Did Nature produce superheavy elements?

a general review, combined with recent results from collaborations with I. Petermann, G. Martinez-Pinedo, K. Langanke (GSI) and I. Panov, I. Korneev (ITEP)

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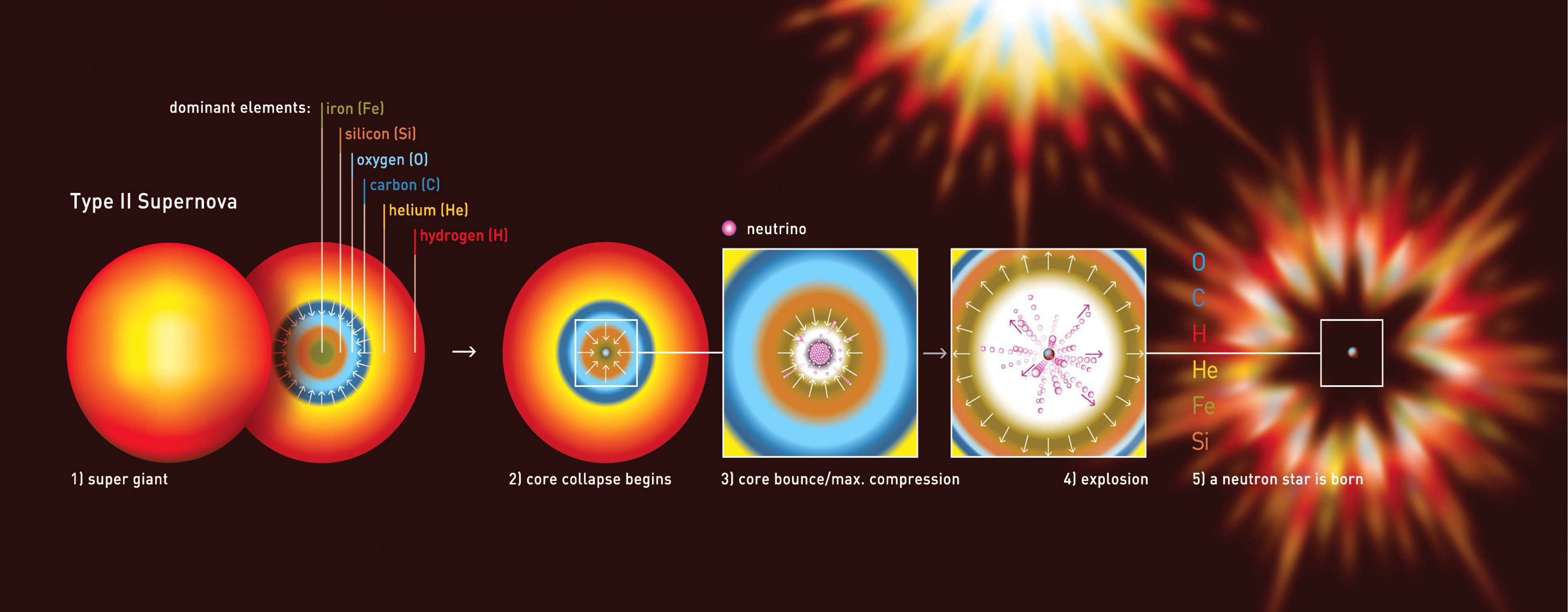
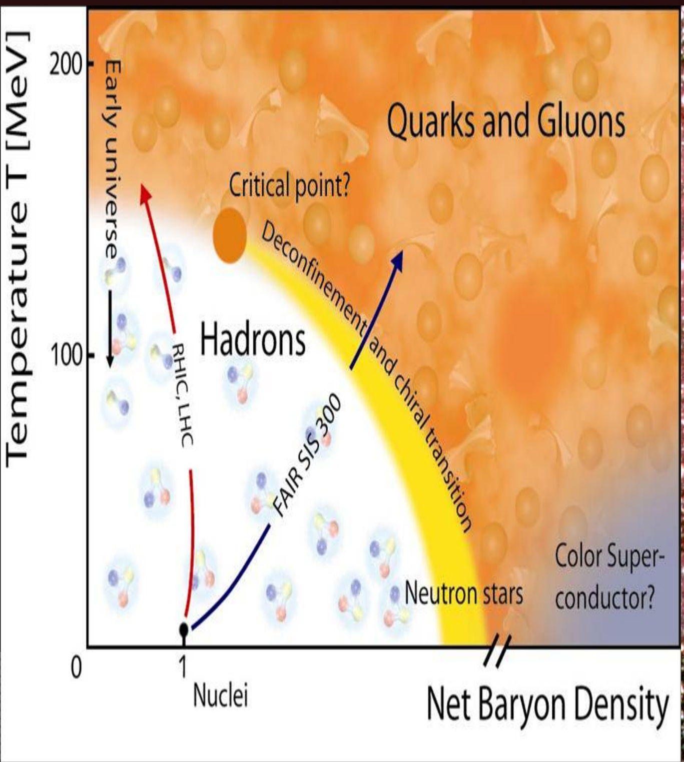
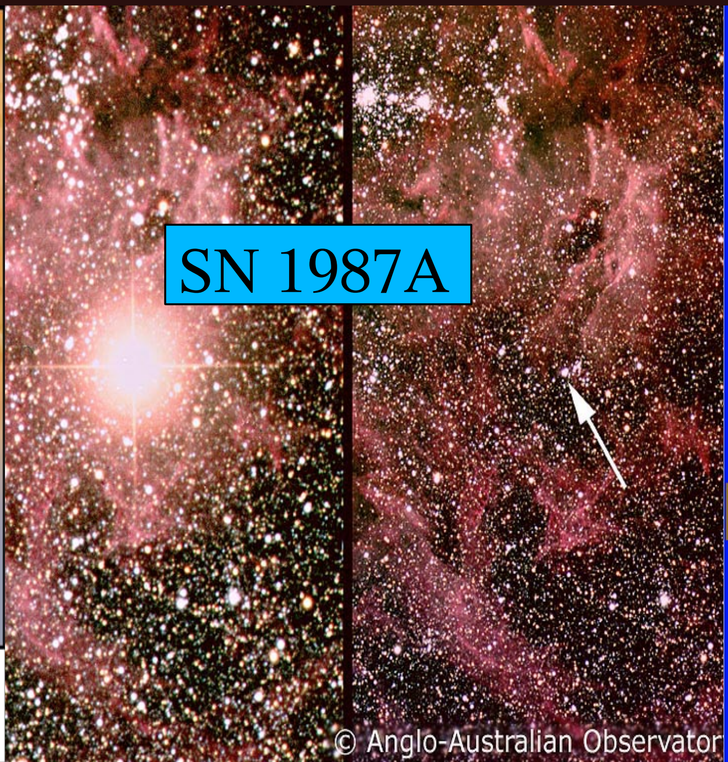
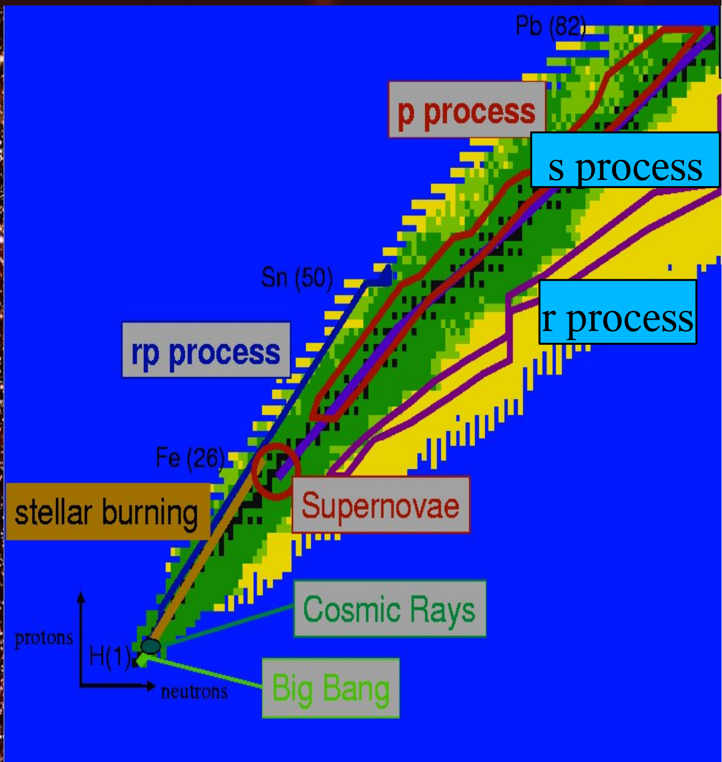
UNI BASEL

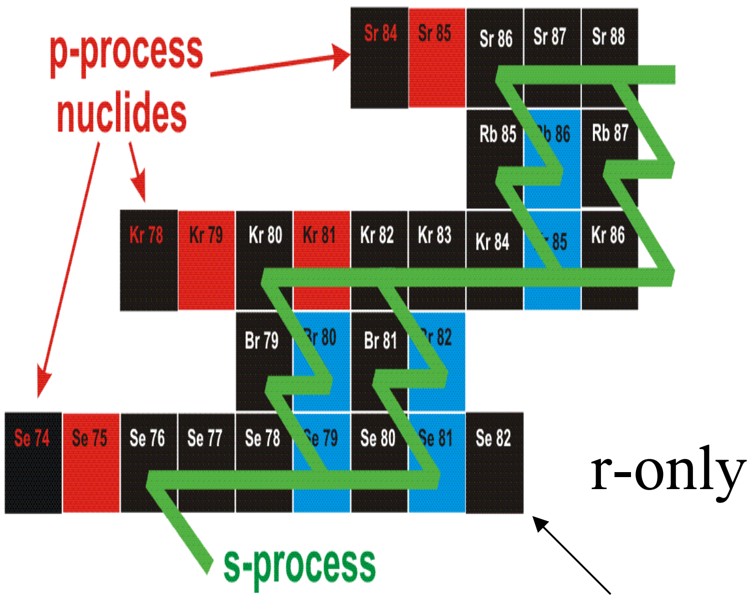

Type II Supernova
dominant elements:
iron (Fe)
silicon (Si)
oxygen (O)
carbon (C)
helium (He)
hydrogen (H)
neutrino
O
C
H
He
Fe
Si
1) super giant
2) core collapse begins
3) core bounce/max. compression
4) explosion
5) a neutron star is born

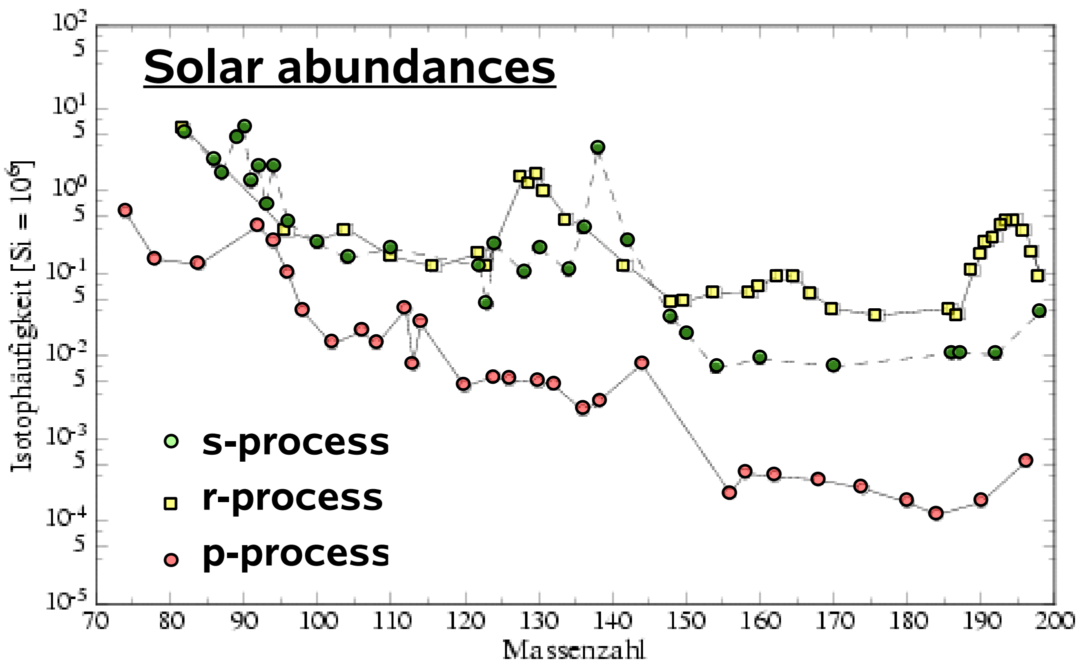

Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density
Early universe
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Hadrons
RHIC, LHC
FAIR SIS 300
Neutron stars
Color Super-
conductor?

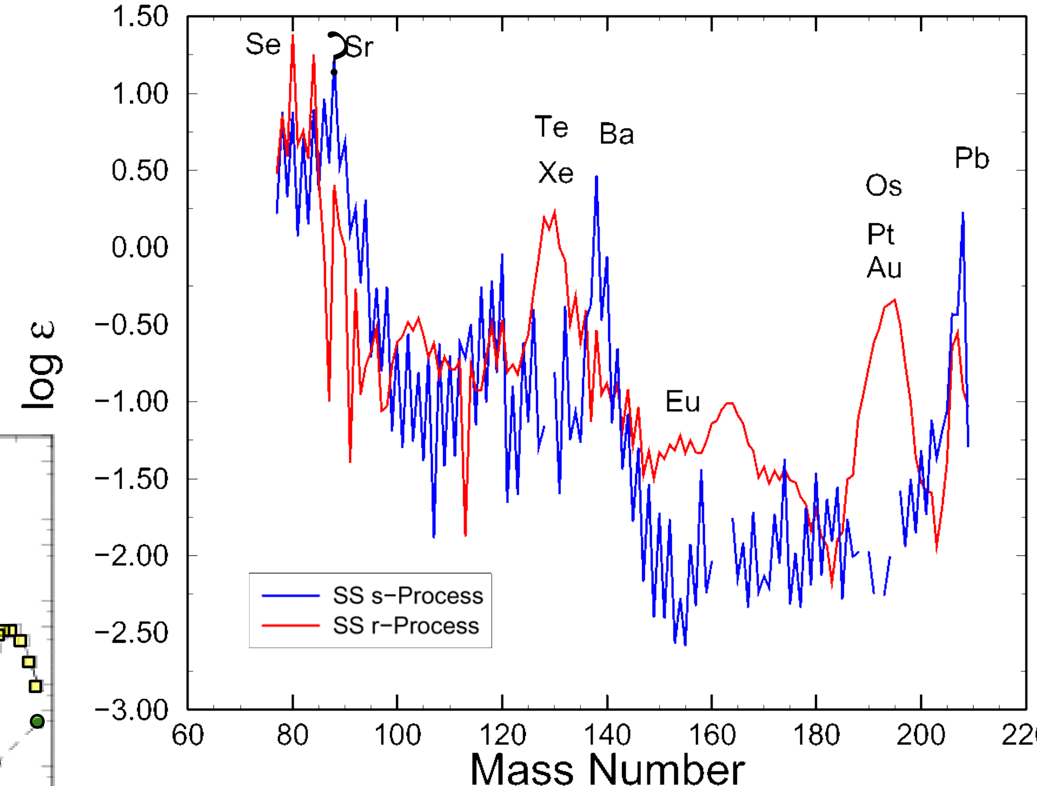

SN 1987A
© Anglo-Australian Observator


Pb (82)
p process
s process
Sn (50)
r process
rp process
Fe (26)
stellar burning
Supernovae
Cosmic Rays
protons
H(1)
neutrons
Big Bang

Decomposition of the heavy elements







How do massive stars contribute to s-, r-, and p-process abundances?

The classical r-process

- Explosive burning at high temperatures (>5 10^9K) leads to abundances based on a chemical equilibrium of reactions in the entire nuclear chart (NSE), or in local regions (QSE). The expansion and temperature decline causes a freeze-out of charged-particle reactions (≈3 10^9K)
- Assume conditions where after a charged-particle freeze-out the heavy QSE-group splits into QSE-subgroups containing each one isotopic chain Z, and a high neutron density is left over
- these QSE-groups are connected by beta-decays from Z to Z+1
- neutrons are consumed to form heavier nuclei

High neutron densities lead to nuclei far from stability, experiencing nuclei with short half-lives

Nuclear Reactions to be considered: (n,γ), (γ,n)

(β,xn), (β,f), (n,f), inelastic ν-scattering, (ν_e,e^-)

The classical r-process

How to predict abundance changes?

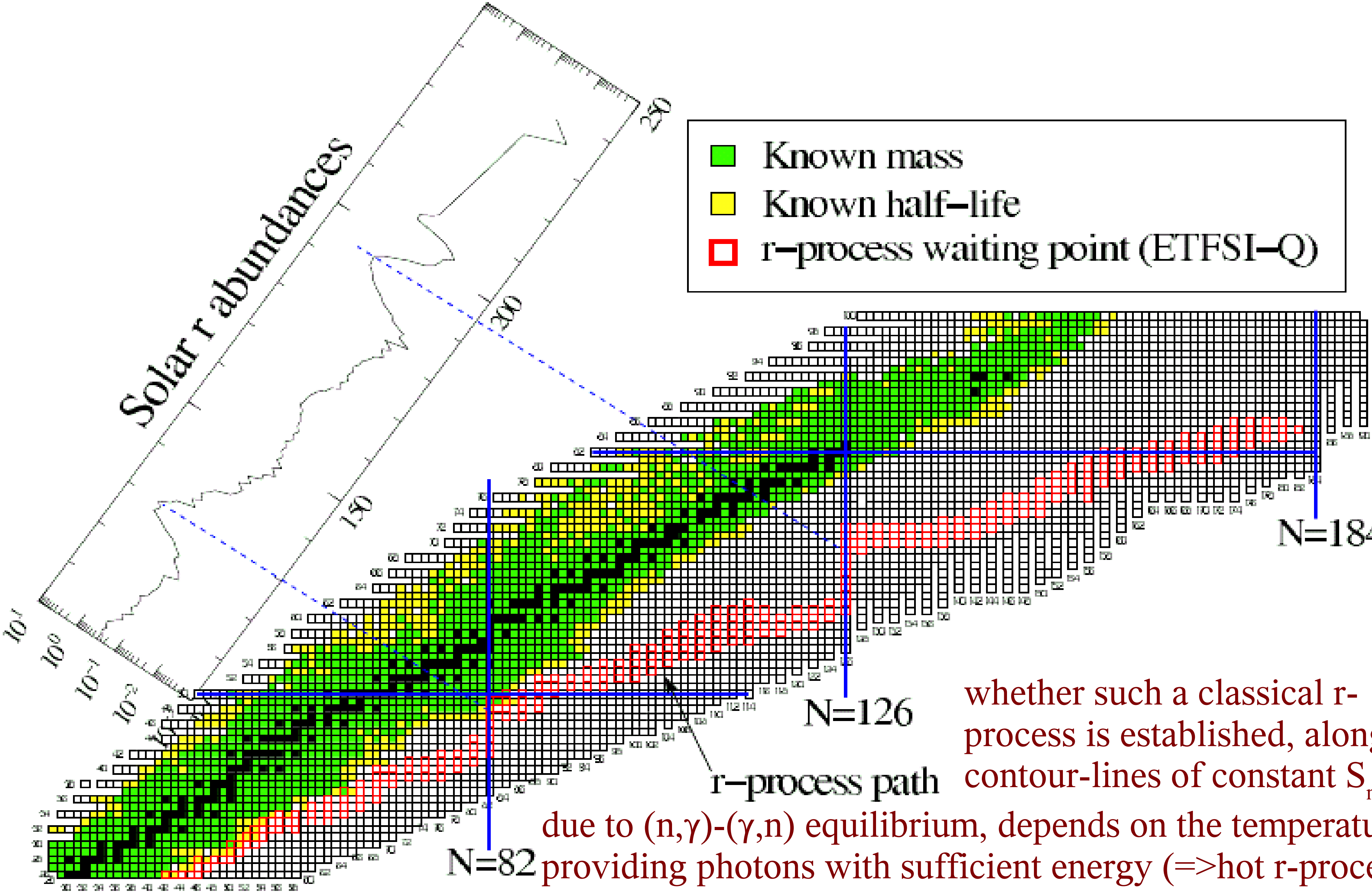
- $\dot{Y}(Z,A) = \sum \lambda_{Z',A'} Y_{Z',A'} + \sum \rho N_A < \sigma v >_{Z',A'} Y_{Z',A'} Y_n$ with $n_n = \rho N_A Y_n$
- $\dot{Y}(Z,A) \approx \lambda_\gamma(Z,A+1)Y(Z,A+1) - < \sigma v >_{Z,A} Y_{Z,A} n_n$ in case (n,γ), (γ,n) rates dominate
- $\dot{Y}(Z,A) = 0$ in chemical equilibrium, $Y(Z,A+1)/Y(Z,A) = f(n_n, T, S_n)$ due to detailed balance relation between $\lambda_\gamma(Z,A+1)$ and $< \sigma v >_{Z,A}$
- abundance maxima for all Z's at same S_n
- $\dot{Y}(Z) = \lambda_\beta(Z-1)Y(Z-1) - \lambda_\beta(Z)Y(Z)$ for summed abundances in isotopic chain and averaged decay rates

$$\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{< \sigma v >_{n,\gamma}(A)}{\lambda_{\gamma,n}(A+1)} n_n$$

$$\lambda_{\gamma,n}(A+1) = \frac{2G(Z,A)}{G(Z,A+1)}\left[\frac{A}{A+1}\right]^{3/2}\left[\frac{m_u kT}{2\pi\hbar^2}\right]^{3/2} \langle\sigma v\rangle_{n,\gamma}(A)\exp(-S_n(A+1)/kT)$$

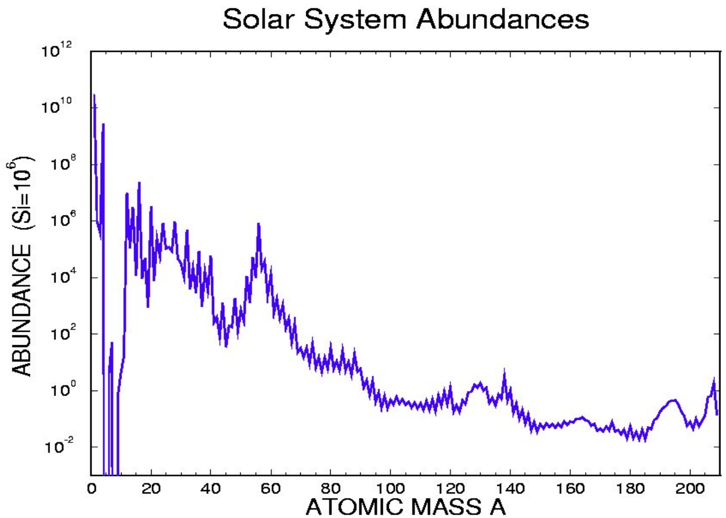
$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \frac{G(Z,A+1)}{2G(Z,A)}\left[\frac{A+1}{A}\right]^{3/2}\left[\frac{2\pi\hbar^2}{m_u kT}\right]^{3/2}\exp(S_n(A+1)/kT)$$

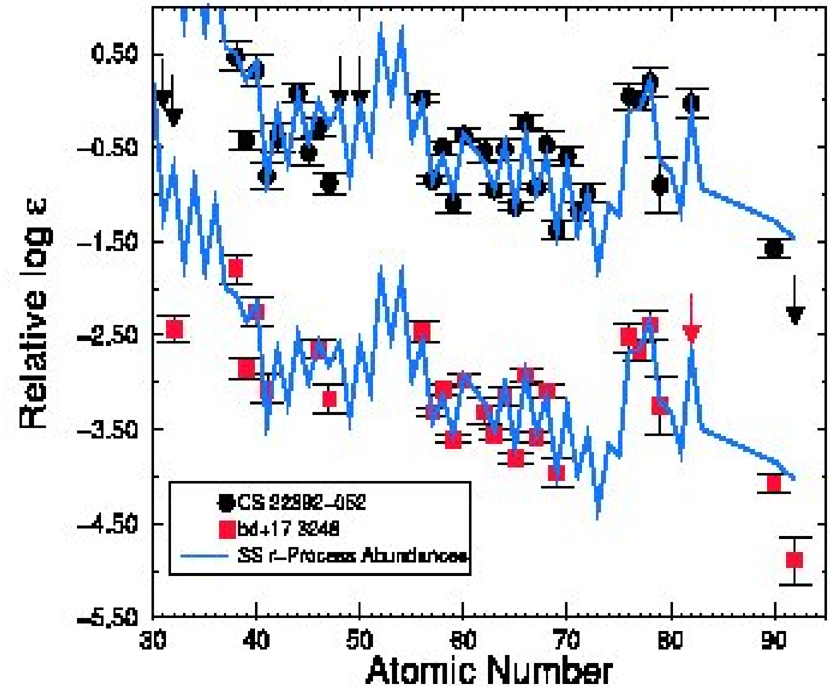
r-Process Path



G. Martinez-Pinedo

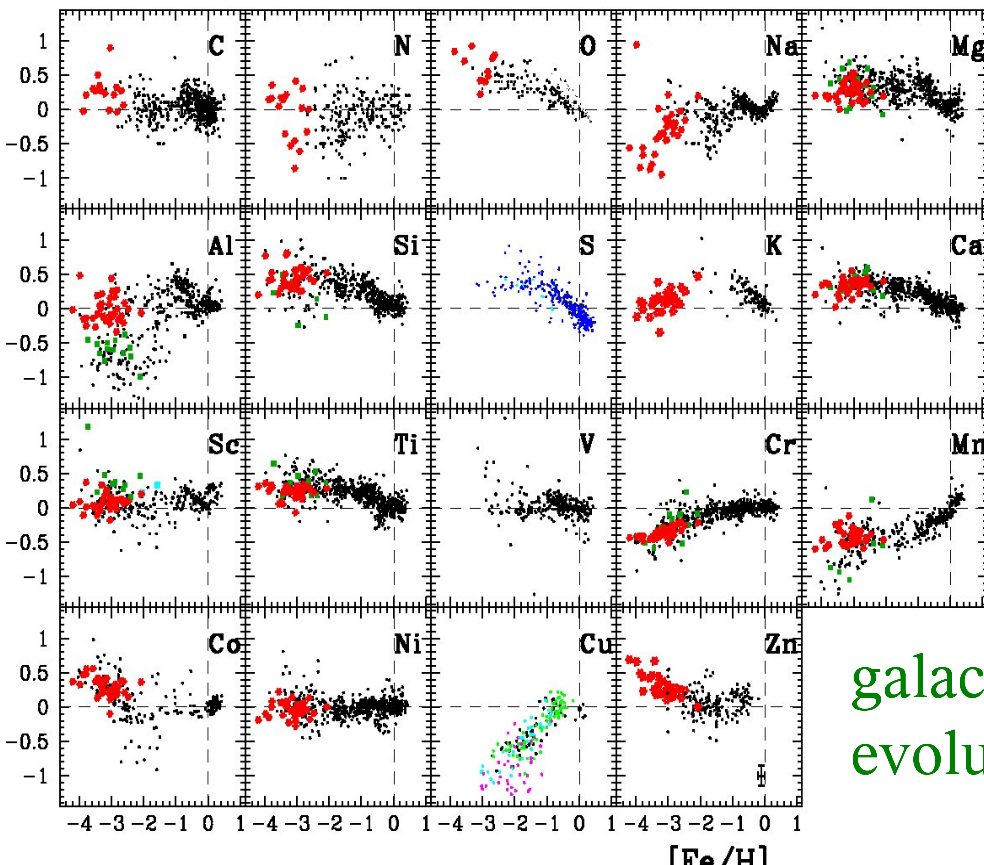
whether such a classical r-process is established, along contour-lines of constant $S_{n,}$ due to (n,γ)-(γ,n) equilibrium, depends on the temperature, providing photons with sufficient energy (=>hot r-process). In matter with fast expansion and still high neutron densities at low temperatures this might not be established (=>smeared-out distribution, cold r-process)



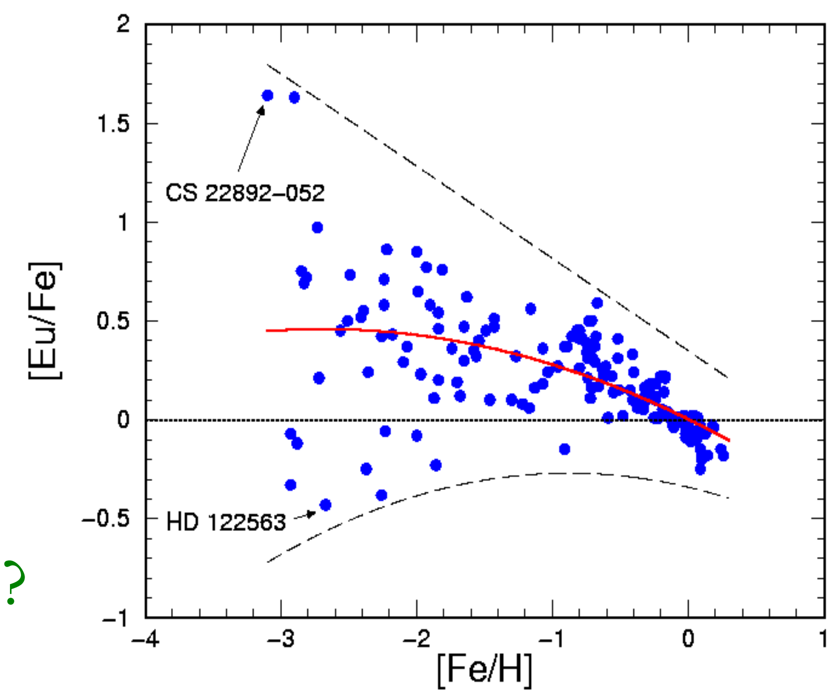


How do we understand: solar system abundances..

low metallicity stars ...



galactic evolution?



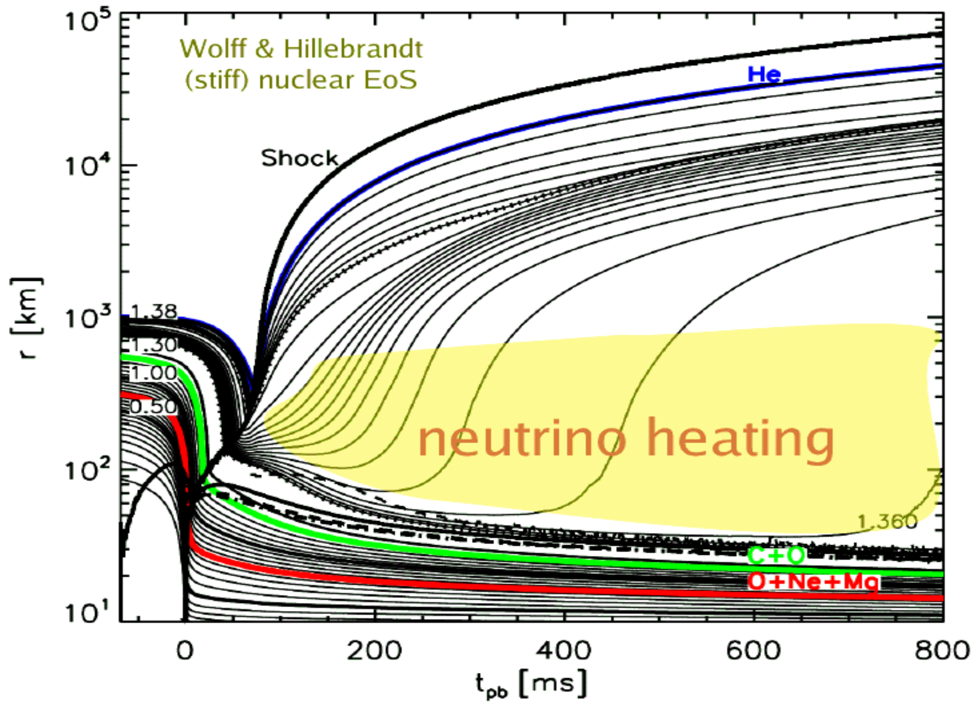
Possible Sites of the r-Process

- Core Collape Supernovae and their Mechanism
- The role of neutrinos for the innermost ejecta
- The late neutrino wind and the r-process?
- Alternative scenarios based on decompression of neutron-rich material (neutron star mergers, polar jets)

Supernovae in 1D

SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

"Electron-capture supernovae"
or "ONeMg core supernovae"

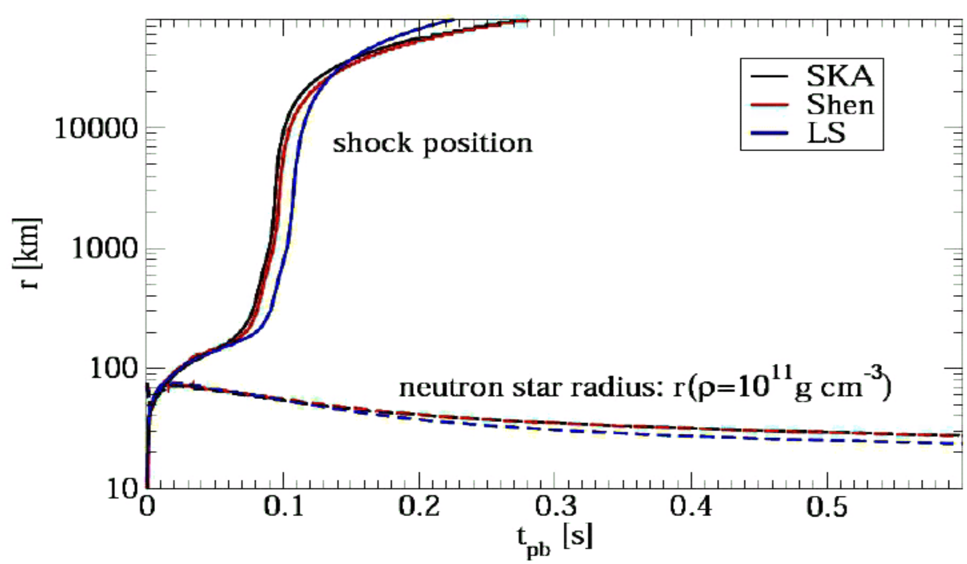


Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199

Convection is not necessary for launching explosion
but occurs in NS and in neutrino-heating layer

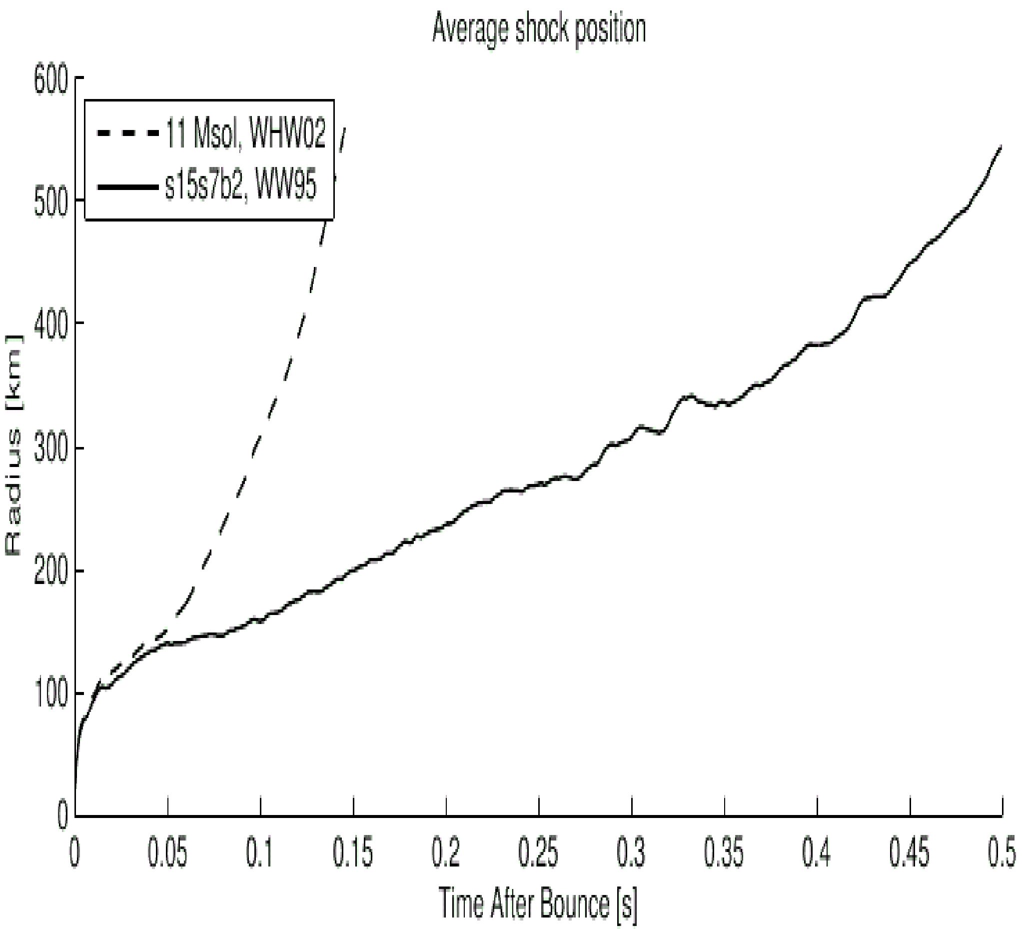
- No prompt explosion !
- Mass ejection by "neutrino-driven wind"
  (like Mayle & Wilson 1988
  and similar to AIC of WDs;
  see Woosley & Baron 1992, Fryer et al. 1999;
  Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)

Fischer et al.
2010

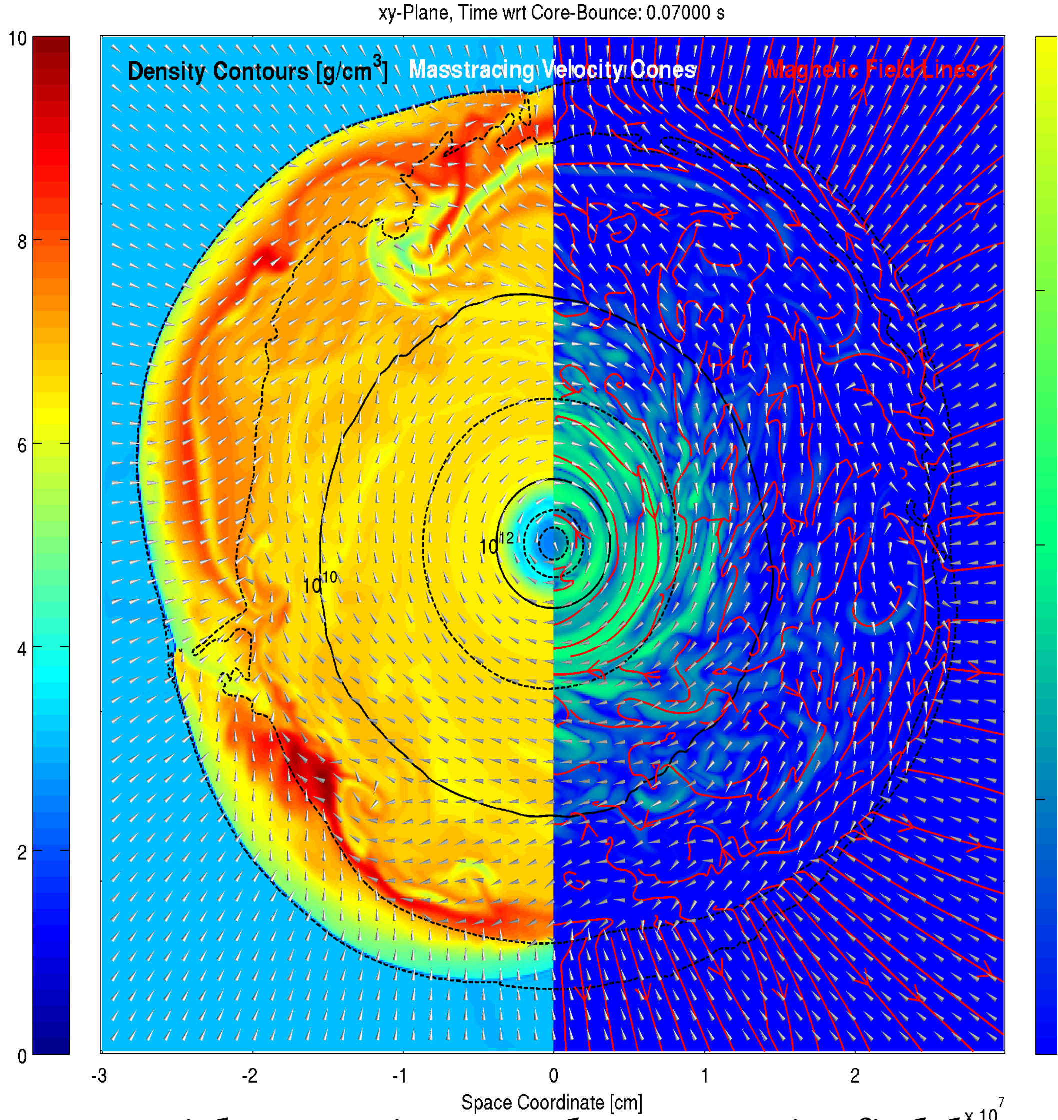


Simulations in 3D

Liebendörfer et al.



3D hydro without rotation



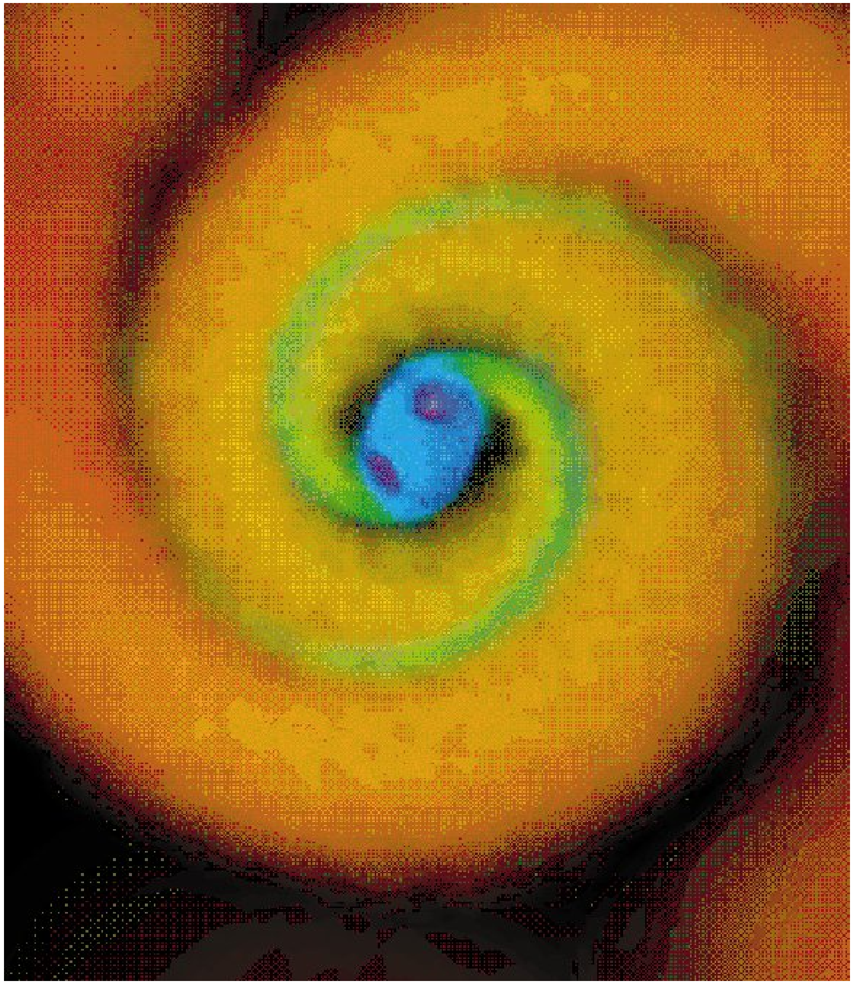
with rotation and magnetic fields

Multi-D explosion calculations are optimistic! (but EoS dependence!)
no explosions, yet; but still outward moving shockwave after 100s of ms
(similar results by Basel, Garching, Oak Ridge, Princeton/Caltech and Tokyo groups).

What is the site of the r-process?

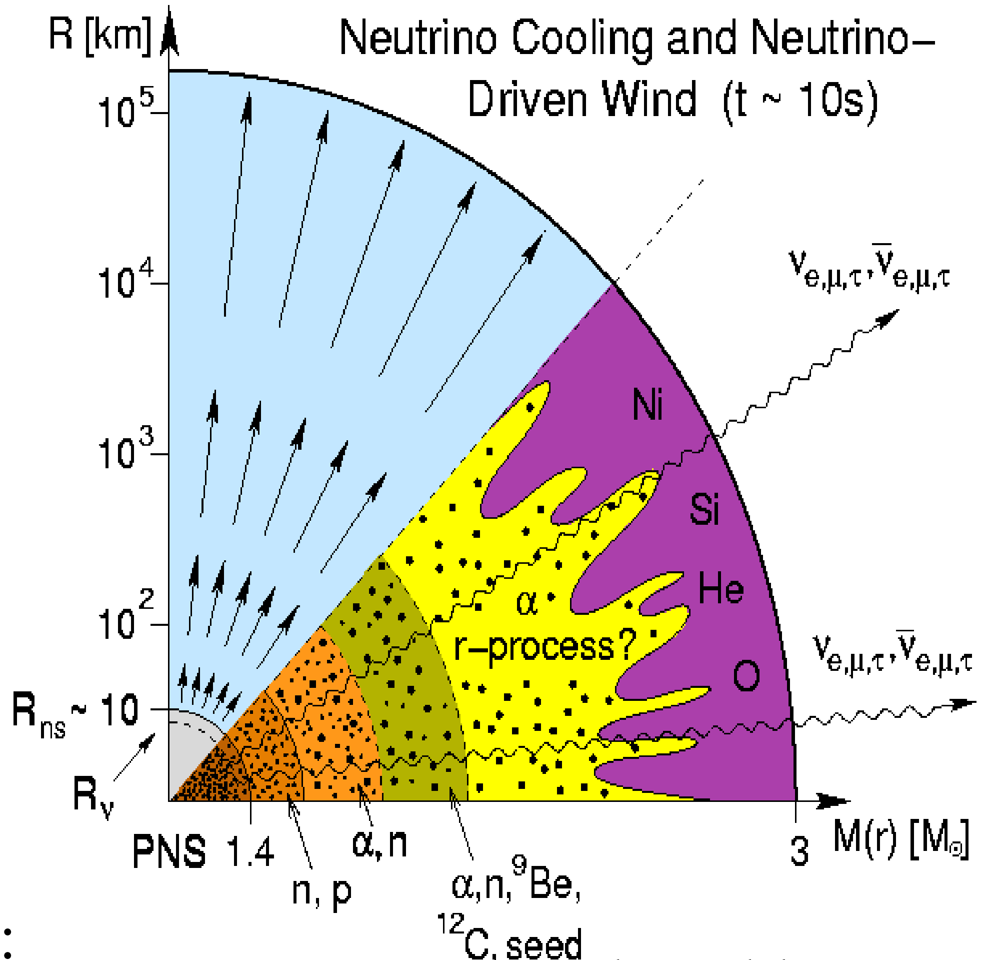
(requires n/seed>150-200!!, function of entropy S and Y_e)

from S. Rosswog



NS mergers, BH-NS mergers, problems:
ejection too late in galactic evolution
(or alternatively polar jets from supernovae,
Cameron 2003, Fujimoto et al. 2008)

from H.-T. Janka



SN neutrino wind, problems:
high enough entropies attained?
neutrino properties???

In exploding models matter in innermost ejected zones becomes proton-rich (Y_e>0.5)

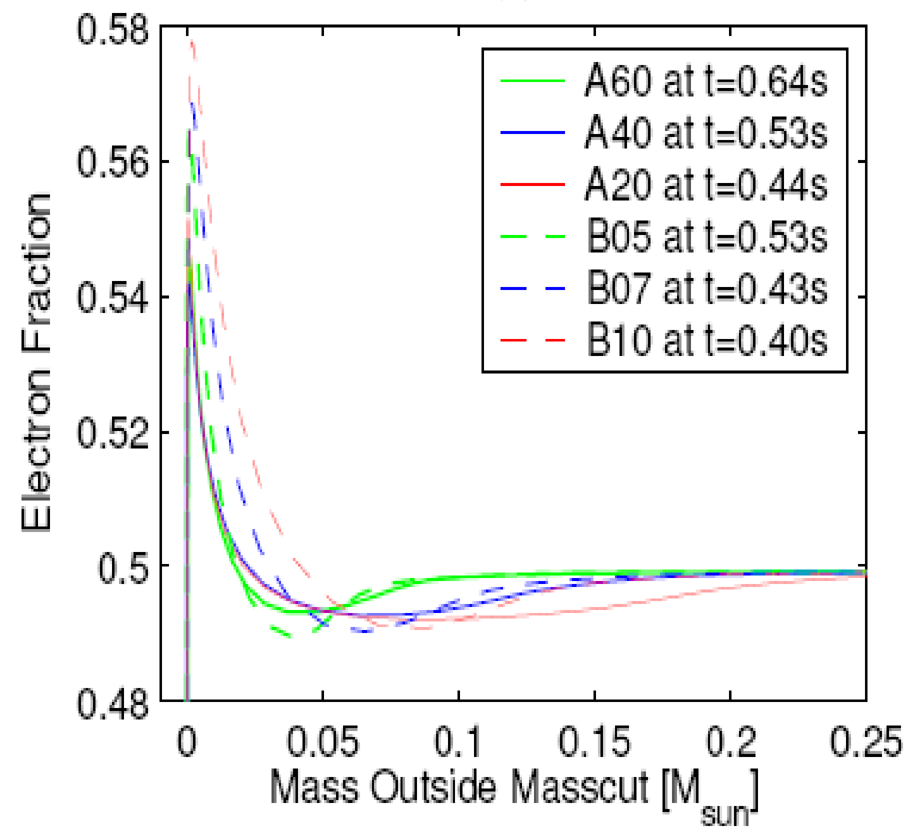
if the neutrino flux is sufficiant (scales with $1/r^2$)! :

Y_e dominantly determined by $e^{\pm}$ and ν_e, $\bar{\nu}_e$ captures on neutrons and protons

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

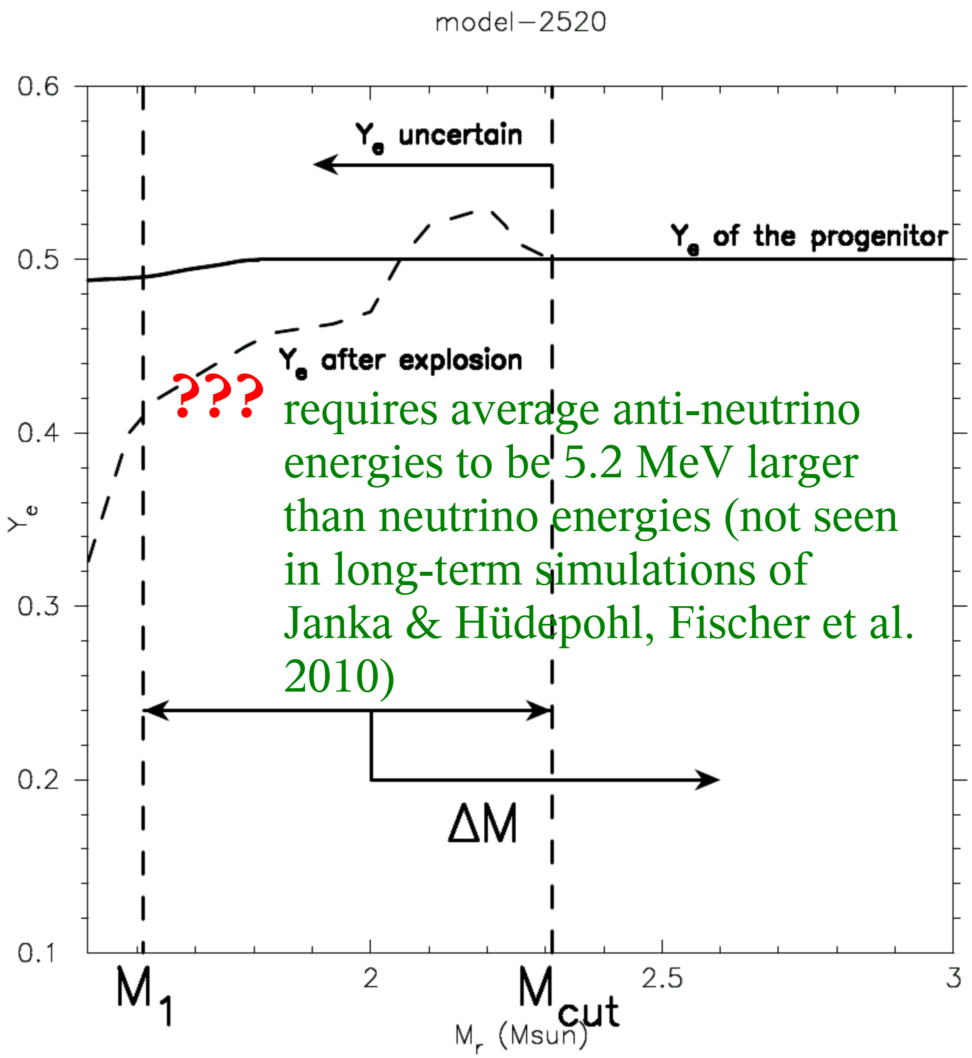
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

- high density / low temperature → high E_F for electrons → e-captures dominate → n-rich composition
- if el.-degeneracy lifted for high T → ν_e-capture dominates → due to n-p mass difference, p-rich composition
- in late phases when proto-neutron star neutron-rich, $\bar{\nu}_e$'s see smaller opacity → higher luminosity, dominate in neutrino wind → neutron-rich ejecta ?



Liebendörfer et al. (2003), Fröhlich et al. (2006ab), Pruet et al. (2005,2006), Wanajo (2007)

Possible Variations in Explosions and Ejecta

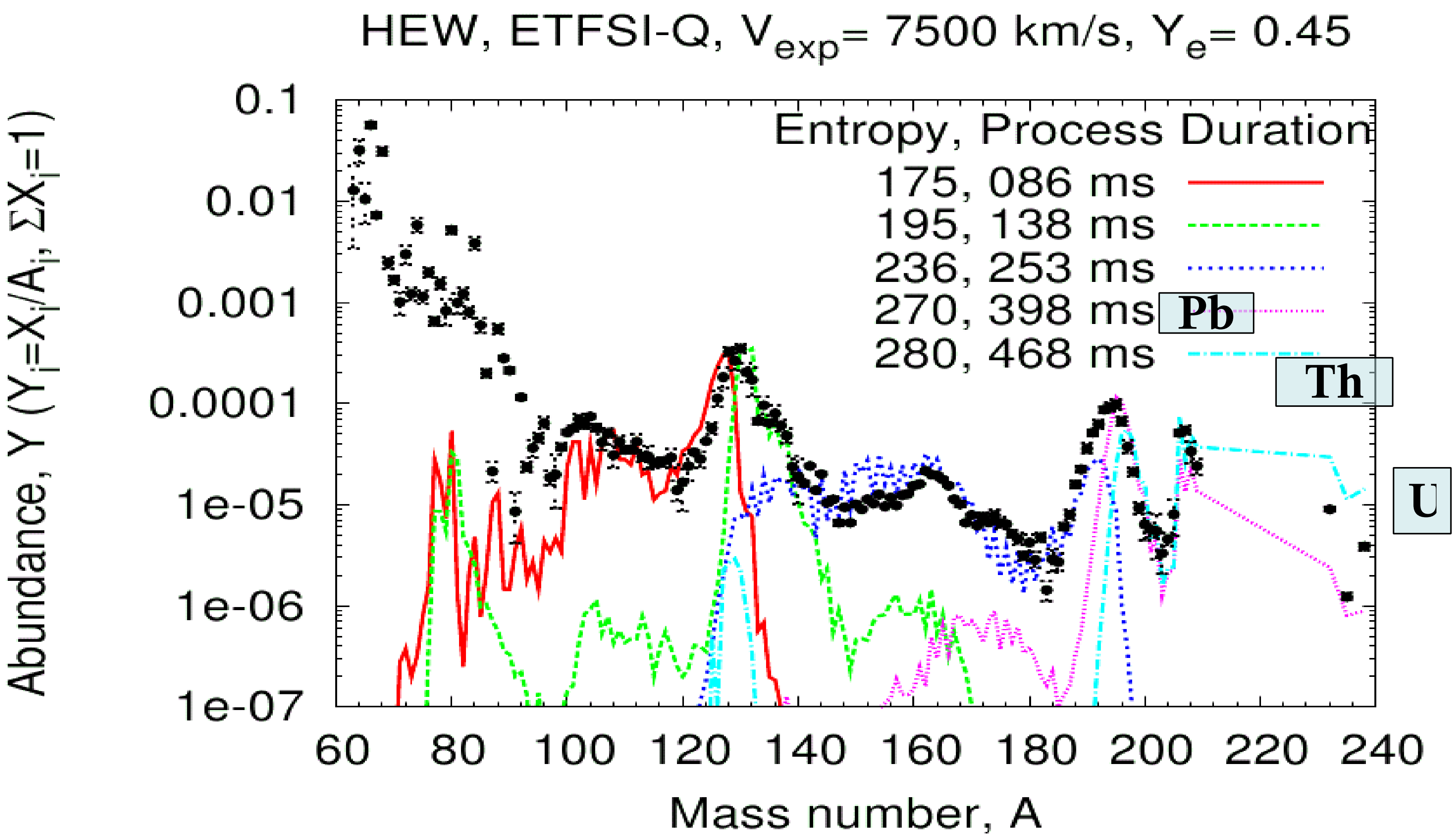


Izutani et al. (2009)

- *regular explosions with neutron star formation, neutrino exposure, early p-rich conditions, later moderately neutron-rich neutrino wind and weak r-process?? (see e.g. Arcones & Montes 2011, Roberts et al. 2010)*
- *under which (special?) conditions can very high entropies or very neutron-rich ejecta be obtained which produce the main r-process nuclei? (Wanajo et al. 2010, neutron-rich lumps in EC-Supernovae?? jets: e.g. Cameron 2003, Fujimoto et al. 2008?; very high entropy and neutron-rich neutrino wind?)*

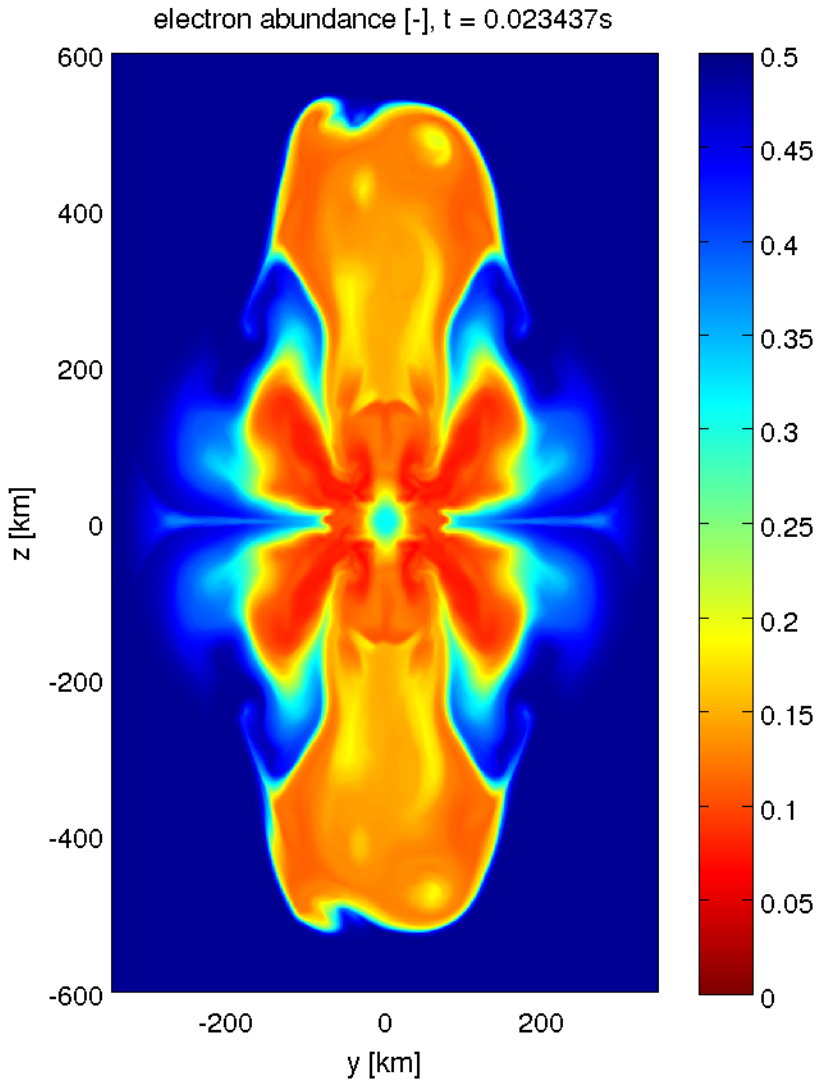
Individual Entropy Components in high entropy neutrino wind (hot r-process)

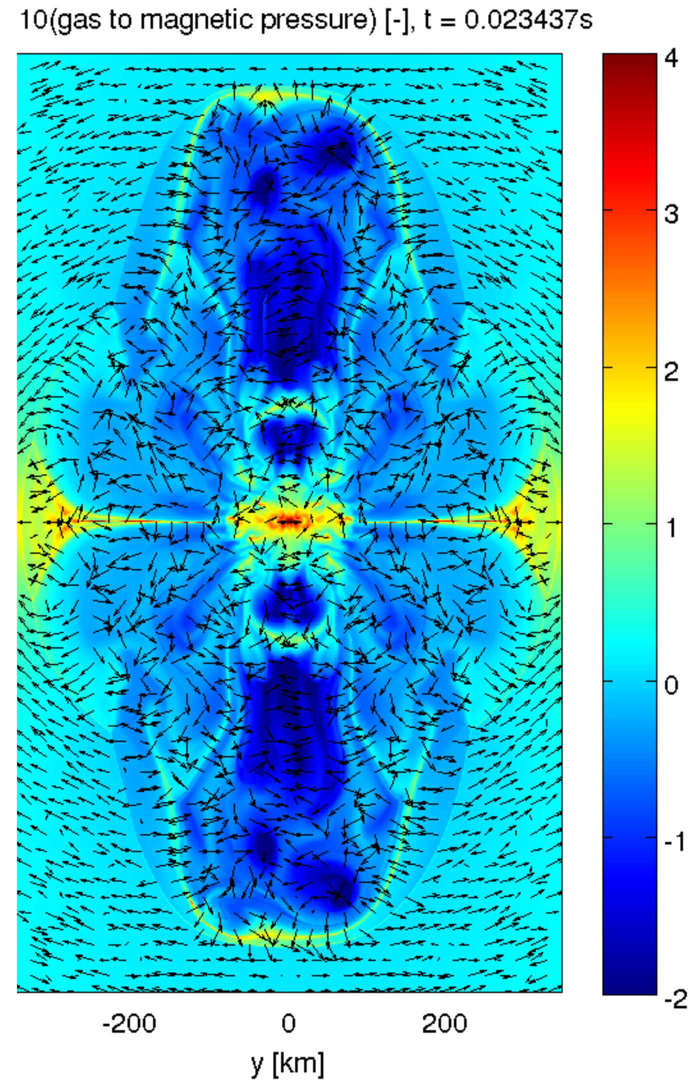
Farouqi et al. (2010), above S=270-280 fission back-cycling sets in



3D Collapse of Fast Rotator with Strong Magnetic Fields:

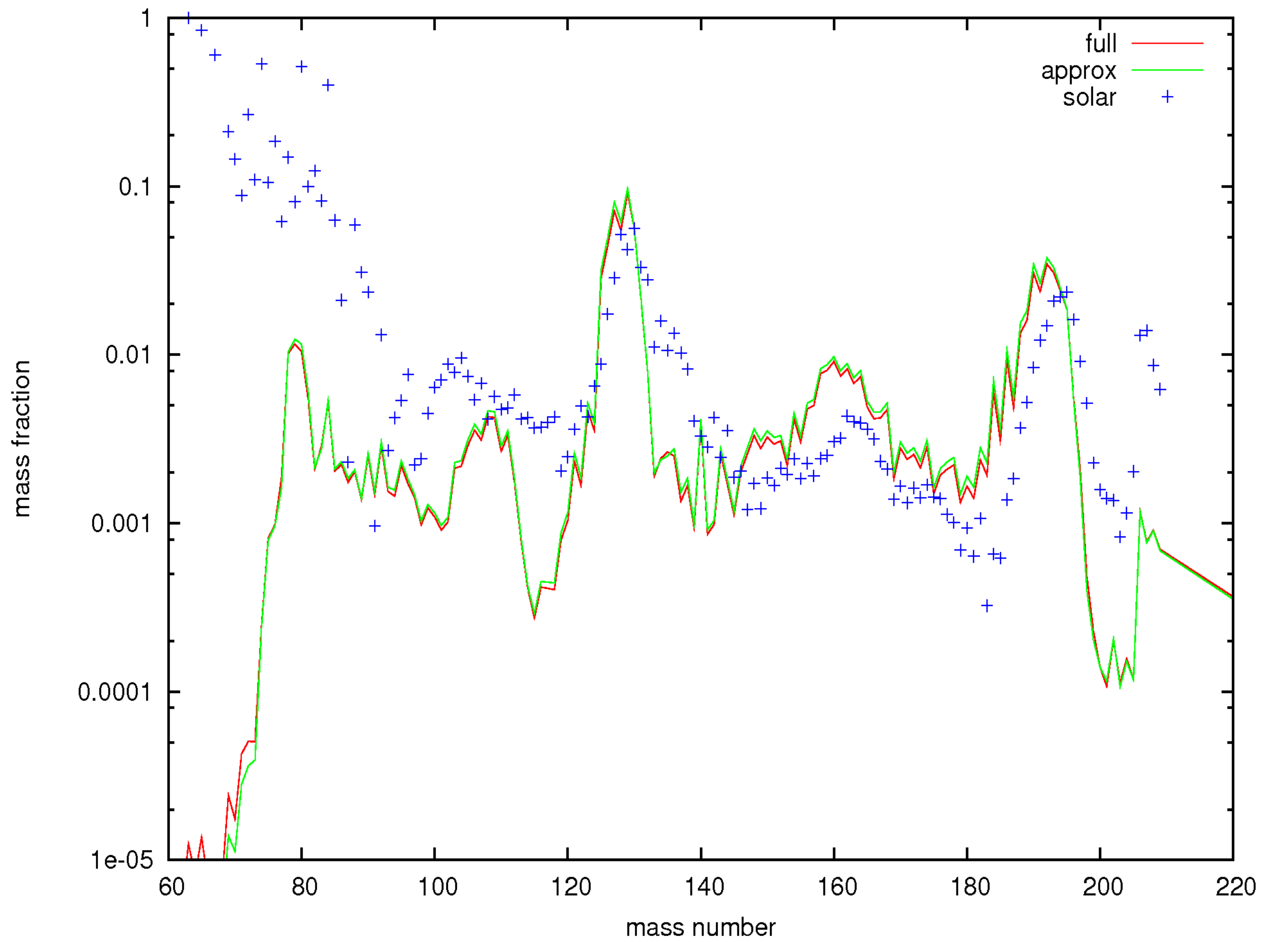
15 M_{sol} progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5 $\times 10^{12}$ Gauss





3D simulations by R. Käppeli, M. Liebendörfer et al. 2011 , preliminary results!

Preliminary Results of Jet Ejection from fast rotating collapse with large magnetic fields

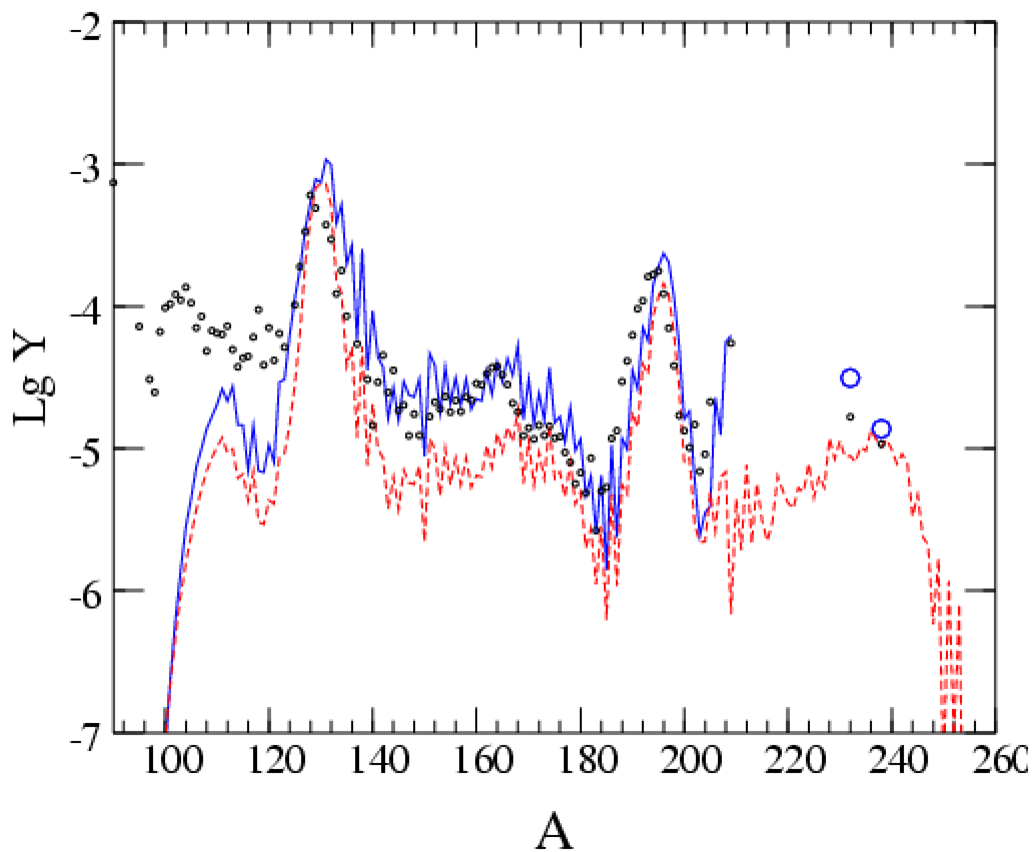


such matter experiences a fast expansion with still high neutron densities (=> close to a cold r-process)

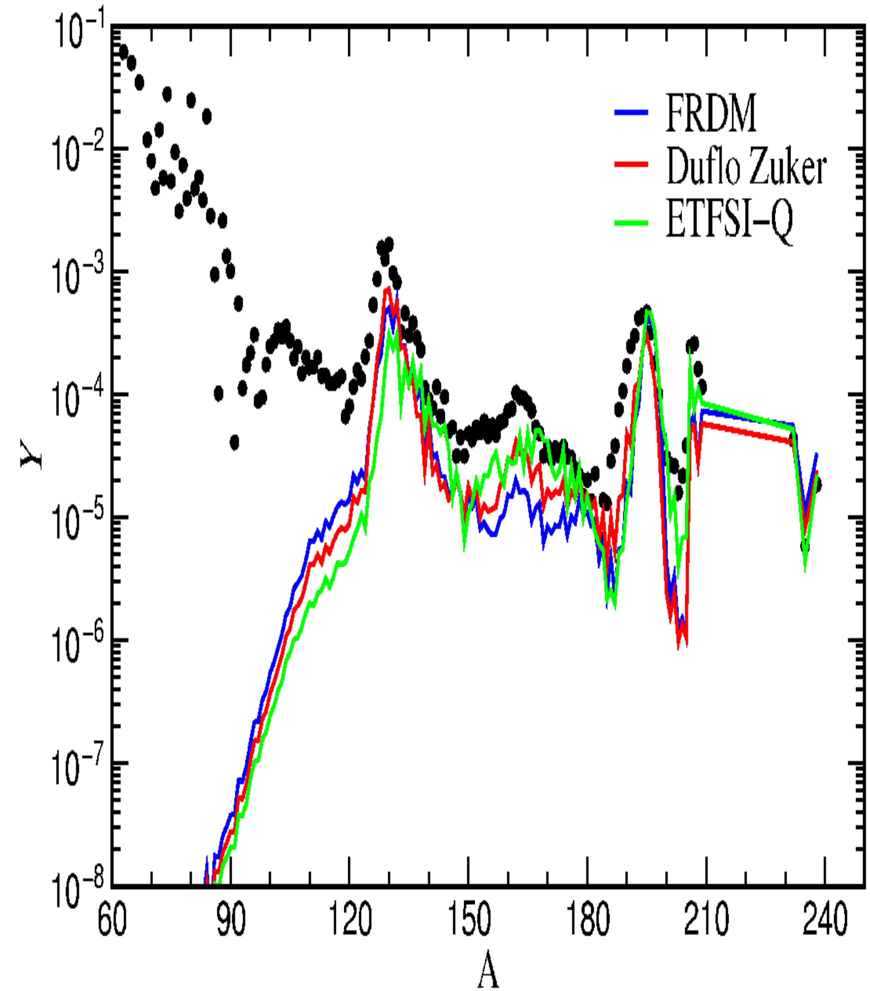
total ejected mass: few times 10^{-3} M_{sol}; C. Winteler, N. Nishimura, R. Käppeli et al. 2011, in prep., final abundances depend on extrapolated expansion after end of present hydro simulation.

Fission Cycling in Neutron Star Mergers

Trajectory from Freiburghaus, Rosswog, and Thielemann 1999
$(Y_e = 0.1, n/Seed = 238)$.



Panov, Korneev and Thielemann (2007, 2009)
with parametrized fission yield contribution
(see also Goriely, Bauswein, Janka 2011)



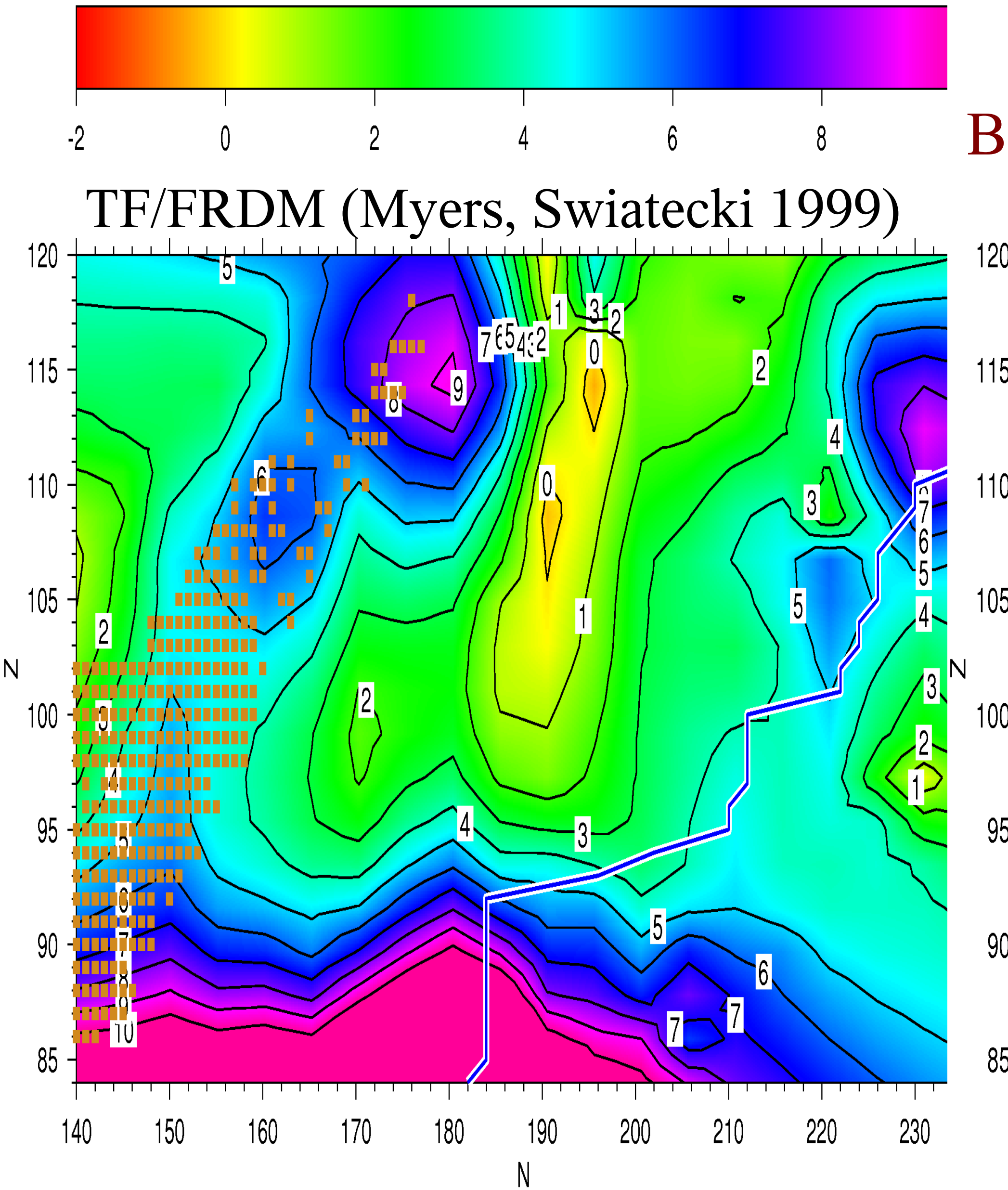
Martinez-Pinedo et al. (2006)

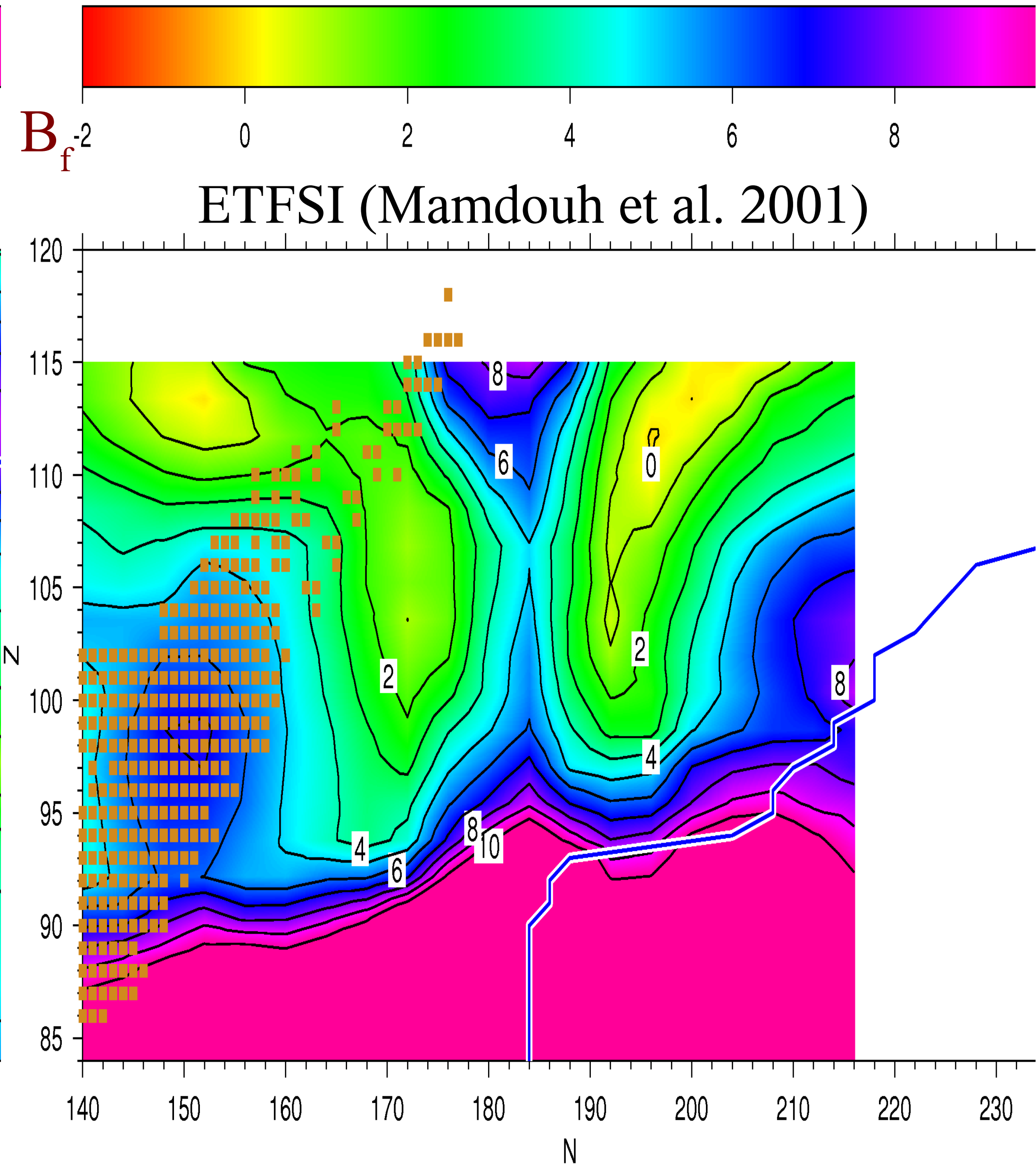
in principle contradicted from gal. evol. calc. (however, see Ishimura & Wanajo 2010), but similar conditions in SN polar jets? (Cameron 2003, Fujimoto 2008)

How far does the r-process proceed?

(suggested first by Schramm & Fowler 1971)

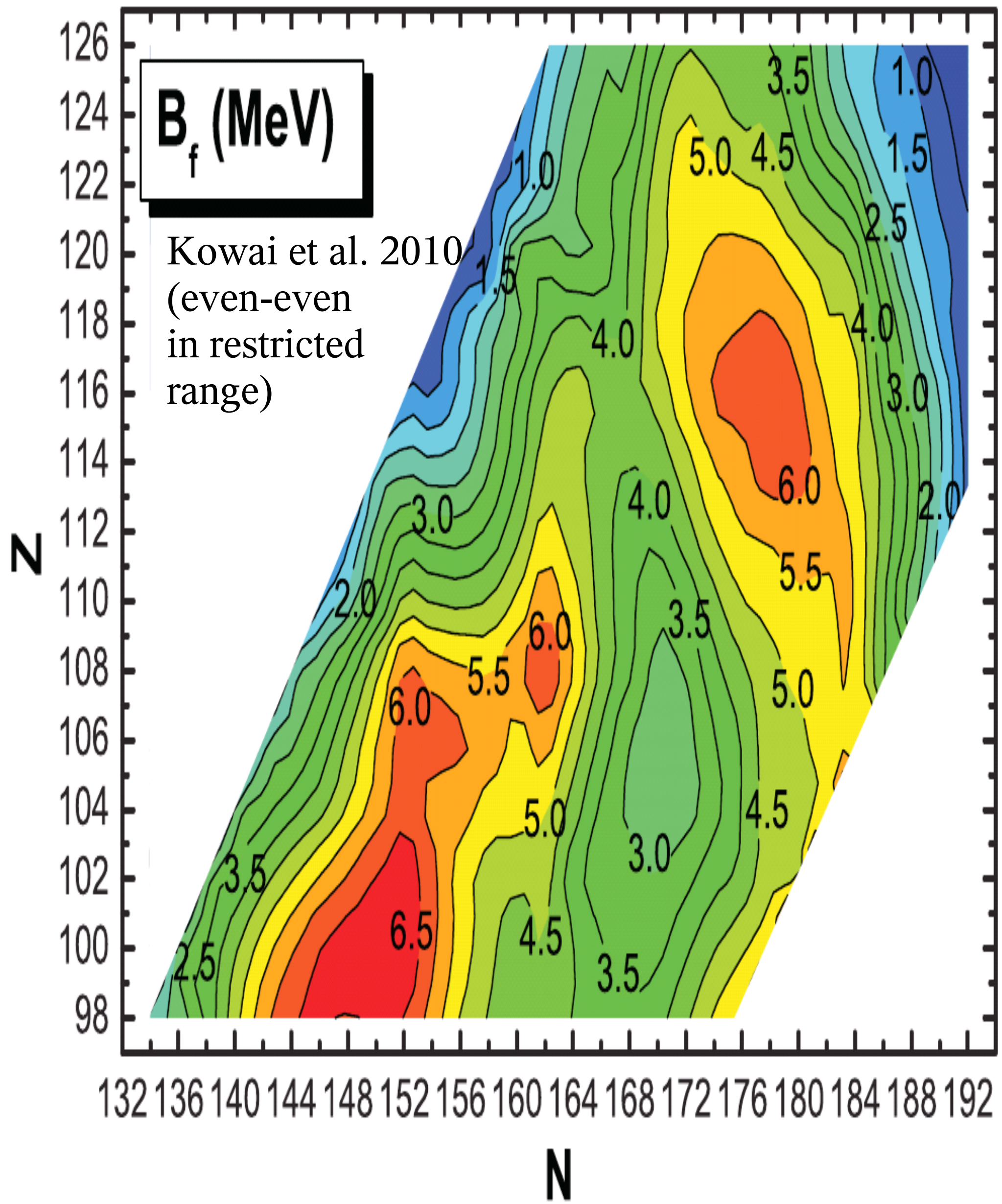
We need complete and accurate nuclear input (masses, fission barriers, reactions, decay channels)!!

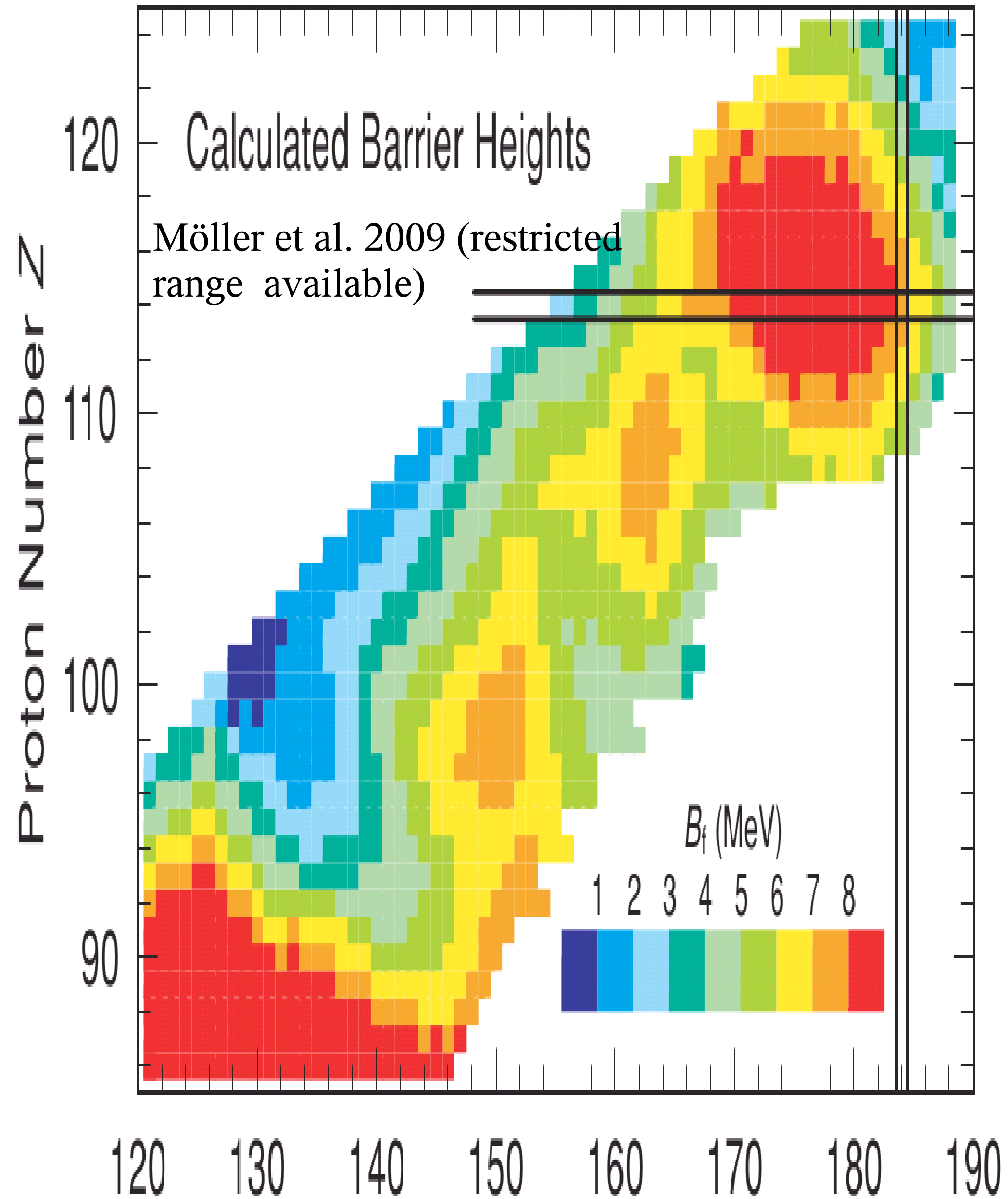




Other recent predictions (we require complete sets)

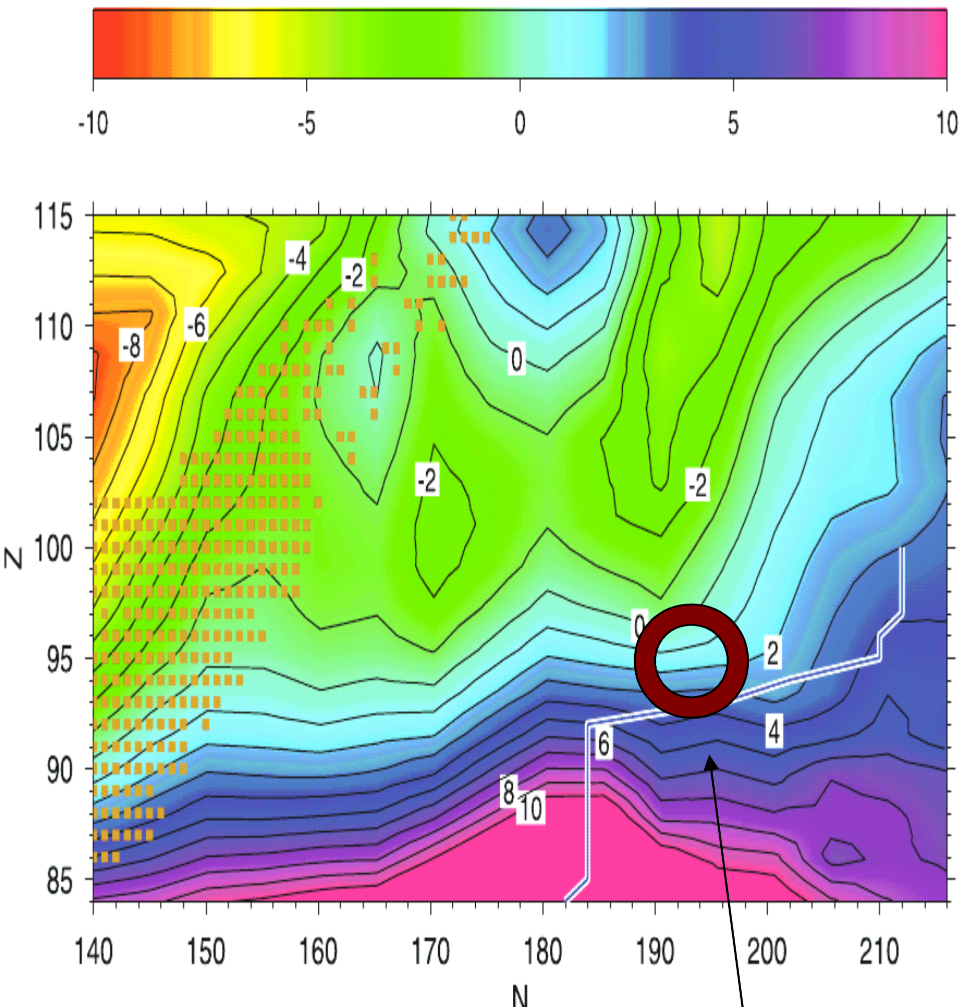
in the making: Goriely et al. (HFB, up to now selected results), Erler, Langanke, Loens, Martinez-Pinedo, P.-G. Reinhard (SHF)

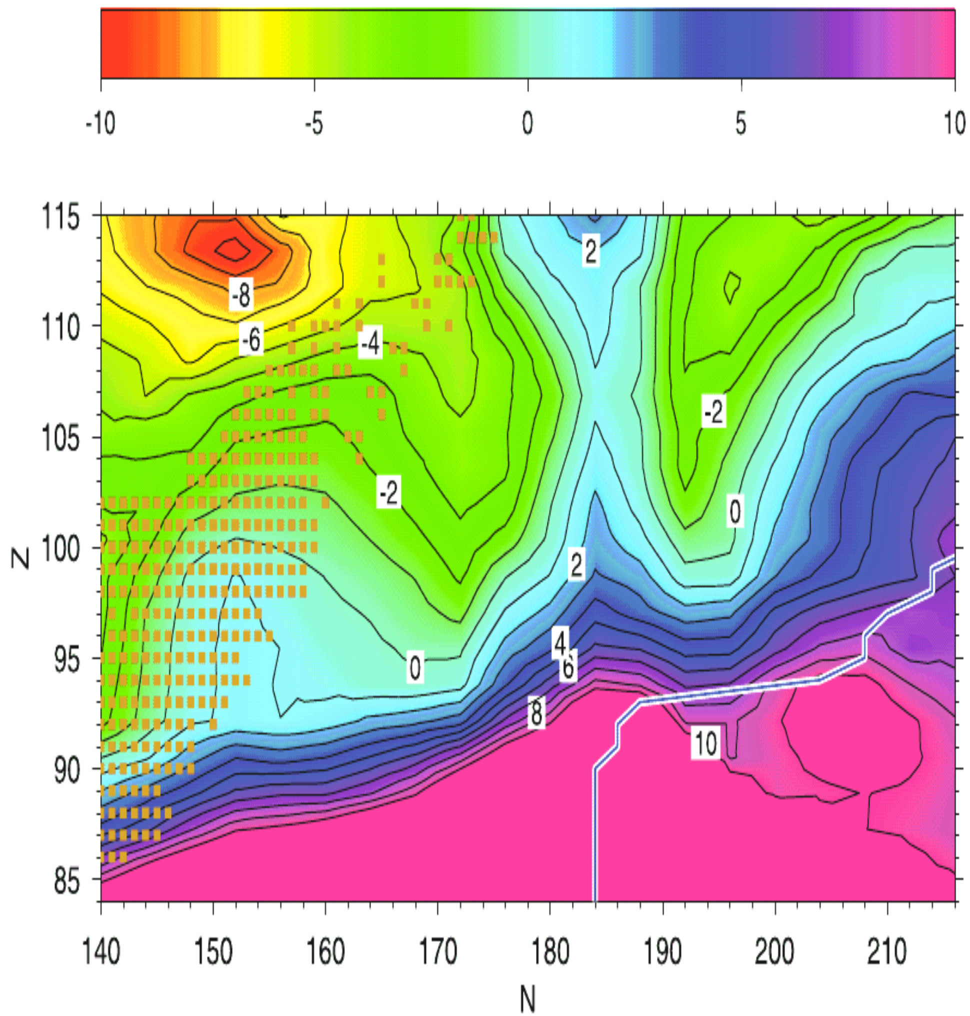




Fission Barriers (B_f-S_n) and the r-Process

(if negative => neutron-induced fission)





Myers & Swiatecki barriers (TF/FRDM)

narrow path without n-induced fission!

Mamdouh et al. barriers (ETFSI)
typically higher barriers

we will perform our calculations with these sets

Preparing for the heaviest elements

neutron-induced fission and n,γ-calculations (Panov et al. 2010)

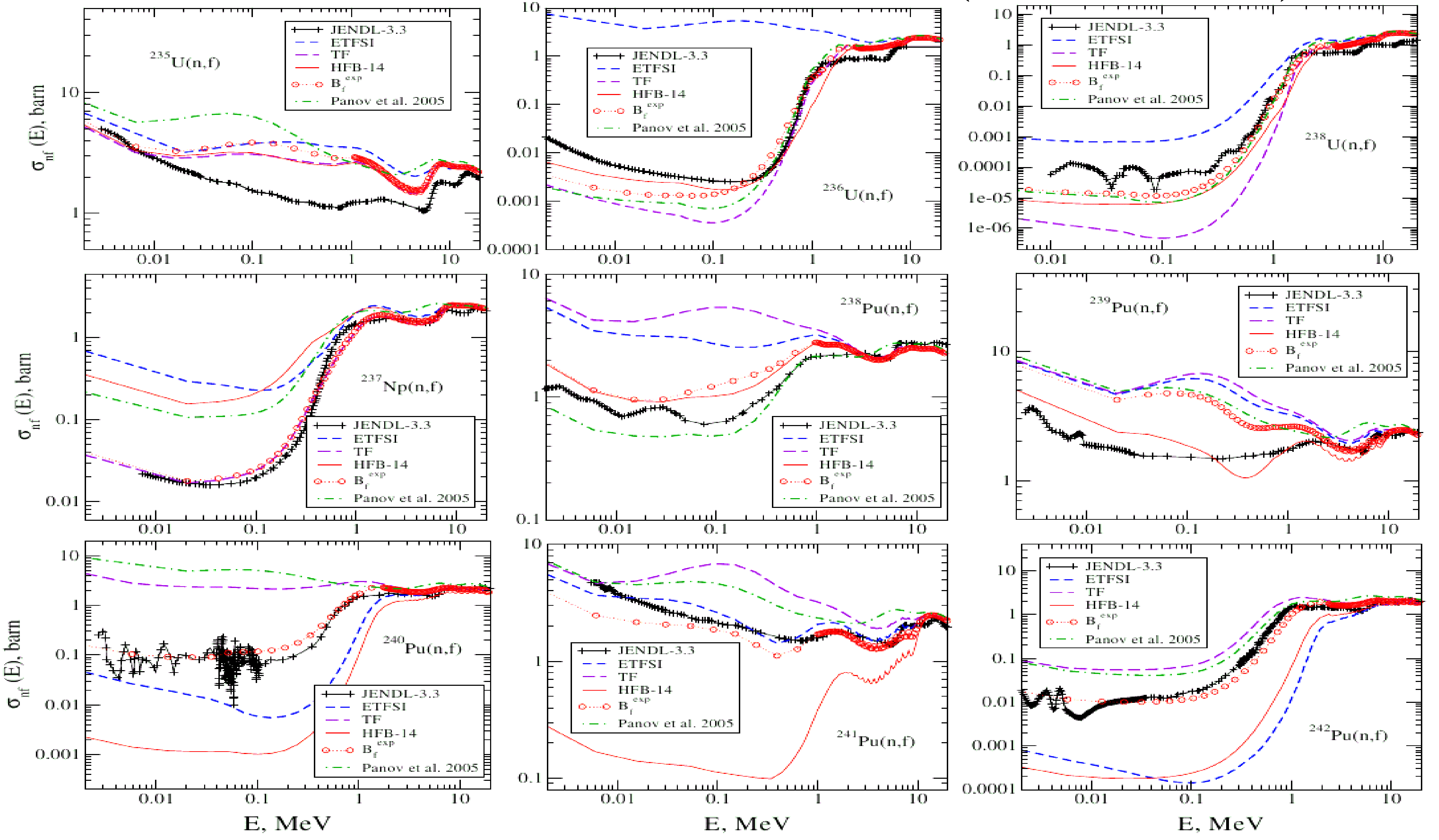
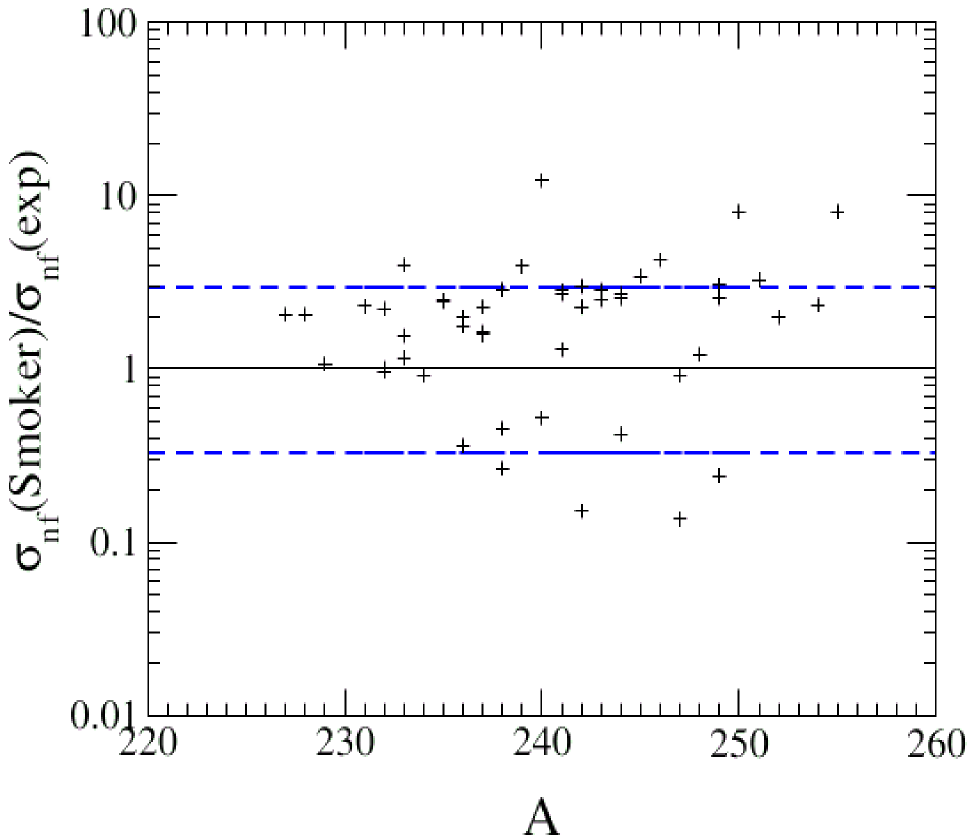
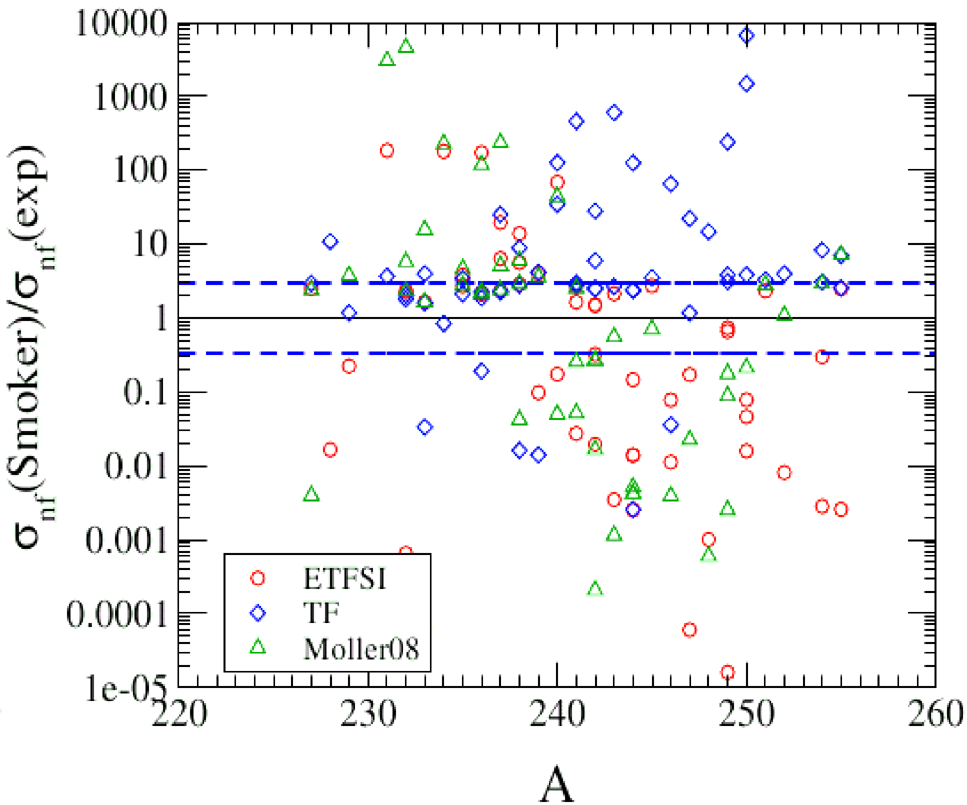


Fig. 1. Present predictions of energy-dependent (n, f) cross sections $\sigma_{nf}(E)$ for some target nuclei of U, Np and Pu calculated in the framework of different mass and fission barrier predictions (ETFSI, TF, HFB-14) and experimental data, marked B_f^{exp} as well. Experimentally measured cross-sections were used after JENDL-3.3 (Nakagawa et al. 2005), averaged by the code JANIS Soppera et al. (2008), displayed by a black line. All the predictions are given for a ground-state population. Our previous results (Panov et al. 2005) are shown as well.

Tests with experimentally known and theoretical barriers (Panov et al. 2010)



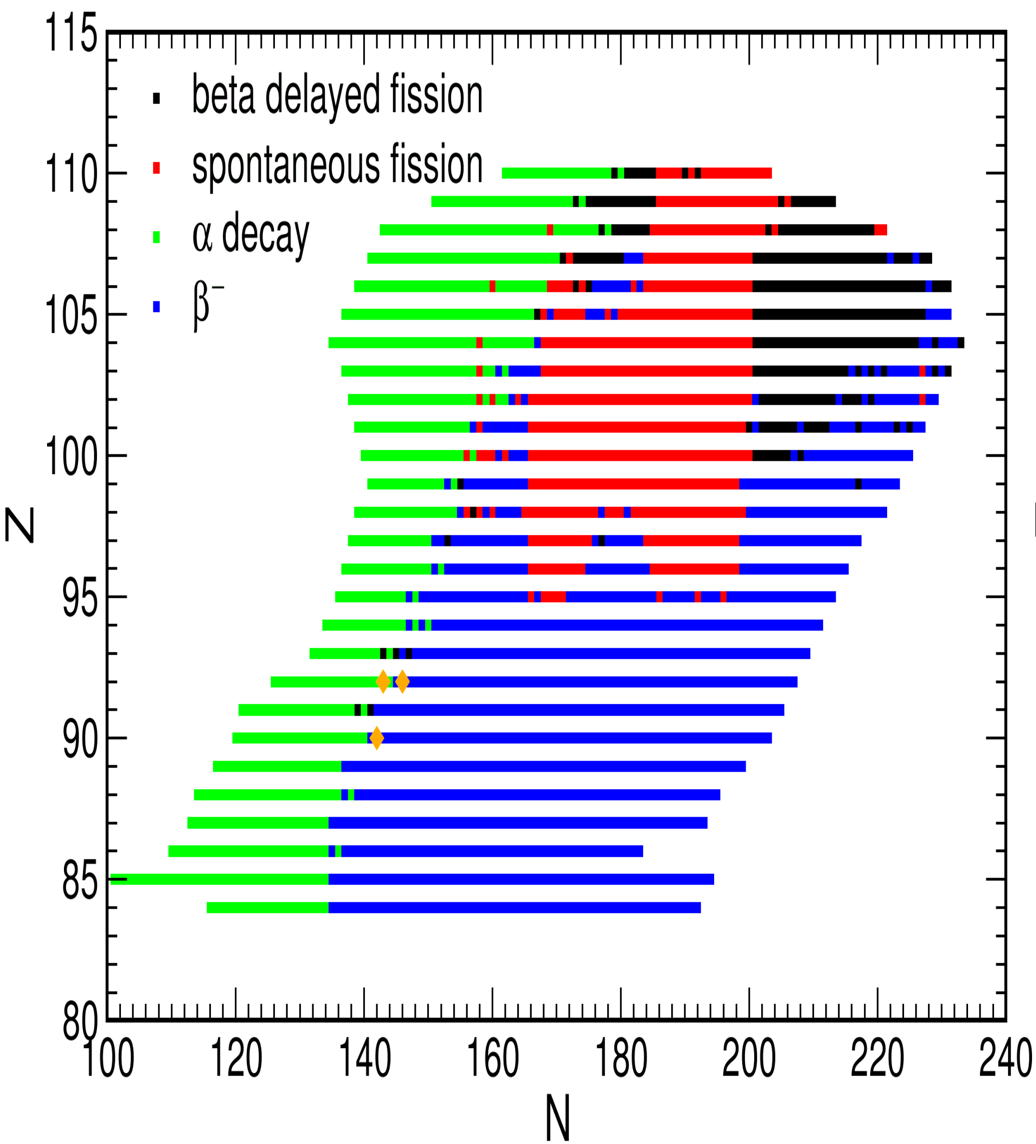


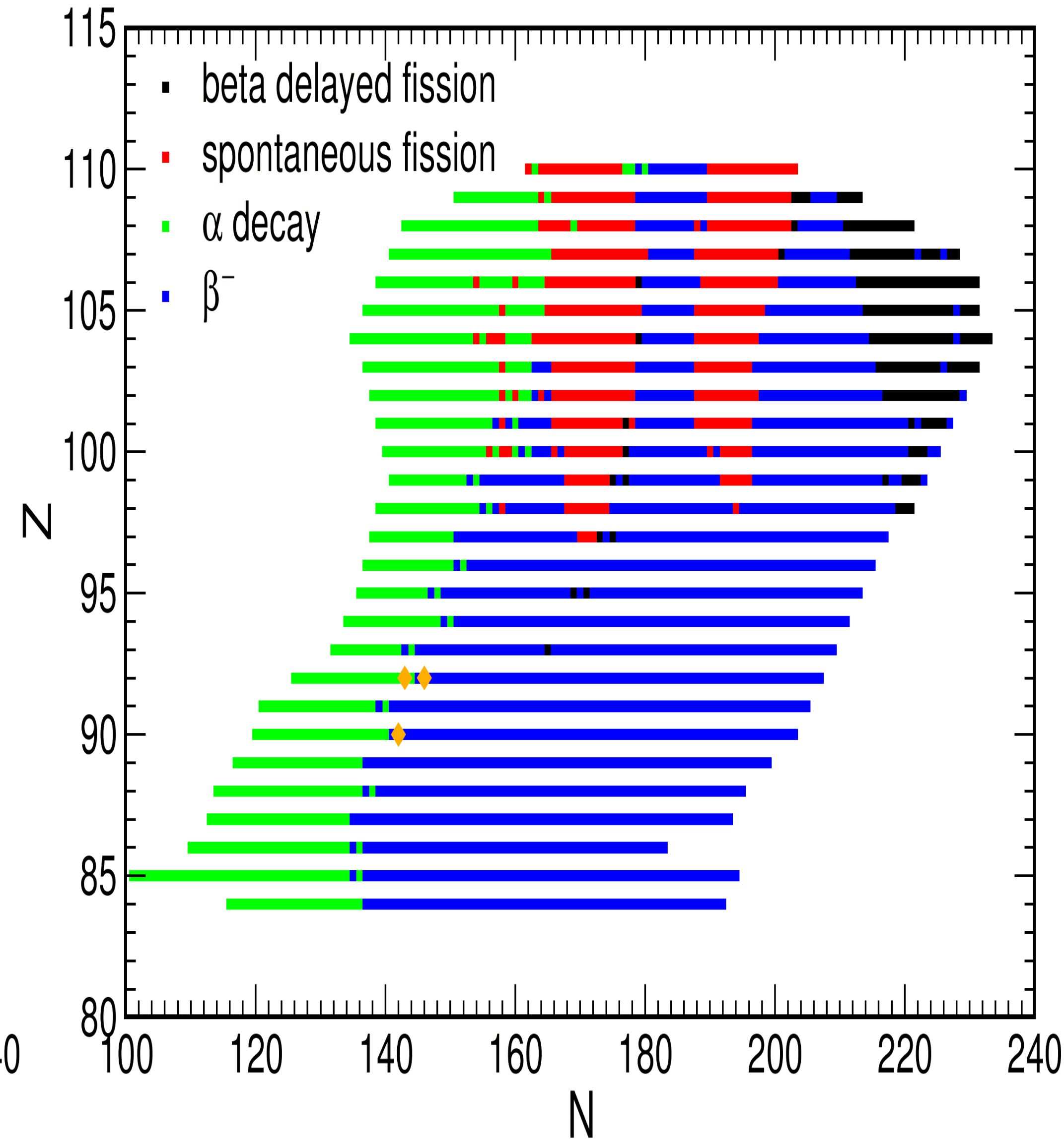
comparison to experimental cross sections via also utilizing experimentally determined fission barriers -> results in typical uncertainties of factor 2

making use of fission barrier predictions from Thomas-Fermi (Myers & Swiatecky), ETFSI (Mamdouh) and recent FRDM (Möller) fission barrier predictions

Inclusion of Decay Channels

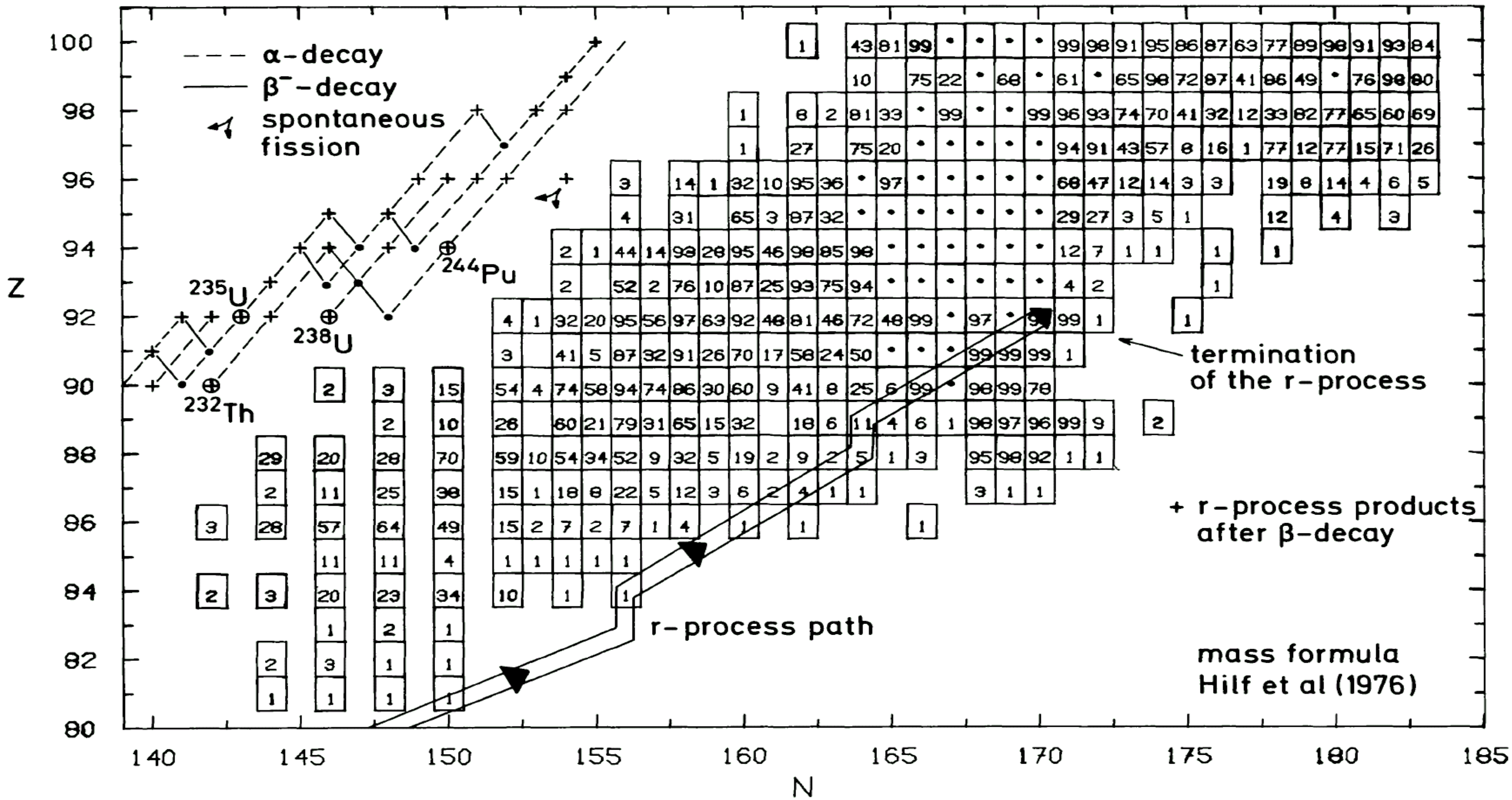
Petermann et al (2010), Martinez-Pinedo et al. (2007), Panov et al. (2005), see also Panov (next talk), fragment distributions (Kelic et al.)





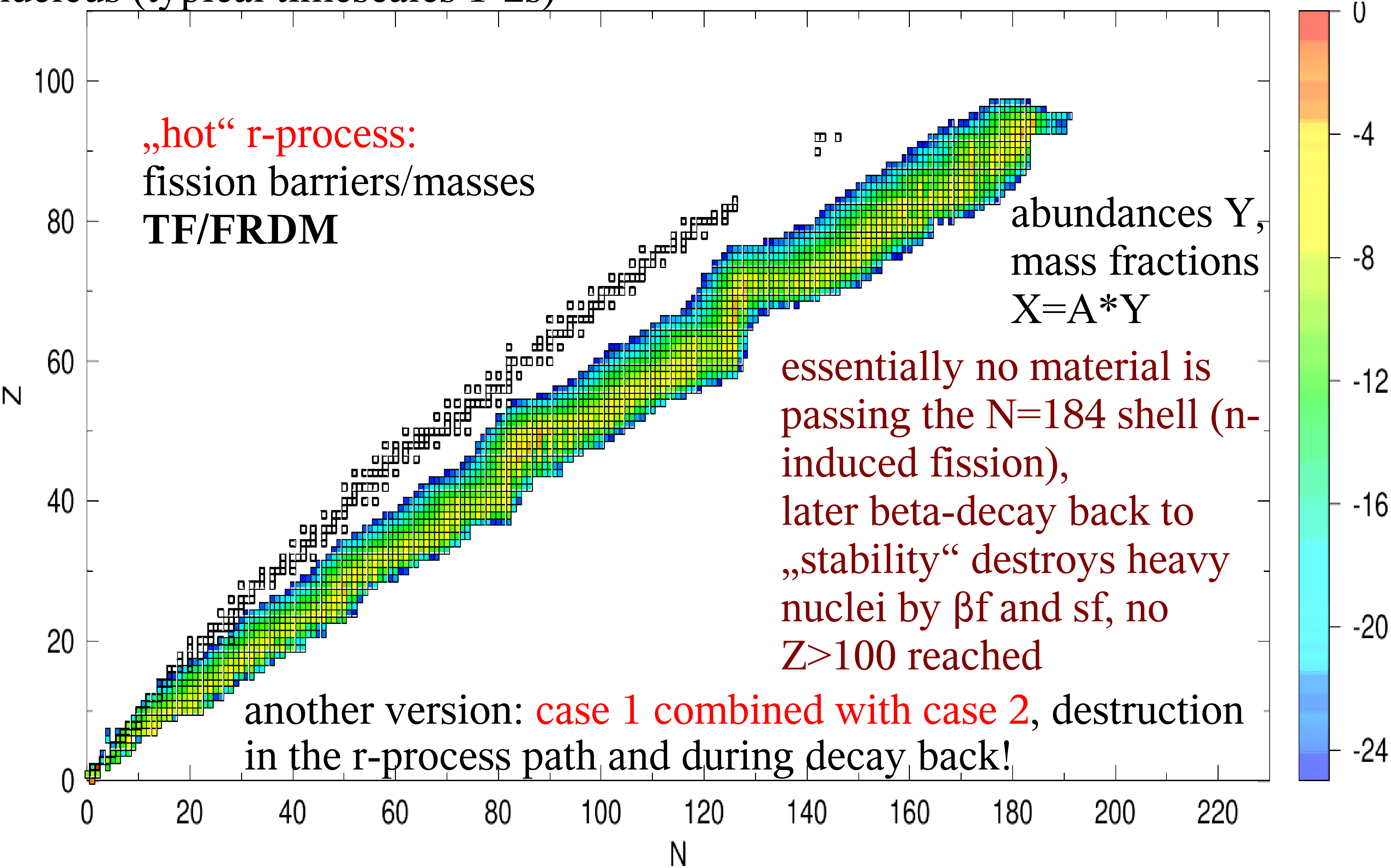
dominant decay channels indicated, important to utilize consistent sets (i.e. based on same mass model), spontaneous fission preliminary results ...

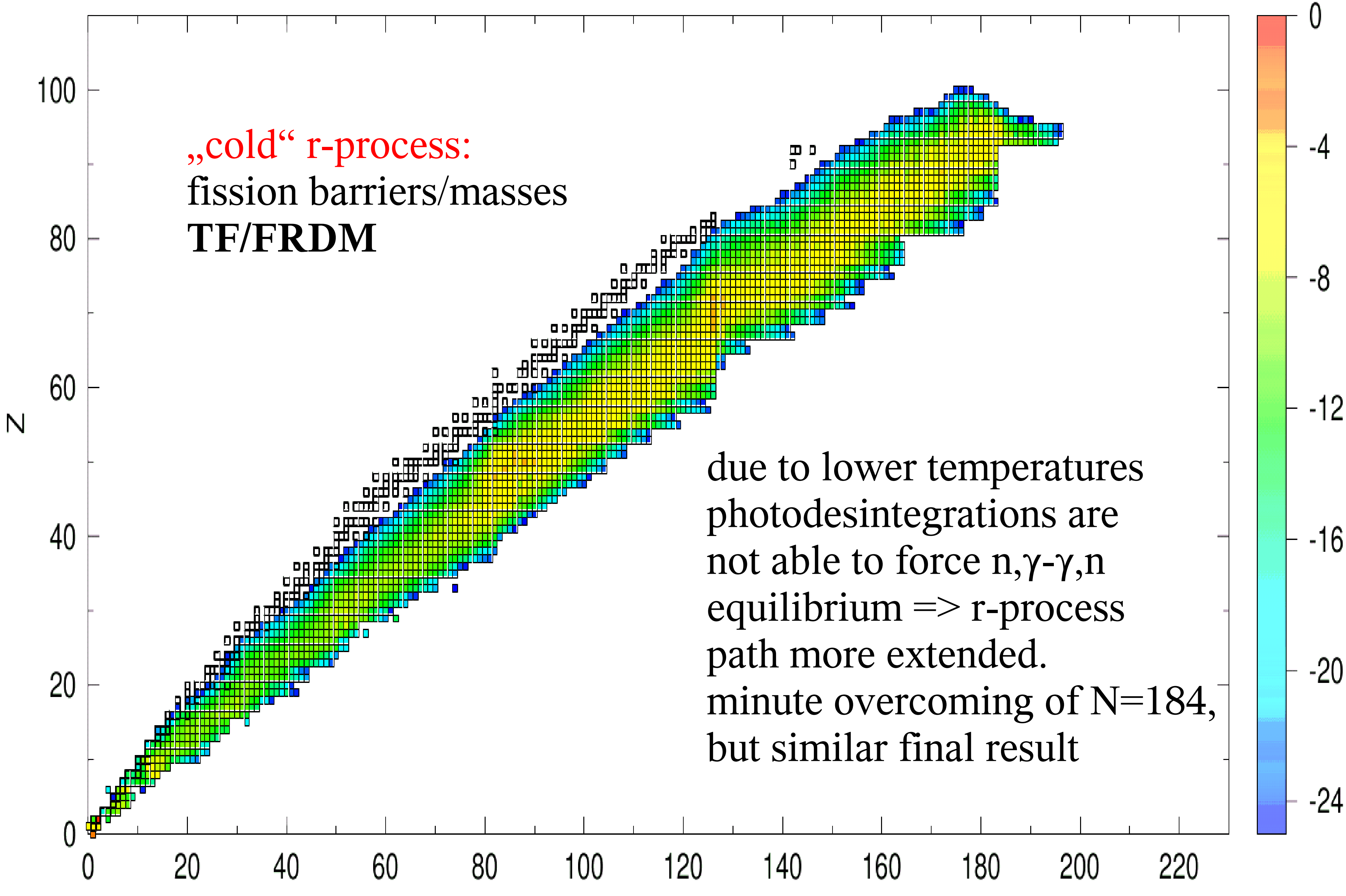
Some History: Thielemann, Metzinger, Klapdor (1983)



Case 1: the r-process ends in a region of 100% beta-delayed fission, no chance to produce SHE! Background, inconsistent data sets (fission barriers from Howard & Möller 1980 – underestimation, mass formula too steep – overestimation of Q_β)

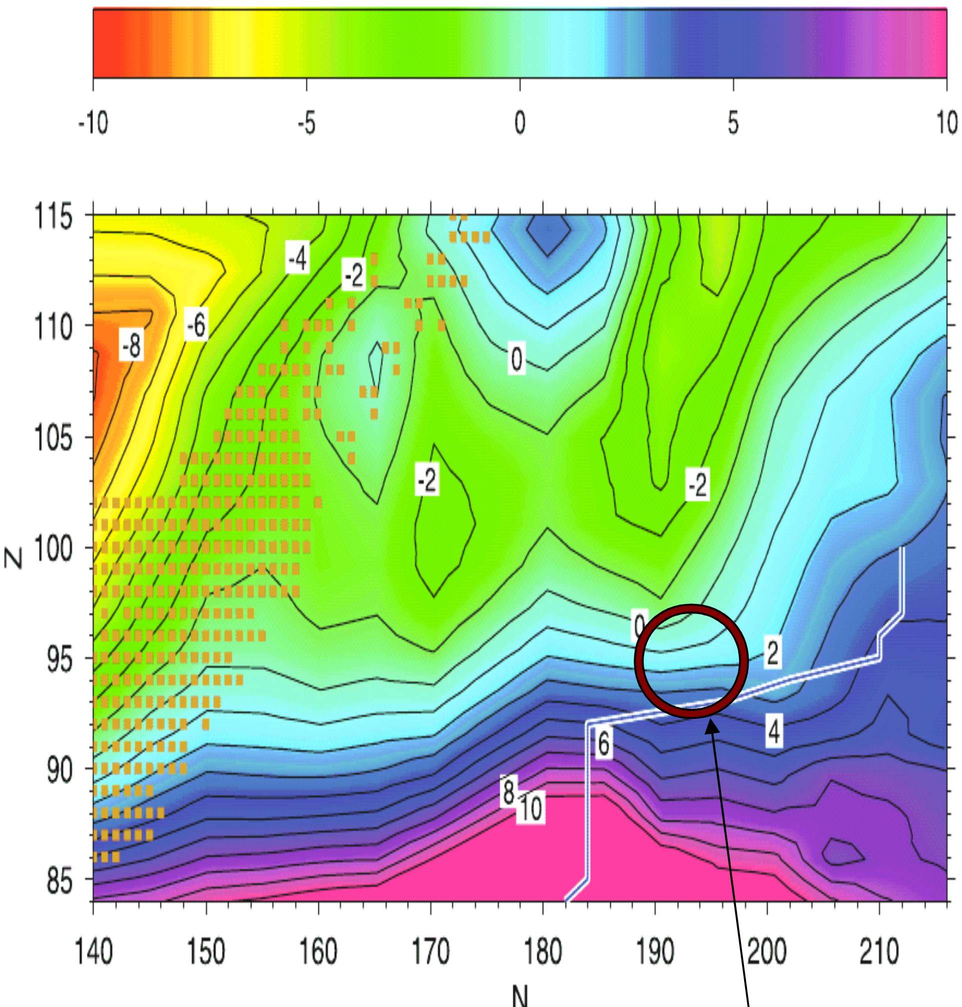
Series of parametrized r-process calculations for a hot and a cold r-process:
starting with a n/seed ratio of 200, results shown when 1 neutron left per heavy nucleus (typical timescales 1-2s)




„cold“ r-process:
fission barriers/masses
TF/FRDM
due to lower temperatures
photodesintegrations are
not able to force n,γ-γ,n
equilibrium => r-process
path more extended.
minute overcoming of N=184,
but similar final result
Z
0
20
40
60
80
100
0
20
40
60
80
100
120
140
160
180
200
220
0
-4
-8
-12
-16
-20
-24

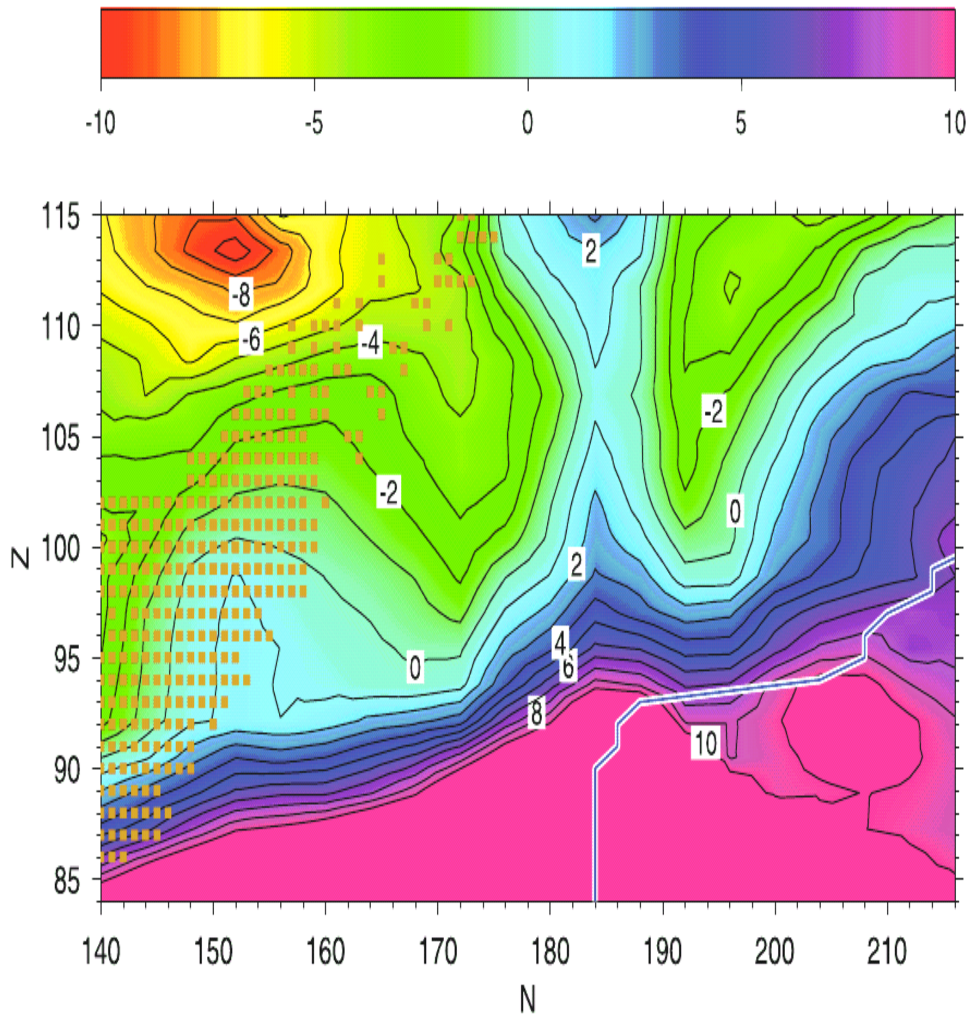
Fission Barriers (B_f-S_n) and the r-Process

(if negative => neutron-induced fission)



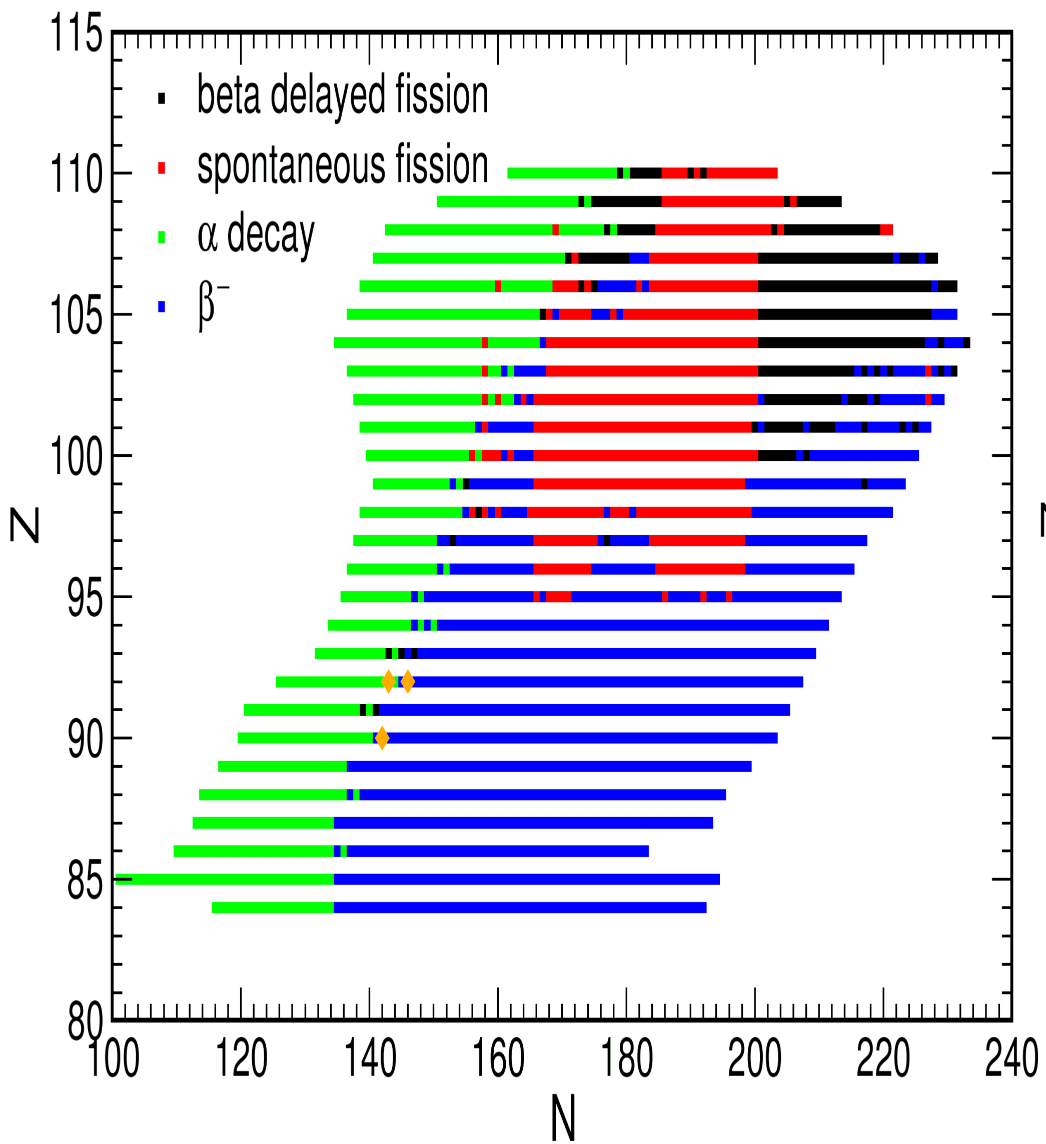
Myers & Swiatecki barriers (TF/FRDM)

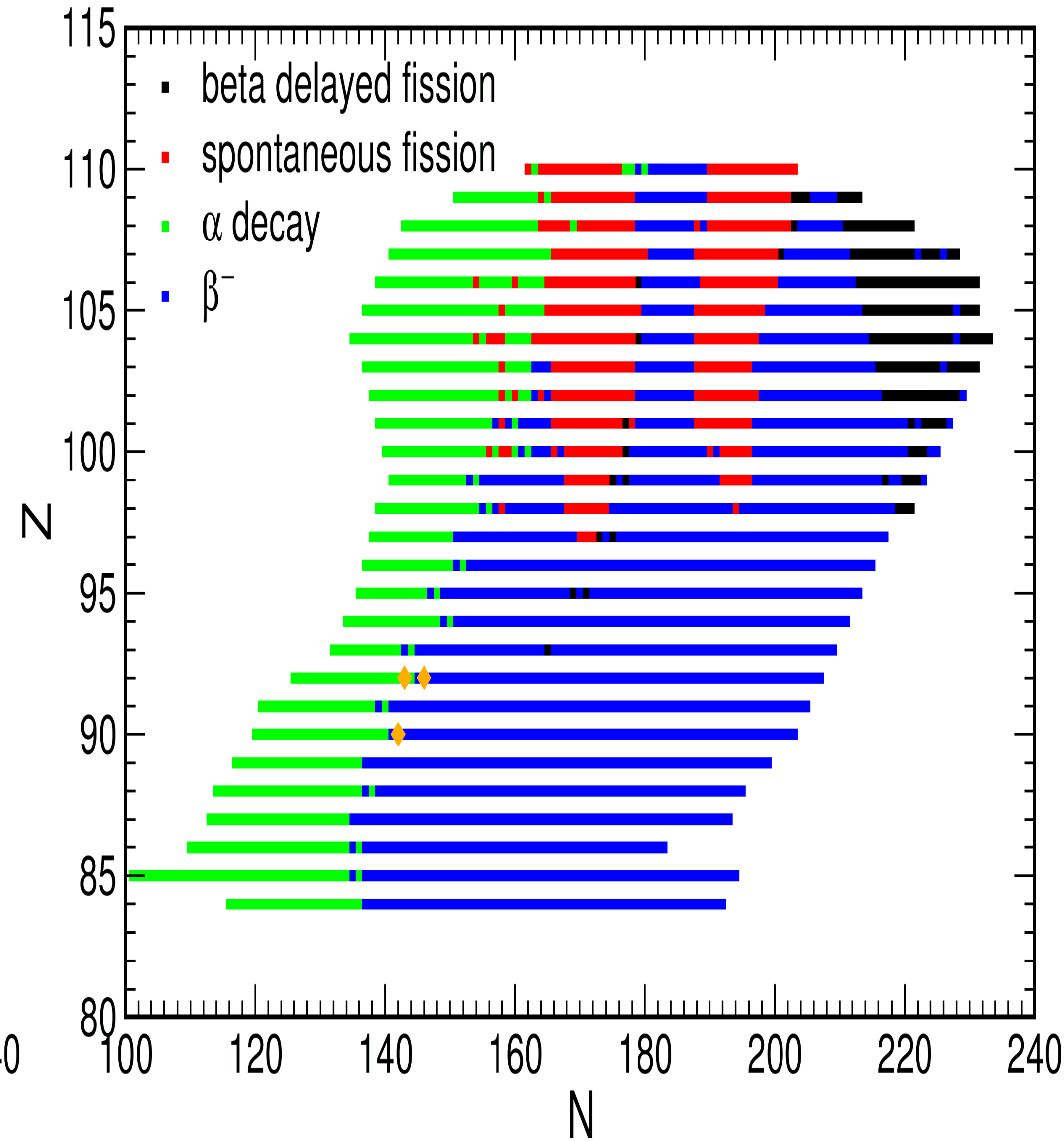
narrow path without n-induced fission!



Mamdouh et al. barriers (ETFSI)

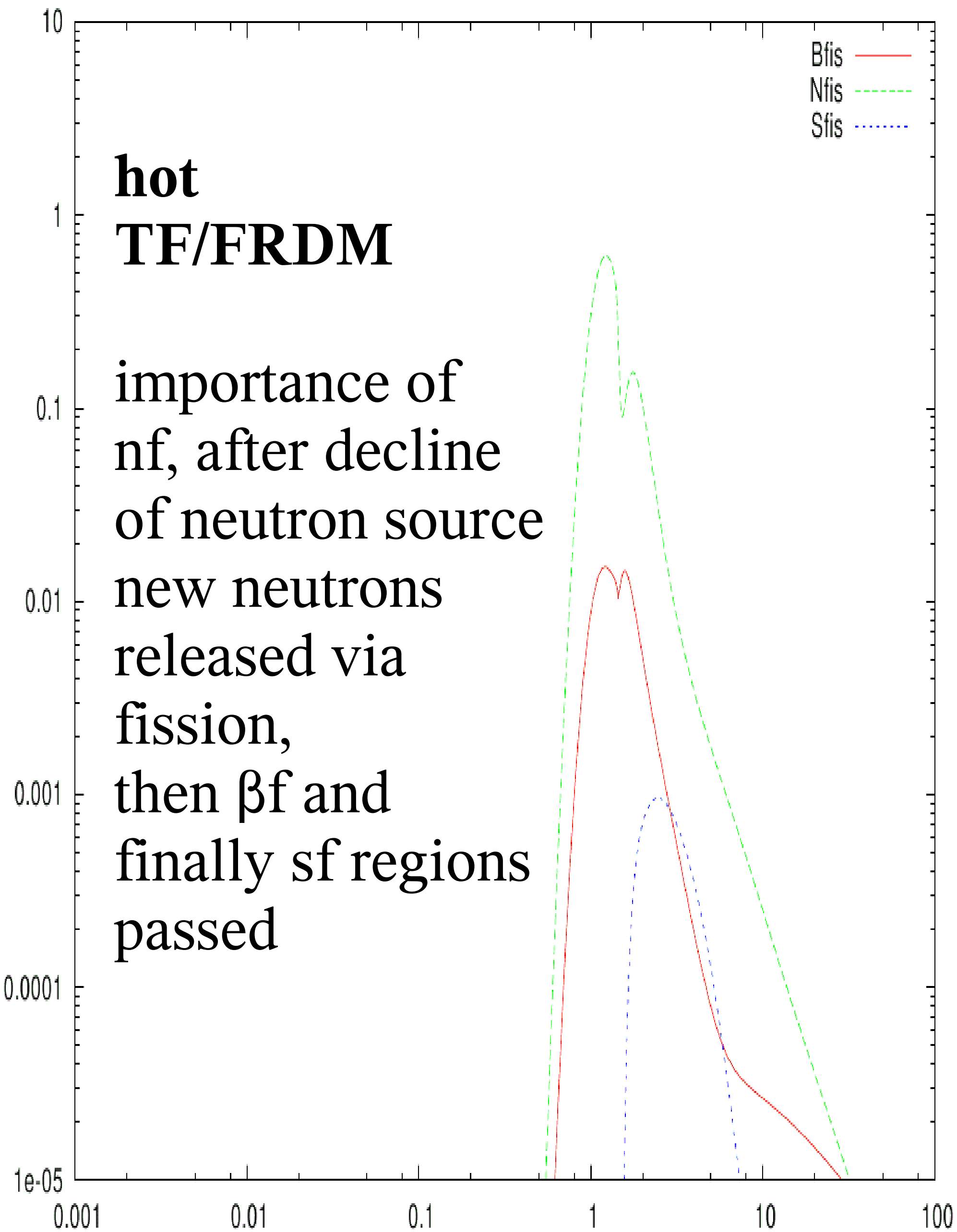
Decay Channels

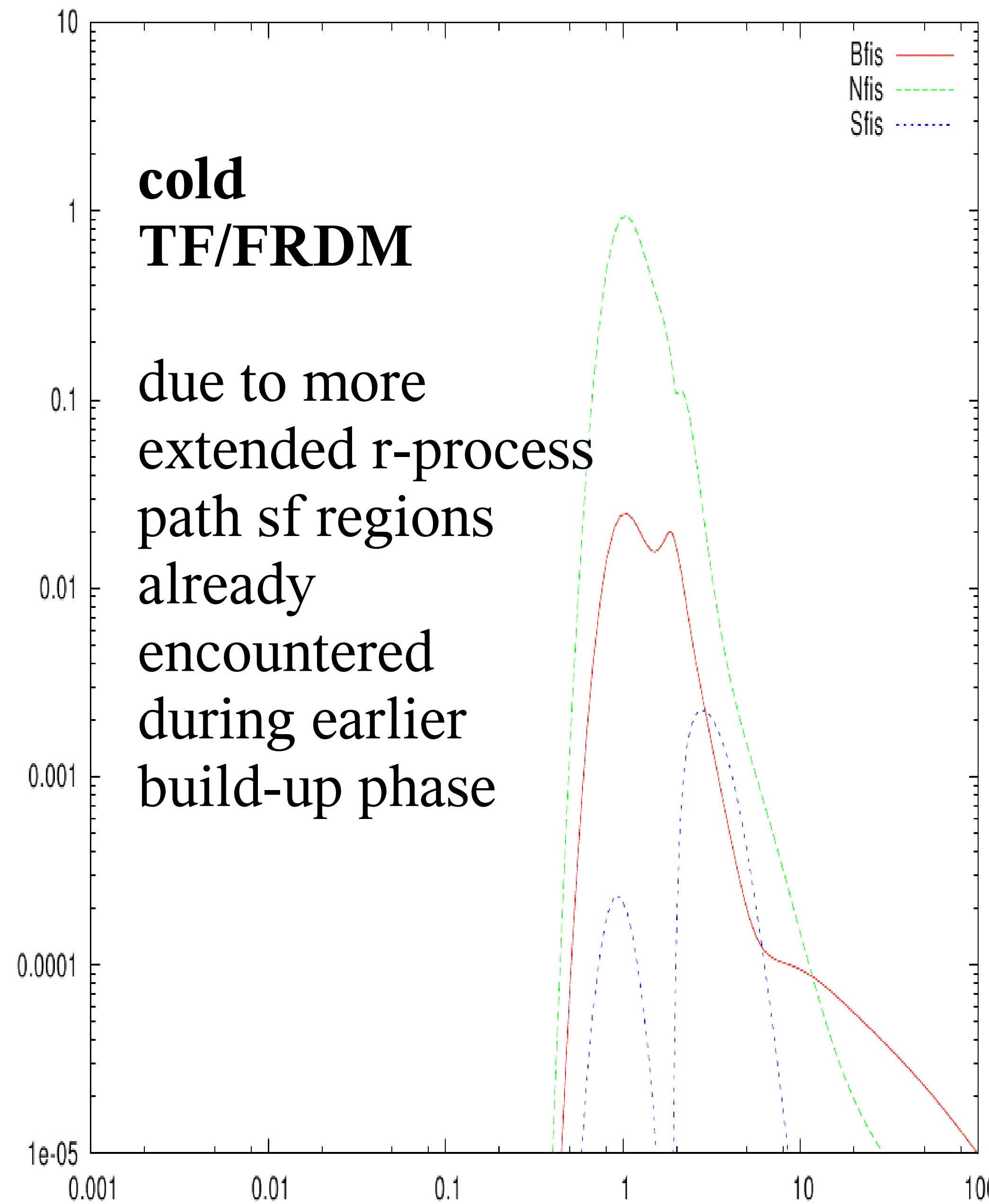


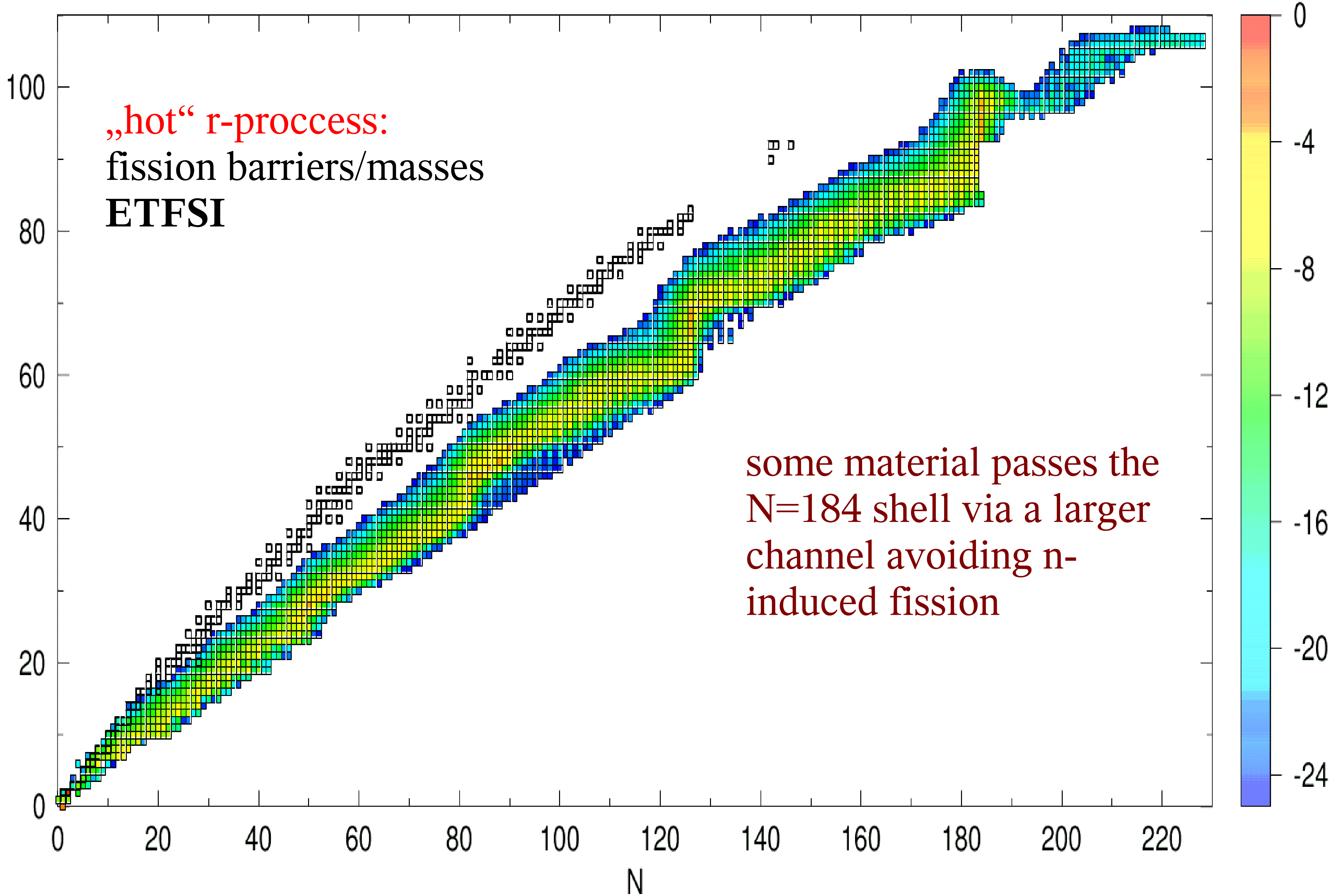


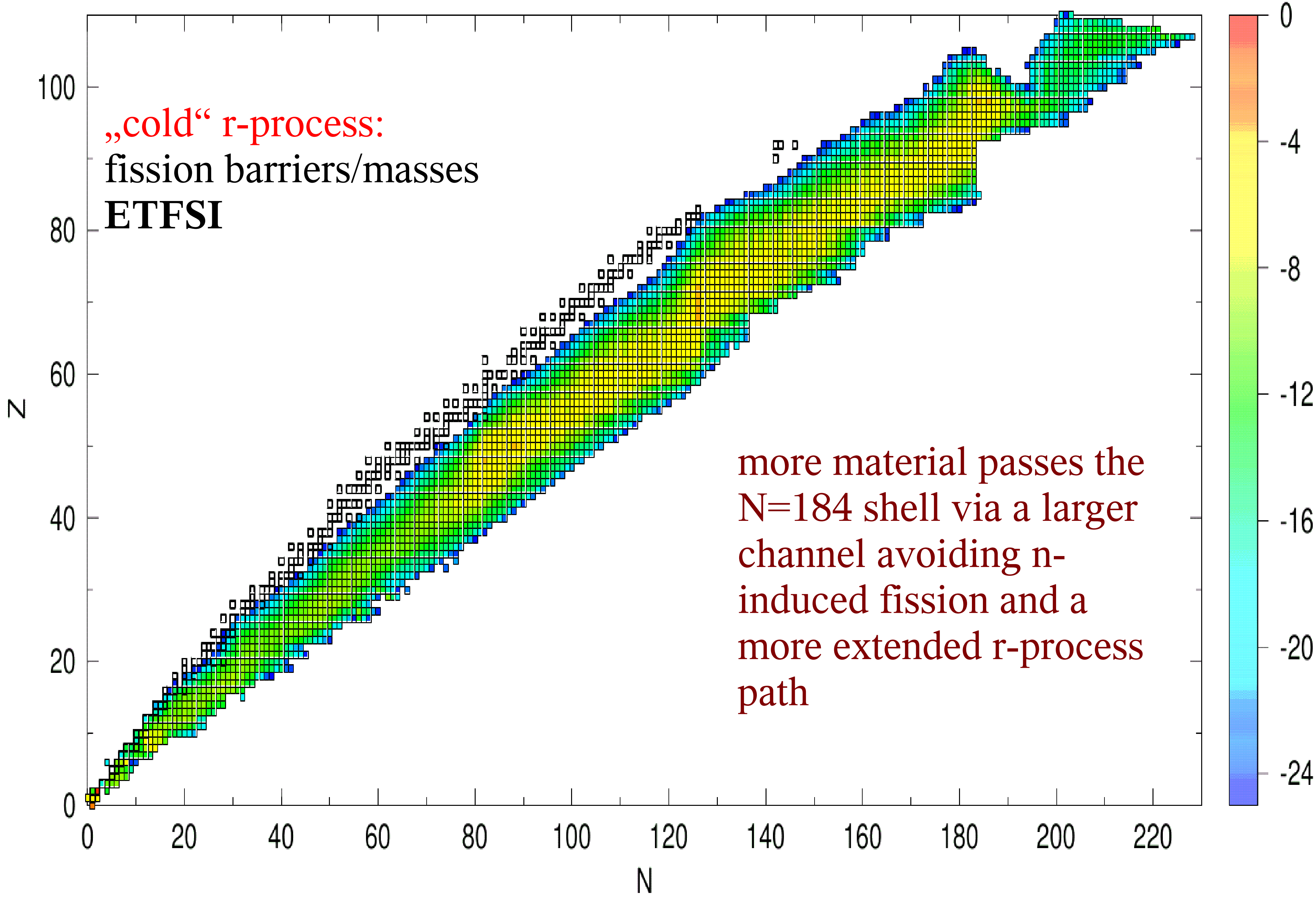
dominant decay channels indicated, important to utilize consistent sets (i.e. based on same mass model), spontaneous fission preliminary results ...

Preliminary!! plots to study influence of nf, βf and sf

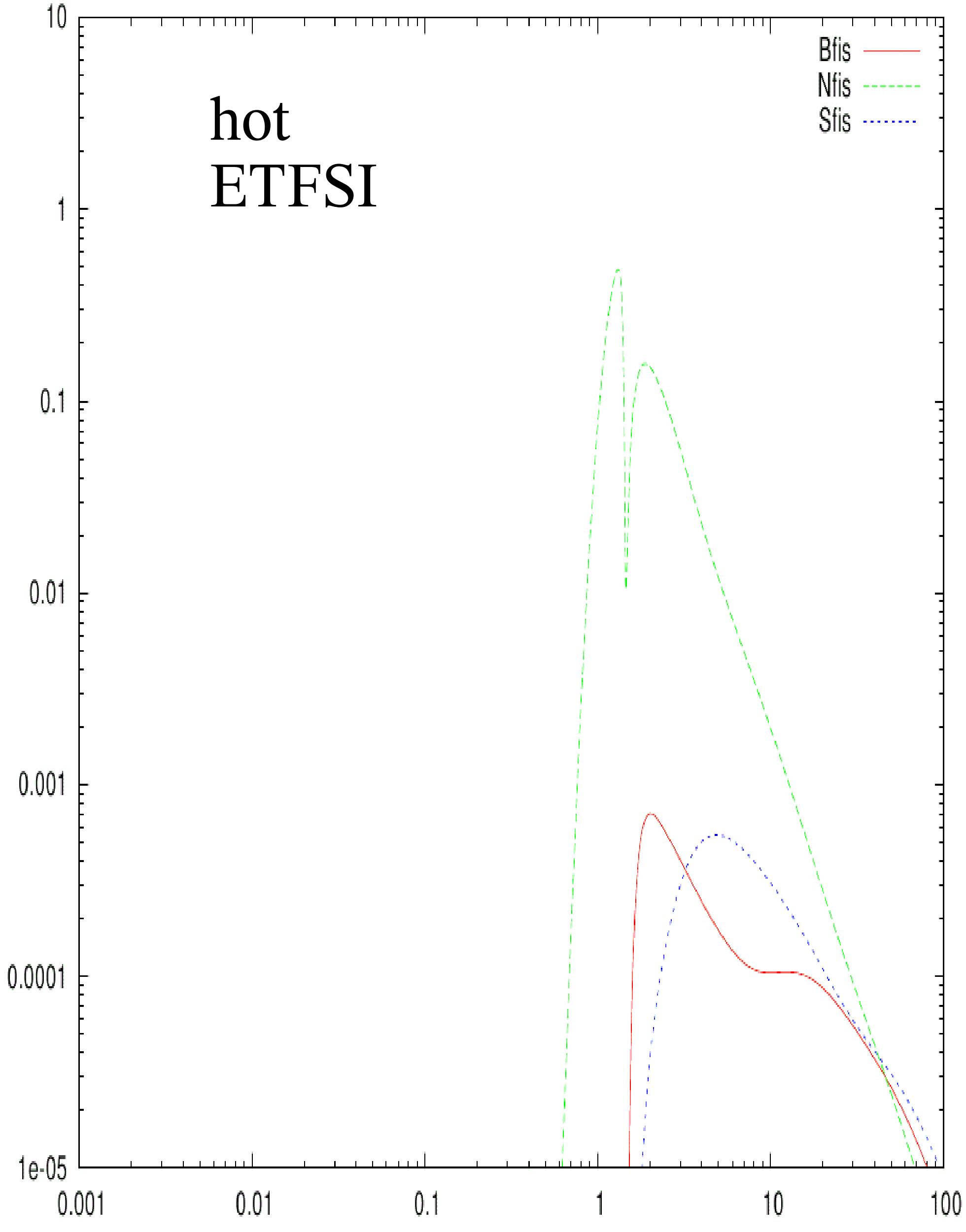


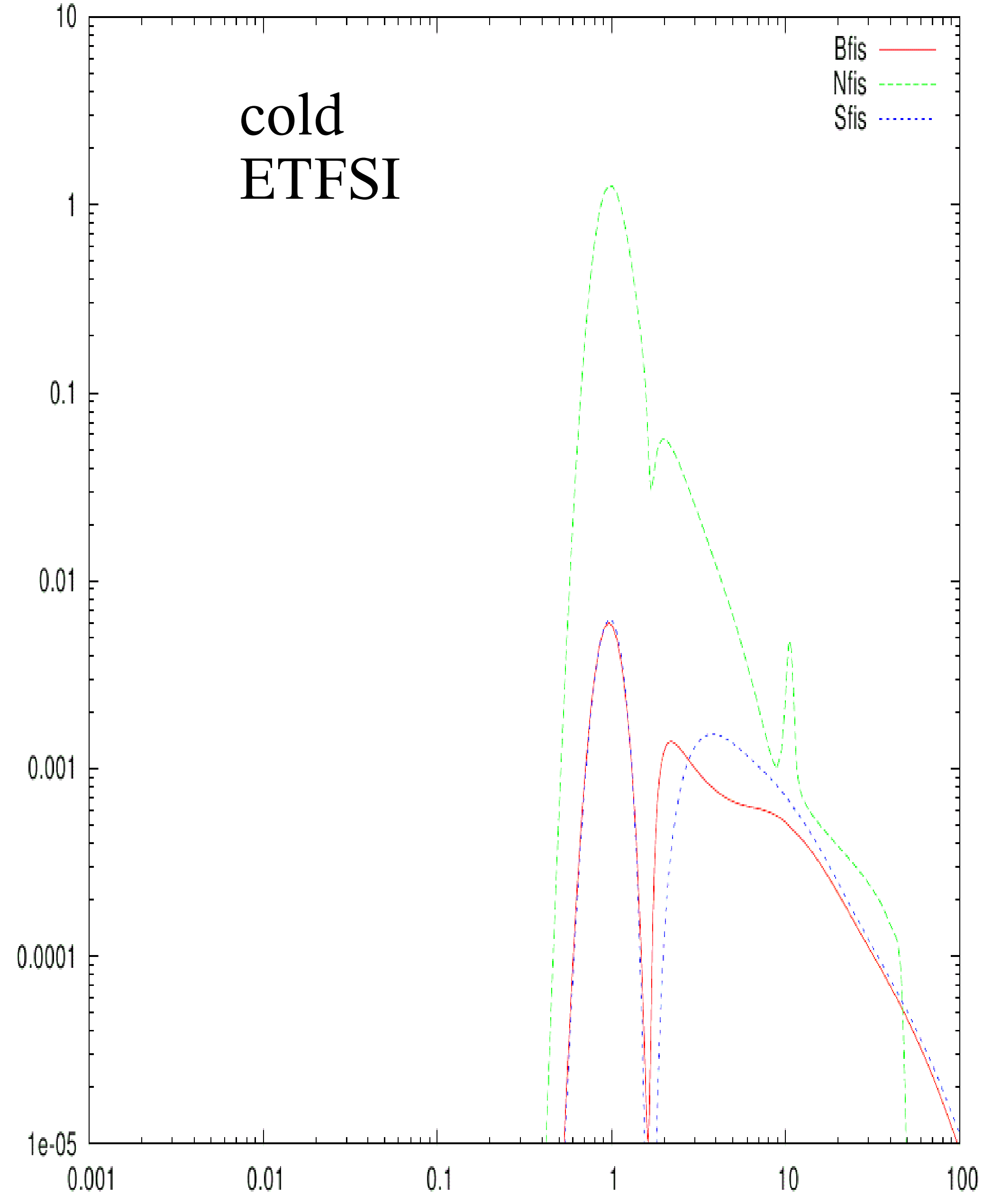



„hot“ r-proccess:
fission barriers/masses
ETFSI
some material passes the N=184 shell via a larger channel avoiding n-induced fission
N
0
20
40
60
80
100
120
140
160
180
200
220
0
-4
-8
-12
-16
-20
-24


„cold“ r-process:
fission barriers/masses
ETFSI
more material passes the N=184 shell via a larger channel avoiding n-induced fission and a more extended r-process path
Z
N
0
20
40
60
80
100
120
140
160
180
200
220
0
-4
-8
-12
-16
-20
-24

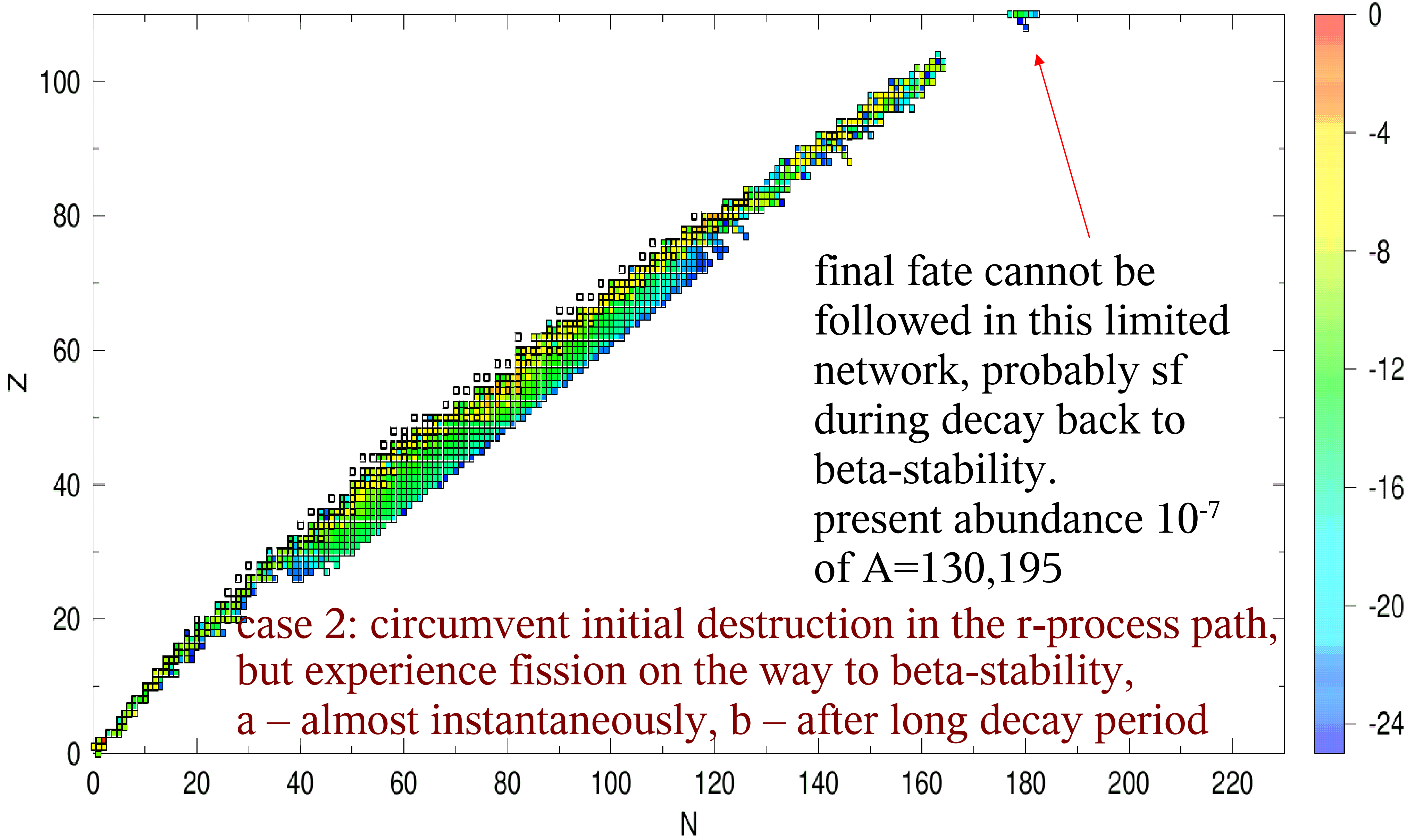
ETFSI Tests





beta-delayed fission of smaller importance and comparable to sf

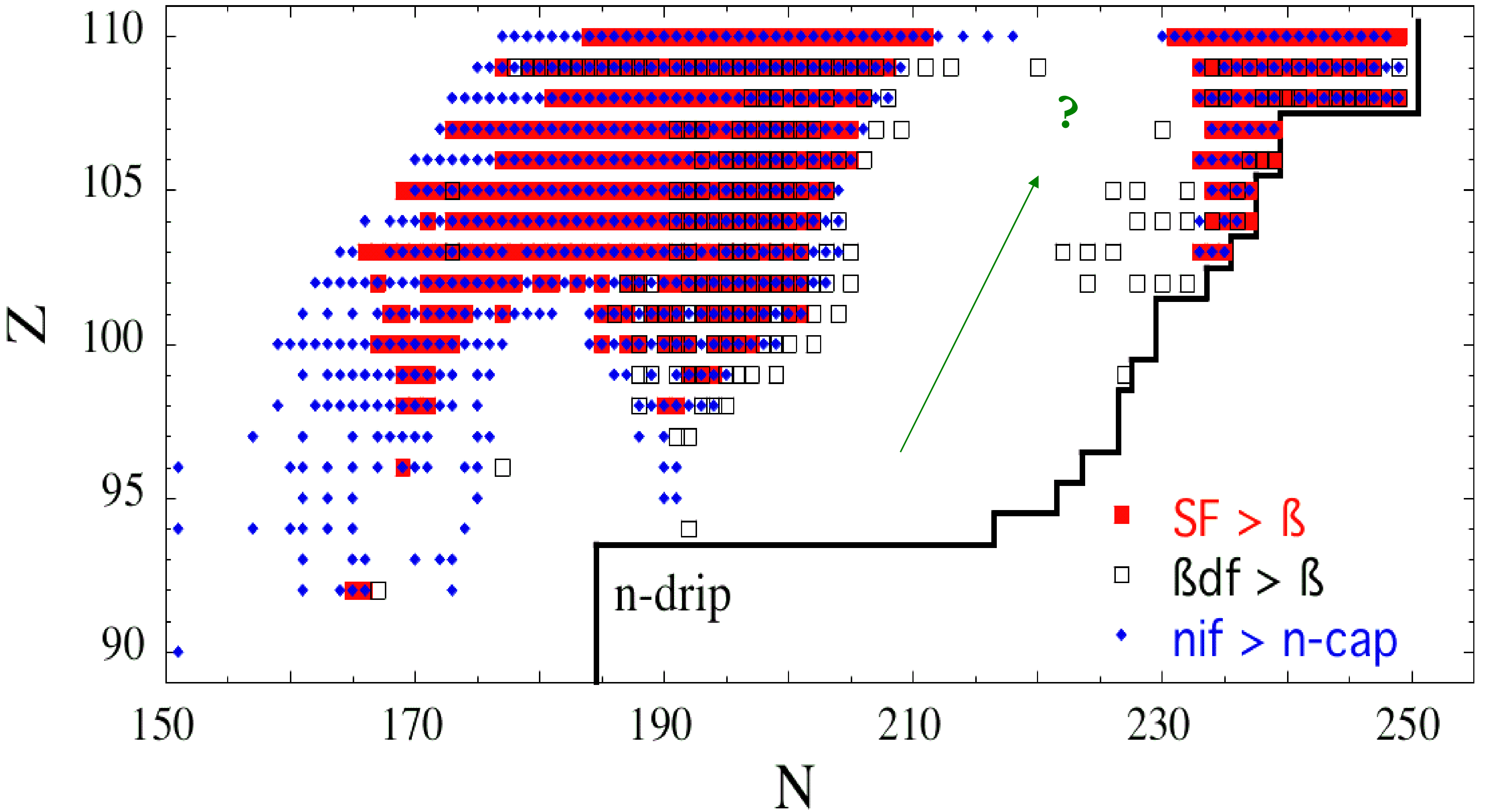
Products of cold r-process (ETFSI) after 1.3 10^6 s (15 days)



final fate cannot be followed in this limited network, probably sf during decay back to beta-stability.
present abundance 10^{-7} of A=130,195

case 2: circumvent initial destruction in the r-process path, but experience fission on the way to beta-stability,
a – almost instantaneously, b – after long decay period

Goriely et al. (2011) HFB, very recent results



a) double finger shape of sf exists, but moves to lower Z (=102)

b) nf reaches close to the dripline at N=190

c) is there a chance to pass around the „fission island?" to higher Z and reach stability? **(case 3), further investigations beyond Z=110!** (P.G. Reinhard!)