

Dark matter searches with AION-10 (and beyond)

Christopher McCabe

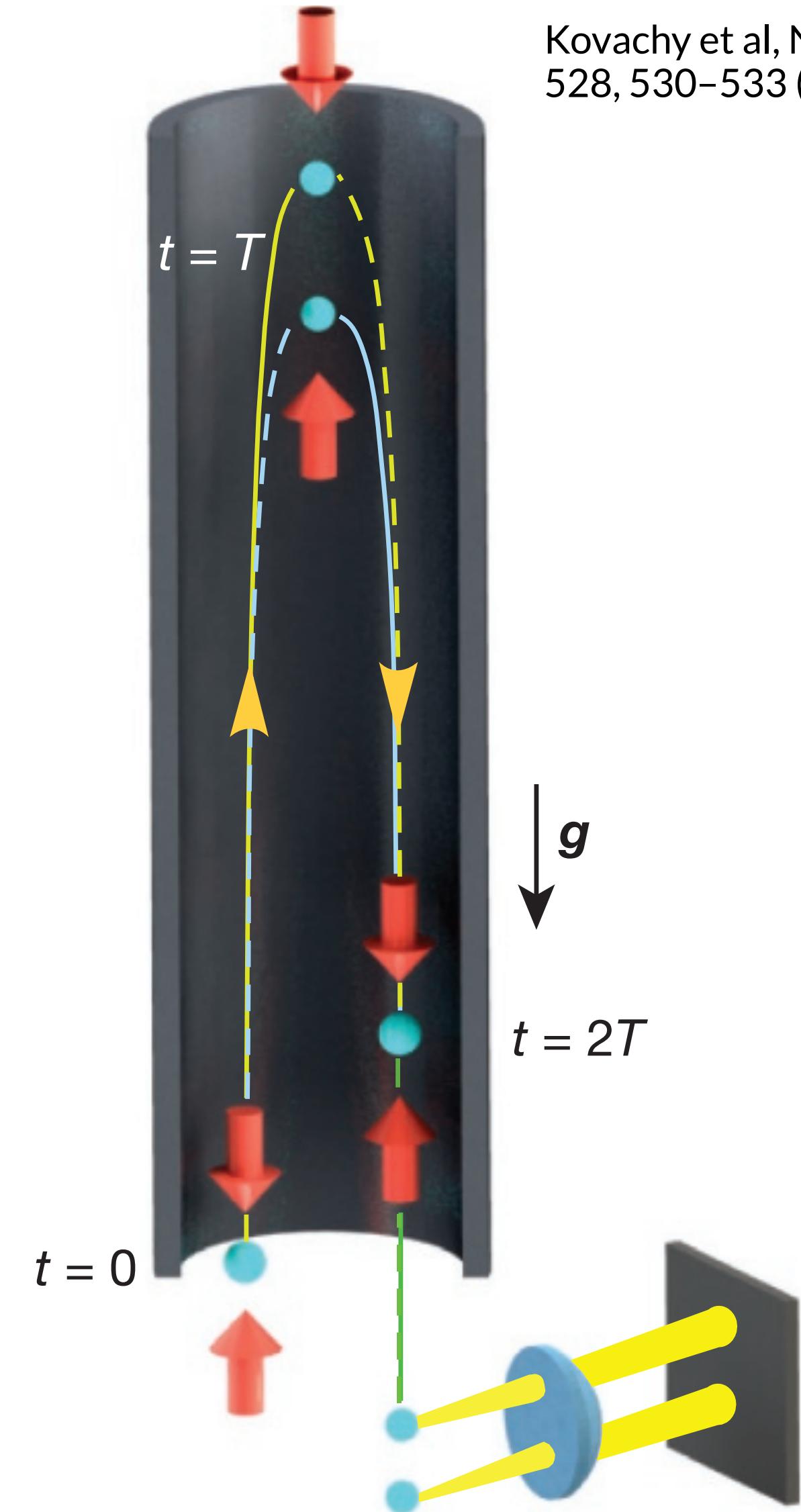
in collaboration with Leonardo Badurina, Ankit Beniwal, Diego Blas, John Carlton, John Ellis, Val Gibson, Jeremiah Mitchell, and others in AION

Setting the scene

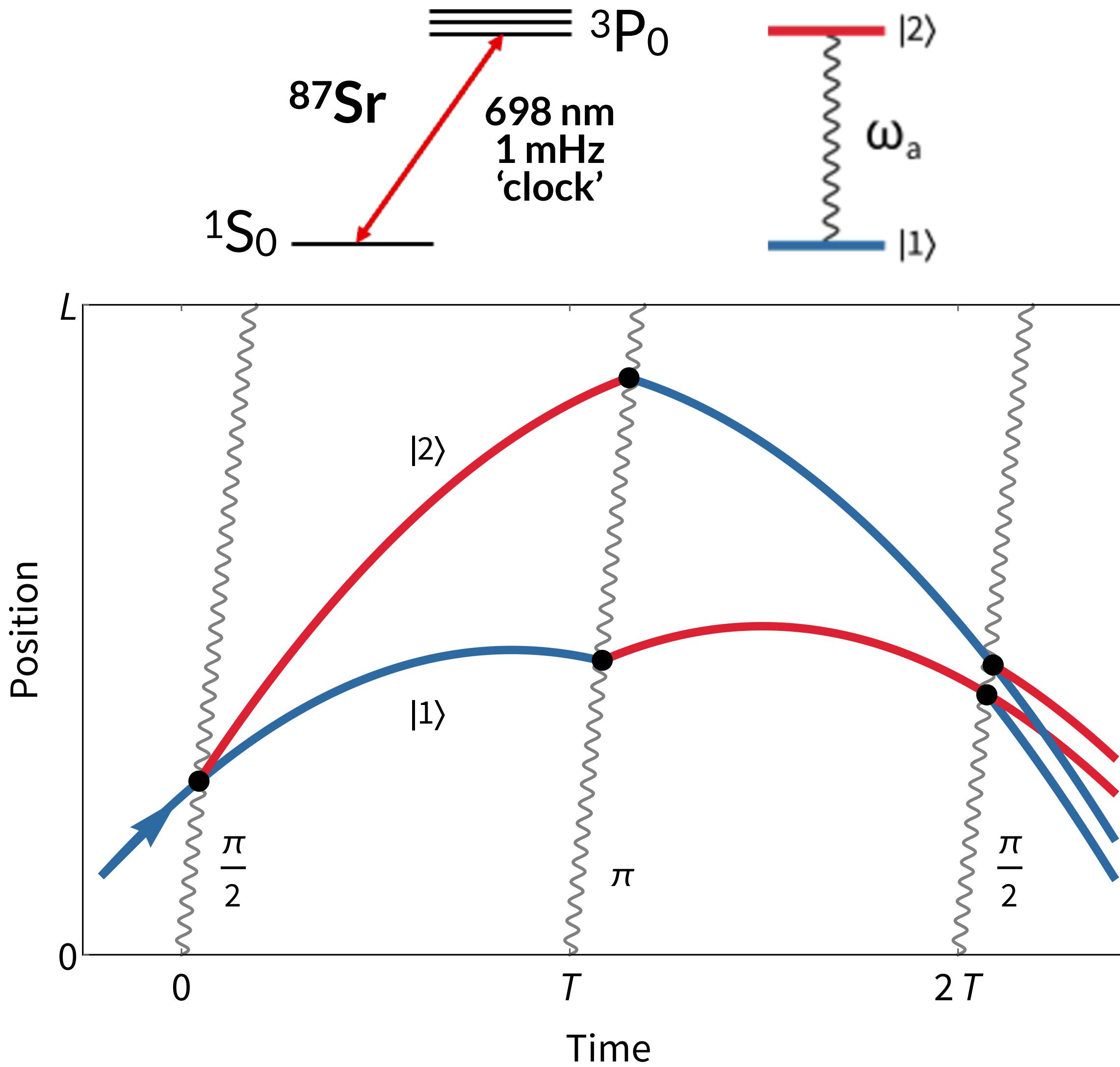
Light pulse atom interferometry (physical-space)

Kovachy et al, Nature
528, 530–533 (2015)

- Launch ultra-cold cloud of atoms in 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
- Repeat: aim for ~Hz sampling rate



Light pulse atom interferometry (space-time)



Two-level system separated by optical frequency difference ω_a

Initial pulse: ‘beamsplitter’

Middle pulse: ‘mirror’

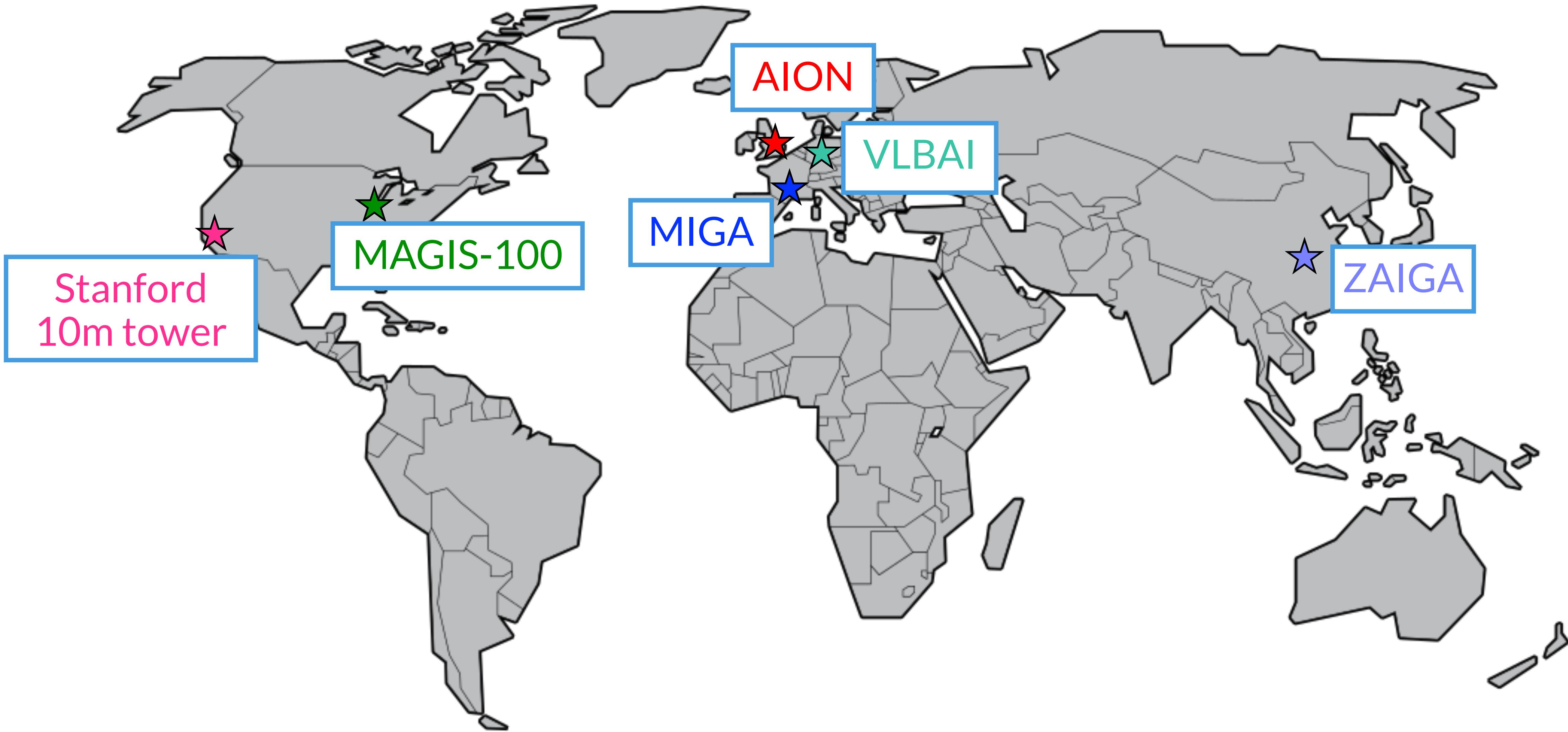
Final pulse: ‘beamsplitter (interfere)’

Atom evolves extra clock phase:

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

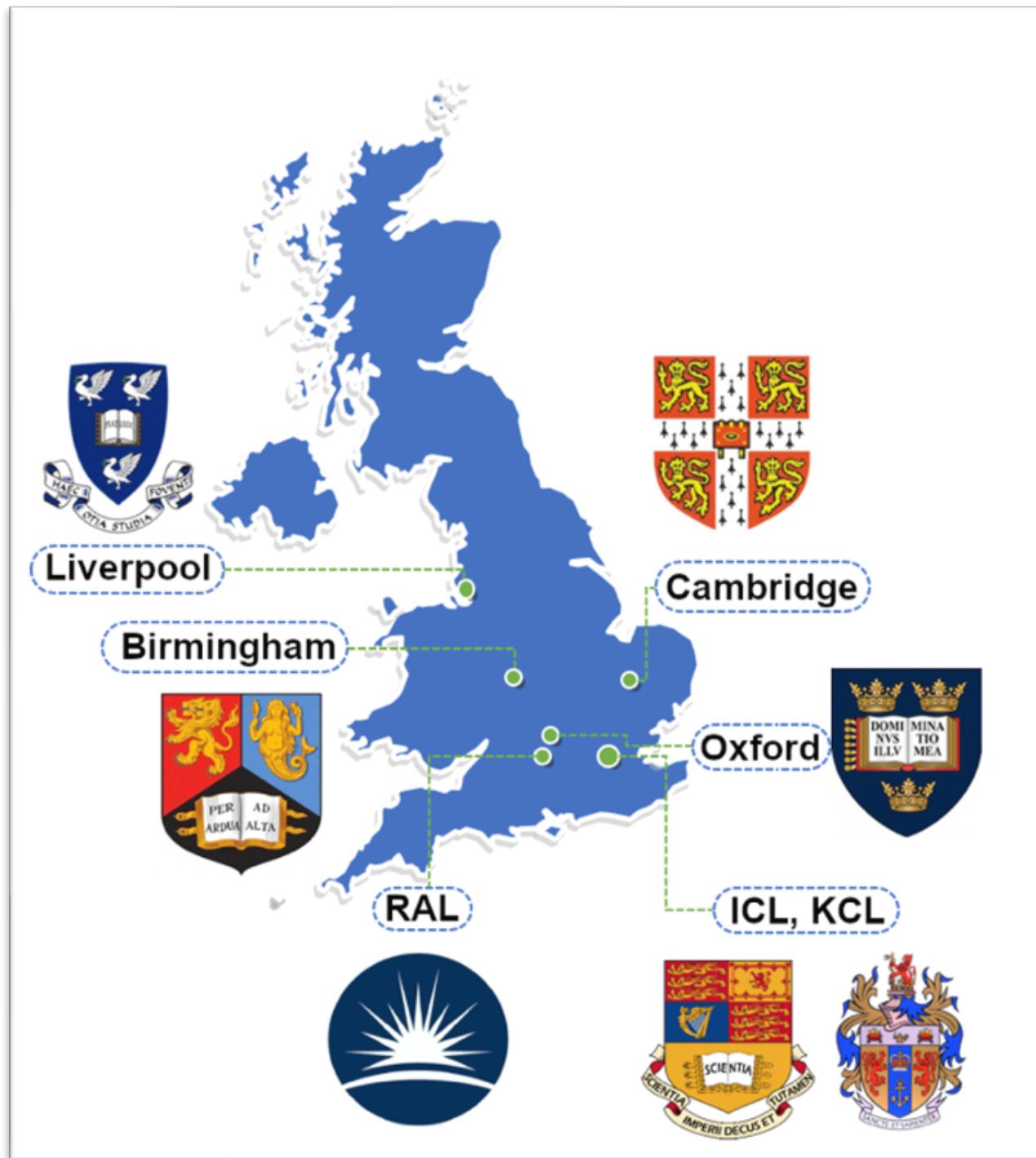
**Phase sensitive to changes in timings,
atomic structure, and local accelerations**

New atom interferometers across the world coming online



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

AION: Atom Interferometer Observatory and Network



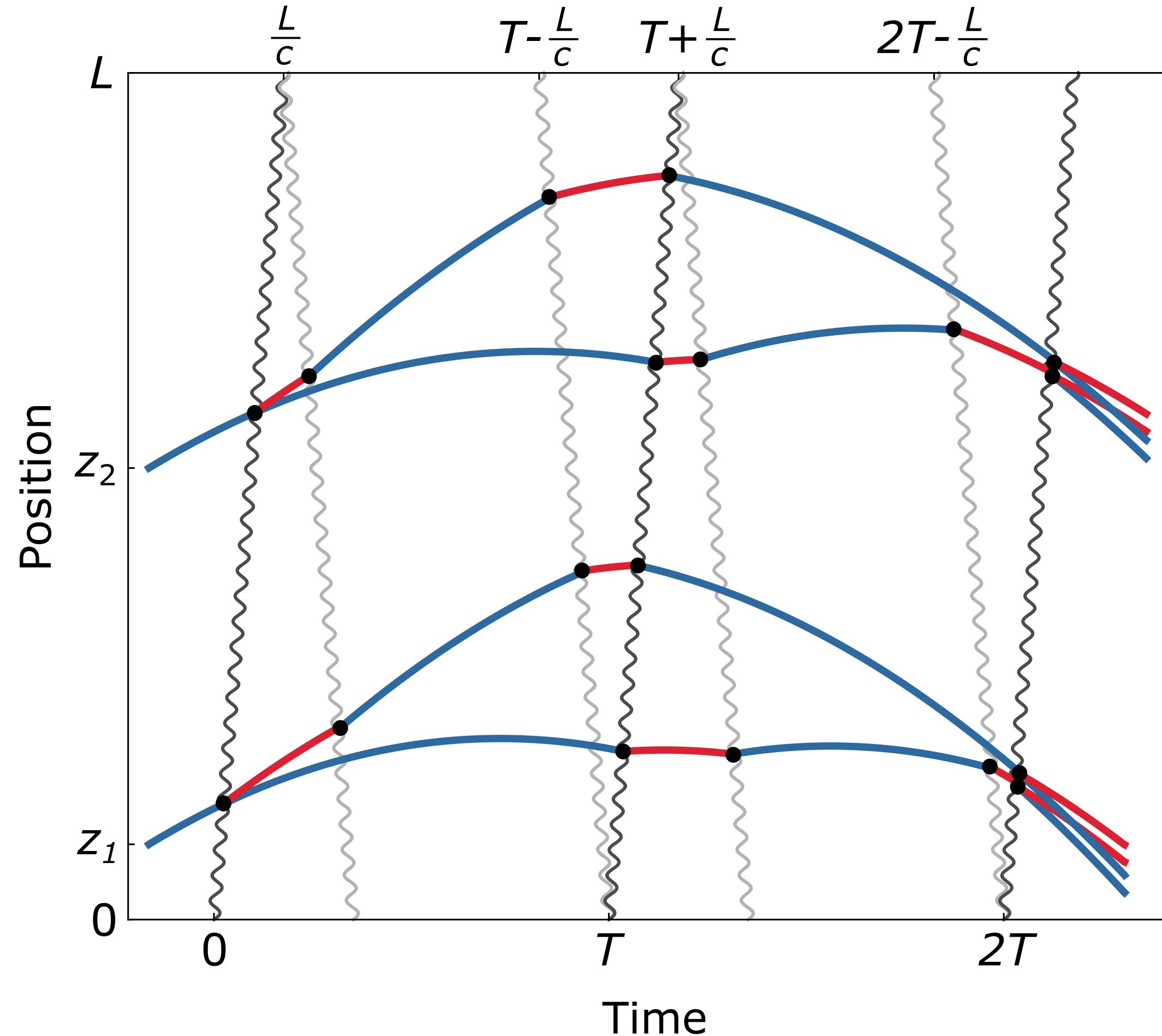
7 institutes in the UK



Autumn 2021

Collaboration ~65 people
Cold atom: fundamental physics ratio is ~2:1

AION: key features



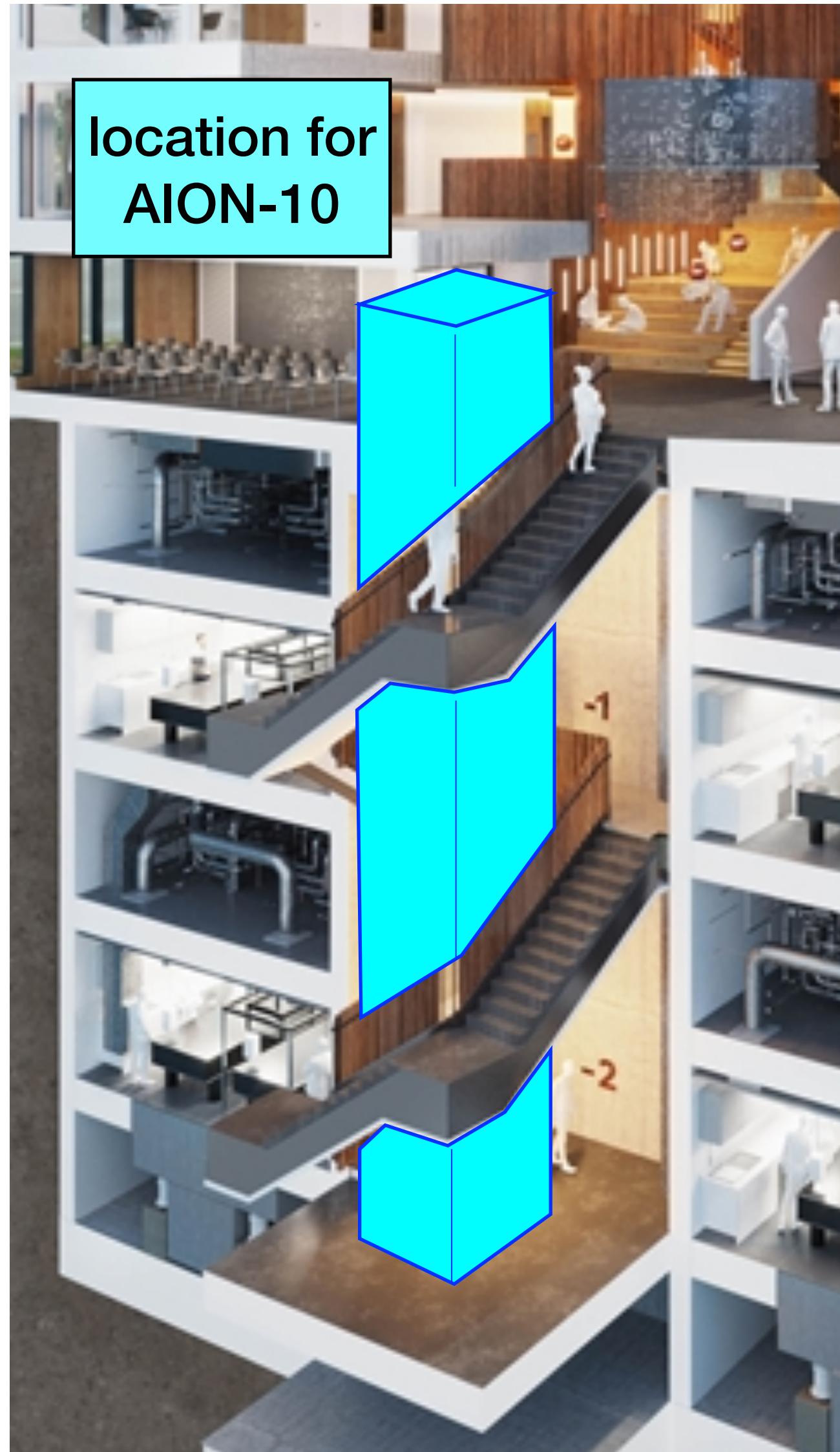
Run **two atom interferometers** simultaneously with the same laser ('gradiometer')

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

Most sensitive to '**mid-band**' (0.1 - 10 Hz) frequencies

Partnering with MAGIS-100 in the US

AION: envisaged as a multi-stage project



Stage 1: AION-10

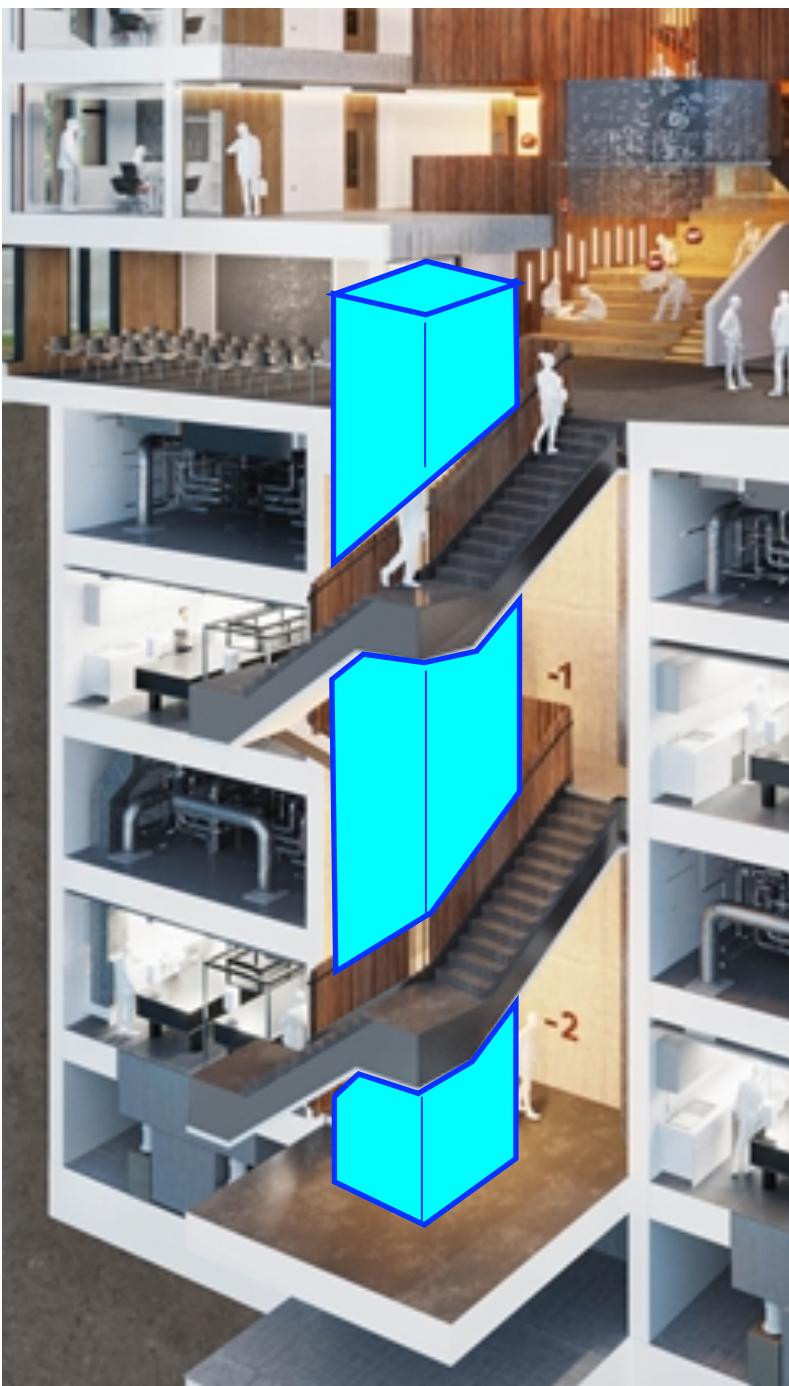
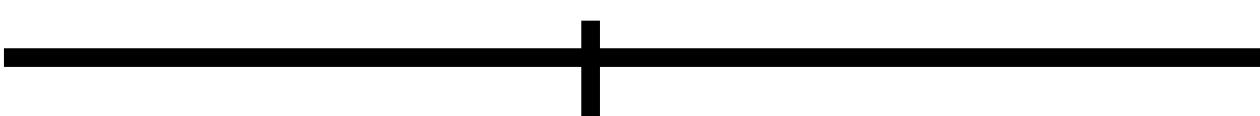
~10m tower in the Beecroft building in Oxford

Now: 5 new Sr labs and design
'24-'26: construction
'26-'27: commissioning
2028+: science

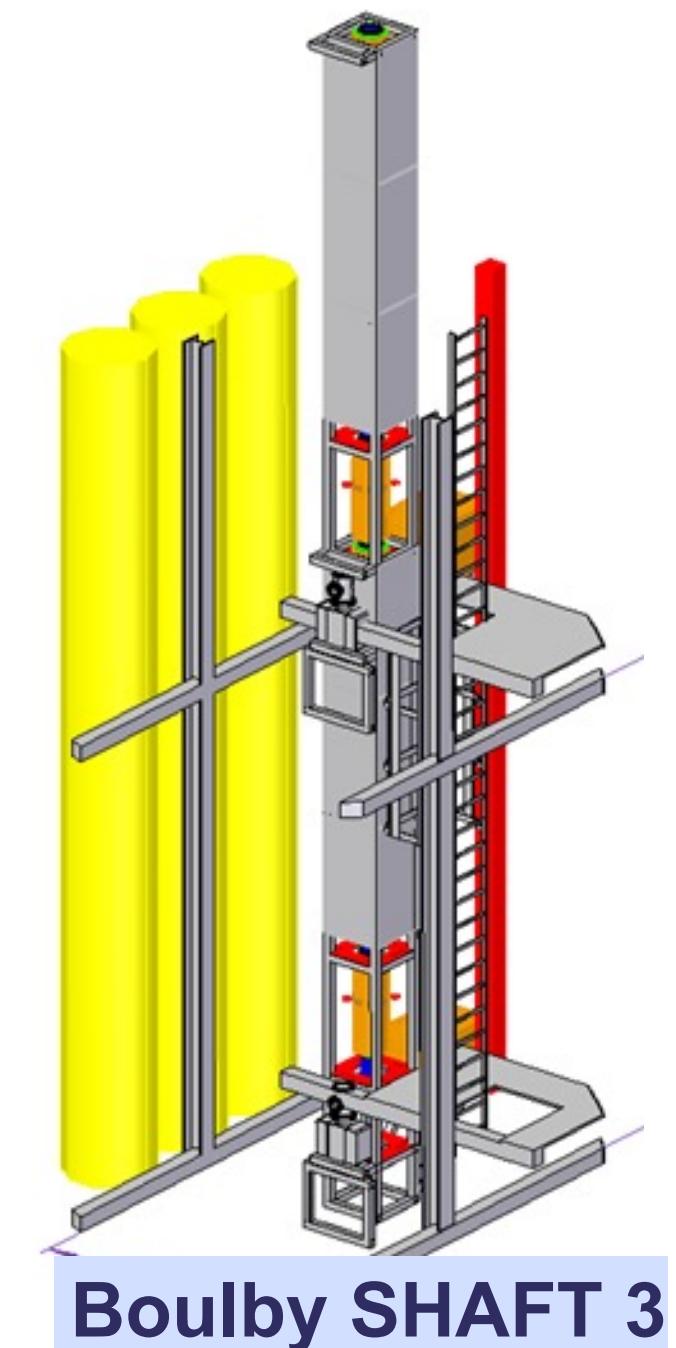
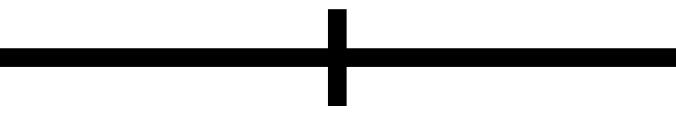
AION Sr lab design and production: arXiv:2305.20060

AION: envisaged as a multi-stage project

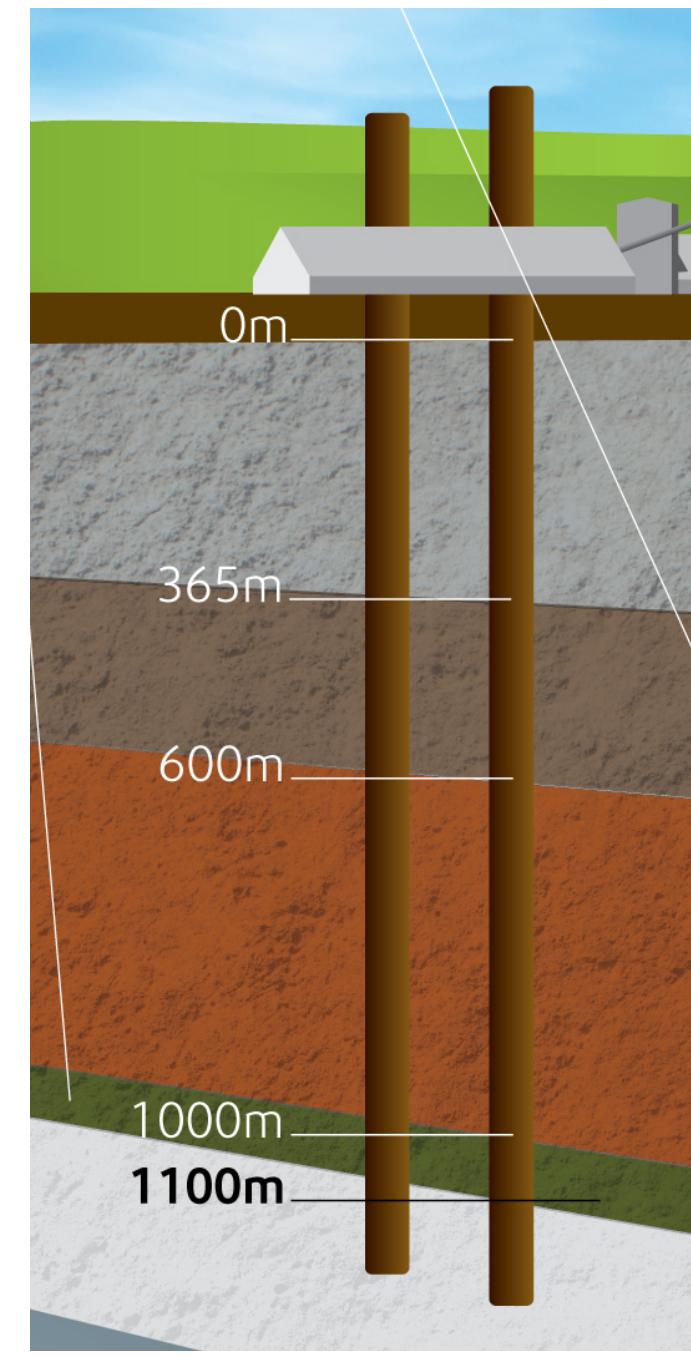
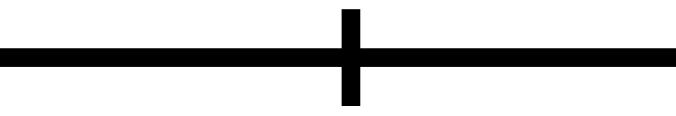
AION-10
2020s ~10m
instrument in
Oxford



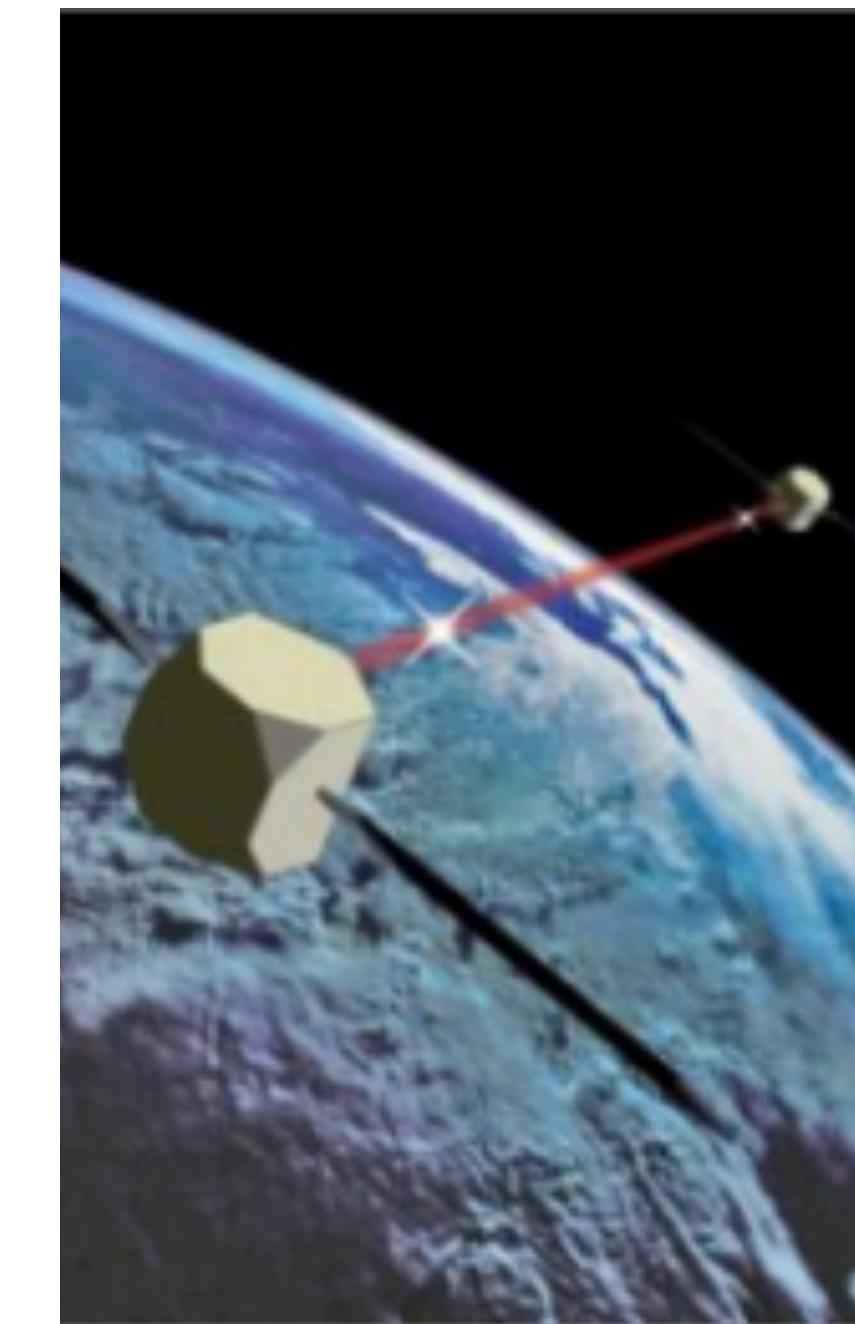
AION-100
2030s ~100m
instrument at
Boulby/CERN/...?



km-instrument
2040s major
international
project



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

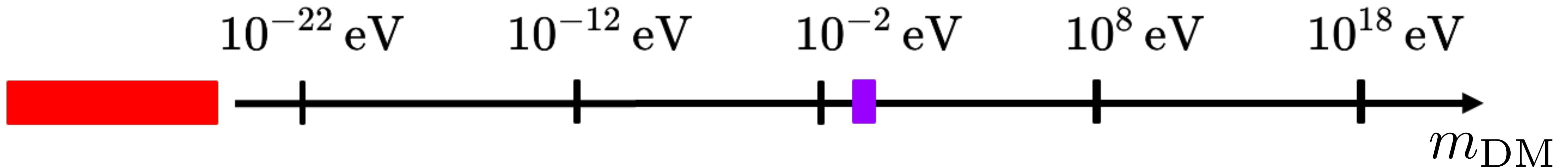


CERN study: arXiv:2304.00614 ; AEDGE, arXiv:1908.00802; Cold atoms in Space, arXiv:2201.07789

Probing dark matter

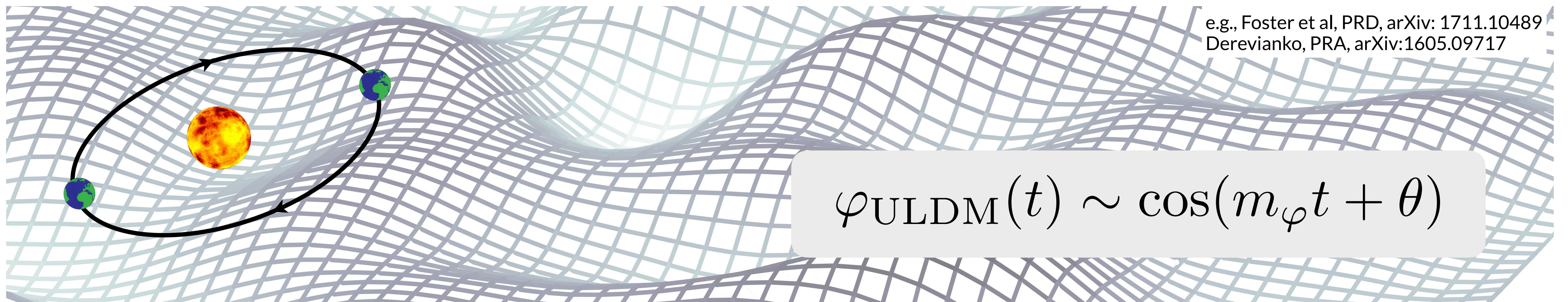
Badurina, Blas, **CM**, PRD, arXiv:2109.10965;
Badurina, Beniwal, **CM**, arXiv:2306.16477
Badurina, ..., **CM**, et al, Phil.Trans.Roy.Soc.Lond.,
arXiv:2108.02468

Ultra-light dark matter



DM lighter than \sim few eV behaves as a classical wave

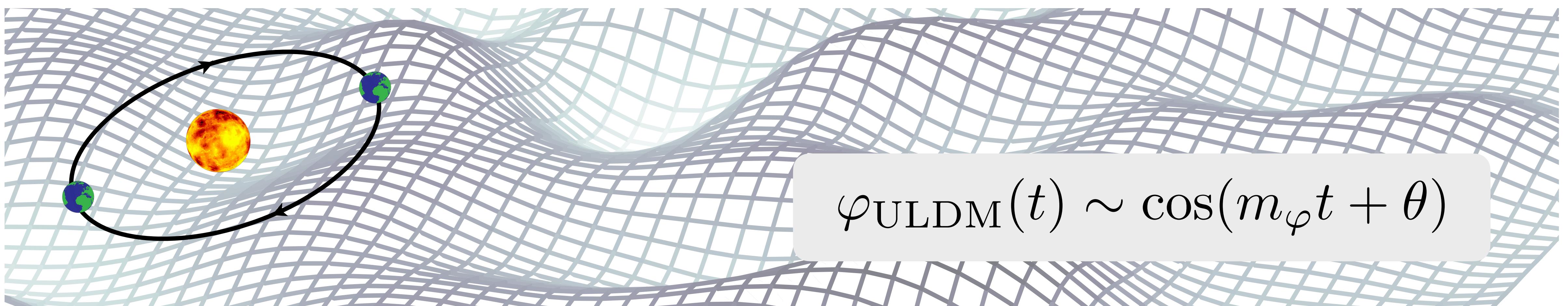
Angular frequency set by the ULDM mass: $\omega \simeq m_\varphi (1 + \mathcal{O}(v^2))$



Induced time-dependent signals

An oscillating ULDM field can induce several signals testable with Al's:

1. Changes in fundamental constants (scalar ULDM)
2. Accelerations on test masses (vector ULDM)
3. Precession of spins (pseudoscalar ULDM)



Changes in fundamental constants (Scalar)

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

↓
↓

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

Oscillations in the field lead to oscillations in optical transitions:



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

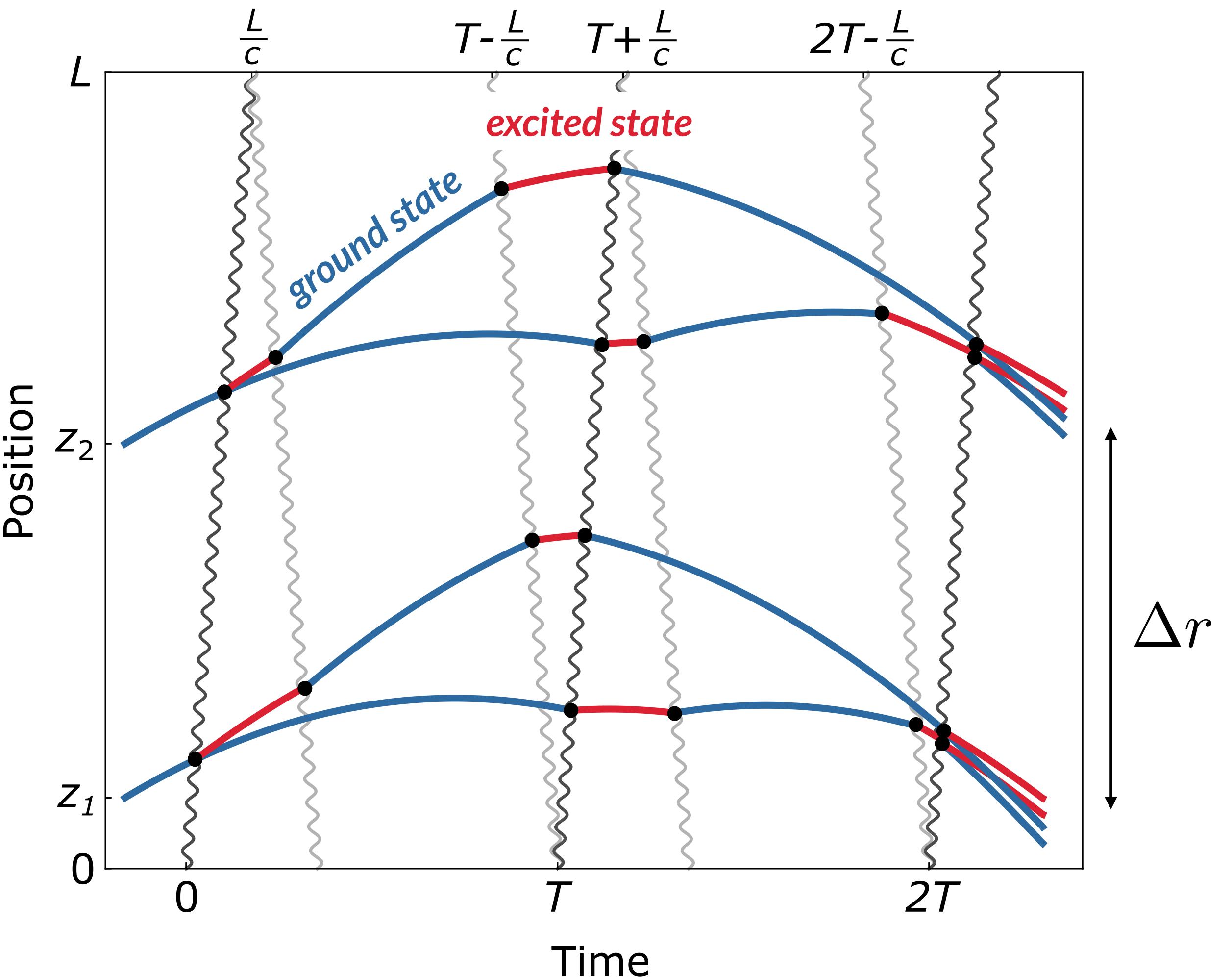
Phase induced by Scalar ULDM

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

$$\Phi_{t_1}^{t_2} = \int_{t_1}^{t_2} \Delta\omega_A(t) dt$$

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

t_1, t_2 = time in excited state



AION-10 sensitivity projections

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

Handles to optimise (in order of priority):

$T \sim 1\text{s}$ (interrogation time)

$C \sim 0.1 - 1$ (contrast)

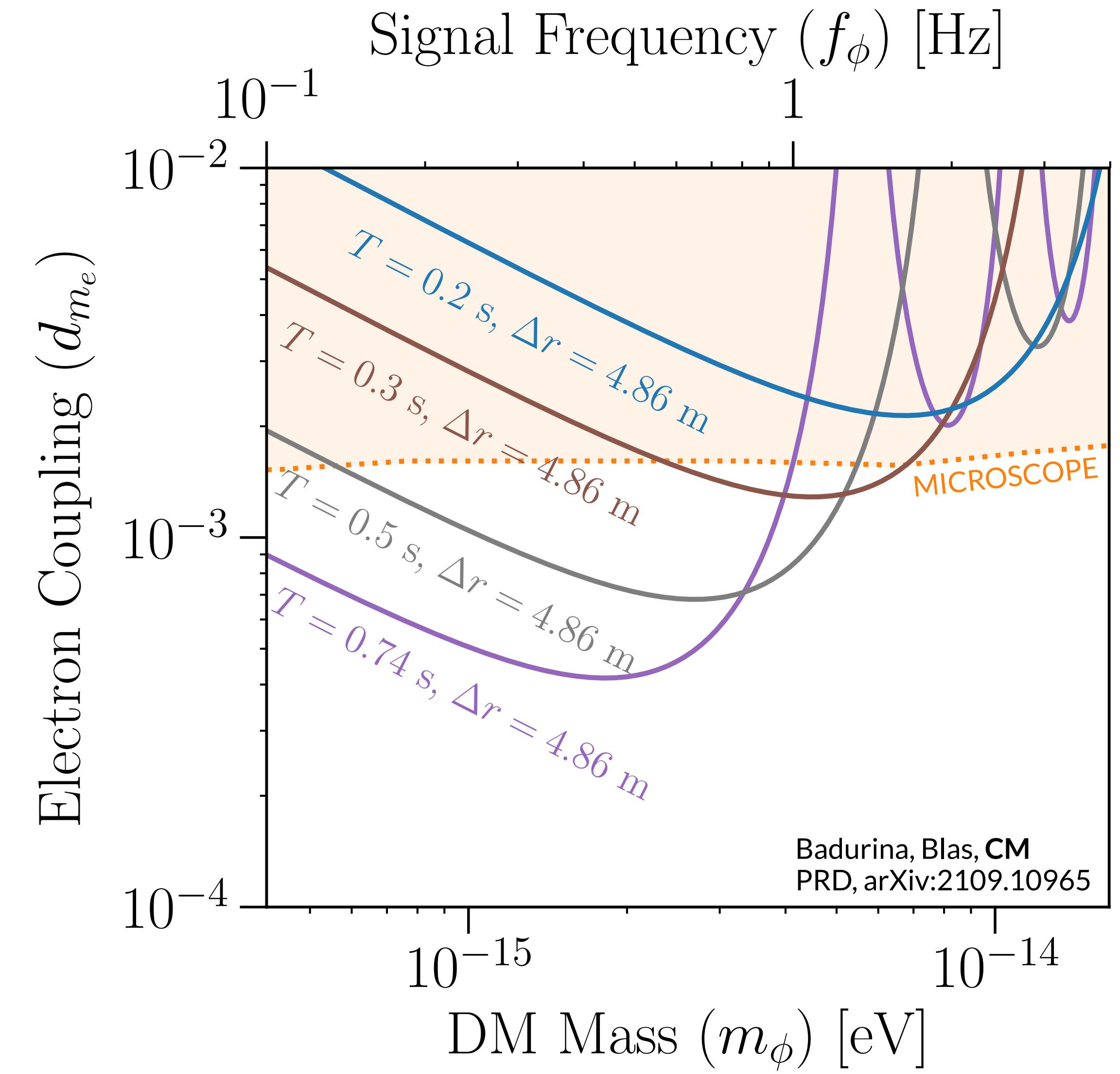
$n \sim 1000$ (LMT)

$\Delta r \sim \text{Al separation}$

$\Delta t \sim \text{sampling time}$

$N_a \sim \text{atoms in cloud}$

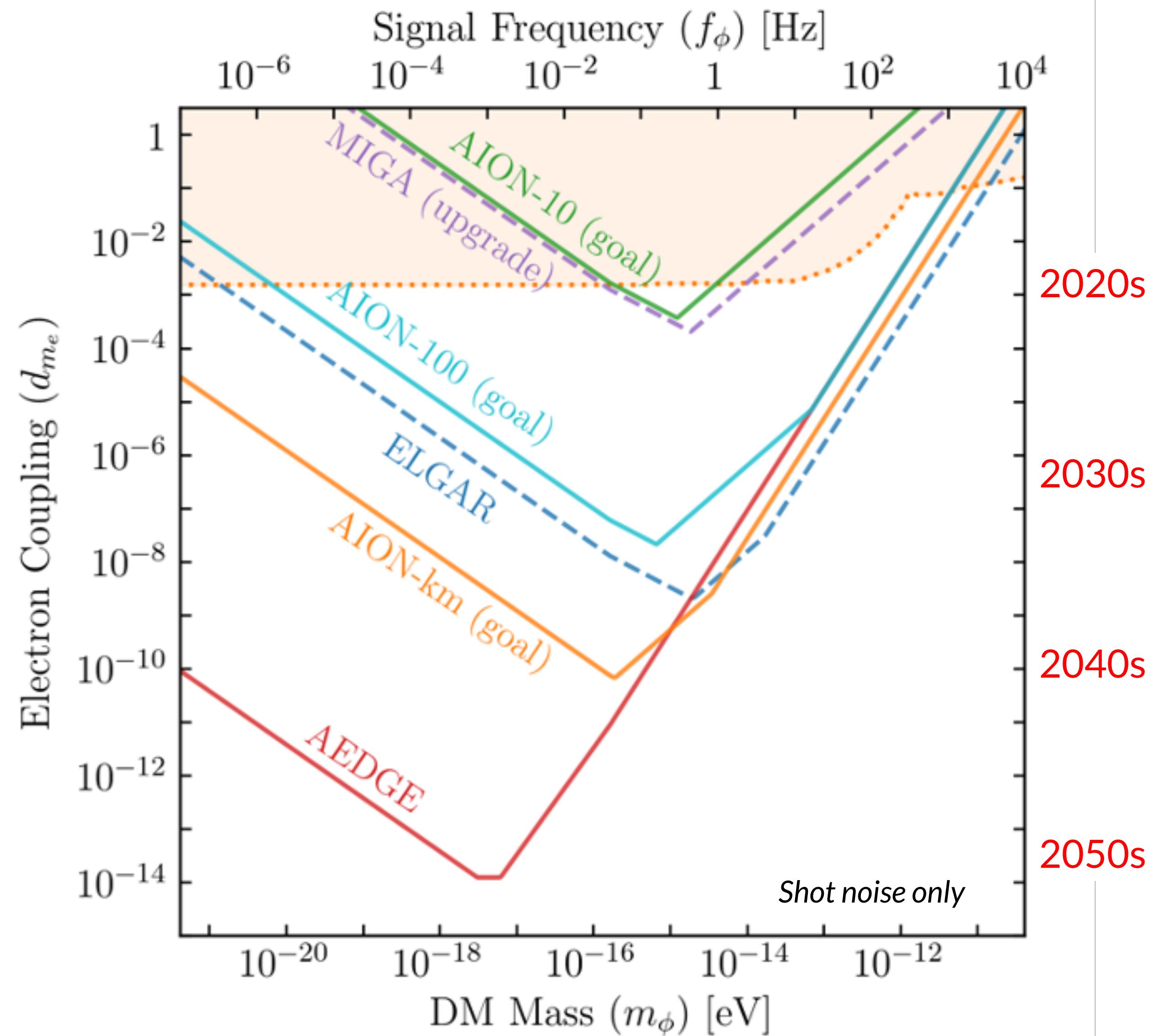
$T_{\text{int}} \sim 10^7\text{s}$ (integration time)



Longer-term sensitivity projections (Scalar)

Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{noise}$ [$1/\sqrt{\text{Hz}}$]	LMT number n
AION-10 (initial)	10	1.4	10^{-3}	100
AION-10 (goal)	10	1.4	10^{-4}	1000
AION-100 (initial)	100	1.4	10^{-4}	1000
AION-100 (goal)	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000

Badurina, CM, et al, arXiv:1911.11755, 2108.02468



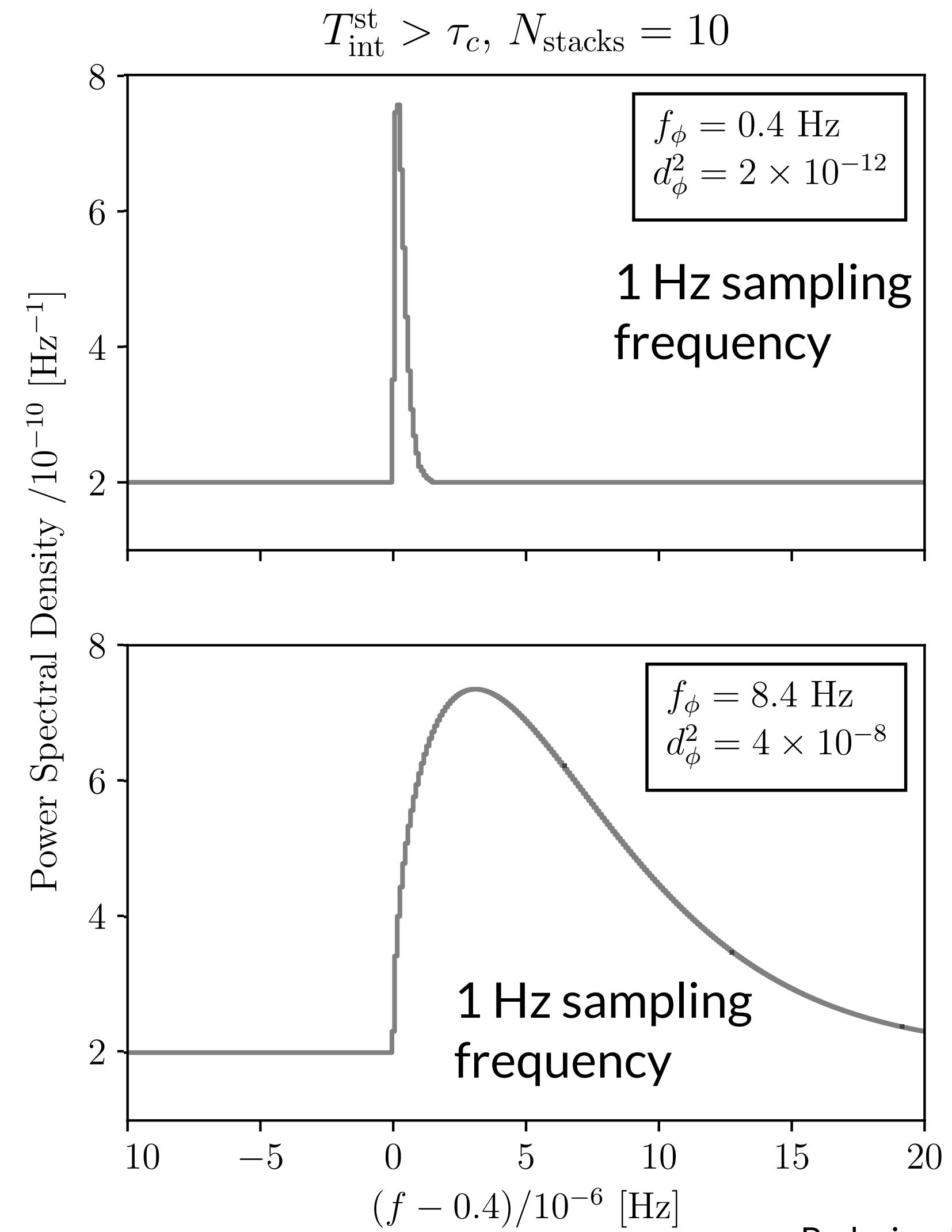
Signal reconstruction (Scalar): aliasing is important

Atomic fountain has \sim Hz sampling rate

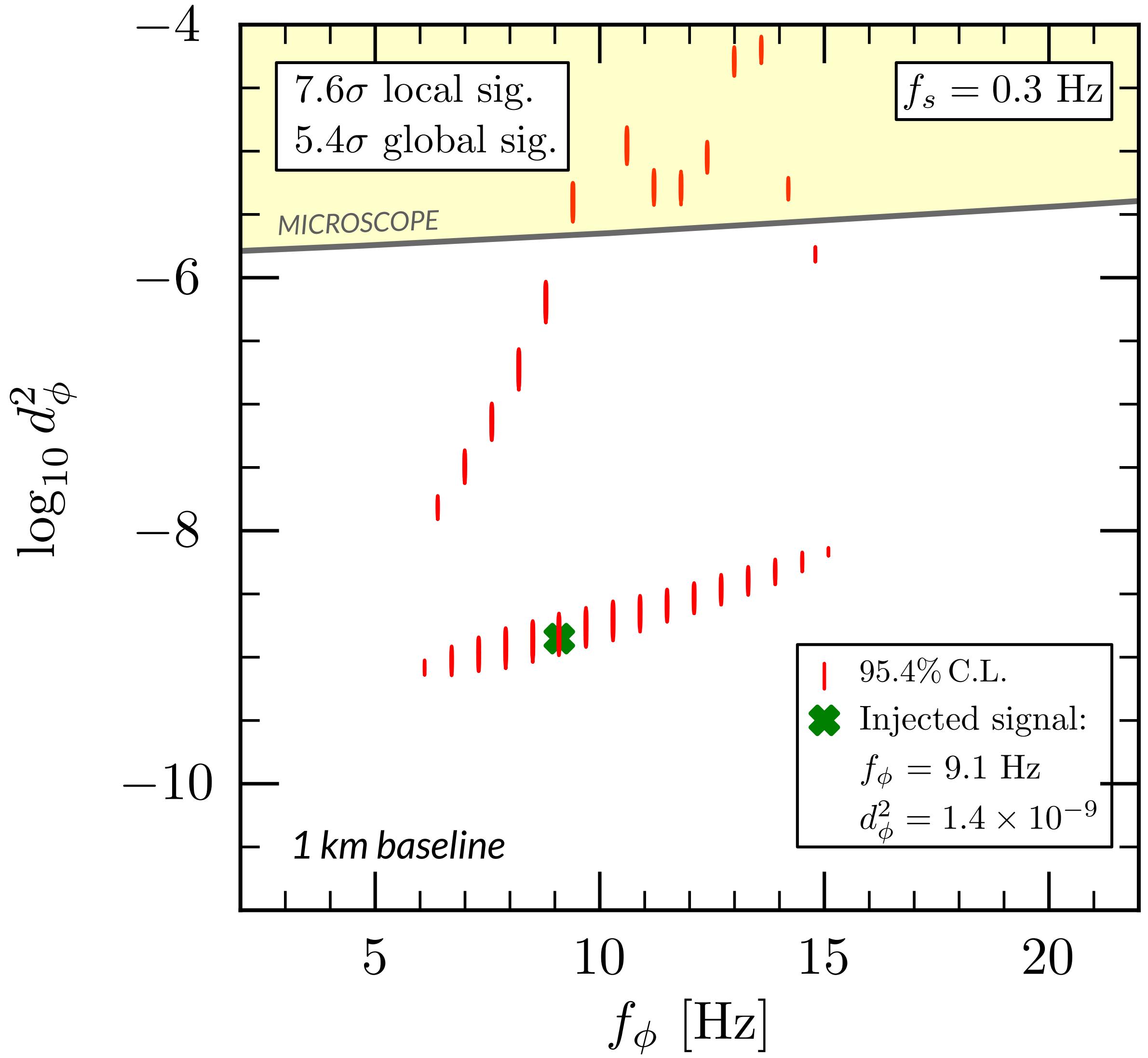
Signals above the Nyquist frequency are aliased...

...but signal width $\propto f_\phi$ (or ULDM mass) and this width stays the same when aliased

Implication: we still have discrimination power for super-Nyquist signals



Signal reconstruction (Scalar)



Because of aliasing:
multiple ‘islands’ in parameter space
consistent with the injected signal

High precision within each island: $\sim 10^{-6}$ Hz

(No aliasing of sub \sim Hz signals)

Other exciting work...

In 12 minutes, I don't have time to discuss all of the other great work by my PhD students and postdocs:

- Challenges from working in a university building with multiple noise sources, and mitigation techniques

From RATs to riches: mitigating anthropogenic and synanthropic noise in atom interferometer searches for ultra-light dark matter, John Carlton, CM, arXiv:2308.10731

- Challenges from seismic noise, and mitigation strategies

Ultralight dark matter searches at the sub-Hz frontier with atom multigradiometry, Leonardo Badurina, V. Gibson, CM, J. Mitchell, arXiv:2211.01854 (PRD)

- Data analysis strategies to reconstruct signals

Super-Nyquist ultralight dark matter searches with broadband atom gradiometers, Leonardo Badurina, Ankit Beniwal, CM, arXiv:2306.16477

Summary

Atom interferometers are a promising experimental technique to:

Probe ultralight dark matter

- Mass $< 10^{-12}$ eV
- Scalar-, vector- and pseudoscalar-coupled DM candidates
- Time-varying energy shifts, accelerations, and spin-coupled effects

Detect ‘mid-band’ gravitational waves (1 km - scale)

- LISA sources before they reach LIGO band
- Early-Universe cosmological sources

And more...

- Tests of quantum mechanics at macroscopic scales
- Probe of seismic activity...

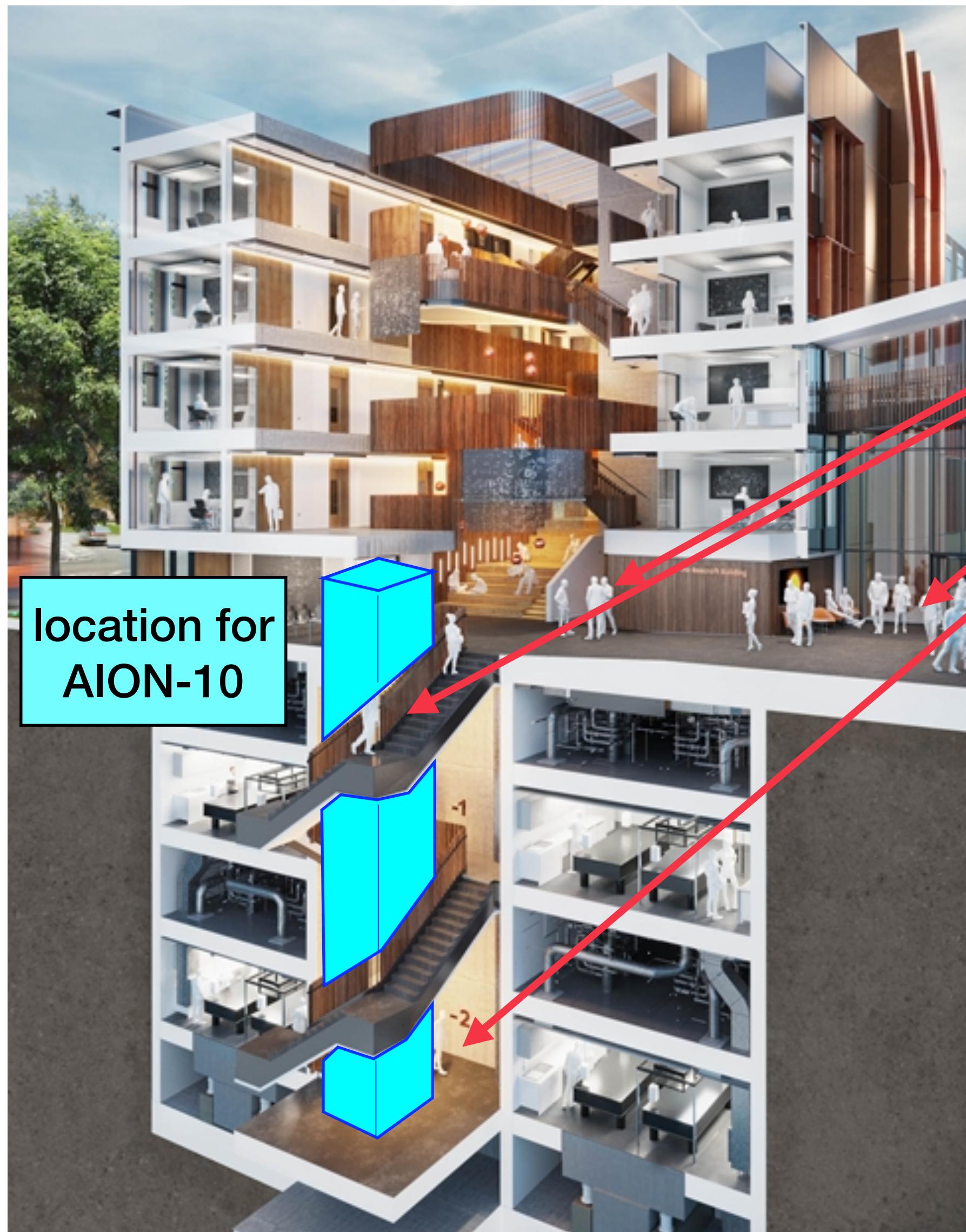
Thank you



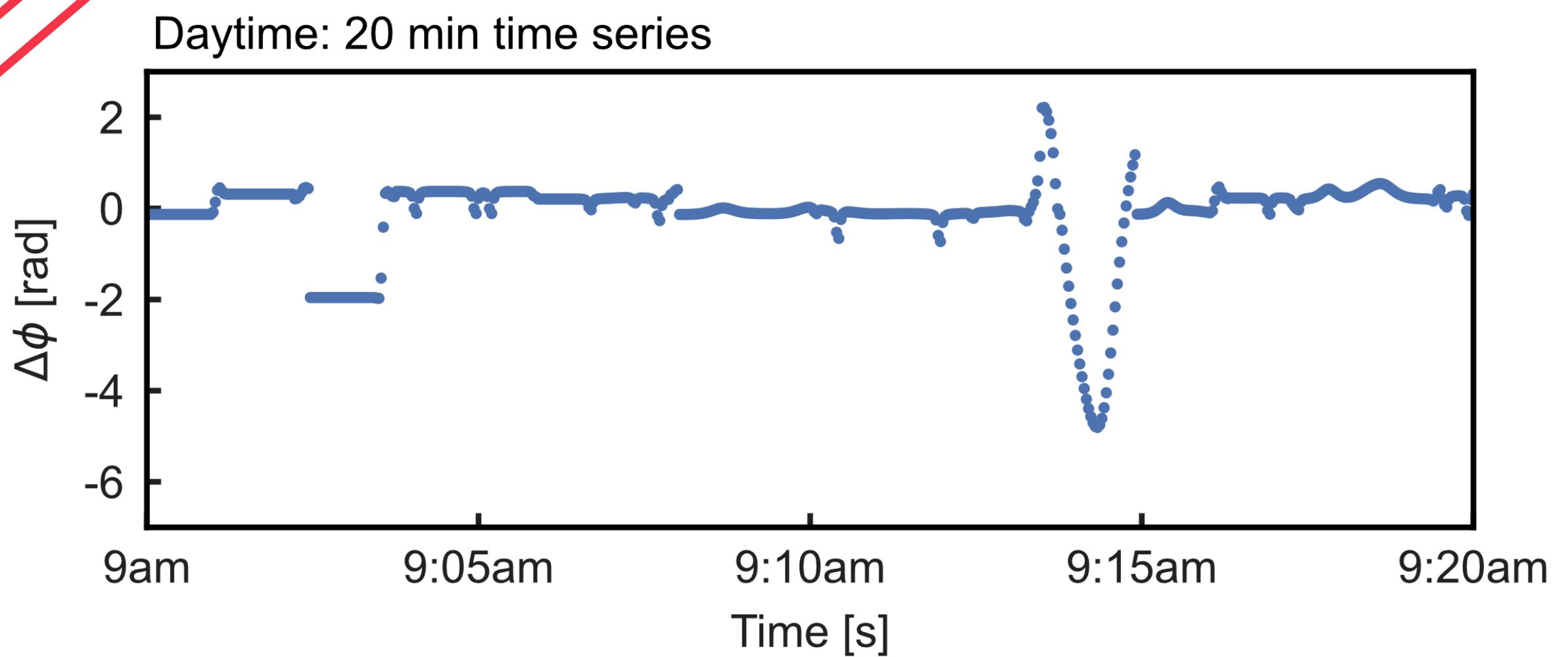
**Science and
Technology
Facilities Council**

Backup: operating in a university building

Short-terminer challenge: operating in a university building



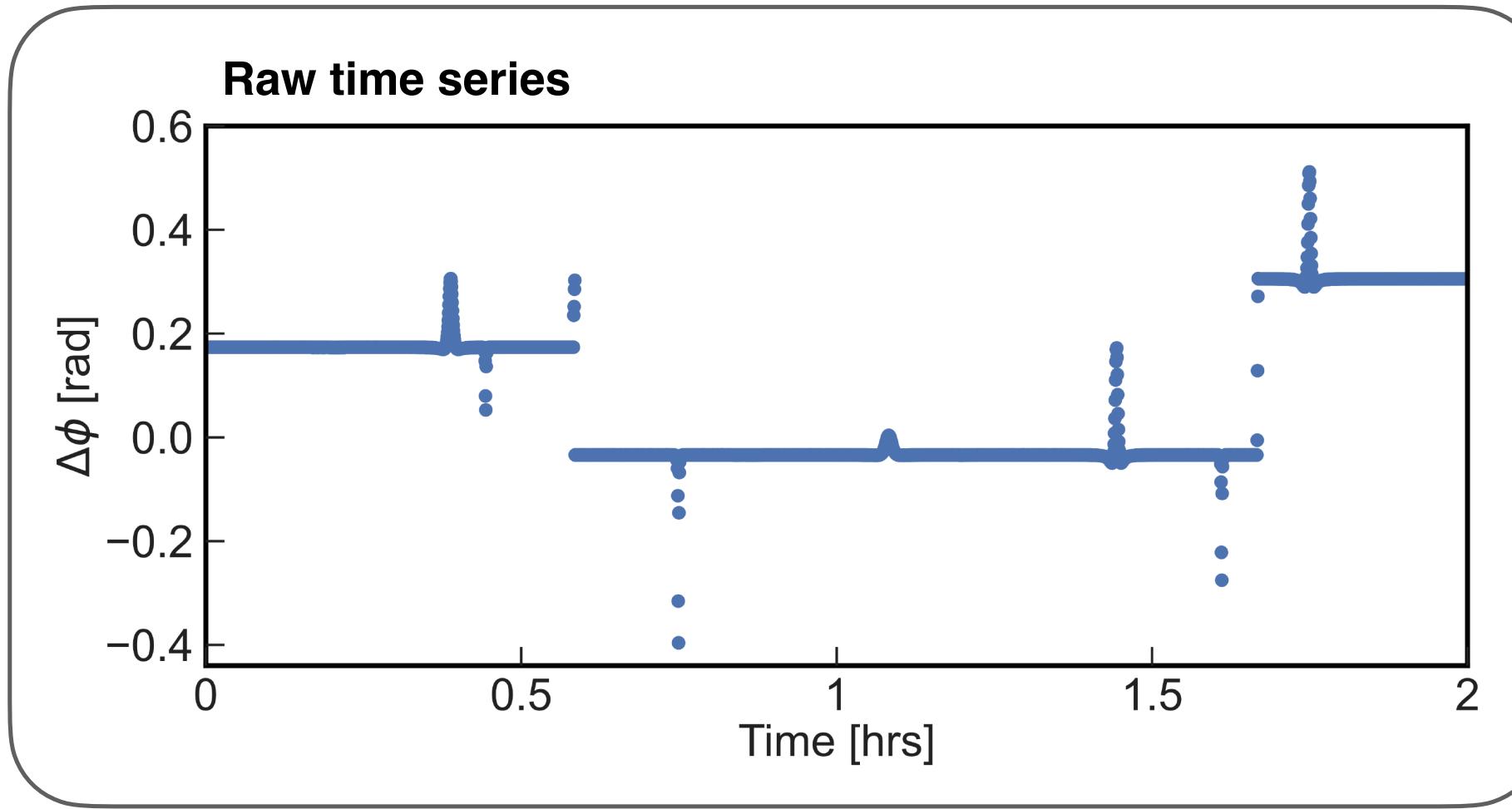
Moving 'test masses' contribute to the phase:



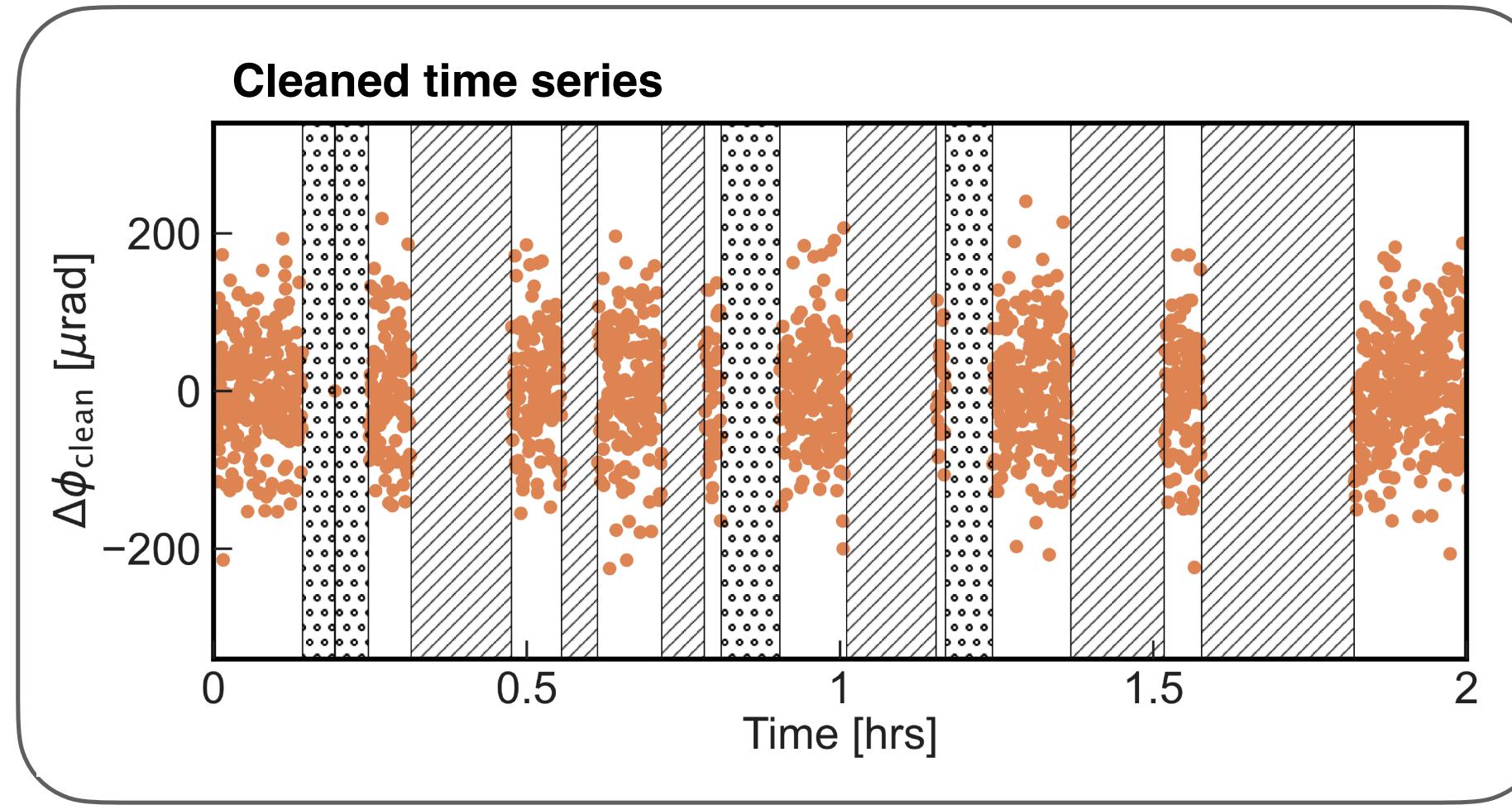
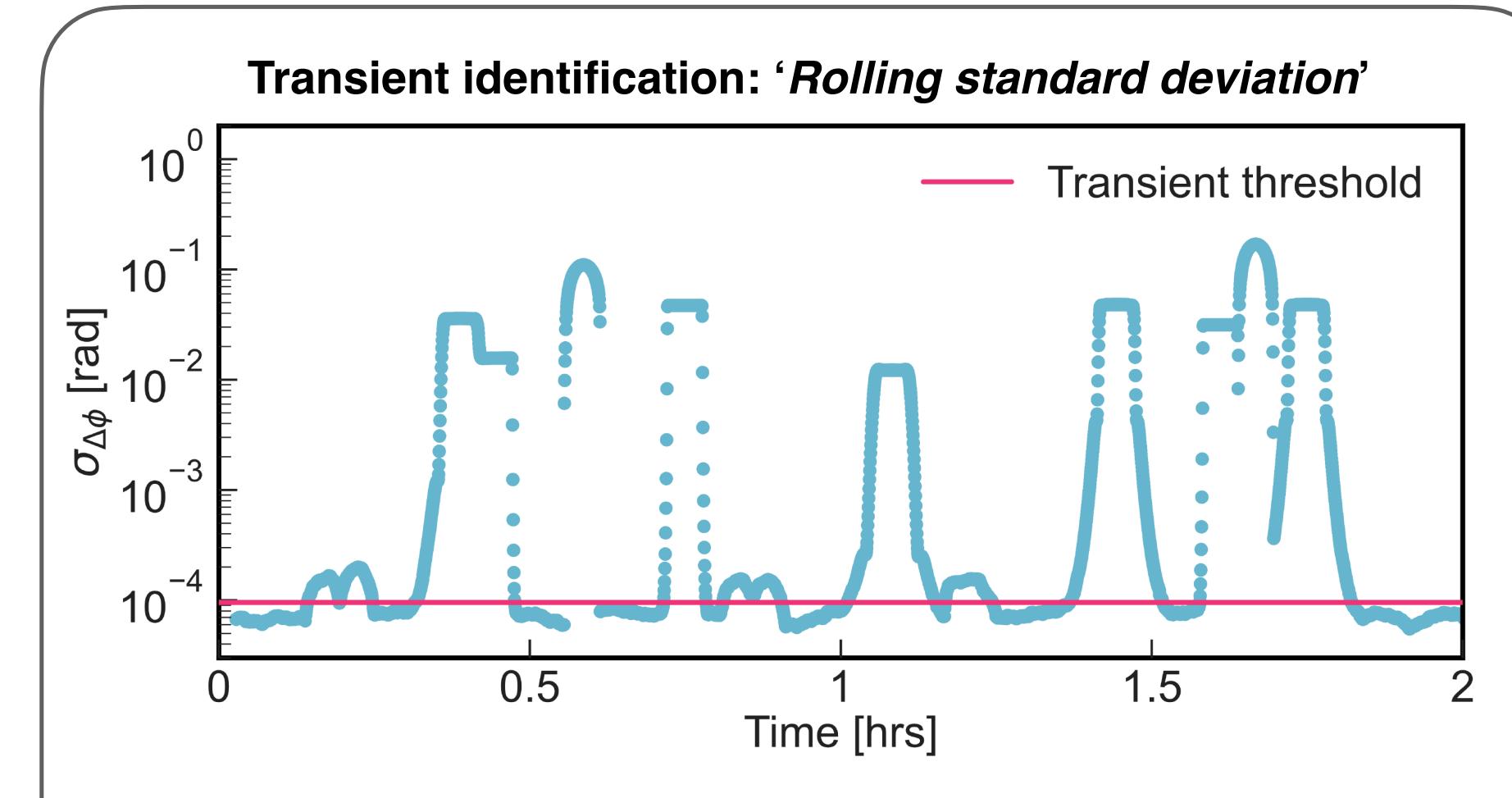
ULDM searches run for many months:
Could the busy environment hide a ULDM signal?

Carlton, CM, arXiv: 2308.10731

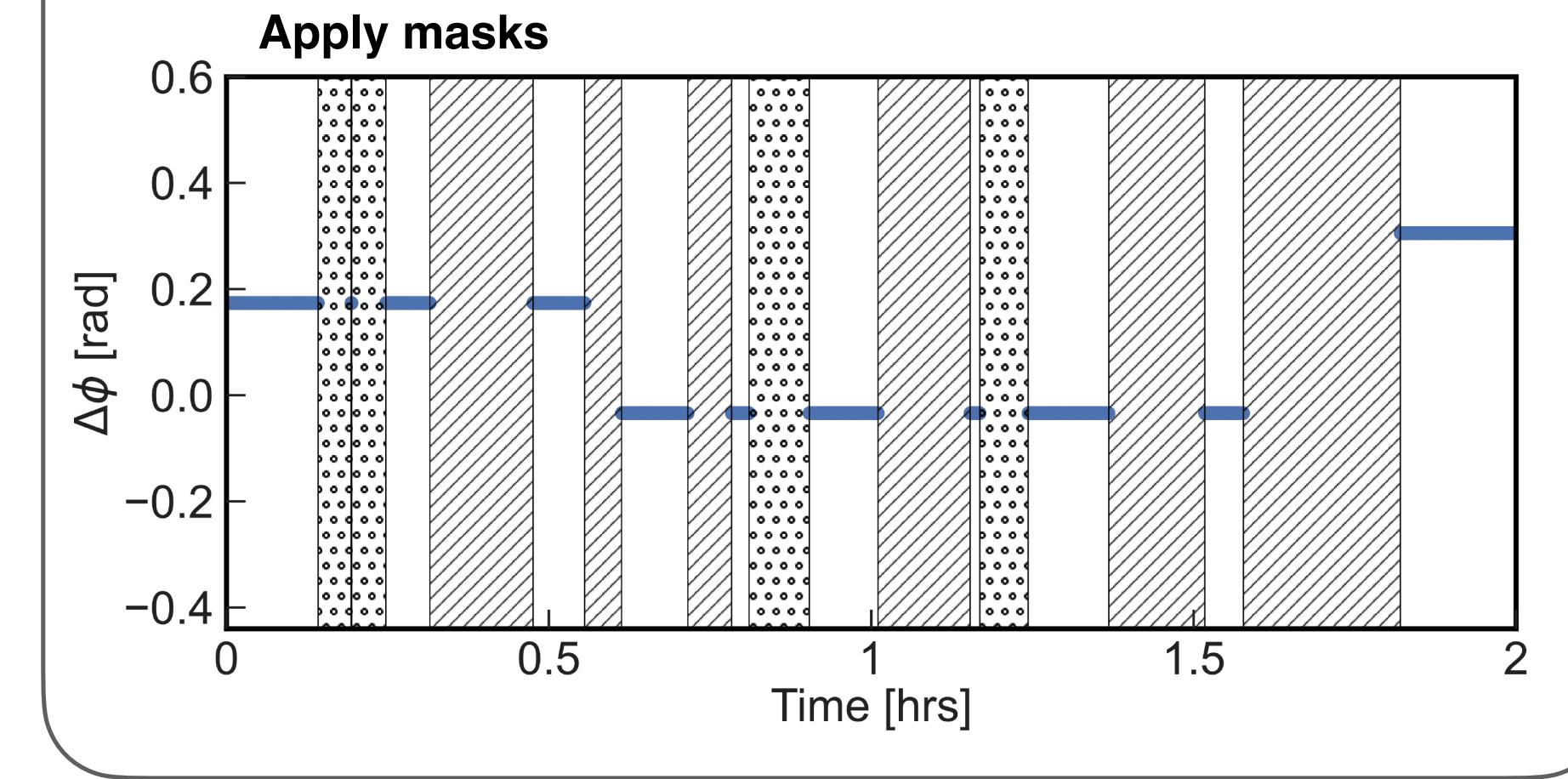
Mitigation strategy



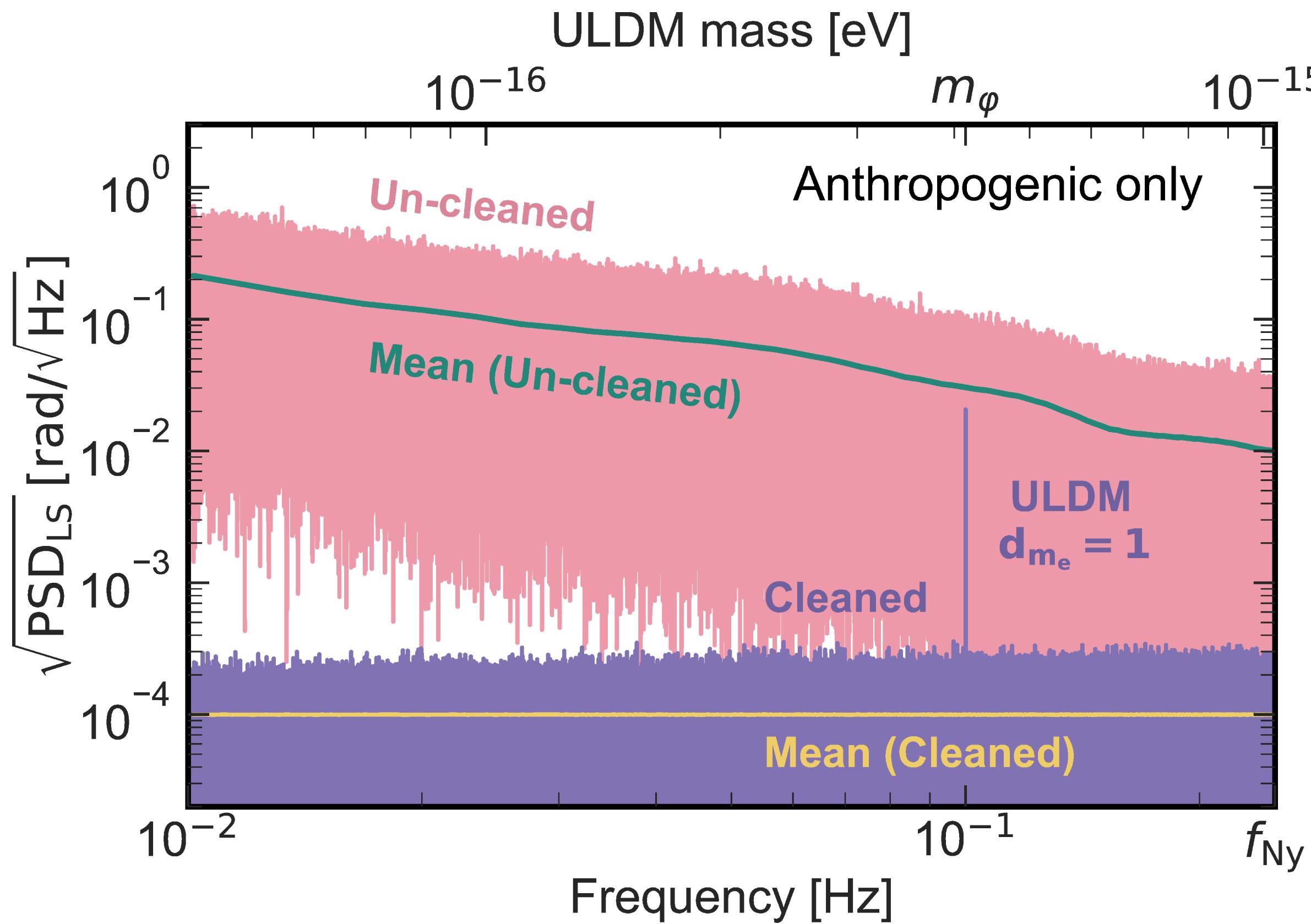
Transient removal
→



Detrend
←



Mitigation strategy



Running at night, identifying transients,
masking, and de-trending time series
provides effective mitigation:
from the pink PSD to the purple PSD

Recover shot-noise limited sensitivity

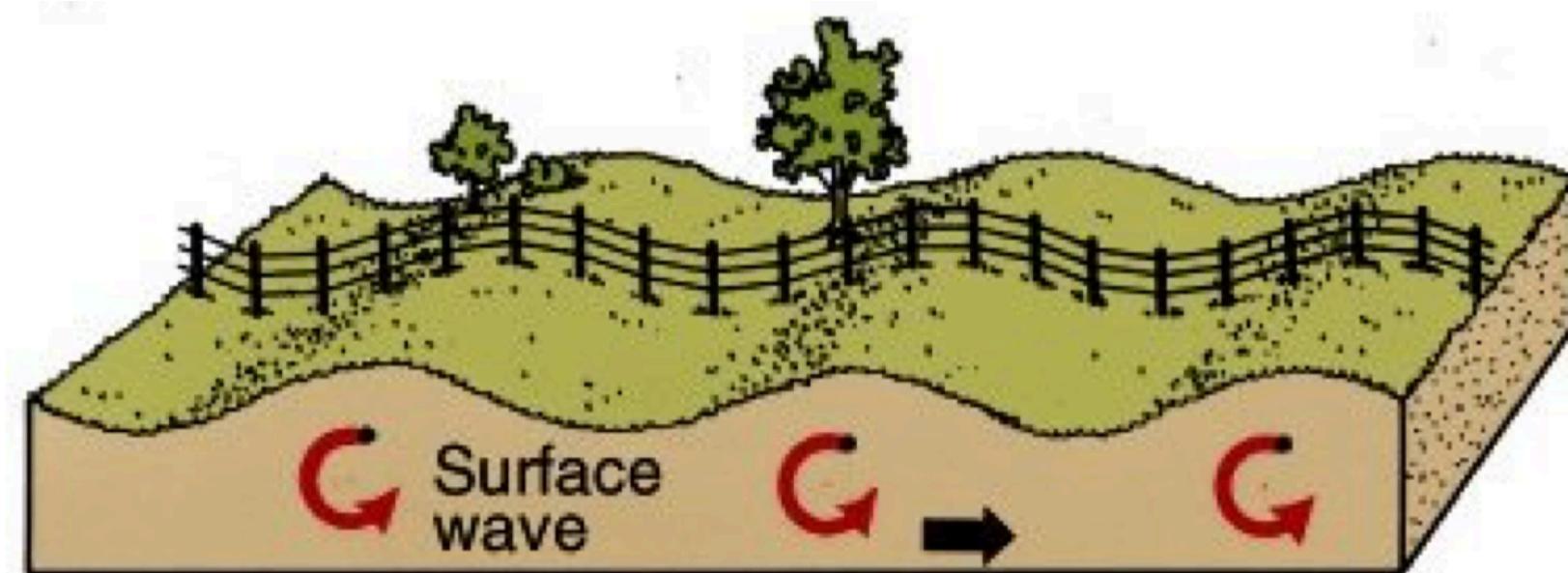
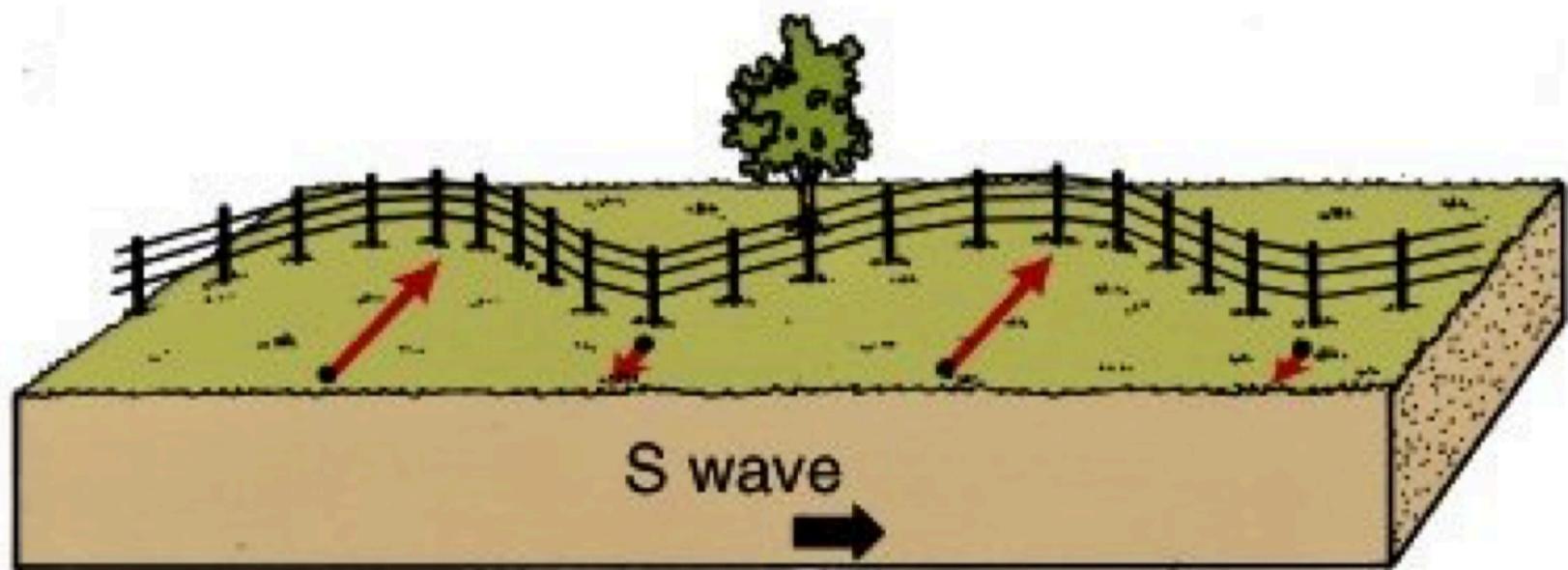
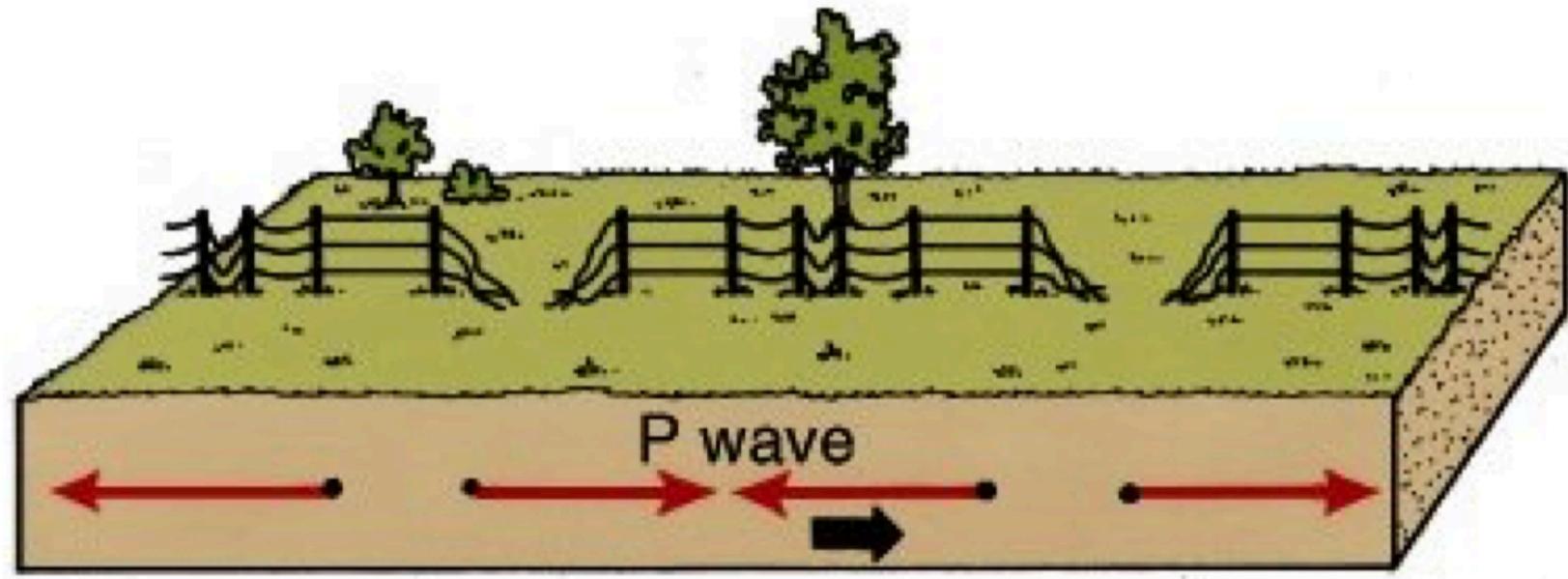
Backup: seismic noise and mitigation

Longer-term challenge: seismic noise

Seismic activity induces Gravity Gradient Noise (GGN)

Expectation: will limit low-frequency searches

Rayleigh waves give the largest density variations so considered the most dangerous

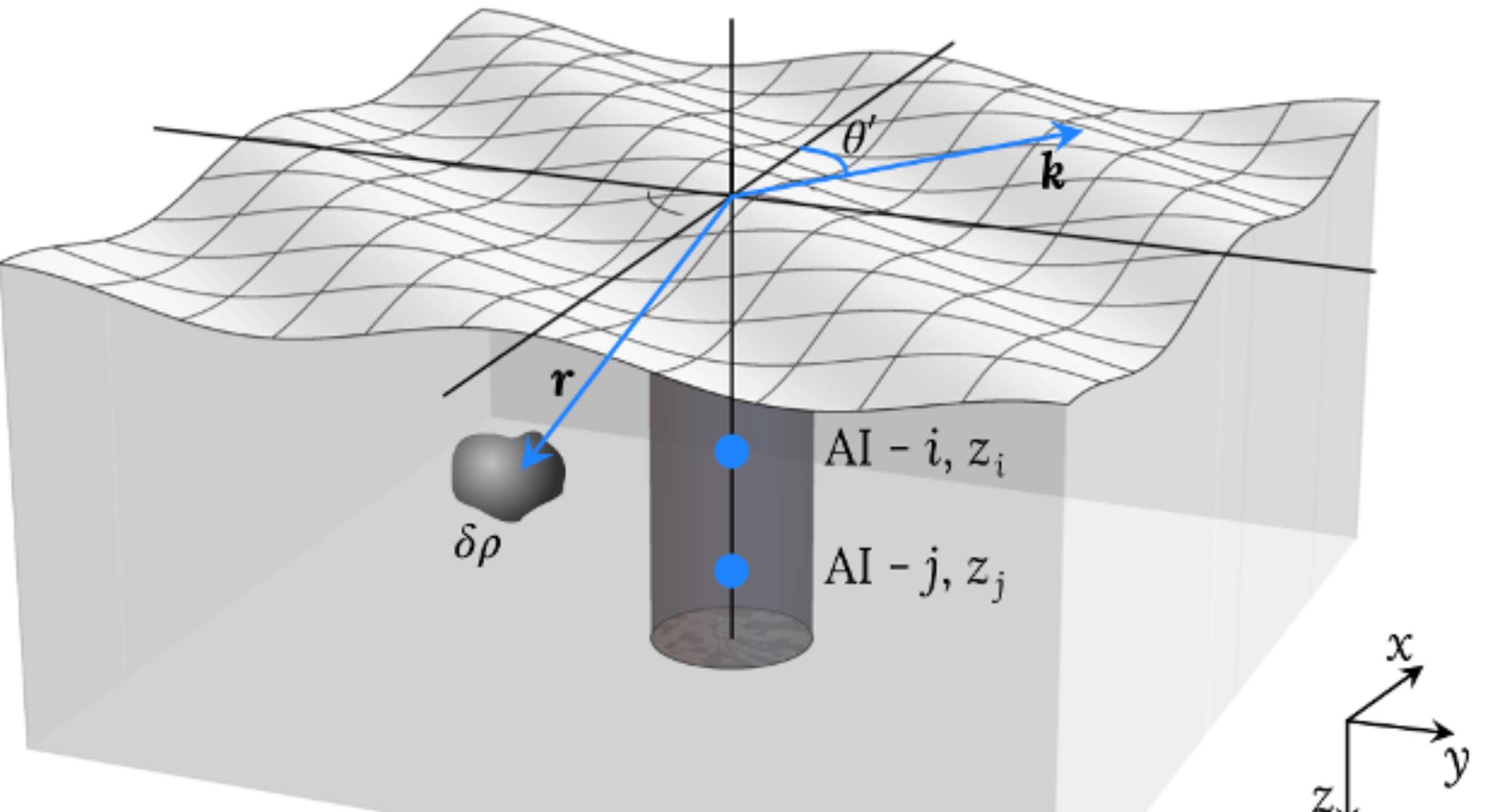


Rayleigh waves

Model wave travelling across the surface as:

$$\vec{\xi}(\varrho, \theta, z, t) = \left(\xi_H(z) \hat{k} - \xi_V(z) \vec{e}_z \right) e^{i(k\varrho \cos(\theta - \theta') - \omega t)}$$

Horizontal displacement Vertical displacement



Induces density fluctuations below the surface:

$$\frac{\delta\rho(z > 0)}{\rho_0} = [\xi_V \delta(z) + \mathcal{R}(z)] e^{i(k\varrho \cos(\theta - \theta') - \omega t)}$$

$$\mathcal{R}(z) = k\xi_V \frac{(q^2 - 1)}{q} \left(\frac{1 + s^2}{1 - s^2} \right) e^{-qkz} \quad \text{where} \quad q, s \sim \mathcal{O}(1)$$

Rayleigh waves: induced phase

Density fluctuations imply a time dependent gravitational potential:

$$\langle \delta\phi(z_0, t) \rangle = -2\pi G \rho_0 \xi_V e^{-i\omega t} \frac{1}{qk} \left(\frac{1+s^2}{1-s^2} \right) \left((1+\sqrt{q/s})e^{-kz_0} - 2e^{-qkz_0} \right)$$

Vertical
displacement

Amplitude decays
exponentially
with depth

Induces a phase in the interferometers:

$$\Phi_{\text{Rayleigh}} = \left(\tilde{A}e^{-qkz_0} + \tilde{B}e^{-kz_0} \right) \xi_V \cos(\omega T + \Theta)$$

Amplitude decays
exponentially

Vertical
displacement

(Partially) mitigated with multi-gradiometer configuration

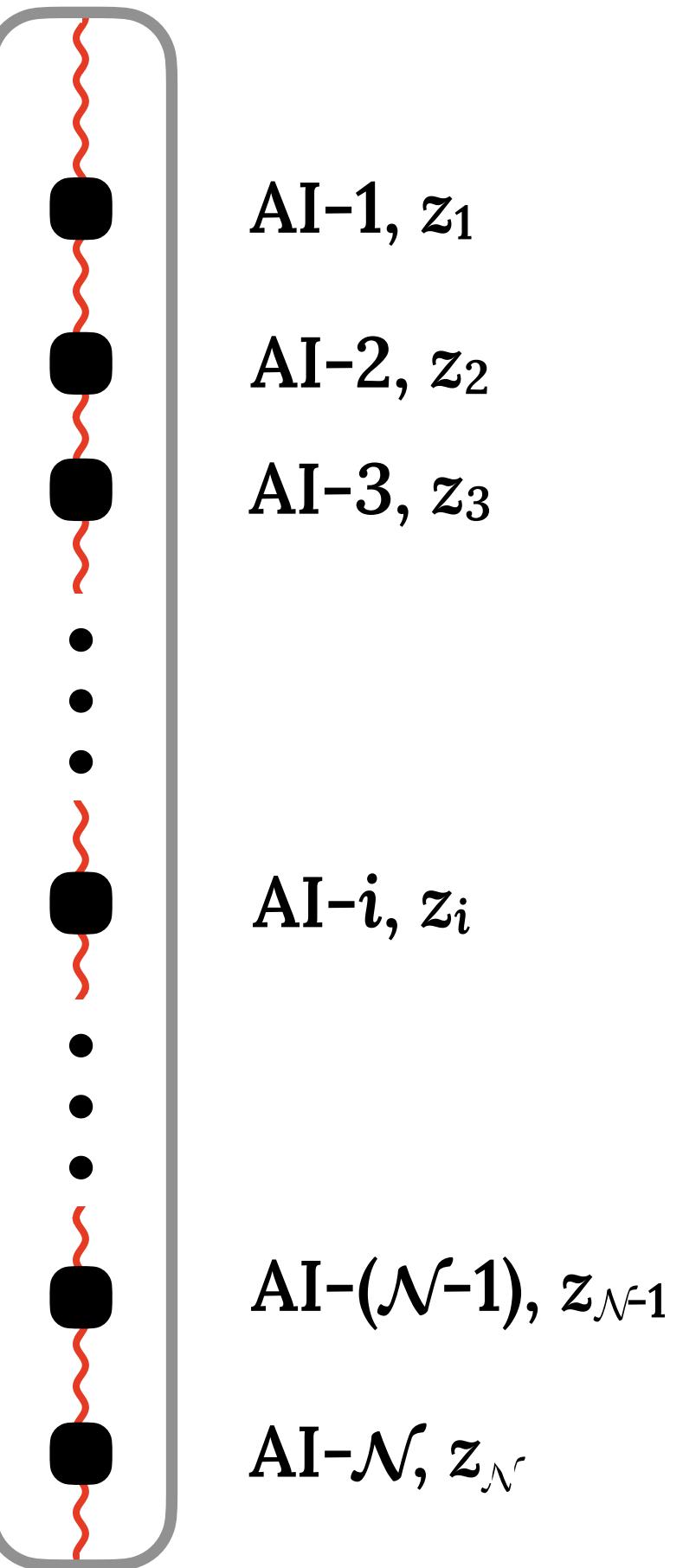


GGN signal decays exponentially from the surface

$$\Phi_{\text{Rayleigh}} = (\tilde{A}e^{-qkz_0} + \tilde{B}e^{-kz_0})$$

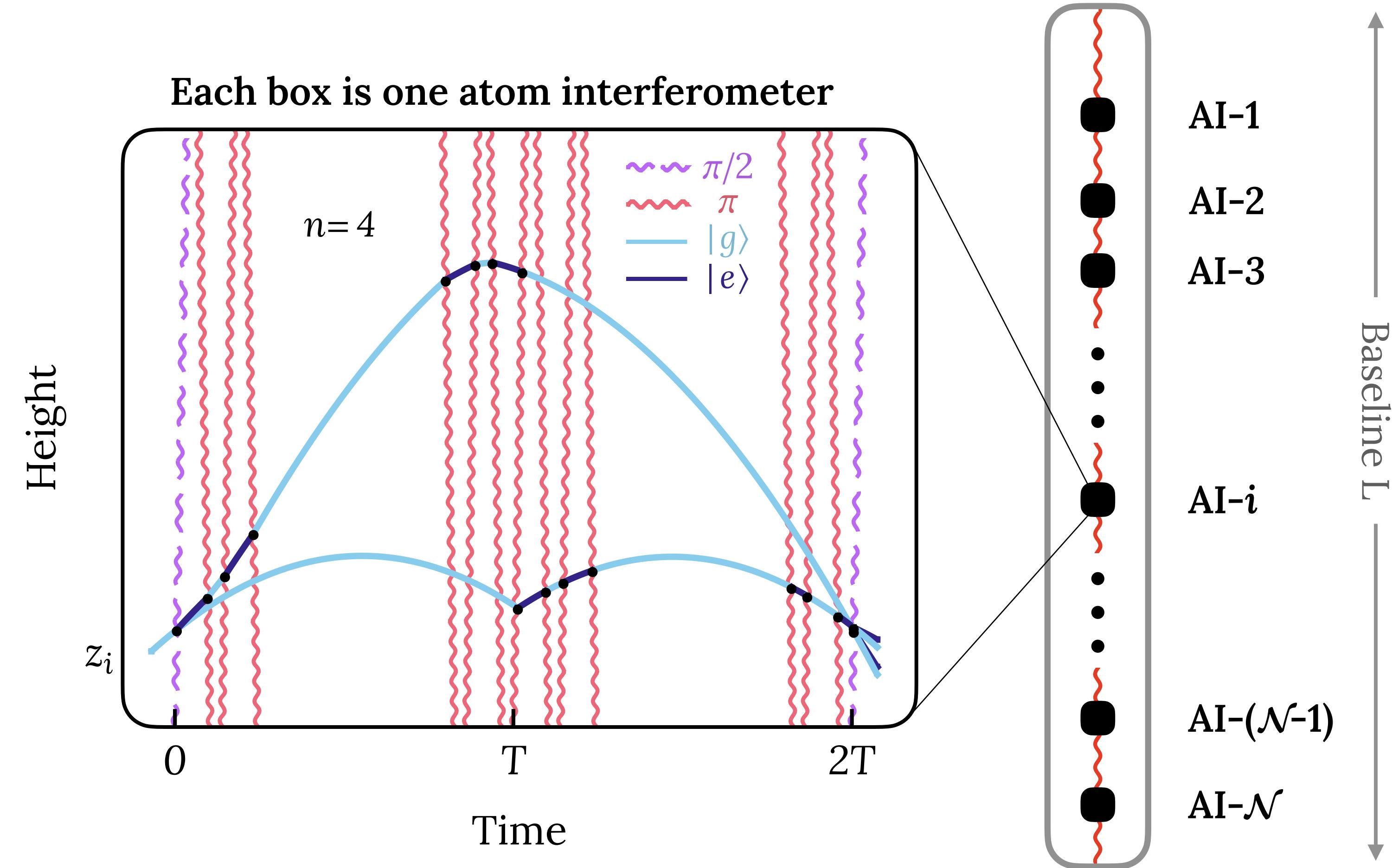
ULDM (or GW) signals scale linearly with AI separation

$$\Phi_{\text{ULDM}} \sim \frac{\Delta z}{L}$$



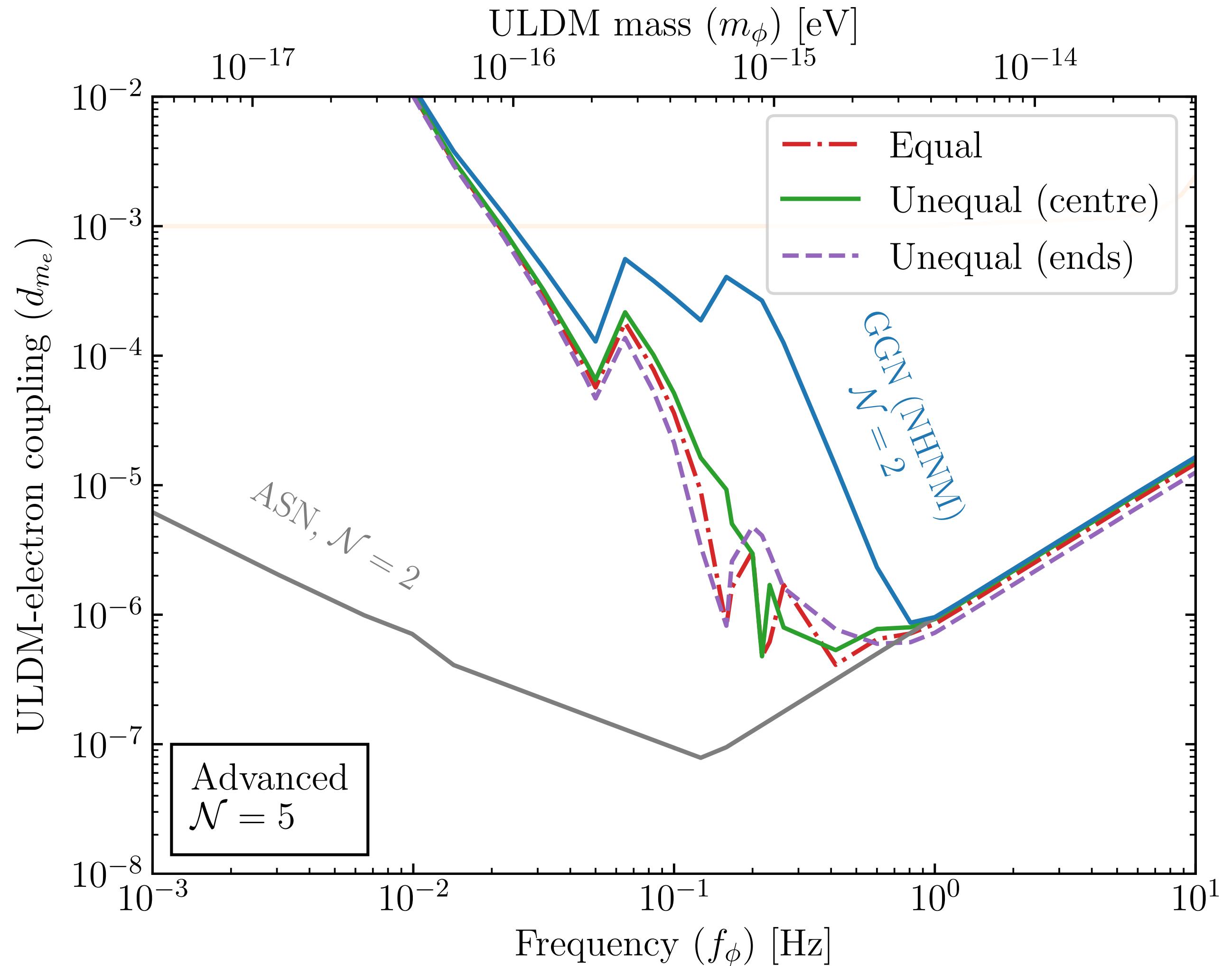
Cross-correlation with N-AI signals to find linear signal

Multi-gradiometer configuration



*Lots of space for
multiple atom
interferometers
on km-baseline!*

Multi-gradiometer: probe depth-scaling of signal and background



ULDM Projections for km-baseline

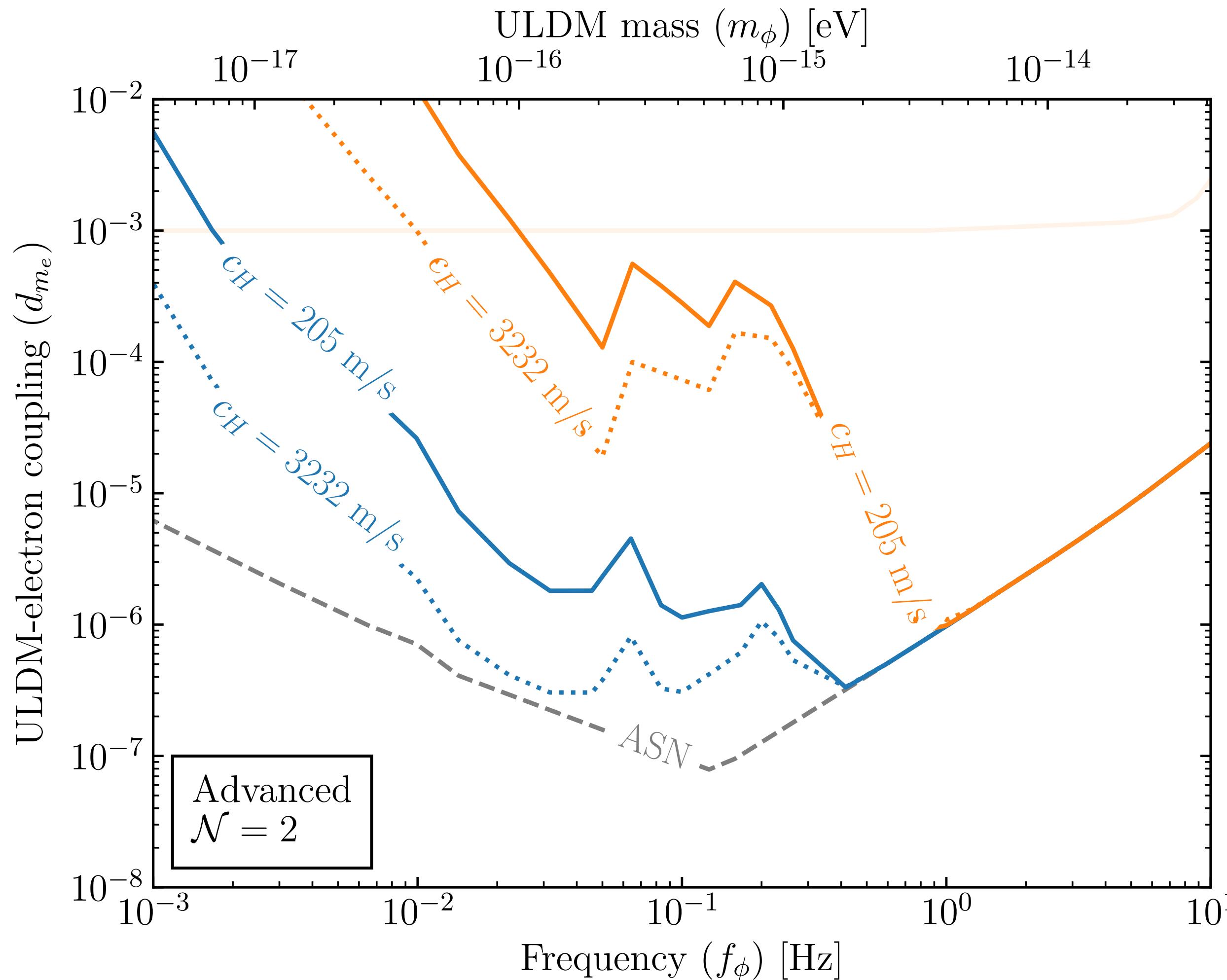
ASN = best-case sensitivity

Blue: New High Noise Model with
two interferometers

Other curves: New High Noise Model
with **five** interferometers

Increased sensitivity for ~0.1 to 1 Hz

Alternative suppression: Build in a favourable location



Projections for km-long baseline

ASN = target sensitivity

Orange: Peterson's New **High** Noise Model

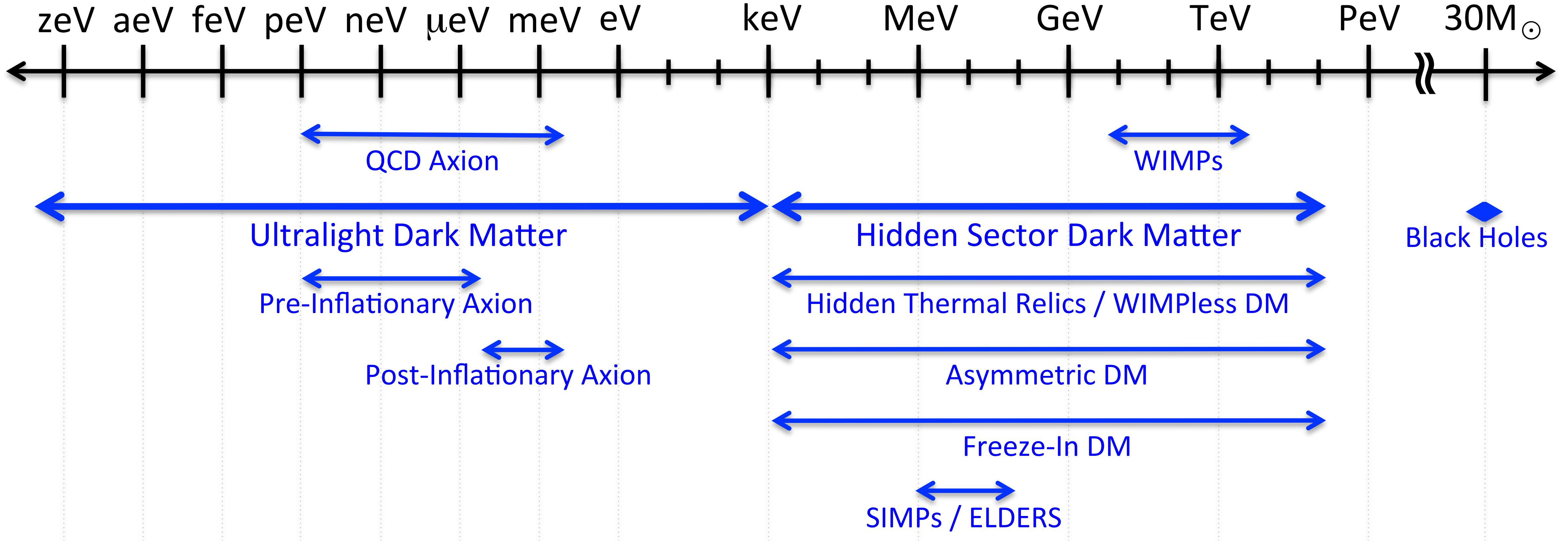
Blue: Peterson's New **Low** Noise Model

c_H parameterises decay length of Rayleigh wave density variation:

$$\lambda_{GGN} = \frac{c_H}{\omega_a} \simeq 100 \text{ m} \left(\frac{250 \text{ m s}^{-1}}{c_H} \right)^{-1} \left(\frac{2.5 \text{ Hz}}{\omega_a} \right)$$

Backup: other ULDM candidates and DM properties

A wide landscape of DM candidates



US Cosmic Visions

Classifying atom interferometer signals

ULDM-induced signal

Static vs Time-dependent



Difficulty: high

Careful analysis of systematic effects needed, which may be hard to quantify

Difficulty: medium

Characteristic DM signal allows for greater signal discrimination

Initial focus: time-dependent signals

Accelerations on test masses (Vector)

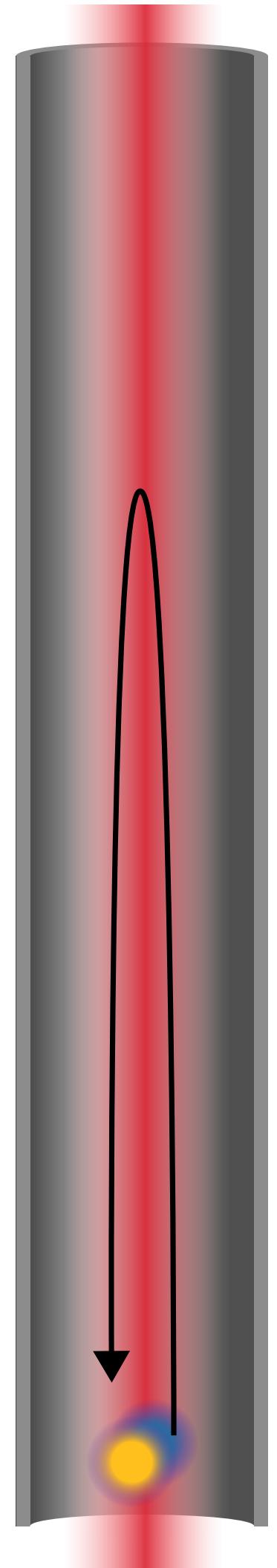
$B - L$ coupled vector appears in many extensions of the Standard Model

As ULDM, this generates background ‘dark electric field’:

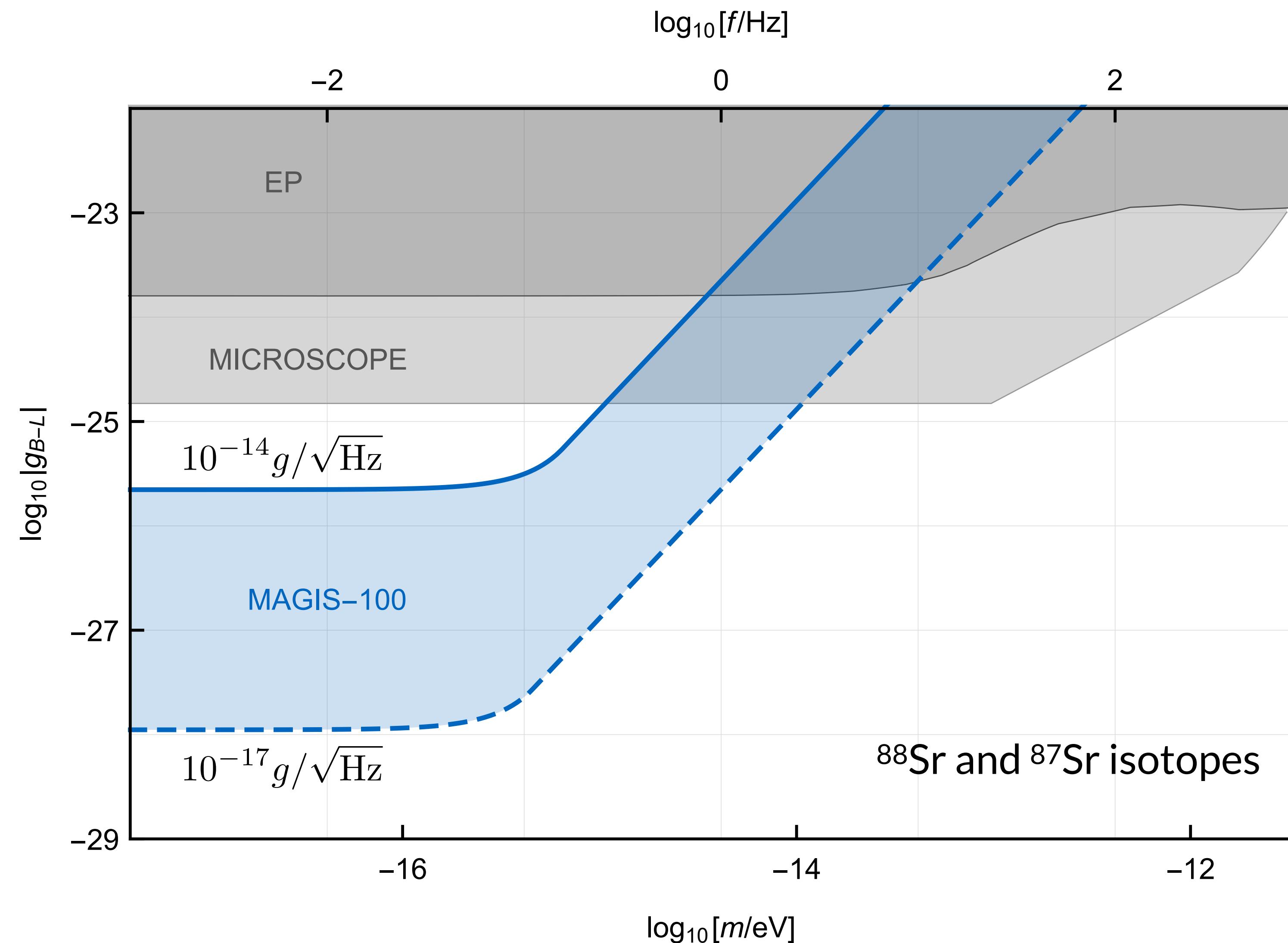
$$E_{B-L} \sim \cos(m_{\text{DM}} t + \theta)$$

In a *dual-species interferometer*, isotopes experience a different forces (accelerations):

$$\Delta F_{B-L} \sim g_{B-L} \left(\frac{Z_1}{A_1} - \frac{Z_2}{A_2} \right) E_{B-L}$$



Near- and long-term prospects (Vector)



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

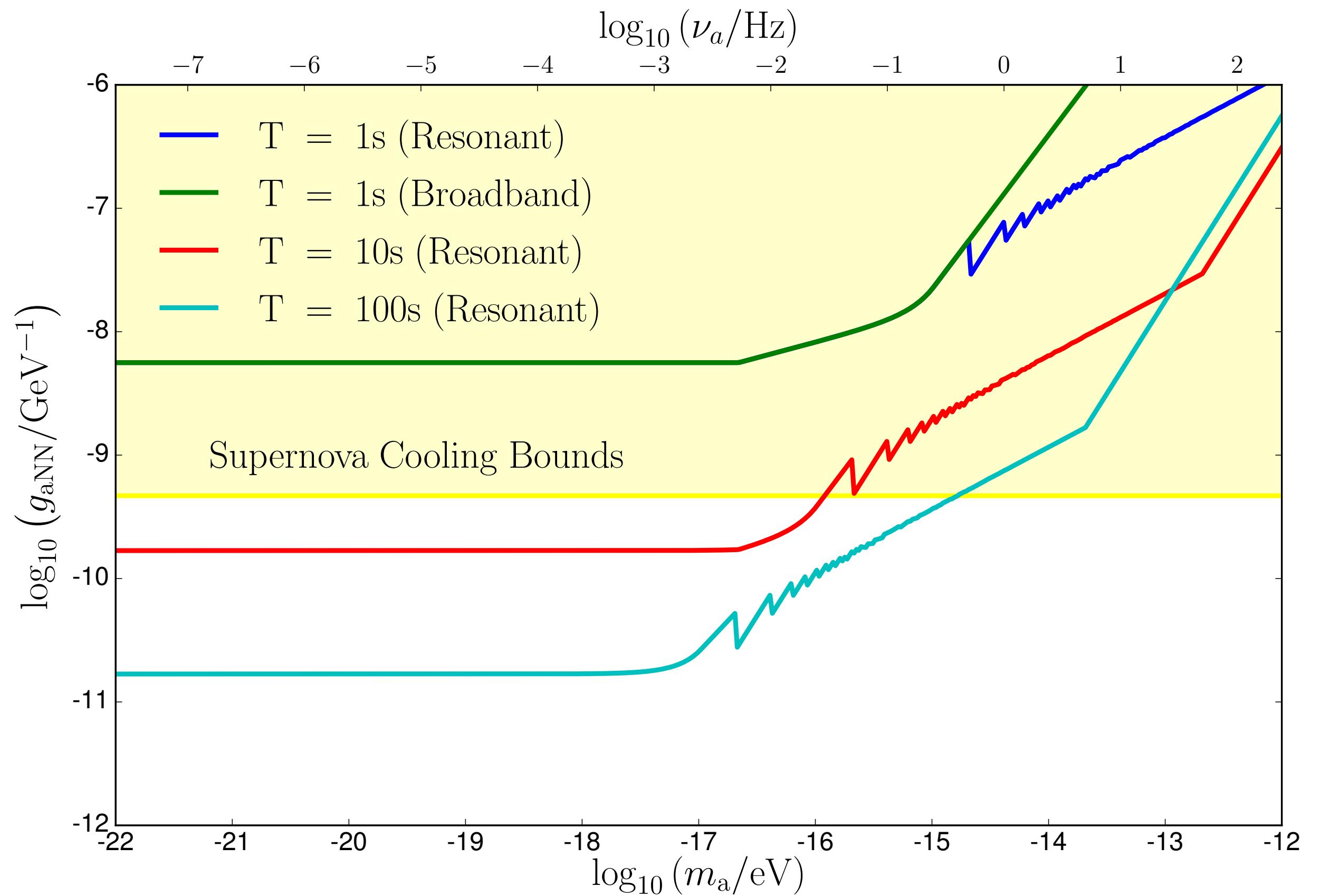
Precession of spins (Pseudoscalar)

Light pseudoscalar (axions) are ubiquitous in extensions of the Standard Model

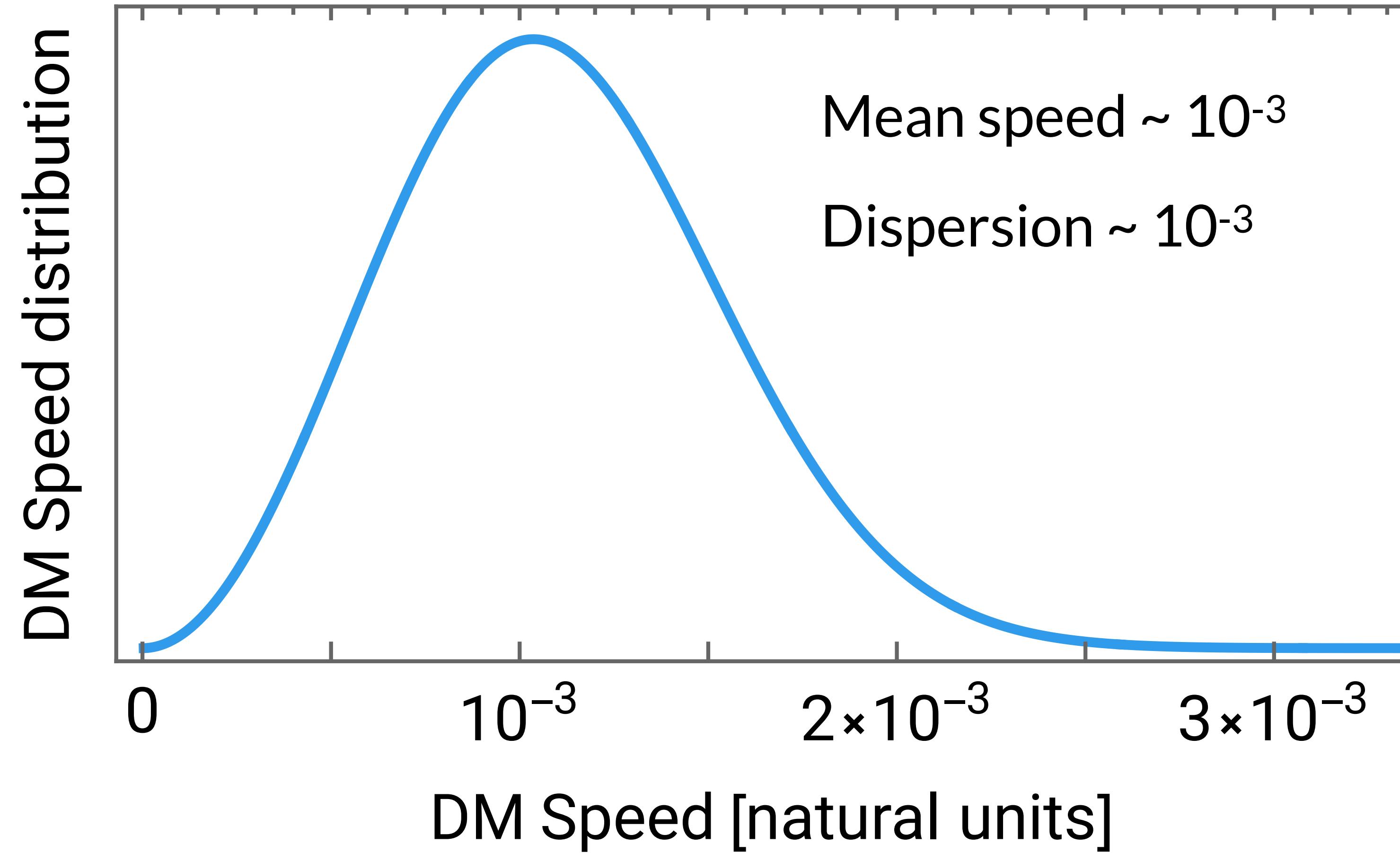
In a *dual-species interferometer*,
pseudoscalars couple to the
different spin of the isotopes:

$$\text{Phase} \sim (m_{S,1} - m_{S,2}) \cos(m_a t + \theta)$$

Challenging: km-baseline, high-repetition rate (10 Hz), long interrogation time, good control of magnetic fields $\delta B \sim 10^{-15} \text{ T}$

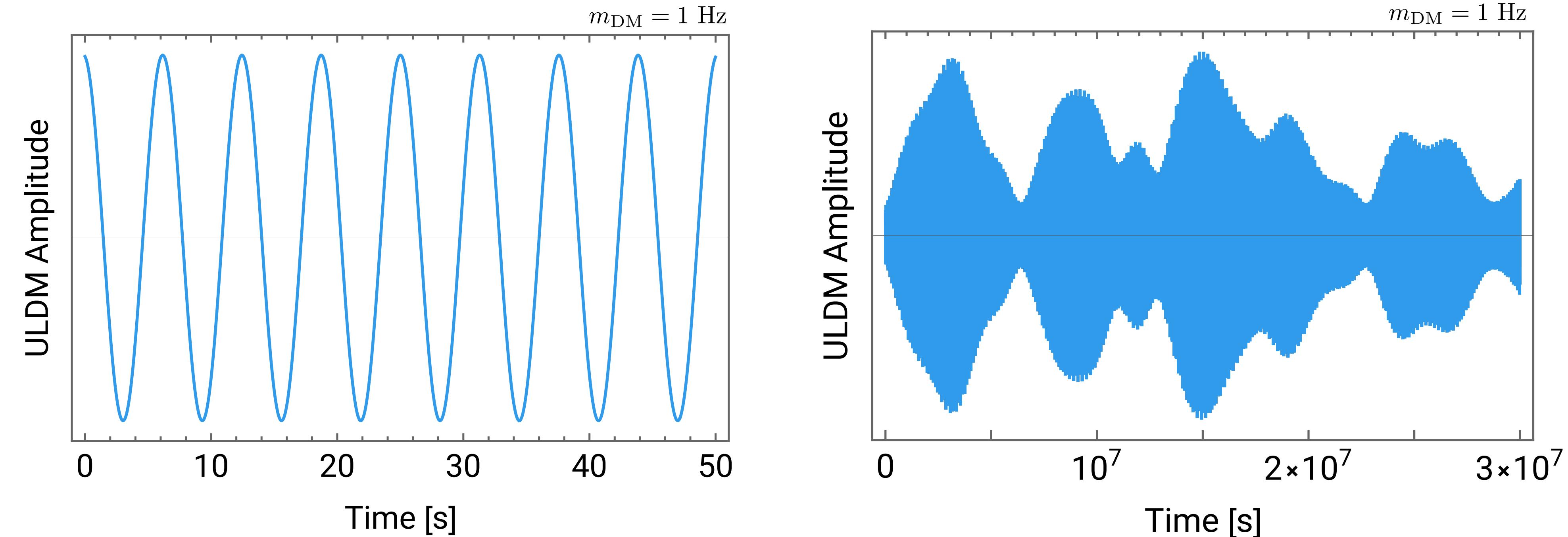


Speed distribution in our galaxy



Many models also predict some substructure in the distribution, see e.g.,
O'Hare, CM, et al, PRD arXiv:1807.09004, 1810.11468, 1909.04684

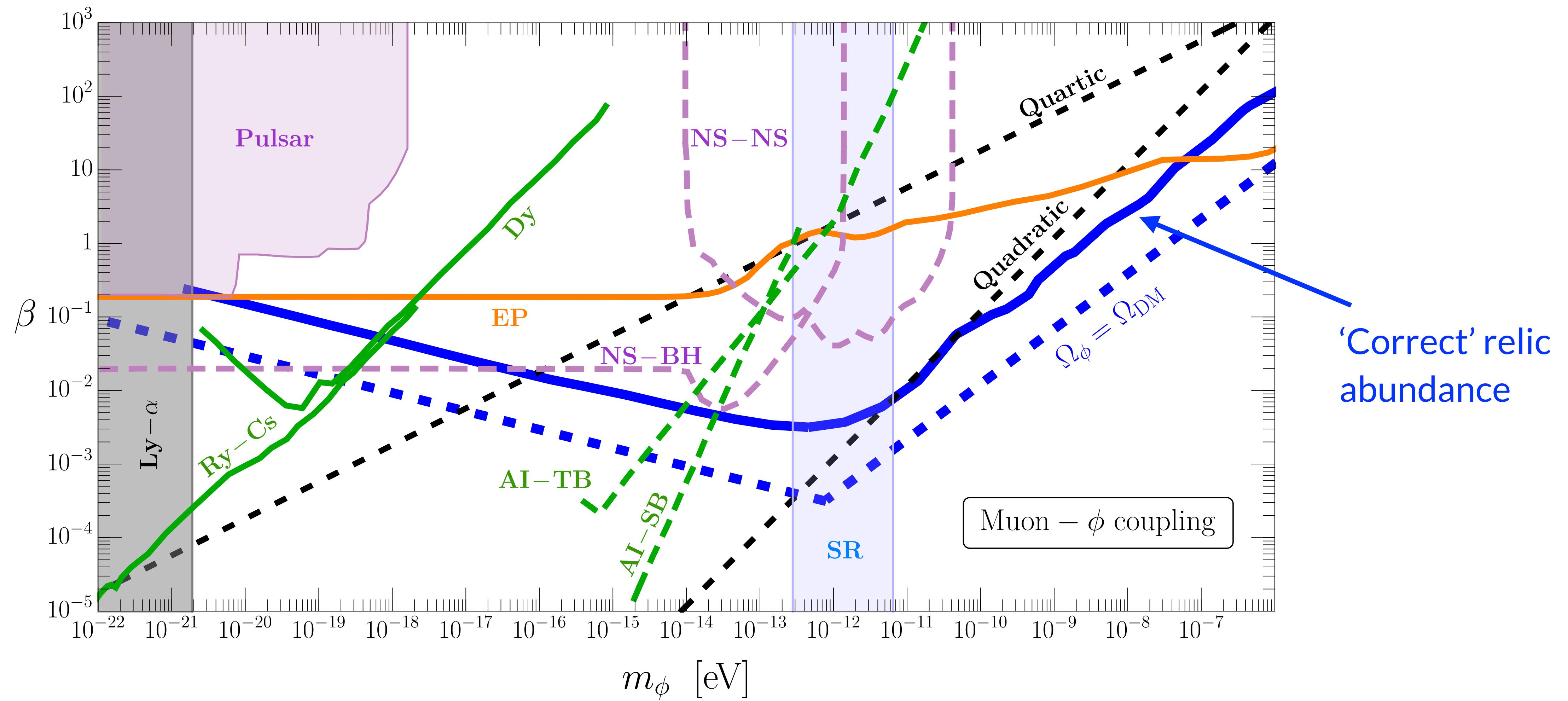
Coherence of the field



Impact of the speed distribution apparent over long time-scales:
field amplitude evolves with a ‘coherence time’ $\tau \sim (m_{\text{DM}} \sigma_v^2)^{-1}$

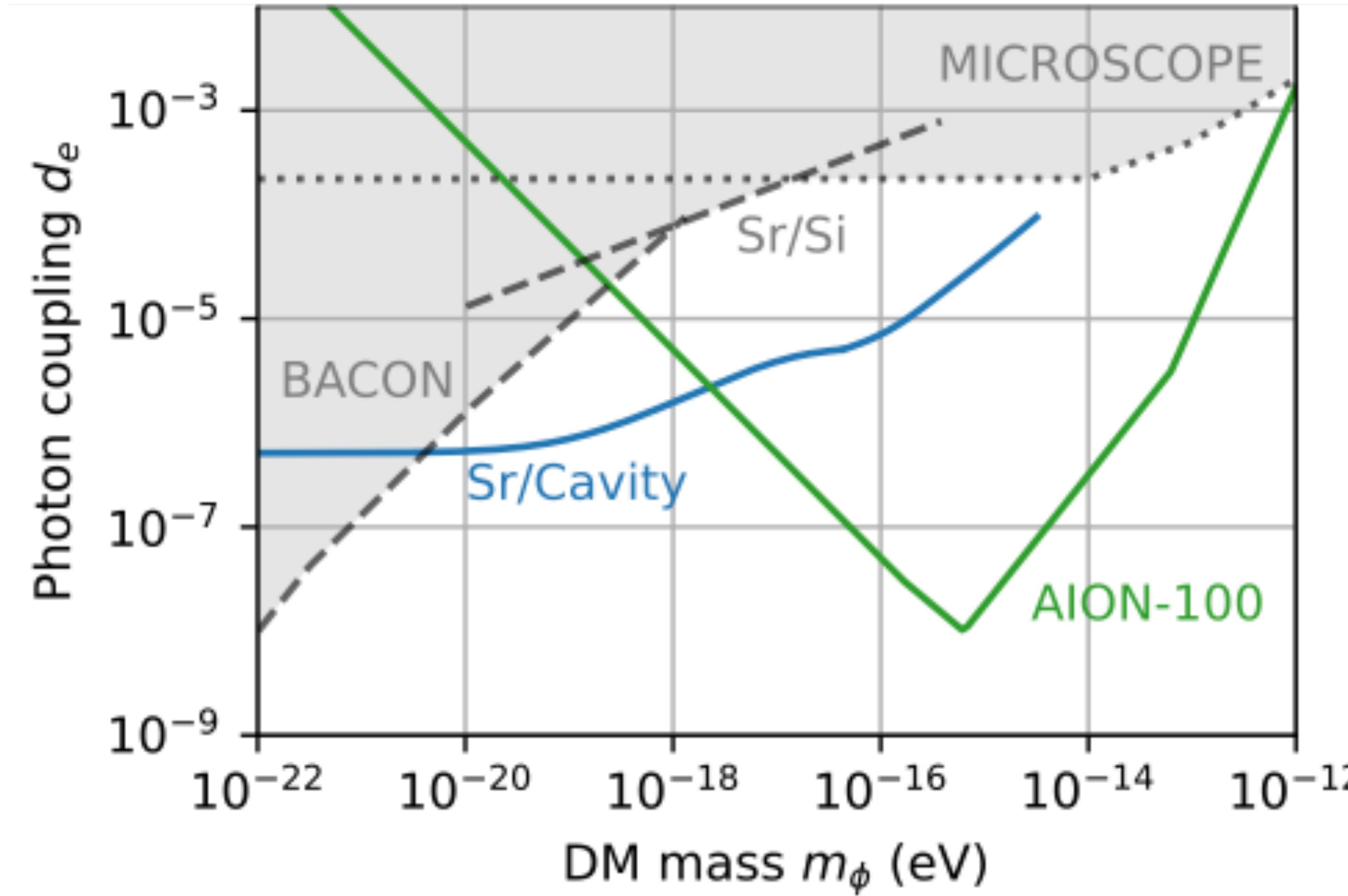
All signals depend on the field amplitude \Rightarrow will also vary with a coherence time

Scalar ULDM abundance predictions ('thermal misalignment')



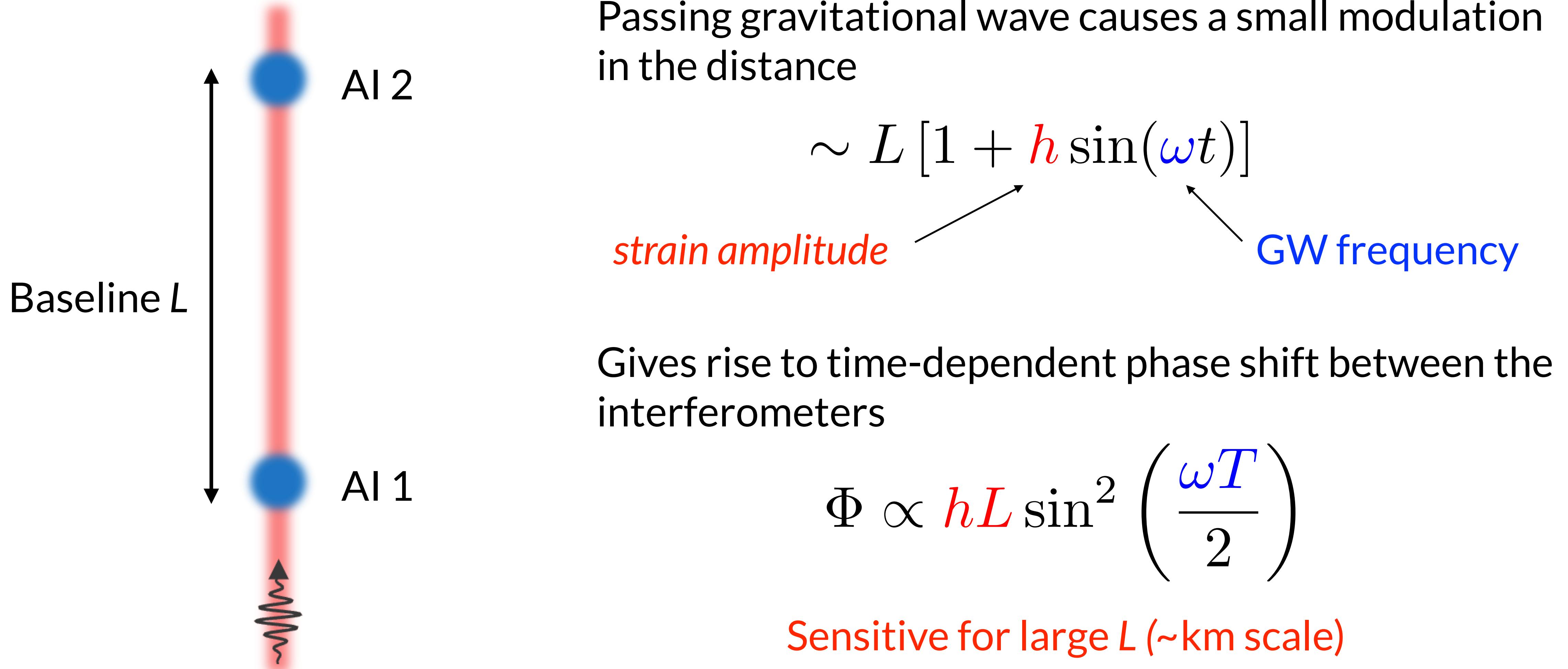
Backup: complementarity with other searches

Complementarity with atomic clocks



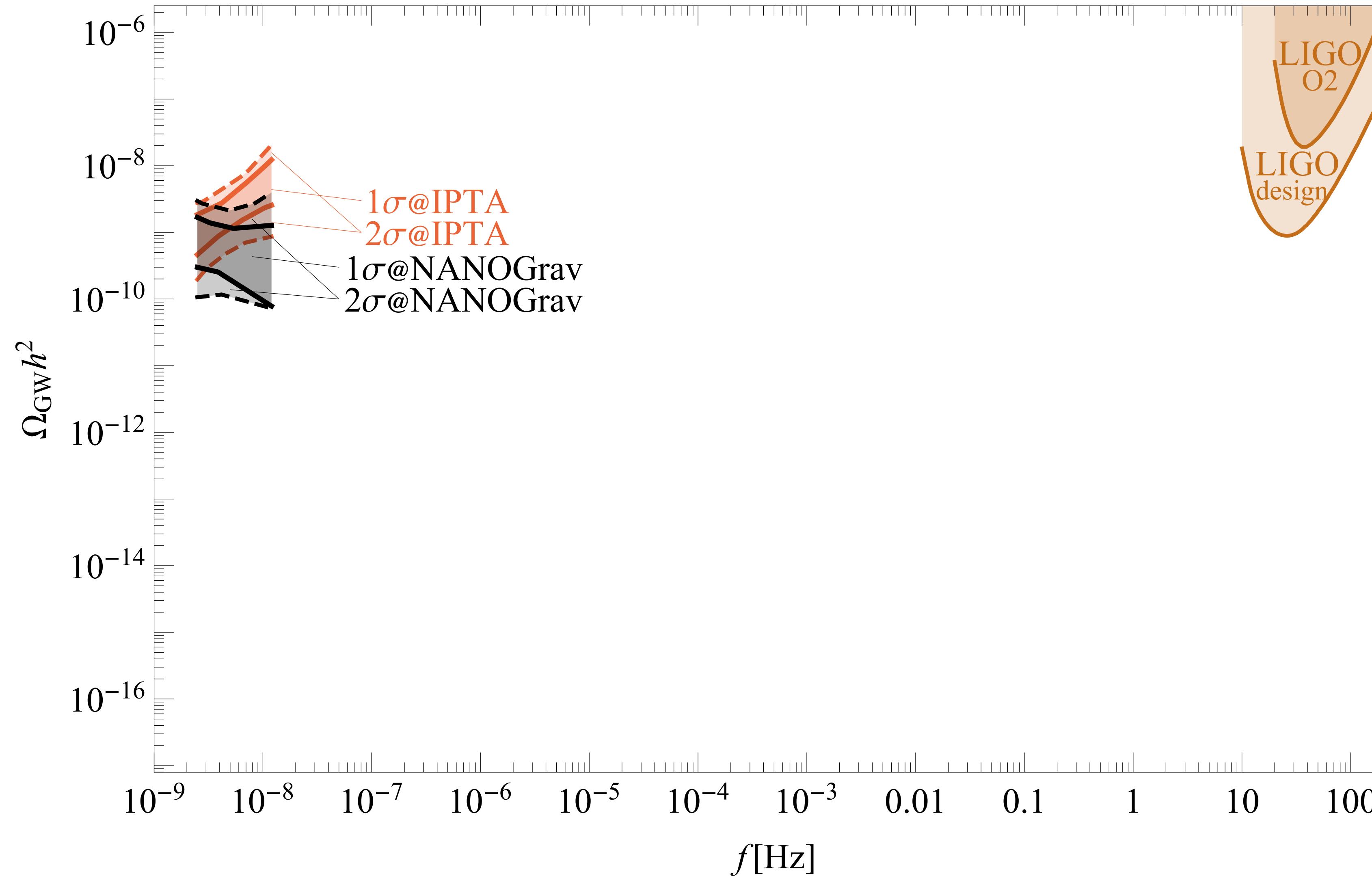
Backup: gravitational wave searches

Gravitational wave detection

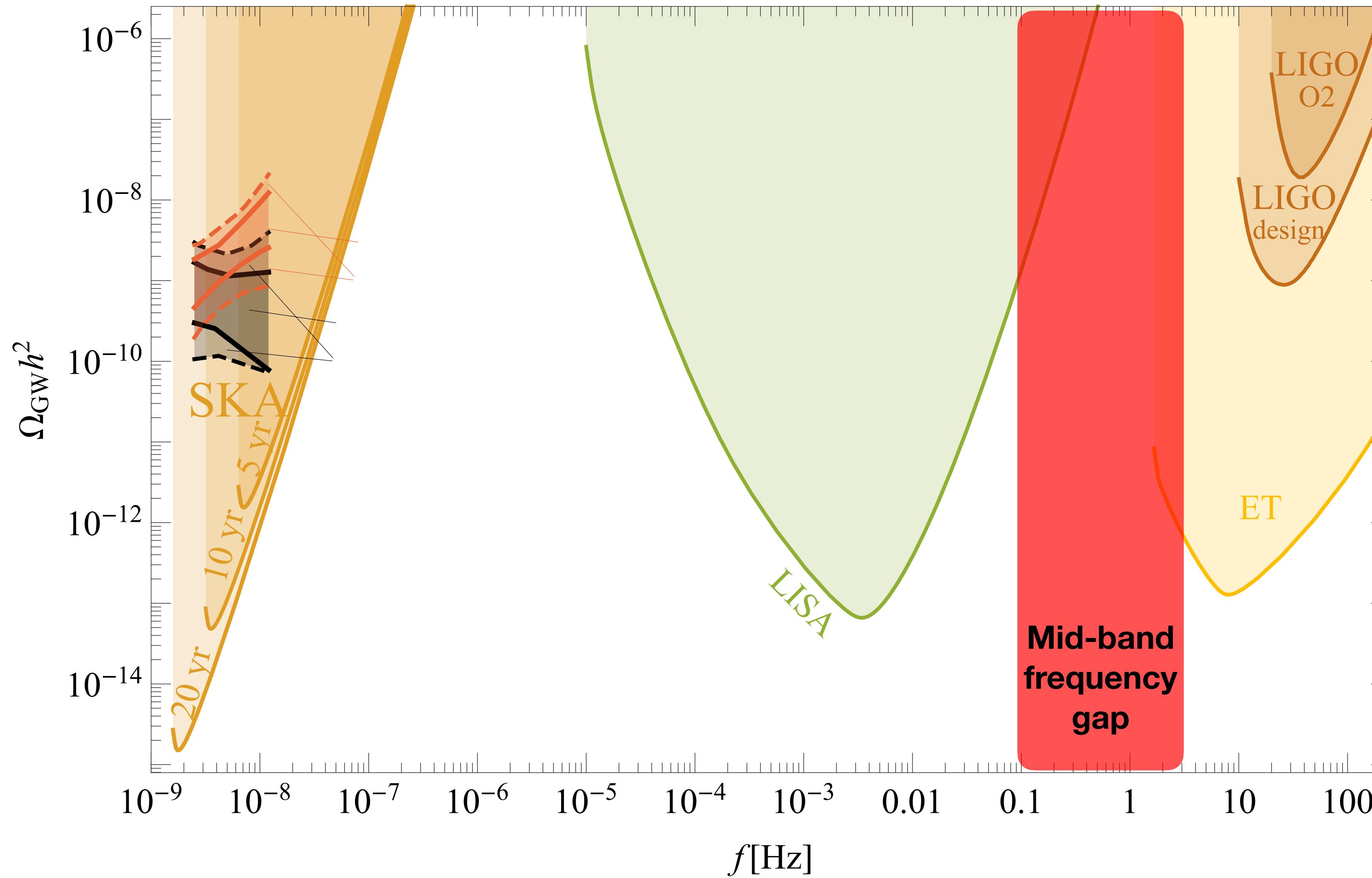


Dimopoulos et al, PRD arXiv:0802.4098, PRD arXiv:0806.2125
Graham et al, PRL arXiv:1206.0818, PRD arXiv:1606.01860

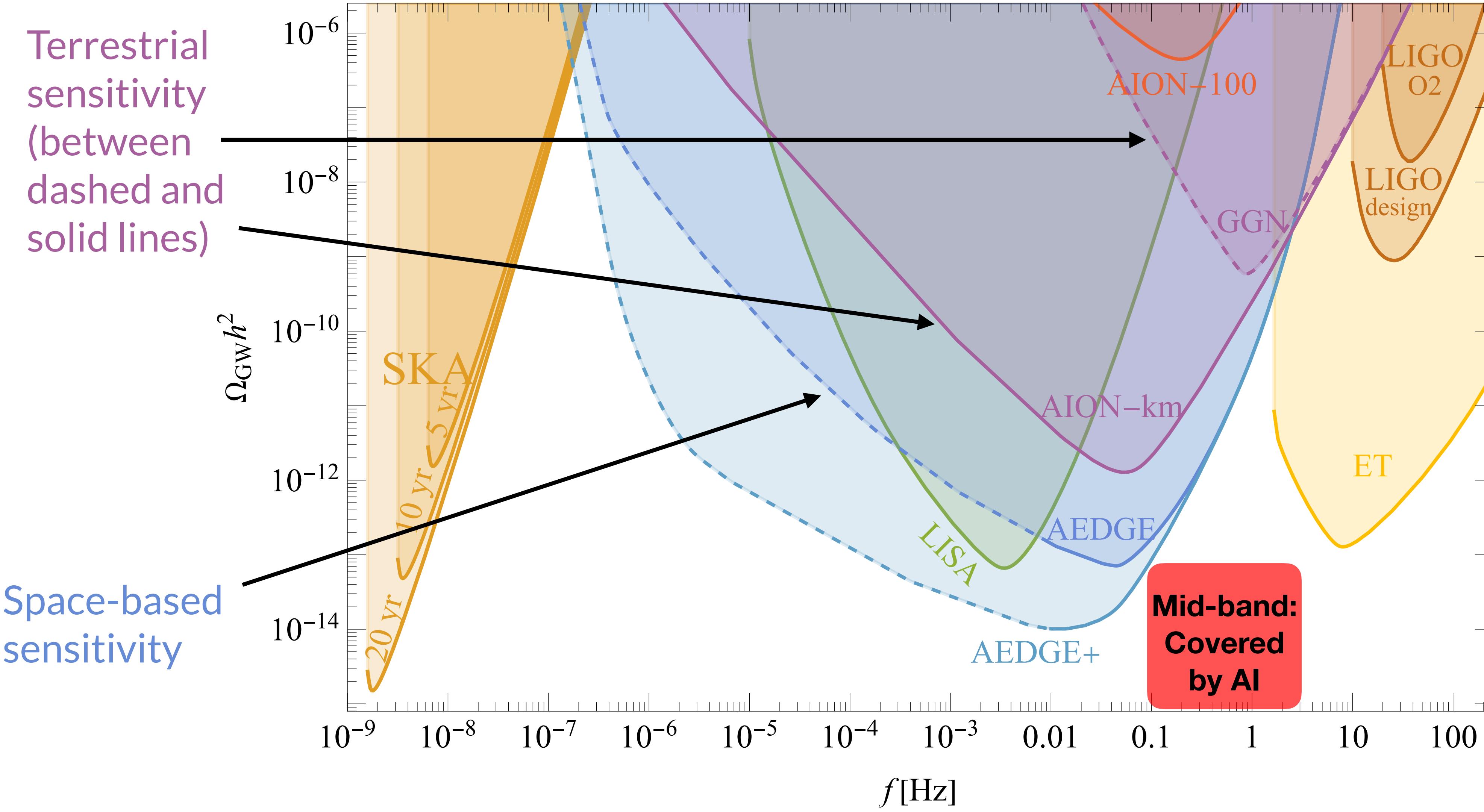
GW soundscape today



Conventional GW soundscape ~2040

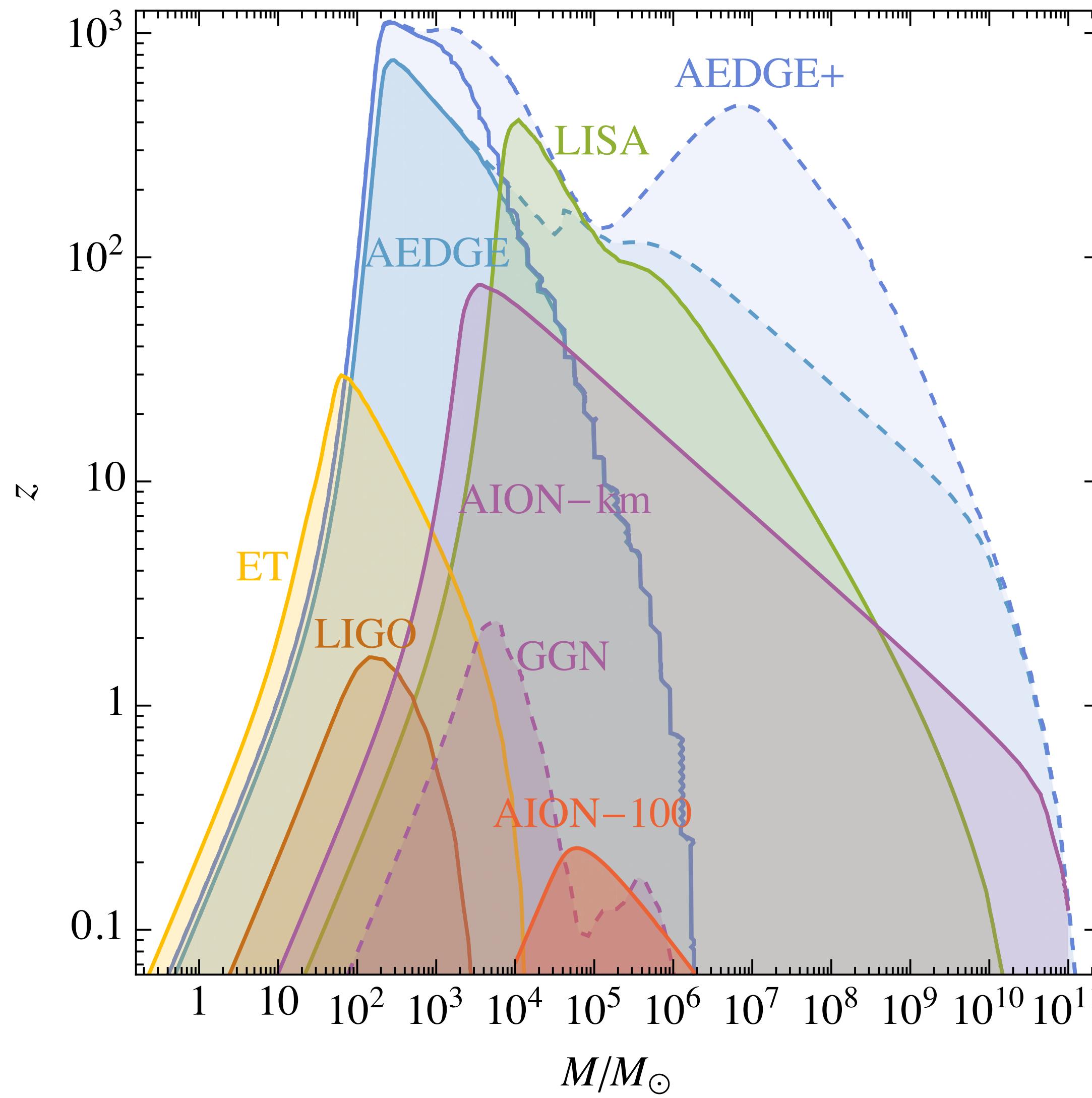


GW soundscape (~2040s) with atom interferometers



Badurina, Buchmueller,
Ellis, Lewicki, **CM**, Vaskonen
Phil.Trans.Roy.Soc.Lond.,
arXiv:2108.02468

GWs: sensitivity to binary mergers (equal masses)



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