

■ January 2025

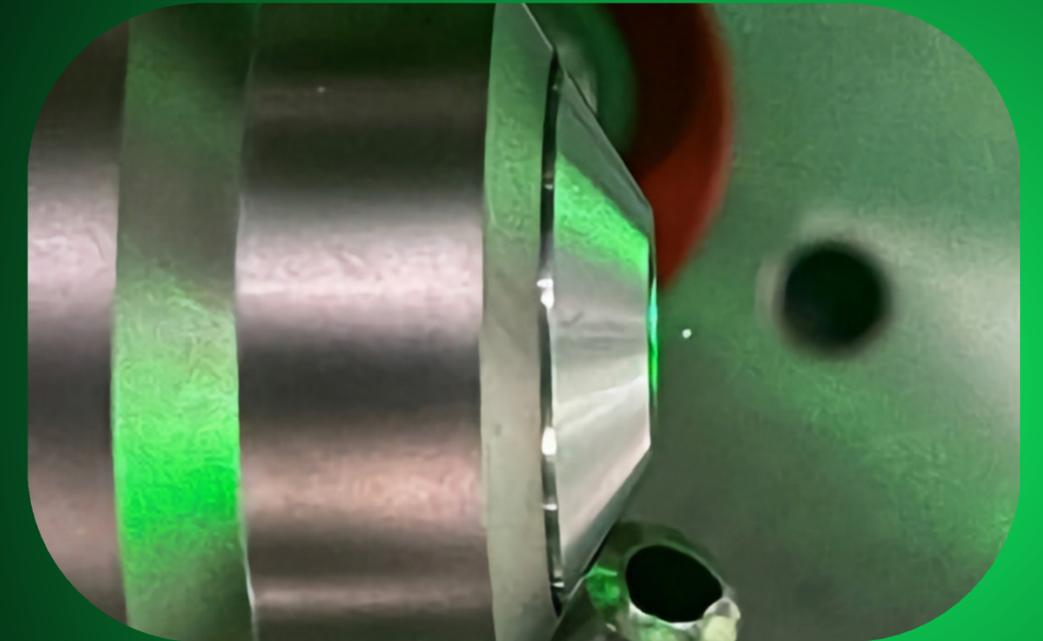


UK NATIONAL  
QUANTUM  
TECHNOLOGIES  
PROGRAMME

# Q-SENSE

Quantum-Sensors for Exploration of Non-baryonic  
Signals and Events

# A DIRECTIONAL DARK MATTER SEARCH



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 **Q-SENSE**



**CHAMKAUR GHAG**

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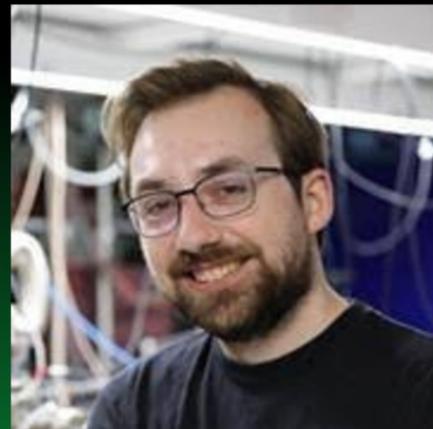
**ROBERT JAMES**



**EVA KILIAN**



**JONATHAN GOSLING**

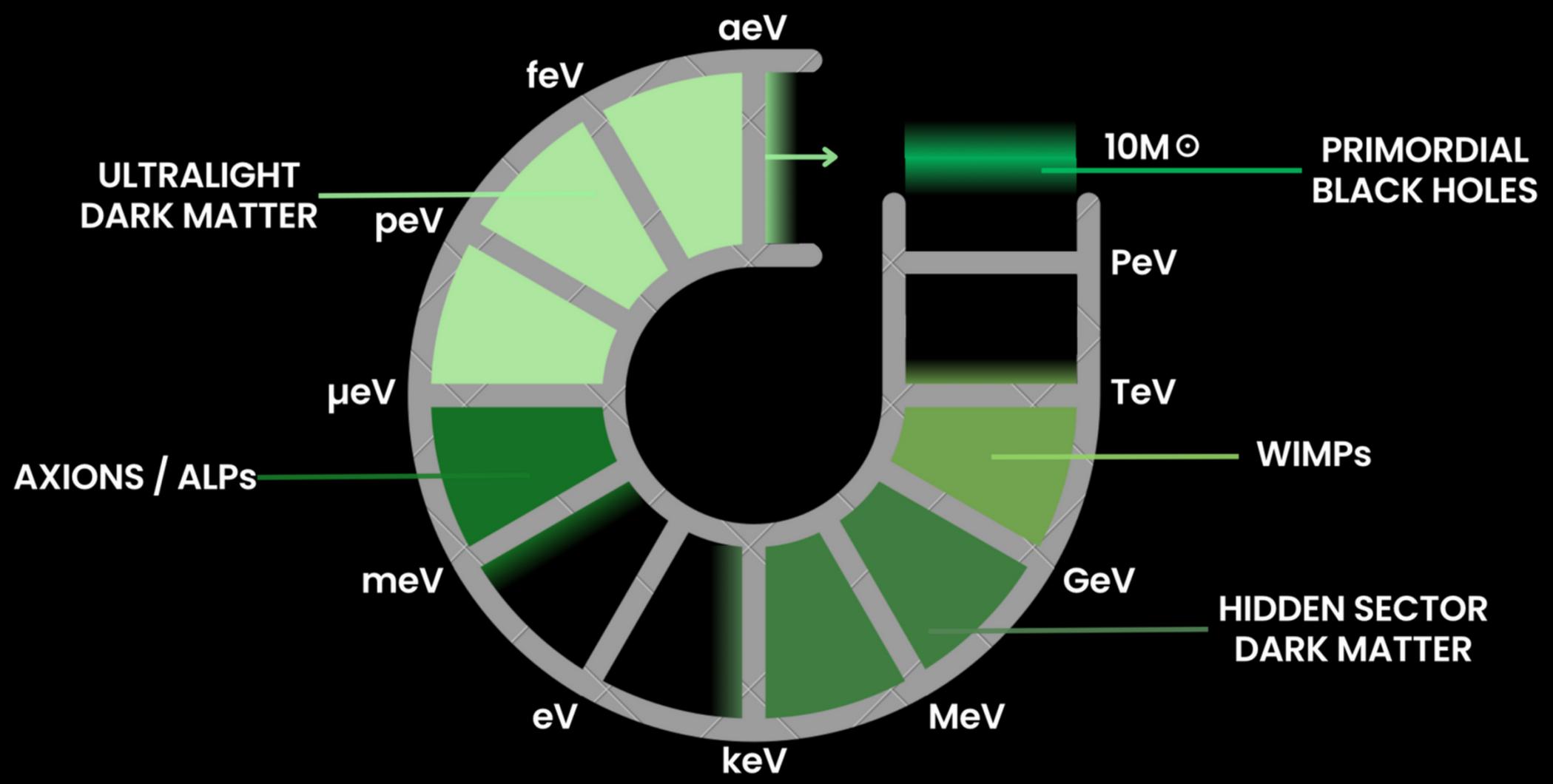


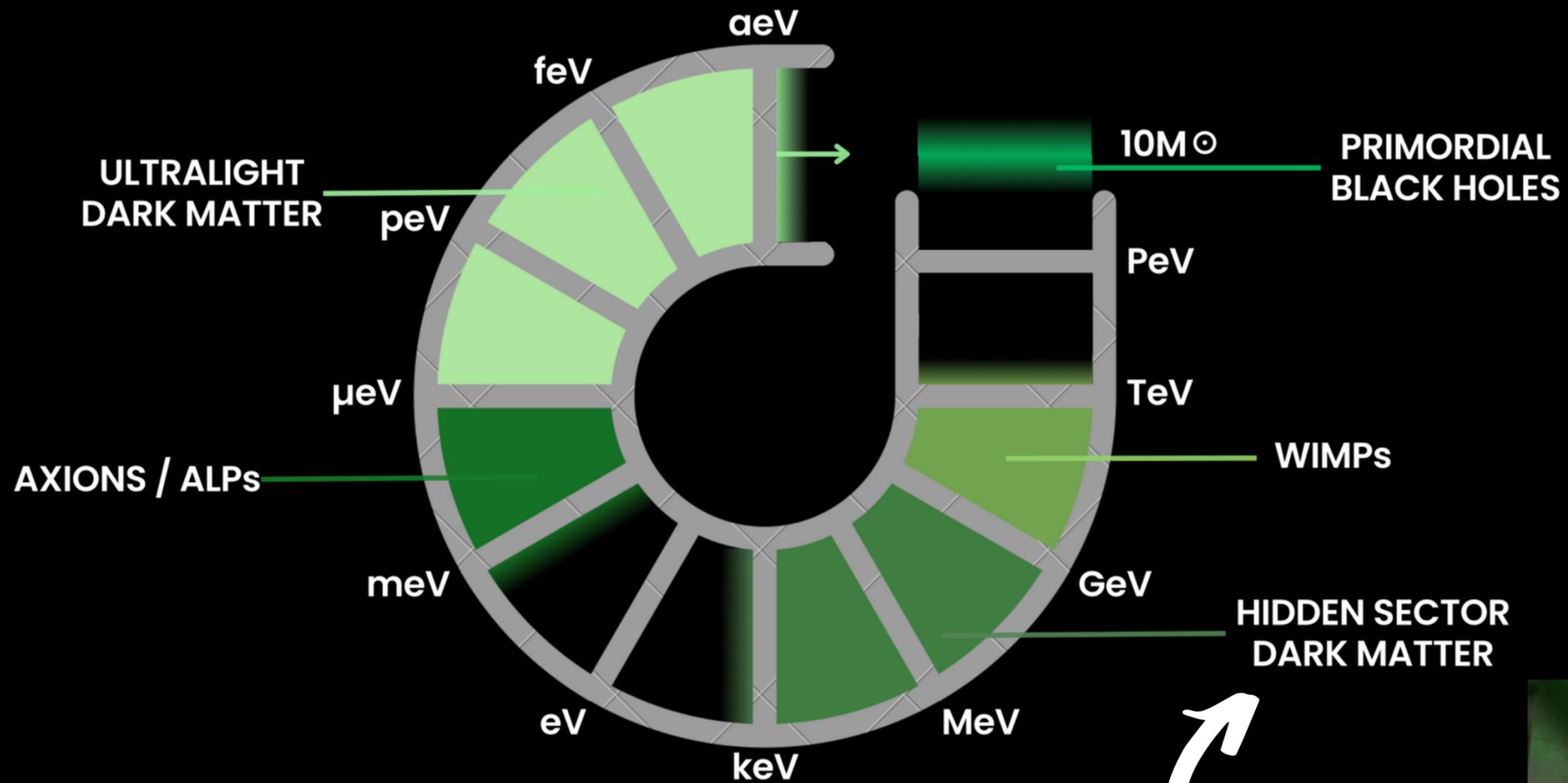
**ANTONIO PONTIN**



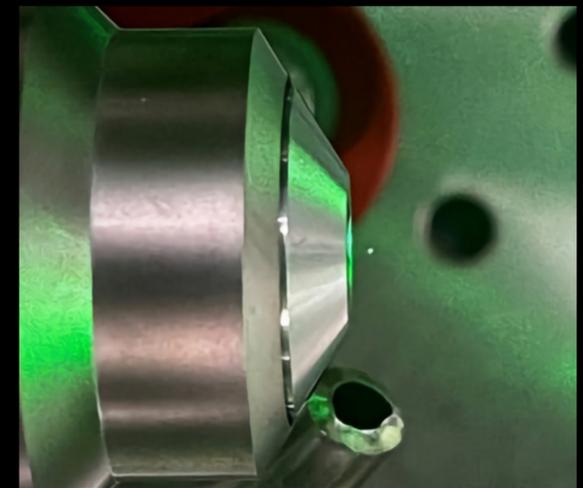
**LOUIS HAMAIDE**

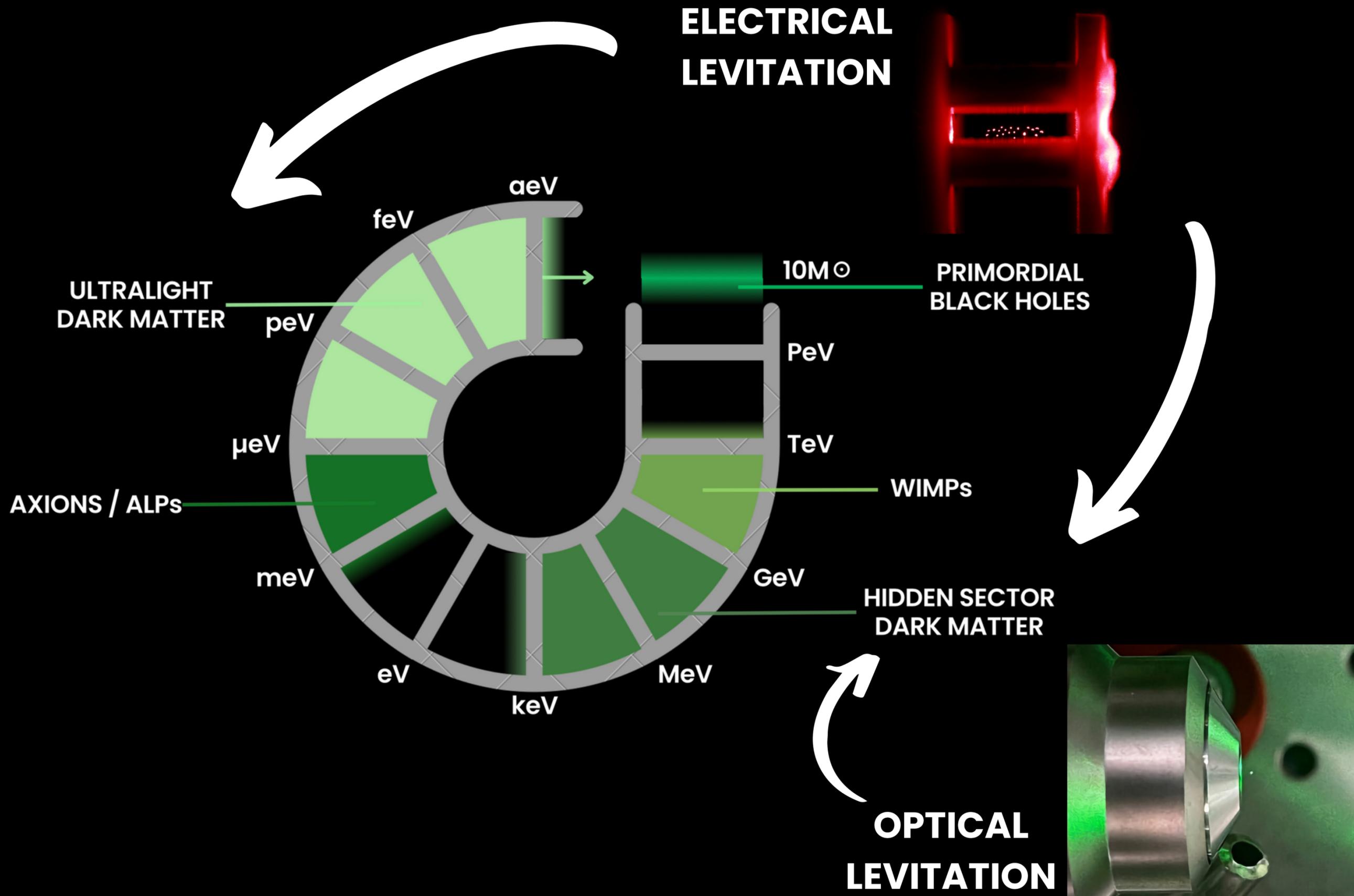


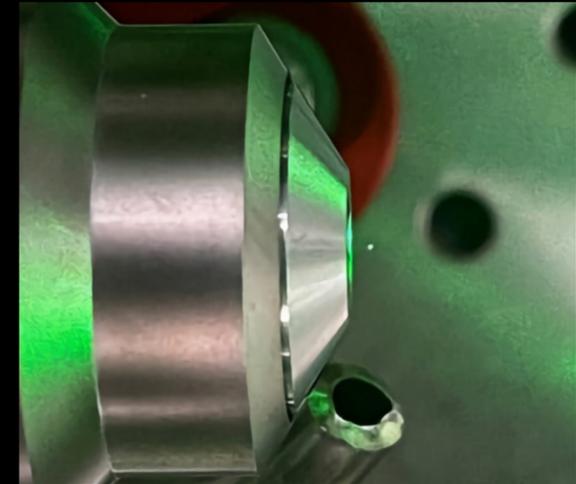
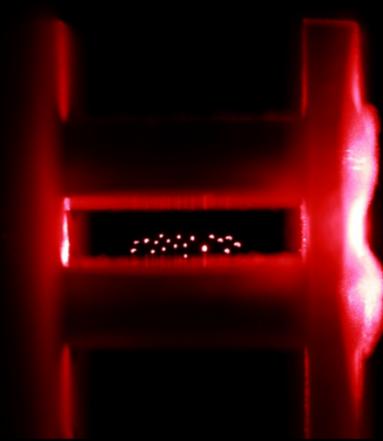
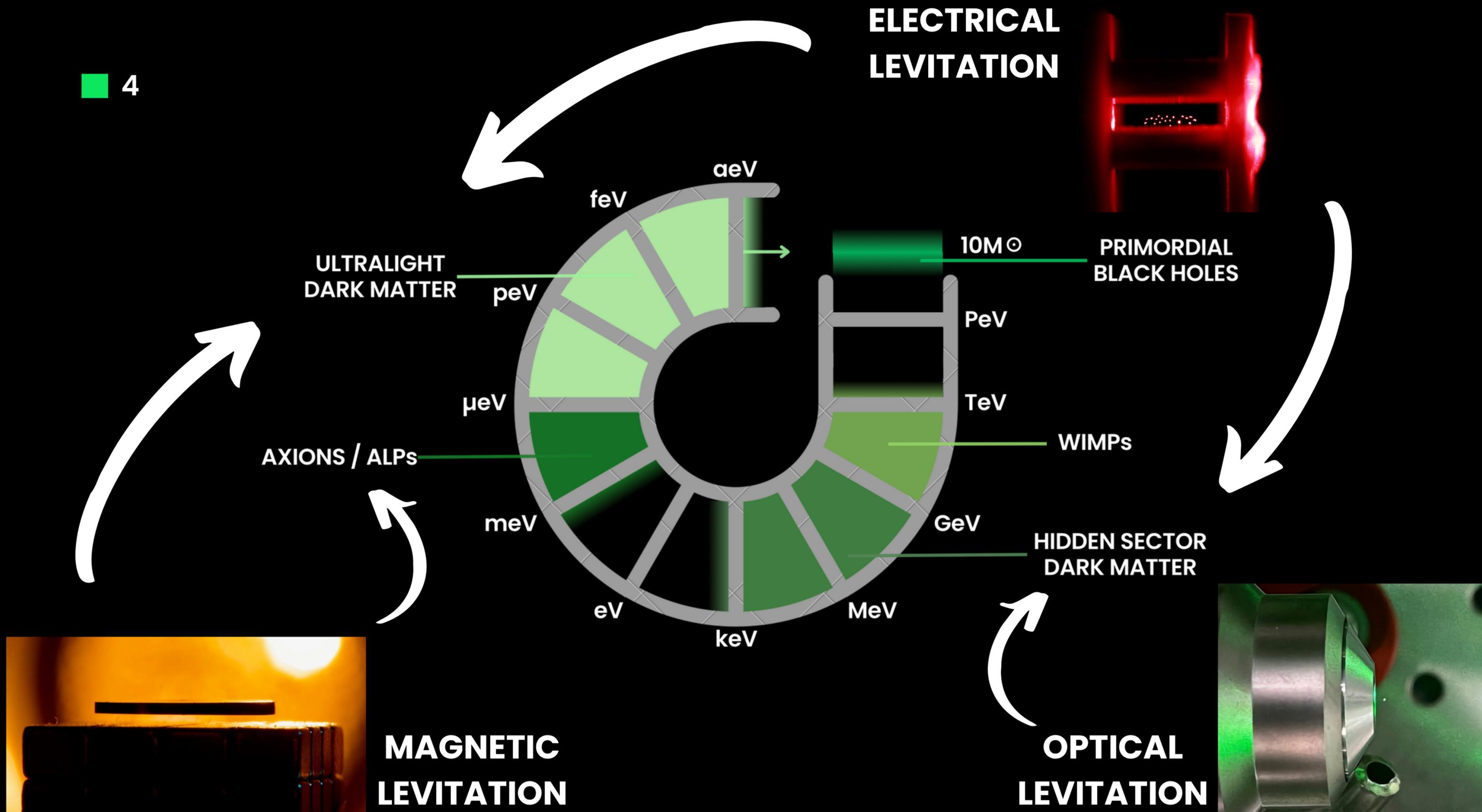




**OPTICAL LEVITATION**

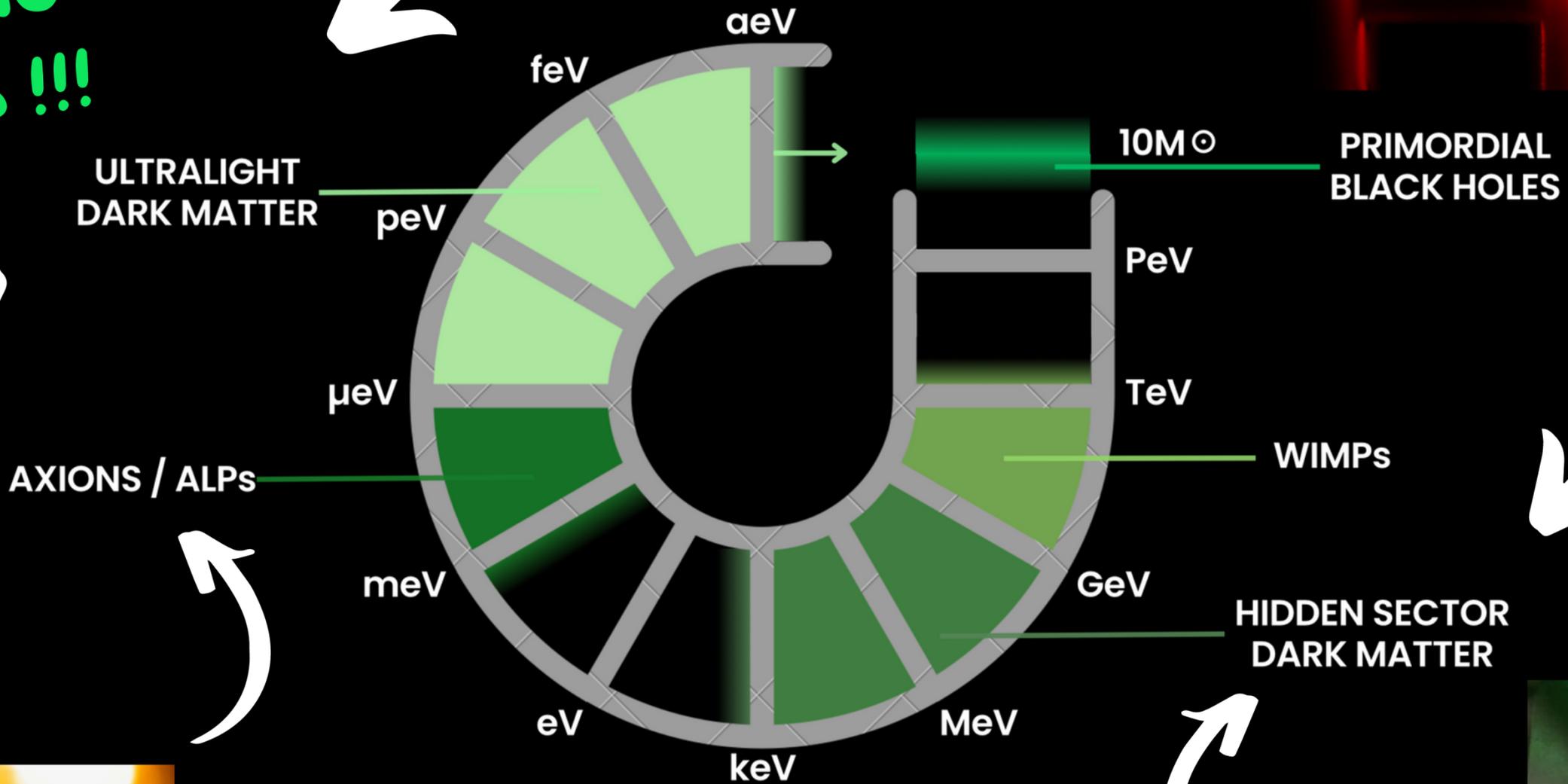




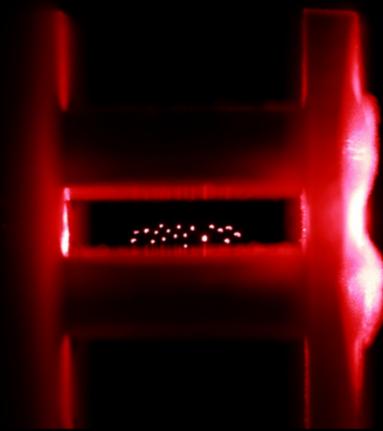


■ 5

NEUTRINO PHYSICS !!!



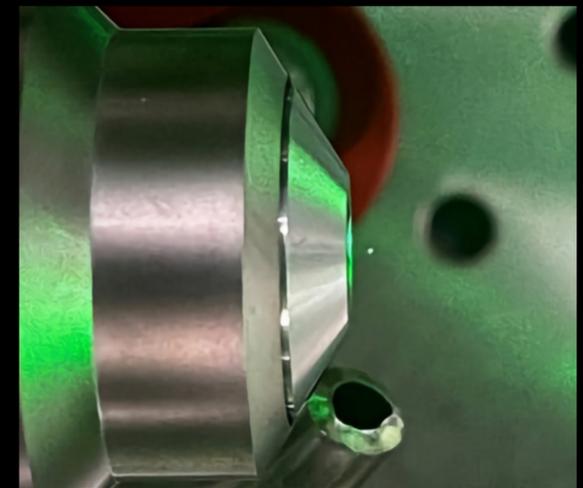
ELECTRICAL LEVITATION



PRIMORDIAL BLACK HOLES

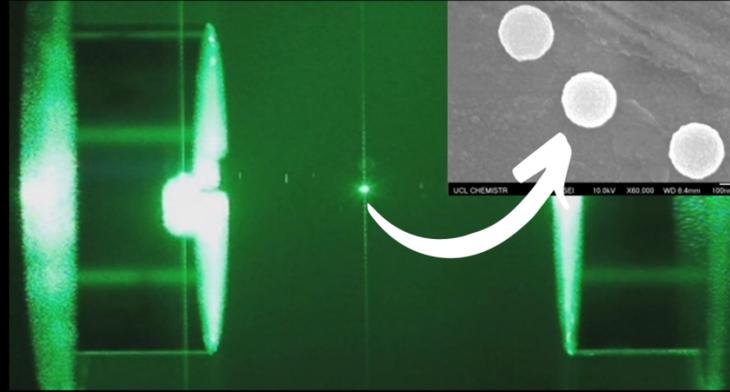


MAGNETIC LEVITATION



OPTICAL LEVITATION

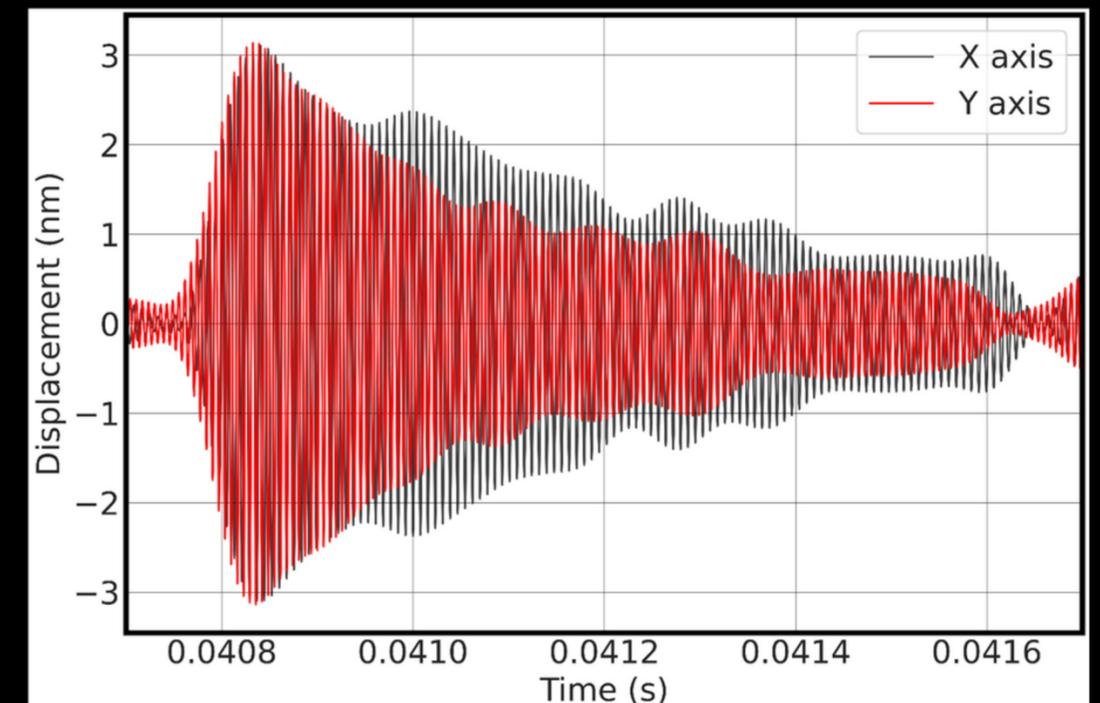
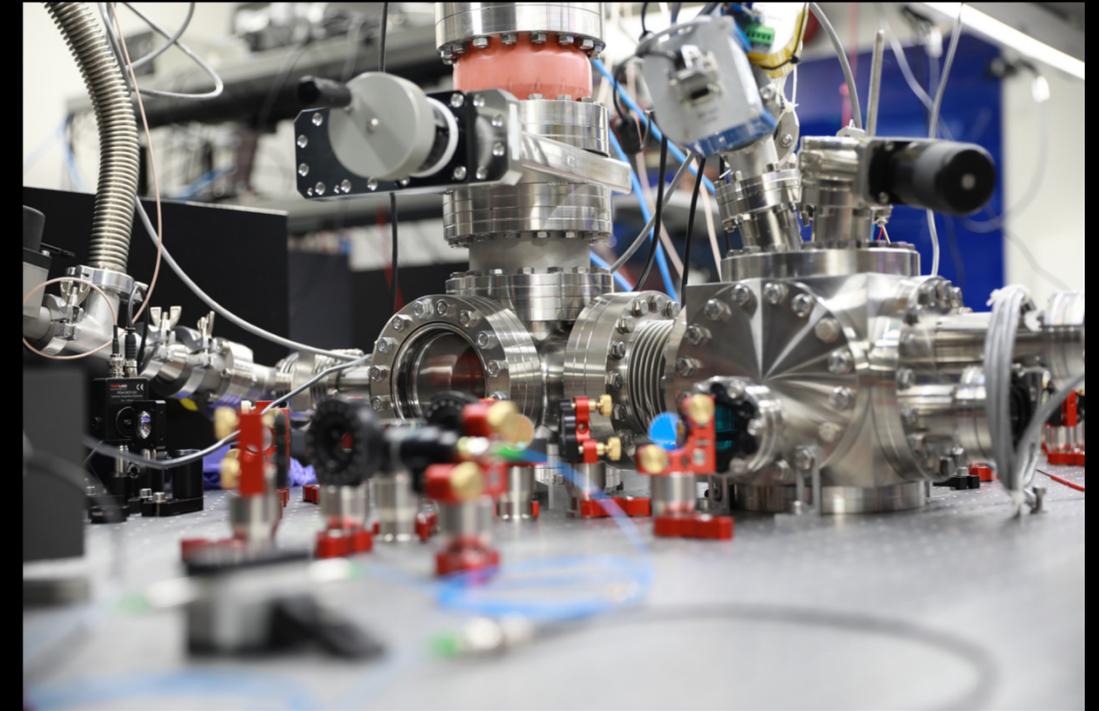
6



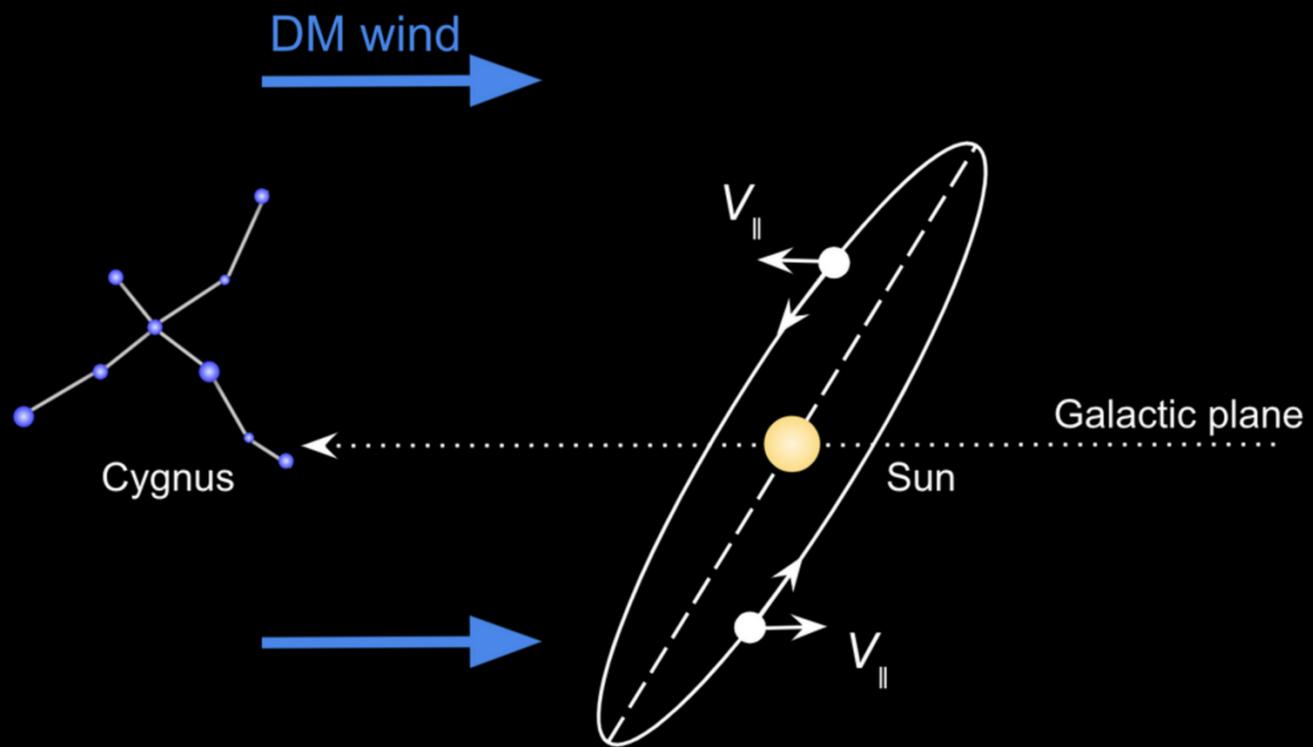
SILICA  
NANOPARTICLES

# OPTICAL TWEEZERS

- ➔ NANO/MICRO SCALE PARTICLES TRAPPED AND LEVITATED USING LASER LIGHT
- ➔ TRAPPING POTENTIAL FORMED THROUGH STRONG FOCUSING OF EM FIELDS
- ➔ INCREDIBLY ISOLATED FROM ITS ENVIRONMENT
- ➔ ZEPTONEWTON FORCE SENSING
- ➔ 3D MOTIONAL TRACKING



# DIRECTIONALITY

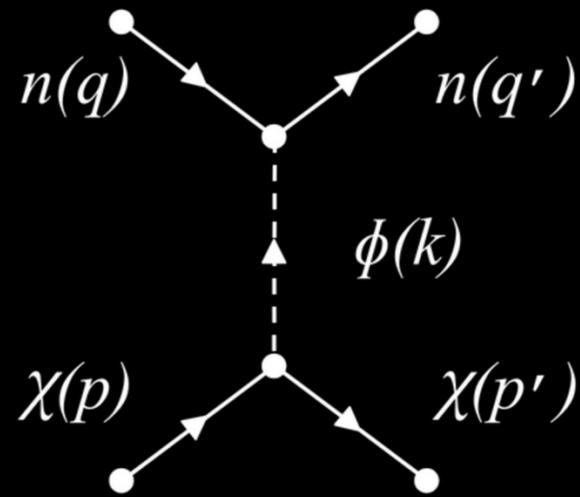


MOTION OF THE EARTH THROUGH THE GALACTIC DM HALO INDUCES A PREFERENTIAL INTERACTION DIRECTION

ANNUAL MODULATION IN THE RATE CAUSED BY THE EARTH'S SOLAR ROTATION

PROVIDES A 'SMOKING GUN' SIGNAL, THAT CAN BE USED TO DISCRIMINATE A DM SIGNAL FROM BACKGROUNDS

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## SELF INTERACTING DM

INTERACTS WITH STANDARD MODEL PARTICLES VIA A LIGHT MEDIATOR

PROVIDING A DELTA-LIKE 'KICK' TO THE LEVITATED OBJECT

INTERACTION IS MODELLED AS CLASSICAL SCATTERING IN A YUKAWA POTENTIAL, MODIFIED BY THE SPATIAL FORM FACTOR OF THE TARGET (NEUTRONS)

$$V(r) = (-) \frac{g_{\chi} g_n e^{-r m_{\phi}}}{4\pi r}$$

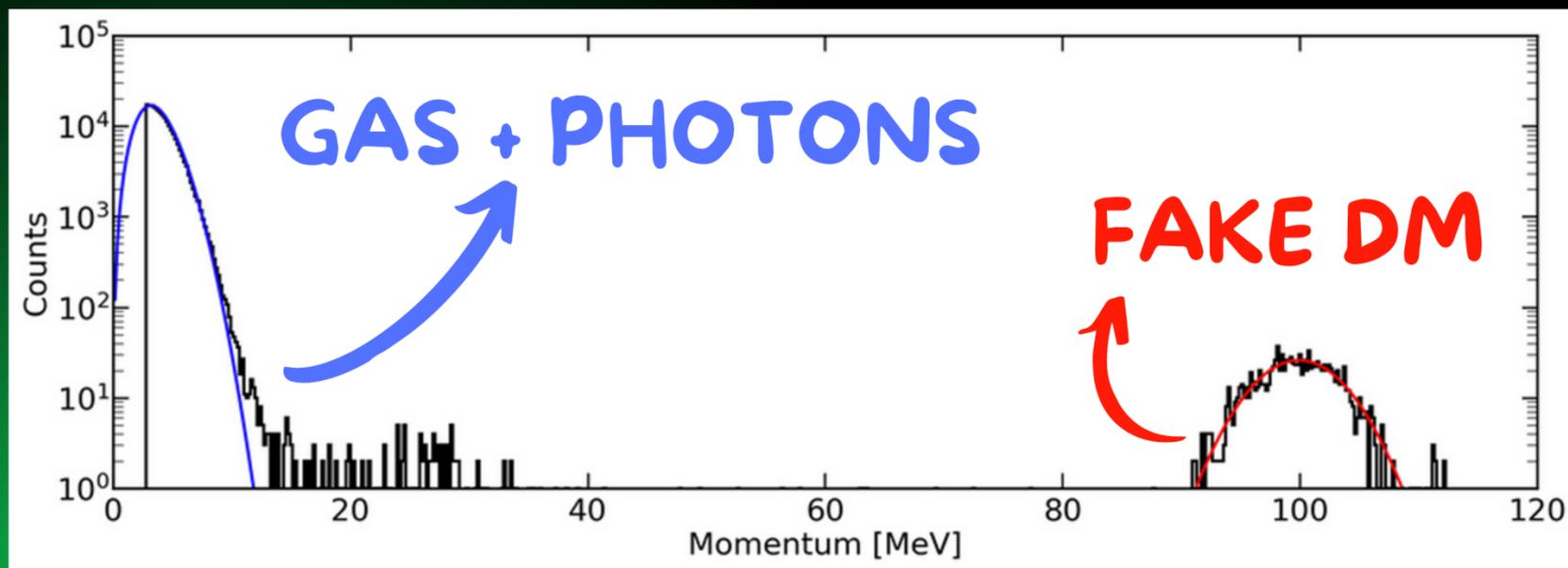
THIS PROVIDES COHERENCE OVER THE NUGGET, AND PARTIAL TO FULL COHERENCE OVER NEUTRONS IN THE TARGET OBJECT

$$\mathcal{L} \supset -g_{\chi} \phi \chi^* \chi - g_n \phi \bar{n} n$$

STELLAR COOLING AND 5TH FORCE CONSTRAINTS BOUND  $g_n$ , HOWEVER  $g_{\chi}$  IS BOUNDED ONLY BY UNITARITY\*

# BACKGROUNDS

Backgrounds, in the context of rare event searches, are used to describe any events which are unrelated to the phenomenon of interest, but can mimic or interfere with the desired signal



## PARTICLE INTERACTIONS

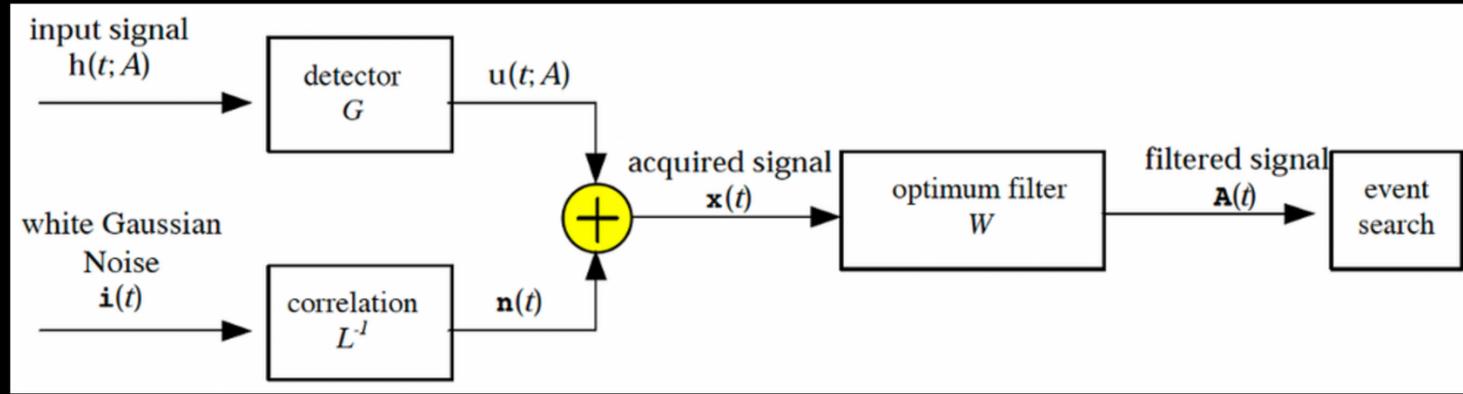
- Particle interactions – e.g. radioactive decays or cosmic ray interactions

## GAS DAMPING

- Gas molecules damp the levitated particle (modelled as a stochastic force)

## PHOTON BACK ACTION NOISE

- Photons from the trapping laser impart momentum to the particle
- This will provide the ultimate noise floor to impulse measurements



# OPTIMAL FILTERING

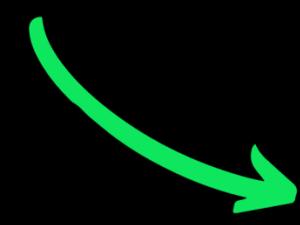
## Matched Wiener-Kolmogorov filter

THE MATCHED FILTERING TECHNIQUE IS KNOWN TO BE THE BEST LINEAR FILTER TO EXTRACT A SIGNAL OF KNOWN FORM SWAMPED IN STATIONARY GAUSSIAN NOISE

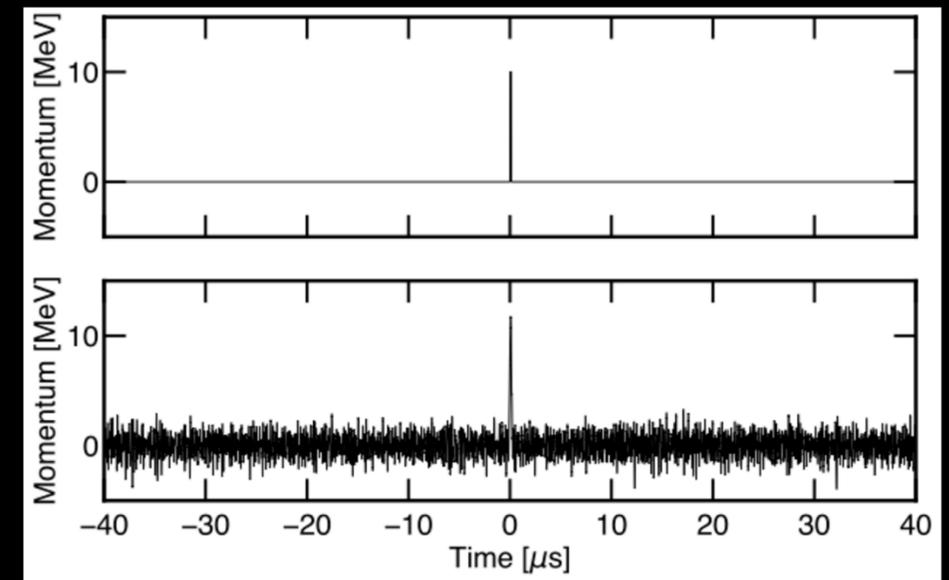
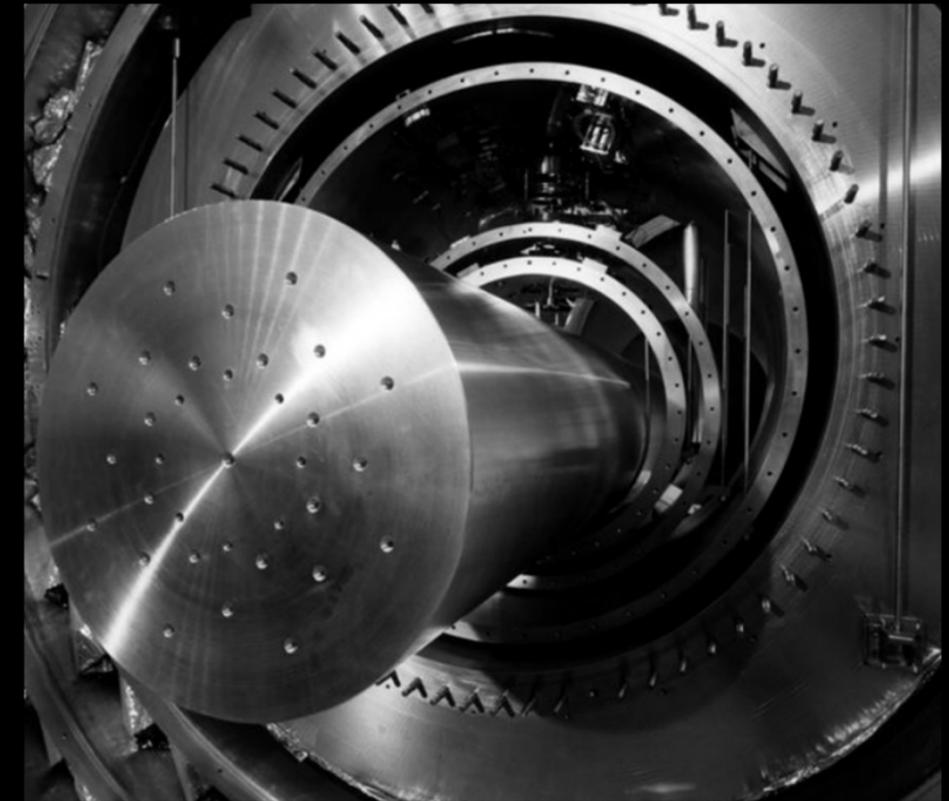
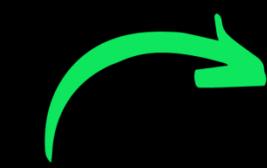
$$W(\omega) = M^C(\omega) M^A(\omega)$$

$$M^C(\omega) = \frac{1}{L(\omega)} \quad M^A(\omega) = \sigma_A^2 \frac{T^*(\omega)}{L^*(\omega)}$$

SIGNAL TO 'MATCH'

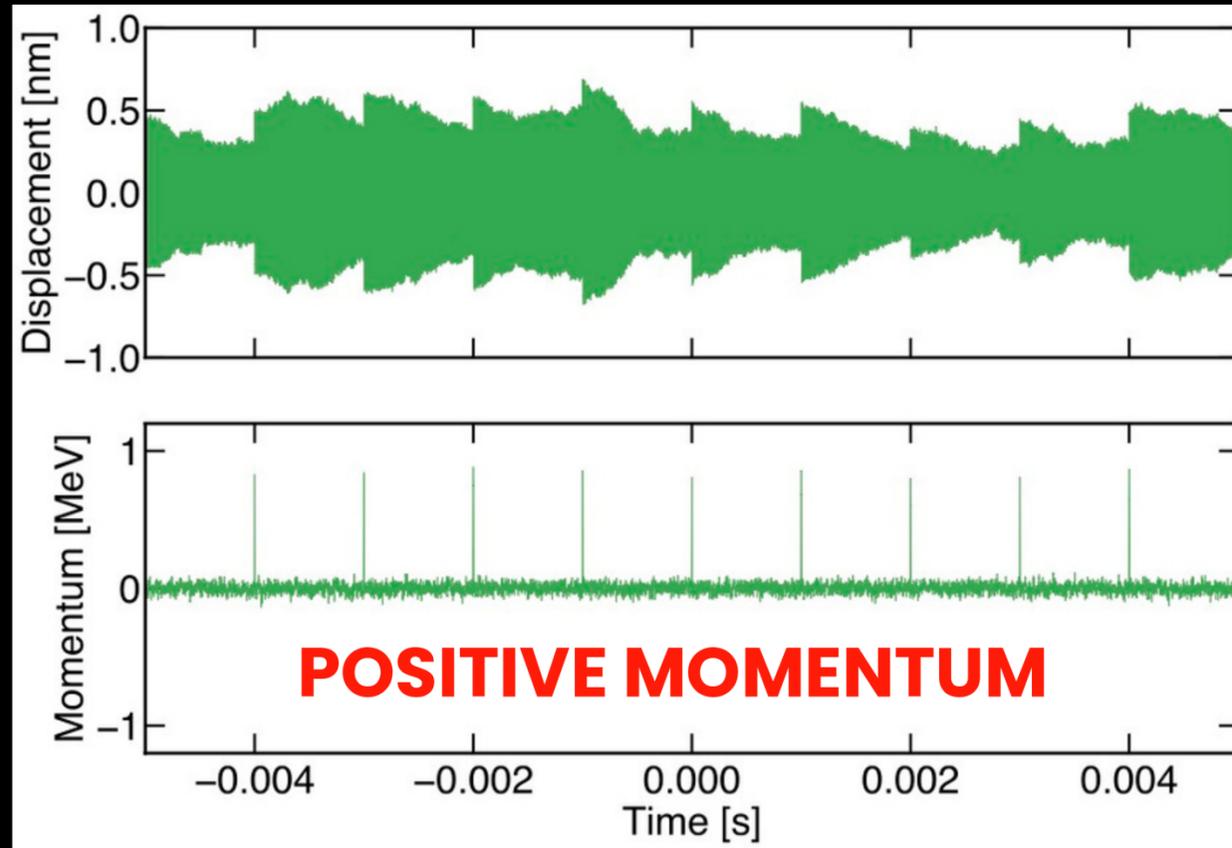


RECOVERED IN DATA



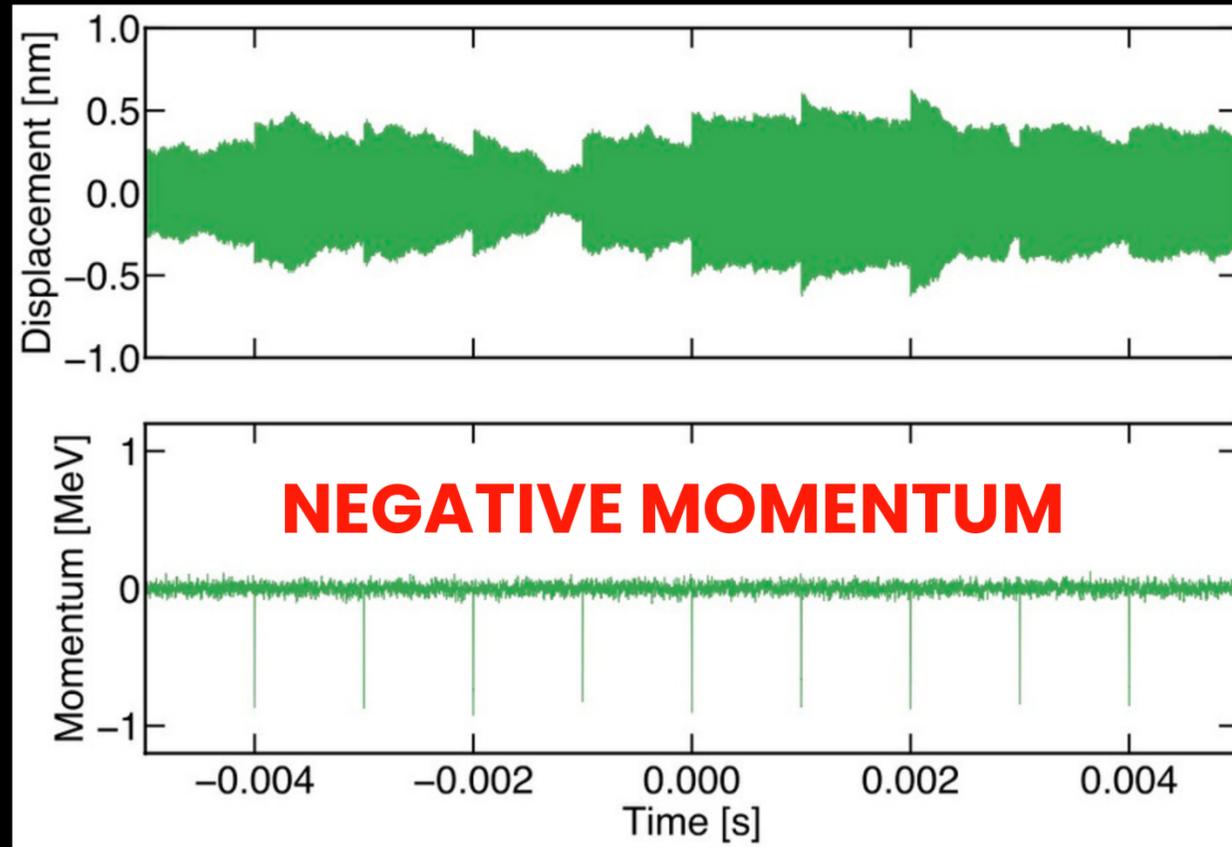
# WK FILTER RECONSTRUCTION

**DIRECTIONALITY !!!**



**UNFILTERED**

**FILTERED**



**UNFILTERED**

**FILTERED**

# UNSALTING THE FIRST 24H

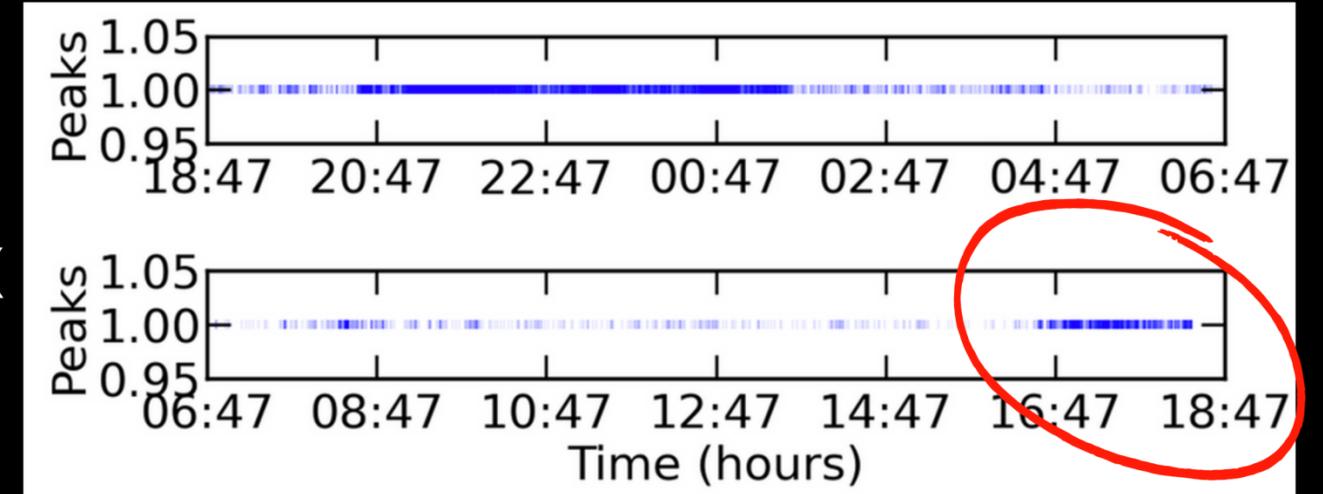
15 coincident events found  
(i.e. triggered in >1 channels within event window)

SALT EVENTS = 7

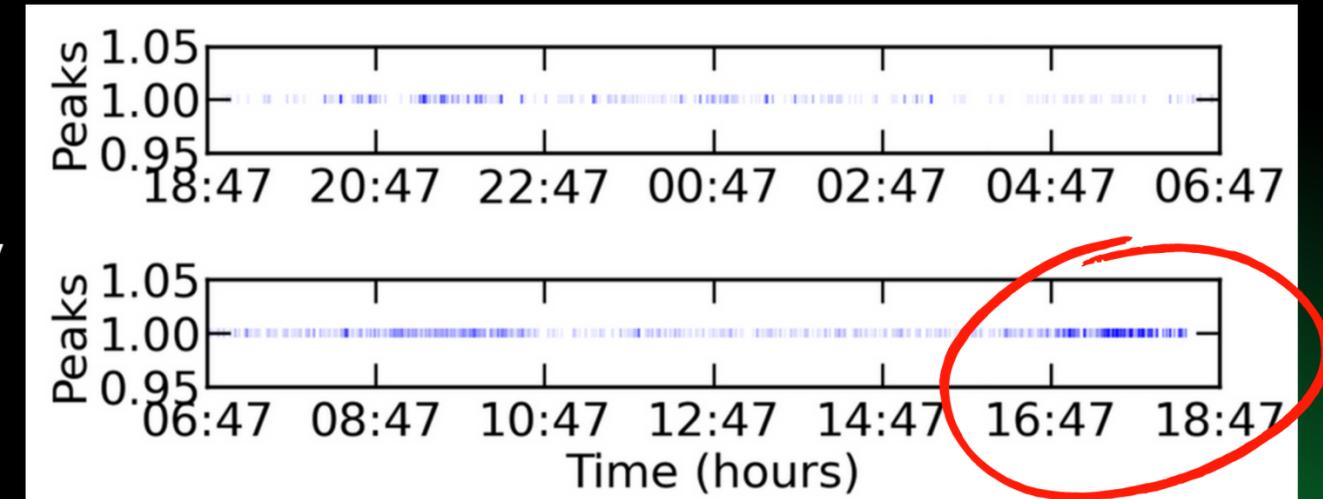
ELECTRONIC NOISE EVENTS = 6

CANDIDATE EVENTS = 2

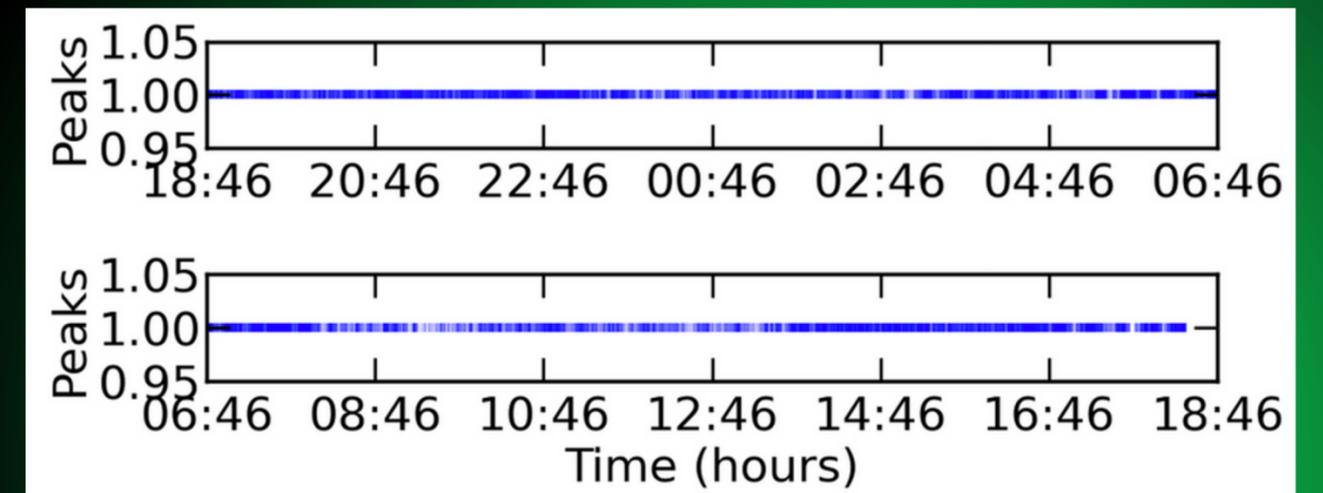
x

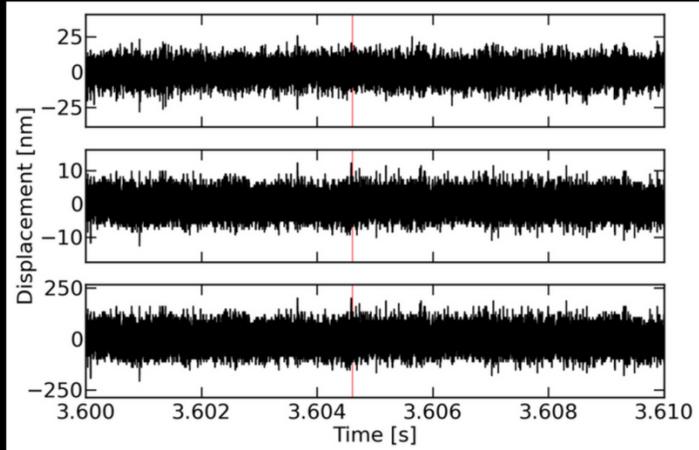


y

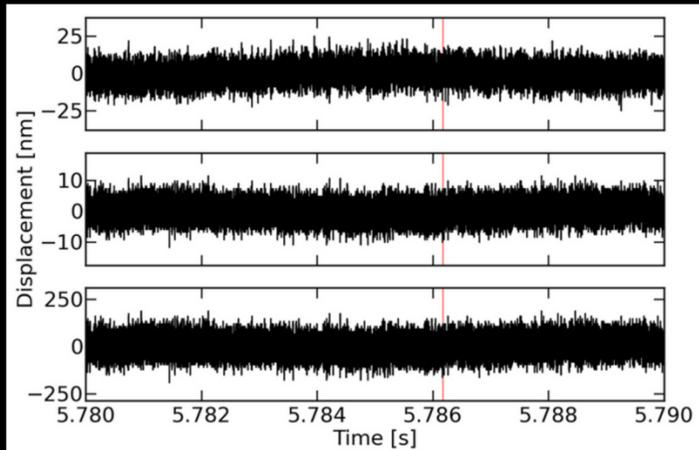


z

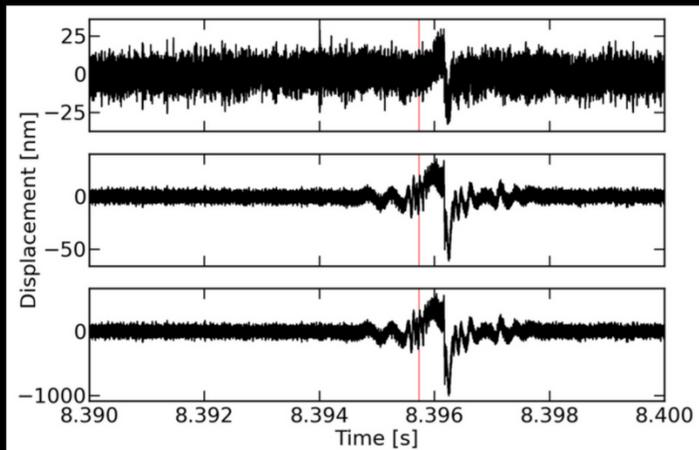




**SALT KICK EVENT**

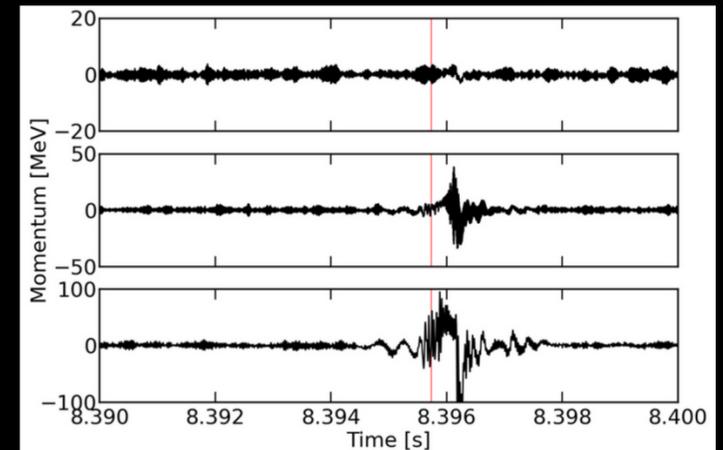
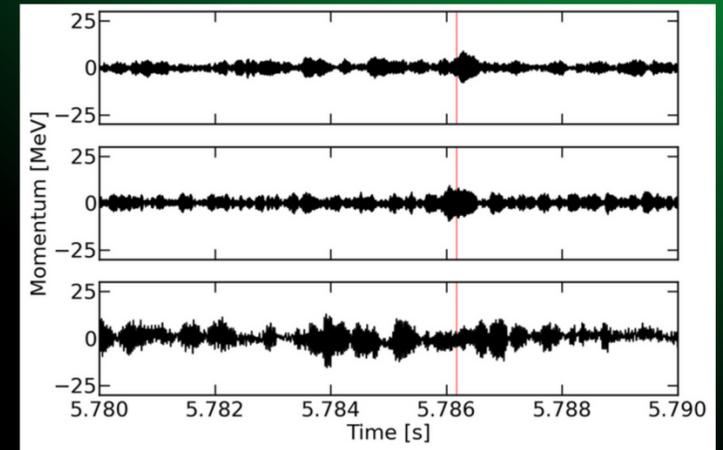
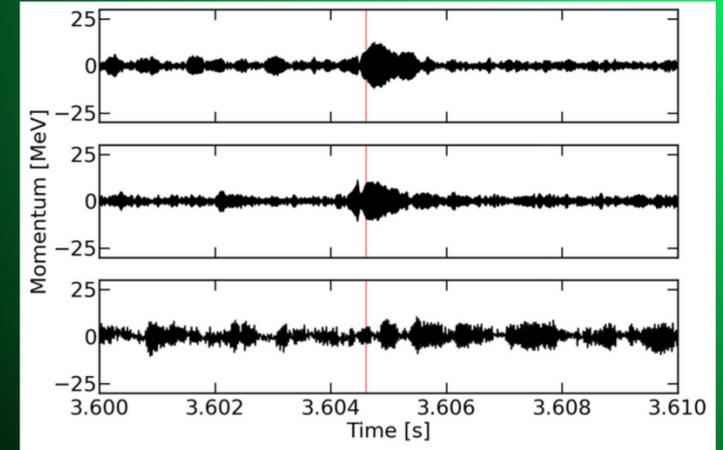


**UNKNOWN CANDIDATE  
EVENT**



**UNFILTERED**

**EVENT TYPES**

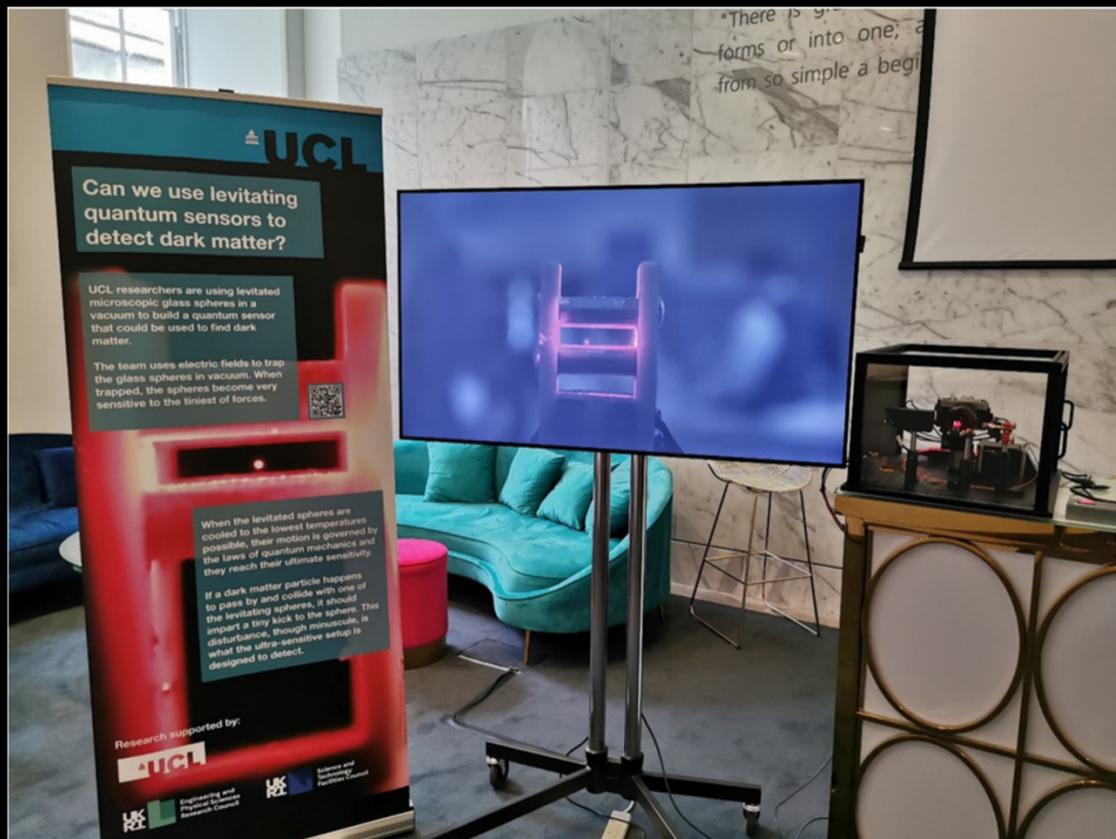


**FILTERED**



Partnering Researchers  
with Schools

<https://www.orbyts.org>



# OUTREACH - EDU-QS

# SUMMARY

- Optical tweezer setup commissioned and calibrated
  - First Science Run (SR1) data taken, processed and analysed
  - First 24h of SR1 unsalted and events classified
  - Future – SR2 and statistical analysis of SR1
- Magnetic levitation setup in commissioning stages
  - Undergoing steps to reduce noise before calibration and SR1
- New filtering protocol established – showing directional reconstruction of individual events
  - Has uses in detection of other small impulse-like events (not just DM)



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**CHAMKAUR GHAG**

# Thank You

**FIONA ALDER**



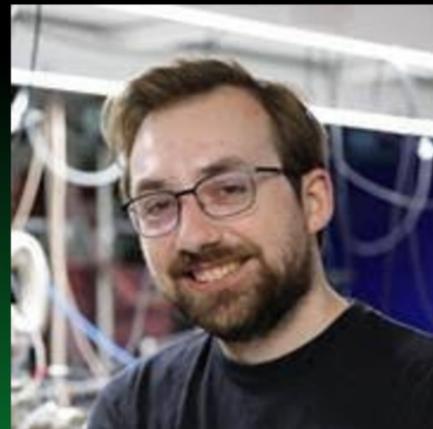
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**ANTONIO PONTIN**



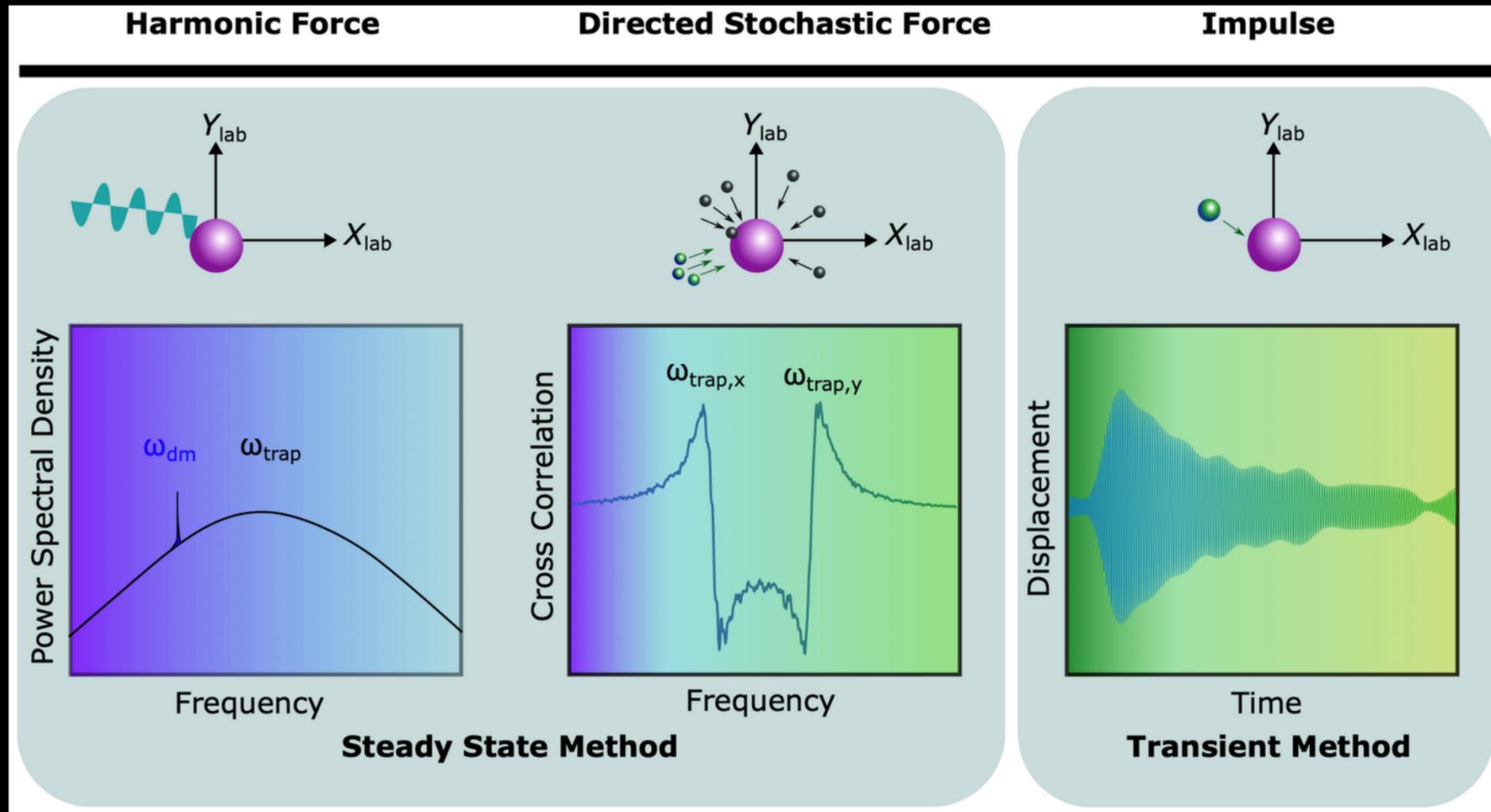
**LOUIS HAMAIDE**



# EXTRA SLIDES

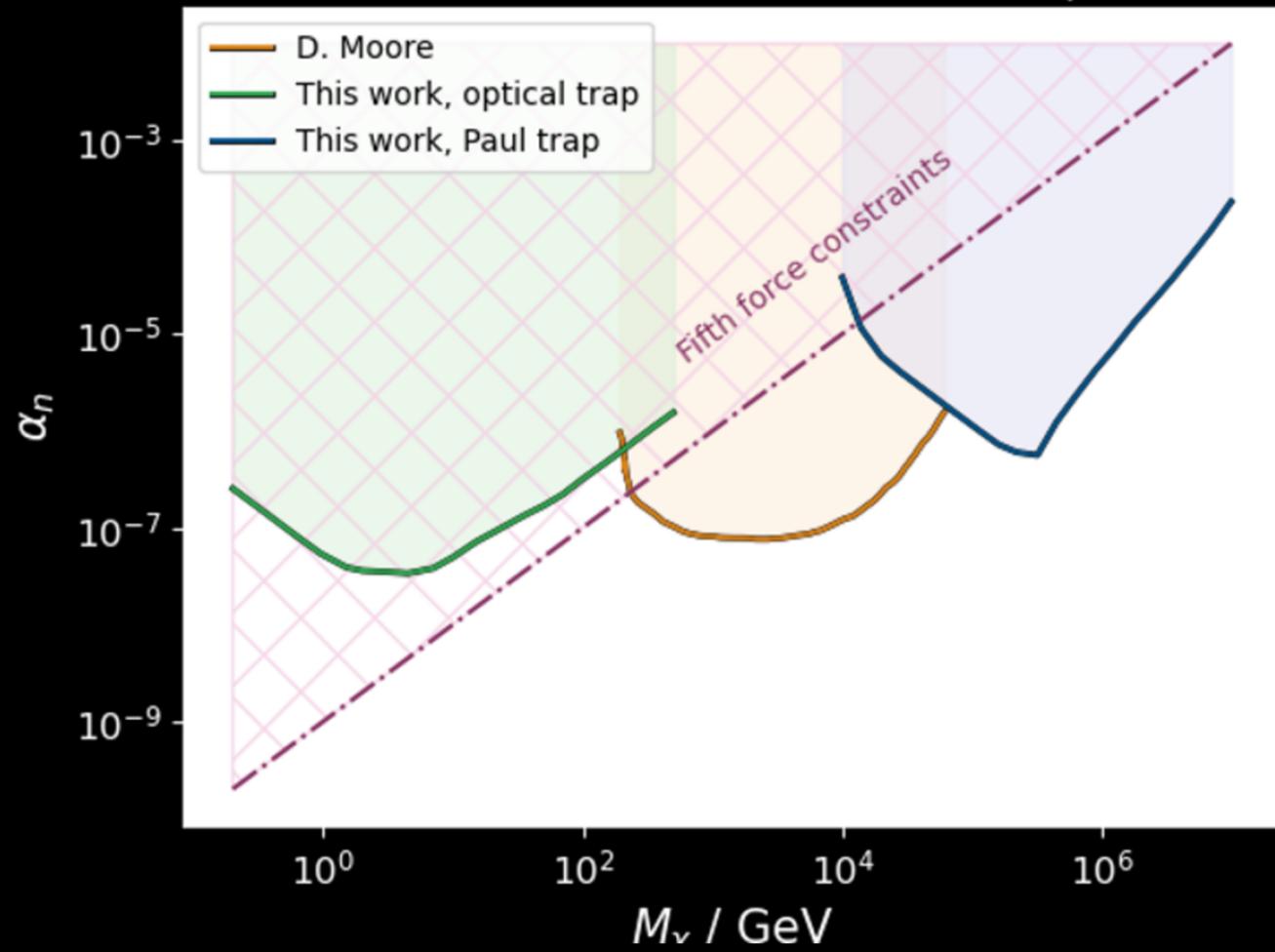
Levitated System	Mechanical Sensitivity		Testable DM Candidates	DM Parameter Space probed [DM Mass range]
	$\sqrt{S_a}$ (g/ $\sqrt{\text{Hz}}$ )	$\sqrt{S_F}$ (N/ $\sqrt{\text{Hz}}$ )		
Optically trapped (fg-ng) <sup>[16,19]</sup>	$\sim 6 \times 10^{-6} - 9 \times 10^{-8}$	$\sim 1 \times 10^{-18} - 6 \times 10^{-21}$	Millicharge Composite Low-mass particle Sterile $\nu$	Charge [e] $\sim 10^{-4}$ [GeV - TeV] <sup>[68]</sup> $\sigma_{\chi n}$ [cm <sup>2</sup> ] $\sim 10^{-28}$ [10 <sup>3</sup> - 10 <sup>4</sup> GeV] <sup>[99]</sup> $\sigma_{SI}$ [cm <sup>2</sup> ] $\sim 10^{-30}$ [0.1 - 100 MeV] <sup>[14]</sup> $ U_{e4} ^2 \sim 10^{-4} - 10^{-6}$ [0.1 - 1 MeV] <sup>[72]</sup>
Magnetically trapped ( $\mu\text{g}$ -mg) <sup>[17,53]</sup>	$\sim 1 \times 10^{-10} - 9 \times 10^{-12}$	$\sim 5 \times 10^{-12} - 5 \times 10^{-19}$	ALPs Axions Dark photons ULDM	$g_{aee} \sim 10^{-14}$ [10 <sup>-13</sup> to 10 <sup>-18</sup> eV] <sup>[74]</sup> $g_{a\gamma}$ [GeV <sup>-1</sup> ] $\sim 10^{-10}$ [10 <sup>-12</sup> - 10 <sup>-14</sup> eV] <sup>[75]</sup> $\epsilon \sim 10^{-8}$ [10 <sup>-12</sup> - 10 <sup>-14</sup> eV] <sup>[75]</sup> $g_{B-L} \sim 10^{-25}$ [10 <sup>-14</sup> to 10 <sup>-16</sup> eV] <sup>[56]</sup>
Electrically trapped (40 fg) <sup>[35]</sup>	$\sim 5 \times 10^{-6}$	$\sim 2 \times 10^{-21}$	ULDM <sup>[100]</sup> Composite	no concrete experimental proposals beyond trapped atomic ions

E. Kilian et al, AVS Quantum Science, 6, 3 (2024)



EXTRA SLIDES

90% CL projected sensitivity,  $m_\phi = 0.1$  eV



90% CL projected sensitivity, 10 livedays

