“An experimentalist’s guide to the outer crust of accreting neutron stars”

or:

“Nuclear masses and nuclear processes in the crust of neutron stars”

Alfredo Estrade
The University of Edinburgh

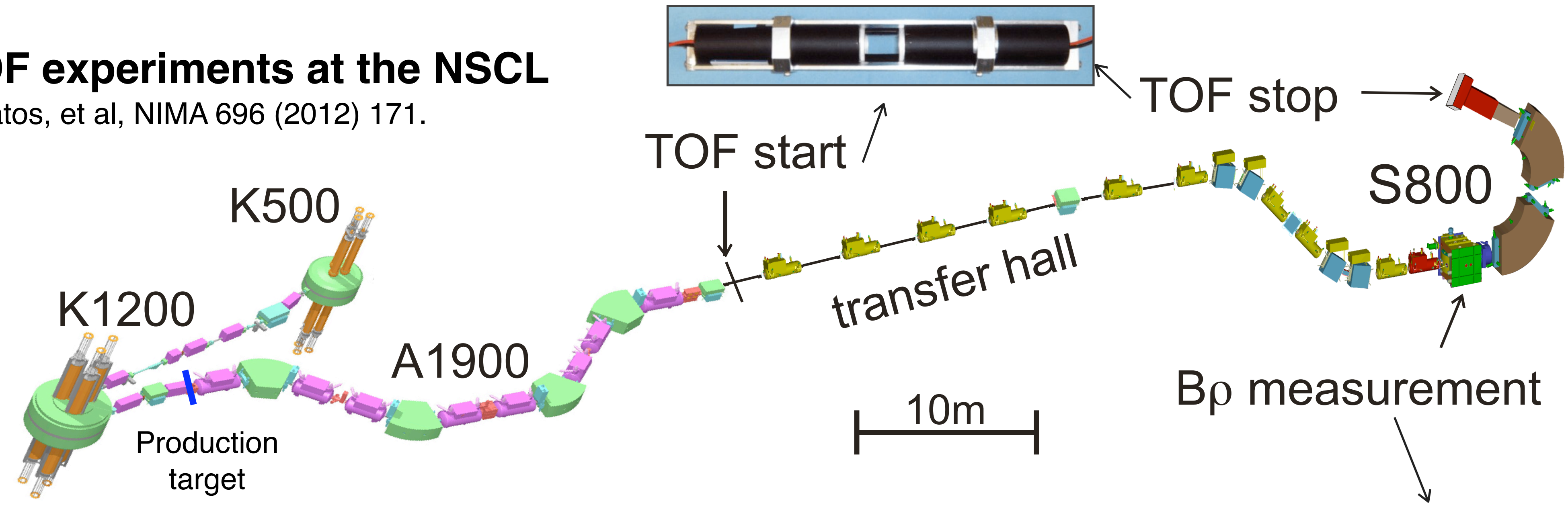
530th WE Heraeus Seminar, Bad Honnef, April 2012

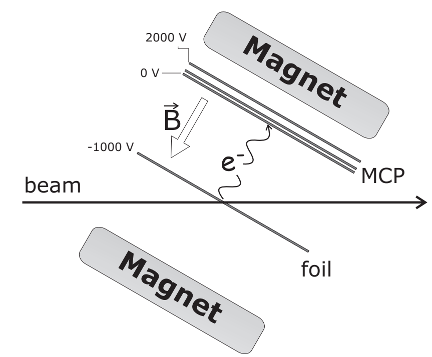
Outline

- TOF mass measurements of very neutron-rich nuclei: the case of 66Mn.
- Electron Capture processes in accreting neutron stars.
- Nuclear mass models for EC calculations.
- Regions of interest for future experiments?

TOF mass measurement technique

TOF experiments at the NSCL
Matos, et al, NIMA 696 (2012) 171.



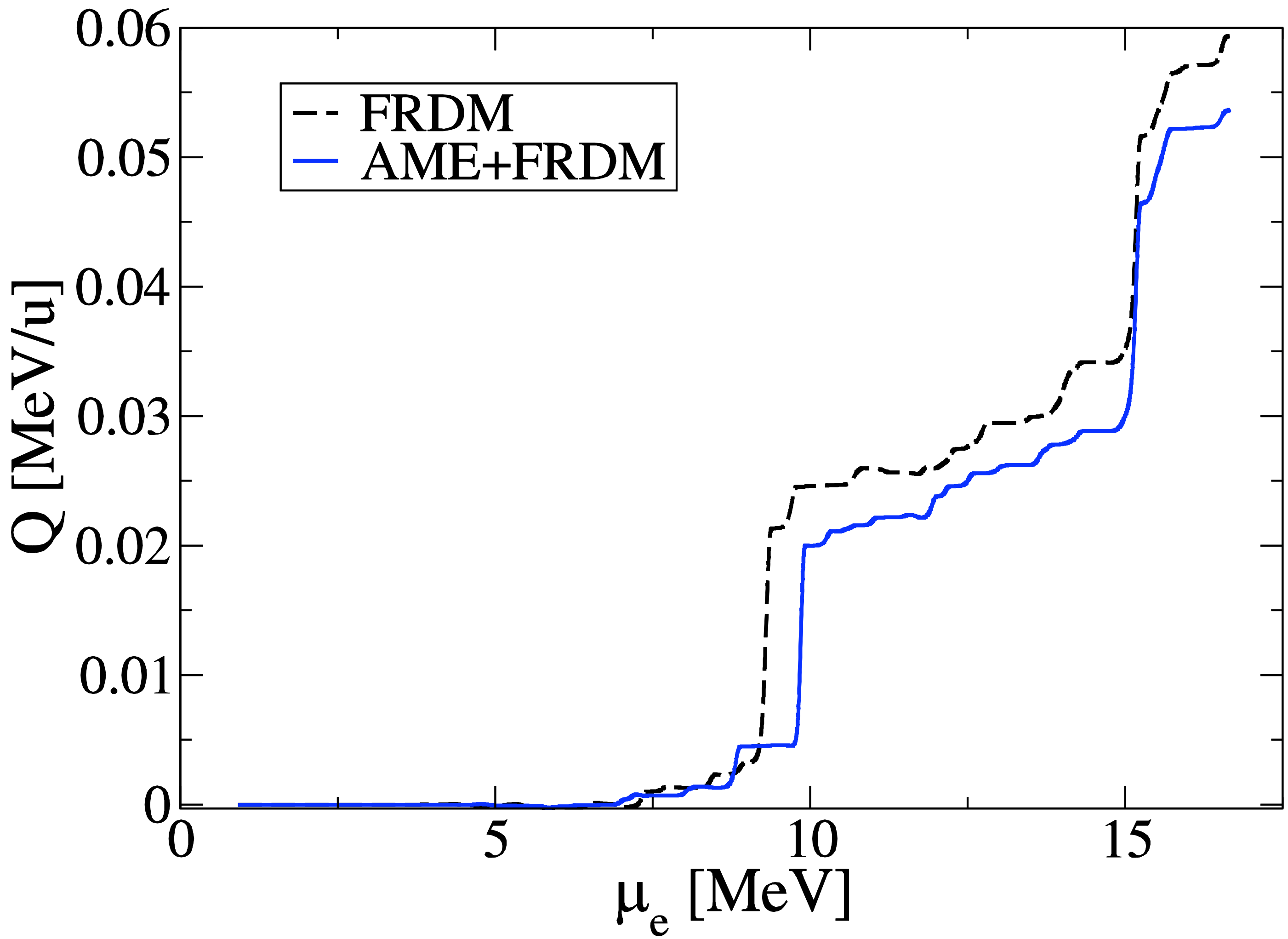


Mass derived from equation of motion of ions in beamline:

$$B\rho = \frac{\gamma p}{q} = \frac{\gamma m_0}{q}\left(\frac{L}{TOF}\right)$$

See talk by Z. Meisel on Thursday

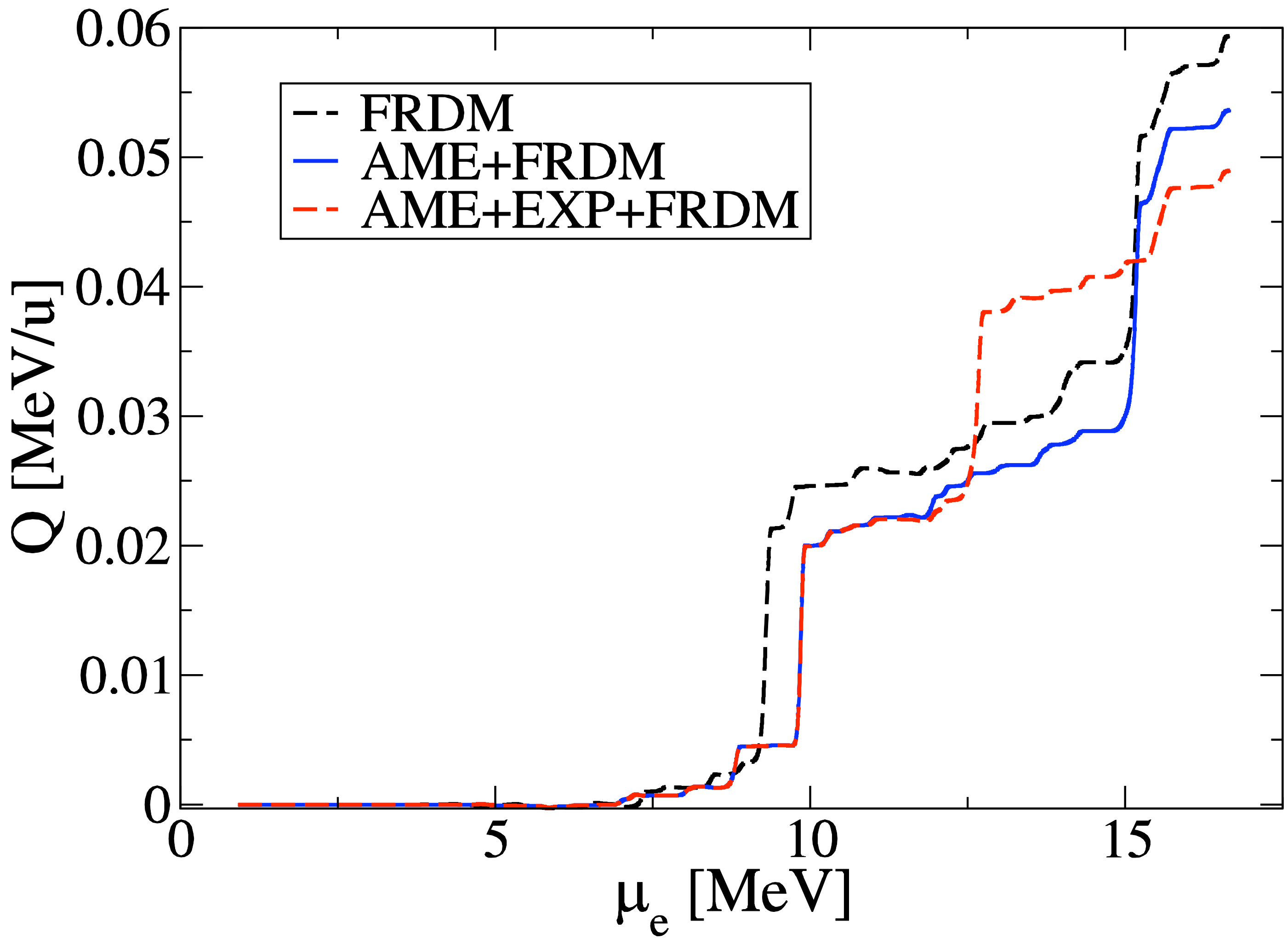
Experimental data and crust calculations



FRDM: Q_{EC}(^{66}Ni) = **-9.35** MeV

AME: Q_{EC}(^{66}Ni) = **-9.9** MeV

Experimental data and crust calculations



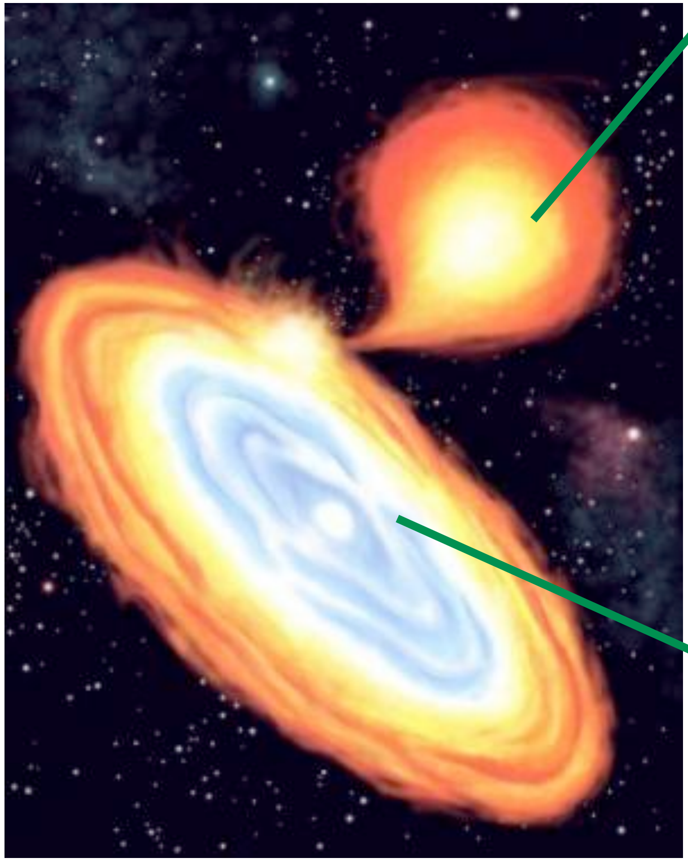
FRDM: $Q_{EC}(^{66}Ni)$ = **-9.35** MeV
AME: $Q_{EC}(^{66}Ni)$ = **-9.9** MeV

FRDM: $Q_{EC}(^{66}Fe)$ = **-15.3** MeV
EXP: $Q_{EC}(^{66}Fe)$ = **-12.7** MeV

A. Estrade et al, 2011

Accreting Neutron Stars

An artist's rendition...



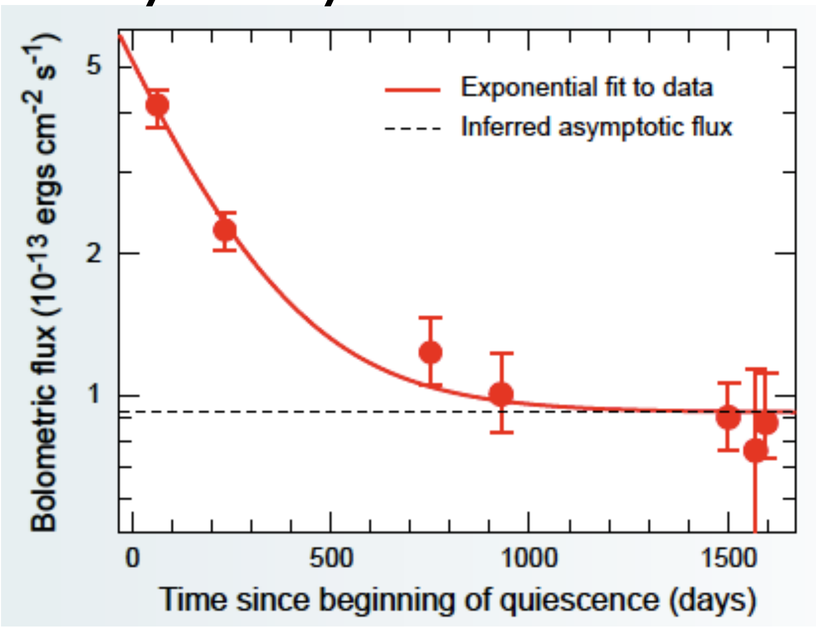
low mass companion

neutron star

The Chandra X-ray observatory.

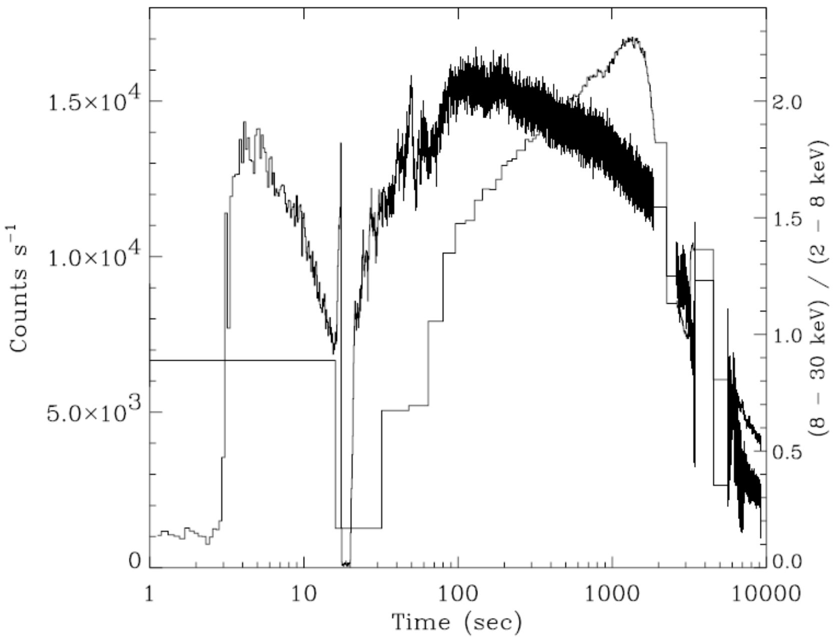
Observables affected by thermal properties of the neutron star

Cooling curve from transient X-ray binary



E. Cackett 2006

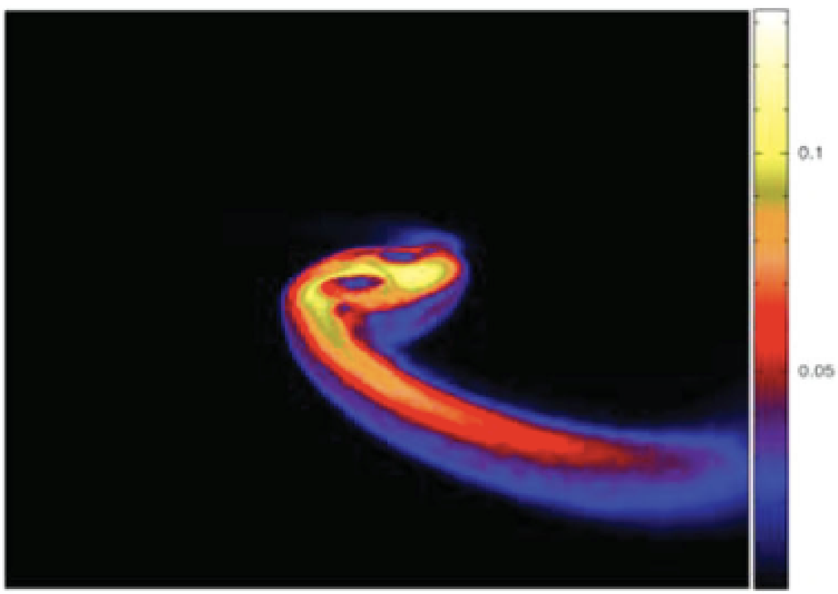
Superburst event from 4U 1820-30



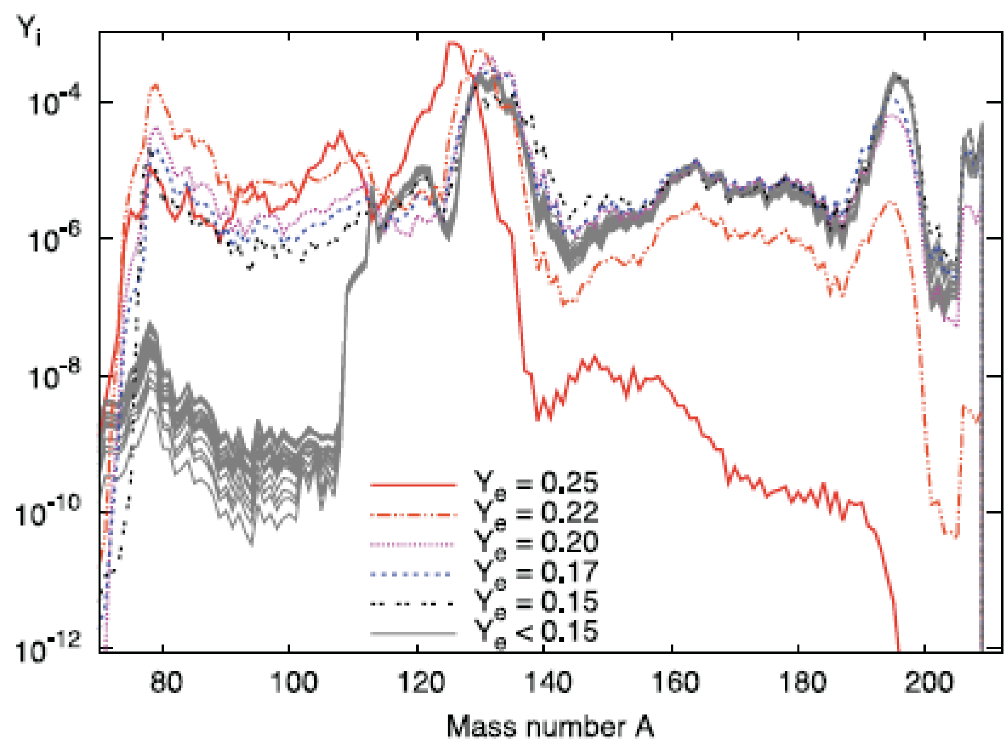
T.Strohmayer and E. Brown 2003

Crust chemical composition and nucleosynthesis in NS-NS mergers

Y_e distribution in merger event

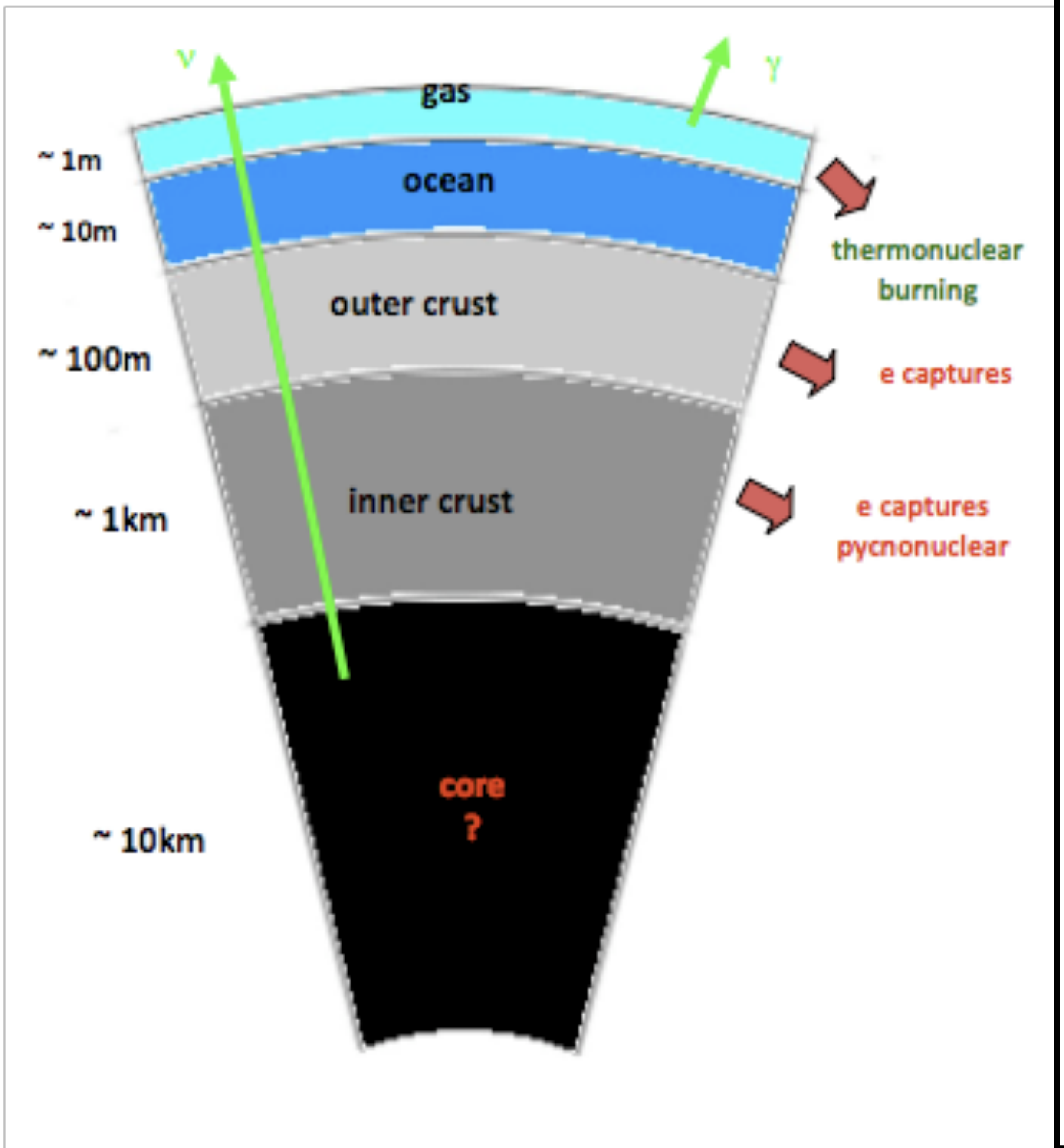


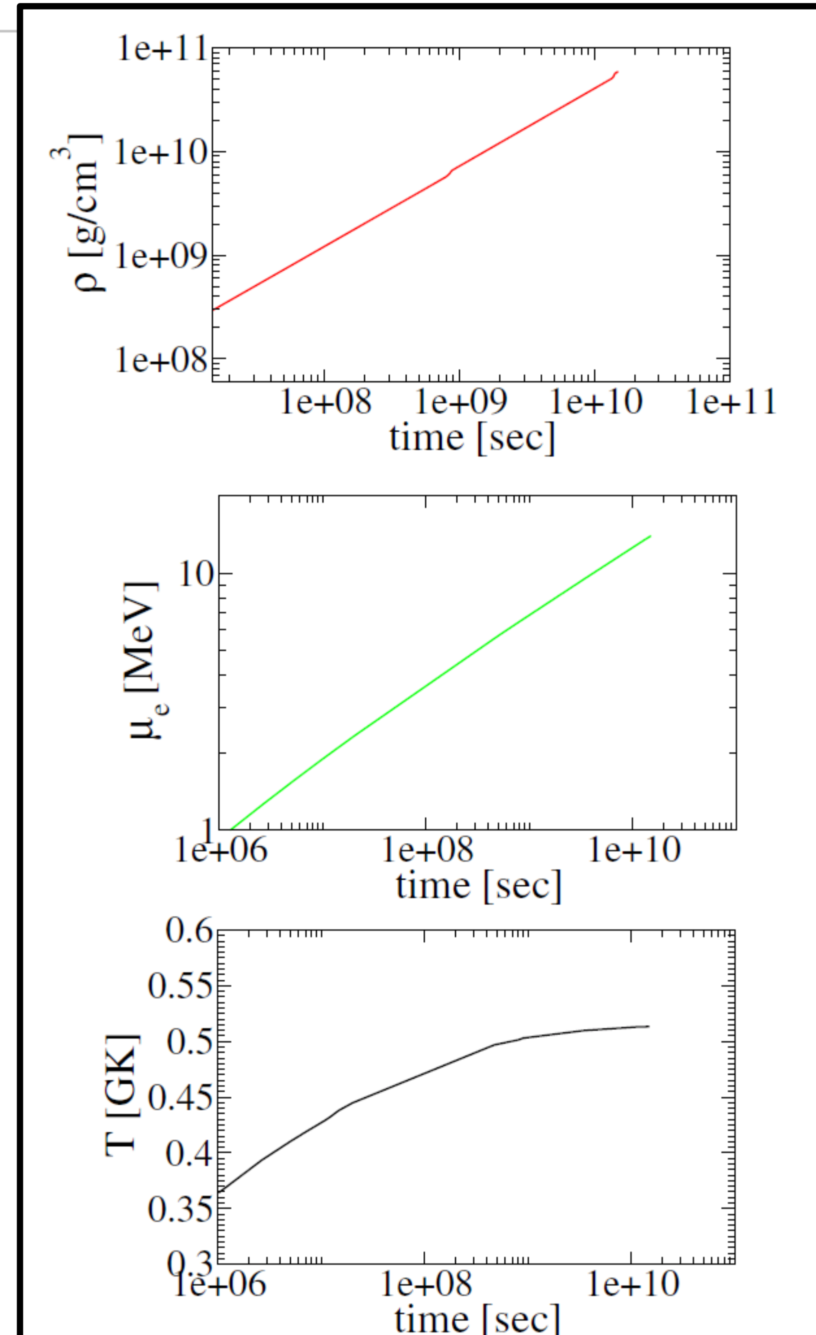
Abundance distributions resulting of trajectories with different Y_e



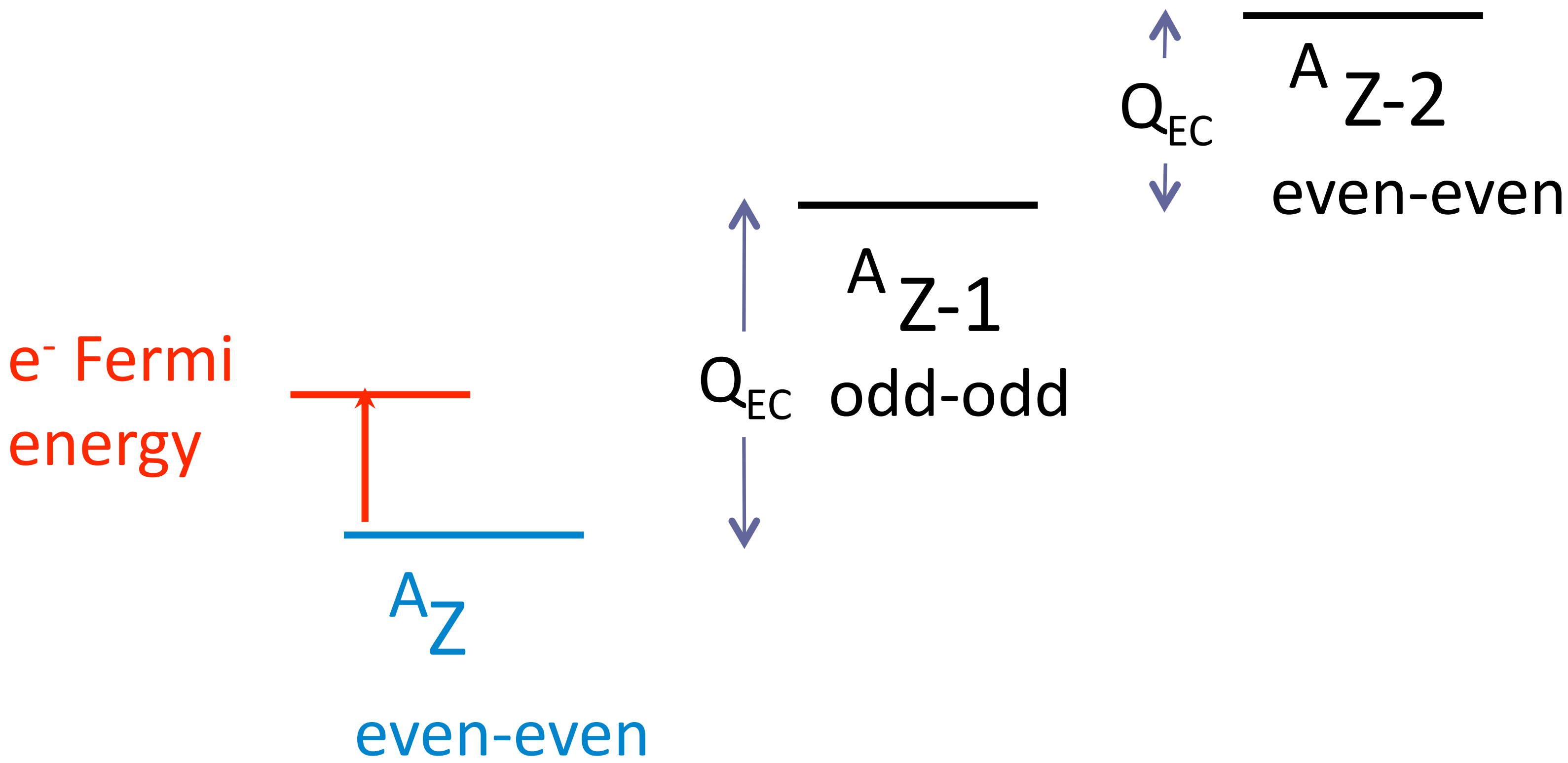
O. Korobkin et al 2012
talk by S. Rosswog on Friday

Density-driven nuclear processes in accreting neutron stars





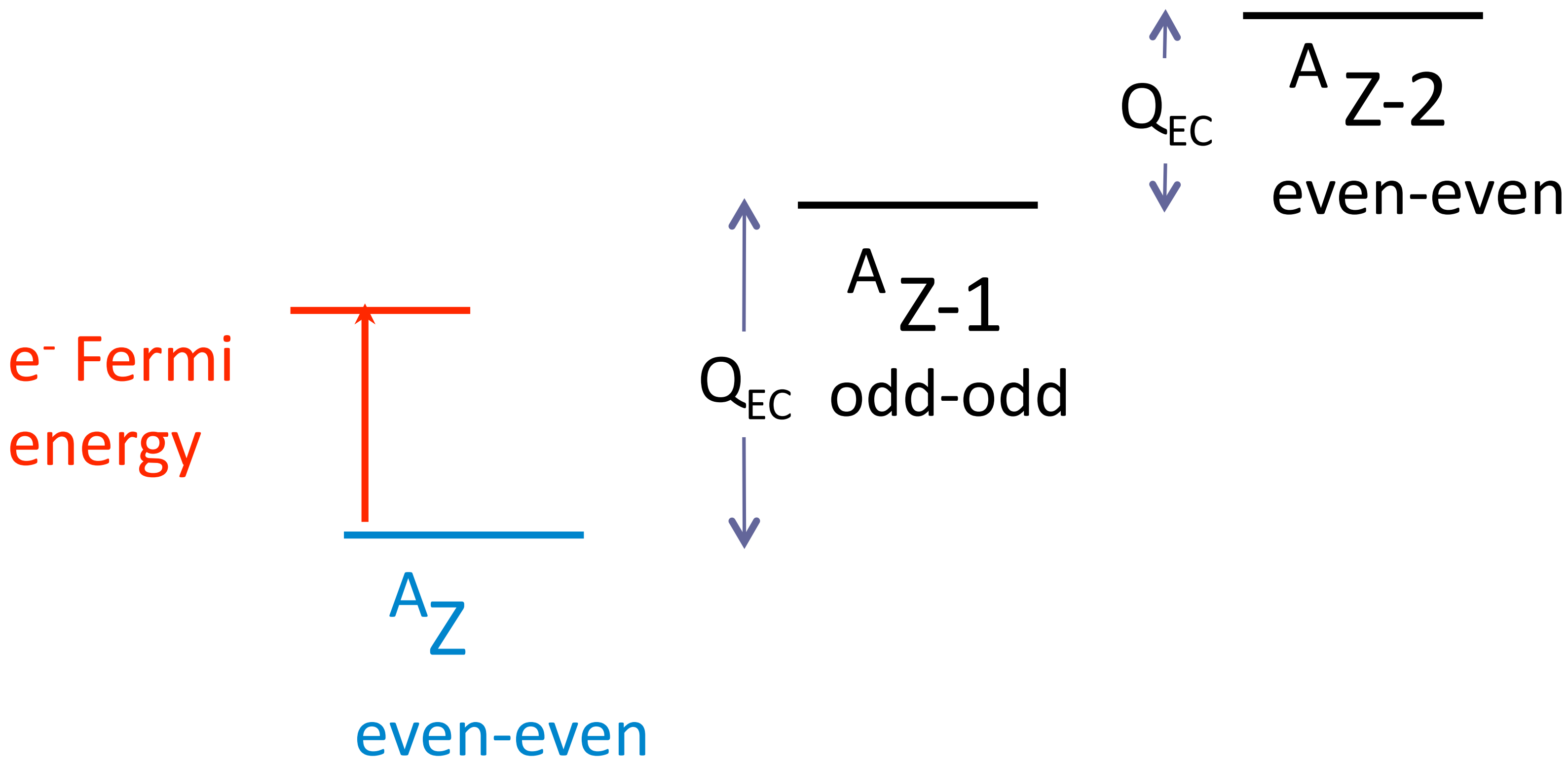
Electron capture processes in the outer crust



For even A isobaric chain

$$Q_{\mathrm{EC}} = M(\mathrm{A},\mathrm{Z}) - M(\mathrm{A},\mathrm{Z}-1)$$

Electron capture processes in the outer crust



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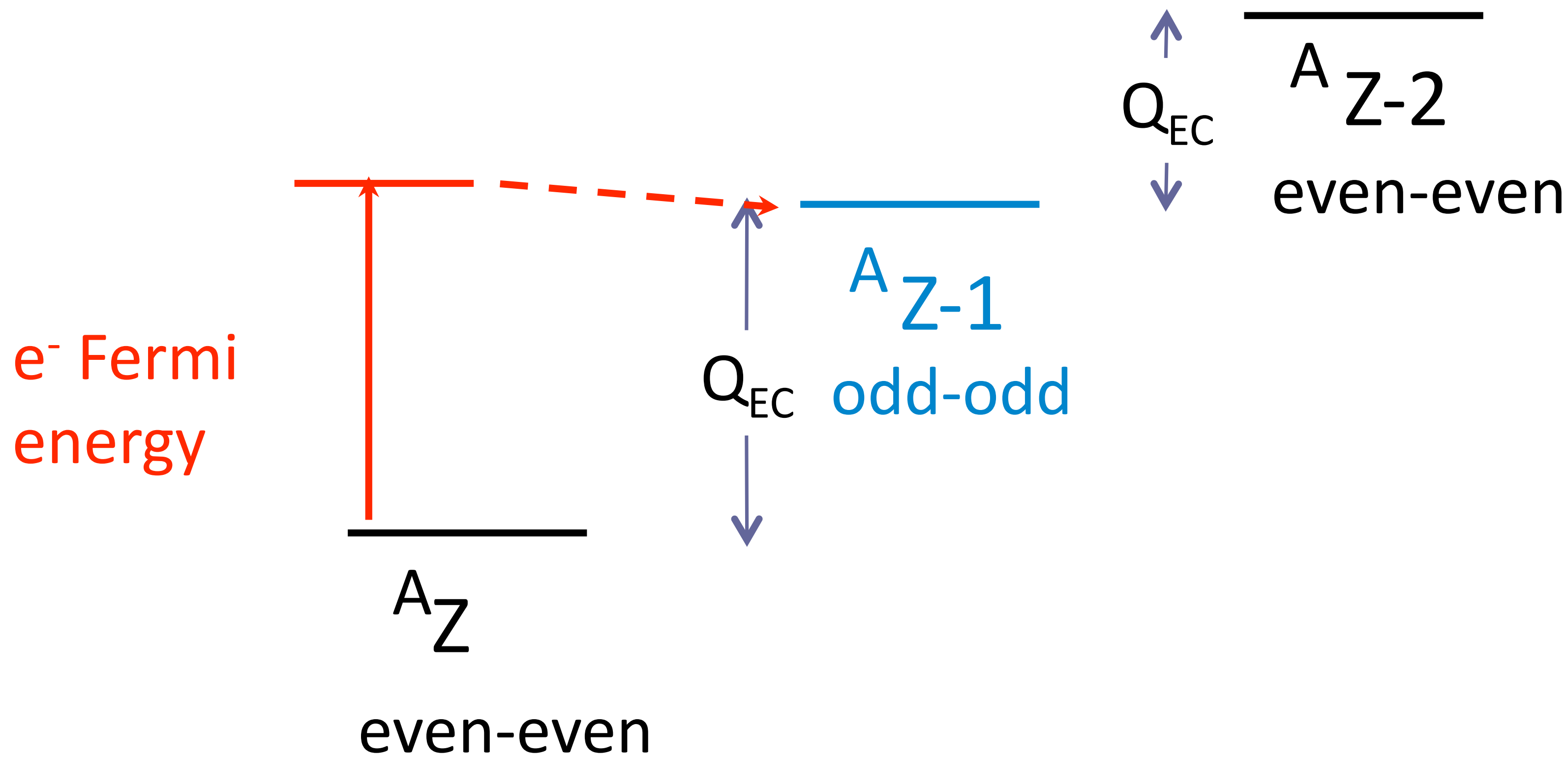

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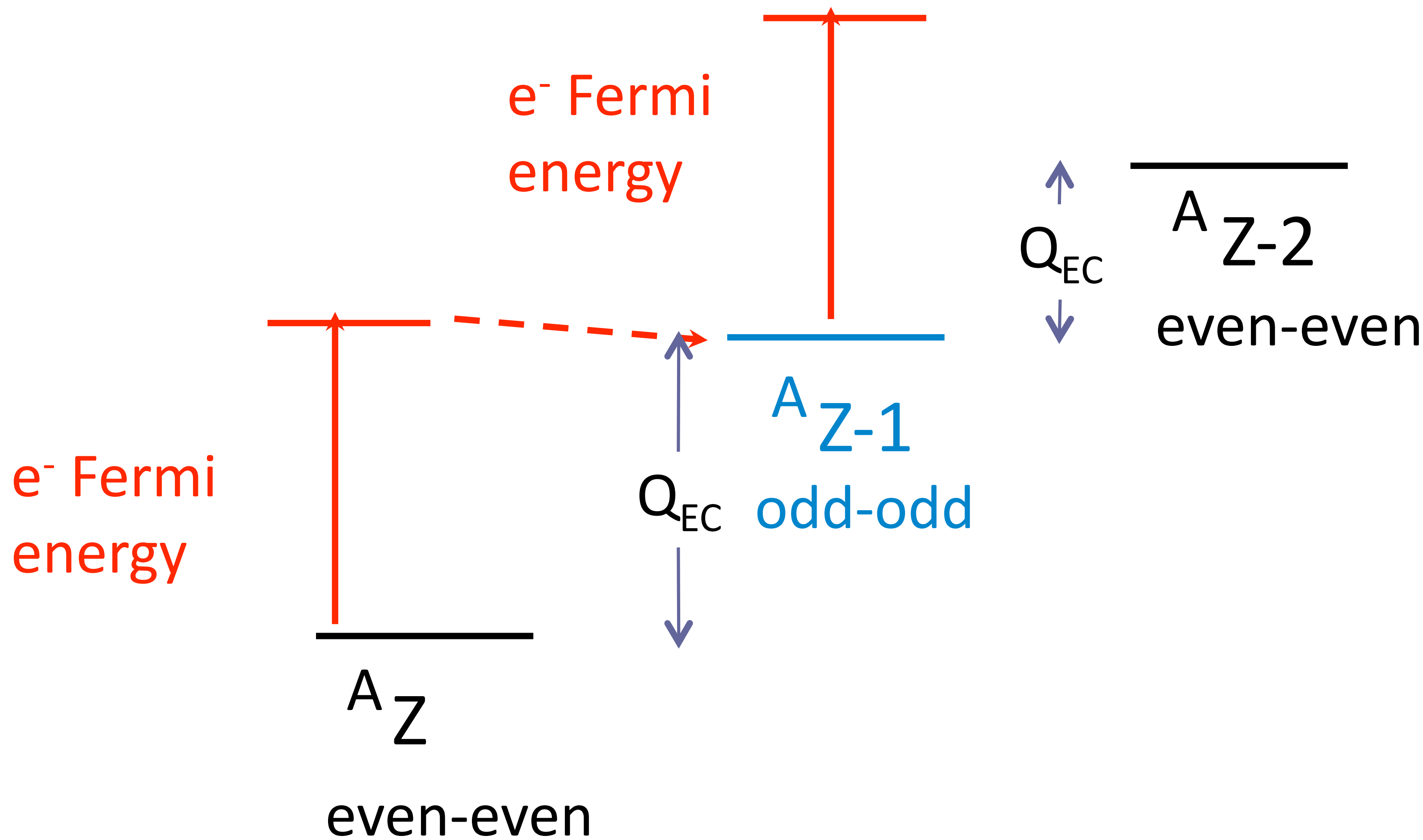

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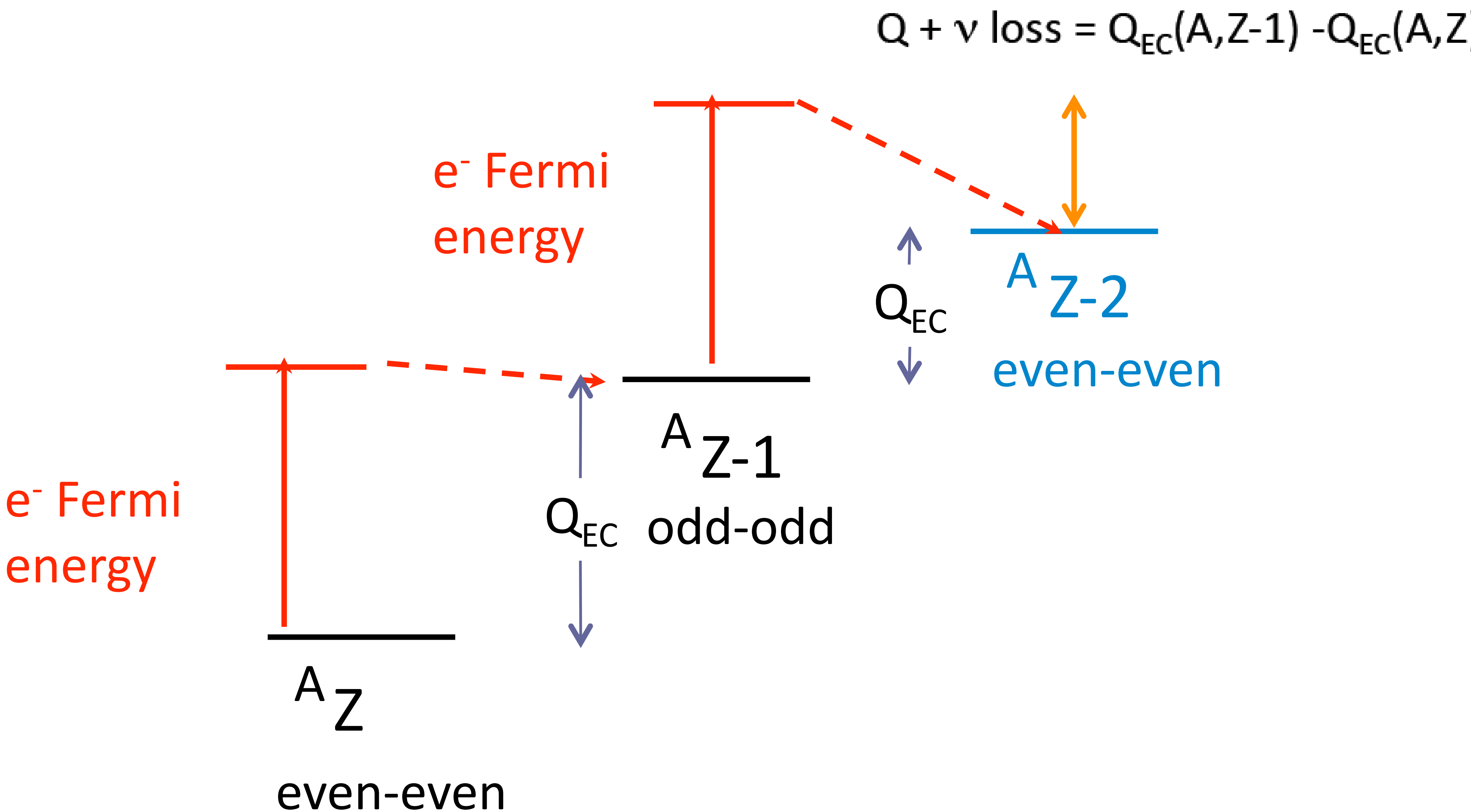
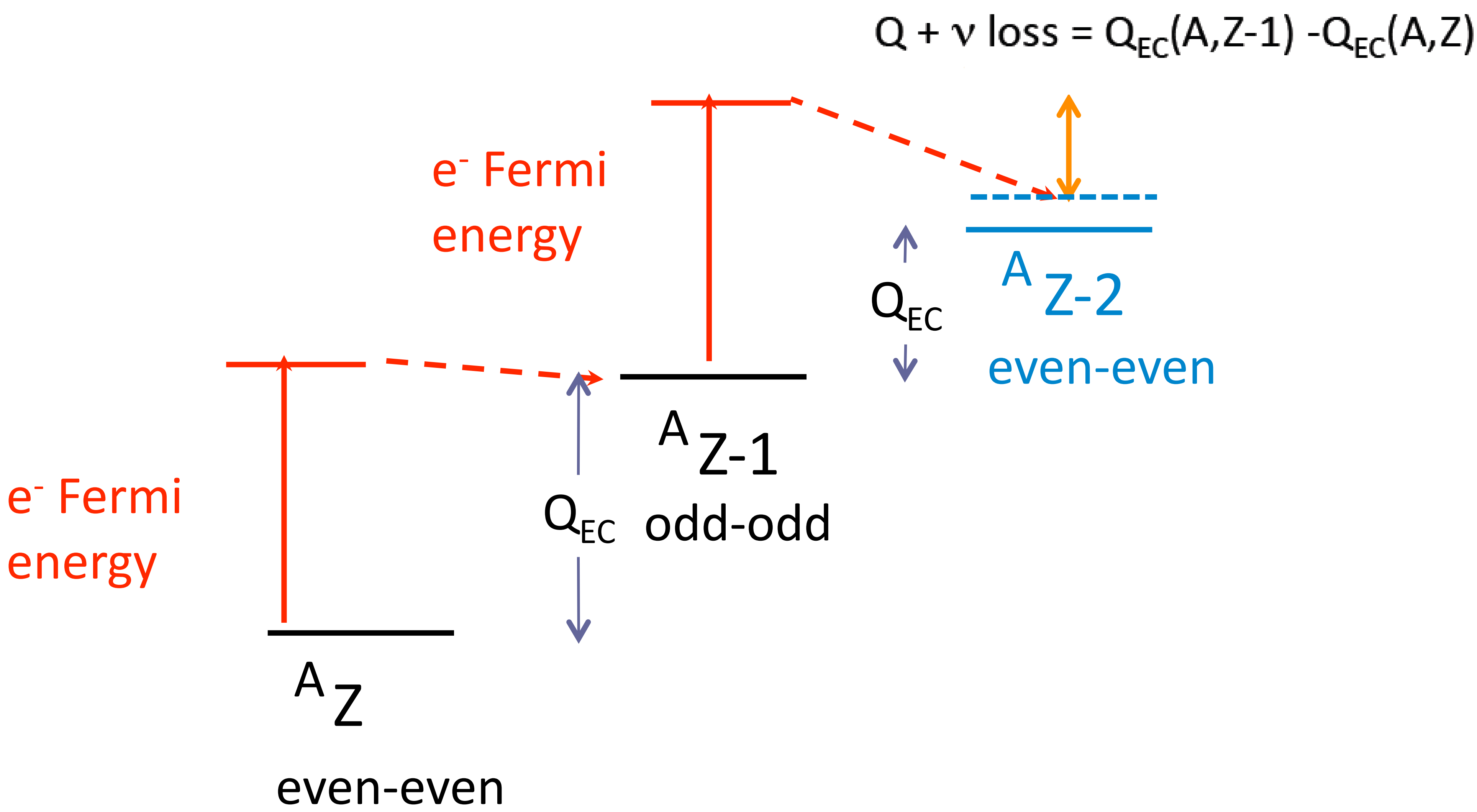


For even A
isobaric chain

$$Q_{\mathrm{EC}} = M(\mathrm{A},\mathrm{Z}) - M(\mathrm{A},\mathrm{Z}-1)$$



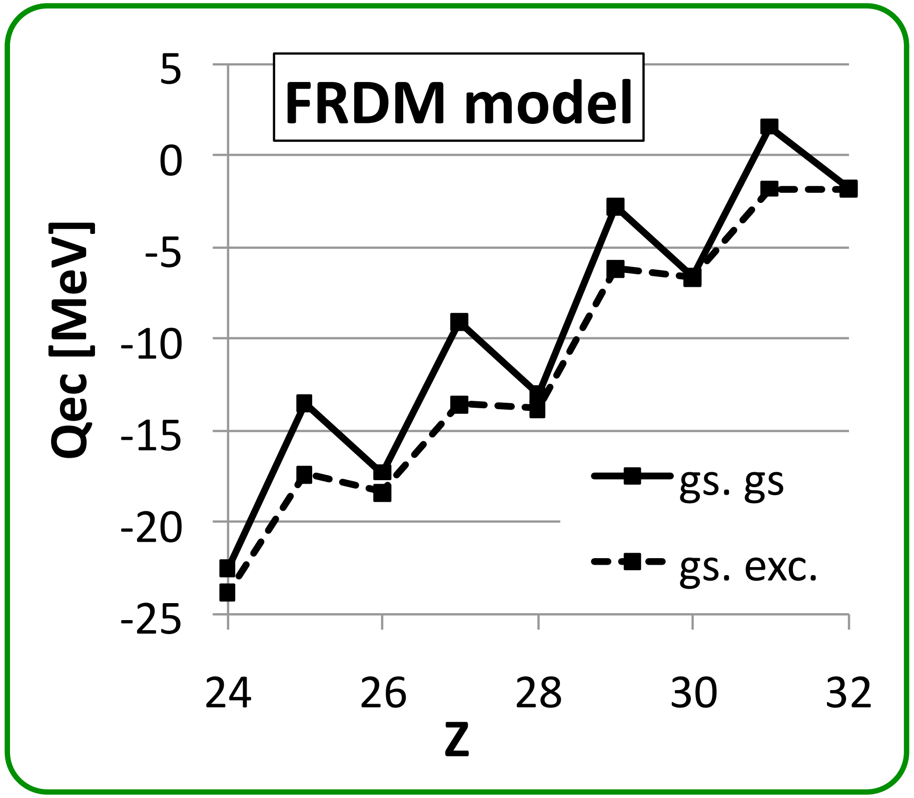
Masses (and excitation energies) set **location** of and **strength** of nuclear heating sources.

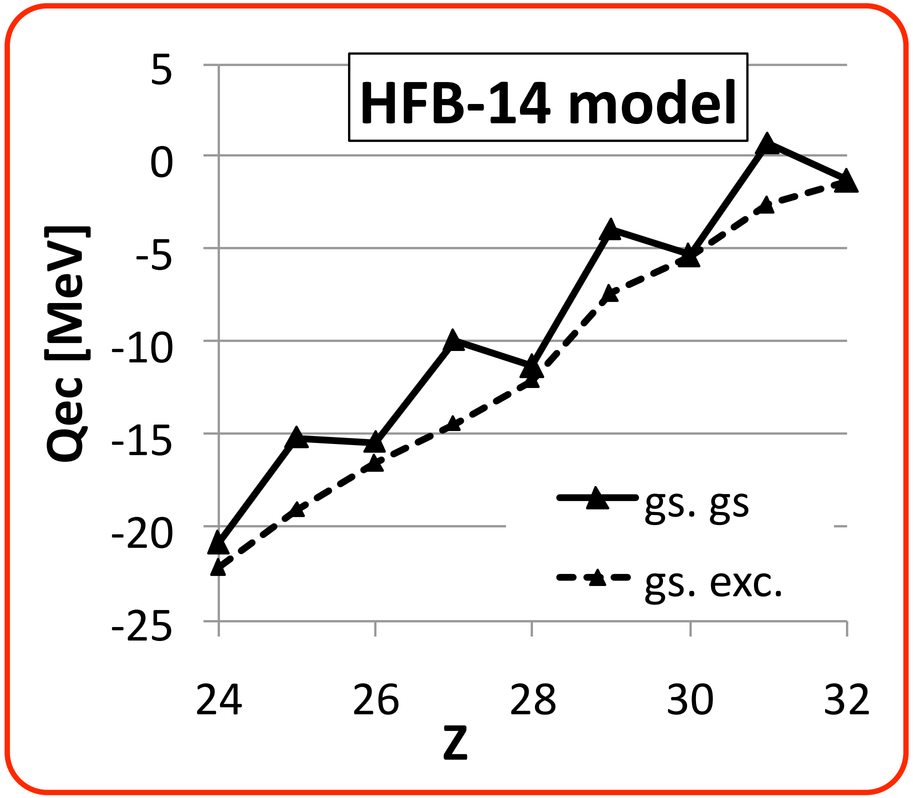
$$Q_{\rm EC} = M(\mathrm{A,Z}) - M(\mathrm{A,Z-1})$$

Electron captures for A=70 mass chain

MOVIES!

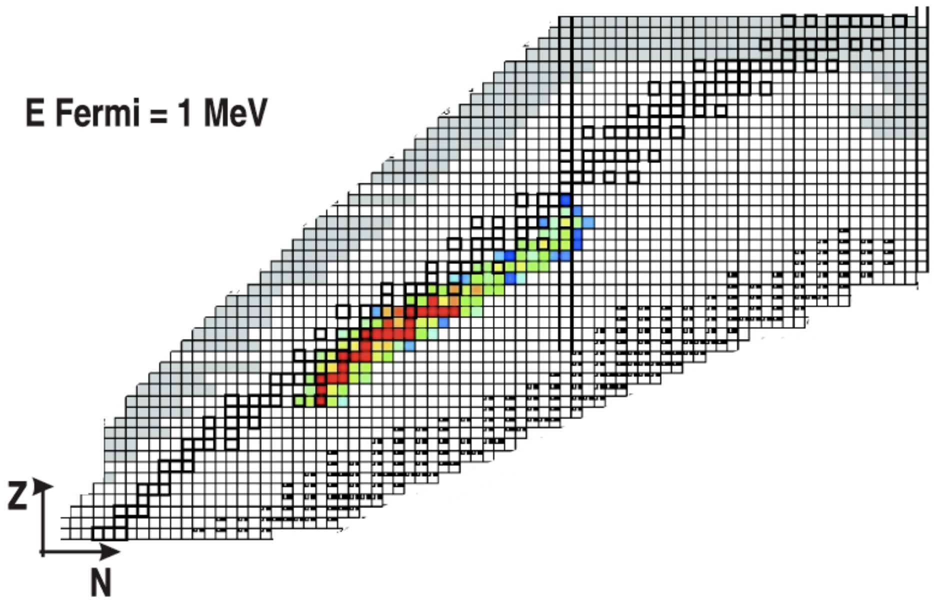
Electron captures for A=70 mass chain





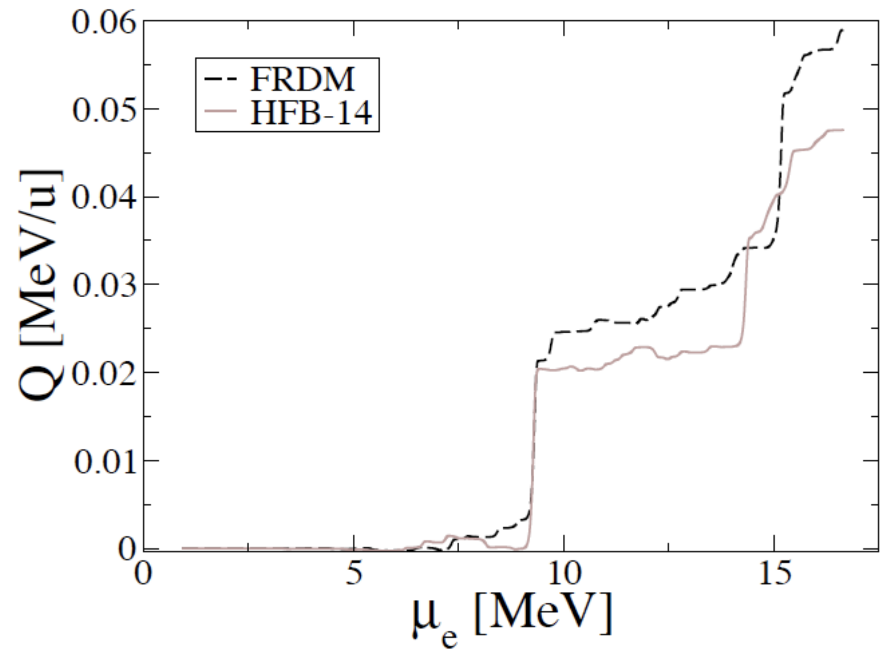
Different staggering of EC Q-value results in different behavior of electron captures along this isobaric chain.

Results for Carbon superburst ashes



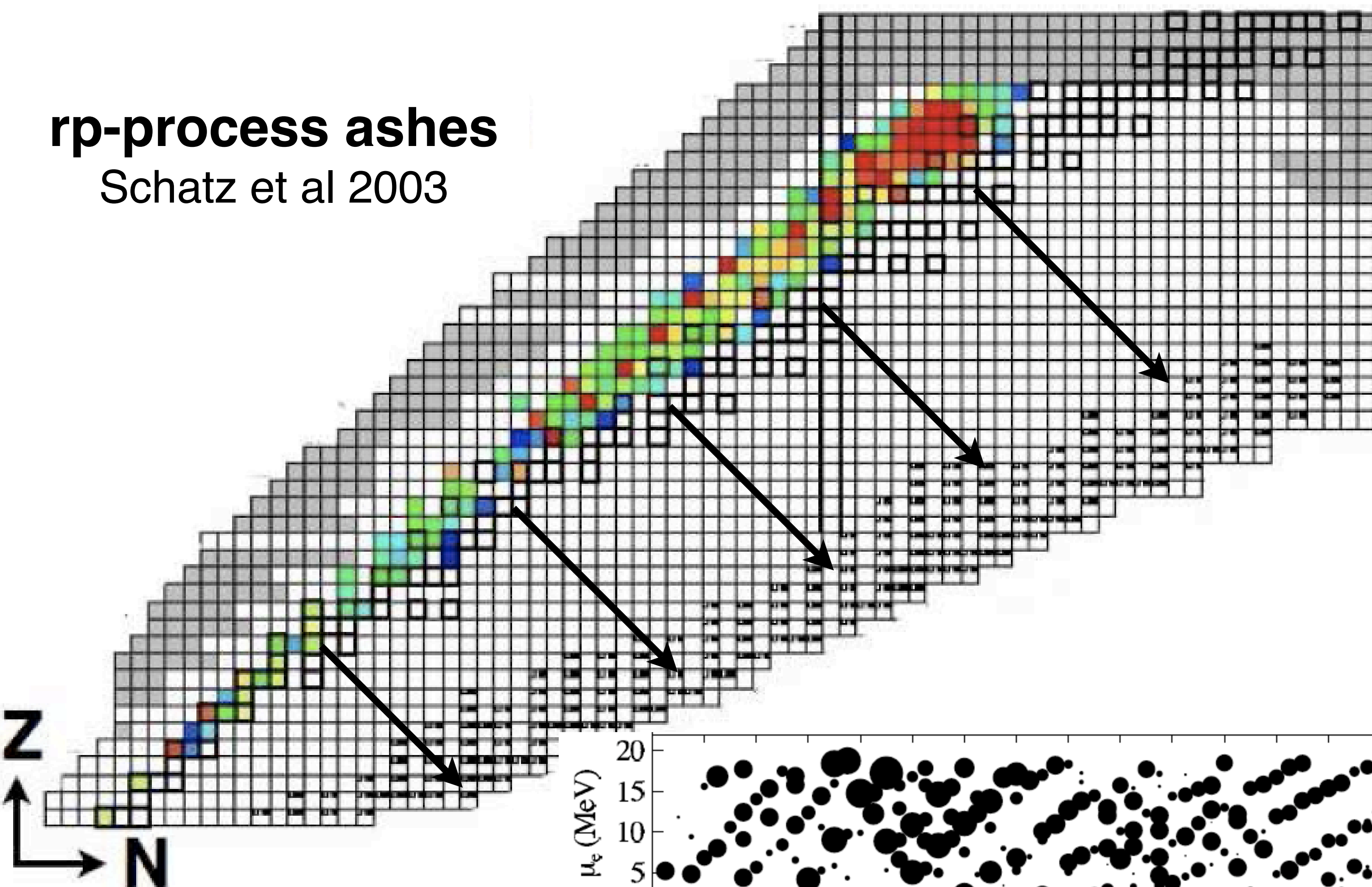
Carbn superburst ashes in 48<A<70 range

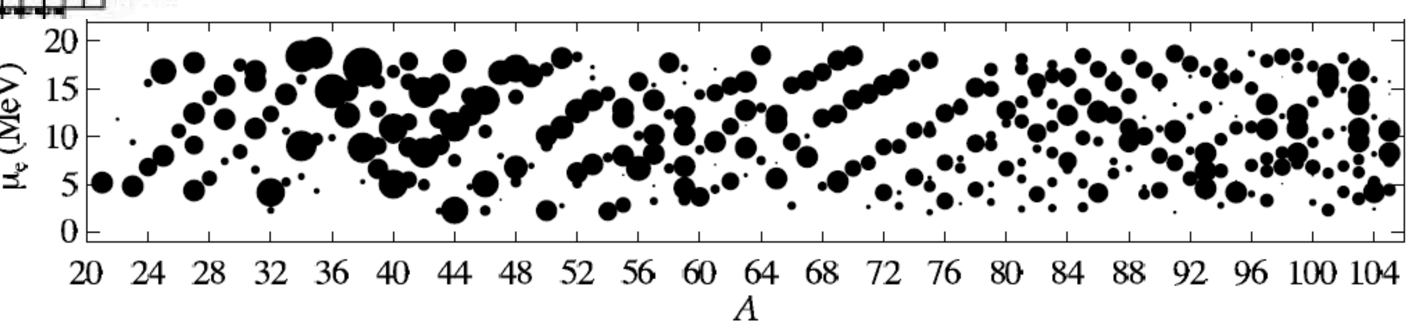
Heat deposition in outer crust



Nuclear masses relevant to nuclear processes in neutron star crusts

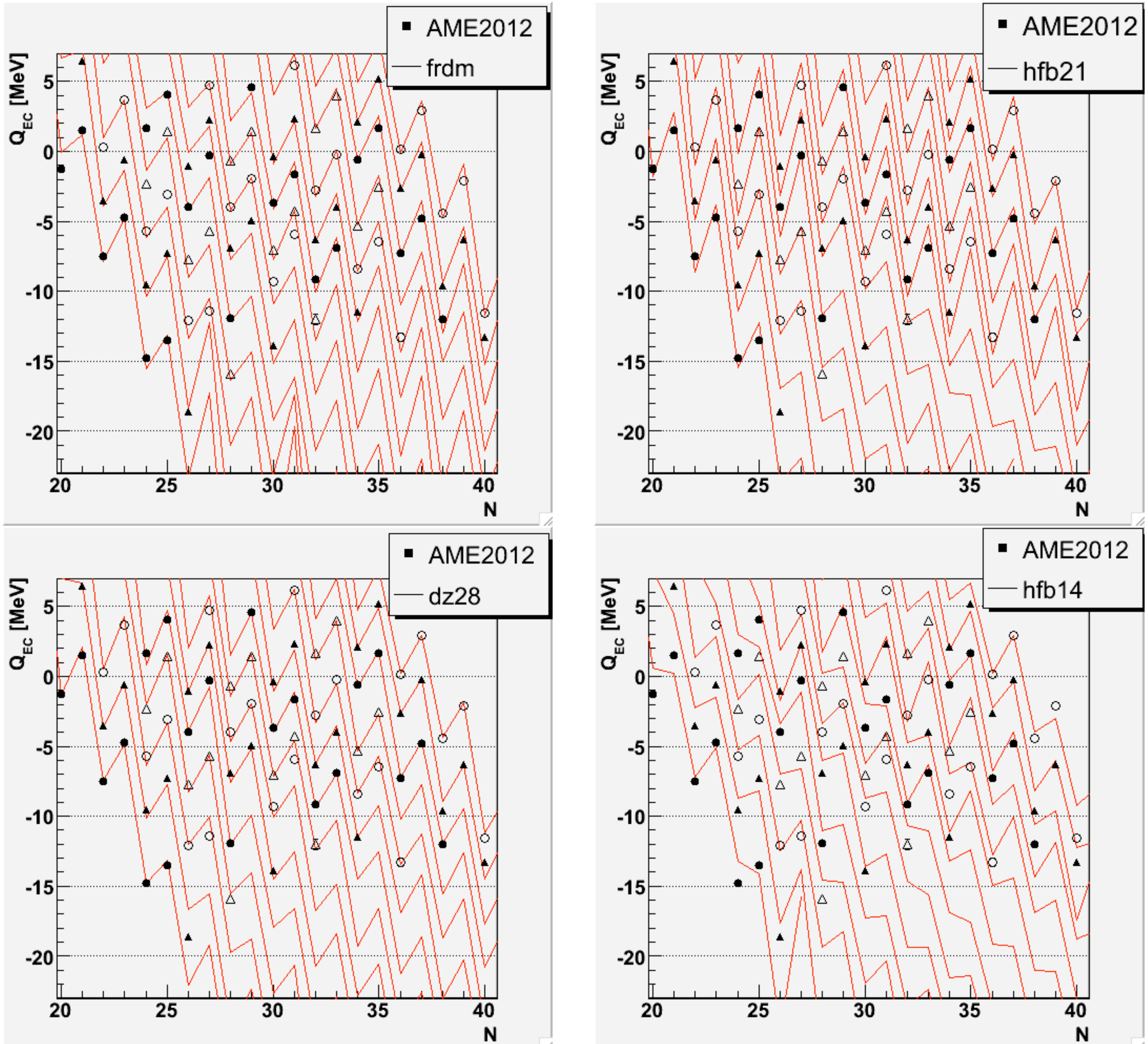
rp-process ashes
Schatz et al 2003



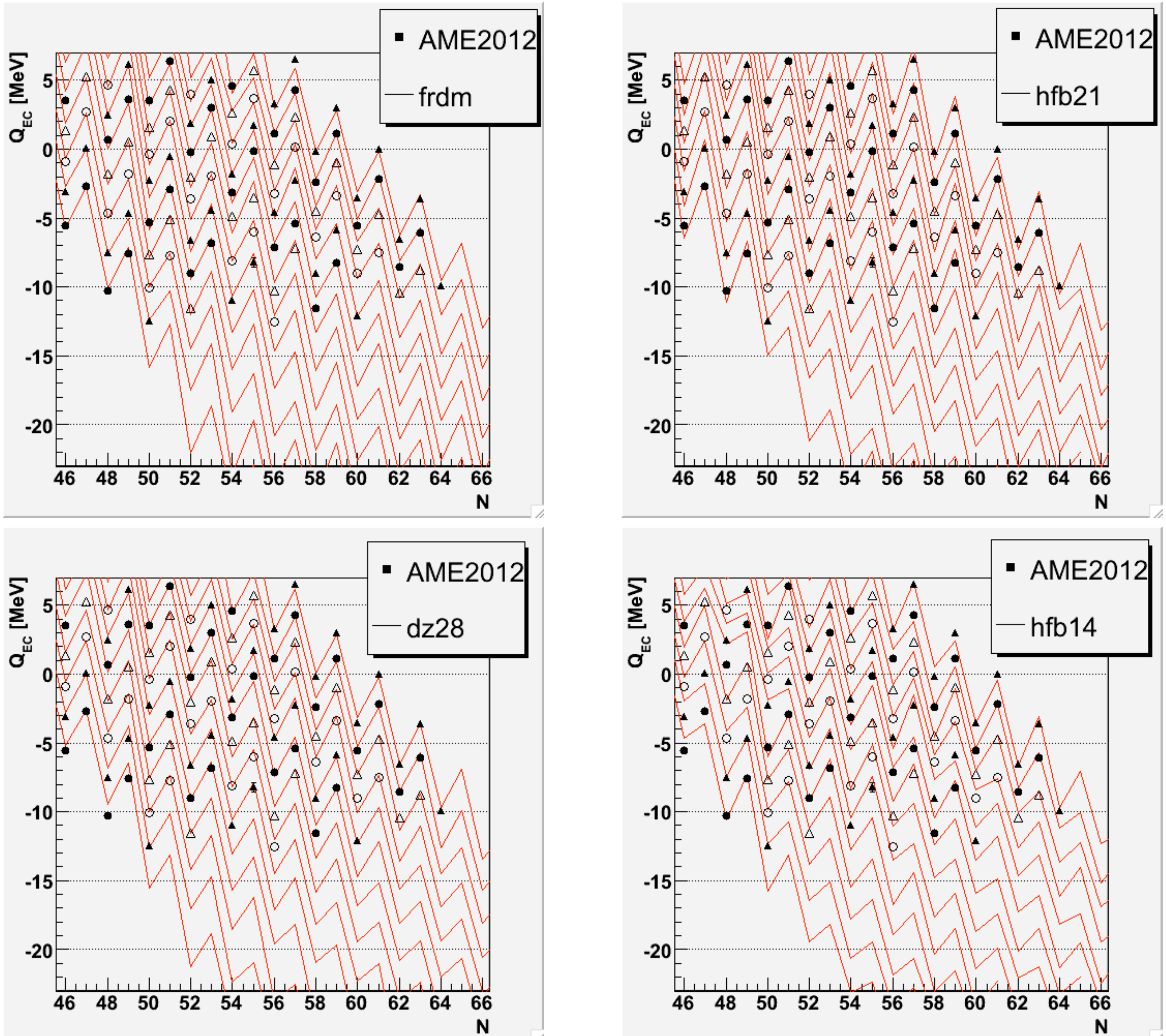


Gupta et al 2007

Models vs AME2012: Q_{EC} for C burst ashes

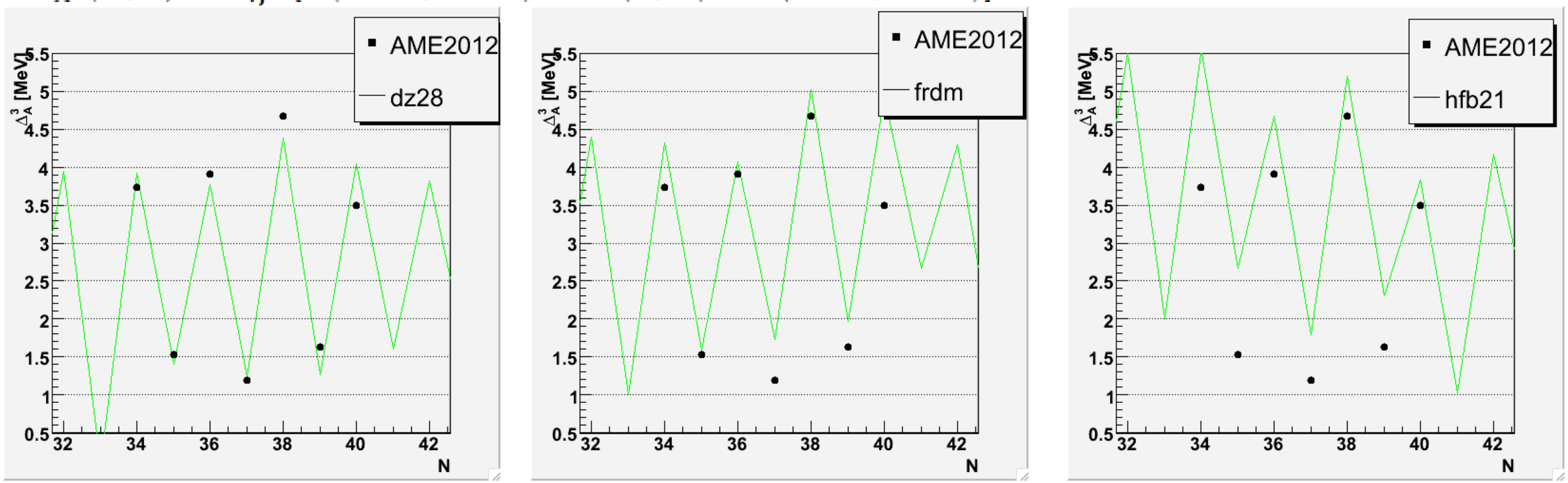


Models vs AME2012: Q_{EC} for rp-process ashes

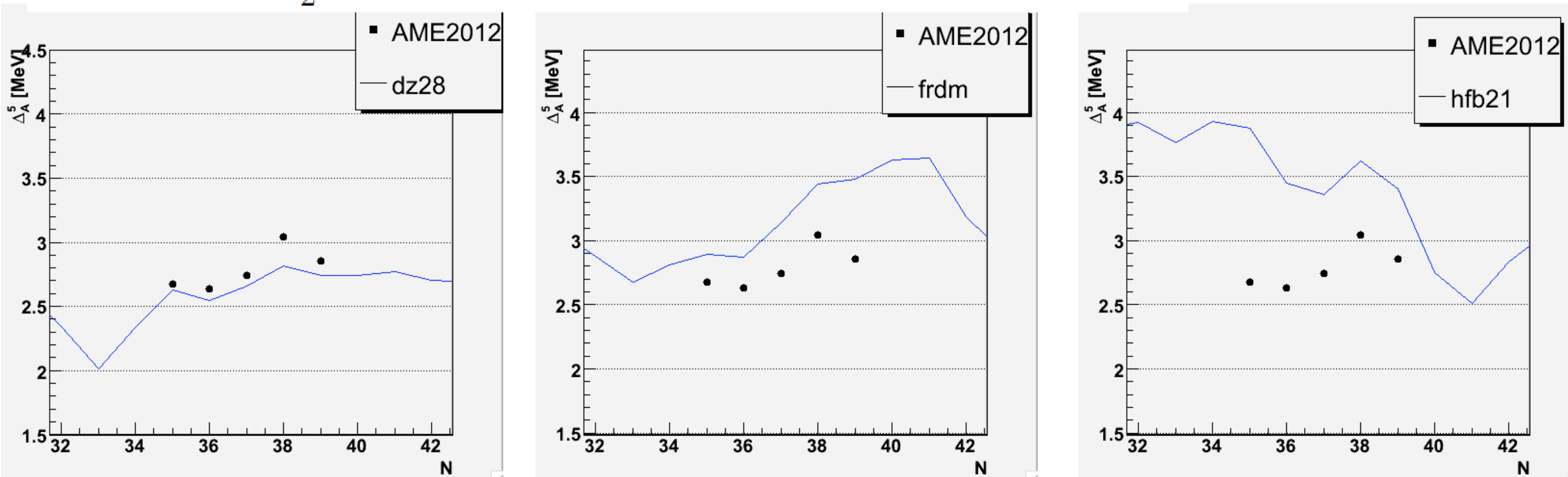


A=66 isobaric chain: 3- and 5-point mass differences

$$\Delta_A^{(3)}(N,Z) = \frac{-1^N}{2}[E(Z+1,N-1) - 2E(Z,N) + E(Z-1,N+1)]$$

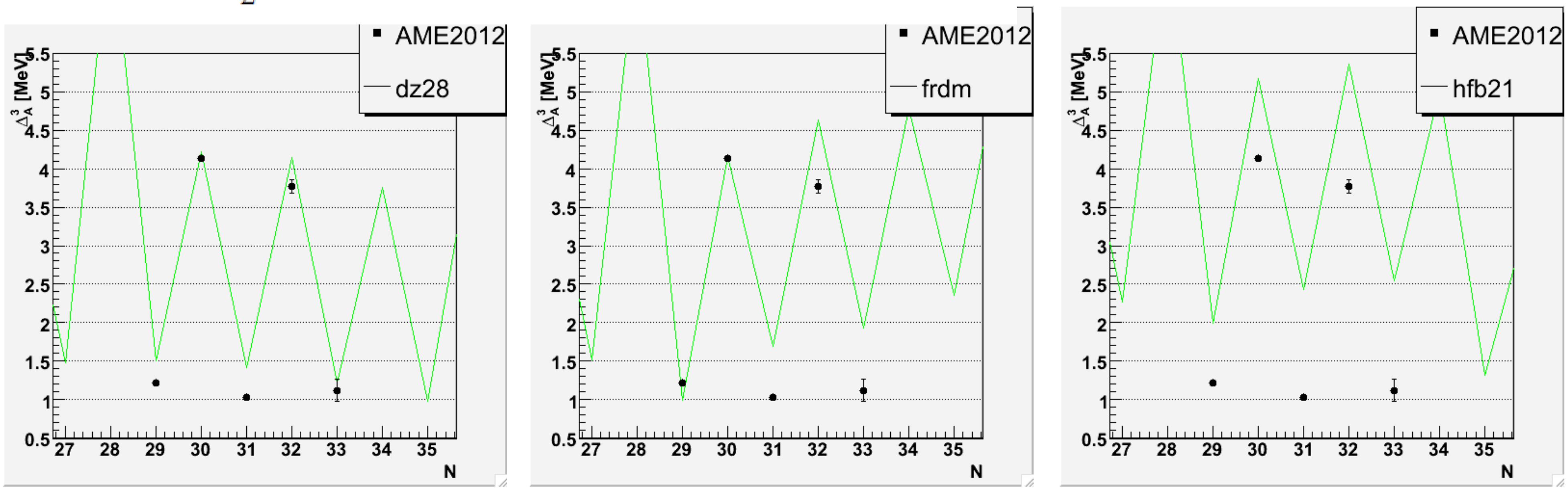


$$\Delta_A^{(5)}(N,Z) = -\frac{(-1)^N}{2}[E(Z+2) - 4E(Z+1) + 6E(Z) - 4E(Z-1) + E(Z-2)]$$

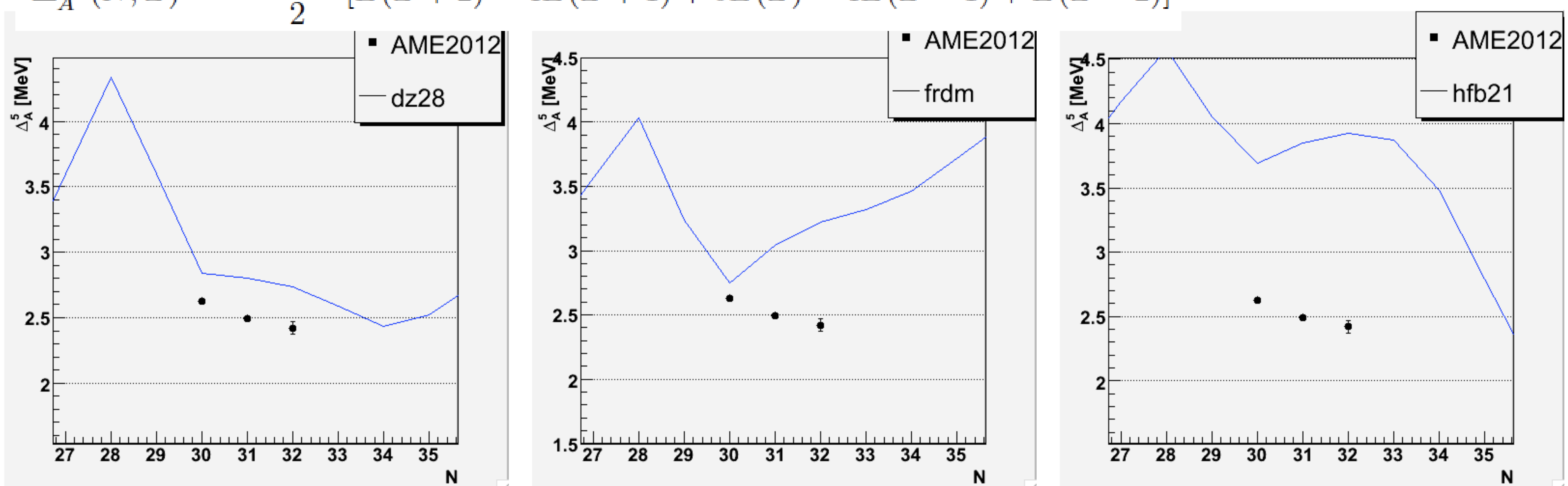


A=56 isobaric chain: 3- and 5-point mass differences

$$\Delta_A^{(3)}(N,Z) = \frac{-1^N}{2}[E(Z+1,N-1) - 2E(Z,N) + E(Z-1,N+1)]$$

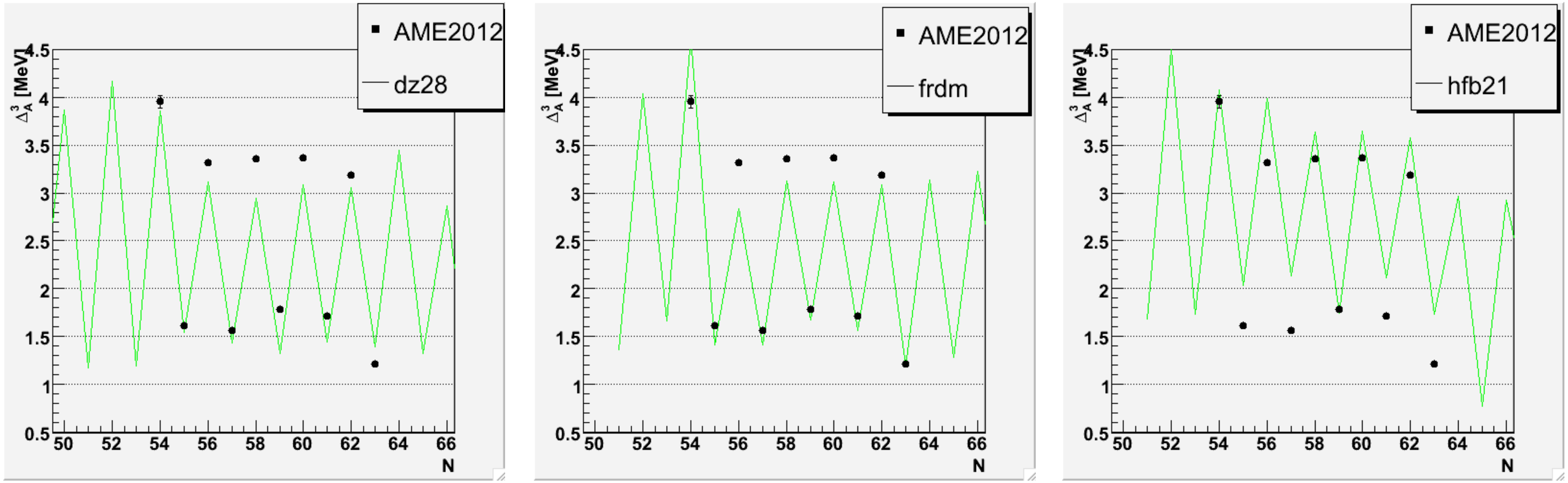


$$\Delta_A^{(5)}(N,Z) = -\frac{(-1)^N}{2}[E(Z+2) - 4E(Z+1) + 6E(Z) - 4E(Z-1) + E(Z-2)]$$

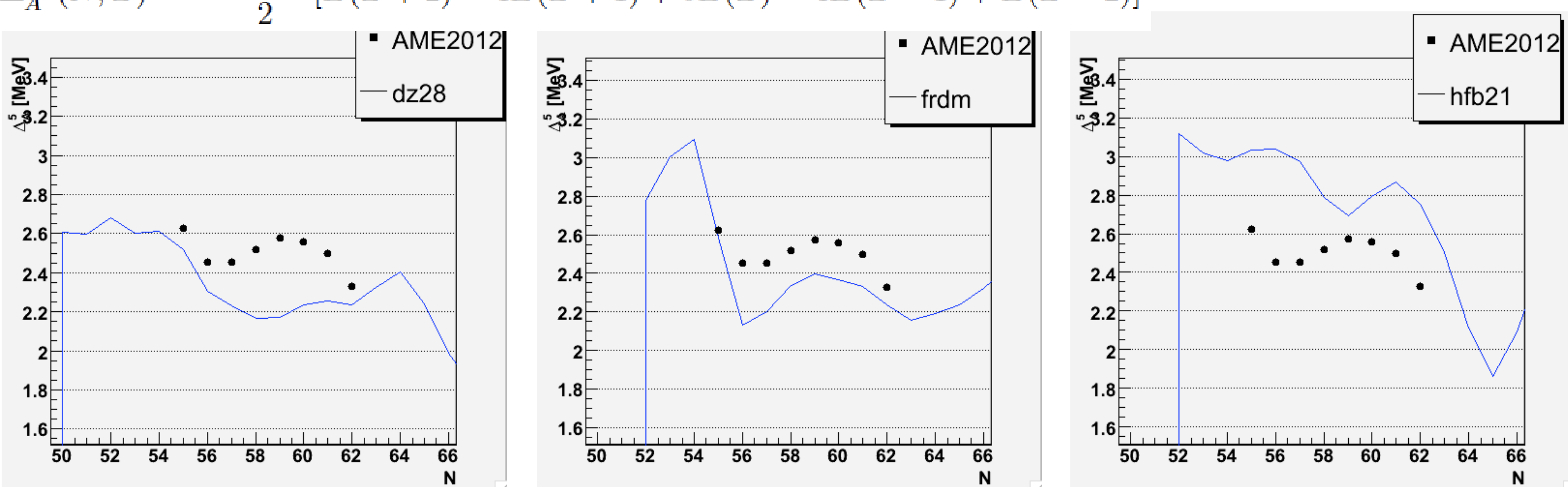


A=104 isobaric chain: 3- and 5-point mass differences

$$\Delta_A^{(3)}(N,Z) = \frac{-1^N}{2}[E(Z+1,N-1) - 2E(Z,N) + E(Z-1,N+1)]$$



$$\Delta_A^{(5)}(N,Z) = -\frac{(-1)^N}{2}[E(Z+2) - 4E(Z+1) + 6E(Z) - 4E(Z-1) + E(Z-2)]$$



RMS versus AME2012

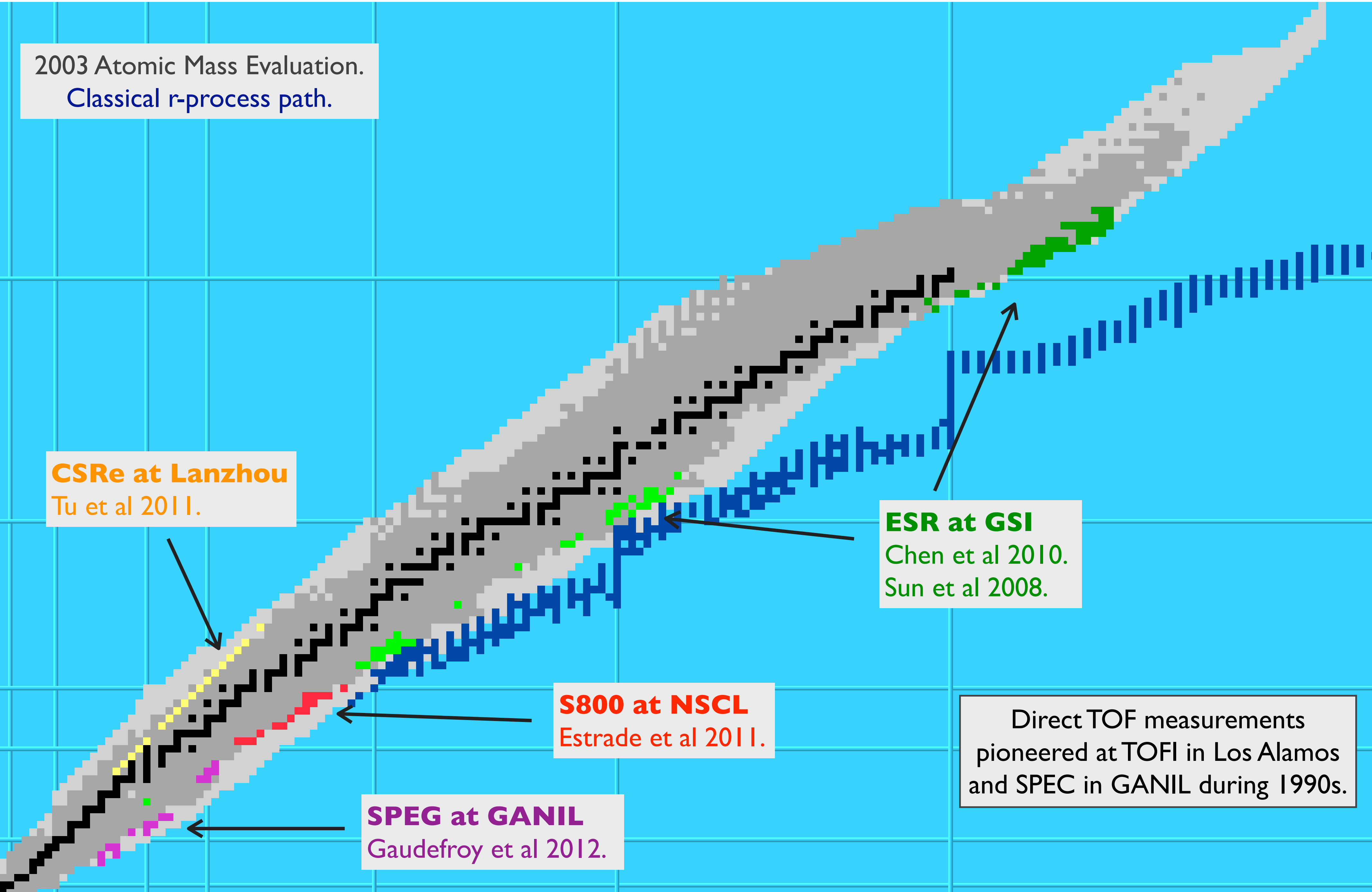
RMS(delta^3) [keV]

model	20<A<106	20<A(even)<106	40<A(even)<68
DuZu	369	360	331
FRDM	456	445	500
HFB21	541	538	609
HFB14	692	595	508

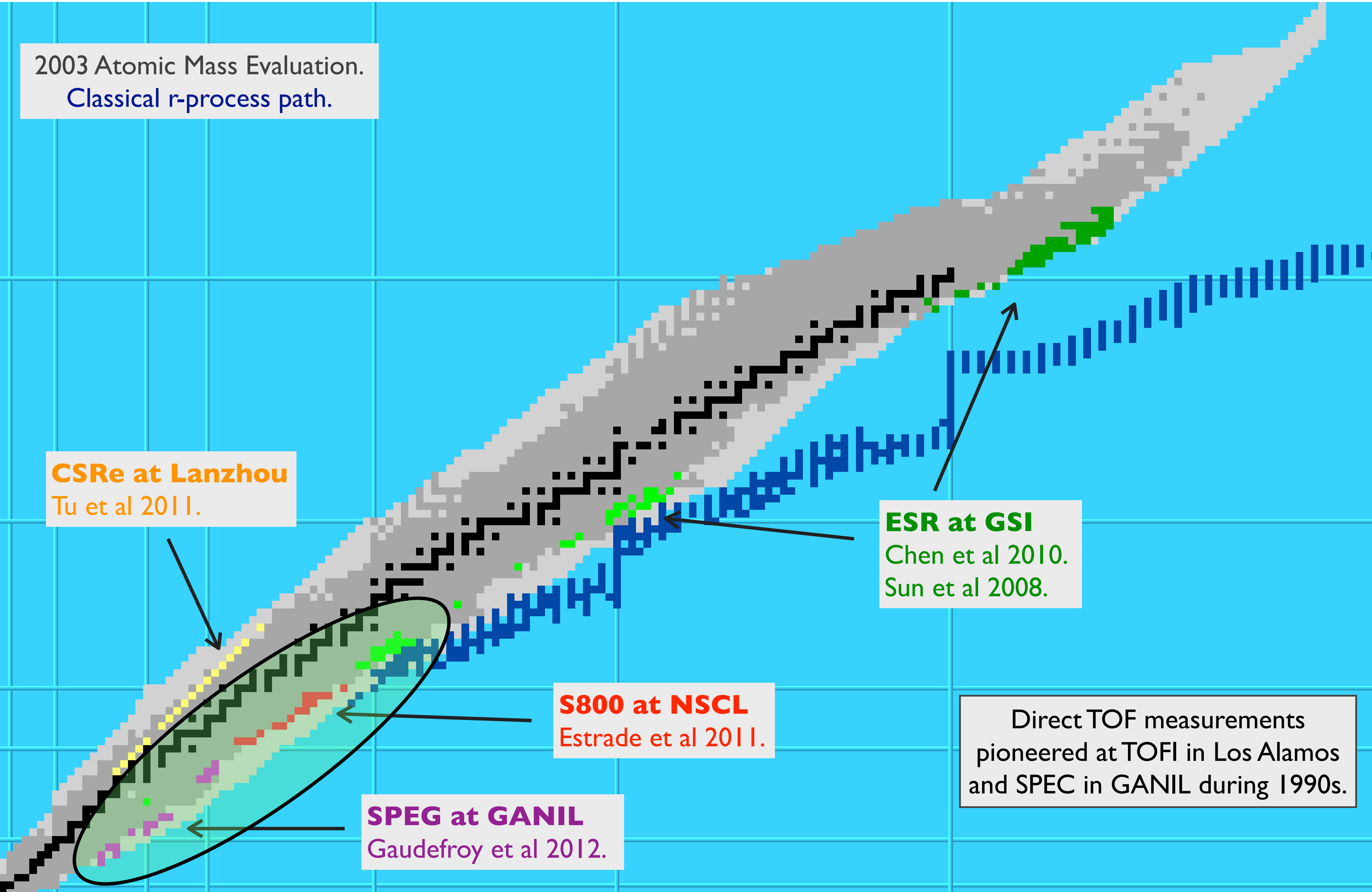
RMS(Qec) [keV]

model	20<A<106	20<A(even)<106	40<A(even)<68
DuZu	539	558	601
FRDM	748	780	942
HFB21	826	914	1104
HFB14	867	956	933

Recent TOF mass measurements

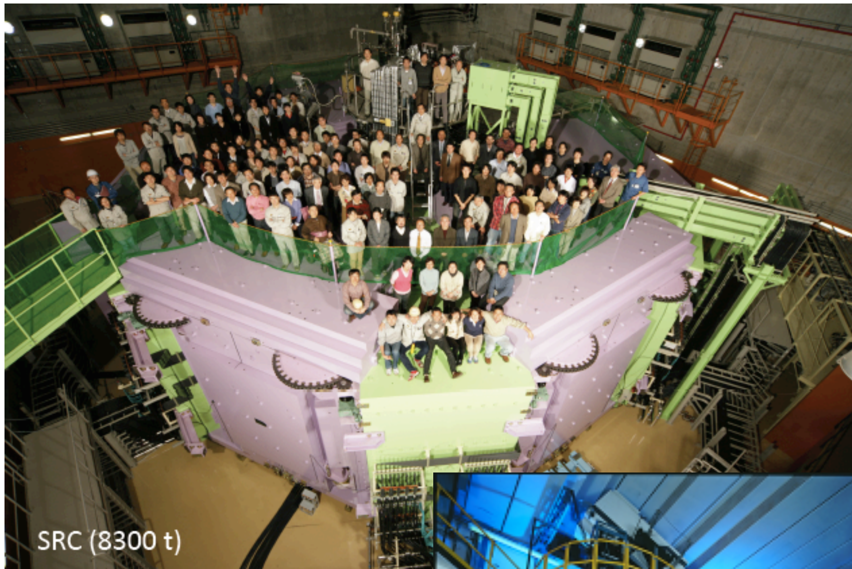


Recent TOF mass measurements



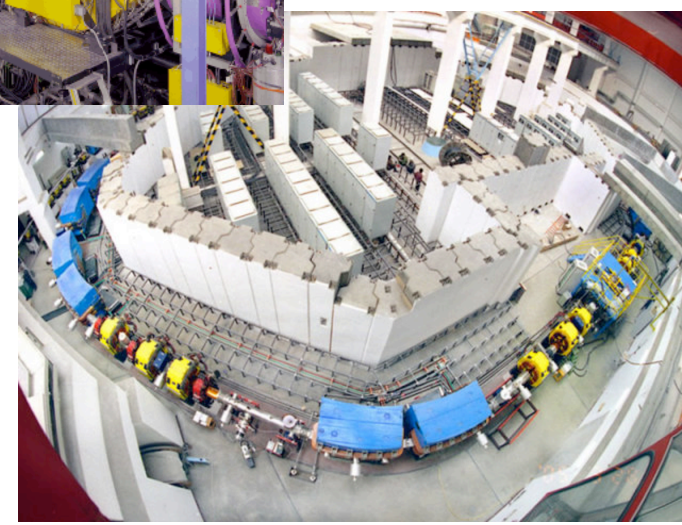
The future is bright for TOF experiments but...

RIBF at RIKEN

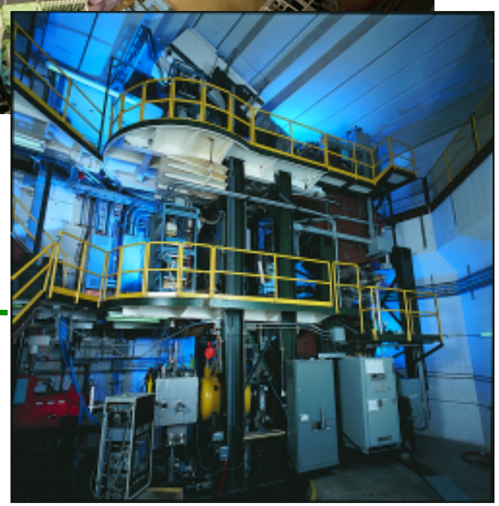


ESR at GSI (FAIR)

CSRe at IMP



S800 at NSCL (FRIB)



... do we measure relevant along isobaric chains (large abundance/highly excited transitions)**, or can we constrain models better?**

Collaborators

TOF experiment: Hendrik Schatz, Milan Matos, Sebastian George, Zach Meissel, Ana Becerril, Matt Amthor, Daniel Bazin, Thom Elliot, Alexandra Gade, Daniel Galaviz, Rita Lau, Giuseppe Lorusso, Jorge Pereira, Andrew Rogers, Andreas Stolz, John Yurkon (NSCL), Dan Shapira (ORNL), Mark Wallace (LANL), Ed Smith (OSU), Mike Famiano (WMU).

EC simulations: Hendrik Schatz, Ed Brown, Rita Lau (NSCL/MSU), Mary Beard, Michael Wiescher (Notre Dame), Sanjib Gupta, Peter Moller (LANL).