Explosive H/He Burning during Type I X-Ray Bursts on Neutrons Stars

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with the main contributions from :

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and early significant collaborations with:

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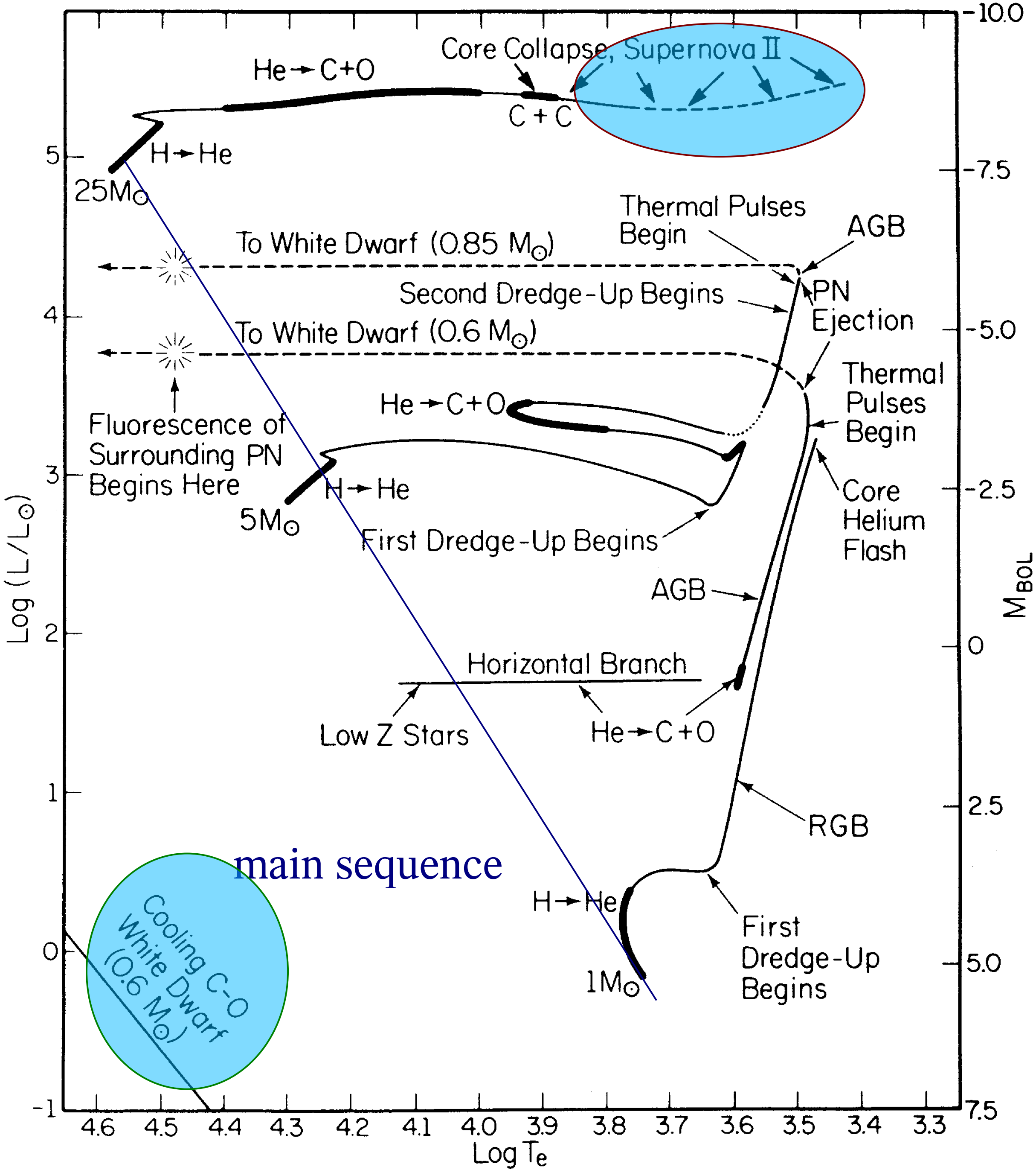
University of Notre Dame

Stellar Evolution Endpoints



Hertzsprung-Russell Diagram of Stellar Evolution from Iben, showing as end stages

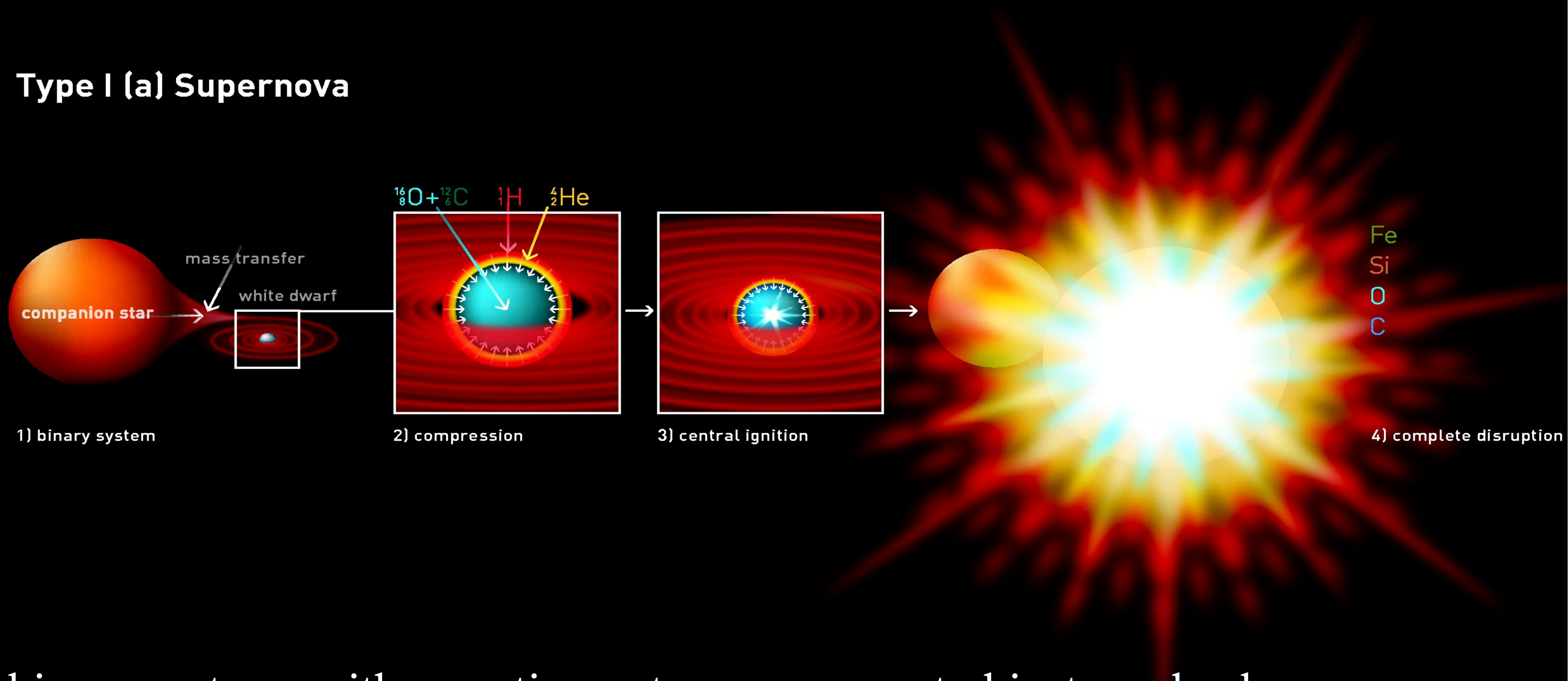
- white dwarfs

and

- core collapse (supernovae/neutron stars, black holes, GRBs?)

influence of reaction cross sections, e-capture in late burning stages, metallicity, rotation, magnetic fields, stellar winds on final outcome

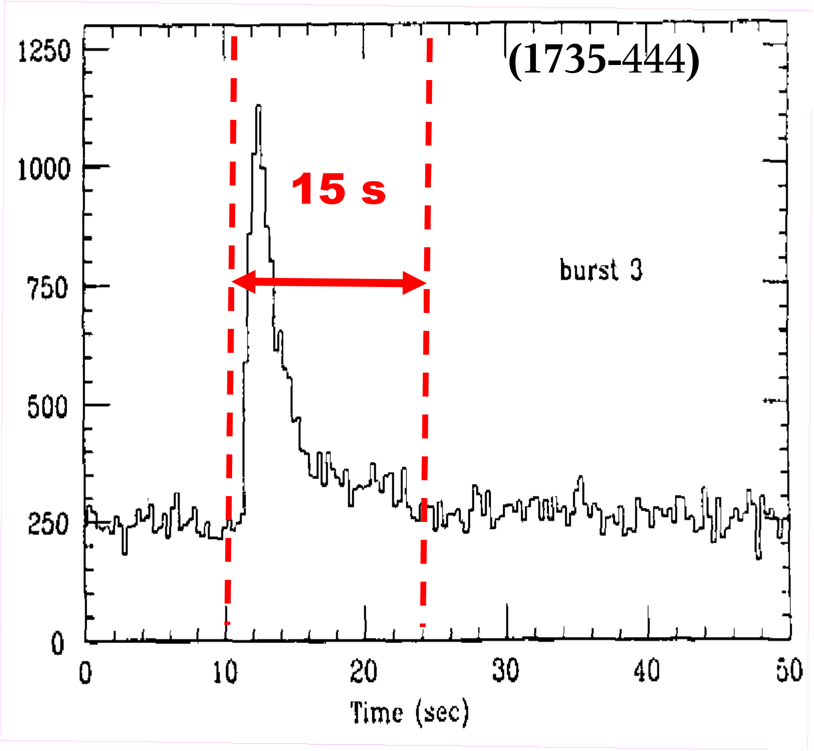
Accretion in Binary Stellar Systems



binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions)

- white dwarfs (novae, type Ia supernovae)
- neutron stars (type I X-ray bursts, superbursts?)

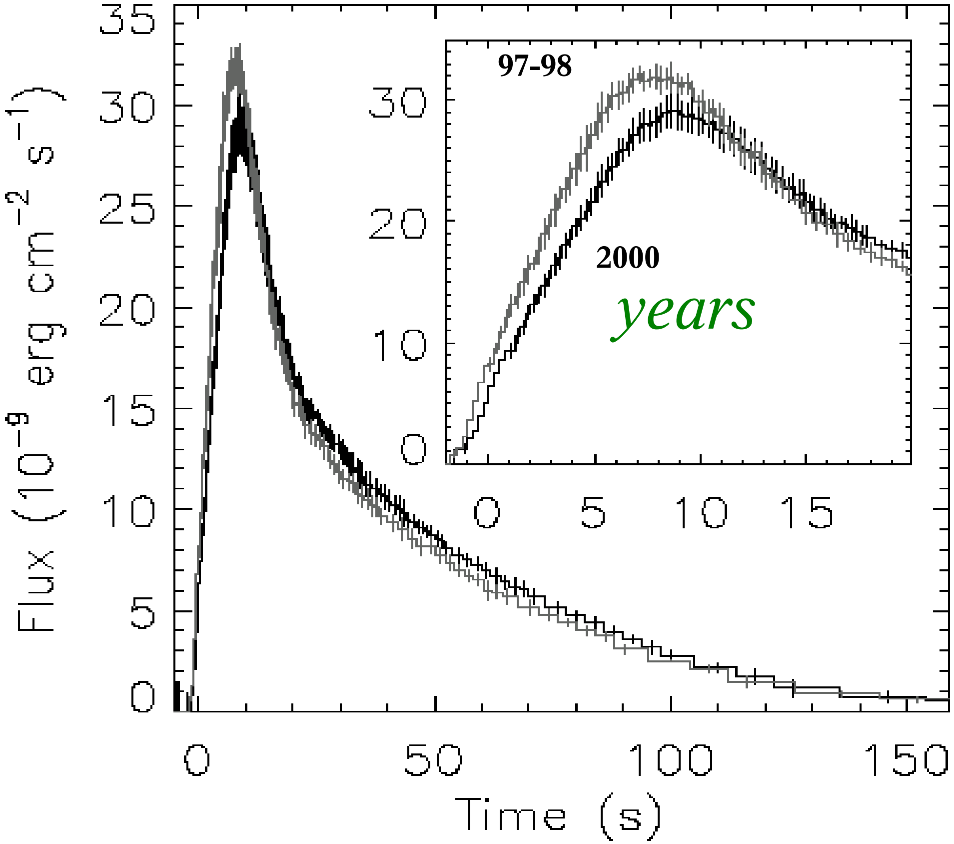
X-ray burst observations



typical X-ray burst

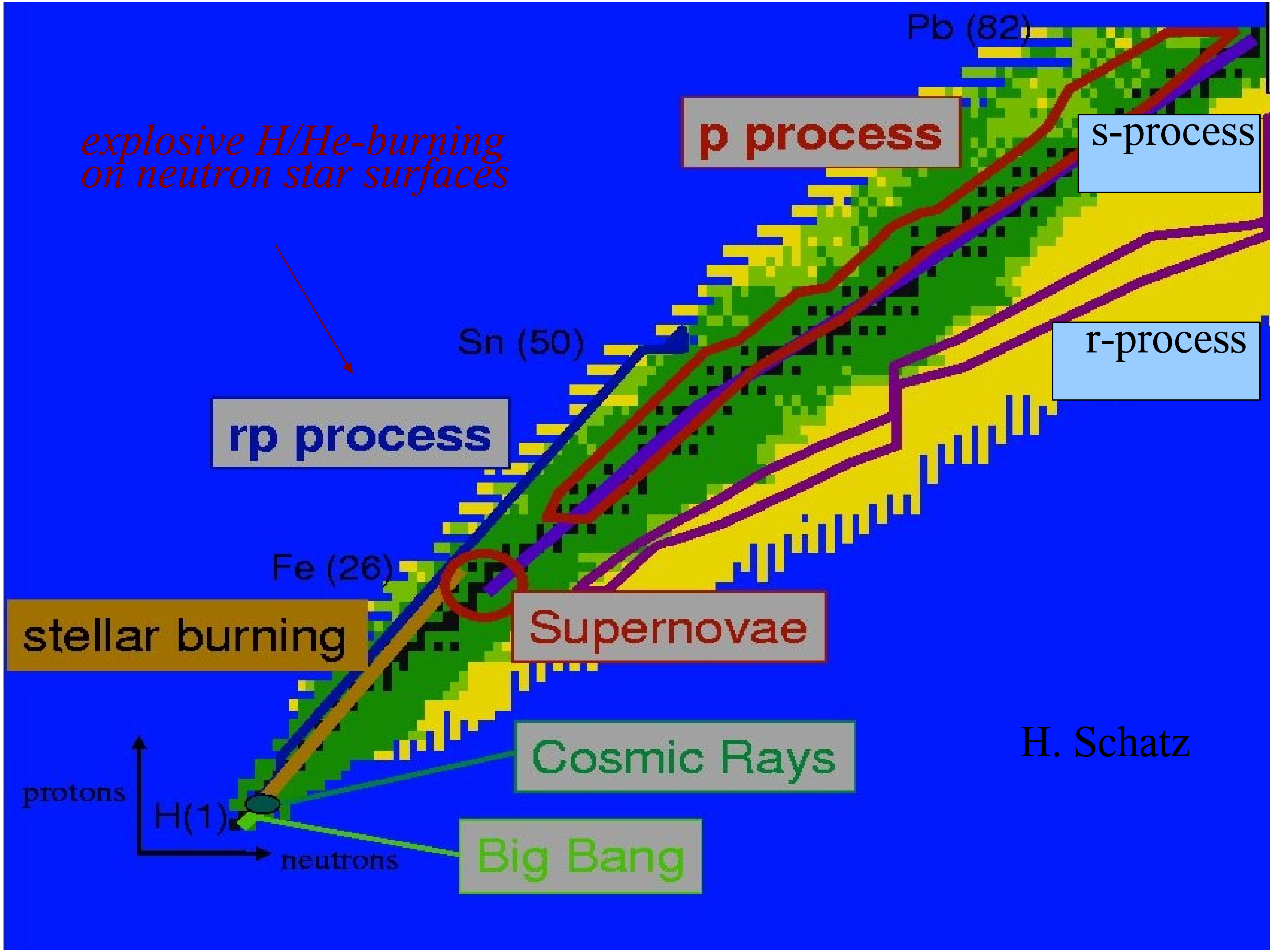
NASA RXTE: GS 1826-24 burst shape changes !

(Galloway 2003 astro/ph 0308122)



not identical, and slow but continuous evolution in burst features, physics behind this ?

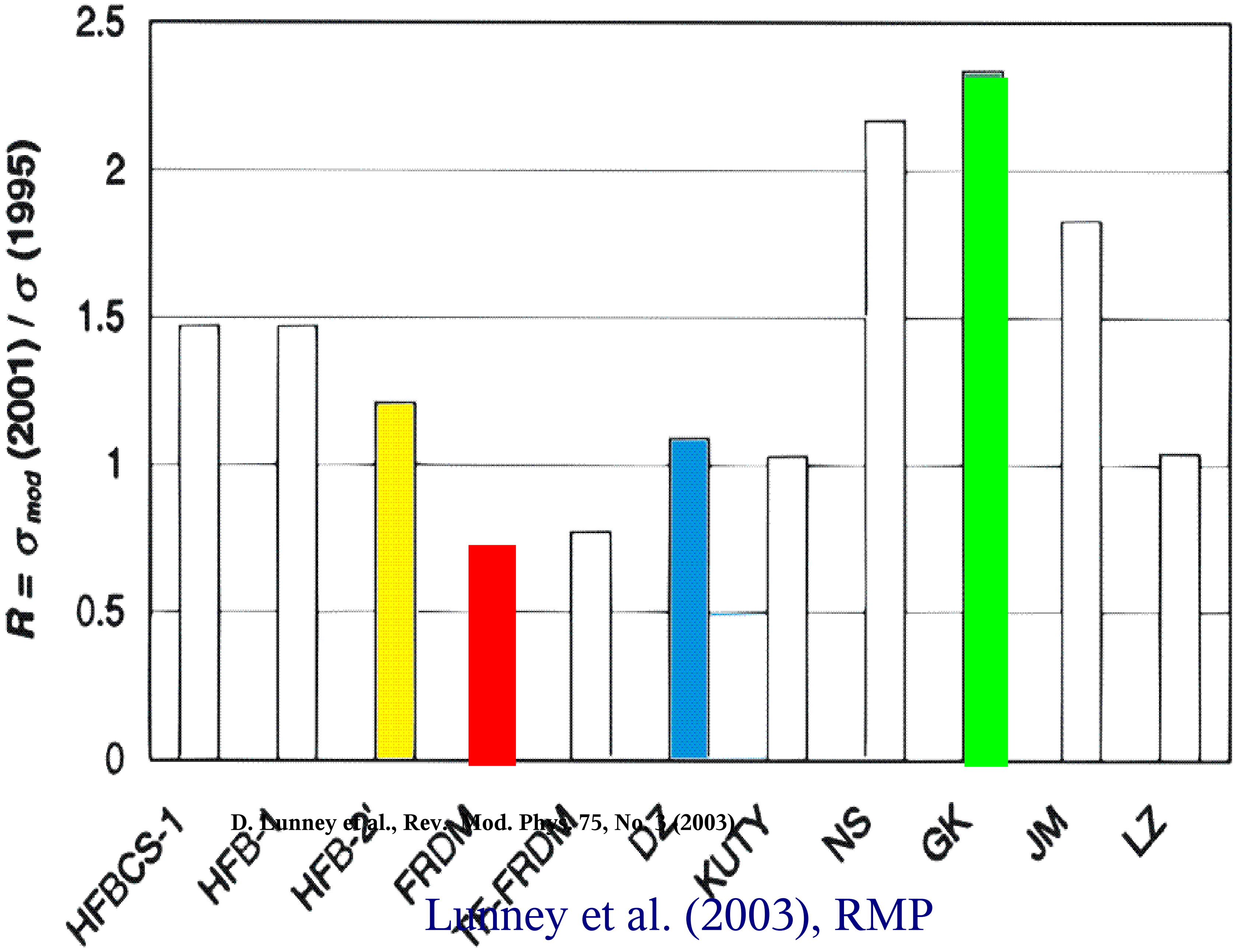
Processes in the Nuclear Chart



Nuclear Data for Astrophysics

- 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

RMS deviations of nuclear mass predictions



D. Lunney et al., Rev. Mod. Phys. 75, No. 3 (2003)

Lunney et al. (2003), RMP

Mass predictions (far from stability):

Is there an accuracy limit?

Comparison to NUBASE (2001) // (2003)

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

ETFSI-Q (1996) σ_{rms} = 0.818 // **0.72**

existing approaches:
Finite Range Droplet Model,
Extended Thomas Fermi,
Hartree-Fock Boguliubov

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

HFB-2 (2002) σ_{rms} = 0.6

HFB-3 (2003) σ_{rms} = 0.65

HFB-4 (2003) σ_{rms} = 0.6

HFB-8 (2004) σ_{rms} = 0.6

HFB-9 (2005) σ_{rms} = **0.7**

Other microscopic approaches

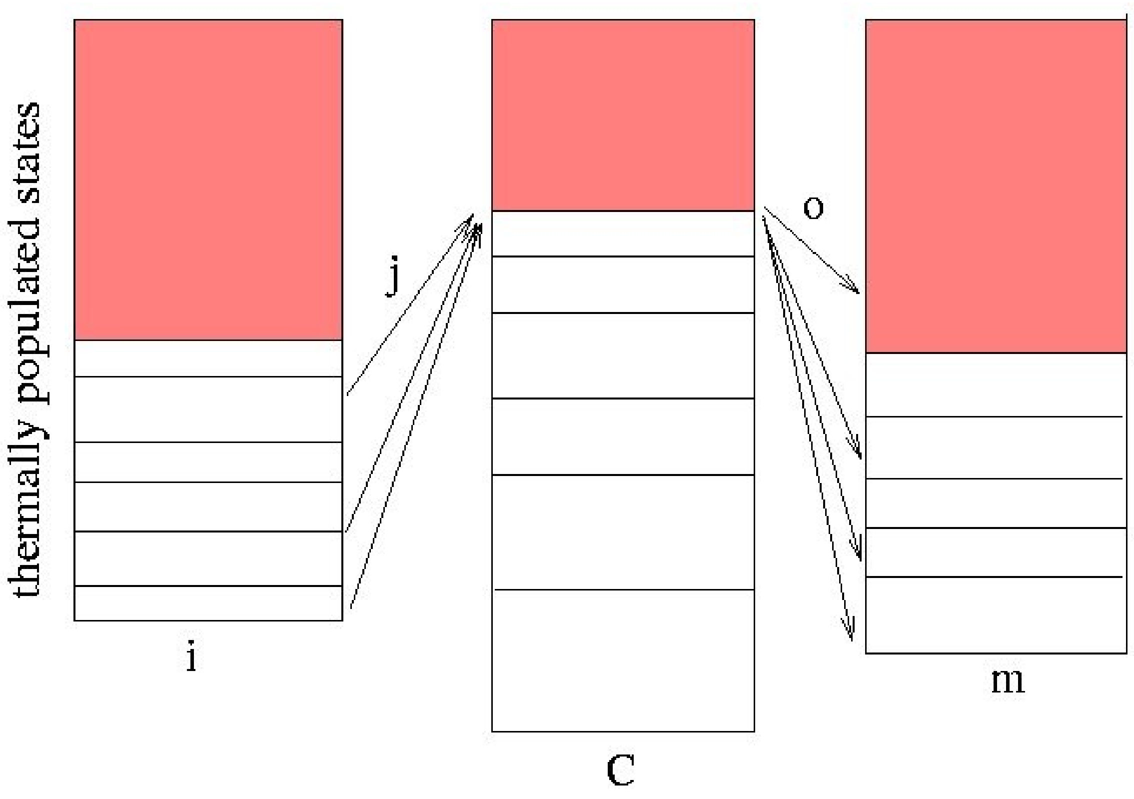
- united energy density functional (UENDEF)
- relativistic mean field

Test with Rare Isotope Beam Facilities

- RIKEN, GSI/FAIR, RIA2?
- and related theory efforts (e.g. ENSAR)

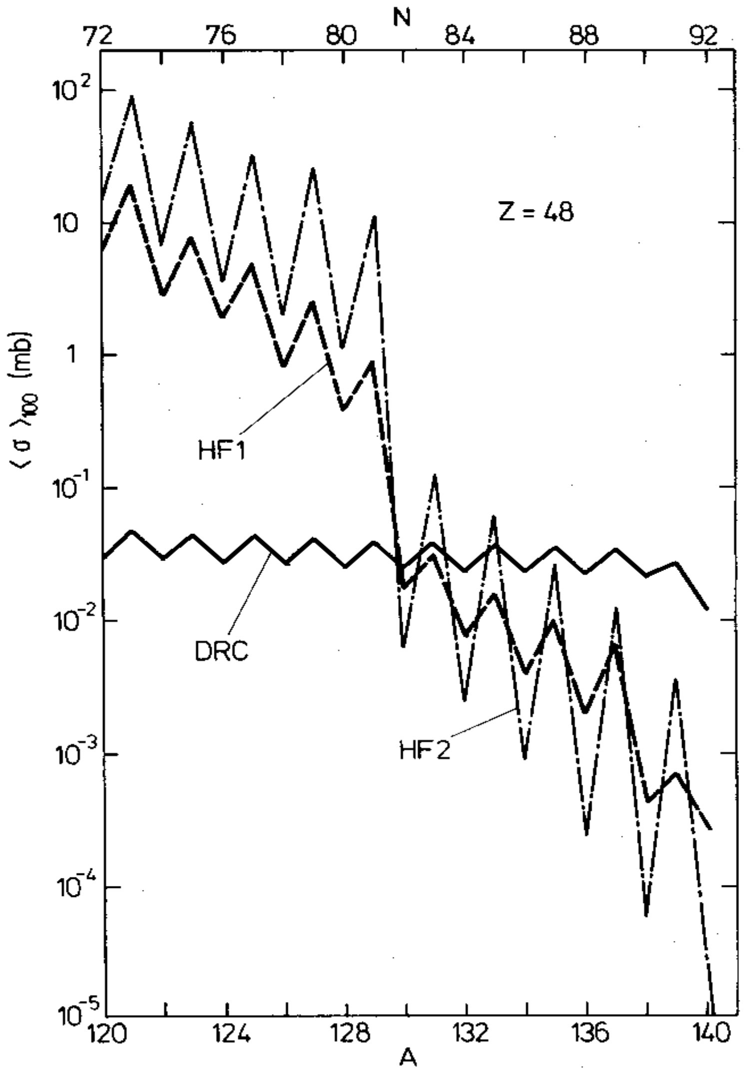
HFB-14 (2007) σ_{rms} = 0.729 [MeV]

Compound cross section vs. direct capture



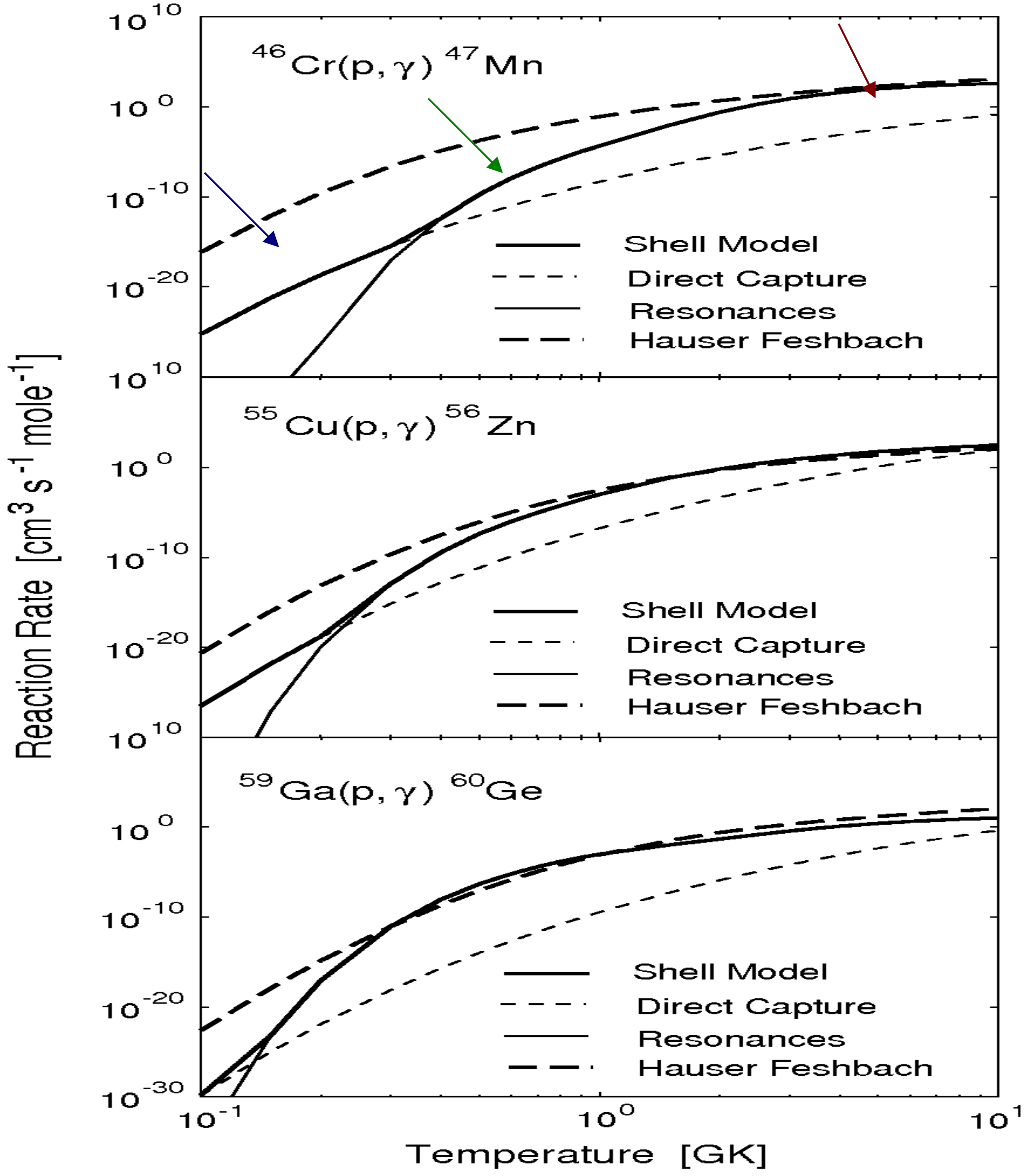
$$\sigma_i(j,o) = \frac{\pi}{k_j^2}\frac{(1+\delta_{ij})}{(2I_i+1)(2I_j+1)}\sum_{J,\pi}(2J+1)\frac{T_j(E,J,\pi)T_o(E,J,\pi)}{T_{tot}(E,J,\pi)}$$

www.nucastro.org for statist. model cross sections NON-SMOKER-rates (T. Rauscher, F.-K. Thielemann) parity-dep. level density (Mocelj et al. 2007, Loens et al. 2008), n-induced fission (Panov et al. 2005, 2008) www-astro.ulb.ac.be/Html/bruslib.html for MOST-rates (Goriely et al.)



Cd-chain from Mathews, Mengoni, FKT, Fowler (1984), more recent investigations by Rauscher, Goriely

Contributions to rates close to proton drip-line



close to proton drip-line number of excited states in compound nucleus is at low energies that low that at lowest temperatures (energies)

1. *direct capture dominates*
2. *individual resonances dominate the rate*
3. *resonance averaging is possible, i.e. Hauser-Feshbach*

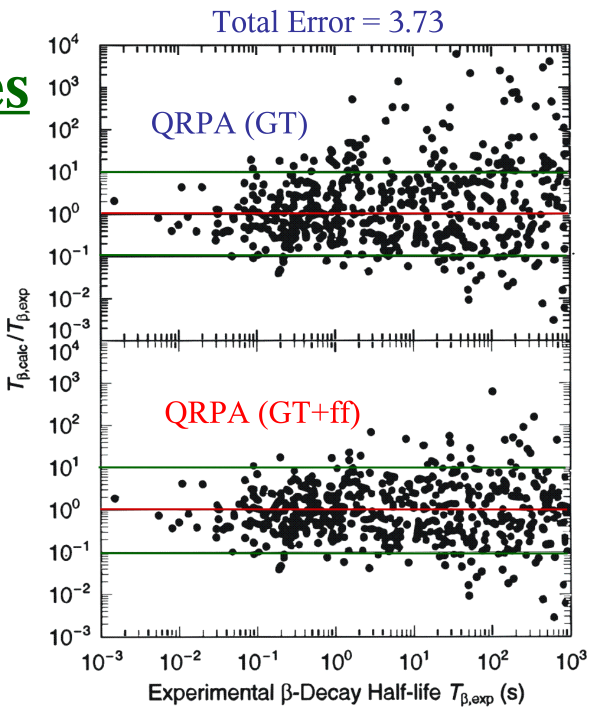
from Wiescher, Fisker et al. (2003)

Weak interaction **β-Decays** Kratz, Möller, Nix, Pfeiffer

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

Requests: (I) prediction / reproduction of correct experimental **data**
(II) full understanding of nuclear-structure

Half-lives

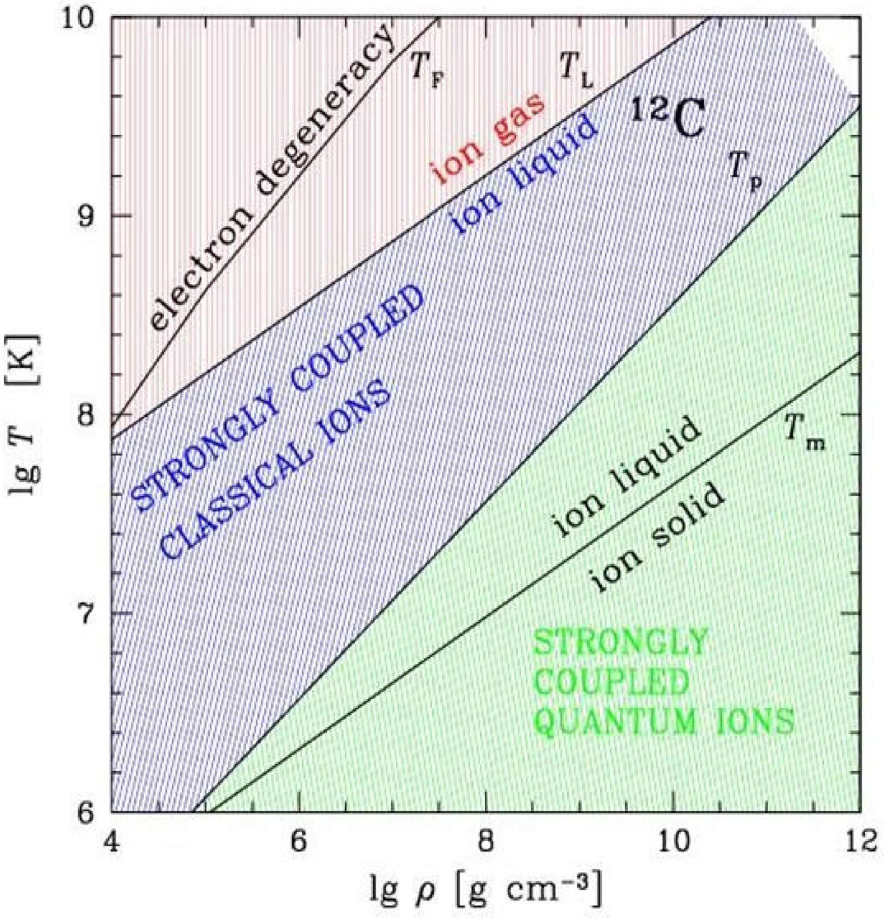


(P. Möller et al.,
PR **C67**, 055802 (2003))

Total Error = 3.08

beta-decay and e-capture up to pf-shell in shell model calculations (Langanke & Martinez-Pinedo 2003, new rates from QRPA by Gupta et al. 2008)

Strong Screening and Pycnonuclear Reactions



change from freely moving ions in high density electron background to also strongly coupled ions and finally an ion lattice where reactions only happen due to lattice vibrations as a function of temperature:

The experts are in St. Petersburg: Gasques et al. (2005), Yakovlev et al. (2007), Chugunov et al. (2008); our early calculations used Itoh et al. (1993) and Ogata et al. (1997)

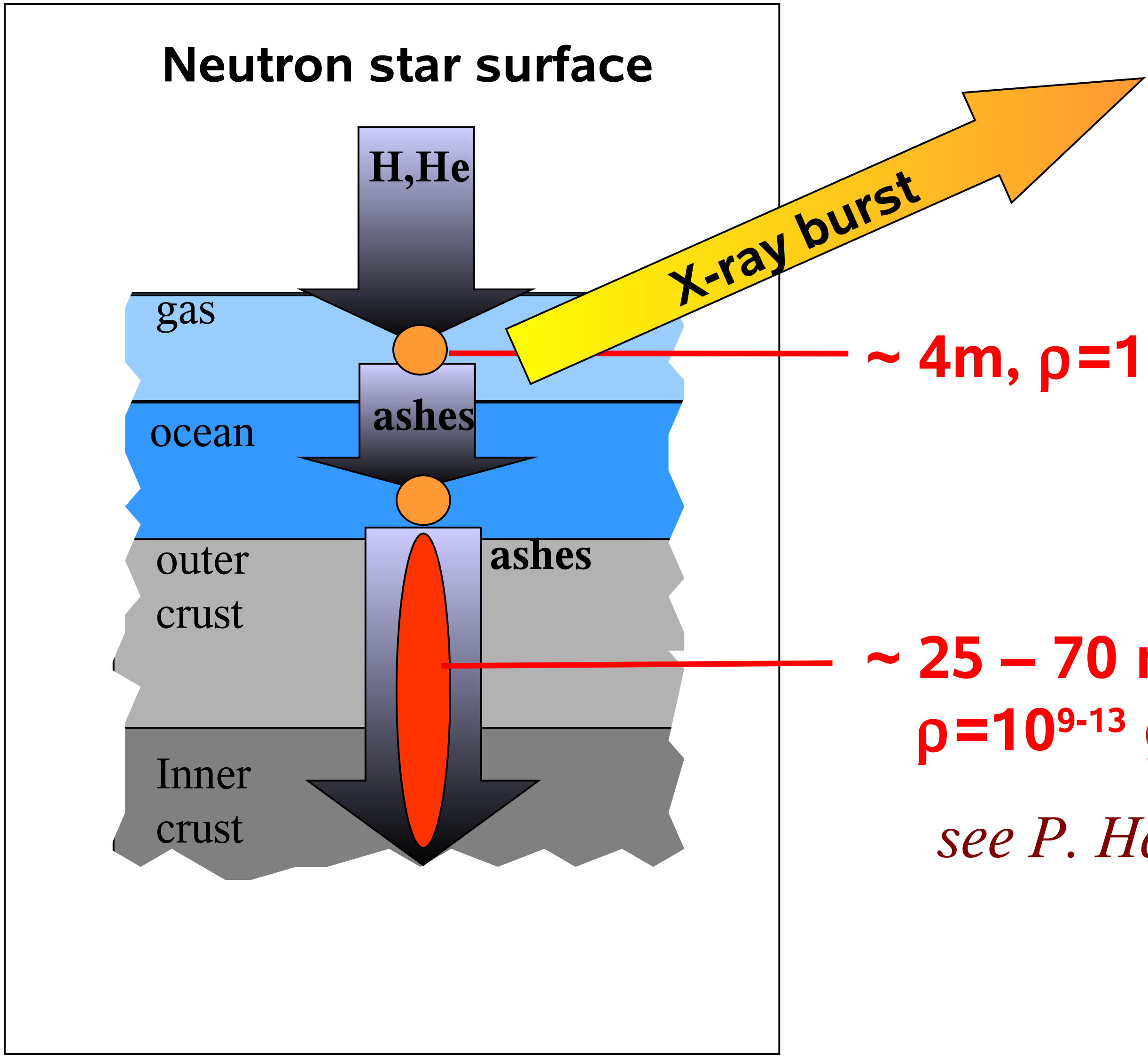
Low Mass X-Ray Binaries

- A binary system with a low and a high mass star leads to early SN explosion and a neutron star
- Roche lobe overflow from unevolved lower mass star after gravitational wave induced energy loss and inspiral
- with a NS of 20-25 km diameter and a distance between the binaries of 10^5-10^6 km there is excess angular momentum in the accretion disk
- due to disk viscosity matter spirals in, slows down and hits NS photosphere with $v=0.1c$
- kinetic energy transformed into heat and radiated through X-ray transparent photosphere
- matter accumulates onto NS atmosphere

Surface of an accreting neutron star

graph from
H. Schatz

approx. $10^{-12} M_{sol}$ at ignition, with an accretion rate of 10^{17} g/s this corresponds to a repetition rate of about 4 hours



this talk

~ 4m, $\rho=10^{6}$ g/cm^{3}

~ 25 – 70 m
$\rho=10^{9-13}$ g/cm^{3}

see P. Haensel

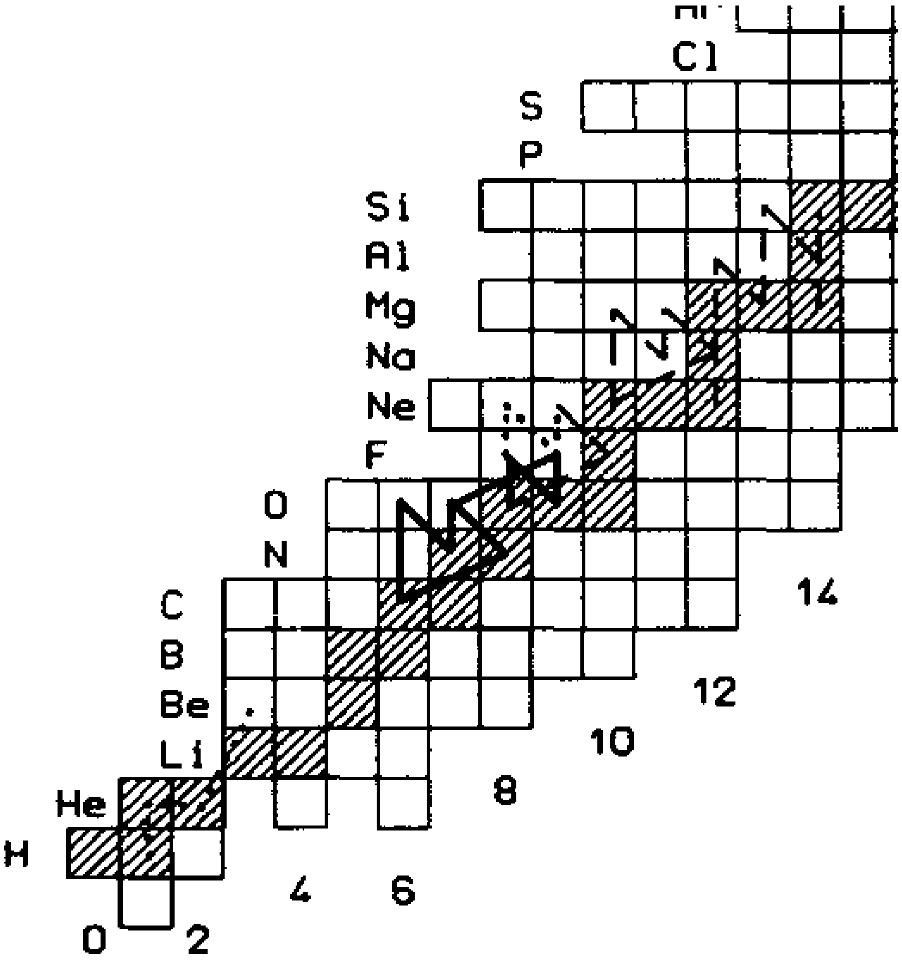
Ignition and Burst

- Nuclear reactions release heat causing more reactions . . . runaway iff $\frac{d\epsilon_{nuc.}}{dT} > \frac{d\epsilon_{cool}}{dT}$
- A nondegenerate star would expand and cool, but here $dP_{total}/dT \approx 0$, so pressure work is not an option.
- Explosion energy is transported to the surface and increases luminosity steeply – light curve decay corresponds to cooling of the envelope.
- Accreted material – Solar abundances: Mostly Hydrogen (71%) and Helium(28%)
- (p,γ), (γ,p), (α,γ), (γ,α), (α,p), (p,α), and β^+.

P=P(dens.) degenerate electron EoS!

thermonuclear runaway

Test calculations as functions of T



T=1.5 10^8 K

hot CNO cycle

no break-out yet

for T=2-3 10^8 K more CNO-type cycles develop up to Ca

Uncertainties in:

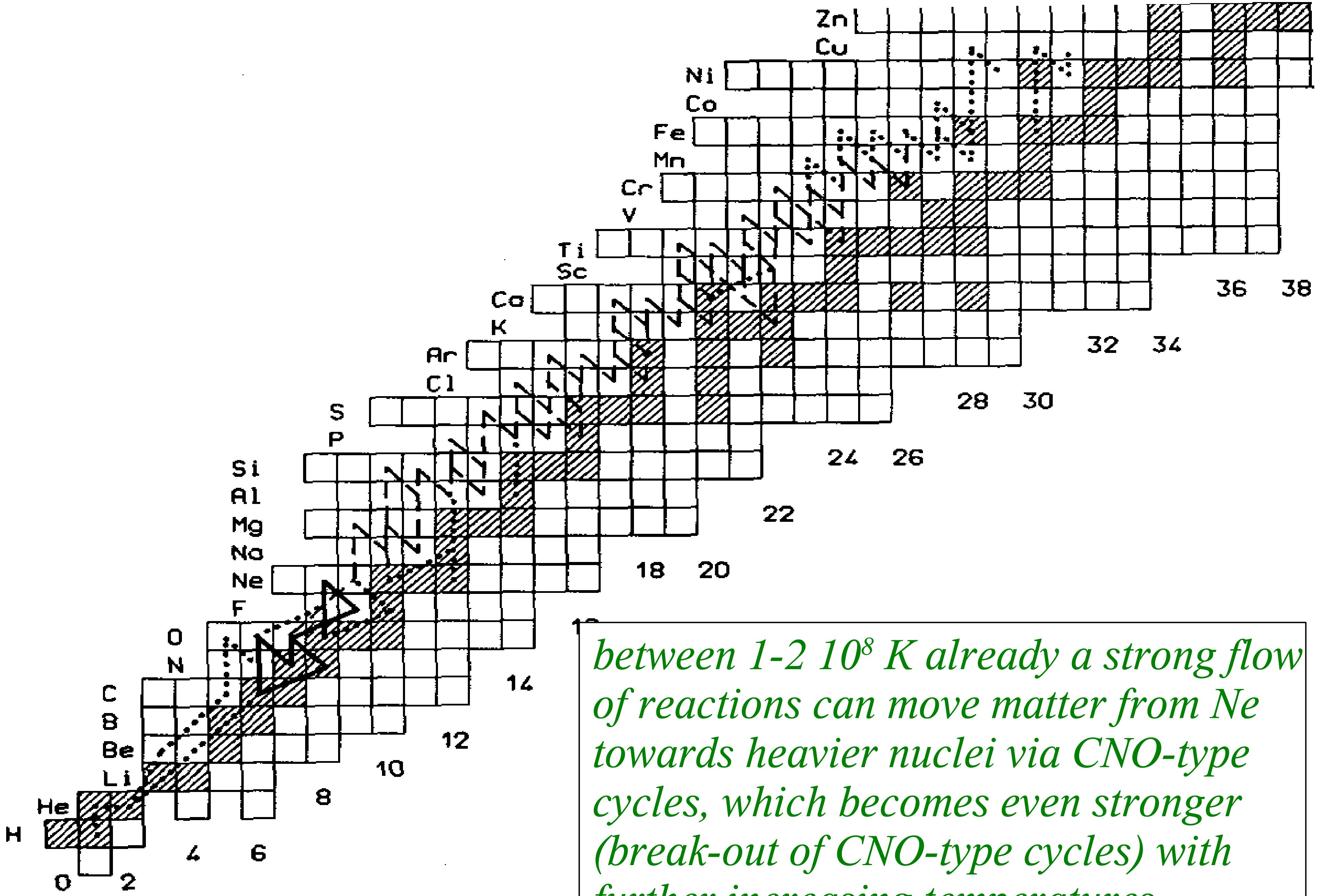
^{14}O$(\alpha,p)^{17}$F, ^{17}F$(p,\gamma)^{18}$Ne,

^{18}Ne$(\alpha,p)^{21}$Na

^{15}O$(\alpha,\gamma)^{19}$Ne, ^{19}Ne$(p,\gamma)^{20}$Na

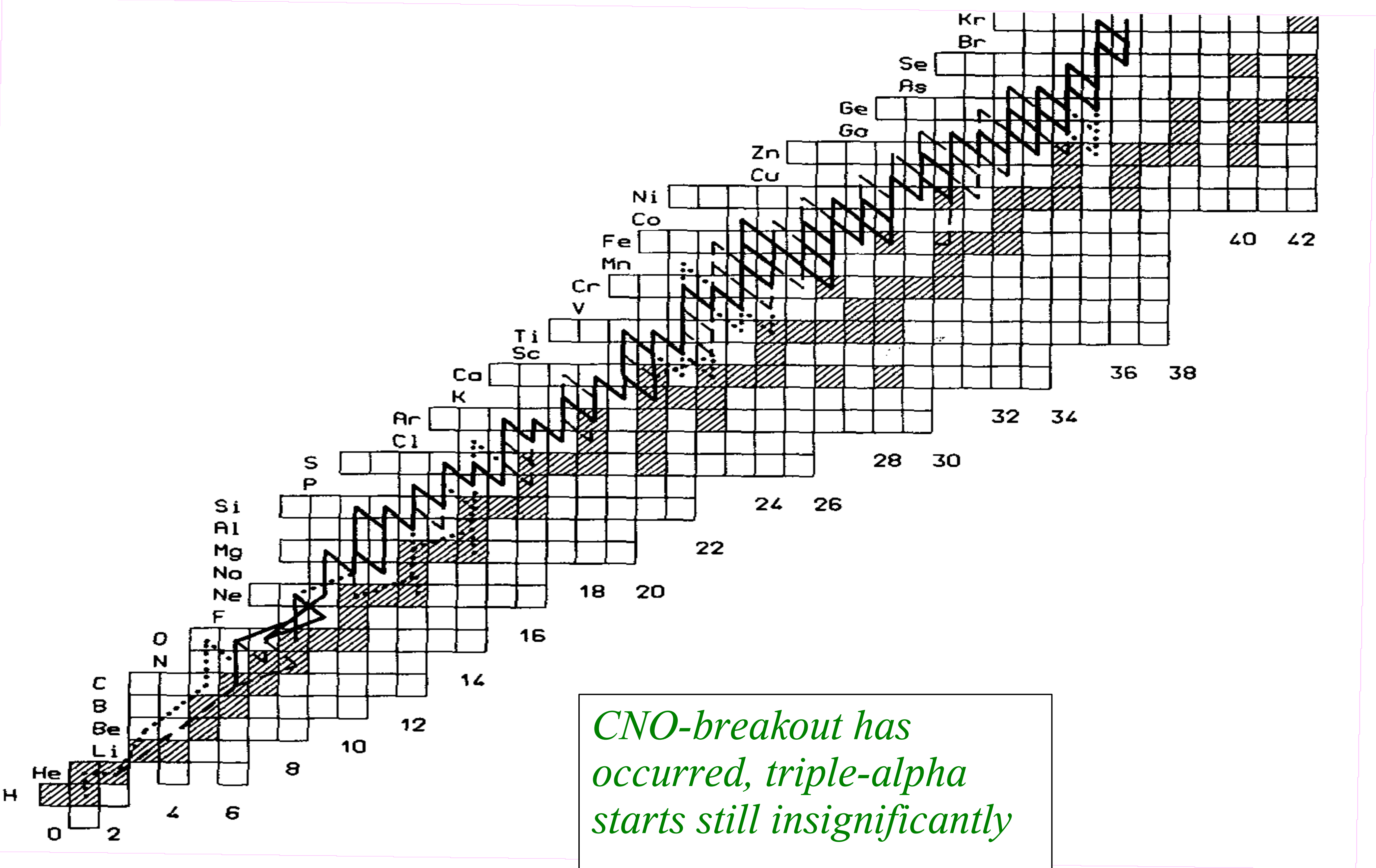
early evaluations: van Wormer et al. (1994)

$T = 4 \times 10^8$ K



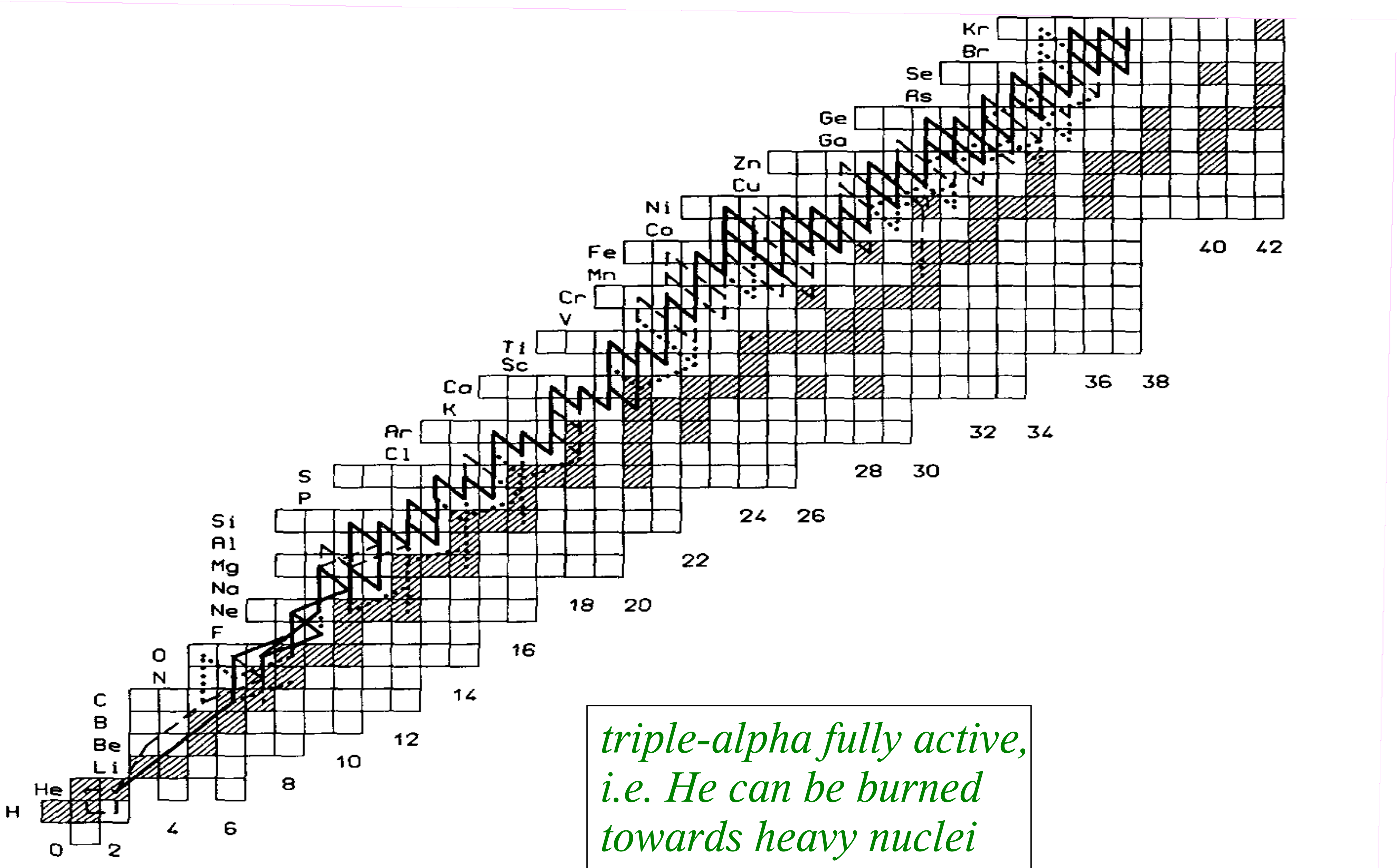
between 1-2 10^8 K already a strong flow of reactions can move matter from Ne towards heavier nuclei via CNO-type cycles, which becomes even stronger (break-out of CNO-type cycles) with further increasing temperatures

$T = 6 \times 10^8$ K



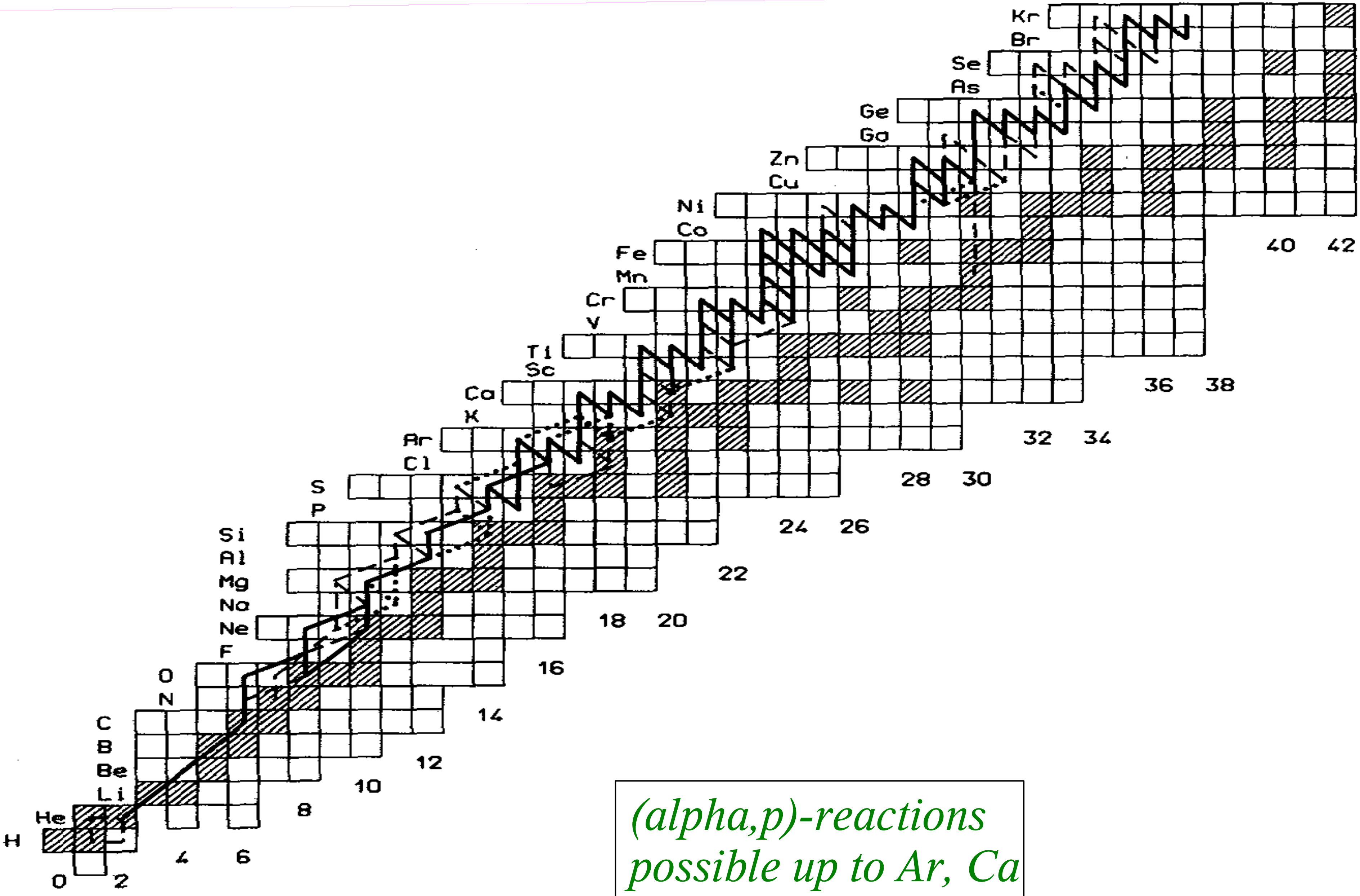
CNO-breakout has occurred, triple-alpha starts still insignificantly

$T = 8 \times 10^8$ K



triple-alpha fully active, i.e. He can be burned towards heavy nuclei

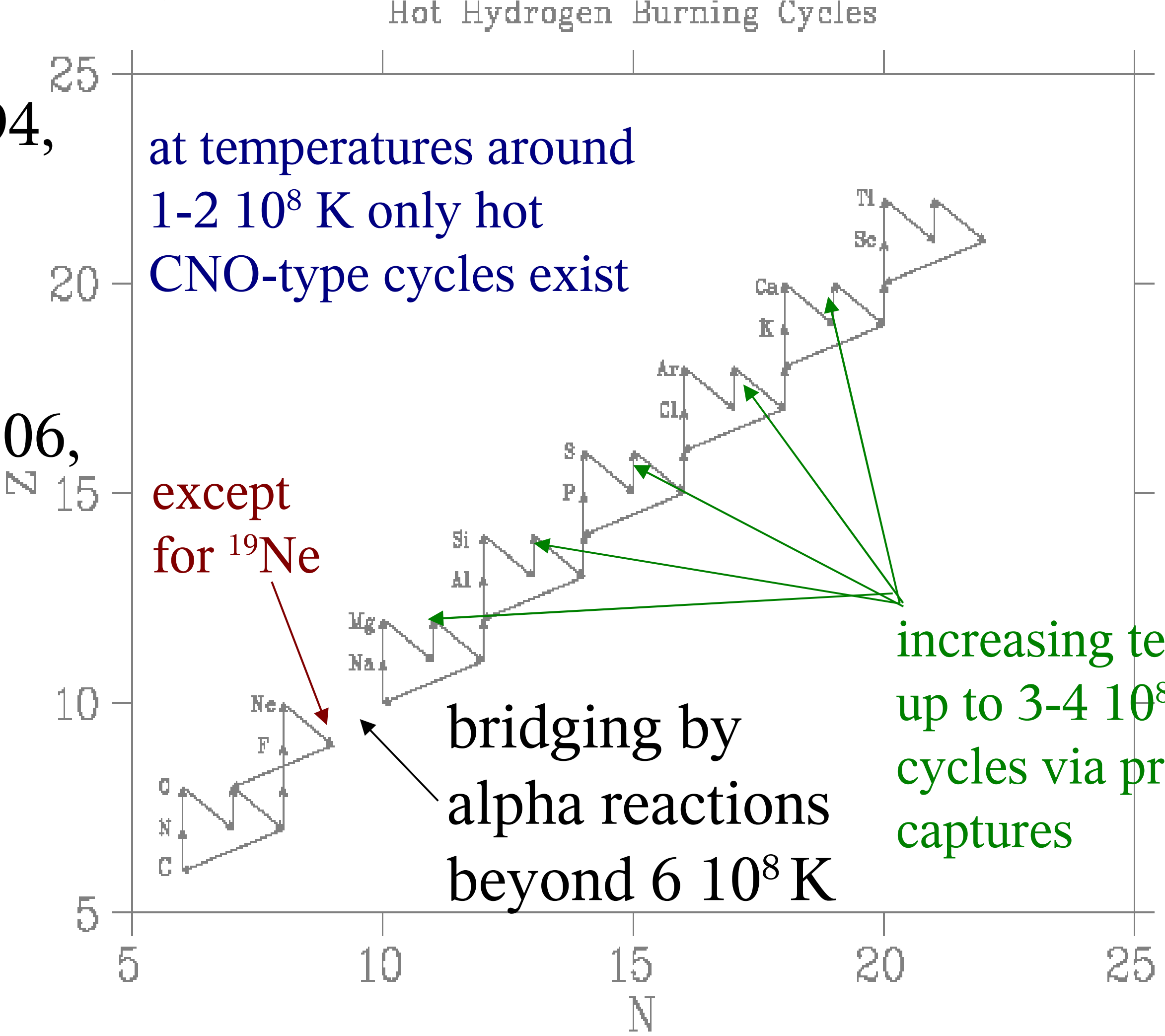
$T = 1.5\ 10^9$ K



(alpha,p)-reactions possible up to Ar, Ca

Explosive H/He-burning and the onset of the rp-process

Wallace & Woosley 1982,
Wiescher et al. 86,
van Wormer et al. 94,
Rembges et al. 97,
Schatz et al. 98, 01,
....
Cooper & Narayan 06,
...



at temperatures around 1-2 10^8 K only hot CNO-type cycles exist

except for ^{19}Ne

bridging by alpha reactions beyond 6 10^8 K

increasing temperatures up to 3-4 10^8 K break up cycles via proton captures

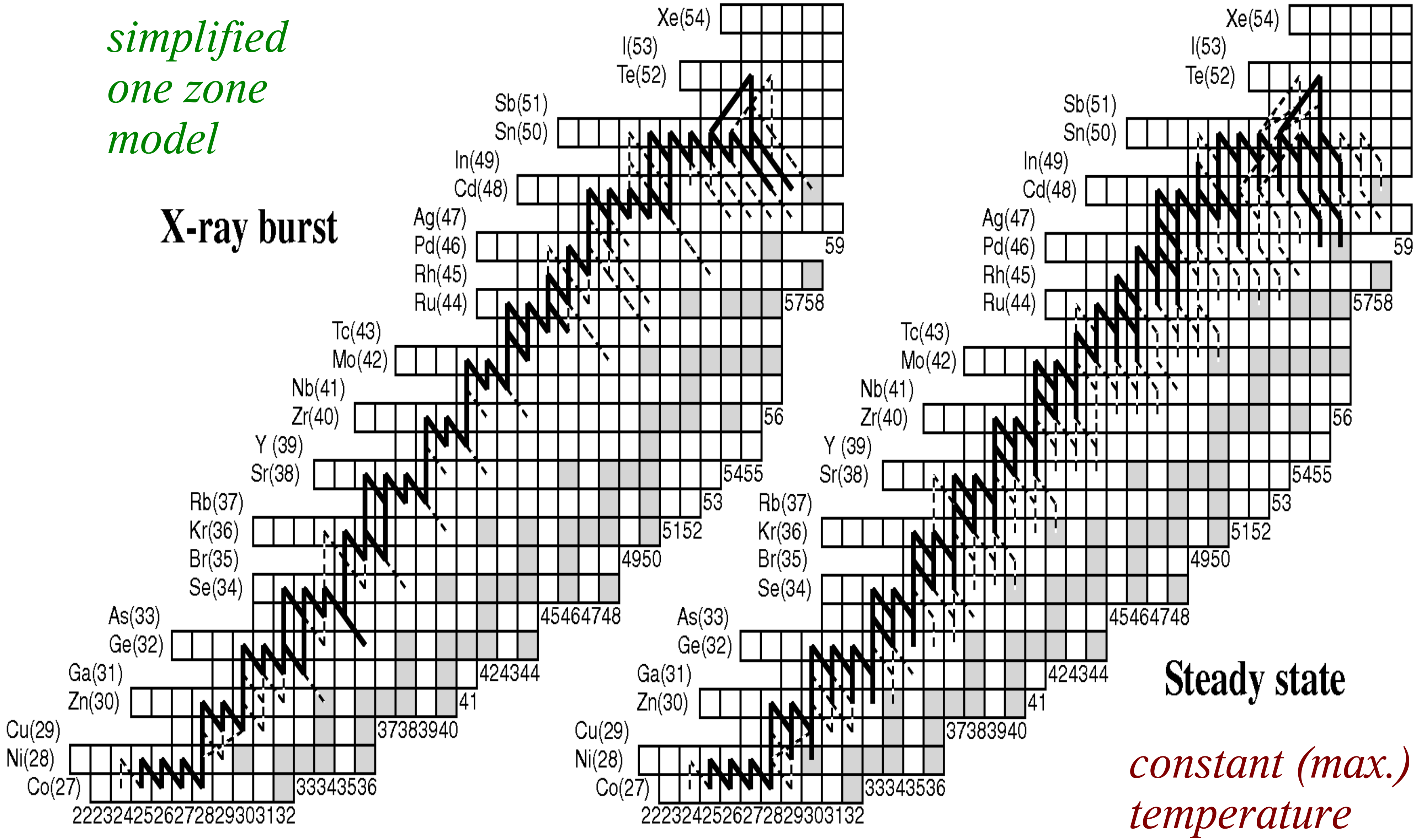
detailed modeling is more complex and identifies reaction sensitivities and drip-line dependence (Fisker, FKT, Wiescher 2005, Fisker, Schatz, FKT 2008)

Endpoint of the rp-process

Schatz et al. (2001)

simplified
one zone
model

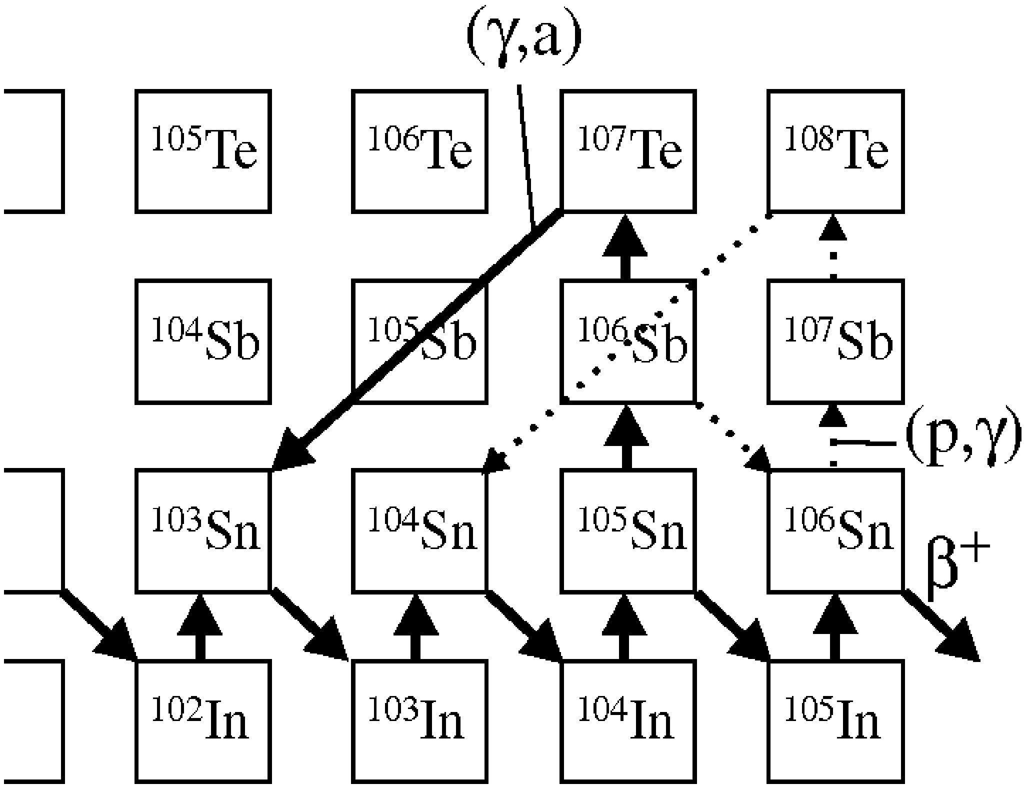
X-ray burst



Steady state

constant (max.)
temperature

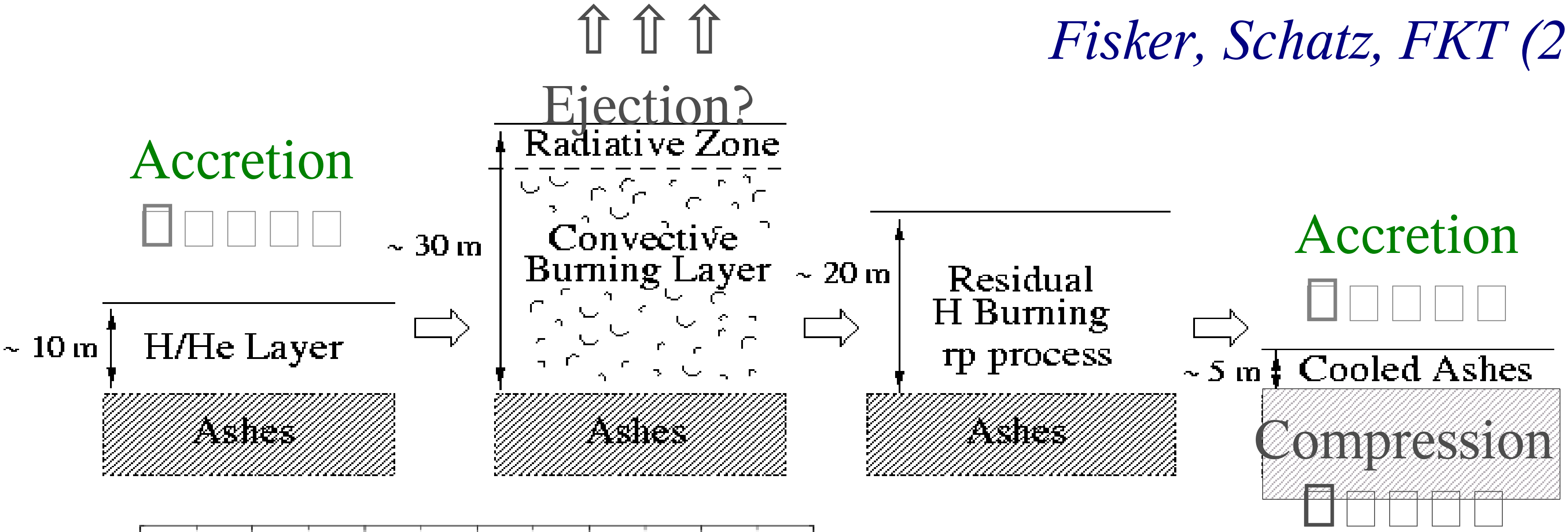
Final alpha back-cycling



SnSbTe cycle occurs because $^{106\text{-}108}$*Te are alpha-unbound by approximately 4 MeV*

Explosive H/He-burning and rp-process in realistic hydro models for X-ray Bursts

Fisker, Schatz, FKT (2008)



Accretion

~ 10 m

H/He Layer

Ashes

⇧ ⇧ ⇧

Ejection?

Radiative Zone

~ 30 m

Convective Burning Layer

Ashes

~ 20 m

Residual H Burning rp process

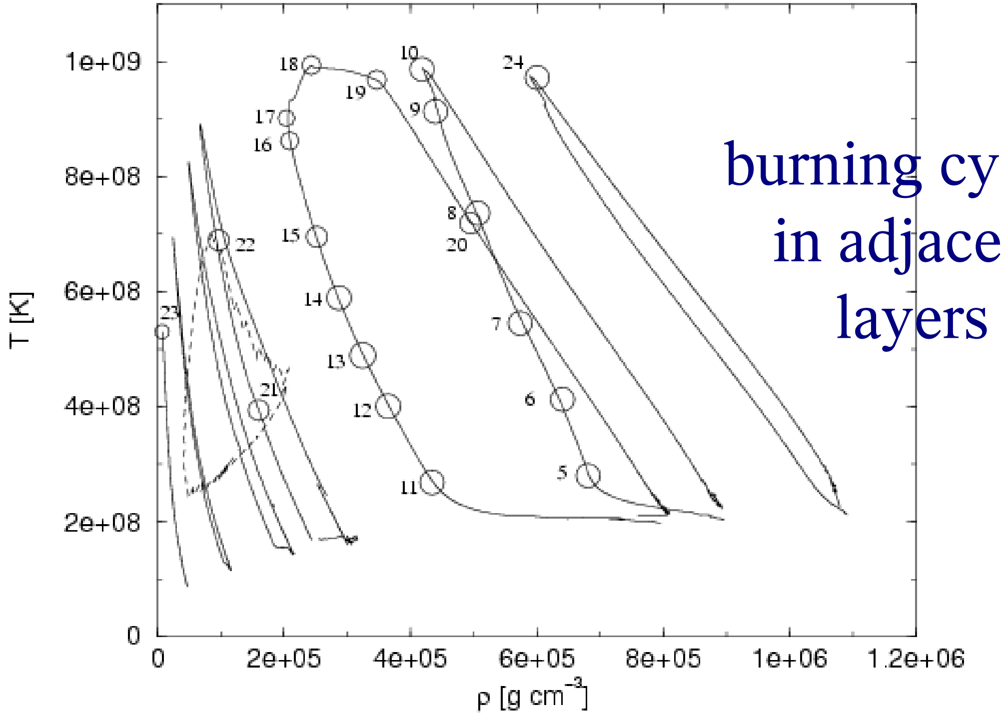
Ashes

Accretion

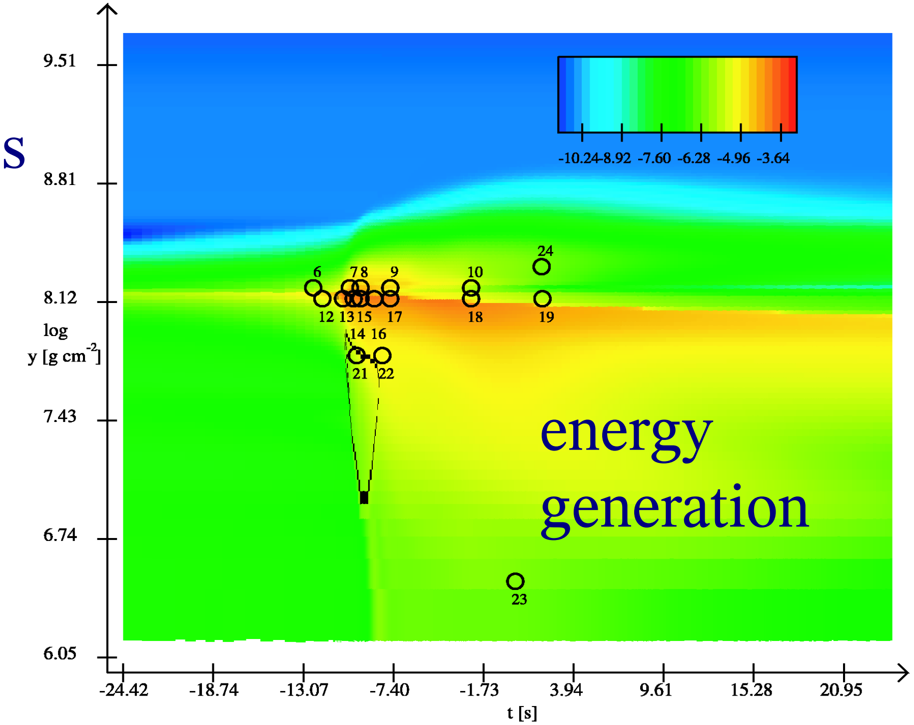
~ 5 m

Cooled Ashes

Compression

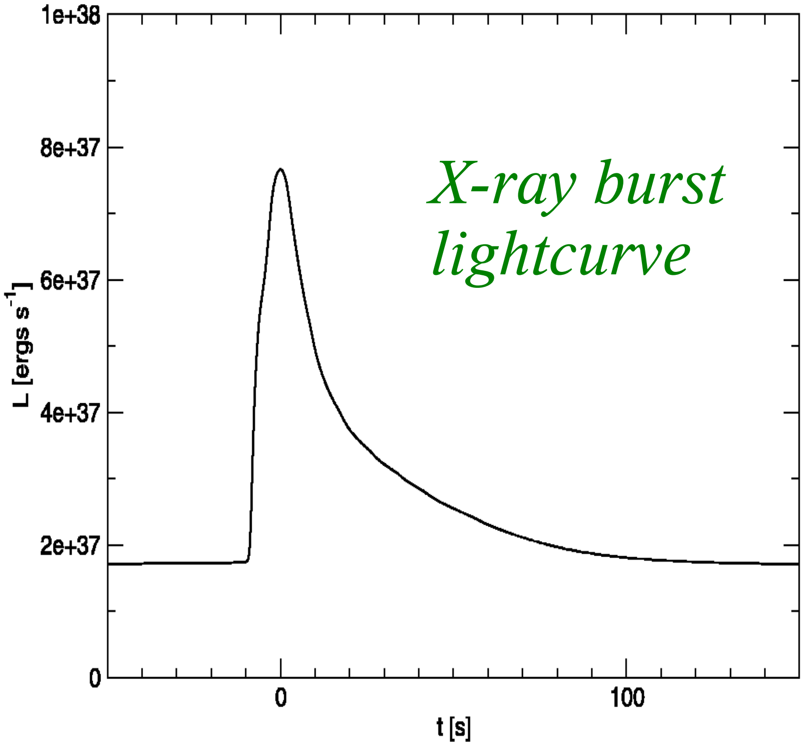


burning cycles in adjacent layers



energy generation

Temperatures and Lightvurves



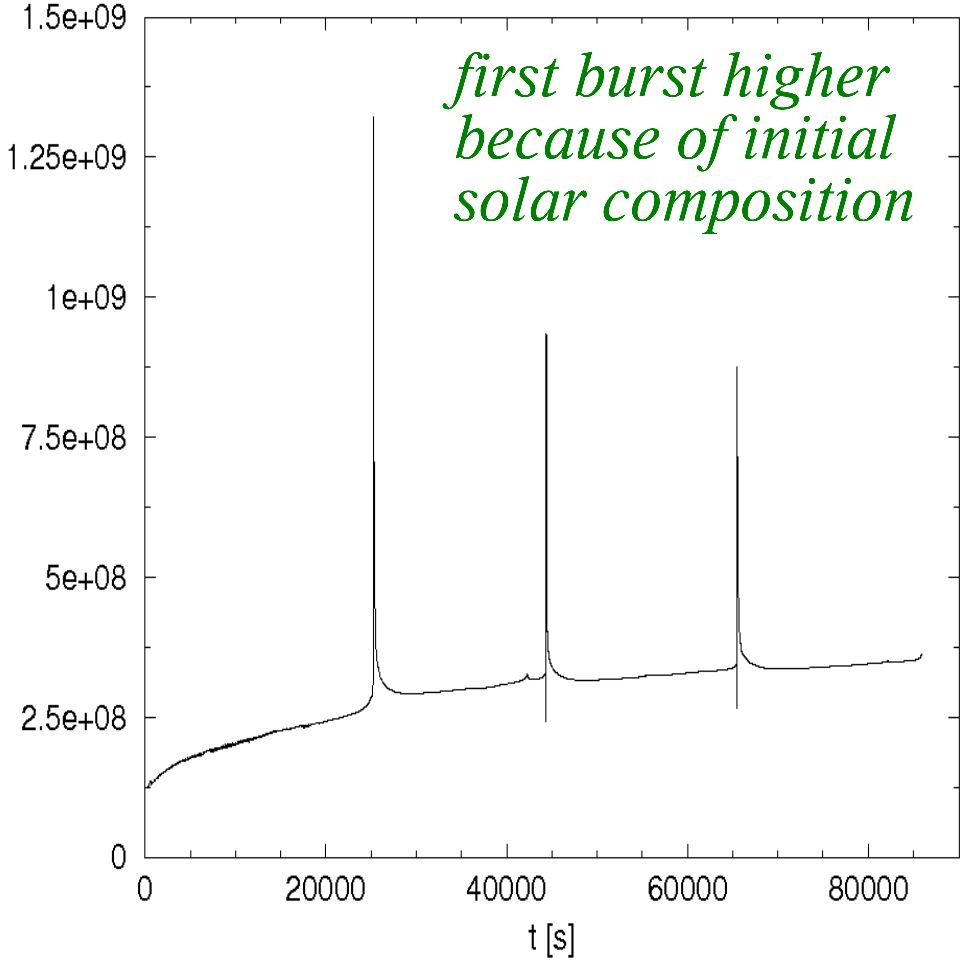
X-ray burst lightcurve

Duration 10-20s

from Fisker et al. (2004, 2005)

Temperature of element

Lagrange coordinates



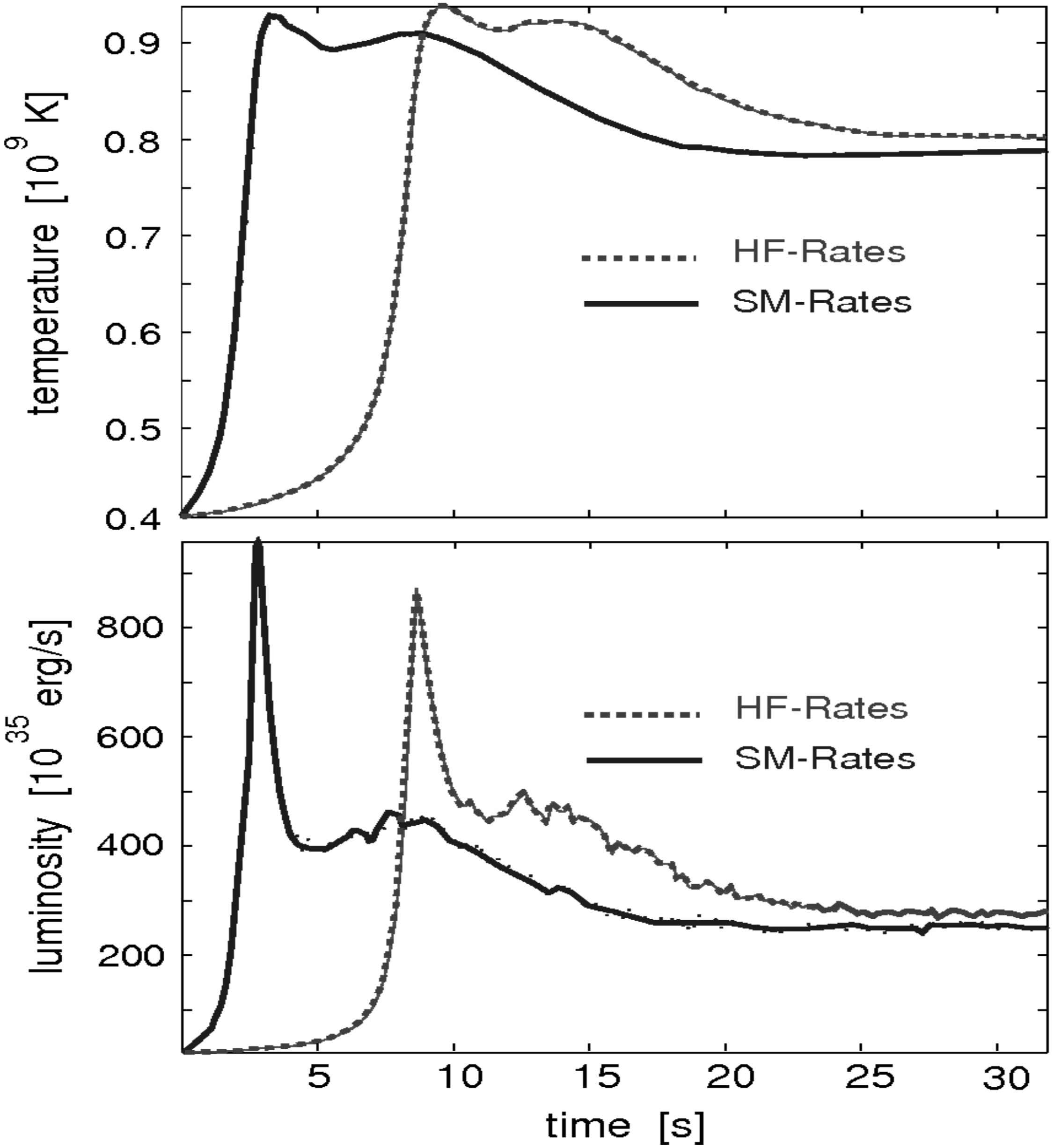
first burst higher because of initial solar composition

repetition about every 20000s

Summary of Burning/Ignition

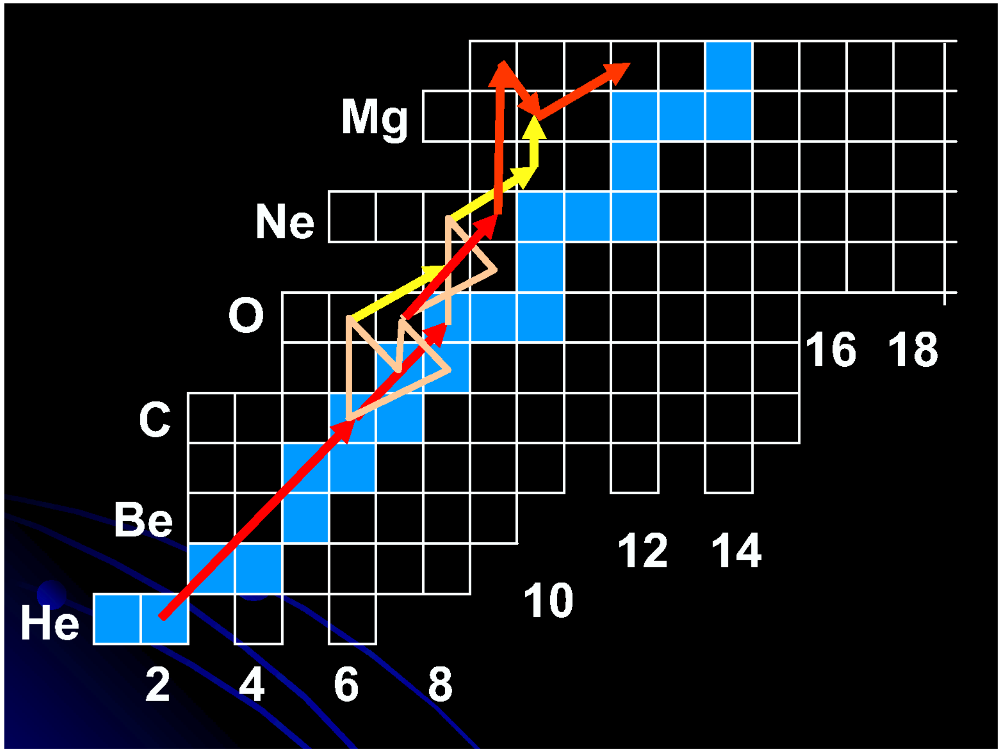
- hot CNO(-type)-cycles develope at moderate temperatures up to Ca (beta-limited and therefore essentially stable) and burn matter (H->He) either in „the“ hot CNO-cycle or also move matter above Ne up to Ca.
- if energy generation leads to temperatures above $4x10^8$ K, the heavier hot CNO-type cycles break up and are not beta-limited anymore (begin of a weak runaway).
- this energy input leads also to break-out from hot CNO via ^{15}O(alpha,gamma)^{19}Ne which then also opens ^{14}O(alpha,gamma)^{18}Ne (ignition!)
- energy generation also triggers triple-alpha (^{4}He->^{12}C) and thus opens the full flux from He via CNO to heavy nuclei with alpha-induced reactions operating until Coulomb barriers inhibit further capture (alpha,p)-process,
- followed by hydrogen/proton capture (rp-process) as long as temperatures permit.

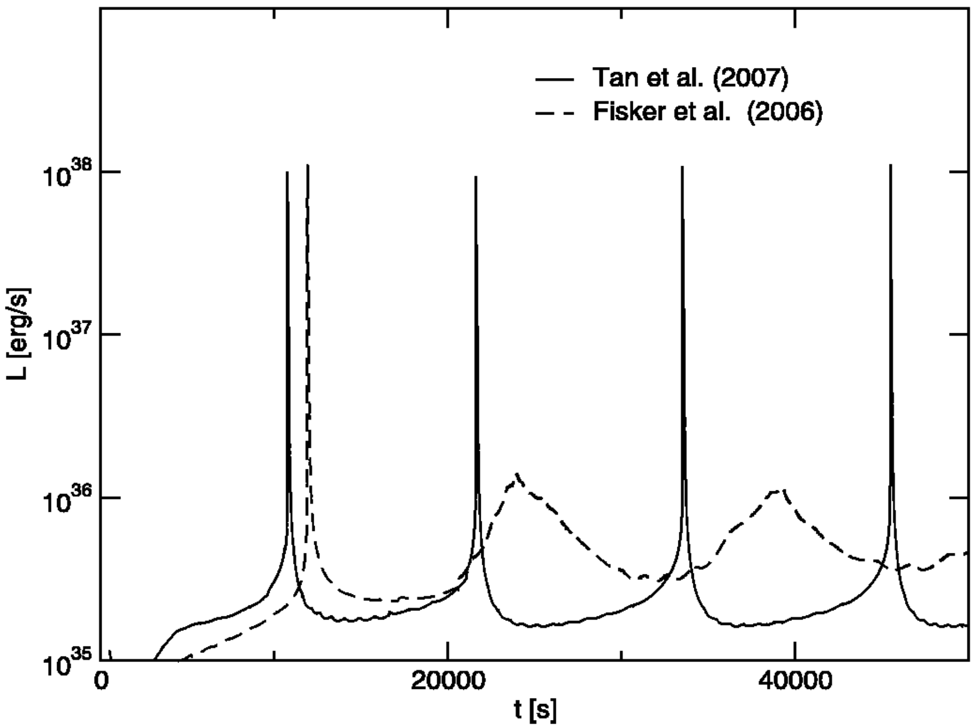
Testing early ignition phase



faster shell-model plus direct-capture rates permit early/ faster break-out from hot CNO-type cycles and lead to faster ignition
(Wiescher, Fisker et al. 2003)

Break-out Reactions and the Stability of Burning



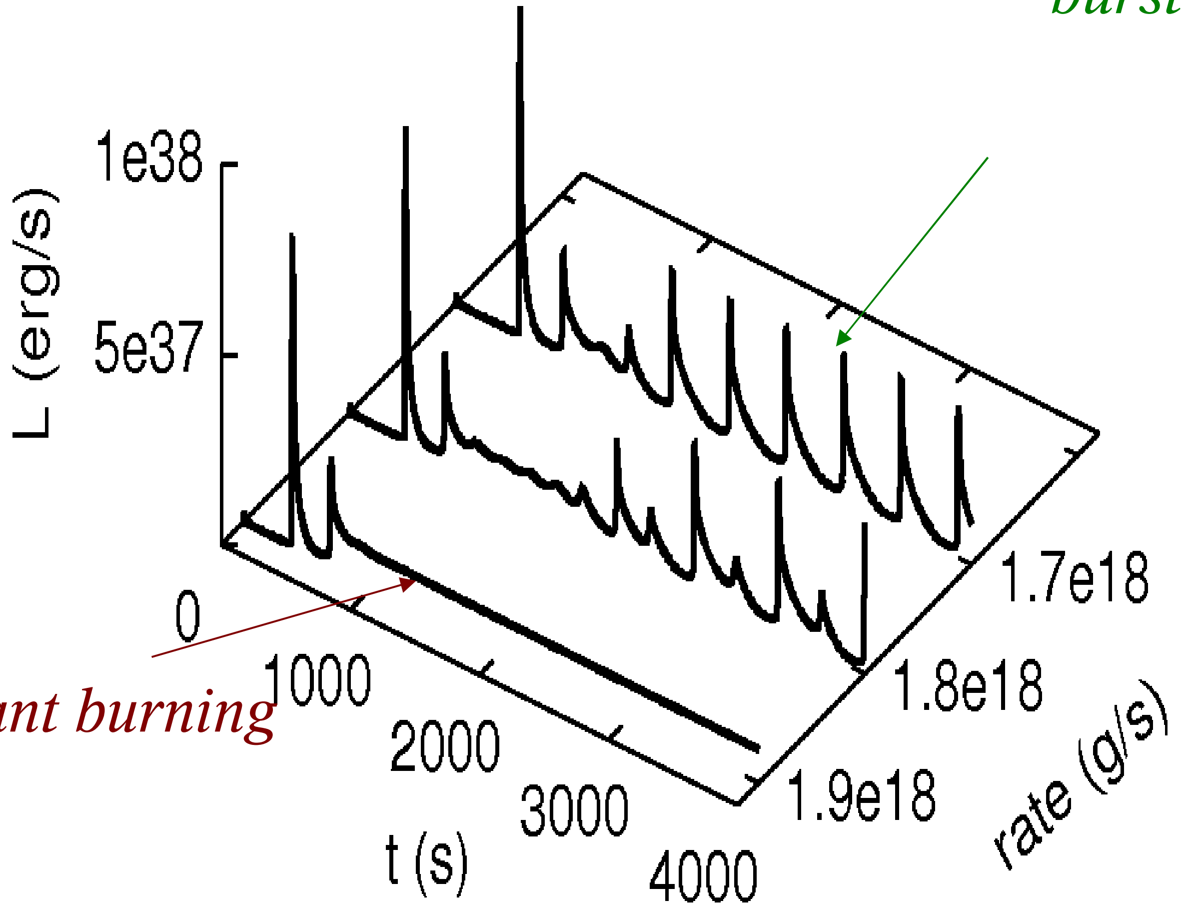


Uncertainties in:

$^{14}\text{O}(\alpha,p)^{17}\text{F}$, $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$, $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$
$^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$, $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$

Change in stable burst conditions due to new ^{15}O reaction cross section (Fisker et al. 2007)

Determines also the critical accretion rate between constant and unstable (bursts) burning

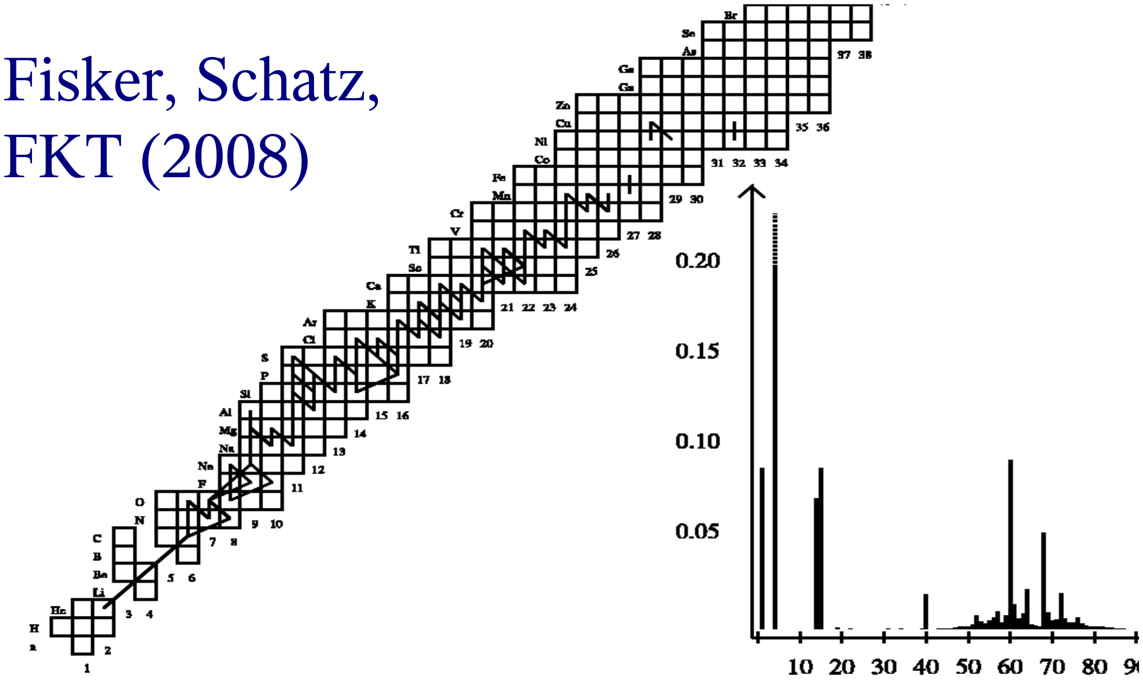


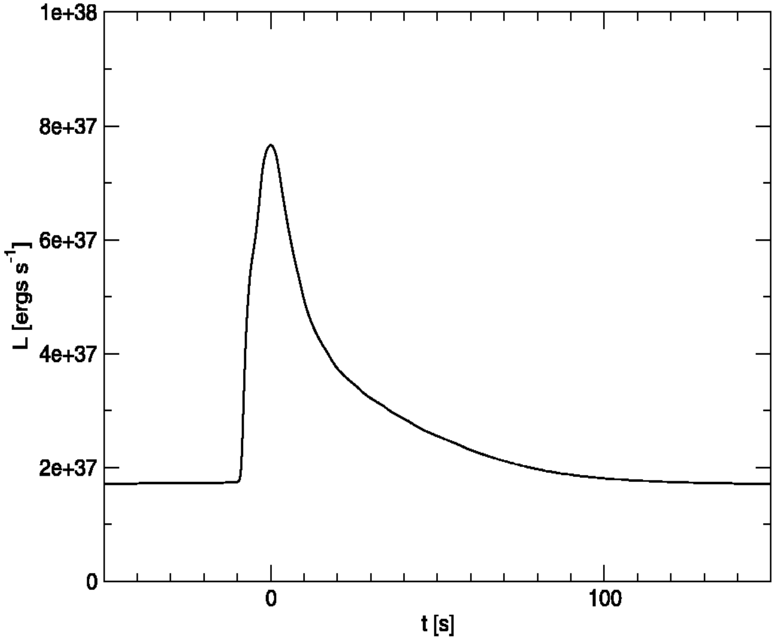
bursts

constant burning

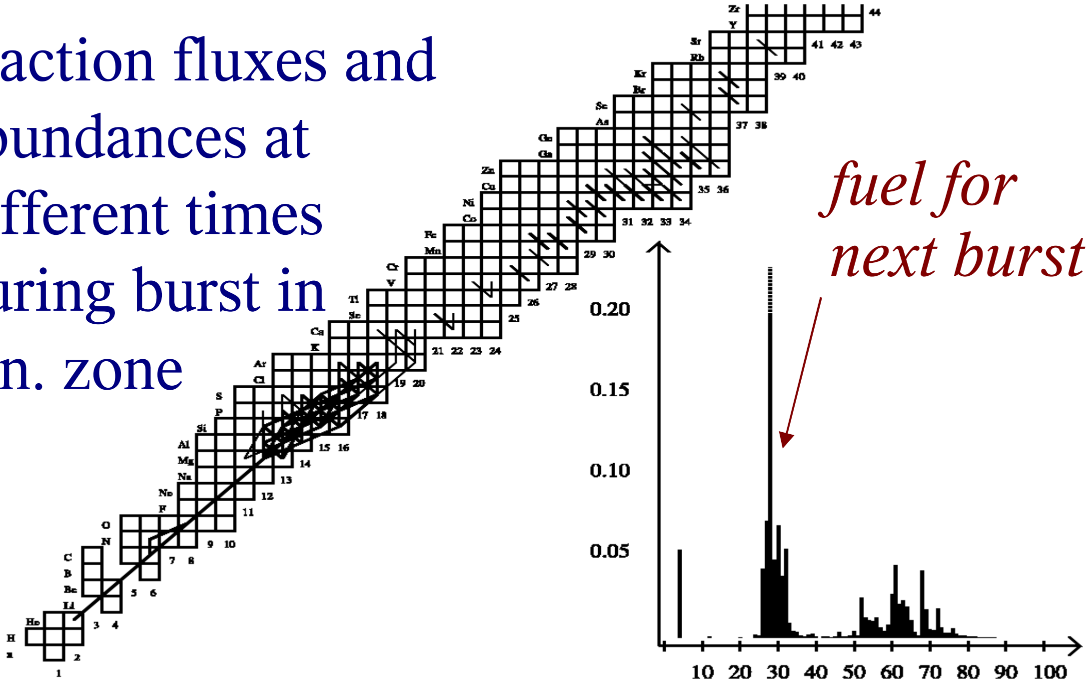
Tan et al. (2007)

Fisker, Schatz, FKT (2008)

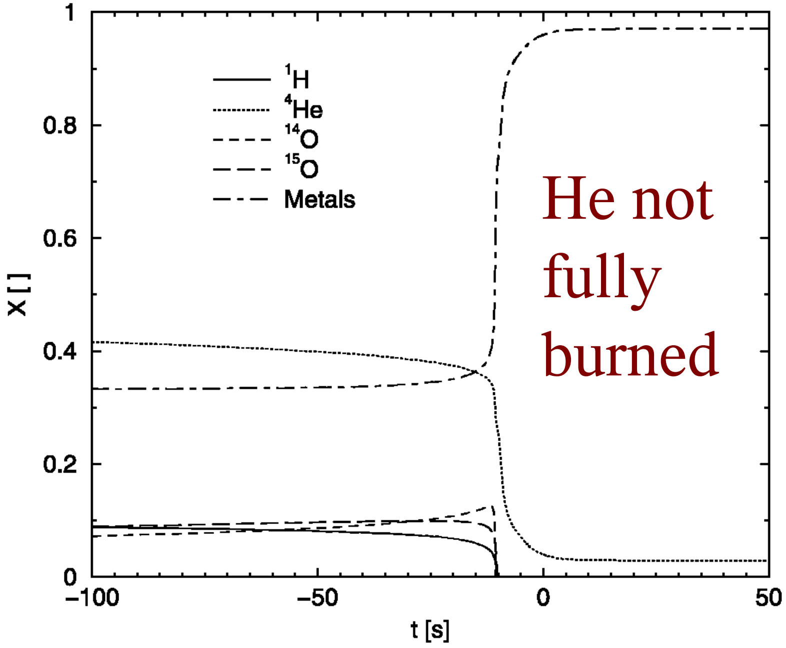




reaction fluxes and abundances at different times during burst in ign. zone



fuel for next burst

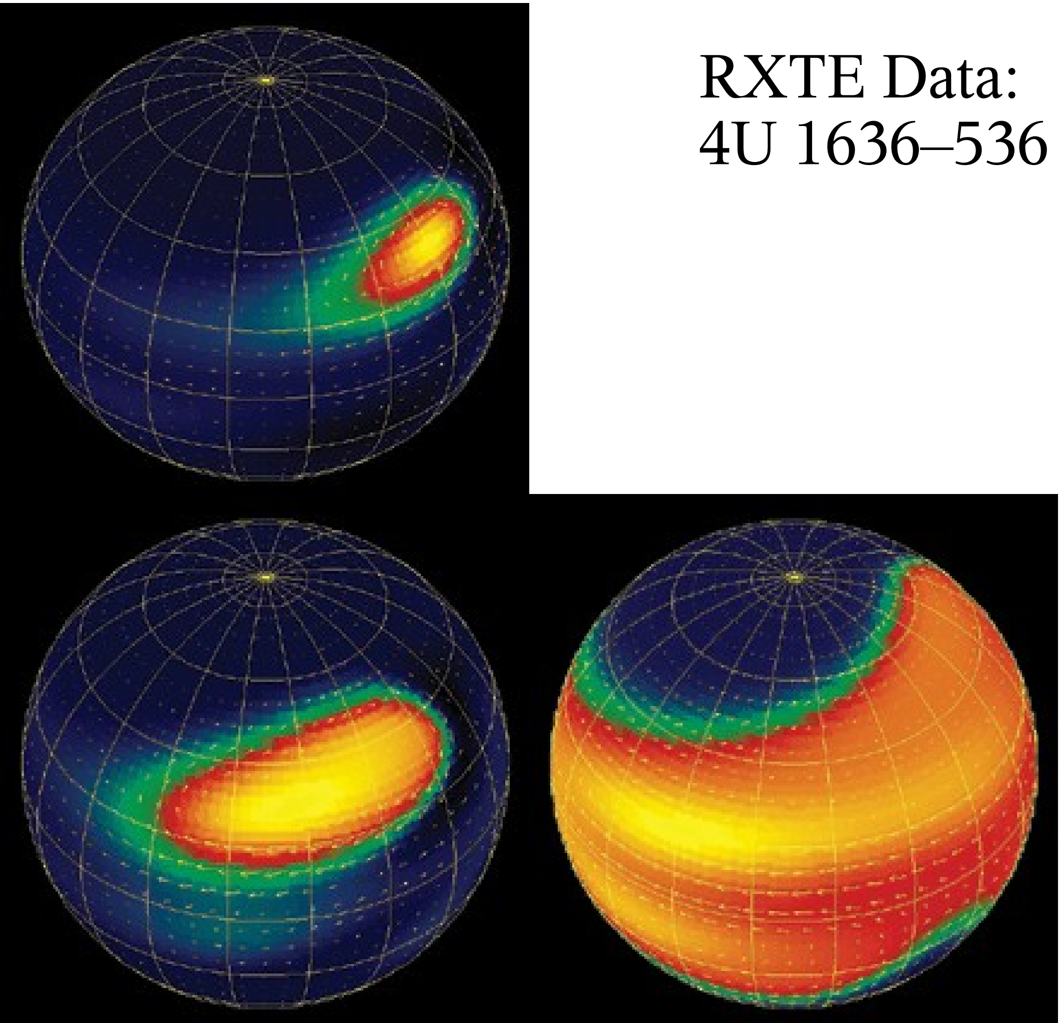


He not fully burned

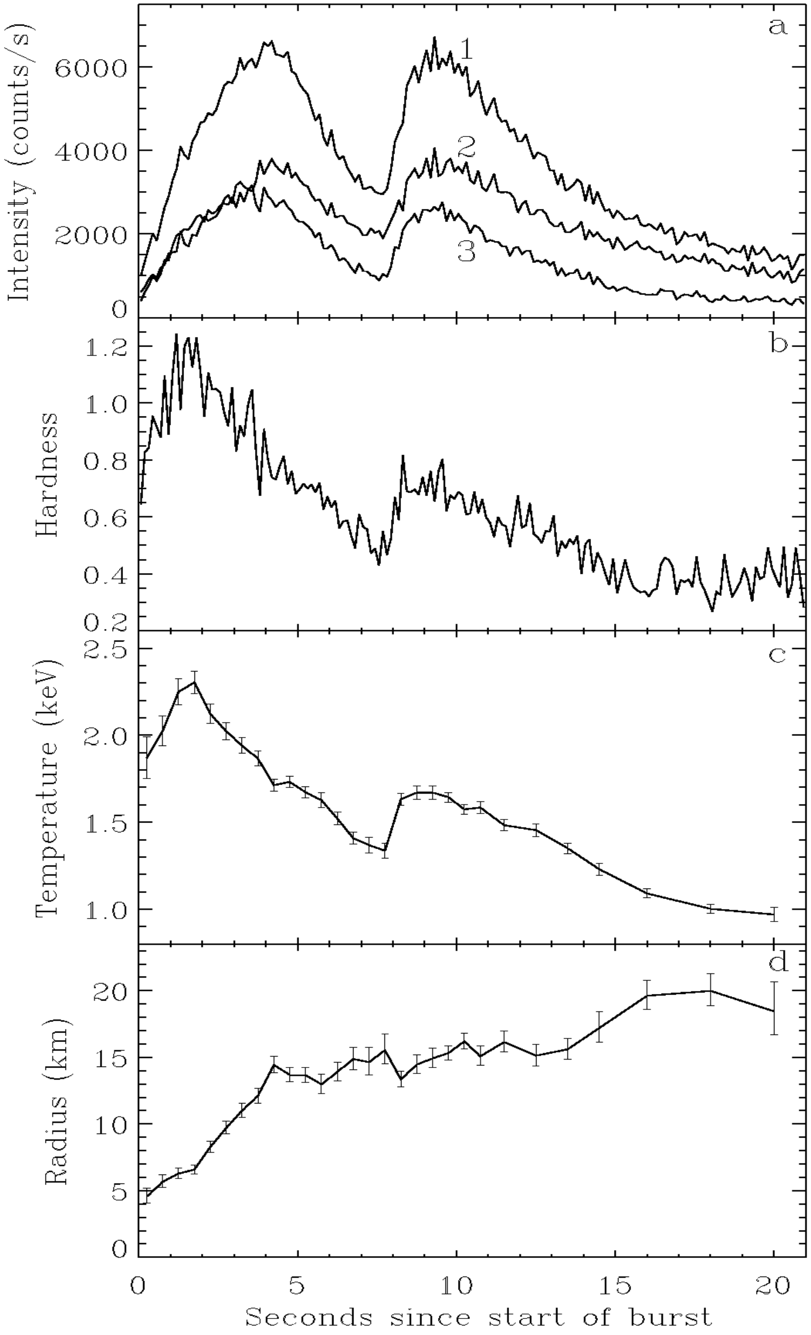
dependent on details of mass zone, H can run out shortly after seize of alpha-process

Multi-peak Lightcurves

- possible explanations?
- nuclear burning or
- spreading of burning front

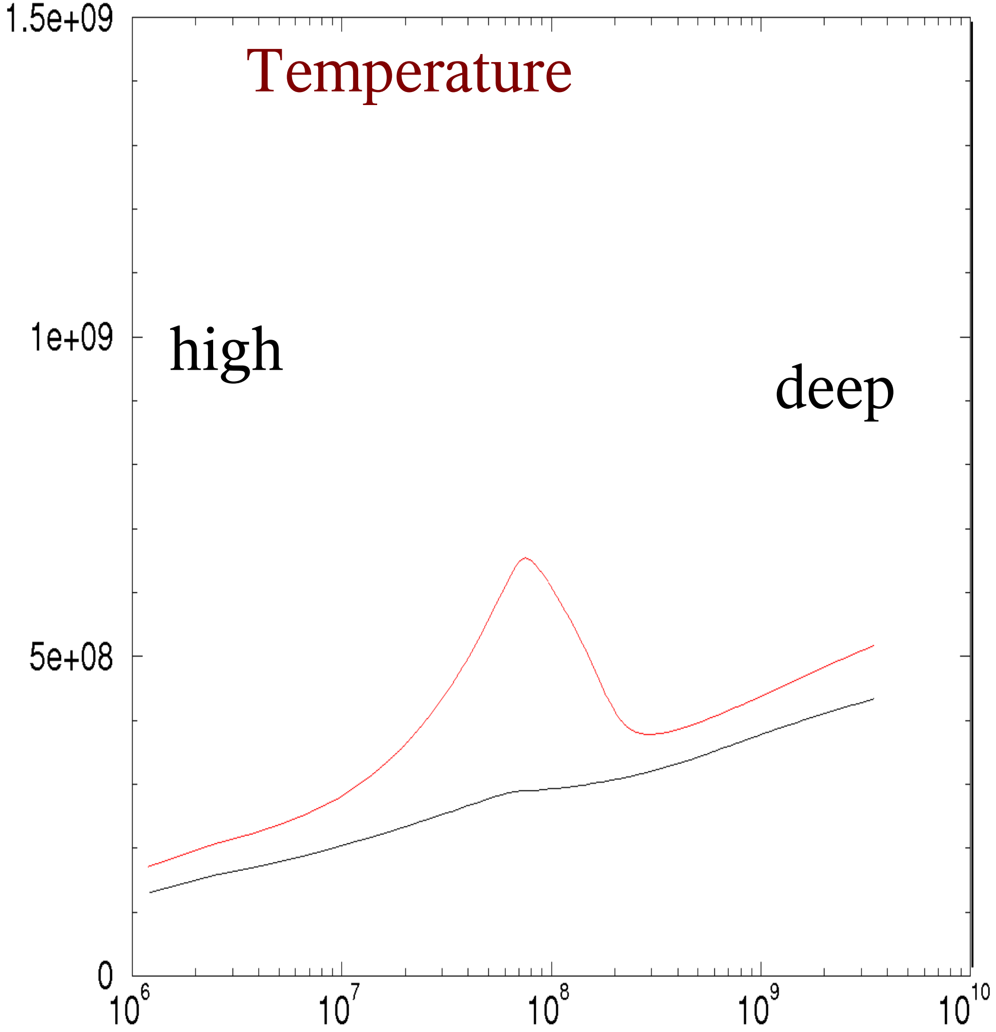


RXTE Data:
4U 1636–536



Ignition/Burning as a Function of Accretion Rate

t-8.0 s

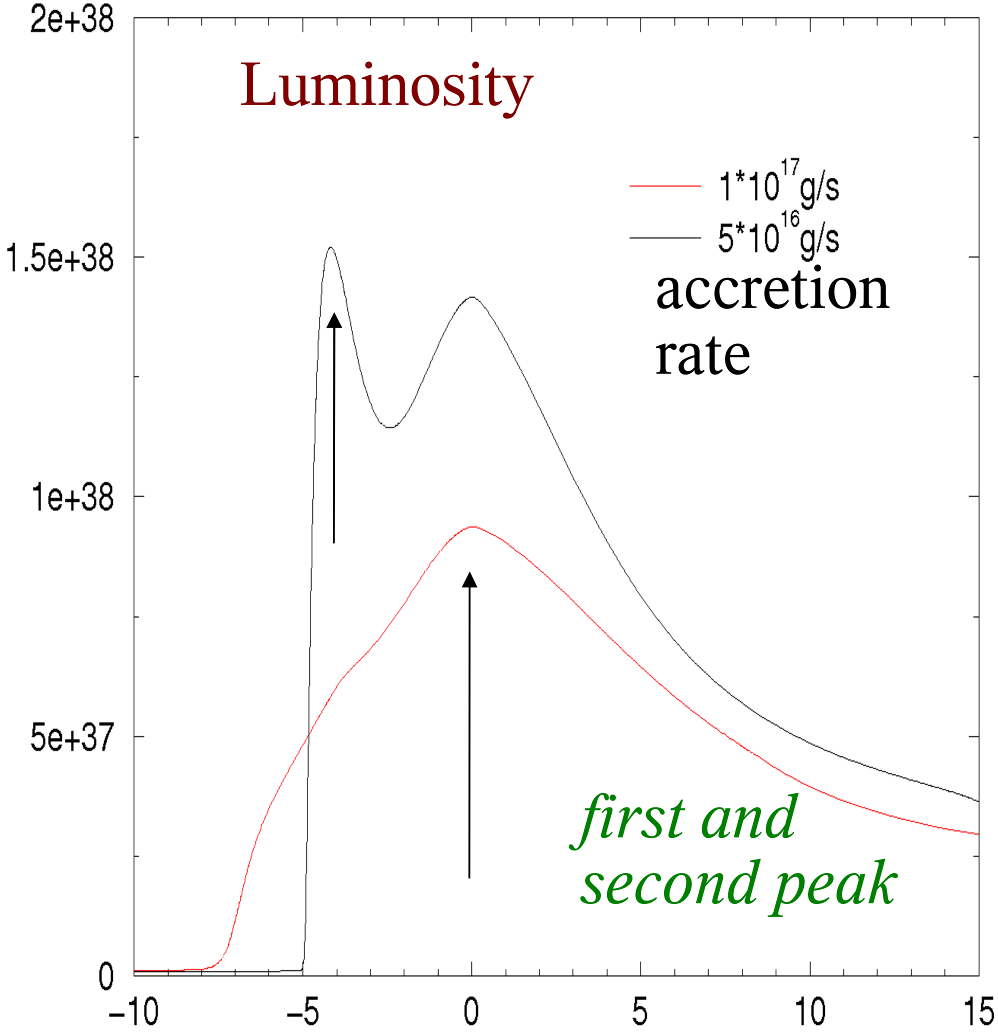


Temperature

high

deep

T/K as f(column dens.)[g/cm^2]



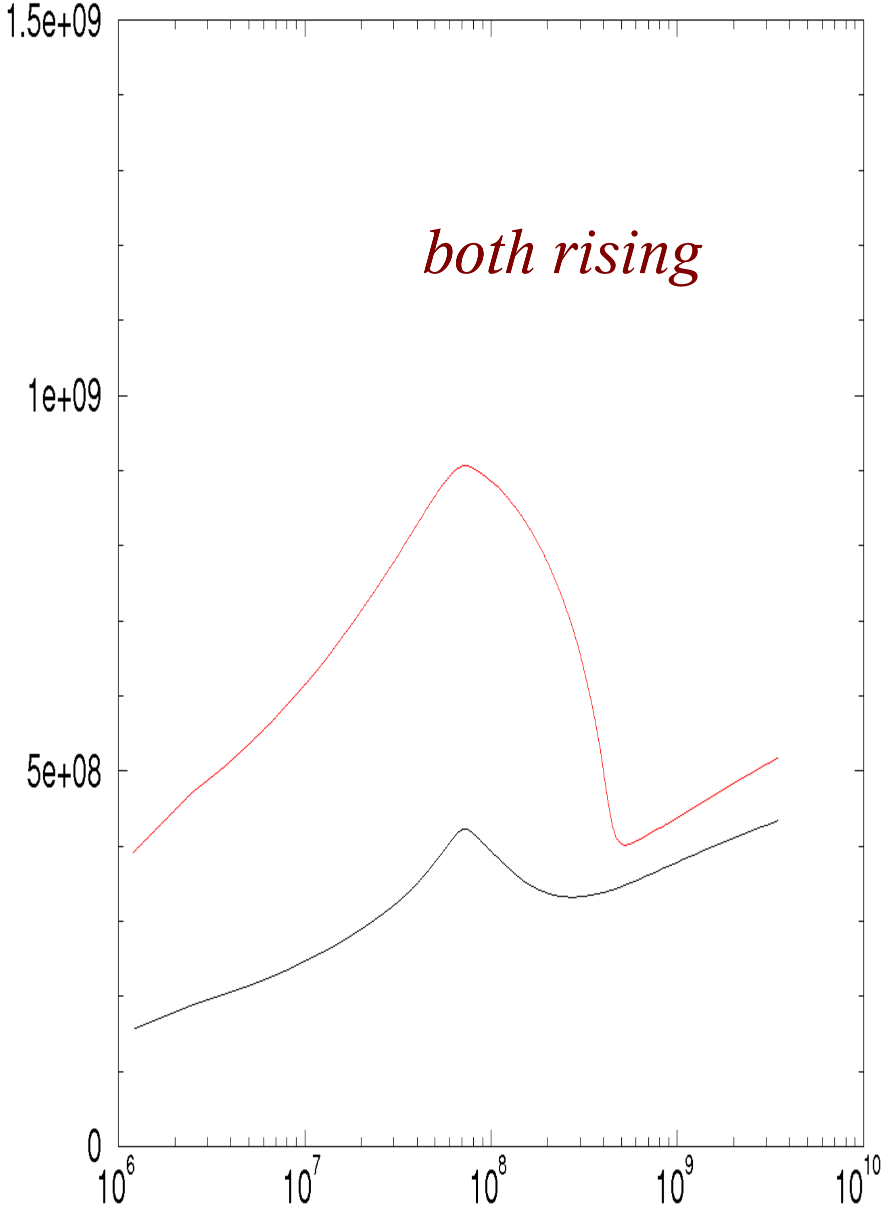
Luminosity

accretion rate

first and second peak

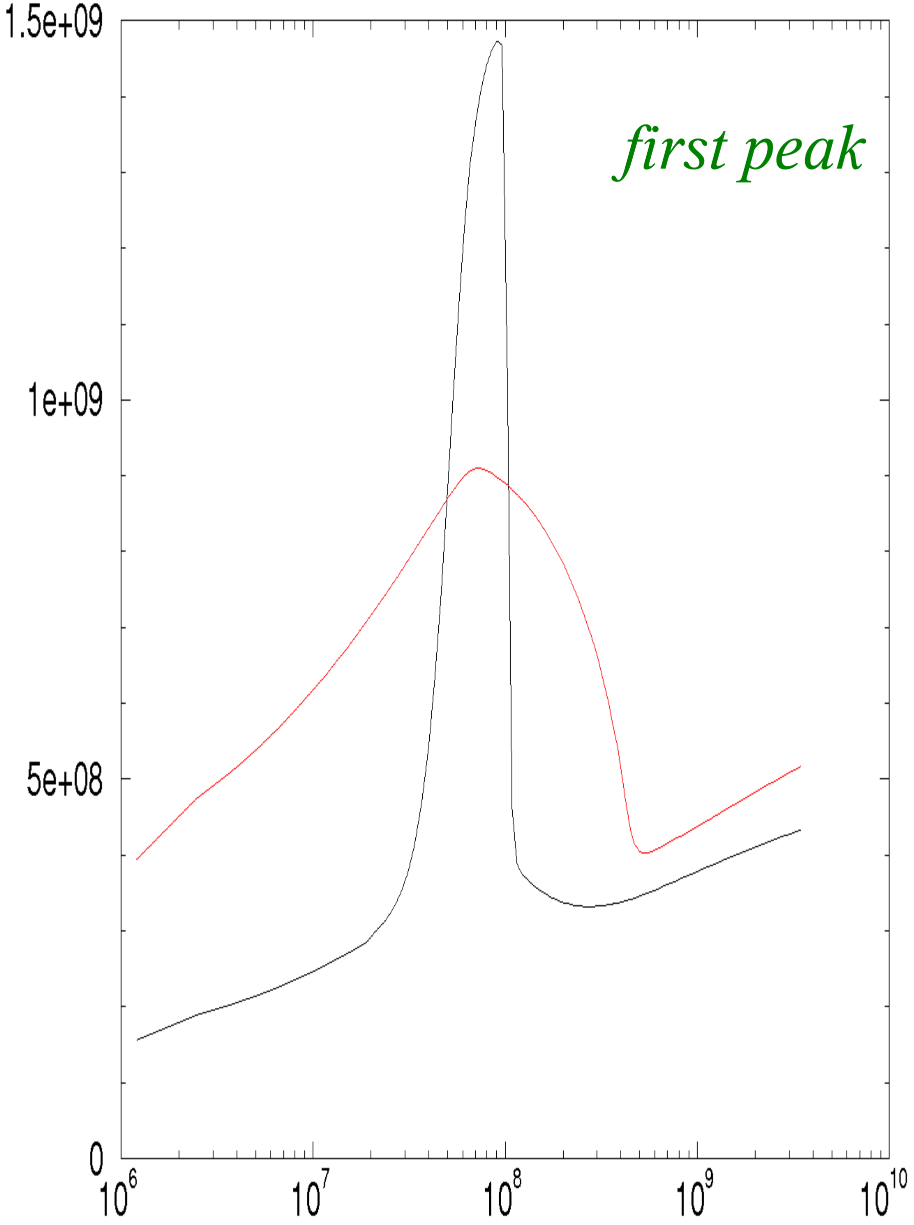
Luminosity (erg/g/s) as f(t)

two accretion rates



t-5.2

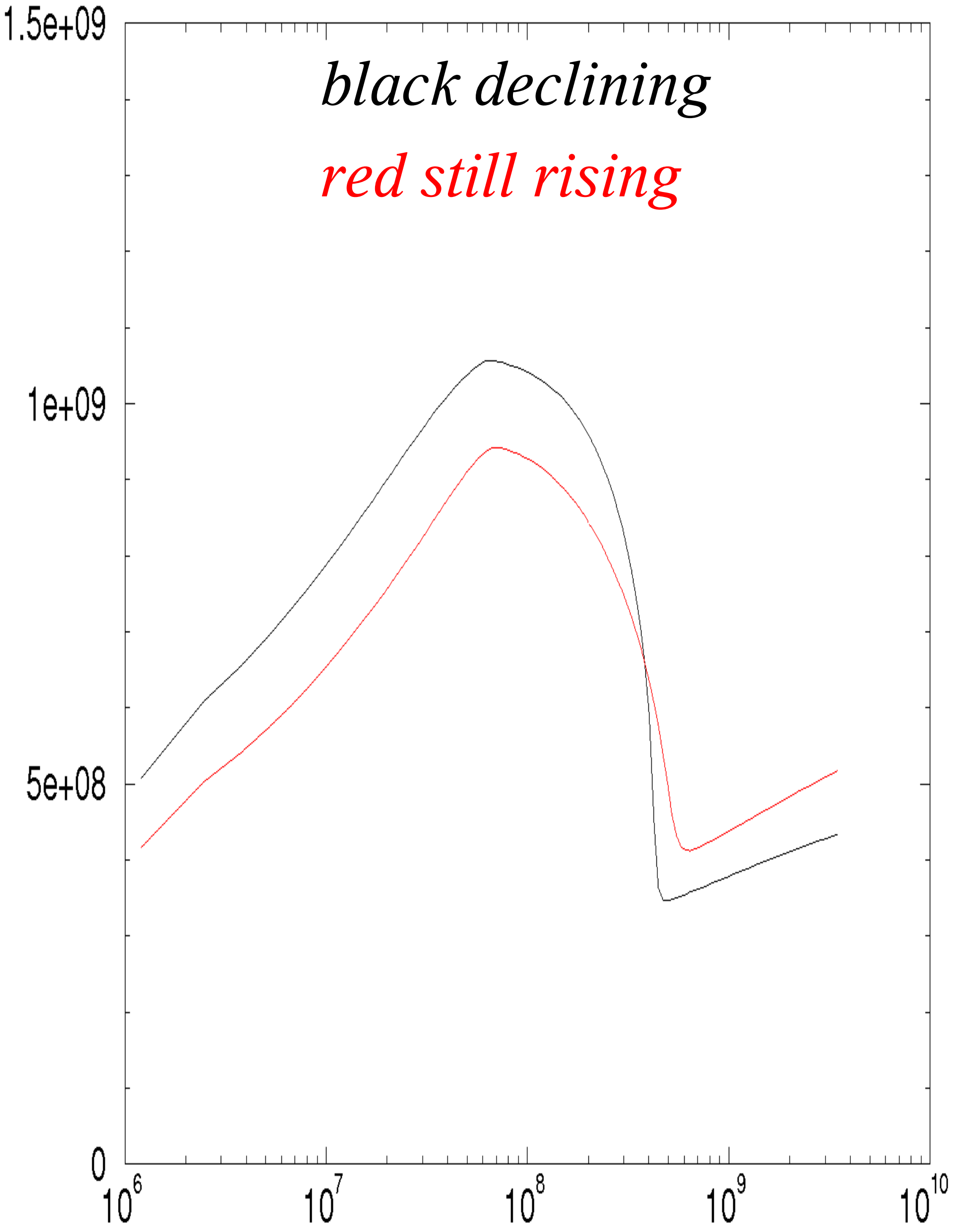
both rising



t-5.13

first peak

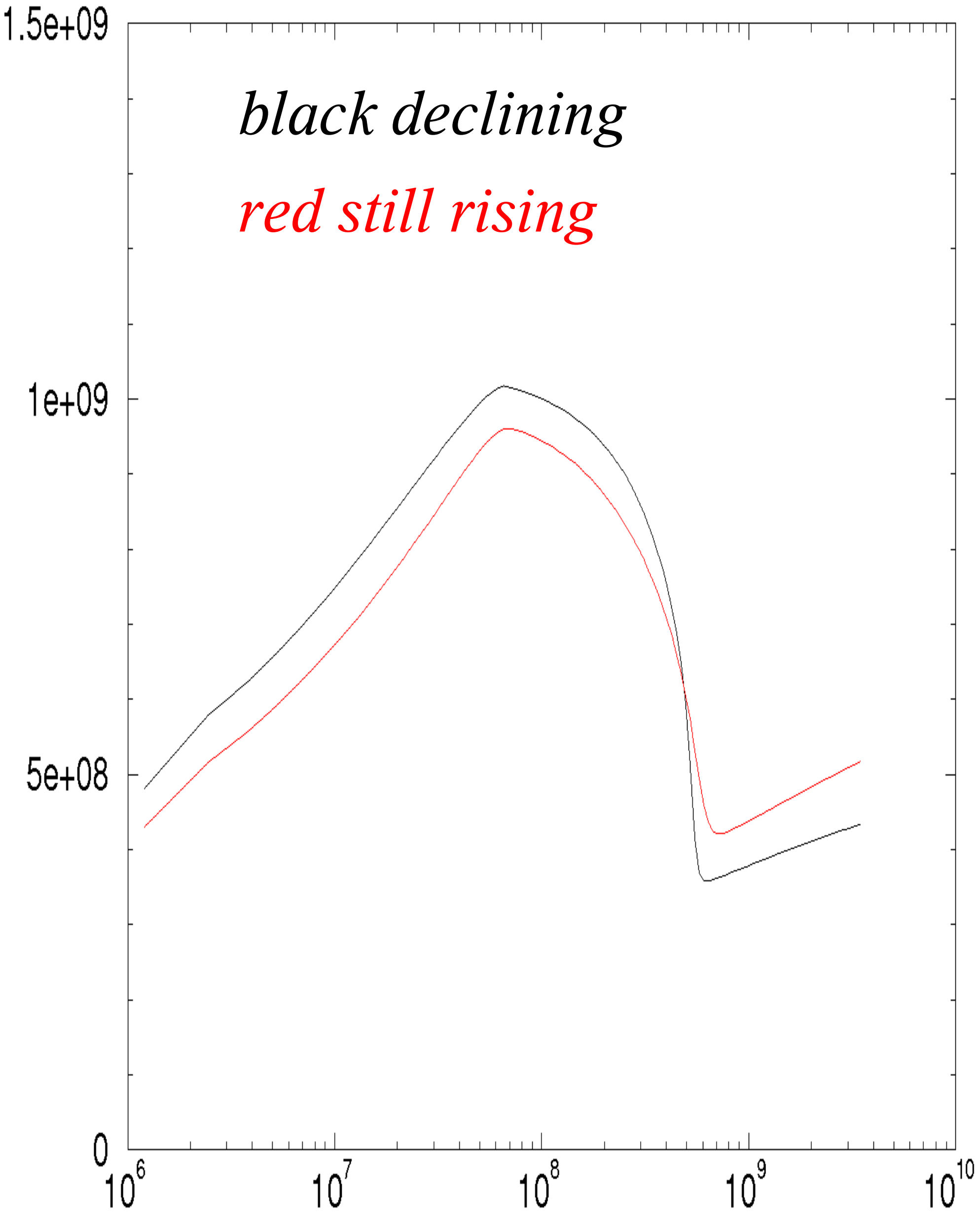
t-4.0



black declining

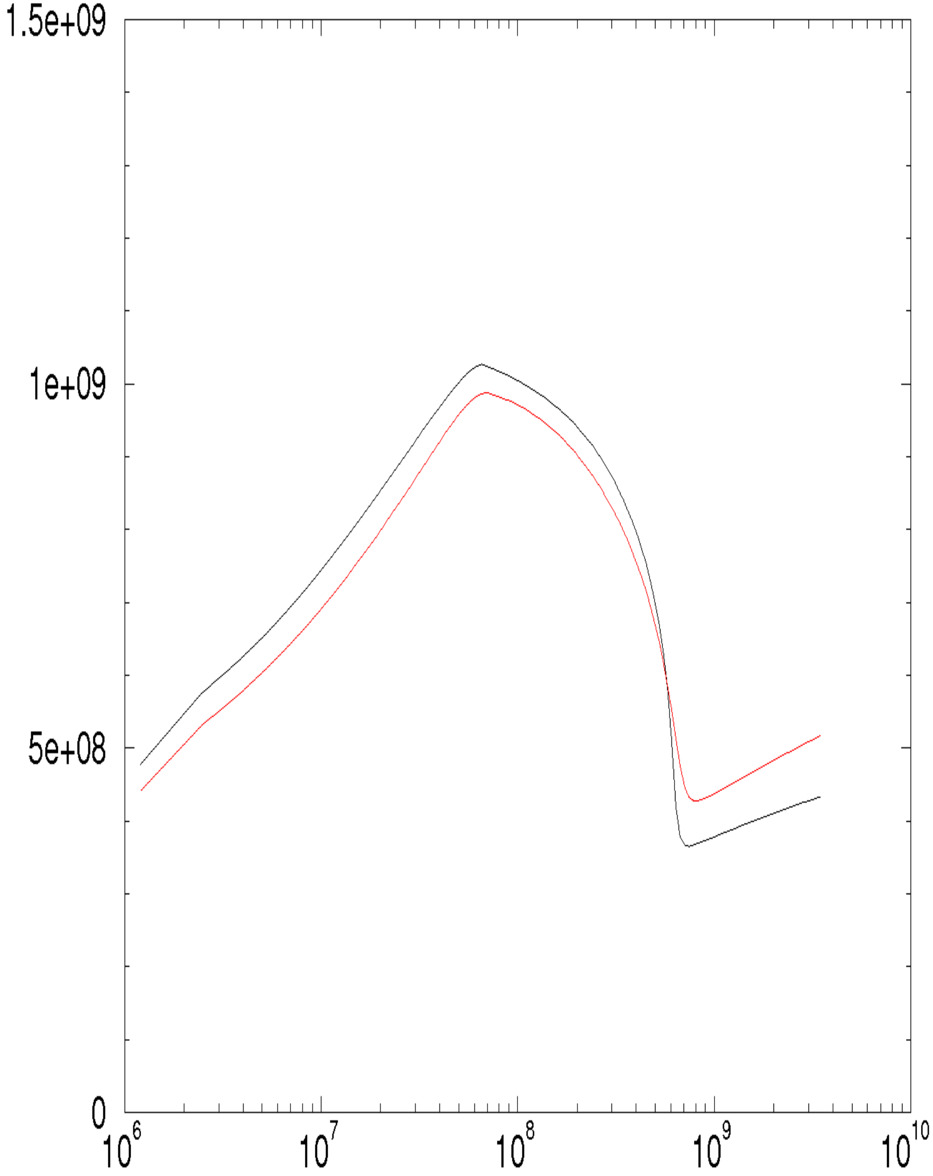
red still rising

t-3.0

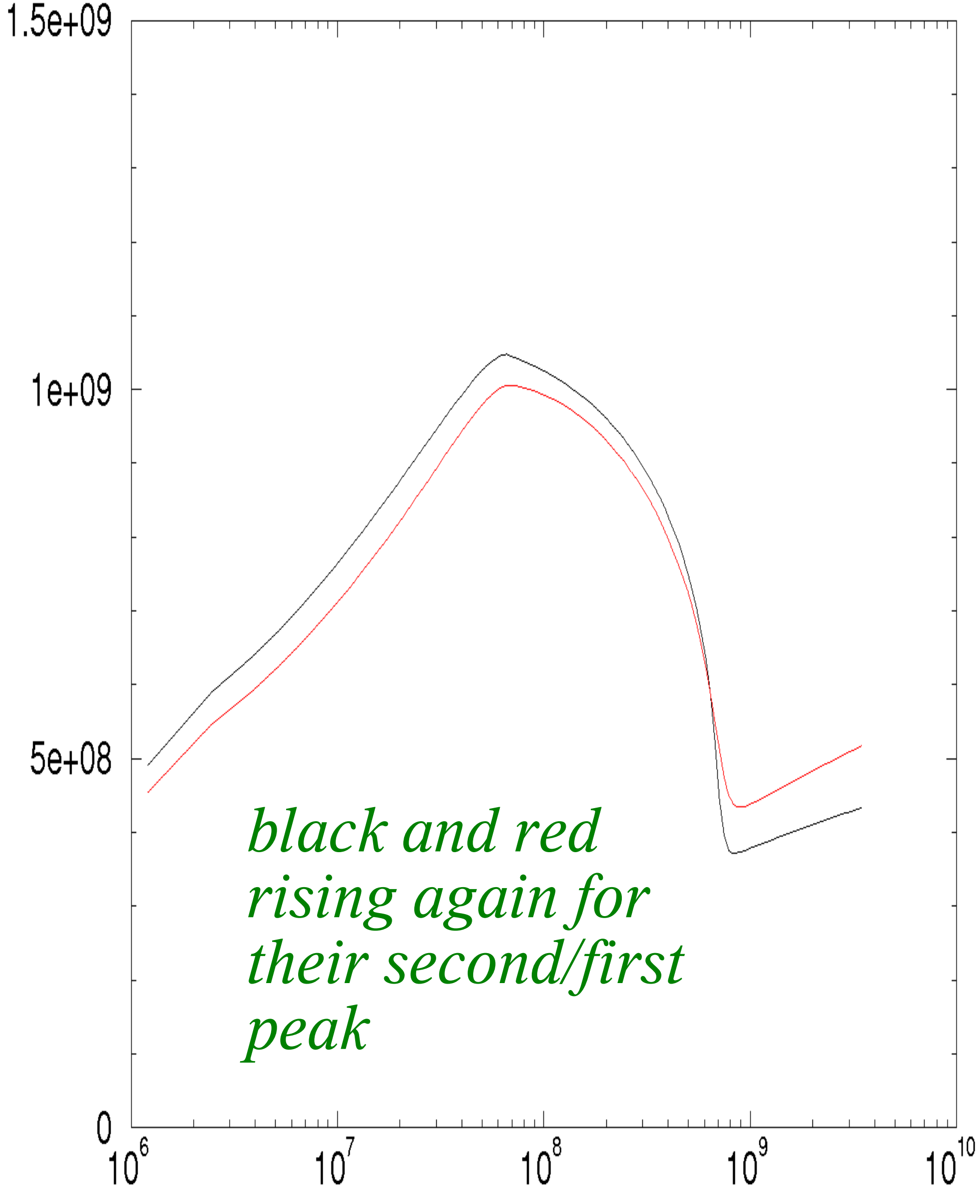


black declining

red still rising



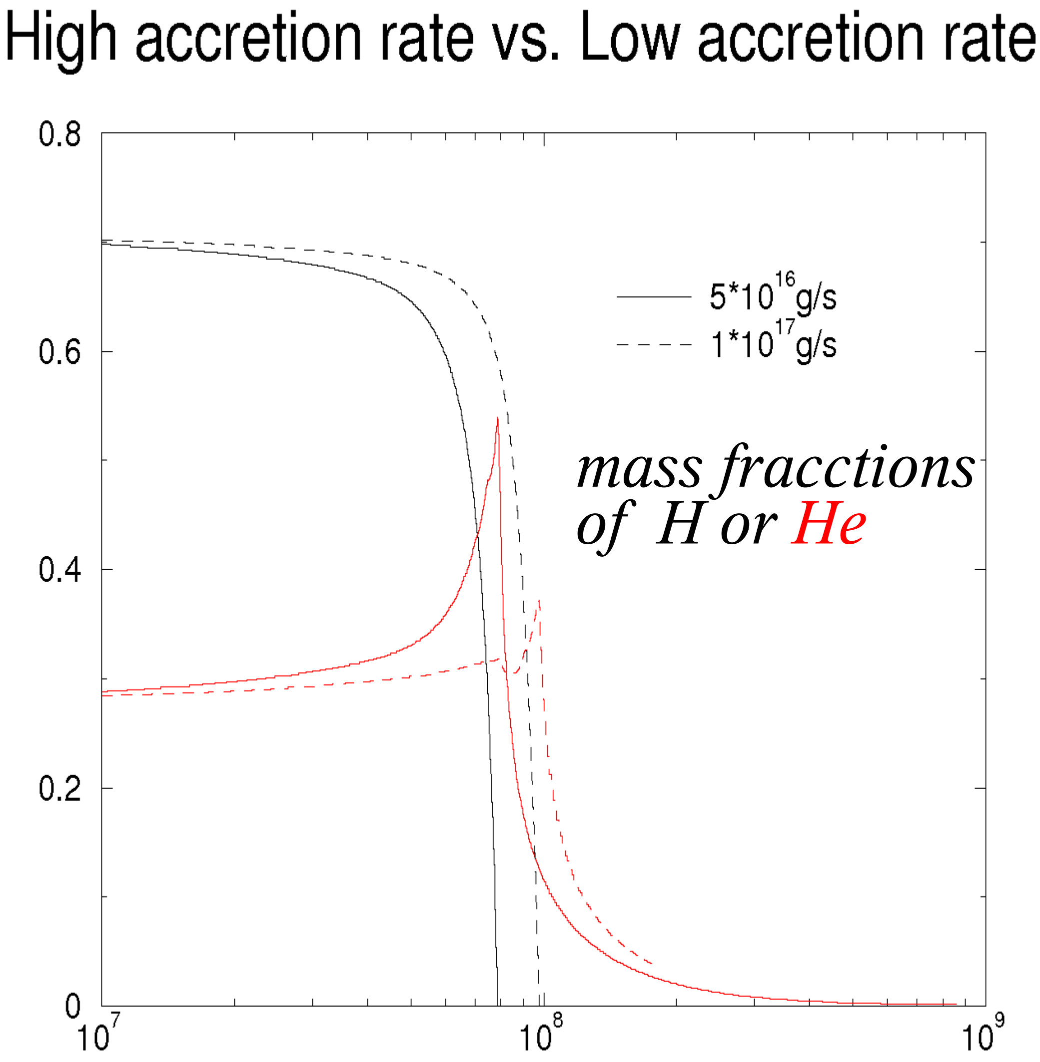
t-2.0



t-1.0

black and red rising again for their second/first peak

H/He distribution as function of accretion rate

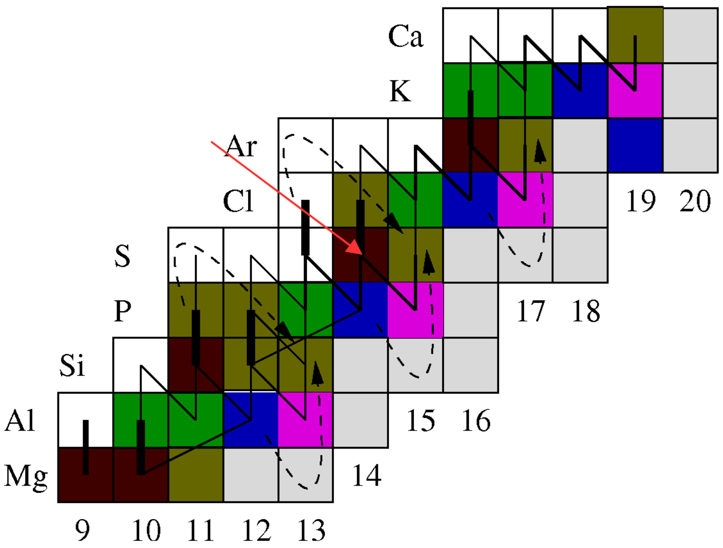


mass fracctions of H or He

pure He-flash has a faster run-away than mixed H/He-flash, but then experiences low densities when encountering so-called waiting points

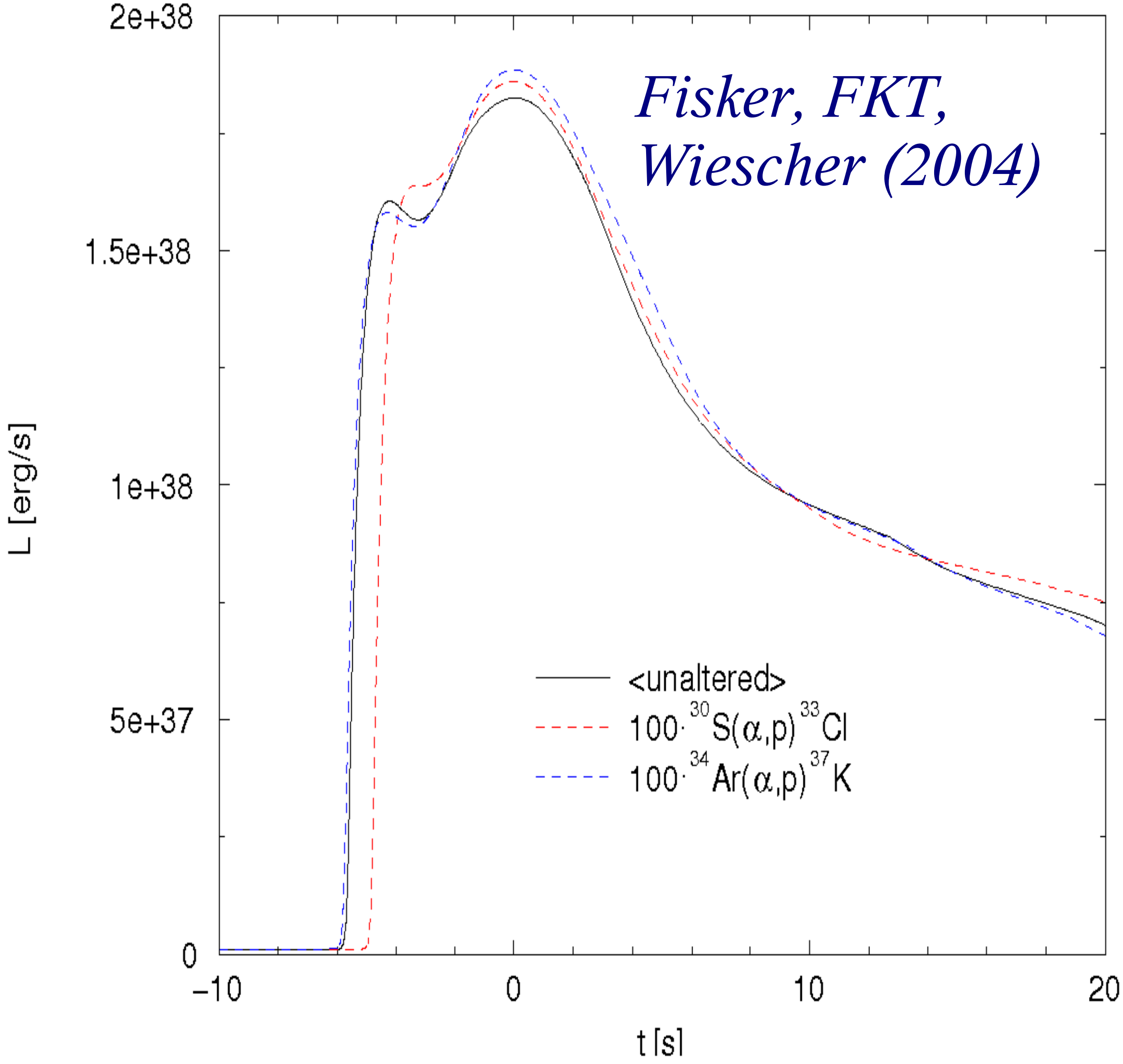
The (α, p)-process is important because it is a temperature-dependent process unlike the *rp*-process that contains temperature-independent β^+-decays. The (α, p)-process therefore influences the characteristic timescale of the reaction flow up to $A = 36$ after which the Coulomb barrier becomes prohibitive. Furthermore, as shown in Fisker et al. (2004) the (α, p)-reactions in the (α, p)-process lie on waiting points with ^{30}S being the most significant one. Other potential waiting points are ^{34}Ar and ^{26}Si.

Double Peak Lightcurves due to Waiting Points



Competition between beta-decays and alpha-capture for inhibited p-captures

alternative explanation by Bhattacharyya & Strohmayer (2006): Burning spreading over neutron star surface with intermediate slow-down phase



Fisker, FKT, Wiescher (2004)