Massive graviton dark matter searches with long-baseline atom interferometers

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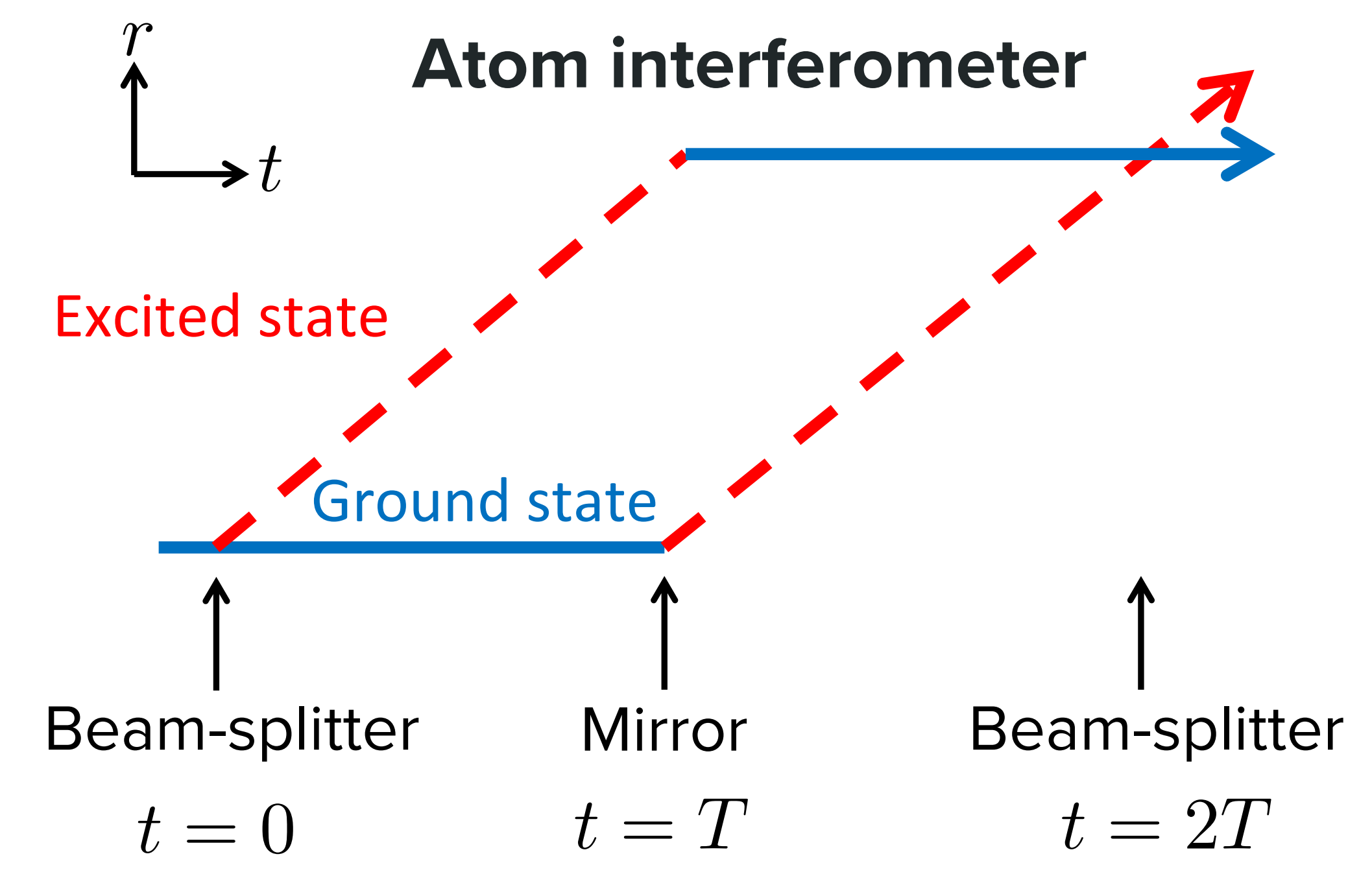
Atom interferometry

Atom interferometry is an experiment that compares the phase differences between quantum superpositions of a two-level system (excited/ground state) of spatially separated clouds of atoms. Laser pulses act as beam-splitters and mirrors to direct the clouds[1].



Phase shifts

At the end of the sequence the arms interfere, and a ***phase*** is measured.

The leading order phase is:

$$\phi = kgT^2$$

where:

- k : atom-light interactions
- g : gravitational field
- T : time

The peak sensitivity of atom interferometers is $\sim 0.1\mathrm{Hz}$ or $10^{-16}\mathrm{eV}$. This makes them excellent detectors of ***ultra-light dark matter (ULDM)*** (from atom-light interactions) and ***mid-band gravitational waves*** (time measurements)[1]. Previous work explores ***scalar and vector ULDM*** couplings to atomic energy levels in atom interferometers, but so far ***tensor ULDM*** is unexplored…

What about spin-2 dark matter?

Due to a high occupation number ULDM is ***wavy*** and acts like a coherent field. Pauli exclusion restricts candidates to be bosons. So far, we have studied:

- **Spin-0:** *Scalars* e.g. dilatons, coupling to electron mass and fine-structure
- **Spin-1:** *Vectors* e.g. dark photons, B-L coupling

But a previously unexplored candidate in atom interferometers is ***spin-2 ULDM***

- **Spin-2:** *Tensors* e.g. dark gravitons[2,3]

Given the sensitivity of atom interferometers to other dark matter candidates and gravitational waves we expect them to be sensitive to spin-2 ULDM as well.

Massive gravitons

There is no UV complete theory of quantum gravity. Instead, we describe gravity using effective field theories. Massive gravitons couple to matter through the stress-energy tensor $T^{\mu\nu}$ just as massless gravity does, but there is an additional ***scalar coupling***[4] at the linear level to the trace T:

$$\mathcal{L} \supset \frac{\alpha}{M_{\mathrm{Pl}}}\widetilde{\varphi}_{\mu\nu}T^{\mu\nu} + \frac{\beta}{M_{\mathrm{Pl}}}\pi T$$

Here $\widetilde{\varphi}_{\mu\nu}$ are the ***tensor*** modes while π are the ***scalar*** modes. In Lorentz invariant massive gravity, the couplings are universal, $\alpha = \beta$ but this is not necessarily true for ***Lorentz violating*** theories.

Modelling ULDM

Ultra-light dark matter can be modelled as a ***classical oscillating field***[2,5,6]. We model the scalar and tensor modes separately:

$$\widetilde{\varphi}_{ij}(t) = \sum_{\lambda} \widetilde{\varphi}_{0,\lambda} e^{\lambda}_{ij} \cos(\omega_{\widetilde{\varphi}} t)$$

$$\pi(t) = \pi_0 \cos(\omega_\pi t)$$

The frequency of each field is set by the ULDM mass with a small velocity correction. The tensor modes sum over the ***polarisation tensor***[3] e^{λ}_{ij}.

Scalar mode affects the electron!

The coupling to the trace of the stress-energy tensor gives these interactions:

$$\mathcal{L} \supset \frac{\beta}{M_{\mathrm{Pl}}}\pi\left[3\overline{\psi}i\gamma^\mu D_\mu\psi - 4m_\psi\overline{\psi}\psi\right]$$

Here the scalar mode couples to a fermion ψ, oscillating its ***kinetic energy*** and ***mass***. In an atom this oscillates the electronic energy level resulting in a ***phase shift*** in an interferometer.

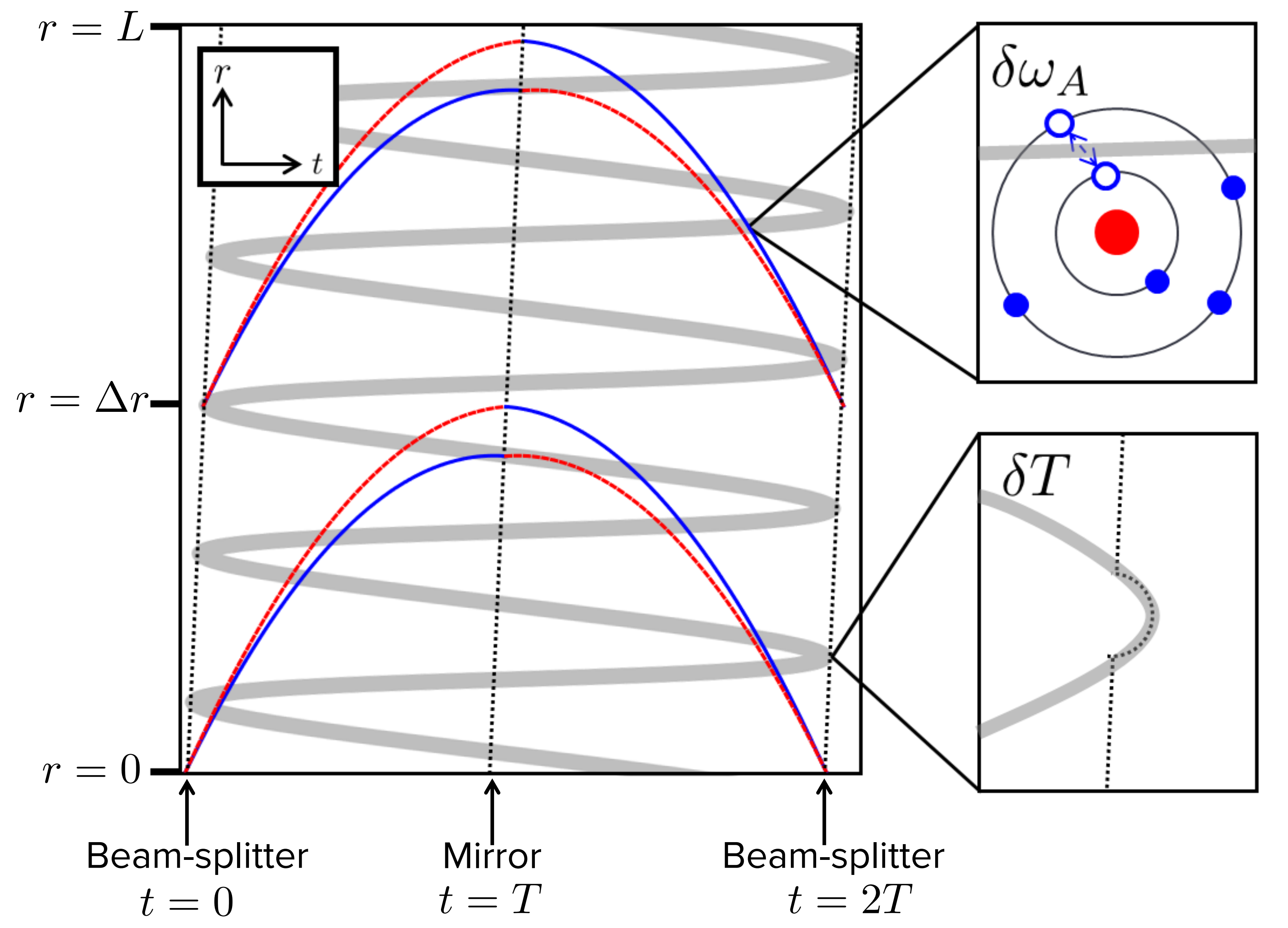
Tensor mode just like GWs?

The tensor mode will act as an ***oscillating gravitational wave background*** in our detector. Treating it as a perturbation on a flat background[3]:

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{\alpha}{M_{\mathrm{Pl}}}\widetilde{\varphi}_{\mu\nu}$$

it's clear we're looking for a ***strain***. This strain changes the time the laser pulses interact with the atoms, imprinting a measurable ***phase***.

Atom gradiometer in a spin-2 ULDM field



Two channels for detection!

Now we consider spin-2 dark matter in an ***atom gradiometer***. Two sequences are operated in a vertical fountain configuration, coupled by the same lasers[1,5].

Two distinct effects occur from the scalar and tensor modes. This ***enhances the sensitivity*** compared to scalar ULDM searches without altering the experimental setup at all!

The phase shifts induced by each mode depend on the ***couplings***, ***local dark matter density***, and the ***mass***:

$$\phi_{\widetilde{\varphi}} \sim \delta T \sim \frac{\alpha}{M_{\mathrm{Pl}}}\frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_{\widetilde{\varphi}}}$$

$$\phi_{\pi} \sim \delta\omega_A \sim 10\frac{\beta}{M_{\mathrm{Pl}}}\frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_{\pi}}$$

The scalar mode dominates!

Constraints?

The leading constraints on spin-2 ULDM come from ***fifth-force experiments***. The presence of a massive spin-2 field would cause small oscillating deviations from general relativity[2], altering the Newtonian gravitational potential separated by a distance r by $\delta V_{\mathrm{Newt}} \propto \alpha^2 e^{-mr}$. The strongest constraints in the atom interferometer sensitivity band come from ***planetary*** and ***lunar laser ranging***[7].

A global network of experiments!

Several terrestrial long-baseline atom interferometer experiments are currently in development. ***AION***[1] in the UK, ***MAGIS-100***[9] in the US, ***MIGA*** in France, ***VLBAI*** in Germany, and ***ZAIGA*** in China. Several 10m and 100m towers are to be built in the next decade followed by a km scale instrument and space-based projects like ***AEDGE***[10].

Stability bounds

In addition to experimental constrains, in a De-Sitter universe, the mass of spin-2 must satisfy the ***Higuchi bound:***

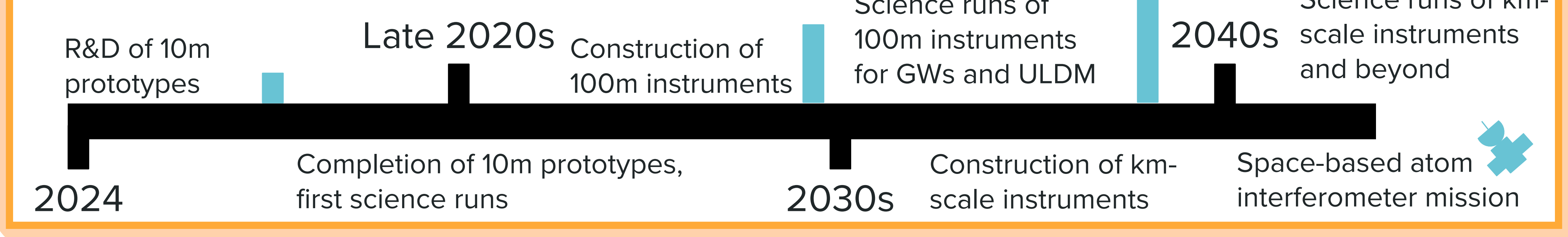
$$m^2 \geq 2H^2$$

The least conservative bound on H from Big Bang Nucleosynthesis sets a minimum mass $m \sim T_{\mathrm{BBN}}/M_{\mathrm{Pl}}^2 \sim 10^{-16}\mathrm{eV}$, just below the atom interferometer sensitivity band[8].

Lorentz violating theories?!

In the projected detection limits we assume Lorentz invariance such that masses and couplings for the scalar and tensor mode are identical: $\alpha = \beta,\ m_{\widetilde{\varphi}} = m_\pi$. But in ***Lorentz violating theories*** this isn't necessarily true[4] and only one of the modes may be the dark matter. The ***scalar mode dominates*** the sensitivity in atom interferometers while LIGO and LISA are only sensitive to the tensor mode[3].

Projected experimental timeline[10]



R&D of 10m prototypes

Late 2020s

Construction of 100m instruments

Science runs of 100m instruments for GWs and ULDM

2040s

Science runs of km-scale instruments and beyond

2024

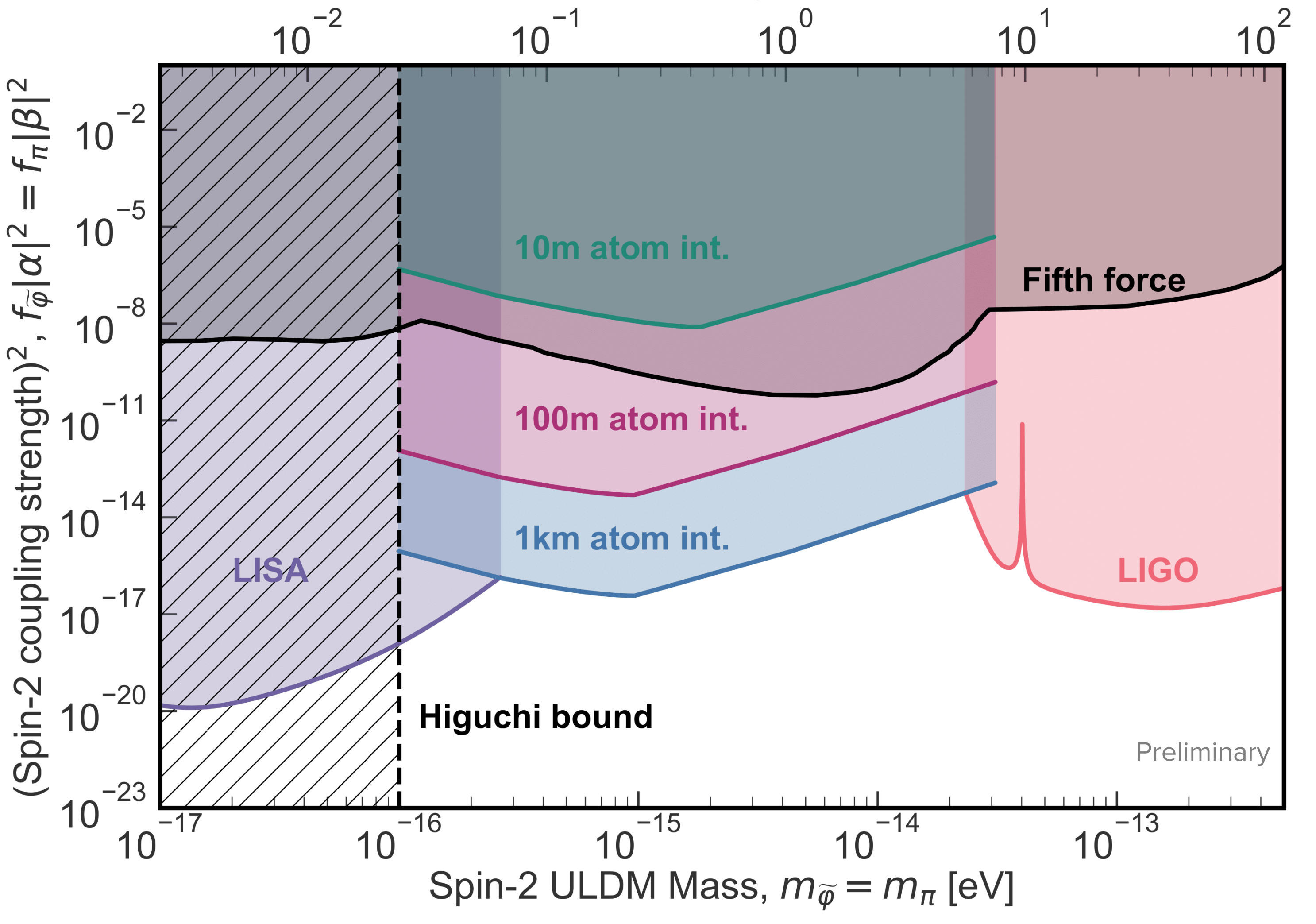
Completion of 10m prototypes, first science runs

2030s

Construction of km-scale instruments

Space-based atom interferometer mission

Projected detection limits



Detection limits for Lorentz invariant massive graviton dark matter for three example atom interferometer experiments compared to LIGO and LISA in a 2-year measurements campaign. The leading constraints from fifth-force experiments and the Higuchi bound are also shown.

[1] L. Badurina et al., *AION: An Atom Interferometer Observatory and Network*, 1911.11755
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[3] J. M. Armaleo et al., *Searching for spin-2 ULDM with gravitational waves interferometers*, 2012.13997
[4] C. de Rham, *Massive Gravity*, 1401.4173
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[7] E.G. Adelberger et al., *Tests of the Gravitational Inverse-Square Law*, 0307284
[8] M. Jain et al., *Polarized solitons in higher-spin wave dark matter*, 2109.04892
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[10] S. Abend et al., *TVLBAI Workshop Summary*, 2310.08183