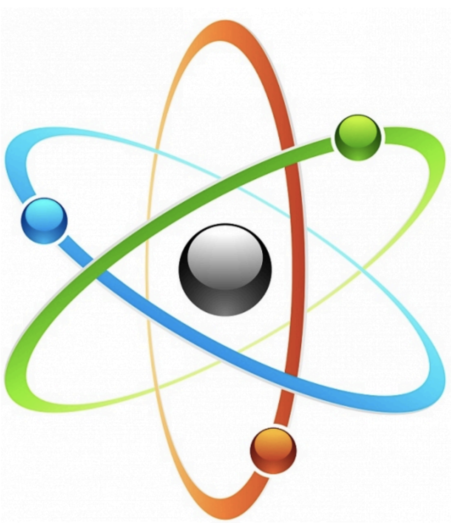
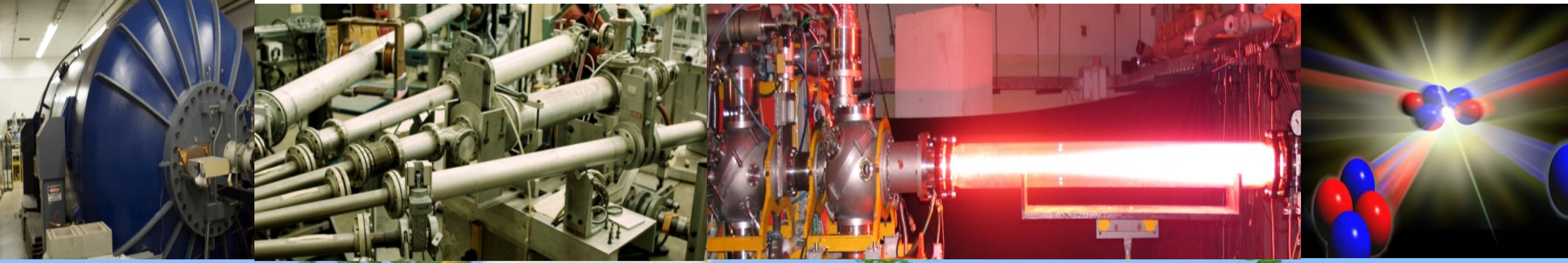
Institute for Structure & Nuclear Astrophysics

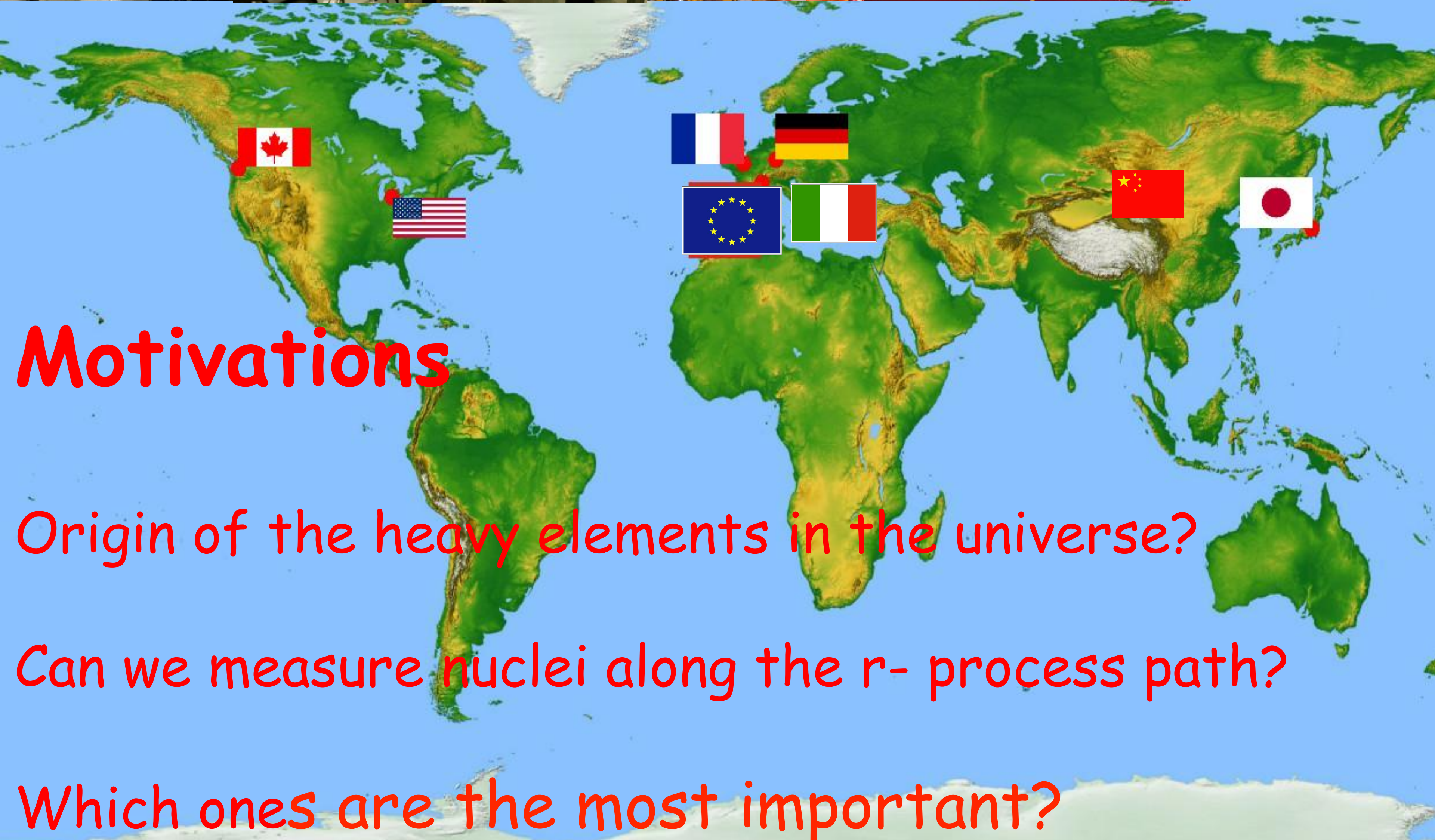
Apologies to Martinez Pinedo

Explosive Nucleosynthesis: Interesting Measurements that could be done at SPES?



Ani Aprahamian
University of Notre Dame





Motivations

Origin of the heavy elements in the universe?

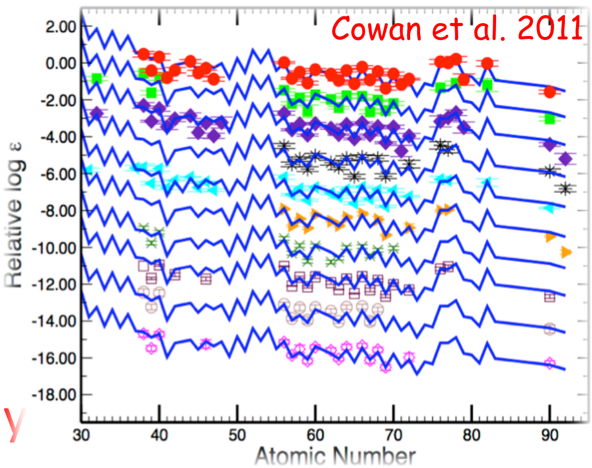
Can we measure nuclei along the r- process path?

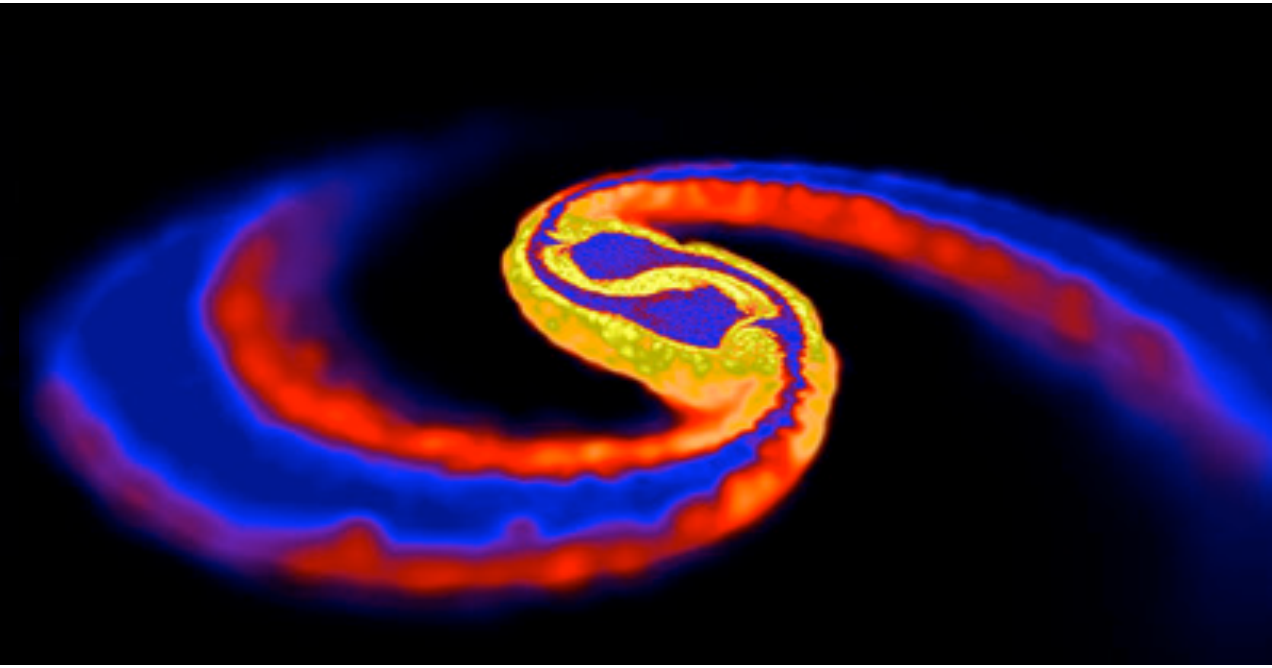
Which ones are the most important?

r-process

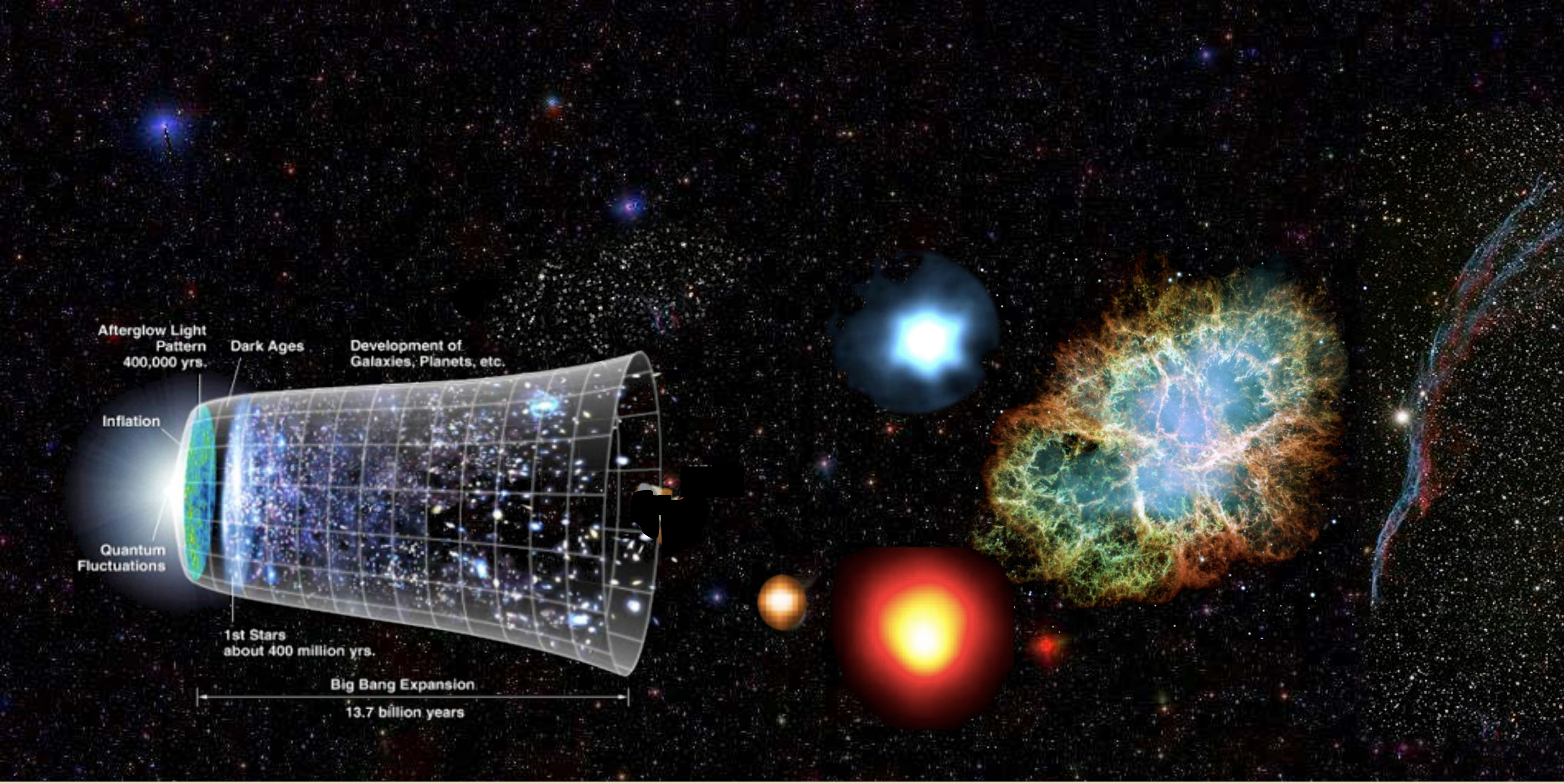
Origin of more than 50% of all the elements beyond iron

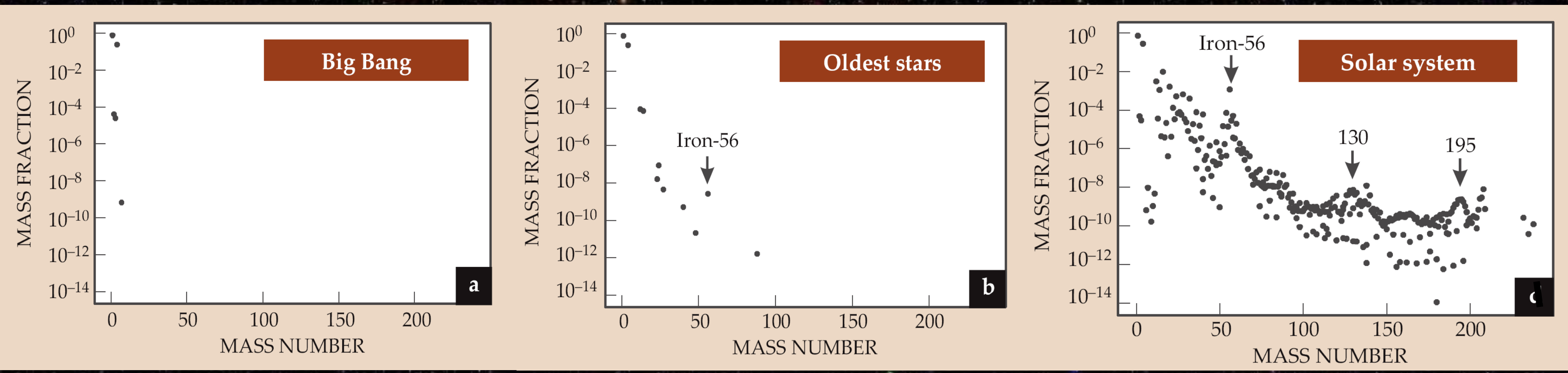
Site of r-process is one of open challenges in all of physics today





Temperature, density as a function of time, initial compositions, neutrons

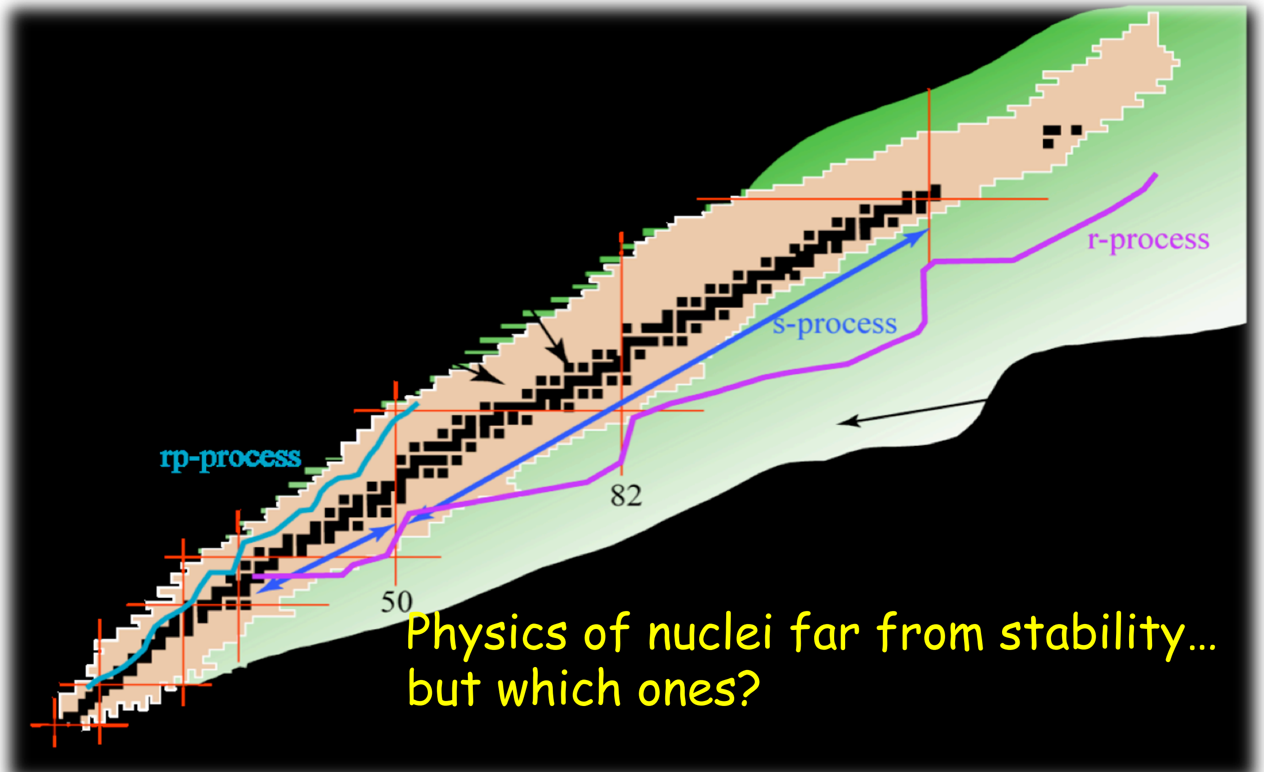

Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years


Big Bang
a
Oldest stars
Iron-56
b
Solar system
Iron-56
130
195
c
MASS FRACTION
MASS NUMBER
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
0
50
100
150
200

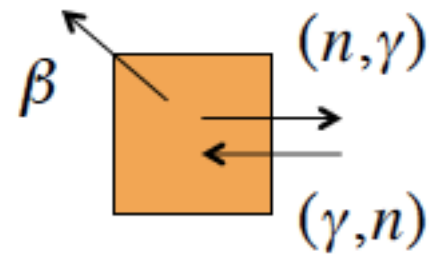
Goal:

to unravel the impact of nuclear physics from the complications of the Astrophysical scenarios: theory and experiment.

How? Measure. Which ones do we measure?

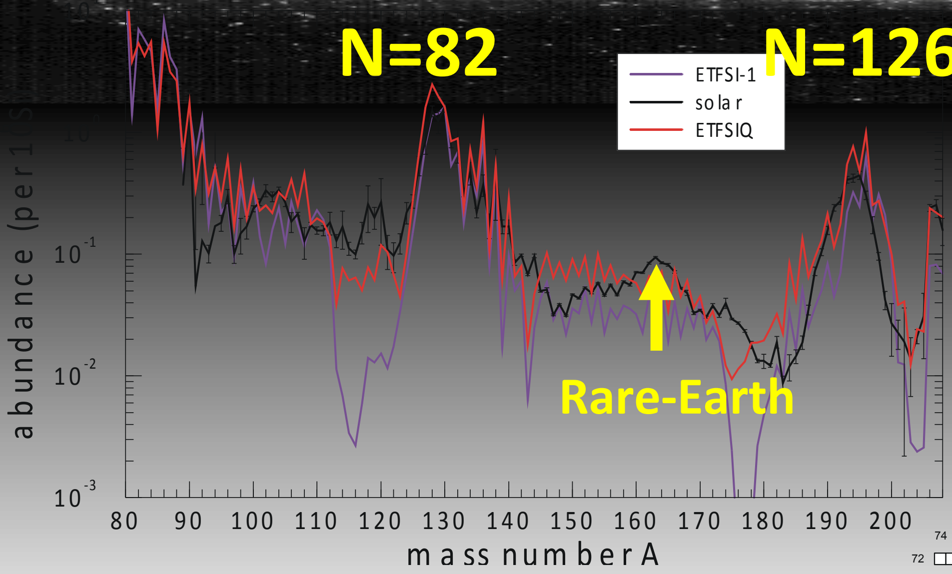


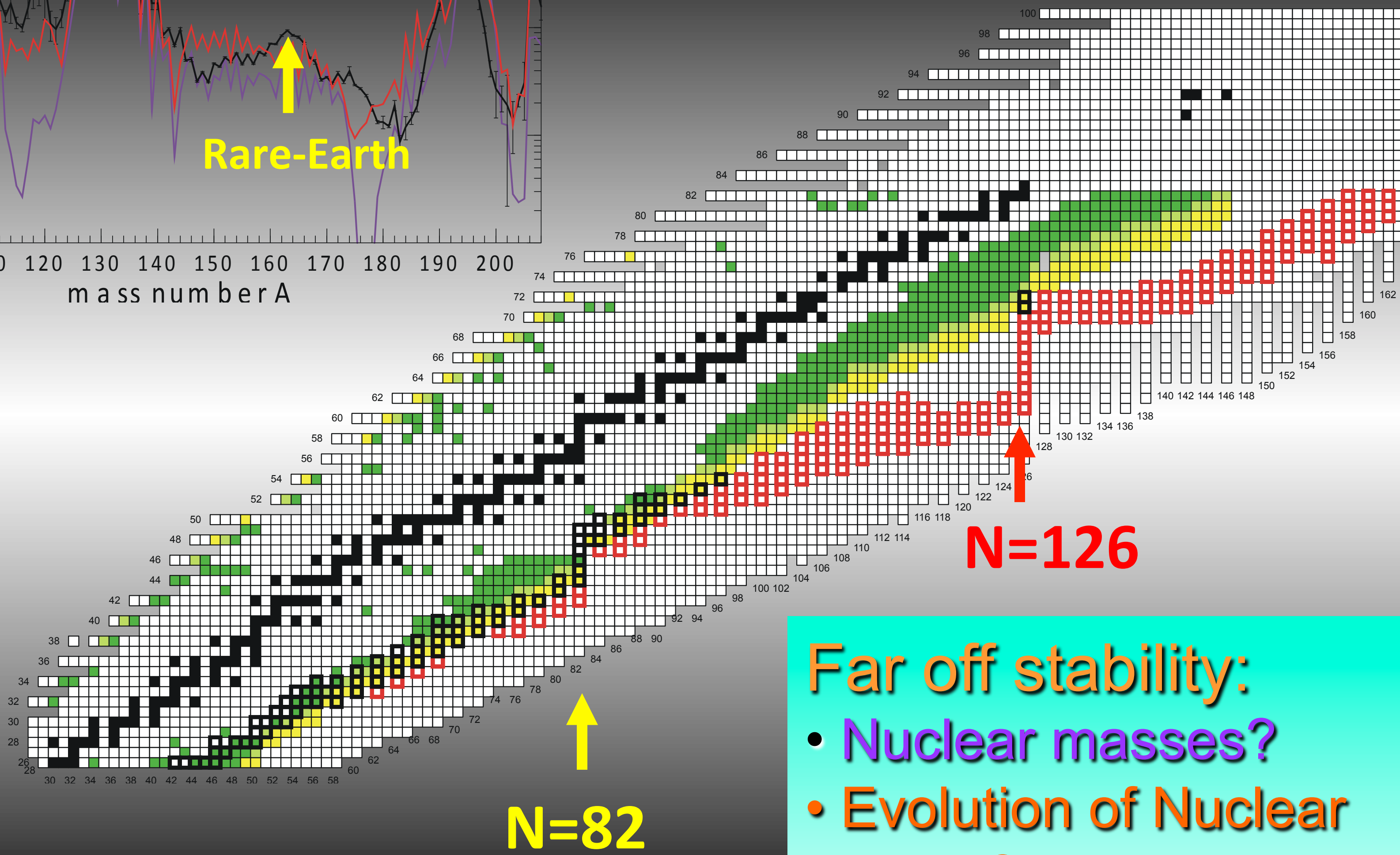
Nuclear masses
β-decay rates
n- capture
β-delayed n-emission



r-process

Wiescher





Far off stability:

- Nuclear masses?
- Evolution of Nuclear shapes?

Nucleosynthesis in the r-process

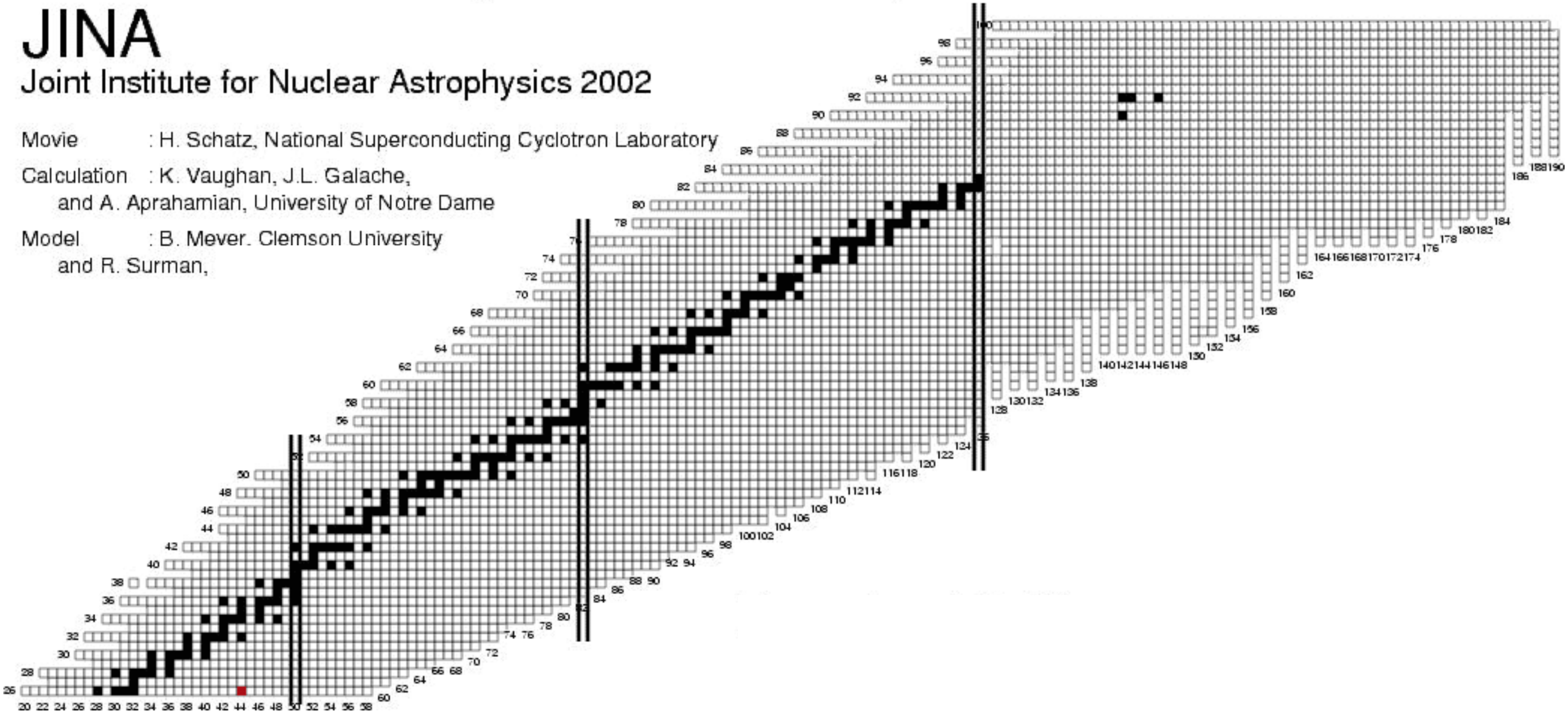
JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, National Superconducting Cyclotron Laboratory

Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Mever. Clemson University
and R. Surman,



Nuclear masses
β-decay rates
n- capture
β-delayed n-emission

r-process sensitivity studies

dynamic r-process simulations developed by R. Surman et al.

Approach:

Choose a baseline simulation

Vary one piece of nuclear data by a set amount, rerun the simulation,

compare the final abundance pattern to the baseline

Repeat for each nucleus in the network

How we measure the effect of the changes

$$F = 100 \times \sum_A |X_{\mathrm{baseline}}(A) - X(A)|.$$

r-process sensitivity studies

dynamic r-process simulations developed by R. Surman et al.

- neutron capture rates
- masses/neutron separation energies/binding energies
- beta decay rates
- Beta-delayed neutron emission probabilities
- **masses/capture rates/beta decay rates (propagated)**

Example: varied **mass models**-
FRDM, Duflo-Zuker, ETFSIQ, HFB-21, F-spin
Adjusted the binding energy of each nucleus ± 1MeV
(**3010 nuclei twice….**)

Sensitivity studies for the main r process: nuclear masses

A. Aprahamian,[1] I. Bentley,[2] M. Mumpower,[1] and R. Surman[3]

AIP Adv. 4, 041101 (2014).

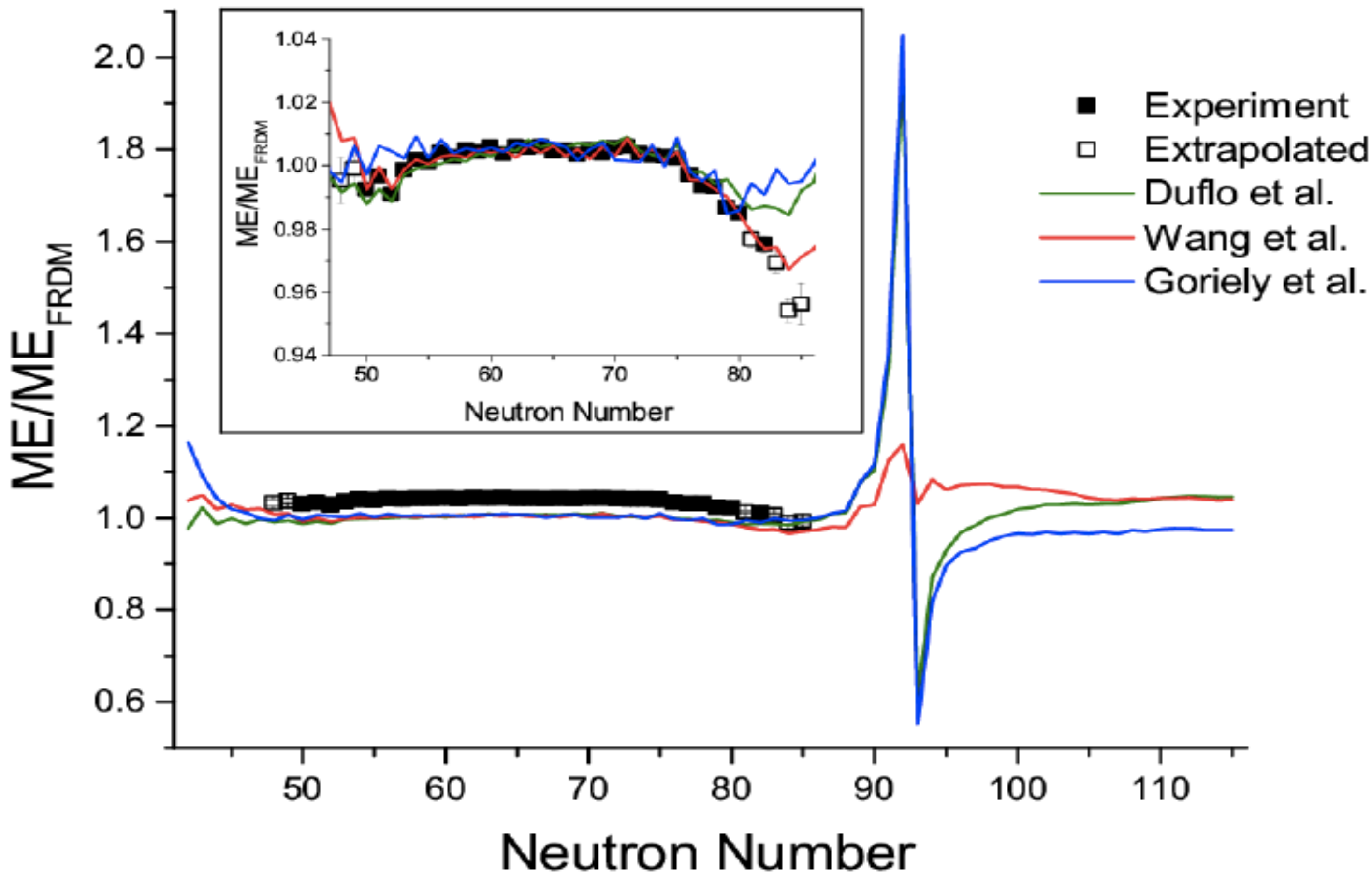
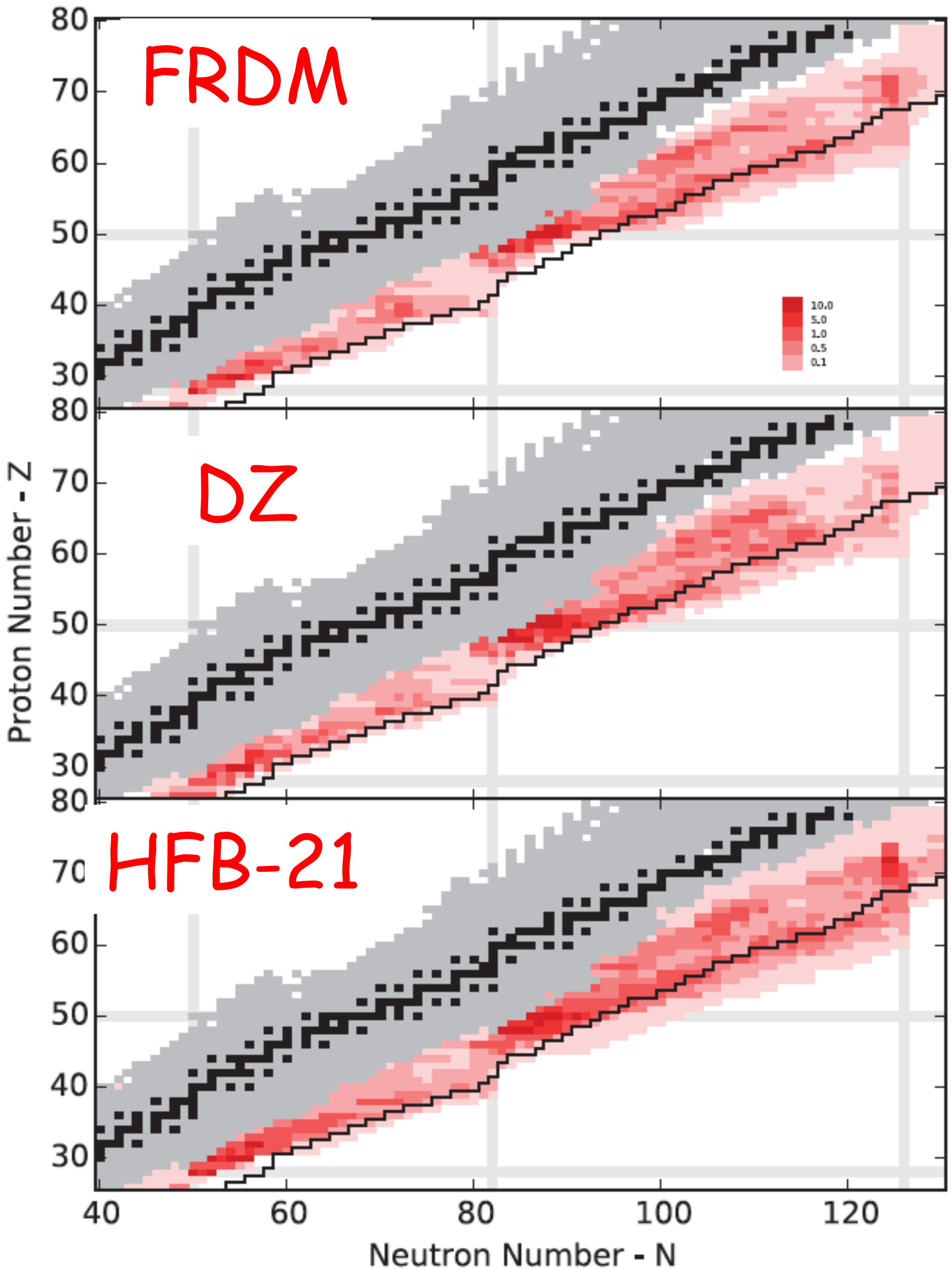


FIG. 1. The mass excess of cadmium isotopes consisting of experimental (filled boxes) and extrapolated (open boxes) values from AME2012[19] compared to theoretical values from Duflo & Zuker[20], Goriely et al.[21], and Wang et al.[22], all scaled to the mass excess from the FRDM[18].

Same astrophysical trajectory (hot r-process): 3 different mass models

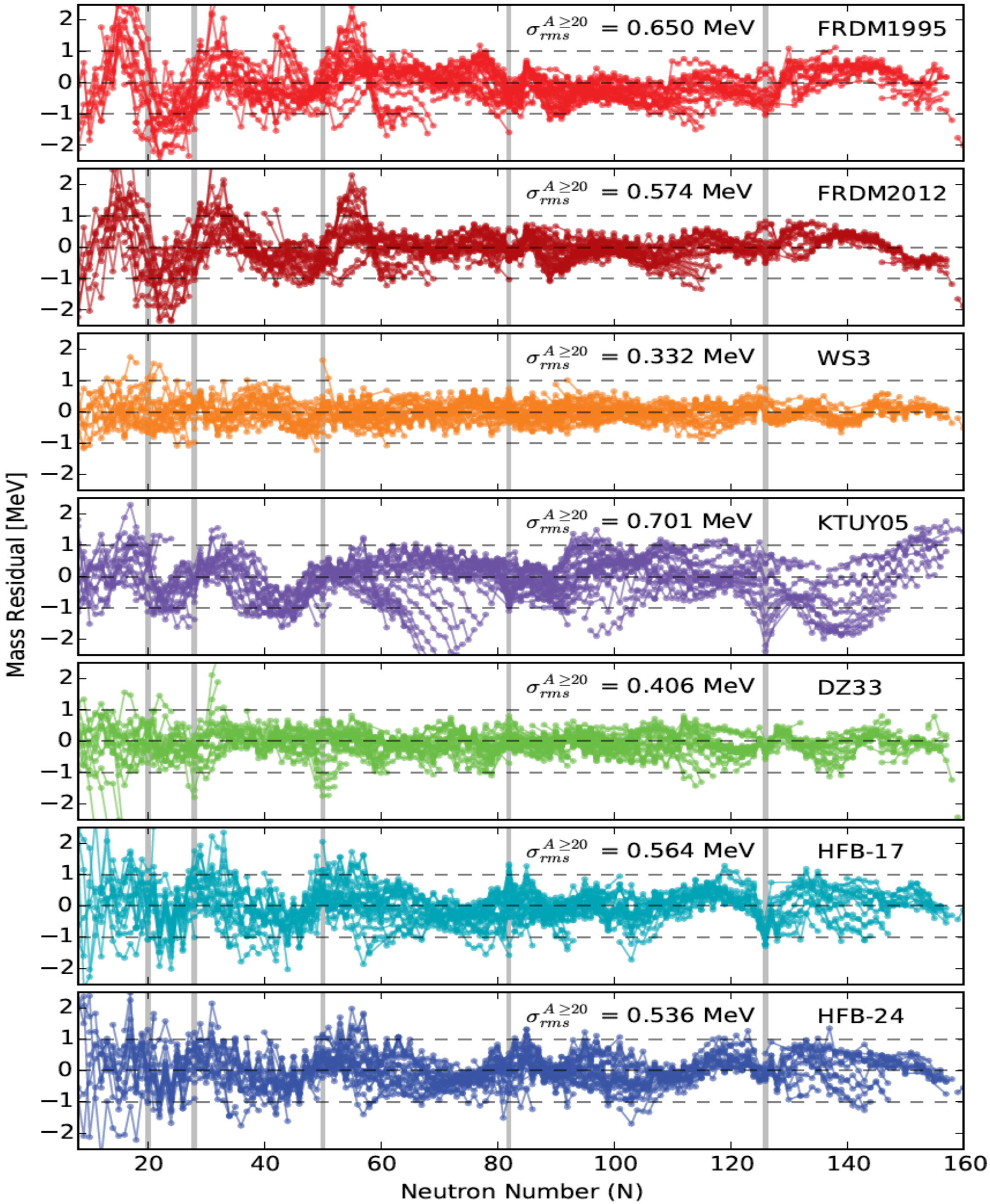


ΔBE=+/-1 MeV

FRIB

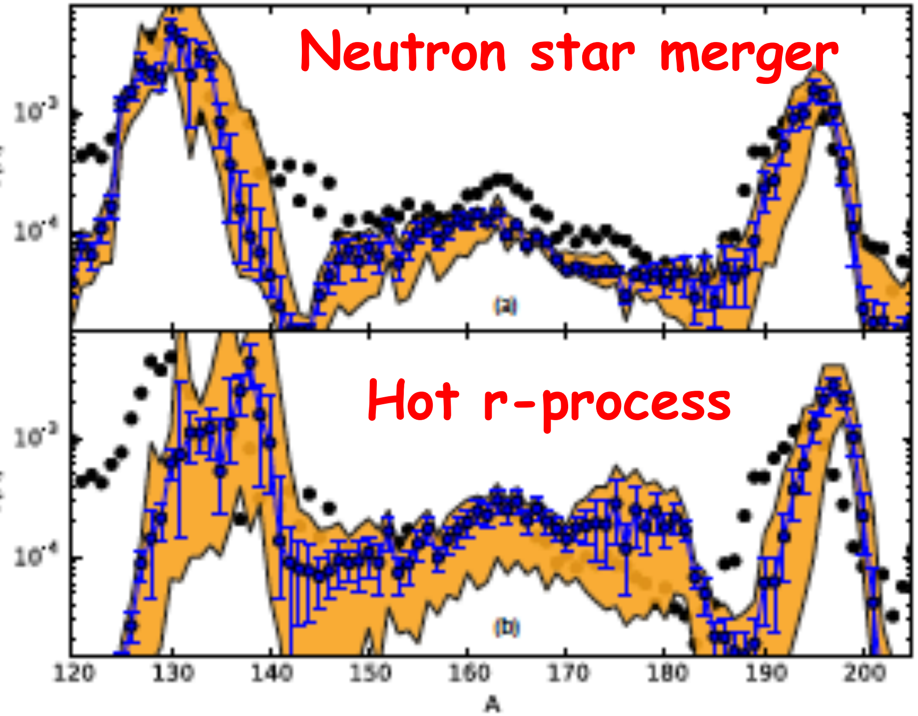
Sensitivity studies for the main r process: nuclear masses

A. Aprahamian,[1] I. Bentley,[2] M. Mumpower,[1] and R. Surman[3]

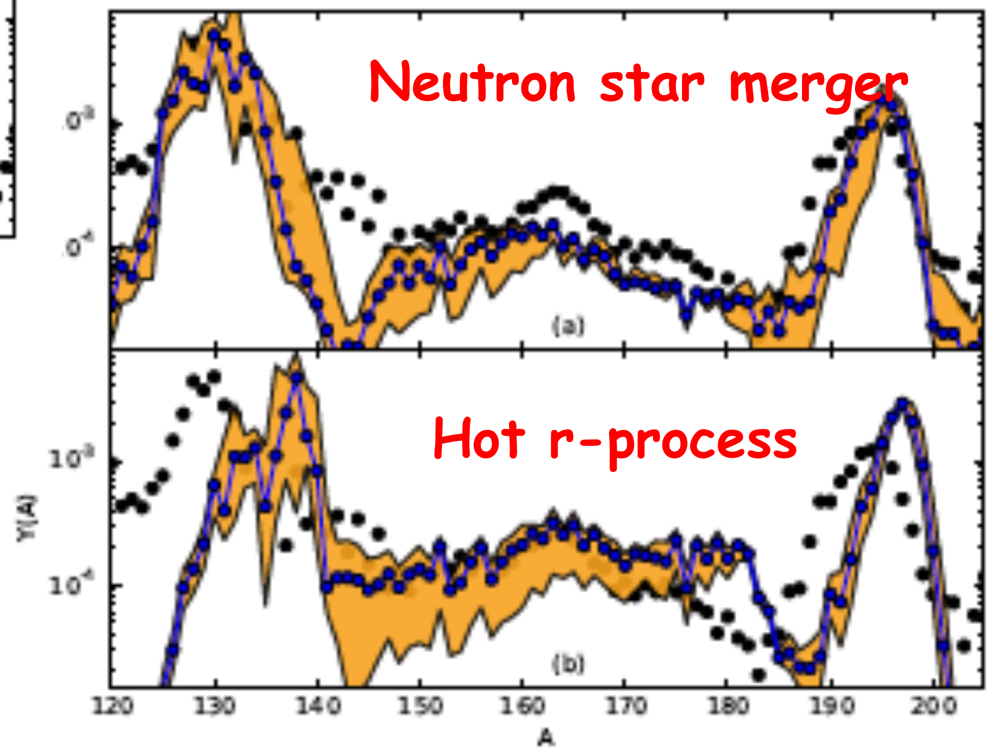


$\sigma_{rms}^{A\geq20}$ = 0.650 MeV
FRDM1995
$\sigma_{rms}^{A\geq20}$ = 0.574 MeV
FRDM2012
$\sigma_{rms}^{A\geq20}$ = 0.332 MeV
WS3
$\sigma_{rms}^{A\geq20}$ = 0.701 MeV
KTUY05
$\sigma_{rms}^{A\geq20}$ = 0.406 MeV
DZ33
$\sigma_{rms}^{A\geq20}$ = 0.564 MeV
HFB-17
$\sigma_{rms}^{A\geq20}$ = 0.536 MeV
HFB-24
Mass Residual [MeV]
Neutron Number (N)

ΔBE=+/- 0.5 MeV

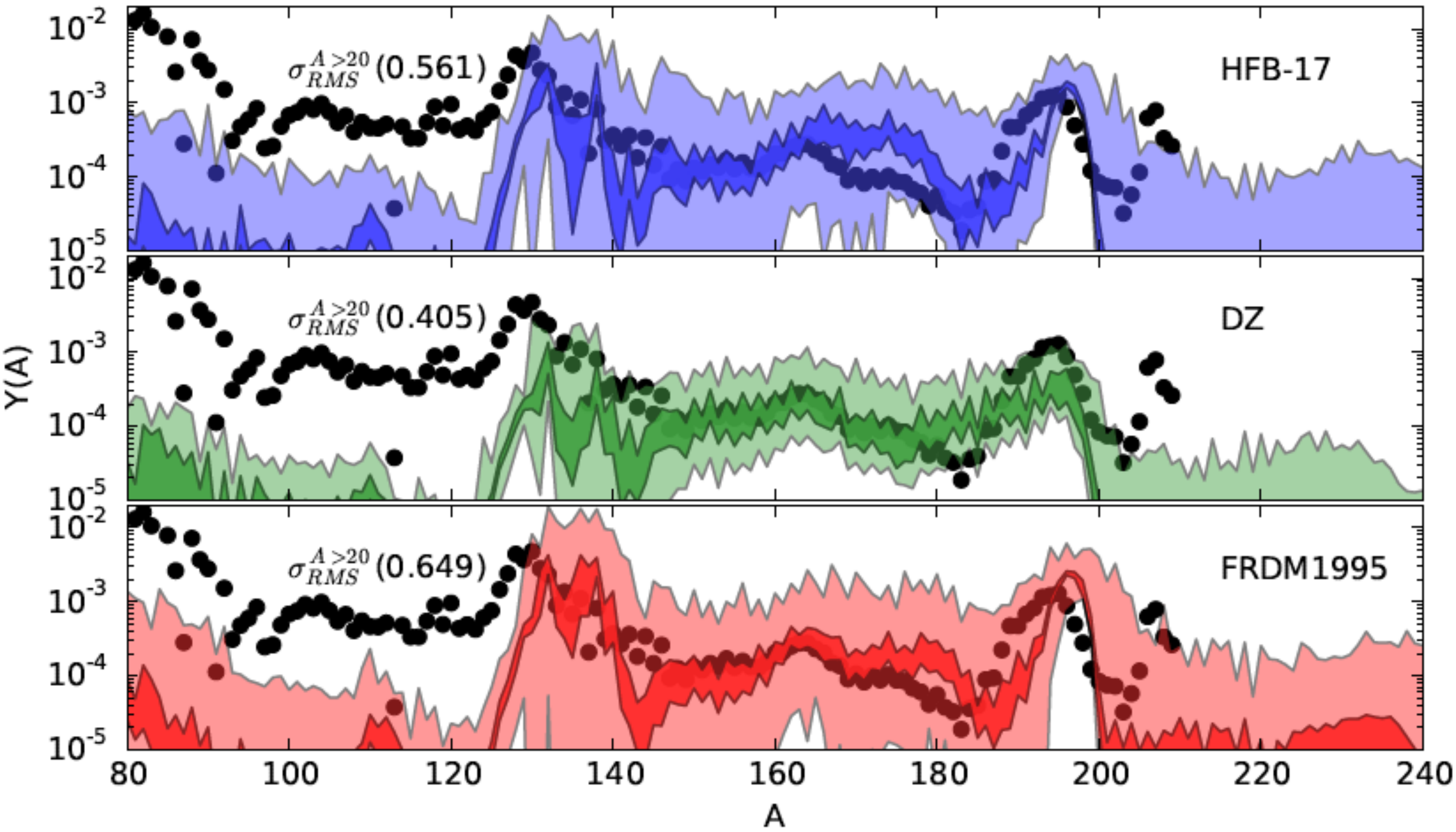


ΔBE = +/-1 MeV



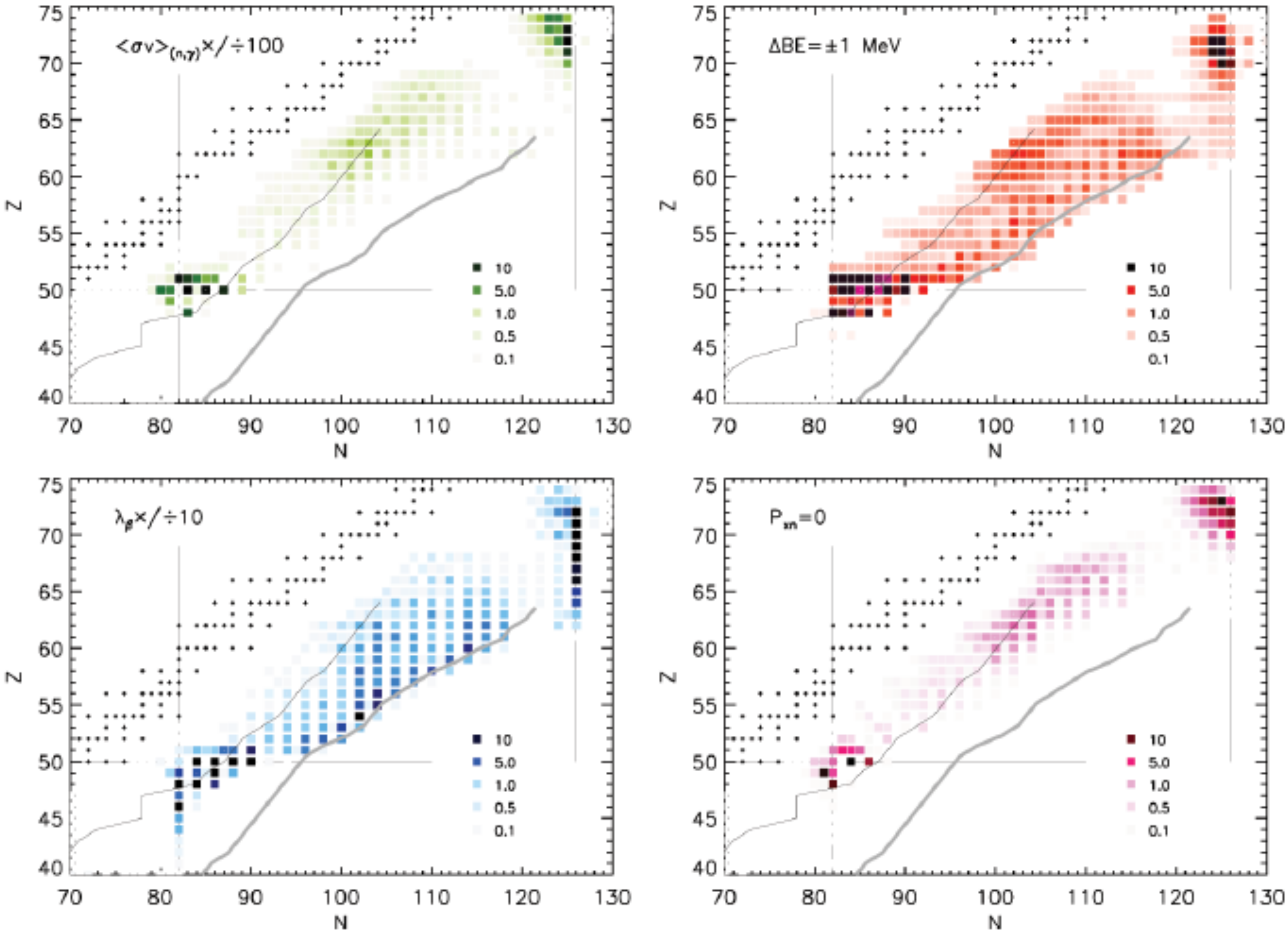
ΔBE =+/-0.5 MeV

Hot r-process trajectory



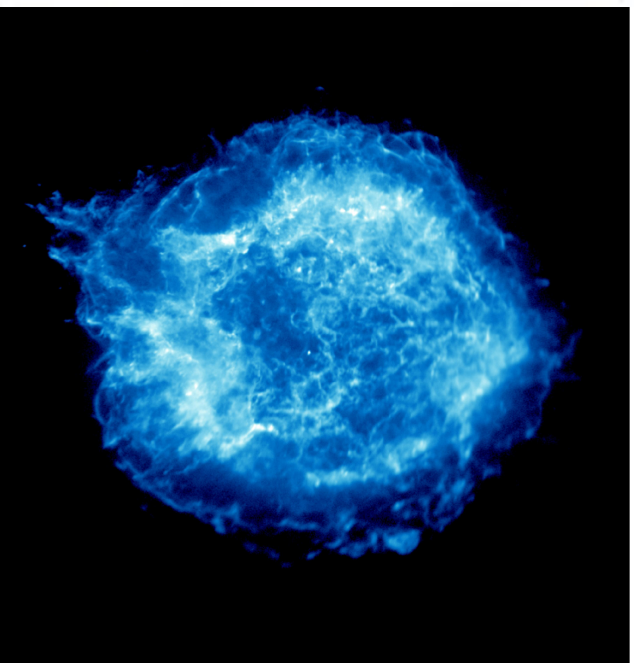
Mumpower, Surman, Aprahamian, CGS15 proceedings (2015)

Wind r-Process Sensitivity Study Results



Accessibility Limits CARIBU Predicted FRIB

Potential r-process sites: Neutron richness,
High entropy, and fast outflow to reach U/Th, Temperature/density variations as a function of time.

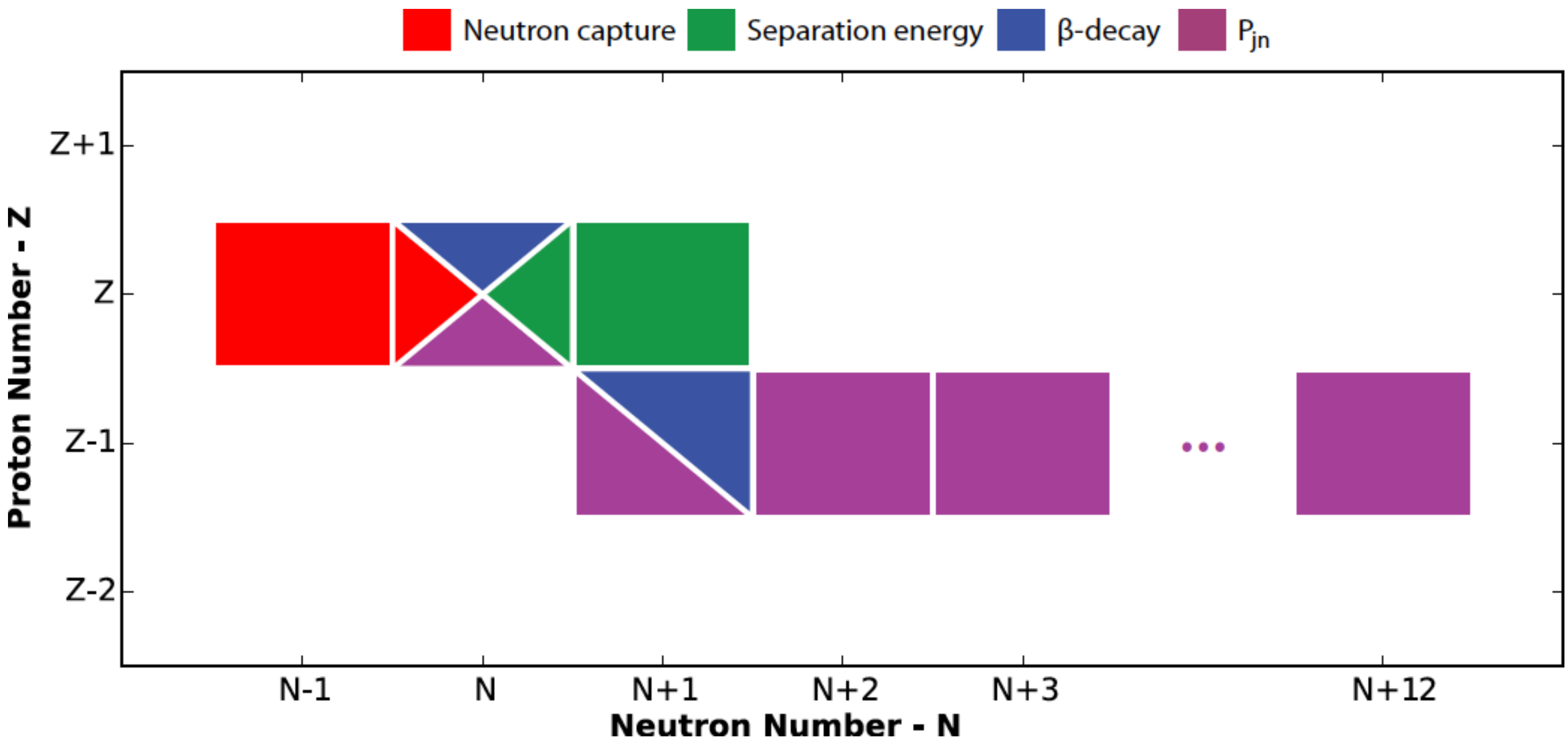


Trajectories describing four scenarios

1. Hot low entropy 0.20 Ye 70ms
2. Hot high entropy 0.25 Ye 80ms
3. Cold neutrino driven wind 0.31 Ye
4. Neutron star merger (Bauswein & Janka)fission recycling

Putting it all together…

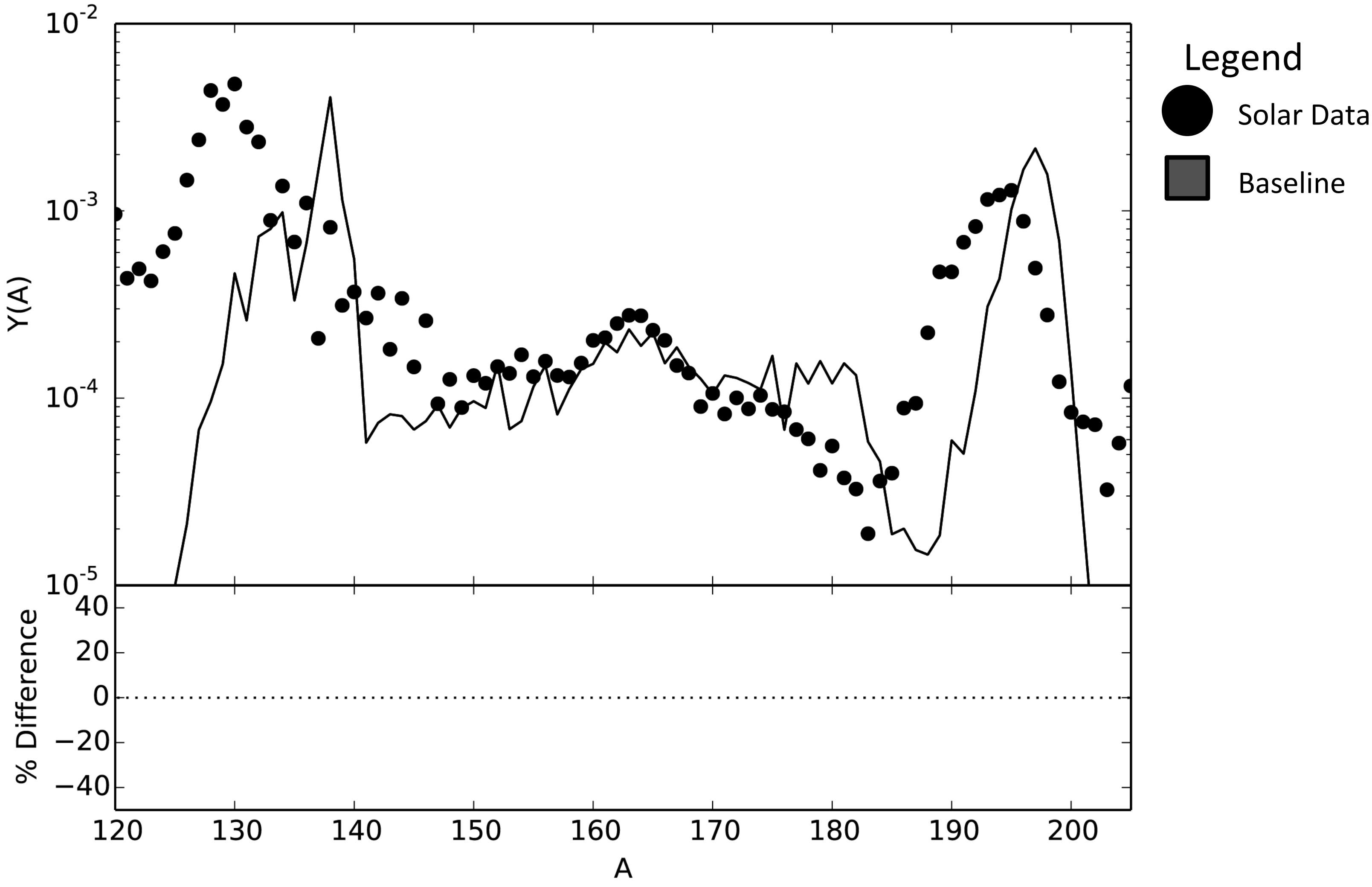
Building a fully self-consistent sensitivity study

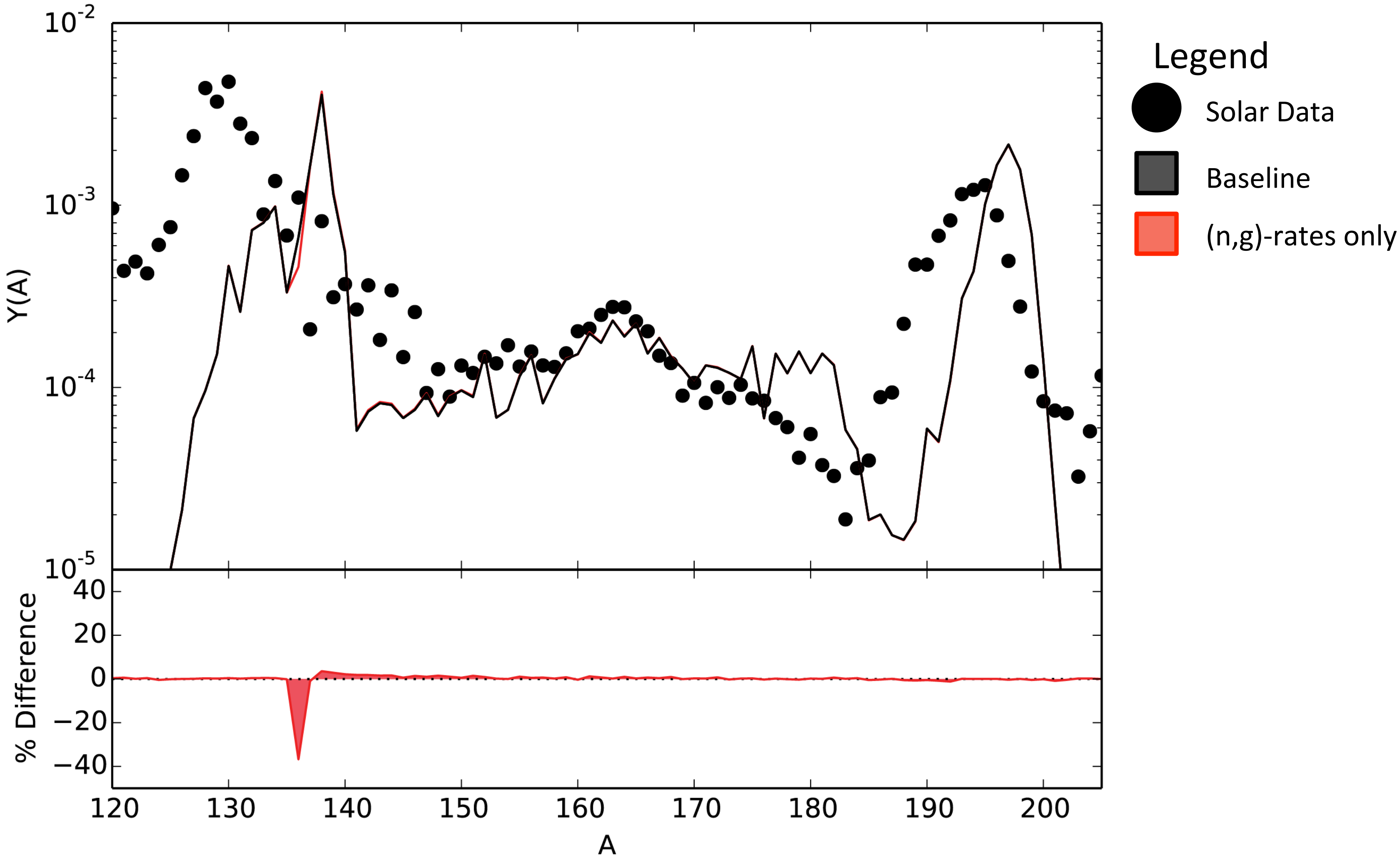


N=82: Mumpower, Surman, Fang, Beard, Aprahamian (2015)**; J. Phys G 42, 034027**

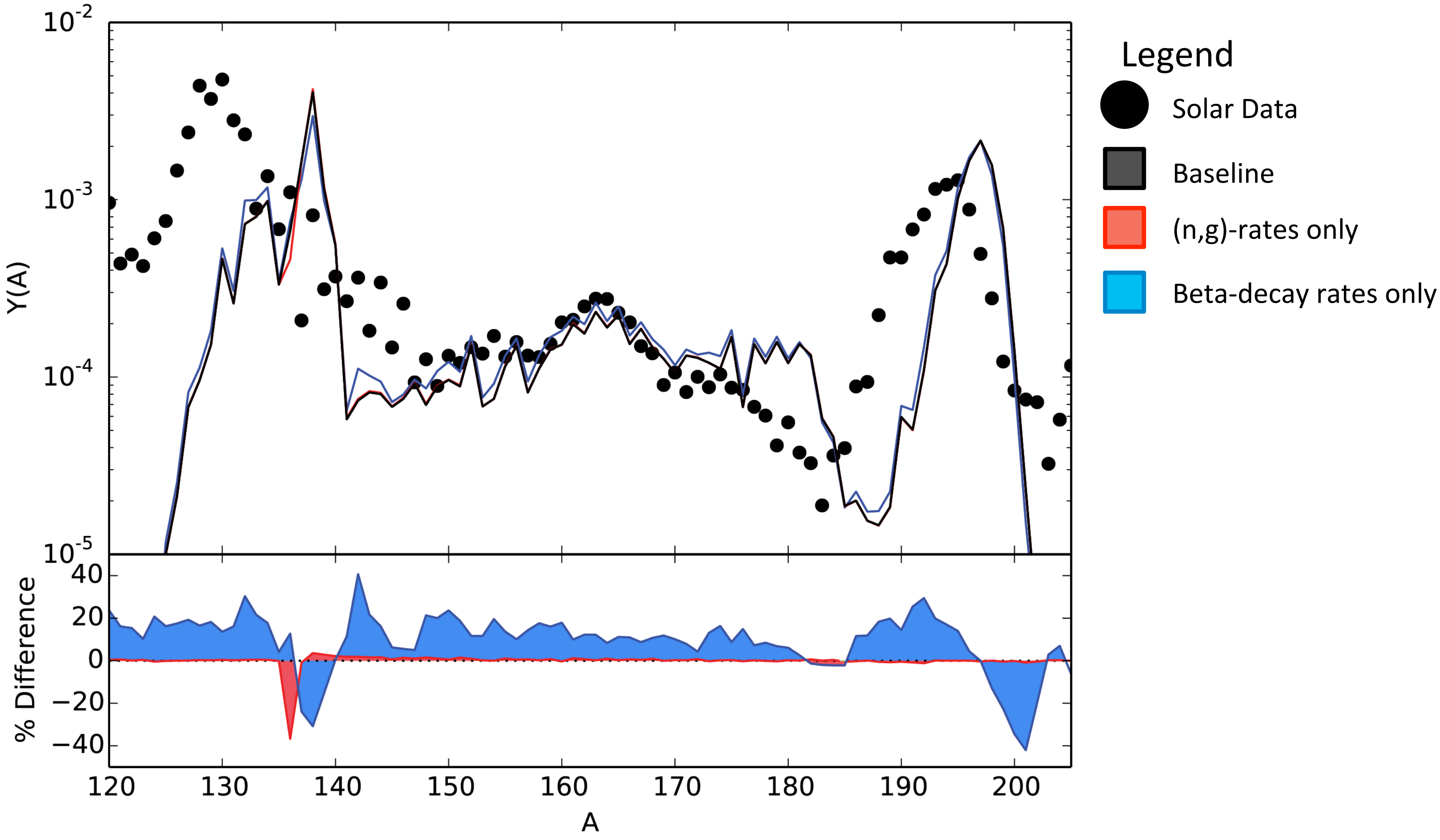
N=126: Mumpower, Surman, Fang, Beard, Moller, Aprahamian (2015); **Phys. Rev. C 92, 035807**

Baseline calculation for ^{140}Sn

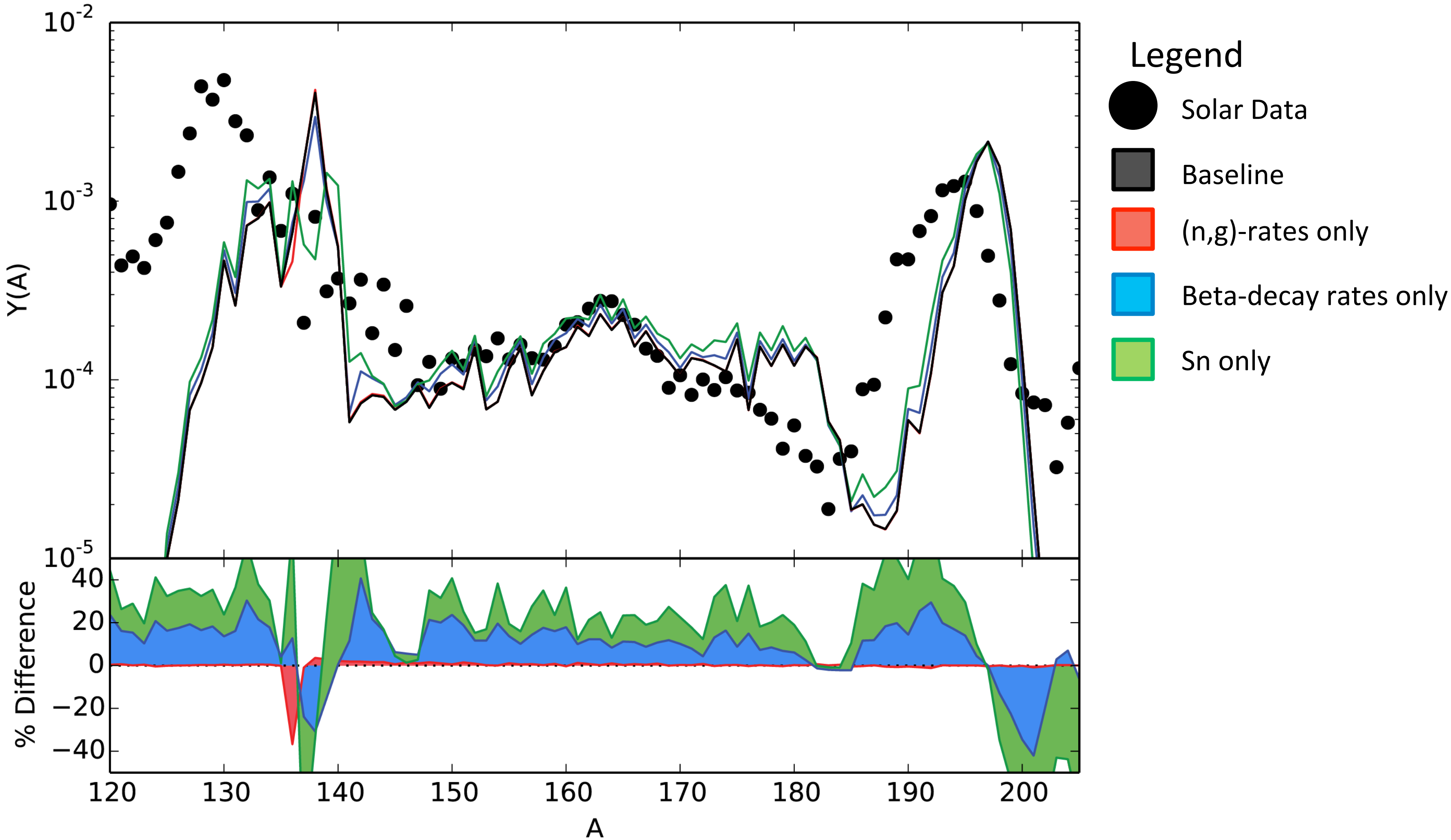




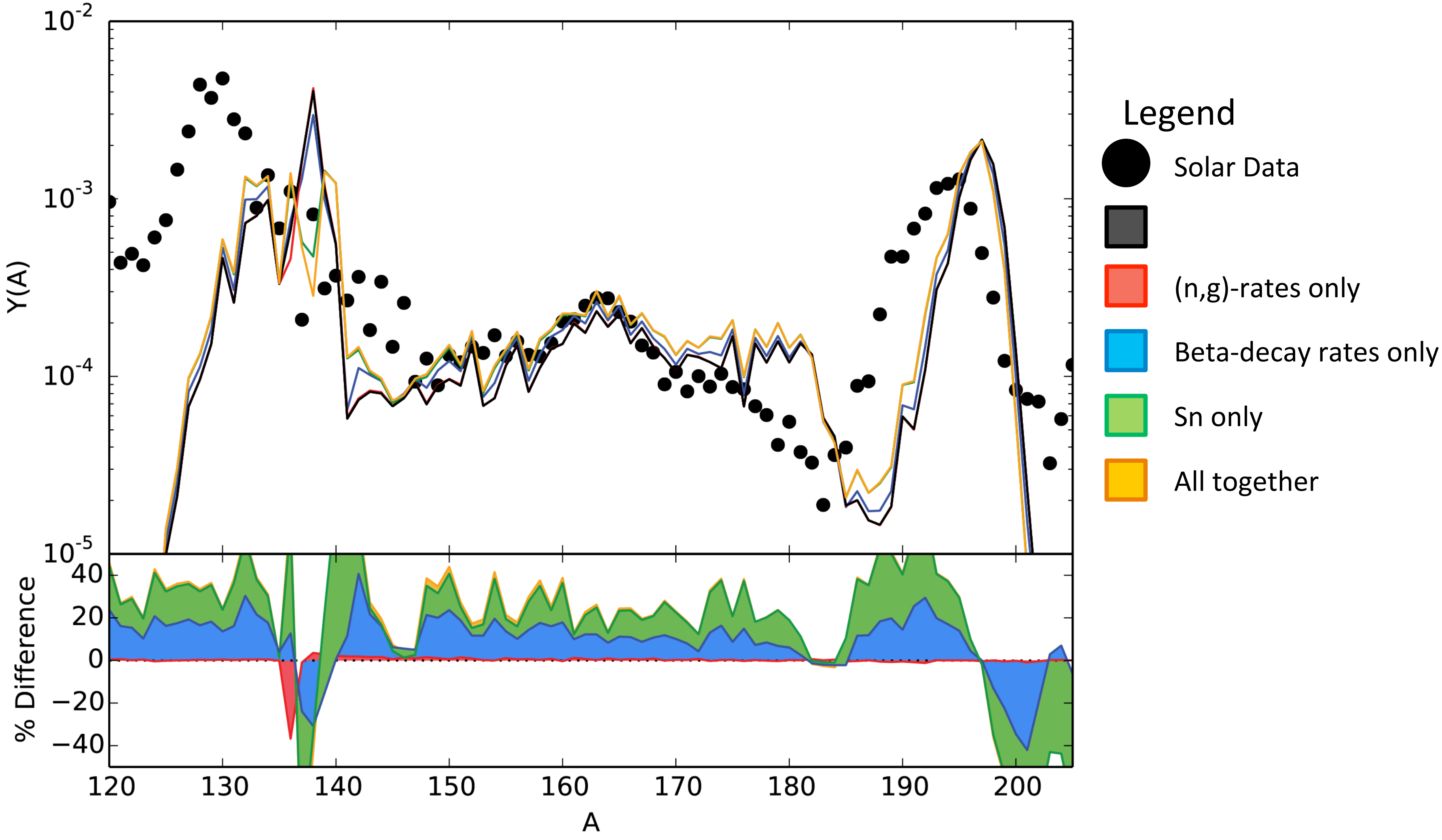
Legend
Solar Data
Baseline
(n,g)-rates only
Y(A)
% Difference
A
10^-2
10^-3
10^-4
10^-5
40
20
0
−20
−40
120
130
140
150
160
170
180
190
200



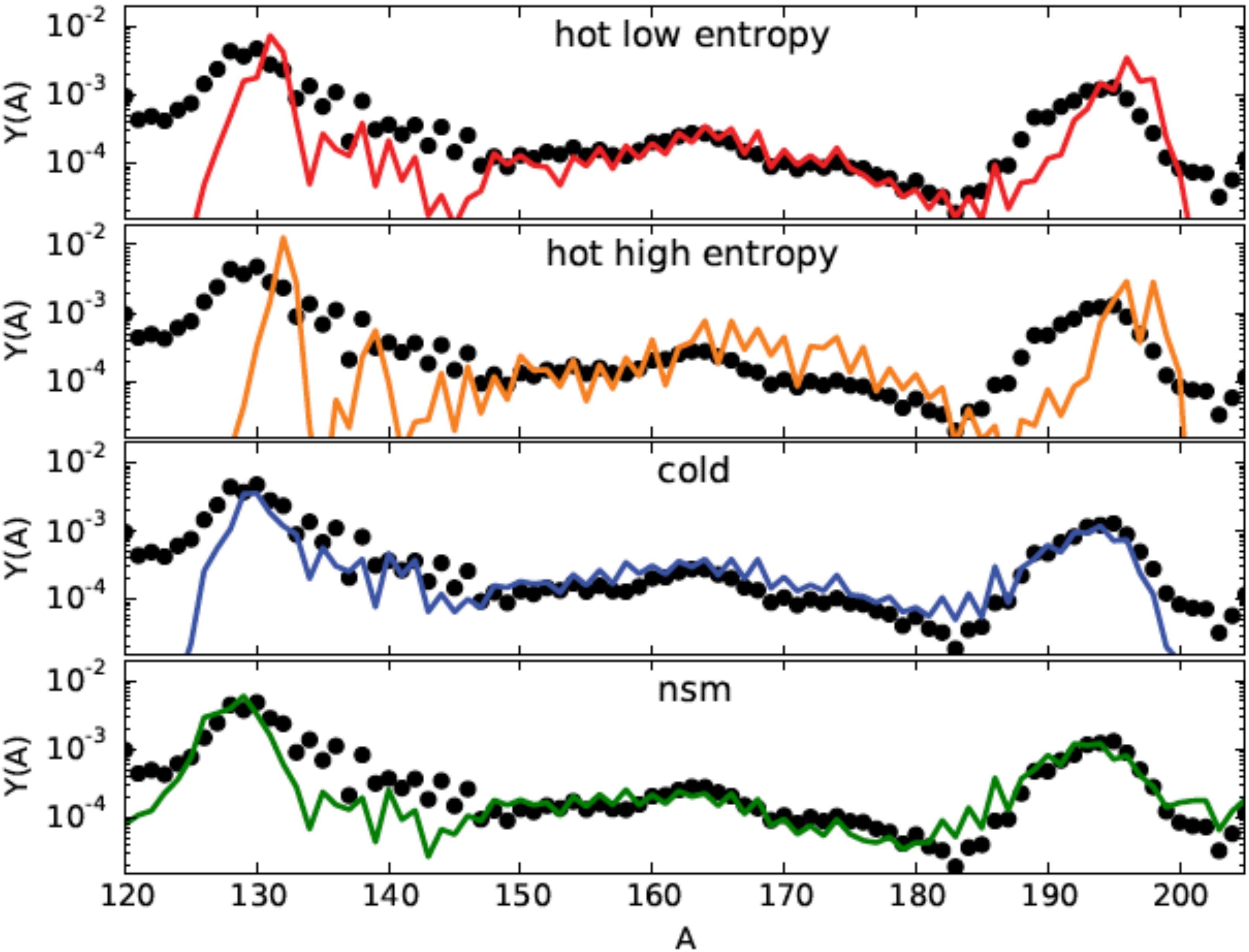
Legend
Solar Data
Baseline
(n,g)-rates only
Beta-decay rates only
Y(A)
% Difference
A
10^-2
10^-3
10^-4
10^-5
40
20
0
−20
−40
120
130
140
150
160
170
180
190
200



Legend
Solar Data
Baseline
(n,g)-rates only
Beta-decay rates only
Sn only
Y(A)
% Difference
A



Over an *order of magnitude* difference in the Y(A) for **0.5MeV** addition in mass of 140-Sn!


hot low entropy
hot high entropy
cold
nsm
Y(A)
A
120
130
140
150
160
170
180
190
200

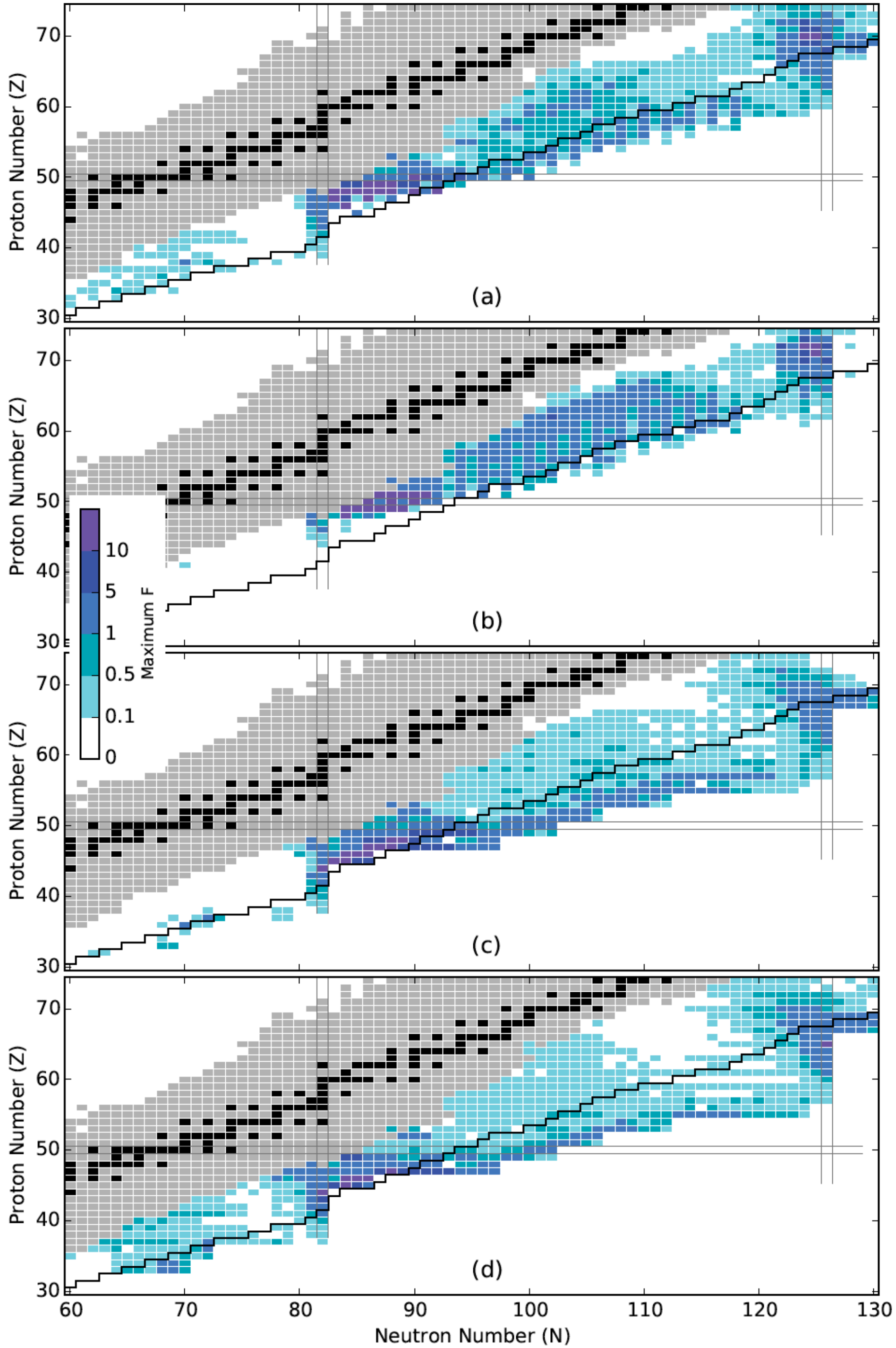
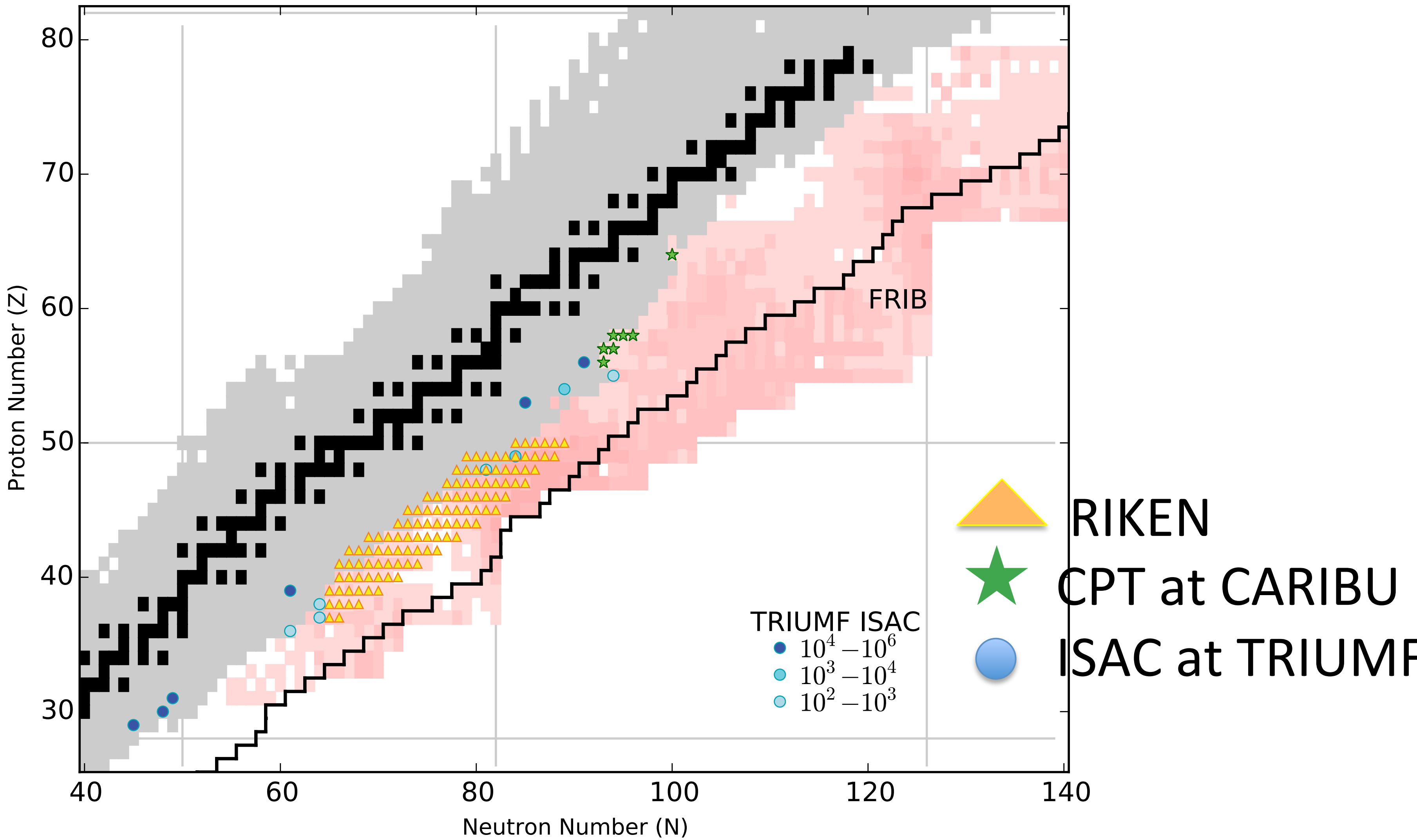

Proton Number (Z)
Neutron Number (N)
Maximum F
(a)
(b)
(c)
(d)
Low entropy hot wind
High entropy hot wind
Cold wind
Neutron Star Merger

TABLE I. Important nuclei from Fig. 2 with $F_{max} \geqslant 20$. The abbreviation nsm denotes neutron star merger.

Z	N	A	F_{max}	Trajectory
48	84	132	101.39	High-entropy hot
50	86	136	83.68	High-entropy hot
49	84	133	74.59	High-entropy hot
49	86	135	73.82	High-entropy hot
49	85	134	72.84	High-entropy hot
49	87	136	71.04	High-entropy hot
49	88	137	68.08	High-entropy hot
49	89	138	66.43	High-entropy hot
48	88	136	58.42	Low-entropy hot
46	86	132	55.56	nsm
48	86	134	52.38	Low-entropy hot
46	86	132	48.67	Cold
46	84	130	43.73	Cold
48	90	138	37.86	Low-entropy hot
46	85	131	34.81	Cold
50	88	138	29.64	High-entropy hot
46	84	130	24.19	nsm
48	88	136	24.10	Cold
48	85	133	23.38	Low-entropy hot
48	87	135	21.12	Low-entropy hot
48	89	137	20.63	Cold

Phys. Rev. C 92, 035807 (2015) Mumpower et al.

Experimental reach for the present and future…



JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS Volume: 42 Article Number: 034027 (Published: MAR 2015)

Conclusions

Comprehensive sensitivity studies of the r-process to individual nuclear properties

Propagation of mass changes to all dependent properties
(self-consistence)

Identifying the site of the r-process path….
Disentangling Nuclear Physics uncertainties
from the Astrophysical uncertainties…Progress.

We need much better precision on nuclear models

some insight to the r-process with nuclear physics.....

Sensitivity Study Masses

Samuel Brett

Ian Bentley

Nancy Paul

Matthew Mumpower

Rebecca Surman

A^2

Sensitivity Study β-decay rates

Julie Cass

Giuseppe Passucci

Mathew Mumpower

Rebecca Surman

A^2

Sensitivity Study β-delayed neutron emission rates

Mathew Mumpower

Rebecca Surman

A^2

Fully Consistent Sensitivity Studies

Matthew Mumpower

Mary Beard

D. Liang

G. McLaughlin

P. Moller

Rebecca Surman

A^2