Future DM experiments (non-XLZD)

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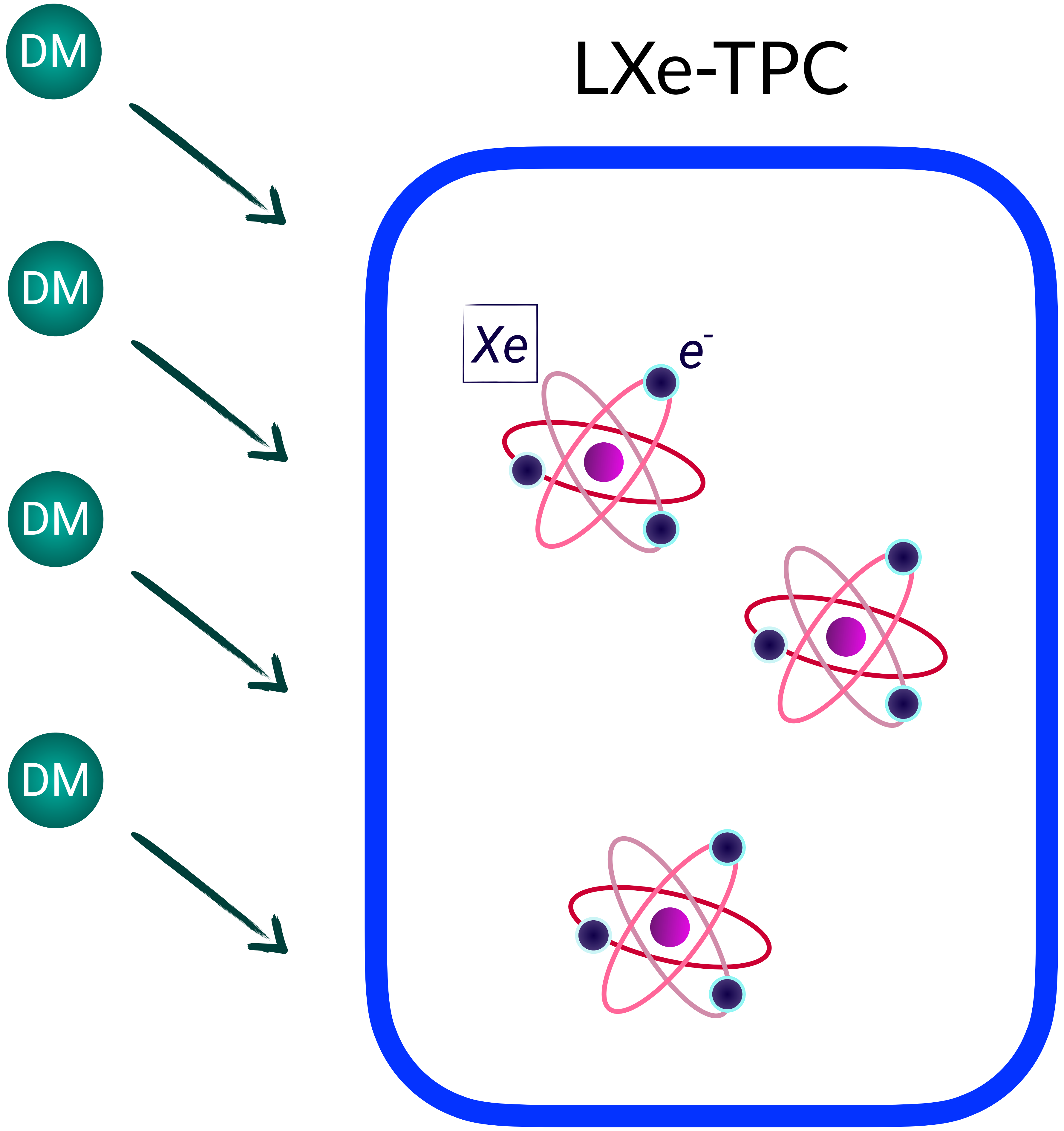
UK HEP Forum, Coesner's House, 22 October 2025

Motivation: what does ‘non-XLZD’ mean?

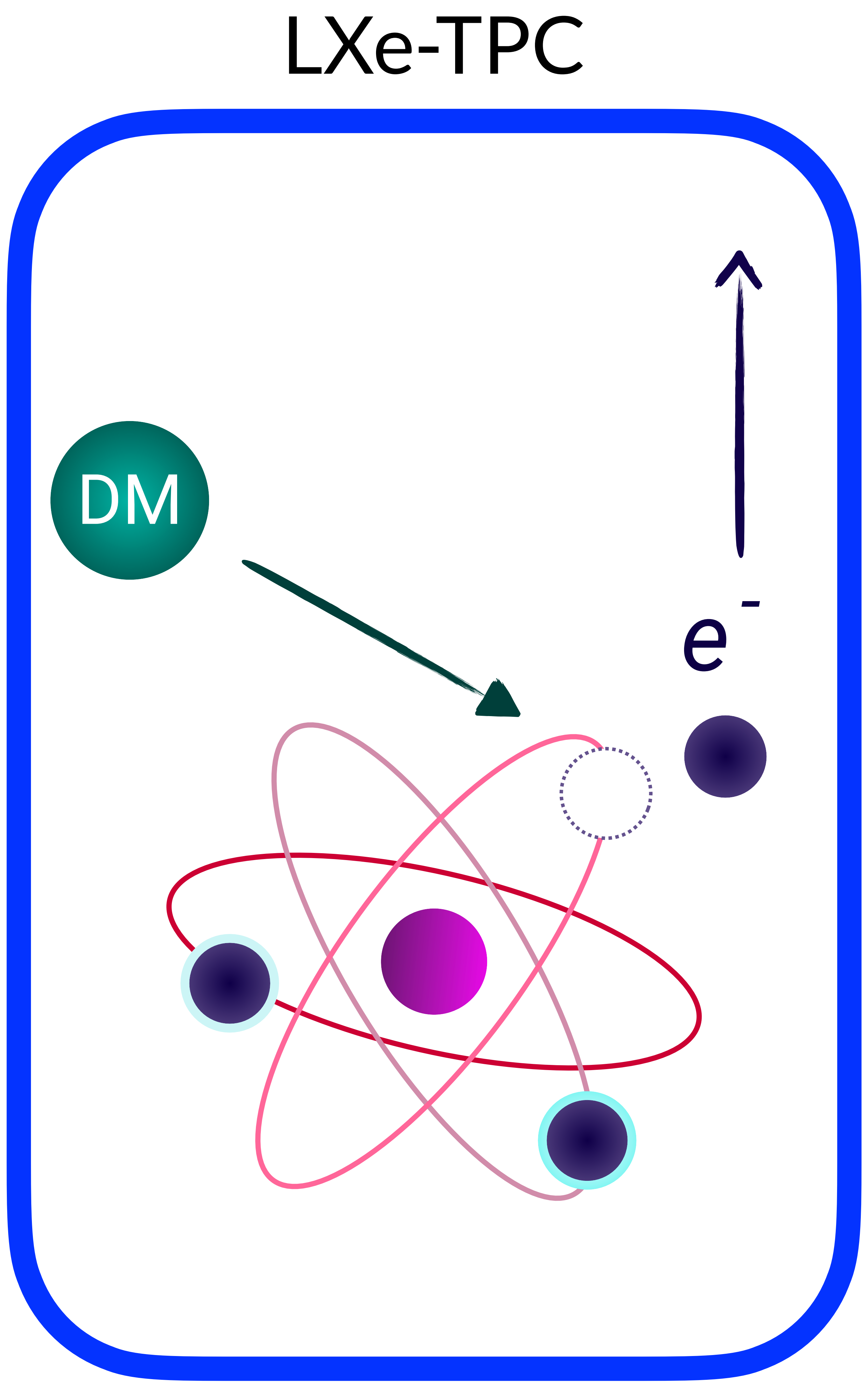
My simple minded view of XLZD



Detector technology with:
- Single-electron threshold
- Metre-scale
- Operate for a few years

These define boundaries of:
- Lightest dark matter mass
- heaviest dark matter mass

Lightest dark matter mass



Signal generation if dark matter can deposit an energy above the electron binding energy

- Scattering: $E_{\rm DM} \sim m_{\rm DM} v_{\rm DM}^2$

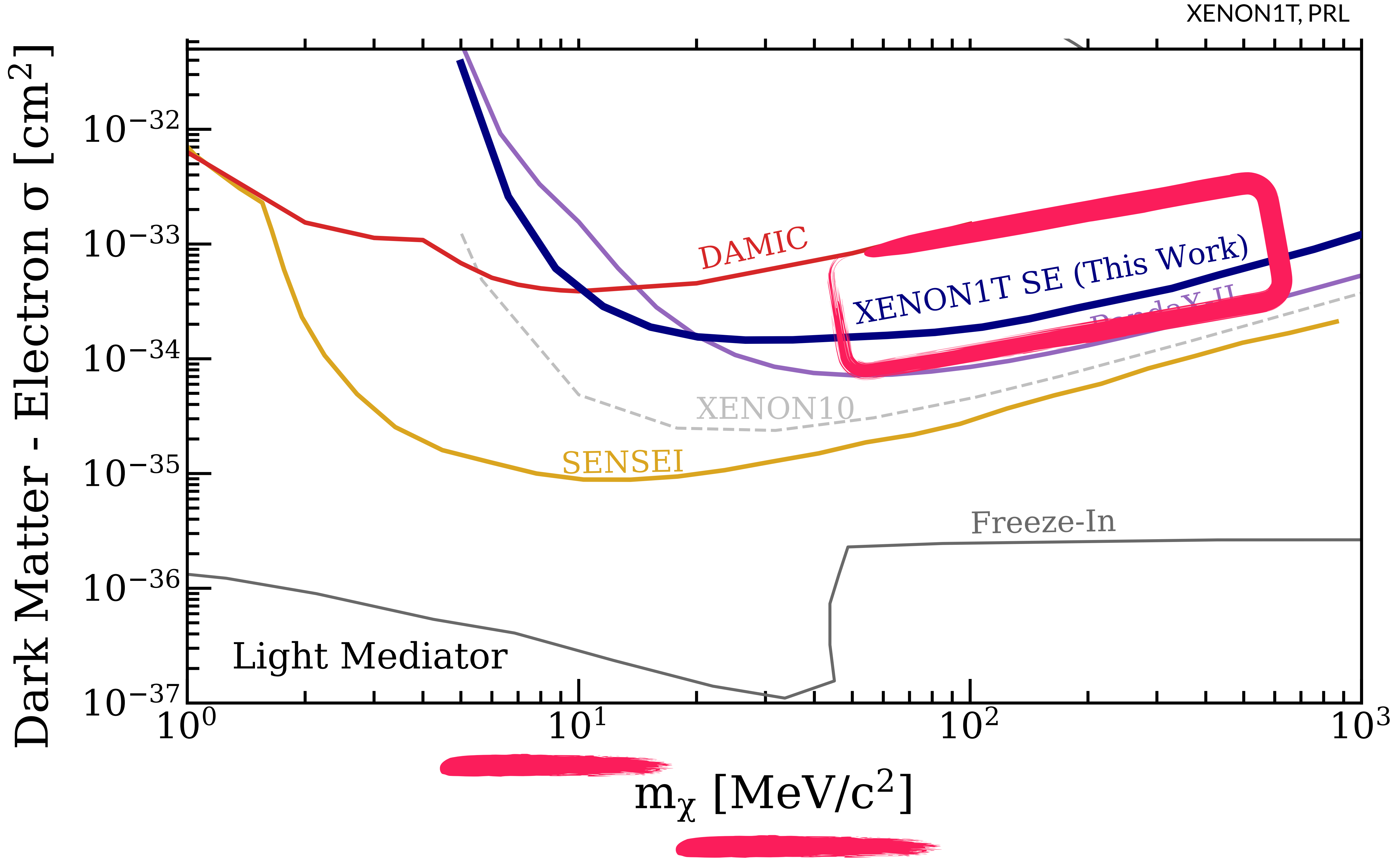
$$\sim 10 \text{ eV} \left(\frac{m_{\rm DM}}{10\,\rm MeV}\right)$$

- Absorption: $E_{\rm DM} \sim m_{\rm DM}$

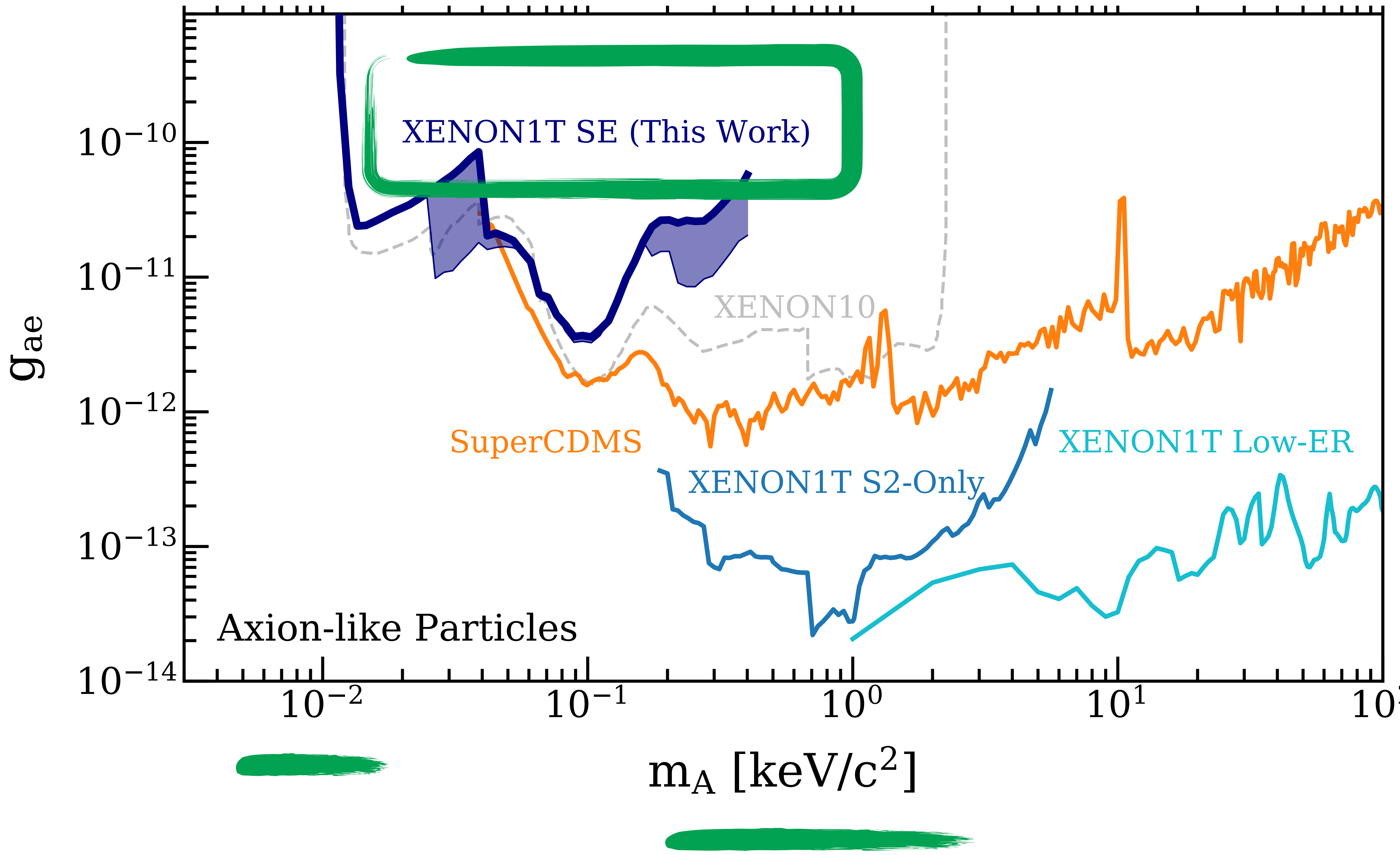
$$\sim 10\,\text{eV} \left(\frac{m_{\rm DM}}{10\,\rm eV}\right)$$

Lightest dark matter mass

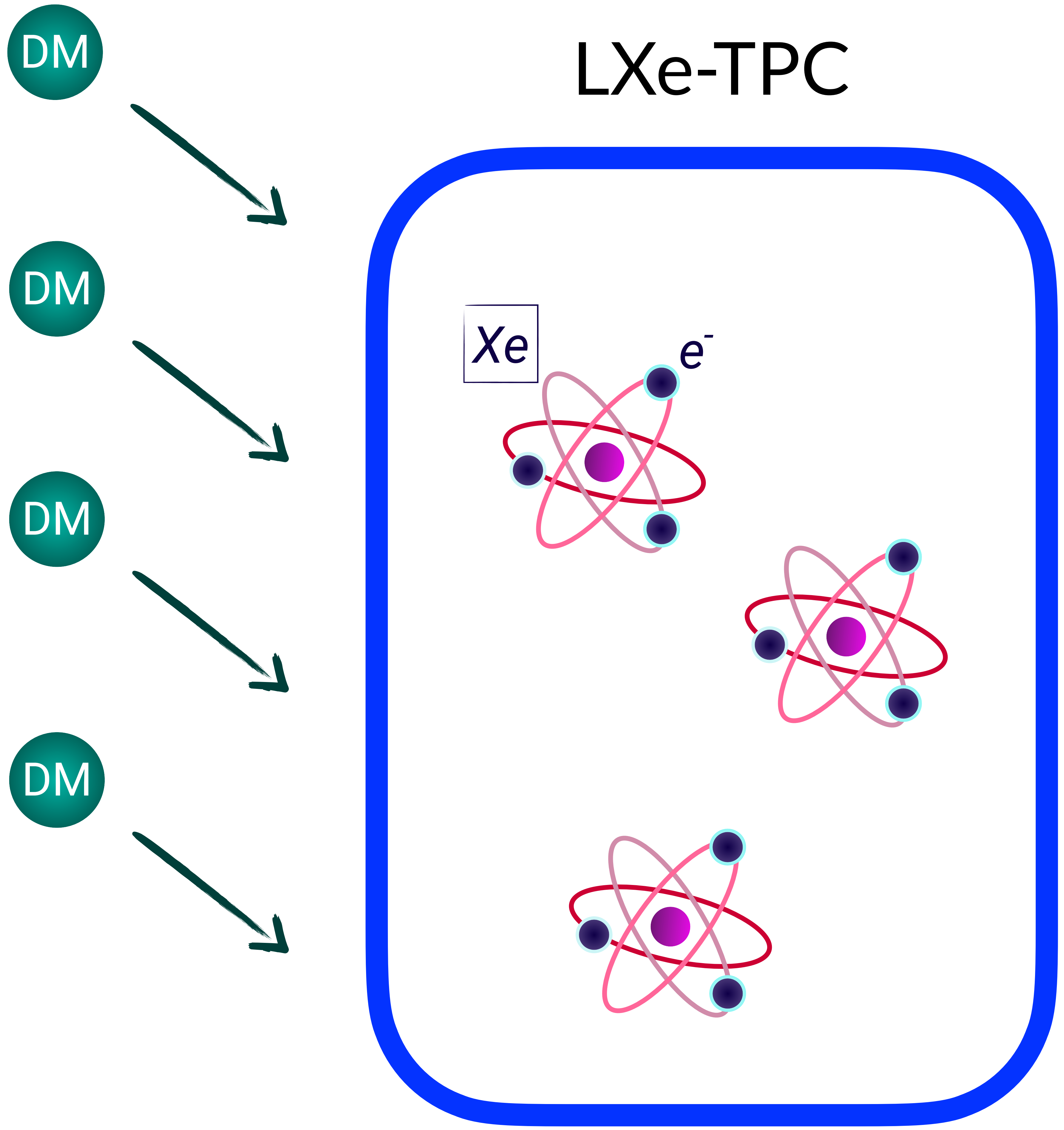
Scattering



Absorption



Heaviest dark matter mass

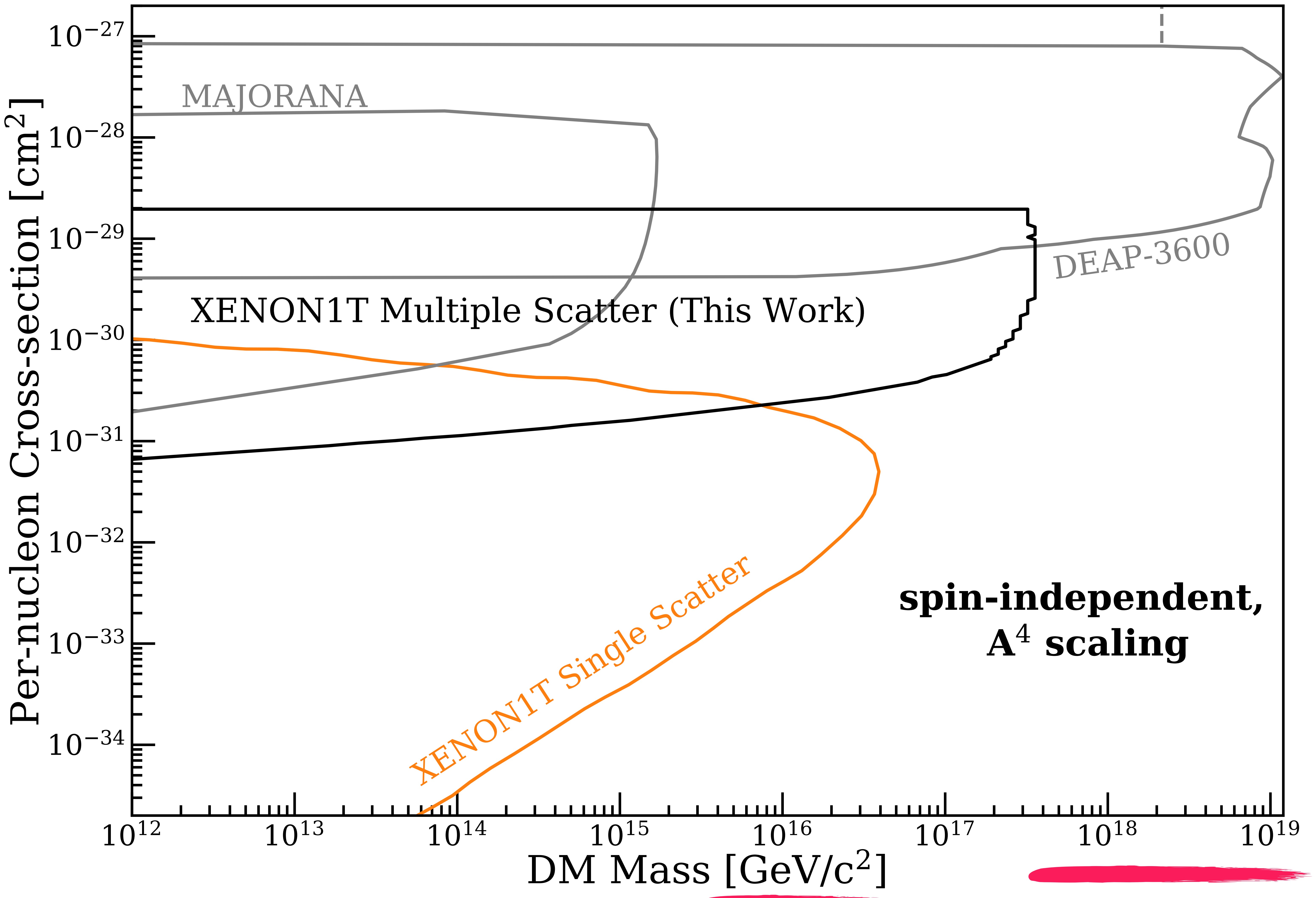


Signals generation if dark matter passes through the detector

$$\Phi_{\rm DM} \sim 0.3 \left(\frac{10^{19}\,{\rm GeV}}{m_{\rm DM}} \right) \, {\rm m}^{-2}{\rm yr}^{-1}$$

Heaviest dark matter mass

XENON, PRL, arXiv:2304.10931



$$M_{\rm Pl} \approx 10^{19}\,\text{GeV}$$

XLZD is a broadband, multi-purpose particle dark matter experiment sensitive to dark matter from the 10 eV to Planck scale

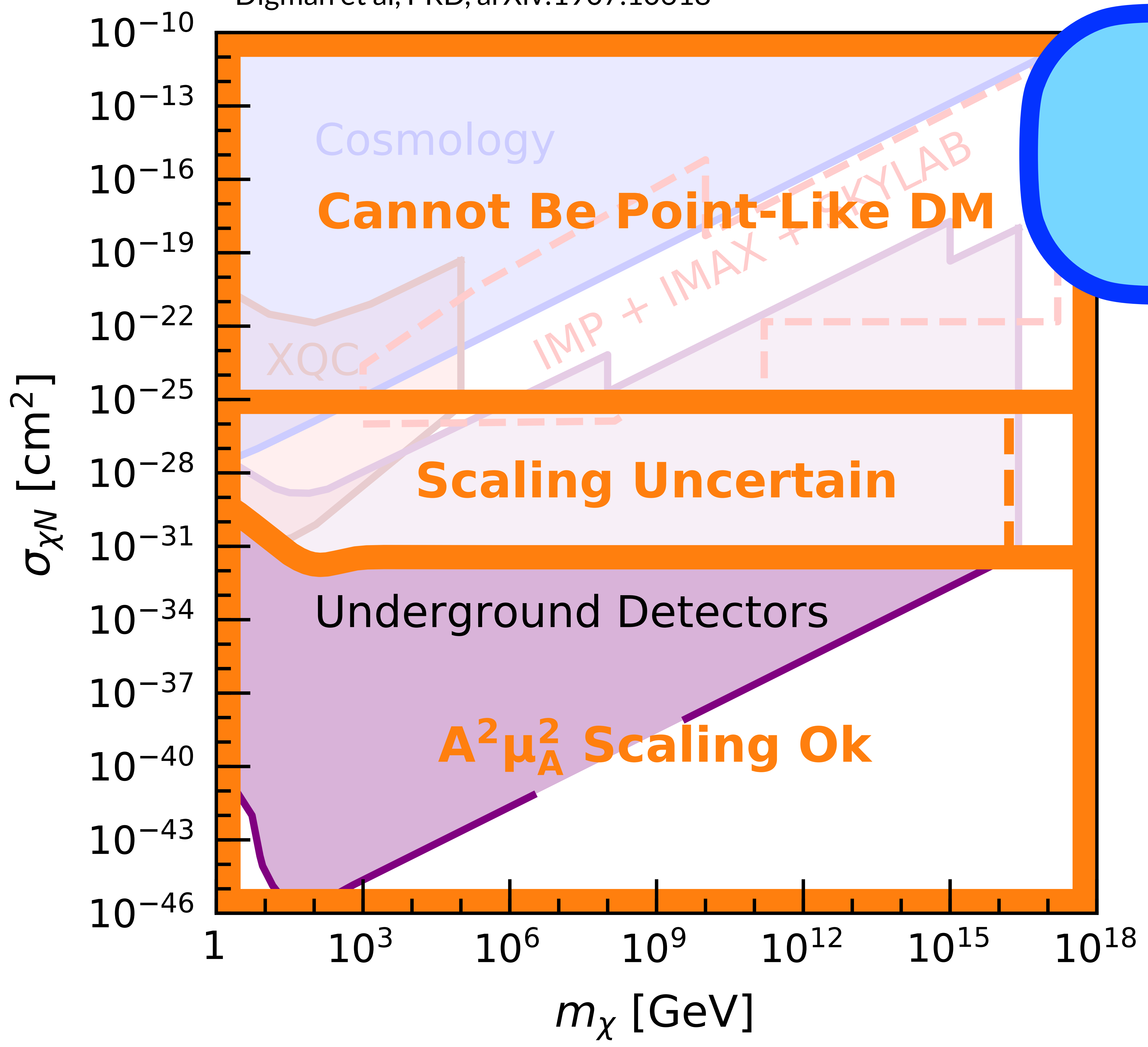
to me, non-XLZD means:

1. Beyond the Planck scale
2. Below the eV scale

1. Dark matter (particles) beyond the Planck scale

Theory landscape

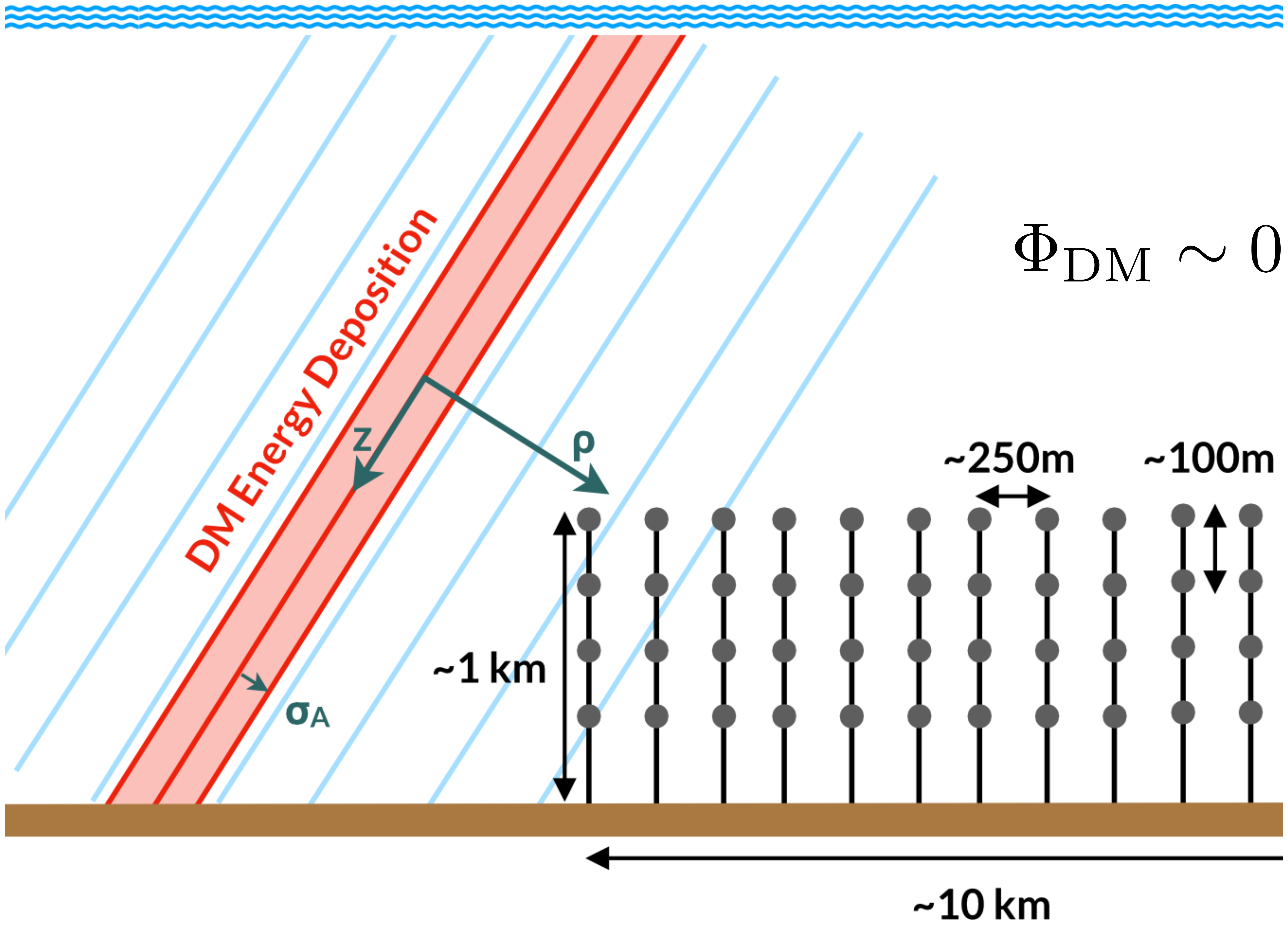
Digman et al, PRD, arXiv:1907.10618



When looking just beyond XLZD:

"For $\sigma > 10^{-25}$ cm^2, dark matter cannot be point-like. Contact interactions cannot achieve cross sections larger than the geometric cross section $\sigma \simeq 4\pi r^2$. ***Dark matter with cross sections in this range must be composite.****"*

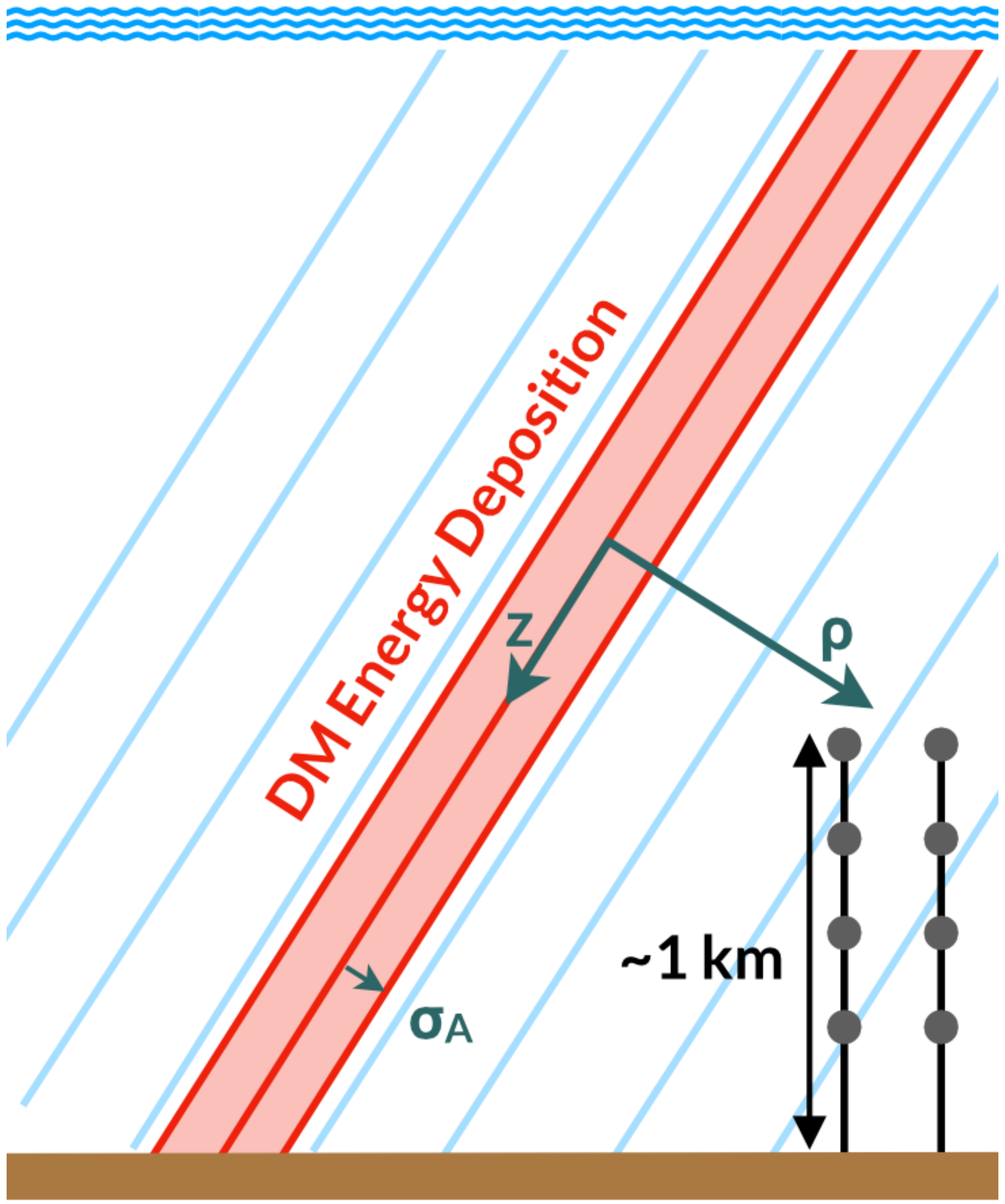
(Speculative) new proposal: large area instrument in seawater



$$\Phi_{\rm DM} \sim 0.3 \left(\frac{10^{19}\,{\rm GeV}}{m_{\rm DM}} \right) {\rm m}^{-2}{\rm yr}^{-1}$$

Cleaver, CM, O'Hare, PRD, arXiv:2502.17593

Track properties: very long and very thin

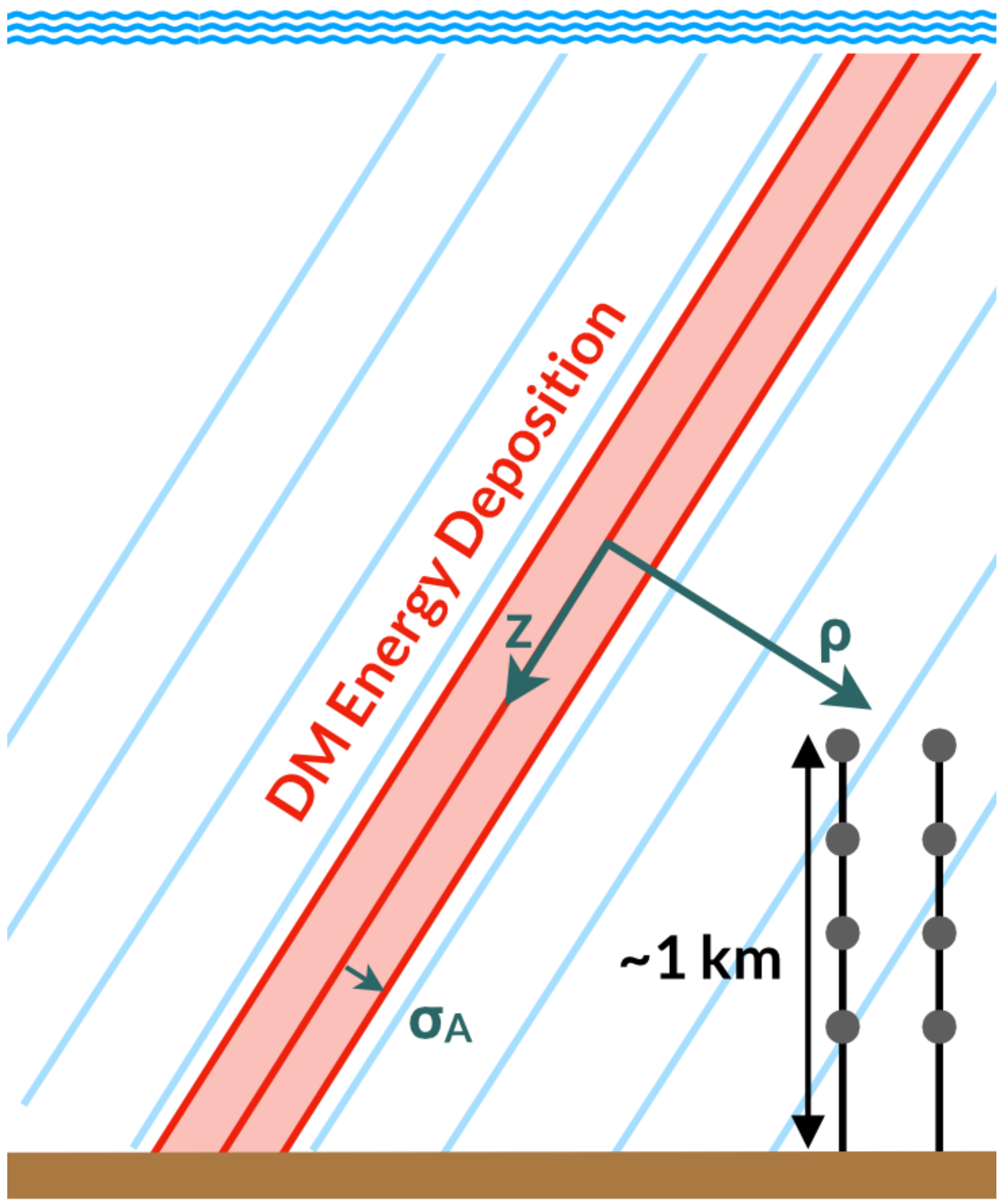


Cleaver, CM, O'Hare, PRD, arXiv:2502.17593

Dark matter scatters with every water nucleus in its path:

$$\lambda_\chi \simeq 10^{-15}\,\mathrm{m} \times (10^{-10}\,\mathrm{cm}^2)/\sigma_\chi$$

Track properties: very long and very thin



Dark matter scatters with every water nucleus in its path:

$$\lambda_\chi \simeq 10^{-15}\,\mathrm{m} \times (10^{-10}\,\mathrm{cm}^2)/\sigma_\chi$$

…but energy loss inefficient, so long tracks:

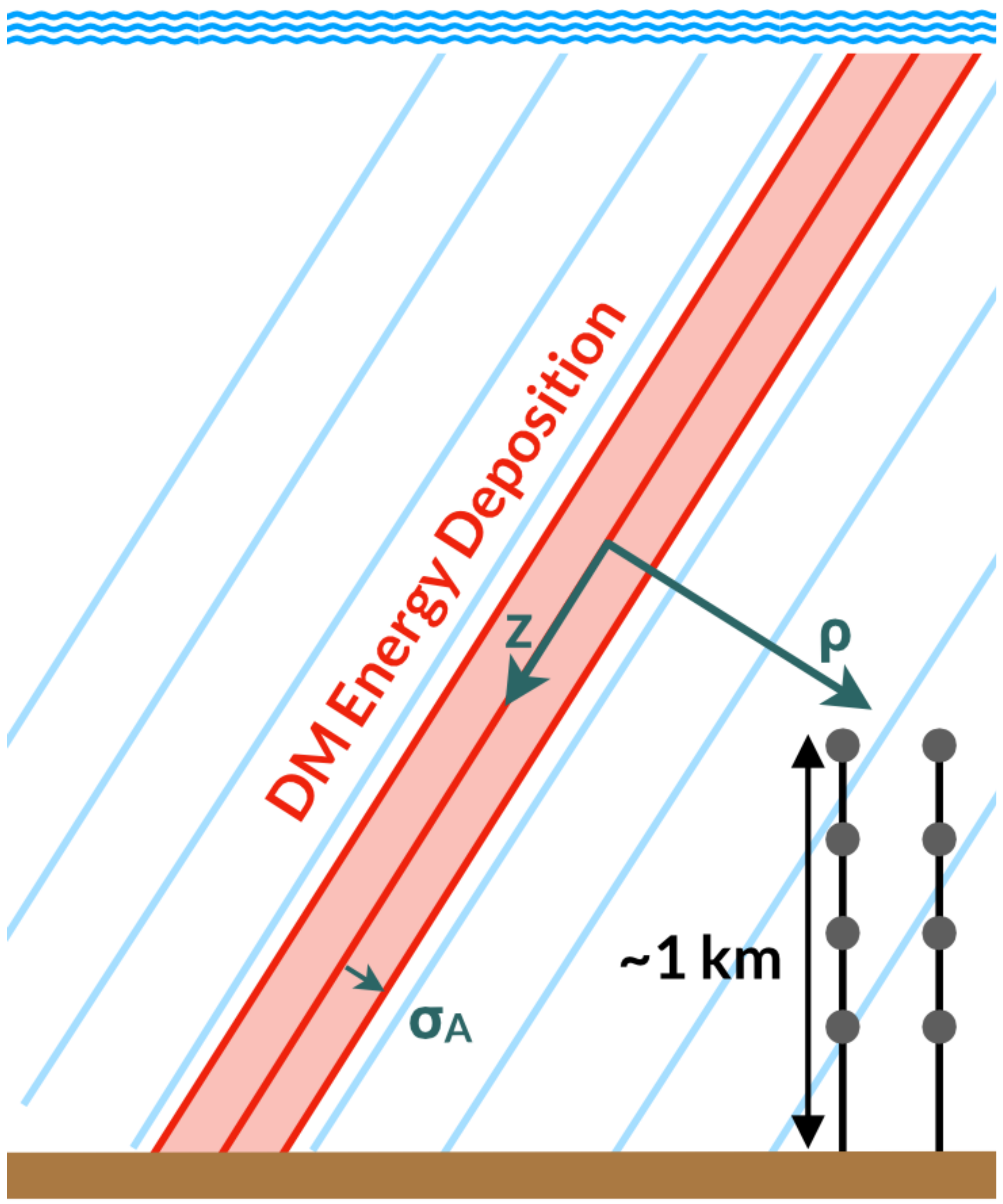
$$\frac{\mathrm{d}E_\chi}{\mathrm{d}z} = -\rho_{\mathrm{sea}}\sigma_\chi v_\chi^2 \exp\left(-\frac{z}{\ell_{\mathrm{sea}}}\right)$$

$$\ell_{\mathrm{sea}} = \frac{m_\chi}{2\rho_{\mathrm{sea}}\sigma_\chi}$$

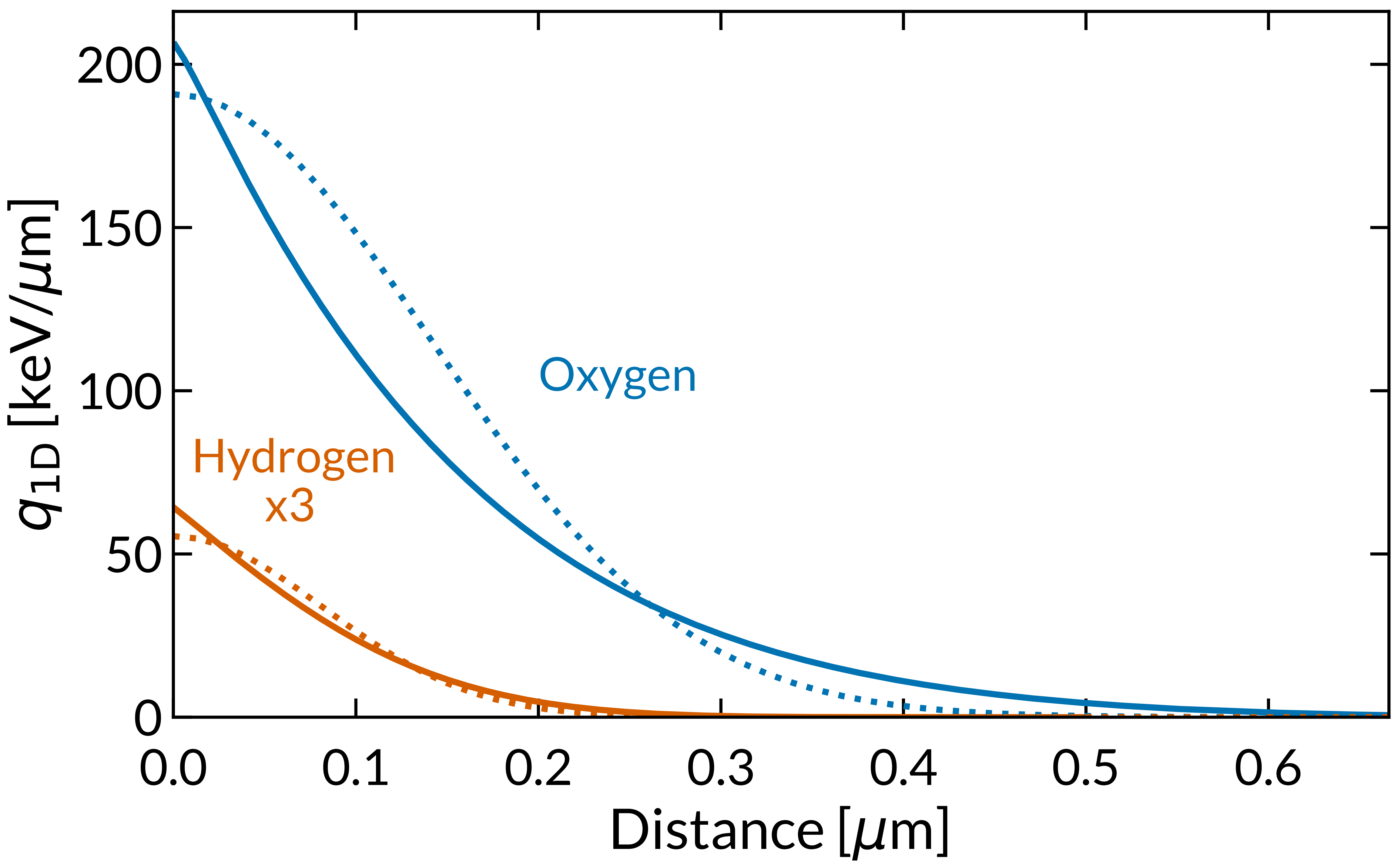
$$\simeq 485\,\mathrm{km} \times \left(\frac{m_\chi}{10^{-2}\,\mathrm{g}}\right)\left(\frac{10^{-10}\,\mathrm{cm}^2}{\sigma_\chi}\right)$$

Cleaver, CM, O'Hare, PRD, arXiv:2502.17593

Track properties: very long and very thin



Recoiling nuclei don't travel far:



Energy deposition in very long and thin cylinder

Cleaver, CM, O'Hare, PRD, arXiv:2502.17593

Energy deposition = sound waves

Thermo-acoustic model:
Rapid energy deposition creates localised heating, which instantaneously expands the seawater and produces a propagating acoustic pressure wave

Thermal expansion coefficient

$$\nabla^2 p - \frac{1}{c_s^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\alpha}{c_p}\frac{\partial^2 q(\boldsymbol{r},t)}{\partial t^2}$$

Speed of sound

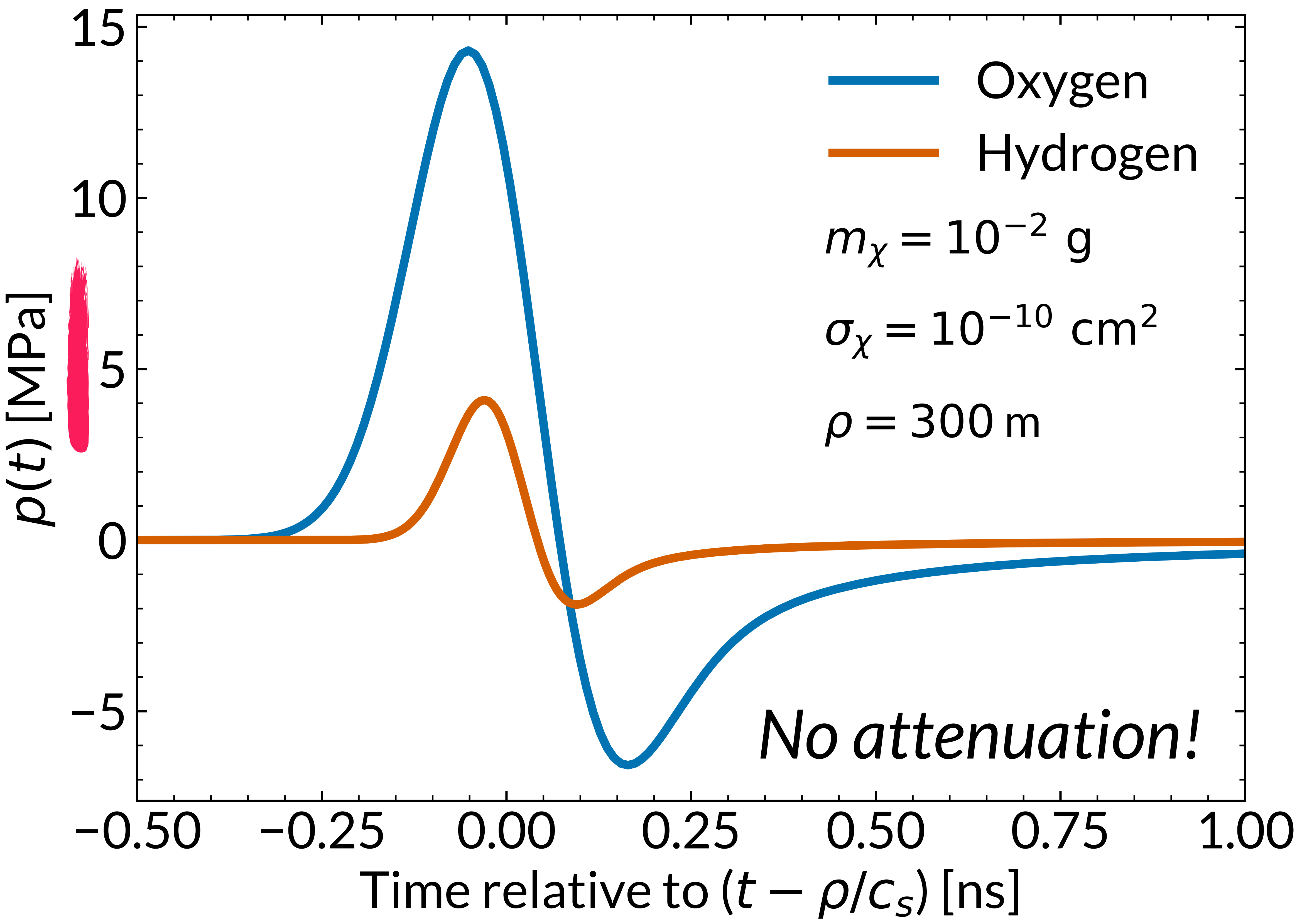
Specific heat capacity

Energy deposition density

Energy deposition = sound waves

At first sight: extremely promising!

Hydrophone detection threshold ~ 5 mPa



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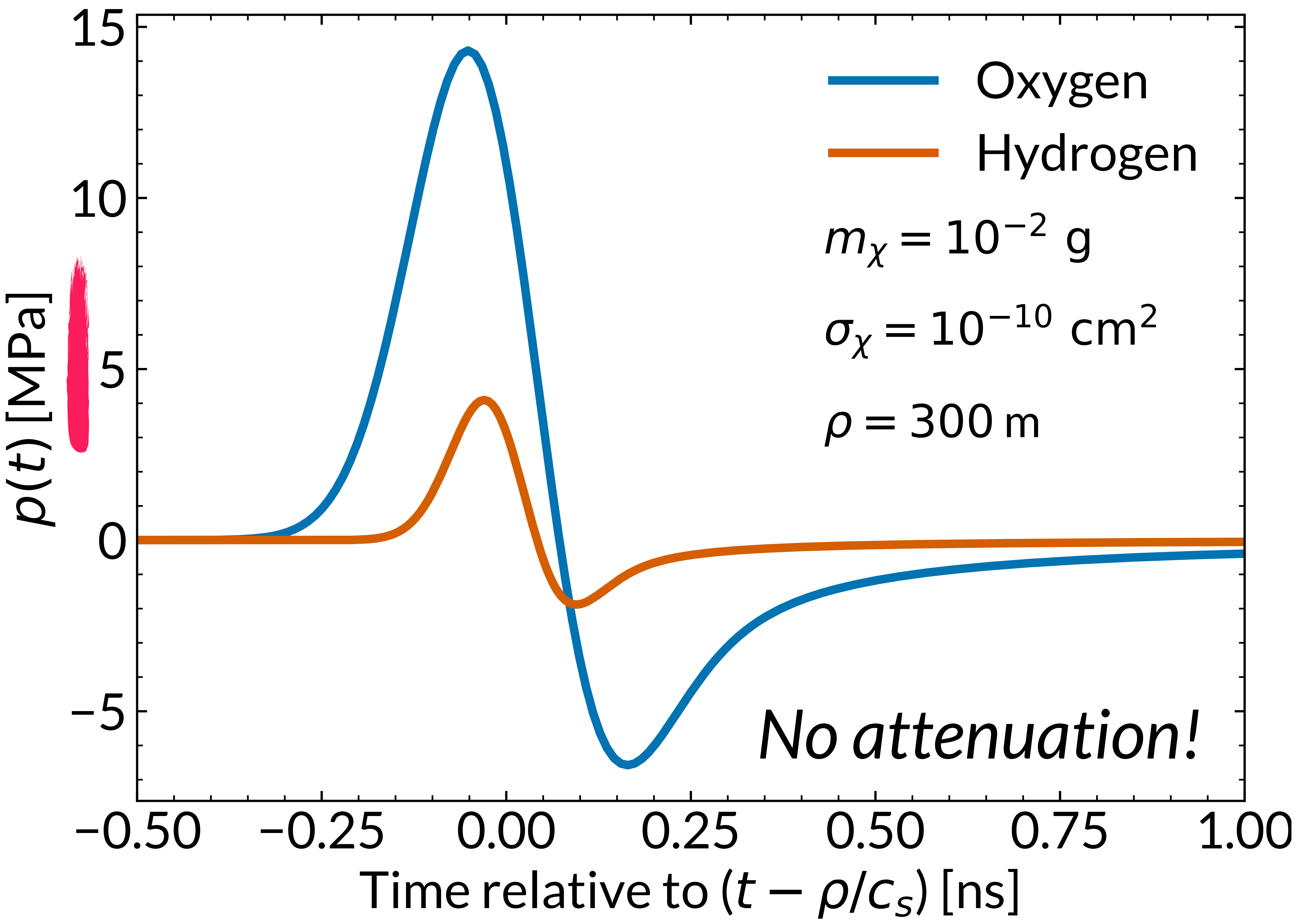
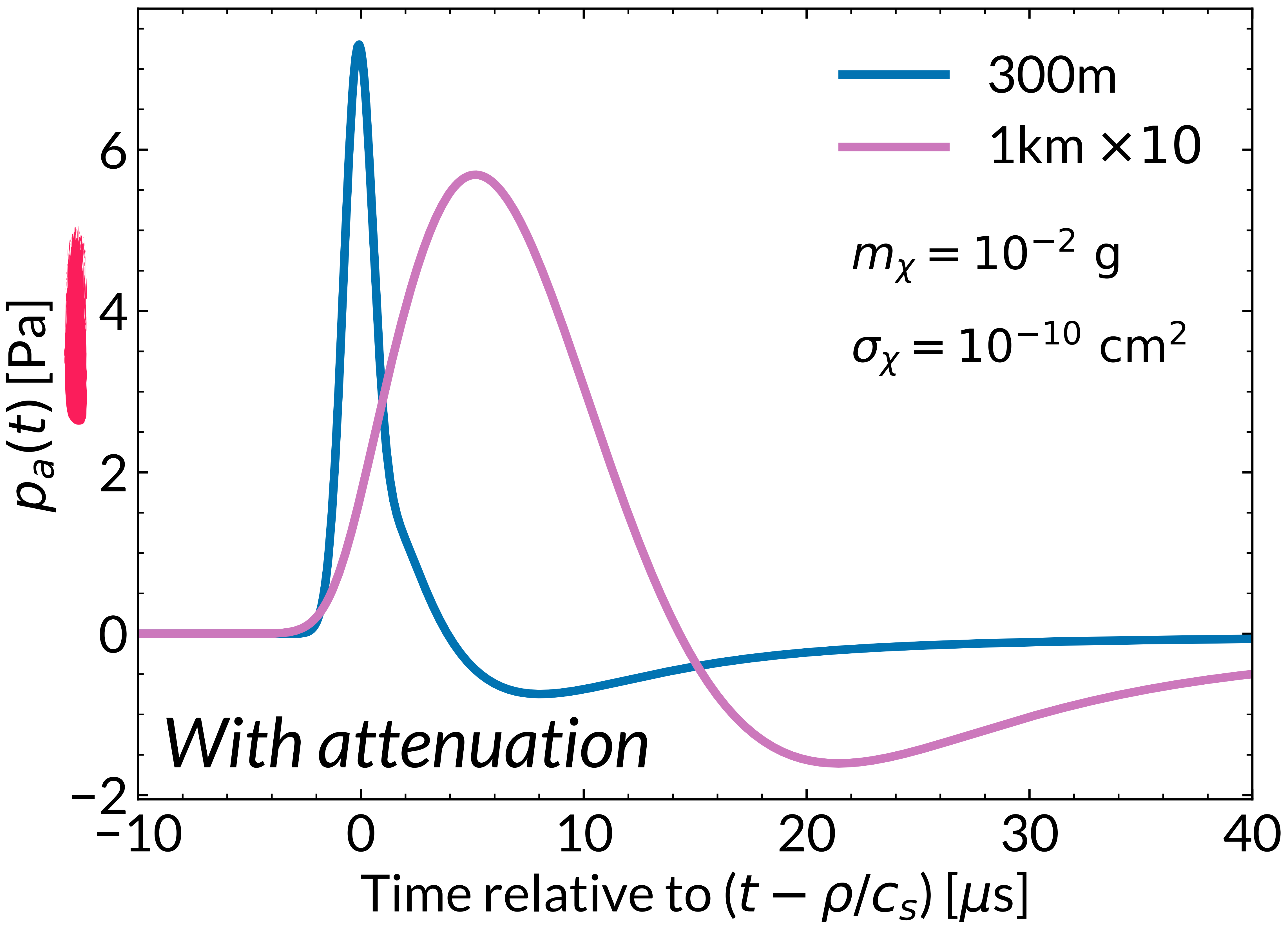


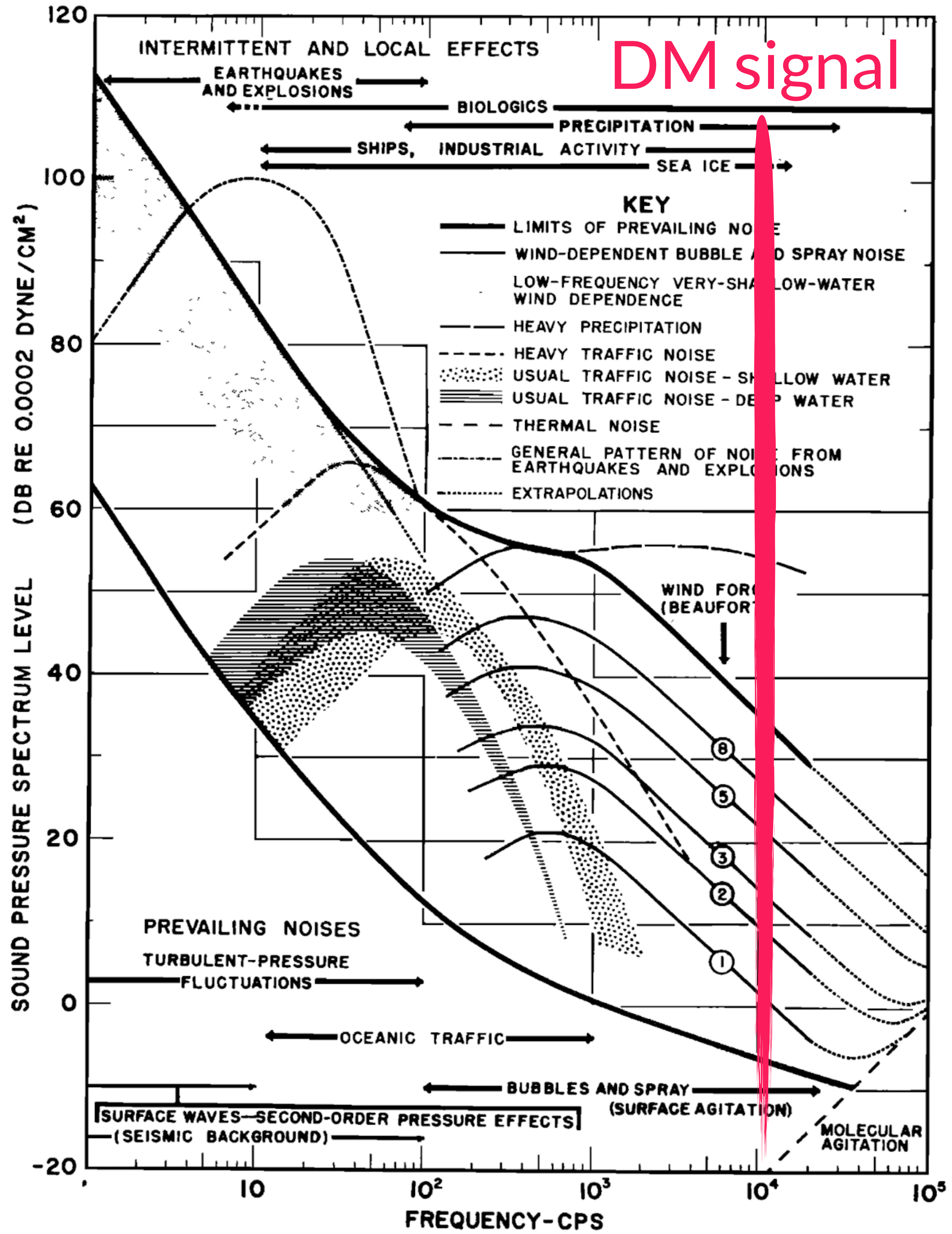


…still interesting even after attenuation included

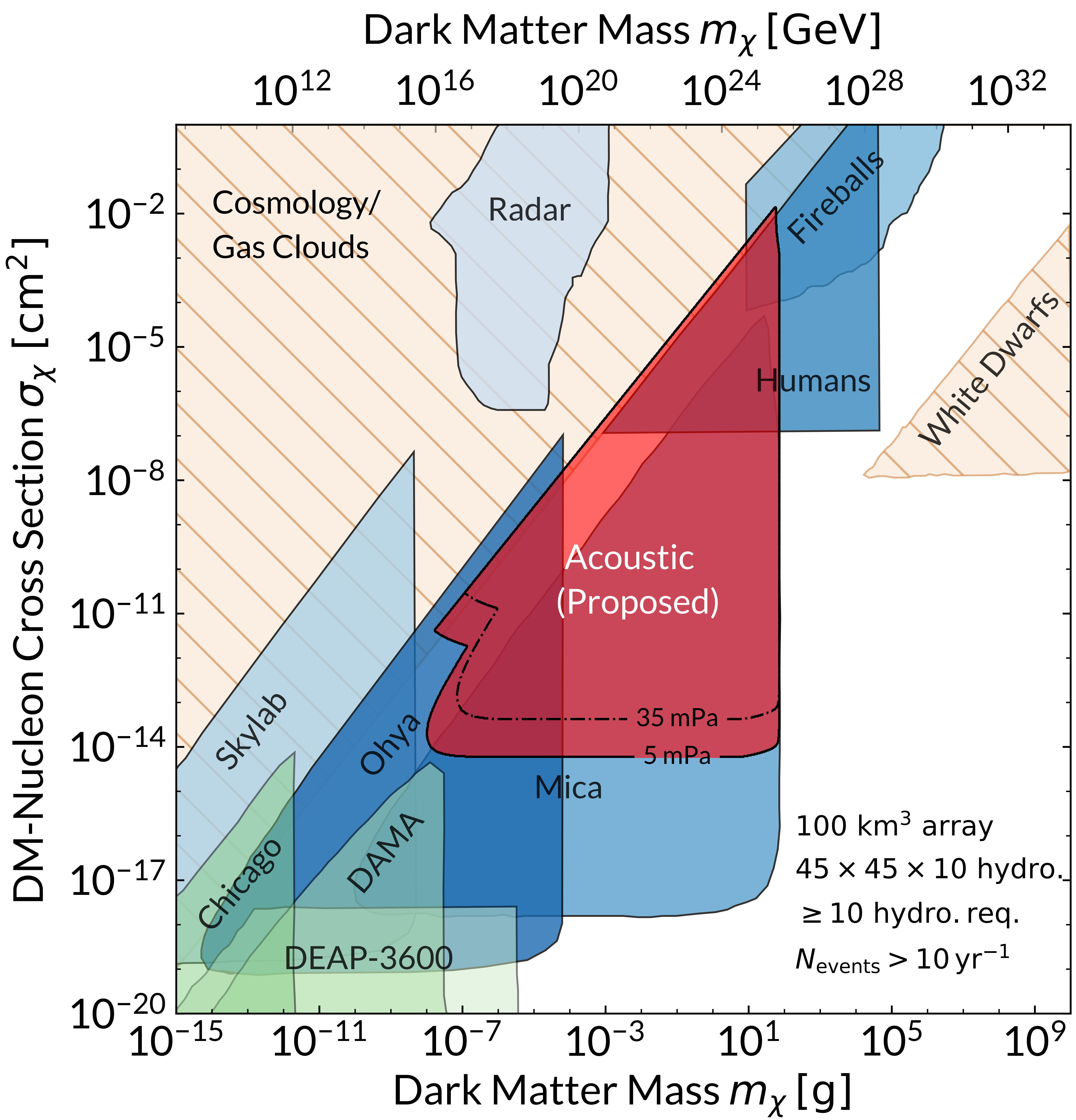
Backgrounds

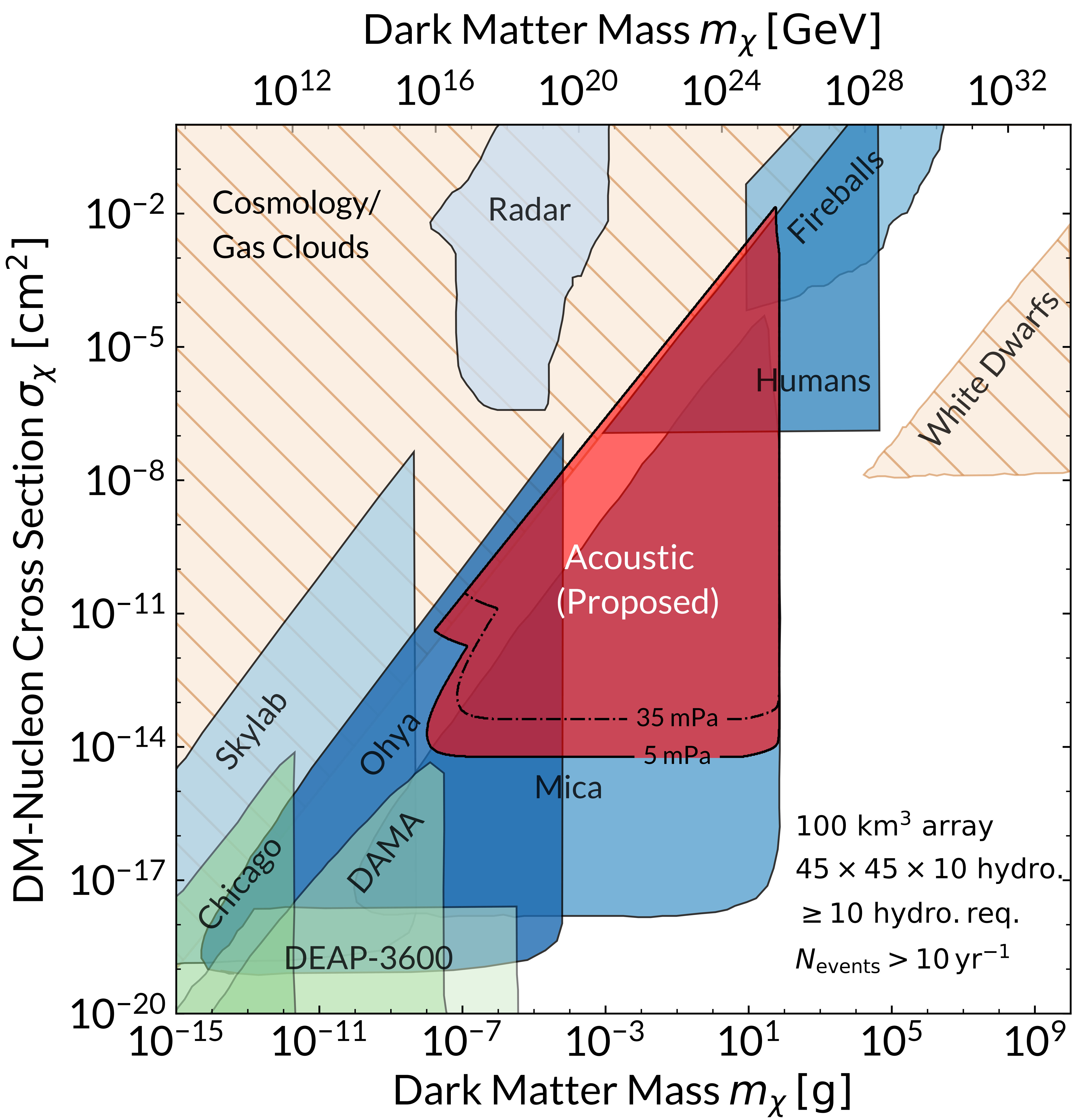
Backgrounds understood:
- Seawater waves
- Sea traffic (ships)
- Animals (dolphins, shrimps)

Can produce pulses similar to dark matter
…but none extend over km-long tracks



Wenz, J. Acoust. Soc. Am 1962


Dark Matter Mass m_χ [GeV]
10^{12}
10^{16}
10^{20}
10^{24}
10^{28}
10^{32}
DM-Nucleon Cross Section σ_χ [cm^2]
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{-20}
Cosmology/
Gas Clouds
Radar
Fireballs
Humans
White Dwarfs
Acoustic
(Proposed)
35 mPa
5 mPa
Skylab
Ohya
Mica
Chicago
DAMA
DEAP-3600
100 km^3 array
$45 \times 45 \times 10$ hydro.
≥ 10 hydro. req.
$N_{\text{events}} > 10\,\text{yr}^{-1}$
10^{-15}
10^{-11}
10^{-7}
10^{-3}
10^{1}
10^{5}
10^{9}
Dark Matter Mass m_χ [g]



Challenge:

$$\Phi_{\rm DM} \sim 0.3 \left(\frac{10^{19}\,\text{GeV}}{m_{\rm DM}}\right) \text{m}^{-2}\text{yr}^{-1}$$

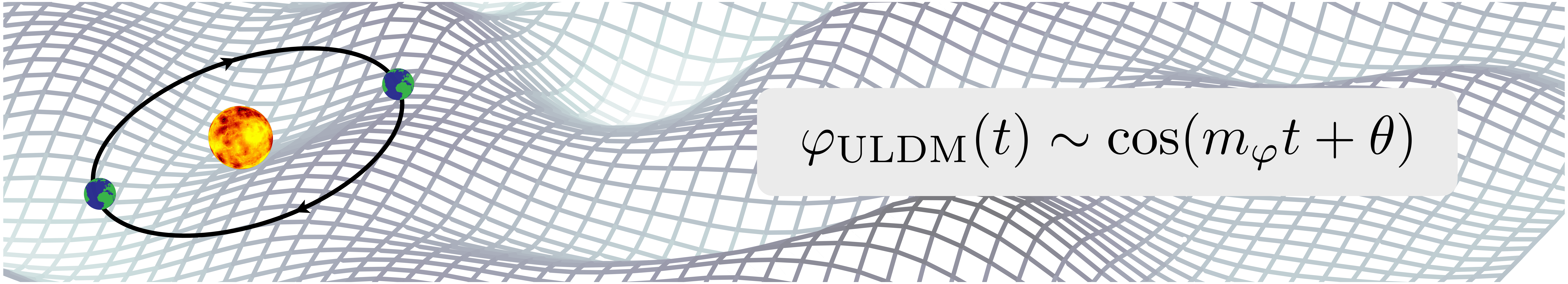
Solution:
To go beyond XLZD, need large exposure through larger areas, larger measuring times, or both!

2. Dark matter below the eV scale

Ultra-light dark matter

DM lighter than ~few eV behaves as a classical wave

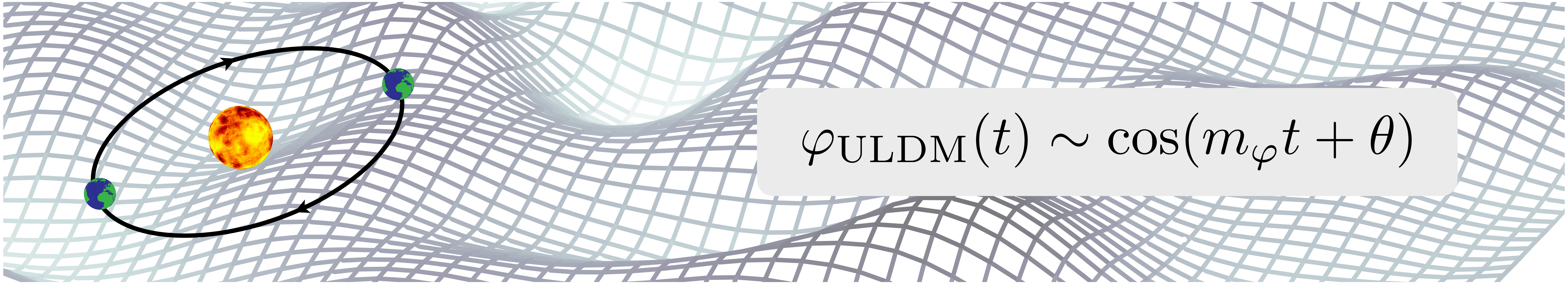
Angular frequency set by the ULDM mass: $\omega \simeq m_\varphi \left(1 + \mathcal{O}(v^2)\right)$



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

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

Ultra-light scalar dark matter candidates



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

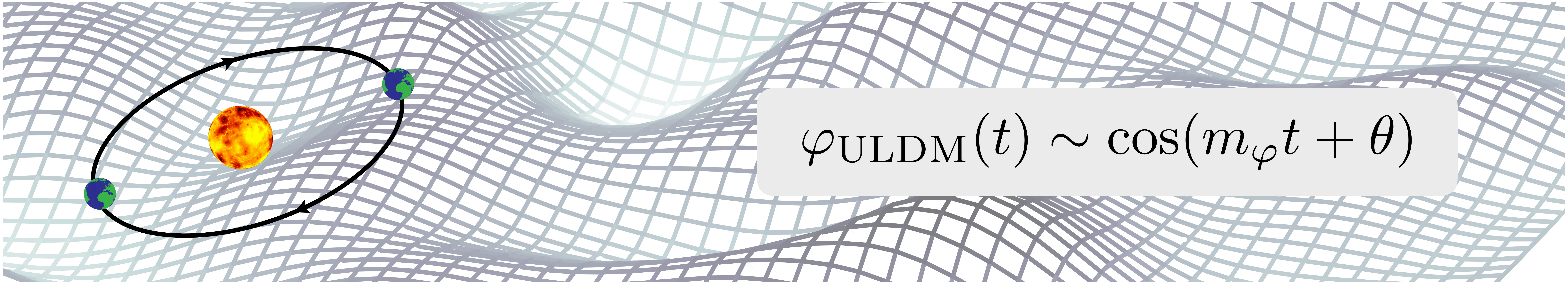
$$\mathcal{L} \supset \sqrt{4\pi G_N}\phi\left[d_{m_e} m_e \bar{e} e - \frac{d_e}{4} F_{\mu\nu}F^{\mu\nu}\right]$$

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

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

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

Ultra-light scalar dark matter candidates



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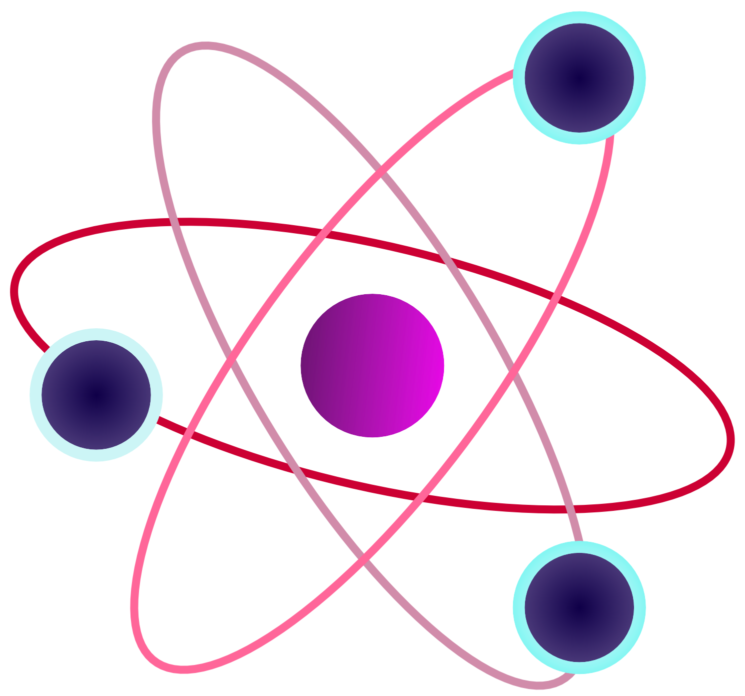
Impact of scalars is to make ‘fundamental constants’ time-dependent with oscillation frequency set by the ULDM mass

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

Ultra-light scalar dark matter induces changes in atoms

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

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



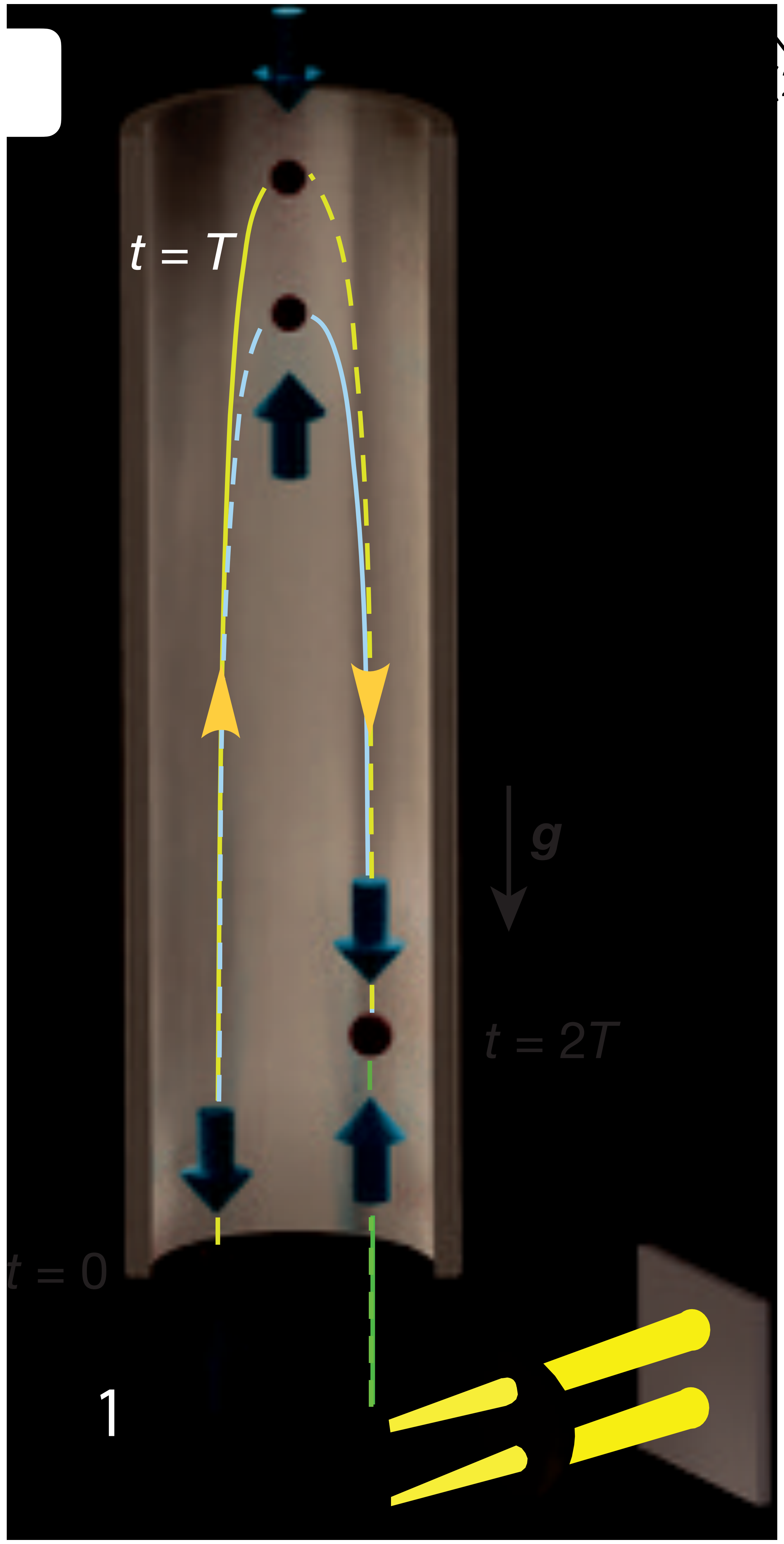
Typical atomic size ~ Bohr radius $a_0 \sim \dfrac{1}{m_e \alpha}$

Typical atomic energy ~ Rydberg energy $R_\infty \sim m_e \alpha^2$

Recent developments:
use very precise quantum sensors to search for these changes

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

Light-pulse atom interferometry (physical-space)



Nature (2015)

Launch ultra-cold cloud of atoms into an atomic fountain

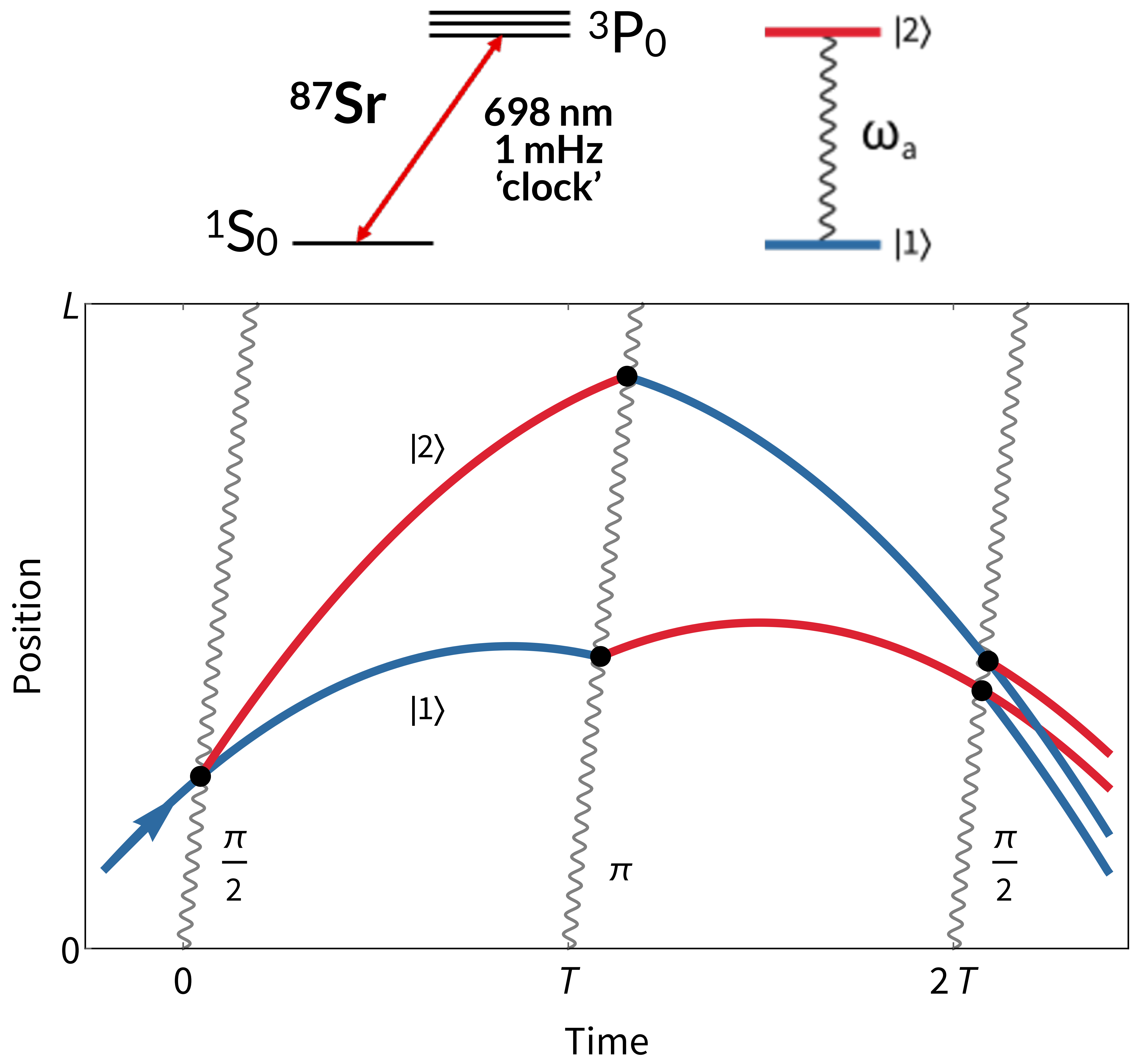
Sequence of optical pulses manipulate the atoms

Quantum superposition over macroscopic distances (>50cm achieved)

Interfere using a final optical pulse when they spatially overlap

Image the two interferometer output ports

Light-pulse atom interferometry (space-time)



Abe et al (MAGIS-100) arXiv:2104.02835

Two-level system separated by optical frequency difference ω_a

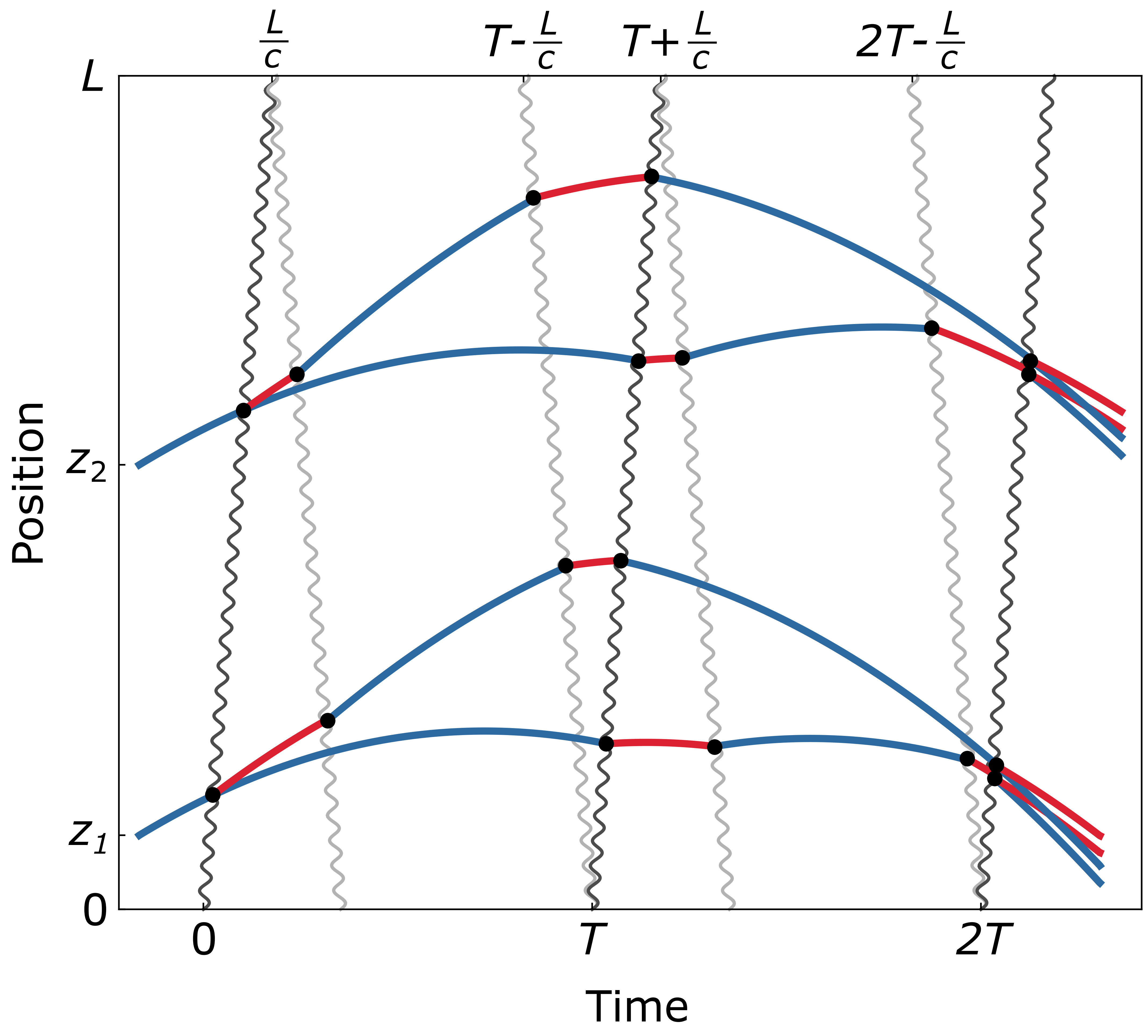
Initial pulse: 'beamsplitter'
Middle pulse: 'mirror'
Final pulse: 'beamsplitter (interfere)'

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

A bit more involved… operate as a gradiometer



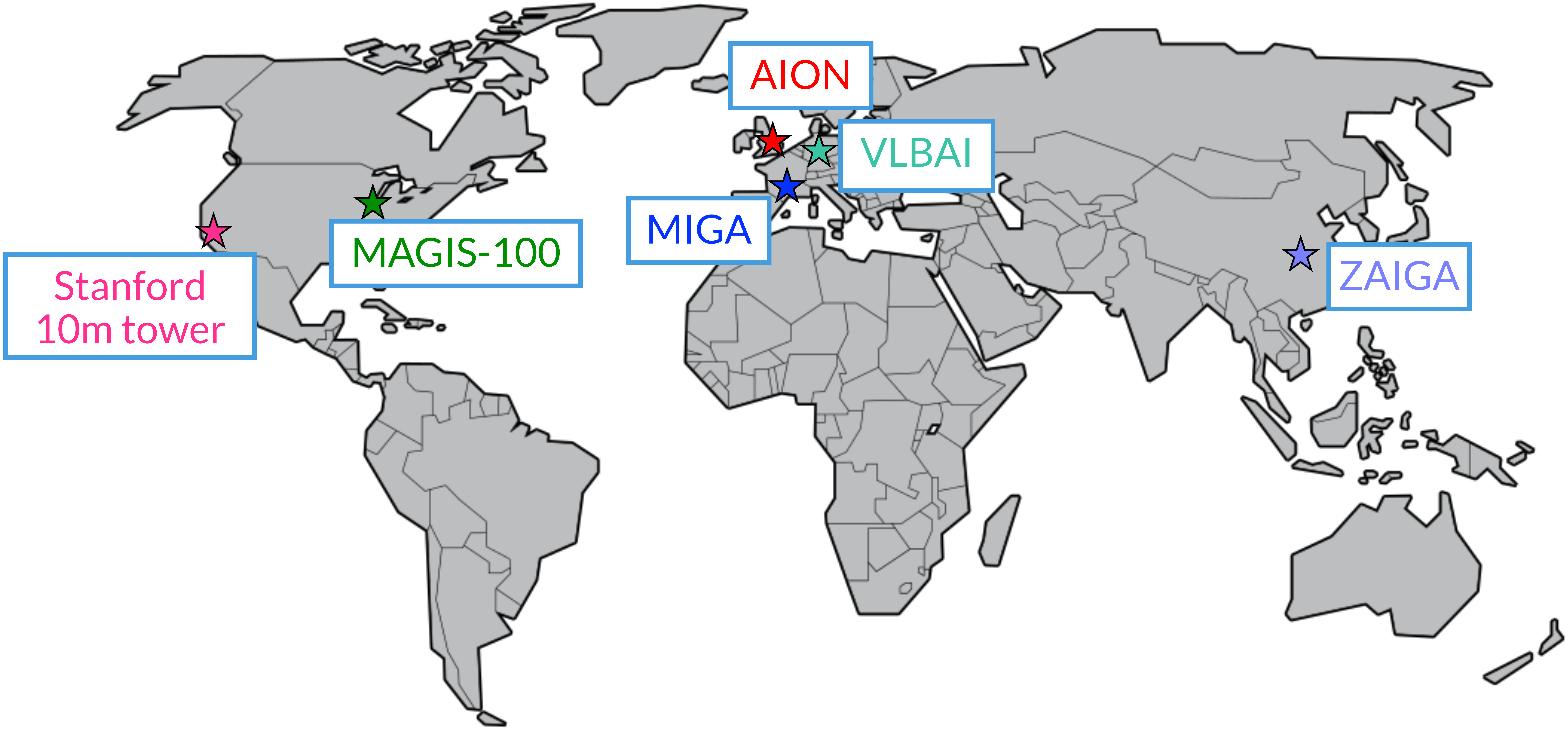
Run two atom interferometers simultaneously with the same laser ('gradiometer')

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

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

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

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

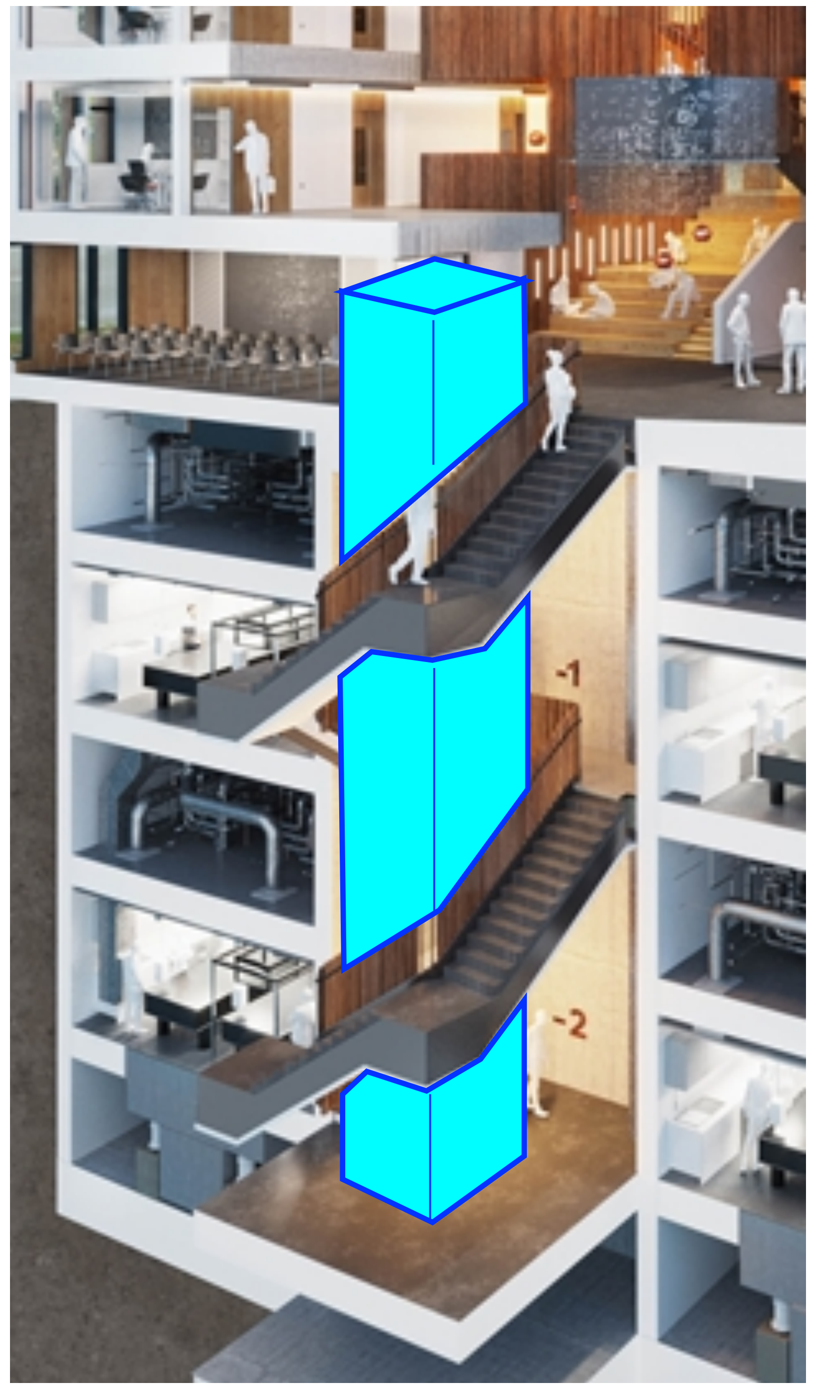
AION & TVLBAI: Towards very-long baselines

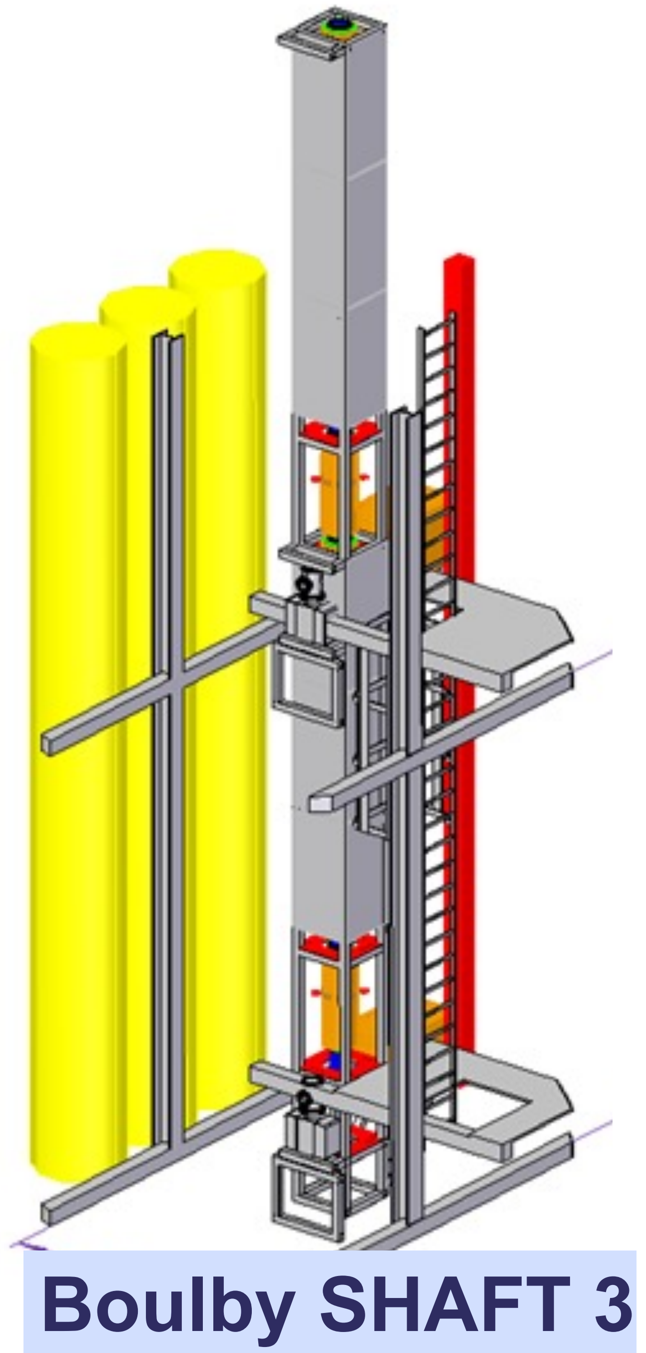
AION-10
2025+ ~10m instrument in Oxford

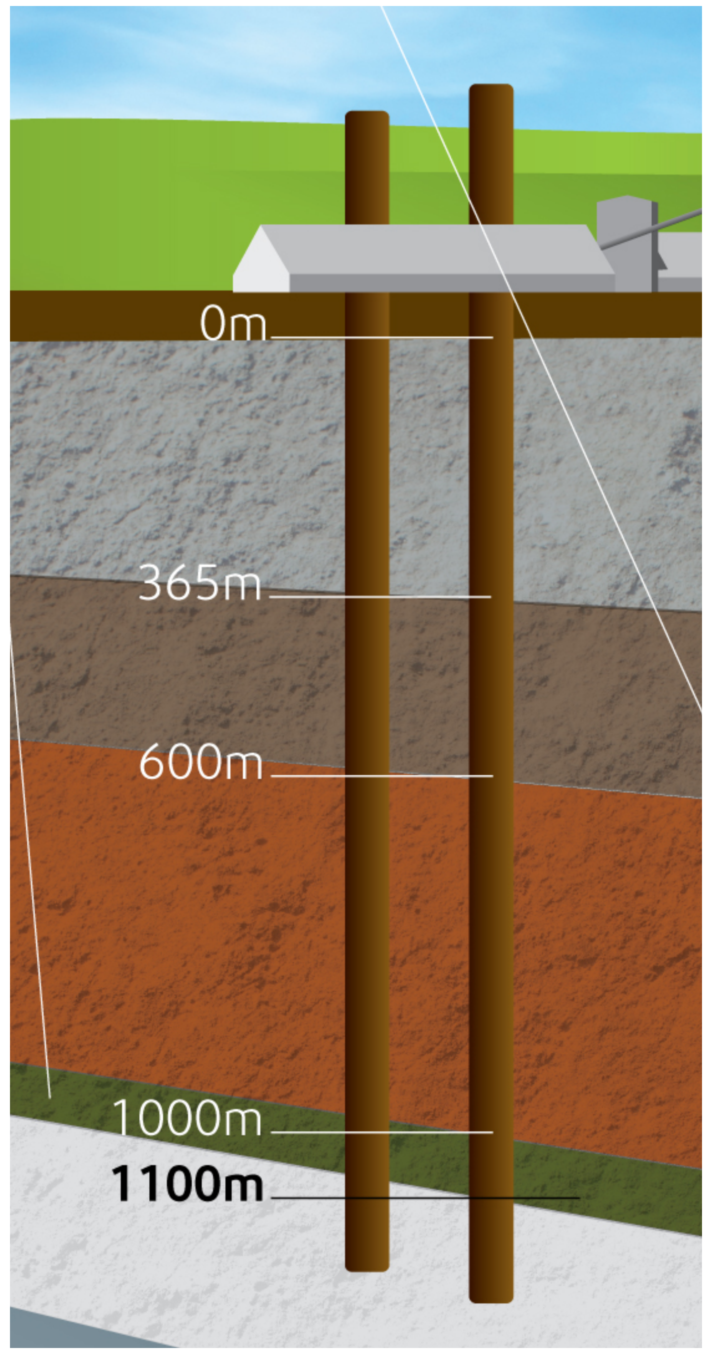
AION-100
2030s ~100m instrument at Boulby/CERN/…?

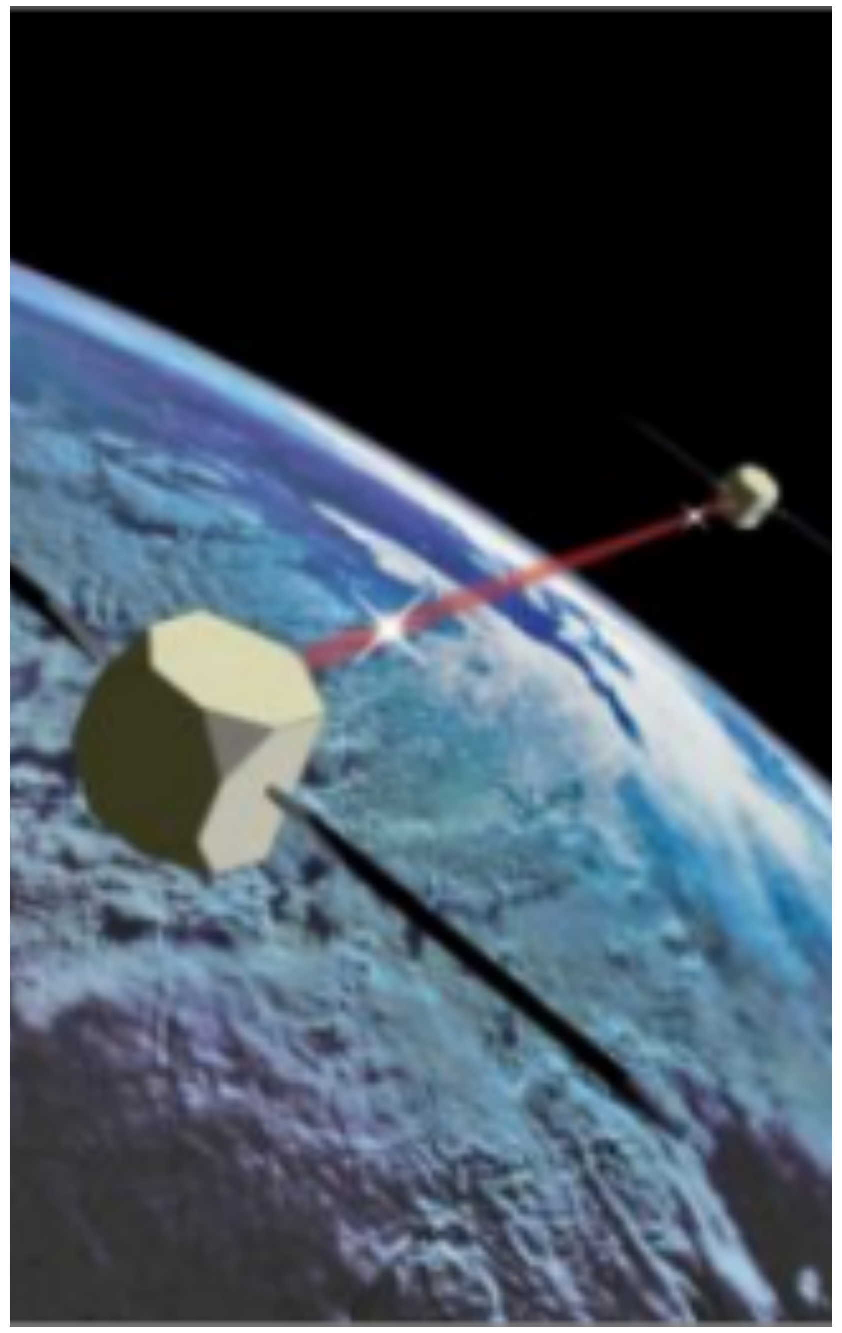
km-instrument
2040s major international project(s)

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

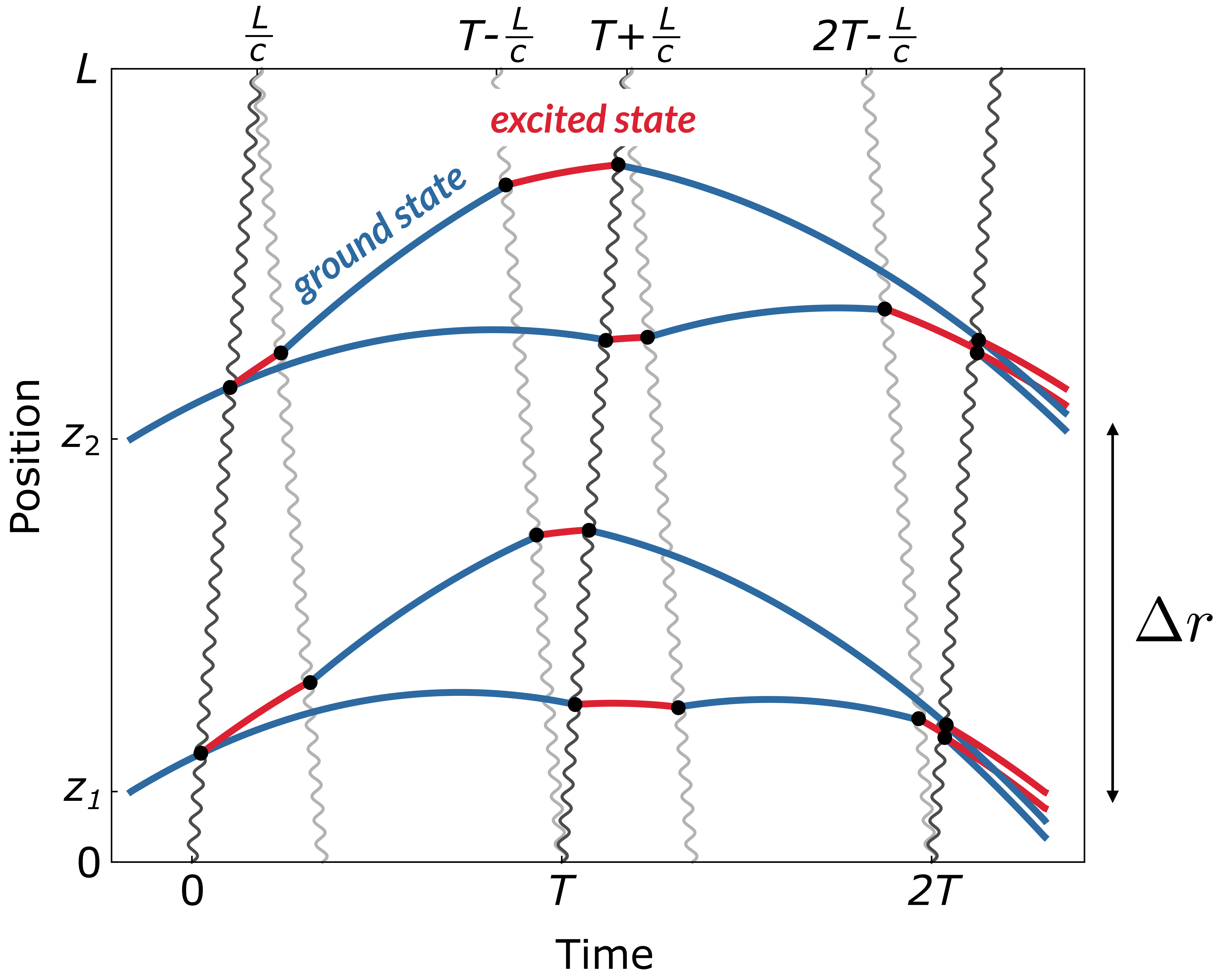
Scalar ULDM signal

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

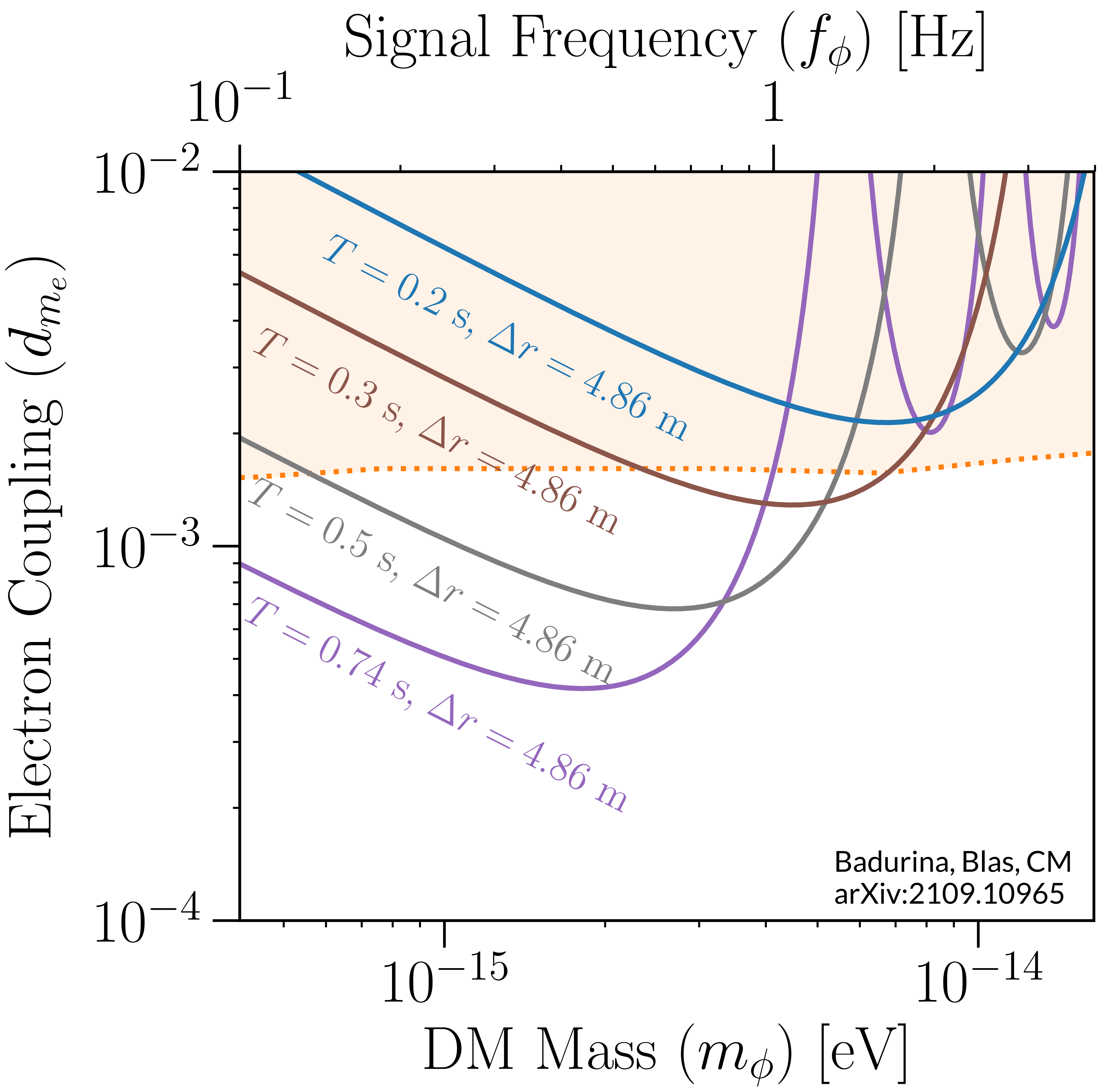


Many parameters to tune to reach sensitivity

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

Handles to optimise (in order of priority):

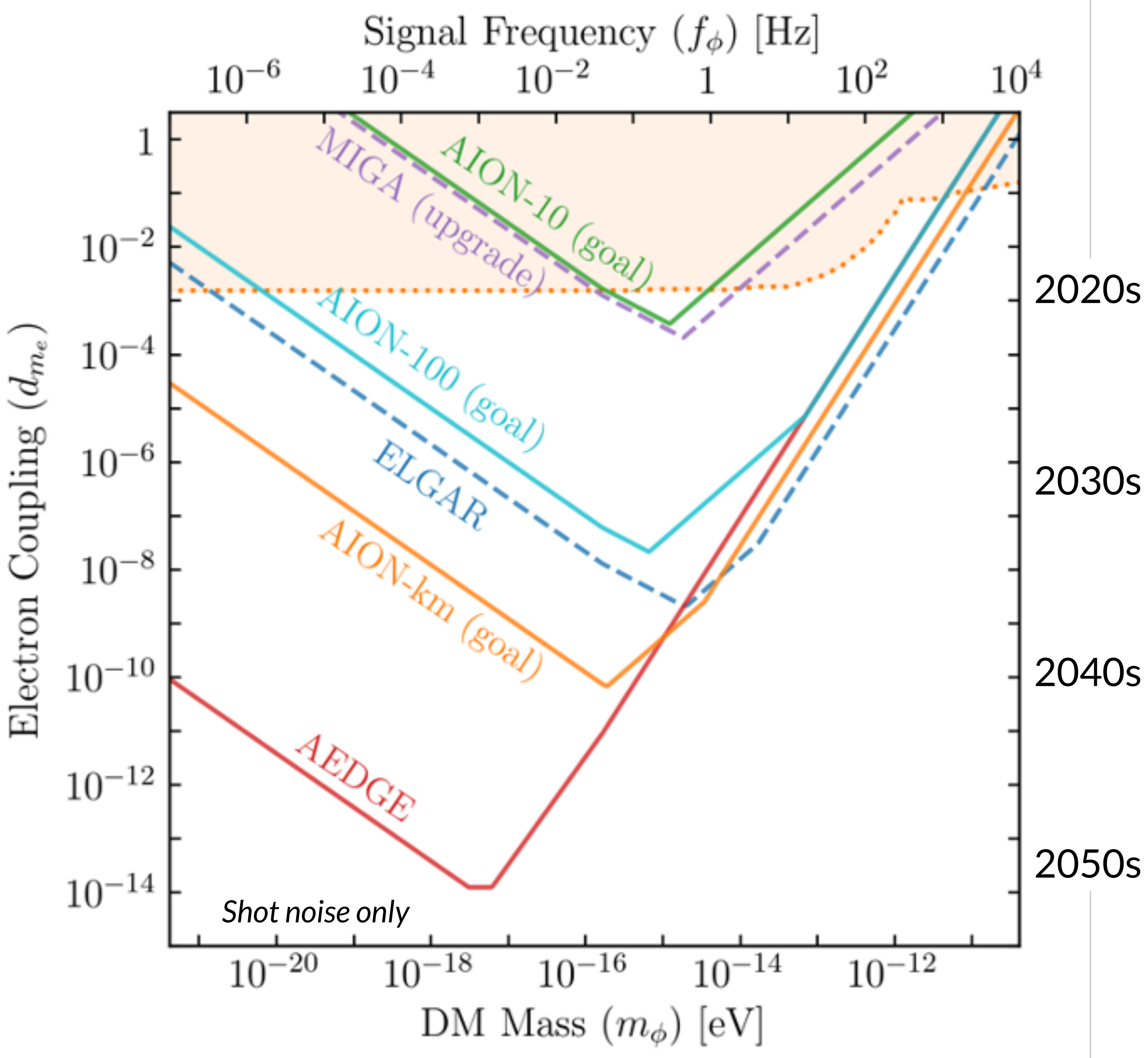
T ~ 1s (interrogation time)
C ~ 0.1 - 1 (constrast)
n ~ 1000 (LMT)
Δr ~ AI separation
Δt ~ sampling time
$N_a \sim$ atoms in cloud
$T_{\mathrm{int}} \sim 10^7\mathrm{s}$ (integration time)



Near- and long-term prospects (Scalar ULDM)

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

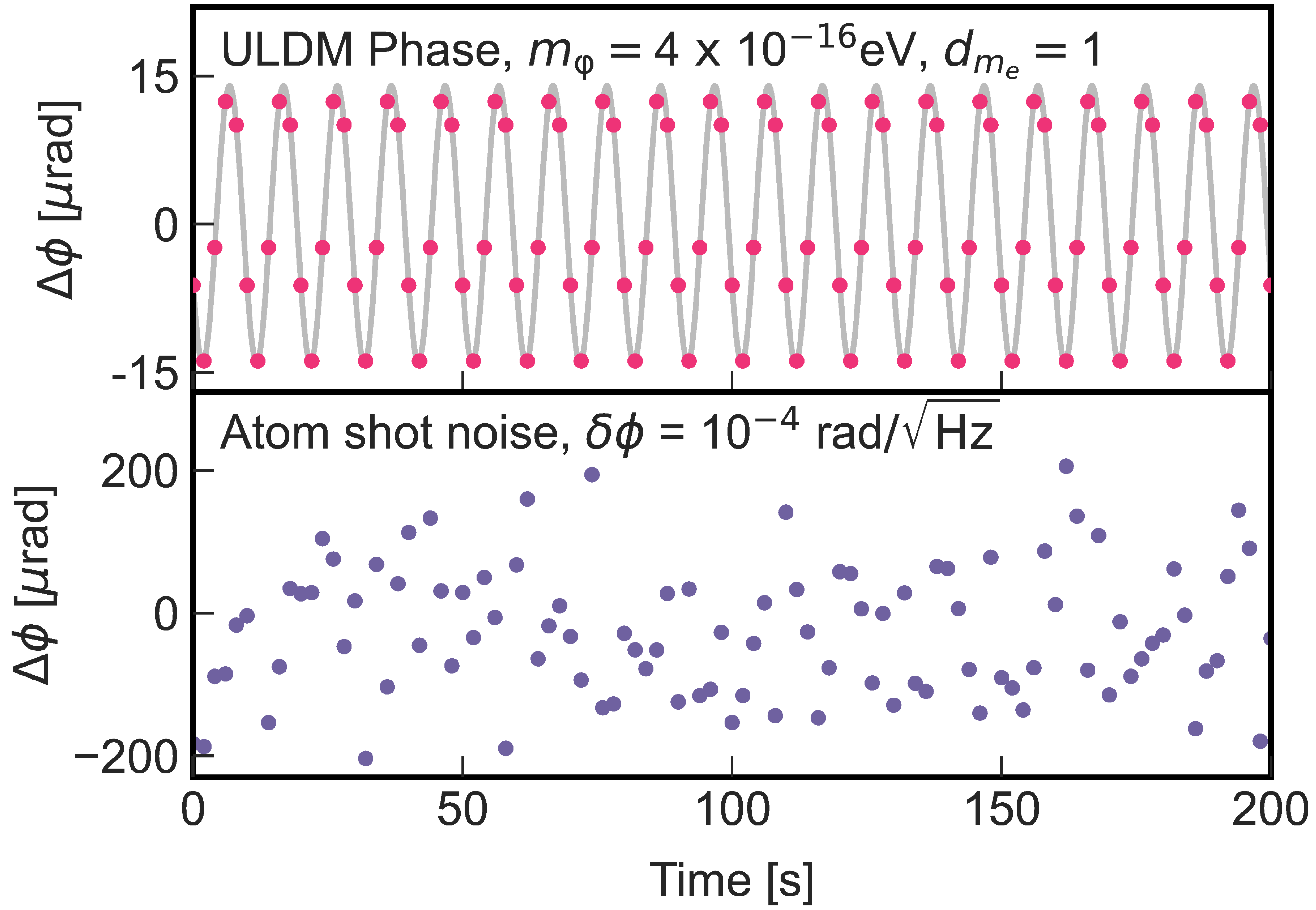
Badurina, CM, et al, arXiv:1911.11755, 2108.02468

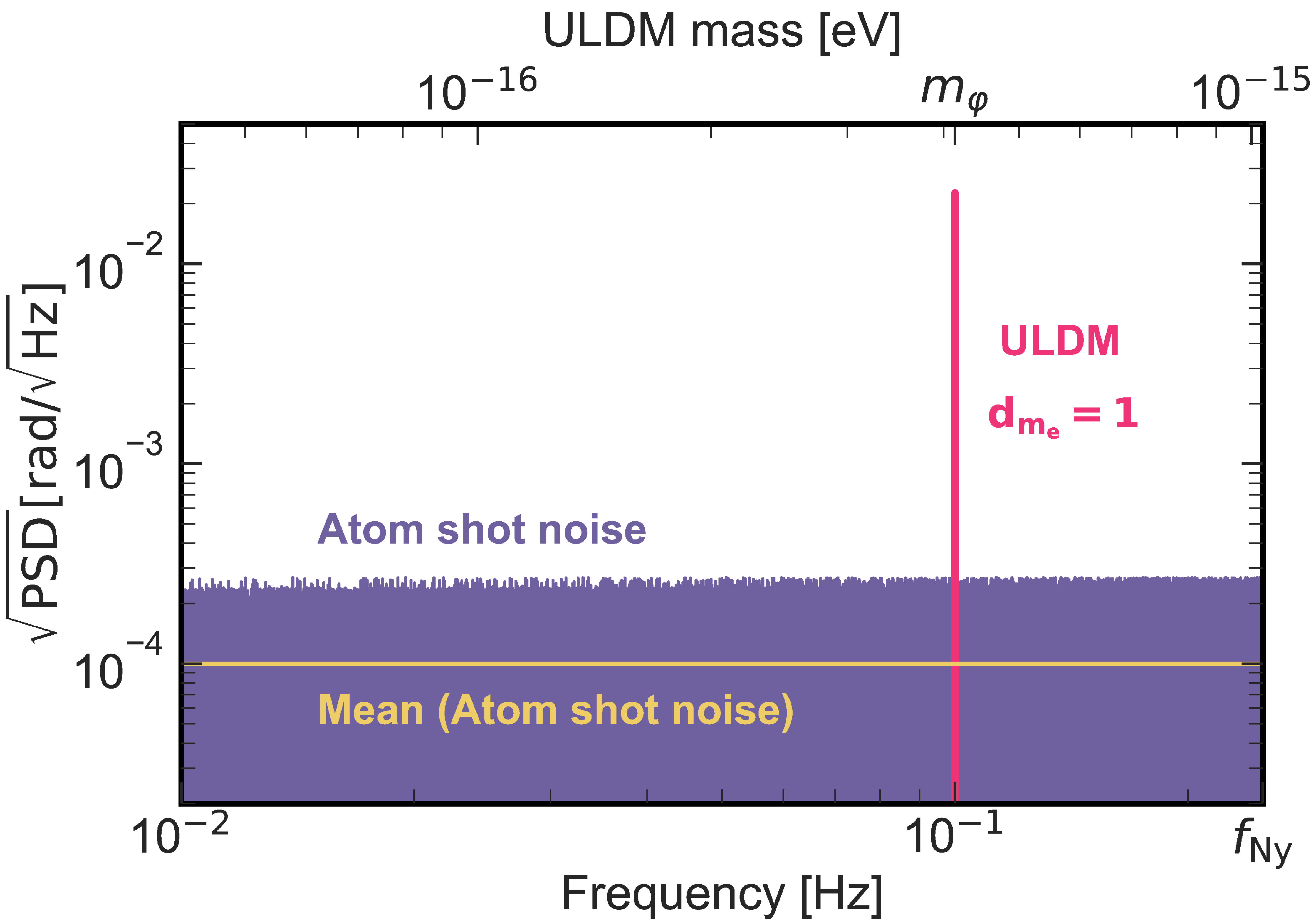


Searching for a signal (ideal setup)

ULDM signal has frequency set by the ULDM mass

Most natural to search for ULDM in frequency space (power spectral density)

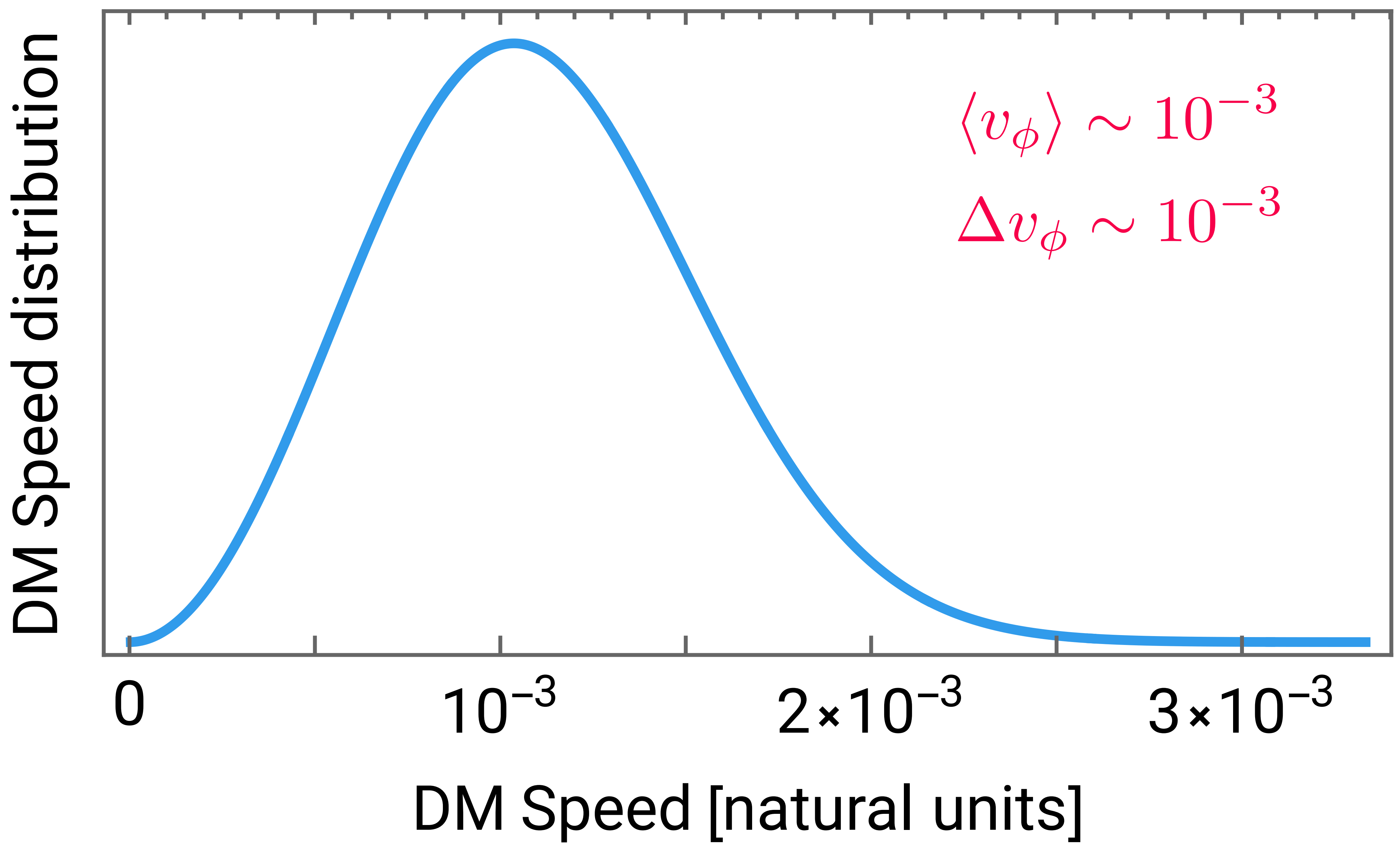


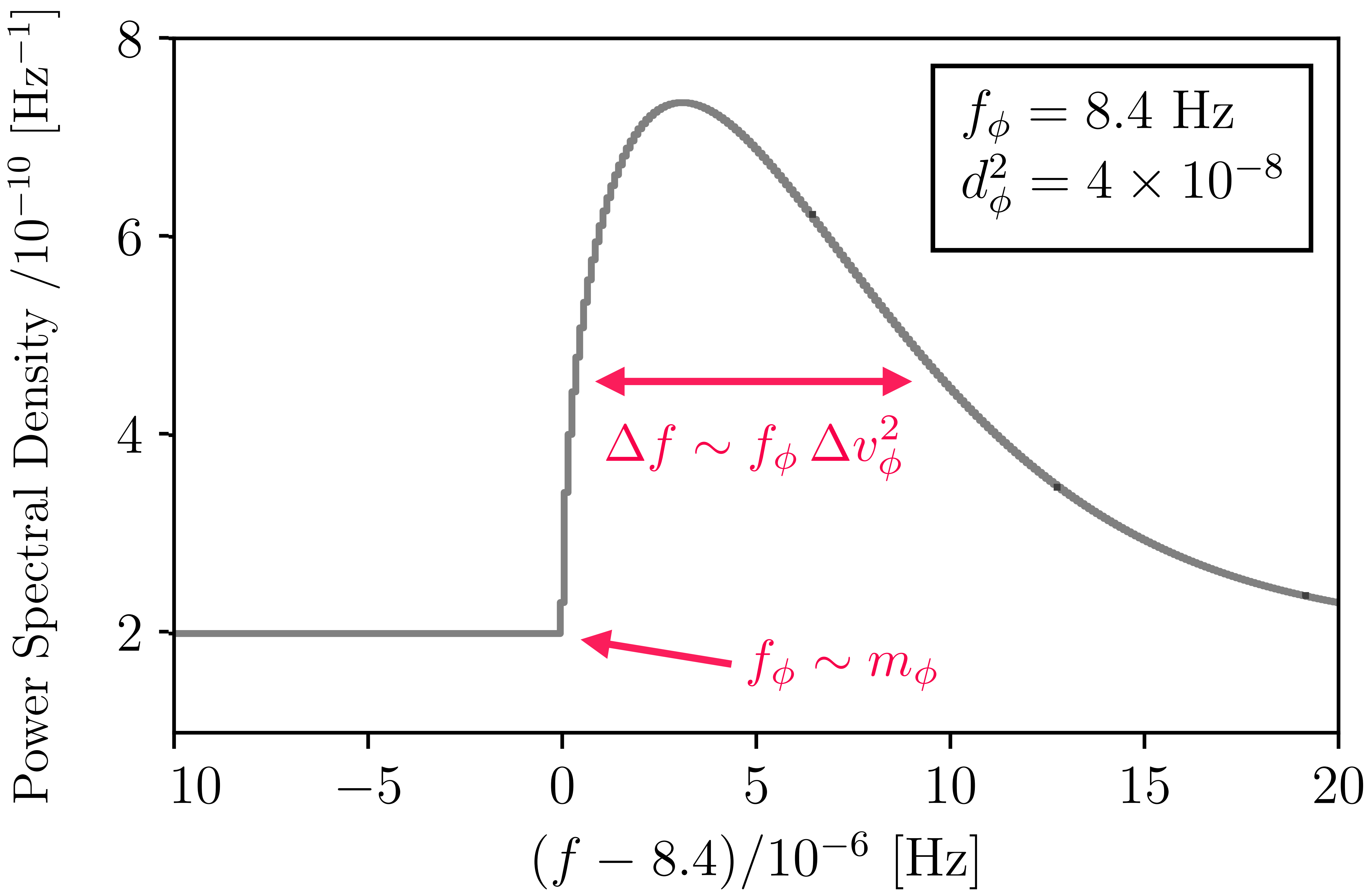


Carlton, **CM**, PRD, arXiv:2308.10731

Zooming in on ULDM ‘spike’

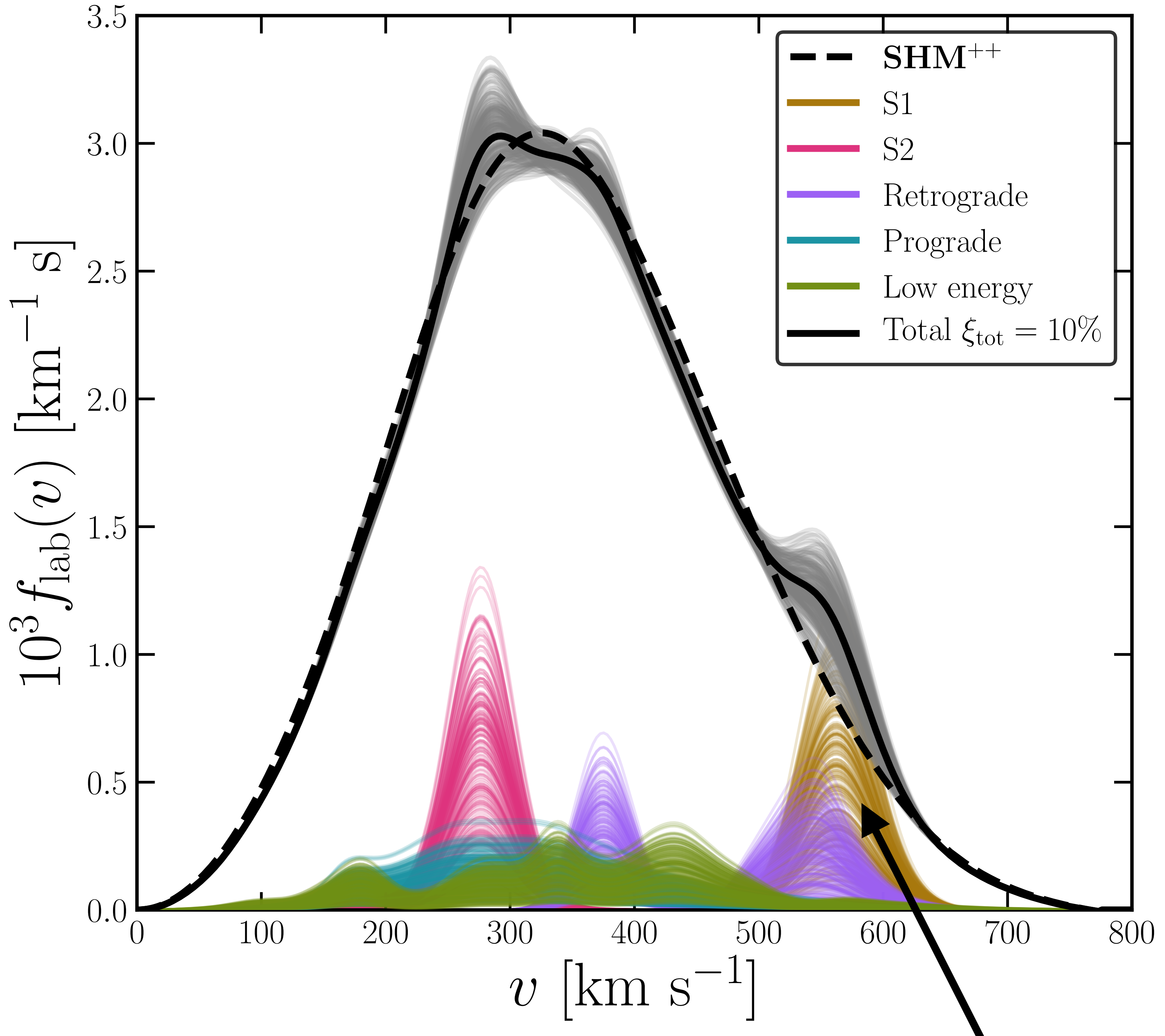
The ‘spike’ has a characteristic distribution set by ULDM properties in the Solar System

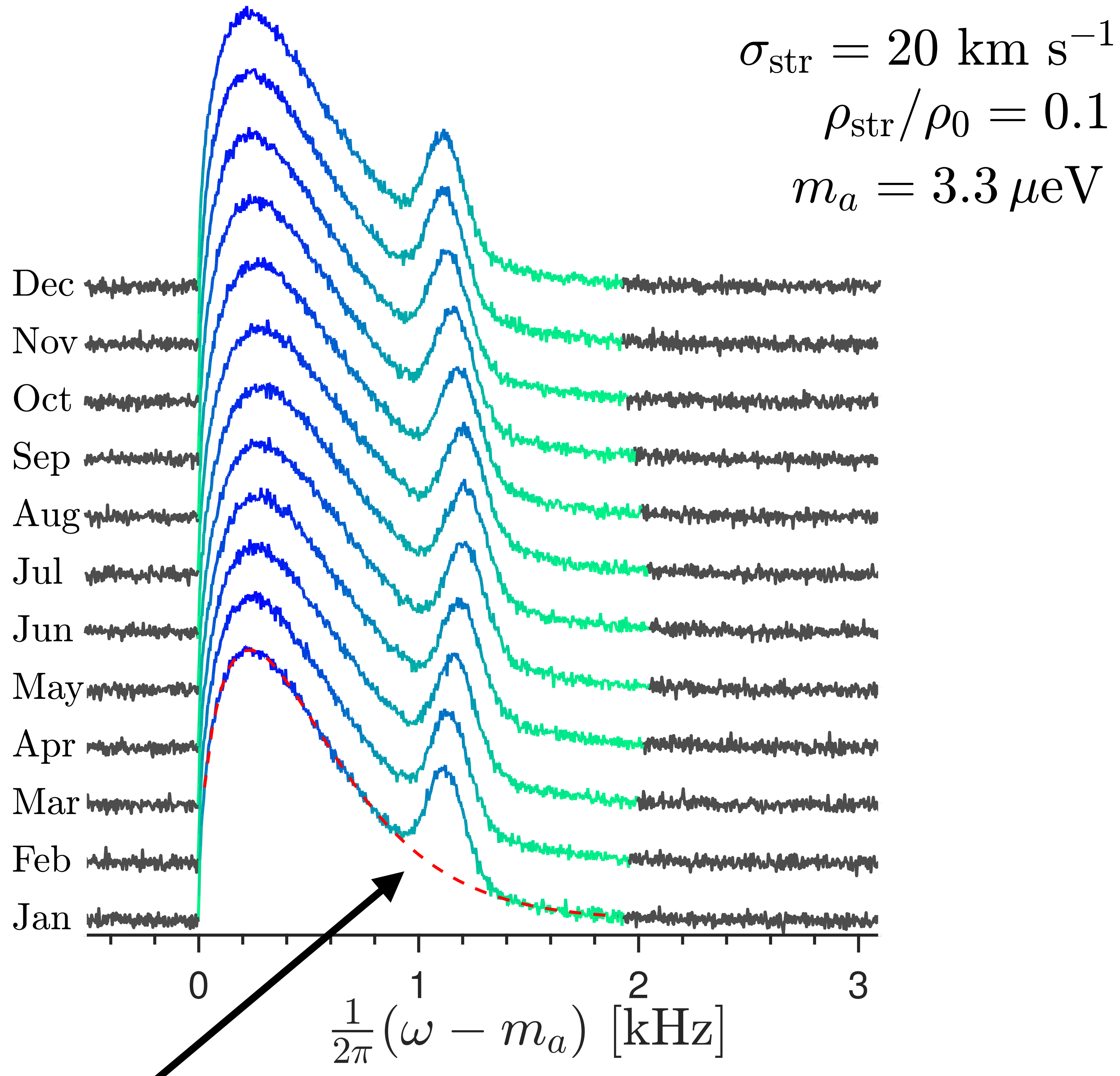




Badurina, Beniwal, **CM**
PRD, arXiv:2306.16477

Zooming in on ULDM ‘spike’

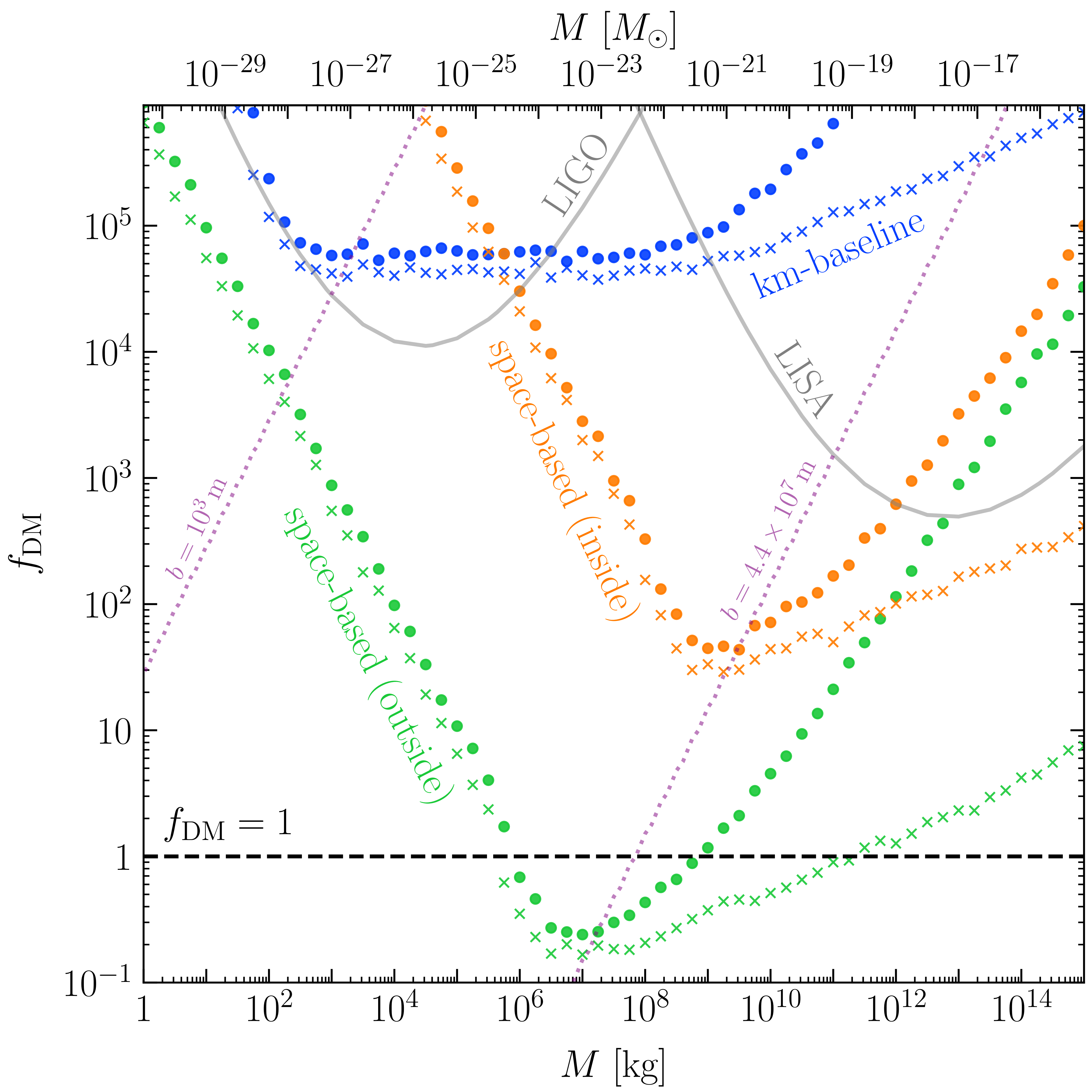


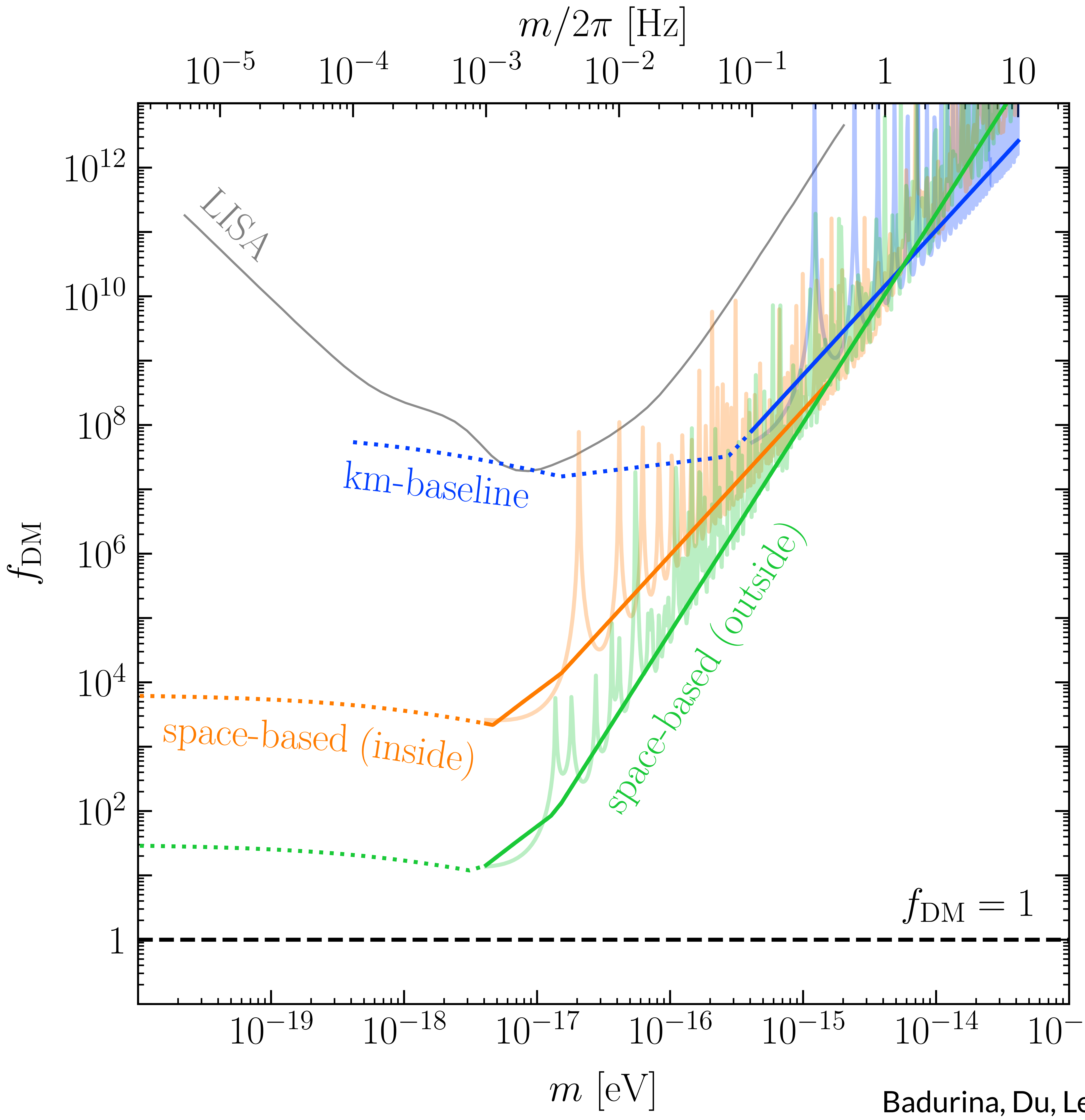


Features in the speed distribution would show up in the measured signal

O’Hare, Evans, CM, arXiv:1807.09004, PRD

Very long-term: dark matter gravitational interactions

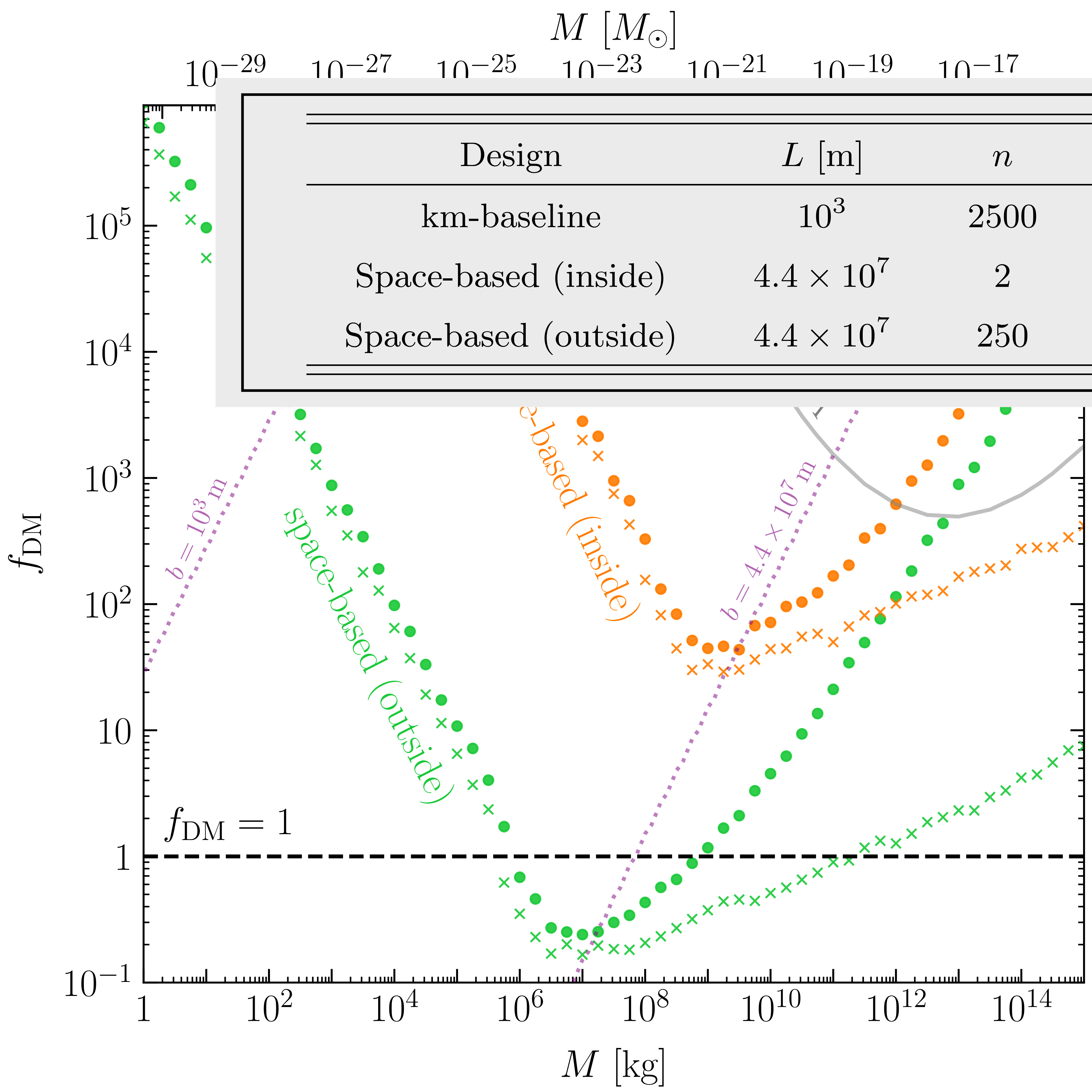


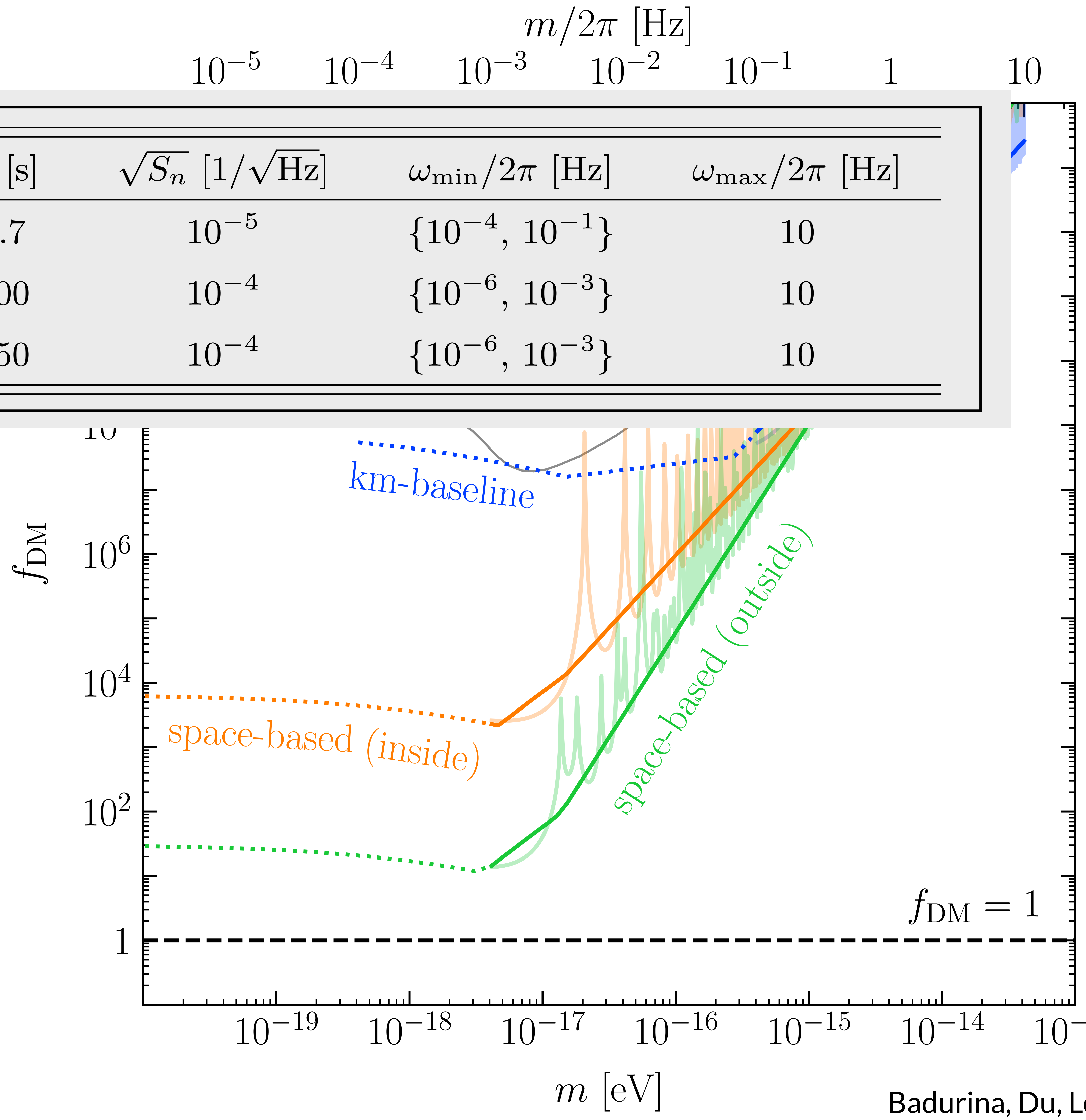


Badurina, Du, Lee, Wang, Zurek, arXiv:2505.00781

Very long-term: dark matter gravitational interactions

Design	L [m]	n	T [s]	$\sqrt{S_n}$ $[1/\sqrt{\mathrm{Hz}}]$	$\omega_{\min}/2\pi$ [Hz]	$\omega_{\max}/2\pi$ [Hz]
km-baseline	10^3	2500	1.7	10^{-5}	$\{10^{-4}, 10^{-1}\}$	10
Space-based (inside)	4.4×10^7	2	100	10^{-4}	$\{10^{-6}, 10^{-3}\}$	10
Space-based (outside)	4.4×10^7	250	150	10^{-4}	$\{10^{-6}, 10^{-3}\}$	10



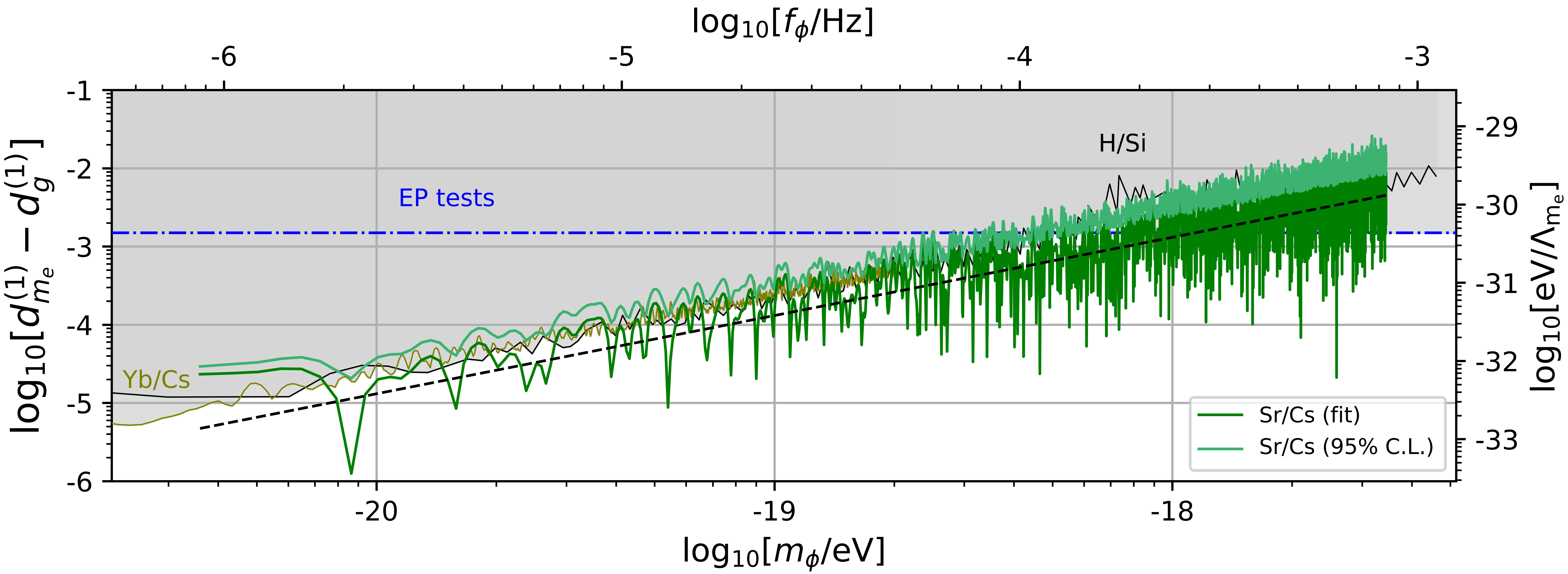


Badurina, Du, Lee, Wang, Zurek, arXiv:2505.00781

Atomic clocks are complementary (lower mass)

Atomic clocks also sensitive to changes in energy levels

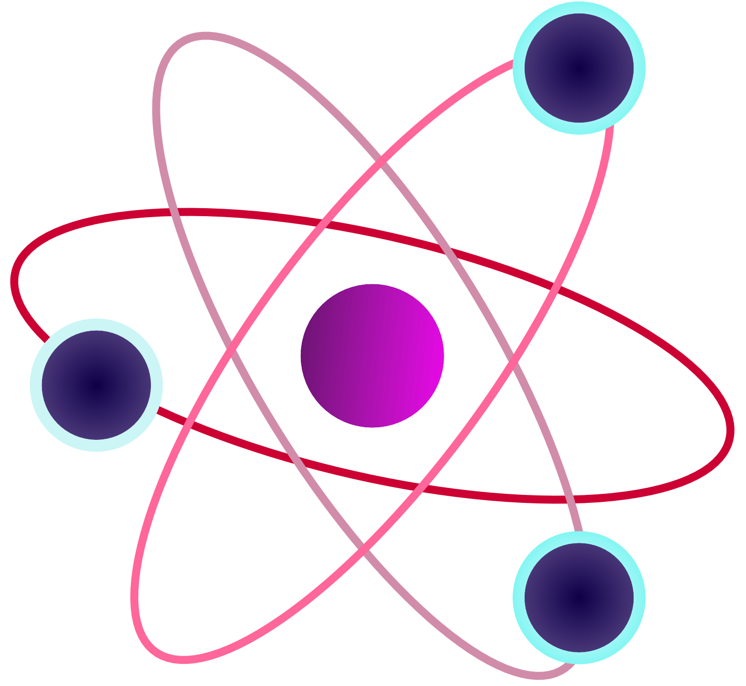
Always need to compare two clocks (use one as a reference)



[atom interferometers probe ~ 10^{-16} to 10^{-13} eV]

QSNET
New J. Phys. 25 093012 (2023)

Laser interferometers are complementary (higher mass)

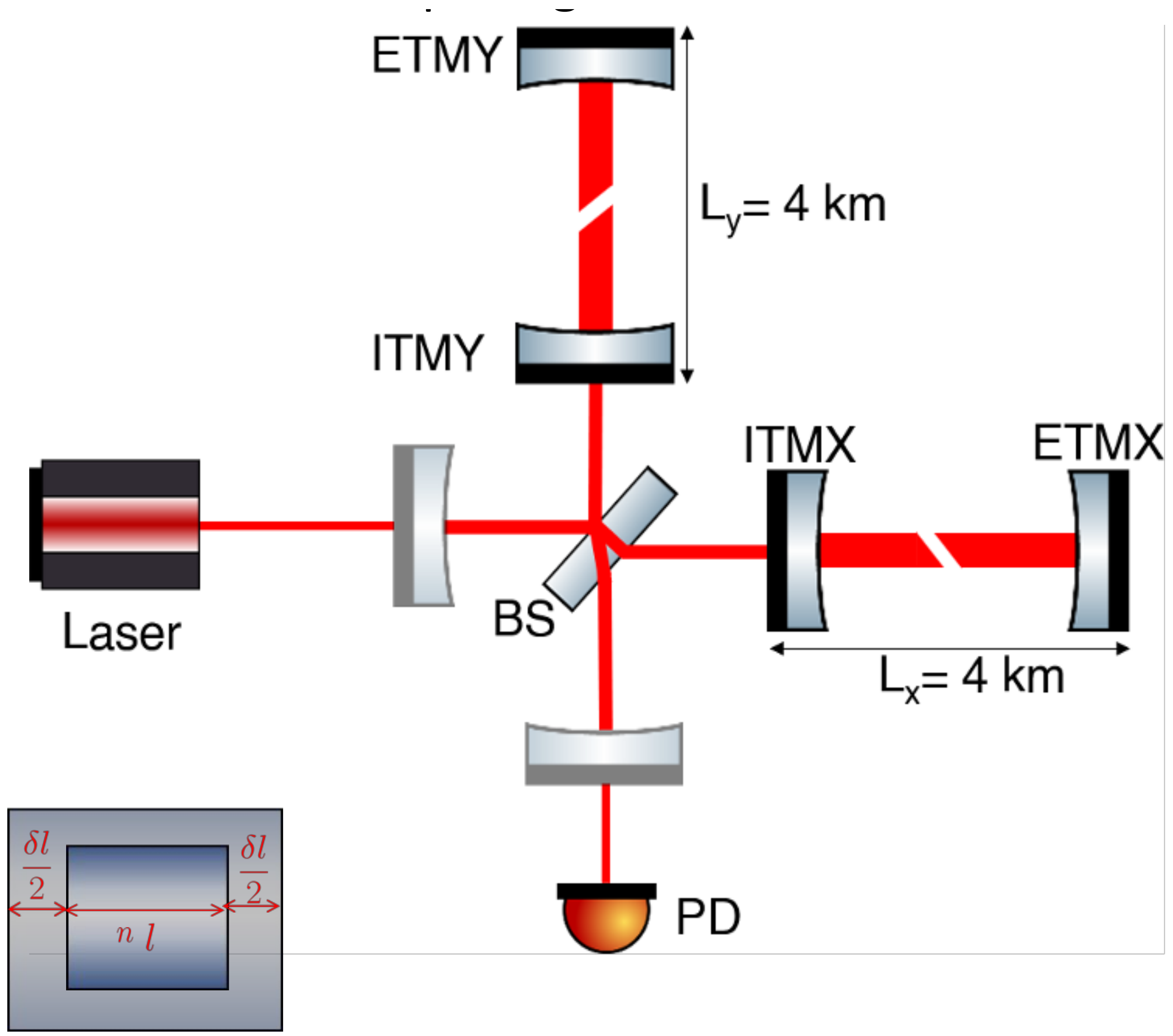


Typical atomic size ~ Bohr radius $a_0 \sim \dfrac{1}{m_e \alpha}$

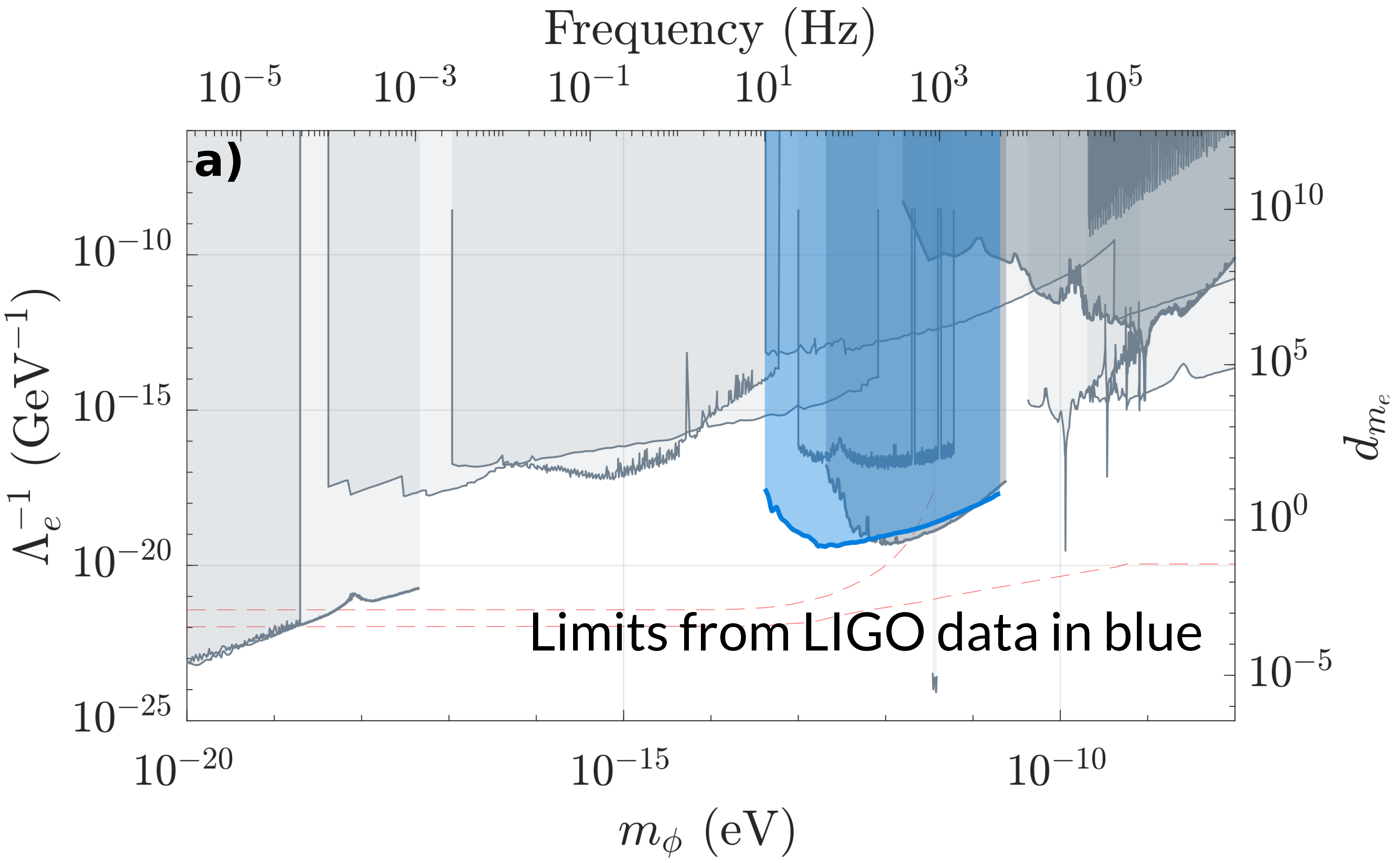
Scalar ULDM leads to oscillations in the beamsplitter and the test masses

$$\frac{\delta_l}{l} = -\left(\frac{\delta_\alpha}{\alpha} + \frac{\delta_{m_e}}{m_e}\right),$$

$$\frac{\delta_n}{n} = -5 \cdot 10^{-3}\left(2\frac{\delta_\alpha}{\alpha} + \frac{\delta_{m_e}}{m_e}\right)$$



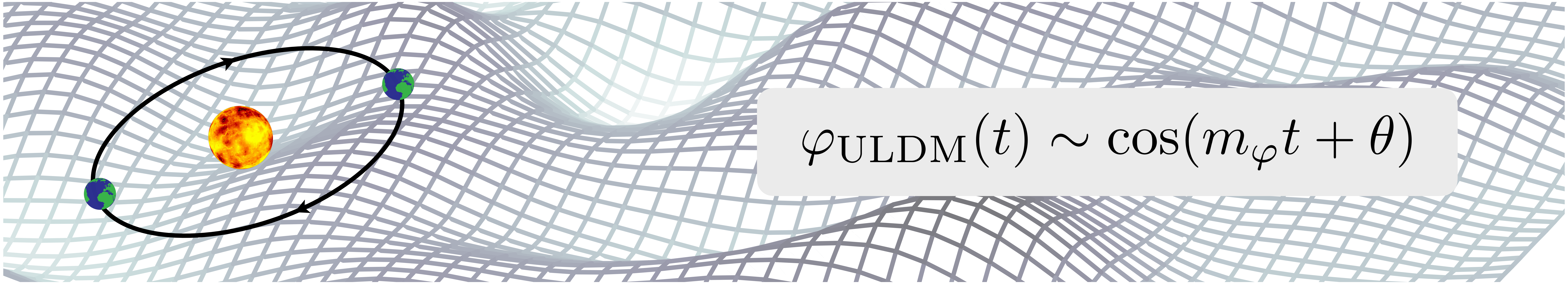
Laser interferometers are complementary (higher mass)



[atom interferometers probe ~ 10^{-16} to 10^{-13} eV]

Göttel et al, PRL
arXiv:2401.18076

Much more could be said…



ULDM can give rise to:

1. Changes in fundamental constants (scalar ULDM)
2. Accelerations on test masses (vector ULDM)
3. Precession of spins (pseudoscalar ULDM)
4. Mimic GW signals (spin-2 ULDM)

Lots of activity in this area, including many groups in the UK
(apologies to all of those I wasn't to mention)

Summary

XLZD is an incredible detector with potential
to detect many types of particle dark matter candidate

And there is a very active and comprehensive programme
of activity to search for dark matter across