Recent Developments in Nuclear Astrophysics

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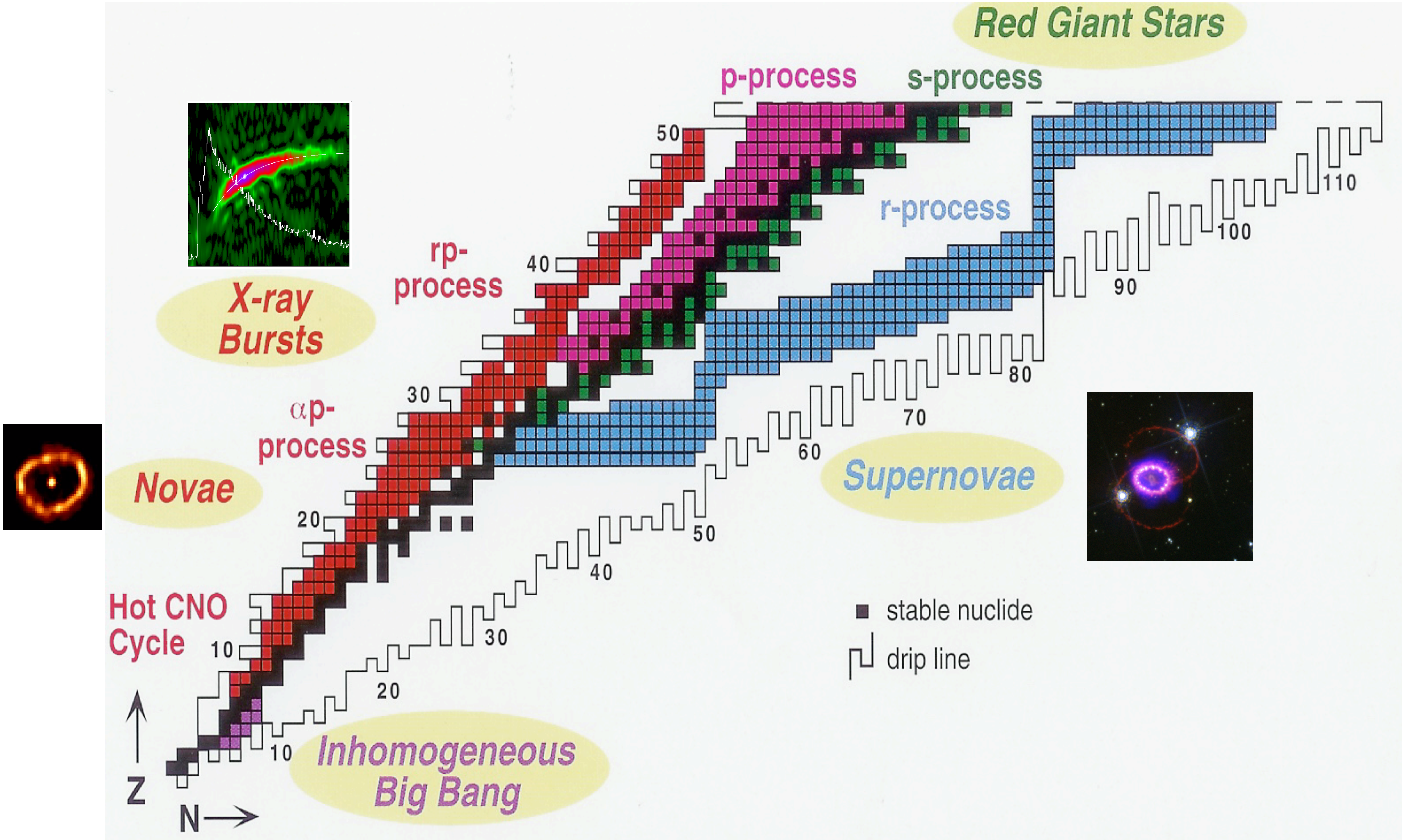
- Over 80 talks
- Over 200 posters
- Talks covering
  - Observations
  - Modeling
  - **Nuclear structure**



Red Giant Stars
p-process
s-process
r-process
rp-
process
αp-
process
X-ray
Bursts
Novae
Supernovae
Hot CNO
Cycle
Inhomogeneous
Big Bang
stable nuclide
drip line
Z
N
10
20
30
40
50
60
70
80
90
100
110

Big Bang Nucleosynthesis: Li problem(s)

- Well known discrepancy between observed primordial ^{7}Li abundance and theoretical predictions (factor of 3 larger)

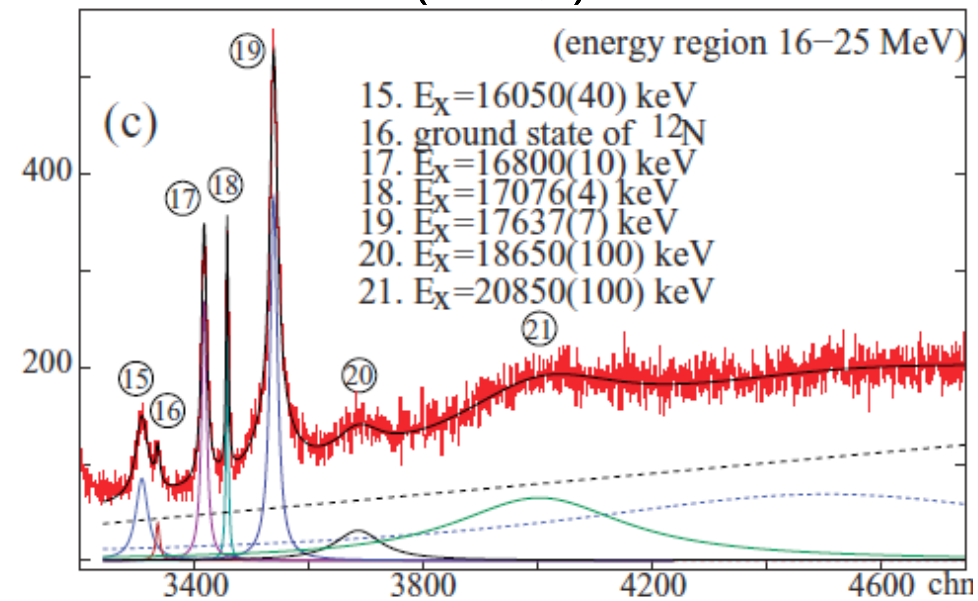
- Nuclear physics as a solution?
  - destruction of ^{7}Be through ^{7}Be + d resonance?

- Current experimental and theoretical studies show there is not a nuclear solution to the ^{7}Li problem
  - ^{9}Be(3He,t)^{9}B: Ex = 16.800(10) MeV, Γ_{cm} = 81(5) keV
  - ^{10}B(3He,α)^{9}B: Ex $\approx$ 16.8 MeV

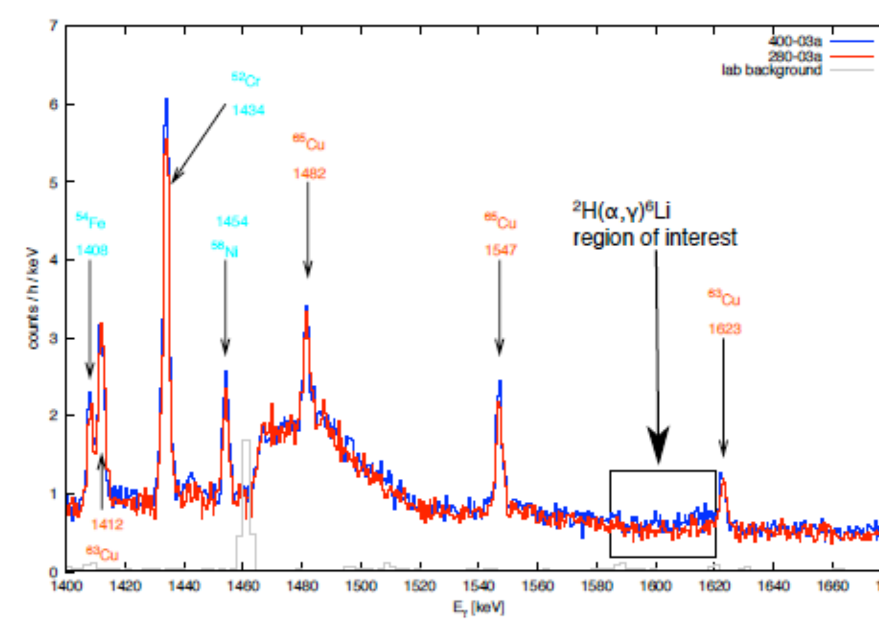
- Possible ^{6}Li problem as well → ^{6}Li detected in some metal-poor halo stars

- Current experimental work ongoing at LUNA to determine ^{2}H(α,γ)^{6}Li rate at BBN conditions
  - preliminary results indicate insignificant ^{2}H(α,γ)^{6}Li rate to account for observed ^{6}Li abundances

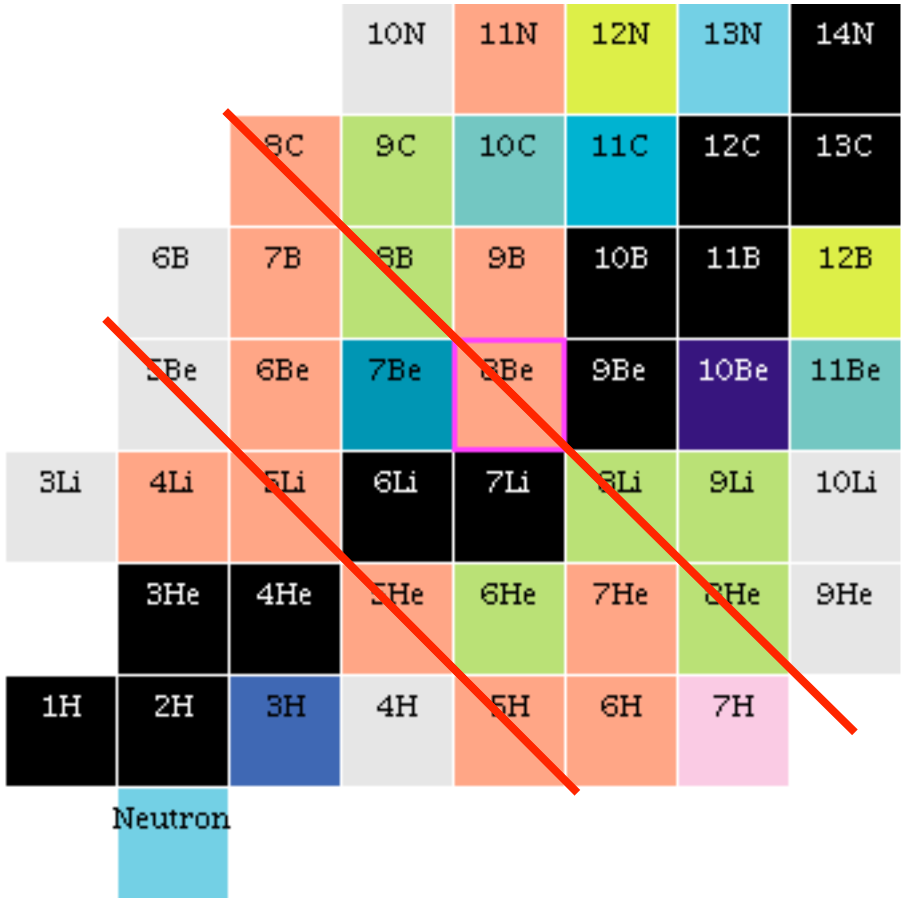
^{9}Be(^{3}He,t)^{9}B data



C. Scholl *et al.*, PRC **84**, 014308 (2011).



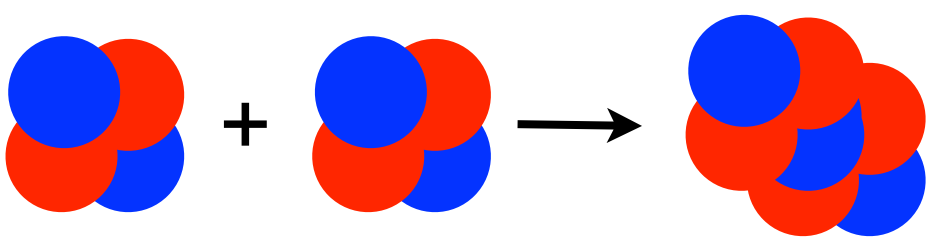
M. Anders *et al.*, Mem. S.A.It.Suppl. **22**, 181 (2012).



Triple-α Reaction

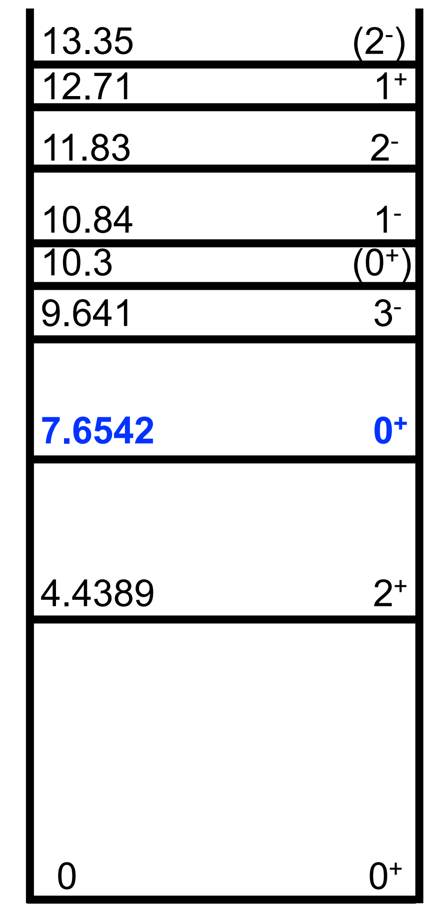
- Mass gaps at A = 5 and 8 responsible for the end of BBN

Fred Hoyle

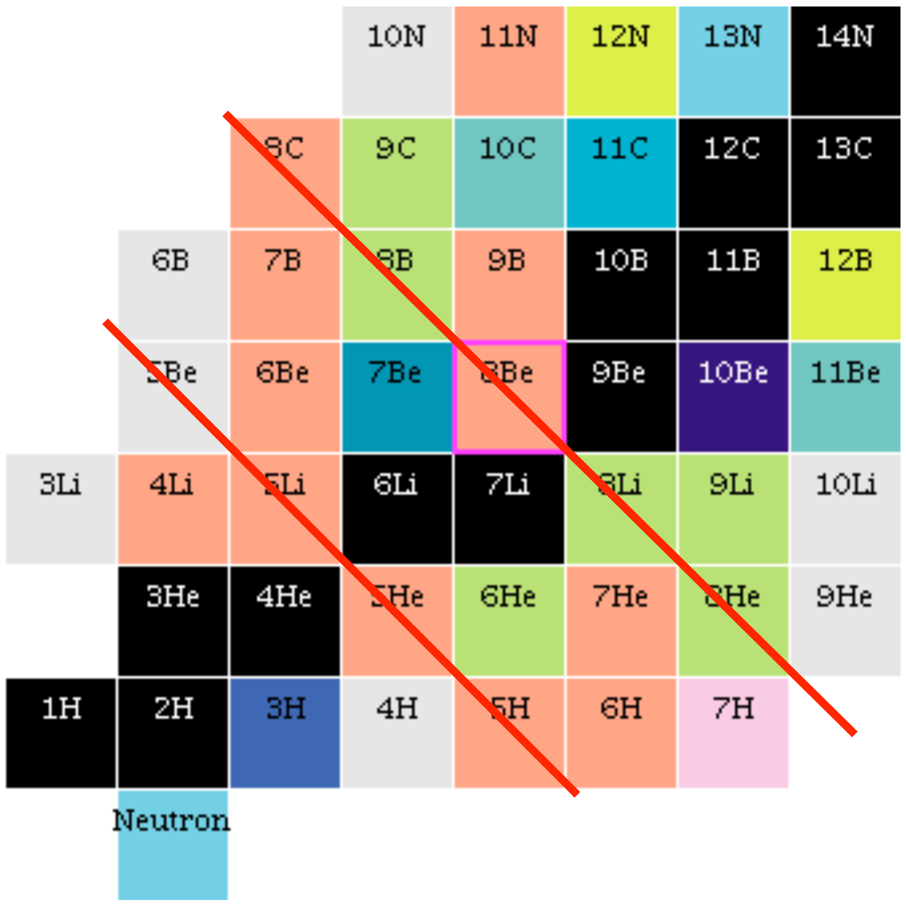


$$\alpha + \alpha \rightarrow {}^{8}\text{Be}$$

$$\tau = 2.6 \times 10^{-16}\ \text{s}$$



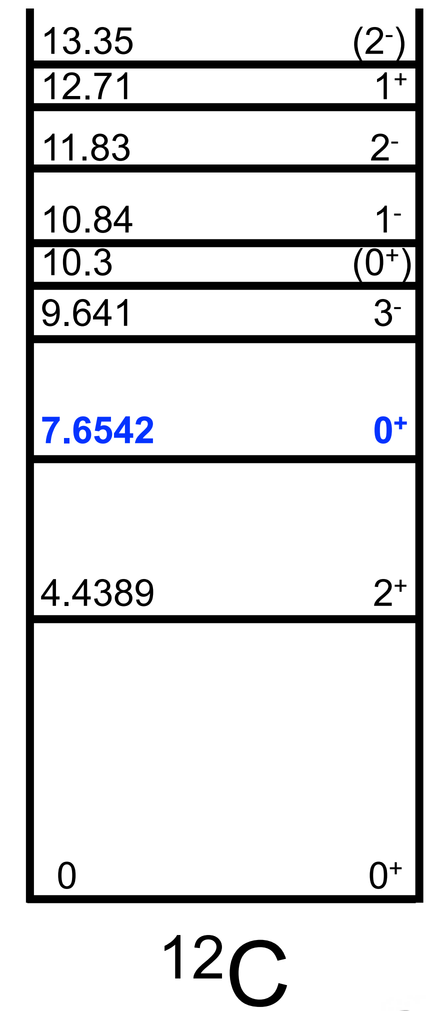
^{12}C

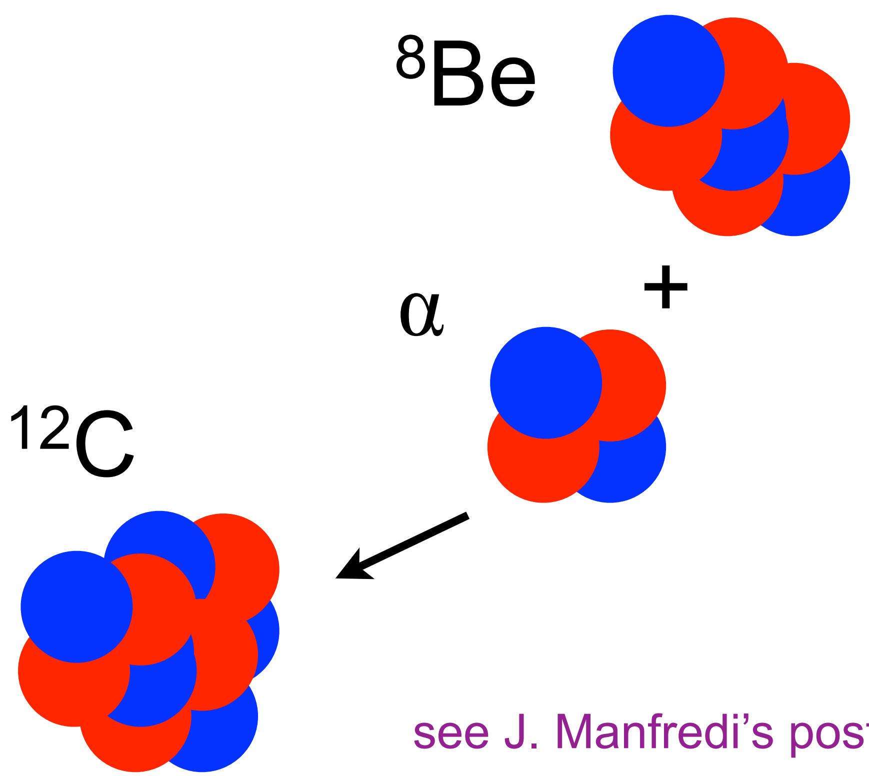


Triple-α Reaction

- Mass gaps at A = 5 and 8 responsible for the end of BBN
- To produce enough ^{12}C to account for life on earth needed a resonance close to $^{8}Be + \alpha$ threshold of 7.367 MeV (predicted by Hoyle 1954)

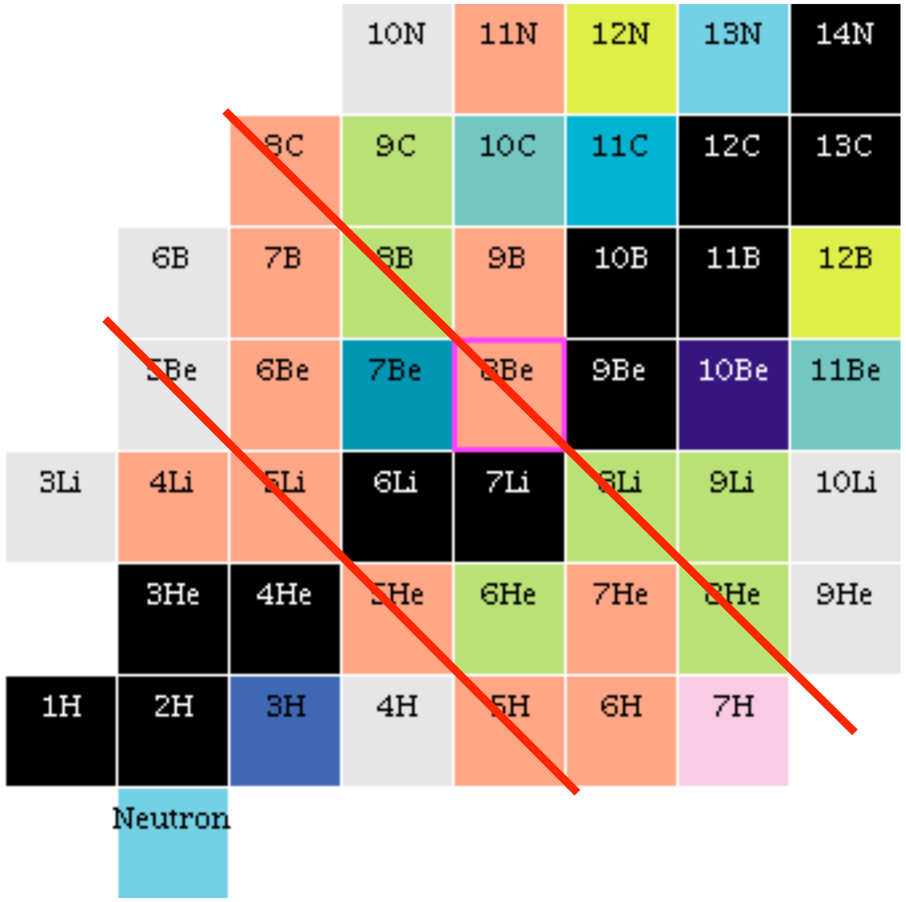
Fred Hoyle

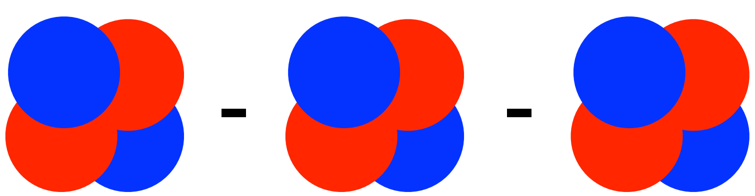




see J. Manfredi's poster

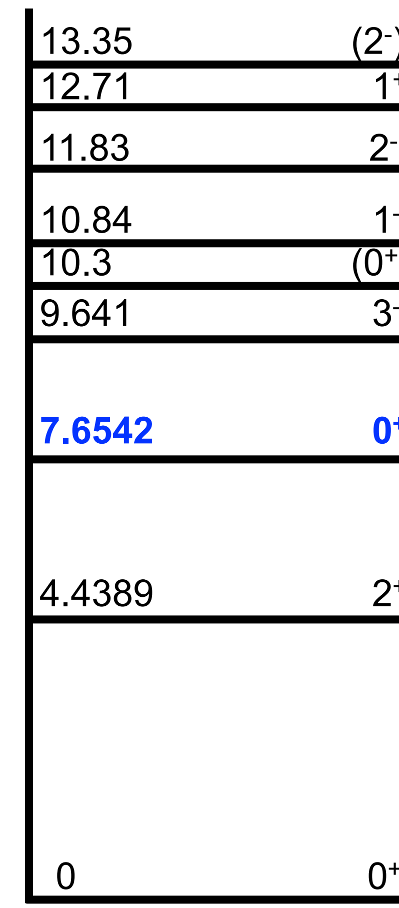
Triple-α Reaction





- Mass gaps at A = 5 and 8 responsible for the end of BBN
- To produce enough ^{12}C to account for life on earth needed a resonance close to ^{8}Be + α threshold of 7.367 MeV (predicted by Hoyle 1954)
- Experimentally found in 1957 (Cook *et al*.) to be at **7.654 MeV**
- Structure of the Hoyle state is of interest; observation of 2^+ collective excitation of Hoyle state is on-going

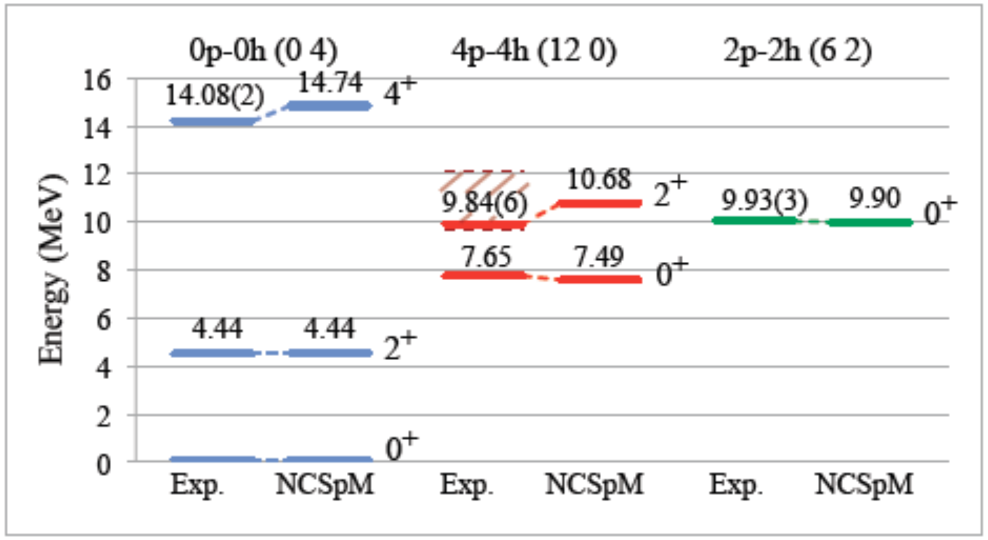
Fred Hoyle



^{12}C

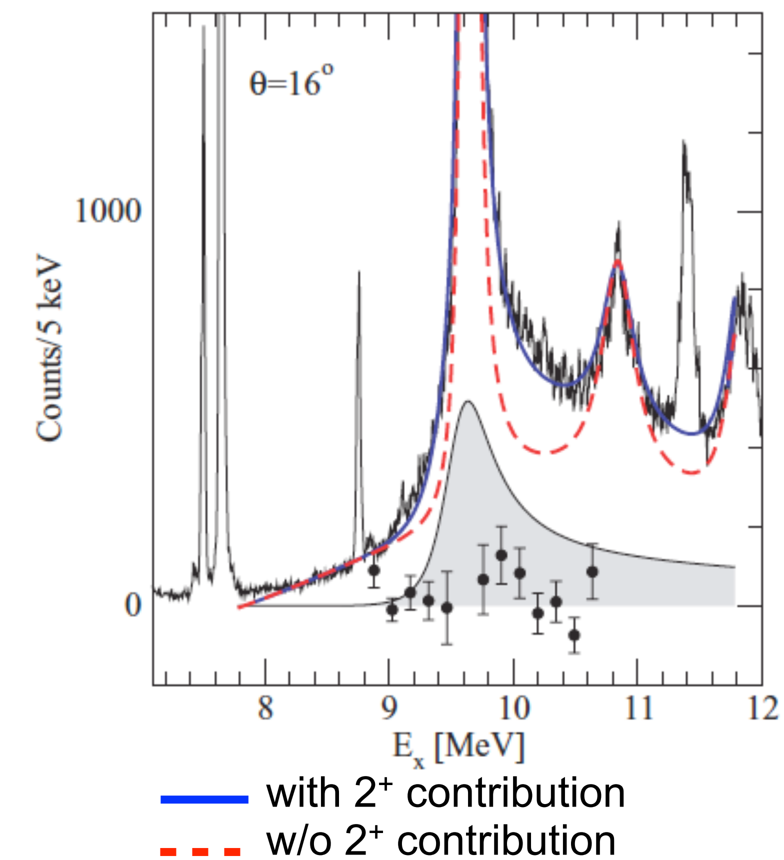
2^+ excitation of the Hoyle state

- Theoretical predictions of 2^+ excitation energy
  - 9.1 MeV (NACRE)
  - 10.68 MeV (LSU group - no-core symplectic model)



A. C. Dreyfuss *et al.*, in prep.

- Recent experimental measurements:
  - $^{12}C(p,p`)^{12}C$ scattering (S. Africa, Yale, Osaka)
    - ➡ data show 2^+ state at ~9.8 MeV
  - β decay of ^{12}B and ^{12}N (ANL)
    - ➡ preliminary R-matrix analysis shows no indication of 2^+ state
  - Gammasphere study (ANL)
    - ➡ observe 2^+ state at ~11.1 MeV
  - γ decay from higher-lying states in ^{12}C
    - ➡ observe 2^+ resonances in both 9-10 and 11-12 MeV regions



M. Freer *et al.*, PRC **80**, 041303(R) (2009).

- Disagreements clearly still exist . . .

Explosive nucleosynthesis: Classical Novae

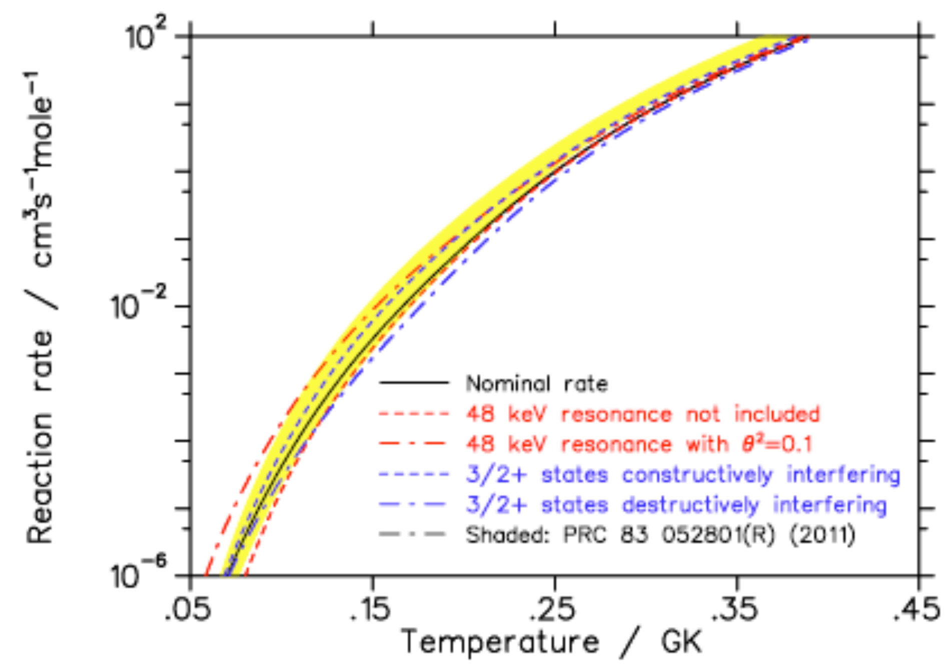
- Most "well-understood" astrophysical events
  - most important reaction rates known, except . . .
    - ^{25}Al(p,γ)^{26}Si (see S. Pain's talk)
    - ^{30}P(p,γ)^{31}S
    - ^{18}F(p,α)^{15}O

$$N_A\langle\sigma v\rangle = \frac{1.599\times10^{11}}{(\mu T_9)^{3/2}}\sum_r(\omega\gamma)_r\, e^{-11.605E_r/T_9}$$

$$\text{where } \omega = \frac{(2J+1)(\delta_{01}+1)}{(2j_0+1)(2j_1+1)} \text{ and } \gamma = \frac{\Gamma_a\Gamma_b}{\Gamma}$$

- Many reaction rates measured directly (still need indirectly measured nuclear structure data)

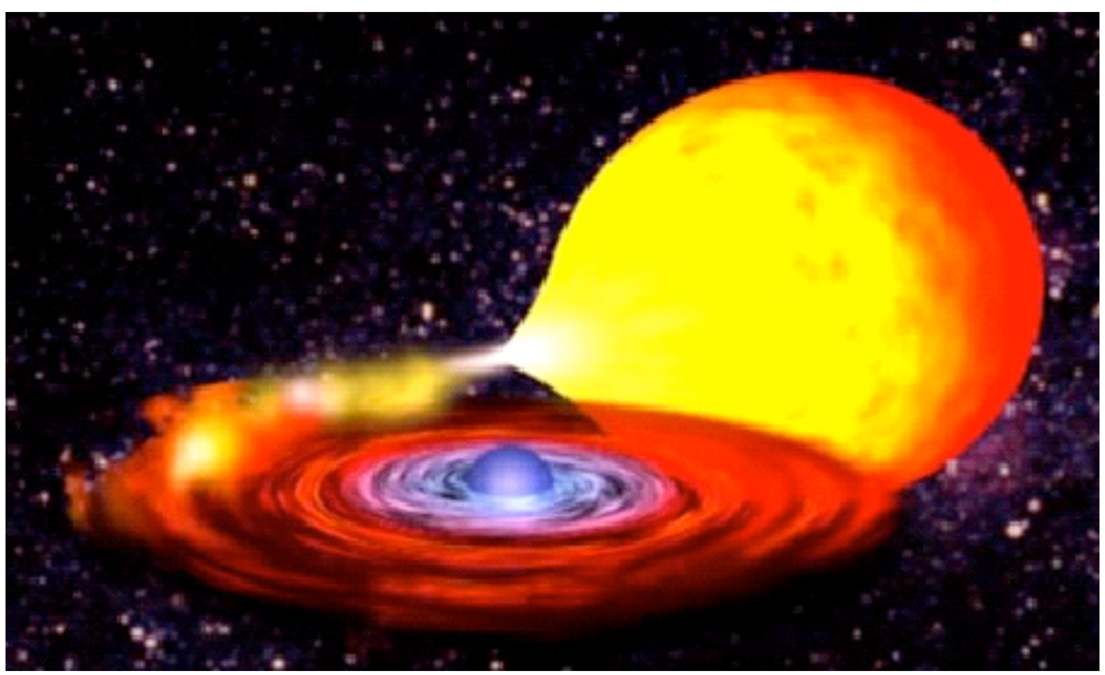
- For example, ^{18}F(p,α)^{15}O
  - traditionally rate thought to be dominated by two $3/2^+$ resonances @ E_r = 8 and 38 keV and one $3/2^-$ resonance at E_r = 330 keV
  - new data shows the E_r = 8 and 38 keV states are a triplet of E_r = 5, 29, and 48 keV none of which are $3/2^+$
  - the unconstrained proton width of the 48 keV state causes large uncertainties in the reaction rate

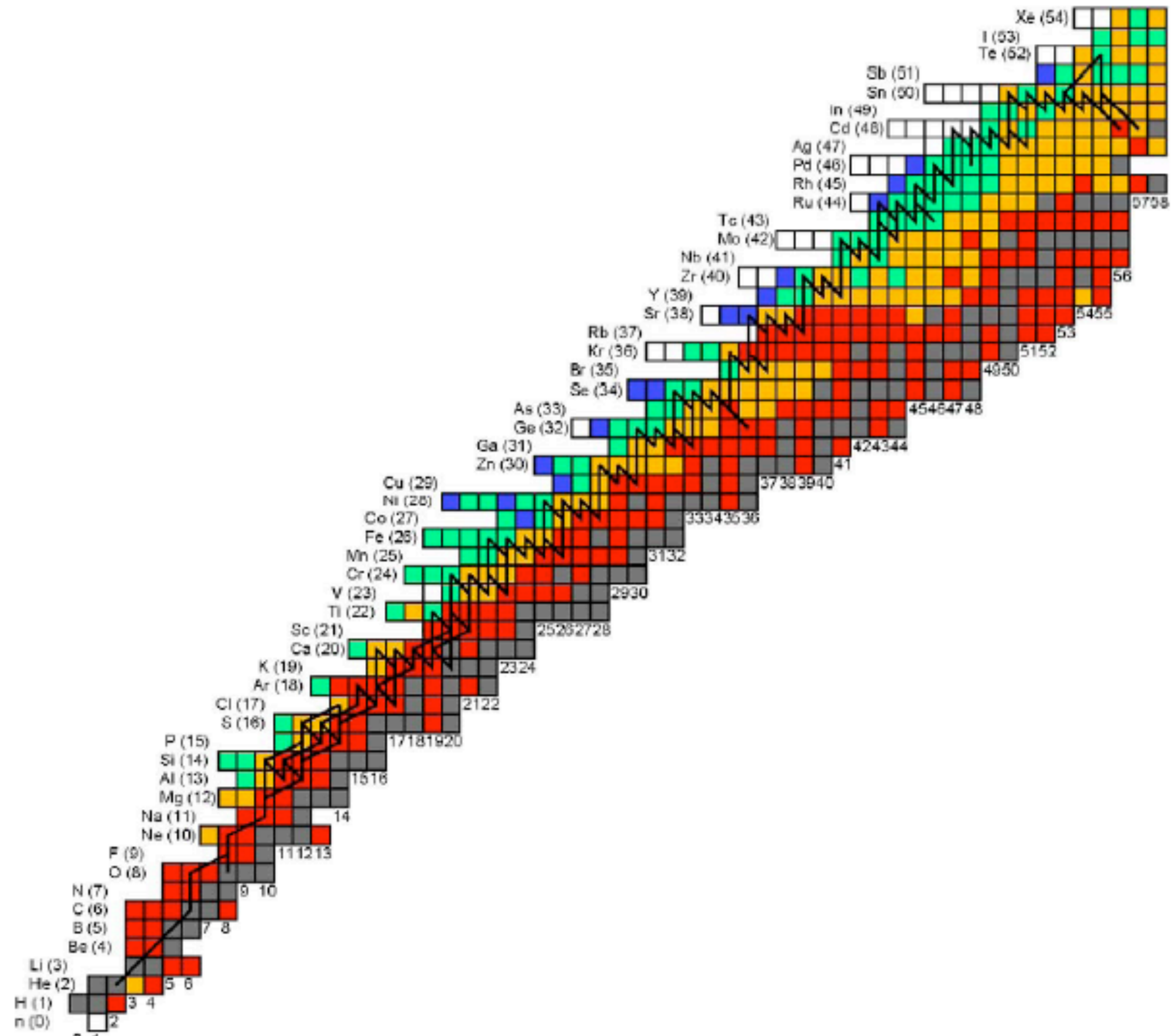


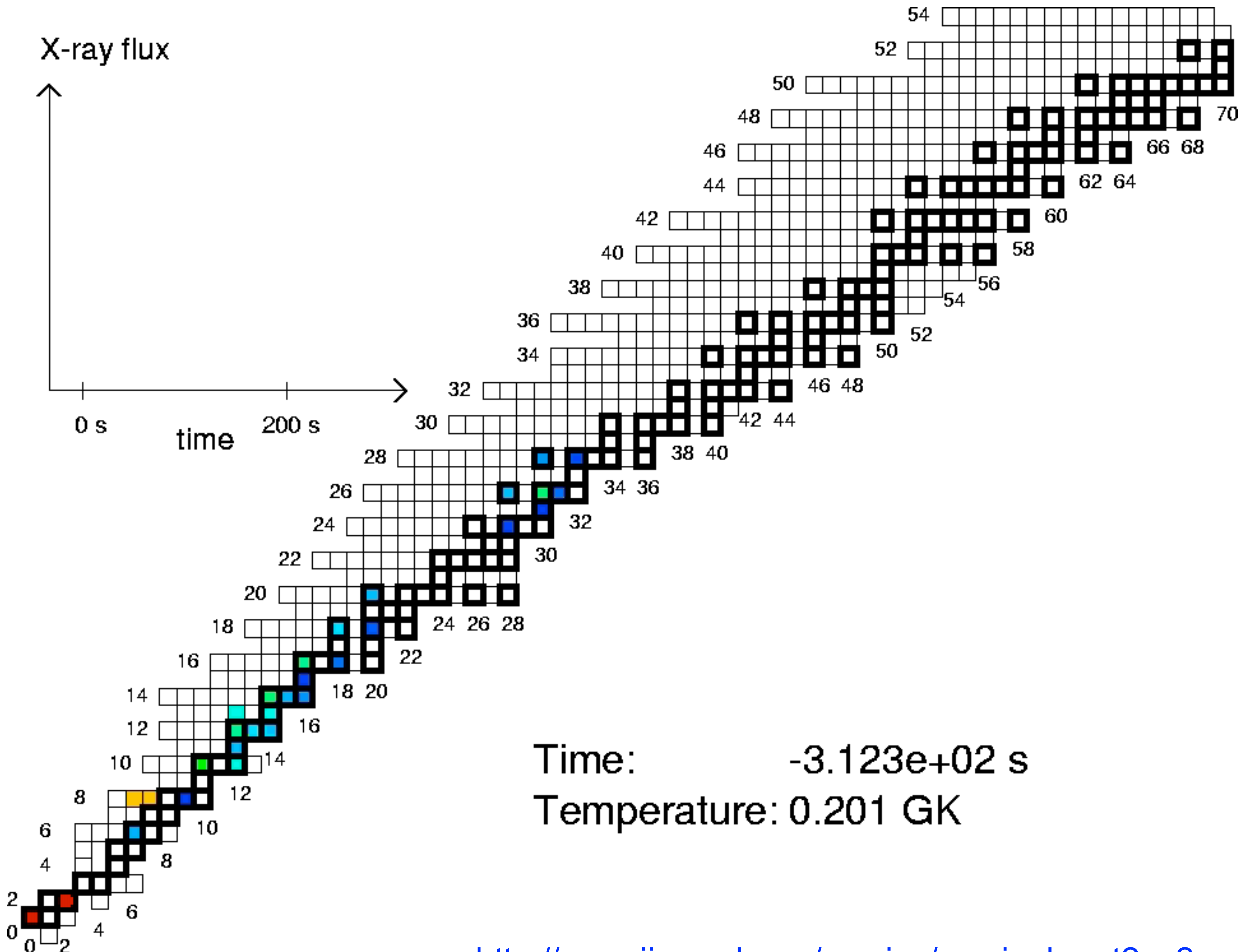
A. Laird *et al.*, (2012) *in preparation*

Explosive nucleosynthesis: X-ray bursts

- Explosive nucleosynthesis in type I X-ray bursts (XRBs) powered by
  - triple-α reaction
  - (α,p) process
  - *rp* process

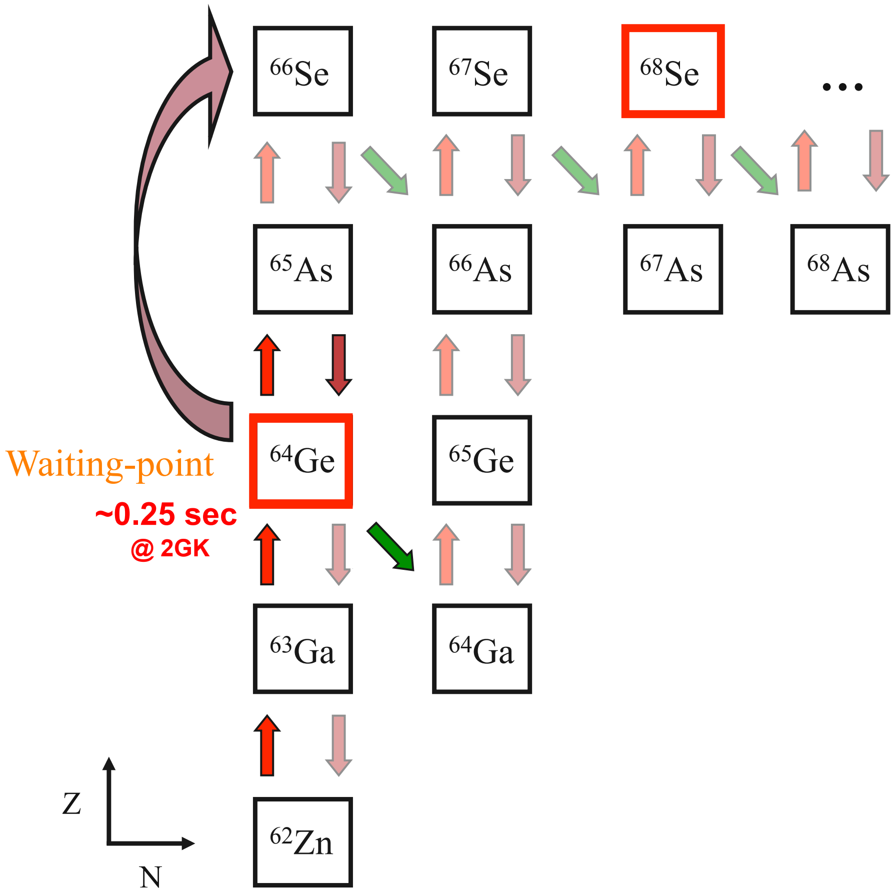






Time: -3.123e+02 s
Temperature: 0.201 GK

http://www.jinaweb.org/movies/movie_burst2_v2.mov

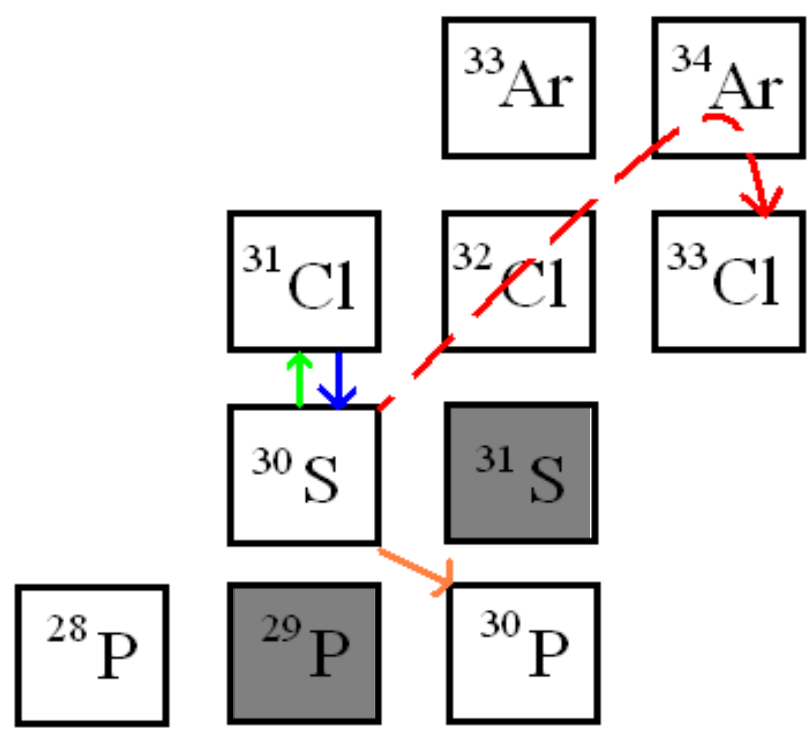


Waiting points in XRBs

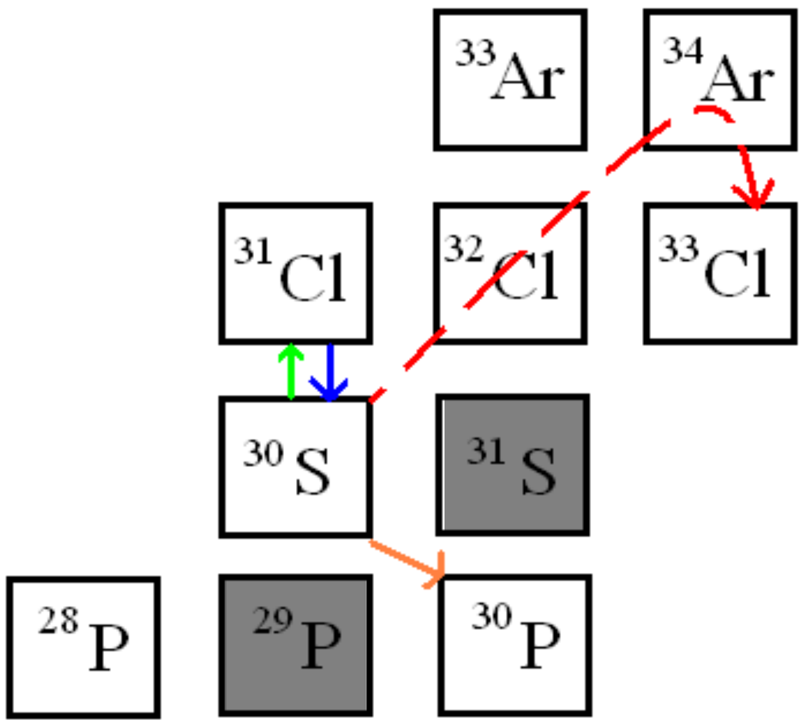
- High-mass waiting points in XRBs determine shape of light-curve tail
- Main waiting points: ^{64}Ge, ^{68}Se, ^{72}Kr
- Lifetimes well known, but not S_p's of Z+1 nuclei
- ^{69}Br and ^{73}Rb both experimentally known to have negative S_p, supporting ^{68}Se and ^{72}Kr as waiting points, respectively
- S_p for ^{65}As is not well-known due to unknown mass of - is ^{64}Ge really a waiting point?

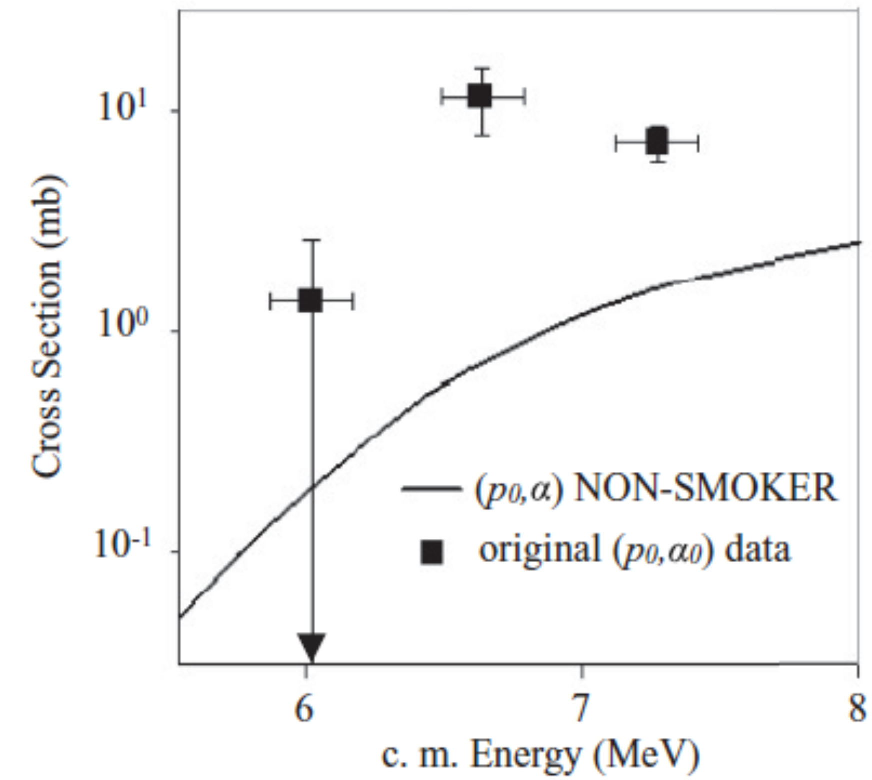
- (α,*p*) process waiting points effect
  - energy generation near the beginning of XRB nucleosynthesis
  - final elemental abundances
  - luminosity profile

- Possible (α,*p*) process waiting points
  - ^{22}Mg
  - ^{26}Si
  - ^{30}S
  - ^{34}Ar

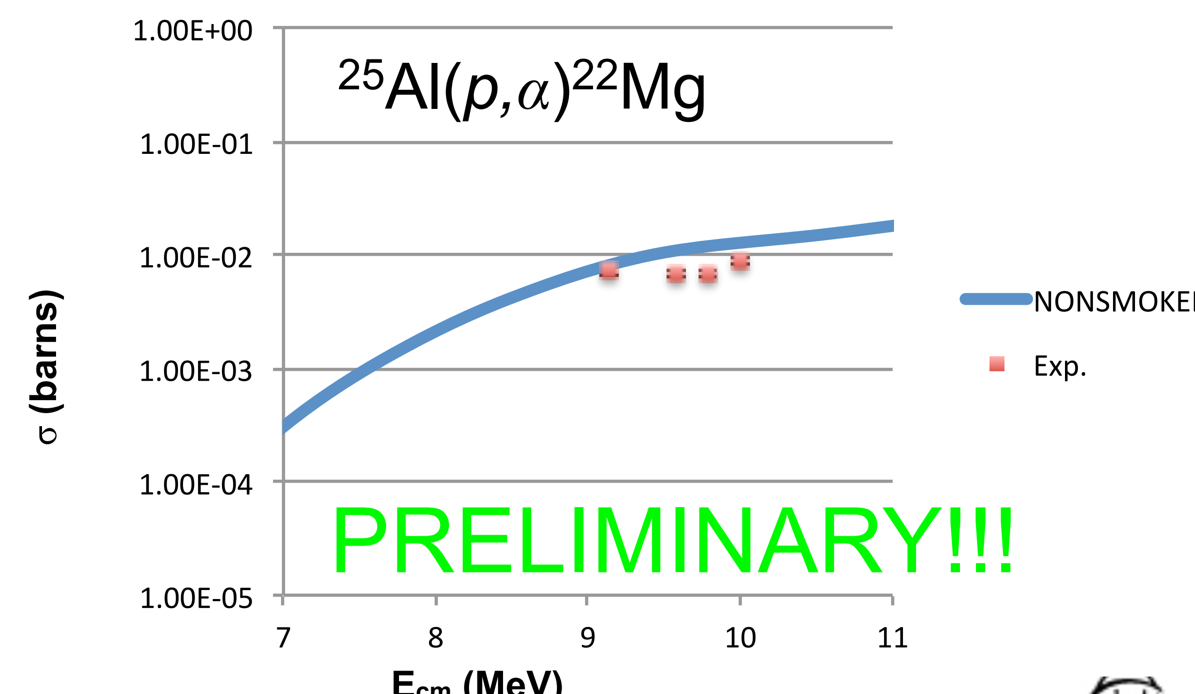


Waiting points in XRBs



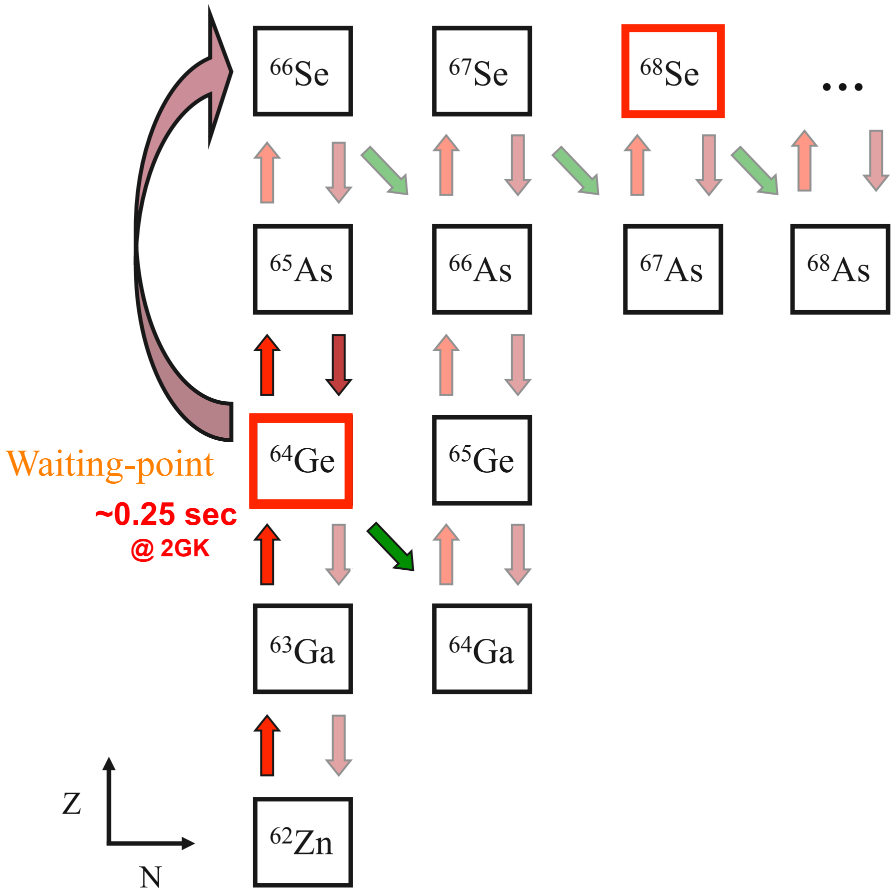


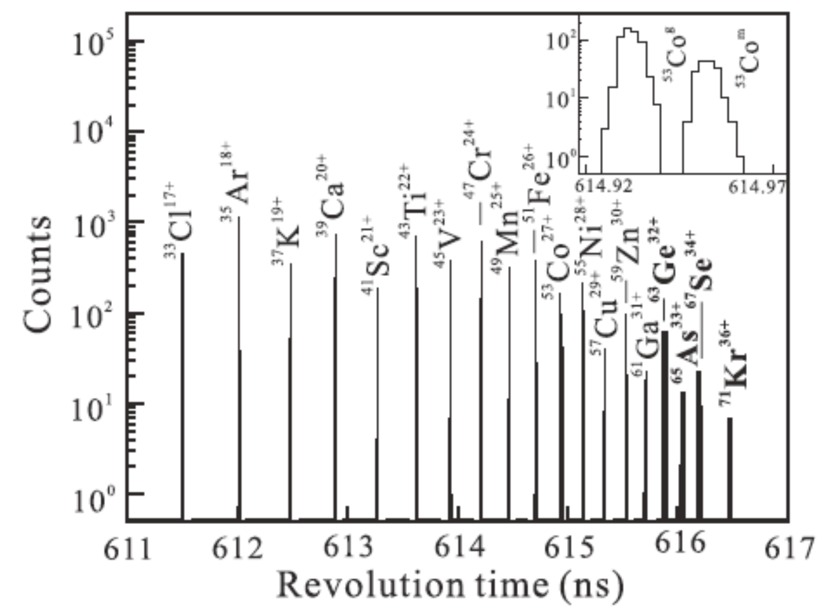
C.M. Deibel *et al*, PRC **84**, 045802 (2011).

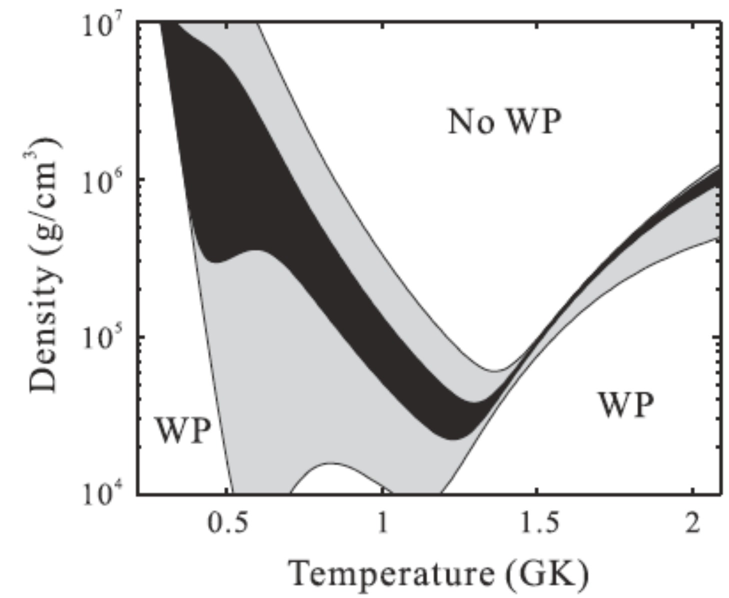


- Time-inverse (p,α) reactions studied in inverse kinematics with RIB from ATLAS using coincidences from DSSDs (α-particles) and spectrograph (heavy recoils)
  - ^{33}Cl(p,α)^{30}S (published)
  - ^{25}Al(p,α)^{22}Mg
  - ^{29}P(p,α)^{26}Si
  - ^{37}K(p,α)^{34}Ar
- Indirect studies of compound nuclei at RCNP, Osaka via (p,t) reactions (Notre Dame group)

Waiting points in XRBs



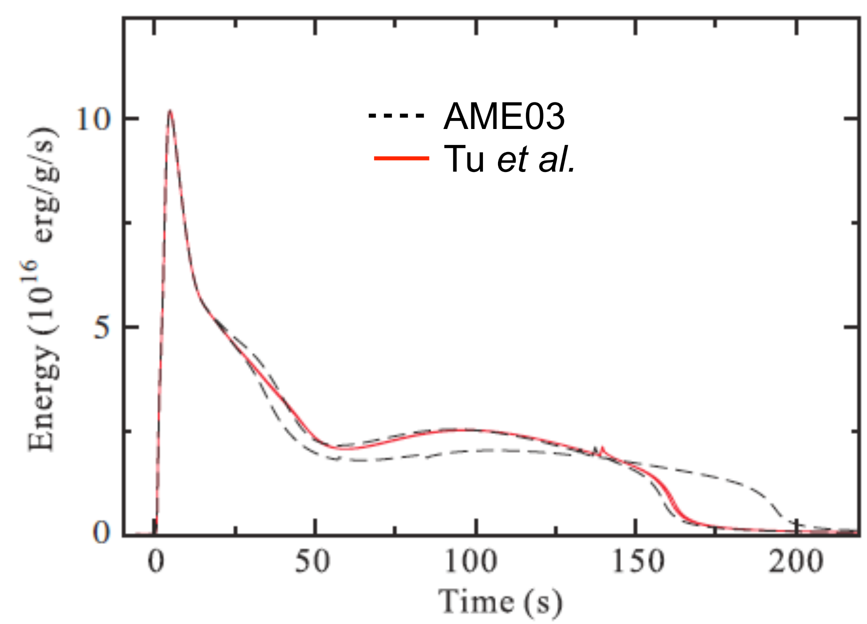




X. L. Tu *et al.*, PRL **106**, 112501 (2011).

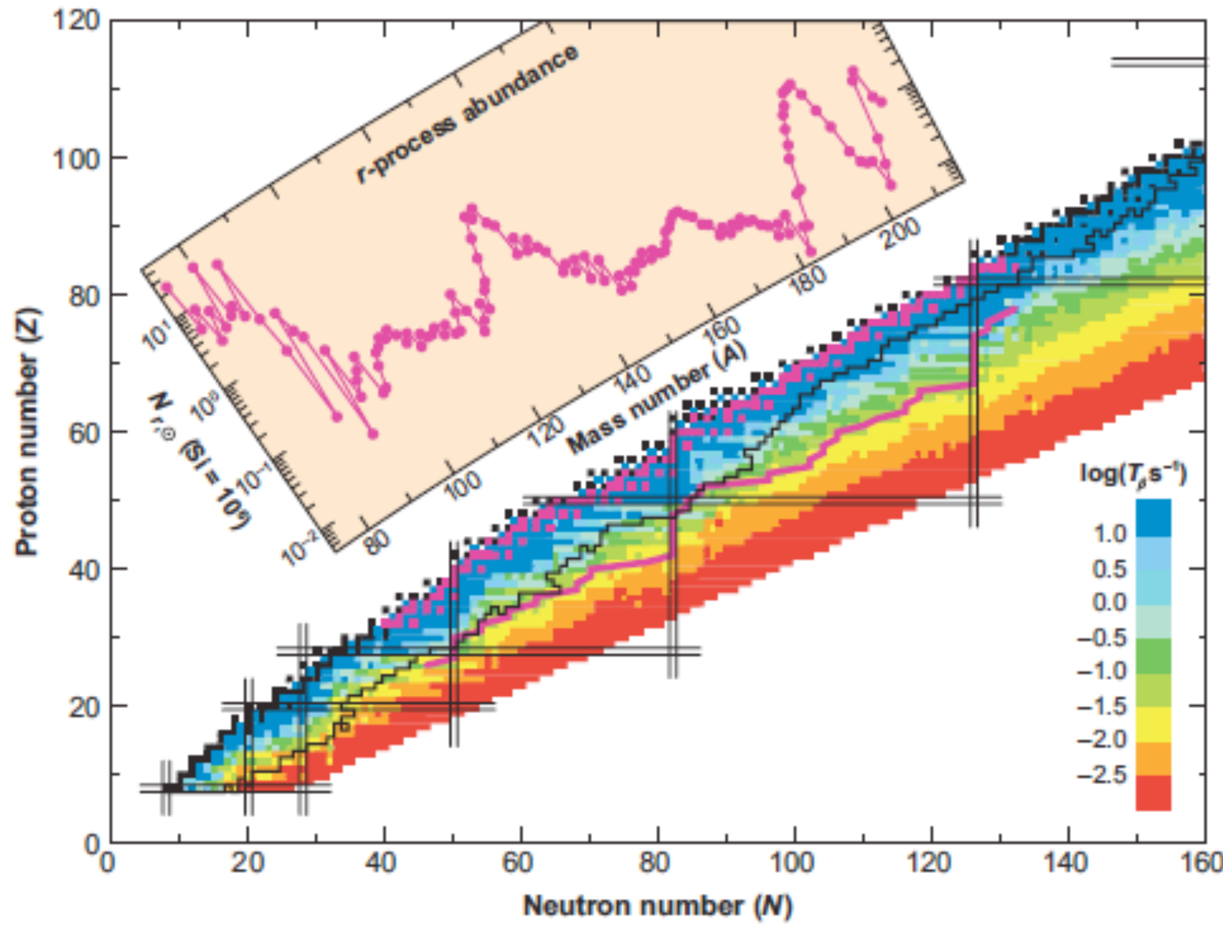
- Mass measurement of ^{65}As done at Lanzhou with the HIRFL-CSR (Cooler-Storage Ring)
- Projectile fragmentation of ^{78}Kr
- $S_p(^{65}As)$ = -90(85) keV:
  - ➡ confirms ^{65}As is proton-unbound at 68.3% C.L.
  - ➡ Coulomb Displacement Energy (CDE) calculations predictive
  - ➡ defines when ^{64}Ge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

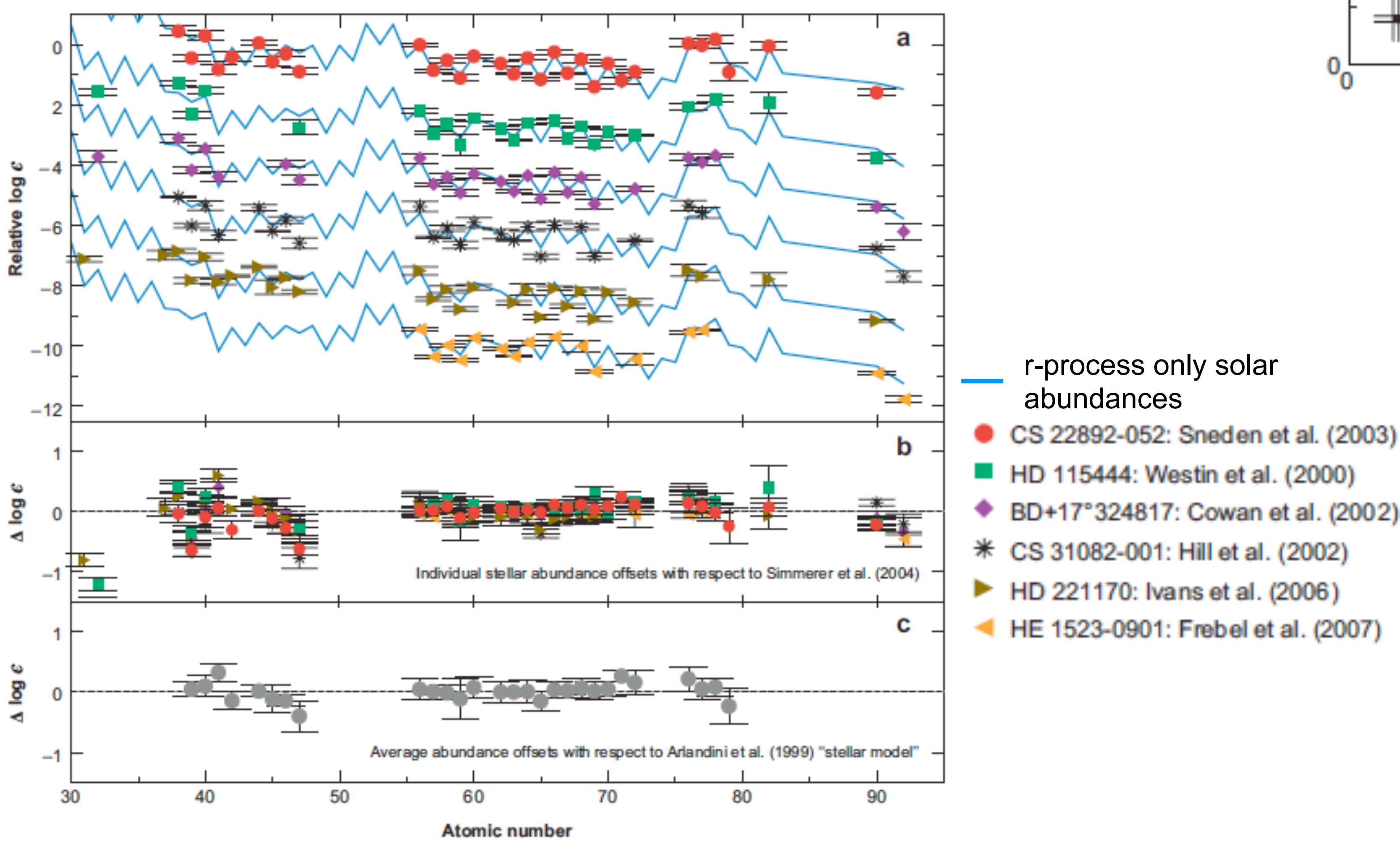
Effect of new ^{65}As mass on XRB light curve



r-process

- Observations from very metal-poor stars show unique isotopic signature of r-process for Z > 56
- Disagreement of Z < 56 abundances suggests multiple sites for the r-process

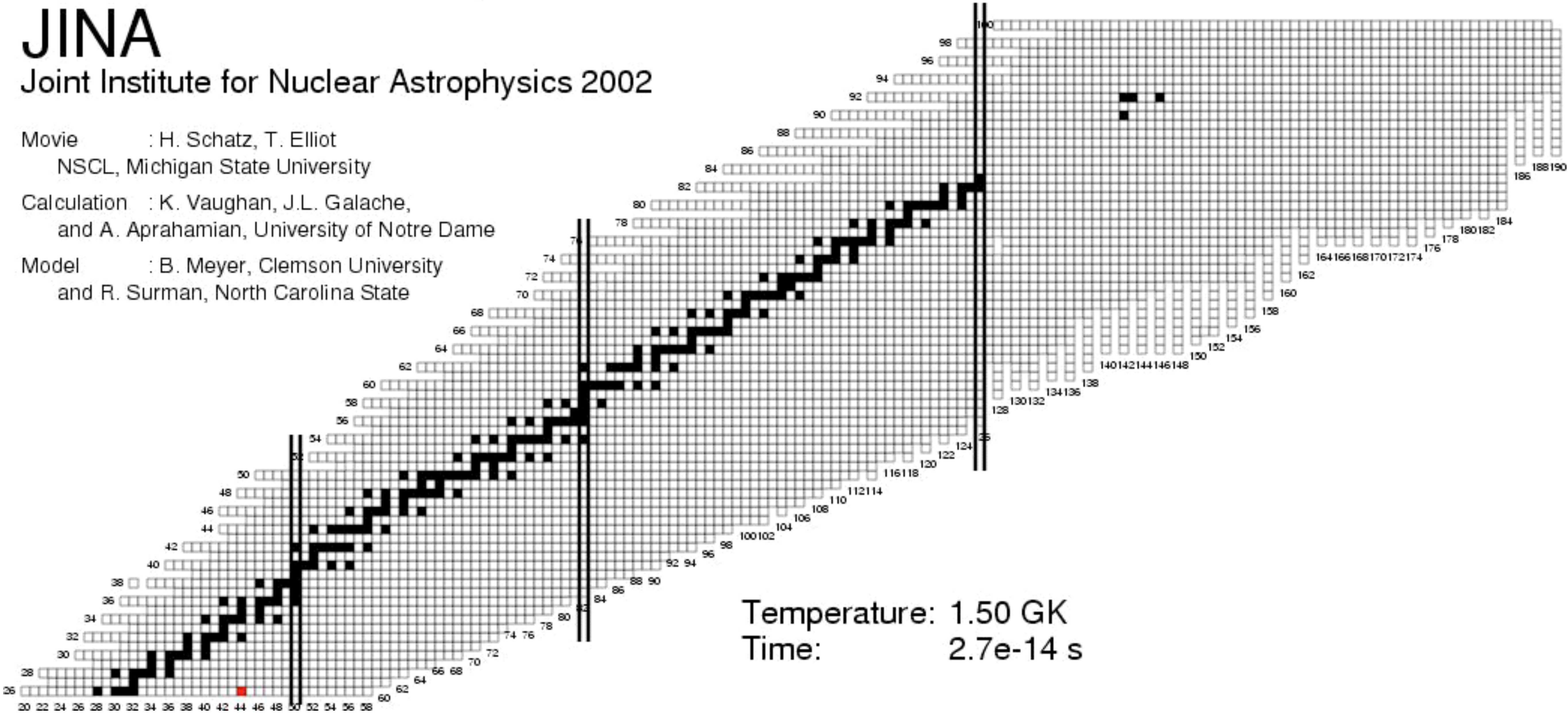




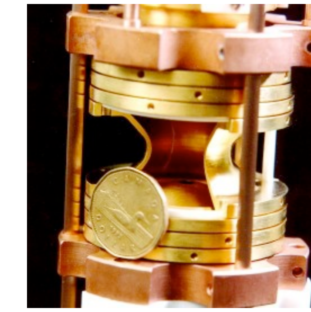
- Possible sites of the r-process
  - core collapse supernova
  - neutron star mergers
- r-process path determined via S_n values, β decay lifetimes and masses
- New processes (e.g. LEPP) to explain abundances of A<120

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

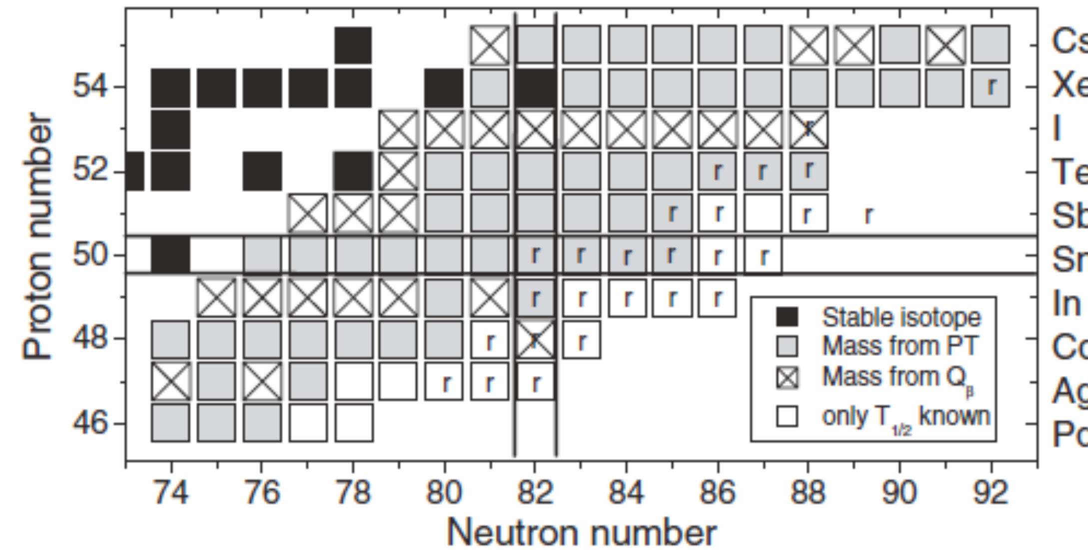
Nucleosynthesis in the r-process



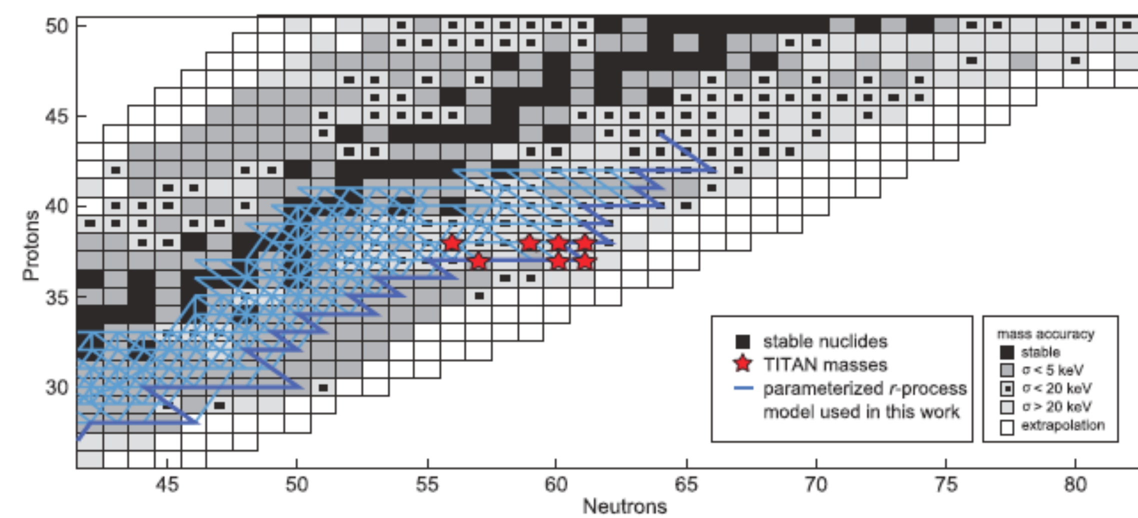
r-process Mass Measurements



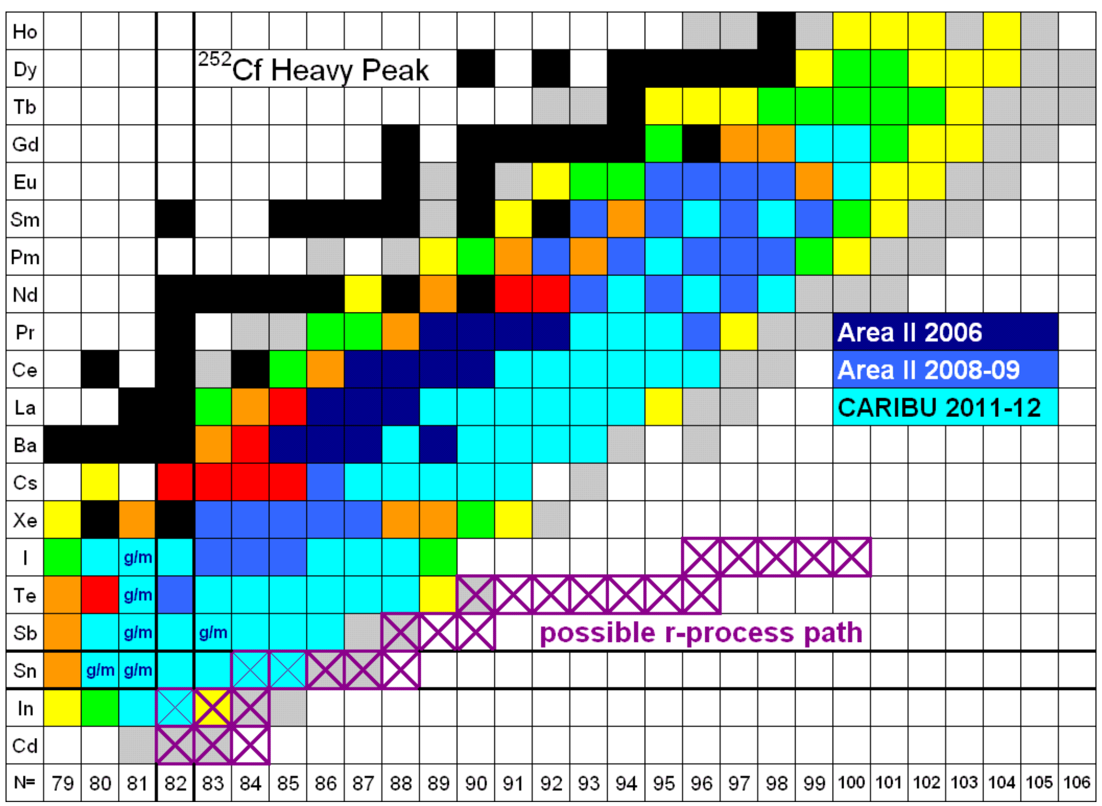
- Mass measurements of r-process nuclei have now been made with a variety of Penning traps
  - CPT/CARIBU (ANL)
  - JYFLTRAP (Jyväskylä)
  - TITAN (TRIUMF)



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



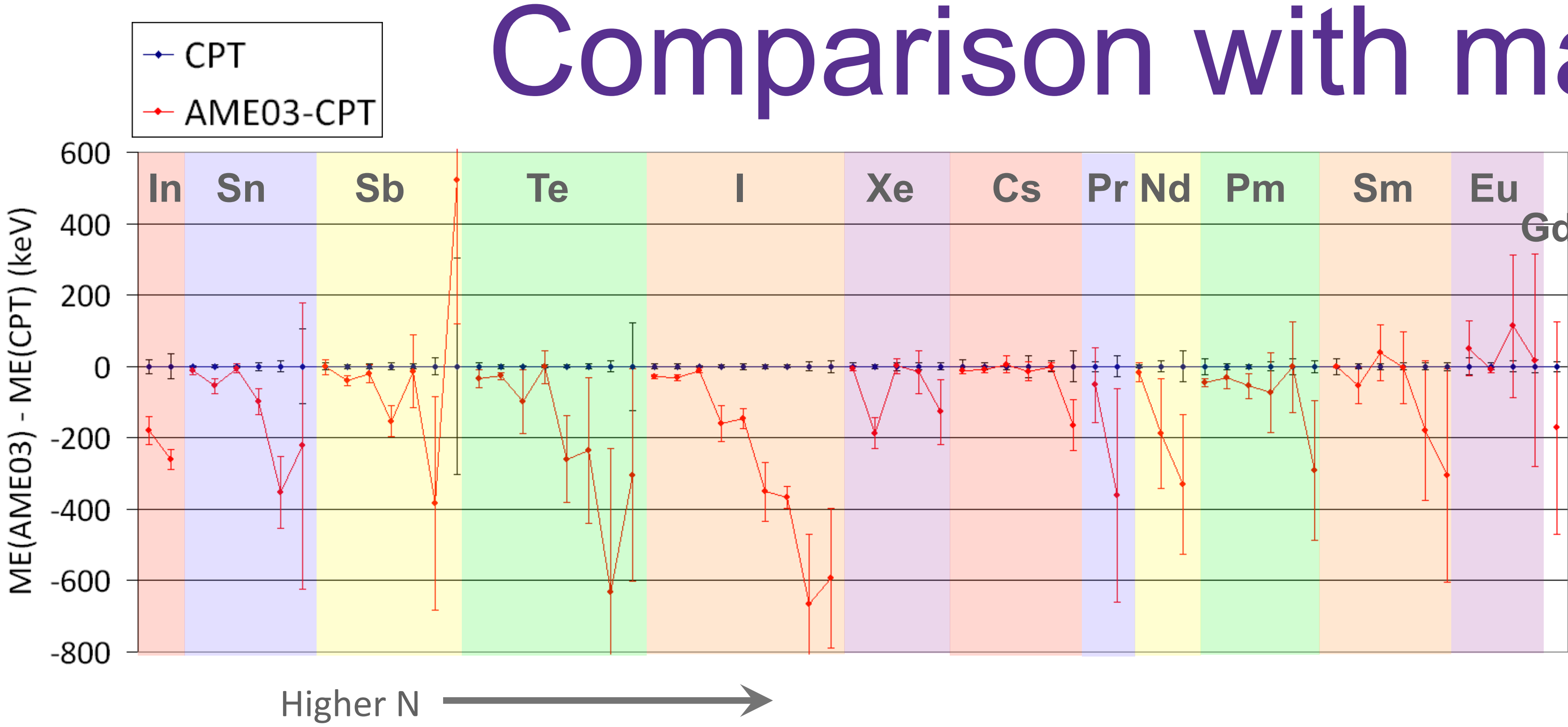
V. V. Simon *et al.*, PRC **85**, 064308 (2012).



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

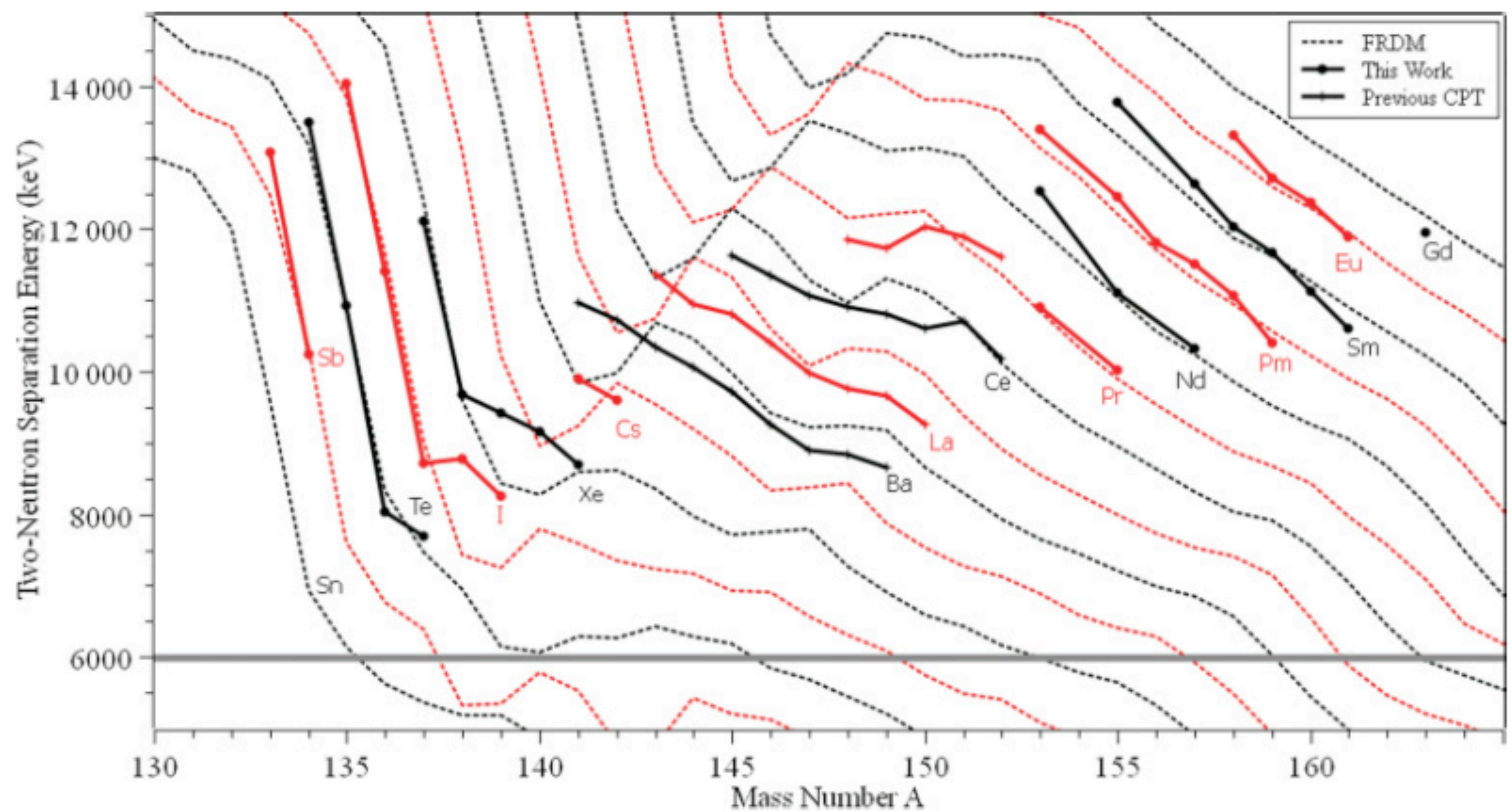
Mass measurements near N = 50 shell closure, e.g. ^{82}Zn - see M. Maduga's talk

Comparison with mass models



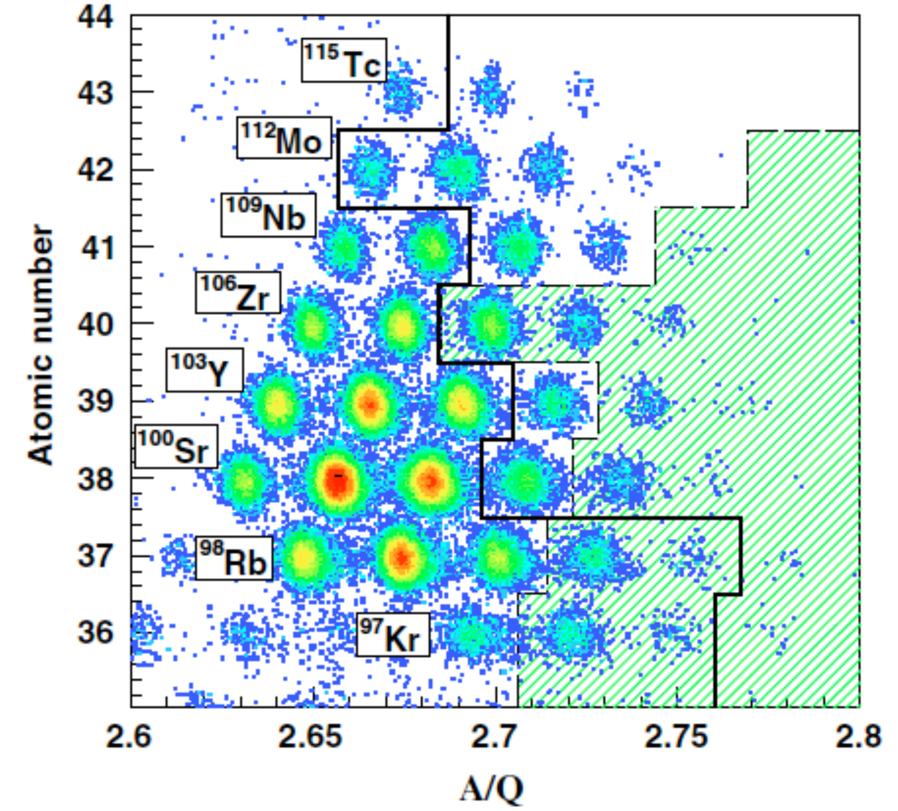
trend away from stability (less bound with neutron excess)

Clear discrepancies when S_{2n} are calculated with FRDM vs. measured values

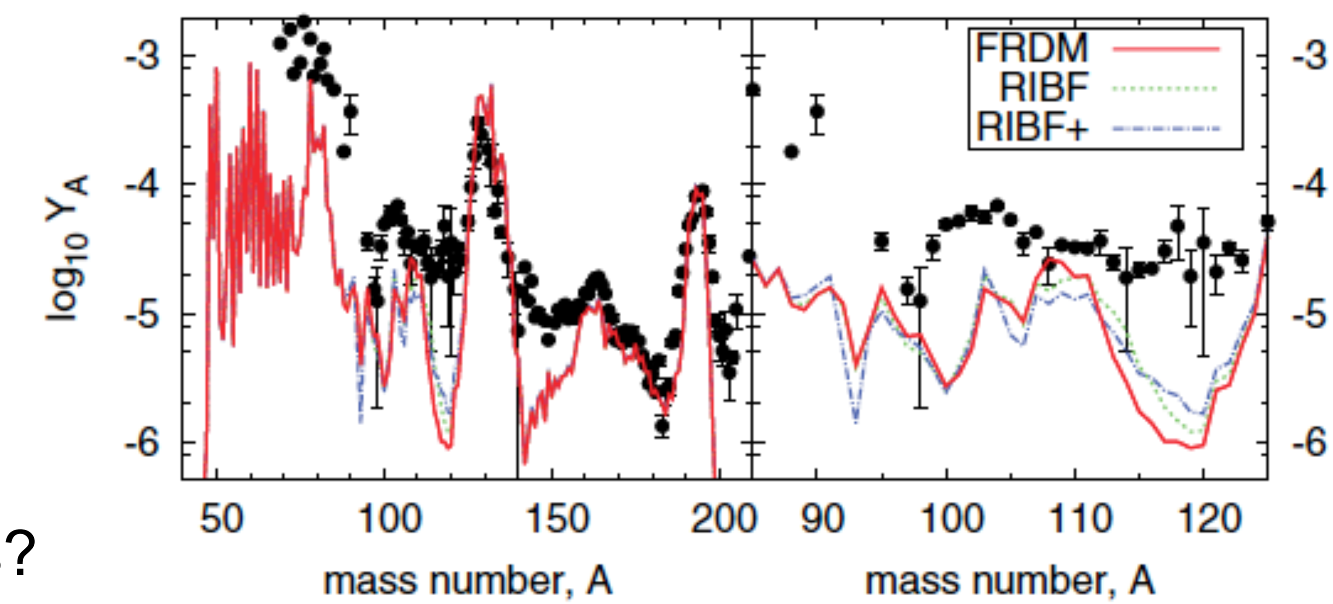


β-decay lifetime measurements

- Theoretical r-process yields under-predict abundances in A = 110 - 125 region
- Mass models attempting to explain this differ mainly in strength of shell closures
- One solution is shell quenching of N = 82 shell gap
- Systematic study of β decay lifetimes done at RIBF at RIKEN via in-flight fission of ^{238}U on Be target
- New lifetimes included in magnetohydrodynamic (MHD) supernova models
- New lifetimes alleviate discrepancy somewhat, but disagreement still exists!
  - ➡ More physics needed? New processes?

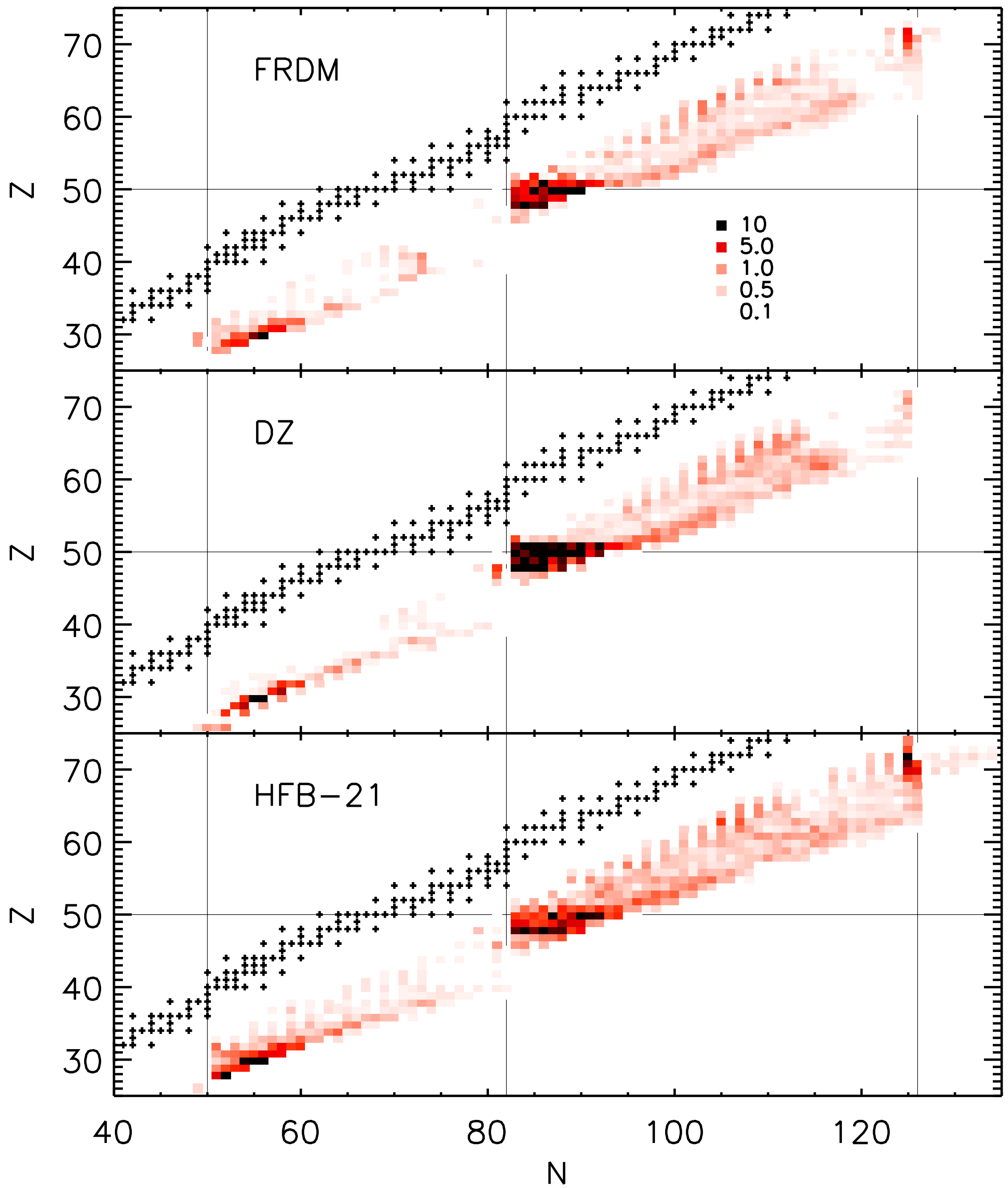


S. Nishimura *et al.*, PRL **106**, 052502 (2011)



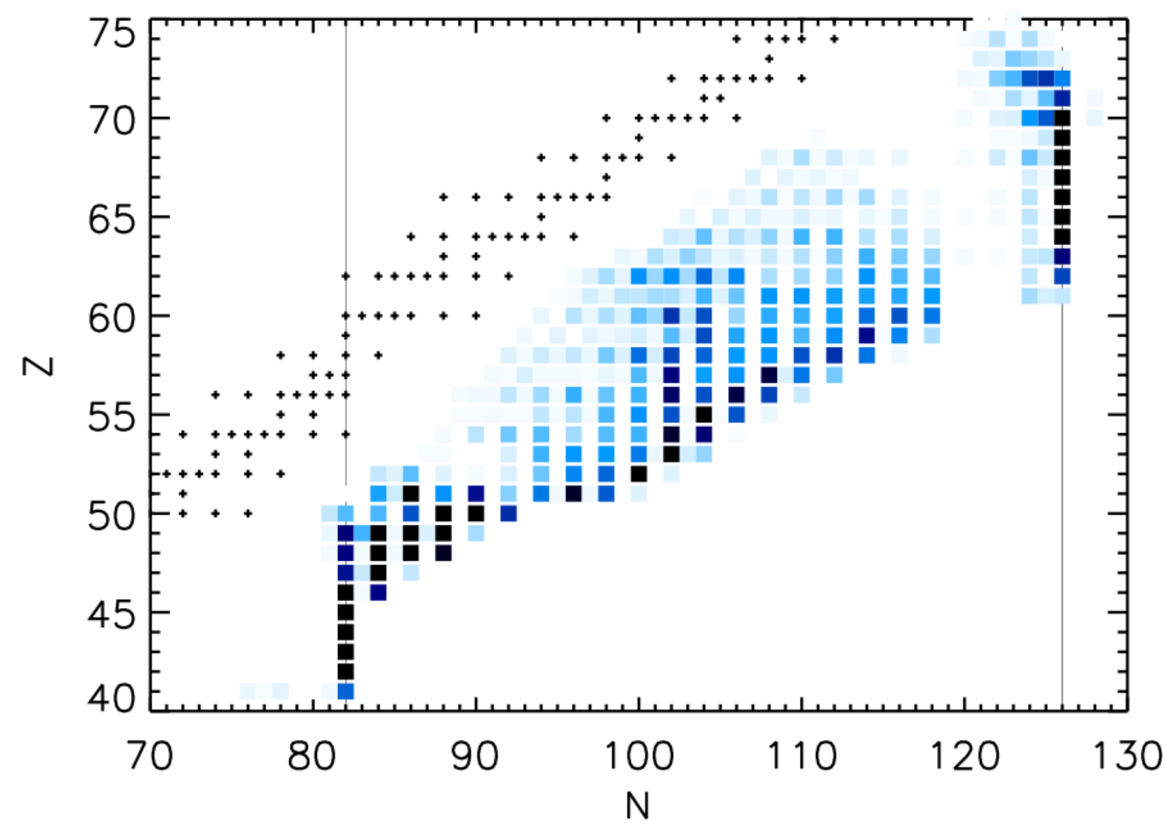
S. Nishimura, PRC **85,** 048801 (2012).

Nuclear Data needs for the r-process



S. Brett, I. Bentley, N. Paul, and A. Aprahamian

- neutron separation energy sensitivity study
- $\Delta Y_{S_n(Z_i,A_i)\pm 25\%} = \sum_{A} \left[Y_{baseline}(A) - Y_{S_n(Z_i,A_i)\pm 25\%}(A) \right]$



J. Cass, G. Passucci, R. Surman, A. Aprahamian

- β decay rate sensitivity study
- varied a single β decay rates by one order of magnitude
- white - black = 0 - 10% change in final abundances

Non-Structure Developments

- Sensitivity studies
  - νp process reactions
  - Core-collapse supernovae (CCSNe) reactions
  - X-ray bursts
- Observational data
  - more metal poor stars (SDSS/Segue)
  - Supernova observables
  - Galactic radioactivity
  - presolar grains
- Stellar modeling
  - CCSNe - explosions work!
  - neutron star mergers
  - X-ray bursts and superbursts
- Stellar evolution

Summary

- Major advances in nuclear astrophysics in past few years with both stable and radioactive ion beams
- New RIB facilities and upgrades allow access to more nuclei of interest
  - r process nuclei can now be created and studied
  - reaction rates important for explosive nucleosynthesis on proton-rich side
  - structure information on nuclei away from stability
- Still much to be done!
  - more mass measurements and decay lifetimes on or near r-process path are needed to constrain models
  - low background measurements
  - reaction rate measurements: direct *and* indirect

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THANK YOU!!!!