Atom Interferometry for dark matter and gravitational waves

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

34th Rencontres de Blois, 18 May 2023

Setting the scene

Light pulse atom interferometry (physical-space)

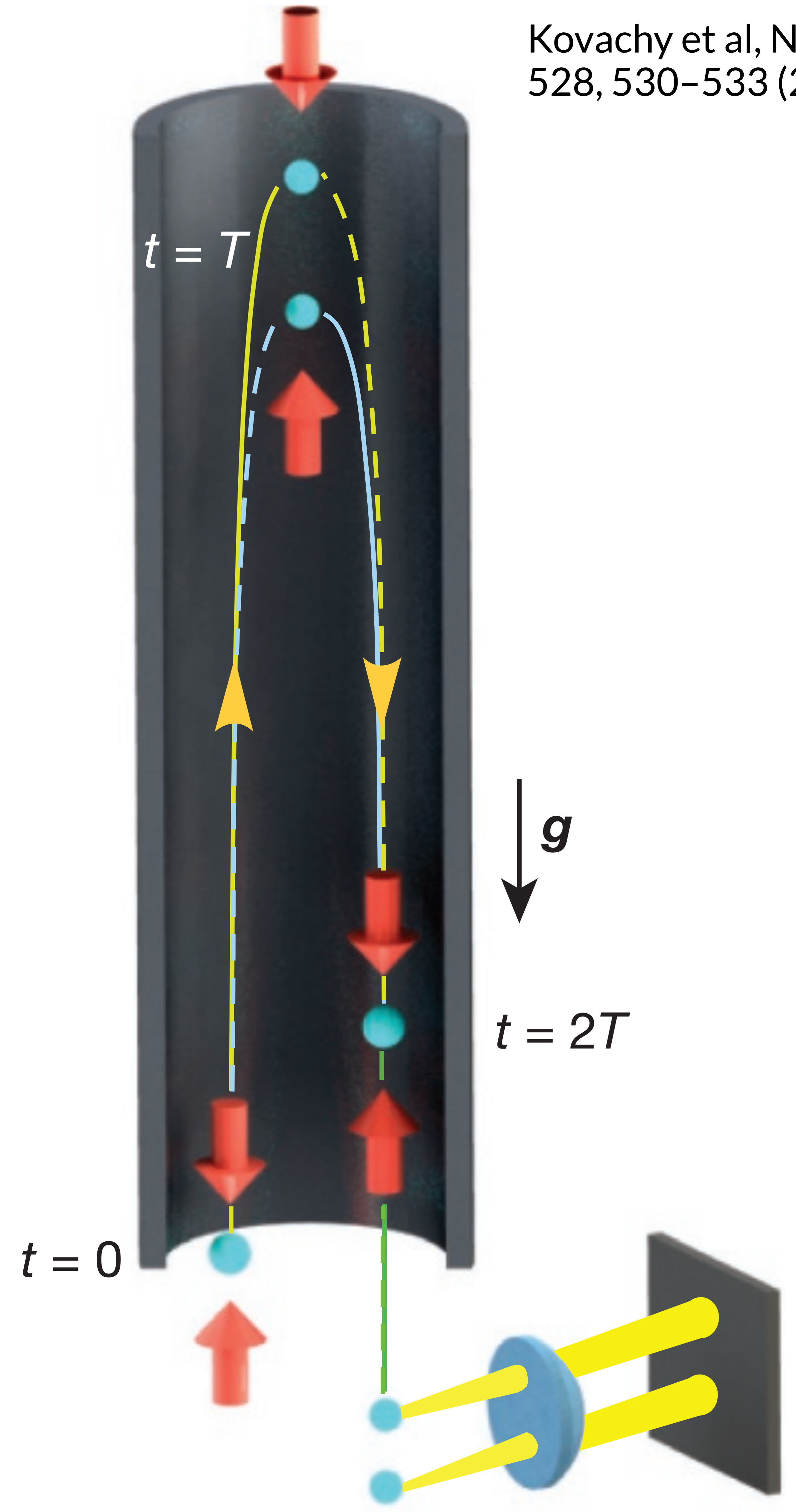
Launch ultra-cold cloud of atoms into an atomic fountain

Sequence of optical pulses manipulate the atoms

Quantum superposition over macroscopic distances (>50cm achieved)

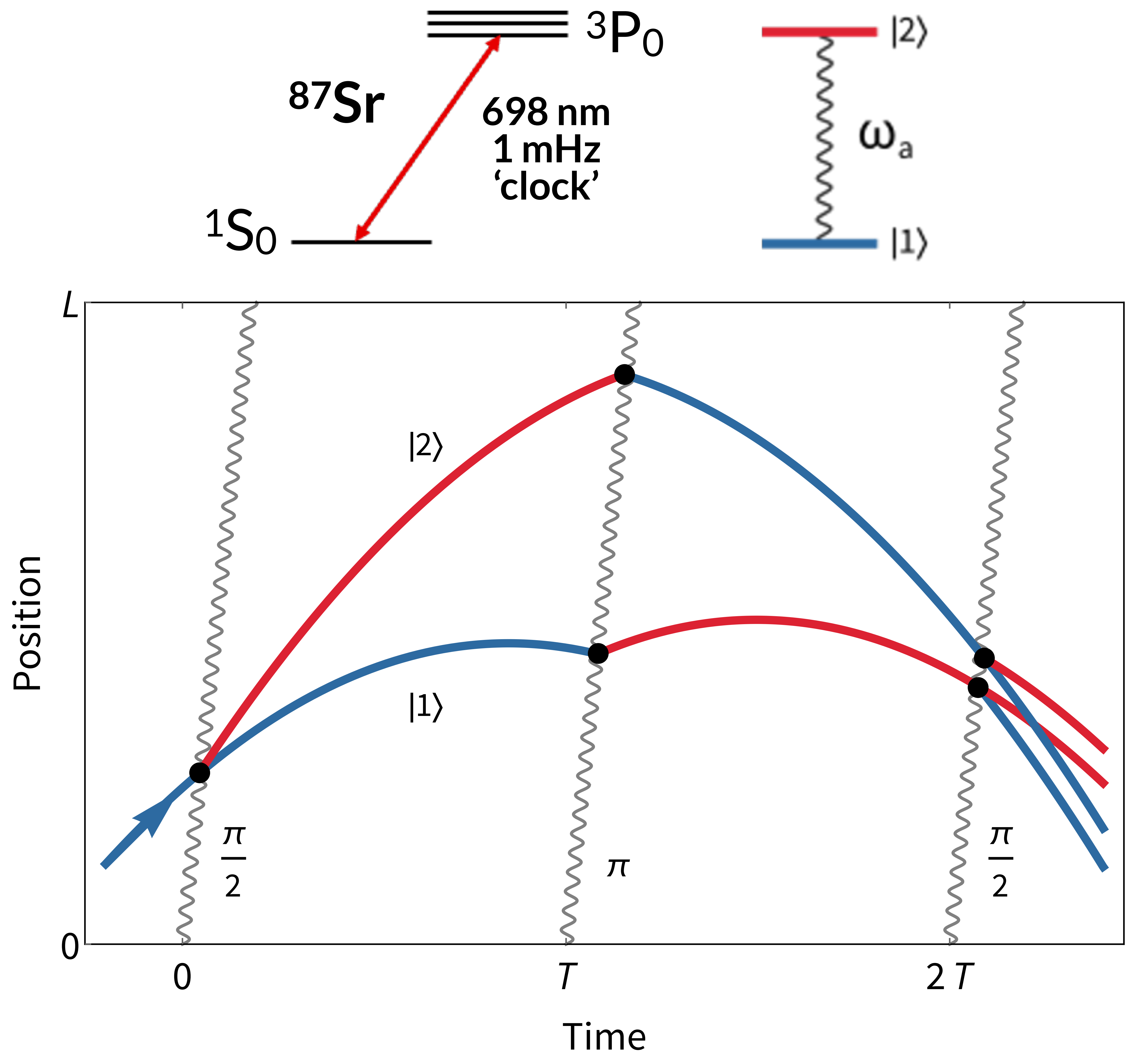
Interfere using a final optical pulse when they spatially overlap

Image the two interferometer output ports



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

Light pulse atom interferometry (space-time)



Abe et al (MAGIS-100) arXiv:2104.02835

Two-level system separated by optical frequency difference ω_a

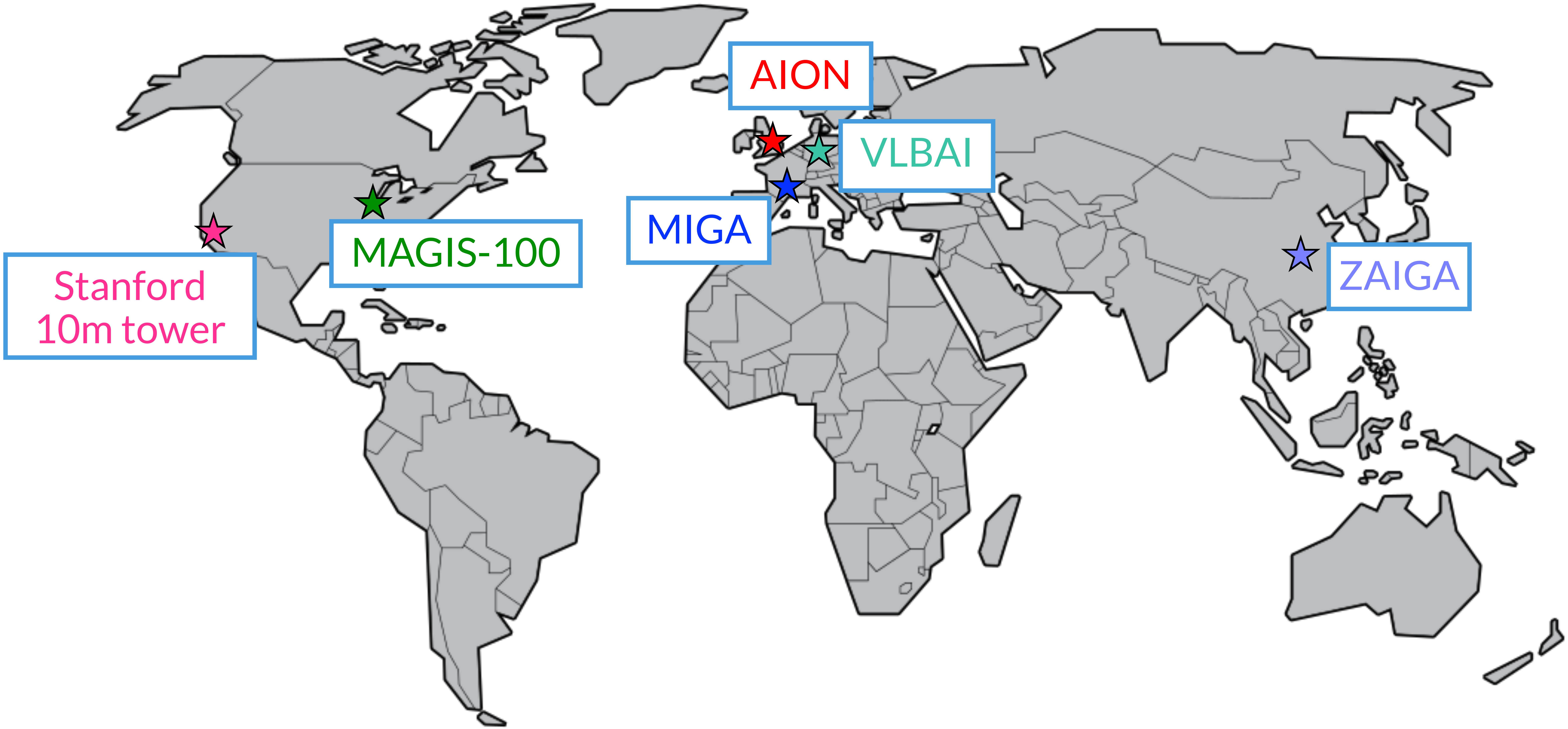
Initial pulse: 'beamsplitter'
Middle pulse: 'mirror'
Final pulse: 'beamsplitter (interfere)'

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 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

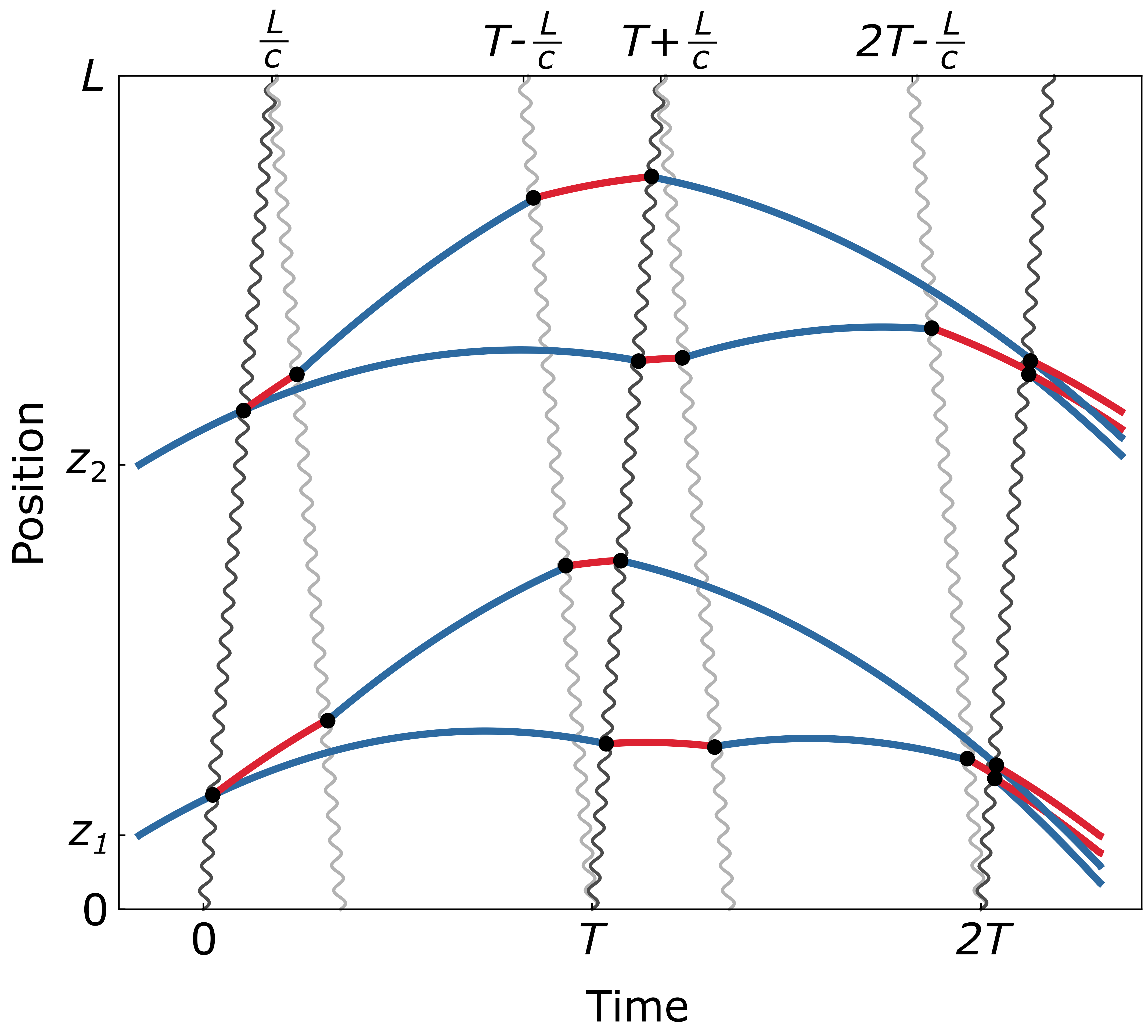
AION: Atom Interferometer Observatory and Network

7 institutes in the UK

Collaboration ~50 people
Cold atom: fundamental physics ratio is ~50:50

AION, arXiv:1911.11755

AION: key features



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

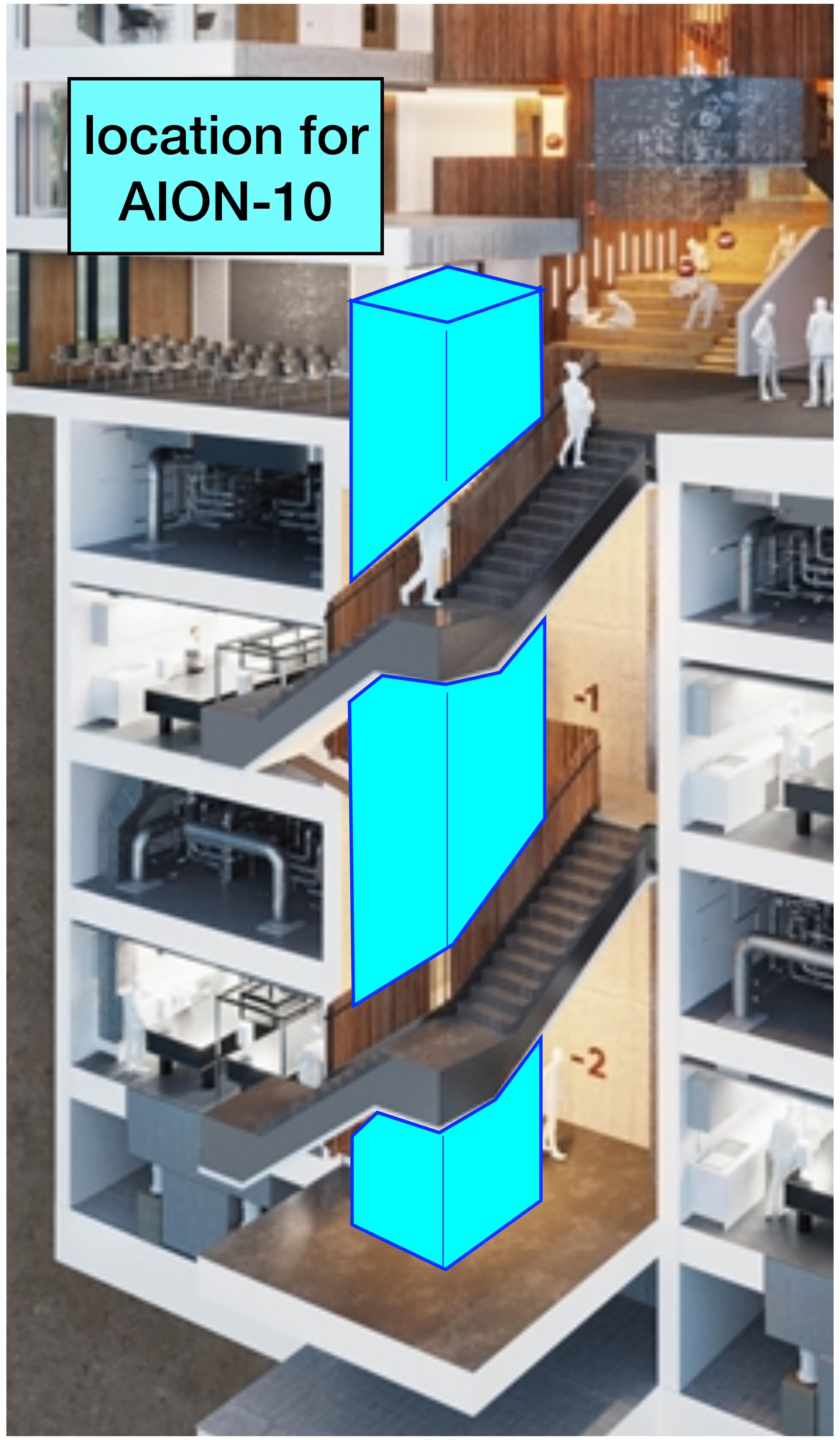
Pushing state-of-the-art single photon strontium atom interferometry

Partnering with MAGIS-100 in the US

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

Badurina , CM, et al (AION), arXiv:1911.11755
Image from Abe et al (MAGIS-100) arXiv:2104.02835

AION: envisaged as a multi-stage project



Stage 1: AION-10

~10m tower in the Beecroft building in Oxford
(new, low-vibration building)

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

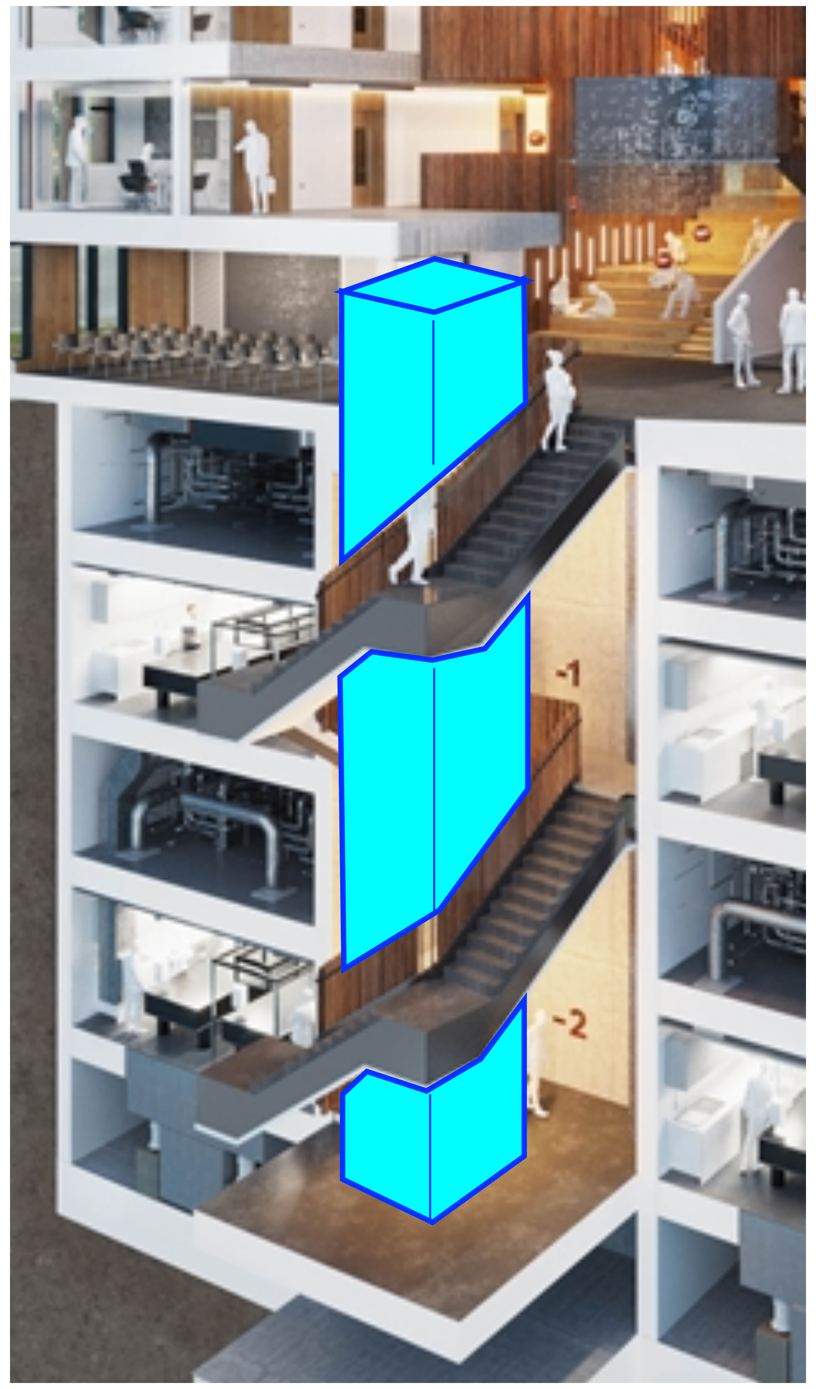
AION: envisaged as a multi-stage project

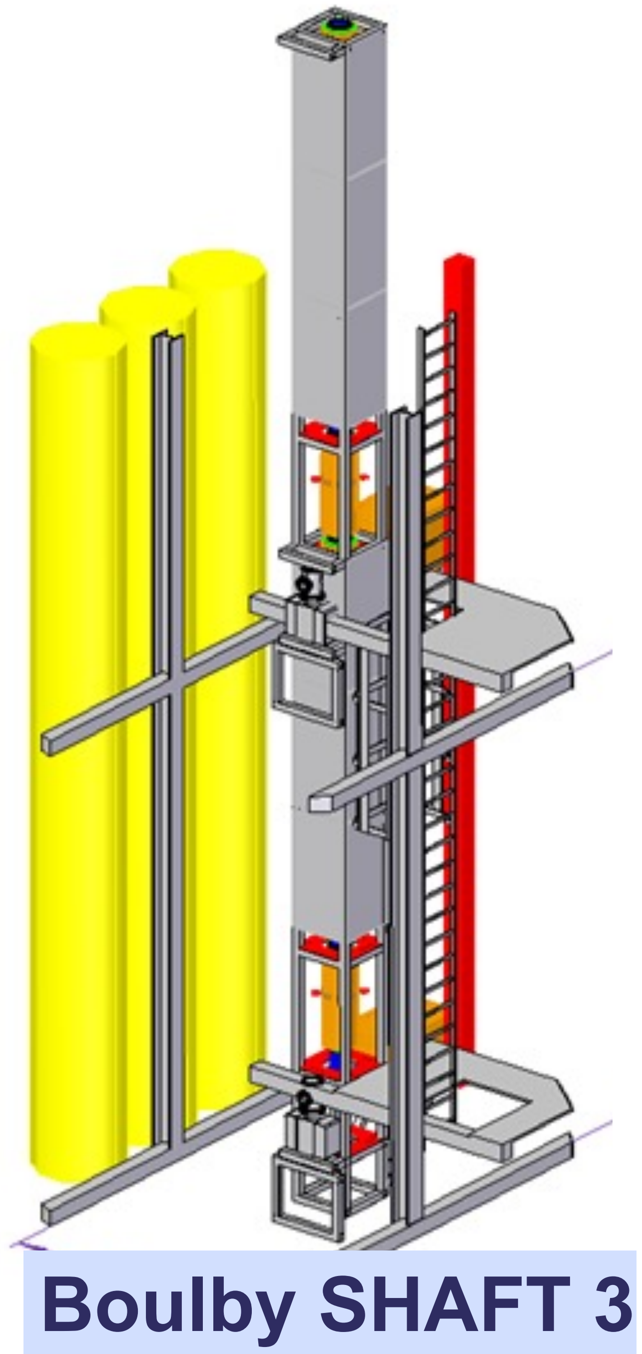
AION-10
2020s ~10m instrument in Oxford

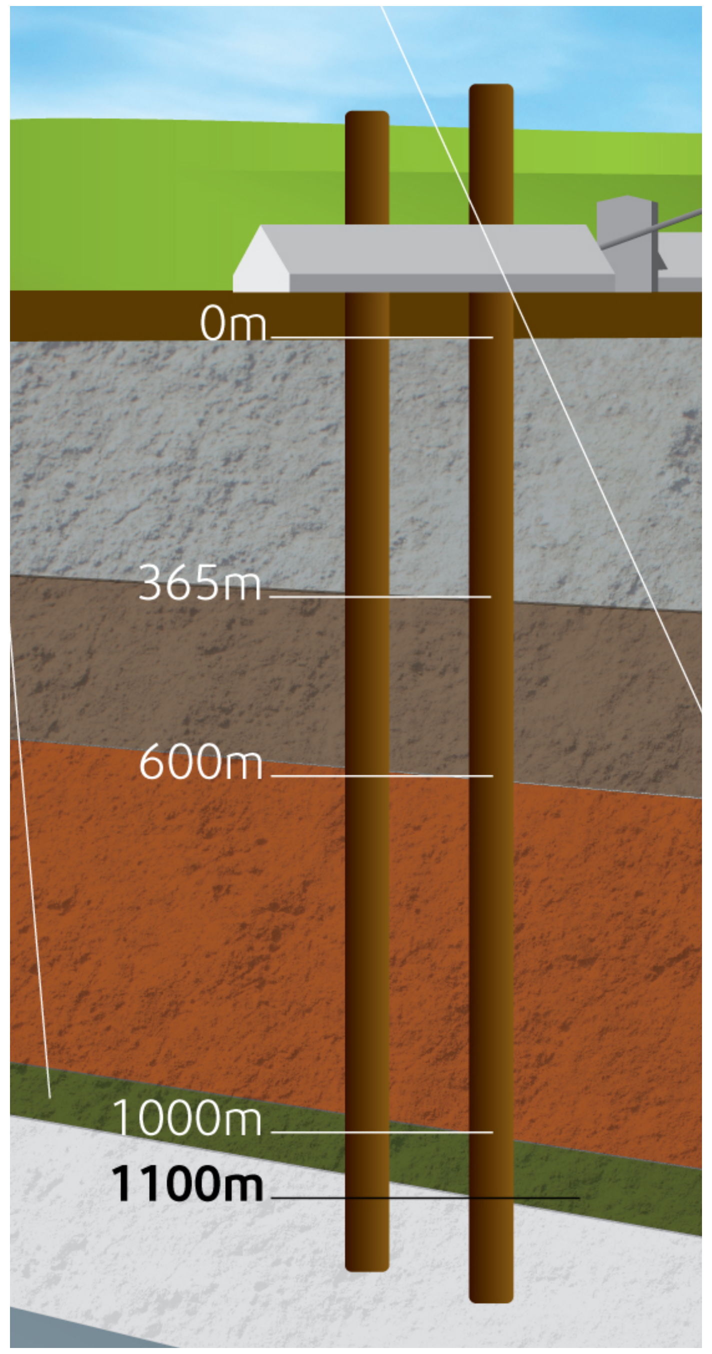
AION-100
2030s ~100m instrument at Boulby/CERN/…?

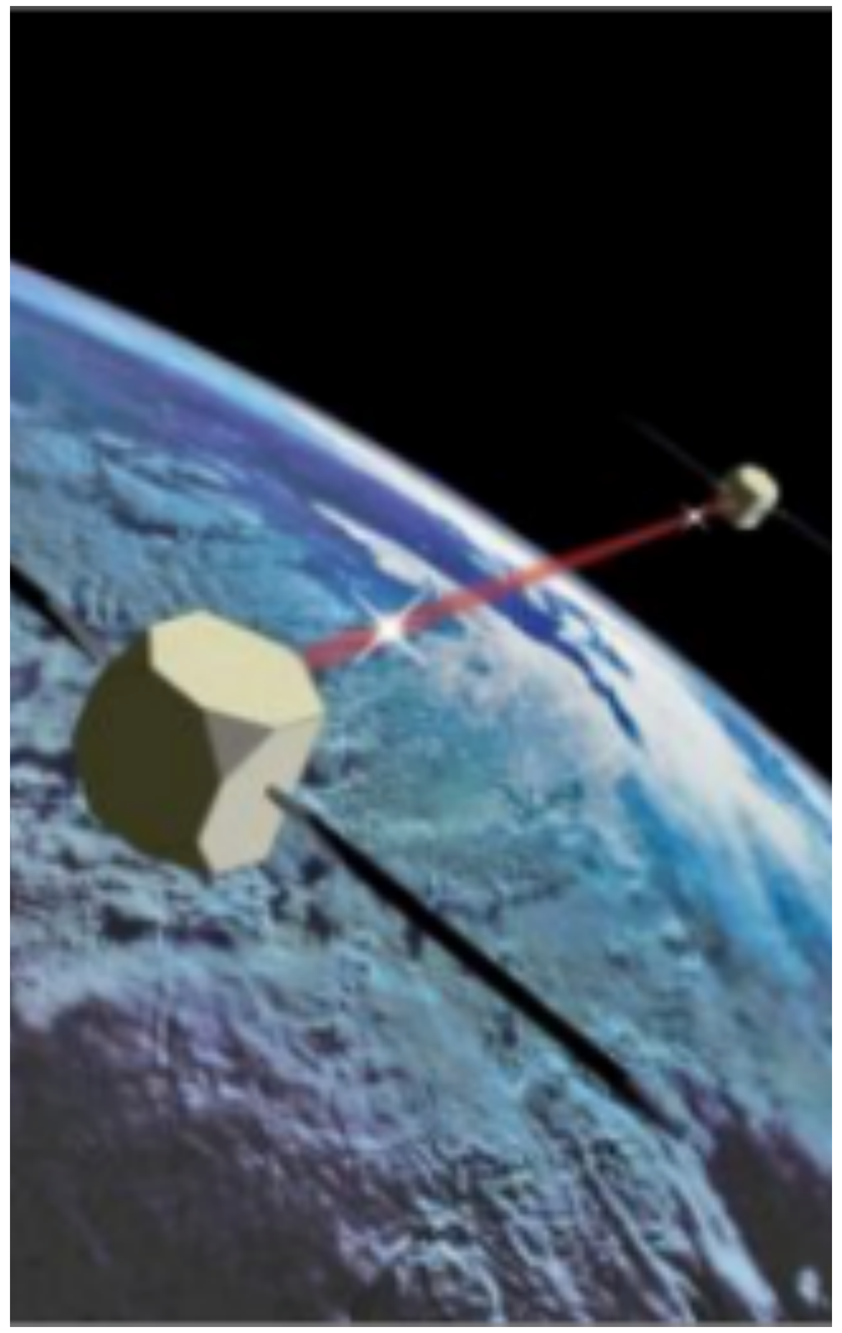
km-instrument
2040s major international project

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







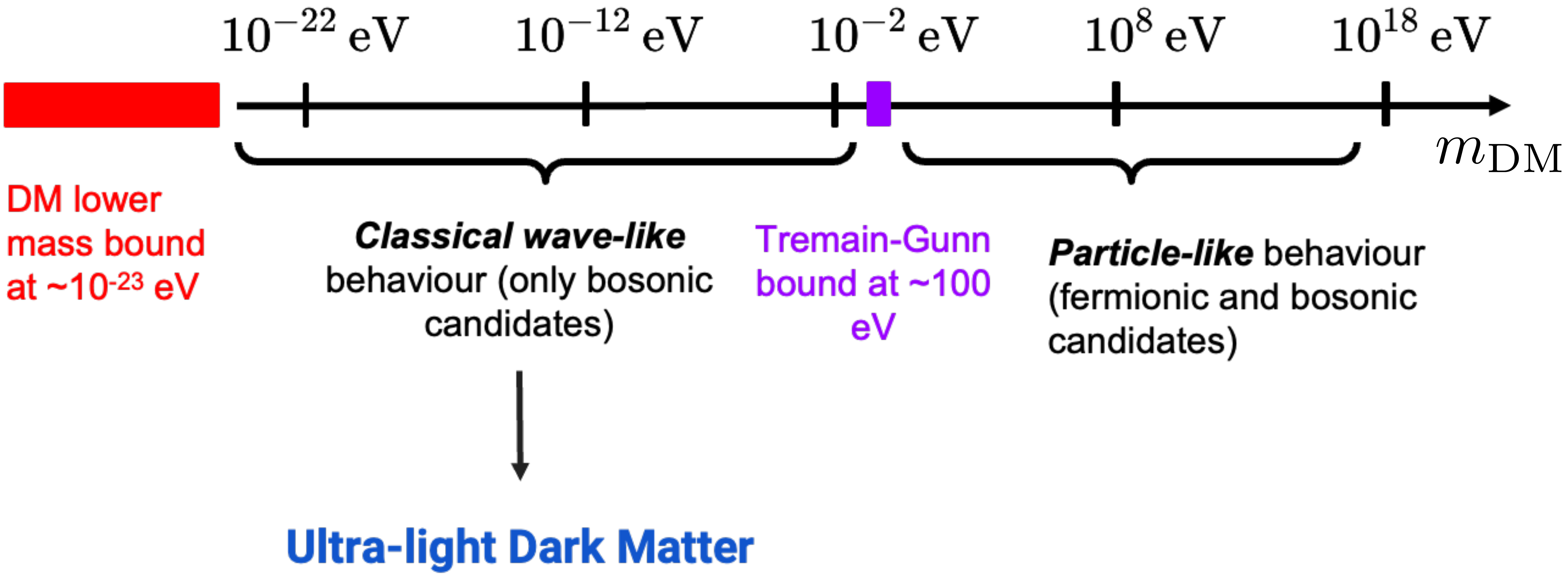


CERN study: arXiv:2304.00614 ; AEDGE, arXiv:1908.00802; Roadmap, arXiv:2201.07789

Near-term aim: probe dark matter

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

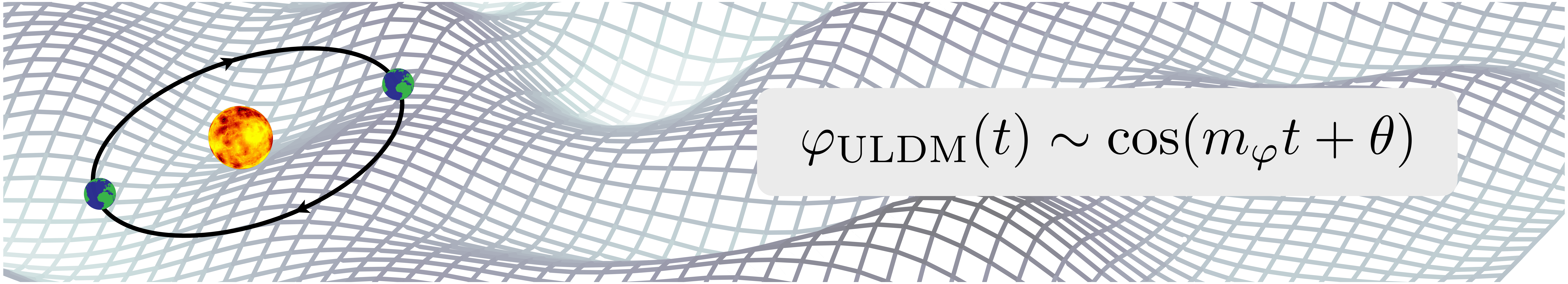
DM landscape: classifying by mass



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 arXiv: 1711.10489
Derevianko arXiv:1605.09717

Classifying atom interferometer signals

ULDM-induced signal

Static vs Time-dependent

Difficulty: very high
Careful analysis of systematic effects needed, which may be hard to quantify

Difficulty: medium
Characteristic DM signal allows for greater signal discrimination

Focus initially on 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:

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

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

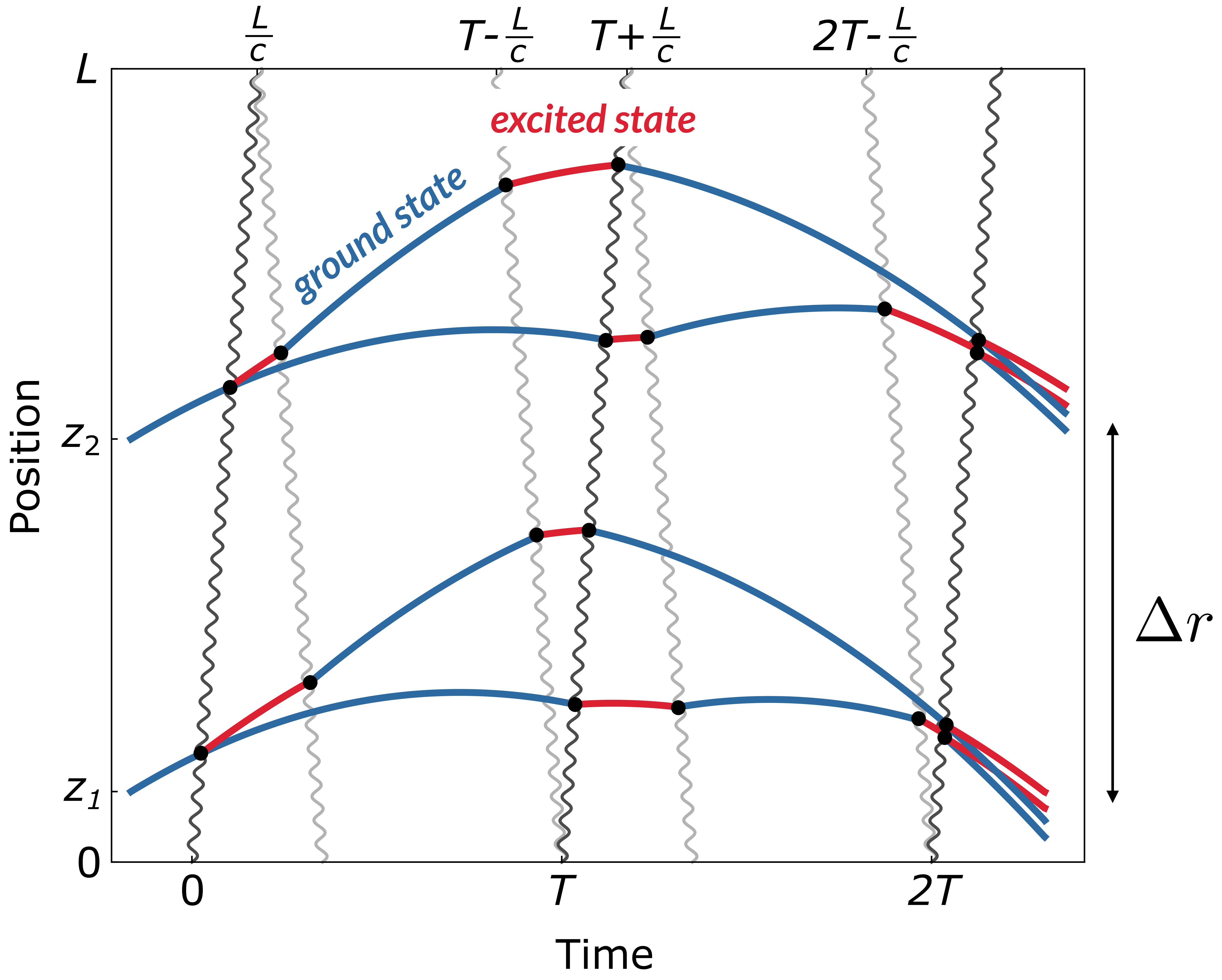
Scalar ULDM signal

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

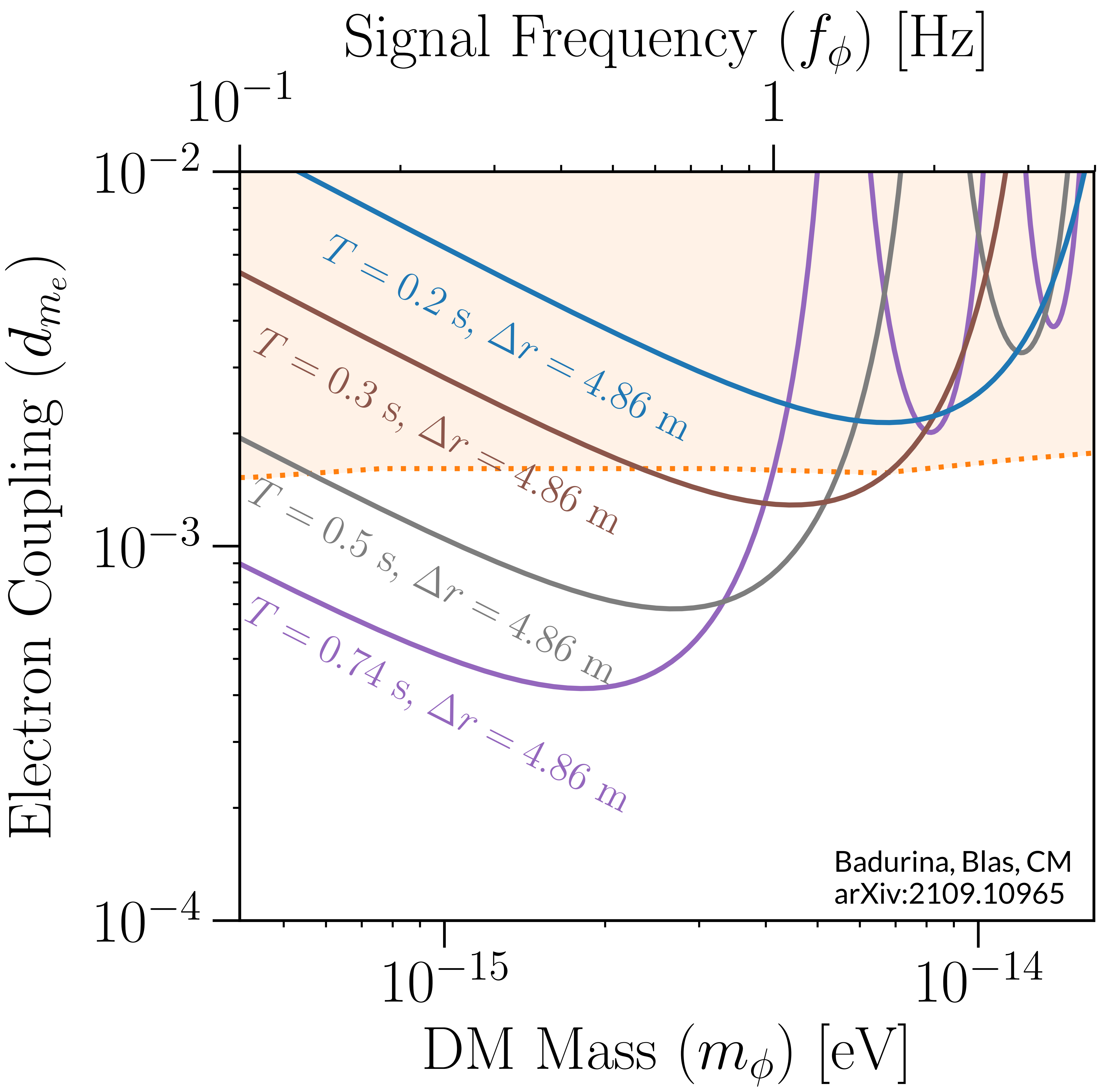


Many parameters to tune to reach sensitivity

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

Handles to optimise (in order of priority):

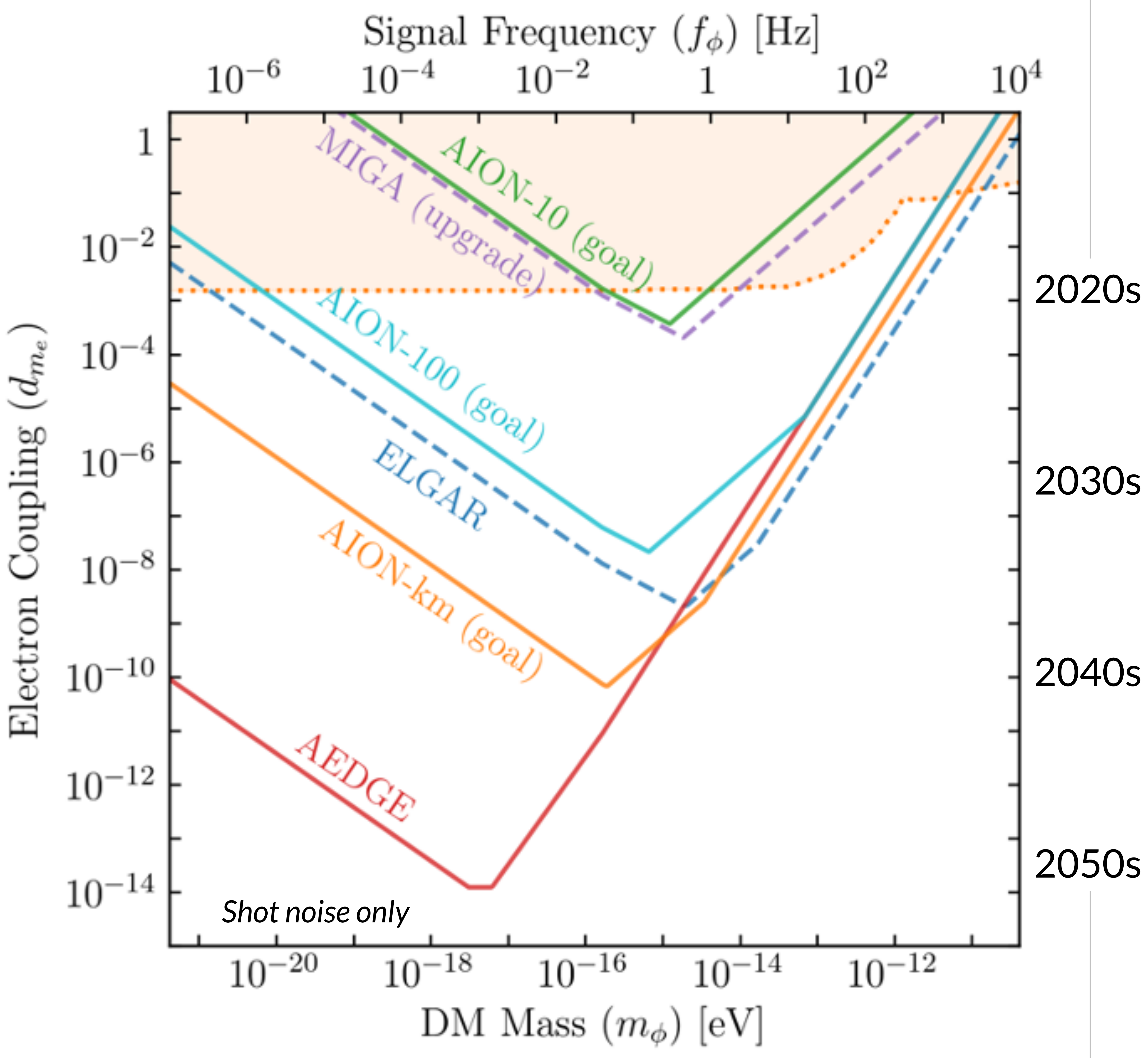
T ~ 1s (interrogation time)
C ~ 0.1 - 1 (constrast)
n ~ 1000 (LMT)
Δr ~ AI separation
Δt ~ sampling time
$N_a \sim$ atoms in cloud
$T_{\rm int} \sim 10^7{\rm s}$ (integration time)



Near- and long-term prospects (Scalar)

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

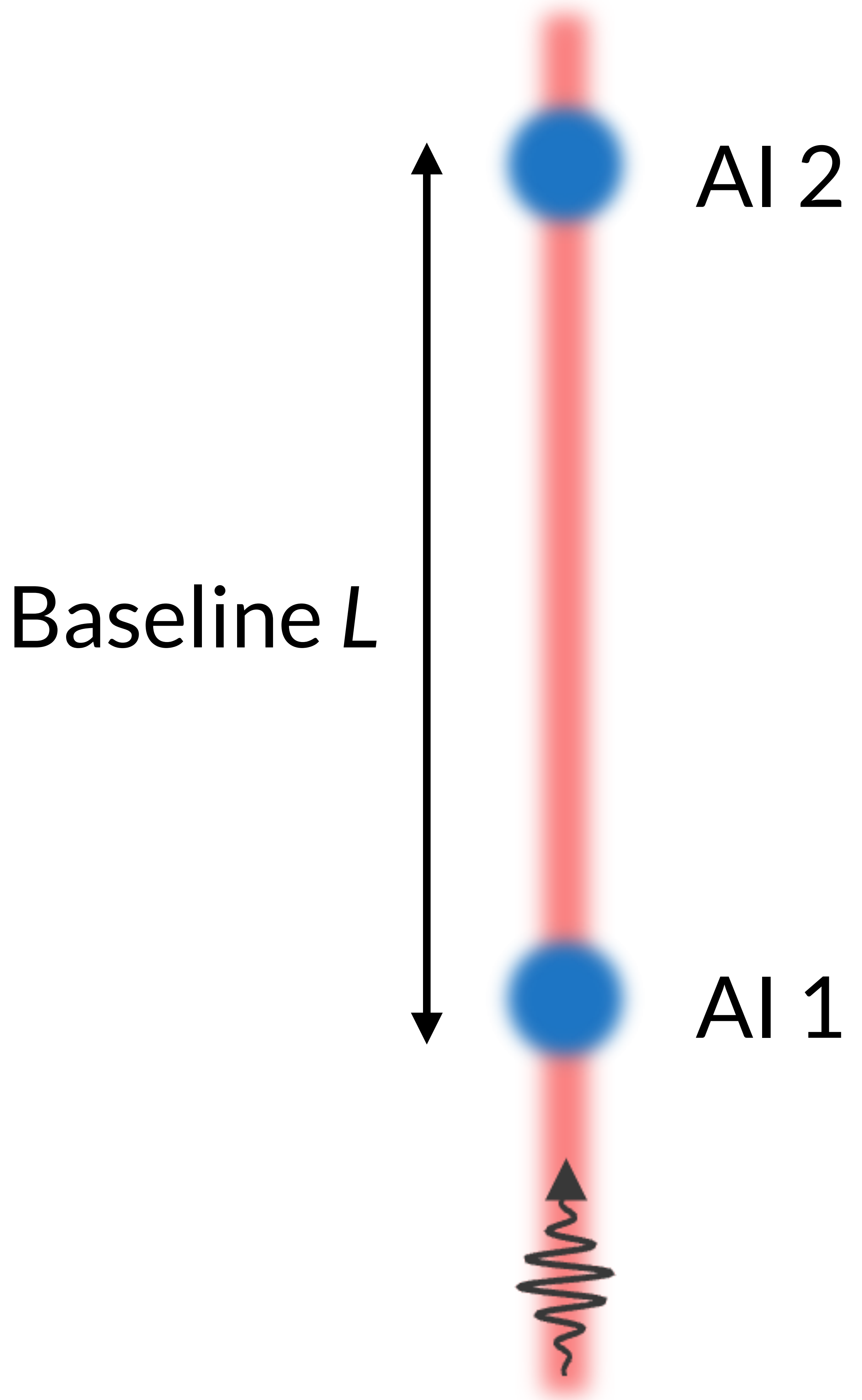
Badurina, CM, et al, arXiv:1911.11755, 2108.02468



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

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

strain amplitude — GW frequency

Gives rise to time-dependent phase shift between the interferometers

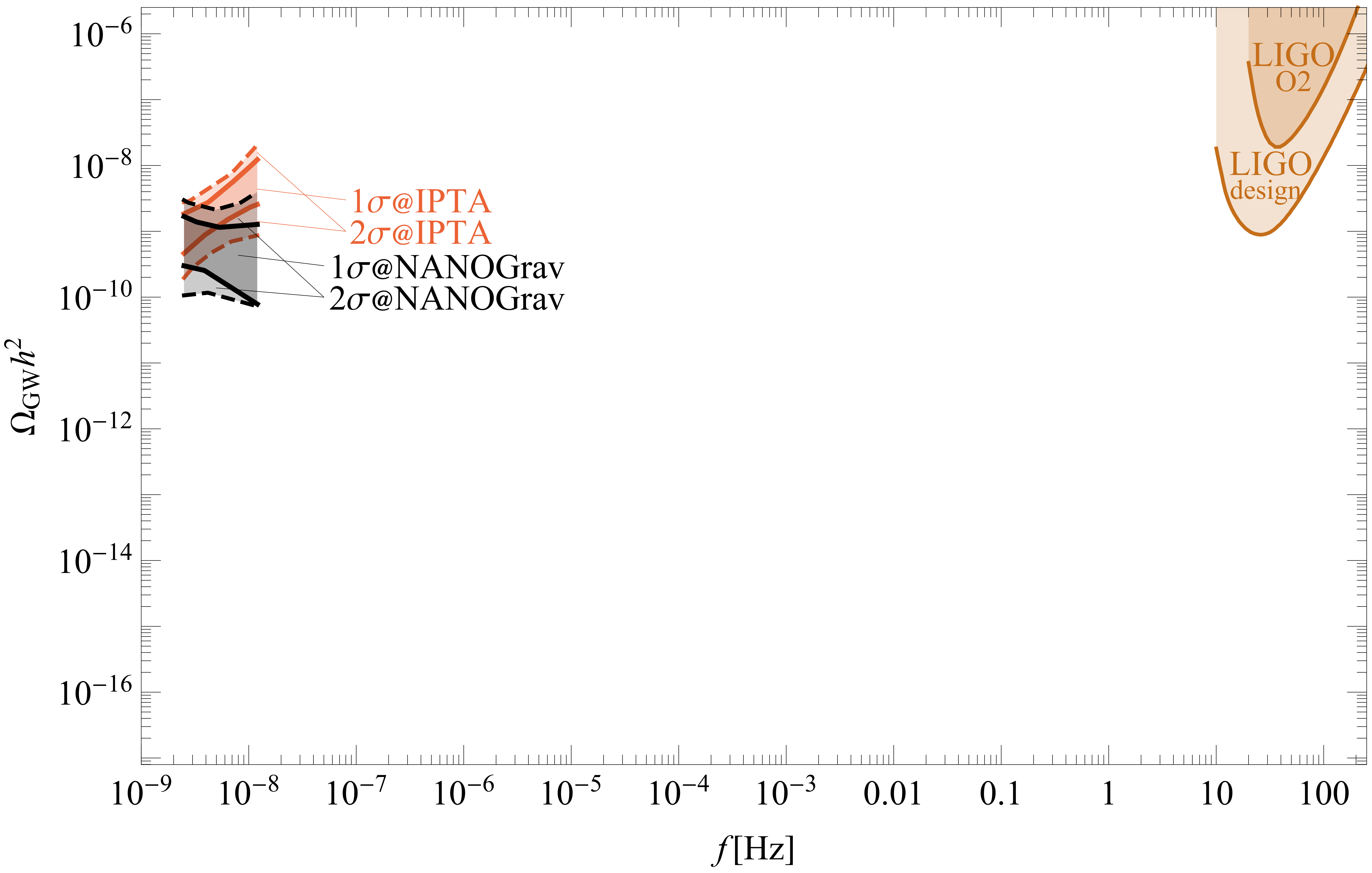
$$\Phi \propto hL\sin^2\left(\frac{\omega T}{2}\right)$$

Sensitive for large *L* (~km scale)

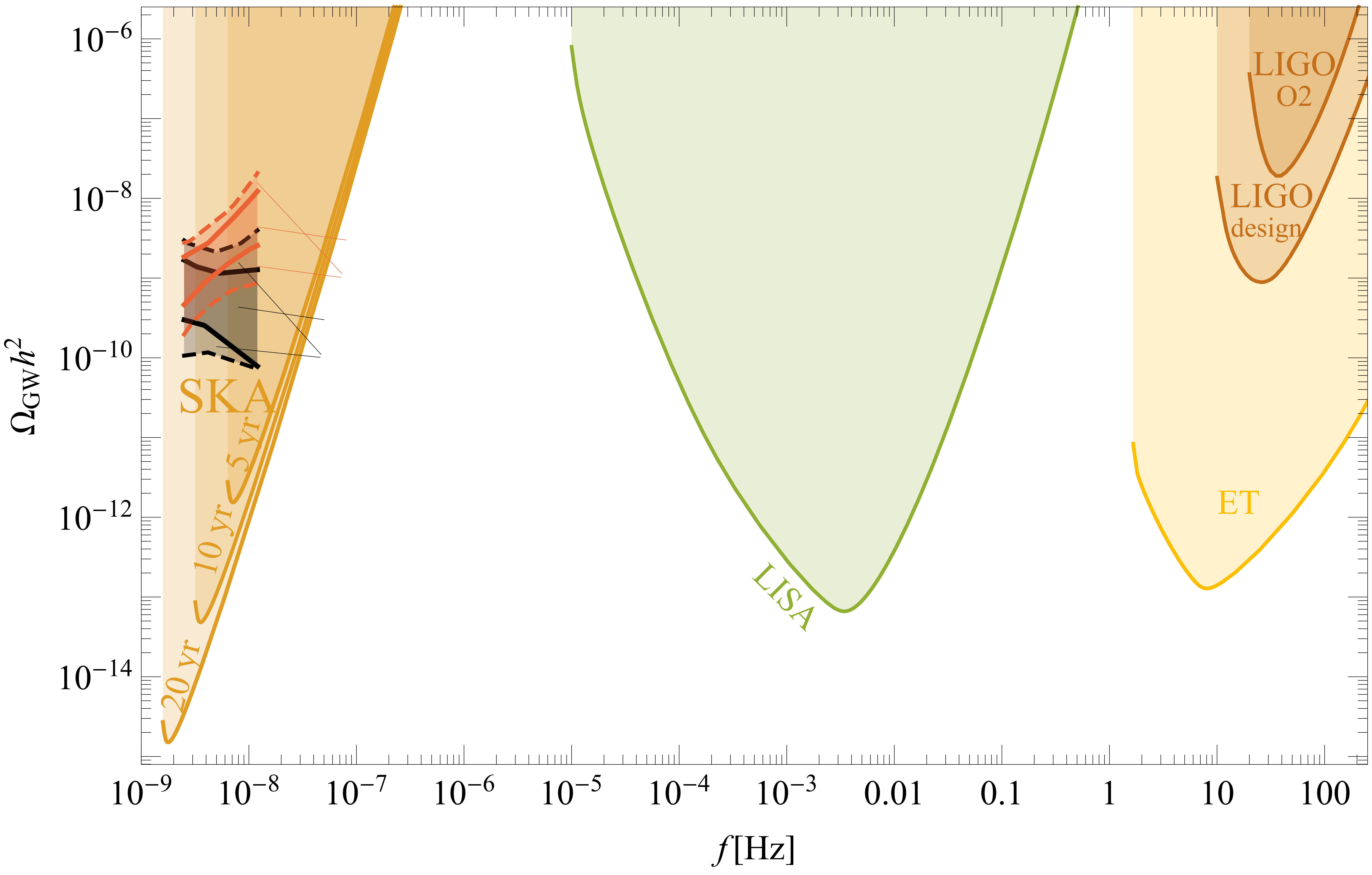
Sensitive to GW frequencies ~ *1/T* ~ Hz

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



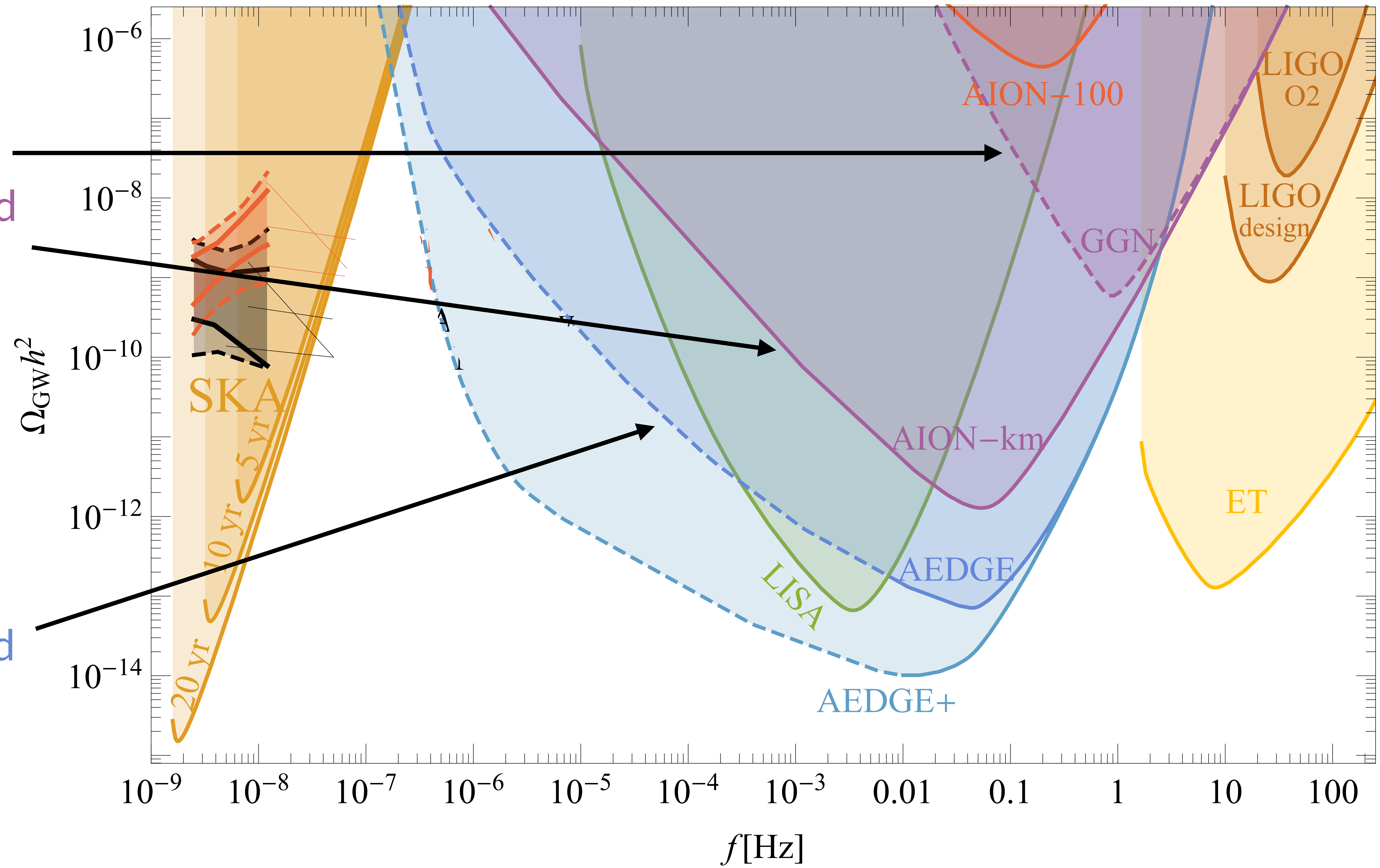
Conventional GW soundscape ~2040



GW soundscape (~2040s) with atom interferometers

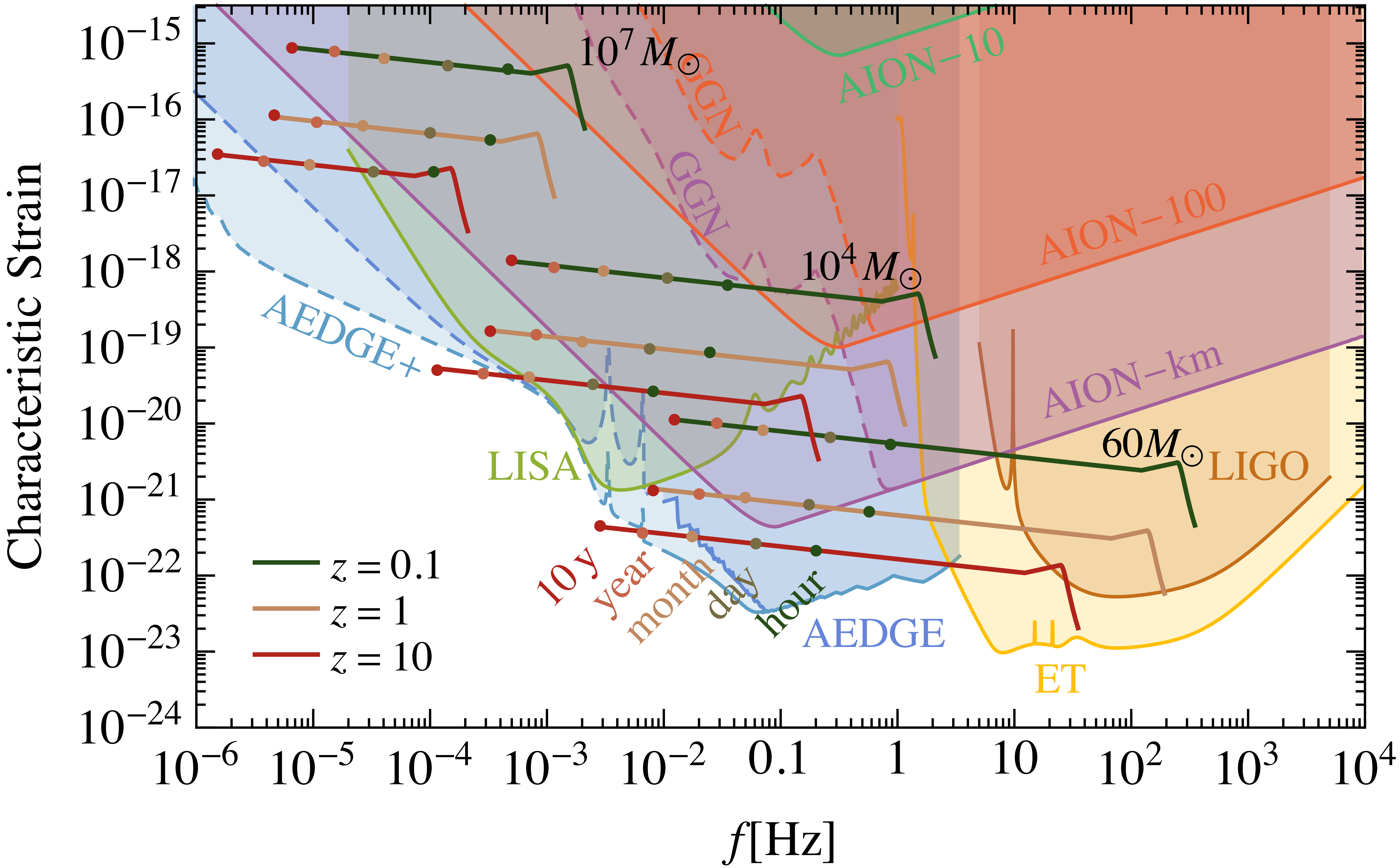
Terrestrial sensitivity (between dashed and solid lines)

Space-based sensitivity



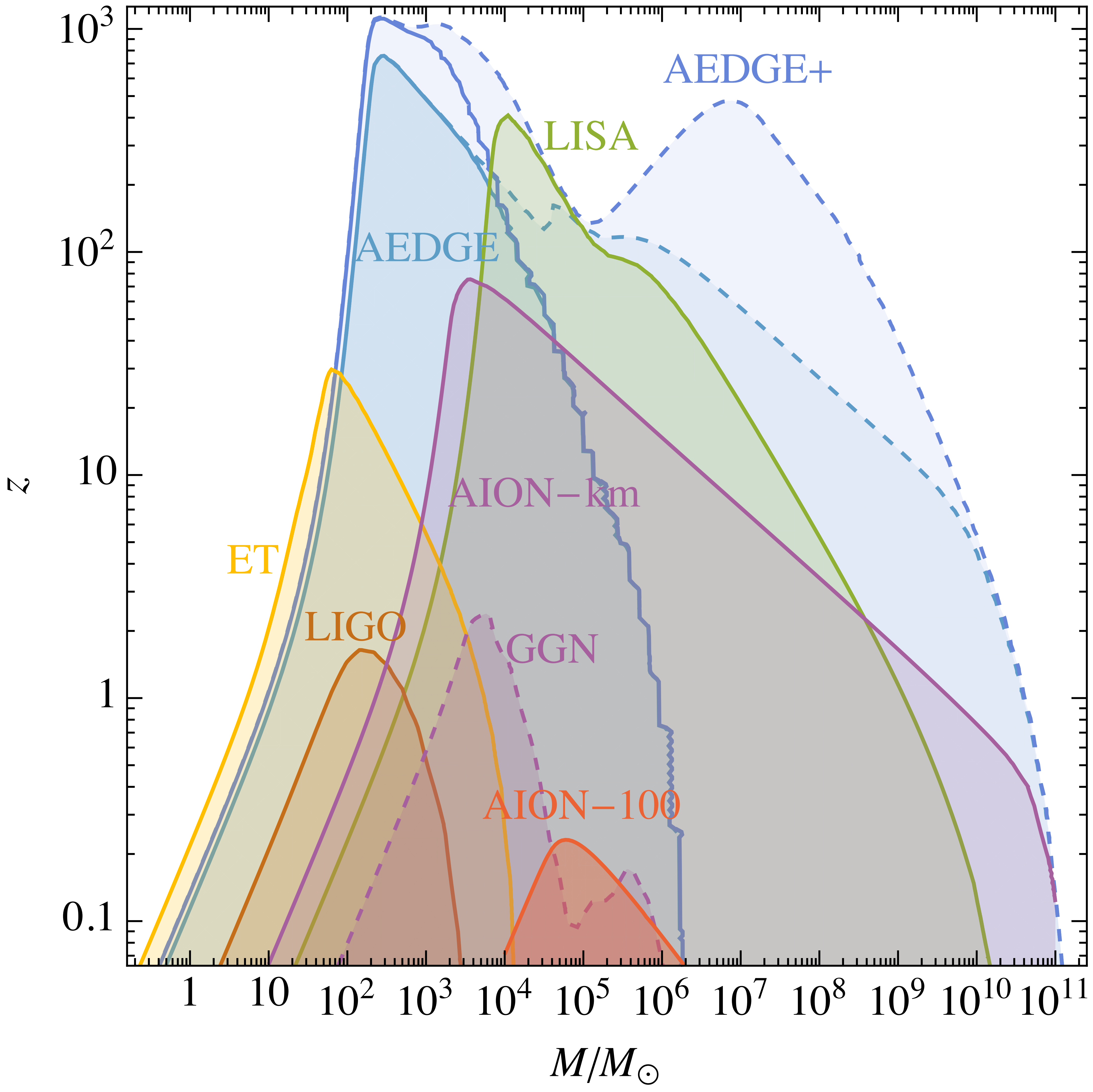
Badurina, Buchmueller, Ellis, Lewicki, CM, Vaskonen Phil.Trans.Roy.Soc.Lond., arXiv:2108.02468

Example: sensitivity to binary mergers (equal masses)



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

Example: sensitivity to binary mergers (equal masses)

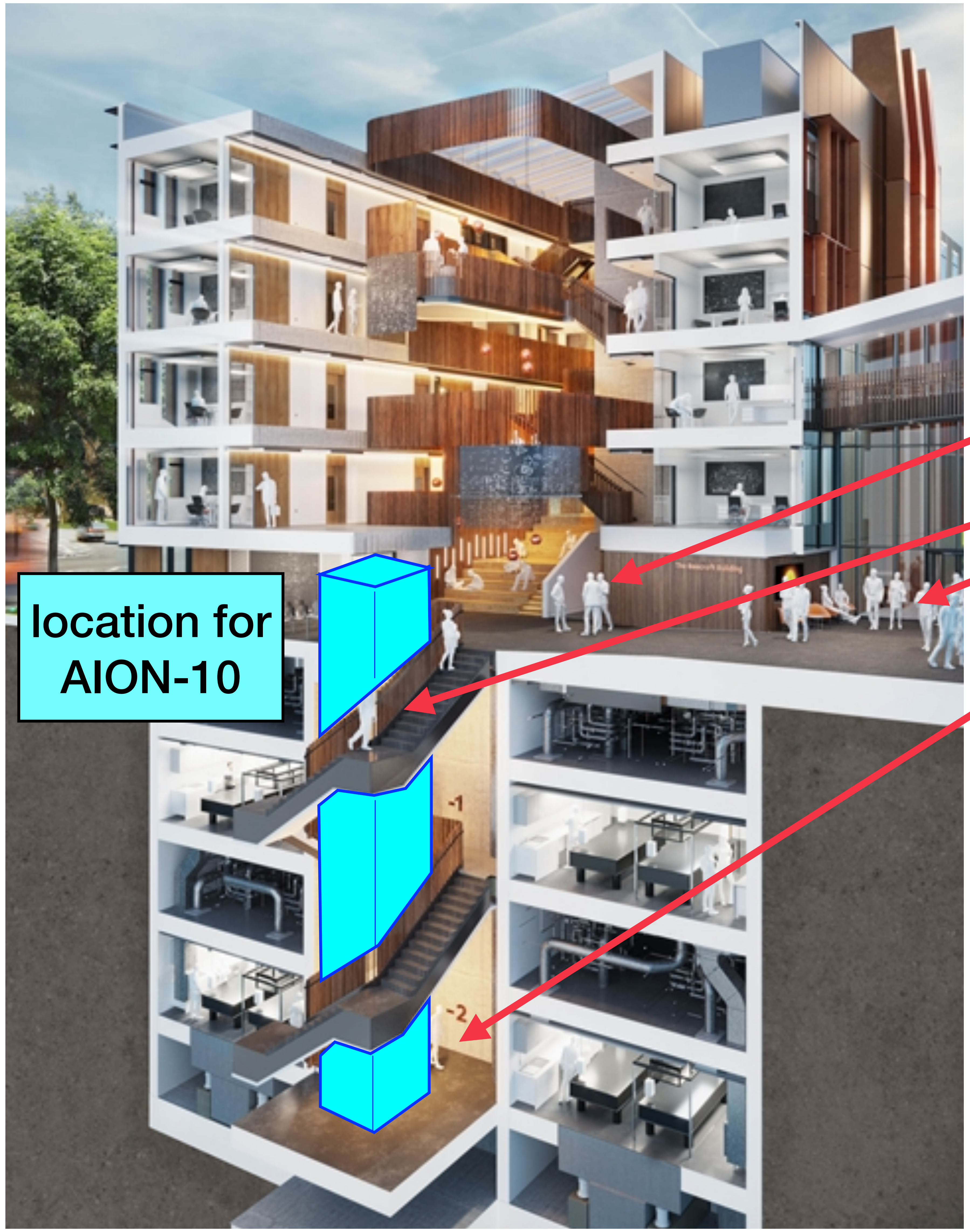


Badurina, Buchmueller, Ellis, Lewicki, CM, Vaskonen Phil.Trans.Roy.Soc.Lond., arXiv:2108.02468

Ongoing work: mitigating backgrounds

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

Short-termer challenge: operating in a university building

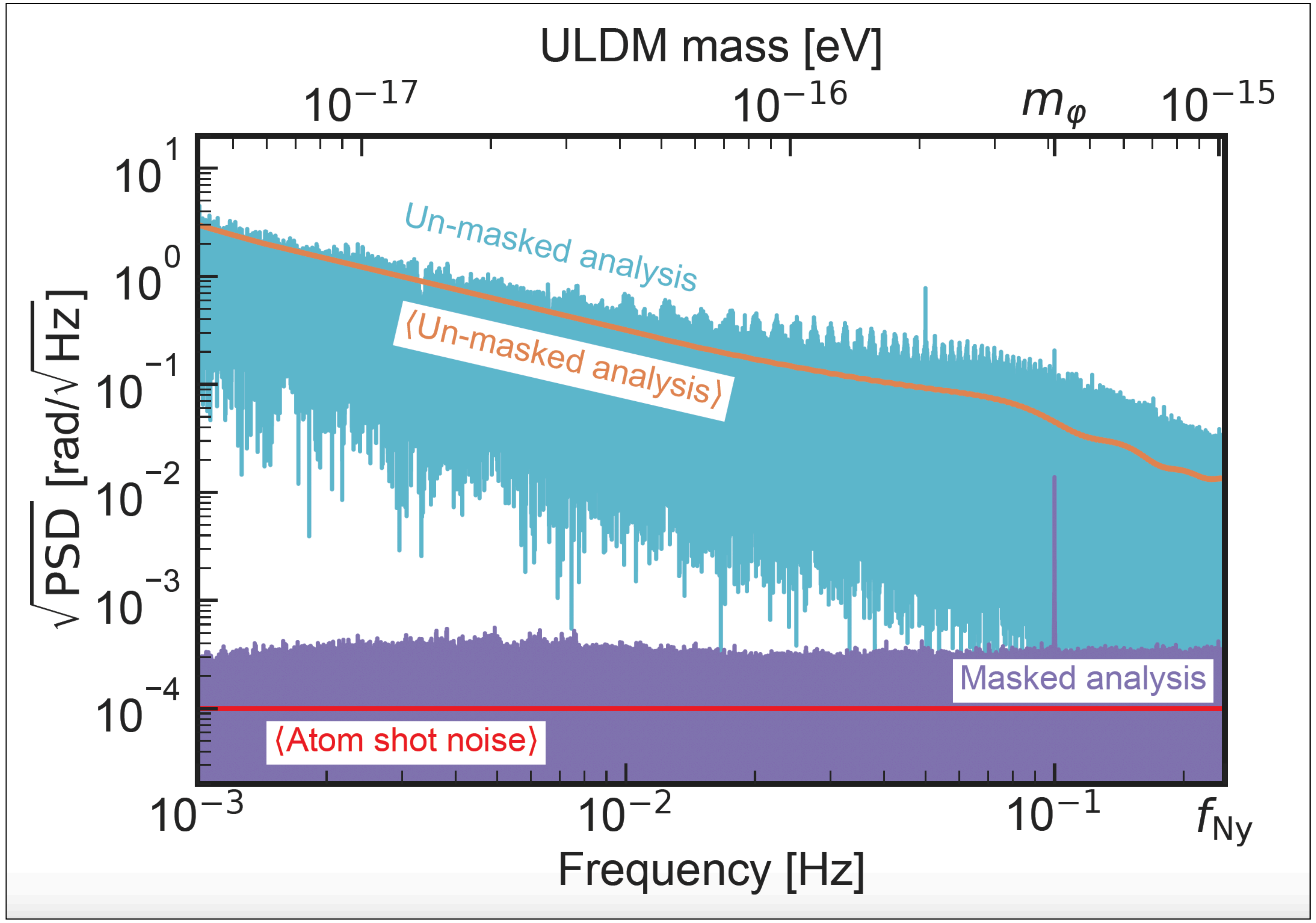


Many moving
'test masses'

ULDM searches run for many months

Could the busy environment hide a fundamental physics signal?

Mitigation through data analysis



Preliminary: Carlton, CM, to appear

Simple strategy works:
mask noisy periods in analysis

Loss in sensitivity small since:

$$d_{m_e}^{\mathrm{best}} \sim \left(\frac{1}{T_{\mathrm{int}}}\right)^{1/4}$$

Recover shot-noise limited sensitivity

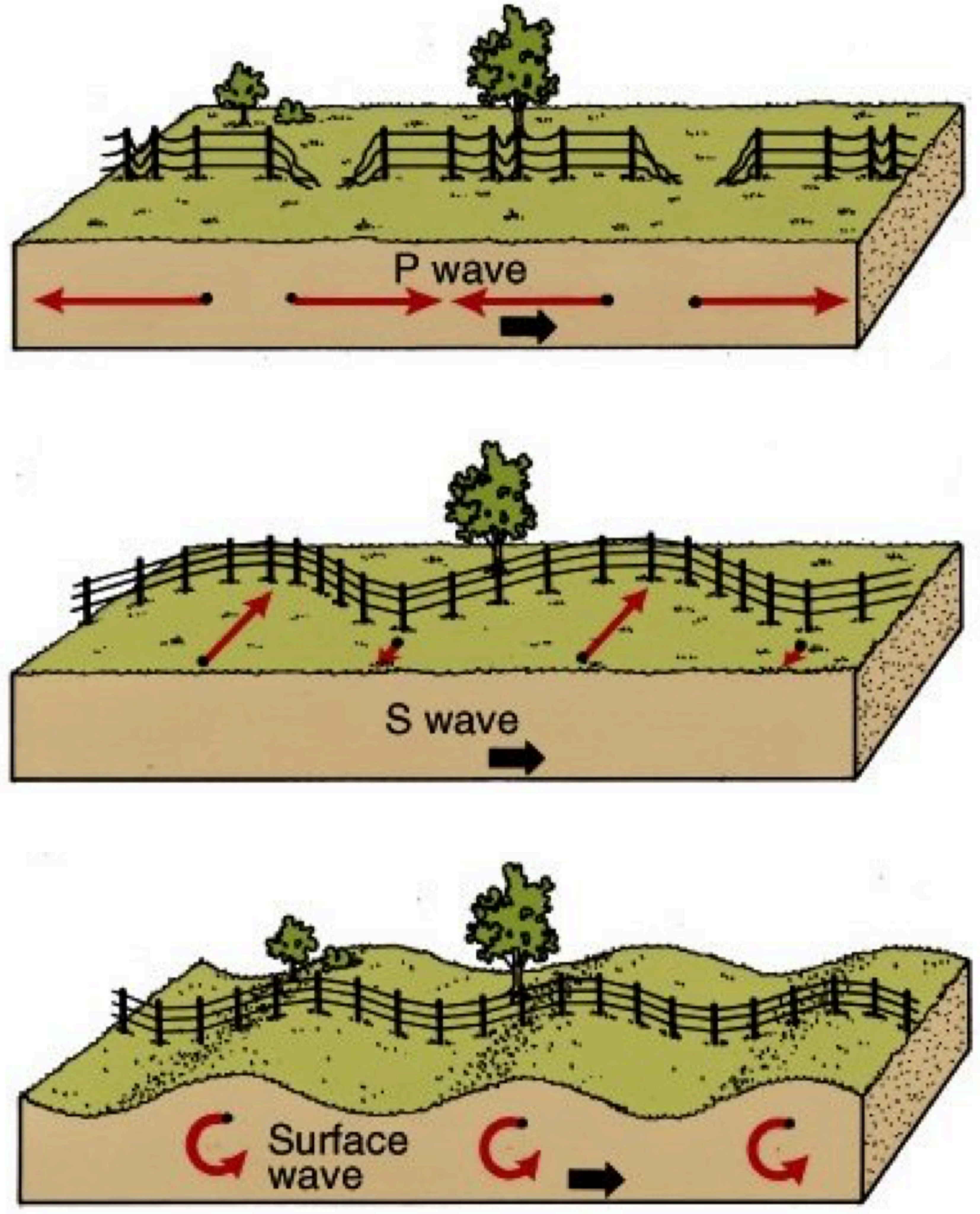
Exploring methods to keep all data

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

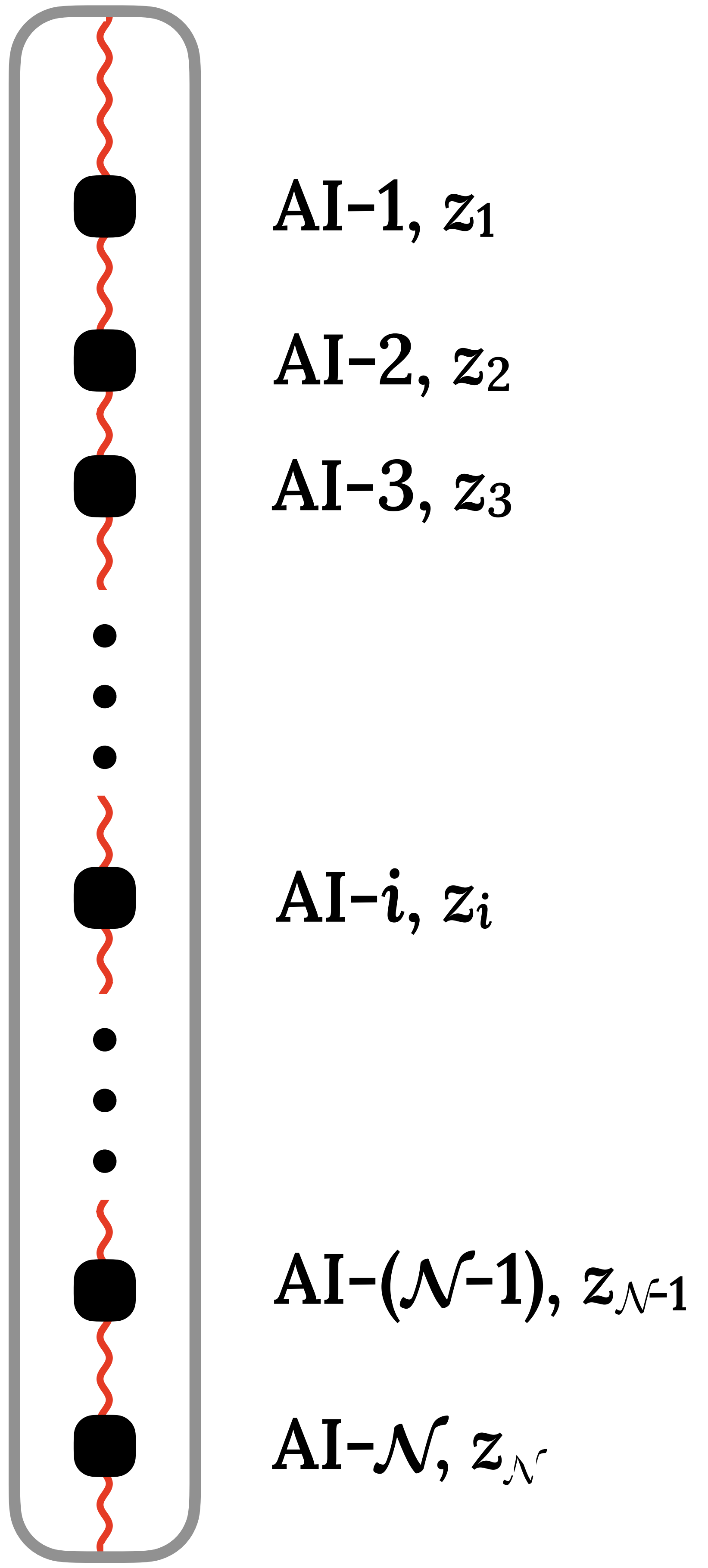
GGN signal decays exponentially from the surface

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

ULDM (or GW) signals scale linearly with AI separation

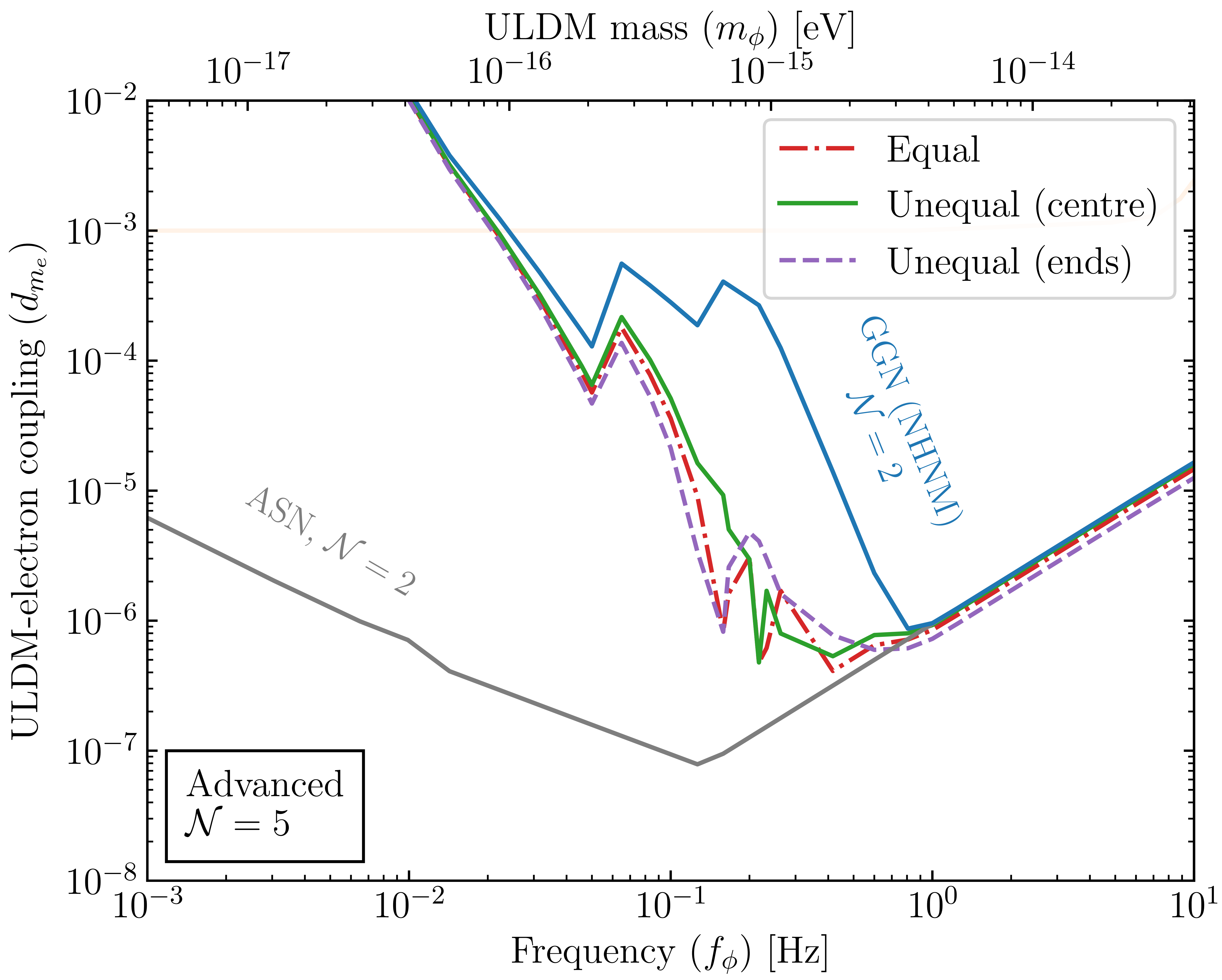
$$\Phi_{\text{ULDM}} \sim \frac{\Delta z}{L}$$

Cross-correlation methods to search for the 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

Historically, new observational techniques have led to new discoveries

Ultralight dark matter probe

- Mass < 10^{-12} eV
- Scalar-, vector- and pseudoscalar-coupled DM candidates
- Time-varying energy shifts, EP-violating new forces, spin-coupled effects

Mid-band gravitational wave detection

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

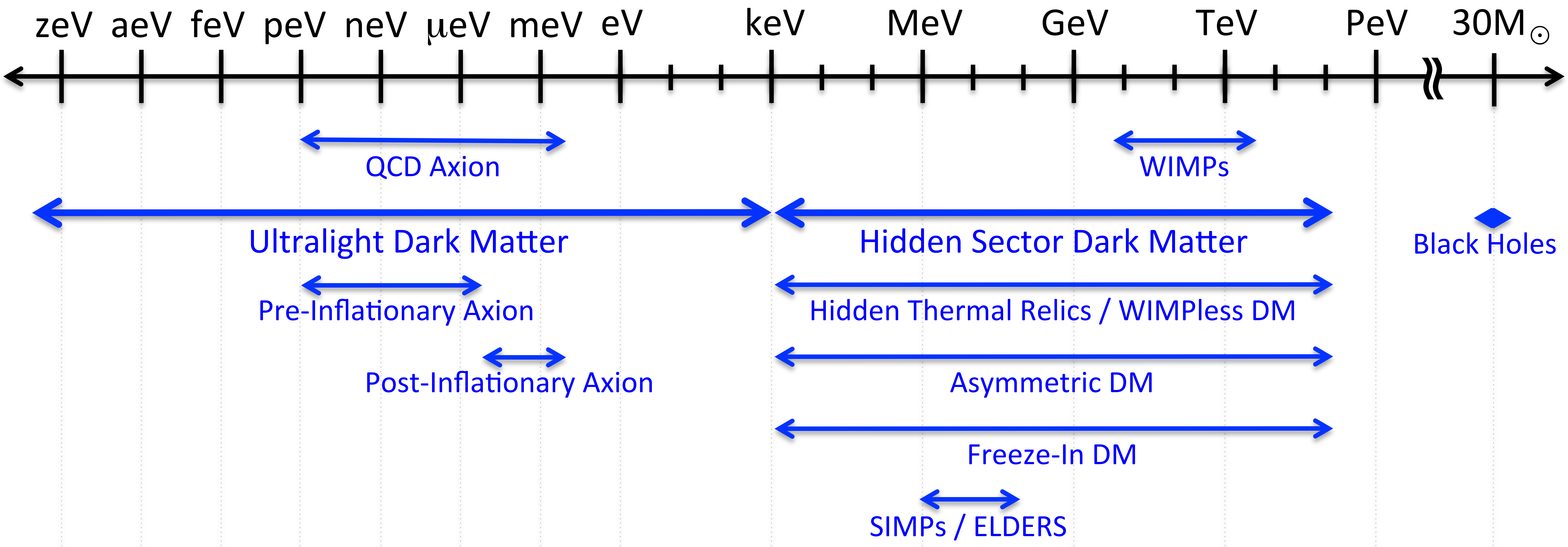
And more…

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

Thank you

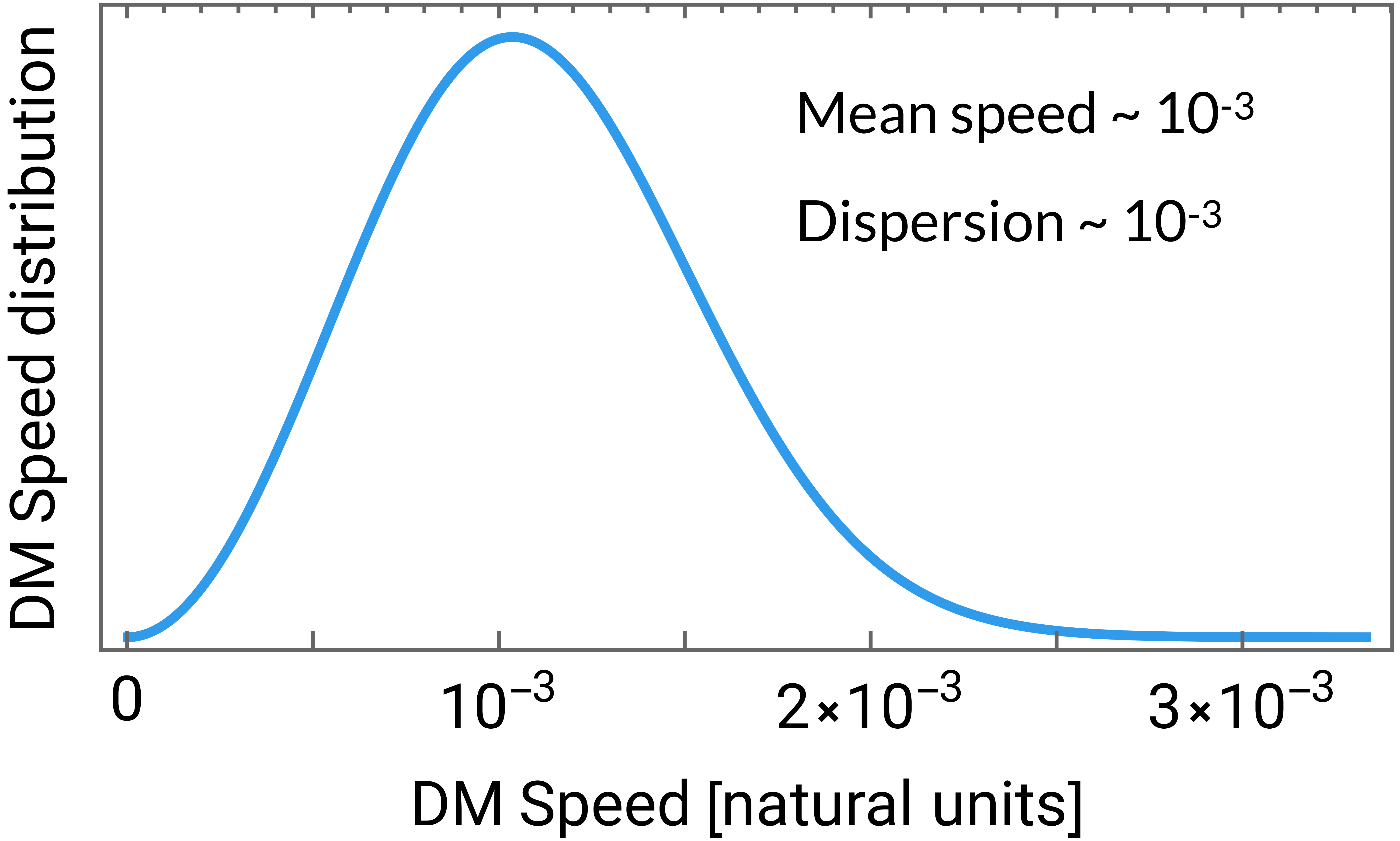
Science and Technology Facilities Council

A wide landscape of DM candidates



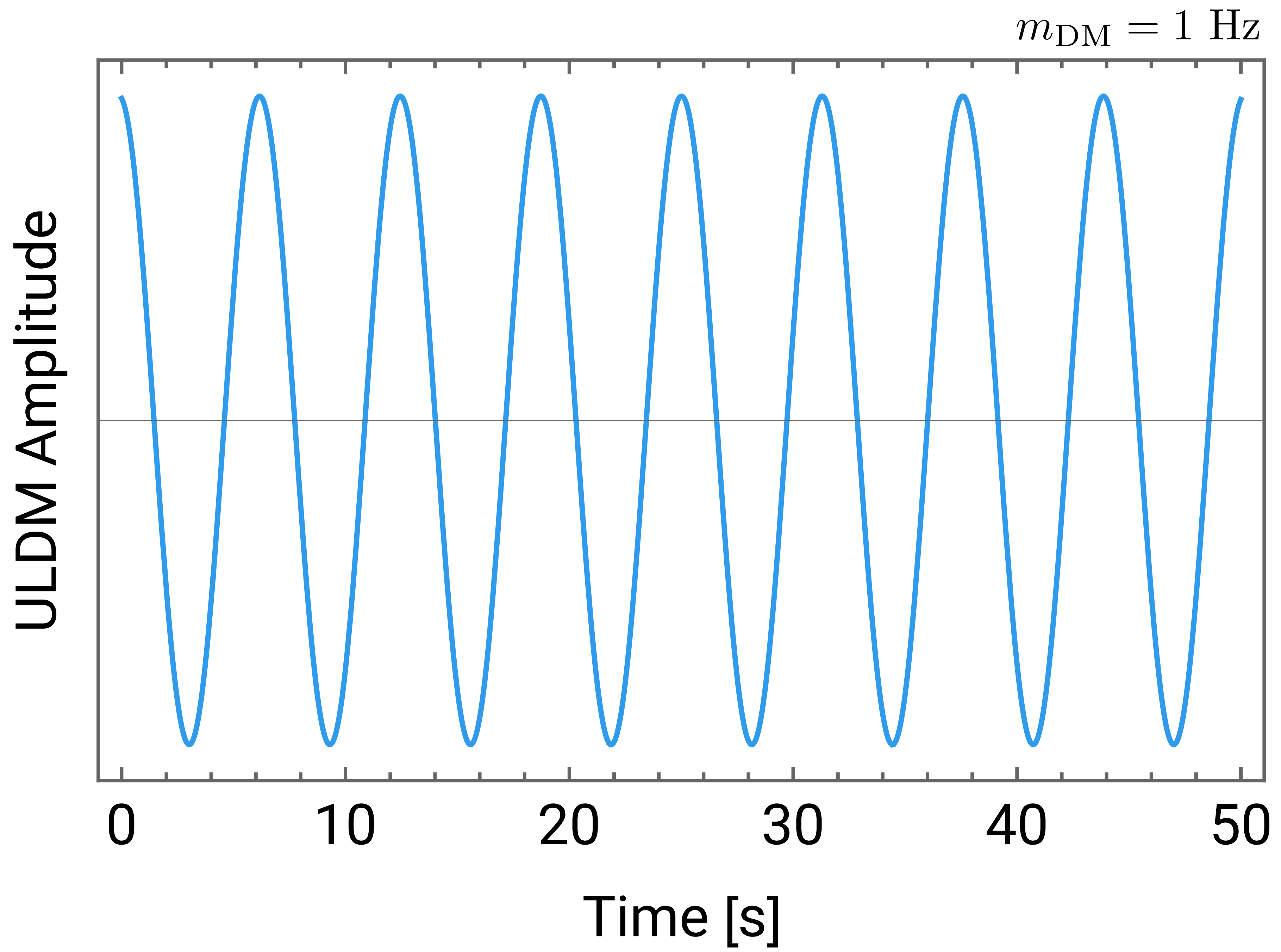
US Cosmic Visions

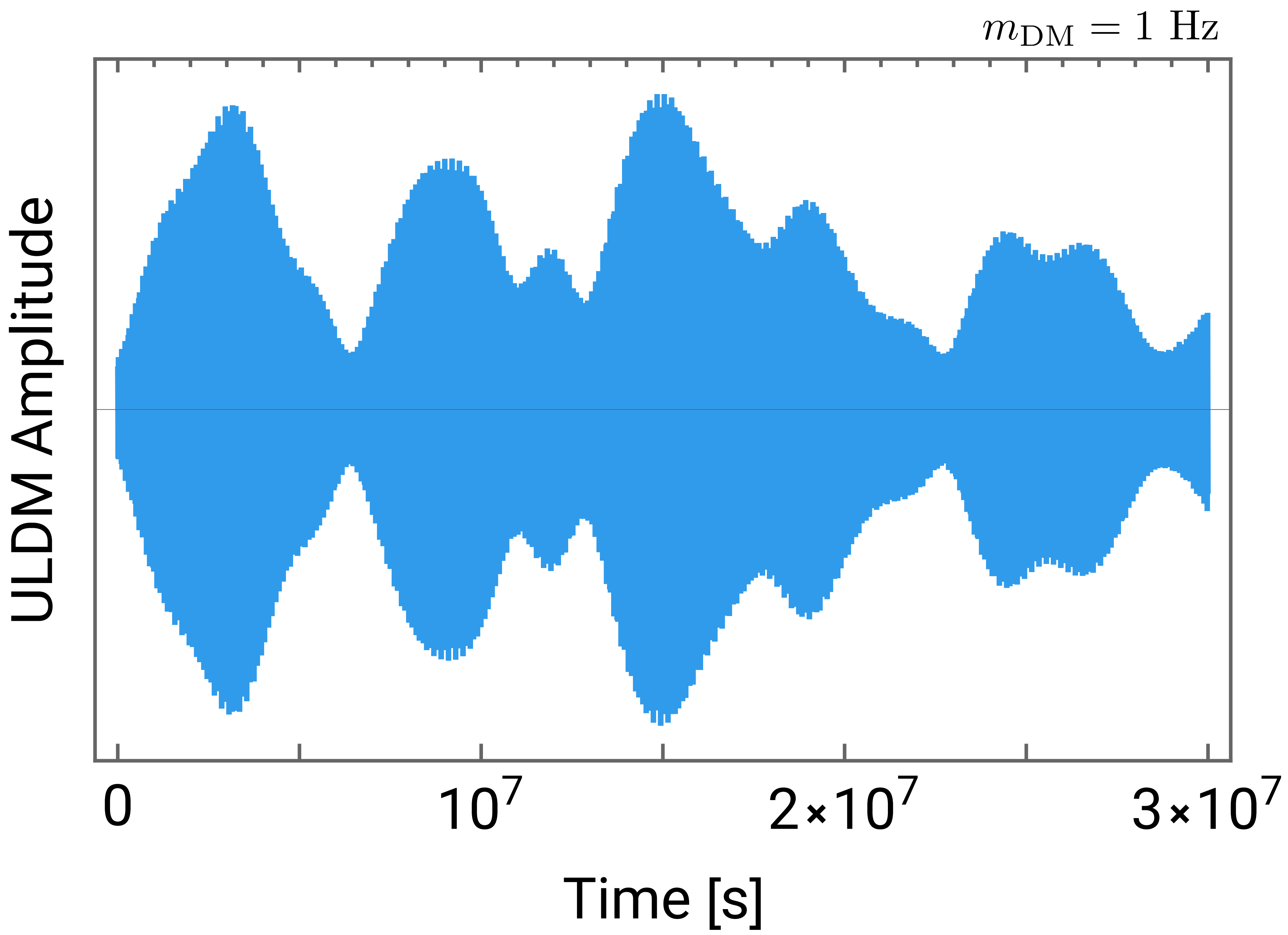
Speed distribution in our galaxy



Many models also predict some substructure in the distribution,
see e.g., O'Hare et al 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 arXiv:1605.09717

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

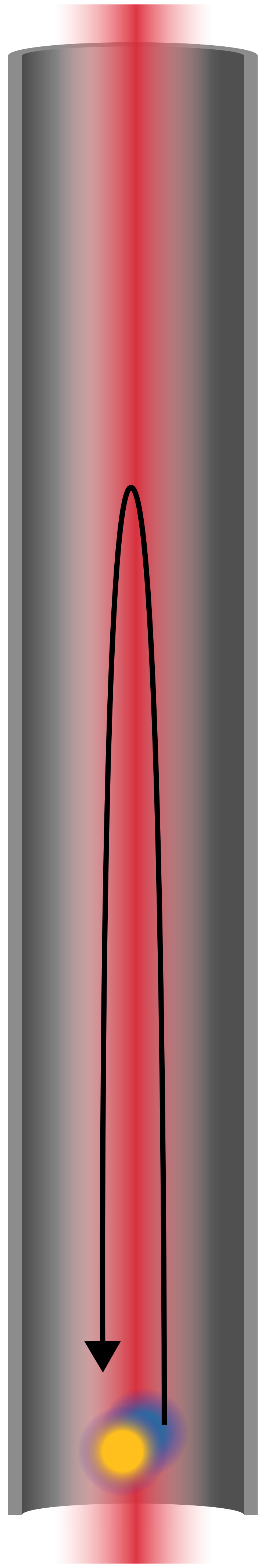
B − L coupled vector appears in many extensions of the Standard Model

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

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

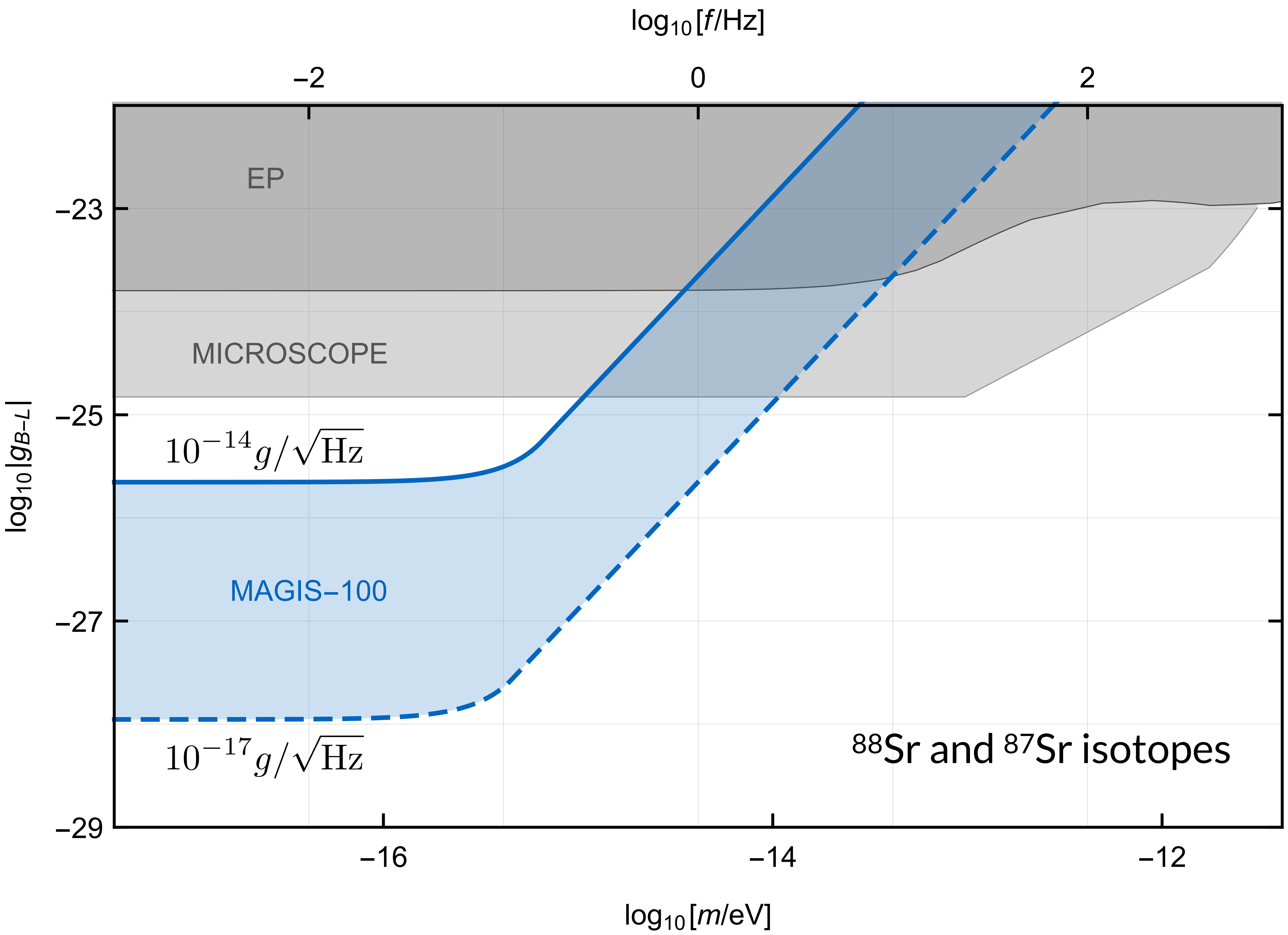
In a *dual-species interferometer*, isotopes experience a different forces (accelerations):

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



Graham et al arXiv:1512.06165

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



Abe et al arXiv:2104.02835

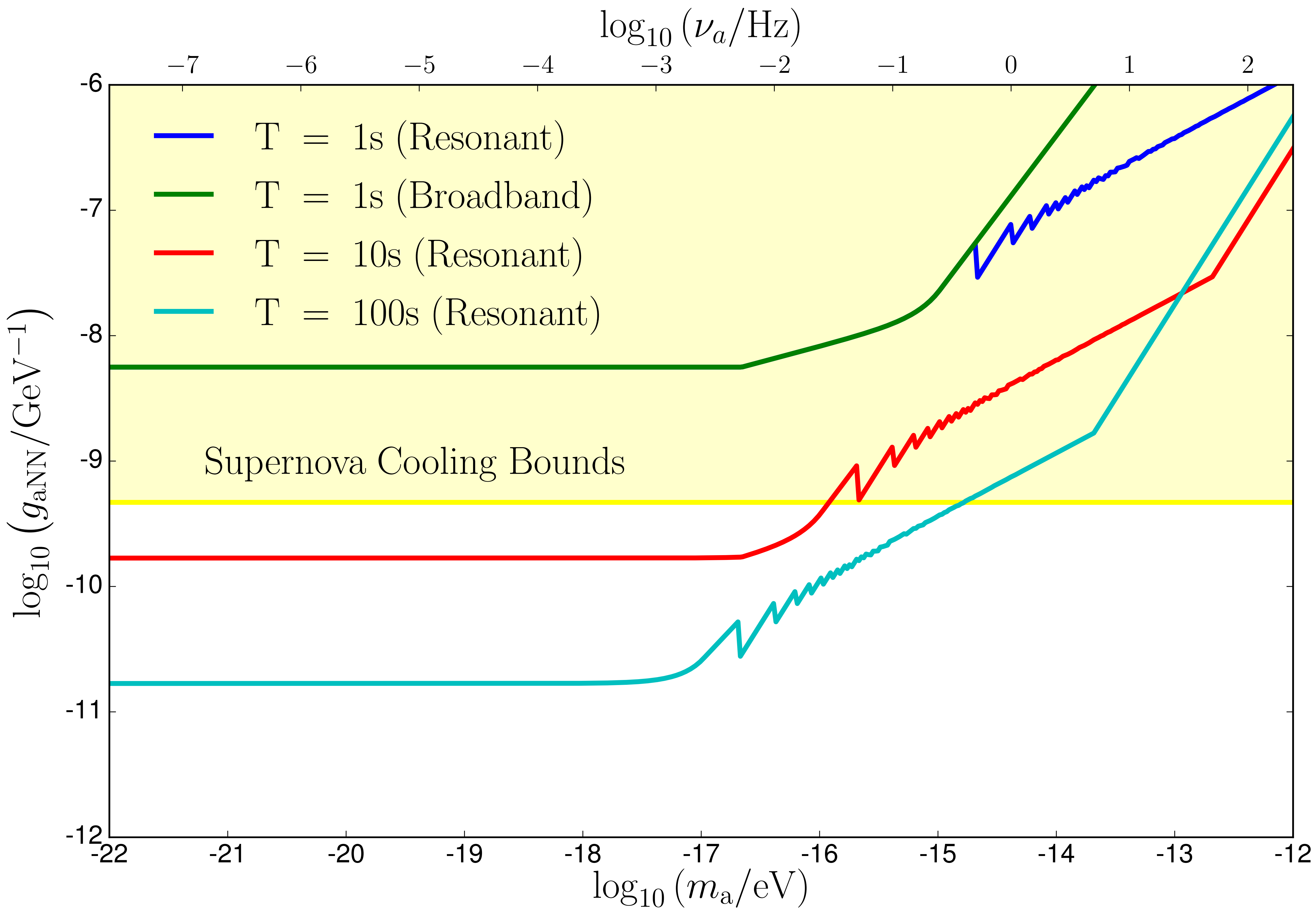
Other ULDM signals (2): Precession of spins (Pseudoscalar)

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:

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

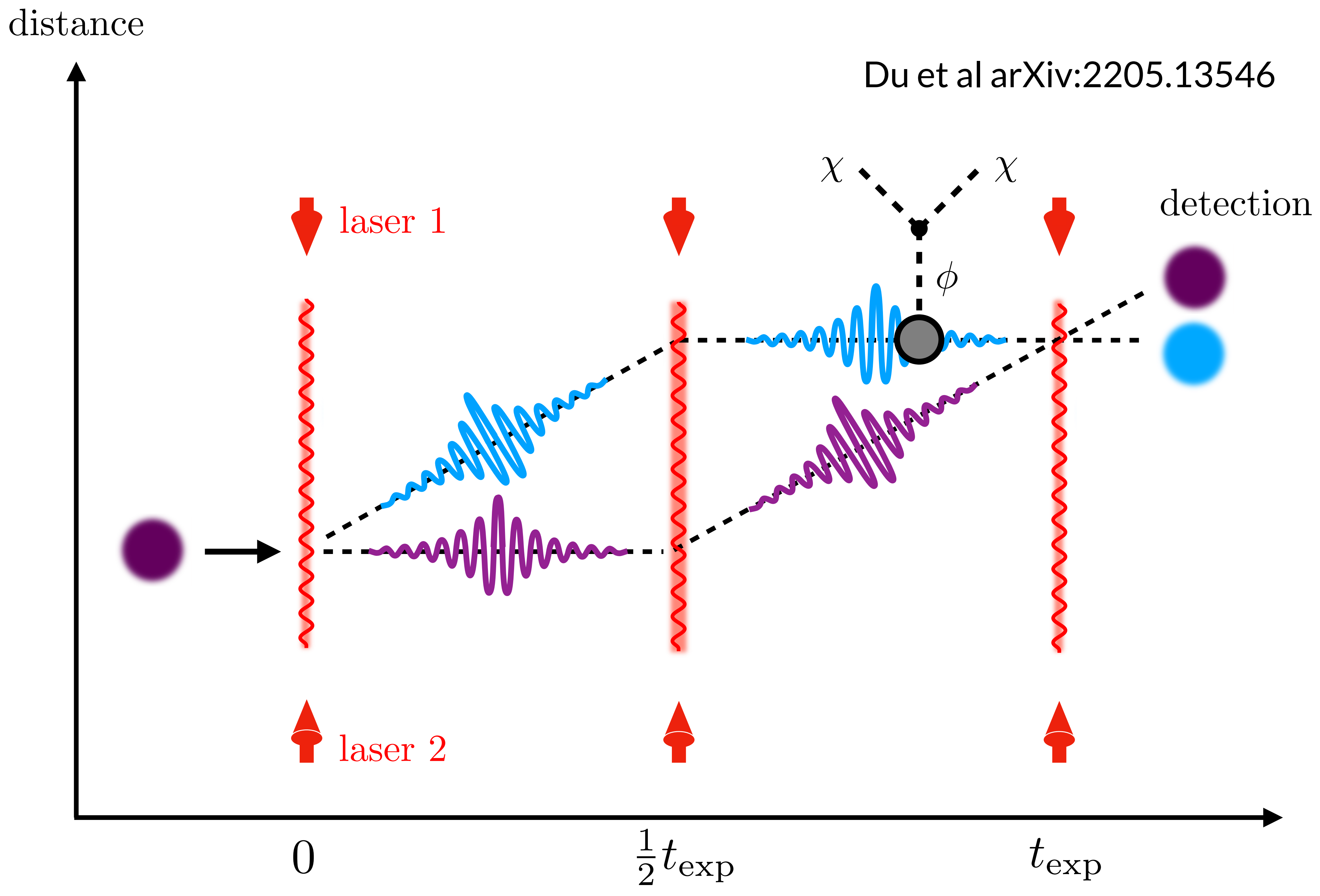
Challenging: km-baseline, high-repetition rate (10 Hz), long interrogation time, good control of magnetic fields $\delta B \sim 10^{-15}\mathrm{T}$



Graham et al arXiv:1709.07852

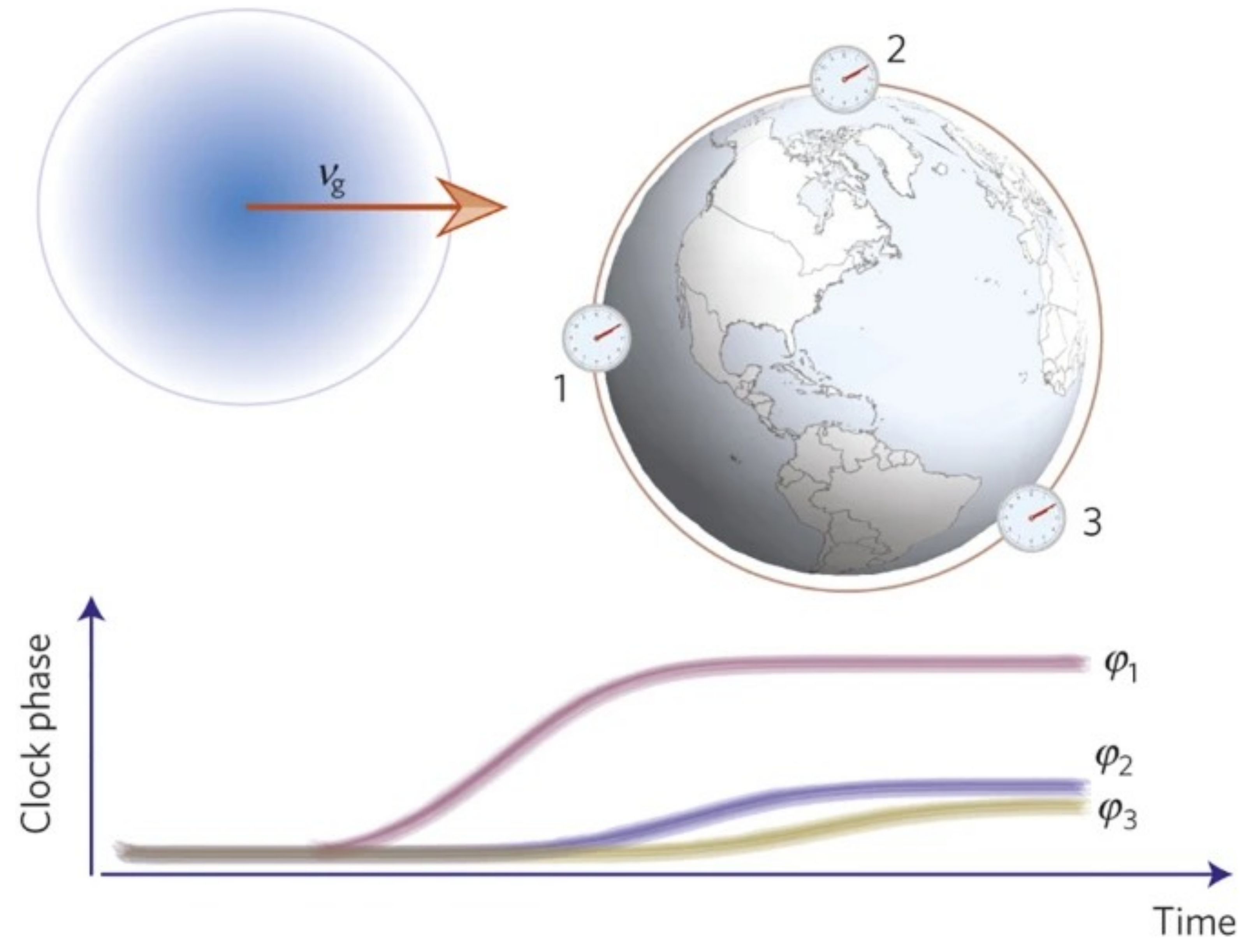
Beyond oscillating field signals…

Dark matter scattering in one AI arm causes decoherence



See also Riedel et al arXiv:1212.3061, 1609.04145

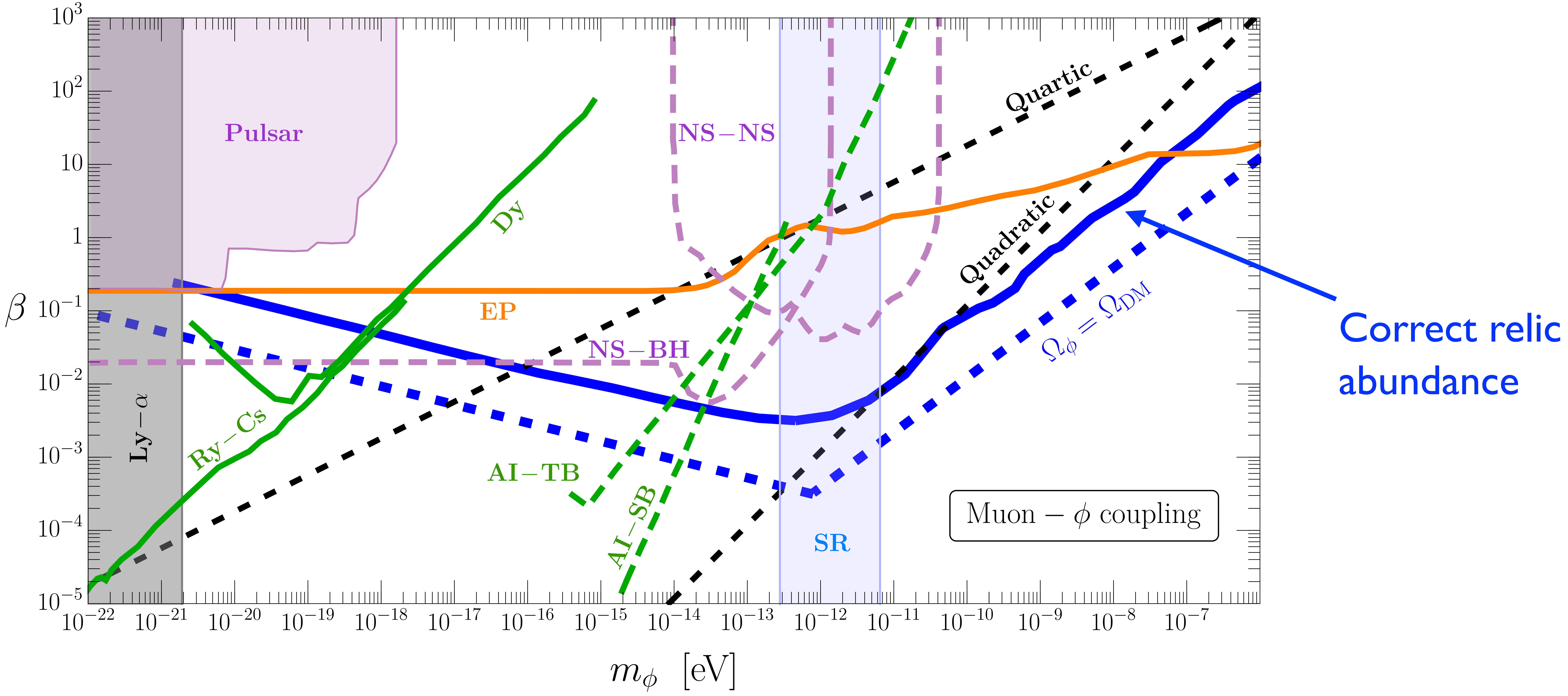
Transient signals utilising a global network of AIs]



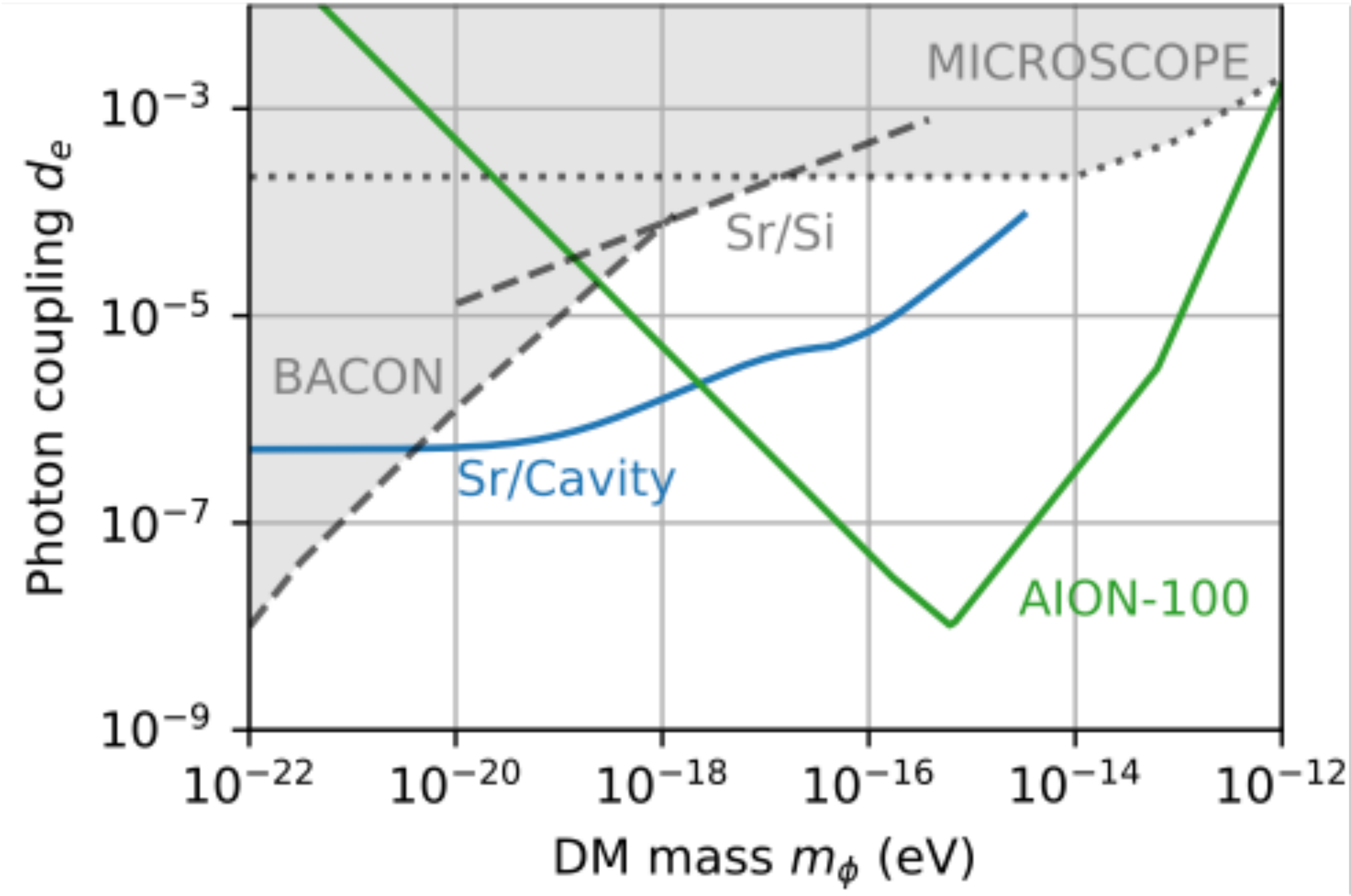
See e.g., Derevianko arXiv:1311.1244 or Gorghettoa arXiv:2203.10100

Some work in the direction of the DM abundance

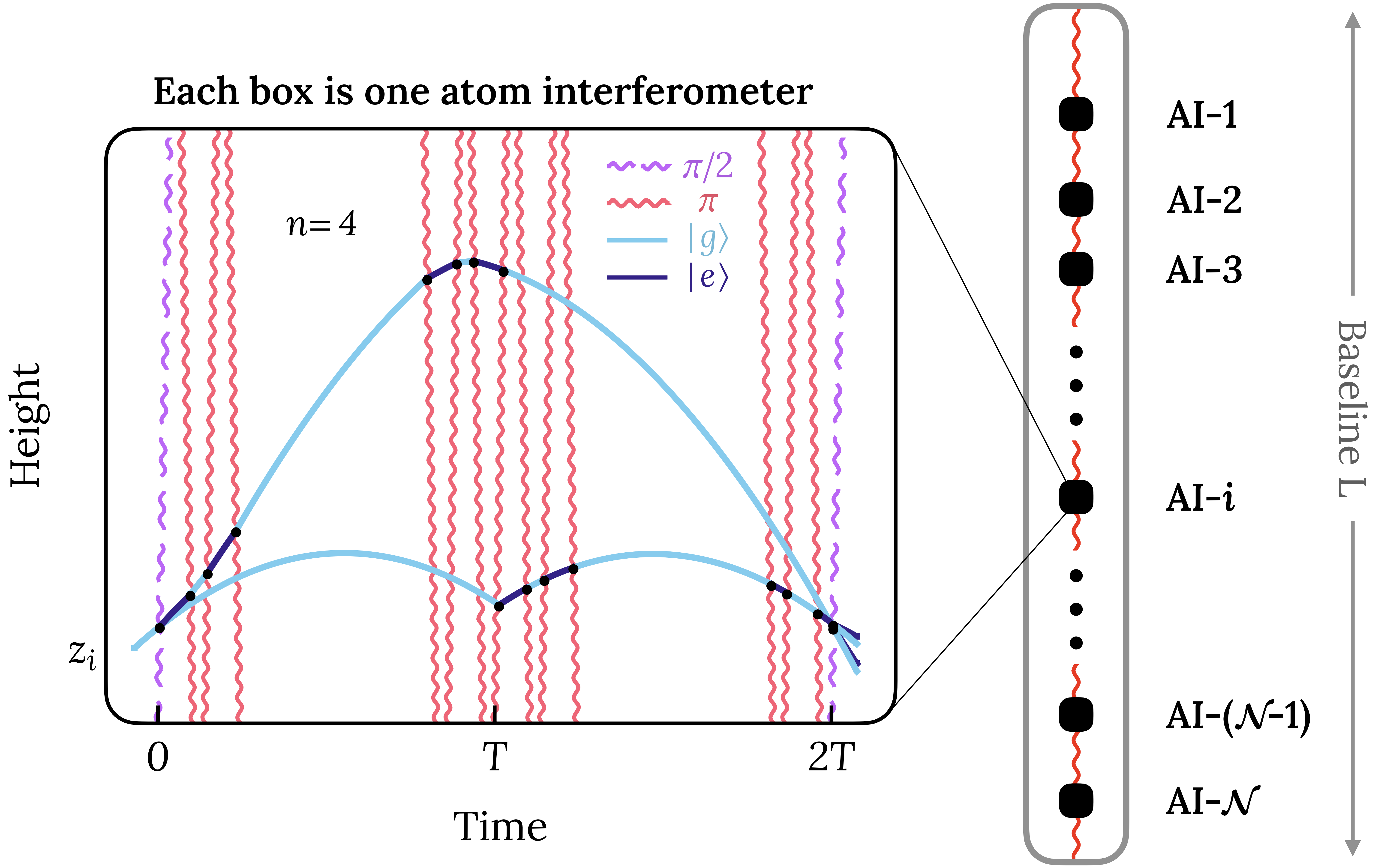
e.g. 'Thermal misalignment of scalar dark matter' Batell & Ghalsaia, arXiv:2109.04476



Complementarity with atomic clocks



Multi-gradiometer configuration



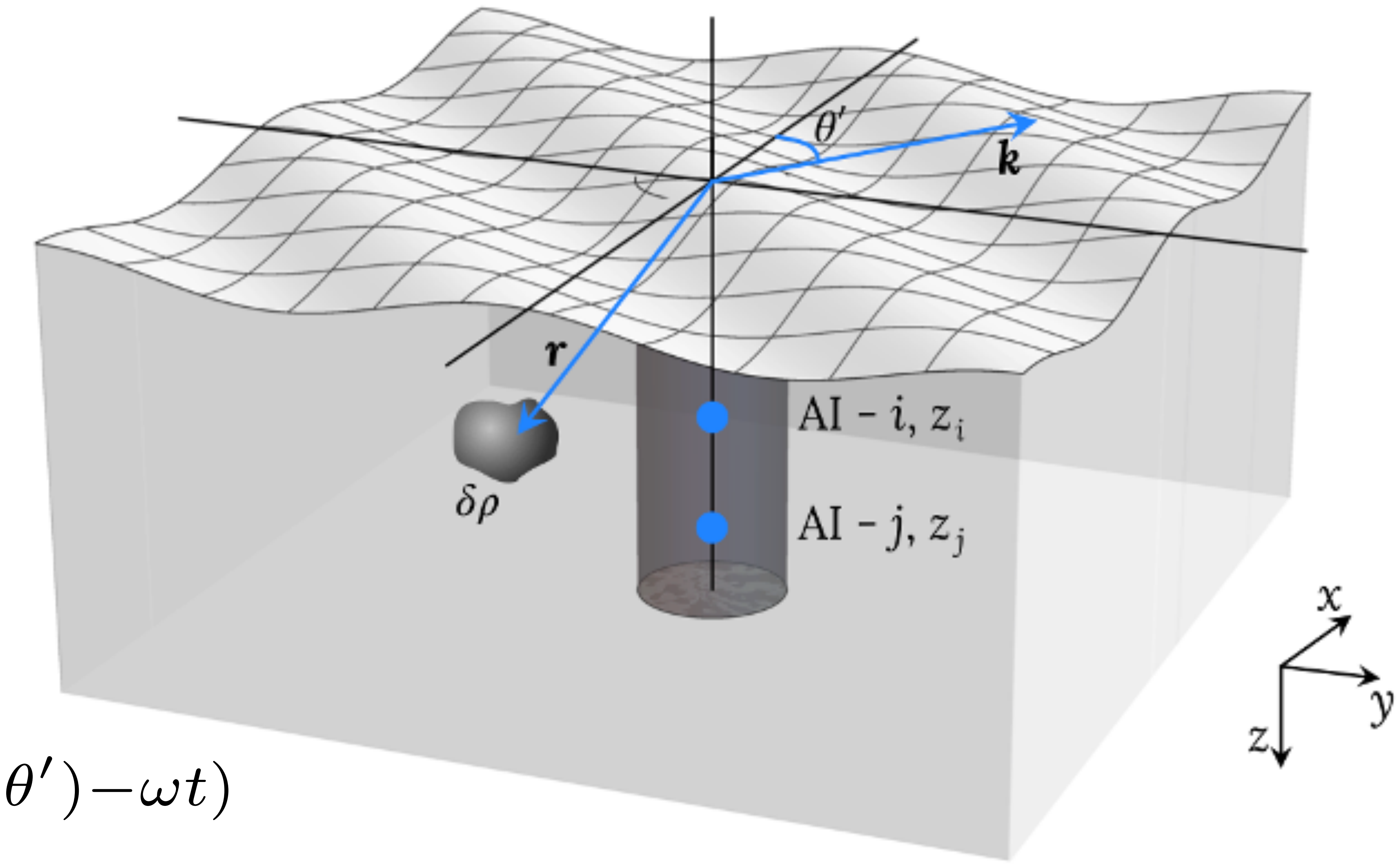
Lots of space for multiple atom interferometers on km-baseline!

Effect of 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:

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

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

Effect of Rayleigh waves

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

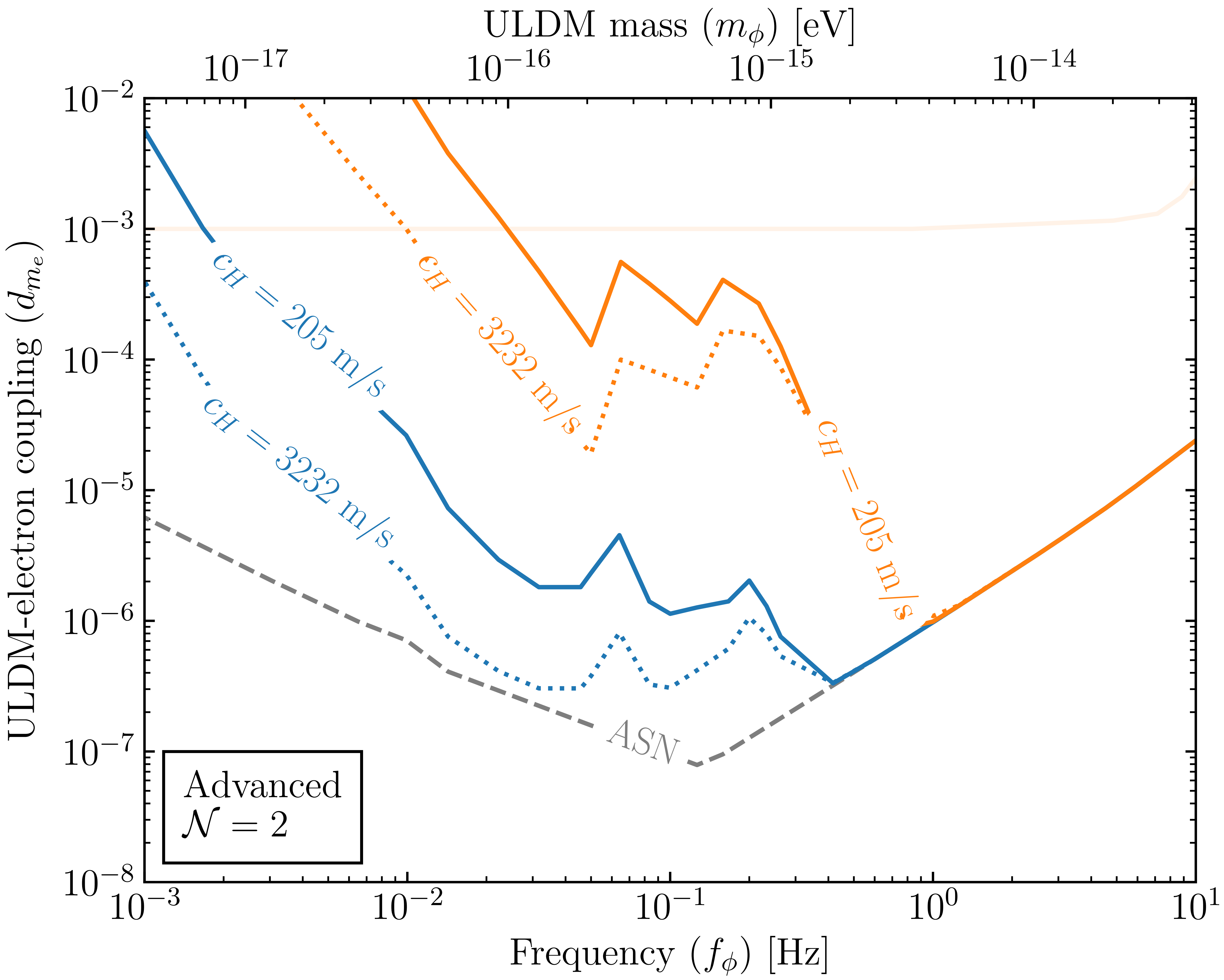
Induces a phase in the interferometers:

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

Amplitude decays exponentially

Vertical displacement

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 et al, arXiv:2211.01854