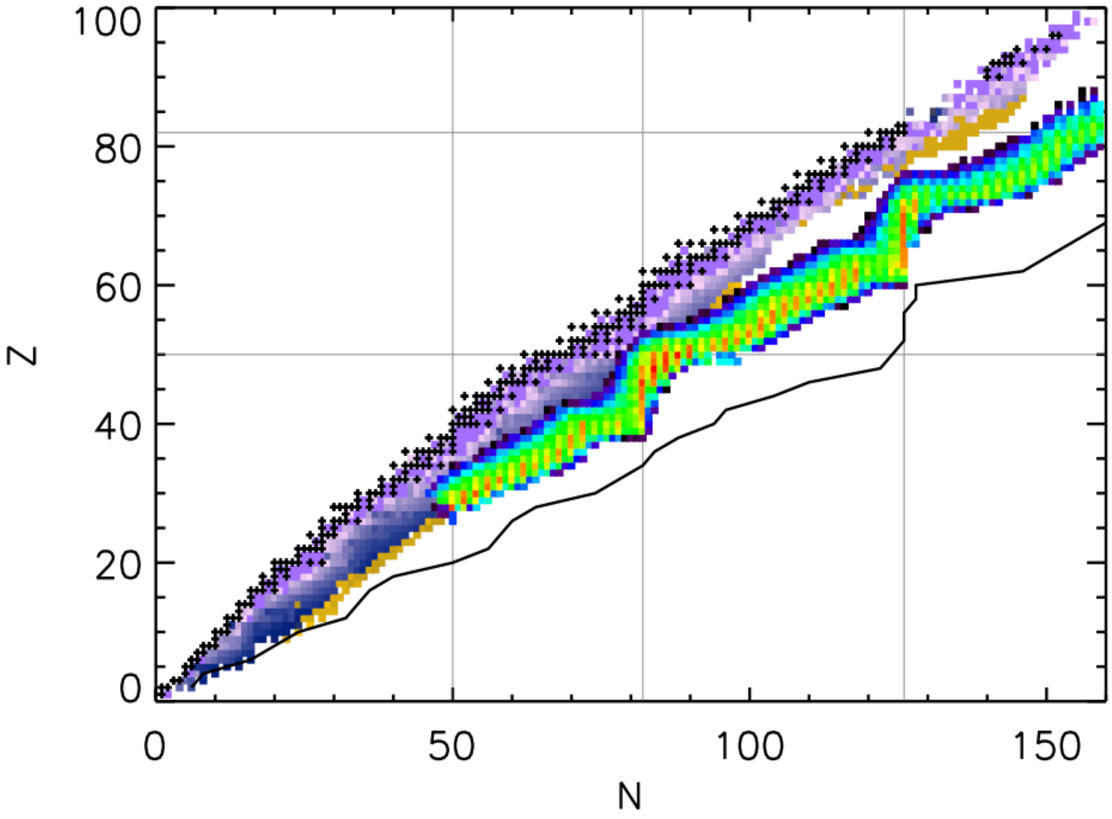
sensitivity studies for *r*-process nucleosynthesis



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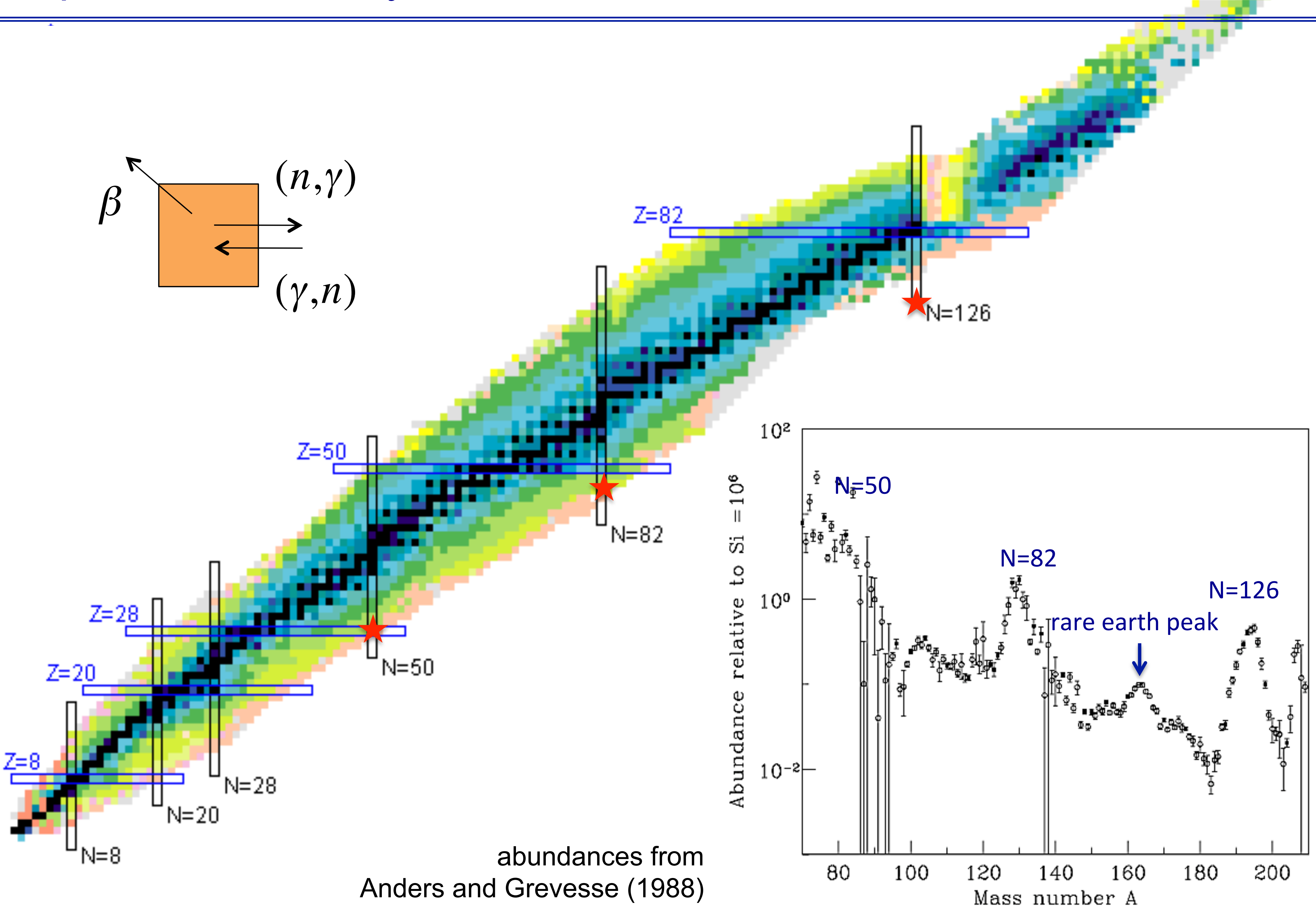
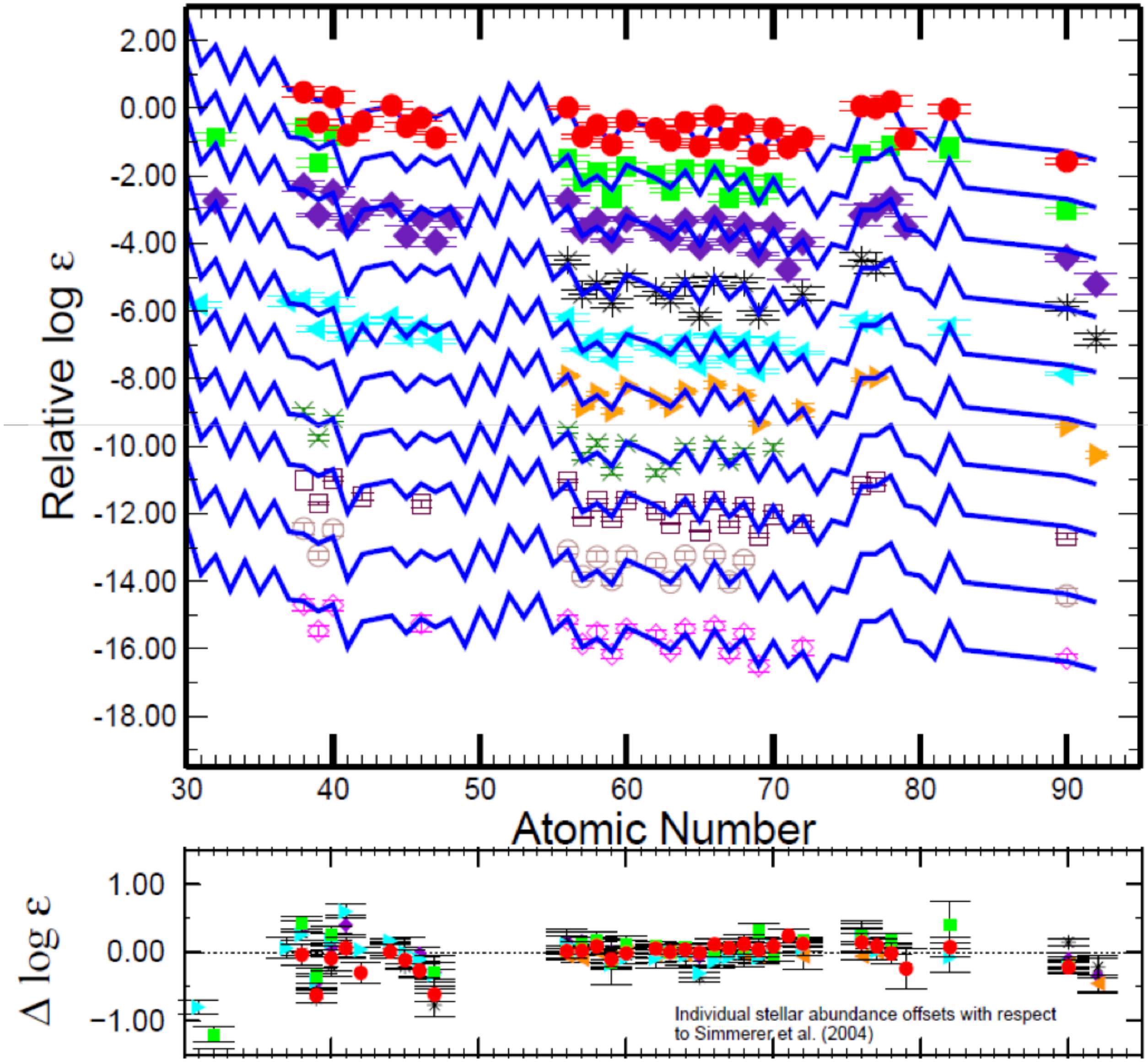
ARIS 2014
2014 June 4

r-process nucleosynthesis



abundances from
Anders and Grevesse (1988)

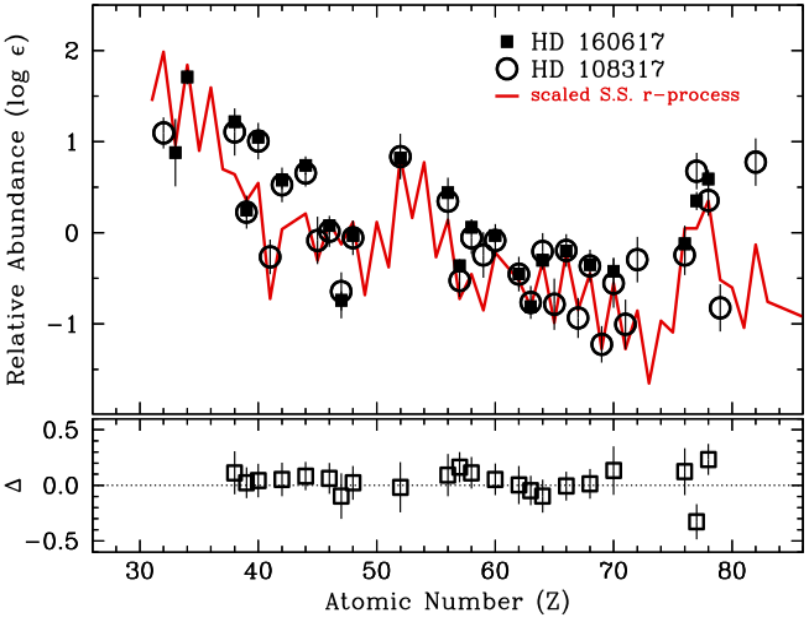
r-process observations



Cowan et al (2011)

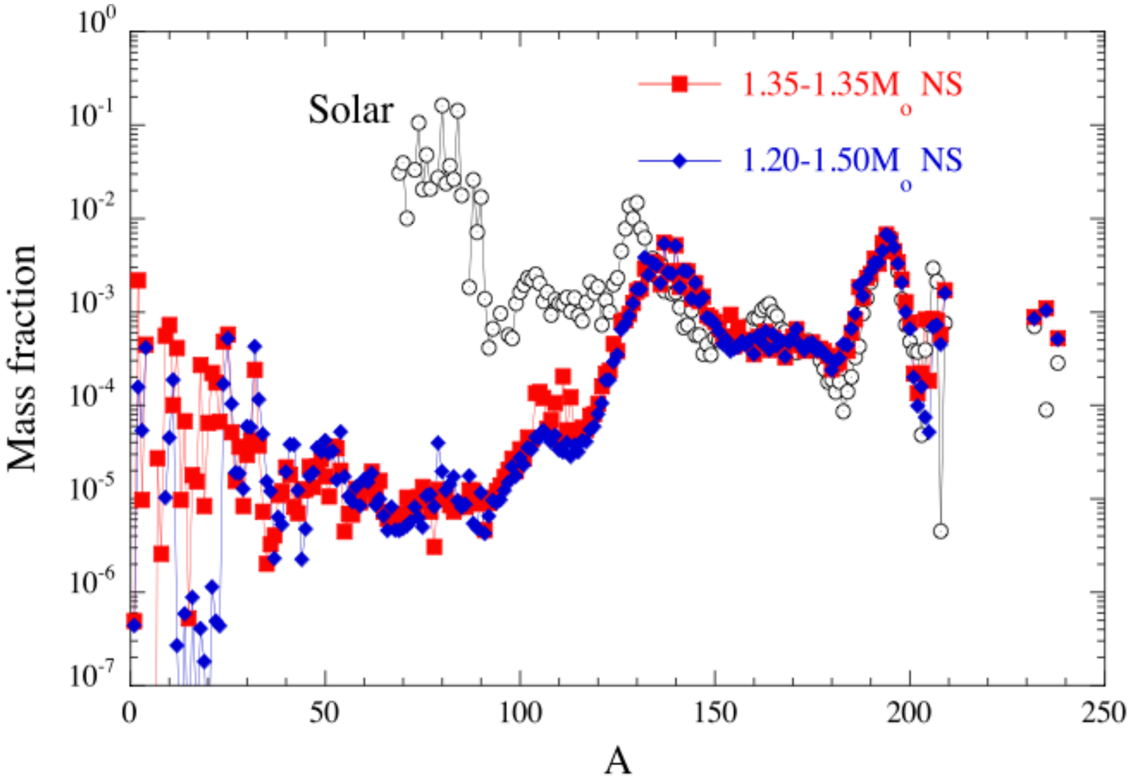
Observations suggest the *r*-process site:

- produces a robust *A*>130 abundance pattern
- was in operation early in galactic history



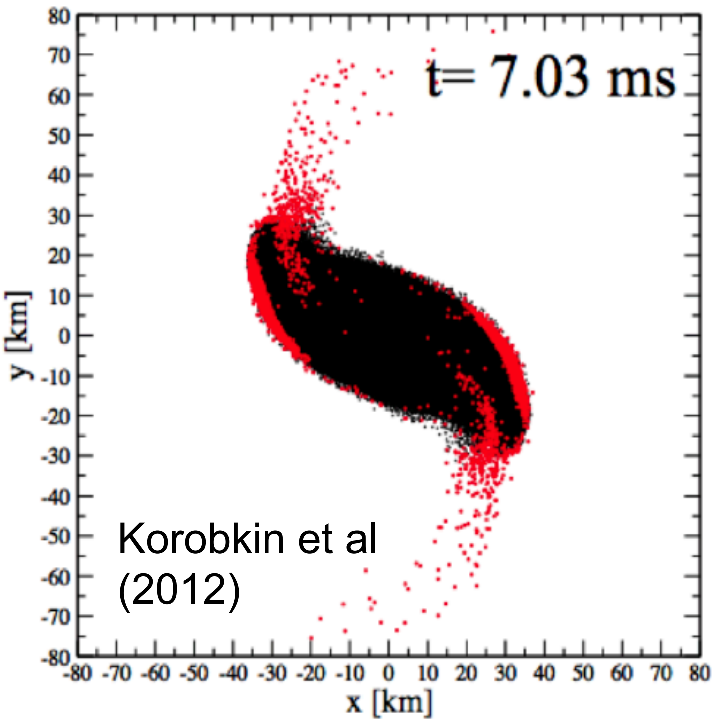
Roederer & Lawler (2012)

r-process astrophysical site: compact object mergers?



Goriely et al (2012)

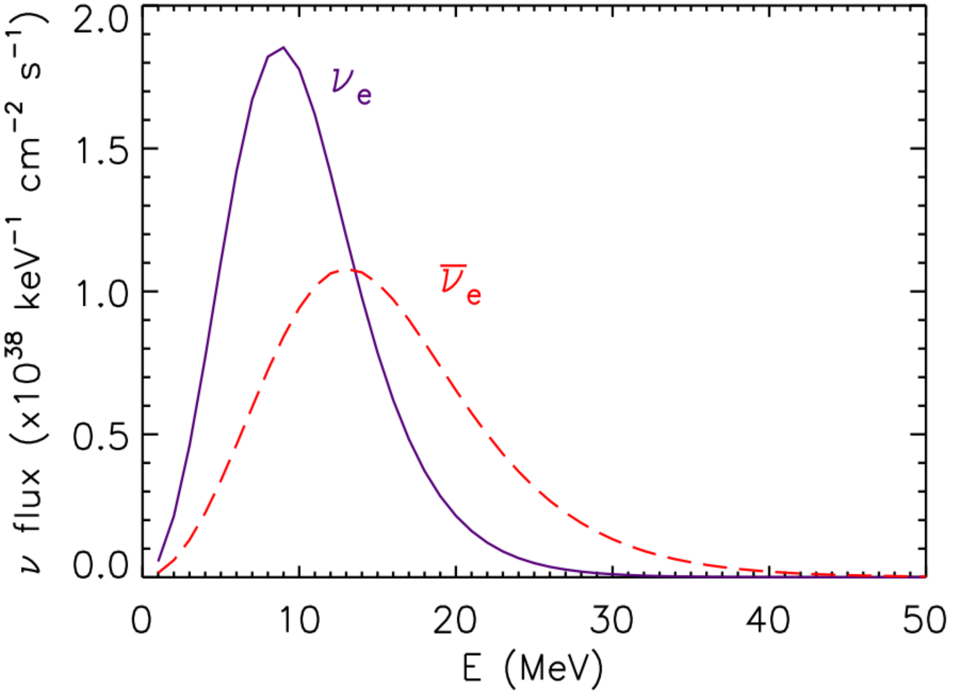
neutron star-neutron star or black hole-neutron star mergers



Korobkin et al (2012)

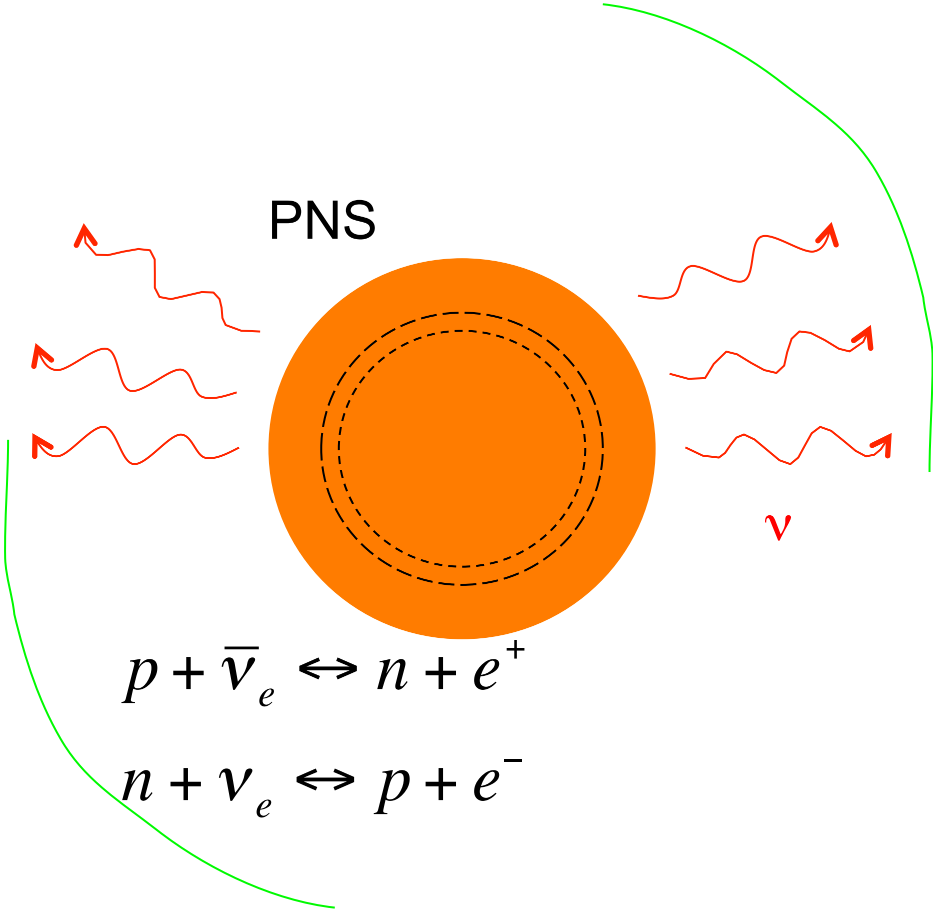
e.g., Lattimer & Schramm (1974, 1976), Meyer (1989), Frieburghaus et al (1999), Goriely et al (2005), Wanajo & Ishimaru (2006), Oechslin et al (2007), Nakamura et al (2011), Goriely et al (2012), Korobkin et al (2012), Rosswog el at (2013), Wanajo et al (2014)

r-process astrophysical site: core-collapse supernovae?



late-time ν fluxes from Keil et al (2003)

supernova neutrino-driven wind



$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$$n + \nu_e \leftrightarrow p + e^-$$

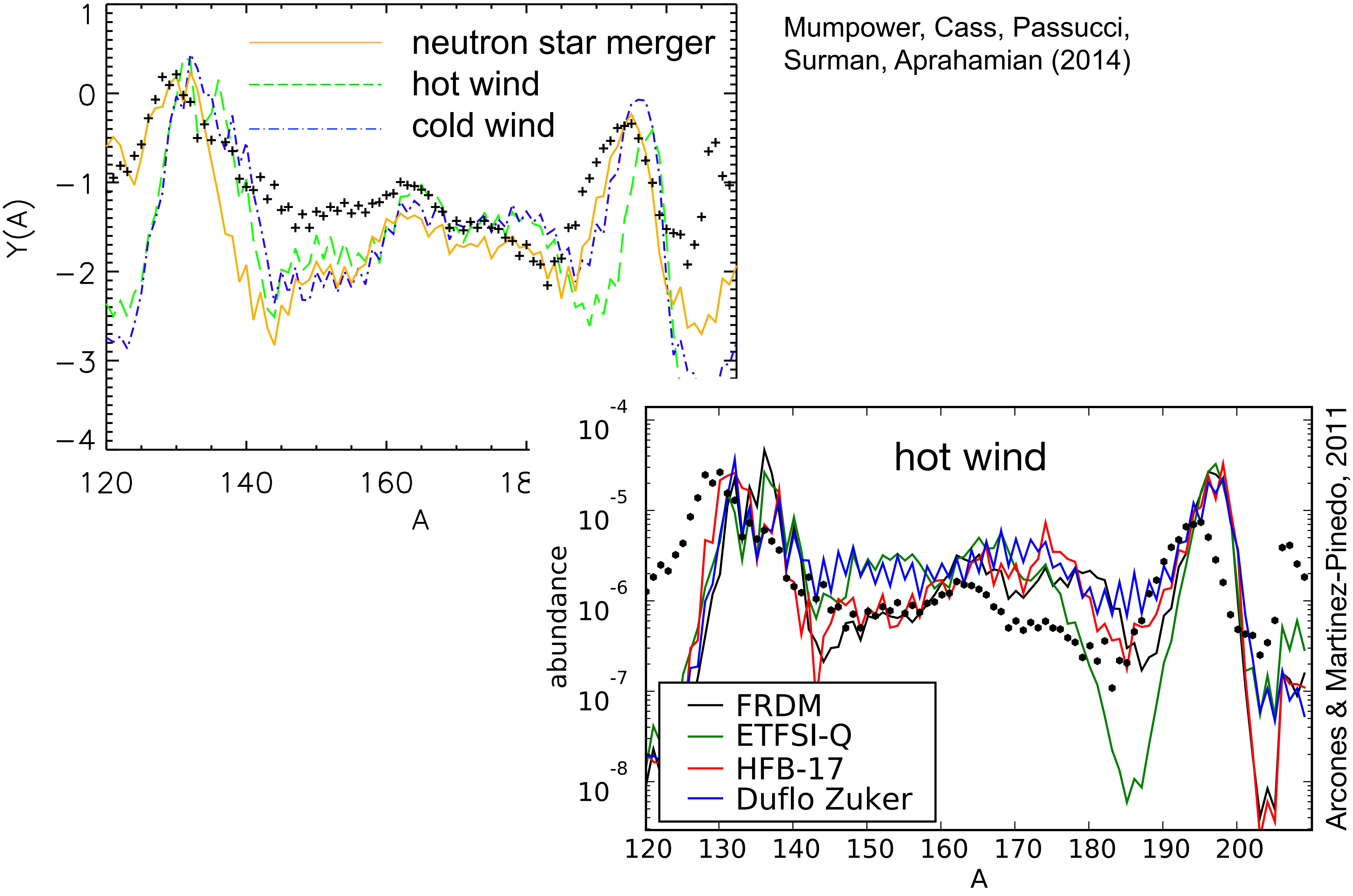
e.g., Meyer et al (1992), Woosley et al (1994), Takahashi et al (1994), Witti et al (1994), Fuller & Meyer (1995), McLaughlin et al (1996), Meyer et al (1998), Qian & Woosley (1996), Hoffman et al (1997), Cardall & Fuller (1997), Otsuki et al (2000), Thompson et al (2001), Terasawa et al (2002), Liebendorfer et al (2005), Wanajo (2006), Arcones et al (2007), Huedepohl et al (2010), Fischer et al (2010), Roberts & Reddy (2012), Wanajo (2013), Martinez-Pinedo et al (2014), etc.

r-process astrophysical site: current status

Compact object mergers have plenty of neutrons, but may not evolve on short enough timescales to explain the halo star data

Core-collapse supernovae evolve on the correct timescale to explain the halo star data, but may not produce enough neutrons

r-process abundance pattern: site vs nuclear data



Mumpower, Cass, Passucci, Surman, Aprahamian (2014)

Arcones & Martinez-Pinedo, 2011

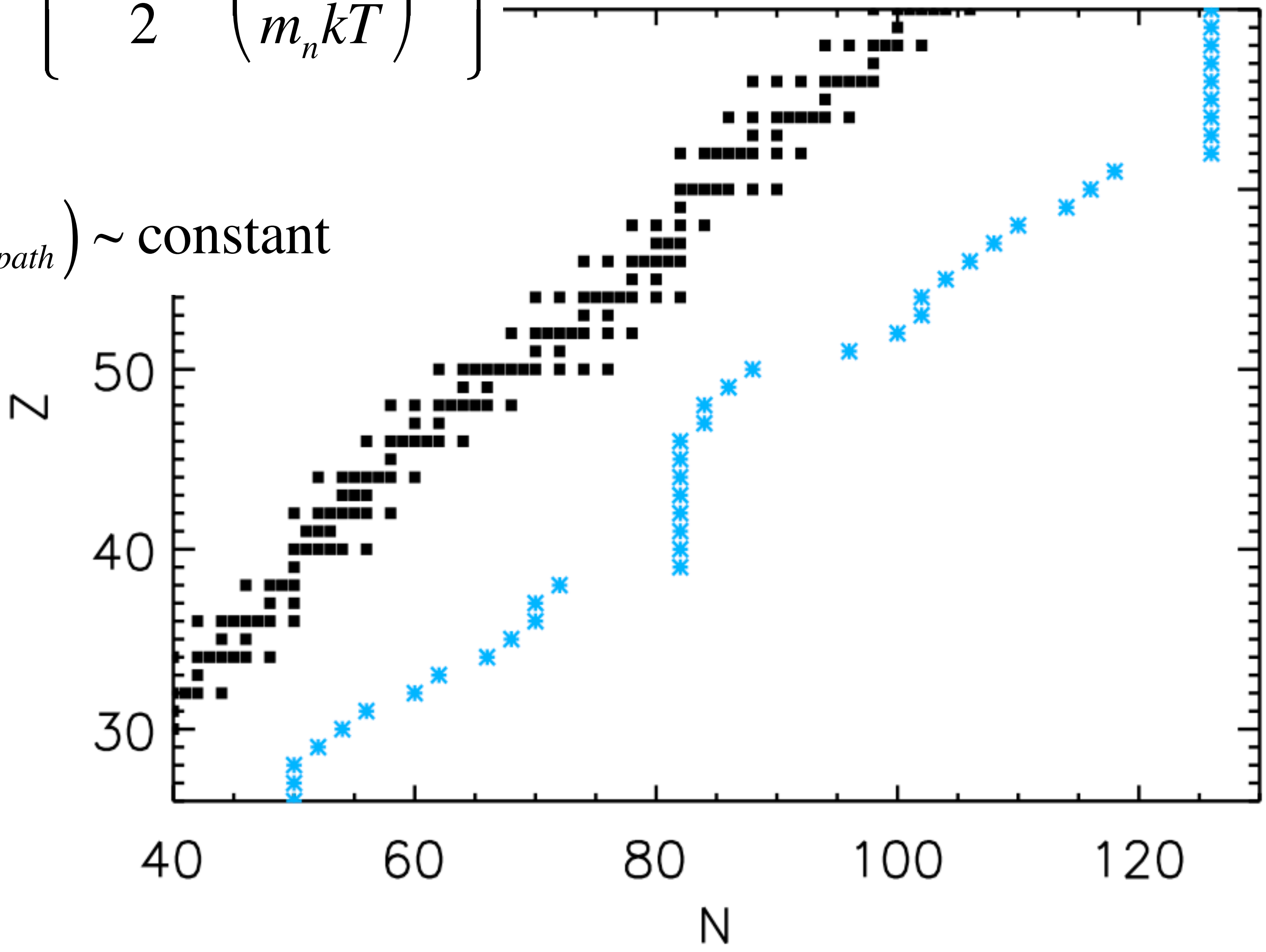
classic (n,γ)-(γ,n) equilibrium *r* process

equilibrium path:

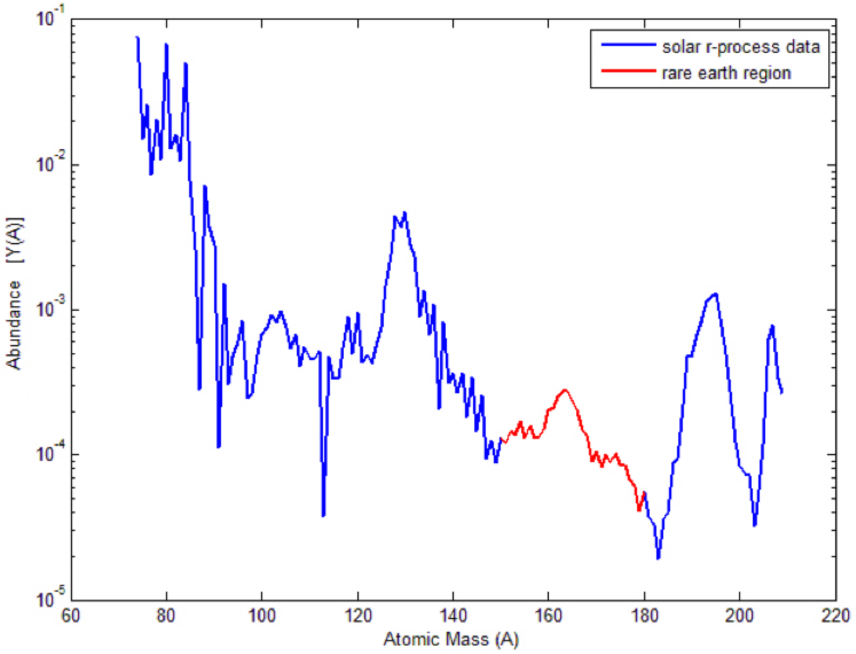
$$S_n\left(Z,A_{path}\right) \sim -kT\ln\left\{\frac{\rho N_A Y_n}{2}\left(\frac{2\pi\hbar^2}{m_n kT}\right)^{3/2}\right\}$$

steady beta flow:

$$\lambda_\beta\left(Z,A_{path}\right)Y\left(Z,A_{path}\right) \sim \text{constant}$$

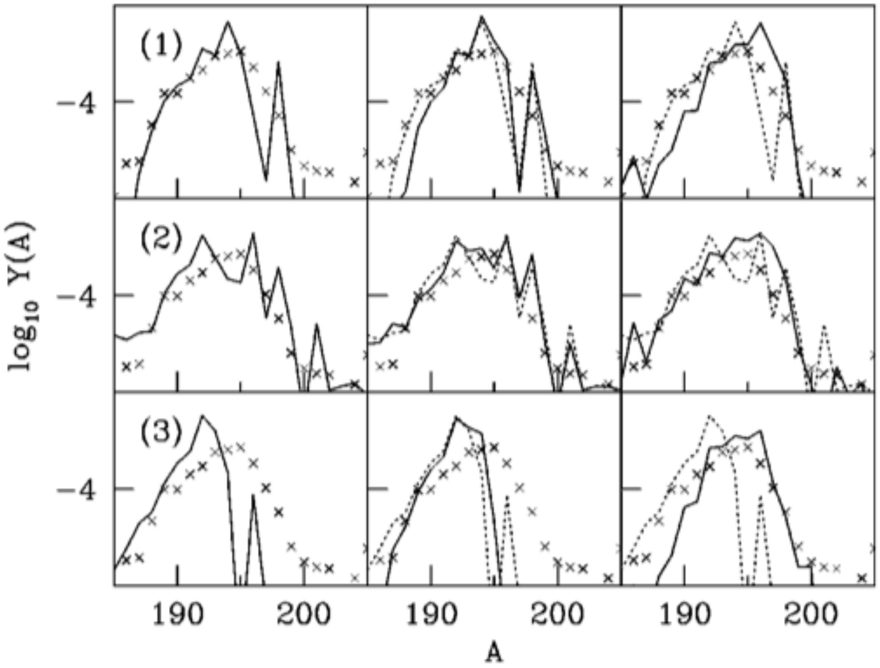


freezeout from (n,γ)-(γ,n) equilibrium



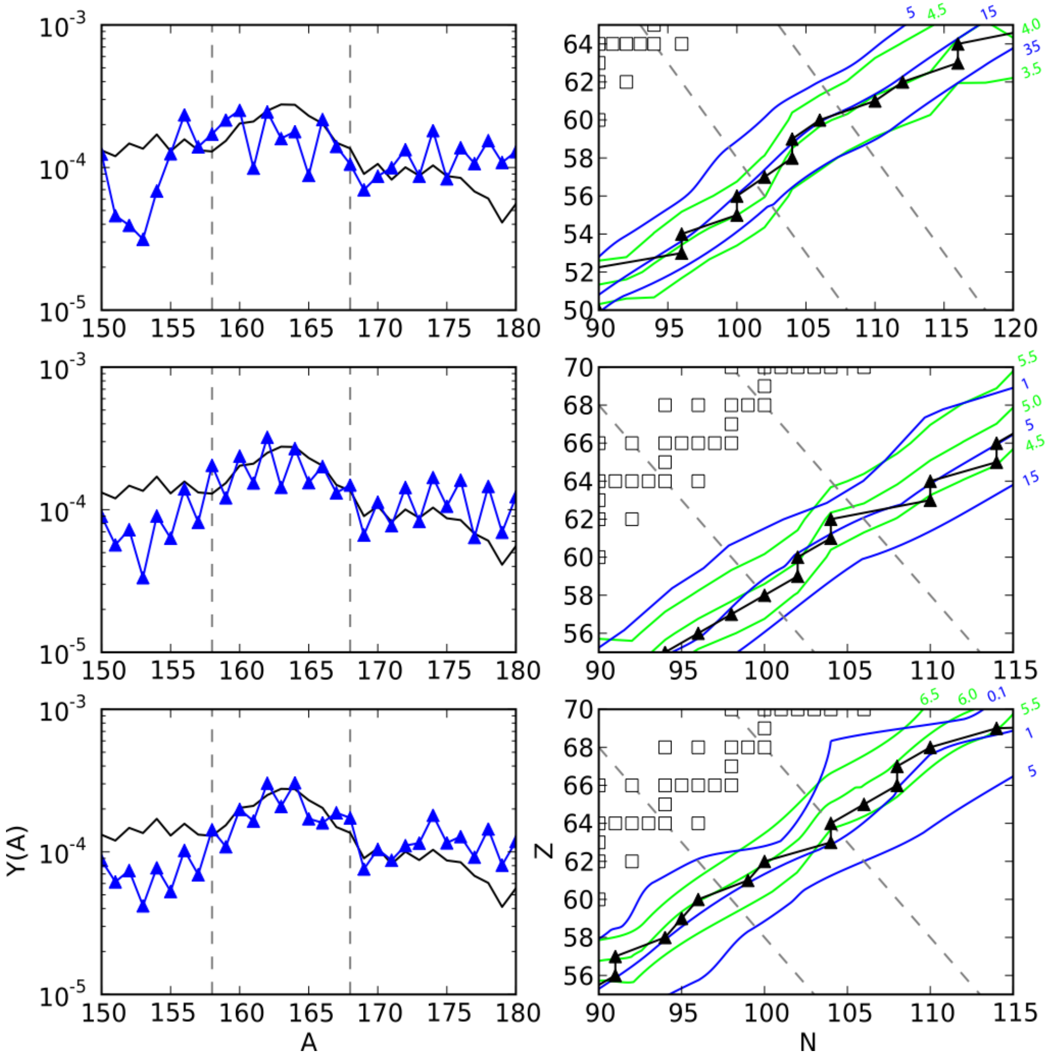
- rare earth peak forms
- main peaks can shift, spread, or narrow

Mumpower, McLaughlin, & Surman (2012)



Surman & Engel (2001)

freezeout and nuclear data



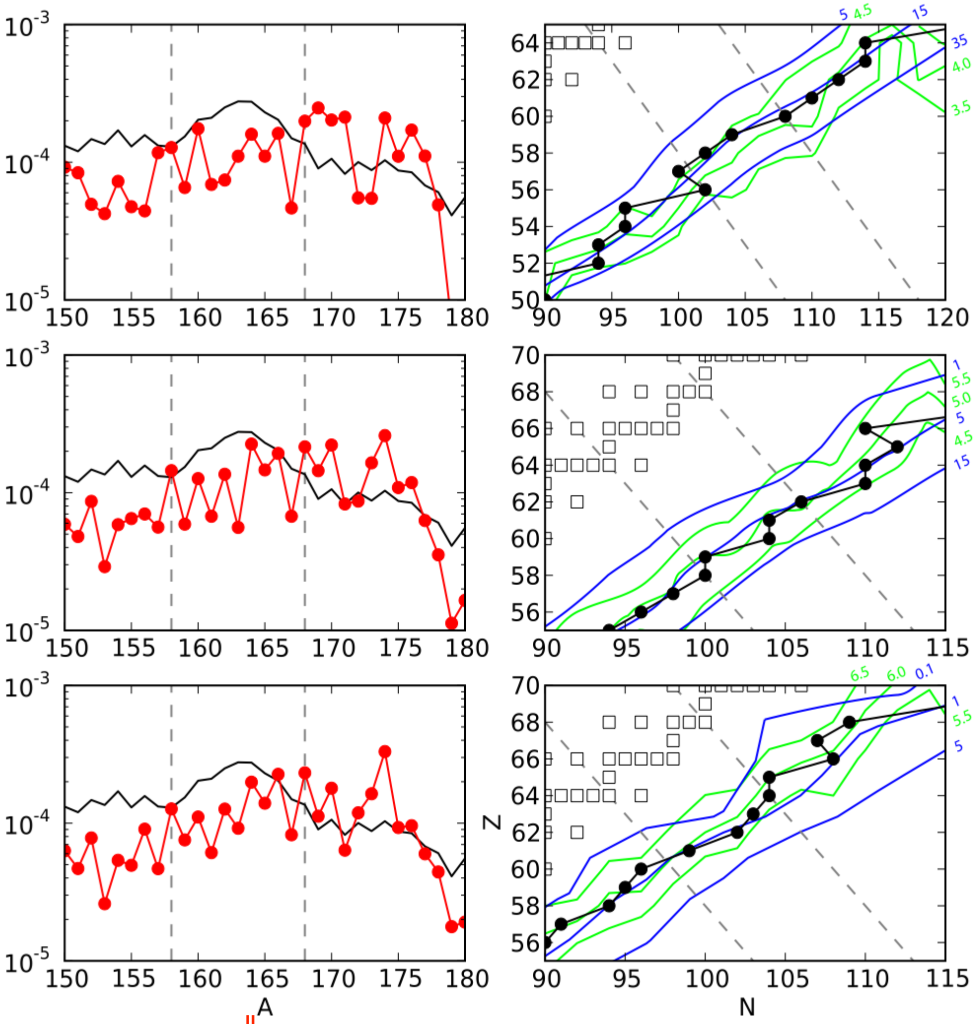
FRDM

β decay contours

neutron separation energy contours

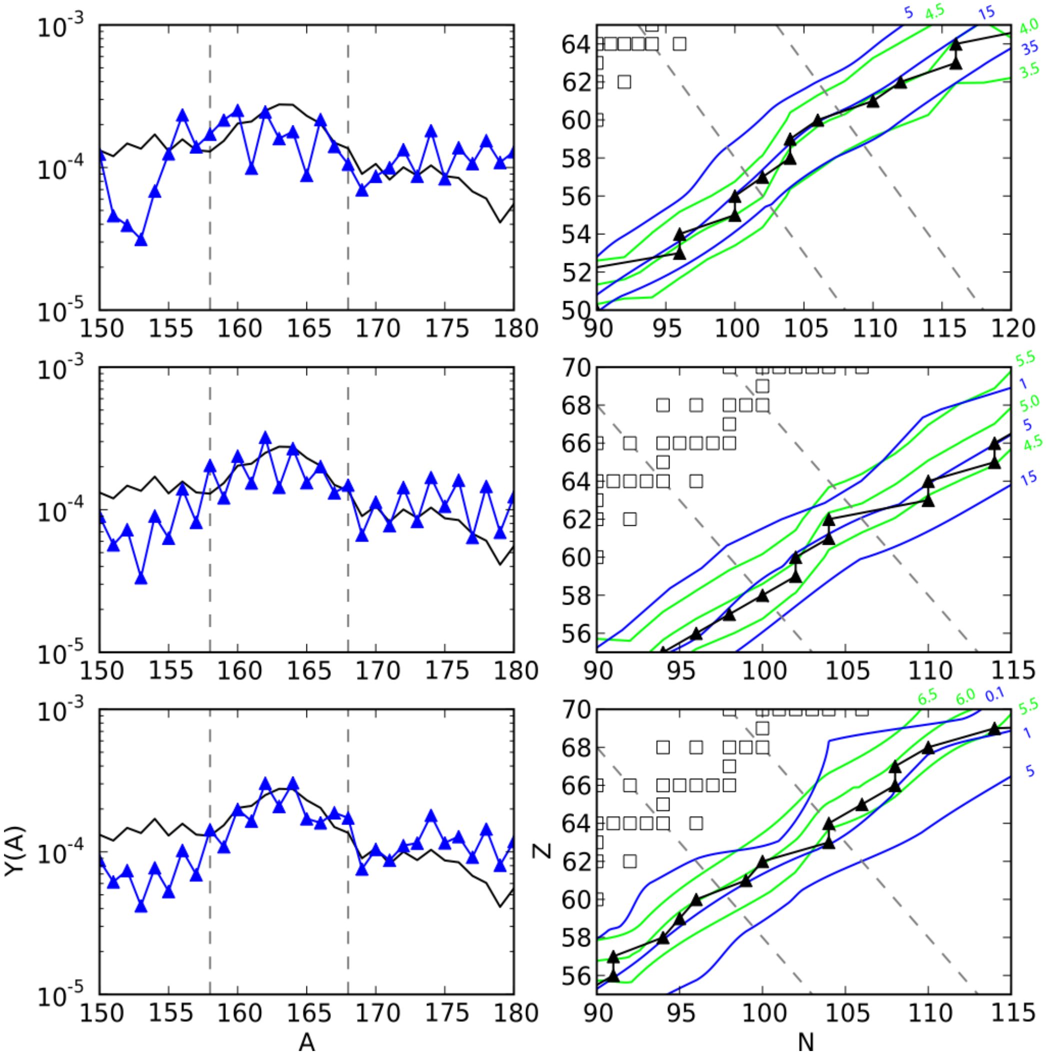
Mumpower, McLaughlin, and Surman, PRC (2012)

HFB-17



→ no REP formation

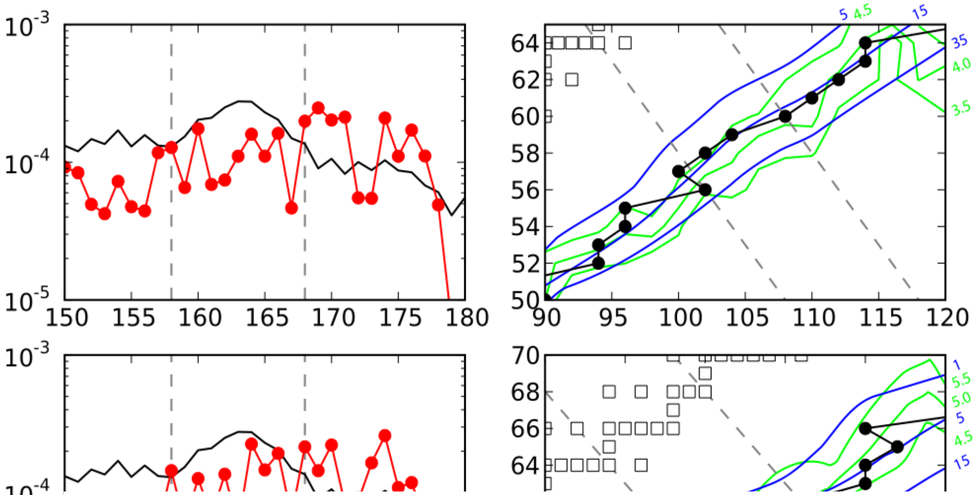
freezeout and nuclear data

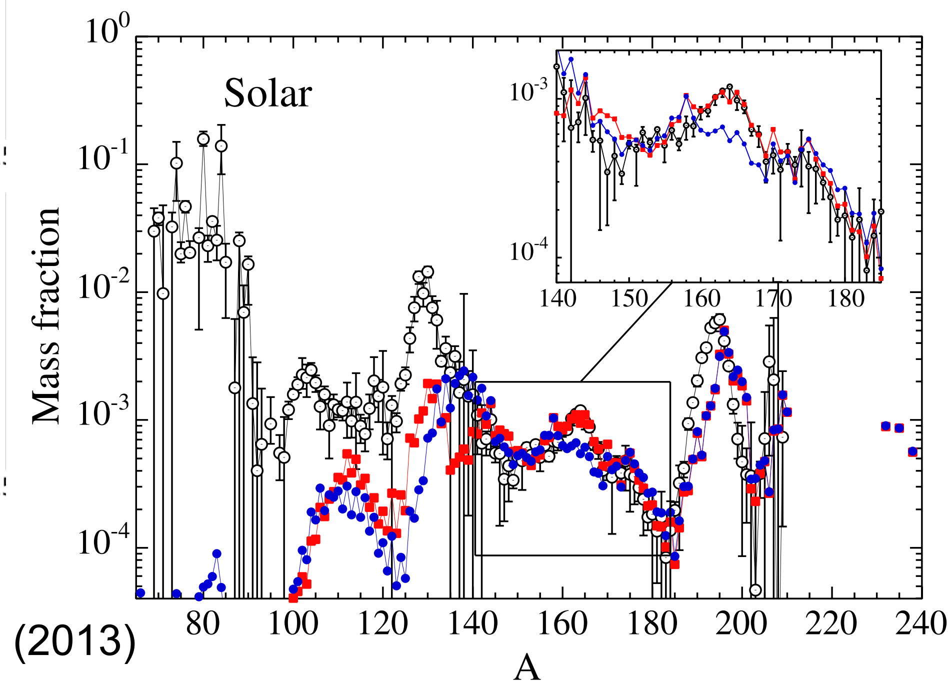


FRDM

Mumpower, McLaughlin, and Surman, PRC (2012)

HFB-17





Goriely et al (2013)

β decay contours

neutron separation energy contours

r-process sensitivity studies

Choose a baseline simulation

Vary one piece of nuclear data by a set amount, rerun the simulation, and compare the final abundance pattern to the baseline

Repeat for each nucleus in the network

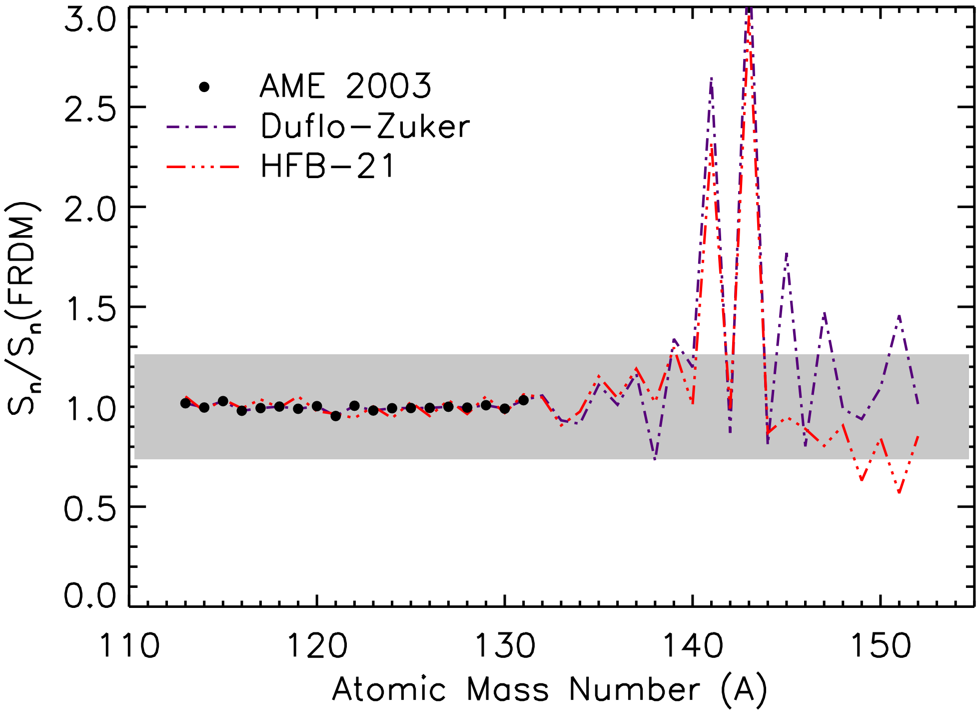
neutron capture rates
- Beun, Blackmon, Hix, McLaughlin, Smith, Surman, J. Phys. G (2008)
- Surman, Beun, McLaughlin, Hix, PRC (2009)
- Surman, Sinclair, Hix, Jones, Mumpower, McLaughlin, CGS-14 (2011)
- Mumpower, McLaughlin, Surman, PRC (2012)
- Surman, Mumpower, Sinclair, Jones, Hix, McLaughlin, AIP 'Stardust' (2014)

masses/neutron separation energies
- Brett, Bentley, Paul, Aprahamian, Surman, EPJA (2012)
- Surman, Mumpower, Cass, Aprahamian, ICFN5 proceedings (2013)
- Aprahamian, Bentley, Mumpower, Surman, AIP 'Stardust' (2014)

beta decay rates
- Cass, Passucci, Surman, Aprahamian, NIC proceedings (2012)
- Mumpower, Cass, Passucci, Surman, Aprahamian, AIP 'Stardust' (2014)

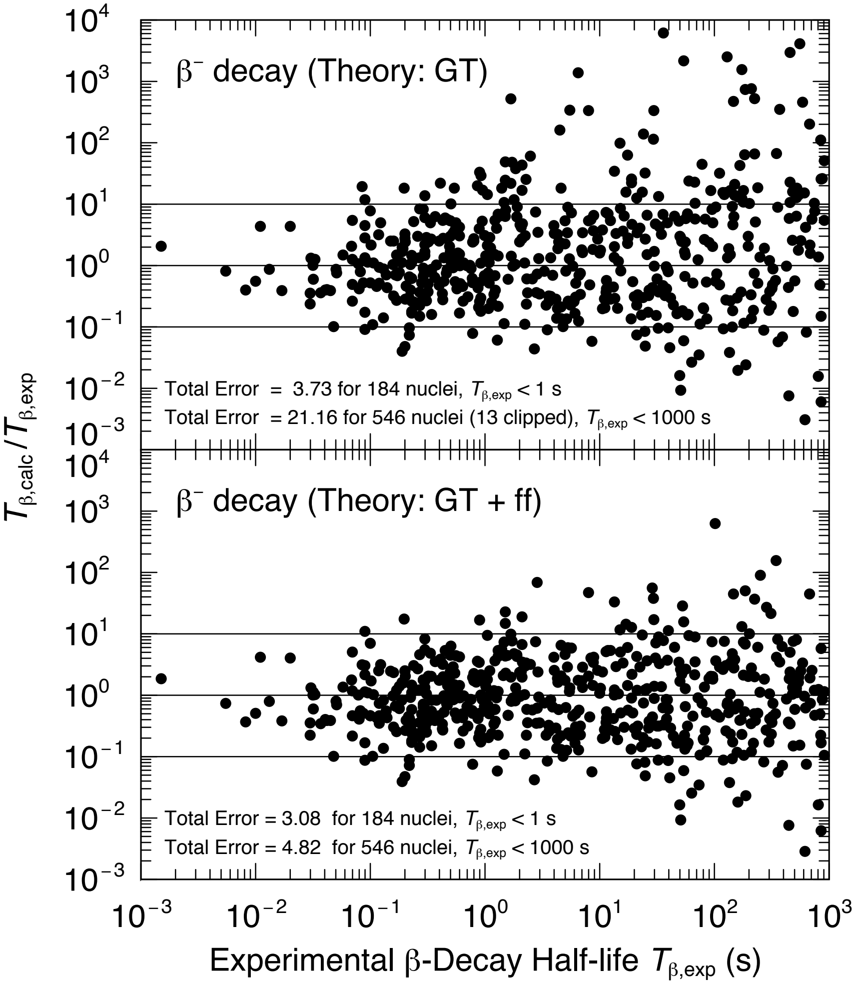
masses/capture rates/beta decay rates
- Surman, Mumpower, Cass, Bentley, Aprahamian, McLaughlin, INPC proceedings (2013)

nuclear data uncertainties far from stability



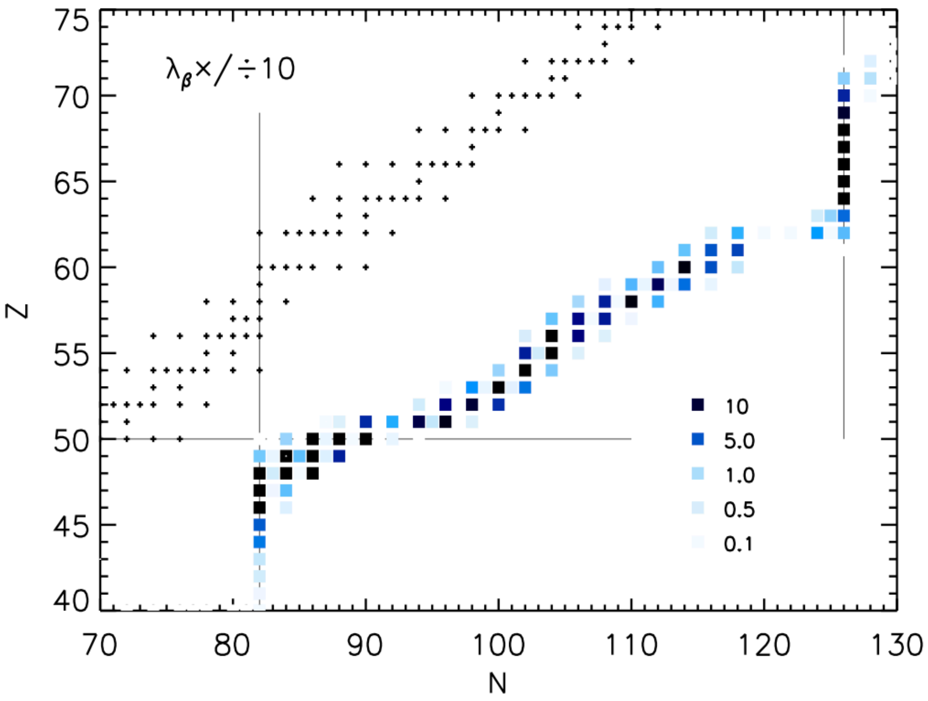
one-neutron separation energies for the tin isotopes, compared to FRDM values

Brett, Bentley, Paul, Aprahamian, Surman, EPJA (2012)



Möller et al (2003)

r-process sensitivity studies: β-decay rates

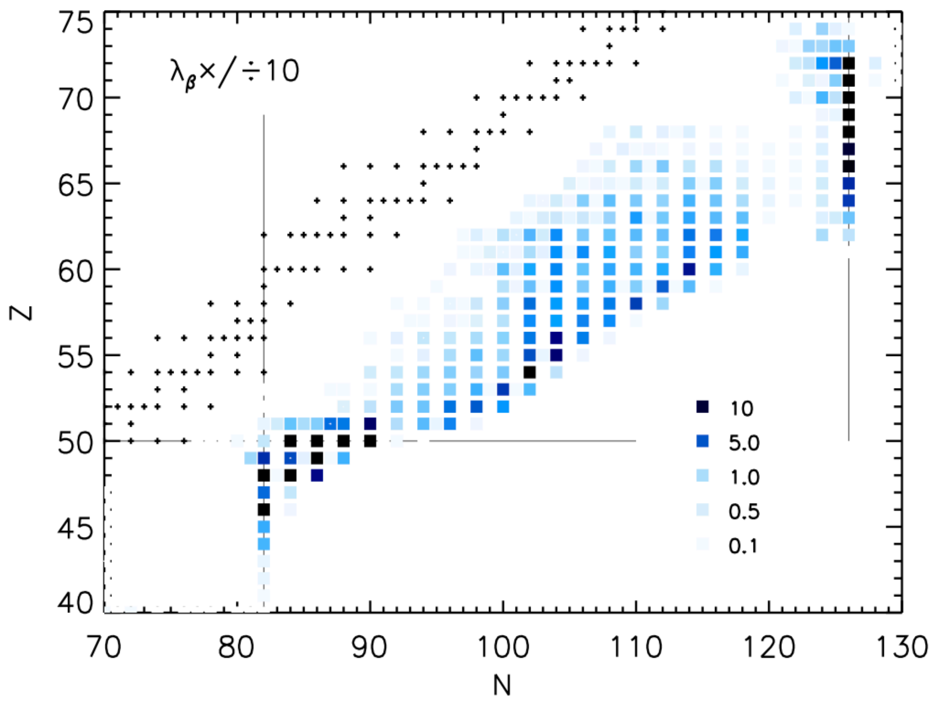


hot wind *r* process

parameterized as in Meyer (2002) with *s/k* = 100, Y_e = 0.25

$$F = 100 \times \sum_A \left| X_{baseline}(A) - X(A) \right|$$

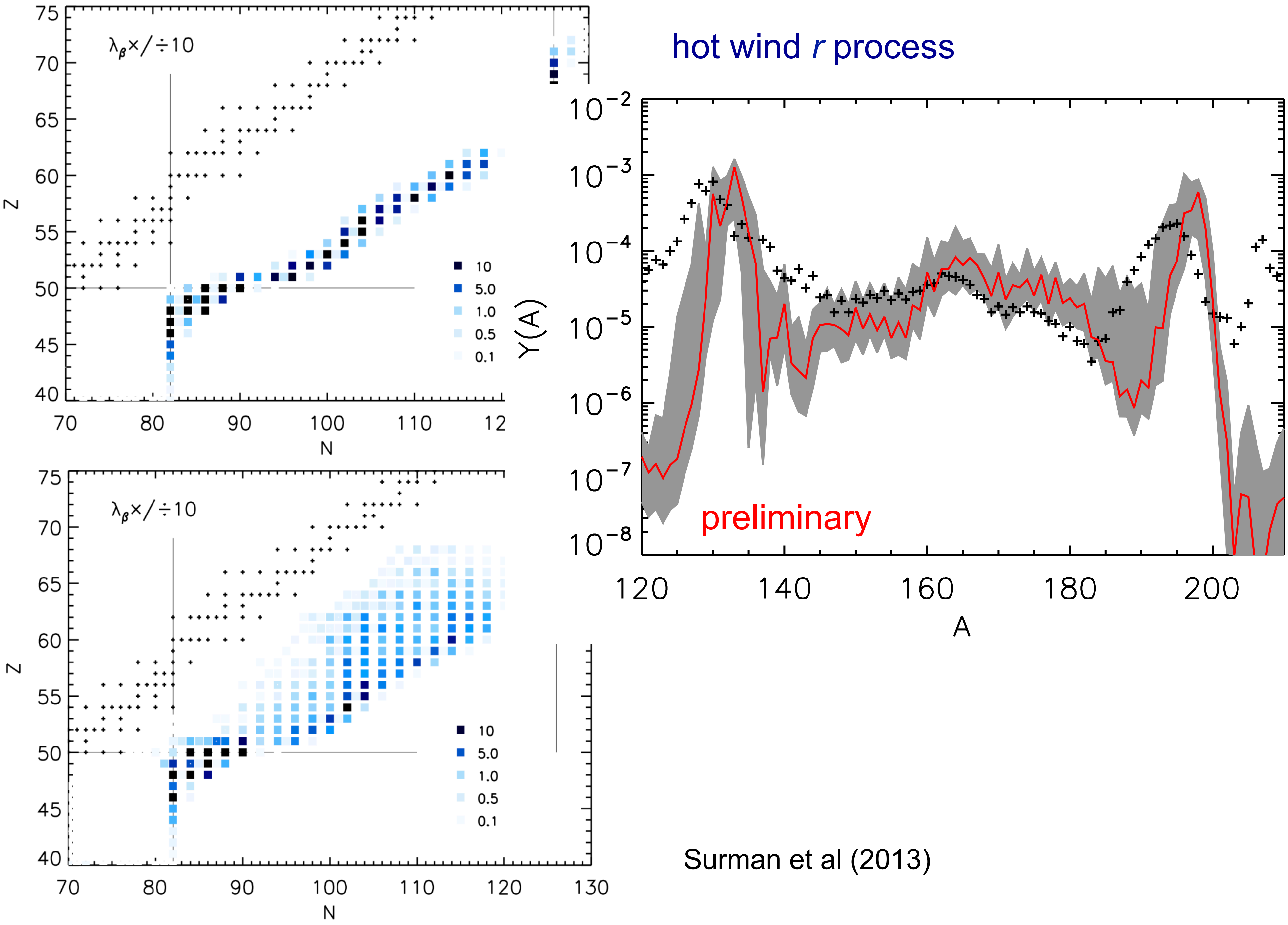
equilibrium phase only



full simulation

Surman et al (2013)

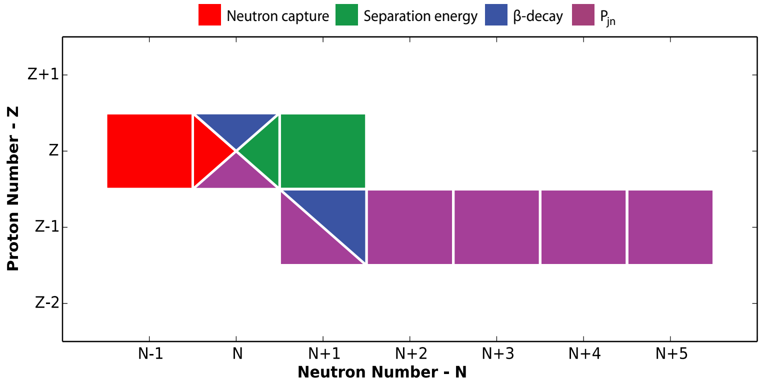
r-process sensitivity studies: *β*-decay rates



hot wind *r* process

Surman et al (2013)

r-process sensitivity studies: nuclear masses



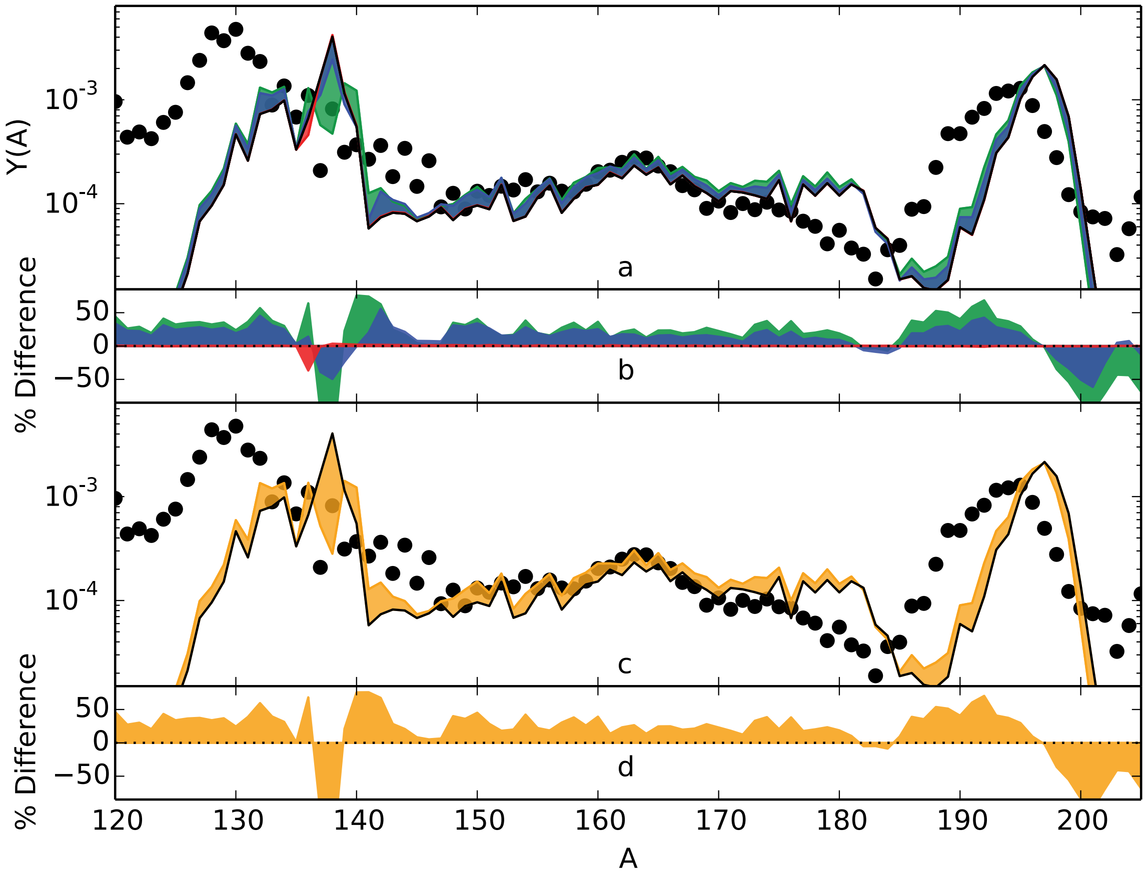
a change in the mass of nucleus *(Z, A)* also modifies:

neutron separation energies for *(Z, A)* and *(Z, A+1)*

neutron capture rates for *(Z, A)* and *(Z, A-1)*

beta decay rates for *(Z, A)* and *(Z-1, A)*

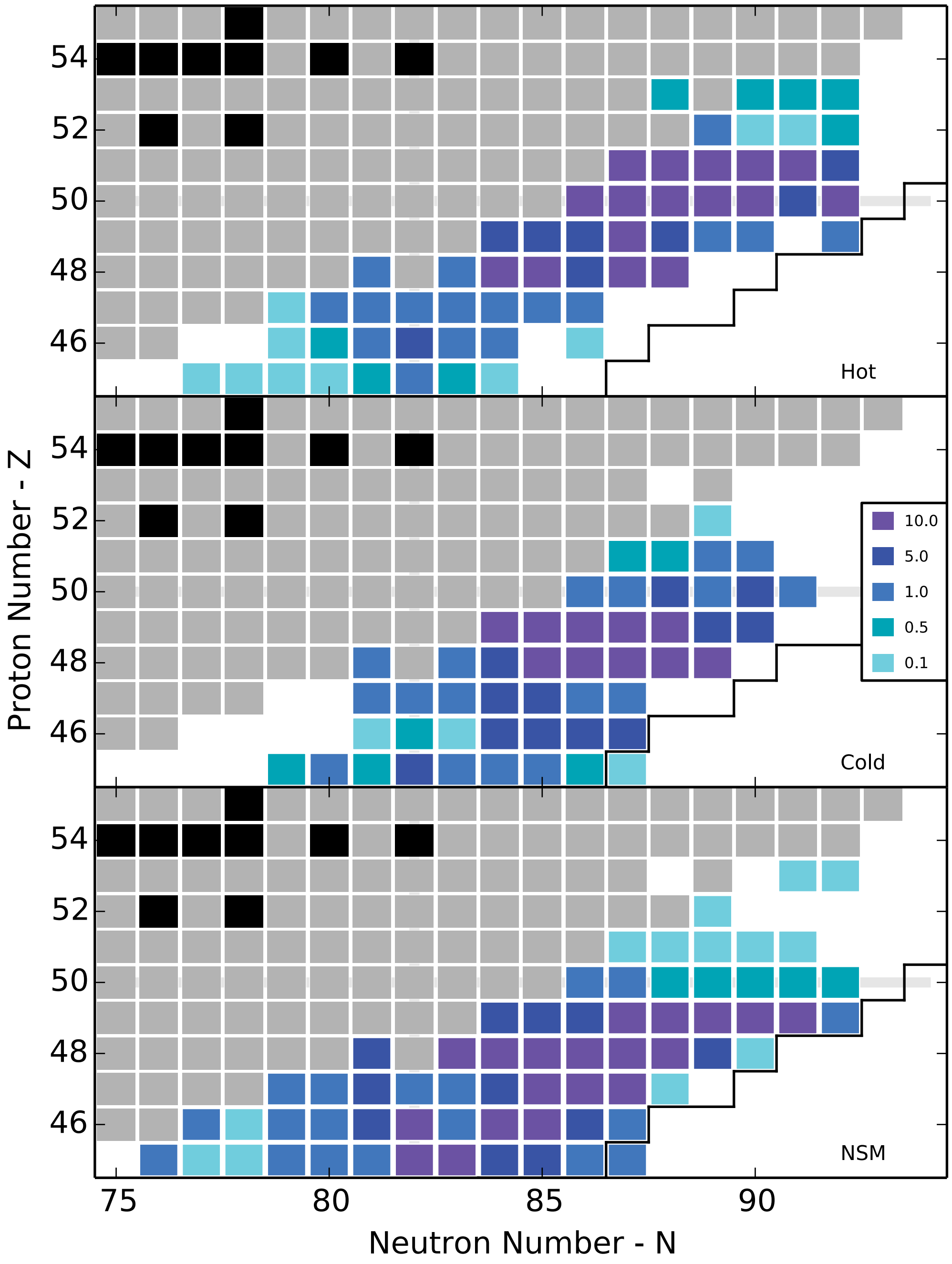
beta-delayed neutron emission probabilities for *(Z-1, A)-(Z-1, A+3)*



Mumpower, Fang, Surman, Beard, Aprahamian, submitted (2014)

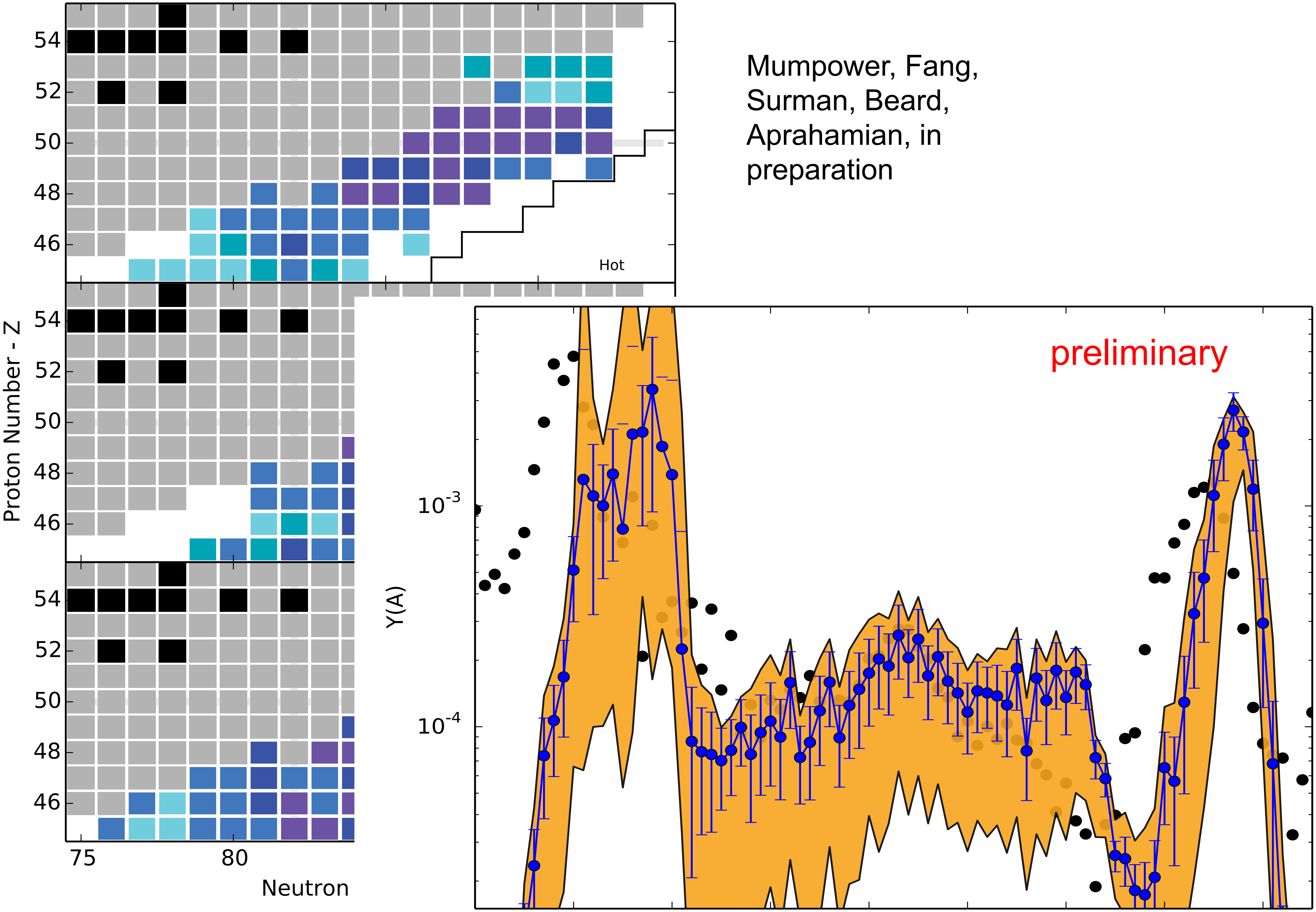
R Surman
ARIS 2014
2014 June 4

r-process sensitivity studies: nuclear masses



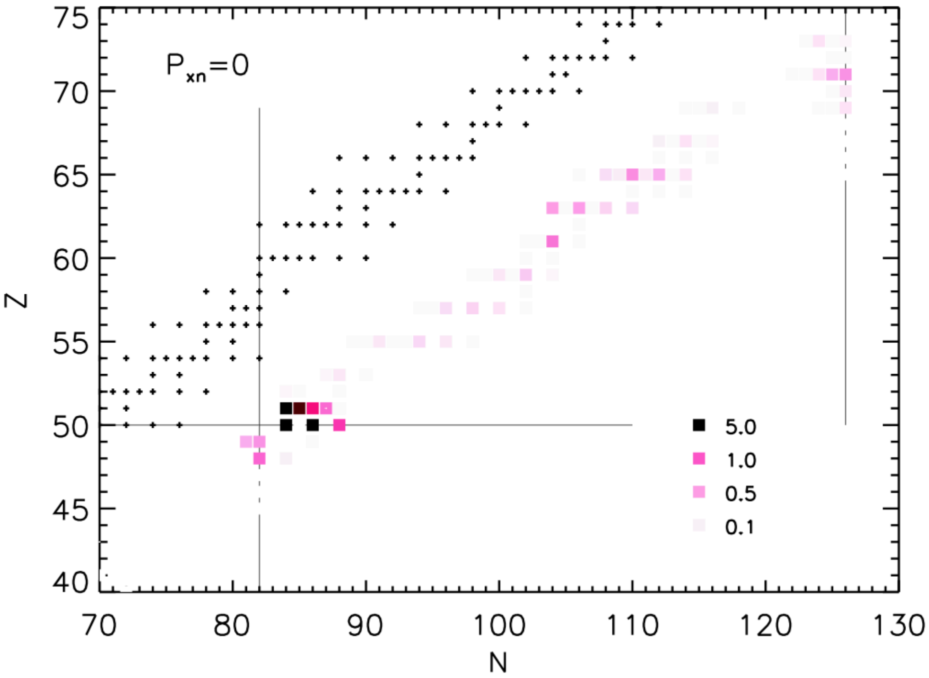
Mumpower, Fang, Surman, Beard, Aprahamian, in preparation

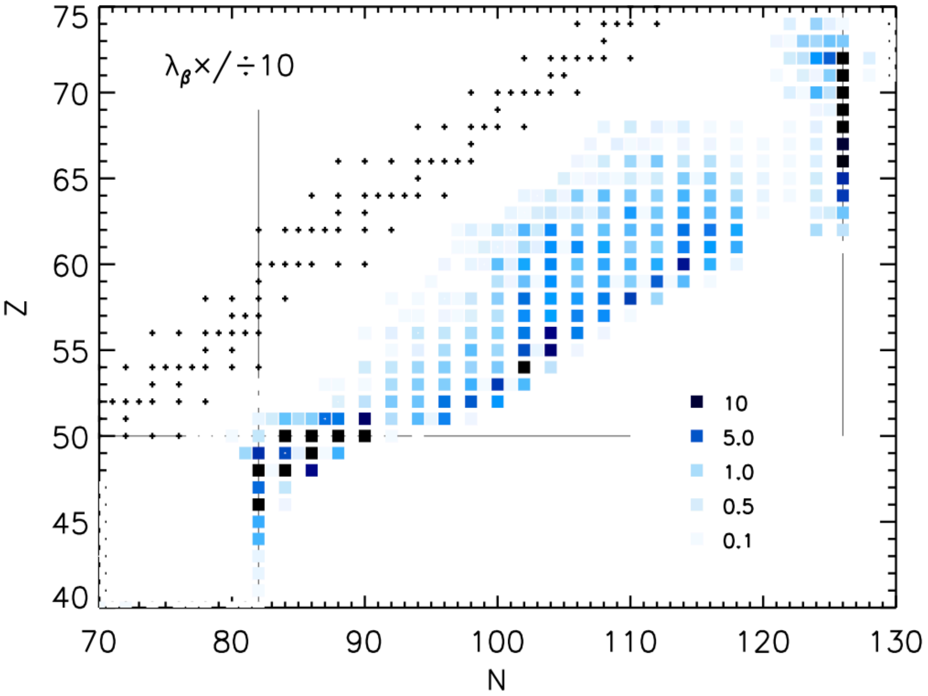
r-process sensitivity studies: nuclear masses



Mumpower, Fang, Surman, Beard, Aprahamian, in preparation

r-process sensitivity studies: β-delayed neutron emission





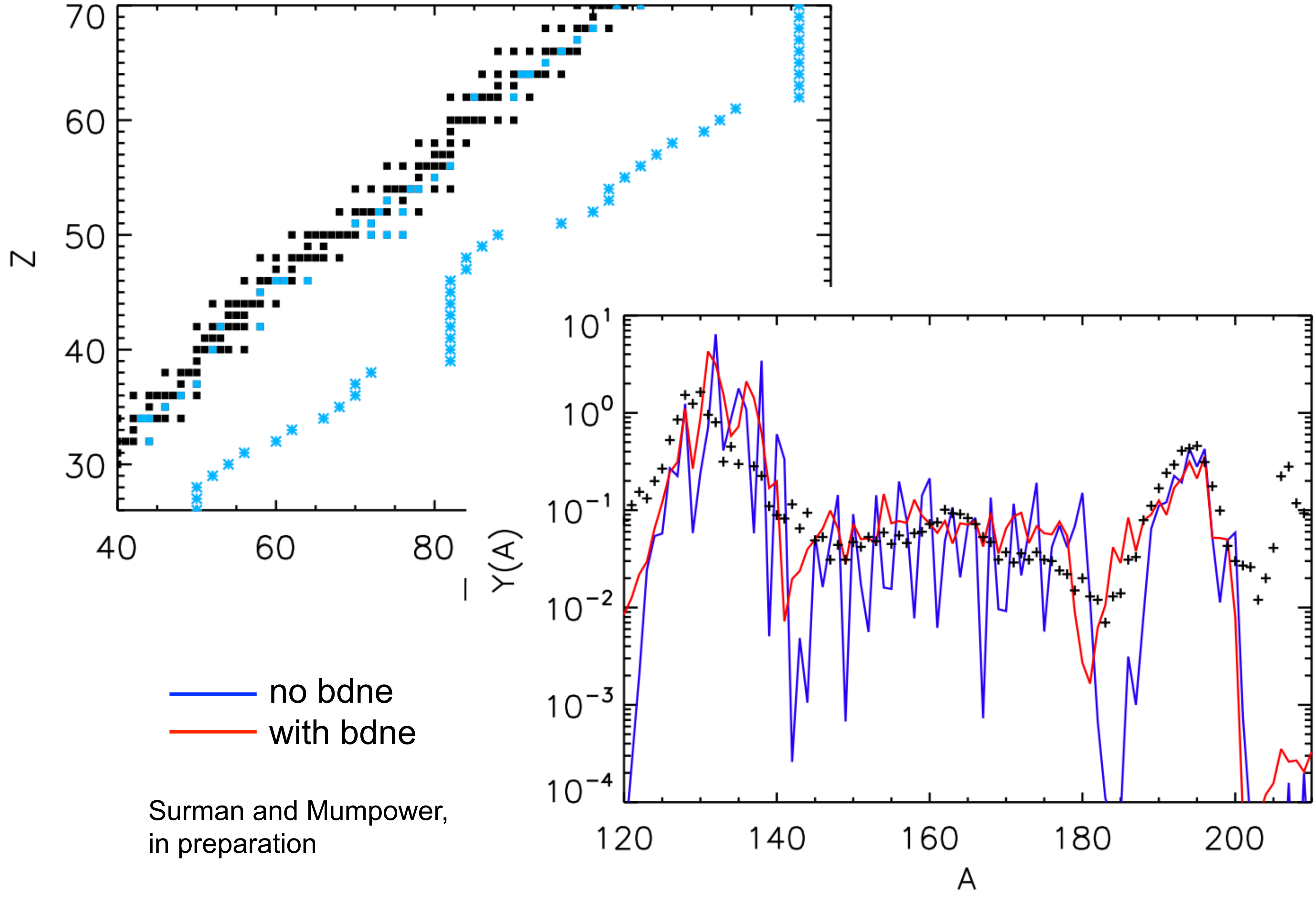
hot wind *r* process

parameterized as in Meyer (2002) with s/k = 100, Y_e = 0.25

$$F = 100 \times \sum_A \left| X_{baseline}(A) - X(A) \right|$$

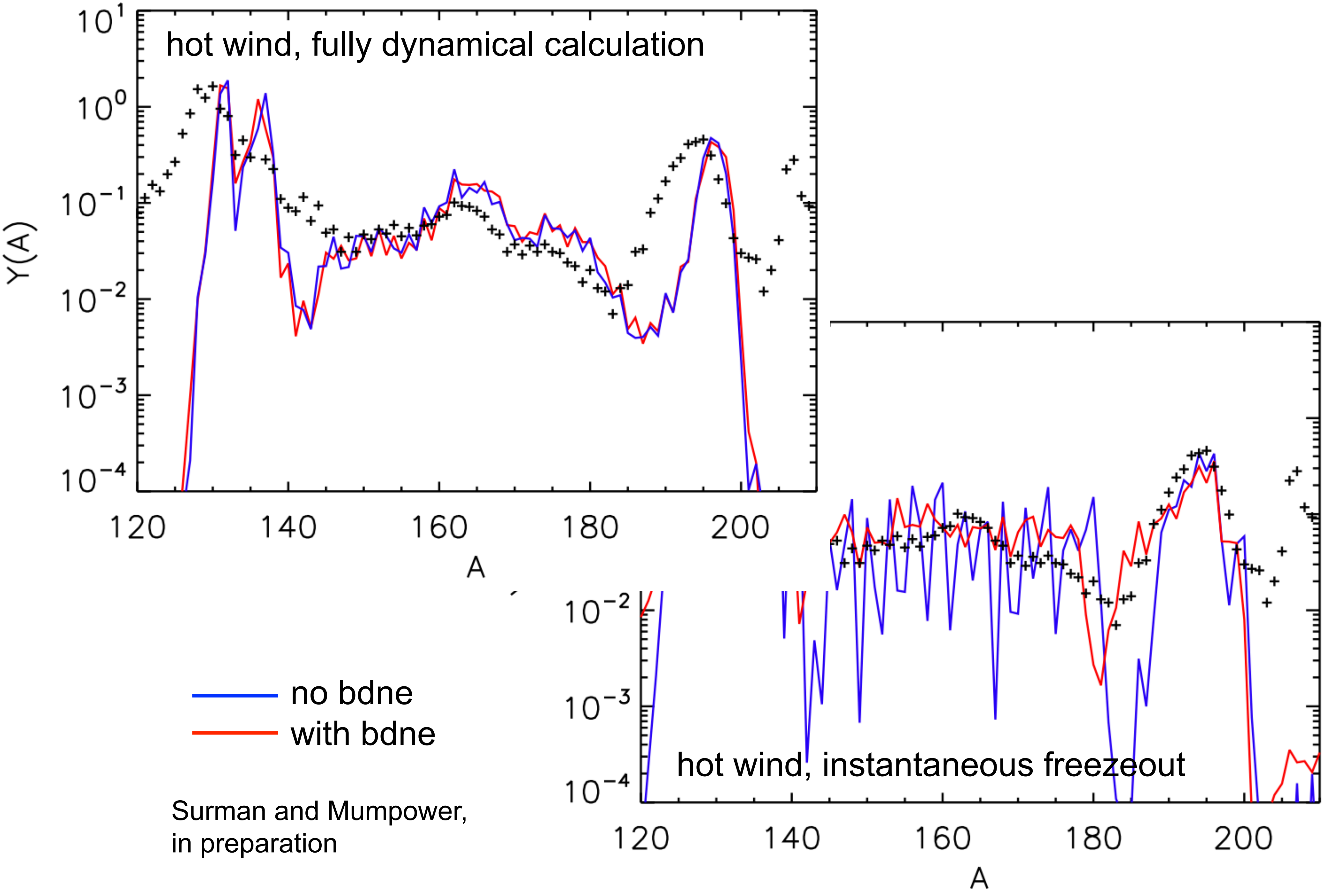
Surman and Mumpower, in preparation

β-delayed neutron emission: instantaneous freezeout



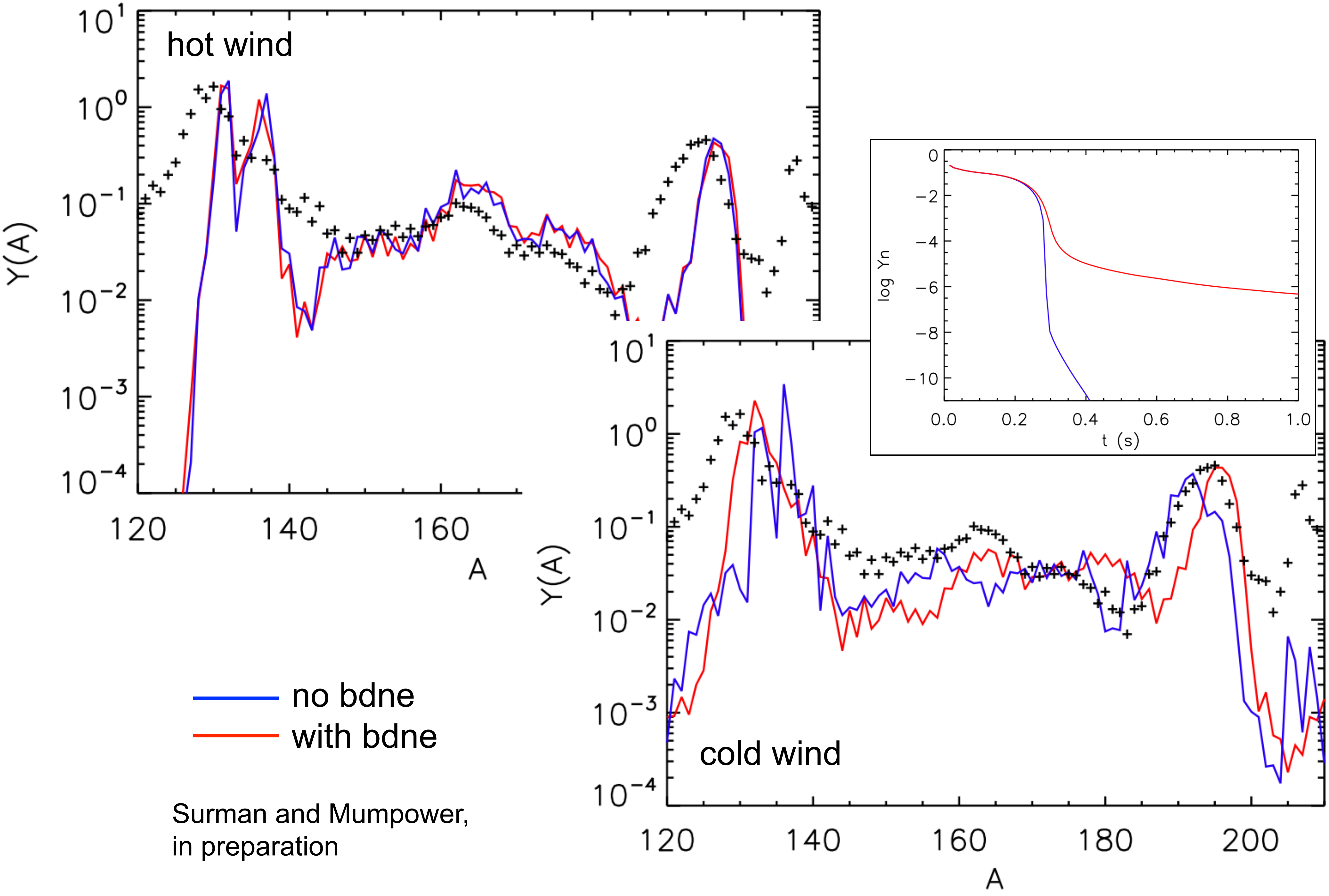
Surman and Mumpower,
in preparation

β-delayed neutron emission: dynamical freezeout



Surman and Mumpower,
in preparation

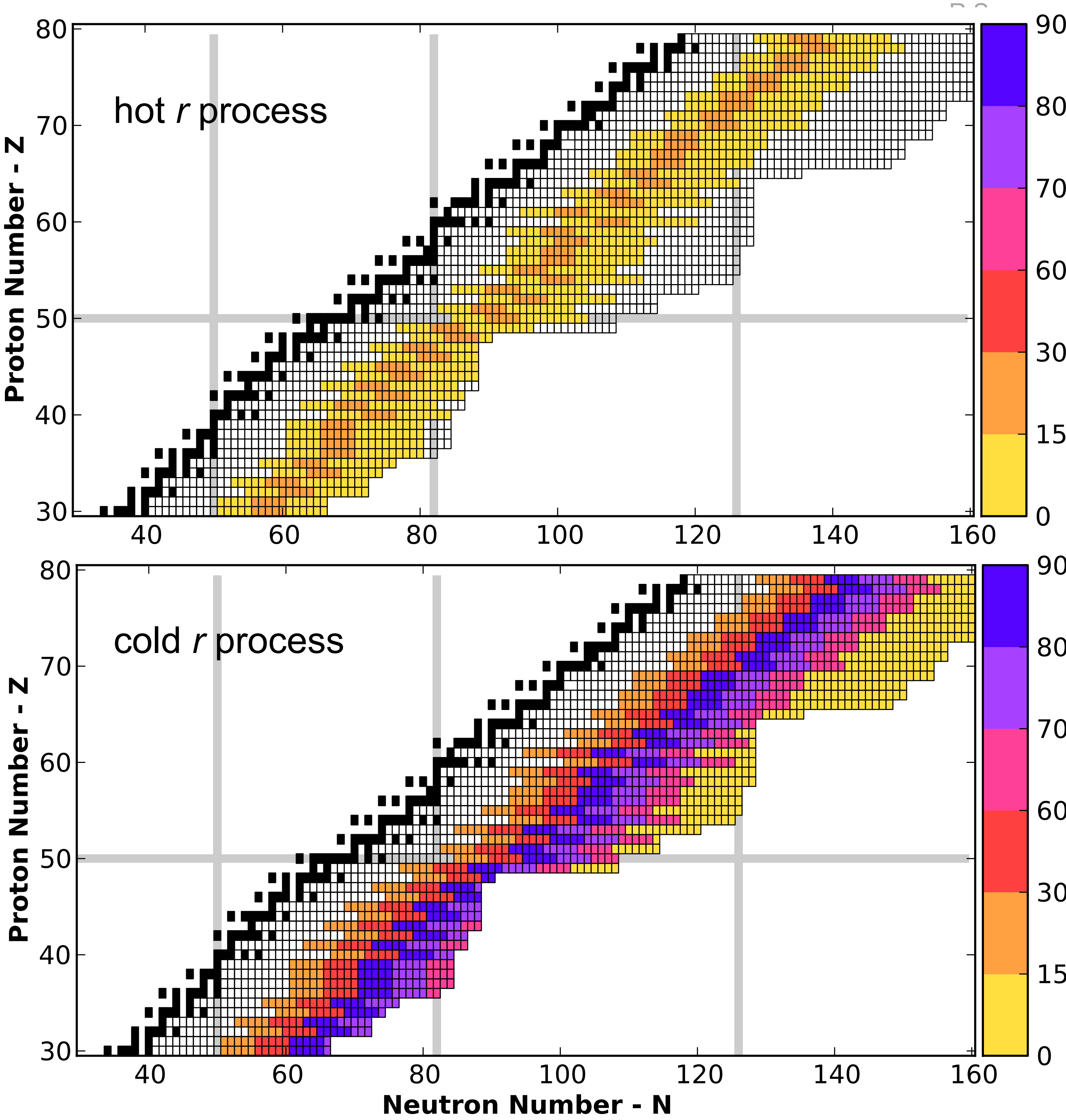
β-delayed neutron emission: dynamical freezeout



Surman and Mumpower,
in preparation

key P_n values

Here BDNE is switched off for ranges of nuclei (0-5, 5-10, 10-15, etc. neutrons from stability)



Surman and Mumpower, in preparation

summary

The site of the *r* process remains one of the greatest mysteries of nuclear astrophysics

After decades of progress the question is still unanswered: mergers or supernovae? (or both??)

Advances in spectroscopic observations, radioactive beam experiments, and the nuclear theory of neutron-rich nuclei have opened up a new avenue of approach to solving this mystery

Once nuclear physics uncertainties are reduced, we can exploit how the abundance pattern is finalized during freezeout to constrain the *r*-process astrophysical conditions