Electron Capture-delayed neutron emissions in Neutron Star Crust simulations using a Hauser-Feshbach model

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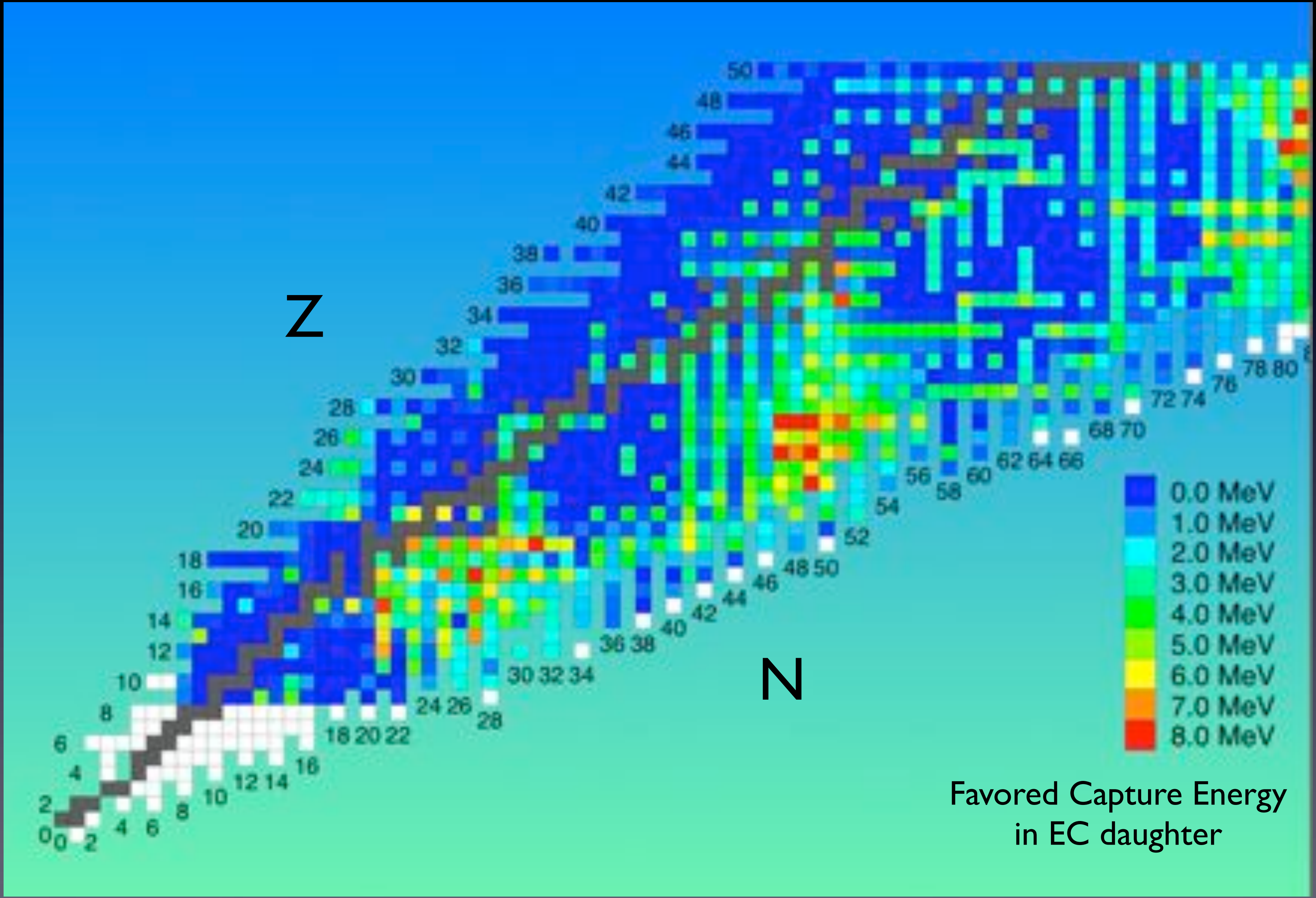
What Kinds of rates do we need?

neutron emissions after a weak interaction has occurred

most important weak interaction in dense,cold stellar env is the Electron Capture, EC-delayed neutron emissions have not been tabulated

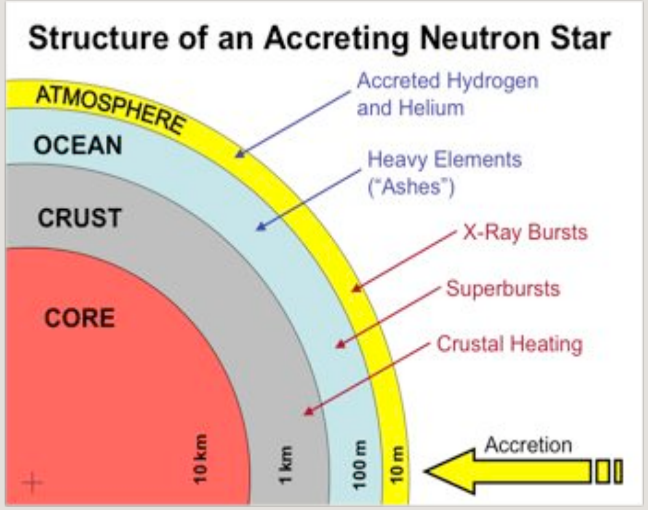
Need global rates for other weak interactions (electron emission, positron emission and capture) for a variety of stellar environments - current compilations have model space limitations

What is the range of nuclei we are interested in?



Favored Capture Energy
in EC daughter

Accreting Neutron Star Nucleosynthesis



* In a LMXB system, the more massive star with shorter lifetime can leave behind a Neutron Star (NS) after core-collapse,which can accrete H/He-rich material from the low-mass companion through a disk.

*Degenerate conditions at the base of the accreted atmosphere can lead to a thermal instability

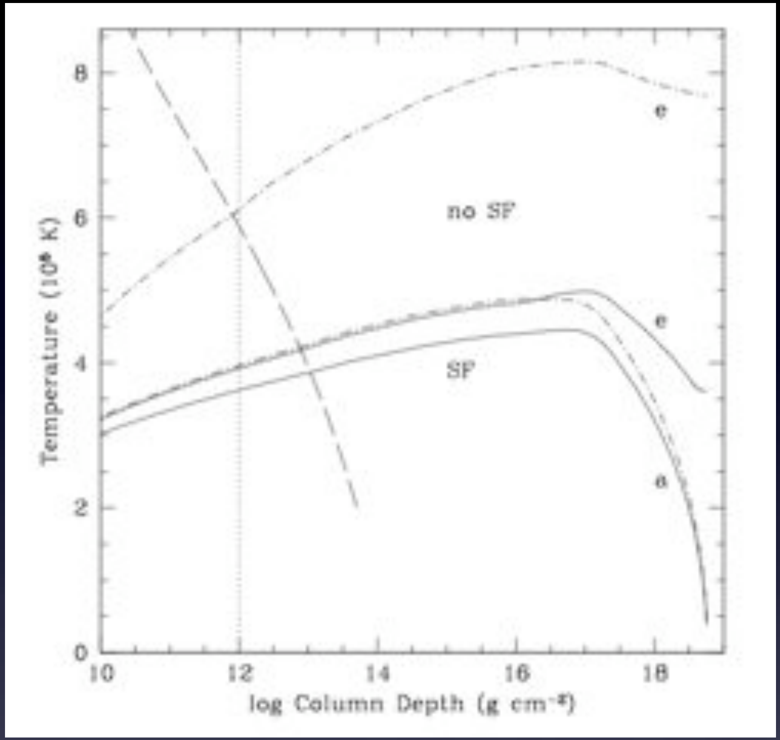
*Hydrogen burning is ignited through the "hot-CNO" cycle, with breakout reactions such as $^{15}O(\alpha, \gamma)^{19}Ne$ at around $4 \cdot 10^8$ K . The hot-CNO-cycle is $^{12}C(p, \gamma)^{13}N(p, \gamma)^{14}O(\beta^+)^{14}N(p, \gamma)^{15}O(\beta^+)^{15}N(p, \alpha)^{12}C$, a catalytic conversion of $4\,^1H$ into ^4He

* At low temperature a slow "rp-process" begins with 2p-captures on an even-even nucleus, a β^+ decay, p-capture, a β^+ decay,and a final (p, α) reaction close to stability on odd-Z targets such as ^{15}N, ^{19}F, ^{23}Na, ^{27}Al, ^{31}P, ^{35}Cl: these are the nuclei at which the H-burning cycles are connected resulting in the CNO-,NeNa-,MgAl-,SiP-,SiCl-cycles. The flow to heavier elements is determined by the $(p,\gamma)/(p, \alpha)$ rate ratio into the next cycle.

* At around $3 \cdot 10^8$ K all the sub-cycles are open except the CNO-, which awaits the $^{15}O(\alpha, \gamma)^{19}Ne$ reaction. Breakouts from these sub-cycles can occur at higher temperatures via p- or α-capture such as the $^{15}O(\alpha, \gamma)$, $^{23}Mg(p, \gamma)$, $^{27}Si(p, \gamma)$,$^{31}S(p, \gamma)$ reactions, which limit storage times in the sub-cycles.

* Higher temperatures from thermal feedback shift the process closer to the proton drip line (higher Coulomb barriers can be overcome) with high (p, γ) reaction rates and the slowest reactions in the sub-cycles become the β^+ decays which act as "Waiting Points" .

An Unsolved Problem.....the heat source of Superbursts

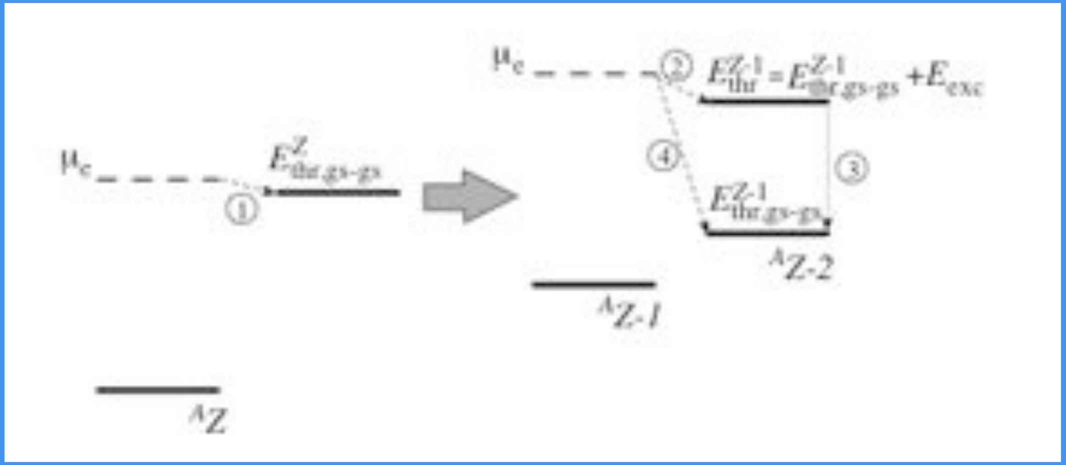


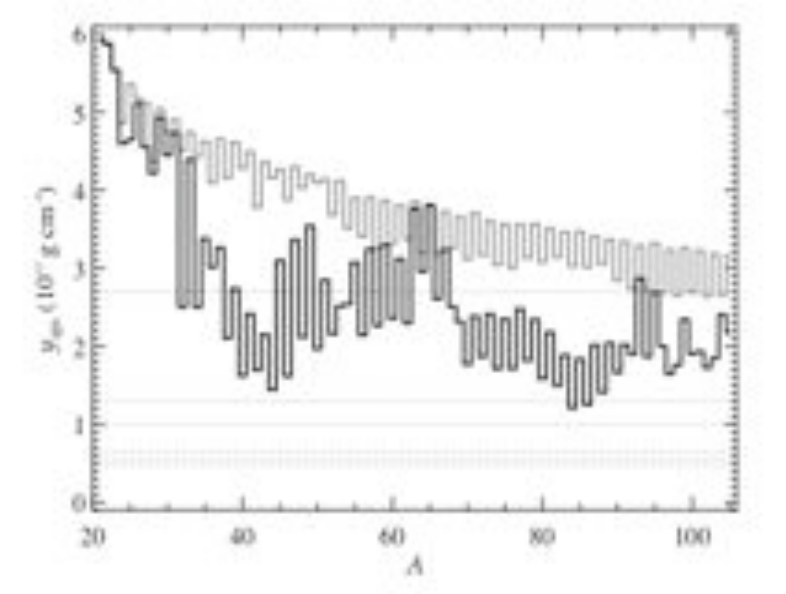
- Superbursts...1000 times more energetic and duration 1000 times longer (about 10^42 ergs and 4-14 hours vs a few tens of seconds

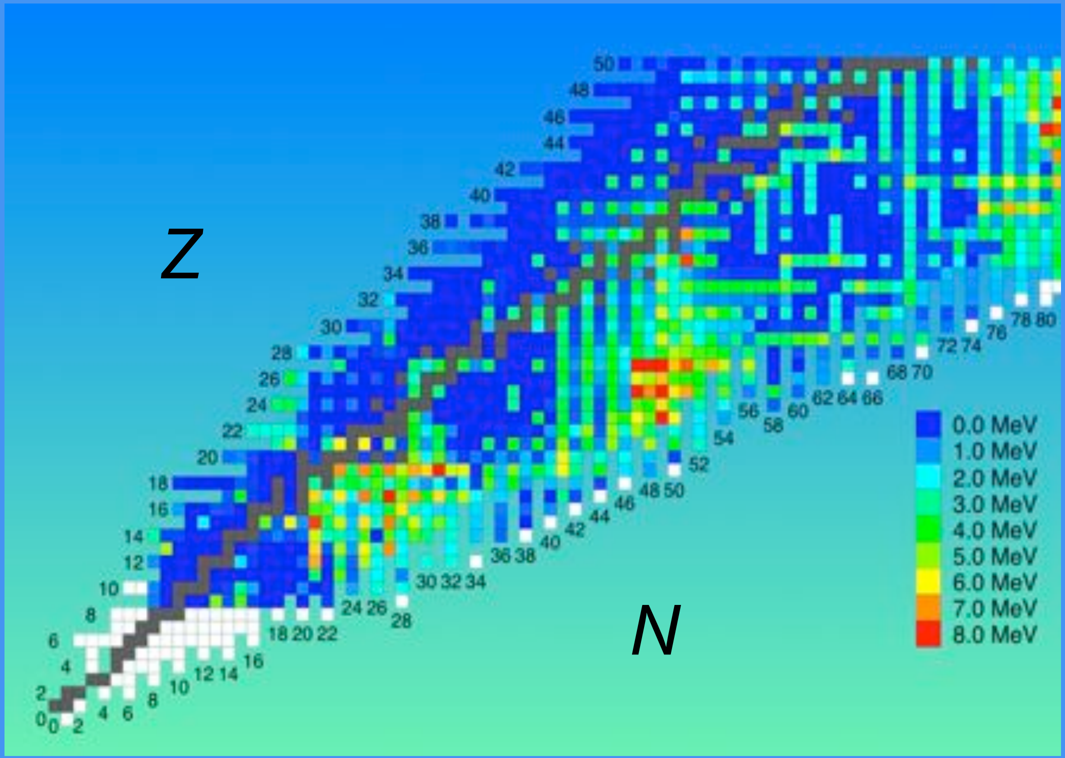
- Initial Composition for Crust Nucleosynth. = XRB ashes
- Heat sources in Crust = EC + pycno
- Pycno rates very uncertain (7-10 orders of magnitude! - Yakovlev et al 2006) but supposed to be dominant source of heat ! (1-1.5 MeV/u)

- What else is going on down there? Need enough heat to ignite Superburst by 12C+12C unstable burning....................

Deep Crustal Heating Mechanisms and the importance of accurate Nuclear Physics input

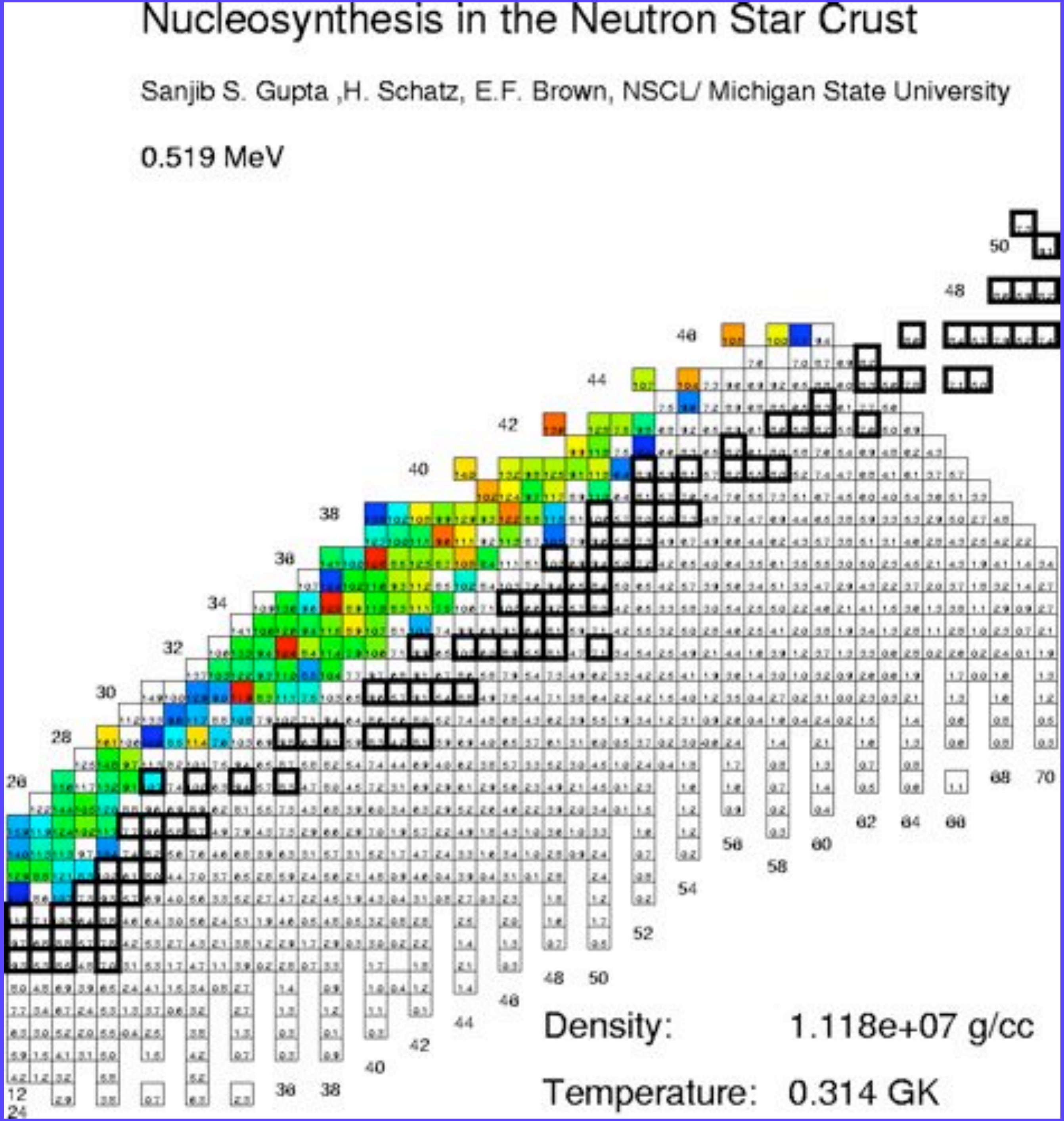






- Gupta et.al. 2007 (ApJ 662:1188) showed the importance of weak interactions into *daughter excited states*
- .We incorporate the capture into excited states with accurate B(GT+) calculations from QRPA model (Moller and Randrup, Nuc. Phys. A 514:1-48 (1990)).
- Importance of B(GT+) shown - now need to incorporate effects from (n,γ) and (EC,*x*n) to determine true heating profile.

But there are neutrons also playing a role! Not just normal (gamma,n) but also (EC,xn) !



Nucleosynthesis in the Neutron Star Crust

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0.519 MeV

Density: 1.118e+07 g/cc

Temperature: 0.314 GK

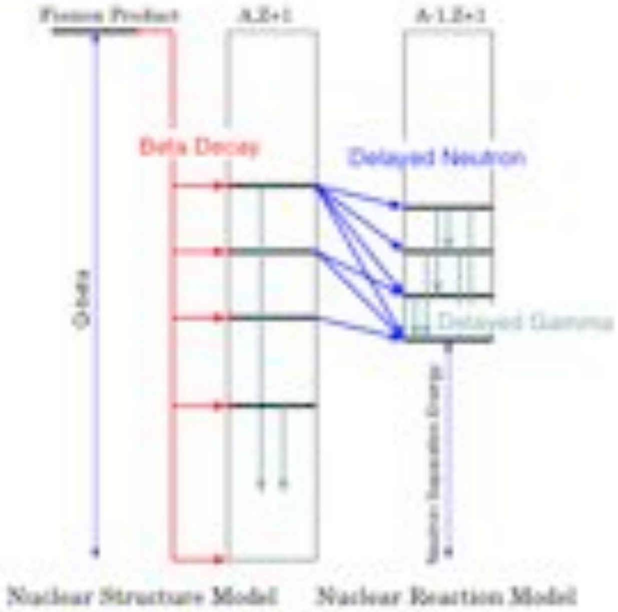
Is It possible to get heating from n-emissions and n-captures significantly shallower than cold neutron-drip? (And depend less on pycnonuclear reactions?

- Since we have a large spread in A-chains, n-emissions from the most n-rich + capture into others can cause net heating. Also by changing the A-distribution, more heating from EC into excited states!
- Ultimately, both electrons and neutrons play a role in the nucleosynthesis, and the high density of neutrons will result in almost instant equilibration along constant Z, very similar to the Waiting Point (n,gamma)-(gamma,n) equilibrium + Steady Flow (beta equil. between Z-chains) Approximation used in (parametrized) r-process calculations! (except we do not have (gamma,n) as the only neutron source but (EC,xn) also play a central role)

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

- BUT we need a new player for these n-rich nuclei under conditions of VERY high electron chemical potential that has never been calculated before....EC delayed neutron emission rates (and branchings 1-n 2-n,3-n,.........). The calculations are similar to beta-delayed n-emission, useful to other appl.

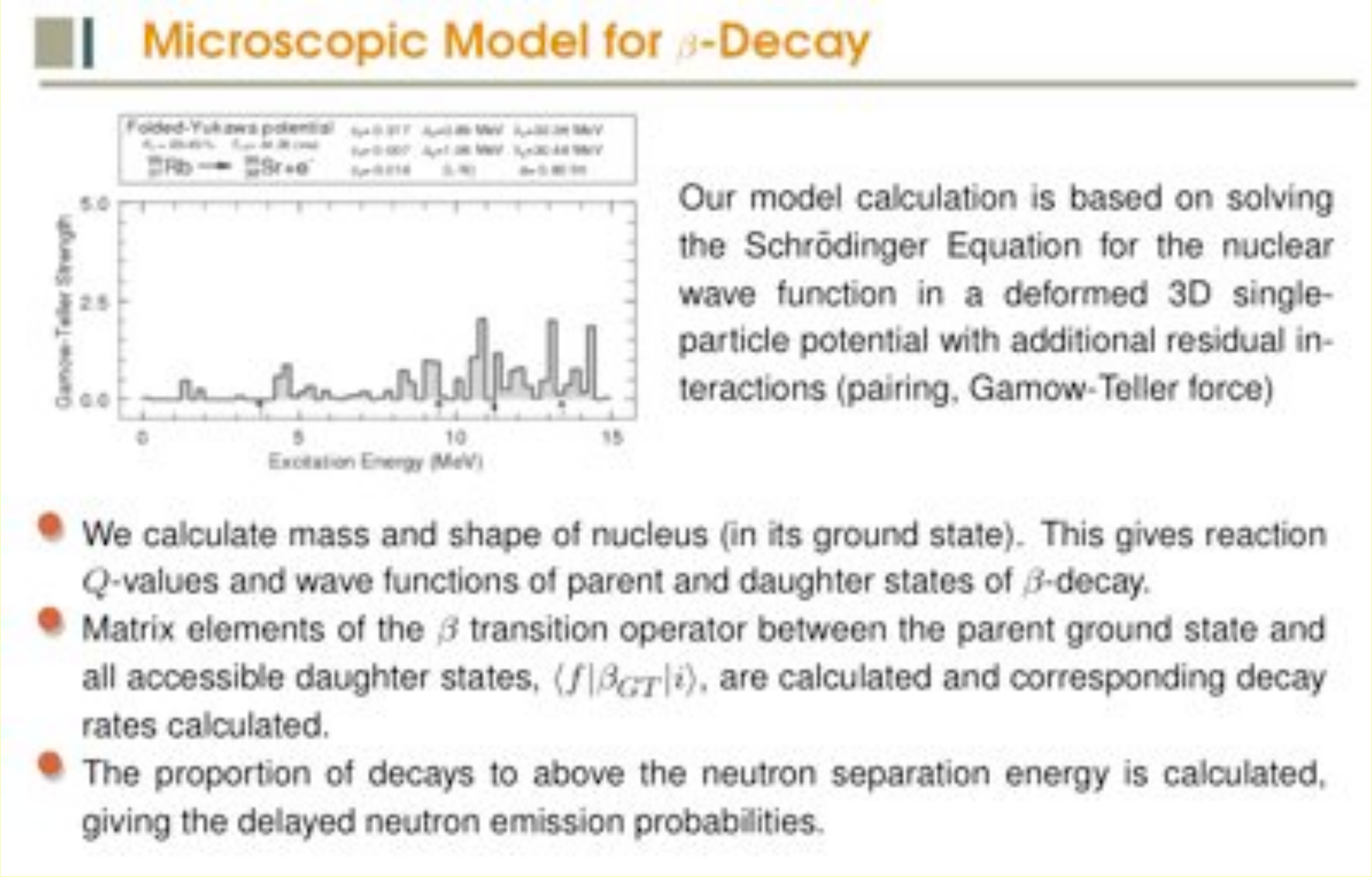
β-Delayed Neutron



- Once photo-fission takes place, two fission fragments (FF) emit prompt neutrons and γ-rays, and they de-excite to their ground state.
- Some fragments β-decay to more stable nuclei, and they can emit a delayed neutron if the final state excitation energy is higher than the neutron separation energy.

Theory Developed

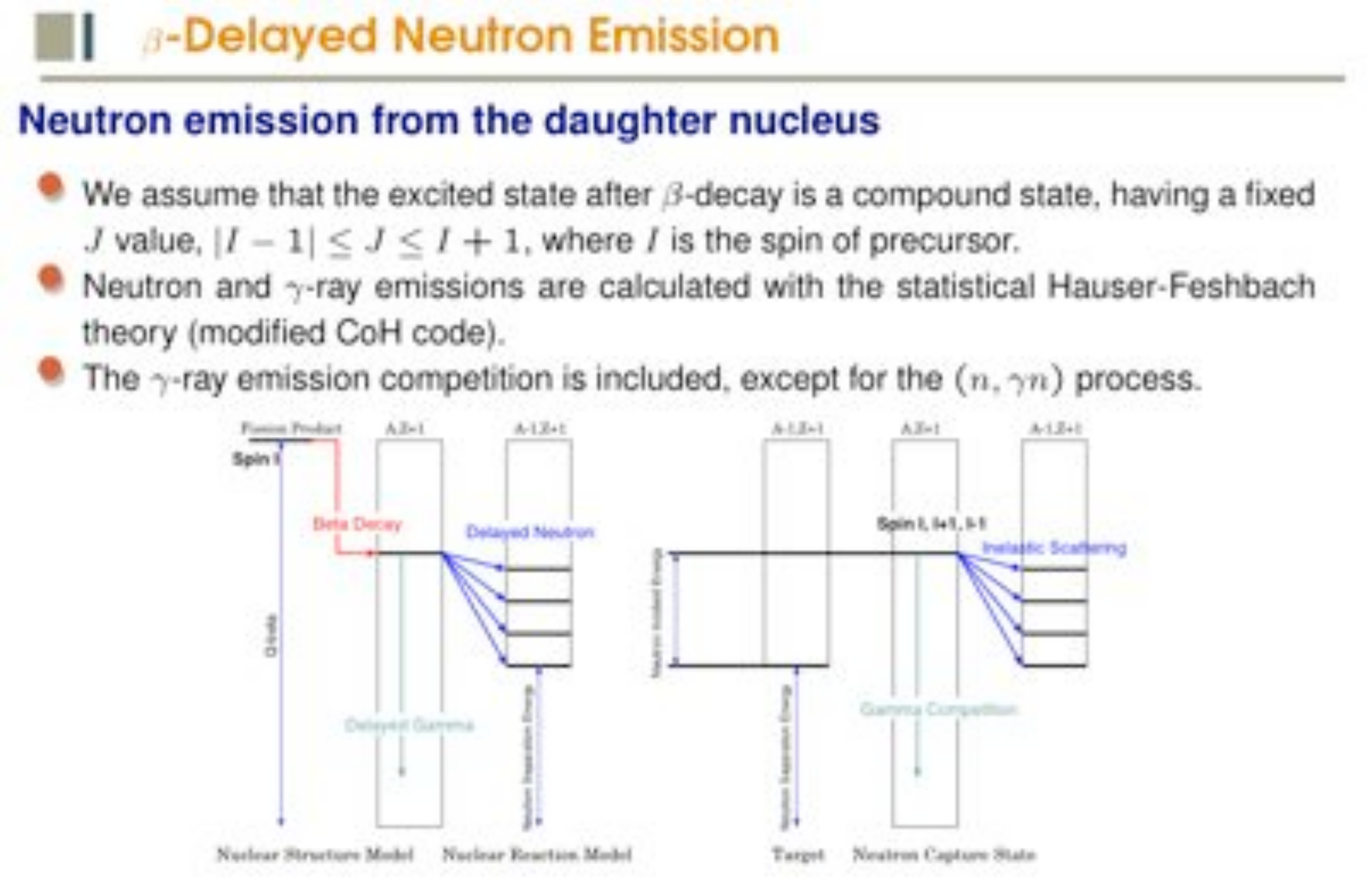
- β-decay rate : Q_β from Möller mass model (FRDM); decay matrix element $\langle f|\beta_{GT}|i\rangle$ from (Möller) QRPA model
- neutron and γ emission range : statistical Hauser-Feshbach model
- nuclear structure data are taken from ENSDF



Microscopic Model for β-Decay

Our model calculation is based on solving the Schrödinger Equation for the nuclear wave function in a deformed 3D single-particle potential with additional residual interactions (pairing, Gamow-Teller force)

- We calculate mass and shape of nucleus (in its ground state). This gives reaction Q-values and wave functions of parent and daughter states of β-decay.
- Matrix elements of the β transition operator between the parent ground state and all accessible daughter states, $\langle f|\beta_{GT}|i\rangle$, are calculated and corresponding decay rates calculated.
- The proportion of decays to above the neutron separation energy is calculated, giving the delayed neutron emission probabilities.



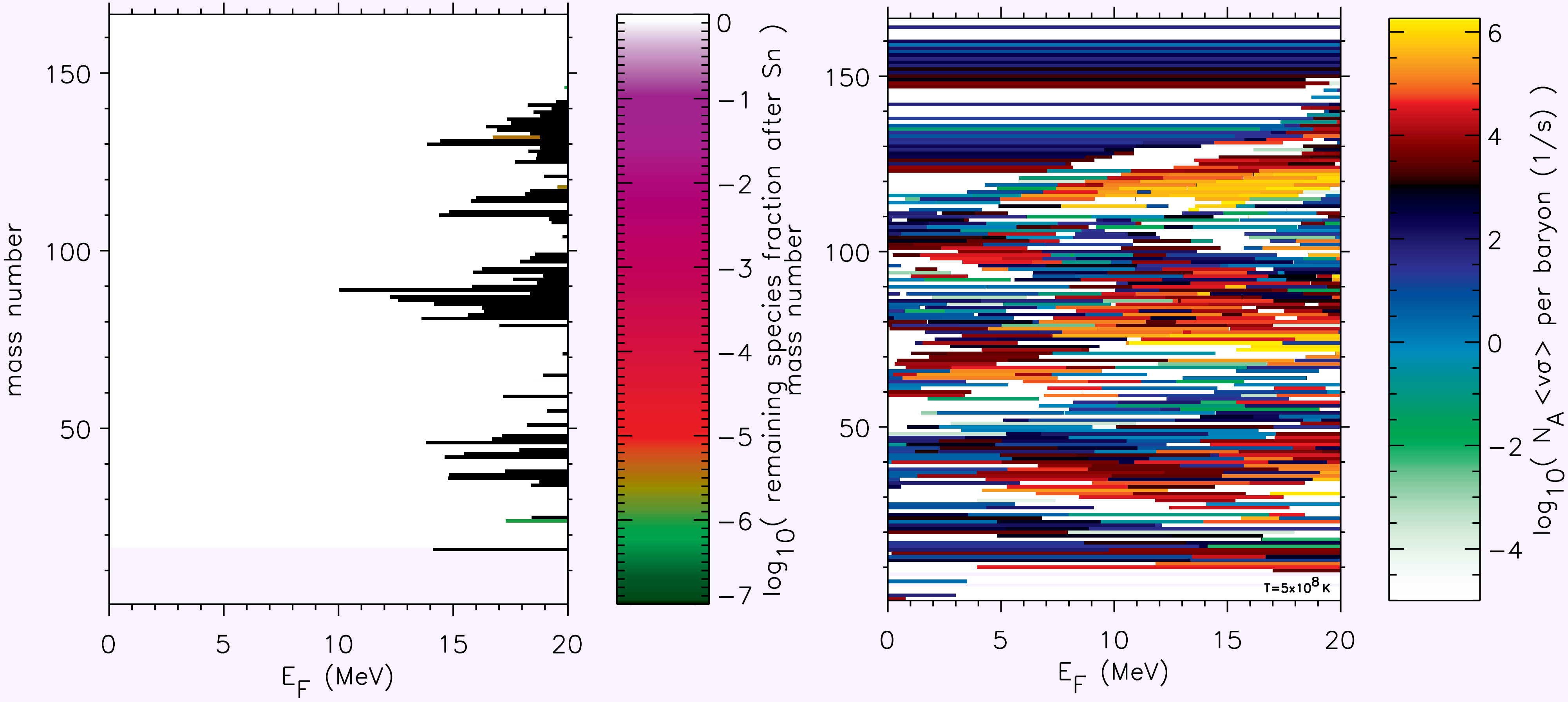
β-Delayed Neutron Emission

Neutron emission from the daughter nucleus

- We assume that the excited state after β-decay is a compound state, having a fixed J value, $|I-1| \leq J \leq I+1$, where I is the spin of precursor.
- Neutron and γ-ray emissions are calculated with the statistical Hauser-Feshbach theory (modified CoH code).
- The γ-ray emission competition is included, except for the $(n, \gamma n)$ process.

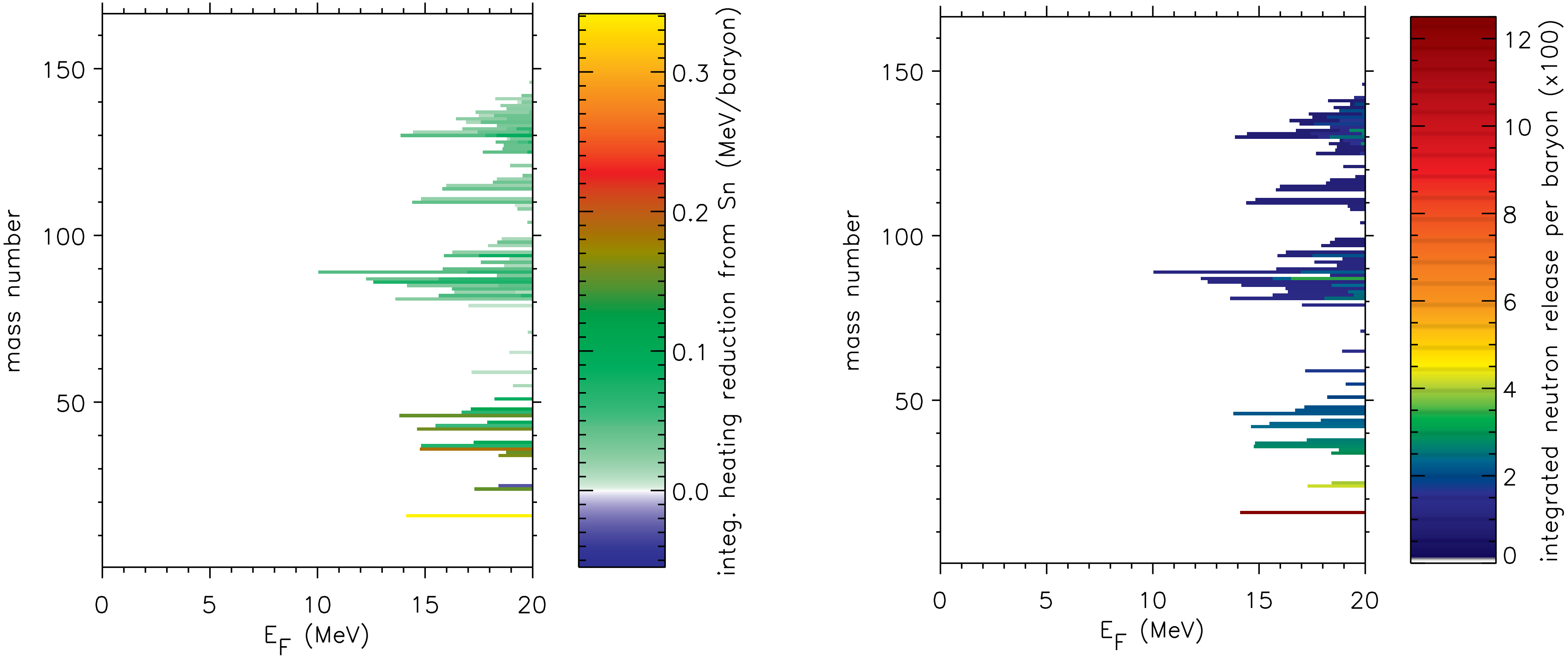
Comparison of n-emission + capture...........prelude to nucleosynthesis: Rearrangement of the abundance distribution (shifts to lower A) + additional EC/ and n heat not calculated before !

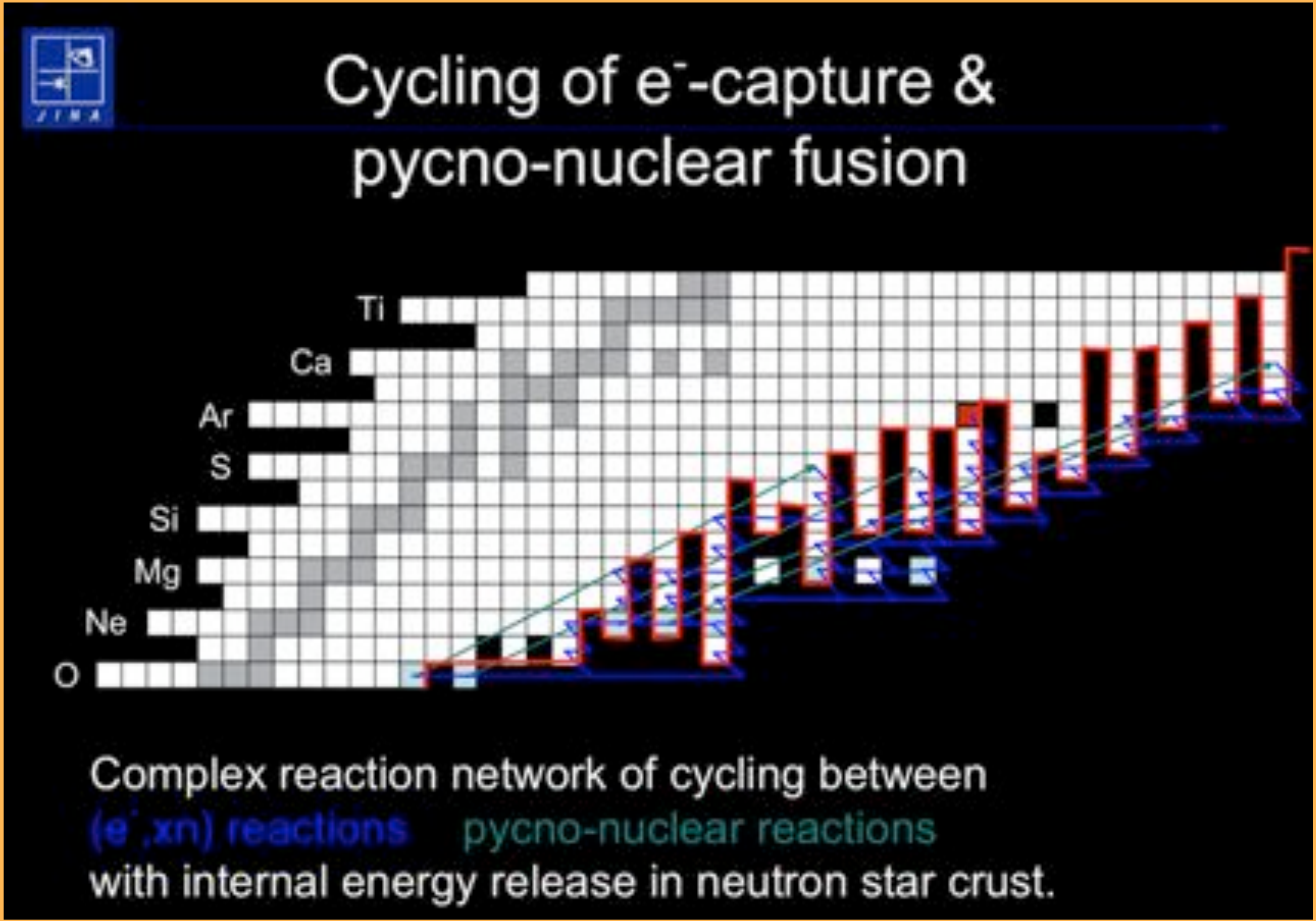
Plasma effects lower neutron c.s. in the dense environment.



We are now folding these with varied XRB compositions......

Integrated Reduction in heating from neutron losses

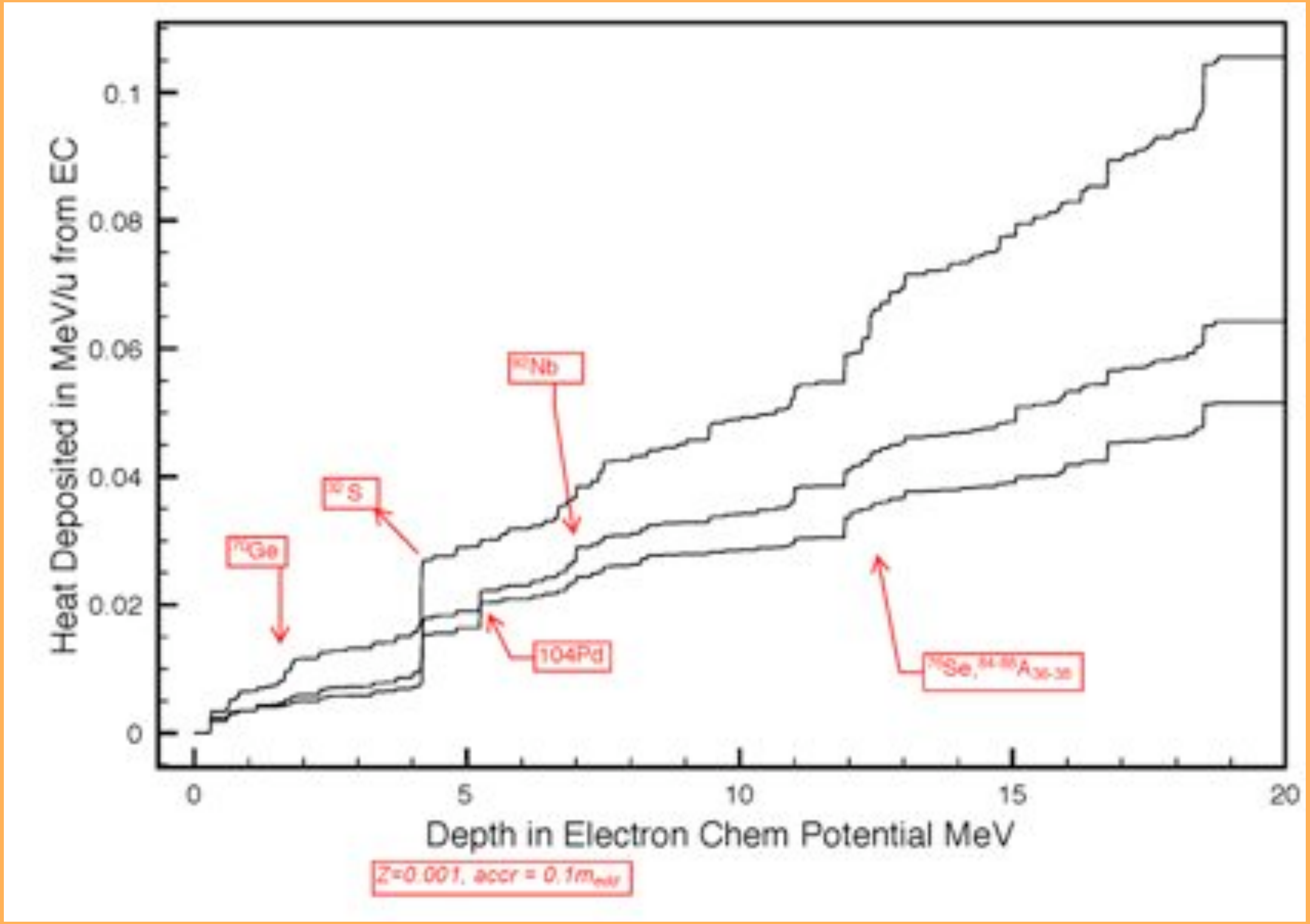




Cycling of e^--capture & pycno-nuclear fusion

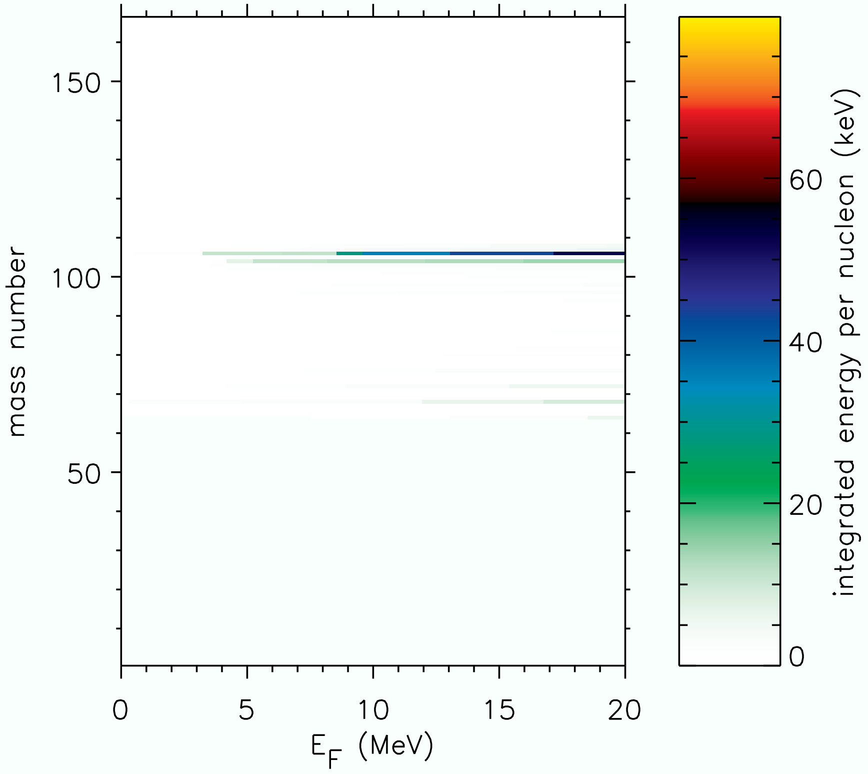
Complex reaction network of cycling between
(e^-,xn) reactions pycno-nuclear reactions
with internal energy release in neutron star crust.

HZ’07 show if pycno is suppressed to Z=4 then alternate routes are heavily (EC to g.s., xn)...same heating as pycno, less concentrated. Effects of excited states for these EC were not taken into account as we are now doing.

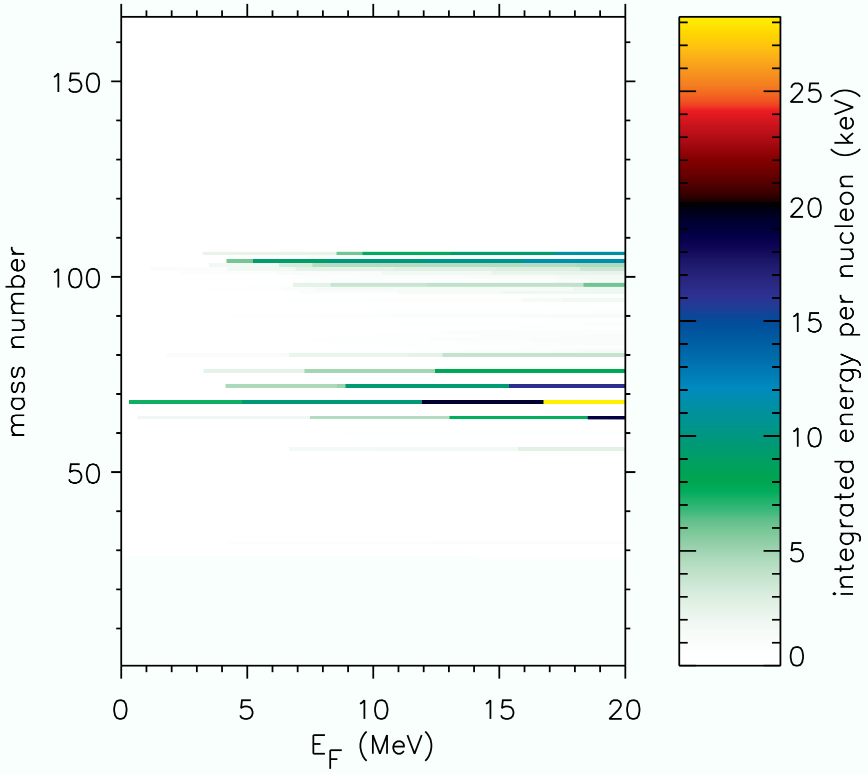


Heat contributions from 3 different XRB zones showing the importance of taking multiple bursts into account and the importance of XRB Waiting Point nuclei for correct crustal heating.

Energy per mass chain from EC at different depths

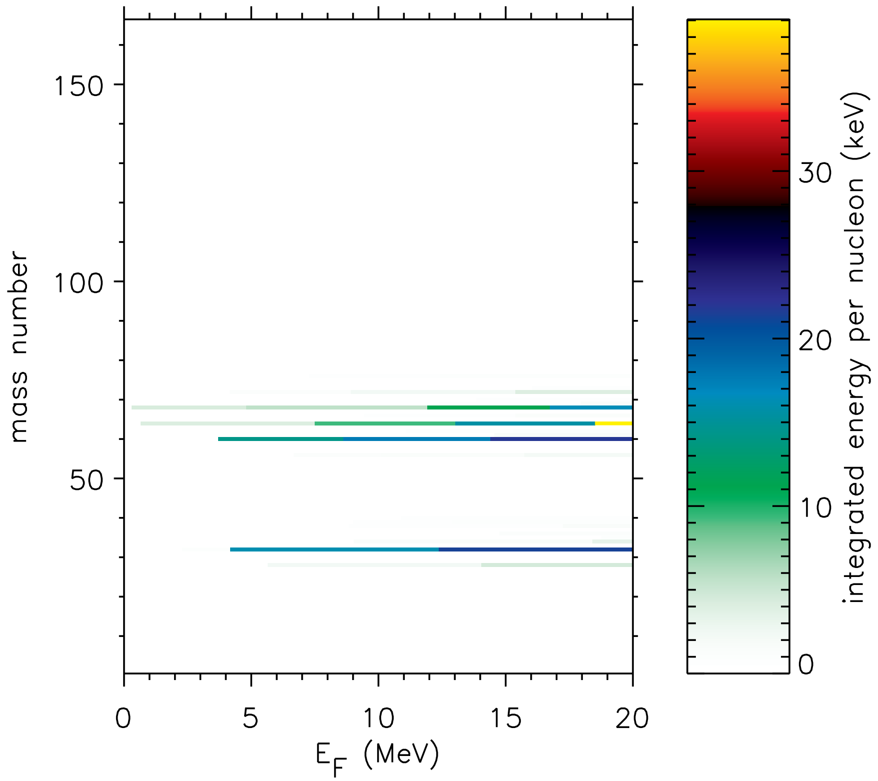


Z=0.001 AND dM/dt=0.1 M_Edd

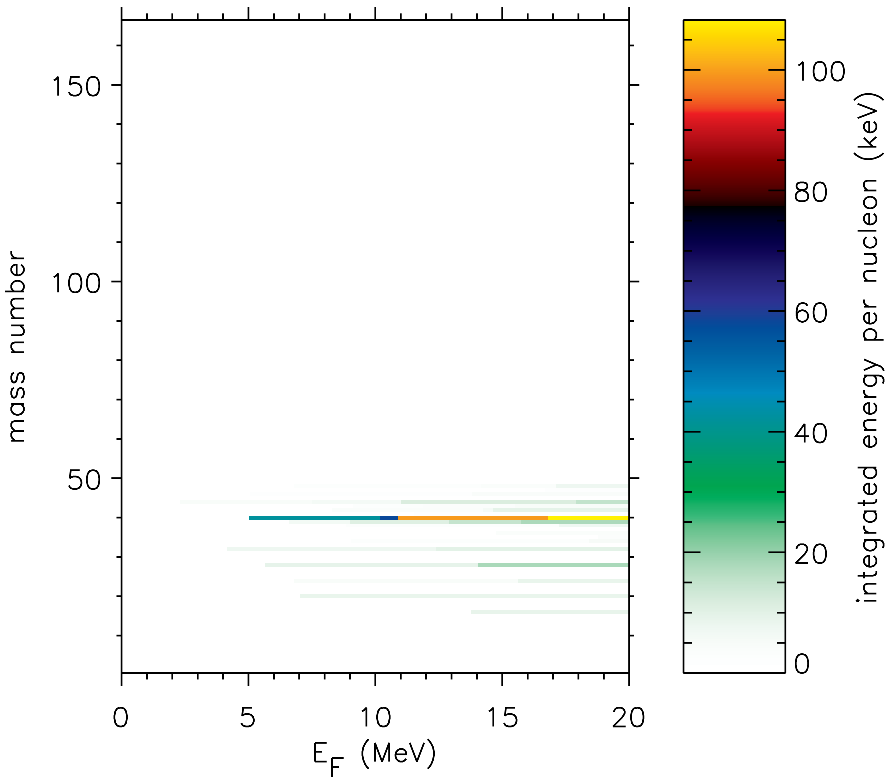


Z=0.001 AND dM/dt=0.02 M_Edd

Energy per mass chain from EC at different depths

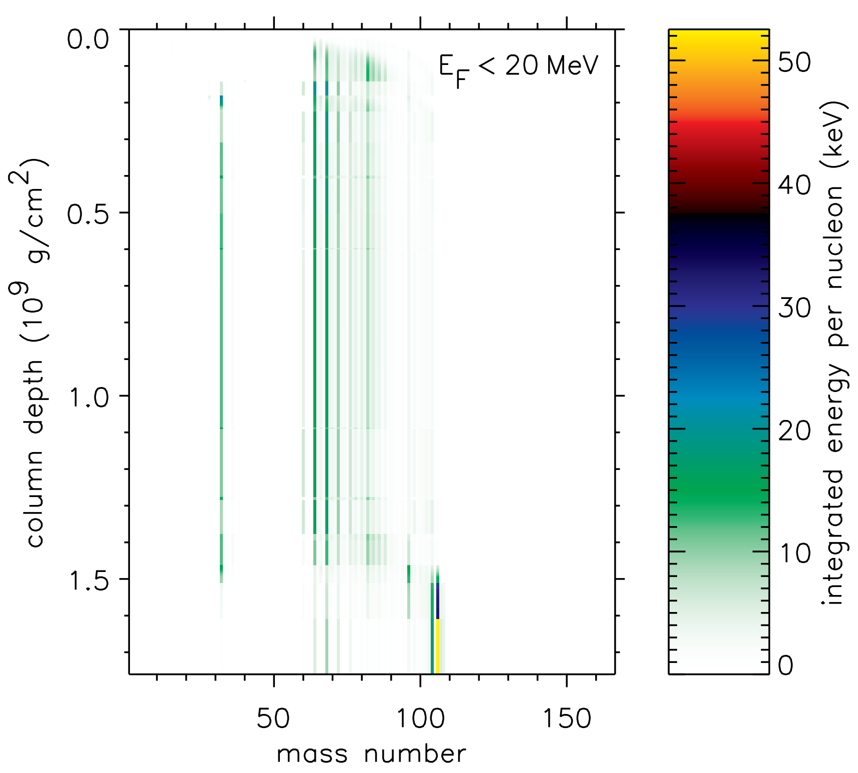


Z=0.02 AND dM/dt=0.1 M_Edd

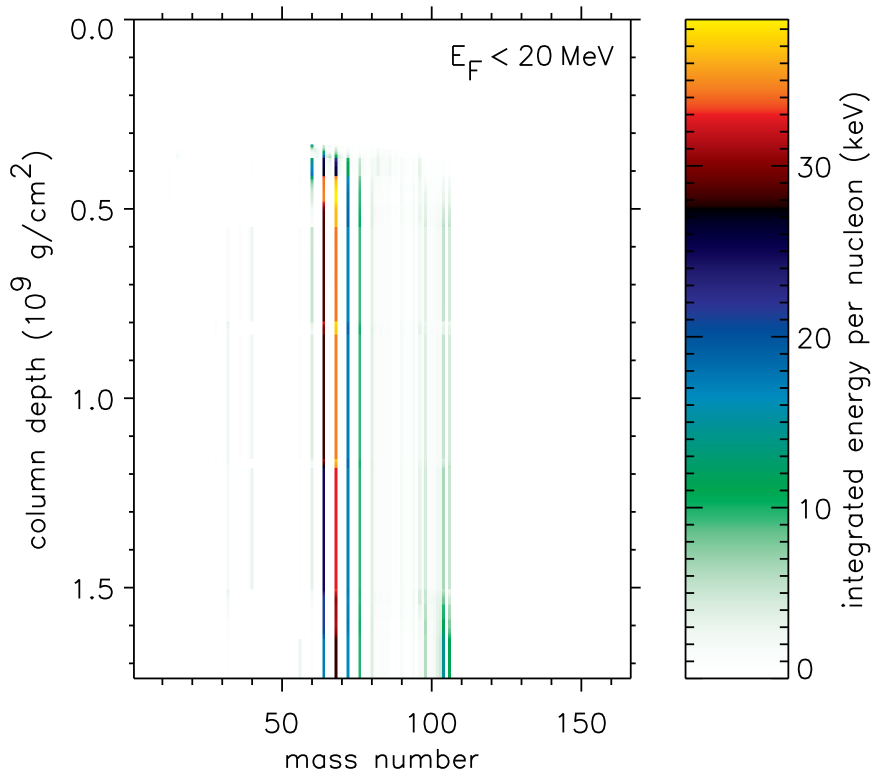


Z=0.02 AND dM/dt=0.02 M_Edd

Energy per mass chain from EC at different depths from different zones in XRB model

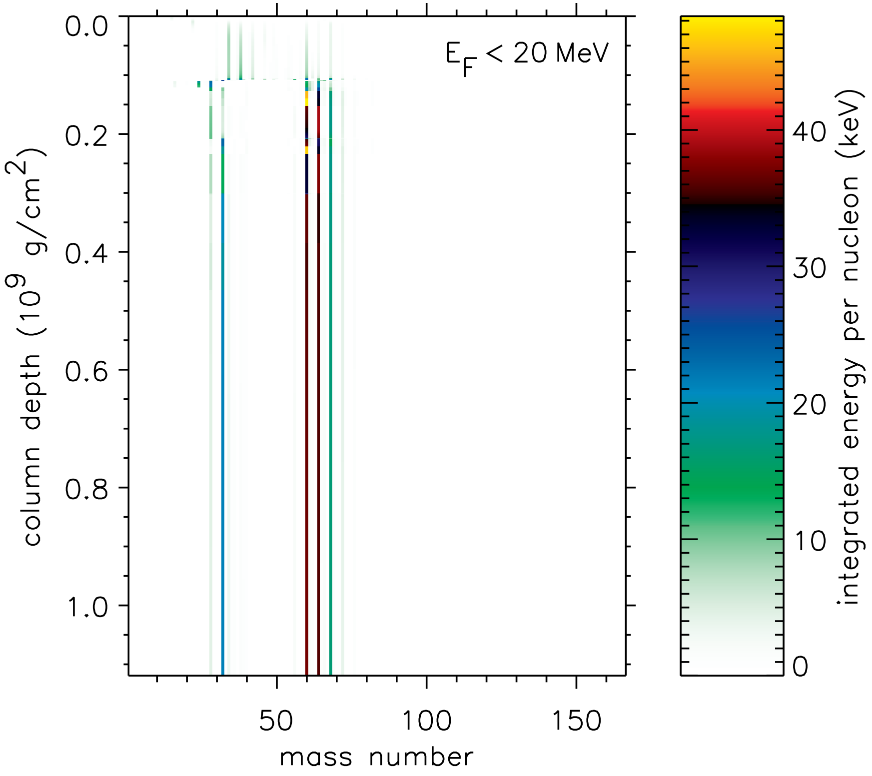


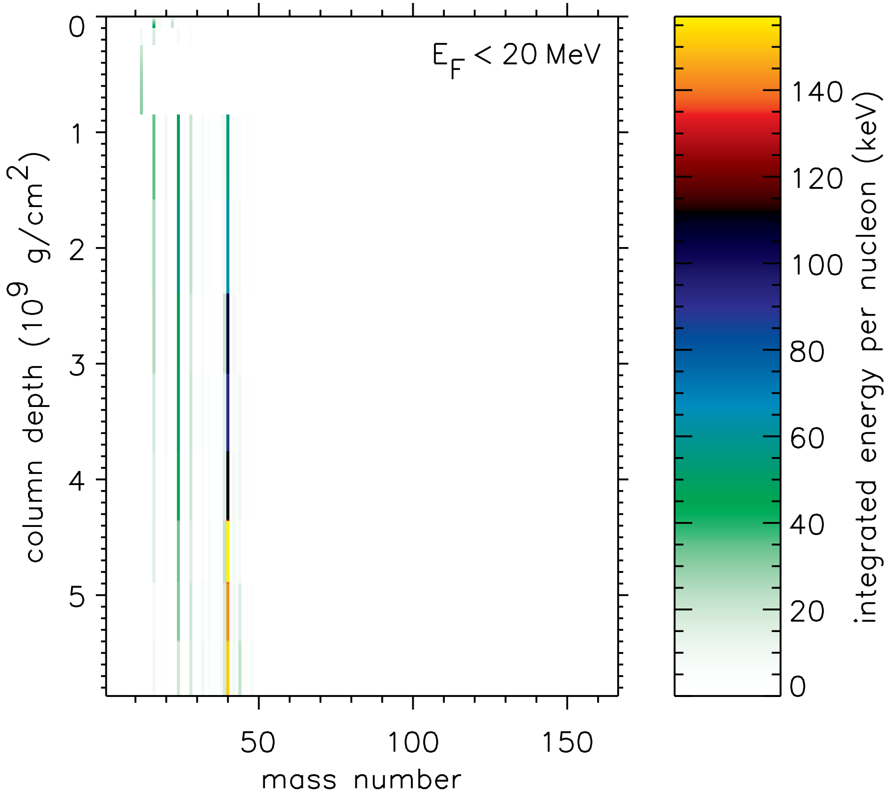
Z=0.001 AND dM/dt=0.1 M_Edd



Z=0.001 AND dM/dt=0.02 M_Edd

Energy per mass chain from EC at different depths from different zones in XRB model





Z=0.02 AND dM/dt=0.1 M_Edd

Z=0.02 AND dM/dt=0.02 M_Edd

SUMMARY AND CONCLUSIONS

- Weak interactions and neutron processes play a critical role in heating the Neutron Star Crust ;
- We are developing the first model of realistic crust nucleosynthesis and using actual X-ray burst compositions from a large range of accretion rates as initial crust fuel ;
- Hauser-Feshbach is critical to correct n-branchings under stellar conditions for very n-rich nuclei ;
- Exciting times are ahead for crust nucleosynthesis - actual network calculations under extreme n-richness very important for............
- Progress towards the holy grail of crust heating - finding out where *pycnonuclear reactions* play a role, and what is the heating from them.