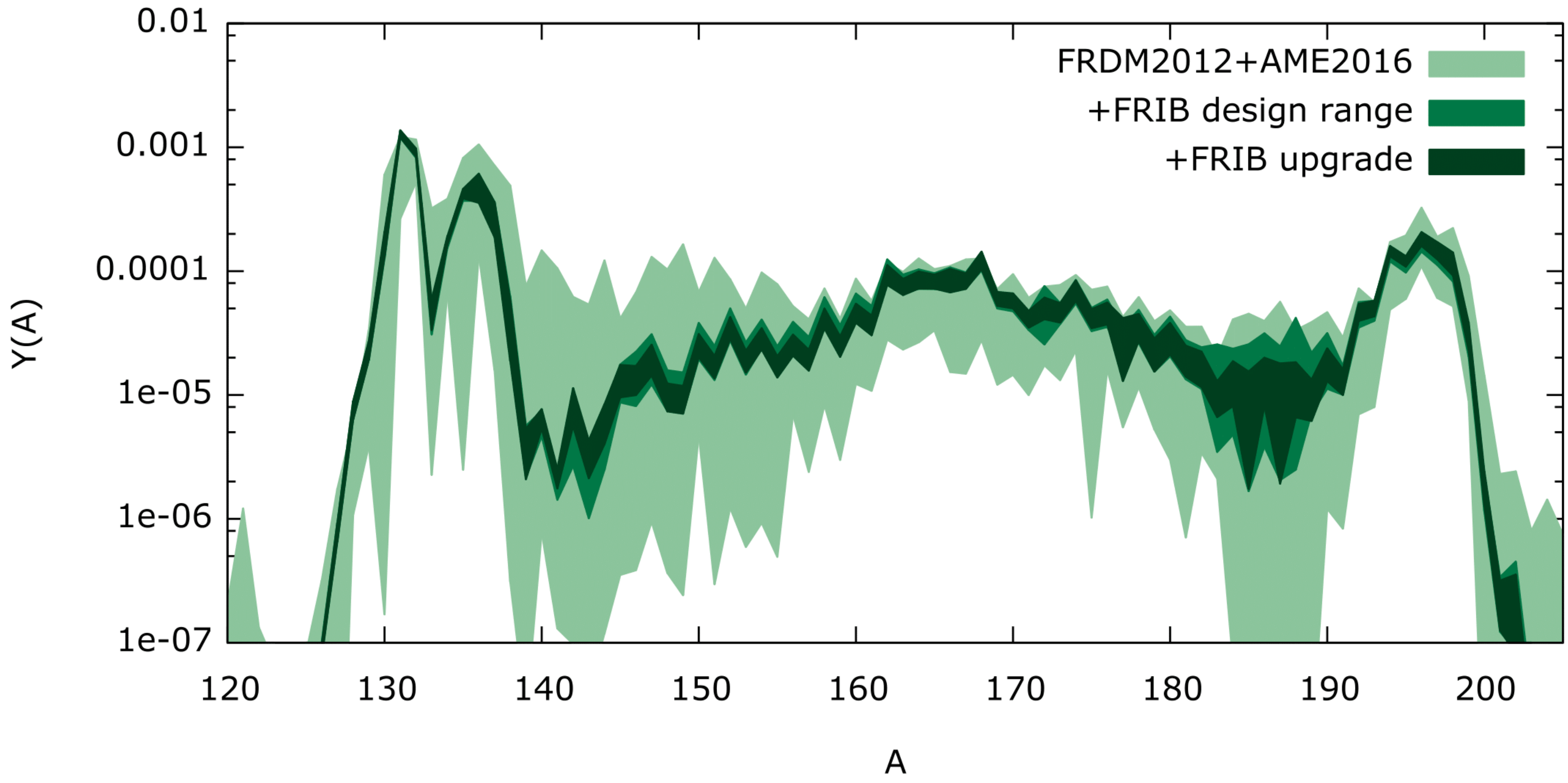
# FRIB UPGRADE: ADVANTAGES FOR r-PROCESS STUDIES



Los Alamos
NATIONAL LABORATORY
EST. 1943

LA-UR-18-27611

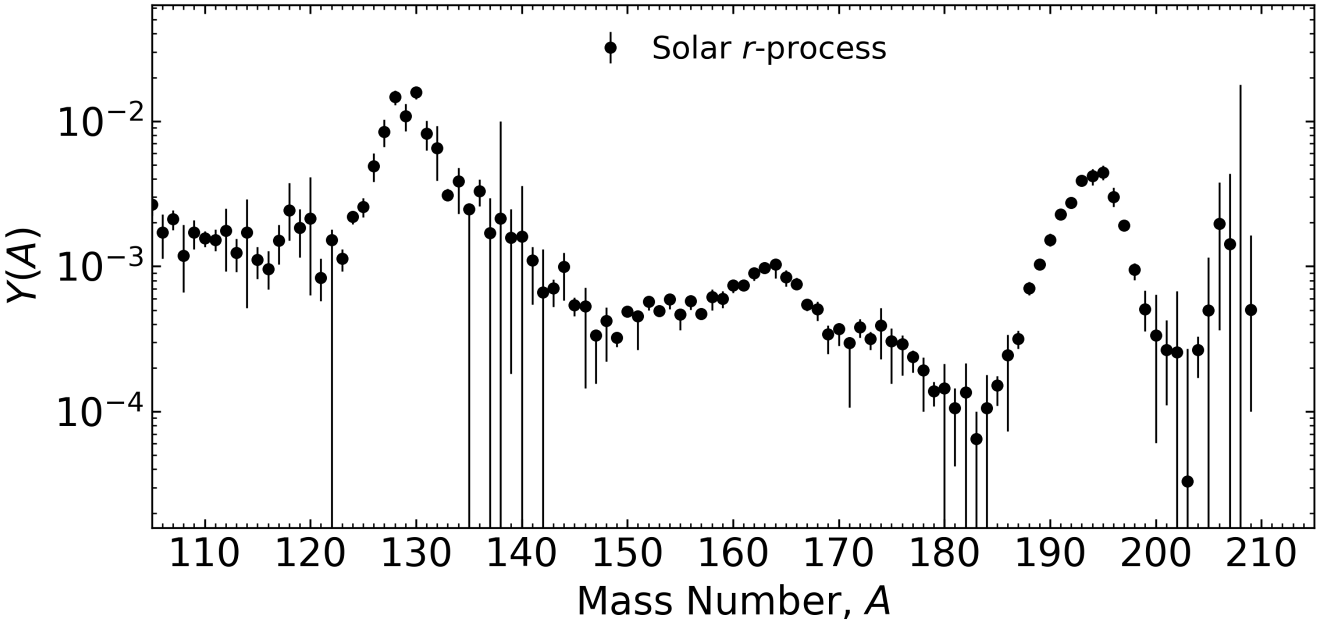
**MATTHEW MUMPOWER**
Los Alamos National Lab

*FRIB Upgrade Workshop*
Thurs. Aug. 9th 2018

JINA-CEE
NSF Physics Frontiers Center

# THE PROBLEM

We want to describe the abundances observed in nature



But there is uncertainty in:

The astrophysical conditions

The nuclear physics inputs

Both are required to model the nucleosynthesis

# INPUTS FROM NUCLEAR PHYSICS

**1st order:** masses, β-decay rates, reaction rates & branching ratios

See review paper: **Mumpower** *et al.* PPNP 86 (2016)

# WHAT DO WE KNOW?

## The chart of nuclides

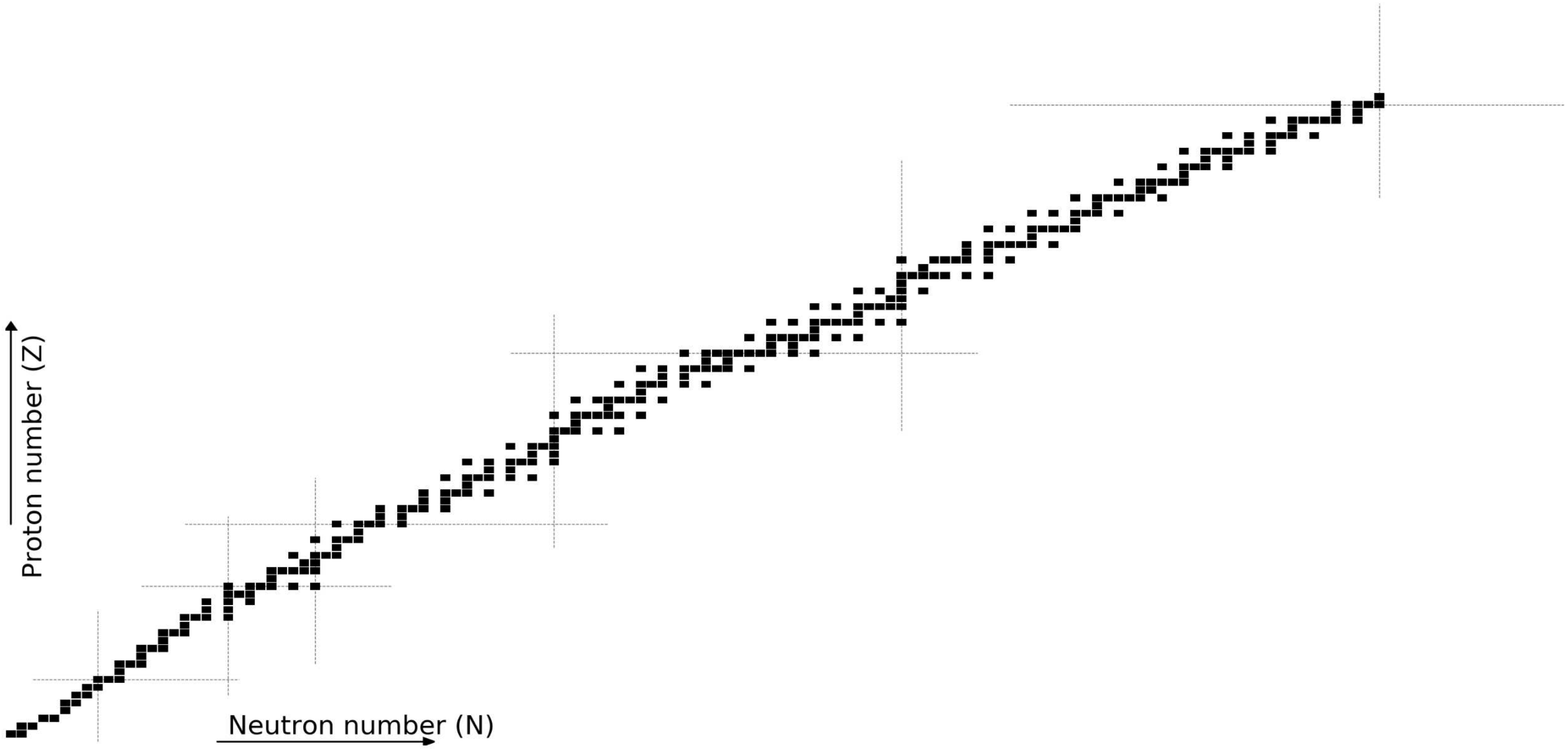


Figure by **Mumpower**

# WHAT DO WE KNOW?

## All half-lives

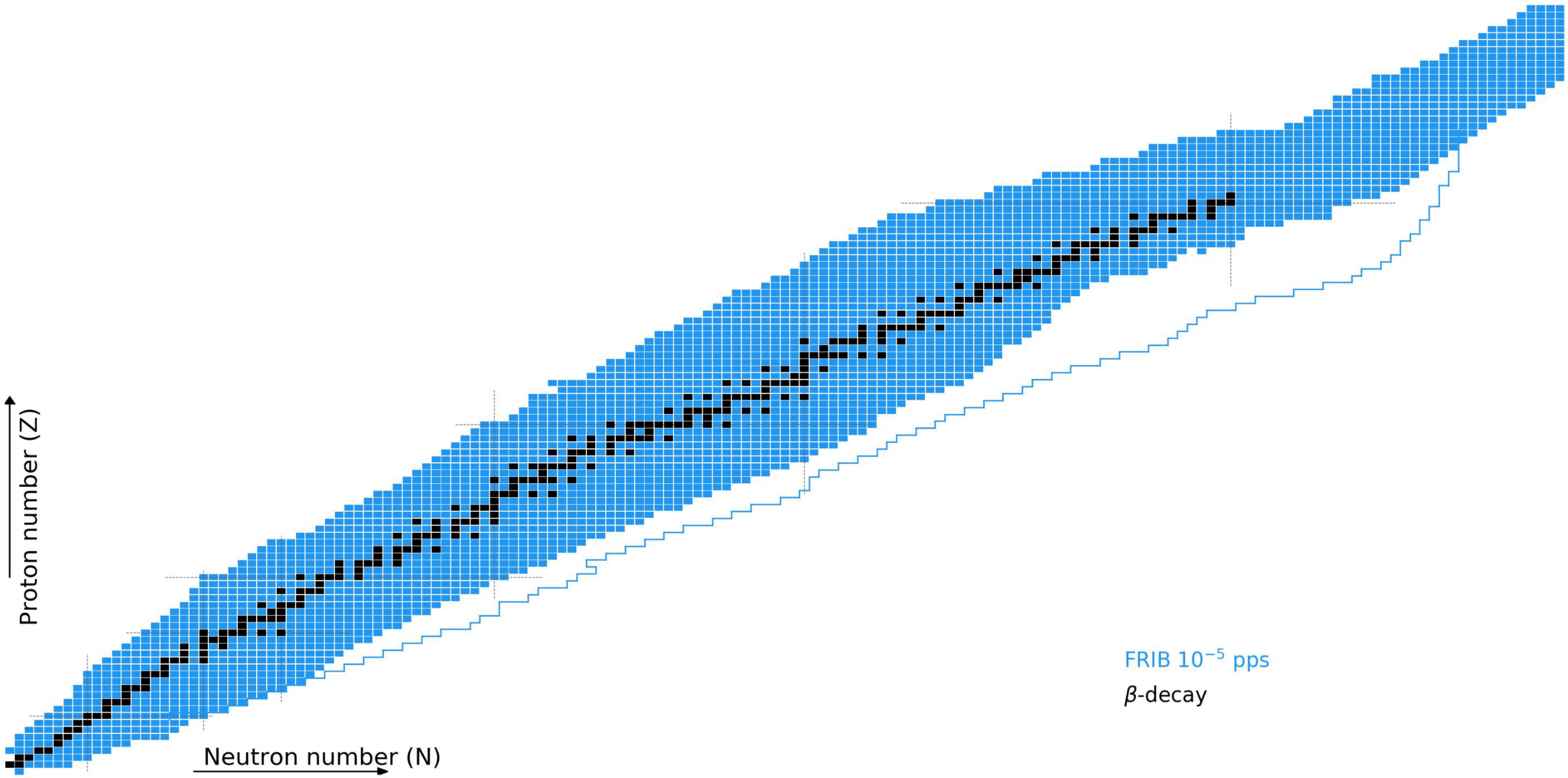


Figure by **Mumpower**

# WHAT DO WE KNOW?

## Neutron capture rates

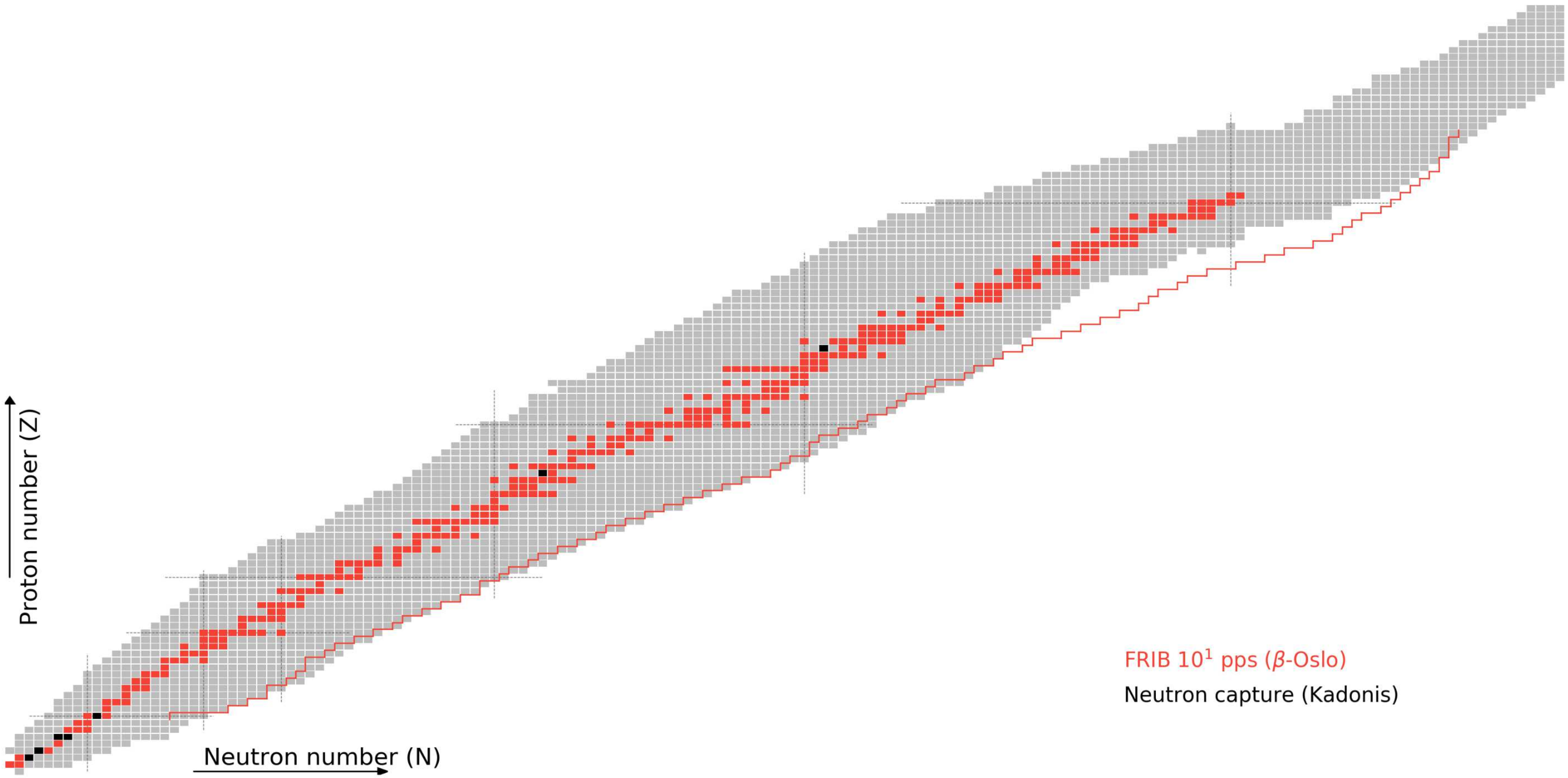


Figure by **Mumpower**

# WHAT DO WE KNOW?

## Nuclear masses

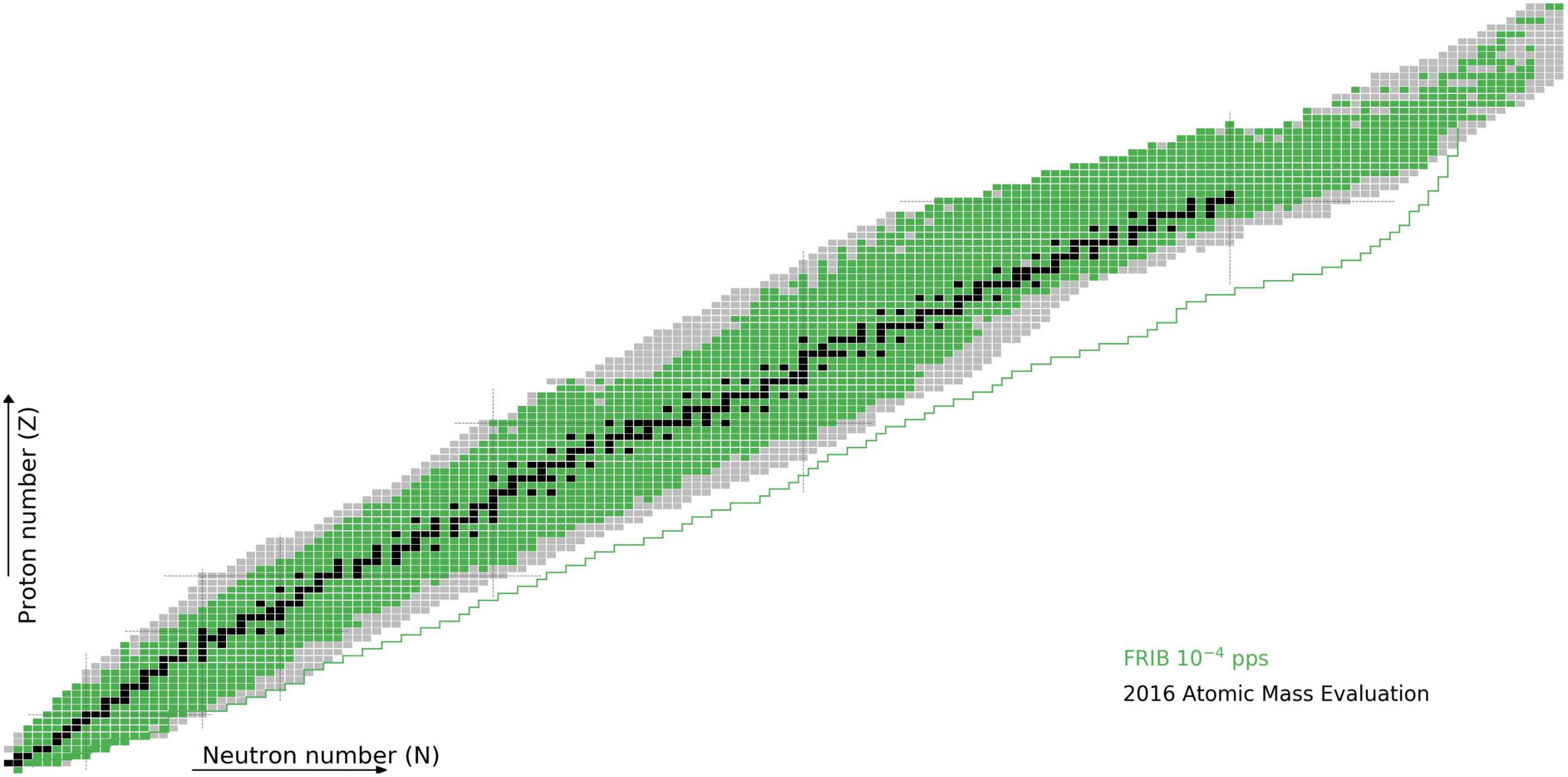


Figure by **Mumpower**

# WHAT DO WE KNOW?

## As of today, to varying degrees of accuracy

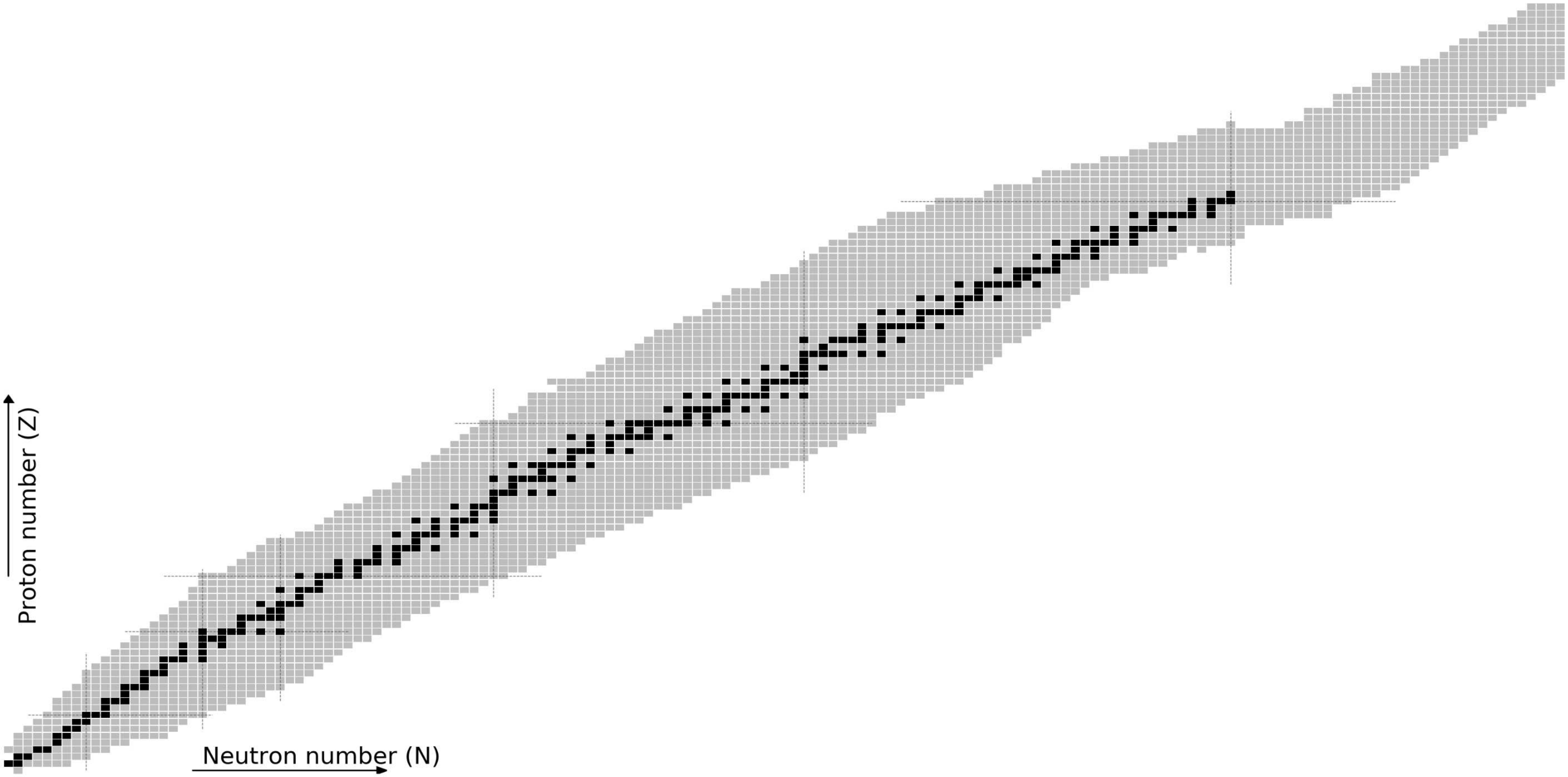


Figure by **Mumpower**

# WHERE WE'RE GOING

## FRIB as the r-process machine

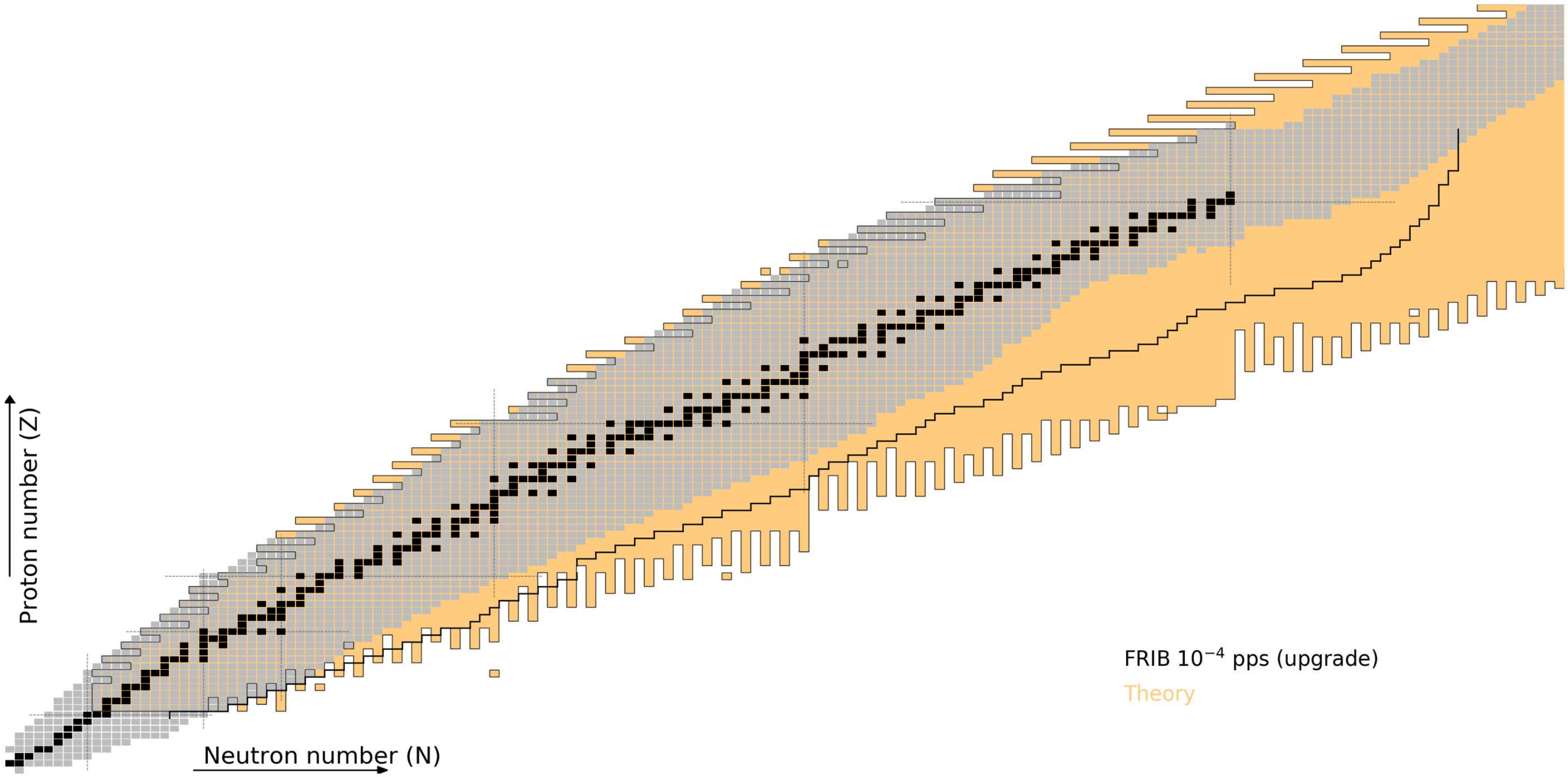


Figure by **Mumpower**

# r-PROCESS CALCULATION

**nuclear physics inputs**
(Sn, β-rates, n-cap rates, … )

PRISM
**reaction network**

**abundances**

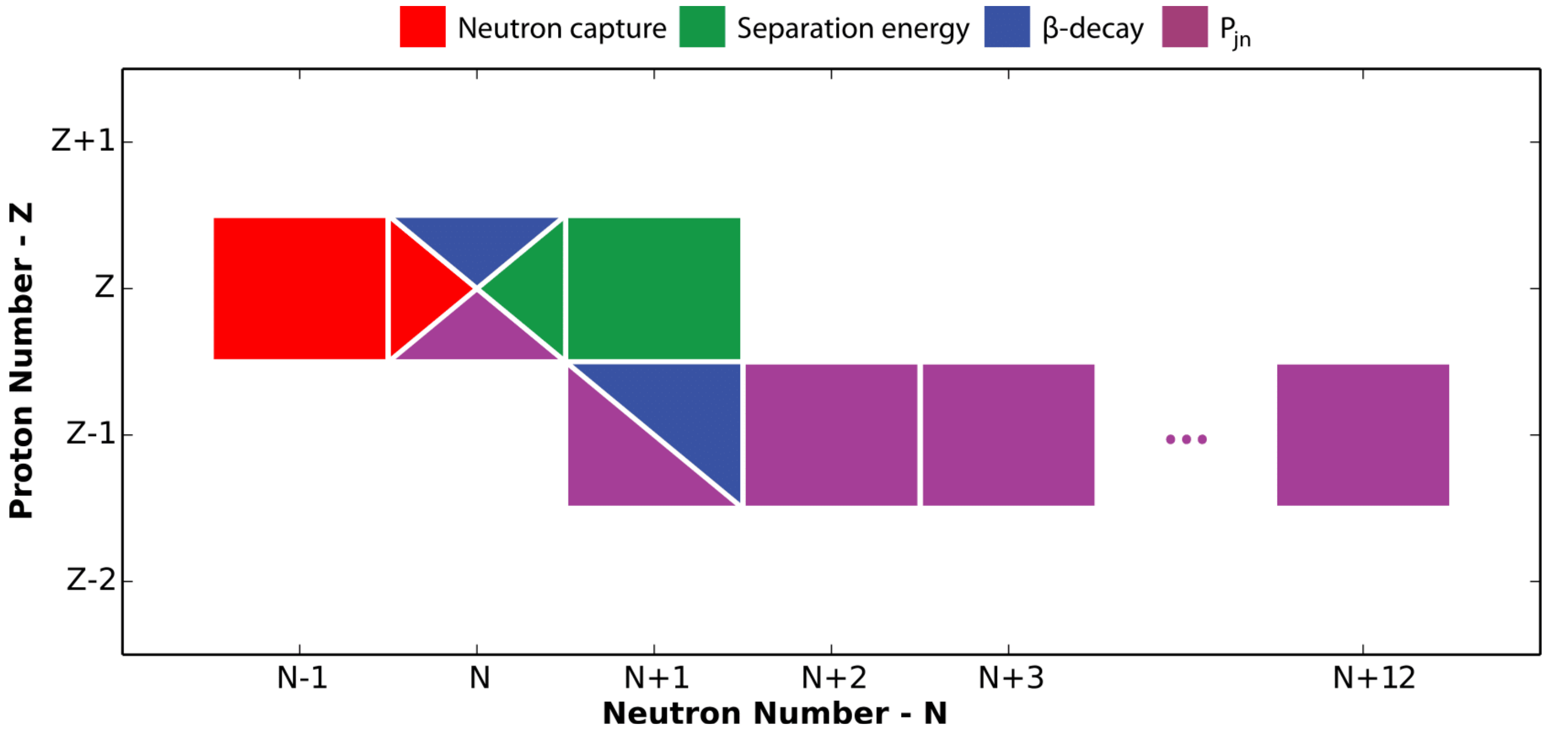
**thermodynamic conditions**

(temperature, density, ... )

Sprouse & **Mumpower** in prep (2018)

PRISM: Portable Routines for Integrated nucleoSynthesis Modeling

# WHY FOCUS ON MASSES?

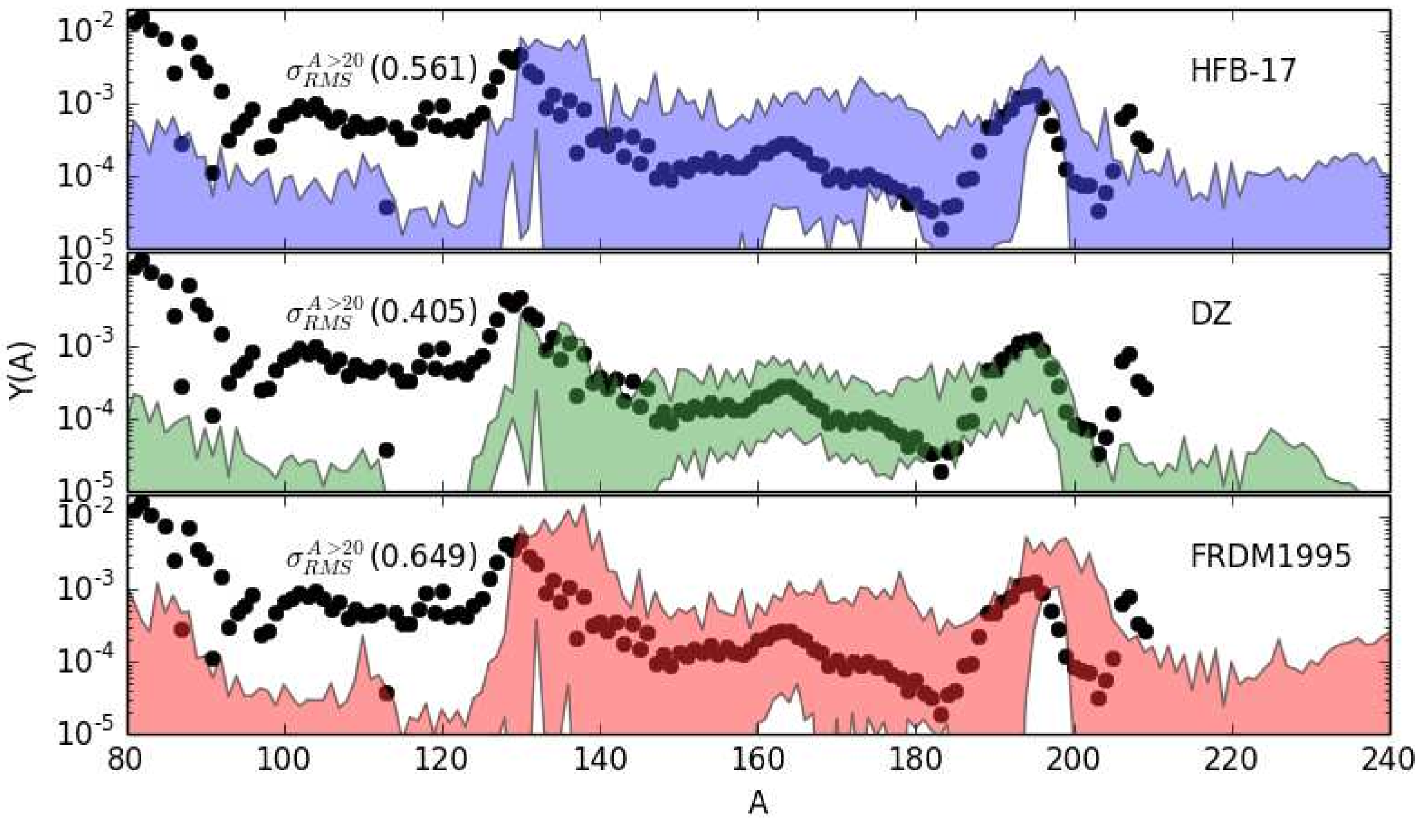


Mumpower *et al.* PRC 92 035807 (2015)

Masses go into the calculation of all other relevant quantities...

# UNCERTAINTIES FROM MASSES

Hot wind: S ~ 200, $\tau$ = 80 ms, $Y_e$ = 0.3

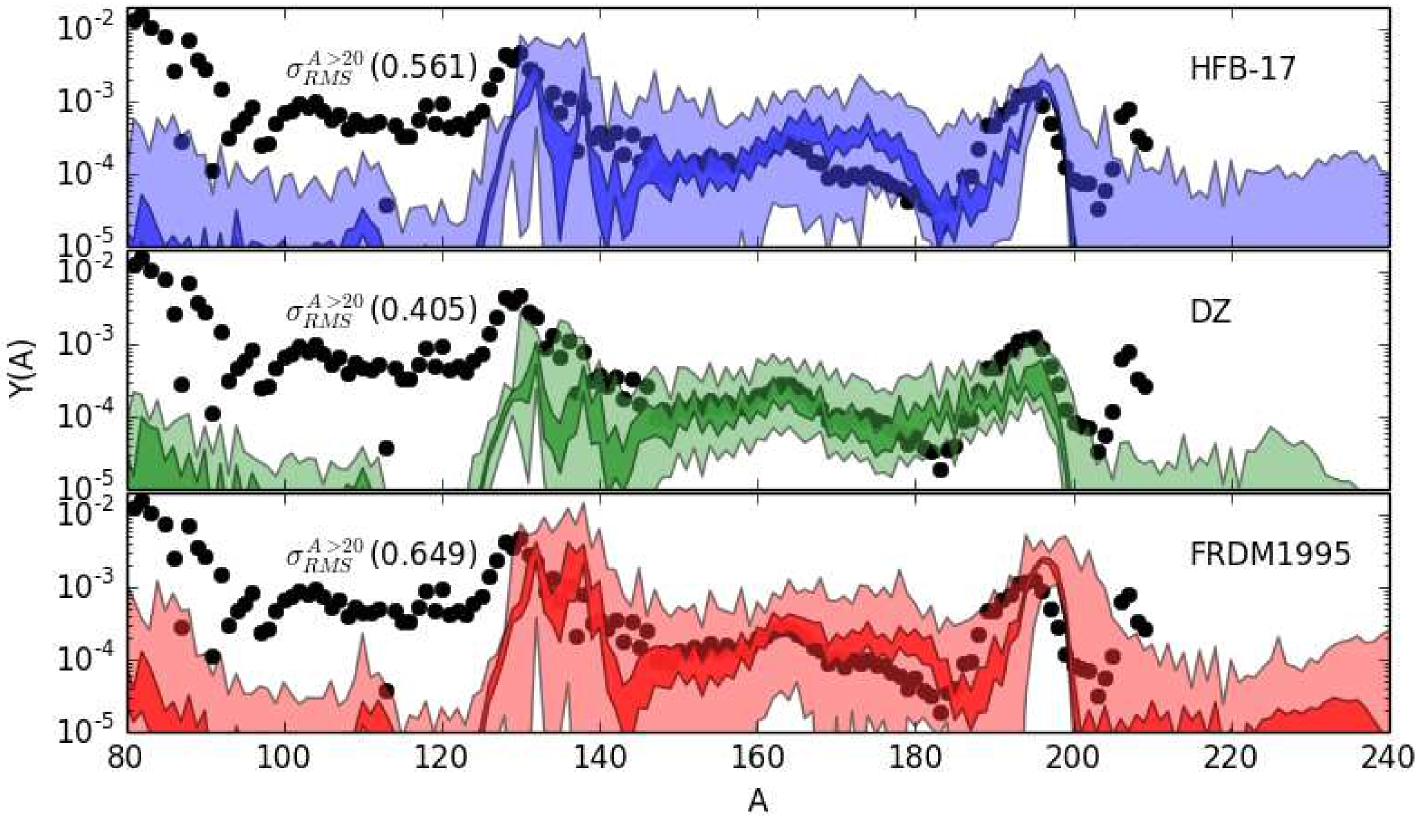


Uncorrelated mass Monte Carlo study; *not full propagation*

Mumpower *et al.* PPNP 86 86-126 (2016)

# UNCERTAINTIES FROM MASSES

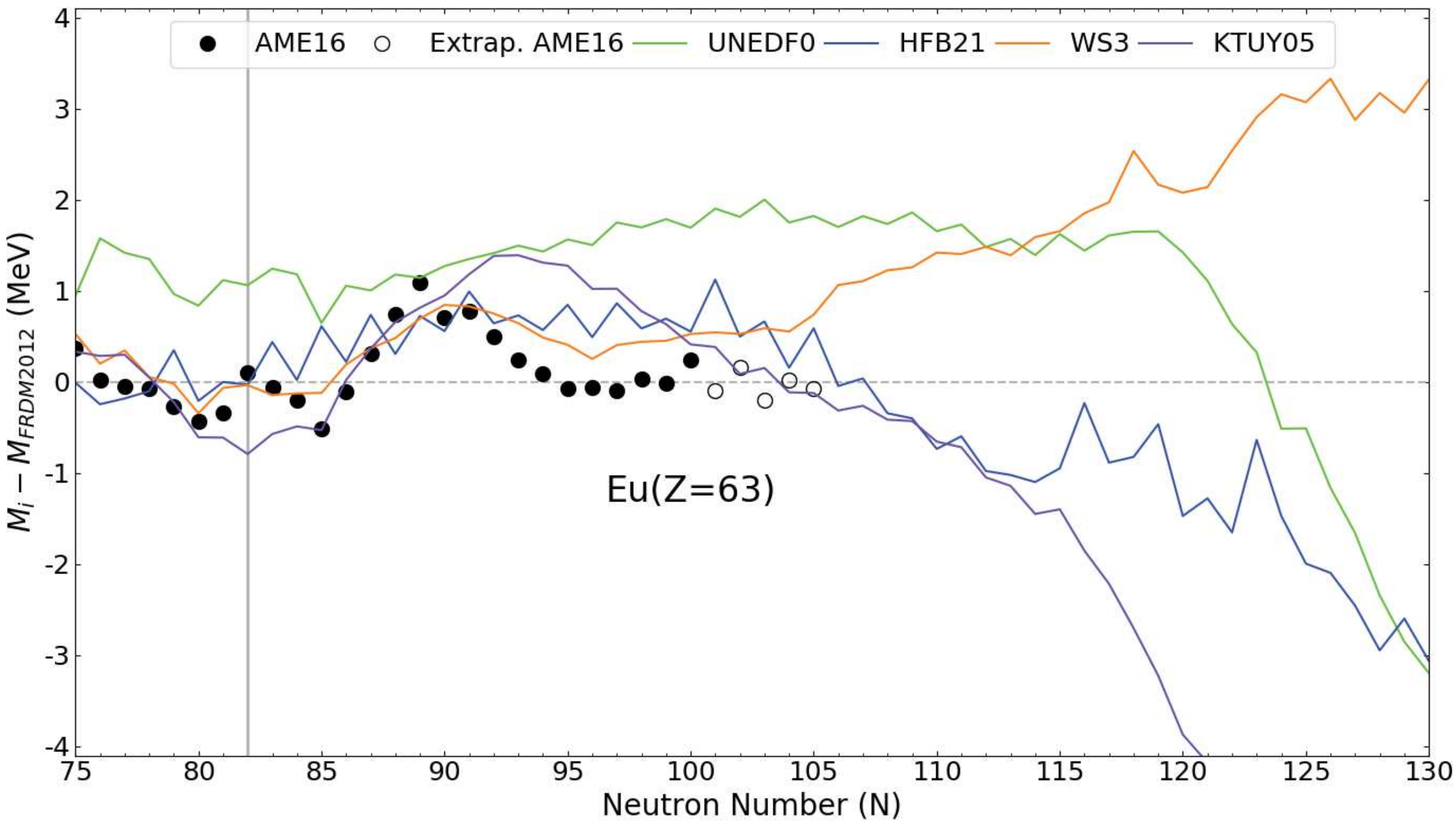
Hot wind: S ~ 200, τ = 80 ms, $Y_e$ = 0.3



Rule of thumb: $\Delta_{mass}$ ~ 500 keV ⇒ $\Delta_Y$ ~ 2 − 3 orders of magnitude

Mumpower *et al.* PPNP 86 86-126 (2016)

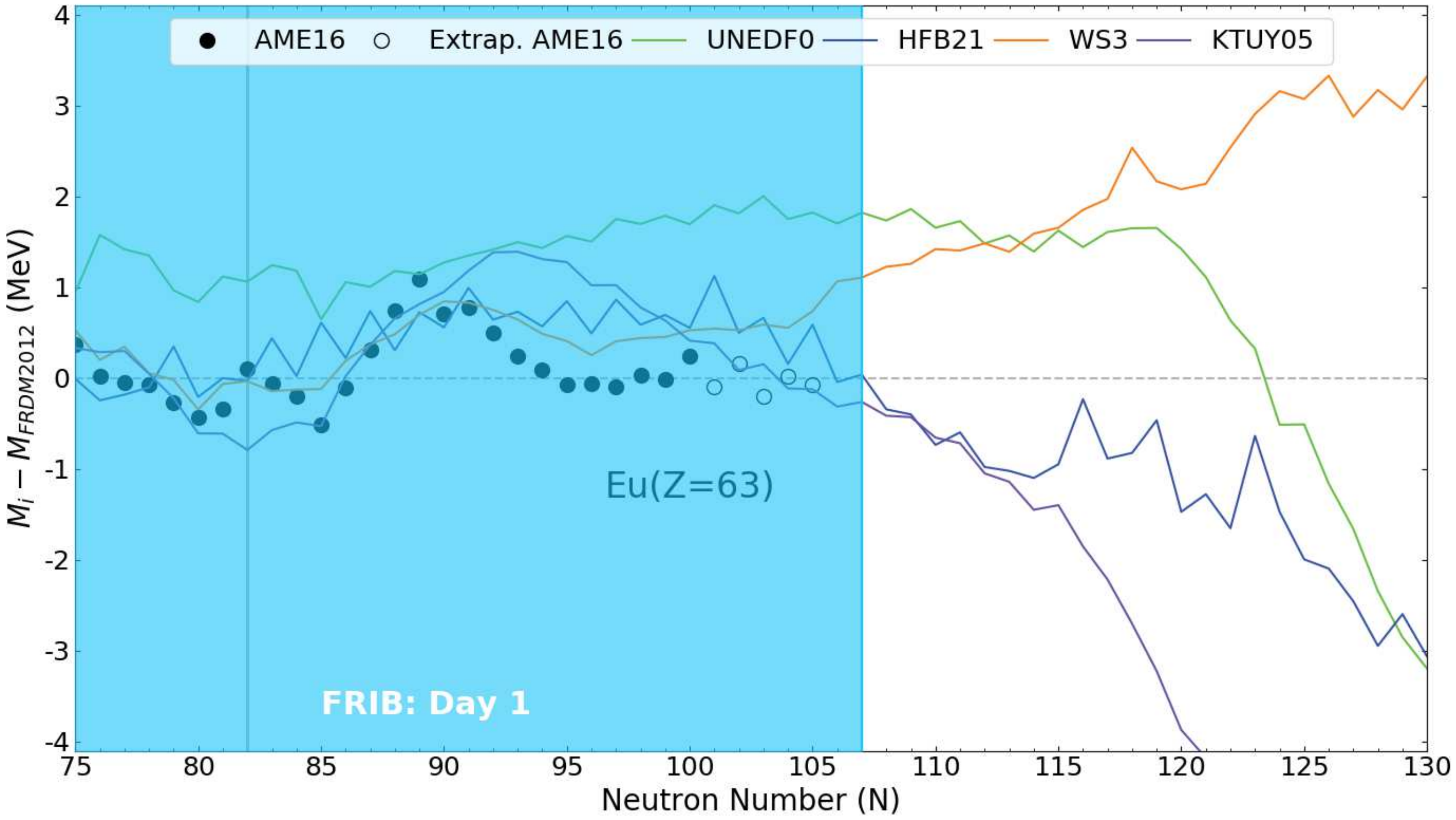
# VARIATION IN MASSES



Large variation in mass model predictions further from stability

Modified from Mumpower *et al.* PPNP 86 86-126 (2016)

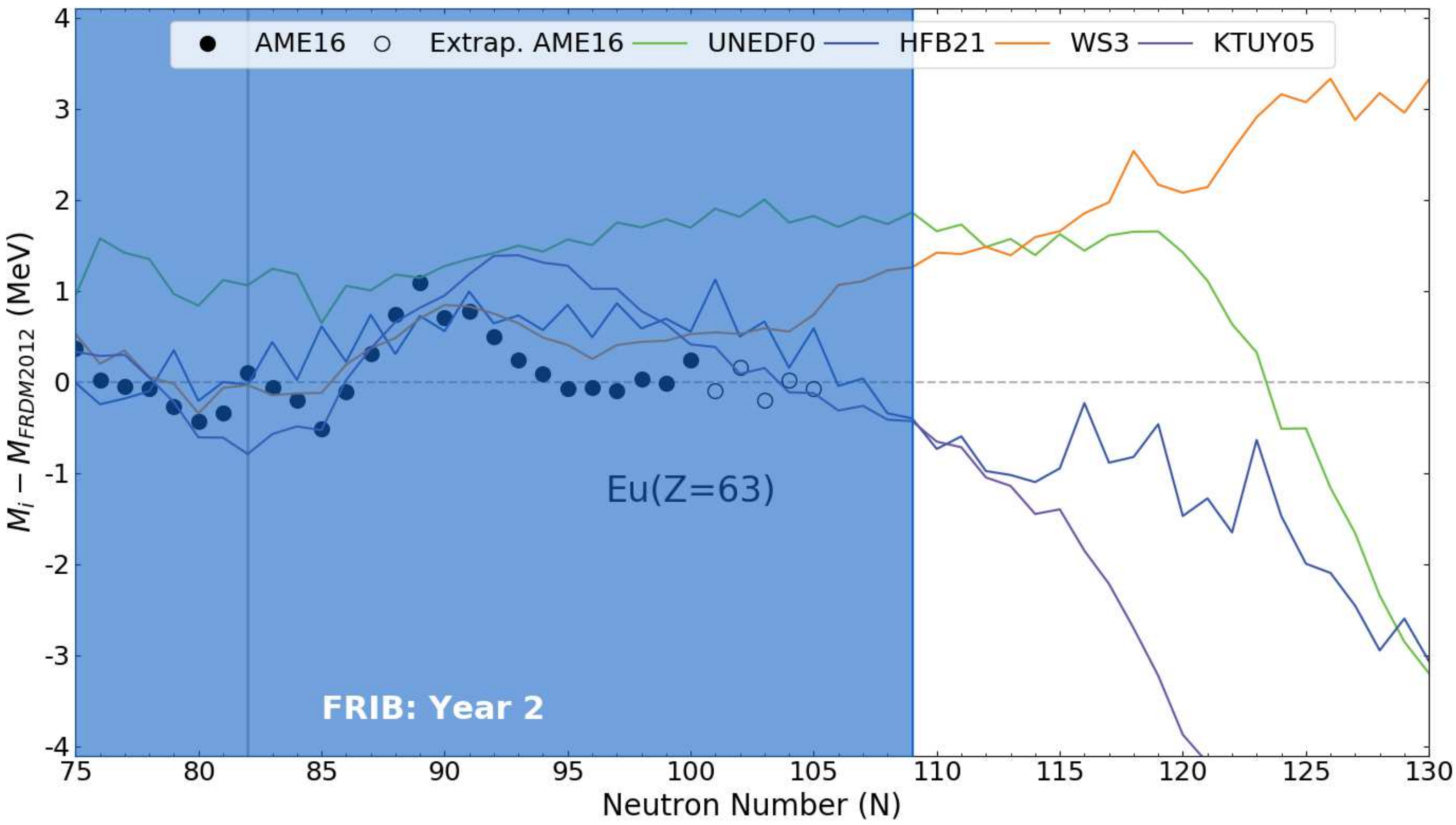
# DISCRIMINATORY POWER



FRIB: Day 1 already allows probing of the N = 104 subshell closure

Modified from Mumpower *et al.* PPNP 86 86-126 (2016)

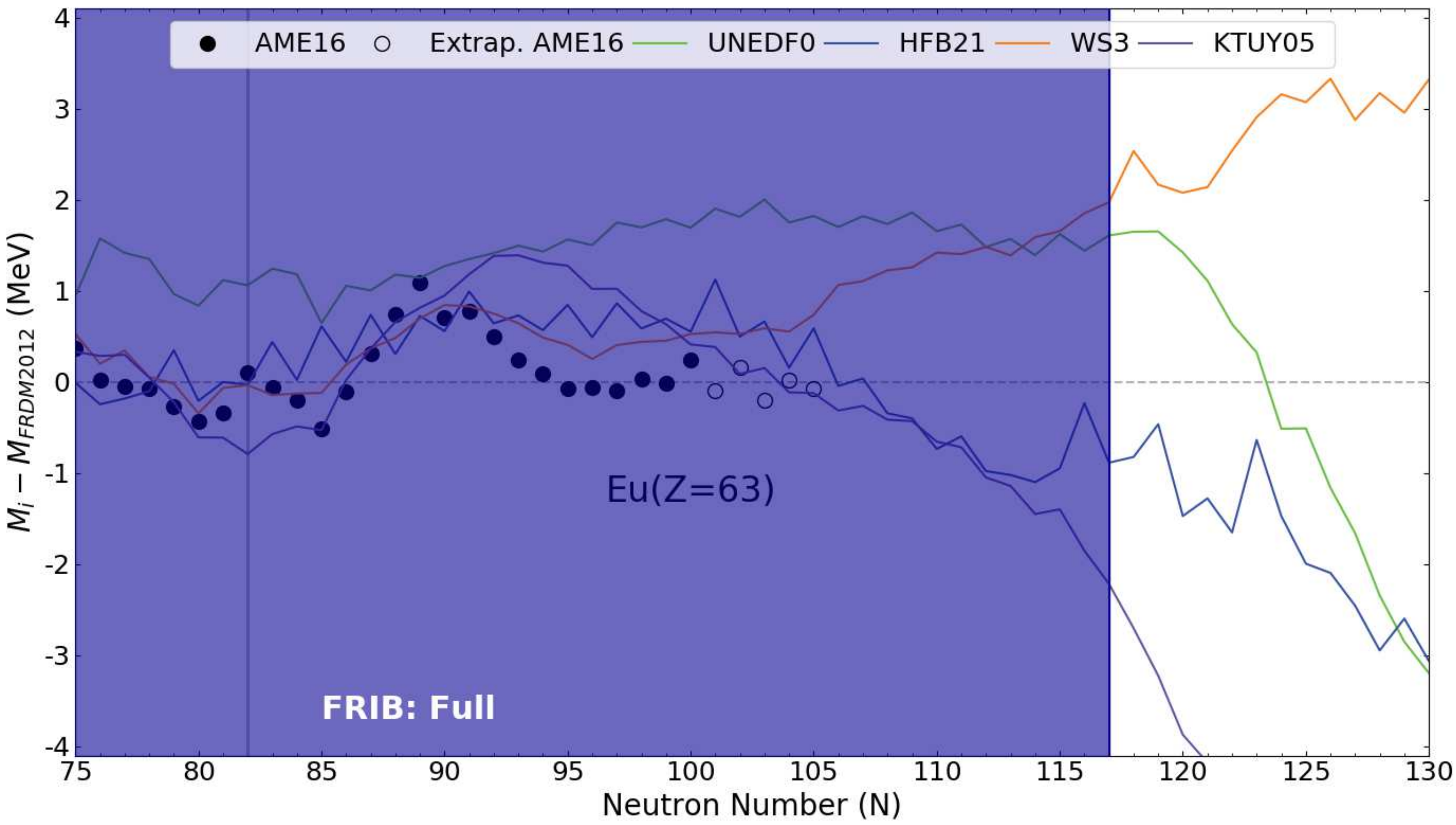
# DISCRIMINATORY POWER



FRIB: Year 2 provides nuclei with several more neutrons

Modified from Mumpower *et al.* PPNP 86 86-126 (2016)

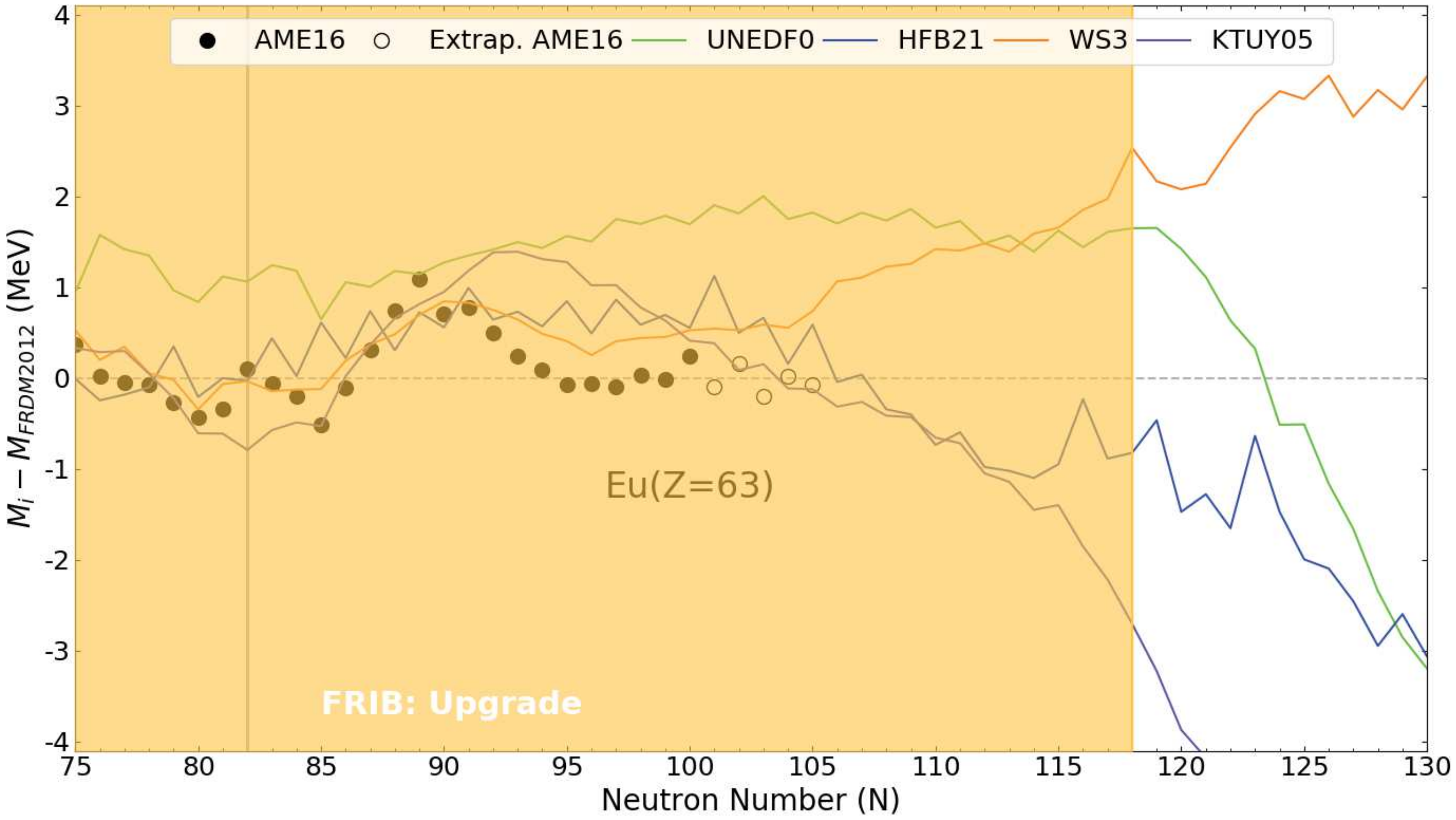
# DISCRIMINATORY POWER



FRIB: Full design spec provides information out to N ~ 117

Modified from Mumpower *et al.* PPNP 86 86-126 (2016)

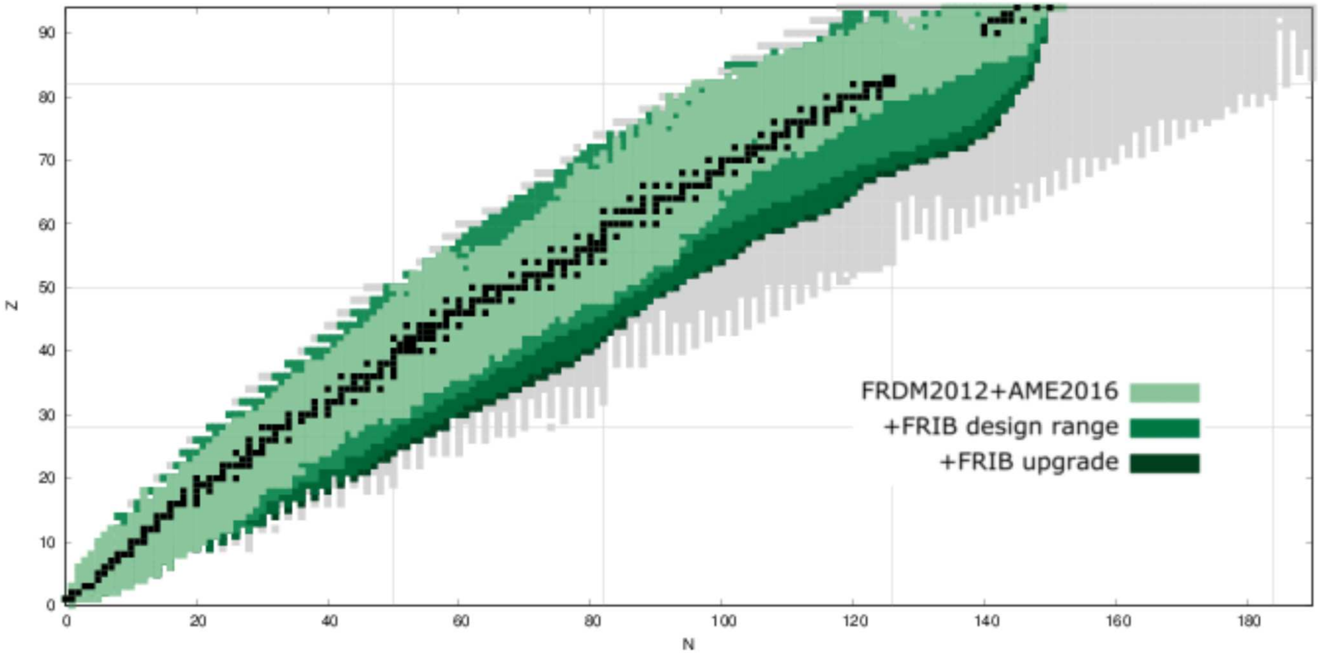
# DISCRIMINATORY POWER



Upgrade provides 1 or 2 more nuclei per isotopic chain… so what?

Modified from Mumpower *et al.* PPNP 86 86-126 (2016)

# MONTE CARLO RESULTS

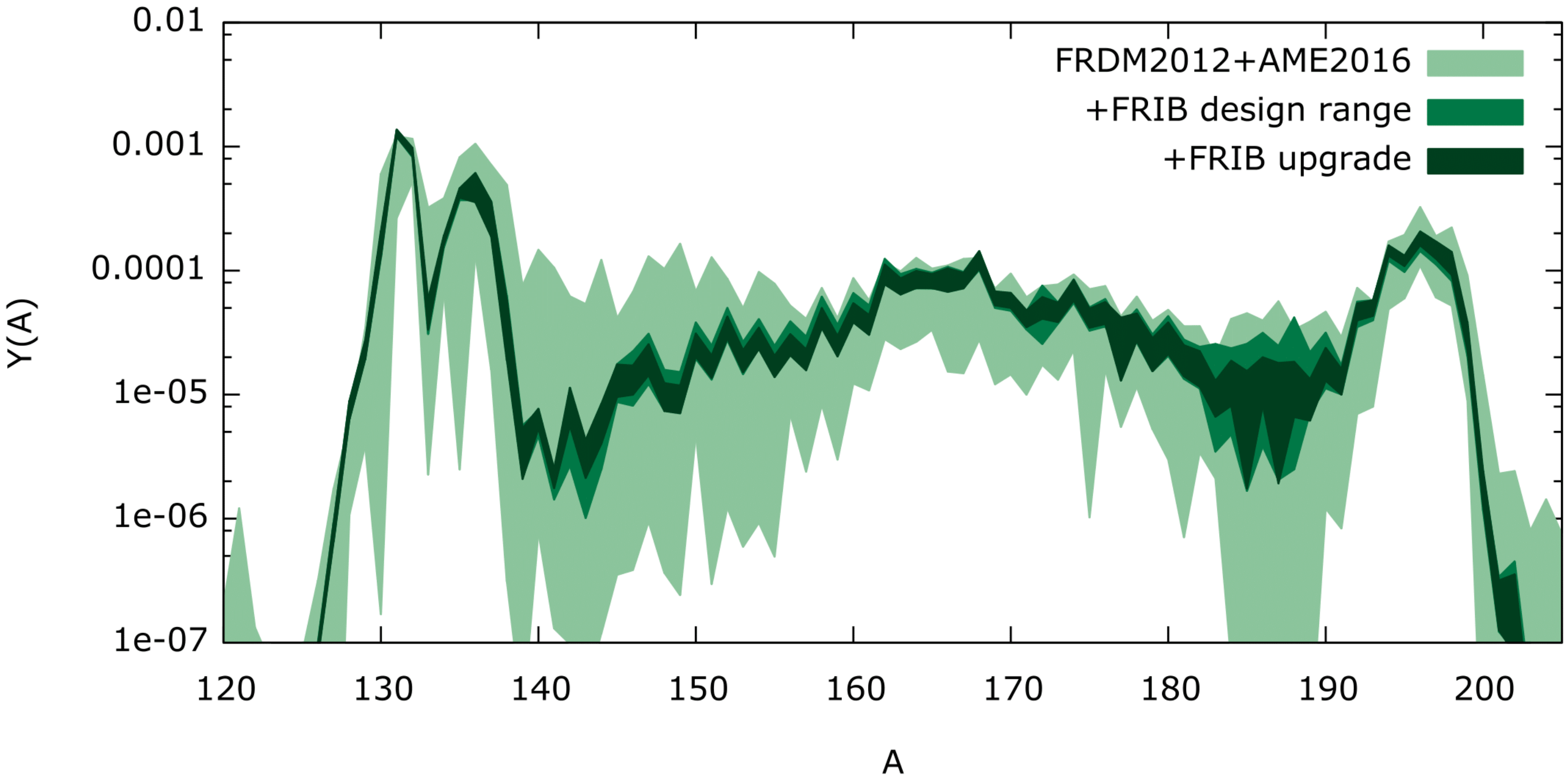


Uncorrelated mass Monte Carlo study; *not full propagation*

What is the impact of the FRIB upgrade?

Surman & **Mumpower** CGS16 in press (2018)

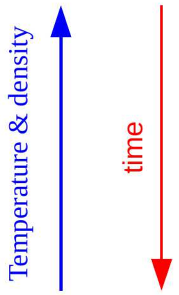
# MONTE CARLO RESULTS



Reduction in uncertainties in Rare Earth and transition regions

Surman & Mumpower CGS16 in press (2018)

# A TYPICAL r-PROCESS CALCULATION



Nuclear Statistical Equilibrium (NSE)

Alpha recombination

(n,γ) ↔ (γ,n) equilibrium & Quasi-equilibrium (QSE)

Freeze-out

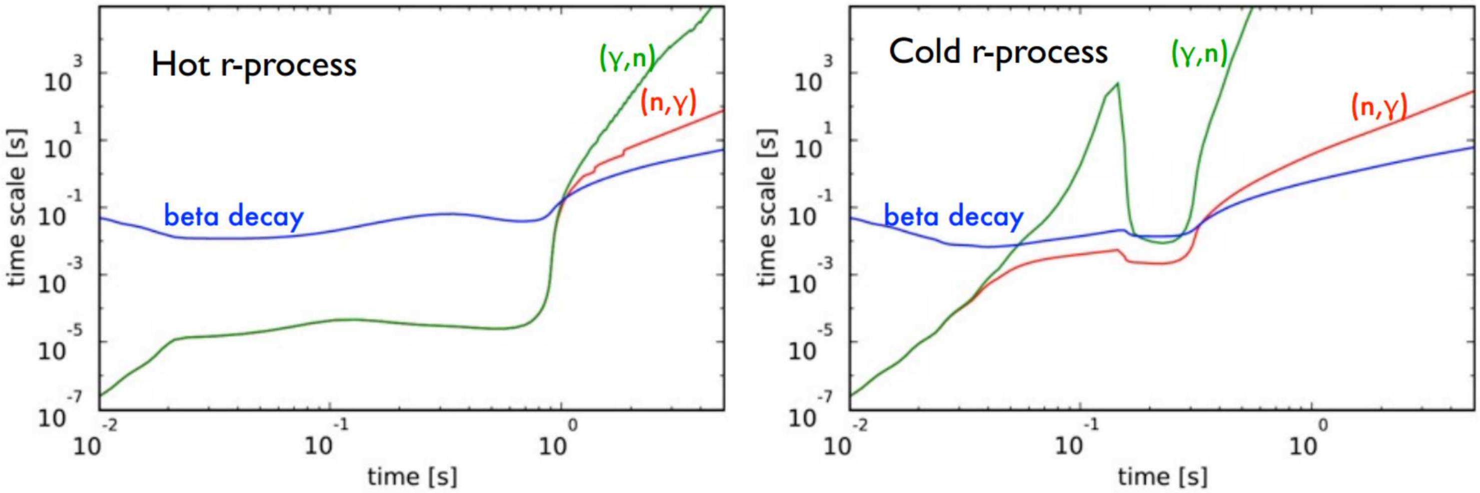


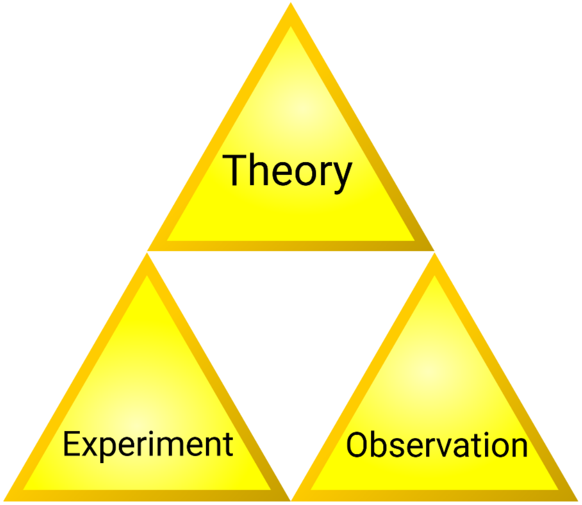
Figure by A. Arcones (2011)

nuclear physics + astrophysics ↦ abundances

# REVERSE ENGINEERING

What if we take a different approach?

Constrain nuclear physics with experiment and *additionally* observation using feedback from our calculated abundances



If we try to fit a particular part of the pattern we can ask what nuclear properties are responsible for its formation and learn how they are required to evolve with neutron excess

# REVERSE ENGINEERING

Our pursuit must satisfy several constraints:

We must be able to make measurements on these nuclei

Limits us to nuclei closer to stability

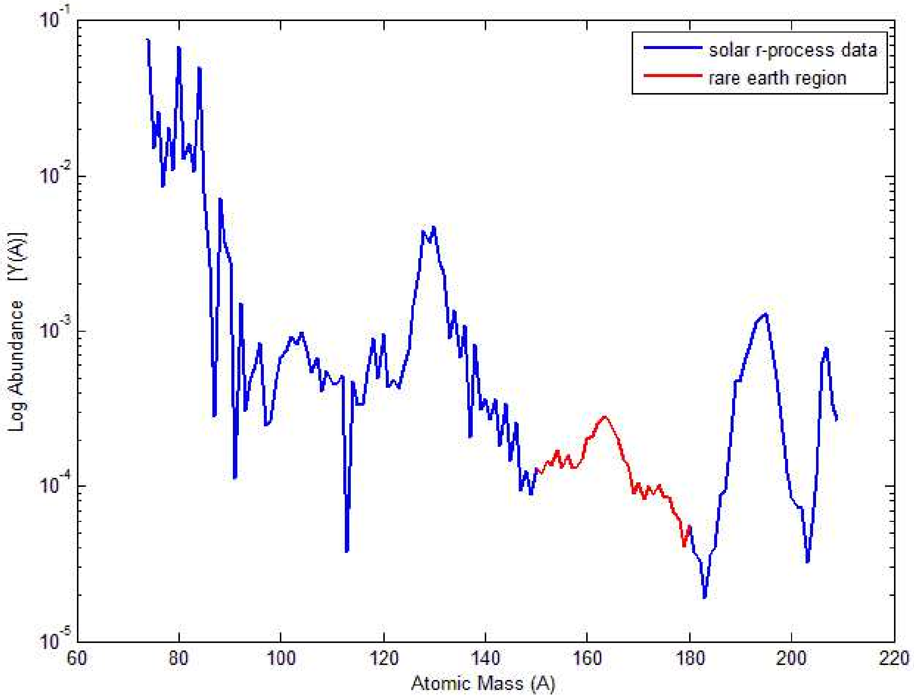
So, we must explore the freeze-out phase of the r process

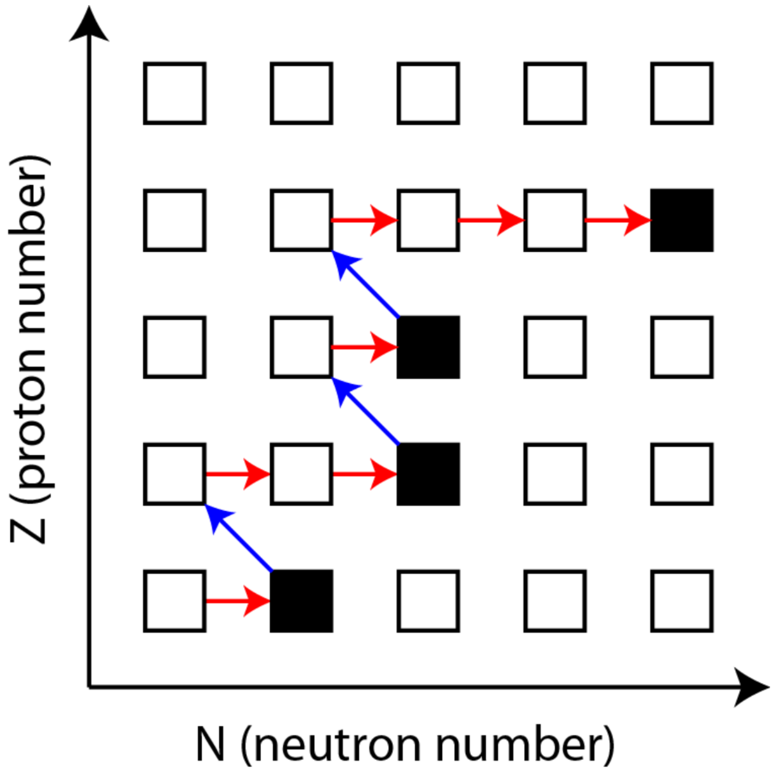
We must be able to use a recognizable signature in the abundances

The rare earth peak

# FORMATION OF THE RARE EARTH PEAK

# PROPOSED WAYS TO FORM THE REP



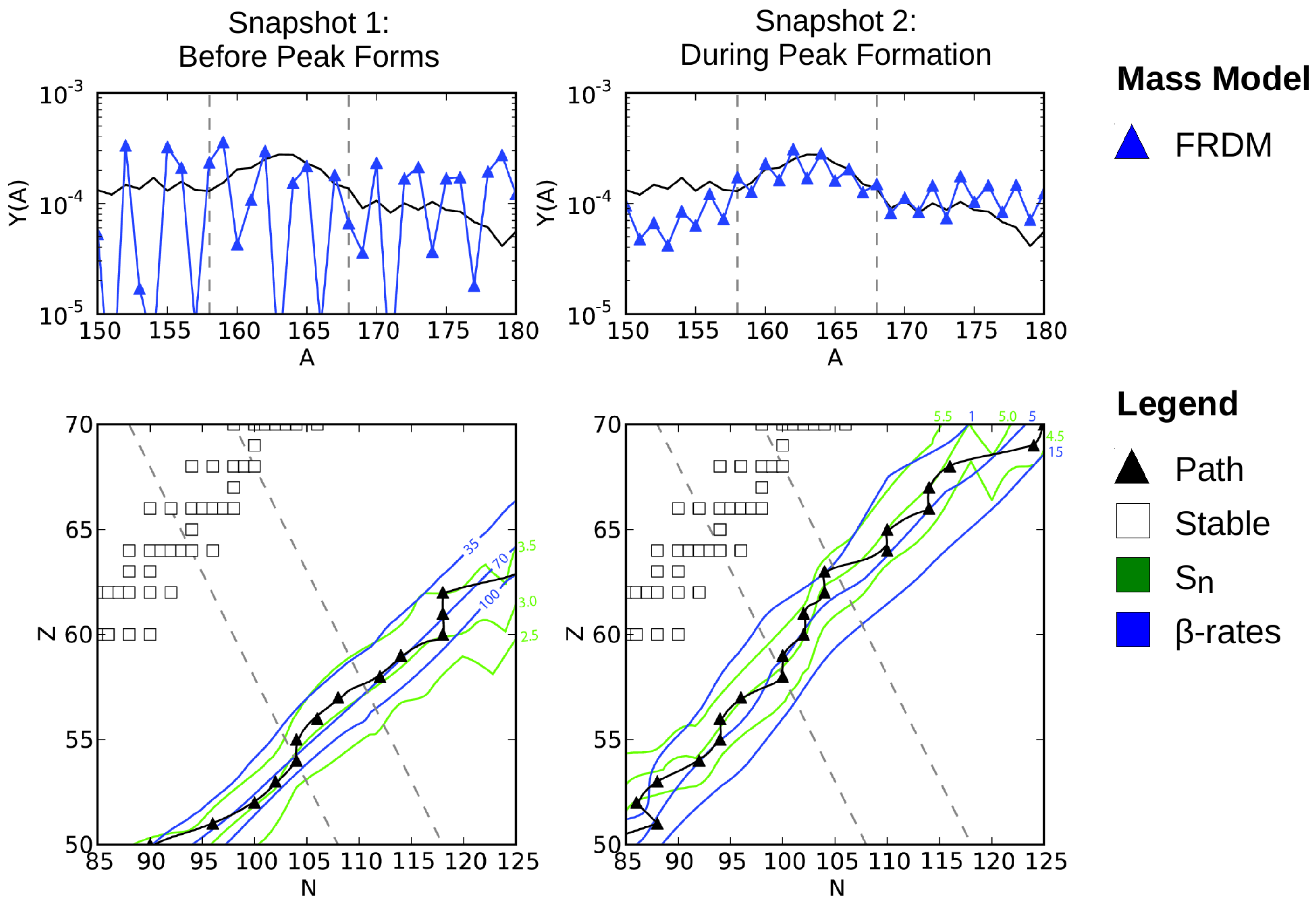


1. Dynamical formation during freeze-out (R ≲ 1)
   Requires a localized nuclear structure effect (kink)
2. Via fission fragment yields
   Requires dumping heavy products in exactly the right spot

Surman & Engel PRL 79 1809 (1997) • **Mumpower** *et al.* PRC 85 045801 (2012) • **Mumpower** *et al.* ApJ 752 117 (2012)

# FORMATION OF REP

## Hot wind: S ~ 200, τ = 80 ms, $Y_e$ = 0.3


Snapshot 1: Before Peak Forms

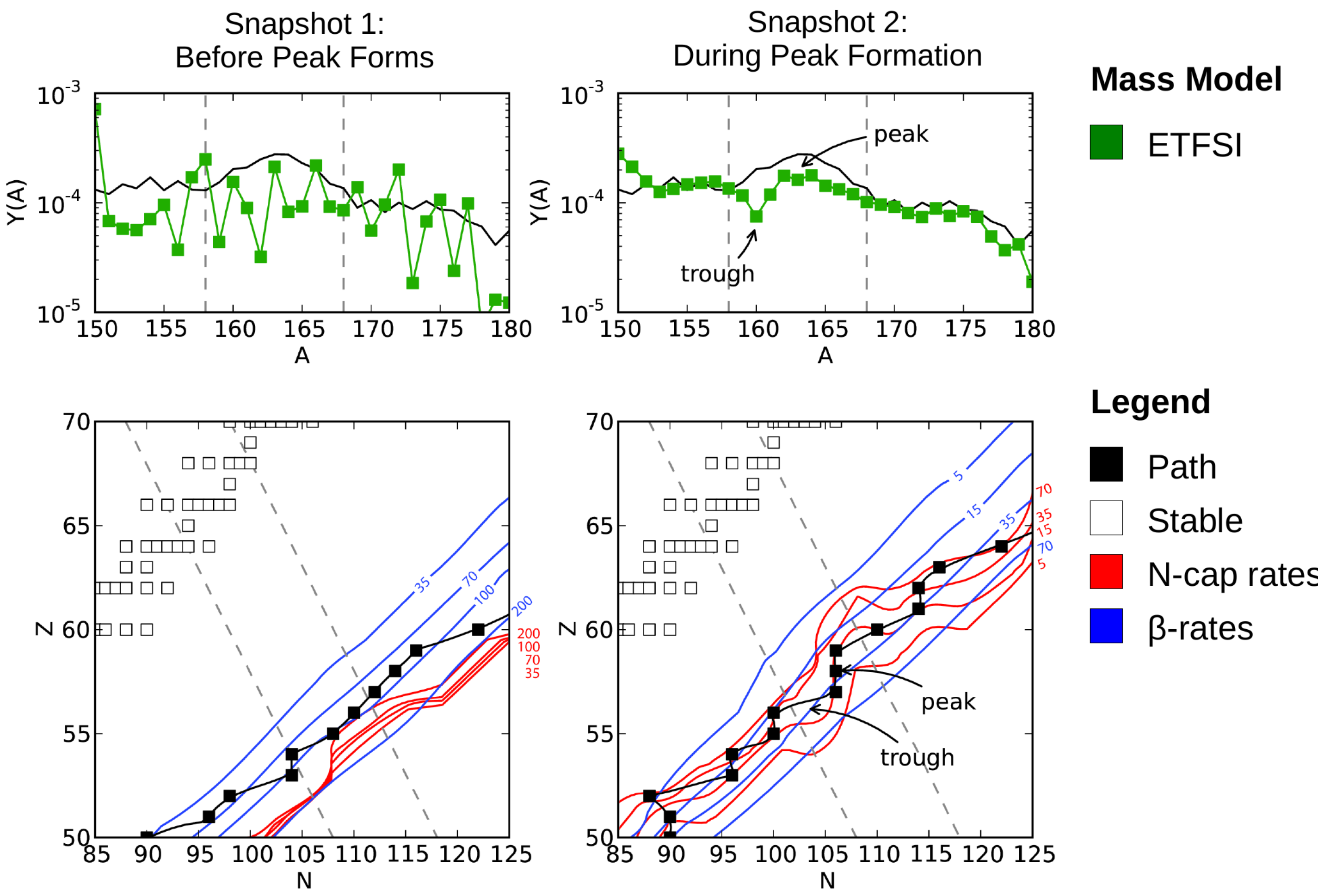
Snapshot 2: During Peak Formation

Kink in separation energies forms peak under hot freeze-out conditions

Mumpower *et al.* PRC 85 045801 (2012)

# FORMATION OF REP

Cold wind: S ~ 300, τ = 80 ms, $Y_e$ = 0.4



Kink in neutron capture rates forms peak under cold freeze-out conditions

Mumpower *et al.* PRC 85 045801 (2012)

# REP FORMATION: IDEAL CANDIDATE

We choose to study method 1 for reverse engineering

1. Dynamical formation during freeze-out ($R \lesssim 1$)

   Requires a localized nuclear structure (kink)

   Relatively few nuclei to measure, close to stability

   Hints from Jin Wu's $T_{1/2}$ measurements

   Very close to making necessary mass measurements

2. Via fission fragment yields

   Requires dumping heavy products in exactly the right spot

   Extreme r-process conditions necessary

   Need to make measurements on hundreds of the heaviest nuclei

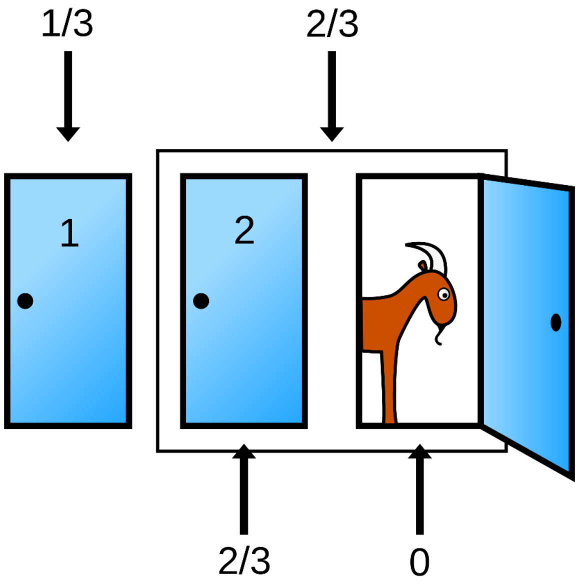
   **Problem:** We can't reach these nuclei, even with FRIB

# THE REVERSE ENGINEERING FRAMEWORK

# THE BAYESIAN APPROACH

An example… The Monty Hall problem

A new car is hidden behind one of the doors



The optimal strategy is to switch the initial pick - twice the chance of winning the new car

We **update** our probabilities based off new information

# APPLY IDEA TO REP FORMATION

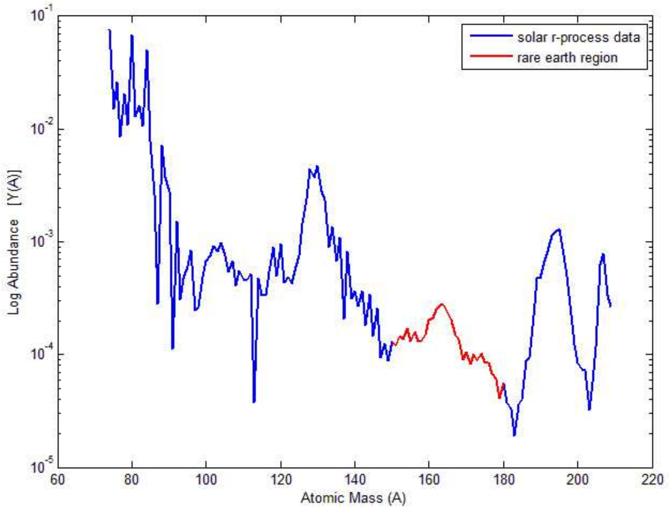
For fixed astrophysical conditions (hot, cold or merger)...

Let's allow the nuclear masses to vary

We have to update all relevant nuclear physics self-consistently

The rare earth abundances provide **feedback** to the change in masses

Use the Metropolis algorithm to traverse the parameter space



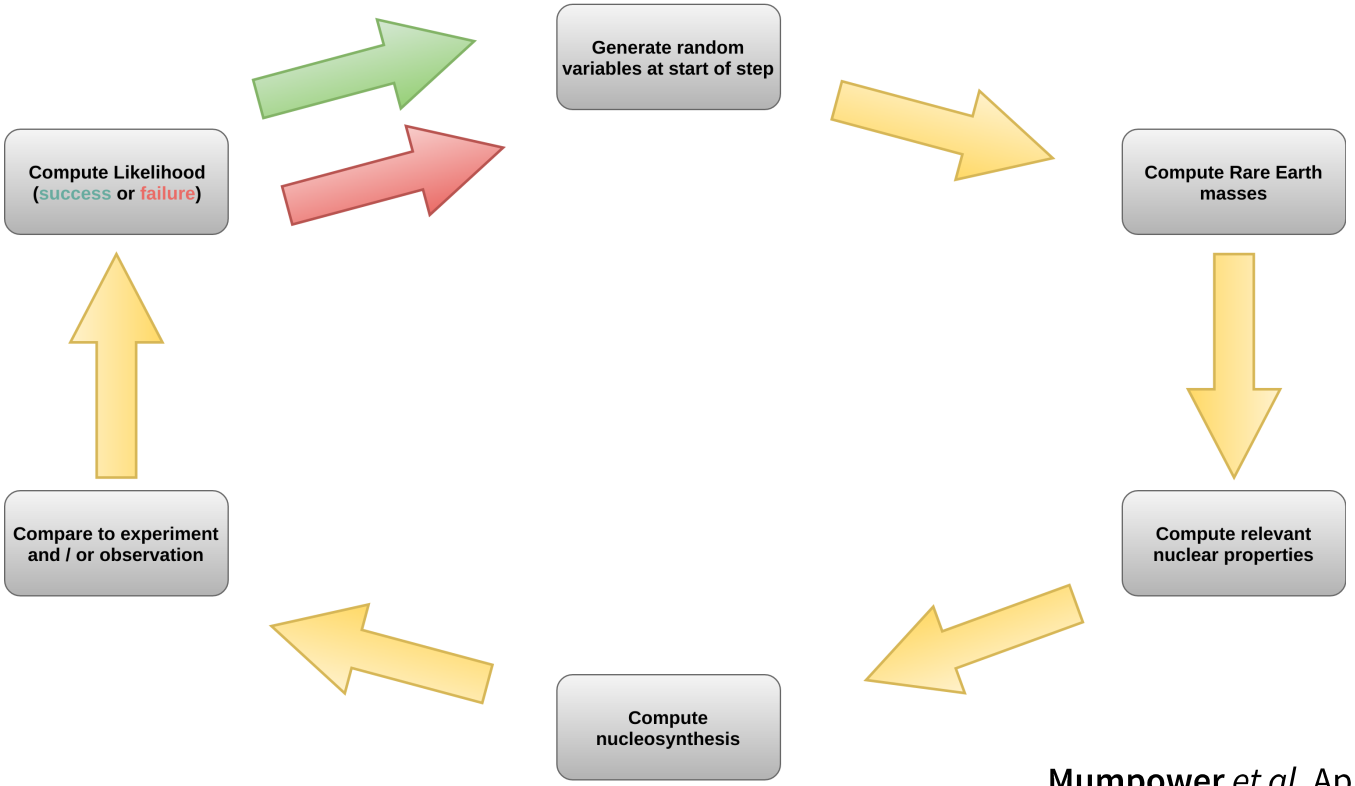
Compute likelihood

L ~ match red abundances

**Mumpower** *et al.* ApJ 833 282 (2016)

# REVERSE ENGINEERING PROCEDURE

## How it works in a nutshell



Generate random variables at start of step

Compute Rare Earth masses

Compute relevant nuclear properties

Compute nucleosynthesis

Compare to experiment and / or observation

Compute Likelihood (success or failure)

**Mumpower** *et al.* ApJ 833 282 (2016)

# UPDATING NUCLEAR PROPERTIES

Every time the masses change we recalculate...

Relevant Q-values

β-decay properties ($T_{1/2}$ and branching ratios)

Neutron capture rates

For hundreds of nuclei...

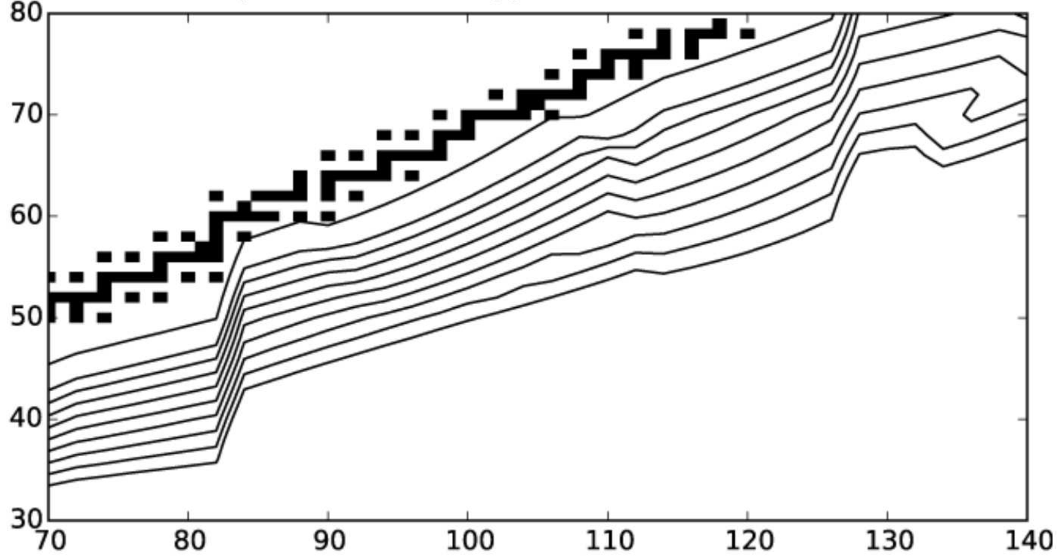
This is computationally expensive but necessary!

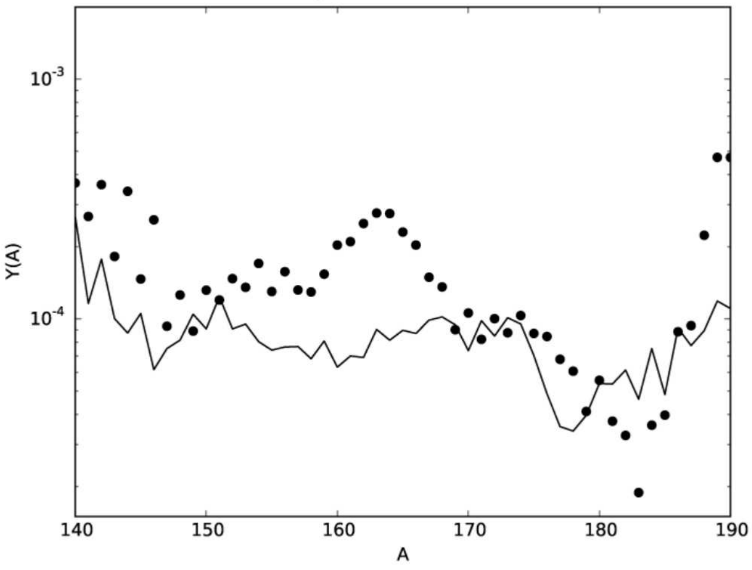
Mumpower *et al.* PRC 92 035807 (2015)

# RESULTS OF REVERSE ENGINEERING

# FIRST ATTEMPT

## Hot wind r-process with default DZ parameters


1 neutron separation energy contours for even-N nuclei


Predicted *r*-process abundances

Success?! ... We found a peak!But there's a problem!

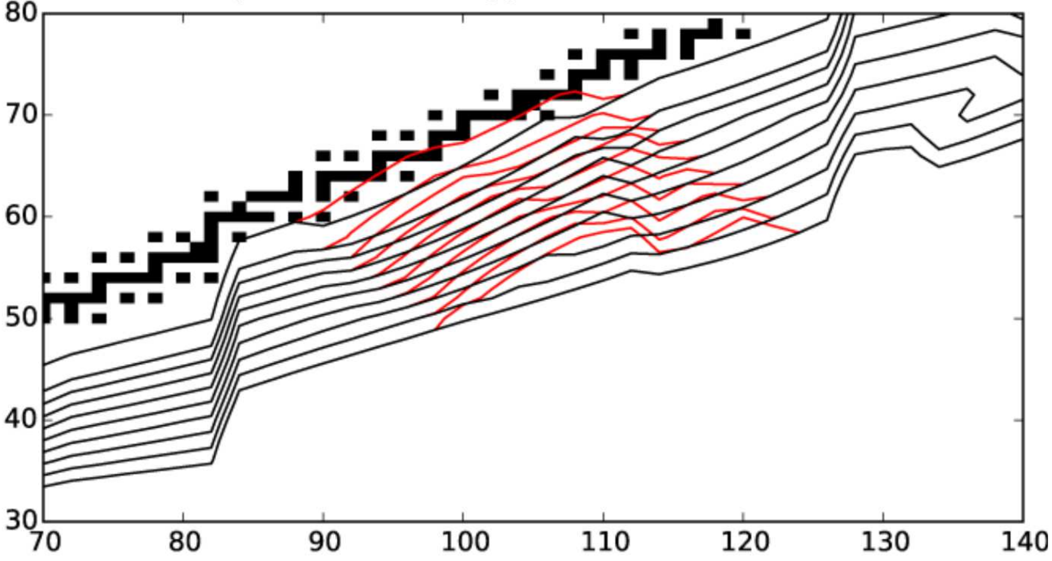
L ~ match red abundances

**Mumpower** *et al.* J. Phys. G 44 3 034003 (2017)

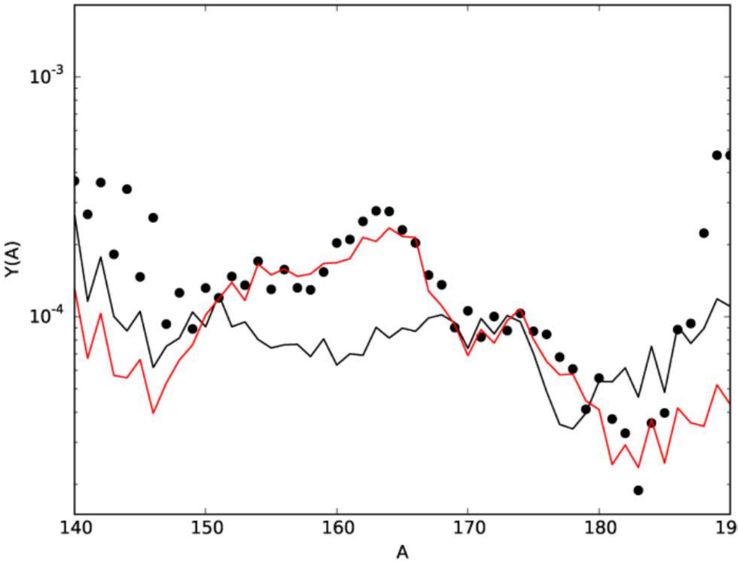
# FIRST ATTEMPT

## Hot wind r-process with new DZ parameters

1 neutron separation energy contours for even-N nuclei



Predicted *r*-process abundances



Success?! ... We found a peak! But there's a problem!

L ~ match red abundances

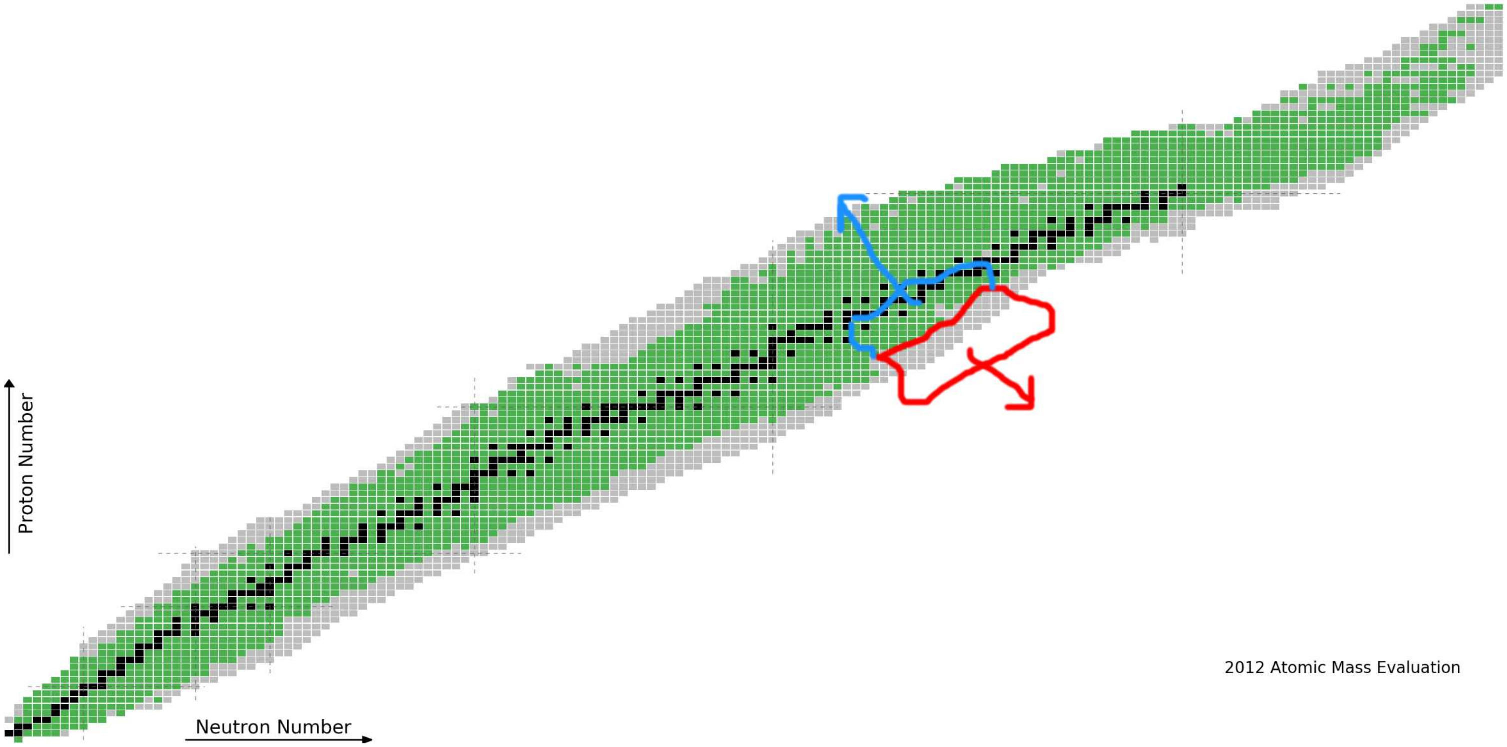
**Mumpower** *et al.* J. Phys. G 44 3 034003 (2017)

# DIDN'T MATCH KNOWN MASSES

We need to tell the Metropolis algorithm to match both

Update Likelihood function:

L ~ match abundances + match known masses



**Mumpower** *et al.* J. Phys. G 44 3 034003 (2017)

# RESULTS WITH DZ ALONE

No combination of DZ parameters can **simultaneously** reproduce the rare earth peak and match the known masses at the same time

The nuclear structure information responsible for the rare earth peak is *missing from the model*

We could move to a nuclear model, but these are more complicated to analyze, with many coupled parameters.

The benefit to DZ is that the abundances are flat to start with.

Let's try to add the missing physics!

**Mumpower** *et al.* J. Phys. G 44 3 034003 (2017)

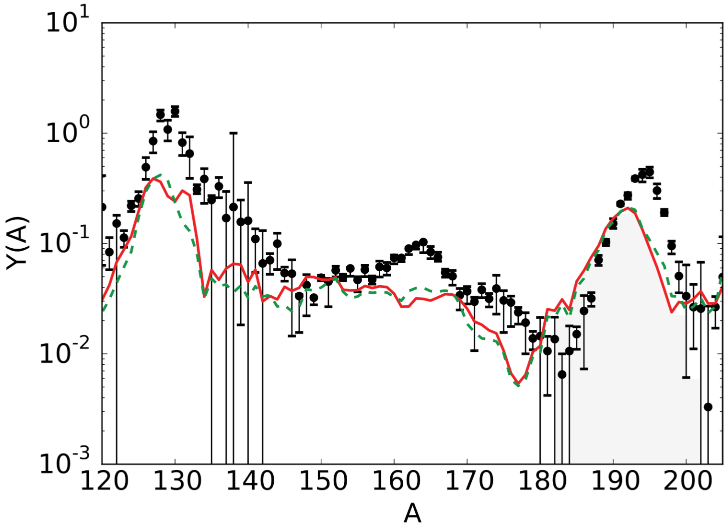
# PARAMETERIZE MISSING PHYSICS

$$M(Z, N) = M_{DZ}(Z, N) + a_N \exp[-(Z-C)^2/2f]$$

$a_N$ - Strength of change for given neutron number in MeV

$C$ - Center of the distribution in proton number

$f$ - Rate of fall off back to stability

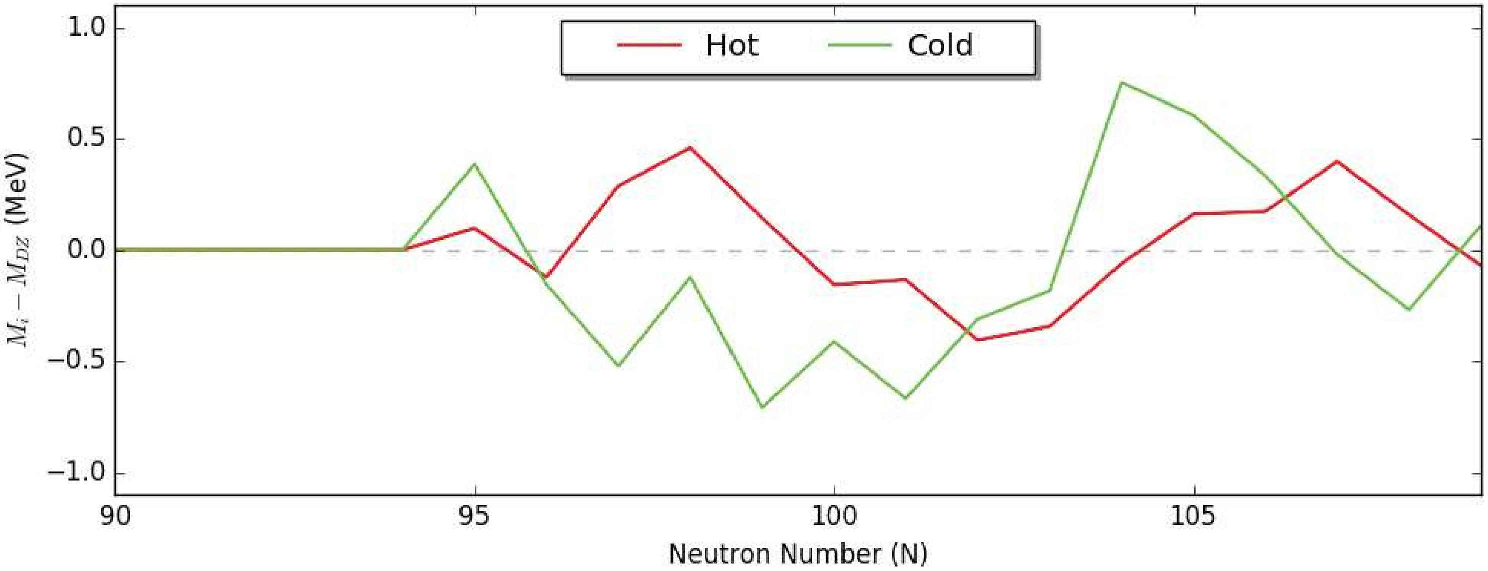


**Mumpower** *et al.* ApJ 833, 282 (2016)

Now we repeat the Monte Carlo calculations, letting these parameters vary

# RESULTS WITH NEW PARAMETERS

The predicted masses for Z = 60 (Nd)



Distinguishable predictions given different astrophysical conditions

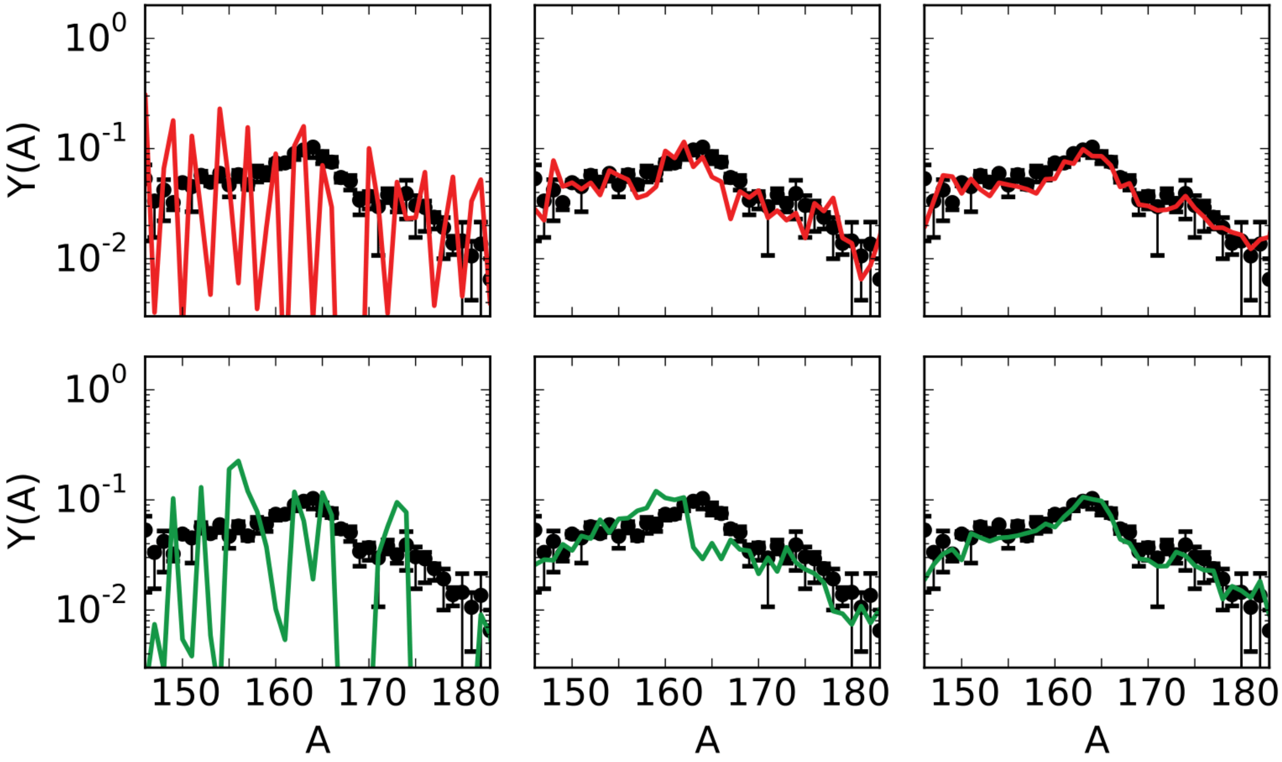
Hot: local min even-N • wider in N • smaller change to masses

Cold: local min odd-N • tighter in N • larger change to masses

Mumpower *et al.* ApJ 833, 282 (2016)

# EVOLUTION OF ABUNDANCES

Before • During • After peak formation



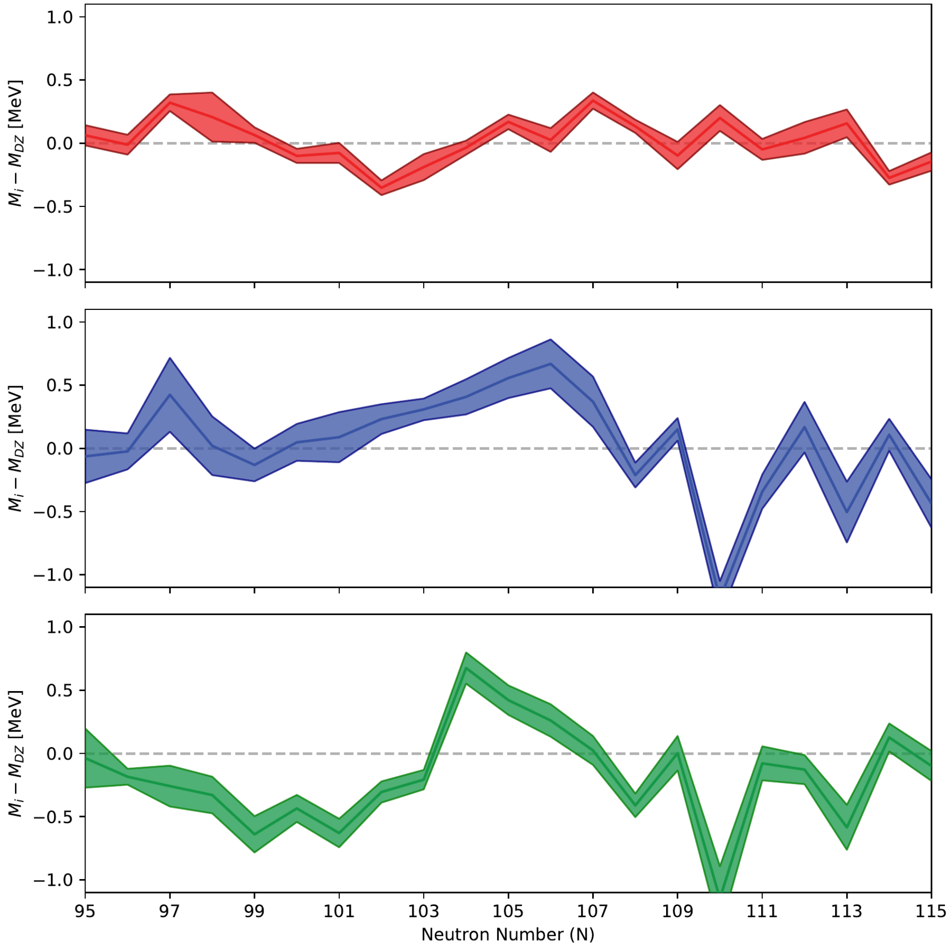
Great success!

Difference is encoded in the astrophysical conditions

Mumpower *et al.* ApJ 833, 282 (2016)

# PREDICTED MASSES

For three astrophysical evolutions: hot, cold or merger

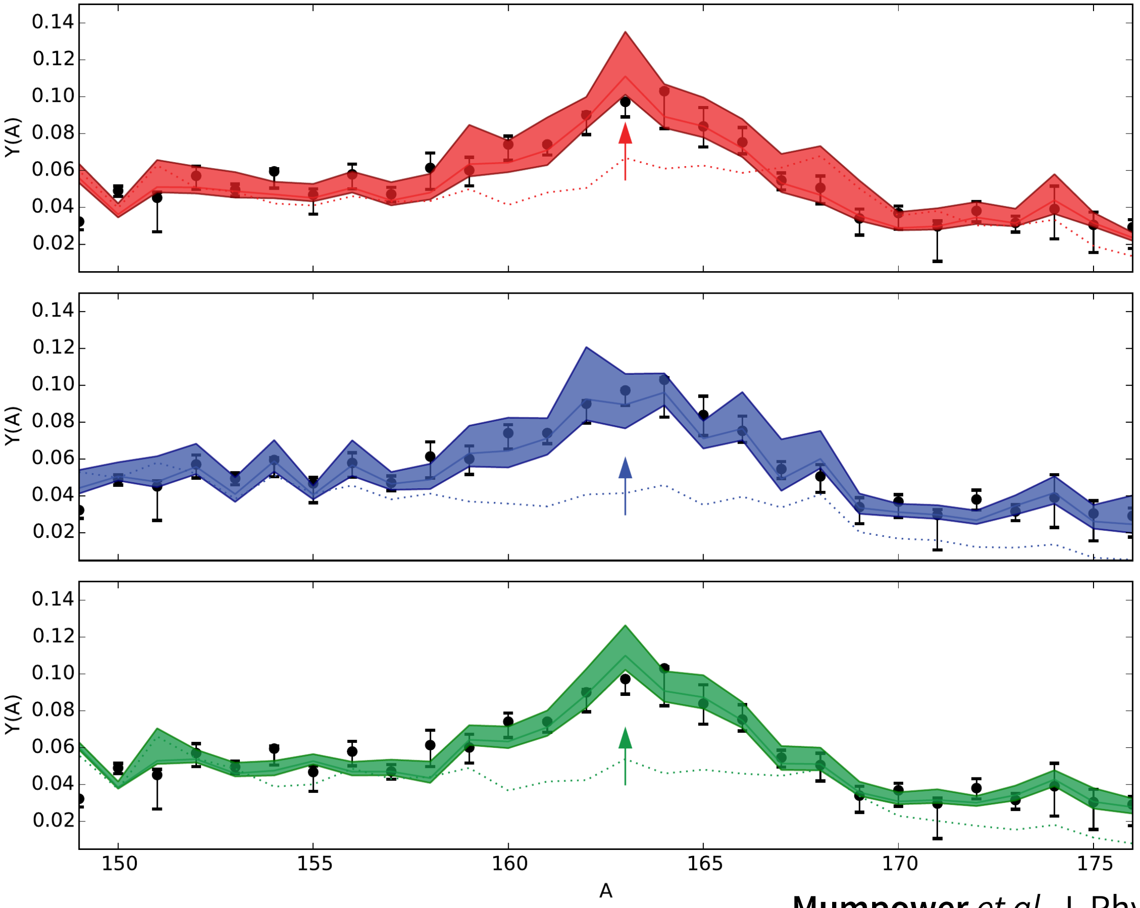


**Mumpower** *et al.* J. Phys. G 44 3 034003 (2017)

The trend in the masses is important for forming the REP

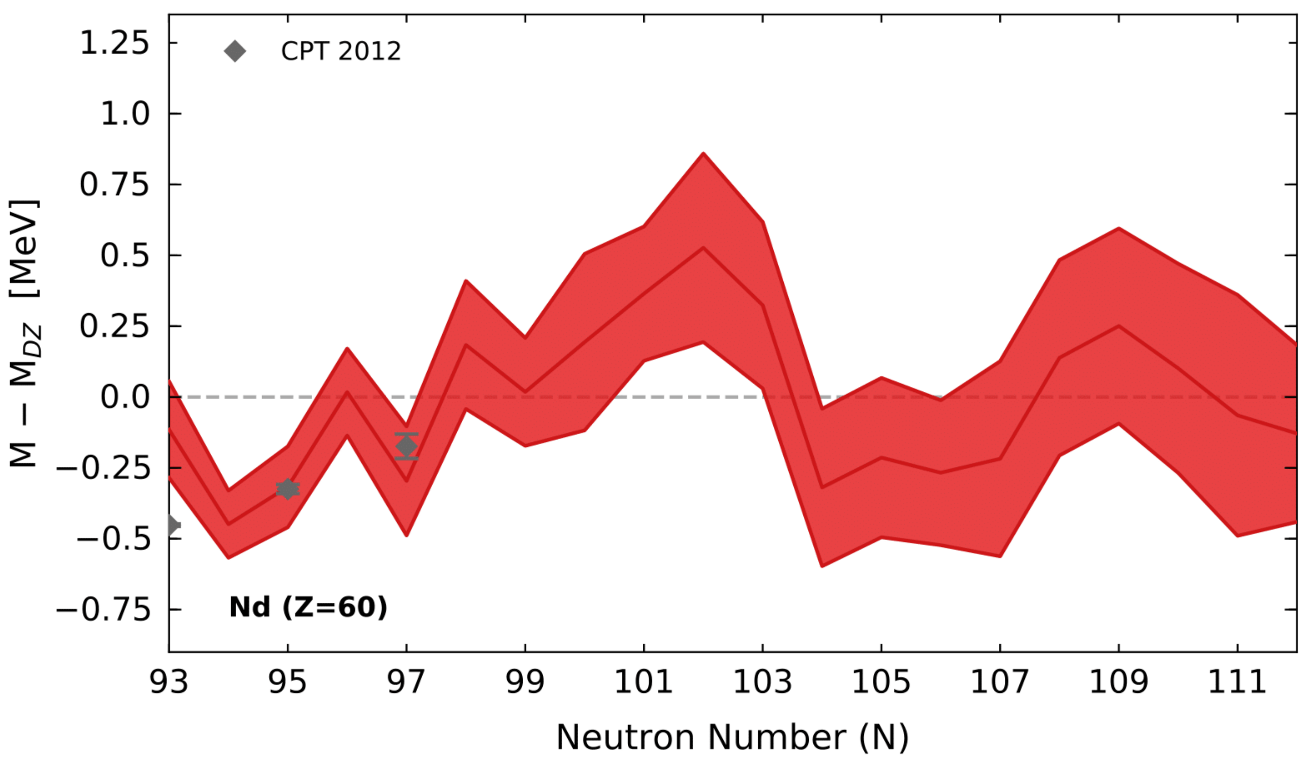
# FIT TO ABUNDANCES

For three astrophysical evolutions: hot, cold or merger



**Mumpower** *et al.* J. Phys. G 44 3 034003 (2017)

# LATEST RESULTS

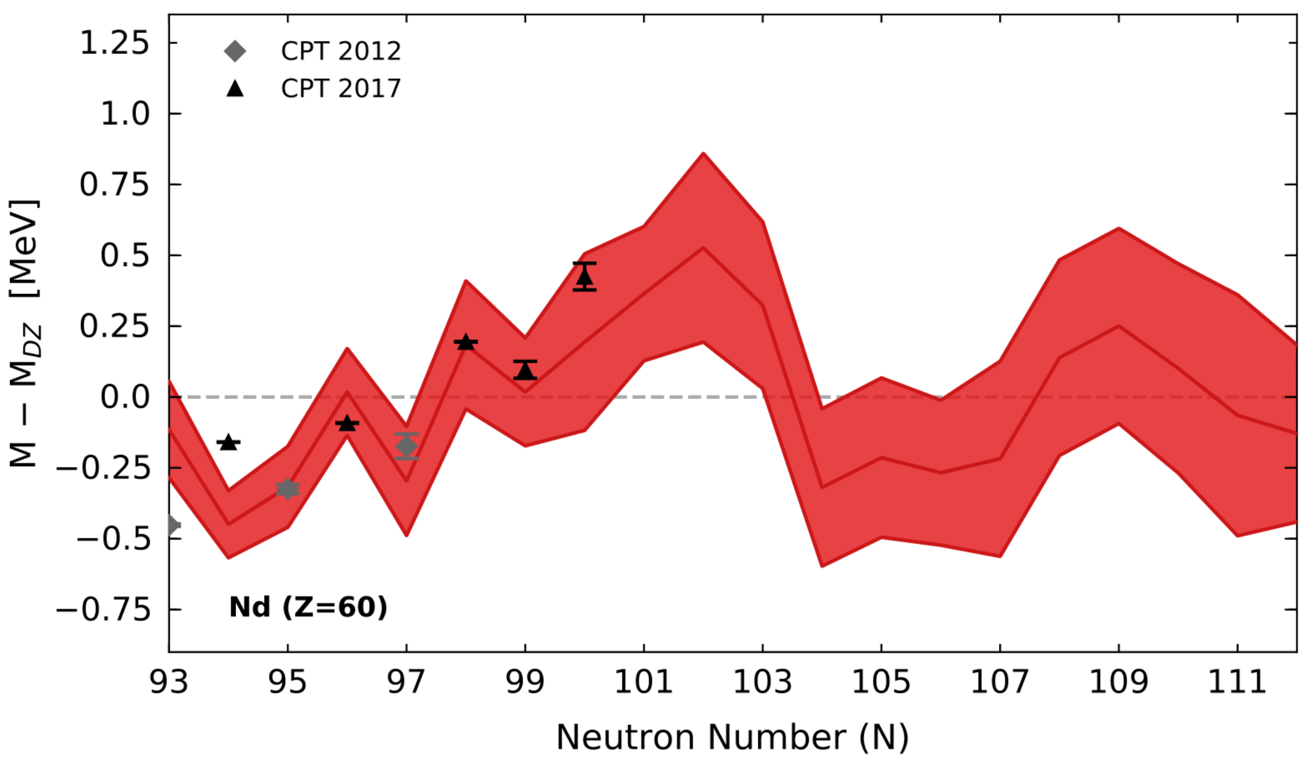


Nicole Vassh has made major upgrades to the algorithm

We now use solar data & uncertainties and also parallel chains Monte Carlo

Vassh *et al.* in prep (2018) ; Orford *et al.* PRL 120 262702 (2018)

# LATEST RESULTS

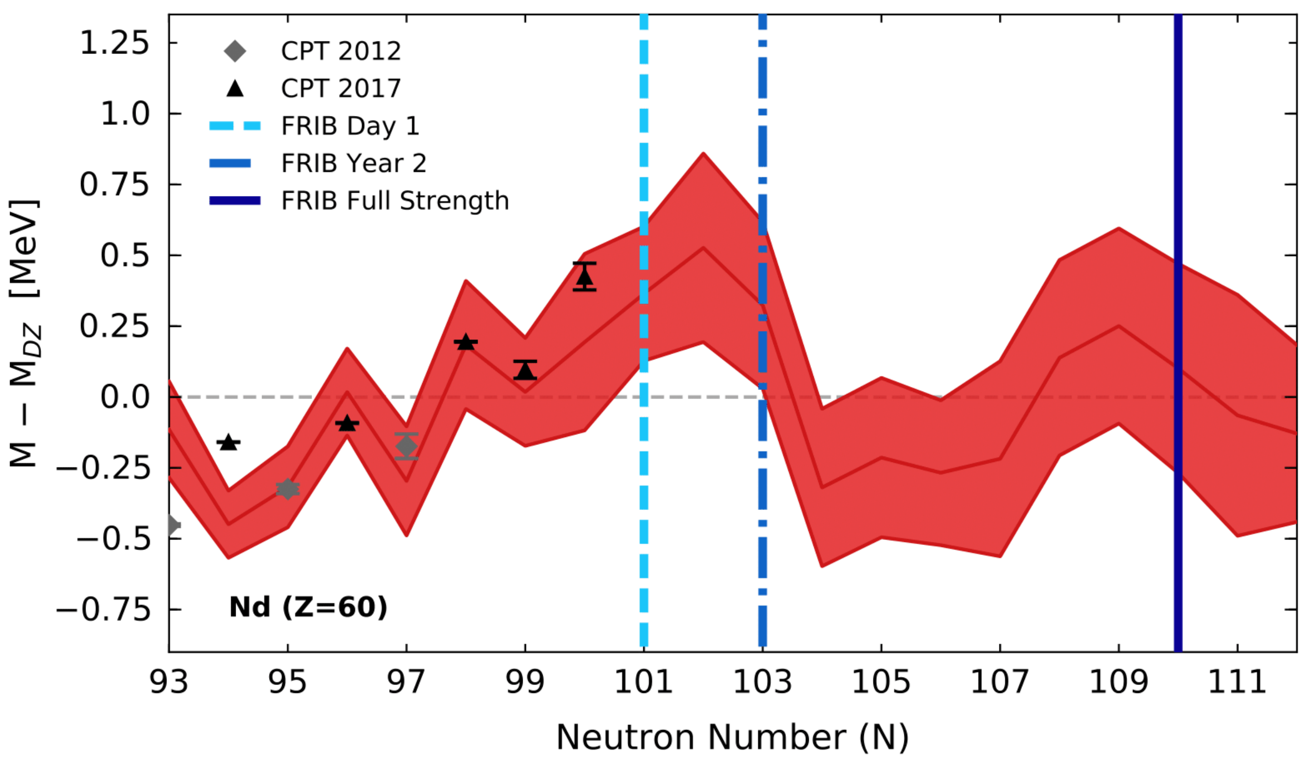


The aglorithm is now ready to be used in matching data

We compared to CARIBU results & independently match this new data

Vassh *et al.* in prep (2018) • Orford *et al.* PRL 120 262702 (2018)

# LATEST RESULTS



FRIB will be able to probe most of relevant regions for REP formation

Only the upgrade will allow the reach out to the potential N = 110 structure

Vassh *et al.* in prep (2018) • Orford *et al.* PRL 120 262702 (2018)

# REVERSE ENGINEERING MASSES

What are the consequences of the future measurements?

Either we find the structure... or we don't

If we do: we favor precise conditions for the main r-process

If we don't: we favor extreme conditions that *REQUIRE* fission recycling... only option is the tidal tails of mergers

Perhaps nature is more complicated than we think... and we learn something even more profound

*Make the measurements to find out!*

Mumpower *et al.* J. Phys. G 44 3 034003 (2017)

# SUMMARY

Theoretical calculations for the r-process are currently data starved

Current models result in orders of magnitude uncertainty in calculated abundances

FRIB will provide a plethora of new nuclear data

This will be invaluable in bechmarking theoretical models

(in particular, for nuclear masses)

As well as constraining the astrophysical conditions of the r-process

Results at MatthewMumpower.com