Light Element Primary Process and Rare Isotope Experiments

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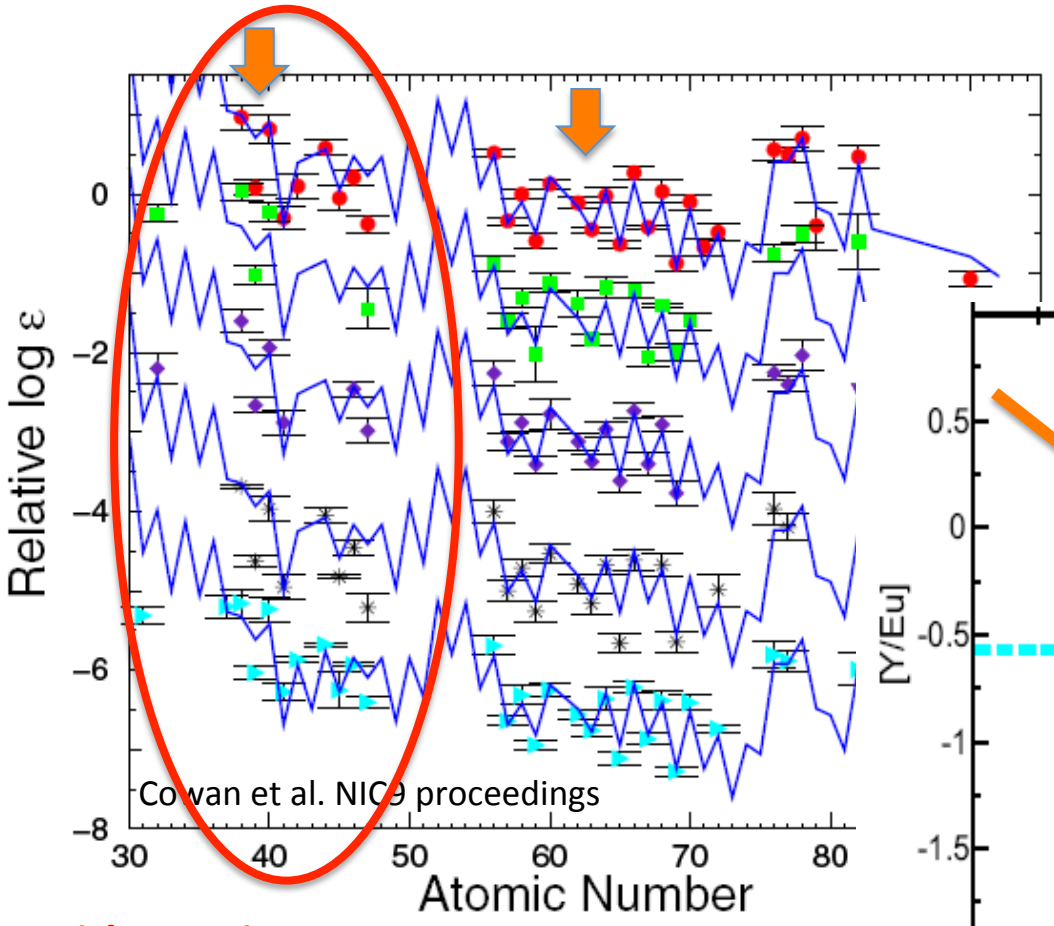
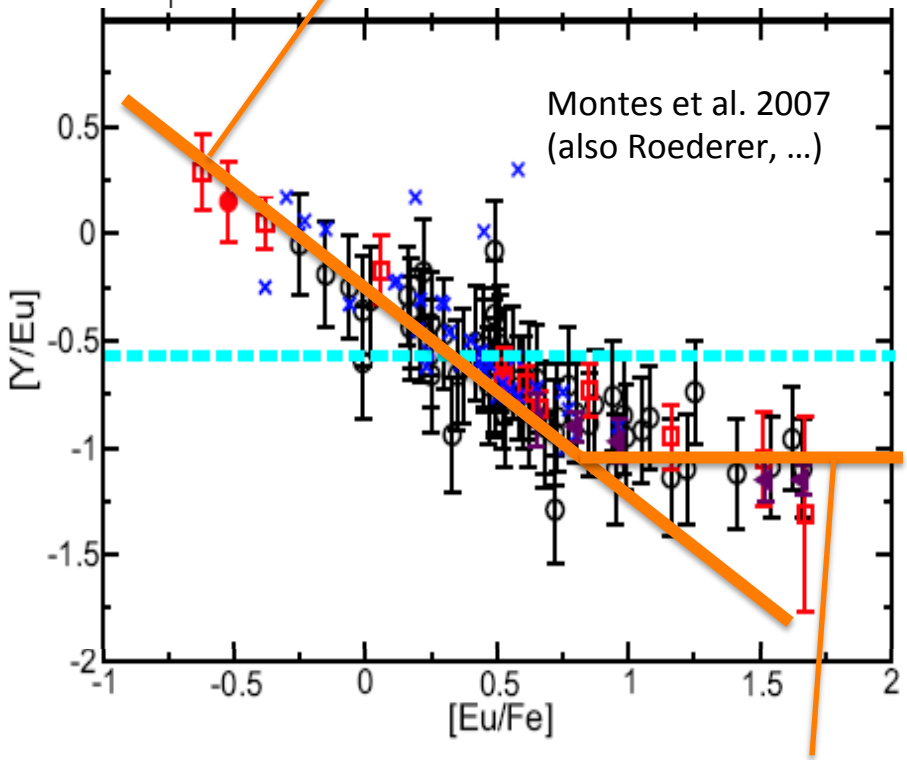
R-process enhanced metal poor stars



Fairly consistent pattern
(not the huge scatter)
→ Part of main r-process??

-1 slope:
[Y/Eu]=[Y/Fe]-[Eu/Fe]
→ uncorrelated production



Hint for horizontal slope:
→ Y is also part of main r pattern
(for large r-enrichment)

See Roederer et al. 2010 for alternative interpretation
Also others e.g. Burris et al. 2009

What is the LEPP ?

Possible "LEPP" mechanisms (need experimental data for all):

No isotopic information → wide range of possibilities
(Except for LEPP needed to fix Travaglio s-process: requires production of s-only nuclei)

- Primary s-process (Pignatari et al. 2008, …)
- Charged particle freezout with no or few neutrons (Farouqi et al. 2010, Qian&Wasserburg 2007)
- A weak r-process (Qian & Wasserburg, …)
- νp-process (Froehlich et al. 2006, Pruet et al. 2006) (can also fix problem of light p-nuclei?)

Rare isotope processes

In addition, for determining solar contribution need experimental data on:

- s-process (to subtract)
- r-process (to subtract as solar minus s is not automatically r anymore)

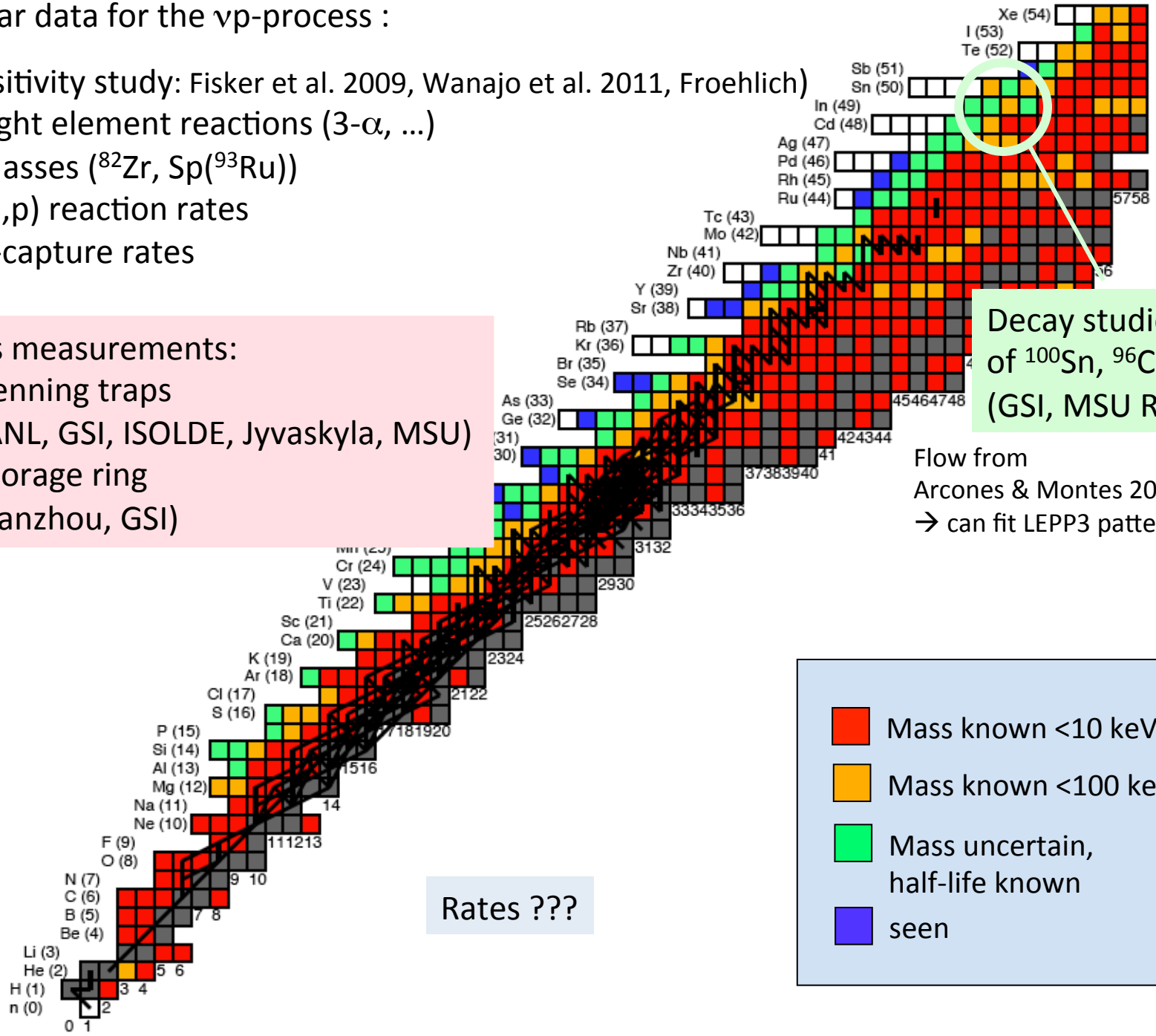
Nuclear data for the νp-process :

(Sensitivity study: Fisker et al. 2009, Wanajo et al. 2011, Froehlich)

- Light element reactions (3-α, …)
- Masses (^{82}Zr, Sp(^{93}Ru))
- (n,p) reaction rates
- p-capture rates

Mass measurements:

- Penning traps
  (ANL, GSI, ISOLDE, Jyvaskyla, MSU)
- Storage ring
  (Lanzhou, GSI)



Decay studies
of ^{100}Sn, ^{96}Cd
(GSI, MSU RFFS)

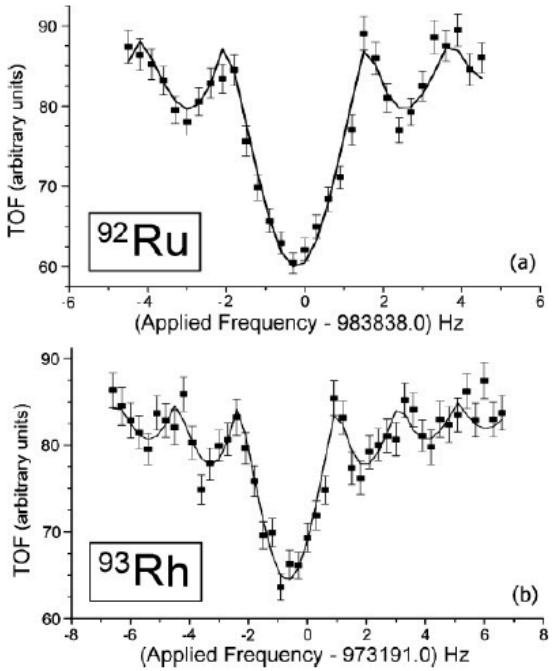
Flow from
Arcones & Montes 2011
→ can fit LEPP3 pattern

Rates ???

- Mass known <10 keV
- Mass known <100 keV
- Mass uncertain, half-life known
- seen

Proton separation energy of ^{93}Rh

Fallis et al. 2008 with CPT@ANL



Also Weber et al. 2008 with SHIPTRAP and JYFLTRAP

(^{93}Ru)

→ $S_p(^{93}Rh)$=2.00(1) MeV

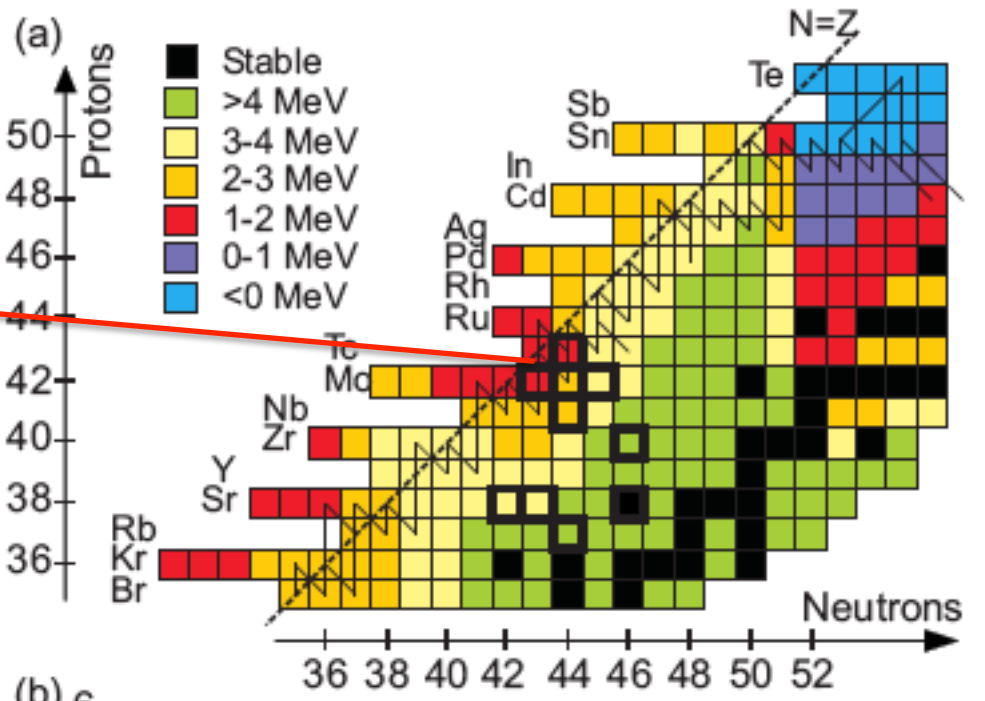
→Fisker: $S_p(^{93}Rh)$=2.00(1) MeV makes solution impossible (previous 2.0(5) MeV was ok – precision matters!

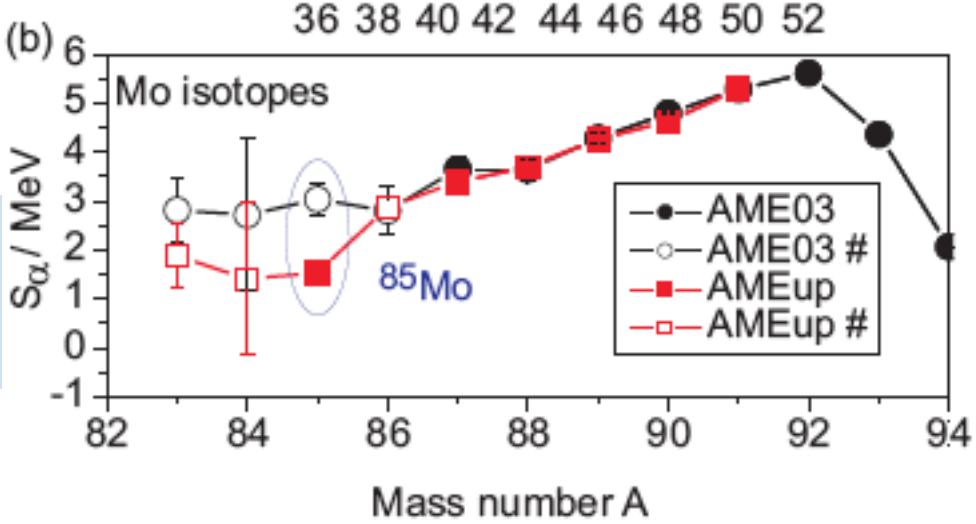
→Wanajo et al. 2011: 2.00(1) MeV is ok in his model ….

Mass measurements: systematic effects

SHIPTRAP (Haettner et al. 2010)

Experimental evidence for island of low α- separation energies



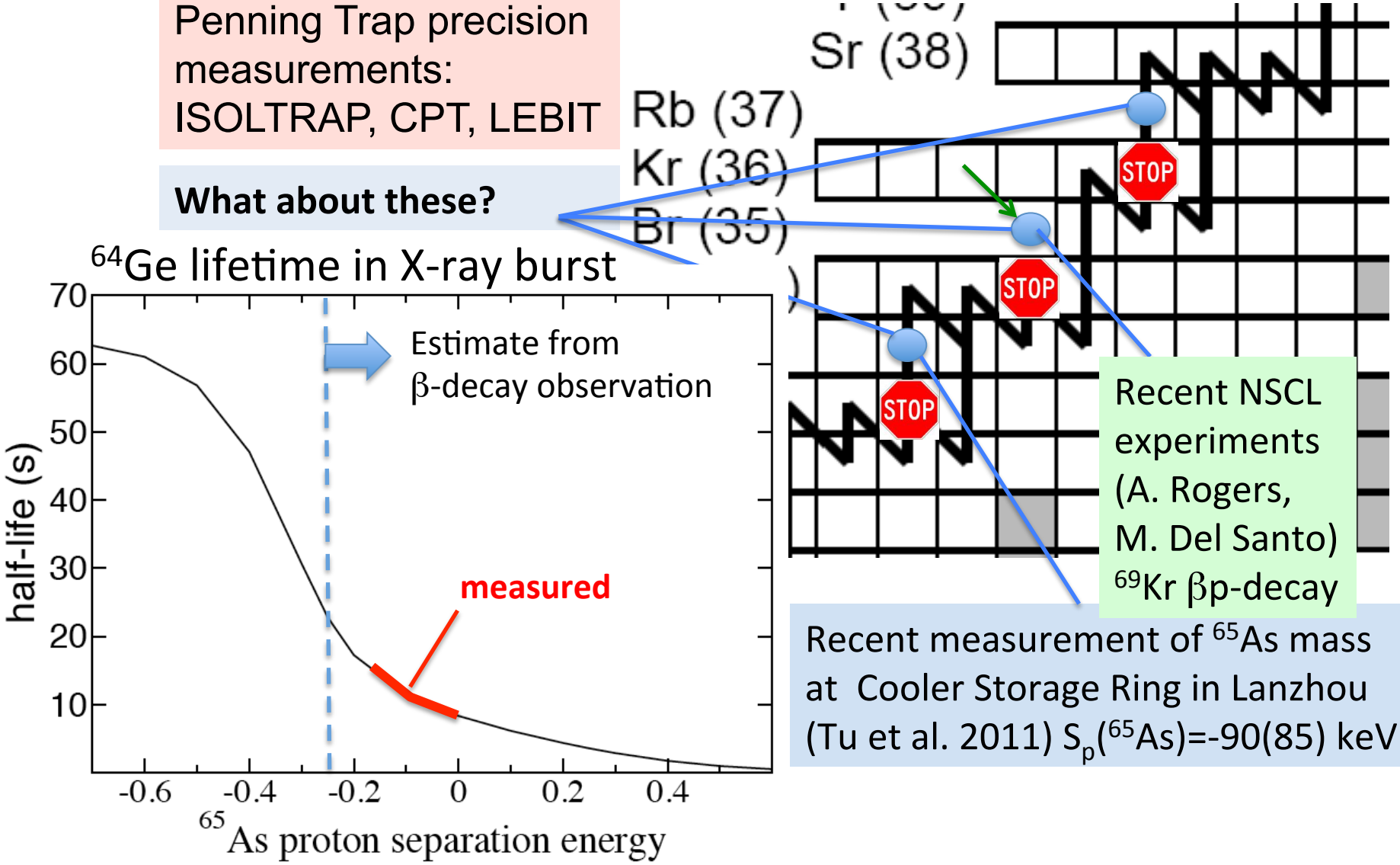


→ Its not just about uncertainties
Major systematic effects possible!

Direct mass measurements

Waiting point masses:
Penning Trap precision measurements:
ISOLTRAP, CPT, LEBIT

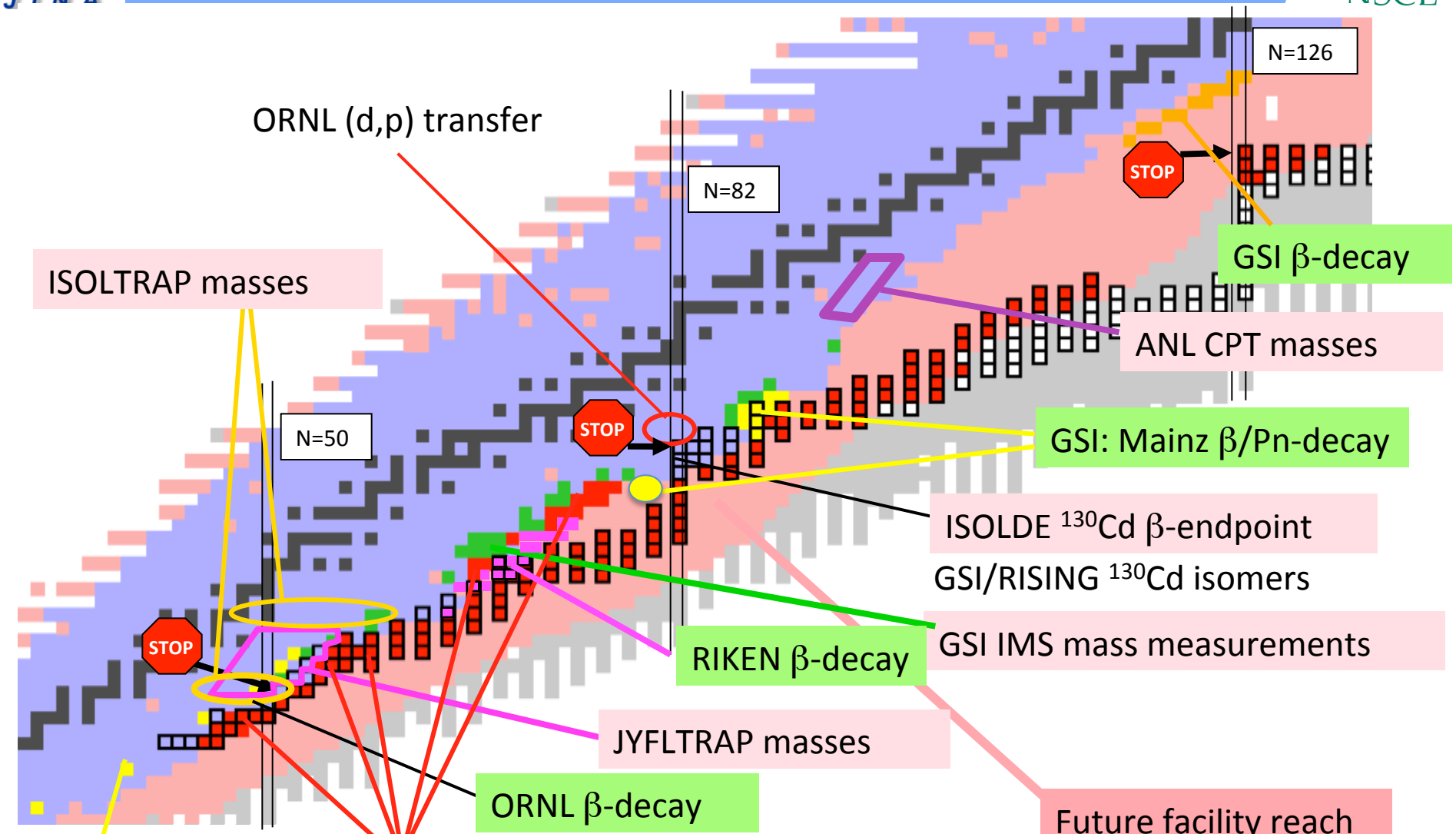
What about these?



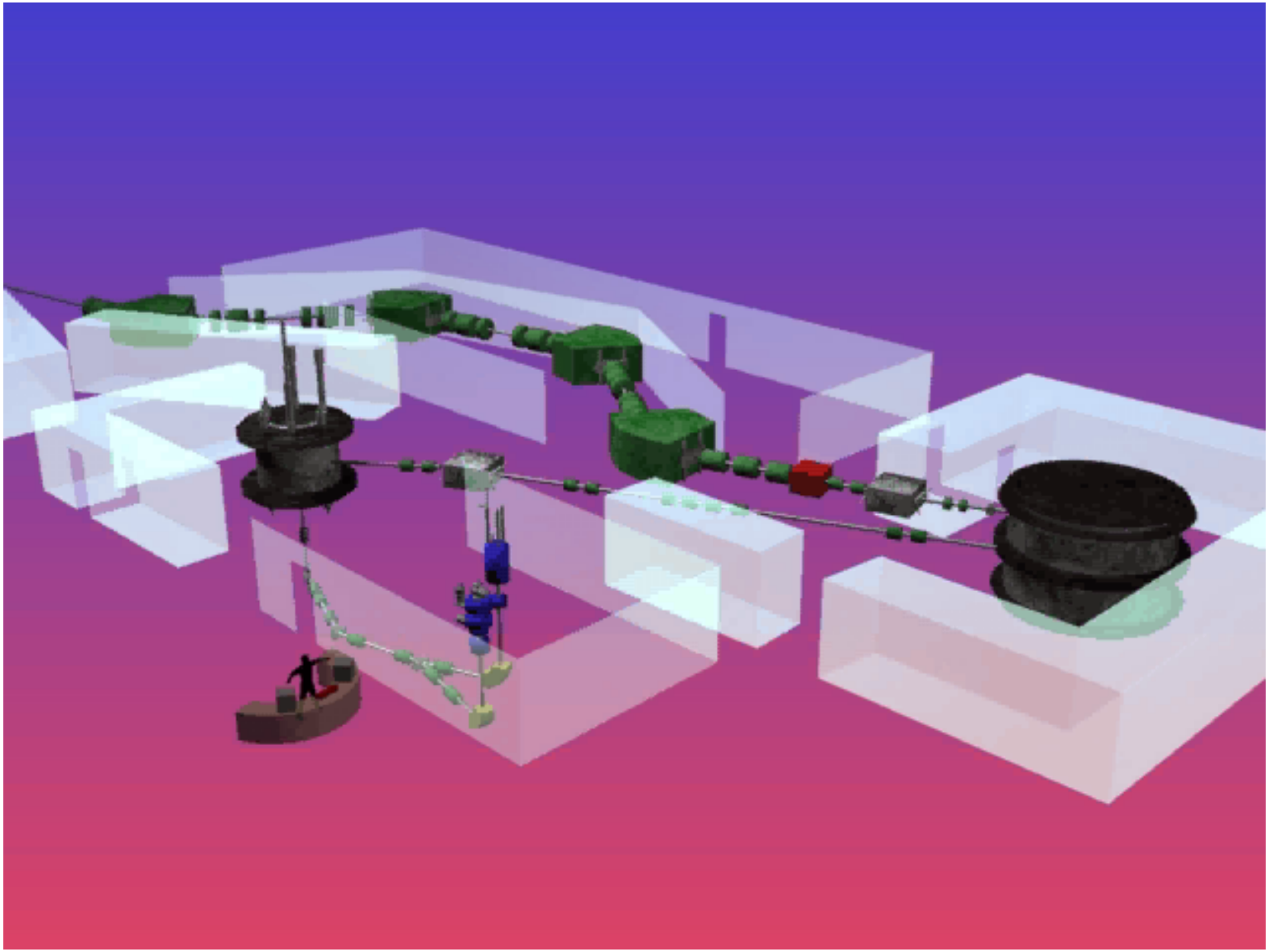
Recent measurement of ^{65}As mass at Cooler Storage Ring in Lanzhou (Tu et al. 2011) $S_p(^{65}As)$=-90(85) keV

The Joint Institute for Nuclear Astrophysics

Recent r-process related experiments



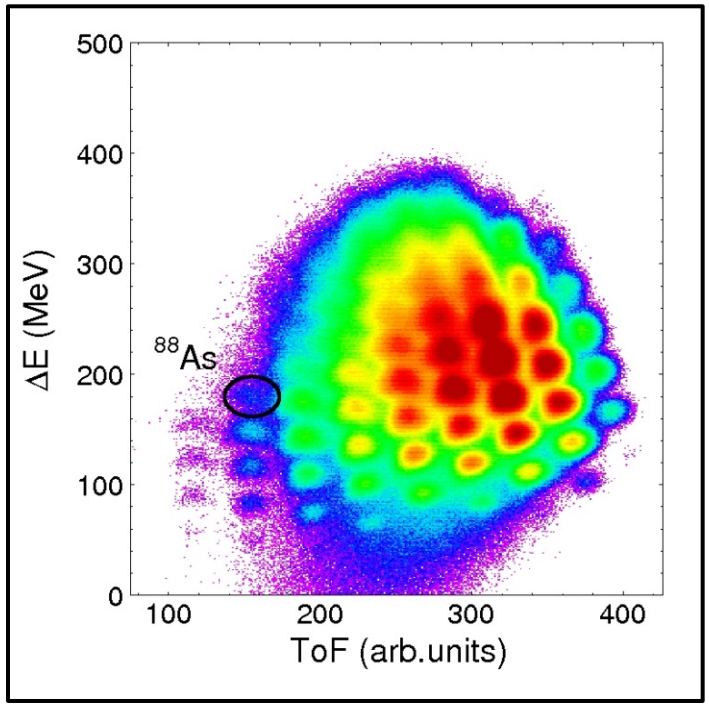
Making r-process nuclei: example MSU

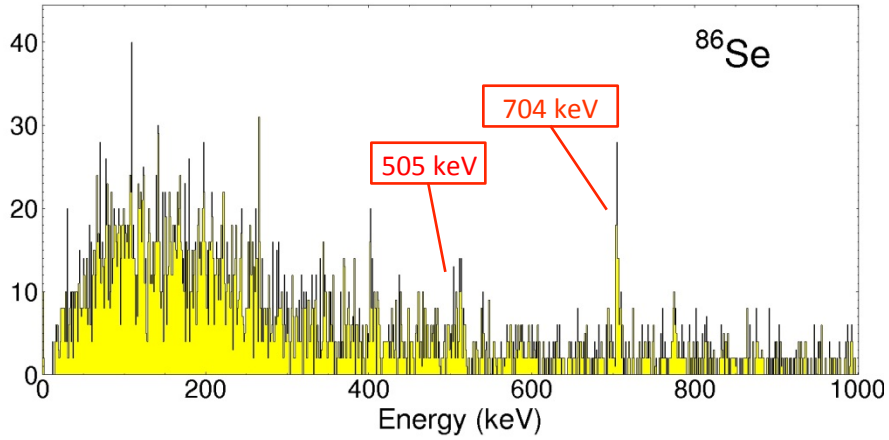


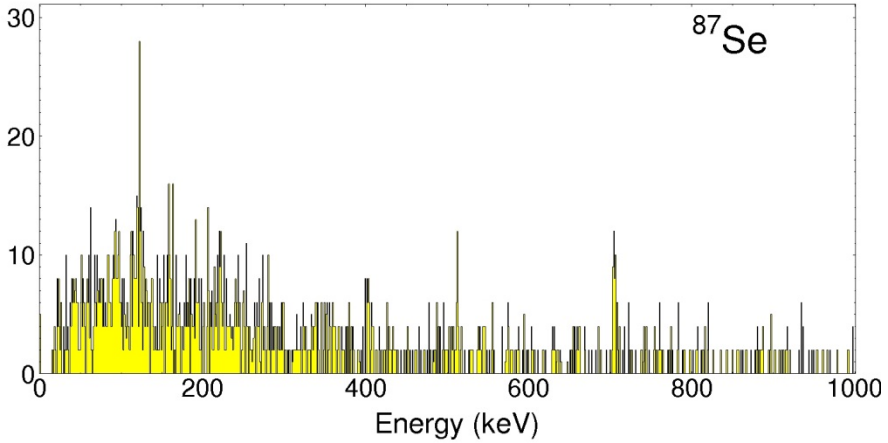
2011 Summer Campaign at NSCL

Analysis in progress

Pereira/Walters

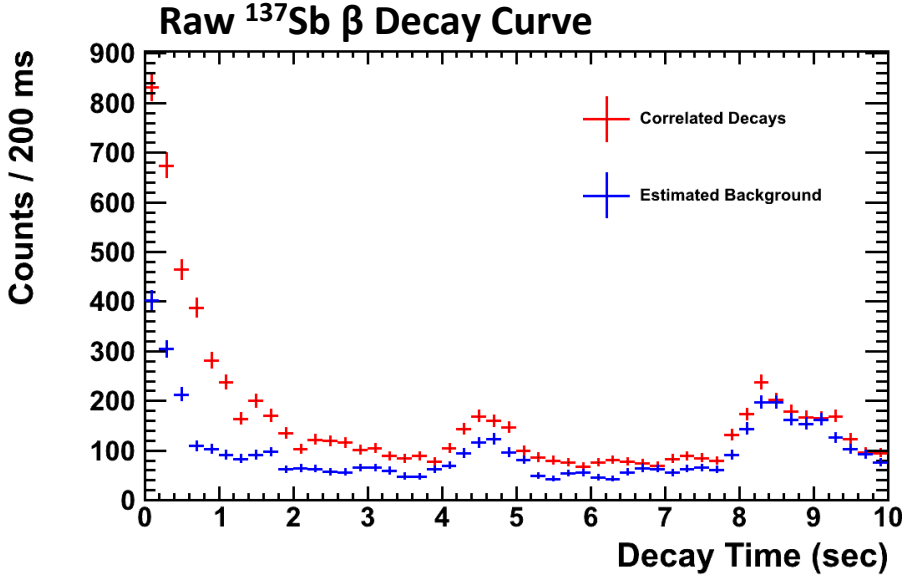


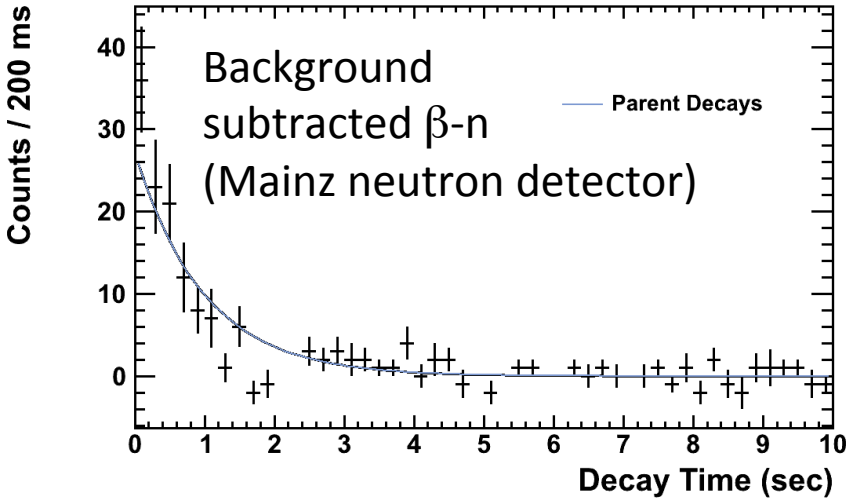


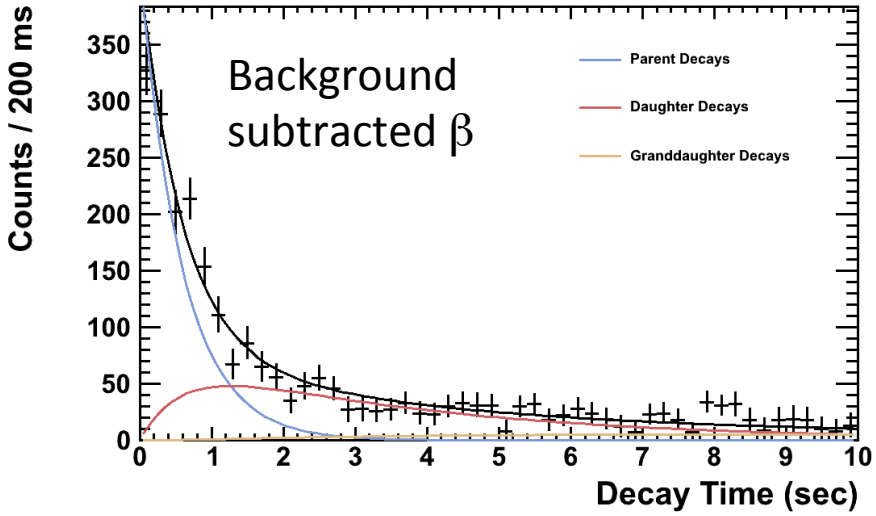


GSI experiment (GSI/Mainz/MSU/ND) (Santi, Kessler, Smith)

36	Cs137	Cs138	Cs139	Cs140	Cs141	Cs142	Cs143	Cs144	Cs145	Cs146	Cs147
0	> 99	> 99	> 99	63.70	24.94	1.70	1.78	1.01	0.59	0.32	0.23
35		Xe137	Xe138	Xe139	Xe140	Xe141	Xe142	Xe143	Xe144	Xe145	Xe146
		> 99	> 99	39.68	13.60	1.73	1.24	0.30	1.15	0.90	
	I135	I136	I137	I138	I139	I140	I141	I142	I143	I144	I145
	> 99	83.40	24.50	6.49	2.28	0.86	0.43				
33	Te134	Te135	Te136	Te137	Te138	Te139	Te140	Te141	Te142	Te143	Te144
	> 99	19.00	17.50	2.49	1.40						
32	Sb133	Sb134	Sb135	Sb136	Sb137	Sb138	Sb139	Sb140	Sb141	Sb142	Sb143
	> 99		1.66	0.82							
31	Sn132	Sn133	Sn134	Sn135	Sn136	Sn137	Sn138	Sn139	Sn140	Sn141	Sn142
0	39.70	1.20	1.12								
0	In131	In132	In133	In134	In135	In136	In137	In138	In139	In140	In141

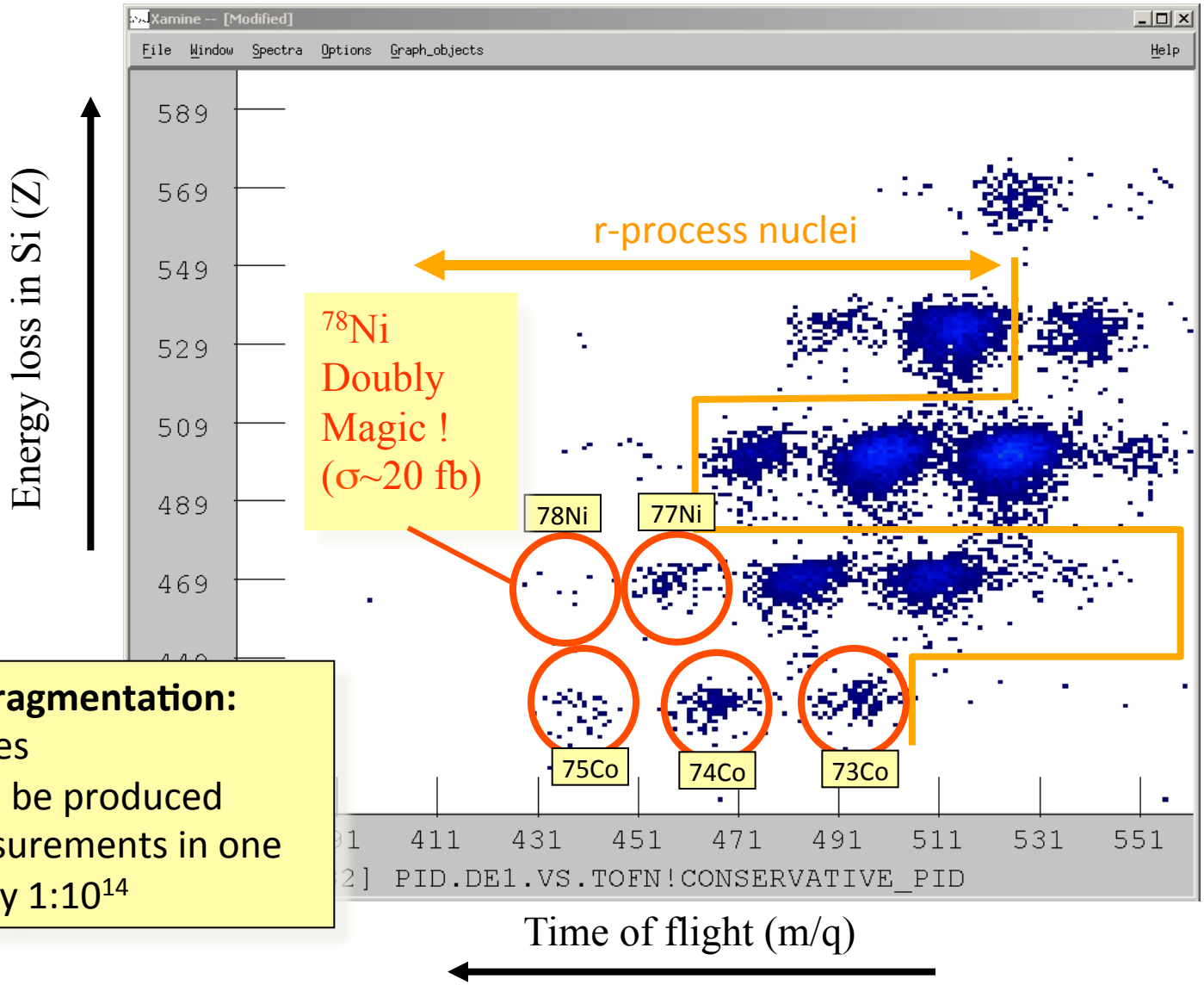






Thanks to Karl Smith

Particle Identification

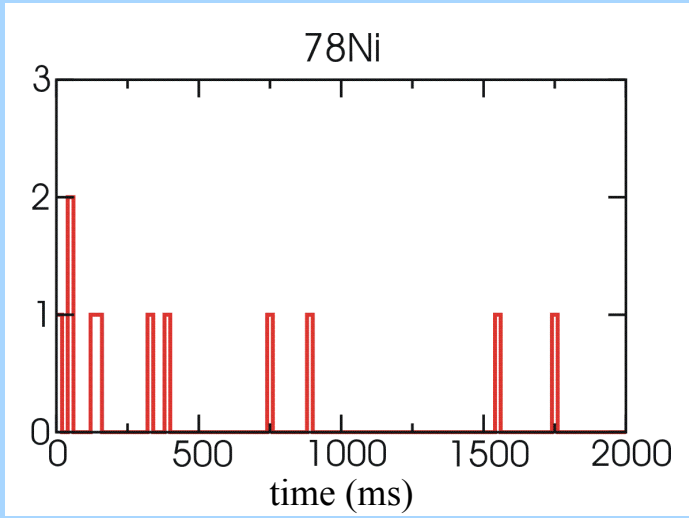


Fast RIB from fragmentation:

- no decay losses
- any beam can be produced
- multiple measurements in one
- high sensitivity 1:10^{14}

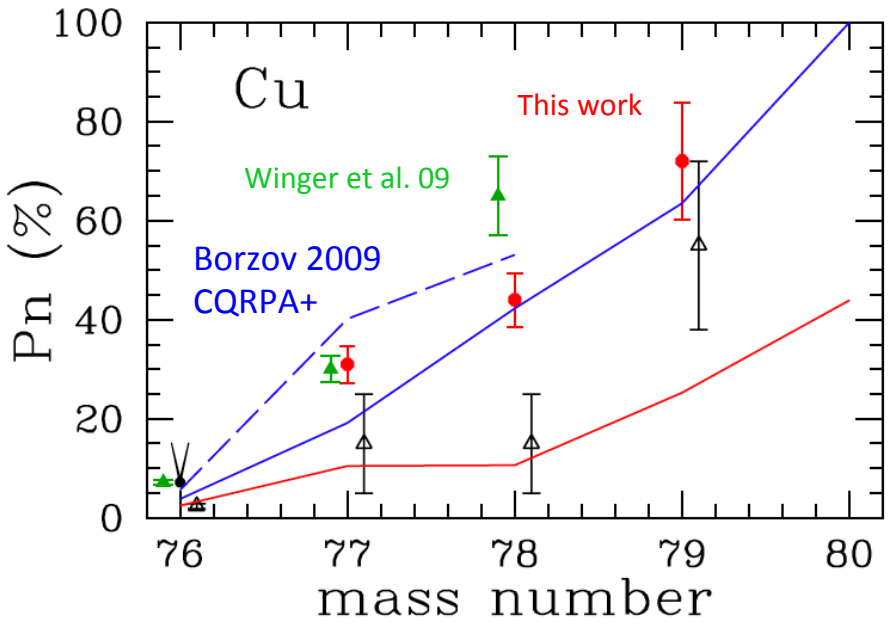
Some results from the Mainz/MSU/Notre Dame campaign

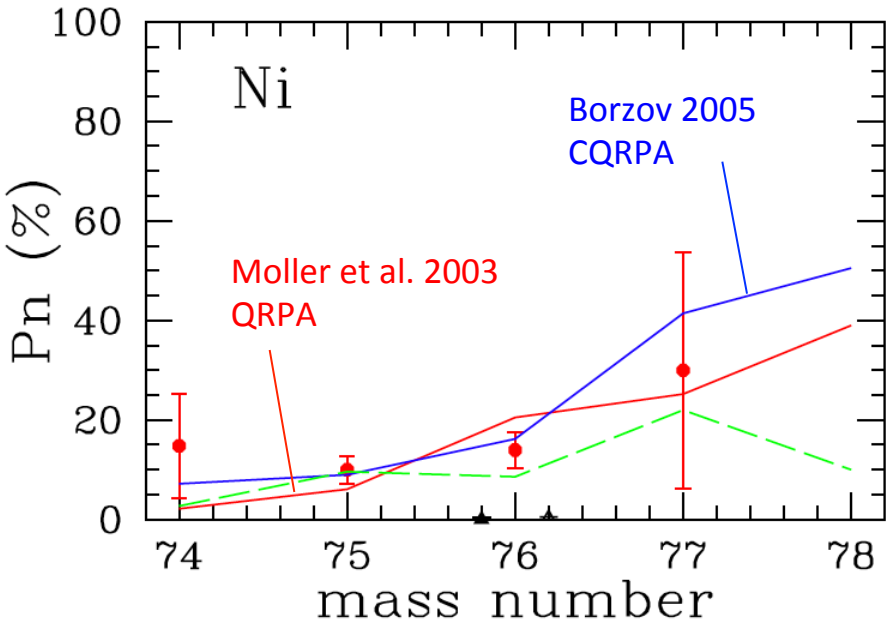
Time between arrival and decays:



Result for half-life: 110 $^{+100}_{-60}$ ms

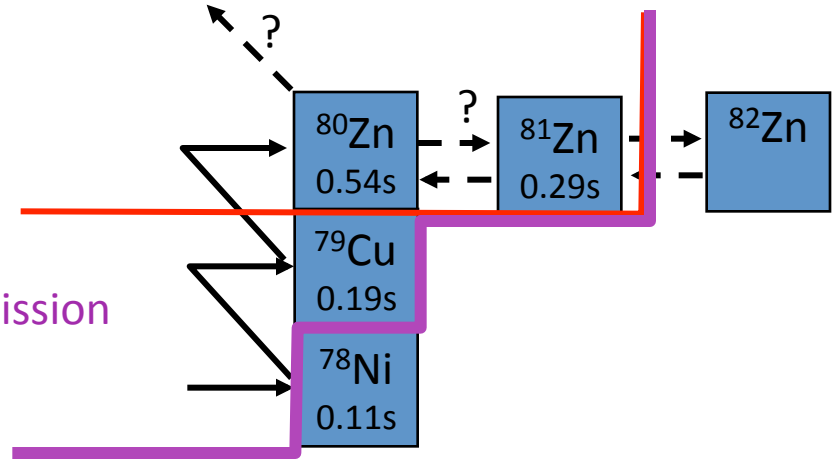
Compare to theoretical estimate used:470 ms





The r-process at A=80

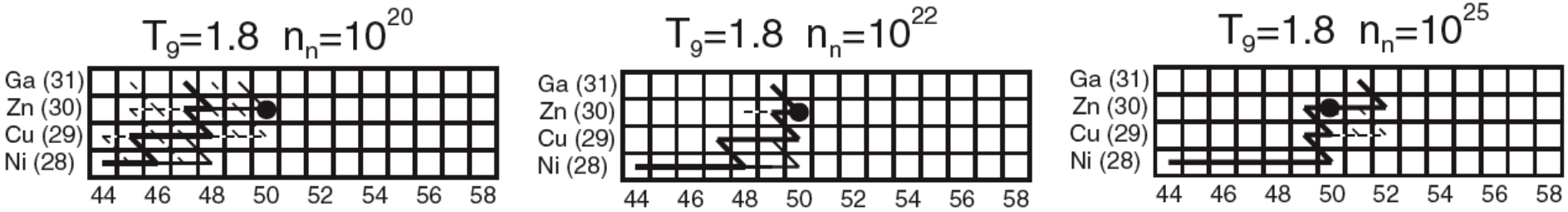
Precision masses
from ion traps (ISOLTRAP, JYFLTRAP)



known n-emission
branchings

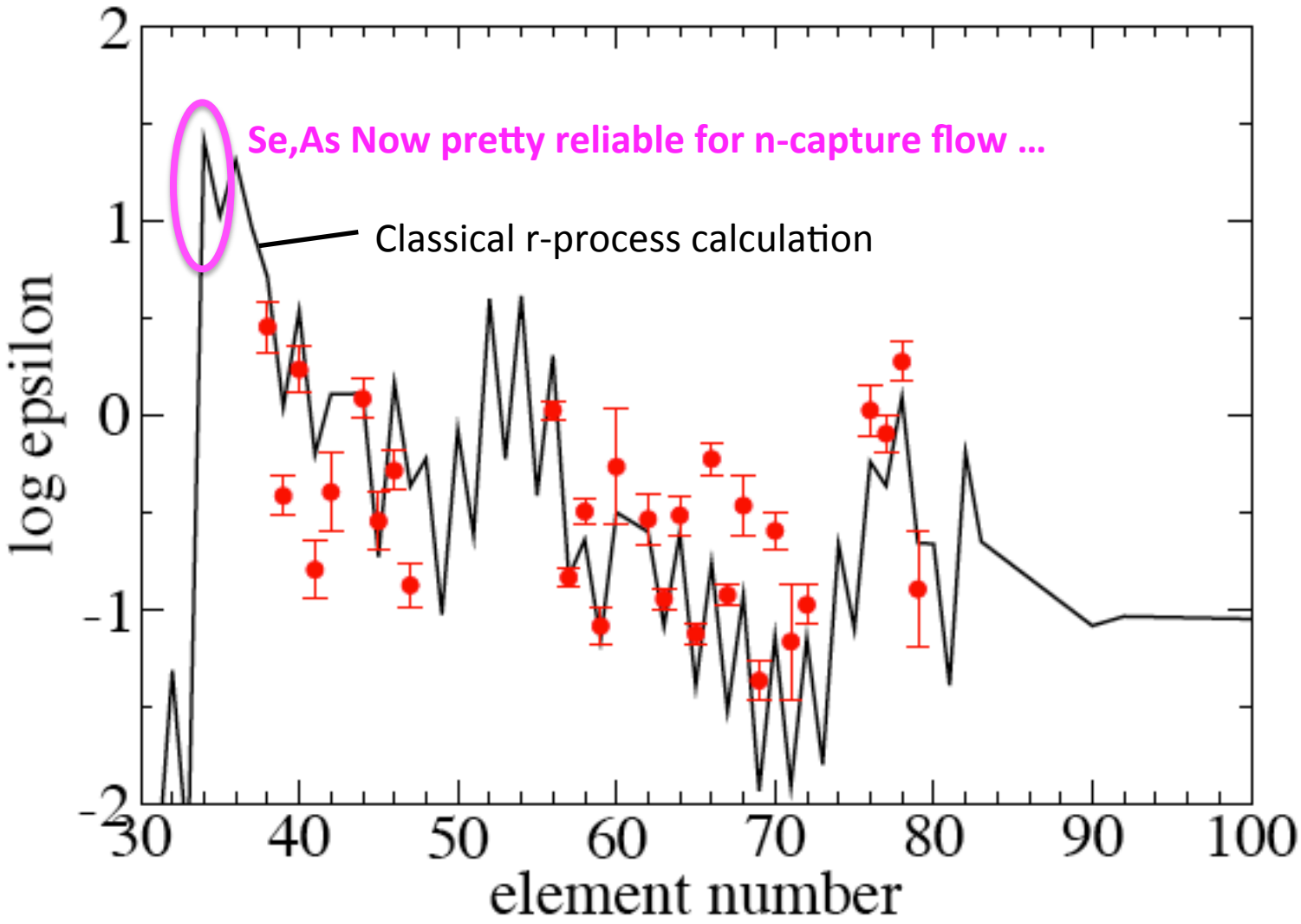
> Unique region where
main nuclear physics
for the r-process is now
experimentally constrained

Network calculation: when is ^{80}Zn a waiting point?



Baruah et al. 2008

Classical r-process calculation with new experimental data



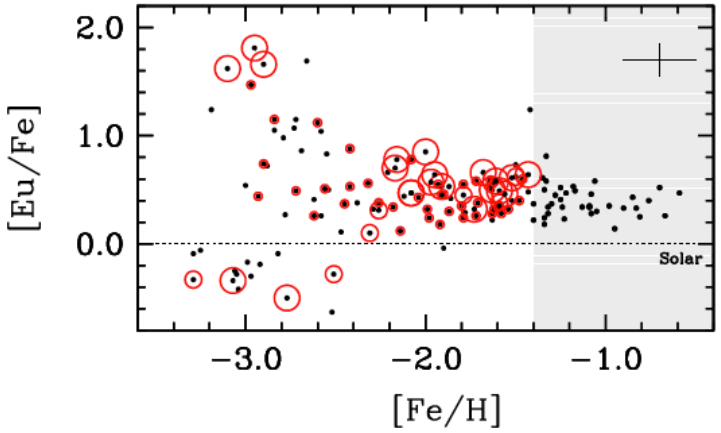
Conclusion

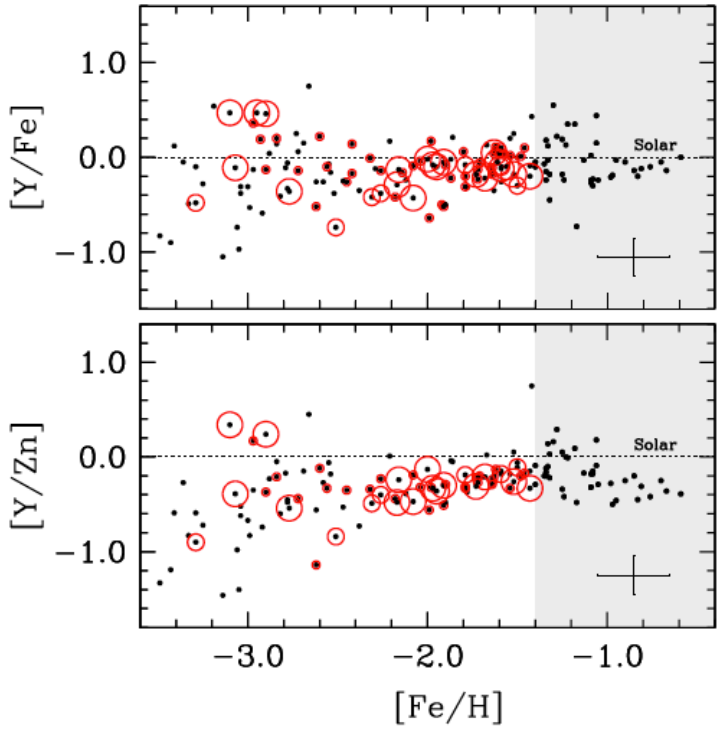
- Lots of hints for "LEPP" existence – something beyond textbook s,r components is needed

- Experimental data are needed to:
  - Verify viablity of a specific LEPP model through comparison with observations
  - Have reliable s-process component to subtract (need models)
  - Have reliable r-process component to subtract
    can use stellar main r as template but
    - Need model to interpolate isotopic abundances
    - Might not work for light n-capture elements where most important

- Need stable beam cross sections, neutron cross sections, and rare isotope properties

- On the rare isotope experiments major progress but not there yet
  → need FRIB/FAIR/RIBF
  → need to figure out how to measure n,p for νp-process
  → need to figure out how to measure n,γ for r-process


2.0
1.0
0.0
[Eu/Fe]
Solar
−3.0
−2.0
−1.0
[Fe/H]


1.0
0.0
−1.0
[Y/Fe]
Solar
1.0
0.0
−1.0
[Y/Zn]
Solar
−3.0
−2.0
−1.0
[Fe/H]

R-process enhanced metal poor stars

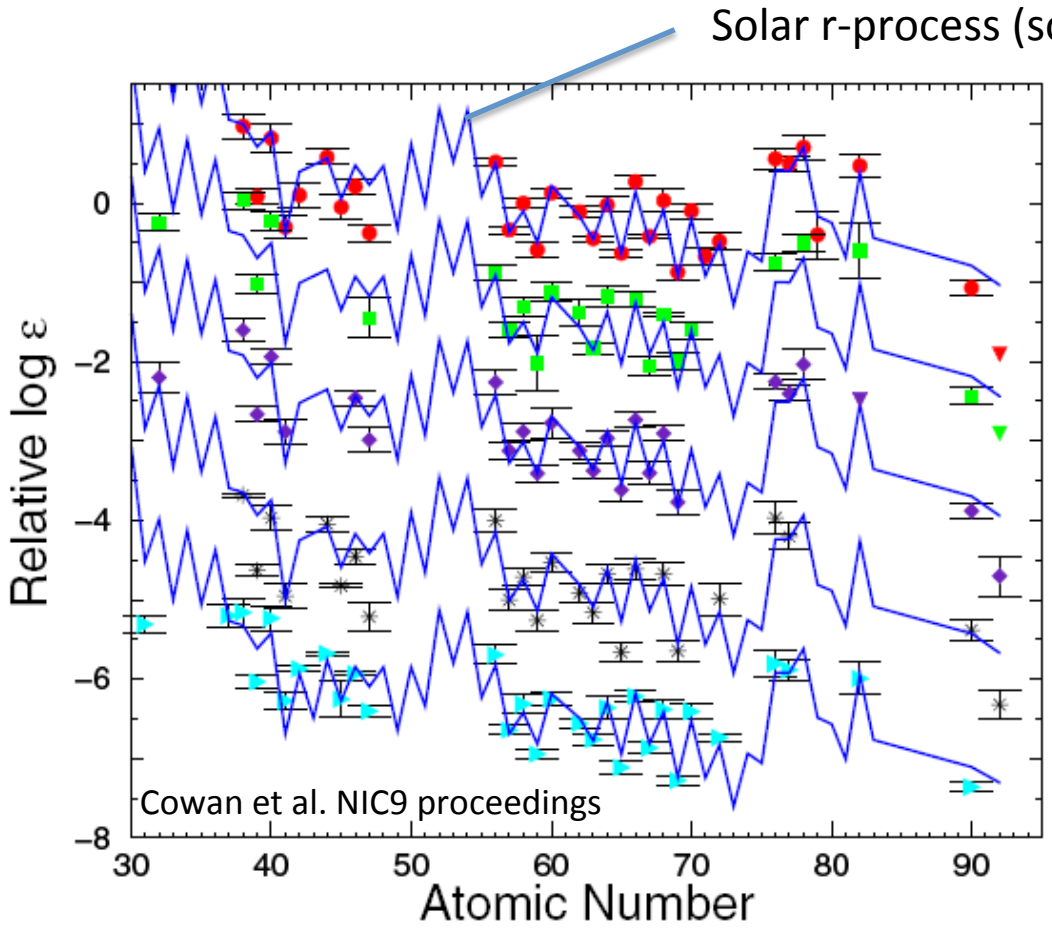
CS22892-052

HD 115444

BD+17^{0}3248

CS 31082-001

HD221170



For highly r-process enriched stars

→ Very consistent pattern throughout

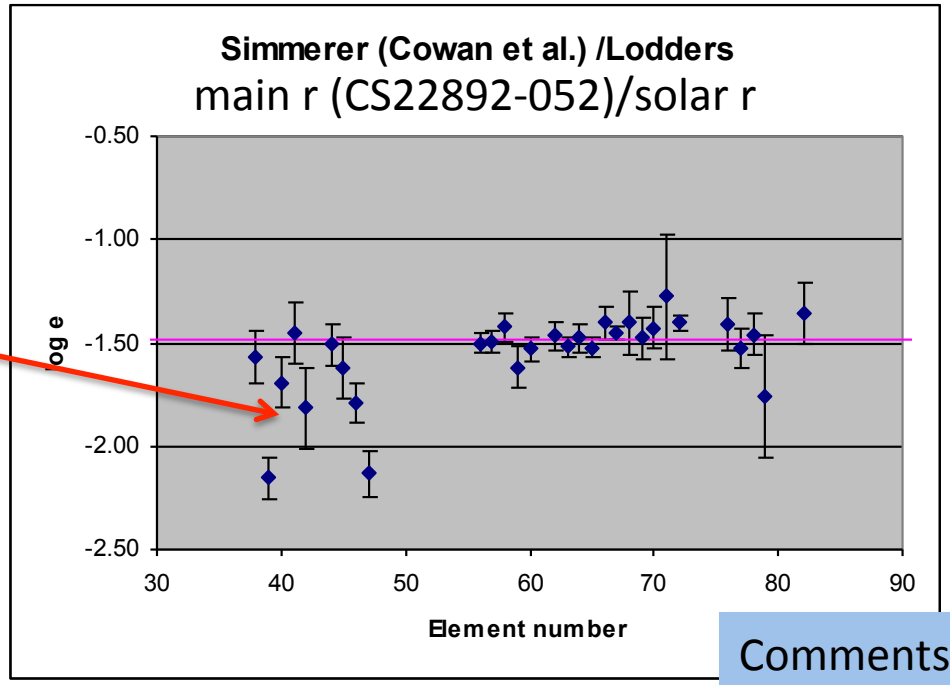
→ **Main r-process**

What is the LEPP ?

Additional primary process for >Ge (?) nucleosynthesis needed in addition to standard picture of weak s, main s, and r-processes.

"LEPP 1:" Fix deficiency of "main r-process" seen in metal poor stars to explain solar

Need a "LEPP" to get this to solar



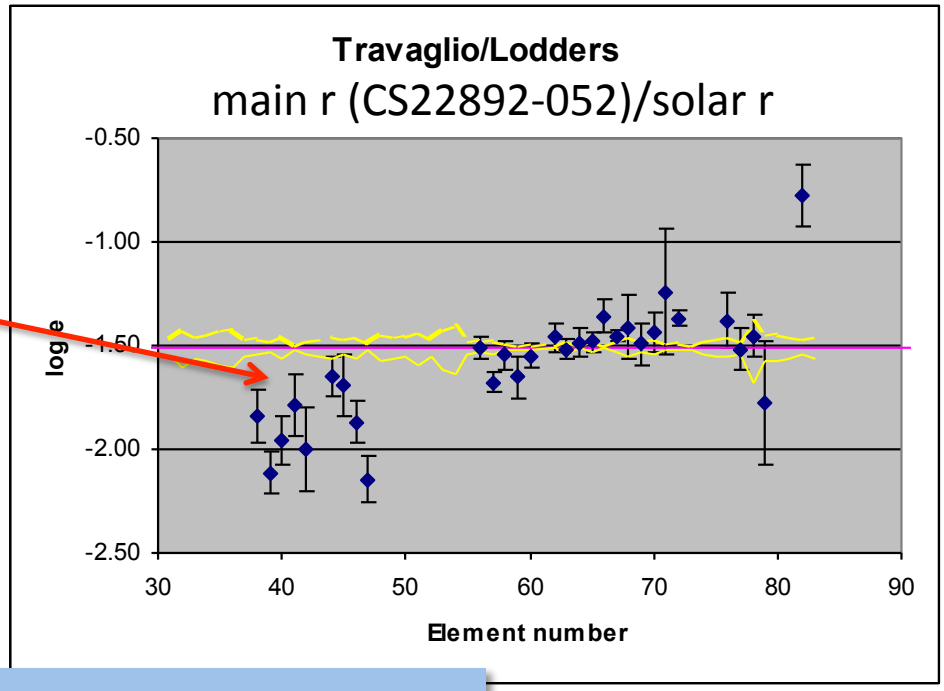
Comments:
- Depends on s-process assumptions
- Only a few elements
- Observational uncertainties?

What is the LEPP ?

"LEPP 2:" Fix deficiency of s-process when using stellar models/GCE

(Travaglio et al. 2004)

Need a "LEPP" to get this to solar s (deficiency now includes s-only isotopes)



Comments:

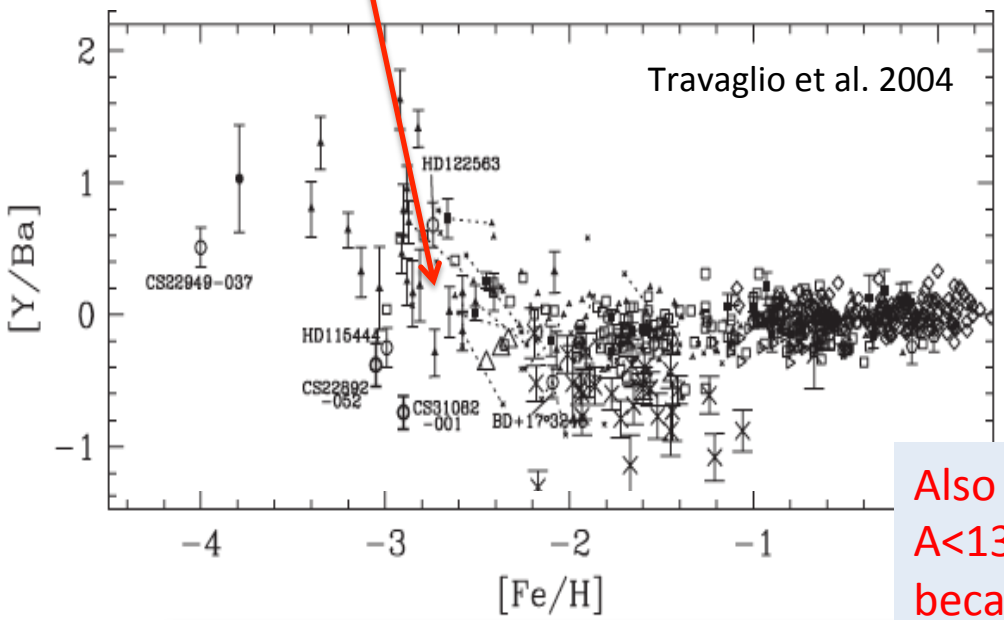
- Might go away if s-process is fixed
- Deficiency in s-only isotopes limits possible scenarios

Same as process as LEPP1? Maybe, but does not have to be

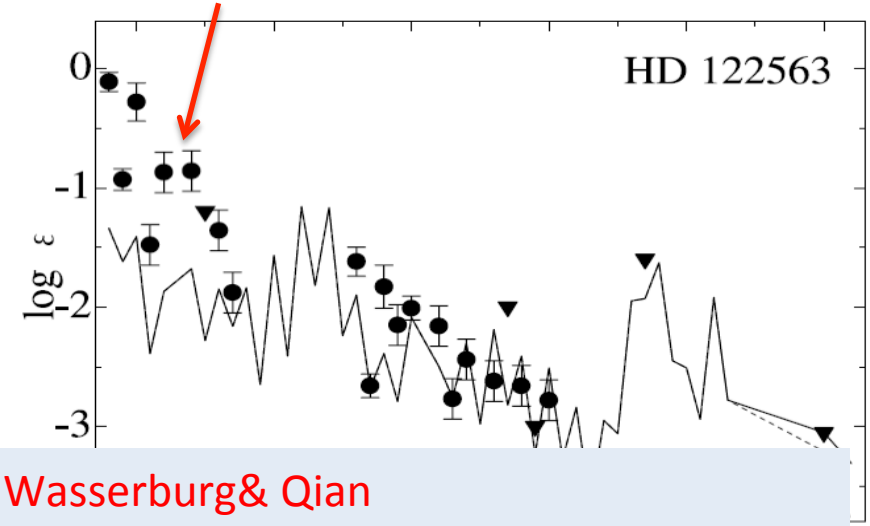
What is the LEPP ?

"LEPP 3:" Additional, primary, independent nucleosynthesis component for light n-capture elements found in metal poor stars

Large scatter of Y/Ba at low [Fe/H]
→ Y and Ba are not made in the same (r-)process



low s and low Eu stars: high Y,Sr,Zr
Pattern neither s- nor r-



Also Wasserburg& Qian
A<130 must be different from A>130
because of early solar system 129I and 182Hf
"LEPP 4"?

Comments:

- Existence is observational fact
- Same as LEPP1+LEPP2? Montes et al. 2007: pattern looks similar, but inconclusive