Dark matter searches with AION-10 (and beyond)

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

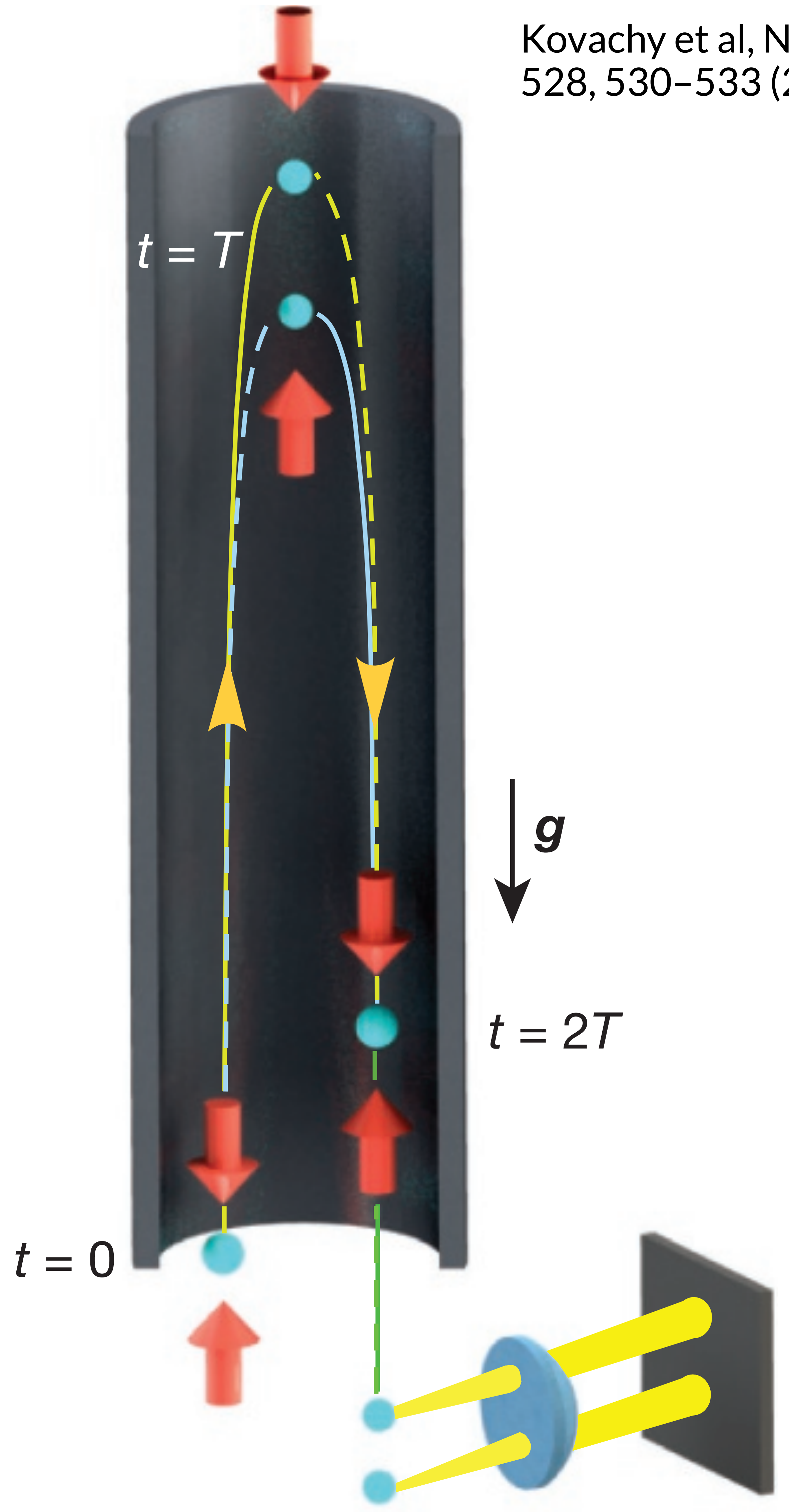
Searching for New Physics at the Quantum Technology Frontier, Ascona, 4 July 2023

Setting the scene

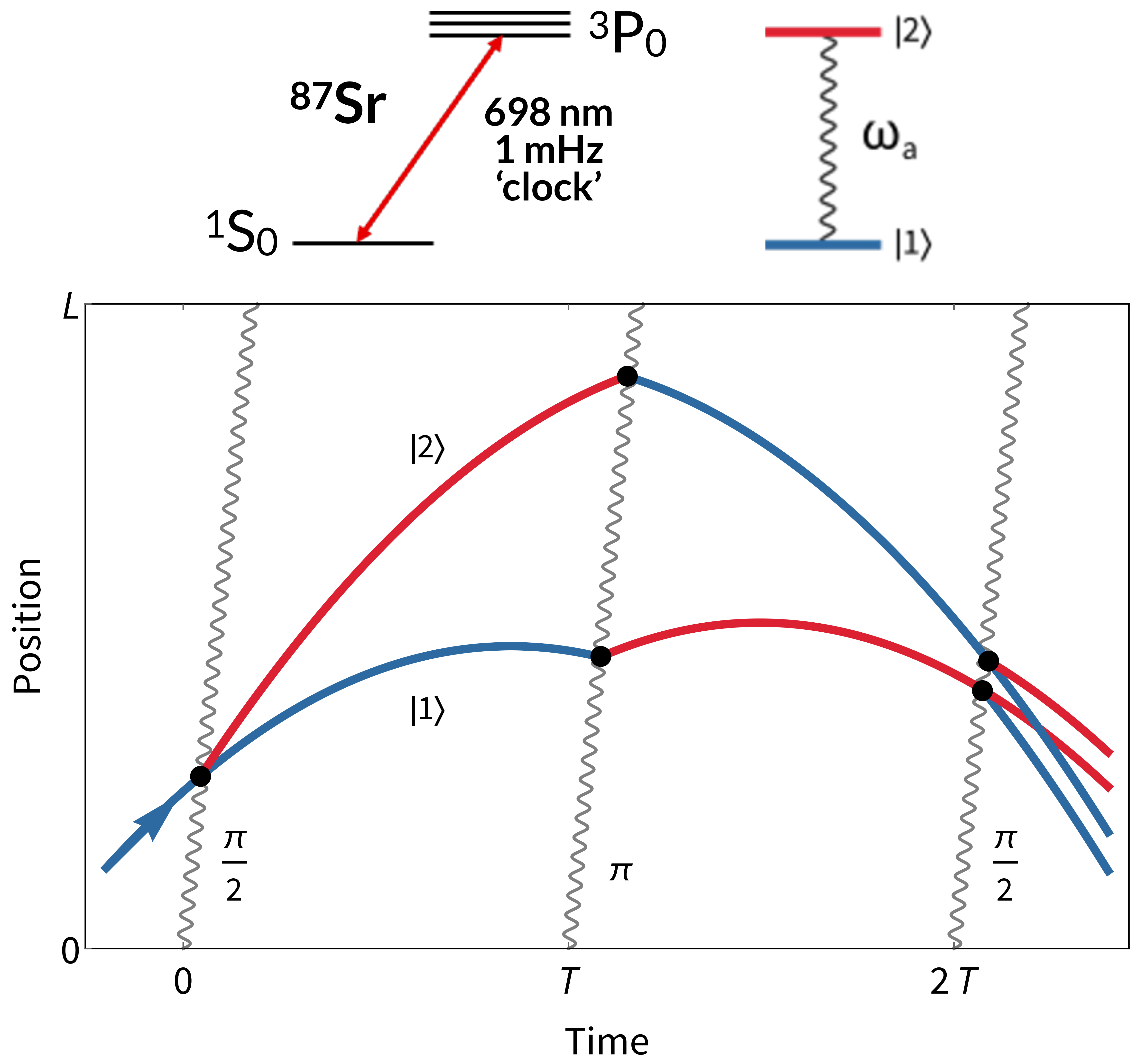
Light pulse atom interferometry (physical-space)

- 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

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



Light pulse atom interferometry (space-time)



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

Two-level system separated by optical frequency difference ω_a

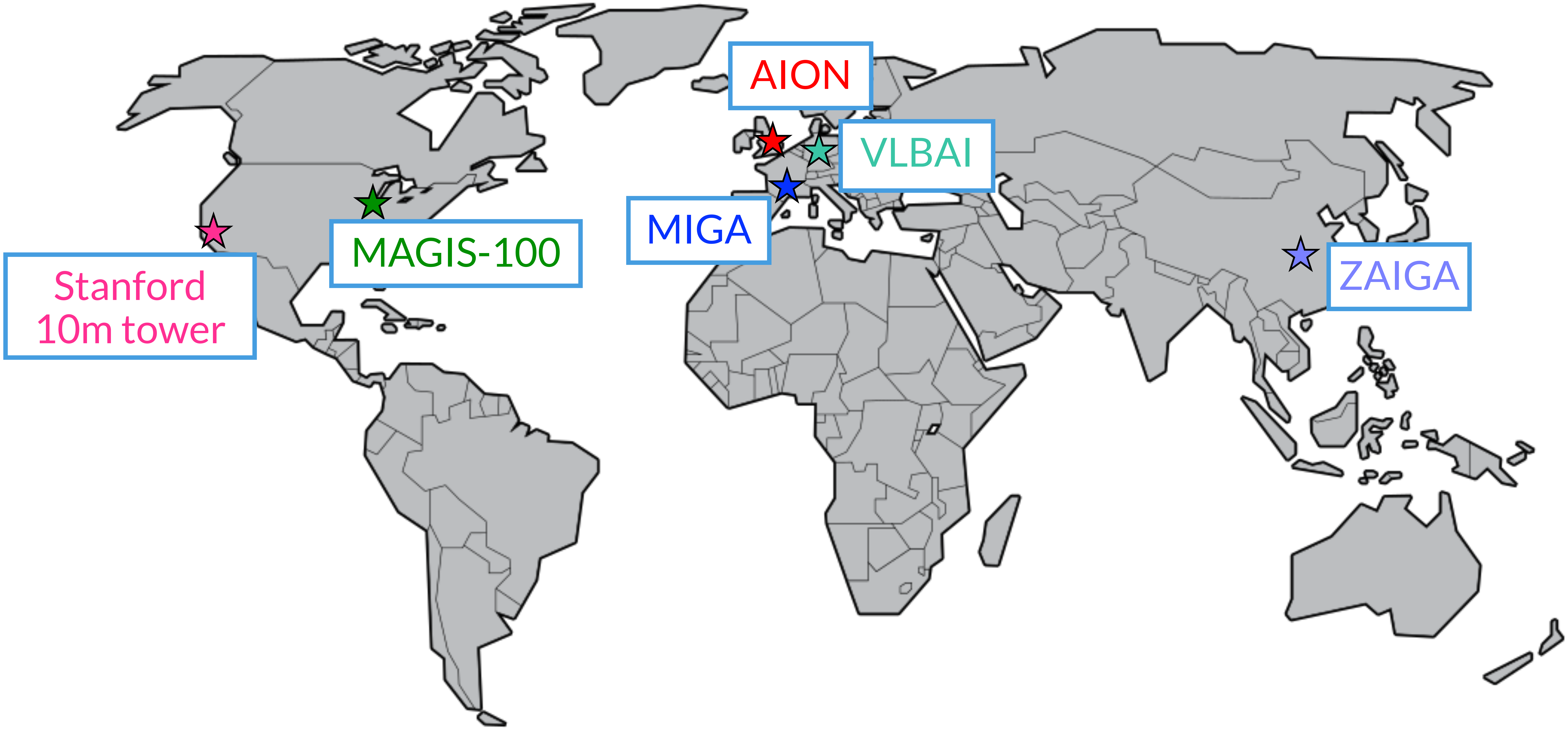
Initial pulse: 'beamsplitter'
Middle pulse: 'mirror'
Final pulse: 'beamsplitter (interfere)'

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 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

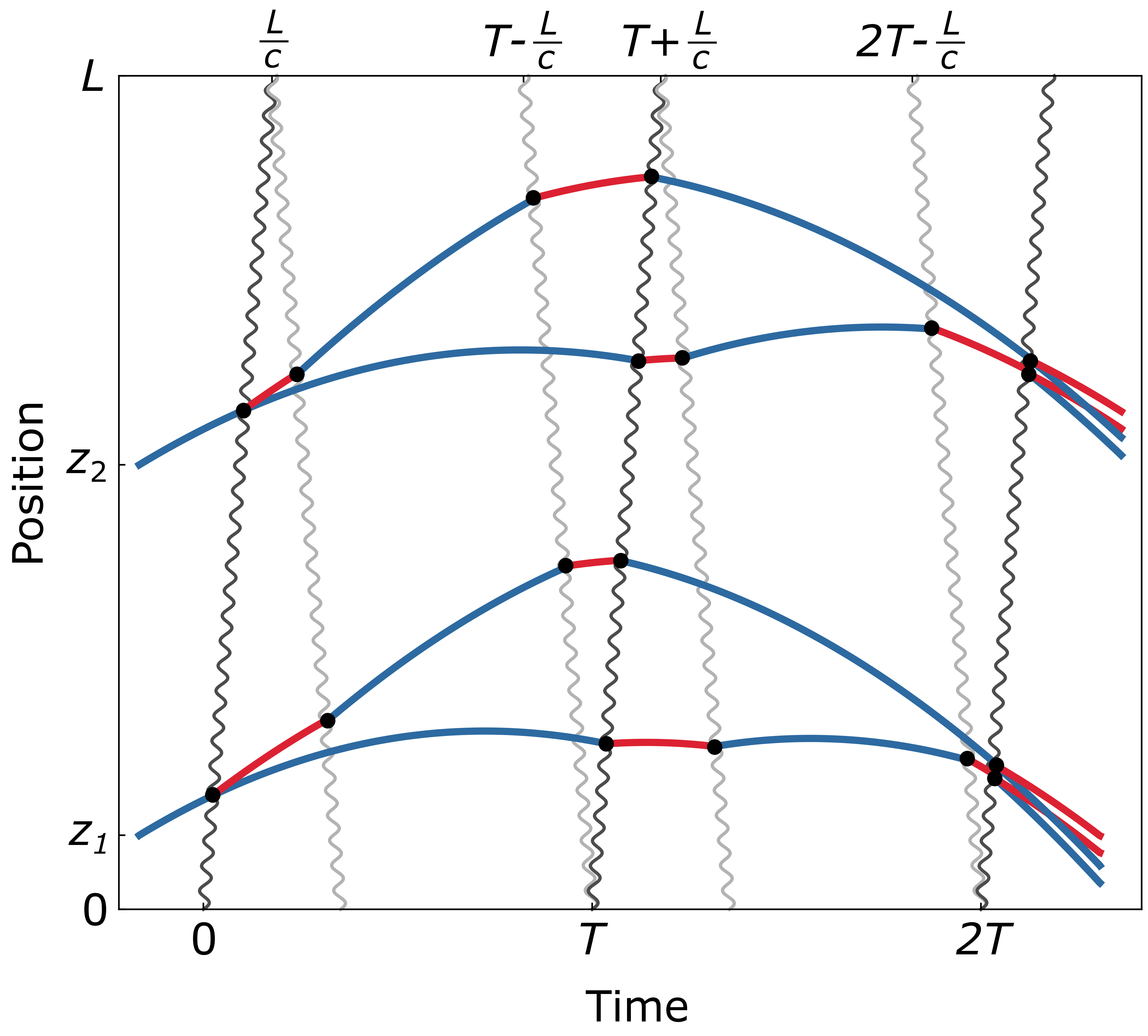
AION: Atom Interferometer Observatory and Network

7 institutes in the UK

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

Badurina, **CM**, et al (AION), JCAP, arXiv:1911.11755

AION: key features



Operate in gradiometer configuration: run two atom interferometers simultaneously with the same laser

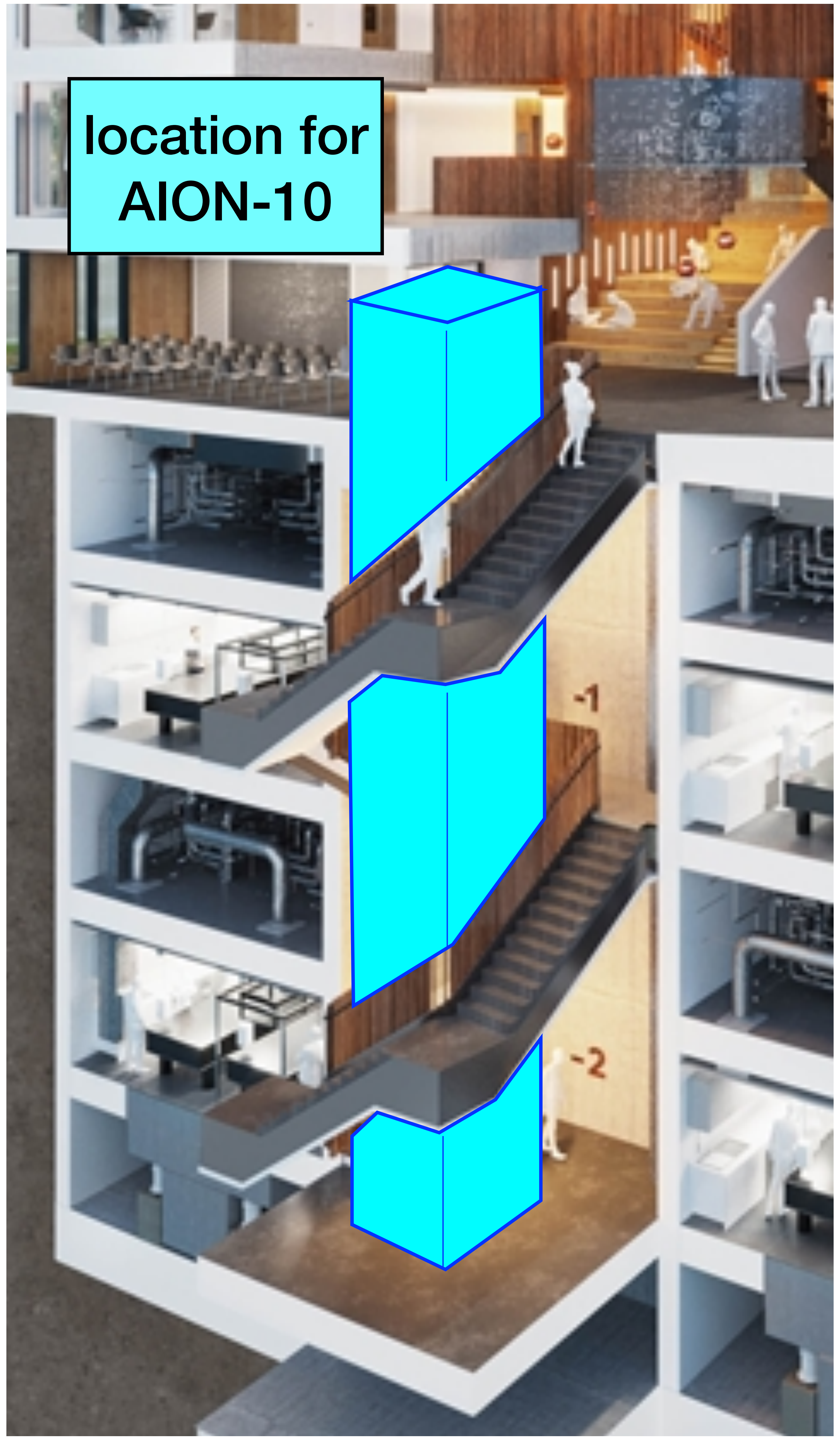
Pushing state-of-the-art single photon strontium atom interferometry with large momentum transfer techniques

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

Partnering with MAGIS-100 in the US

Badurina , **CM**, et al (AION), JCAP, arXiv:1911.11755
Image from Abe et al (MAGIS-100),Quant.Sci.Technol, arXiv:2104.02835

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

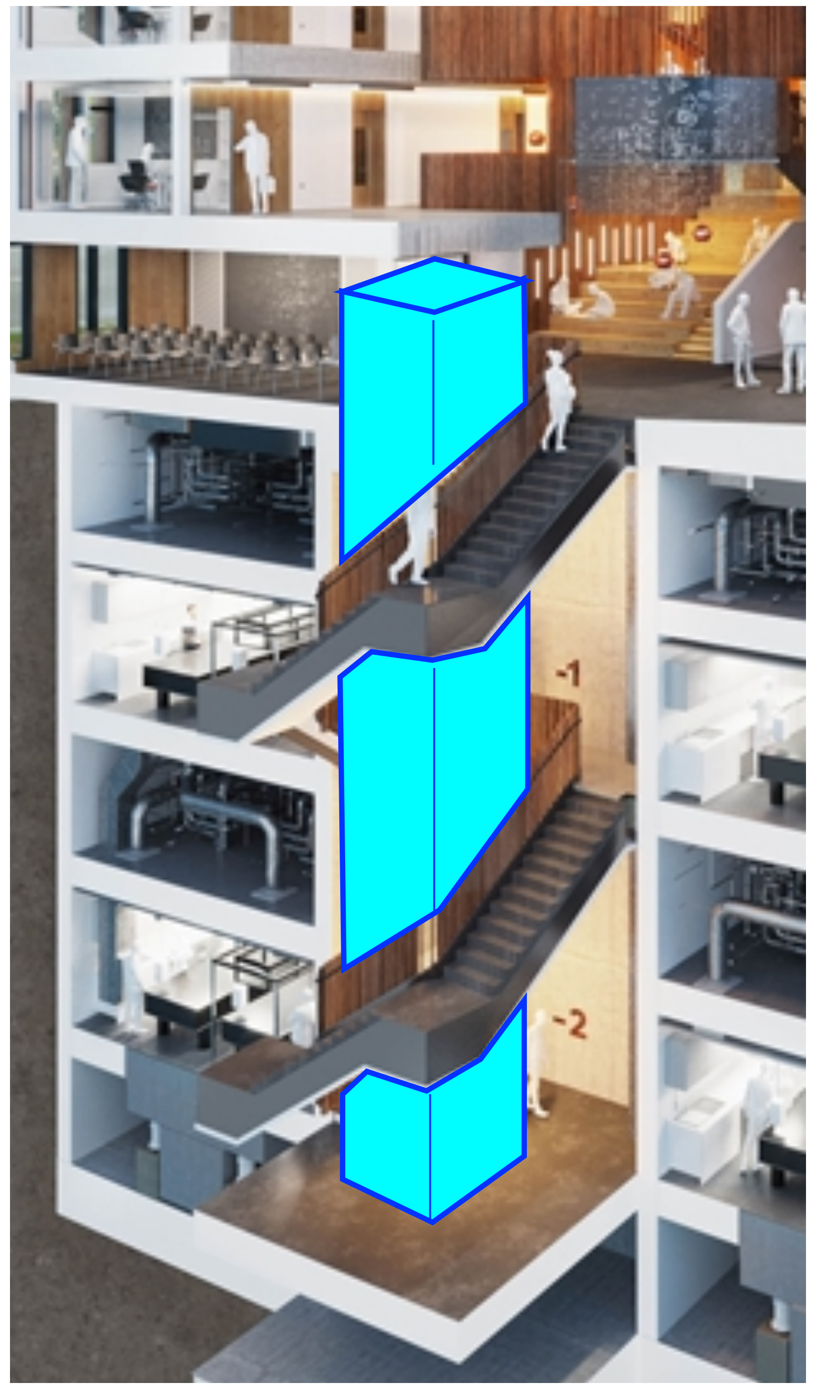
AION: envisaged as a multi-stage project

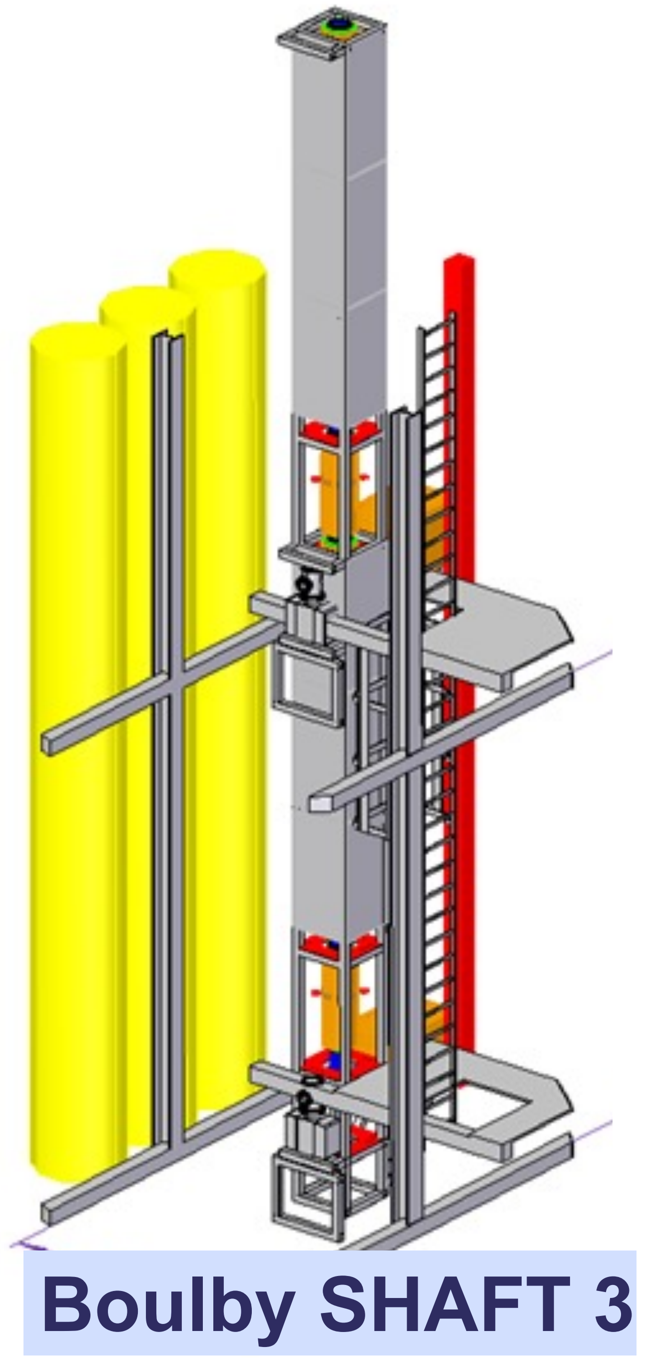
AION-10
2020s ~10m instrument in Oxford

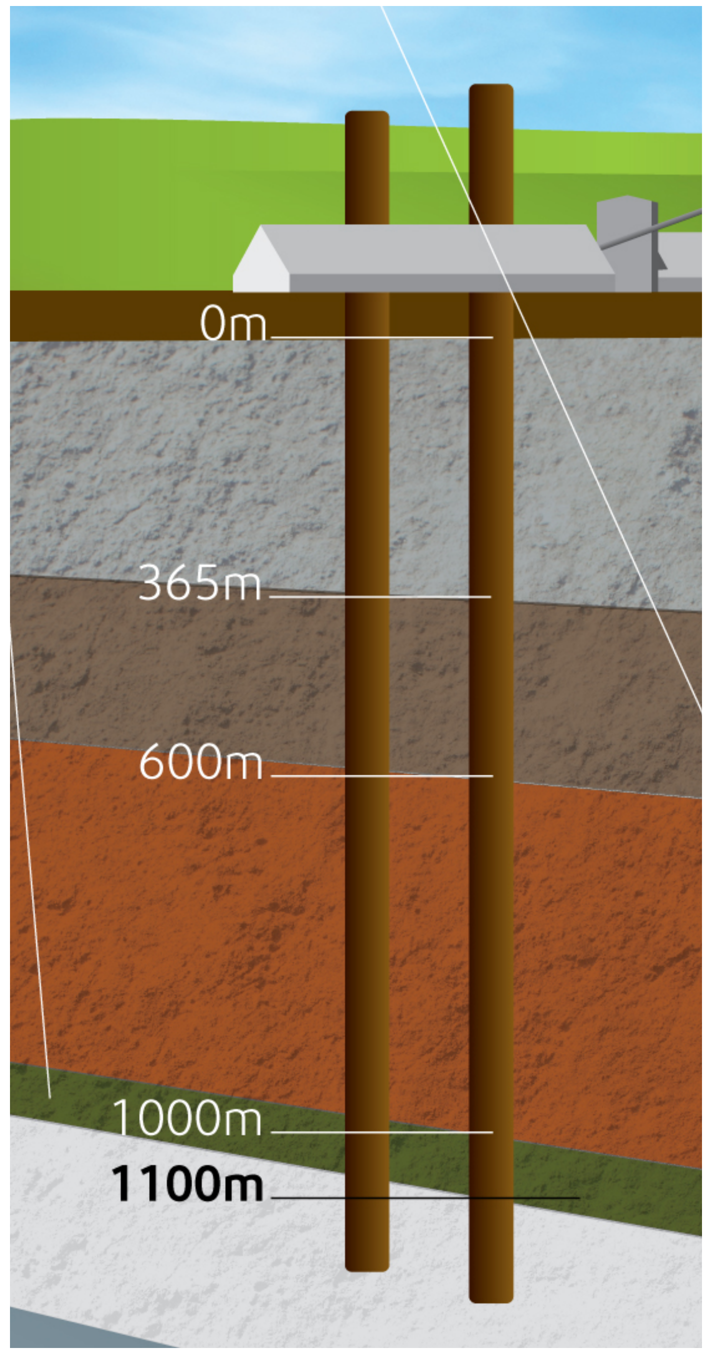
AION-100
2030s ~100m instrument at Boulby/CERN/…?

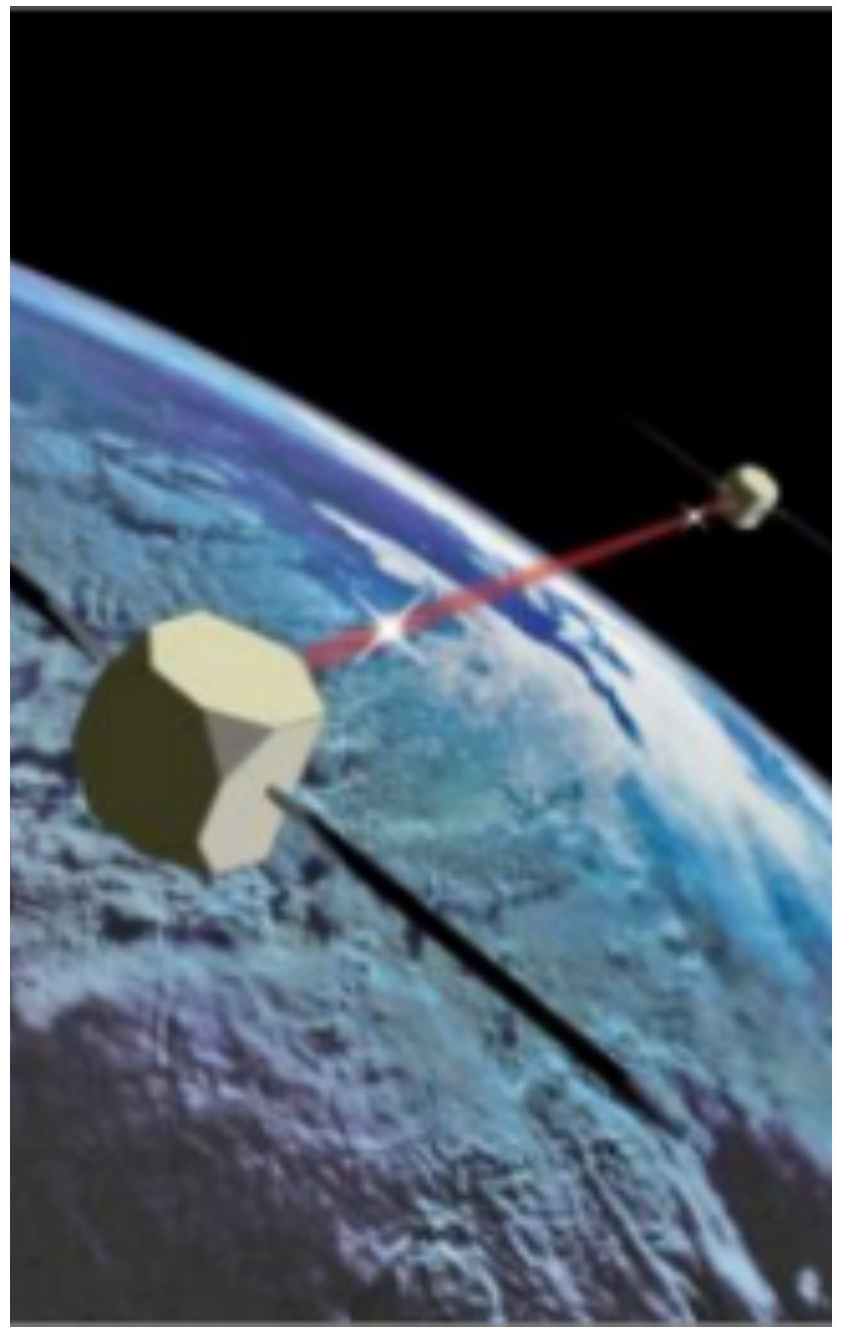
km-instrument
2040s major international project

Space-instrument
2050s detectors with $\sim 10^7$km baseline







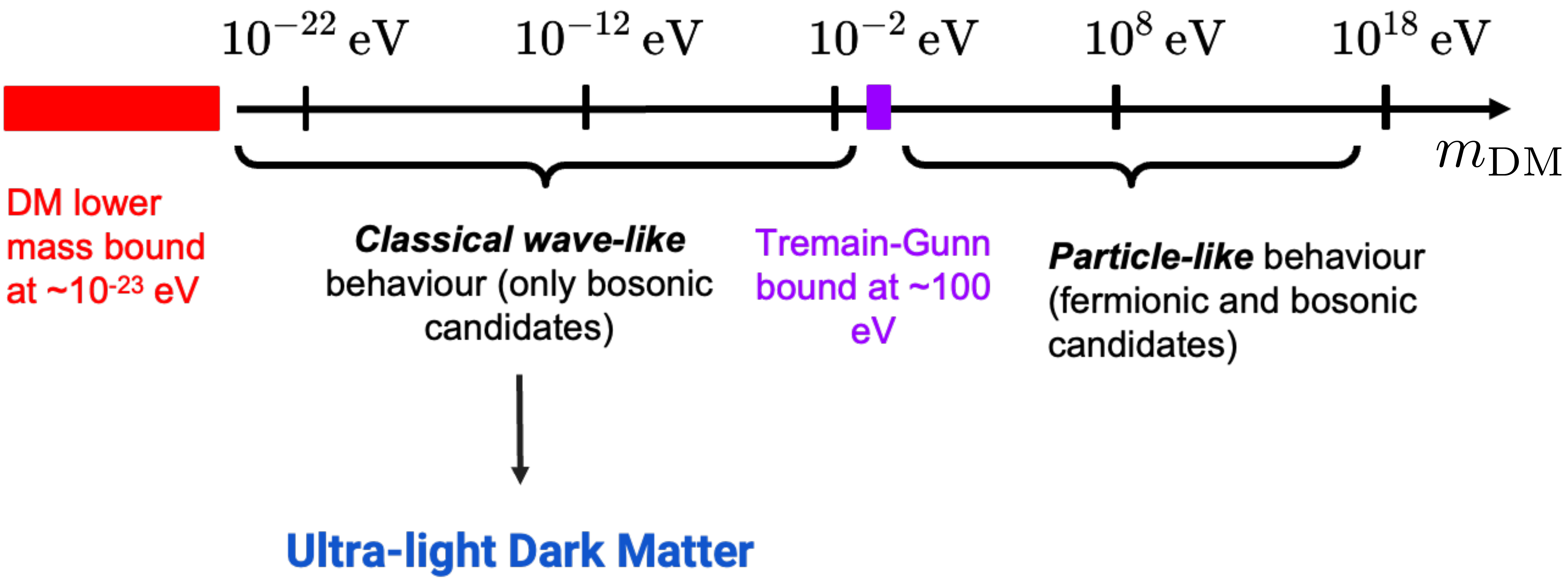


CERN study: arXiv:2304.00614 ; AEDGE, arXiv:1908.00802; Cold atoms in Space, arXiv:2201.07789

Near-term aim: probe 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

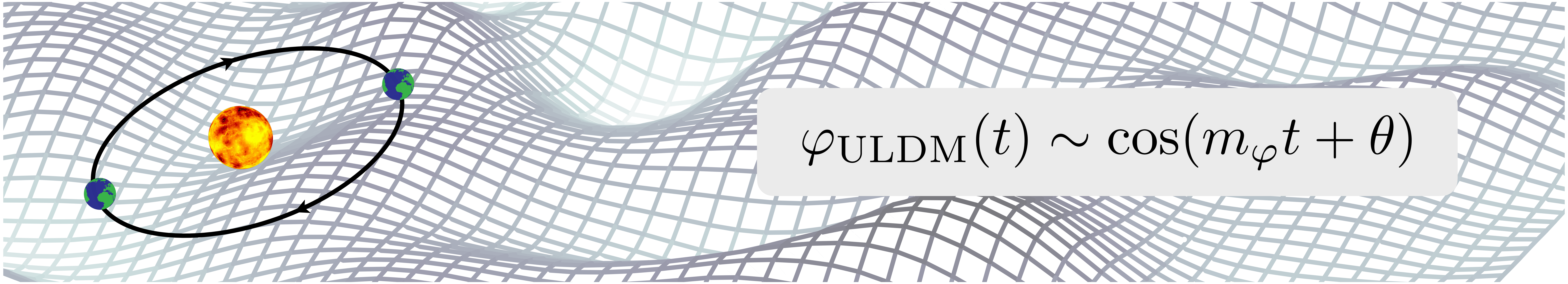
DM landscape: classifying by mass



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, PRD, arXiv: 1711.10489
Derevianko, PRA, arXiv:1605.09717

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

Time-dependent signals

An oscillating ULDM field can induce several signals testable with AIs:

1. Changes in fundamental constants (scalar ULDM)

2. Accelerations on test masses (vector ULDM)

3. Precession of spins (pseudoscalar ULDM)

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

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:

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

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

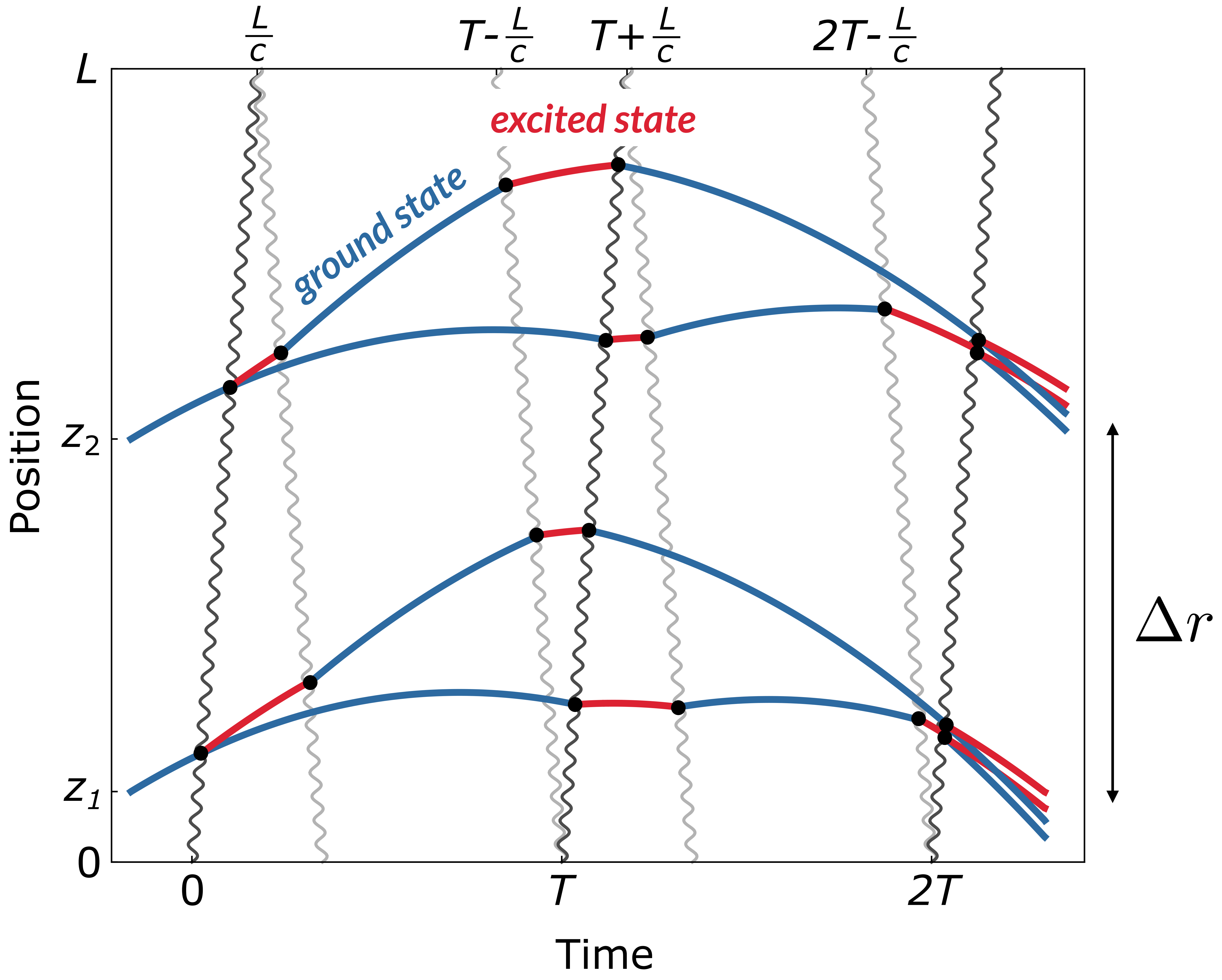
Scalar ULDM signal

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

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

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

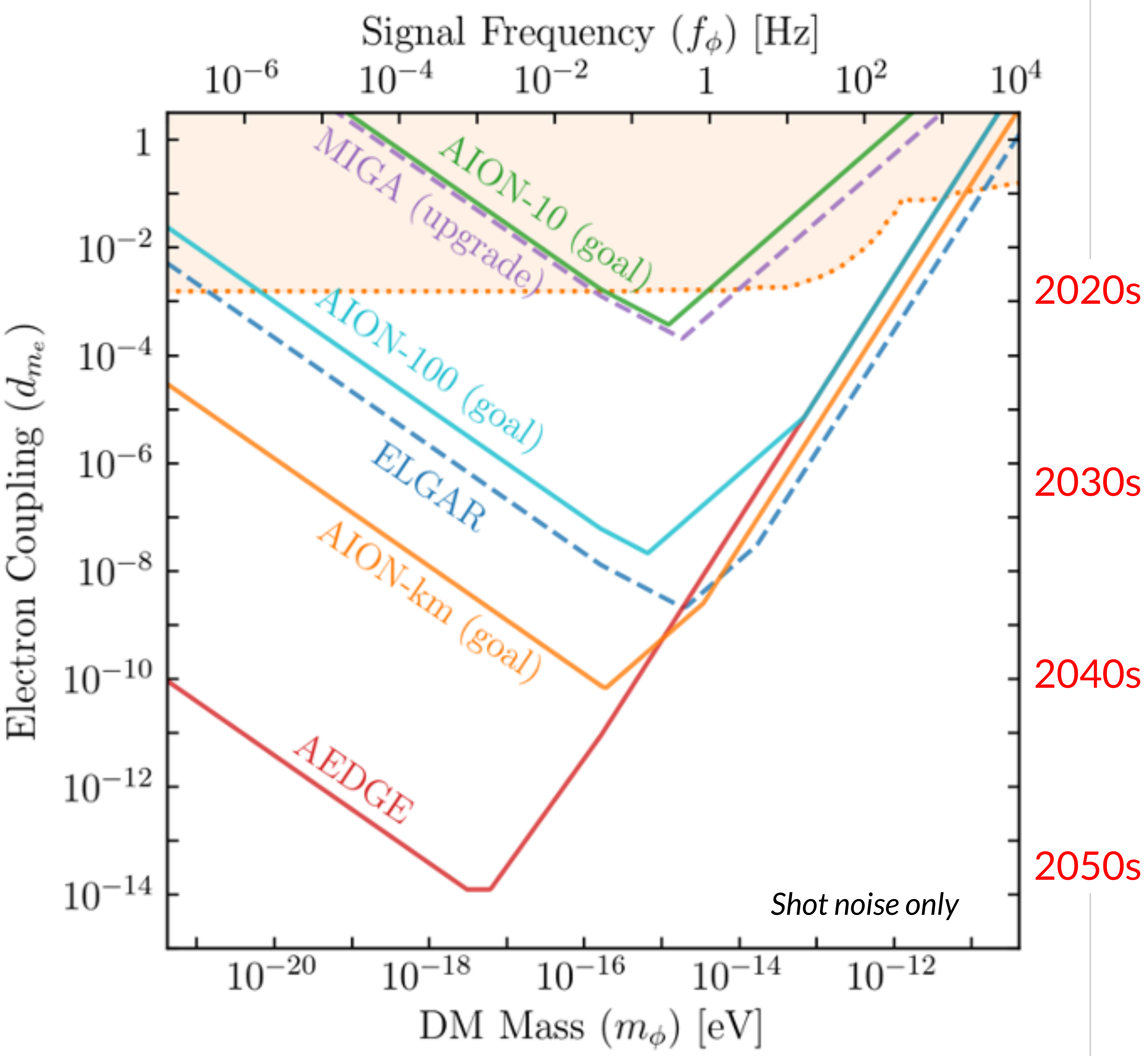
t_1, t_2 = time in excited state



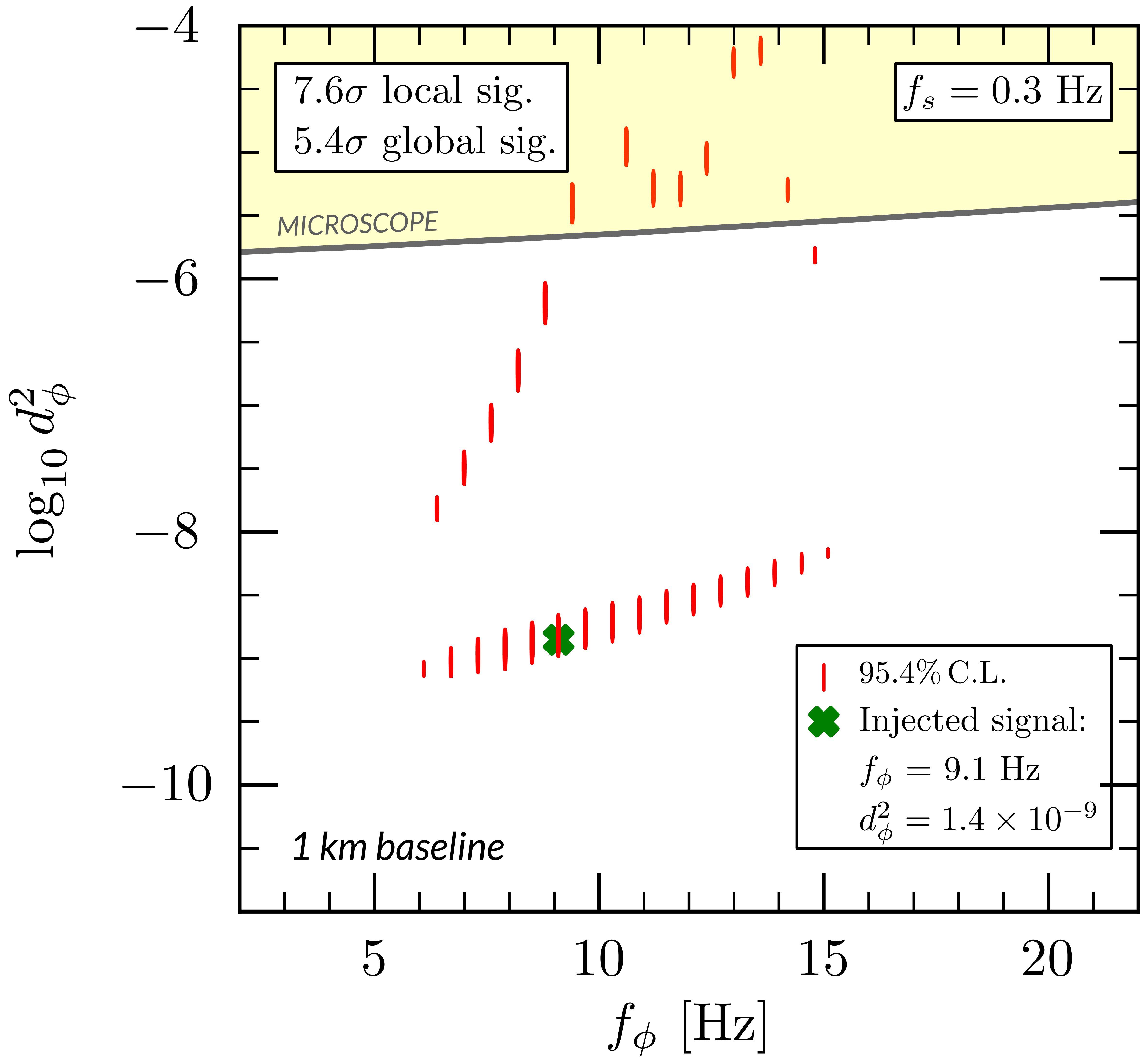
Near- and long-term sensitivity projections (Scalar)

Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{\rm noise}$ $[1/\sqrt{\rm Hz}]$	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



Excellent discovery prospects (Scalar)



Atomic fountain has ~Hz sampling rate

Higher frequency signals are aliased:

multiple 'islands' in parameter space consistent with the injected signal

High precision within each island: ~10^{-6} Hz

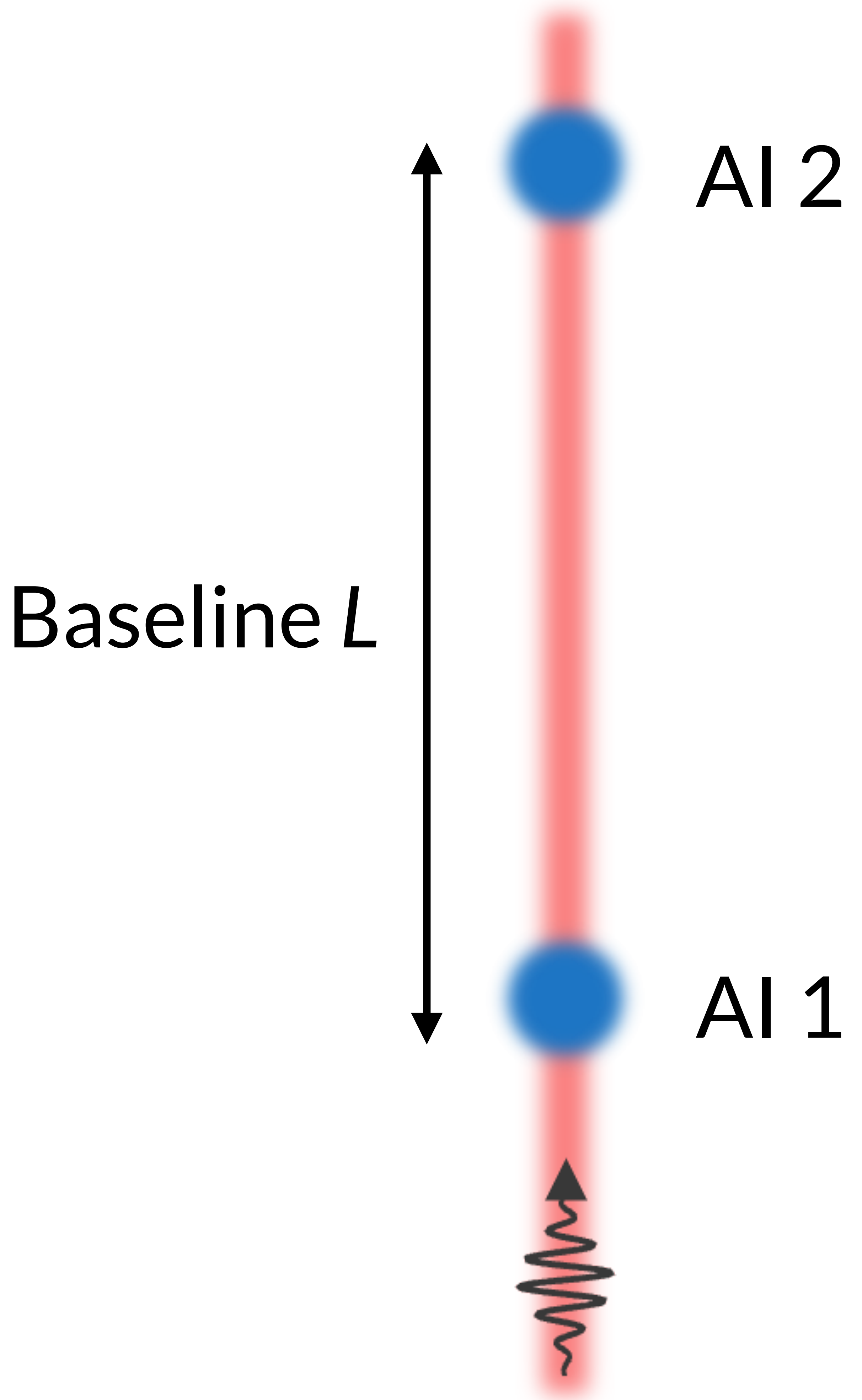
(No aliasing of sub ~Hz signals)

Badurina, Beniwal, **CM**, arXiv:2306.16477

Long-term aim: Gravitational wave searches

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

Gravitational wave detection



Passing gravitational wave causes a small modulation in the distance

$$\sim L\left[1 + h\sin(\omega t)\right]$$

strain amplitude → h

GW frequency → ω

Gives rise to time-dependent phase shift between the interferometers

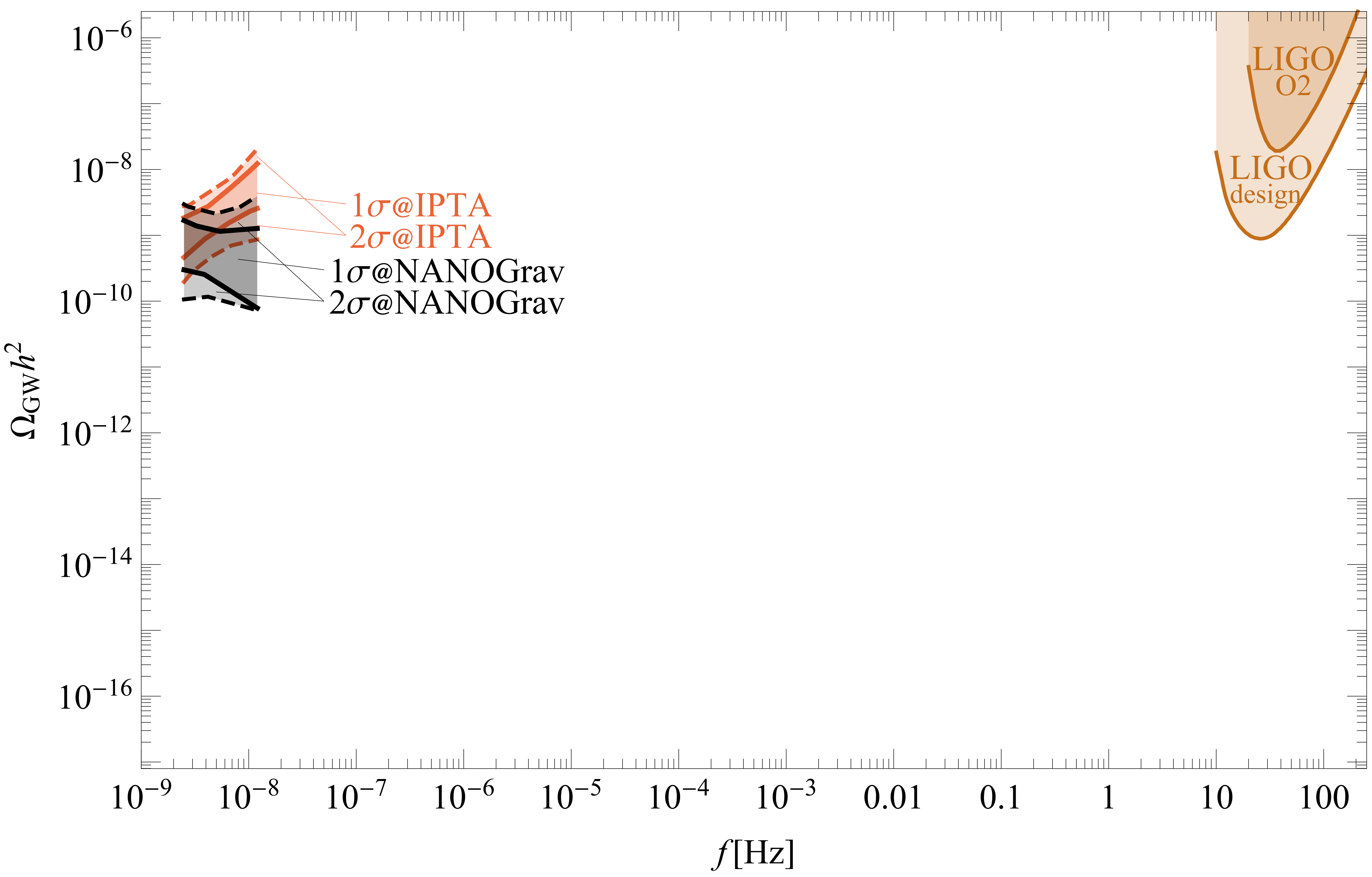
$$\Phi \propto hL\sin^2\left(\frac{\omega T}{2}\right)$$

Sensitive for large *L* (~km scale)

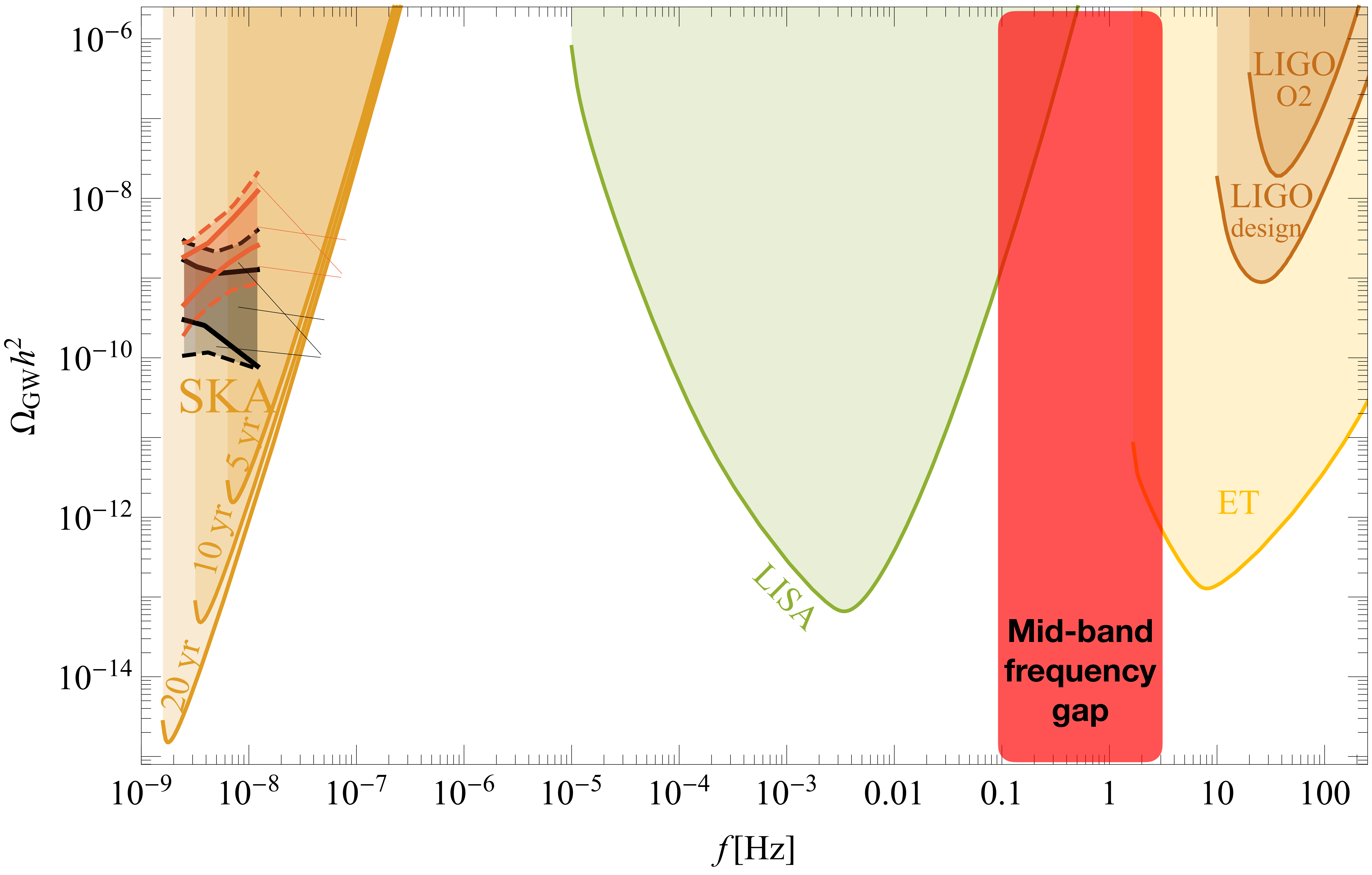
Sensitive to GW frequencies ~ *1/T* ~ Hz

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

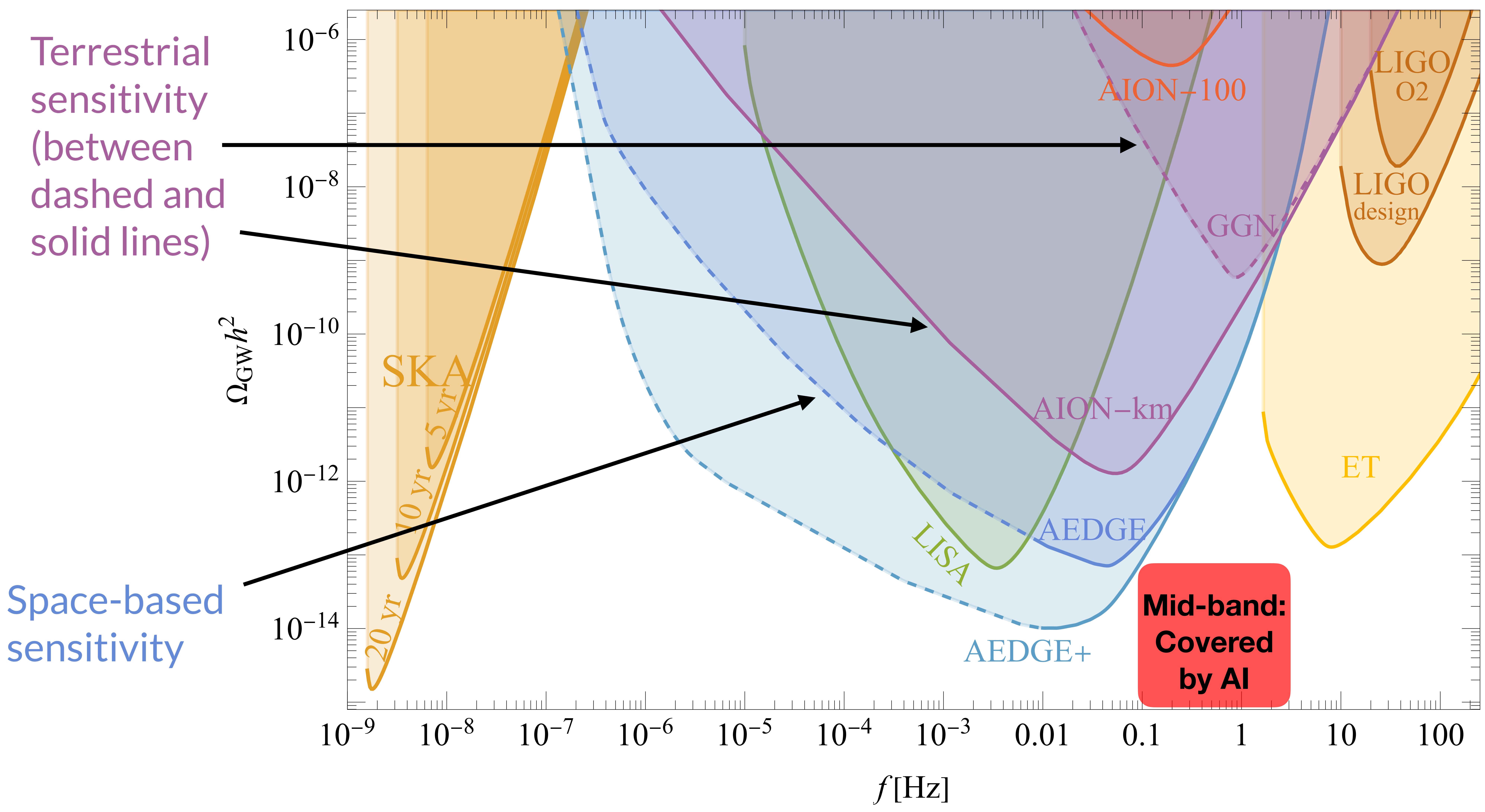
GW soundscape today



Conventional GW soundscape ~2040



GW soundscape (~2040s) with atom interferometers



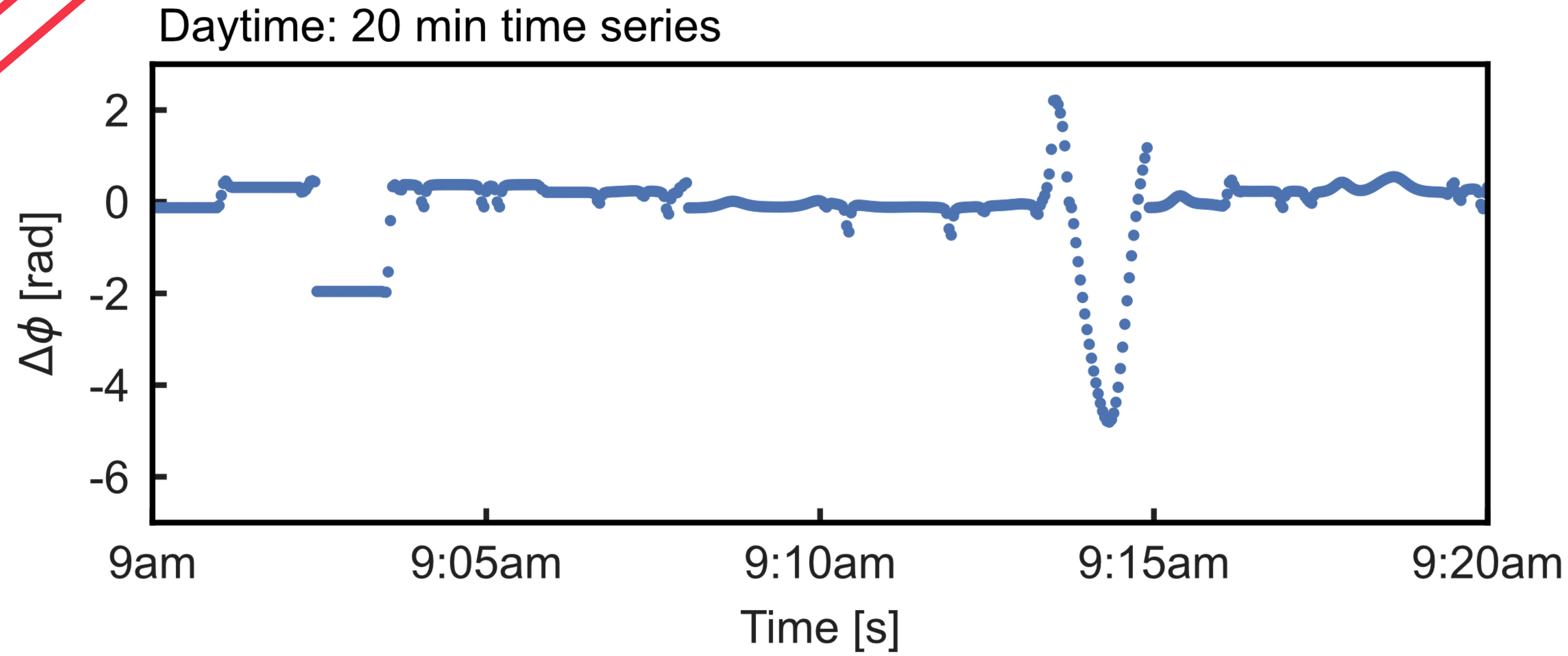
Badurina, Buchmueller, Ellis, Lewicki, **CM**, Vaskonen Phil.Trans.Roy.Soc.Lond., arXiv:2108.02468

Ongoing work: mitigating backgrounds

Badurina, Gibson, **CM**, Mitchell, PRD, arXiv:2211.01854
Carlton, **CM**, to appear

Short-termer challenge: operating in a university building

Moving ‘test masses’ contribute to the phase:

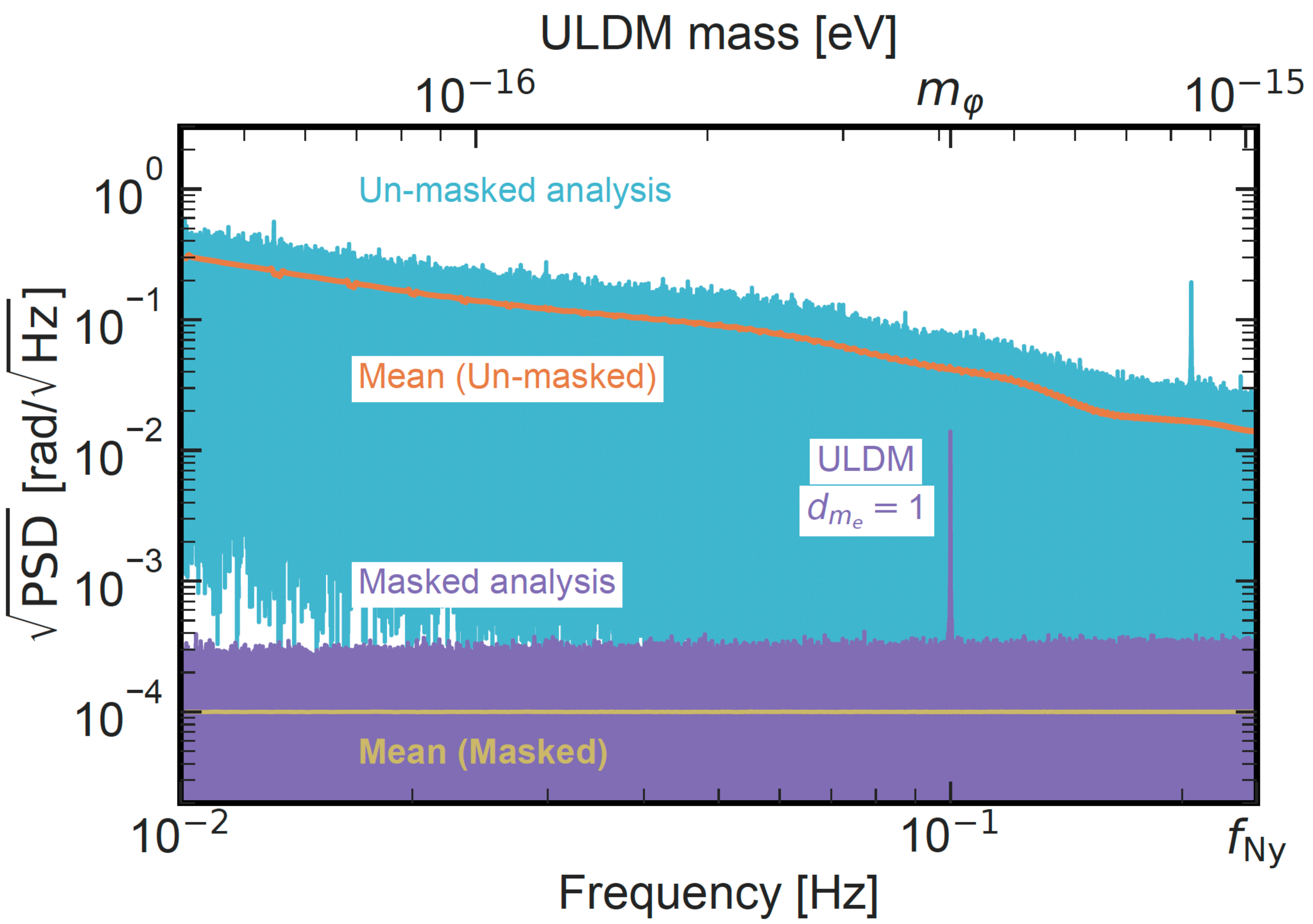


ULDM searches run for many months:

Could the busy environment hide a ULDM signal?

Preliminary: Carlton, **CM**, *to appear*

Mitigation through data analysis



Running at night, identifying transients, masking, and de-trending time series effective:

from the cyan PSD to the purple PSD

Recover shot-noise limited sensitivity and *sensitivity to ULDM signals*

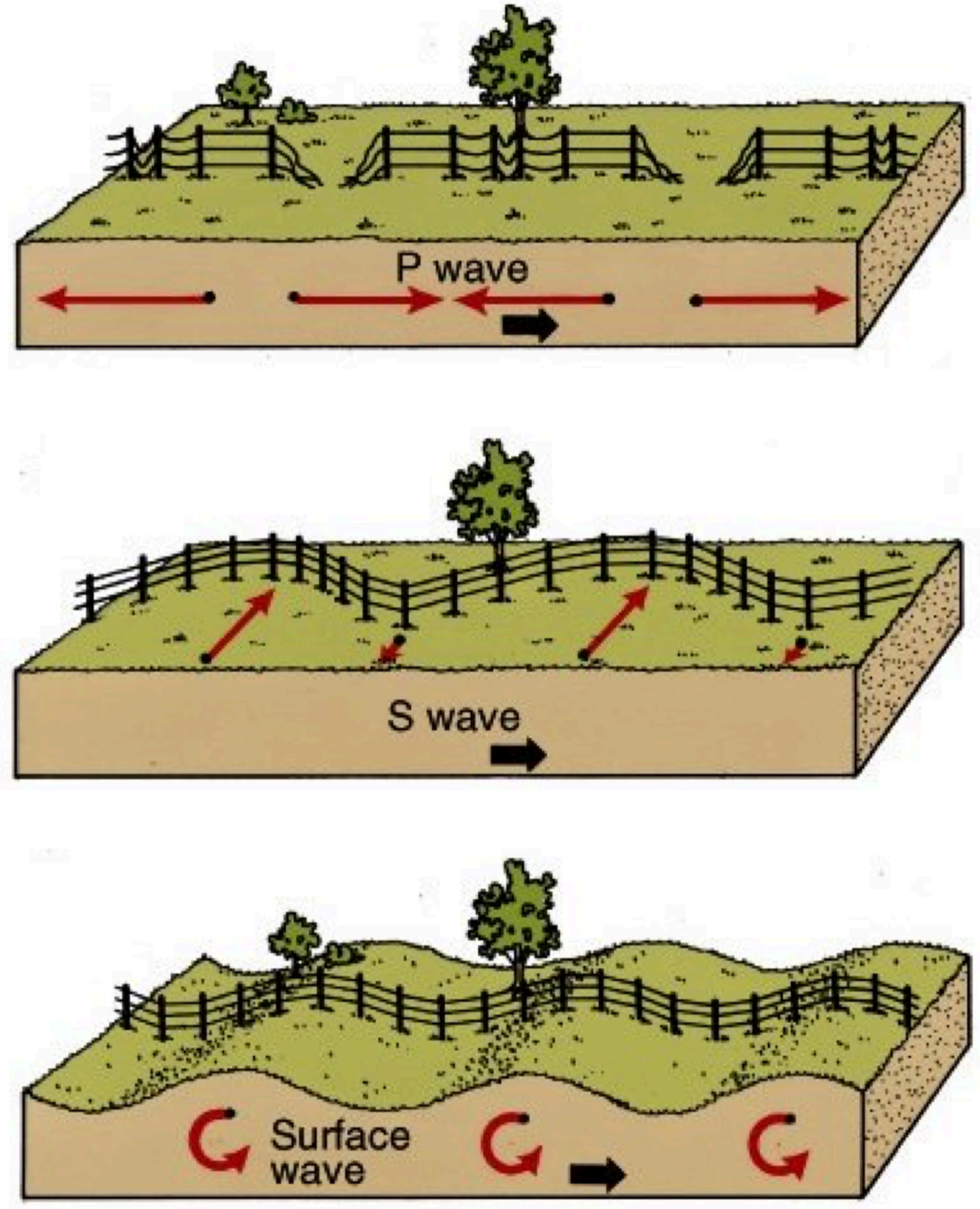
Preliminary: Carlton, **CM**, *to appear*

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



Harms, Living Rev.Rel.18 (2015) 3, arXiv:1507.05850; Baker et al, arXiv:1201.5656; Vetrano et al, arXiv:1304.1702; Harms et al, arXiv:1308.2074; Chaibi et al, arXiv:1601.00417; Junca et al (MIGA), arXiv:1902.05337

(Partially) mitigated with multi-gradiometer configuration

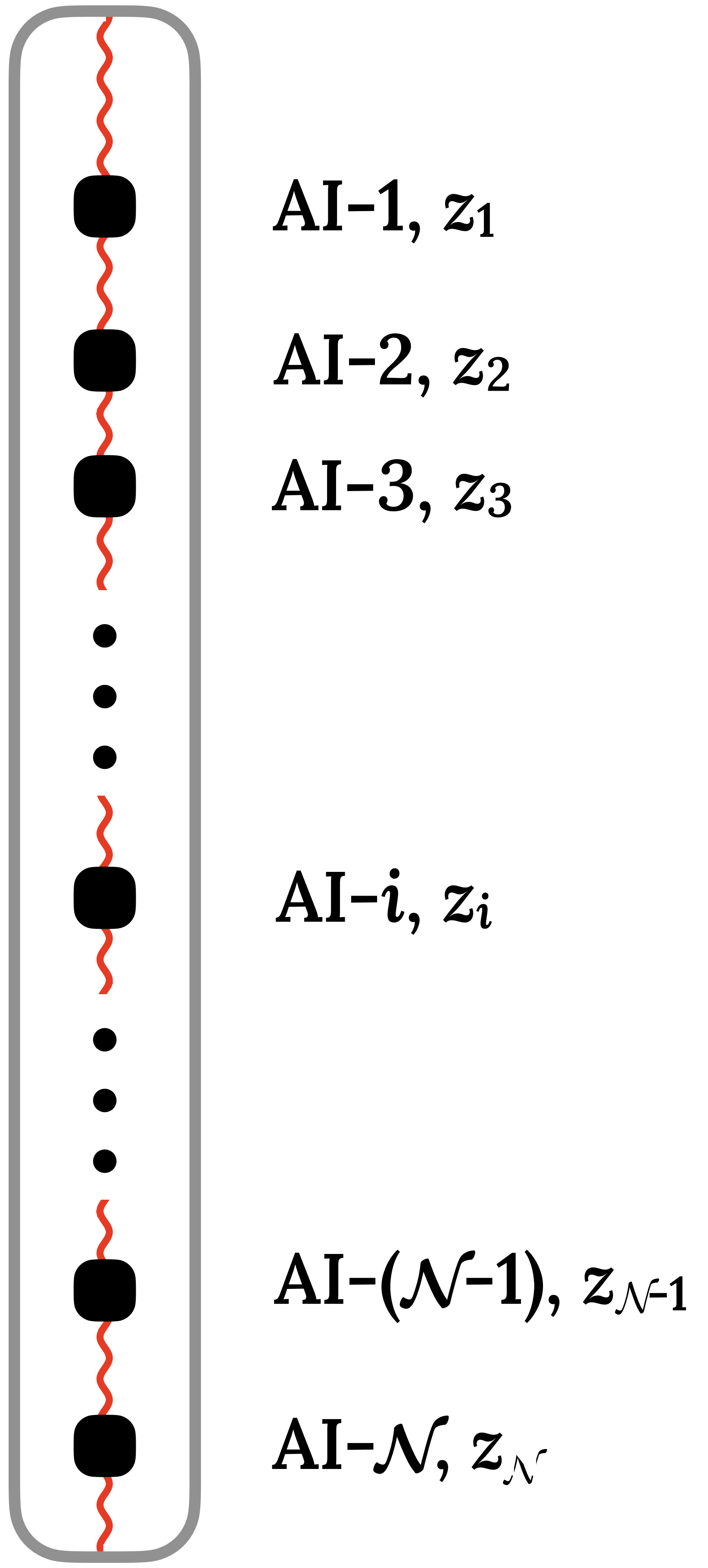
surface

GGN signal decays exponentially from the surface

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

ULDM (or GW) signals scale linearly with AI separation

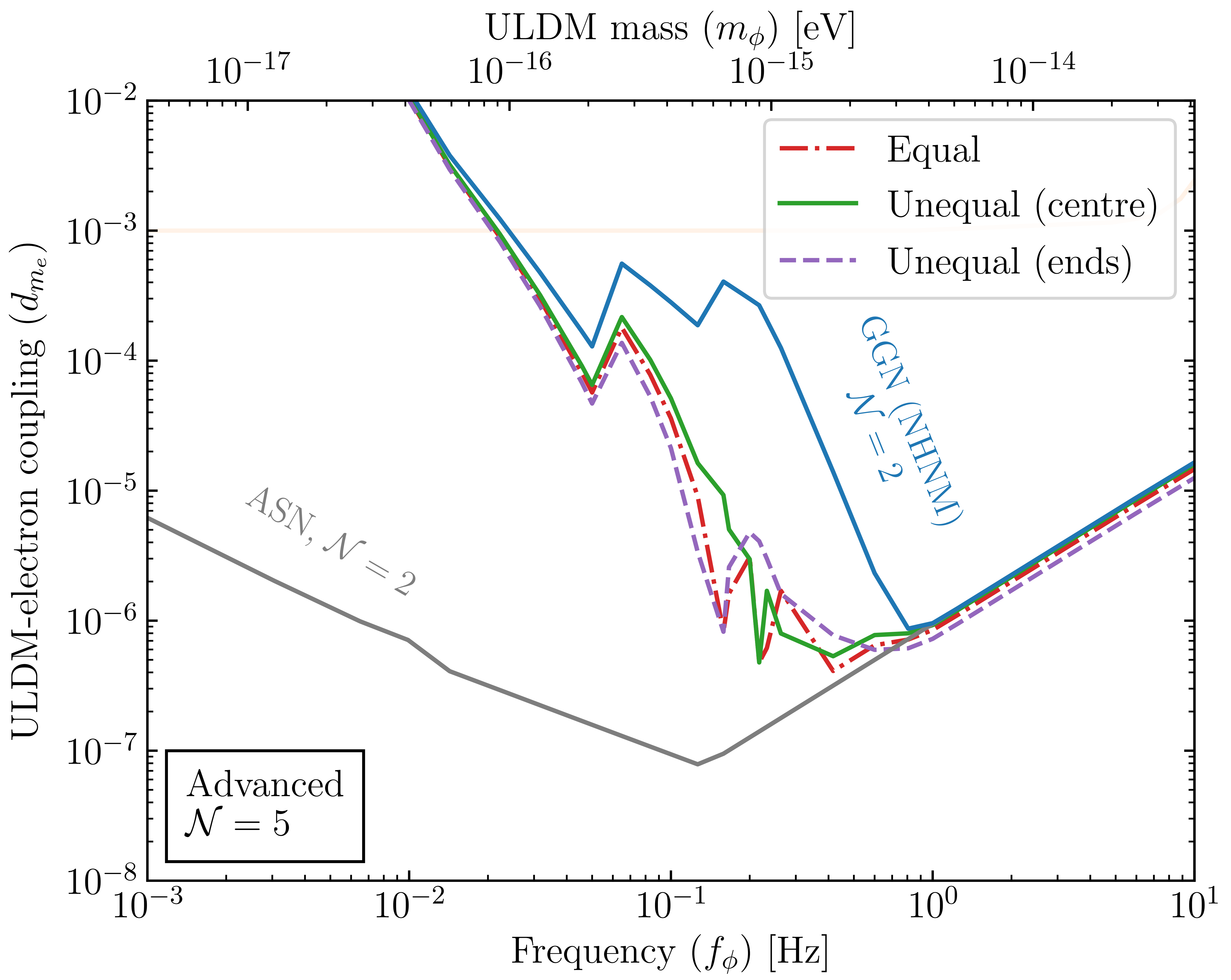
$$\Phi_{\text{ULDM}} \sim \frac{\Delta z}{L}$$



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

Badurina, **CM**, et al, PRD, arXiv:2211.01854

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



Badurina, **CM**, et al, PRD, arXiv:2211.01854

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

Summary

In the coming decades, atom interferometers aim 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

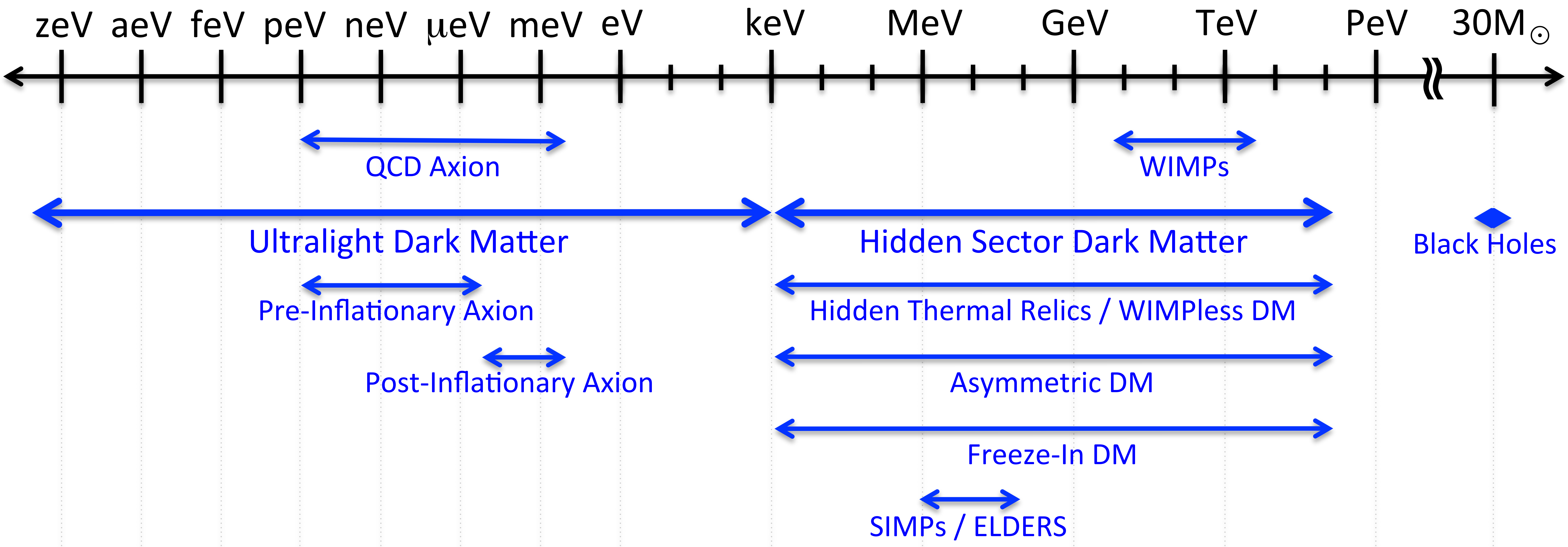
Detect 'mid-band' gravitational waves
- LISA sources before they reach LIGO band
- Early-Universe cosmological sources

And more…
- Tests of quantum mechanics at macroscopic scales
- Probe of seismic activity…

Thank you

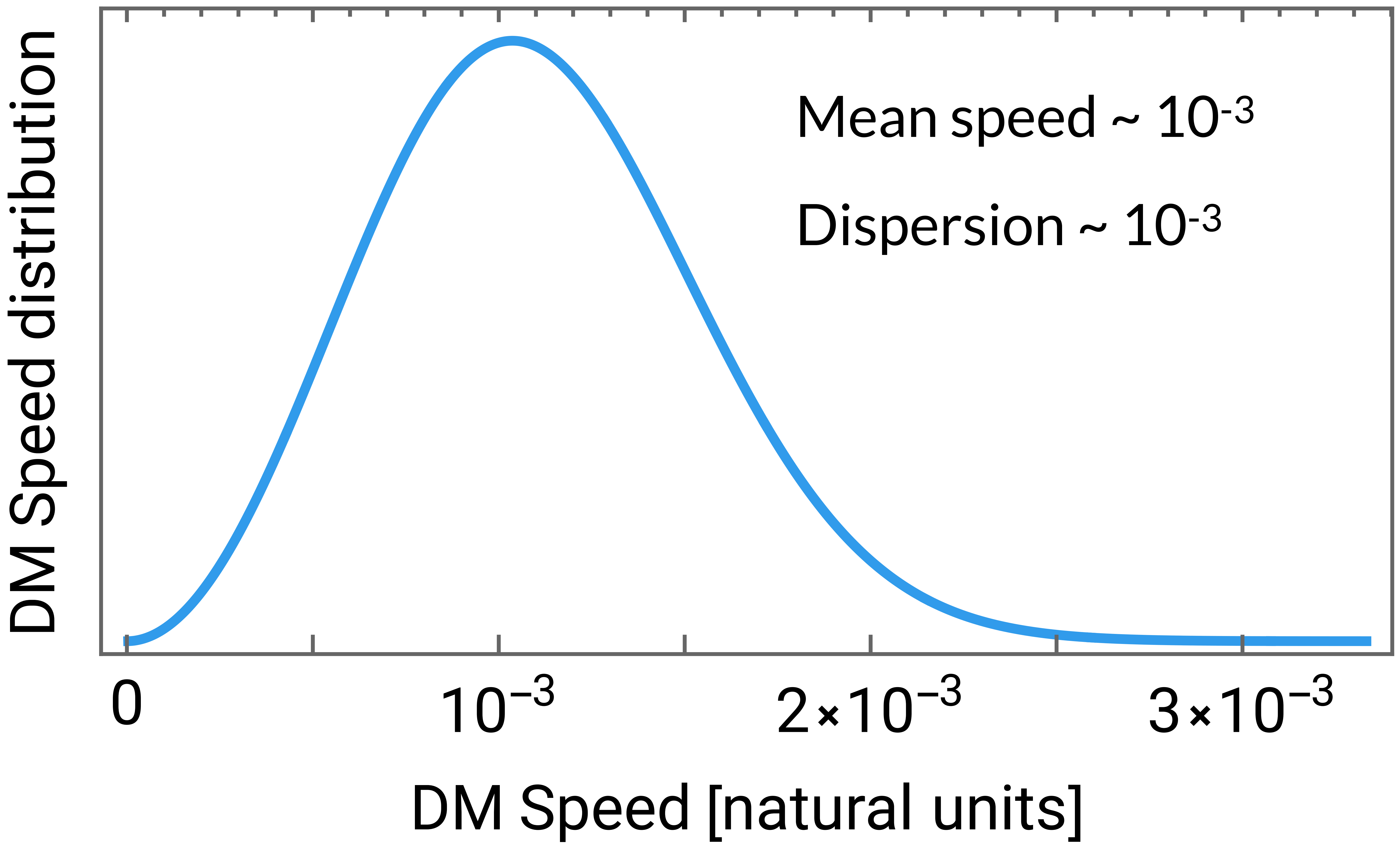
Science and Technology Facilities Council

A wide landscape of DM candidates



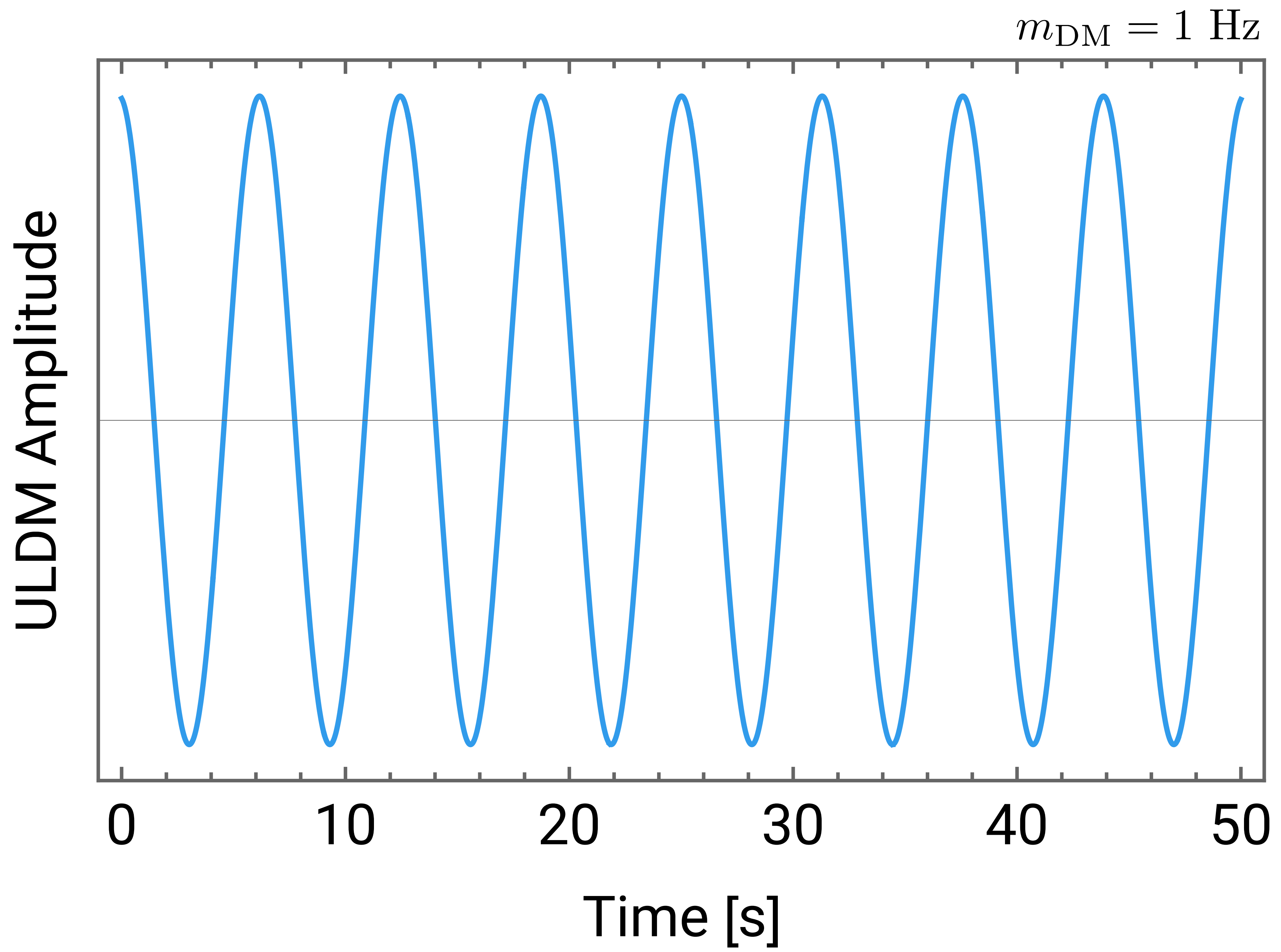
US Cosmic Visions

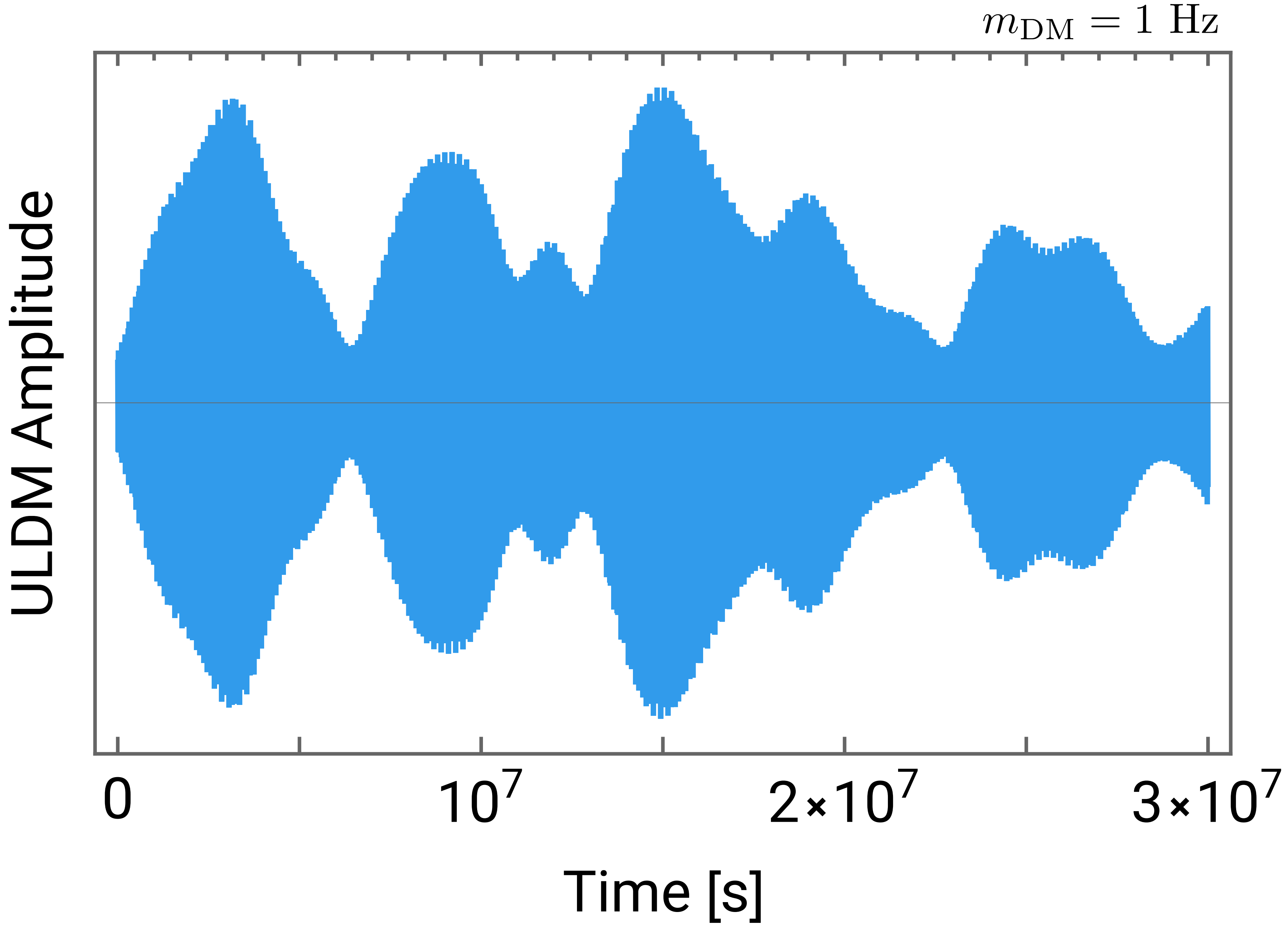
Speed distribution in our galaxy



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' $\tau \sim (m_{\rm DM}\sigma_v^2)^{-1}$

AI signals depend on the field amplitude ⇨ will also vary with a coherence time

Derevianko, PRA, arXiv:1605.09717

Other ULDM signals (1): Accelerations on test masses (Vector)

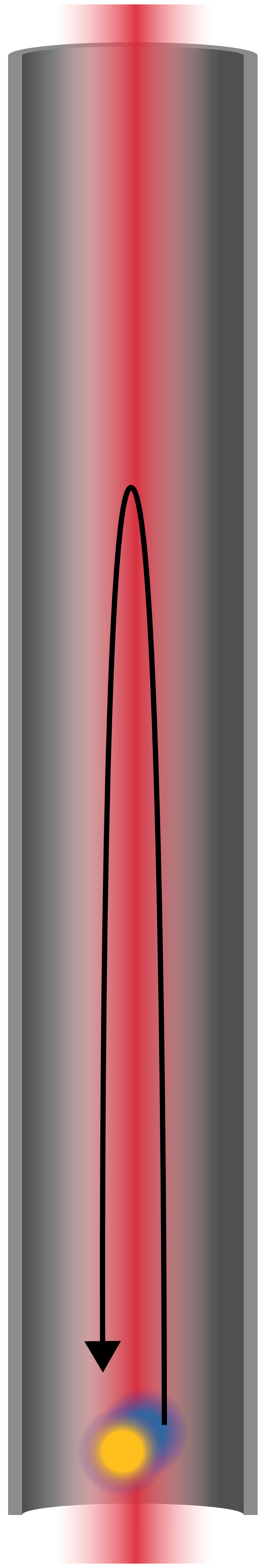
$B - L$ coupled vector appears in many extensions of the Standard Model

As ULDM, this generates background 'dark electric field':

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

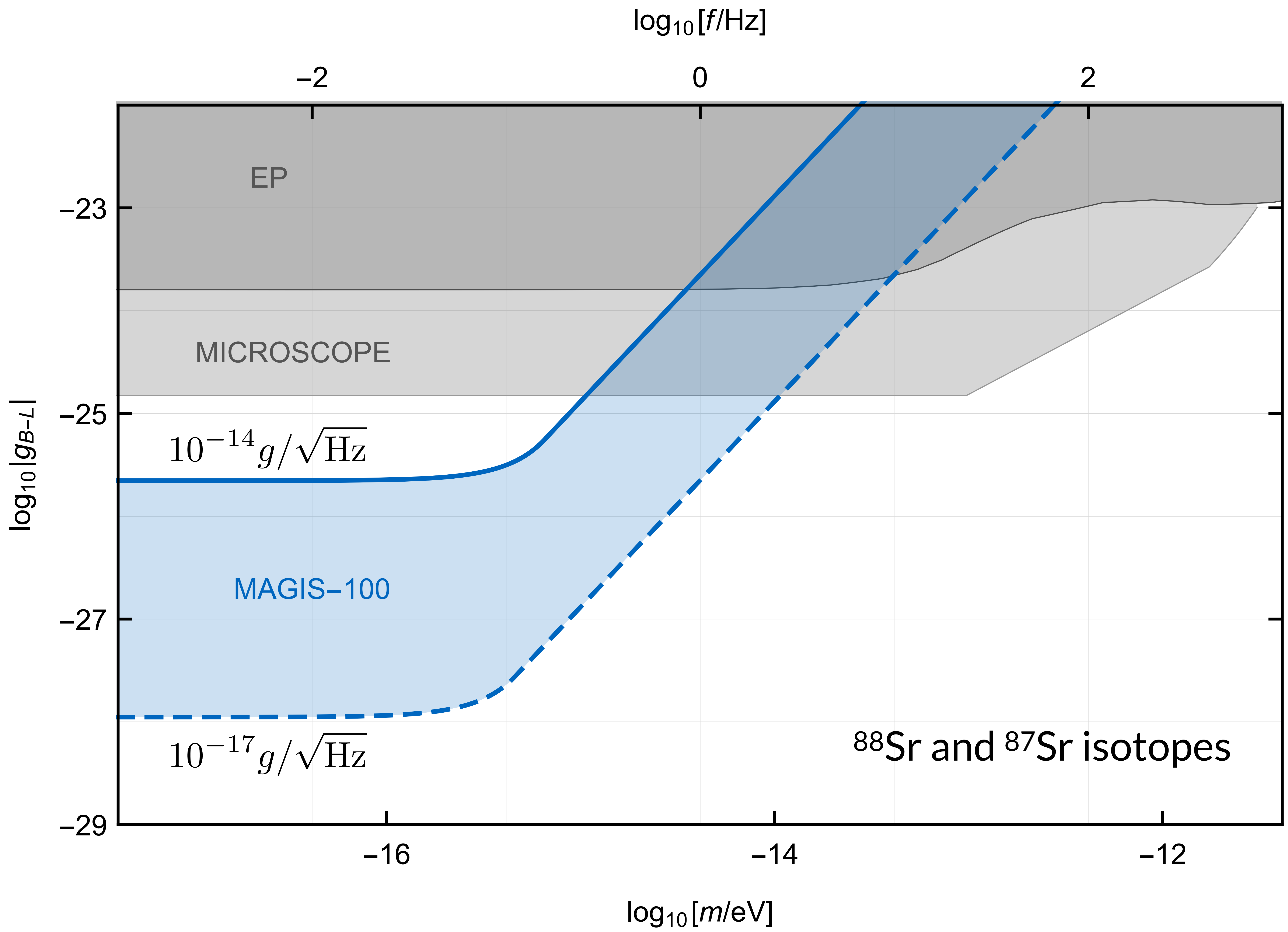
In a *dual-species interferometer*, isotopes experience a different forces (accelerations):

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



Graham et al, PRD, arXiv:1512.06165

Other ULDM signals (1): Near- and long-term prospects (Vector)



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

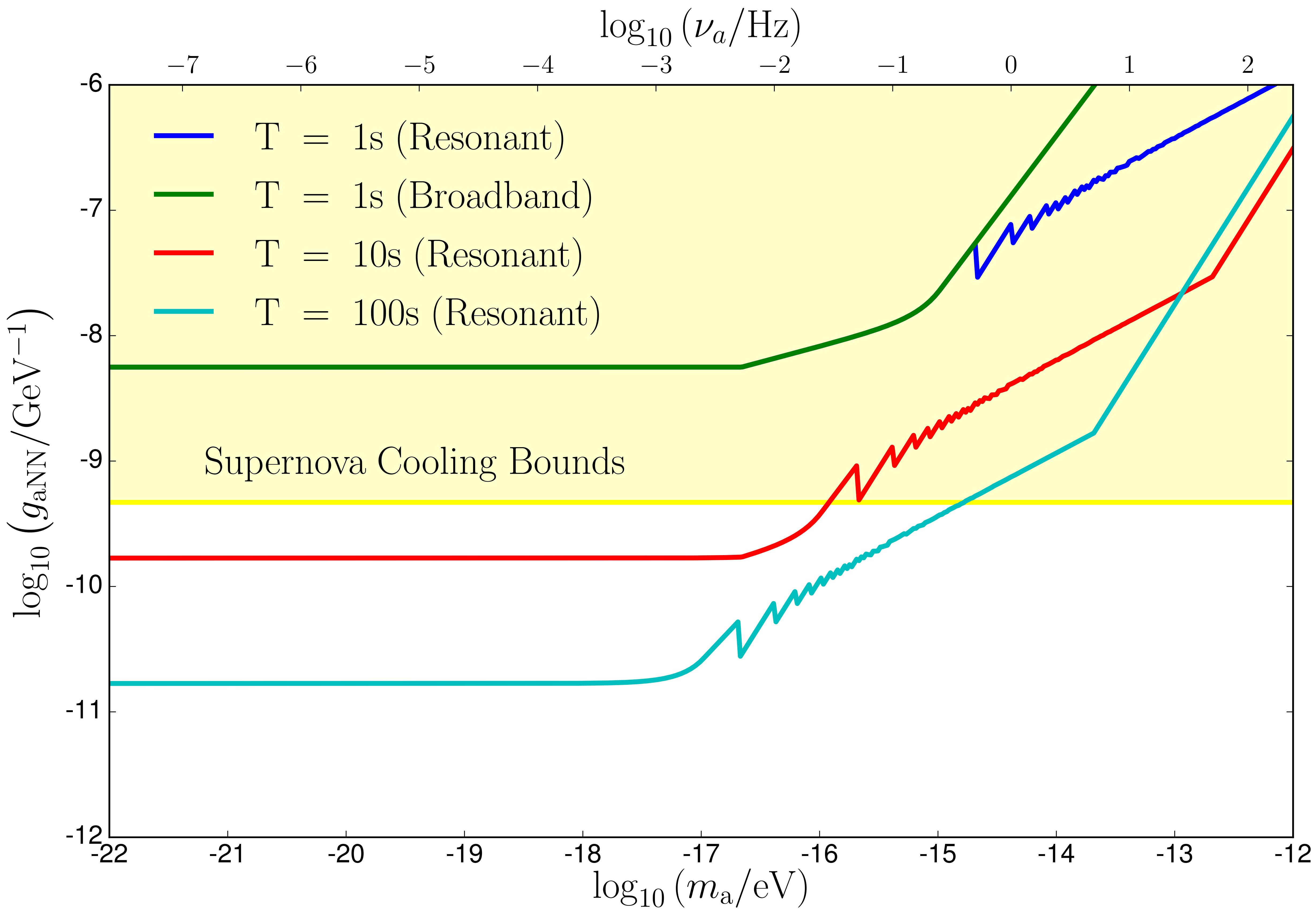
Other ULDM signals (2): Precession of spins (Pseudoscalar)

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 $\delta B \sim 10^{-15}\text{T}$

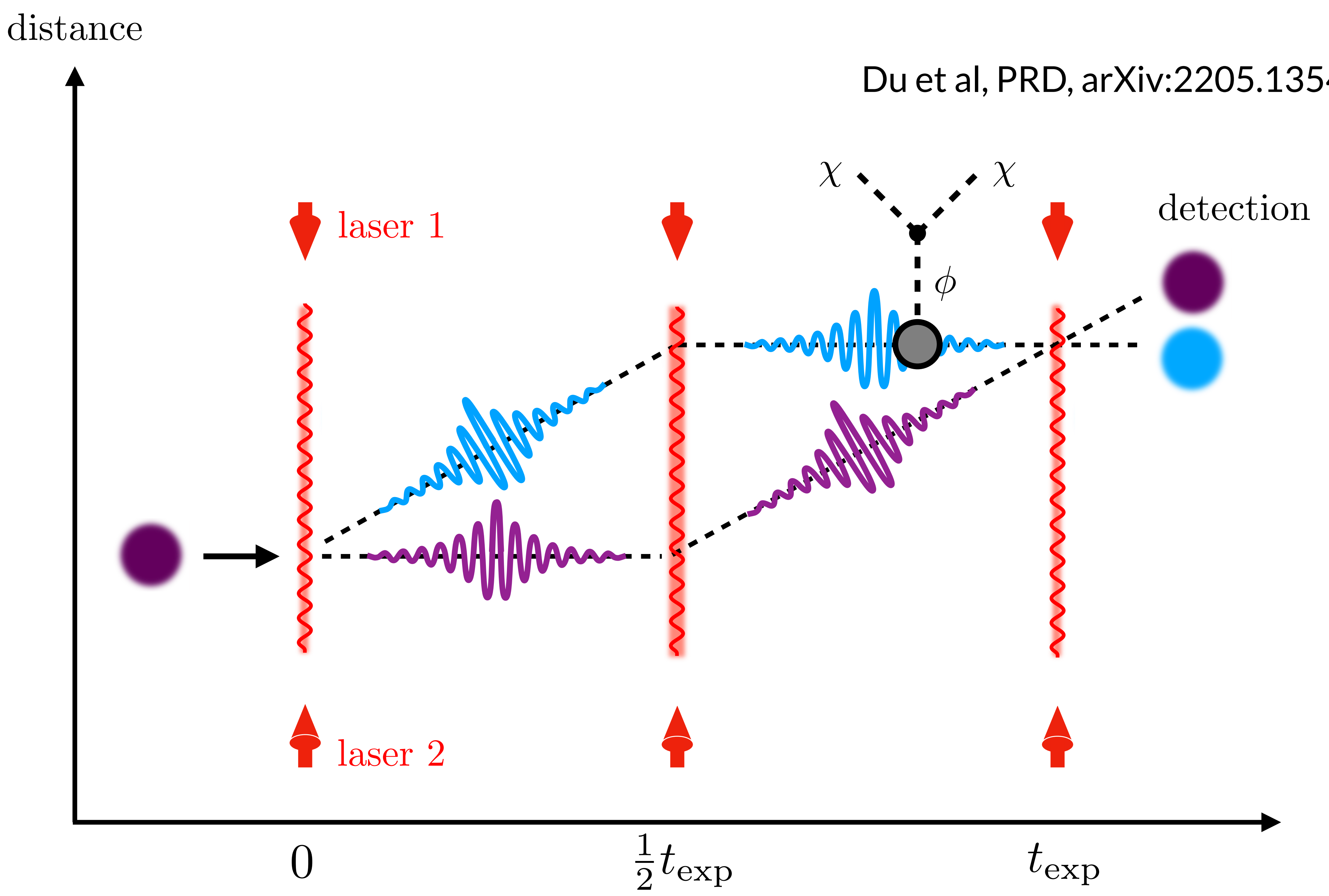


Graham et al, PRD, arXiv:1709.07852

Beyond oscillating ULDM signals…

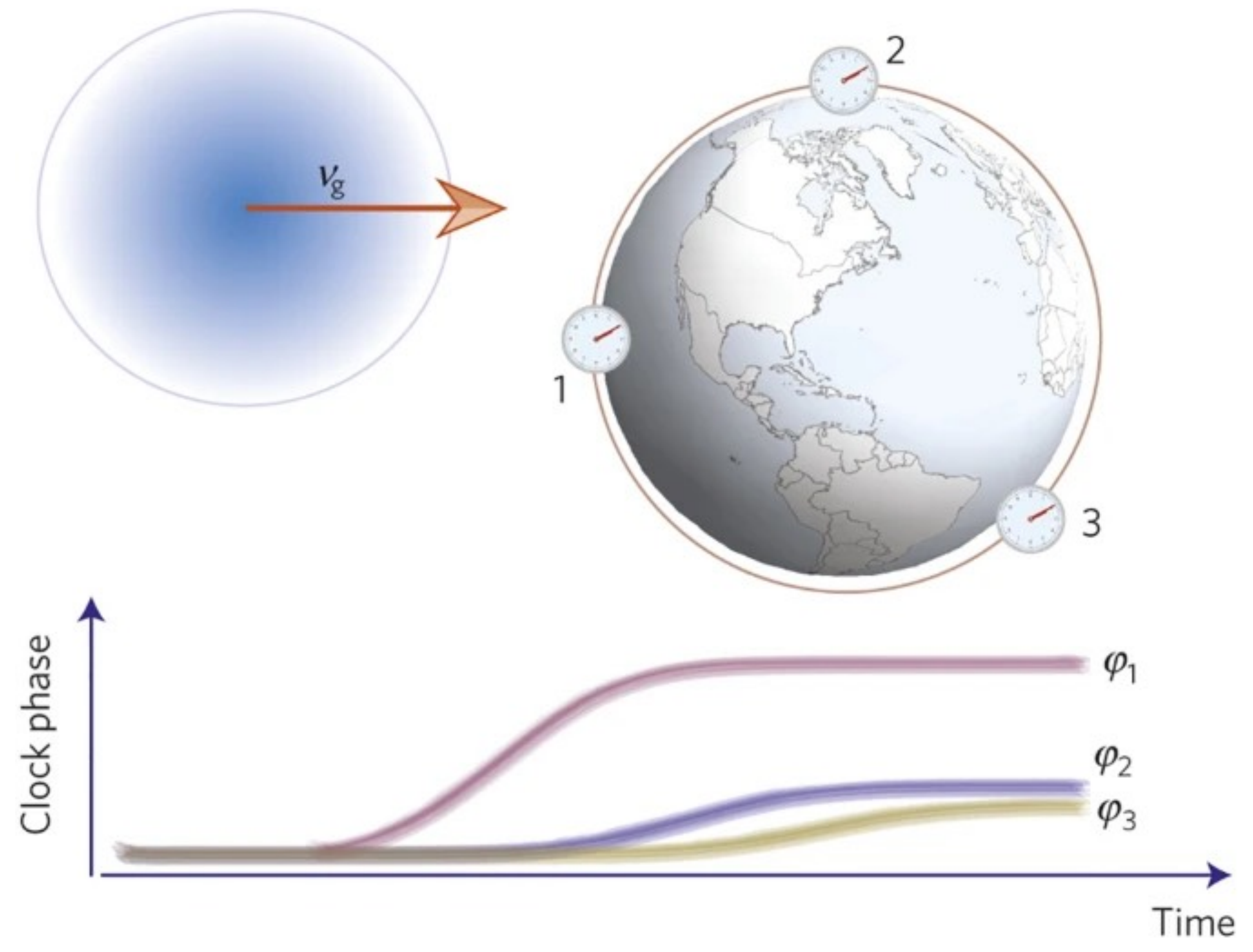
Scattering: Dark matter collisions in one AI arm causes decoherence

Du et al, PRD, arXiv:2205.13546



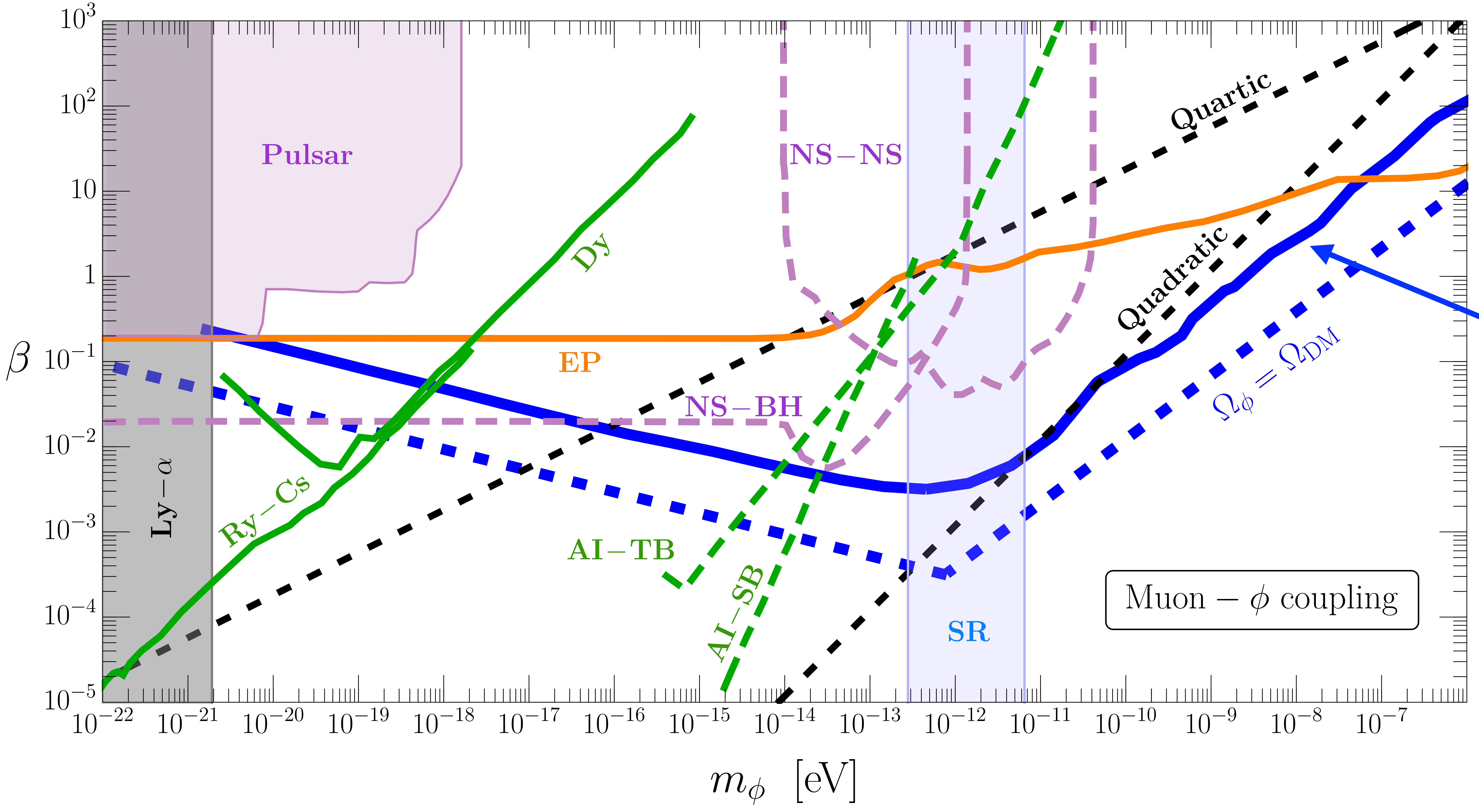
See also Riedel et al, PRD, arXiv:1212.3061, 1609.04145

Transient signals: utilising a global network of AIs for topological states



See e.g., Derevianko et al, Nature Phys. arXiv:1311.1244
or Gorghettoa et al, JCAP, arXiv:2203.10100

Scalar ULDM abundance predictions (‘thermal misalignment’)



‘Correct’ relic abundance

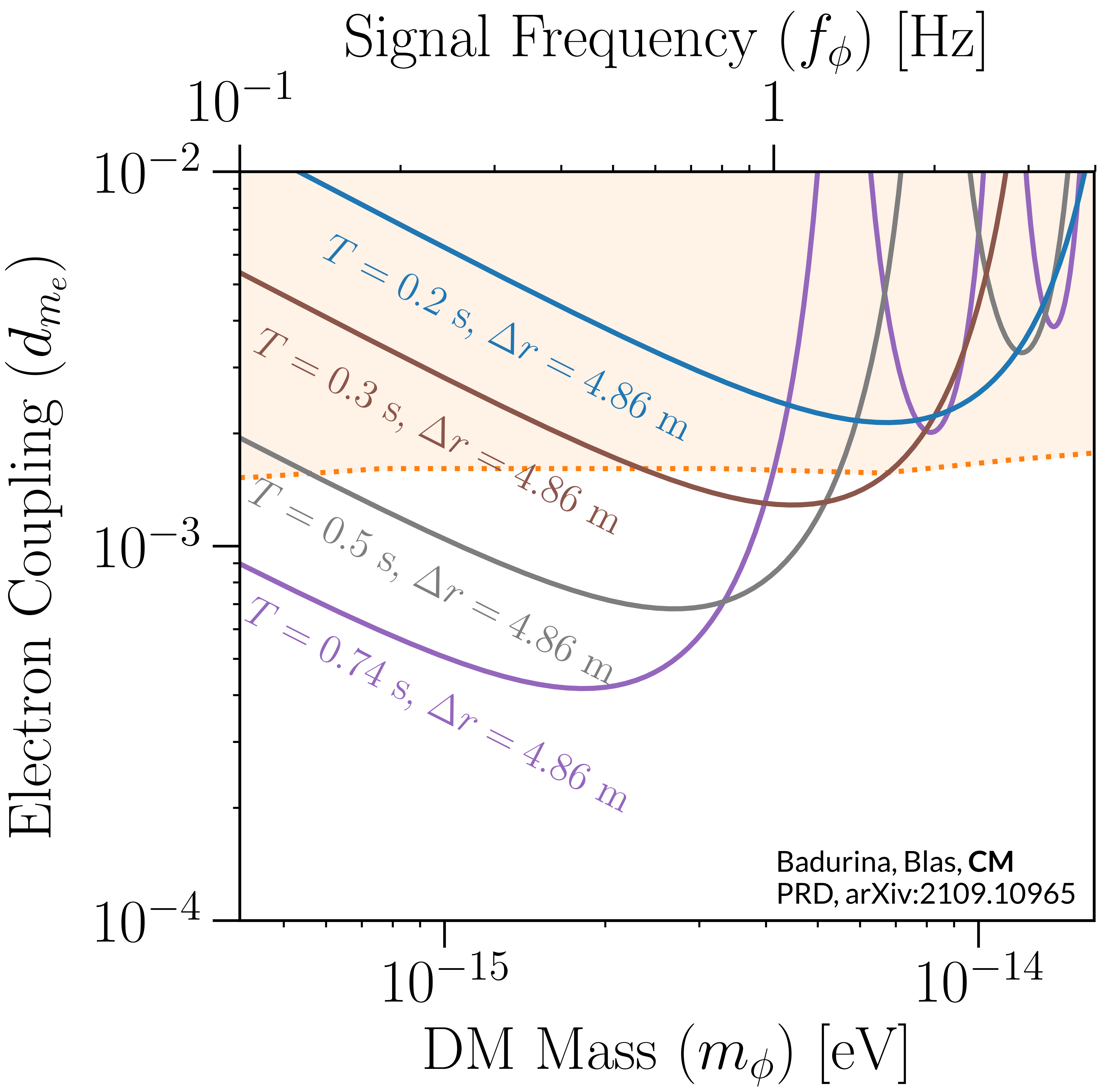
Batell & Ghalsaia, PRD, arXiv:2109.04476

Parameters available to reach sensitivity

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

Handles to optimise (in order of priority):

- *T* ~ 1s (interrogation time)
- *C* ~ 0.1 - 1 (constrast)
- *n* ~ 1000 (LMT)
- Δr ~ AI separation
- Δt ~ sampling time
- $N_a \sim$ atoms in cloud
- $T_{\text{int}} \sim 10^7\text{s}$ (integration time)

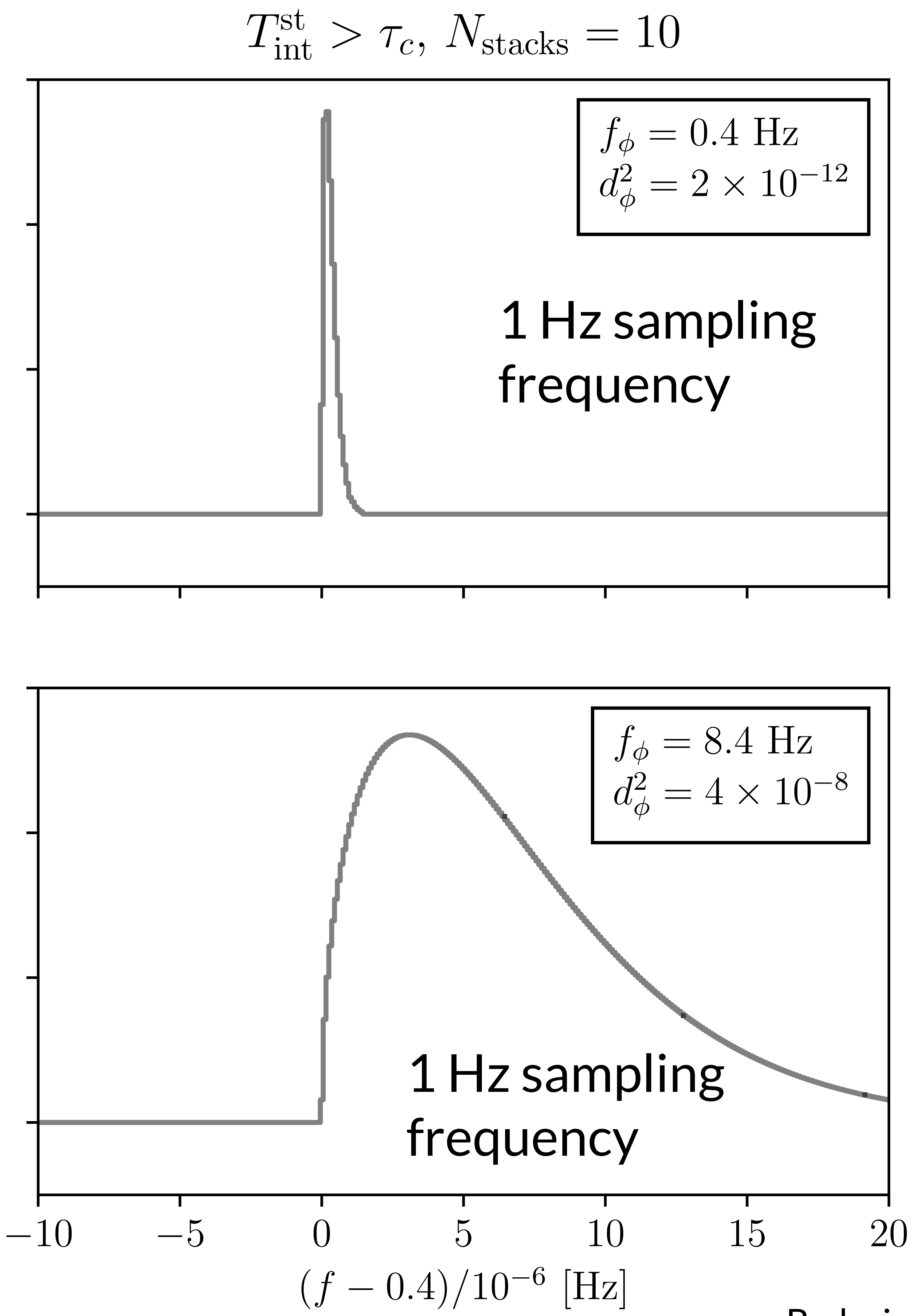


Aliasing (Scalar ULDM)

Signals above the Nyquist frequency are aliased…

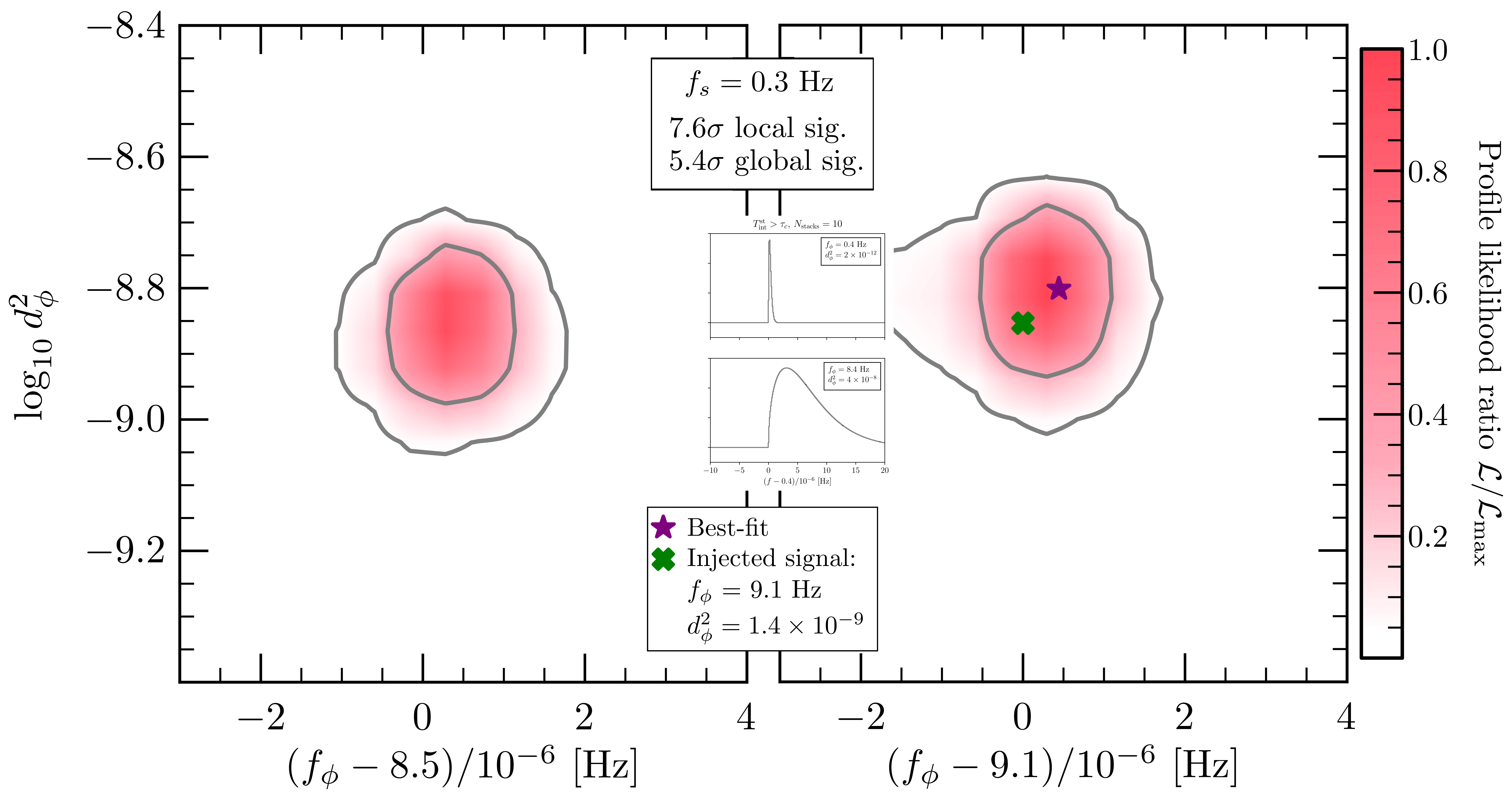
…but the higher frequency signals have a larger width, and this width stays the same when aliased

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



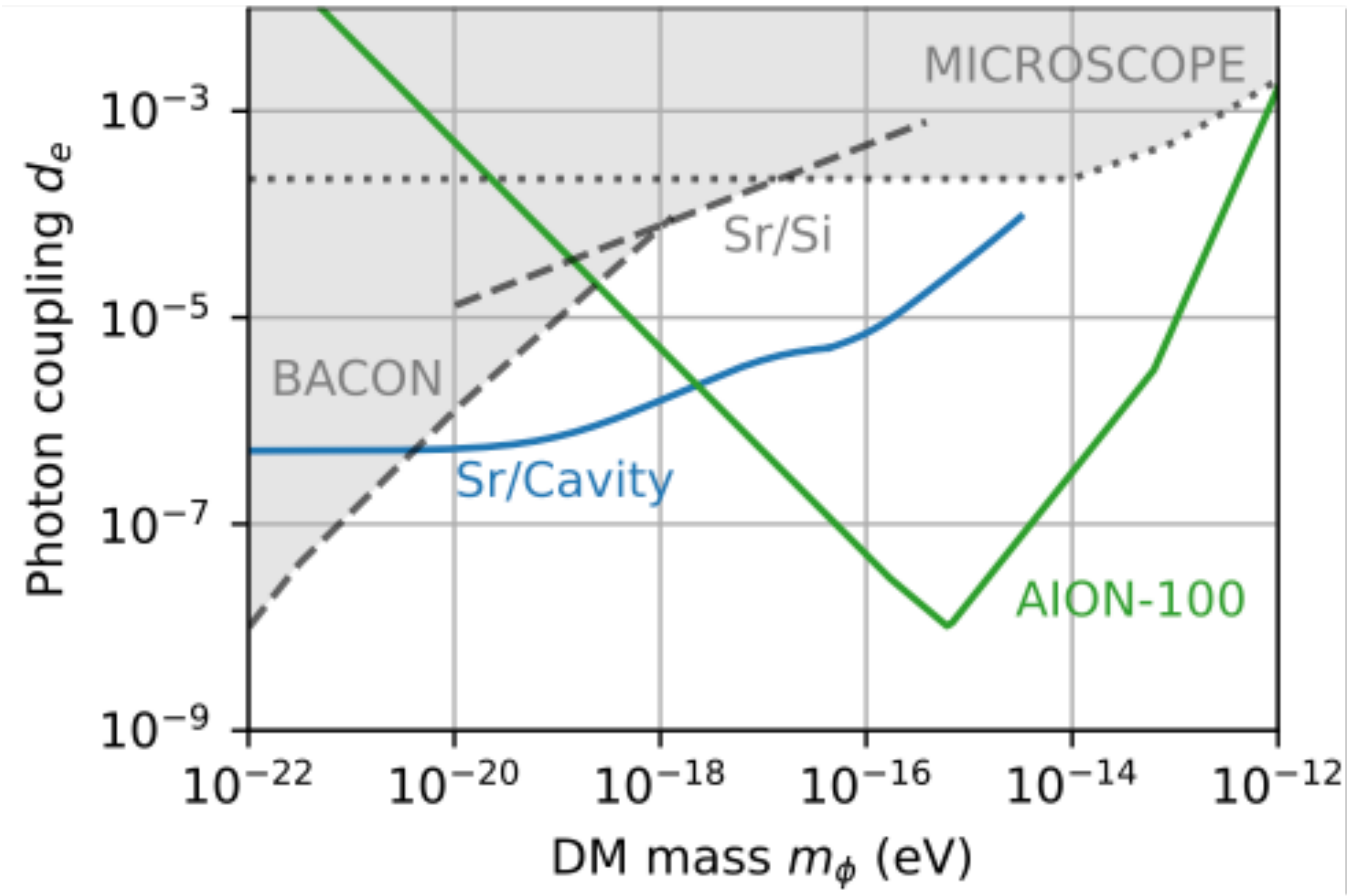
Badurina, Beniwal, **CM**
arXiv:2306.16477

Discovery projects (Scalar): precision within an individual island

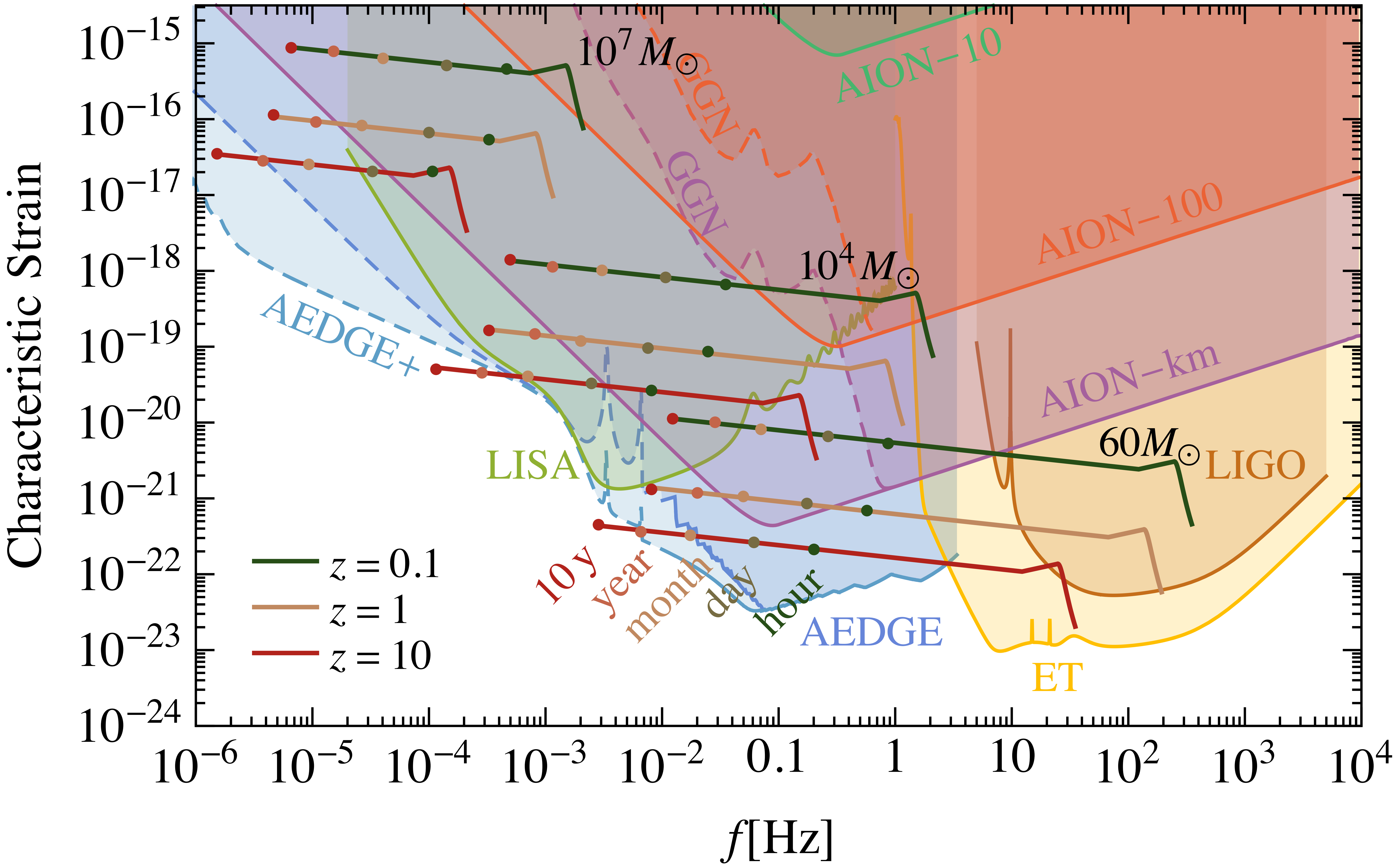


Badurina, Beniwal, **CM**, arXiv:2306.16477

Complementarity with atomic clocks

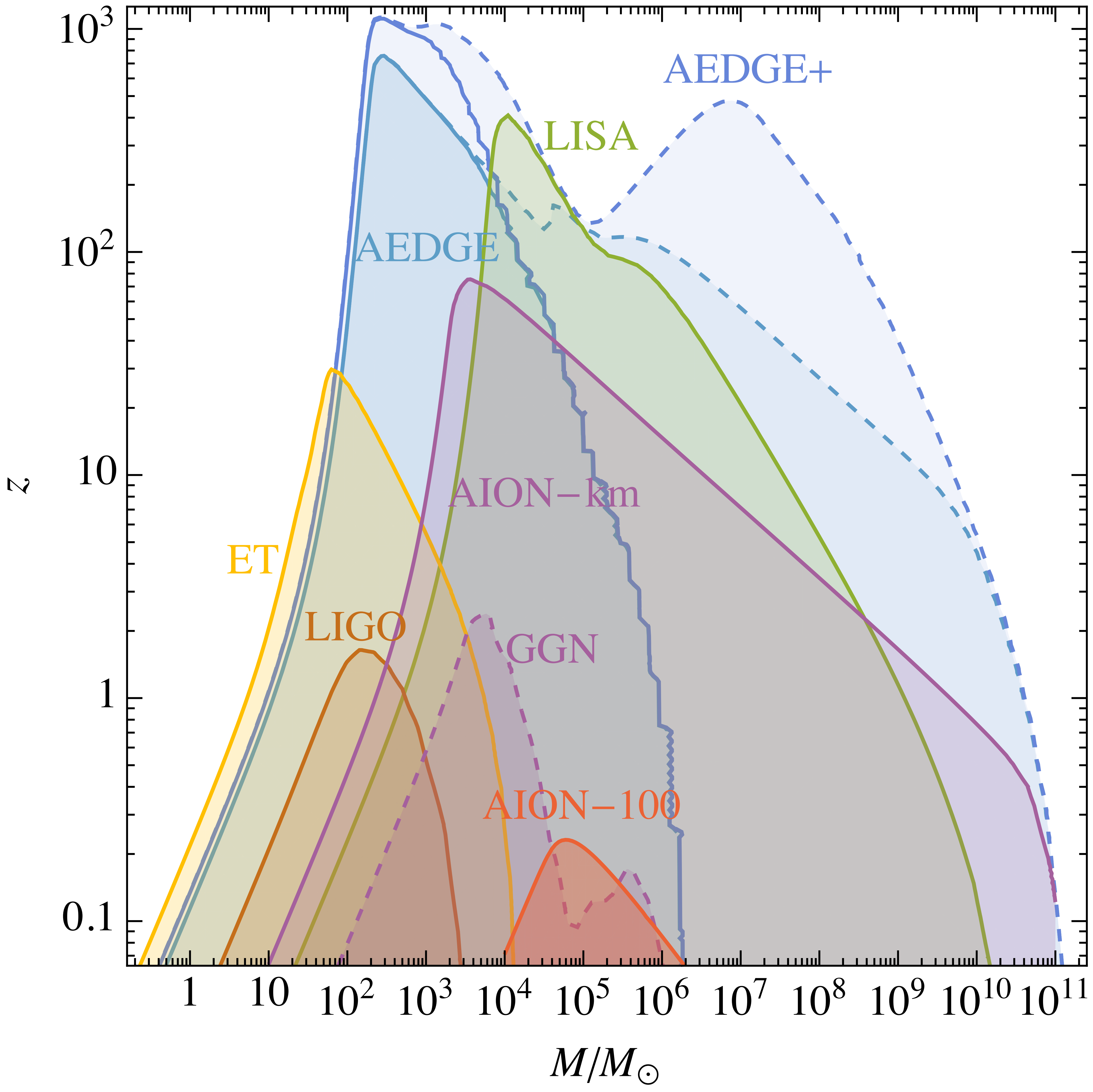


GWs: sensitivity to binary mergers (equal masses)



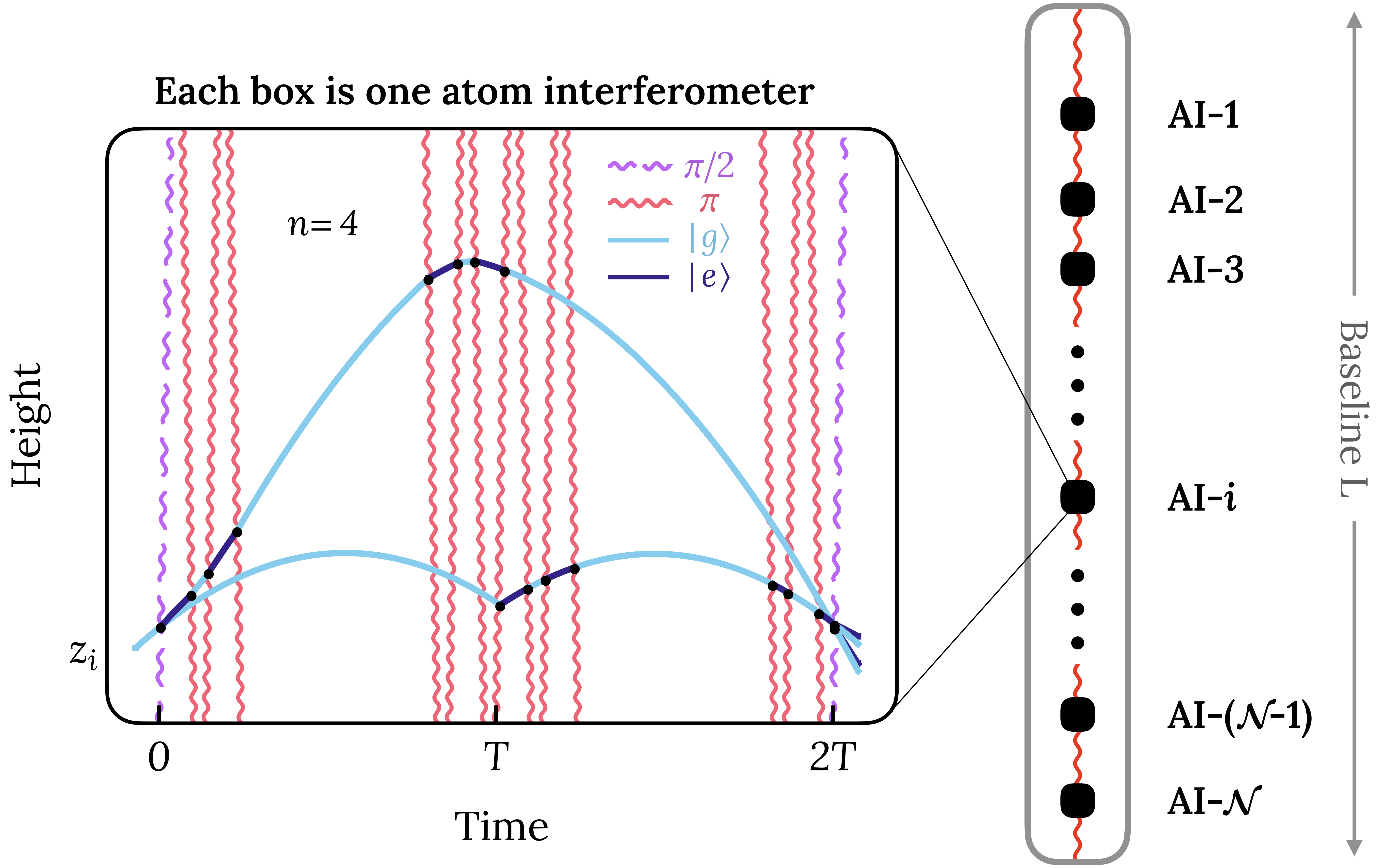
Badurina, Buchmueller, Ellis, Lewicki, **CM**, Vaskonen Phil.Trans.Roy.Soc.Lond., arXiv:2108.02468

GWs: sensitivity to binary mergers (equal masses)



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

Multi-gradiometer configuration



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

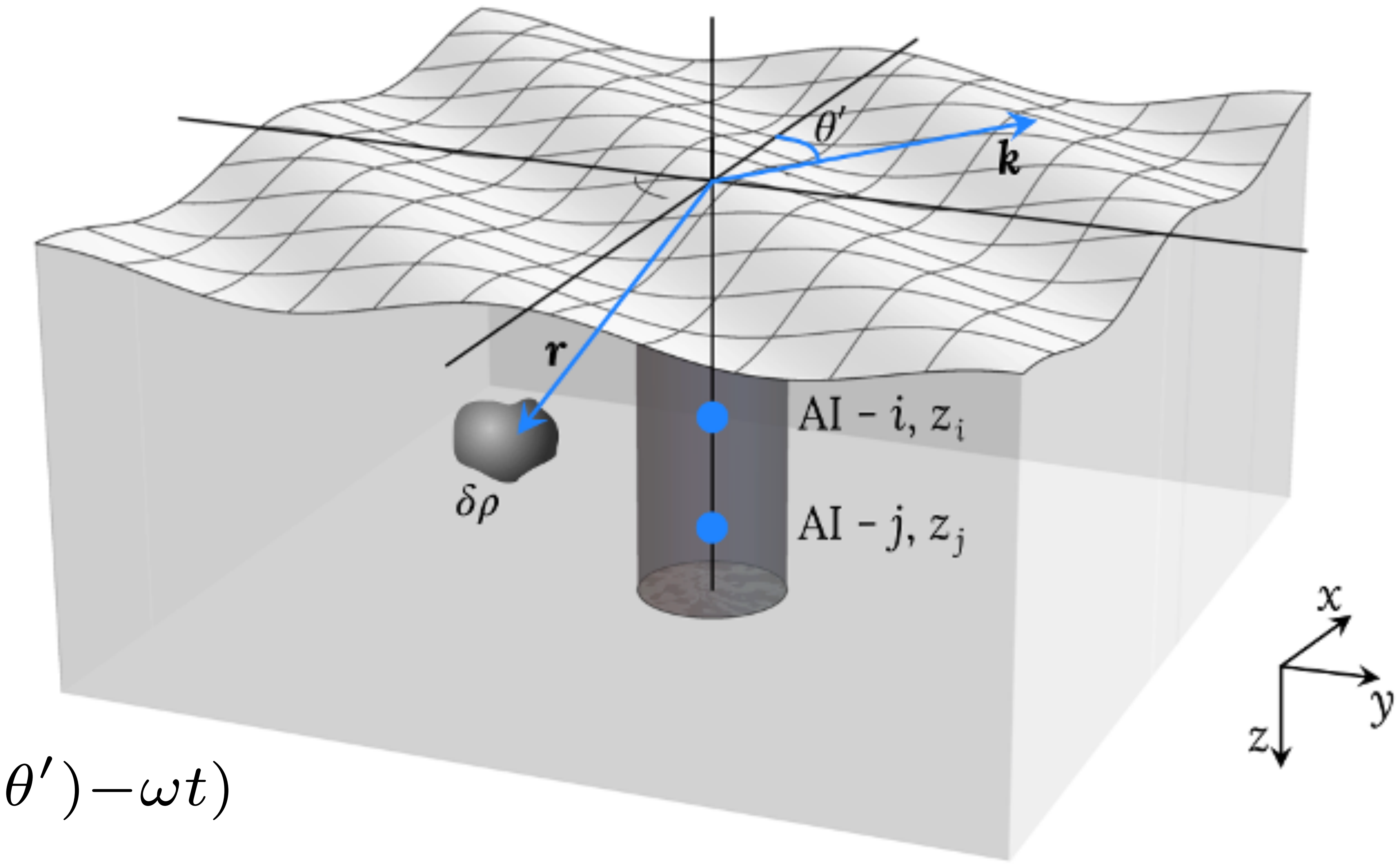
Badurina, **CM**, et al, PRD, arXiv:2211.01854

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:

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

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

Badurina, **CM**, et al, PRD, arXiv:2211.01854

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:

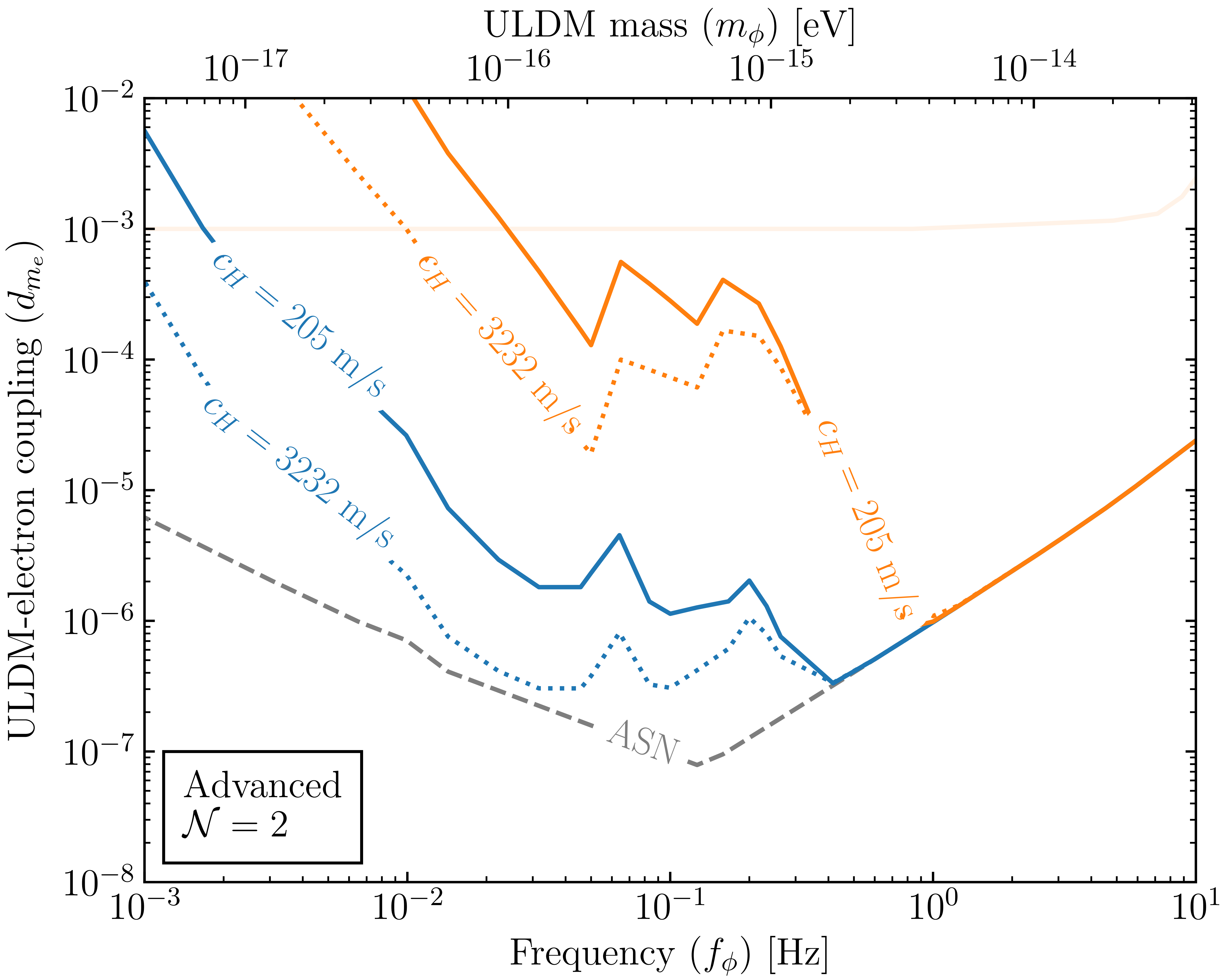
$$\Phi_{\mathrm{Rayleigh}} = \left(\widetilde{A}e^{-qkz_0} + \widetilde{B}e^{-kz_0}\right)\xi_V\cos(\omega T + \Theta)$$

Amplitude decays exponentially

Vertical displacement

Badurina, **CM**, et al, PRD, arXiv:2211.01854

GGN 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:

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

Badurina, **CM**, et al, PRD, arXiv:2211.01854