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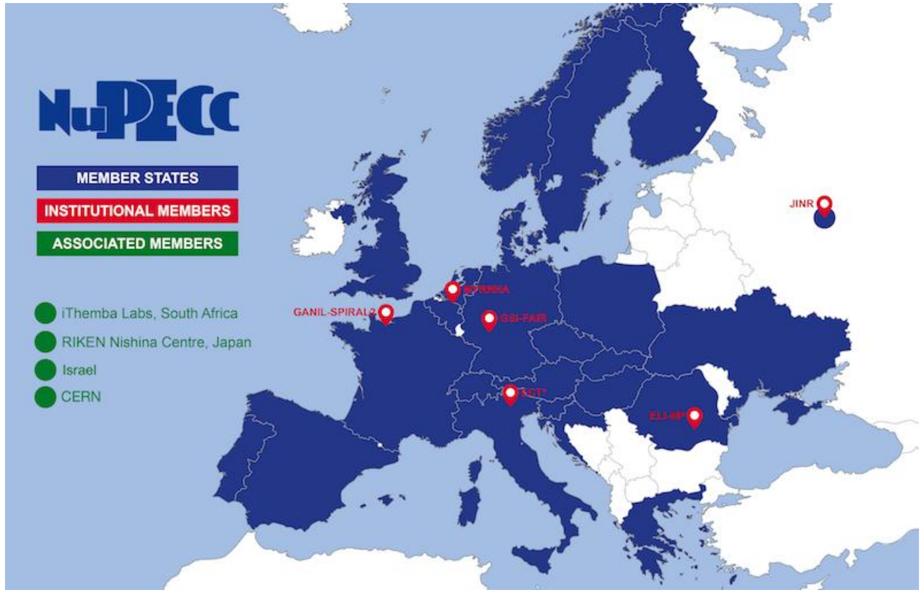
Nuclear masses and astrophysics in the NuPECC Long Range Plan 2024

Anu Kankainen

What is a NuPECC Long Range Plan (LRP)?

- NuPECC (https://nupecc.org)
  = Nuclear Physics European Collaboration Committee
- Expert committee of the European Science Foundation
- Promotes nuclear physics and its applications
- Develops **strategy** for European collaboration
  in nuclear science→ **LRPs are an important part of this**
- Recent NuPECC LRPs published in 2010, 2017 and 2024
- Compare: 2023 Nuclear Science Advisory Committee (NSAC) Long Range Plan for Nuclear Science in the U.S.
  - https://nuclearsciencefuture.org/



NuPECC Long Range Plan 2024

- Collaborative effort involving nuclear physicists from all around Europe
- Anybody could send ideas to be taken into account
- 10 Thematical Working Groups (TWGs)
- TWG 4 on Nuclear Astrophysics
  - Around 20 members
  - Chairs: Jordi Jose and Anu Kankainen
- Many other TWGs with links to nuclear masses, e.g.:
  - TWG 3: Nuclear structure and reaction dynamics
  - TWG 5: Symmetries and fundamental interactions
  - TWG 6: Research infrastructures
  - TWG 8: Nuclear physics tools

Available at: arXiv:2503.15575 [nucl-ex] and https://nupecc.org/lrp2024/Documents/nupecc_lrp2024_web.pdf

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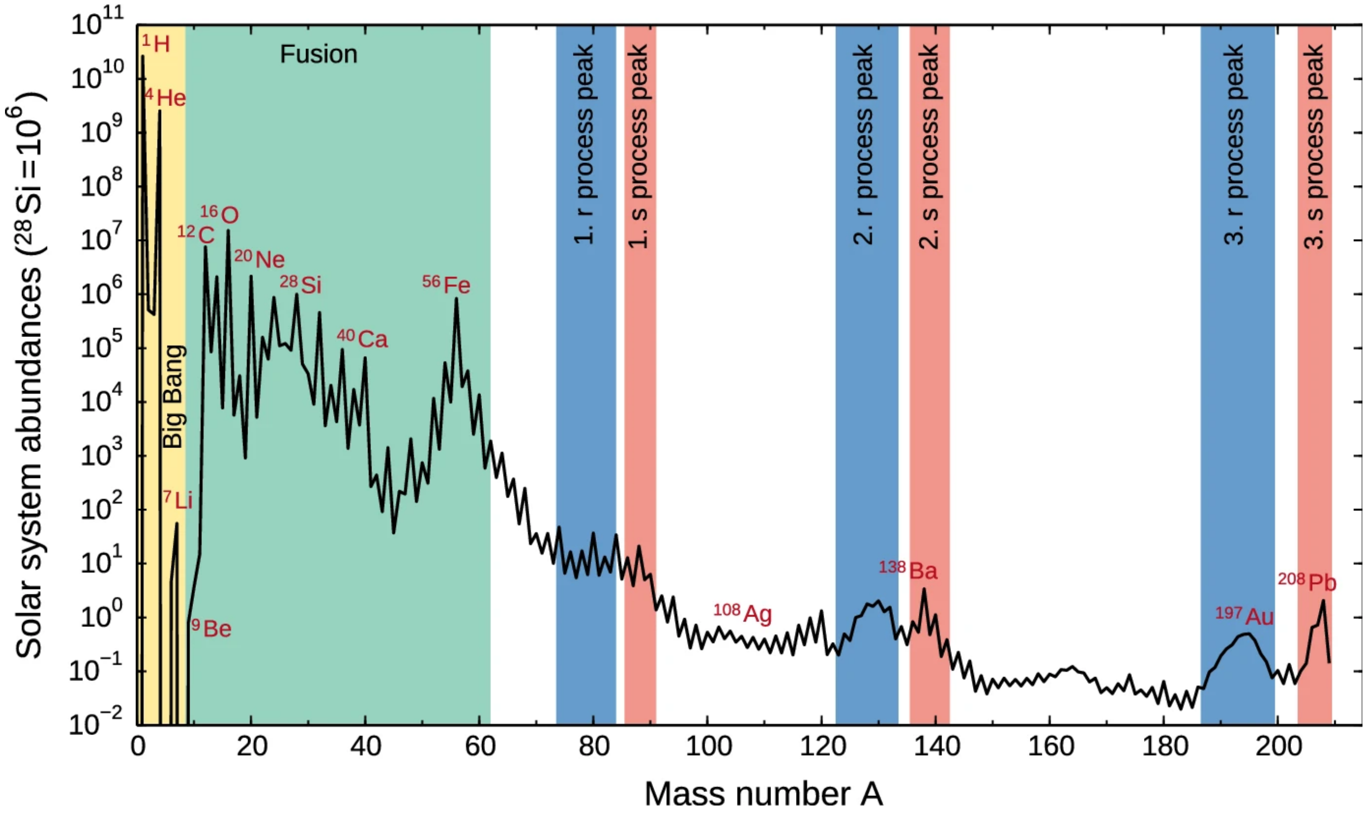
Nuclear astrophysics in the NuPECC Long Range Plan 2024

Where and how are the chemical elements formed in the Universe?

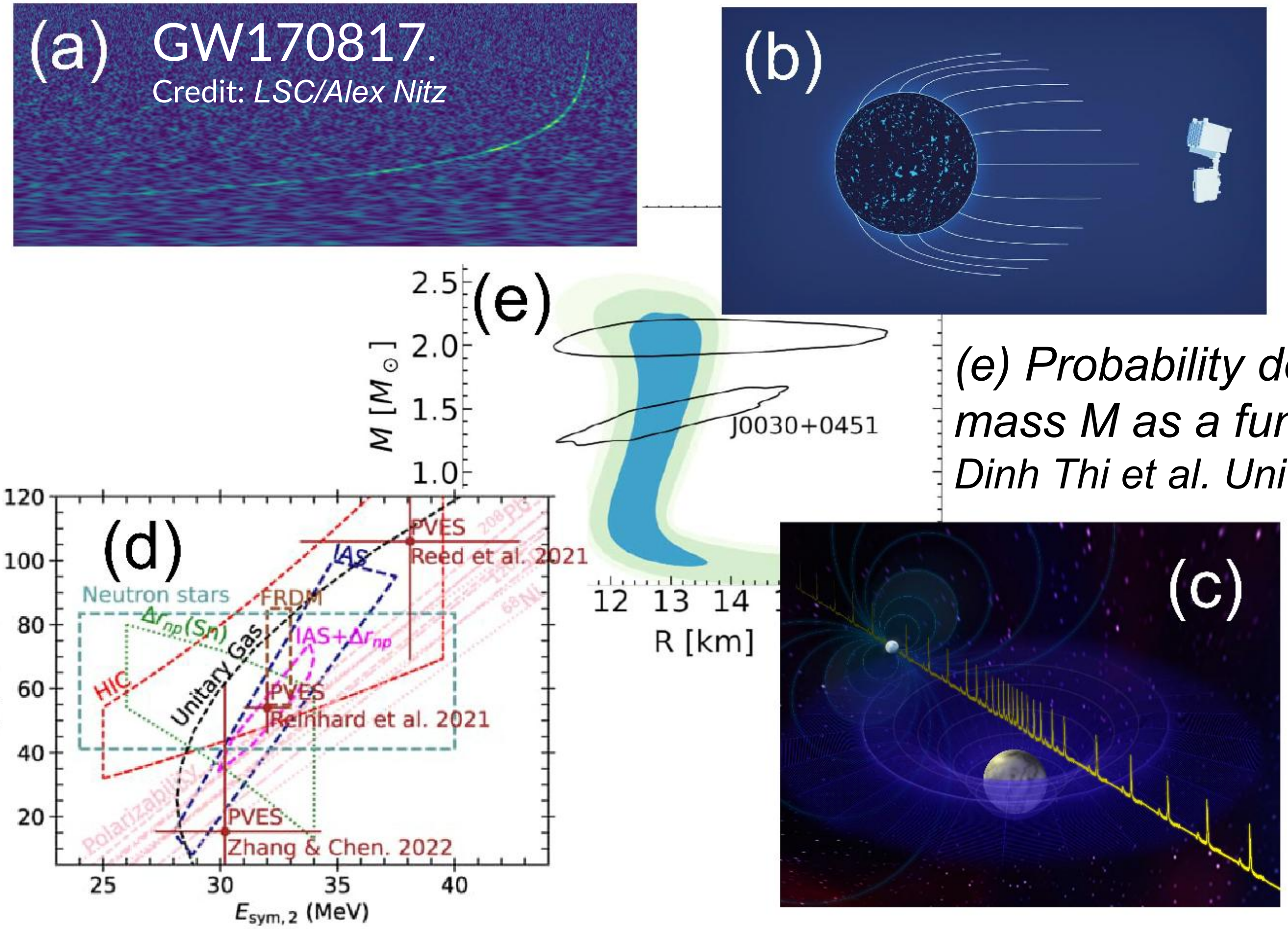


Arcones & Thielemann, Astron. Astrophys. Rev. 31, 1 (2023)

What is the nature of matter in the extreme conditions of compact astrophysical objects such as mergers or pulsars?

(a) Gravitational wave signal from GW170817. Credit: LSC/Alex Nitz.

(b) *NICER: x-ray light from neutron-star surfaces.*
Credit: NASA's Goddard Space Flight Center Conceptual Image Lab.



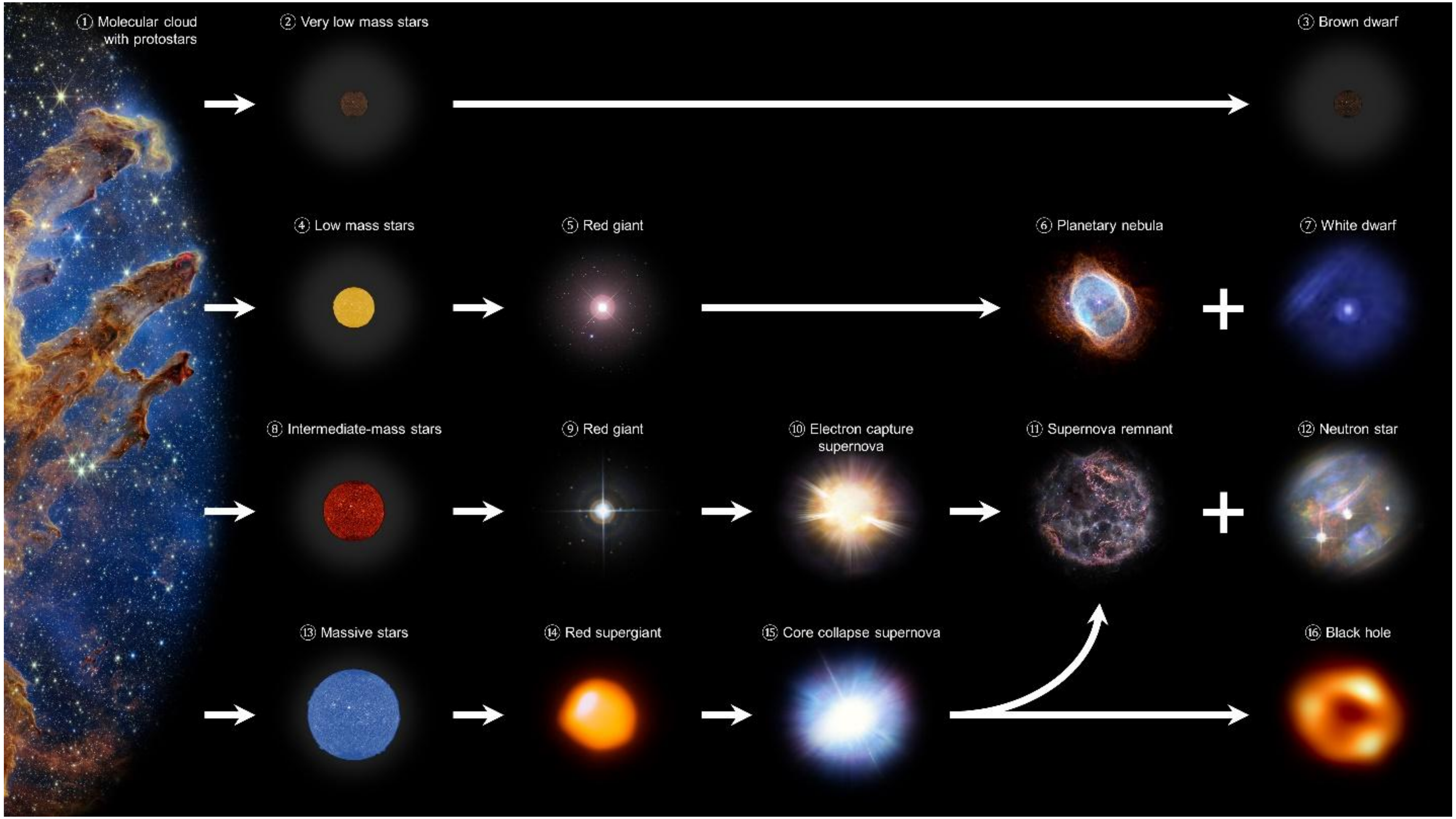
(e) Probability density plots of NS mass M as a function of radius R, Dinh Thi et al. Universe (2021).

(d) Nuclear physics experiments, theory and observations. Carlson et al. PRC 107, 035805 (2023)

(c) Artist impression of a pulse from a massive neutron star.
Credit: BSaxton, NRAO/AUI/NSF

Credit: NuPECC Long Range Plan 2024

What are the nuclear processes driving the evolution of stars ?
What is their impact on the evolution of galaxies and Universe?

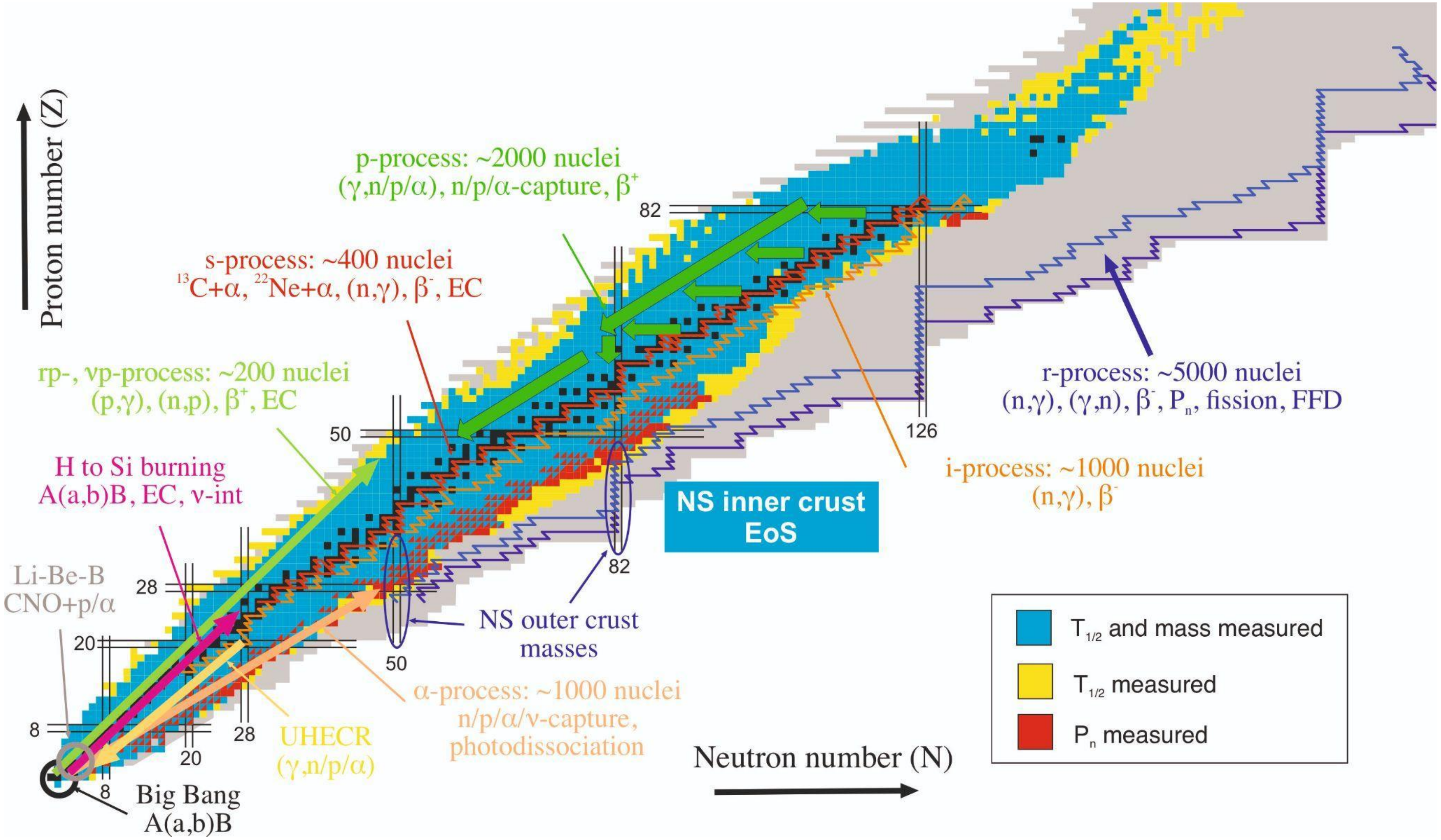


Binary systems:

Type Ia supernovae
Novae
Type I x-ray bursts
Neutron-star mergers

Credit: NuPECC Long Range Plan 2024

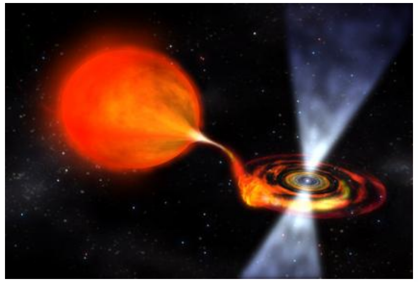
Nuclear astrophysics needs nuclear data!



Credit: NuPECC Long Range Plan 2024

Masses needed in particular for processes proceeding (at least partially) through the Terra Incognita

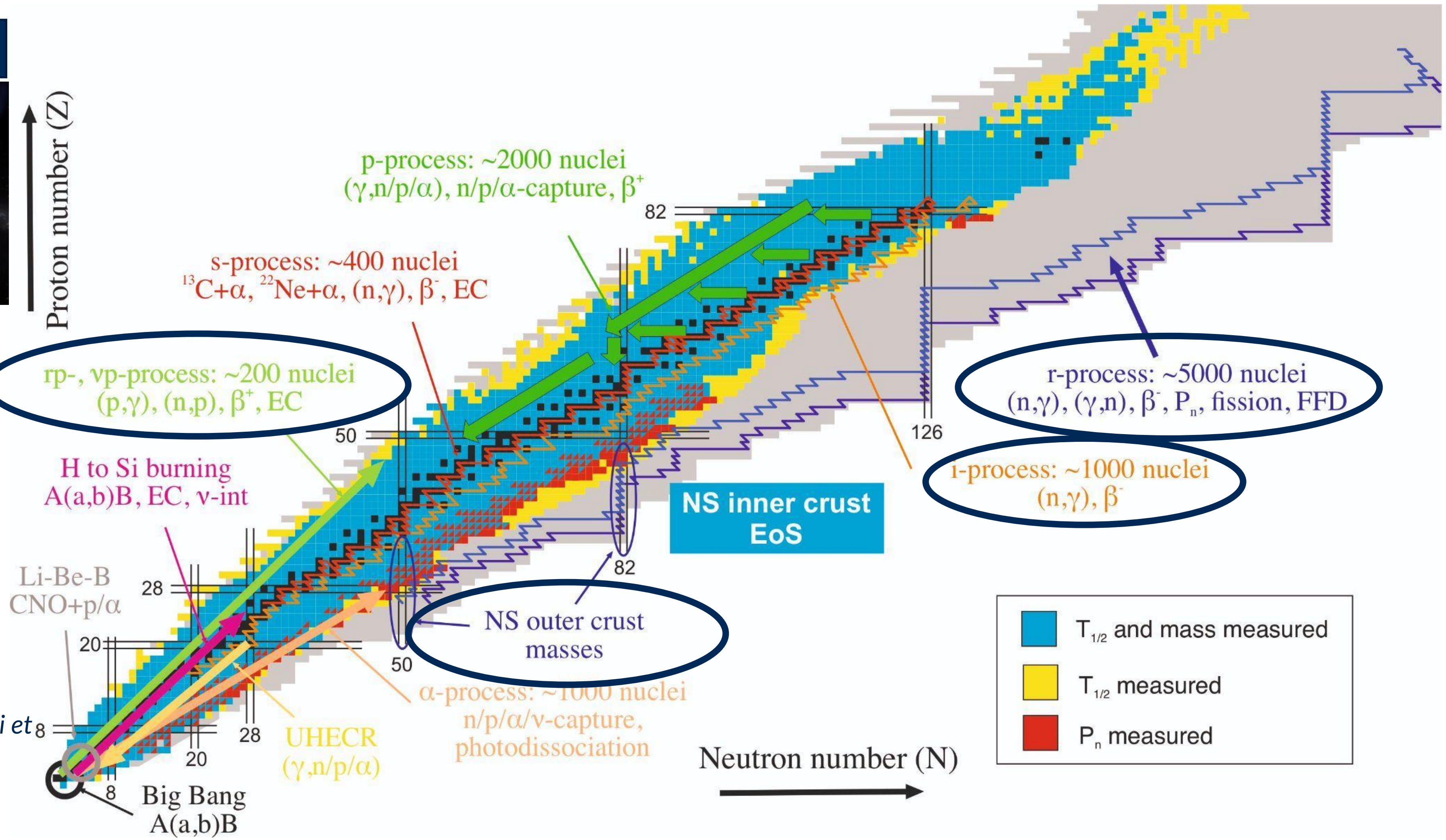
Type I x-ray bursts



Credit: NASA/Dana Berry

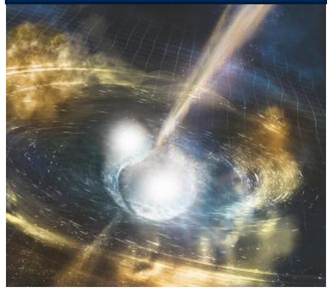
Novae

Credit: X-ray: NASA/CXC/RIKEN/D.Takei et al; Optical: NASA/STScI; Radio: NRAO/VLA



Credit: NuPECC Long Range Plan 2024

Neutron-star mergers



Credit: NSF/LIGO/Sonoma State University/A. Simonnet

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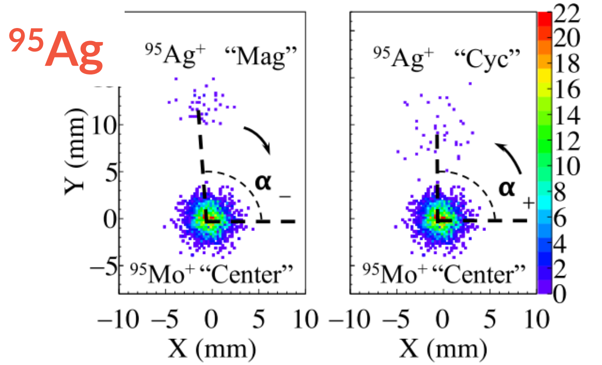
Masses of N~Z nuclei for the rapid proton capture (rp) and νp processes

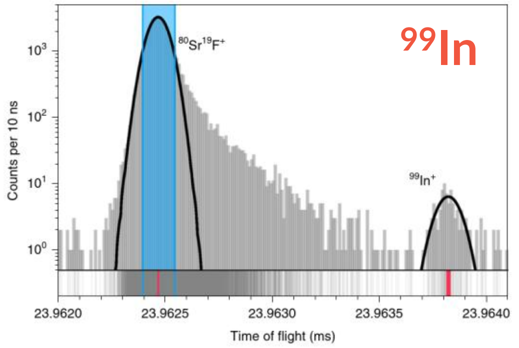
Lots of progress during recent years

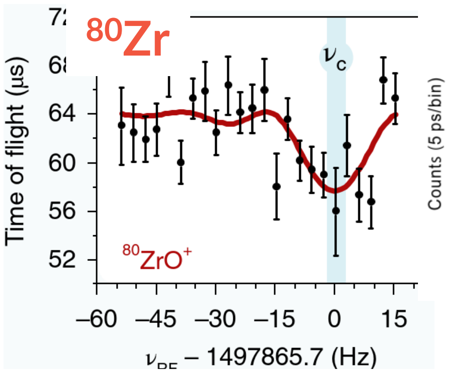
- Schatz & Ong ApJ 844 (2017) 139 sensitivity study identified key nuclei:
  - Light curves: ^{27}P, ^{61}Ga, and ^{65}As
  - Ashes: ^{80}Zr, ^{81}Zr, and ^{82}Nb
  - Extreme H/He burst: ^{58}Zn, ^{61}Ga, ^{62}Ge, ^{65}As, ^{66}Se, ^{78,79}Y, ^{79,80,81,82}Zr, ^{82,83}Nb, ^{86}Tc, ^{91}Rh, ^{95}Ag, ^{98}Cd, ^{99,100,101}In
- Most of these already measured recently
- Variety of methods & facilities used
- BUT: isomers and their role ?

Ge et al.
PRL 133 (2024) 132503

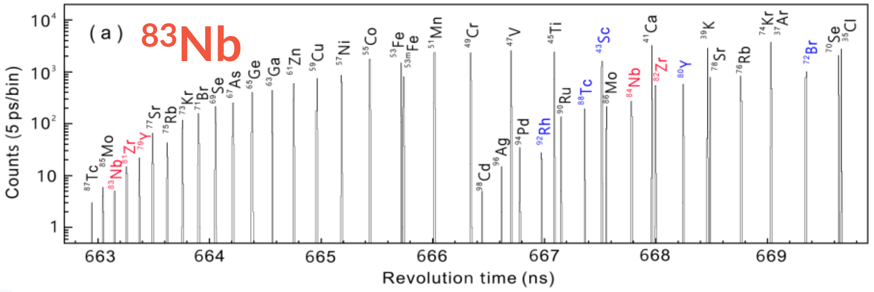


Mougeot et al.,
Nature Phys. 17 (2021) 1099





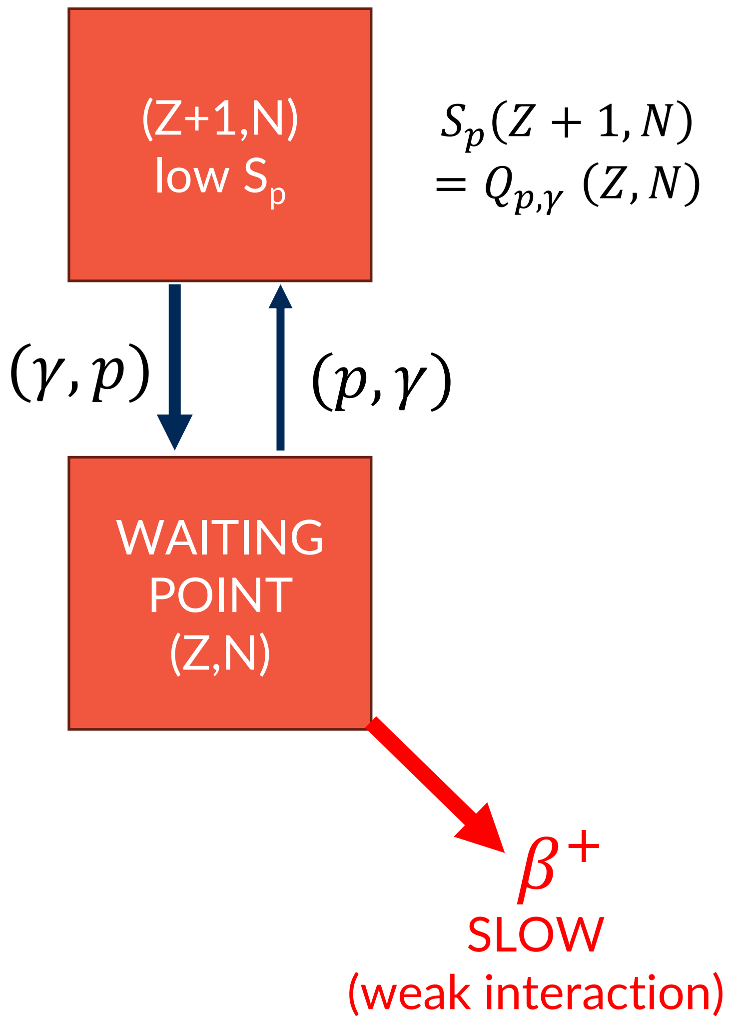
Hamaker et al,
Nature Phys. 17 (2021) 1408



Xing et al. Phys. Lett. B 781 (2018) 358

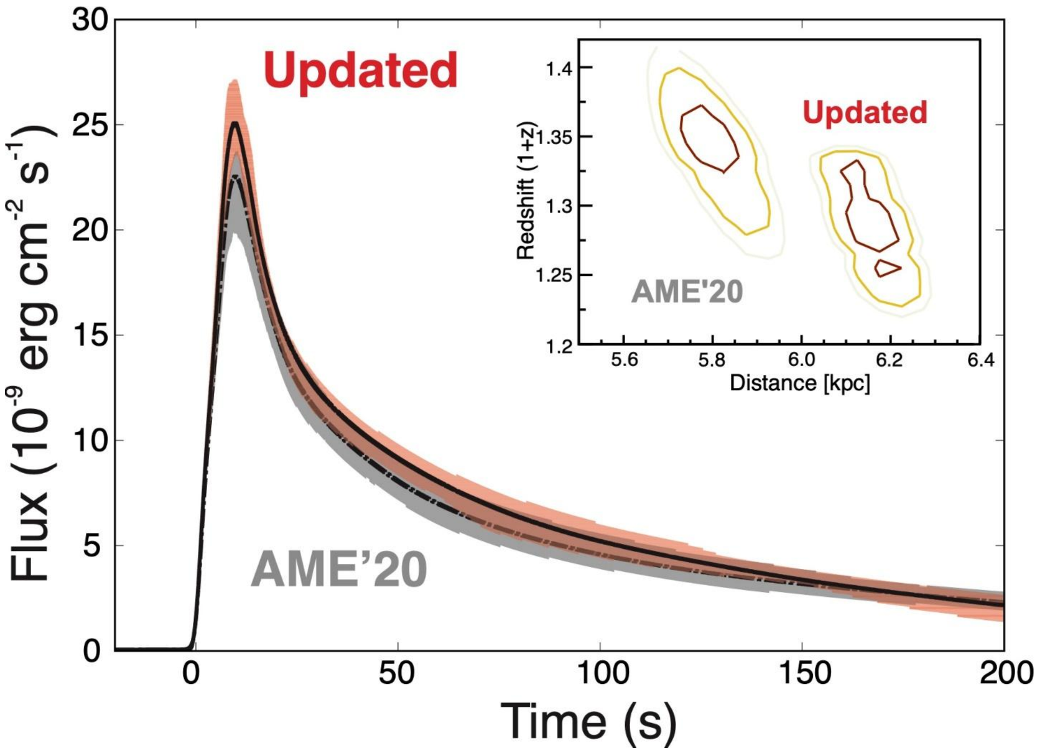
rp-process waiting points

- At waiting point, proton-capture Q-value $Q_{p,\gamma}$ close to zero or negative
  → must wait for much slower β^+ decay
  → accumulation of matter
  → slowing the process towards heavier elements
- Well-known examples: ^{56}Ni and ^{64}Ge



Example from LRP2024: ^{64}Ge waiting point

- Mass measurements of ^{63}Ge, ^{64,65}As and ^{66,67}Se with CSRe storage ring
- Impact on the x-ray burst light curve
- Comparison of the modelled light curves and the observational data:
  - distance to the x-ray burster GS 1826–24 needs to be increased by about 6.5% to match astronomical observations
- Next?
  - ^{68}Se and ^{72}Kr the next most uncertain waiting points for which mass measurements are needed



Credit: NuPECC LRP 2024
Zhou, Wang et al., Nature Phys.19 (2023) 1091

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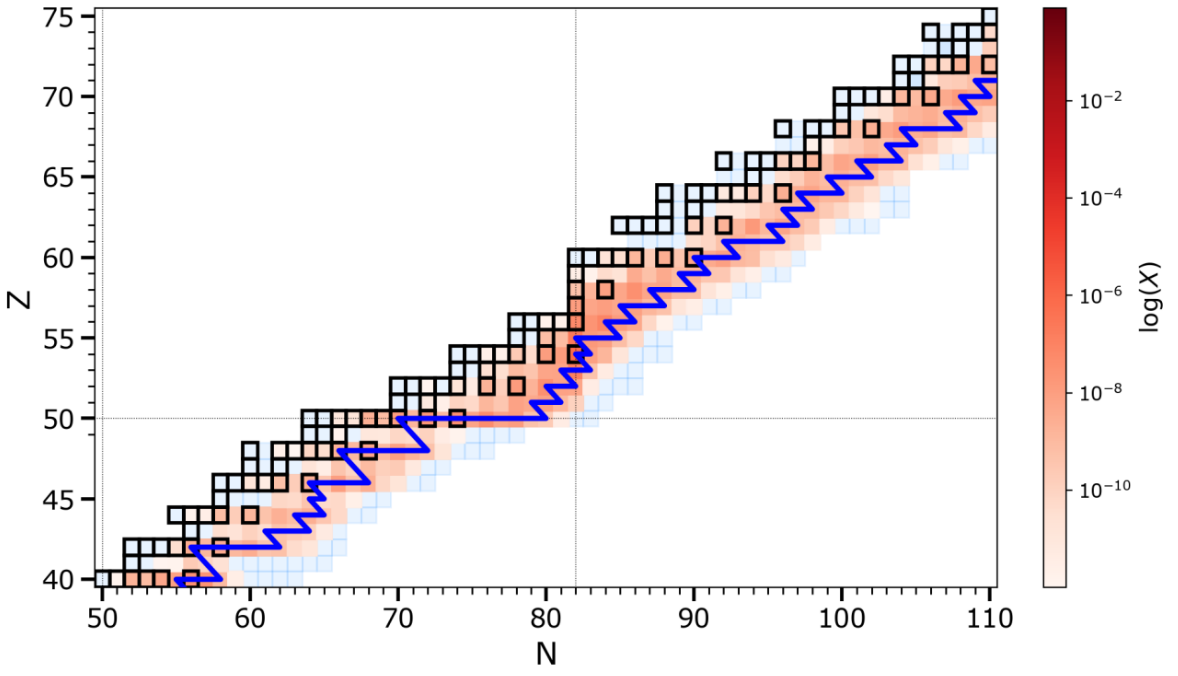
Intermediate neutron-capture process (i process)

Intermediate neutron-capture process

- Intermediate = between s and r process paths
- Proposed by Cowan and Rose, ApJ 212 (1977) 149
- Post-AGB star Sakurai's object:
  extreme enhancements in Sr, Y and Zr
  Asplund et al., A&A 343 (1999) 507
- Nuclei involved in the i-process more accessible experimentally than those in the r-process.
  - Typically 6-10 neutrons away from stable species
- Most of the masses have been/can be measured with existing and new radioactive beam facilities



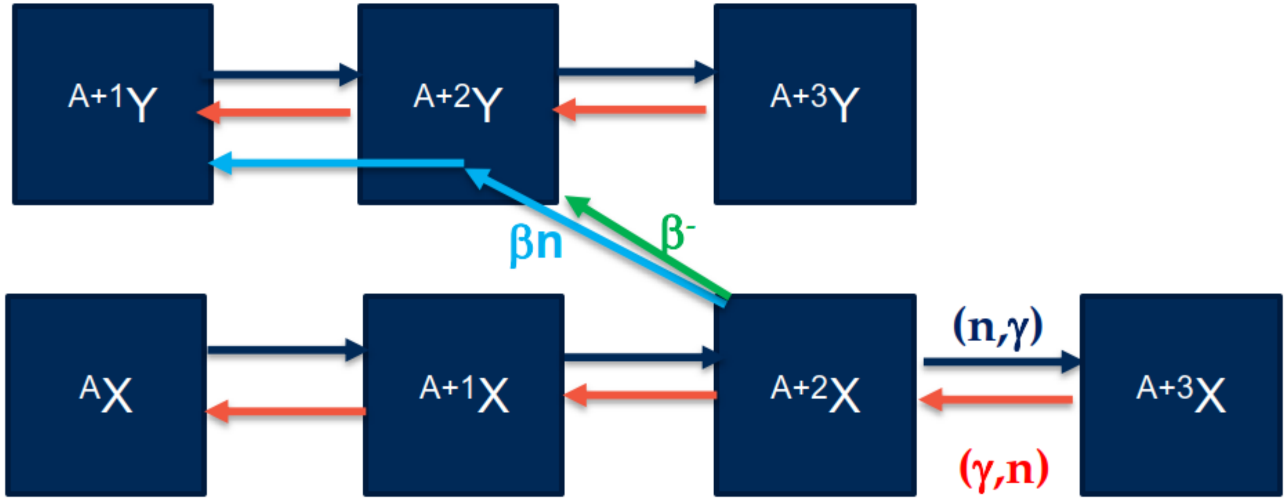
S. Goriely et al. A&A 654, A129 (2021)

Rapid neutron-capture process (r process)

r process

Classic r-process assuming (n,γ)-(γ,n) equilibrium:

- Isotopic abundances (waiting points) set by S_n (masses)
- Elemental abundances set by beta-decay half-lives
- Smoothening → beta-delayed neutron decays



In reality:
equilibrium not always valid and all rates matter
Masses needed to calculate, e.g. the $(n,\gamma),(\gamma,n),\ldots$ reaction rates and other properties if not exp. known

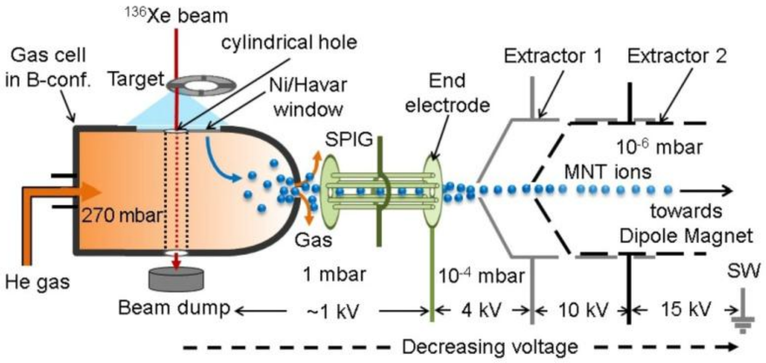
- Masses (most fundamental!)
- Beta-decay $T_{1/2}$ and P_n values

Other properties:

- (n,γ) rates
- Fission for recycling

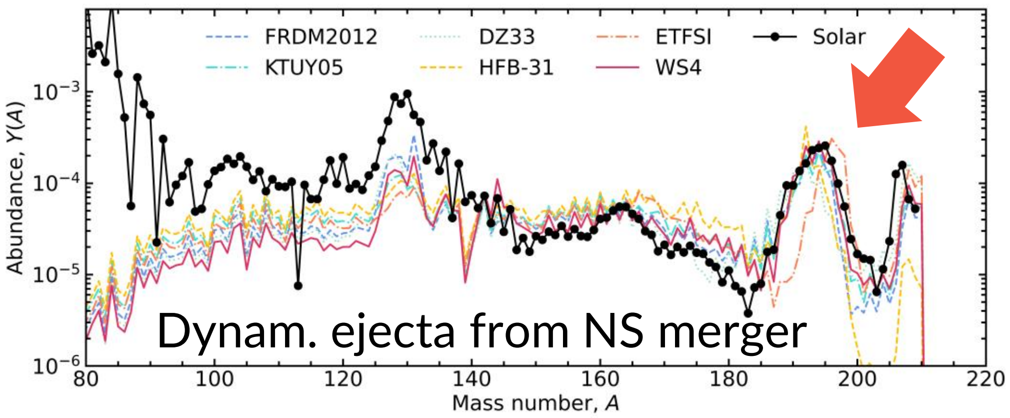
LRP: third abundance peak of the r process highlighted

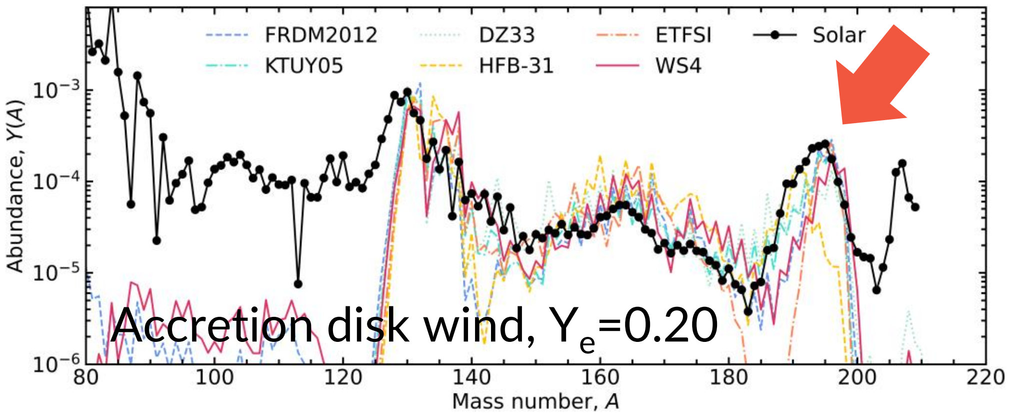
- Third r-process abundance peak at around A=195 still includes large uncertainties due to lack of experimental data, in particular masses
- Need experimental facilities and methods to study this region close to N=126 shell closure
- Traditionally produced via fragmentation
- Multinucleon-transfer reactions provide an alternative way to produce heavy exotic nuclei



IGISOL
MNT gas cell

Kumar et al., Phys. Lett. B 853 (2024) 138654





Clark et al., Eur. Phys. J. A 59 (2023) 204

Mass models essential for the r process

- Many r-process nuclei will remain inaccessible
- Mass models needed but typical root-mean-square (rms) deviations ~600-800 keV → **new experimental values important to benchmark the models**
- Ab-initio methods not yet sophisticated enough
- Microscopic phenomenological models grounded in the density functional theory (DFT) promising, could replace the phenomenological inputs
- DFT approaches also useful for the Equation of State

Prospects for the future:

Impressive progress expected with the development of beyond-mean-field techniques

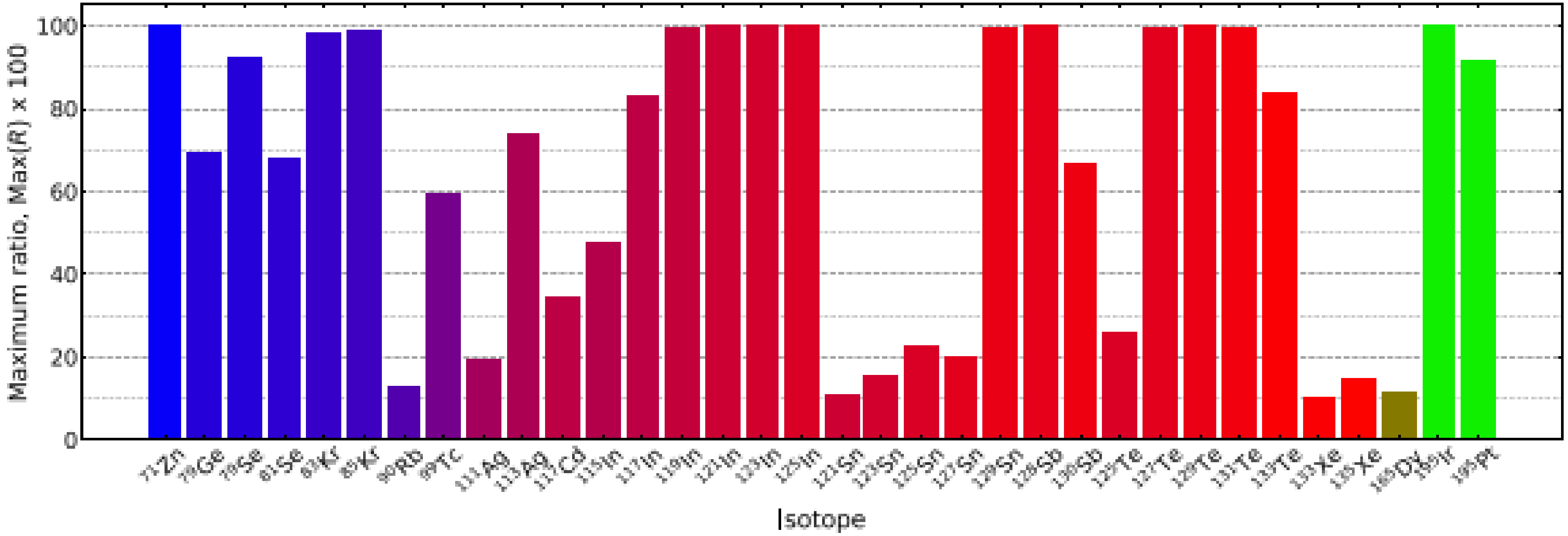
Benchmark with the largest possible pool of experimental data

Controlled treatment of theoretical uncertainties and their propagation.

Development of high-performance computing and controlled machine-learning approaches

Astromers – astrophysically important nuclear isomers

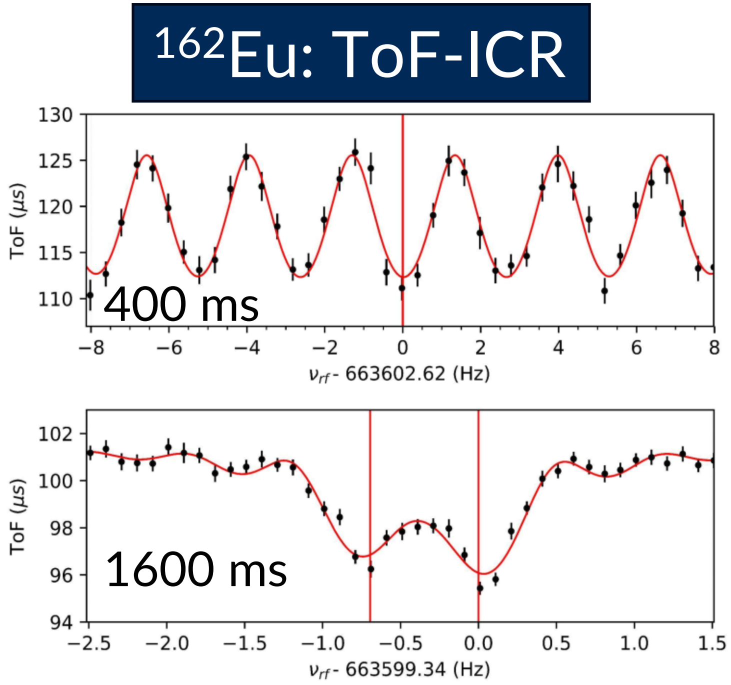
- Isomers not systematically included in the r-process codes although around 2000 isomers known
- Population of isomers can impact the reaction flow and the kilonova light curve (because of different mass, spin-parity, half-life and decay Q-values)
- Several isomeric states are strongly populated in the r-process and are potential “astromers”

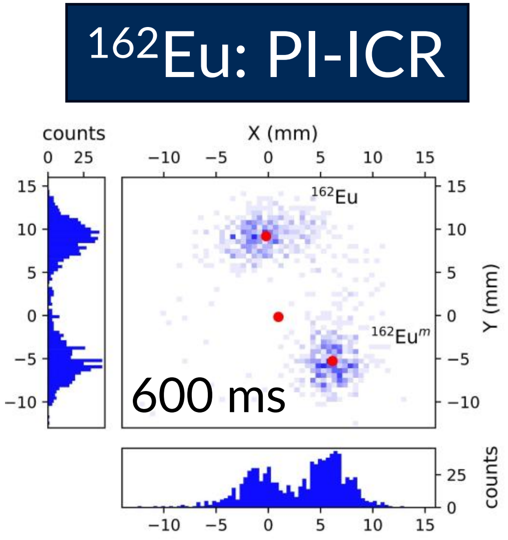


Misch et al., Astrophys. J., 913, L2 (2021)

Progress in mass measurements of isomers with new methods: PI-ICR with Penning traps

- Phase-Imaging Ion Cyclotron Resonance (PI-ICR) has a much higher resolving power than the conventional Time-of-Flight (ToF-ICR) methods
- Enables studies of low-lying isomeric states
  - Also better accuracy for the ground states
  - Example: 156(3) keV isomer in ^{162}Eu
- Dozens of isomers measured with JYFLTRAP after this (see Arthur Jaries talk on Monday), e.g.
  - Phys. Lett. B 853, 138663 (2024); Phys. Lett. B 848, 138352 (2024); Phys. Lett. B 862, 139359 (2025); PRC 107, 014306 (2023); PRC 108, 064315 (2023); PRC 110, 034326 (2024); PRC 110, 014328 (2024); PRC 111, 014329 (2025); PRC 111, 044314 (2025)

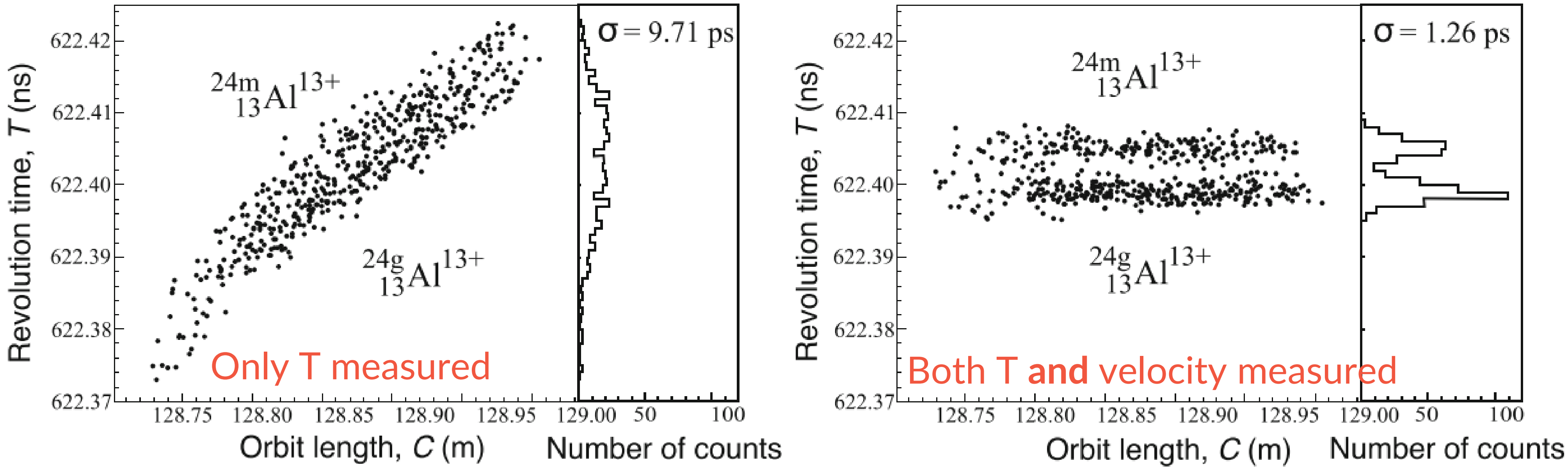




M. Vilén et al., Phys. Rev. C 101, 034312 (2020).

Progress in mass measurements of isomers with new methods: storage rings

- For shorter-lived nuclei (down to a few hundred microseconds), isochronous mass spectrometry (IMS) can be used for mass and lifetime measurements in a storage ring, such as the ESR at GSI.
- Sensitivity and precision of the IMS recently boosted with the new method (both T and v measured)
  - masses with a relative precision of $\sim 2\times10^{-6}$ for production rates smaller than two particles/week



Zhang et al. Eur. Phys. J. A 59, 27 (2023); Litvinov & Korten, Eur. Phys. J. Spec. Top. 233 (2024) 1191

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Recommendations and Outlook

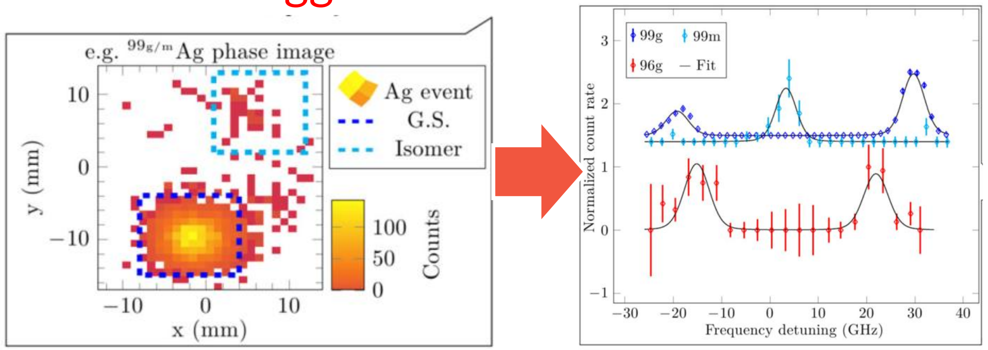
Full utilization of ion traps: combination of techniques

LRP2024: "***<u>Improve synergies between mass spectrometers, lasers and decay stations</u>***, *either through hybrid setups, mass-tagged or decay-tagged laser spectroscopy, trap-assisted experiments or experiments with laser polarised or selectively re-ionised beams."*

- Laser-assisted mass spectrometry (cf. MR-TOF)
- **Trap-assisted laser spectroscopy**
- Isomerically or isobarically purified beams
- **Trap-assisted decay spectroscopy**

PI-ICR as ion counter, laser tagged

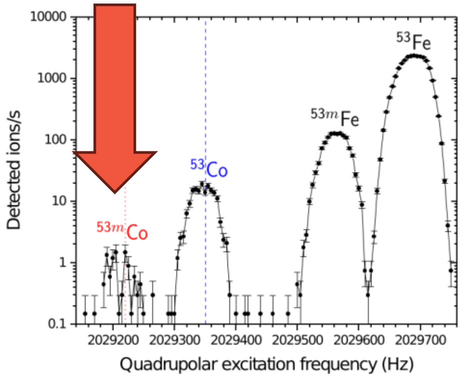
Hyperfine spectrum

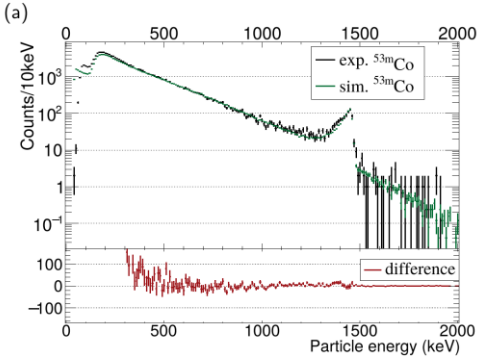


Reponen et al., Nature Comm. 12 (2021) 4596

Select this!

Implant and measure with TASISpec

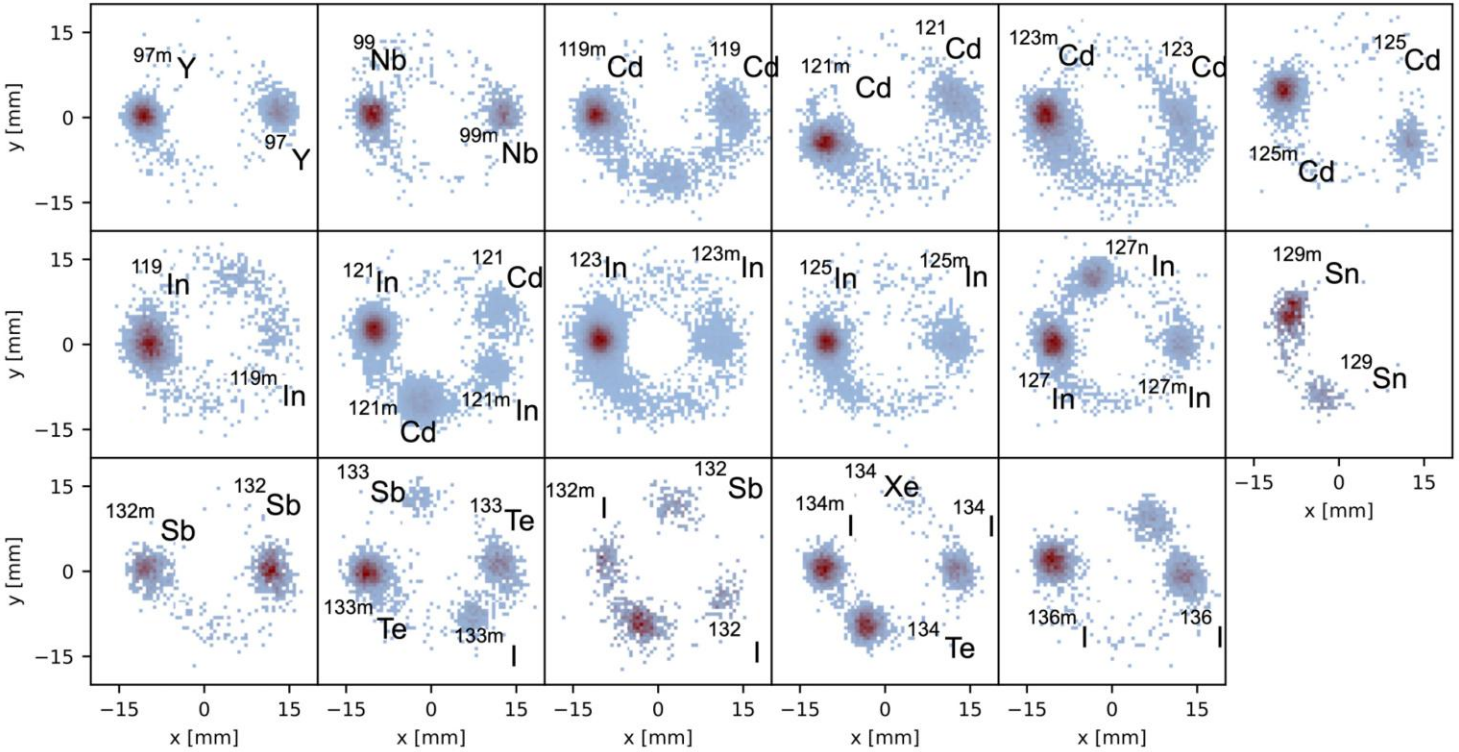




Sarmiento et al., Nature Comm. 14 (2023) 5961

Full utilization of ion traps
Example: traps as ion counters

- Traps as **ion counters** for fission yields and isomeric yield ratios
- Testing fission models, also relevant for the r process



Cannarozzo et al. PRC 111, L031601 (2025)

LRP2024 recommendations: Mass spectrometry

- We need to further improve mass-spectrometry techniques, in particular:
  - efficiency for the study of very exotic isotopes
  - precision for the tests of fundamental symmetries
  - better suppression of contaminants
- Europe's world leadership in the use of heavy ion storage rings should be maintained by the construction of future rings at FAIR and HIE-ISOLDE and by supporting experiments in the existing low energy storage rings of GSI/FAIR (ESR and CRYRING)

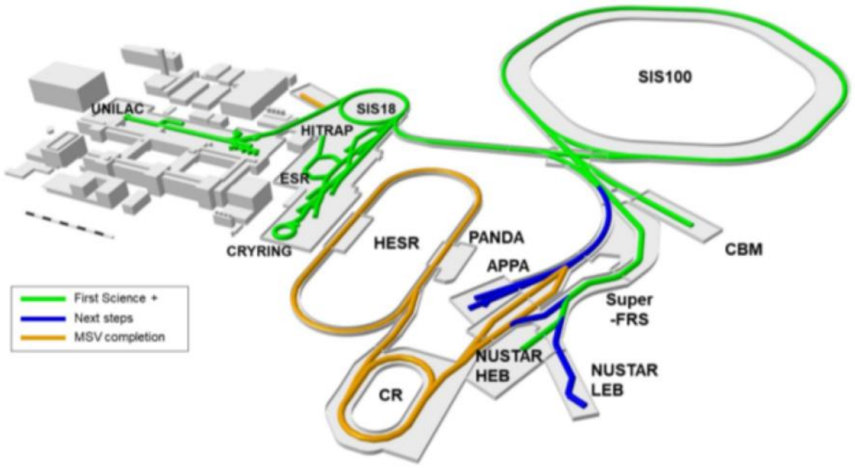


Fig. 8.5: Layout of the FAIR facilities, including the different steps towards completion. (© GSI-FAIR)

Credit: Long Range Plan 2024

Recommendations for nuclear astrophysics: Need evaluated and accessible data for nuclear astrophysics

- To facilitate nuclear astrophysics studies, nuclear data, and also nuclear reaction data, need to be evaluated **with uncertainties** and made **accessible**
- BUT a challenge: “Europe is at risk of losing its expertise in nuclear data evaluation and hence its capacity to maintain its databases and data libraries up-to-date”

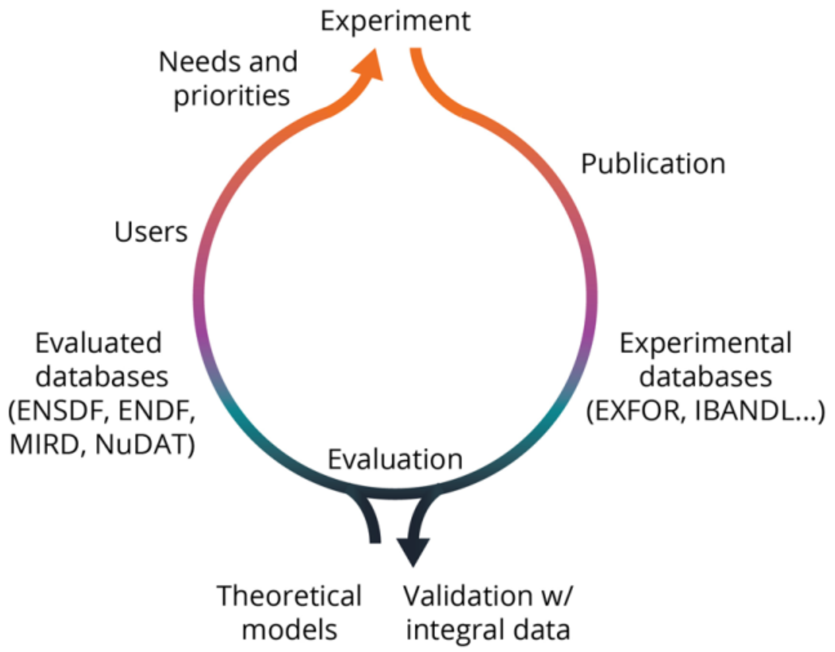
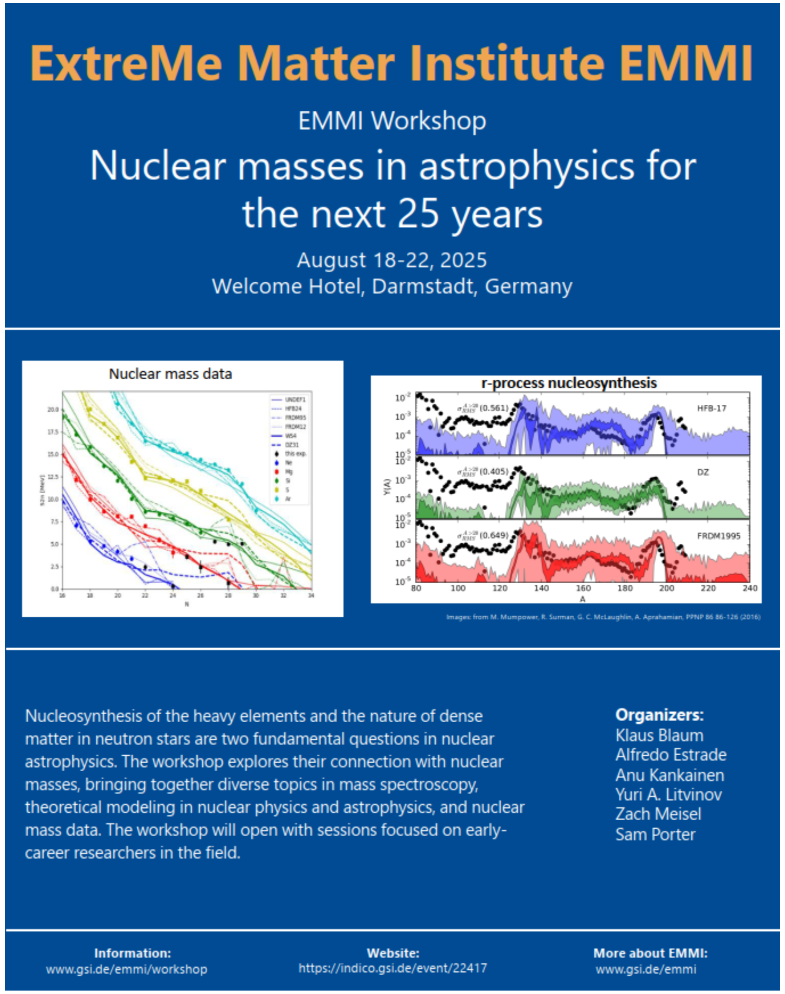


Fig. 11.4: Schematic representation of the research data cycle including the evaluation process and associated databases.

LRP2024: recommendations for nuclear astrophysics

- Nuclear astrophysics research is distributed over many institutions and thus benefits greatly from support for linking research activities and networks throughout Europe.
- We recommend **strengthening nuclear astrophysics networks in Europe** (e.g. ChETEC-INFRA) and making them sustainable
- Such networks are needed **to connect to international topical networks**, e.g. in the U.S. and Asia

→ Exactly what we are doing here this week!



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NuPECC Long Range Plan, in particular TWG 4

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- Sonja Bernitt (Darmstadt, Germany)
- Carlo Bruno (Edinburgh, UK)
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