Nuclear Data for Astrophysics (Theory)

- Nuclear masses and ground state properties
- fission barriers
- weak rates (beta-decay, e-capture, neutrino-nucleus interactions)
- statistical model (Hauser-Feshbach) reaction cross sections
- shell model-based resonance cross sections
- direct capture

Audi Wapstra Mass Evaluations

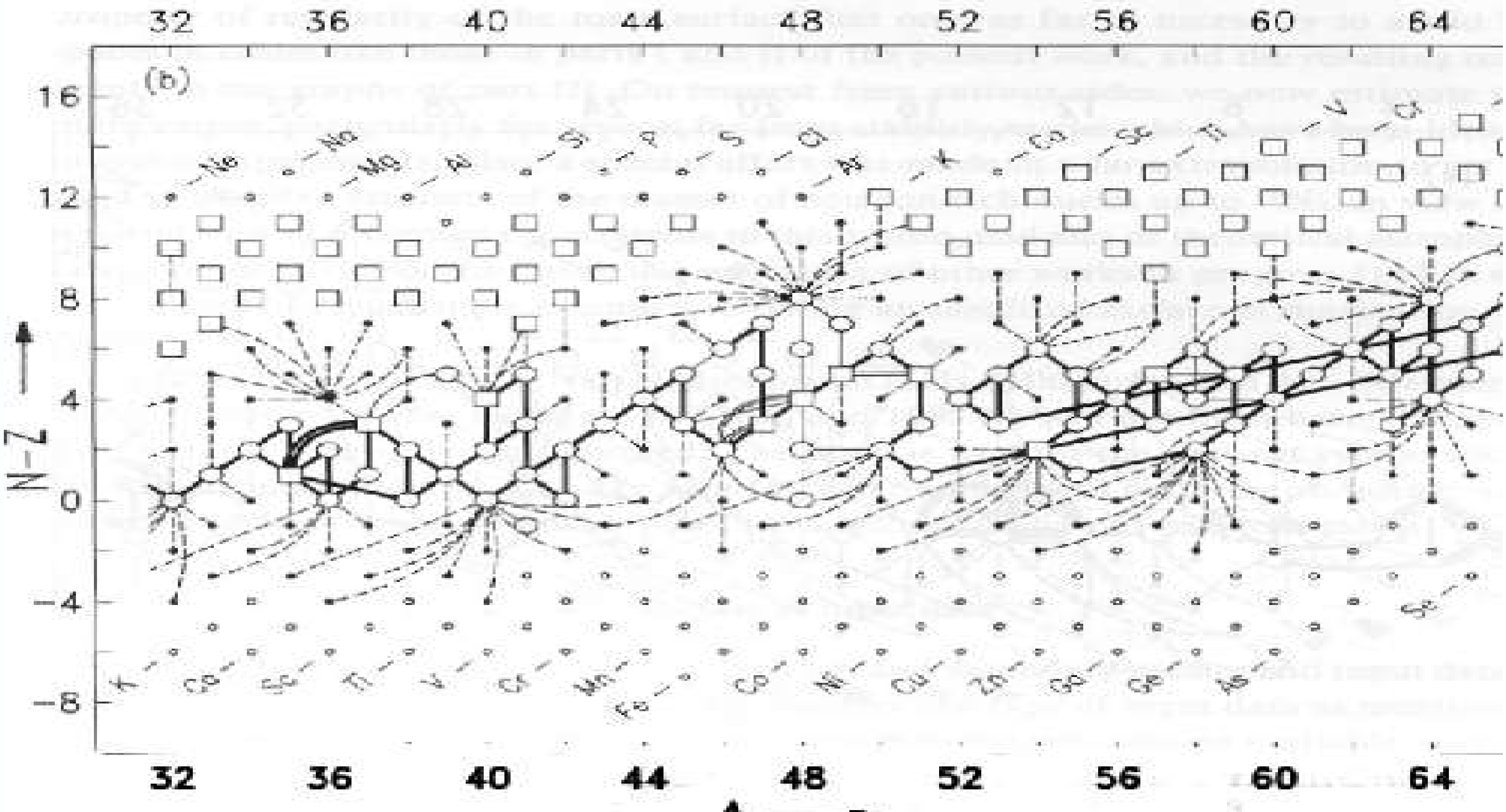


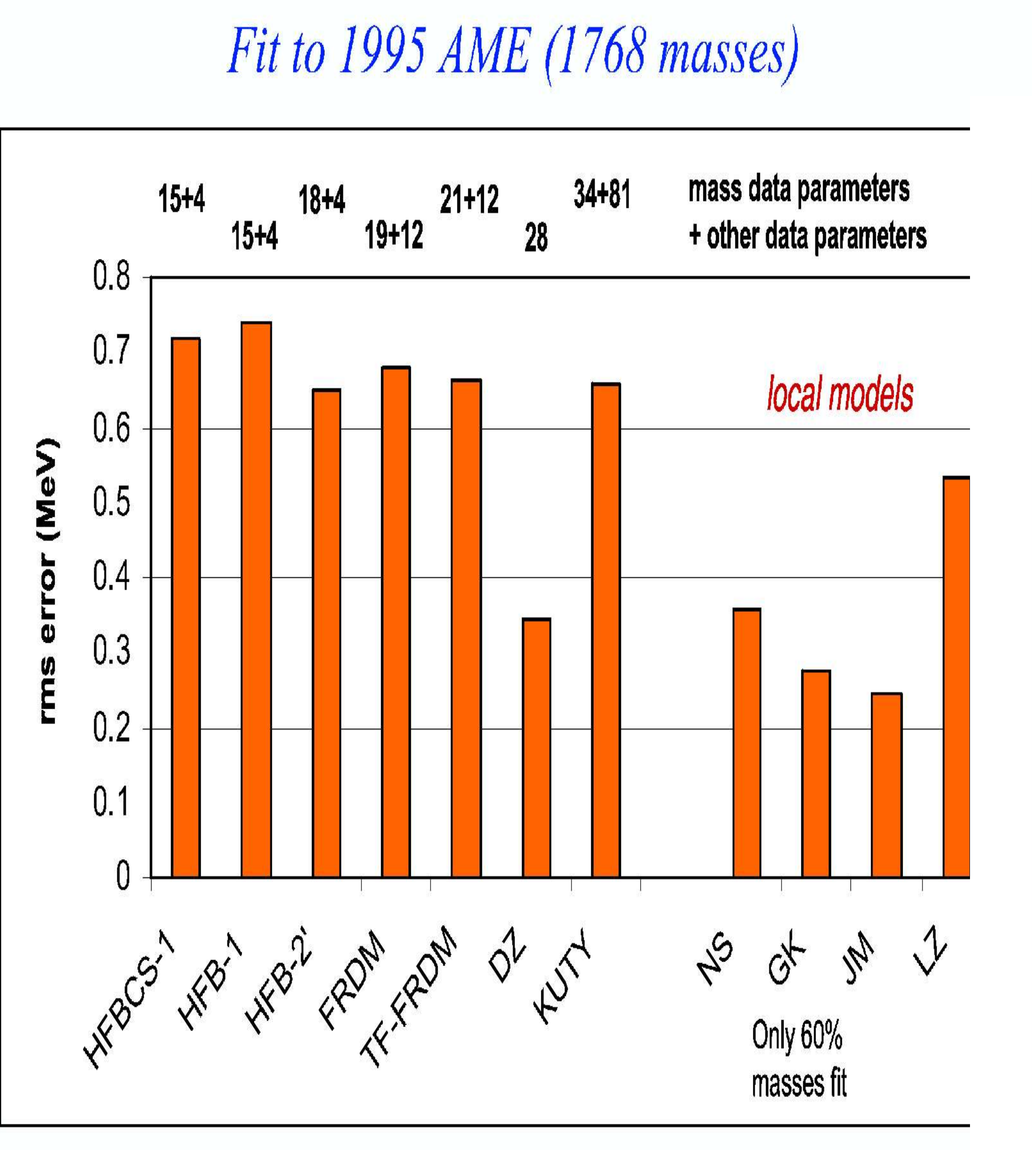
Fig. 1 — continued.

Mass Formulae and Models

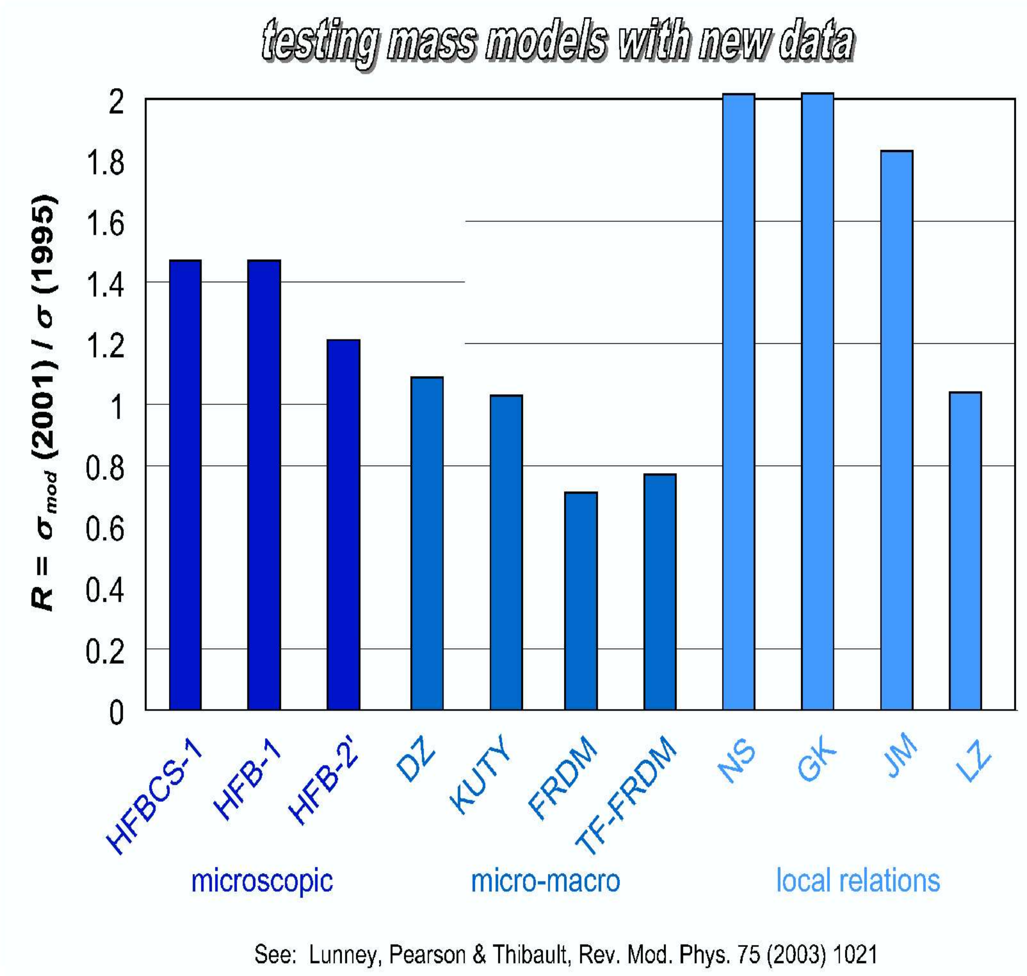
- Bethe-Weizsäcker liquid drop model
- (Strutinsky) shell corrections
- Pairing corrections (phe nomenological to BCS and Lipkin Nogami) FRDM, FRLDM *
- Thomas-Fermi TF-FRDM, ETFSI, ETFSI-Q *
- Hartree-Fock (BCS, Boguliubov) HFBBCS, HFBx (x=1-14) *
- (Relativistic) Mean Field Ring, Lalazissis ...
- Energy density functional theory Sly..., Nazarewicz, Dobaczewski, Bertsch .....
- local mass formulas (e.g. Garvey-Kelson $N_n N_p$)
- global approaches (e.g. Duflo-Zucker, KUTY)

micro-macro

Mass Models



Fit accuracy



Prediction Test

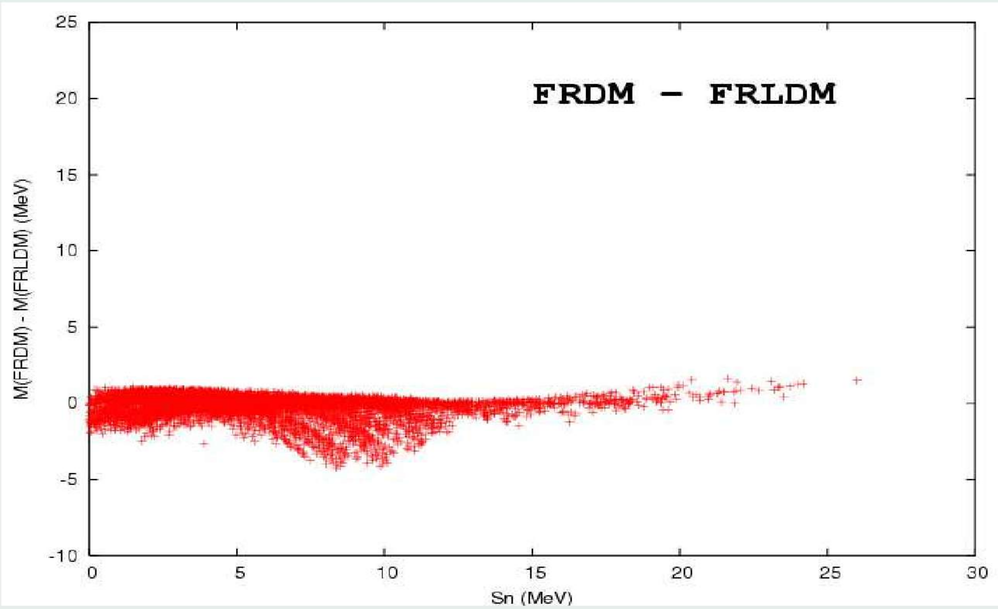
Present Model Prediction

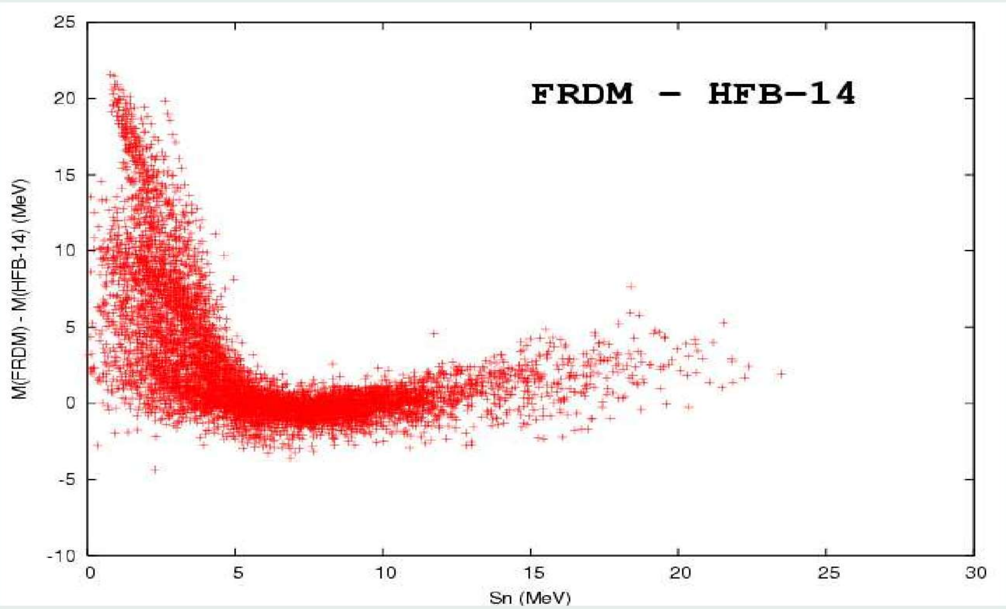
Rms and mean (expt. - model) deviations between data and predictions for various models. The first pair of lines refers to all the 2149 measured masses M of nuclei with Z and $N \geq 8$ given in the 2003 AME, the second pair to the masses M_{nr} of the subset of 185 neutron-rich nuclei with $S_n \leq 5.0$ MeV, and the third pair to the 782 measured charge radii given in the compilation of Angeli (2004). (DZ = Duflo and Zuker (1995).)

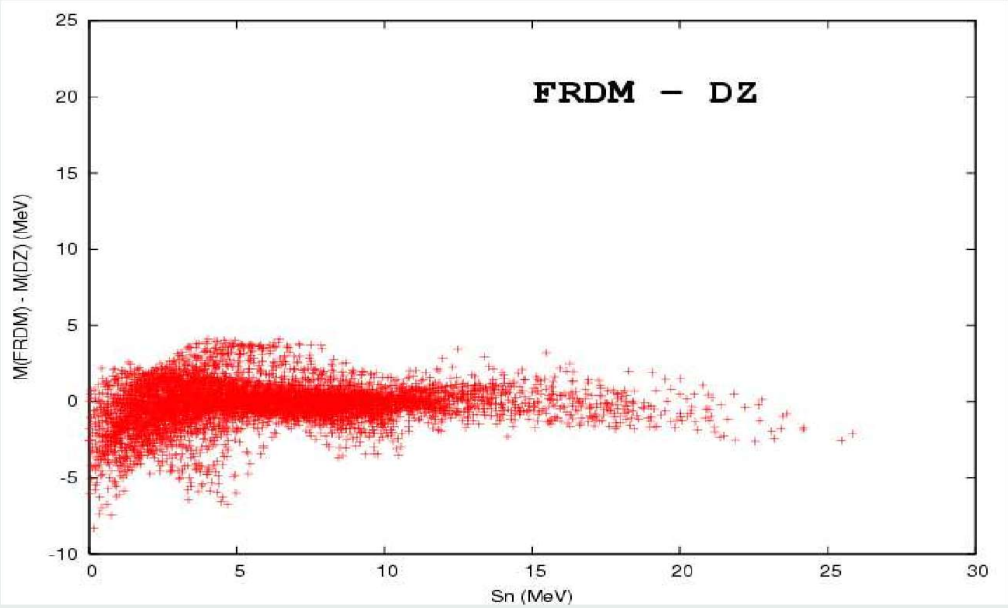
performed by M. Pearson

	FRDM	FRLDM	HFB-8	HFB-14	DZ
$\sigma(M)$ [MeV]	0.656	0.769	0.635	0.729	0.360
$\bar{\epsilon}(M)$ [MeV]	0.058	-0.403	0.009	-0.057	0.009
$\sigma(M_{nr})$ [MeV]	0.910	0.955	0.838	0.833	0.527
$\bar{\epsilon}(M_{nr})$ [MeV]	0.047	-0.078	-0.025	0.261	0.126
$\sigma(R_c)$ [fm]	0.0545	0.159	0.0275	0.0309	-
$\bar{\epsilon}(R_c)$ [fm]	-0.0366	-0.151	0.0025	-0.0117	-

Model Differences







from M. Pearson

Is there an accuracy limit?

Comparison to NUBASE (2001) // (2003)

FRDM (1992) σ_{rms} = 0.669 // **0.616** [MeV]

ETFSI-Q (1996) σ_{rms} = 0.818 // **0.729** [MeV]

with new deformation shapes/symmetries FRDM expects to improve by about 0.1 ✱

HFB-2 (2002) σ_{rms} = 0.674 [MeV]

HFB-3 (2003) σ_{rms} = 0.656 [MeV]

HFB-4 (2003) σ_{rms} = 0.680 [MeV]

HFB-8 (2004) σ_{rms} = 0.635 [MeV] ✱

HFB-9 (2005) σ_{rms} = **0.733** [MeV]

HFB-14 (2007) σ_{rms} = 0.729 [MeV]

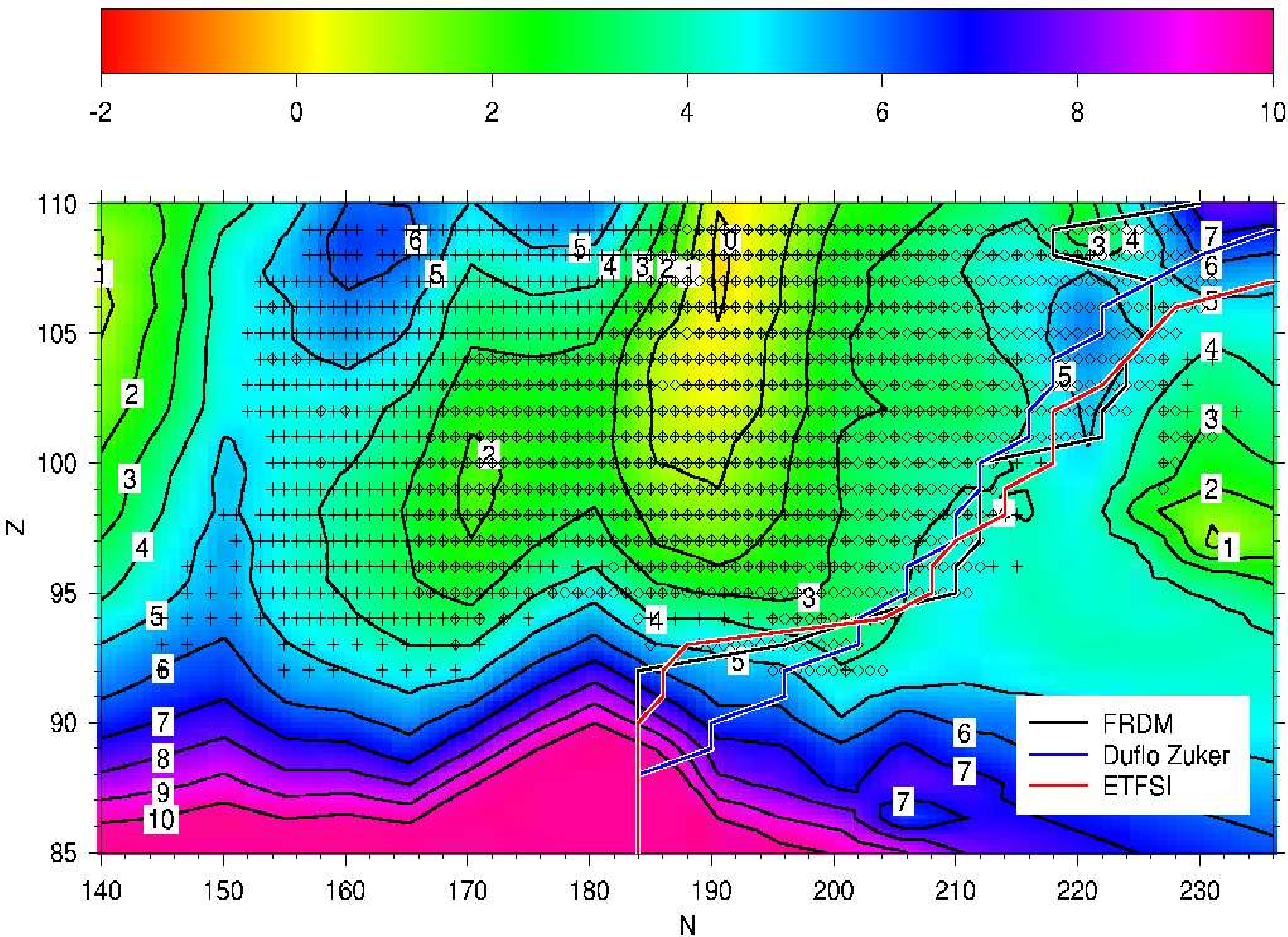
Ground state properties
Spin/parity, deformation

- J,pi only included in models with a Hamiltonian (i.e. models rather than mass formulae) spin/parity assignments correct within about 62% of cases in FRDM (not known from HFB)
- deformation problems in transition regions (set in a bit too late and too strong?)

Fission Barrier Height
(global predictions)

- Howard & Möller (1980) “extrapolations” often too low
- Mamdouh (ETFSI) often too high, correct minimum and path?
- Swiatecki, Myer (1998) (TF-FRDM)
- we clearly wait for a new release !!!!

Myers & Swiatecki Barriers

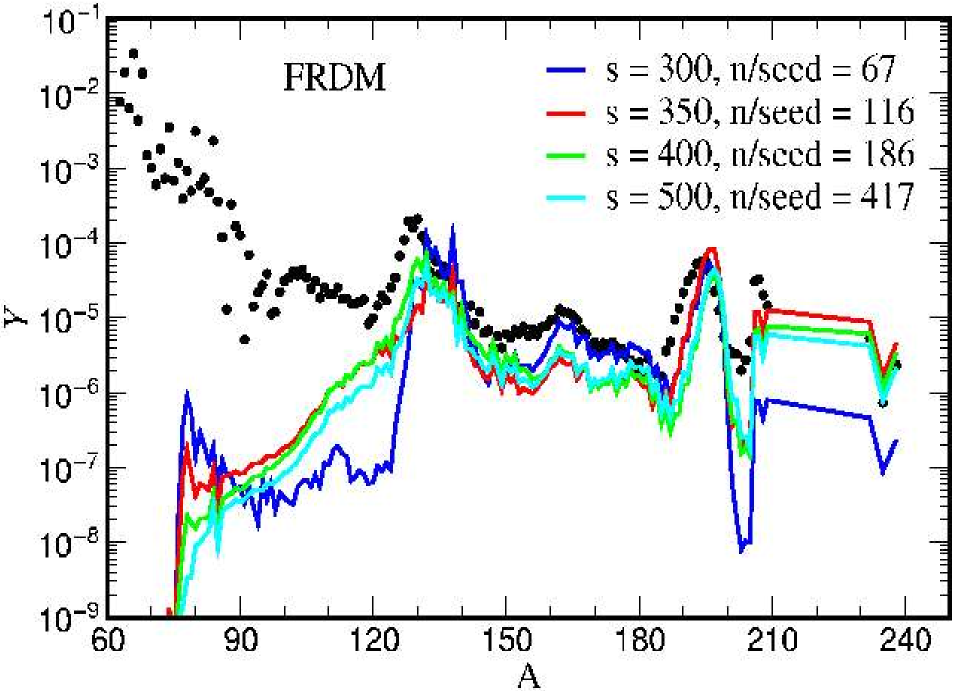


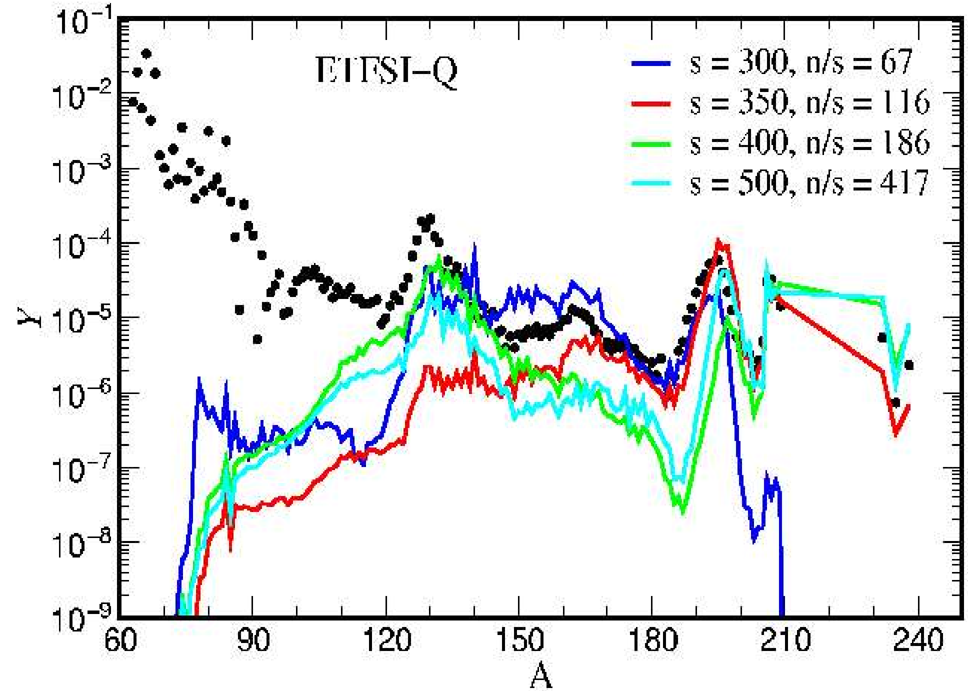
Martinez-Pinedo et al. (2007)

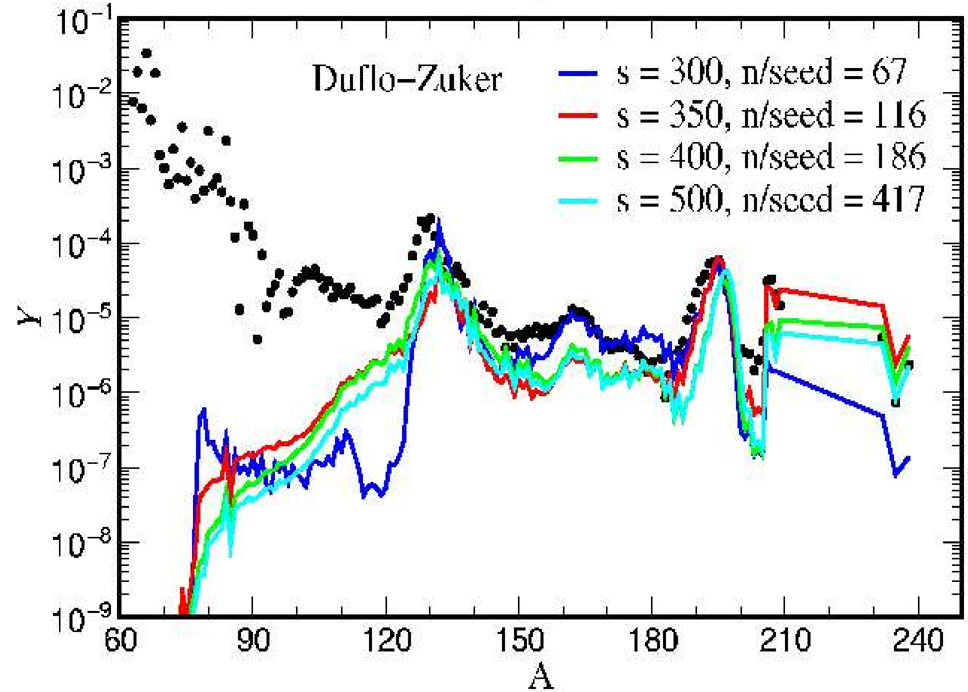
Fission Fragment Yields

- Many historical efforts based on experiment analysis (one spherical closed neutron shell nucleus plus plus a deformed "rest", e.g. Wahl)
- GSI approach (K.H. Schmidt, A. Kelic) based on mass model properties
- room for more.....

Full fission "cycling" for different mass models







Differences are due to different shell structure at $N = 82$

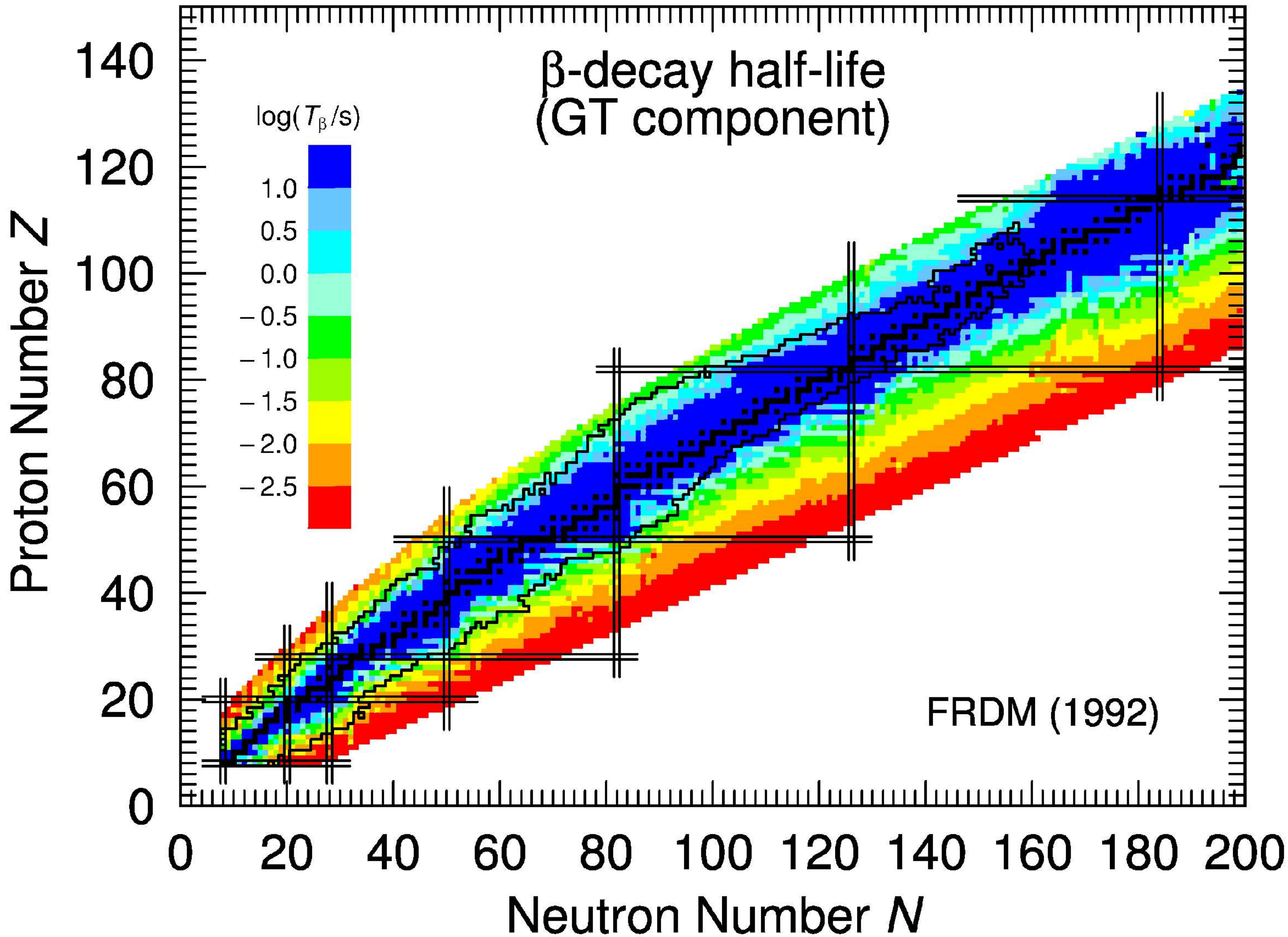
only one entropy component!

Martinez-Pinedo, Mocelj et al. (2007)

Beta-Decay Properties

- "Gross" Theory (Takahashi and others)
- Tamm-Damkoff-Approach (Klapdor and others)
- (Q)RPA (Möller and collaborators, K.-L. Kratz)
- Mean Field (Borzov et al., still spherical approach) ?
- shell model (up to pf-shell and for selected heavier mass regions nearby to shell closures Strasbourg-Madrid and MSU)
- ....?

Gamow-Teller Strength



P. Möller, J. R. Nix, and K.-L. Kratz/Nuclear Properties

β-Decay properties K.-L. Kratz

$T_{1/2}$, P_n → gross **β-strength** properties from theoretical models, e.g. QRPA in comparison with experiments.

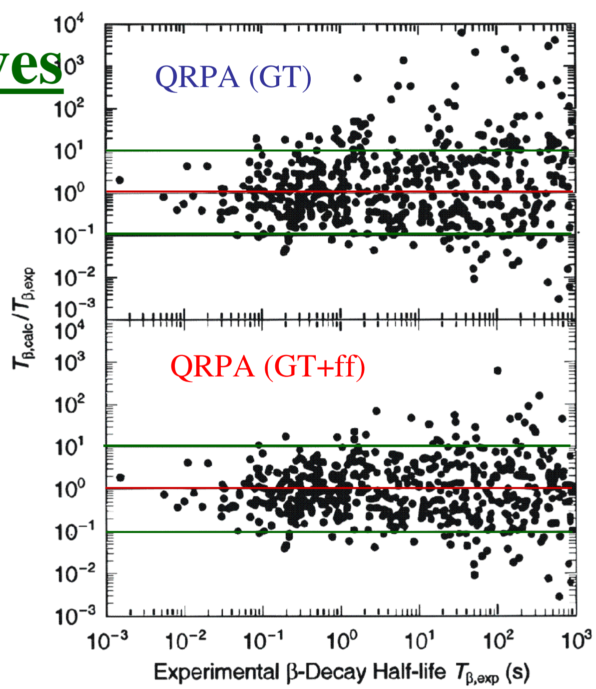
Requests: (I) prediction / reproduction of correct experimental "**number**"

(II) full nuclear-structure understanding

full spectroscopy of "key" isotopes, like $^{80}Zn_{50}$, $^{130}Cd_{82}$.

Half-lives

Total Error = 3.73

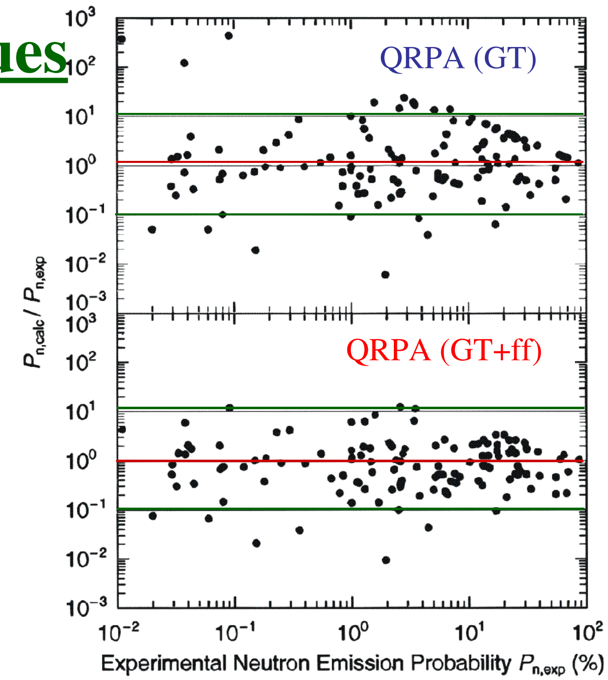


Total Error = 3.08

(P. Möller et al., PR **C67**, 055802 (2003))

P_n-Values

Total Error = 5.54



Total Error = 3.52

Weak Rates, Electron captures

- Hansen & Mazurek (70s)
- Fuller, Fowler, Newman (1980-1985), shell model based in sd-shell, phenomenological above
- Itoh et al. (late 80s), extensions in sd-shell
- Langanke, Martinez-Pinedo (shell model up to pf-shell)
- Pruet et al. (200x), extension of FFN to A=110
- Gupta & Möller (2007), QRPA and FRDM

Neutronization via electron capture

(high Fermi energies at central densities)

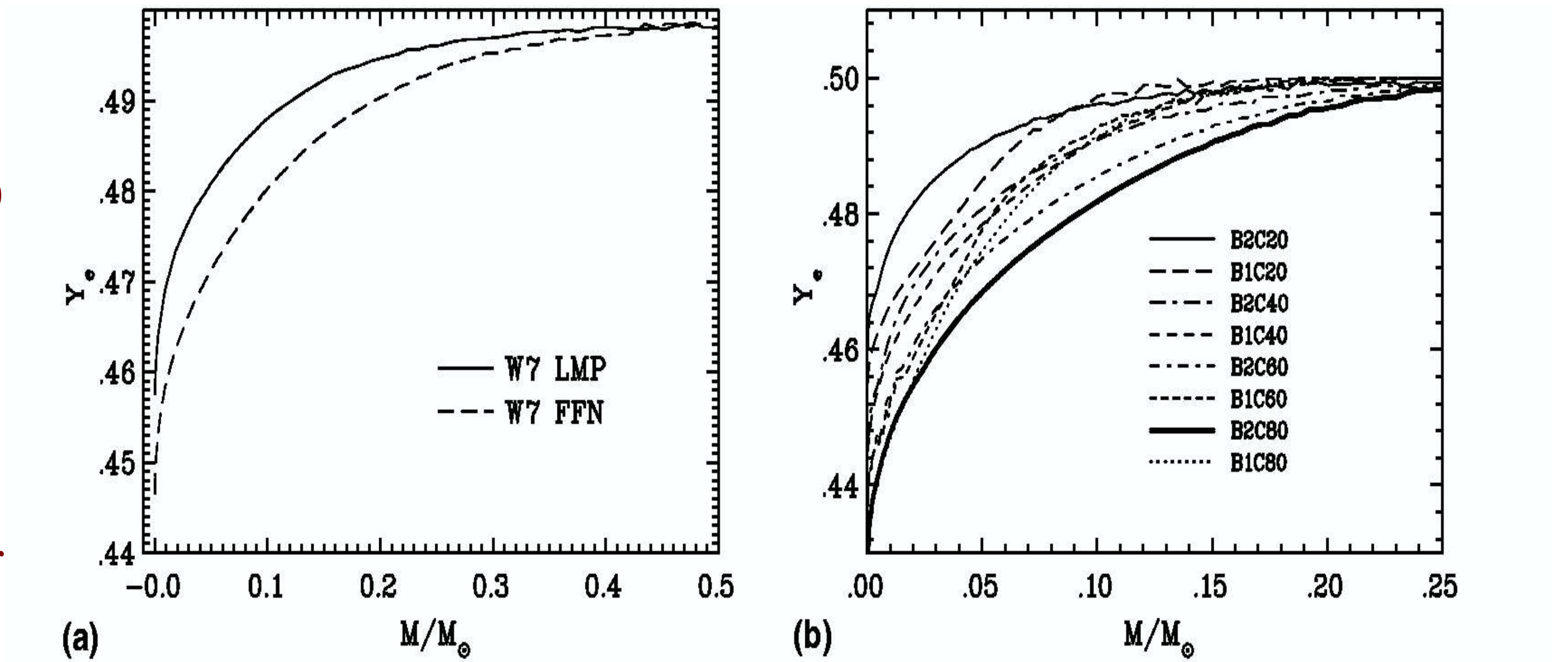
dominant NSE-abundance

^{56}Ni

^{54}Fe (^{58}Ni)

^{56}Fe

^{50}Ti, ^{54}Cr



(a) Test for influence of new shell model electron capture rates (LMP)

(b) Test for burning front propagation speed

Neutrino-Nucleus Interactions

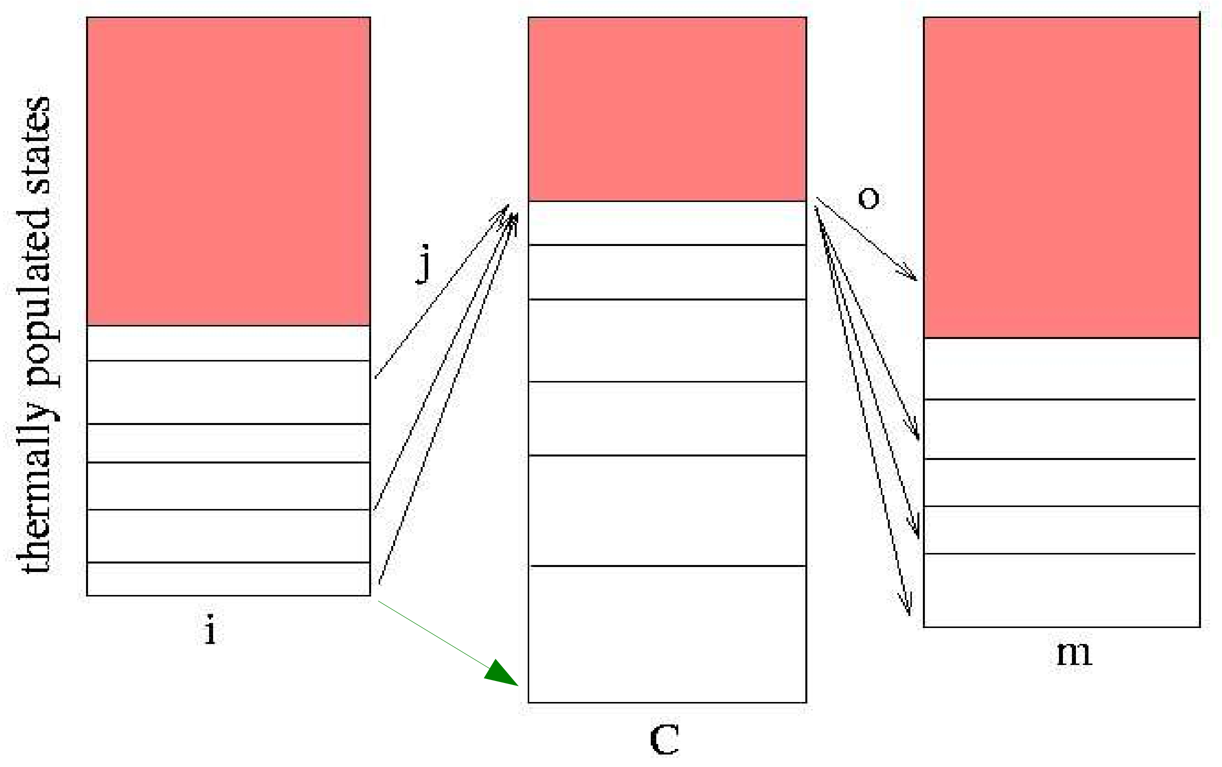
- Bruenn & Haxton (1991) *
- Reddy, Burrows, Saywer (in medium)
- inelastic (neutral current) neutrino scattering and charged current neutrino captures (CRPA, Kolbe, Langanke et al.) *
- McLaughlin, Fuller, Surman (use where not otherwise availble)
- Zinner, Sampaio, Langanke, Martinez-Pinedo (shell model and CRPA with correlations) *
- neutrino-induced fission (Zinner, Kolbe et al.) *

Theoretical Cross Sections

- direct capture

see Descouvemont & Rauscher (2006)

- individual resonance contributions -> Breit-Wigner
- high resonance densitiy -> statistical model, Hauser-Feshbach



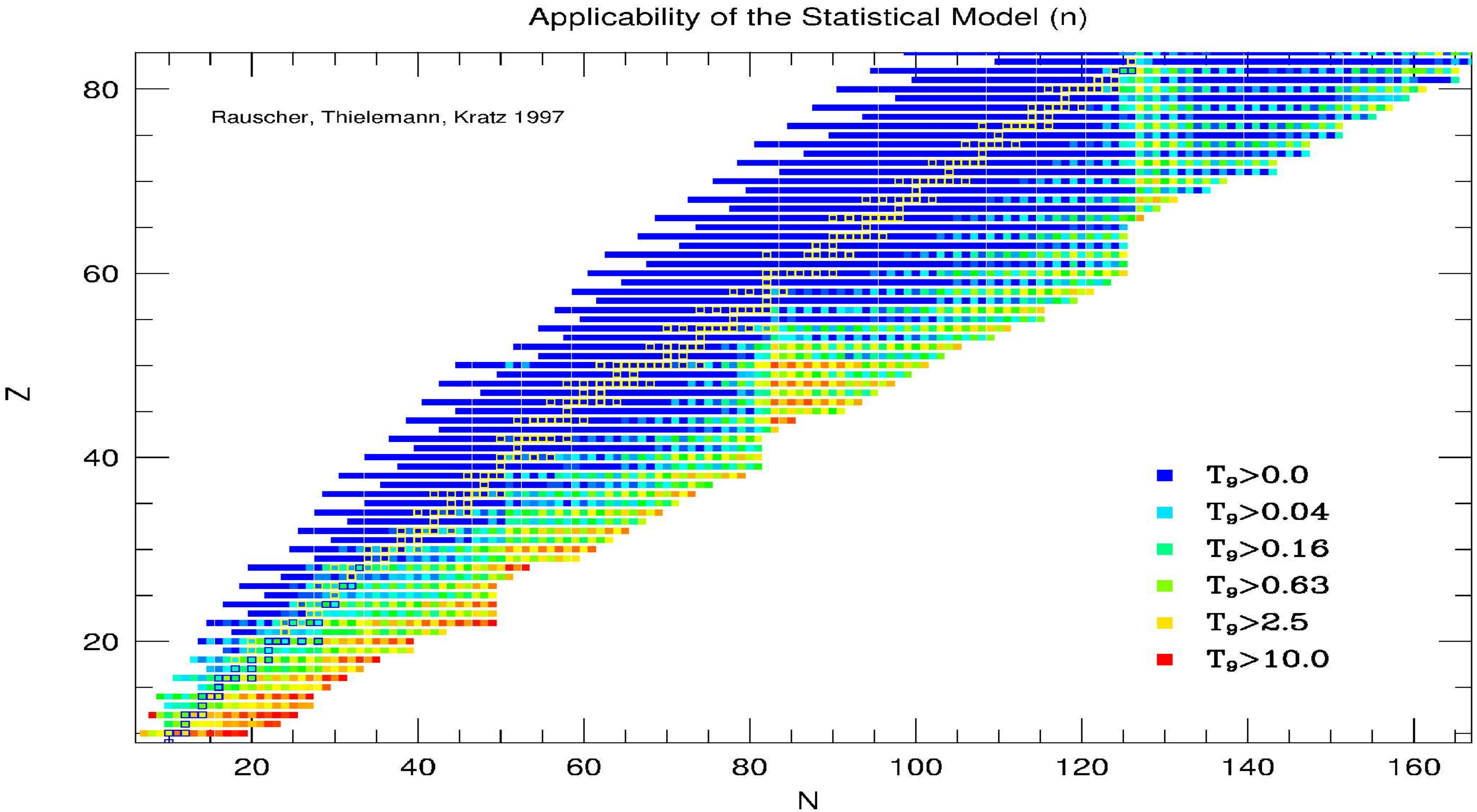
Individual Resonances

- experimental cross sections based on measured resonances
- theoretical cross sections based on resonance predictions
  - resonating group method for light nuclei
  - Fisker et al. (2003) shell model resonances for the rp-process
  - in preparation C, N, O – Ne isotopes up to ^{20}C and ^{24}O for n-capture on neutron-rich nuclei

Temperatures which permit SM cross sections

$$\sigma_i(j,o) = \frac{\pi}{k_j^2} \frac{(1+\delta_{ij})}{(2I_i+1)(2I_j+1)} \sum_{J,\pi} (2J+1) \frac{T_j(E,J,\pi)T_o(E,J,\pi)}{T_{tot}(E,J,\pi)}$$

assumption: there exists a resonance for all spins and parities at all energies



Statistical Model Ingredients

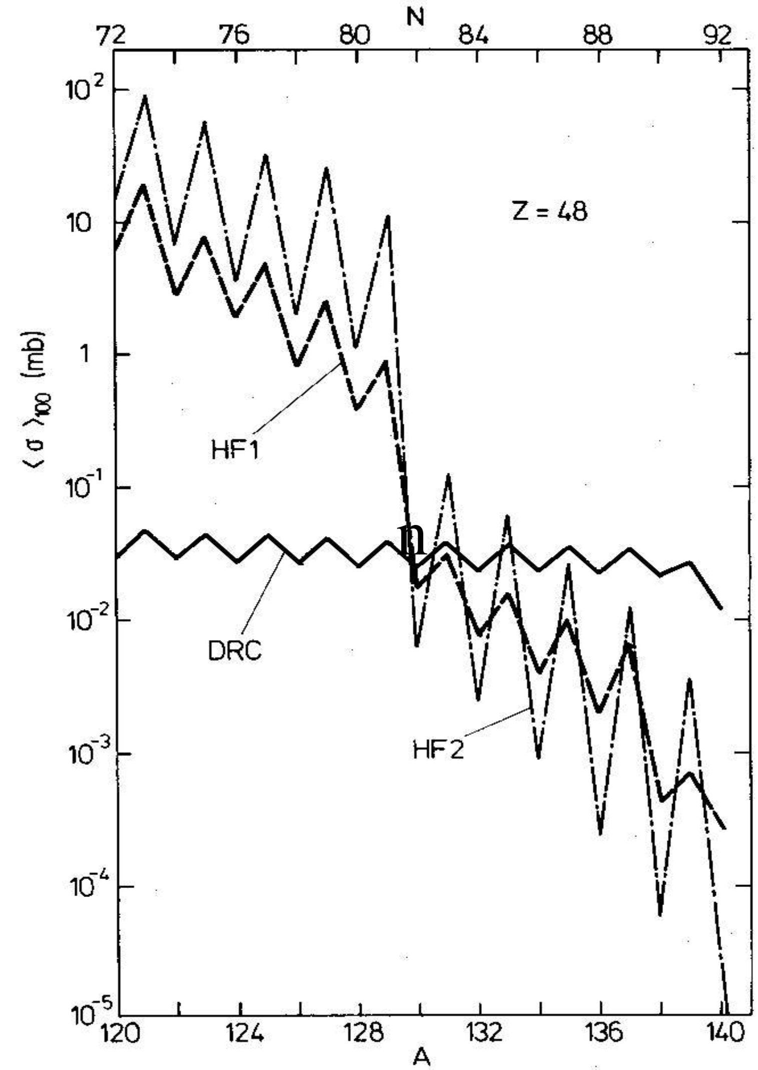
- Optical potentials to predict transmission coefficients (phenomenological potentials from 60s, Jeukenne, Lejeune, Mahaux 1977, new versions of JLMB, problems with alpha-optical potential)
- Gamma transmission coefficients from giant resonances (pygmi resonances)
- level densities (including spin and parity dependence and partition functions)
- masses and ground state spins and parities!

Existing Stat. Model Codes for astrophysical rates

- historical: Truran, Cameron, Michaud
- Woosley, Fowler, Holmes, Zimmermann (1979, ESW, BSFG)
- SMOKER (Thielemann, Arnould, Truran 1985, JLM, improved BSFG, GDR-DM)
- NON-SMOKER (Rauscher, Thielemann 2000-, mostly new level density treatment with Ignatuk approach; Mocelj et al 2007, parity-dependent level density treatment in exit channels) www.nucatro.org
- MOST (Goriely et al., microscopic combinatorial level densities, microscopic gamma-widths, JLMB potentials) bruslib
- MOD-SMOKER (Loens et al., parity-dependent level density weights also in entrance channel) (still exploration status)
- "commercial/open access" codes (TALYS, the question is the physics input)

Direct Capture

- early treatments in experimental papers
- simple test in comparison to stat. model (Mathews, Mengoni, Thielemann, Fowler 1983)
- extended work by Rauscher et al. since 80s
- recent work by Goriely et al.
- needed!!! in many light nuclei, in some (close to shell closures) heavier nuclei, in the r-process far from stability



Cd-chain from Mathews, Mengoni, Thielemann, Fowler (1983)