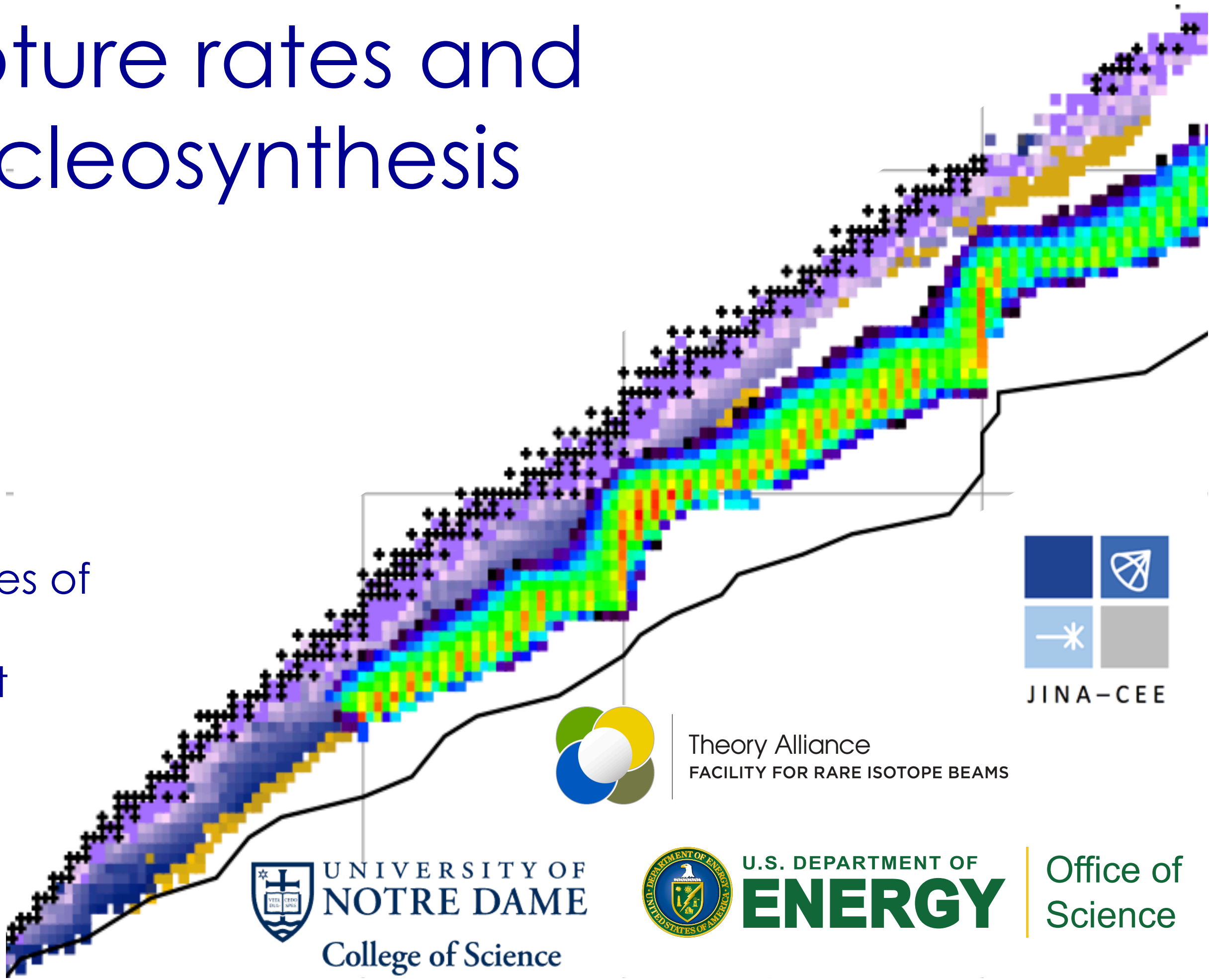
neutron capture rates and *r*-process nucleosynthesis

Rebecca Surman
University of Notre Dame

INT Program INT-17-1a:
Toward Predictive Theories of Nuclear Reactions Across the Isotopic Chart

Seattle, Washington
15 March 2017



JINA–CEE

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

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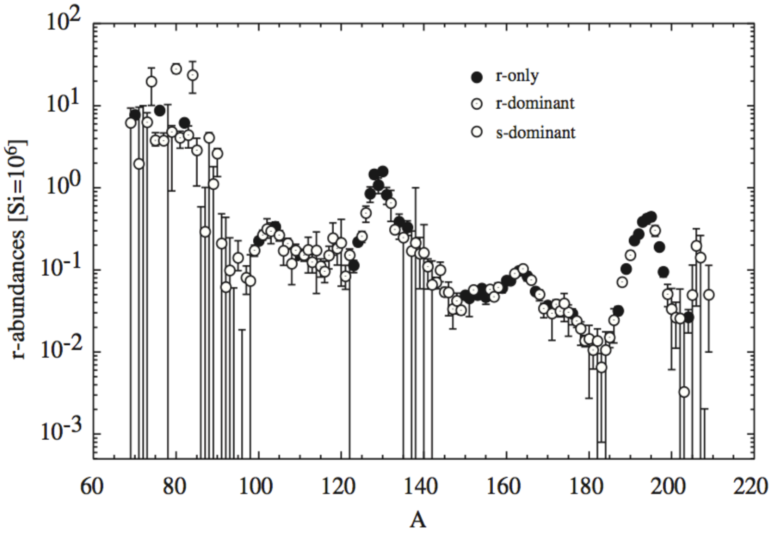
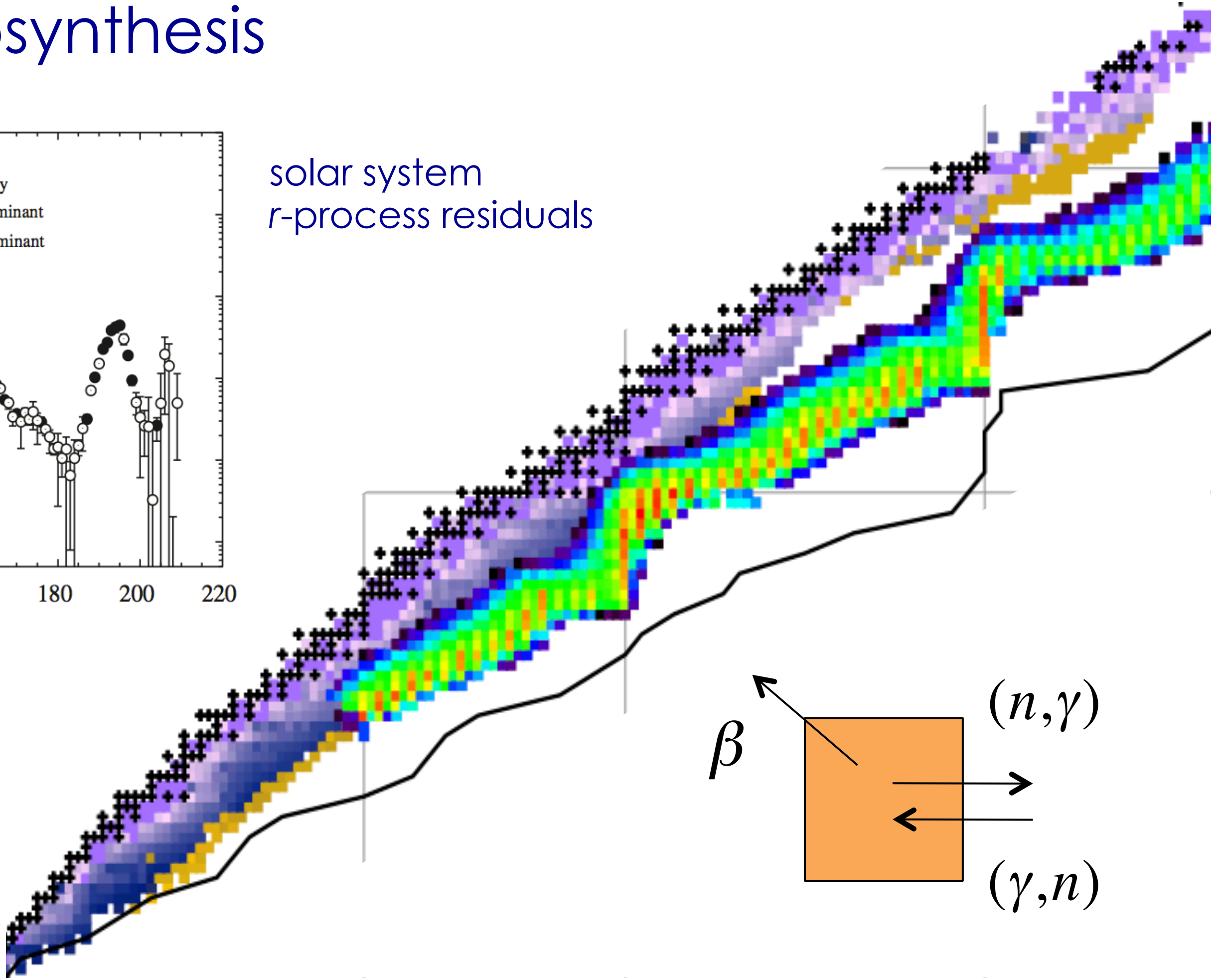
r-process nucleosynthesis



Arnould+2007

solar system
r-process residuals



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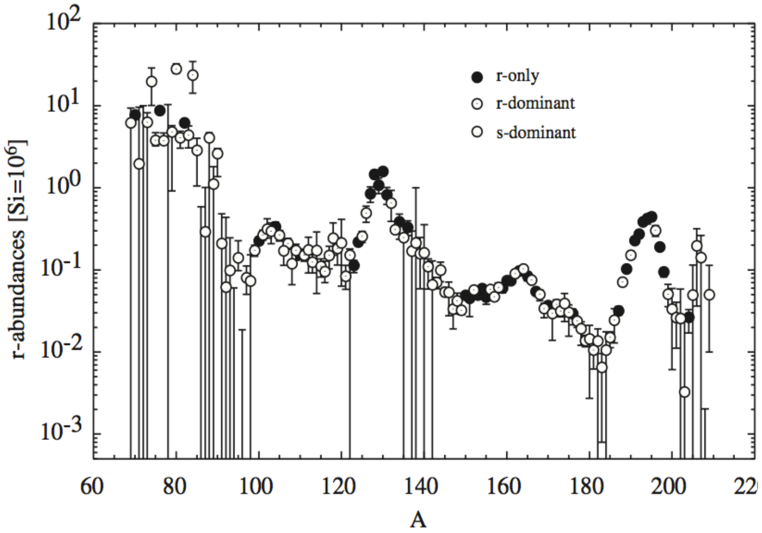
r-process nucleosynthesis



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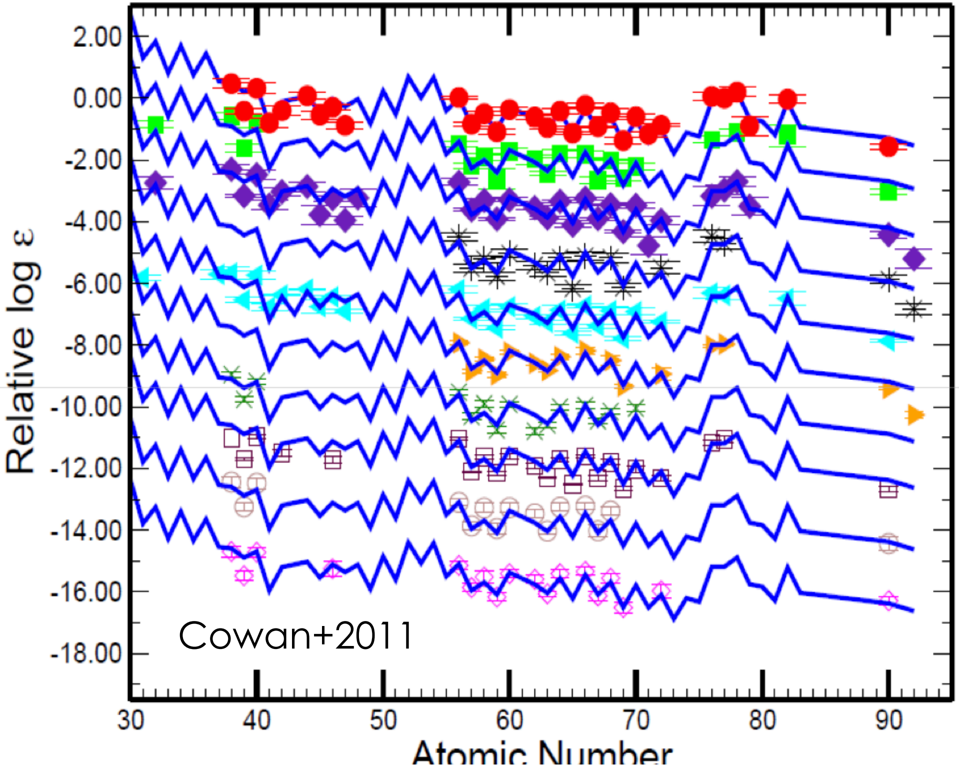
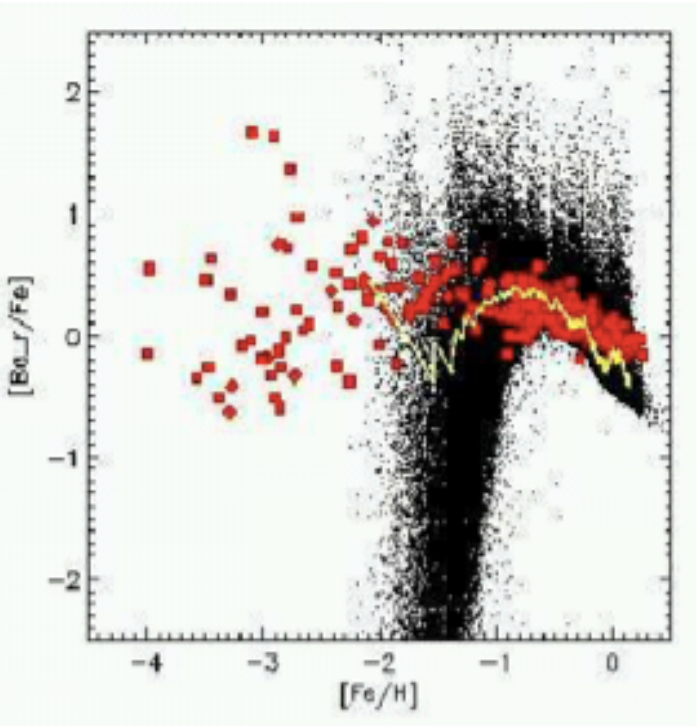


Cowan+2011

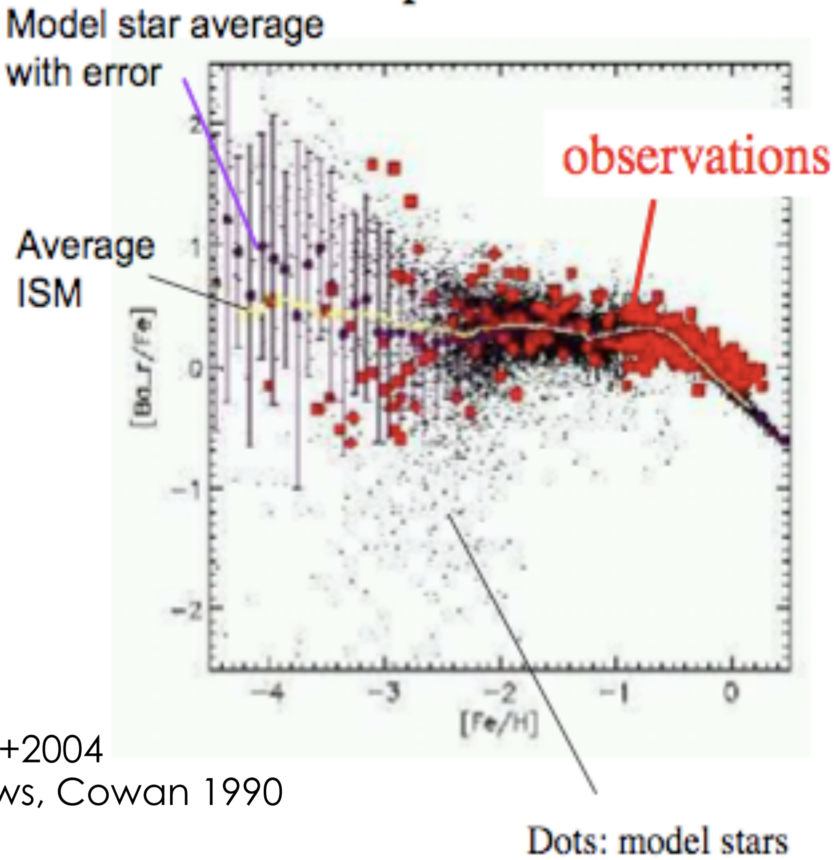
elemental abundances
from *r*-process-enhanced
metal-poor stars

r-process nucleosynthesis: core-collapse supernovae?

NS mergers

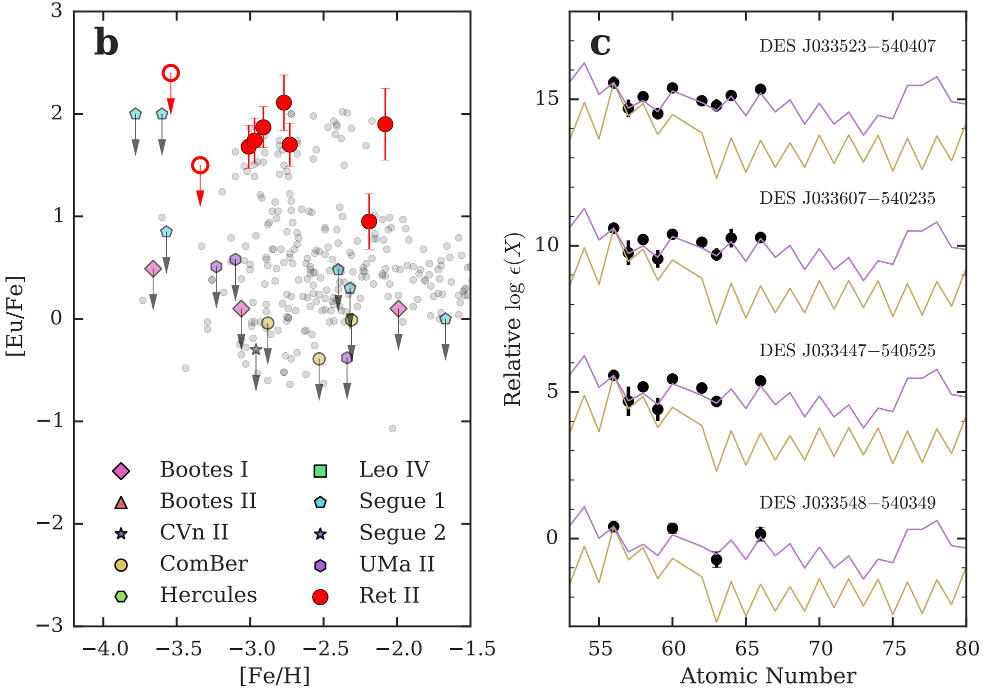


Supernovae

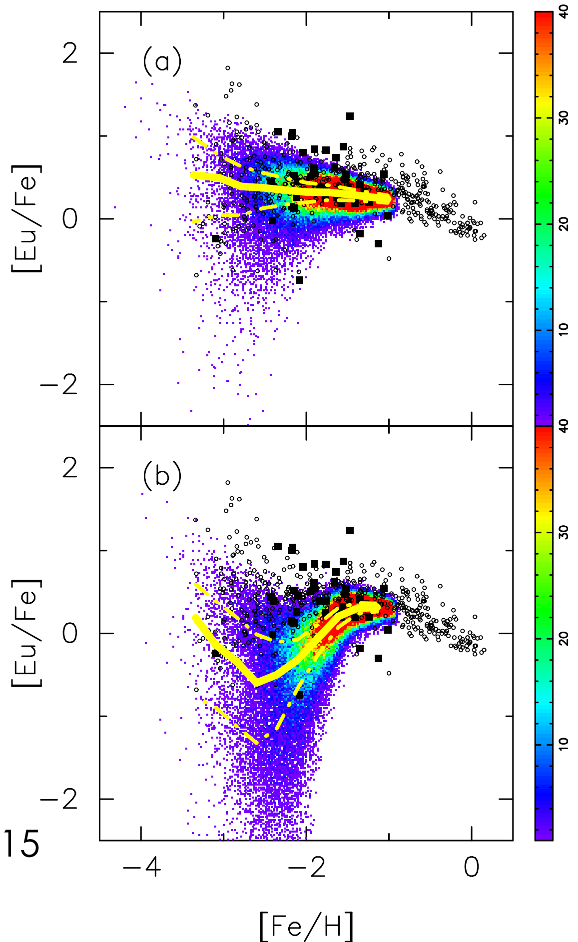


Argast+2004
see also Matthews, Cowan 1990

r-process elements in metal-poor stars: new evidence



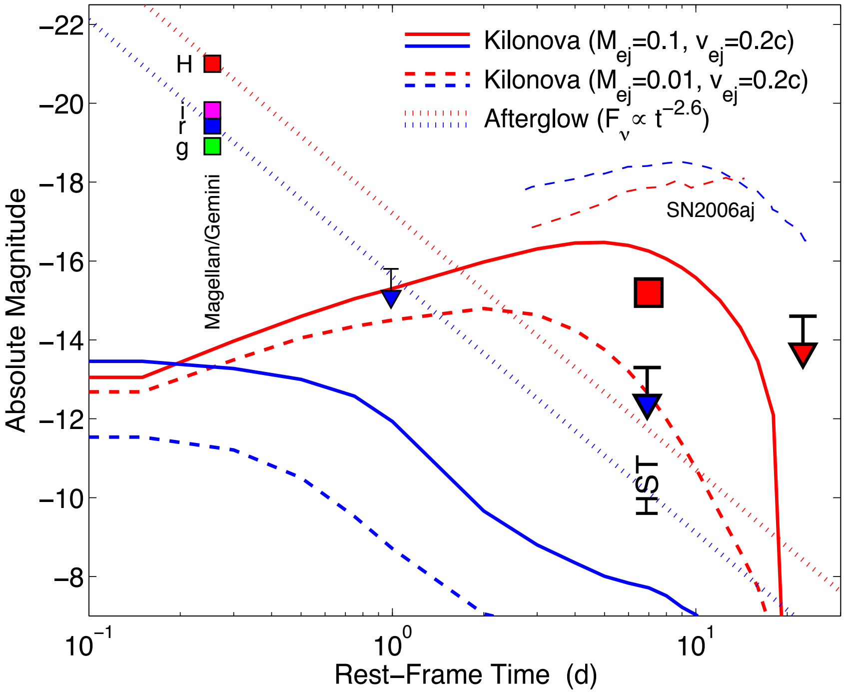
Ji+2016



Hirai+2015

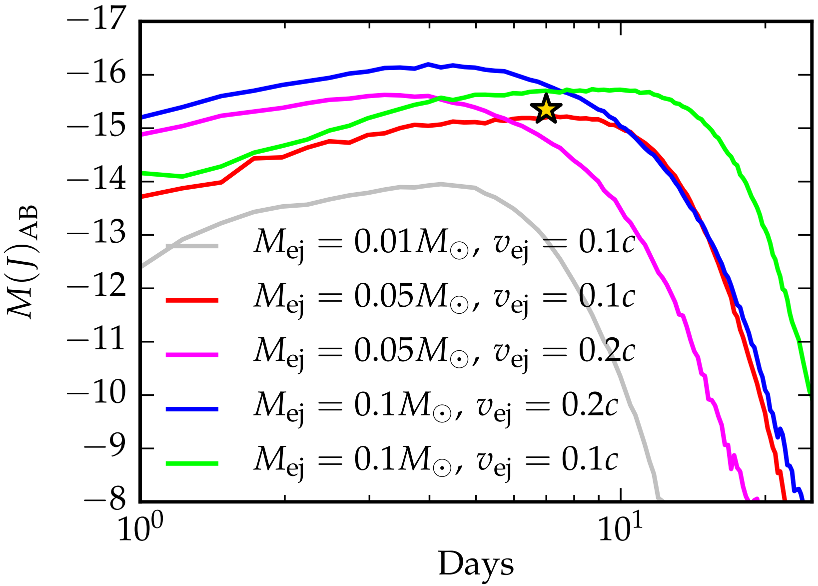
ultrafaint dwarf (UFD) galaxies can
account for low-metallicity enrichment

electromagnetic signatures of merger events



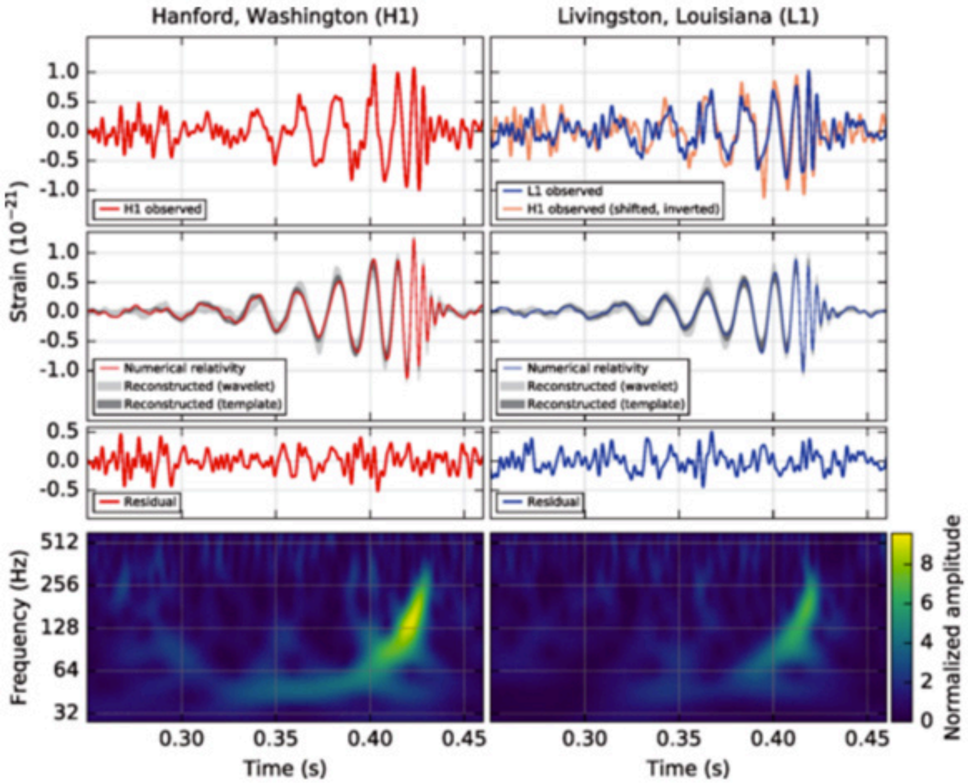
Berger+2013

Tanvir+2013, Berger 2013:
observations of a macronova candidate
sGRB 130603B



Barnes+2016

compact object mergers: gravitational waves



LIGO collaboration

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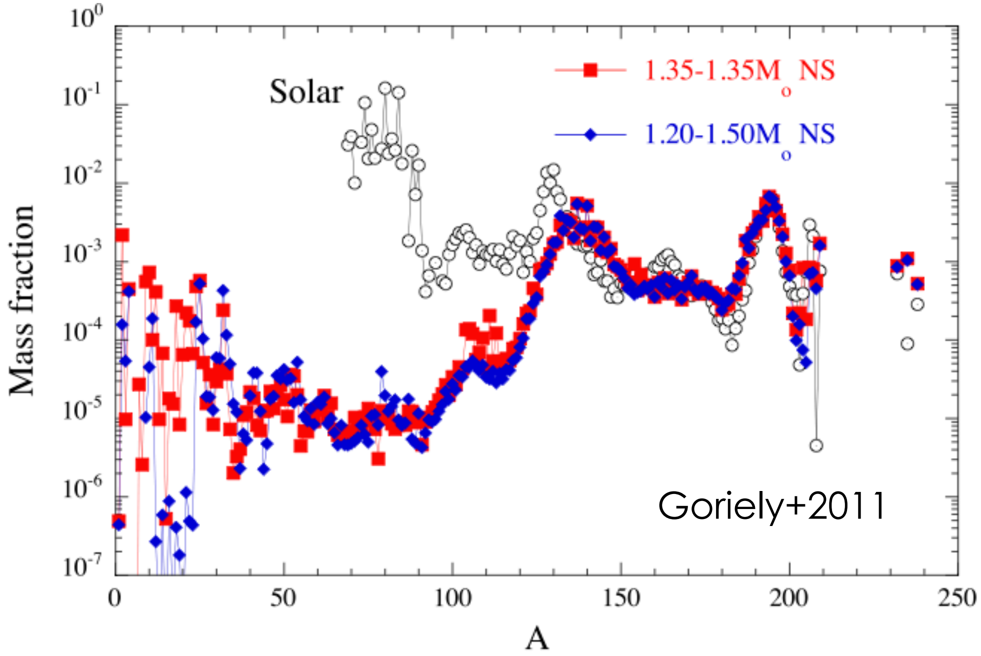
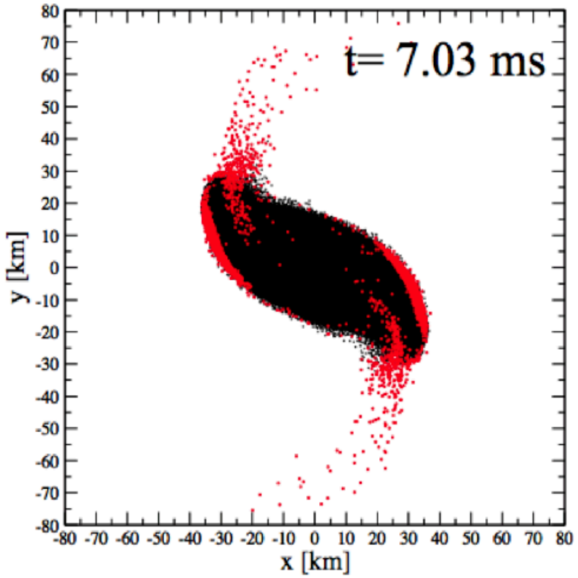
compact object mergers: environments for element synthesis

cold/mildly heated prompt ejecta

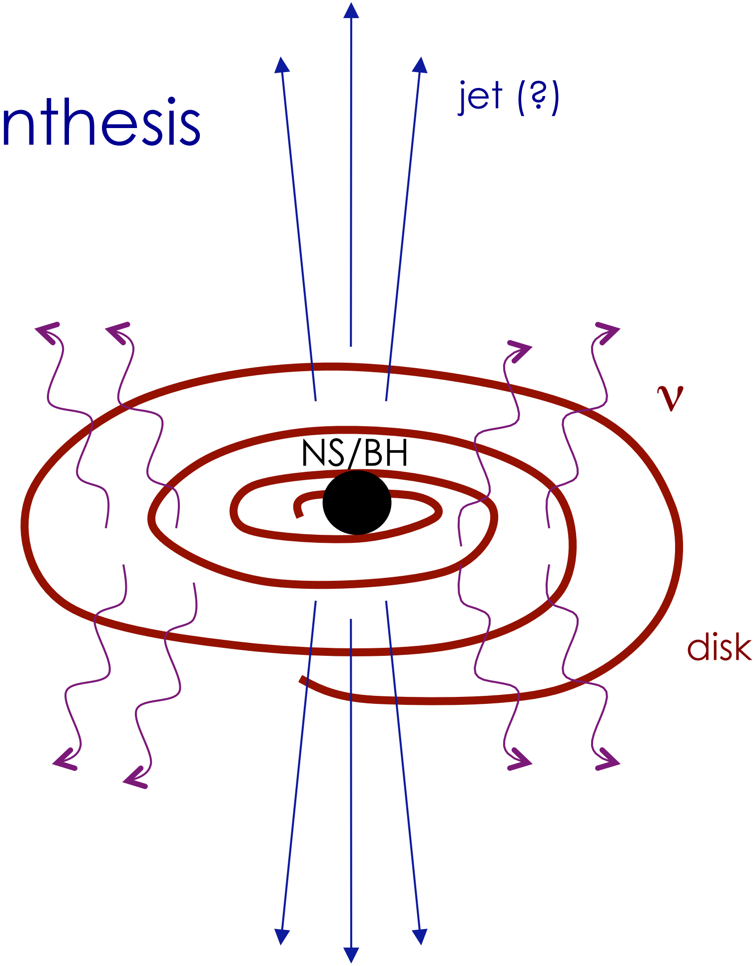




Korobkin+2012

compact object mergers: environments for element synthesis

ejecta from the accretion disk



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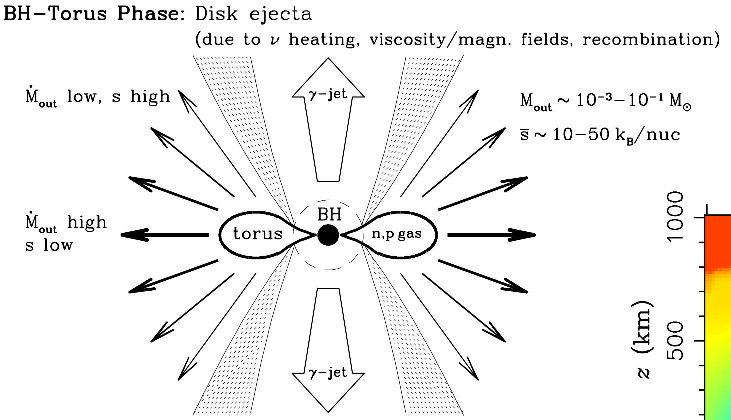
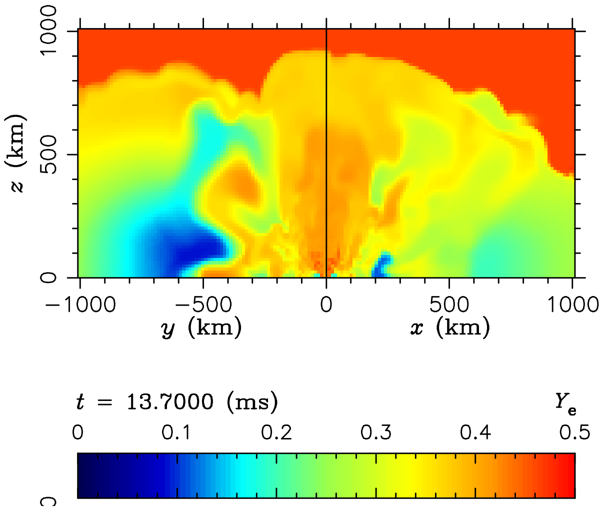
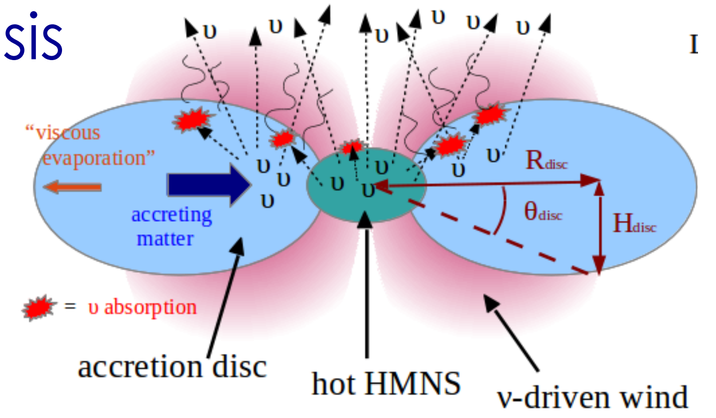


viscous outflows
e.g., Just+2015





neutrino-driven wind
e.g., Perego+2014

Shock-heated, neutrino-processed ejecta
e.g., Wanajo+2014

r-process nucleosynthesis: required nuclear data

masses
beta-decay rates
beta-delayed neutron emission probabilities
neutron capture rates

fission rates
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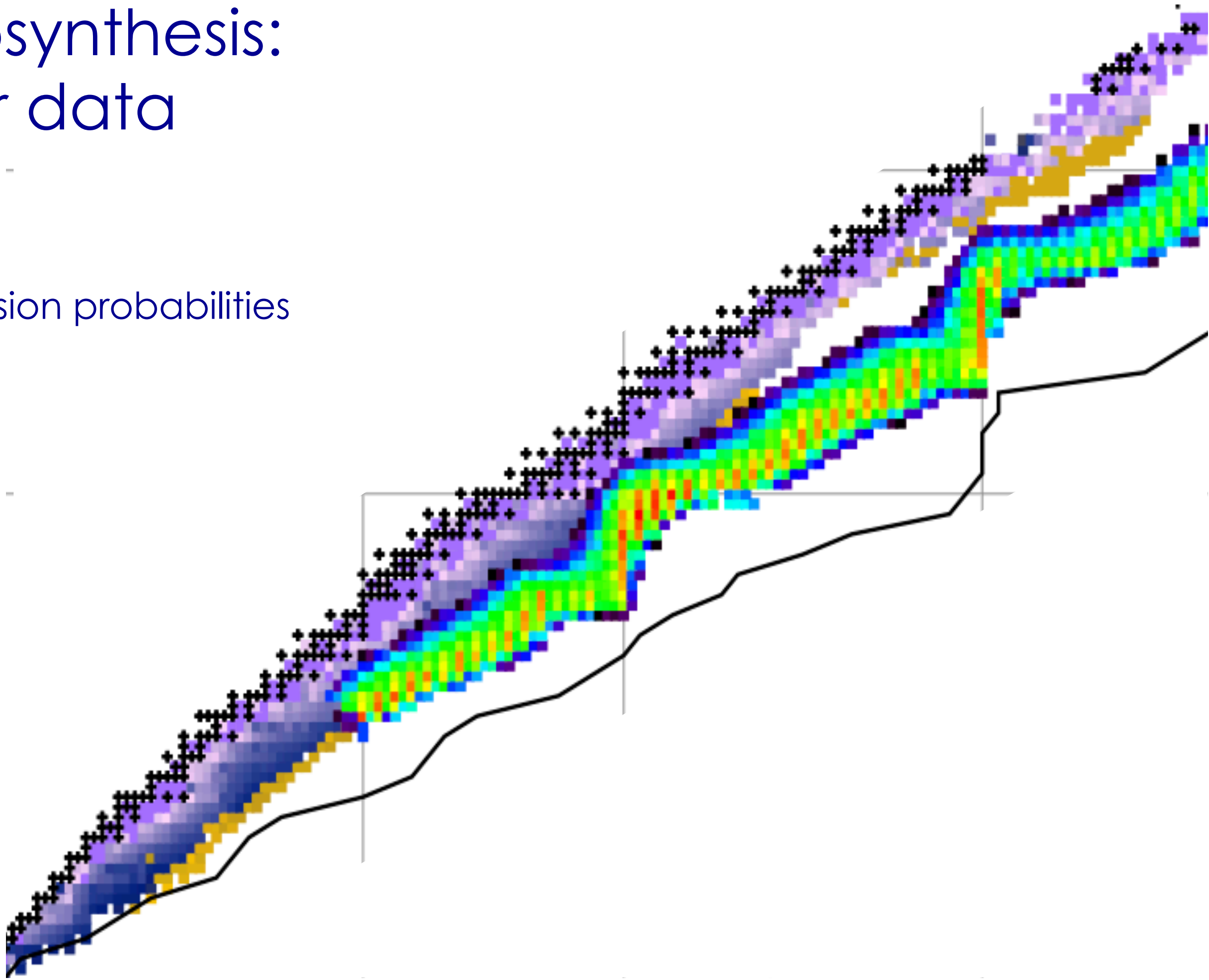

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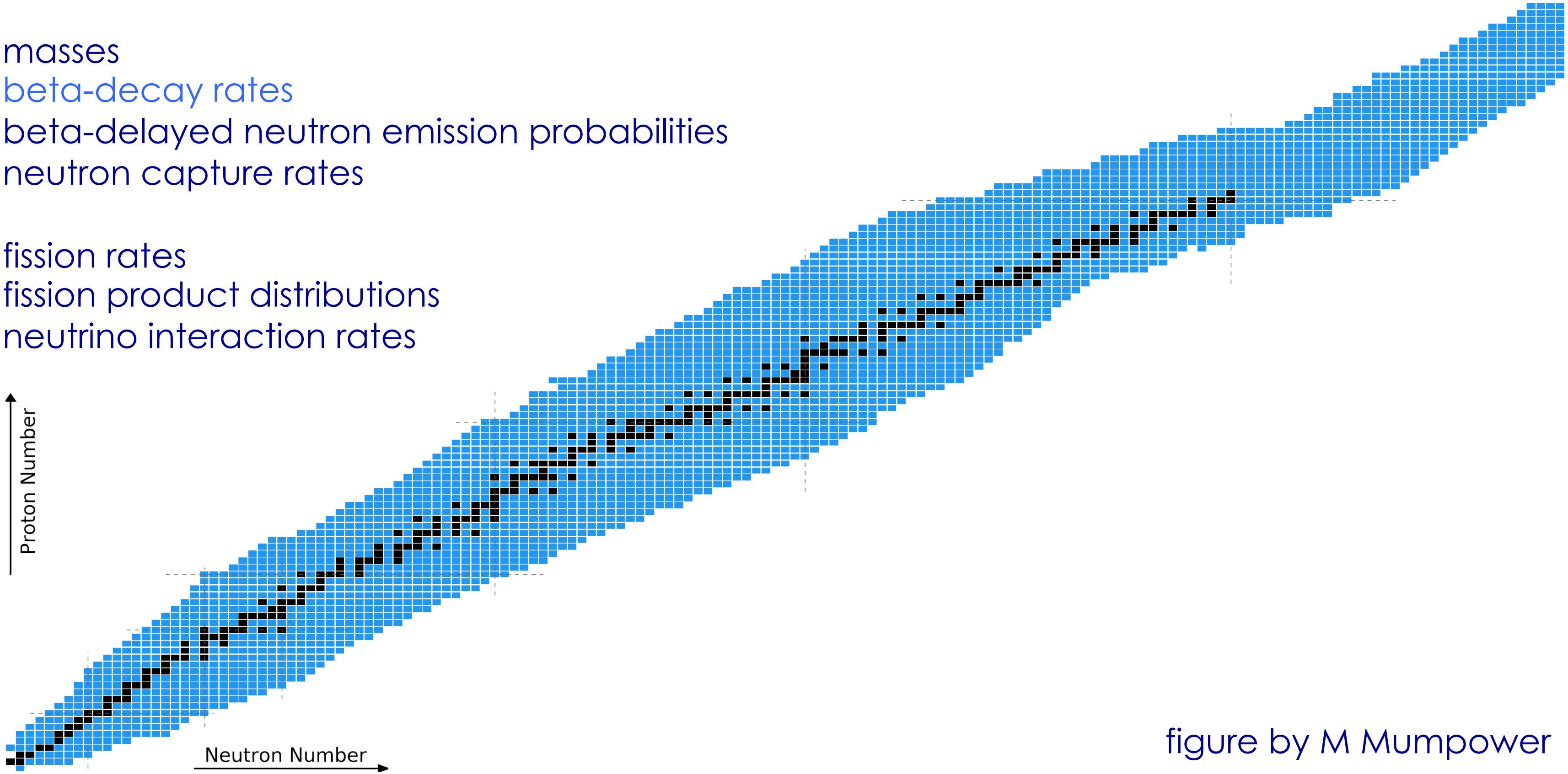
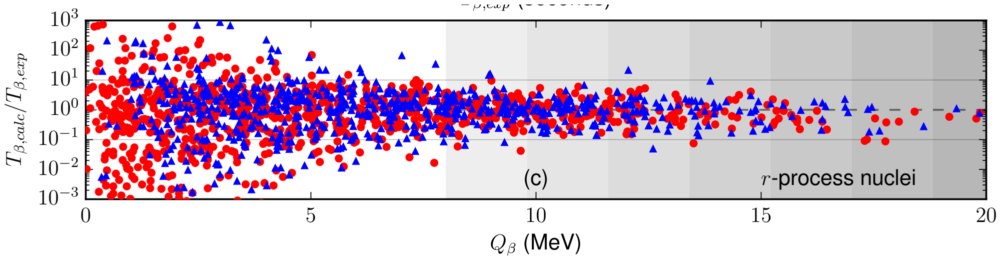


figure by M Mumpower

r-process nucleosynthesis: required nuclear data

Mumpower, Surman, McLaughlin, Aprahamian 2016



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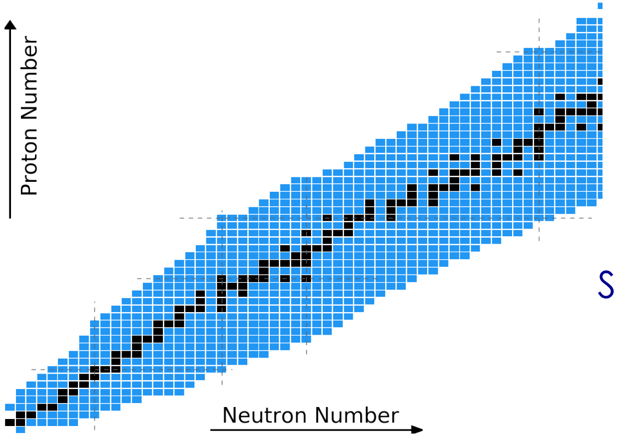

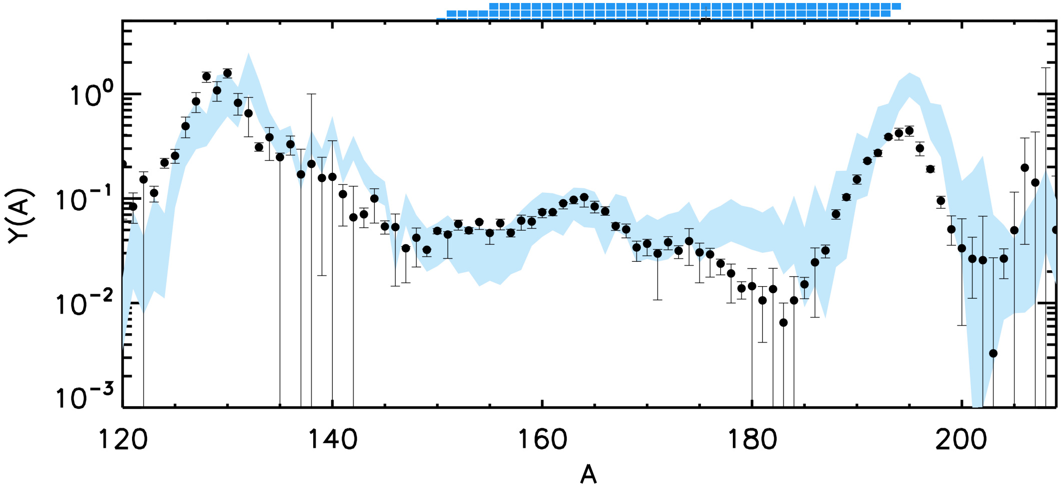

Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman 2016

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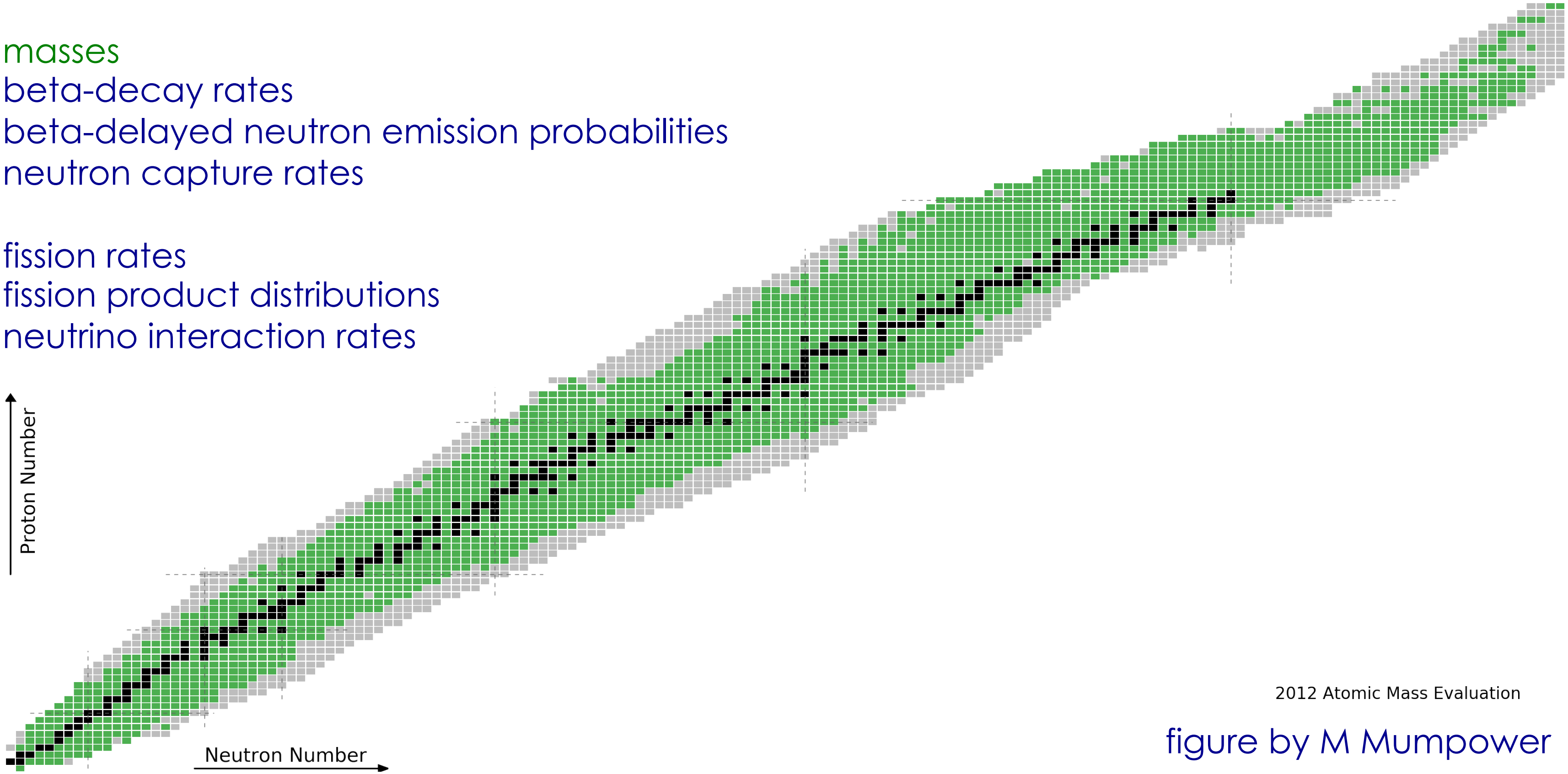

2012 Atomic Mass Evaluation

figure by M Mumpower

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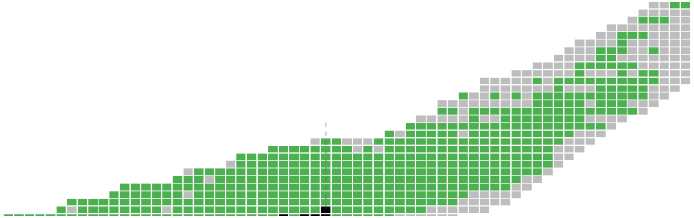
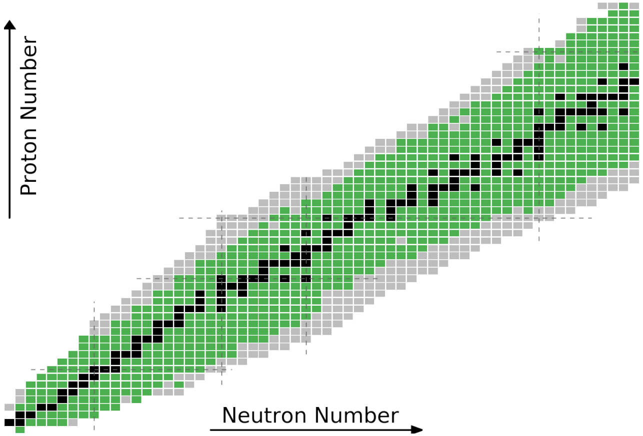
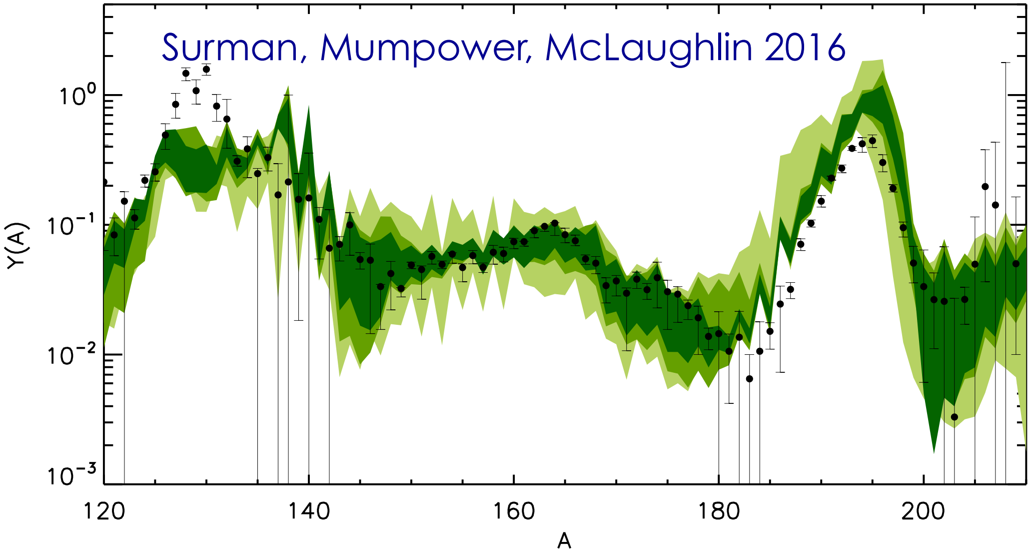
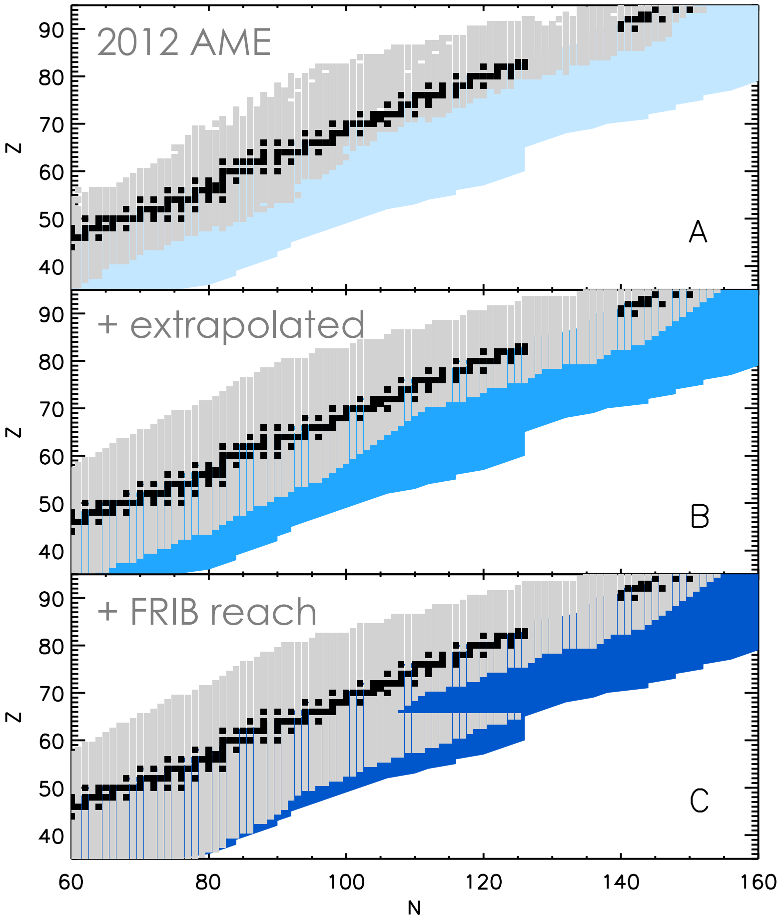
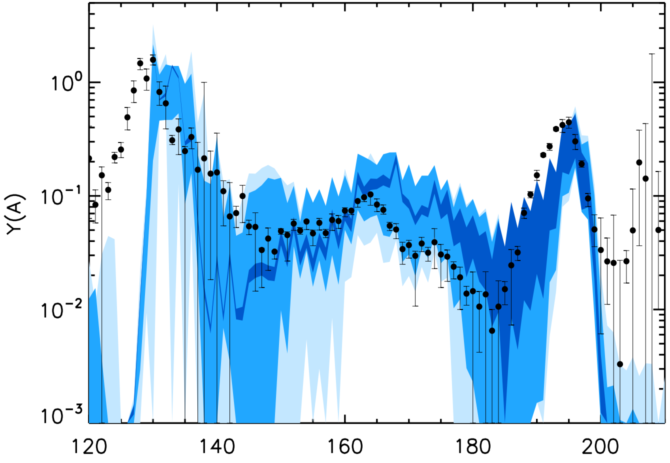




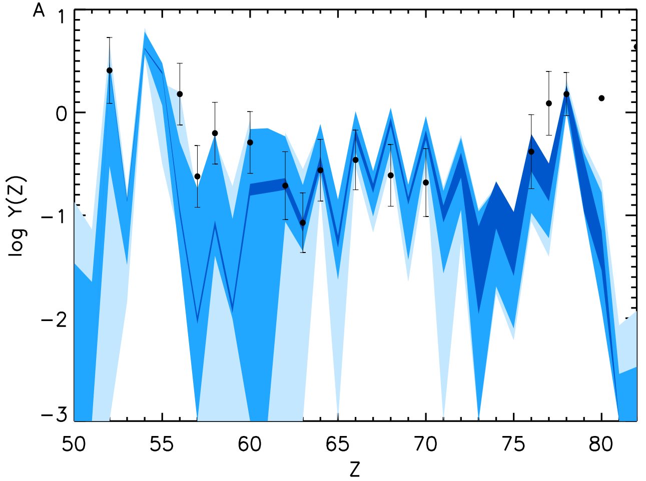


impact of upcoming mass measurements





Surman,
Mumpower,
Aprahamian
2016



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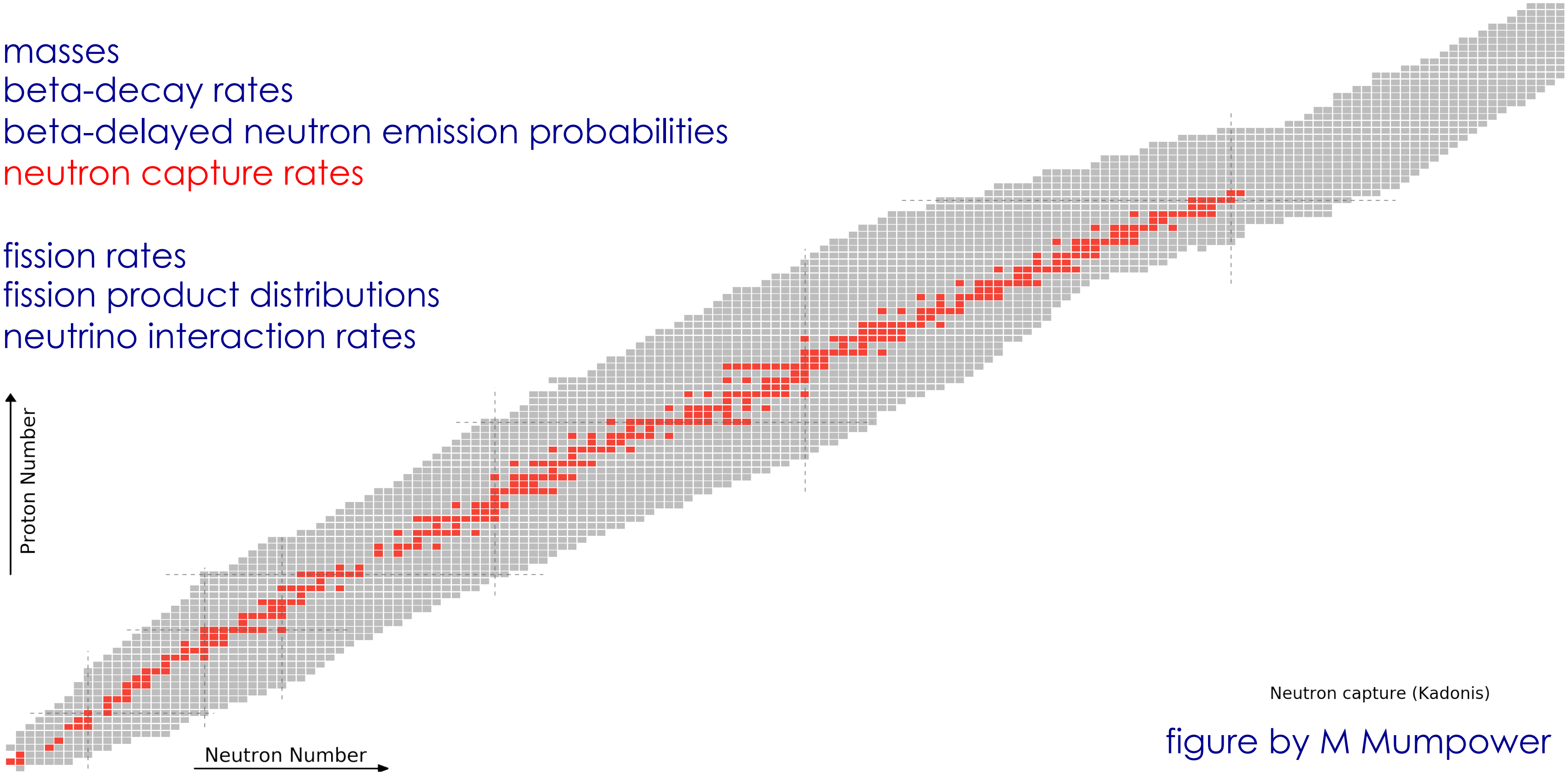

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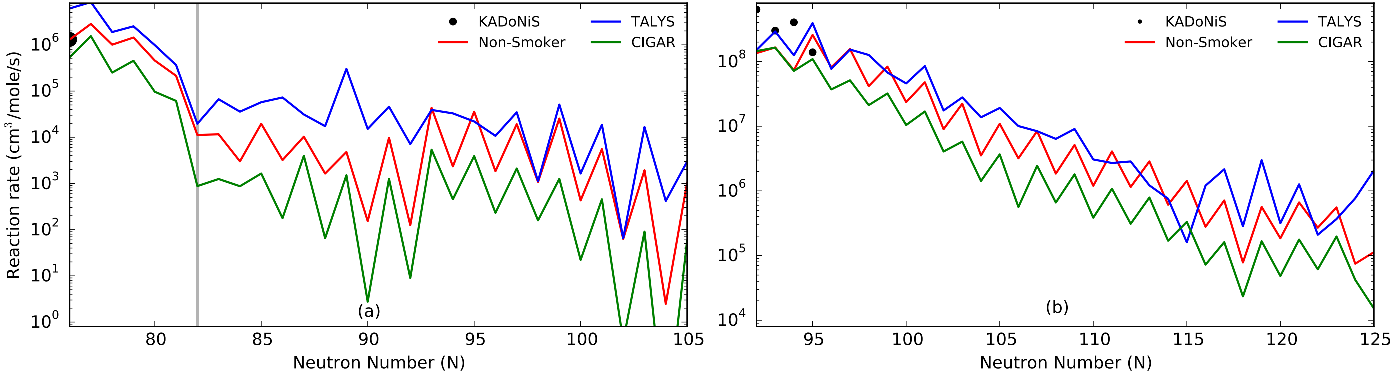
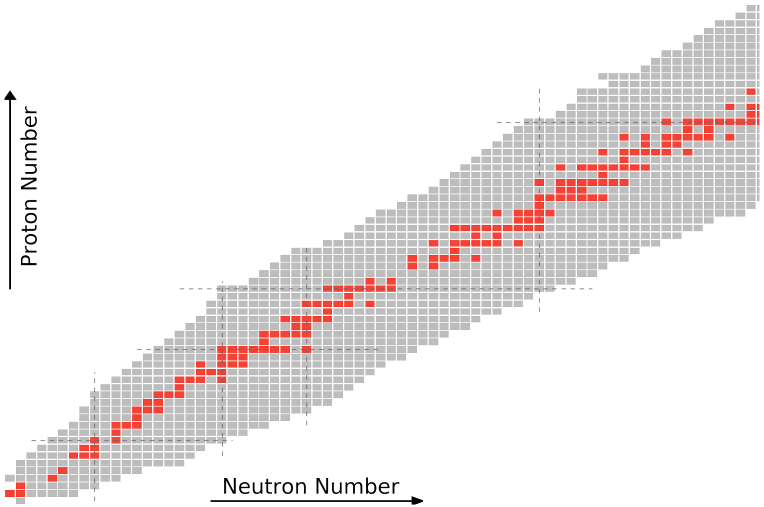
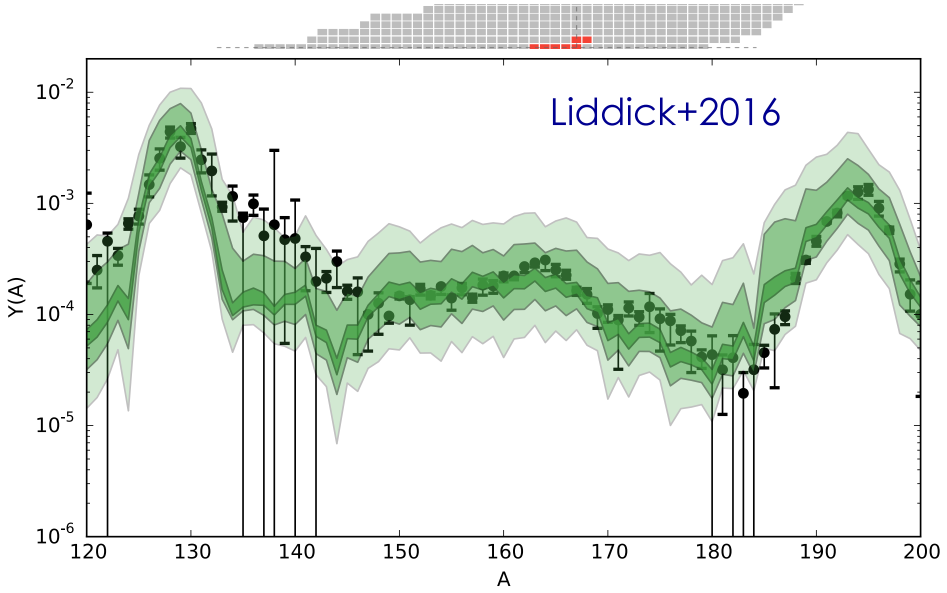
Mumpower, Surman, McLaughlin, Aprahamian 2016



neutron capture rates





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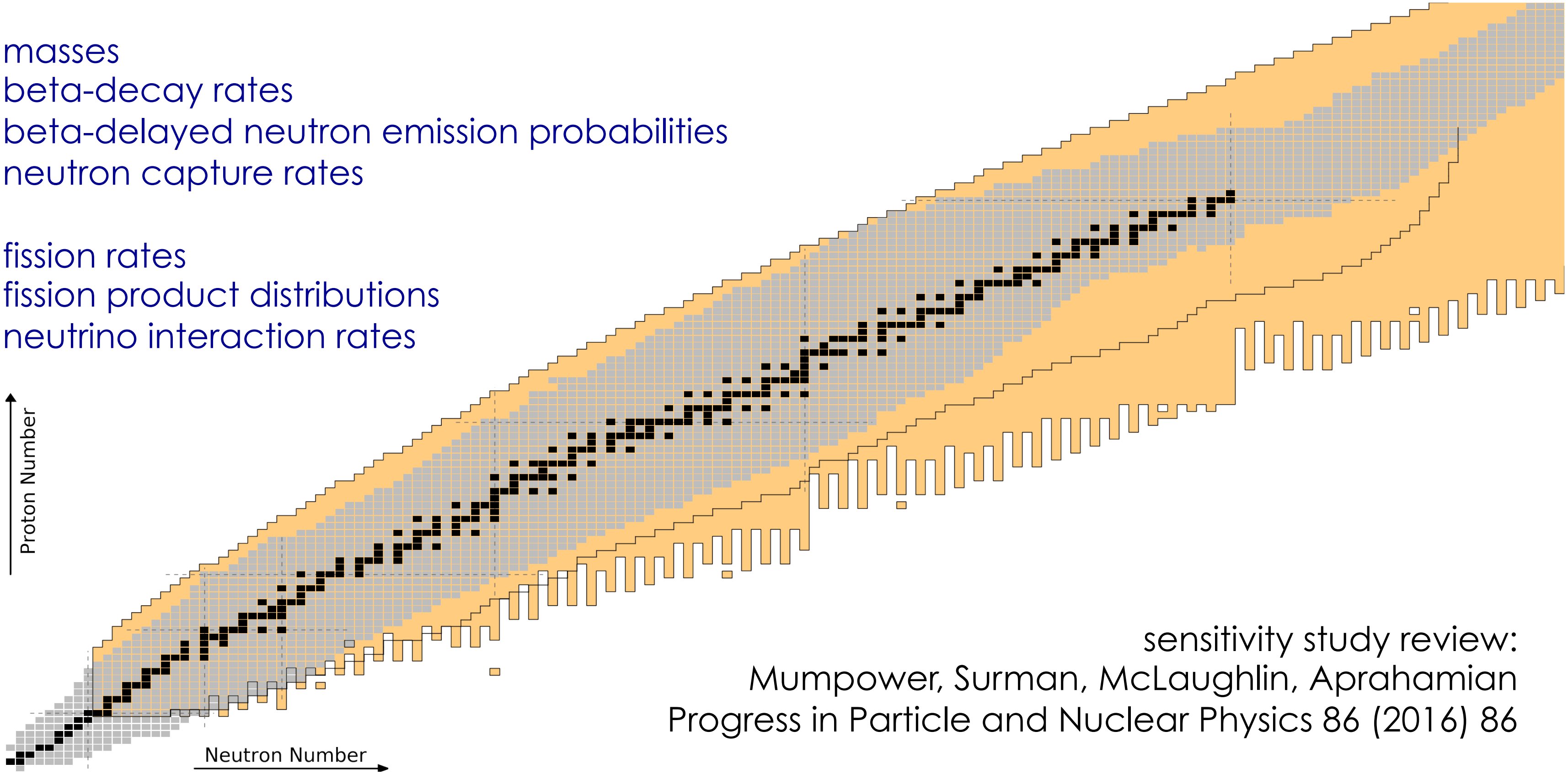

sensitivity study review:
Mumpower, Surman, McLaughlin, Aprahamian
Progress in Particle and Nuclear Physics 86 (2016) 86

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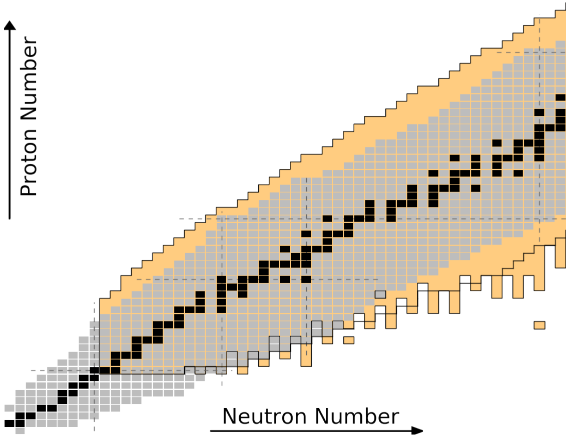
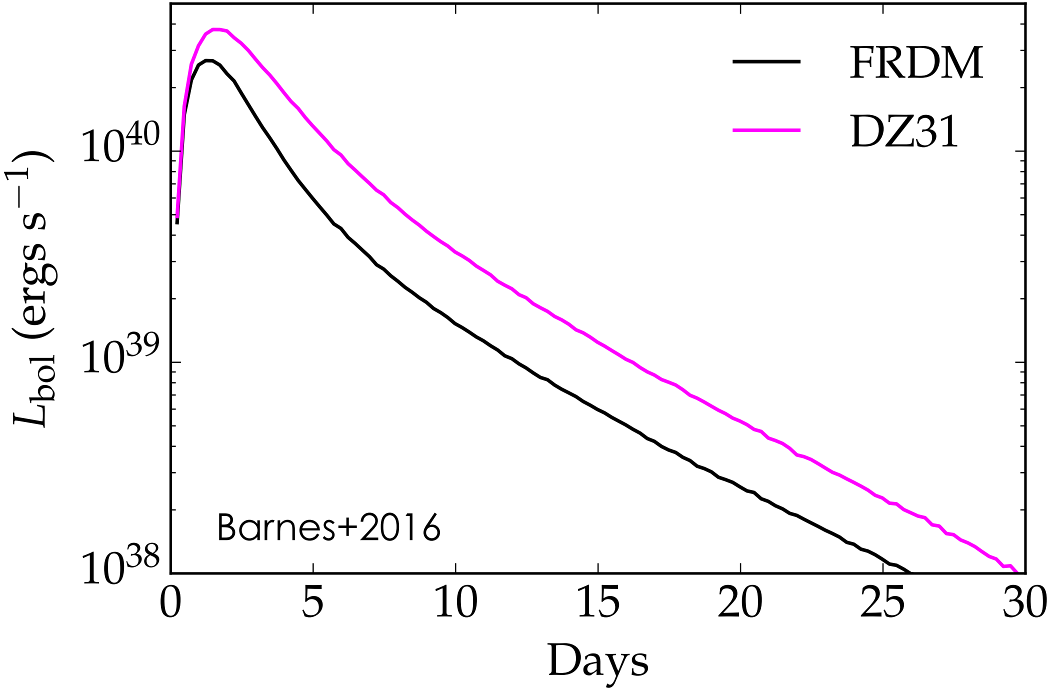
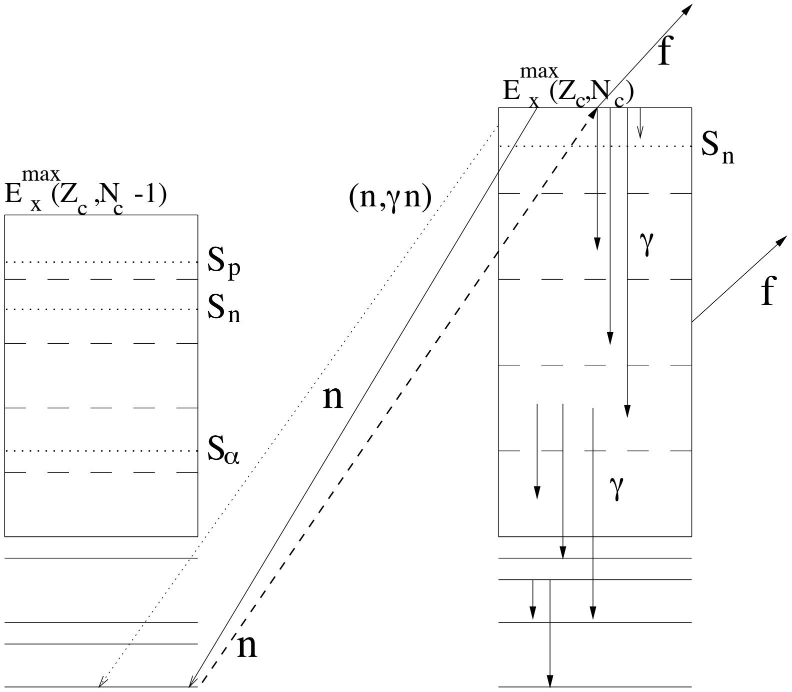




HF neutron capture rate calculations



$$\sigma^{\mu}_{n,\gamma}(E) \propto \sum_{J^{\pi}} (2J+1) \frac{T^{\mu}_{n}(J^{\pi}) T_{\gamma}(J^{\pi})}{T_{tot}(J^{\pi})}$$

Nuclear physics ingredients:

- neutron separation energies
- optical potential
- level densities
- gamma strength functions

TALYS neutron capture rates

We used Talys 1.6

-Range of T = 0.0001-10 GK
-Range of Z = 8-100

Optical Model

- *Koning-Delaroche*
- JLM

Nuclear Level Density (LD)

- *Constant Temperature matched to the Fermi Gas model (CT+BSFG)*
- *Back-shifted Fermi Gas model (BSFG)*
- *Generalized Superfluid model (GSM)*
- Hartree-Fock using Skyrme force (HFS)
- Hartree-Fock-Bogoliubov (Skyrme force) +combinatorial method (HFBS-C)

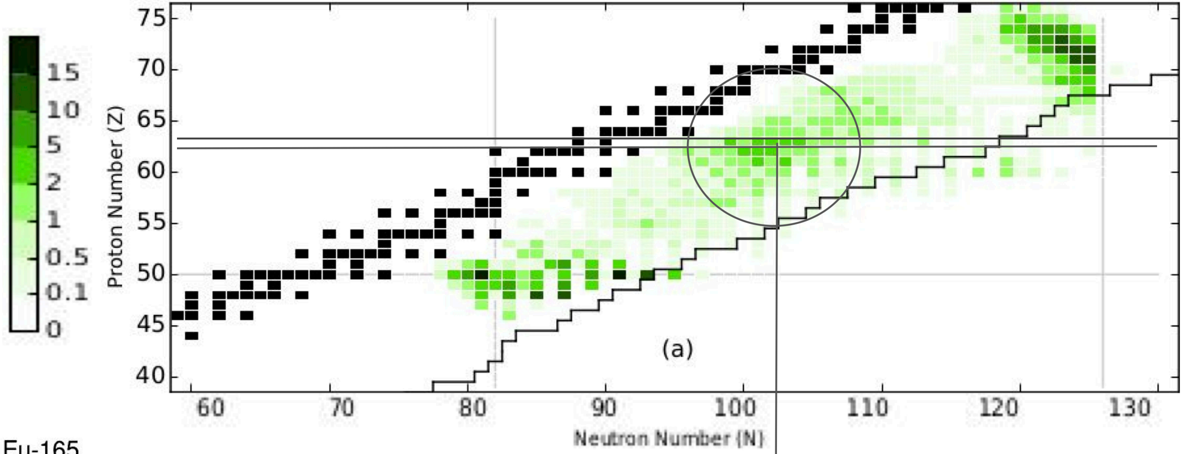
γ-ray Strength Functions (GSF)

- *Kopecky-Uhl generalized Lorentzian (KU)*
- Hartree-Fock BCS (HF-BCS)
- Hartree-Fock-Bogolyubov (HFB)
- *Modified Lorentzian (Gor-ML)*

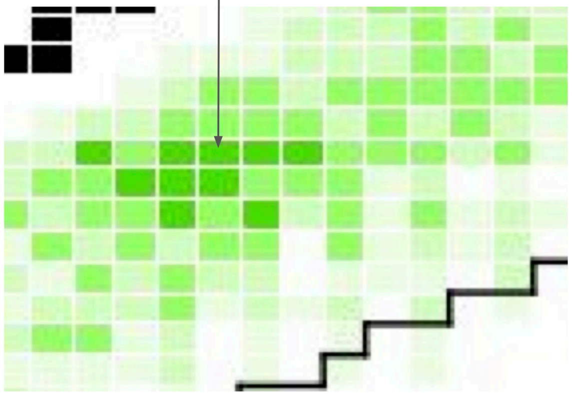
Calculations by S. Nikas, G. Perdikakis (CMU)
in collaboration with M. Beard, M. Mumpower, R. Surman

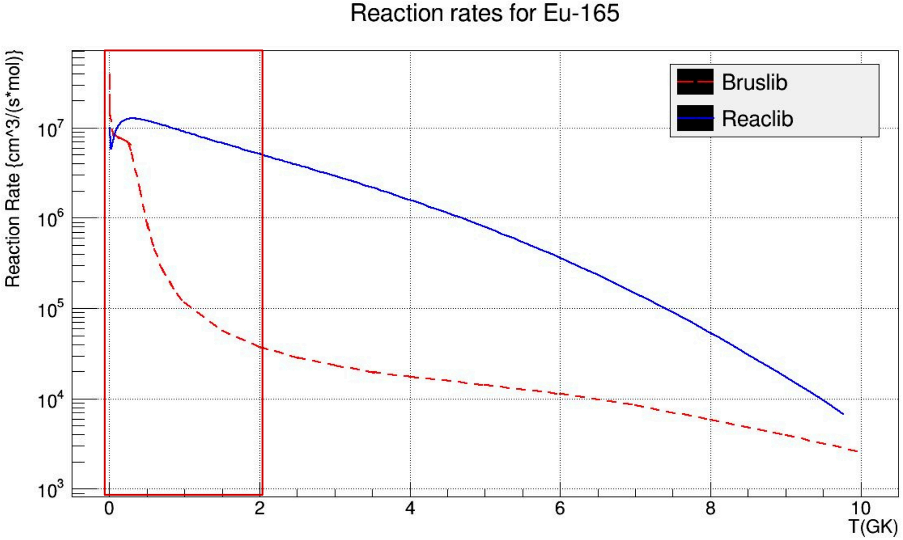
example: ^{165}Eu

slide from S. Nikas

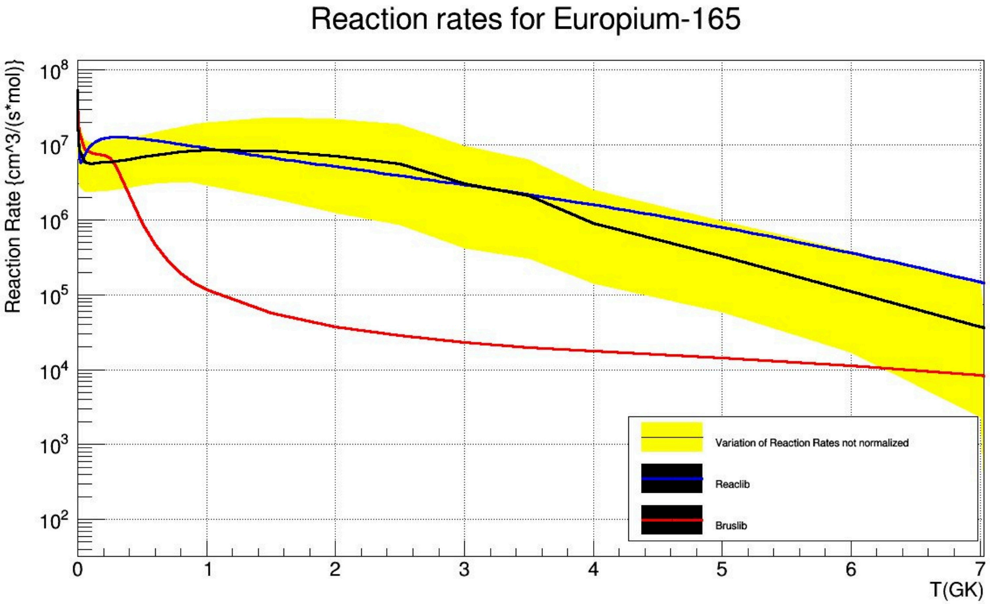


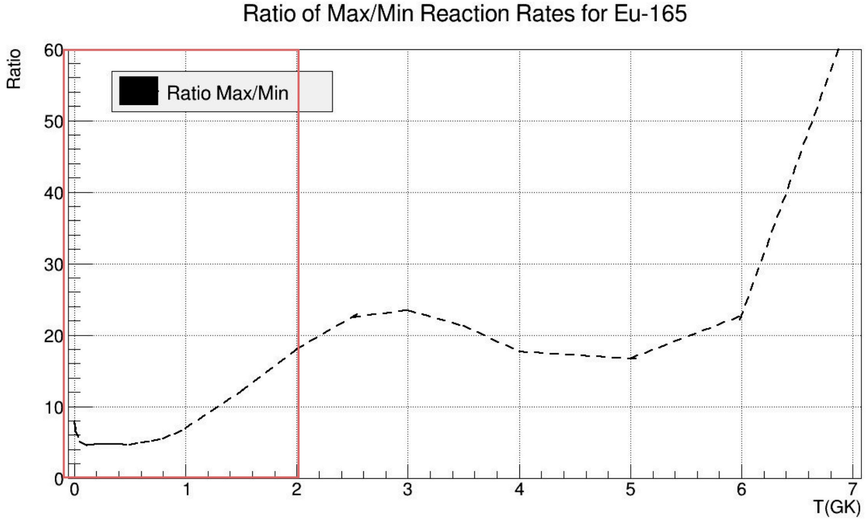
M. Mumpower et al. 2015





example: ^{165}Eu -> variations of LD and GSF





Nikas, Perdikakis, Beard, Mumpower, Surman, in preparation

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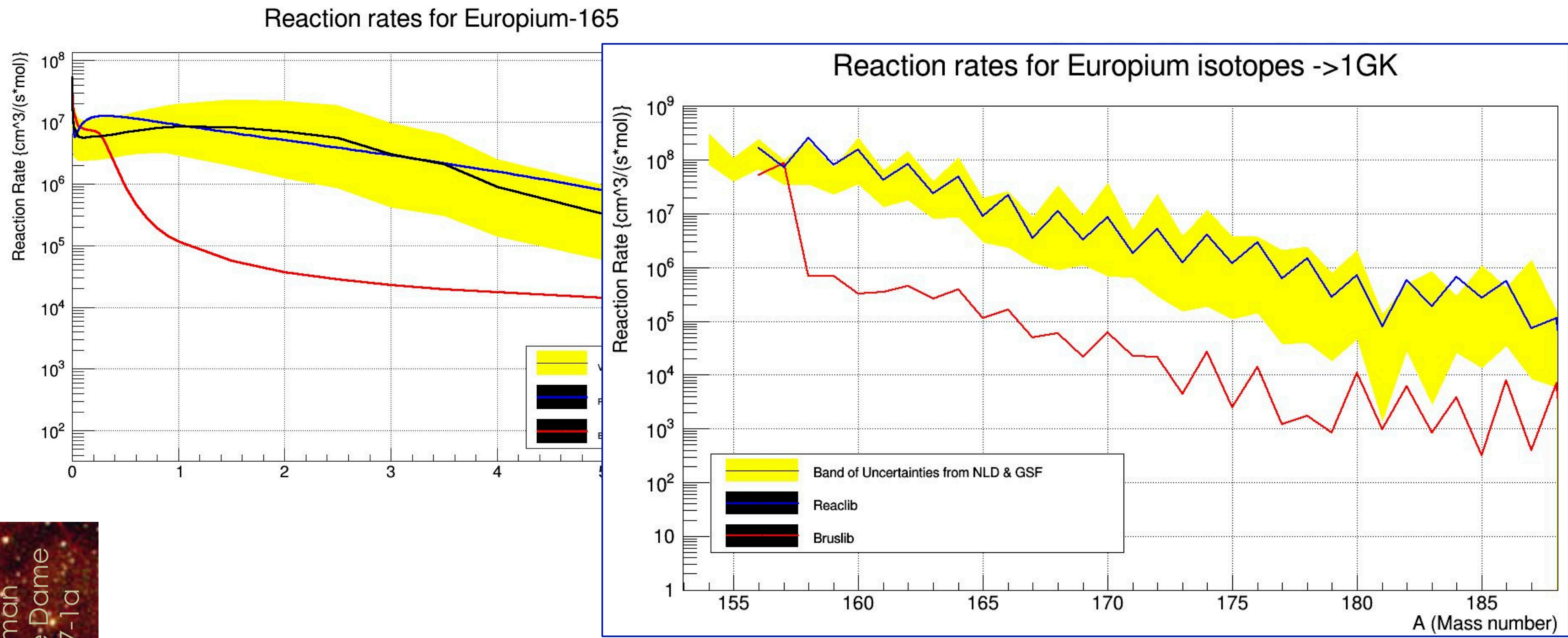
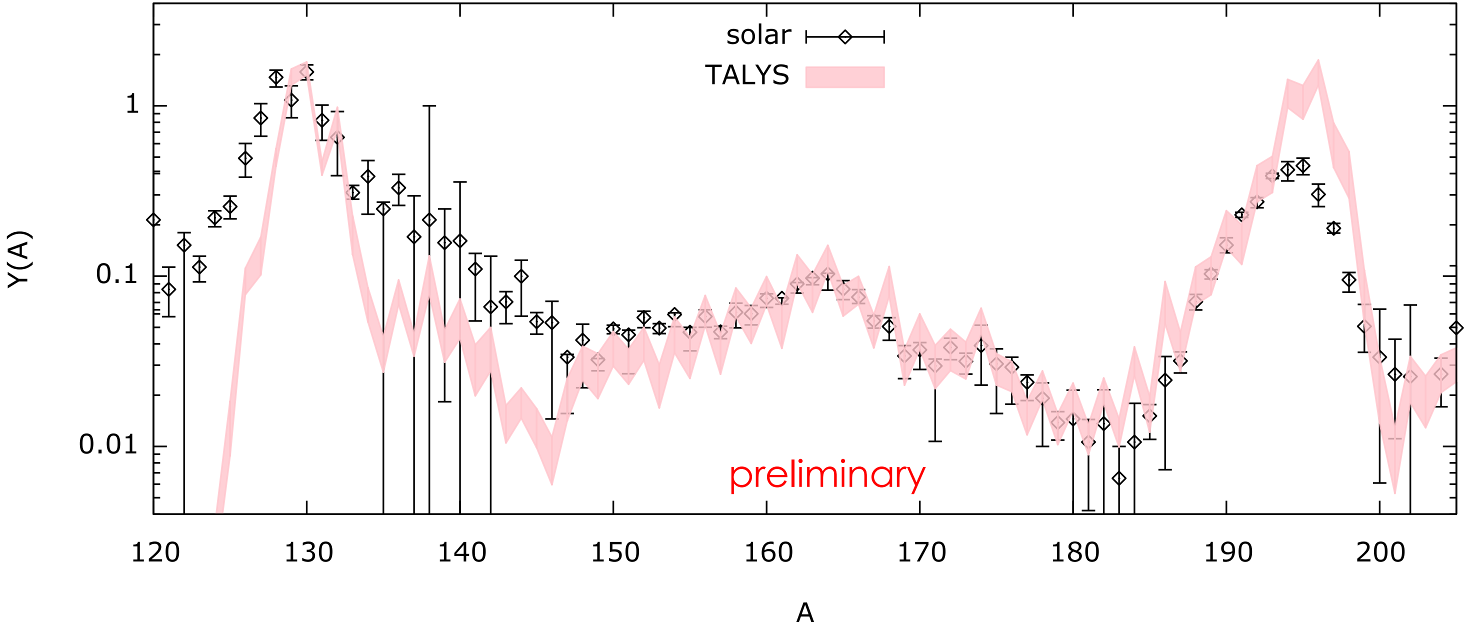


Nikas, Perdikakis, Beard, Mumpower, Surman, in preparation

r process impact estimate



hot, low entropy wind

Nikas, Perdikakis, Beard, Mumpower, Surman, in preparation

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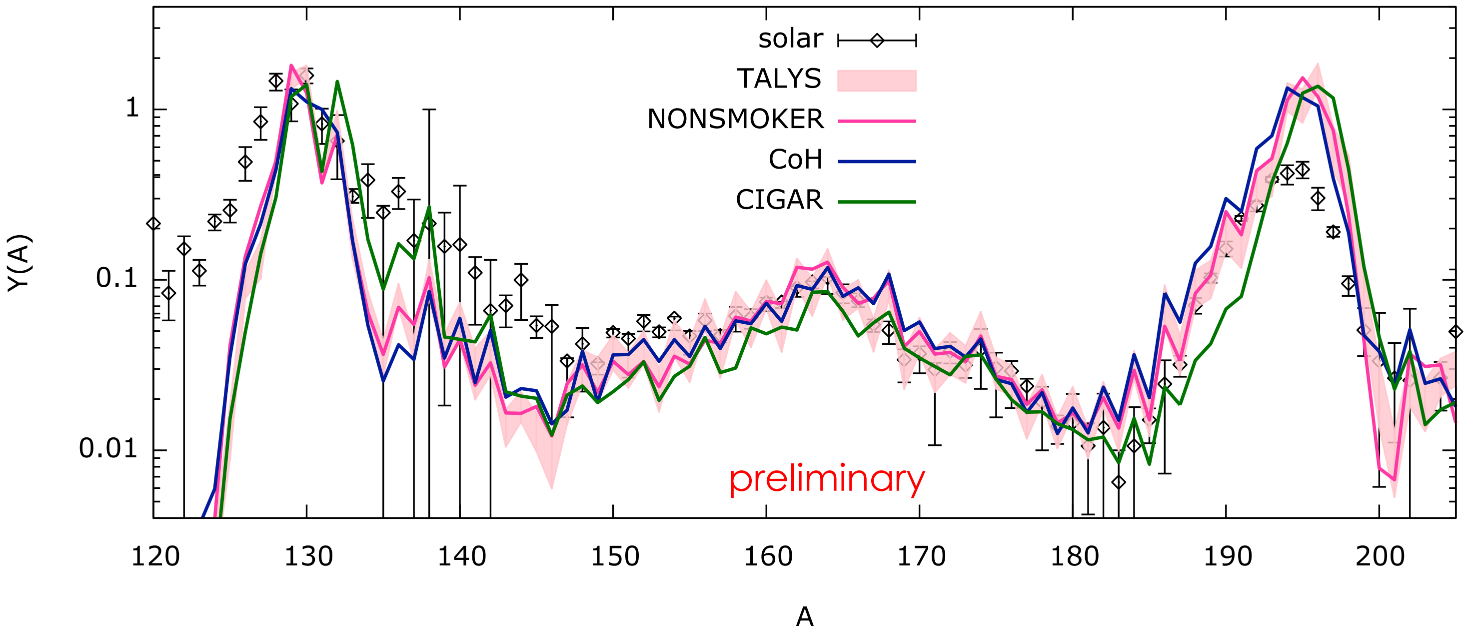

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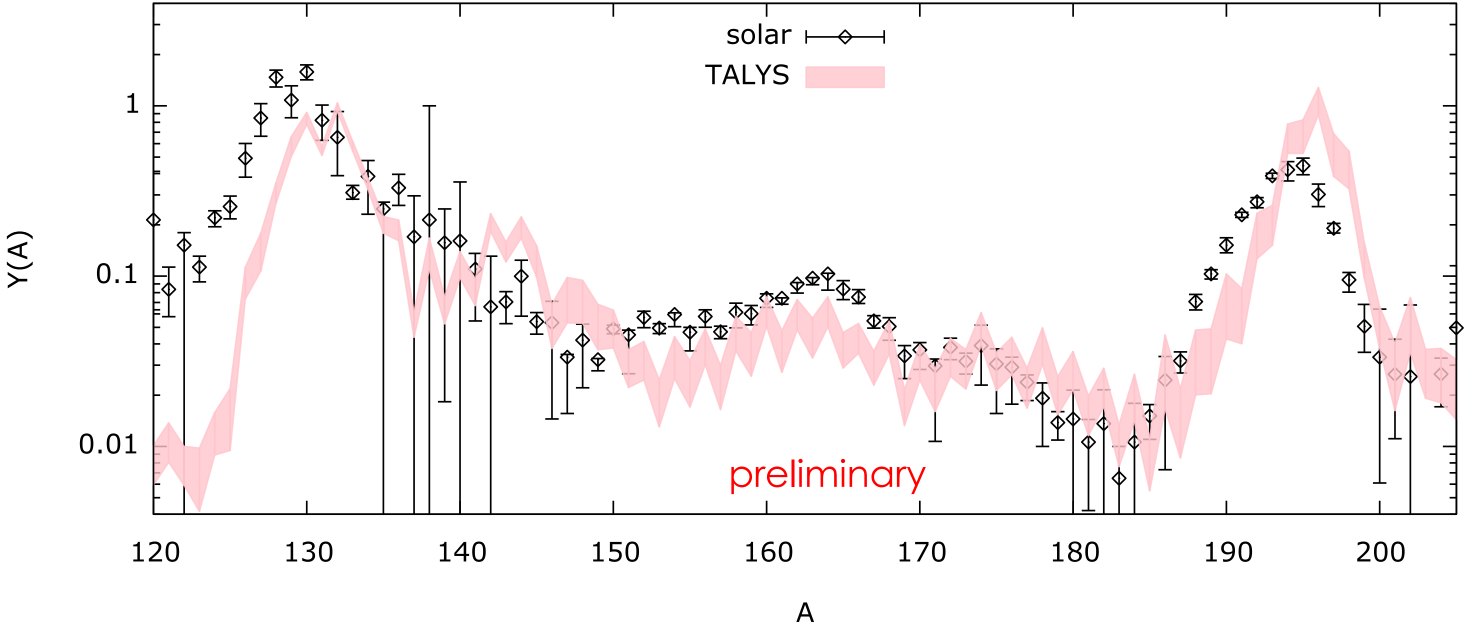

cold merger trajectory

Nikas, Perdikakis, Beard, Mumpower, Surman, in preparation

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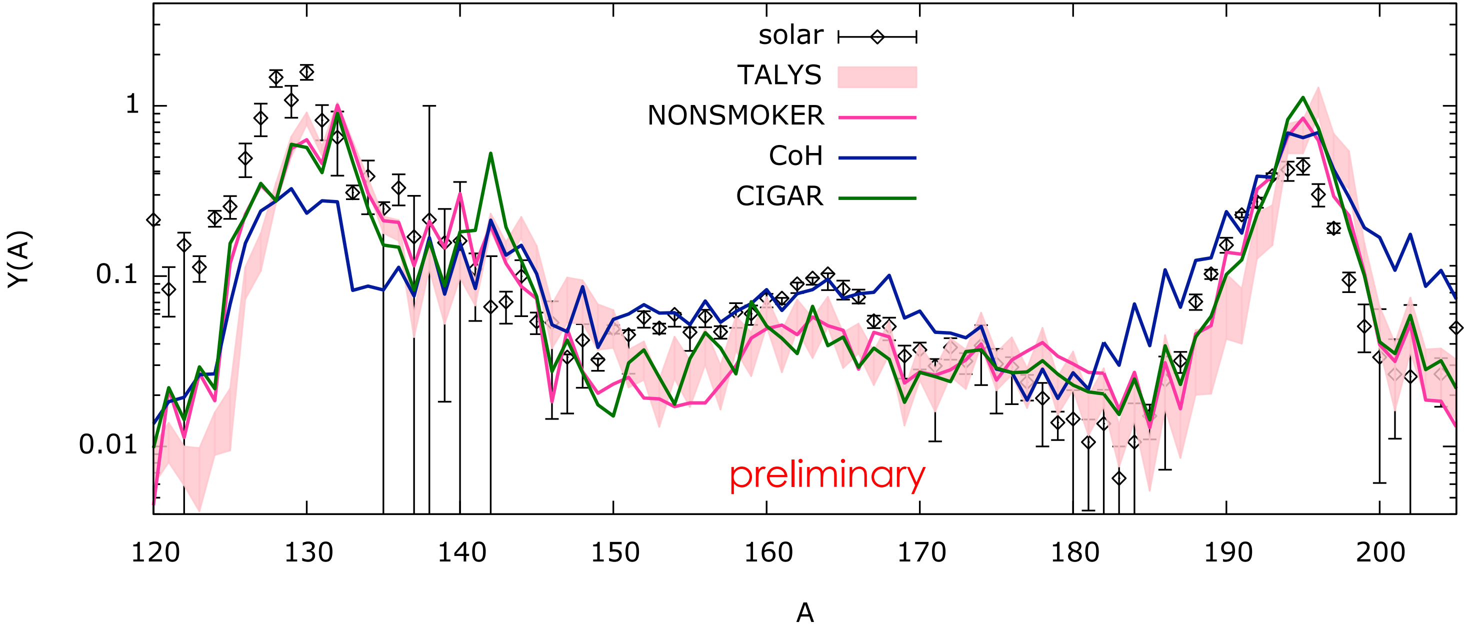

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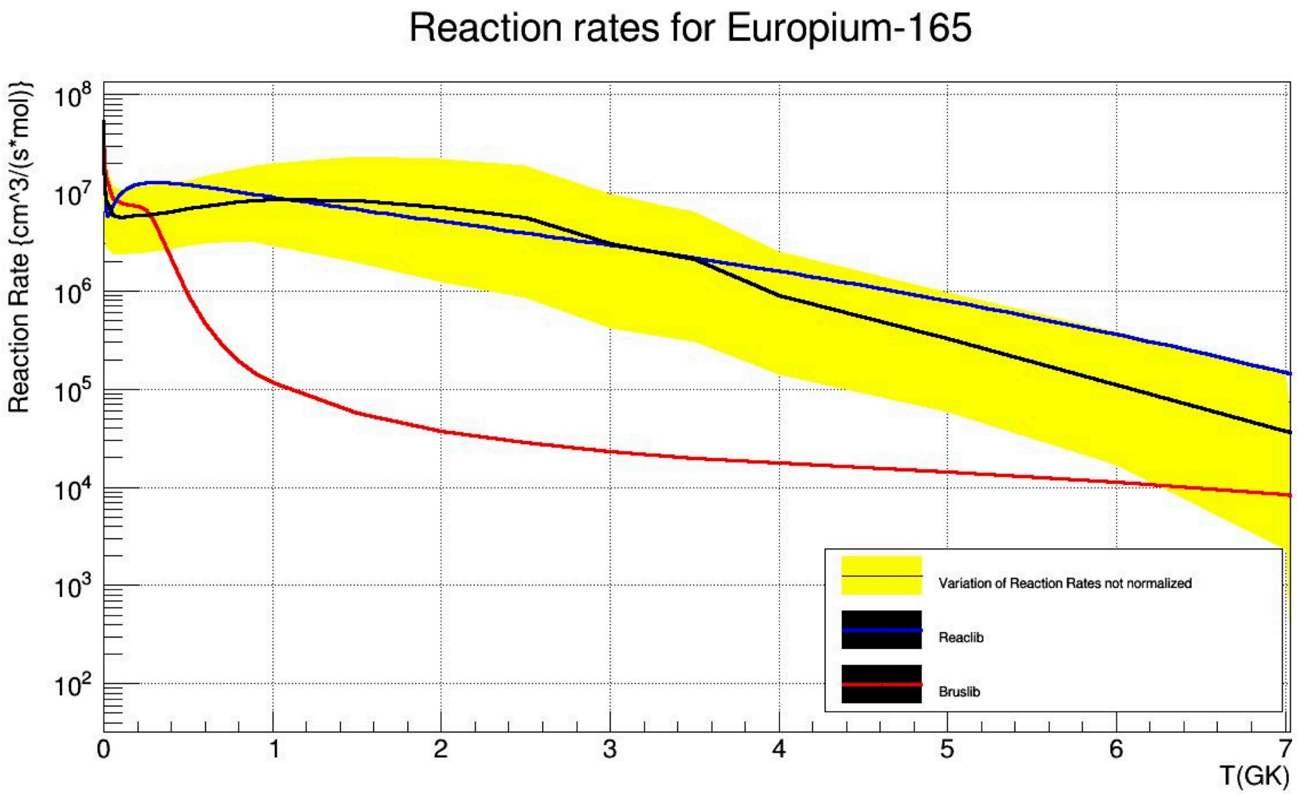
example: ^{165}Eu -> energy binning



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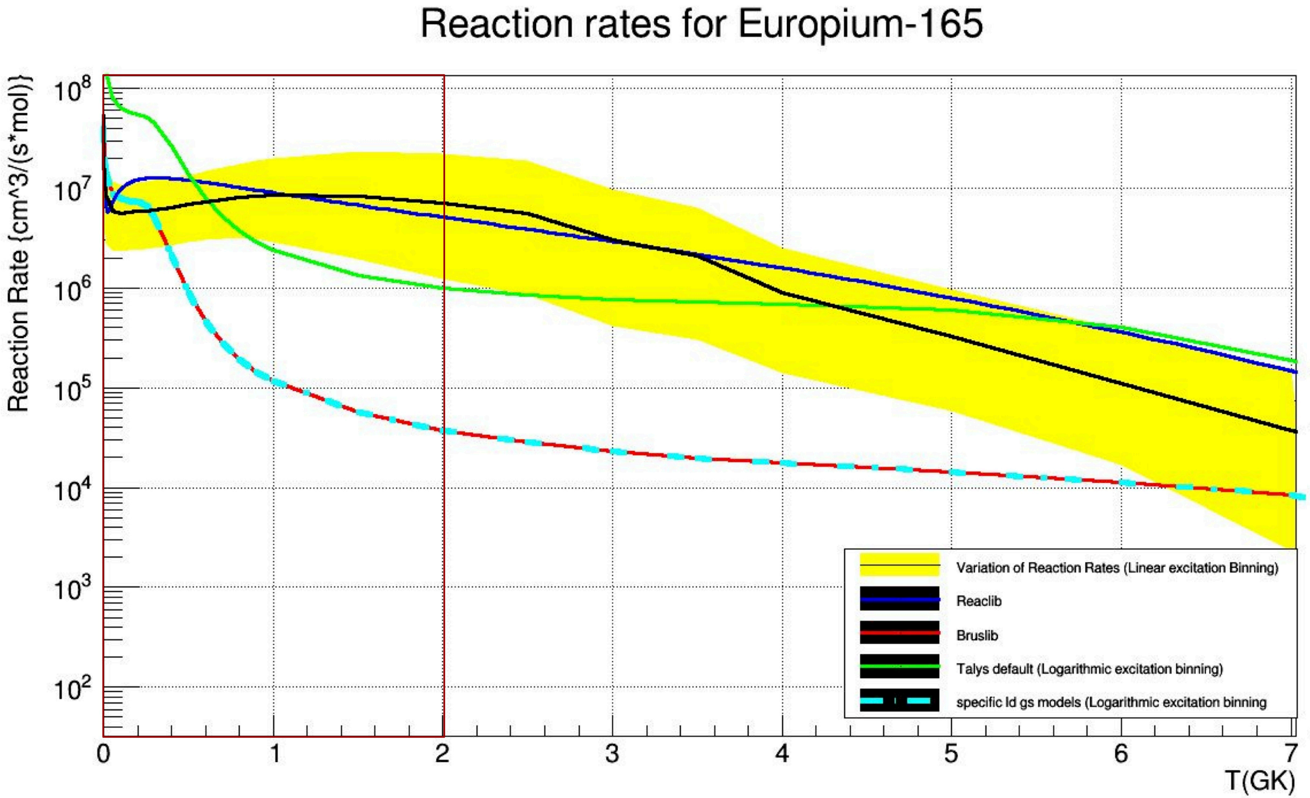

Nikas, Perdikakis, Beard, Mumpower, Surman, in preparation

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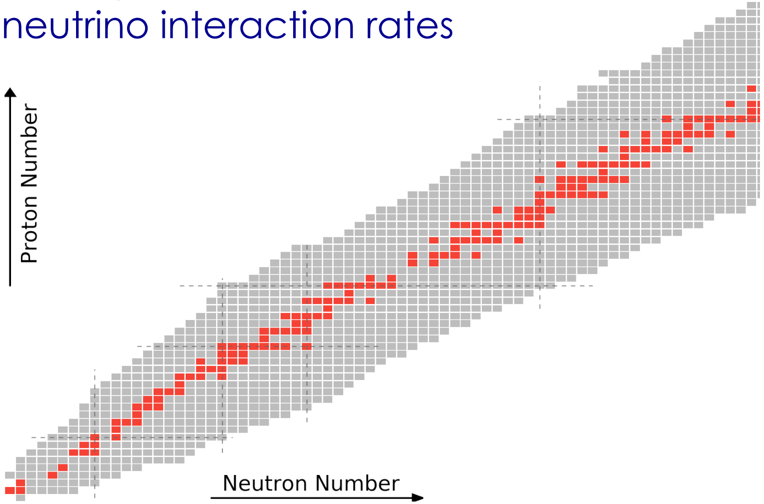

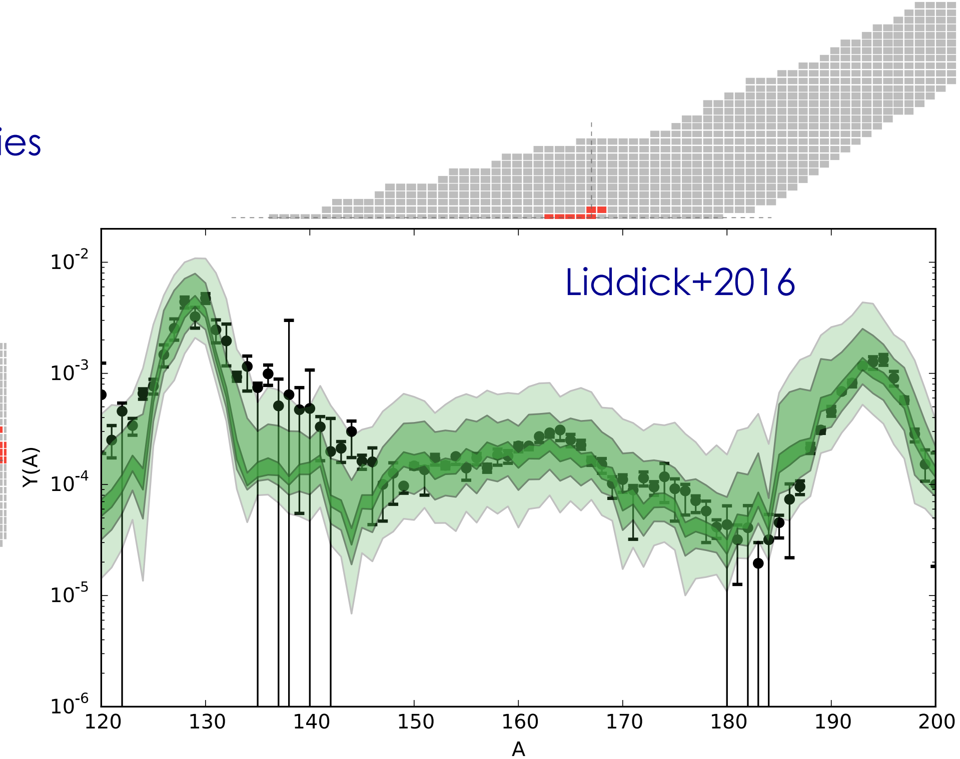

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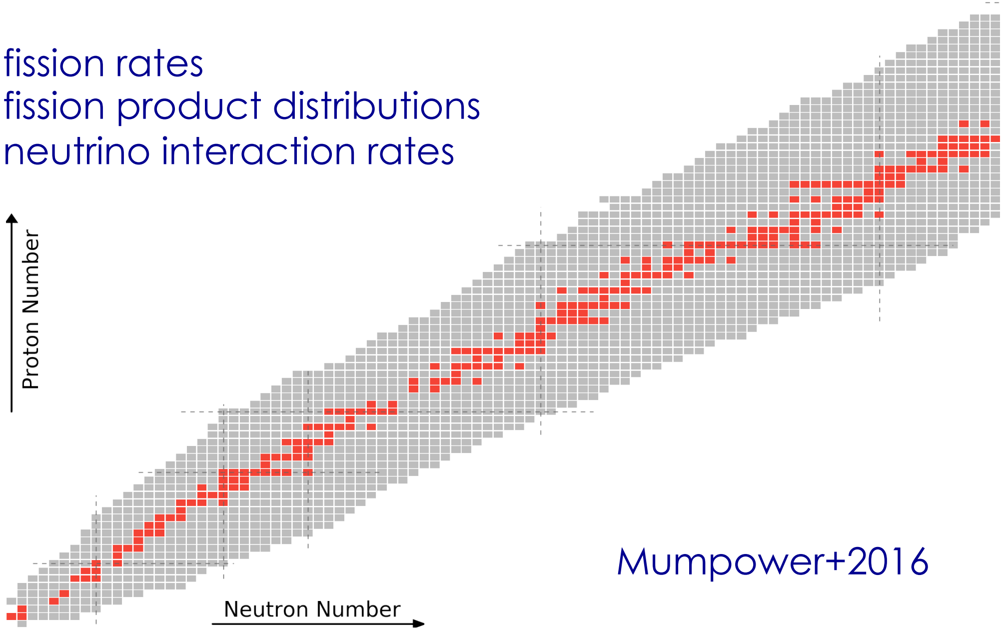
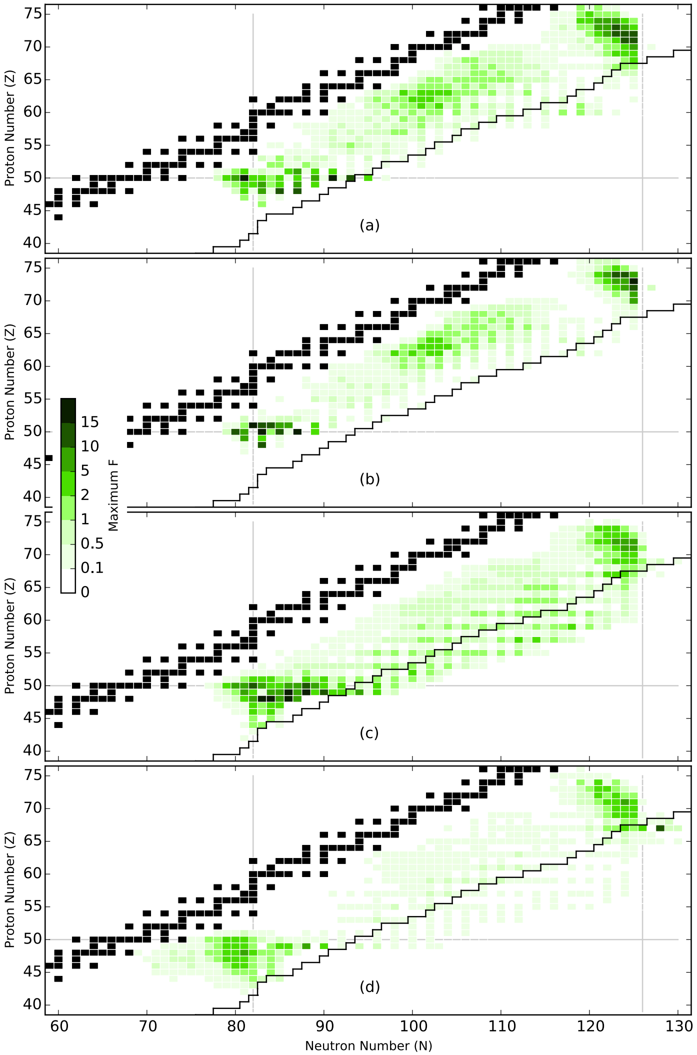


Mumpower+2016



summary

The origin of the heaviest elements in the *r*-process of nucleosynthesis has been one of the greatest mysteries in nuclear astrophysics for decades.

Evidence from a variety of directions increasingly points to neutron star mergers as the primary source of main *r*-process elements. A merger *r* process may depend more sensitively on neutron capture rates than ‘standard’ (n,γ)-(γ,n) equilibrium *r*-process scenarios.

Neutron capture rates have few experimental constraints far from stability, and different HF approaches can disagree by orders of magnitude. Advances in experiment (transfer reactions, nuclear resonance fluorescence, β-Oslo method) and reaction theory are therefore crucial for reducing neutron capture rate uncertainties and producing precise *r*-process predictions.