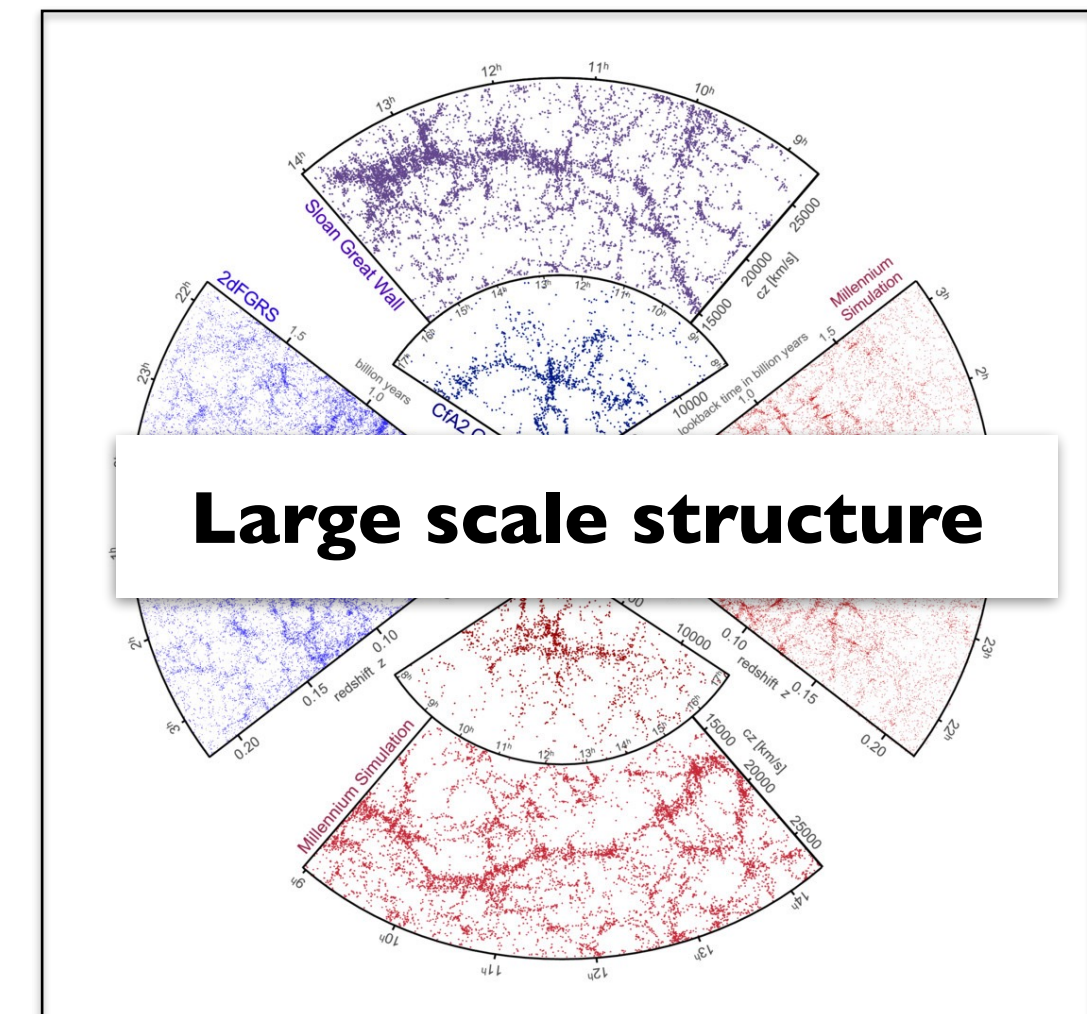
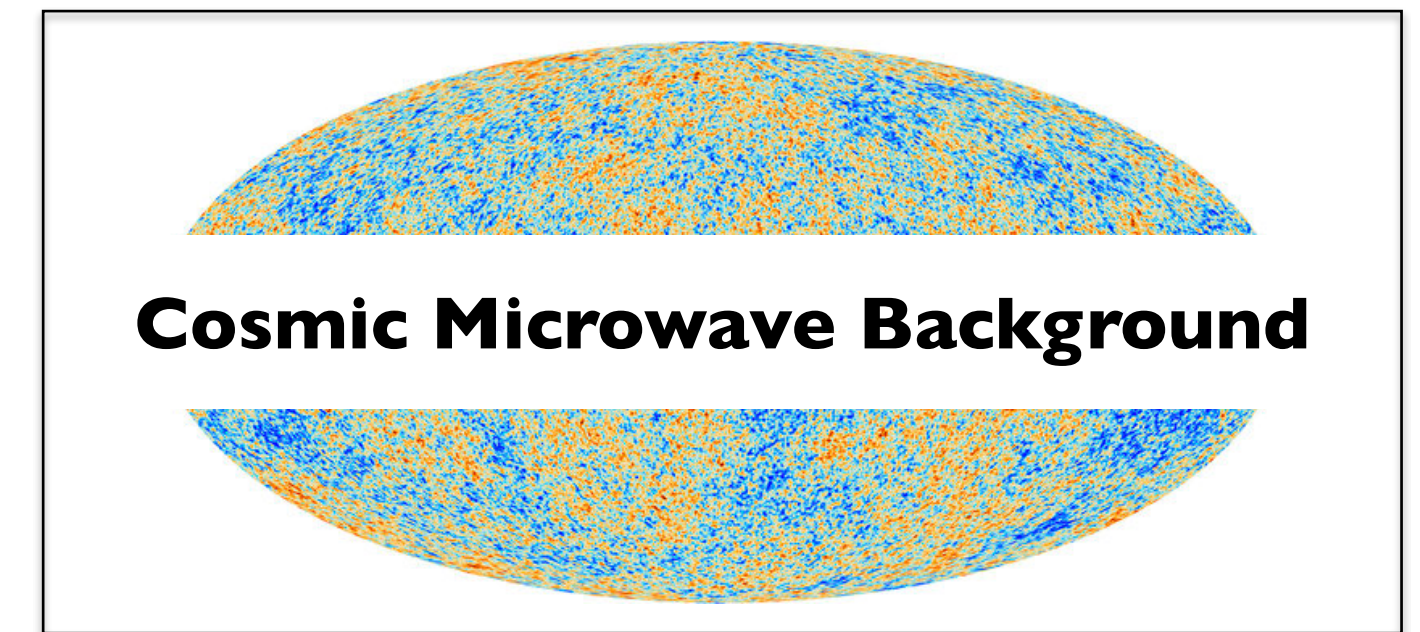
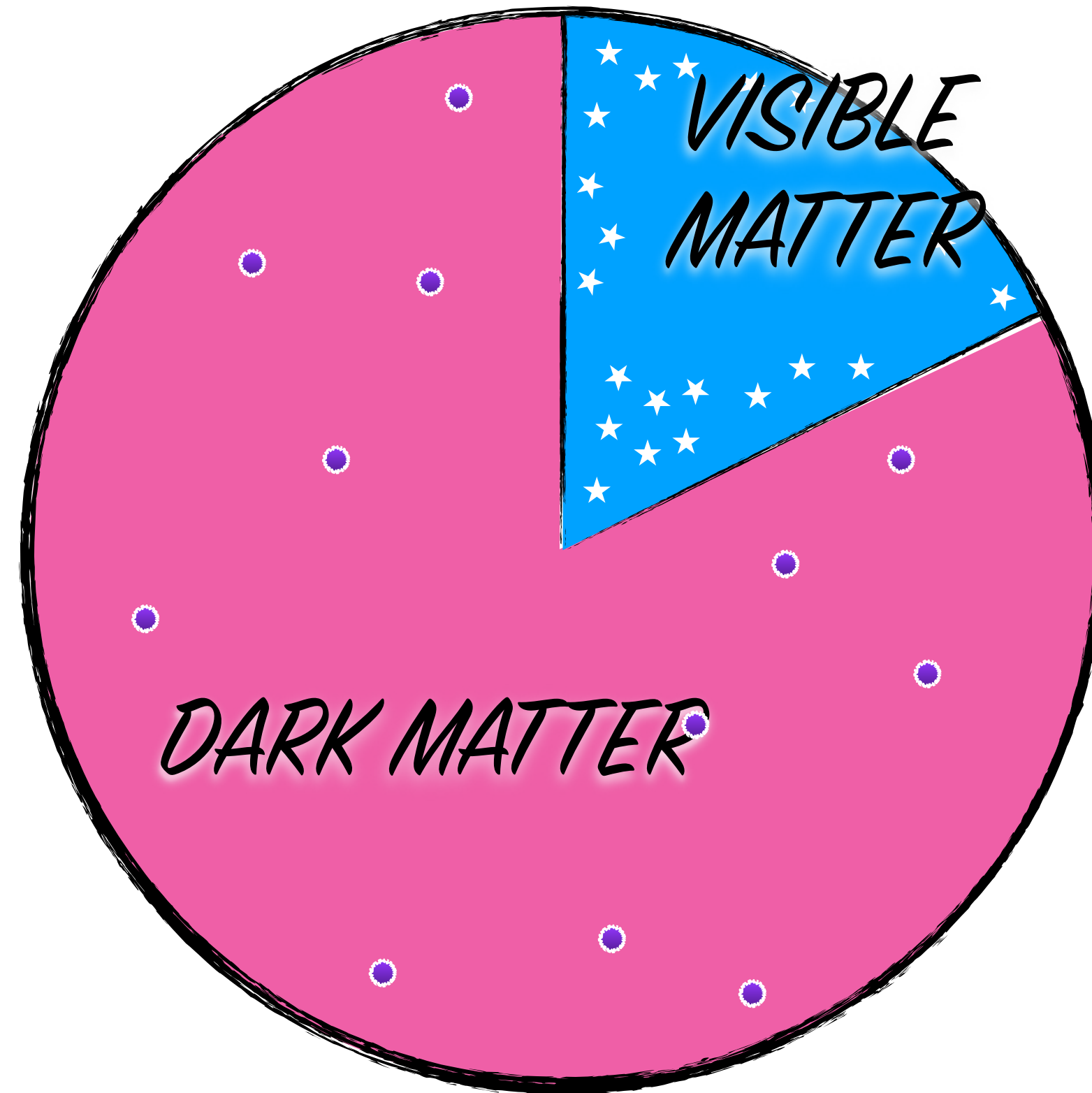
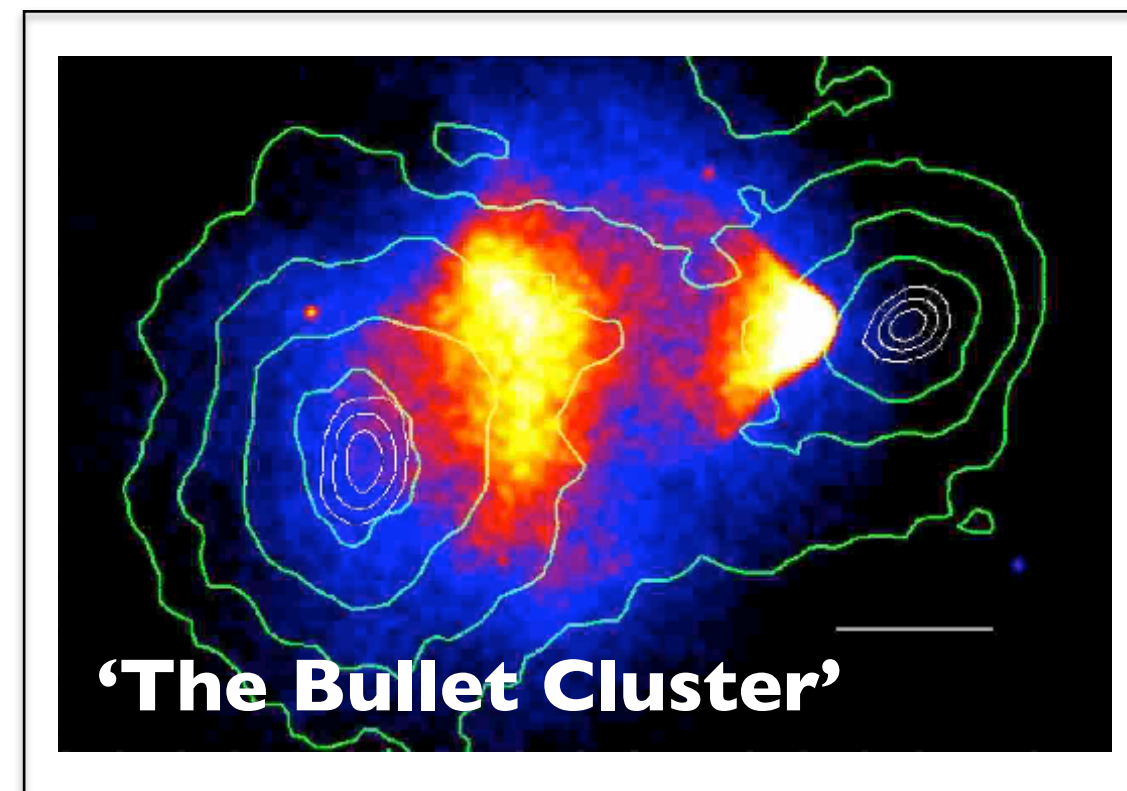
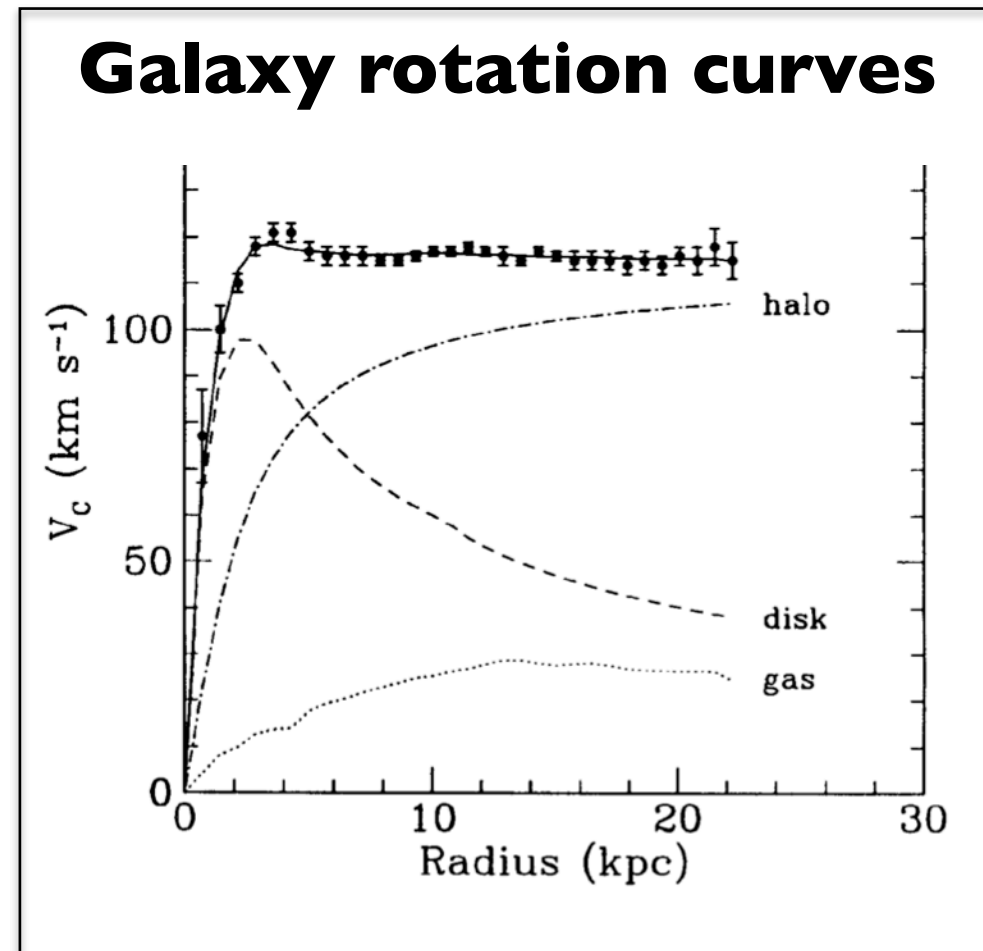


Dark Matter Detection

Christopher McCabe

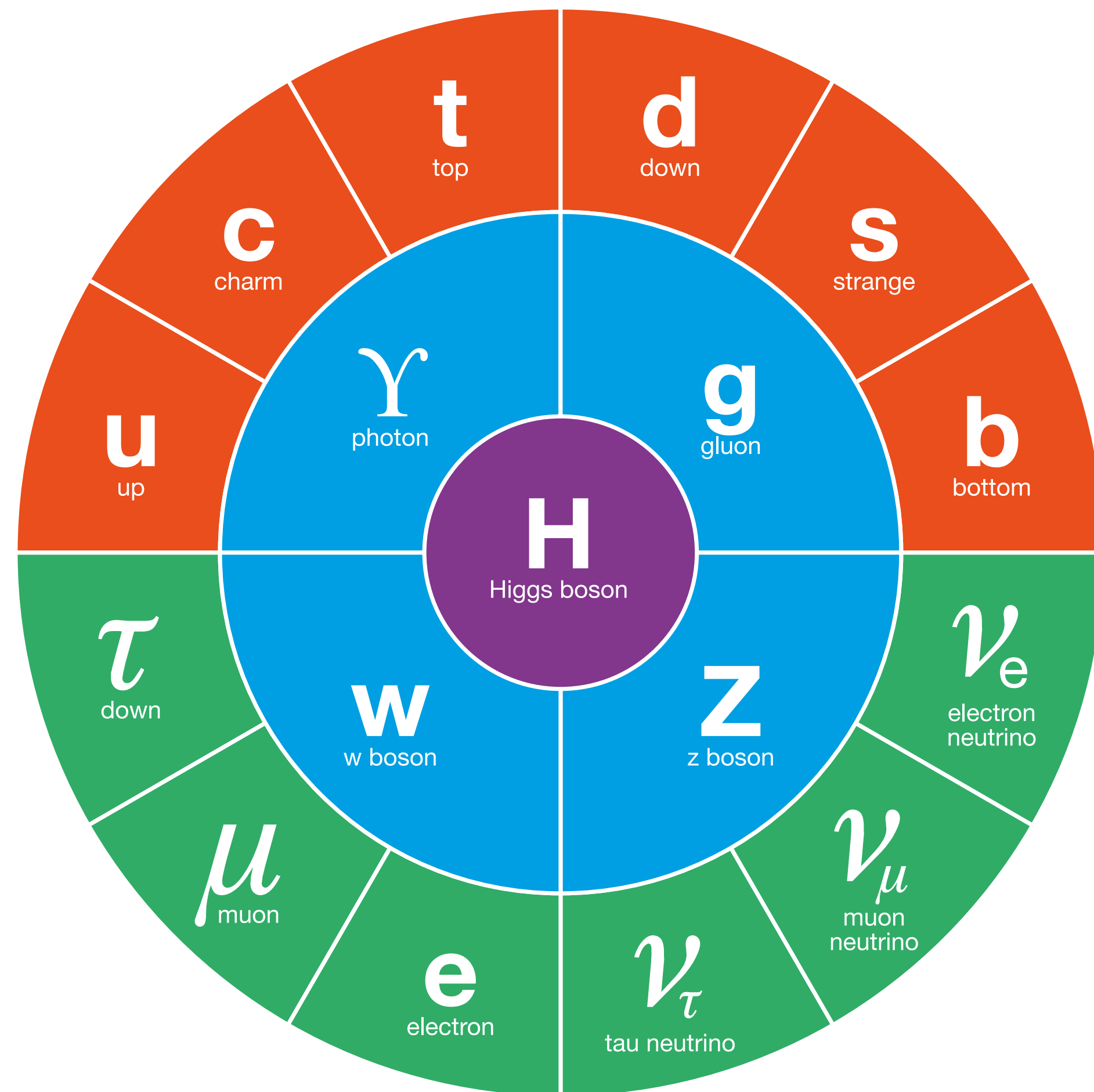
Dark matter candidates and their interactions

Reminder: we have detected dark matter



Evidence from gravitational interactions...
...over many distance scales

Do we need to do anymore? Yes...



Dark Matter Particle (X^0)

X^0 mass: $m = ?$

X^0 spin: $J = ?$

X^0 parity: $P = ?$

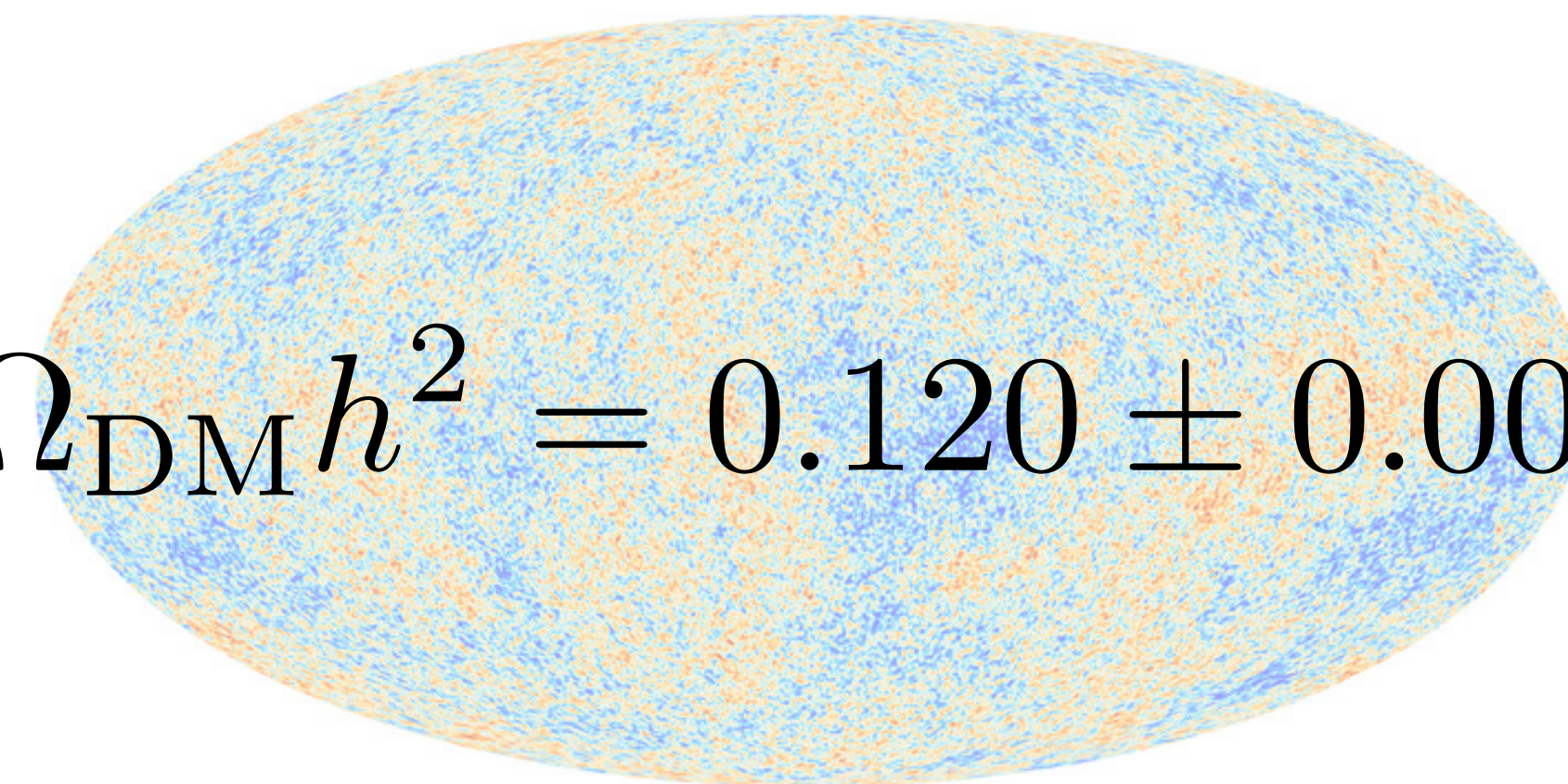
X^0 lifetime: $\tau = ?$

X^0 interactions with normal matter?

Why should DM interact with normal matter?

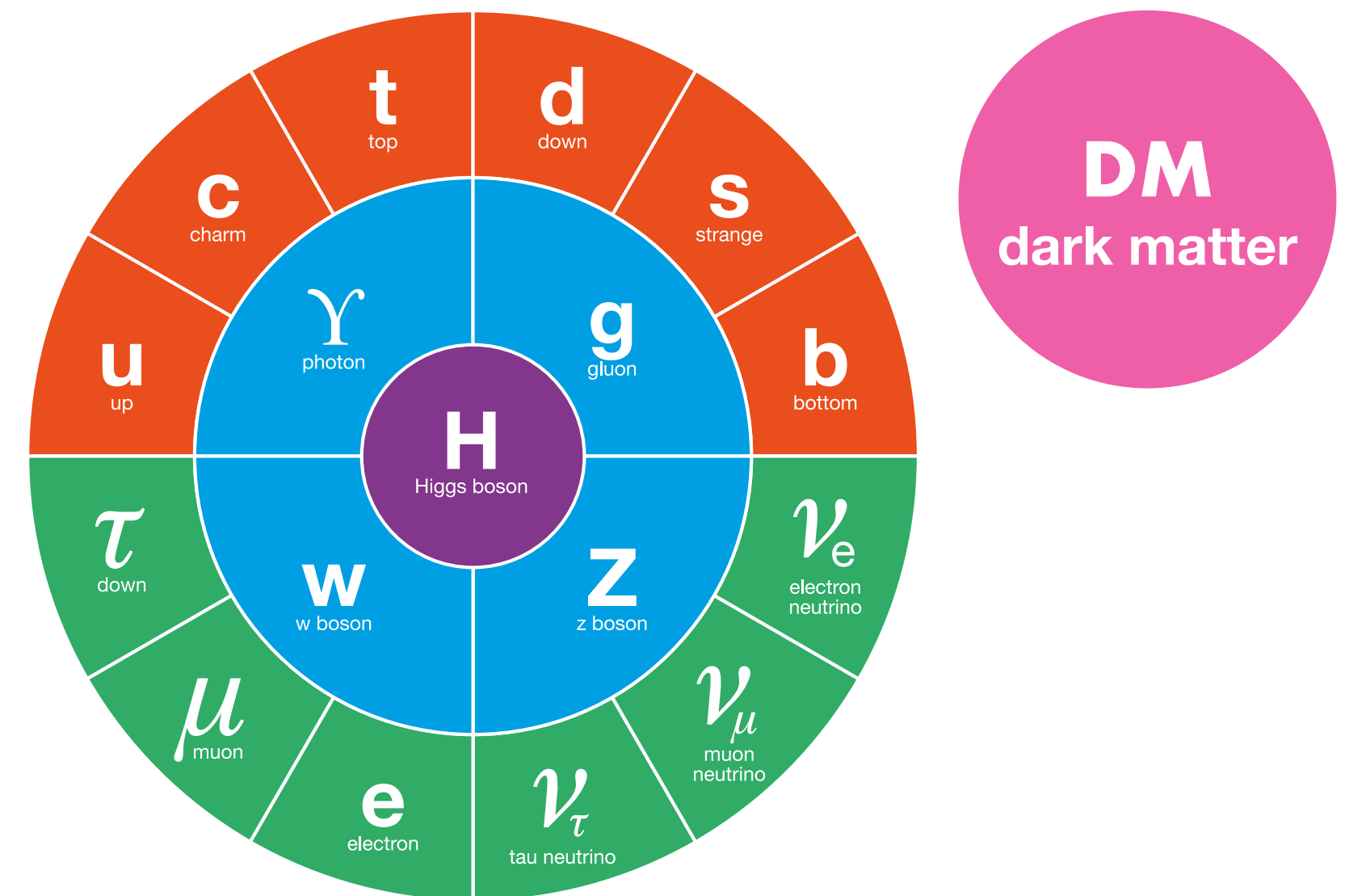
“Up to a point the stories of cosmology and particle physics can be told separately. In the end though, they will come together.” Steven Weinberg

Cosmology


$$\Omega_{\text{DM}} h^2 = 0.120 \pm 0.001$$

Explaining this value suggests dark and visible matter interactions are generic

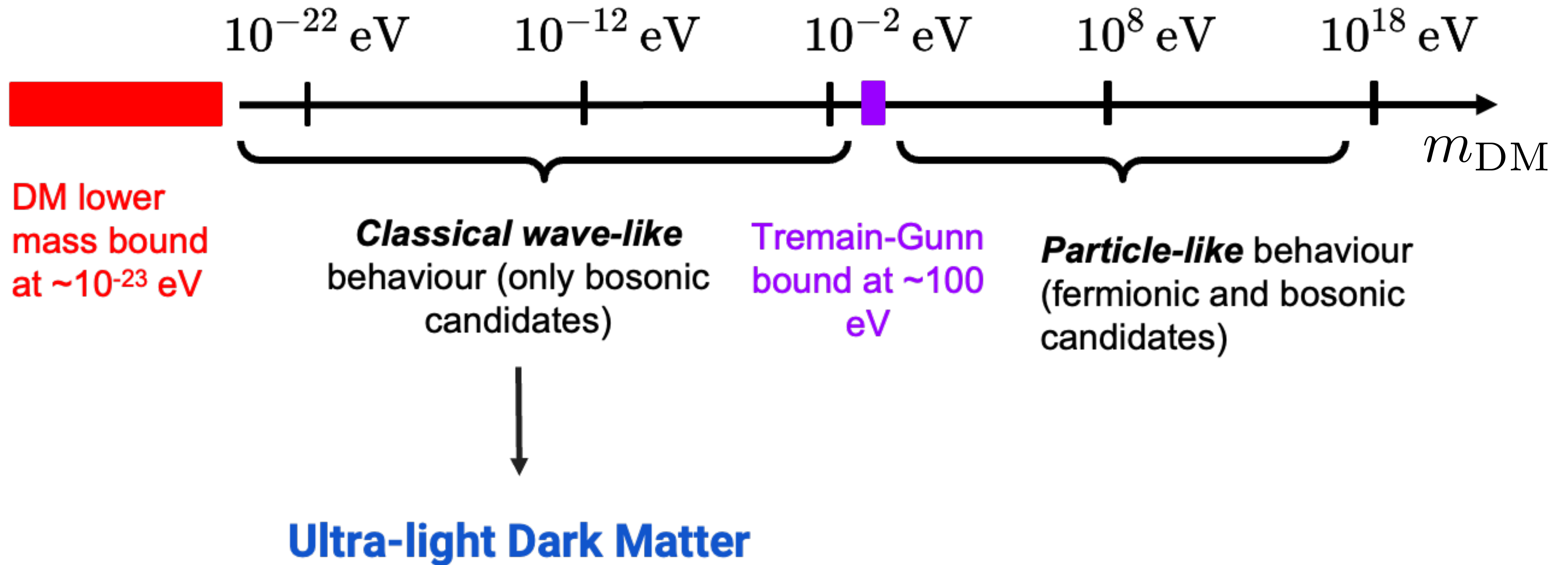
Particle Physics



&

Informs and limits the possible interactions

DM landscape: classifying by mass



Ultra-light dark matter

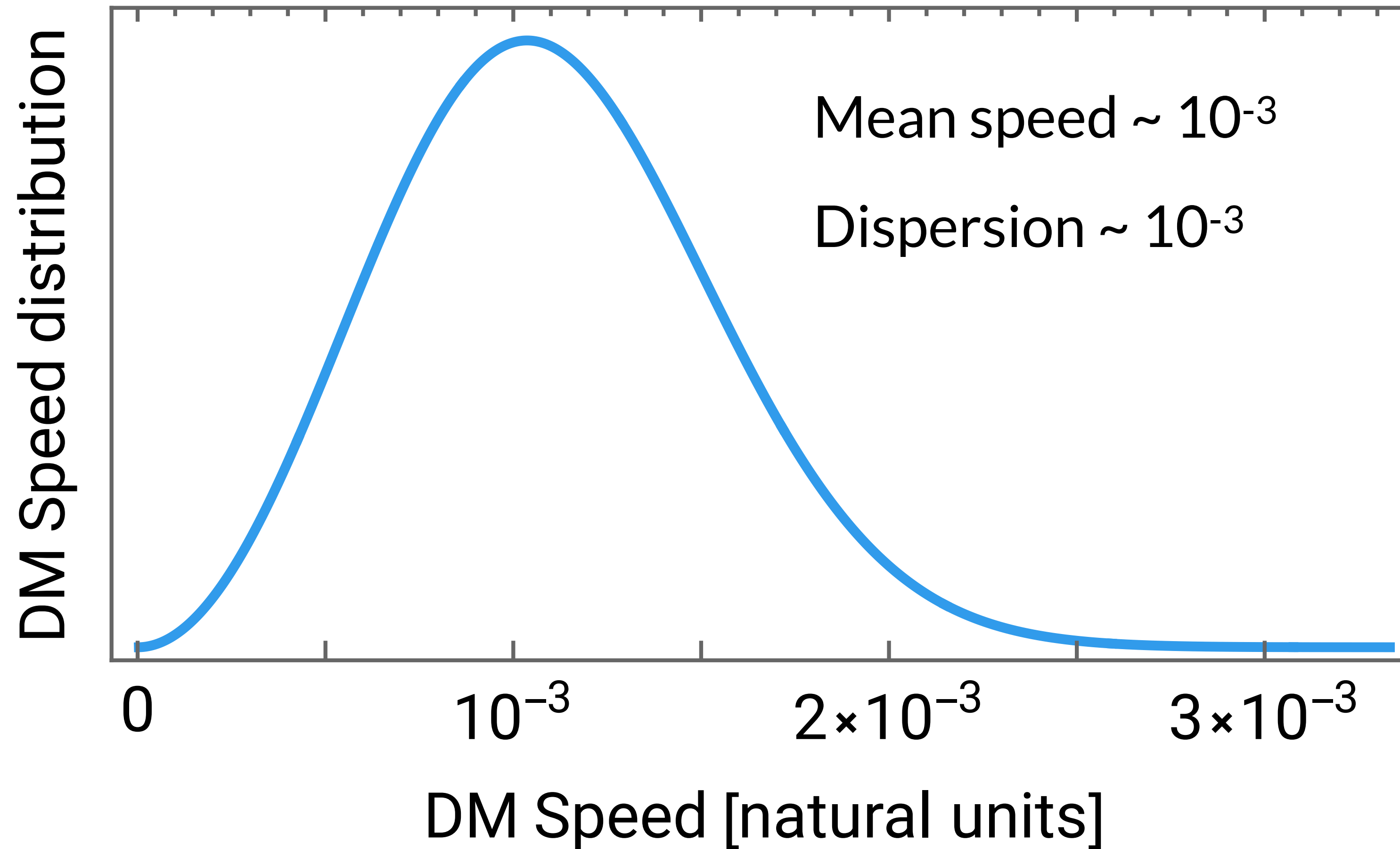
DM lighter than ~ 1 eV: **behaves as a classical wave** since mode occupation

number is macroscopic $n_{\text{DM}}(\lambda_{\text{deB}})^3 \sim \frac{\rho_{\text{DM}}}{m_{\text{DM}}^4 v_{\text{vir}}^3} \gg 1$

Model ULDM field as superposition of modes: $\varphi(t) \sim \sum_i A_i \cos(\omega_i t + \theta_i)$

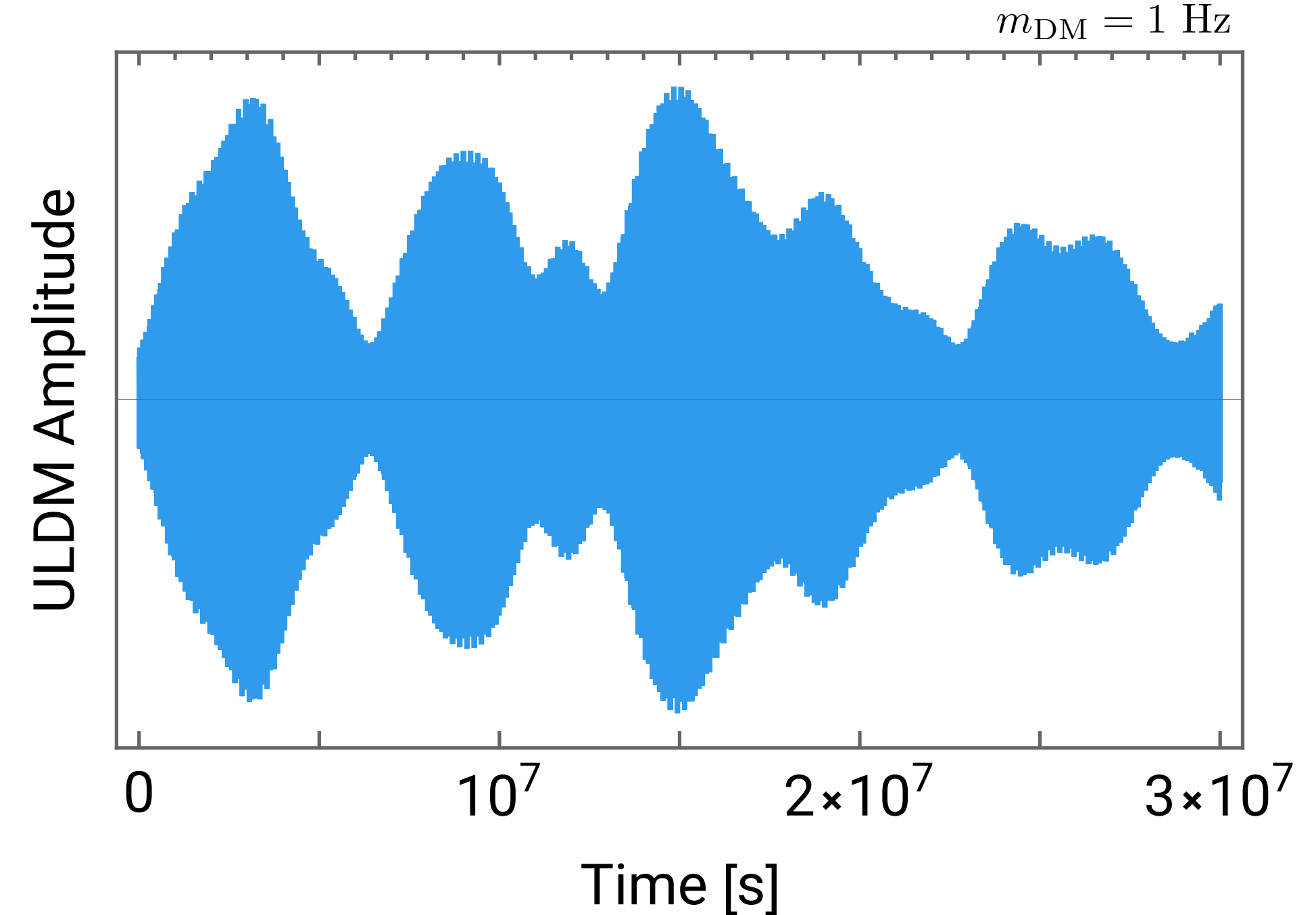
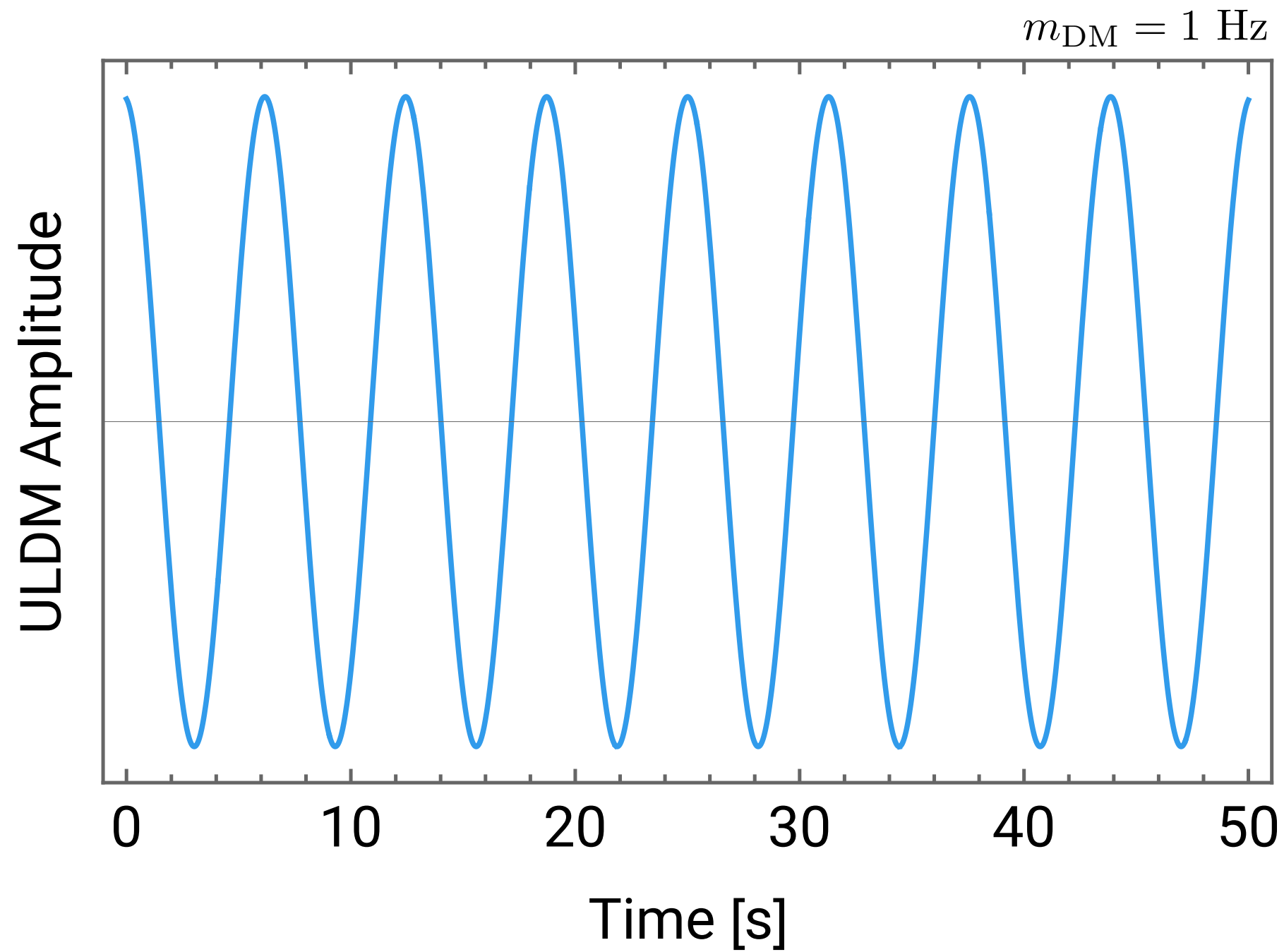
Angular frequency set by the ULDM mass: $\omega_i \simeq m_{\text{DM}} \left(1 + \frac{v_i^2}{2} \right)$
[DM in our galaxy is non-relativistic $v_i \sim 10^{-3}c$]

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

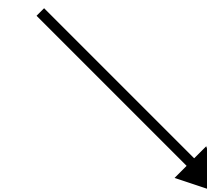
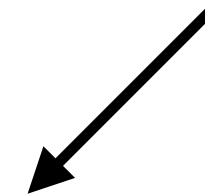
All signals depend on the field amplitude \Rightarrow will also vary with a coherence time

Phenomenology of ULDM

Classifying signals

ULDM-induced signal

Static vs **Time-dependent**



Difficulty: very high

Competing with non-ULDM static effects, which may be hard to quantify

Difficulty: medium

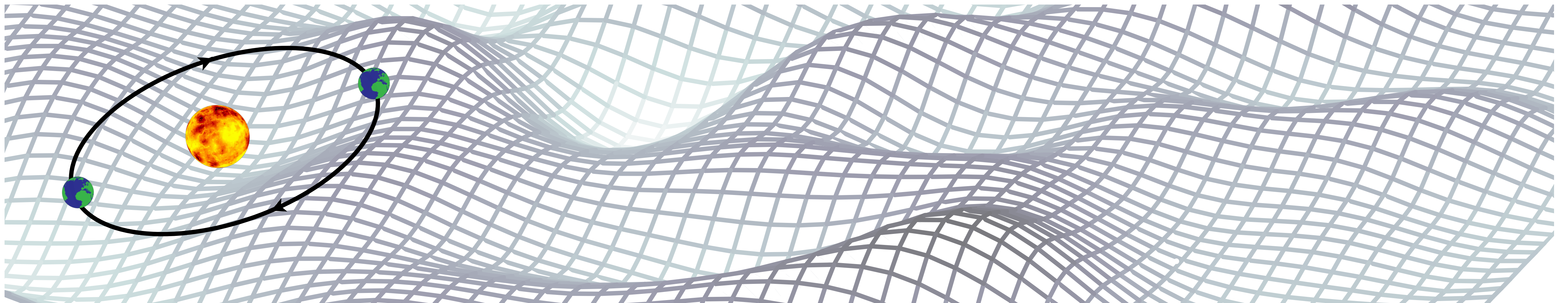
Search for the characteristic DM signal to allow for greater signal discrimination

Focus initially on time-dependent signals

Classifying 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)



I. Changes in fundamental constants (Scalar)

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

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

Oscillations in the field lead to oscillations in optical transitions (e.g., in Sr):



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

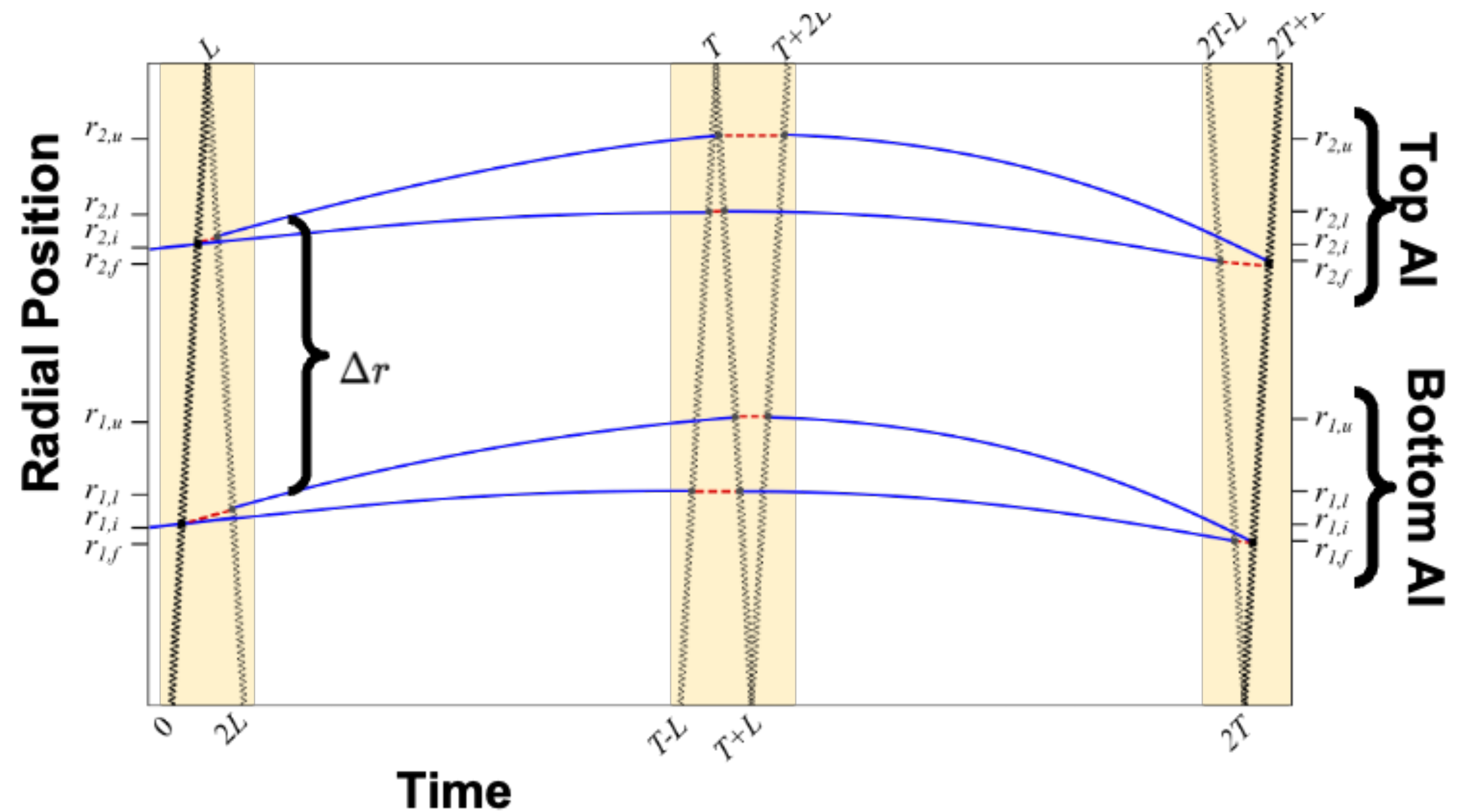
Phase in gradiometer configuration

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

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

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

t_1, t_2 = time in excited state



Gradiometer configuration: sensitivity

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

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

$C \sim 0.1 - 1$ (contrast)

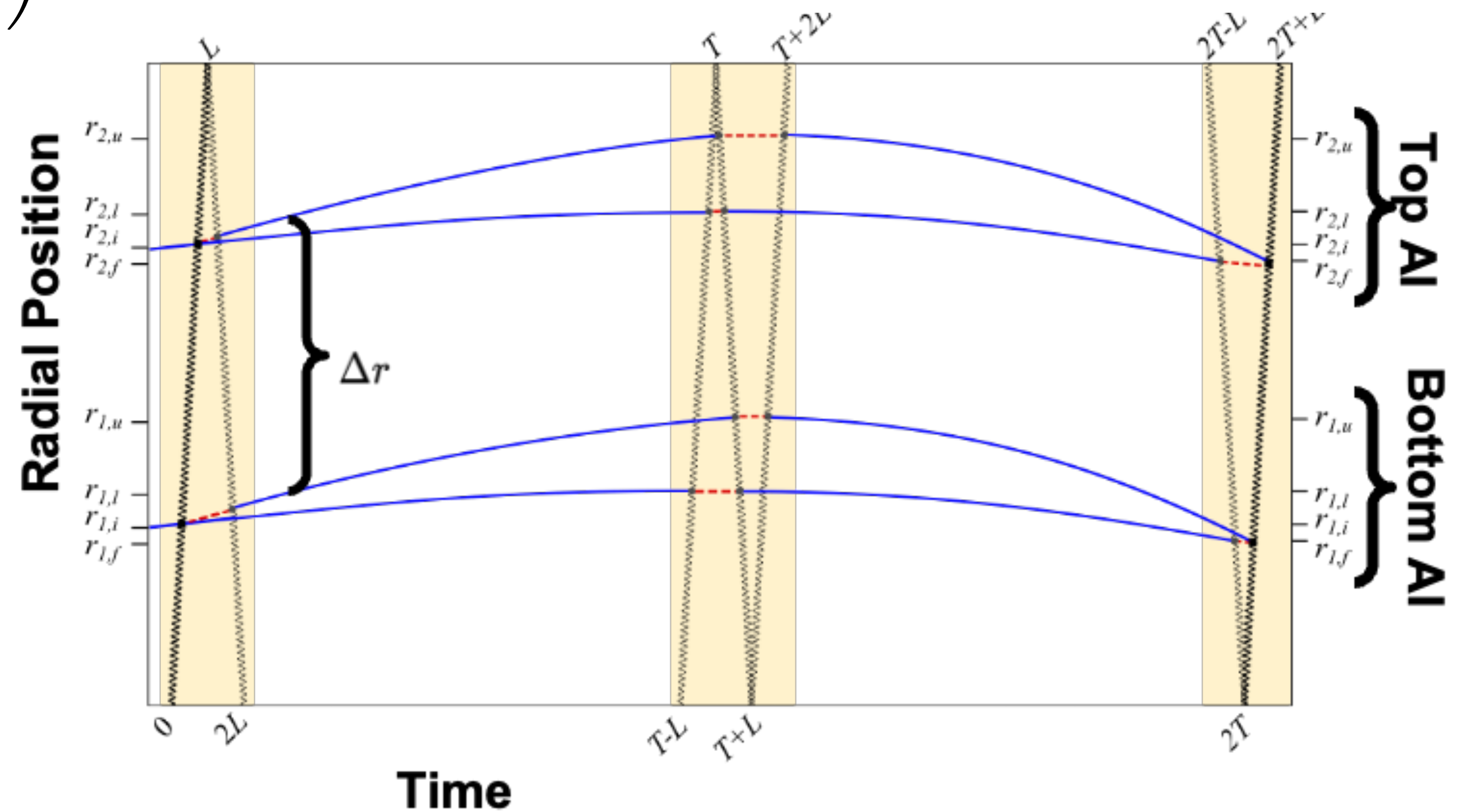
$n \sim 1000$ (LMT)

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

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

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

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



Gradiometer configuration: sensitivity

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

$T \sim 1$ s (interrogation time)

$C \sim 0.1 - 1$ (contrast)

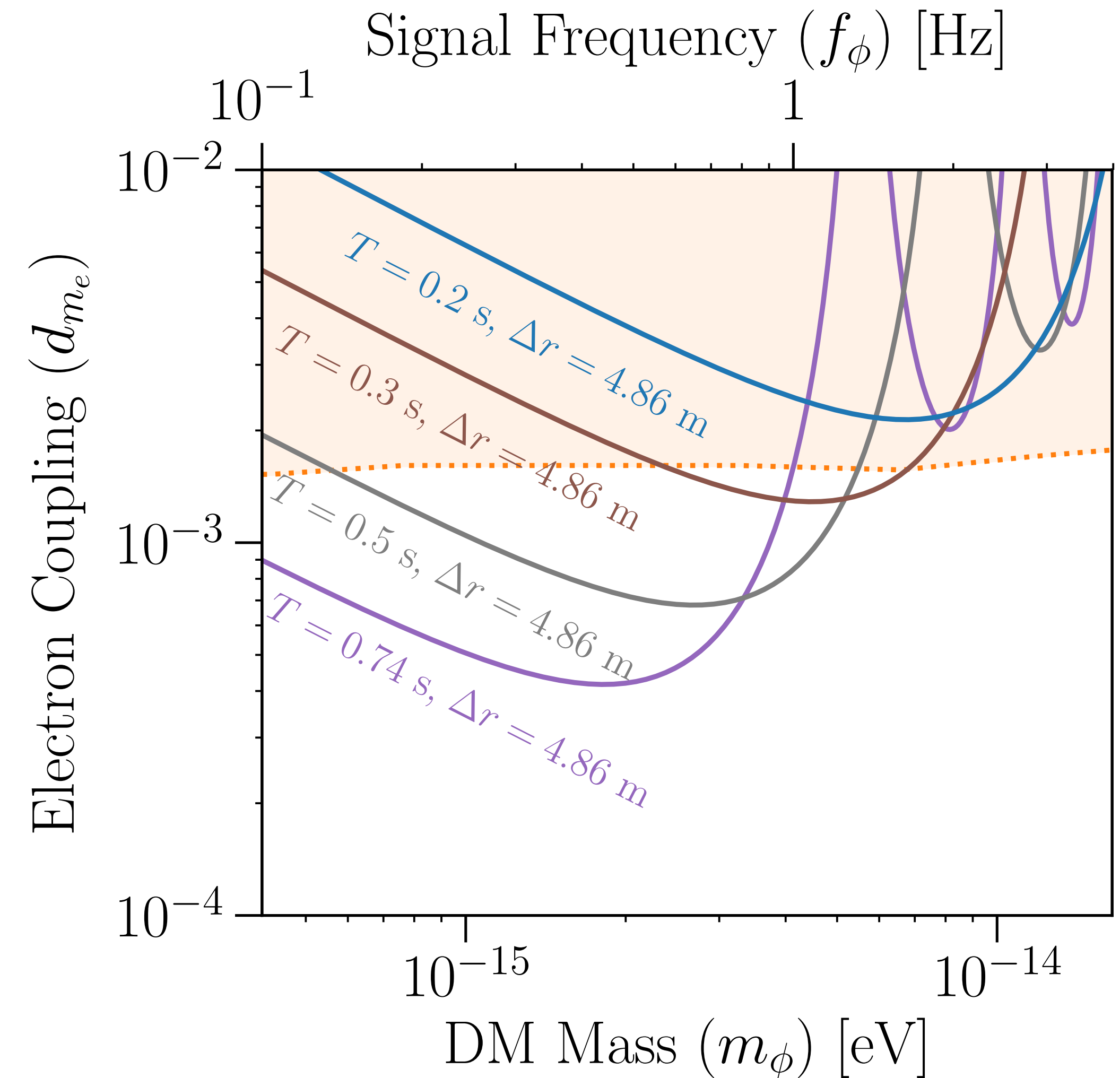
$n \sim 1000$ (LMT)

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

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

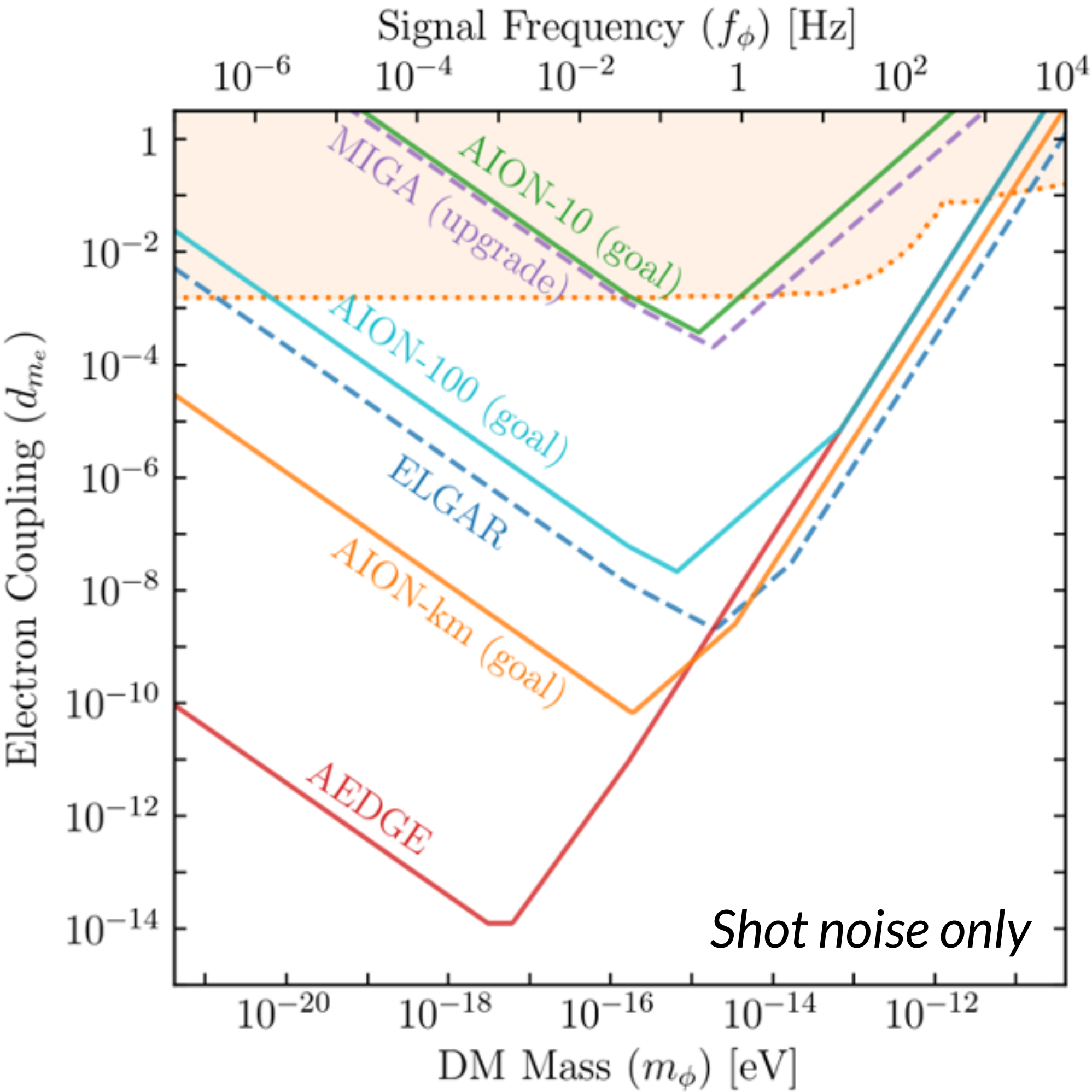
$N_a \sim \text{atoms in cloud}$

$T_{\text{int}} \sim 10^7$ 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 et al, arXiv:1911.11755, 2108.02468

2. 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 force (acceleration)

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

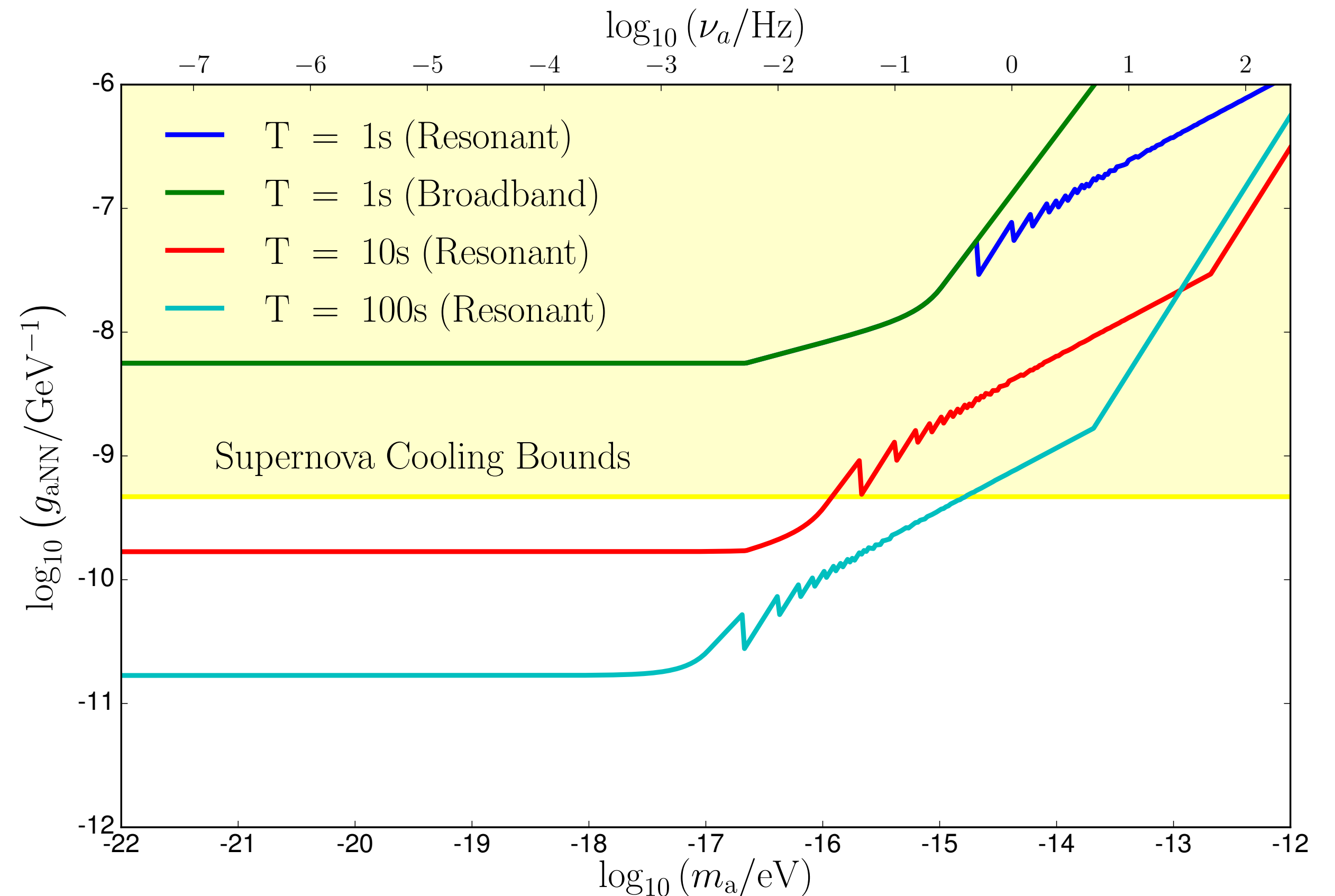
3. Precession of spins (Pseudoscalar)

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:

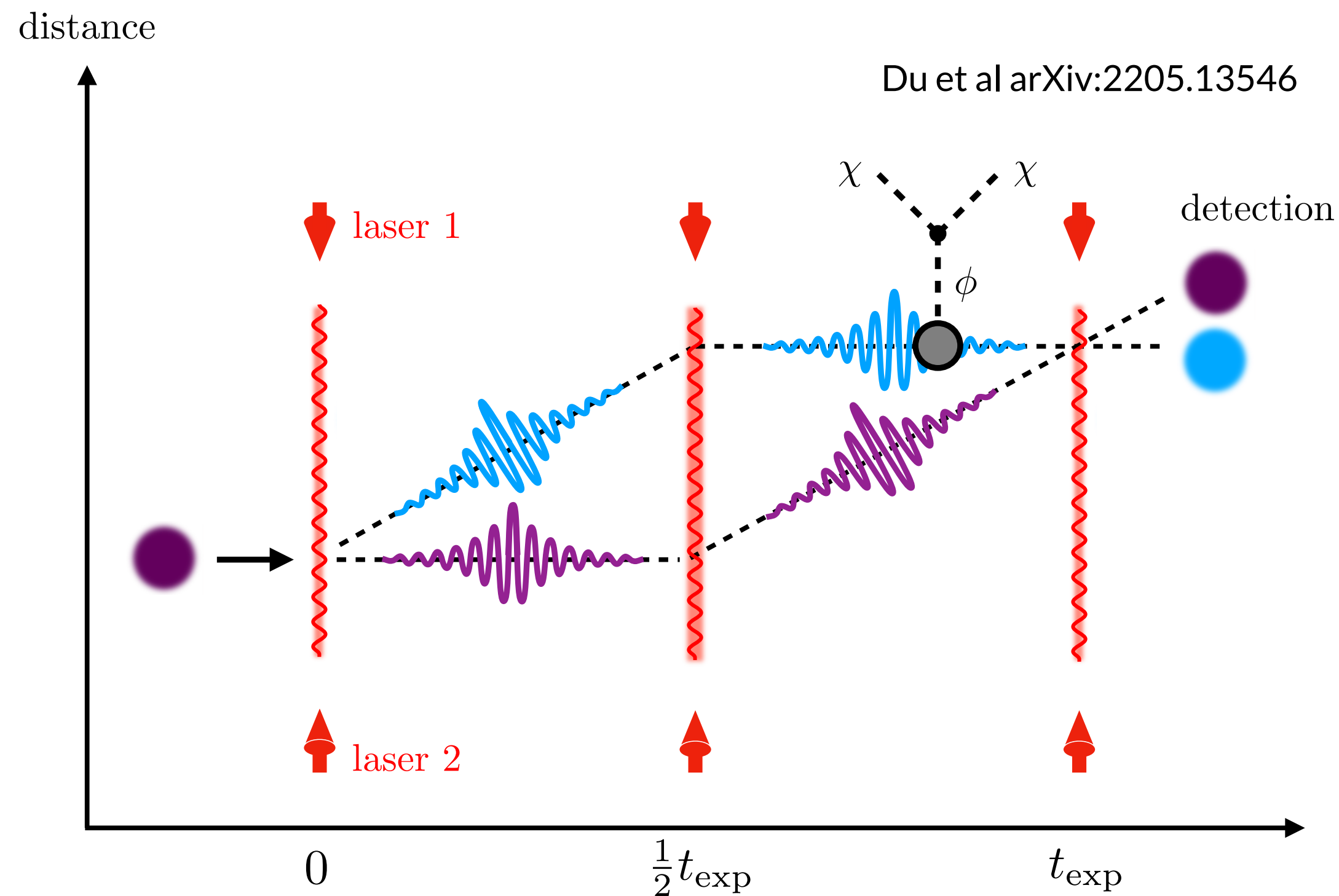
$$\text{Phase} \sim (m_{S,1} - m_{S,2}) \cos(m_a t + \theta)$$

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



Other ideas in the literature

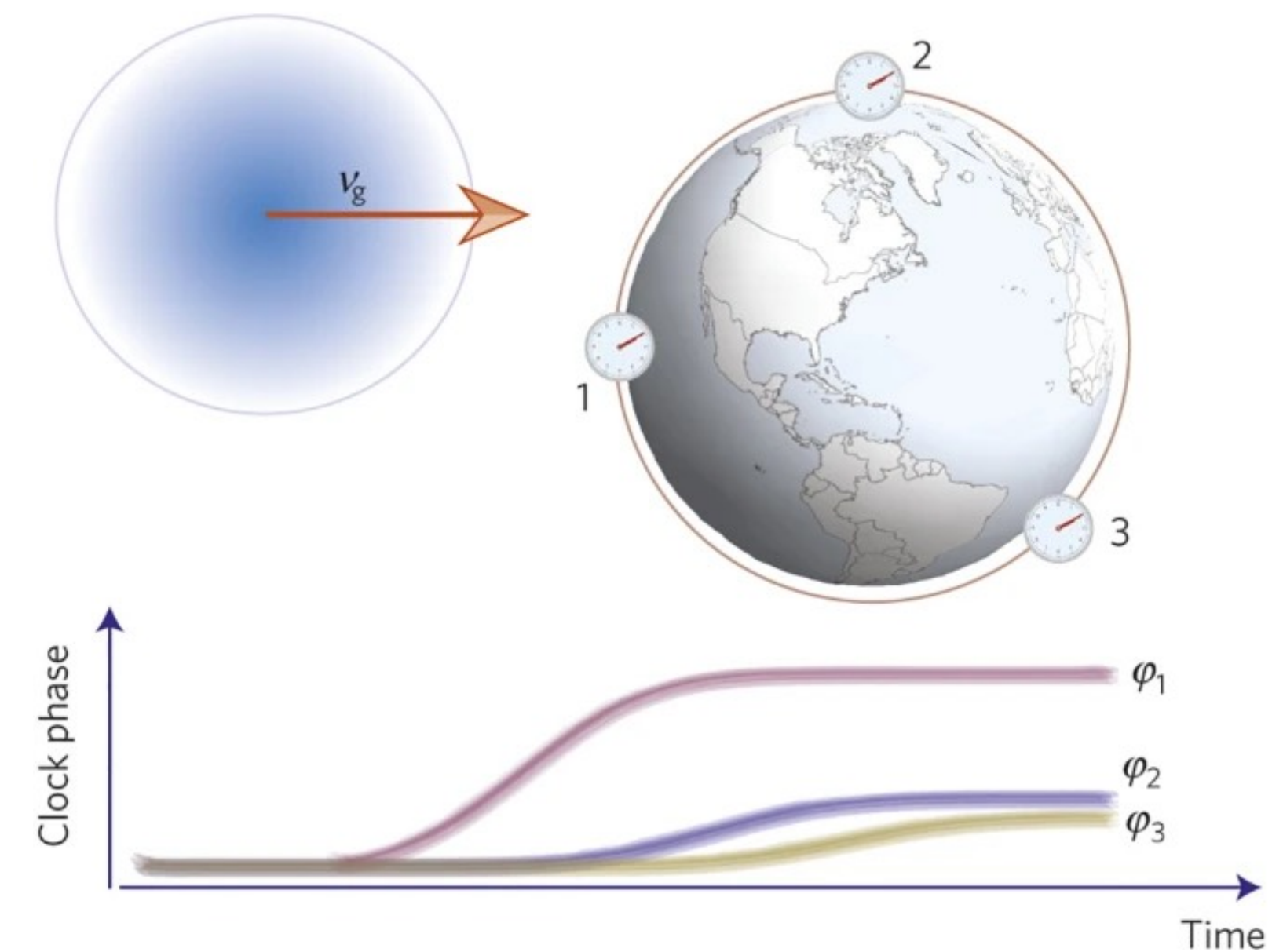
Dark matter scattering in one AI arm causes decoherence - could this realistically be observed?



See also Riedel et al arXiv:1212.3061, 1609.04145

Transient signals utilising a global network of AIs

Signals from e.g., topological or compact DM substructure

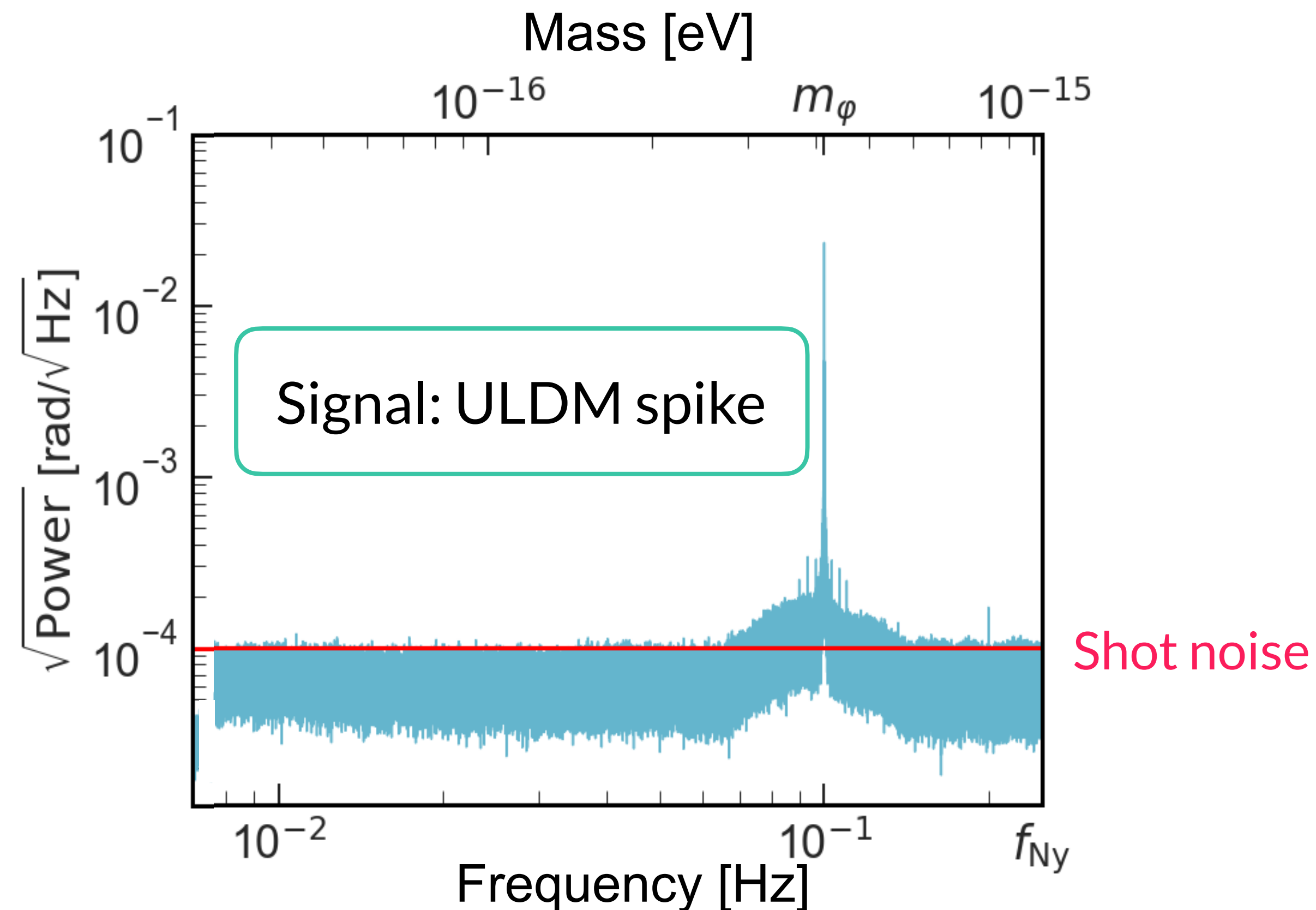


See e.g., Derevianko arXiv:1311.1244 or Gorghetto arXiv:2203.10100

Analysis strategies and potential challenges

Searching for a signal (ideal setup)

Recall, for time-dependent signals the frequency is set by the ULDM mass
Most natural to search for ULDM in frequency space (power spectral density)



Searching for a signal (actual setup)



Many moving
'test masses'

ULDM searches assume long integration
times (months to years)

Could the busy environment hide a
fundamental physics signal?

Searching for a signal (actual setup)



location of
AION-10

Short answer: impact of moving masses seems to be minimal after a careful analysis of the data

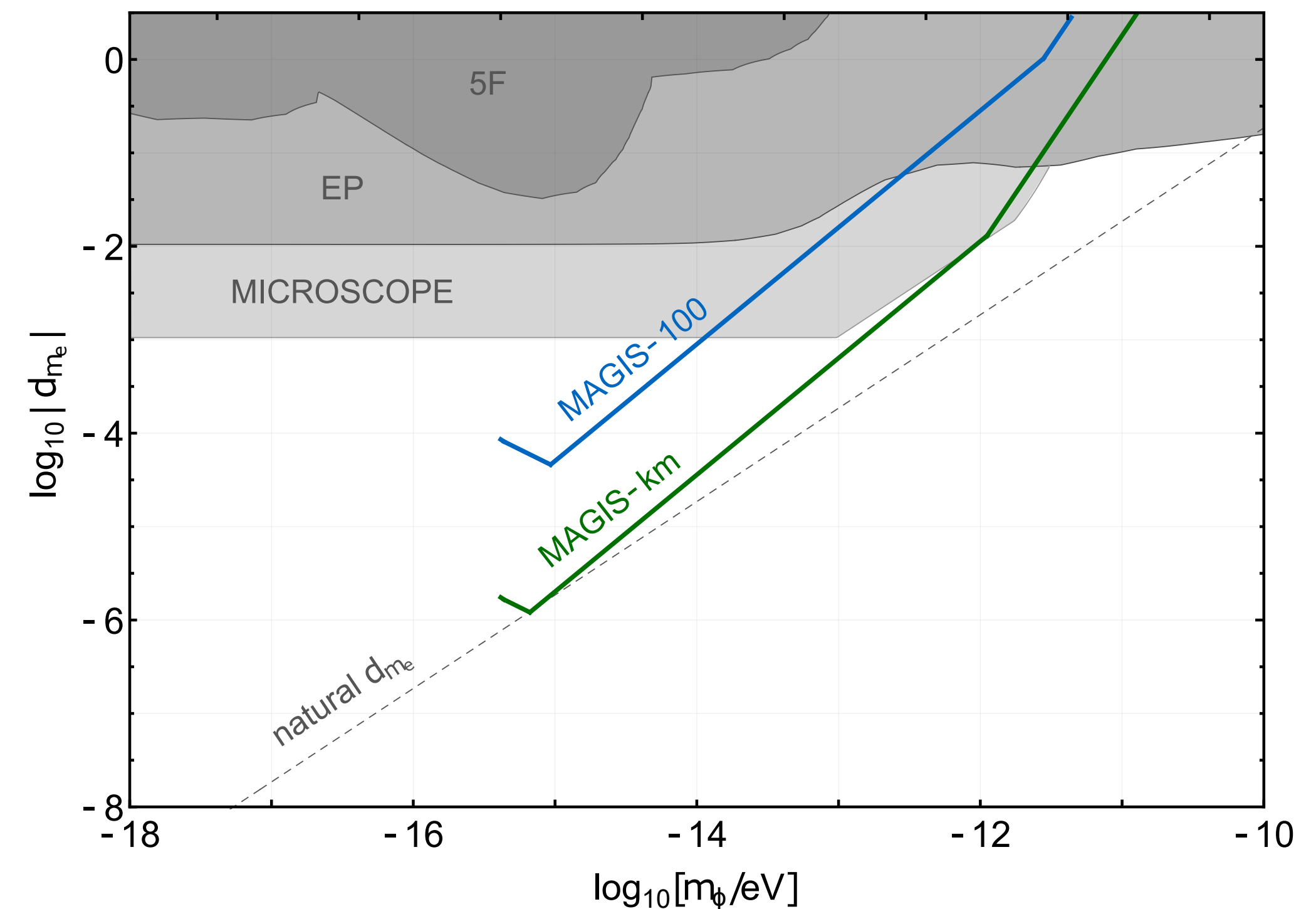
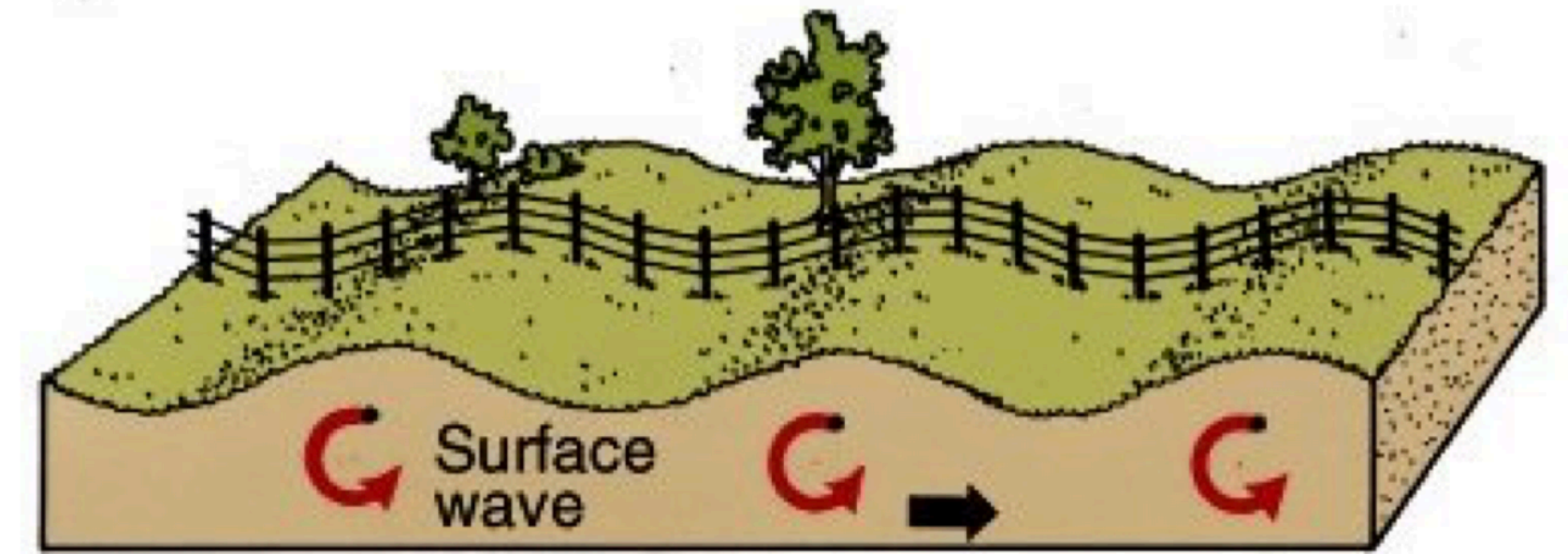
-> See John Carlton's poster for more details

Longer-term challenge: seismic noise

Gravity gradient noise (GGN) from seismic activity is a well known background for laser interferometry searches (limits sensitivity below ~ 1 Hz)

Conservative approach: limit sensitivity plots to parameter regions not impacted by seismic noise

Better approach: account for GGN in the analysis procedure -> See Leonardo Badurina's talk tomorrow



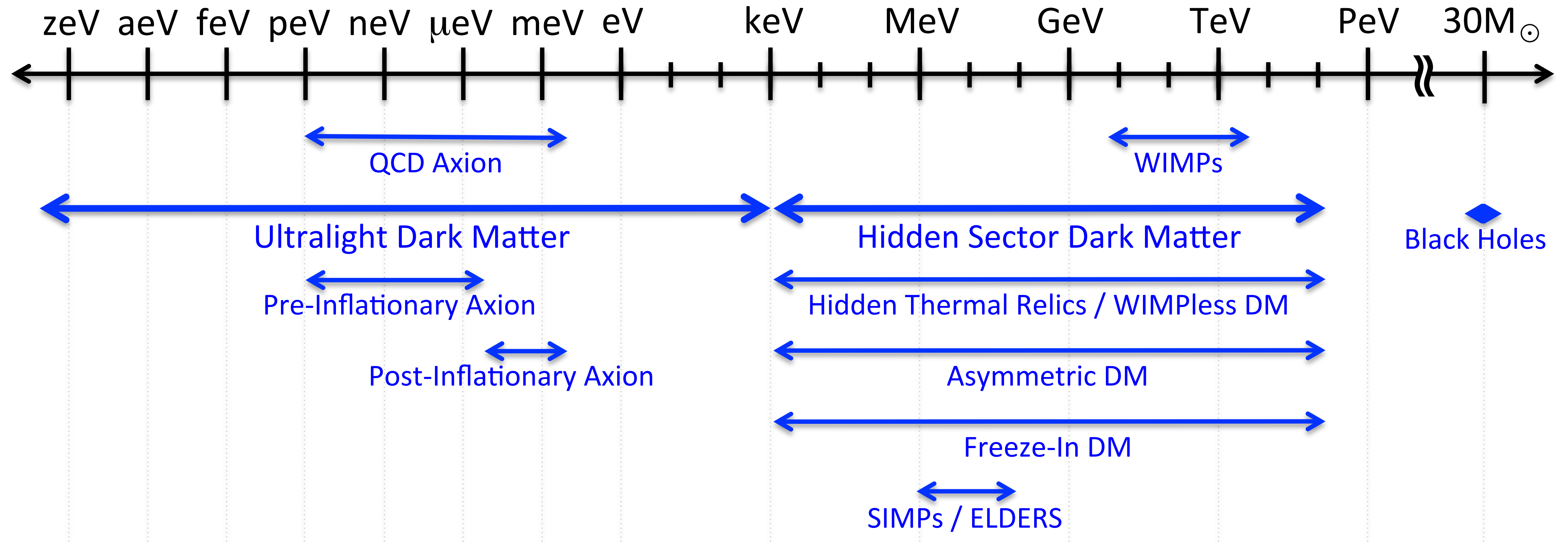
Summary

- Big open question: what are the properties of dark matter?
- Ultra-light dark matter (ULDM) behaves like a background classical field and can give rise to
 1. Changes in fundamental constants (scalar ULDM)
 2. Accelerations on test masses (vector ULDM)
 3. Precession of spins (pseudoscalar ULDM)
- Atom interferometers are well-suited to search for all of these signals
- Key discriminant: search for signals oscillating at a characteristic frequency (set by the ULDM mass)

Thank you



A wide landscape of DM candidates



US Cosmic Visions

Complementarity with atomic clocks

