The University of Manchester

Phenomenological Modelling of Light Dark Matter with Optically Levitated Sensors

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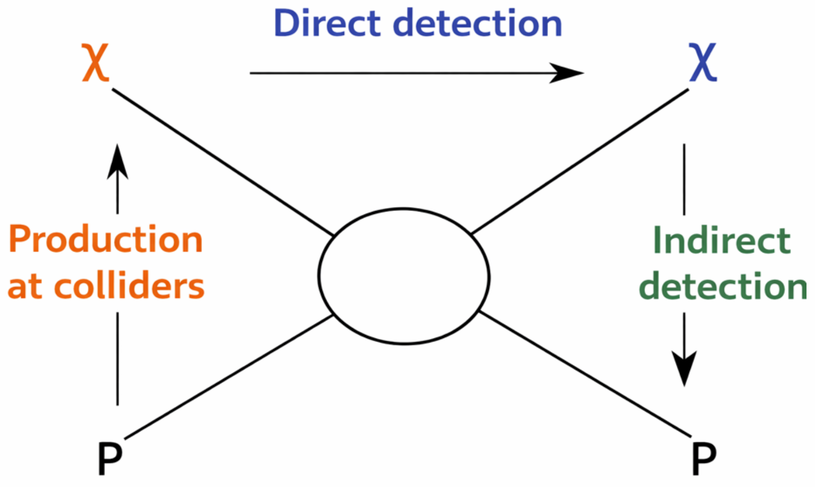
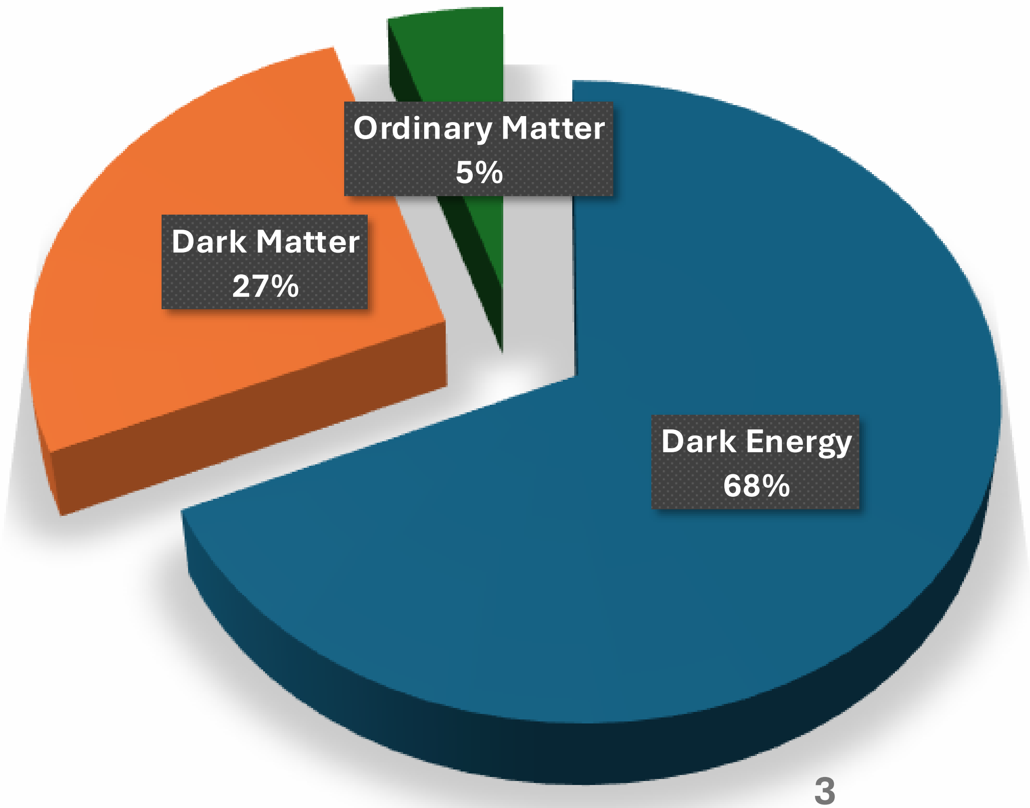
Dark matter

- Most of the matter in the Universe is **non-luminous** and **non-baryonic**

- Evidence from multiple independent probes:
    - **Galactic dynamics**
    - **CMB anisotropies**
    - **Structure formation**

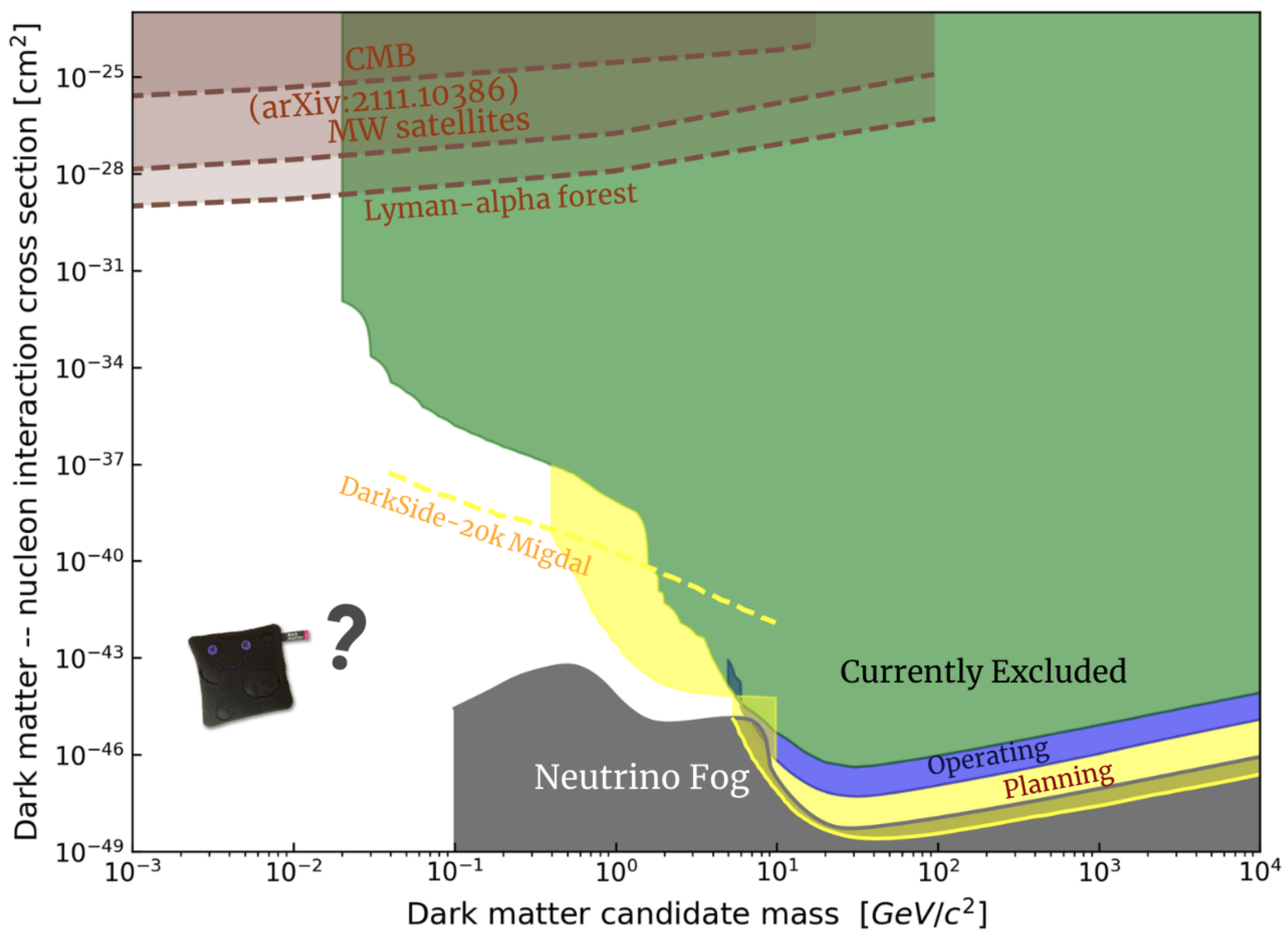
- Viable candidates include:
    - Axions / dark photons / fuzzy dark matter
    - **WIMPs** and other particle candidates
    - MACHOs / primordial black holes





Beyond the WIMP Paradigm

- WIMPs have been the leading dark matter paradigm for decades
- Direct detection now probes deeply into the parameter space above ~GeV masses, nearing the **neutrino floor**
- The **absence** of a signal places increasing **pressure** on conventional **WIMP parameter space**
- This motivates a broader experimental program targeting **lower-mass** dark matter with new detection strategies



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Optomechanically levitating nanoparticles

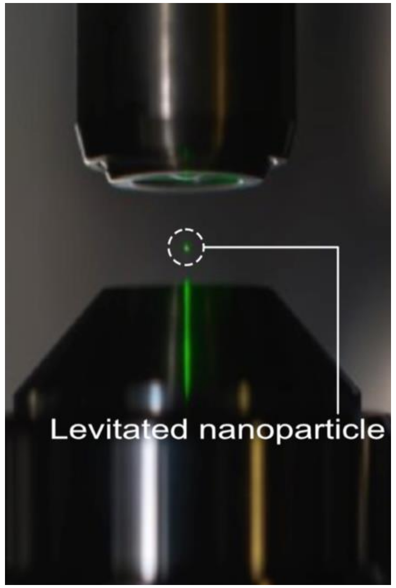
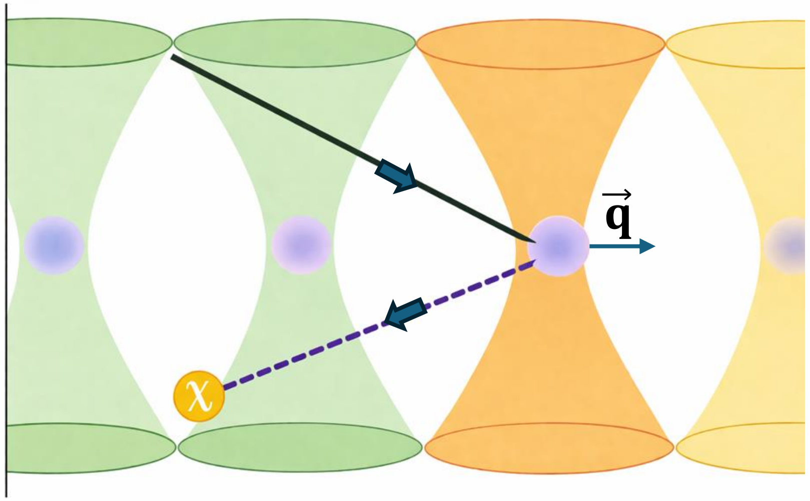


Image courtesy of: **Jayadev Vijayan**

- Optical traps **levitate** particles with masses of order **femtograms** and radii of a few to a few hundred nanometres
- Continuous position readout with **nanometre (or better) precision**
- The system behaves as a **damped harmonic oscillator**
- Ultra-high vacuum setups, with **minimal backgrounds**

\- Several optomechanical levitation experiments are currently under development in **Manchester**



Key advantages for dark matter detection:

- Singal is a **momentum transfer** ($p \propto v$), not energy deposit ($E_R \propto v^2$)
- Enhanced sensitivity to low-velocity/ **low-mass dark matter**

From Detector Response to Dark Matter Limits

Detector Model → Impulse Reconstruction → Dark Matter Scattering characterisation → Rate Folding → Limits

Detector model:

- Inputs:
  - Experimental parameters
- Output:
  - Synthetic displacement time series
  - **Impulse response template**
  - Calibrated PSD model

Time-domain reconstruction:

- Inputs:
  - Inject impulse
  - **Ringdown simulation**
  - **AR whitening**
  - **Matched filtering**
  - Peak SNR extraction
- Output:
  - **Detection efficiency**
  - **Amplitude-recovery map**
  - Null/threshold validation

Detector folding:

- Apply efficiency
- Convolve with reconstruction resolution
- Integrate over analysis window and exposure

$$N_{\text{sig}}(m_\chi, m_\phi, \alpha_n) = T_{\text{exp}} \int dq \, \frac{dR}{dq}(q) \, \epsilon(q) \, P_{\text{rec}}(q)$$

- **dR/dq: true recoil spectrum** from DM module
- $\epsilon(q)$: **detection efficiency** from impulse characterization
- $P_{rec}(q)$: migration into the selected reconstruction window

Theoretical Description of the Sensor

Goal: detect **impulsive momentum transfer** to the centre-of-mass mode of a levitated nanosphere.

Observable: $q \equiv \Delta p = m_s \, \Delta v$

With m_s as the mass of the sensor and Δv is the impulse-induced **velocity step**

Equation of motion:

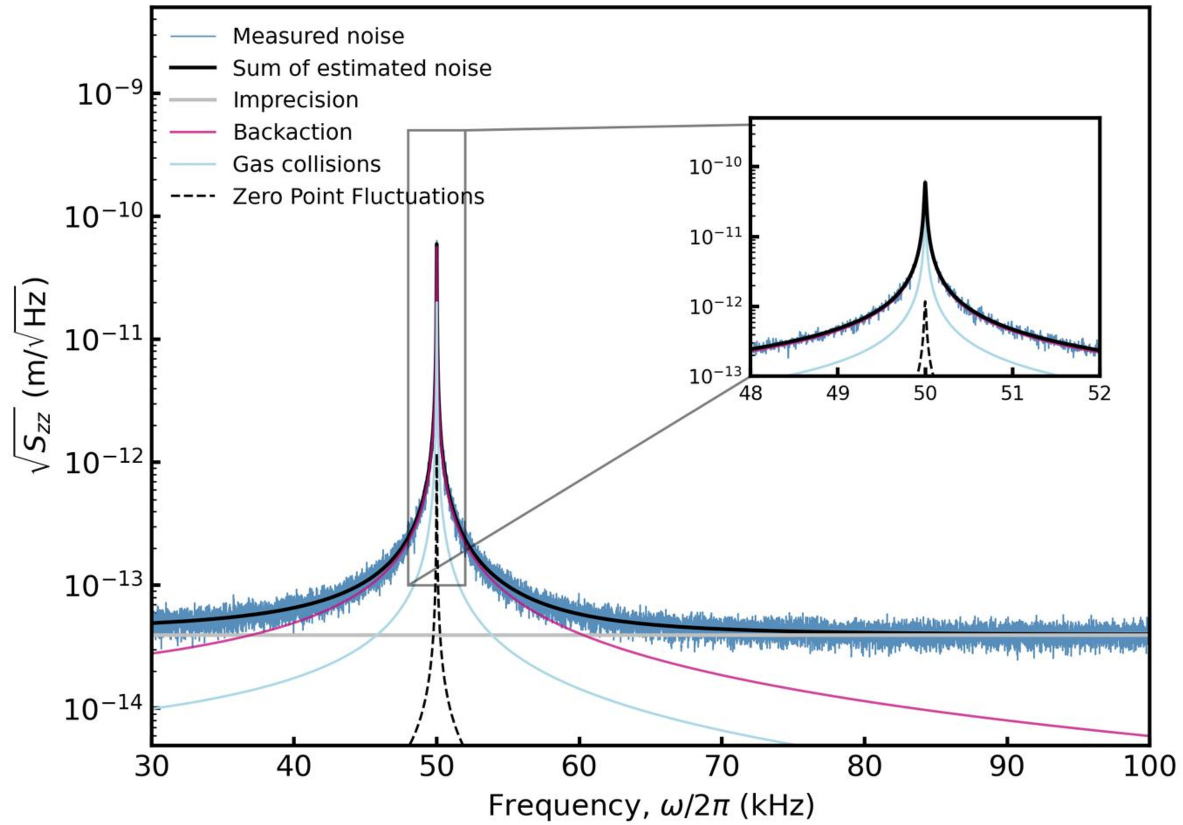
$$m_s \ddot{z} + m_s \gamma \dot{z} + m_s \omega_0^2 z = F_{\text{noise}}(t) + q\,\delta(t - t_0)$$

Mechanical susceptibility:

$$\chi(\omega) = \frac{1}{m_s\left(\omega_0^2 - \omega^2 - i\gamma\omega\right)}$$

Displacement-noise model:

$$S_{zz}(\omega) = |\chi(\omega)|^2 \left(S_{FF}^{\text{ba}} + S_{FF}^{\text{gas}}\right) + S_{zz}^{\text{imp}} + S_{zz}^{\text{zpf}}$$



- Silica nanosphere: $m_s \simeq 4.8\,\text{fg}$, $r \simeq 166\,\text{nm}$
- Centre-of-mass z-mode at $\sim 50\,\text{kHz}$
- Readout efficiency: $\eta \sim 0.1$
- Near resonance, the noise is backaction-dominated, with subleading gas contribution

Time-Domain of the Sensor

Equation of motion (Langevin form):

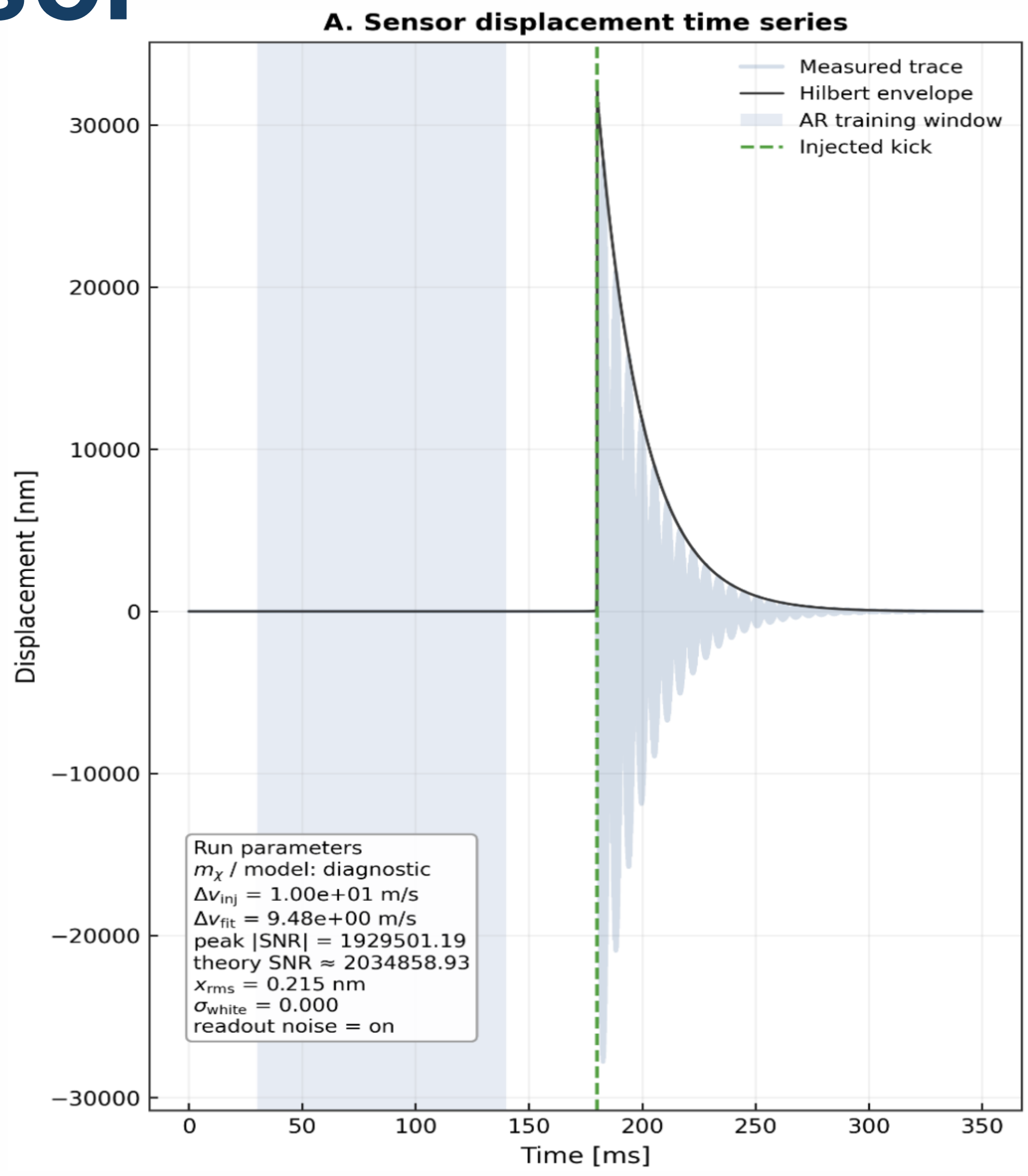
$$m_s\ddot{z} + m_s\Gamma\dot{z} + m_s\Omega_0^2 z = F_{\mathrm{th}}(t) + F_{\mathrm{ba}}(t) + F_{\mathrm{tech}}(t) + q\,\delta(t - t_0)$$

- m_s: sensor mass
- Ω_0: resonance frequency of the readout mode
- Γ: effective linewidth
- $q = \Delta p = m_s \Delta v$

$$\dot{z}(t_0^+) - \dot{z}(t_0^-) = \Delta v \qquad \omega_d = \sqrt{\Omega_0^2 - \Gamma^2/4}$$

$$z_{\mathrm{sig}}(t) = \Theta(t - t_0)\,\frac{q}{m_s\omega_d}\,e^{-\Gamma(t-t_0)/2}\,\sin\left[\omega_d(t - t_0)\right]$$

The readout mode is modelled as a noisy **damped harmonic oscillator**. A dark-matter interaction is represented by an **instantaneous momentum transfer** q, equivalently a velocity step $\Delta v = q/m_s$ .The observable is the resulting **ringdown,** simulated in the time domain with stochastic force noise and readout imprecision, and used as the template for **matched-filter reconstruction.**



Impulse Reconstruction Algorithm

Step 1: Noise realisation

The code simulates the experimental noise over the analysis window

Step 2: Signal template

The calibrated sensor model is used to generate the expected ringdown from an impulsive momentum transfer

Step 3: Whitening

- An autoregressive (AR) model is applied to both the data and the template
- This whitens the local noise, preventing bias from the resonator line shape or readout colouring

Step 4: Matched filtering

- The template is scanned across the whitened data
- The largest match is recorded as the event statistic

Simulated trace with injected impulse

- Pre-event noise segment
- AR whitening filter
- Whitend data + whitened template
- Matched-filter scan over event time
- Peak SNR

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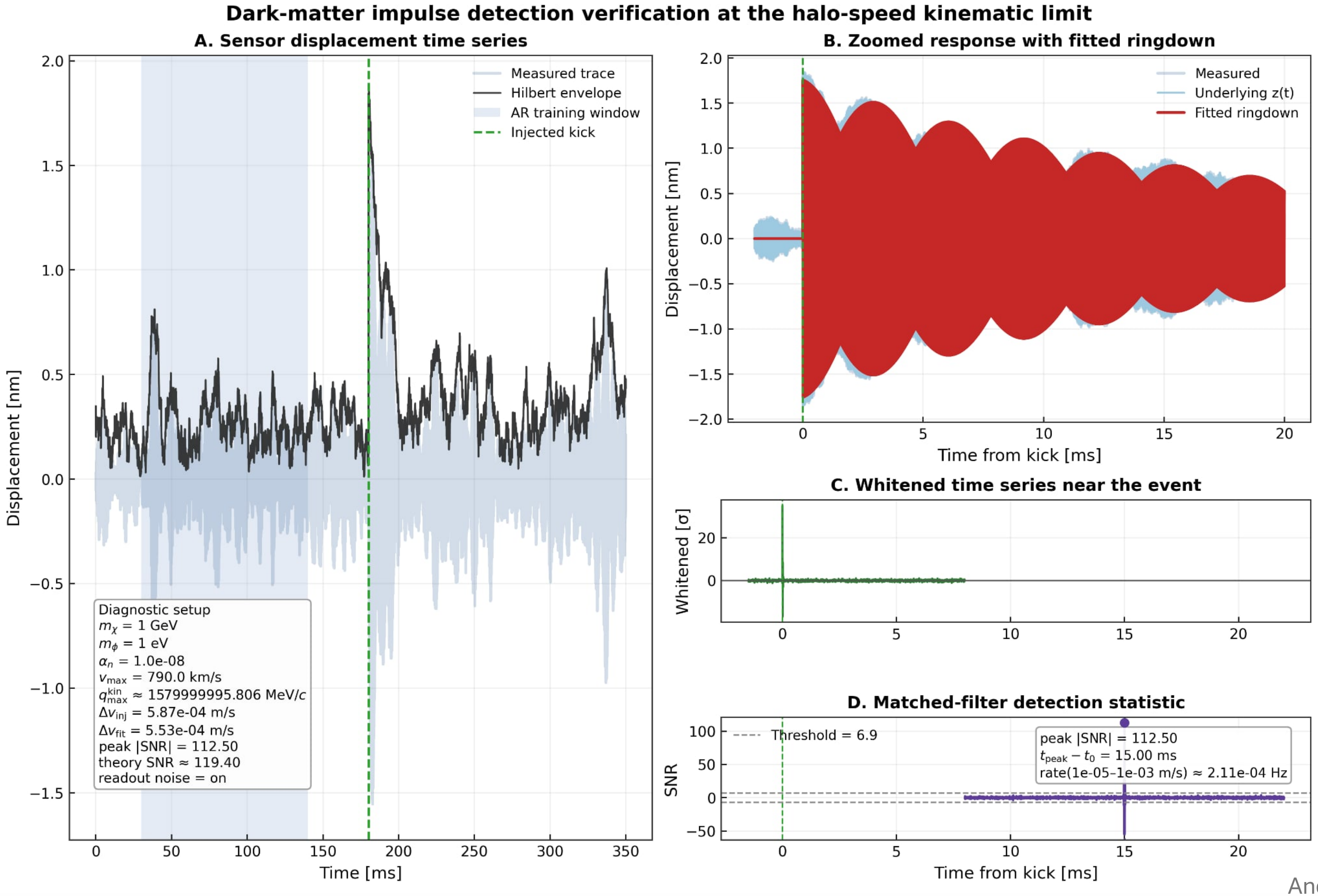
Impulse reconstruction



Simulated trace with injected impulse

- Pre-event noise segment
- AR whitening filter
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- Peak SNR

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Validation of the Reconstruction Pipeline

Plot A: Representative null matched-filter trace

- Even in the absence of an injected signal, local peaks are present
- The selected peak remains well below the analysis threshold, SNR = 6.9

Plot B: Distribution of the null statistics

- Distribution of the maximum matched-filter statistics obtained from each null trial
- Among the 10000 trials, none exceeds the analysis threshold

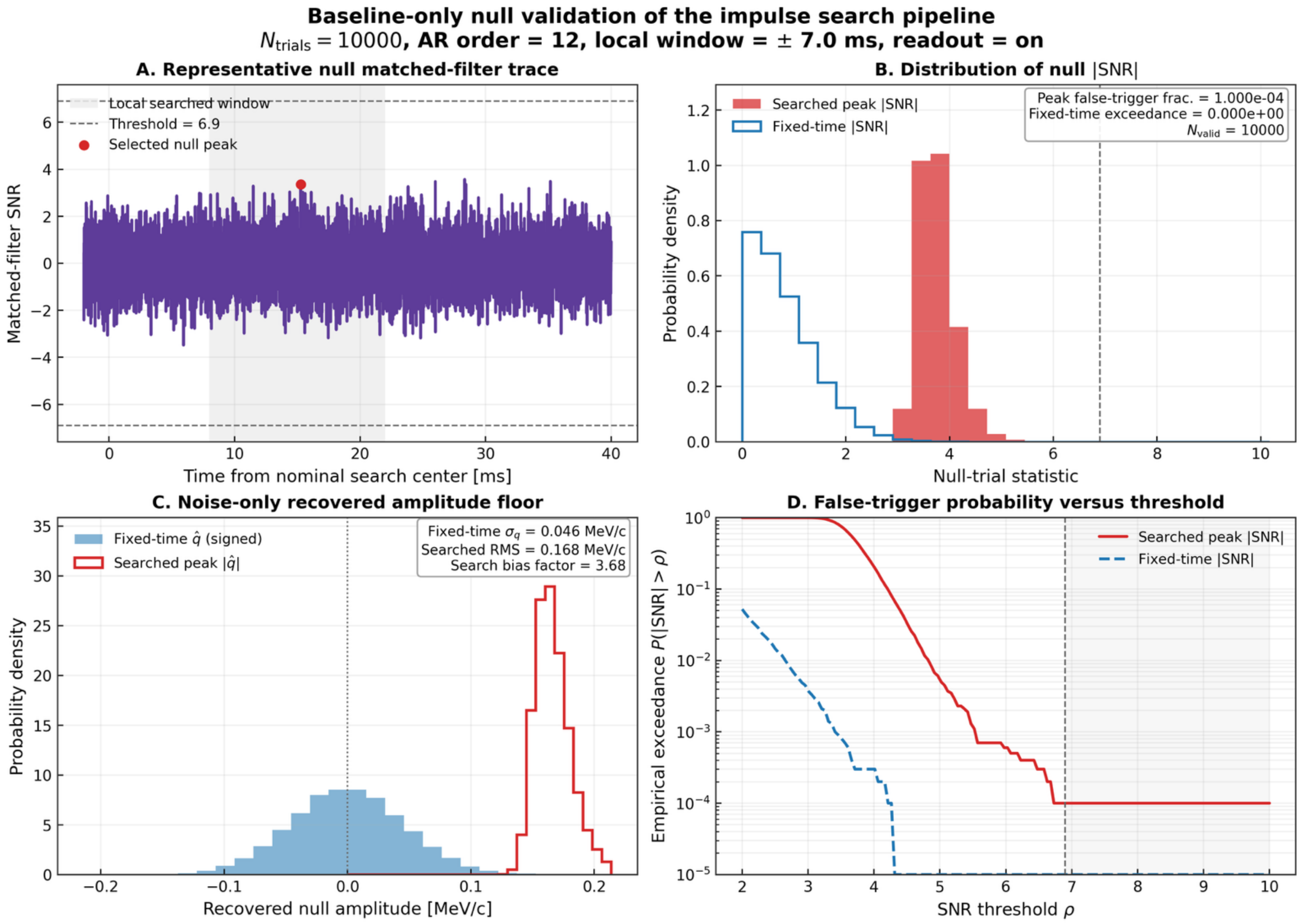
Plot C: Noise-only recovered amplitude

- Blue histogram: reconstructed amplitude at a fixed time
- Red histogram: magnitude of the best-fit amplitude for the largest match

Plot D: False-trigger probability

- Exceedance probability for the fixed-time and search-peak statistics
- The SNR threshold is way above the observed null background

When scanning a finite local time window, how large is the maximum fluctuation expected under the null hypothesis?



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Yukawa-Mediated Dark Matter Levitated Sensors

Interaction Model: $\mathcal{L} \supset g_\chi \bar{\chi}\chi\phi + g_n \bar{n} n \phi, \qquad \alpha_n \equiv \frac{g_\chi g_n}{4\pi}, \qquad \lambda = \frac{\hbar}{m_\phi c}.$

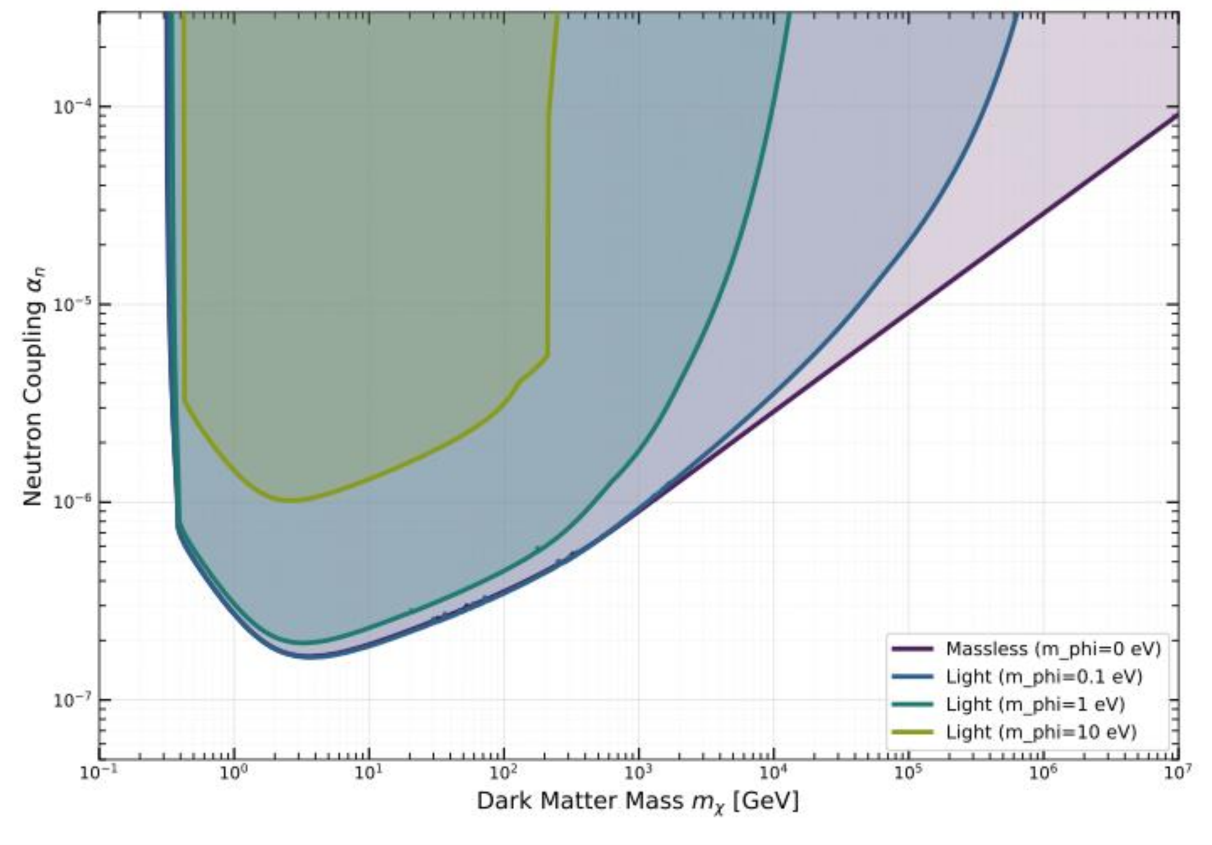
This gives a Yukawa potential: $V(r) \propto \alpha_n \frac{e^{-r/\lambda}}{r}$

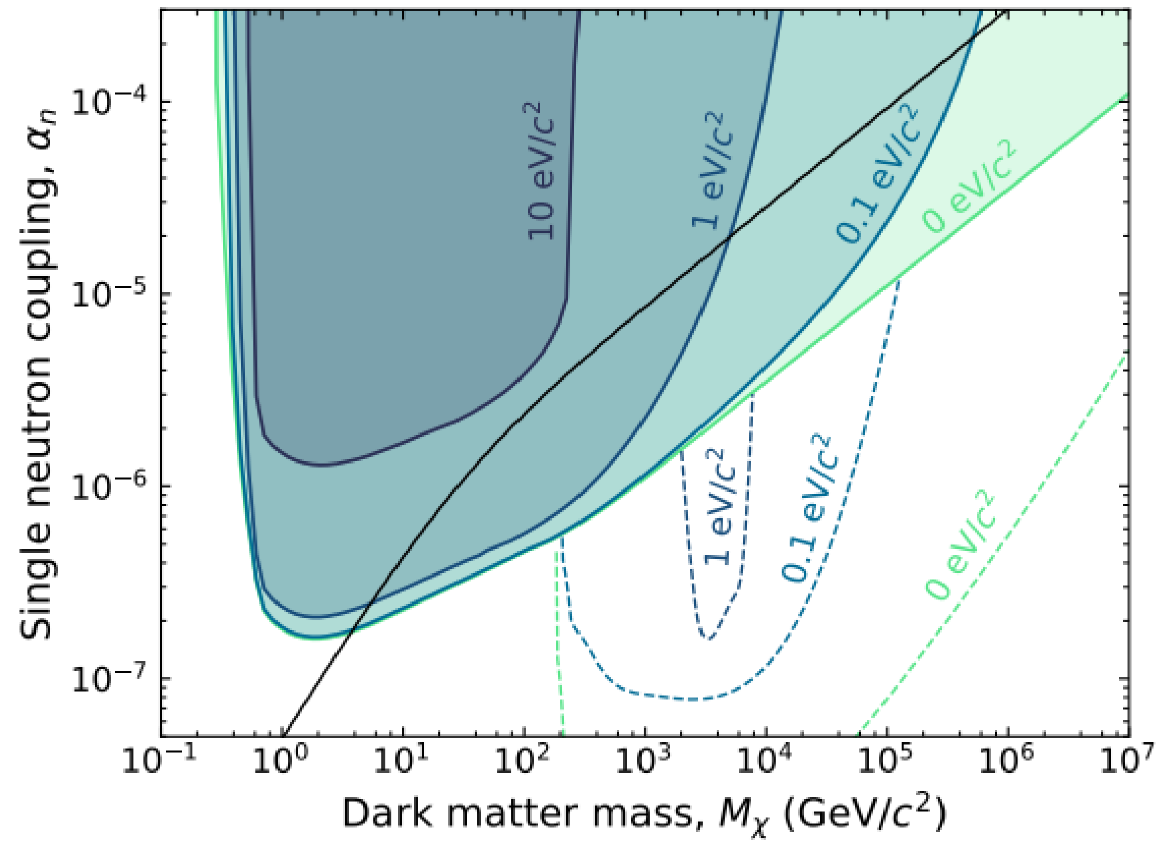
Sensitivity to the new "fifth force":

- **Dark matter particle scatters on the sensor via a light mediator**
- **Coherent nanosphere response → N^2 enchancment**
- **Impulse-sensitive readout →** Strong reach for soft, low-q scattering
- **Classical scattering regime,** not Born
- $dR/d(\Delta v) \otimes \varepsilon(\Delta v)$ → **limits on α_n**

The following results correspond to a **specific** experimental configuration, used here for **validation** and **exploratory** studies. The **modularity** of the framework will allow future extensions aimed at identifying the **optimal setup** for such searches.

Computational Reproduction of the Experimental Yukawa Limits





Near-quantitative agreement between the **computational reconstruction** (left) and the published **experimental exclusion curves** (right).

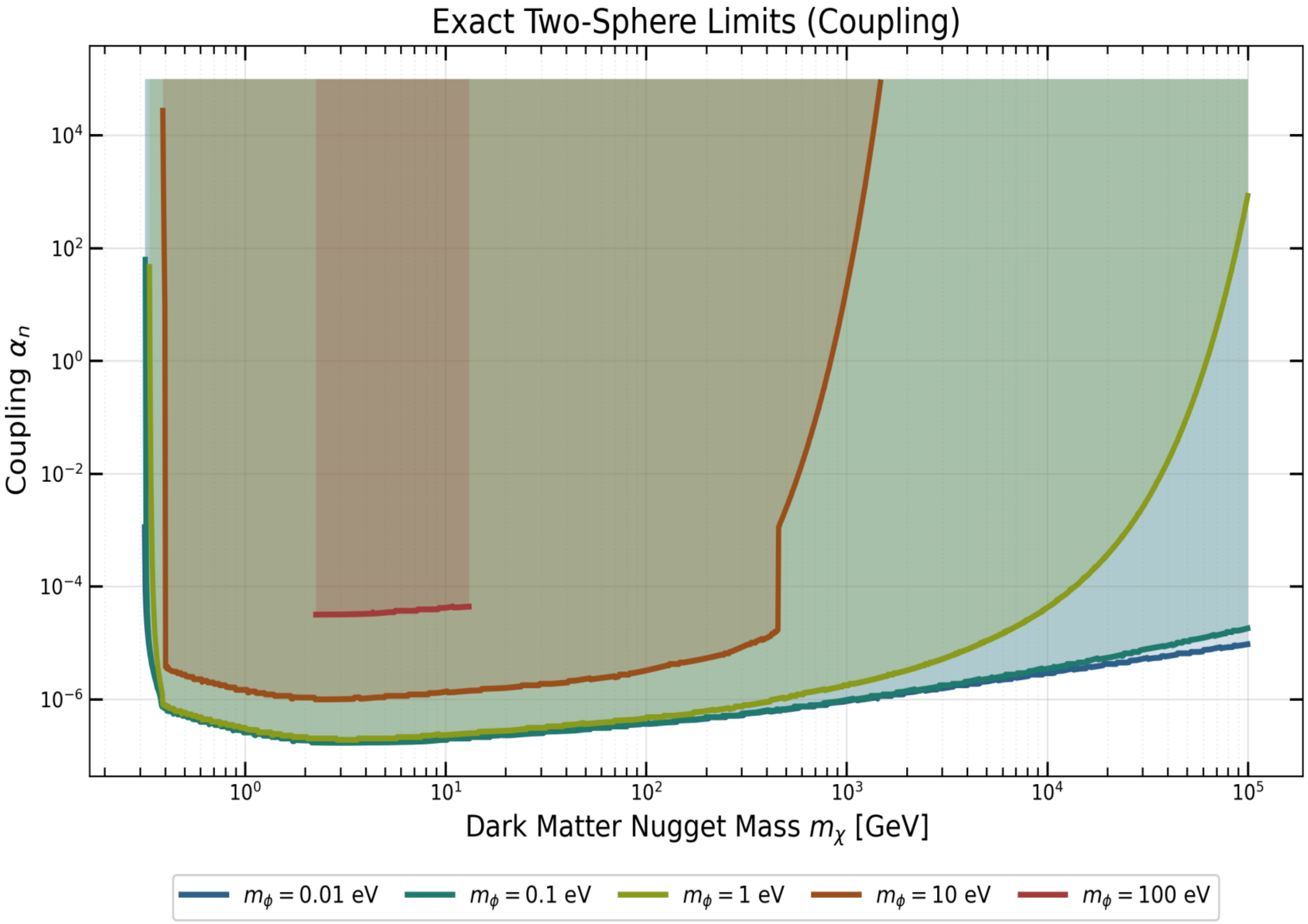
Tseng et al., *Search for Dark Matter Scattering from Optically Levitated Nanoparticles*, **PRX Quantum 6 (2025) 040367**, arXiv:2508.00815 [hep-ex]

Puffy Dark Matter coupling limits

"Puffy" DM (composite DM) refers to DM particles that are not elementary nor point like, this are **composite microscopic** bound states with a finite spatial Radius.

The central technical step is an exact real-space force law between two uniform spheres, obtained via **a 1D Fourier–Bessel integral**, coupled to a trajectory inversion that handles the non-monotonic mapping between impact parameter and momentum transfer.

The graph presents **future experimental** constraints on the α_n coupling constant.



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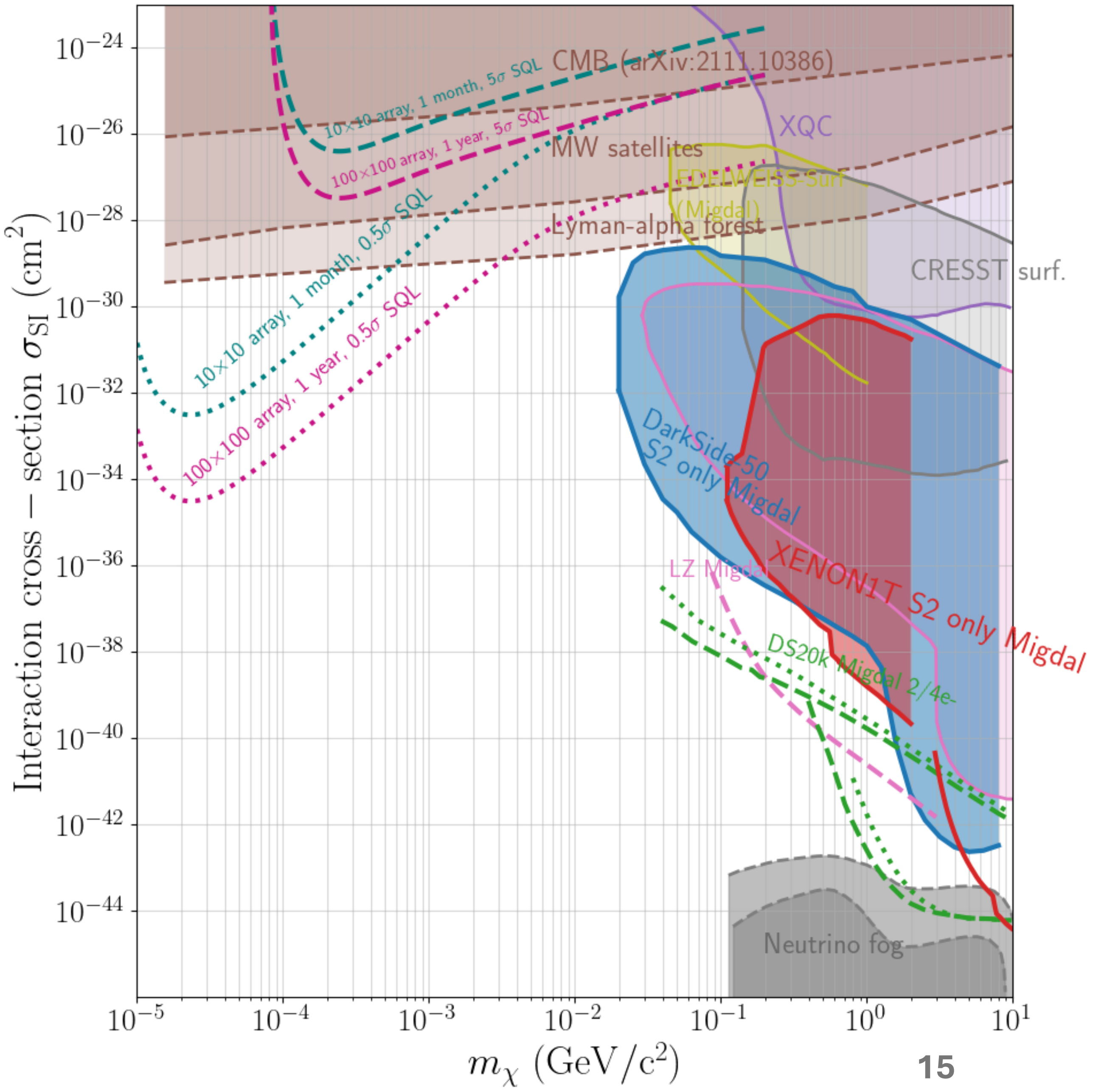
Levitating sensors for low SI searches

- **Theory best-case projections** for coherent low-mass DM scattering with levitated-sensor arrays: 10×10 and 100×100 sensors, shown for the corresponding benchmark exposures alongside existing DM experiments.
- Sensitivity shown for a **specific** target configuration consisting of **SiO2 spheres** with radius of 15nm.
- **Background-free / SQL-limited benchmark**: expected backgrounds < 1 over the exposure.
- **Coherent low-mass DM scattering** extends sensitivity to very small $m_\chi < 10\text{MeV}$.
- Probes **low-mass SI parameter space beyond current large-scale TPCs.**
- **A further goal is to identify the optimal experimental configuration for this study.**



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Conclusion

- Optically levitated sensors provide a distinctive probe of previously **unexplored** regions of low-mass dark-matter parameter space

- These sensors offer a comparatively cost-effective experimental platform

- The simulation framework developed here enables modular and efficient exploration of a broad class of dark-matter models

- It streamlines the connection between detector calibration, sensor response, and phenomenological rate predictions across different experimental configurations

- The long-term goal is to identify experimentally optimal configurations for probing well-motivated dark-matter scenarios

- **With the possible construction of the experiments by the Manchester group!**

Thank you for listening
Any Questions?

Near-Threshold Detection Efficiency

Plot A: Near-Threshold detection efficiency

- For very small injected impulses, the probability of detection is small, as the signal remains bellow the noise floor

Plot B: Detection statistics across threshold

- The panel shows how the event statistics evolves as the true injected signal increases

Plot C: Amplitude recovery and search bias

- Bellow threshold, the search often locks on the largest fluctuation, rather than the true injected signal → This produces the low-amplitude flattening and a non-zero recovered scale even under the null

Plot D: Reconstruction width versus floor

- This panel quantifies the reconstruction width
- Once the signal is sufficiently above threshold, the 68% half-width approaches the baseline fixed time amplitude
- Above threshold, the pipeline is therefore not only efficient, but also reasonably precise

How does the search behave in the presence of a real signal close to the detection threshold?