Searches for (unscreened and screened) scalars *with long-baseline atom interferometers*

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in collaboration with
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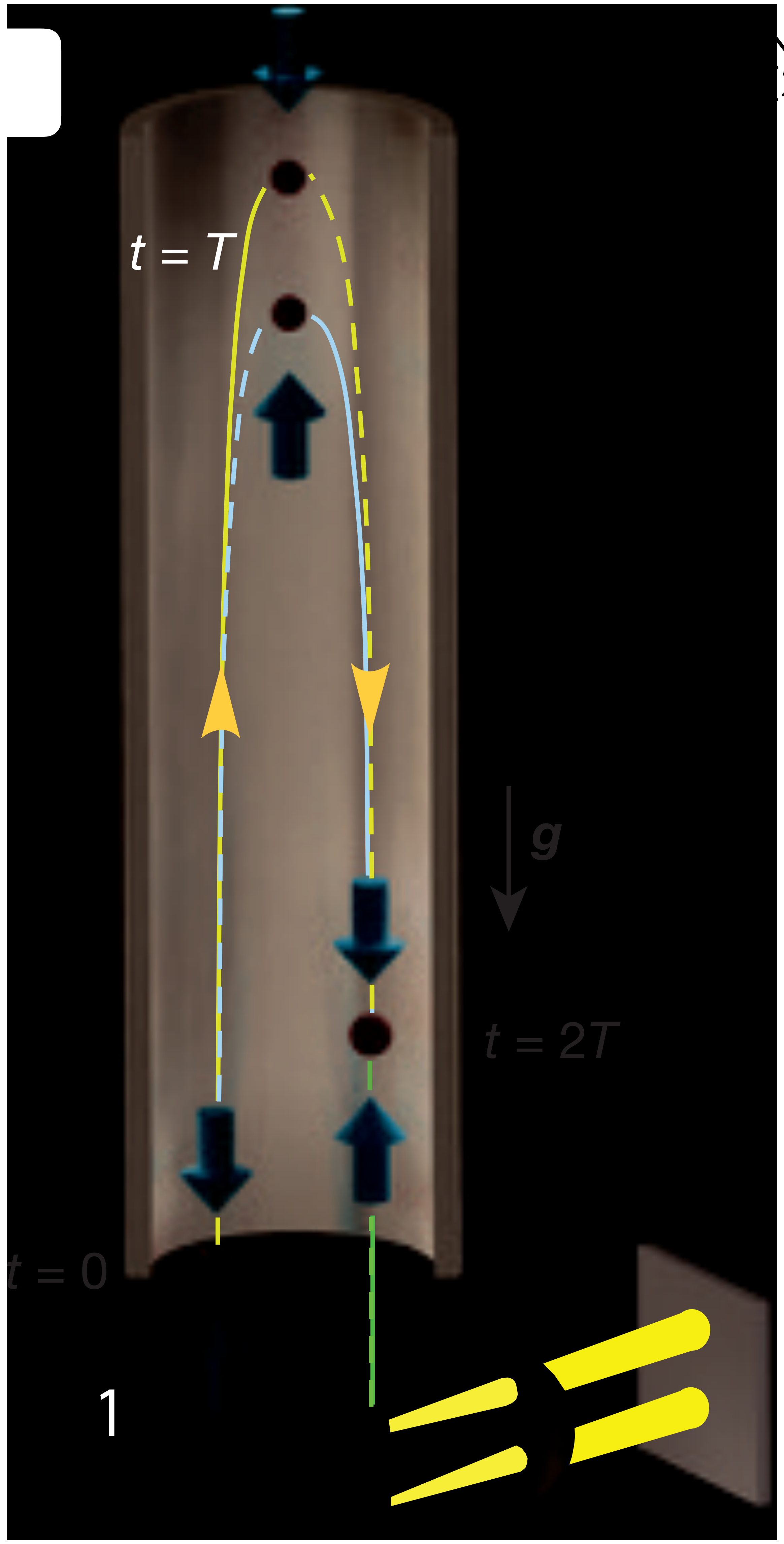
and the AION Collaboration, AICE & TVLBAI

PASCOS 2026, Sheffield, 26 June 2026

A brief overview of atom interferometers

(from a phenomenologist's point of view)

Light pulse atom interferometry (physical-space)



Launch ultra-cold cloud of atoms into an atomic fountain

Sequence of optical pulses manipulate the atoms

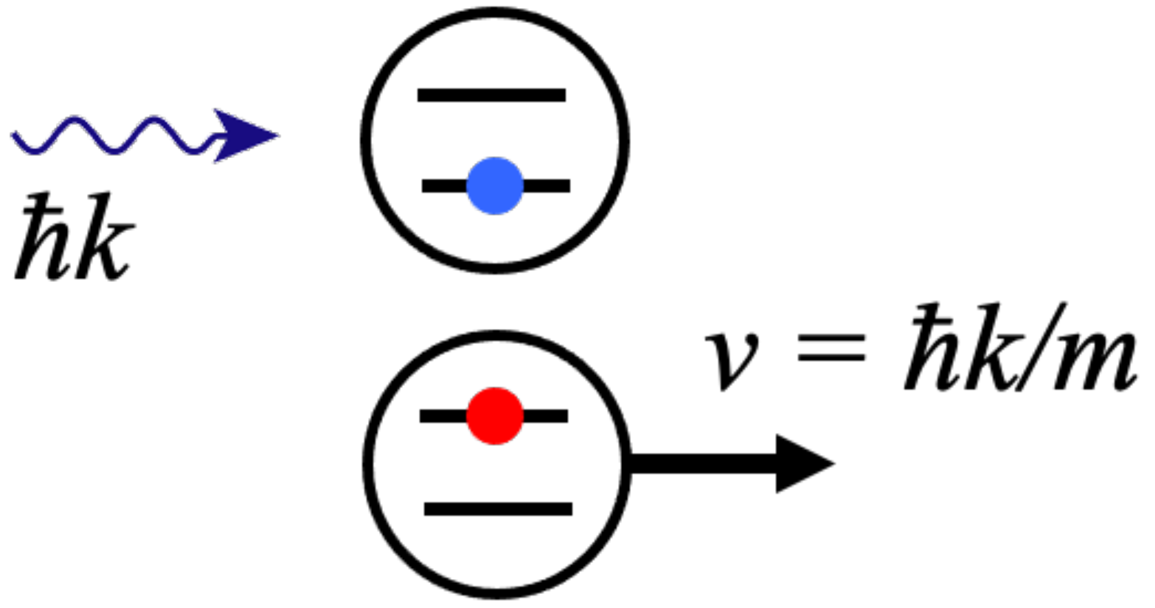
Quantum superposition over macroscopic distances
(>50cm achieved)

Interfere using a final optical pulse when they spatially overlap

Image the two interferometer output ports

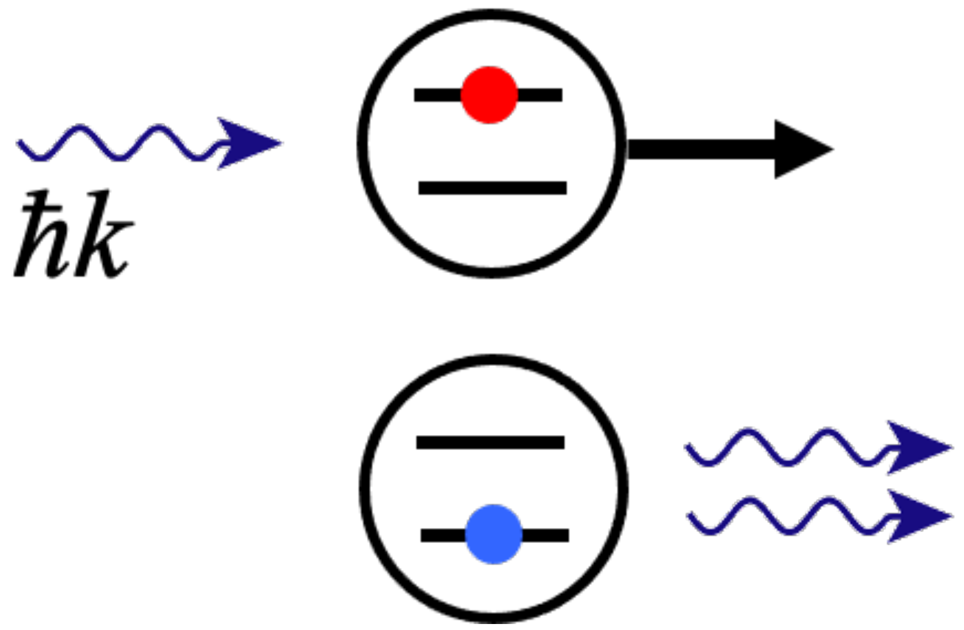
Manipulating atoms with light pulses 1

(1) Light absorption:



Atom is 'kicked' forwards so starts moving

(2) Stimulated emission:

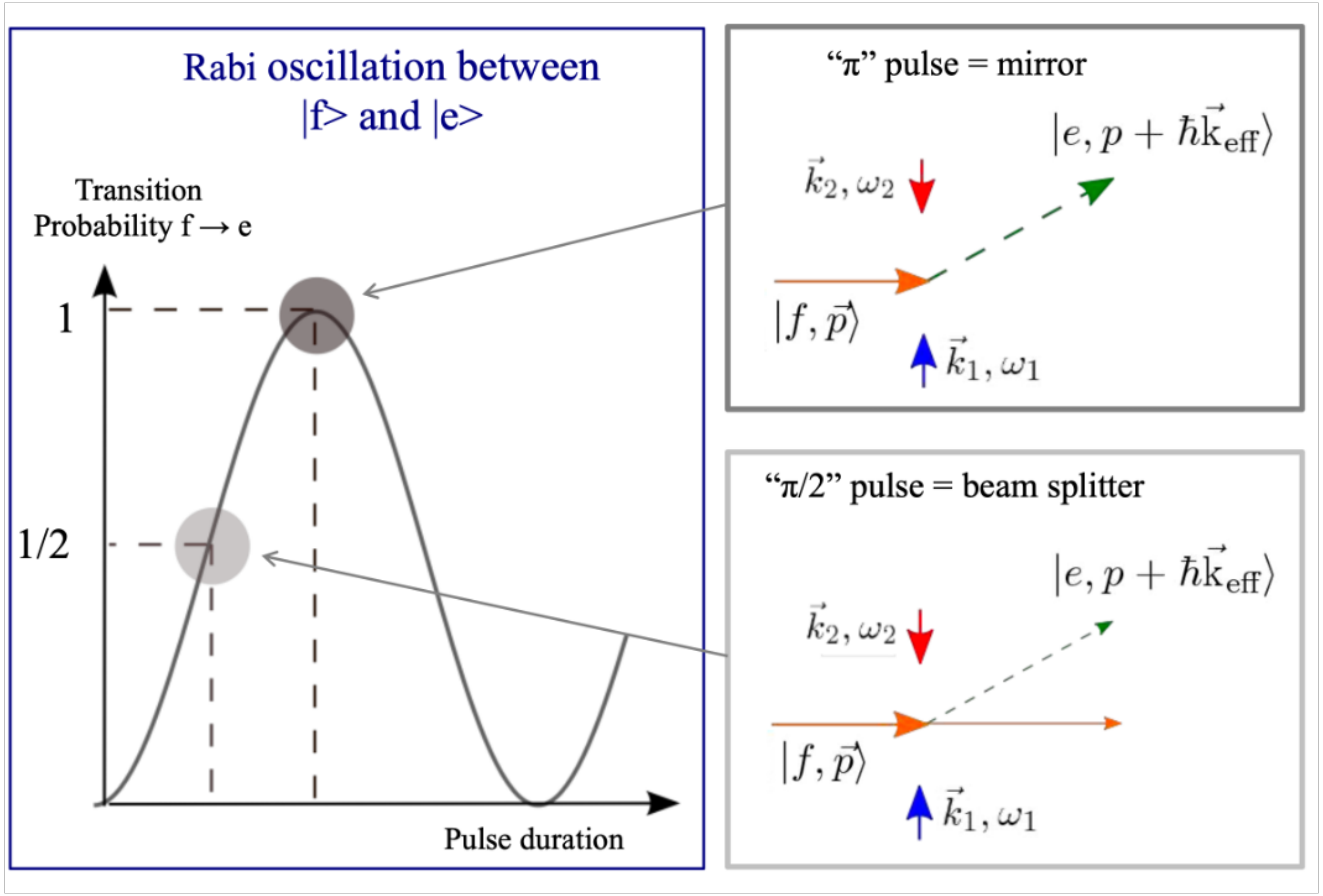


Emitted photon 'kicks' atom backwards so comes to rest

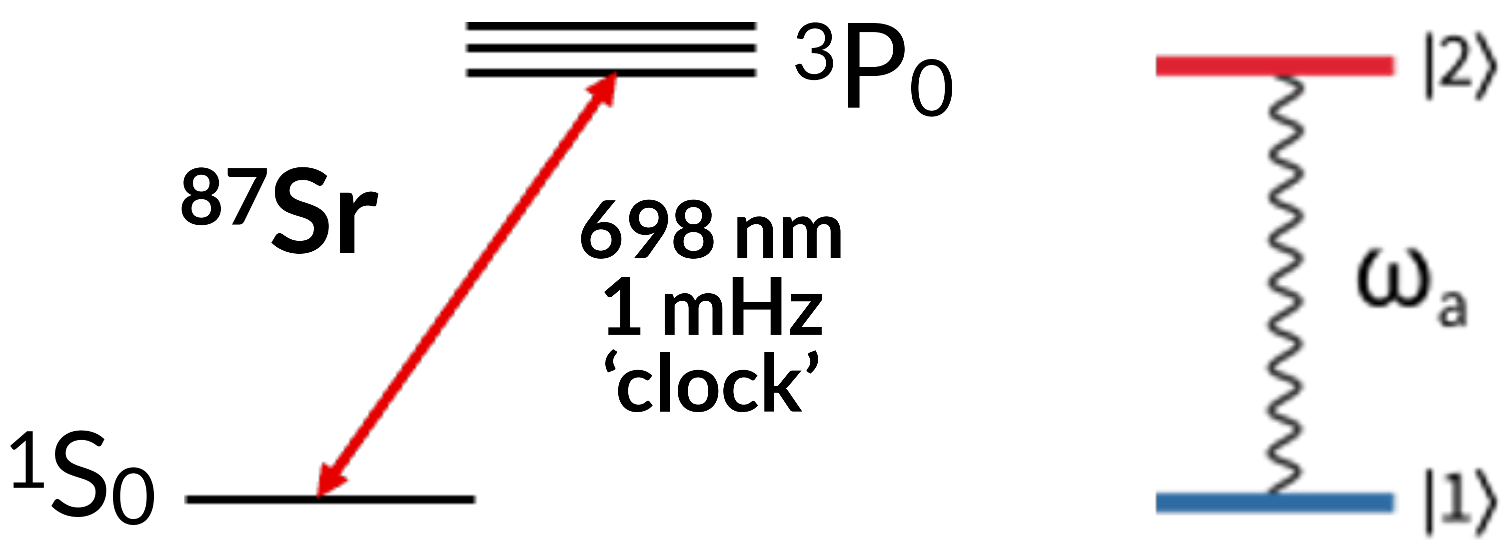
(3) In principle also spontaneous emission but choose atoms with long lifetimes (Sr) so this can be ignored

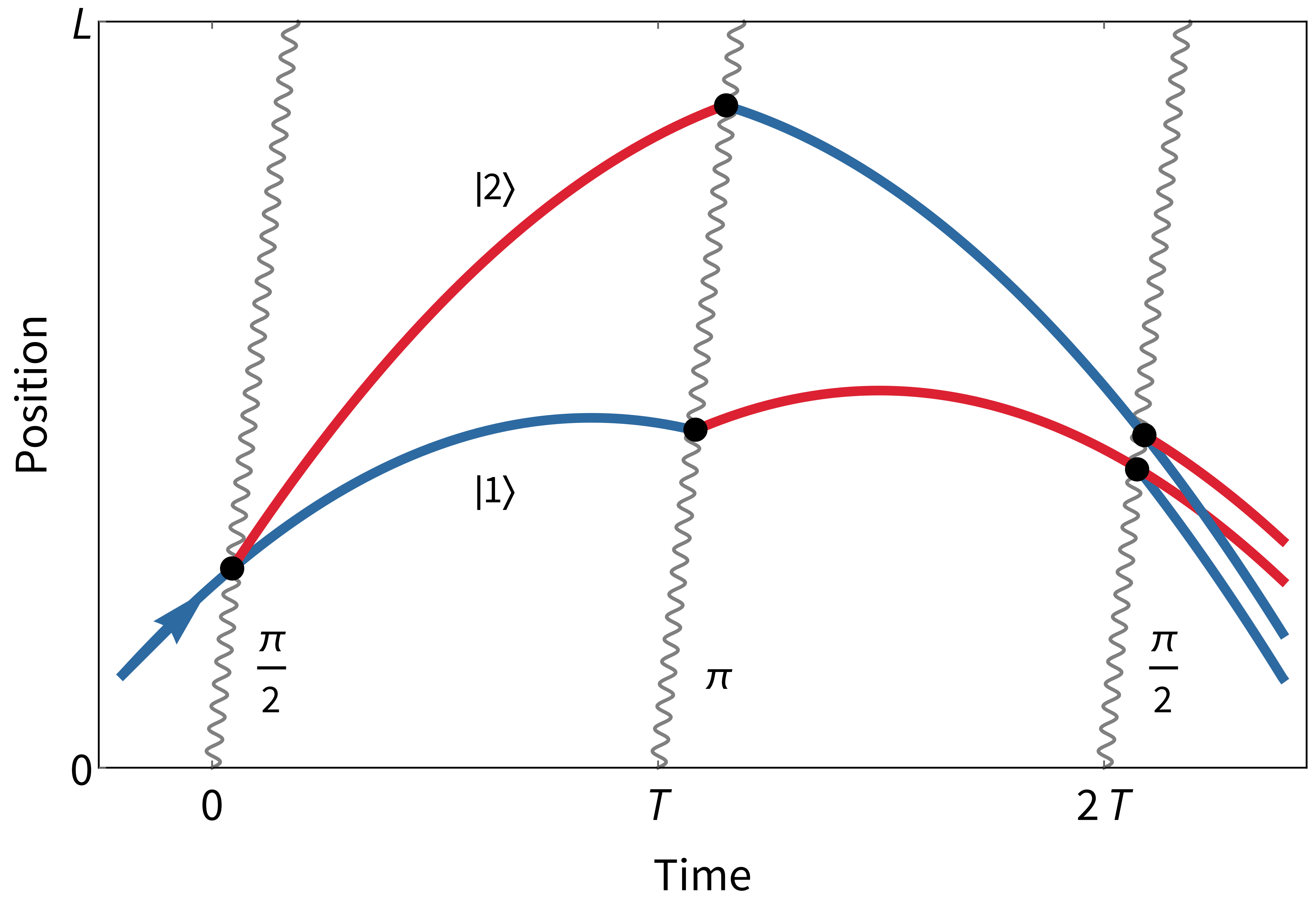
Manipulating atoms with light pulses 2

Duration of pulse controls atom population levels:



Light pulse atom interferometry (space-time)





Abe et al (MAGIS-100) arXiv:2104.02835

Two-level system separated by optical frequency difference ω_a

Initial pulse: 'beamsplitter'
Middle pulse: 'mirror'
Final pulse: 'beamsplitter (interfere)'

Atom evolves extra clock phase:

$$\frac{1}{\sqrt{2}}|1\rangle + \frac{1}{\sqrt{2}}|2\rangle e^{-i\omega_a T}$$

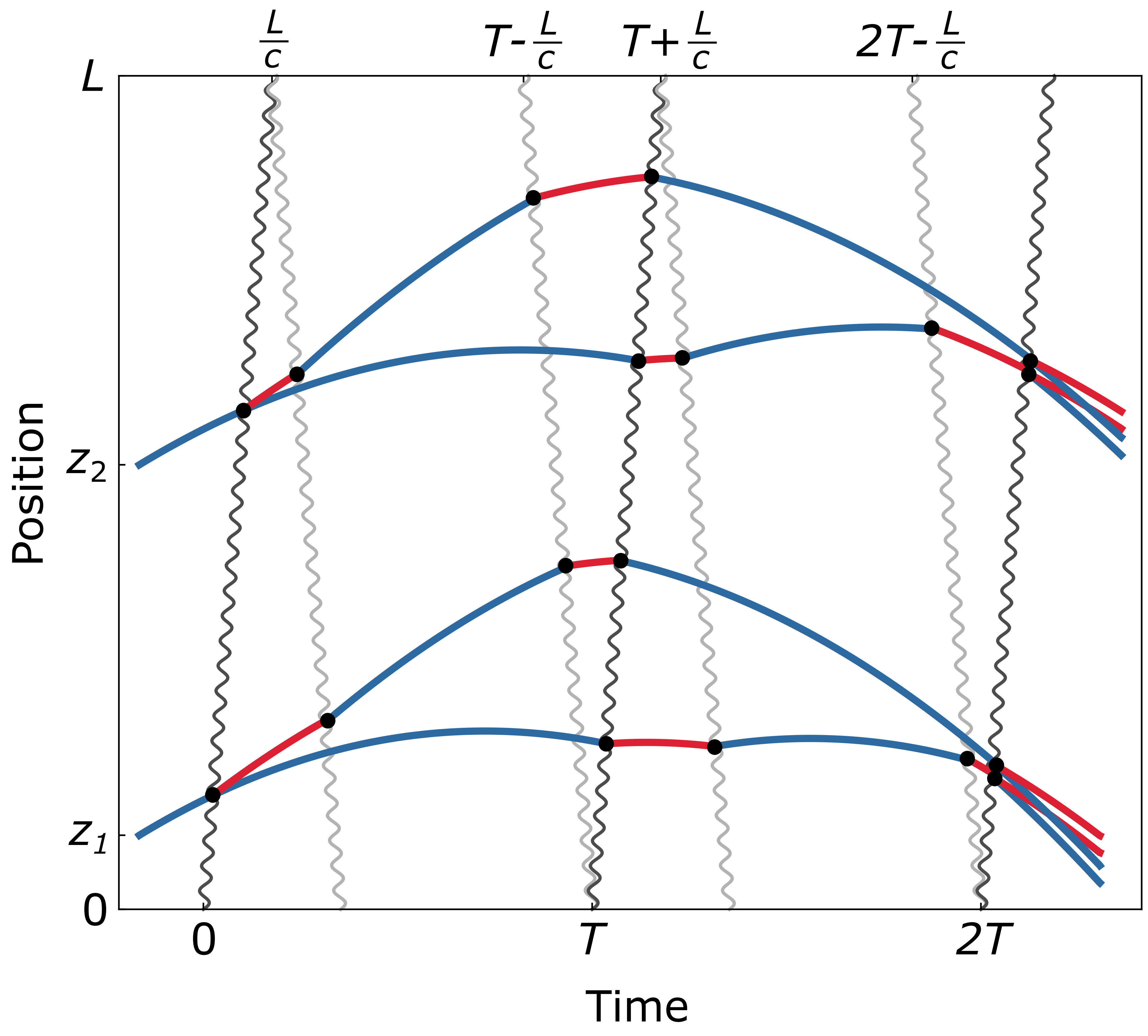
Phase sensitive to changes in:

1. atomic structure (scalar ULDM)

2. local accelerations (screened scalars)

[3. timings (gravitational waves)]

Even more involved… operate as a gradiometer



State-of-the-art single-photon strontium atom interferometry with large momentum transfer (LMT) techniques

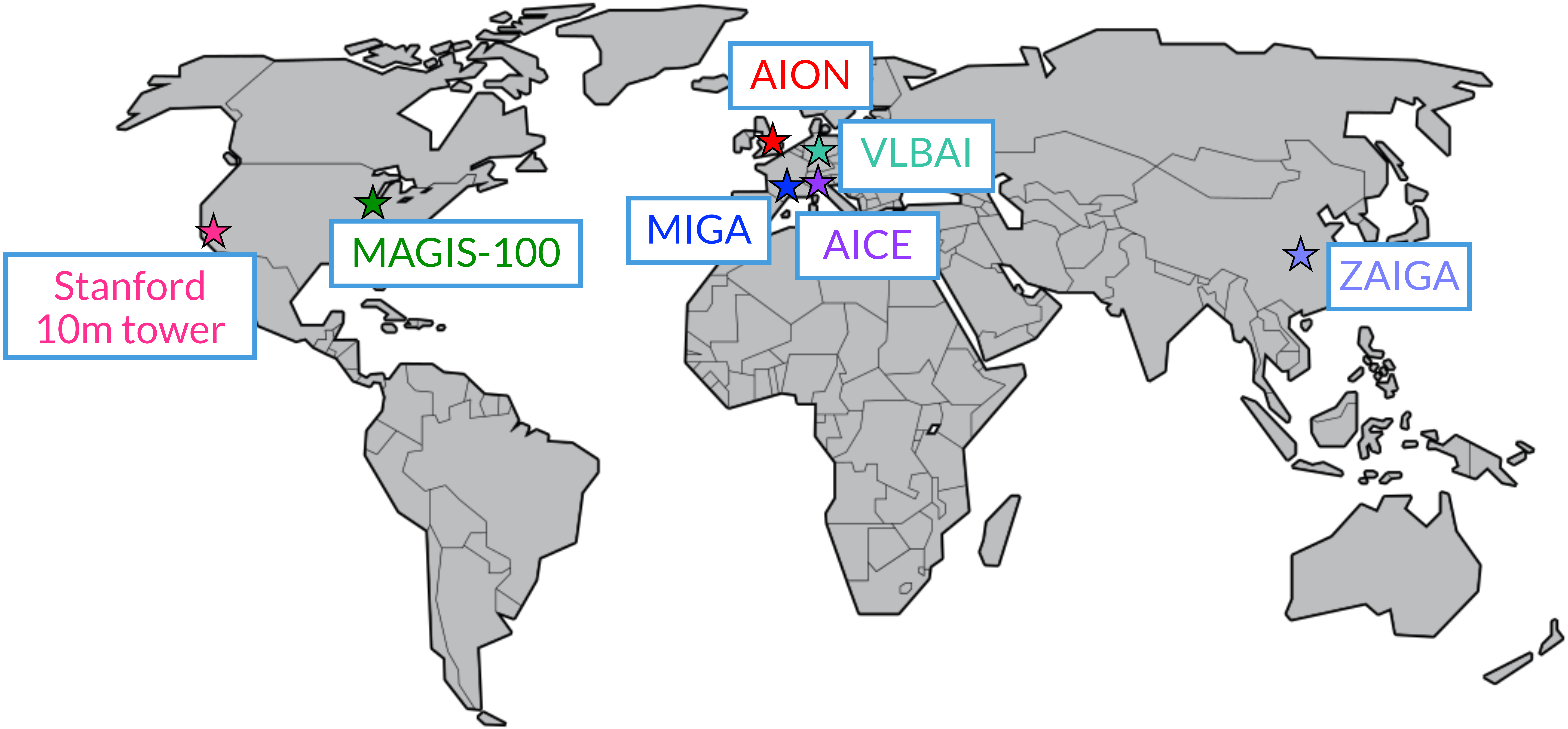
Run two or more atom interferometers simultaneously with the same laser ('gradiometer')

Cancels one of the leading noise sources (laser phase noise)

Nature 654, 622–628 (2026)
First demonstration in Sr-87 by the AION Collaboration

Image from Abe et al (MAGIS-100)
Quant.Sci.Technol, arXiv:2104.02835

Atom interferometer activities across the world



MAGIS-100 arXiv:2104.02835; MIGA arXiv:1703.02490; AION arXiv:1911.11755; VLBAI arXiv:2003.04875; ZAIGA arXiv:1903.09288; AICE arXiv: 2509.11867

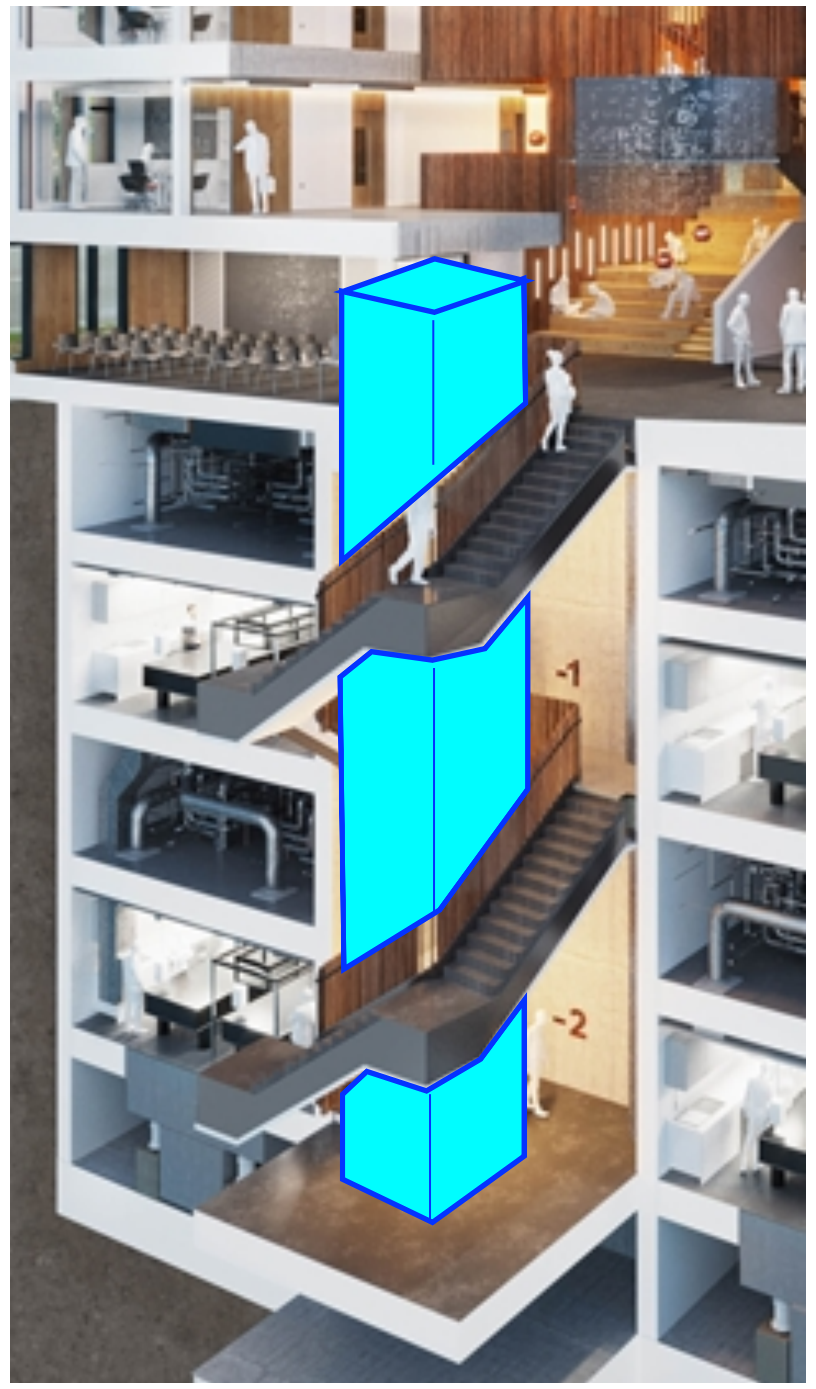
TVLBAI: Towards very-long baselines

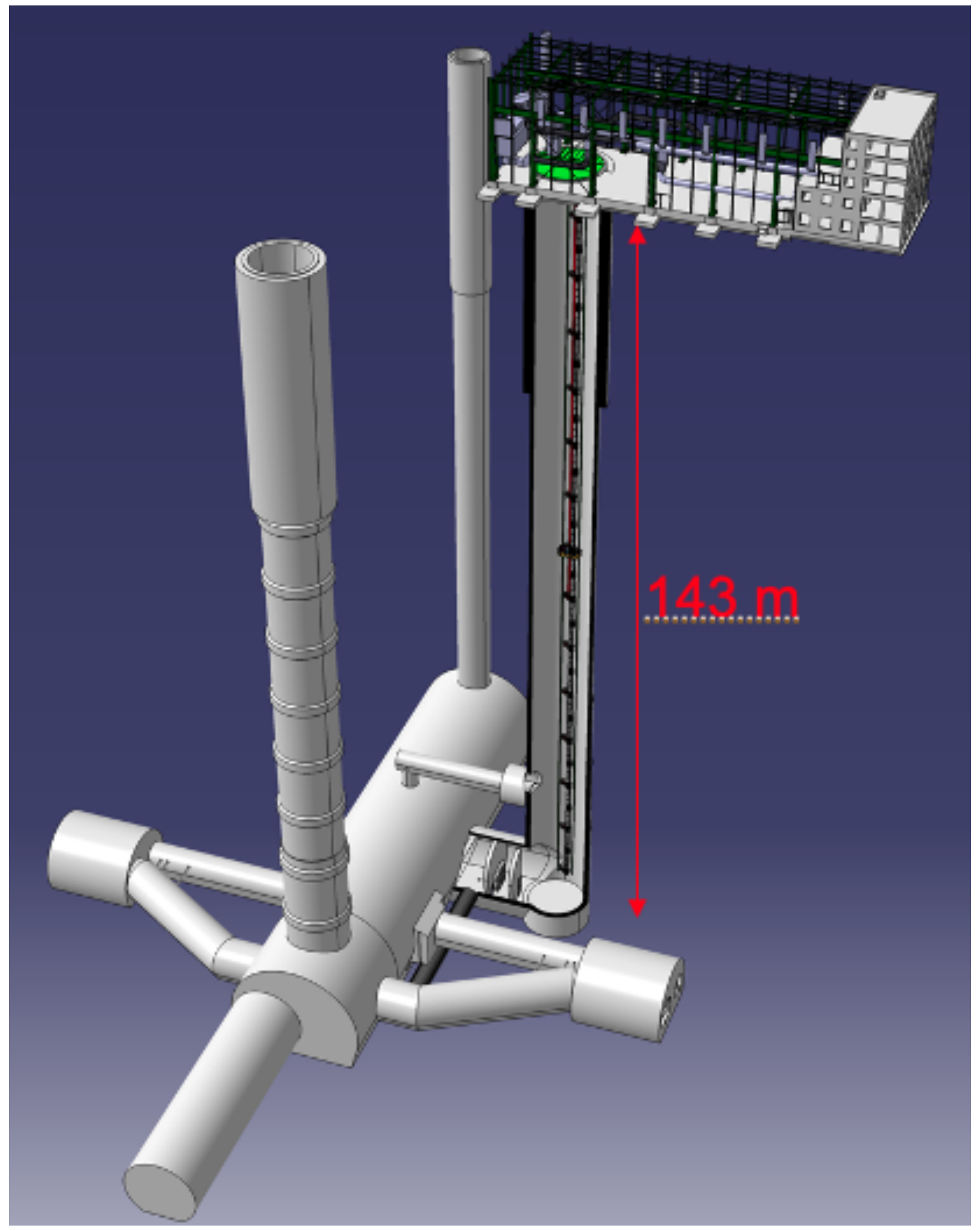
10m ~ 2026+
Stanford
VLBAI
AION-10

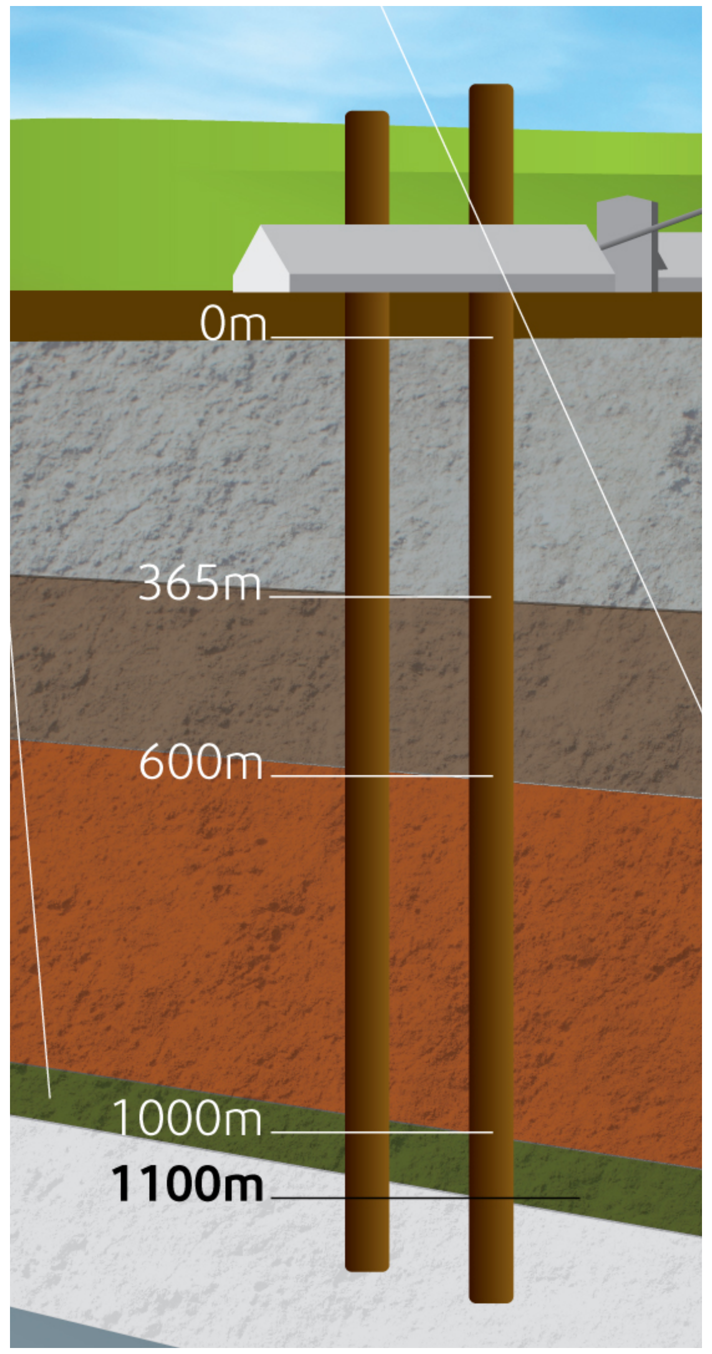
100m ~2030s
MAGIS-100
MIGA, ZAIGA
AICE (CERN)

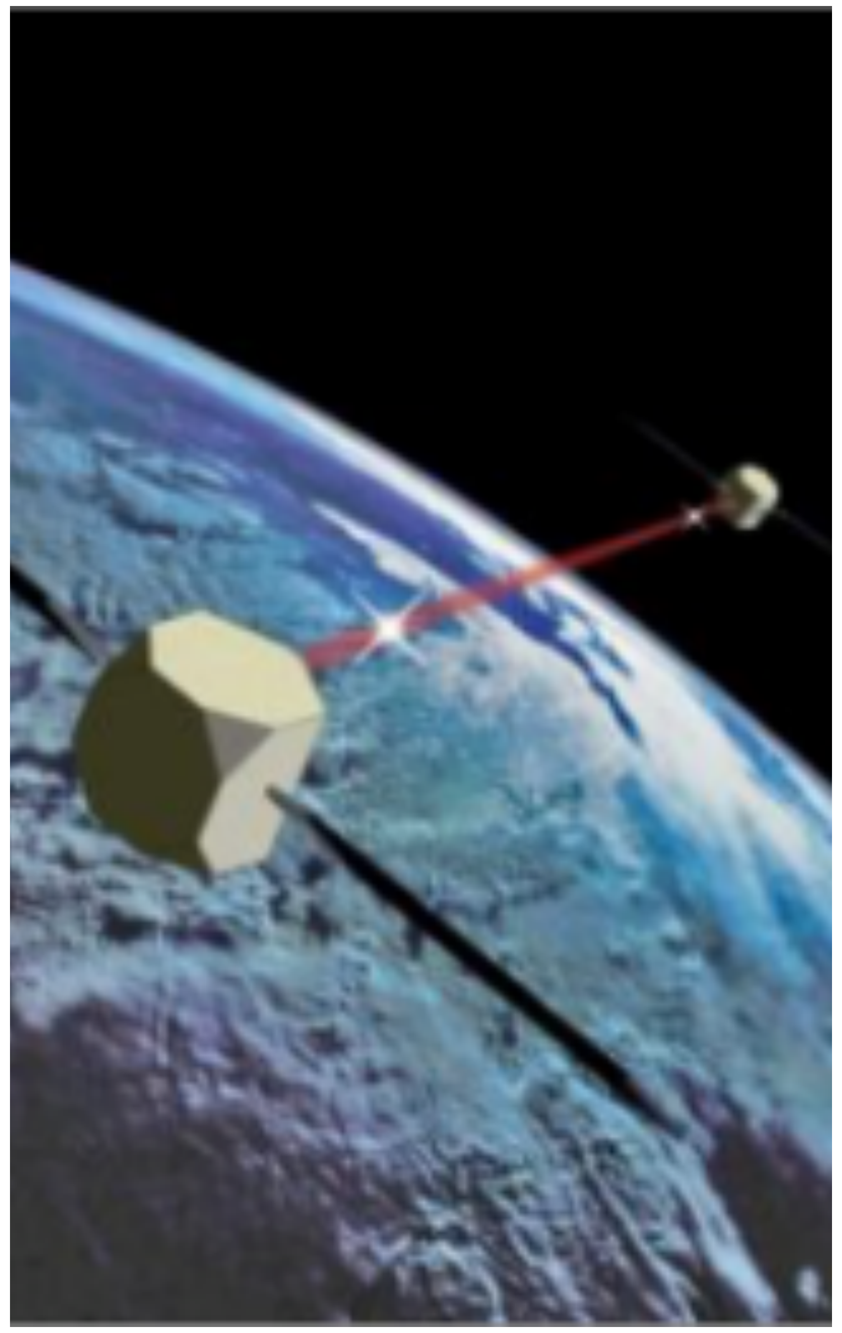
km-instrument
2040s major
international
project(s)

Space-instrument
2050s...
detectors with
~10^7km baseline



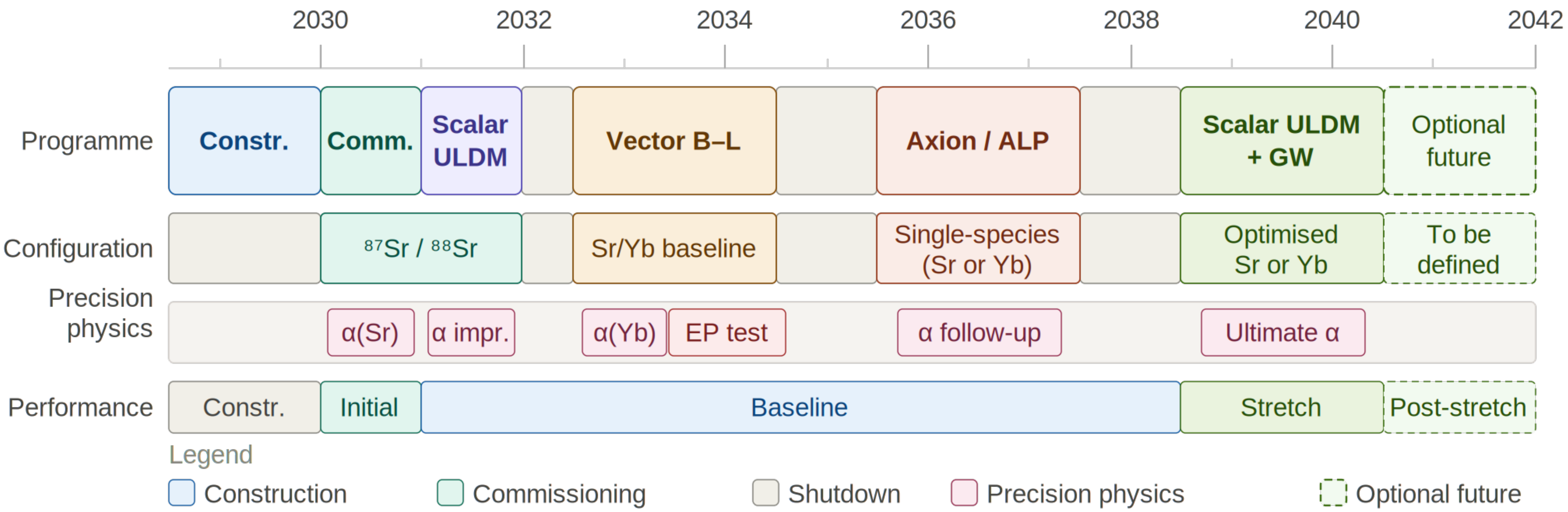






AION-10 technical design: arXiv:2508.03491; CERN studies: arXiv:2304.00614 & 2509.11867; AEDGE, arXiv:1908.00802; Cold atoms in Space, arXiv:2201.07789; TVLBAI arXiv:2503.21366; AICE arXiv: 2509.11867

Possible timeline for AICE (CERN) facility



Searches for (unscreened and screened) scalars

Classifying scalar-field signals

Time-dependent vs **Static**

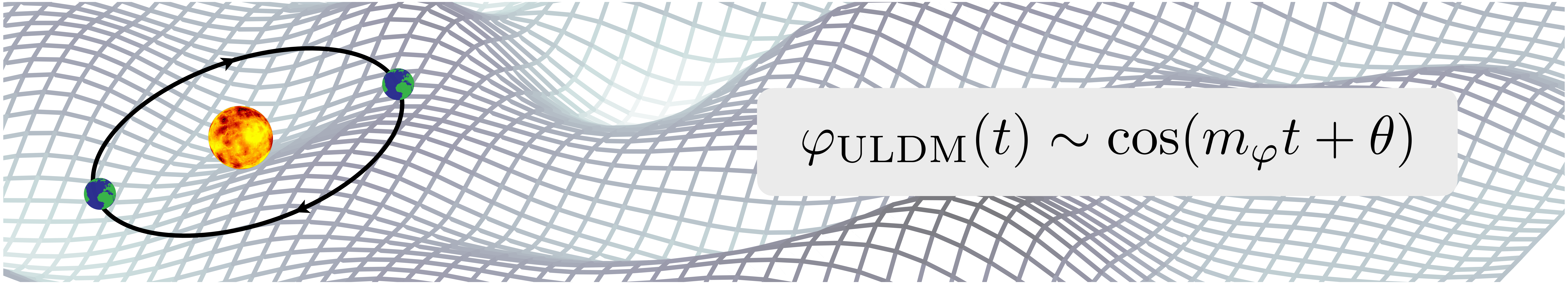
Characteristic frequency of DM signal allows for greater signal discrimination

Careful analysis of systematic effects needed

Time-dependent: ultra-light dark matter

DM lighter than ~few eV behaves as a classical wave

Angular frequency set by the ULDM mass: $\omega \simeq m_\varphi \left(1 + \mathcal{O}(v^2)\right)$



$$\varphi_{\rm ULDM}(t) \sim \cos(m_\varphi t + \theta)$$

e.g., Foster et al arXiv: 1711.10489
Derevianko arXiv:1605.09717

Time-dependent changes in fundamental constants

$$\mathcal{L} \supset \sqrt{4\pi G_N}\phi\left[d_{m_e} m_e \bar{e} e - \frac{d_e}{4} F_{\mu\nu}F^{\mu\nu}\right]$$

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

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

Atom interferometers are extremely sensitive to changes in atomic energy levels

$$\Delta\omega_A(t) \sim [d_{m_e} + \xi_A d_e]\cos(m_\phi t + \theta)$$

See e.g., Geraci et al, arXiv:1605.04048
and Arvanitaki et al, arXiv:1606.04541

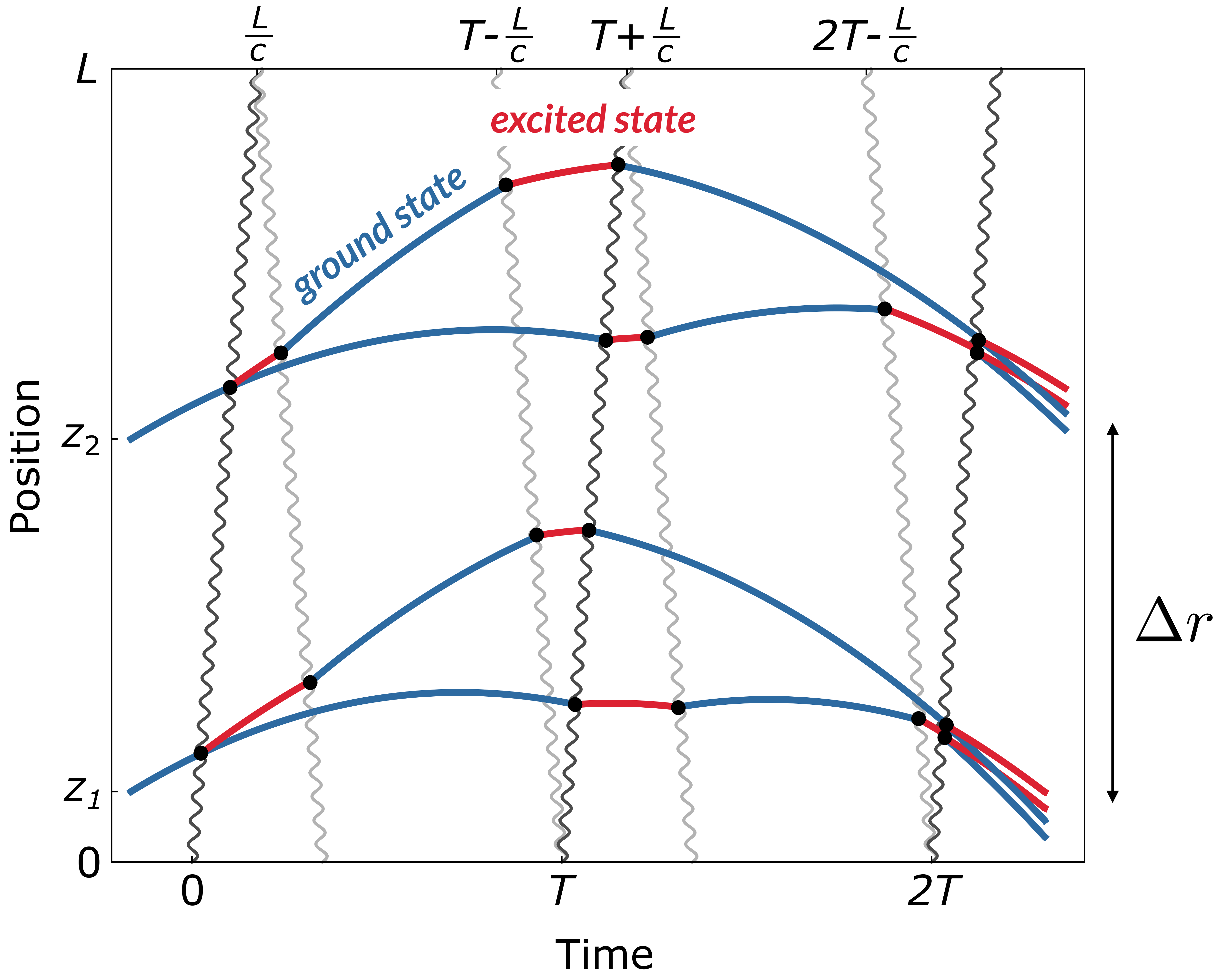
Scalar ULDM signal

Phase is accumulated by the excited state relative to the ground state along all paths:

$$\Phi_{t_1}^{t_2}(\mathbf{r}) = \int_{t_1}^{t_2} \Delta\omega_a(t,\mathbf{r})dt$$

$$\Delta\omega_A(t) \sim [d_{m_e} + \xi_A d_e] \cos(m_\phi t + \theta)$$

t_1, t_2 = time in excited state



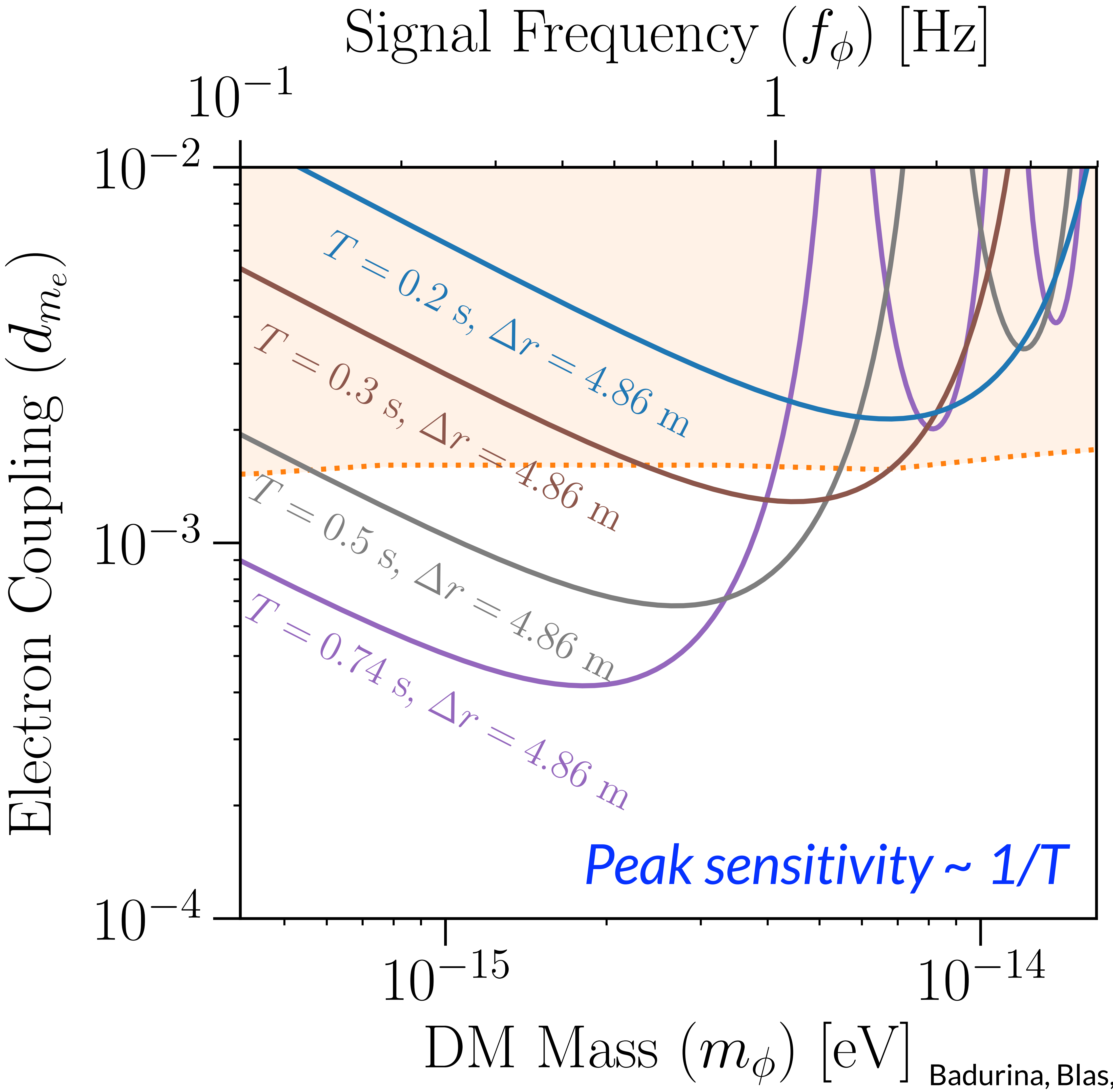
Can go beyond existing constraints at ~10m scale

$$d_{m_e}^{\text{best}} \sim \left(\frac{1}{T}\right)^{5/4} \frac{1}{C\,n\Delta r} \left(\frac{\Delta t}{N_a}\right)^{1/2} \left(\frac{1}{T_{\text{int}}}\right)^{1/4}$$

Handles to optimise (in order of priority):

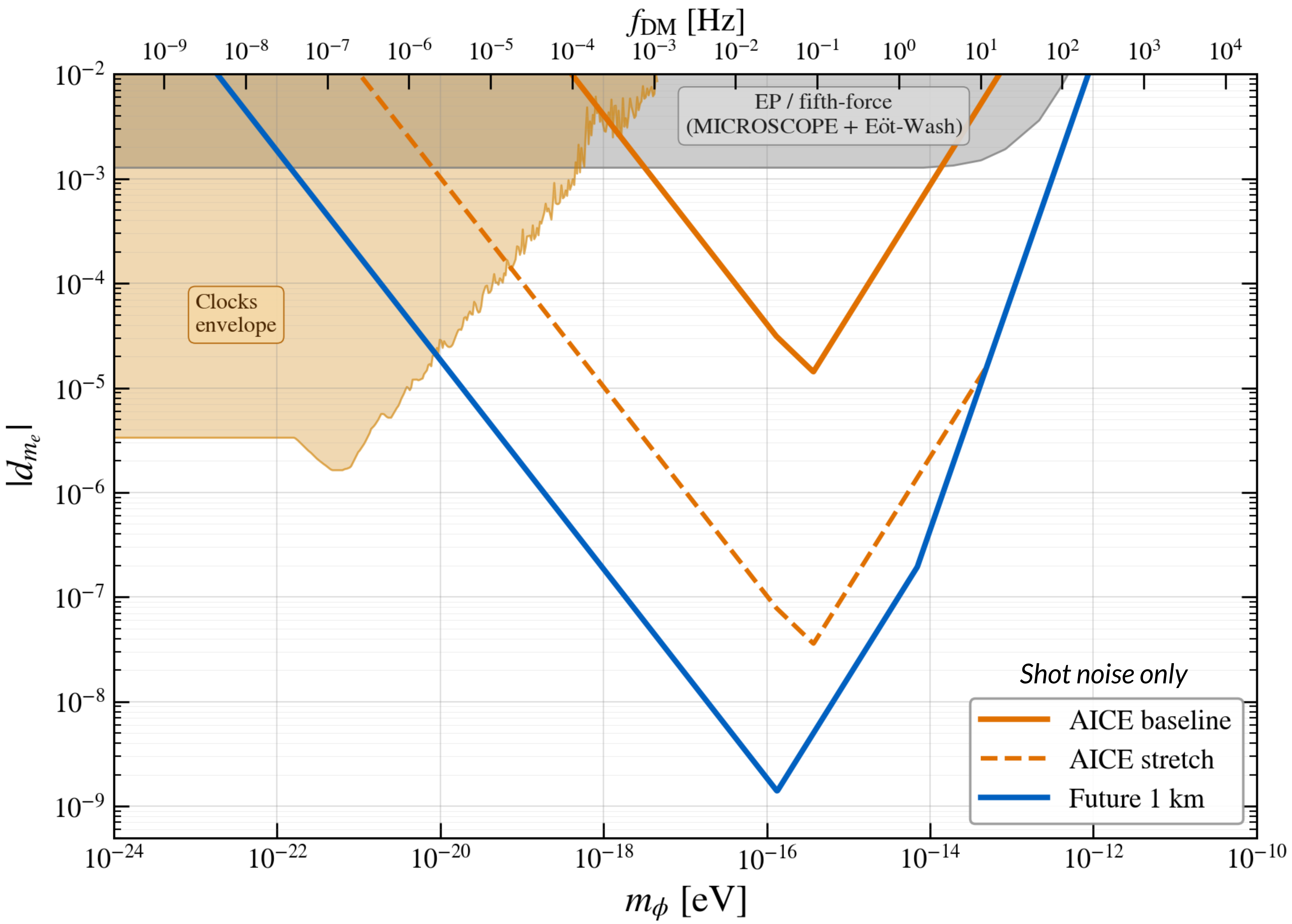
T ~ 1s (interrogation time)
n ~ 1000 (LMT)
Δr ~ AI separation

C ~ 0.1 - 1 (constrast)
Δt ~ sampling time
$N_a \sim$ atoms in cloud
$T_{\text{int}} \sim 10^7\text{s}$ (integration time)



Badurina, Blas, CM
arXiv:2109.10965

~100m and ~1km prospects for scalar ULDM



Parameter	Initial	Baseline	Stretch	1 km
Programme phase	Comm. / Fund. Phys.	Baseline	Stretch Goal	Future Facility
Baseline L [m]	140	140	140	1000
$T_{\rm grad}$ [s]	2.5	2.5	2.5	7.0
$T_{\rm MZ}$ [s]	5.0	5.0	5.0	14.0
$T_{\rm ax}$ [s]	5.0	5.0	5.0	14.0
n (LMT)	~ 10–100	10^3	4×10^4	4×10^4
$N_{\rm source}$	3	5–10	10–20	$\mathcal{O}(100)$
$\delta\phi_{\rm noise}$ [rad/$\sqrt{\rm Hz}$]	$\sim 10^{-3}$–10^{-4}	$\sim 10^{-4}$	10^{-5}	10^{-5}
$t_{\rm int}$	—	1 yr	1 yr	1 yr

Static: Screened scalar (fifth) forces

Matter coupling

$$S_\varphi = \int \mathrm{d}^4x\,\sqrt{-g}\left(-\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - A(\varphi)\rho_\mathrm{m}\right)$$

Real scalar field

Self-interaction potential

Two very well studied classes of theories that lead to screening effects:

$$V_\mathrm{ch}(\varphi) = \frac{\Lambda^5}{\varphi}\,, \quad A_\mathrm{ch}(\varphi) = \frac{\varphi}{M}$$

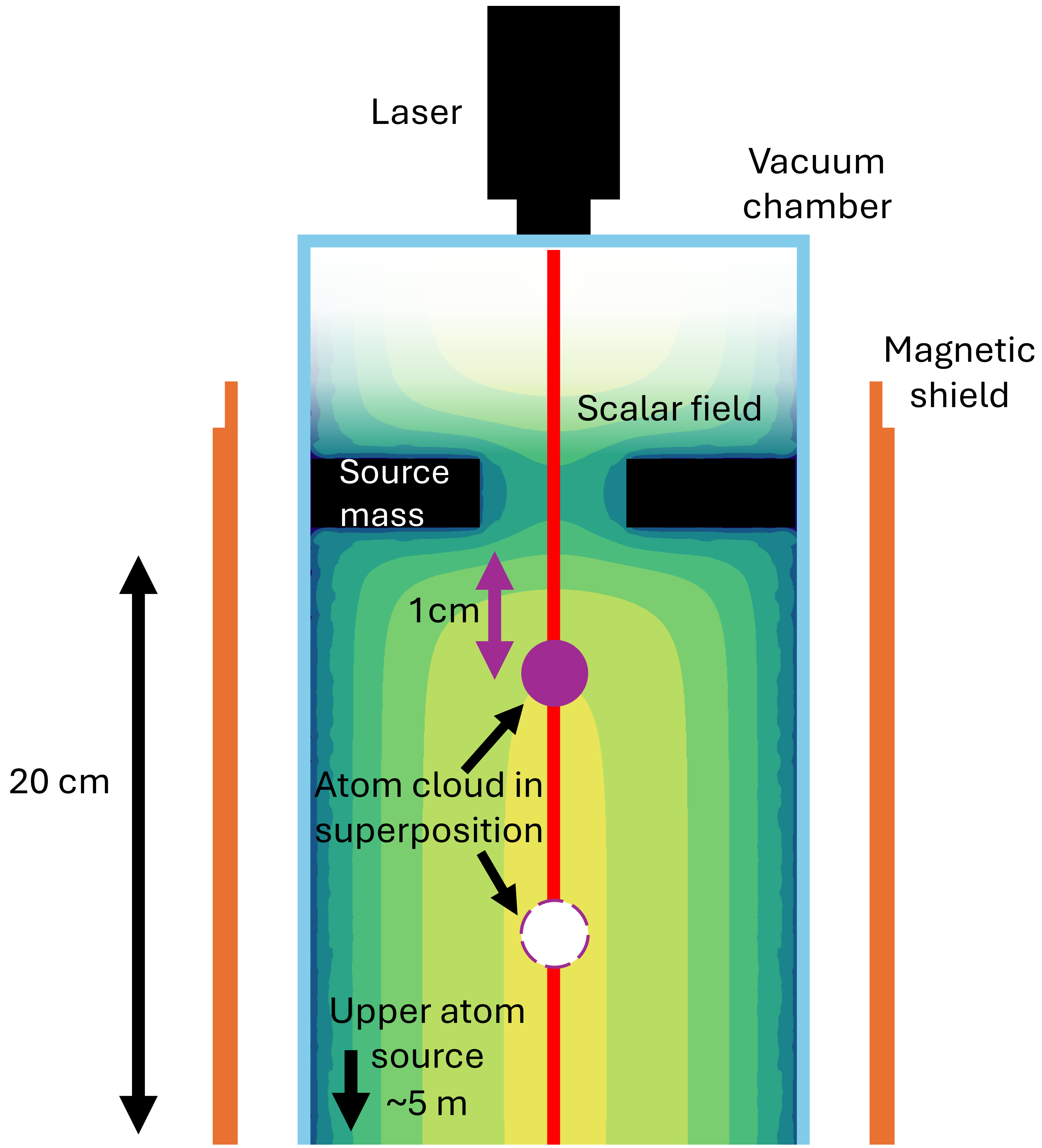
Chameleon

$$V_\mathrm{sym}(\varphi) = -\frac{1}{2}\mu^2\varphi^2 + \frac{\lambda}{4}\varphi^4\,, \quad A_\mathrm{sym}(\varphi) = \frac{\varphi^2}{2M^2}$$

Symmetron

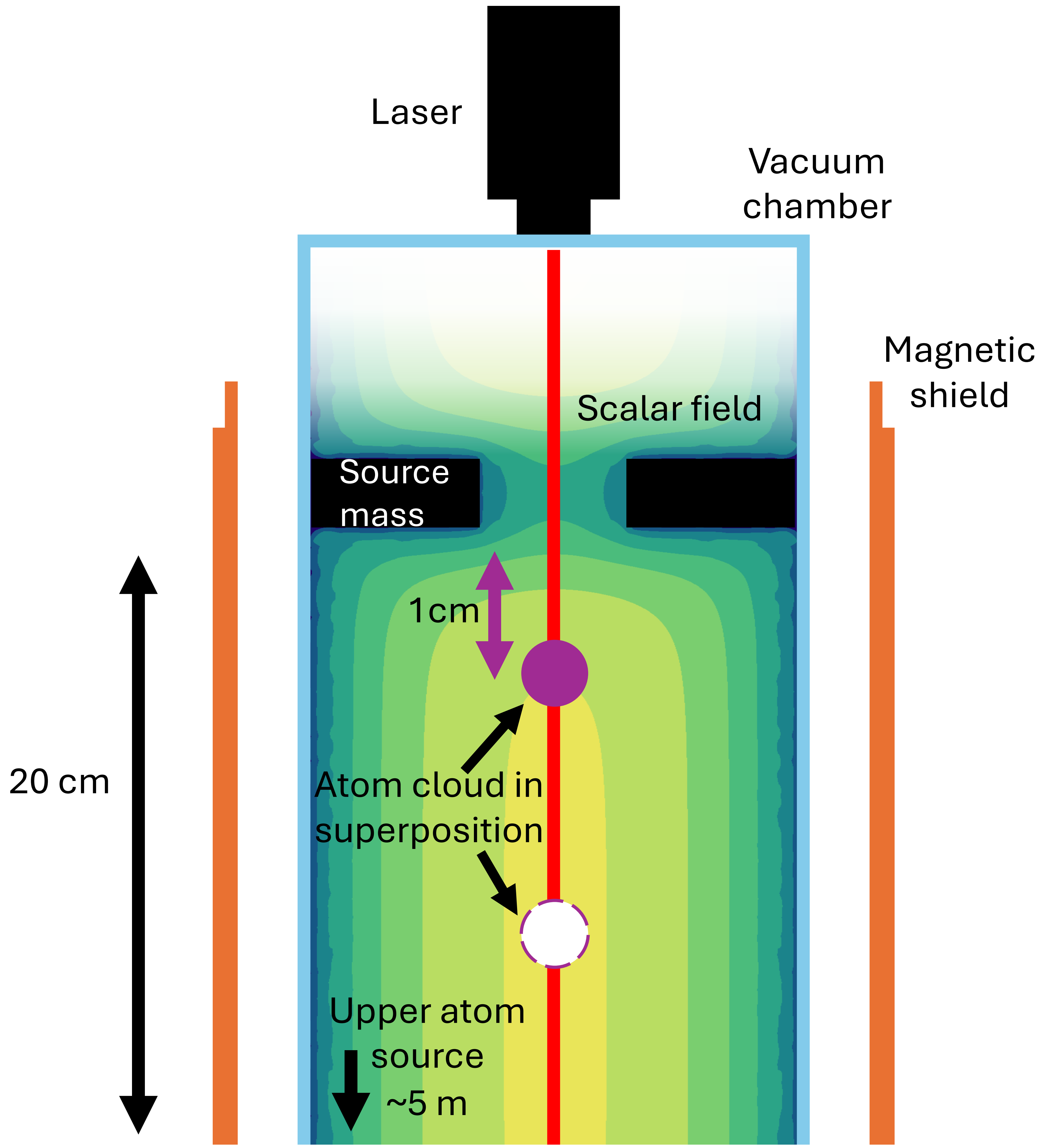
Khoury et al, PRL (2004), PRD (2004)
Hinterbichler et al PRL (2010), PRD (2011)

Static: Screened scalar (fifth) forces



Static scalar field sourced by a mass placed inside the vacuum chamber

Static: Screened scalar (fifth) forces



Static scalar field sourced by a mass placed inside the vacuum chamber

Scalar field induces acceleration on extended objects:

$$\vec{a}_\varphi = -\lambda_a \frac{\mathrm{d}A}{\mathrm{d}\varphi} \vec{\nabla}\varphi(\vec{x})$$

Key parameter is (model-dependent) screening factor

$$\lambda_a \ll 1 \text{ for macroscopic objects}$$

$$\lambda_{\mathrm{a,ch}}^{\mathrm{atom}} = \min\left(10^8 \left(\frac{\Lambda}{\mathrm{meV}}\right)^{5/3} \left(\frac{M}{M_{\mathrm{Pl}}}\right), 1\right) \text{ for atoms}$$

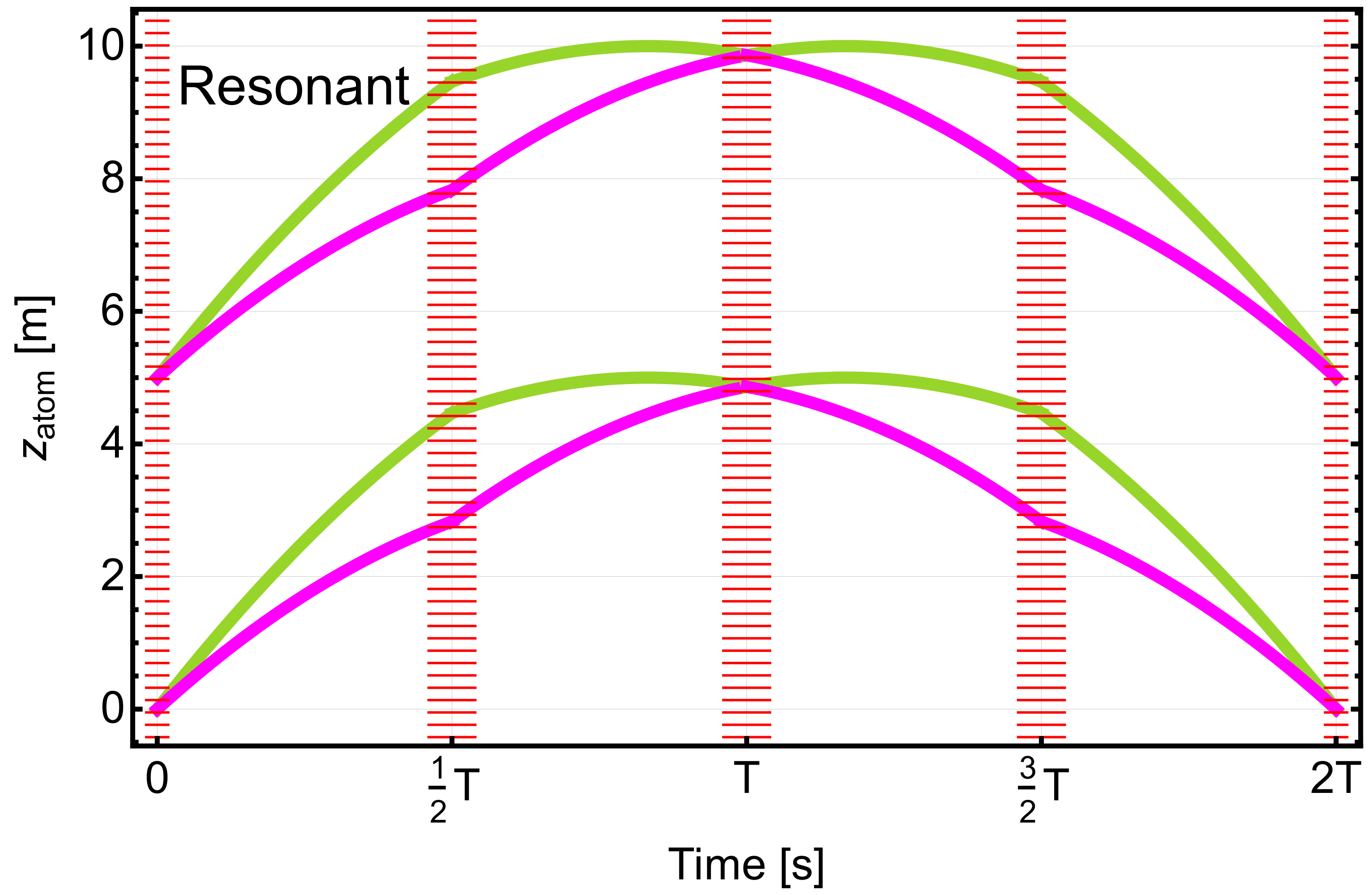
Advantages brought by atom interferometers:

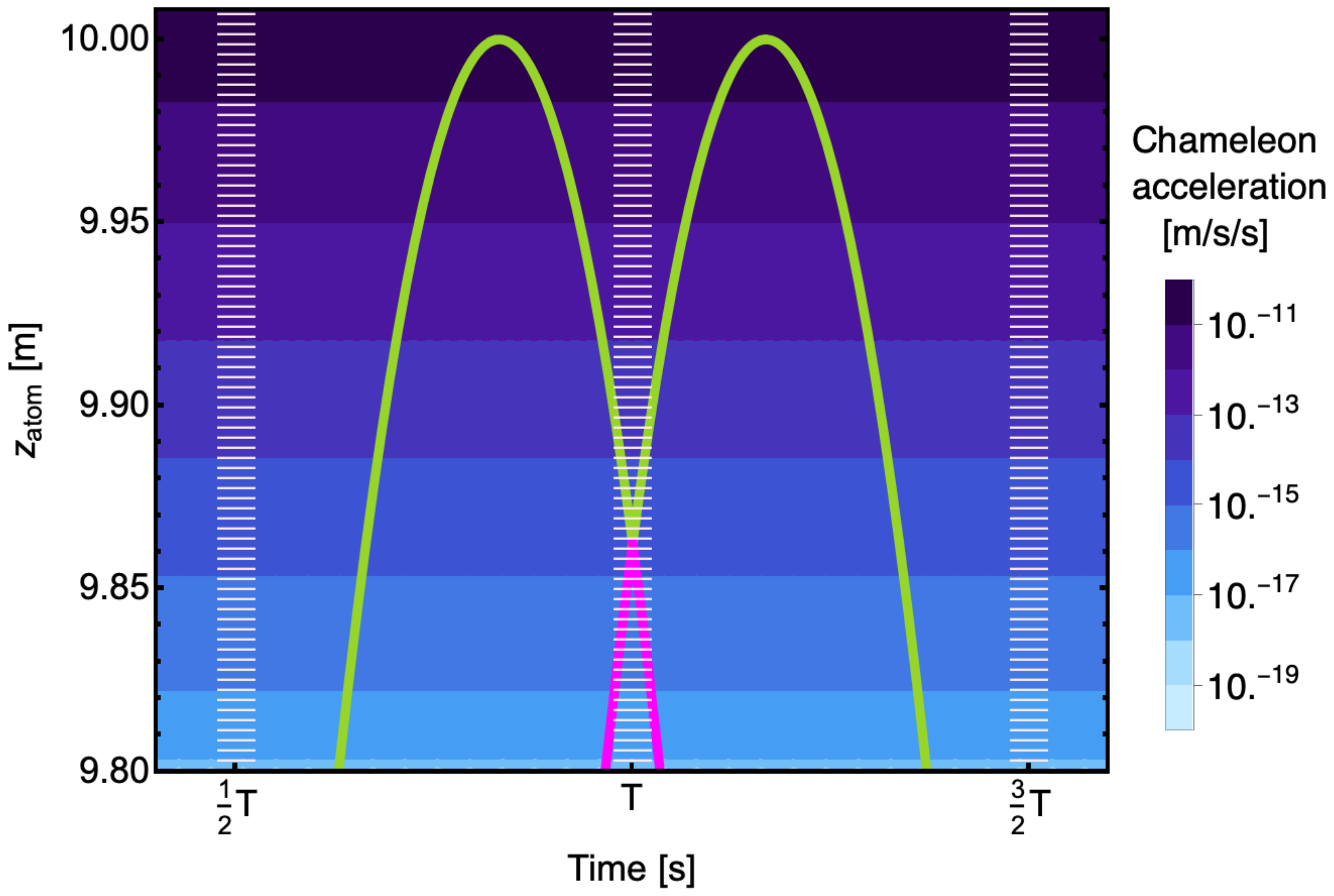
1. ***utilise atoms where screening is reduced***
2. ***are exceptionally sensitive to accelerations***

Burrage et al, JCAP (2015)

Q-flip protocol

Banks, CM, et al,
PRD (2026),
arXiv:2511.09750





Acceleration drops off quickly as you move away from the plate:

want to enhance time atoms spend near the plate

Q-flip protocol

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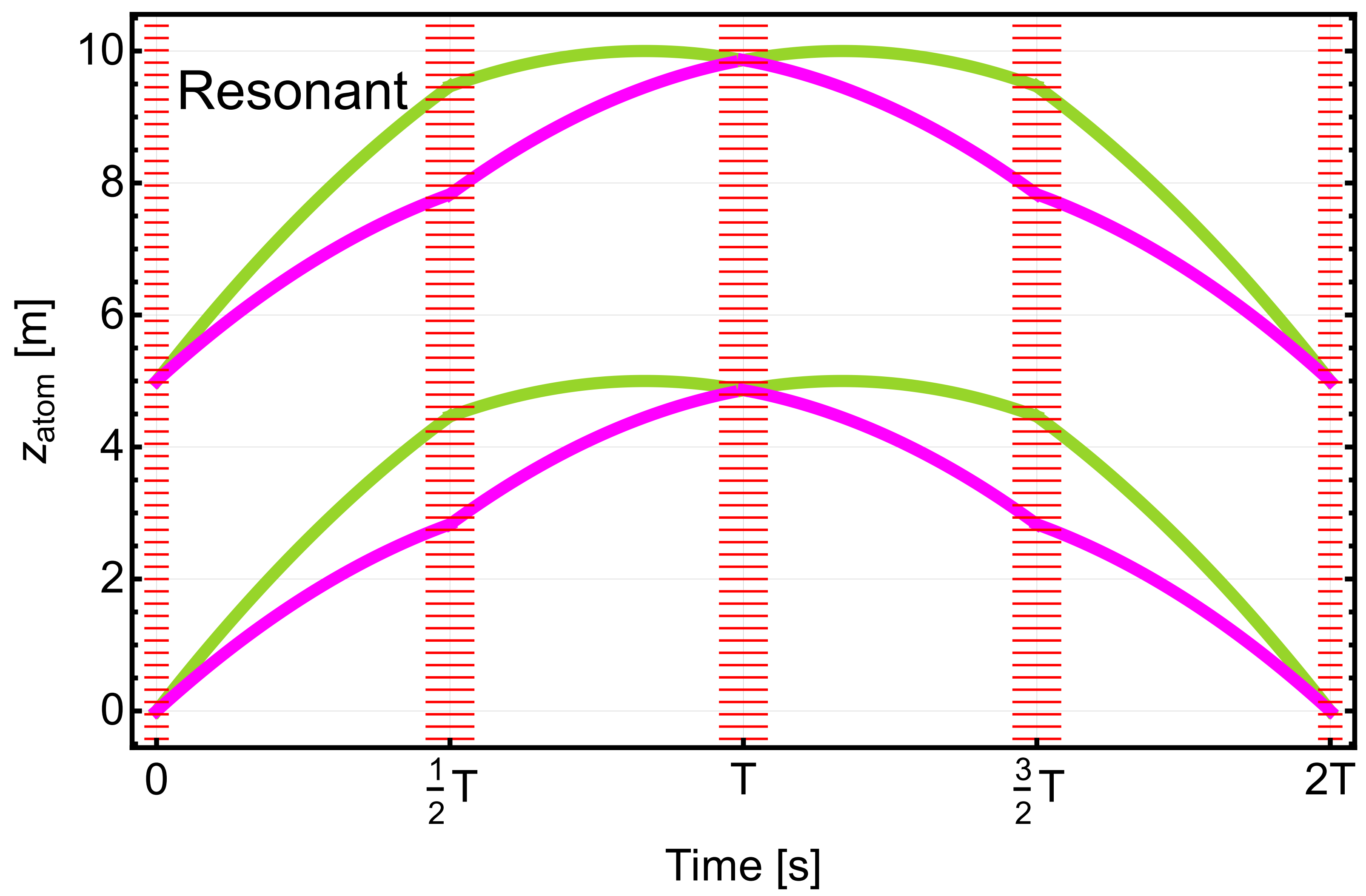

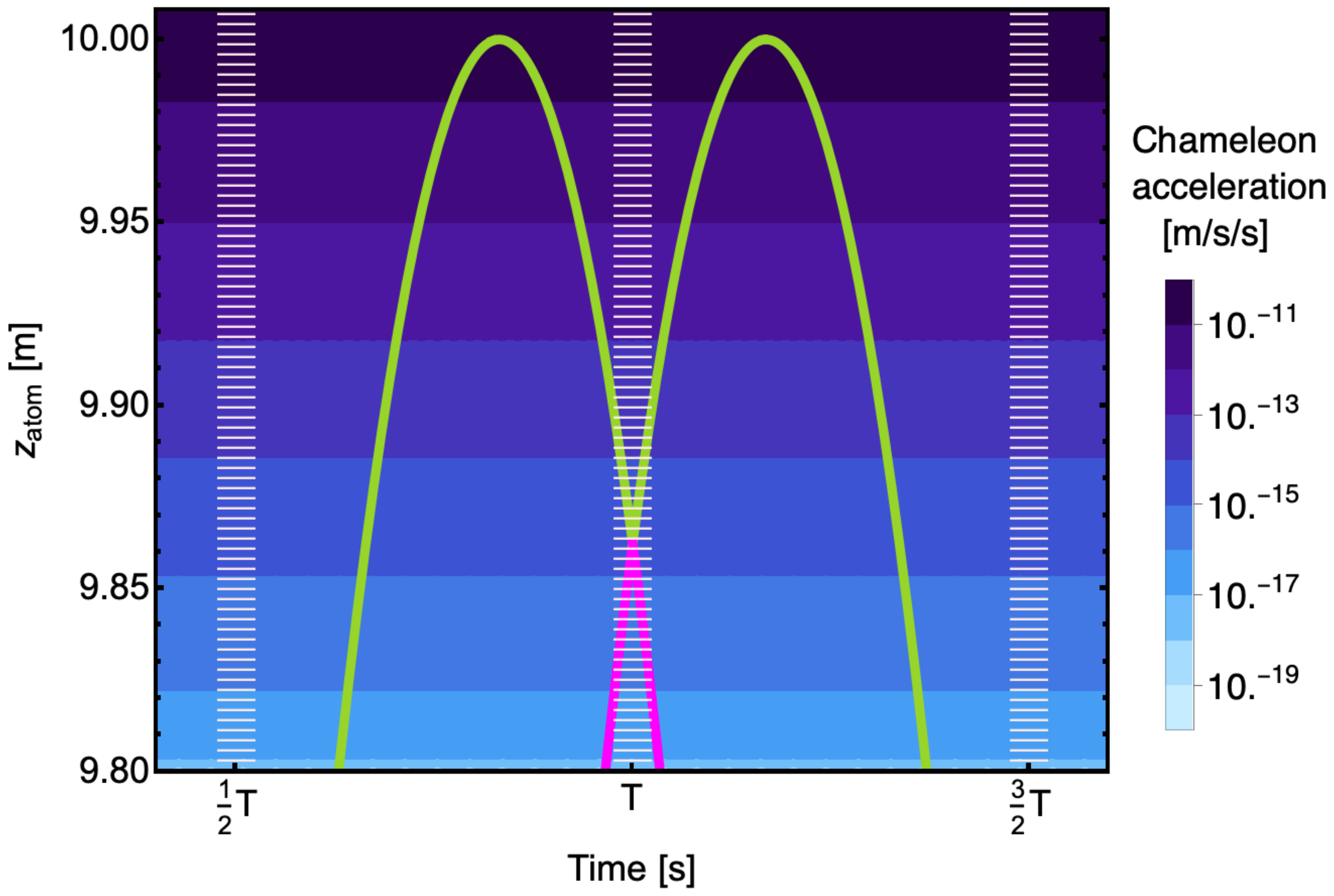

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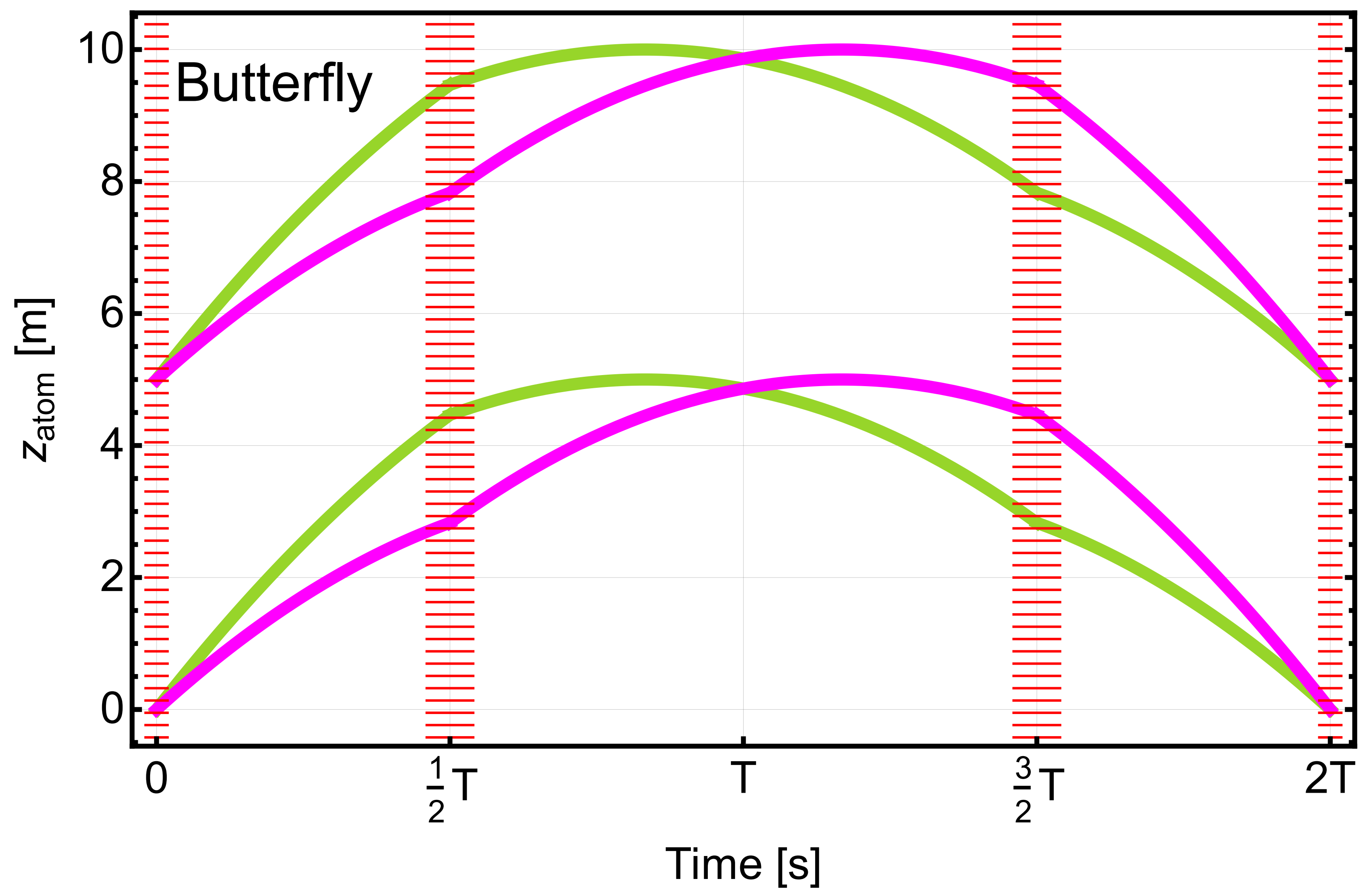

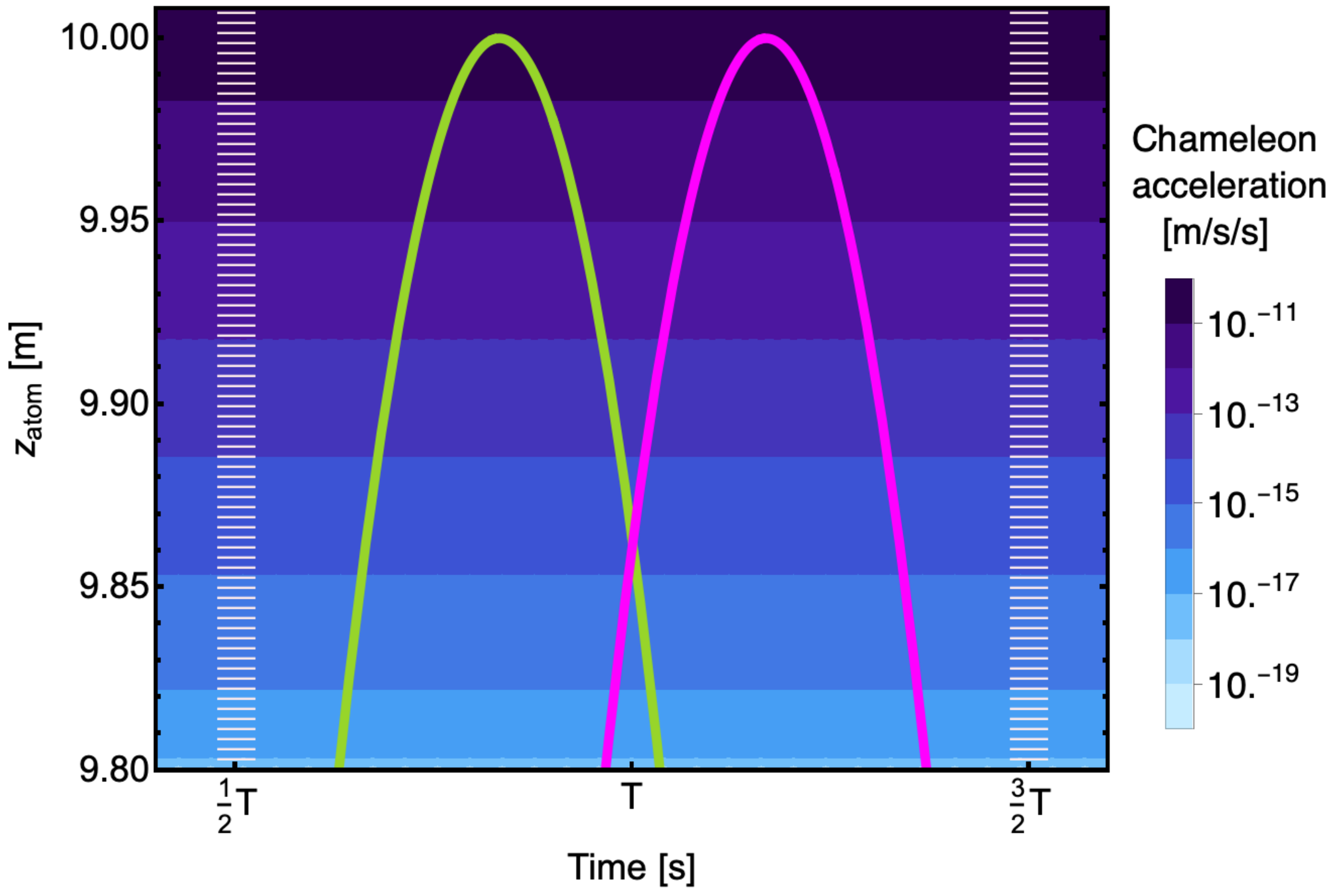

To minimise systematics, alternate sequences with one where the signal cancels

Q-flip protocol

Banks, CM, et al,
PRD (2026),
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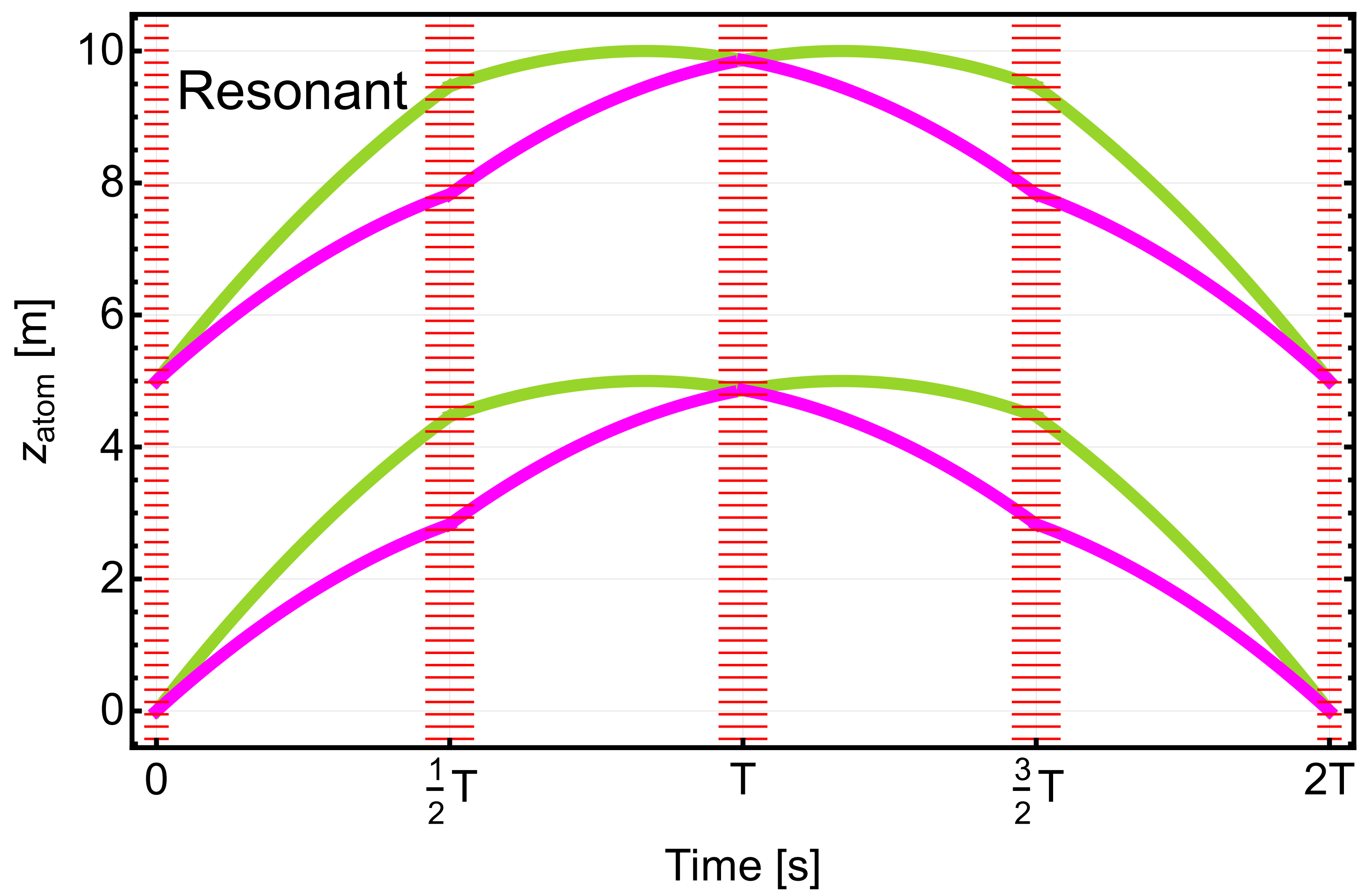
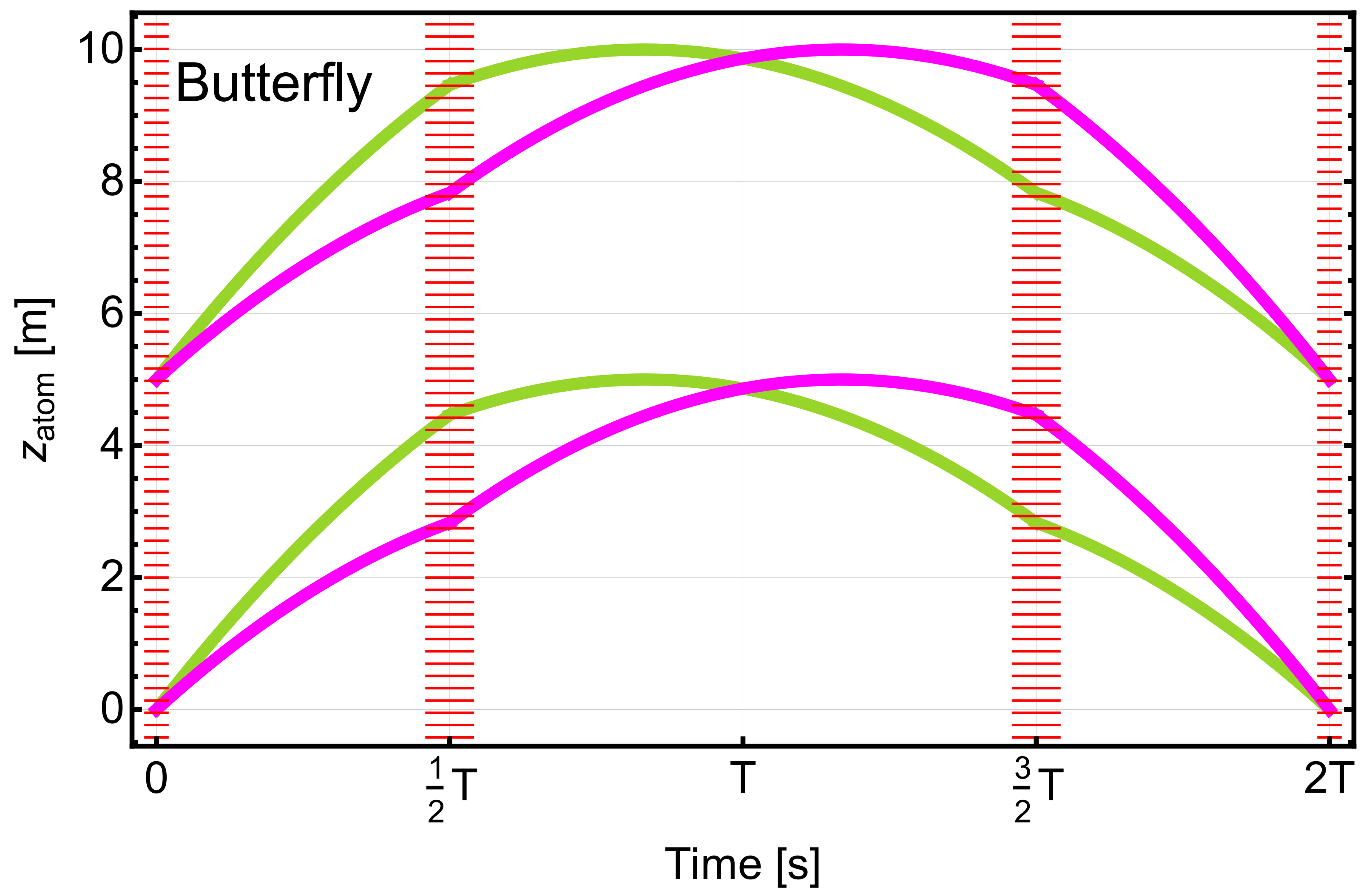
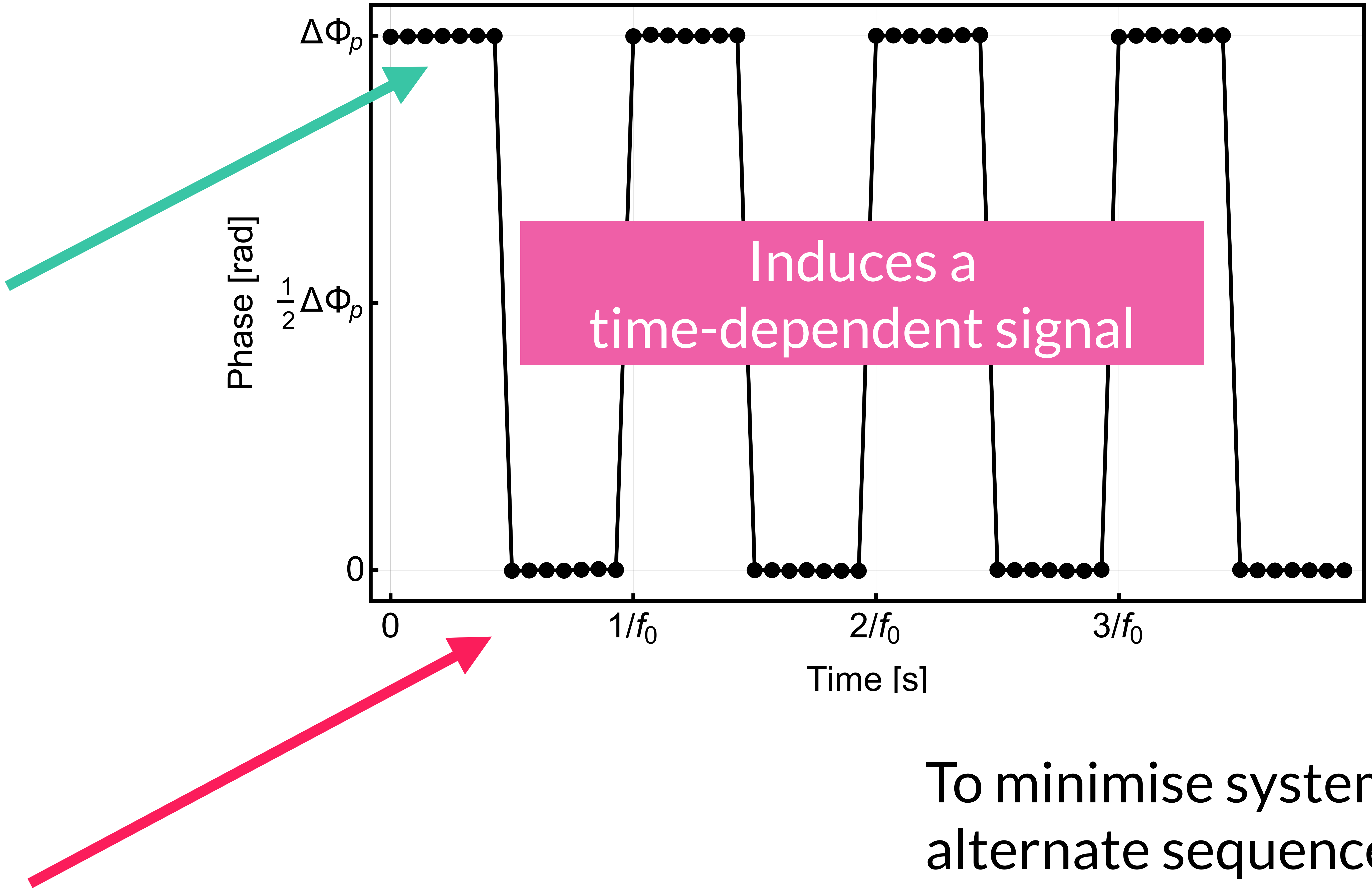




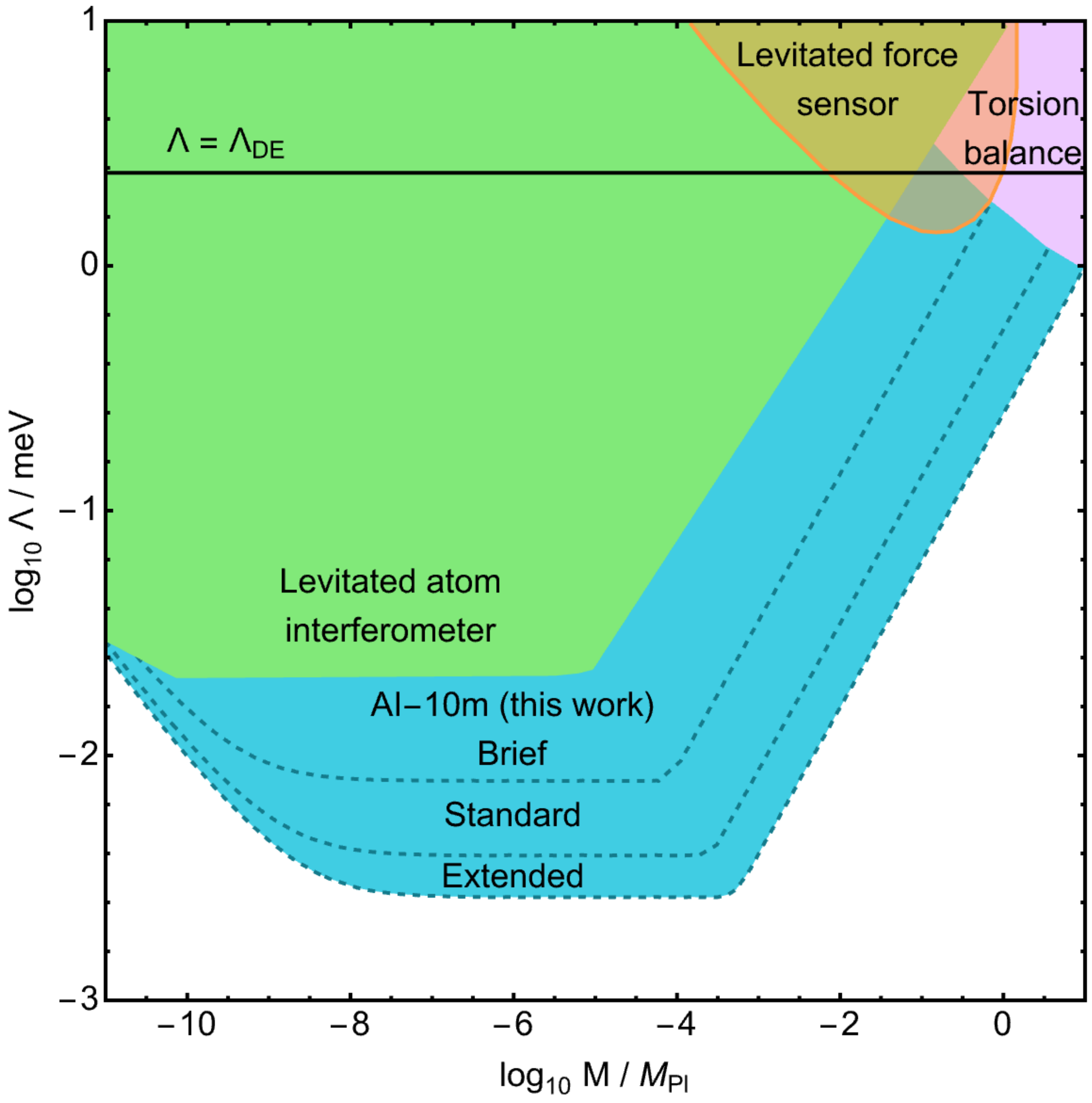


To minimise systematics, alternate sequences with one where the signal cancels

Chameleon sensitivity projections at 10m

Banks, CM, et al,
PRD (2026),
arXiv:2511.09750

AI-10 m	$T_{\rm int}$
Brief	400 s
Standard	12 hrs
Extended	1 week



Get involved...

The AICE Community Workshop 2026 will bring together members of the international atom interferometry, quantum sensing, particle physics, cosmology, gravitational physics, and precision-measurement communities to review the progress of the Atom Interferometer CERN Experiment (AICE), a proposed long-baseline atom interferometer facility at CERN:

https://cds.cern.ch/record/2941923

Summary

- Long-baseline atom interferometers provide a platform to search for ULDM and fifth forces, gravitational waves, test the equivalence principle, and measure the fine structure constant

- Experimental landscape maturing rapidly: first Sr-87 gradiometer demonstration (AION, Nature 2026); concurrent progress across MAGIS-100, MIGA, VLBAI, ZAIGA; TVLBAI roadmap (10m → 100m → km → space) provides credible path to scale

- Scalar ULDM: sensitivity scales as T^(5/4); 10m instruments already competitive, AICE projects orders of magnitude of new parameter space in ULDM-couplings

- Screened scalars: atoms are unscreened where macroscopic objects are not — the key advantage; Q-flip protocol converts static signal to time-dependent, enabling spectral discrimination and systematic rejection