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Quantum R&D in Particle Physics Cluster and Beyond

Jonathan Tinsley

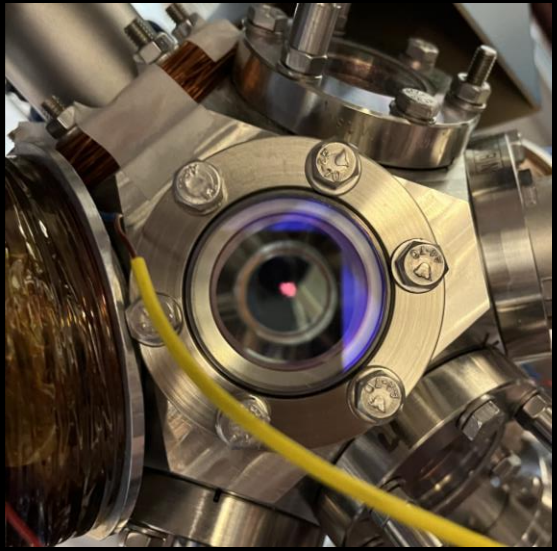
20/05/2025, HEP Annual Meeting

Physics Research activities and quantum science

- **Quantum science** has been an integral part of our research programme for more than a decade, with a strong focus on enabling novel fundamental physics experiments
- The Department has established a coordinated group on **Quantum Science and Technology Developments (QSTD)** that builds upon the existing expertise within the 'classic' research clusters to boost activities, achieve competitiveness and identify USPs

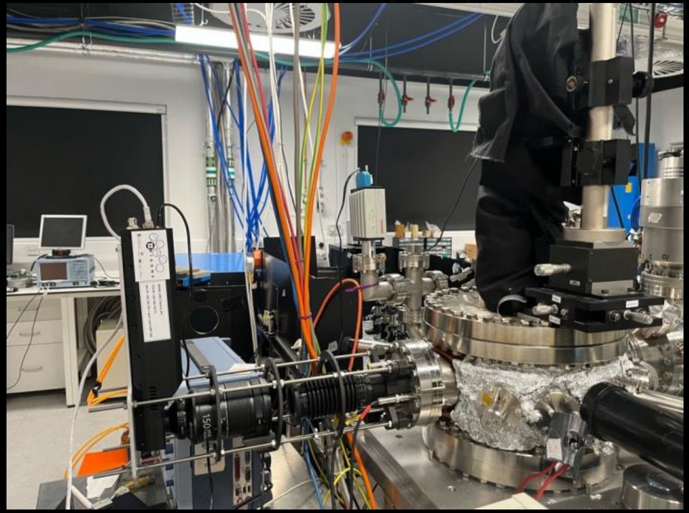
Coordinators: B Heazelwood, G Casse

  - Exploit current infrastructure, nurture **collaborations,** also with other departments (i.e. Math and EEE)



The **Liverpool PP Laser laboratory** is one of the few existing UK labs with in-house capability to develop **atom interferometry** devices and the design of **new cold atom sources**

The **cold chemical physics laboratory** offers possibility to study complex ion-neutral reaction systems at low temperature (cryogenic ion-trap)



QTFP-related projects

UoL is a key partner in the **Quantum Technology for Fundamental Physics** programme, initiated in 2019 to enable advanced quantum technologies for physics exploration. **UoL partner in 3 of them**:

- **AION** *(A UK atom interferometer observatory and network)* : to set up 5 ultra-cold strontium labs in consortium institutes, and develop atomic interferometer technology to complete the design for a 10 m prototype
  - UoL Leadership in national and international programme, 2 academics involved, postdocs and students

J Coleman, J Tinsley, + team (see A Carroll's slides)

- **QUEST-DMC** *(Quantum enhanced superfluid technologies for dark matter and cosmology)* : use superfluid helium-3 (He3) and develop of ultra-sensitive quantum sensors, underpinned by cryogenic and theoretical expertise:
  - Key contributions from recent UKRI Future Leadership Fellow (Math), partnership with RHUL cryogenic facility

J Smirnov (Maths)

- **QSHS** *(Quantum sensors for the hidden sector)* : to develop ultra-low-noise quantum electronics necessary to achieve the sensitivity required to underpin axion searches
  - Initiated by UoL academic now moved to another institute, re-growing partnership for test of quantum devices in cryostat, which incorporates an 8T magnet, at Sheffield

Past: E Hardy – Math
Aspirational: C Casse, M D'Onofrio

Key strengths and activities: build communities; share knowledge and expertise; train ECRs

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DRD5 / RDquantum – Quantum Sensor R&D for Particle Physics

Joined the DRD5 proto-collaboration at CERN with expertise across a broad range of proposed activities:

- WP1a: precision experiments with trapped ions (spectroscopic measurements, laser cooling), new detection methods.
- WP1b: atom interferometry.
- WP2a: radiation hardness.
- WP2b: aperiodic tiling, superconducting nanowires, spintronic materials.
- WP3: SQUIDs, cryogenic detectors.
- WP5: sensor development plans.
- WP6: education.

Proposal on R&D on quantum sensors: the DRD5/RDq proto-collaboration

(signatory list in section 13.2)

ABSTRACT

The detector R&D roadmap initiated by ECFA in 2020 highlighted the large number of particle physics opportunities that targeted and collaborative R&D in the field of quantum sensors and related technologies can enable. The involved communities and the roadmap's Task Force 5 (TF5) have established a list of the most promising areas for investment and defined the R&D that would be needed to bring these to the level at which experiments building on them can be envisaged. This proposal lays out the resulting high level work packages with deliverables and milestones and proposes the structure of a collaboration (the DRD5 / RDq collaboration) that would enable such R&D to be pursued at a global scale.

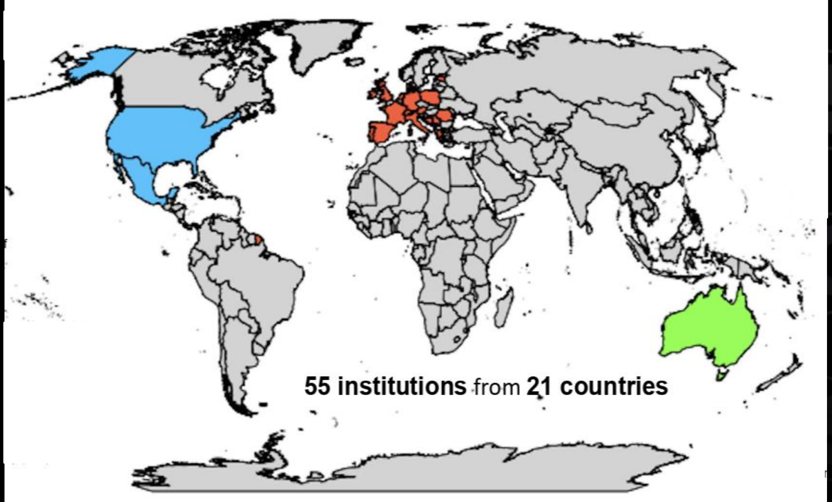
Keywords: quantum sensors, particle physics, BSM

WP-1	WP-2	WP-3	WP-4	WP-5	WP-6
Atomic, Nuclear & Molecular Systems in traps & beams	*Quantum Materials (0-, 1-, 2-D)*	*Quantum Superconducting Devices*	*Scaled-up large ensembles (spin-oriented, hybrid or optomechanical devices)*	*Quantum Techniques for Sensing*	*Capacity Expansion and Exchanges*

Table 1. Families of quantum sensors (structured in form of Work Packages) and WP-spanning activities corresponding to the DRD5 proposal.

Atom interferometry research

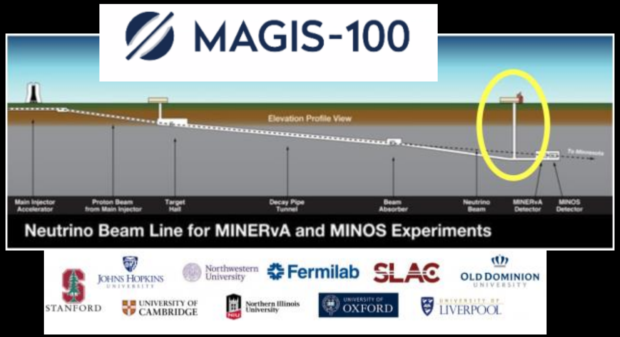
Terrestrial Very-Long Baseline Atom Interferometry (TVLBAI)



Quantum sensors based on the coherent manipulation of matter waves

- Light pulses used to create superpositions of momentum states
- Wave packets recombined after evolution time
- Sensitive to inertial forces and atomic potentials

Part of international collaborations AION (UK) and MAGIS (US-UK), supported by **STFC-EPSRC QTFP programme**

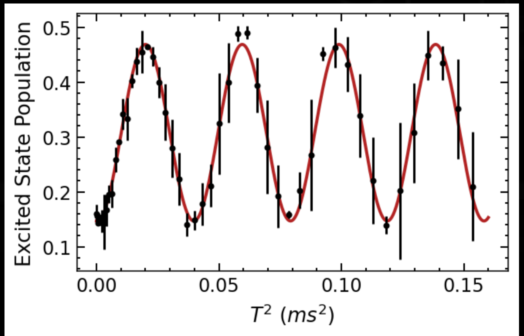


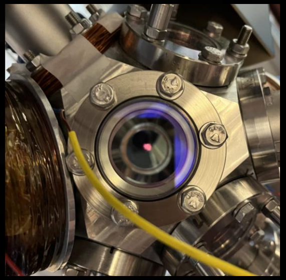
DOE & STFC partnership on quantum technologies

Main target is to probe **new physics**:

- Ultralight dark matter searches
- Gravitational waves detection
- Fundamental quantum mechanics

https://arxiv.org/abs/2305.20060





In-house rubidium-based interferometry programme

Development & Exploitation of SQUIDs

Research projects involving Superconducting Quantum Interference Devices (SQUIDS):

- Successfully developed very thin (< 10 nm) Nb superconducting nanowires and films for sensor fabrication and single photon detectors

Electrical Engineering & CMP – Liam O'Brien

- Development of co-planar superconducting waveguides and resonators terminating on a SQUID to create a tuneable 'mirror' for highly sensitive quantum photonics experiments
  - Collaboration of UoL silicon-based quantum sensor experts, quantum theorists and international lab (FBK – Trento) for development and reproducibility

J Tinsley, J Smirnov, G Casse, M D'Onofrio

- FLASH experiment to search for QCD axions using resonant microwave cavities

P Beltrame

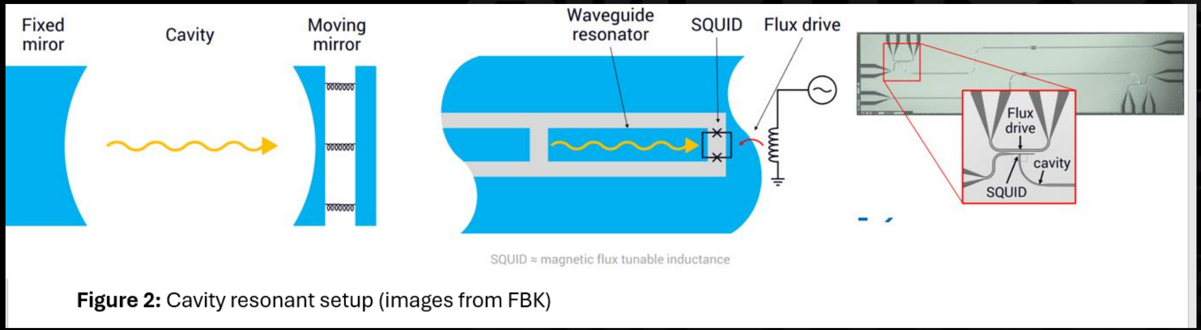
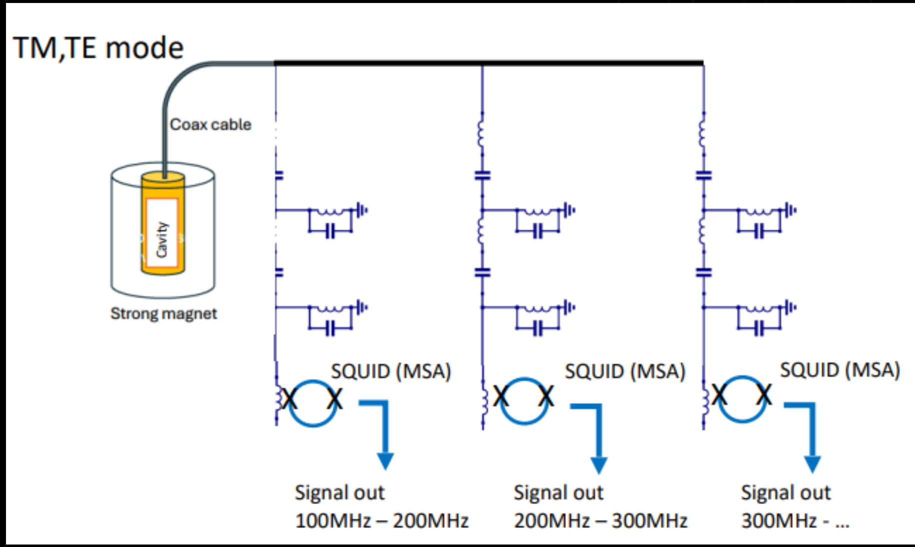


Figure 2: Cavity resonant setup (images from FBK)



Cold ion-neutral reaction for QS

- Extensive efforts in CMP research on low-temperature chemical physics.
    - Quantum information and precision measurements
    - Devise new detection methods for monitoring trapped ions
    - Study quantum effects in reactions at low temperatures

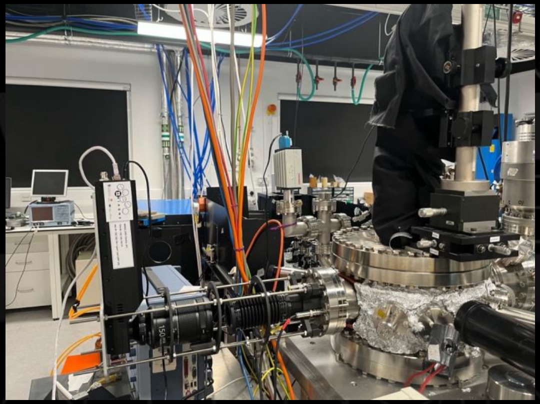
- Once generated, ion Coulomb crystal can be detected with methods developed to facilitate quantitative study of complex ion-neutral reaction systems

B Heazelwood
S Burdin, A Roberts, K Mavrokoridis

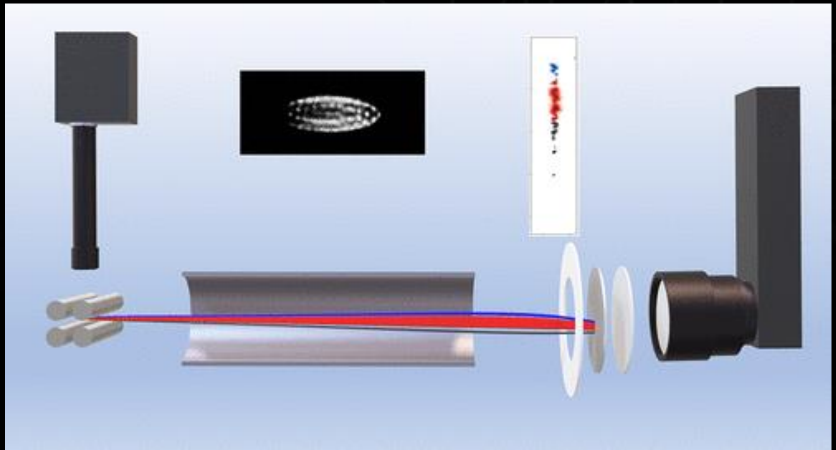
- Cryogenic ion trap environment with integrated MS expands the range of systems we can examine under cold, controlled conditions

By controlling reaction parameters, can test theories of reactivity and improve understanding of the **transition from classical to quantum dynamics**

Liverpool cold chemical physics laboratory



simultaneous recording of temporal and structural distribution of al ions that strike the detector



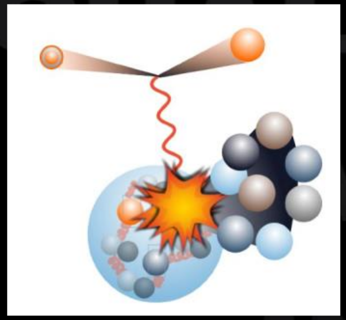
M. Hejduk & B Heazelwood, *Rev. Sci. Instrum.* **90**, 123701 (2019)
J. A. Diprose et al., *J. Phys. Chem. A* **128**, 3900 (2024)

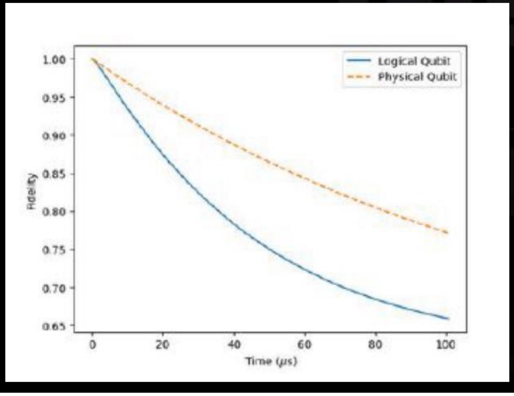
In progress: applications to healthcare (e.g. magnetometry for biosensing)

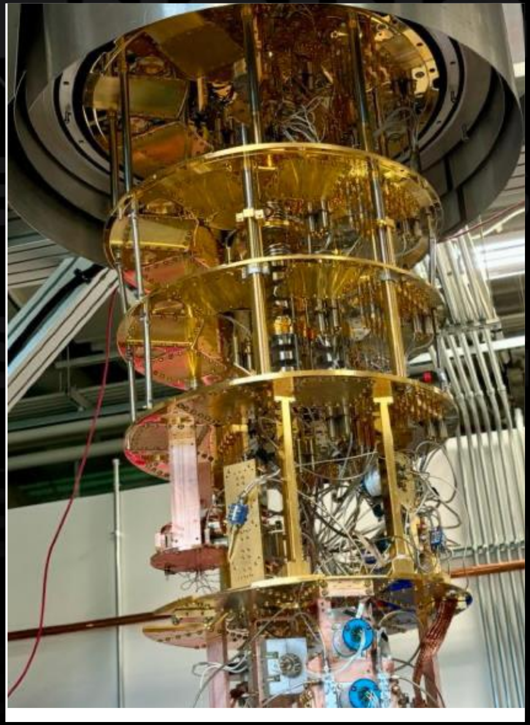
Quantum computing & simulation

- QCs are well suited for simulating quantum systems (i.e. interaction of ν with nuclei – the nuclear many-body problem)
  - Exploring quantum error correction (QEC) to achieve fault-tolerant quantum computing
  - Simulating performance of QEC codes under realistic quantum noise
  - Collaborative research conducted at the Superconducting Quantum Materials and Systems (SQMS) Center/Fermilab (2 PhD students)

C Andreopoulos







- Activities on-going on the theoretical side (Dept of Math):
  - E.g. Digital quantum simulation of quantum field theories using ‘NISQ’ devices without error correction; Noise/error mitigation; Transmon qubits & Qiskit Pulse and more

[arXiv:2301.02230, arXiv:2112.07651];

D Schaich (Maths)

E Rodriguez

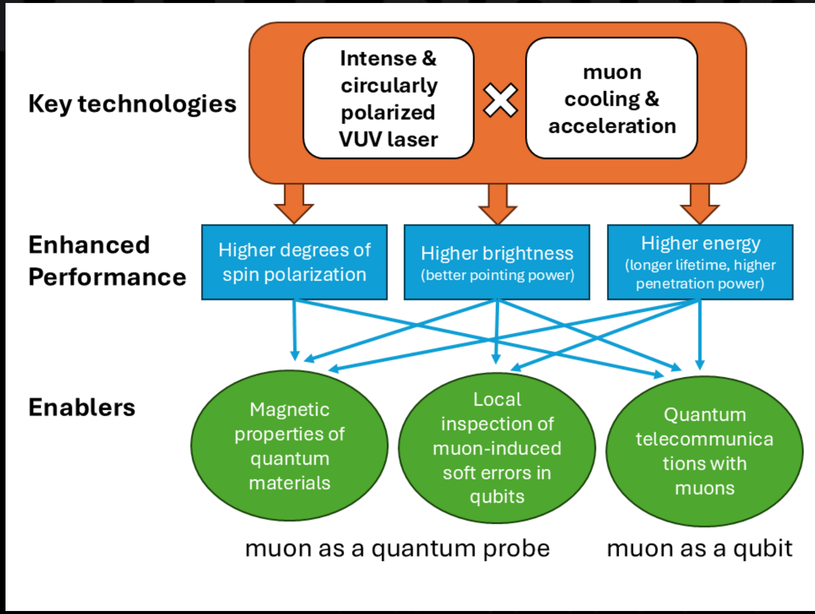
+ **Quantum Machine Learning** for LHC data

JHEP08(2022)014

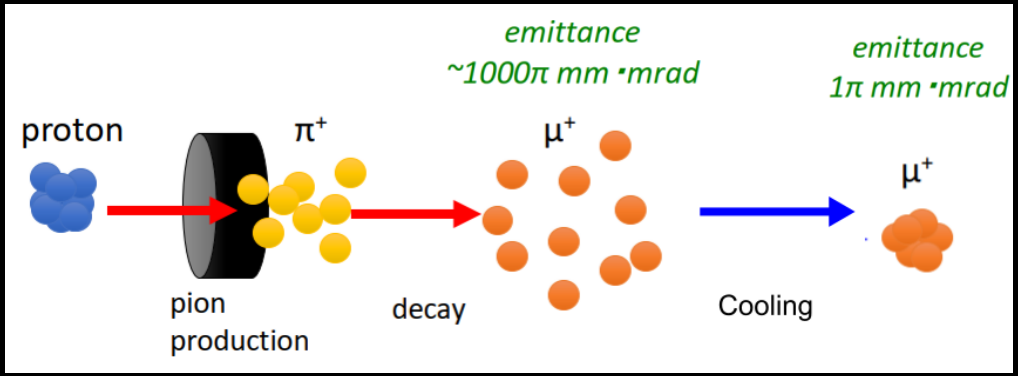
High-Brightness Muon Beams at J-PARC

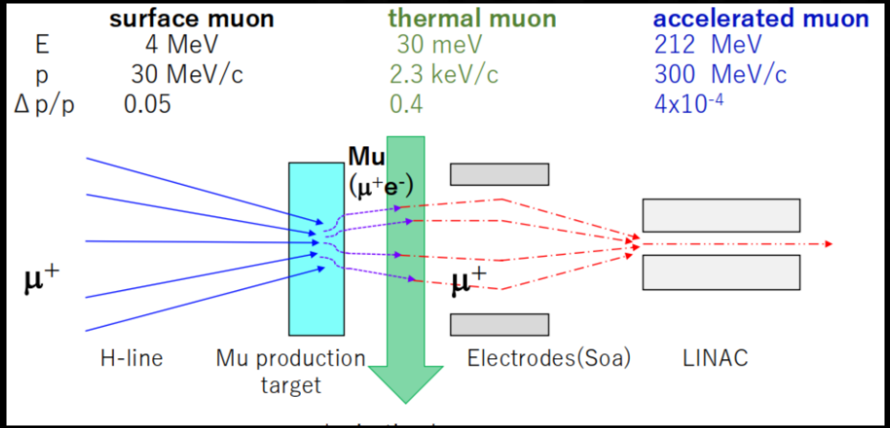
- J-PARC muon facility has demonstrated the production and acceleration of a cold muon beam
    - Enhanced measurements of muon g-2 and EDM
    - Development of a muon microscopy
    - Cargo scanning with muons
- Production method gives muon polarisation of 50%
- **Proposal:** produce cooled and polarised muon beam
    - Enhanced muon spin relaxation spectroscopy for quantum materials
    - Muons for quantum telecommunication

J Tinsley, G Casse, G Venanzoni



S. Aritome, et al., arXiv: 2410.11367 (2024) (accepted in Phys. Rev. Lett.)

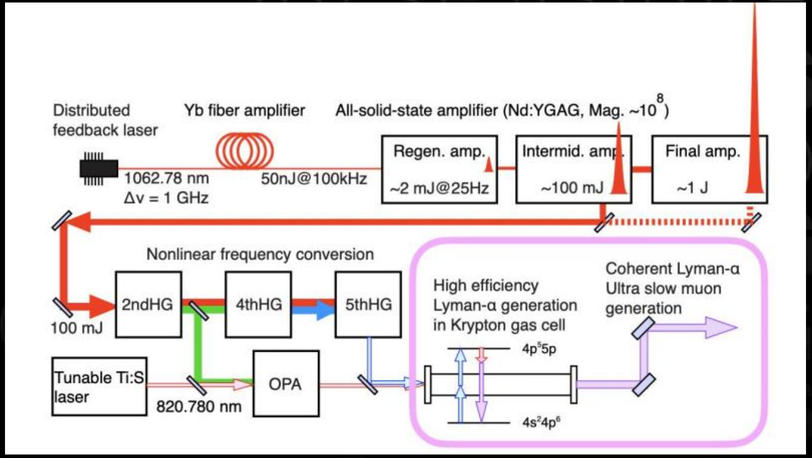




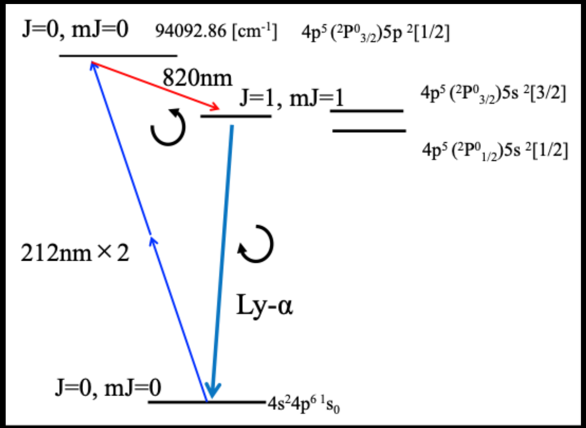
Adapted from Slides by T. Mibe, KEK, Japan

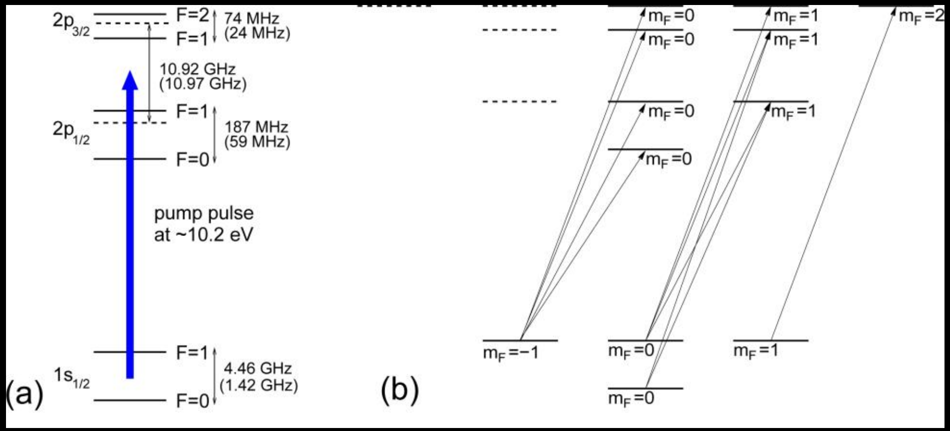
Polarised Muon Production with VUV Lasers

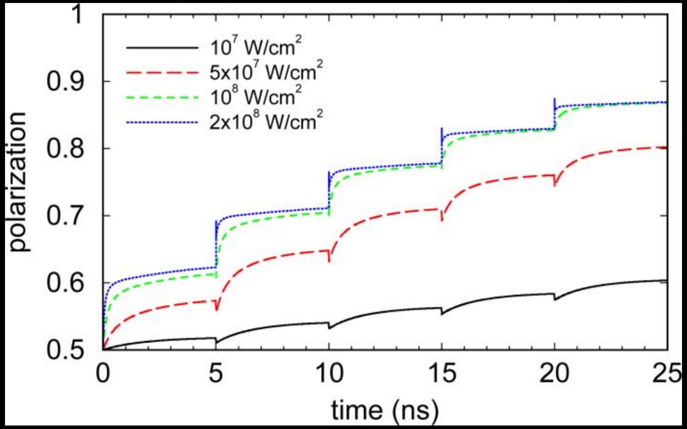
- Use the ionisation process to enhance the polarisation of the produced muons
  - Requires high-intensity 122 nm light
  - Circularly polarised light to optically pump the muonium into the required magnetic sub-state before ionisation
- VUV lasers will be of broad interest as an enabling technology
  - Nuclear clocks
  - Molecules for quantum simulation
  - Laser cooling of muonium and anti-hydrogen



Y. Oishi *et al*., *J. Phys.: Conf. Ser.* **2462**, 012026 (2023)
T. Nakajima, *Optics Express* ***18***, 27468-27480 (2010)

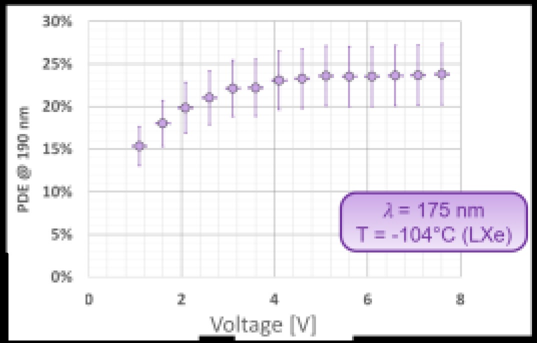


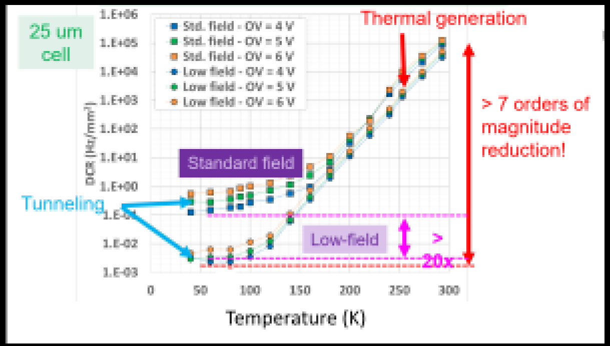




Diagnostic Tools for the VUV

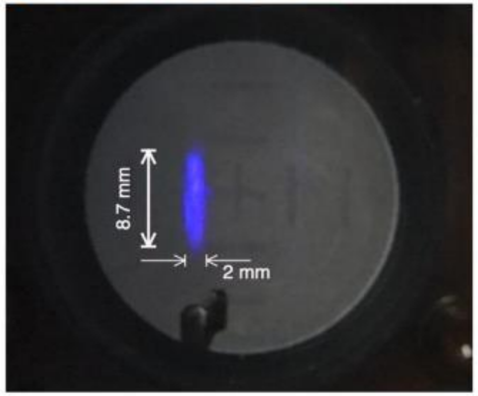
- VUV lasers suffer from a dearth of optics and diagnostic tools and sensors
- Leverage significant effort towards silicon photomultipliers (SiPM) with high efficiency and low noise rate in 170 – 190 nm range
  - DUNE, DarkSide, nEXO
- Sensor for measuring the VUV pulse energies
- Fast readout (~200 ps) to enable laser pulse shapes to be resolved





Sodium salicylate plate + CMOS camera

Lyman-α beam profile



F. Acerbi, *et al*., IEEE Transactions on Electron Devices **64.2**, 521-526 (2017)
G. Gallina, et al., IEEE Transactions on Electron Devices **66.10**, 4228-4234 (2019)

Summary

- Existing programme covering a broad range of activities
  - Collaborations throughout the department, university and externally
  - Quantum sensing with atom interferometry
  - Quantum simulation of high-energy physics

- Quantum Science and Technology Developments (QSTD) across-cluster group
  - Regular meetings and Teams channel
  - Open to all

- New collaborations and experiments in development
  - Superconducting sensors for dark matter detection and QED tests
  - Production of polarised muons via the development of VUV laser technology