Echoes from ECOs:

Hunting for **Exotic Compact Objects** (ECOs) with Gravitational Waves at **Atom Interferometers**

Hannah Banks

Based on **arXiv:2302.07887** with Matthew McCullough & Dorota Grabowska

The Low Down...

1. **Landscape** of **viable Dark Matter candidates is extremely vast** and there is **motivation to explore it as thoroughly as possible**

2. **Quantum Sensors** offer **many exciting opportunities** in this direction

3. **Long baseline atom interferometers** will open the window to **mid-band gravitational waves** of frequency ~ 0.1 - 10 Hz and offer a **unique way to probe complexity** in the dark sector through the mergers of exotic compact objects

Motivation

- **Abundance** of ('gravitational') evidence for **Dark Matter**

- **No evidence for non-gravitational interactions** seen in experiment yet....

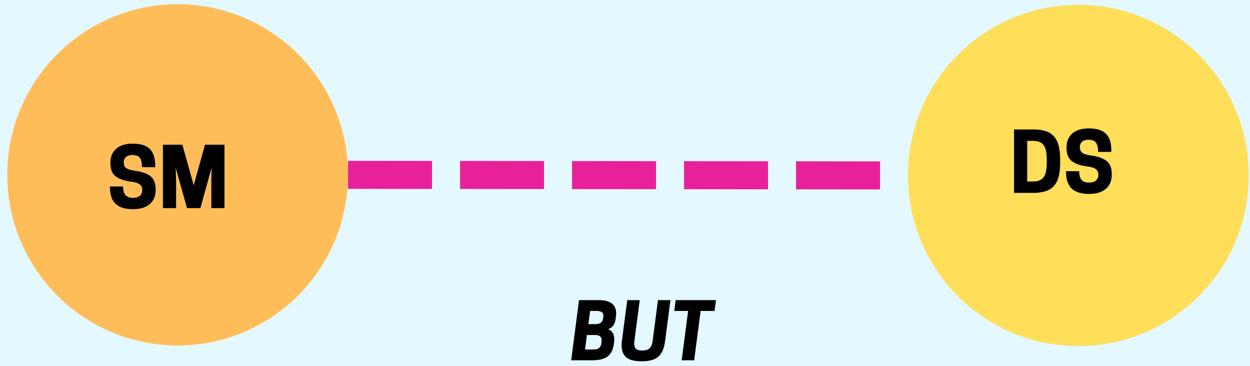
Are we looking in the right places?

- Standard Model is **incredibly complex**

- Likely that **dark matter** is part of an extended **dark sector** comprising of a suite of new states and /or `dark' forces over a **range of scales**

DARK SECTOR POSSIBILITIES:

1 *May* be weakly coupled to the SM via some portal interaction

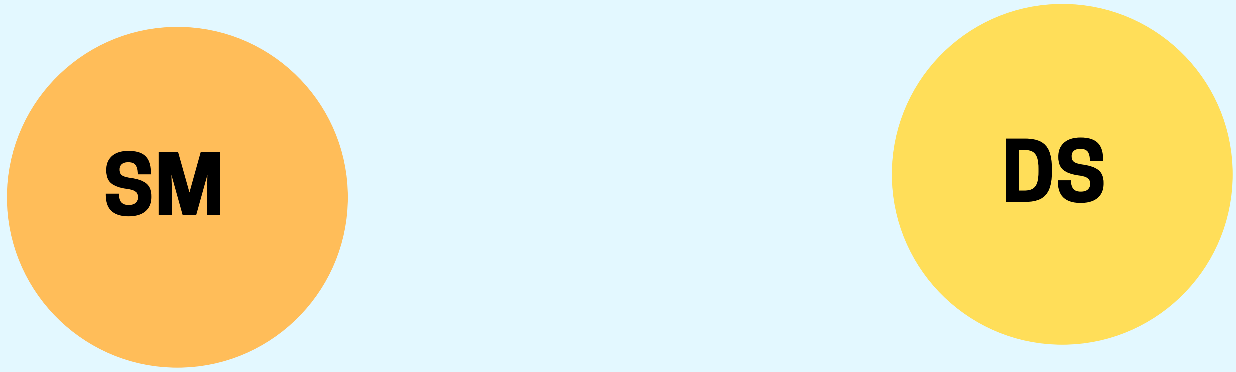


BUT

it may not be '*the DM*' which reveals itself first in experiment ....

Might subdominant states hold the key ?

2 *Or* perhaps the only coupling is gravitational...



Gravitational Waves to the rescue!

Gravitational Wave Astronomy gives us **unique eyes** to the **dark sector**

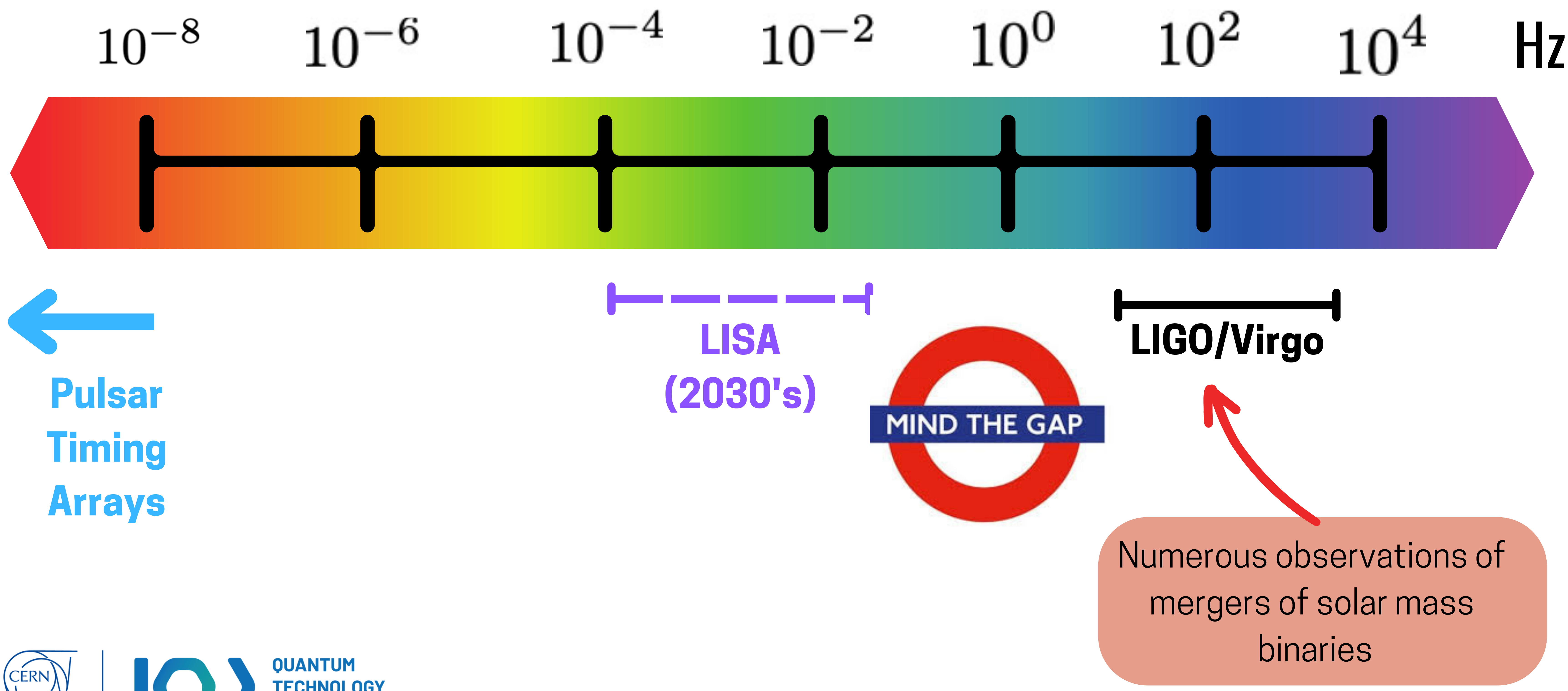
GW crash course

- **Prediction** of Einstein's theory of **General Relativity**
- Correspond to **propagating curvature perturbations**
- Sourced by **mass distributions** with **time varying quadrupole moment**

Possible Sources

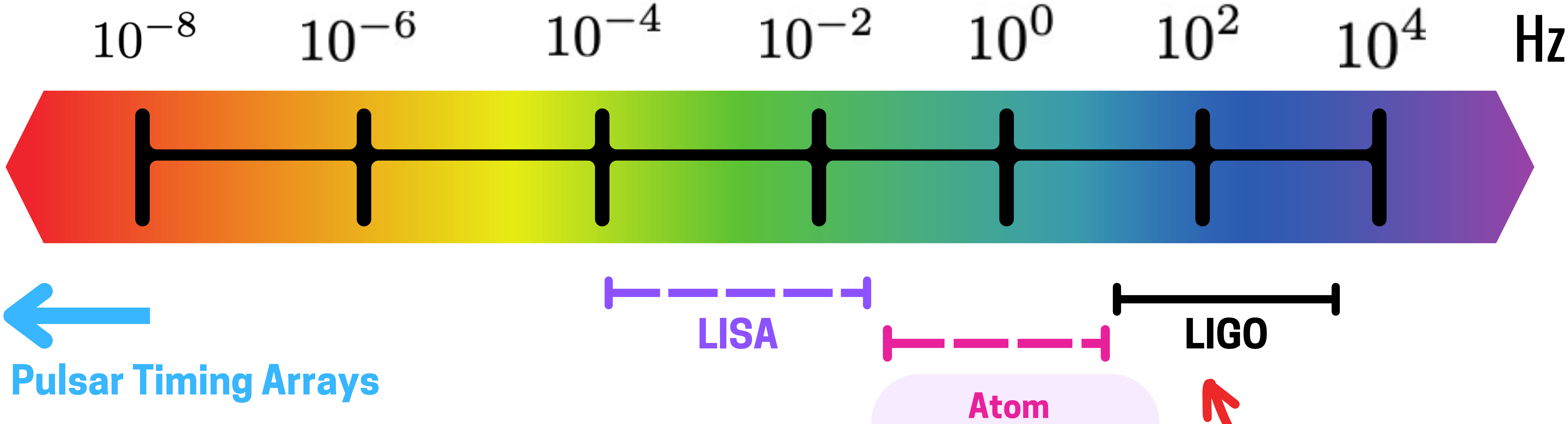
- Inspiraling Binary Systems
- First order **cosmological phase transitions** / cosmic strings
- Black hole superradiance

The GW Landscape



CERN | QUANTUM TECHNOLOGY INITIATIVE

The GW Landscape



- Complimentary to other GW observatories
- Unique access to mid-band frequencies
- New sources of GW?

Numerous observations of mergers of solar mass binaries

CERN | QUANTUM TECHNOLOGY INITIATIVE

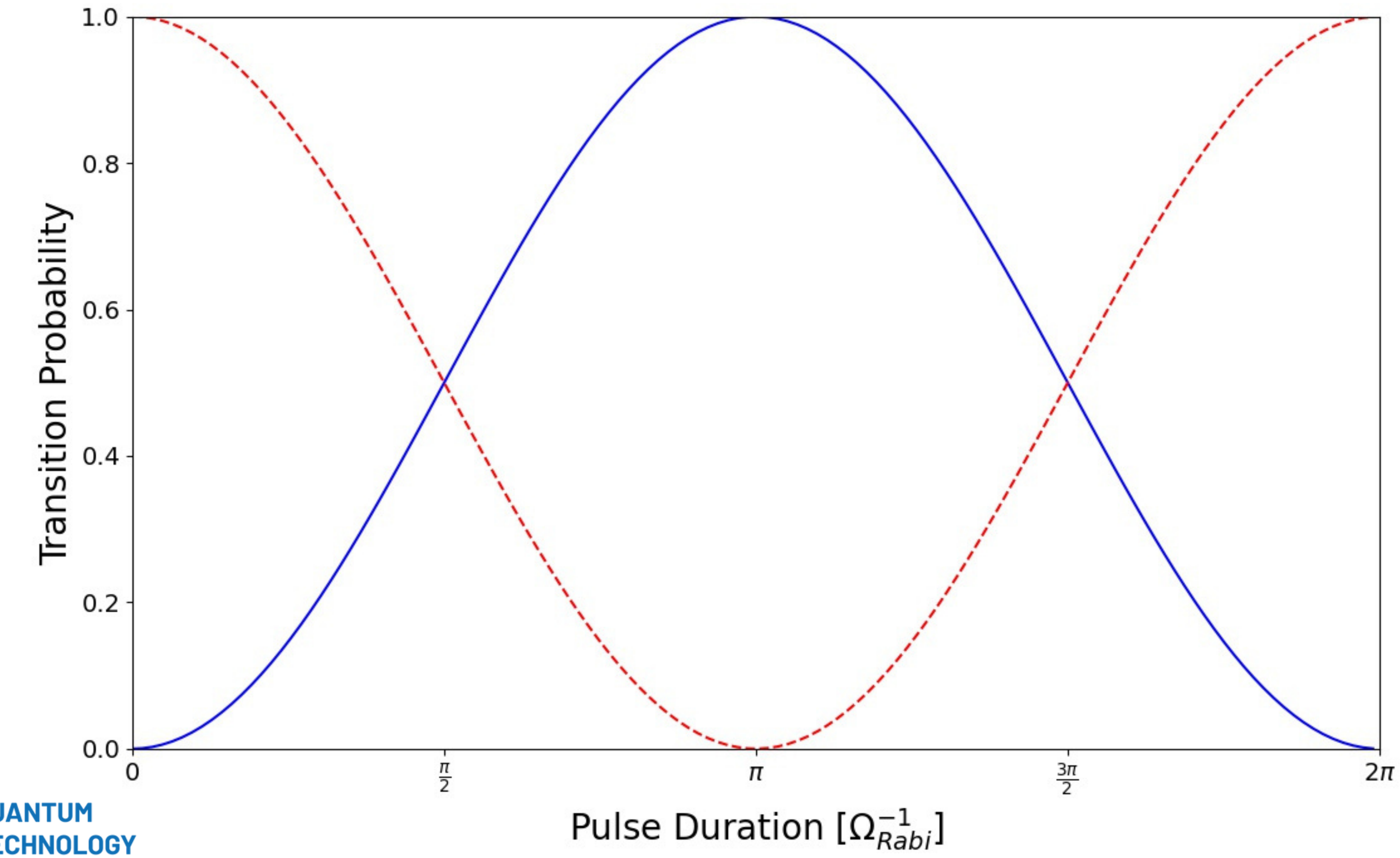
A brief (theorists) guide to....

Atom Interferometers

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

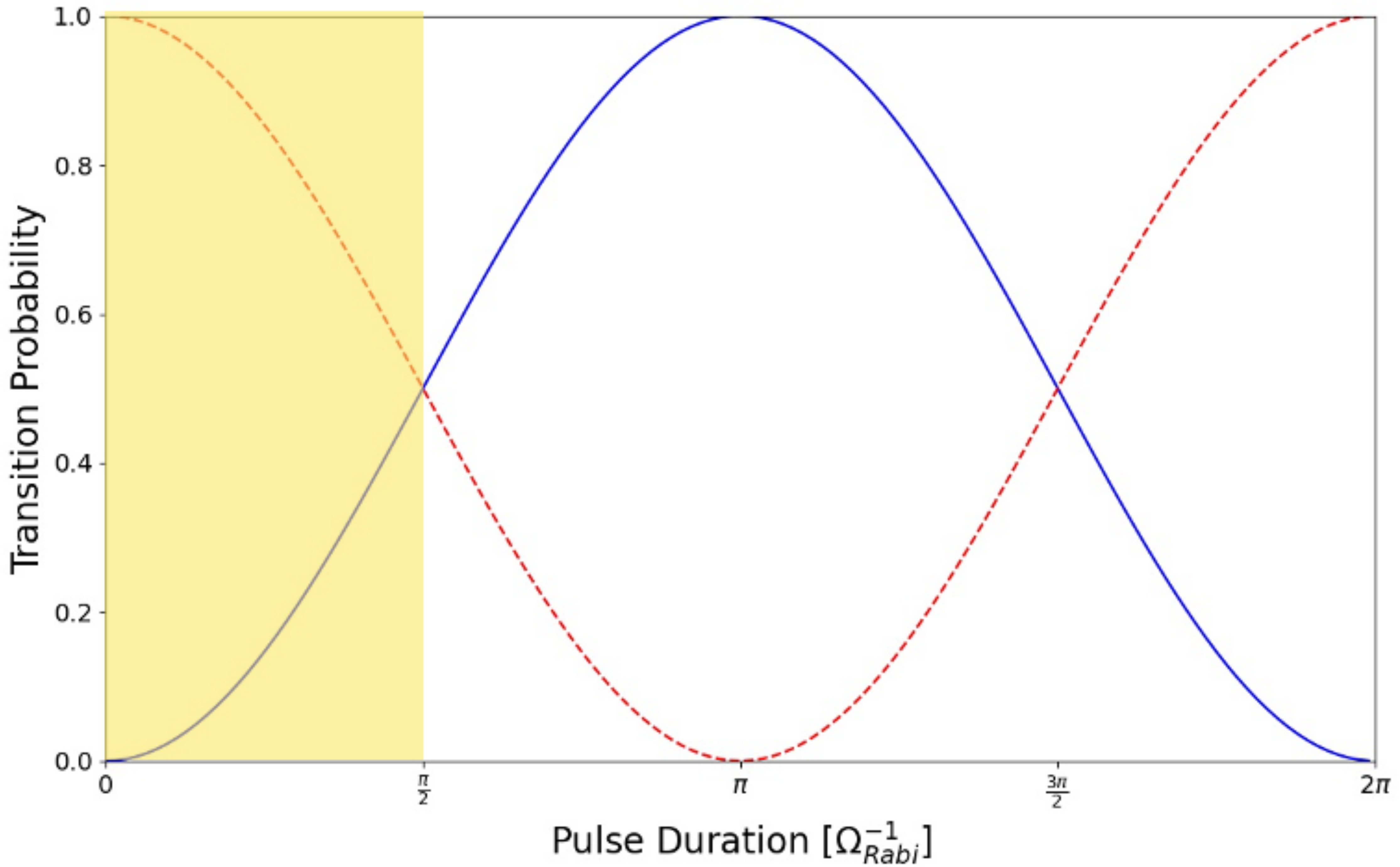
Manipulating atoms with light

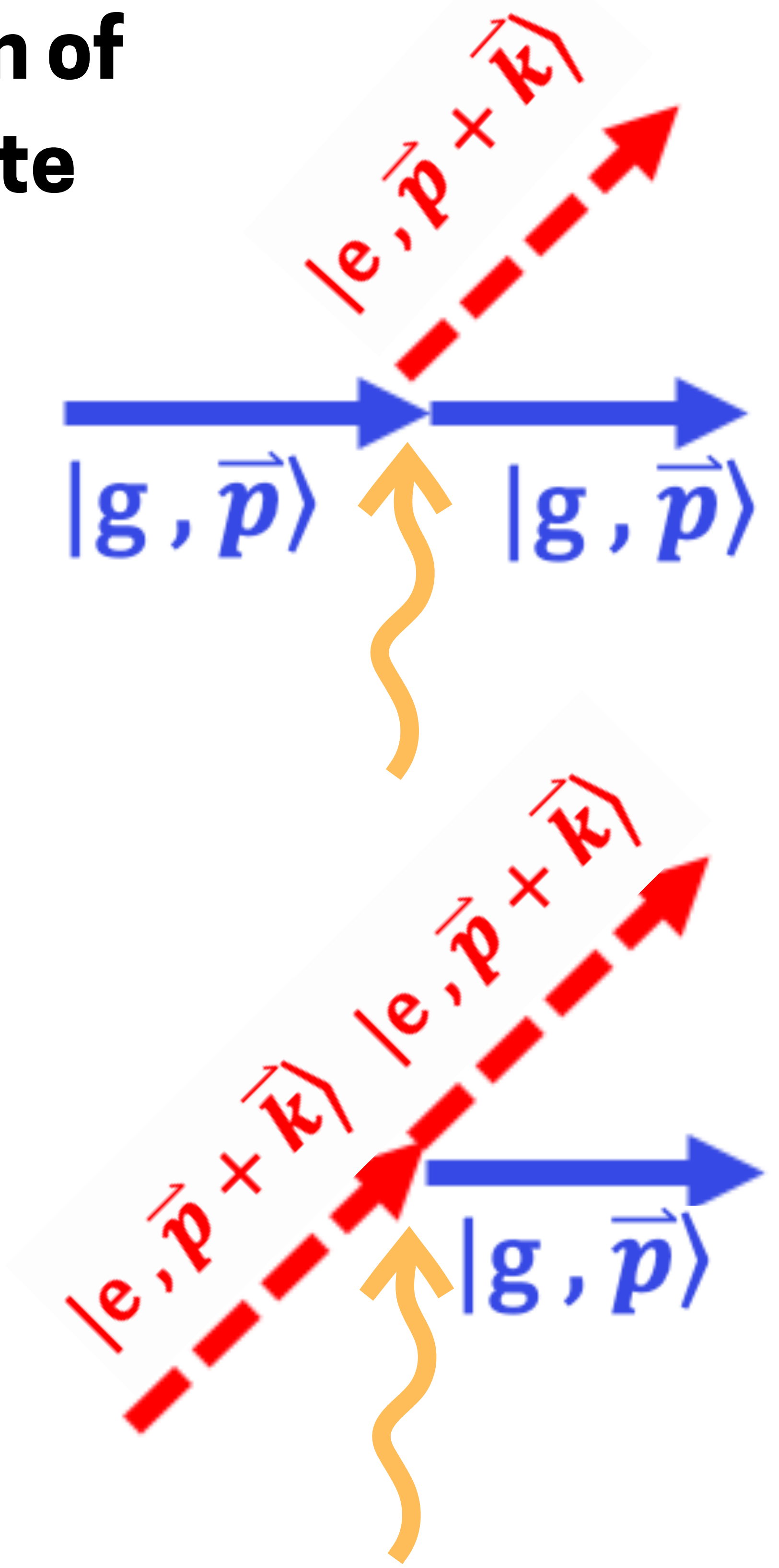
A **two level system** (i.e an atomic clock) coupled to a **driving force** (i.e. a laser) undergoes **Rabi Oscillations** between the ground $|\mathbf{g}, \vec{p}\rangle$ and excited $|\mathbf{e}, \vec{p} + \vec{k}\rangle$ states



Manipulating atoms with light

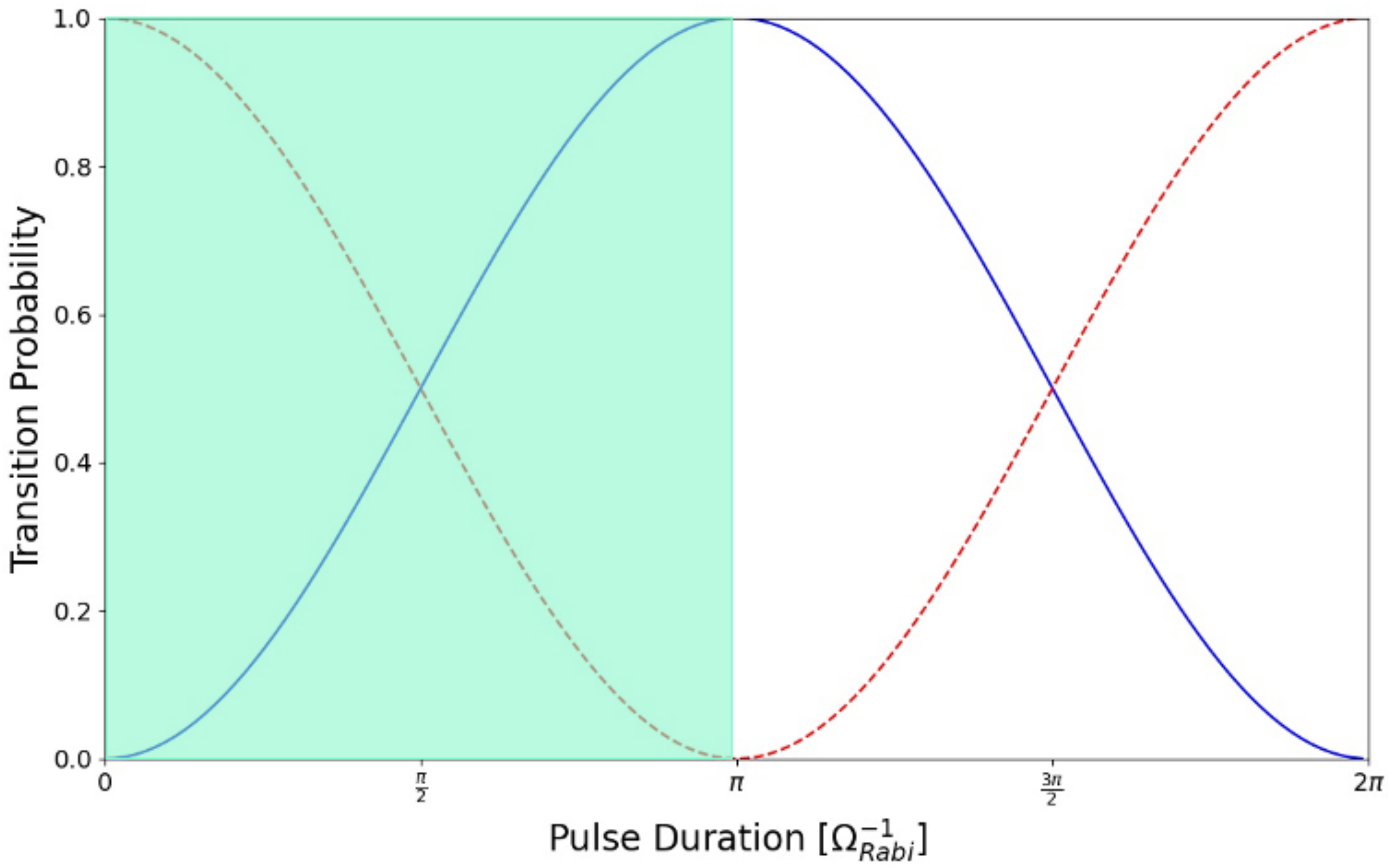
$\frac{\pi}{2}$ pulse (beamsplitter) → Coherent superposition of ground + excited state

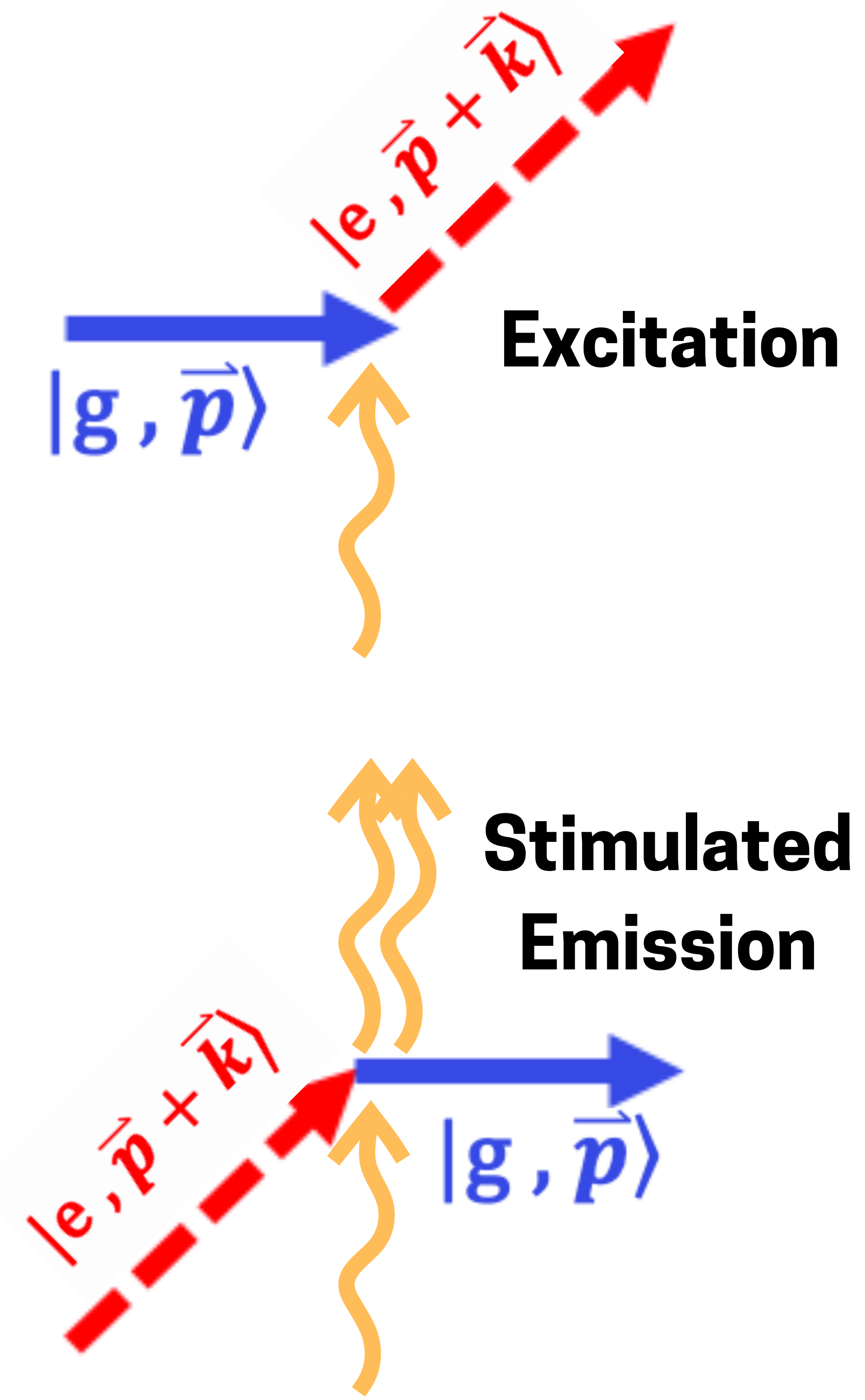




Manipulating atoms with light

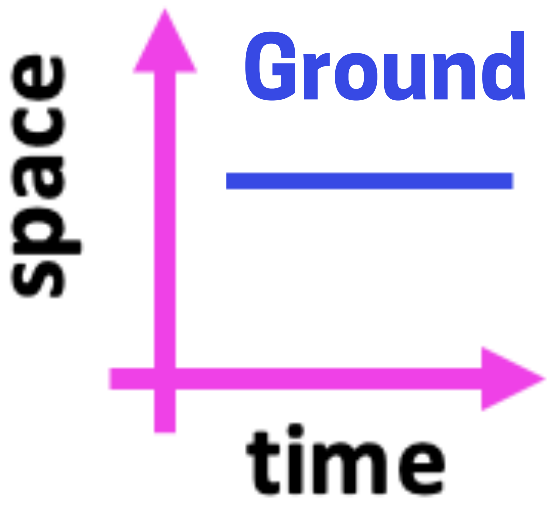
π pulse (mirror)





Single Photon Interferometry

Spacetime Diagram

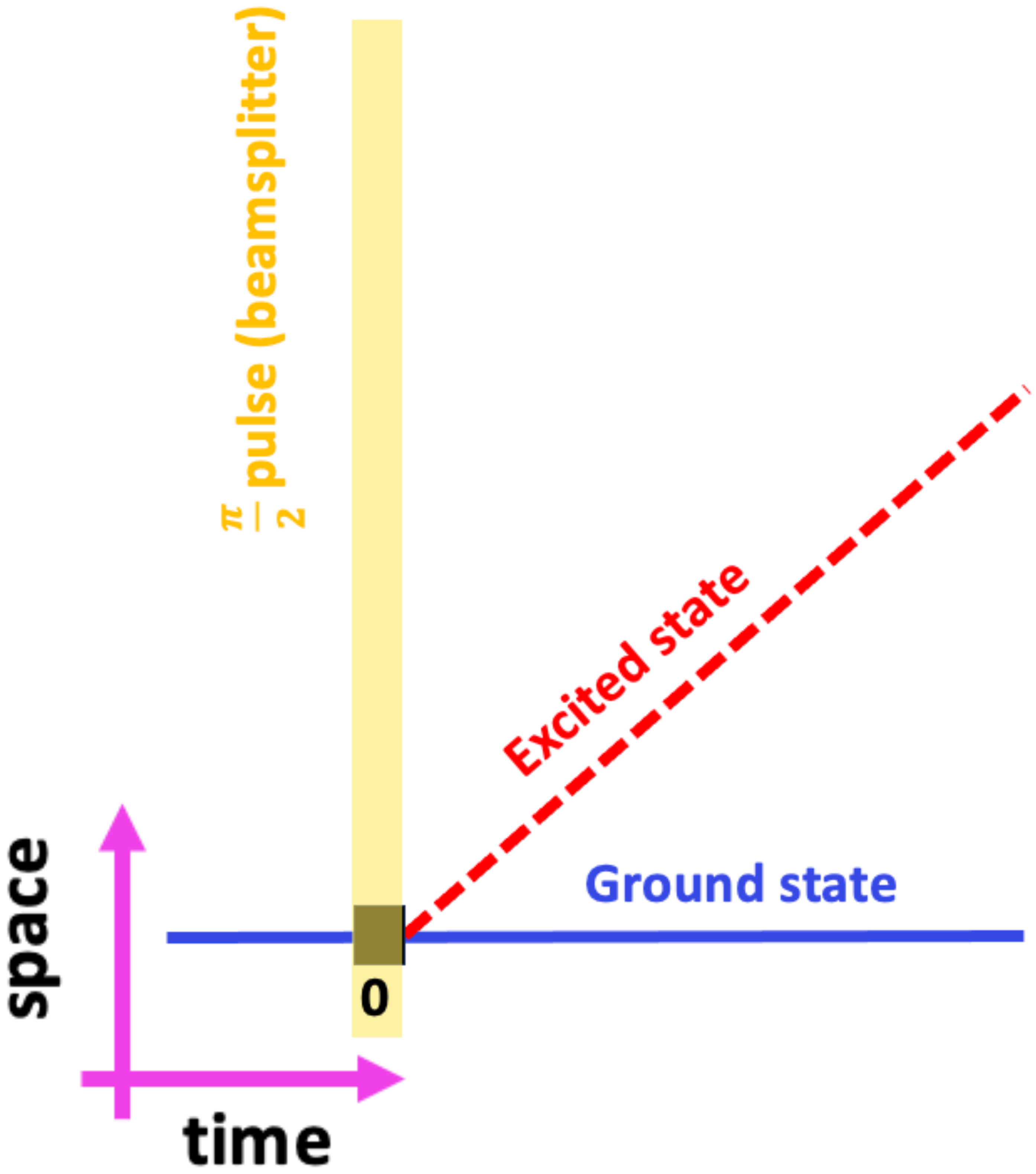


Quantum State

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

Single Photon Interferometry

Spacetime Diagram

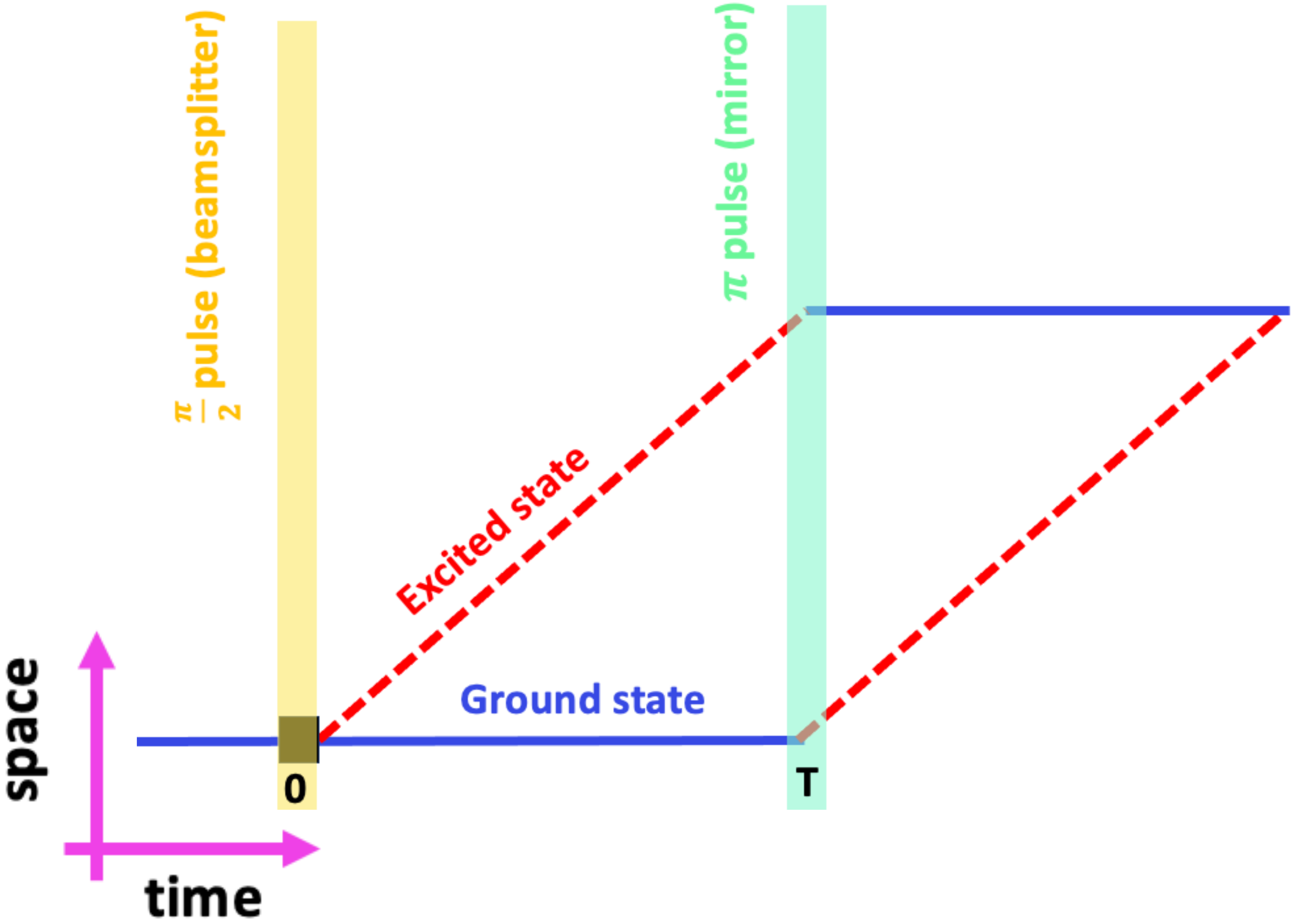


Quantum State

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

Single Photon Interferometry

Spacetime Diagram

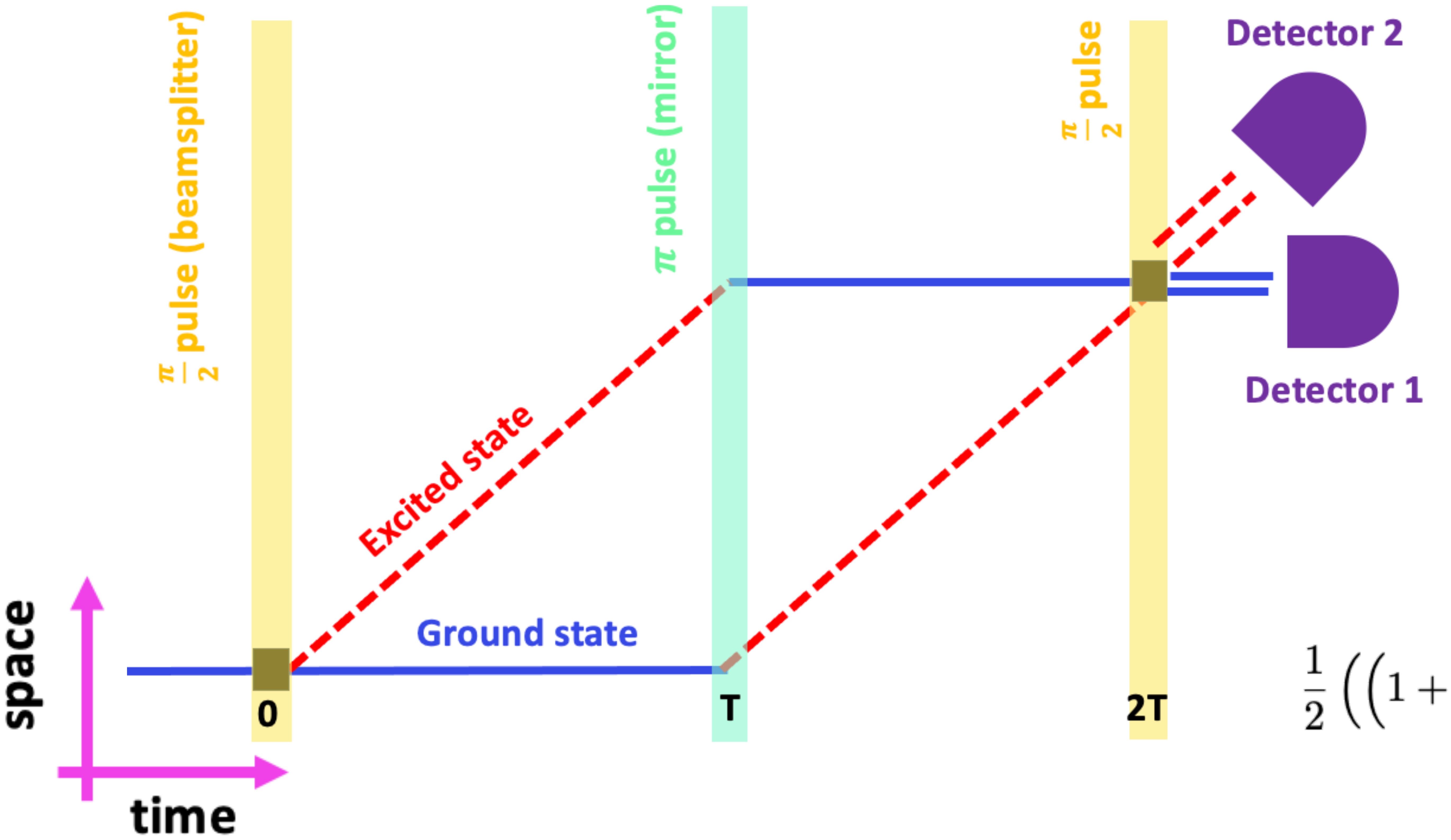


Quantum State

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

Single Photon Interferometry

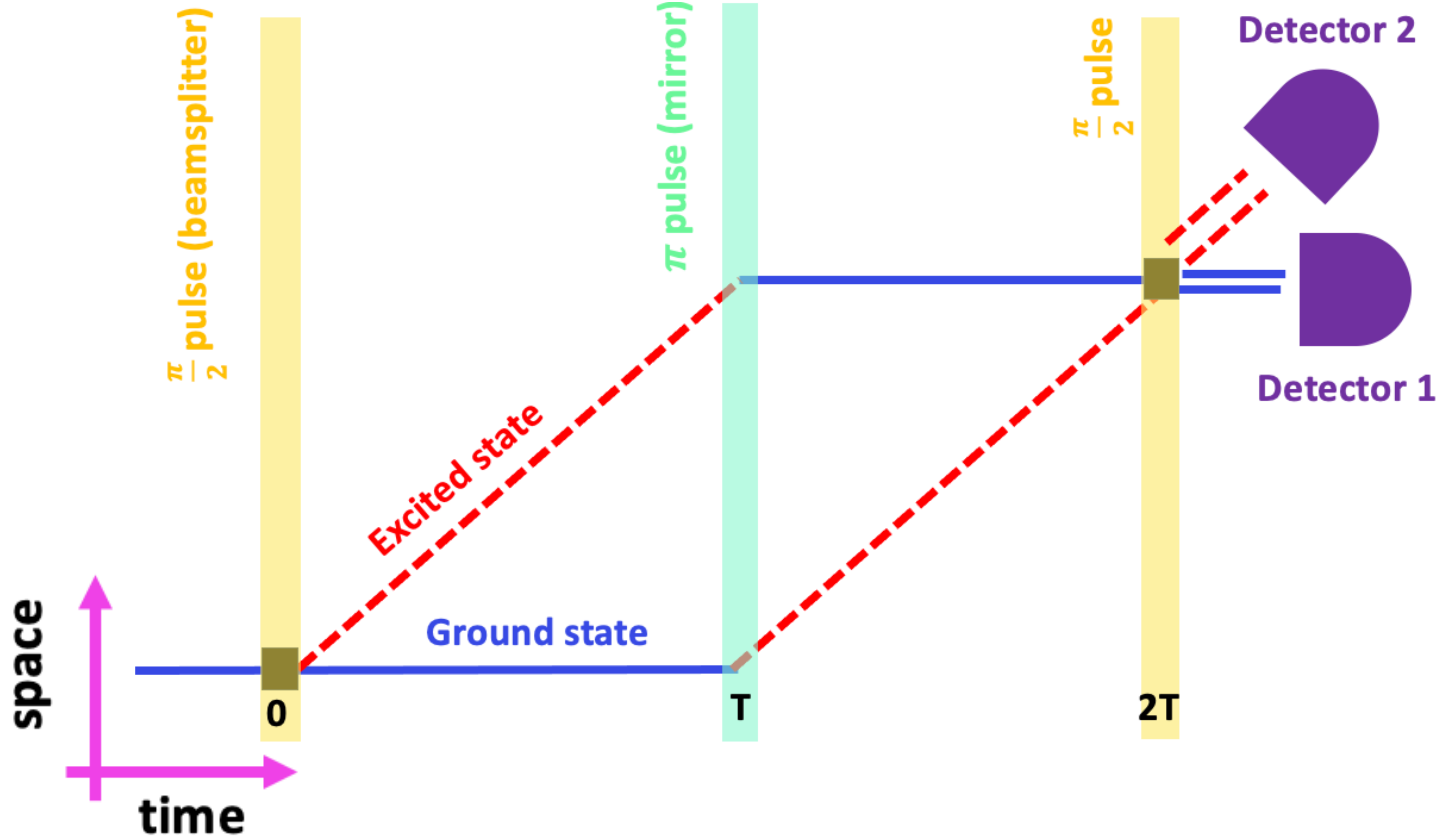
Spacetime Diagram



Quantum State

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

Single Photon Interferometry



Probabilities:

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

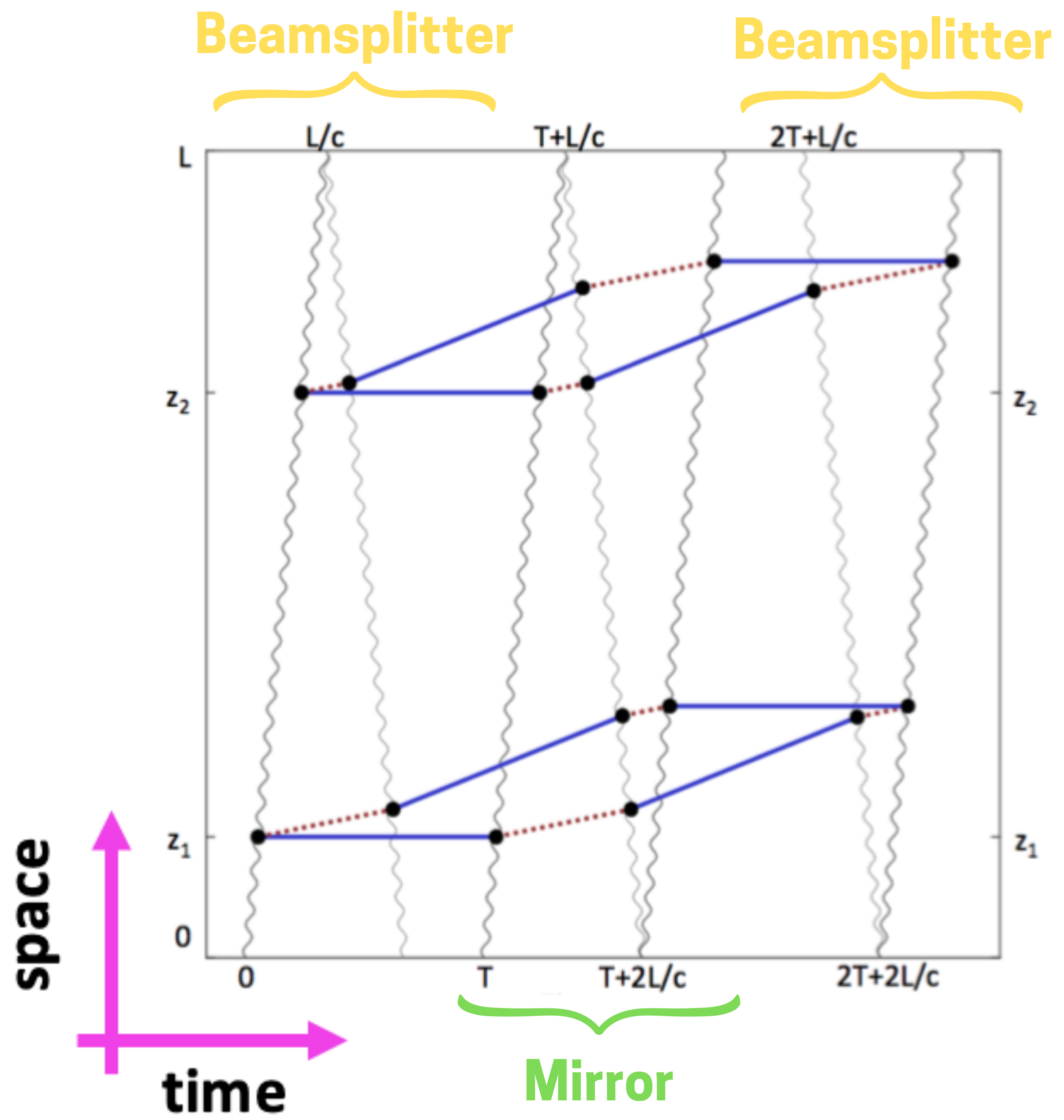
$$P_e = \sin^2\left(\frac{\Delta\phi}{2}\right)$$

$\Delta\phi(2T)$ = **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**

In Practice...



1 Operate in **'gradiometer' configuration**: Look at the **difference in phase differences** measured by two atom interferometers separated by a distance ~ L and referenced with common lasers

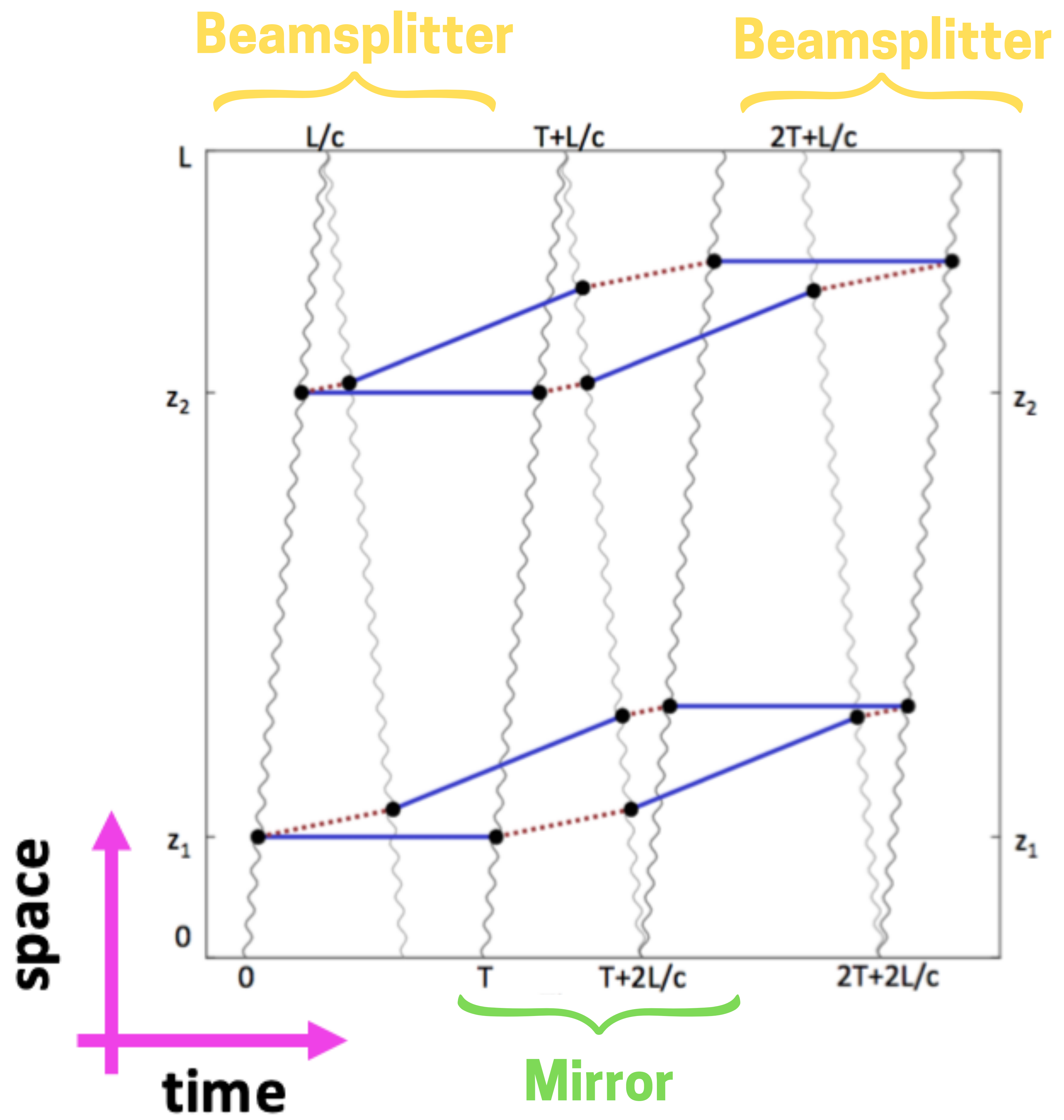
$$\Delta\phi_g = \Delta\phi_1 - \Delta\phi_2$$

→ Cancellation of common laser phase noise

2 Mirrors and Beamsplitters realised by **extended pulse sequences** involving additional π pulses from a secondary counter-propagating laser

→ **increases momentum transfer** between 2 arms and in turn the phase difference

As a gravitational wave detector...



In the absence of new physics, $\Delta\phi_g = 0$

- Gravitational wave of strain amplitude *h* causes L to oscillate in time
- Light travel time across baseline modified
- Times that the arms spend in excited state different between the two interferometers
- Gradiometer phase shift depends on strain

$$\Delta\Phi_g \sim 2khL\sin^2\left(\frac{\omega_{GW}T}{2}\right)$$

Long Baseline Atom Interferometers

Prototypes	km -scale	space based
AION-10/AION-100 MAGIS-100 MIGA VLBAI ZAIGA	AION-km MAGIA-advanced ELGAR MAGIS-km advanced ZAIGA	AEDGE
In development...	mid 2030's..	2040's

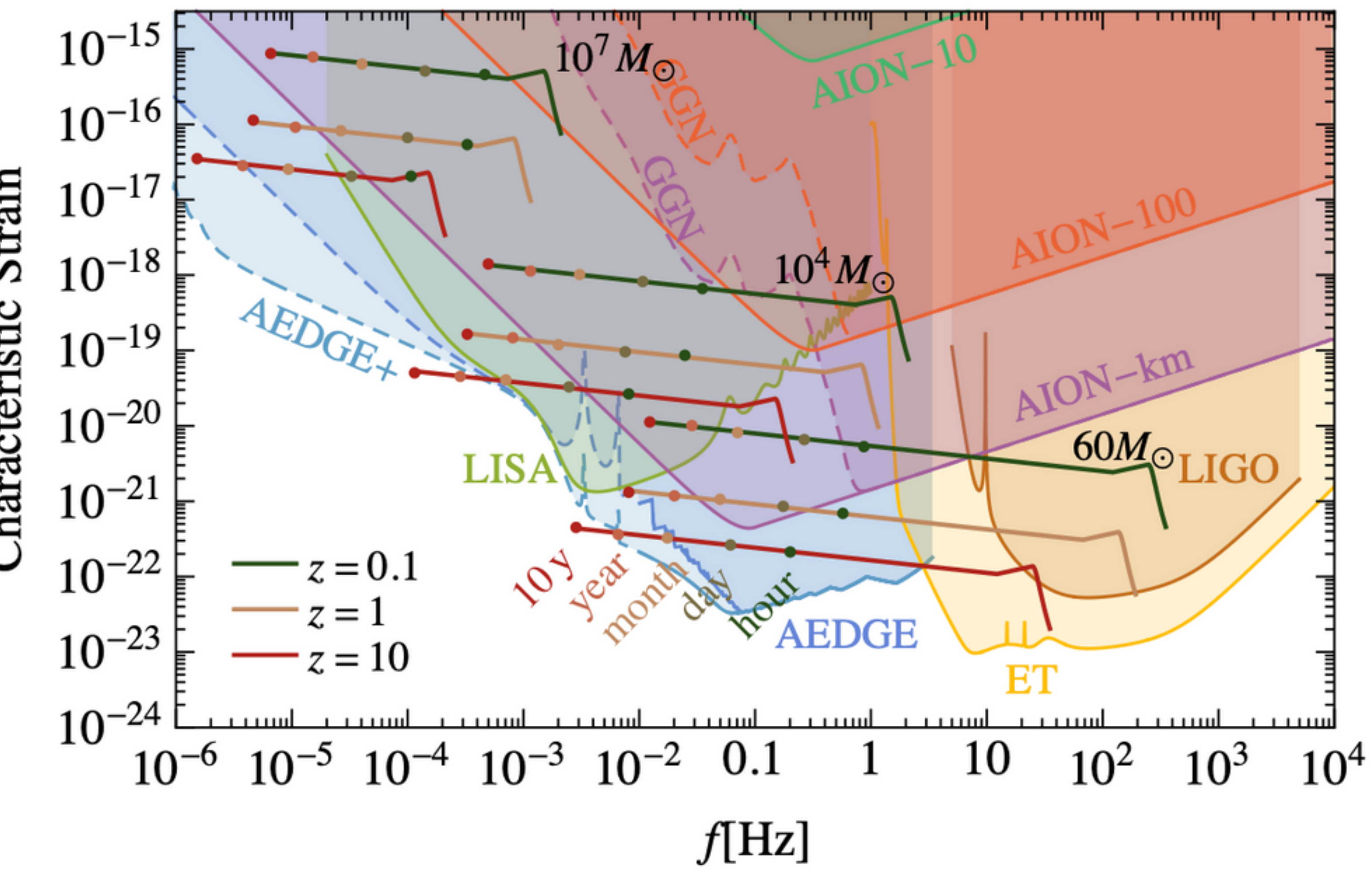
Mid-Frequency Gravitational Waves

Searches for Ultra-Light-Dark Matter

Types of Gravitational Wave Search

1 **Resolved mergers of binaries**

by template fitting

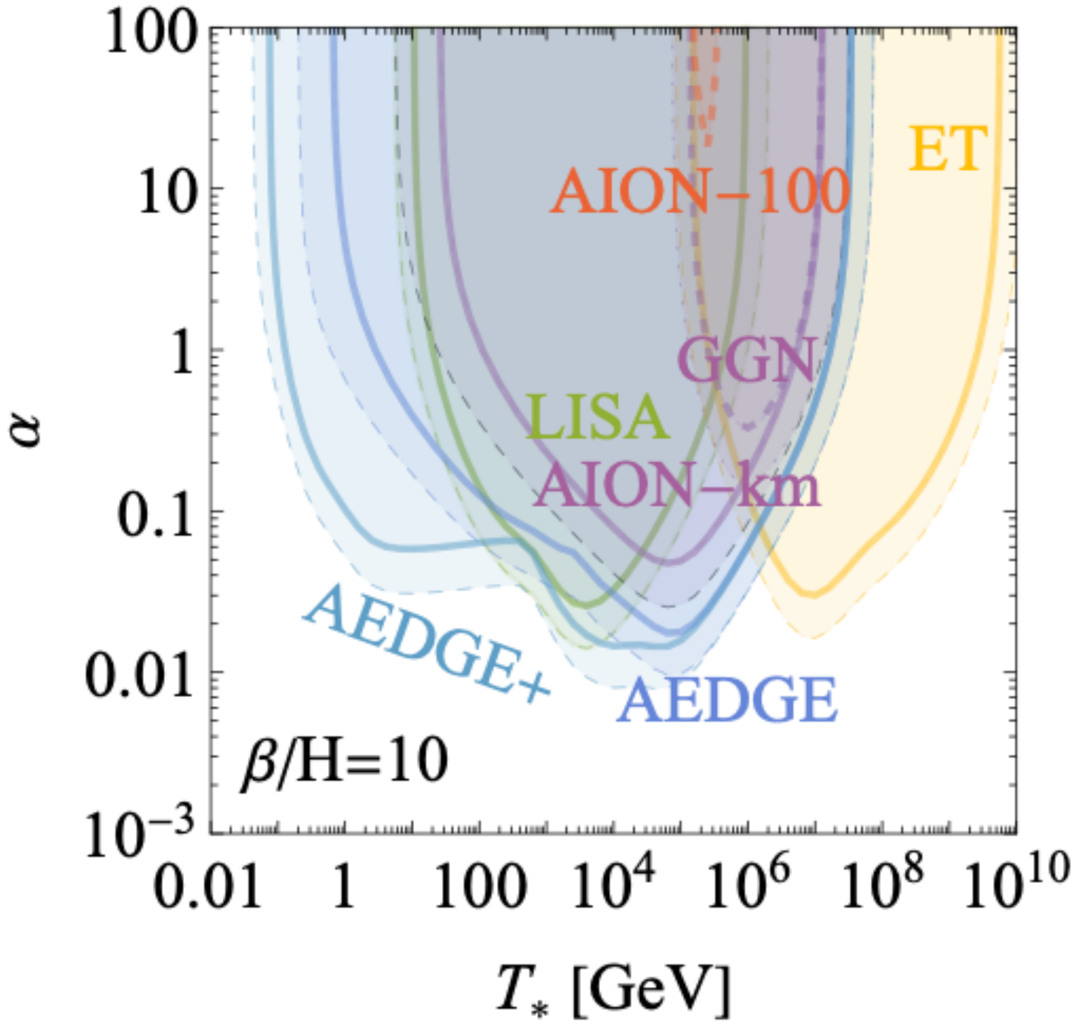


Intermediate Mass Black Hole binaries

so far

arXiv:2108.02468

2 **(Stochastic) Backgrounds**



e.g. Phase Transitions/ cosmic strings

A New Lens

Gravitational Wave Background (GWB) = **Total GW energy density** emitted by a **population of binaries**, including **resolved & unresolved signals**

Characterise by:

$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{\mathrm{d}\rho_{GW}(f)}{\mathrm{d}f}$$

This lens:

- Reveals an **important astrophysical signal** well with reach of Atom interferometers
  - Needs accounting for in other searches
  - Has a lot of information to reveal
- Offers a **unique** new **way to probe the Dark Sector**

CERN | QUANTUM TECHNOLOGY INITIATIVE

Gravitational Wave Backgrounds

For a population of binary compact objects:

Cosmology — Differential Merger Rate — Energy Density spectrum for a single binary

$$\Omega_{\mathrm{GW}} = \int \mathrm{d}m_1 \mathrm{d}m_2 \int \frac{1}{\rho_c} \frac{\mathrm{d}V_c}{1+z} \frac{\mathrm{d}\mathcal{R}(z)}{\mathrm{d}m_1 \mathrm{d}m_2} \frac{\mathrm{d}\tilde{\rho}_{\mathrm{GW}}(m_1, m_2)}{df}$$

- Present merger rate
- Mass Distribution
- Redshift Distribution

Waveforms of Inspiral, Merger and Ringdown Phases

During inspiral: $\Omega_{GW} \propto f^{2/3}$ independently of system

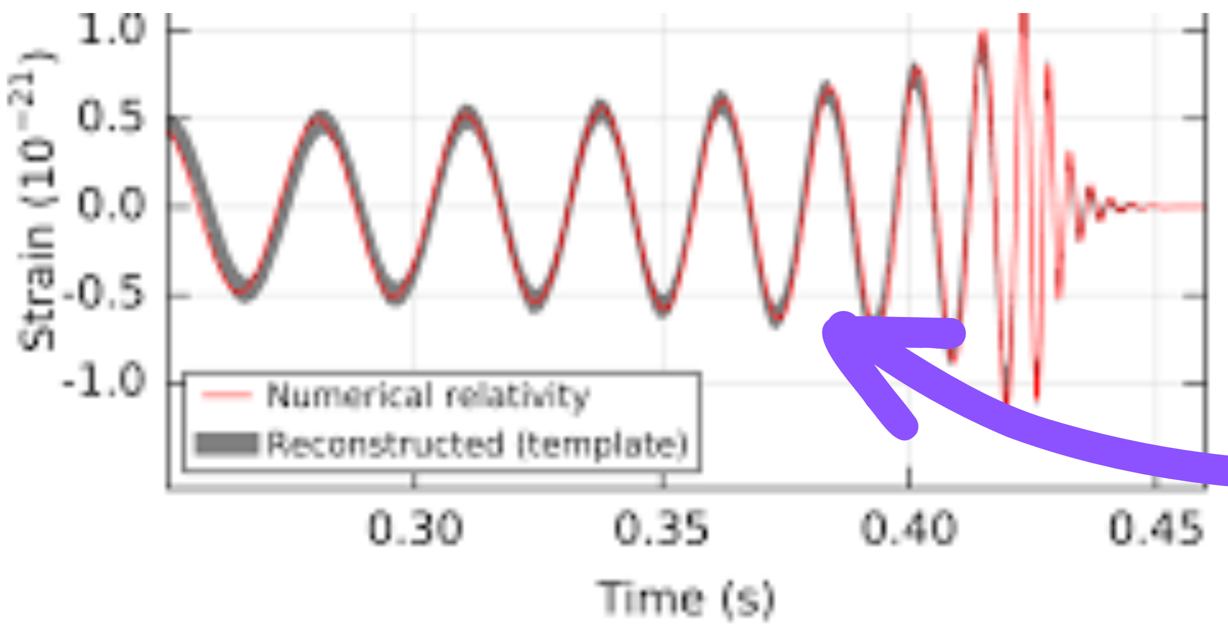
Source: LIGO Stellar Mass Compact Binaries

LIGO has observed many **stellar-mass binaries** merging @ $10^2 - 10^4\text{Hz}$

- Hundreds of **stellar mass Binary Black Holes (BBH)**
- 2 confirmed **Binary Neutron Star (BNS)**
- 4 **black hole-neutron star (BHNS)**

- Extract **Mass distribution**
- Extract **present event rate**

Stellar-mass populations are **well characterised!**

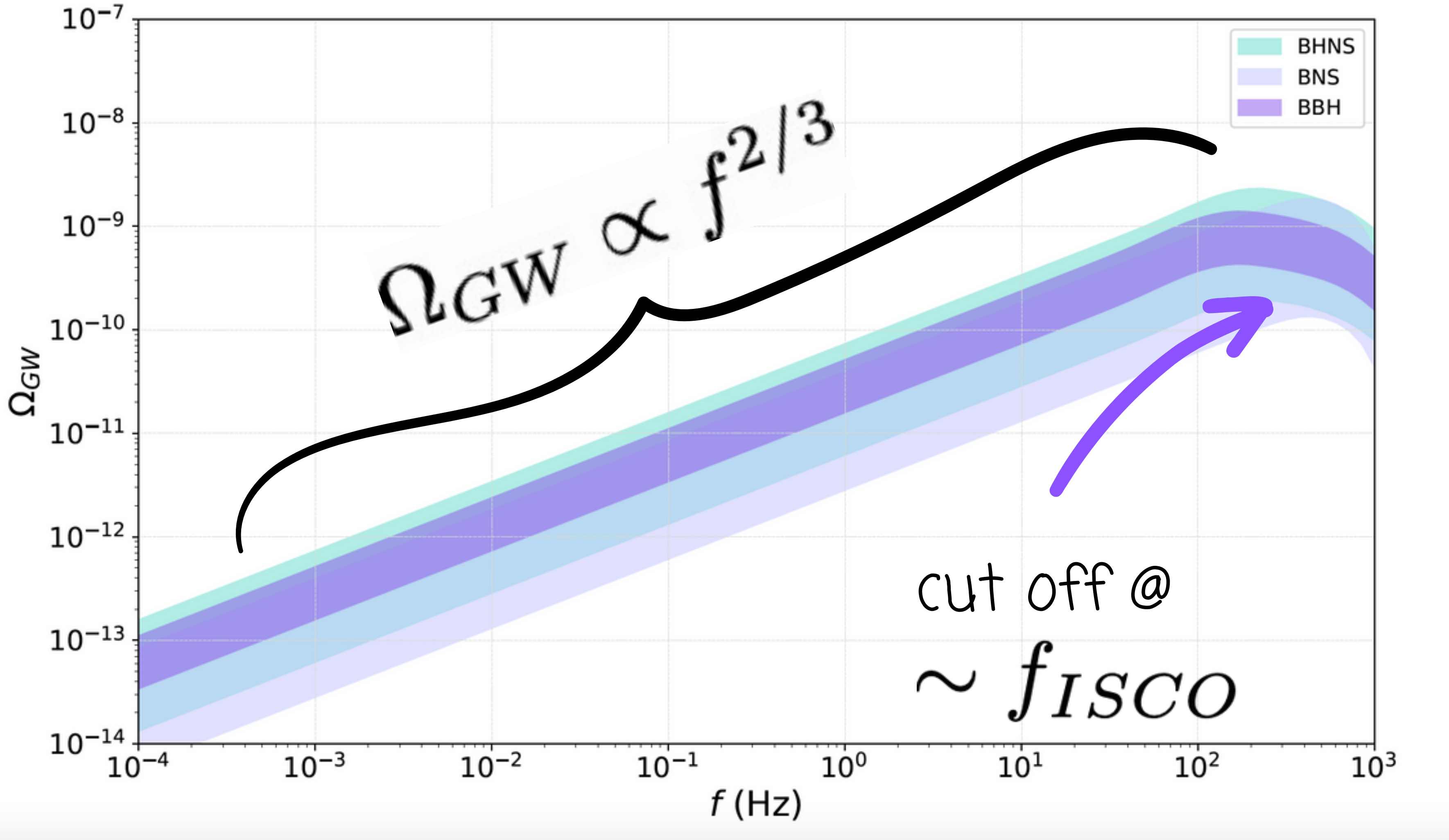


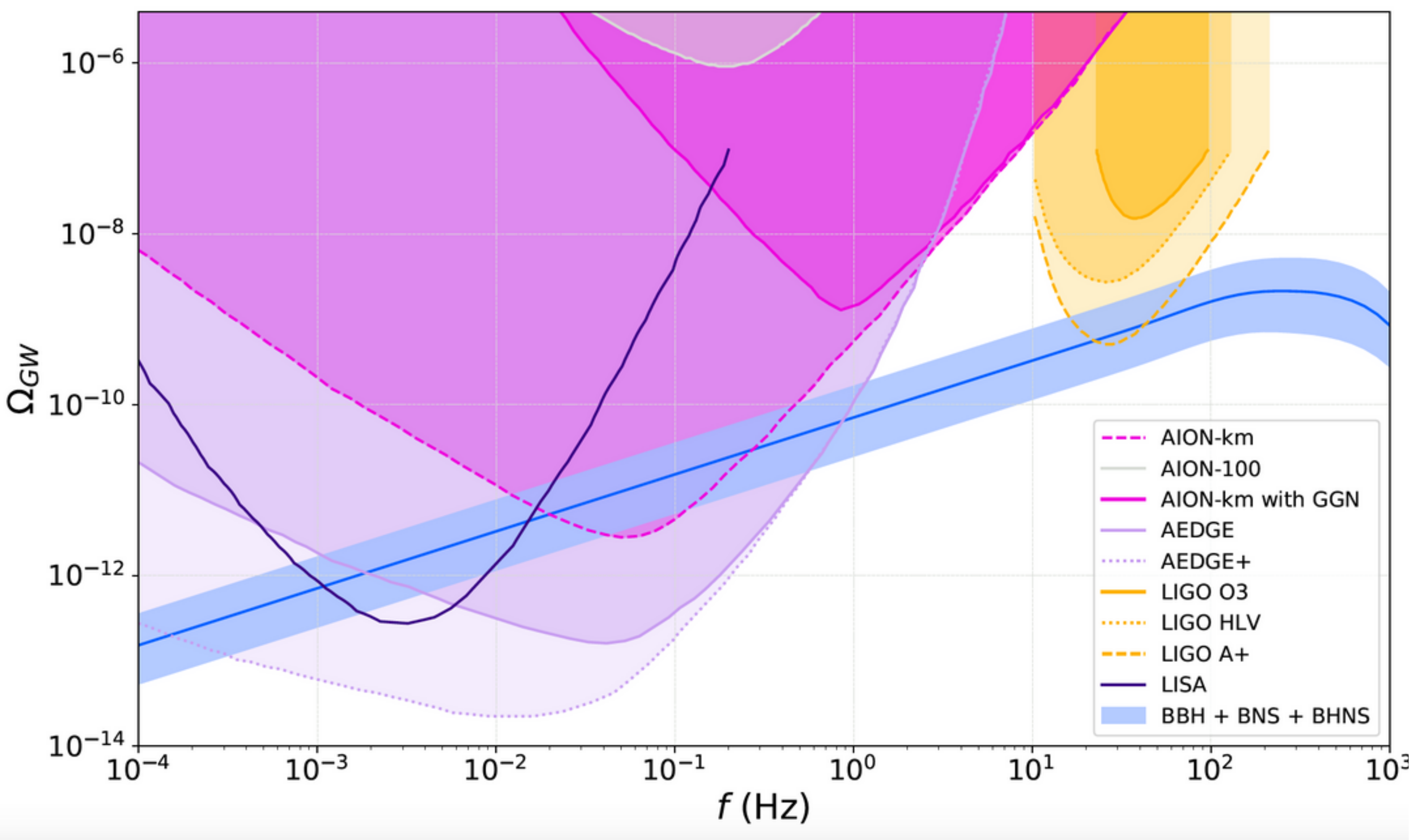
Emit **lower frequency** radiation during **inspiral** phase

Observable at Atom Interferometers?

CERN | QUANTUM TECHNOLOGY INITIATIVE

LIGO Stellar Mass Compact Binaries





Predicted **astrophysical background** from **known populations** of compact binaries **well within reach** !

CERN | QUANTUM TECHNOLOGY INITIATIVE

Implications & Opportunities

1

Relevant **background** to searches for other sources (both resolved & stochastic) that **needs to be taken into account**.

2

Interesting Signal:

- **Complimentary** to individual mergers - **probes higher z**
- Determine **population characteristics** and their **redshift dependence** e.g. masses, binary occurrence rate, BH angular momentum, NS ellipticity, NS magnetic fields
- **Test astrophysics** e.g. stellar formation rates, evolution of metallicity with redshift
- **Probe** possibility of **Primordial Black Holes**
- **Quantum sensing community** should be **aware of potential opportunites to benefit astrophysics**

Exotic Compact Objects (ECOs) ?

- SM is **extraordinarily rich and diverse** generating a variety of **astrophysical compact objects**
- Possibility of **new states over a great range of scales in the dark sector** which could **coalesce** under gravity to form **extended macroscopic objects**
- **A generic prediction** of many well-motivated DM models (e.g. ultra-light scalars, axions)

ECOs may include:

Fermion Stars

Boson Stars e.g. axions

Dark Matter Stars

Proca Stars

If form **binaries**, would produce **GWs**!

CERN | QUANTUM TECHNOLOGY INITIATIVE

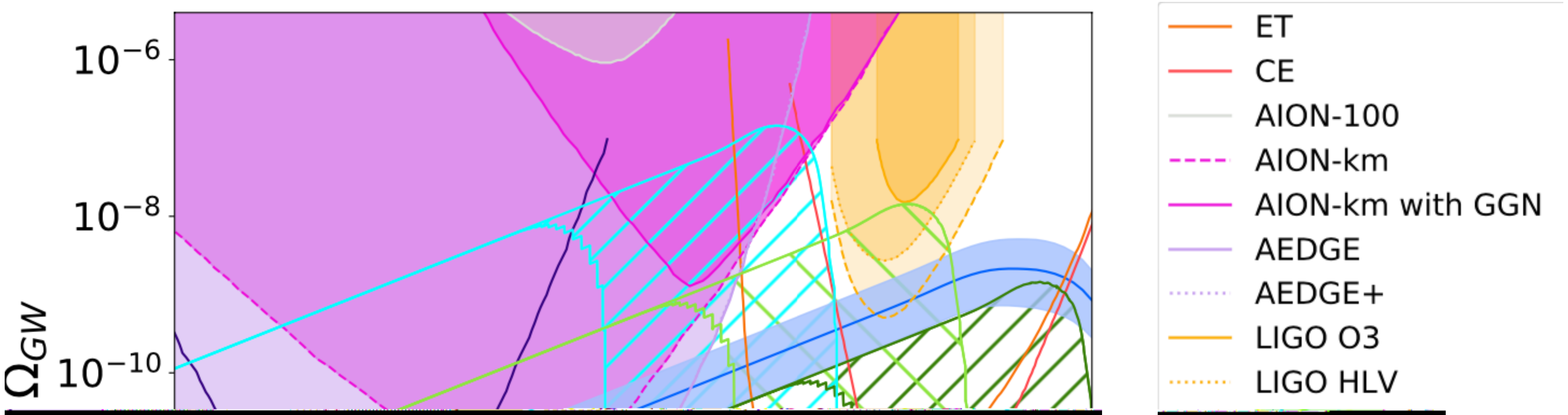
GWs from ECOs...

Assume:

- Population of equal mass objects in binaries
- Same redshift distr. & merger rate as LIGO BH
- Either:
    - Inspiral only up to

$$f_{ISCO}^{ECO} = \frac{C^{3/2}}{3^{3/2}\pi G M} \qquad C = \frac{M}{R}$$

-
    - BH waveforms for ringdown/merger



[redacted]

Higher masses = lower cut-off

Mismatch between detectors = **probe** of **dark sector complexity**

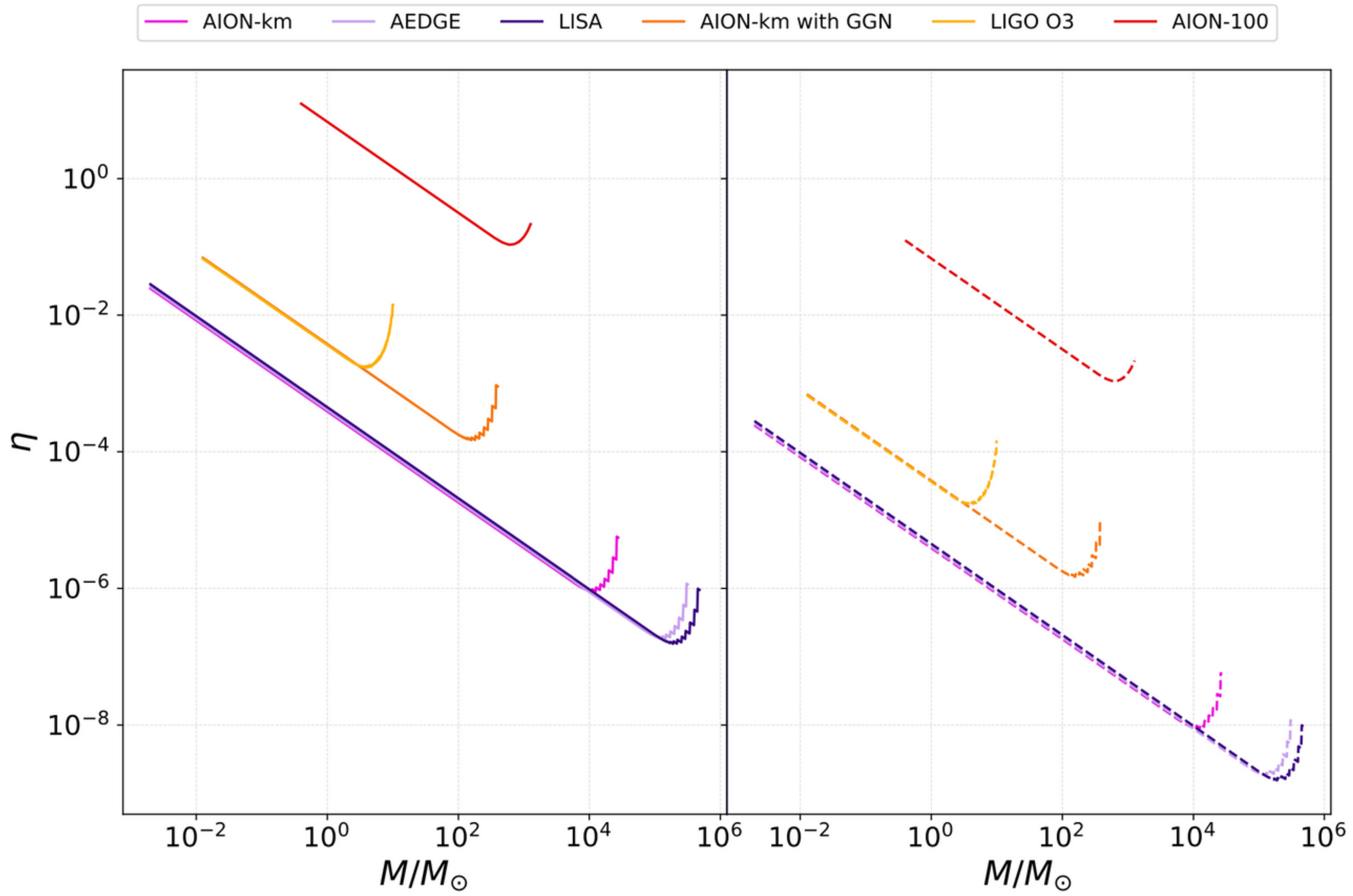
Is this reasonable?

Let η be **fraction of Dark Matter** in **ECO binaries**

$$\eta = \frac{\rho_{\mathrm{ECO}}}{\rho_{\mathrm{DM}}} \approx 6.4 \times 10^{-7} \times \left(\frac{R}{10}\right) \times \left(\frac{M}{2M_\odot}\right) \times \left(\frac{0.01}{\epsilon}\right)$$

What fraction is required to exceed astrophysical background + instrument sensitivity?

Sizeable signals even if ECOs harbour just a **tiny fraction** of **Dark Sector energy**



QUANTUM TECHNOLOGY INITIATIVE

Summary

- **Background** from LIGO stellar mass binaries **will be observable** at atom interferometers - **needs to be accounted for in searches for new physics!**
- Opportunity to **extract** lots of **interesting astrophysical information**

- **ECOs** harbouring just **tiny fractions of DM** abundance could produce **significant signals**
- **Mismatch** between extrapolated and observed signals at different detectors could be a **smoking gun** for a **new binary population**
- Spectrum **cut-off sensitive to ECO mass** - probe of **dark sector complexity**