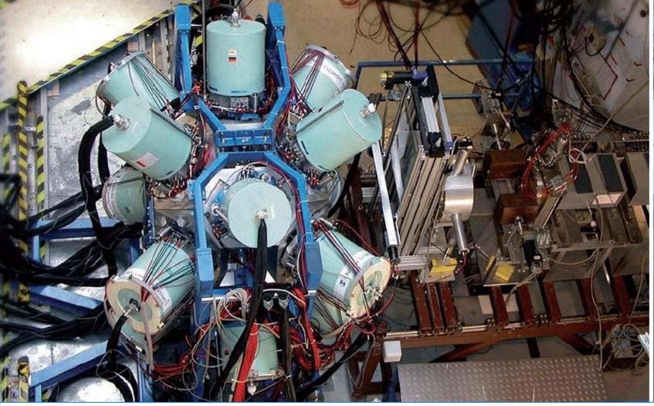
  

WG4: Nuclear Astrophysics

NuPECC

Nuclear Physics European Collaboration Committee

NuPECC Long Range Plan 2017, Town meeting

Gabriel Martínez Pinedo and Alison Laird
(Conveners)

Acknowledgements

- WG members: Dimiter Balabanski, Beyhan Bastin, Andreas Bauswein, Carlo Broggini, Cristina Chiappini, Roland Diehl, Cesar Domingo Pardo, Daniel Galaviz Redondo, Gyürky György, Matthias Hempel, Raphael Hirschi, Samuel Jones, Jordi Jose, Anu Kankainen, Jérôme Margueron, Micaela Oertel, Nils Paar, Rene Reifarth, Friedrich Röpke, Dorothea Schumann, Nicolas de Seréville, Aurora Tumino, Stefan Typel, Christof Vockenhuber
- NuPECC liaisons: Alex Murphy, María José García Borge, Pierre Descouvemont
- 46 participants at the Nuclear Astrophysics Town Meeting (GSI Darmstadt, February 16-17, 2016)

What is Nuclear Astrophysics?

Interdisciplinary field of research that combines astronomical observations, astrophysical modelling and experimental and theoretical nuclear physics to address key scientific questions:

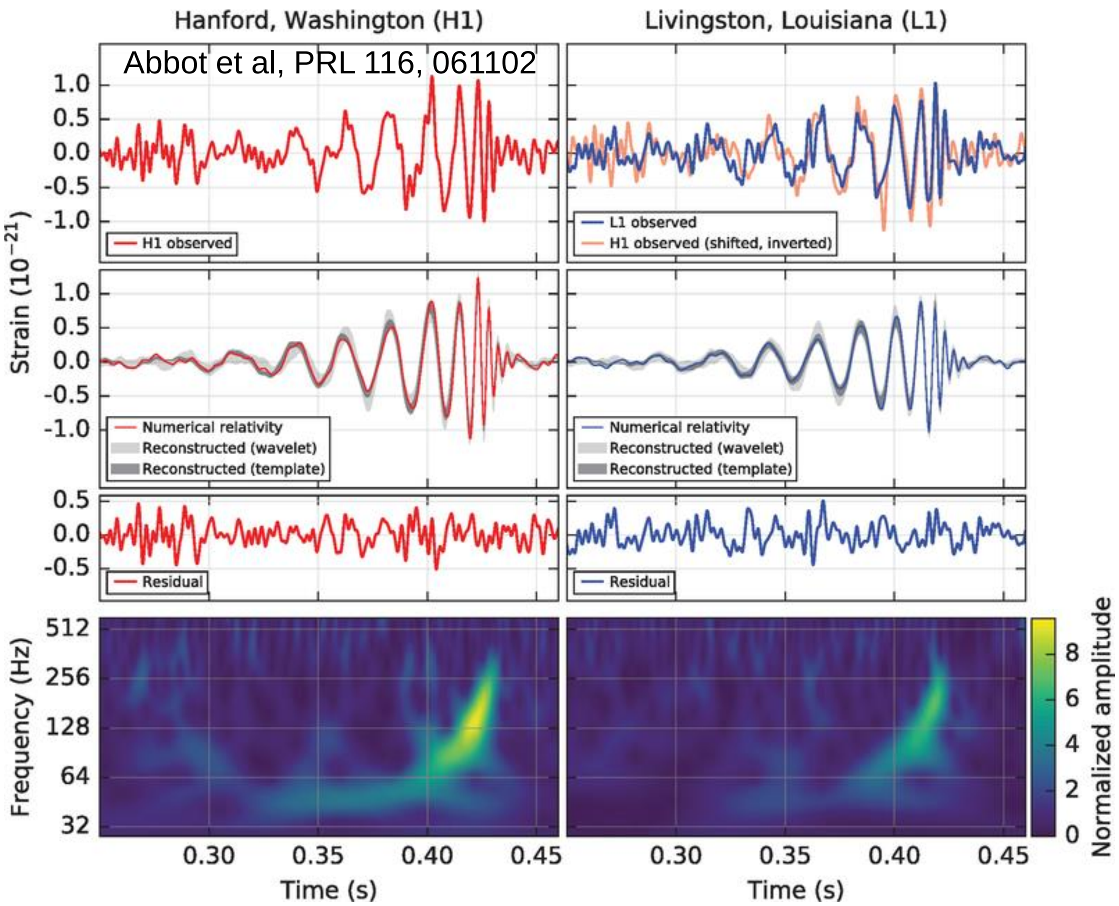
- What are the nuclear processes that drive the evolution of the stars, galaxies and the Universe?
- Where are the building blocks of life created?
- What are the different nucleosynthesis processes and how do they evolve with time?
- What is the nature of matter at extreme conditions and densities? Can multi-messenger observations provide access to conditions not reached at present laboratories?

Opportunities: new multi-messenger capabilities

- Detection of Gravitational Waves opens a new window to the Universe

- A fundamental probe of supernova and binary mergers dynamics

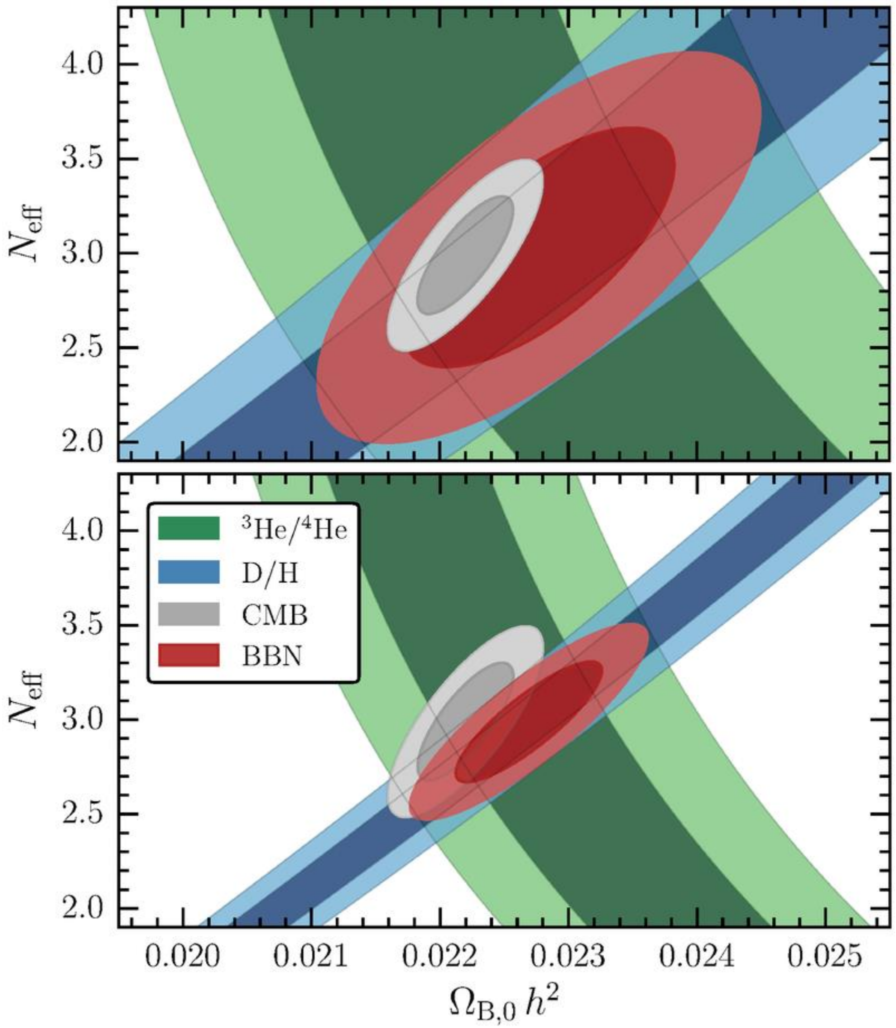
- Gravitational waves carry the signature of the high density equation of state



Combined with electromagnetic and neutrino observations represents the beginning of the multi-messenger astrophysics era

Opportunities: precision frontier

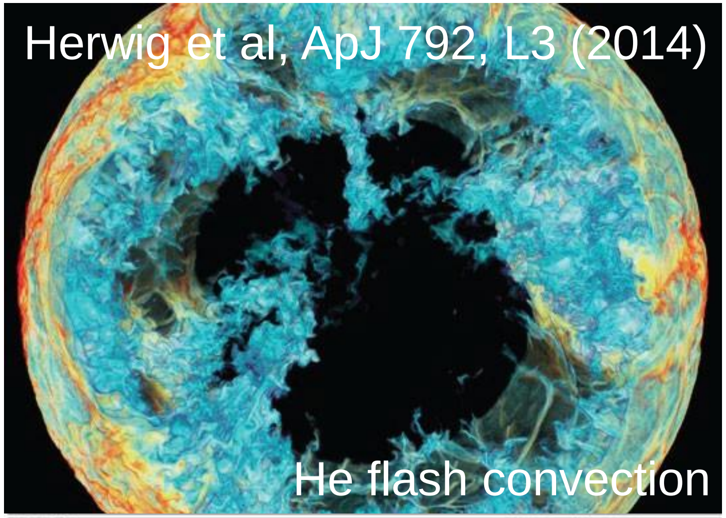
- Both Big Bang Nucleosynthesis and Solar Models have achieved such precision that nuclear reactions at 1% precision level are required.
- Achievable by a combination of experiment and theory:
  - Higher intensities at the LUNA underground facility
  - Ab-initio calculations based on chiral effective field theory
- BBN will probe New Physics in the early Universe at a level competitive to CMB observations
- Solar models will address the “Solar abundance problem” by providing accurate predictions of CNO neutrino fluxes (Borexino, SNO+)

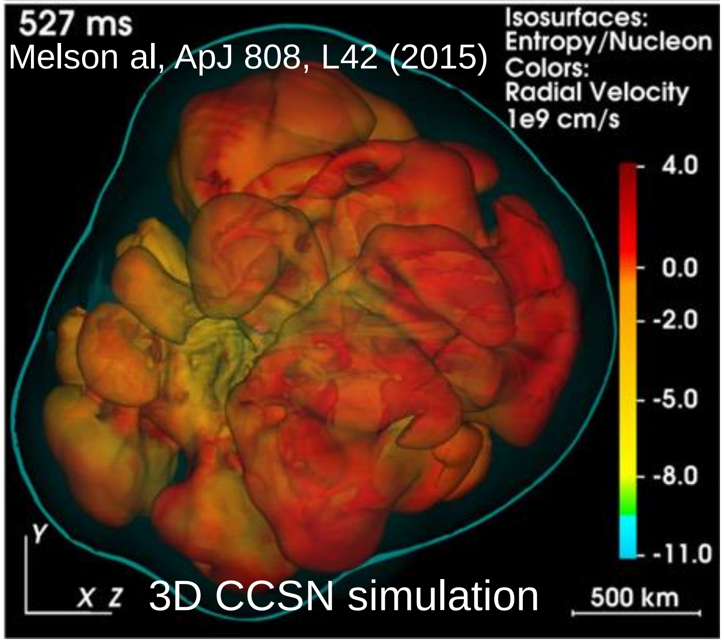


R. J. Cooke, Astrophys. J. 812, L12 (2015)

Opportunities: The 3D modelling frontier

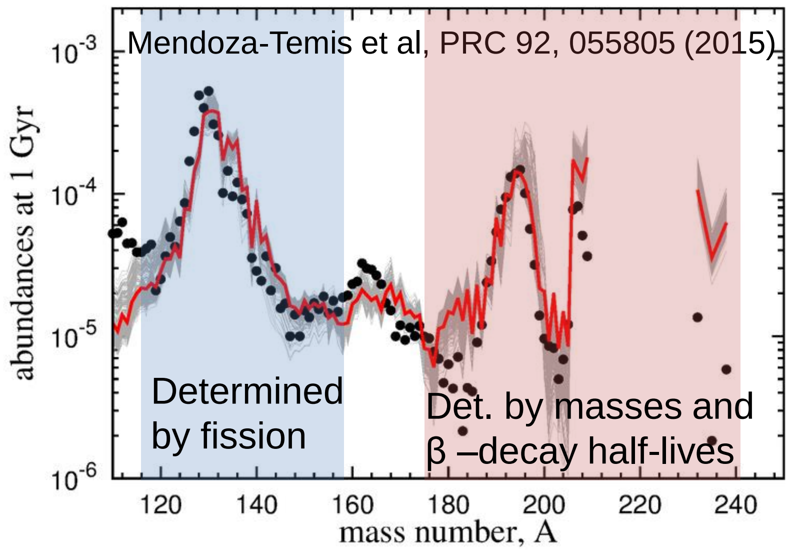
- 3D stellar models are becoming available:
  - Stellar evolution
  - Supernova explosions
- Nuclear input becomes fundamental to validate these models against observations
- Open Source versions of standard 1D codes are now available
- Strong potential in education
- Nuclear sensitivity studies based on realistic astrophysical conditions are becoming fundamental to guide experiments

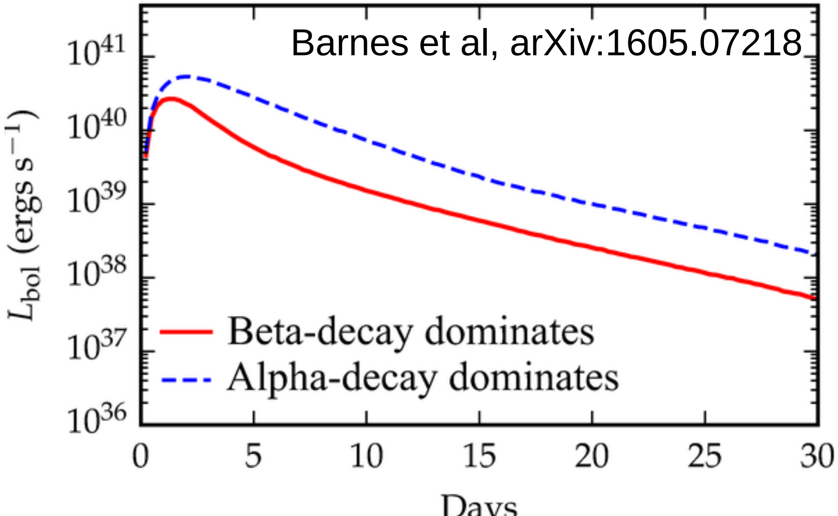




Opportunities: Identifying the r process site

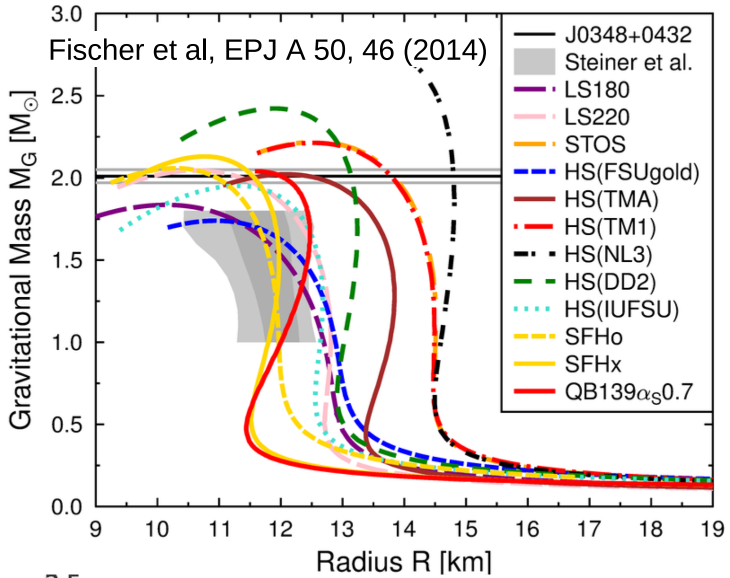
- Neutron star mergers are very likely the main r process site. Contribution of different ejection mechanisms is unclear.
- Gravitational waves measurements will determine the frequency of merger events
- Is there an electromagnetic signature associated with the decay of r process material (kilonova)?
- Its detection will be an unambiguous proof that the r process occurs in mergers.
- It may even characterize the production of actinides by their alpha decay imprint in the light curve

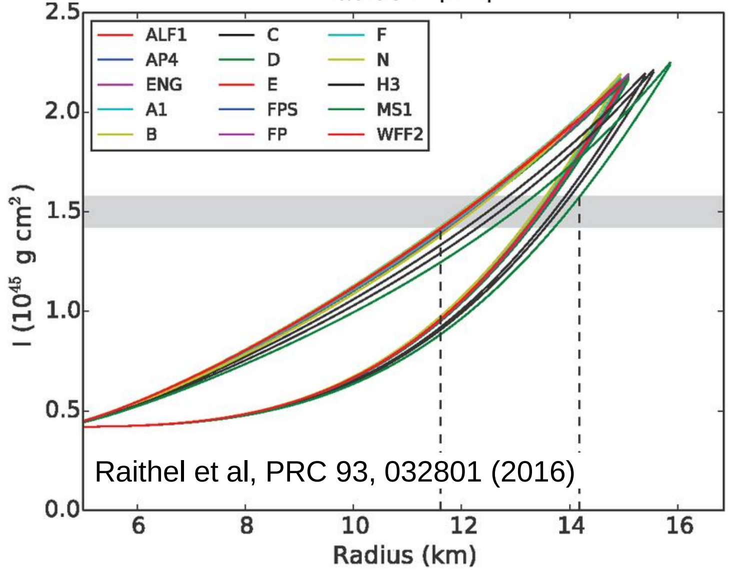




Opportunities: equation of state neutron stars

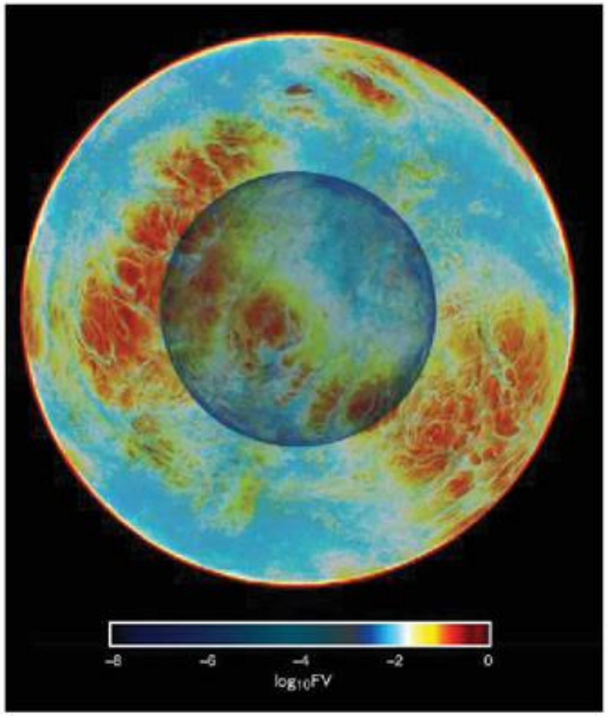
- High precision pulsar mass measurements above 2 $M_\odot$ place stringent constraints on the equation of state.
- A measurement of pulsar radius is expected in the next 5 years by X-ray timing or from the moment of inertia.
- Role of hyperonic degrees of freedom: poorly understood YN, YNN, YY and YYN interactions
- Challenge: Extension to the broad range of densities, temperatures and isospin asymmetries demanded by simulations

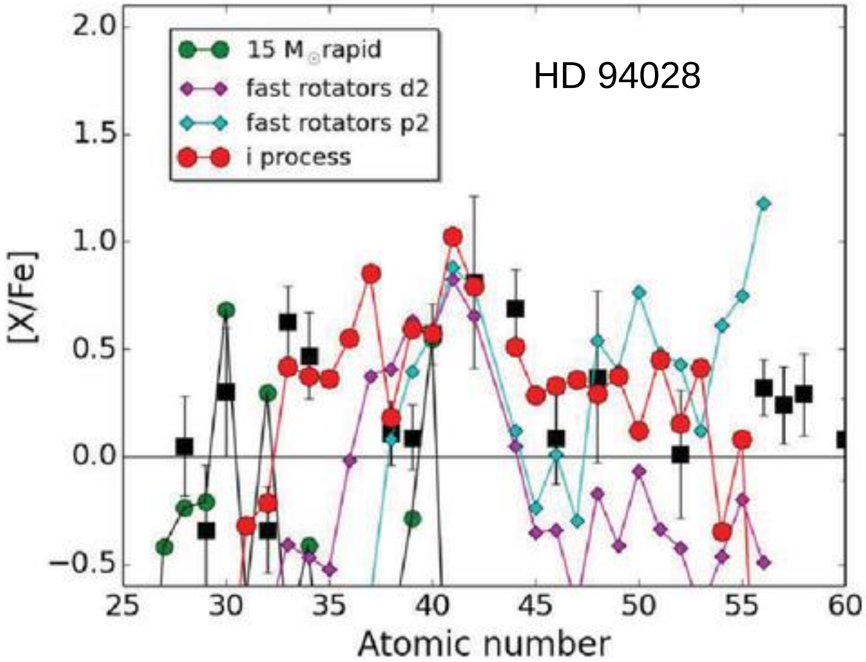




Box 1: Stellar models in three-dimensions

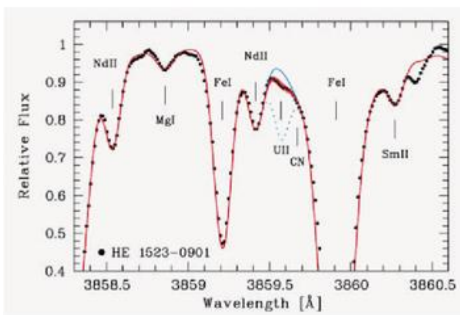
A major challenge in stellar modelling is the treatment of multi-dimensional effects such as convection and rotation. Three dimensional models are currently being developed that explore the impact of convection and rotation in the evolution and explosion of massive stars, and the production of heavy elements by the s- and i- processes. Addressing the combined role of convection, rotation, magnetic fields, binary interactions, and nuclear reactions remains a major challenge in stellar evolution. Precise measurements of a large number of chemical species can play a crucial role to help constraining these complex stellar models.

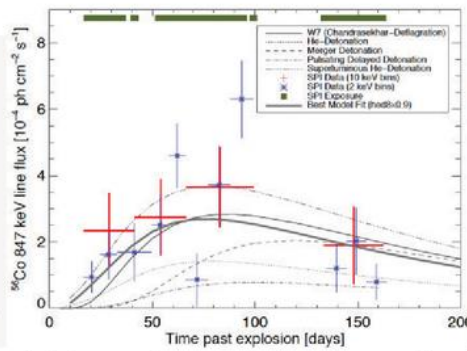


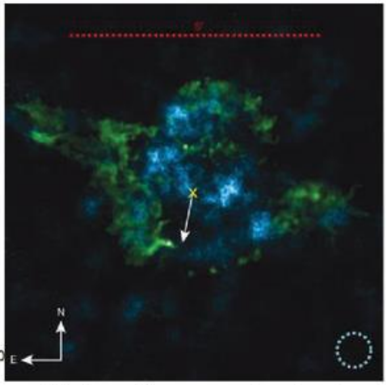


Box 2: Astronomical Observations vs models

Elemental abundances have been the foundation of nuclear astrophysics. One of the recent findings was the detection of Uranium with ESO's Very Large Telescope (left). Much better data are now becoming available for a vast number of stars in our Galaxy, thanks to ESA's Gaia space satellite instrumentation, and new and planed multi-object spectrographs such as WEAVE and 4MOST. These enable us to discriminate abundance pattern systematics for stars of different origins and ages, "Galactic archaeology", and the test of modern descriptions of chemical evolution of cosmic gas in and between galaxies.



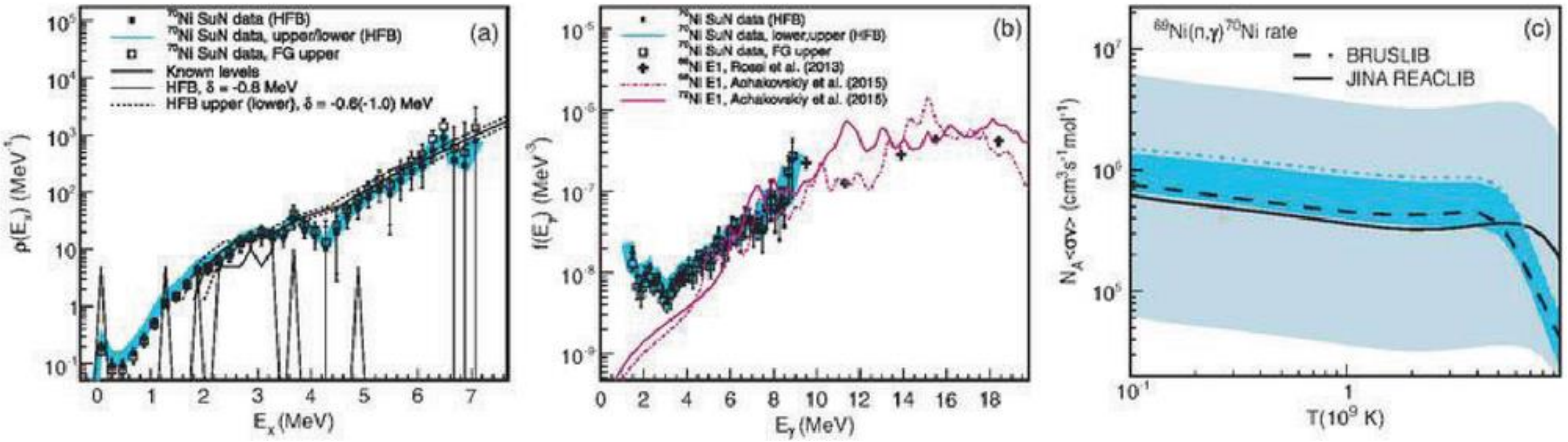




Multi-messenger data complement the astronomical observations. Meteorites and stardust embedded therein had been essential for isotopic ratios, from solar system material, and also tracing dust from nucleosynthesis sources (AGB stars, novae, supernovae) with characteristic nuclear reaction products. Astronomical observations at other wavelengths, from radio and sub-mm molecules to X- and gamma-ray nuclear lines also carry isotopic information. X and gamma-ray space observatories allow measurements directly at individual nucleosynthesis sources. So, supernova gamma-rays from the ^{56}Ni decay chain have been discovered for the first time from a supernova of type Ia (center). With SN2014J at a distance of 3.5 Mpc, such a supernova occurred sufficiently close for current telescopes. Similarly, the Cas A supernova remnant at only 3.4 kpc distance allowed analysing, and even imaging, the ejection of nucleosynthesis products. The ^{44}Ti image of the spatial distribution within the remnant is a recent breakthrough (right). ^{44}Ti is expected to be produced near to the boundary between the material falling back onto the collapsing core and that ejected into the surrounding medium. Its spatial distribution directly probes the explosion asymmetries. Key nuclear reactions, including $^{44}\mathrm{Ti}(\alpha,p)$, determining the production are being studied in several European labs.

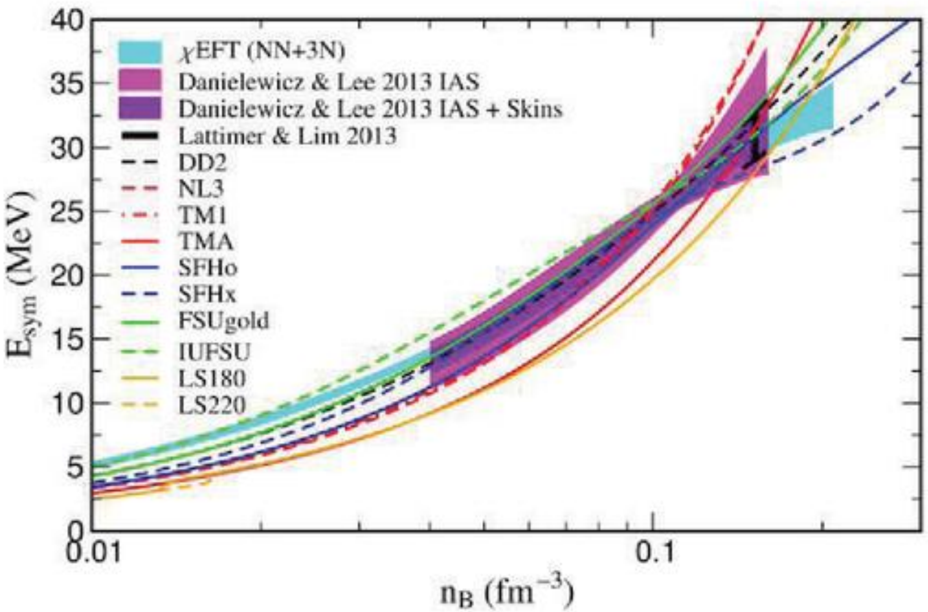
Box 3: Experimental constraints on reactions

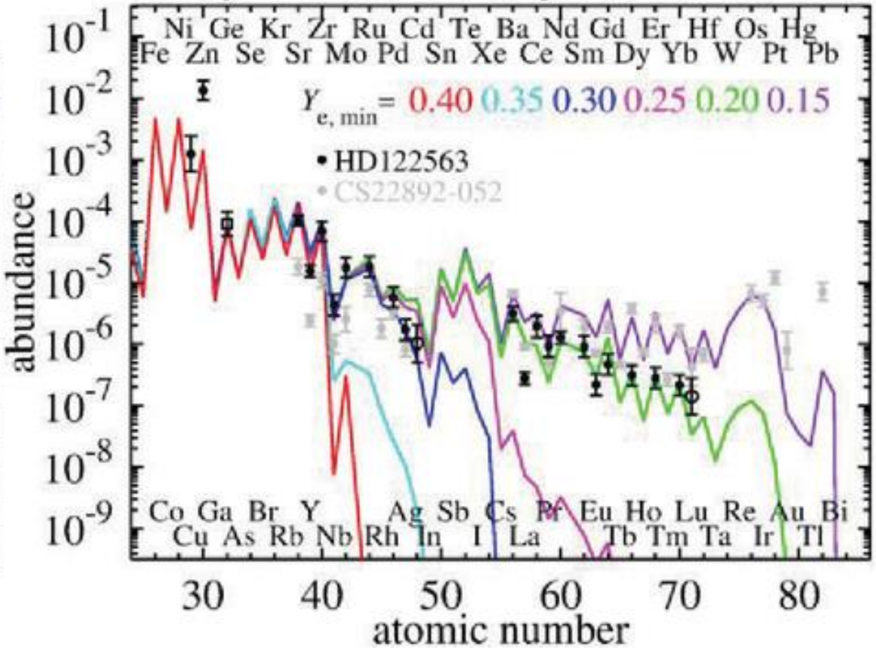
One of the major challenges in modelling nucleosynthesis in explosive environments is the fact that the nuclear properties of the many nuclei involved are not known experimentally. This is particularly the case for the r process that requires neutron captures and beta-decay rates for neutron-rich nuclei. Beta-decay experimental data for r process nuclei has dramatically contributed to improve theoretical calculations. The situation is different for neutron capture rates. However, recent experimental developments offer the possibility of constraining neutron capture rates far from stability.



Box 4: Heavy element nucleosynthesis in CCSNe

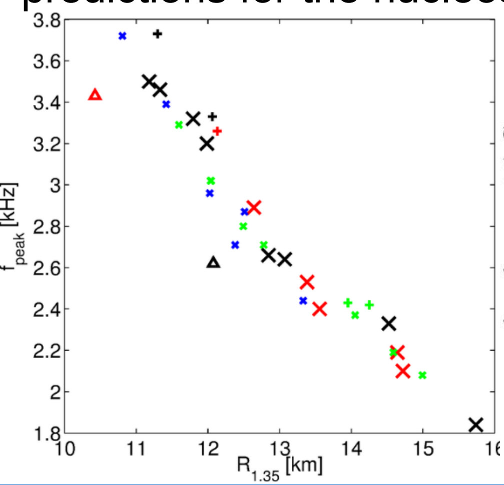
The determination of the heavy elements produced in core-collapse supernova requires accurate predictions for the spectral differences between electron neutrinos and antineutrinos. These differences are related to the nuclear symmetry energy at sub saturation densities. A combination of nuclear experiments and theory and astronomical observations have greatly contributed to constrain the density dependence of the symmetry energy. This puts strong constrains on equations of state used in core-collapse supernova simulations and furthers contributes to determine the neutron richness, Y_e, of the ejected material. This is the main parameter affecting the nucleosynthesis in the ejected material.

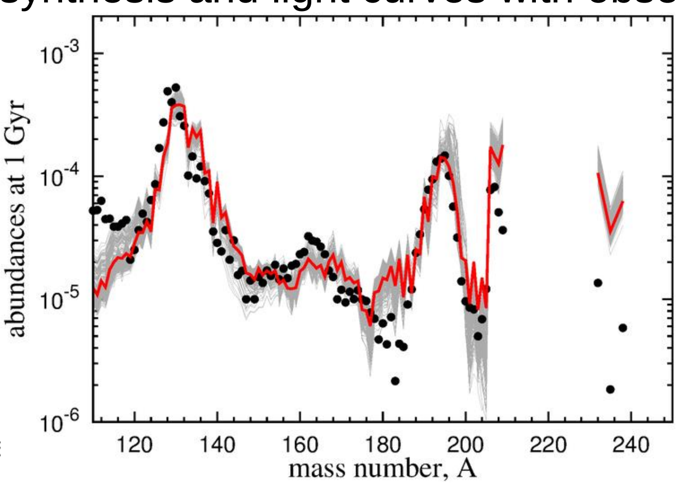


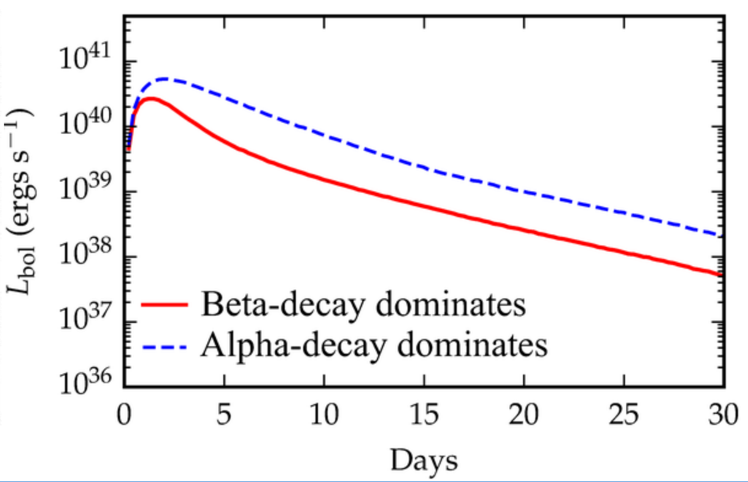


Box 5: Mergers and r-process nucleosynthesis

The direct detection of gravitational waves by the LIGO collaboration has opened a new window to the Universe. A future observation of the gravitational signal from a neutron star-neutron star or neutron star-black hole system will provide valuable information about the merger dynamics, which reflects neutron star properties such as its compactness. The peak frequency in the signal is directly correlated with the radius of a cold neutron star, providing a model independent determination of this fundamental property. Mergers are discussed to be a major source of r process elements. The frequency at which mergers occur in the present Universe will be also determined by Gravitational wave detections providing constrains on the amount of material ejected in individual events. The radioactive decay of r-process material ejected in the merger could be responsible for an electromagnetic transient known as kilonova. An observation of a kilonova light curve will provide direct evidence that the r process has indeed taken place in the merger. . Other astronomical messengers (MeV gamma-ray bursts, GeV gamma-rays, positron annihilation emission) will contribute to understand such events and their aftermath. An improved description of the properties and reactions involving neutron rich exotic nuclei is fundamental to confront our predictions for the nucleosynthesis and light curves with observations.







Nuclear Physics Theory

- Light and medium nuclei
  - Systematic description of nuclear interaction and associated electroweak currents based on chiral effective field theory
  - Novel many-body methods allow for ab initio description of nuclear structure and **reactions**

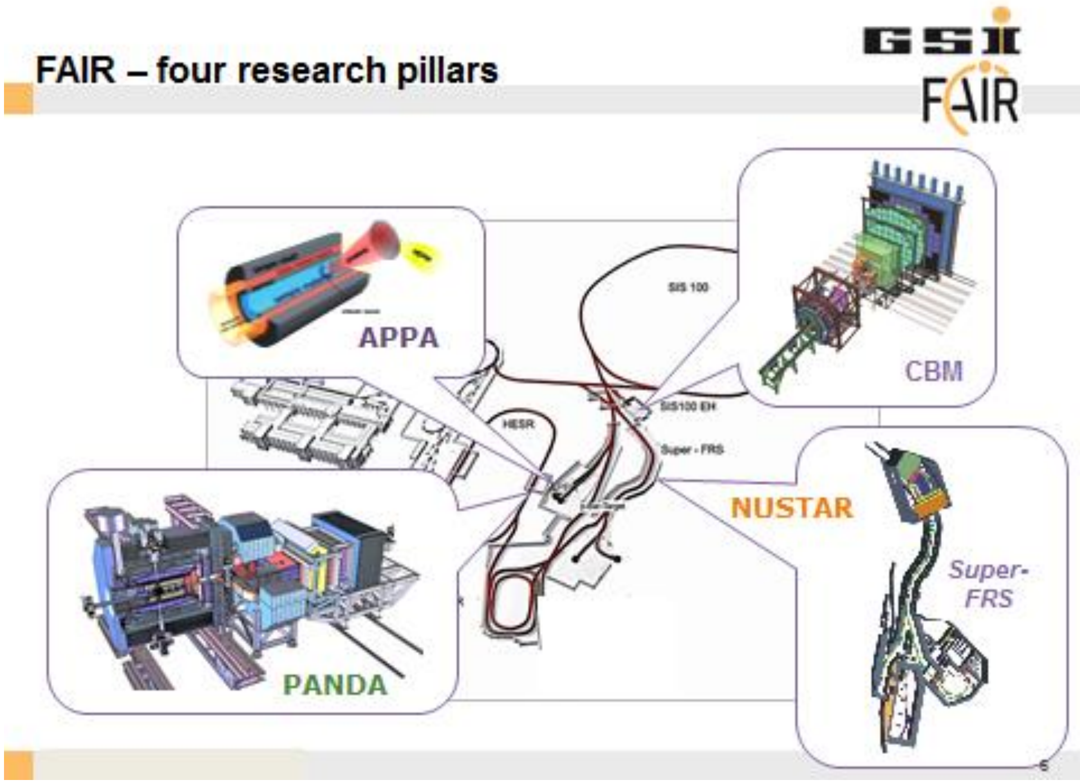
- Heavy nuclei
  - Extension of current techniques to account for beyond-mean-fields effects and odd and odd-odd nuclei.
  - Unified description of nuclear masses, beta-decay half-lives, fission, gamma-strength functions
  - Relevant parameters determined by covariant analysis
  - Uncertainty estimates: Bayesian analysis.
  - Determination of key reactions for experimental measurements

Experiment

- Most nuclear physics input to stellar models is based on theory
  - Quiescent burning and HCNO cycles are exception
  - Novae are only explosive site where most nuclear reaction rates are experimentally determined.
- Nuclear astrophysics measurements provide
  - direct measurement of specific nuclear physics input, e.g. key cross sections, masses, lifetimes
  - indirect determination of specific nuclear physics input
  - data for testing model predictions
- Require all types of beam facilities with a range of beam energies, qualities and intensities:
  - Large international facilities
  - Small university/research facilities
  - Neutron facilities
  - Underground facilities
  - Laser/gamma facilities

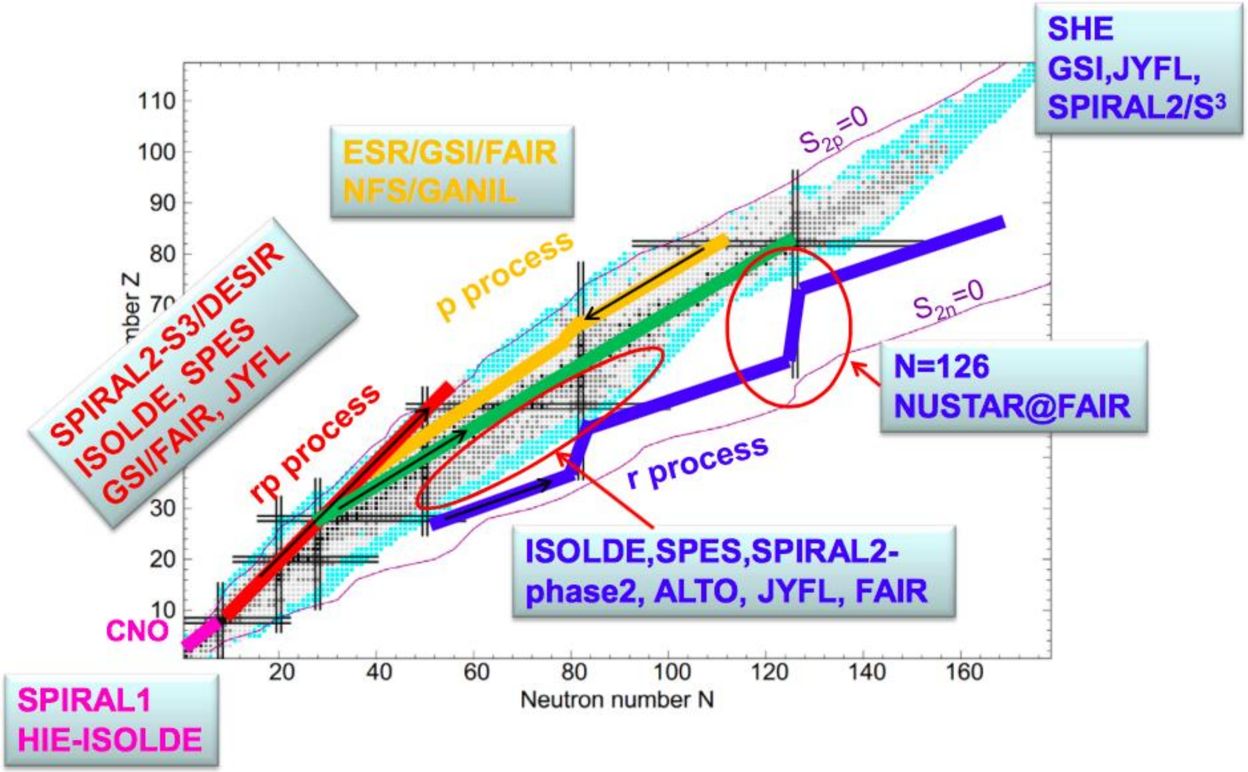
FAIR – multipurpose facility

- Deliver new capabilities across a range of areas important to nuclear astrophysics
- Access to nuclei far from stability, in particular r-process nuclei around N=126
- Matter under extreme conditions:
  - high densities and the equation of state
  - extreme electromagnetic fields
  - Stellar plasmas and gaseous planets.



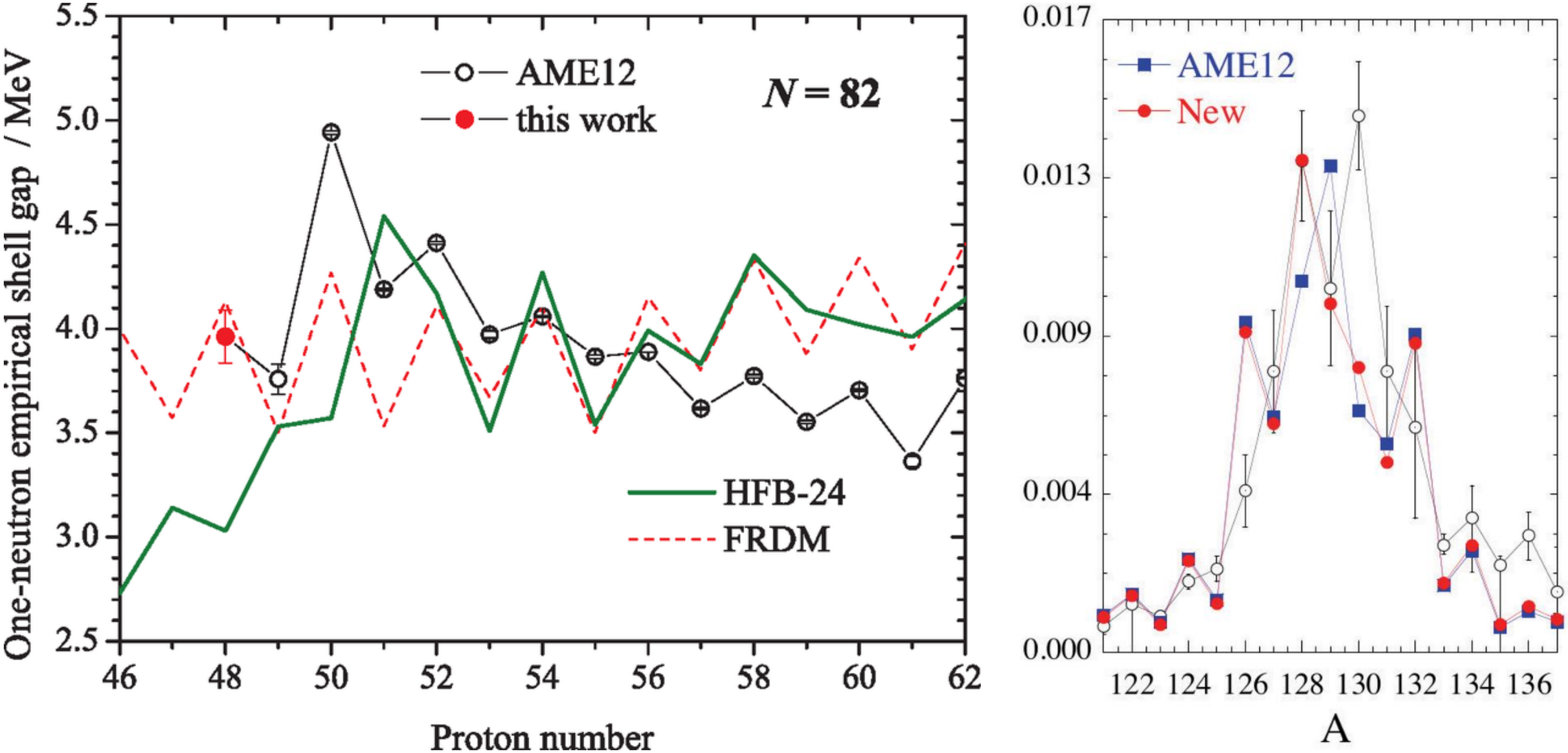
(Paolo Giubellino)

Radioactive beams



- High quality (energy, time, etc.) radioactive beams for studying reaction cross sections (direct) at stellar energies – typically 0.5 – 2 MeV/u
- High quality (energy, time, etc.) radioactive beams for spectroscopy
- Can require significant beam development for specific beams.

Measurements away from stability: example

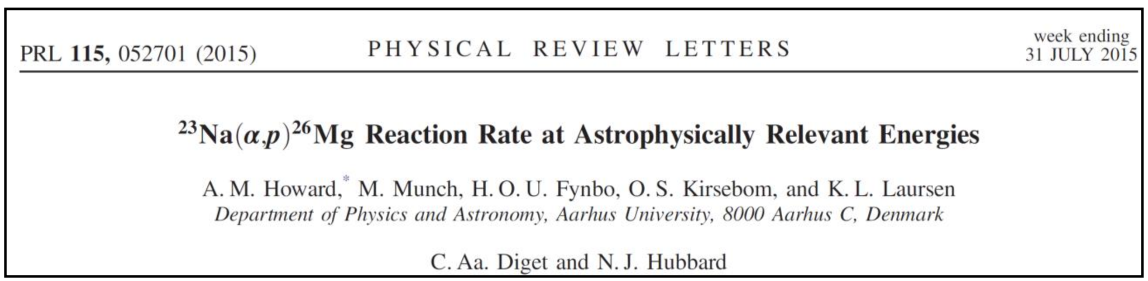


Atanasov et al, PRL 115, 232501 (2016)

- Unique capabilities to access the properties of neutron-rich nuclei relevant for the r process (masses, beta-decay half-lives, gamma-strength functions, …)
- Crucial for testing theoretical models
- Fundamental to understand r process in neutron star mergers

Small-scale facilities

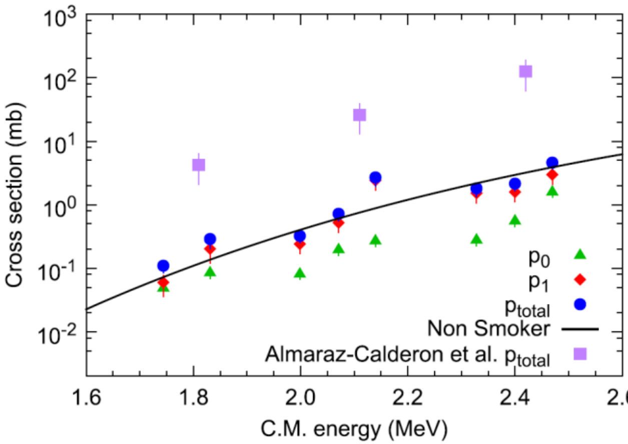
- Critical reactions in quiescent burning still not sufficiently understood, and new observational data need improved rates
- Important for direct measurements of H and He burning – need for high precision studies
- Provide AMS measurements
- Ongoing substantial output from ‘small’ laboratories, but several **at risk** without support to maintain existing expertise and infrastructure
- **Crucial to continued European success**


PRL **115,** 052701 (2015) PHYSICAL REVIEW LETTERS week ending 31 JULY 2015

$^{23}Na(\alpha,p)^{26}Mg$ Reaction Rate at Astrophysically Relevant Energies

A. M. Howard,* M. Munch, H. O. U. Fynbo, O. S. Kirsebom, and K. L. Laursen
Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark

C. Aa. Diget and N. J. Hubbard



Done with 5 MV Van de Graaff accelerator!

Underground facilities

- Crucial for direct measurements of H and He burning at stellar energies – need for high precision studies
- Europe currently leads world with LUNA
- Felsenkeller shallow facility will provide additional beamtime for selected measurements

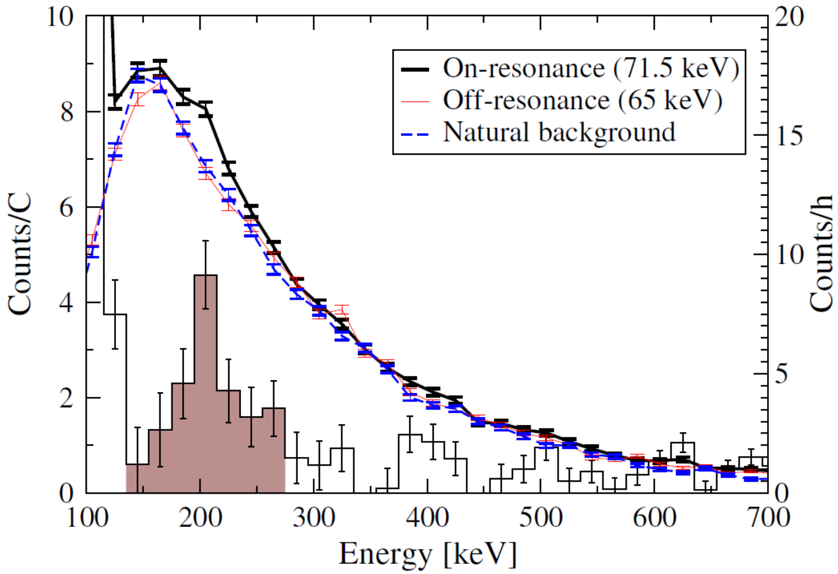
PRL **117,** 142502 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Improved Direct Measurement of the 64.5 keV Resonance Strength in the $^{17}O(p,\alpha)^{14}N$ Reaction at LUNA

C. G. Bruno,[1,*] D. A. Scott,[1] M. Aliotta,[1,†] A. Formicola,[2] A. Best,[3] A. Boeltzig,[4] D. Bemmerer,[5] C. Broggini,[6] A. Caciolli,[7] F. Cavanna,[8] G. F. Ciani,[4] P. Corvisiero,[8] T. Davinson,[1] R. Depalo,[7] A. Di Leva,[3] Z. Elekes,[9] F. Ferraro,[8] Zs. Fülöp,[9] G. Gervino,[10] A. Guglielmetti,[11] C. Gustavino,[12] Gy. Gyürky,[9] G. Imbriani,[3] M. Junker,[2] R. Menegazzo,[6] V. Mossa,[13] F. R. Pantaleo,[13] D. Piatti,[7] P. Prati,[8] E. Somorjai,[9] O. Straniero,[14] F. Strieder,[15] T. Szücs,[5] M. P. Takács,[5] and D. Trezzi[11]

(LUNA Collaboration)

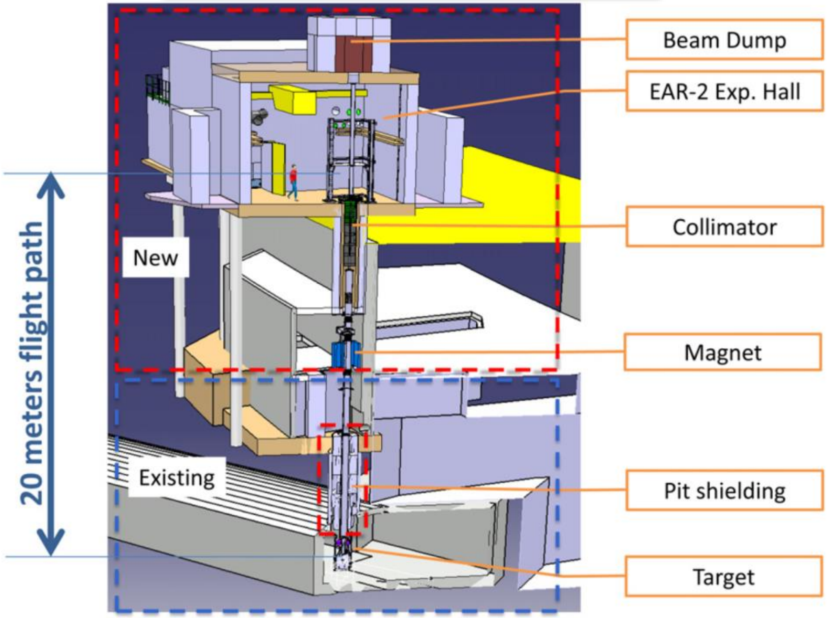
The most accurate resonance strength for the 64.5 keV resonance to date:
ωγ=10.0 ± 1.4stat ± 0.7syst neV



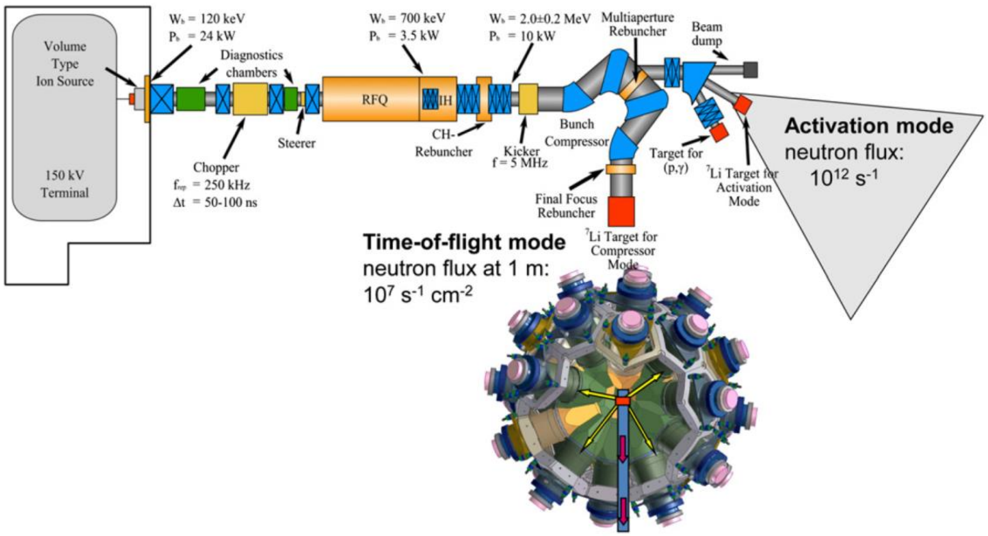
Neutron Beams

- Provide key data on neutron capture rates at or near stability
- Accurate s-process yields for understanding galactic heavy element abundances
- New facilities providing higher intensities and capability to use shorter-lived species as targets

CERN n_TOF/EAR-2



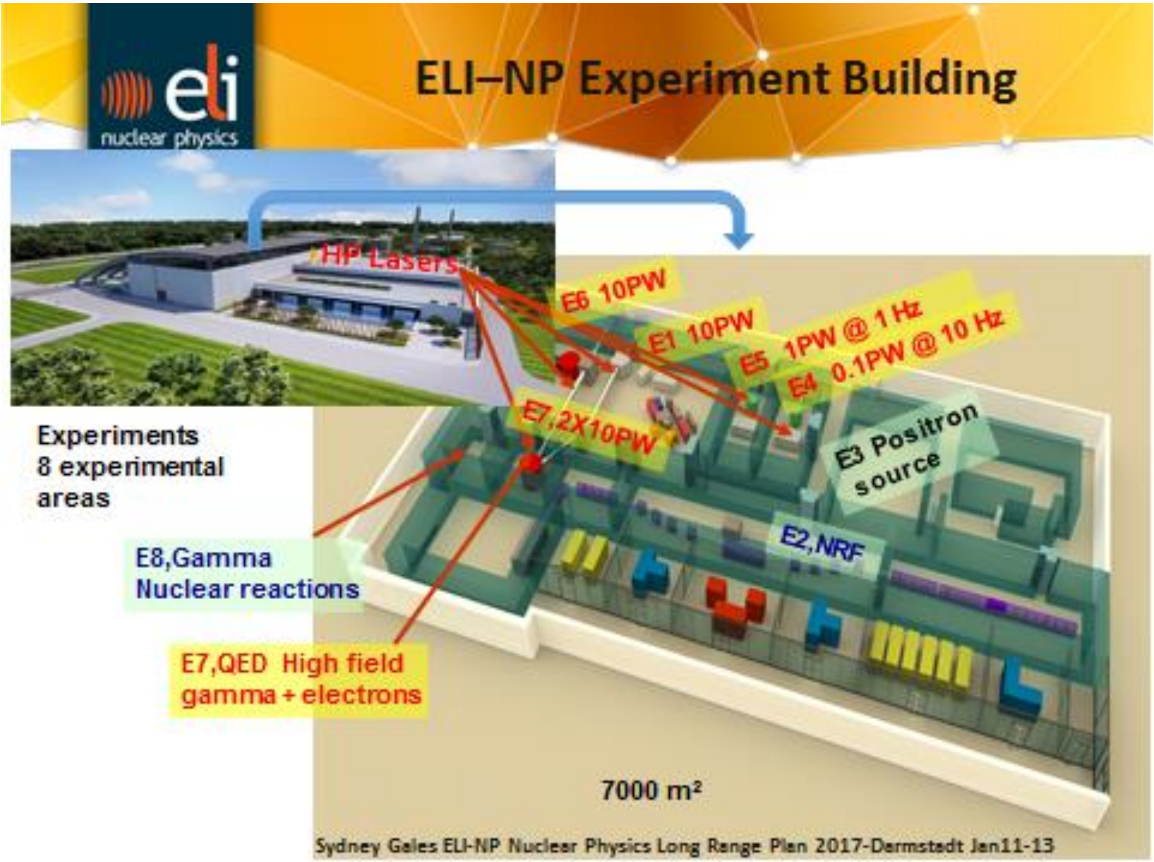
FRANZ



R. Reifarth et al., JPG ***41*** *(2014) 053101*

ELI-NP

- Unique opportunities to study photodisintegration reactions and time reverse radiative capture reactions
- Production of radioactive nuclei via photofission and laser-driven fission-fusion → r process



Detectors, tools and targets

- Sufficient investment needed to maximise science return from major new infrastructure
  - Synergy with nuclear structure experiments (see WG 3)
  - Limited lifespans of the detectors
  - Maintenance and operation funding for existing infrastructure (also small facilities)

- Indirect methods (e.g. ANC, THM) are an alternative approach for providing constraints on astrophysical reaction rates.

- Extraction of nuclear material to produce long-lived radioactive targets coupled with radioactive beams facilities for direct reactions and spectroscopic studies

Recommendations (overview)

- Completion of FAIR
- Completion ISOL facilities
- Upgrade LUNA
- Continue programs at small labs
- Develop ELI-NP research program
- Training efforts both experiment and theory
- European centre on nuclear astrophysics
- Target preparation network.
- Support for astronomical nuclear observations

Recommendations – FAIR

- **We strongly support the completion of the FAIR facility. Its worldwide unique multifaceted approach, exploited by its four experimental pillars APPA, CBM, NUSTAR and PANDA, opens a new era for nuclear astrophysics and promises to deepen our understanding of the Universe and the objects therein**. FAIR and the instrumentation of the NUSTAR collaboration will provide unparalleled access to unstable nuclei far from stability, in particular to the heavy neutron-rich r-process nuclei around N=126. CBM will study the properties of matter at the high densities achieved in neutron stars and will constrain the supernova equation of state. With its ability to produce high rates of hypernuclei PANDA will contribute to our understanding of the nucleon-hyperon and NN-hyperon interactions. The APPA collaboration will explore the behaviour of matter, in storage ring experiments, under the extreme electromagnetic fields achieved on neutron star surfaces and, in ion-beam and laser experiments under the astrophysical conditions expected in stellar plasma and in gaseous planets.

Recommendations – RIB facilities

- **We strongly support the completion of the next generation of radioactive ion beam facilities, including SPIRAL2, SPES-INFN. For HIE-ISOLDE, which is completing in 2018 its phase 2, we highly recommend the implementation of the phase 3, enabling capture reactions of astrophysical interest and the installation of a new storage ring at HIE-ISOLDE**. The complementary capabilities of these facilities will guarantee European leadership in nuclear astrophysics and supplement the strong European efforts in astrophysics, cosmology and astroparticle research. Furthermore, we recognise the necessity for the ISOL facilities to expand their coordinated approach to beam development, as lack of specific radioactive species of sufficient intensity is a major limitation. In the longer term, progress towards EURISOL-DF is vital

Recommendations – LUNA and Small facilities

- The Laboratory for Underground Nuclear Astrophysics (LUNA) at Gran Sasso is a world-leading facility, which has performed high impact nuclear reaction studies of astrophysical importance, at the relevant stellar energies. **We strongly support the upgrade of LUNA with a multi-MV accelerator allowing the access to a new range of nuclear reactions.**

- The improvements in observations and astrophysical models have highlighted the need for high precision cross section measurements. These, and other high impact studies, reflect the strong programme of nuclear astrophysics research carried out at small facilities. **We strongly recommend to continue and to extend the dedicated nuclear astrophysics programs at universities and small research centres, and maintain access to such facilities through the transnational access programme.**

Recommendations – ELI-NP

- The ELI-NP facility at Bucharest, which will become operational as a user facility in 2019, will provide high-power laser pulses and high-intensity narrow-bandwidth gamma beams. Studies of laser-driven nuclear reactions in controlled plasma conditions will become possible together with measurements on photodissociation reactions with unprecedented precision. This will provide new research opportunities for the nuclear astrophysics community in Europe. **We strongly recommend that the instrumentation needed for the implementation of this research program be built and the suggested experiments are performed with high priority**.

Programmatic recommendations

- Both small and large scale facilities educate the next generation of researchers on the broad range of techniques necessary to run and analyse experiments. **We strongly recommend the continuation and extension of the training efforts to guarantee enough skilful people at future facilities.**

- Nuclear Astrophysics requires an extensive contact and exchange of ideas between theoretical and experimental nuclear physicists, astrophysicists and astronomical observers. **We recommend a strong initiative to develop a European centre for nuclear astrophysics that coordinates specific nuclear astrophysics needs such as up-to-date and exhaustive databases of nuclear reactions, astrophysical models and observations.** This should follow the successful example of the JINA Center for the Evolution of the Elements and extend available but geographically limited initiatives like the Nuclear Astrophysics Virtual Institute in Germany or COST Actions NewCompStar and ChETEC, complementing these networks with funding for cross-disciplinary research projects and students

Programmatic recommendations

- A key issue in experimental nuclear astrophysics research is the availability of high quality target material, tailored for the special envisaged experiment. Especially radioactive targets require big efforts in production of the isotope, its chemical separation and purification as well as elaborated target manufacturing and handling. **The establishment of a target preparation network and a strong support of target producing research groups will be a precondition for successful future experiments.**

- **Scientific support is necessary of astronomical observation facilities which are aimed at, or include, information on nuclear physics and processes in cosmic objects**. While nuclear astrophysics is a small part in the wide range of astrophysical themes, **nuclear astrophysics arguments need to be made more aggressively and in a more accessible way,** so that the relevant science connections are clear also to decision bodies that have to evaluate the promises and effectiveness of billion Euro investments into major new or enhanced astronomical facilities. While cosmology and search for life on other planets are obviously convincing drivers of new investments, the more complex and deep meaning of nuclear processes in cosmic objects needs dedicated efforts to communicate its scientific merits.

Programmatic recommendations

- Theoretical nuclear astrophysics deals with extrapolations of experimental advances to the astrophysical relevant energies or temperatures. Those are coupled with large nuclear networks and sophisticated astrophysical modelling to allow for the full exploitation of the possibilities offered the experimental facilities. **Given the broad range of techniques needed and the access to powerful computers it becomes fundamental to have a comprehensive education program to train the next generation of researchers. The above recommended European Centre can play a leading role coordinating such education, supplementing activities already carried out at ECT* Trento.**