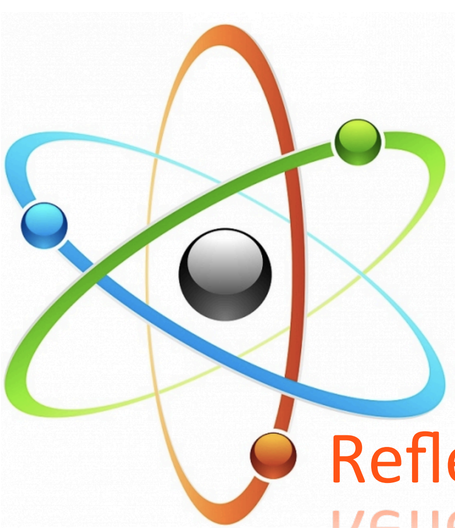
Institute for Structure & Nuclear Astrophysics

Nuclear structure to constrain the site(s) of the r-process?

Ani Aprahamian

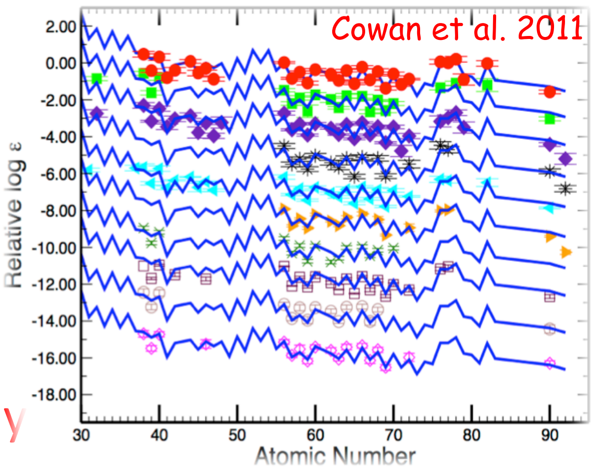


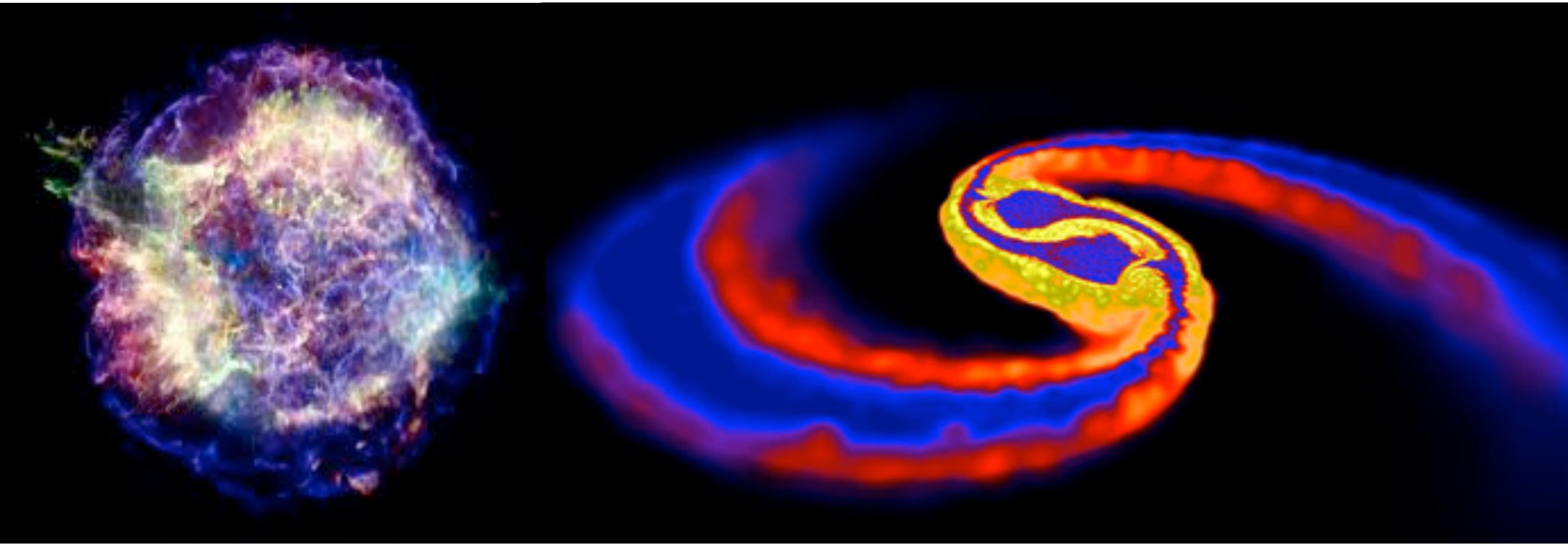
Reflections on the atomic nucleus, July 28-30, 2015

r-process

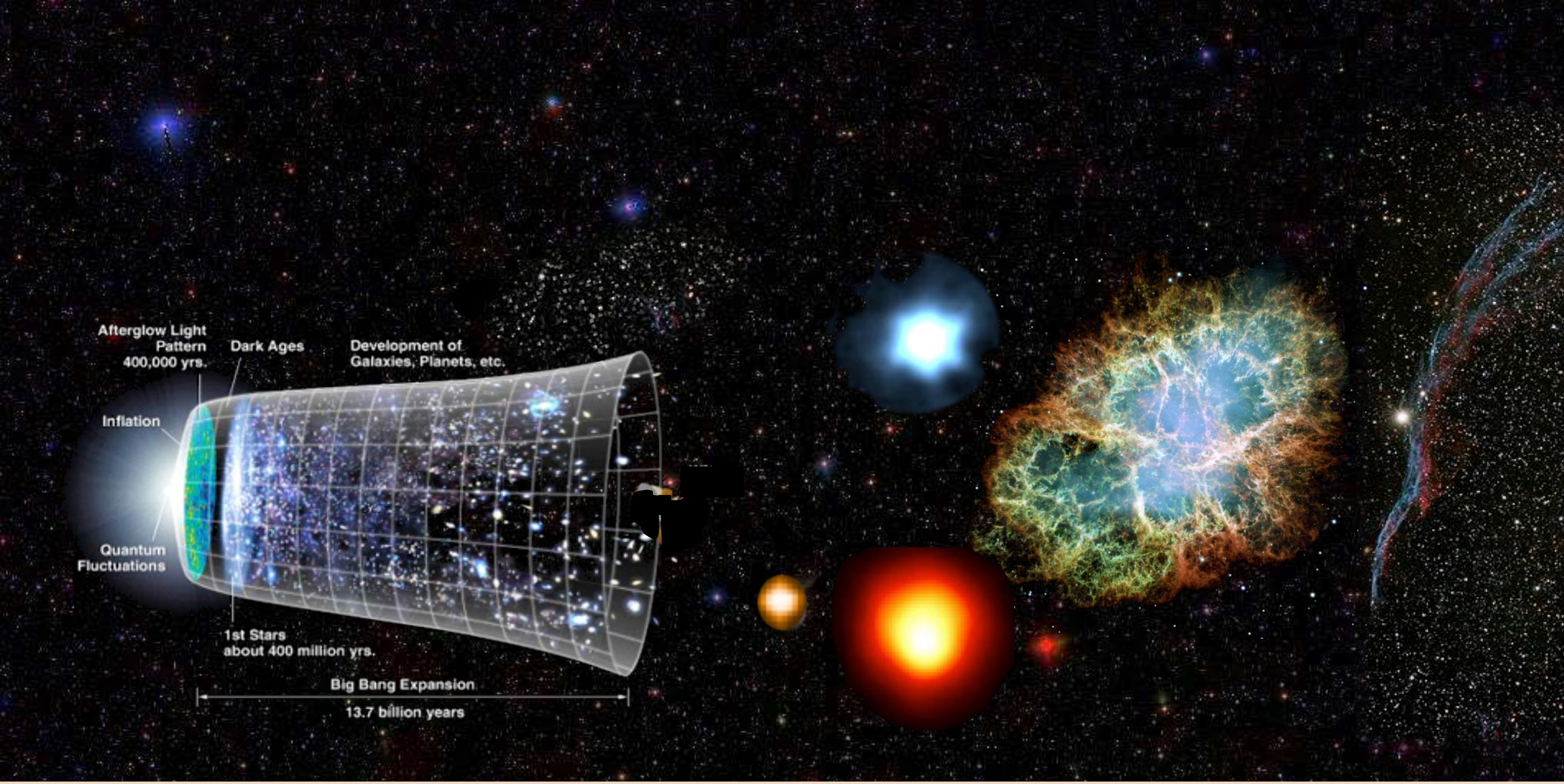
Origin of more than 50% of all the elements beyond iron

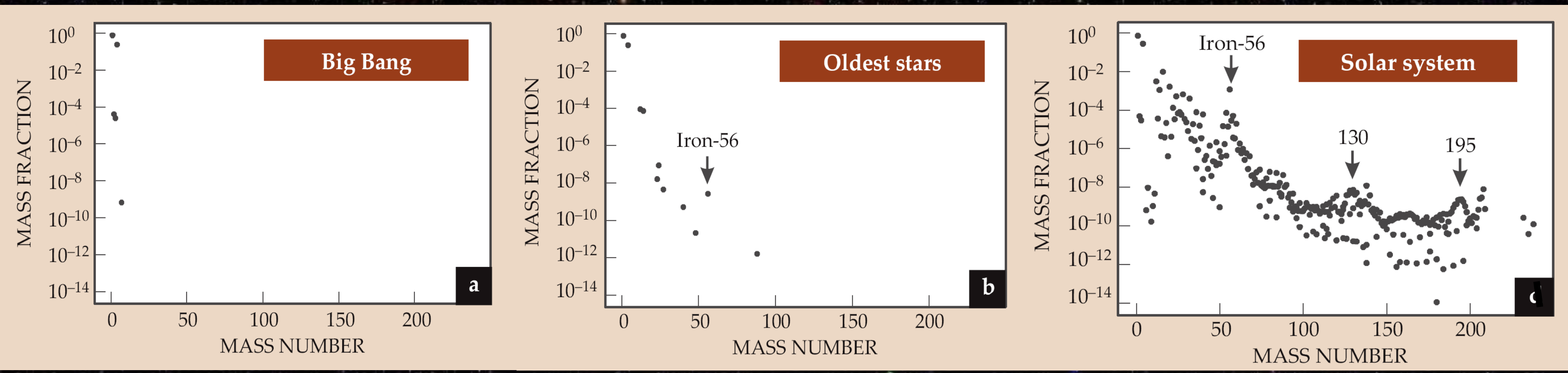
Site of r-process is one of open challenges in all of physics today





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

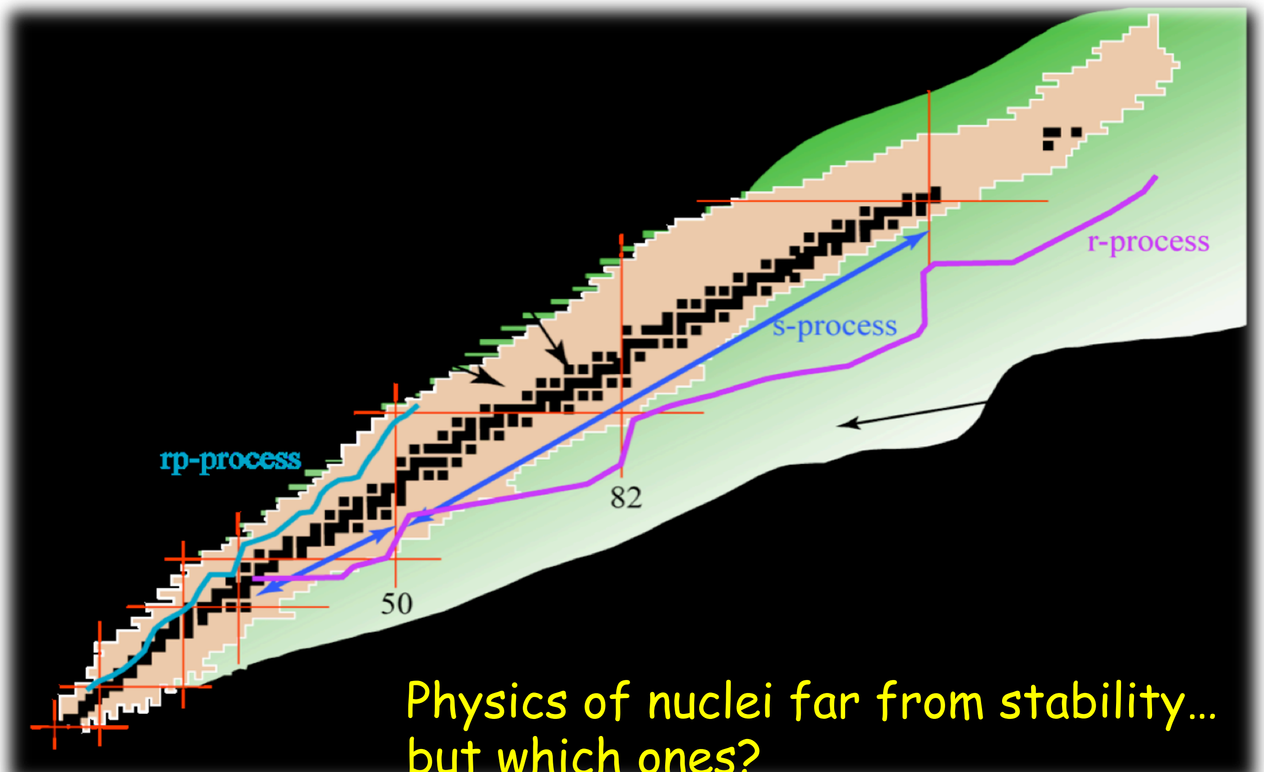

Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years


Big Bang
a
Oldest stars
b
Iron-56
Solar system
Iron-56
130
195
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

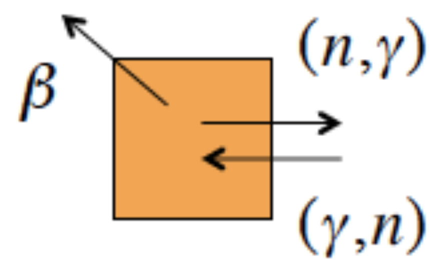
Goal:

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

How? Measure. Which ones do we measure?

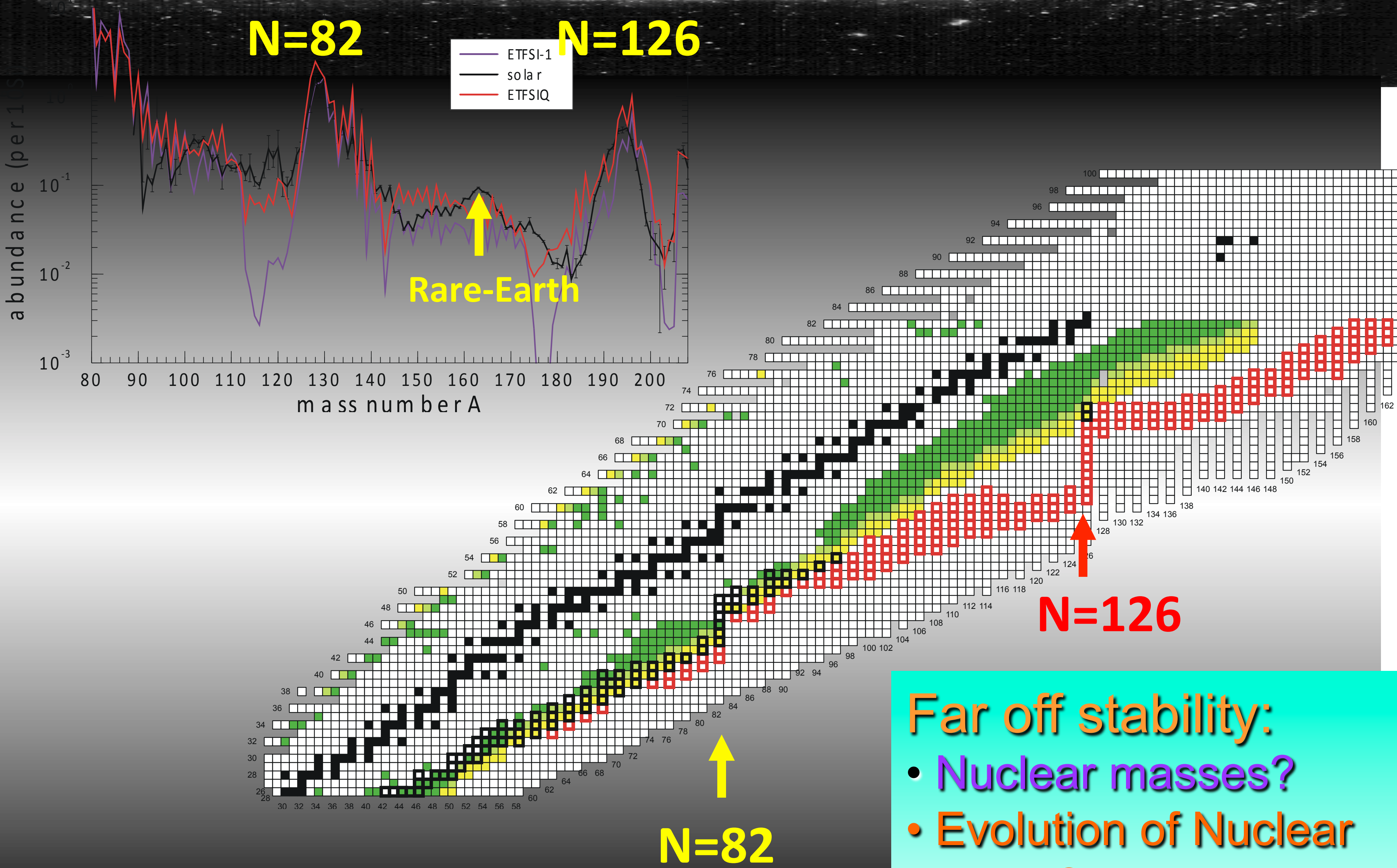


Nuclear masses
β-decay rates
n- capture
β-delayed n-emission



Reflections on the atomic nucleus, July 28-30, 2015

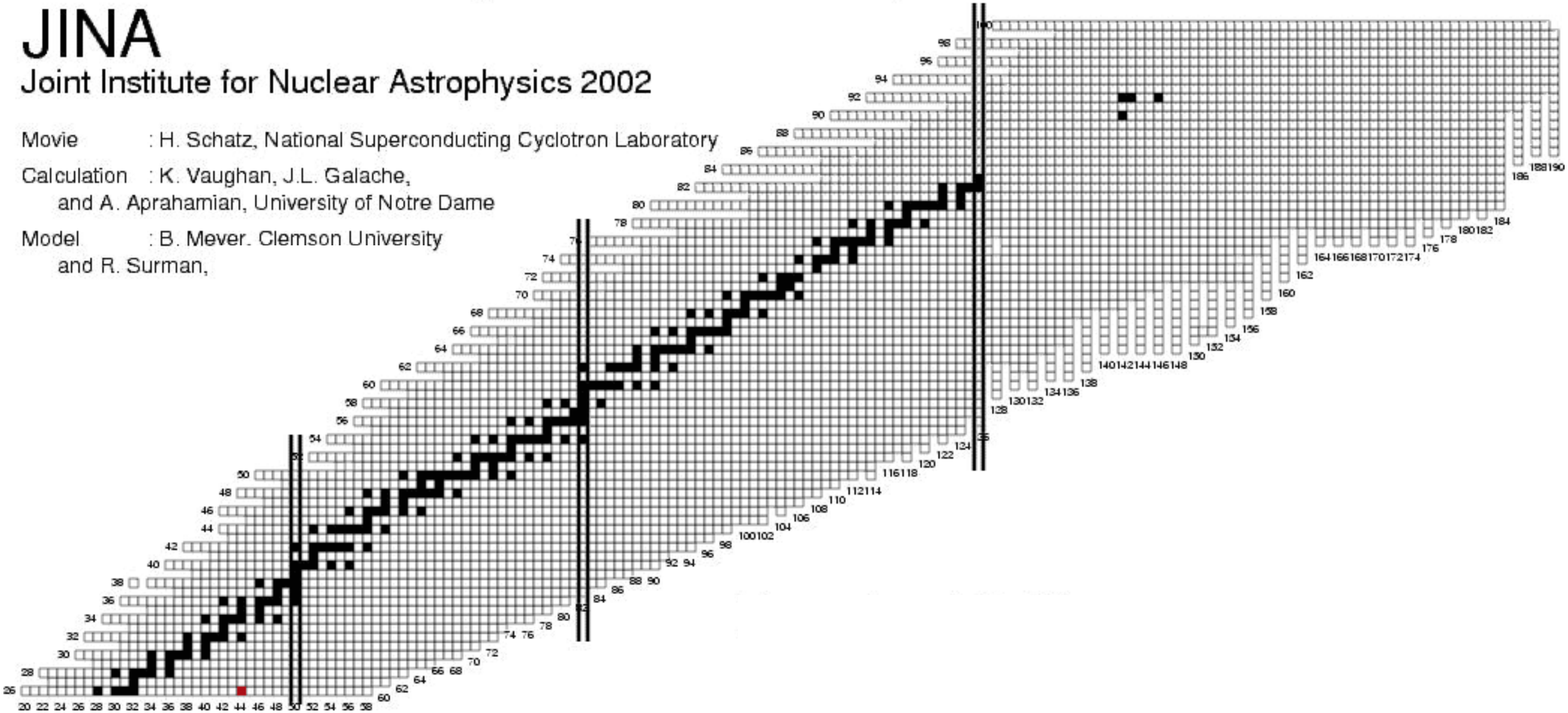
r-process



Far off stability:

- Nuclear masses?
- Evolution of Nuclear shapes?

Nucleosynthesis in the r-process



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**….)

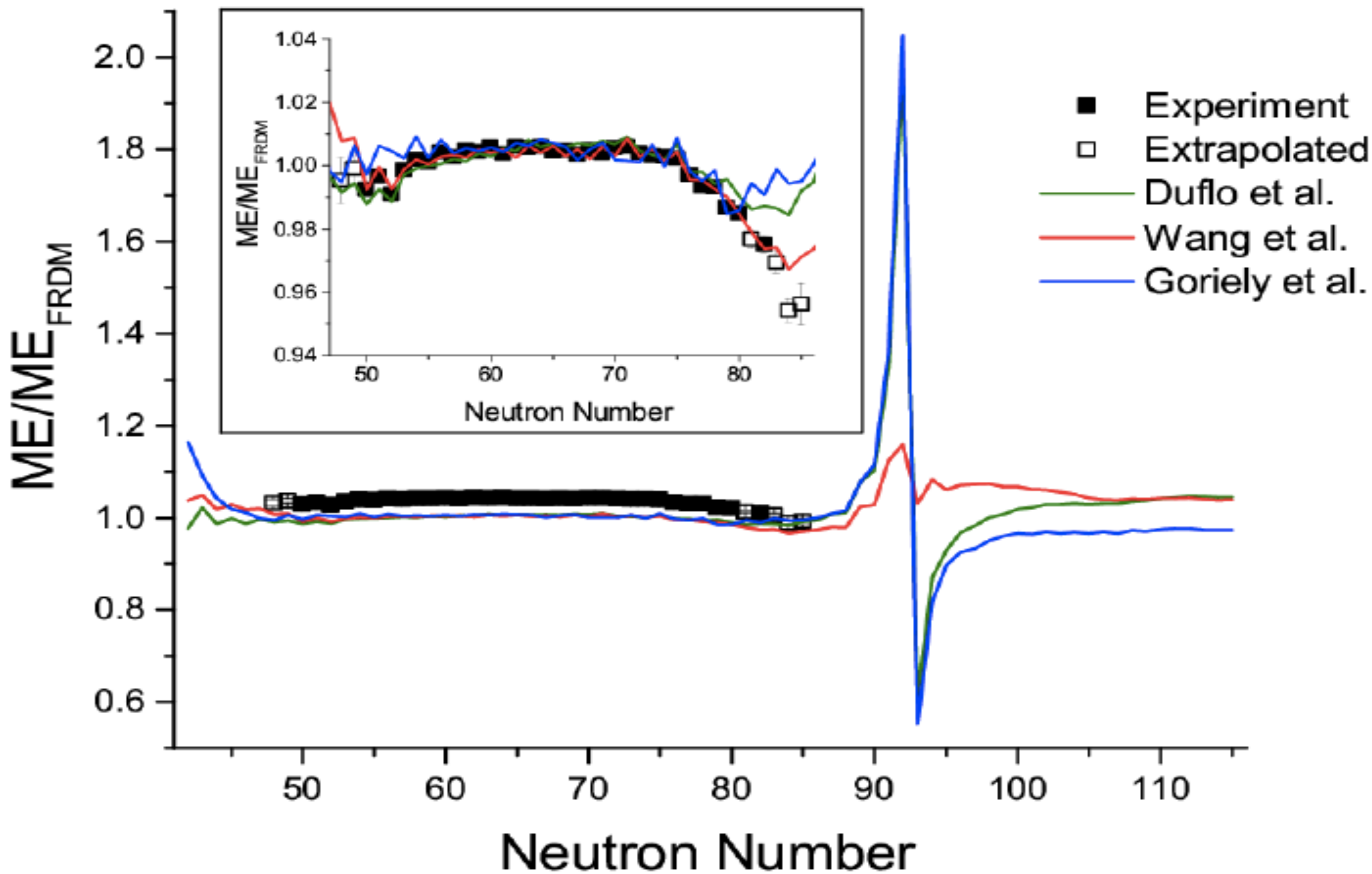
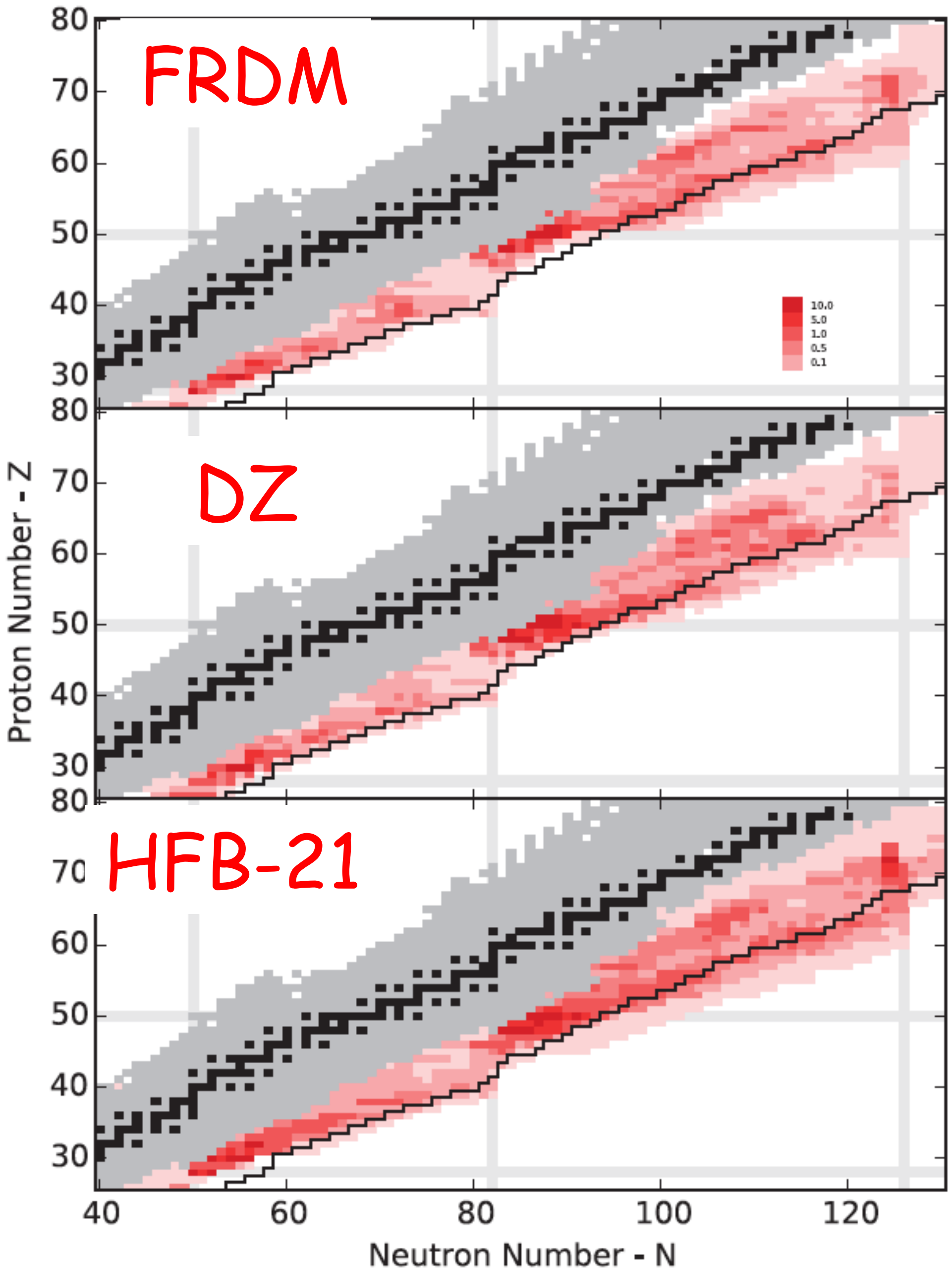


FIG. 1. The mass excess of cadmium isotopes consisting of experimental (filled boxes) and extrapolated (open boxes) values from AME2012[19] compared to theoretical values from Duflo & Zuker[20], Goriely et al.[21], and Wang et al.[22], all scaled to the mass excess from the FRDM[18].

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

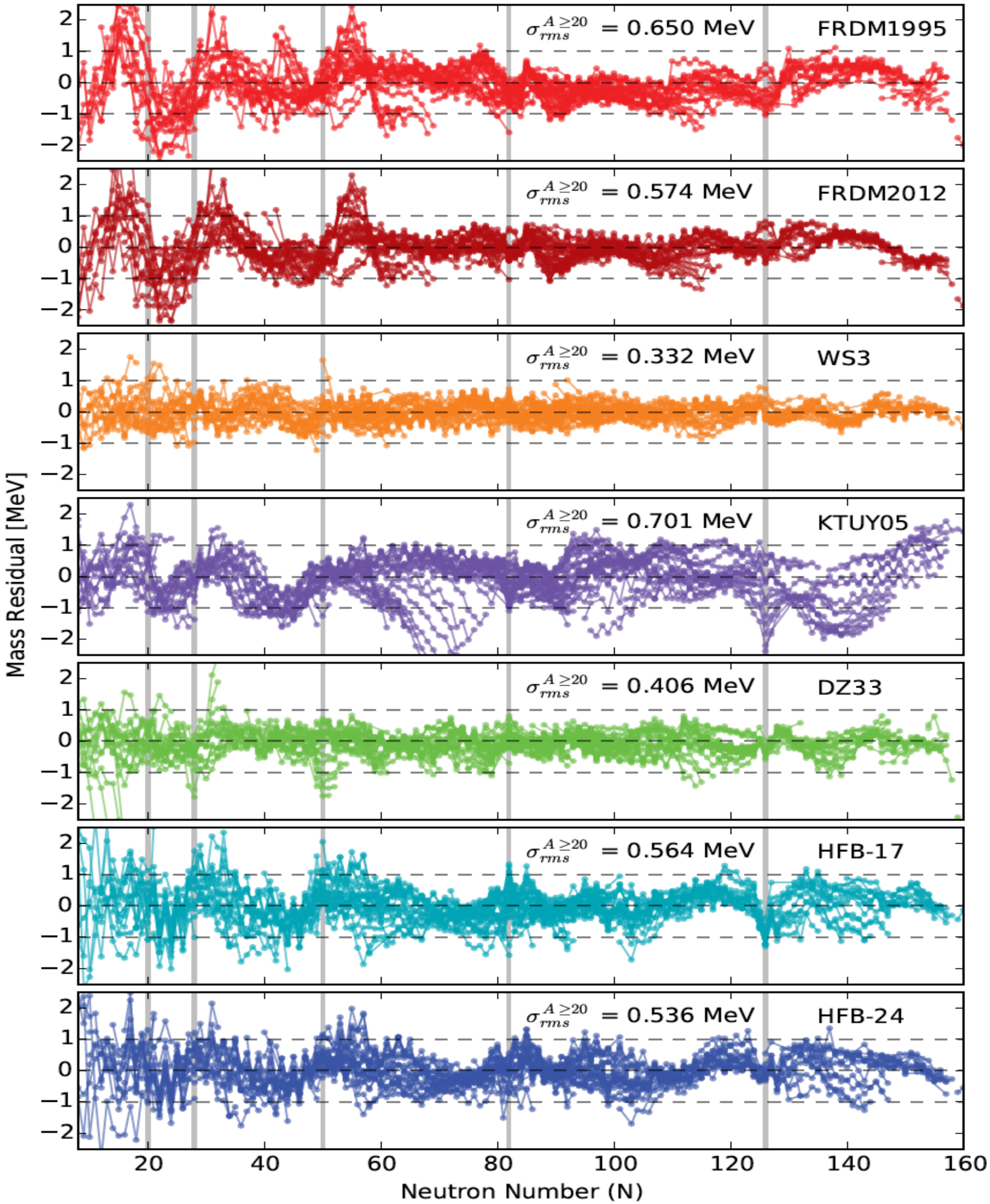


ΔBE=+/-1 MeV

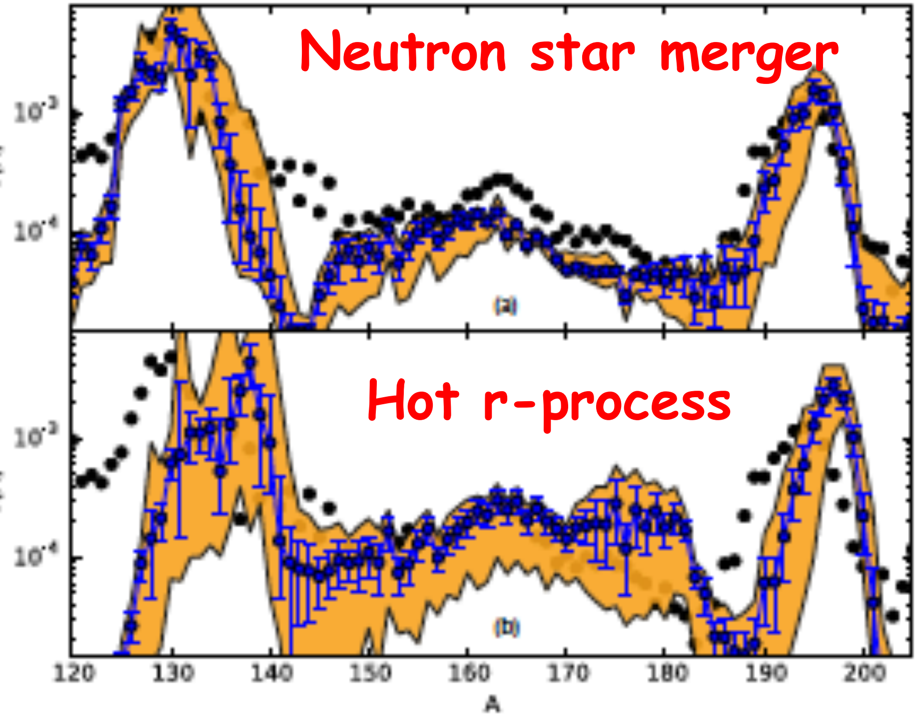
FRIB

Sensitivity studies for the main r process: nuclear masses

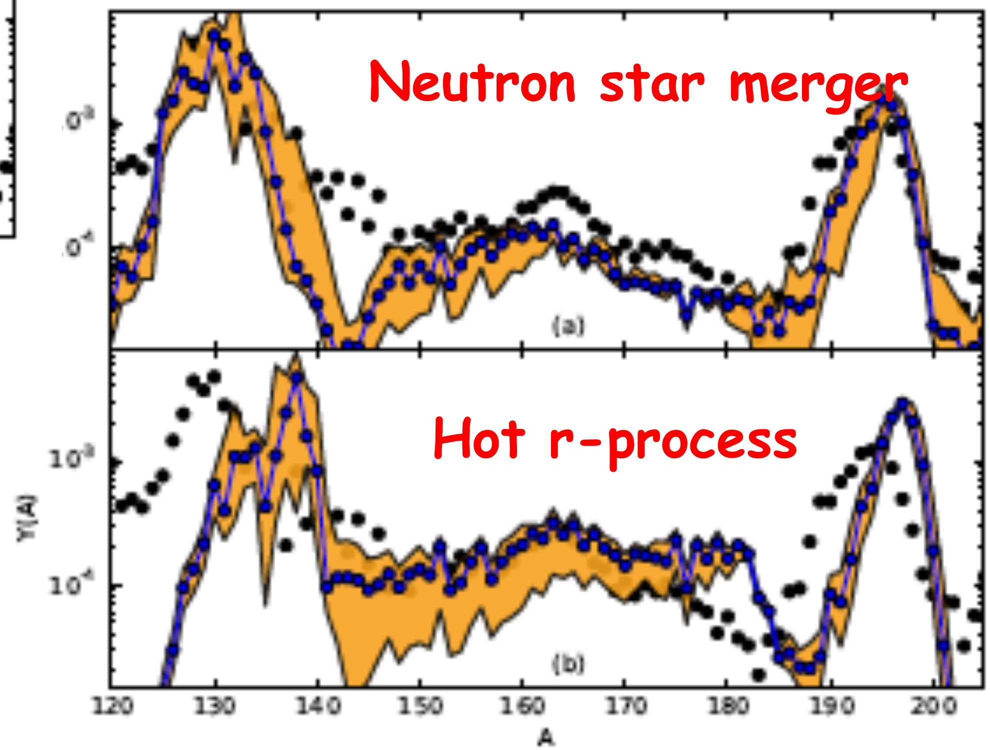
A. Aprahamian,[1] I. Bentley,[2] M. Mumpower,[1] and R. Surman[3]


$\sigma_{rms}^{A\geq20}$ = 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)
20
40
60
80
100
120
140
160

ΔBE=+/- 0.5 MeV

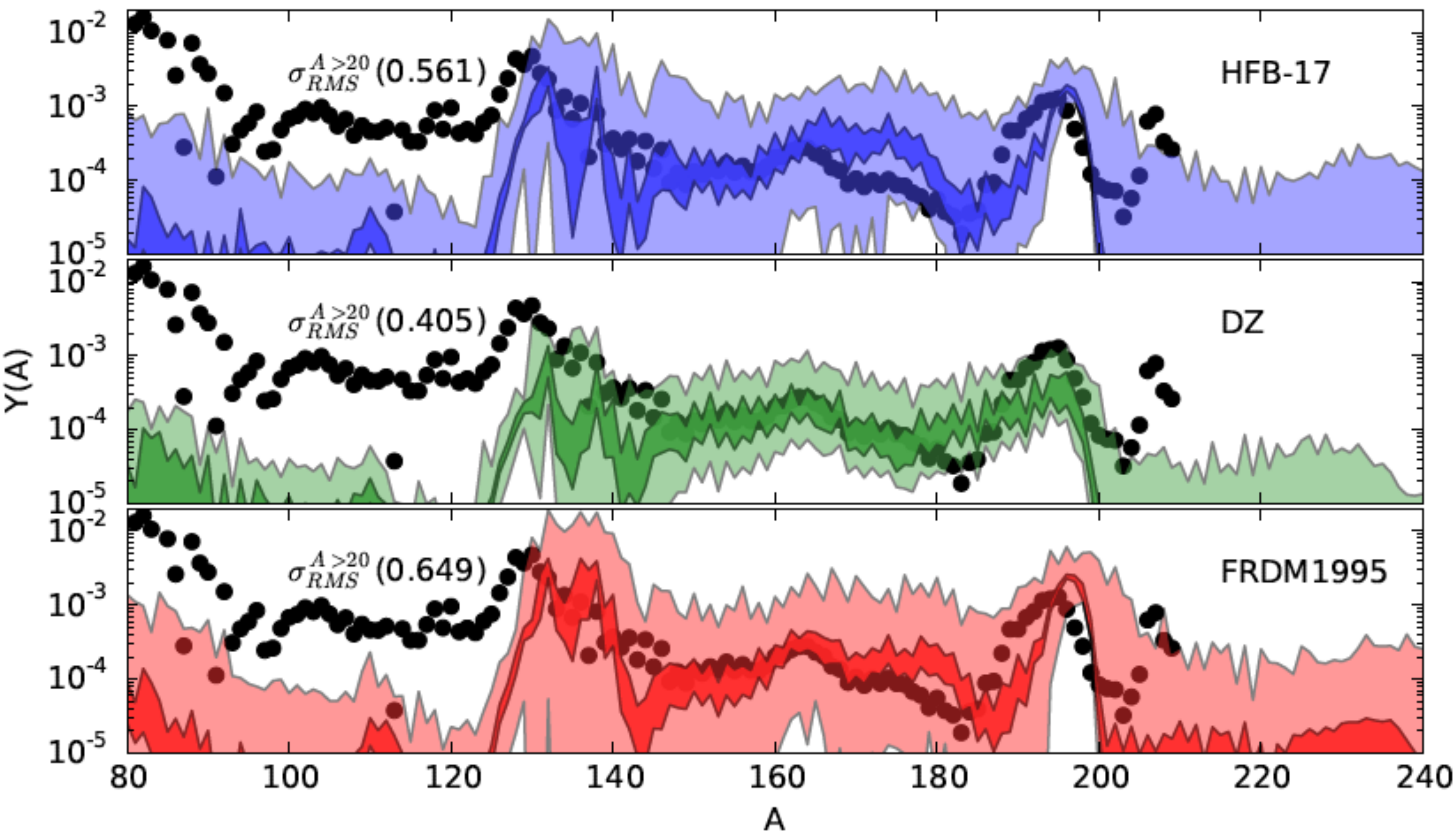


ΔBE = +/-1 MeV



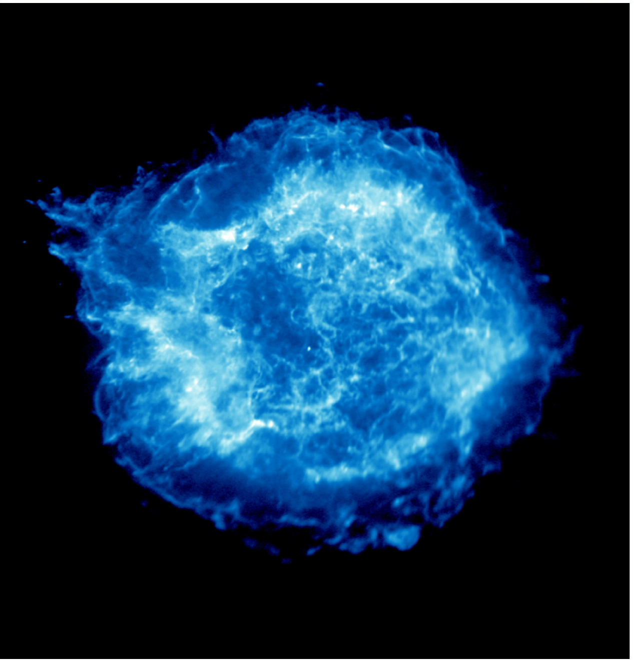
ΔBE =+/-0.5 MeV

Hot r-process trajectory



Mumpower, Surman, Aprahamian, CGS15 proceedings (2015)

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

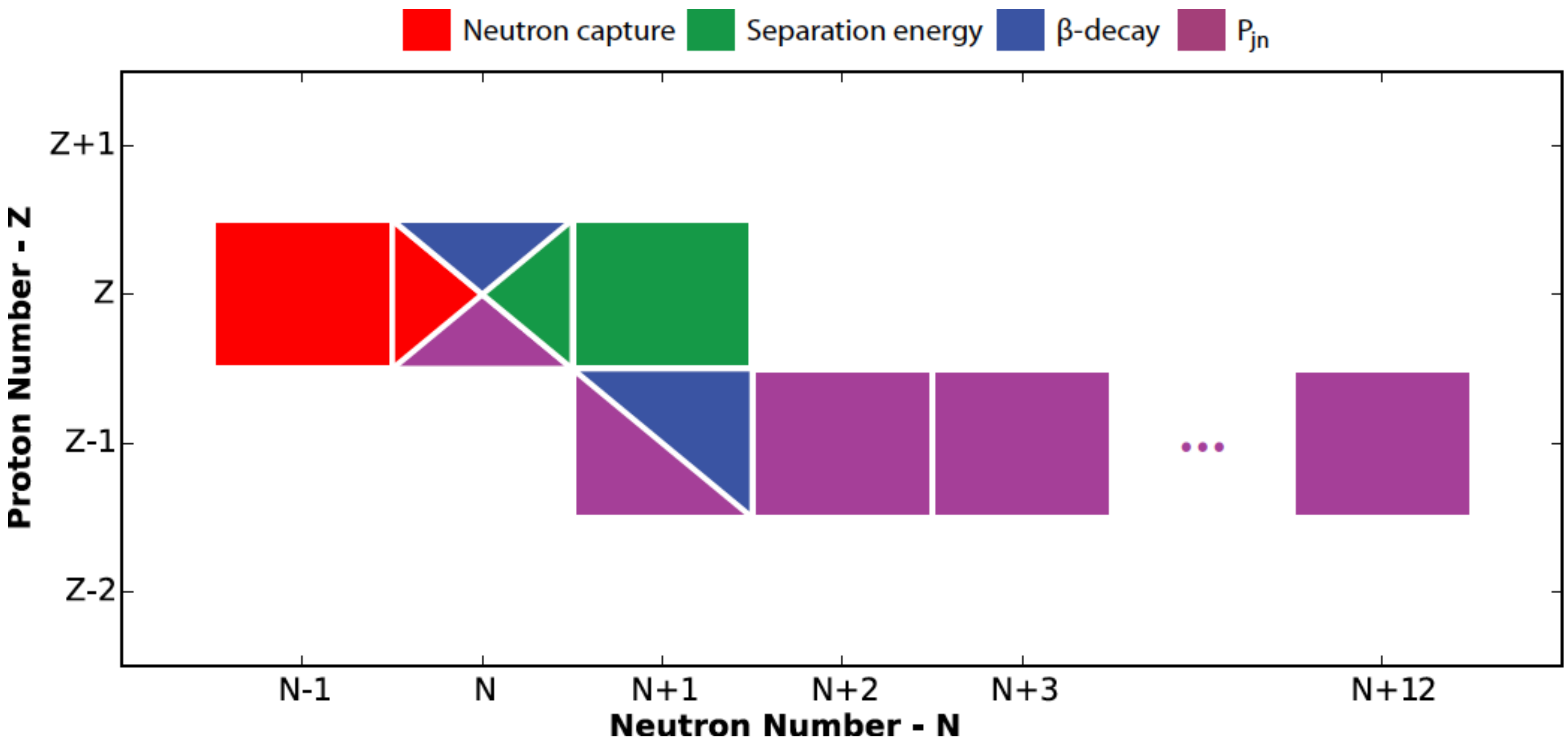


Trajectories describing four scenarios

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…

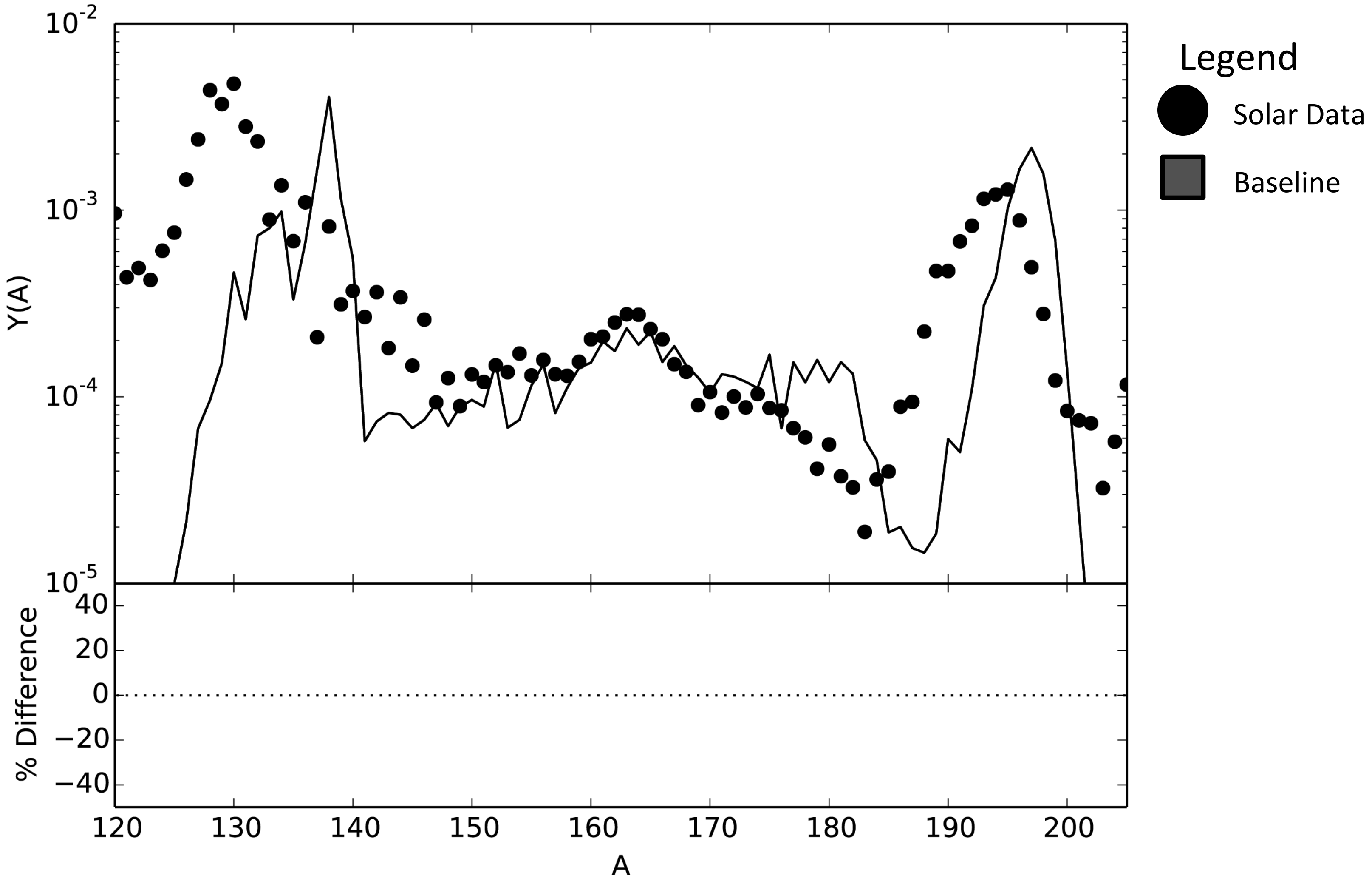
Building a fully self-consistent sensitivity study

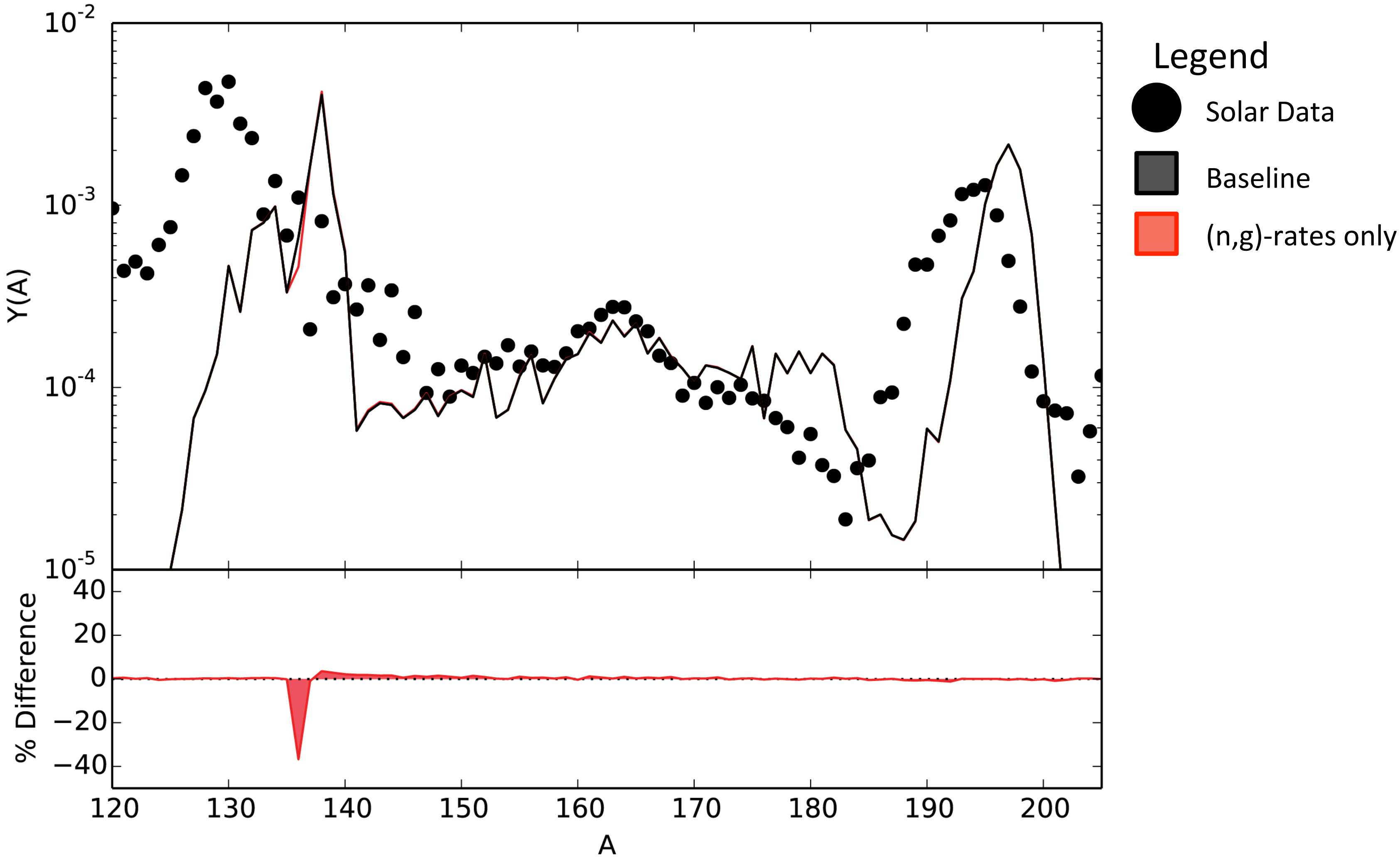


N=82: Mumpower, Surman, Fang, Beard, Aprahamian (2015); J. Phys G 42, 034027

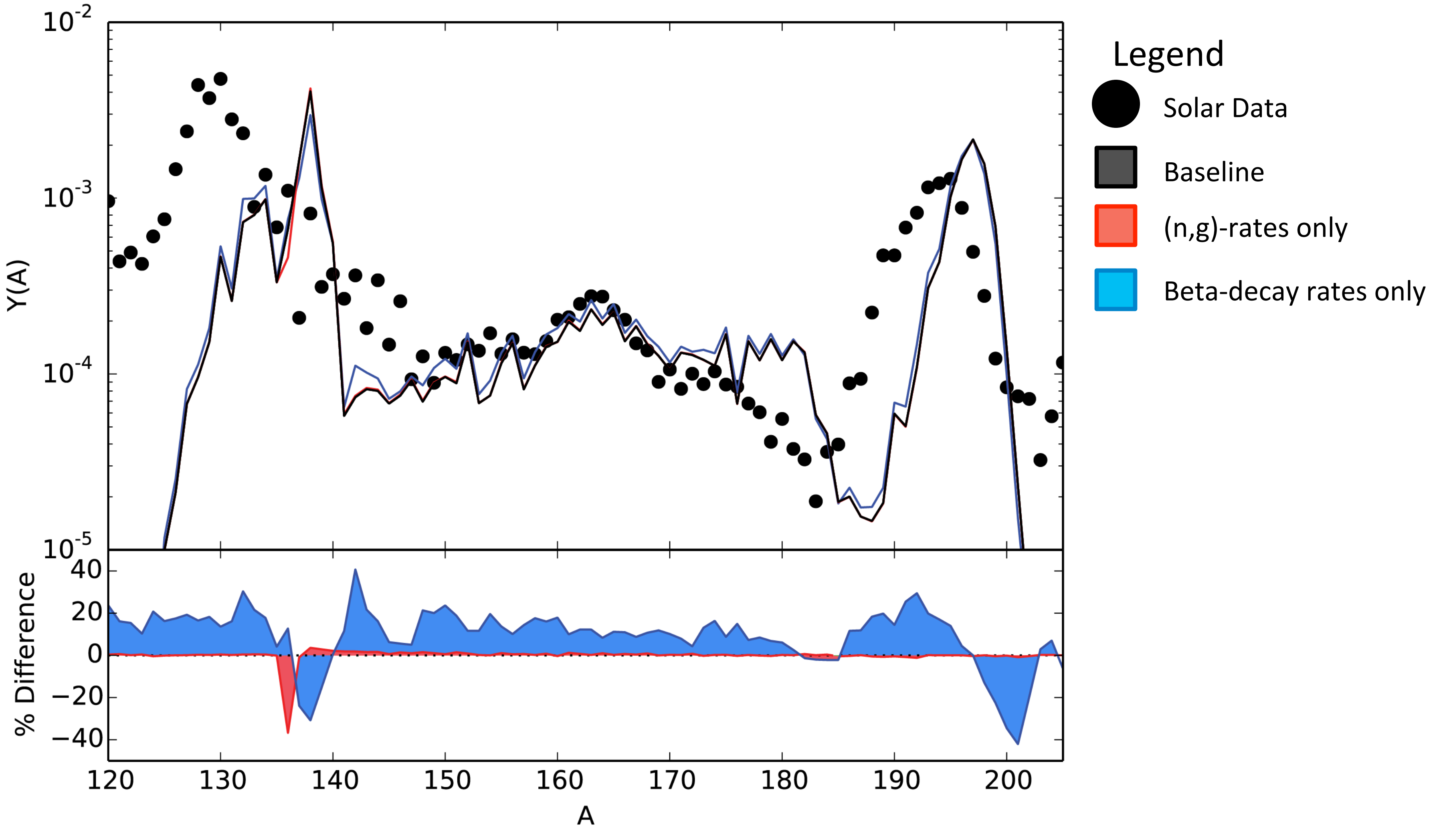
N=126: Mumpower, Surman, Fang, Beard, Moller, Aprahamian (2015); subm.

Baseline calculation for ^{140}Sn

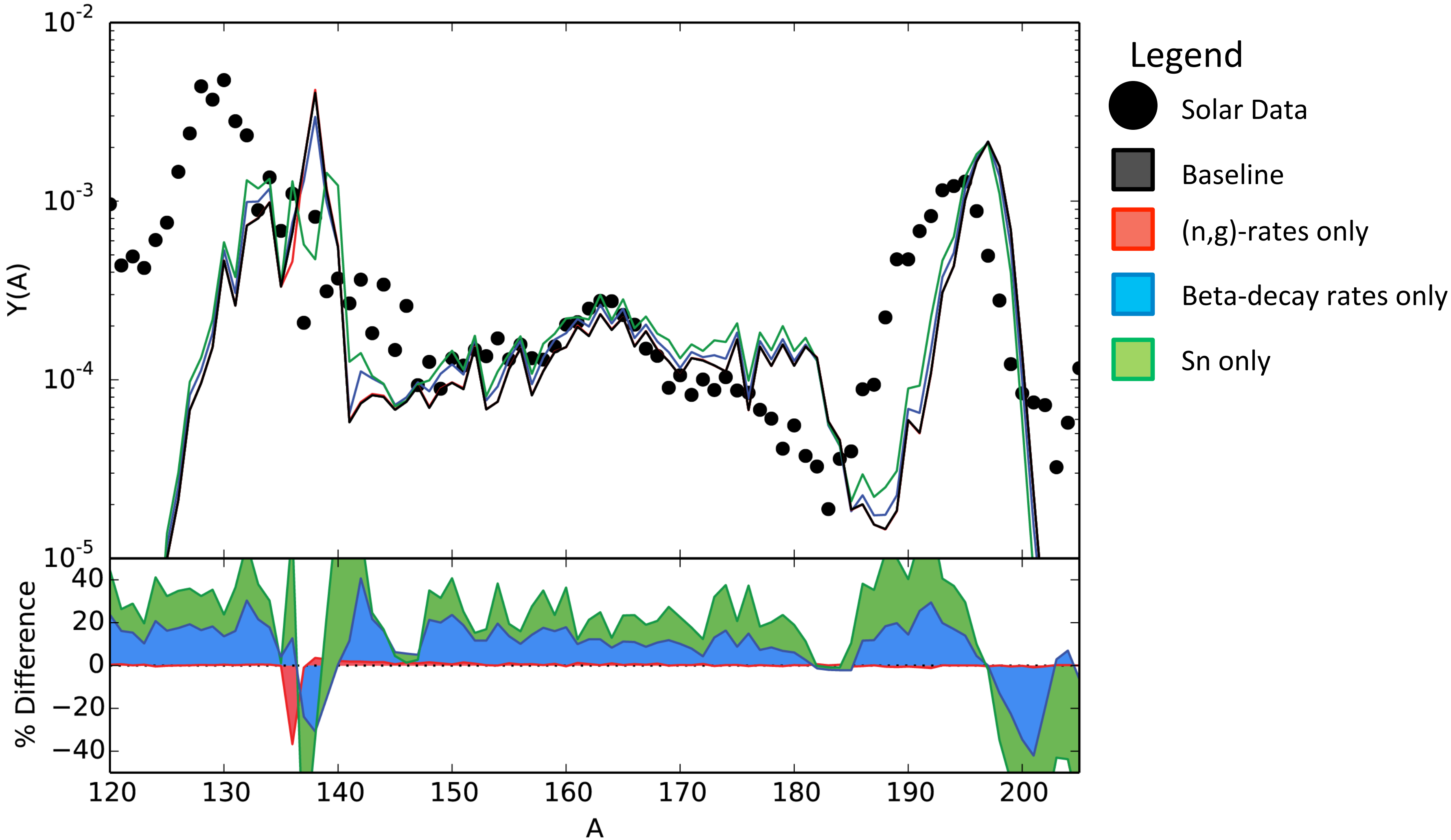




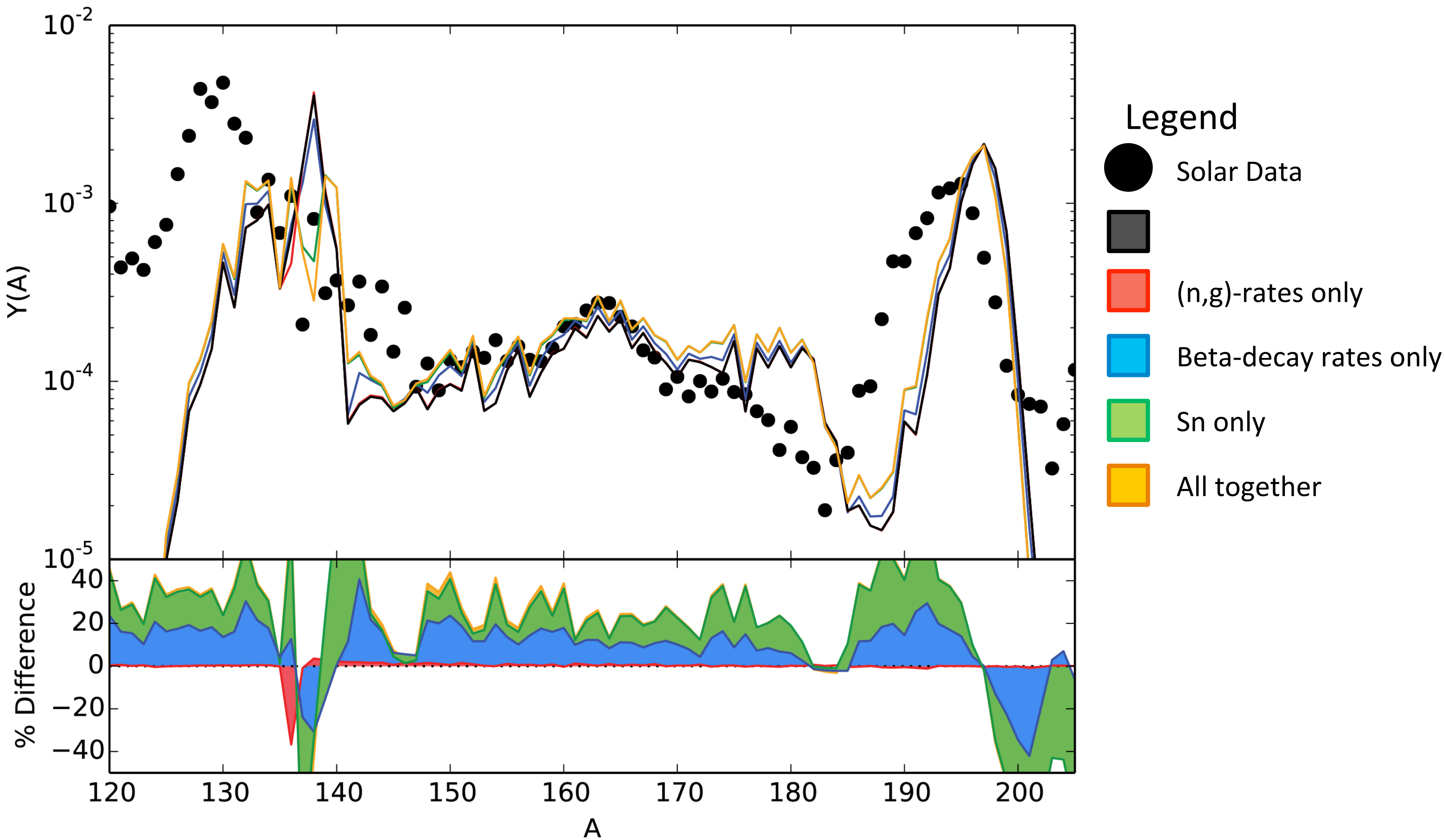
Legend
Solar Data
Baseline
(n,g)-rates only
Y(A)
% Difference
A
10^-2
10^-3
10^-4
10^-5
40
20
0
−20
−40
120
130
140
150
160
170
180
190
200



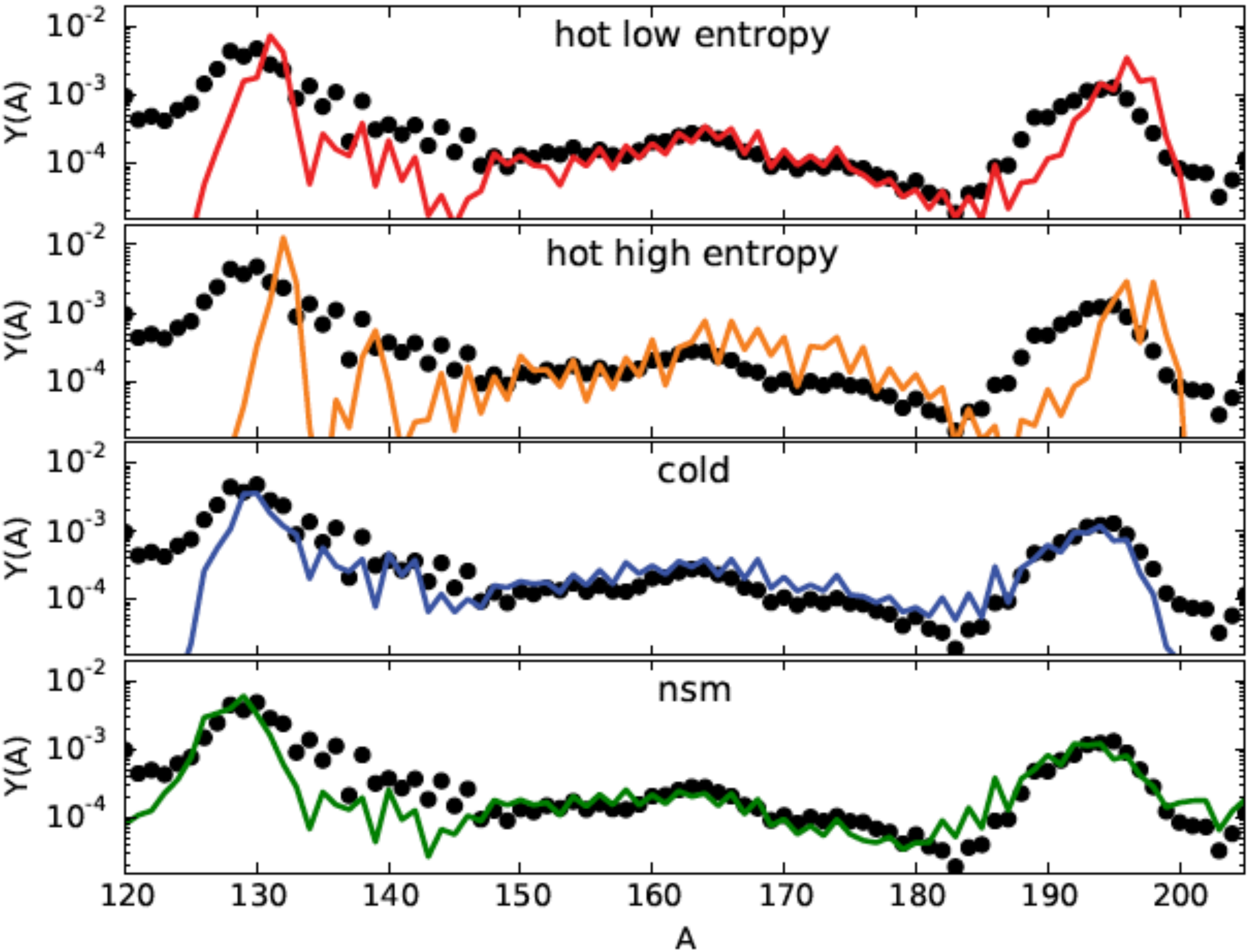
10^-2
10^-3
10^-4
10^-5
Y(A)
40
20
0
−20
−40
% Difference
120
130
140
150
160
170
180
190
200
A
Legend
Solar Data
Baseline
(n,g)-rates only
Beta-decay rates only



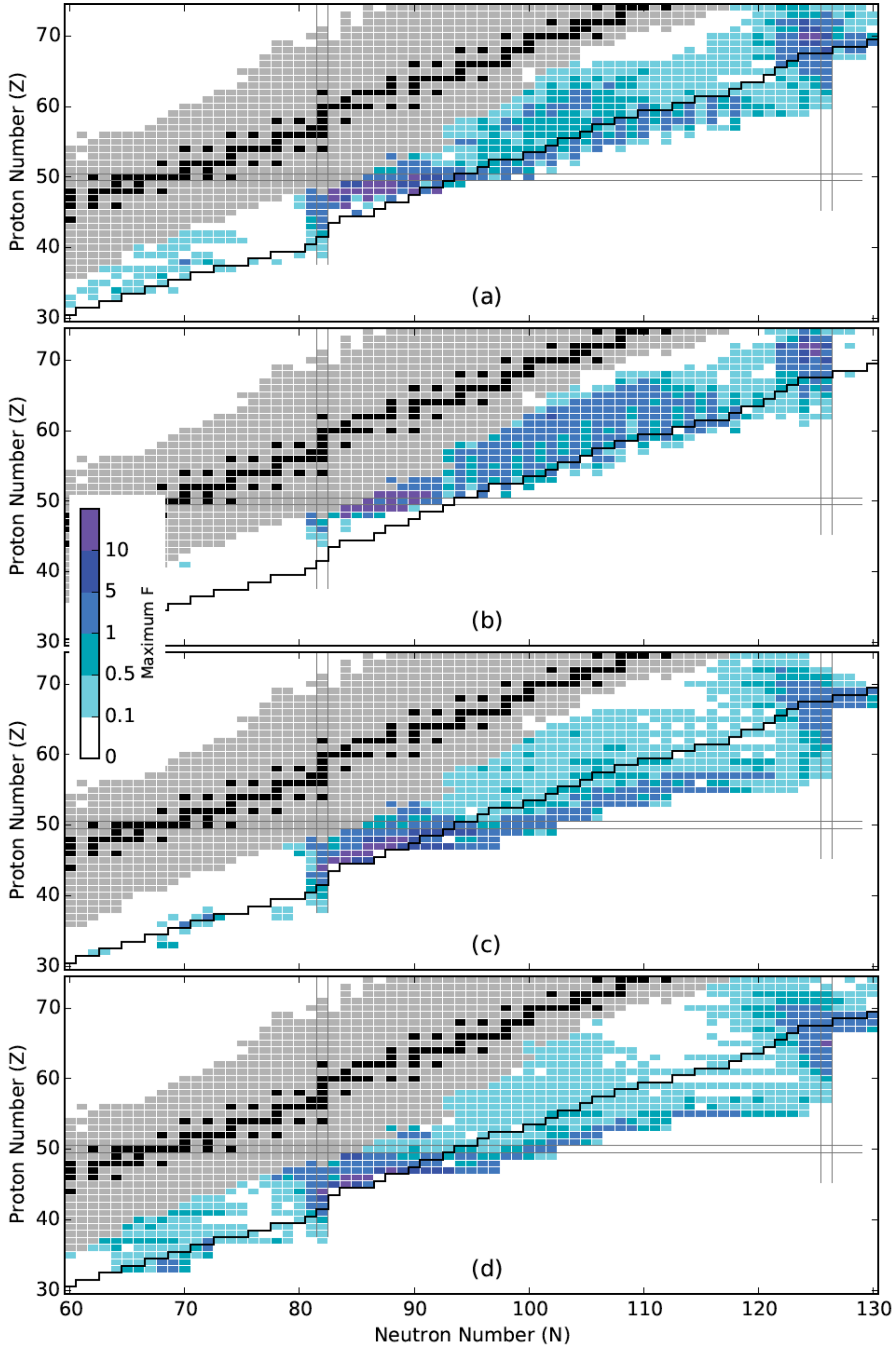
Legend
Solar Data
Baseline
(n,g)-rates only
Beta-decay rates only
Sn only
Y(A)
% Difference
A
10^-2
10^-3
10^-4
10^-5
40
20
0
−20
−40
120
130
140
150
160
170
180
190
200



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)
10^{-2}
10^{-3}
10^{-4}
120
130
140
150
160
170
180
190
200
A



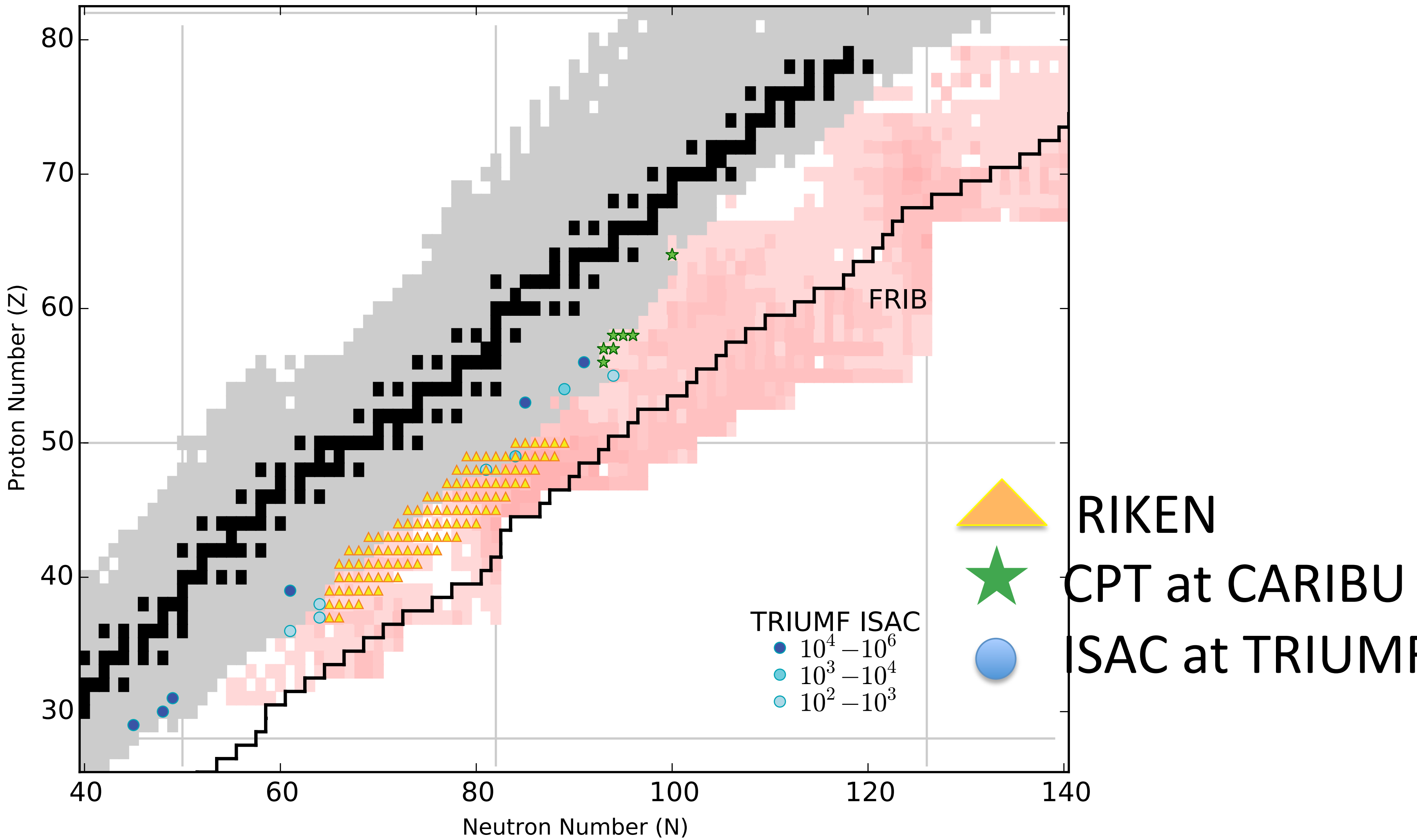
Low entropy hot wind

High entropy hot wind

Cold wind

Neutron Star Merger

Experimental reach for the present and future...



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 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

Sensitivity Study Masses

Samuel Brett

Ian Bentley

Nancy Paul

Matthew Mumpower

Rebecca Surman

A^2

Fully Consistent Sensitivity Studies

Matthew Mumpower

Mary Beard

D. Liang

G. McLaughlin

P. Moller

Rebecca Surman

A^2