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Research and Impact Highlights: where we stand and future vision

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Head of Research & Impact

14/07/2023, Department Away Day on R&I

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OVERVIEW

- Research activities in our department are distributed in five clusters: **Accelerator Science, Condensed Matter, Nuclear Physics and Particle Physics** and the recently added **Physics Education Research**
  → playing key roles in interdisciplinary institutes and in national and international collaborations.

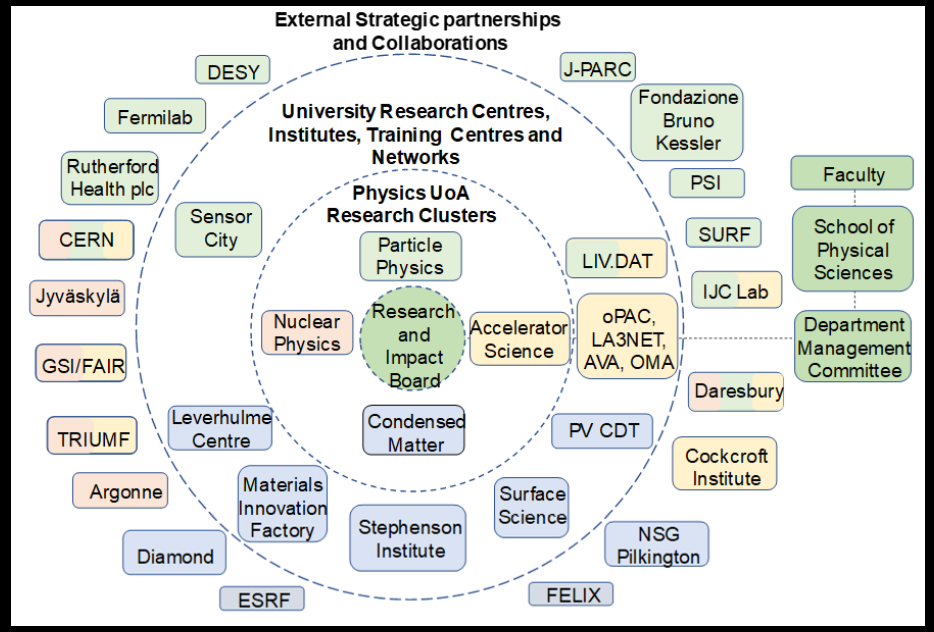

Figure 1 of our REF Environment submission

- **44 FTE (47 headcount)** returned in REF2021 - small increase since then, joined appointments (e.g. B. Merk with EEE), Leverhulme Professorship (G.Venanzoni)
- more than **50 full time research** and computer physicists, professional, technical and electronic support staff
- About **120 PhD students** enrolled in our programmes (STFC CDT on Big Data Science (LIV.DAT), Innovation in Data Intensive Science (LIV.INNO), EPSRC CDT's on New and Sustainable Photovoltaics and Risk & Uncertainty, and EU ITN on Medical Accelerators and Antimatter Physics).

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STRATEGIC PRIORITIES

SP1 further develop and **lead research** on physics questions of international significance
[summary and vision from each cluster presented here]

SP2 grow cross-cluster **collaboration** and promote **interdisciplinary research** initiatives.
[examples of collaborations among clusters and departments presented here]

SP3 build and enhance a research environment which develops our **people** and embodies **Equality, Diversity and Inclusion**, including Juno and Athena SWAN principles → last year Juno/Athena Swan successes really show we are on an excellent trajectory

SP4 develop **impact** as an integral outcome of our research activities in our focus areas of Energy, Health, Security, and Society → with potential growth e.g. in advanced manufacturing, digital, non-proliferation, advanced (non-medical) instrumentation, automotive , environment, etc.. ~ 30 cases being developed, promoting further pathways to impact *[mention for each cluster in the following]*

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GRANTS AND SUPPORT

From REF2014 to REF2021, **research income has increased by 81%!**
And, it keeps growing:

- indicative target is to have £ 250k/FTE by 2025 per year (Q2)
- This has been nicely surpassed in 2022! ☺
- Engaged in supporting more and more academics to apply for (possibly diversified) funding
  - Individual grants, consortia, collaborations, impact-related funds

We **support** research staff in seeking for funding through:

- Peer-review of grant applications *(e.g. this year ERF/URF review is in progress)*
- Trainings and workshops organised to help preparing applications *(e.g. workshops on narrative CV)*
- Recognition of achievements through nomination to prizes and awards *(e.g. Philip Leverhulme Prize)*
- Promoting collaborations e.g. across clusters and departments through spreading of info (staff meetings, coffee chats, bulletins etc)

We also **support** staff when appointed to key leadership roles (membership of national and international decision bodies, spokesperson of international collaborations and projects …)

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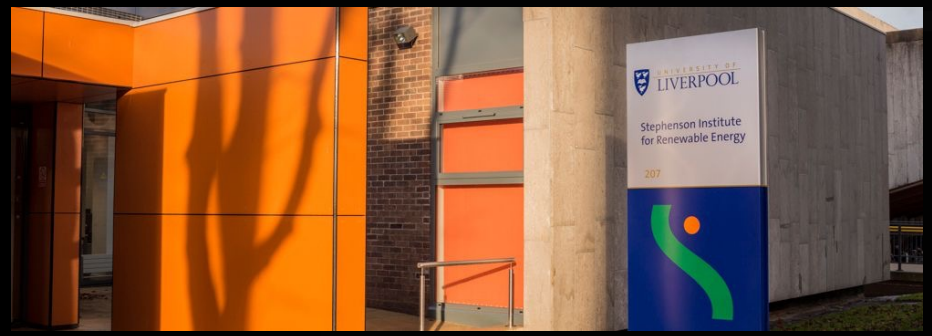
Clusters and infrastructure

- Accelerator Science, CL: Carsten Welsch
- Condensed Matter Physics, CL: Chris Lucas
- Nuclear Physics, CL: Rodi Herzberg
- Particle Physics, CL: Joost Vossebeld
- Physics Education, CL: Dave Joss

Activities carried out and supported by in-house infrastructures to develop and deliver detectors

- Detector Fabrication Facility
- Semi-conductor detector centre
- Advanced material laboratory
- Dedicated detector lab spaces (CMP, NP)
- Computing
- Daresbury
- Cockcroft Institute
- MIF
- SIRE



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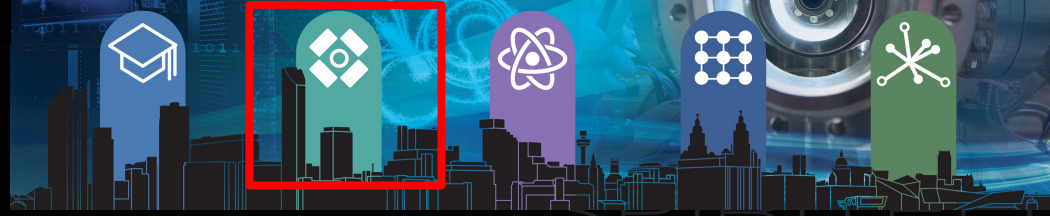
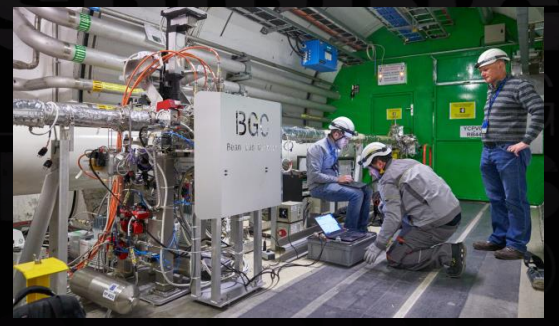


Accelerator Science

Frontier Accelerators

Novel Accelerators

Accelerator Applications



Core activities include substantial work and investment on

- High Luminosity **LHC upgrade** at CERN: lead the development of gas jet monitors
  - *STFC-funded Gas jet monitor already integrated in LHC well ahead of schedule*
- Next-generation FEL technologies exploiting the **CLARA** facility at Daresbury
- Development and exploitation of the new facilities **PERLE and RUEDI**;
- Optimization of low energy beam transport (**AEgIS)**
- **AWAKE -** benefit other large scale plasma accelerator projects such as **EuPRAXIA**

A backbone of all three areas above will be our continued **leadership** in Data Intensive Science through LIV.DAT and **LIV.INNO CDT**.

LIV.INNO

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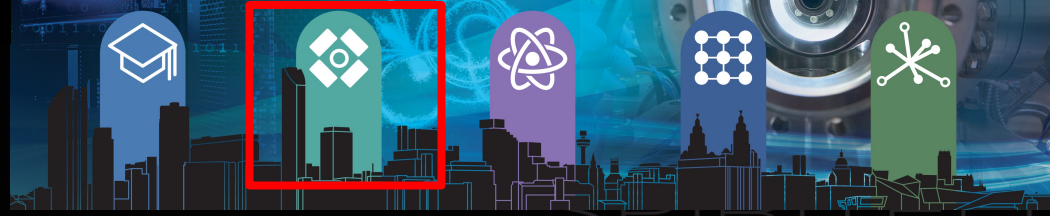


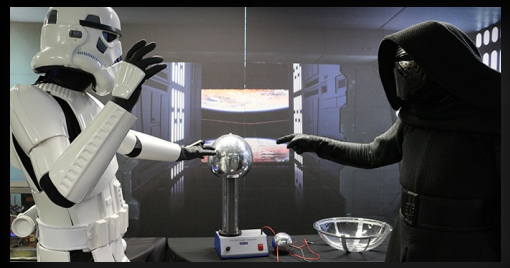
AS RESEARCH THEMES AND R&D STRATEGY

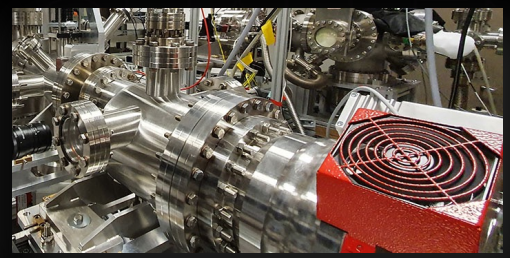
Engagement in **sustainable** technologies and clear alignment with Institution/Faculty themes

- **Green technologies:** Energy Recovery Linac, techniques to reduce energy costs of accelerators
- **Advanced materials:** RUEDI (leading “Materials in Extremes”), quantum Helium atom microscope;
- **Personalized health:** Smart Health Tracking;
- **Heritage:** Movable accelerator for heritage studies (FLF);
- **Digital:** R&D in all three LIV.INNO scientific work packages across all of our research areas;
- **Starting well, living well, ageing well:** In-vivo Dose Monitor for Proton and Ion Beam Therapy, Compact and Mobile 3D X-ray Imaging.

Impact Case Studies

- Accelerator Science Public Engagement
- Commercialization of Beam Diagnostics
- Gas Jet Monitor Applications
- Medical Imaging
- Compact accelerators for cultural heritage studies





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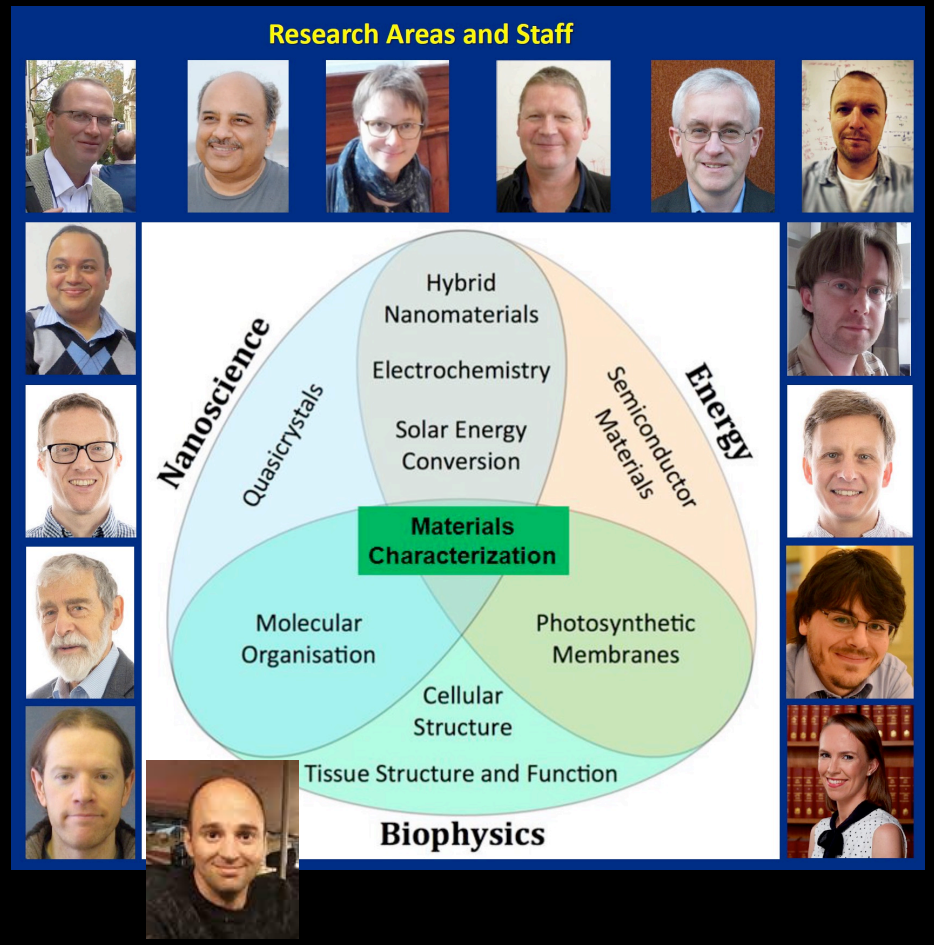
Condensed Matter Physics



Core activities:

Synthesis and characterisation of materials (mostly 2D)

Includes a blend of **discovery** and **applied** physics

Incorporates use of the **large-scale** central facilities (Diamond, ISIS, XMaS at ESRF Grenoble and more).

Strong **collaborative links** in place with Chemistry (SIRE, MIF, Surface Science Centre), Engineering, Computer Science and Health and Life Sciences

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CM Physics Activity Snapshot

Nanoscience – physics of matter and processes on the nanometer scale → fundamental understanding and practical applications: surface physics, electrochemical interfaces and hybrid nanomaterials.

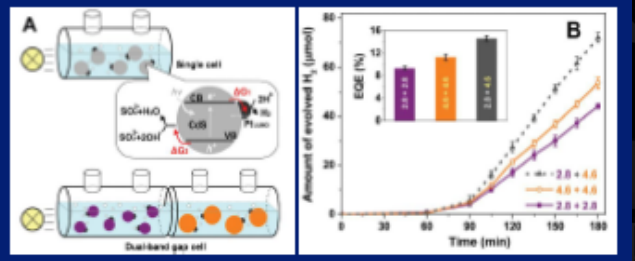
Energy – physics to tackle the biggest problem of our age → sustainable energy: solar fuels, solar photovoltaic materials and devices, materials for thermoelectrics and the physics of advanced sustainable materials for energy applications.

Biophysics - quantitative methodology of physics on biological and medical problems: new tools for cancer diagnostics, advanced investigations of tissue structure, image analysis for medical, biological and other applications.

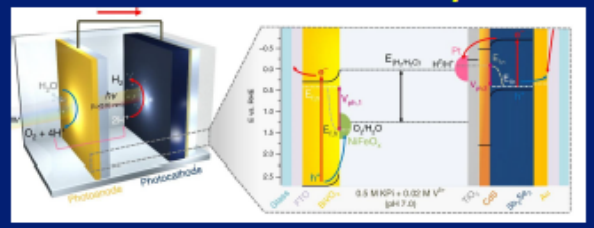
Recent new areas of research: Reactions at ultra-cold temperatures - currently developing collaborations with Computer Science/Engineering.

Soft condensed matter area, i.e. use of 3D printing to build living and biologically inspired materials - joint Chemistry/Physics lecturer (Joe Forth)

Tunable Properties of Nano-photocatalysts

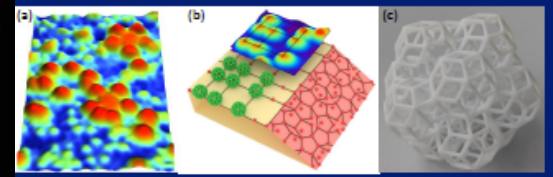


Solar Cells and Photocatalyst



Benchmark performance of low-cost Sb_2Se_3 photocathodes for unassisted solar overall water splitting, Nature Communications 11, 861 (2020)

Multiscale Quasicrystals



(a) Quasicrystalline Pb (*Nature Communications* 4, 2715 (2013)). (b) C_{60} adsorbs atop Fe/Mn atoms forming unique quasicrystalline structures such as Penrose tiling and Fibonacci square Nature Communications 9, 3435 (2018). (c) 3D printed QC structure.

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CMP RESEARCH THEMES AND R&D STRATEGY

- Strongly integrated with UoL activities in **Advanced Materials**, as well as **Climate Futures** and **Personalized Health.**
- Involved in **two current bids for CDTs** (**Digital Materials Chemistry, Leverhulme trust**).

- **Research projects currently under development** include:
  - New materials and new designs for photovoltaics and photocatalysis
  - Nanopatterning and thermal nano-conversion of magnetic materials for computation and data storage applications
  - Spin transport in metals and chiral/topological materials
  - Structure and function of multiferroic and magneto-caloric materials
  - Using quasiperiodic structures to control mechanical, magnetic and photonic properties
  - Electrochemical control of functionality in materials
  - New methods for the precise study of ion-radical reactions
  - Commercialisation of instrumentation for cancer diagnosis

Impact cases **in development covers all of the above areas, i.e. development of instruments for monitoring and for cancer diagnosis, material studies etc.**

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Nuclear Physics

Core activities:

- Nuclear structure
- Applied Physics / Instrumentation
- Hadron Physics

Alignment with NP Advisory Panel and NuPECC Long Range Plans

Cross-collaborations with Particle Physics

Detector developments carried out together with key stakeholders in the nuclear energy sector (e.g. Mirion/Kromek)

Many **international collaborations** with laboratories and facilities (CERN, TRIUMF, LBL etc)

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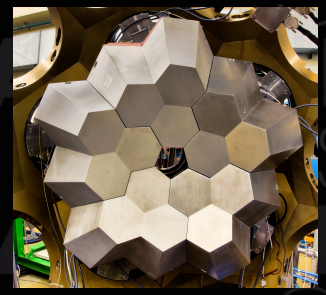
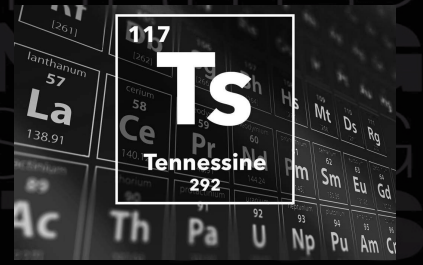
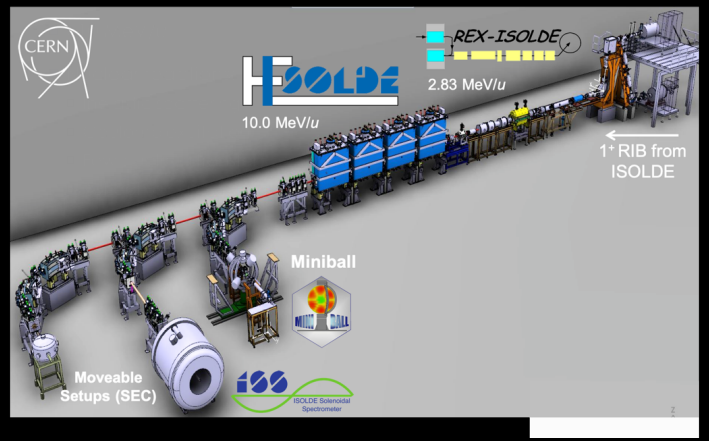
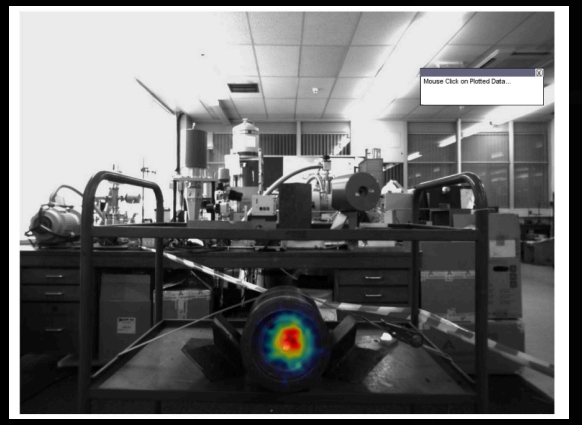
NP Activities Snapshot

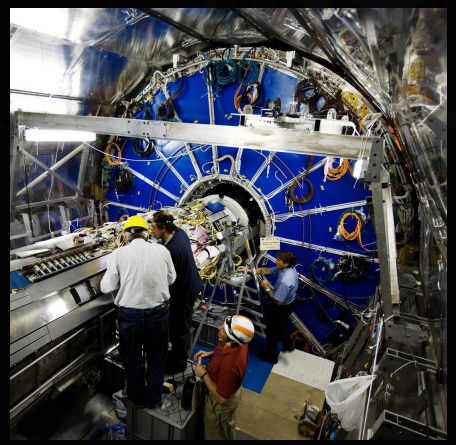




- **Nuclear Structure:**
  - Study of High Spin atoms (AGATA), atom Shapes, Proton Dripline, Ground State Properties, Superheavy structure & Chemistry and more
  - Exploiting facilities such as CERN Isotope mass Separator On-Line facility (**ISOLDE**): unique source of low-energy beams of radioactive nuclides
- **Applied Physics and Instrumentation:**
  - E.g. Gamma ray imaging, medical imaging techniques, phantoms, medical diagnostics, advanced detector concepts and materials, gamma ray tracking.
- **Hadron Physics:**
  - **Main current investment on ALICE experiment at CERN -** Heavy-Ion collisions
  - Major upgrades on silicon tracker carried out by Liverpool (in close collaboration with Daresbury Laboratory)







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NP cross-collaborations, R&D activities and themes

Strong **collaborative links** in place with Particle Physics on new international efforts

- **Mu2e:** technology from NP for PP experiments **(**High purity Germanium detector)
- **LEGEND**: next generation experiment searching for neutrinoless double beta decay
  - Innovative studies on ^{enr}Ge Detectors to achieve unprecedented resolution of σ / $Q_{\beta\beta}$ = 0.05 %
- **EIC (Electron-Ion collider) at BNL (US):**
  - Liverpool involved in core detector activities (tracking)
  - R&D on technologies relevant for detectors at future colliders
  - Recently **awarded funding from UKRI**
- **ELI-NP, SHE** Discovery and more

Forward looking activities include **sustainable technologies** for large scale experiments (newly appointed! E. Rintouil); priorities include **strengthening** the Applied Physics and Hadronic Physics strands

NP fits with the UoL research themes of **Advanced Materials, Personalized Health and Digital** and Fundamental Science ==> newly proposed (Faculty) theme on ***Exploring the Nature of Our Universe***

Impact cases in development are mostly on the area of instrumentations, i.e. gamma camera commercialization, radiation detection, imaging

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PARTICLE PHYSICS

One of the largest of PP groups in the UK: ~ **140 members**
- 24 academics and 38 research staff
- 26 support staff - Eng, Tech, Comp, Admin;
- around 55 PGR students.

Involvement in many experiments worldwide
Technology development for future experiments

Superb facilities for detector R&D and construction

Close collaboration with Theory/Math department

https://www.youtube.com/watch?v=rAWbi5YU9rI

Focus on fundamental questions in subatomic physics

What lies beyond the Standard Model?
What is the origin of neutrino mass?
What is the nature of dark matter and dark energy?
What explains the matter anti-matter asymmetry in the universe today?

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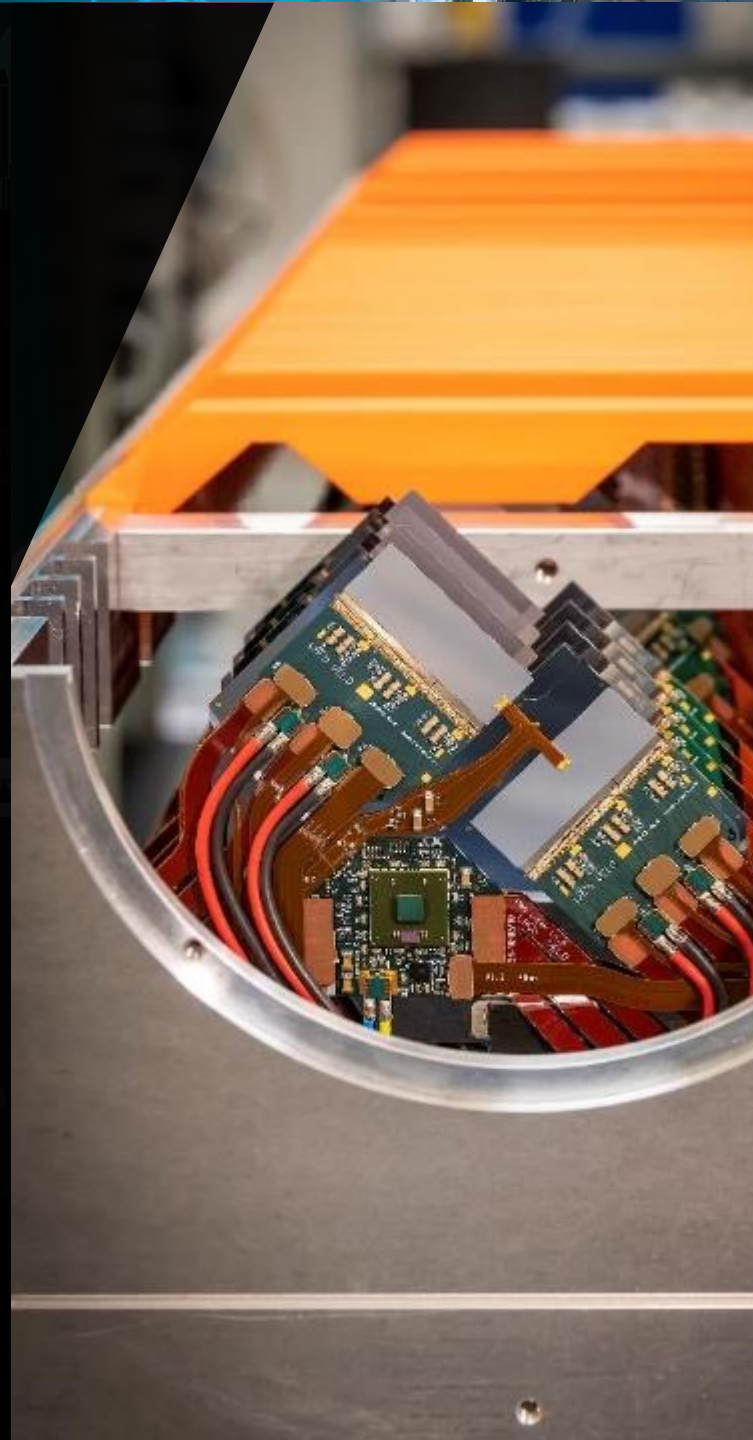
PP research streams

- ***Energy frontier experiments*** - **ATLAS** and future colliders at CERN
- ***Precision, quark and lepton flavour experiments*** – **LHCb** and **MUonE** at CERN, **g-2** and **mu2e** at FNAL, **mu3e** and **muon-EDM** at PSI, **proton-EDM**
- ***Neutrino physics*** - T2K and Hyper-K in Japan, SBND/DUNE in the US, SNO+ at SNOLAB, Legend at Gran Sasso, Button in Boulby
- ***Dark universe*** - **LZ** @ SURF, **DarkSide-20k** @ Gran Sasso, **MAGIS** @ FNAL, **AION** UK, **CTA** in Chile, **FASER** @ CERN

Detector R&D and construction - Internationally recognised expertise and infrastructure for detector development: radiation hard and low mass silicon sensors (e.g. recently awarded grant on sub-micron silicon sensor), Argon TPC technology R&D, silicon photonics R&D for cryogenic noble gas experiments, Atom Interferometry, proton therapy

Advanced computing: development of AI methods to be used for online data-taking and offline analyses, collaborations with Microsoft, CERN and FBK, grant from EPSRC for explainable AI



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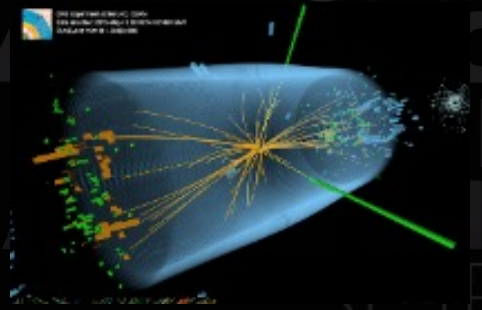
PP Activities Snapshot

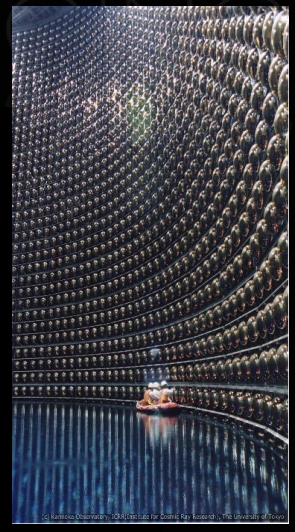


Experiments at CERN:

- **ATLAS:** construction of the semiconductor tracker, Higgs discovery in 2012, >1,000 publications
- **LHC-b:** construction of the silicon sensor modules of the Vertex Locator, > 600 publications
- **FASER:** new experiment to search for dark sectors, physics coordinator @ Liverpool

Neutrino Physics experiments (in Japan, US):

- **T2K / Hyper-K programme** (Japan): Leadership in neutrino oscillation analysis (2016 breakthrough prize in fundamental physics
- **DUNE / SBND programme** (US): strong involvement and leadership in ProtoDune programme at CERN and DUNE construction
- **LEGEND with NP** Collaboration PP and NP groups



Direct Dark matter experiments (in US, Italy, Chile):

- **Lux-Zeplin:** Liquid Xenon detector for dark matter in South-Dakota (started 2021)
- **Darkside20k** – Liquid Argon detector for dark matter, Liverpool: assembly of ~ 1,250 SiPM modules
- **Cherenkov Telescope Array (CTA)** in Chile: Search for gamma rays from DM annihilation in galactic centre

Quantum Technology for Fundamental Physics (in UK and US)

- **AION / MAGIS-100 project** – funded with £10M in UK, Liverpool leads UK involvement in MAGIS-100 **(US)**

Muon precision programme (in US, Switzerland)

- **g-2 @ FermiLab** Magnetic moment of the muon - exciting results in 2021 - Collaboration with Maths/Theory
- **Mu2e @ FermiLab:** Collaboration PP and NP groups on Germanium detectors.
- **Mu3e @ PSI, Switzerland,** Lowest mass silicon tracker ever built.

Large boost through last year £4.3M award of the Leverhulme Professorship to G.Venanzoni).

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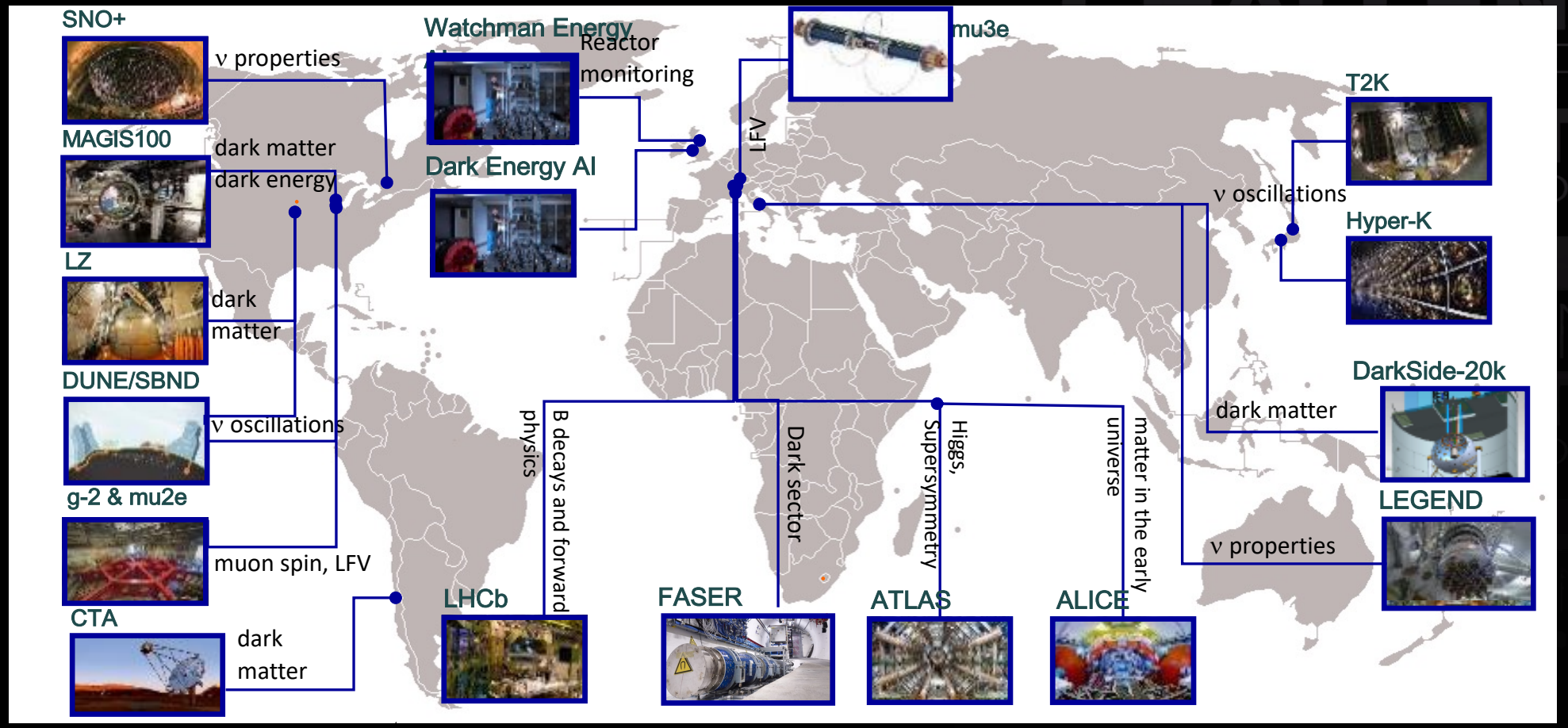
International collaborations and impact



Technology R&D with impact studies: Silicon sensors for proton therapy, water Cerenkov technology for neutrino physics, work with nuclear industry on reactor modelling (VIDARR), Argon TPC readout technologies, beam diagnostics instrumentation, HV-CMOS sensor for hadron beam therapy, patent investigation solutions for increased HV operation with HV-CMOS

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PP Future Activities and themes

PP focus on fundamental science theme on ***Exploring the Nature of Our Universe*** but also on **Digital**, and fits well in other areas such as **Growing, living, ageing well** and **Materials**

Several years of **exploitation**, upgrade and development of **new experiments** as part of the core programme:

- **ATLAS:** Building tracking detectors for the HL-LHC upgrade 2026-2028 and physics exploitation– path to Future Circular Colliders
- **LHC-b:** recently funded by Infrastructure UKRI scheme for further tracker upgrade
- **Hyper-K and DUNE:** complete construction and start data-taking in 2030
- **XLZD:** world-wide effort on large-scale dark matter detector → could be hosted at **Boulby national lab**
- **AION/Magis** –extend to better sensitivity to light DM, new lecturer (J. Tinsley) from 01/08/23
- Developing new involvement in **MUonE** experiment at CERN and **EDM measurements**
- **Advanced AI techniques**: fundamental developments needed for large and complex datasets i.e. such as those expected at next generation LHC experiments and DUNE

New areas being explored:

- **R&D on Silicon sensors** for single UV photon detection (quantum sensors), as well as Liquid Argon detectors etc.
- Further collaborations with Maths/Theory (dark matter and dark sectors, quantum), Computer Science (AI) and Engineering (satellite experiments, quantum) - **CDT and PGT proposals on Quantum/Data Science in pipeline**

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Physics Education Research Cluster

Main mission

Taking an evidence-based approach, using equity as a lens, to investigate physics learning and research spaces.

Research Objectives:

1. To examine the factors that impact student's academic outcomes.
2. To understand the role of external and internal motivational factors on student outcomes and aspirations.
3. Identify opportunities and challenges of AI for physics education
4. To explore institutional and longitudinal data to analyse trends in STEM degrees (including physics)
5. Based on evidence, design course level interventions to enhance the quality of teaching and learning
6. Last but not least, equity-centred research and education practices

On-going projects and activities:

- **Multi-institute interview study** to understand lived experiences of minority groups in physics (Durham PER conference)
- Ogden Trust Grant submitted
- **UKRI Interdisciplinary grant** (in process)
- Faculty Enhancement Fund (applied)
- **ASCENTS project grant £130k awarded** → impact of mentoring on growth mindset and career aspirations
- CuWiP data analysis, in-depth study of historical HESA data and more

Expected outcomes:

- Contribute to the development of evidence-based teaching practices and curriculum design
- Development of research framework and network in UK

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SUMMARY

- The Department has vibrant programme of research activities distributed **in and across** the five clusters, with interdisciplinary collaborations significantly grown recently
- Solid research income and return of investments
- Strong international reputation, impacting the global strategies in all fields
- Well reflected in the REF outcome (75% 4* for environment)
- Good fit with the University/Faculty themes so far, strong potential in emerging Frontiers

In future, we aim to:

- be at the forefront of major breakthroughs in physics
- address the most fundamental questions in physics
- ensure that our technology innovations create wide-ranging impact
- share our enthusiasm for physics with broad and diverse audiences
- increase collaboration within the university

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Today: Discussing departmental Strategy

- It is the foundation of any implementation plan → it is where we do our science and develop impact
- Must be **critically** and **openly** reviewed in terms of:
  - Ambitions and vision
  - New emerging areas
  - Consolidation of current activities
  - Diversification of income
  - Capability to attract new talents and nurture our owns
  - Strengthen or establish new partnerships/collaborations
  - Enhance our international standing
  - Communicate our science
- Must consider important **caveats**
  - we won't be able to do everything we would like to do!
  - we will also need to identify mechanisms how we will make decisions on these priorities

How to move forward on this is the purpose of the Away Day

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SPIRITED
CHALLENGING
INSPIRING
AMBITIOUS
SPIRITED
INSPIRING
CHALLENGING
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SPIRITED

- BACK-UP

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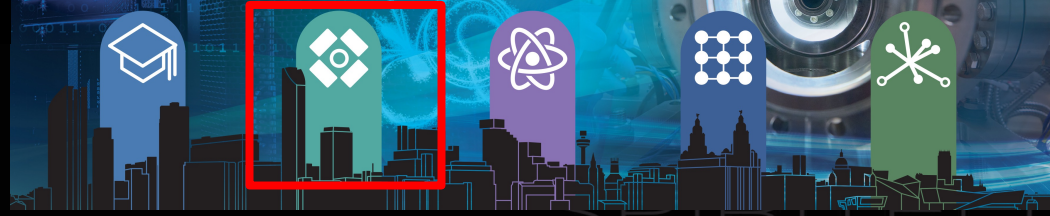

Accelerator Science – current and R&D Strategy

Frontier Accelerators:
In the next decade we will focus on the **LHC at CERN**, where we lead the development of gas jet monitors for the high luminosity upgrade, and other collider options; on the exploitation of the **CLARA facility on Daresbury** campus to explore next-generation FEL technologies; on the development and exploitation of the new facilities **PERLE and RUEDI**; and on the optimization of low energy beam transport and efficient injection into traps at the Antiproton Decelerator, in particular contributions to AEgIS.

Frontier Accelerators

Novel accelerators:
As part of **AWAKE**, we will continue our efforts on novel (high gradient) acceleration techniques. Following the successful demonstration of proton-driven wakefield acceleration in 2018, we are leading the development of novel diagnostics that will give more detailed insight into the physics of the acceleration process and also benefit other large scale plasma accelerator projects such as EuPRAXIA. We will also expand simulation and experimental studies into micro-accelerators using carbon nanotubes and dielectric structures.

Novel Accelerators

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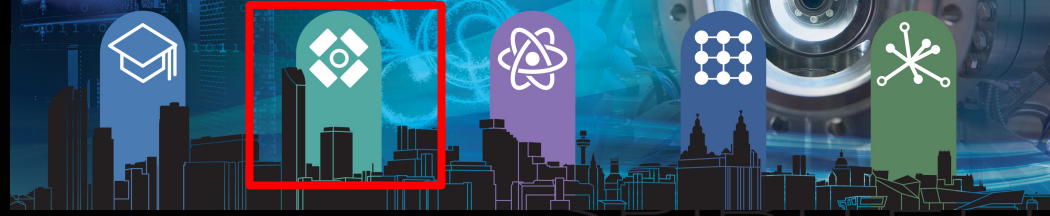

Accelerator Science – current and R&D Strategy (2)

Accelerator applications:

We will carry out R&D into

- a movable accelerator for heritage studies;
- least invasive beam and dose monitors to help improve patient treatment and medical accelerator operation;
- continue to develop and optimize novel low dose 3D X-ray imaging systems with Adaptix;
- carry out R&D into Smart Health Tracking with ViBo Health;
- drive quantum technologies for accelerator applications;
- grow our spinout company D-Beam, targeting a product portfolio that benefits accelerator facilities around the world.

Accelerator Applications

A backbone of all three areas above will be our continued **leadership** in Data Intensive Science through LIV.DAT and **LIV.INNO CDT**.

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CM Physics cross-collaborations and activities

Strong **collaborative links** in place with Chemistry (SIRE, MIF, Surface Science Centre), Engineering, Computer Science and Health and Life Sciences

- Collaborative projects are stimulated by interaction in the research centres (**SIRE**, **MIF**) where informal discussion seeds the development of future research

The CMP group runs **facilities** which are open to University users including:

- X-ray Diffraction Capability for Nanoscale and Thin Film Structure, Nanomaterials Characterisation Laboratory (UHV stations providing techniques to probe surface and interfaces of materials (XPS, UPS, LEED I-V, STM and IPES), Nanoscale lithography suite for prototyping nm-sized devices, compatible with most industry-standard processes, EPSRC National Research Facility XMaS (X-rays for Materials Science) based at the ESRF in Grenoble supporting x-ray diffraction and spectroscopy experiments in complex sample environments.

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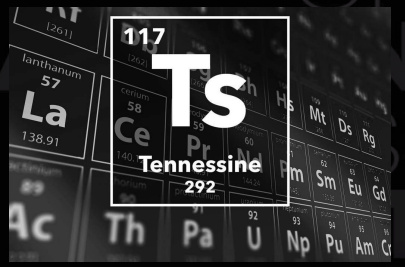
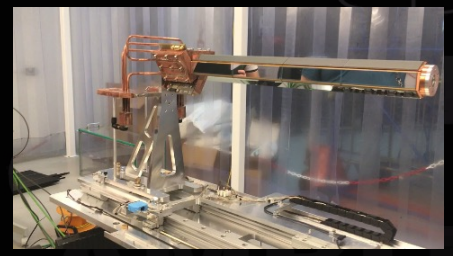
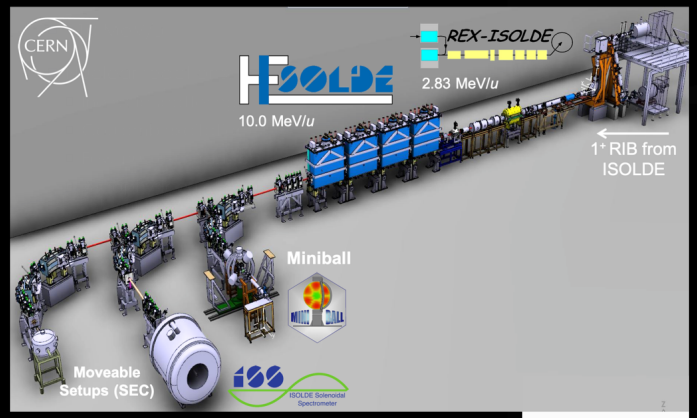
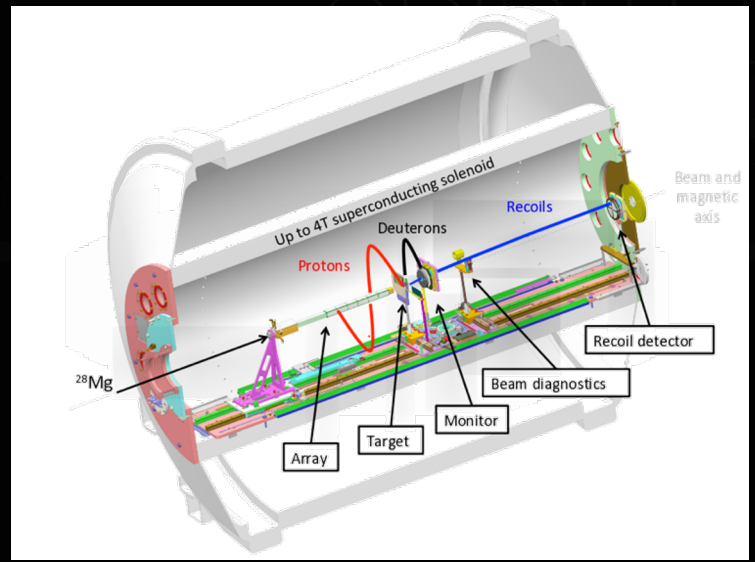
NP Activities Snapshot (1)

- **Nuclear Structure:**
  - Study of High Spin atoms (AGATA)
  - Study of atom Shapes
  - Proton Dripline
  - Ground State Properties
  - Superheavy structure & Chemistry
  - Single Particle Structure
  - Octupoles
- Exploiting facilities such as CERN Isotope mass Separator On-Line facility (**ISOLDE**): unique source of low-energy beams of radioactive nuclides









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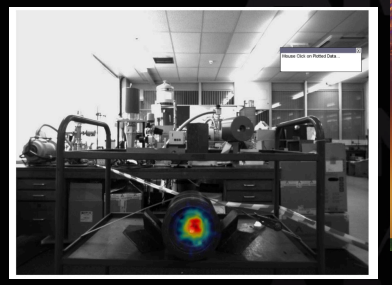
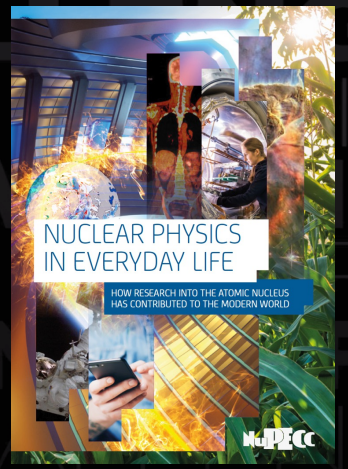
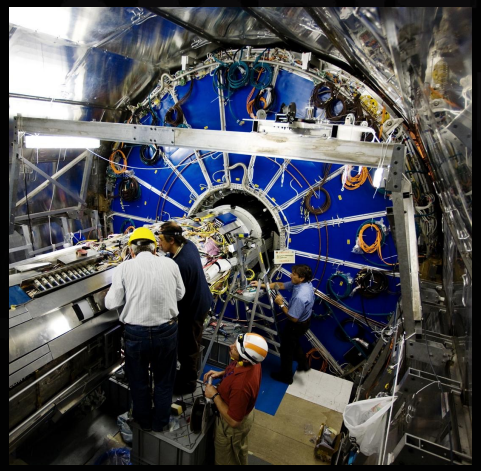
NP Activities Snapshot (2)

- **Applied Physics and Instrumentation:** Gamma ray imaging, medical imaging techniques, phantoms, medical diagnostics, advanced detector concepts and materials, gamma ray tracking. Include:
  - Detector Development (Mirion/Kromek)
  - Gamma Imaging for Medicine and Security
  - Advanced Algorithms for Imaging and processing

- **Hadron Physics:**
  - **Main current investment is on ALICE experiment at CERN**
  - Specialised in Heavy-Ion collisions (Pb-Pb)
  - Major upgrades on silicon tracker carried out by Liverpool (in close collaboration with Daresbury Laboratory)
  - Further upgrades activities for HL-LHC on-going
  - Leading studies on quark-gluon plasma, heavy charm production and jets structure







Impact cases in development are mostly on the area of instrumentations, i.e. gamma camera commercialization, radiation detection, imaging

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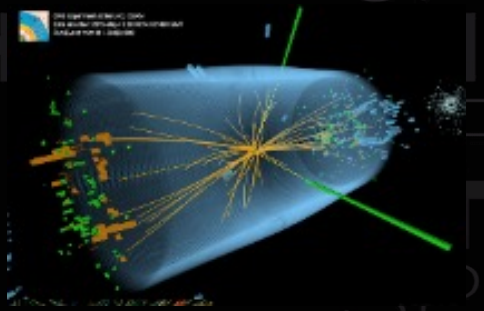
PP Activities Snapshot

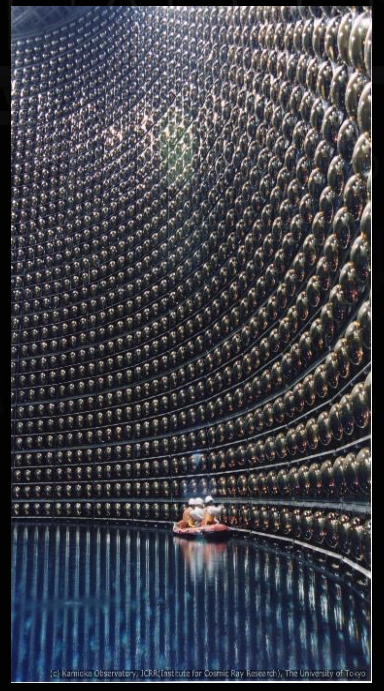
Experiments at CERN (ALICE in NP):

- **ATLAS:** Strong Liverpool involvement from early conception, construction of the semiconductor tracker, Higgs discovery in 2012 and many other physics studies (>1,000 publications), leaderships in precision SM and Higgs measurements, searches for dark matter, dark sectors and resonances
- **LHC-b.** Development and construction of the silicon sensor modules of the Vertex Locator (VELO), study of heavy flavour physics, CP violation, SM physics. (~600 papers published), coordination of experiment wide data analysis framework
- **FASER** Custom experiment to search for long lived weakly interacting particles produced in LHC collisions, physics coordinator @ Liverpool



Neutrino Physics (in Japan, US):

- **T2K / Hyper-K programme** (Japan): Leadership in neutrino oscillation analysis (2016 breakthrough prize in fundamental physics), now building Hyper-Kamiokande (2026)
- **DUNE / SBND programme** (US): strong involvement and leadership in ProtoDune programme at CERN and DUNE production of cathode planes
- **LEGEND with NP** Collaboration PP and NP groups



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PP Activities Snapshot (2)

Direct Dark matter experiments :

- **Lux-Zeplin:** Liquid Xenon detector for dark matter in South-Dakota (start 2021), work on calibration system, analysis and visualisation software
- **Darkside20k** – Liquid Argon detector for dark matter, Liverpool: assembly of ~ 1,250 SiPM modules
- **Cherenkov Telescope Array (CTA)** in Chile: Search for gamma rays from DM annihilation in galactic centre work on camera mechanics small telescopes

Quantum Technology for Fundamental Physics

- New approaches for extreme sensitivity physics measurements, jointly supported by STFC / EPSRC
- **AION / MAGIS-100 project** – funded with £10M in UK, Liverpool leads UK involvement in MAGIS-100 – a 100m dual atomic interferometer at Fermilab. **New lecturer (J.Tinsley) joining in August.**

Muon precision programme

- **g-2 @ FermiLab** Magnetic moment of the muon. We built trackers and were key to exciting results in 2021 with deviation from SM prediction found at about 5 sigma - collaborations with Maths/Theory
- **Mu2e @ FermiLab:** Collaboration PP and NP groups on Germanium detectors.
- **Mu3e @ PSI, Switzerland,** Lowest mass silicon tracker ever built.

Strongly growing area for Liverpool: Large boost to this programme through recent £4.3M award of the Leverhulme International Professorship to Graziano Venanzoni).