QUANTUM TECHNOLOGY INITIATIVE

Searching for Ultra-Light Dark Matter

with nuclear interferometry

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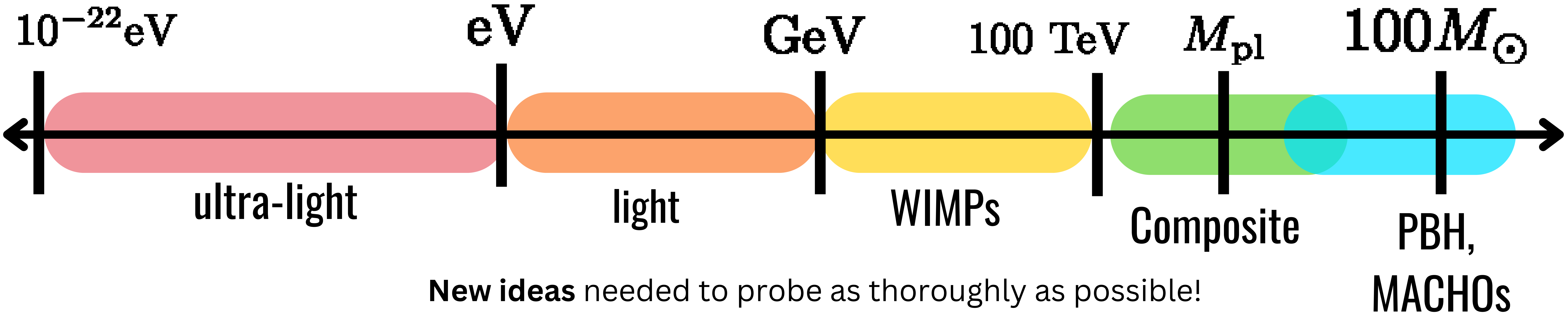
Based on **arXiv:2407.11112**
with Elina Fuchs & Matthew McCullough

The Low Down

1. **Quantum Sensors** offer a number of exciting **new avenues** to **probe fundamental physics** at the **feebly interacting frontier**
2. **Atomic Clocks** and **Atom Interferometers** are leading the way in the search for the **variation** of **fundamental constants**
3. The **“Nuclear Interferometer”** may open a window to new parameter space in the future...

Motivation: The Dark Matter Landscape

Dark Matter landscape is **extraordinary broad** covering a vast array of phenomenology



New ideas needed to probe as thoroughly as possible!

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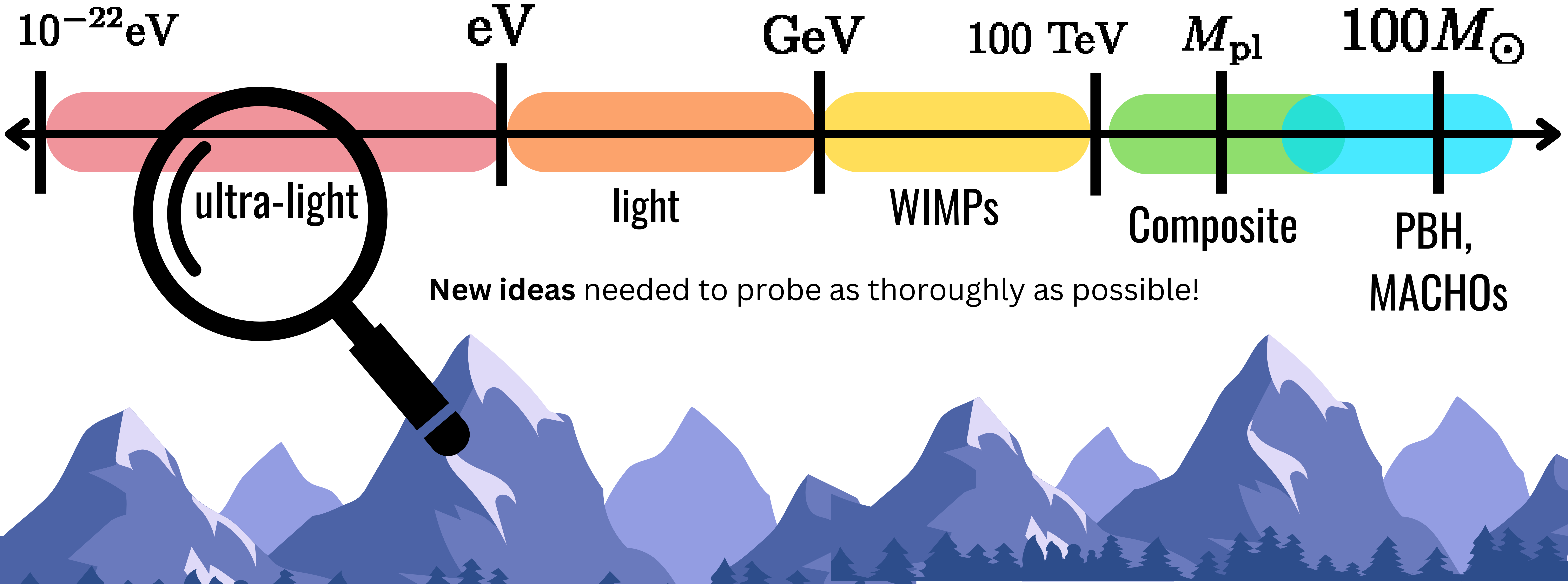
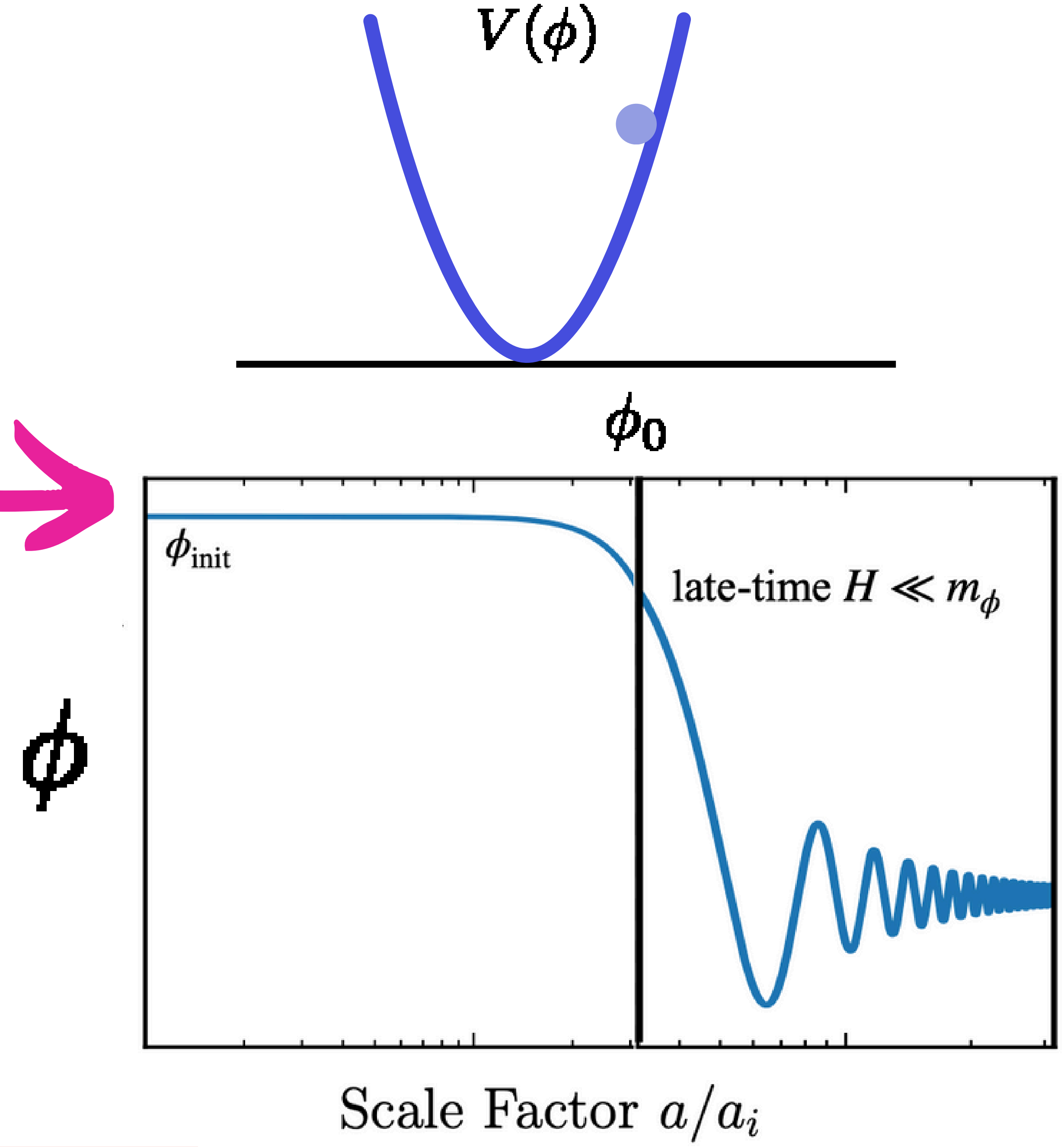


New ideas needed to probe as thoroughly as possible!

Motivation: ULDM

Consider a light, free (pseudo-) scalar field : $\mathcal{L} \in m_\phi^2 \phi^2$ with initial homogeneous condition $\phi_{\text{init}} = \phi_0$

COSMOLOGICAL EVOLUTION



At late times, field oscillates about the minimum

Vacuum Misalignment (non-thermal production)

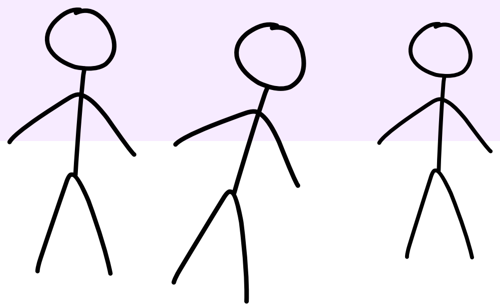
ULDM behaves as a **coherently oscillating classical wave**:

$$\phi(t, \mathbf{x}) = \phi_0 \cos[m_\phi(t - \mathbf{v} \cdot \mathbf{x}) + \theta]$$

Coherent since **cold**

Classical as **phase space density >>1** to saturate DM abundance

The ULDM landscape:



Spin 0

Spin 1

Class

Scalars
(moduli, dilatons, relaxions, Higgs Portal...)

Pseudo-scalars
(Axions, Axion-like particles)

Vectors
(Dark Photons)

Quantum Sensing Signatures

Spatio-temporal variation of fundamental constants

Time Varying **Spin Dependent Effects**

Precession of spins

Motivation: Ultra-Light Dark Matter

Scalar ULDM with (linear) couplings to SM fields:

e.g.

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

causes **fundamental constants to oscillate in time:**

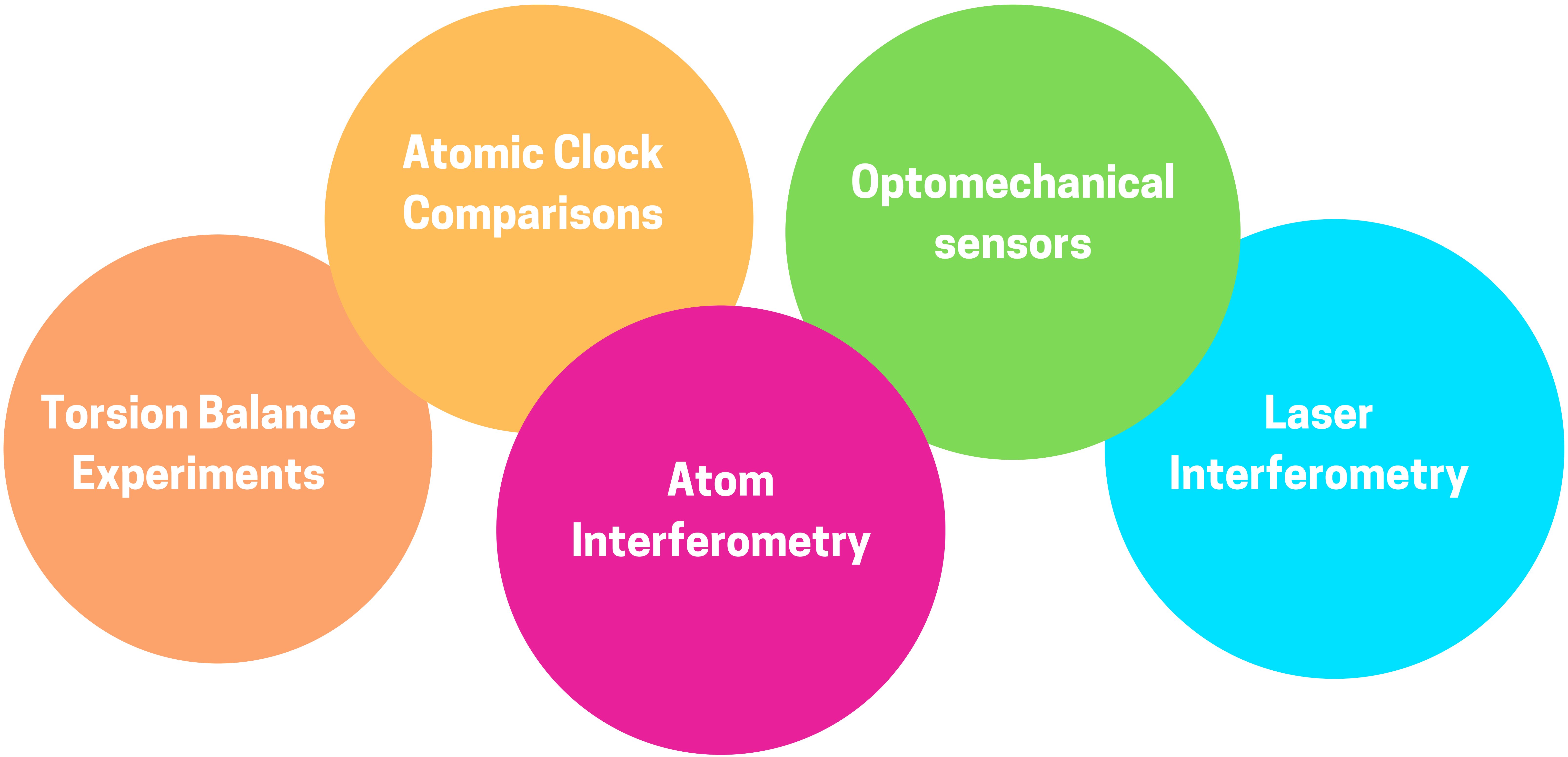
$$m_\psi = m_\psi\left[1 + d_{m_\psi}\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

$$\alpha = \alpha\left[1 + d_e\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

$$\alpha_s = \alpha_s\left[1 + d_g\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

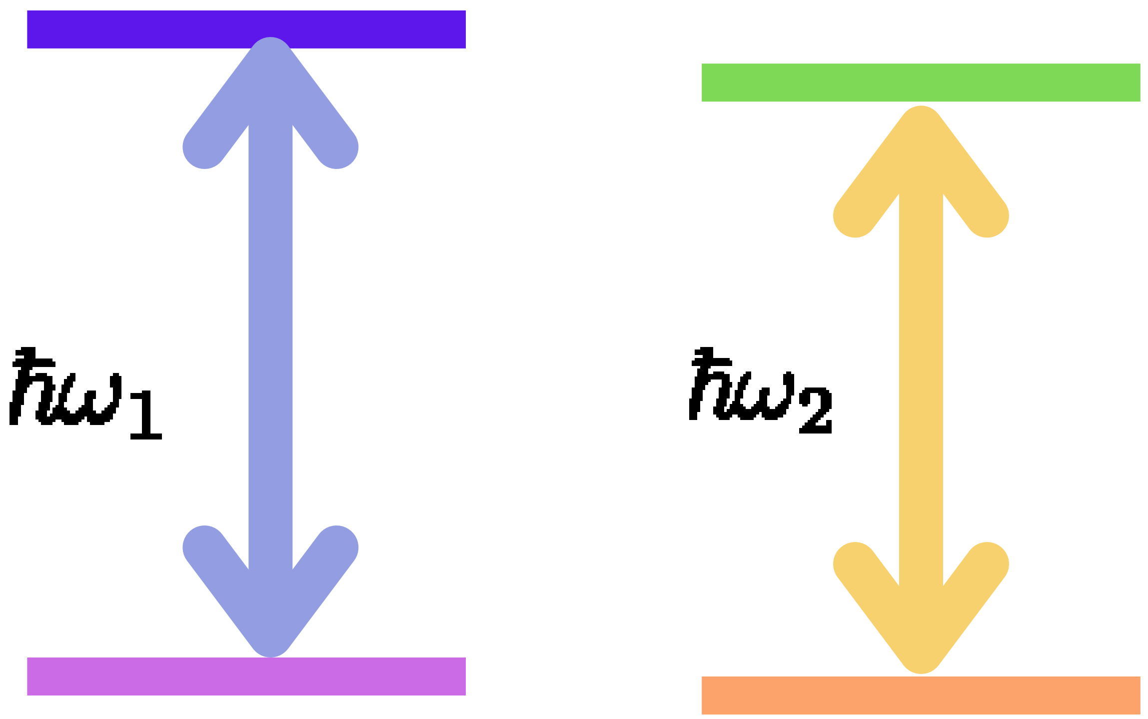
Energy and length scales that depend on these **oscillate in time**

Probes of Oscillating Fundamental Constants



Searches with atomic clocks

Compare 2
different clocks:



Different transitions have different sensitivities to different fundamental constants

$X = \alpha, m_e/m_p$ etc.

Enhancement Factors:

$$K_X = \frac{\partial \omega}{\partial X}\frac{X_0}{\omega}$$

Calculated from atomic theory

$$\frac{\delta\omega_1/\omega_2}{\omega_1/\omega_2} = (K_{X,1} - K_{X,2})\frac{\delta X}{X}$$

Optical Transitions in atomic clocks sensitive to: variations in α, m_e (i.e. d_e, d_{m_e}) with K ~ 1

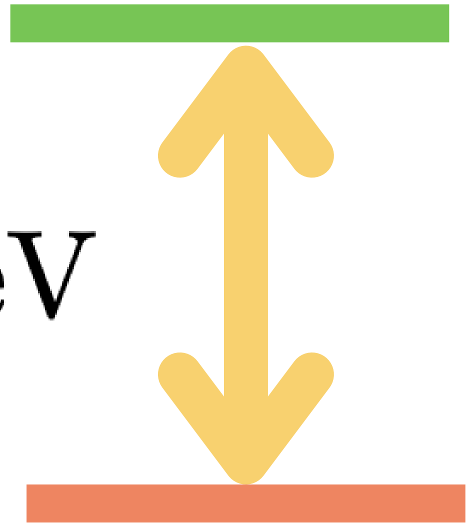
Comparisions between optical and hyperfine (microwave) clocks can give (weak) access to $d_g, d_{\hat{m}}$

Thorium-229 : A Nuclear Clock

Discovery of a low lying **excited isomer of Thorium-229**, $^{229m}\mathrm{Th}$ has led to **proposals for a nuclear clock**

Transition in **optical range**

$8.3\ \mathrm{eV}$



Excited state lifetime in atomic form ~ 10 $\mu\mathrm{s}$ due to internal conversion

- Extended to 10^4 s in ionic form or thorium doped crystals

Many **key developments** in recent months including first radiative excitation:

- PhysRevLett.132.182501
- arXiv:2404.12311
- arXiv:2406.18719

Advantages

- Transition particularly **insensitive to external perturbations** e.g. electromagnetic fields
- **Highly sensitive** to the **variation of fundamental constants**

$$\Delta\omega_N = \omega_N \left(10^4 d_e + 10^5 (d_{\hat{m}} - d_g)\right) \phi(t, \mathbf{x})$$

v.s. atomic optical clock: $\mathcal{O}(1)$ $\mathcal{O}(10^{-5})$

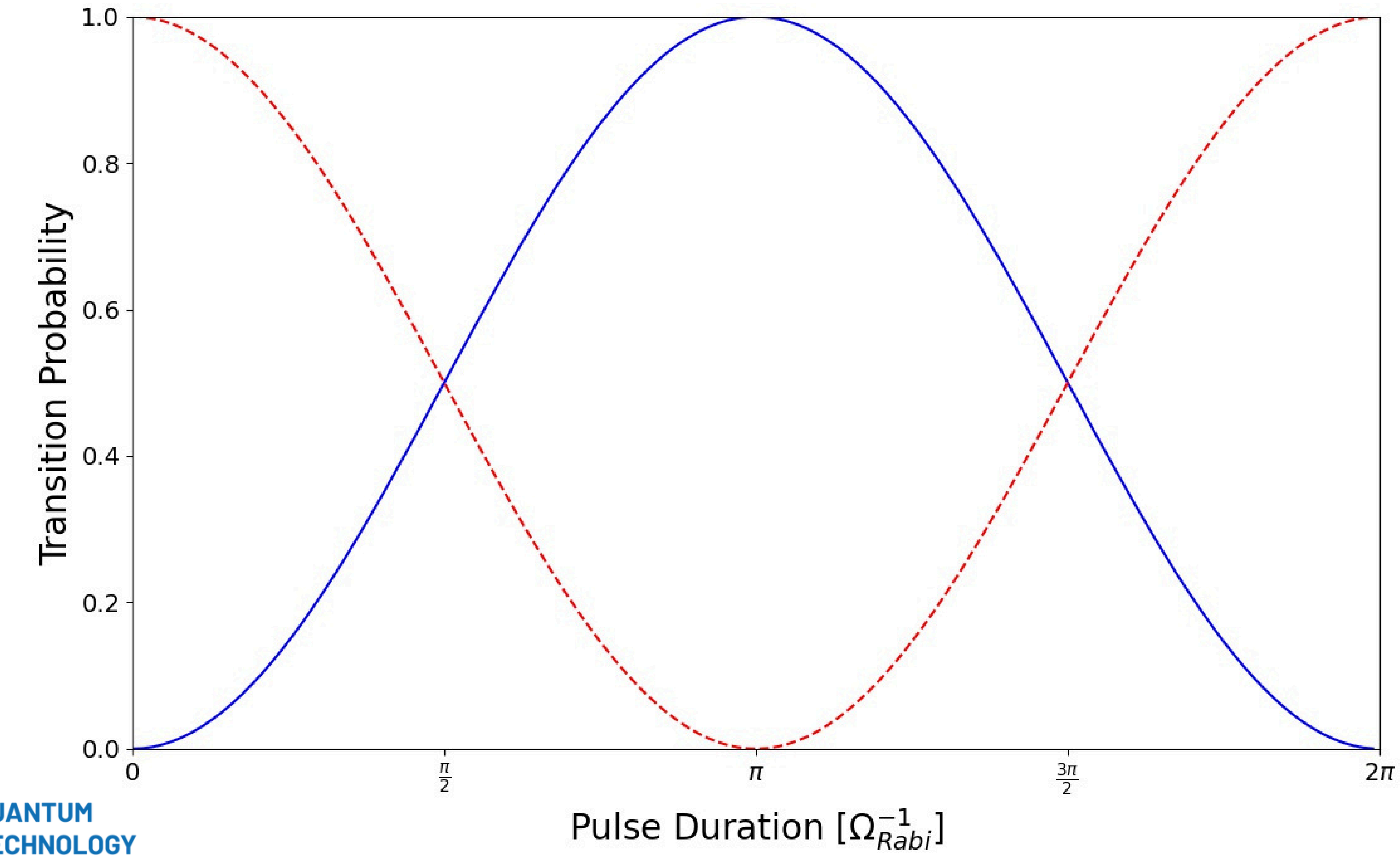
Frequency comparisons between **nuclear and atomic optical clocks** could provide a **highly sensitive probe** of the **variation** of **fundamental constants** *(arXiv:2012.09304)*

Atom Interferometery

Experiment that **measures the phase shift** between **spatially-separated quantum superpositions** of **atomic wavepackets**

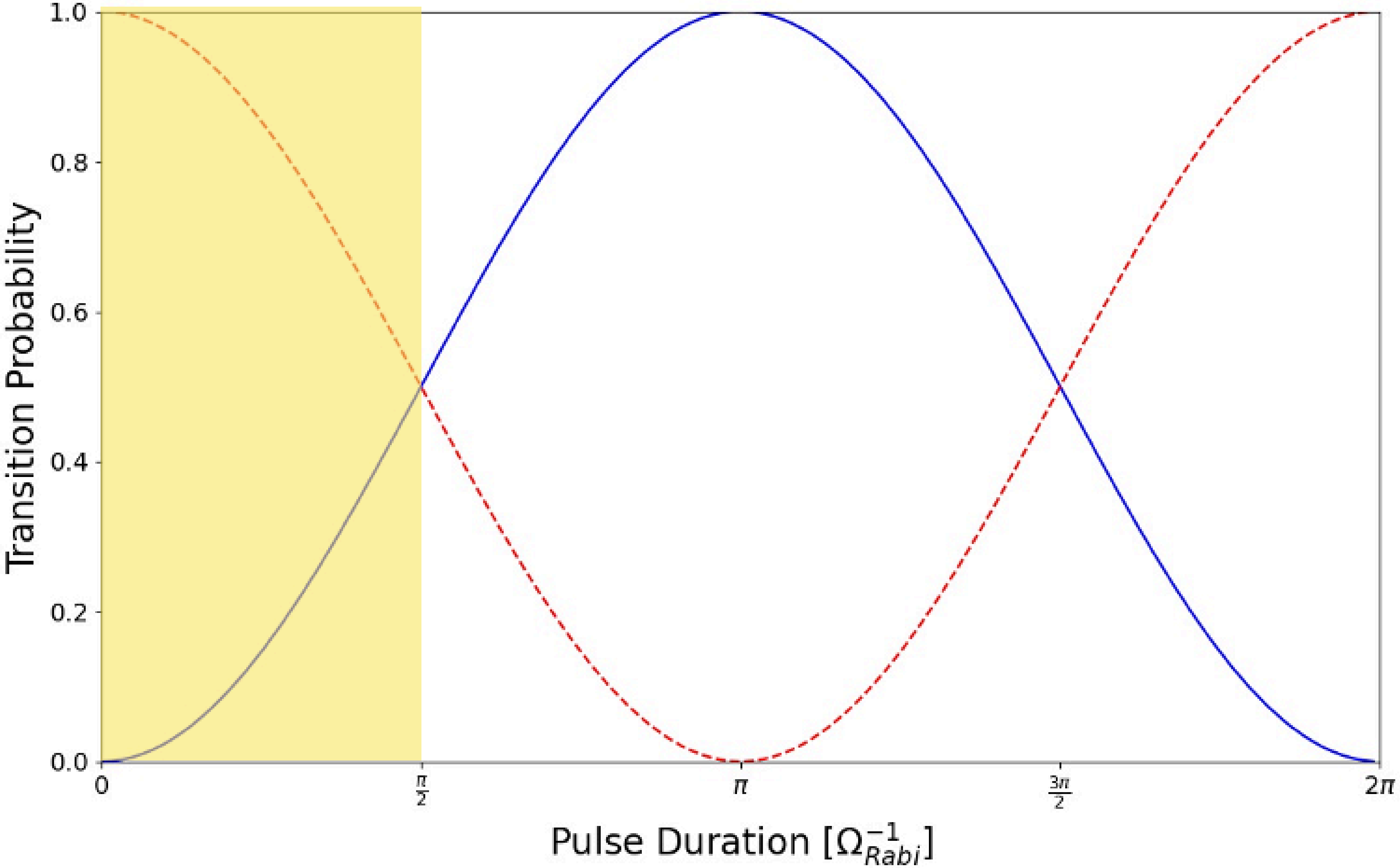
Manipulating atoms with light

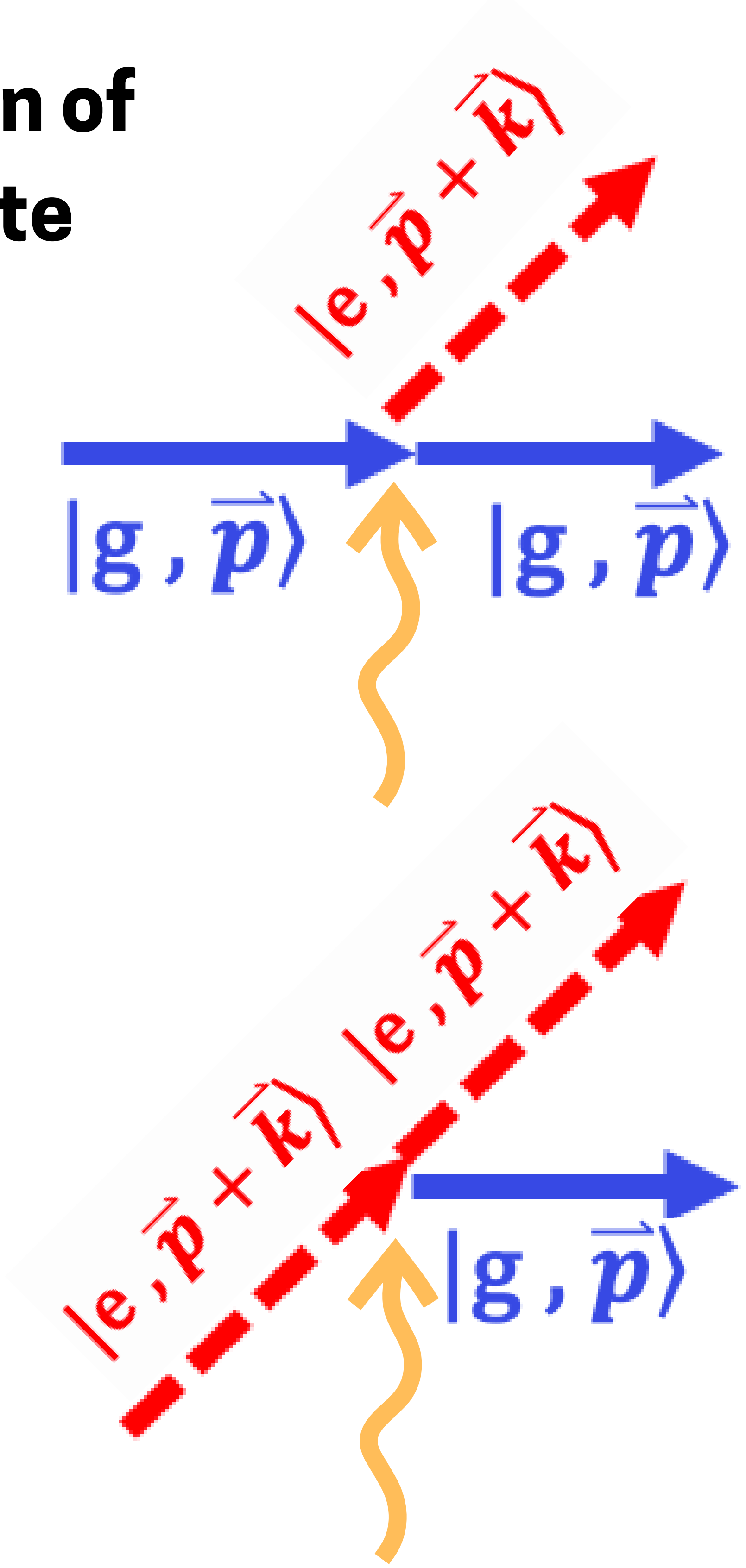
A **two level system** (i.e an atomic clock) coupled to a **driving force** (i.e. a laser) undergoes **Rabi Oscillations** between the ground $|\mathbf{g}, \vec{p}\rangle$ and excited $|\mathbf{e}, \vec{p}+\vec{k}\rangle$ states



Manipulating atoms with light

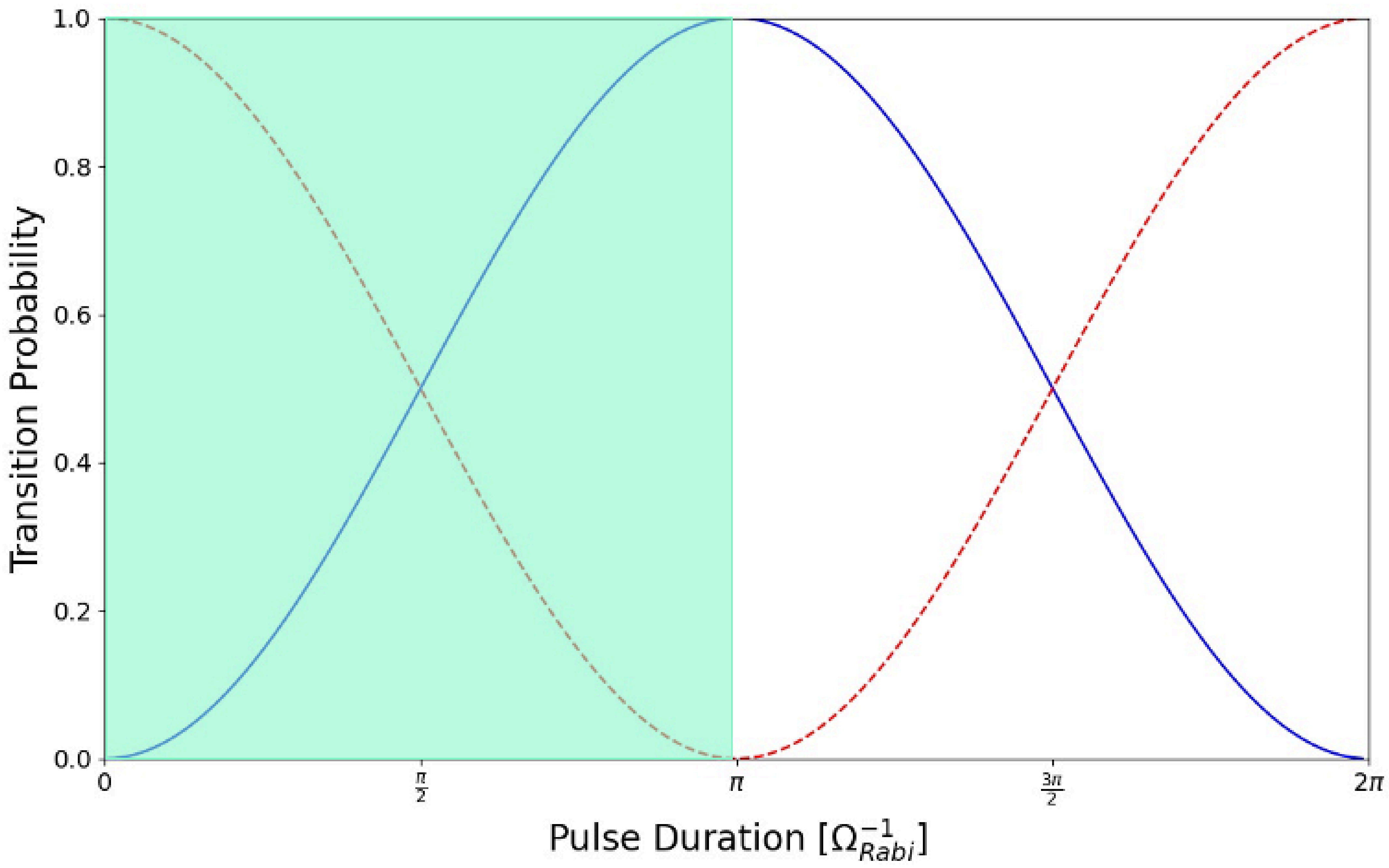
$\frac{\pi}{2}$ pulse (beamsplitter) → Coherent superposition of ground + excited state

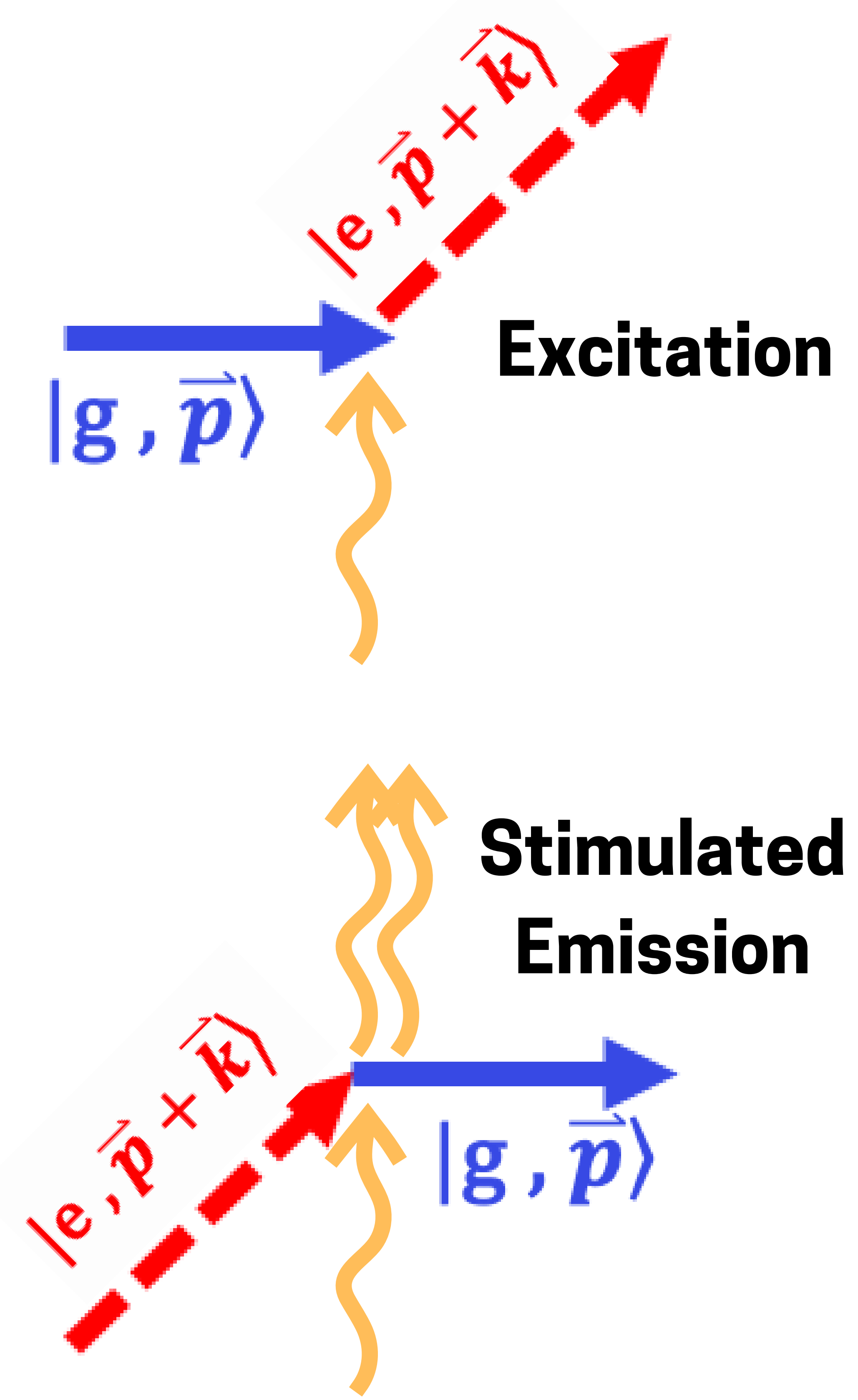




Manipulating atoms with light

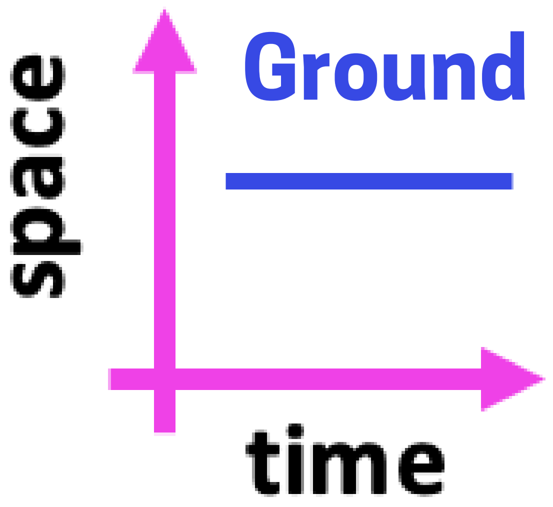
π pulse (mirror)





Single Photon Interferometry

Spacetime Diagram

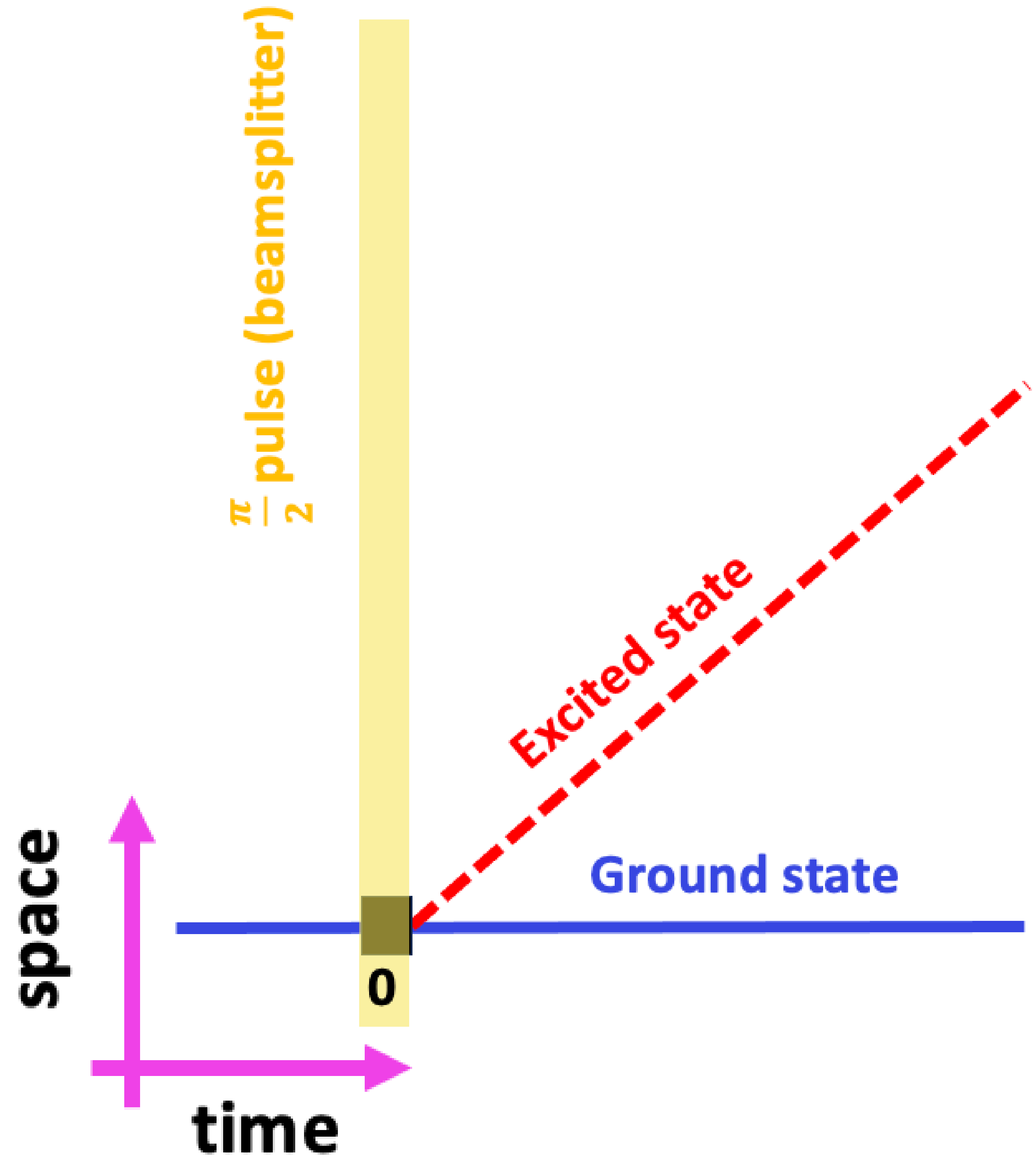


Quantum State

$$|g, \vec{p}\rangle$$

Single Photon Interferometry

Spacetime Diagram

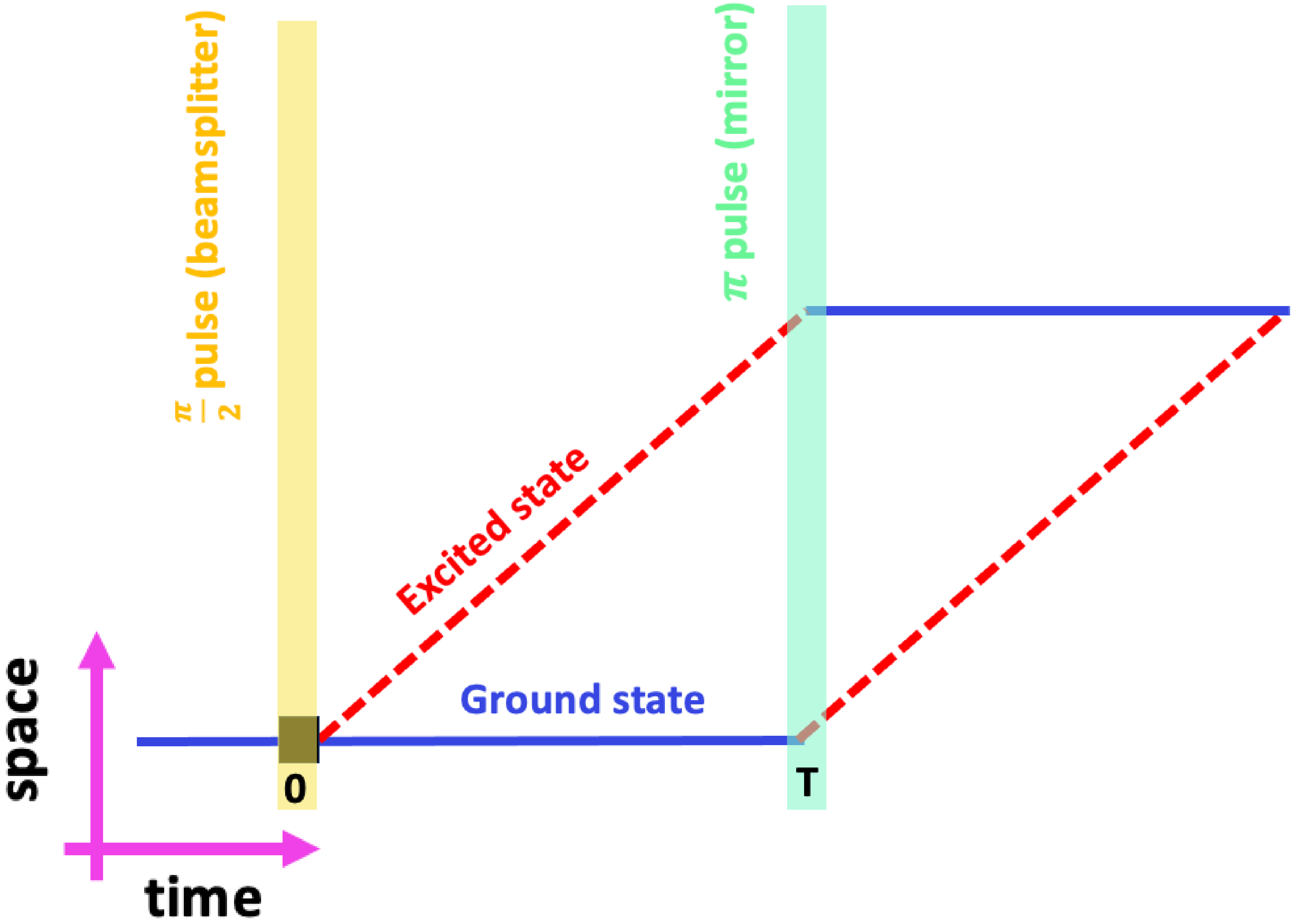


Quantum State

$$\frac{1}{\sqrt{2}}\left(|g,\vec{p}\rangle + e^{i\Delta\phi(t)}\,|e,\vec{p}+\vec{k}\rangle\right)$$

Single Photon Interferometry

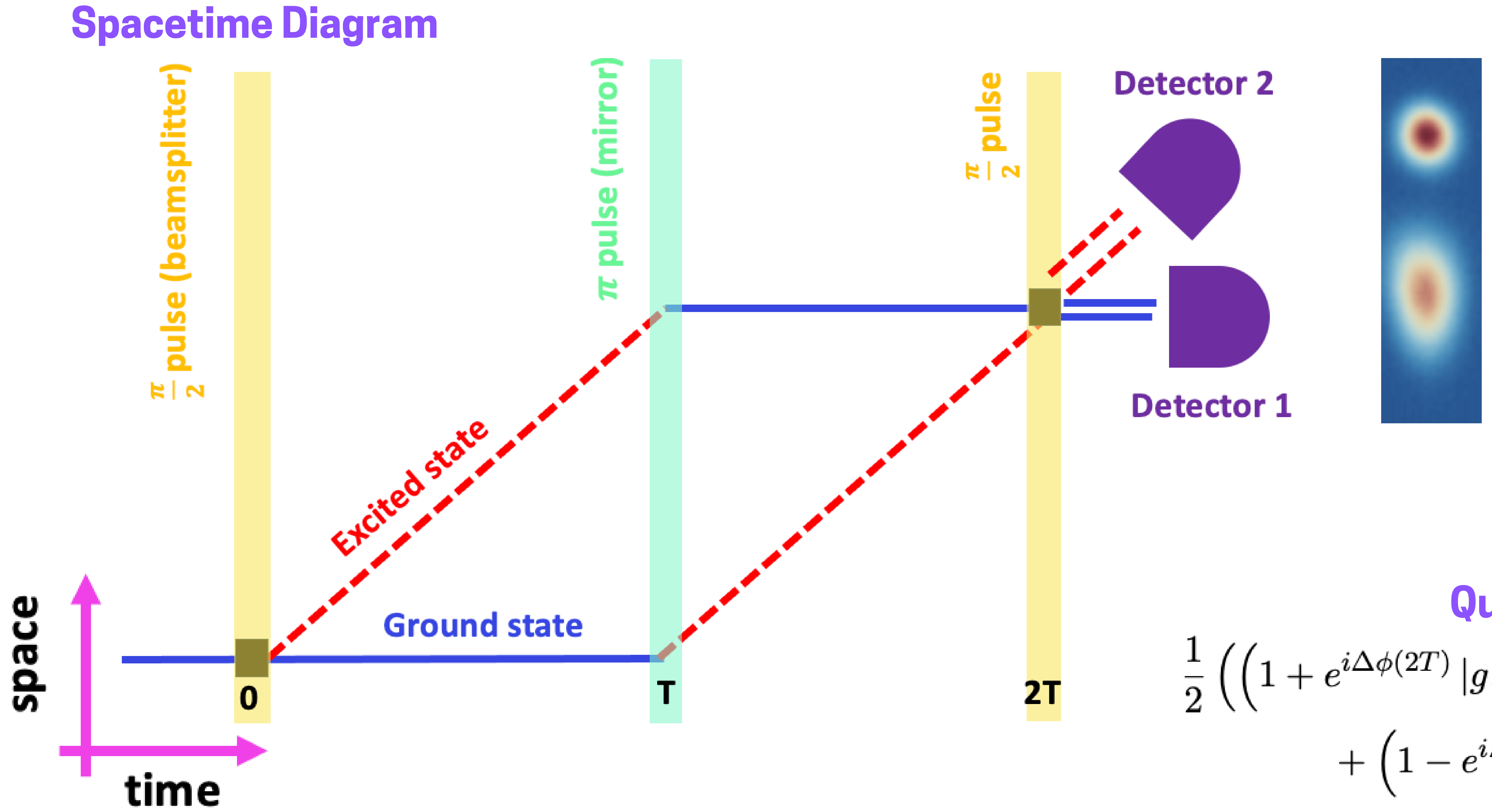
Spacetime Diagram



Quantum State

$$\frac{1}{\sqrt{2}}\left(|e,\vec{p}+\vec{k}\rangle + e^{i\Delta\phi(t)}\,|g,\vec{p}\rangle\right)$$

Single Photon Interferometry

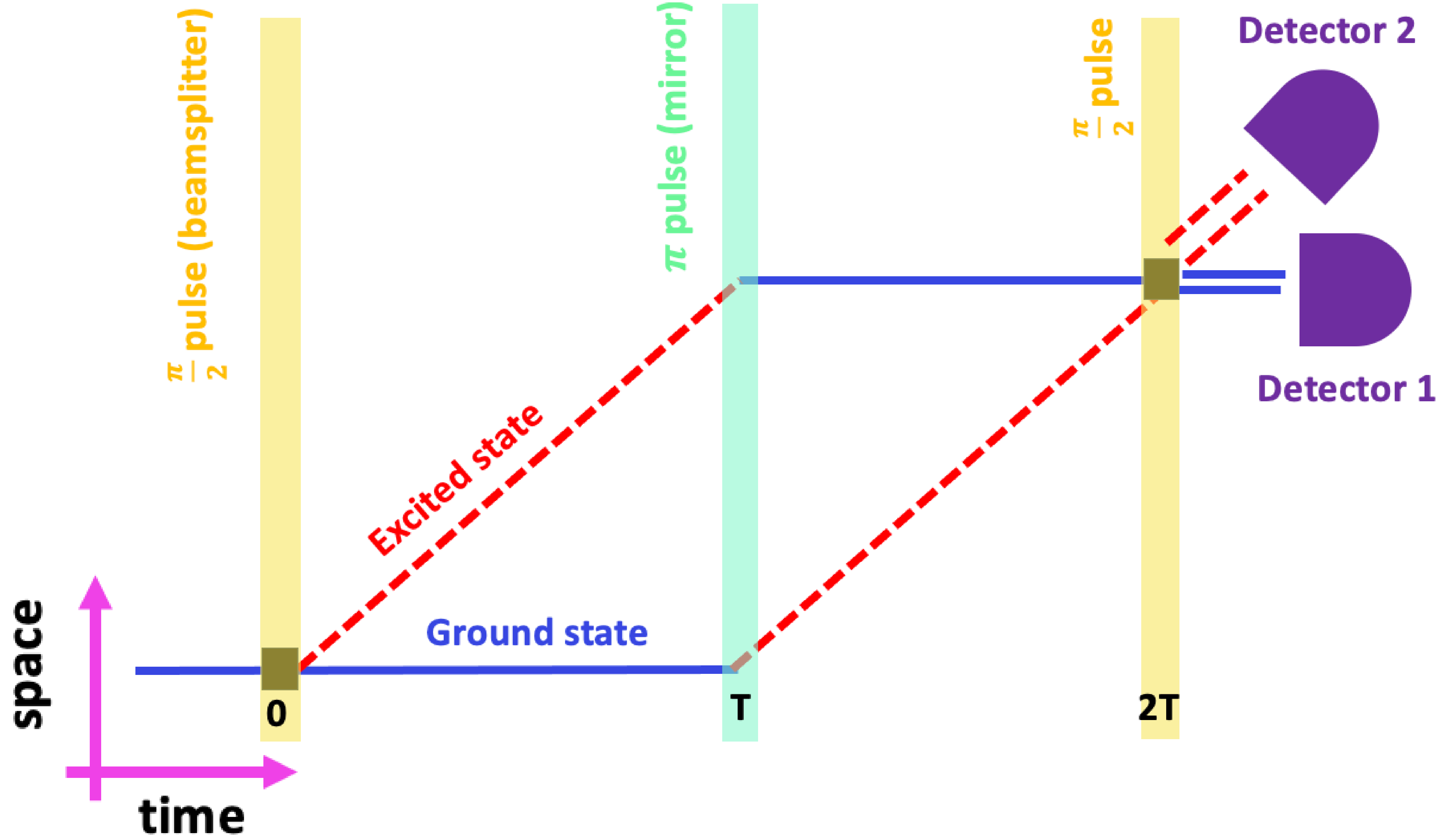


Quantum State

$$\frac{1}{2}\left(\left(1 + e^{i\Delta\phi(2T)}\,|g, \vec{p}\rangle\right) + \left(1 - e^{i\Delta\phi(2T)}\,|e, \vec{p} + \vec{k}\rangle\right)\right)$$

Single Photon Interferometry

Spacetime Diagram



Probabilities:

$$P_g = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

$$P_e = \sin^2\left(\frac{\Delta\phi}{2}\right)$$

$\Delta\phi(2T)$ = **phase difference** between the **two arms** at the end of the interferometer sequence

Arises due to differences in:

- **Evolution** of external or **internal d.o.f**
- Time spent in excited state

RECAP: Traditional ULDM searches with atom gradiometers

e.g. AION, MAGIS, VLBAI

- Operate in **gradiometer** configuration
- Apply **Large-Momentum Transfer** techniques

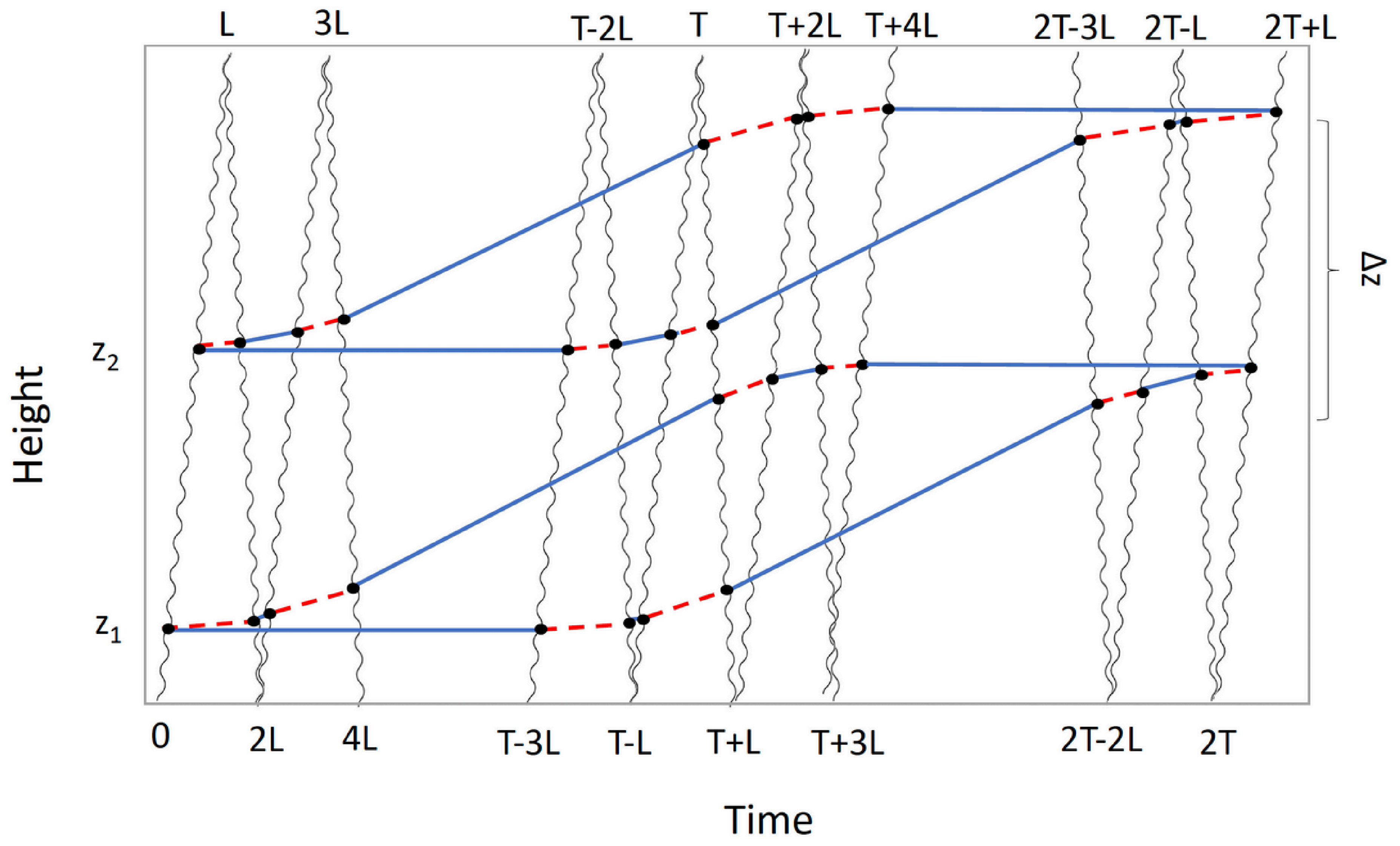


Fig. 1: Single photon atom interferometer with n = 4 LMT

Sensitivity depends on:

Baseline - L
Interrogation time - T
Number of LMT kicks - n
Shot-noise (atomic flux)

To reach sensitivity to ULDM require:

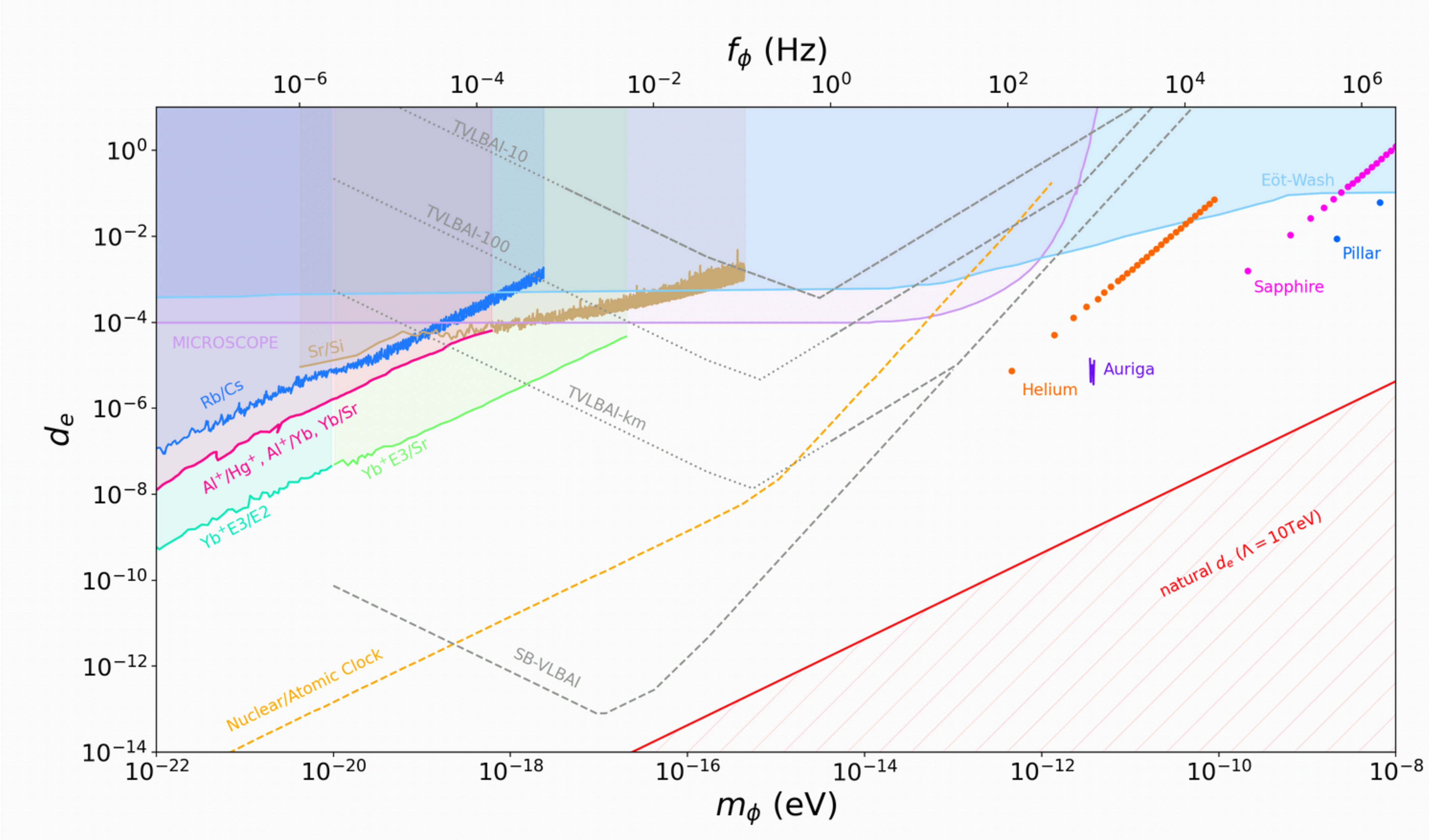
- Long $\mathcal{O}(\text{km})$ baselines
- High LMT atom optics $n \sim \mathcal{O}(1000)$

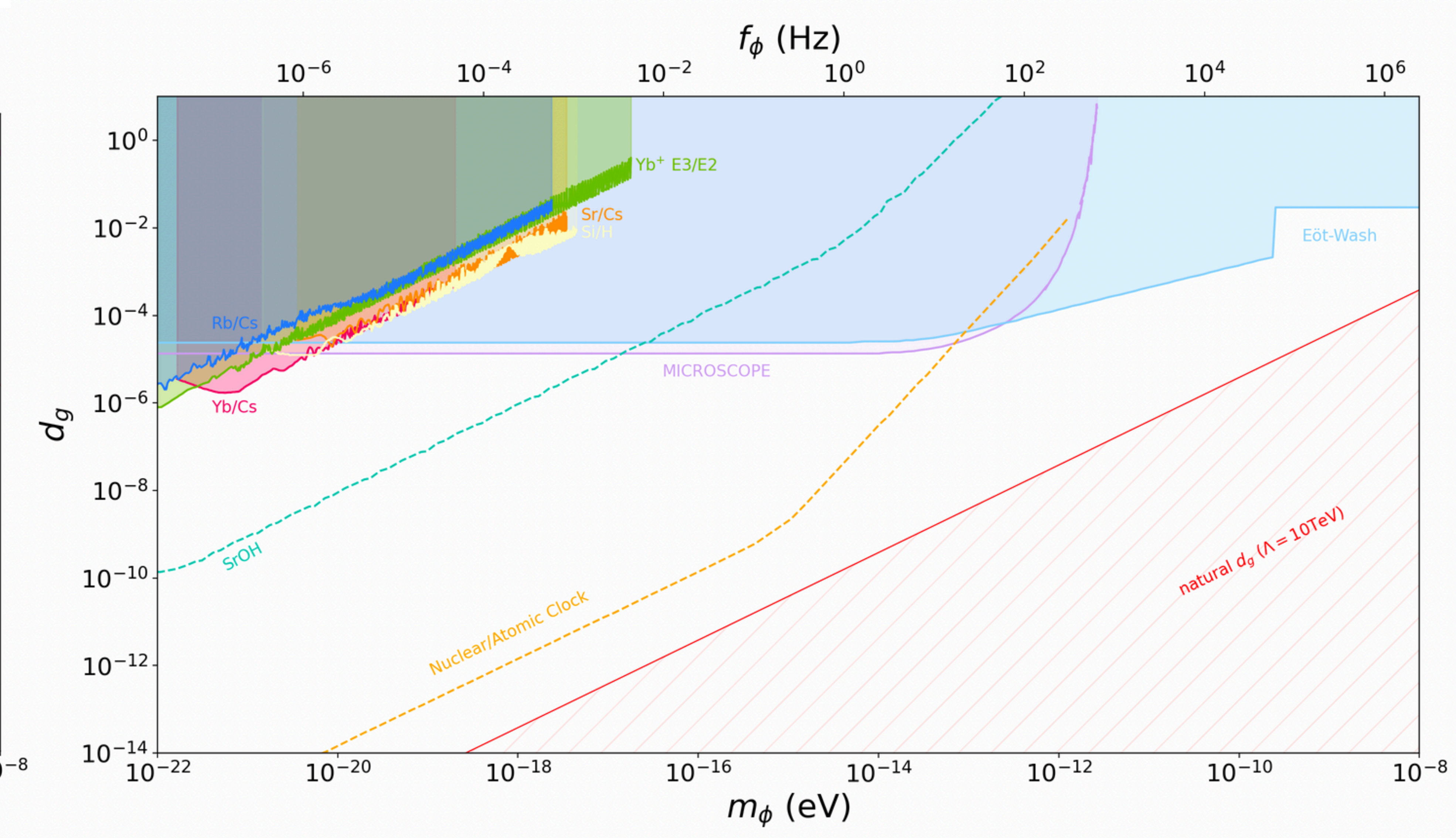
To support this require **ultra-narrow** \`clock' **transitions**

e.g.  clock transition

Gives sensitivity to d_e, d_{m_e}

The current state of play





Could we **combine the nuclear clock** with the **principles of interferometry** to access new parameter space?

1 ATOMS

Excited state lifetime 10 μs

→ **Loss of atoms** due to **spontaneous decay** during propagation:

$$nL \leq 1500 \text{ m}$$

→ Low π pulse efficiencies:

$$n = 2$$

Ionisation potential > nuclear excitation energy

→ Need techniques to suppress ionisation

✓ Neutral - can simultaneously interrogate clouds of $\sim 10^8 - 10^{10}$ atoms

2 IONS

Charged - limited to a **single ion** per shot

→ **High shot noise**

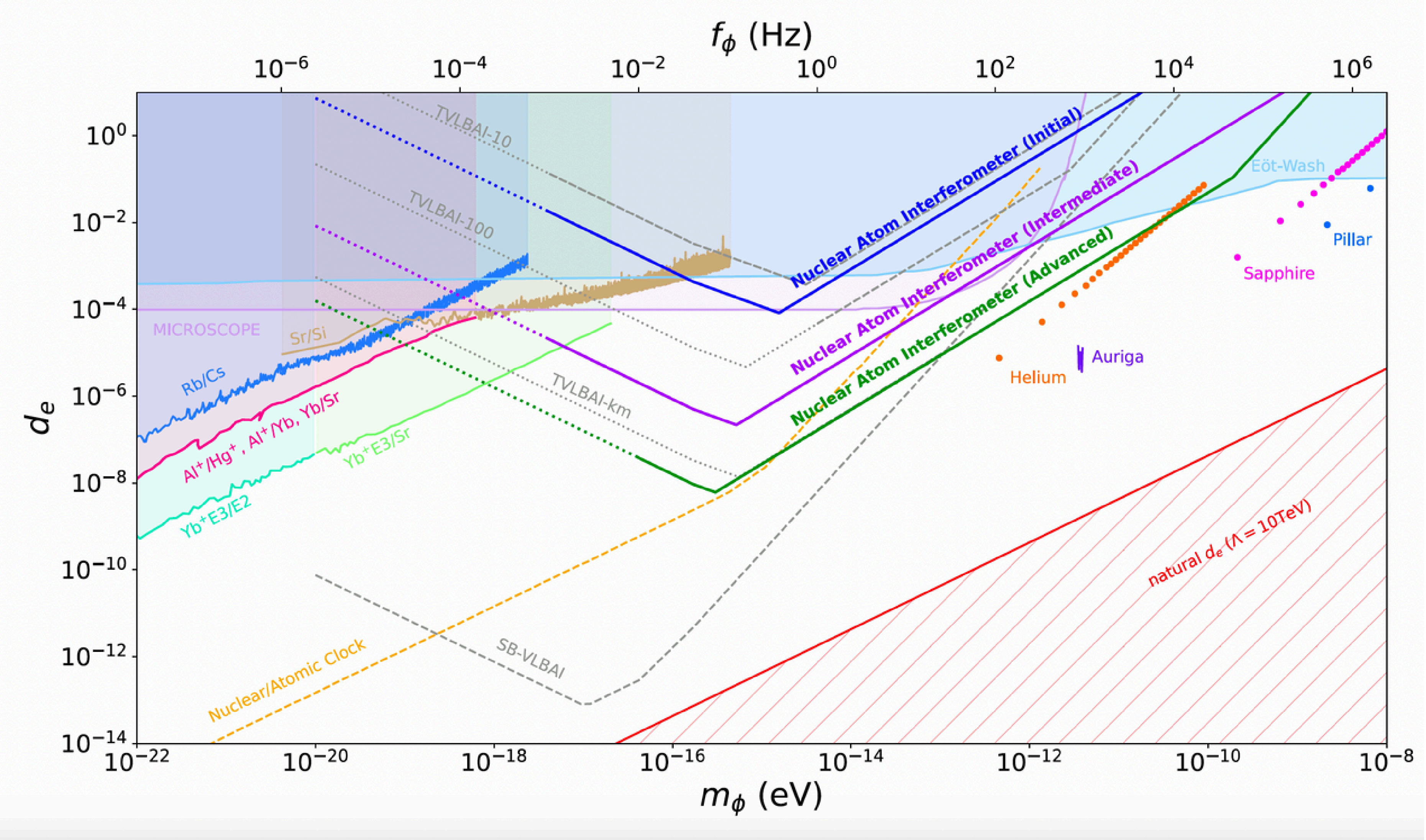
Fluctuations of external **magnetic fields** can induce spurious accelerations and therefore phase noise

✓ **Ultra-narrow transition** supports long baselines and high LMT orders

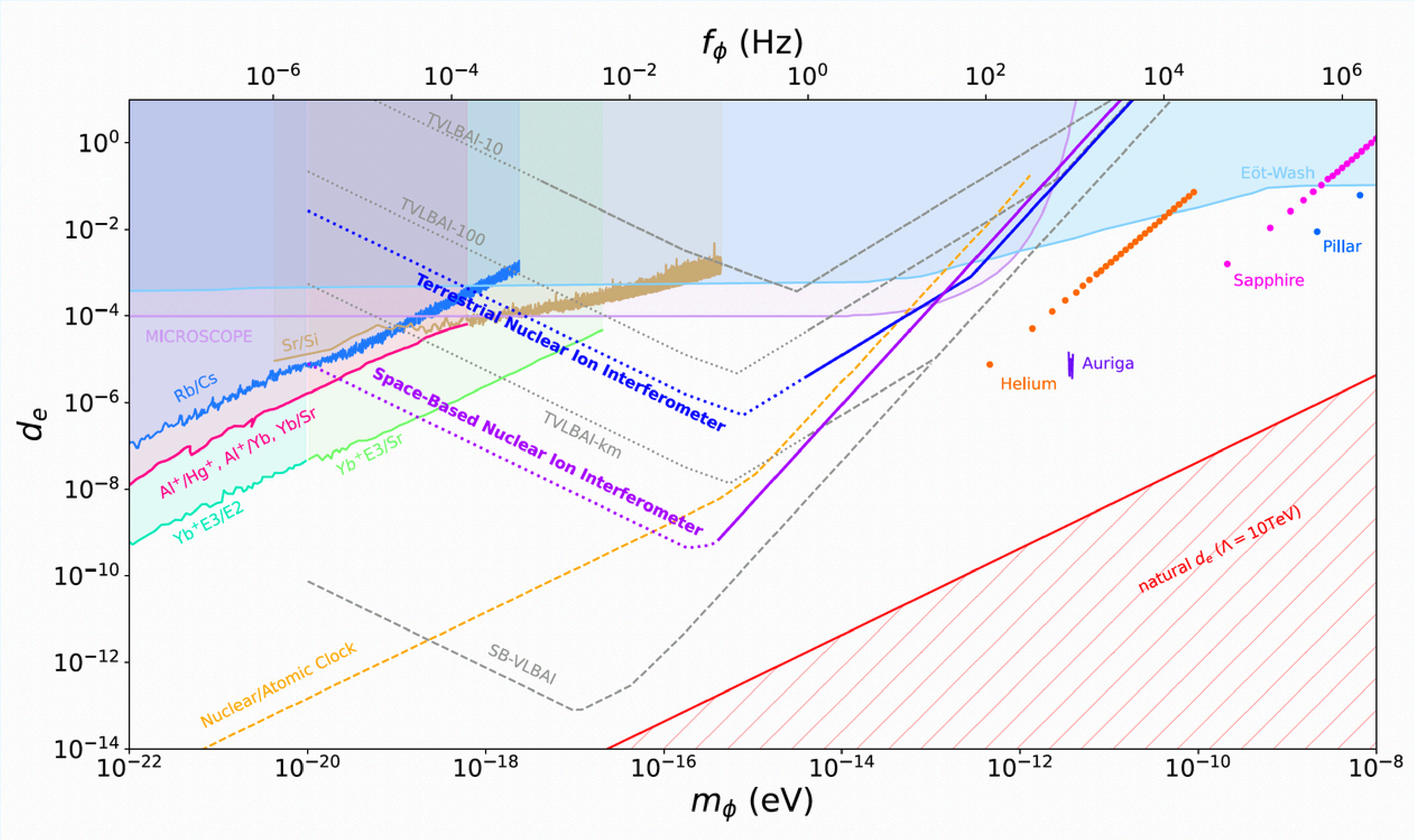
→ Potential to operate in space

Coupling to Photons

Atoms

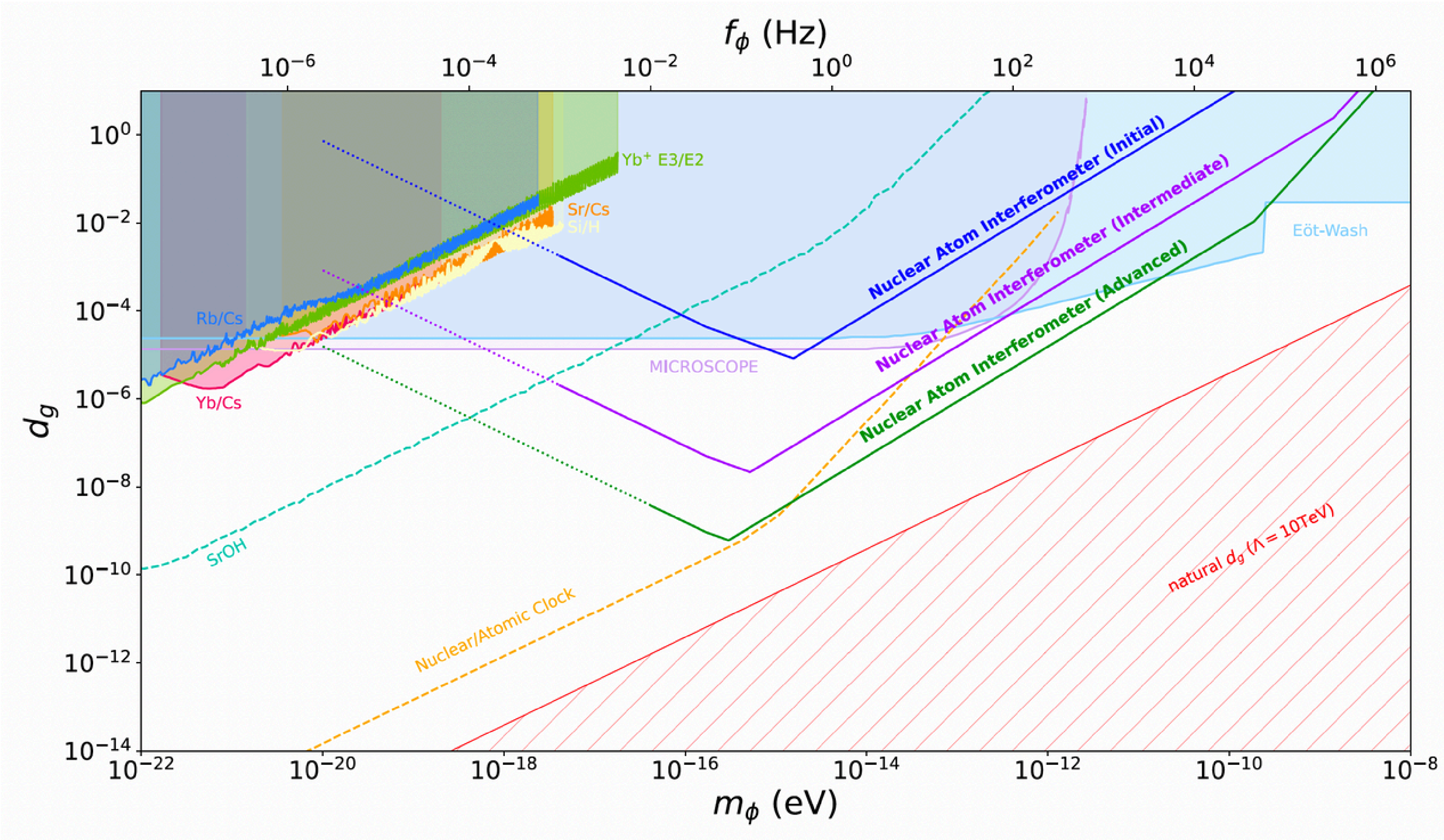


Single Ion

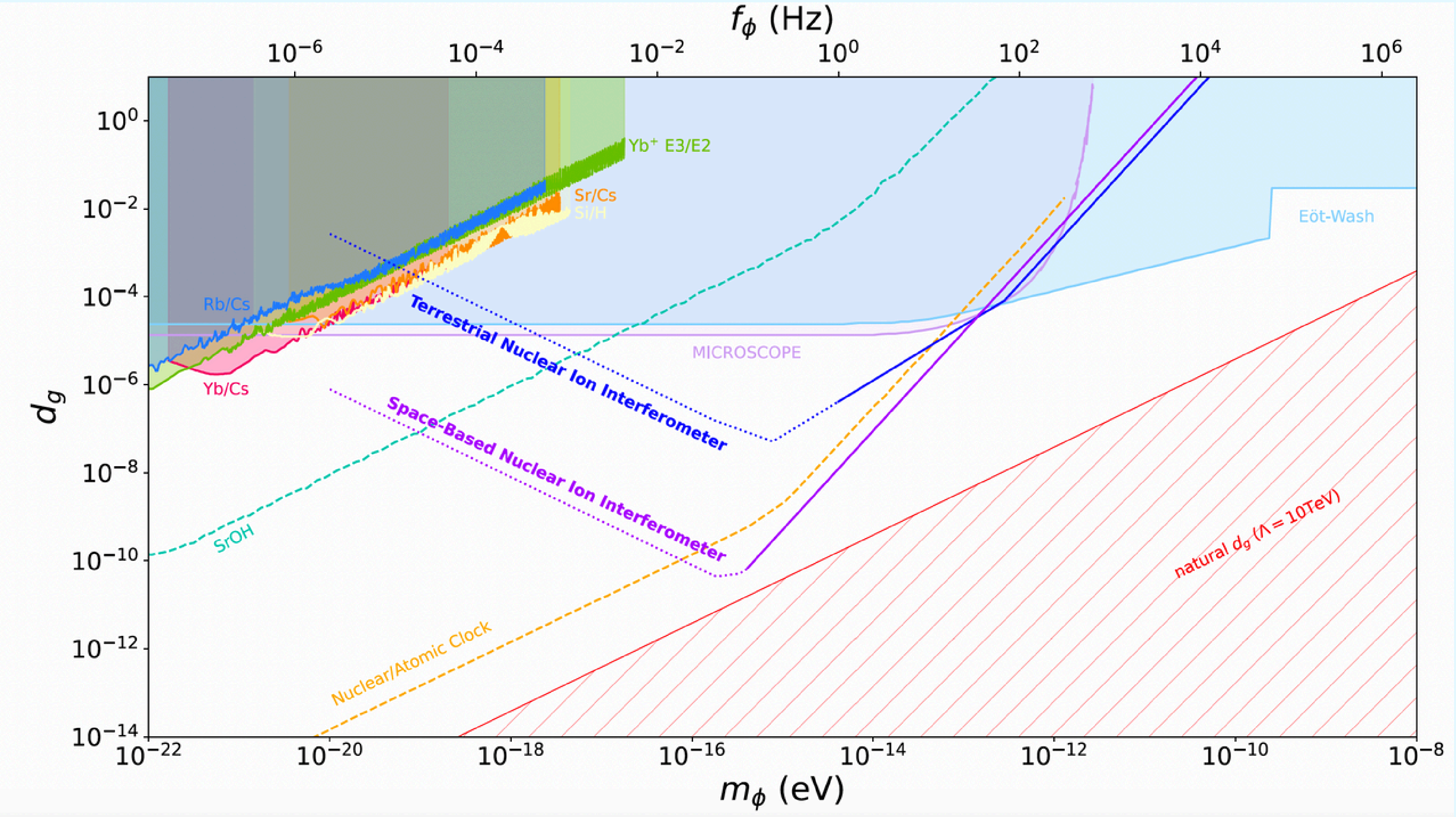


Coupling to Gluons

Atoms



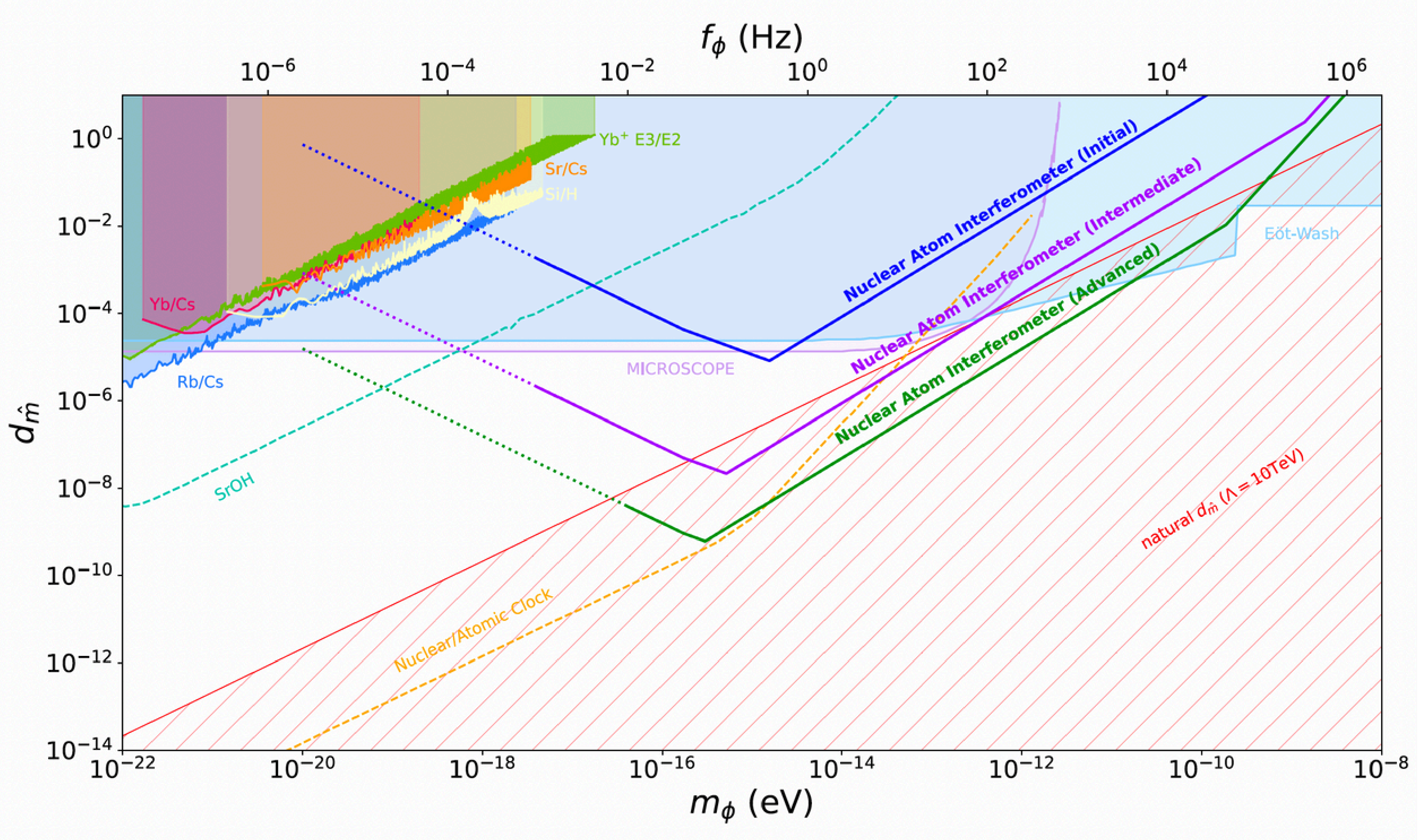
Single Ion

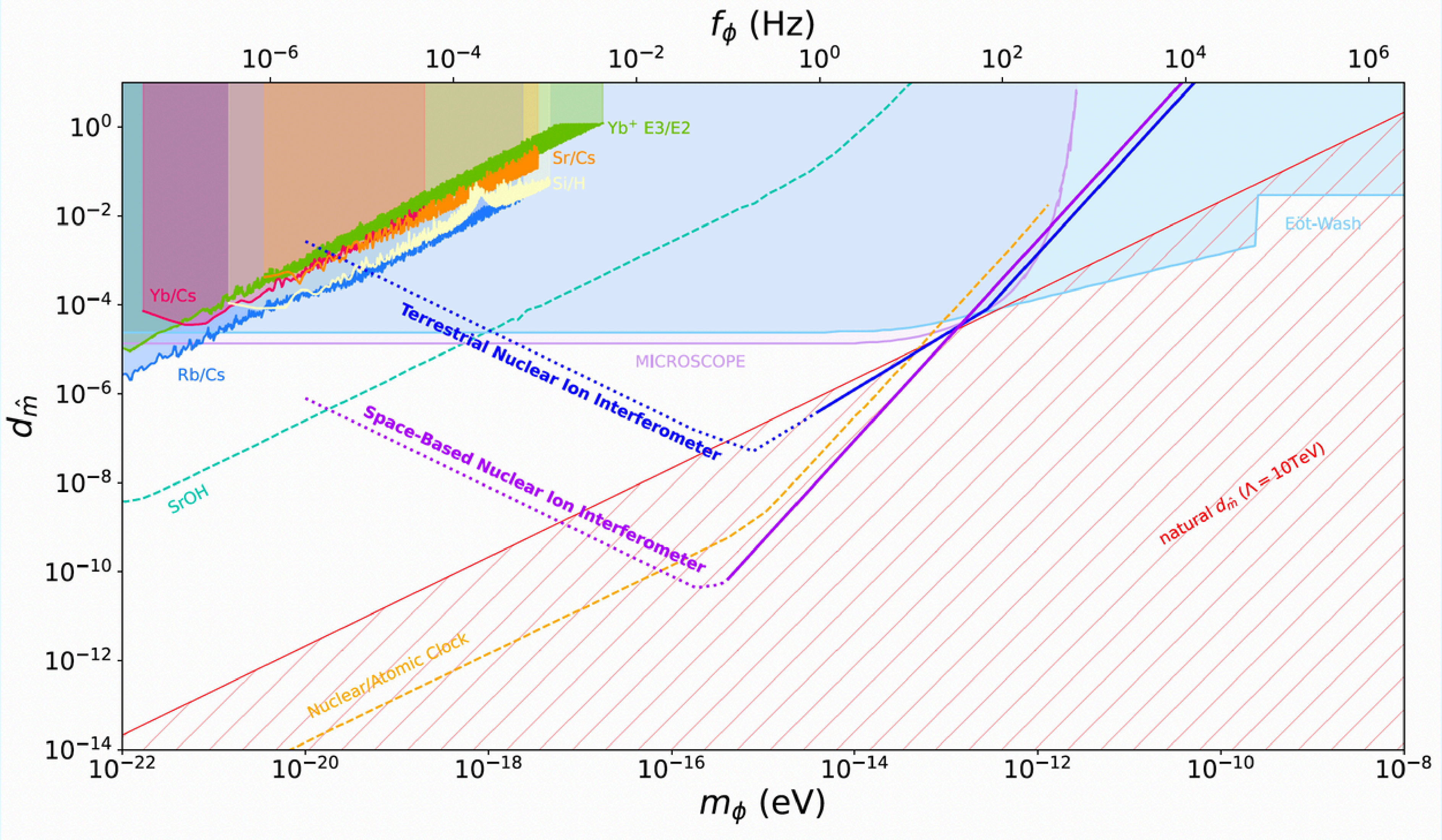


Coupling to Quarks

Atoms

Single Ion





Summary

- Nuclear Interferometry could offer **access to new ULDM parameter space** (provided experimental challenges can be overcome)

- **Unique window to new physics coupling to quarks or gluons** (including axions) with a reach enhancing existing and proposed experiments

  - Motivates a **closer study of the potential of Th-229** to probe fundamental physics in interferometry and beyond

Atom-based configurations

Setup	L [m]	T [s]	n	$\sqrt{\tilde{S}_n}$ [Hz$^{-1/2}$]	Δz [m]
Initial	10	0.6	2	10^{-4}	8.2
Intermediate	100	1.8	2	10^{-5}	84
Advanced	750	3.1	2	0.3×10^{-5}	702

Single-ion configurations

Setup	L [m]	T [s]	n	$\sqrt{S_n}$ [Hz$^{-1/2}$]	Δz [m]
Terrestrial	1000	1.2	2500	2.3	965
Space-based (A)	4.4×10^7	5	16	4.7	4.4×10^7
Space-based (B)	4.4×10^7	70	120	17.6	4.4×10^7