Extreme Environments and the Origin of the Heavy Elements

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Institute for Structure & Nuclear Astrophysics
University of Notre Dame, Notre Dame, IN (USA)

E M M I Physics Days…..

TECHNISCHE UNIVERSITÄT DARMSTADT

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UNIVERSITÄT HEIDELBERG Zukunft. Seit 1386.

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RIKEN NISHINA CENTER

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

EMMI

UPMC SORBONNE UNIVERSITÉS

THE UNIVERSITY OF TOKYO

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

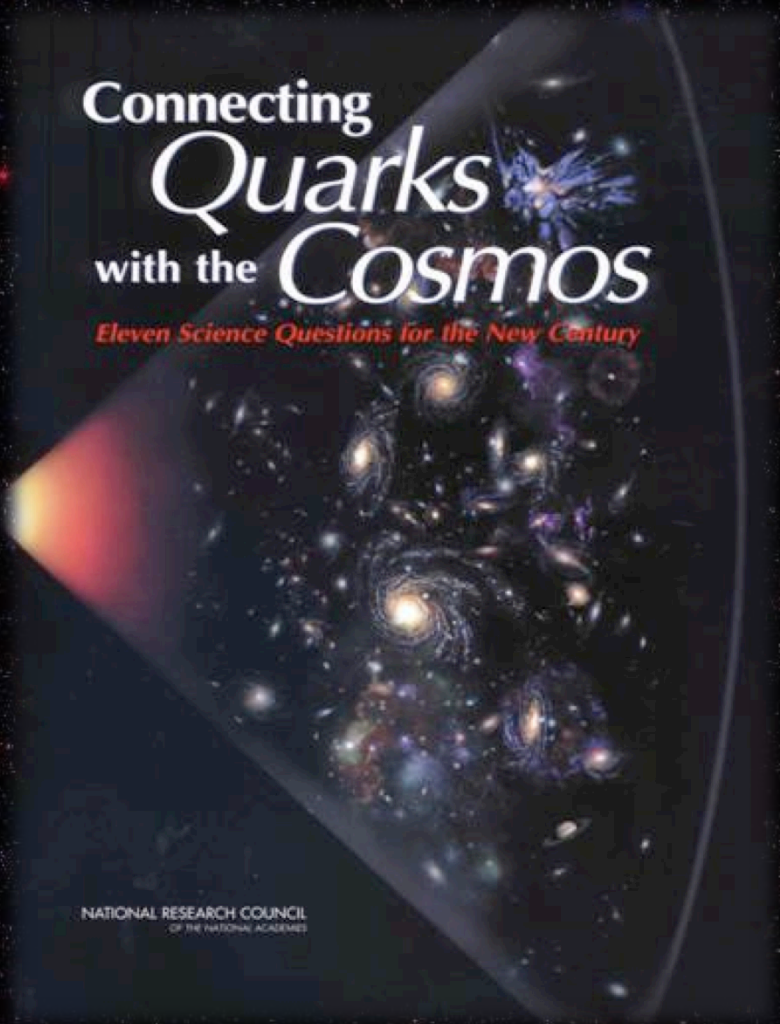
HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

BERKELEY LAB Lawrence Berkeley National Laboratory

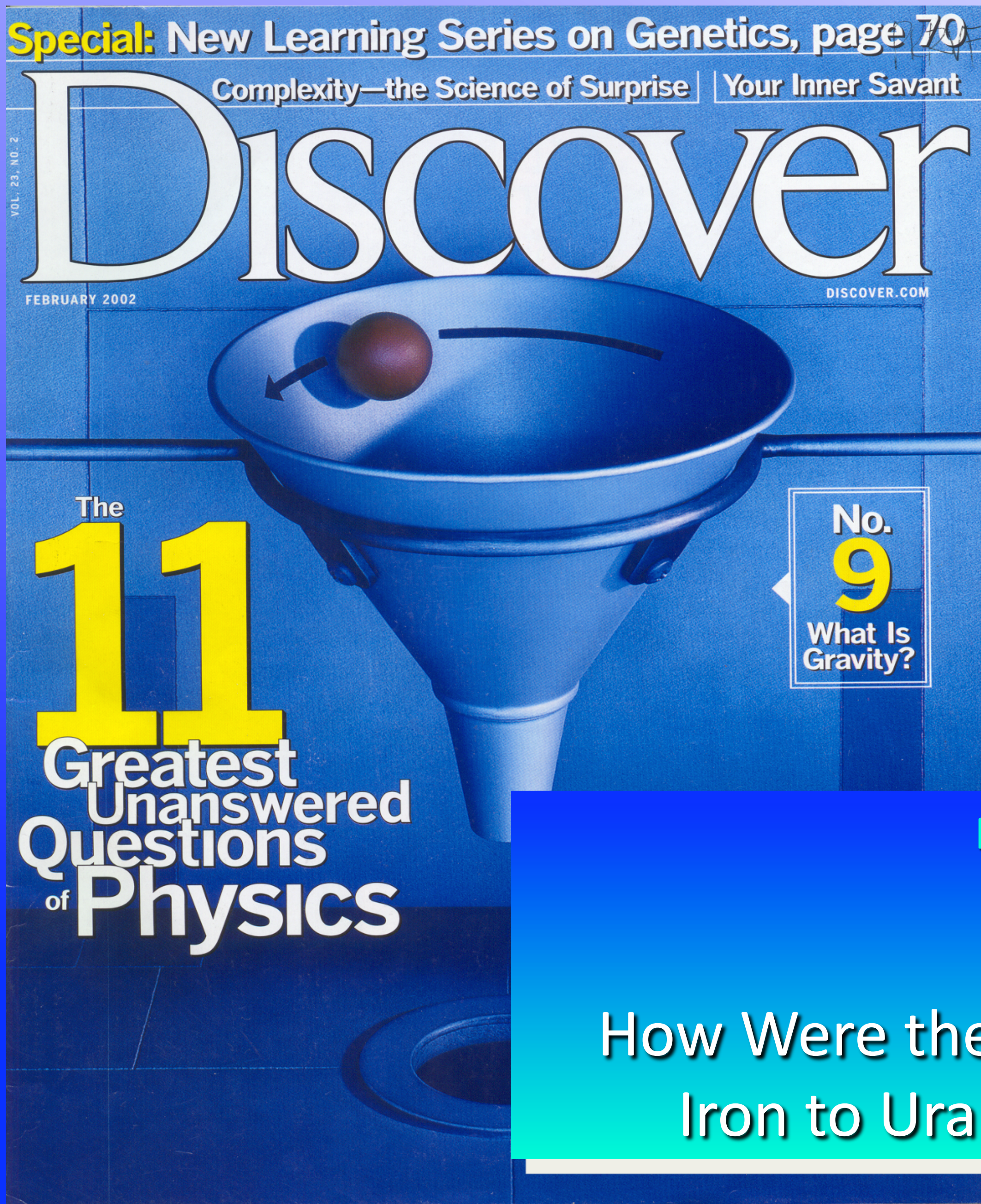
JINA

FIAS Frankfurt Institute for Advanced Studies

H-QM Helmholtz Research School Quark Matter Studies



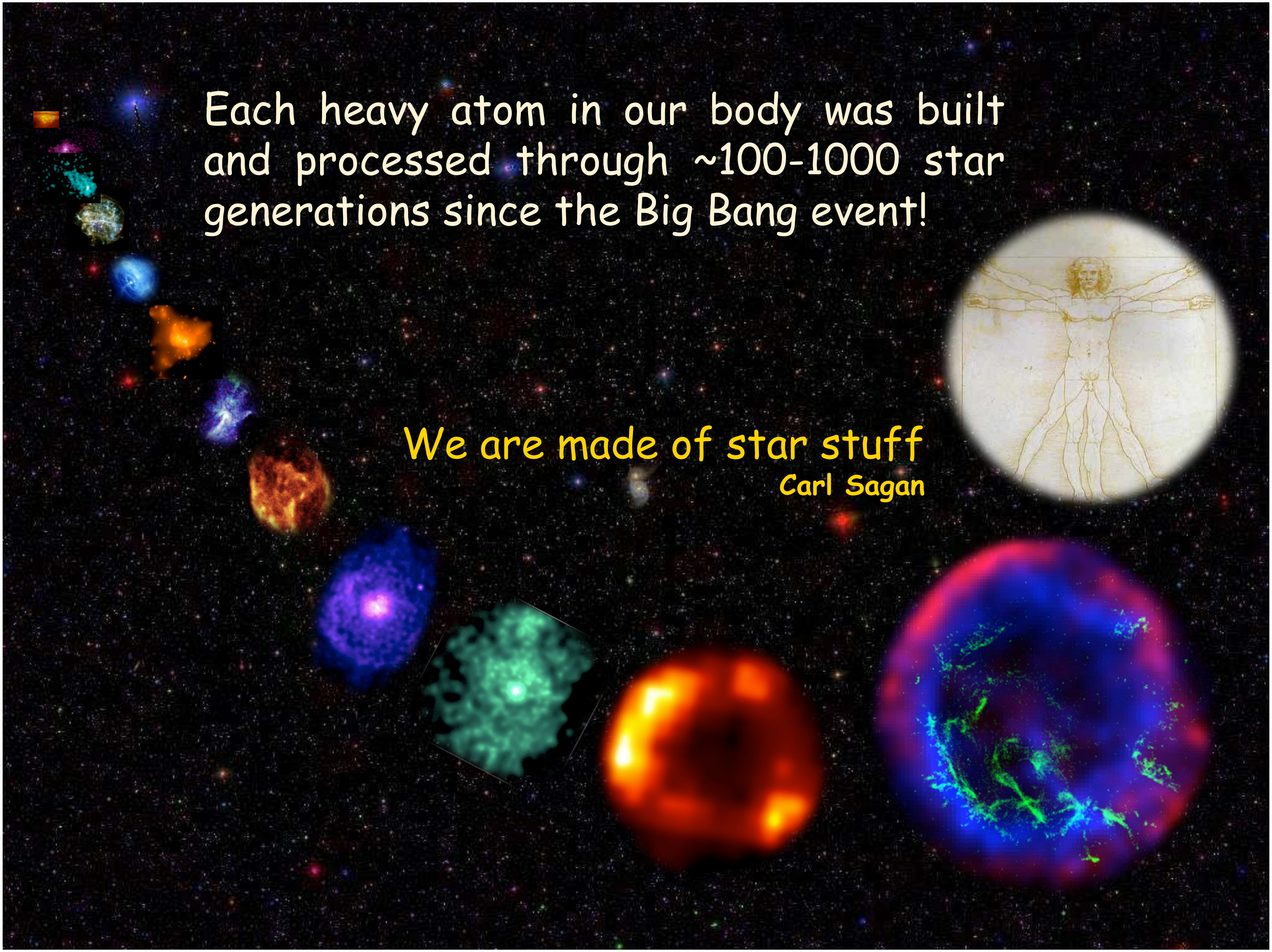
- What is dark matter?
- What is dark energy?
- How did the universe begin?
- Was Einstein right about gravity?
- How have v-s shaped the universe?
- What are nature's most energetic particles?
- Are protons stable?
- Are there new states of matter at exceedingly high density/energy?
- Are there additional dimensions?
- How were elements Fe to U made?
- Is a new theory needed at the highest energies and EM Fields?



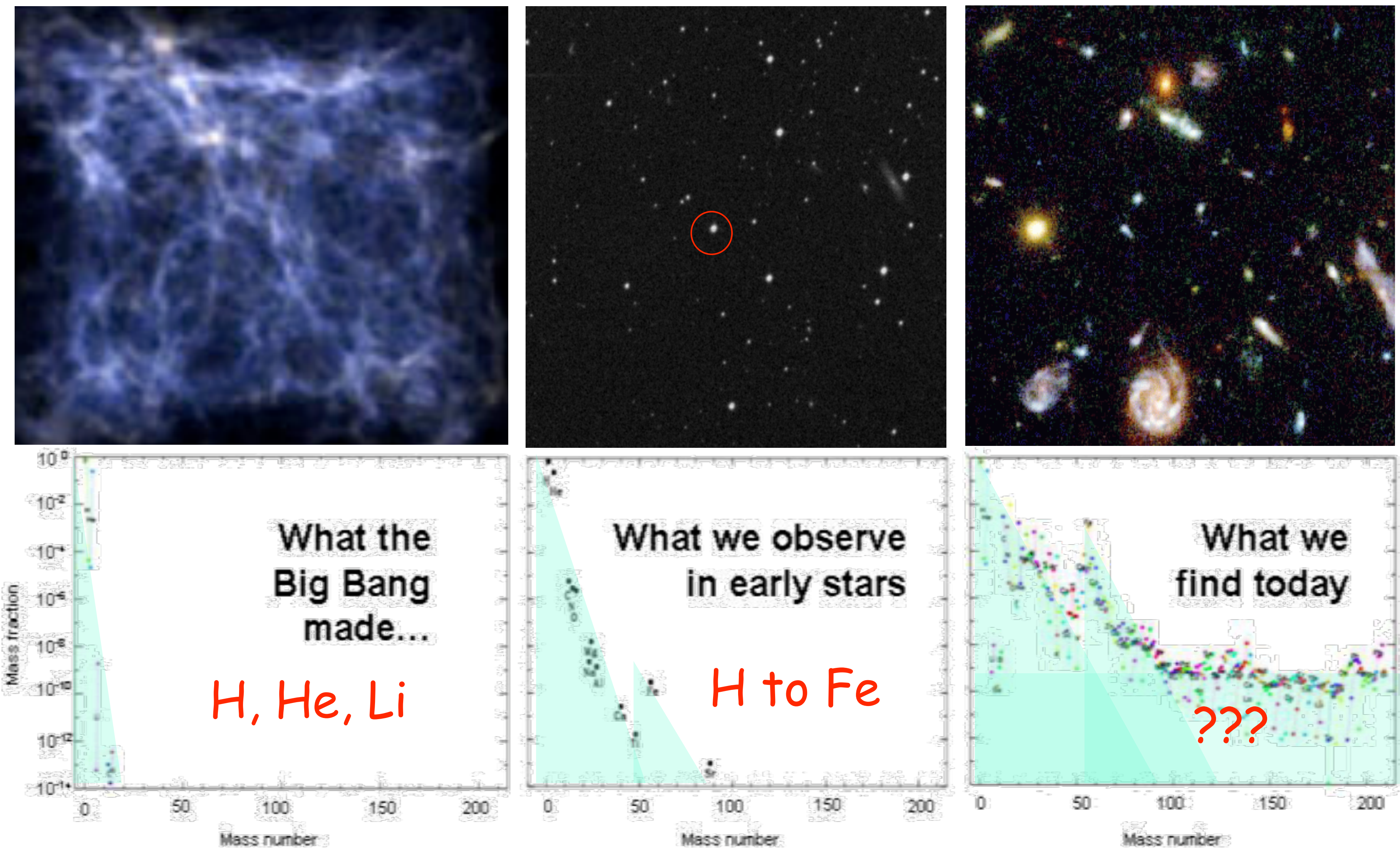
No.

3

How Were the Elements from Iron to Uranium made ?


Each heavy atom in our body was built and processed through ~100-1000 star generations since the Big Bang event!
We are made of star stuff
Carl Sagan

Nuclei are made in Stars

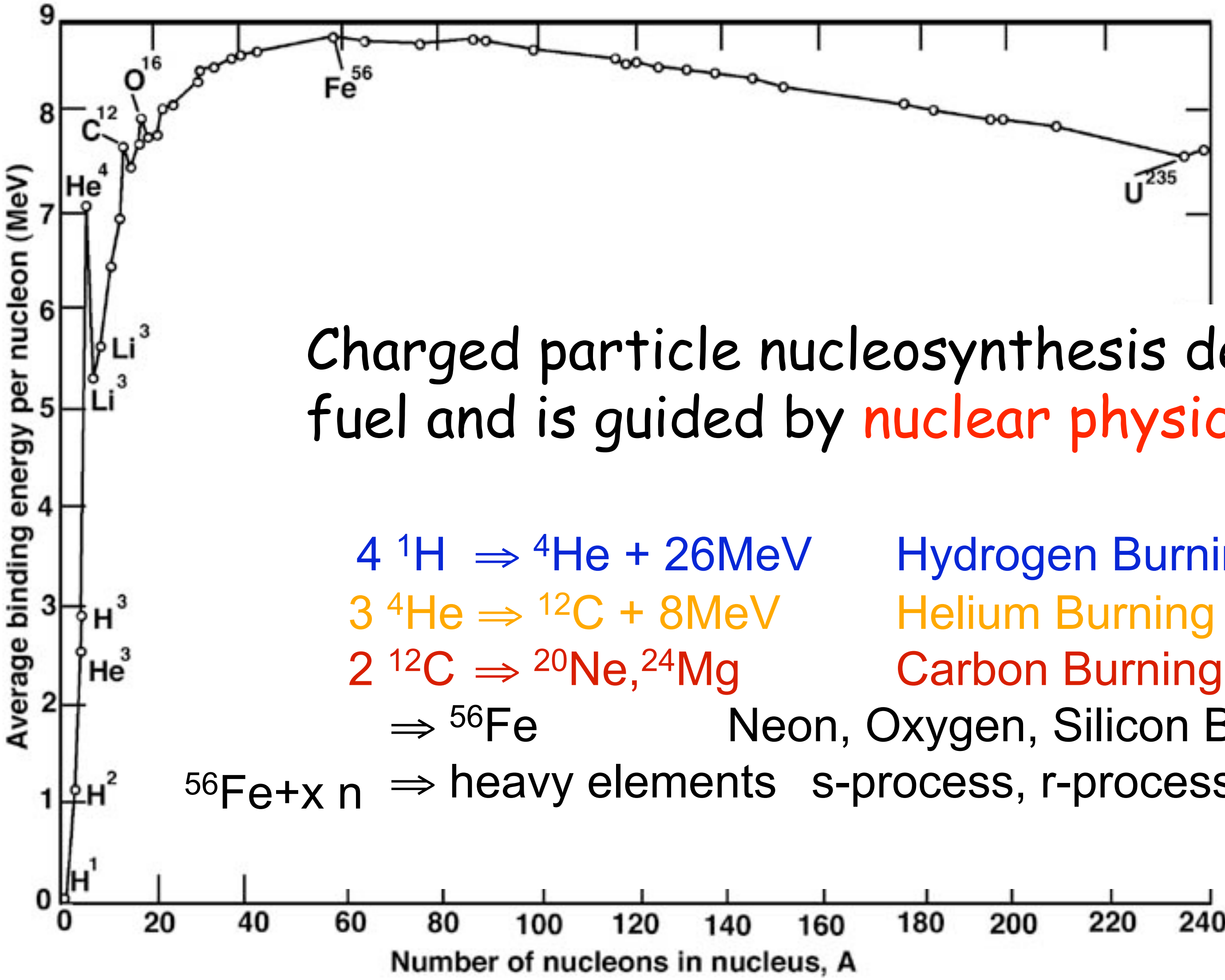


(The primordial abundance pattern)
Brian Fields (2002)

(The abundance pattern in the oldest observed stars He1017 & HH1327)
Anna Frebel (2006)

(The solar abundance pattern)
Grevesse & Noels (1995)

Nucleosynthesis Processes in Stars



Charged particle nucleosynthesis depends on available fuel and is guided by nuclear physics (structure):

$4\ ^{1}H \Rightarrow {}^{4}He + 26MeV$ Hydrogen Burning

$3\ ^{4}He \Rightarrow {}^{12}C + 8MeV$ Helium Burning

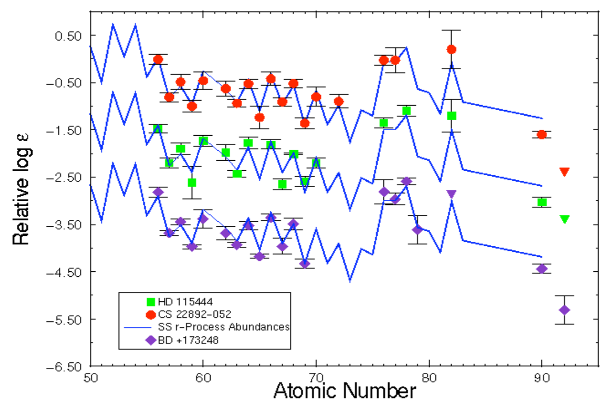
$2\ ^{12}C \Rightarrow {}^{20}Ne, {}^{24}Mg$ Carbon Burning

$\Rightarrow {}^{56}Fe$ Neon, Oxygen, Silicon Burning

$^{56}Fe + x\ n \Rightarrow$ heavy elements s-process, r-process

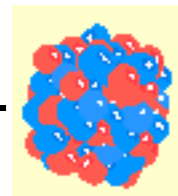
The r-process problem

New precision observations
of r-process elements



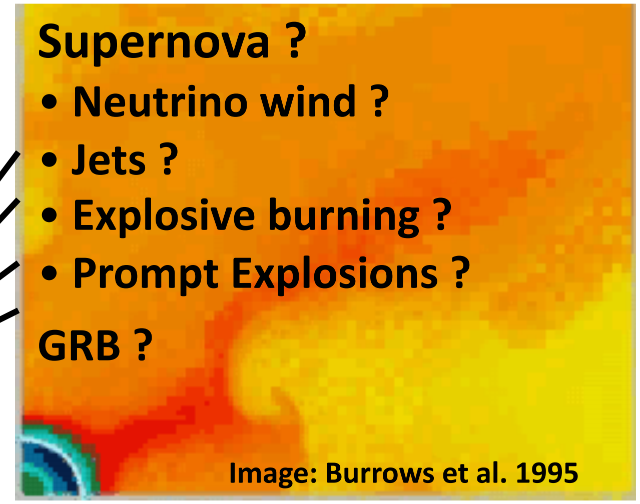
graph by J. Cowan

Nuclear
Physics

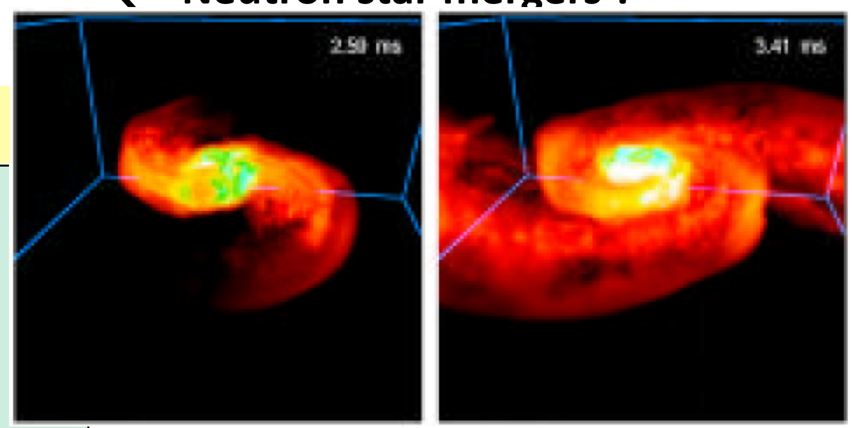


Missing link

r-process models



Neutron star mergers ?



SDSS-2 Nuclear Physics driven observations

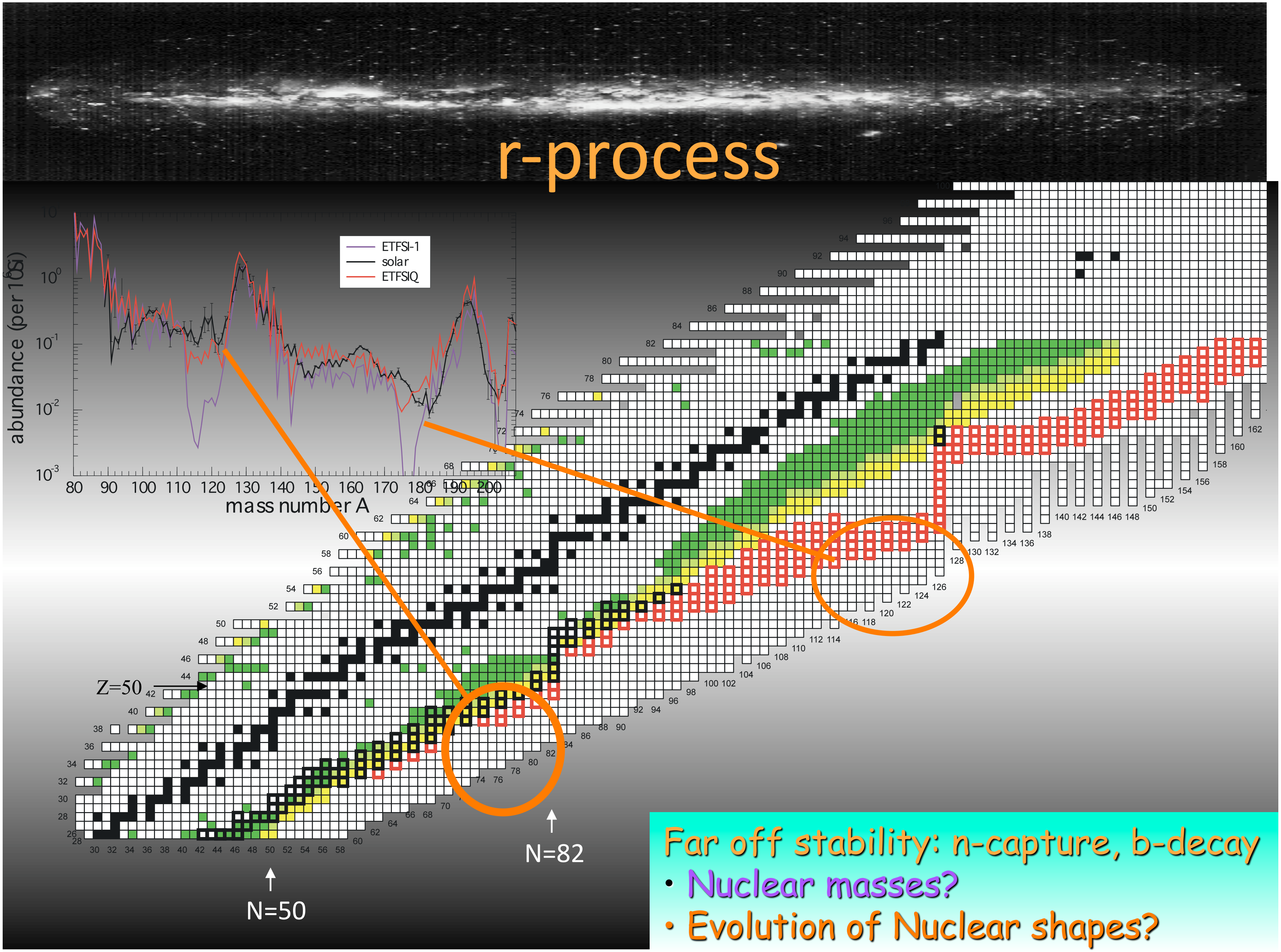
Need nuclear physics:

→ With abundance observations the only experimental constraint of r-process environment

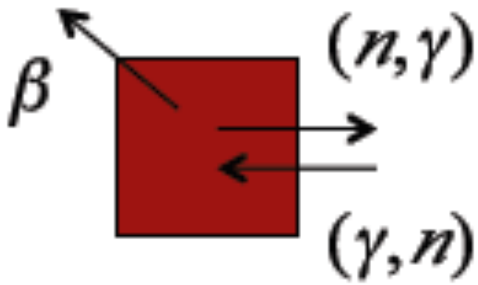
→ Disentangle contributions from various s- and r-processes to observed abundances

→ Use r-process as probe for extreme environment

H. Schatz



r-process
ETFSI-1
solar
ETFSIQ
abundance (per 10^6 Si)
mass number A
Z=50
N=50
N=82
Far off stability: n-capture, b-decay
• Nuclear masses?
• Evolution of Nuclear shapes?



Masses
β-decay rates
n-capture

Major Shells and evolution of shells…

Experimental & Theoretical Challenges

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Progress in Particle and Nuclear Physics 54 (2005) 535–613

Progress in Particle and Nuclear Physics

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Review

Nuclear structure aspects in nuclear astrophysics

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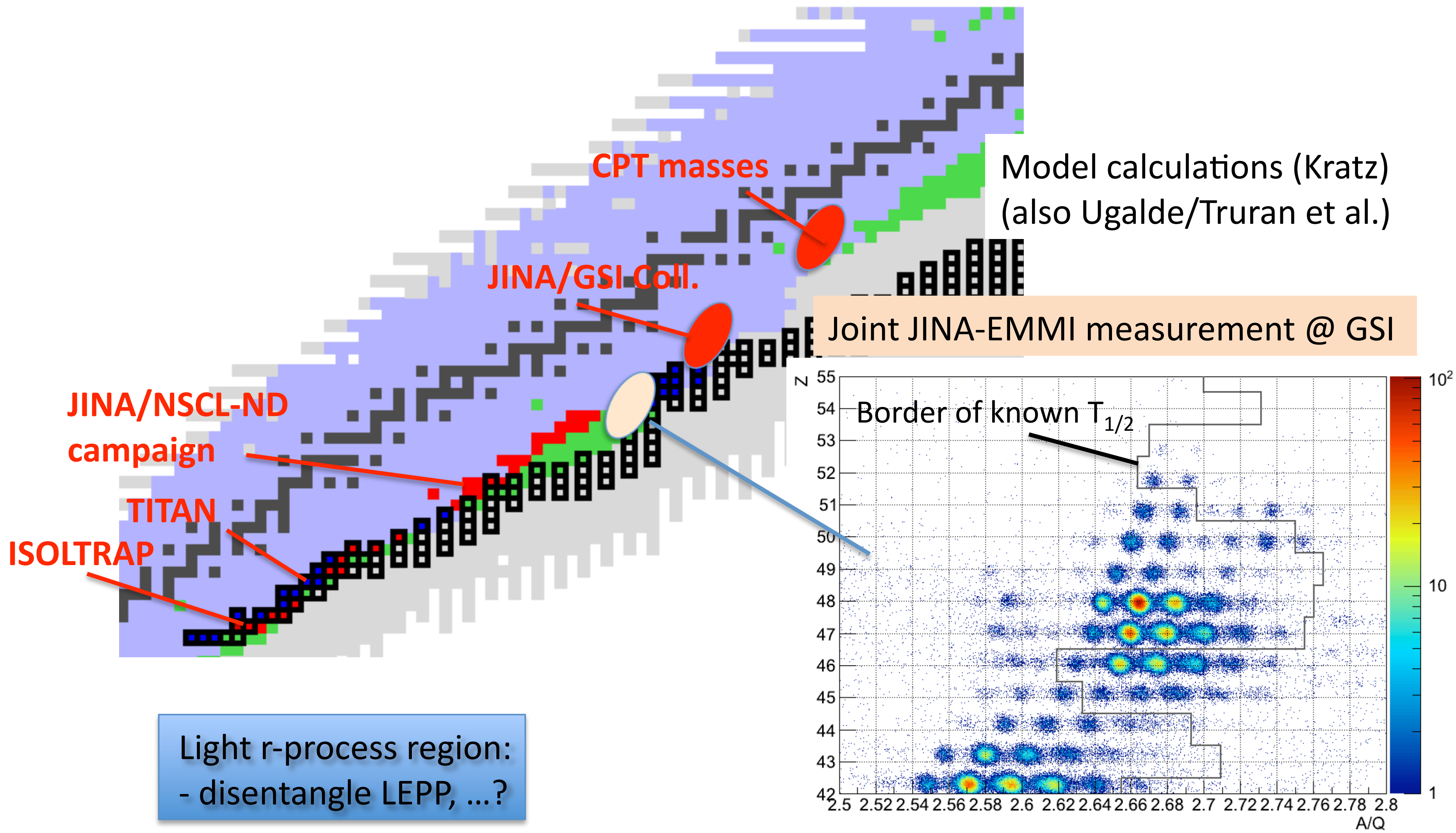
[b] Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark

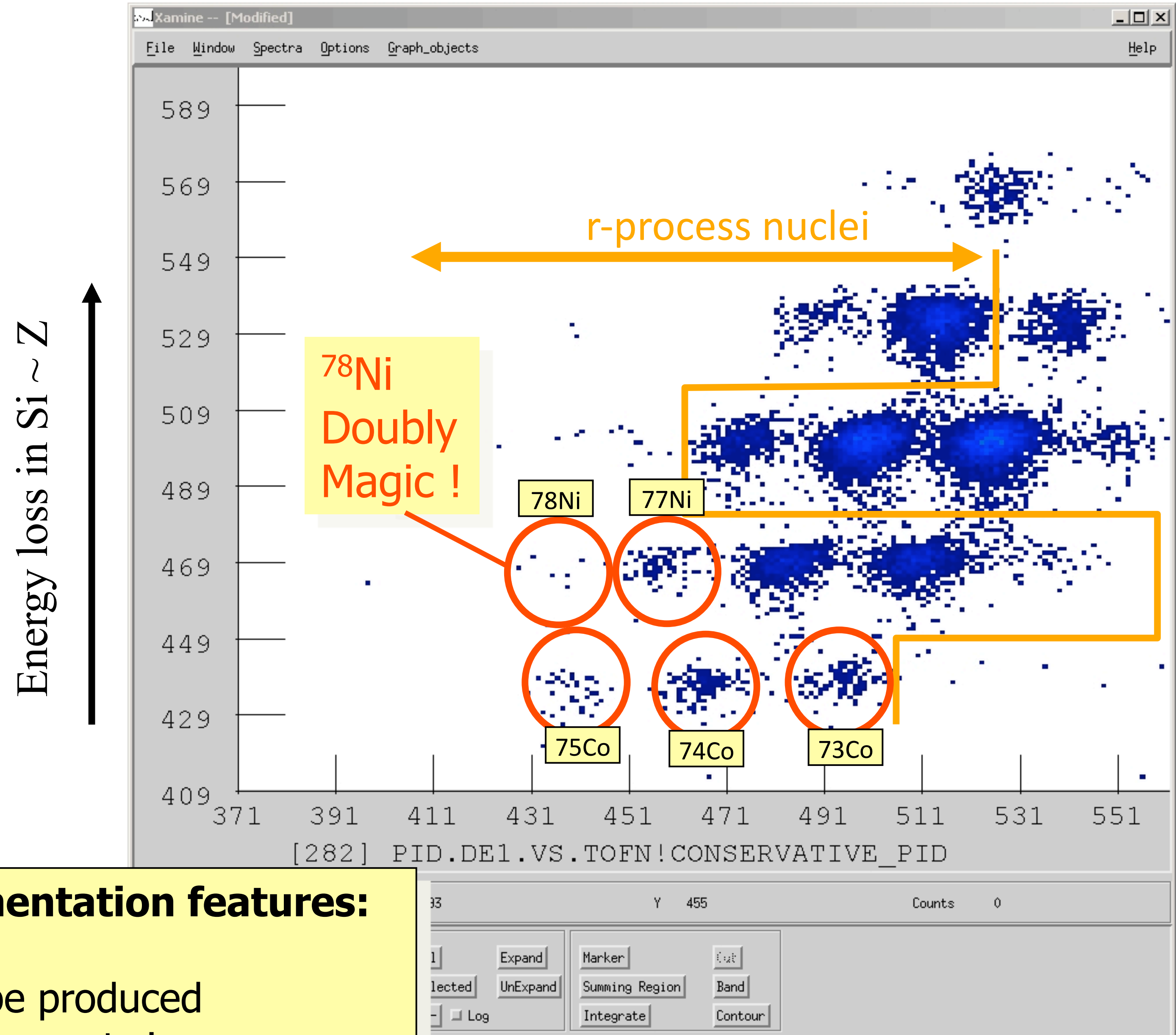
r-process experiments



Light r-process region:
- disentangle LEPP, …?

Montes (MSU), K. Smith (ND), et al.

Particle Identification:



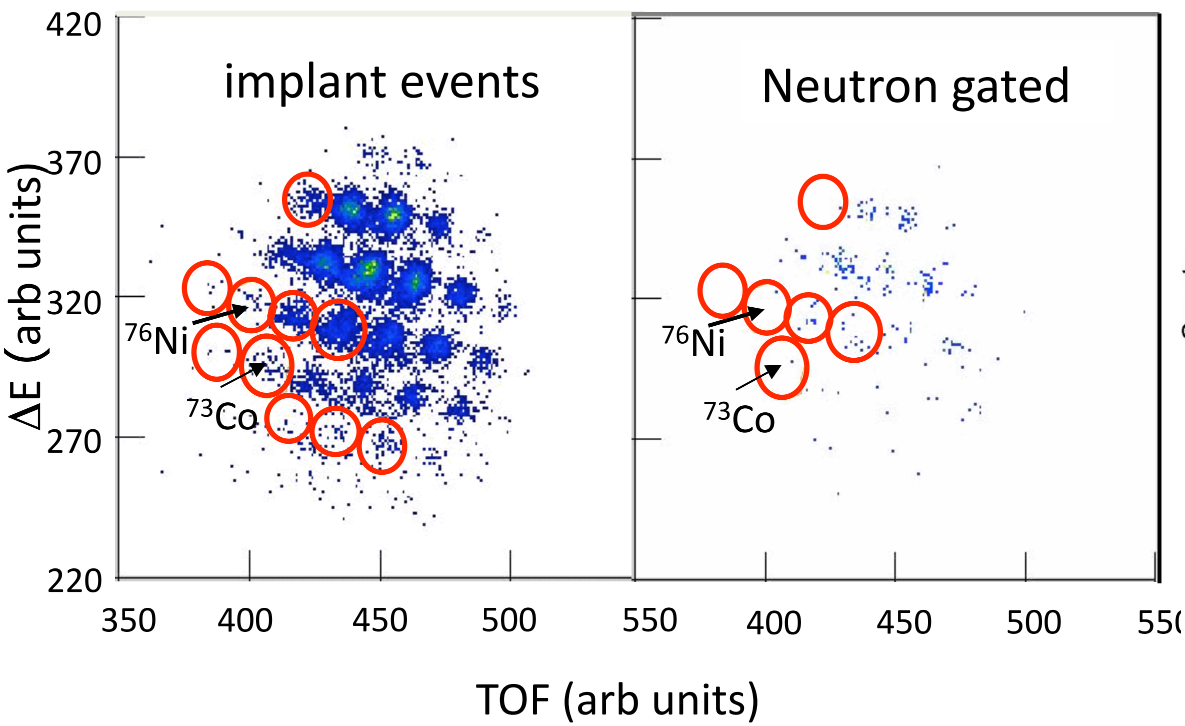
RIB from fragmentation features:

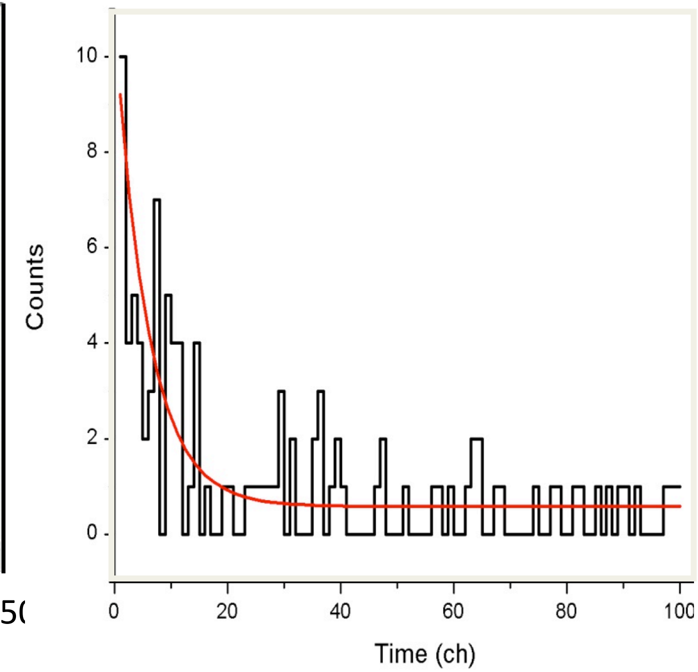
- no decay losses
- any beam can be produced
- multiple measurements in one
- high sensitivity

Time of flight ~ m/q

^{78}Ni , ^{77}Ni first measurement of half-lives — $110^{+100/-60}$ ms; $128^{+27/-33}$ ms

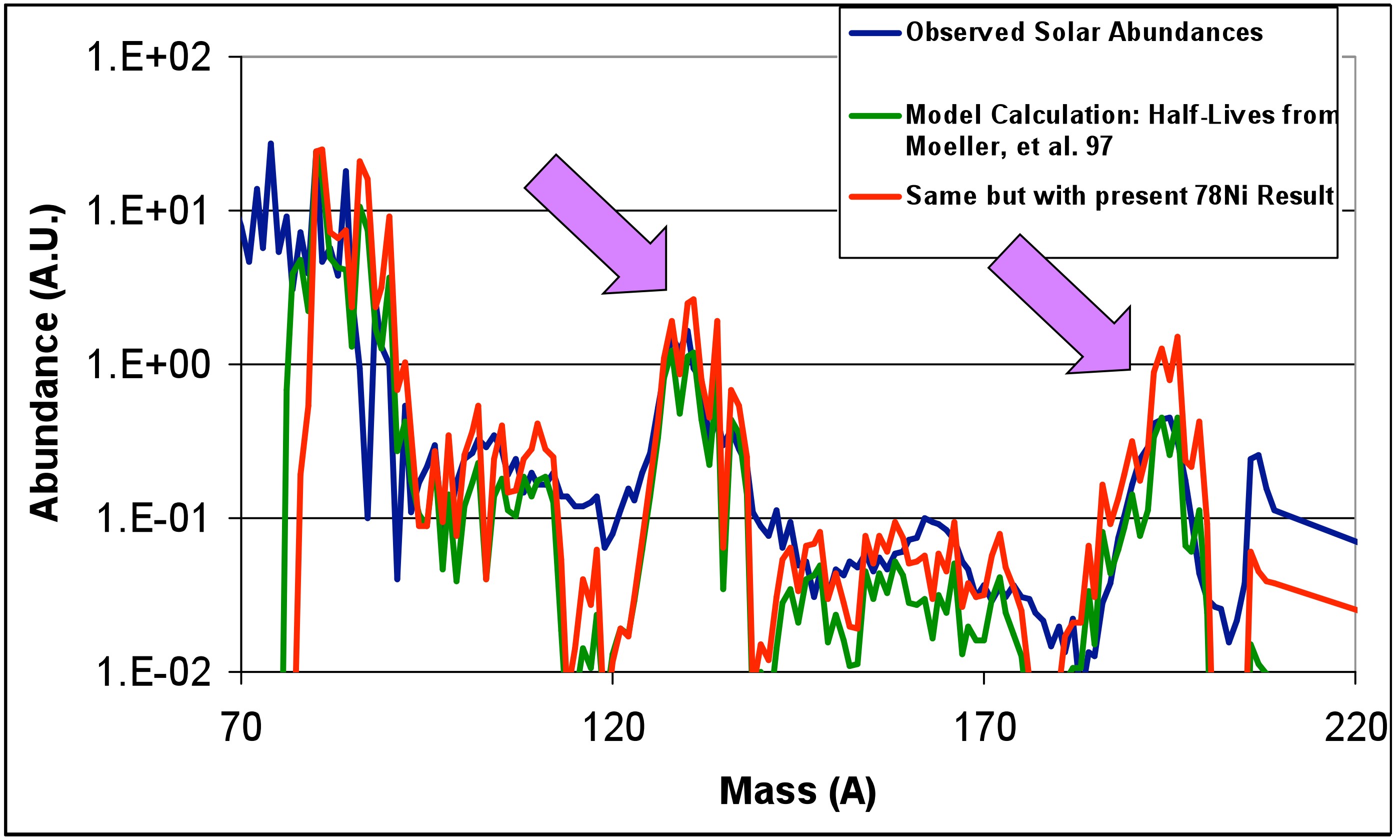
^{76}Ni, ^{75}Ni more precise measurements — $238^{+15/-18}$ ms; $344^{+20/-24}$ ms





Hosmer et al. PRL 94, 112501 (2005)

Impact of ^{78}Ni half-life on r-process models

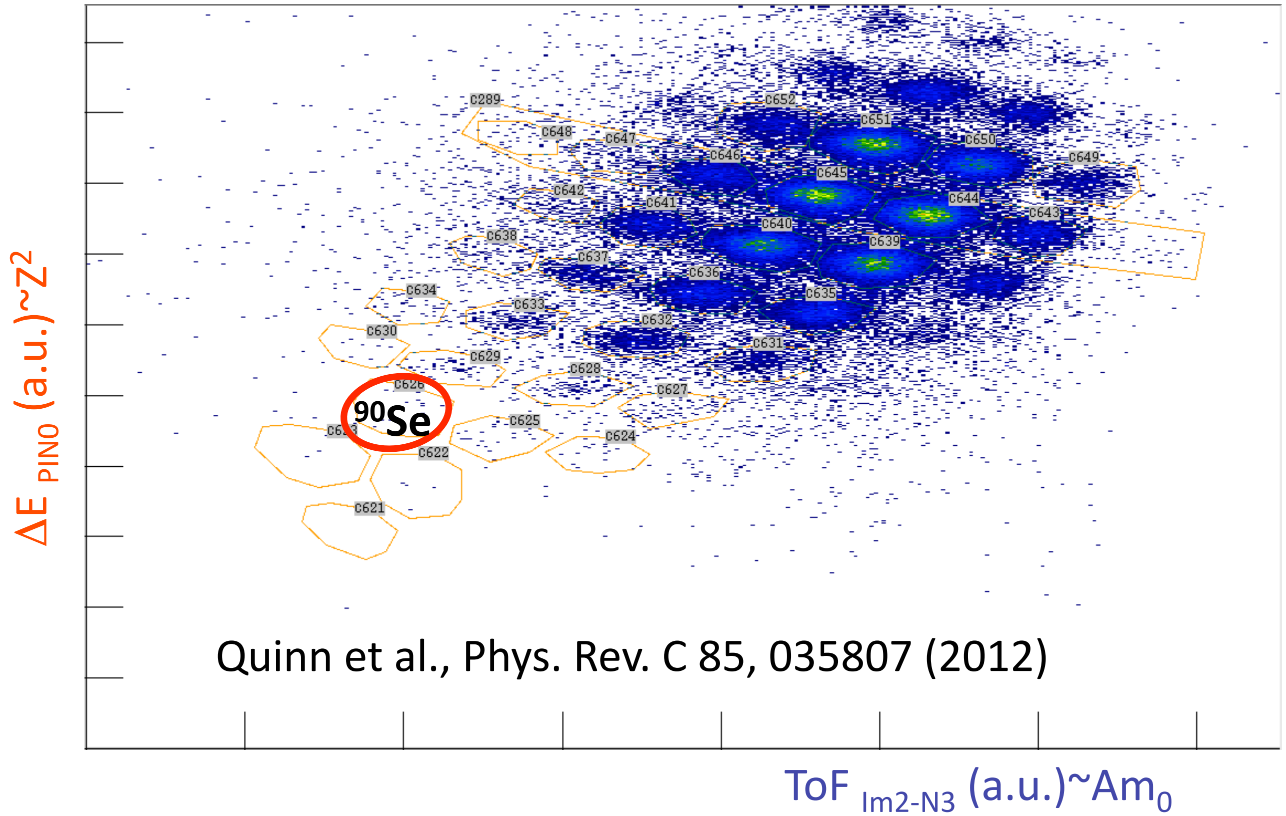


→need to readjust r-process model parameters

→Can obtain Experimental constraints for r-process models from observations and solid nuclear physics

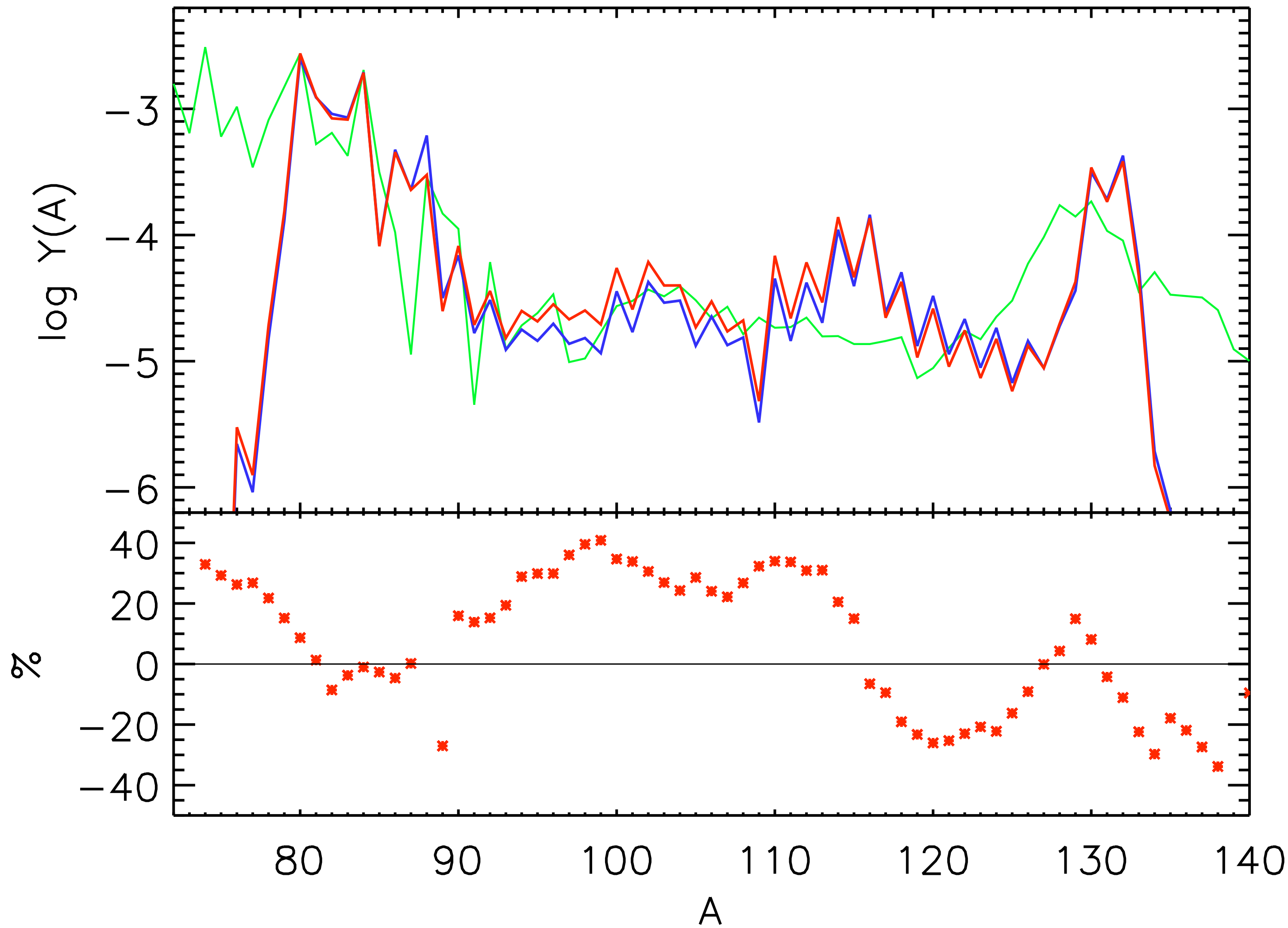
N=56 subshell with Z=34???

Fragmentation of 120 MeV/u ^{136}Xe beam



		Implantations	Maximum Likelihood Method (ms)
^{87}As	27	12	$1450(550)^{+3900}_{-1250}$
^{88}As	16	8	$200(10)^{+200}_{-90}$
^{88}Se	144	74	$650(35)^{+175}_{-140}$
^{89}Se	180	90	$345(25)^{+95}_{-80}$
^{90}Se	70	30	$195(10)^{+95}_{-65}$

Impact of ^{90}Se half-life on r-process models

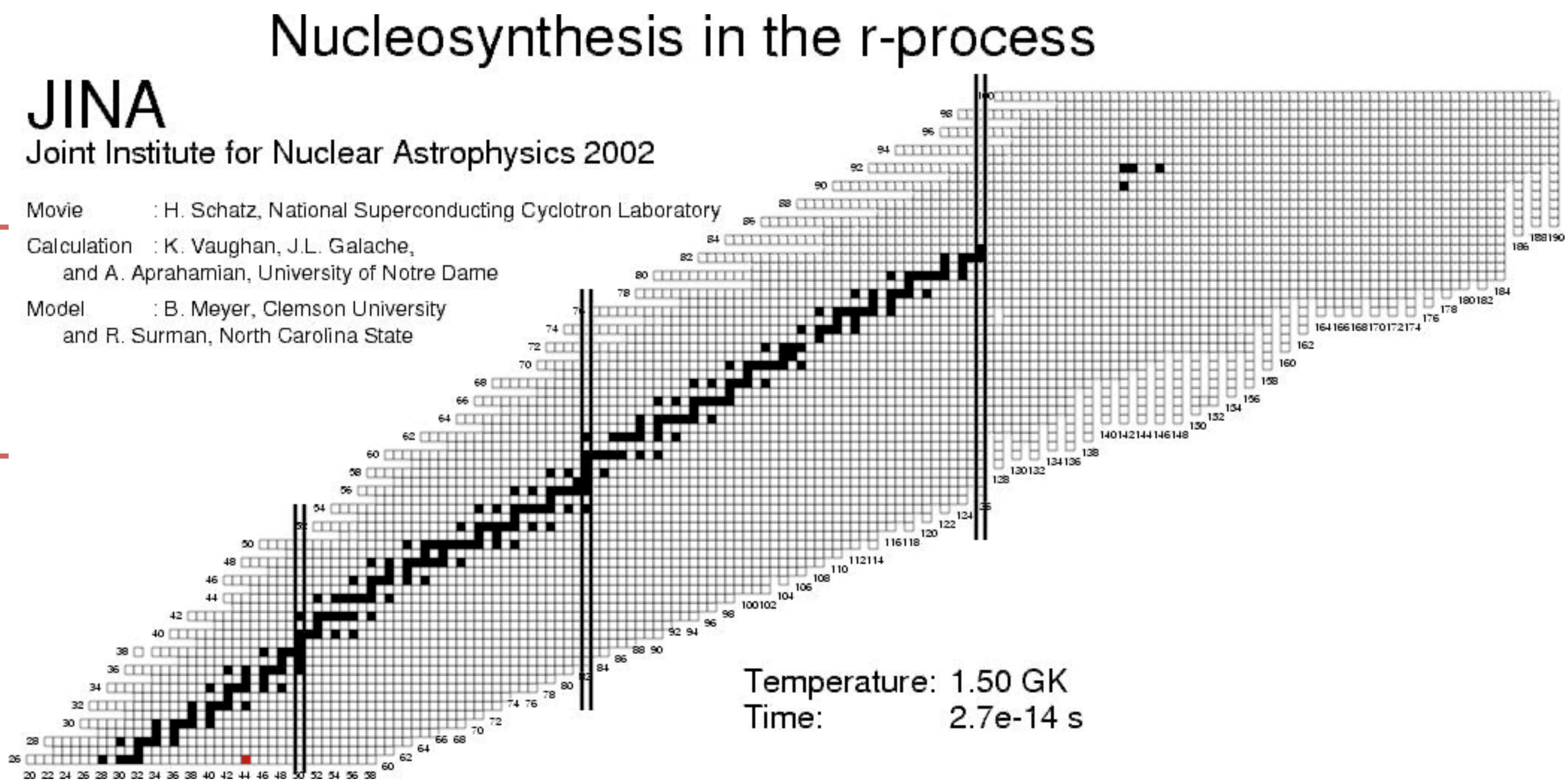


Quinn et al., Phys. Rev. C 85, 035807 (2012)

How do you decide which nuclei to measure???

Pt –

Xe –



Masses
beta-decay half-lives

So, What are we doing?

Simulations….. Varied astrophysical conditions
varied seed nuclei
varied mass models

Input astrophysical conditions

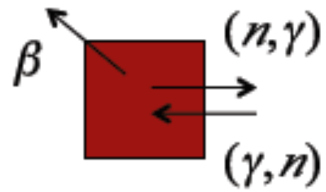
Temperature/density
neutron/seed ratios
Freeze-out times

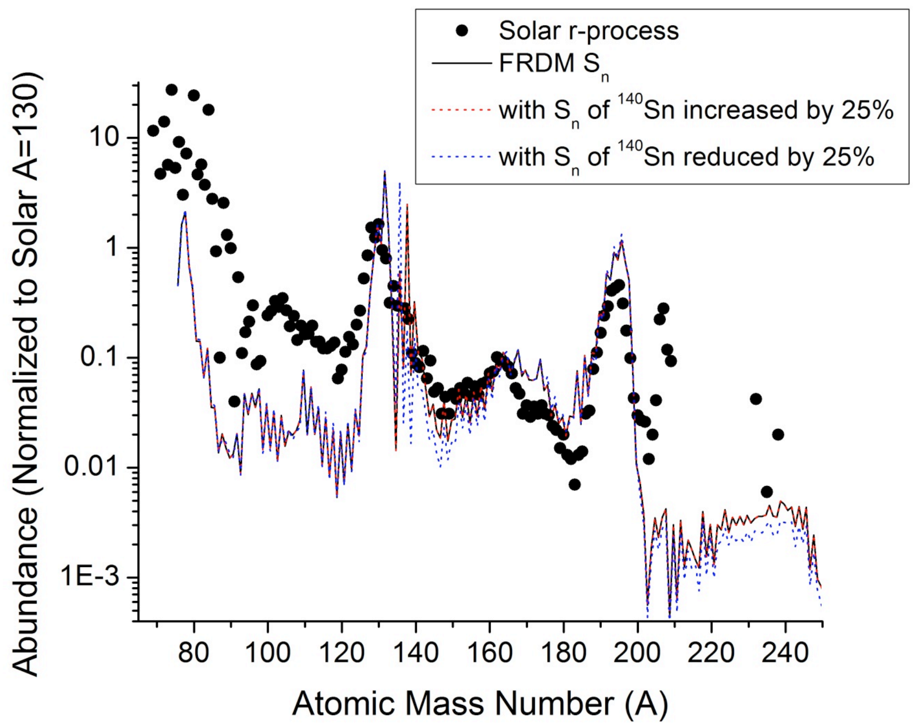
Input nuclear physics

masses
n-capture rates
beta decay half-lives
(fission recycling, alpha recycling, neutrino interactions off)

Neutron separation energy sensitivity study

S. Brett, I. Bentley, N. Paul, R. Surman, A. Aprahamian





plot by I. Bentley

Start with a baseline simulation

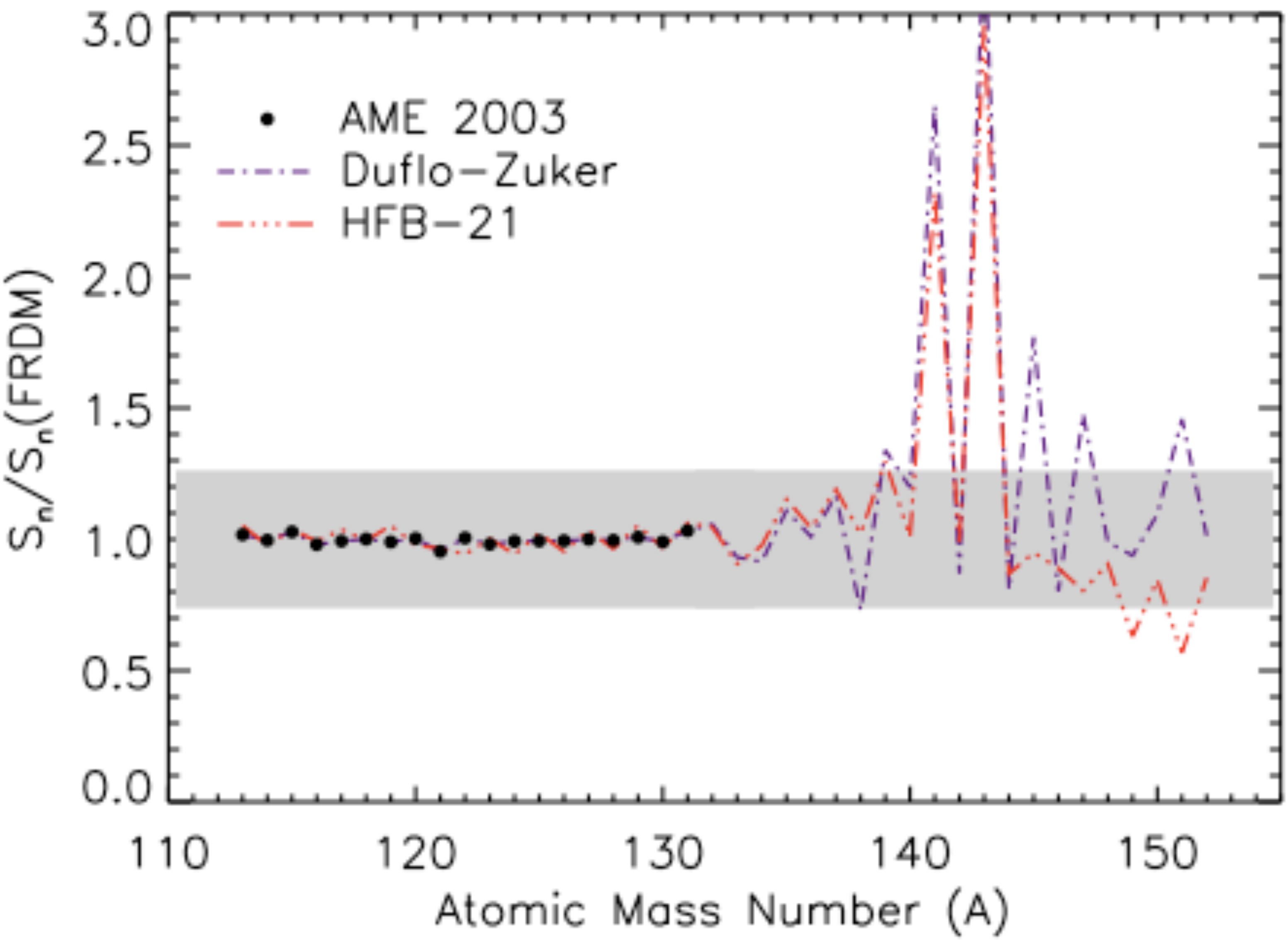
(here, the H-event conditions from Qian et al were used)

Vary one separation energy by 25% and rerun the simulation

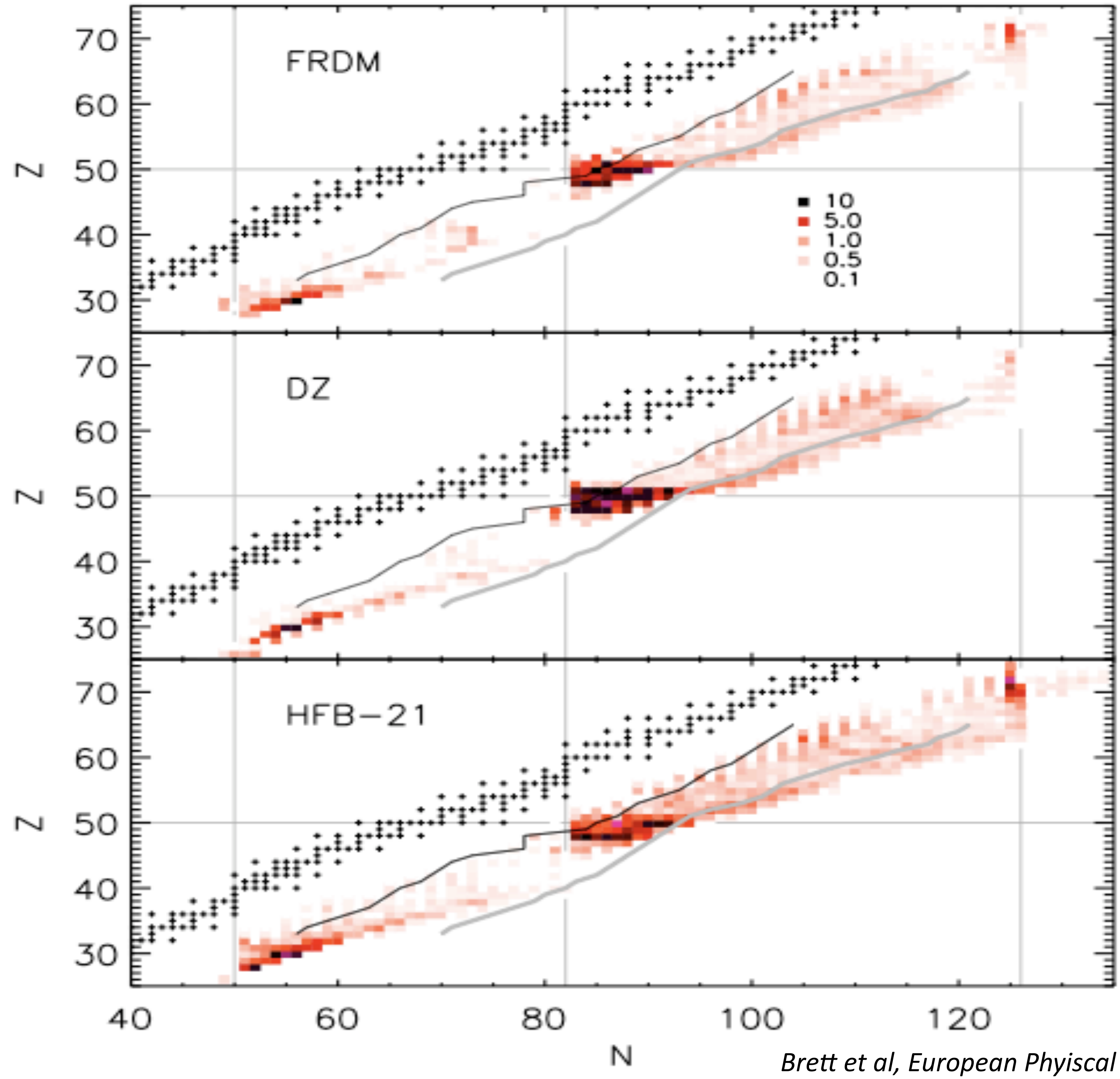
Repeat 6957 times

(twice for each heavy nucleus in the network)

$$\Delta Y_{S_n(Z_i,A_i)\pm 25\%} = \sum_A \left[Y_{baseline}(A) - Y_{S_n(Z_i,A_i)\pm 25\%}(A) \right]$$

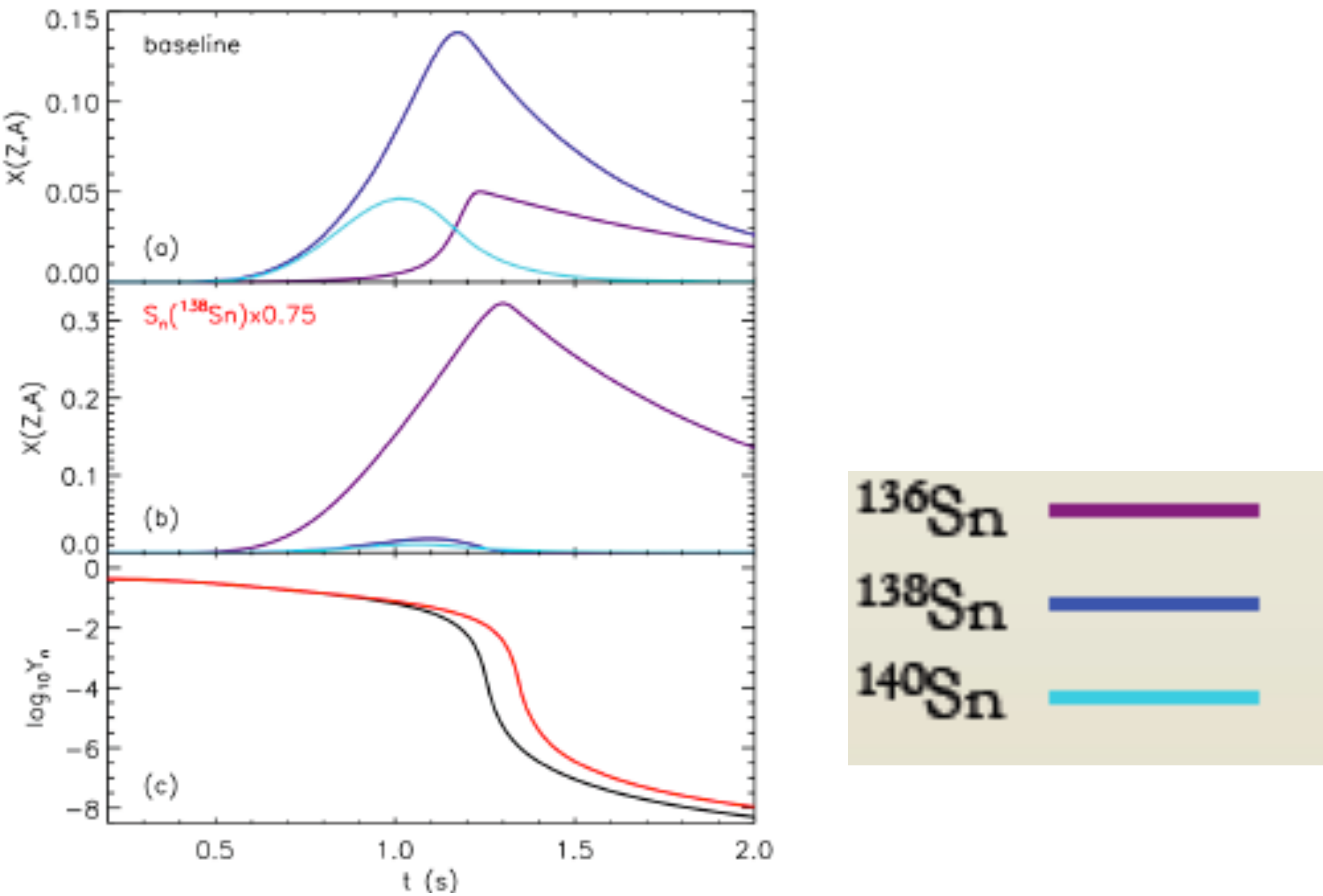


AME 2003
Duflo-Zuker
HFB-21
S_n/S_n(FRDM)
Atomic Mass Number (A)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
110
120
130
140
150



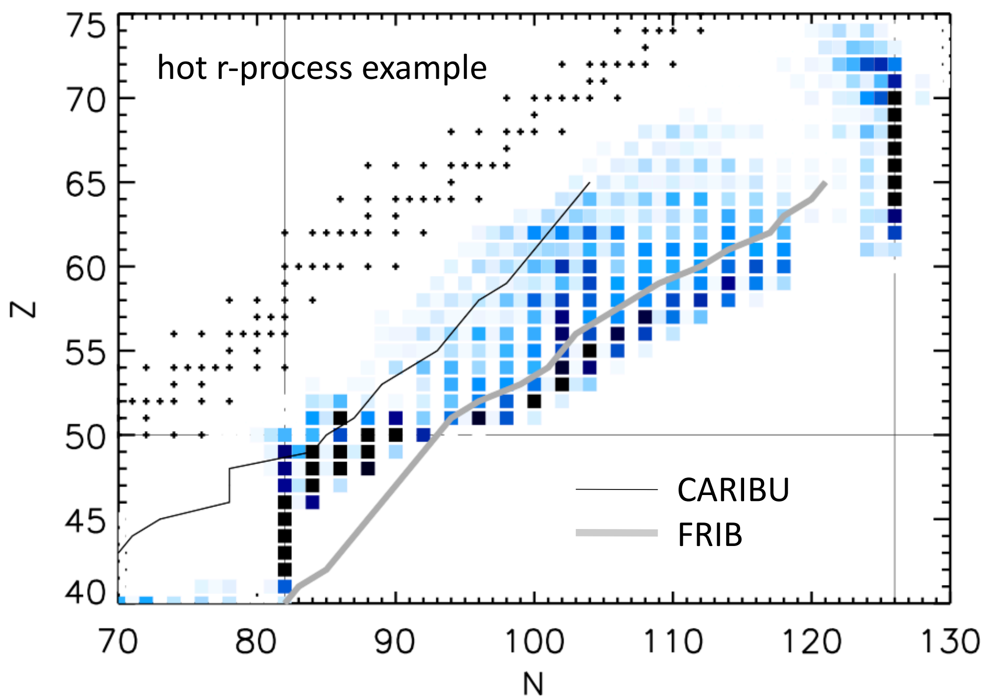
Brett et al, European Phyiscal Journal A (2012)

What is the mechanism behind observed sensitivities?



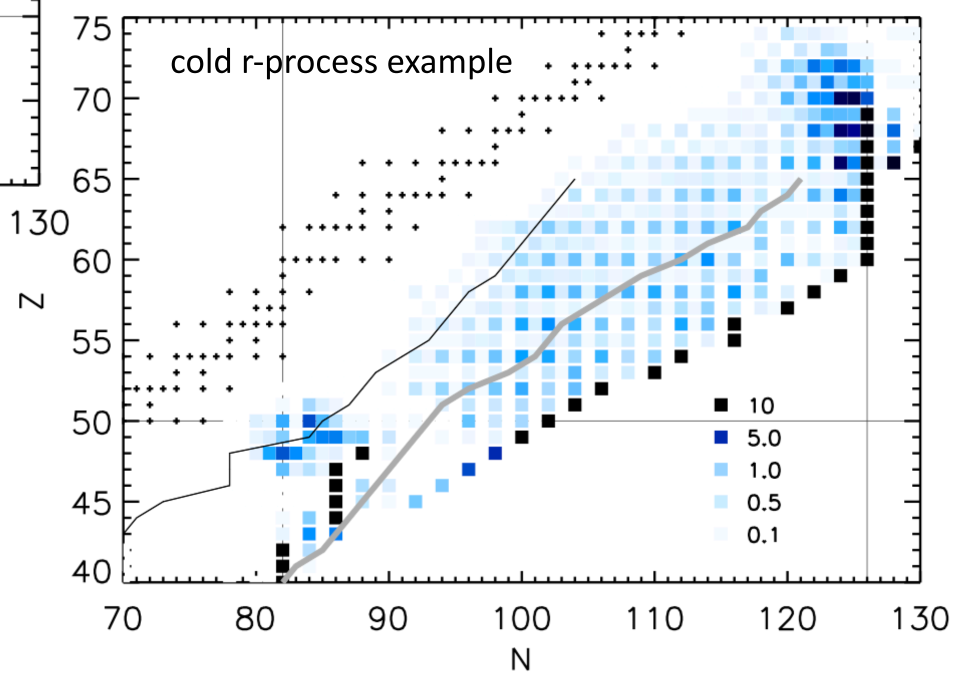
Beta Decay Rates

Cass et al, in preparation (2012)



$$\lambda_\beta(Z,A) \times / \div 10$$

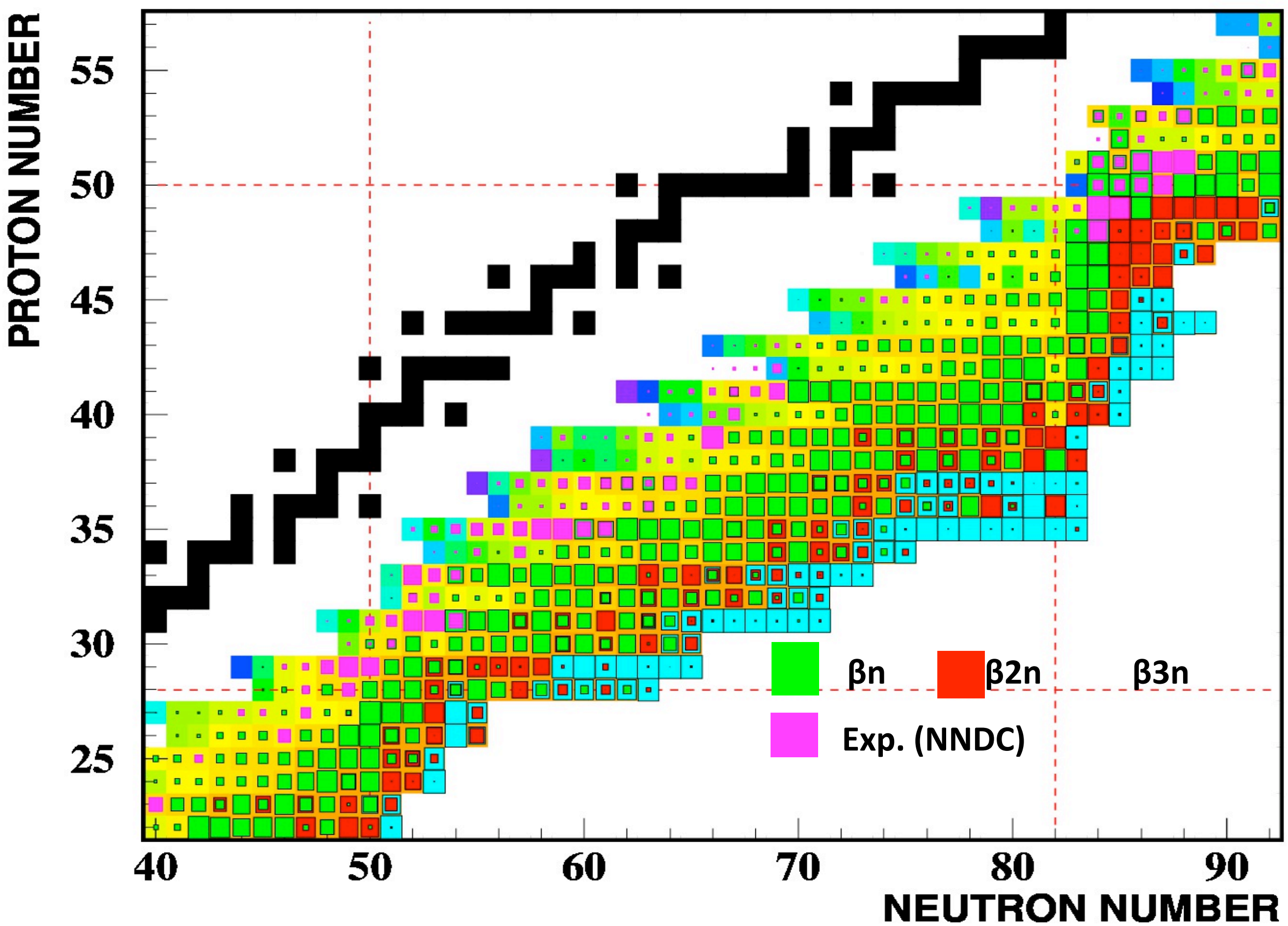
$$F = 100 \sum \left| X_{baseline}(Z,A) - X(Z,A) \right|$$



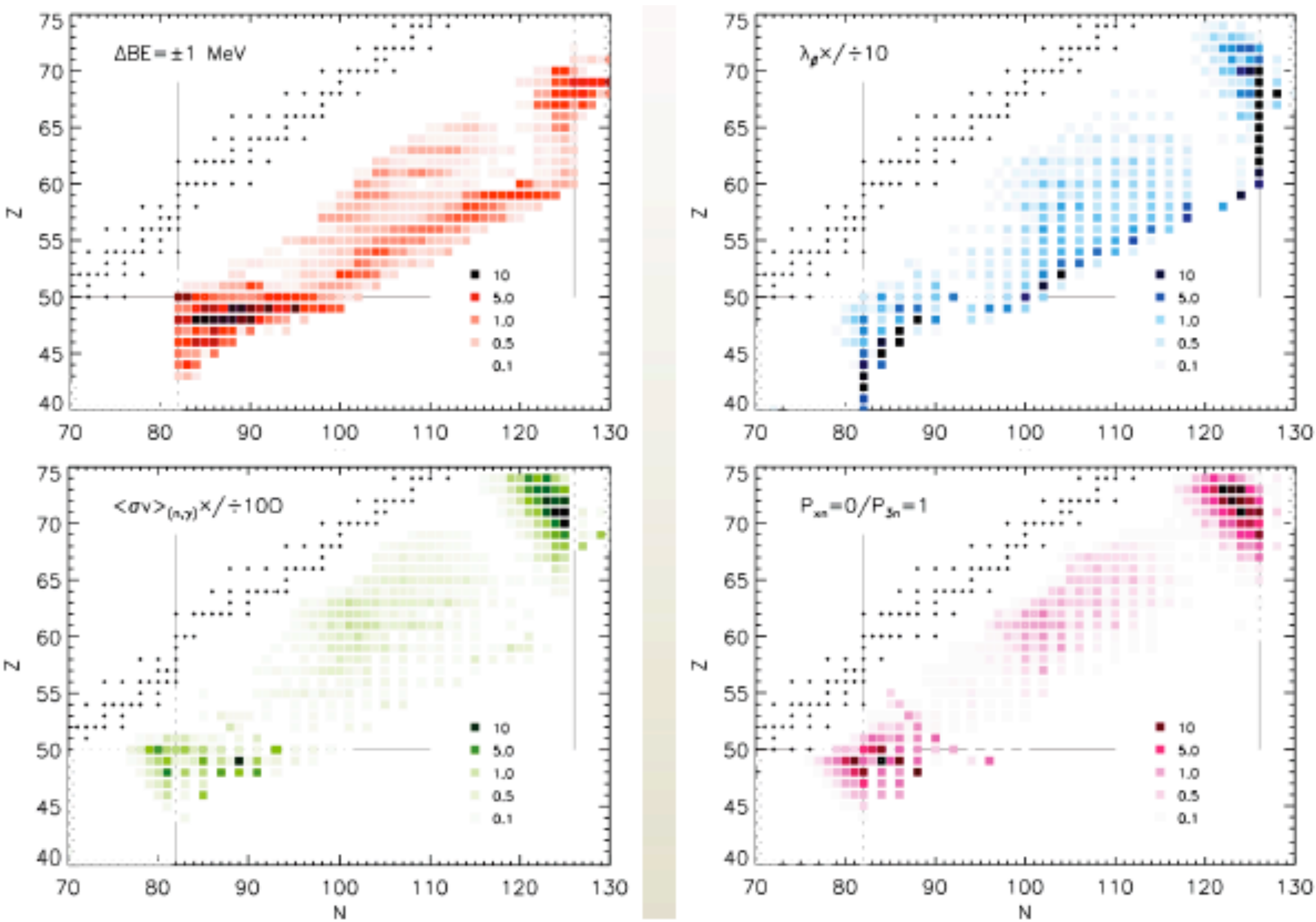
To start, proceed as in neutron separation energy study:

Vary one beta decay rate by an order of magnitude, rerun the simulation, and compare the final abundance pattern to the baseline

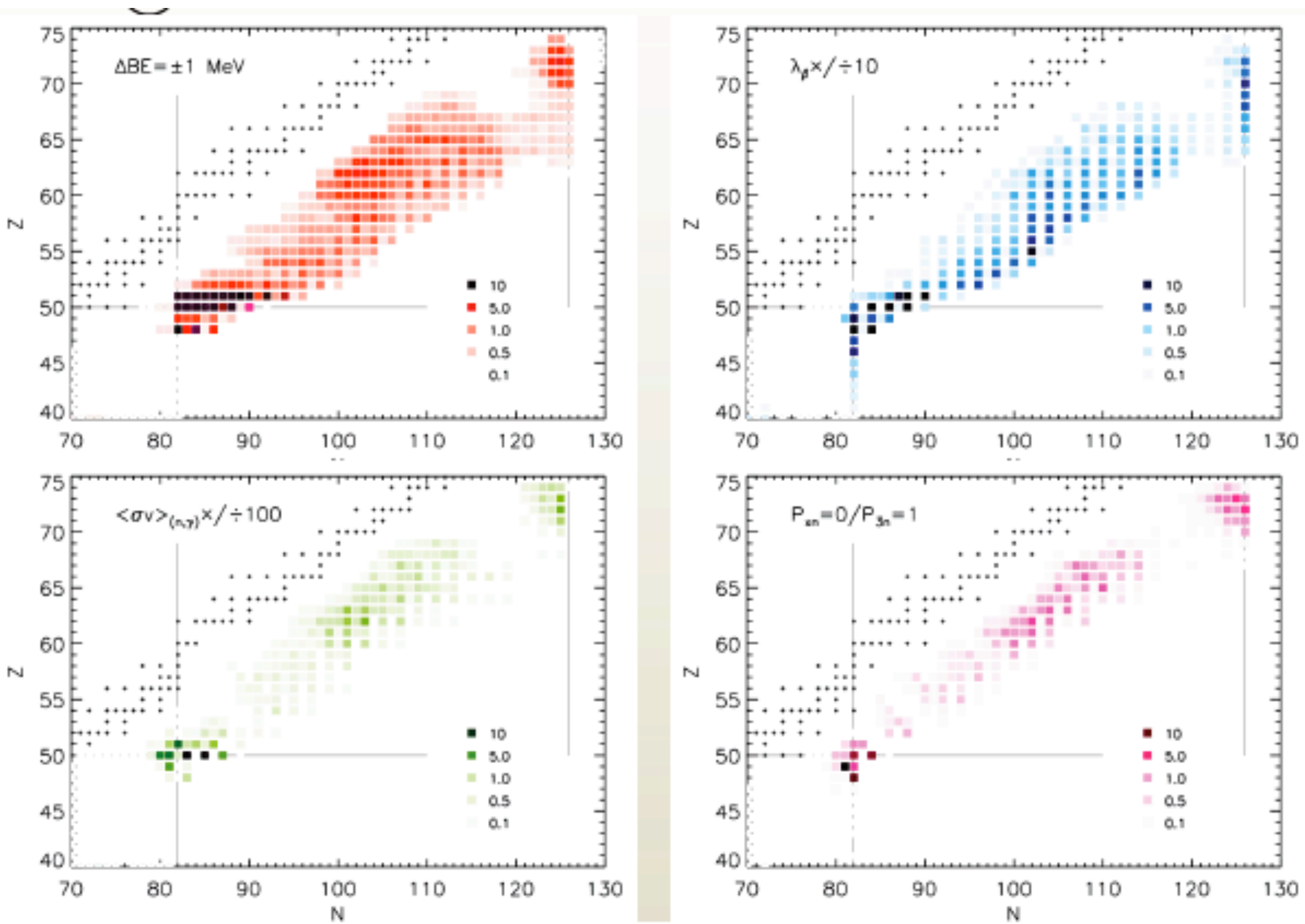
Beta-n channels



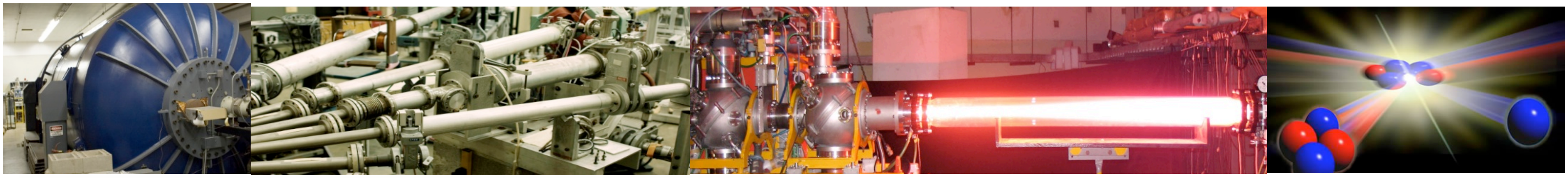
Data from Möller, Nix, Kratz, Atomic Data and Nuclear Data Tables, Vol. 66, p.131
Plot from R. Grzywacz



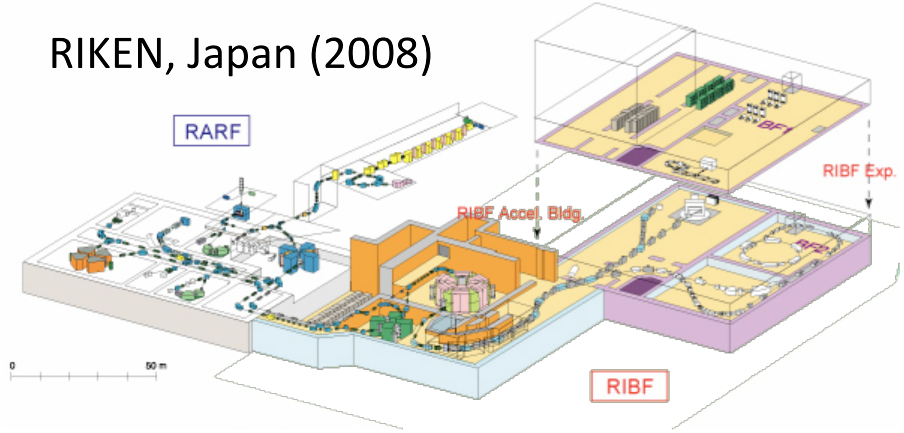
ΔBE=±1 MeV
λ_β×/÷10
<σv>_(n,γ)×/÷100
P_xn=0/P_3n=1
10
5.0
1.0
0.5
0.1
Z
N



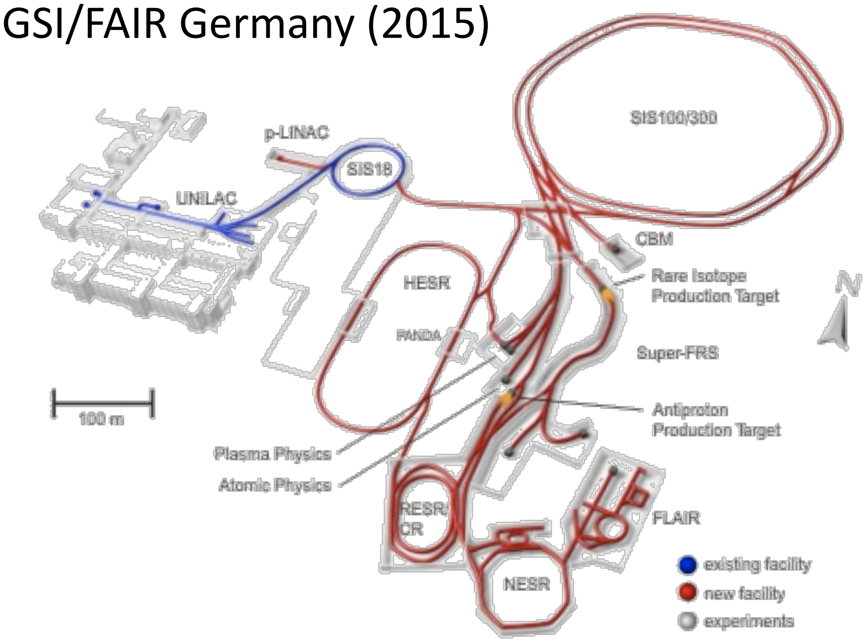
ΔBE=±1 MeV
λβ×/÷10
<σv>(n,γ)×/÷100
Pₙ=0/P₃ₙ=1
Z
N
10
5.0
1.0
0.5
0.1



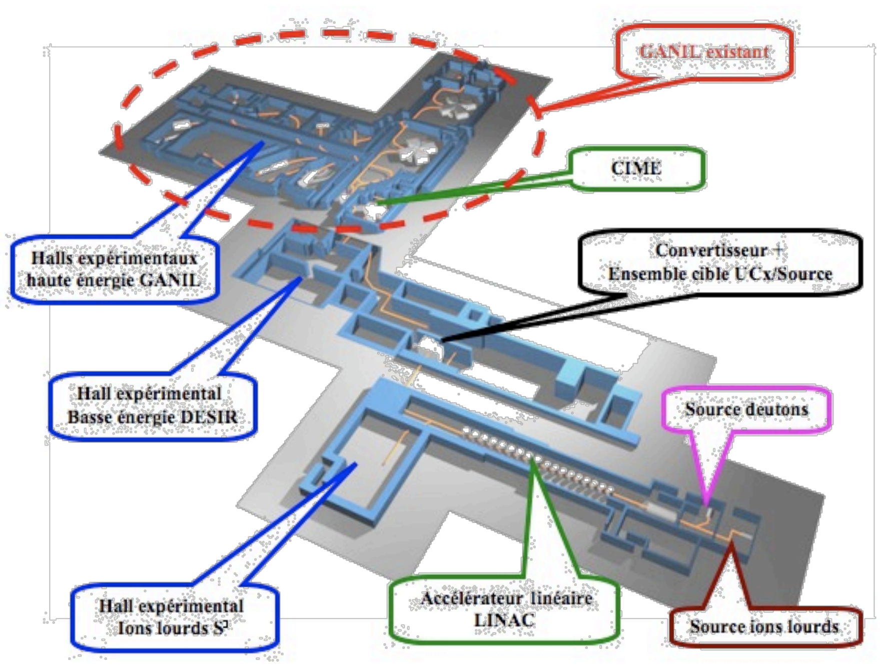
RIKEN, Japan (2008)



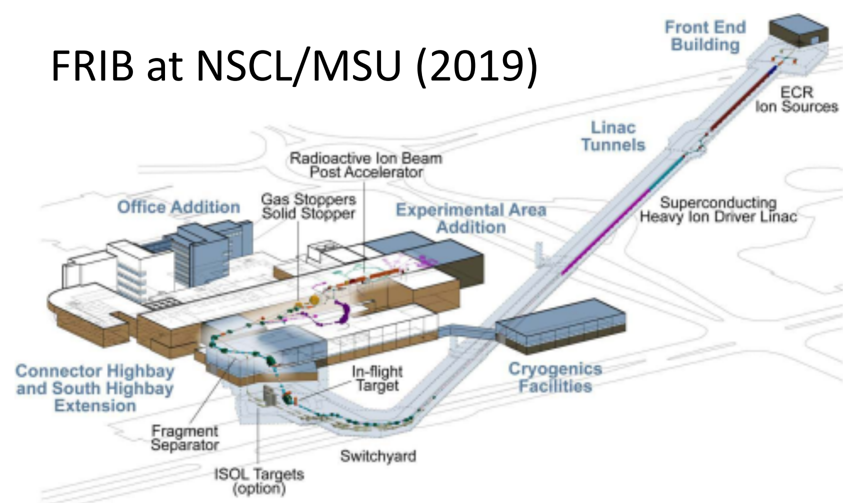
GSI/FAIR Germany (2015)



GANIL, France (2013)



FRIB at NSCL/MSU (2019)



summary

We have carried out the first quantitative/ comprehensive sensitivity study of an r-process simulation to masses, beta decay rates, neutron capture cross sections.

Goal is to use Nuclear Physics to put

Constraints on potential r-process sites.

- consistent set of nuclei that we should measure

Sensitivity Study Masses

Samuel Brett

Ian Bentley

Nancy Paul

Rebecca Surman

A^2

Sensitivity Study β-decay rates

Julie Cass

Giuseppe Passucci

Rebecca Surman

A^2

ΔY for FRDM

Nucleus	ΔY
^{136}Cd	20.2
^{140}Sn	12.1
^{135}Cd	8.80
^{83}Cu	8.42
^{139}Sn	8.19
^{142}Sb	5.64
^{135}Sn	5.44
^{133}Cd	5.38
^{140}Sb	5.25
^{134}Cd	5.23
^{82}Cu	4.14
^{134}In	4.14
^{131}Pd	3.29
^{137}Sn	2.94
^{141}Sn	2.91
^{83}Zn	2.89
^{85}Zn	2.71
^{85}Cu	2.66
^{130}Pd	2.39
^{132}Pd	2.39

ΔY for ETFSI-Q

Nucleus	ΔY
^{140}Sn	20.1
^{136}Cd	19.0
^{142}Sn	17.3
^{137}Cd	15.3
^{79}Ni	12.5
^{80}Ni	12.0
^{135}Cd	11.5
^{134}Cd	11.5
^{138}Cd	8.57
^{132}Pd	7.66
^{130}Pd	7.34
^{132}In	7.33
^{129}Pd	5.12
^{139}Sn	4.63
^{131}Pd	4.37
^{138}In	3.98
^{139}In	3.95
^{86}Zn	3.21
^{141}Sn	2.92
^{85}Zn	2.86

ΔY for DZ

Nucleus	ΔY
^{80}Ni	13.6
^{79}Ni	9.96
^{138}Cd	7.08
^{137}Cd	5.49
^{83}Cu	4.27
^{131}Pd	3.54
^{82}Cu	3.36
^{132}Pd	3.12
^{136}Cd	3.00
^{130}Pd	2.97
^{86}Zn	2.84
^{129}Pd	1.88
^{85}Zn	1.81
^{134}Ag	1.49
^{142}Sn	1.42
^{135}Ag	1.39
^{135}Cd	1.36
^{133}Cd	1.10
^{141}Sn	1.08
^{144}Sn	1.07

ΔY for HFB21

Nucleus	ΔY
^{136}Cd	22.7
^{137}Cd	10.8
^{138}Cd	10.4
^{135}Cd	6.97
^{140}Sn	5.97
^{130}Pd	5.46
^{83}Cu	5.23
^{142}Sn	4.66
^{134}Cd	4.57
^{141}Sn	4.21
^{86}Zn	3.82
^{133}Cd	3.52
^{132}Cd	3.04
^{137}Sn	2.86
^{82}Cu	2.63
^{138}In	2.47
^{139}In	2.23
^{129}Pd	1.95
^{131}Pd	1.81
^{131}Ag	1.69

ISNAP

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