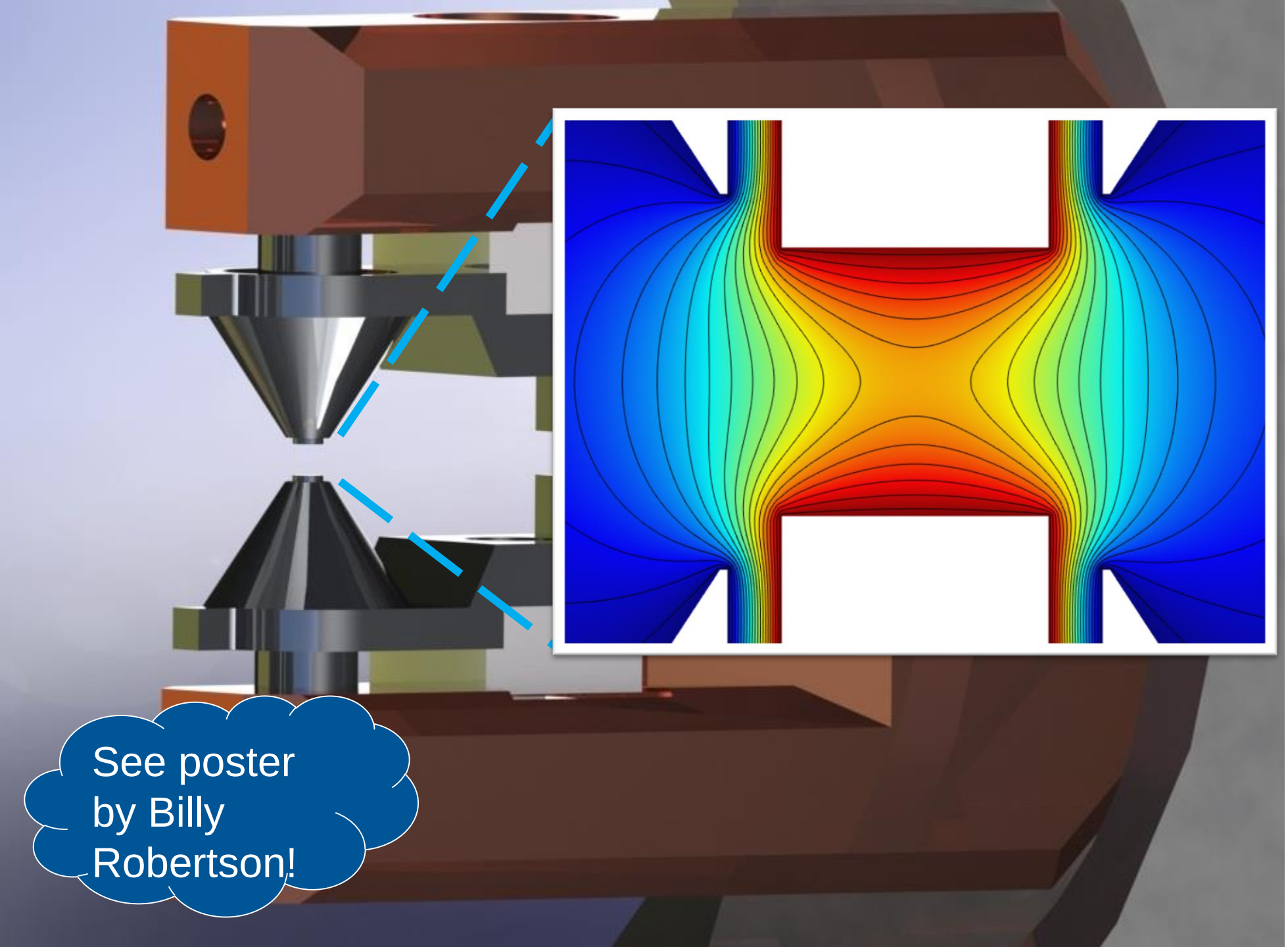
Measurement and readout

Optical frequency comb

$^{171}Yb^{+}$ term scheme



See poster by Alexandra Tofful!



See poster by Billy Robertson!

Endcap-style RF Paul trap

$d = 1\ \mathrm{mm}$
$\Omega_{RF} \approx 2\pi \times 13$ MHz
$\omega_{radial} \approx 2\pi \times 0.5$ MHz

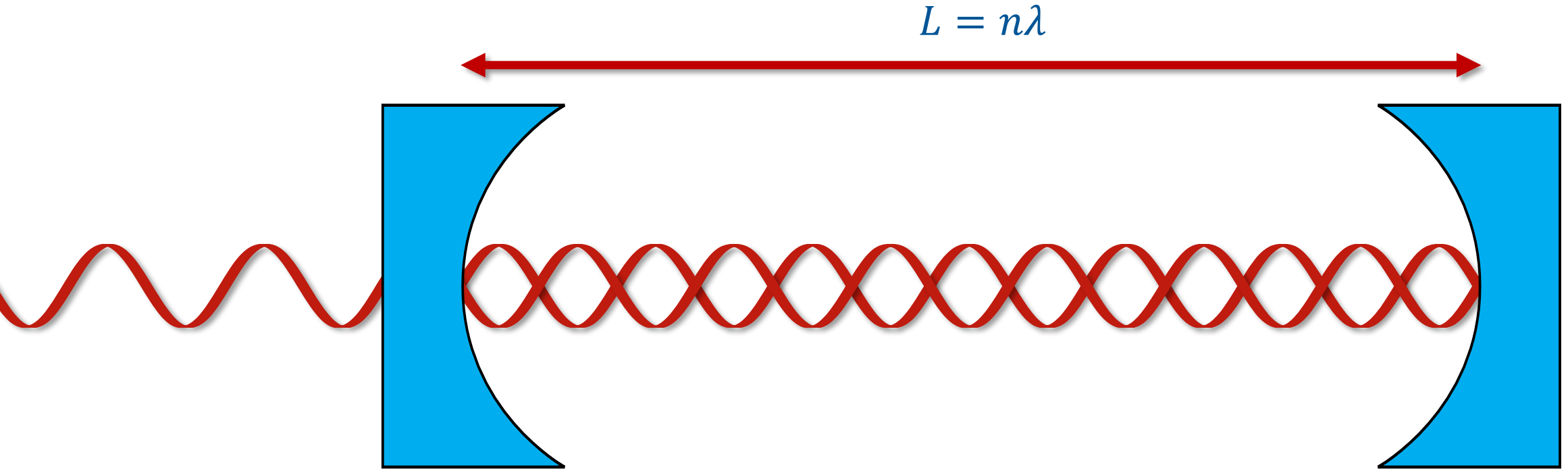
Symmetric RF path avoids uncompensable stray fields at Ω_{RF}

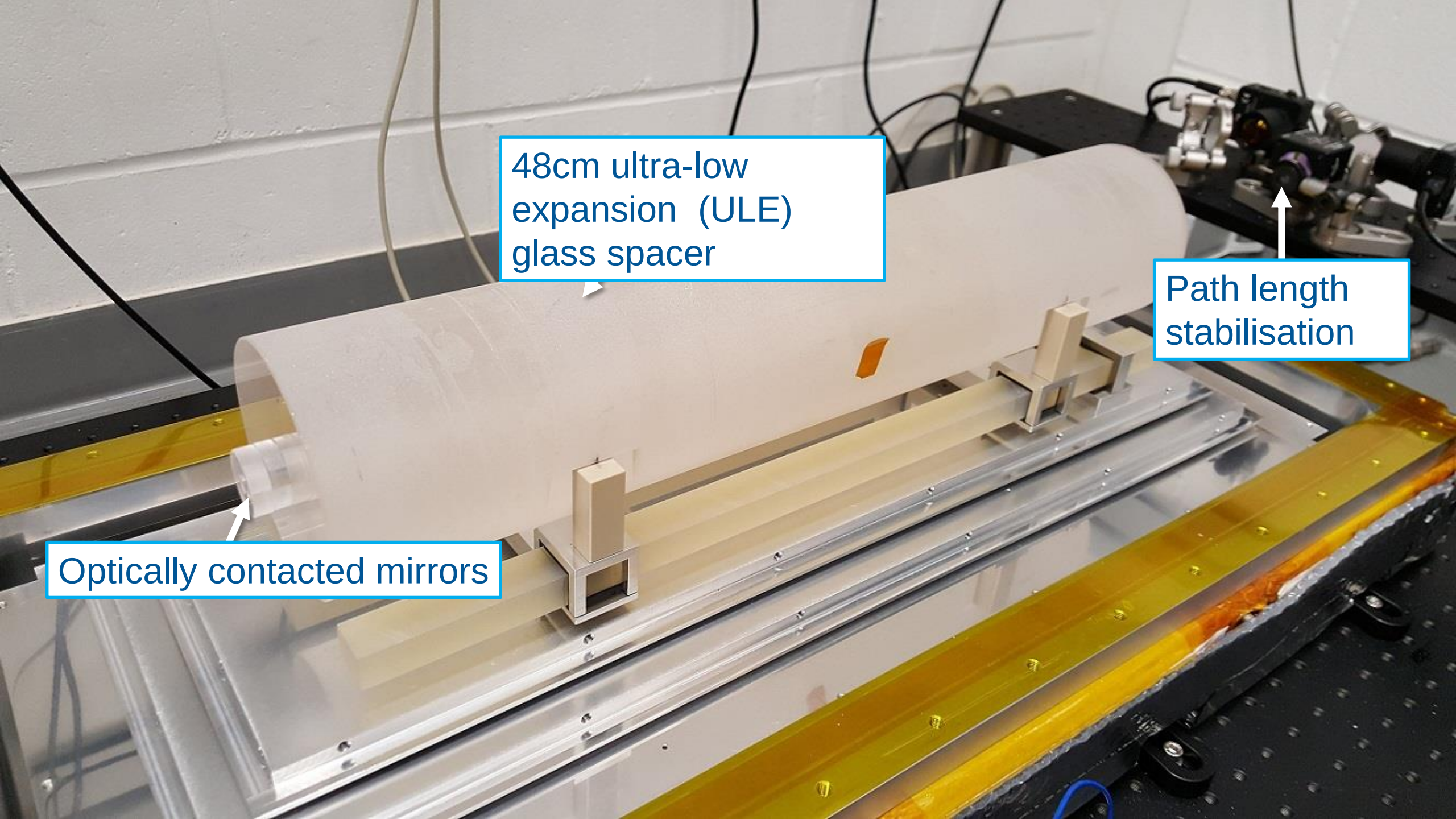
No dielectric near ion to avoid thermal heating (for controlled BBR environment)

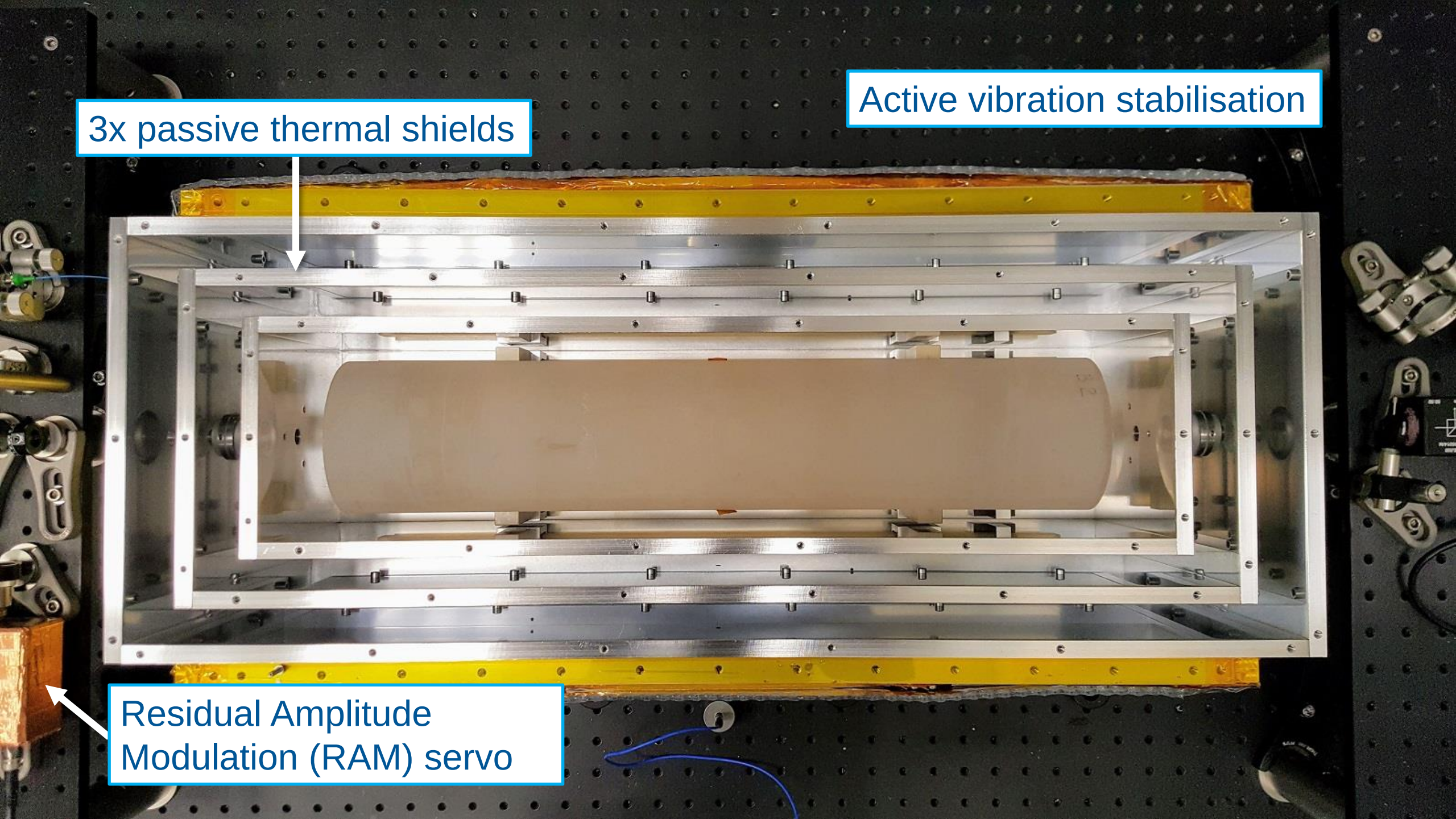
Total trap-related systematic contributions
$< 0.5 \times 10^{-18}$

DOI: 10.1103/PhysRevA.80.022502

Optical cavities

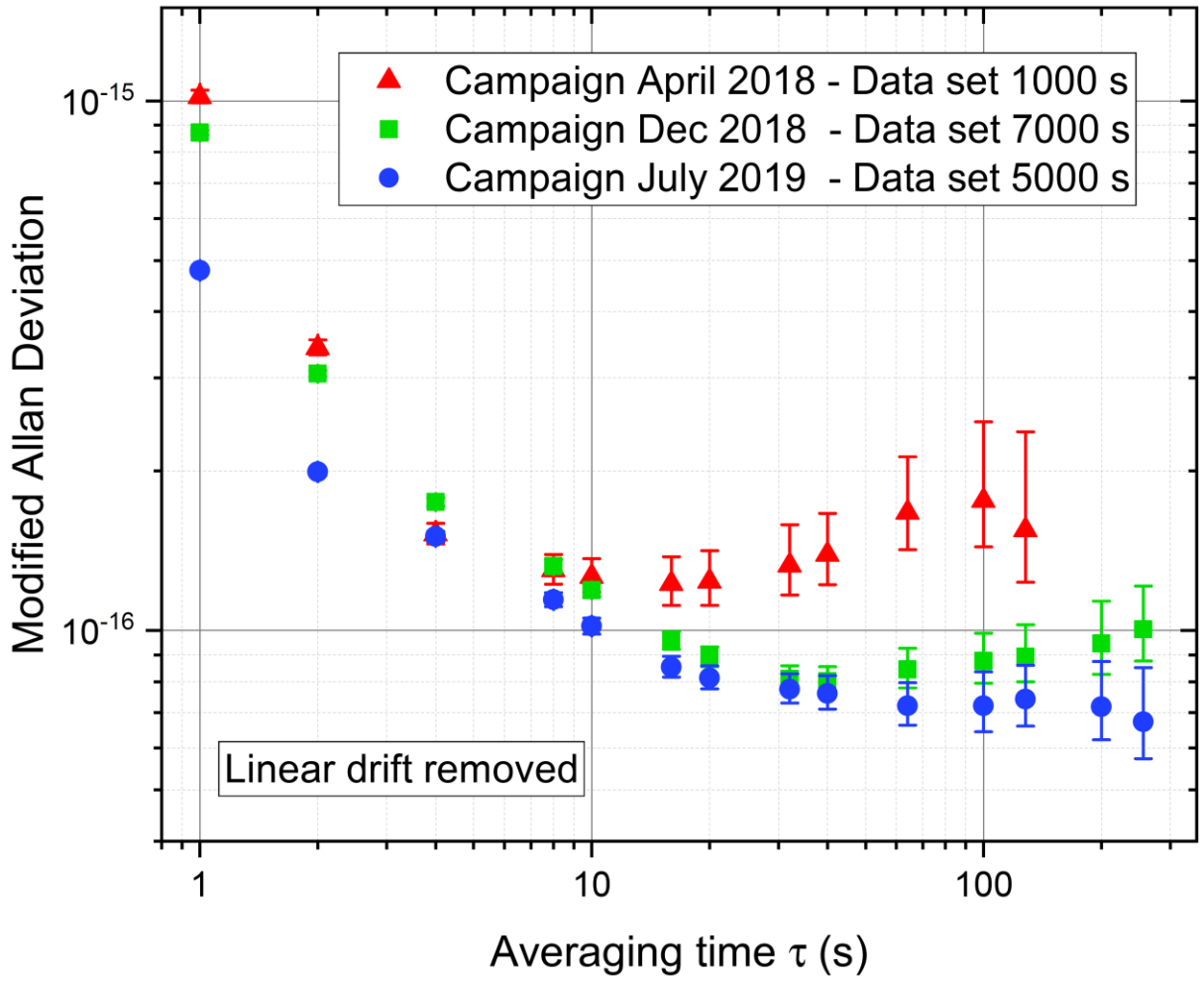



48cm ultra-low expansion (ULE) glass spacer
Path length stabilisation
Optically contacted mirrors


3x passive thermal shields
Active vibration stabilisation
Residual Amplitude Modulation (RAM) servo

Optical cavities

- Fractional thermal noise (fundamental limit) estimated at 6×10^{-17}
- Comparison against PTB cryogenic cavity shows total noise floor of 7×10^{-17} in this room temperature system
- $\approx \frac{1}{25} \times$ diameter of a proton



[PTB cavity] 10.1103/PhysRevLett.118.263202
[This work] Publication upcoming

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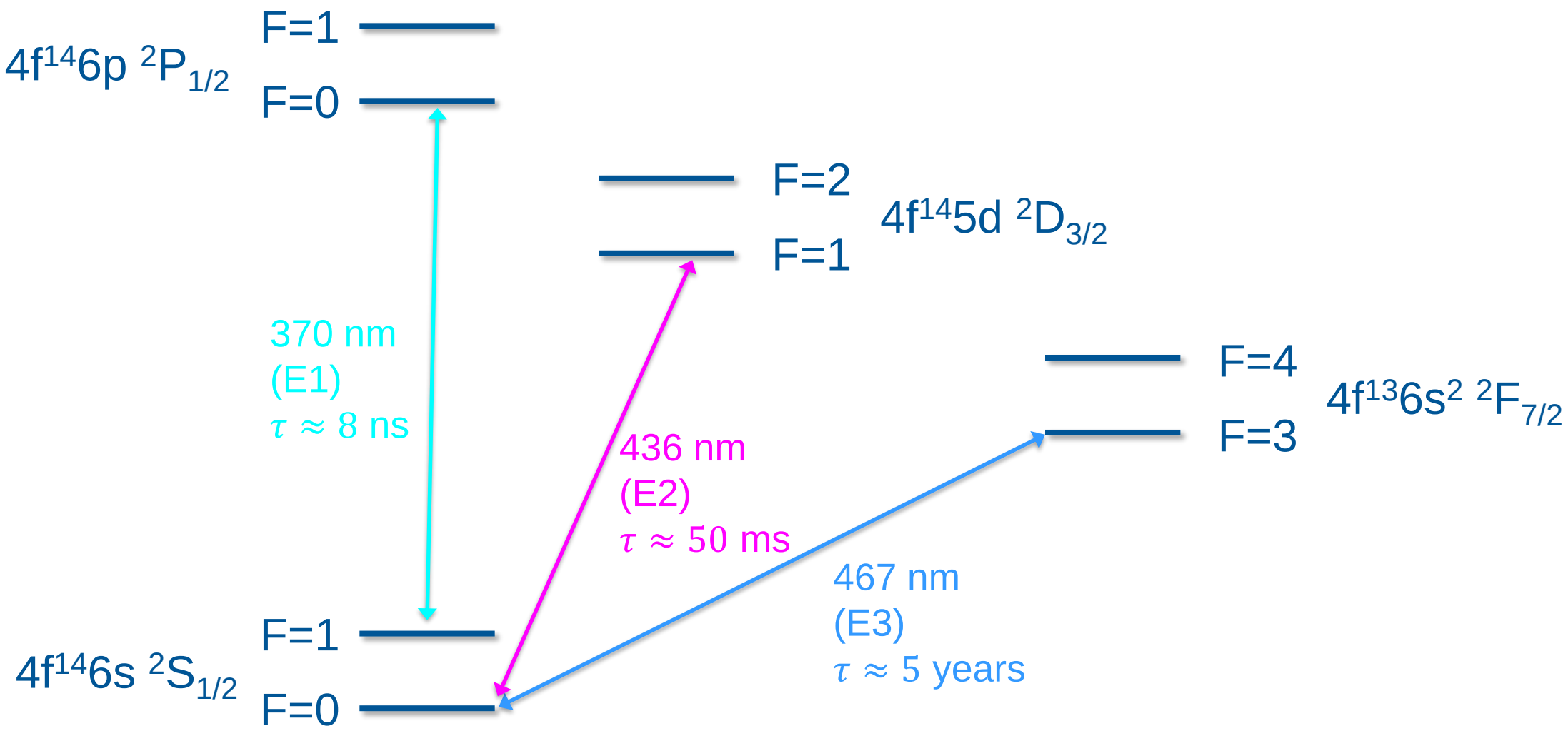
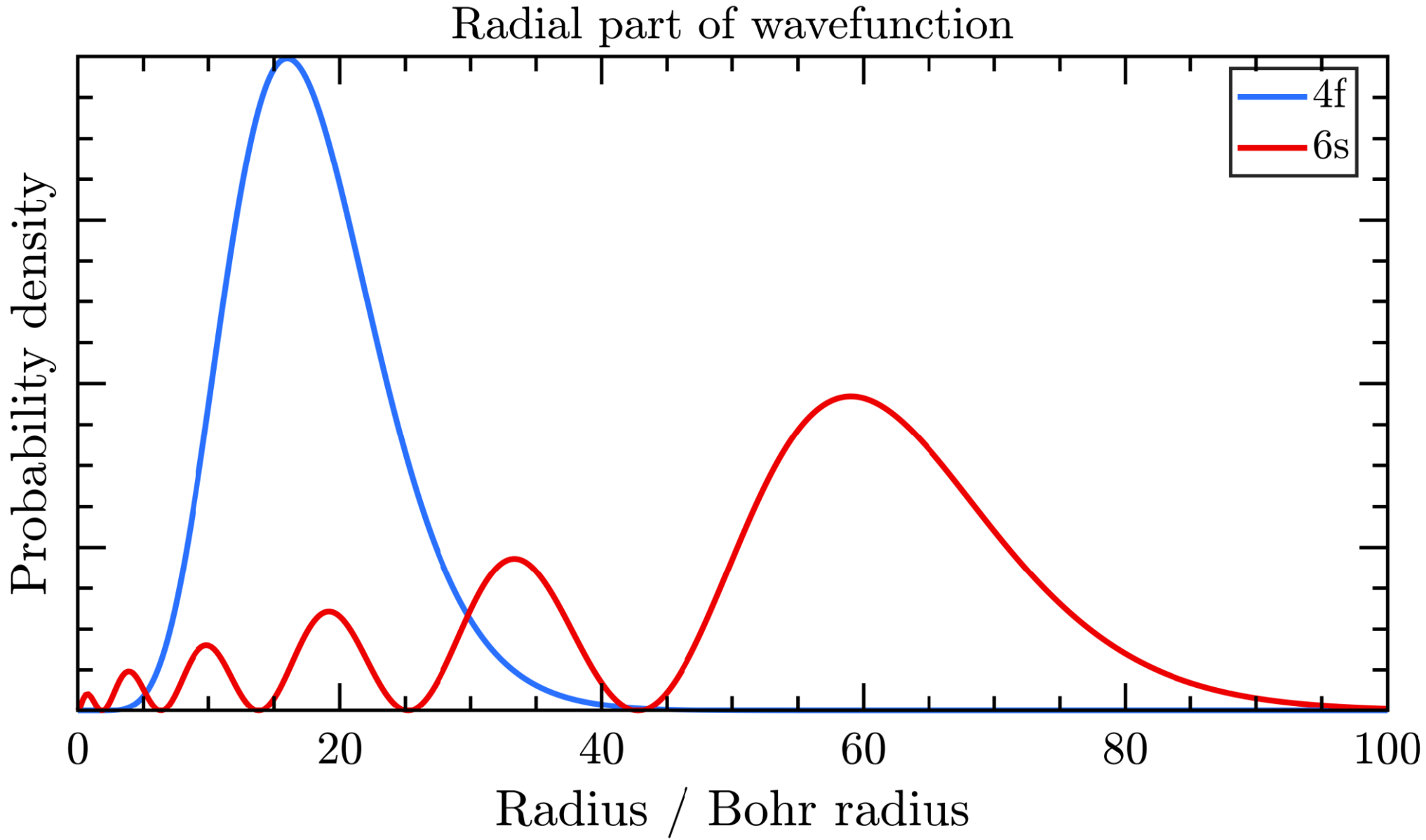
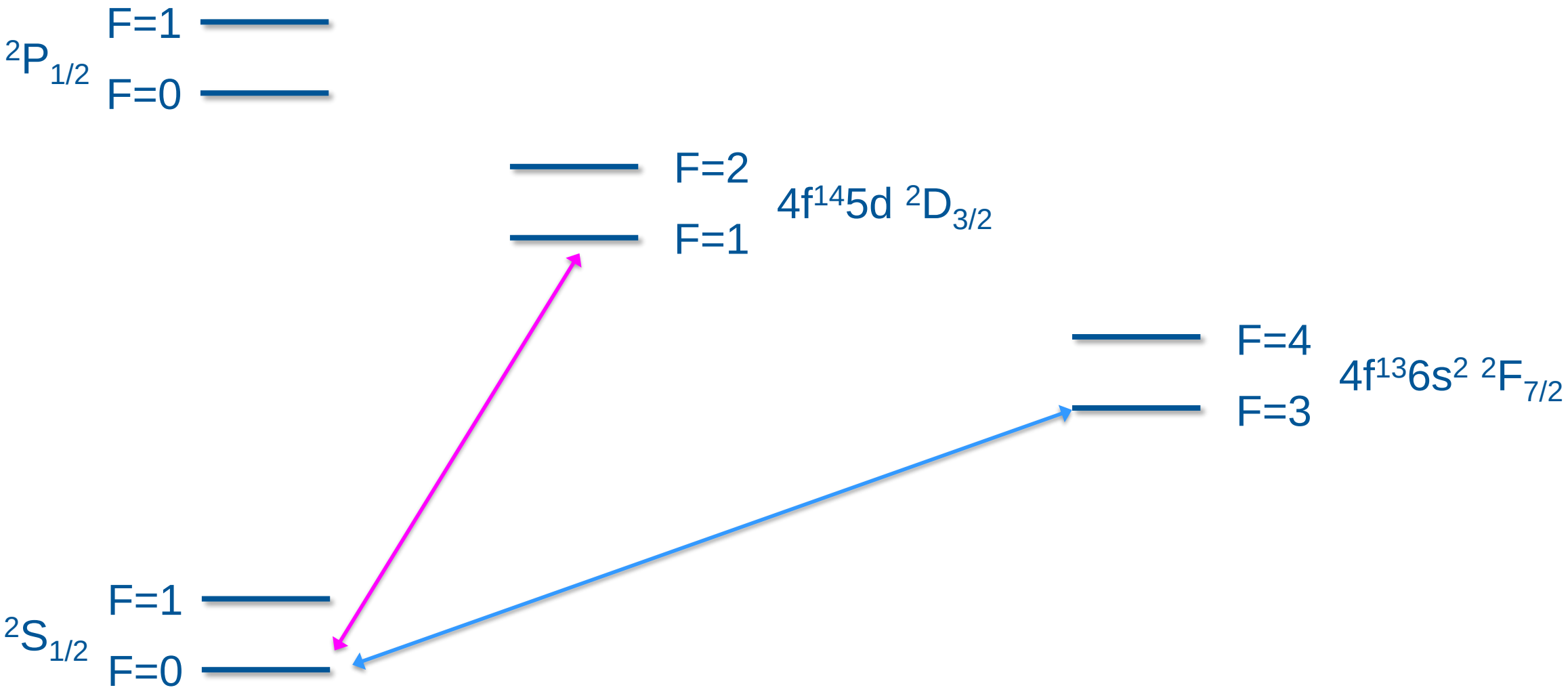
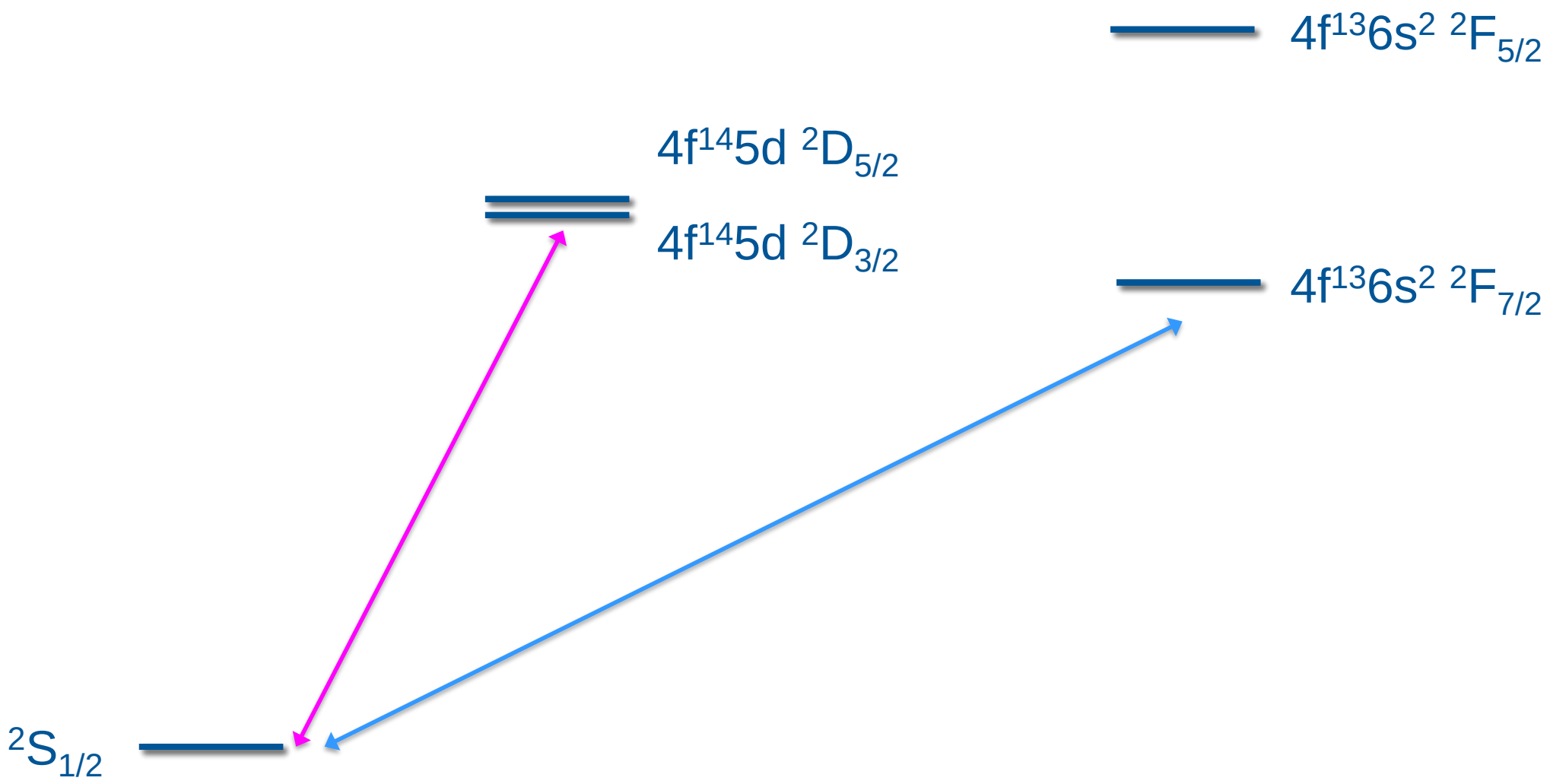
$^{171}Yb^{+}$ term scheme



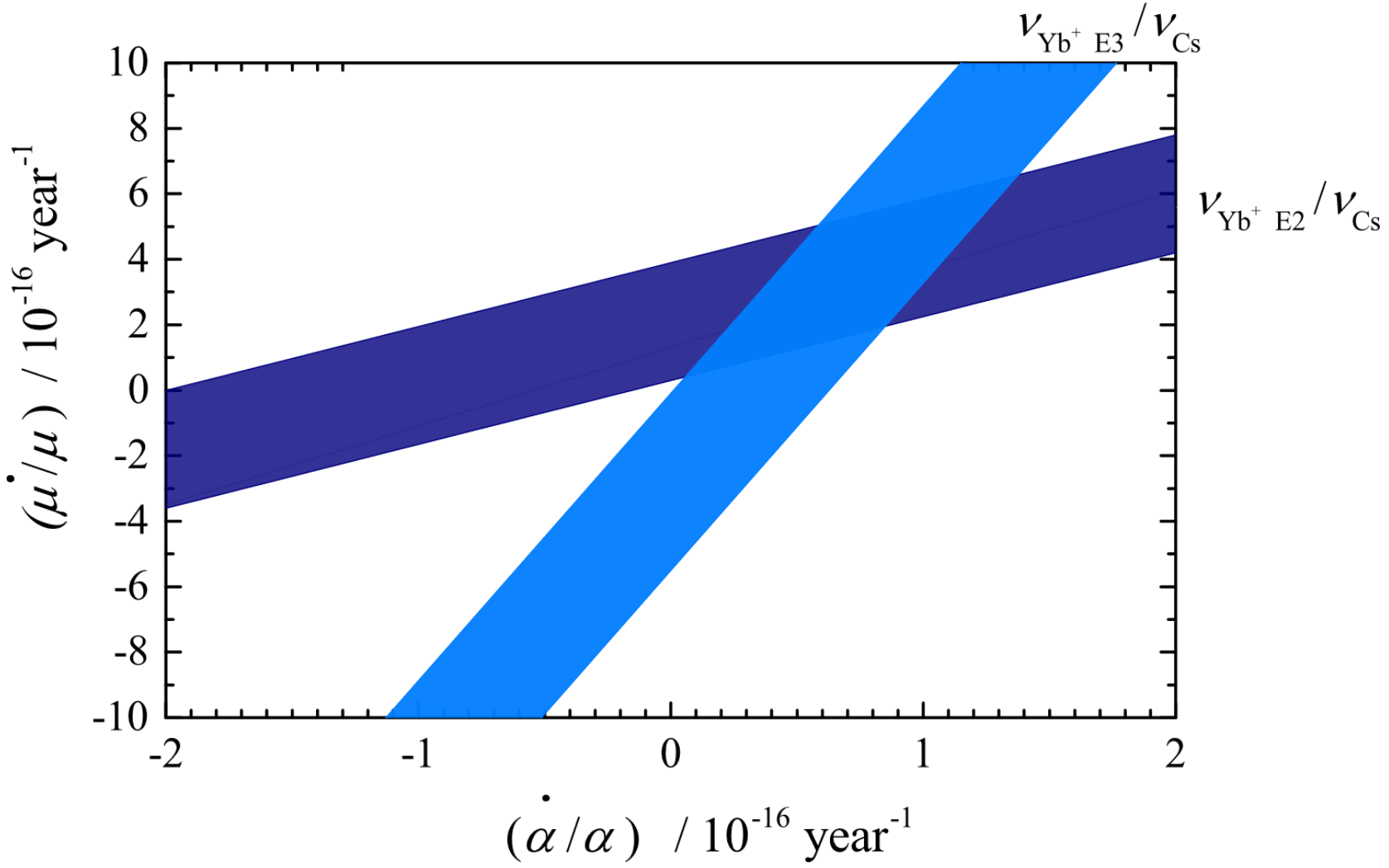
Why Yb+ for physics?




F=1
$^2P_{1/2}$
F=0
F=2
$4f^{14}5d\ ^2D_{3/2}$
F=1
F=4
$4f^{13}6s^2\ ^2F_{7/2}$
F=3
F=1
$^2S_{1/2}$
F=0


$4f^{13}6s^2\ {}^2F_{5/2}$
$4f^{14}5d\ {}^2D_{5/2}$
$4f^{14}5d\ {}^2D_{3/2}$
$4f^{13}6s^2\ {}^2F_{7/2}$
$^2S_{1/2}$

Variation of constants



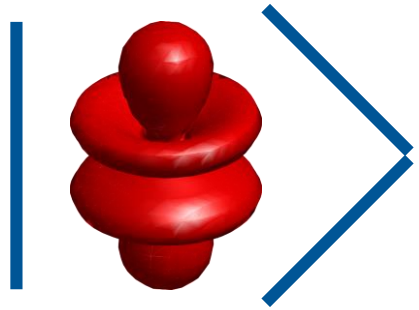
$$\frac{\dot{\alpha}}{\alpha} < -0.7(2.1) \times 10^{-17}\ \text{year}^{-1}$$

$$\frac{\dot{\mu}}{\mu} < 0.2(1.1) \times 10^{-16}\ \text{year}^{-1}$$

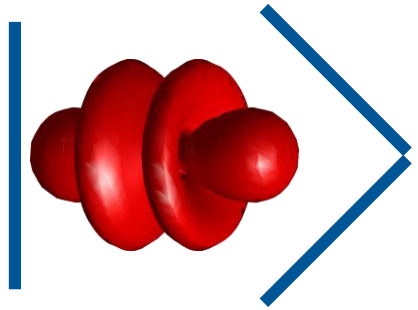
DOI: 10.1103/PhysRevLett.113.210801

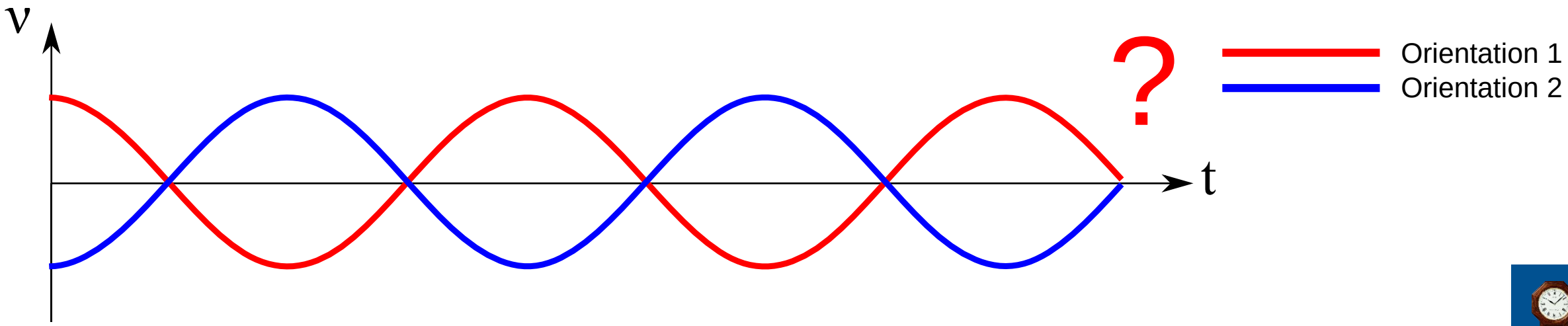
Lorentz invariance

- Large relativistic corrections of the ^{2}F state create sensitivity to LLI violation



vs.





[theory] DOI: 10.1038/nphys3610 [experiment] DOI: 10.1038/s41586-019-0972-2

Dark matter – the motivation

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- …but WIMPs proving elusive

- Alternative explanations include light dark matter:

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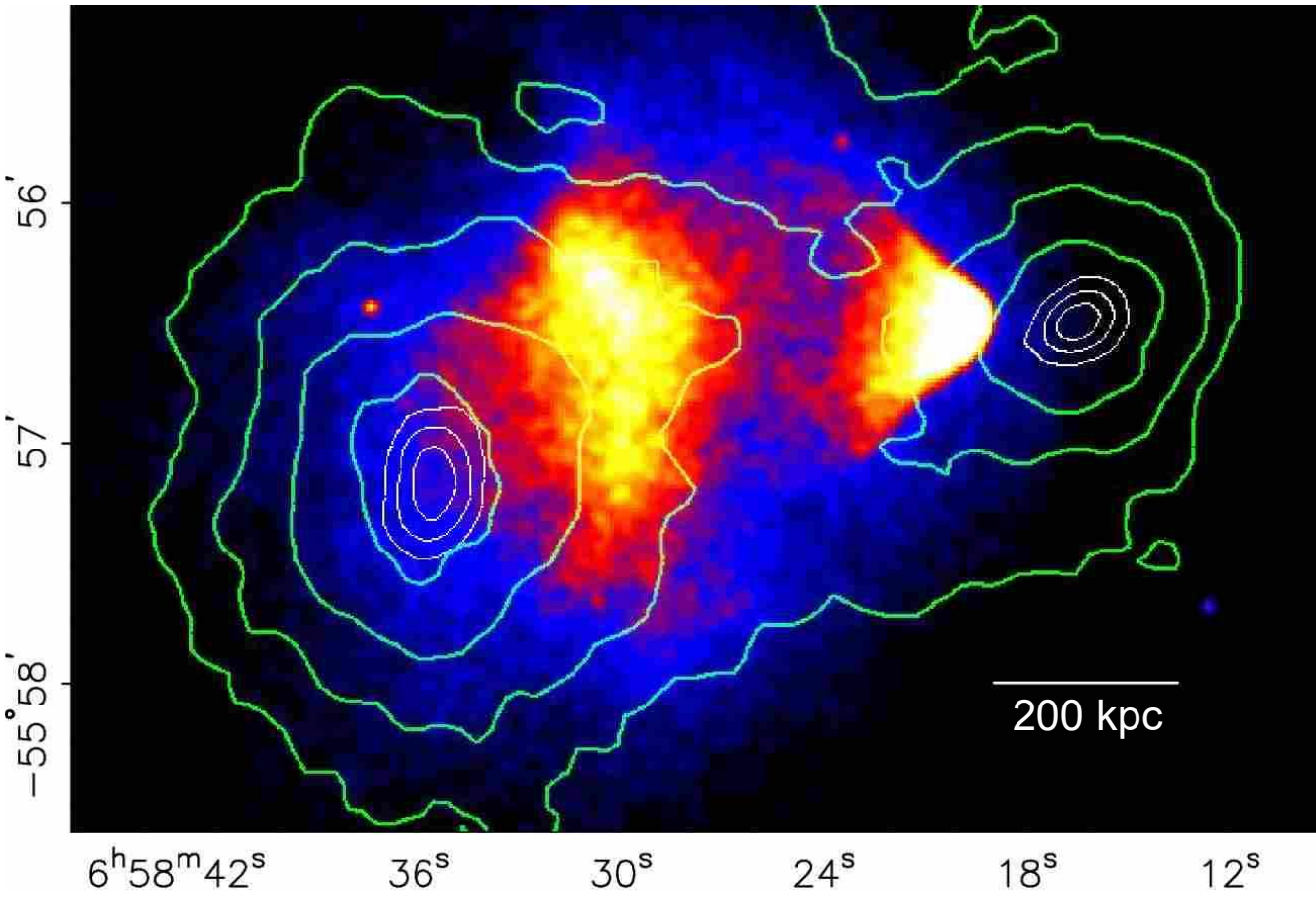
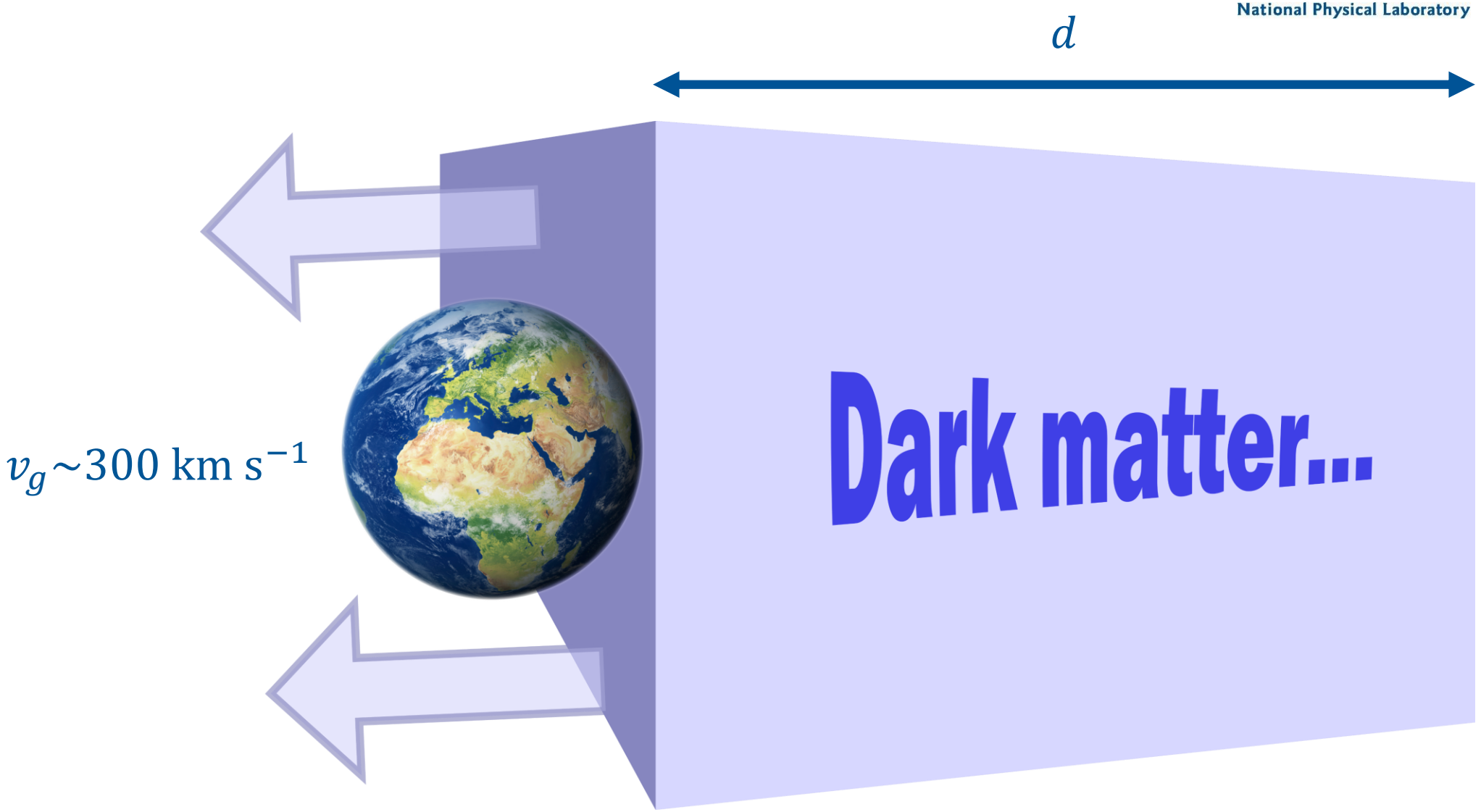
$$\alpha^{\text{eff}} = \alpha\left(1 - \frac{\phi^2}{\Lambda_\gamma^2}\right)^{-1}$$

Detectable by clocks!



[figure] 10.1086/508162 [theory] 10.1038/nphys3137

What would we see?



What would we see?

TD passes Earth

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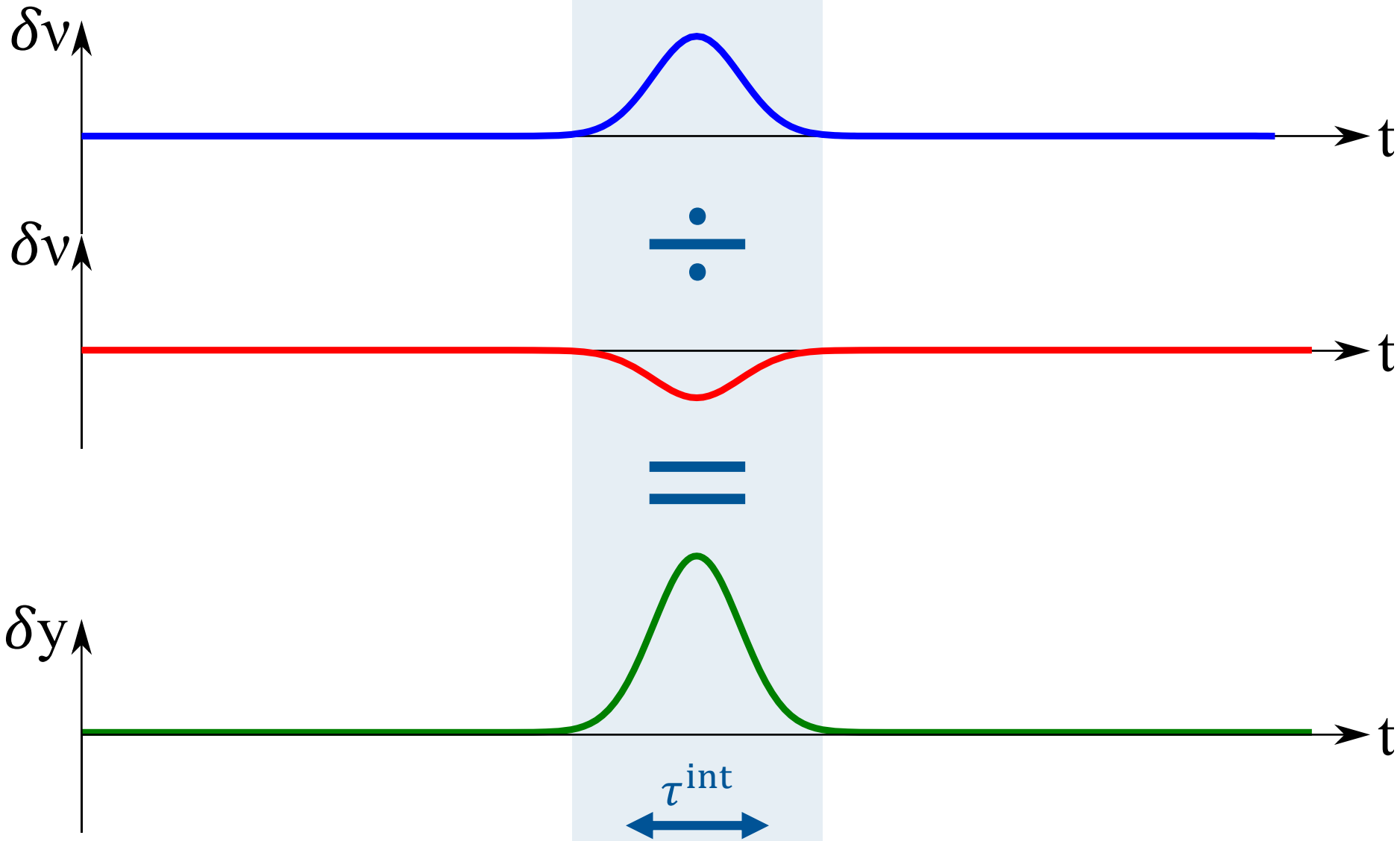
"true" frequencies

Not observable

Frequency ratio

Observable, unit-less



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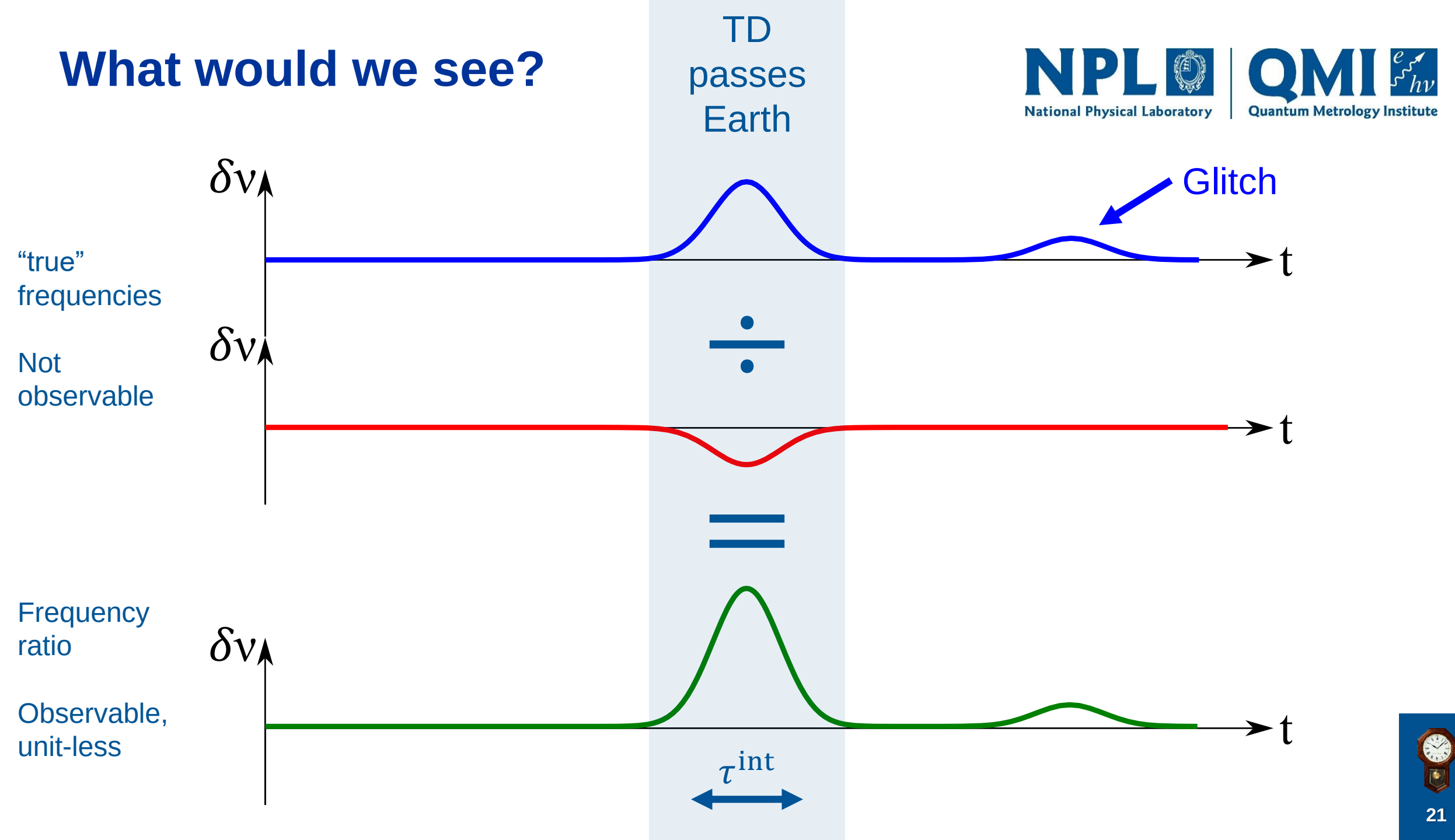


"true" frequencies

Not observable

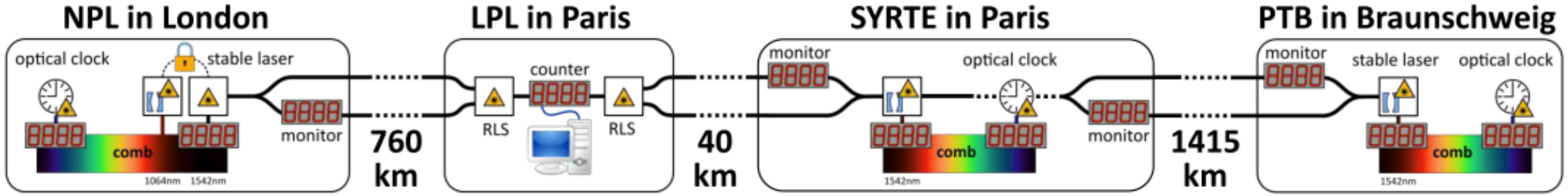
Frequency ratio

Observable, unit-less

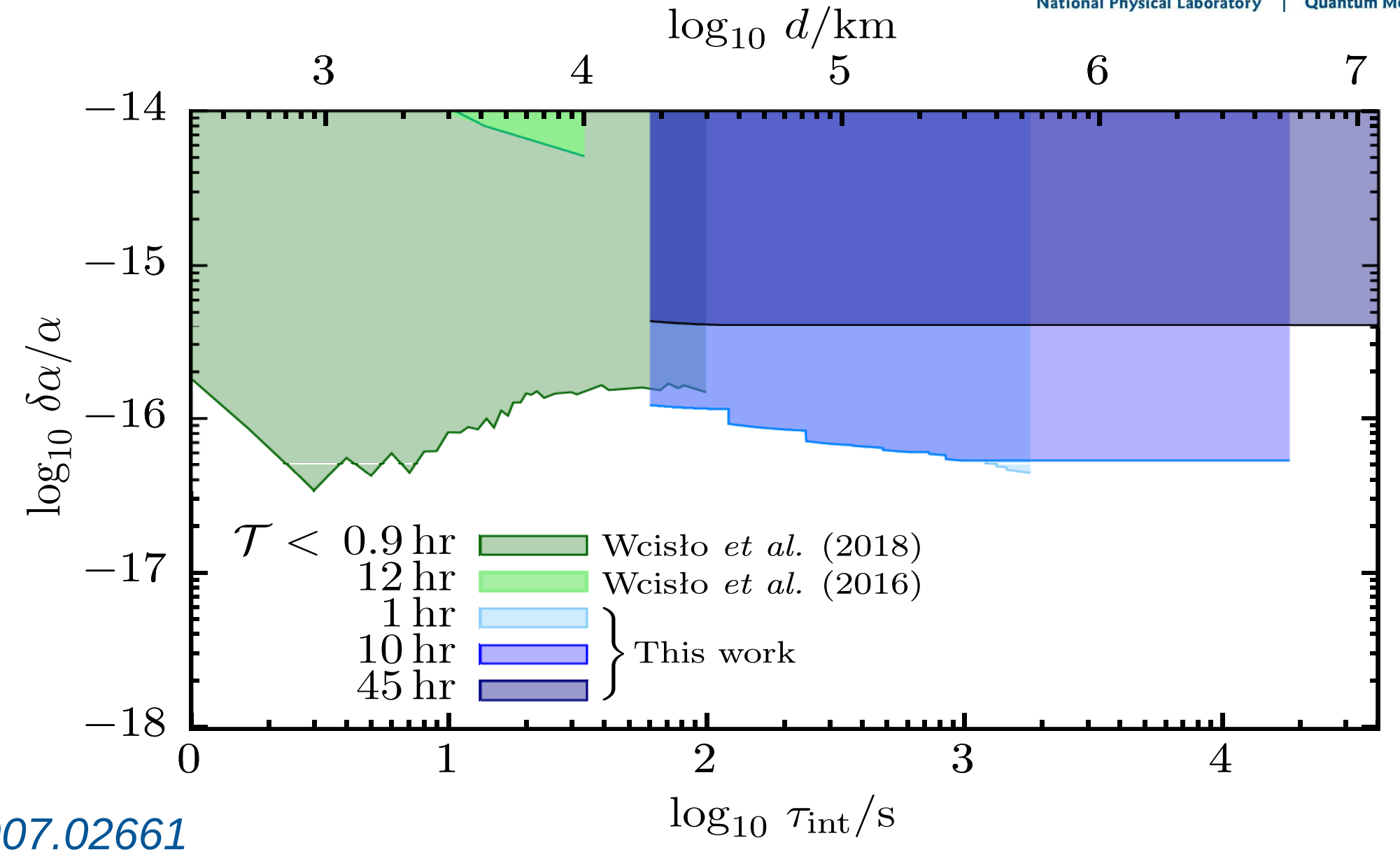
A network of clocks

- Use a network of clocks joining three institutes with 6 optical clocks
- Optical fibre links
  - 2215km
  - Active path-length stabilisation
- Rejects noise on a single clock
- Low correlations between noise sources

DOI: 10.1038/ncomms12443



Limits to transient variation in α



arXiv: 1907.02661

Limits to transient topological defects

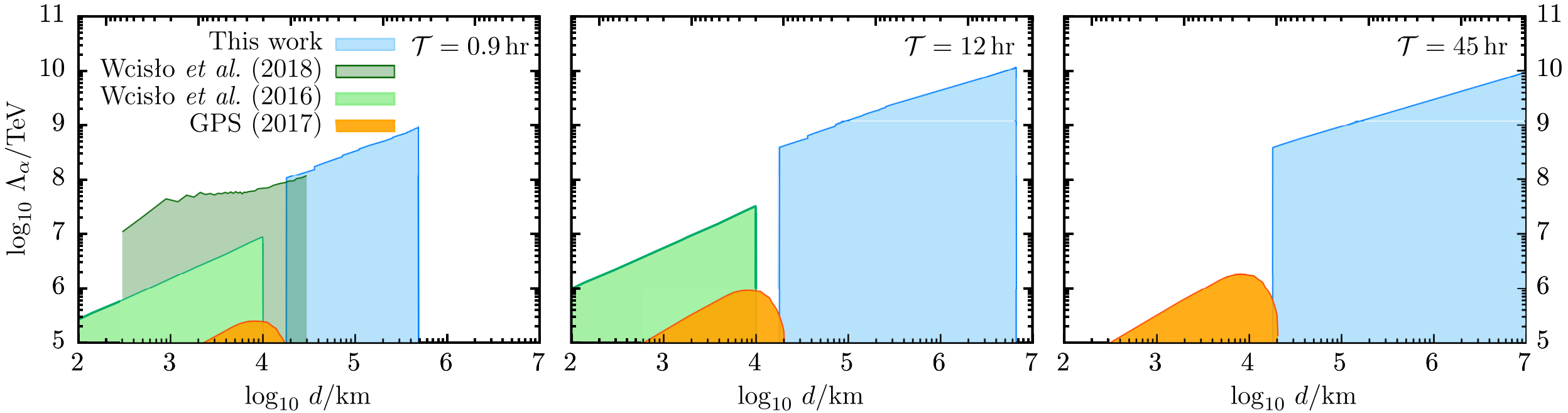
- Add some assumptions:
  - All dark matter is in the form of topological defects
  - Locally, dark matter has a density of

$$\rho_{DM} = 0.3\ \mathrm{GeV\ cm^{-3}}$$

- Pick a model:
  - Scalar field ϕ with quadratic interactions with SM, energy scale Λ_α

- => link between size of defects, frequency of defects and energy scale of interaction with SM matter

Limits to transient topological defects



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Thanks for listening!

And thanks to:

Alexandra Tofful
Rachel Godun
Anne Curtis
Billy Robertson

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Department for Business, Energy & Industrial Strategy

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