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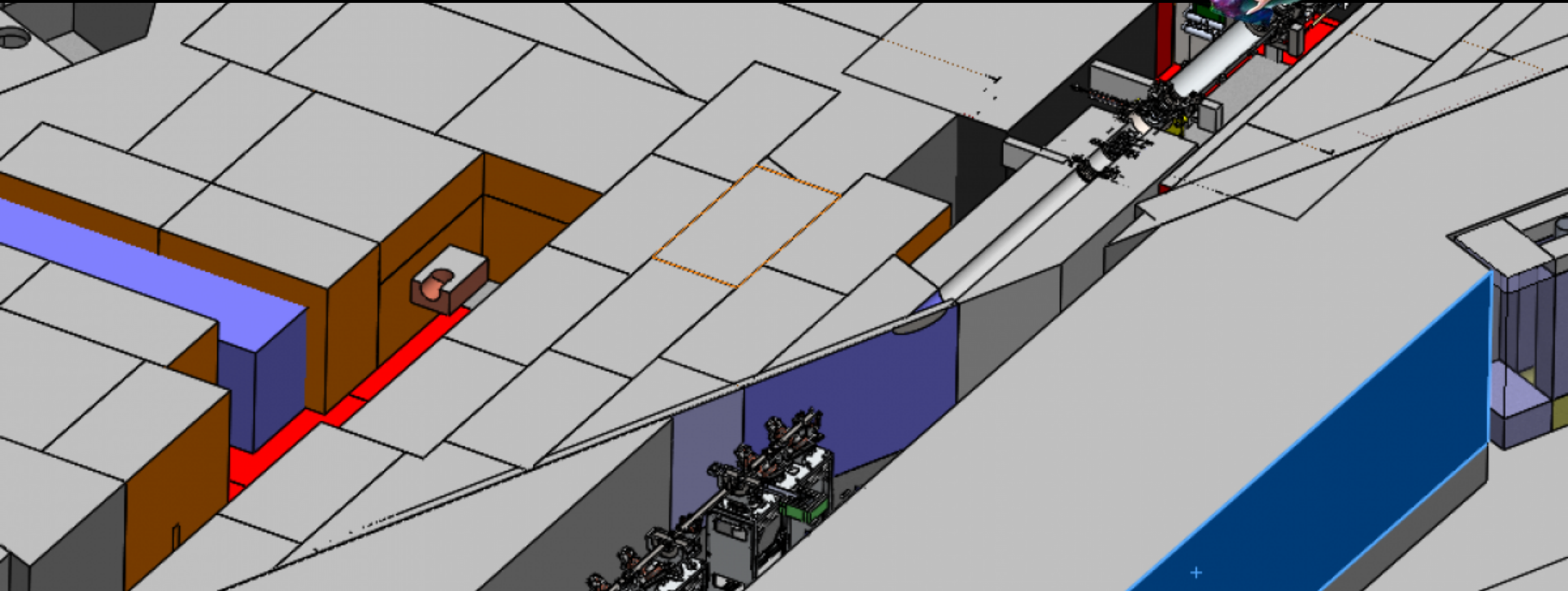
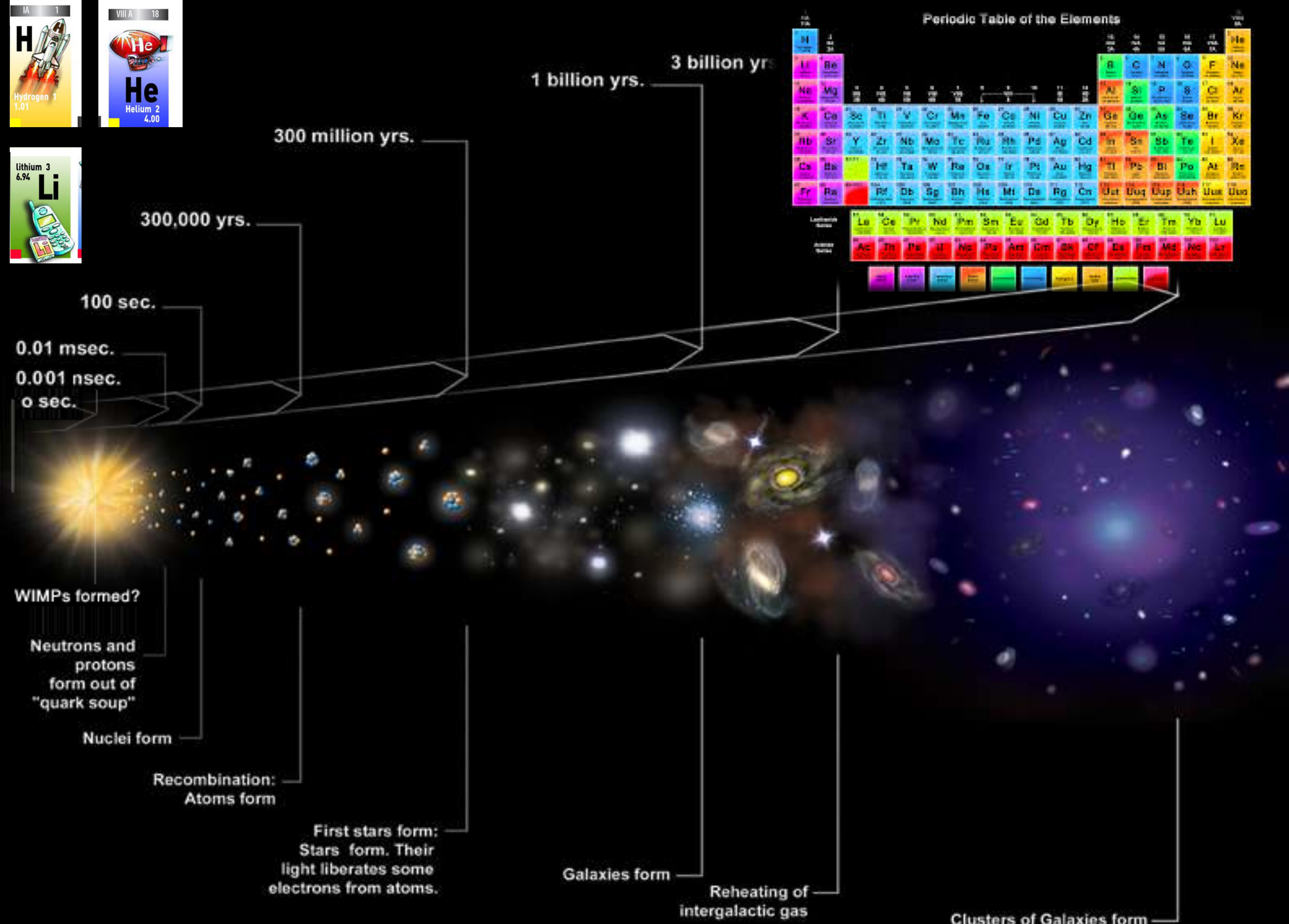
Ani Aprahamian
University of Notre Dame

From ARIEL to the Universe

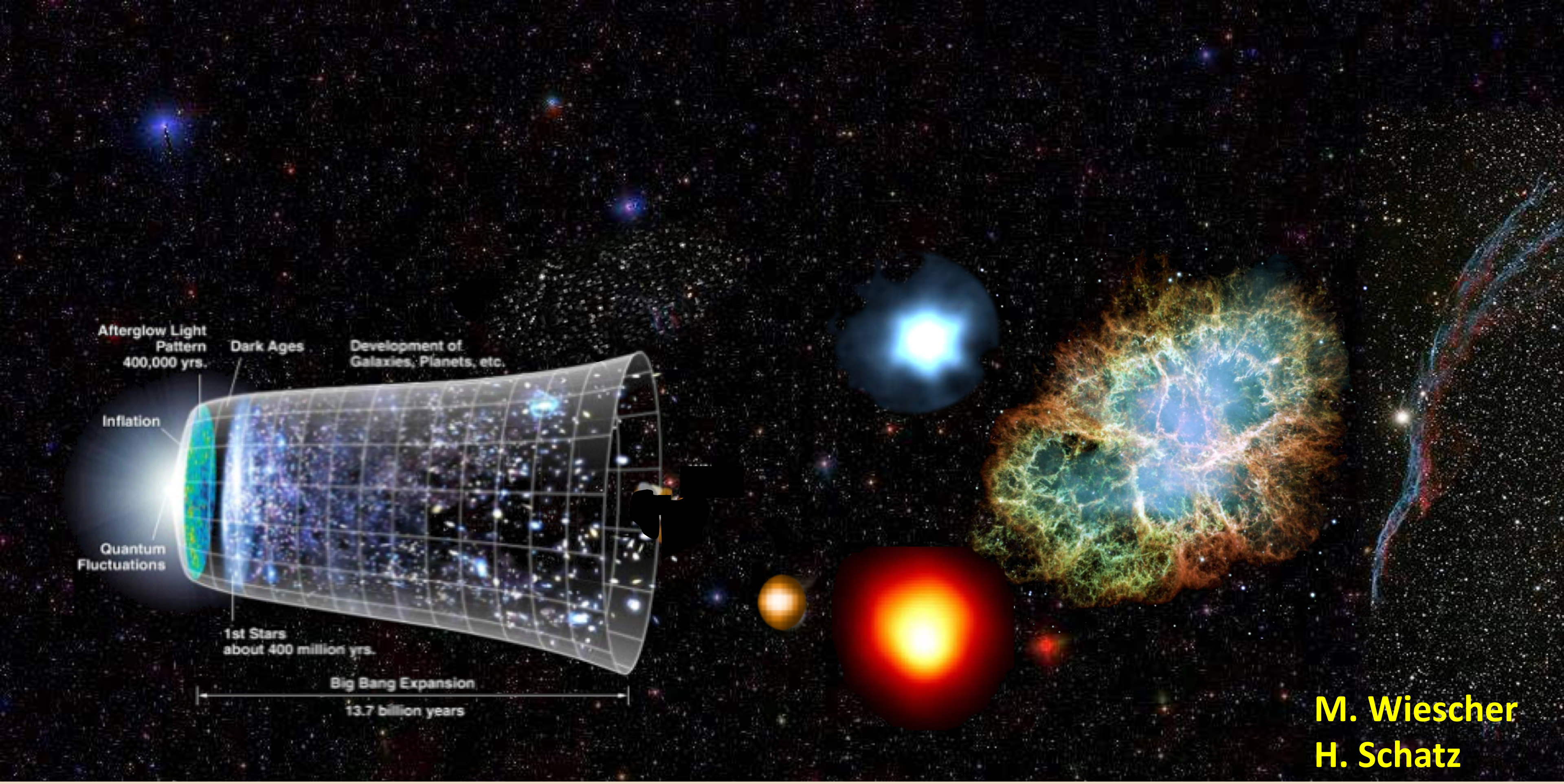


R-process Sensitivities and Measurements

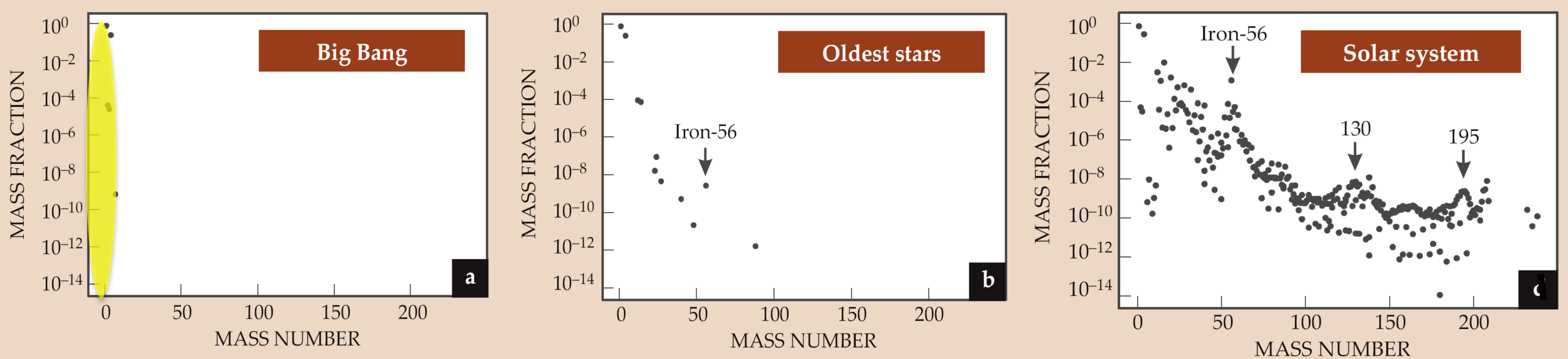
TRIUMF Science Week
July 16-19,2018



Courtesy of H. Schatz



M. Wiescher
H. Schatz



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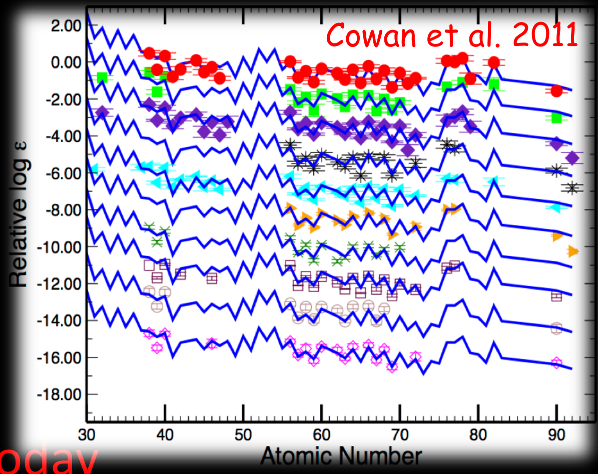
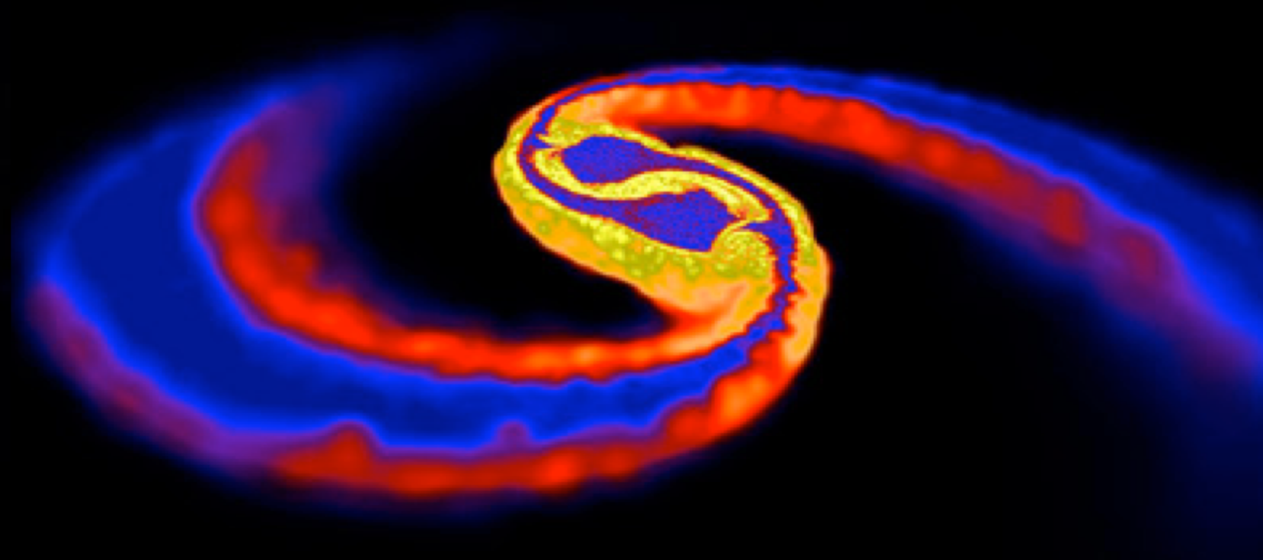
Explosive r-process



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

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



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

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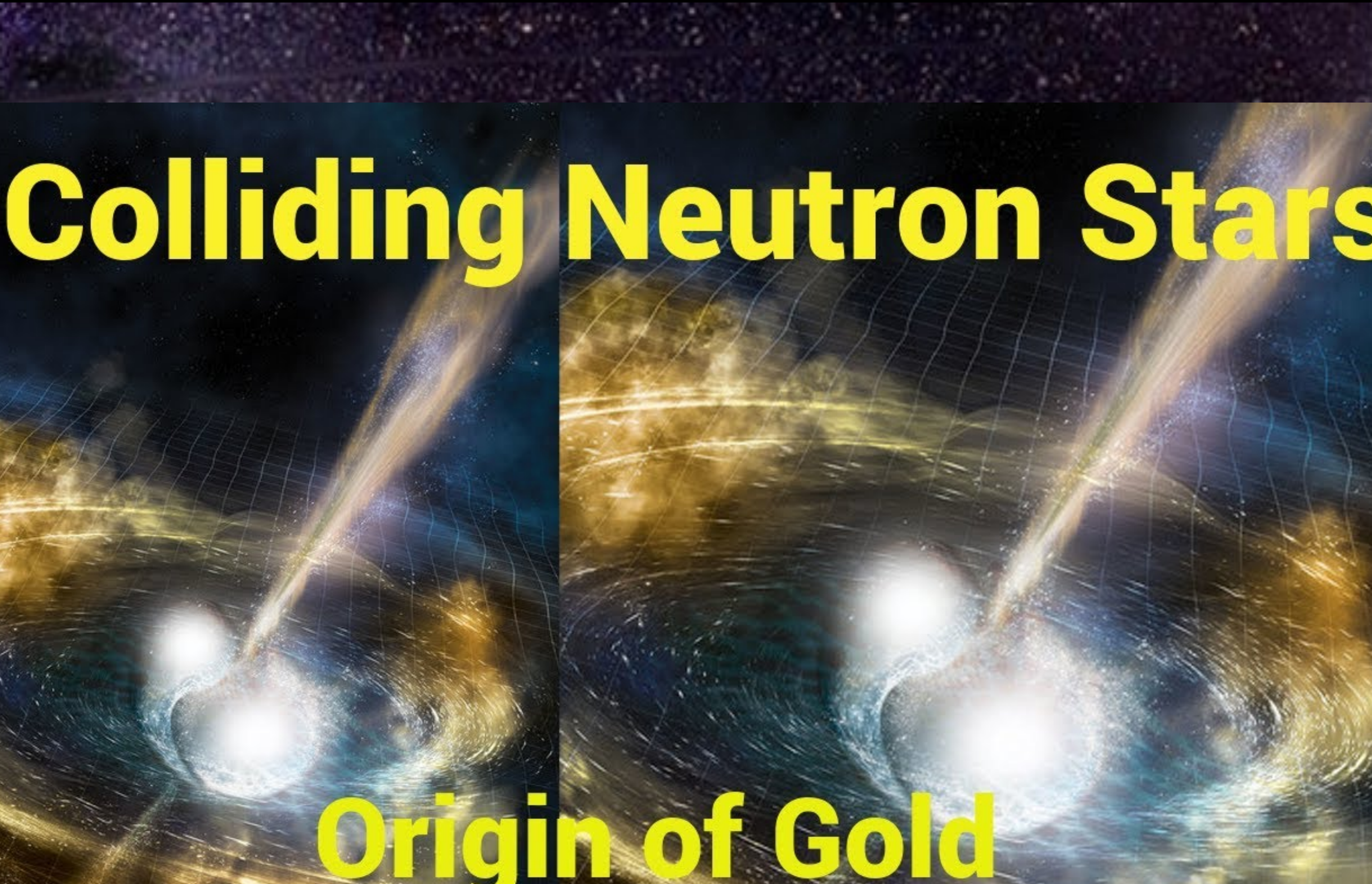
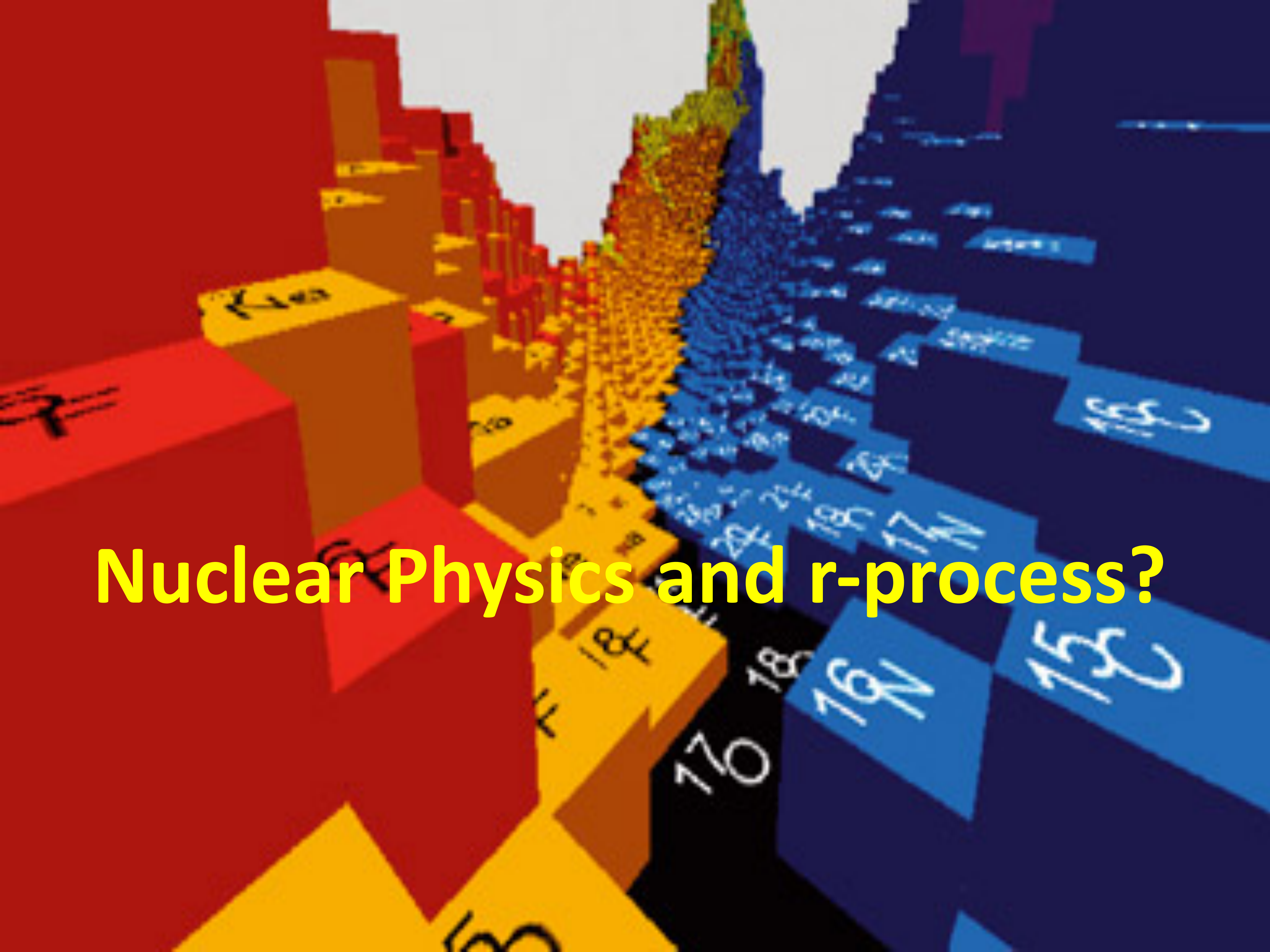
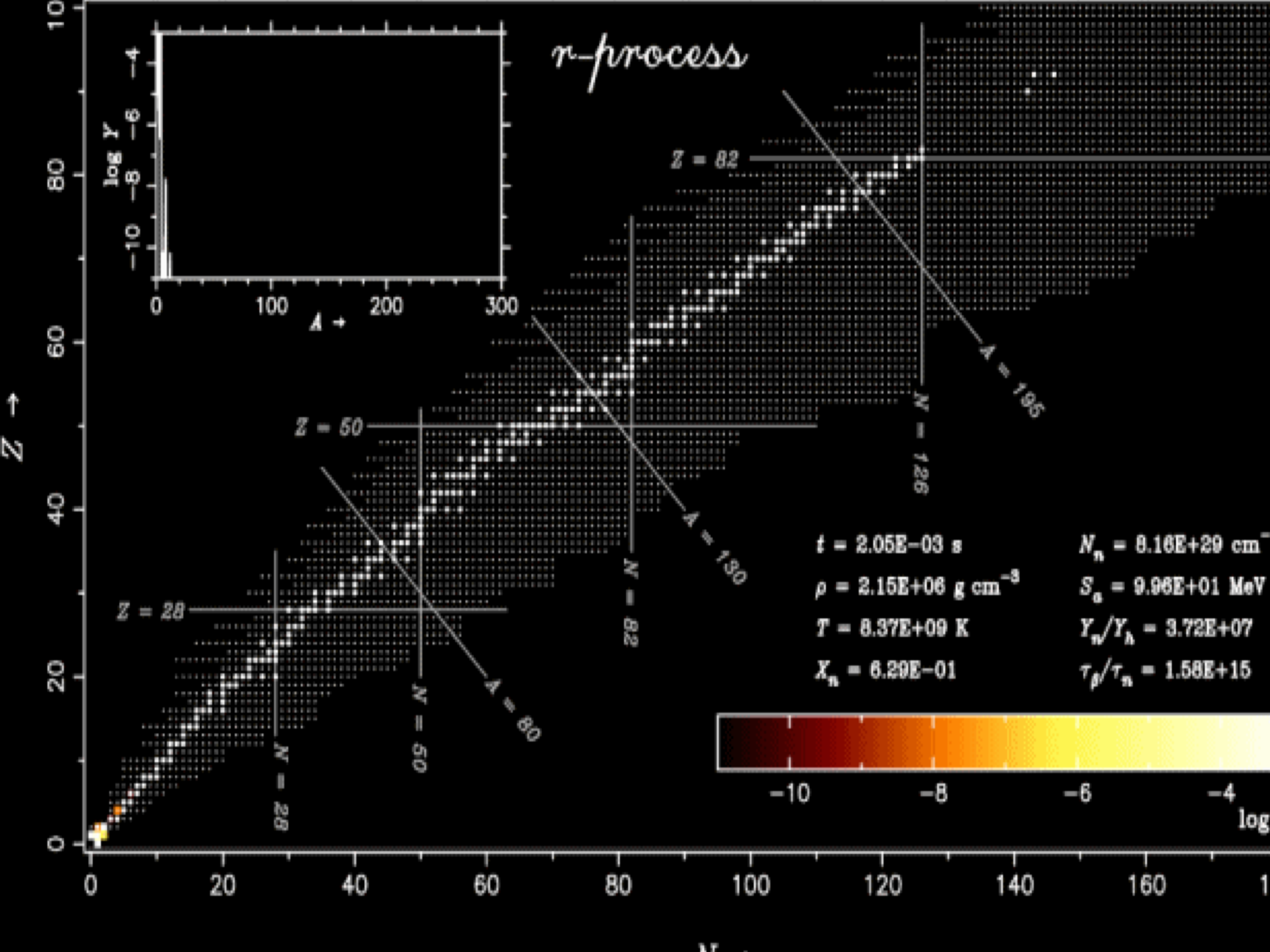
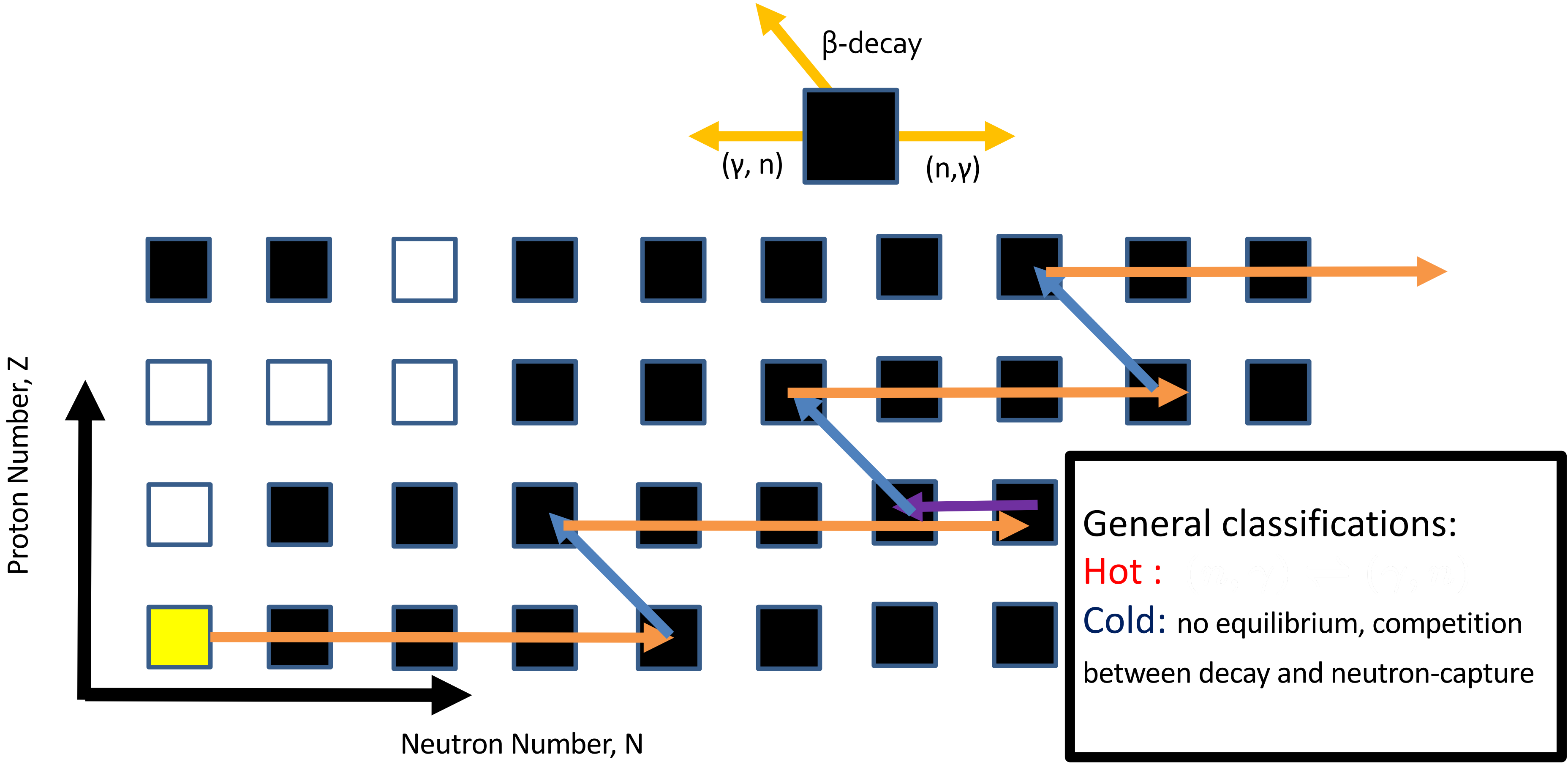


Nuclear Physics and r-process?





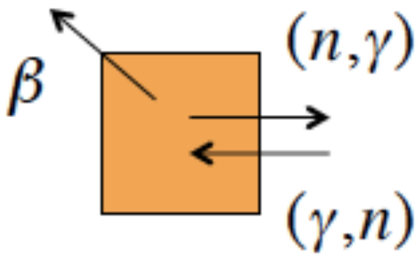
r-process
Z = 82
Z = 50
Z = 28
N = 28
N = 50
N = 82
N = 126
A = 80
A = 130
A = 195
t = 2.05E-03 s
ρ = 2.15E+06 g cm^-3
T = 8.37E+09 K
X_n = 6.29E-01
N_n = 8.16E+29 cm
S_a = 9.96E+01 MeV
Y_n/Y_h = 3.72E+07
τ_β/τ_n = 1.58E+15
log Y
A →
Z →
log


β-decay
(γ, n)
(n,γ)
Proton Number, Z
Neutron Number, N
General classifications:
Hot :
Cold: no equilibrium, competition
between decay and neutron-capture

What are the Nuclear Physics Challenges?

Nuclear Structure

Major Shells and evolution of shells…



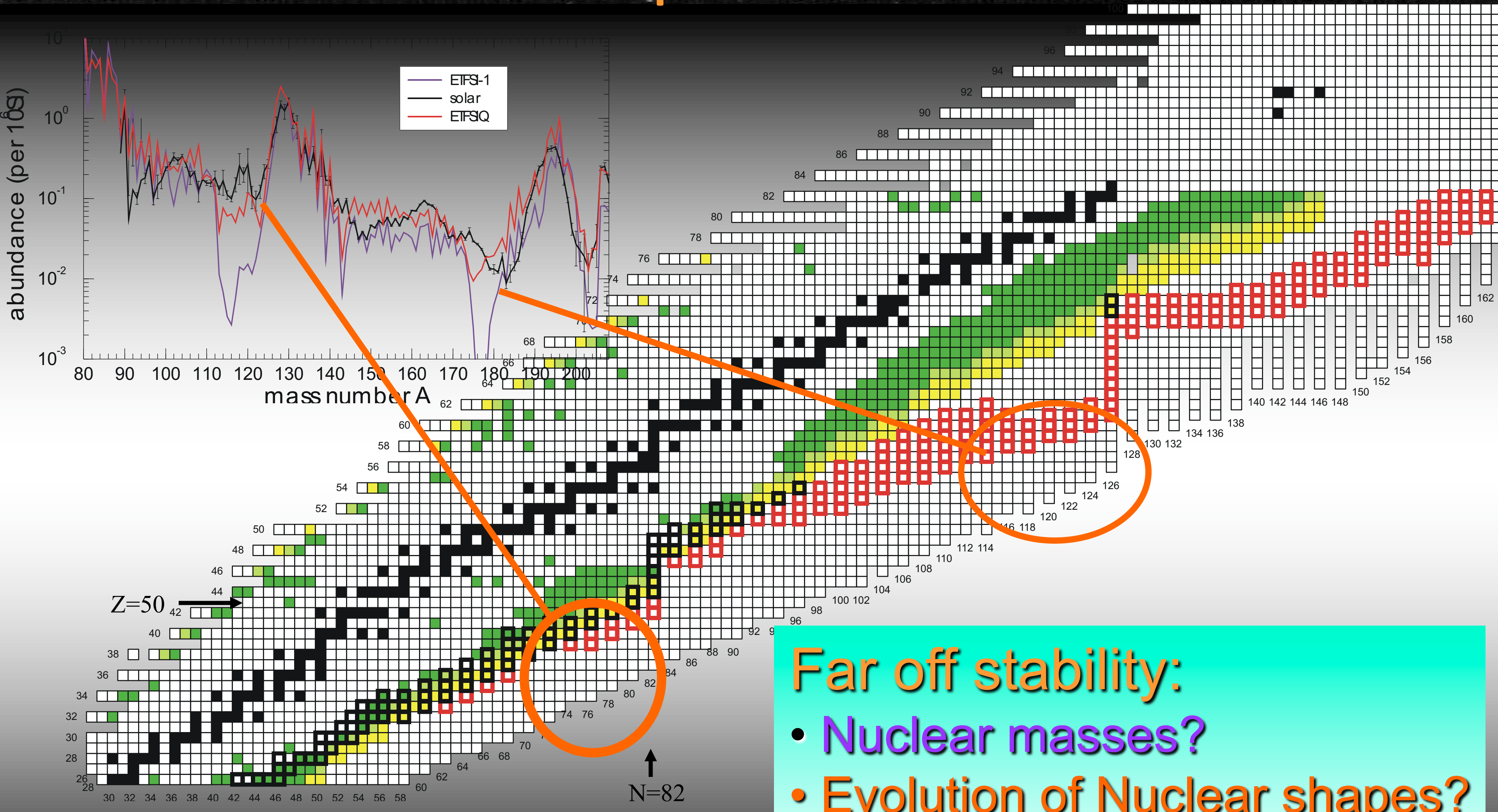
R-process Sensitivity Studies

Mumpower, Surman, McLaughlin, Aprahamian, et al.

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

Onset of deformation

r-process



Far off stability:

- Nuclear masses?
- Evolution of Nuclear shapes?

Onset of deformation

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R-process Sensitivities and Measurements

- How do you decide which nuclei to measure
- What is the required precision?

Courtesy of N. Vassh

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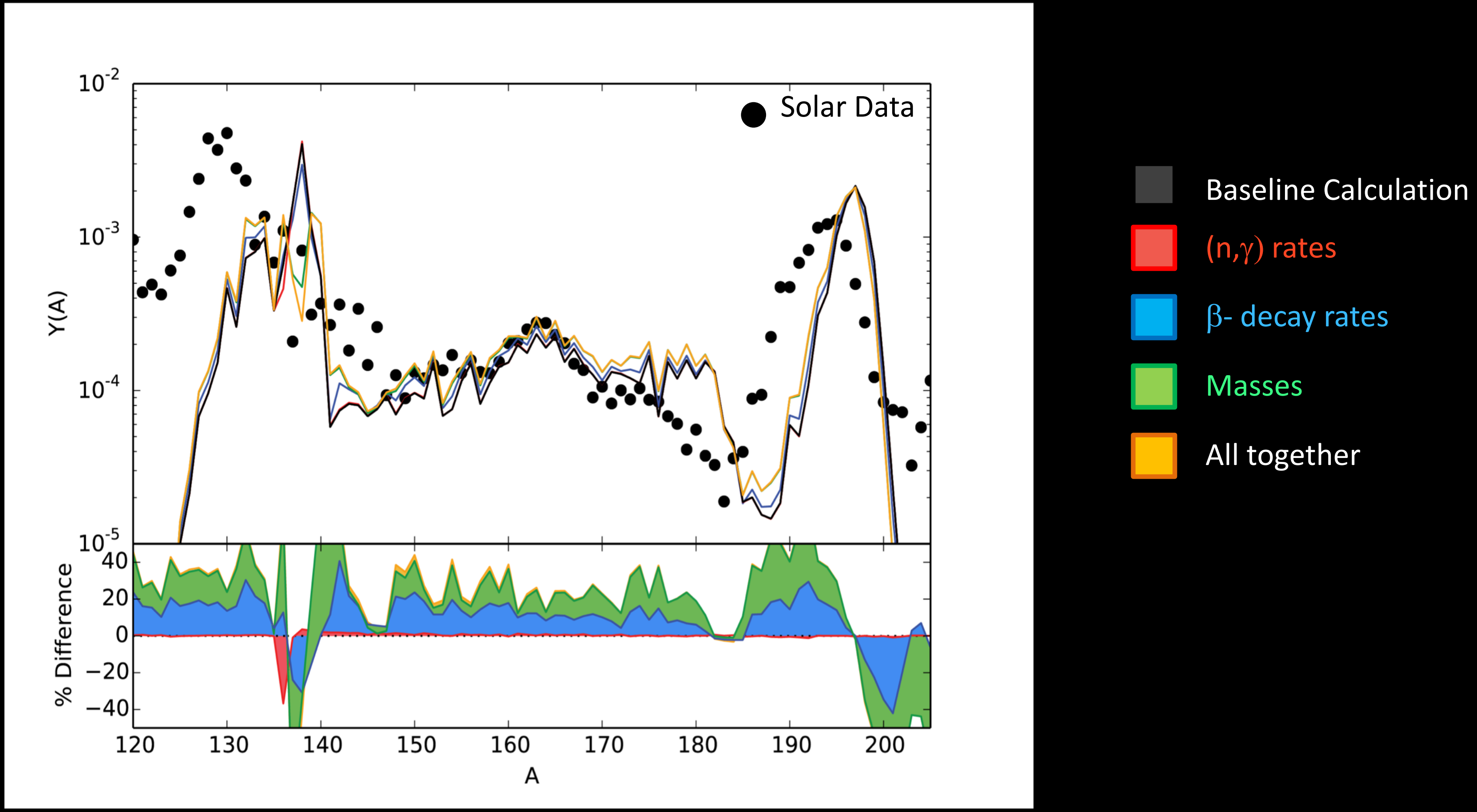

Over an *order of magnitude* difference in the Y(A) for **0.5MeV** addition in mass of 140-Sn!

Mumpower, Surman, Fang, Beard, Moller, Kawano, Aprahamian, Phys. Rev. C 92, 035807, 2015

Mumpower, Surman, McLaughlin, Aprahamian

Progress in Particle and Nuclear Physics 86, 2016

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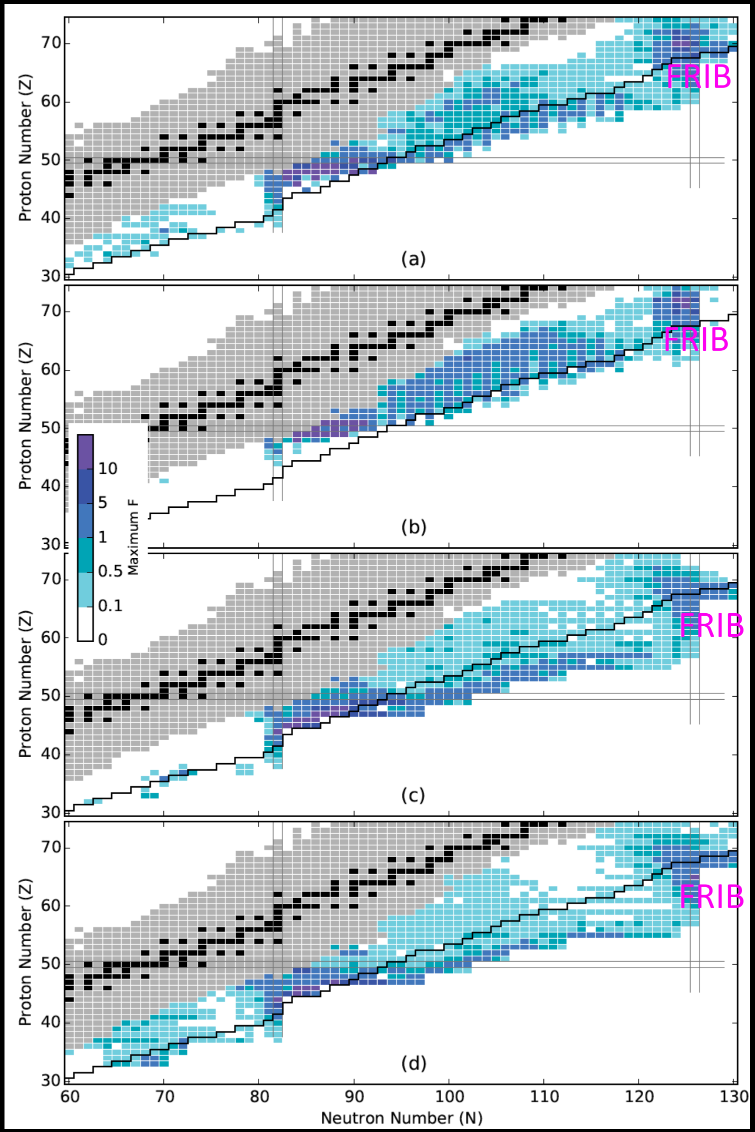

Low entropy hot wind

High entropy hot wind

Cold wind

Neutron Star Merger

F- values available and provide motivations to rib facilities worldwide

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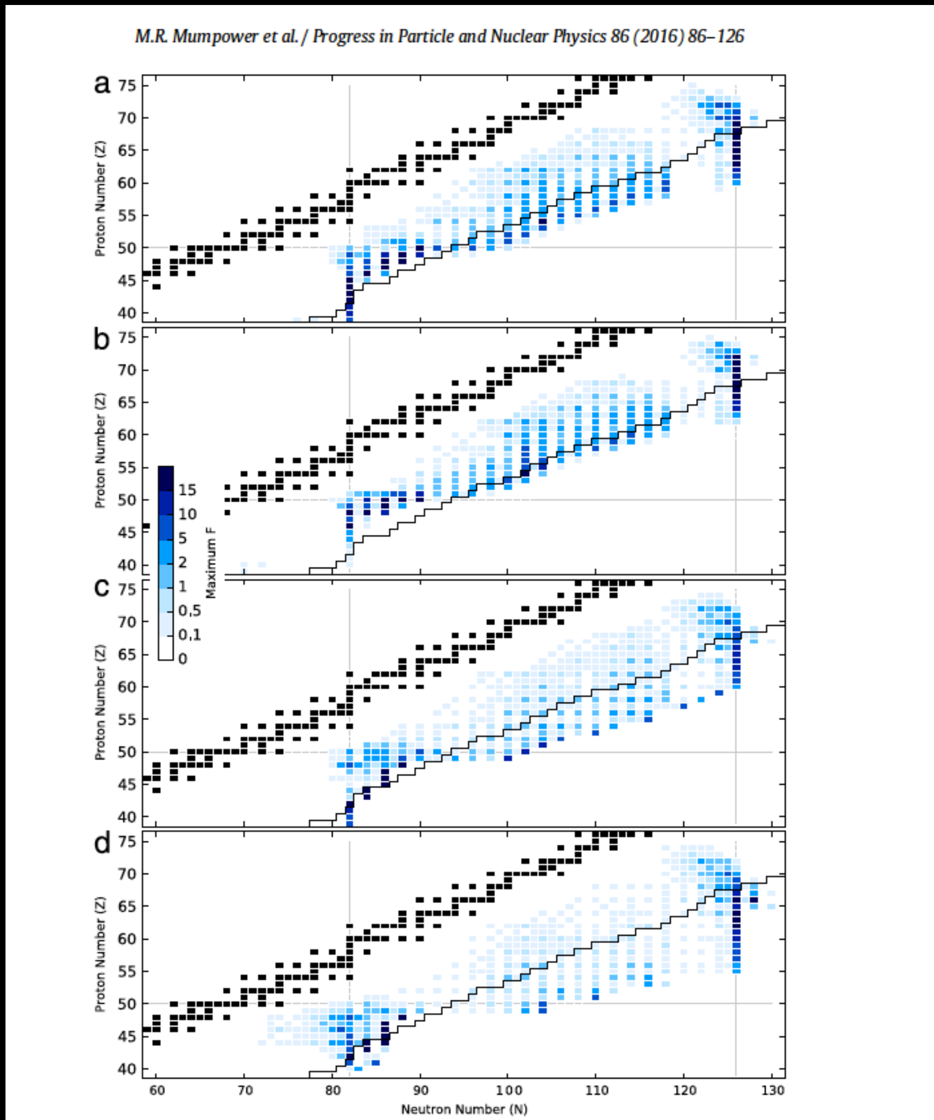
Each sensitivity study has prompted JINA-CEE collaborations

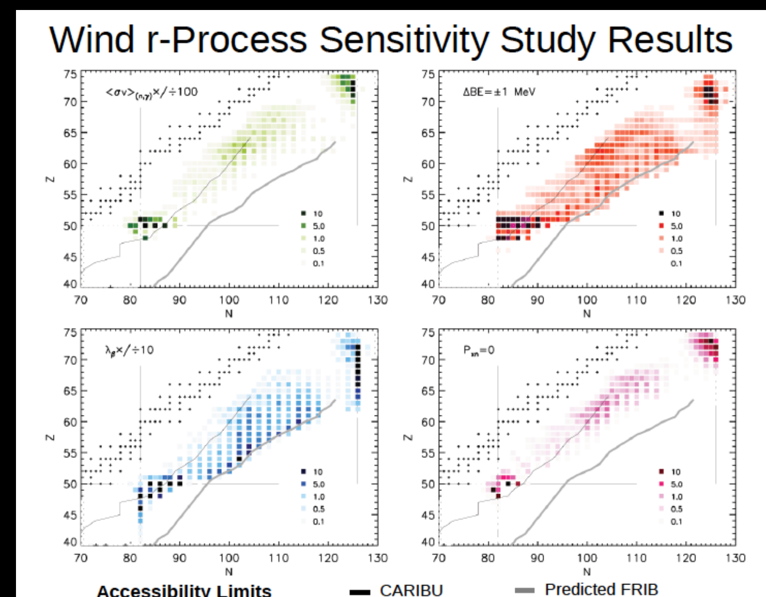


Ani Aprahamian - CPT

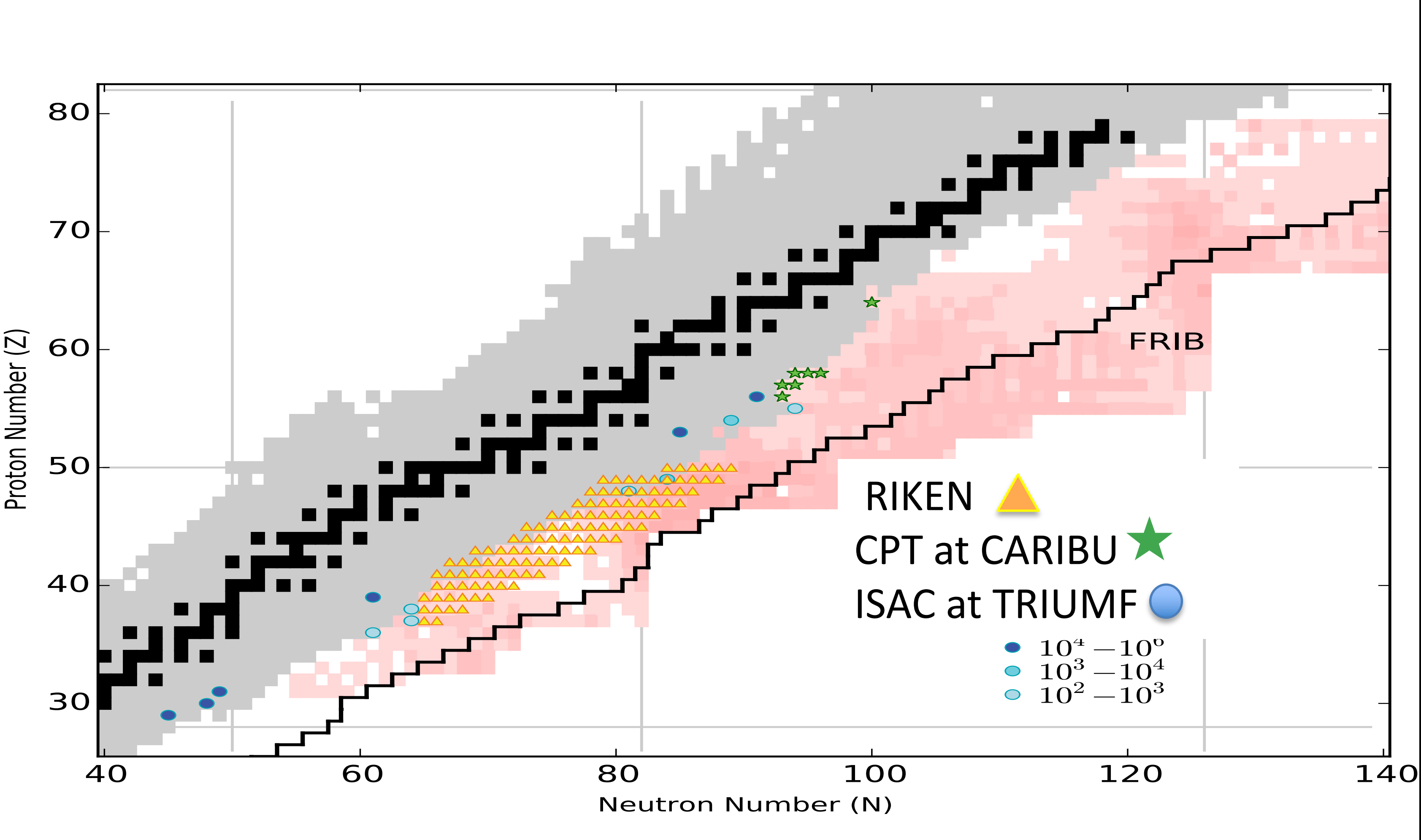
Fernando Montes - RIKEN

Iris Dillmann - BRIKEN

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



Mumpower, Surman, McLaughlin, Aprahamian
Progress in Particle and Nuclear Physics 86, 2016



Experimental reach for the present and future…

Improvements that can be realized with new experiments …

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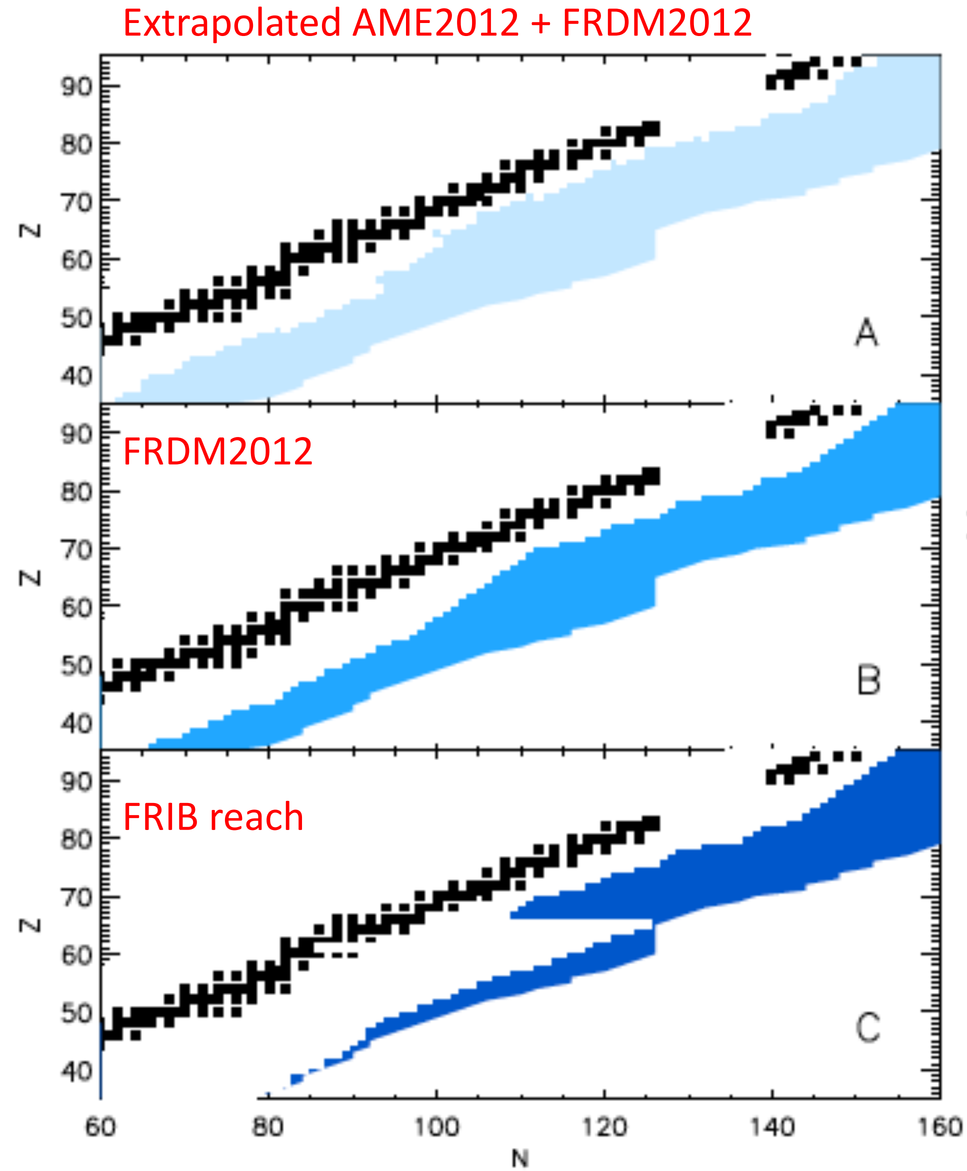
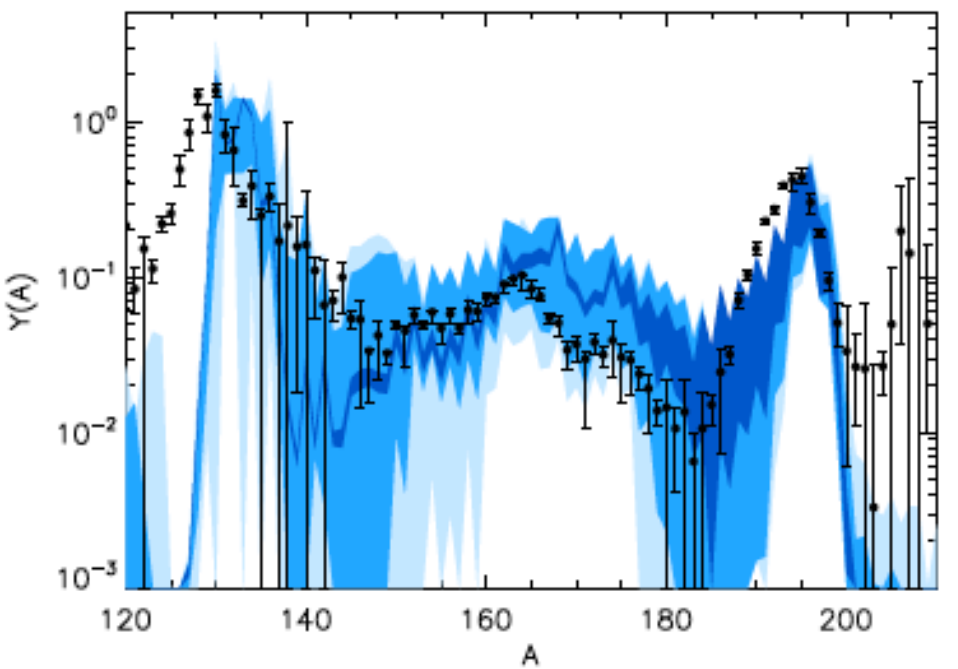


Surman, Mumpower, Aprahamian, Mazurian Lakes, 2015



What is the required precision?

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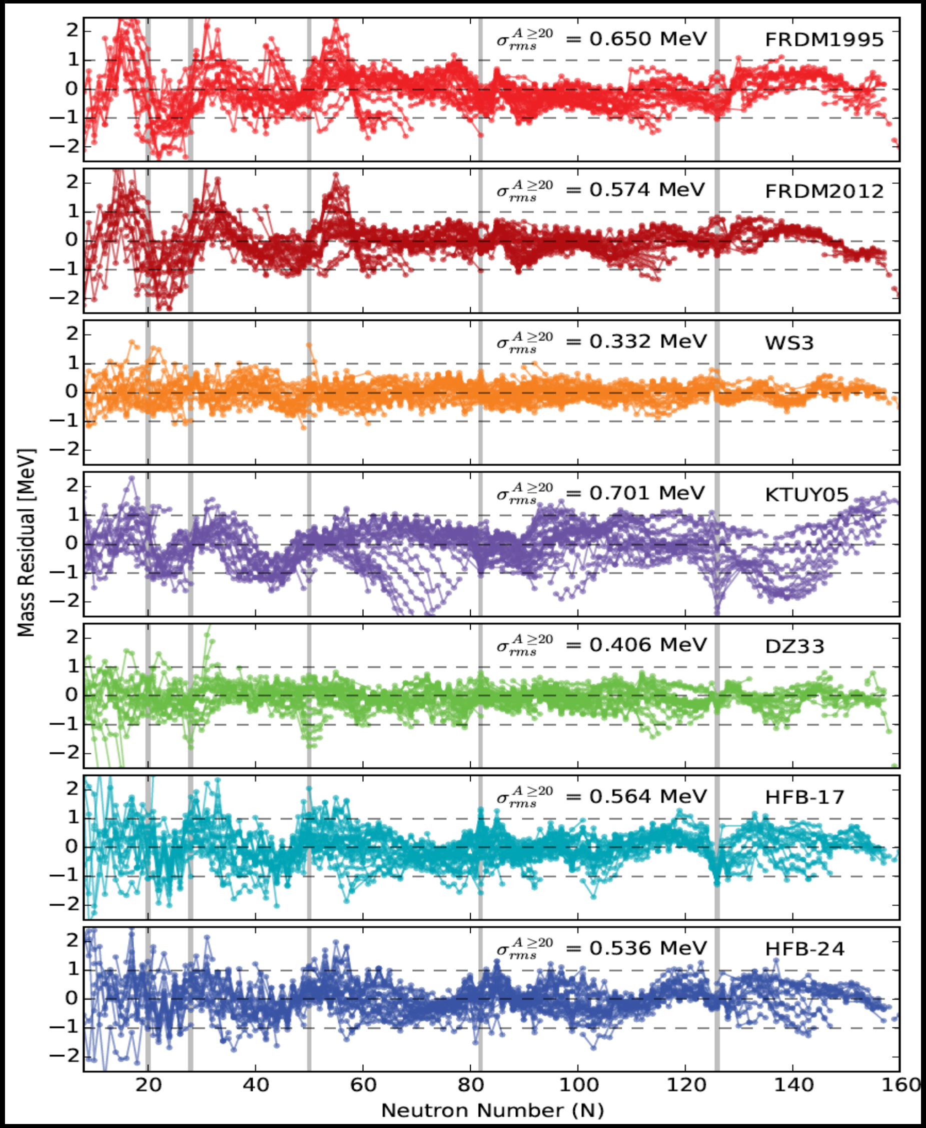
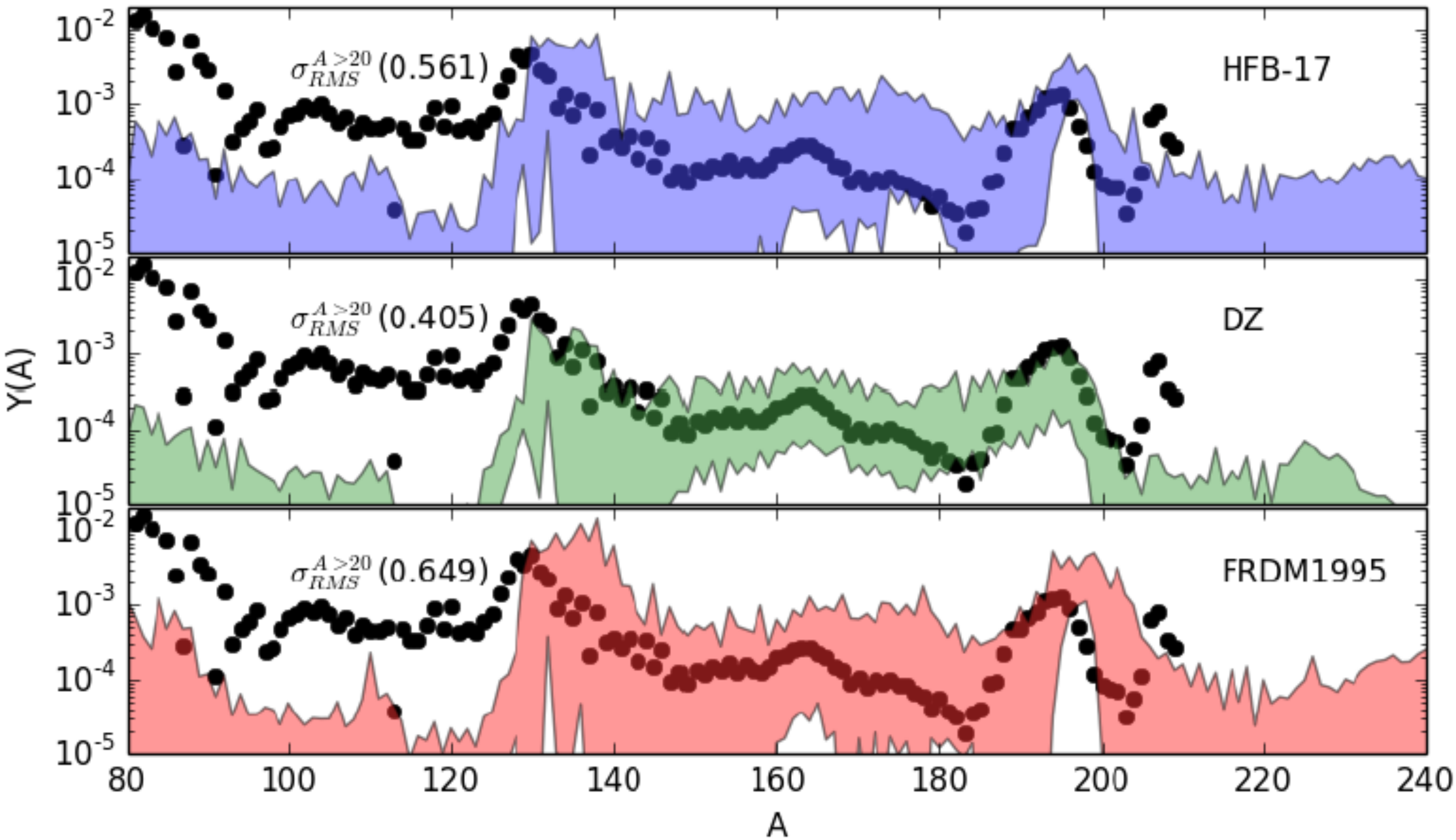


ΔBE=+/- 0.5 MeV

Mumpower, Surman, McLaughlin, Aprahamian, Progress in Particle and Nuclear Physics 86, 2016

Global Uncorrelated Mass Model Uncertainties



Hot r-process trajectory
rms error reduced to 100 keV

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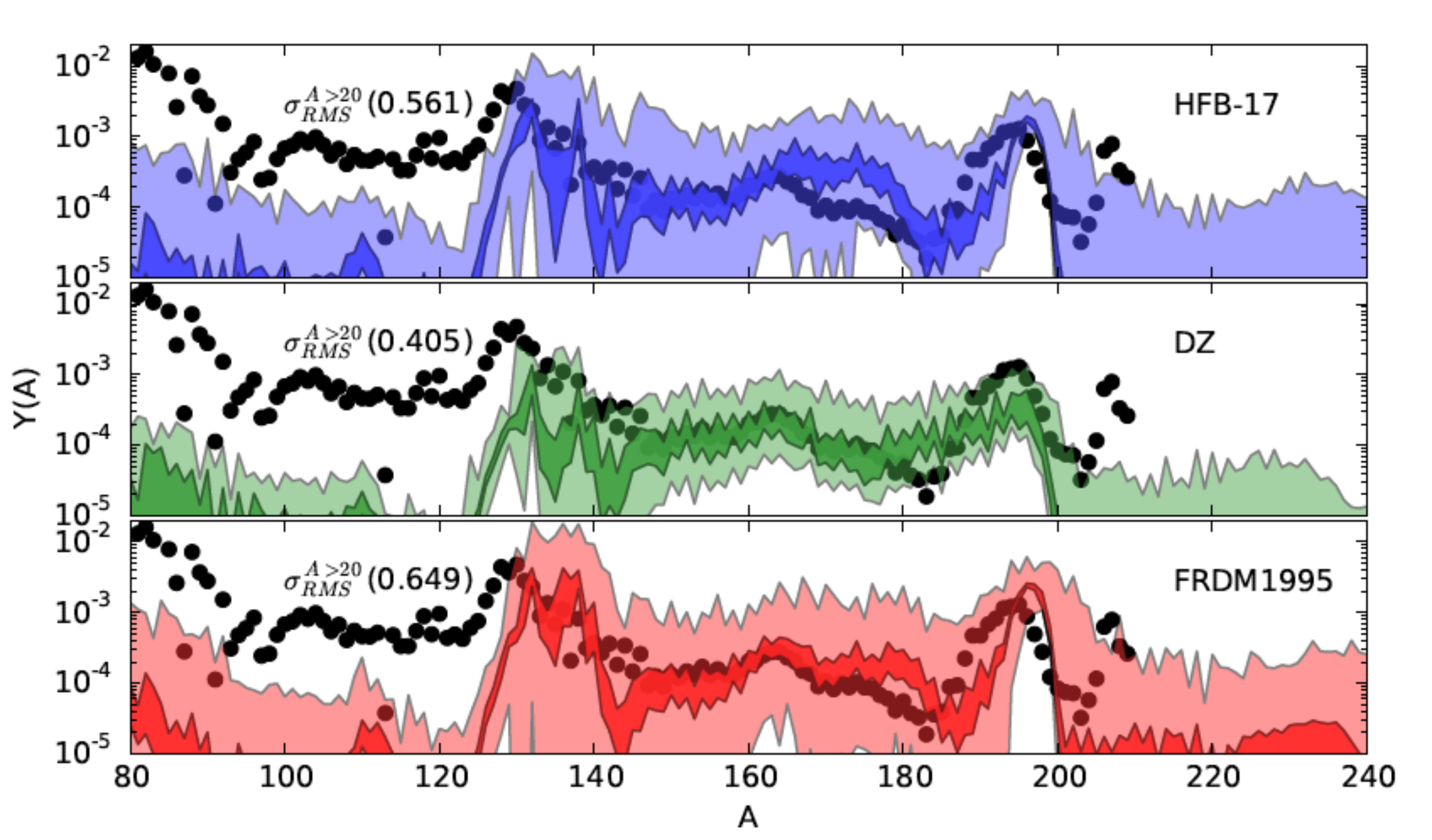

Mumpower, Surman, McLaughlin, Aprahamian
Progress in Particle and Nuclear Physics 86, 2016

CARIBU

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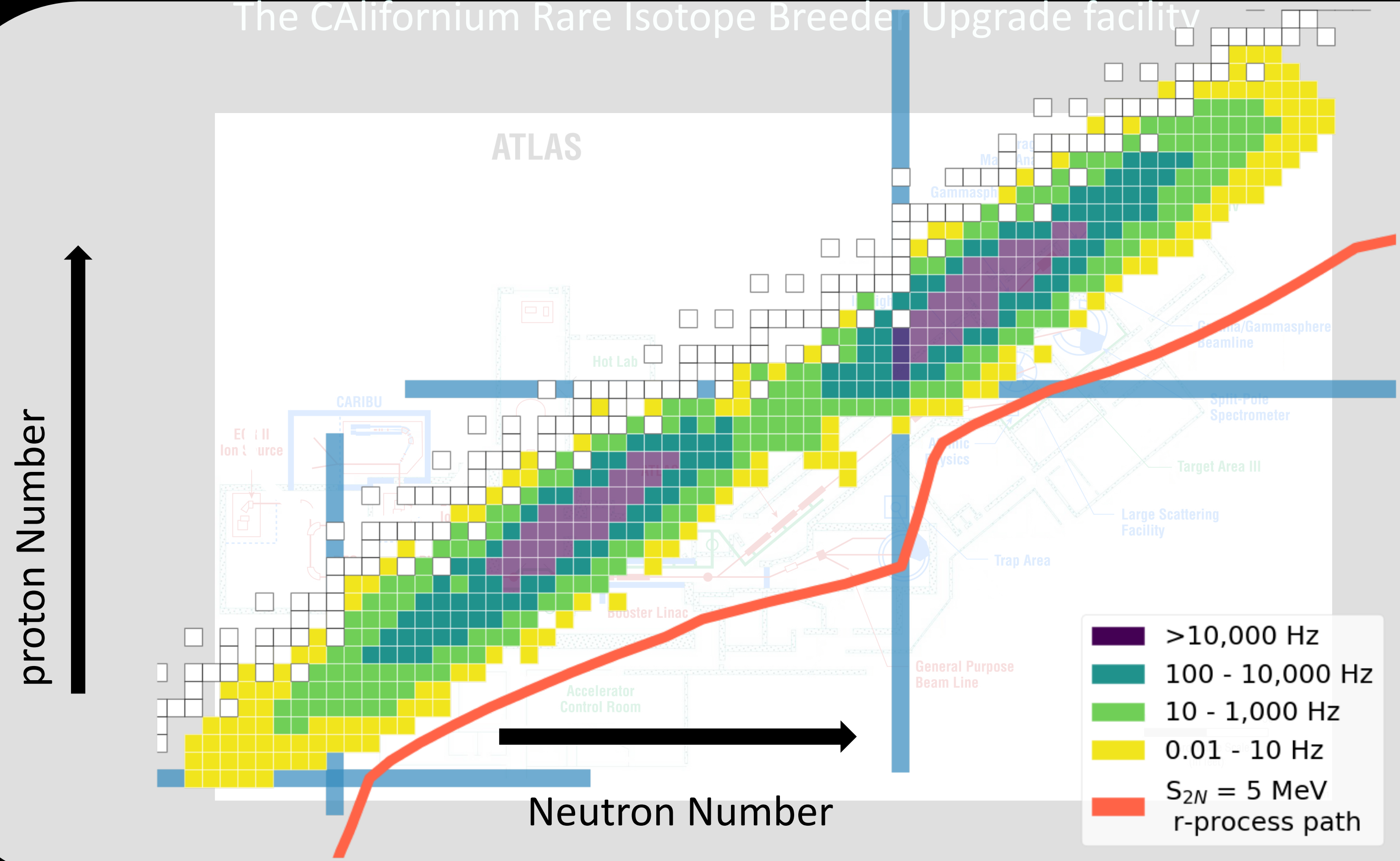
The CAlifornium Rare Isotope Breeder Upgrade facility



Penning Traps

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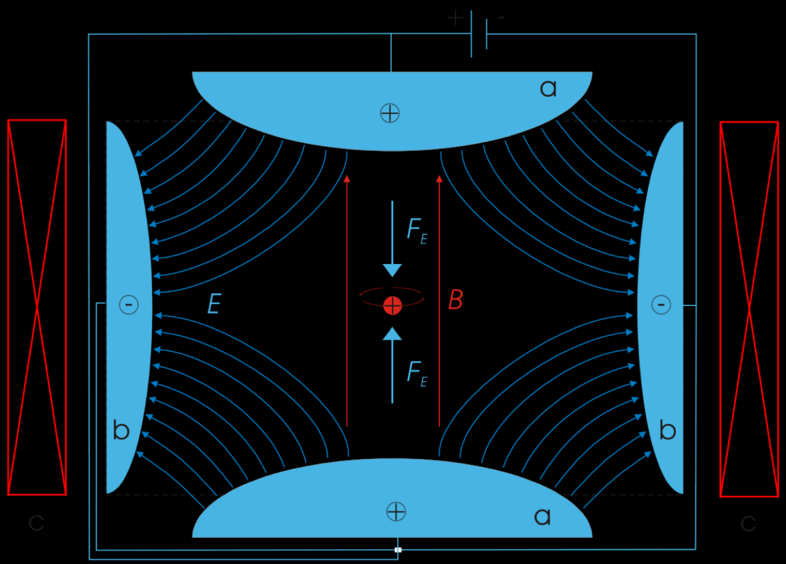
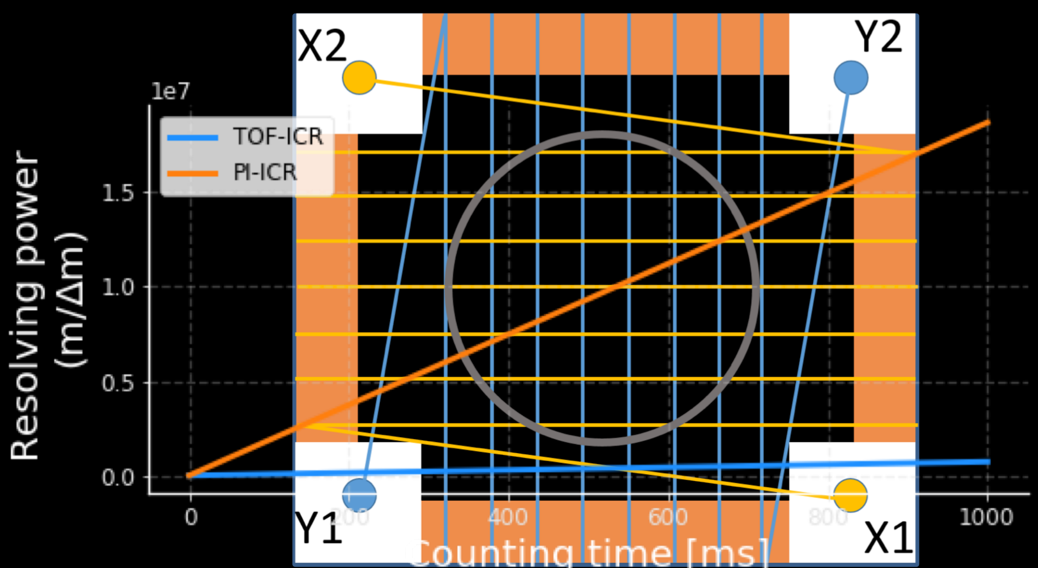
- Strong magnetic field provides radial confinement
- Addition of hyperbolic electric potentials produce axial confinement
- TOF-ICR Method was standard

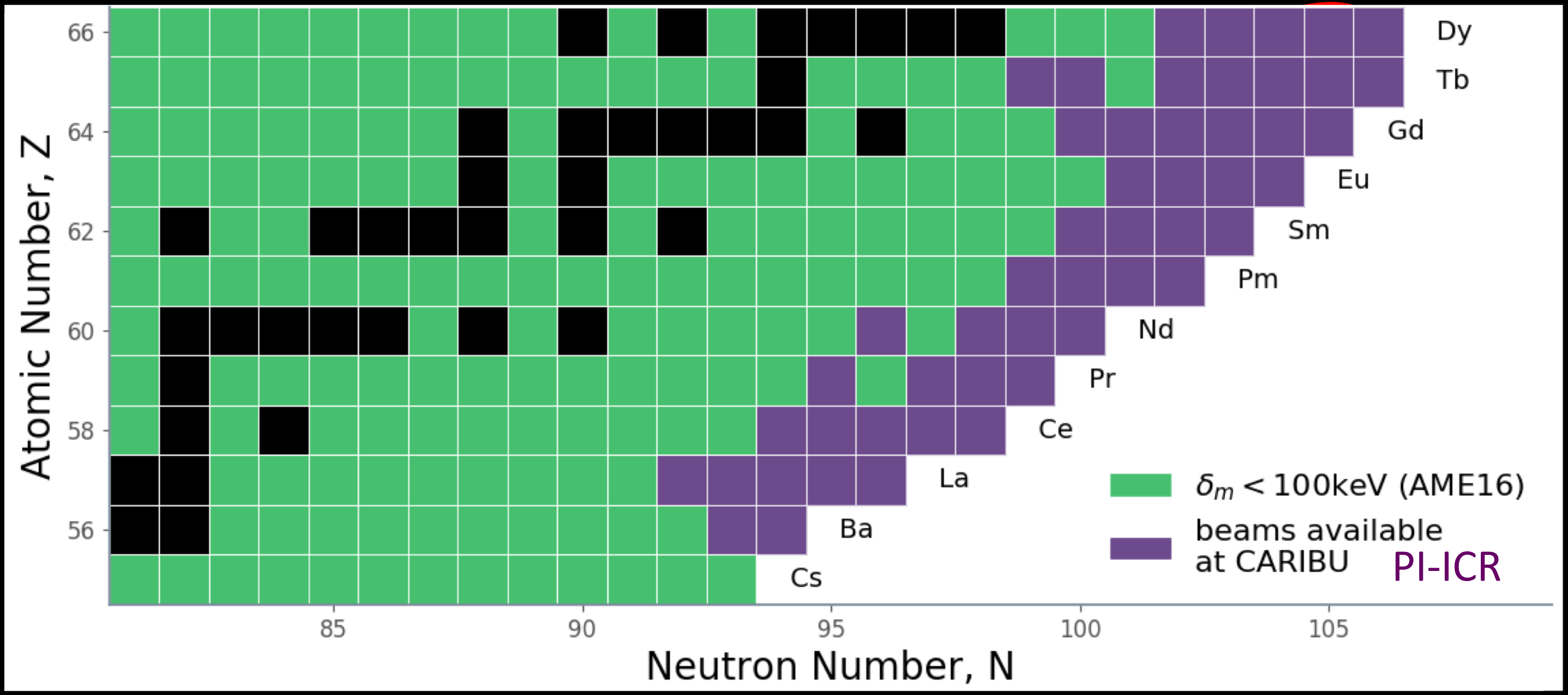


Phase-imaging mass measurements

Use a position-sensitive MCP with delay-line anode to measure the position of ions when they hit the MCP.



Known masses in the rare-earth region



Fission from ^{235}U --- Finland - TOF-ICR
TITAN – TRIUMF -

TOF-ICR: JyFLTRAP

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Phys. Rev. Lett. 120, 262701, 2018

Precision mass measurements on neutron-rich rare-earth isotopes at JYFLTRAP - reduced neutron pairing and implications for the r-process calculations

M. Vilen,[1,*] J.M. Kelly,[2,†] A. Kankainen,[1] M. Brodeur,[2] A. Aprahamian,[2] L. Canete,[1]
T. Eronen,[1] A. Jokinen,[1] T. Kuta,[2] I.D. Moore,[1] M.R. Mumpower,[2,3] D.A. Nesterenko,[1]
H. Penttilä,[1] I. Pohjalainen,[1] W.S. Porter,[2] S. Rinta-Antila,[1] R. Surman,[2] A. Voss,[1] and J. Äystö[1]

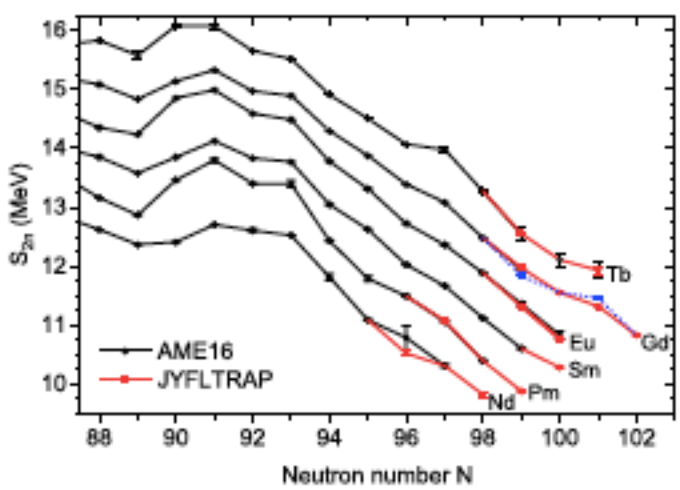

FIG. 2: (Color online) Two-neutron separation energies S_{2n} from this work (red) together with the experimental (solid black circles) values and an extrapolated value for ^{165}Tb (open black circle) from AME16 [62]. The dashed blue lines indicate the values assuming the ground state of ^{163}Gd was measured in this work.

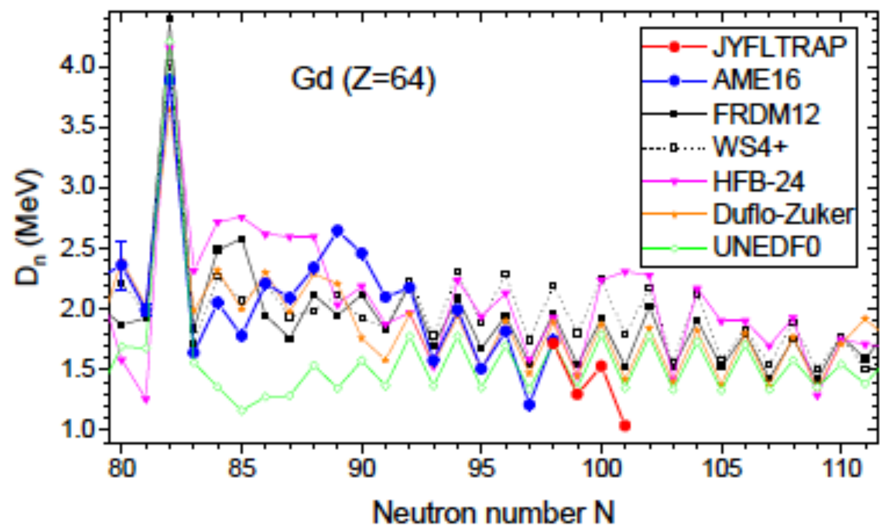

FIG. 3: (Color online) Neutron pairing energies from this work (red circles) and AME16 (blue) in comparison with various theoretical predictions for the Gd isotopes.

No N=100 subshell closure

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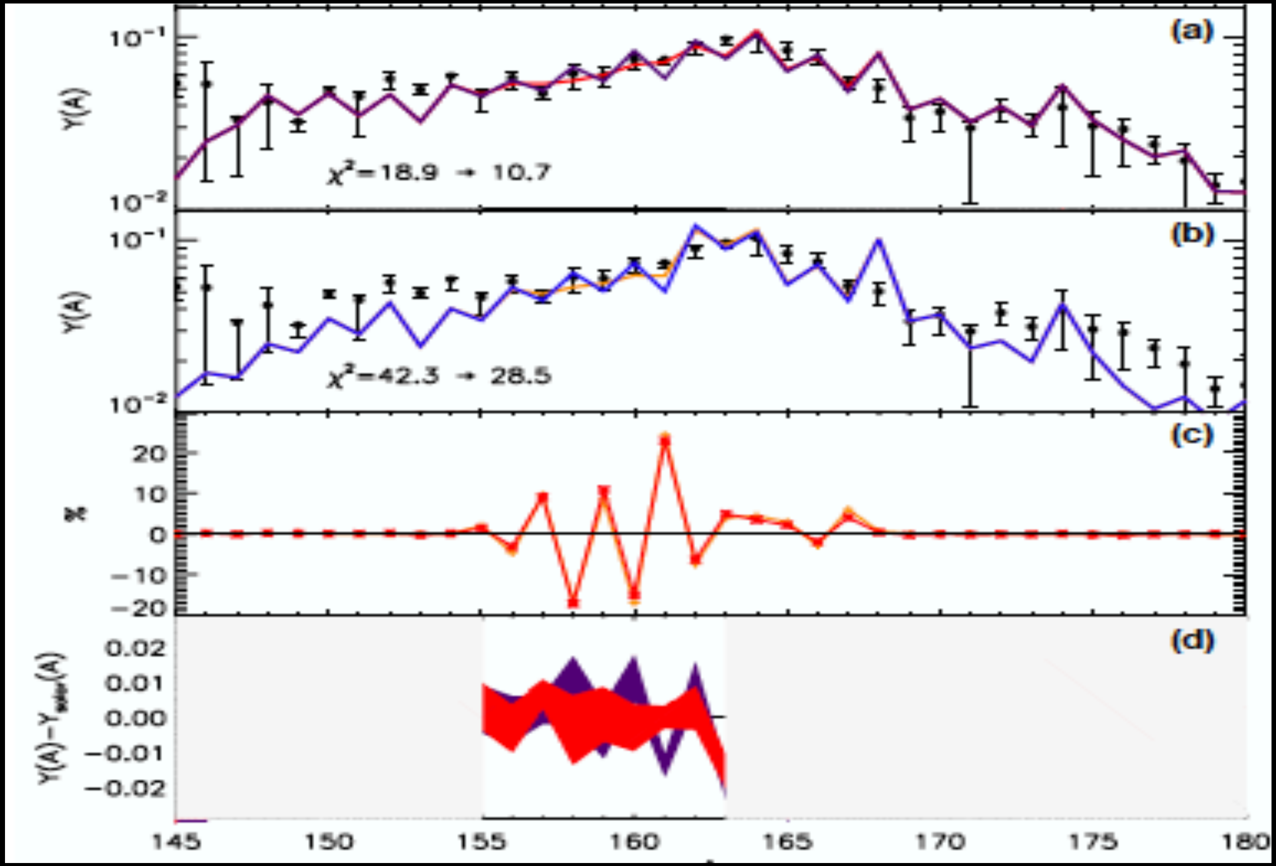
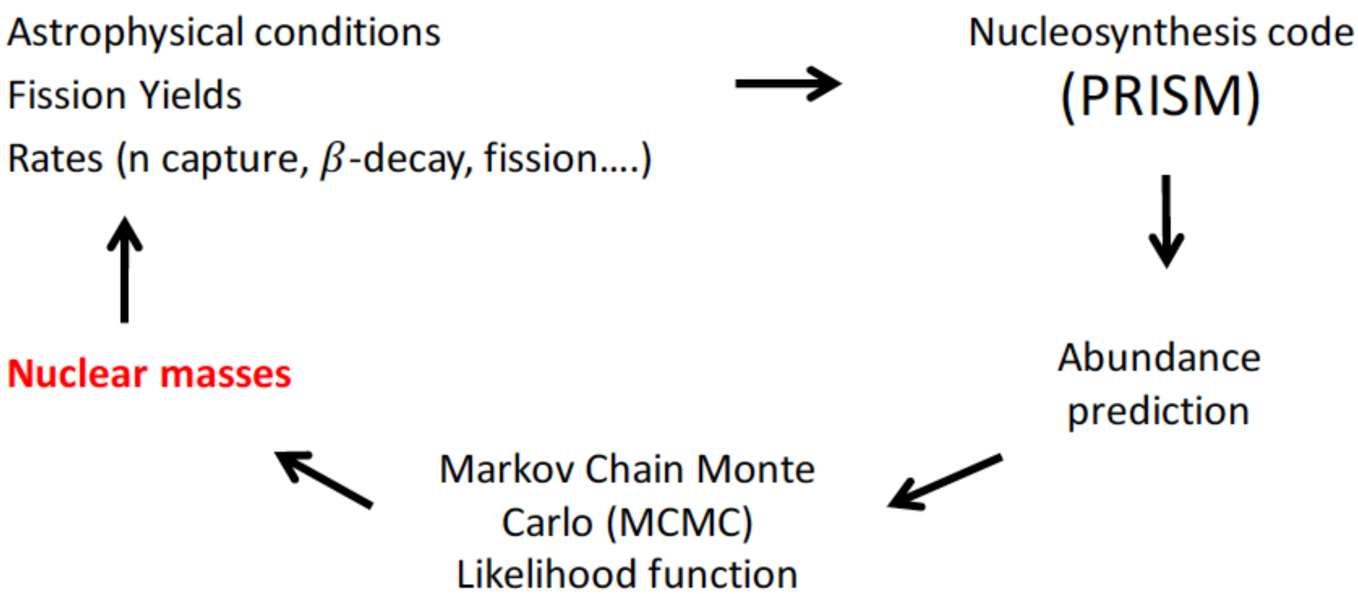


Fission recycling

Without fission recycling

A

Reverse Engineering r-process calculation



Mumpower, McLaughlin, Surman, and Steiner
J. Phys. G: Nucl. Part. Phys. 44, 034003 (2017)

The rare-earth peak

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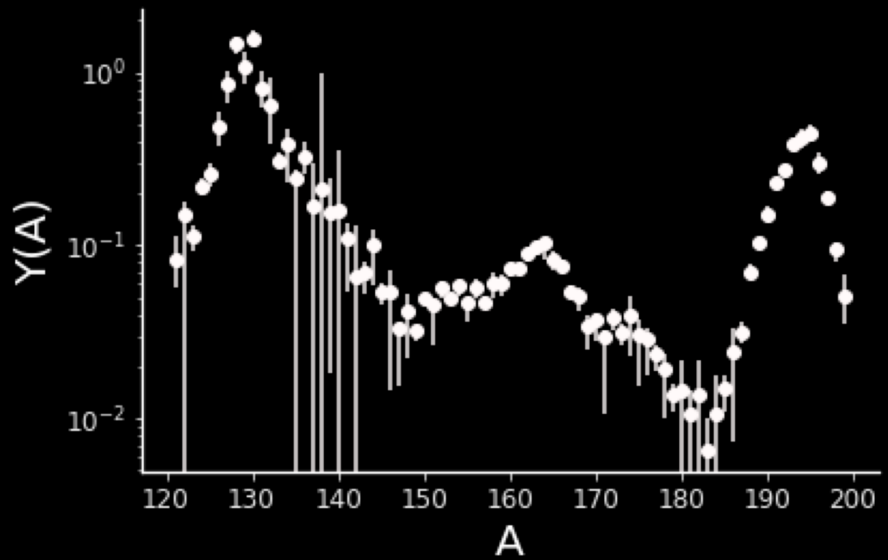
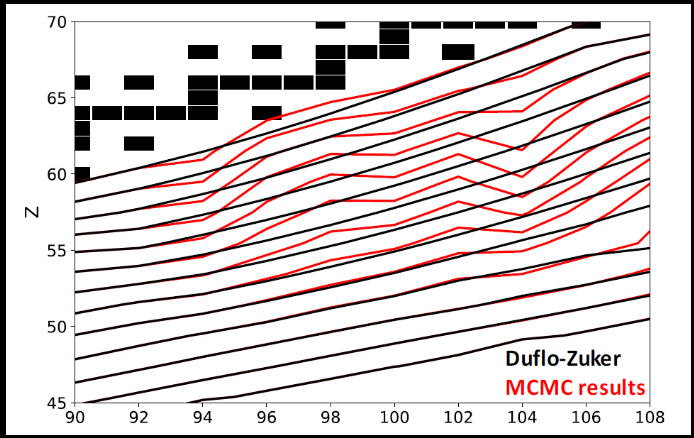
- Two proposed ways to form the rare-earth peak
  1. Dynamical formation during freeze-out
  2. Fission cycling

- Dynamical formalism needs some nuclear structure effect where material can "pile up" as they decay towards stability.



N=82-126



Courtesy of R. Orford

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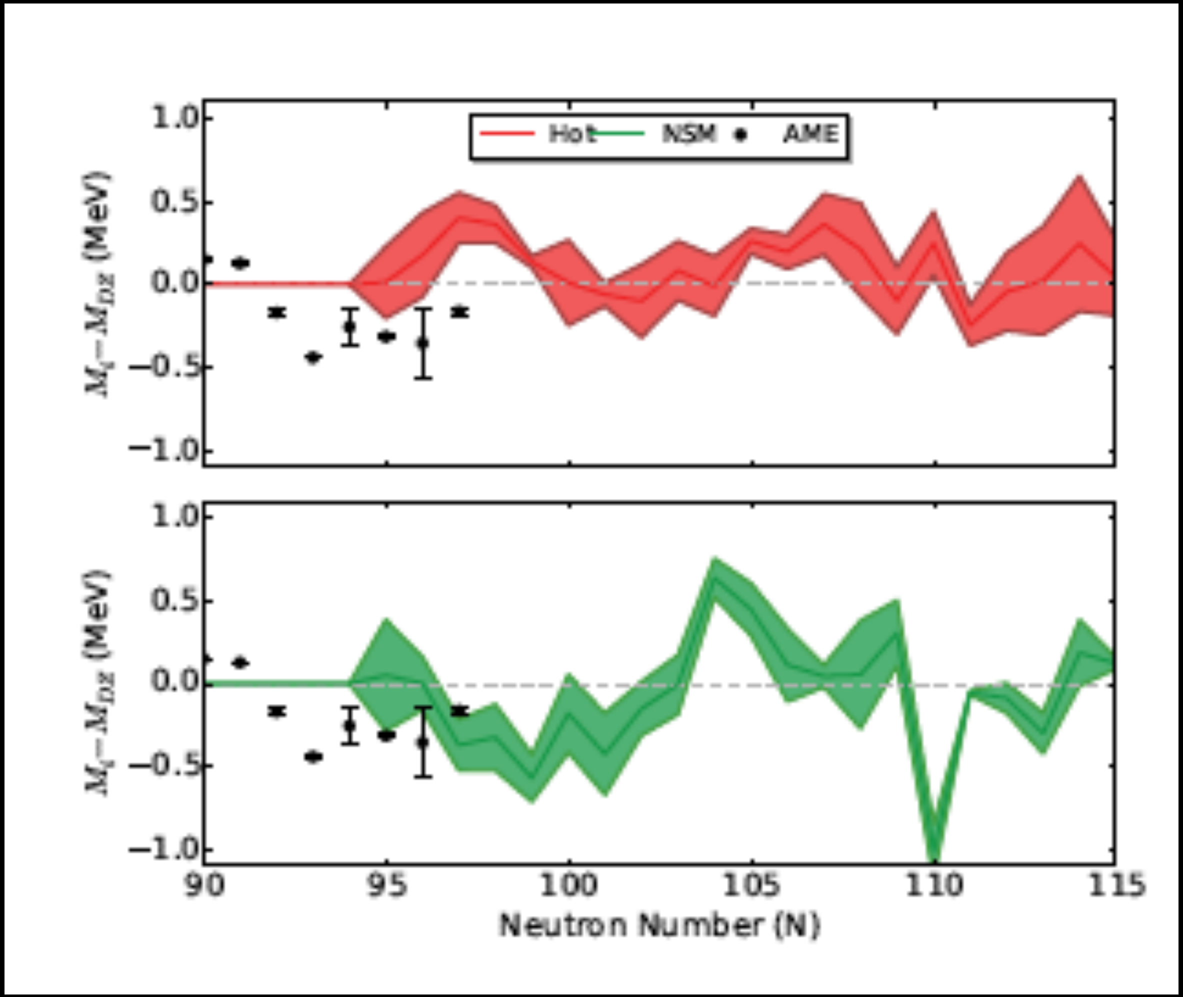

Mumpower, McLaughlin, Surman, and Steiner, Astrophysical Journal, 833:282, 2016

Results

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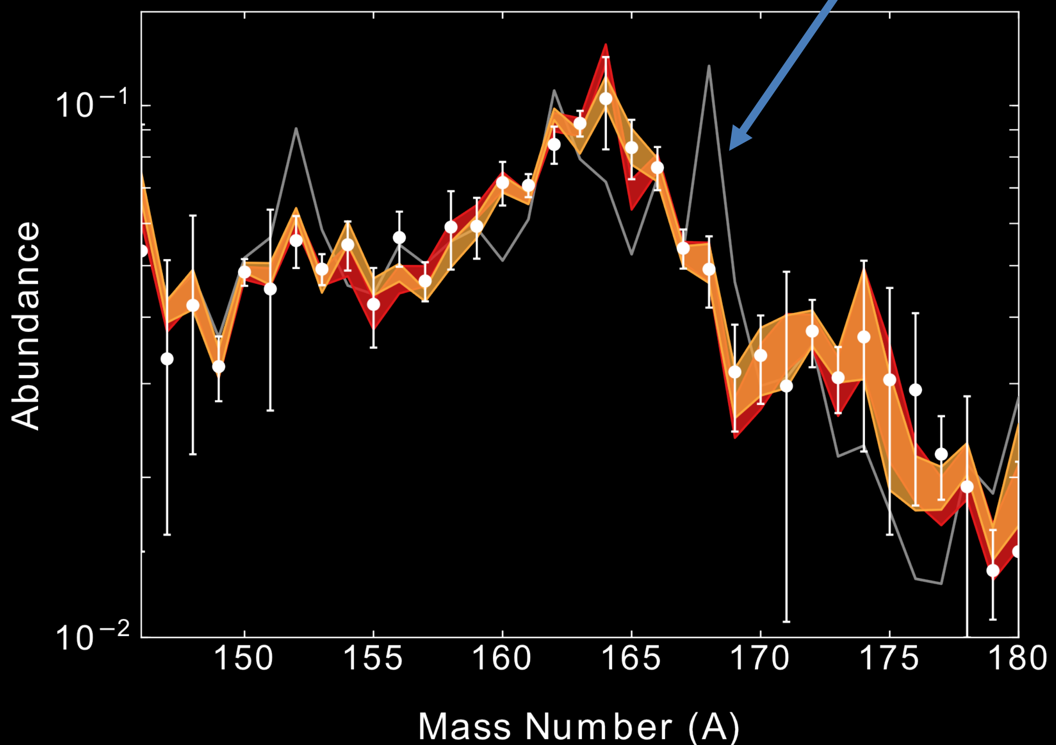
- Considered a hot *r* process environment that you may find in the accretion disk of neutron star merger scenario

$$\chi^2 \sim 20$$

- Comparing predicted masses to measurements allows us to say something about the astrophysical environment.

Duflo Zuker mass model prediction



Phys. Rev. Lett. 120, 262702 (2018)

Precision Mass Measurements of Neutron-Rich Neodymium and Samarium Isotopes and Their Role in Understanding Rare-Earth Peak Formation

R. Orford,[1,2,*] N. Vassh,[3,†] J.A. Clark,[2,4] G.C. McLaughlin,[5] M.R. Mumpower,[6] G. Savard,[2,7] R. Surman,[3] A. Aprahamian,[3] F. Buchinger,[1] M.T. Burkey,[2,7] D.A. Gorelov,[2,4] T.Y. Hirsh,[2,4,8] J.W. Klimes,[2] G.E. Morgan,[2,4] A. Nystrom,[2,3] and K.S. Sharma[4]

Orford et al., Phys. Rev. Lett. 120, 262702 (2018)

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Merger accretion disk wind scenario

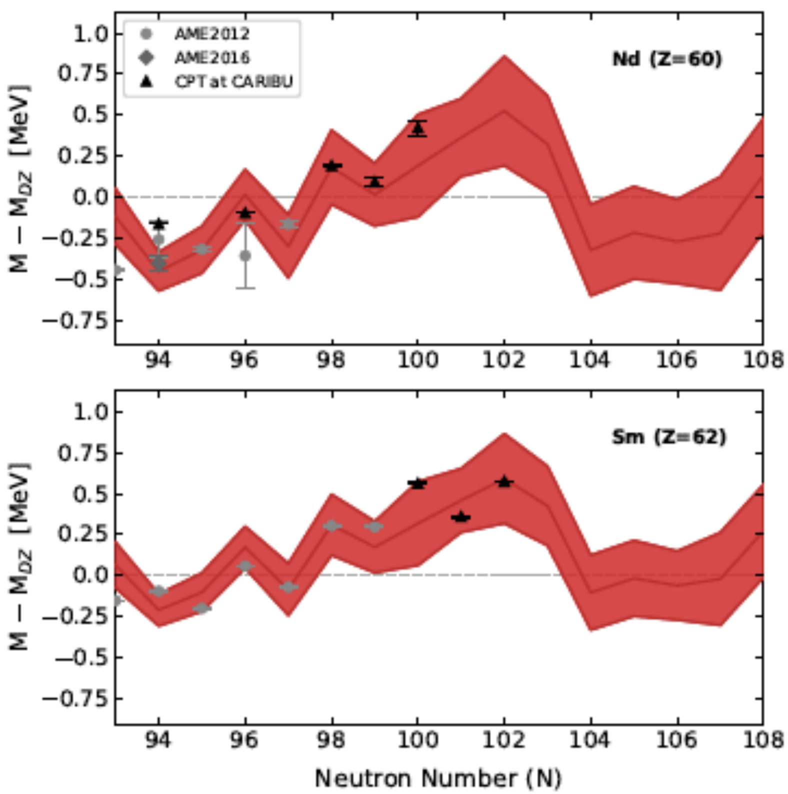


FIG. 2. (Color online) Comparison between experimental values and theoretical predictions (red band) of the nuclear masses relative to the Duflo-Zuker mass model for neodymium and samarium isotopes in a merger accretion disk wind scenario ($s/k_B = 30$, $\tau = 70\,\text{ms}$, and $Y_e = 0.2$).

Varying thermodynamics has little effect

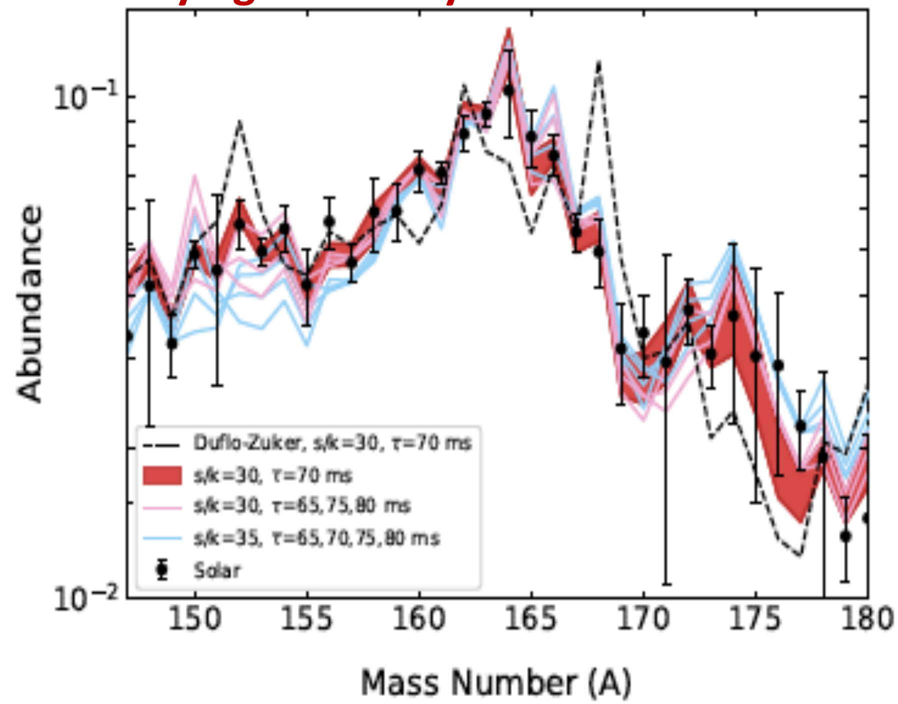


FIG. 3. (Color online) Rare-earth peak abundances using Dulfo-Zuker masses (black dashed) as compared to the result for this same astrophysical trajectory after the algorithm finds the mass predictions of Fig. 2 (solid red band). Pink and blue curves serve to show the change in the abundance pattern obtained from using other disk wind parameters but with the same mass surface.

Conclusions: Are neutron mergers the answer to the big question?

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

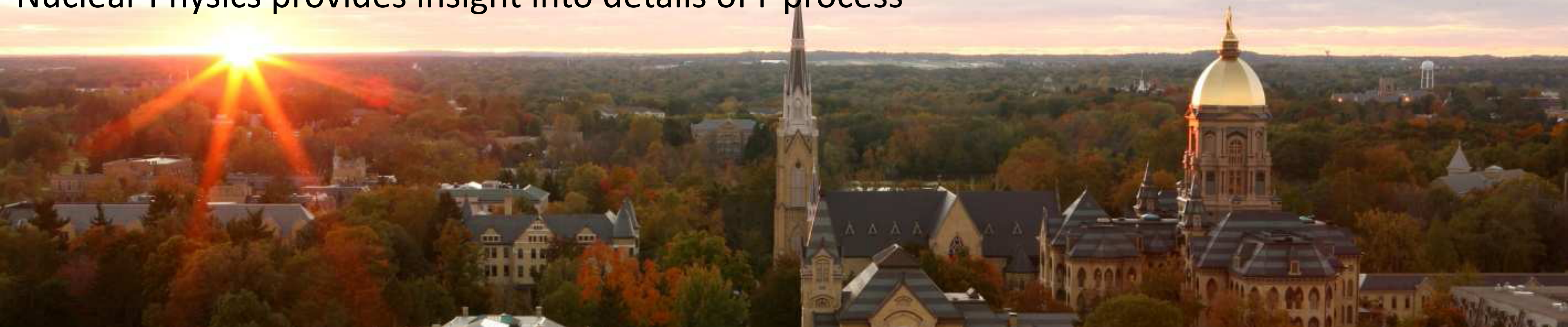
Propagation of mass changes to all dependent properties
(self-consistence)

Identifying the site of the r-process path….

Disentangling Nuclear Physics uncertainties
from the Astrophysical uncertainties…Progress.

Details of neutron merger scenario….nuclear physics

Nuclear Physics provides insight into details of r-process



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R-process Sensitivities and Measurements

McGill

University of Manitoba
EST. 1877

University of Notre Dame

NC STATE

Argonne National Laboratory

Los Alamos National Laboratory
EST. 1943