The hot CNO-cycle and rp-Process

- Hydrogen burning under high T an rho
- rp-process
- hot bottom burning in low mass stars
- Novae
- X-ray Bursters

Literature: Rolfs & Rodney, Chapt. 3; Iliadis, Chap.5,

Hydrogen burning under extreme conditions

Astrophysical Objects:

- Hot bottom burning in massive AGB stars (> 4 solar masses)

  (T9 ~ 0.08)

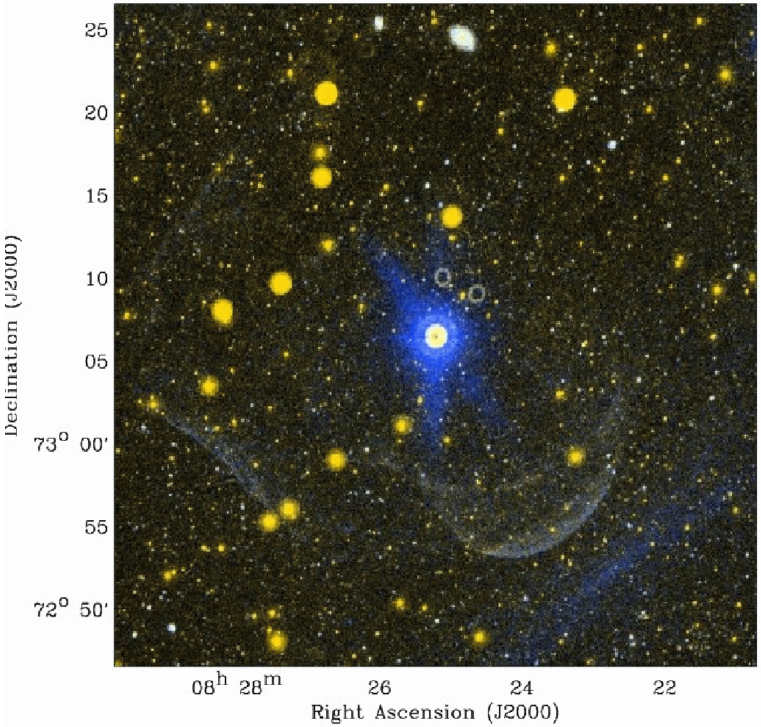
- Nova explosions on accreting white dwarfs

  (T9 ~ 0.4)

- X-ray bursts on accreting neutron stars

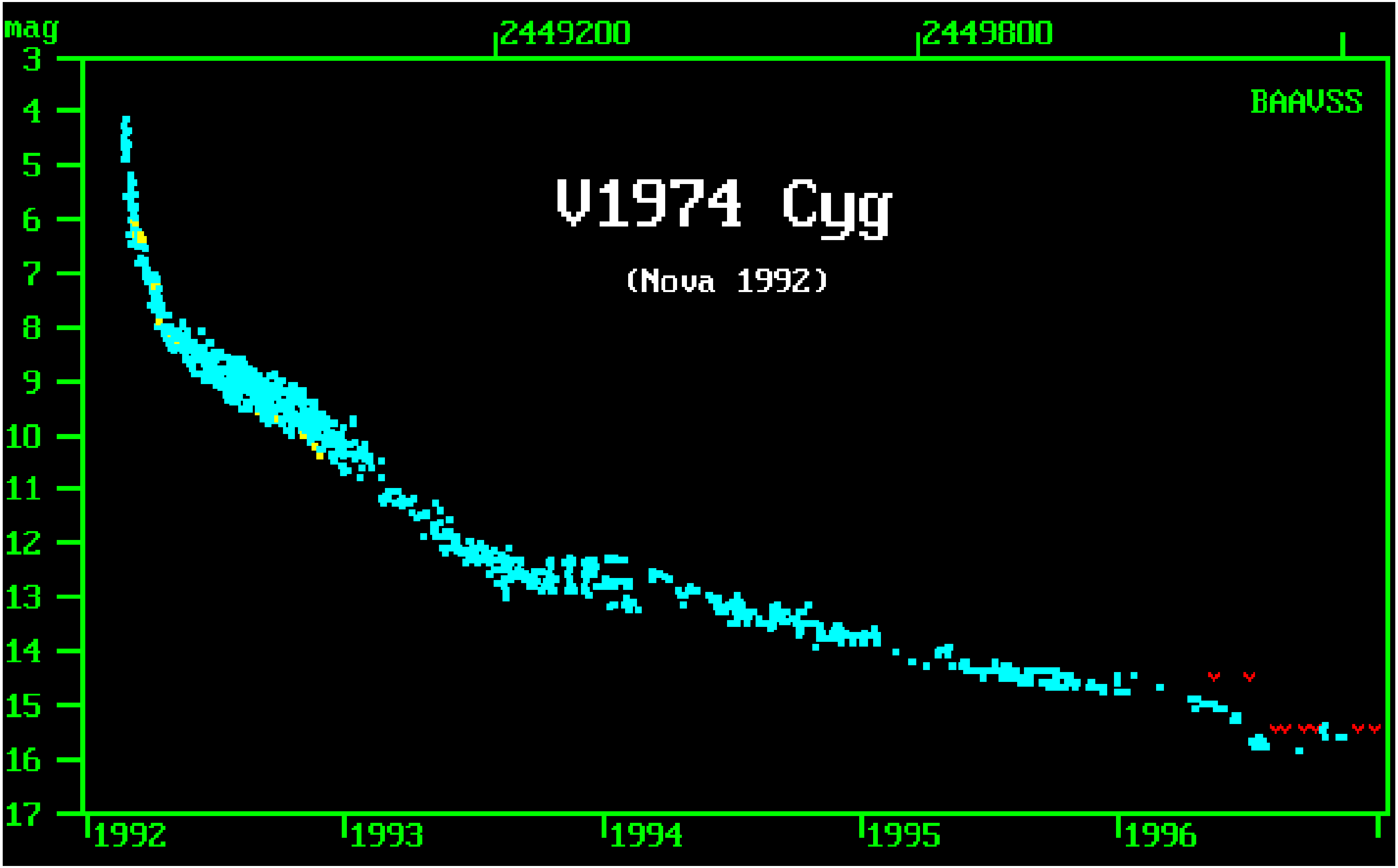
  (T9 ~ 2)

Classical and Recurrent Novae



- it is a quite common phenomenon; there are about 30 ± 10 novae every year in our galaxy
- the energy output of a nova reaches to $\geq 10^4\ L_\odot$
- the mass ejection in a nova is about $10^{-5} - 10^{-4}\ M_\odot$
- the mean velocity of the ejecta is about $10^2 - 10^3$ km/s
- models predict that novae recur with periodicities of order $10^4 - 10^5$ y
- spectra show production of medium-mass elements, but not beyond calcium

Novae Light Curves



Relevant Time Scales for Novae

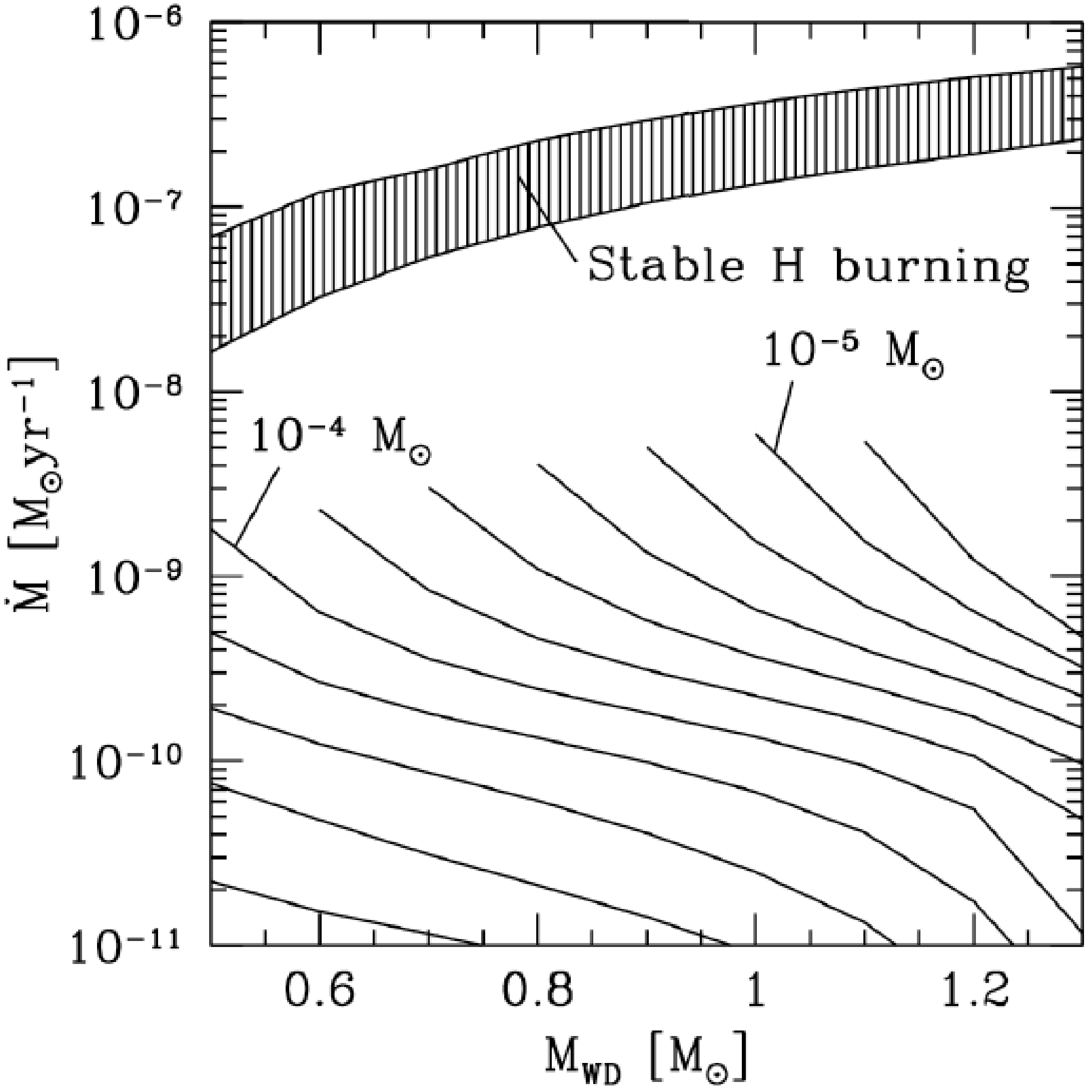
- Accretion time scales $\tau_{acc} \sim M_{acc}/\dot{M}_{acc}$ (1E4 to 1E5 yrs)

- dynamic time scale $\tau_{dyn} \sim \frac{1}{G}\sqrt{P/\rho}$ (1 sec)

  related: T to break degeneracy $T \sim 4 \times 10^{7} K(\frac{\rho}{10^{4} g/cm^{3}})^{2/3}$

- Nuclear time scale

Regimes of Stable Accretion (Sugimoto 1975)



- Stable burning

- hot CNO-cycle in thin shell

- H-He flashes

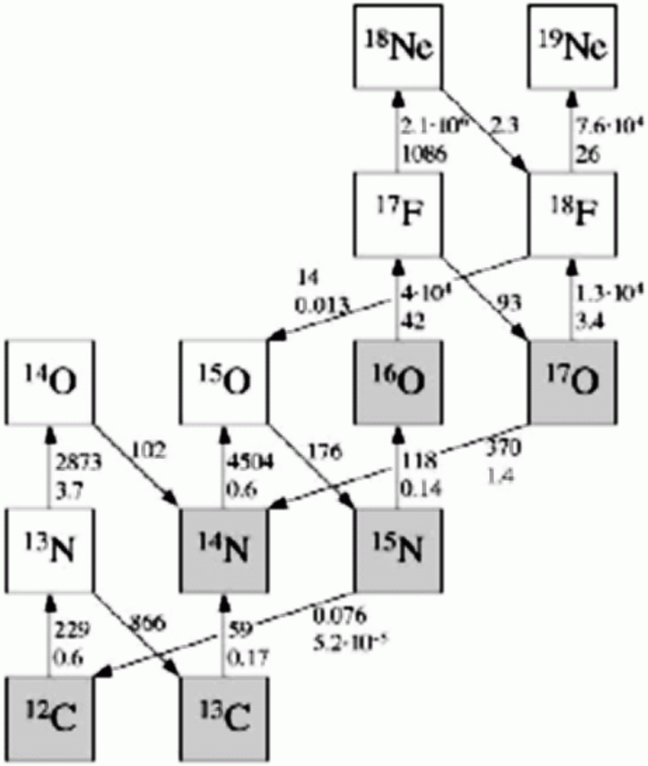
explosive H-burning

explosive He-burning

SNIa: Continous hydrogen burning for 1E-8Mo/year => entire WD explodes
Novae: Periodic hydrogen burning (only surface layers are ejected)
  recurrent: flashes occur frequent (high accretion rate)
  classical: flashes occur at frequencies more than a life-time

Nuclear Time-Scale for the Runaway

Nuclear hydrogen burning occurs within the CNO cycle. There are really two nuclear timescales:



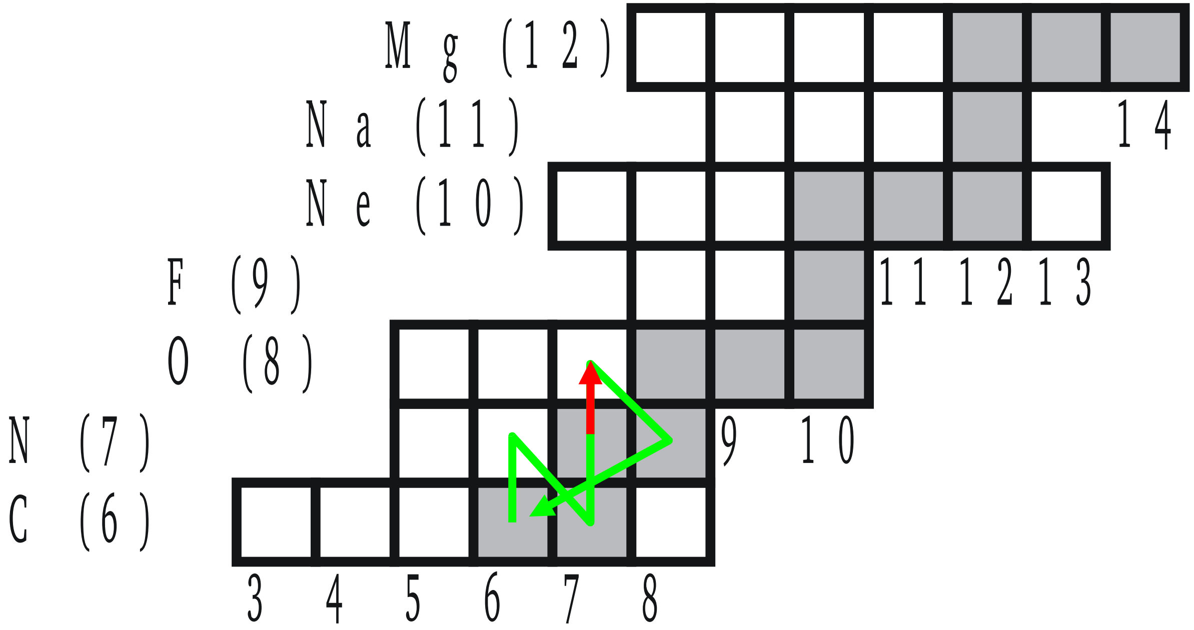
β-lifetimes and reaction lifetimes at $T_8 = 1$ and $T_8 = 2$ are given.

- β-decays: there are several β^+-unstable nuclei with very short halflives (^{13}N, ^{14,15}O, ^{17}F). Under nova conditions, the β timescale τ_β is independent on temperature and density
- proton captures: the rates depend strongly on temperatures; the reaction lifetime is $\tau_p = [\rho X_H / A_H N_A \langle \sigma v \rangle]^{-1}$

“ CNO-Cycle **T < 0.08**

Energy production rate:

$\varepsilon \propto \sigma v>_{14N(p,\gamma)}$



Ne-Na cycle !

Hot CN(O)-Cycle **T ~ 0.08-0.1**

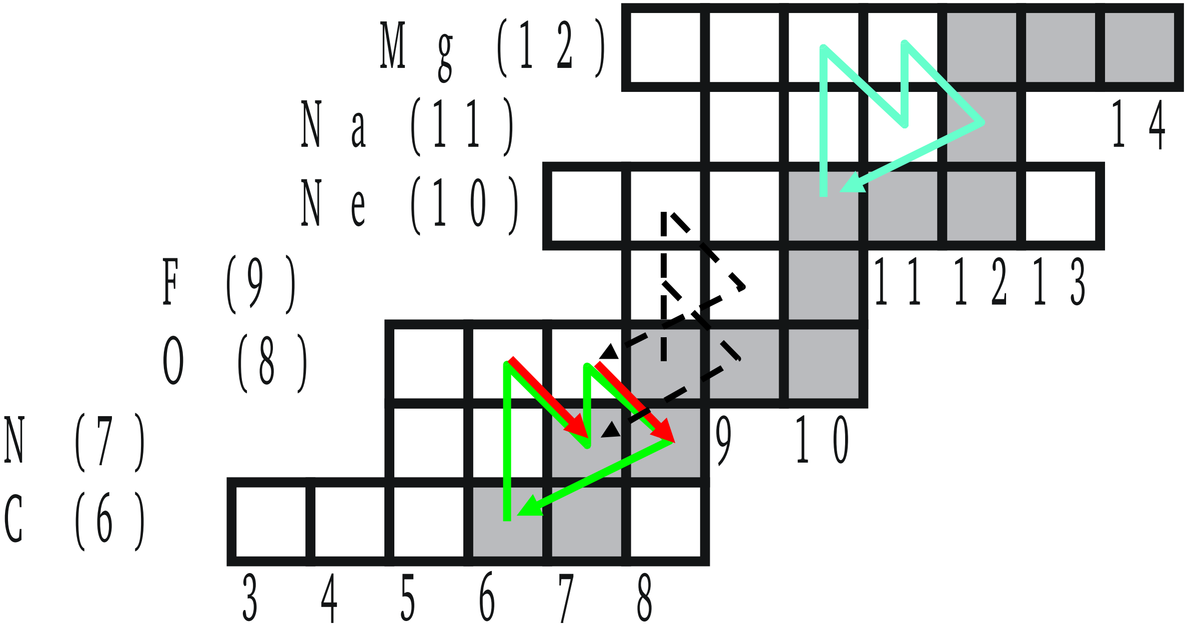
“beta limited CNO cycle”

$$\varepsilon \propto 1/(\lambda^{-1}_{14O(\beta+)} + \lambda^{-1}_{15O(\beta+)}) = \text{const}$$

Note: condition for hot CNO cycle depend also on density and Y :

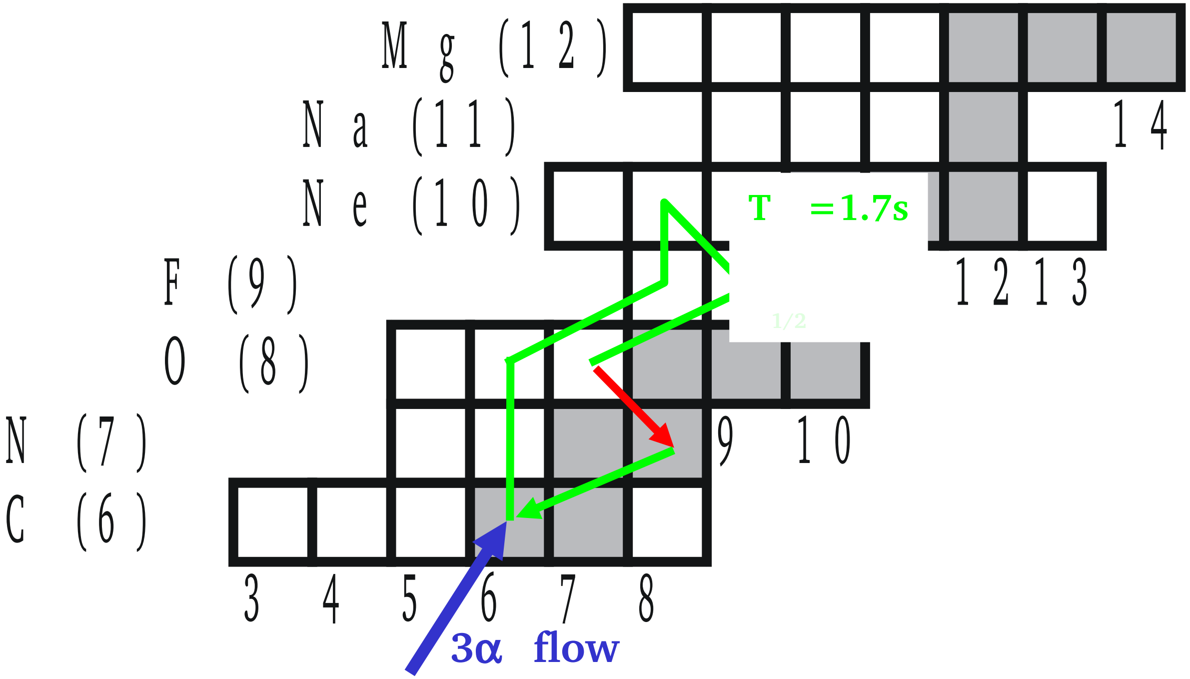
on N: $\lambda_{p,\gamma} > \lambda_{\beta}$

$\Leftrightarrow Y_p \rho N_A <\sigma v> \; > \lambda_\beta$



Very Hot CN(O)-Cycle **$T_9 \sim 0.3$**

still “beta limited”

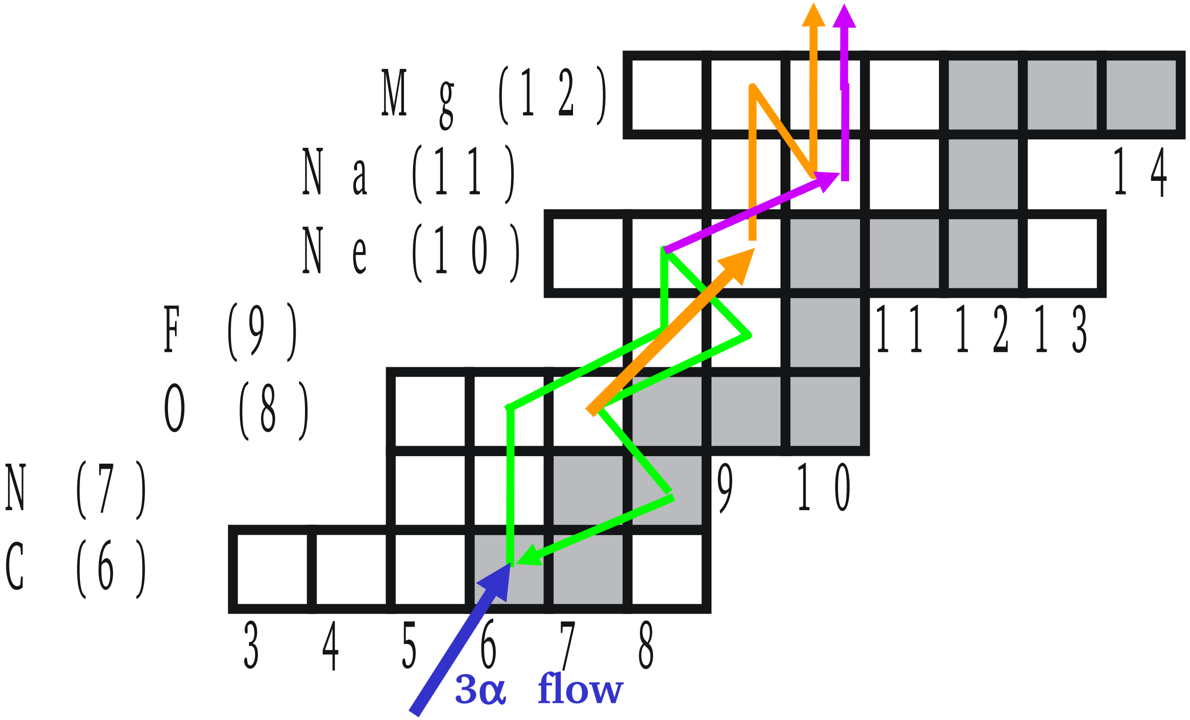


Breakout

processing beyond CNO cycle
after breakout via:

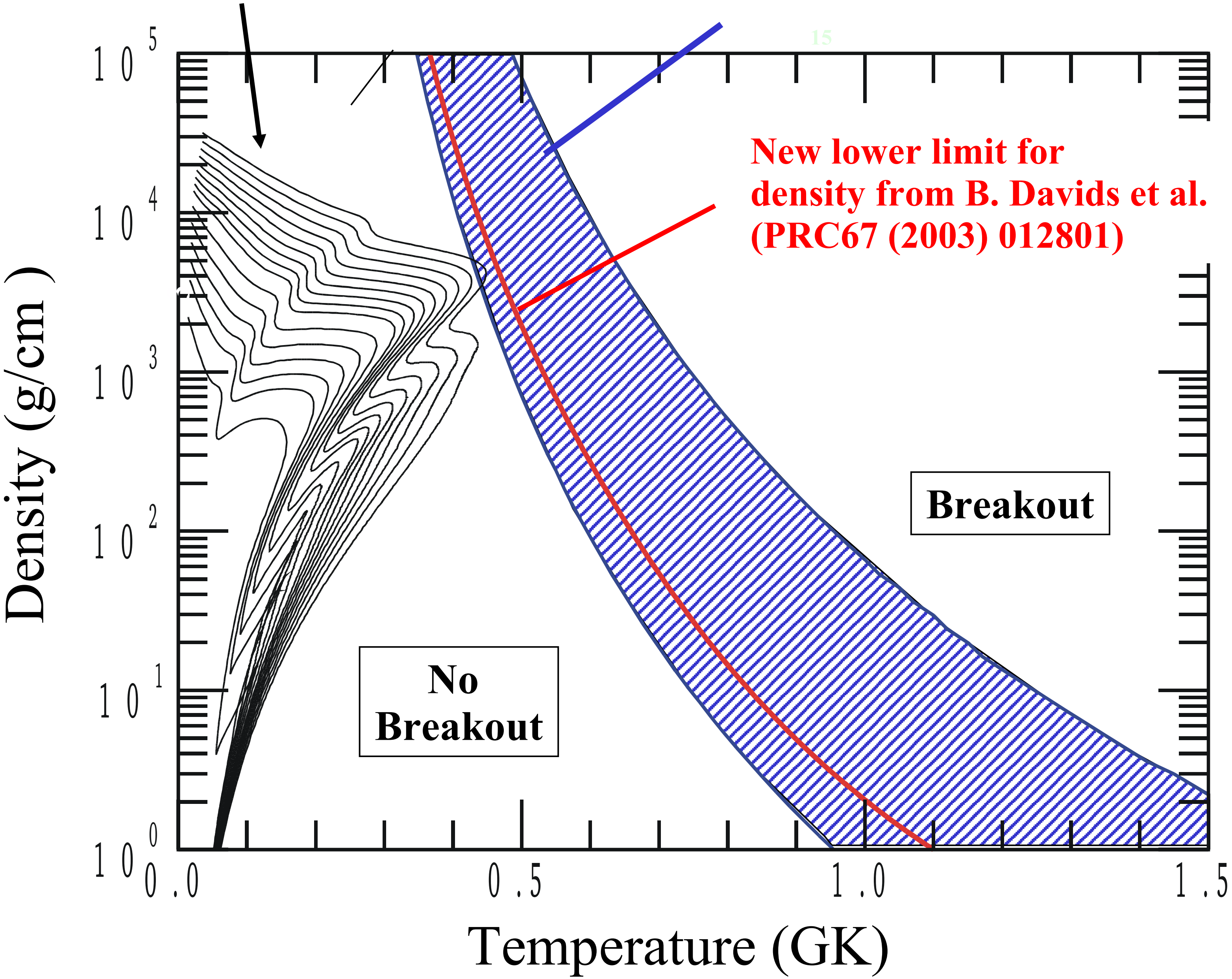
$T_9 \gtrsim 0.3$ **$^{15}O(\alpha,\gamma)^{19}Ne$**

$T_9 \gtrsim 0.6$ **$^{18}Ne(\alpha,p)^{21}Na$**



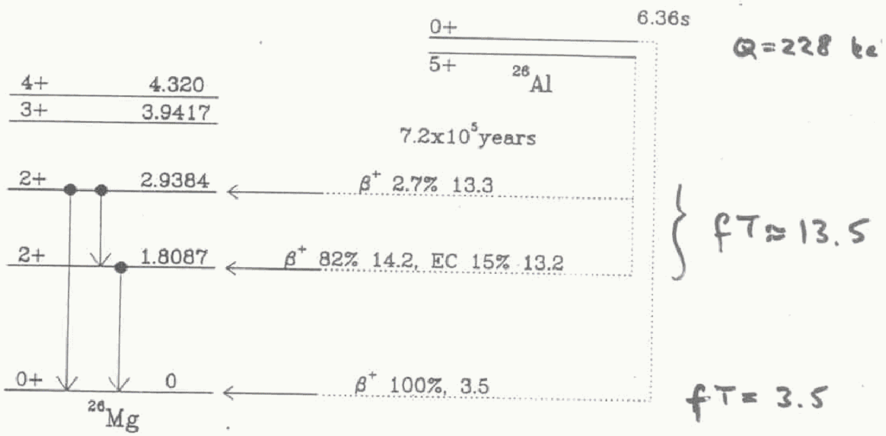
Multizone Nova model (Starrfield 2001)

Current O(α,γ) Rate

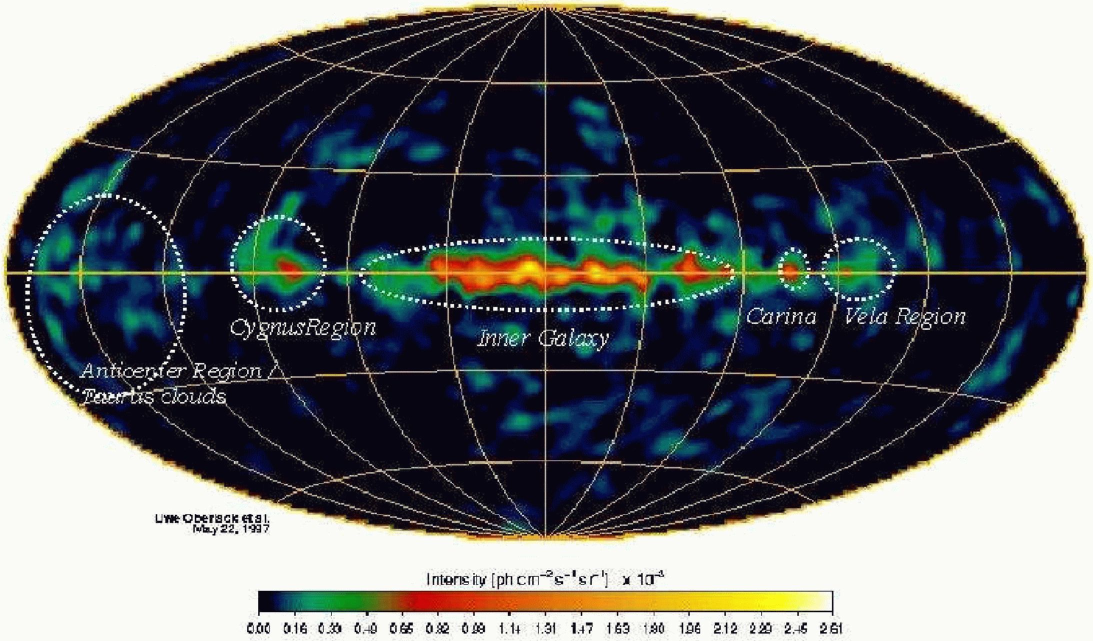


New lower limit for density from B. Davids et al. (PRC67 (2003) 012801)

Al 26 production had been suspected by Novae



COMPTEL All-Sky Map in the 1.809 MeV 26Al Line

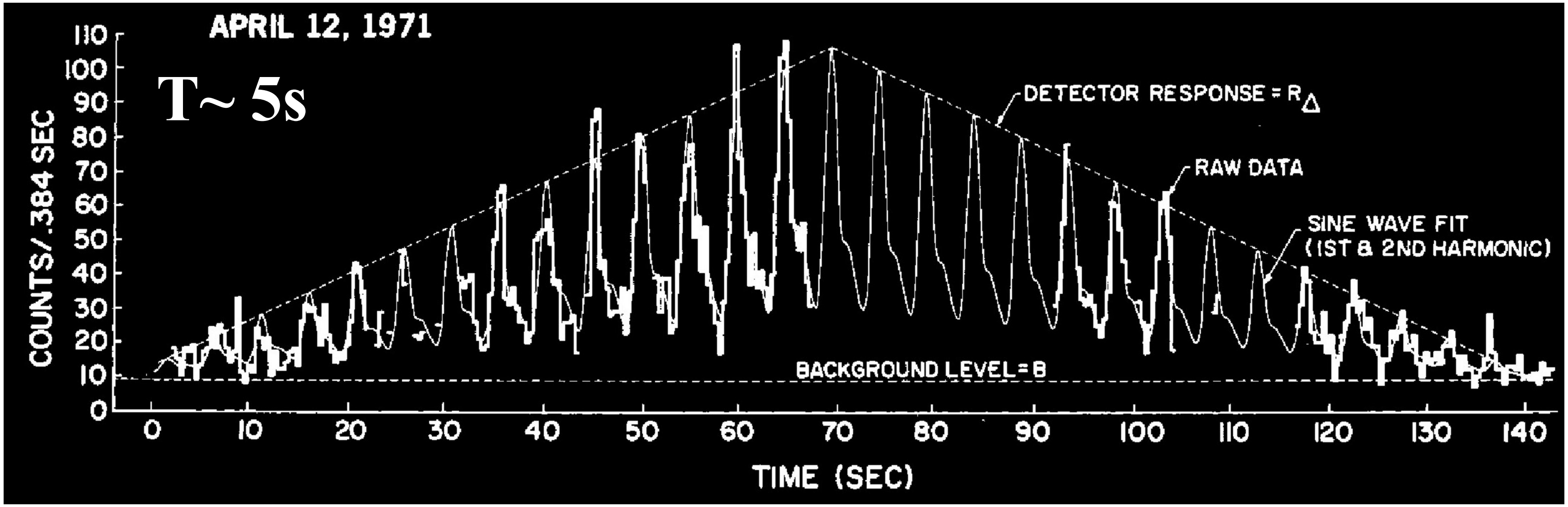


No: Probably massive stars because relation to star forming region & small scale structures

Novae have little contribution to chemical evolution of the Universe

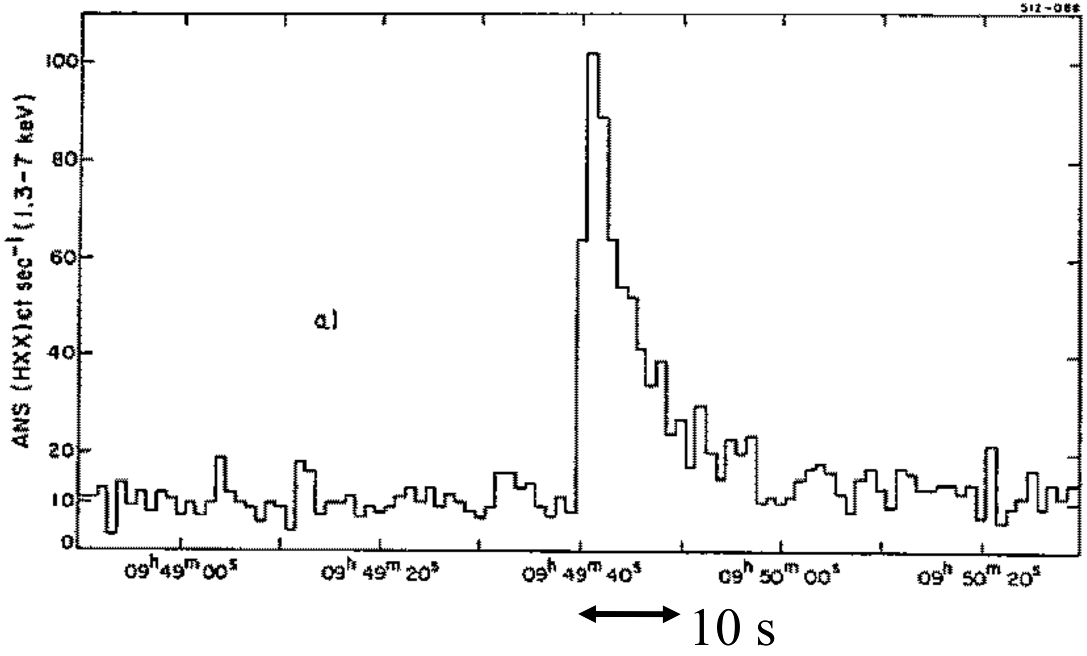
X-Ray Bursts: Discovery

First **X-ray pulsar**: Cen X-3 (Giacconi et al. 1971) with UHURU



Today:
~50

First **X-ray burst**: 3U 1820-30 (Grindlay et al. 1976) with ANS



Today:
~40

Total ~230 X-ray binaries known

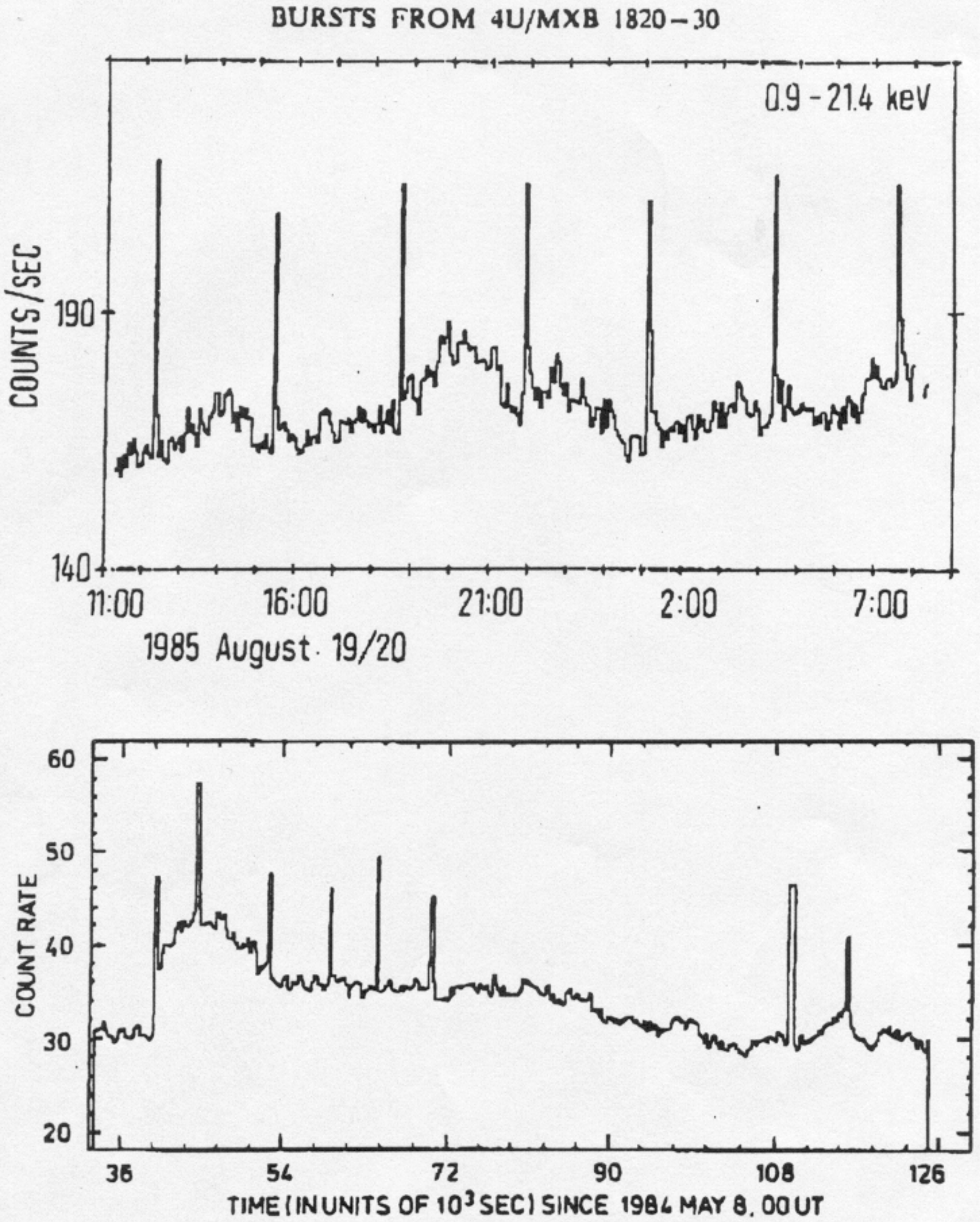


Fig. 3.14. (a) Example of a very regular burst recurrence pattern, observed for 1820–303 (from Haberl *et al.* 1987). (b) Irregular burst recurrence, observed from 1636–536 (from Sztajno *et al.* 1985).

Typical X-ray bursts:

10 -10 erg/s

-

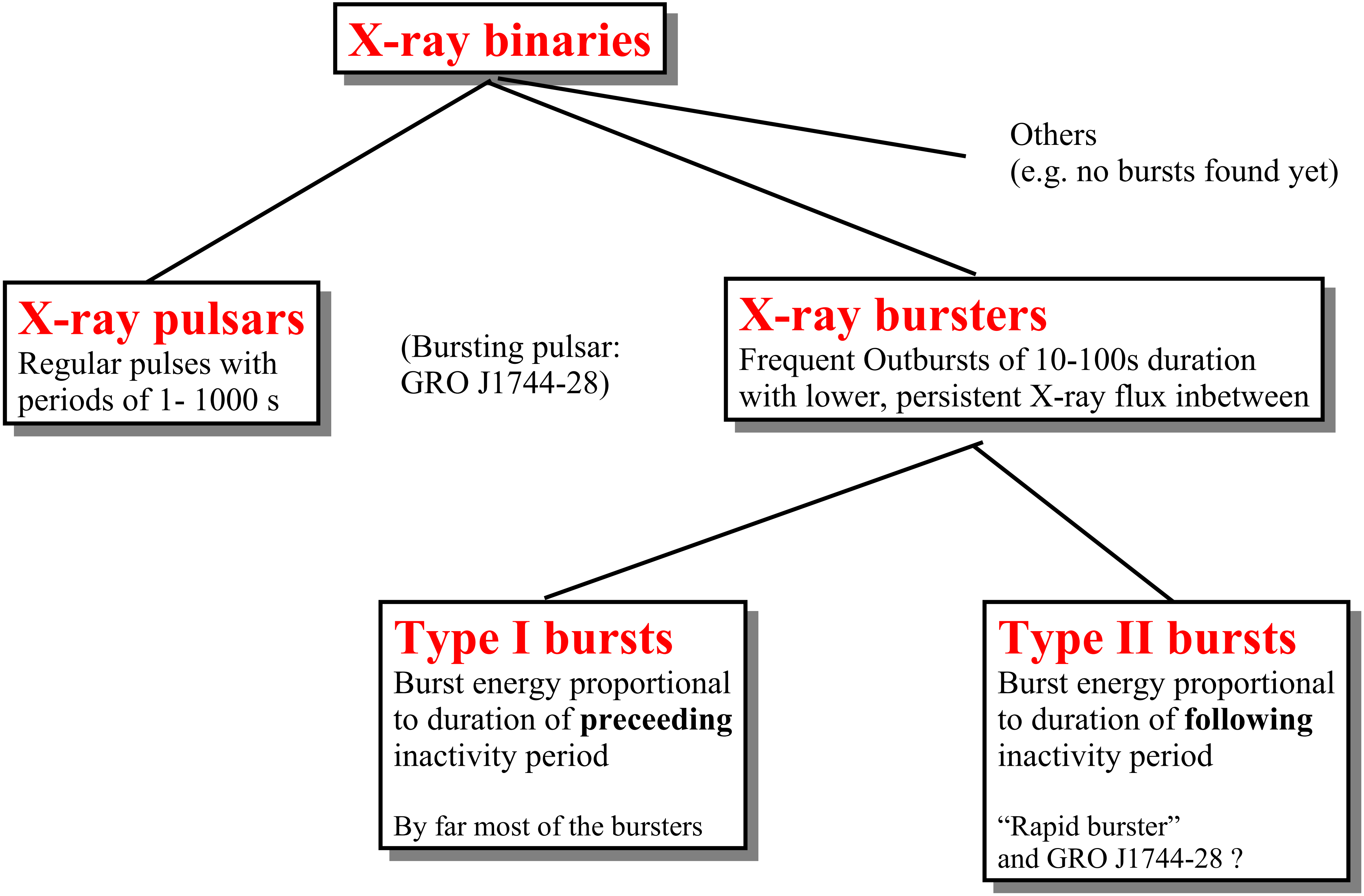
36 38

- duration 10 s – 100s
- recurrence: hours-days
- regular or irregular

Frequent and very bright phenomenon !

(stars 10 -10 erg/s)

33 35



X-ray binaries

X-ray pulsars
Regular pulses with
periods of 1- 1000 s

(Bursting pulsar:
GRO J1744-28)

X-ray bursters
Frequent Outbursts of 10-100s duration
with lower, persistent X-ray flux inbetween

Others
(e.g. no bursts found yet)

Type I bursts
Burst energy proportional
to duration of **preceeding**
inactivity period

By far most of the bursters

Type II bursts
Burst energy proportional
to duration of **following**
inactivity period

“Rapid burster”
and GRO J1744-28 ?

Simulations see http://wonka.physics.ncsu.edu/~blondin/AAS/

Energy generation: thermonuclear energy

$4H \longrightarrow He$ 6.7 MeV/u

$3\ He \longrightarrow C$ 0.6 MeV/u (“triple alpha”)

$5\ He + 84\ H \longrightarrow Pd$ 6.9 MeV/u (rp process)

Energy generation: gravitational energy

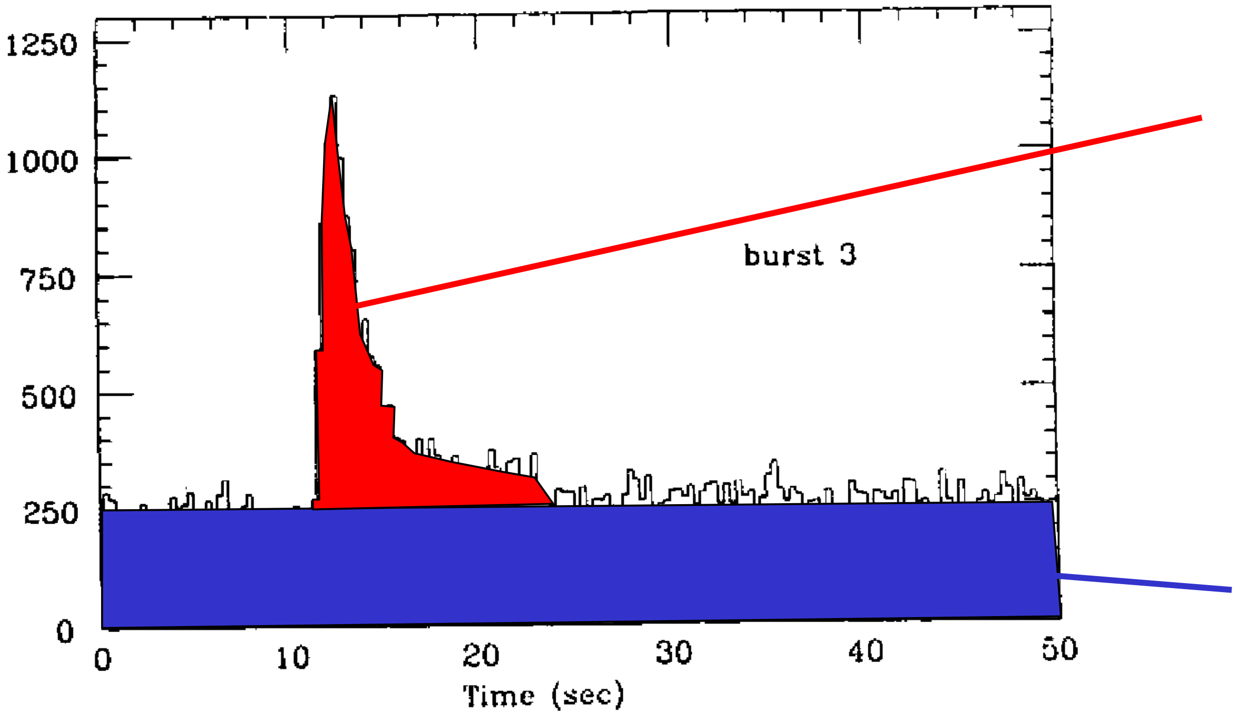
$$E = \frac{G\,M\,m}{R} = 200\ \mathrm{MeV/u}$$

u

Ratio gravitation/thermonuclear ~ 30 - 40

Observation of thermonuclear energy:

Unstable, explosive burning in bursts (release over short time)



Burst energy thermonuclear

Persistent flux gravitational energy

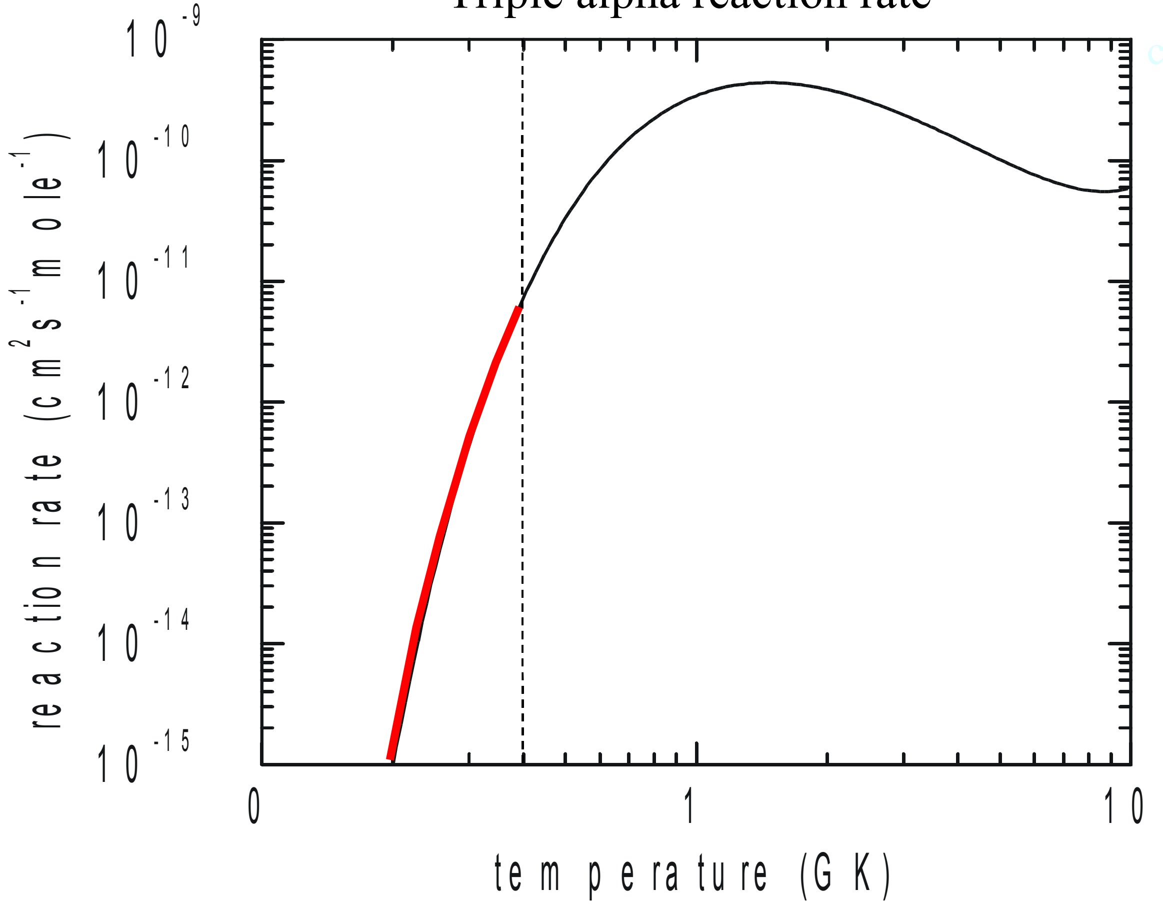
Ignition and thermonuclear runaway

Burst trigger rate is “triple alpha reaction” $3\ \mathrm{He} \longrightarrow \mathrm{C}$

Ignition: $$\frac{d\varepsilon_{nuc}}{dT} > \frac{d\varepsilon_{cool}}{dT}$$

ε_{nuc} Nuclear energy generation rate

$\varepsilon_{cool} \sim T$ Cooling rate


Triple alpha reaction rate

Ignition < 0.4 GK:

unstable **runaway**
(increase in T increases
ε_{nuc} that increases T …)

degenerate e-gas helps !

BUT: energy release dominated by subsequent reactions !

Arguments for thermonuclear origin of type I bursts:

- ratio burst energy/persistent X-ray flux ~ 1/30 – 1/40 (ratio of thermonuclear energy to gravitational energy)
- type I behavior: the longer the preceeding fuel accumulation the more intense the burst
- spectral softening during burst decline (cooling of hot layer)

Arguments for neutron star as burning site

- consistent with optical observations (only one star, binary) Stefan-Boltzmann $L = \sigma\ A\ T_{eff}$ gives typical neutron star radii
-
- Maximum luminosities consistent with Eddington luminosity for a neutron star (radiation pressure balances gravity)

$$L_{edd} = 4\pi\ cGM/\kappa\ = 2.5 \text{ x } 10\ (M/M_\odot)(1+X)\ \text{erg/s}$$

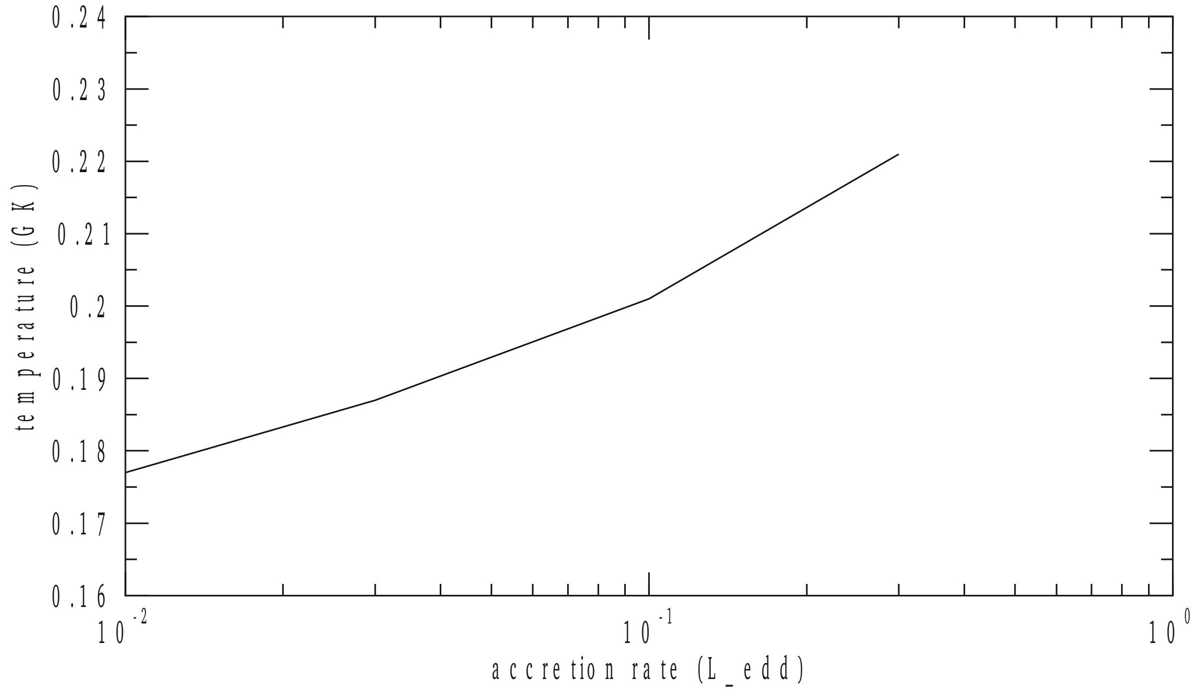
(this is non relativistic – relativistic corrections need to be applied)

κ = opacity, X=hydrogen mass fraction

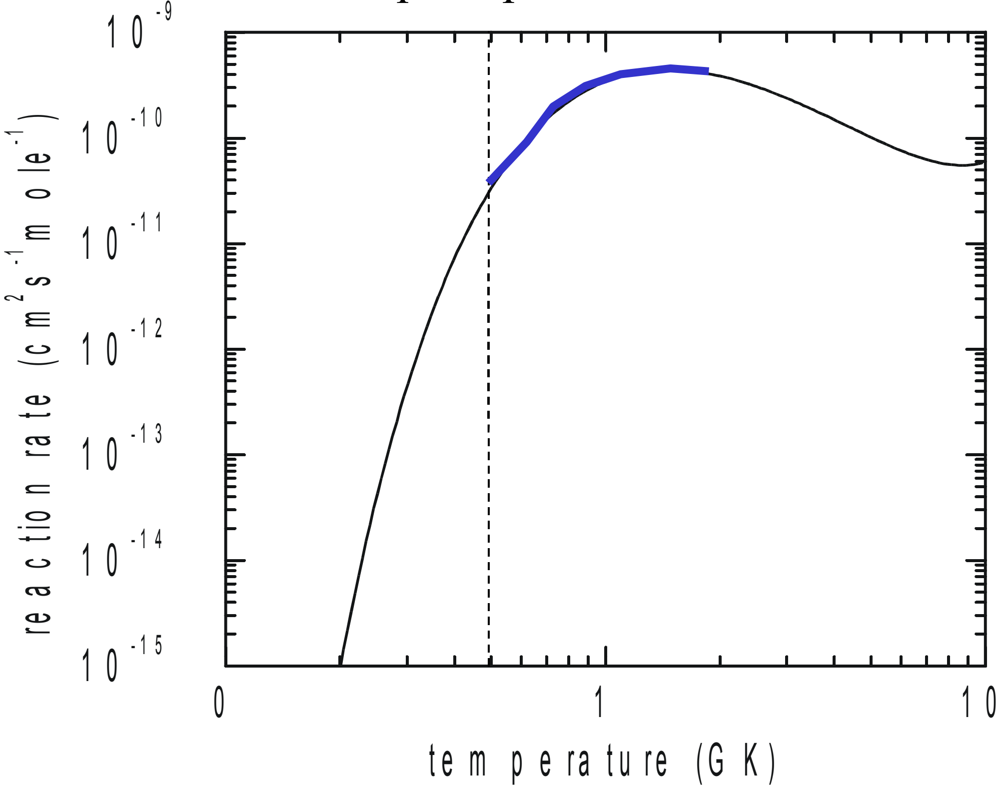
What happens if “ignition temperature” > 0.4 GK

at high local
accretion rates $\dot{m} > \dot{m}_{edd}$

($\dot{m}_{edd}$ generates luminosity L_{edd})

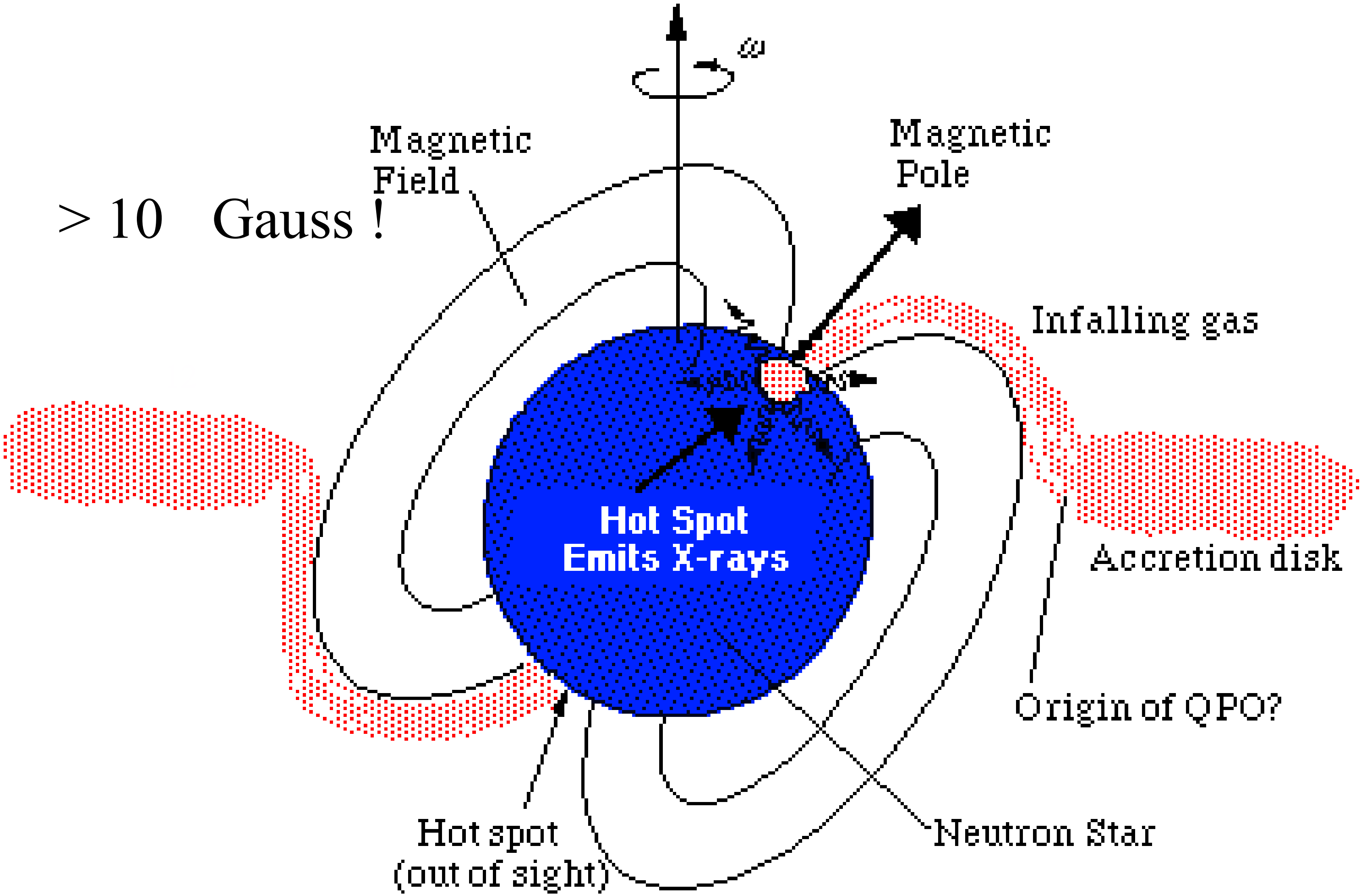


Triple alpha reaction rate



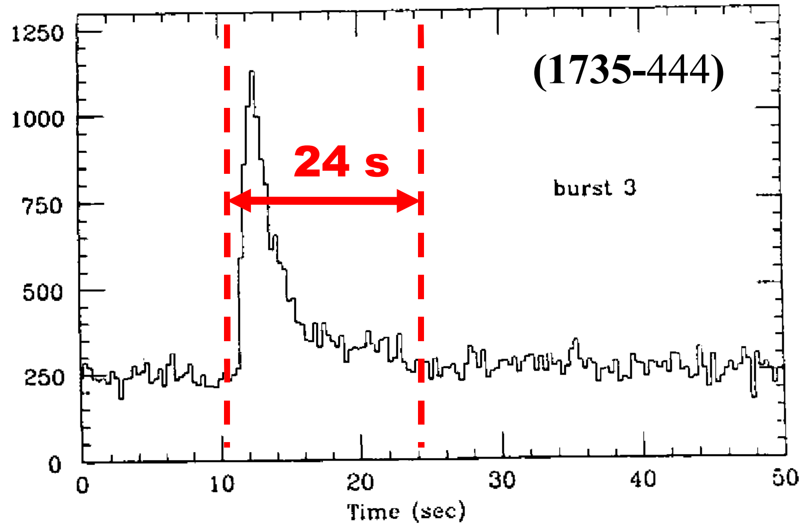
Stable nuclear burning

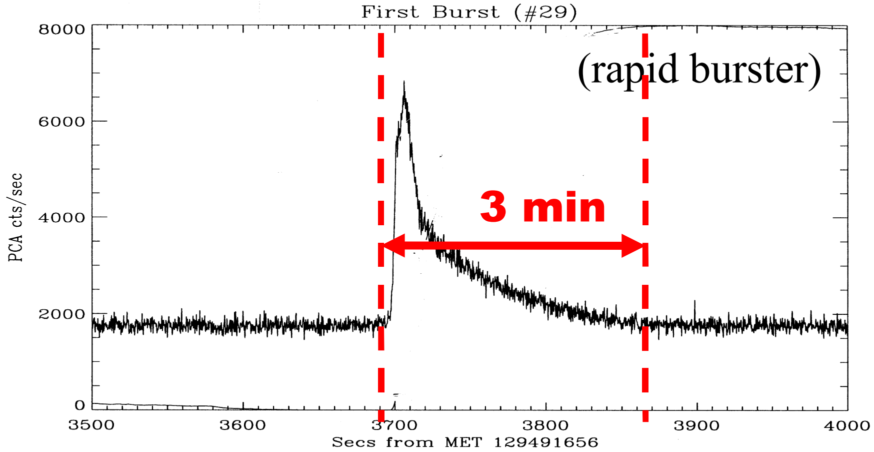
X-ray pulsar



> 10 Gauss !

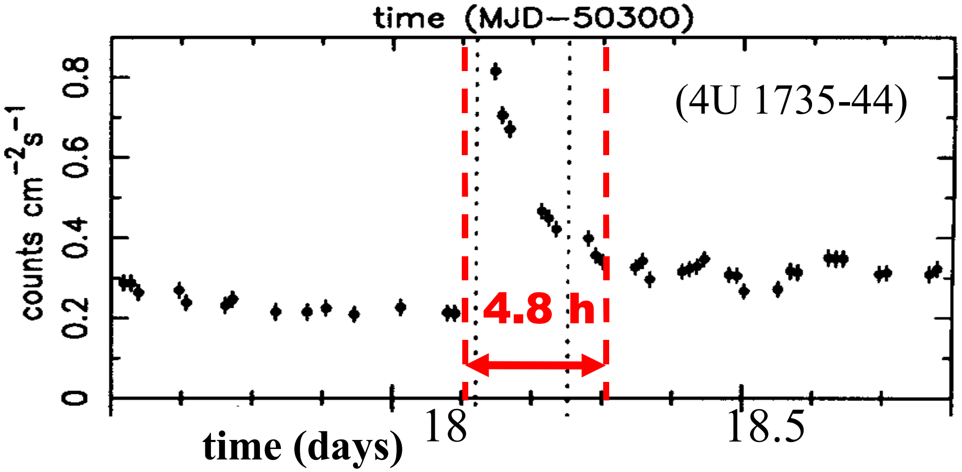
High local accretion rates due to magnetic funneling of material on small surface area





Normal type I bursts:

- duration 10-100 s
- $\sim 10^{39}$ erg



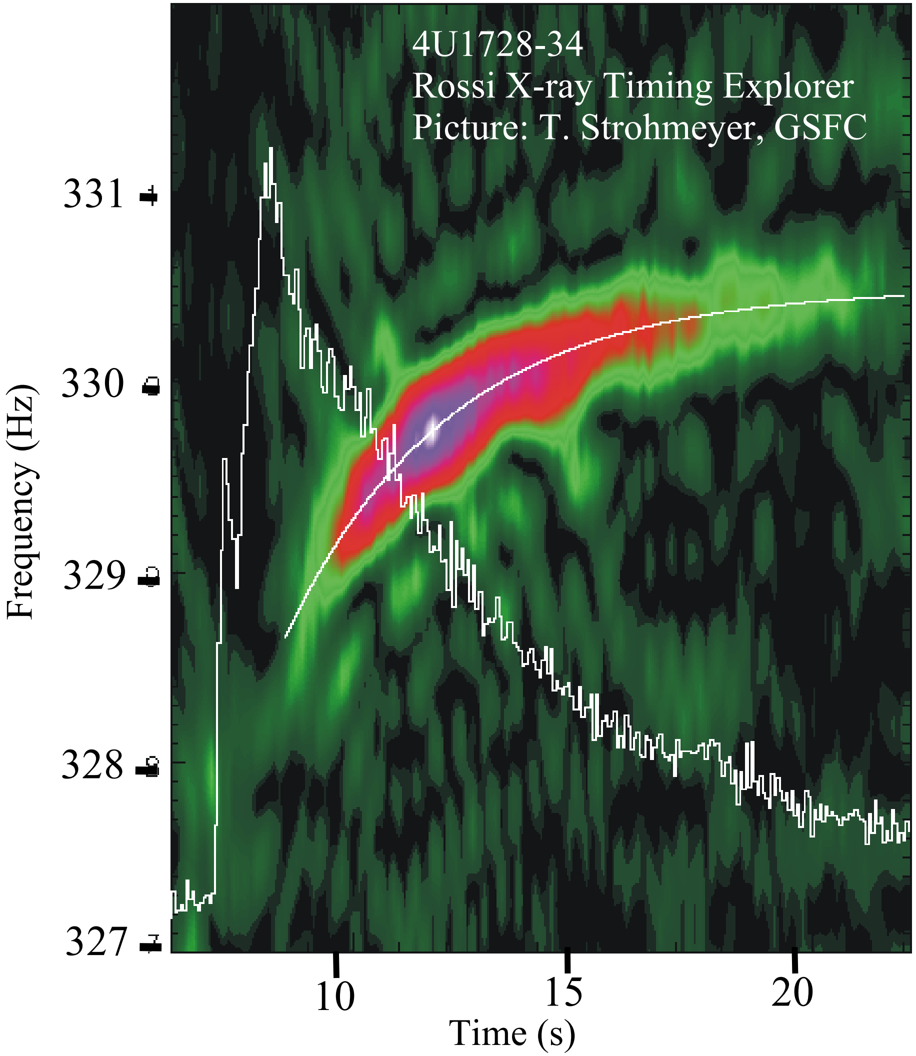
Superbursts:

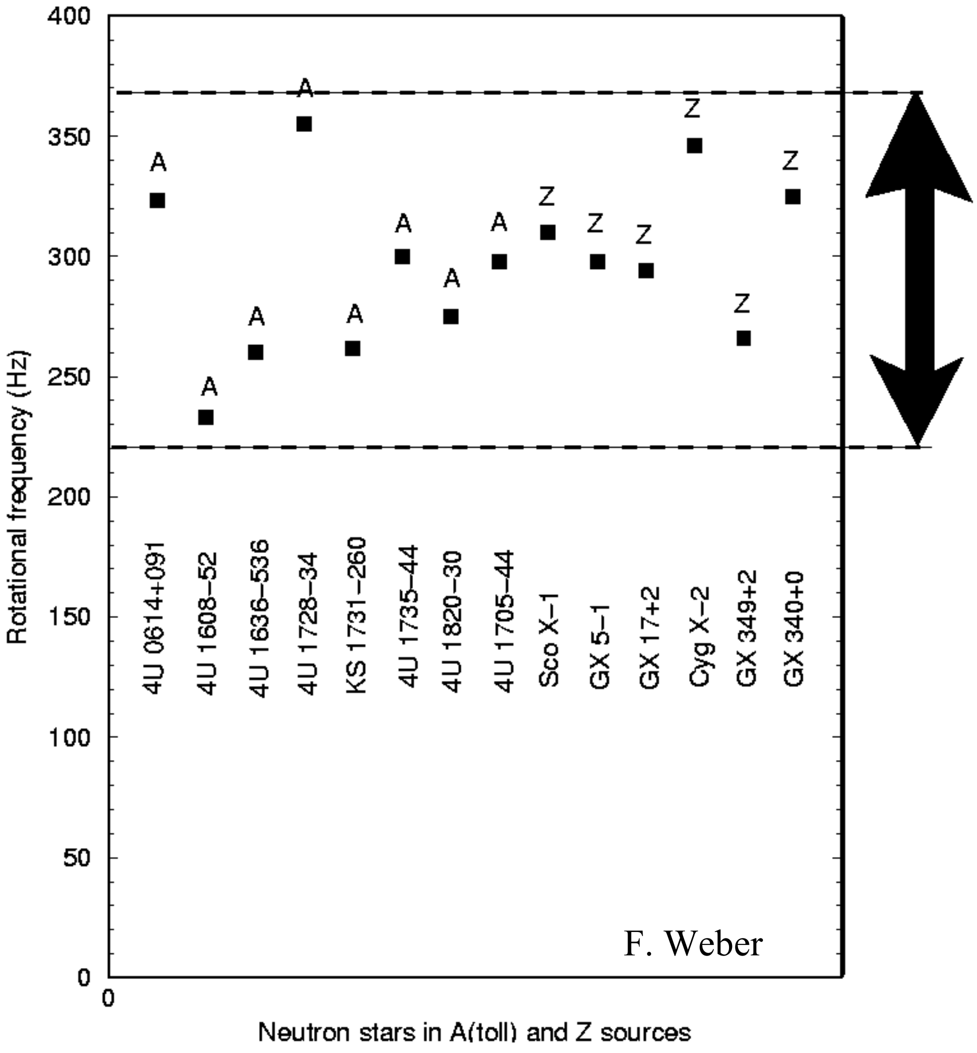
(discovered 2001, so far 7 seen in 6 sources)

- duration …
- $\sim 10^{43}$ erg
- rare (every 3.5 yr ?)

Spin up of neutron stars in X-ray binaries

Unique opportunity to study NS at various stages of spin-up (and mass)

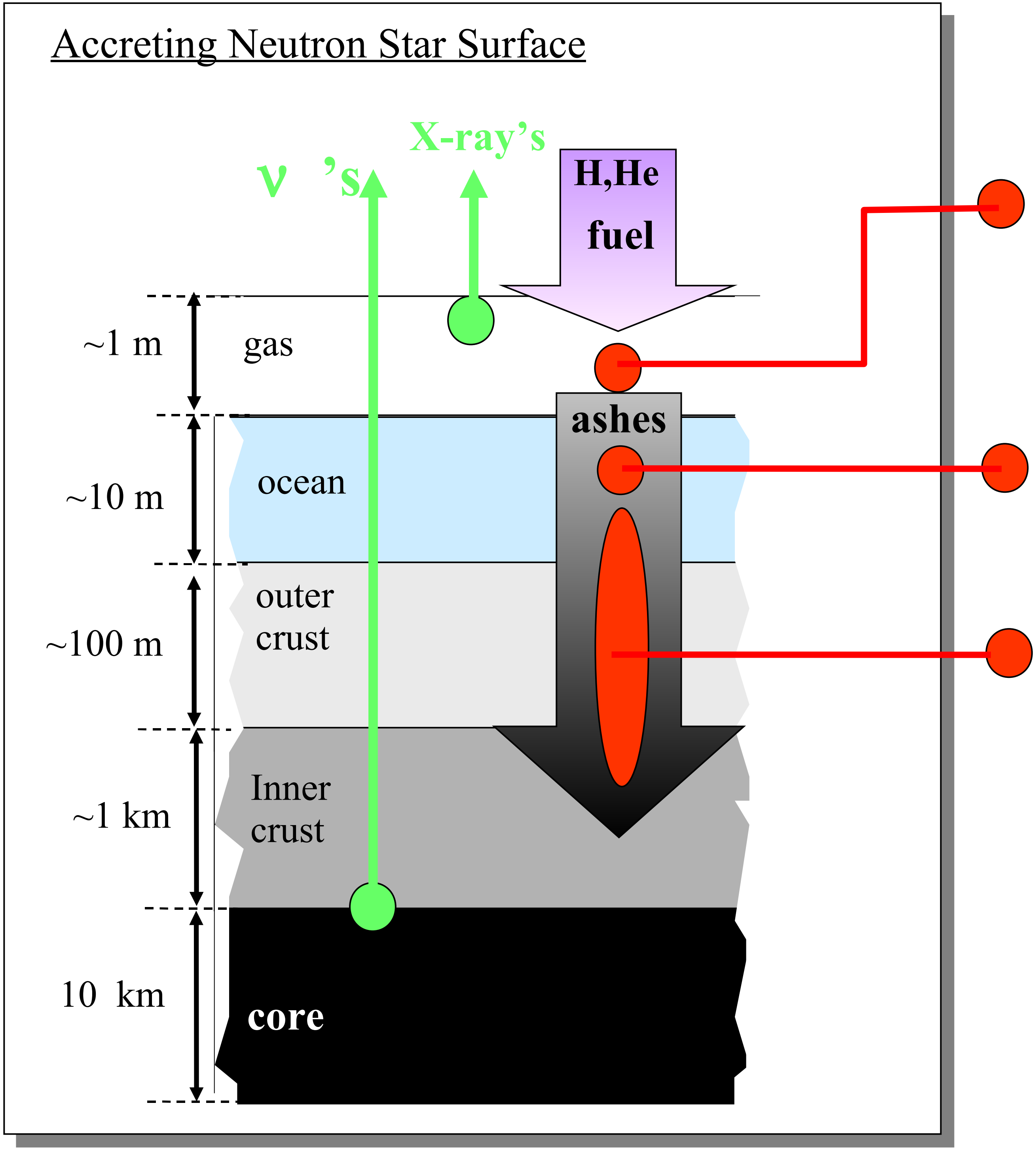




Spin
periods
lie in a
surprisinl
narrow
range!

- Quark matter/Normal matter phase transition ? (Glendenning, Weber 2000)
- Gravitational wave emission from deformed crust ? (Bildsten, 1998)

Nuclear physics overview



Thermonuclear H+He burning
(rp process)

Deep burning
(EC on H, C-flash)

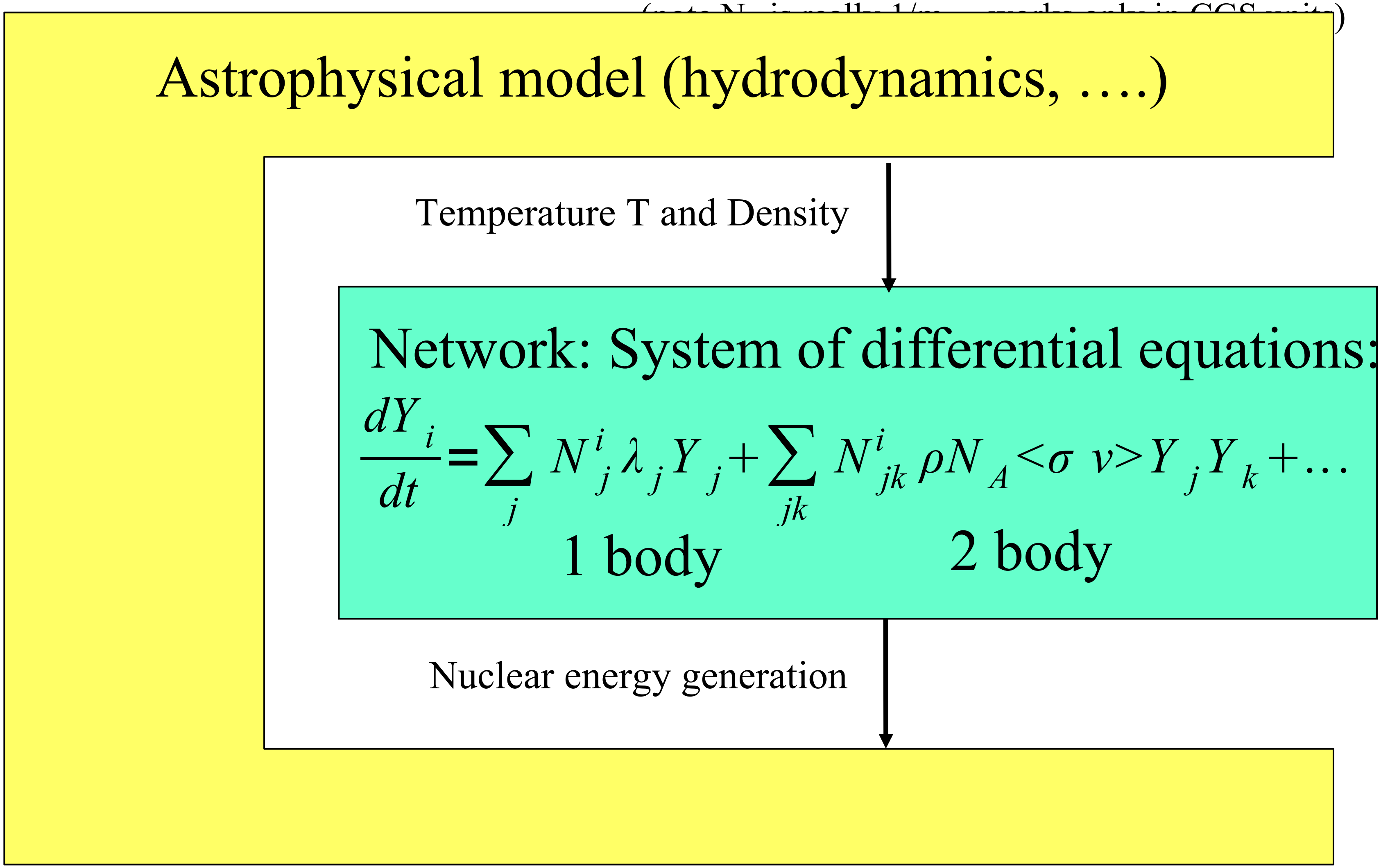
Crust processes
(EC, pycnonuclear fusion)

Nuclear reaction networks

Mass fraction of nuclear species X

Abundance $Y = X/A$ (A=mass number)

Number density $n = \rho N_A Y$ (ρ =mass density, N_A =Avogadro)



Astrophysical model (hydrodynamics, ….)

Temperature T and Density

Network: System of differential equations:

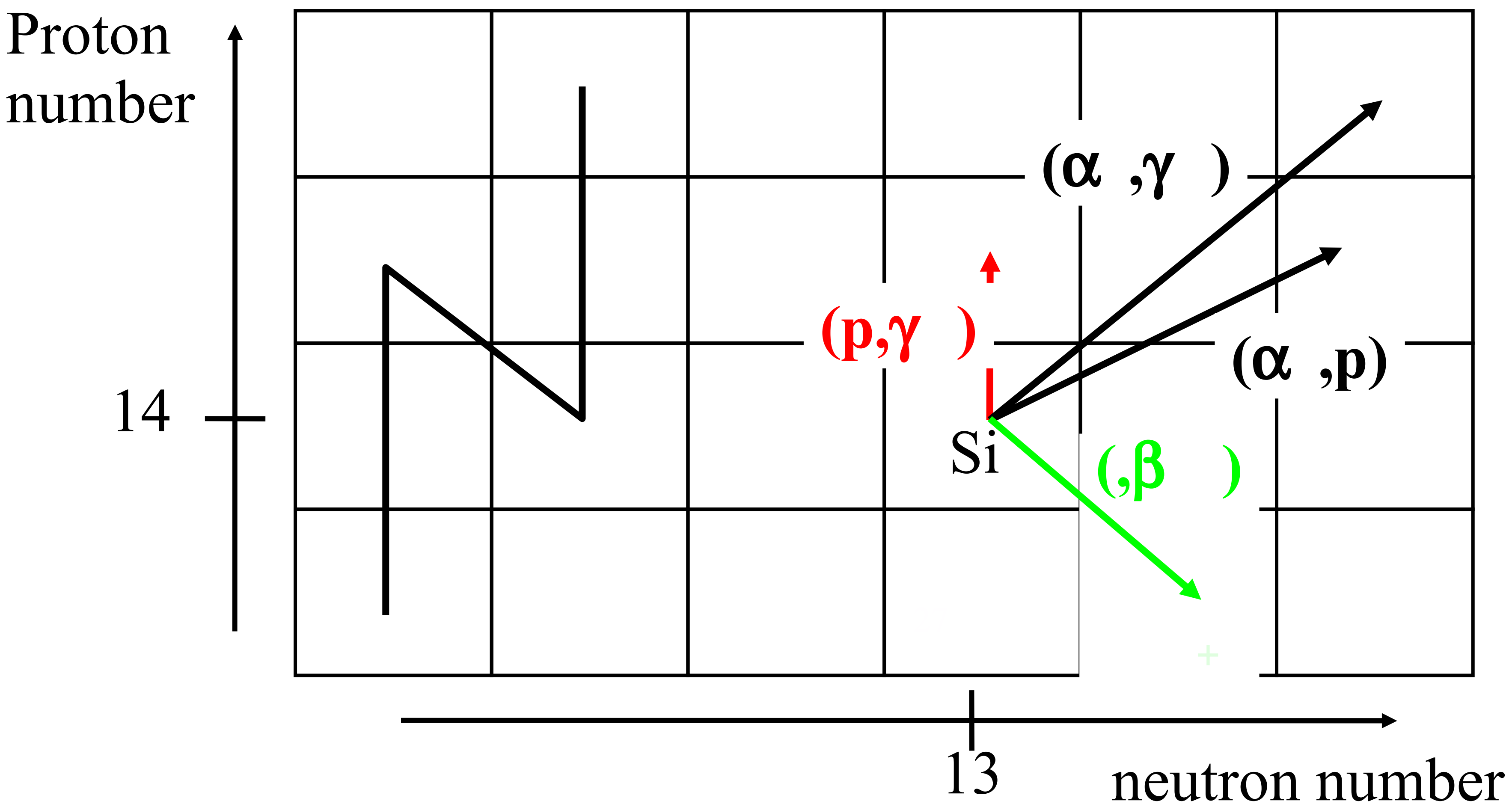
$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{jk} N^i_{jk} \rho N_A <\sigma v> Y_j Y_k + \ldots$$

1 body 2 body

Nuclear energy generation

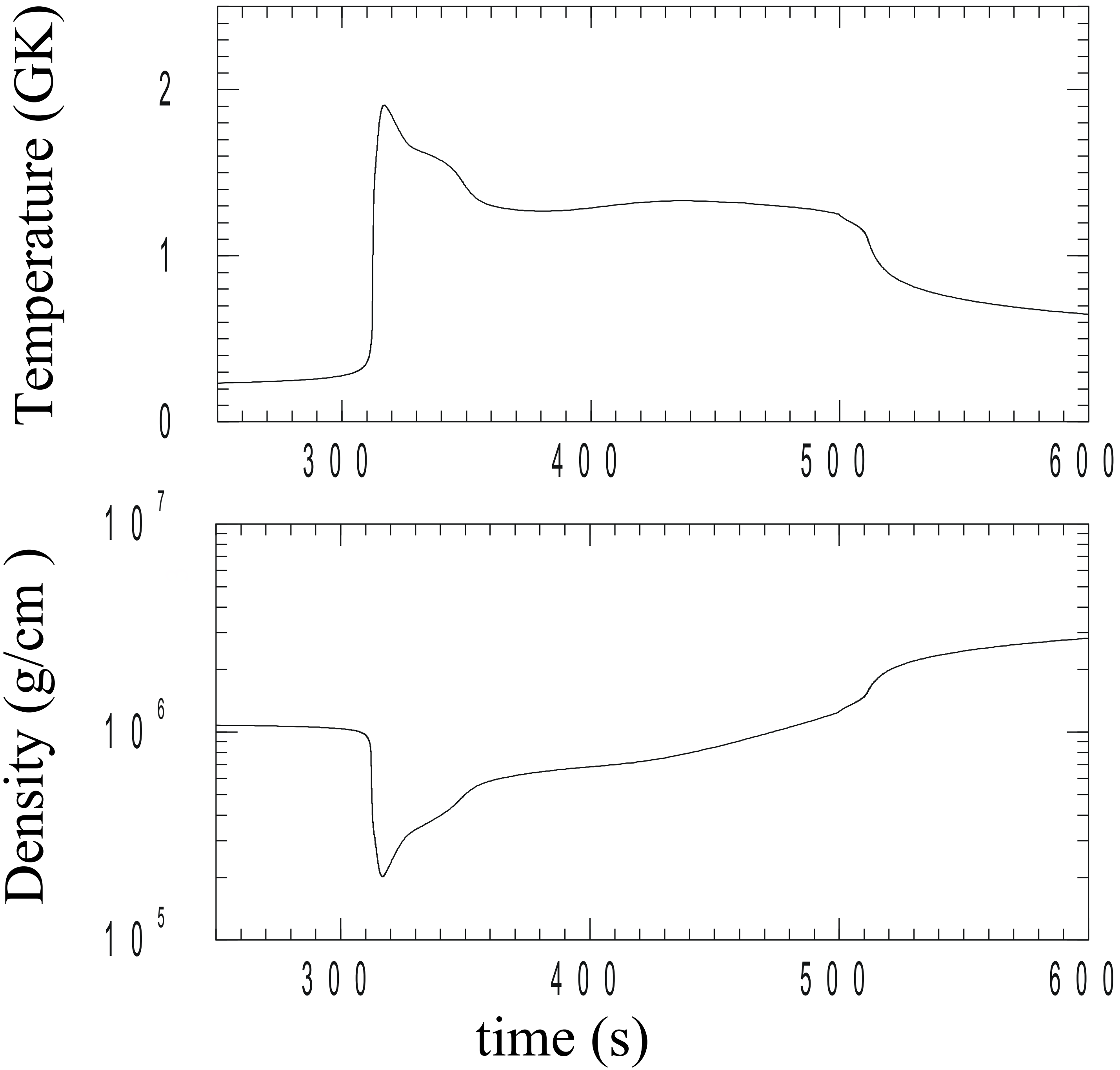
N : number of nuclei of species I produced (positive) or destroyed (negative) per reaction

Visualizing reaction network solutions

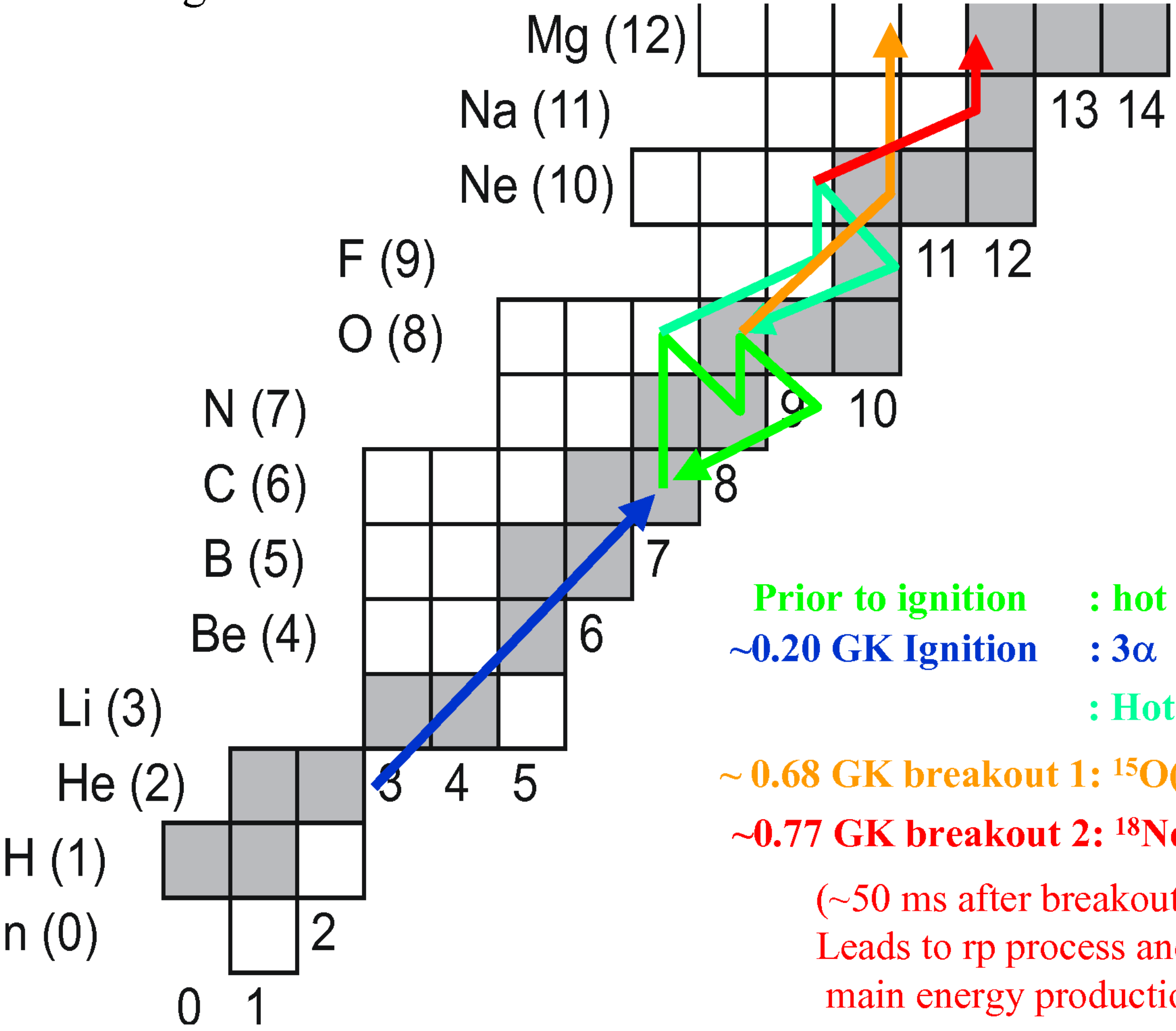


Lines = Flow = $F_{i,j} = \int \left[\frac{dY_i}{dt}_{i-j} - \frac{dY_j}{dt}_{j-i} \right] dt$

Models: Typical temperatures and densities



Burst Ignition:



Prior to ignition : hot CNO cycle

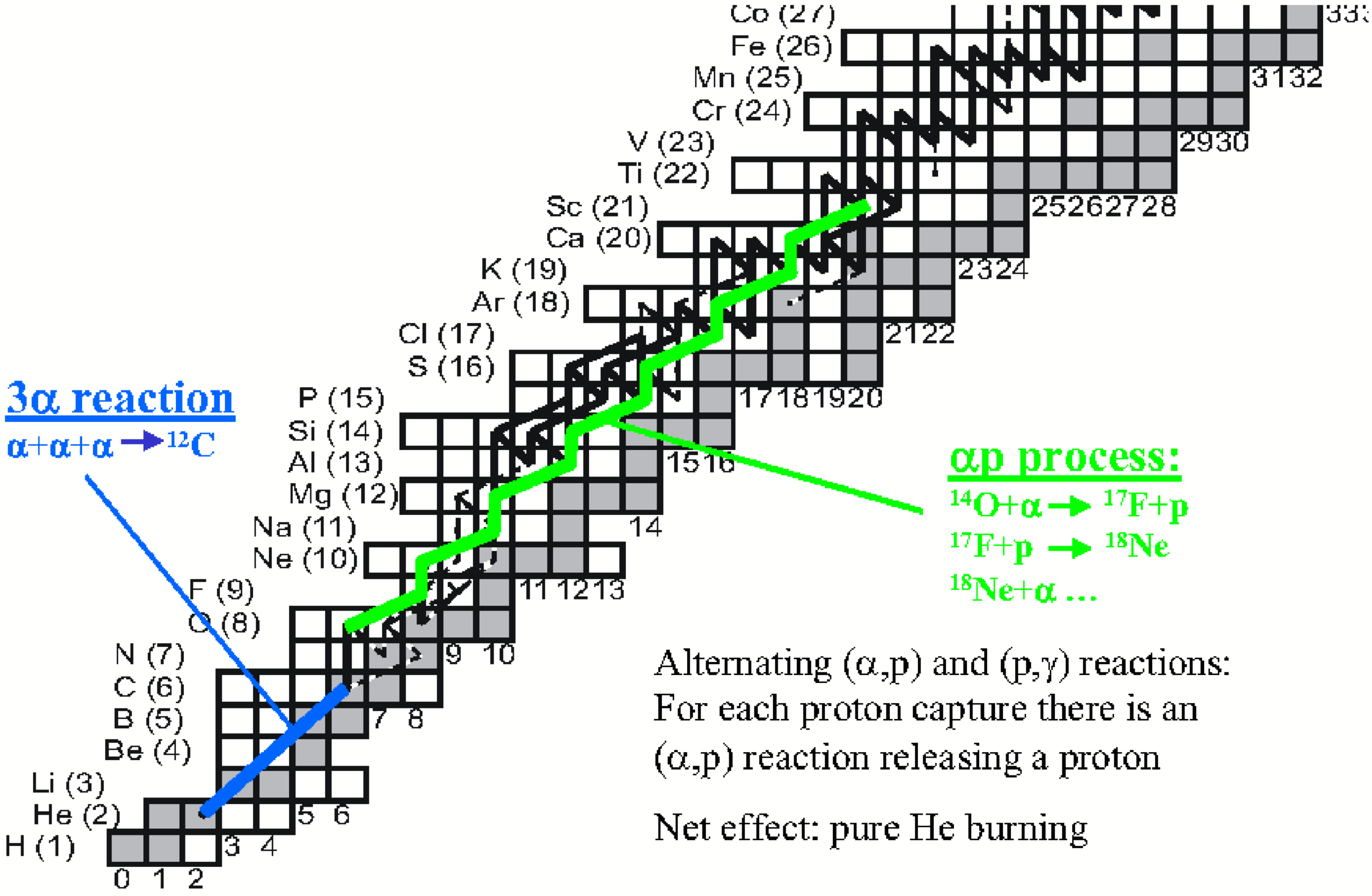
~0.20 GK Ignition : 3α

: Hot CNO cycle II

~ 0.68 GK breakout 1: ^{15}O(α,γ)

~0.77 GK breakout 2: ^{18}Ne(α,p)

(~50 ms after breakout 1)
Leads to rp process and
main energy production



3α reaction

$\alpha+\alpha+\alpha \rightarrow {}^{12}C$

αp process:

$^{14}O+\alpha \rightarrow {}^{17}F+p$

$^{17}F+p \rightarrow {}^{18}Ne$

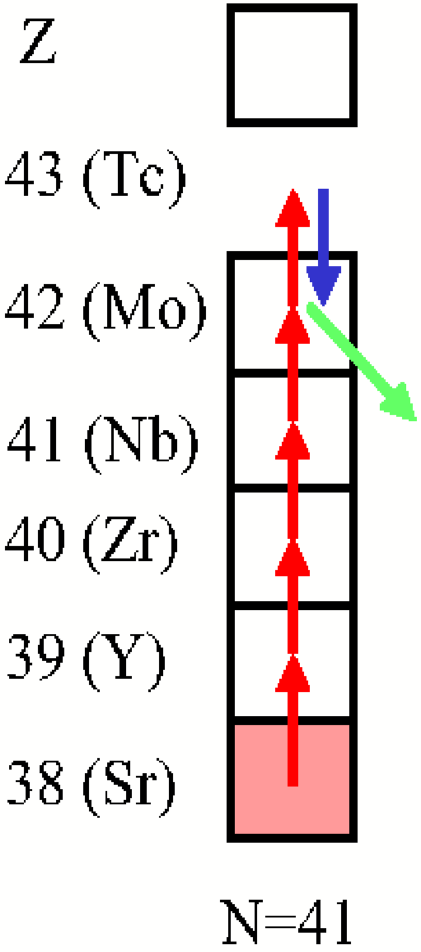
$^{18}Ne+\alpha$ …

Alternating (α,p) and (p,γ) reactions:
For each proton capture there is an (α,p) reaction releasing a proton

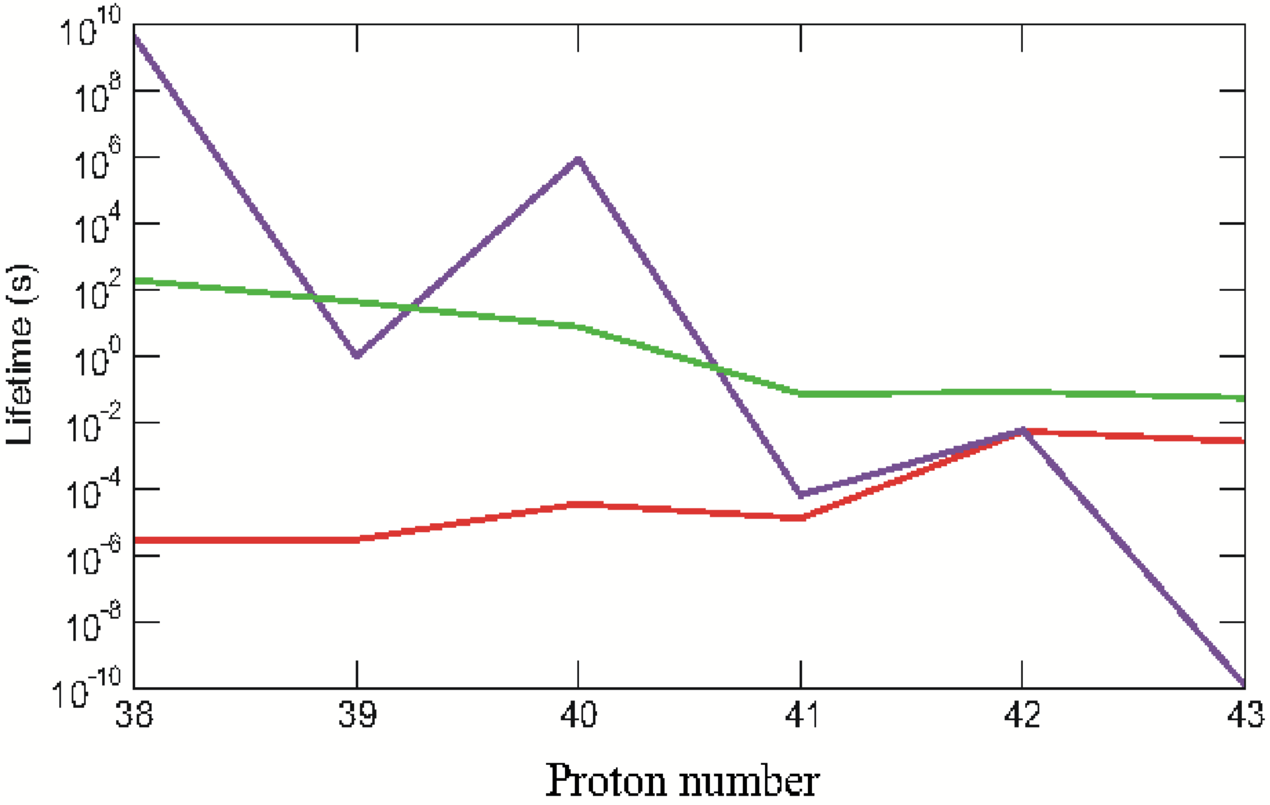
Net effect: pure He burning

Nuclear lifetimes: (average time between a …)

- **proton capture** : $\tau = 1/(Y_p \rho N_A <\sigma v>)$
- **β decay** : $\tau = T_{1/2}/\ln 2$
- **photodisintegration** : $\tau = 1/\lambda_{(\gamma,p)}$



(for $\rho=10^6$ g/cm^3, Yp=0.7)



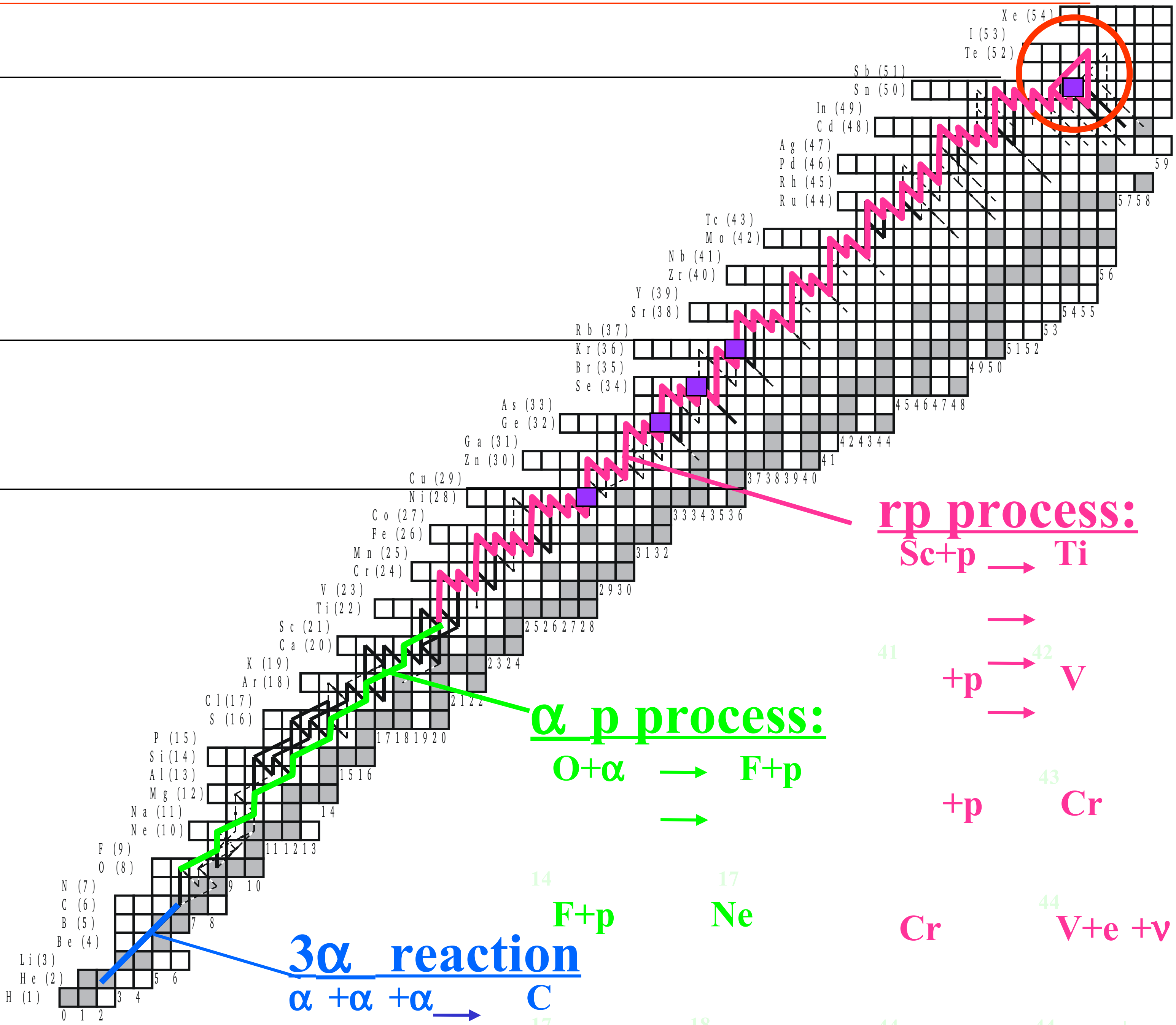
Models: Typical reaction flows

Schatz et al. 2001 (M. Ouellette) Phys. Rev. Lett. 68 (2001) 3471

Schatz et al. 1998

Wallace and Woosley 1981
Hanawa et al. 1981
Koike et al. 1998

Most calculations
(for example Taam 1996)



rp process:

Sc+p → Ti

→

41 42

+p → V

→

43

+p Cr

44

Cr V+e +ν

α p process:

O+α → F+p

→

14 17

F+p Ne

3α reaction

α +α +α → C

17 18

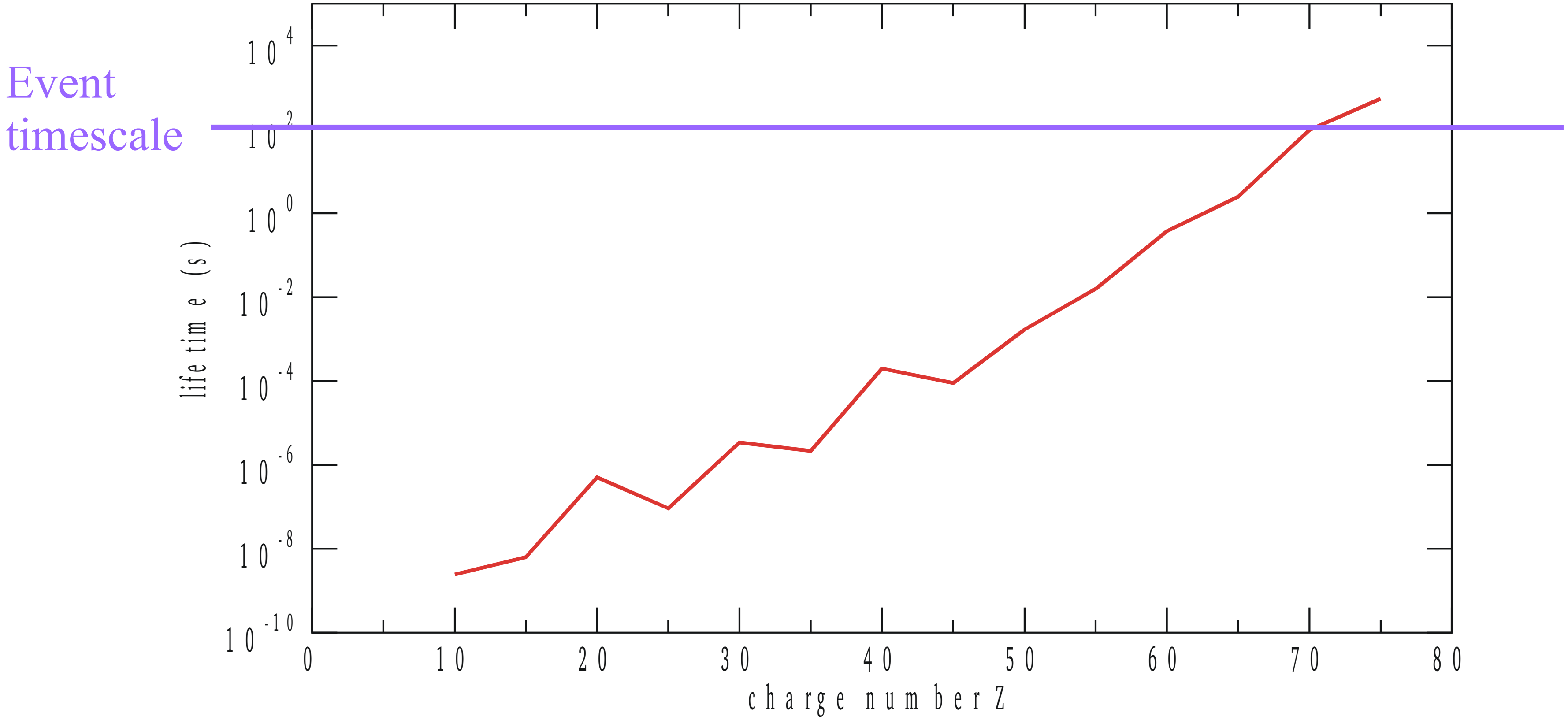
44 44 + e

The endpoint of the rp process

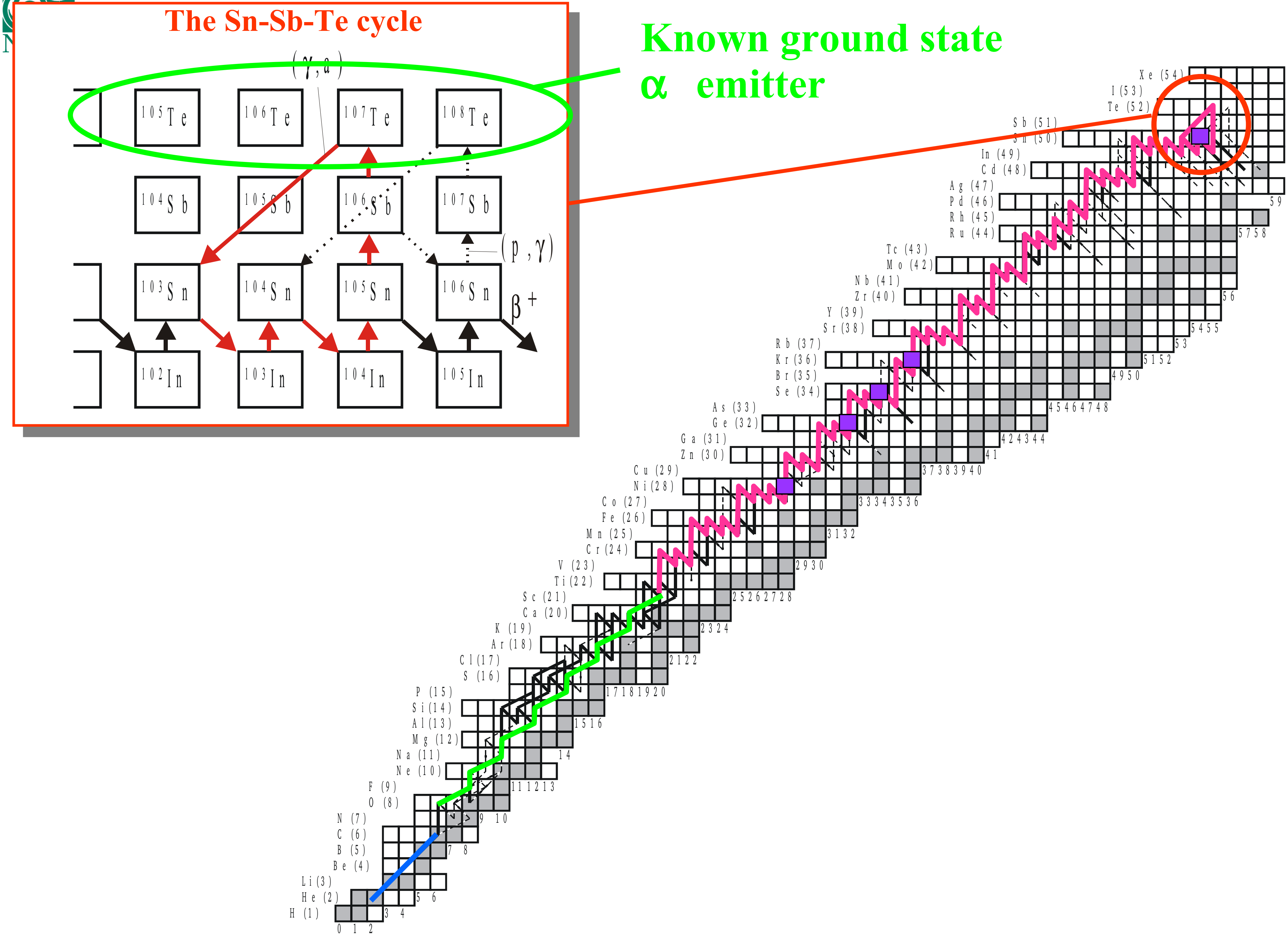
Possibilities:

- Cycling (reactions that go back to lighter nuclei)
- Coulomb barrier
- Runs out of fuel
- Fast cooling

Proton capture lifetime of nuclei near the drip line



Endpoint: Limiting factor I – SnSbTe Cycle



Known ground state
α emitter

The endpoint for full hydrogen consumption:

Solar H/He ratio ~ 9

He burning: 10 He -> Sc

---

90 H per Sc available

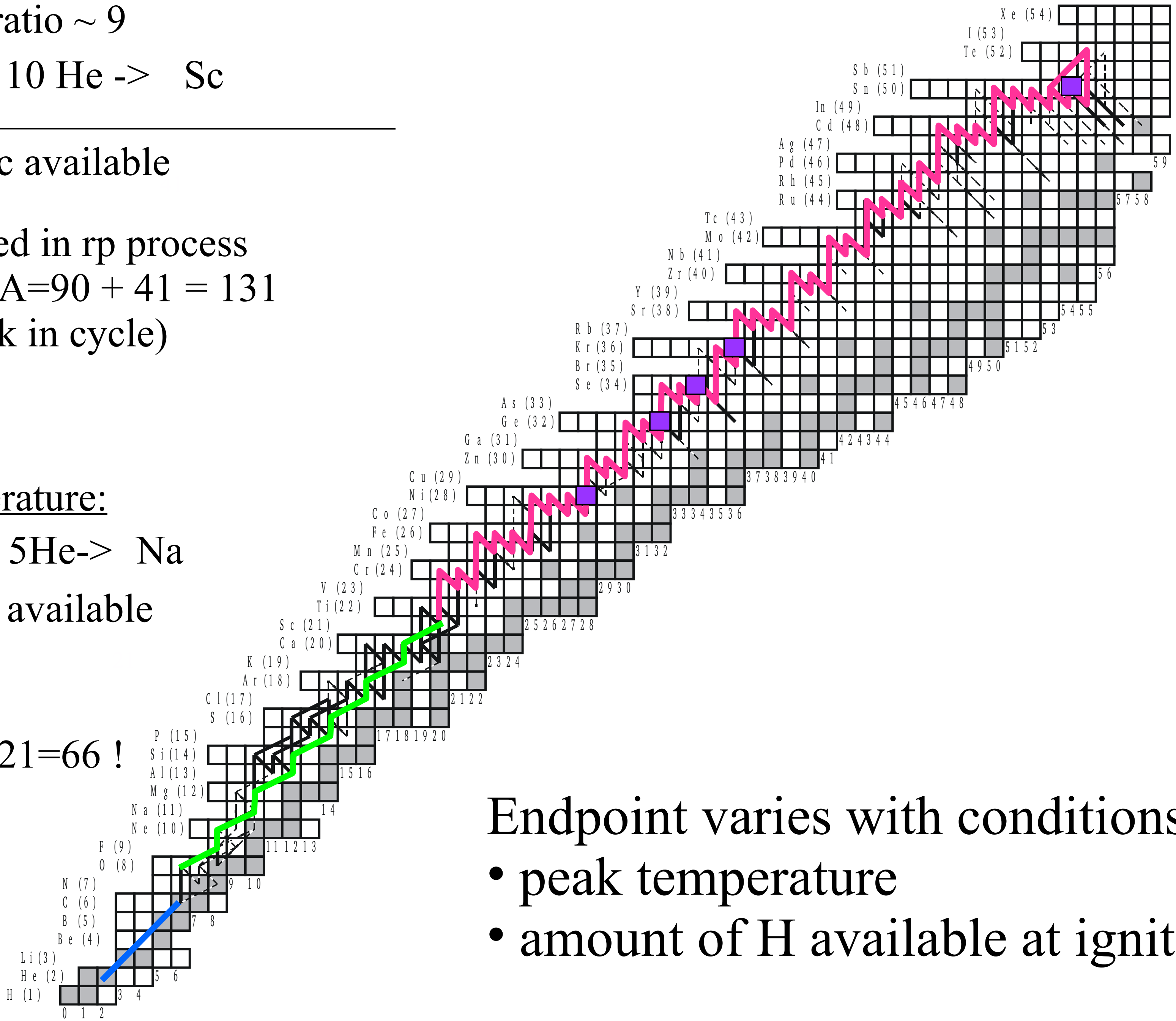
if all captured in rp process
reaches A=90 + 41 = 131
(but stuck in cycle)

Lower temperature:

Assume only 5He-> Na

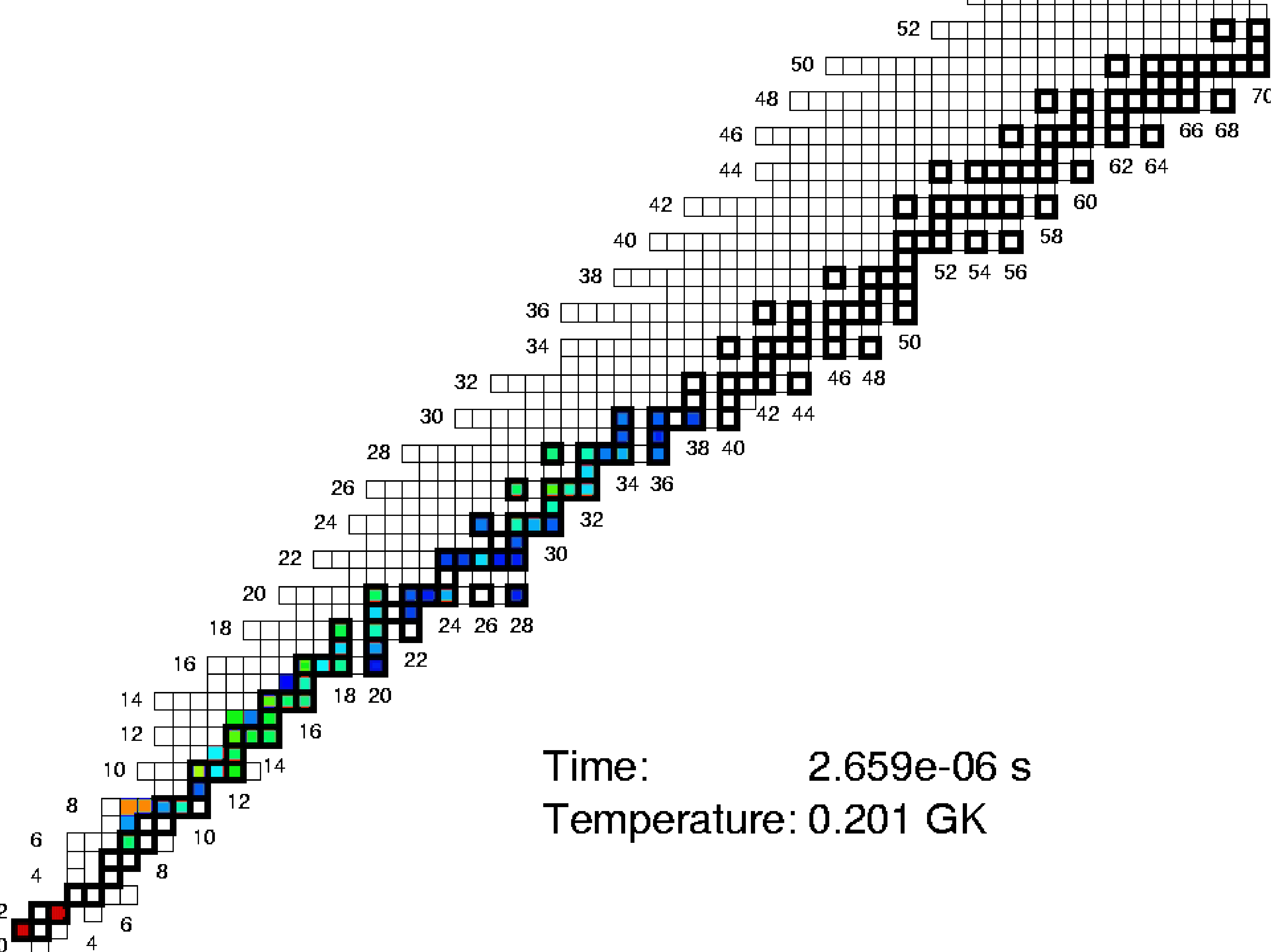
45H per Na available

reach A=45+21=66 !



Endpoint varies with conditions:

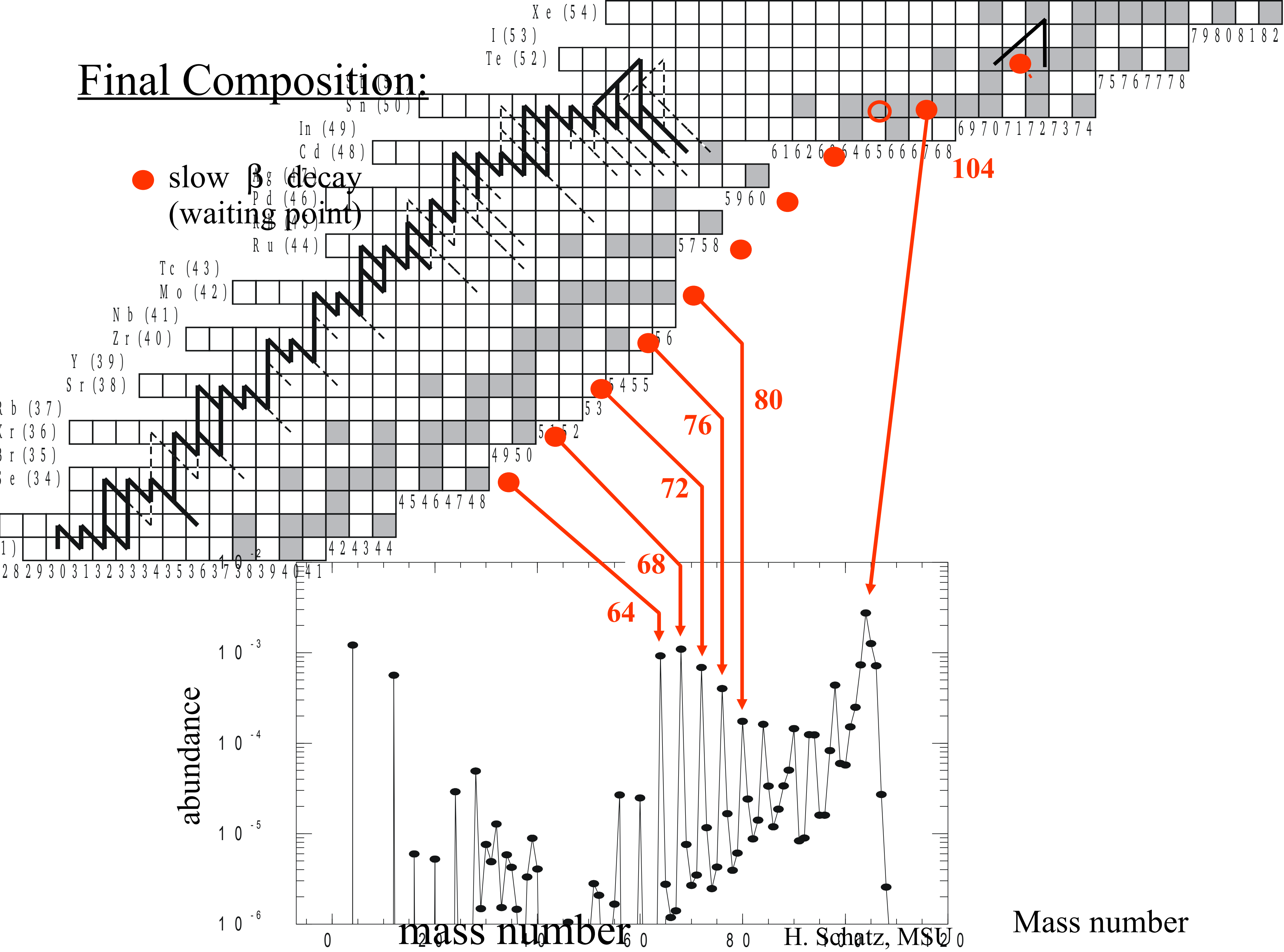
- peak temperature
- amount of H available at ignition



Time: 2.659e-06 s

Temperature: 0.201 GK

Final Composition:



● slow β decay (waiting point)

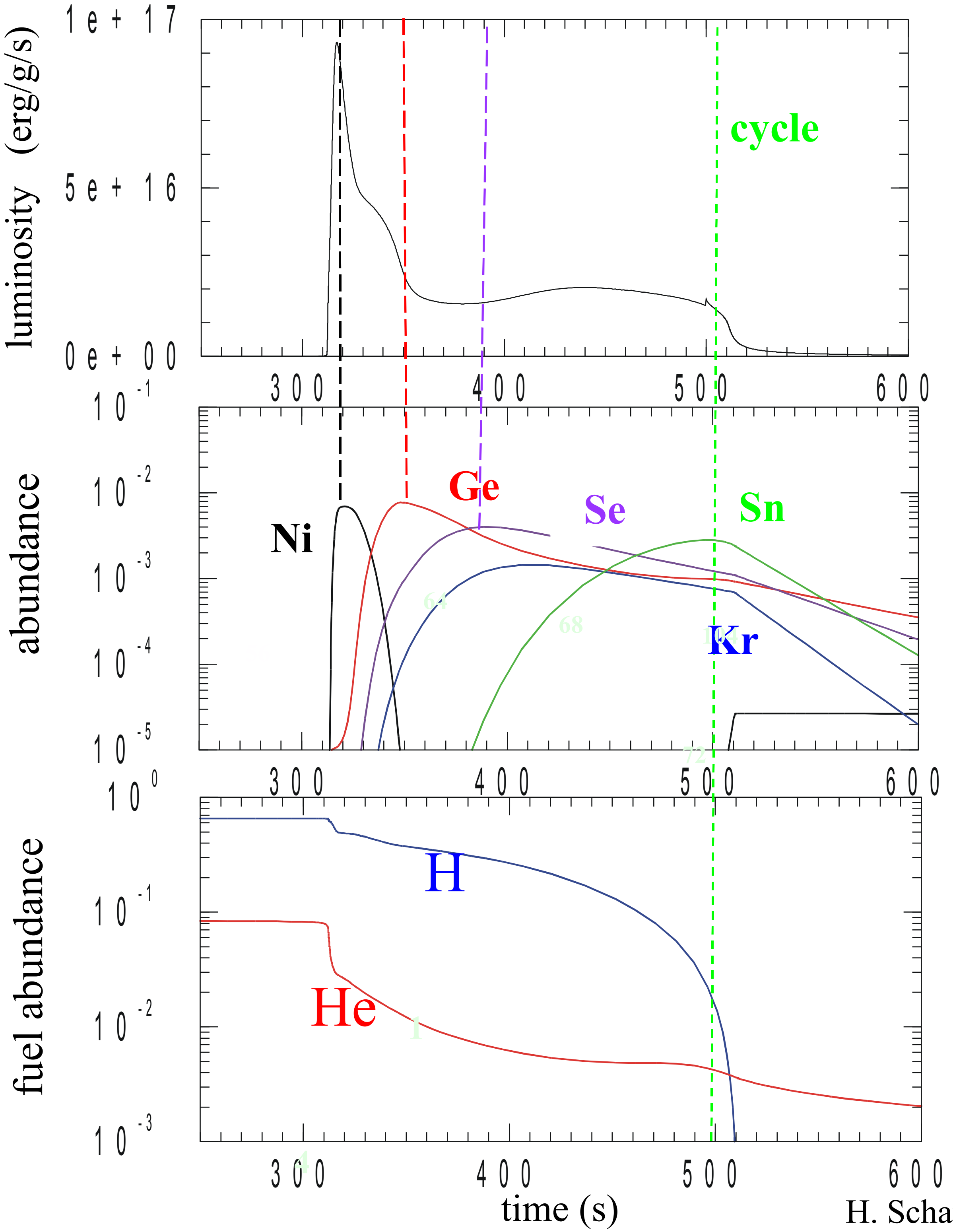
H. Schatz, MSU

X-ray burst:

- Luminosity:

- Abundances of waiting points

- H, He abundance



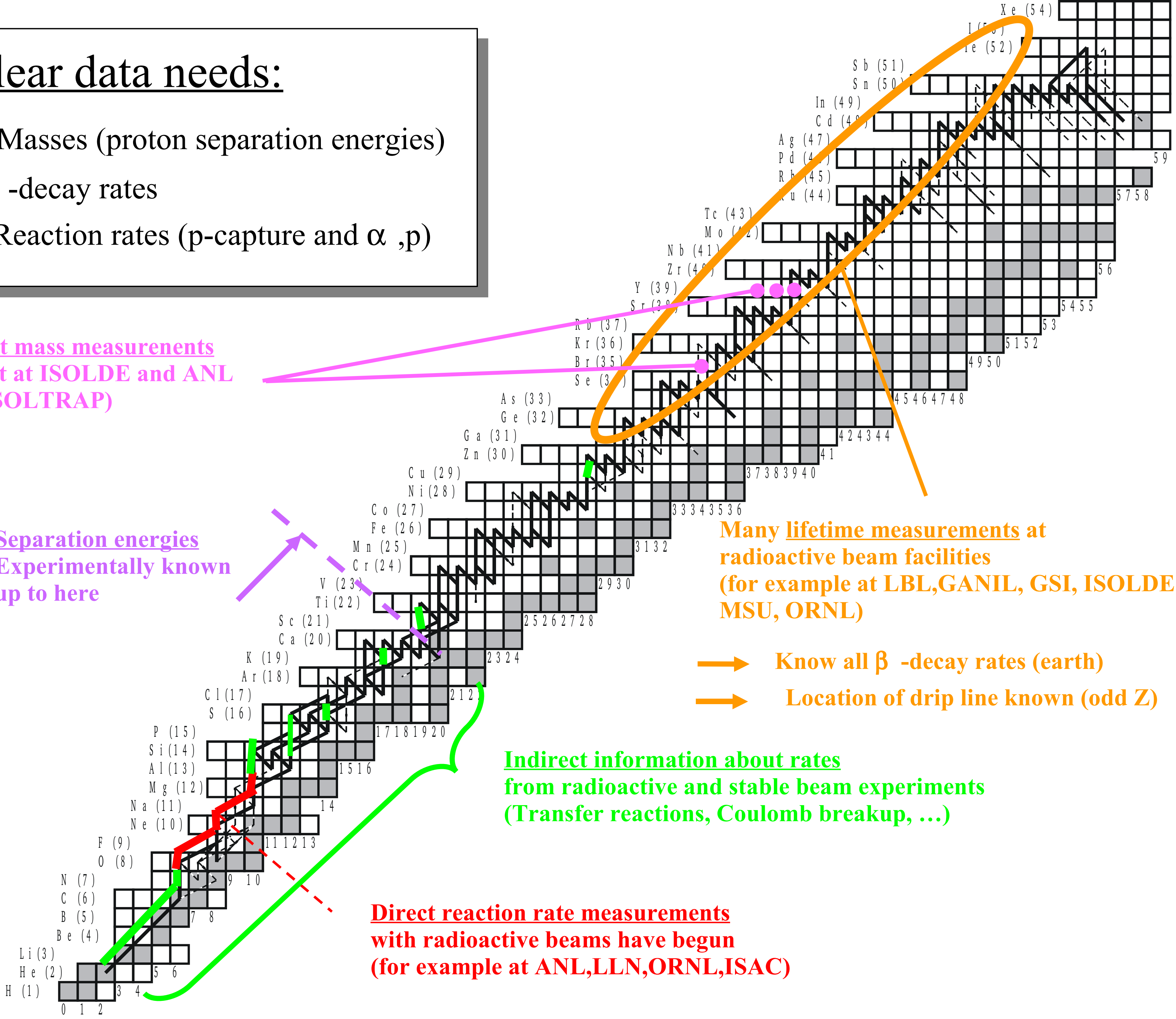
H. Schatz, MSU

Nuclear data needs:

● Masses (proton separation energies)

● β -decay rates

●● Reaction rates (p-capture and α ,p)



Some recent mass measurenents
β -endpoint at ISOLDE and ANL
Ion trap (ISOLTRAP)

Separation energies
Experimentally known
up to here

Many lifetime measurements at
radioactive beam facilities
(for example at LBL,GANIL, GSI, ISOLDE,
MSU, ORNL)

→ **Know all β -decay rates (earth)**

→ **Location of drip line known (odd Z)**

Indirect information about rates
from radioactive and stable beam experiments
(Transfer reactions, Coulomb breakup, …)

Direct reaction rate measurements
with radioactive beams have begun
(for example at ANL,LLN,ORNL,ISAC)