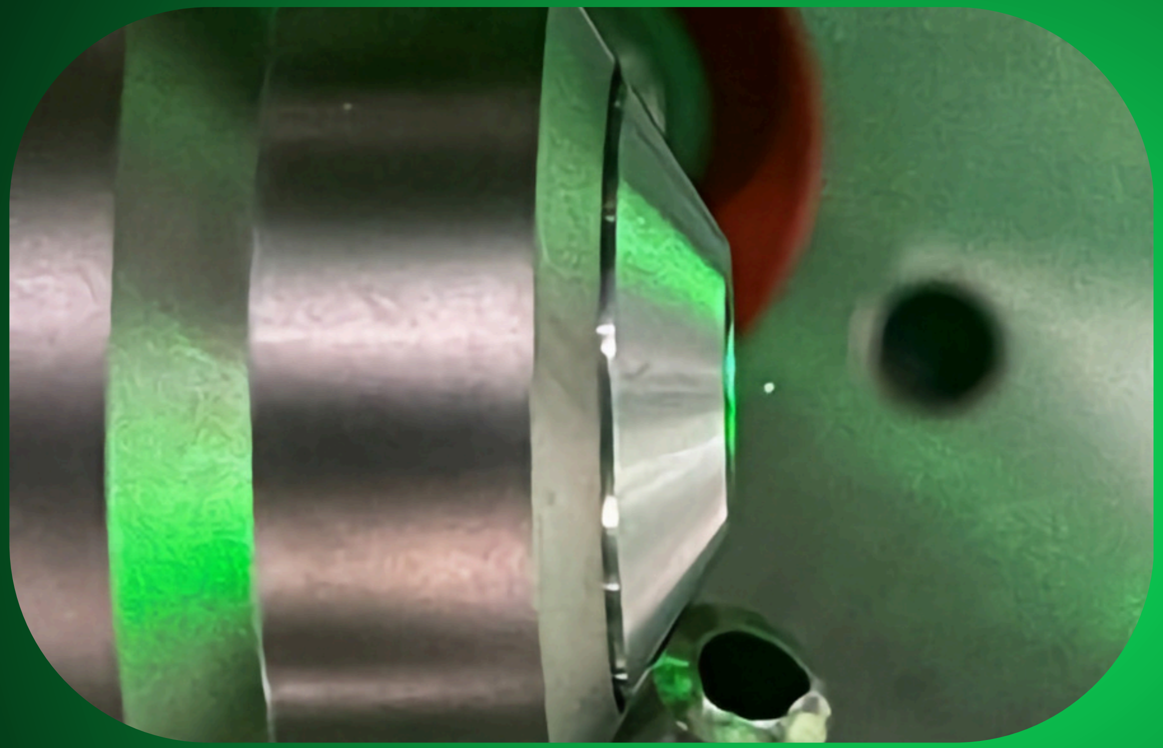
January 2025

Q-SENSE

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

A DIRECTIONAL DARK MATTER SEARCH



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UCL
Science & Technology Facilities Council
Cosmoparticle Initiative UCL

PRESENTATION OUTLINE

MOTIVATION

OPTICAL TWEEZER EXPERIMENT - CURRENT STATUS

OPTIMAL FILTERING AND DIRECTIONALITY

FUTURE DIRECTIONS

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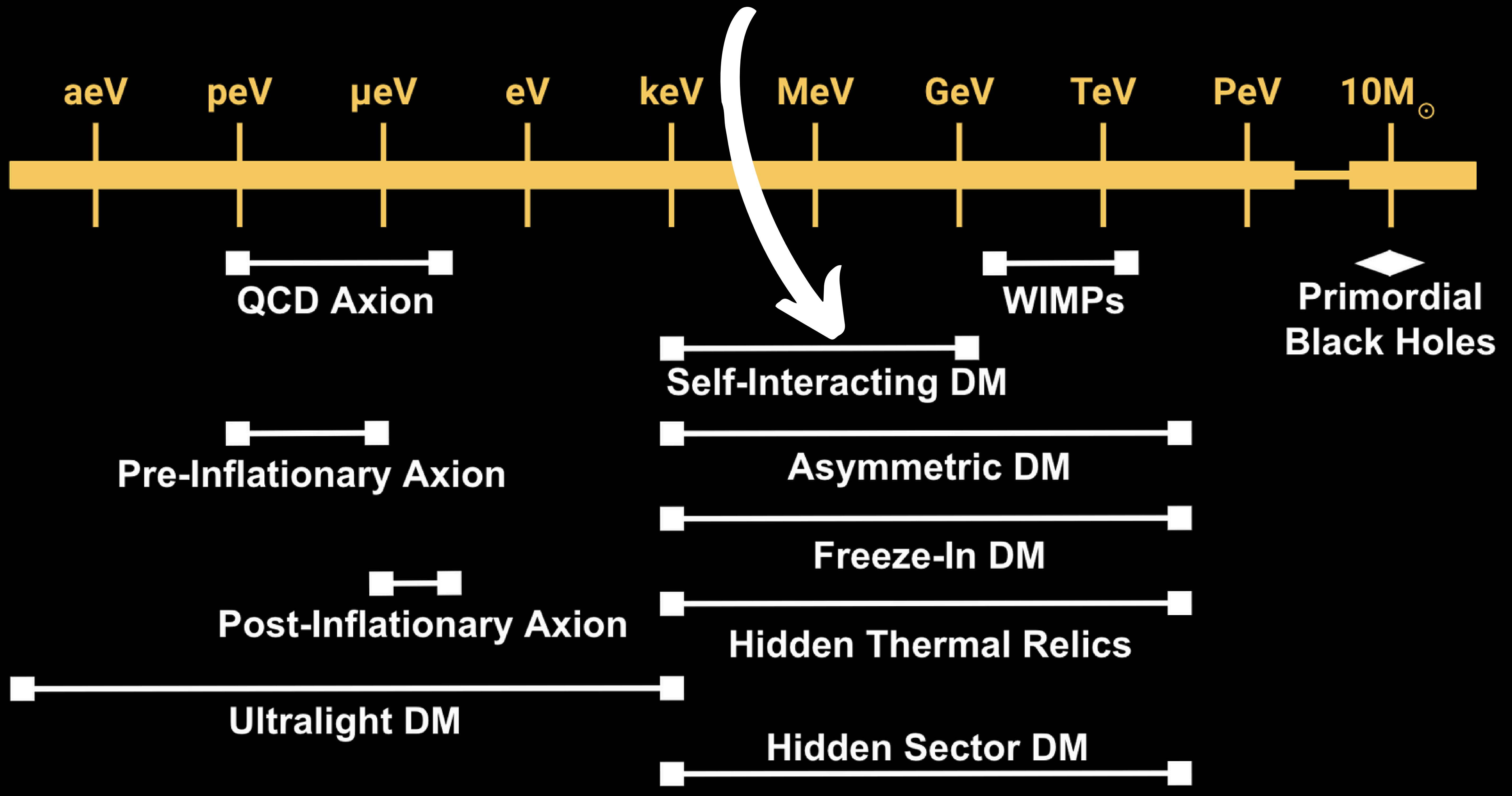
aeV
peV
μeV
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keV
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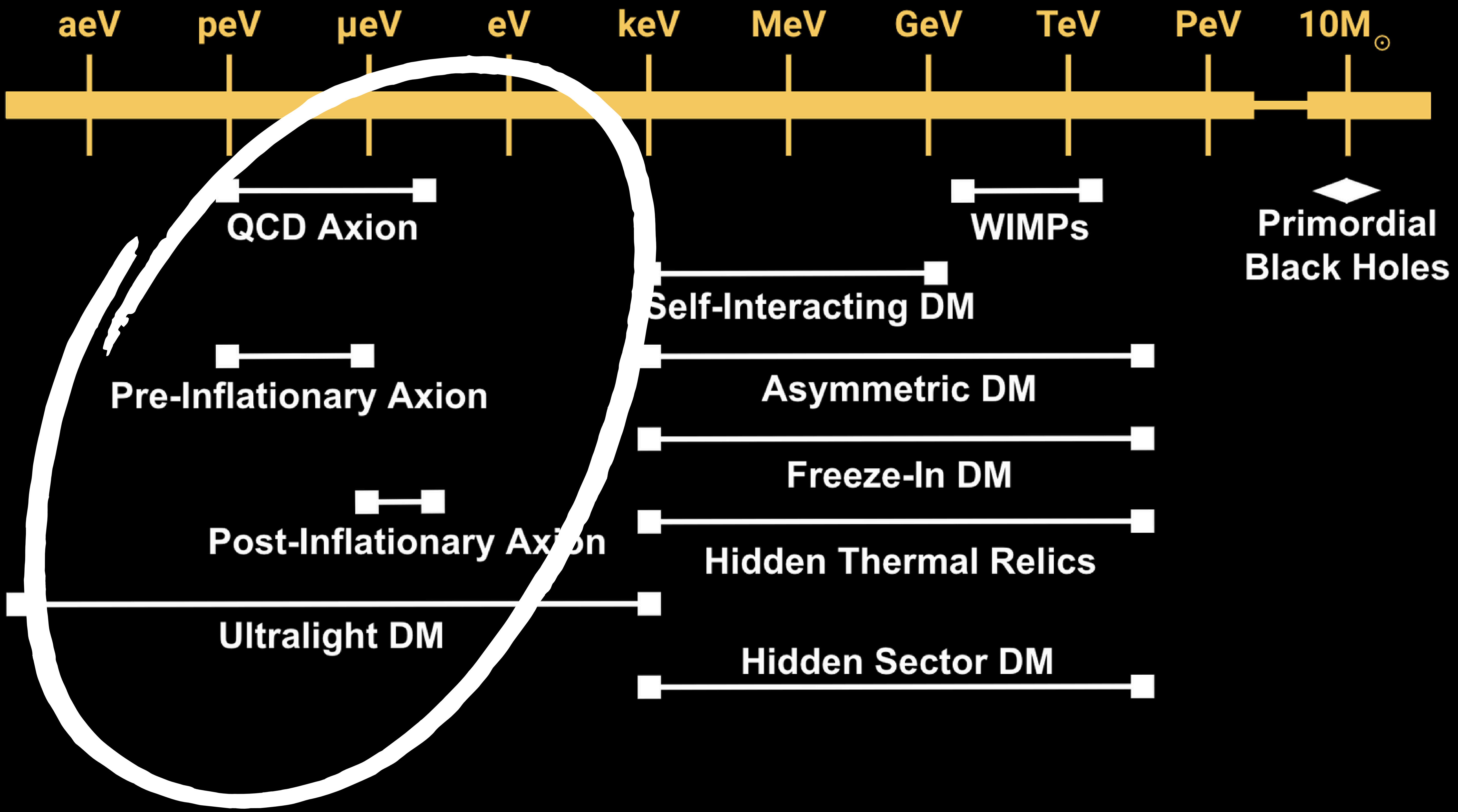
TeV
PeV
10M☉
QCD Axion
WIMPs
Primordial Black Holes
Self-Interacting DM
Pre-Inflationary Axion
Asymmetric DM
Freeze-In DM
Post-Inflationary Axion
Hidden Thermal Relics
Ultralight DM
Hidden Sector DM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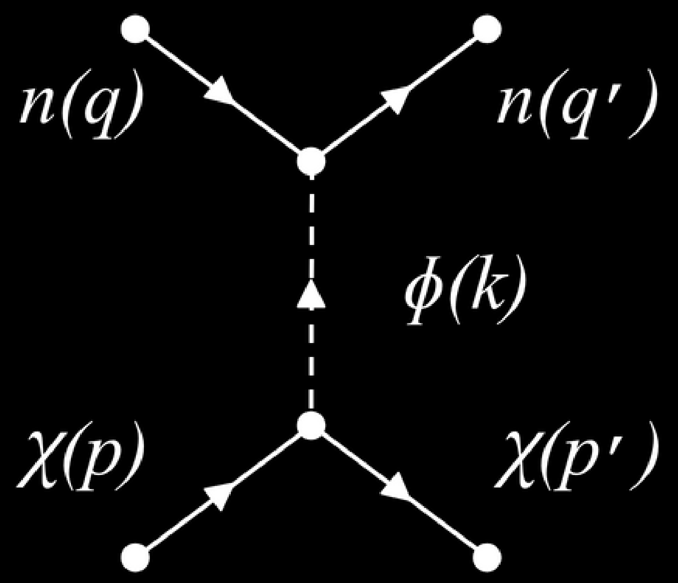


SELF INTERACTING DM

ONE THEORETICALLY MOTIVATED CANDIDATE IS A CLASS OF SELF-INTERACTING DM KNOWN AS DM 'NUGGETS'

IT INTERACTS WITH STANDARD MODEL PARTICLES VIA A LIGHT MEDIATOR

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

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

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

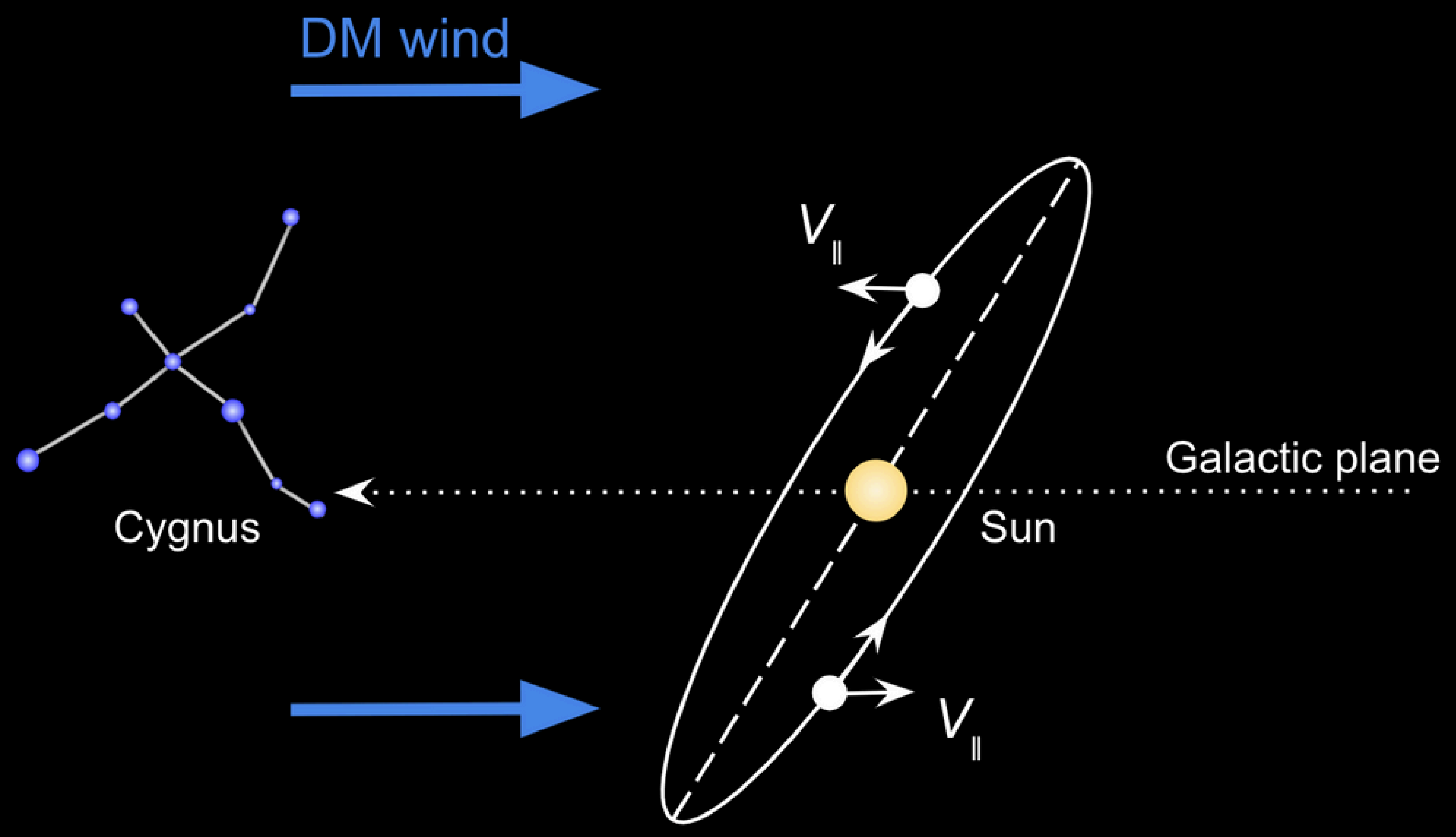
THIS PROVIDES COHERENCE OVER THE NUGGET, AND PARTIAL TO FULL COHERENCE OVER NEUTRONS IN THE TARGET OBJECT

STELLAR COOLING AND 5TH FORCE CONSTRAINTS BOUND GN, HOWEVER GX IS BOUNDED ONLY BY UNITARITY*

S. Knapen, T. Lin and K. Zurek, Phys. Rev. D, 2017
D. Carney et al, Quantum Sci. T echnol., 6, 024002 (2021)

5

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

PRESENTATION OUTLINE

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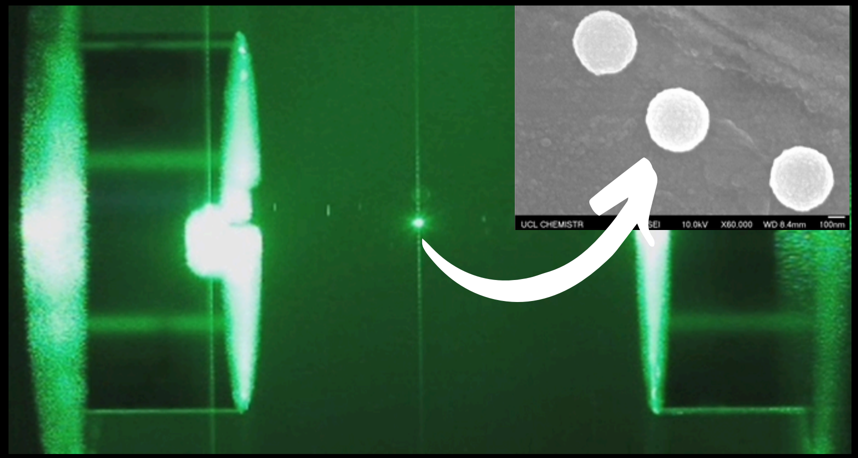
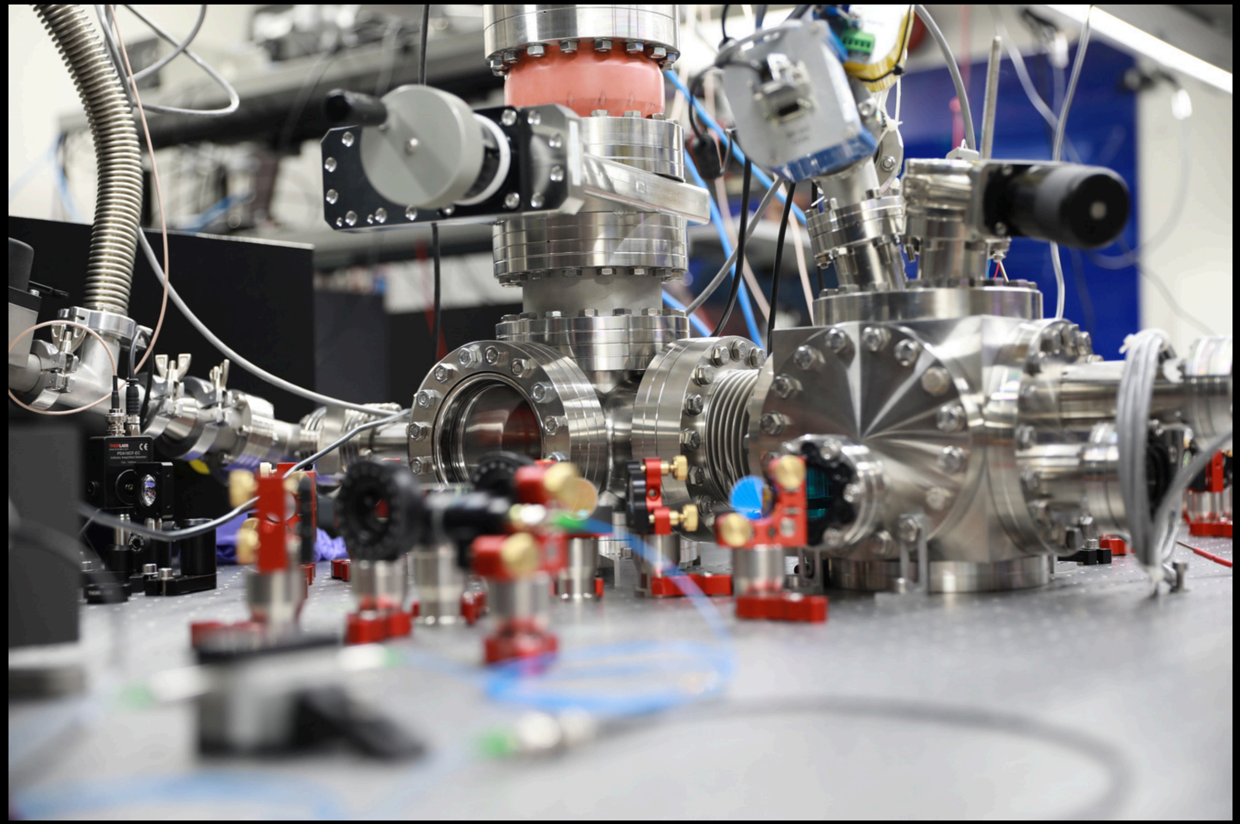


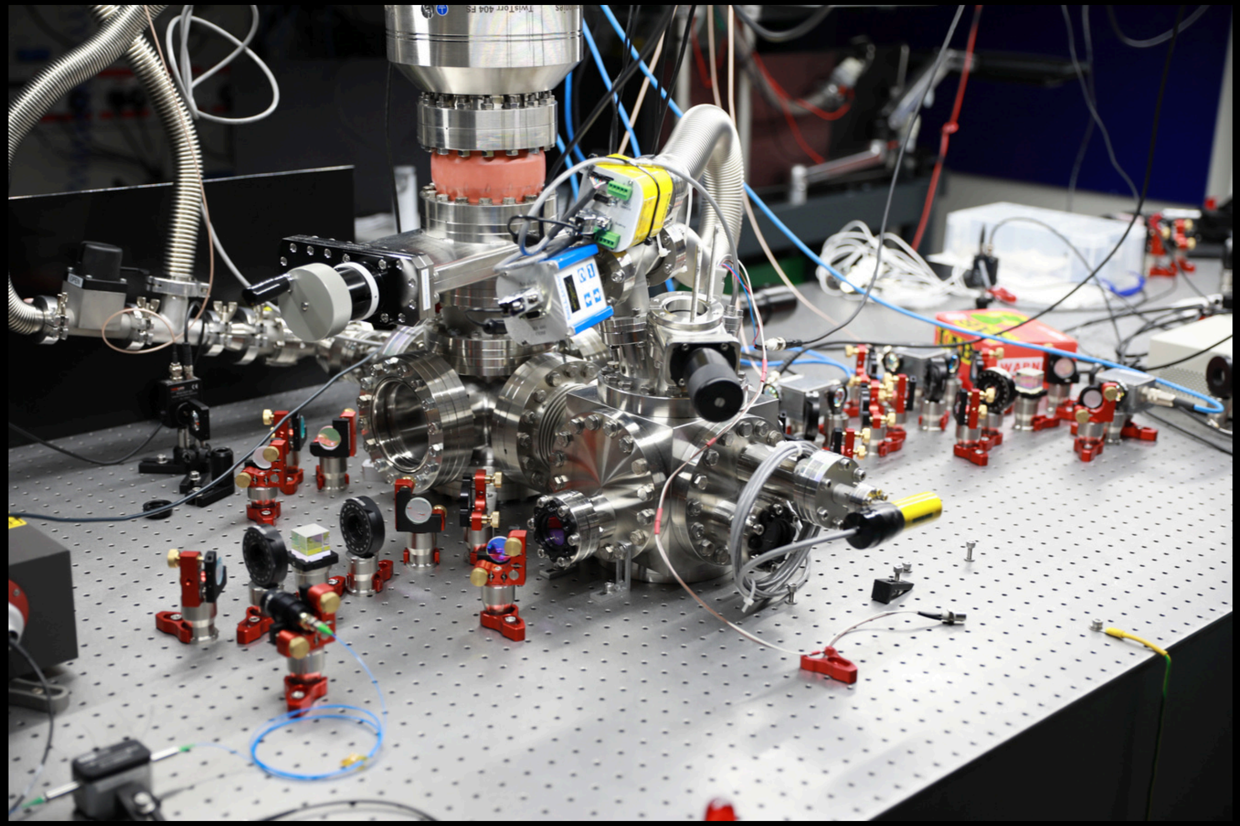
OPTICAL TWEEZERS

TRAPPING POTENTIAL FORMED THROUGH FOCUSING OF EM FIELDS TO THE FOCAL POINT OF AN OPTICAL LENS

INTERFERENCE OF THE INCIDENT LIGHT RAYS OCCURS AT THIS FOCAL POINT

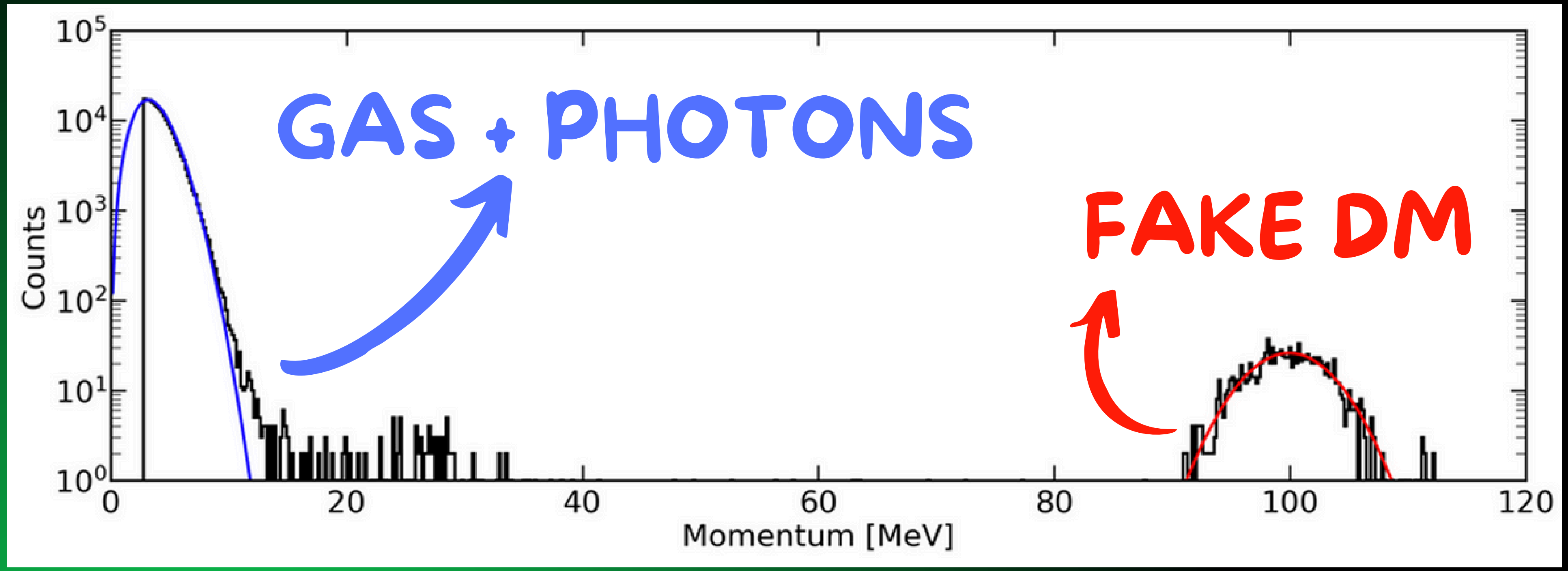
NANO/MICRO PARTICLES OF A VARIETY OF MATERIALS CAN BE LEVITATED IN THIS TRAP





BACKGROUNDS

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



PARTICLE INTERACTIONS

- Particle interactions with the levitated object can mimic the DM interaction (e.g. radioactive decays or cosmic ray interactions)

GAS DAMPING

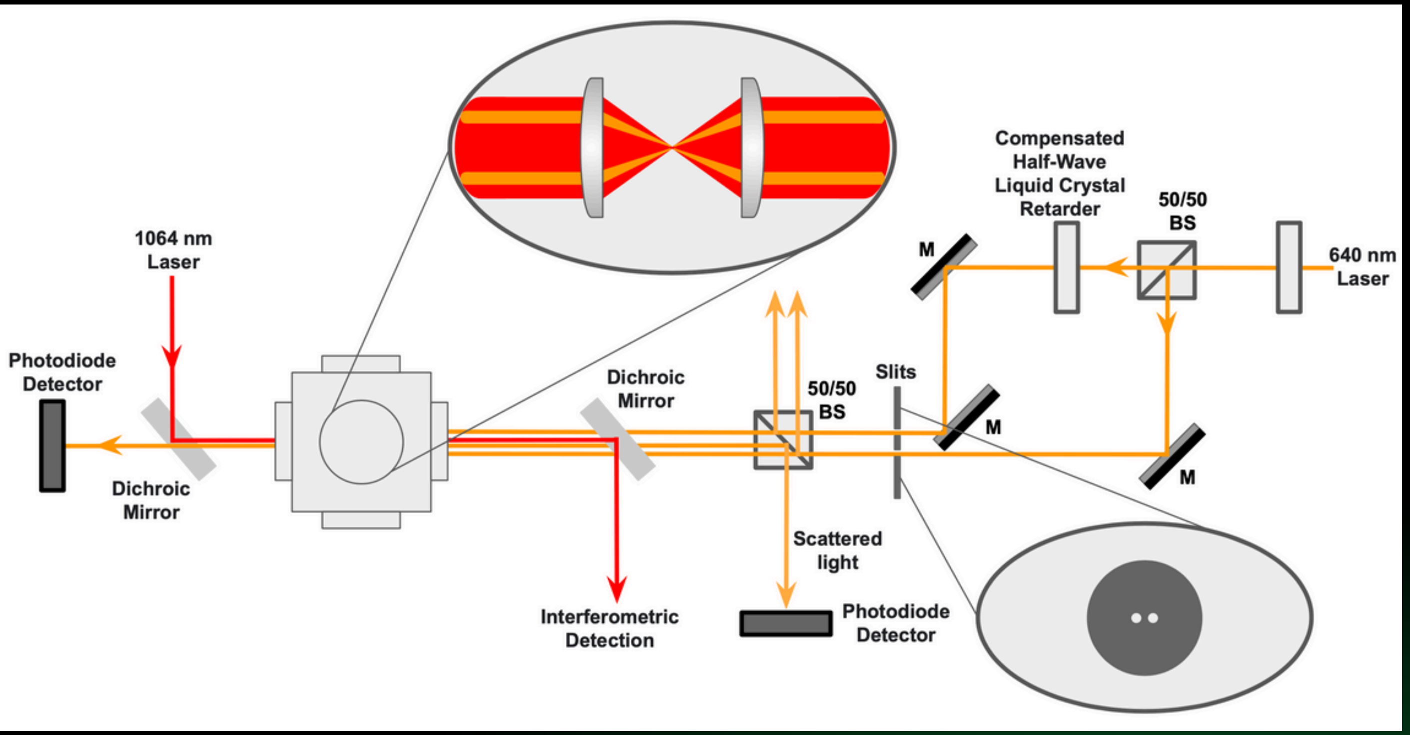
- Gas molecules damp the levitated particle
- This is modelled as a stochastic force obeying the fluctuation dissipation theorem

PHOTON BACK ACTION NOISE

- Photons from the trapping laser impart momentum to the particle whilst also providing damping through scattering
- This will provide the ultimate noise floor to impulse measurements

PREVIOUSLY CALIBRATION UTILISED KNOWLEDGE OF THERMAL PHYSICS - UNCERTAINTIES OF ~35%

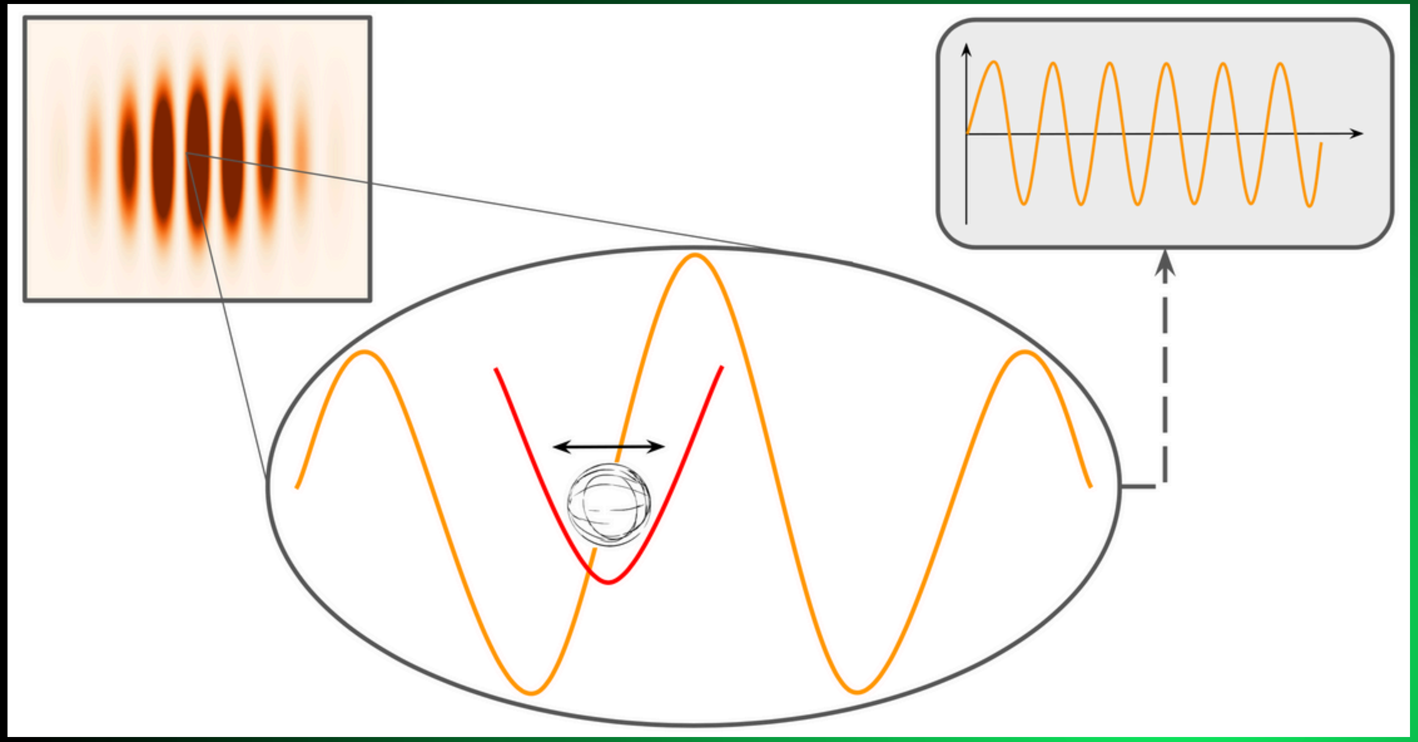
NOVEL CALIBRATION METHOD



640NM LASER USED TO CREATE INTERFERENCE FRINGES

FRINGES ARE OF KNOW WIDTH - DETERMINED THOUGH LASER WAVELENGTH AND NM-PRECISION TRANSLATION STAGE

FRINGES ARE THEN SCANNED ACROSS POTENTIAL WELL AND USED TO PROVIDE A DIRECT INTENSITY TO DISPLACEMENT MEASUREMENT



PRESENTATION OUTLINE

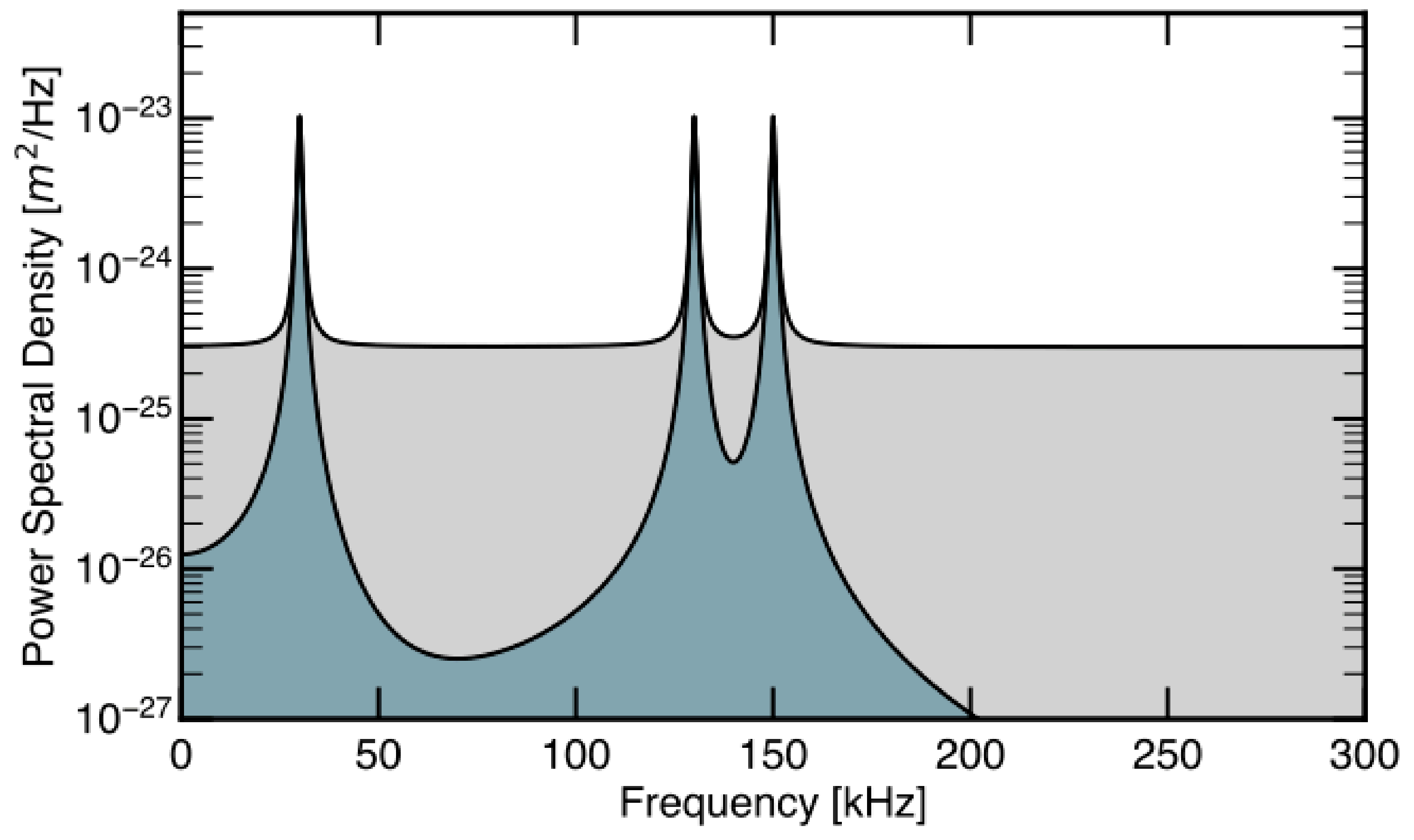
OPTIMAL FILTERING

Matched Wiener-Kolmogorov filter

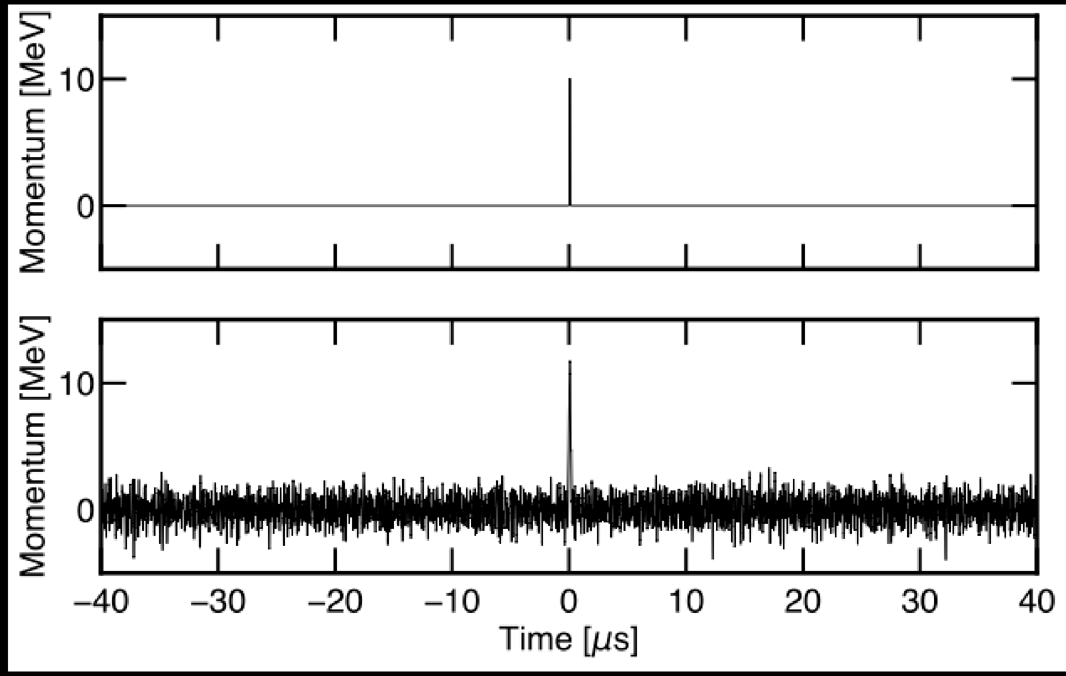
THE MATCHED FILTERING TECHNIQUE IS KNOWN TO BE THE BEST LINEAR FILTER TO EXTRACT A SIGNAL OF KNOWN FORM SWAMPED IN STATIONARY GAUSSIAN NOISE

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

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



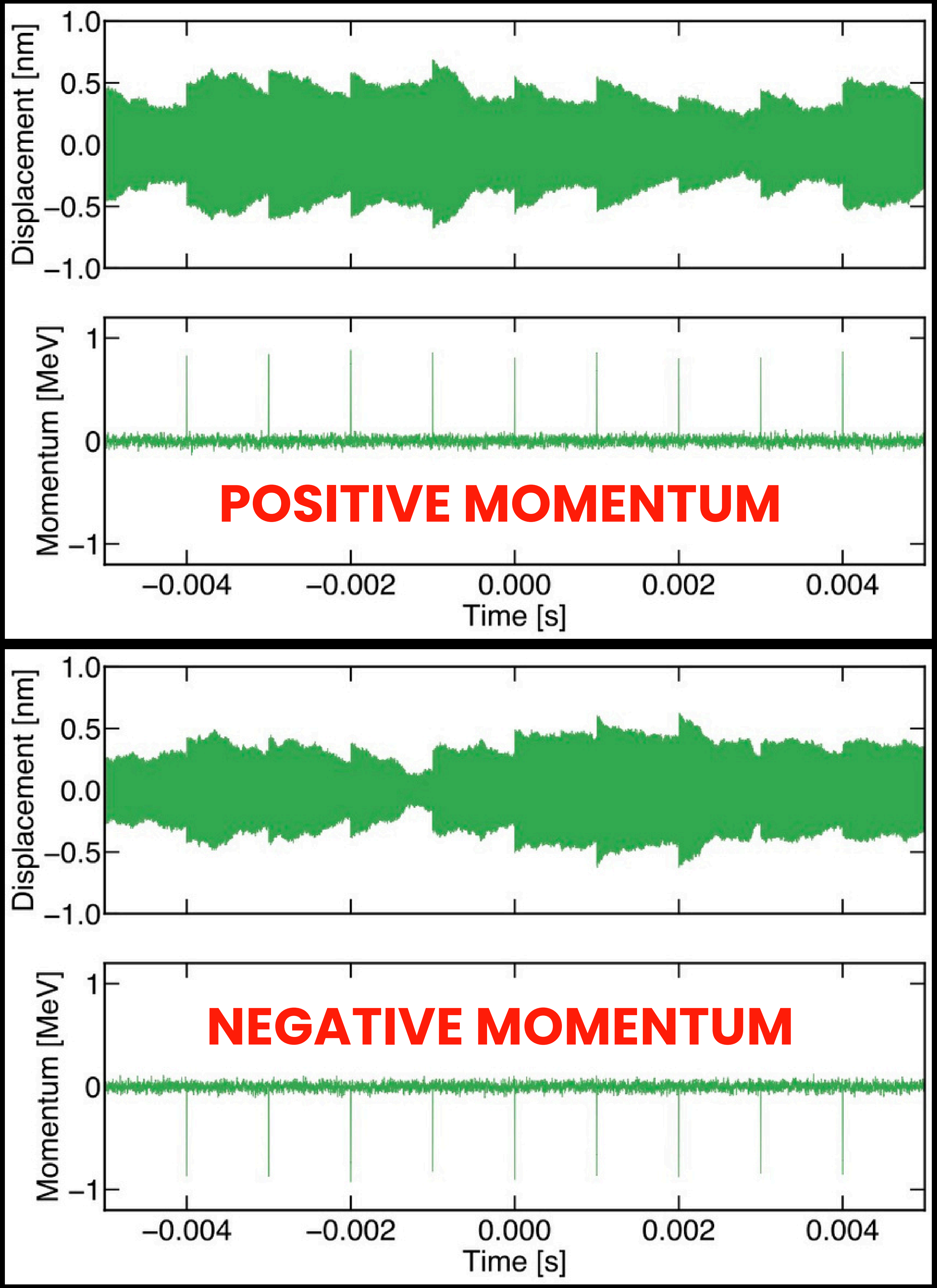
SIGNAL TO ‘MATCH’



RECOVERED IN DATA

WK FILTER RECONSTRUCTION

DIRECTIONALITY !!!



UNFILTERED

FILTERED

UNFILTERED

FILTERED

UNSALTING THE FIRST 24H

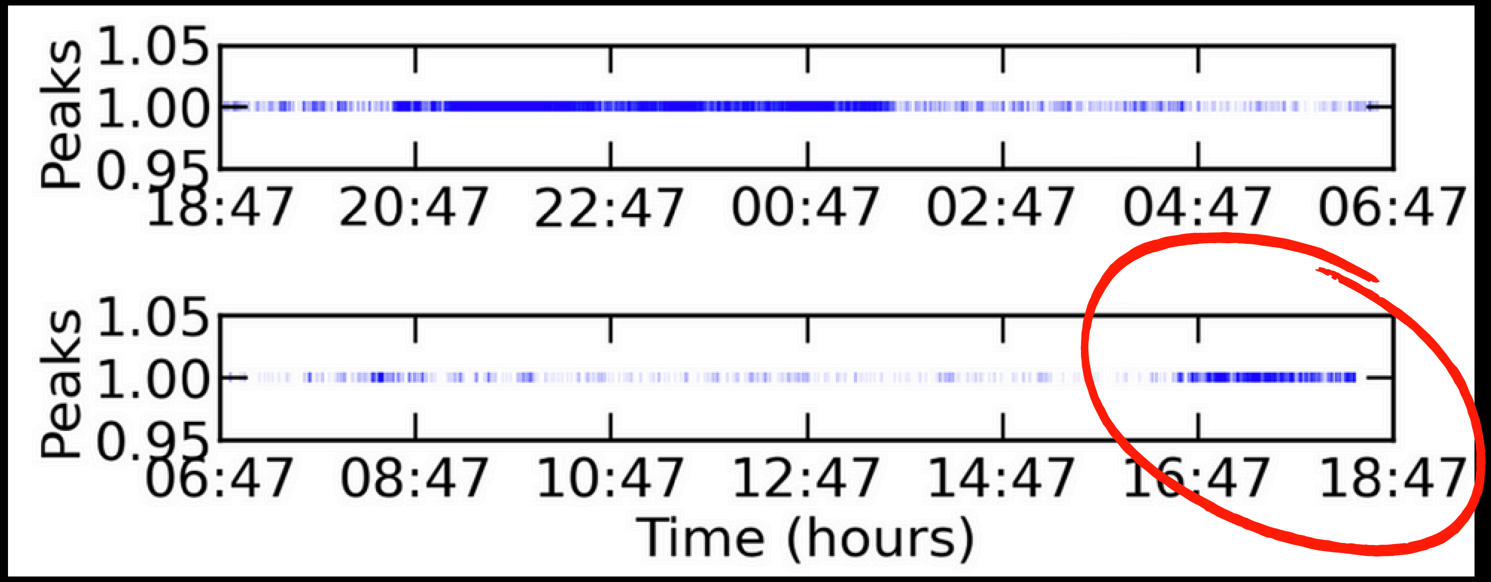
15 coincident events found
(i.e. triggered in >1 channels within event window)

SALT EVENTS = 7

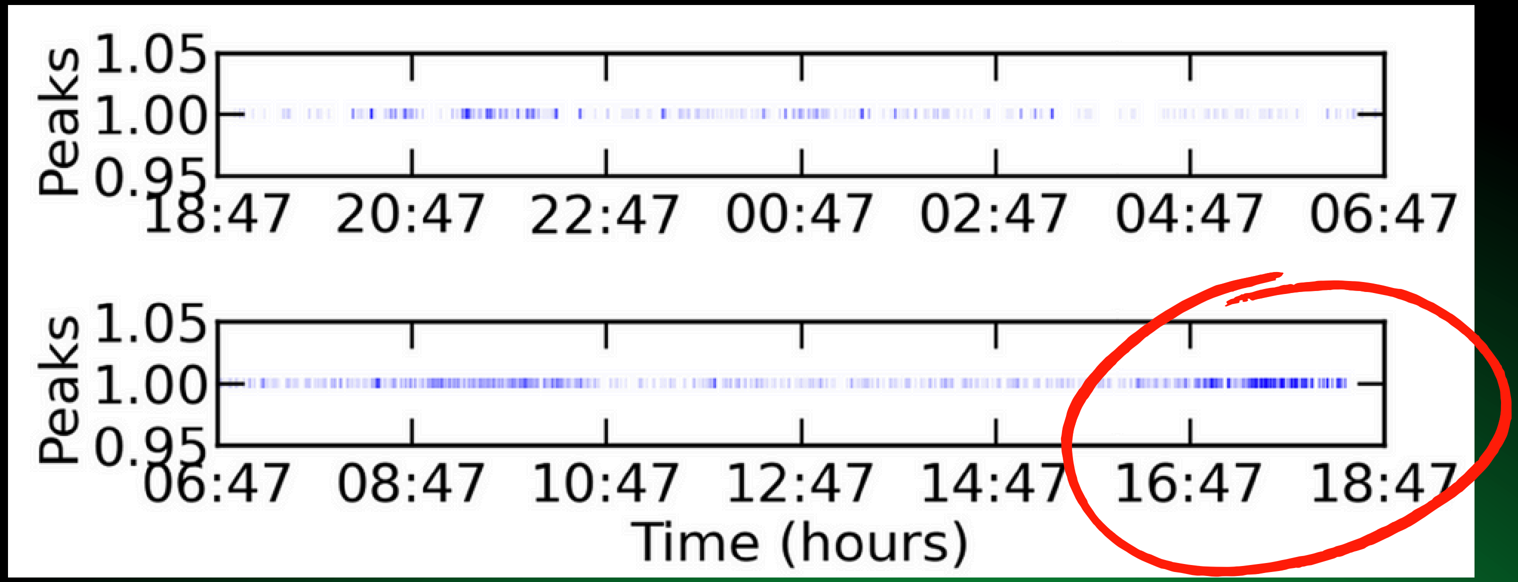
ELECTRONIC NOISE EVENTS = 6

CANDIDATE EVENTS = 2

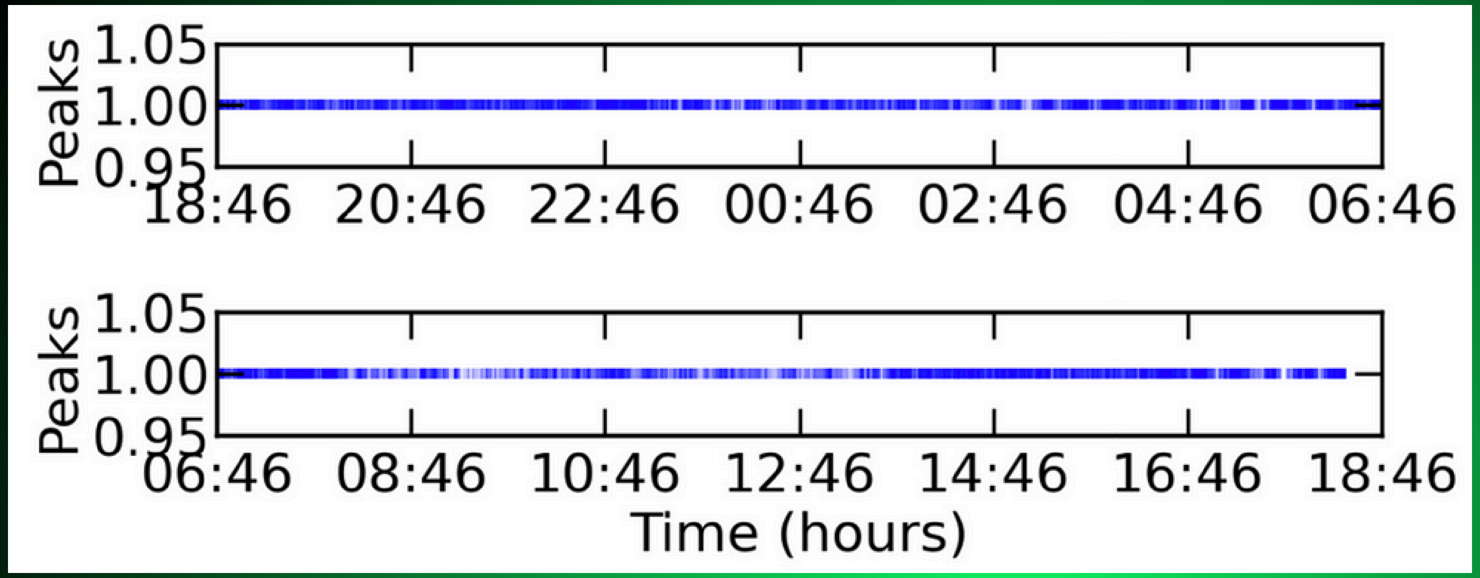
x

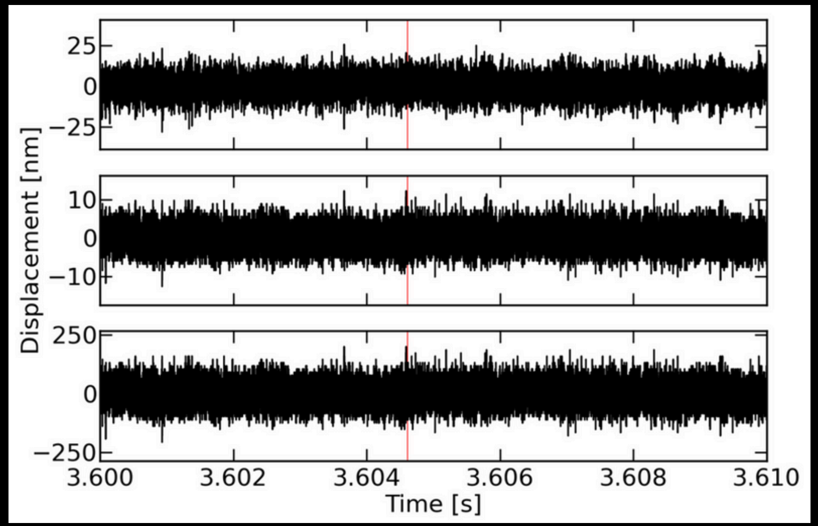


y

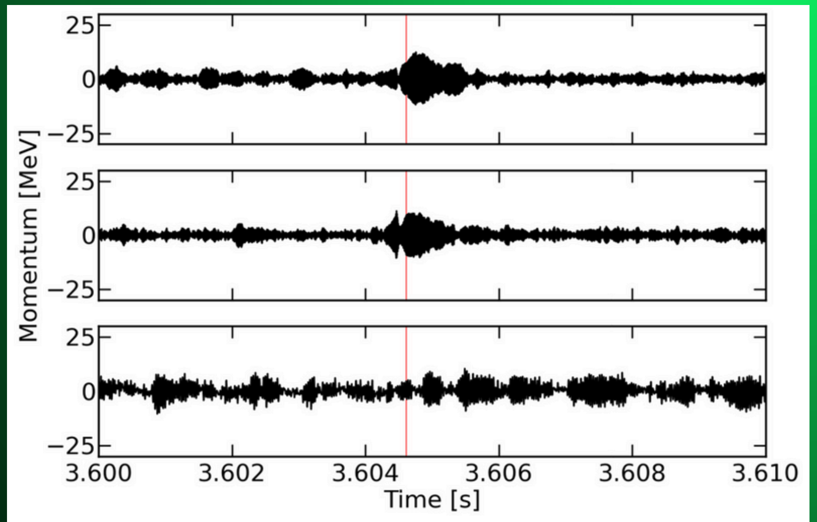


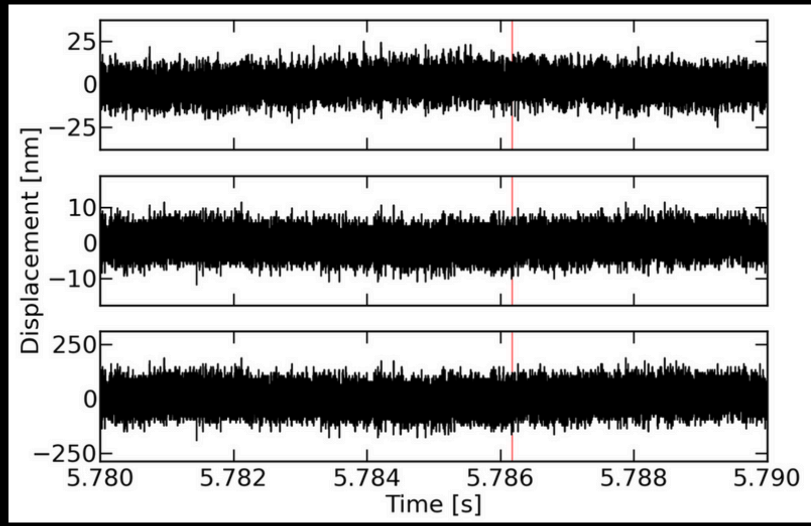
z



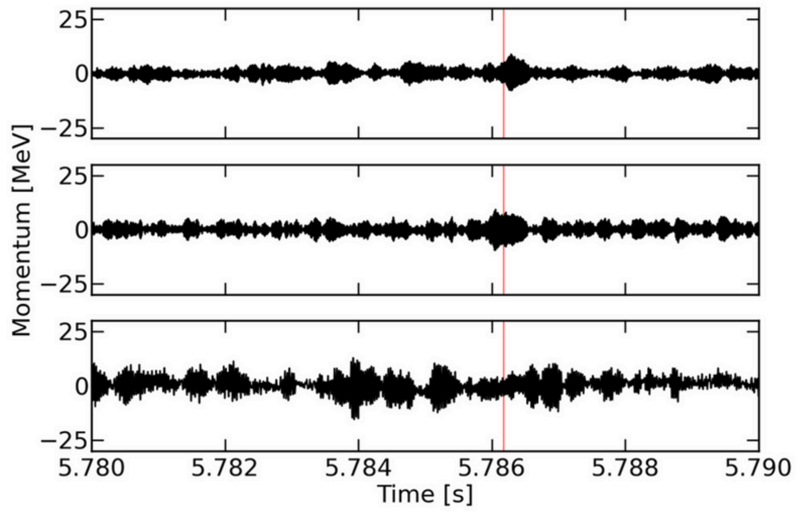


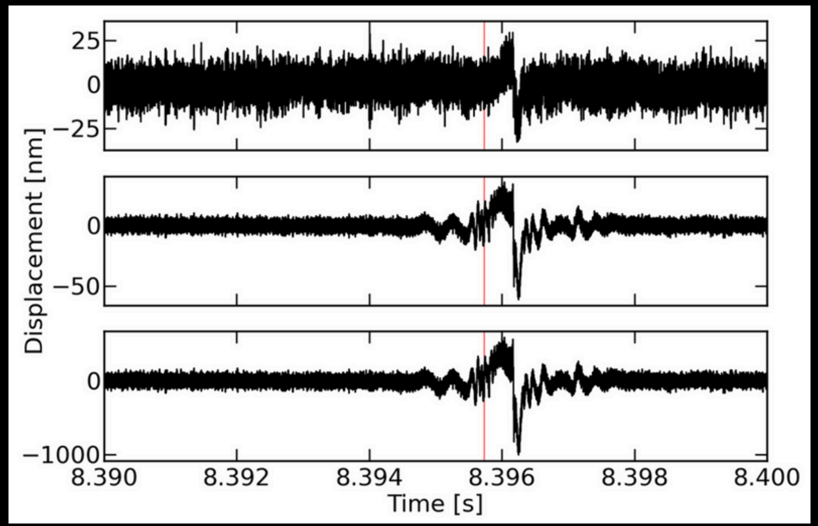
SALT KICK EVENT



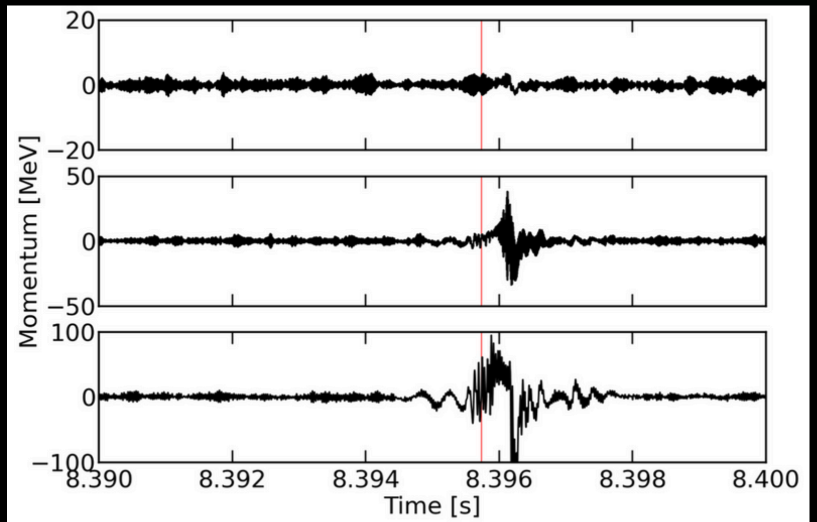


UNKNOWN CANDIDATE EVENT





ELECTRONIC NOISE EVENT



UNFILTERED

EVENT TYPES

FILTERED

PRESENTATION OUTLINE

MOTIVATION

OPTICAL TWEEZER EXPERIMENT - CURRENT STATUS

OPTIMAL FILTERING AND DIRECTIONALITY

FUTURE DIRECTIONS

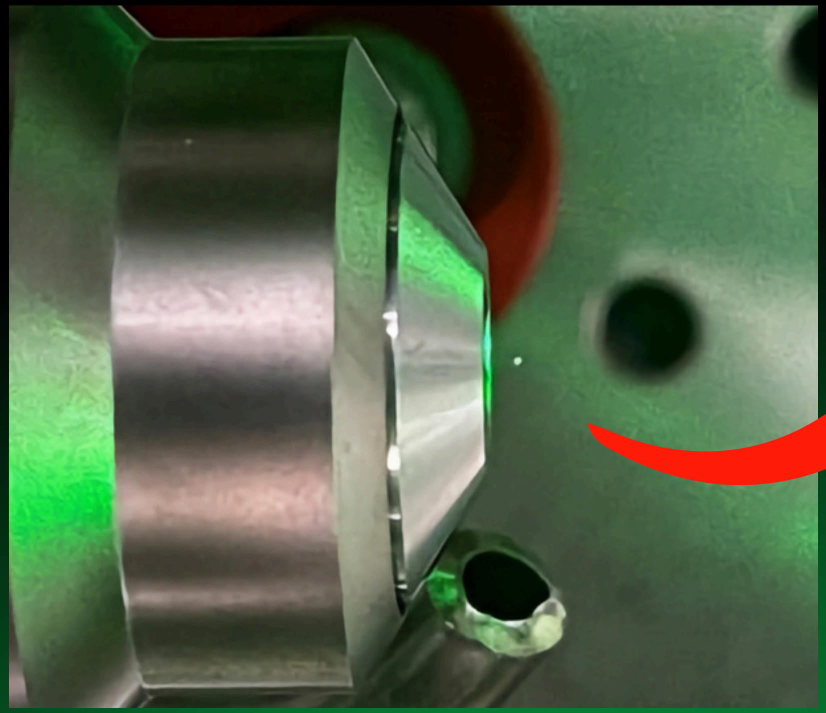
NEUTRINO PHYSICS !!!

FUTURE DIRECTIONS

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

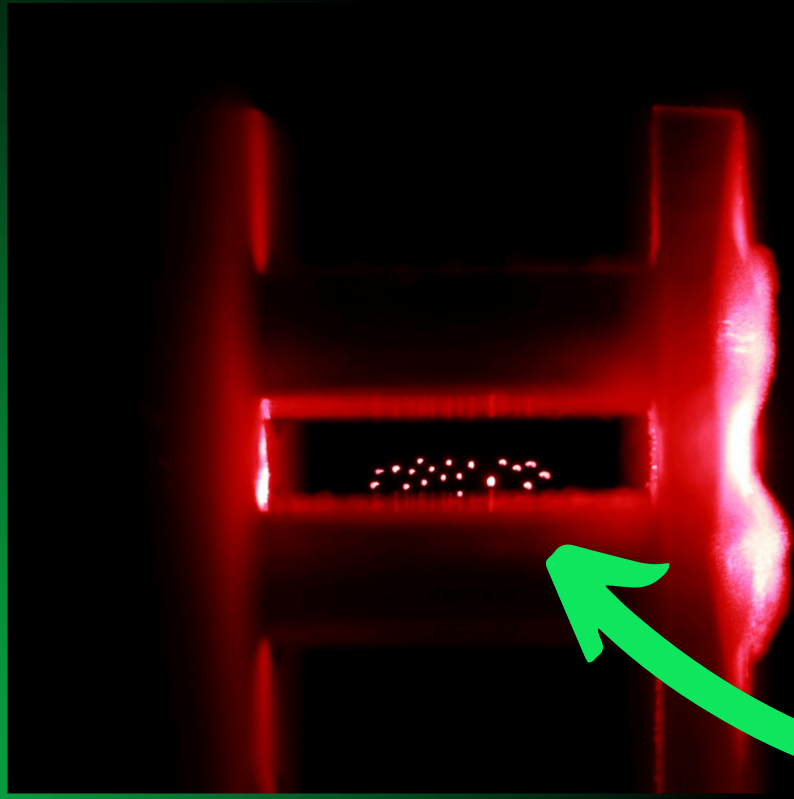
Levitated System	Mechanical Sensitivity $\sqrt{S_a}\,(g/\sqrt{\text{Hz}})$	Mechanical Sensitivity $\sqrt{S_F}\,(\text{N}/\sqrt{\text{Hz}})$	Testable DM Candidates	DM Parameter Space probed [DM Mass range]
Optically trapped (fg-ng)[16,19]	$\sim 6\times10^{-6} - 9\times10^{-8}$	$\sim 1\times10^{-18} - 6\times10^{-21}$	Millicharge Composite Low-mass particle Sterile ν	Charge [e] $\sim 10^{-4}$ [GeV – TeV]†[68] $\sigma_{\chi n}$ [cm^2] $\sim 10^{-28}$ [$10^3 - 10^4$ GeV]†[99] σ_{SI} [cm^2] $\sim 10^{-30}$ [0.1 – 100 MeV]*[14] $\lvert U_{e4}\rvert^2 \sim 10^{-4} - 10^{-6}$ [0.1 – 1 MeV]*[72]
Magnetically trapped (μg-mg)[17,53]	$\sim 1\times10^{-10} - 9\times10^{-12}$	$\sim 5\times10^{-12} - 5\times10^{-19}$	ALPs Axions Dark photons ULDM	$g_{aee} \sim 10^{-14}$ [10^{-13} to 10^{-18} eV][74] $g_{a\gamma}$ [GeV^{-1}] $\sim 10^{-10}$ [$10^{-12} - 10^{-14}$ eV][75] $\epsilon \sim 10^{-8}$ [$10^{-12} - 10^{-14}$ eV][75] $g_{B-L} \sim 10^{-25}$[10^{-14} to 10^{-16} eV][56]
Electrically trapped (40 fg)[35]	$\sim 5\times10^{-6}$	$\sim 2\times10^{-21}$	ULDM[100] Composite	no concrete experimental proposals beyond trapped atomic ions

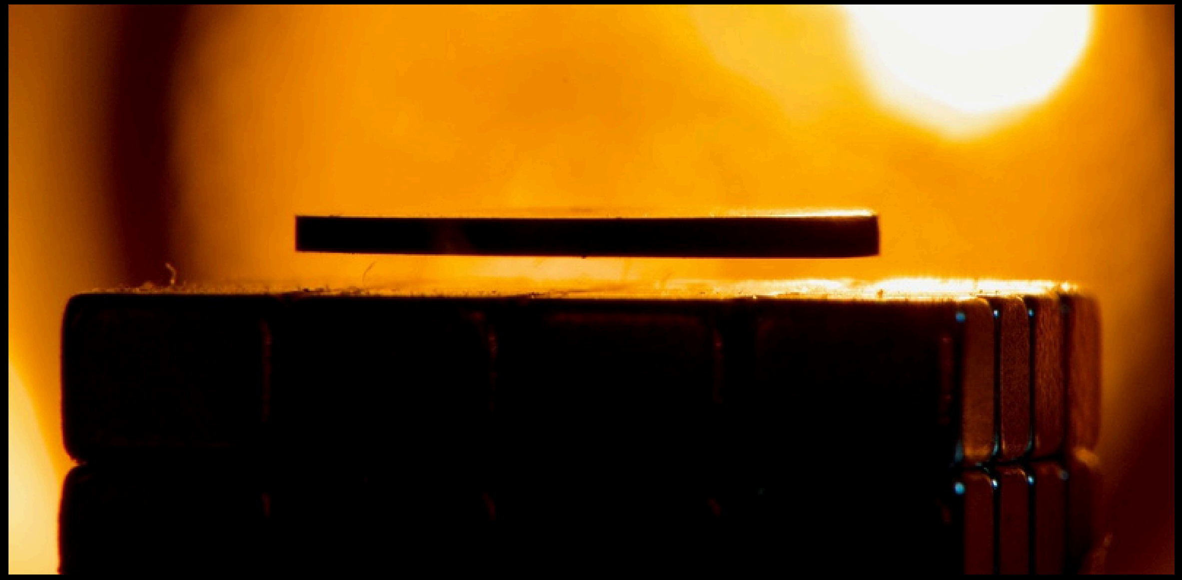
PLR



OPTICAL LEVITATION

ELECTRICAL LEVITATION





MAGNETIC LEVITATION

MULTIPLE PARTICLES !!!

PETER BARKER

Q-SENSE

CHAMKAUR GHAG

Thank You

ANTONIO PONTIN

FIONA ALDER

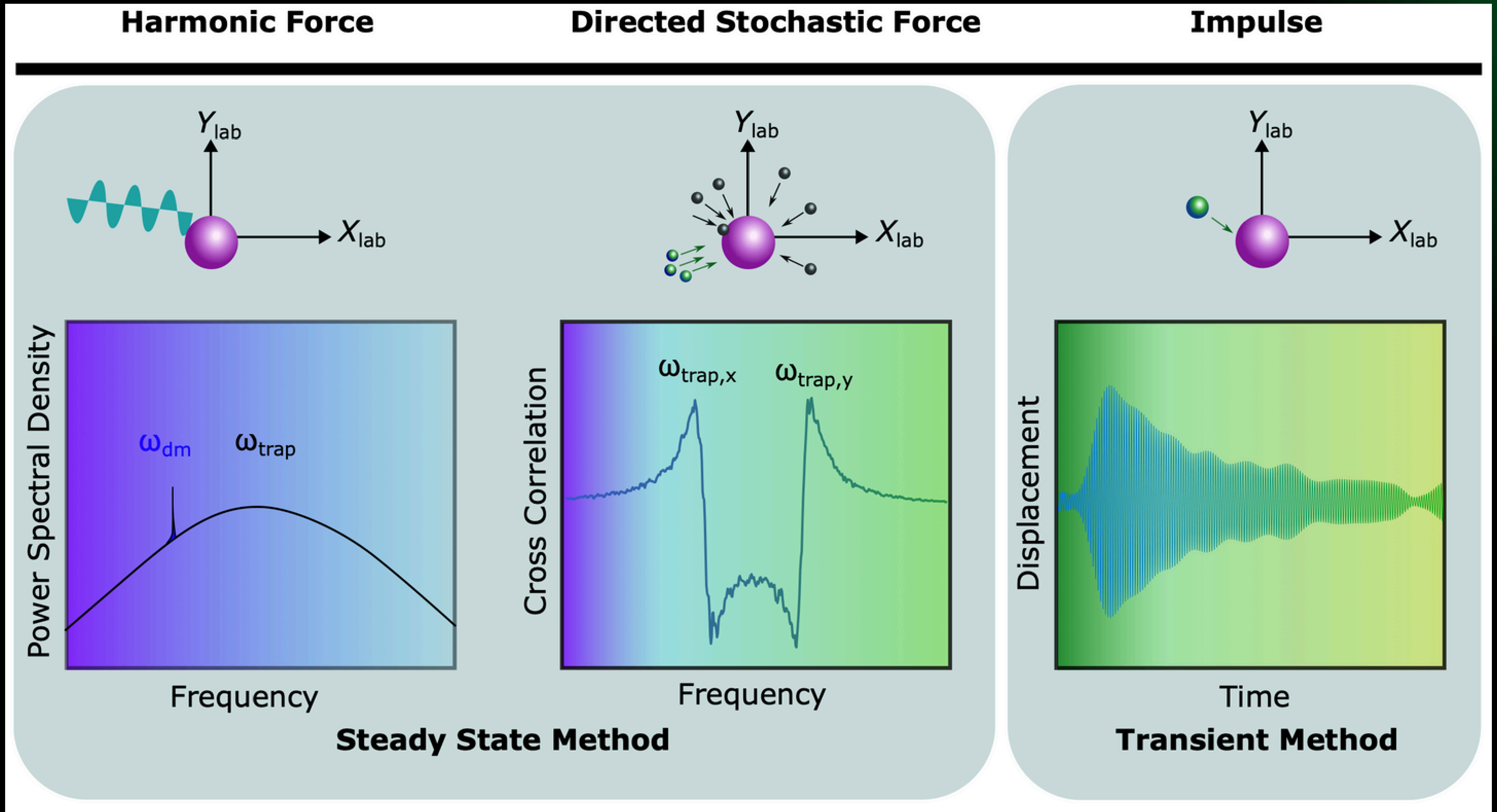
JONATHAN GOSLING

ROBERT JAMES

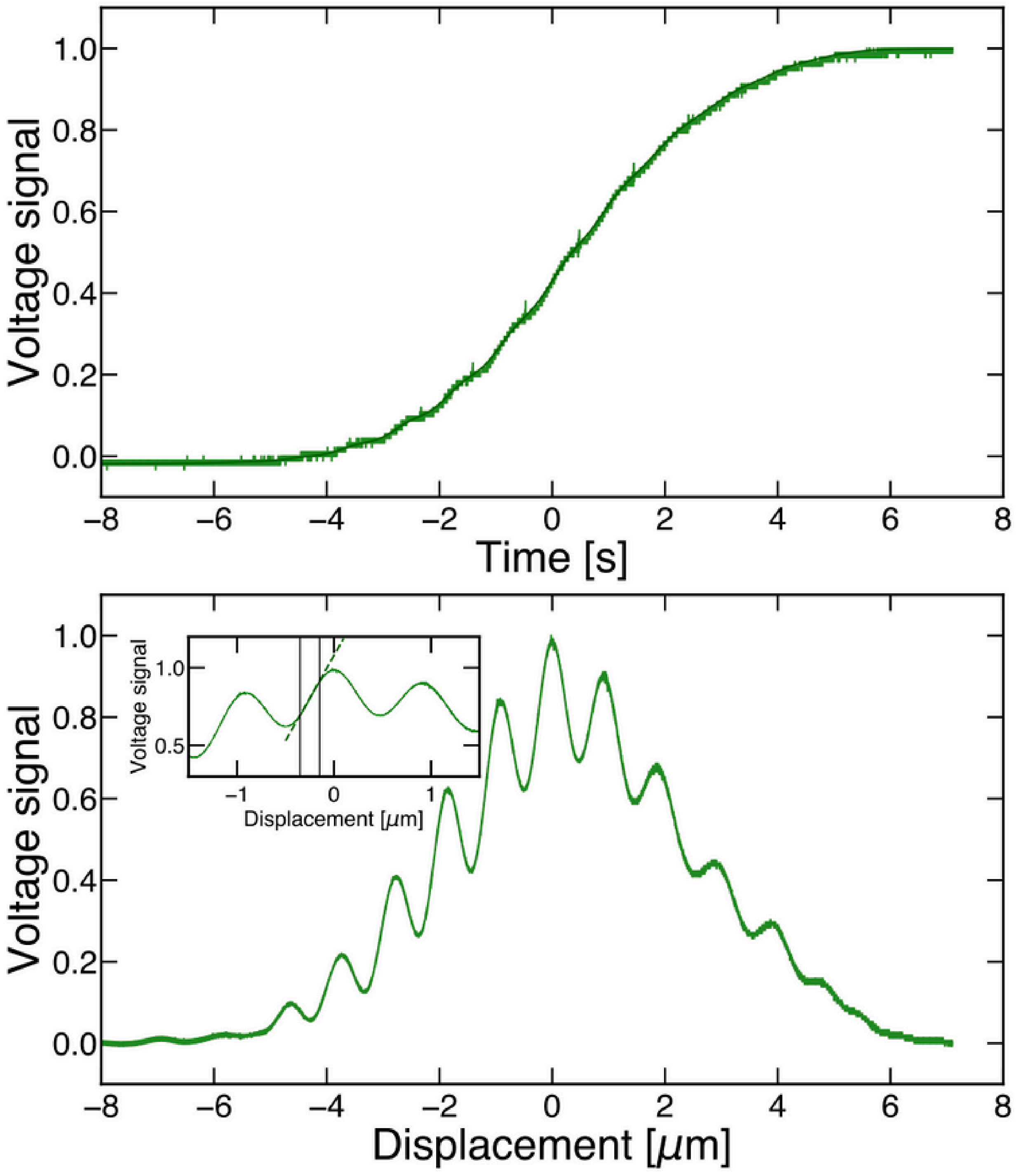
EVA KILIAN

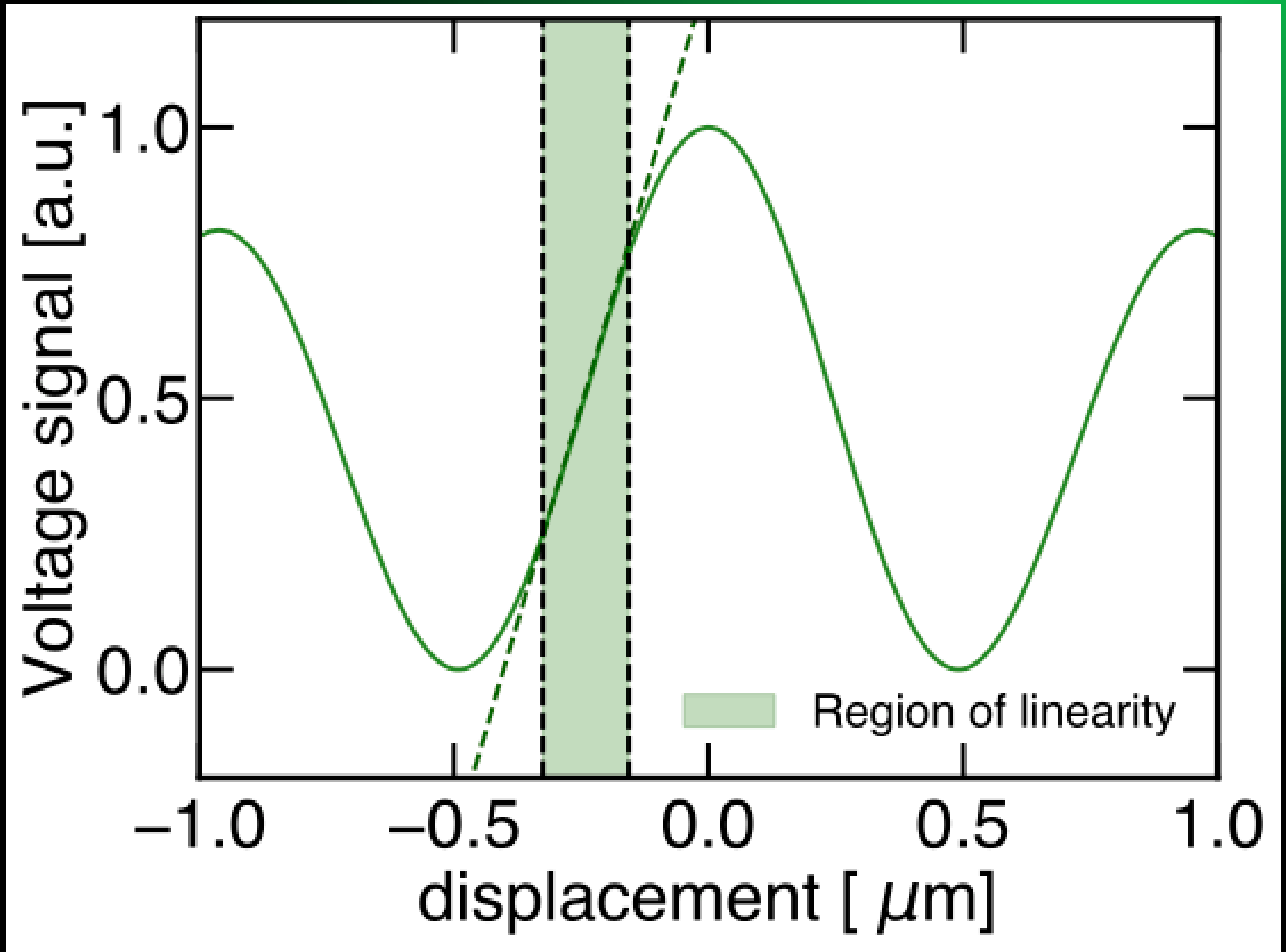
LOUIS HAMAIDE

EXTRA SLIDES



EXTRA SLIDES





EXTRA SLIDES