Indirect Reaction Studies:
X-Ray Bursts

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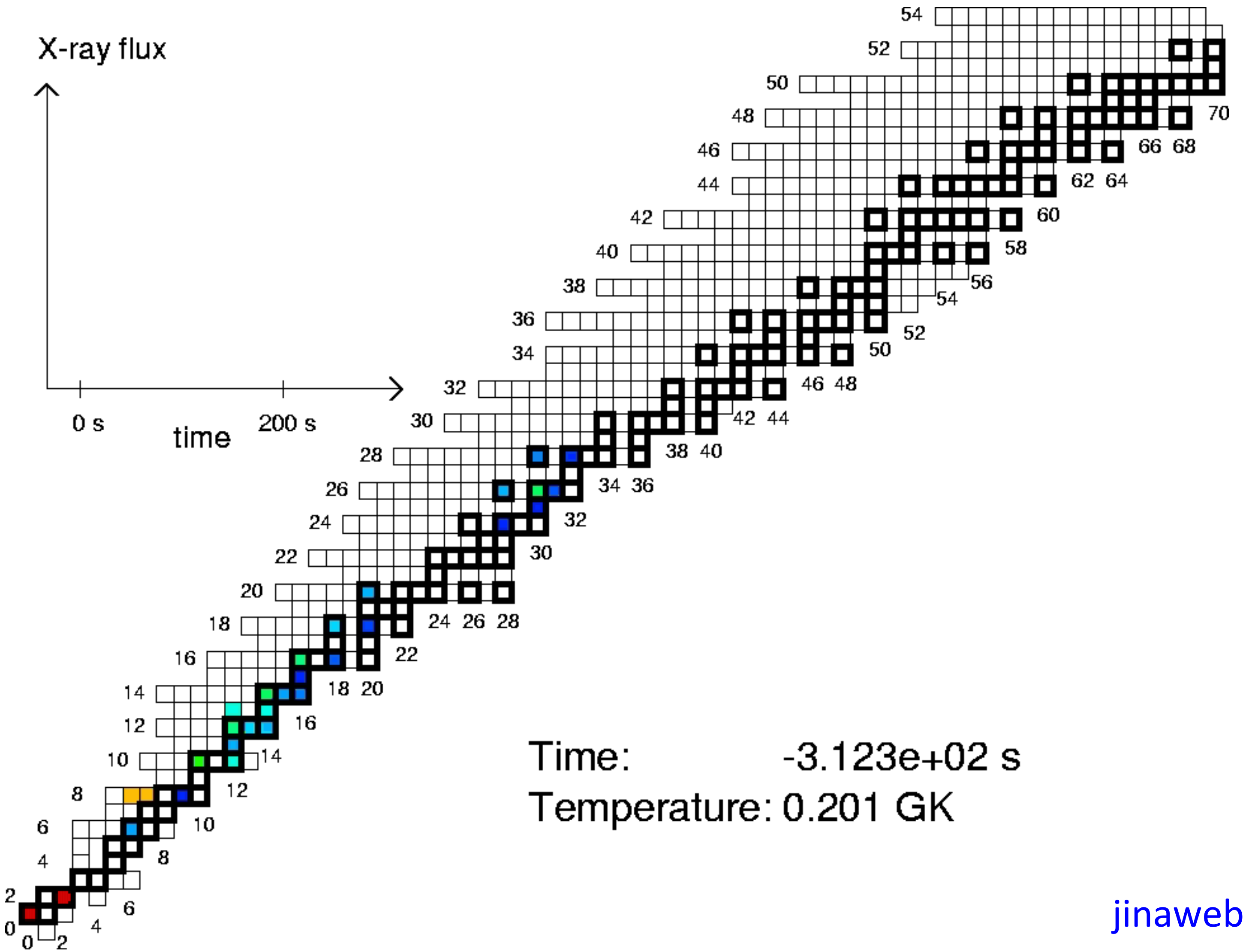


jinaweb.org

XRB Nucleosynthesis

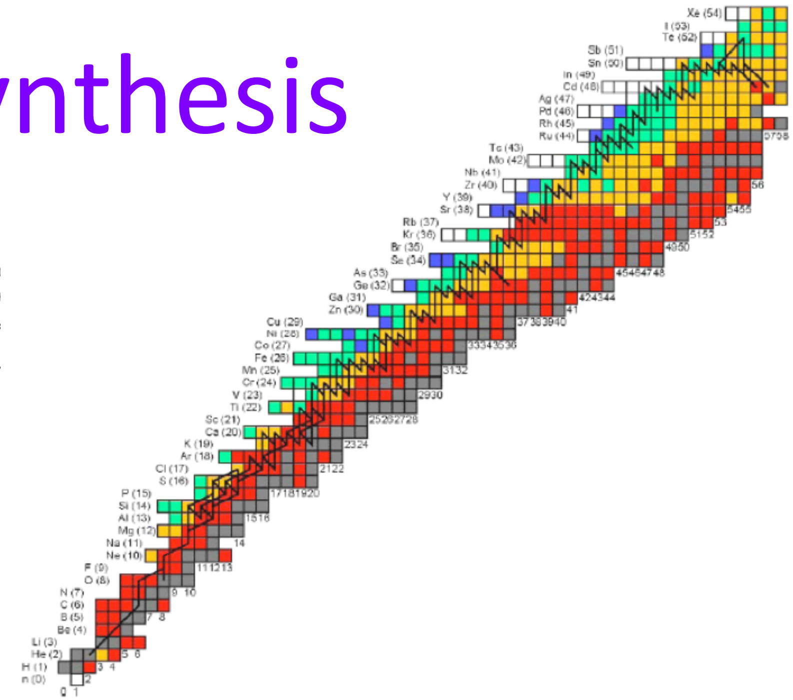


Table 19. Summary of the most influential nuclear processes, as collected from Tables 1–10. These reactions affect the yields of, at least, 3 isotopes when their nominal rates are varied by a factor of 10 up and/or down. See text for details.

Reaction	Models affected
$^{12}C(\alpha,\gamma)^{16}O^a$	F08, K04-B2, K04-B4, K04-B5
$^{18}Ne(\alpha,p)^{21}Na^a$	K04-B1^b
$^{25}Si(\alpha,p)^{28}P$	K04-B5
$^{26g}Al(\alpha,p)^{29}Si$	F08
$^{29}S(\alpha,p)^{32}Cl$	K04-B5
$^{30}P(\alpha,p)^{33}S$	K04-B4
$^{30}S(\alpha,p)^{33}Cl$	K04-B4^b, K04-B5^b
$^{31}Cl(p,\gamma)^{32}Ar$	K04-B1
$^{32}S(\alpha,\gamma)^{36}Ar$	K04-B2
$^{56}Ni(\alpha,p)^{59}Cu$	S01^b, K04-B5
$^{57}Cu(p,\gamma)^{58}Zn$	F08
$^{59}Cu(p,\gamma)^{60}Zn$	S01^b, K04-B5
$^{61}Ga(p,\gamma)^{62}Ge$	F08, K04-B1, K04-B2, K04-B5, K04-B6
$^{65}As(p,\gamma)^{66}Se$	K04^b, K04-B1, K04-B2^b, K04-B3^b, K04-B4, K04-B5, K04-B6
$^{69}Br(p,\gamma)^{70}Kr$	K04-B7
$^{75}Rb(p,\gamma)^{76}Sr$	K04-B2
$^{82}Zr(p,\gamma)^{83}Nb$	K04-B6
$^{84}Zr(p,\gamma)^{85}Nb$	K04-B2
$^{84}Nb(p,\gamma)^{85}Mo$	K04-B6
$^{85}Mo(p,\gamma)^{86}Tc$	F08
$^{86}Mo(p,\gamma)^{87}Tc$	F08, K04-B6
$^{87}Mo(p,\gamma)^{88}Tc$	K04-B6
$^{92}Ru(p,\gamma)^{93}Rh$	K04-B2, K04-B6
$^{93}Rh(p,\gamma)^{94}Pd$	K04-B2
$^{96}Ag(p,\gamma)^{97}Cd$	K04, K04-B2, K04-B3, K04-B7
$^{102}In(p,\gamma)^{103}Sn$	K04, K04-B3
$^{103}In(p,\gamma)^{104}Sn$	K04-B3, K04-B7
$^{103}Sn(\alpha,p)^{106}Sb$	S01^b

Table 20. Nuclear processes affecting the total energy output
the yield of at least one isotope, when their nominal rates ar
factor of 10 up and/or down, for the given model. S

Reaction	Models affected
$^{15}O(\alpha,\gamma)^{19}Ne^a$	K04, K04-B1, K04-B6
$^{18}Ne(\alpha,p)^{21}Na^a$	K04-B1, K04-B6
$^{22}Mg(\alpha,p)^{25}Al$	F08
$^{23}Al(p,\gamma)^{24}Si$	K04-B1
$^{24}Mg(\alpha,p)^{27}Al^a$	K04-B2
$^{26g}Al(p,\gamma)^{27}Si^a$	F08
$^{28}Si(\alpha,p)^{31}P^a$	K04-B4
$^{30}S(\alpha,p)^{33}Cl$	K04-B4, K04-B5
$^{31}Cl(p,\gamma)^{32}Ar$	K04-B3
$^{32}S(\alpha,p)^{35}Cl$	K04-B2
$^{35}Cl(p,\gamma)^{36}Ar^a$	K04-B2
$^{56}Ni(\alpha,p)^{59}Cu$	S01
$^{59}Cu(p,\gamma)^{60}Zn$	S01
$^{65}As(p,\gamma)^{66}Se$	K04, K04-B2, K04-B3
$^{69}Br(p,\gamma)^{70}Kr$	S01
$^{71}Br(p,\gamma)^{72}Kr$	K04-B7
$^{103}Sn(\alpha,p)^{106}Sb$	S01

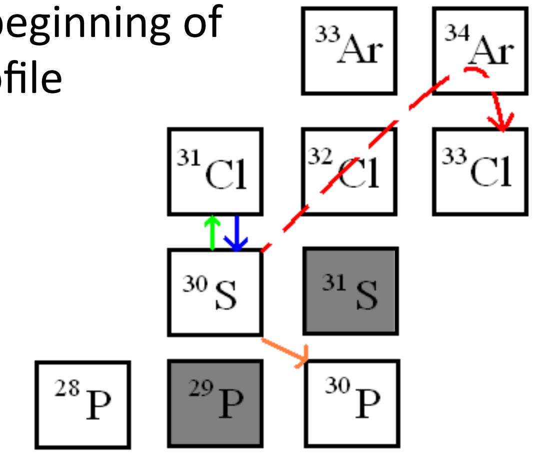
[a] Reaction experimentally constrained to better than a factor of ~10 at XRB temperatures. See Section 5.

A. Parikh *et al.*, ApJ SS **178**, 110 (2008).

- Sensitivity studies show 28 reactions that affect final elemental abundances and/or energy output
- New RIB facilities will allow access to more of these radioactive nuclei important in XRBs

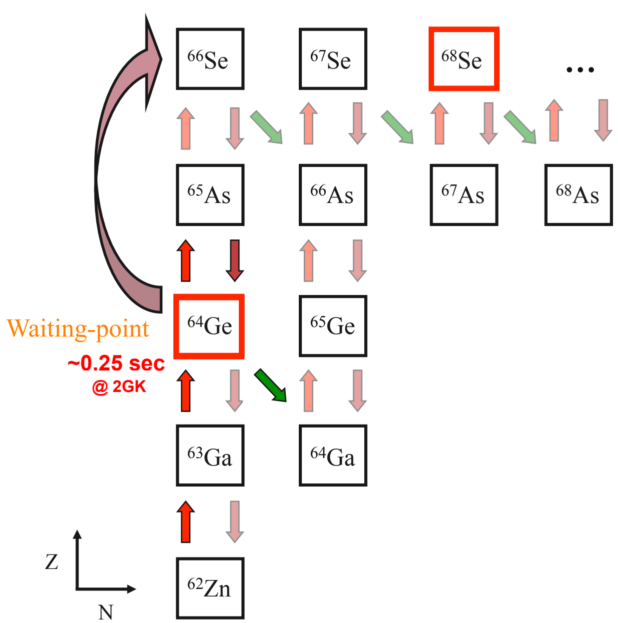
XRB Waiting Points

(α,p) process waiting points affect energy generation near the beginning of XRB nucleosynthesis final elemental abundances luminosity profile



Possible (α,p) process waiting points

- ^{22}Mg
- ^{26}Si
- ^{30}S
- ^{34}Ar



High-mass waiting points in XRBs determine shape of light-curve tail

Main waiting points: ^{64}Ge, ^{68}Se, ^{72}Kr

Lifetimes well known, but not S_p's of Z+1 nuclei

^{69}Br and ^{73}Rb both experimentally known to have negative S_p, supporting ^{68}Se and ^{72}Kr as waiting points, respectively

S_p for ^{65}As is not well-known due to unknown mass of - is ^{64}Ge really a waiting point?

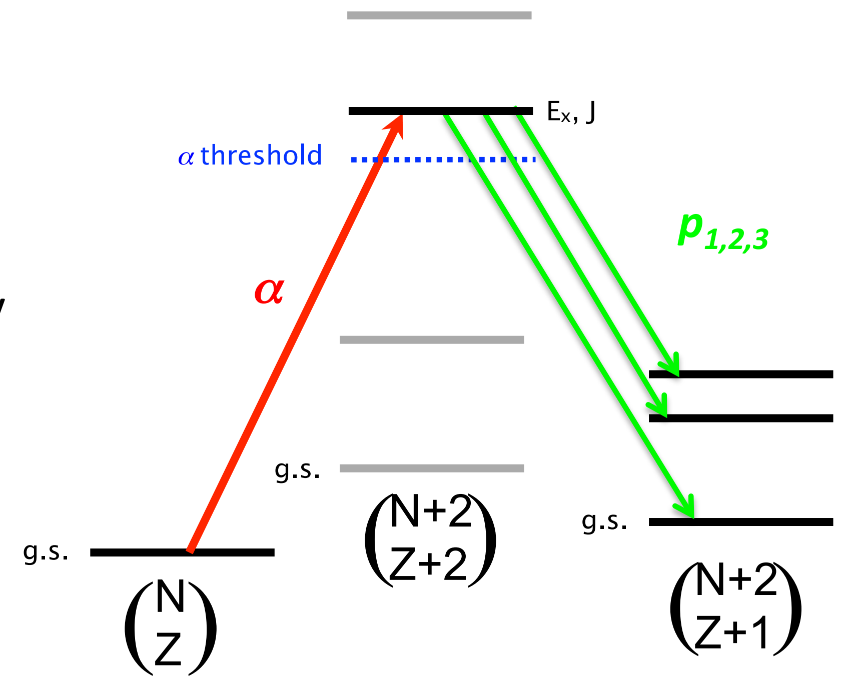
Indirect Studies of (α,*p*) Reactions

- Direct (α,*p*) reaction studies are hard!
  - high Coulomb barrier
  - gas targets
  - radioactive ion beams 2 nucleons away from stability

- At masses of A < 40, reaction rate is dominated by resonances

- Indirect measurements:
  - transfer reaction measurements with stable beams [e.g. (^{3}He,*n*), (*p*,*t*), etc.]
  - elastic and in-elastic scattering
  - time-inverse reaction measurements

- Almost no direct measurements!



$$N_A\langle\sigma v\rangle = \frac{1.5399\times10^{11}}{(\mu T_9)^{3/2}}\sum_i(\omega\gamma)_i\, e^{-11.605E_i/T_9}$$

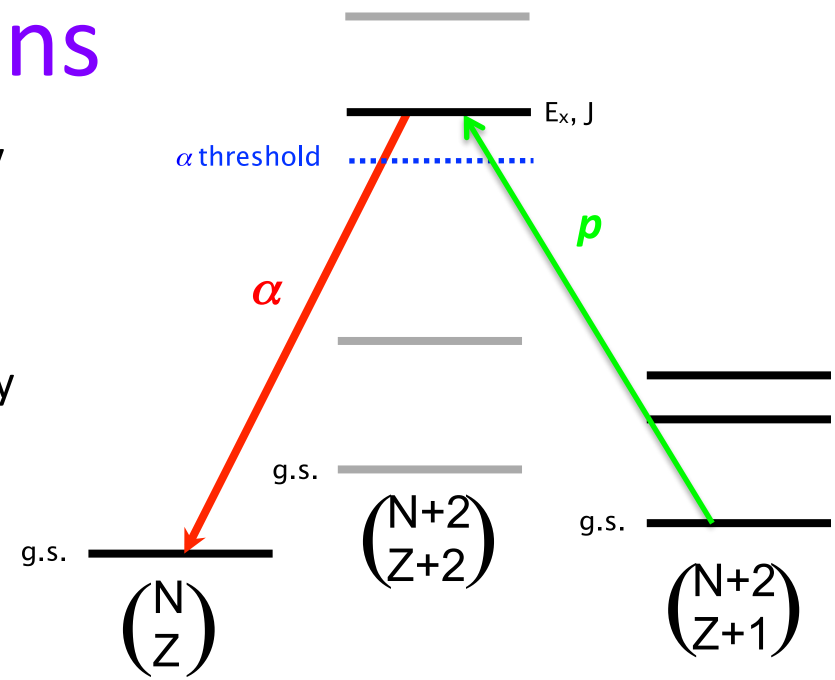
$$(\omega\gamma)_i = \frac{(2J_i+1)}{(2J_0+1)(2J_1+1)}(1+\delta_{01})\frac{\Gamma_a\Gamma_b}{\Gamma_{tot}}$$

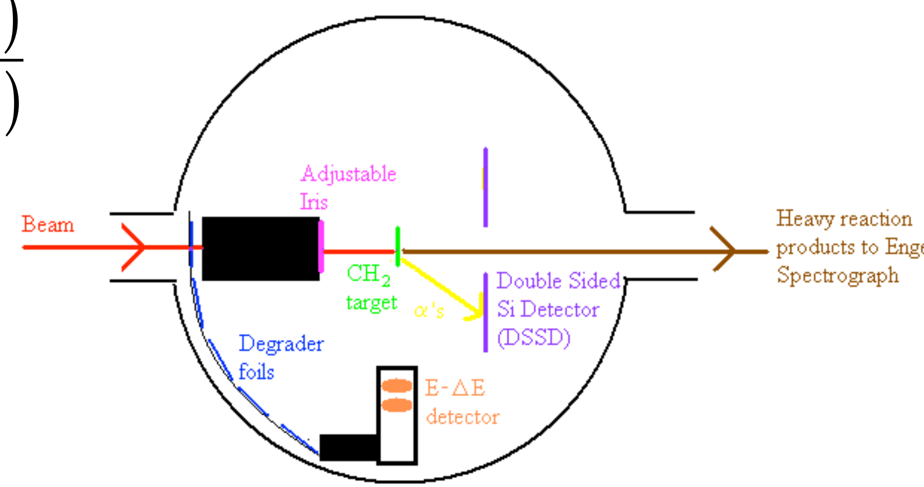
Reverse Reaction Studies of (α,p) Reactions

- Time reverse reactions can be used to study (α,p) reactions
  - solid CH_2 target
  - RIB closer to stability
  - ground state → ground state transitions only

- Cross section can be converted into time-reverse reaction cross section via detailed balance/reciprocal equation

$$\frac{\sigma_{Aa}}{\sigma_{Bb}} = \frac{m_B m_b E_{Bb}(2J_B+1)(2J_b+1)(1+\delta_{Aa})}{m_A m_a E_{Aa}(2J_A+1)(2J_a+1)(1+\delta_{Bb})}$$





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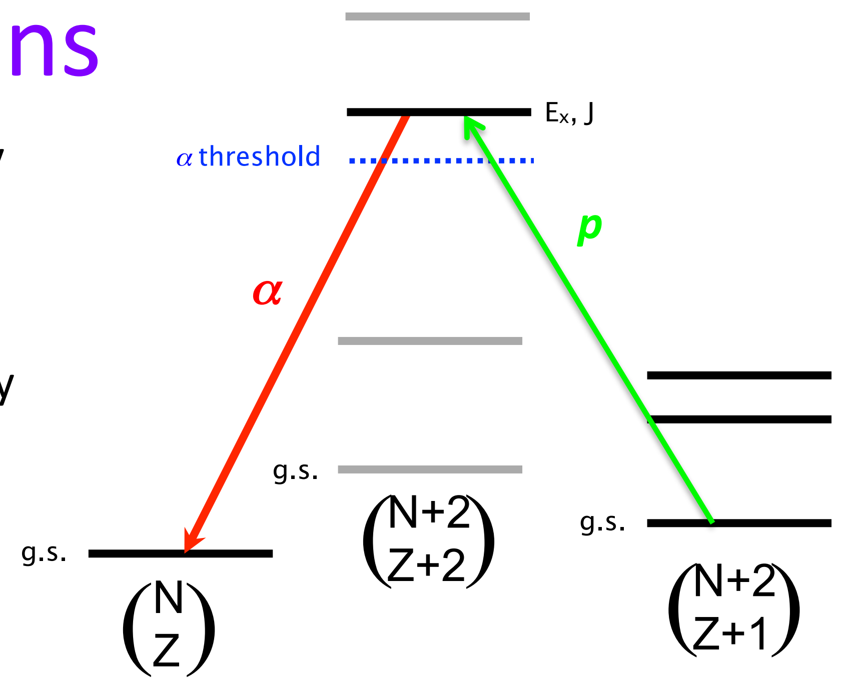

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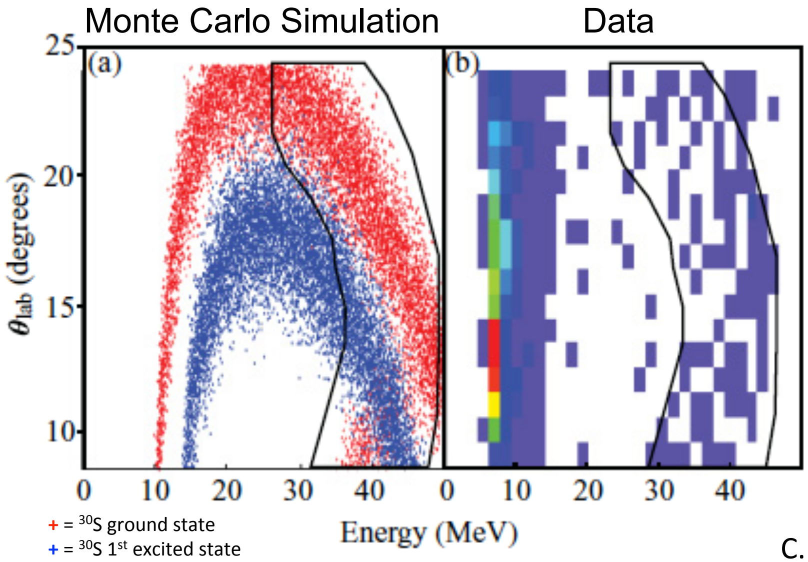
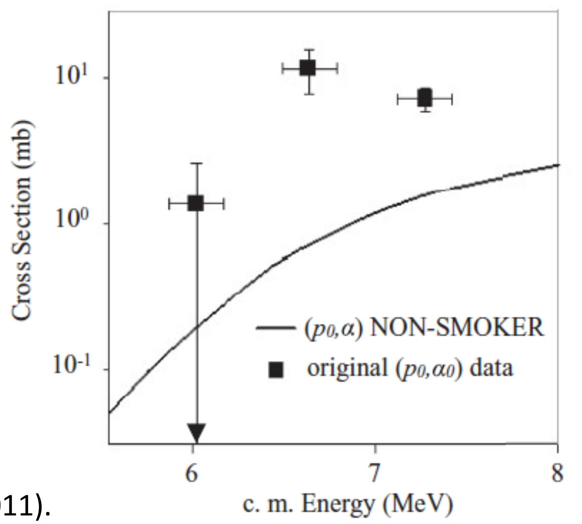


^{33}Cl(p,α)^{30}S Data ANL

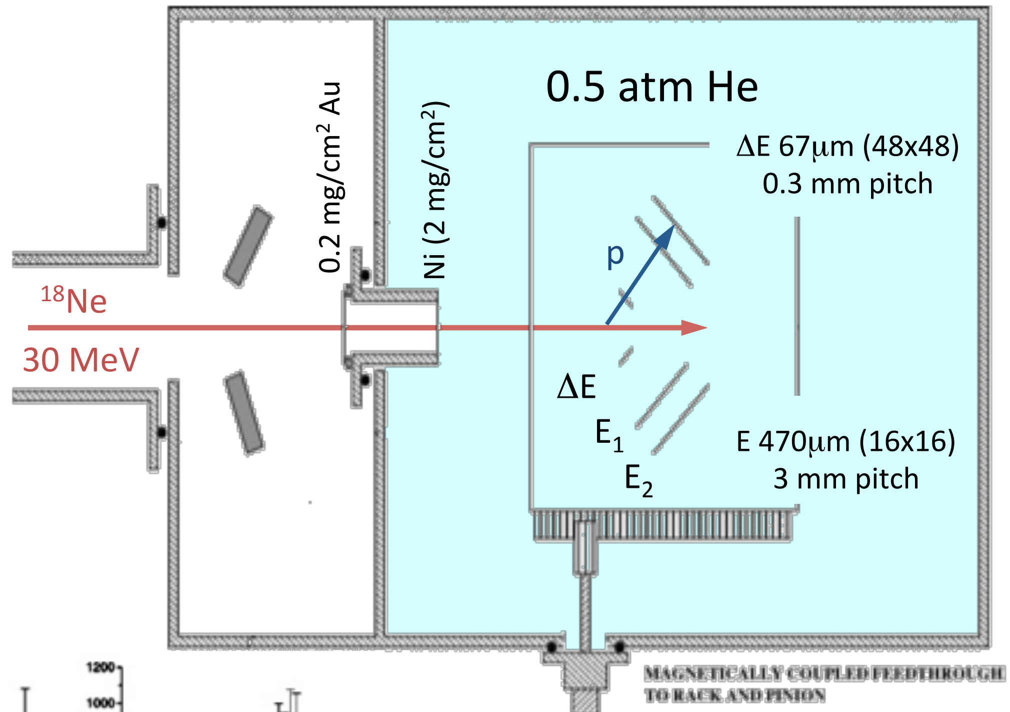


C.M. Deibel *et al*, PRC **84**, 045802 (2011).

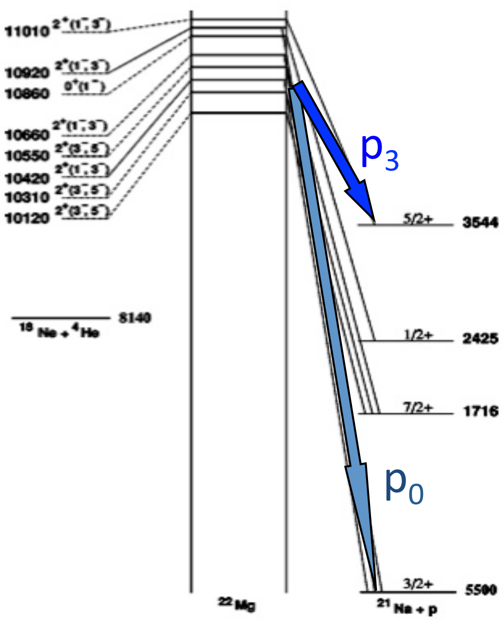
Direct (α,p) measurements

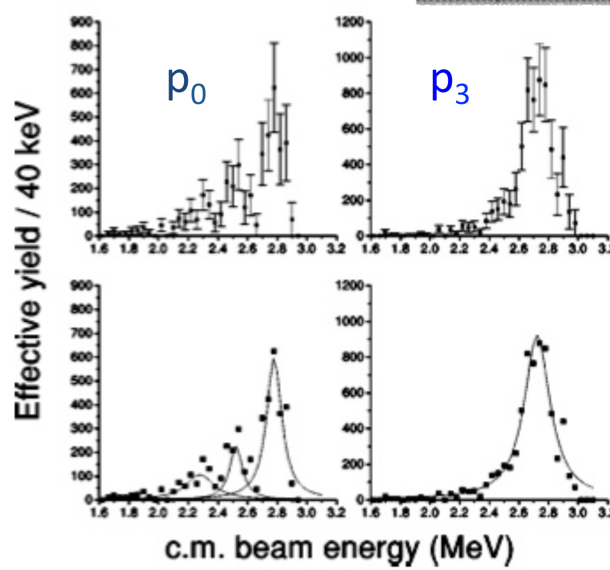
http://www.cyc.ucl.ac.be/

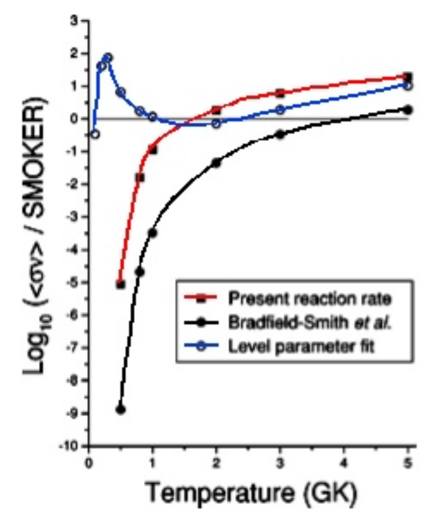
- Louvain-le-Neuve direct measurement of ^{18}Ne(α,p)^{21}Na
- Extended gas target



D. Goombridge *et al.*, PRC 66 (2002) 055802.

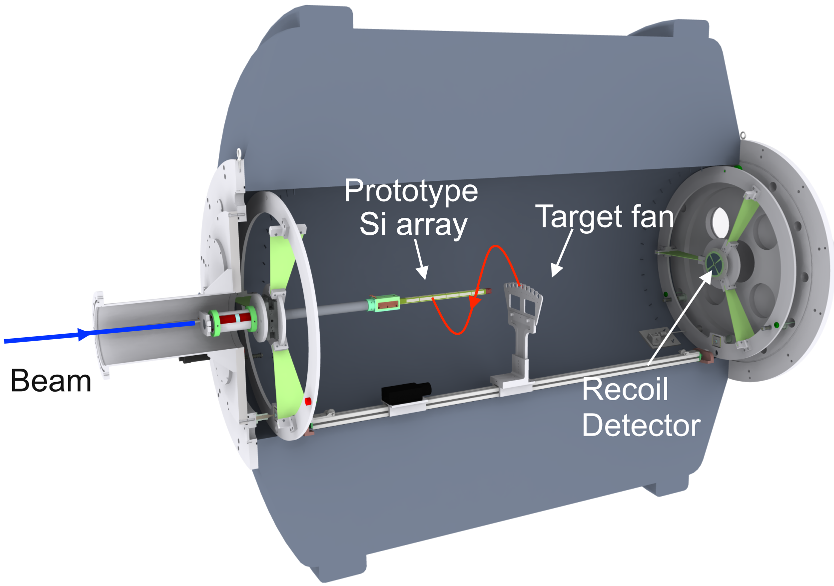


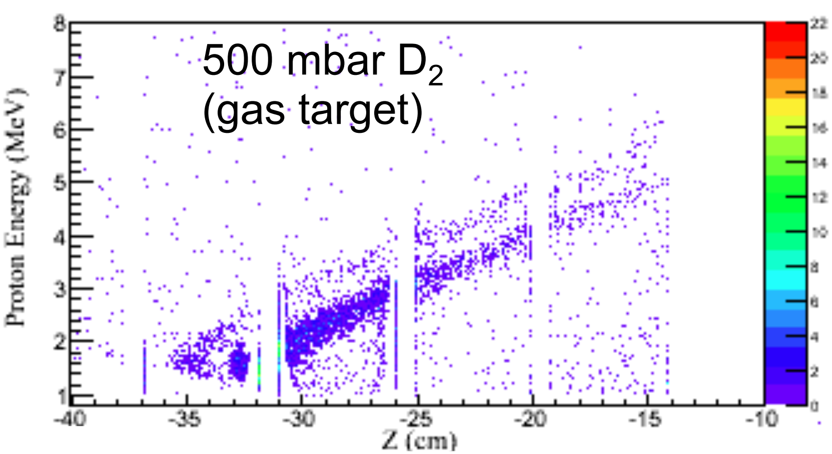




Direct Studies of (α,p) Reactions

- (α,p) reactions can be studied directly:
  - radioactive ion beams
  - ^{4}He gas target
  - inverse kinematics techniques
- HELIOS with in-flight beams at ANL
  - gas target
  - high rate ionization chamber for coincidence measurement
- ^{14}C(d,p)^{15}C commissioning run with full setup:





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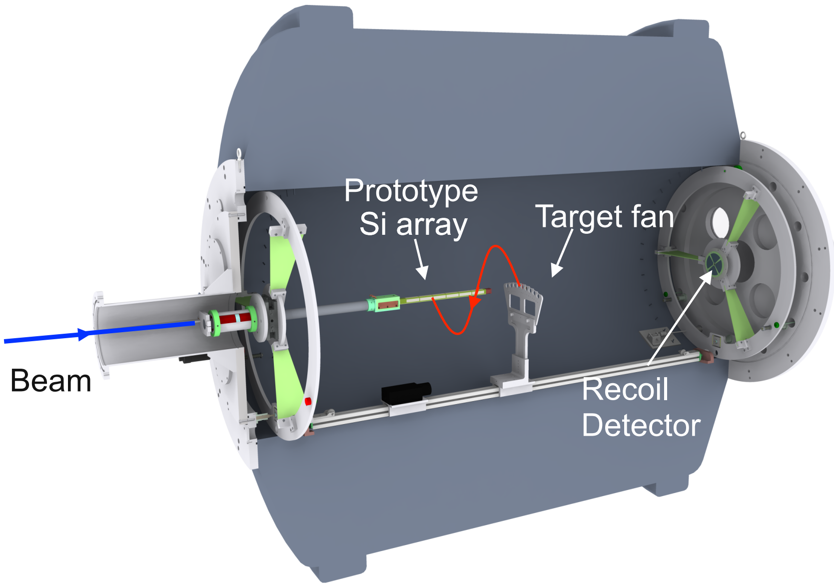
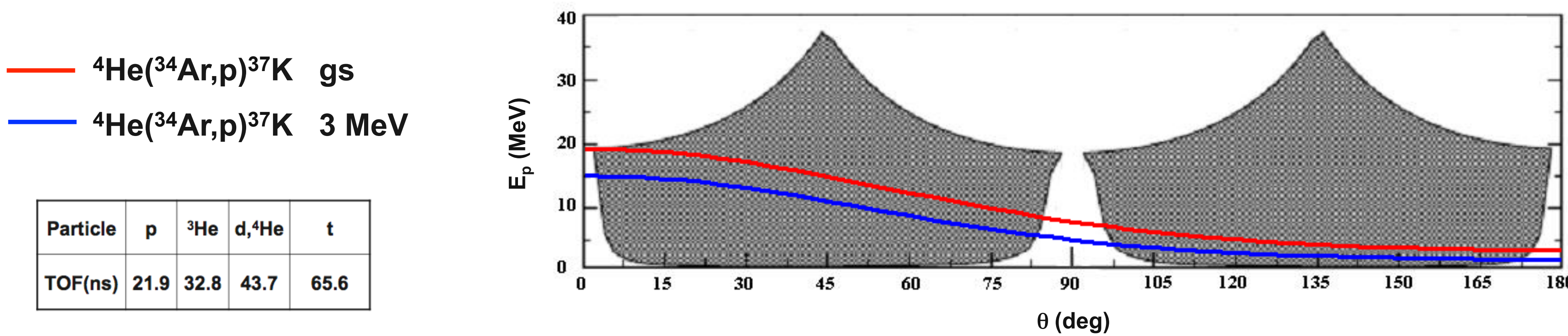
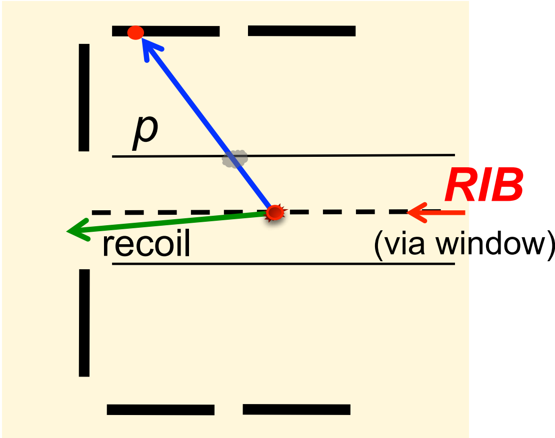


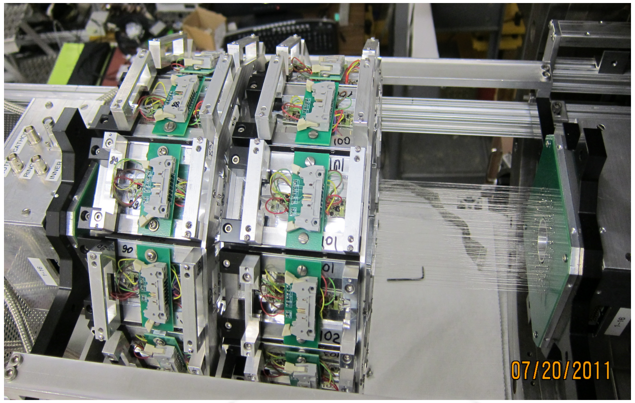


Particle	p	^{3}He	d,^{4}He	t
TOF(ns)	21.9	32.8	43.7	65.6

Direct (α,*p*) studies with ANASEN



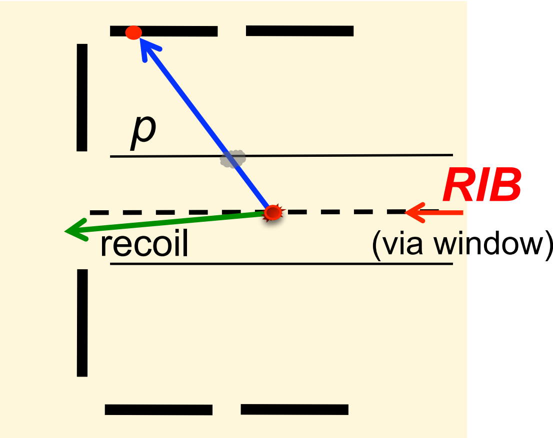
- Array for Nuclear Astrophysics and Structure with Exotic Nuclei (ANASEN)



- Active target detector
  - gas is both target and detector!
- Measures entire excitation function in one bite
- Preliminary data:
  - $^{14}N(\alpha,p)^{17}O$ (stable beam test)
  - $^{18}F(\alpha,p)^{21}Ne$ (CNO breakout to *rp*-process)

19 Anode PC

Direct (α,*p*) studies with ANASEN



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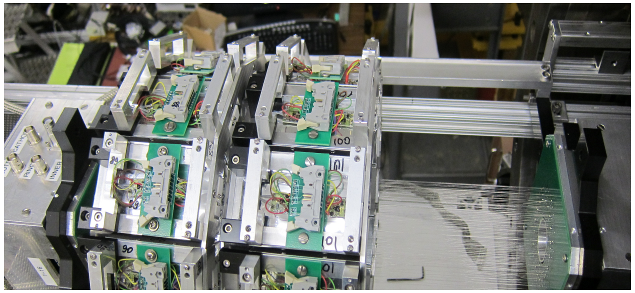
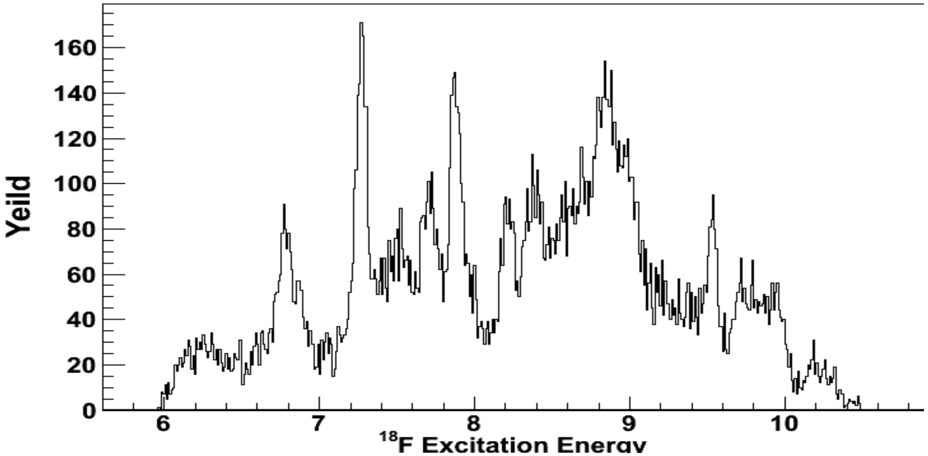
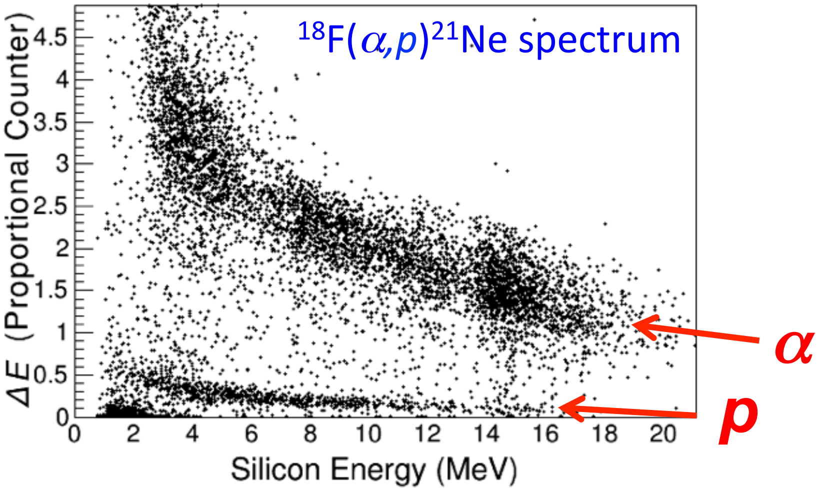
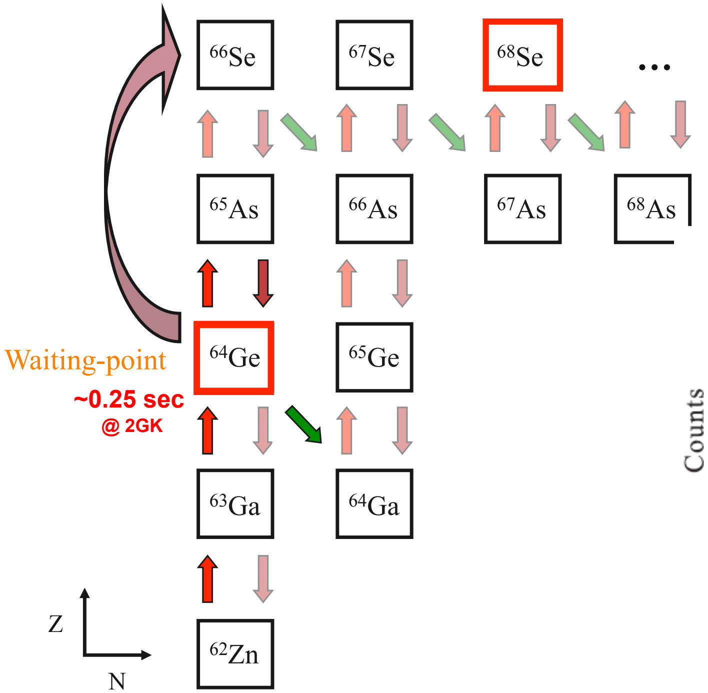
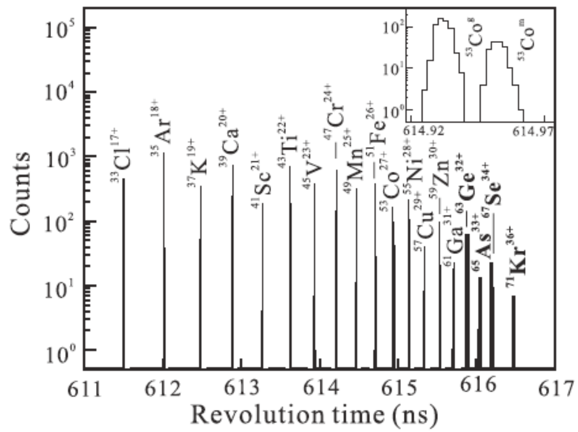


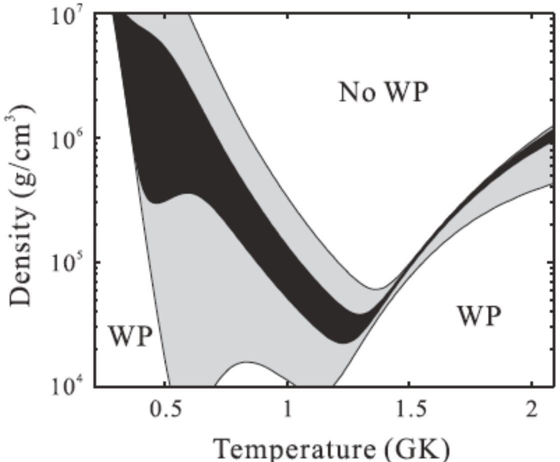




rp – process waiting points



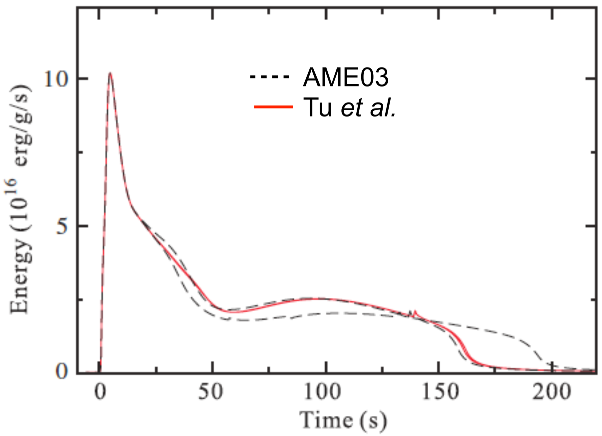




X. L. Tu *et al.*, PRL **106**, 112501 (2011).

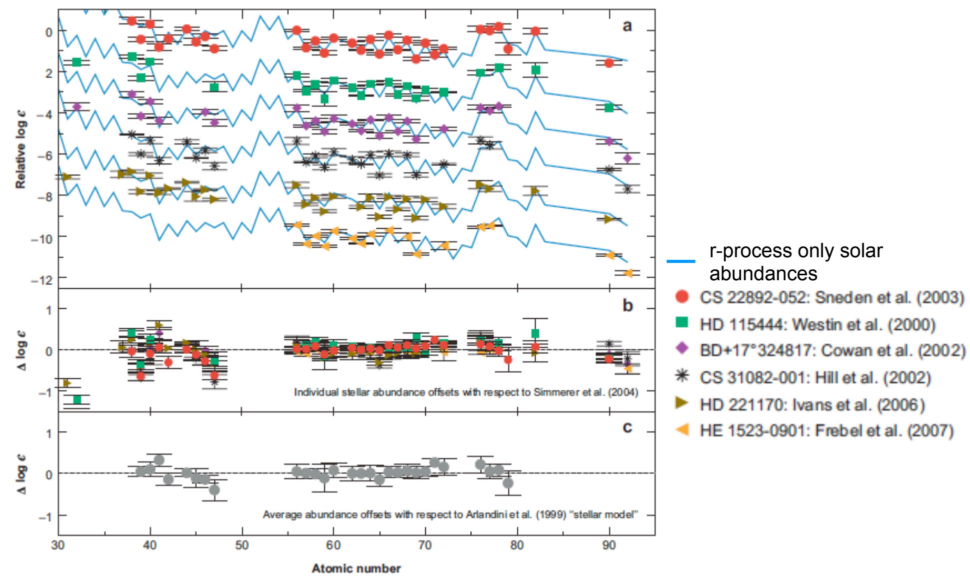
- Mass measurement of ^{65}As done at Lanzhou with the HIRFL-CSR (Cooler-Storage Ring)
- Projectile fragmentation of ^{78}Kr
- $S_p(^{65}As)$ = -90(85) keV: confirms ^{65}As is proton-unbound at 68.3% C.L. Coulomb Displacement Energy (CDE) calculations predictive defines when ^{64}Ge is a w. p.

Effect of new ^{65}As mass on XRB light curve

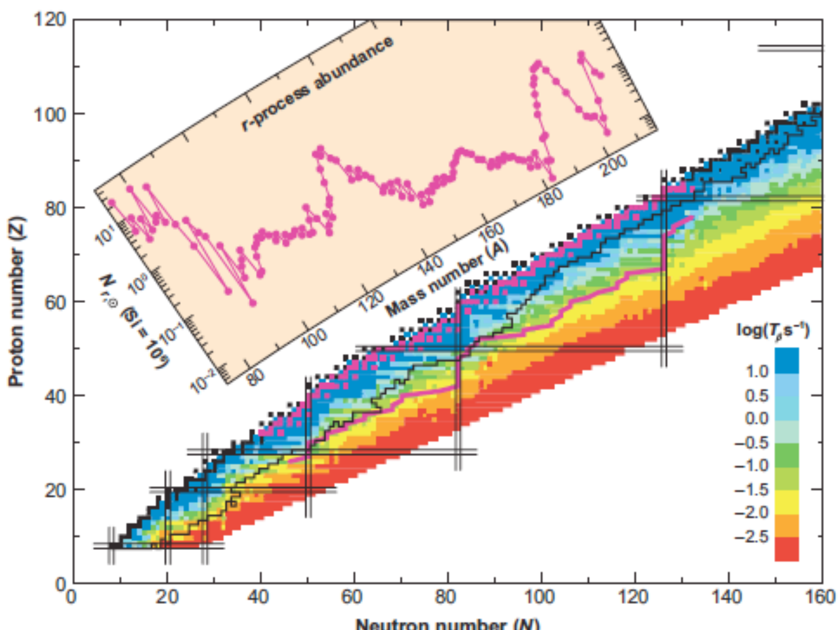


r-process site(s)

- *r*-process site unknown!!! (CCSNe? Neutron star mergers? Other?)
- Disagreement of Z < 56 abundances suggests multiple sites for the r-process
- New processes (e.g. LEPP) to explain abundances of A<120
- Site also dictates the *r*-process path
  - hot *r*-process
  - cold *r*-process



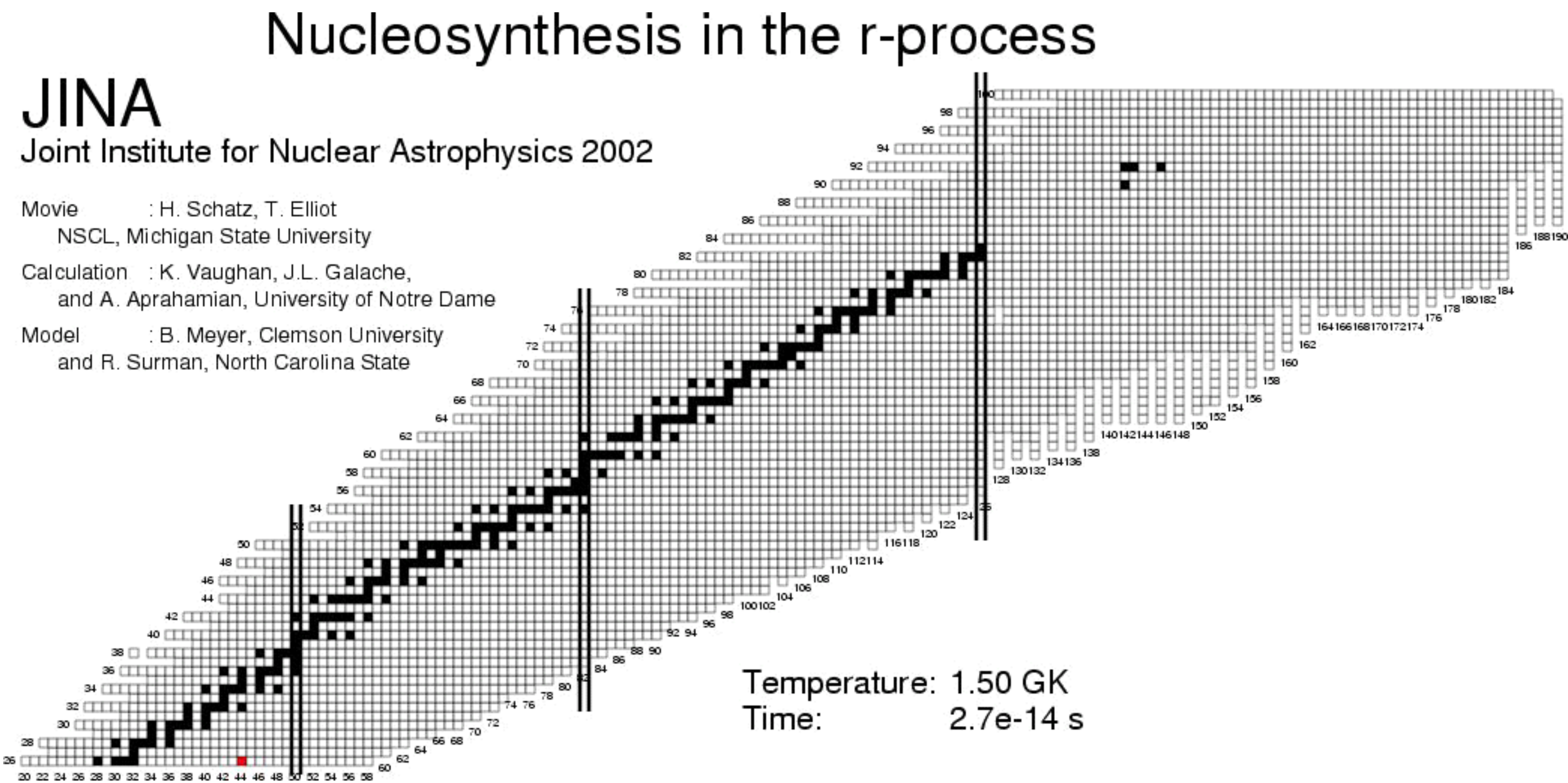
C. Sneden, J.J. Cowan, and R. Gallino, ARAA **46**, 241 (2008).



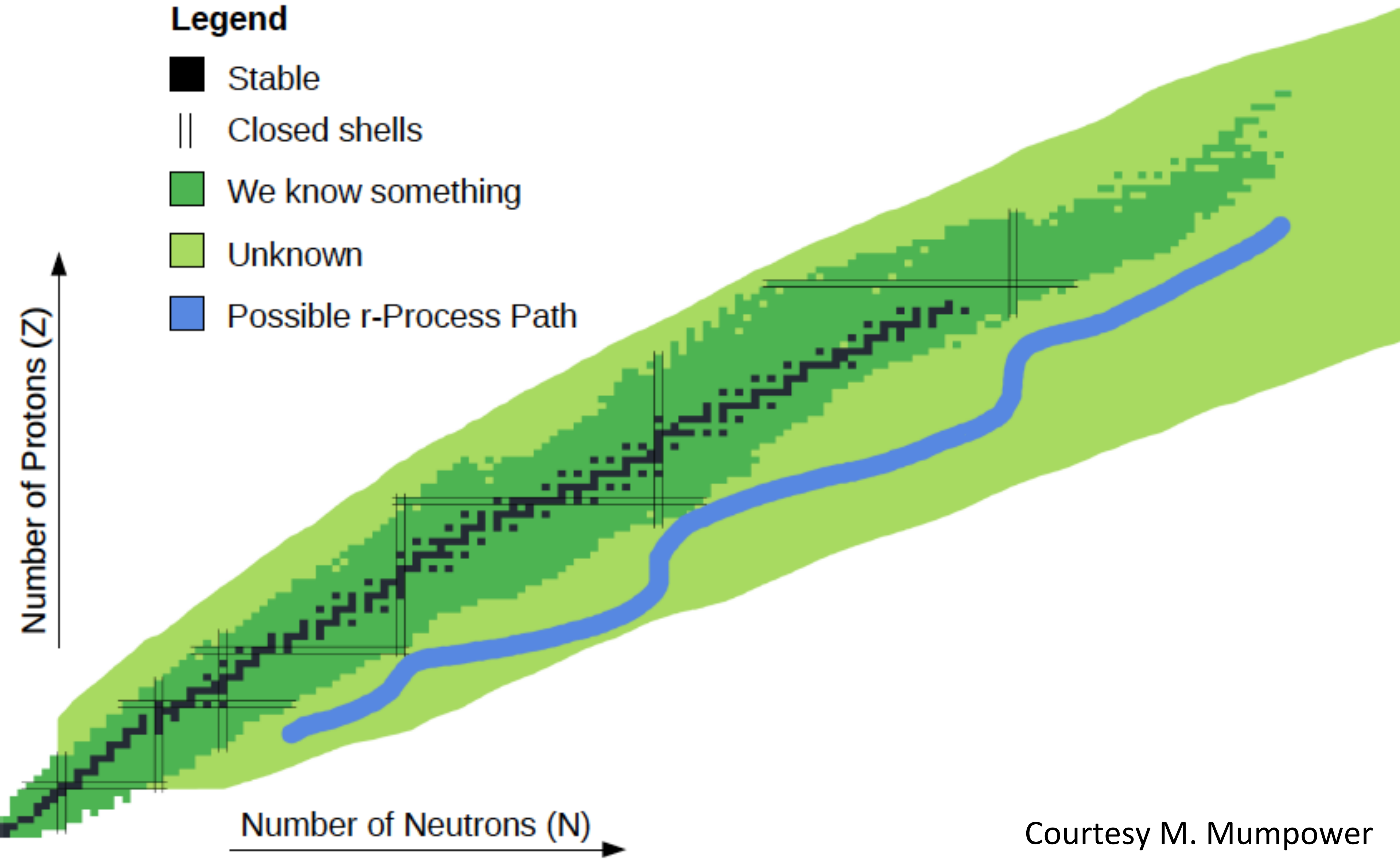
Nuclear data needed:

- nuclear masses
- decay lifetimes
- P_n values
- (n,γ) reaction rates

r-process Nucleosynthesis

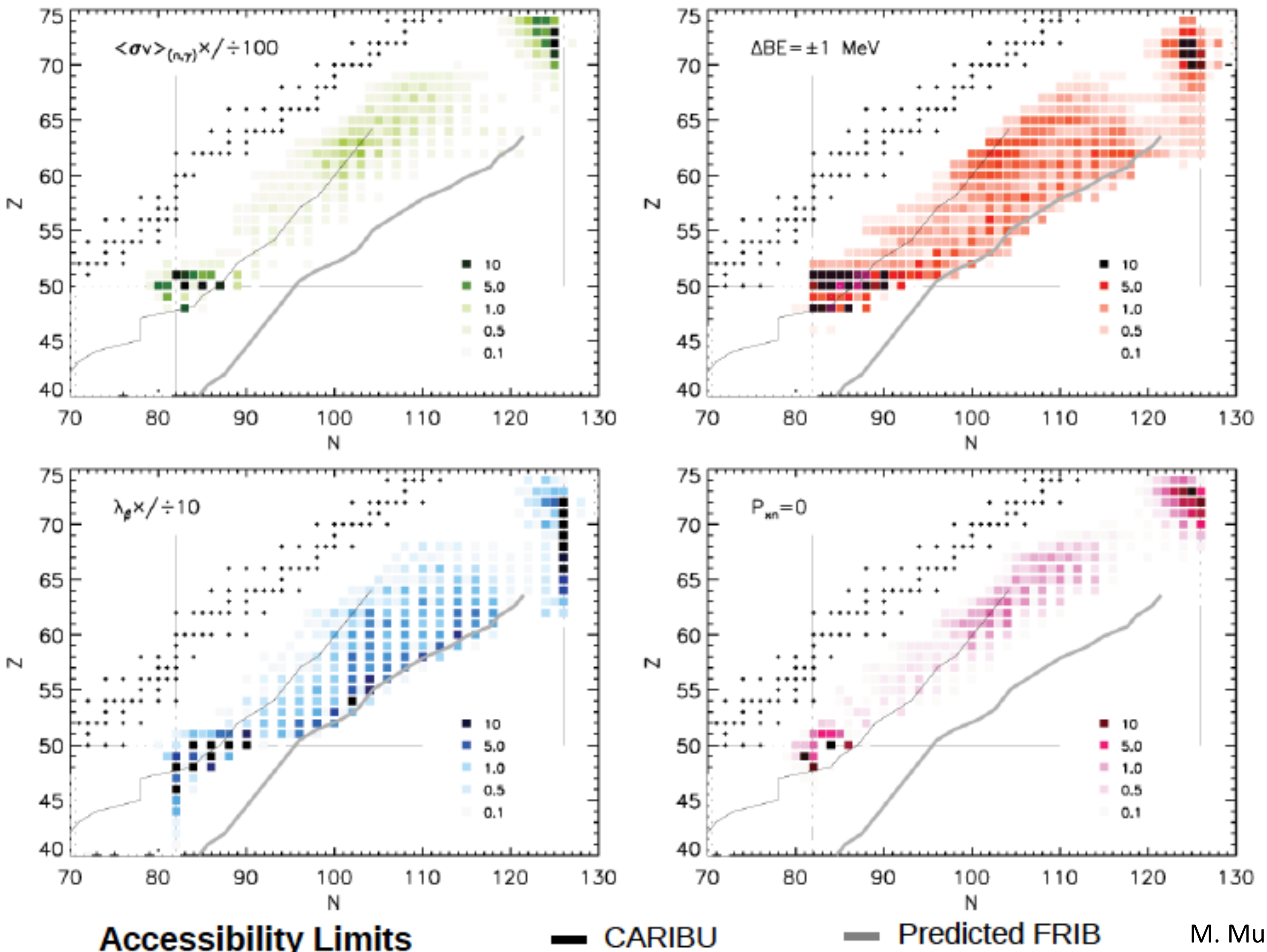


r-process nuclei



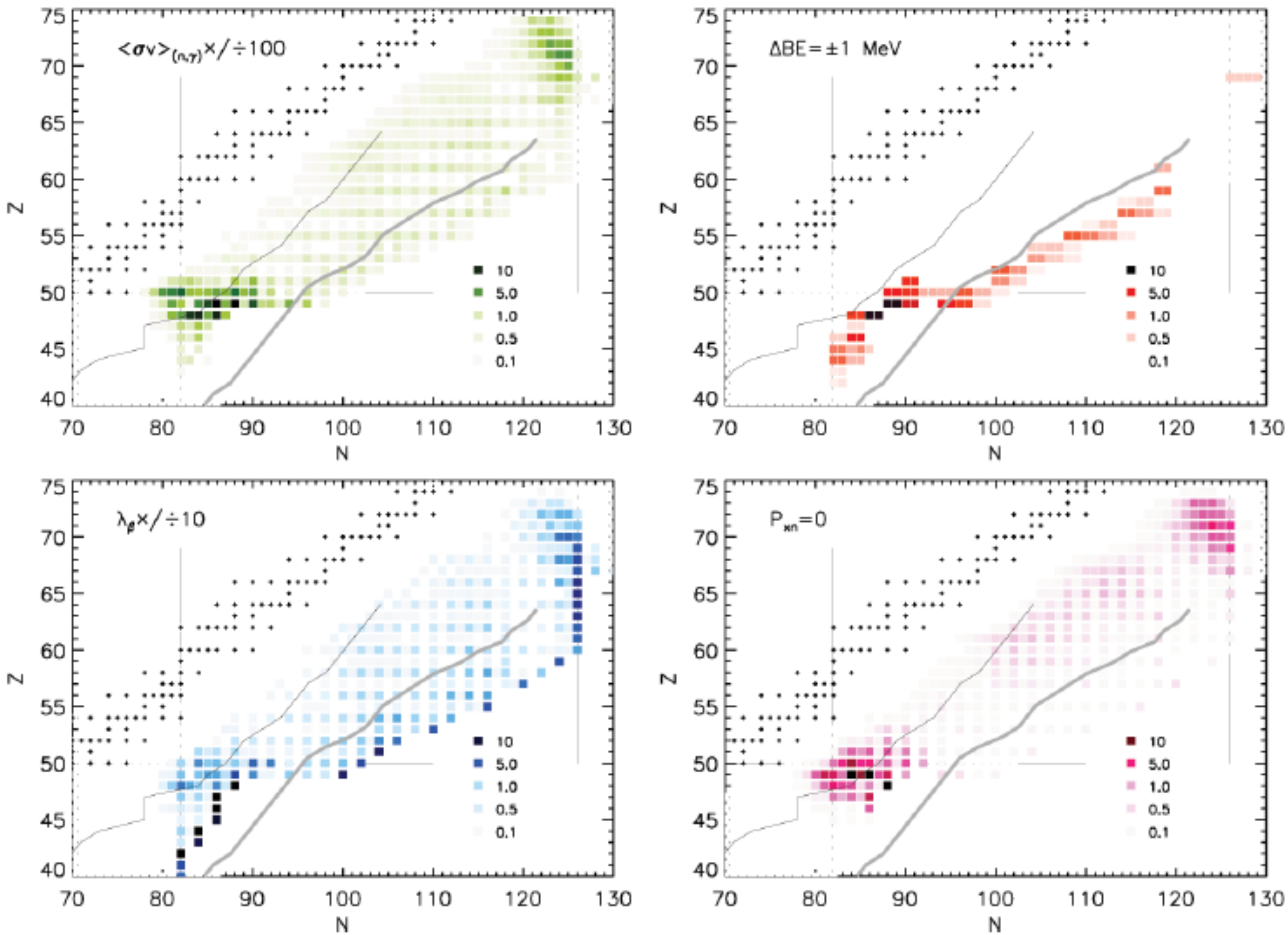
Courtesy M. Mumpower

Hot *r*-process Sensitivity Studies



M. Mumpower

Cold *r*-process Sensitivity Studies

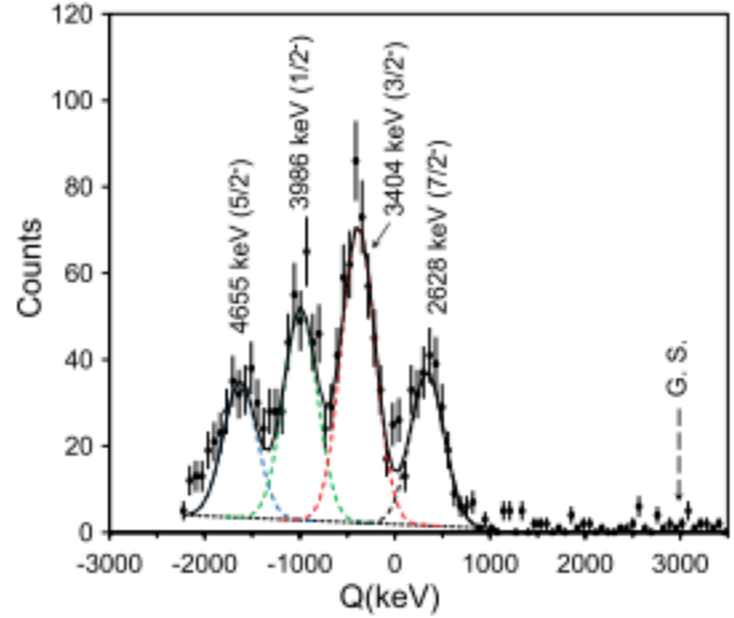


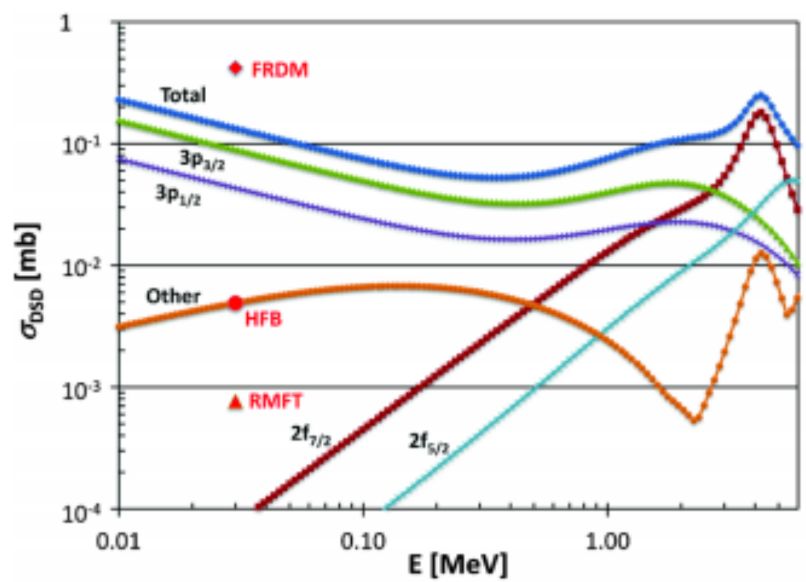
Accessibility Limits — CARIBU — Predicted FRIB

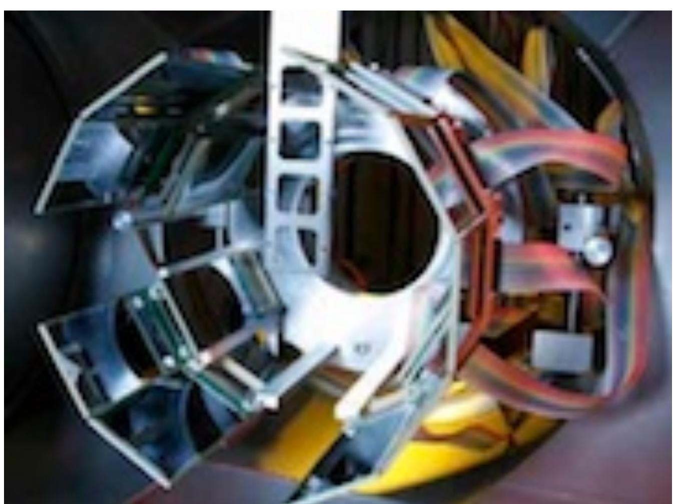
M. Mumpower

(n,γ) reaction rates

- In the *r*-process (n,γ) reactions often occur on *very* neutron rich nuclei
- Can you use a radioactive ion beam on a neutron target??
  - No! Neutrons are unstable!!
- Surrogate reactions [e.g. ($d,p\gamma$)] must be used to for indirect reaction rate determinations:
  - example: ^{130}Sn(d,p)^{131}Sn @ ORNL with ORRUBA

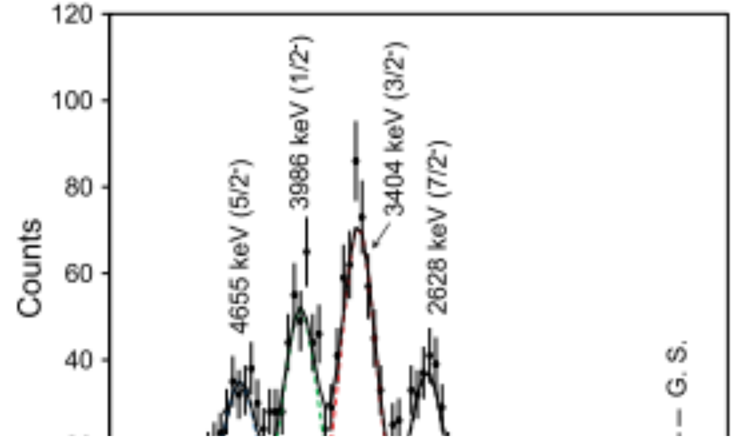






R. L. Kozub *et al.*, PRL **109**, 172501 (2012)

(*n,γ*) reaction rates



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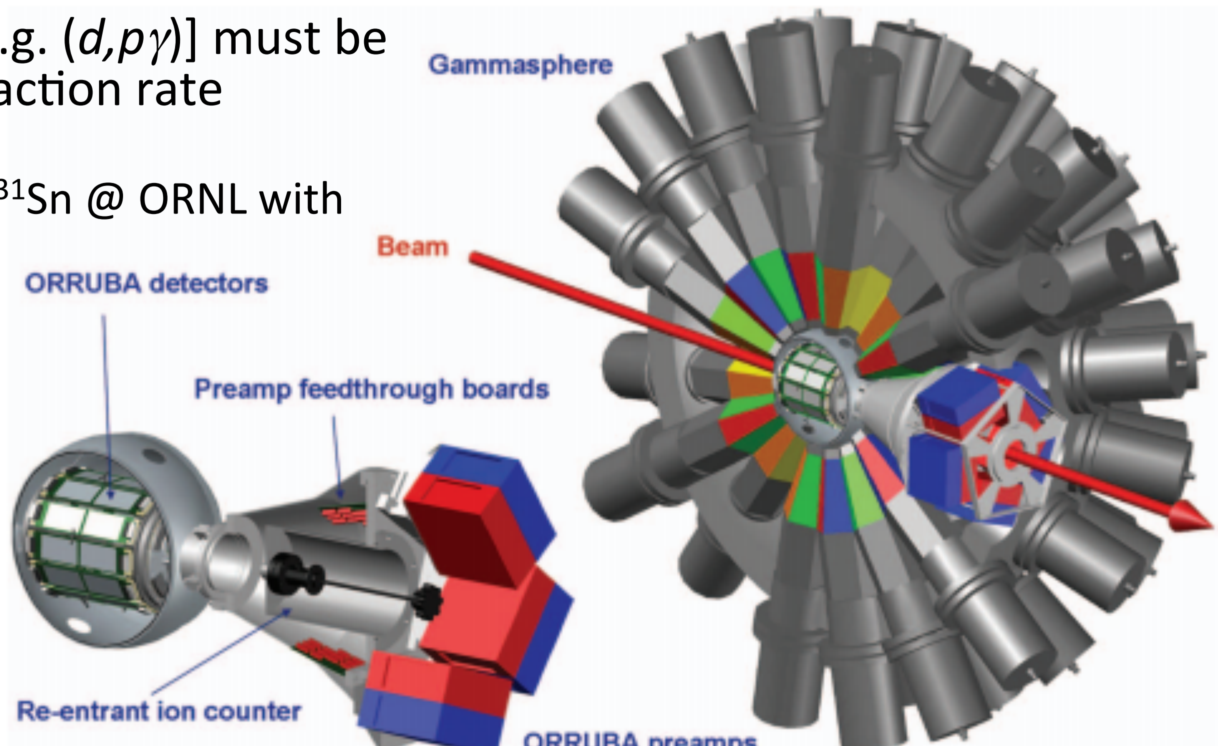
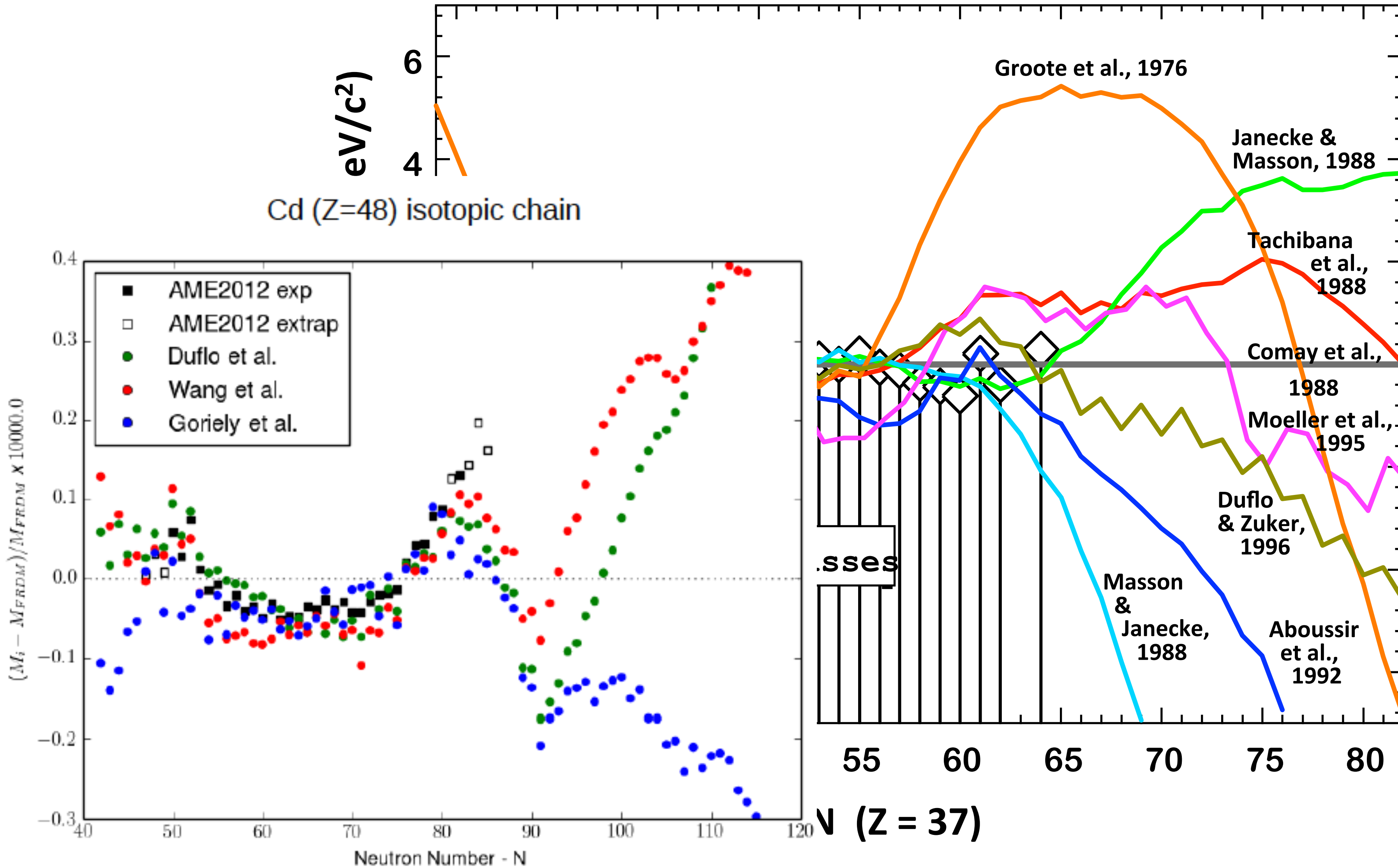


The future:
ORRUBA @
Gammasphere

→ **GODDESS**

S. D. Pain, AIP Advances **4**, 041015 (2014)

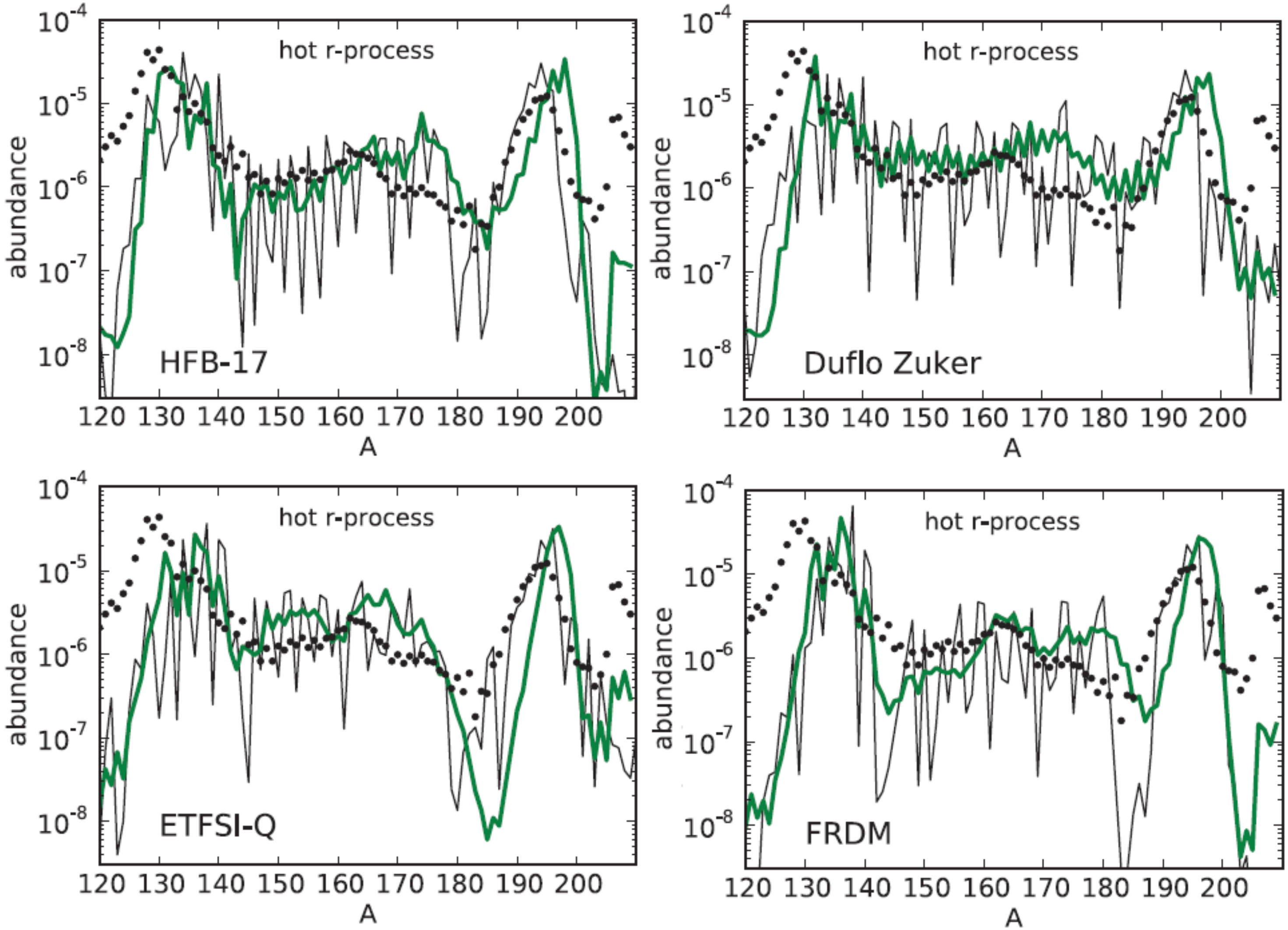
Theoretical Masses



M. Mumpower

Courtesy J. Clark

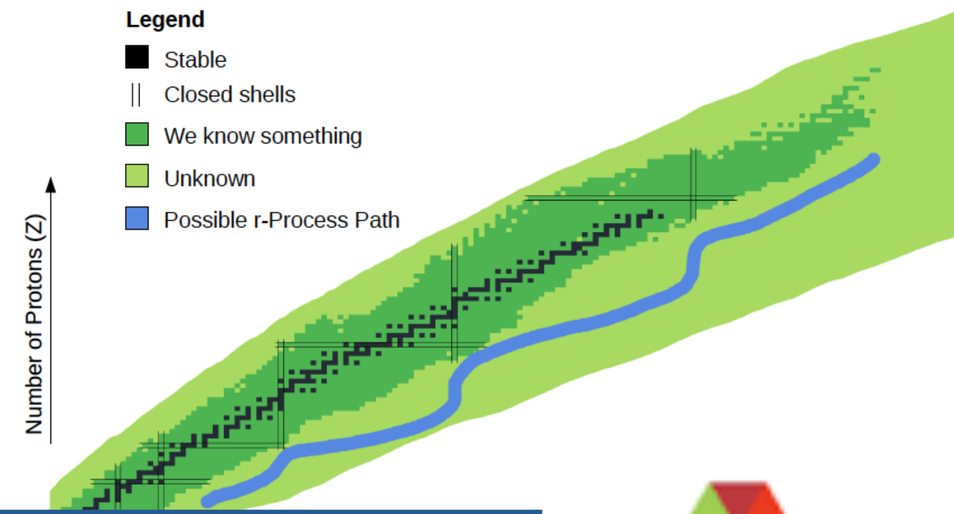
Effects of theoretical masses on *r*-process abundances



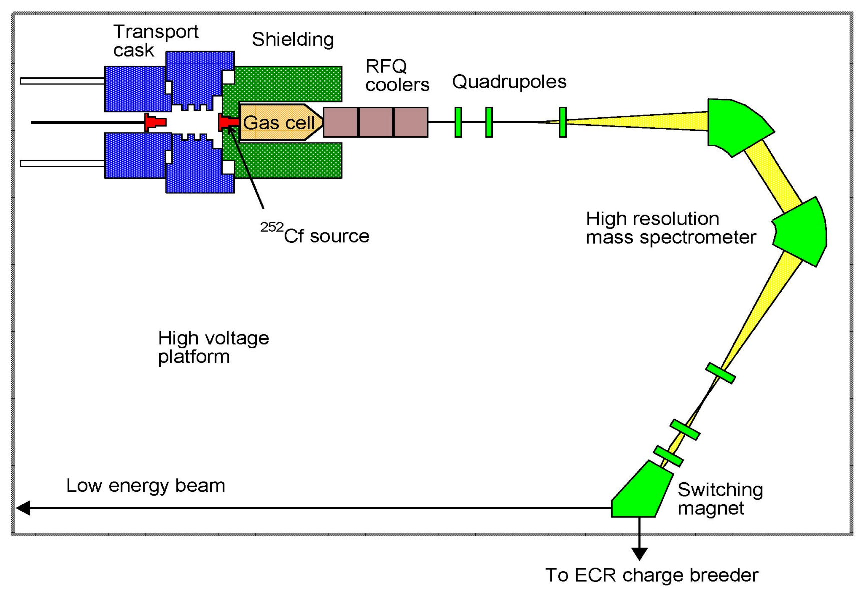
A. Arcones and G. Martinez-Pinedo, Phys. Rev C **83**, 045809 (2011).

Measuring *r*-process Masses

- What do we need to measure neutron rich nuclear masses?
  - neutron-rich nuclei
  - measurement device
    - measure small number of nuclei accurately



'Stopped' beam experimental area



CARIBU

CAlifornium
Rare
Isotope
Breeder
Upgrade

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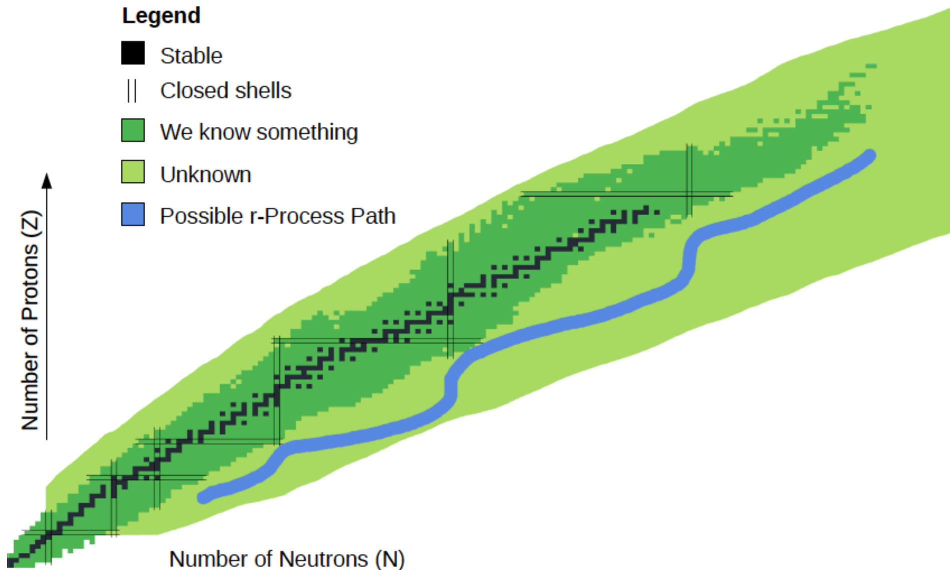
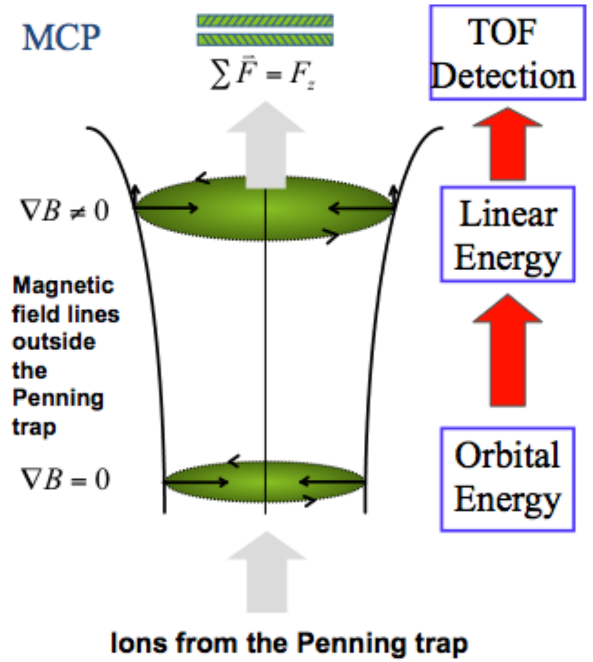
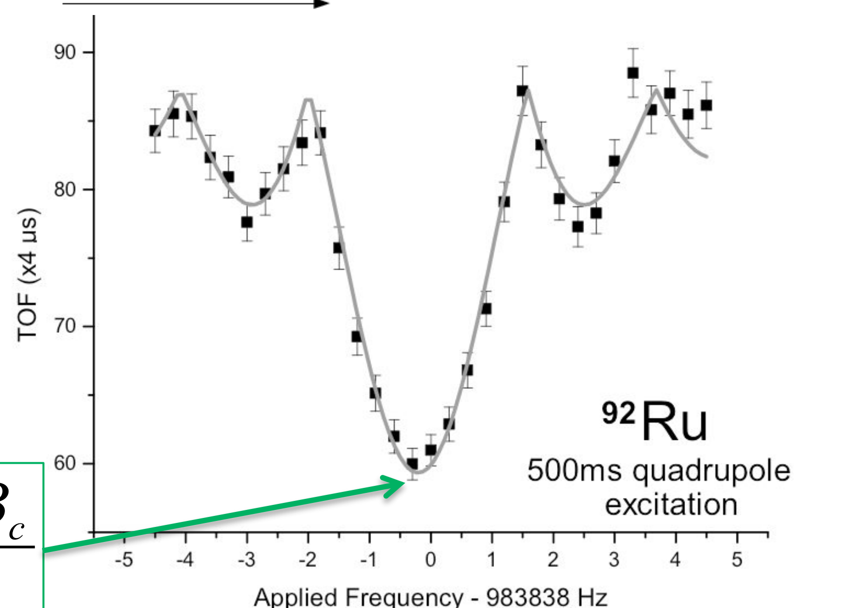
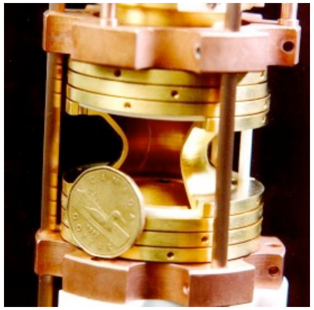


Penning Traps





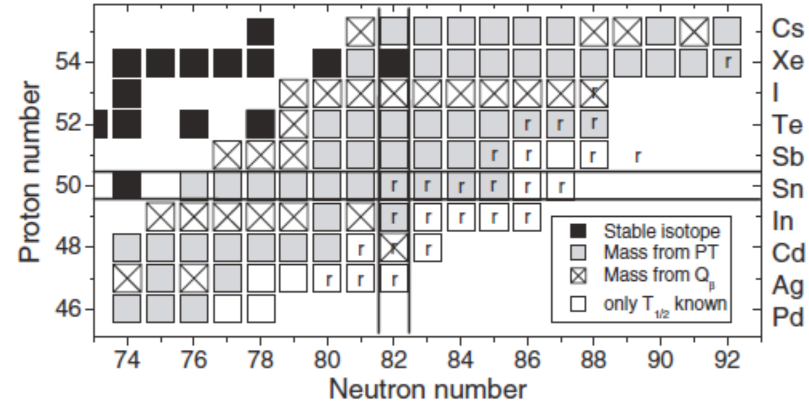
$$\omega_c = \frac{q_c B_c}{m_c}$$



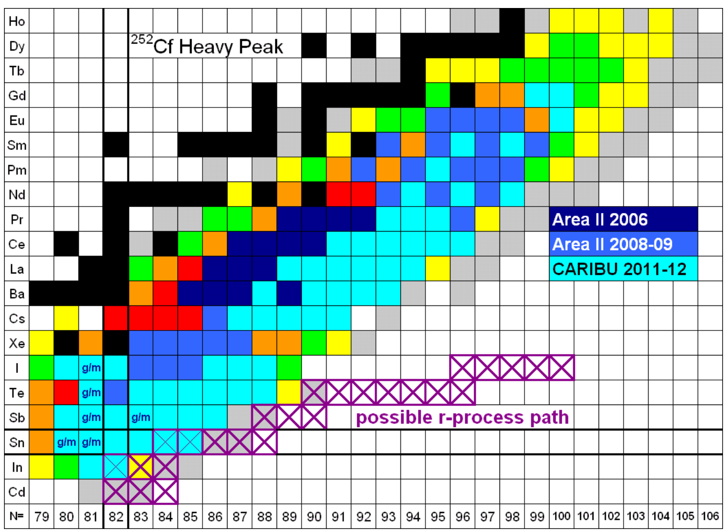
r-process Mass Measurements

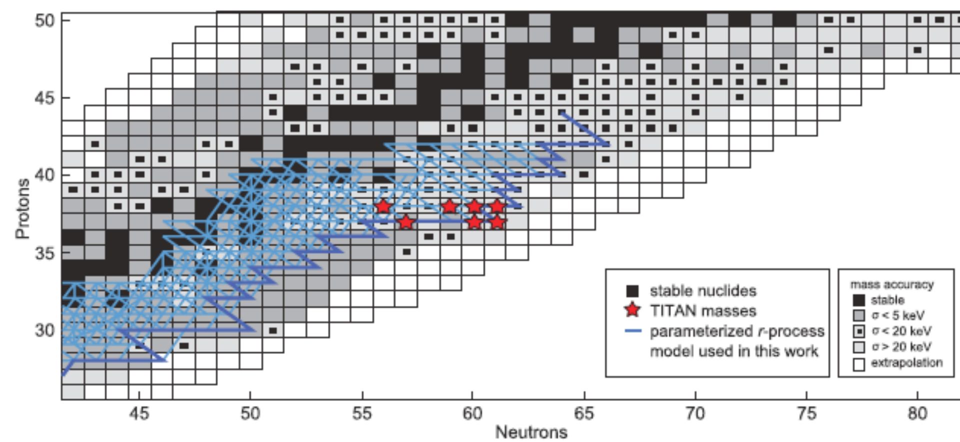
Mass measurements of r-process nuclei have now been made with a variety of Penning traps:

- CPT/CARIBU (ANL)
- JYFLTRAP (Jyväskylä)
- TITAN (TRIUMF)



J. Hakala *et al.*, PRL **109**, 032501 (2012).



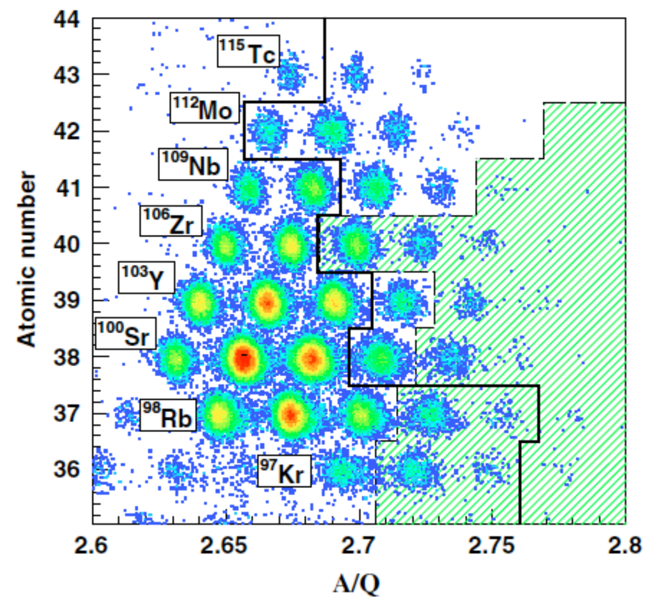


V. V. Simon *et al.*, PRC **85**, 064308 (2012).

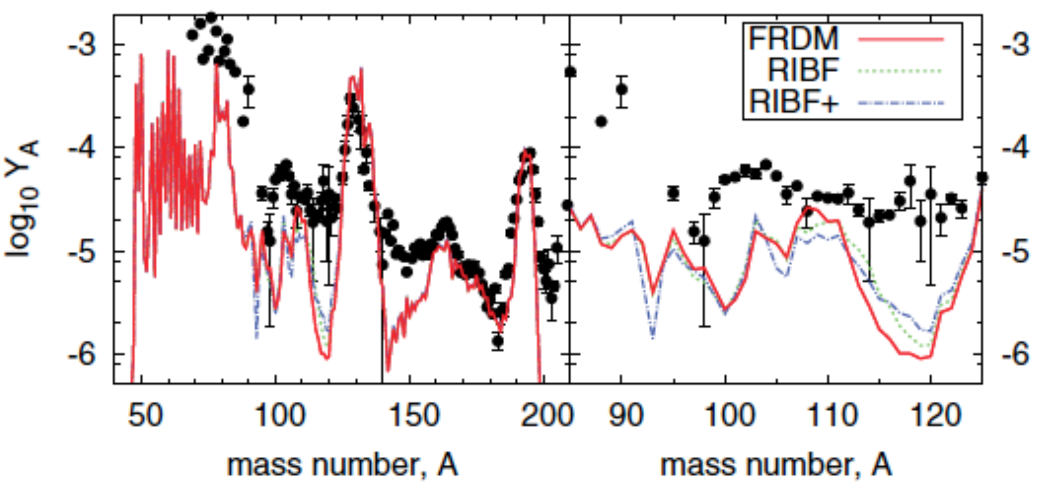
J. van Schelt *et al.*, PRC **85**, 045805 (2012).

β-decay Lifetime Measurements

- Theoretical *r*-process yields under-predict abundances in A = 110 – 125 region
- Mass models attempting to explain this difference in terms of shell closures
- Systematic study of β–decay lifetimes done a RIBF at RIKEN via in-flight fission of ^{238}U on Be target
- New lifetimes included in magnetohydrodynamic (MHD) supernova models
- New lifetimes alleviate discrepan somewhat, but disagreements st exits
  - more physics needed? different physics needed?



S. Nishimura *et al*., PRL **106**, 052502 (2011).



S. Nishimura, PRC **85,** 048801 (2012).

Things I didn't discuss

- Concepts:
  - electron screening
  - interference with broad resonances
  - R-matrix
  - ANCs
  - *p*-process, *s*-process, νp-process
  - etc.

- Experimental methods
  - elastic and inelastic scattering
  - Atomic Mass Spectroscopy
  - Bubble chambers
  - etc.

Still MUCH to do!!

- Low energy, low background direct reaction measurements with high beam intensities
- Proton-rich reaction rate measurements for *rp*-process
  - indirect and direct
  - stable and radioactive ion beams
- Neutron-rich mass and lifetime measurements for the *r*-process
- Surrogate reactions for (n,γ)
- Non-experimental needs:
  - Improved stellar modeling
  - Observations of specific isotopes (not just elements)

Resources

- Historical reading:
  - **B^{2}FH**: Burbidge, Burbidge, Fowler and Hoyle, Rev. Mod. Phys. **29**, 15 (1957)

- Textbooks:
  - **Rolfs & Rodney**, *Cauldrons of the Cosmos,* Cambridge University Press (1988)
  - **C. Iliadis**, *Nuclear Physics of Stars*, Wiley (2007)
  - **I. Thompson & F. Nunes**, *Nuclear Reactions for Astrophysics,* Cambridge University Press (2009)

Thanks for your attention!!