Fission In R-process Elements (FIRE)

NSAC Meeting

March, 5th 2020

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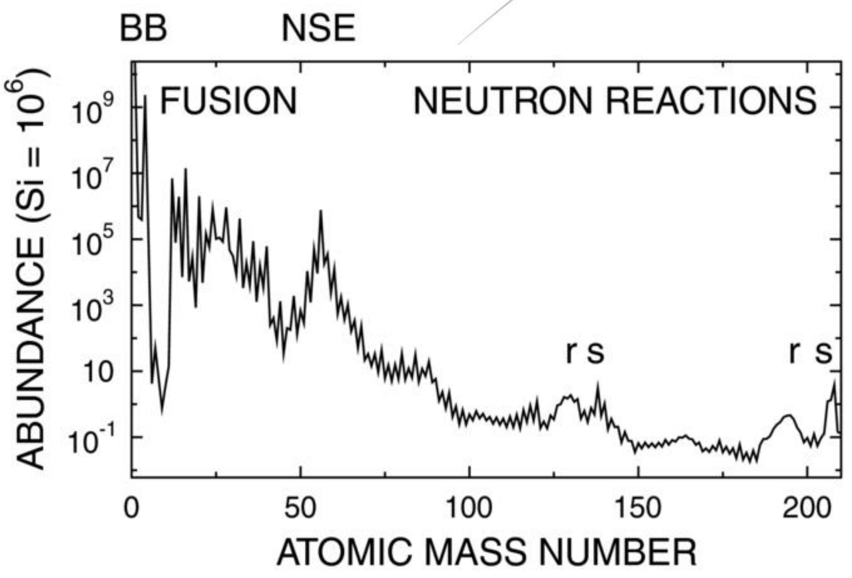
Factsheet

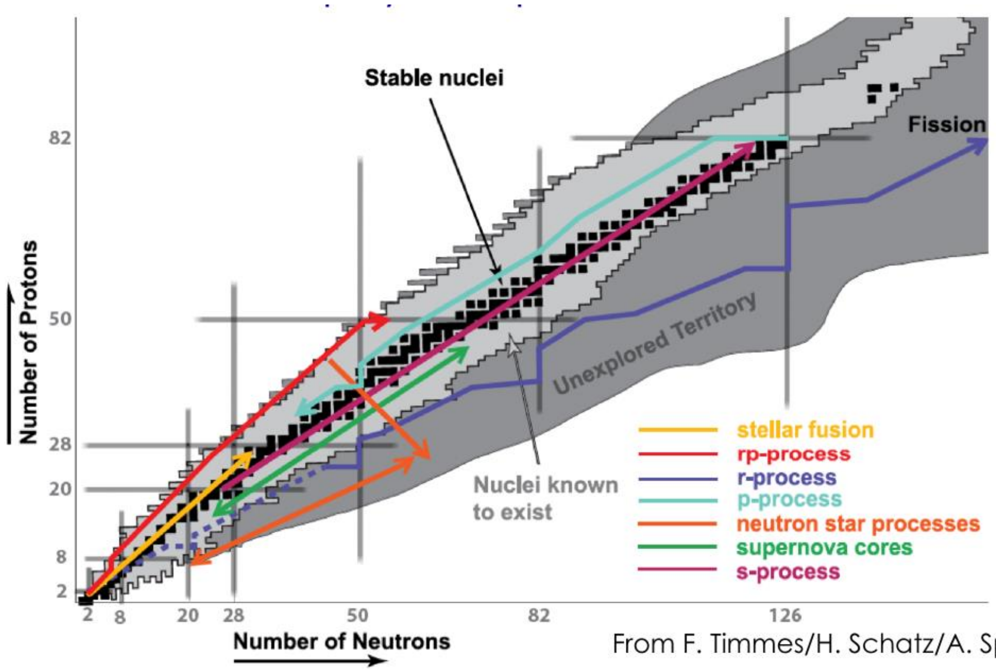
The goal of the FIRE collaboration is to understand the formation of heavy elements in the universe

- Three main topical areas
  - Astrophysics
  - Nuclear physics (structure and reactions)
  - Nuclear data
- Budget: $500k/year
  - 2 postdocs (ND and LANL)
  - 1 graduate student (NCSU)
  - 1 summer student (LLNL)
- 3 funding agencies
  - DOE/NP: $100k/year
  - DOE/USNDP: $100k/year
  - NA22: $300k/year
- Metrics (current)
  - 14 published articles
  - 3 submitted articles
  - >29 colloquia, invited talks, seminars
  - 1 FRIB TA Topical Program

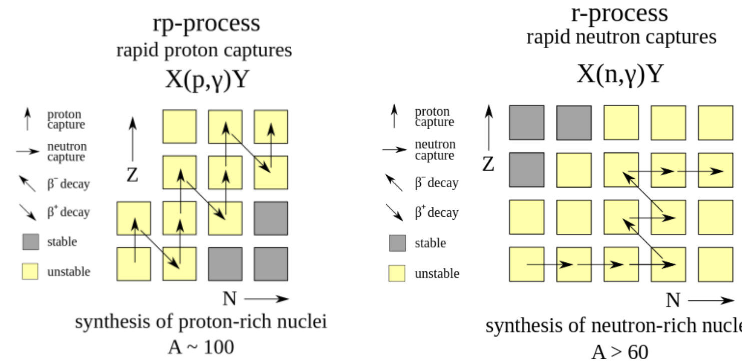


Nucleosynthesis

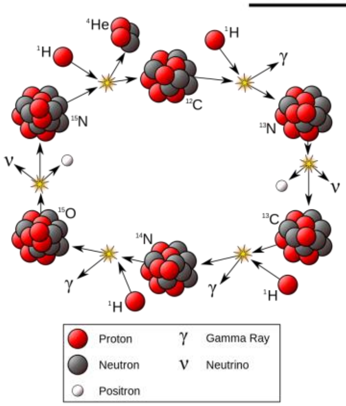
Elements are formed in several different networks of nuclear reactions taking place in various astrophysical environments

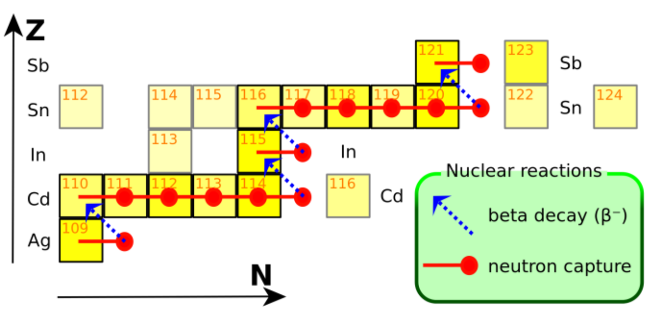


From F. Timmes/H. Schatz/A. Spyrou



- Stellar processes involve reactions with light nuclei
  - Reaction rates can be measured accurately
  - Astrophysical conditions drive remaining uncertainty
- Heavy elements are formed in neutron-rich environments
  - No experimental data
  - Rely on theoretical models





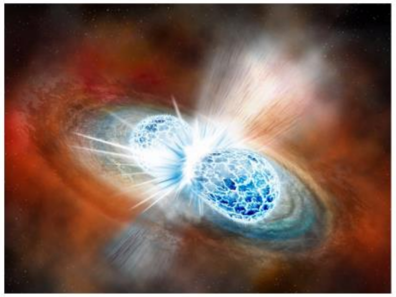
The R Process

Heavy elements are formed through rapid neutron capture reactions in very neutron-rich environments

- Exact conditions still under debate
- Multi-messenger observation of neutron star merger (GW170817) suggests NN mergers are definite candidates
- Supernovae, black-hole collisions, etc. still not completely ruled out

Astronomers just proved the incredible origin of nearly all gold, platinum, and silver in the universe

Dave Mosher Oct. 16, 2017, 10:35 AM



An illustration of two neutron stars colliding. NASA

Berkeley News Research People

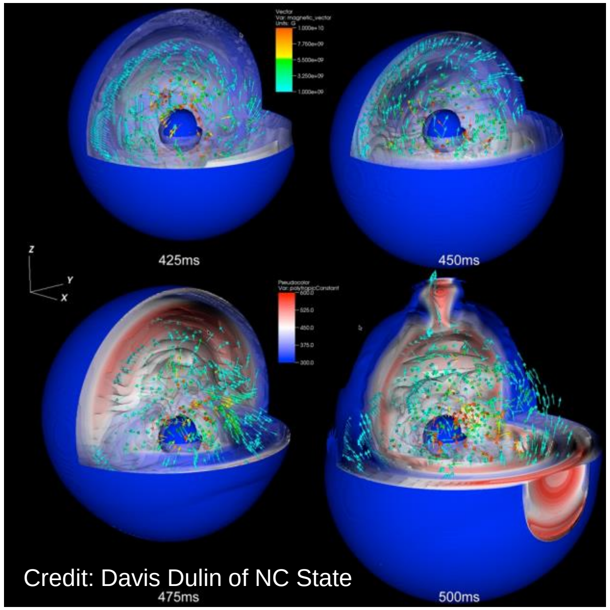
RESEARCH, SCIENCE & ENVIRONMENT

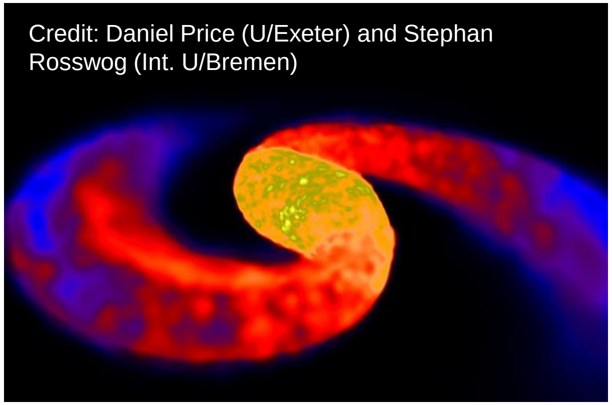
Astronomers strike cosmic gold

By Robert Sanders, Media relations | OCTOBER 16, 2017

Scientists witness huge cosmic crash, find origins of gold

Doyle Rice, USA TODAY Published 10:21 a.m. ET Oct. 16, 2017 | Updated 9:06 a.m. ET Oct. 17, 2017

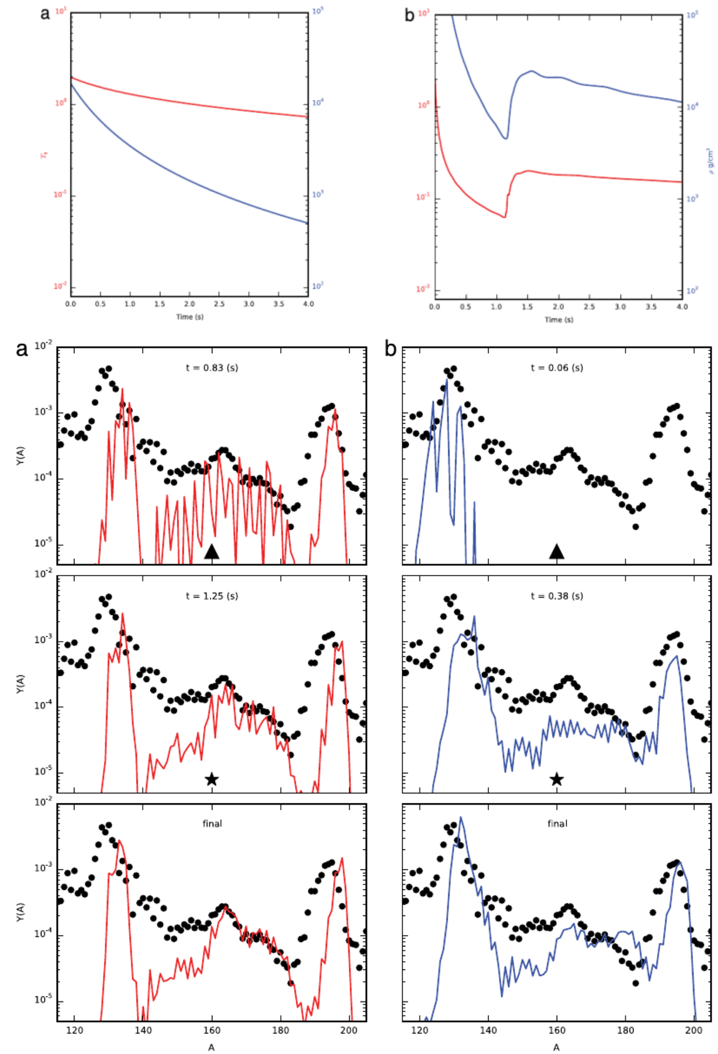




Ingredients of r-process Simulations

Theoretical simulations require complete and precise nuclear data for all nuclei in the nuclear chart, as well as astrophysical conditions

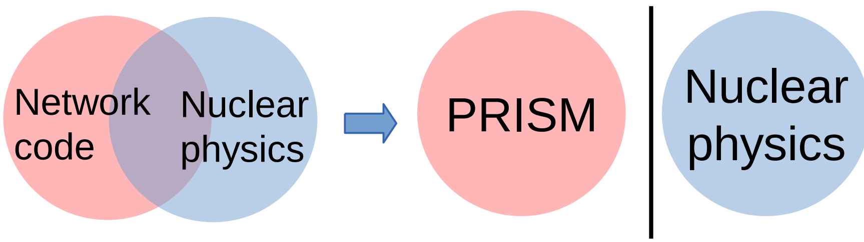
- To calculate: relative abundances of given elements $Y_Z(t)$, $Y_A(t)$, etc.
- Astrophysical inputs = Simulation of supernova explosion or NN merger
  - Provide density and temperature for Maxwell-Boltzmann statistics
- Nuclear physics inputs for given (Z,N)
  - Q-values for all decays
  - Decay rates: α-, β-, γ-decay, fission(s)
  - Reaction rates: n-capture, photoreactions
  - Decay products
- Nuclear reaction network is set of coupled differential equations giving variations of abundances as a function of nuclear rates
- Compare with stellar and solar abundances



Nucleosynthesis Codes

The FIRE collaboration uses PRISM to compute r-process abundances based on a set of nuclear and astrophysics inputs

- Code co-developed under SciDAC and JINA support
- Clear-cut separation of nuclear models and reaction network

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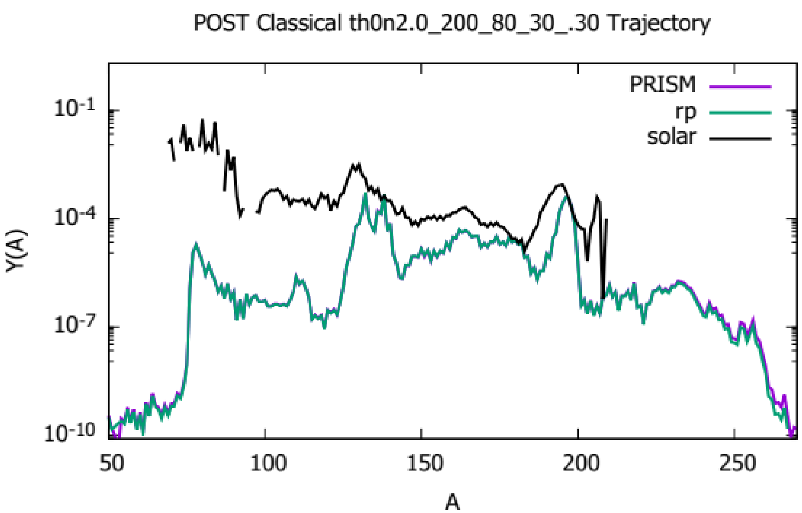
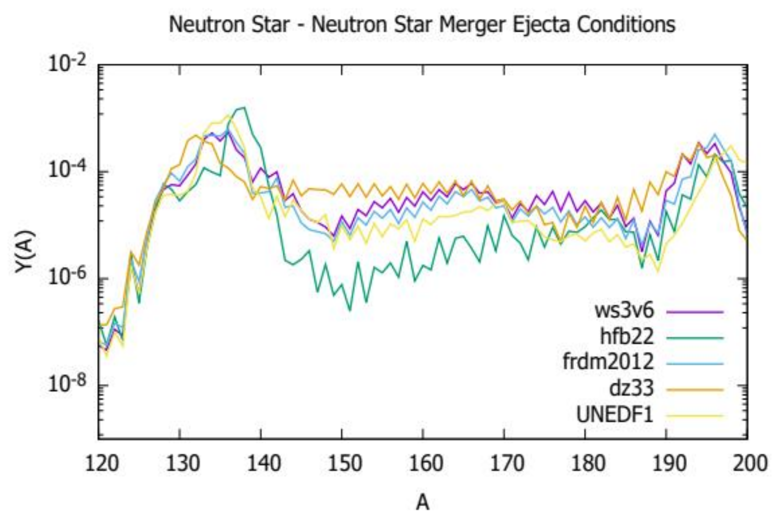
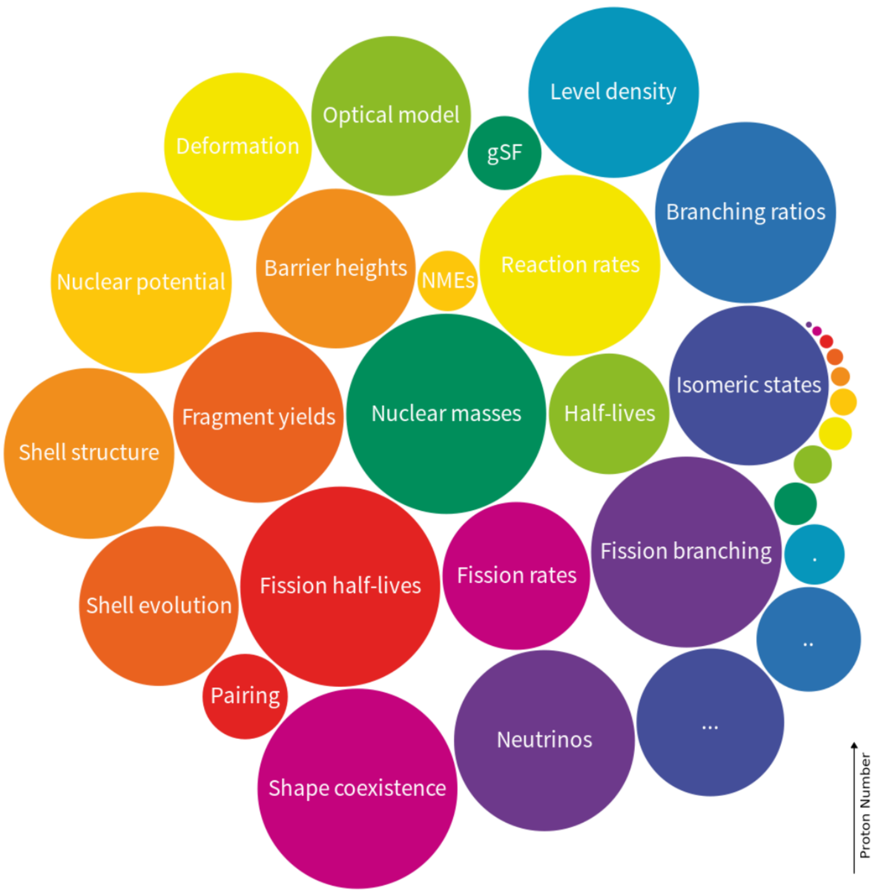




Nuclear Inputs

Complete information about the structure, decay and reactions of all atomic nuclei is needed

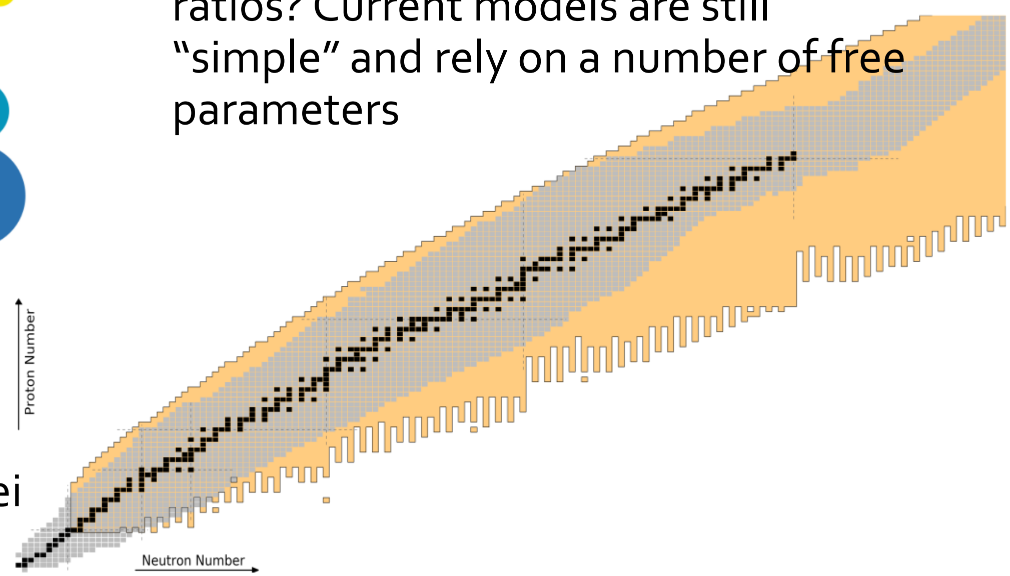


- Ground-state properties ⇒ Q-values
- Consistent description of β- and γ-decay
- Direct calculation of fission yields
- Couplings between fission and reaction theory

FIRE

- Capture rates? α decay? Branching ratios? Current models are still "simple" and rely on a number of free parameters

We need this information for 1000's of nuclei



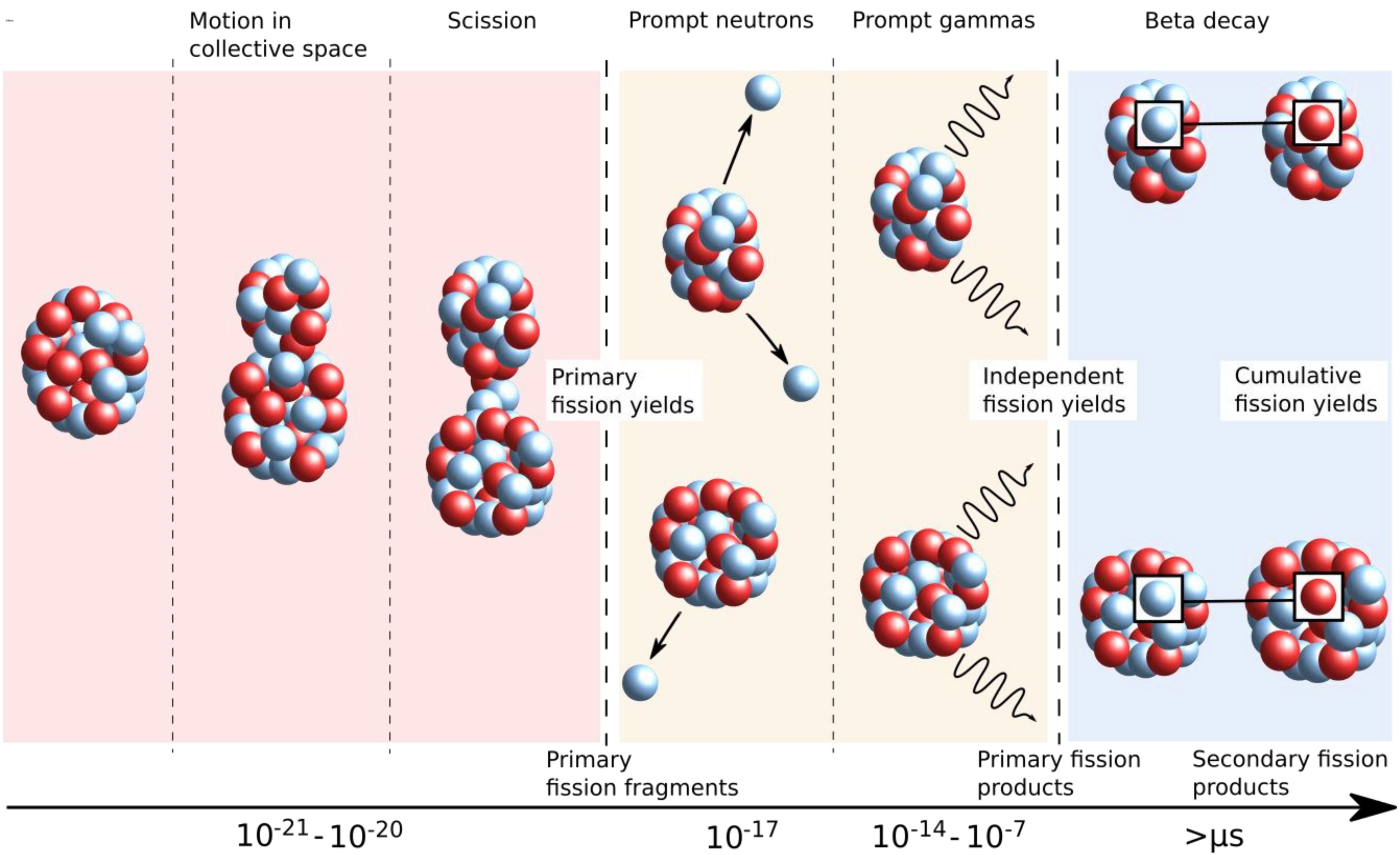
Highlights

The FIRE collaboration has integrated state-of-the-art calculations of fission and β-decay into the most advanced r-process simulations

- List of highlights
  - Table of initial fission fragment distributions for all Z > 80
  - R-process simulations with physics-based fission fragment distributions
  - Impact of neutron emission from all fission fragments on r-process simulations
  - Discovery of the role of β-delayed fission in r-process
  - Special nuclei: the crucial role of spontaneous fission in ^{254}Cf
- Other notable achievements
  - Fully-microscopic calculation of β-decay rates: toward a fully self-consistent theory of nuclear data for r-process
  - Reverse engineering of nuclear masses: what masses are needed to reproduce features of the r-process peaks?
  - (Nuclear) data mining: the role of β-decay spectrum of fission fragments in shaping the anti-neutrino anomaly of nuclear reactors

Fission

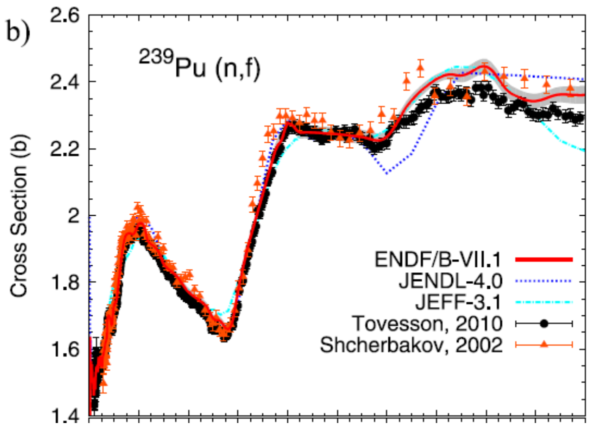
All fission channels (spontaneous, induced, β-delayed) must be accounted for in a r-process calculation

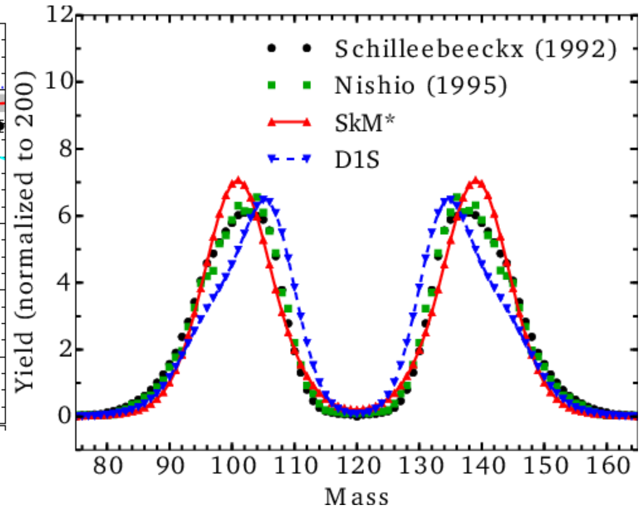


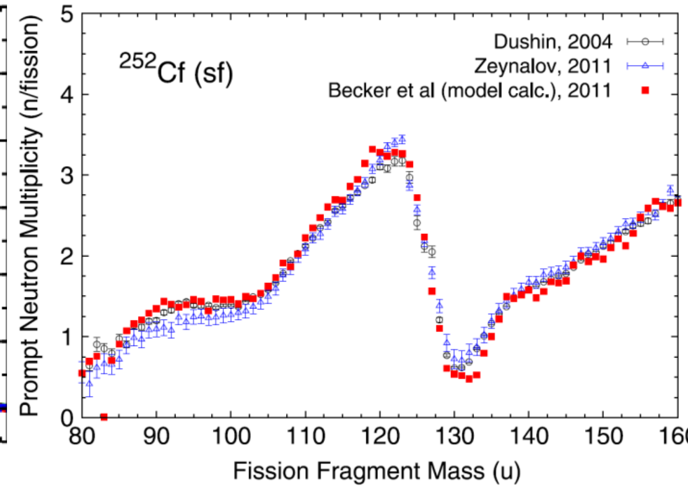
Fission Theories

Both microscopic and semi-microscopic fission models have predictive power, but a full-scale, complete description remains beyond reach

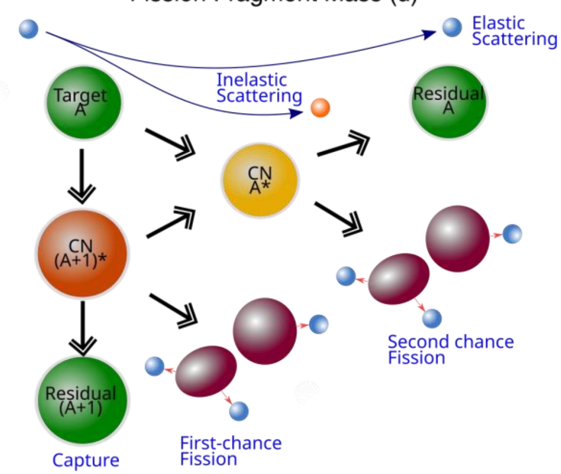
Probability → **Yields** → **Spectrum**







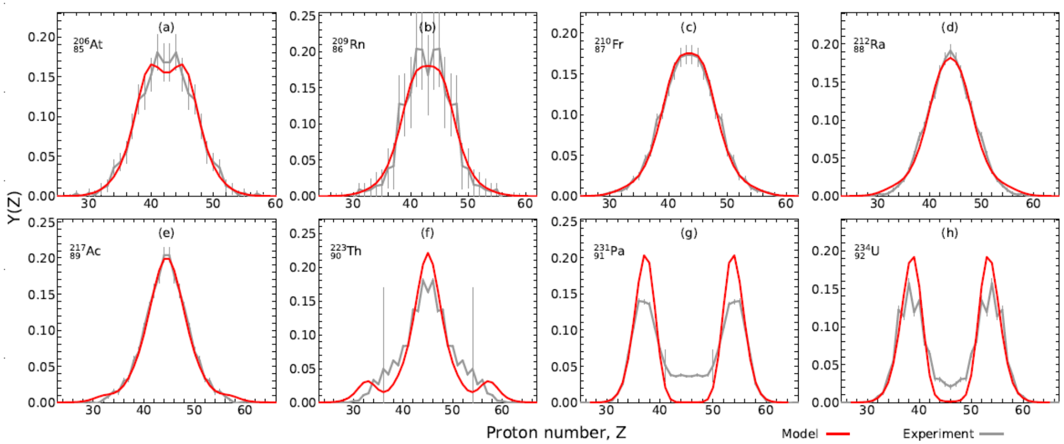
- Fission rates remain a challenge, especially for induced fission (competition with other decays)
- Fission fragment distributions well understood
- Fragments must be deexcited properly
- In complex channels such as β-delayed fission, uncertainties pile up

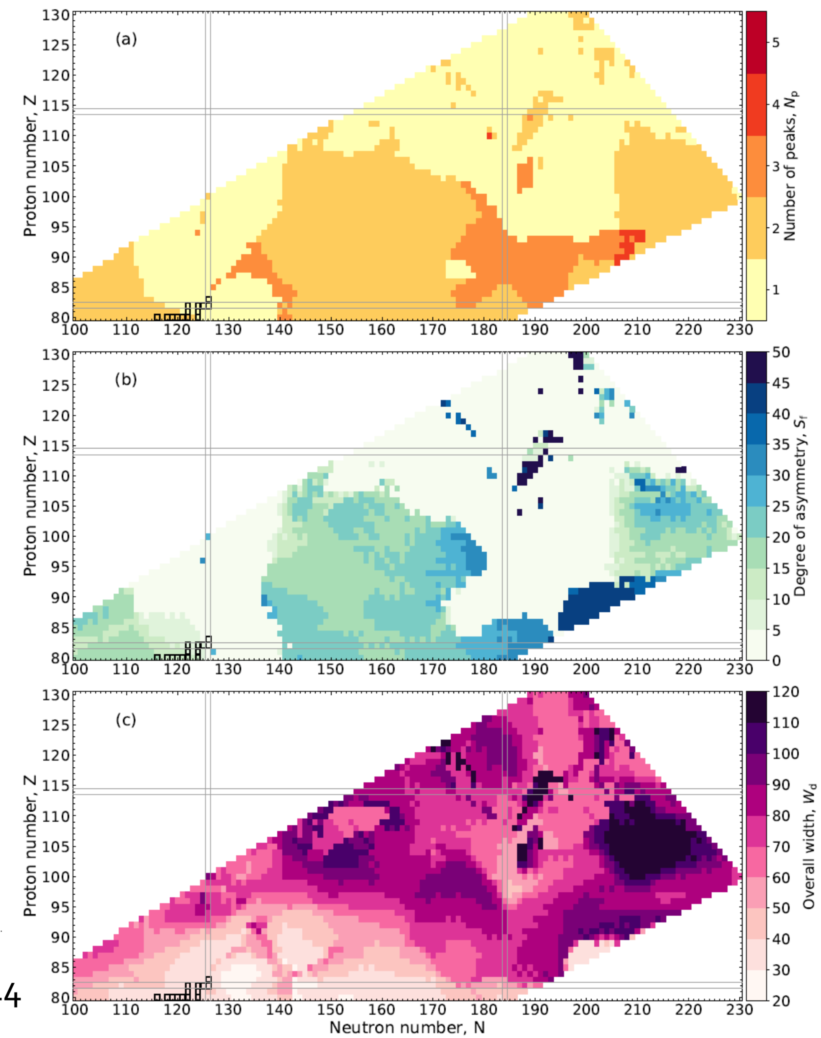


Highlight 1

We computed the first-ever full table of fission fragment distributions for all Z > 80 nuclei by simulating fission dynamics explicitly

- Two-step process
  - Calculate potential energy surfaces in 5-dimensional deformation space
  - Random walk on this surface
- Database of results has been made publicly available to the community

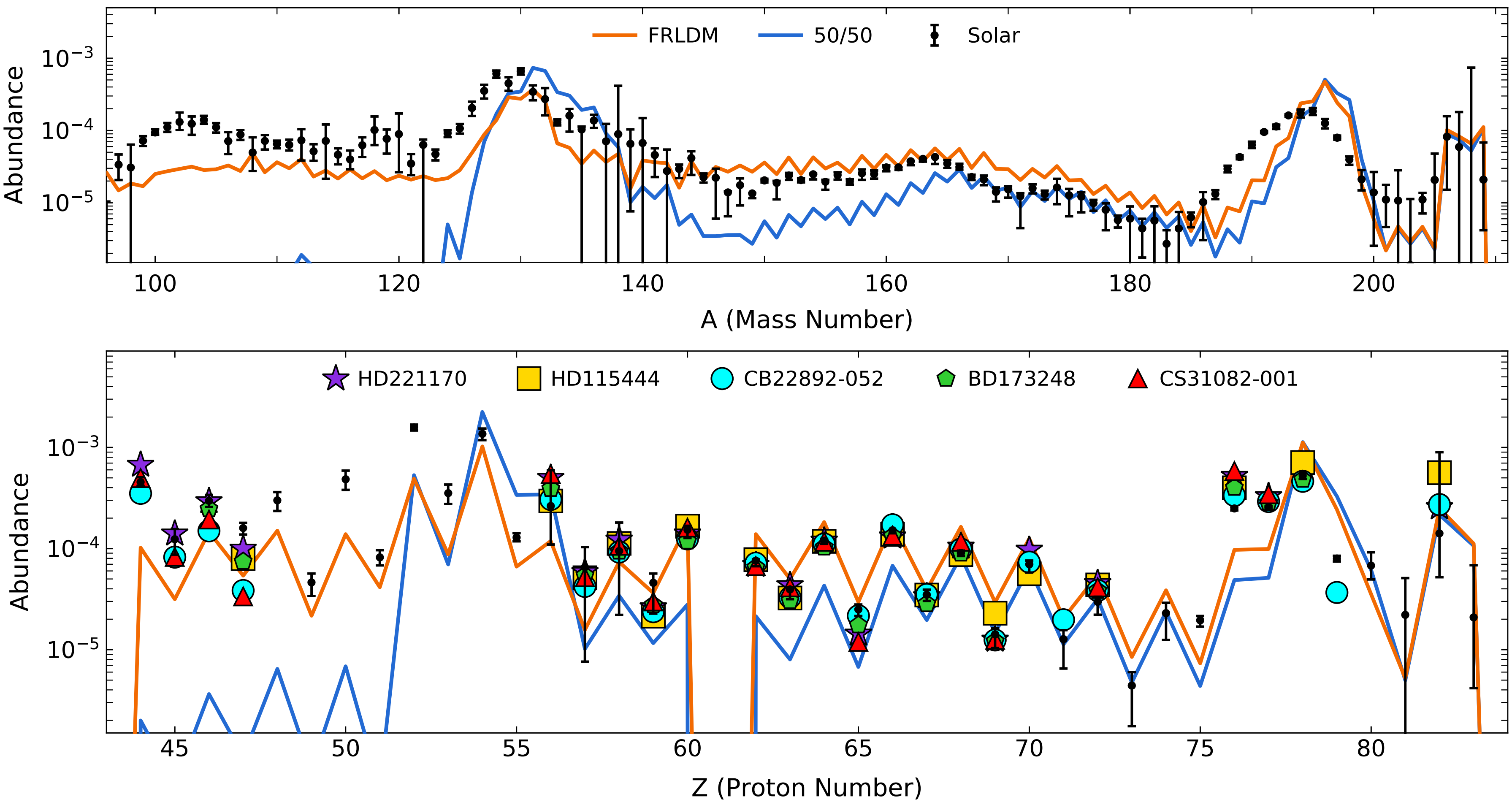




M. R. Mumpower, P. Jaffke, M. Verriere, J. Randrup, arXiv:1911.06344

Highlight 2

We performed the first r-process calculations with fission yields from a nuclear physics calculation rather than systematics

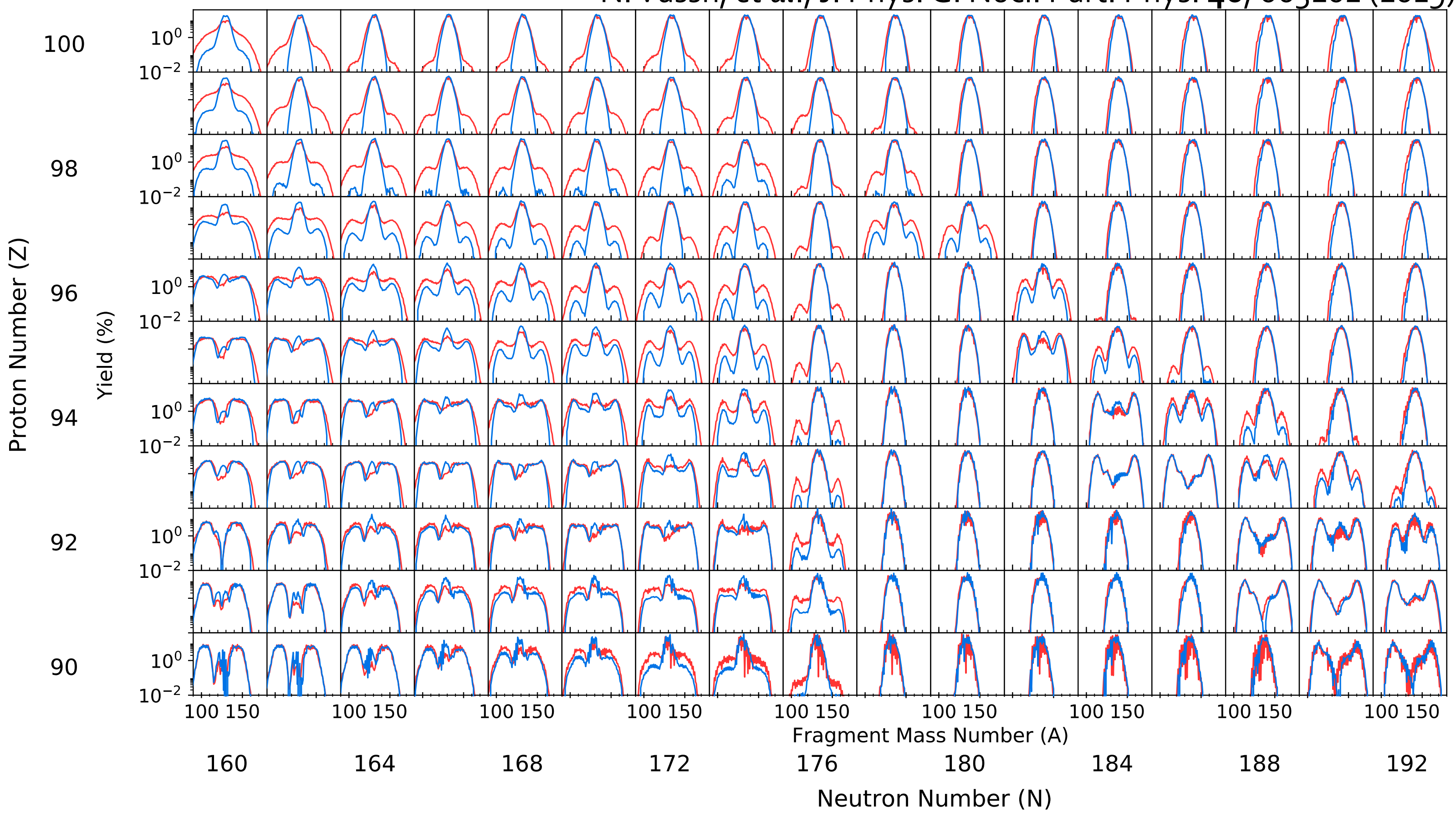


N. Vassh, M.R. Mumpower, G.C. McLaughlin , T.M. Sprouse, and R. Surman, arXiv:1911.07766

Highlight 3

We have added the capability to compute the number of neutrons and photons emitted by the fission fragments in r-process simulations

N. Vassh, *et al.*, J. Phys. G: Nucl. Part. Phys. **46**, 065202 (2019)

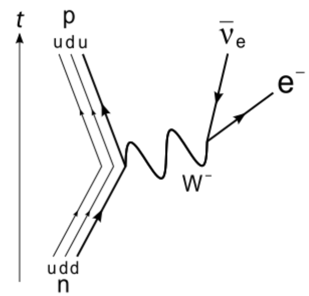


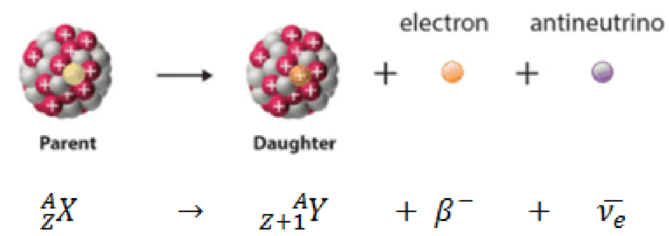
- Couple Q-value and daughter nucleus information from β-decay with fission yields
- Compute neutron emission with FREYA

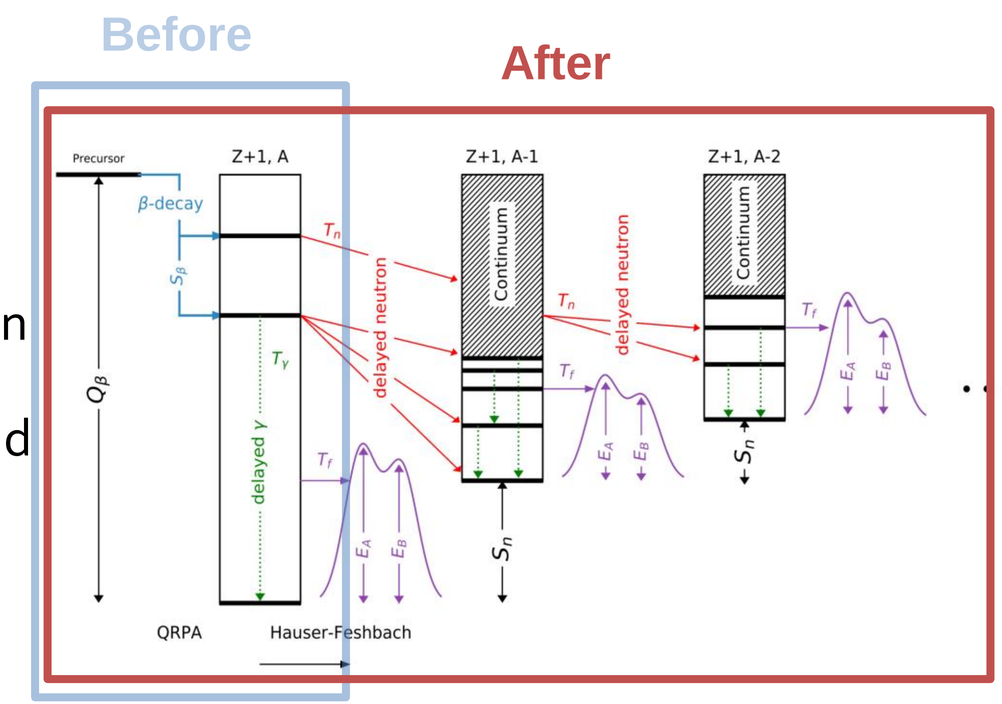
β-decay Theory

β-decay is a key mechanism of several nucleosynthesis processes and is also involved in fission

- β-decay is the primary mechanism that allows synthesizing higher-Z elements in nucleosynthesis
- Weak process embedded in strongly-interacting many-body system
- Transitions induced by β-decay operators are treated within linear response theory – QRPA with weak external field
- We have coupled QRPA with reaction theory (Hauser-Feshbach) to handle competition between β-, γ-decay and fission



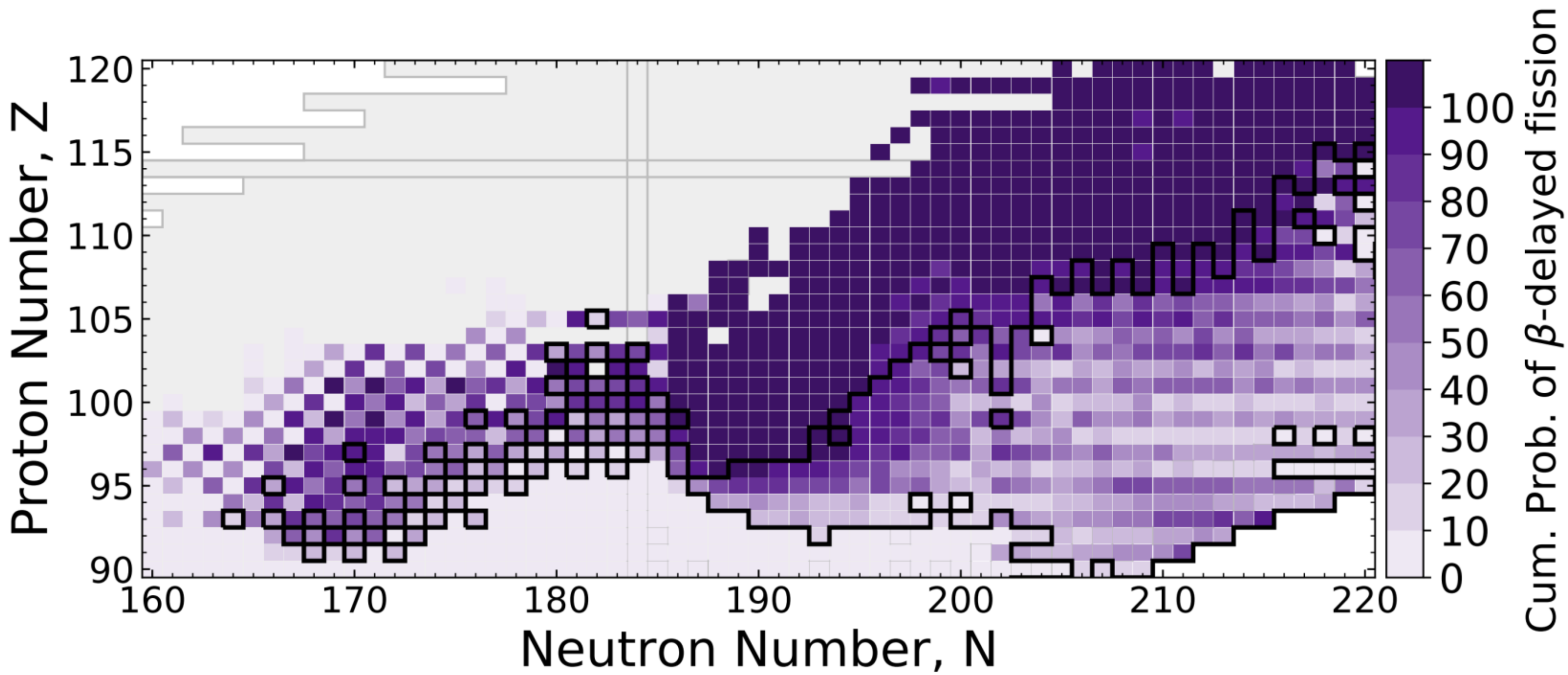




Highlight 4

We have quantified the impact of beta-delayed fission using direct simulation of decay fission channels

M. R. Mumpower, T. Kawano, T. M. Sprouse, N. Vassh, E. M. Holmbeck, R. Surman, and P. Möller, ApJ 869, **14** (2018)
N.Vassh, et al., J. Phys. G: Nucl. Part. Phys. **46**, 065202 (2019)

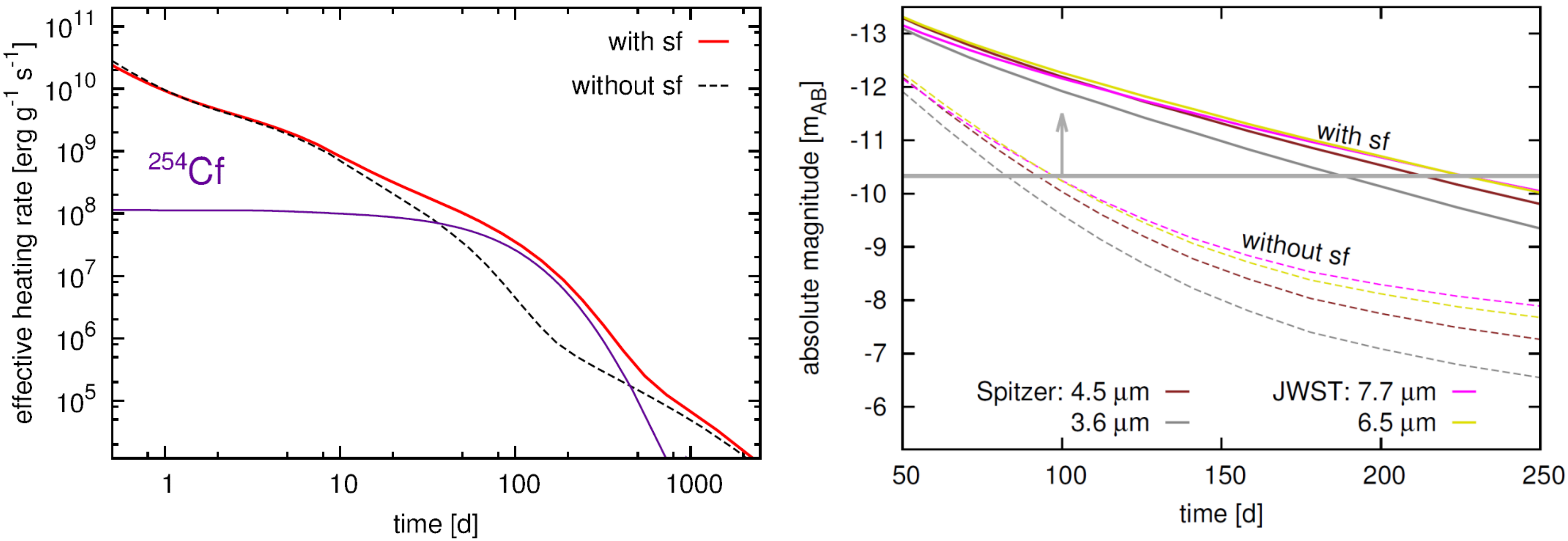


- Darker regions: elements where β-delayed fission occurs the most
- Profound implications for the production of actinides and superheavy elements

Highlight 5

We have identified what is so far the only “smoking gun” that actinides could be produced in a neutron star merger

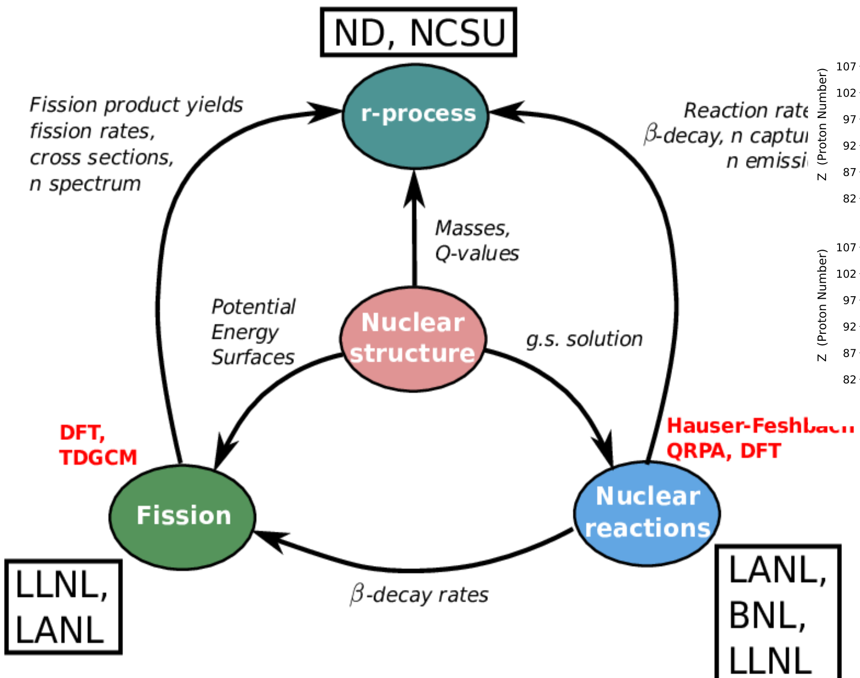
Y. Zhu, et al. ApJL **L23**, 863 (2018)



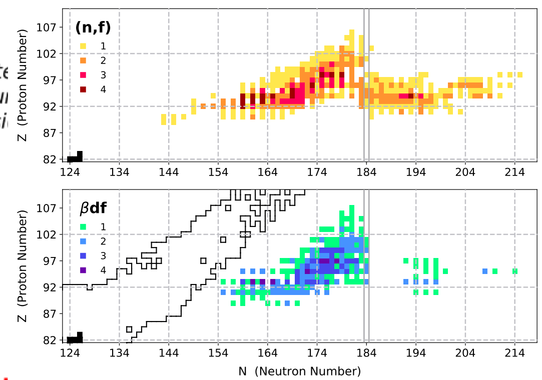
- Extra heating comes from the spontaneous fission of a single nucleus, ^{254}Cf because of late-time β-decay feeding
  - Nuclear theorists back to work on spontaneous fission of Cf isotopes…
  - Our calculations have observational consequences that can be tested

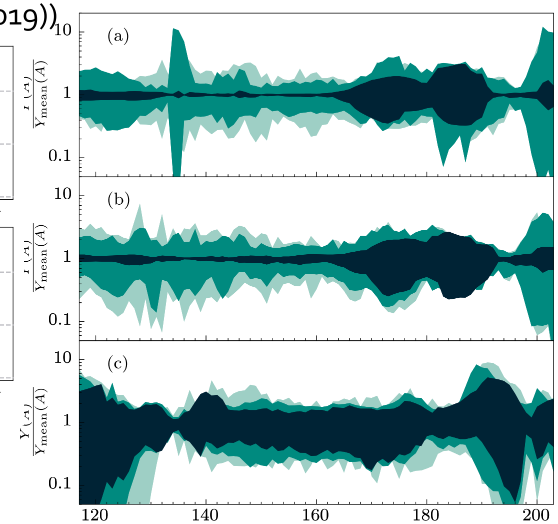
Summary

The FIRE collaboration has delivered a unique, US-based, capability to tackle the problem of the origin of elements in the universe



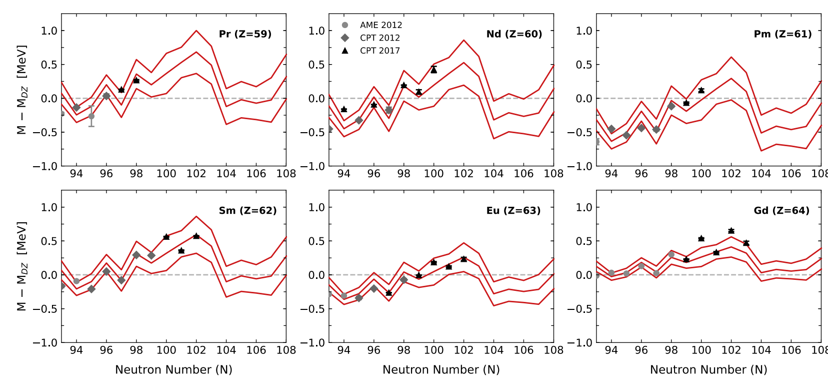
N. Vassh, et al. JPG. **46**, 065202 (2019))



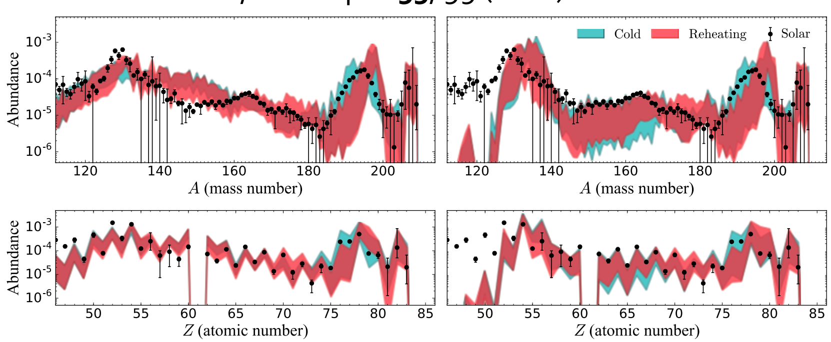


T. Sprouse, et al. arXiv:1901.10337

R. Orford, et al. PRL **120**, 262702 (2018)



B. Côté, et al. ApJ **855**, 99 (2018)



Outlook

This is a "perfect storm" of multi-messenger observations, FRIB, and theory enabled by HPC and machine learning techniques

- FIRE has made great progress in
  - Incorporating realistic models of fission in r-process simulations
  - Describing β- and γ-decay in a single framework
  - Connecting network calculations with astronomical observations
  - Educating new workforce: two FIRE postdocs hired as staff at national laboratories
- Consistency of theoretical inputs is key to reduce nuclear physics uncertainties in r-process simulations
- Next frontiers:
  - Start from nuclear forces and compute nuclear data within a fully quantum-mechanical theory
  - Propagation of uncertainties and the role of machine learning
- Collaborative model works!

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