Advances and Opportunities in Experimental Nuclear Astrophysics

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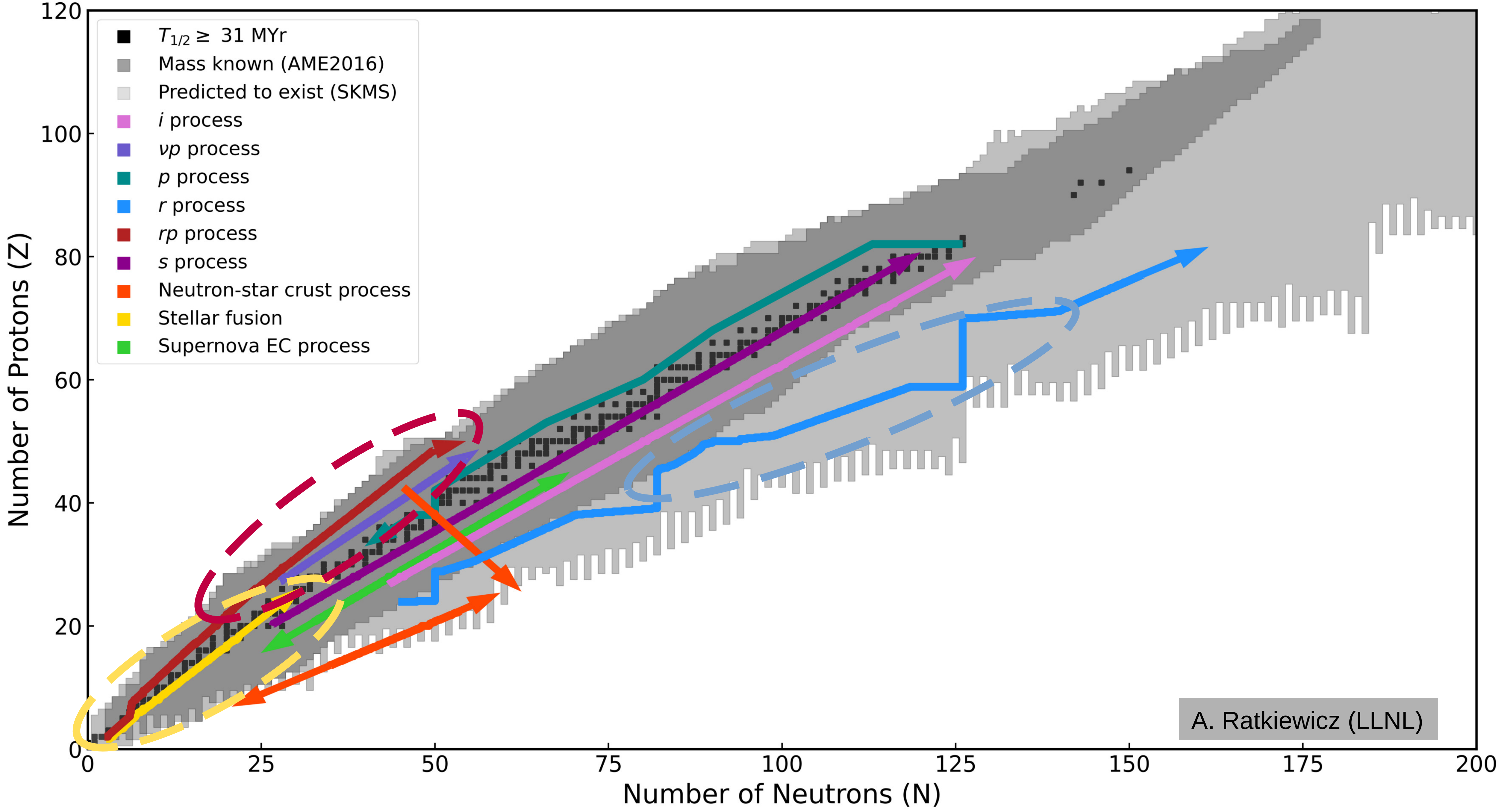
Where Did We Start? - Open Questions from 2015 LRP

Where do the chemical elements come from, and how did they evolve?

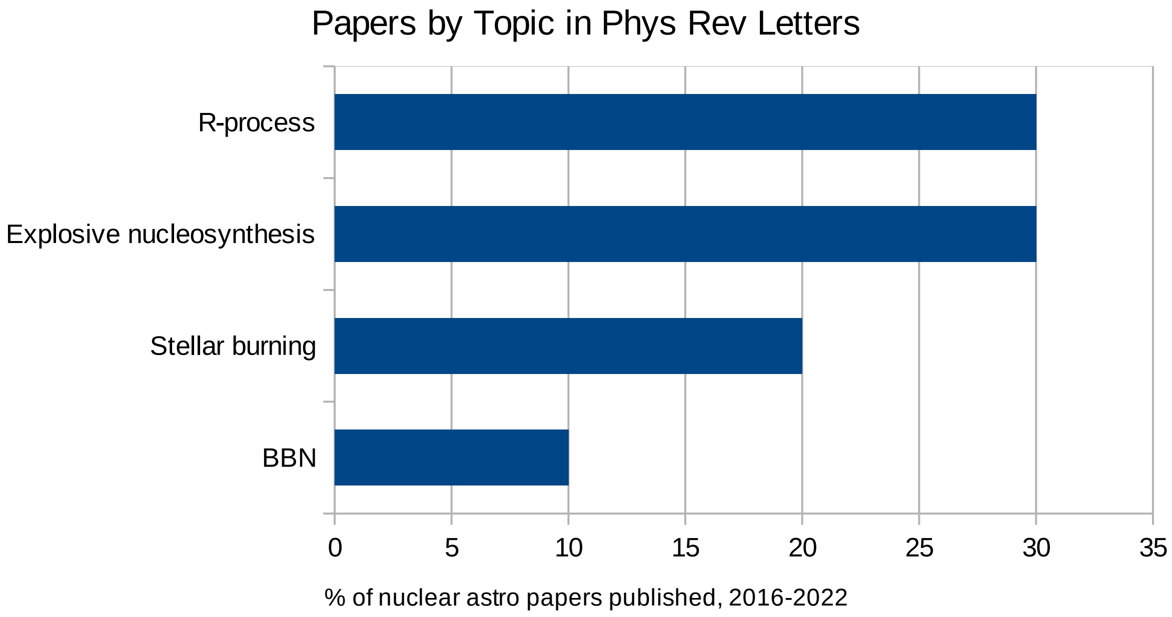
- How did visible matter come into being and how does it evolve? (Nat’l Res Coun 2013)
- How does structure arise in the universe, and how is this related to the emergence of the elements in stars and explosive processes? (LRP 2015)
- What are the rates of the key nuclear reactions in stars that define the sequence of stellar evolution and characterize the patterns of stellar life? (Astro Town Hall 2014)
- Where are the 54 elements beyond iron created, that are traditionally attributed to a rapid neutron capture process (r-process)? (Astro Town Hall 2014)
- Why is the r-process so robust, producing similar abundance patterns event by event? (Astro Town Hall 2014)
- What is the contribution of neutrino-driven winds in core collapse supernovae to nucleosynthesis? And what role do neutrino properties play? (Astro Town Hall 2014)
- What is the origin of the unexpectedly high abundance of the neutron deficient stable isotopes of molybdenum and ruthenium that are traditionally attributed to a p-process? (Astro Town Hall 2014)
- How can we use element abundance observations in stars and presolar grains to validate complex stellar models? (Astro Town Hall 2014)

The Big Picture...



How Are We Doing?

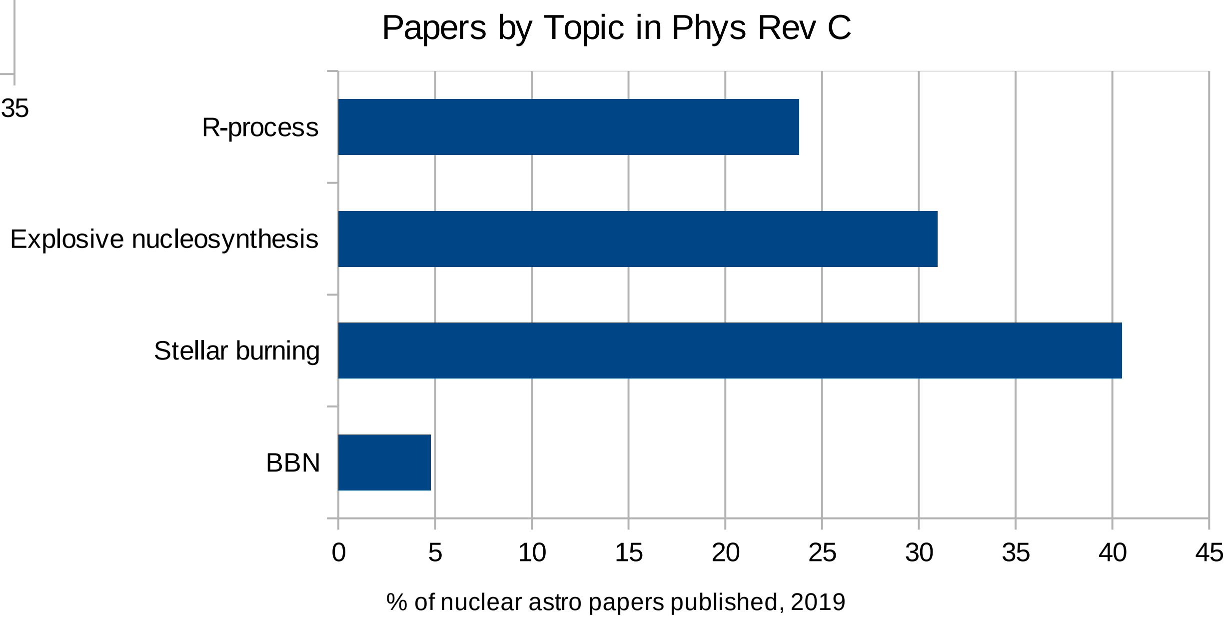
A few highlights to show the progress we've made toward answering those open questions...



GW170817 - THE FIRST OBSERVATION OF GRAVITATIONAL-WAVES FROM A BINARY NEUTRON STAR INSPIRAL

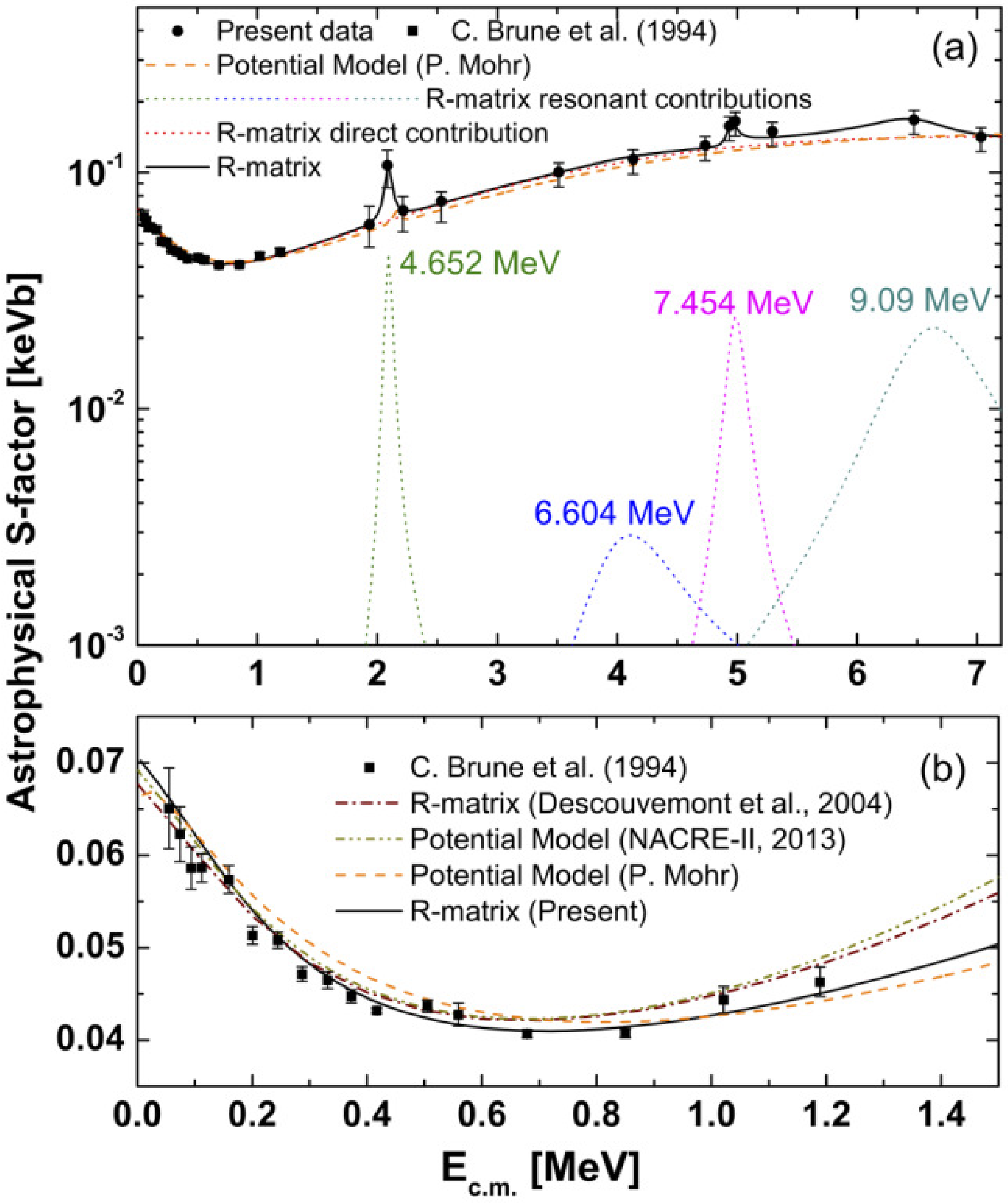
On October 16, 2017, the LIGO Scientific Collaboration, Virgo Collaboration, and its partners announced the first observation of gravitational-waves from a pair of inspiraling neutron stars. Electromagnetic emission from the resulting collision was also observed in multiple wavelength bands. This occured on August 17, 2017 and represents the first time a cosmic event was observed with both gravitational waves and light.

2022 DNP:
8 nuclear astrophysics sessions
(highest number of any sorting category!)
+2 dedicated workshop sessions
+4 dedicated minisymposia sessions



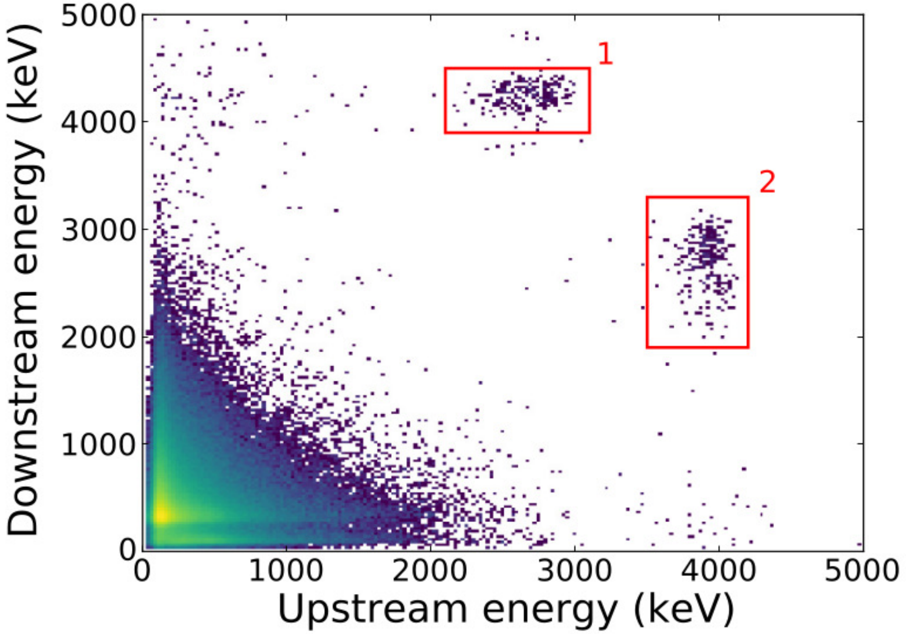
How Are We Doing? - BBN & Stellar Burning

PRC101, 055801

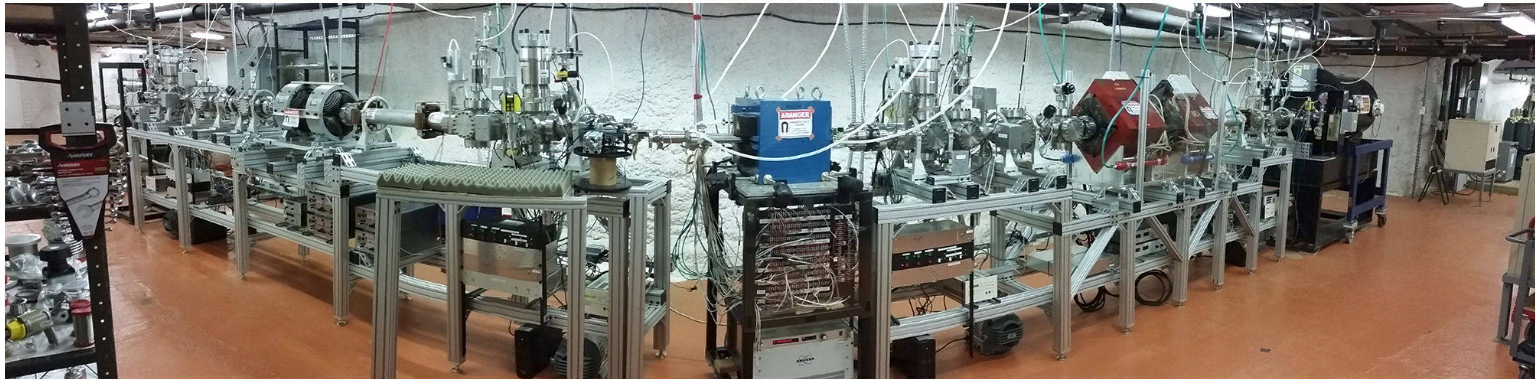


Probing the cosmological lithium problem using gamma beams

→ lithium observations in metal poor stars do not match predictions based on WMAP baryon density
→ t(α,γ)^{7}Li could compete with main ^{3}He(α,γ)^{7}Be if baryon density is lower than expected
→ novel use of a gamma beam to study time-inverse, allowing coincident detection of two charged reaction products

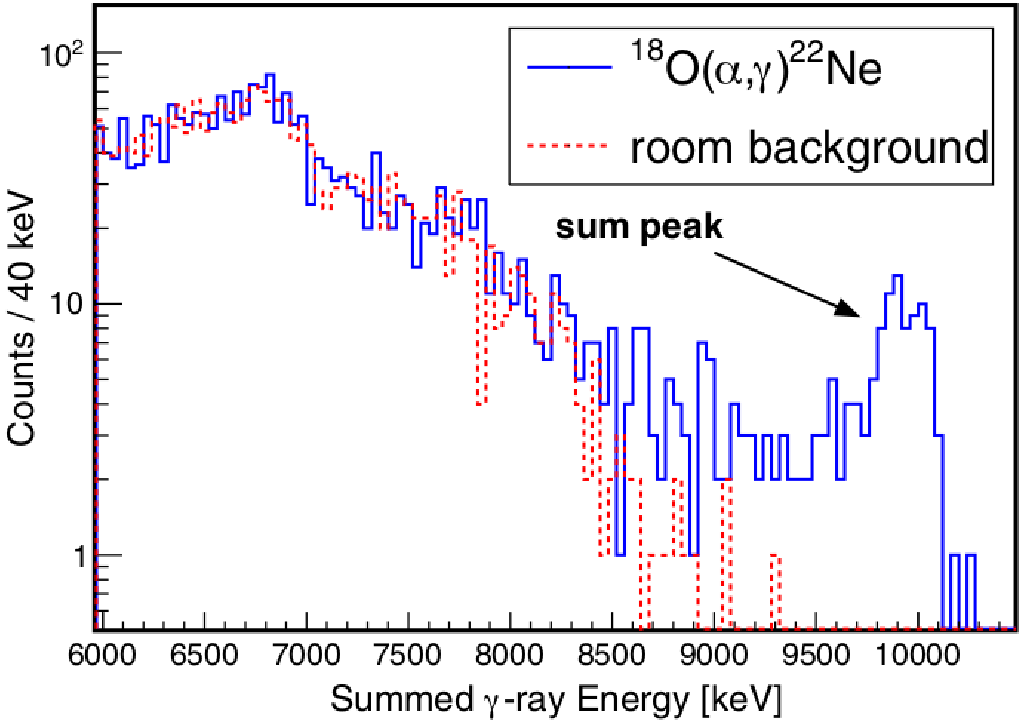


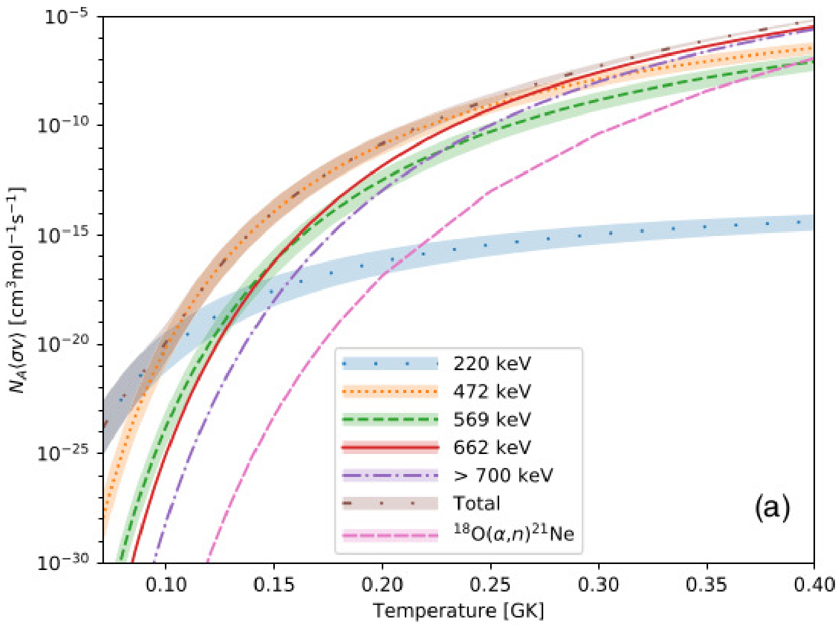
How Are We Doing? - Stellar Burning

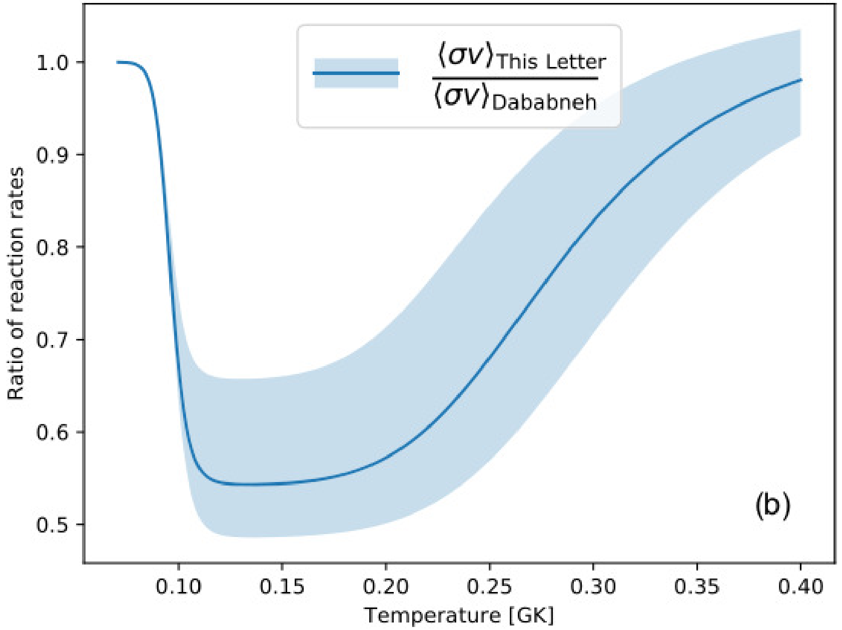


Dedicated measurements at CASPAR elucidate $^{18}O(\alpha,\gamma)^{22}Ne$ resonance strengths

→ produces ^{22}Ne in AGB stars, which is a neutron source for the s-process
→ bg reduction underground allows measurement of sub-μeV resonance strengths

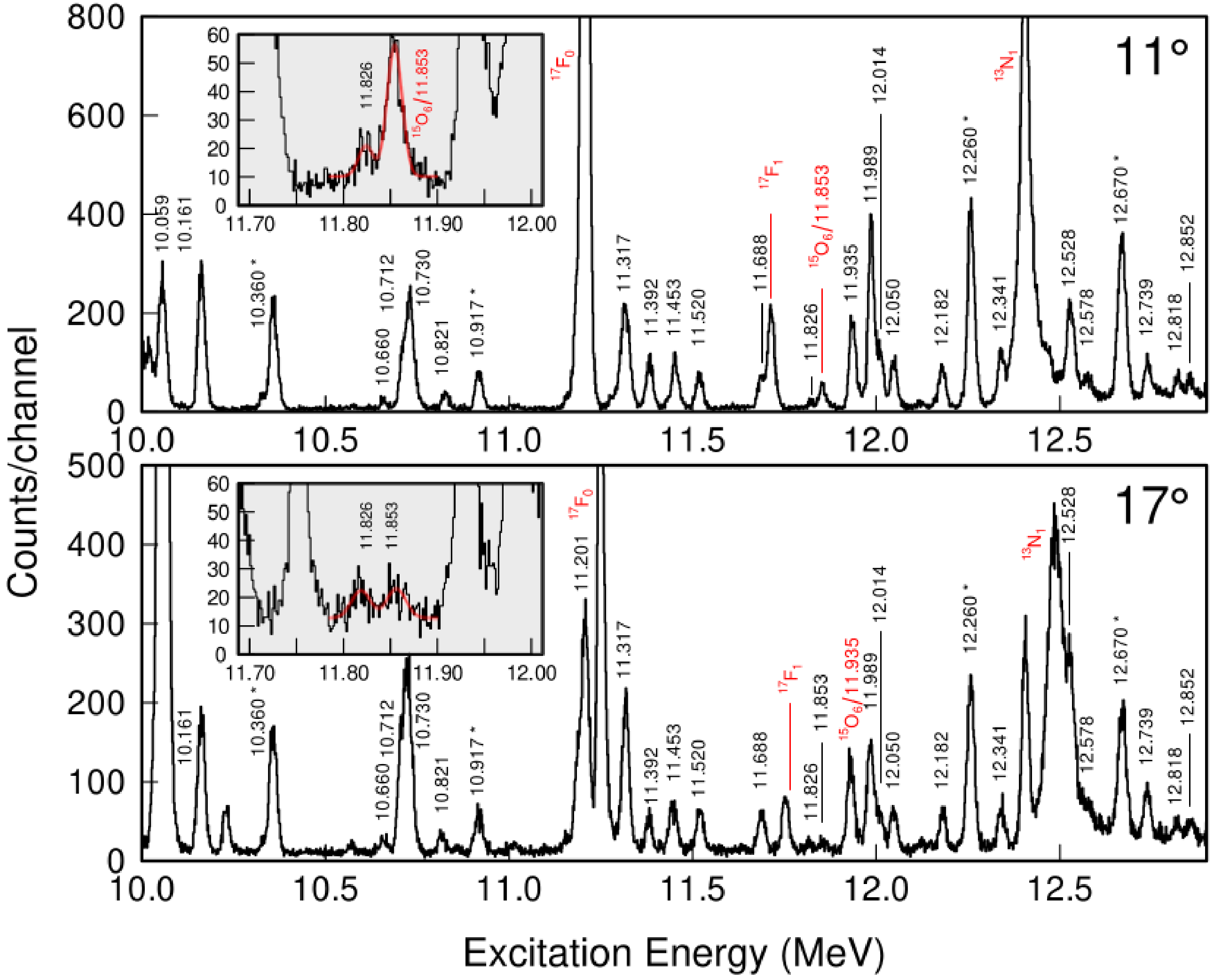


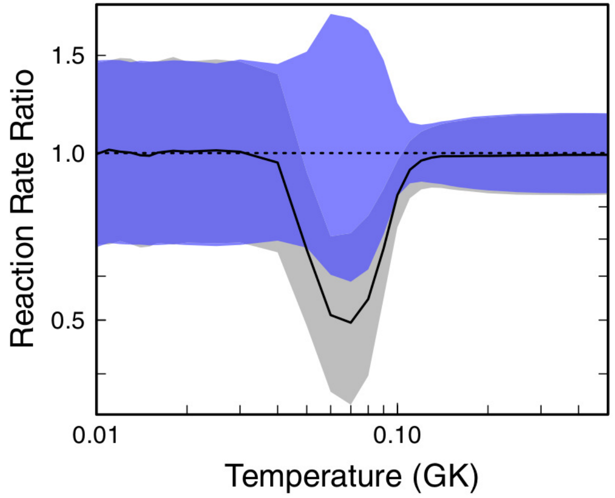




PRL128, 162701

How Are We Doing? - Stellar Burning





Resurrection of TUNL Enge leads to precision measurement of levels critical for $^{23}Na(p,\gamma)^{24}Mg$

→ anticorrelation of O/Na in atmospheres of stars in globular clusters
→ source must be “polluter” stars: impacts effectiveness of globular clusters as isolated stellar laboratories
→ 5 keV shift = x2 impact on rate

PRC104, L032801

BBN and Stellar Burning

Progress?

- Development of new techniques and application of existing techniques using different facilities, such as gamma sources, neutron sources, and underground facilities
- Revisiting literature data with precision techniques such as spectrographs
- Probing weak stellar rates with charge exchange reactions

Impact?

- Removing uncertainties in cosmological lithium production (WMAP)
- Removing uncertainties in neutron production for the s-process (stellar abundance patterns)
- Understanding how globular clusters act as stellar laboratories (oldest stars)
- Reducing uncertainties in element production in massive stars (^{60}Fe deposits)

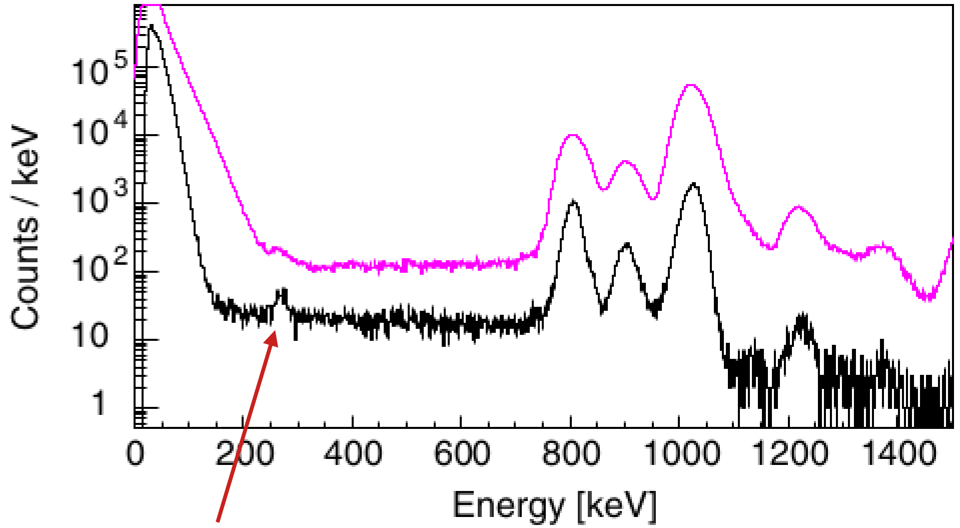
Needs?

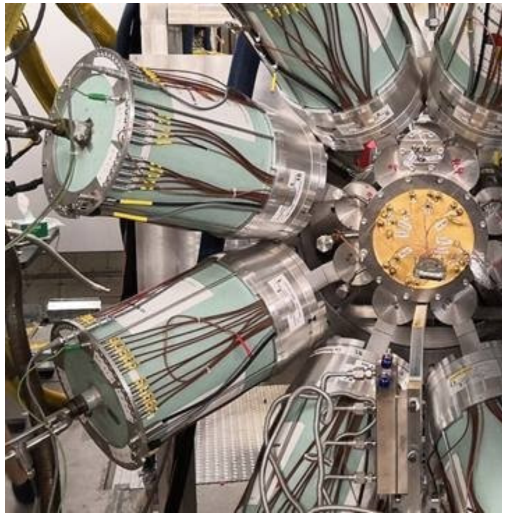
- Resources and support for these different/unique/dedicated facilities (eg ARUNA, AMUU)
- Resources and support for development and use of these instruments
- Target development – chemical forms, isotopic enrichment, windowless gas targets
- Access to up-to-date nuclear data (eg masses, levels) and models (eg quiescent burning, multi-dataset R-matrix, ab initio)

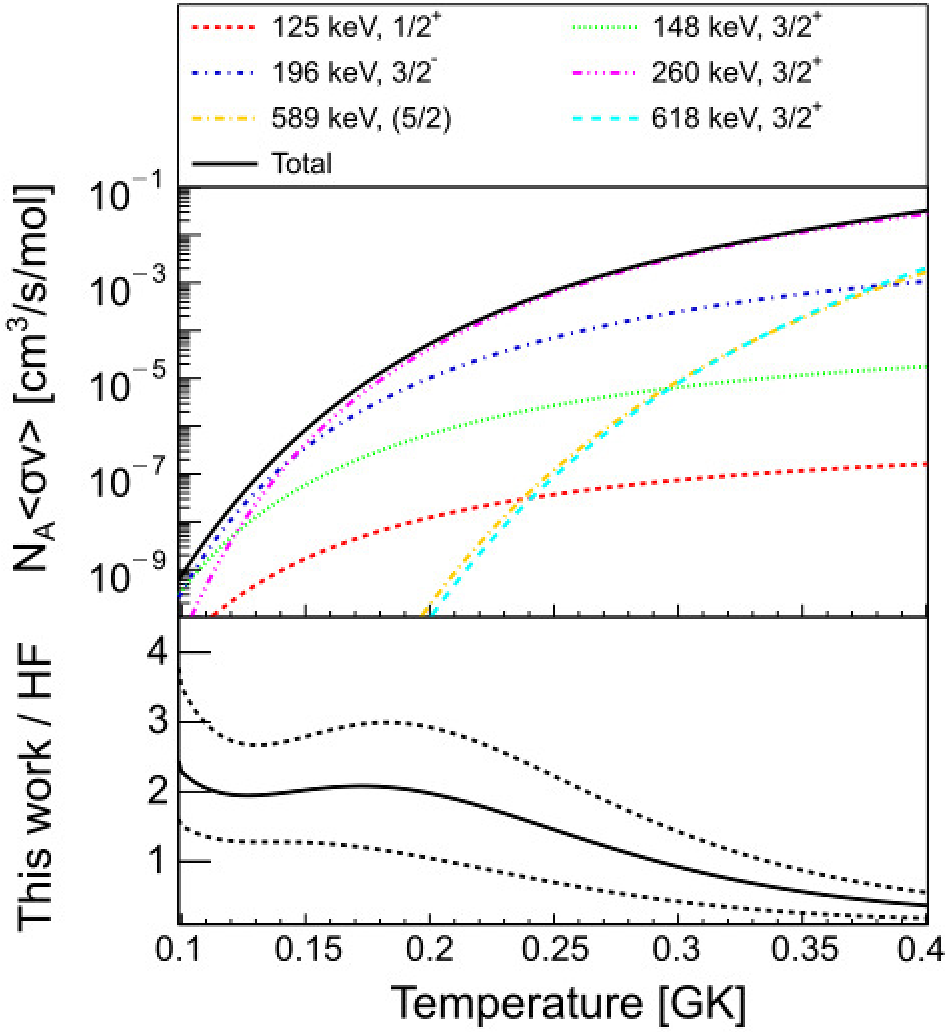
How Are We Doing? - Explosive Nucleosynthesis

Combination of particle and gamma decay allows direct observation of a proton resonance important for $^{30}P(p,\gamma)^{31}S$

→ reaction is bottleneck to nucleosynthesis of higher masses in novae
→ potential identification of nova presolar grains depends on reducing uncertainties in this rate
→ access the proton decay of this particle-unbound state using TPC+HPGe veto+fragmentation beam

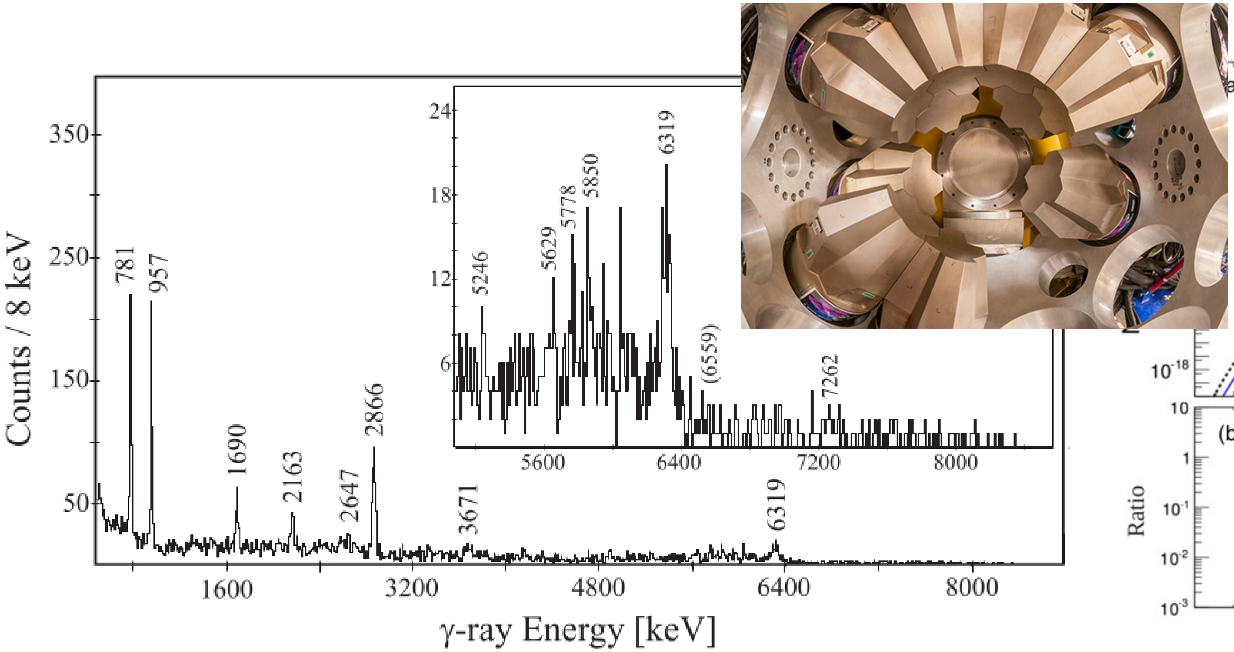


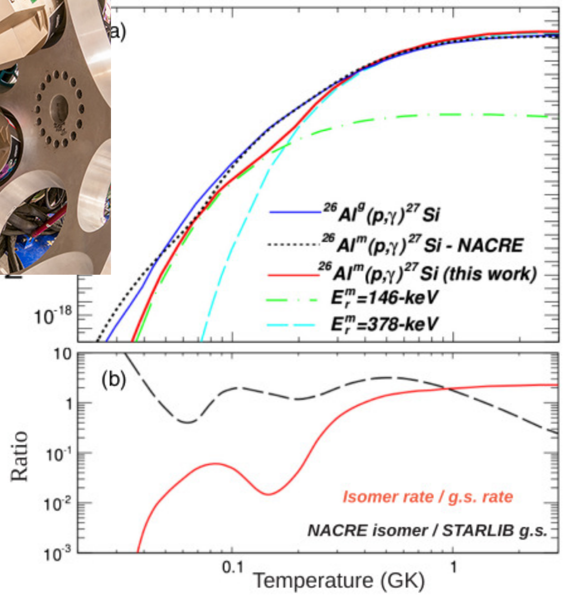


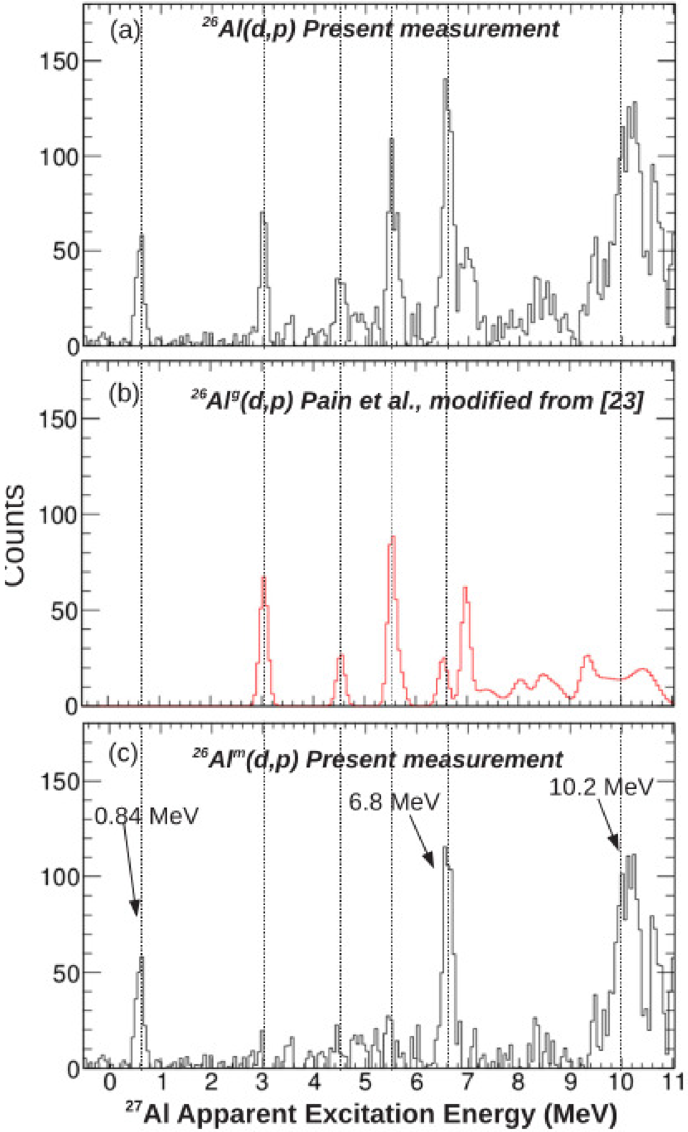


PRL128, 182701

How Are We Doing? - Explosive Nucleosynthesis





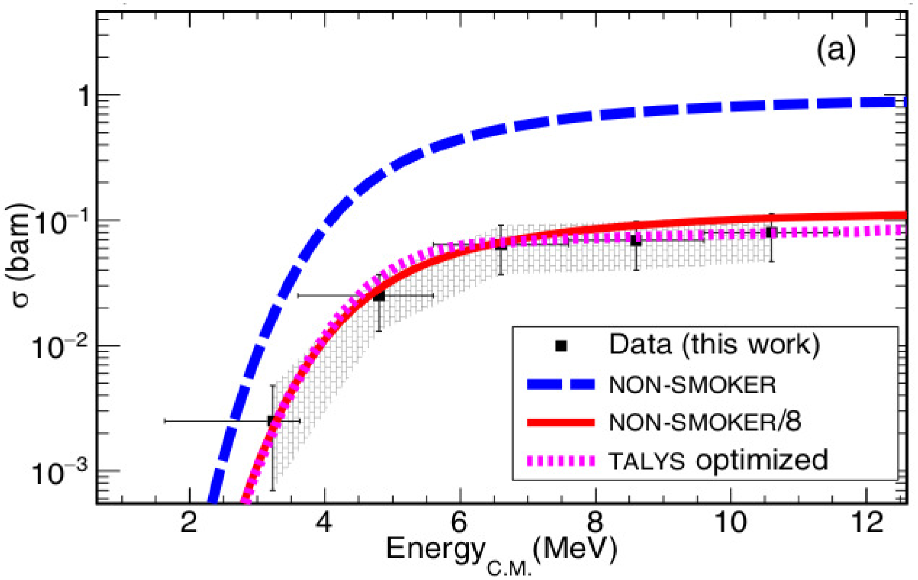


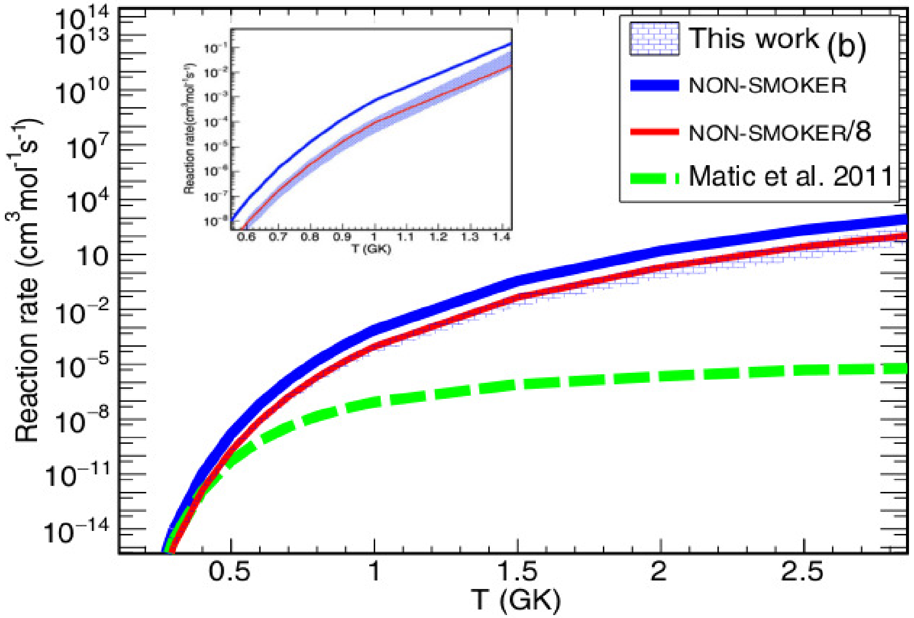
Assessing the impact of astrophysical isomers using isomeric beams and isospin symmetry

→ ^{26}Al is a well-known astrophysical observable, but isomer must be considered in reaction network
→ capture on isomer relevant to AGB stars & novae but assumption of thermal equilibrium/scaled rate may not be valid
→ study mirror states in the final nucleus with transfer on ^{26m}Al beam and study transfer on ^{26}Si gs which is mirror of ^{26m}Al

PRL119, 072701 & PRL126, 042701

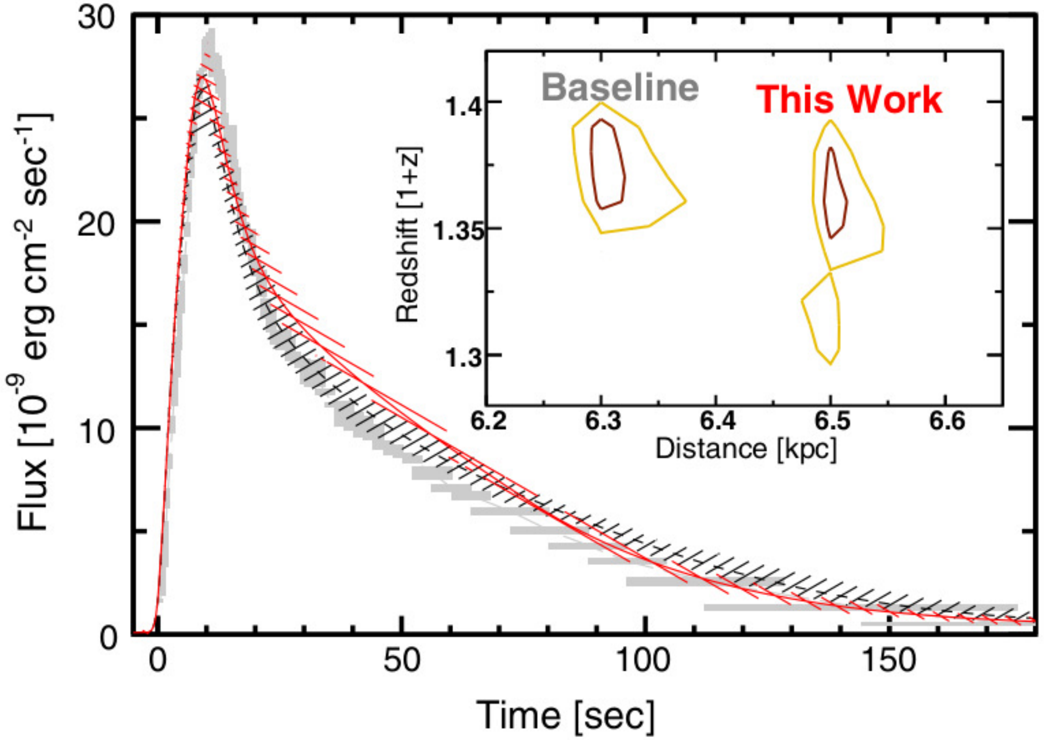
How Are We Doing? - Explosive Nucleosynthesis



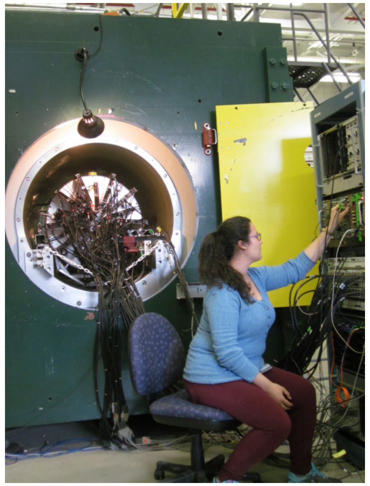


Direct measurement of ^{22}Mg(α,p)^{25}Al suggests a less compact neutron star in the x-ray burst source GS1826-24

→ indirect measurements provided a lower limit, but rate was otherwise experimentally unknown
→ disagreement with Hauser-Feshbach by almost an order of magnitude leads to changes to assumed redshift and distance of xrb
→ use of active targets (AT-TPC, MUSIC, ANASEN, etc) allows constraint of multiple energies at once



PRL125, 202701



Explosive Nucleosynthesis

Progress?

- Exploiting new and improved techniques, such as high-precision-high-efficiency particle-gamma coincidences, active targets, isospin symmetry, isomeric beams
- Probing the limits of statistical model validity, testing the shell model

Impact?

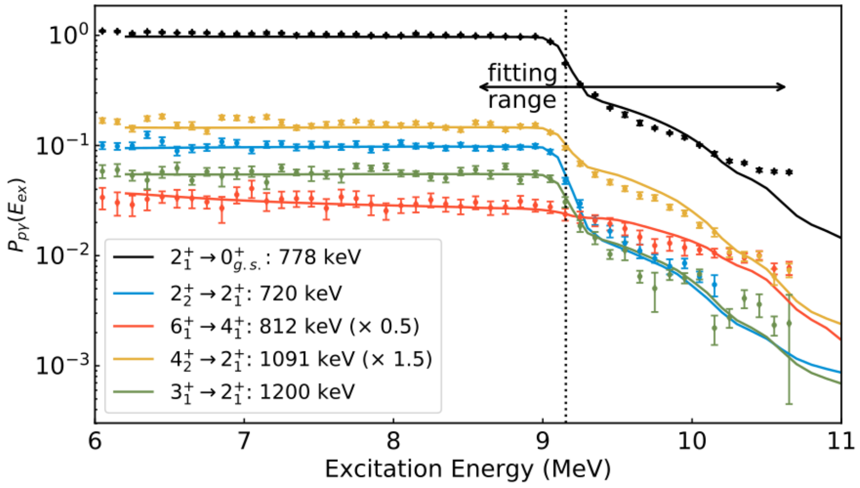
- Narrowing down contributions from production sites of galactic ^{26}Al (Integral)
- Reducing uncertainties on A~30 bottlenecks (presolar grains, xrb light curves)
- Constraining x-ray burst waiting points (xrb light curves)

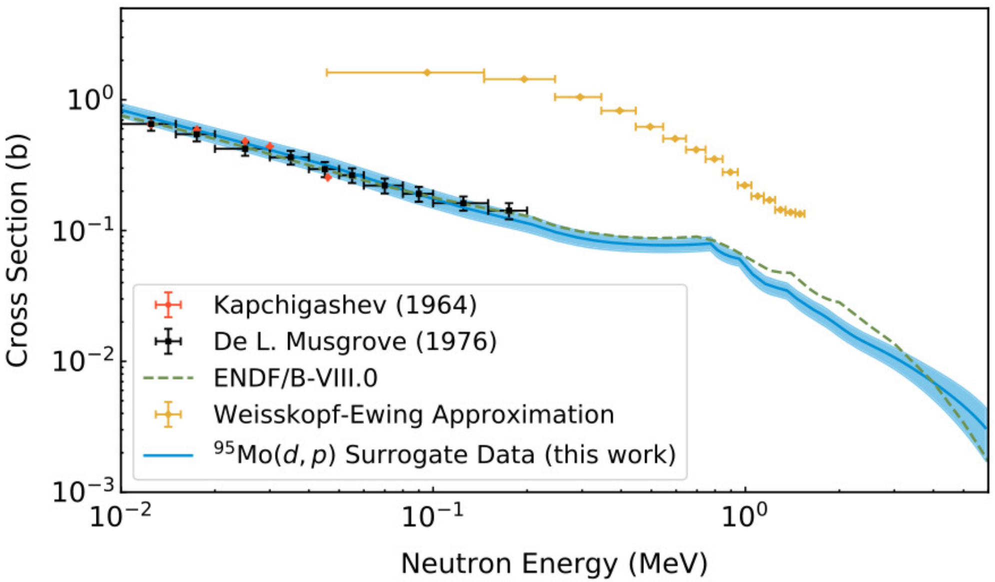
Needs?

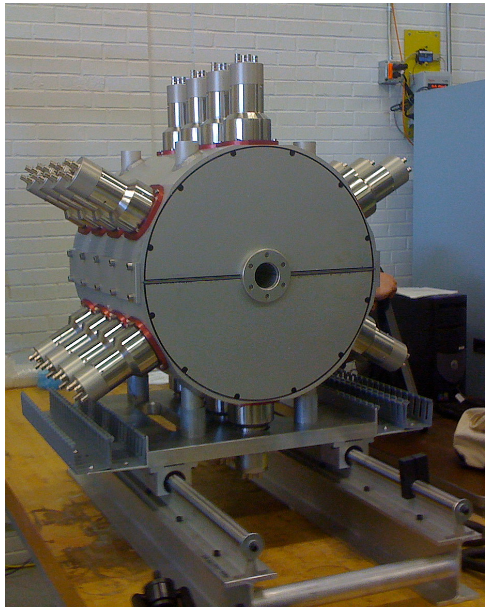
- Resources and support for ATLAS (RAISOR, stable), FRIB (ReA), and ARUNA facilities
- Resources and support for development, expansion, and use of community instruments (eg GRETA, SECAR, ReAX+ISLA) and collaborative instruments
- Target development – novel chemical forms, isotopic enrichment, jets, frozen targets, active targets
- Access to up-to-date nuclear data (eg masses, levels, deformation) and models (eg astromers, shell model interactions, QRPA, Hauser-Feshbach vs clustering)

How Are We Doing? - Heavy Elements

PRL122, 052502
& PRL117, 142701



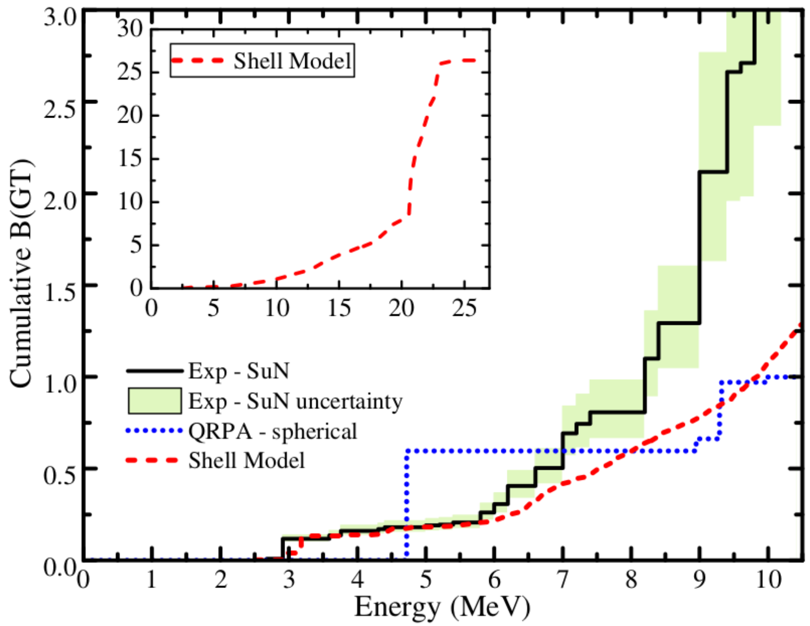




We now have a variety of indirect methods to constrain neutron capture on exotic i- and r-process isotopes

→ Surrogate Reaction Method (SRM) measures the decay of the same compound nucleus formed in a different reaction as a function of its excitation energy; the measured decay probabilities for a given exit channel are used to constrain HF calculations

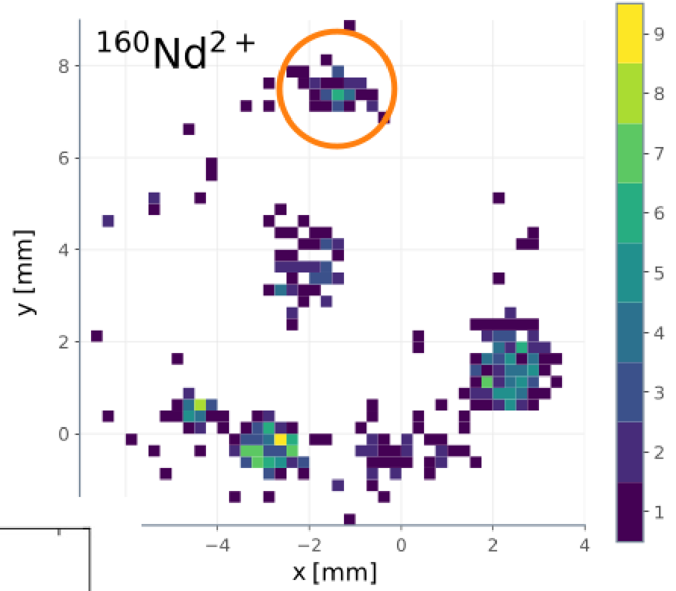
→ Oslo, Beta-Oslo, and Shape methods measure the nuclear level densities (NLD) and gamma strength functions (gSF) of the compound nucleus, which are then used to constrain inputs to HF calculations (as well as GT strength functions)

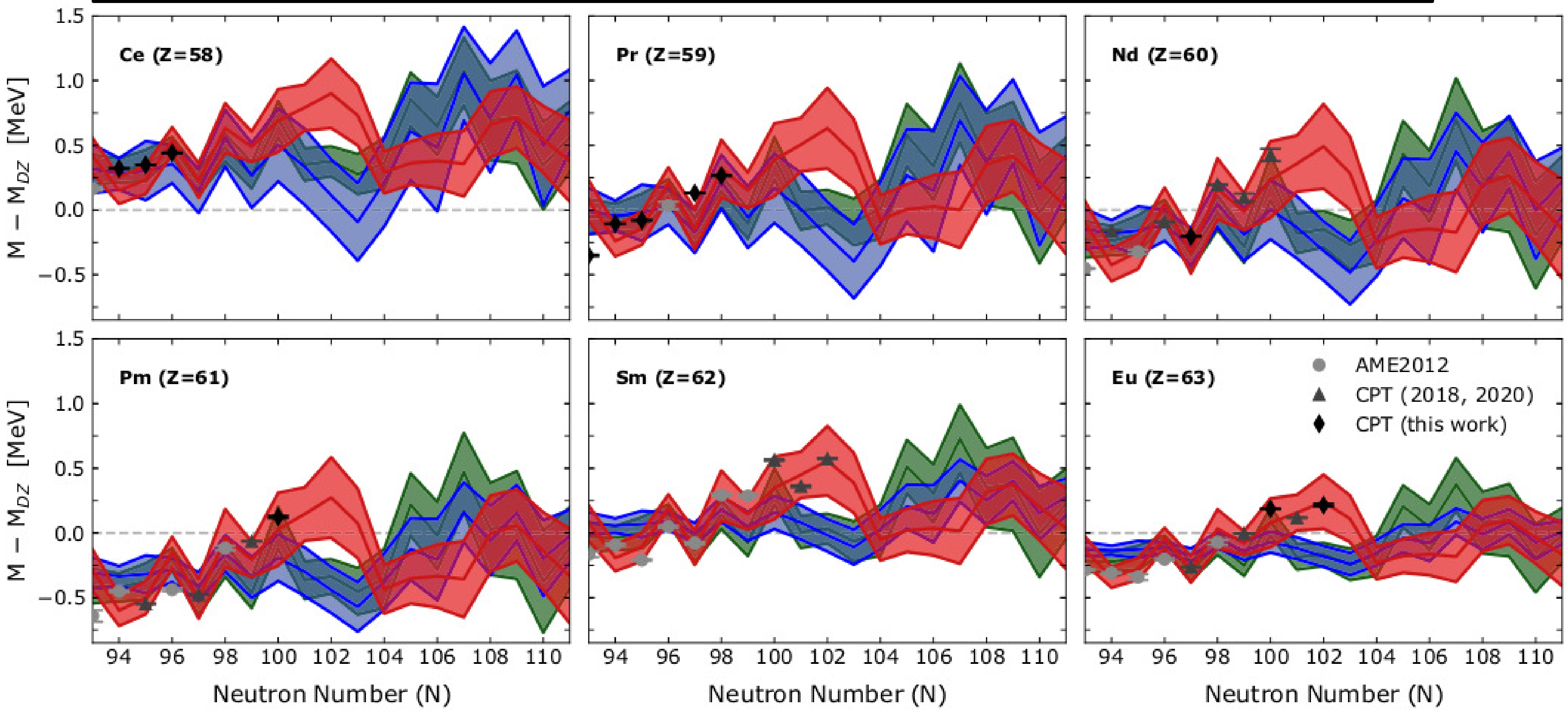


How Are We Doing? - Heavy Elements

Precision mass measurements of most neutron-rich CARIBU isotopes using PI-ICR at the CPT pins down astrophysical outflow conditions

→ masses near N=100, A=164 r-process “rare earth peak”
→ data compared to MCMC reverse engineering of mass surface needed to reproduce observed solar abundance patterns given a particular NSM outflow model (hot, cold, mixed)





PRL120, 262702
& PRC105, L052802

Heavy Elements

Progress?

- Validating multiple techniques for constraining neutron capture rates
- Building large datasets of beta and beta-xn decays
- Using mirror pair charge radii to constrain symmetry energy/ heavy ion reactions for EOS of neutron matter
- Measuring masses approaching the r-process path

Impact?

- Reducing uncertainties in nuclear data for NSM physics (multimessenger astronomy)
- Constraining the different sources of r-process elements (stellar abundance patterns)

Needs?

- Resources and support for ATLAS (N=126, nuCARIBU), FRIB (FRIB400) facilities
- Resources and support for development, expansion, and use of community instruments (eg FDS, GRETA, HRS) and collaborative instruments
- Target development – isotopic enrichment, variety of high-A materials
- Access to up-to-date nuclear data (eg masses, decay branches) and models (eg dynamical neutron-rich matter, reaction theory, mass models, gSFs)

How Are We Doing? - A Nowhere-Near-Exhaustive Recap

- New or newly-improved techniques allowed for increases in sensitivity and reach (this is just a tiny fraction!) and set us up for future impactful measurements
- An entire suite of complementary facilities and instruments were used (so much is happening all across the US and internationally!)
- Measurements spanned the range of astrophysical processes and environments (I haven't come close to covering everything!)
- Results had impact on other aspects of astrophysics, as well as astrophysical models and nuclear theory (not to mention pushing the facility and instrumentation needs!)

Prior LRP Recommendations

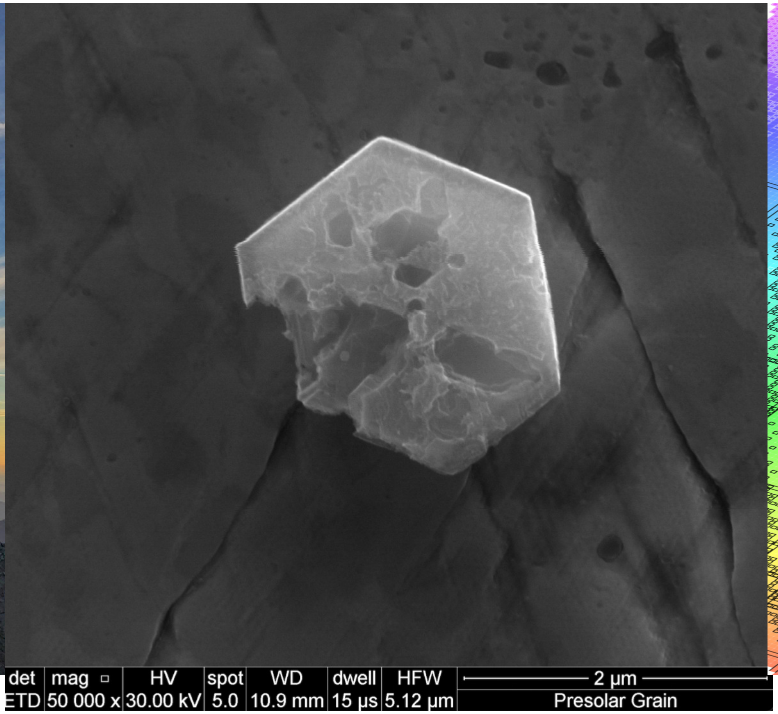
- The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made. […] Expeditiously completing the Facility for Rare Isotope Beams (FRIB) construction is essential. Initiating its scientific program will revolutionize our understanding of nuclei and their role in the cosmos.

- We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

- *Initiative: Workforce, Education, and Outreach* – Support the creation of a prestigious fellowship program designed to enhance the visibility of outstanding postdoctoral researchers across the field of nuclear science.

So Where Do We Go From Here?

A few highlights of open and compelling questions in the field...



Stellar Burning

Can nuclear reactions critical to the CNO neutrino flux from the Sun be measured with the required precision?

TABLE 8 | Dominant theoretical error sources for neutrino fluxes and for the main characteristics of the SSM.

Quant	**Dominant theoretical error sources in %**			
$\Phi(pp)$	$L_\odot$: 0.3	S_{34}: 0.3	κ: 0.2	Diff: 0.2
$\Phi(pep)$	κ: 0.5	$L_\odot$: 0.4	S_{34}: 0.4	S_{11}: 0.2
$\Phi(hep)$	S_{hep}: 30.2	S_{33}: 2.4	κ: 1.1	Diff: 0.5
$\Phi(^7Be)$	S_{34}: 4.1	κ: 3.8	S_{33}: 2.3	Diff: 1.9
$\Phi(^8B)$	κ: 7.3	S_{17}: 4.8	Diff: 4.0	S_{34}: 3.9
$\Phi(^{13}N)$	C: 10.0	S_{114}: 5.4	Diff: 4.8	κ: 3.9
$\Phi(^{15}O)$	C: 9.4	S_{114}: 7.9	Diff: 5.6	κ: 5.5
$\Phi(^{17}F)$	O: 12.6	S_{116}: 8.8	κ: 6.0	Diff: 6.0

Astrophysical S factor differences of just a few percent can cause solar models to disagree with observations by $>1\sigma$

→ 1/3rd of major sources of uncertainty in neutrino flux are nuclear physics

→ measurements are needed at 10s of keV; extrapolations can be unreliable due to lack of structure info, plasma effects...

Connections to neutrino astronomy, stellar modeling

Villante Frontiers 618356 (2021)

Explosive Nucleosynthesis

What is the role of "astromers" in nucleosynthesis?

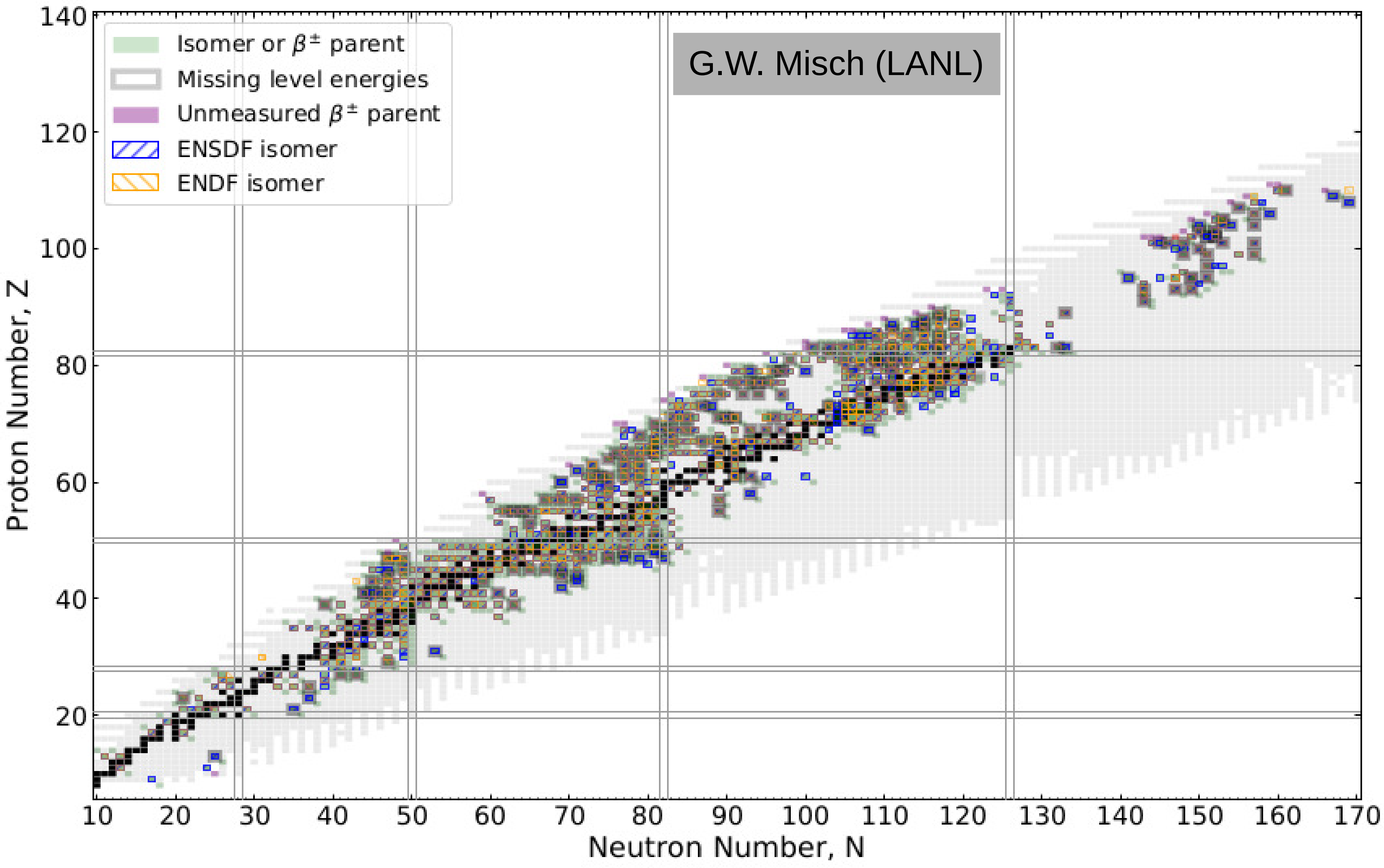
^{26}Al is the most well-known, but many isomers exist along the rp-process path

→ long-lived isomers can be populated thermally or as a decay endproduct

→ assumptions of thermal equilibrium may not be valid due to high angular momentum barriers, large differences in lifetime, coupling through higher-lying states needs large partial widths

→ mixed populations impact effective lifetimes and stellar enhancement factors

Connections to x-ray astronomy, presolar grain analysis, post-processing models



Heavy Elements

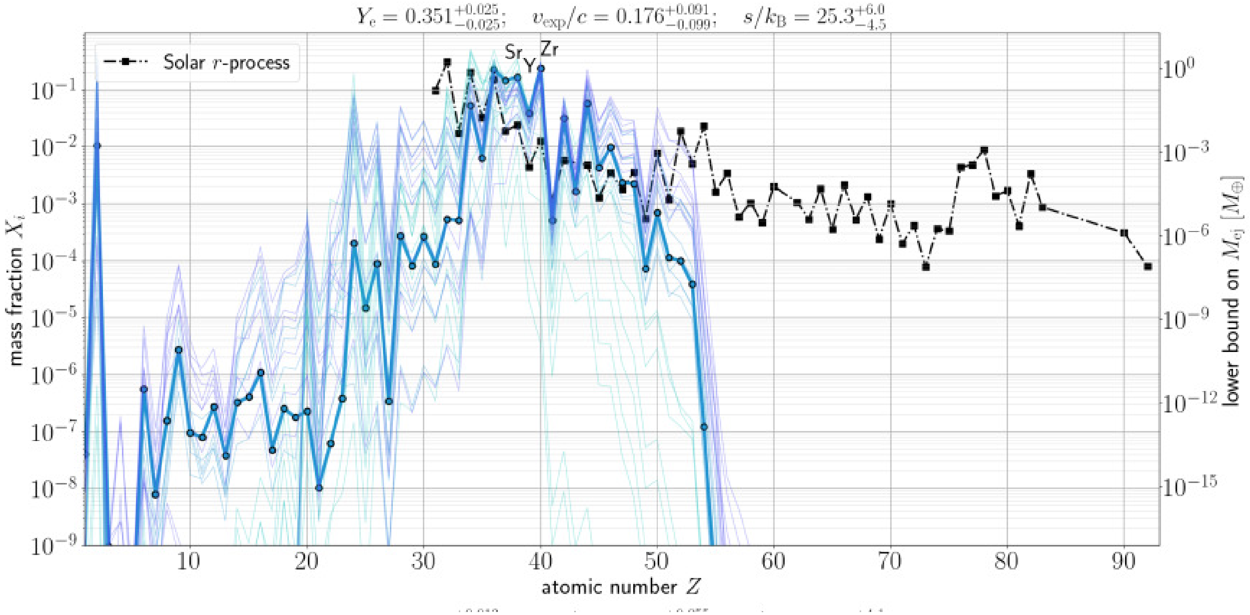
Can we constrain the various astrophysical contributions to r-process abundances with nuclear data?

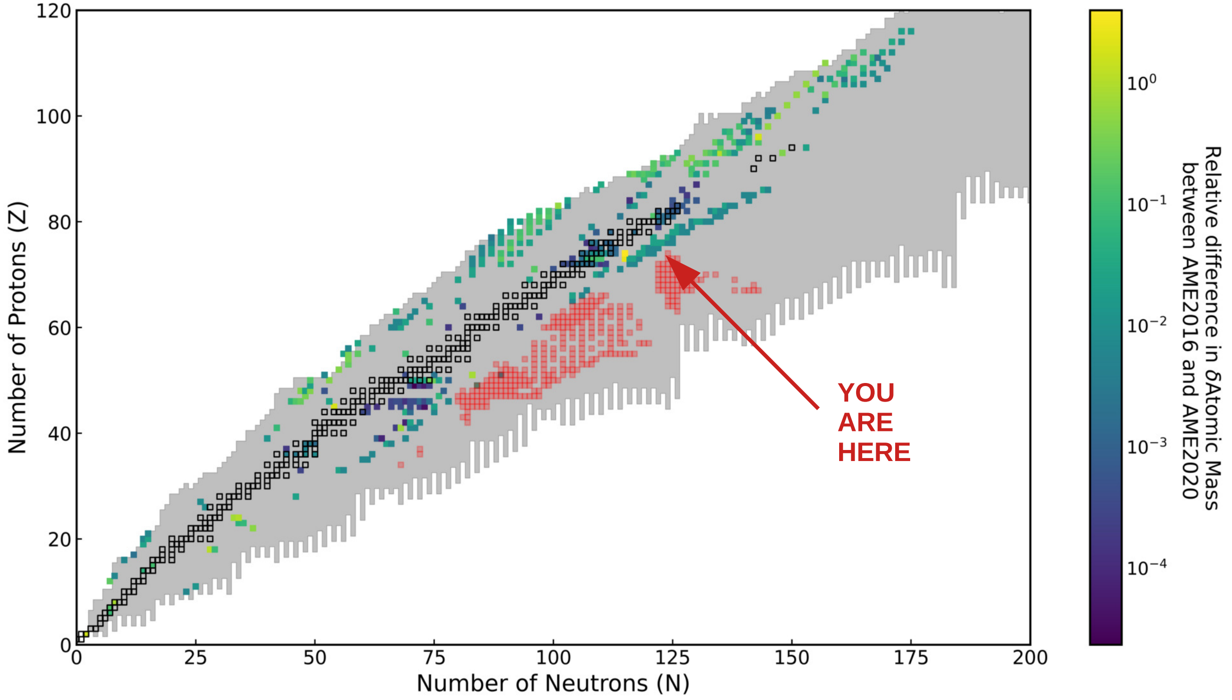
More precise knowledge of nuclear masses, decay branches, neutron capture, fission probabilities, spallation reactions can help (especially when combined with new and next-gen observational data) pin down the astrophysics of r-process sites

→ still some places, like the first r-process peak, where the uncertainty in the masses are driving abundance pattern changes on par with the uncertainties in the astrophysics

→ reverse engineering from the nuclear physics data and the observational data are allowing more meaningful constraints on the astrophysical conditions

Connections to MMA, machine learning, atomic physics





Vieira arxiv2209:06951,
A. Ratkiewicz (LLNL)

What Do We Need? - Recap

- Support for **research** groups at universities and labs across the US – these are the **people driving the science**, we need to **support** and **grow** the community!
- Support for our **facilities** – we cannot do the science if we have nowhere to do it
  - → **Operations** and maintenance
  - → **Upgrades** and community-driven initiatives
  - → **Staffing**/resources (eg targets, detectors)
- Support for nuclear **data** – we need timely evaluations and regularly maintained and updated standardized libraries of masses, rates, branches
- Support for **theory** – we need astro/network/GCE models to incorporate potentially important effects that have not been considered fully, such as isomers, spallation, fission cycling; and we need developments in nuclear theory to support our understanding of astrophysically-important reactions
- Robust observations of isotopic abundances in stars and meteoritic grains; more kilonovae observations; up-to-date atomic spectra; and national/international centers to bring it all together

Thanks

Rebecca Surman, Grisha Rogachev, Sofia Quaglioni, Alex Gade, Hendrik Schatz, Melina Avila, Aaron Couture, Dan Bardayan, Catherine Deibel, Richard Longland, Alan McIntosh, Frank Strieder, Manoel Couder, Wei Jia Ong, Raph Hix, Fernando Montes, Nicole Vassh, Ben Crider, Biying Liu, Adrian Valverde, Wendell Misch, Andrew Ratkiewicz,
and the good people at Counter Culture Coffee and Vienna Coffee

Backup Slides

What Are the Remaining Open Questions? - 2022 Horizons Whitepaper

BBN & Stellar Burning

- What are the rates of proton-, neutron-, and alpha-capture reactions, photodissociation, and carbon and oxygen fusion in stars, and how do we measure at stellar energies?
- What are the nuclear reactions in first stars after Big Bang, and what elements did they produce?

Explosive Nucleosynthesis

- How much galactic ^{26}Al is produced, and what are heaviest elements synthesized in novae?
- What unique isotopic signatures can be used to identify nova origin presolar grains?
- What are isotopic abundances of iron group elements produced in Type I supernovae, and do these contribute to p-nuclei?
- What do nucleosynthesis signatures tell us about Type I SN progenitors?

R-Process, Dense Neutron Matter, and the Heavy Elements

- What are astrophysical sources of heavy elements (&relative contributions), and how have these evolved?
- What are properties of heavy radioactive isotopes and their reaction rates far from stability, how do they affect nucleosynthesis, and how do we push experimental technologies to access this full range?
- How do we use latest experimental developments to improve accuracy and quantify uncertainty in isotopic yield predictions?
- How do we distinguish multiple possible origins of light trans-Fe isotopes (Ge to Cd)?
- How does nucleosynthesis beyond lead/bismuth proceed, what is the role of fission, and how do these isotopes manifest in observation?
- How robust are different nuclear physics models in describing the interiors of neutron stars?
- How can we best connect nuclear experiments with properties of neutron-rich matter in crust and core of neutron stars?
- Do we fully understand systematic uncertainties in analysis of observational data combined with nuclear structure and heavy ion reaction data?

What Do We Need? - 2022 Horizons Whitepaper

- Underground facilities and high sensitivity techniques
- Advanced neutron and gamma facilities
- Radioactive target development for reaction studies
- Capabilities to probe reactions in plasma
- Advanced rare isotope beam facilities that push neutron-rich isotope production (eg FRIB, nuCARIBU, N=126)
- Advanced rare isotope beam facilities that make high intensity neutron deficient isotopes
- A full range of instrumentation to take advantage of these beams
- Storage ring and/or isotope harvesting for direct neutron capture measurements
- Intense beams at or near stability for weak r-, νp-, rp-, and p-processes
- Systematic analysis of uncertainties in nuclear models and data from nuclear experiments
- FRIB400 upgrade to compress neutron rich matter in heavy ion collisions to 2x nuclear density
- Experimental data on masses and weak interactions of neutron-rich isotopes
- Broad community buy-in and a concerted effort to make DEIA goals equal footing with scientific goals

highlighted here are the experimental nuclear astro needs and open questions;
see https://arxiv.org/abs/2205.07996 for more details!