OVERVIEW OF UK’S NUCLEAR PHYSICS PROGRAMME

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with contributions from

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Paul Stevenson (Surrey)

Outline

- World Context
- UK Nuclear Physics Community
- UK Nuclear Theory
- …

World Context

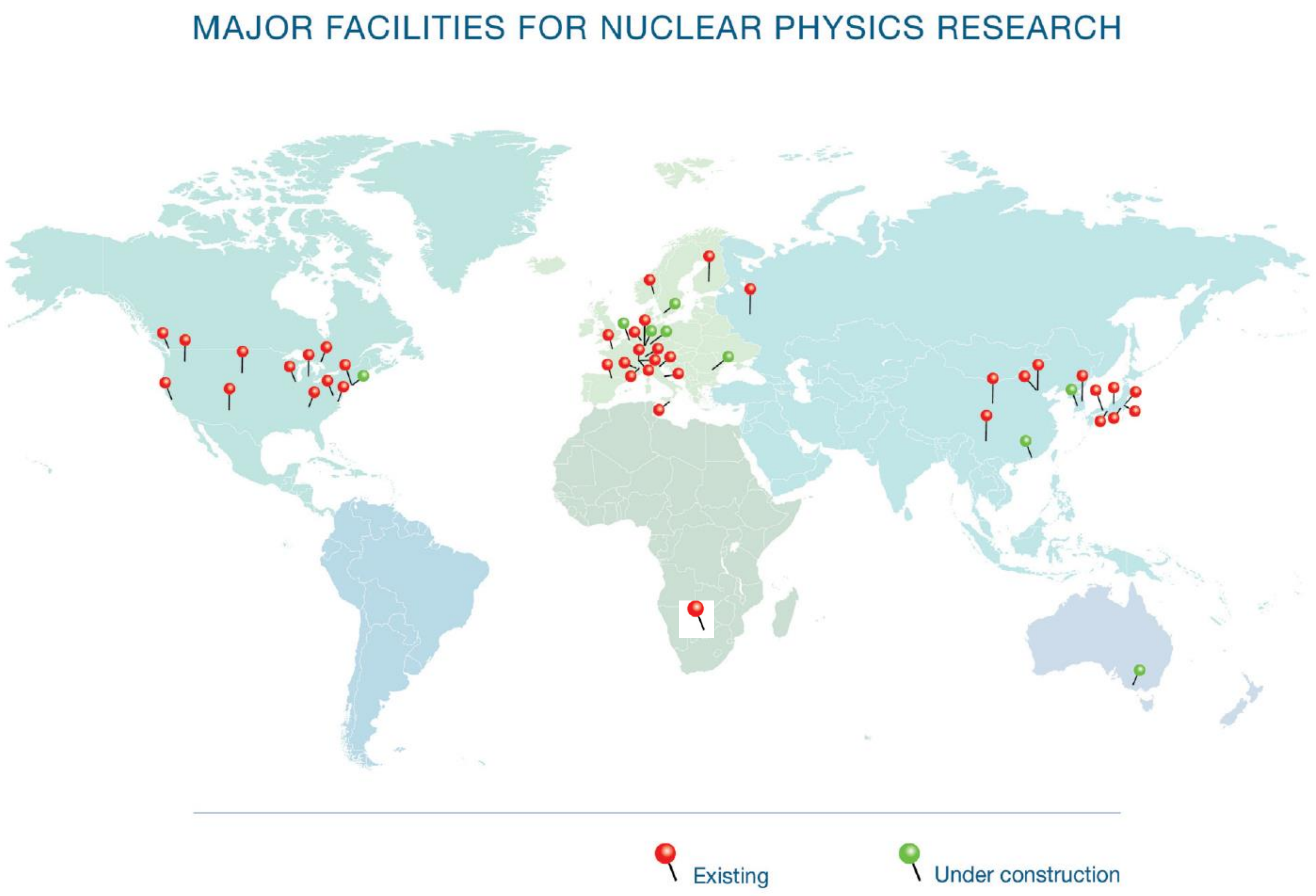
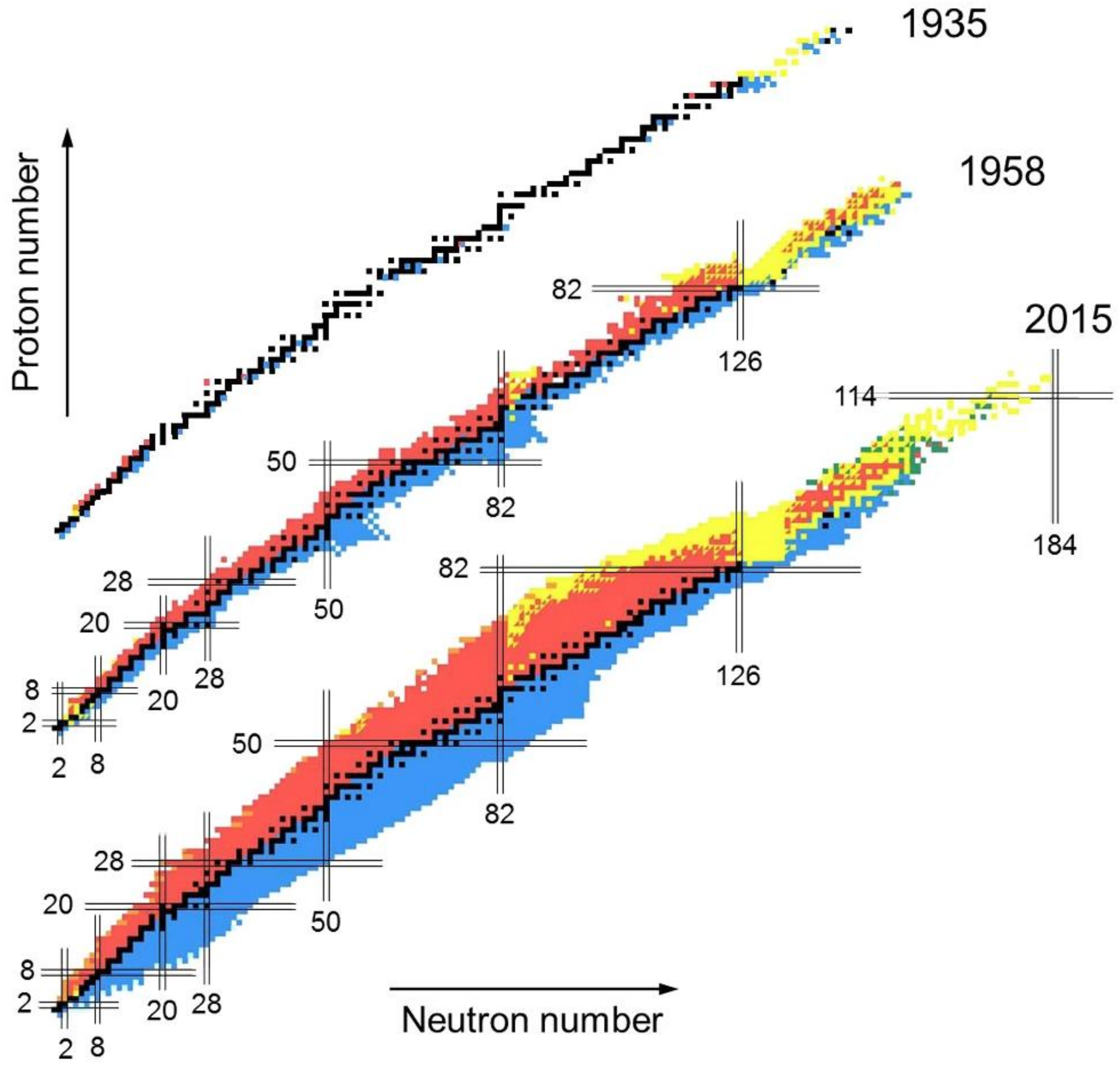
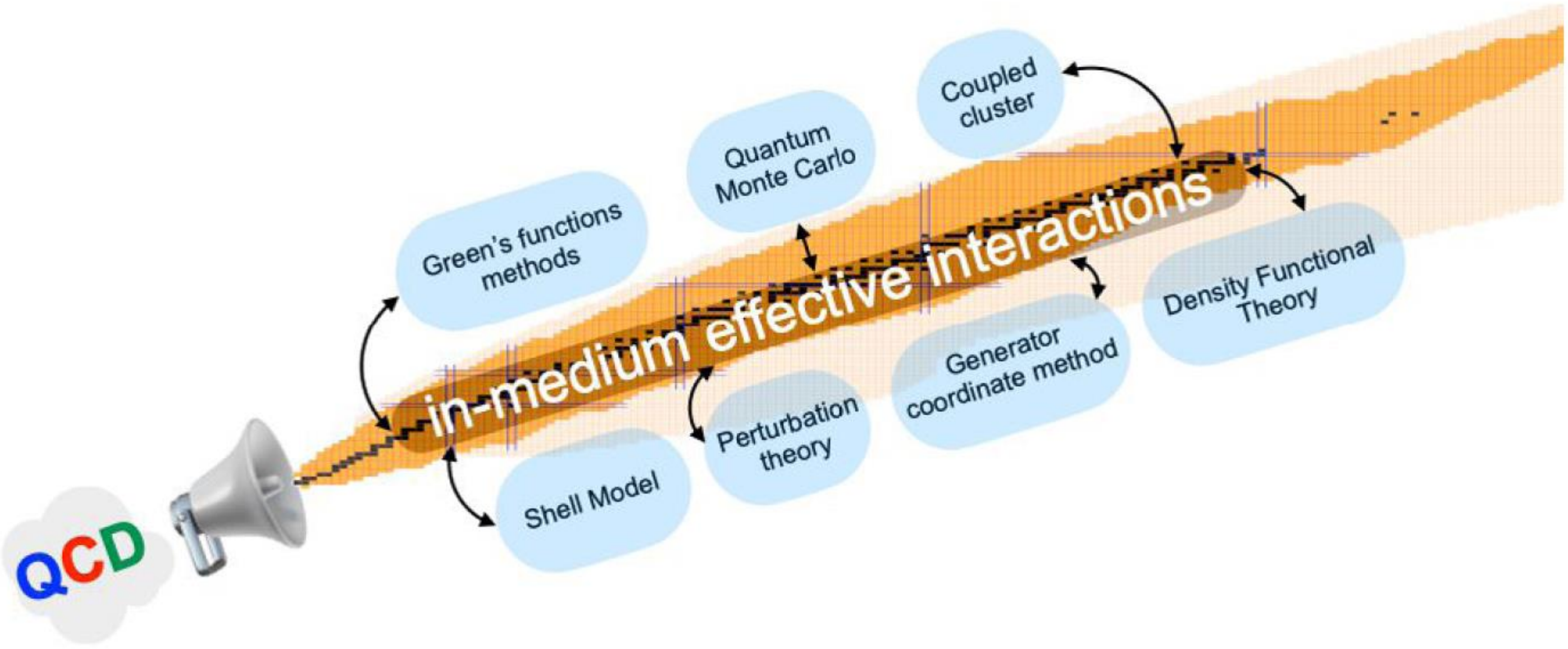


Chart of Nuclides

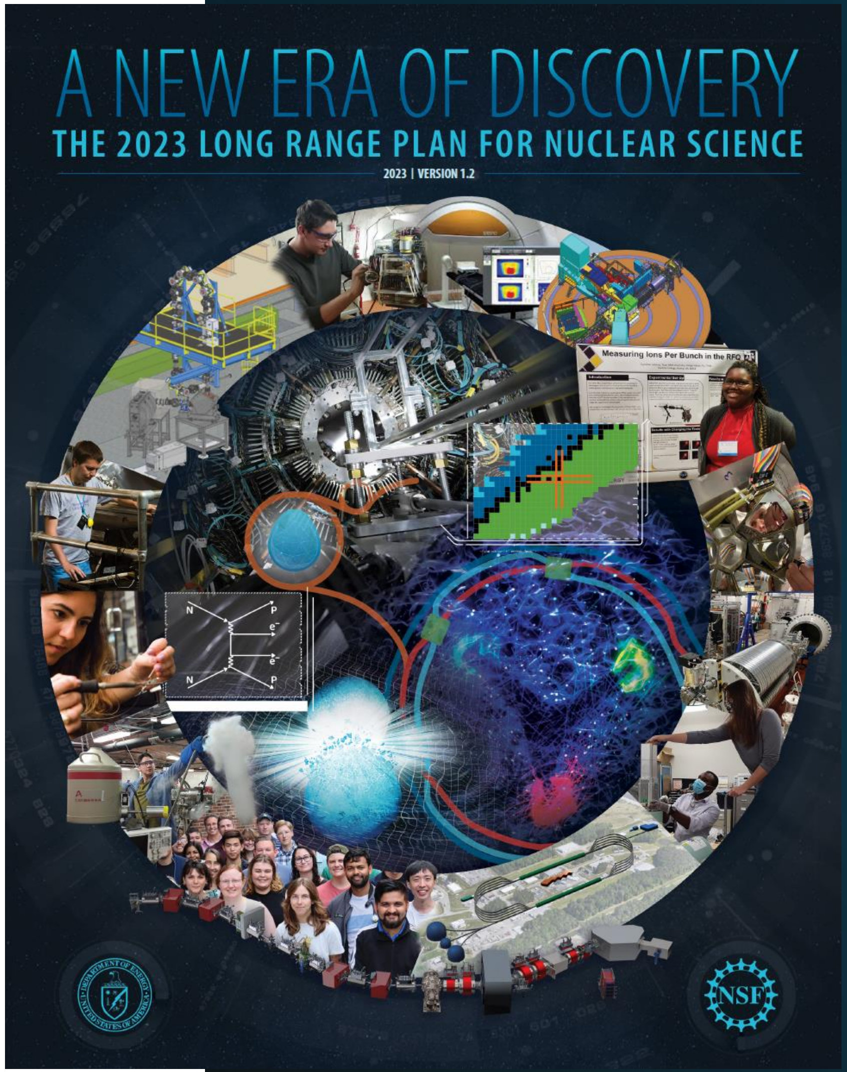




Calculating Nuclear Properties

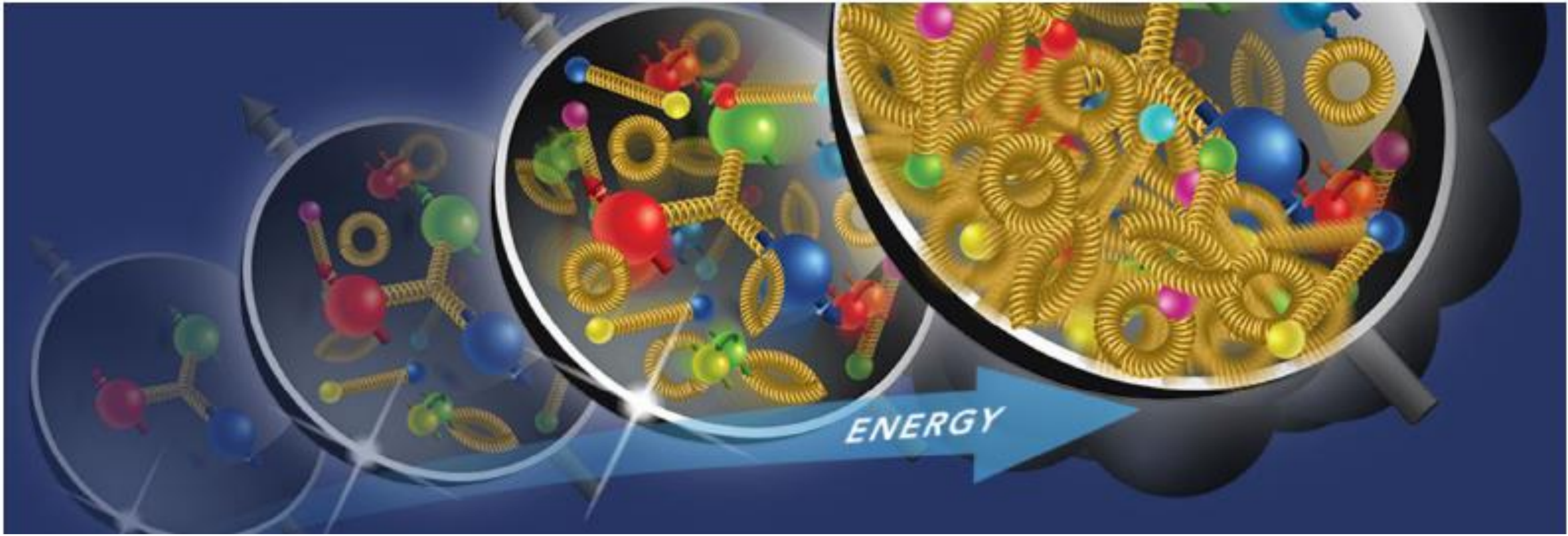
NSAC Long Range Plan 2023 – Science Questions

- How do quarks and gluons make up protons, neutrons, and, ultimately, atomic nuclei?
- How do the rich patterns observed in the structure and reactions of nuclei emerge from the interactions between neutrons and protons?
- What are the nuclear processes that drive the birth, life, and death of stars?
- How do we use atomic nuclei to uncover physics beyond the Standard Model?



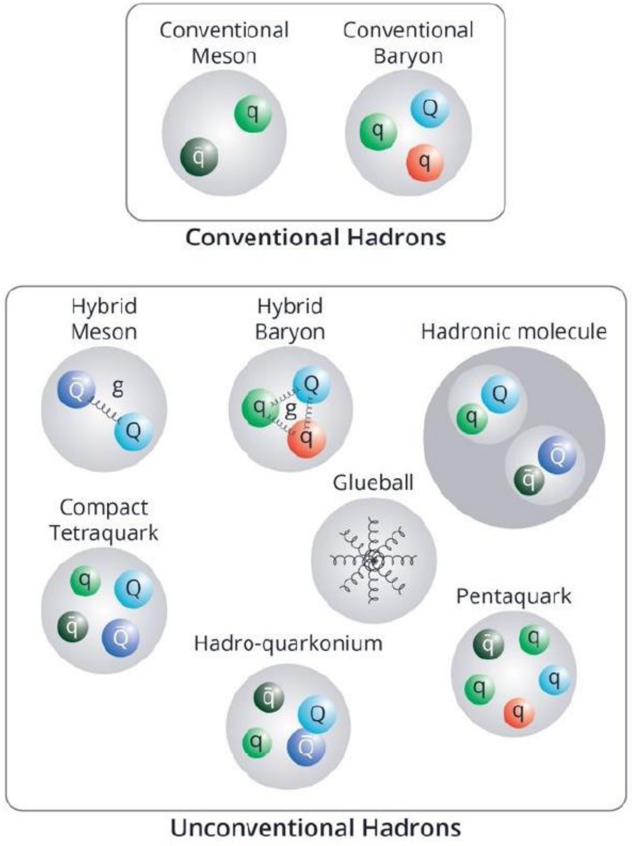
NuPECC Long Range Plan 2024

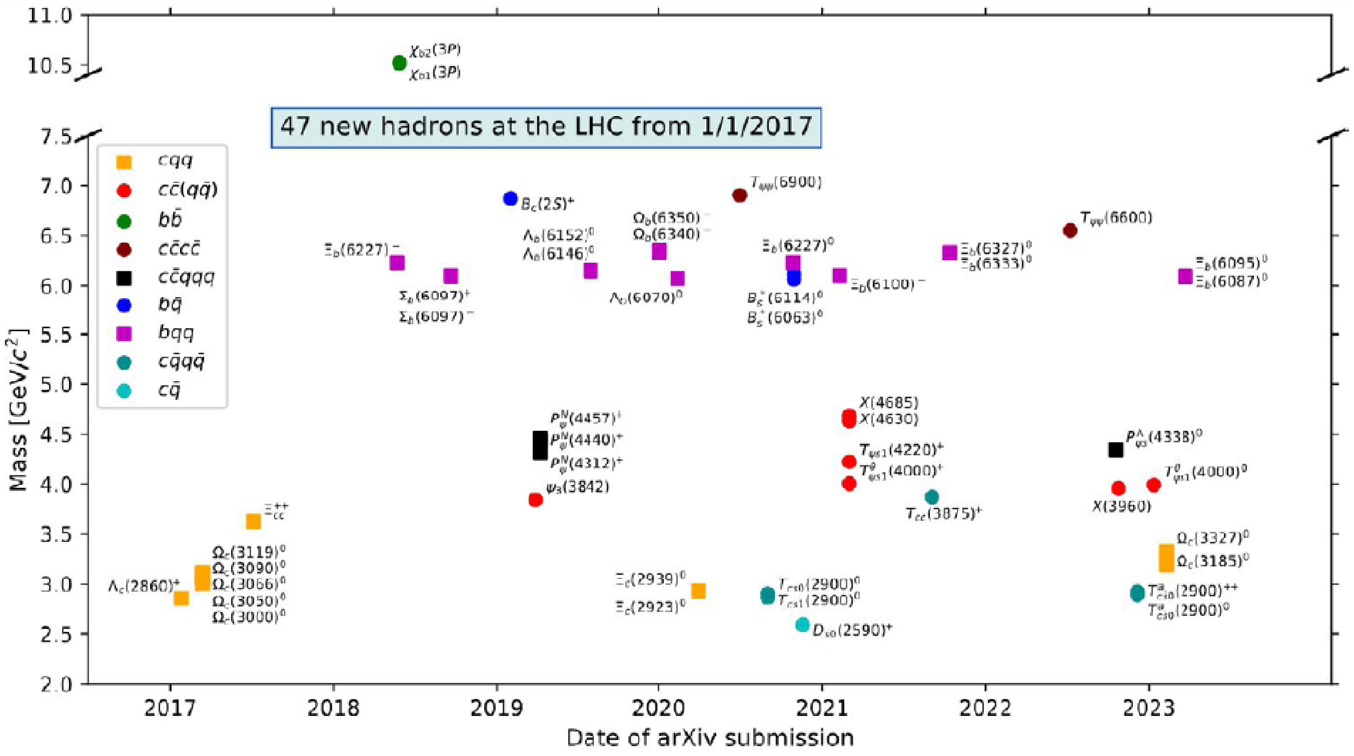
- How does the majority of the visible mass of the universe emerge from the almost massless quarks?
- What are the properties of the quark-gluon plasma, what is the qualitatively novel state of nuclear matter at extreme conditions of temperature and density?
- How do nuclei and nuclear matter emerge from the underlying fundamental interactions?
- What shapes can nuclei take, how do nuclear shells evolve, and what role do nuclear correlations play?
- What are the limits of the existence of nuclei, and what phenomena arise from open quantum systems?
- What are the mechanisms behind nuclear reactions and nuclear fission?
- How can we better understand the synthesis of heavy elements and the chemical evolution of the visible universe?
- What is the role of the strong interaction in stellar objects?
- What can nuclear physics teach us about the limits of the Standard Model of Particle Physics?
- How might nuclear physics strengthen its role in society’s sustainable development?



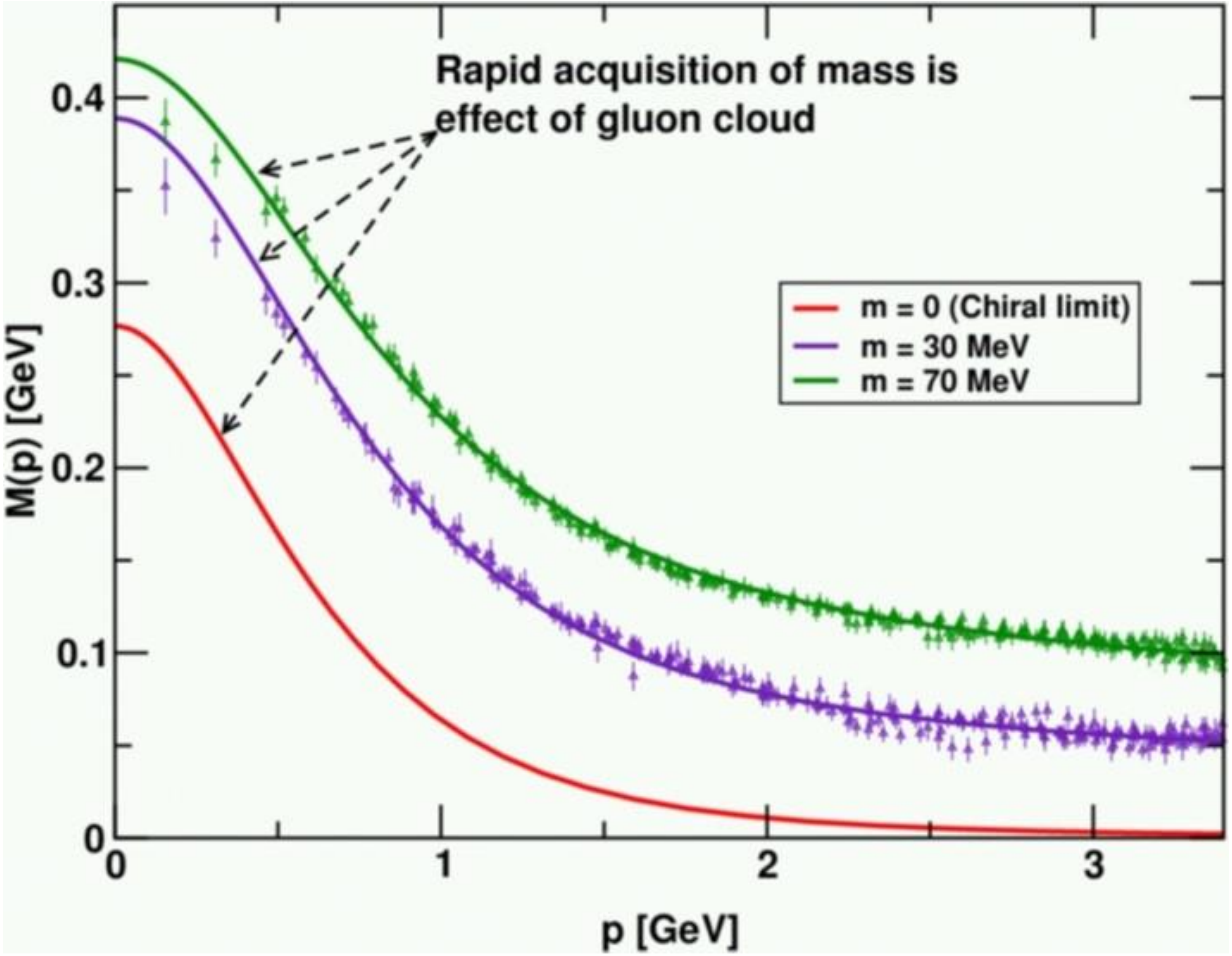
Hadron Physics

Hadron Resonances

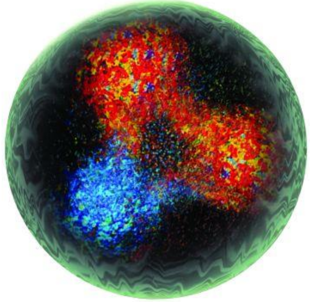




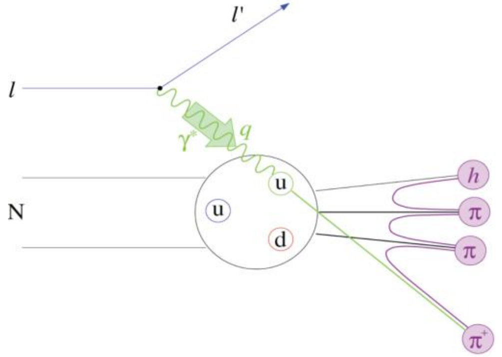
Origin of Hadronic Mass



Images of the nucleon



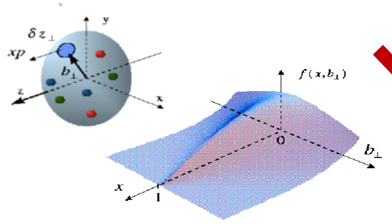
Wigner function:
full phase space parton
distribution of the nucleon

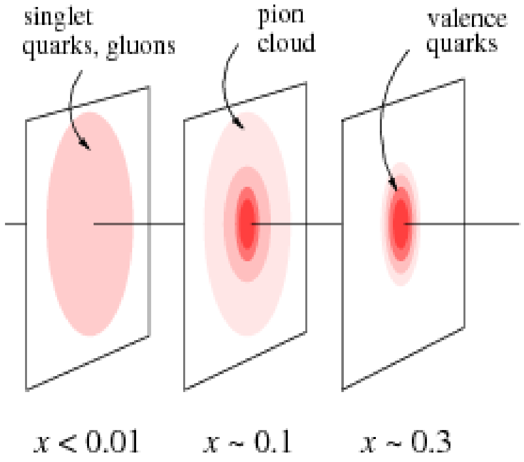


$$\int d^2k_T$$

$$\int d^2b_T$$

Generalised Parton Distributions (GPDs)

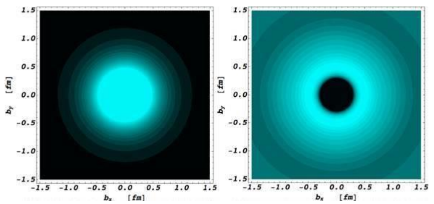




Transverse Momentum Distributions (TMDs)

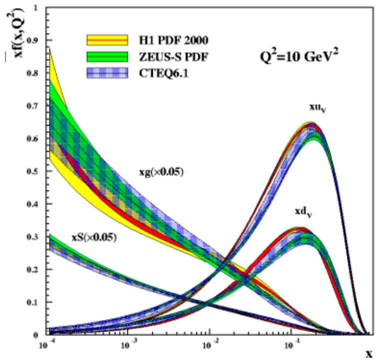
$$\int dx$$

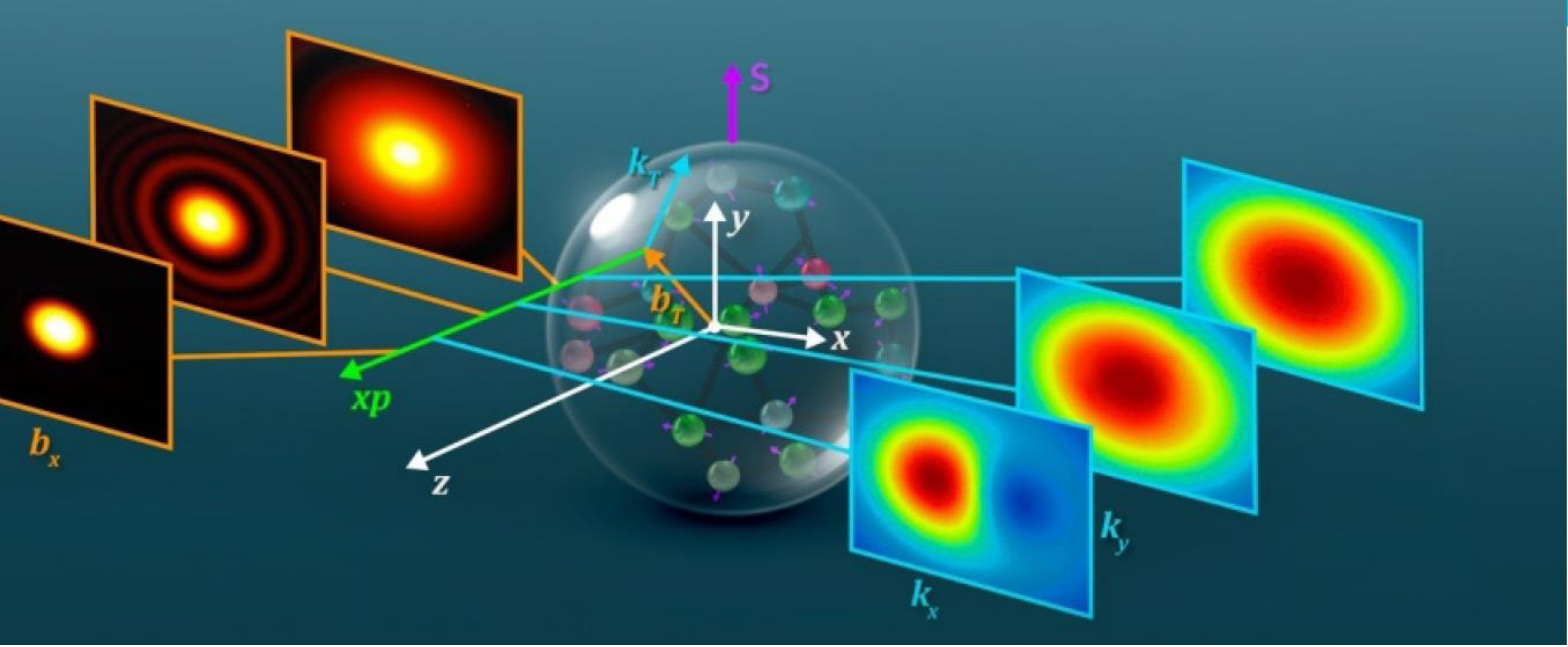
$$\int d^2k_T$$



Form Factors
eg: $G_{E,}$ G_M

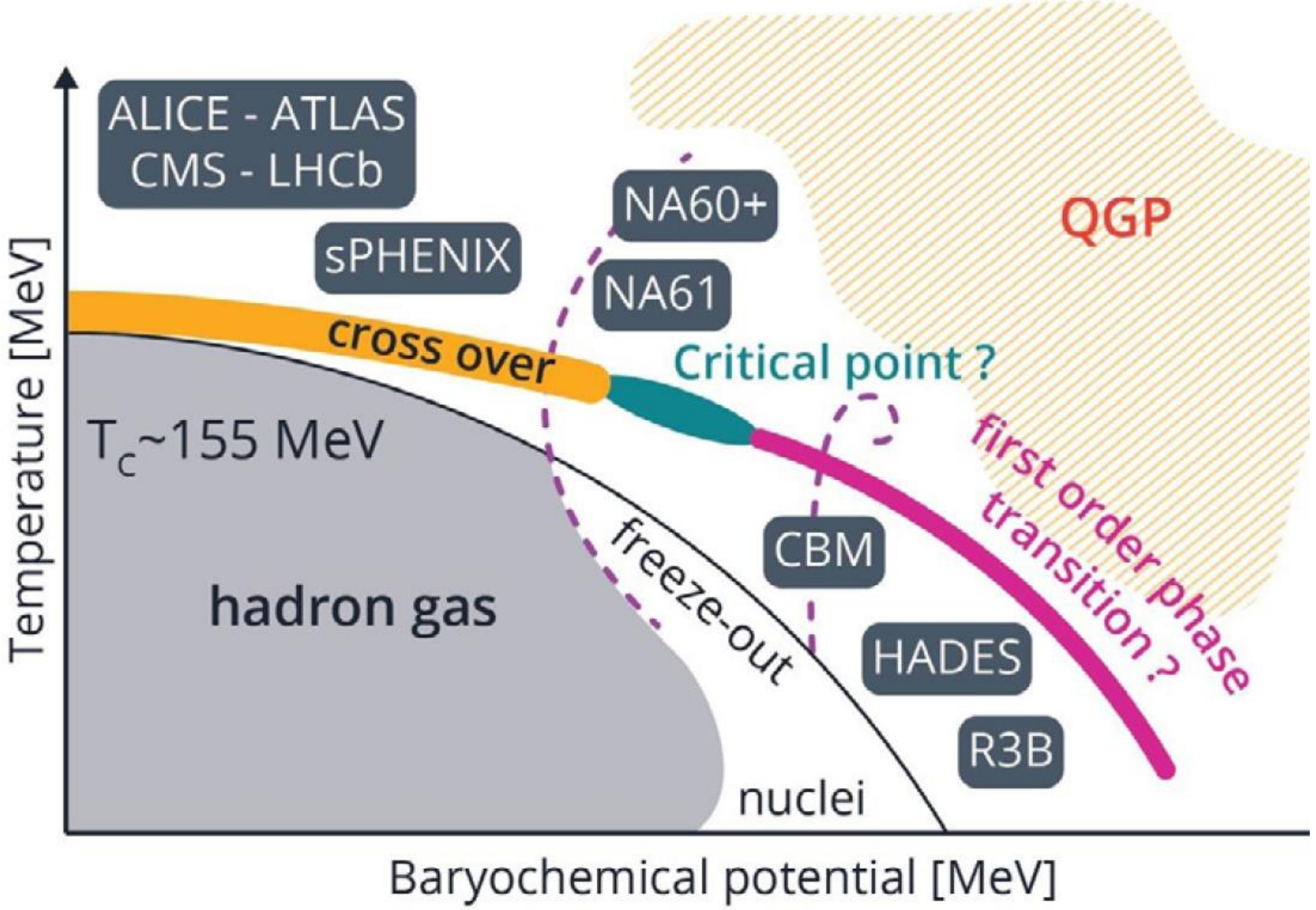
Parton Distribution Functions (PDFs)



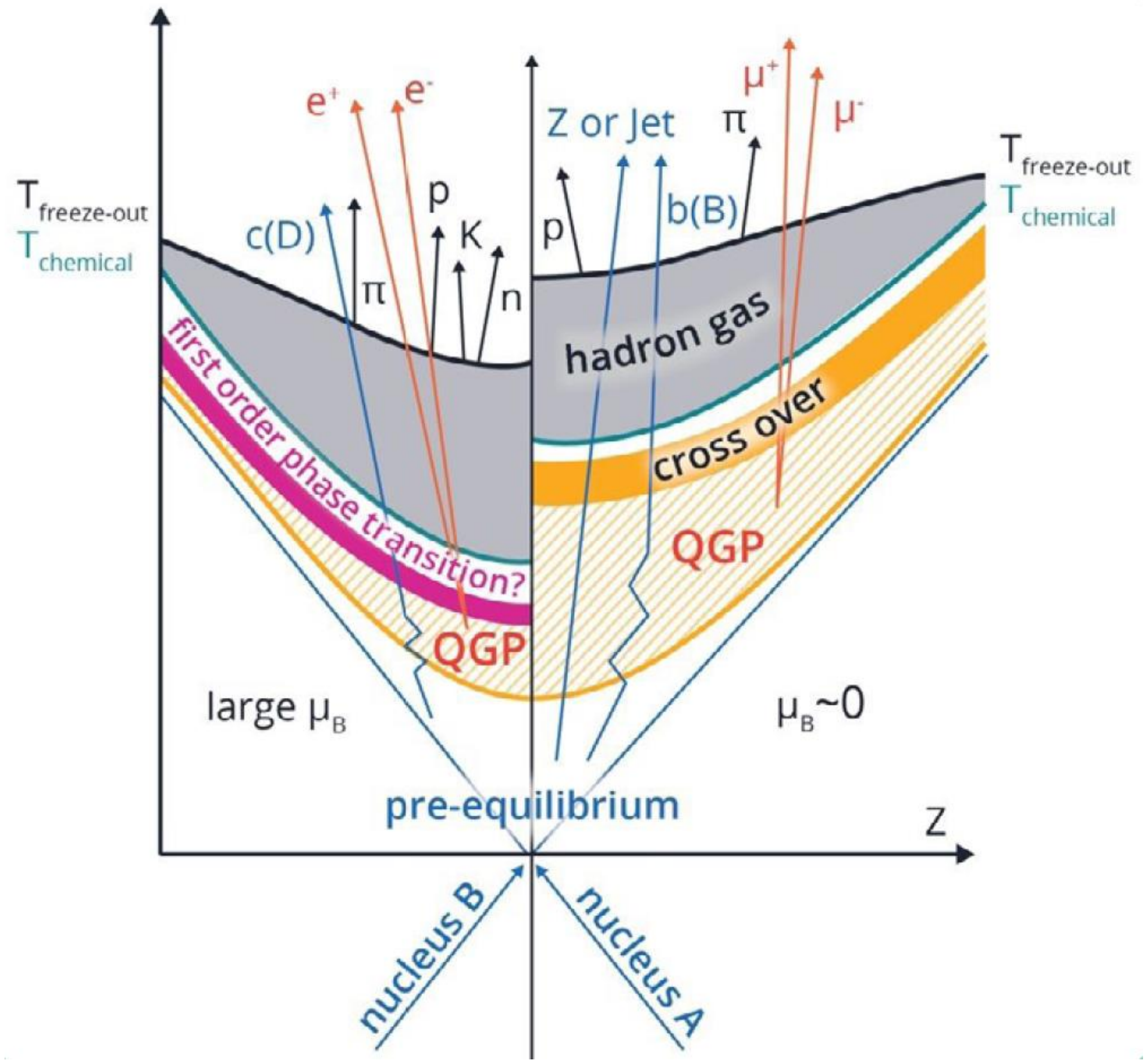


Tomography in Position and Momentum

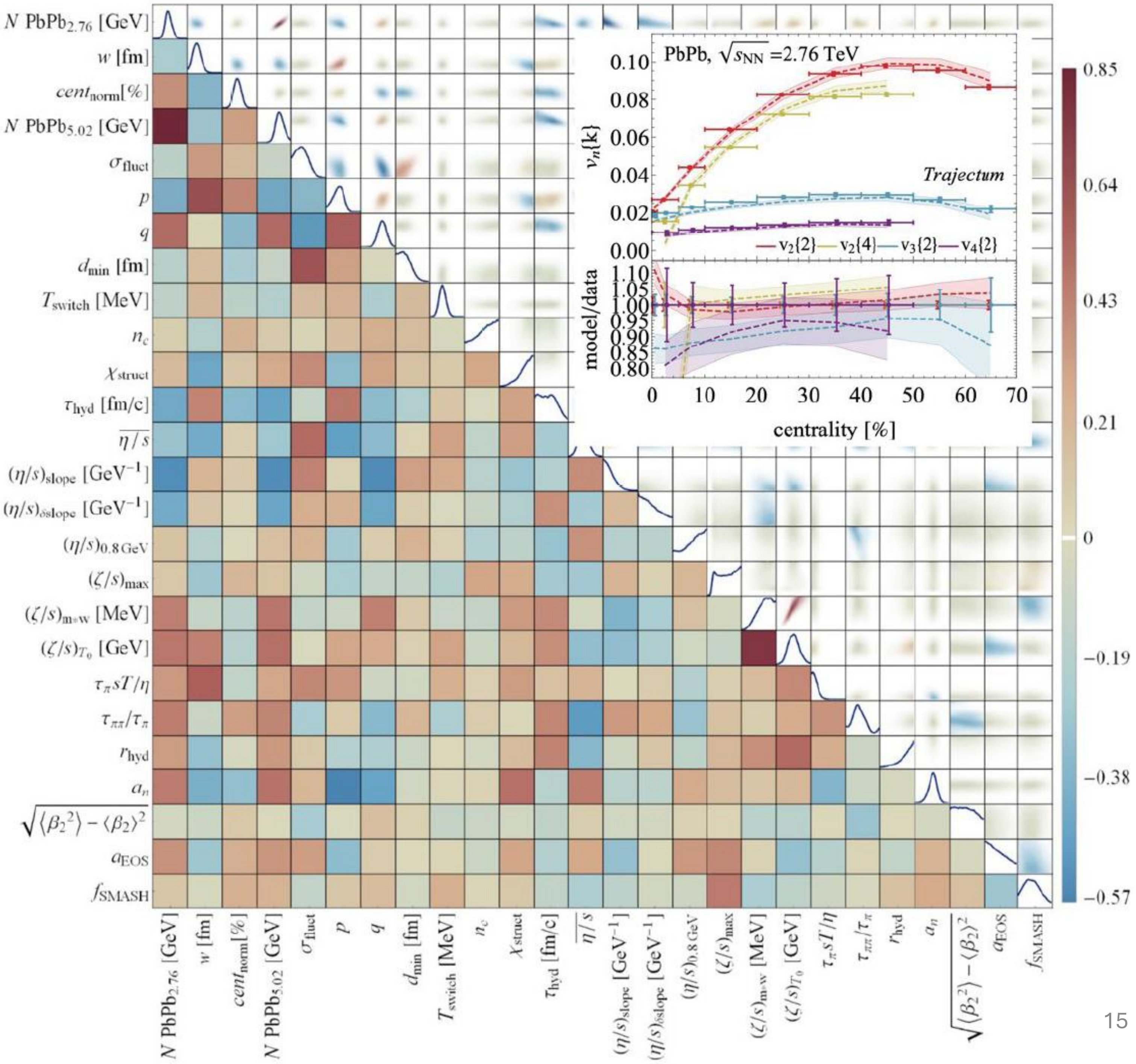
Strongly Interacting Matter



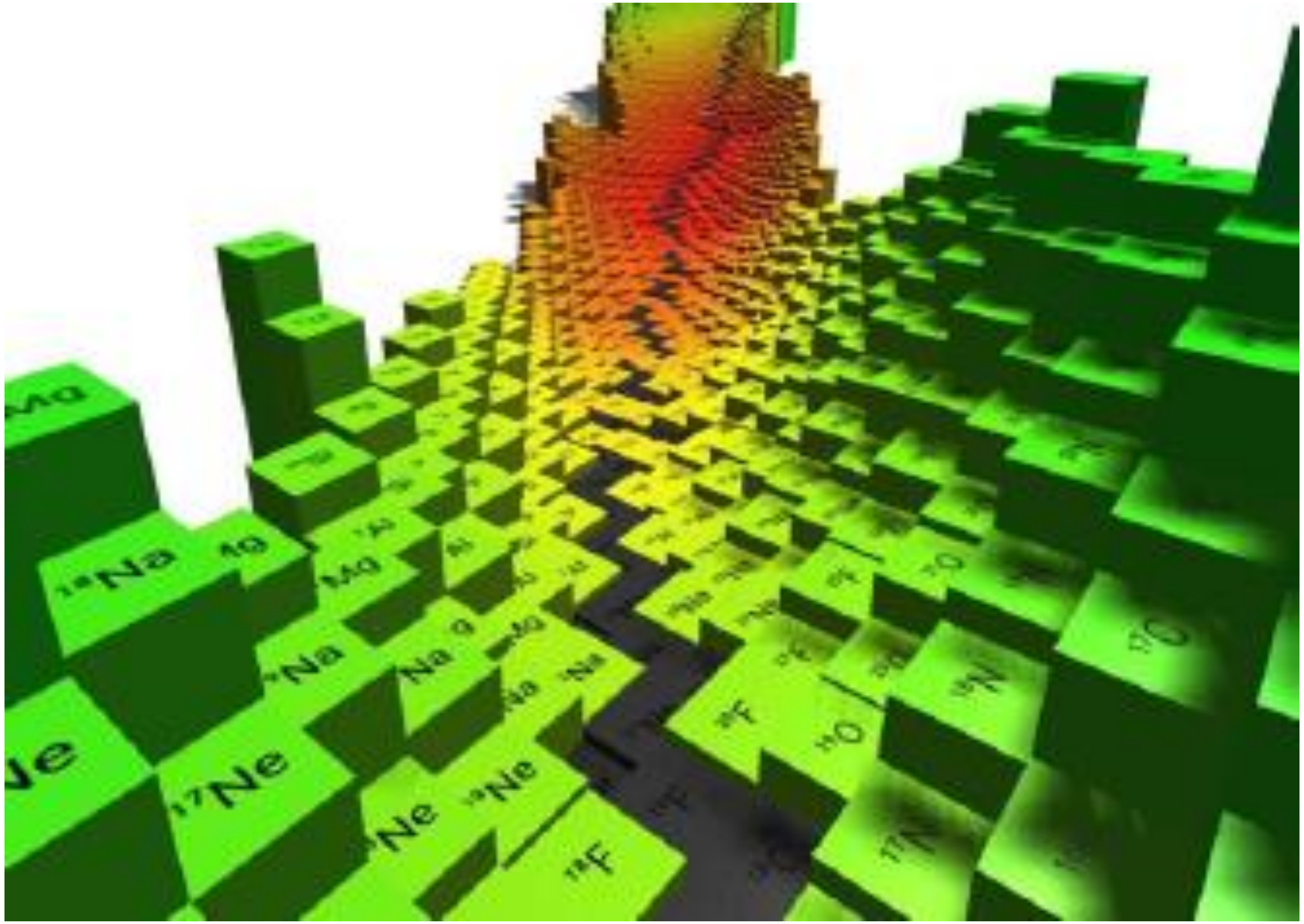
QCD Phase Transition



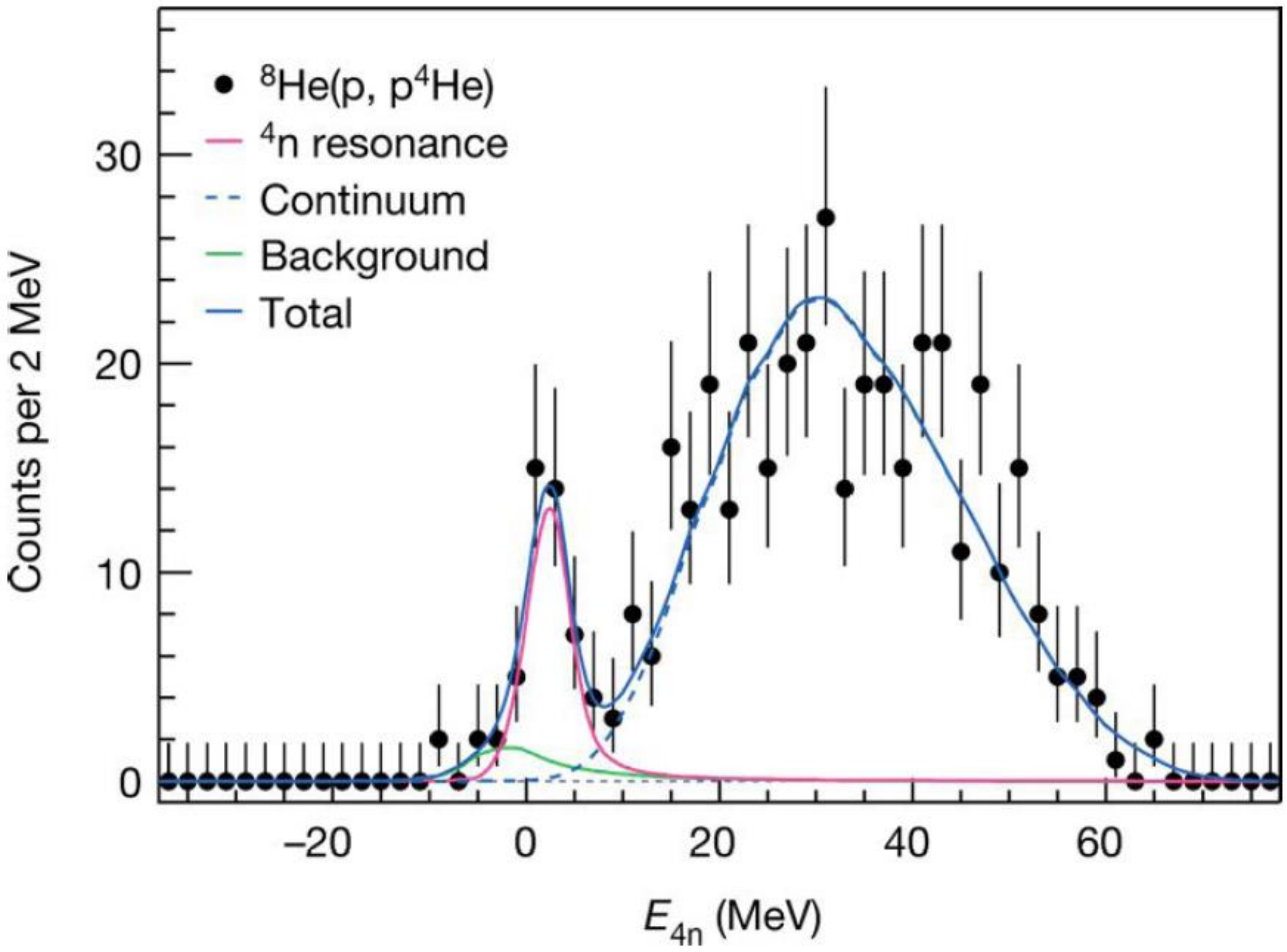
QGP Evolution



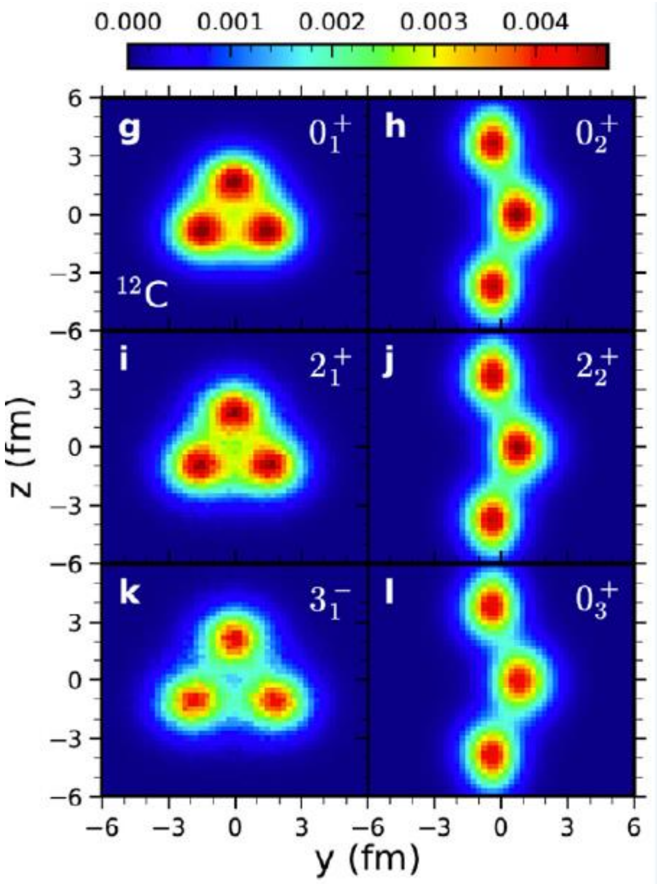
Nuclear Structure and Reactions

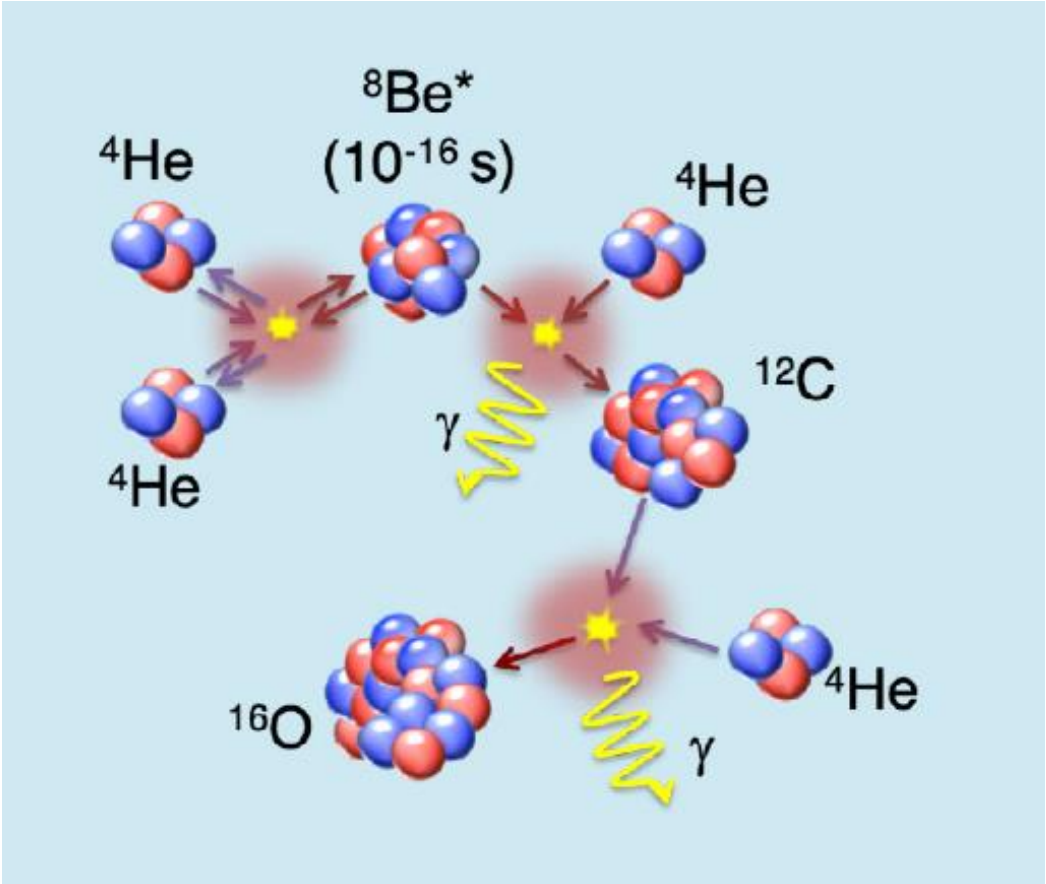


Tetraneutron

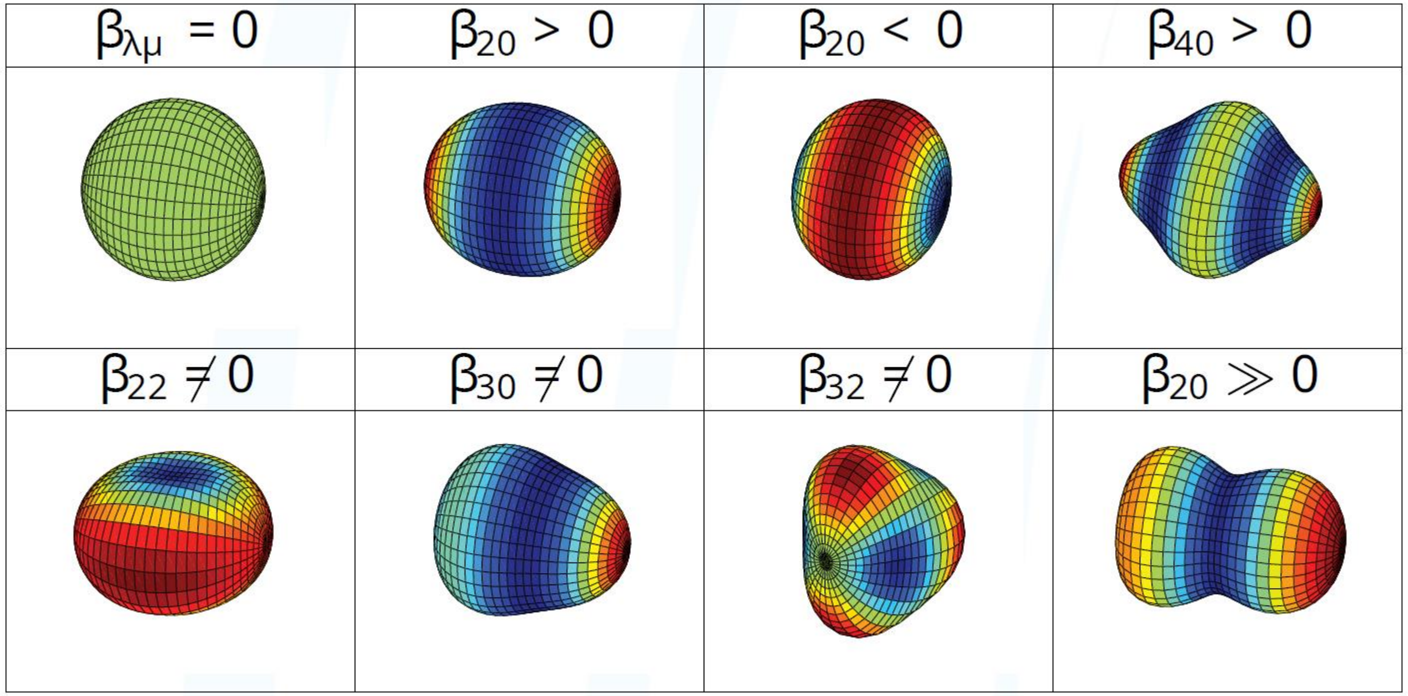


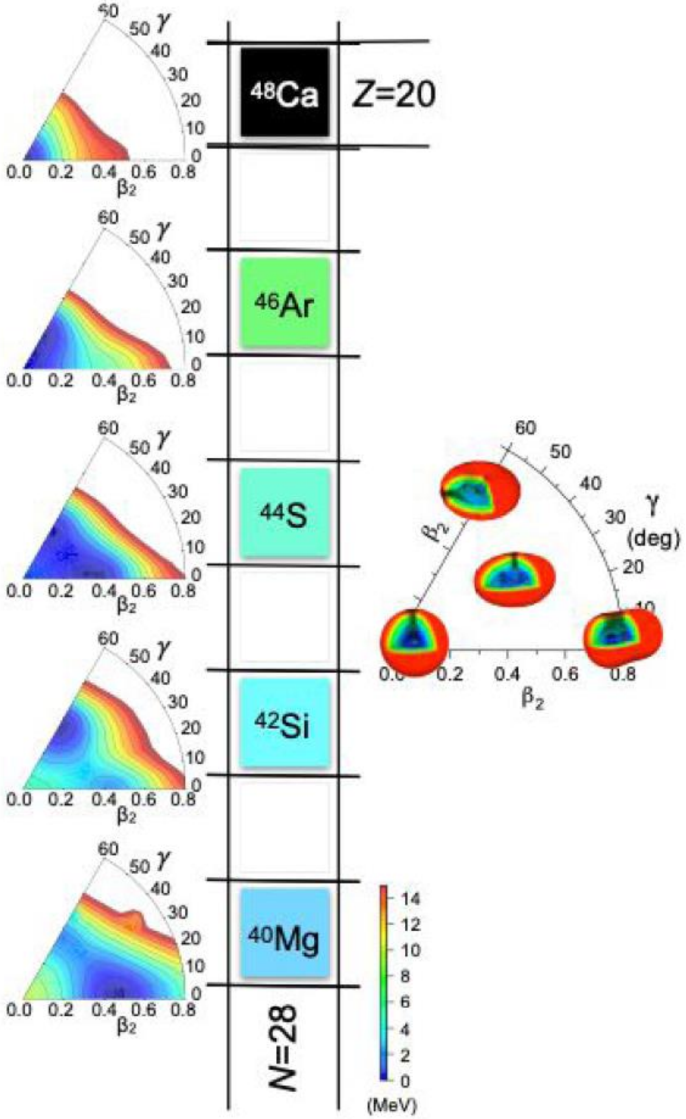
Alpha Clustering



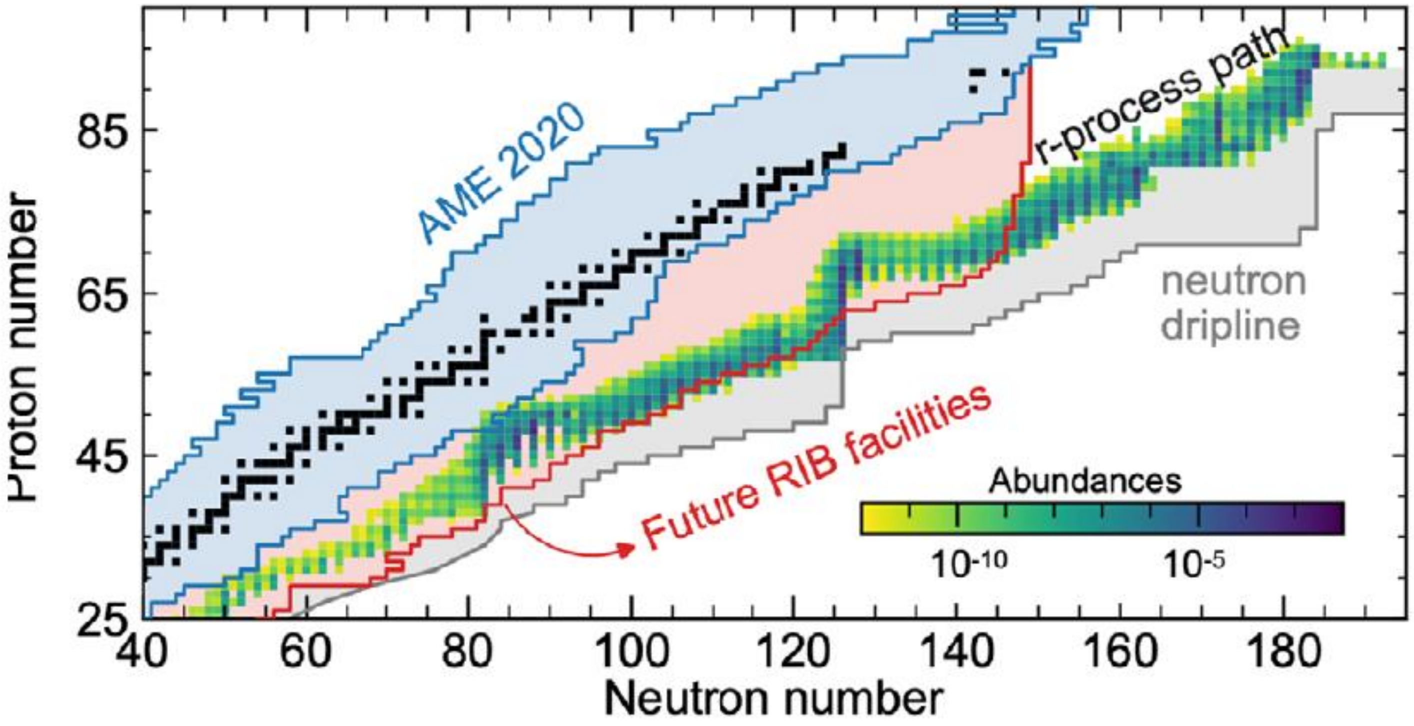


Nuclear Deformation

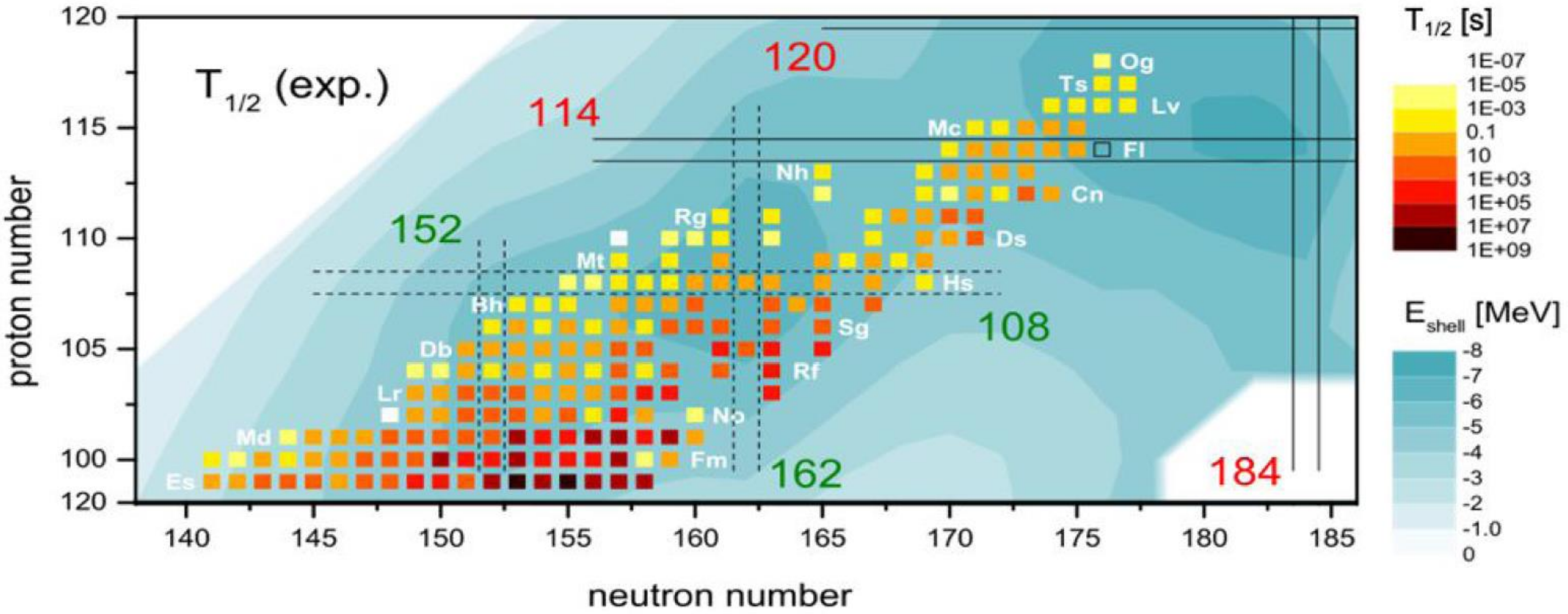




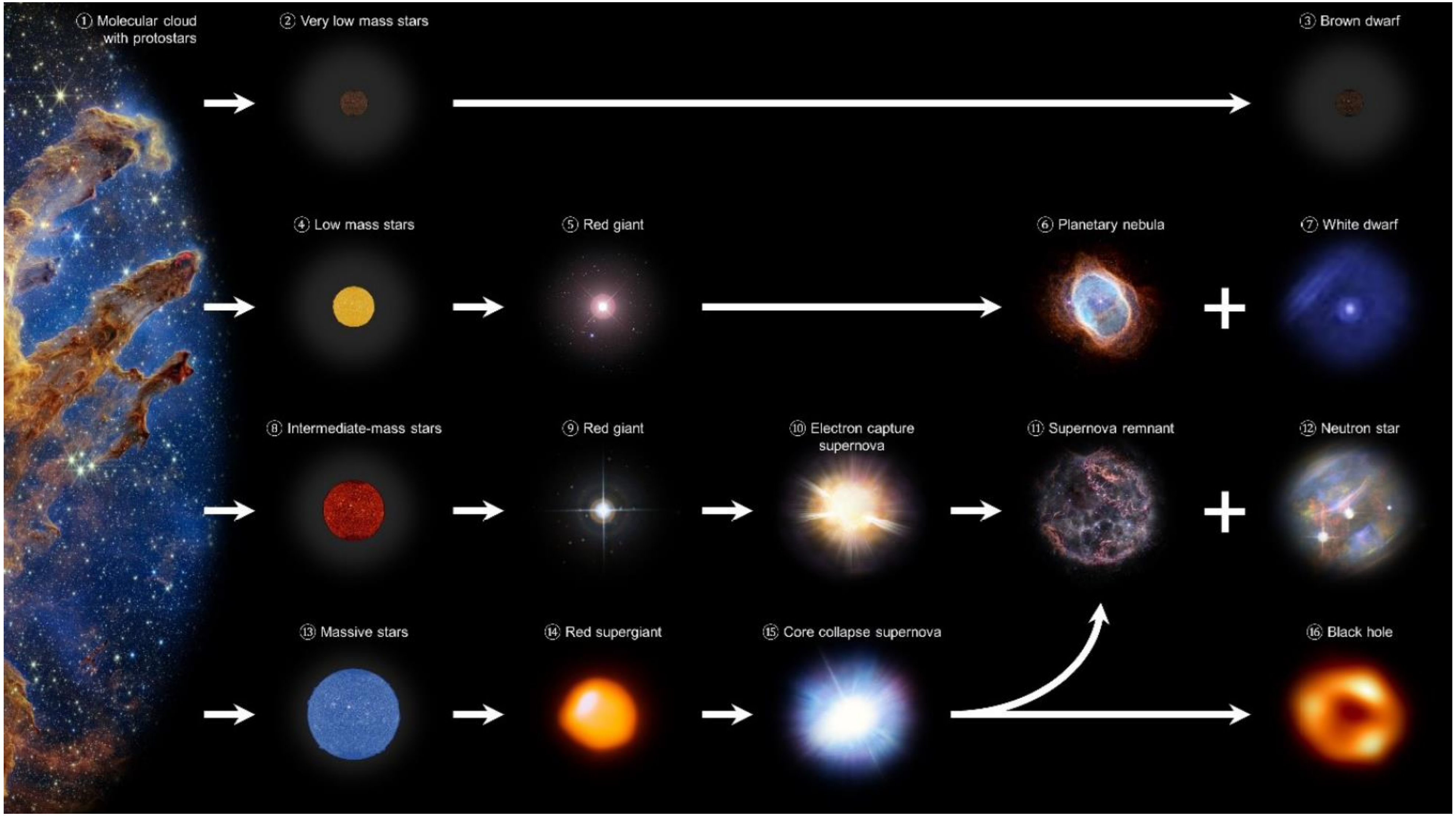
Radioactive Beams

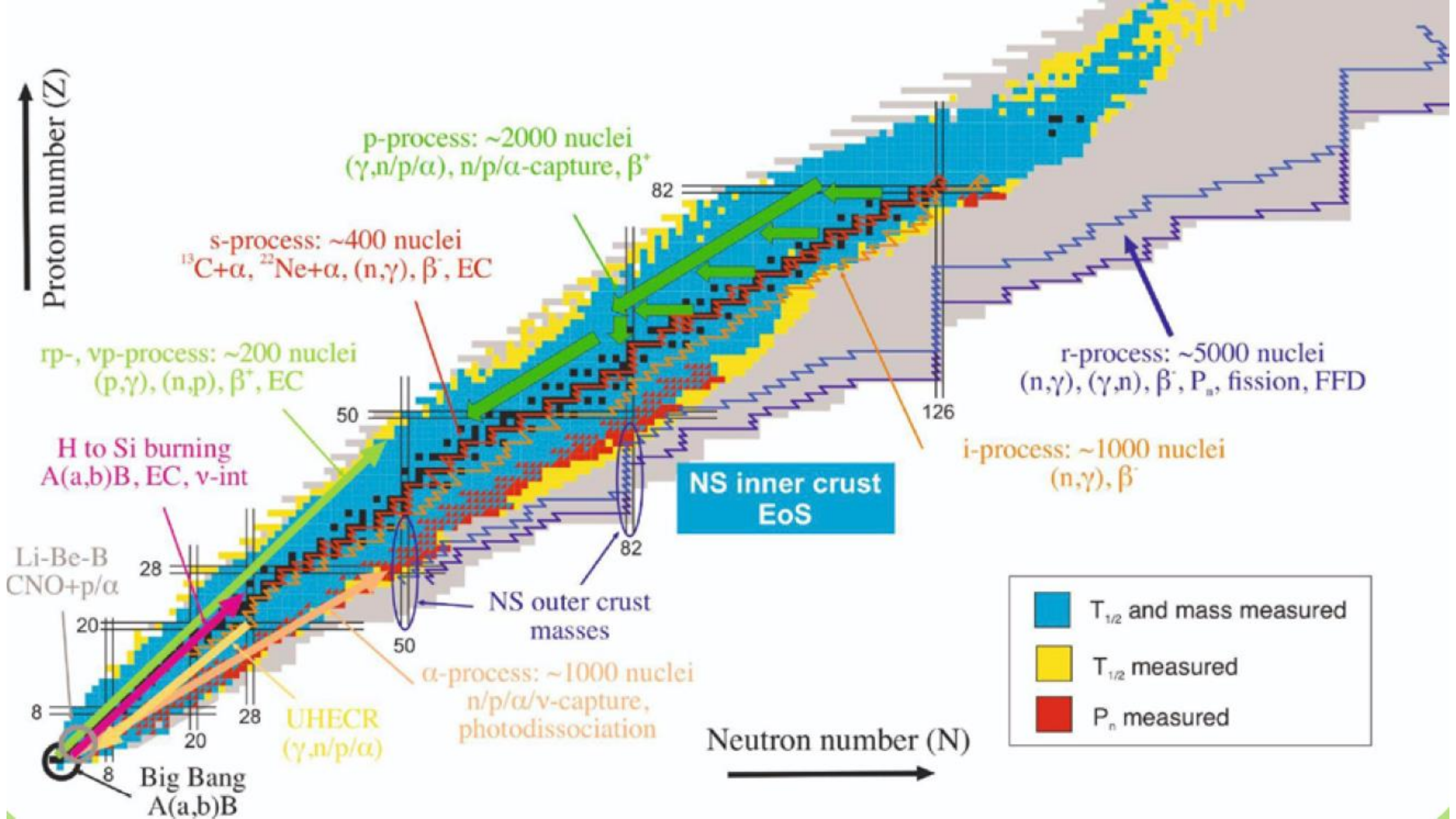


Superheavy Nuclei



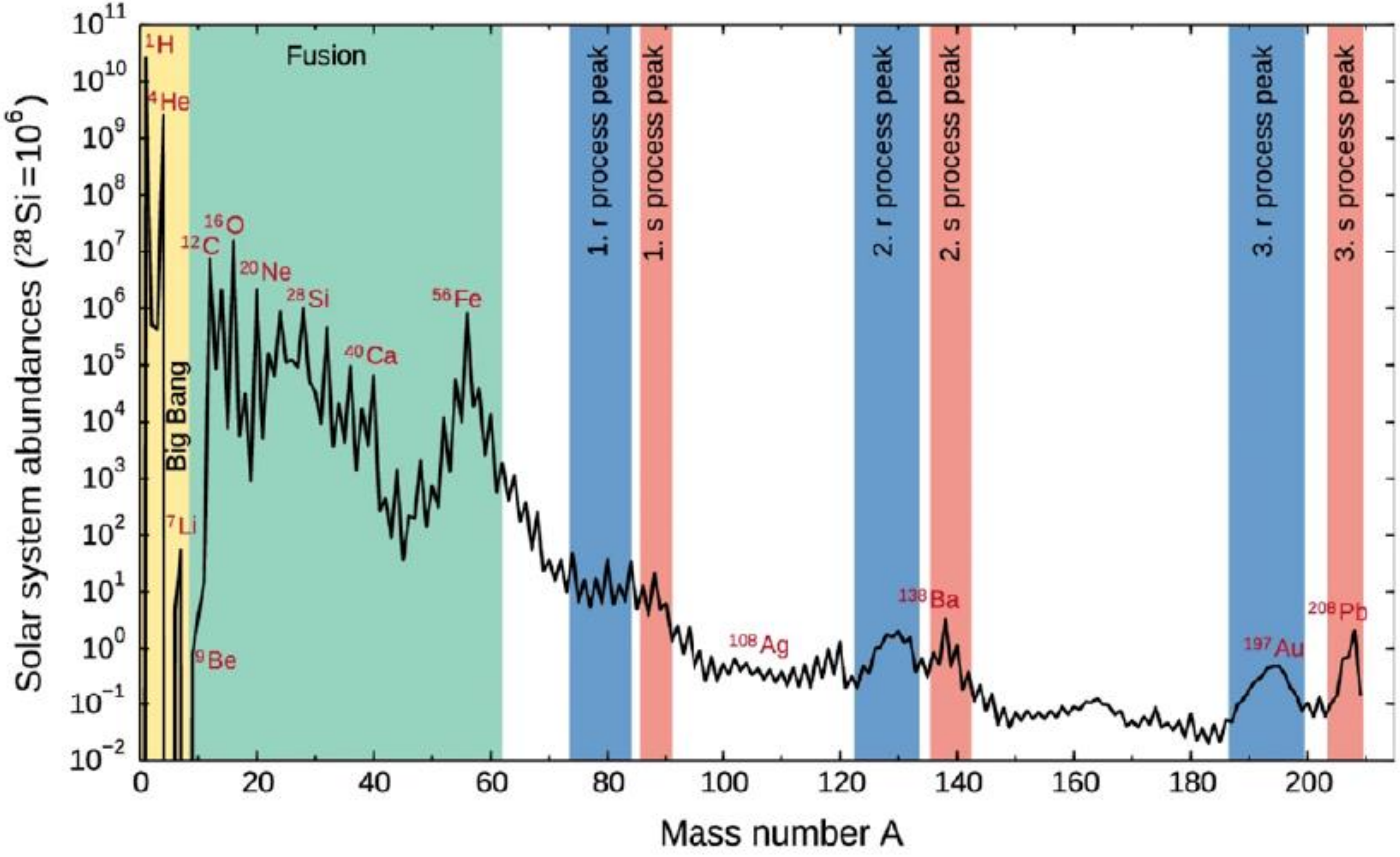
Nuclear Astrophysics

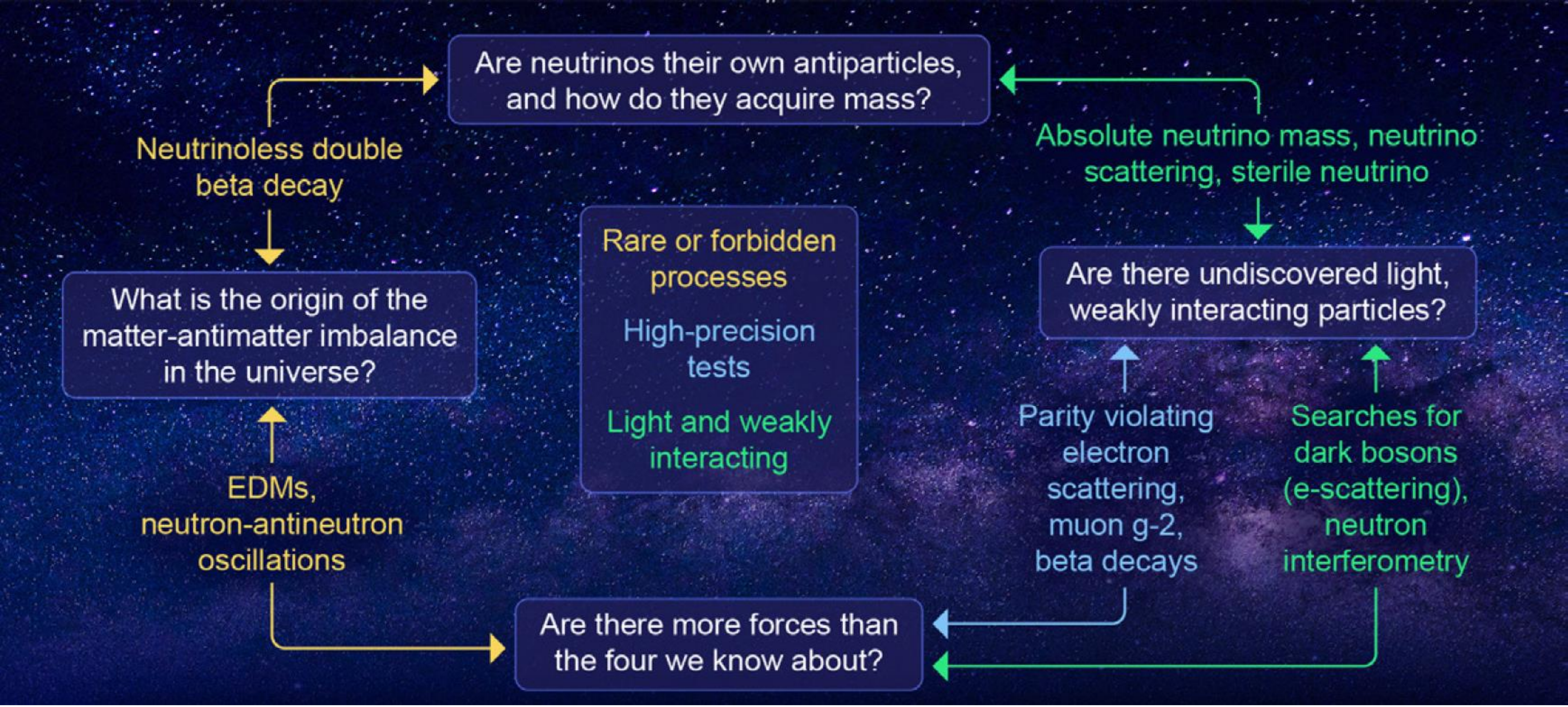




Proton number (Z)
p-process: ~2000 nuclei
(γ,n/p/α), n/p/α-capture, β+
s-process: ~400 nuclei
13C+α, 22Ne+α, (n,γ), β-, EC
rp-, νp-process: ~200 nuclei
(p,γ), (n,p), β+, EC
H to Si burning
A(a,b)B, EC, ν-int
Li-Be-B
CNO+p/α
Big Bang
A(a,b)B
UHECR
(γ,n/p/α)
α-process: ~1000 nuclei
n/p/α/ν-capture,
photodissociation
NS outer crust
masses
NS inner crust
EoS
r-process: ~5000 nuclei
(n,γ), (γ,n), β-, Pn, fission, FFD
i-process: ~1000 nuclei
(n,γ), β-
Neutron number (N)
T1/2 and mass measured
T1/2 measured
Pn measured
82
50
28
20
8
126

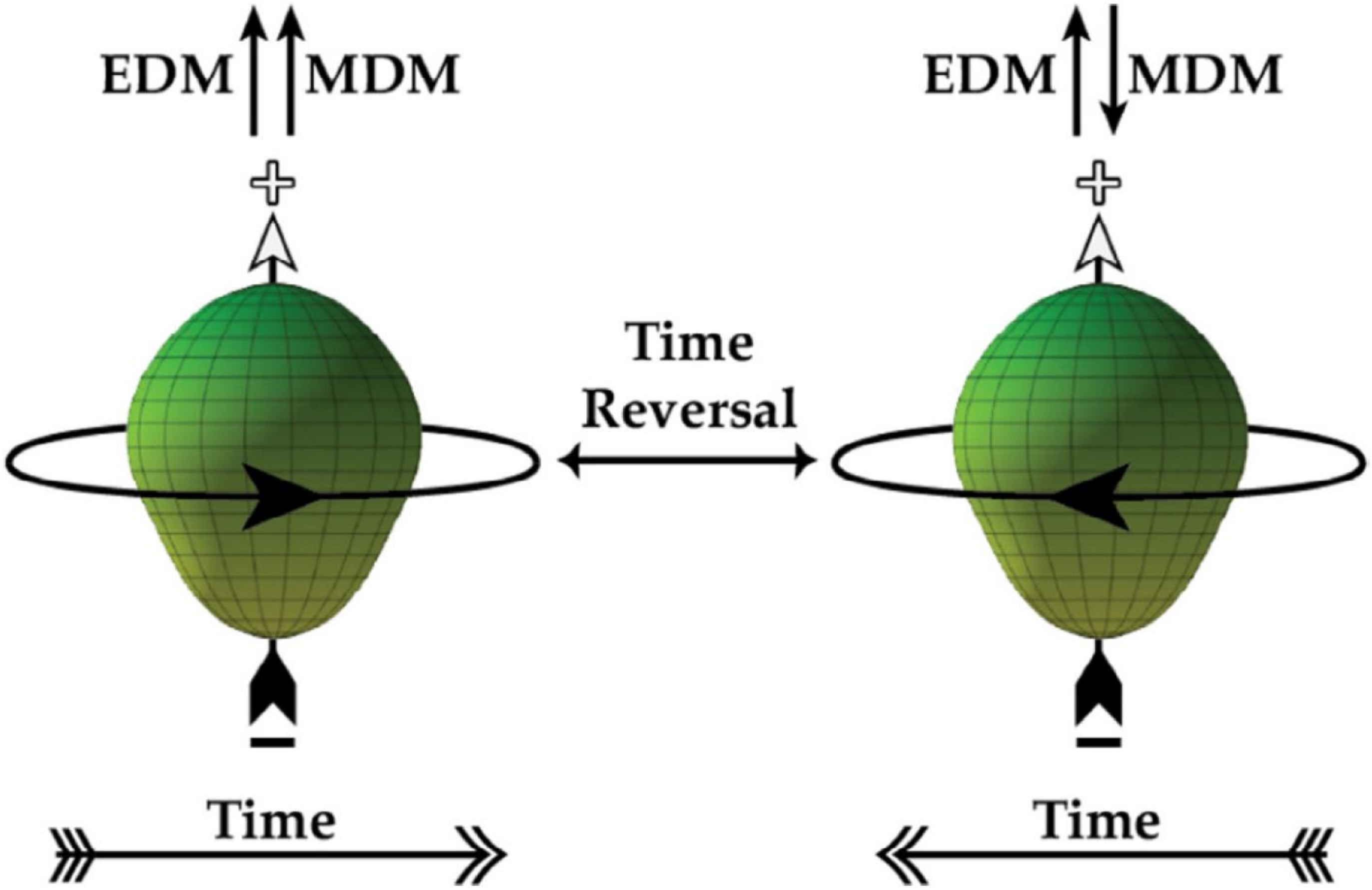
Abundances of Elements



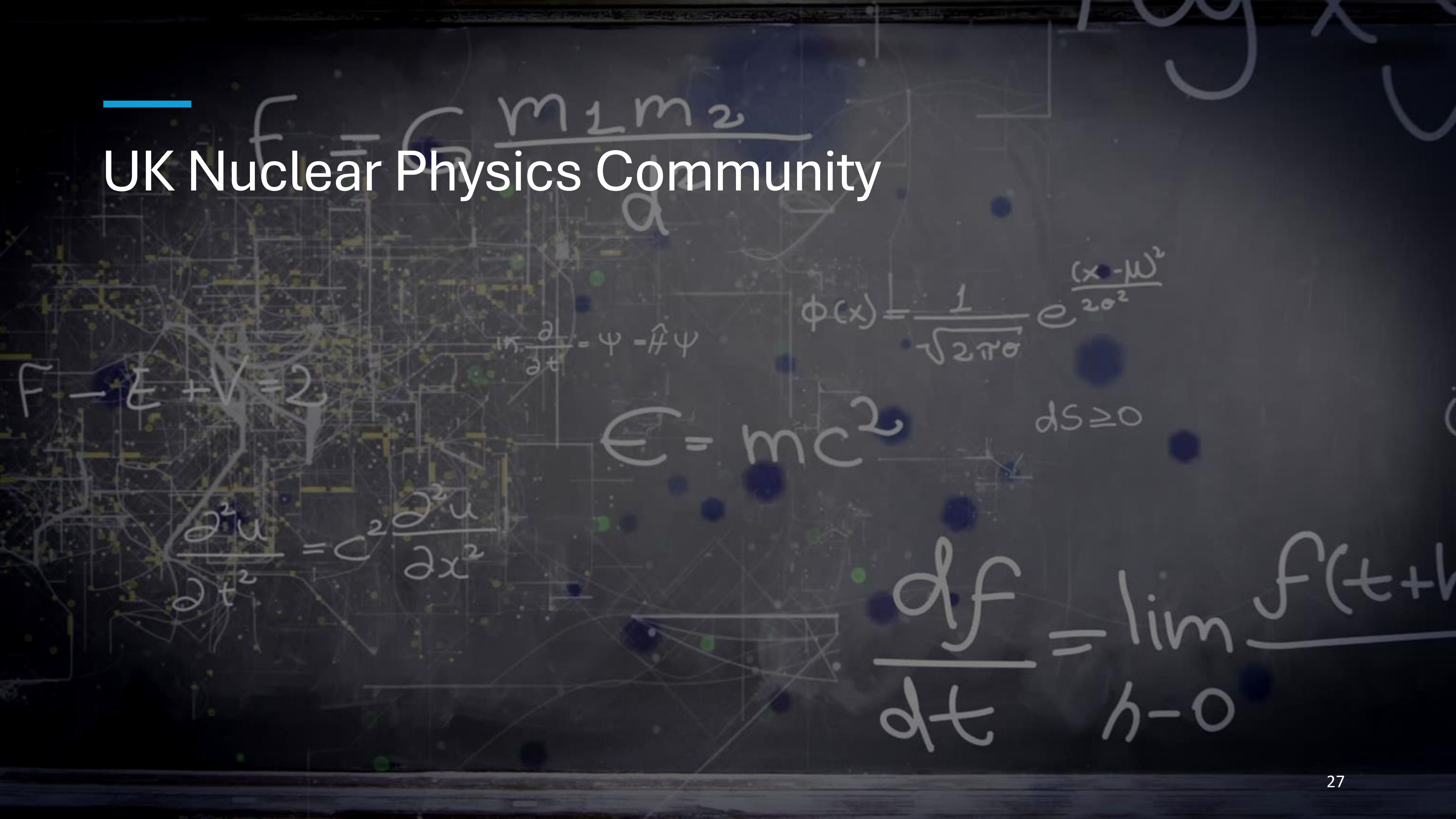


Symmetries and Fundamental Interactions

Time Reversal Asymmetry

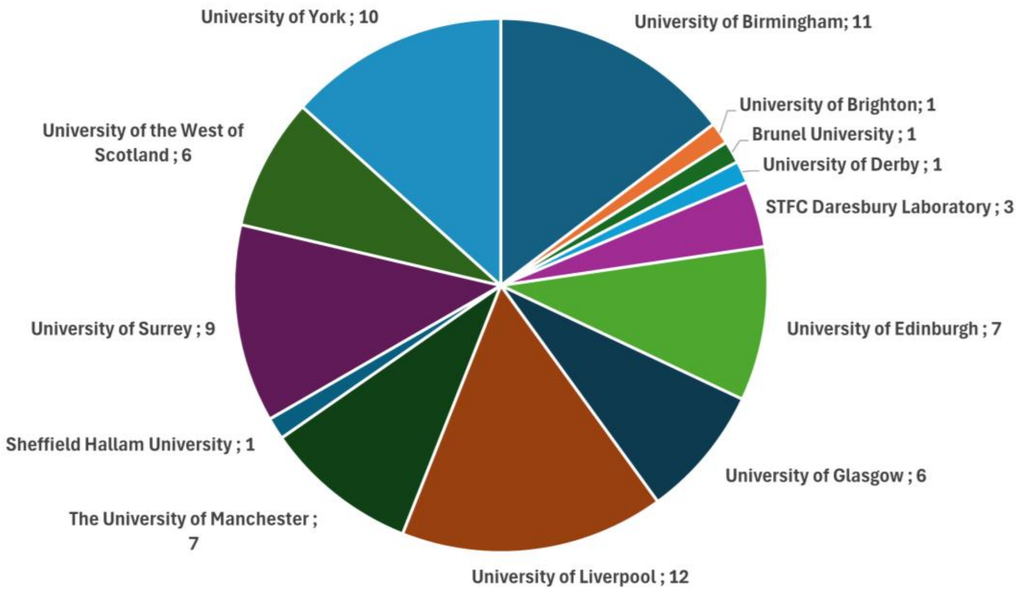


UK Nuclear Physics Community



Nuclear Physics in the UK

- 12 Universities
- 1 national laboratory
- 1 accelerator facility (MC40)



Number of NP academics per institute

Scotland
UWS (NS/NA)
Glasgow (HP)
Edinburgh (NS/NA)

North of England
Liverpool (NS/NA /HP)
Manchester(NS/NA /HT)
Sheffield (HP)
York (NS/NA /HP/NT)

Midlands
Birmingham (NS/NA /HP)
Derby (HP)

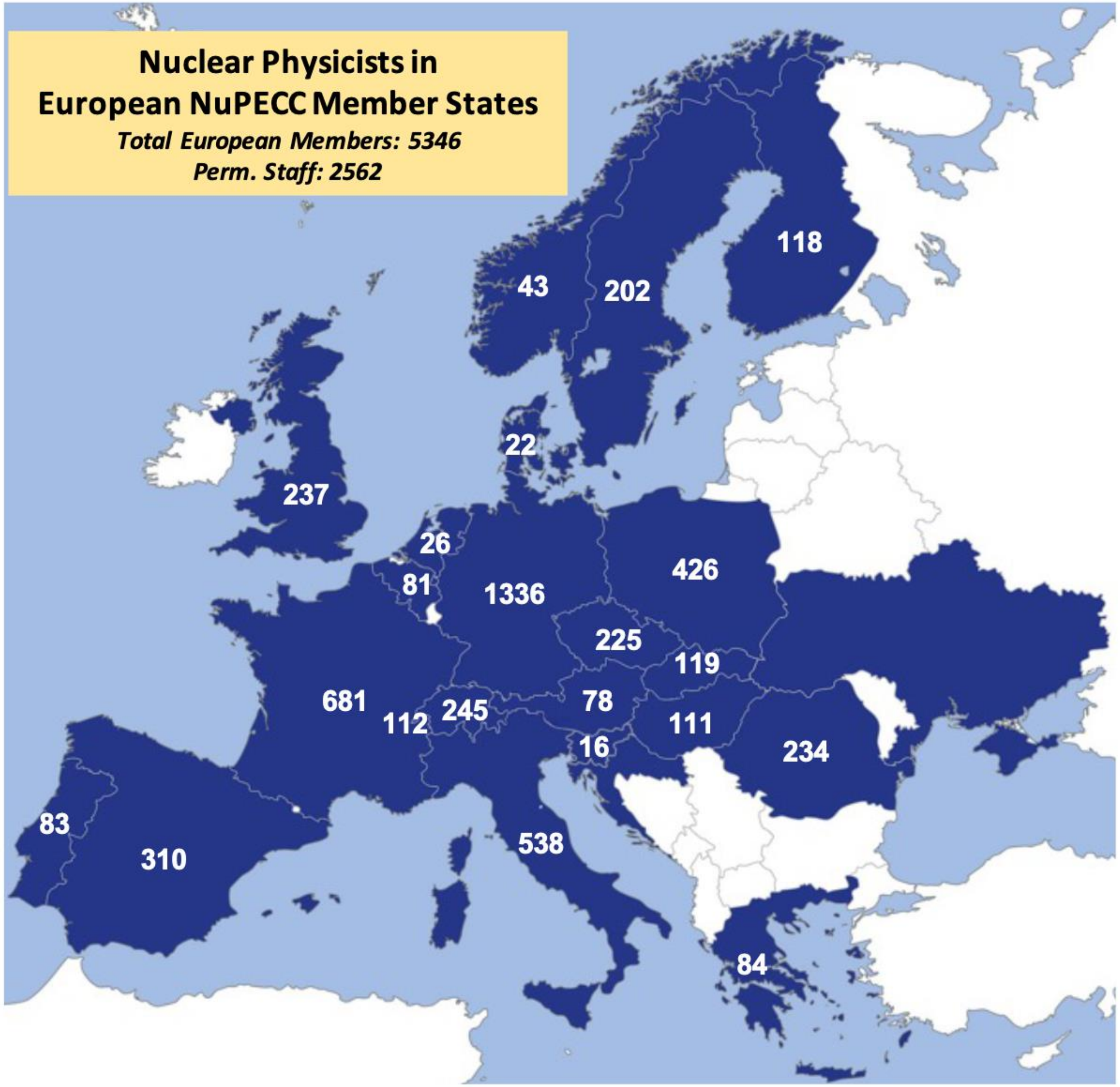
Southern England
Surrey (NS/NA/NT)
Brighton (NS/NA)
Brunel (HP)

Daresbury lab (NS/NA /HP)

MC40 proton/neutron beam facility (NS/NA)

Context within Europe

- UK NP community is smaller than comparable economies in mainland Europe
- Relative contribution of nuclear theory (~5% of academics) is smaller than in Europe, US and Asia – current priority to increase theory support

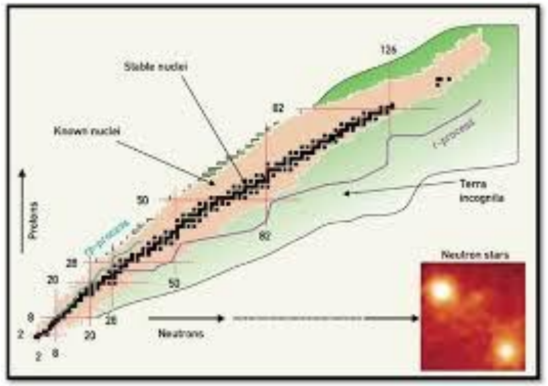


Nuclear physicists in the European NuPECC Member countries and the Associated Member CERN(source: NuPECC survey 2021 and 2023).

Fundamental science questions

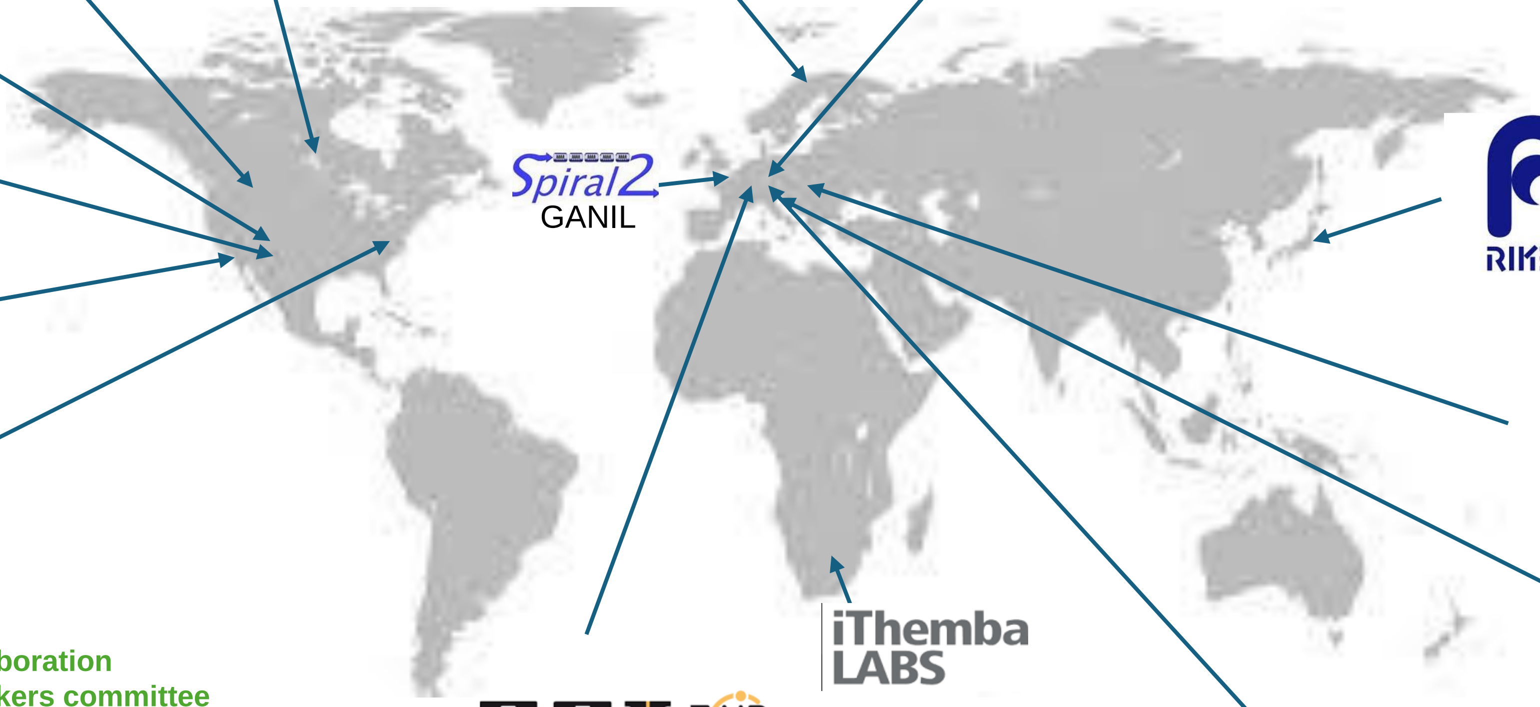
- Where are the limits of nuclear existence?
- How does nuclear structure evolve in exotic nuclear systems, what mechanisms drive new structural phenomena?
- How well are nuclei described in terms of the underlying fundamental interactions based on QCD?

- What are the nuclear processes responsible for the synthesis of the elements in various astrophysical sites/conditions?



- Can the dynamics of QCD fully explain hadron (and exotic hadron) properties e.g. structure, confinement, mass, excitation, spin,..?
- Is there evidence of gluon saturation in high-energy nuclear collisions?
- What is the nature of the quark-gluon plasma, and how does it emerge from fundamental interactions?
- How do hadron and nuclear properties relate to neutron stars, black hole formation or matter during the early evolution of the Universe?

Facility map and recent UK leadership roles



Argonne NATIONAL LABORATORY

TRIUMF
Chair NP Expt. Eval. Committee
User exec committee

JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ
JYFL

CERN

ALICE, ISOLDE, nTOF, CRIS, IDS, ISS
ALICE Collaboration Board (Chair)
ISOLDE Spokesperson and Collab chair
CRIS, IDS, ISS Spokespersons

FRIB
Univ of Michigan

TUNL Triangle Universities Nuclear Laboratory
HIGS

Spiral2
GANIL

RIKEN

BERKELEY LAB
LBNL

eli nuclear physics

Jefferson Lab

Halls A, B, C and D
Hall B Chair of CLAS12 collaboration
Hall B Chair of CLAS12 speakers committee
Hall-C Collaboration user board
Hall A SBS coord committee

iThemba LABS

GSI FAIR

NUSTAR, R3B
NUSTAR spokesperson (+LS, SHE)
AGATA steering committee/management board
FAIR/GSI scientific council

mami MAINZER MIKROTRON

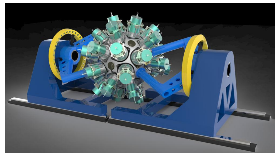
A2
A2 Collab Board

INFN Istituto Nazionale di Fisica Nucleare

ILL, LUNA, LNL
LUNA Collab Board

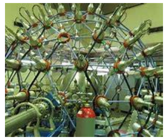
Recent infrastructure leadership

FRIB
Univ of MIchigsn



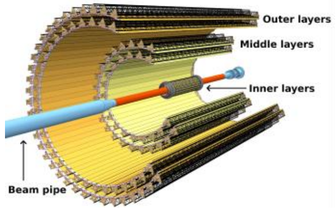
FAUST

TRIUMF



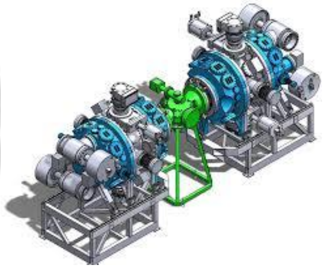
DEMAND neutron array
(Also for FRIB)

CERN



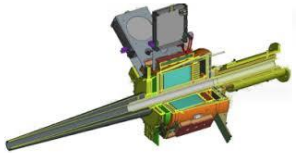
ALICE inner tracker

ALICE central trigger system

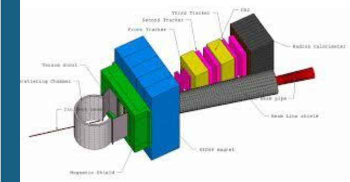


ISOL SRS

Jefferson Lab

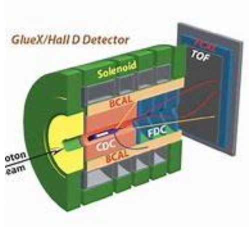


Forward tagger (Hall B)



SBB spectrometer (Hall A)

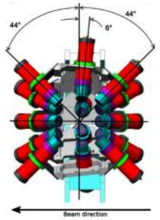
Neutral Kaon beam Facility (Hall D)



FAIR GSI

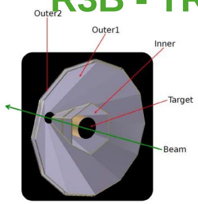
AGATA

AIDA

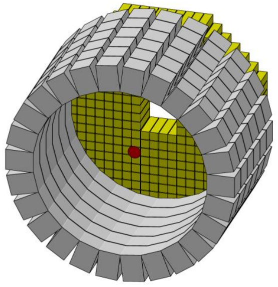


DESPEC/
HISPEC

R3B - TRT

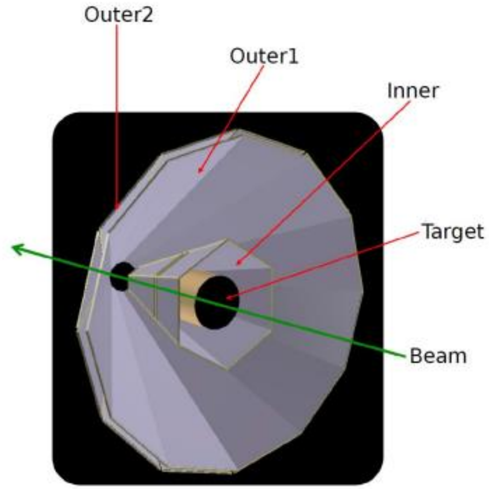


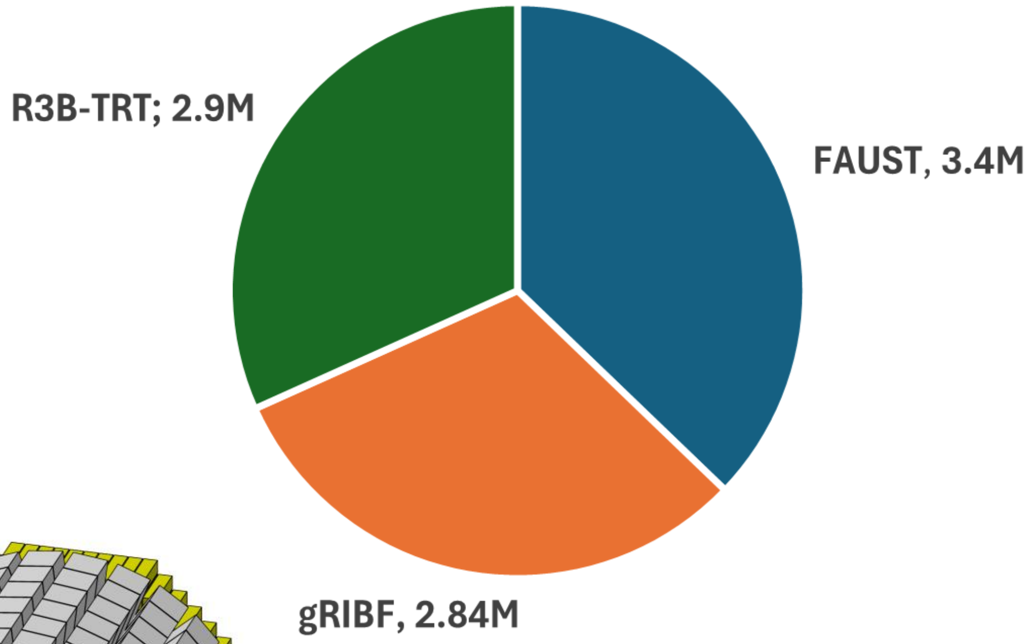
RIKEN

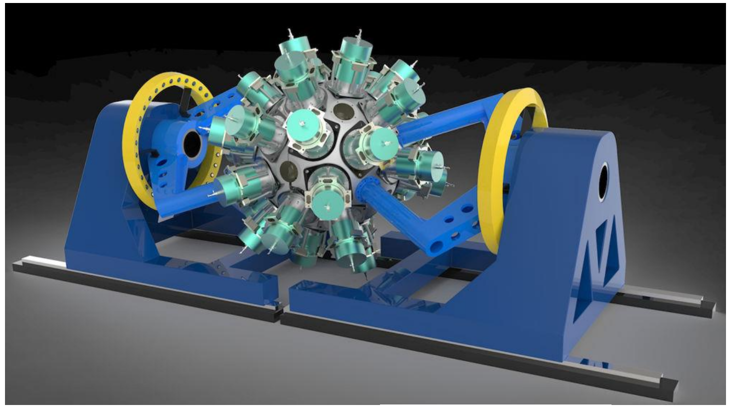


HYPATIA array
γRIBF

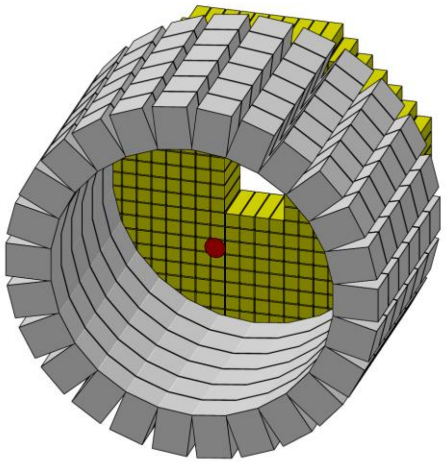
Projects funded in most recent STFC Projects (PPRP) round in 2023





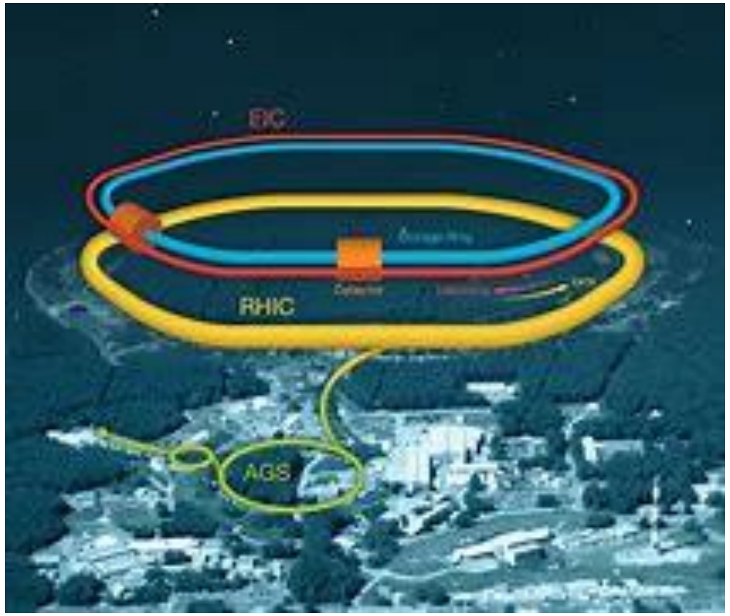


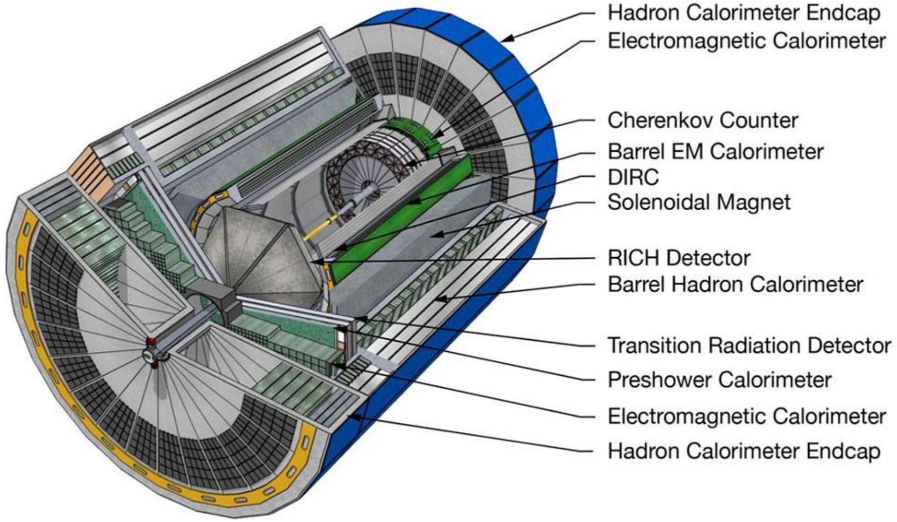
FRIB
Univ of MIchigan



Previous rounds saw significant investment in ALICE@LHC, SRS@ISOLDE

UKRI infrastructures project – Electron ion collider (Brookhaven)

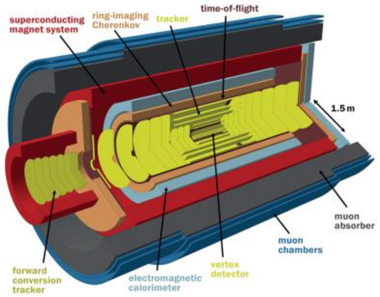




- Image the gluonic contribution of matter, nature of strong force, mass generation, hadron spectroscopy, …
- UK contribution recently funded by UKRI infrastructure fund Seven universities and two national laboratories (£58M)
- Contributions to ePIC detector :
  - SVT (MAPS)
  - Electron tagger (TIMEPIX)
  - AI-guided Calorimetry
- Also – collaboration in delivery of EIC accelerator infrastructure
- Expected to be online in 2032

(Some of the) Future projects in the UK roadmap

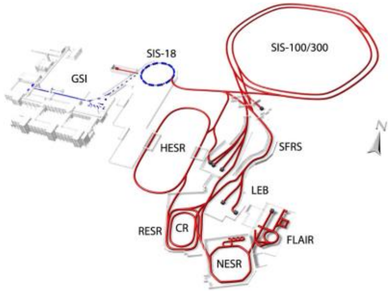
AGATA upgrade – Progress from 3π to 4π spectrometer



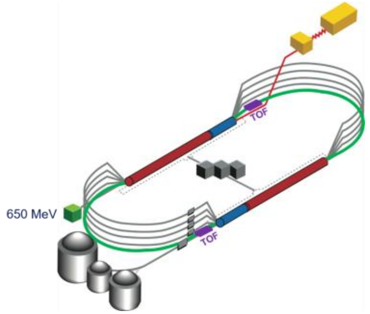
ALICE upgrade - Collaboration proposes a novel detector - ALICE3 - with high readout rate, superb pointing resolution and excellent tracking and particle ID using advanced silicon (MAPS) detectors. LHC Runs 5,6 (2035).

Legend 1000 – Neutrinoless double β decay; isotopically enriched ^{76}Ge

E1-M2 Mössbauer – Nuclear CP violating moment in odd mass pear shaped nucleus.

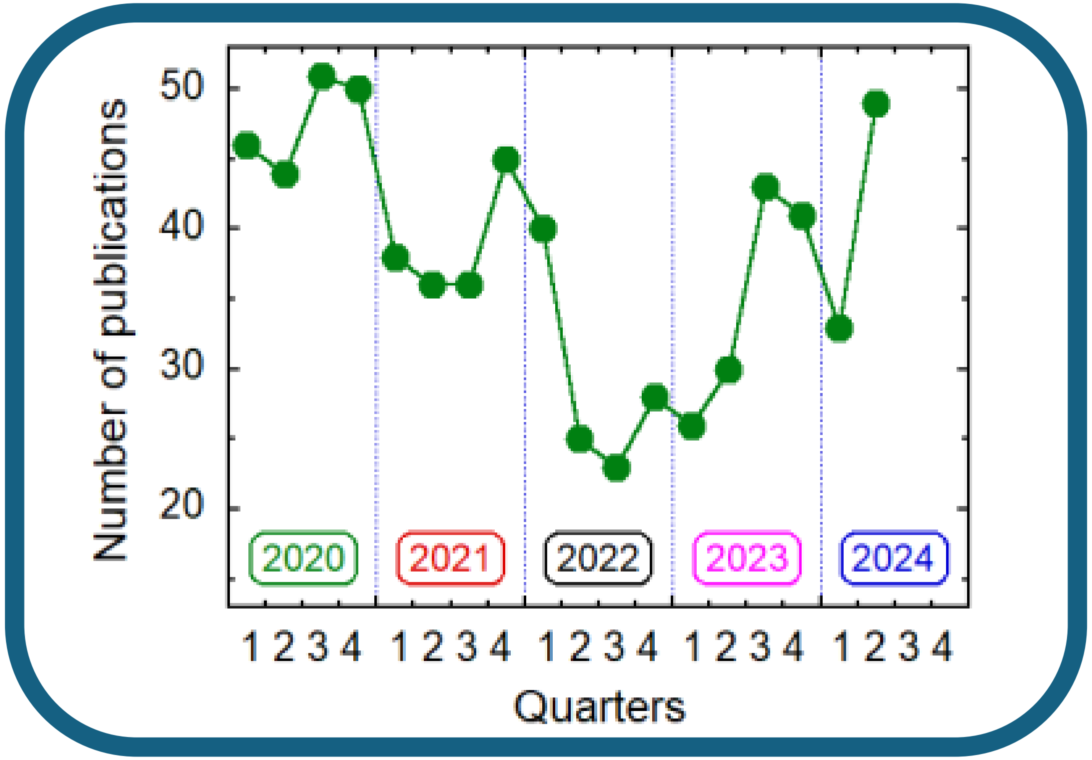


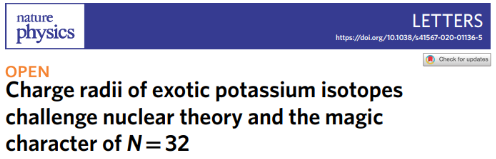
GSI/FAIR upgrade - New storage ring taking beams directly from the new SIS100 - SuperFRS accelerator/fragment separator. Increased beam intensities, transmission → new detector infrastructure

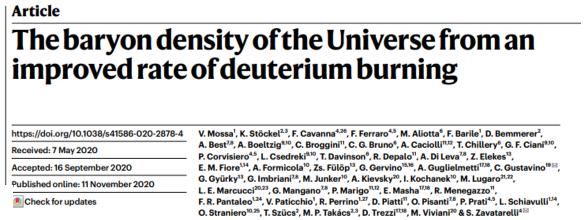


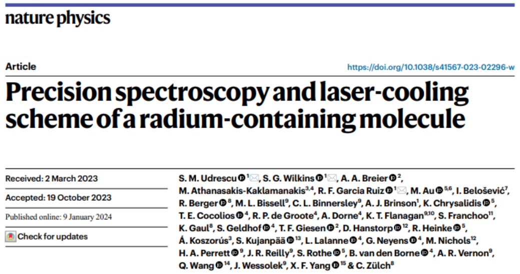
JLAB upgrade – Upgrade from 12 GeV to 22 GeV proposed. Enhanced capabilities for 3D imaging of nucleon; exceed J/psi threshold, new meson structure programmes, new possibilities for neutral Kaon beam

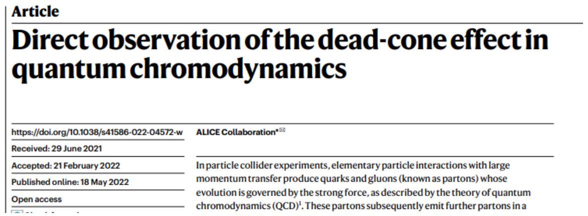
UK NP publications in refereed journals

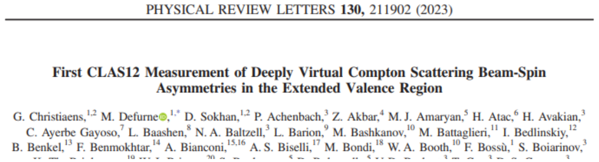


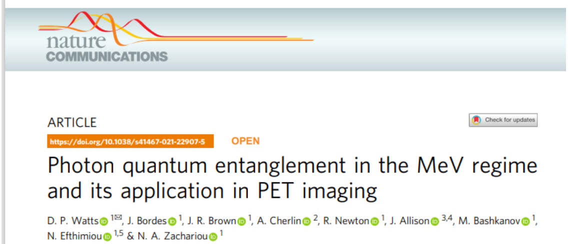








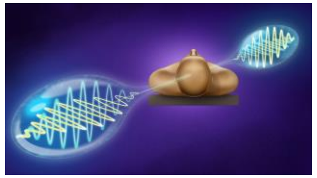


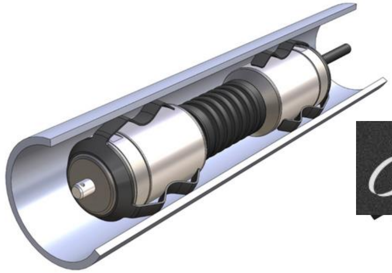


2020-2024: Nature Journals (17),
Phys. Rev. Lett.(105)
Phys. Lett. B (64)

For a list of recent research highlights from UK NP - see backup slides

(Some) recent examples of societal impact from NP





Quantum information in PET imaging – dose reduction (QTFP)

Nuclear waste management/security: LINKEOS

Oil industry, industrial imaging: AevaSpec

Radiation monitors for personnel e.g. D3S developed for Kromek (recent $6M purchase by US authorities)

Medical isotope production using γ-beams at intensity frontier

Ultra-fast rf photon detectors (with timepix) for medical imaging and quantum optics

MAPS technologies in medical physics : OPTima

AWE collaborations e.g. VENOM, a new neutron facility for nuclear research and isotopic assay

Binding blocks - One of UK's largest outreach activities reaching 1000's of school students (in-person) + online materials for educators

LINKEOS TECHNOLOGY LTD

AevaSpec

Quantum DETECTORS

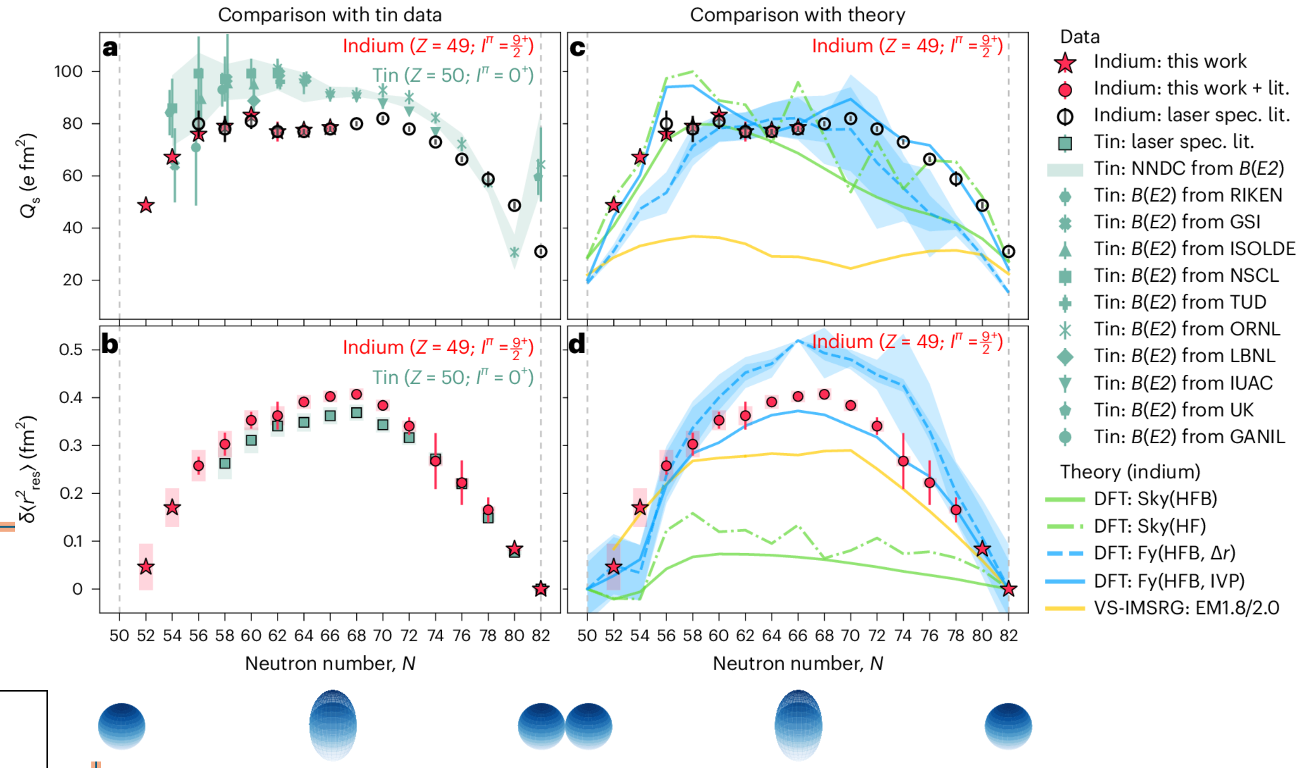
OPTima
Optimising Proton Therapy through Imaging

+ high-level training in nuclear physics, cutting-edge detector technologies, advanced simulation – skills sought for medical/industrial imaging, medical physics, nuclear industry, finance, ..

UK Nuclear Physics Theory

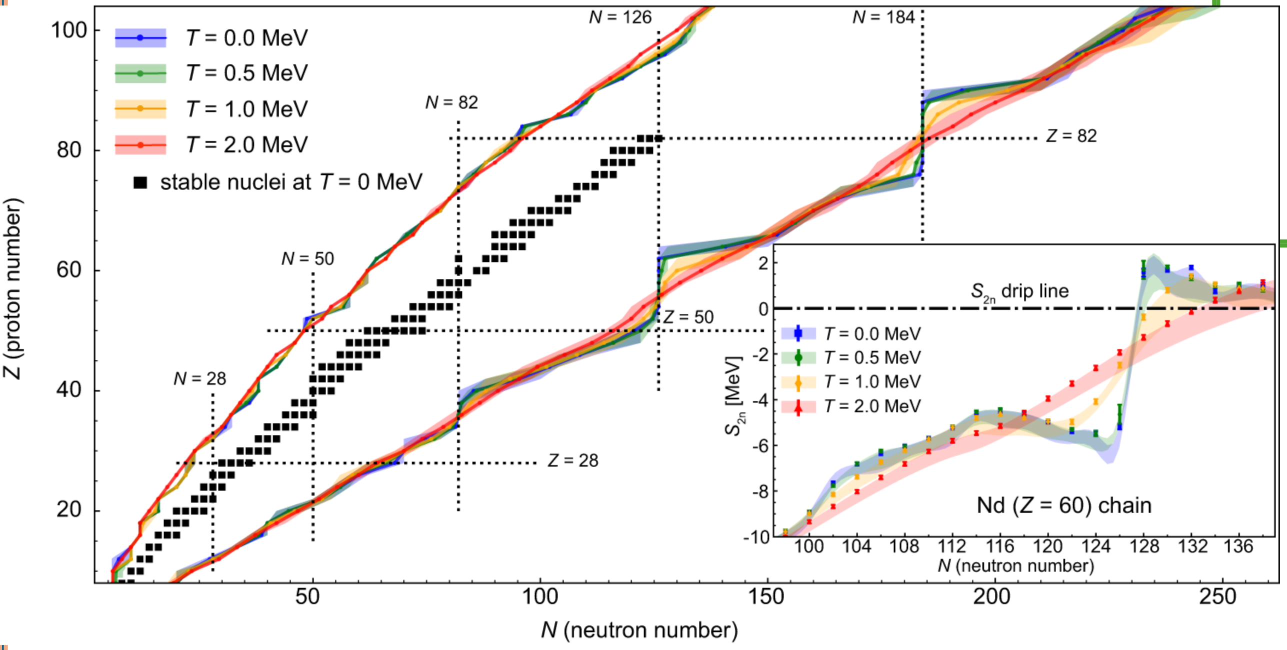
Nuclear Energy Density-Functional Approaches

Dobaczewski (York), Yüksel (Surrey), Stevenson (Surrey)



Karthein, ..., Dobaczewski, *et al.* Nature Physics **20**, 1719 (2024)

Ravlić, Yüksel, Nikšić & Paar, Nature Commun. **14**, 4834 (2023)

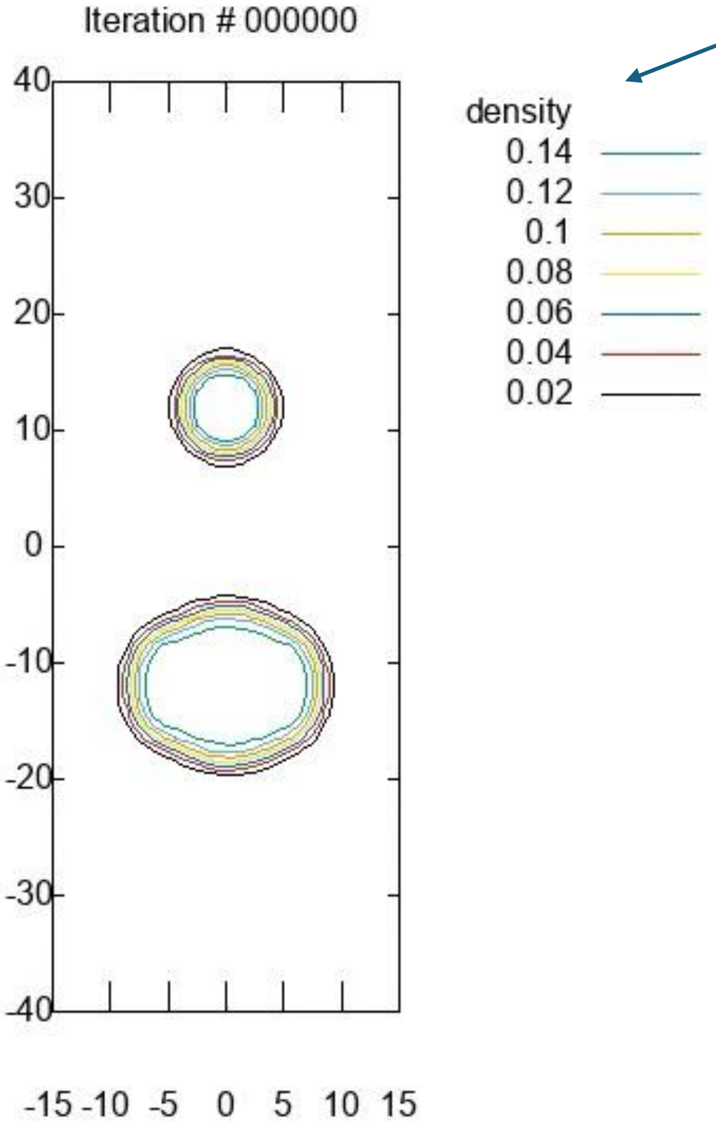


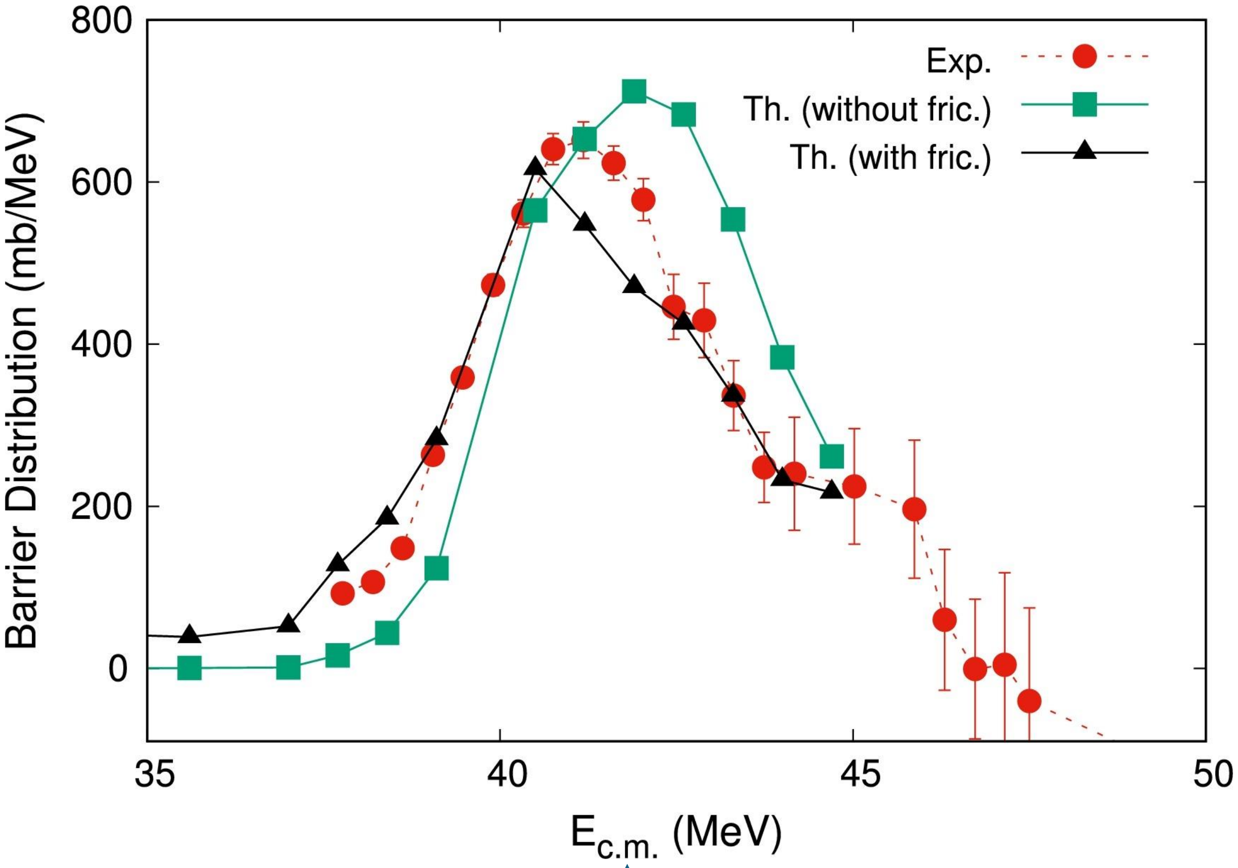
see also

Arrowsmith-Kron, ..., **Dobaczewski**, ... et al., Opportunities for fundamental physics research with radioactive molecules *Rep. Prog. Phys.* **87** 084301 (2024): DFT input to beyond-standard model physics

Nuclear Reactions: Stevenson (Surrey), Timofeyuk (Surrey), Diaz-Torres (Surrey)

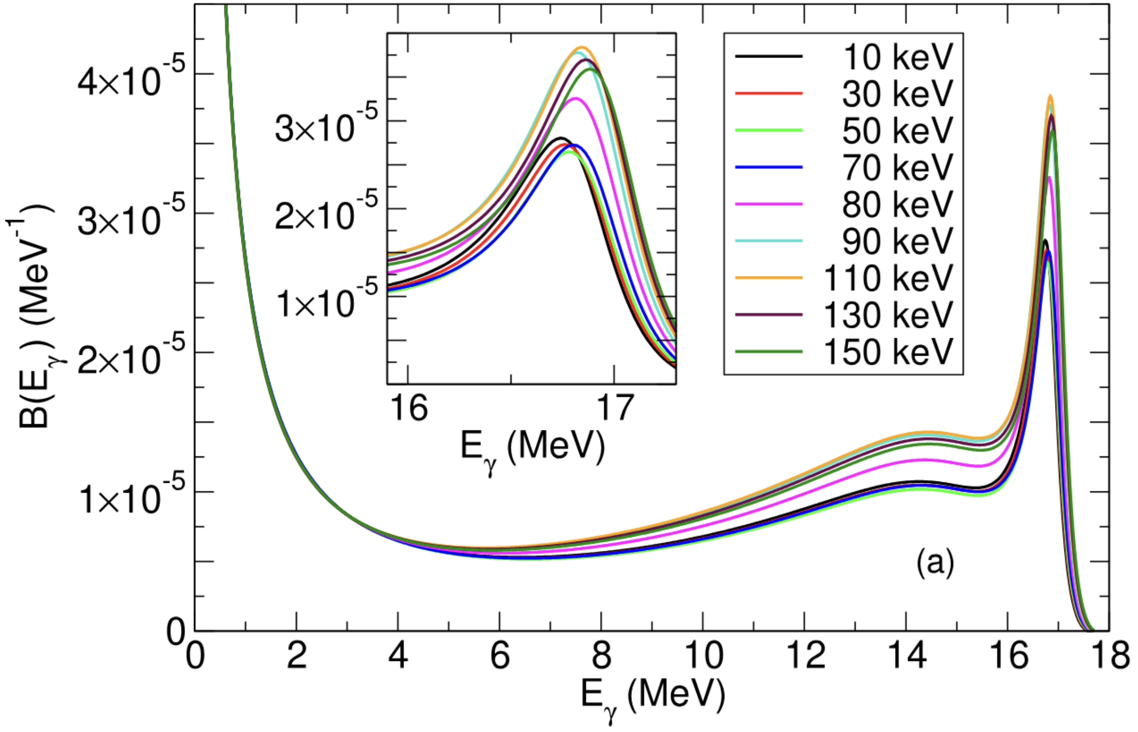
Time-dependent density-functional simulation of fusion of ^{48}Ca + ^{254}Es as potential reaction to create element 119. Movie @220 MeV CM energy.
Stevenson, Frontiers in Physics **10**, 1019285 (2022)



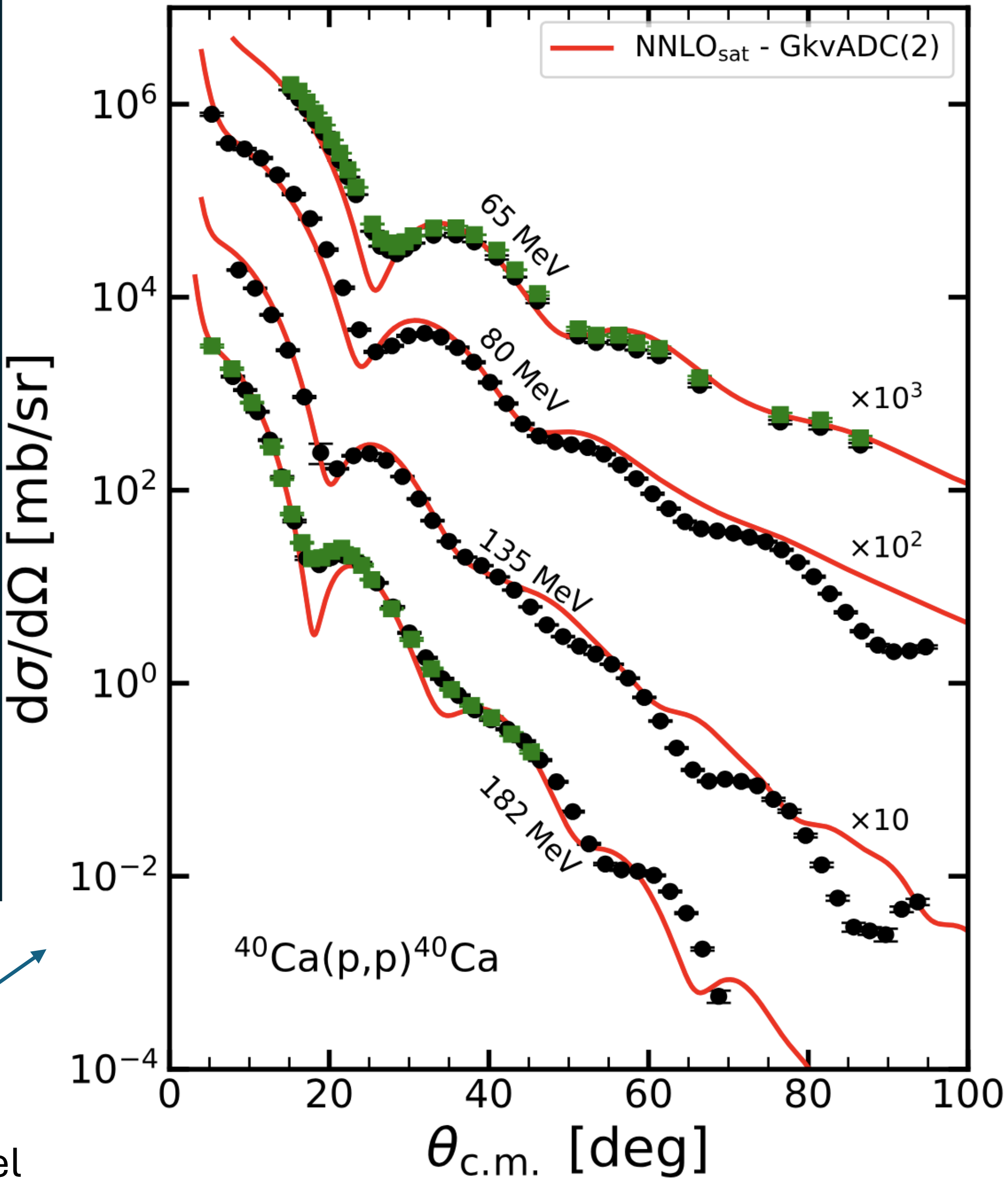


Quantum friction effects in heavy-ion collision between ^{16}O and ^{92}Zr.
Lee, Stevenson, Diaz-Torres, Phys. Lett. B **854**, 138755 (2024)

Nuclear Reactions



Timofeyuk, Bailey and Gilbert, Phys. Rev. C **110**, 014612 (2024)
UKAEA collaboration on D-T fusion
Gamma-branching ratios in D-T fusion as diagnostic



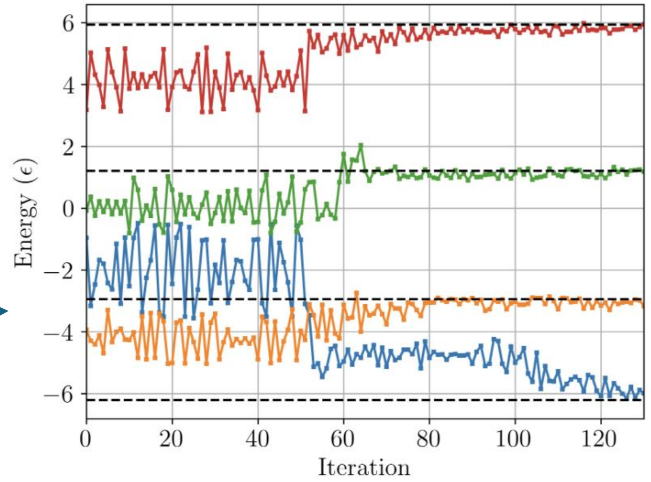
Ab-initio structure and reactions: Vorabbi (Surrey)

Vorabbi *et al.*, Physical Review C **109**, 034613 (2024): Optical potentials derived from ab initio structure model: essentially model free from interaction to scattering data

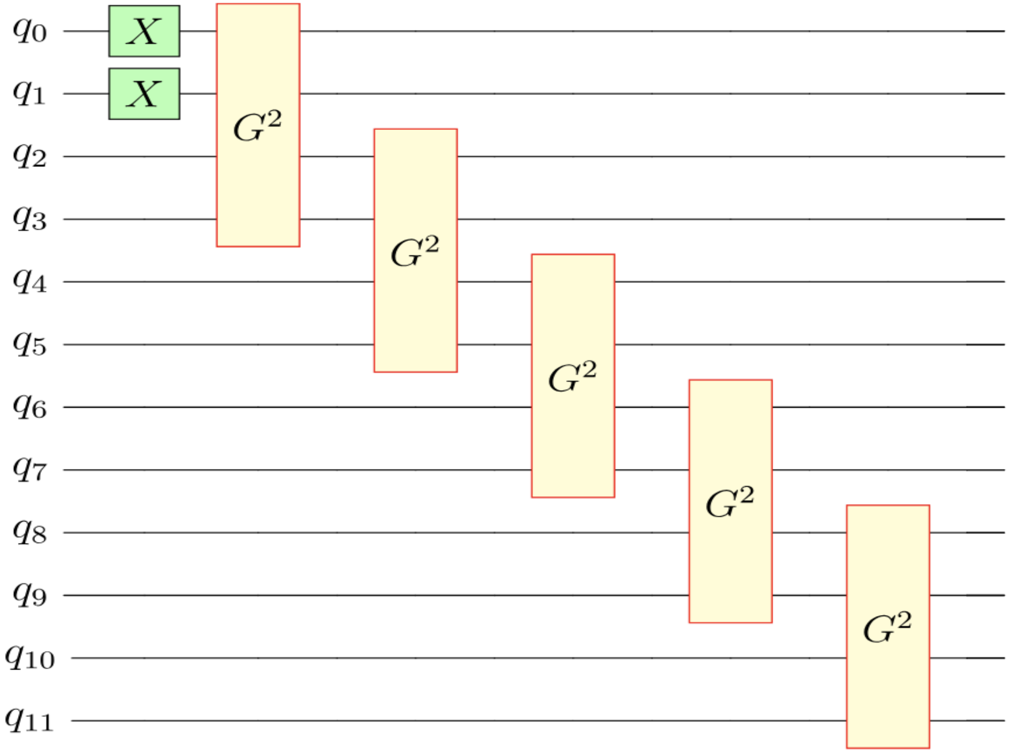
Quantum Computing for Nuclear Theory

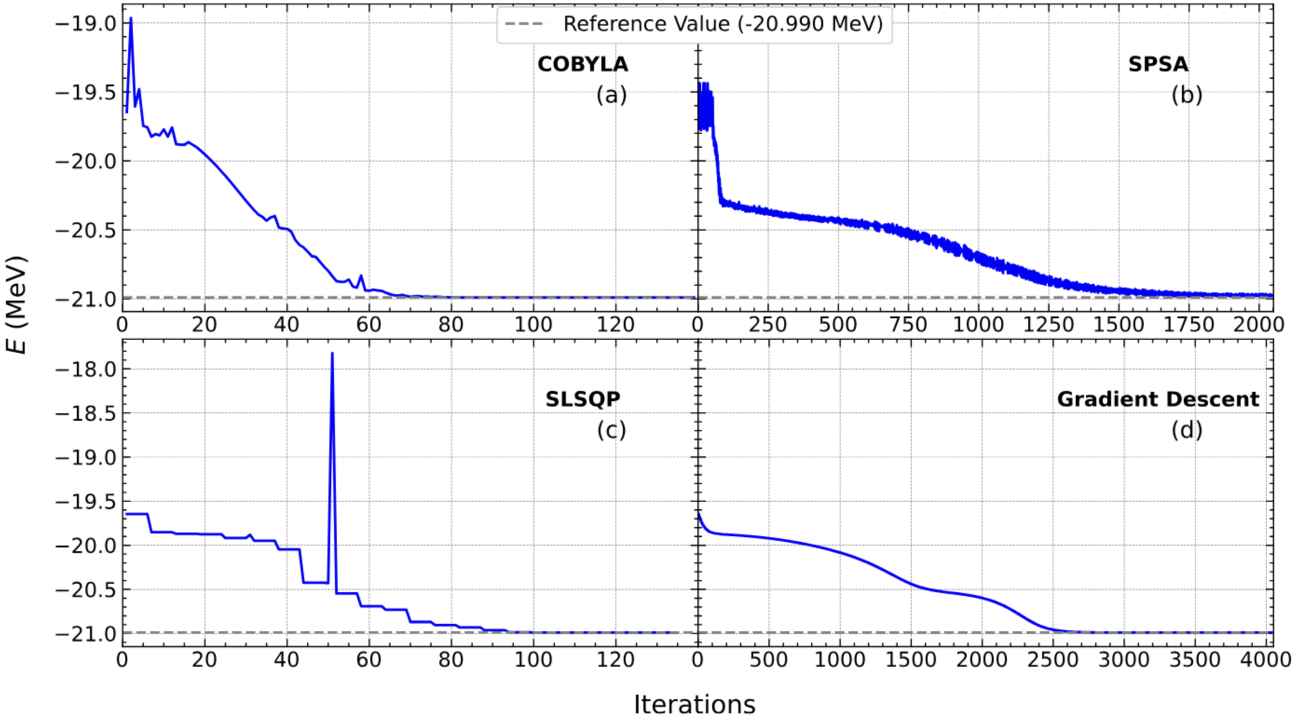
Stevenson (Surrey)

Hobday, Stevenson & Benstead, arXiv 2403.08625
Variational algorithm to target excited states, on IBM_Nairobi quantum computer



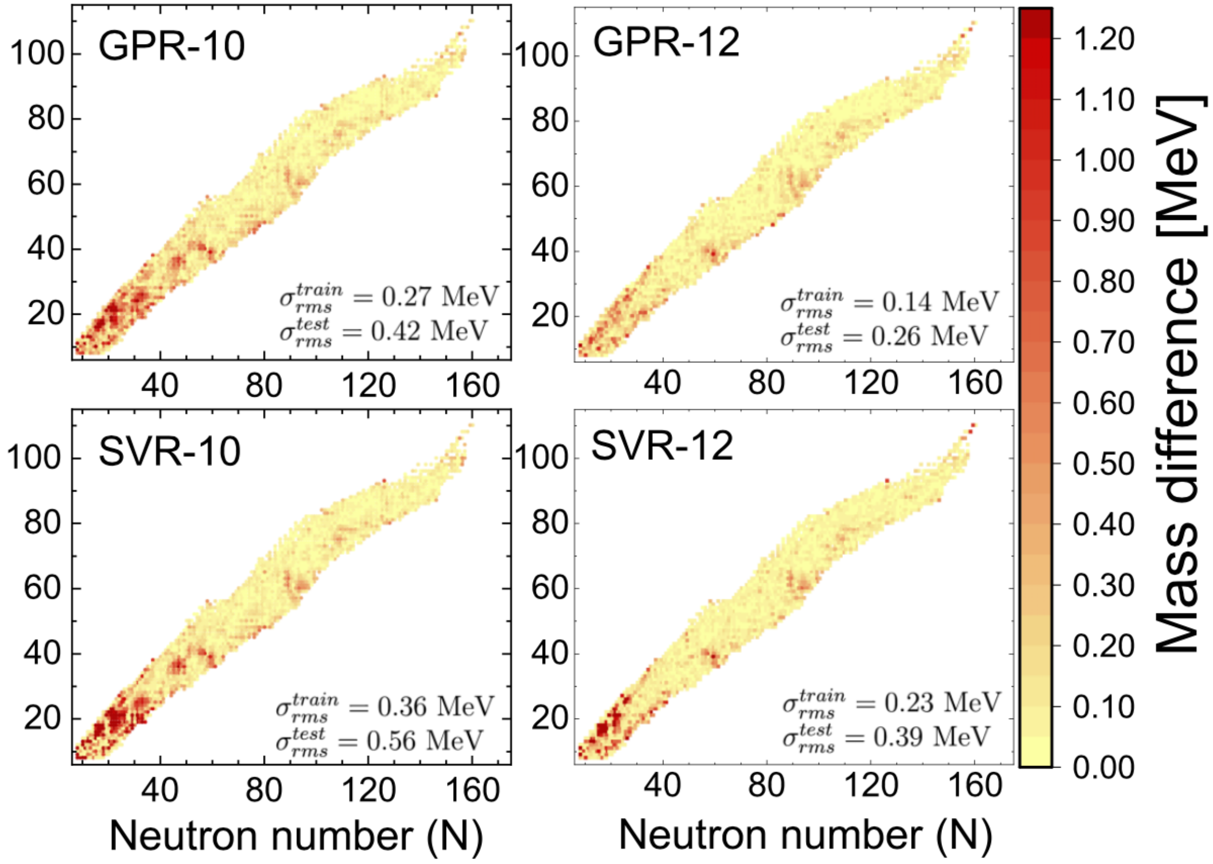
Bhoy and Stevenson, New J Phys **26**, 075001 (2024) quantum circuit to prepare ^{58}Ni state in shell model & variational determination of gate parameters



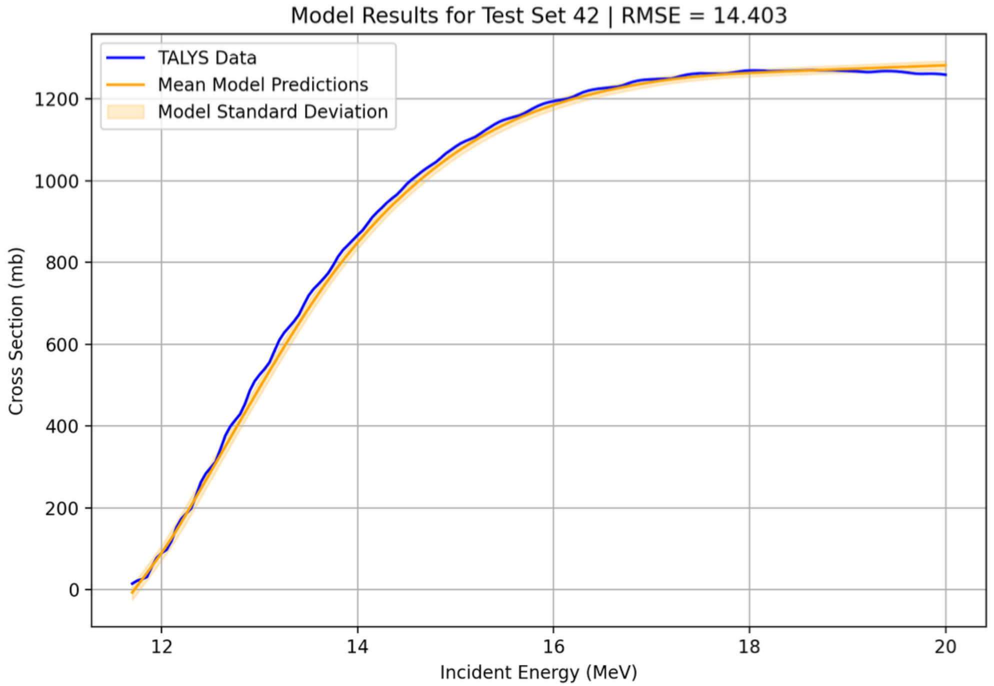


Machine Learning in Nuclear Theory: Yüksel (Surrey), Stevenson (Surrey)

Esra Yüksel, Derya Soydaner and Hüseyin Bahtiyar, [Phys. Rev. C 109, 064322 (2024)]



Sullivan, Stevenson, Benstead & Morgan (Surrey / AWE): TALYS neural-network emulator for (n,2n) reaction (Sullivan thesis work, unpublished):



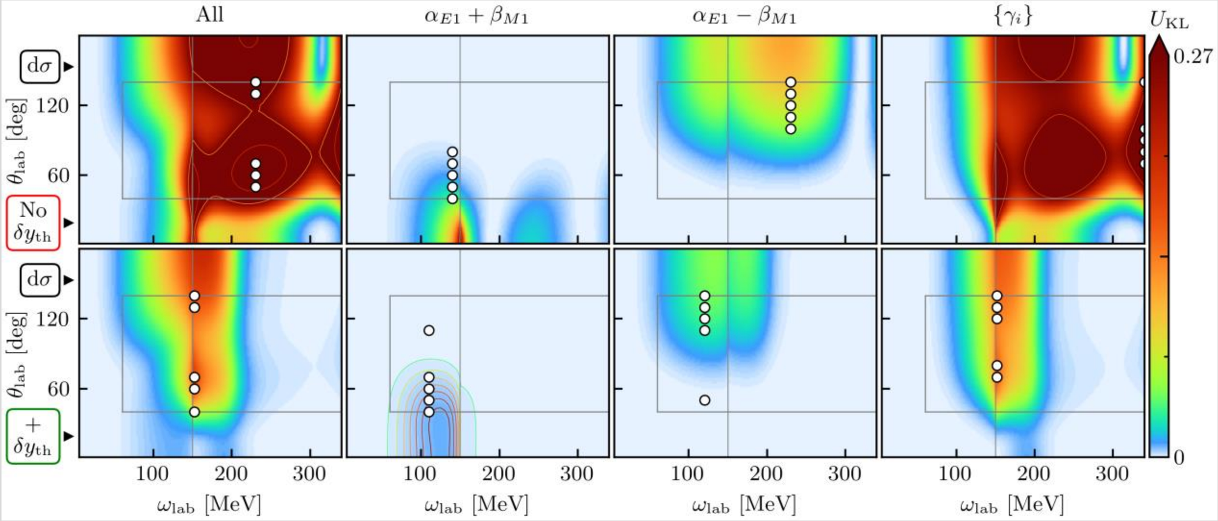
Few-body and hadronic aspects of nuclear physics

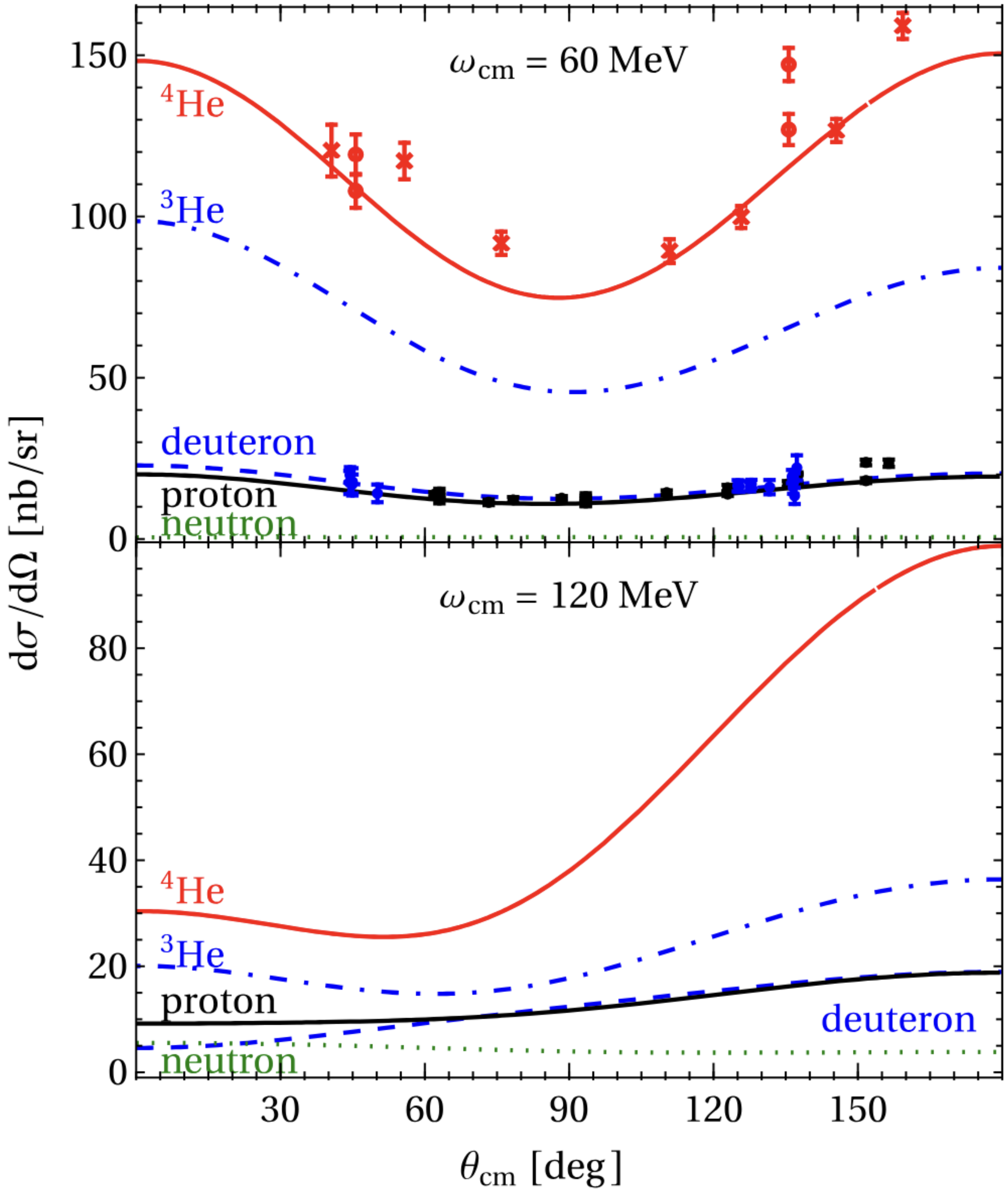
McGovern (Manchester)

First ab initio calculations of elastic Compton scattering from ^{4}He
Uses chiral effective field theory to N^{3}LO

Grießhammer, Liao, McGovern, Nogga, and Phillips
Eur. Phys. J. A 60, 132 (2024)

Bayesian Experimental Design

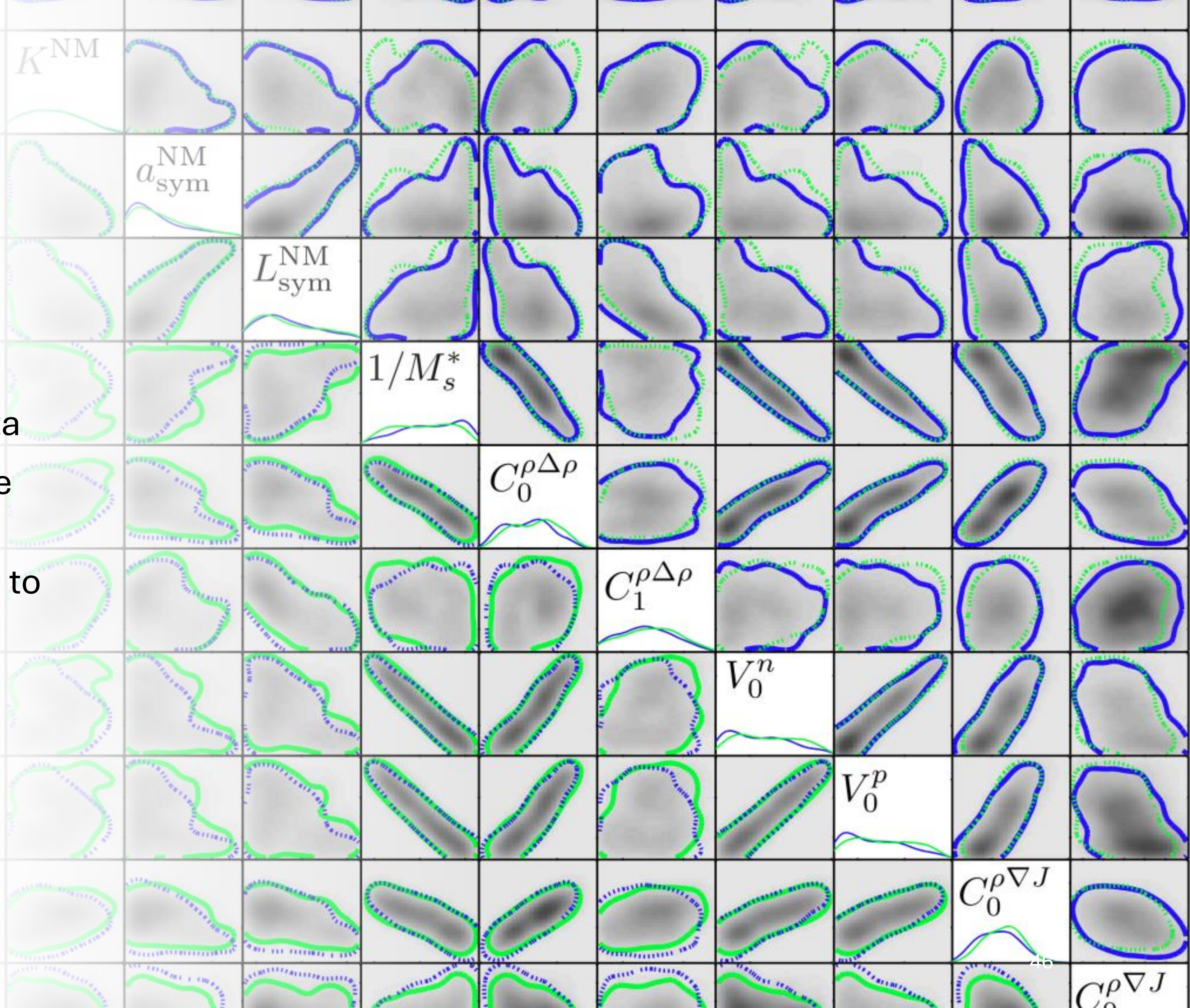




Information and Statistics in Nuclear Experiment and Theory (ISNET)

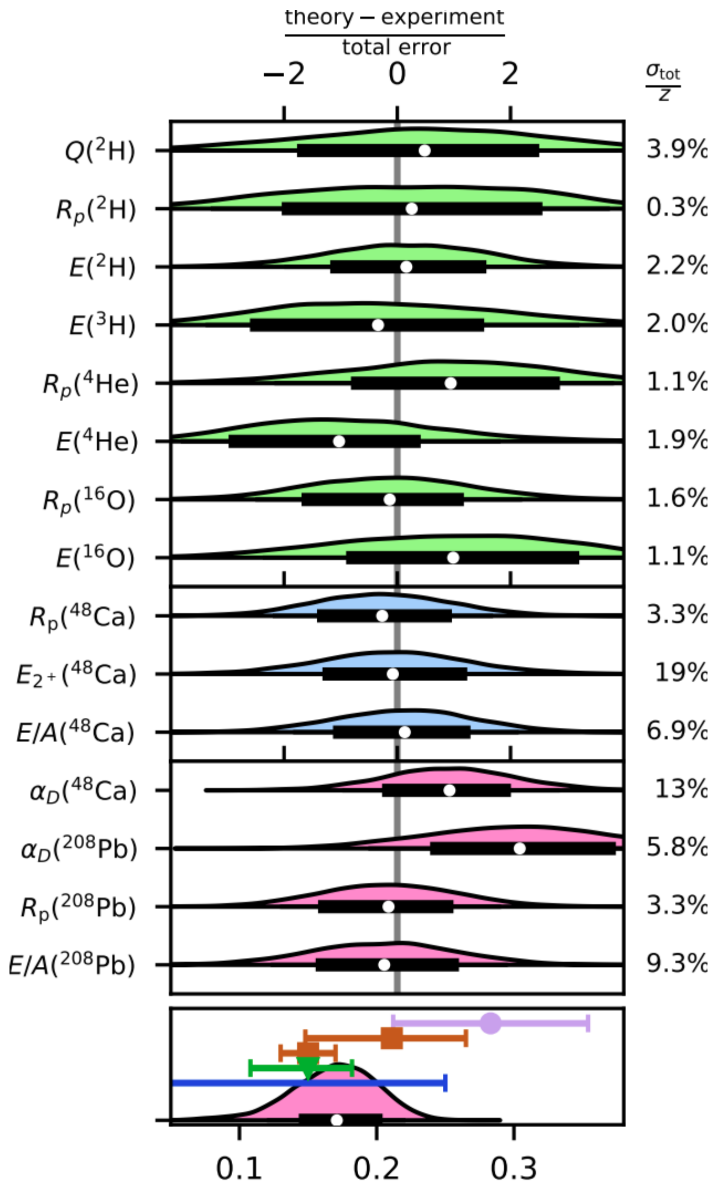
DFT Parameters Estimation using Gaussian Process Emulators

- Large amount of heterogeneous nuclear data
- Location of neutron dripline plus uncertainty
- What mass measurements to carry out



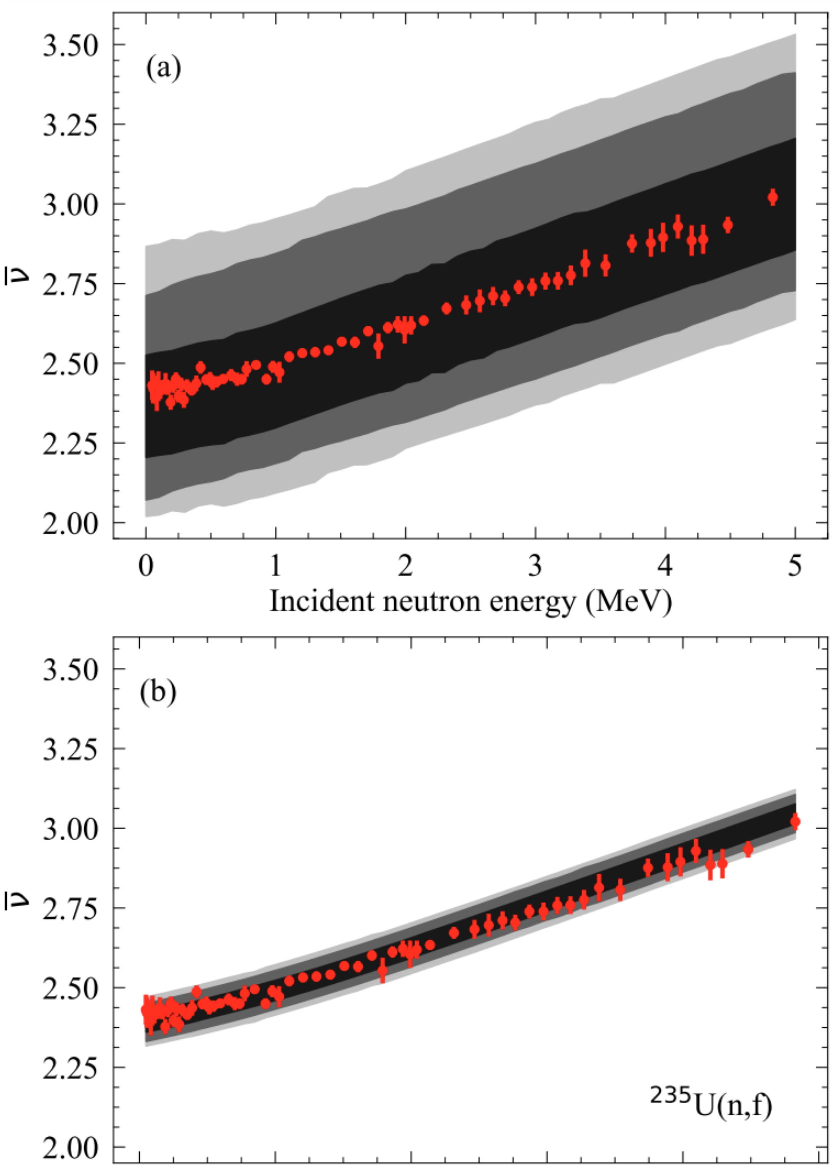
History Matching for Neutron Skin Thickness

- Many (34) interactions with sensitivity to neutron skin
- 10^9 force parameterisations from χEFT
- HM eliminates implausible parameterisations
- Result consistent with other measures

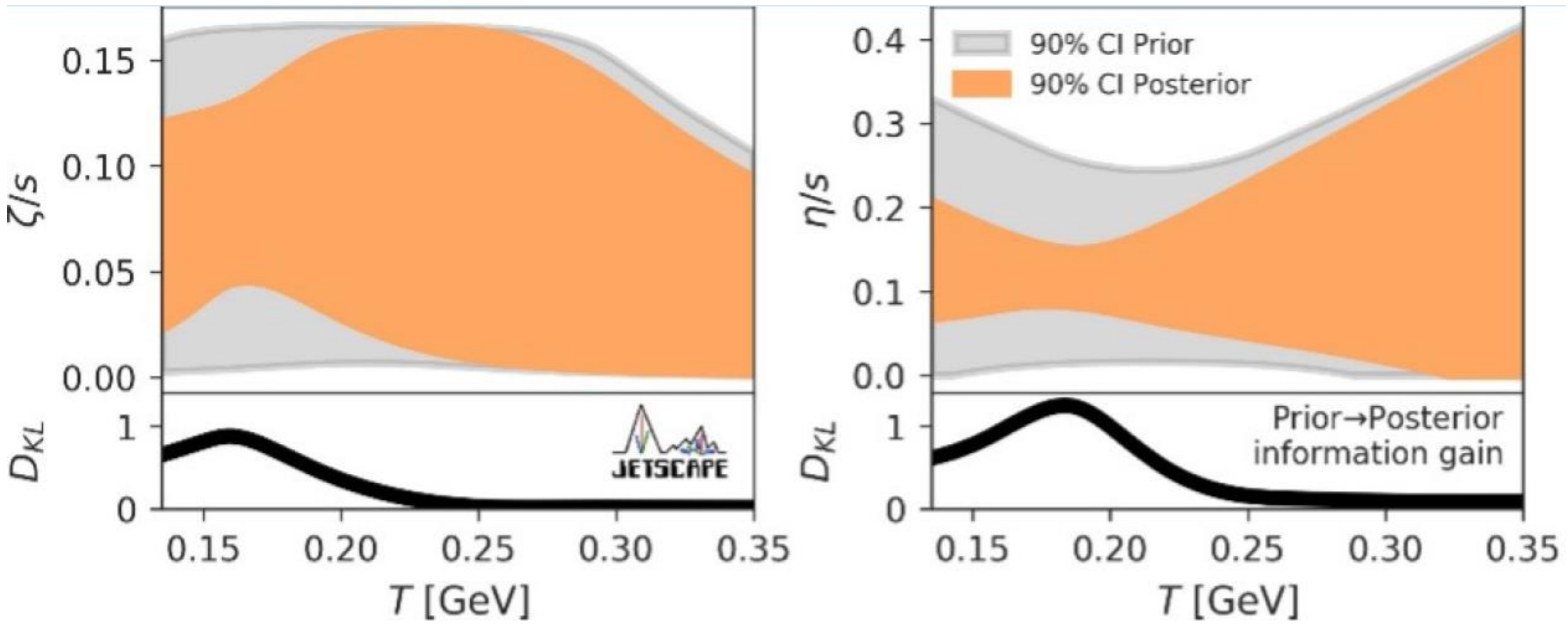


Estimate of Prompt Neutron Emission for Nuclear data Evaluation

- GP emulator of sophisticated fission fragment code
- Uncertainties significantly reduced



Quantitative and Rigorous Inference in Heavy Ion Physics



Summary

- World context: Grand challenges from QCD to superheavies
- UK Nuclear Physics community:
  - Modest size
  - Leadership across several world-leading labs
  - Key roles in several large projects
  - NP Theory active but very small
- Many overlapping topics of interest

Some recent research highlights from UK NP

- Improved cross-sections of the deuterium burning D(p,γ)^{3}He reaction led to BBN estimates of the baryon density at the 1.6 percent level, in excellent agreement with a recent analysis of the cosmic microwave background Nature **587**, 210 (2020).
- Measuring correlations in the momentum space between hadron pairs, produced in ultrarelativistic proton–proton collisions at the CERN Large Hadron Collider (LHC), provided a precise method with which to obtain the missing information on the interaction dynamics between any pair of unstable hadrons Nature 588, 232 (2020).
- The spin polarization of the recoiling neutron in deuterium photodisintegration was measured. The results could be related to the excitation of the d*(2380) hexaquark Phys. Rev. Lett. **124**, 132001 (2020).
- High-precision measurements of states above threshold in ^{34}Ar have constrained the astrophysically important 33Cl(p,gamma)34Ar reaction, decisive in identifying the origins of pre-solar grains Phys. Rev. Lett. **124**, 252702 (2020).
- The first *ab initio* calculations of radii and charge densities for open-shell nuclei beyond Sn have been made, comparing well to experiment and paving the way for *ab initio* studies of exotic charge density distributions at the limit of the present *ab initio* mass domain Phys. Rev. Lett. **125**, 182501 (2020).
- The first a-priori lattice QCD calculation showing the presence of a hadron resonance with an exotic combination of spin, parity and charge conjugation quantum numbers Phys. Rev. D 103, 054502 (2021).
- The first mass measurements of neutron-deficient Yb isotopes at TITAN, TRIUMF, established the existence of the N=82 neutron shell up to the proton drip line. Further, the detection and mass measurement of ^{150}Yb marked the first ever discovery of an isotope at TRIUMF Phys. Rev. Lett. **127**, 112501 (2021)
- The predicted quantum entanglement in linear polarisation for annihilation gamma photons was proposed as a method to quantify and remove the unwanted backgrounds in Positron Emission Tomography (PET) Nature Communications **12**, 2646 (2021).
- Joint mass measurements at TRIUMF and NSCL/FRIB investigate the evolution of the exotic N=32 and 34 neutron shell closures in combination with state of the ab-initio calculations Phys. Rev. Lett. **126**, 042501 (2021).
- The experiment performed at CEBAF utilized the Large Acceptance Spectrometer (CLAS) detector to study the Λp→Λp elastic scattering cross section in the incident Λ momentum range 0.9–2.0 GeV/c Phys. Rev. Lett. **127**, 272302 (2021).
- A first ever measurement of timelike Compton scattering which provides a way to test the universality of the generalized parton distributions has been made with the CLAS12 detector at JLab Phys. Rev. Lett. **127**, 262501 (2021).
- ALICE confirmed the dead-cone effect and important prediction from perturbative QCD. Careful measurements using charmed quarks as partons show that small angle radiative splittings in jet evolution are suppressed for larger parton masses Nature 605, 440 (2022).
- A recent highlight from the nucleon tomography program at JLab includes a first experimental extraction of all four helicity-conserving Compton form factors (CFFs) of the nucleon as a function of Bjorken x, while systematically including helicity flip amplitudes with extremely high precision. Phys. Rev. Lett.**128**, 252002 (2022).
- From the nucleon tomography program at JLab, a first experimental extraction of all four helicity-conserving Compton form factors (CFFs) of the nucleon as a function of Bjorken x with extremely high precision has been performed Phys Rev. Lett. **128**, 252002 (2022), and a first CLAS12 measurement of deeply virtual Compton scattering beam-spin asymmetries in the extended valence region Phys. Rev. Lett. **130**, 211902 (2023).
- Measurements performed at the Triangle Universities Nuclear Laboratory were interpreted in the chiral effective field theory framework to extract the electromagnetic dipole polarizabilities of the proton Phys. Rev. Lett. **128**, 132502 (2022).
- A resonance-like structure near threshold in the four-neutron system that is consistent with a quasi-bound tetraneutron state existing for a very short time was observed Nature **606**, 678 (2022).
- First mass measurements of neutron-rich Cr isotopes established the summit of the N=40 island of inversion Phys. Lett. B **833**, 137288 (2022)
- An abrupt change in the nuclear dipole moment at N = 82 was observed. Together with the accompanying theoretical findings, it led to an understanding of how seemingly simple single-particle phenomena naturally emerge from complex interactions among protons and neutrons Nature **607**, 260 (2022).
- Recent results from two-nucleon knockout reactions in inclusive elastic electron scattering from hydrogen-3 and helium-3 mirror nuclei have yielded new insights on the pairing up of nucleons inside the nucleus Nature **609**, 41 (2022).
- Simultaneous γ-ray and electron spectroscopy demonstrated a step-up in experimental sensitivity and paves the way for systematic studies of electric monopole transitions in this region Communications Physics **5**, 213 (2022).
- Nucleon drip lines were determined using several relativistic energy density functionals with different underlying interactions, demonstrating considerable alterations of the neutron drip line with temperature increase, especially near the magic numbers Nature Comm. 14 4834 (2023)
- A new technique for determining fission barriers was demonstrated which will open the way for the study of fission properties with short-lived nuclear species Phys. Rev. Lett. **130**, 202501 (2023).
- Direct mass measurements of neutron-deficient nuclides at GSI closing on ^{100}Sn Phys. Lett. B **839**, 137833 (2023)
- ALICE measured the hypertriton $_{\Lambda}^{3}$H lifetime and Λ separation energy solving a puzzle as their values previously seemed inconsistent with models of the particle Phys. Rev. Lett. 131, 102302 (2023).
- Measurements of the vibronic structure of radium monofluoride molecules were reported, which demonstrated an improvement in resolution of more than two orders of magnitude compared to the state of the art Nature Physics **20**, 202 (2024).
- The calculations using the ^{16}O + ^{92}Zr collision showed that the inclusion of nuclear friction effects increased the fusion probability significantly, improving the agreement between the theoretical and experimental fusion barrier distributions Phys. Lett. **B 854**, 138755 (2024).
- First measurement of neutron capture on radioactive ^{204}Tl leads to reduced uncertainty in predicted ^{204}Pb abundance, which is in agreement with solar system observations Phys. Rev. Lett. **133**, 052702 (2024)
- The role of the underlying single-particle structure for the Pygmy Dipole Resonance was established Phys. Rev. Lett. **125**, 102503 (2020)