# Hydrogen burning under extreme conditions

Scenarios:

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

  ($T_9 \sim 0.08$)

- Nova explosions on accreting white dwarfs

  ($T_9 \sim 0.4$)

- X-ray bursts on accreting neutron stars

  ($T_9 \sim 2$)

- accretion disks around low mass black holes ?

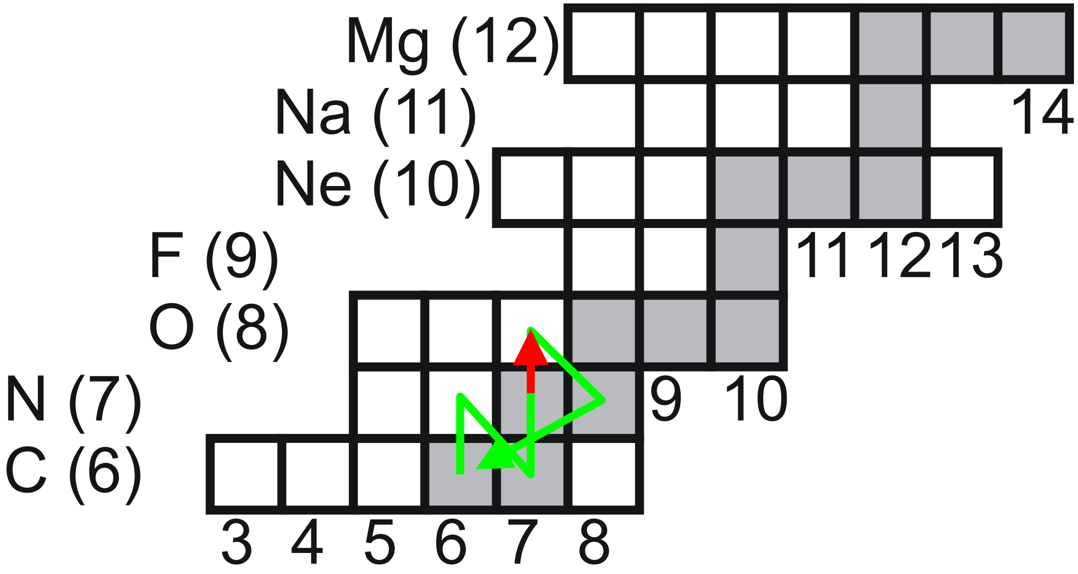
- neutrino driven wind in core collapse supernovae ?

further discussion assumes a density of $10^6$ g/cm$^3$ (X-ray burst conditions)

## “Cold” CN(O)-Cycle $T_9 < 0.08$

Energy production rate:

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



## Hot CN(O)-Cycle $T_9 \sim 0.08\text{-}0.1$

“beta limited CNO cycle”

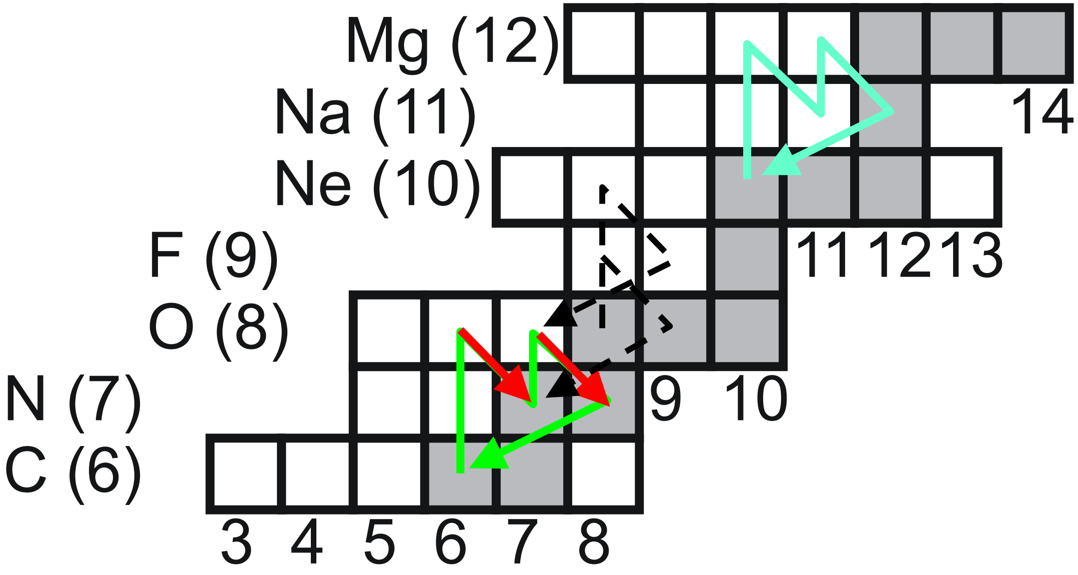
$$\varepsilon \propto 1/(\lambda^{-1}_{^{14}O(\beta+)} + \lambda^{-1}_{^{15}O(\beta+)}) = \text{const}$$

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

on $^{13}$N: $\lambda_{p,\gamma} > \lambda_\beta$

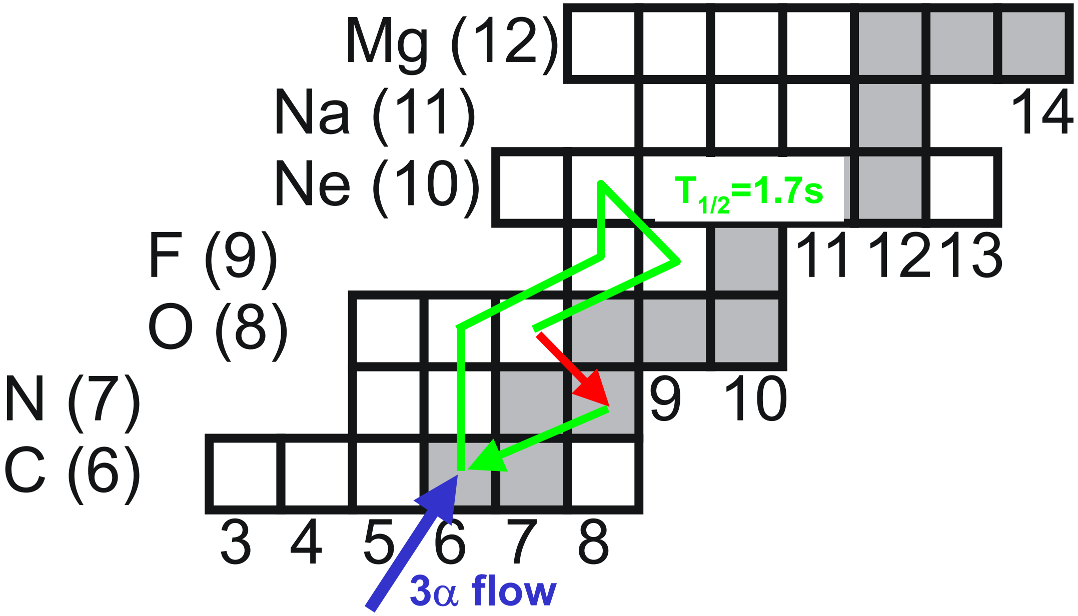
$$\Leftrightarrow Y_p \rho N_A <\sigma v> \; > \lambda_\beta$$

**Ne-Na cycle !**



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

still “beta limited”

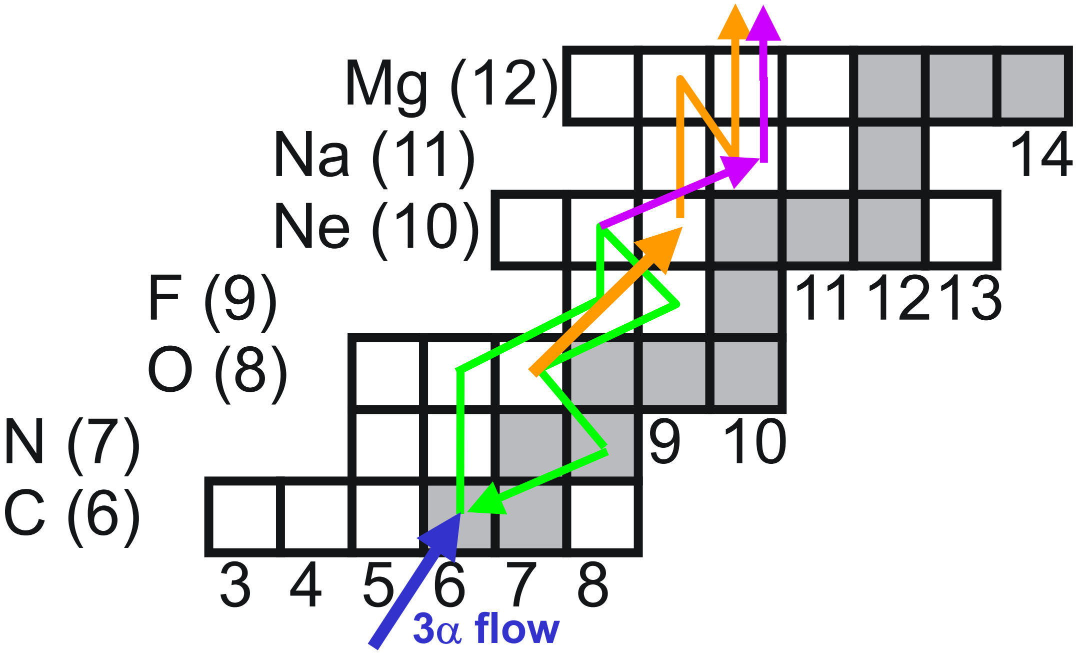


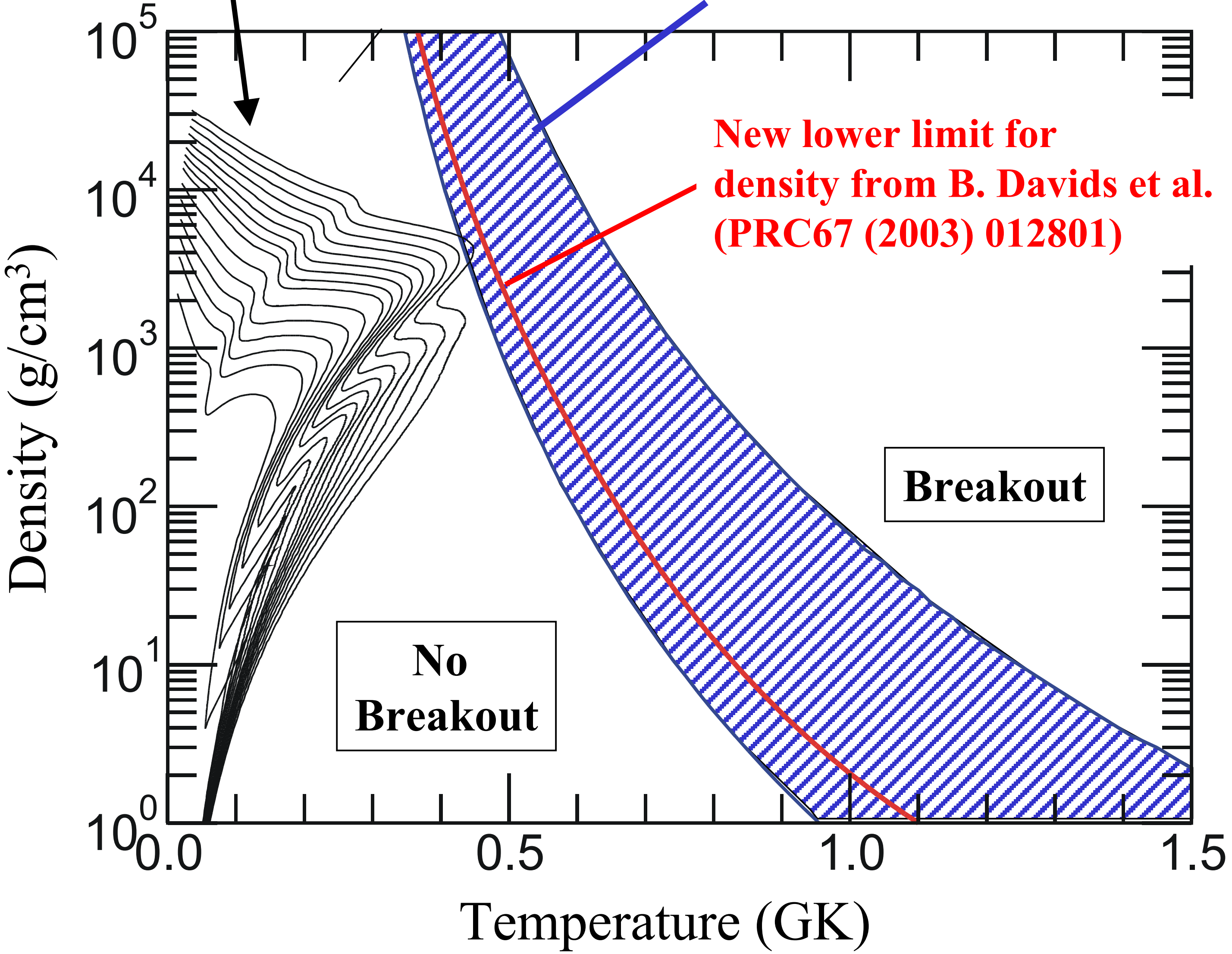
## Breakout

processing beyond CNO cycle
after breakout via:

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

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





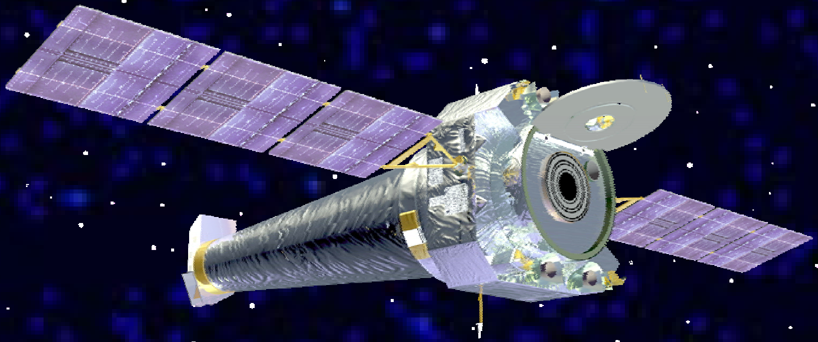
Multizone Nova model (Starrfield 2001)

Current $^{15}O(a,\gamma)$ Rate with X10 variation

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

# X-ray binaries
## – nuclear physics at the extremes

Outline

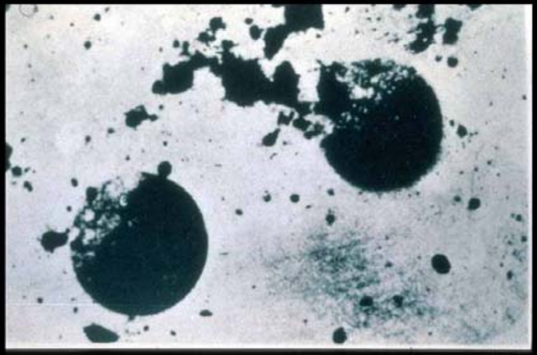


1. Observations
2. Model
3. Open Questions
4. Nuclear Physics – the rp process

# X-rays

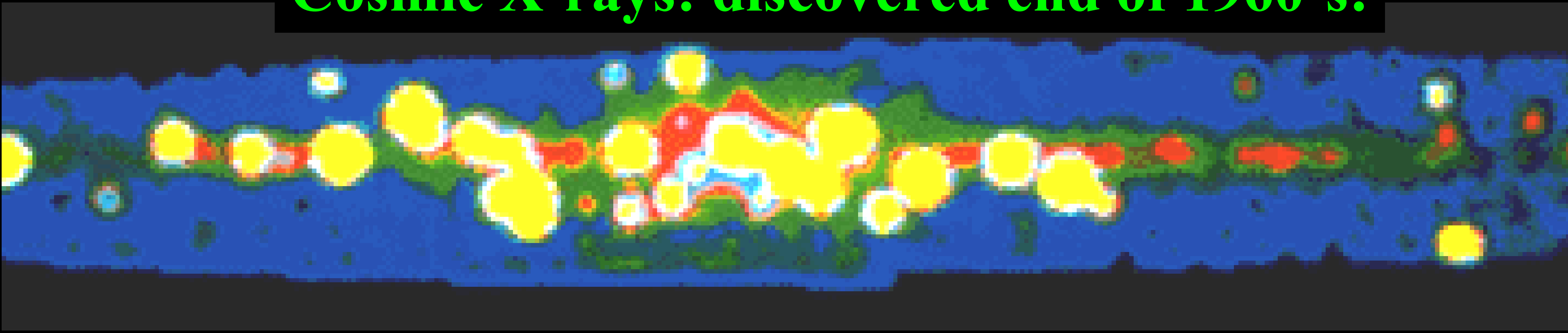
**Wilhelm Konrad Roentgen, First Nobel Price 1901 for discovery of X-rays 1895**

Ms Roentgen's hand, 1895



First X-ray image from 1890
(Goodspeed & Jennings, Philadelphia)

# Cosmic X-rays: discovered end of 1960’s:

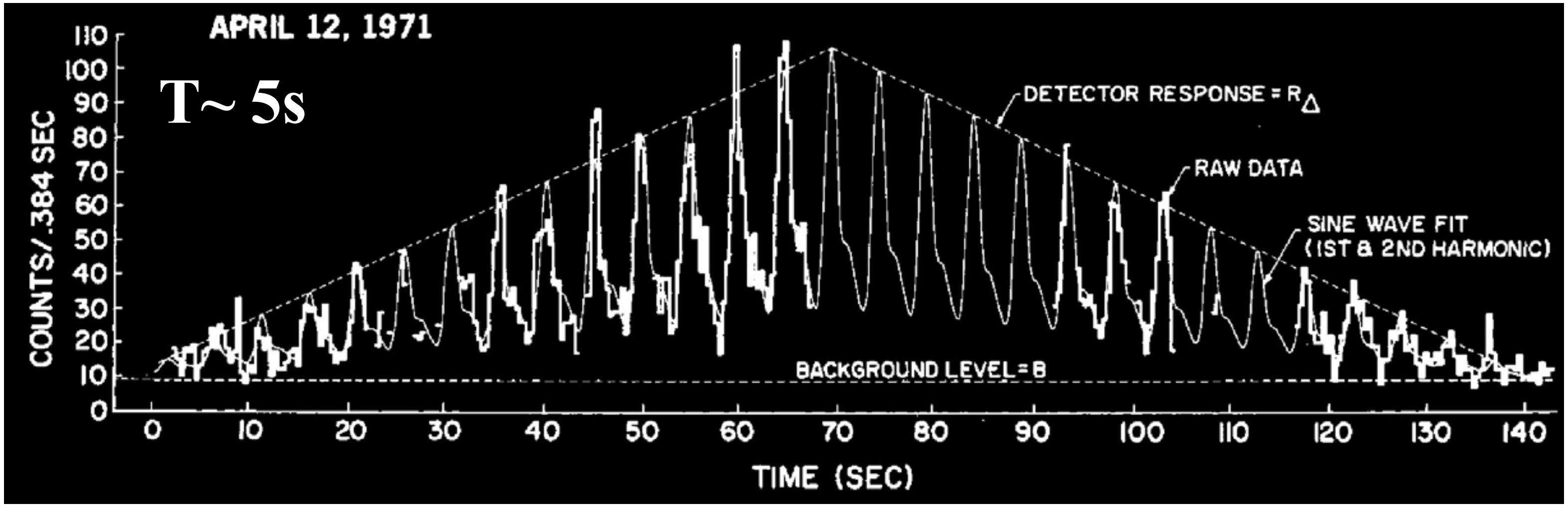


0.5-5 keV (T=E/k=6-60 x $10^6$ K)

Again Nobel Price in Physics 2002
for Riccardo Giacconi

# Discovery

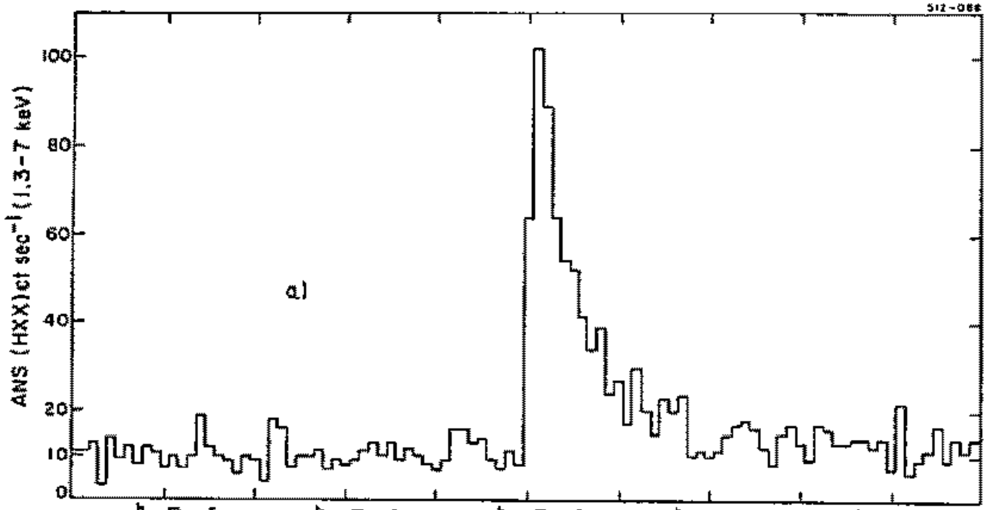
First **X-ray pulsar**: Cen X-3 (Giacconi et al. 1971) with UHURU



**T~ 5s**

Today: ~50

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



10 s

Today: ~40

Total ~230 X-ray binaries known

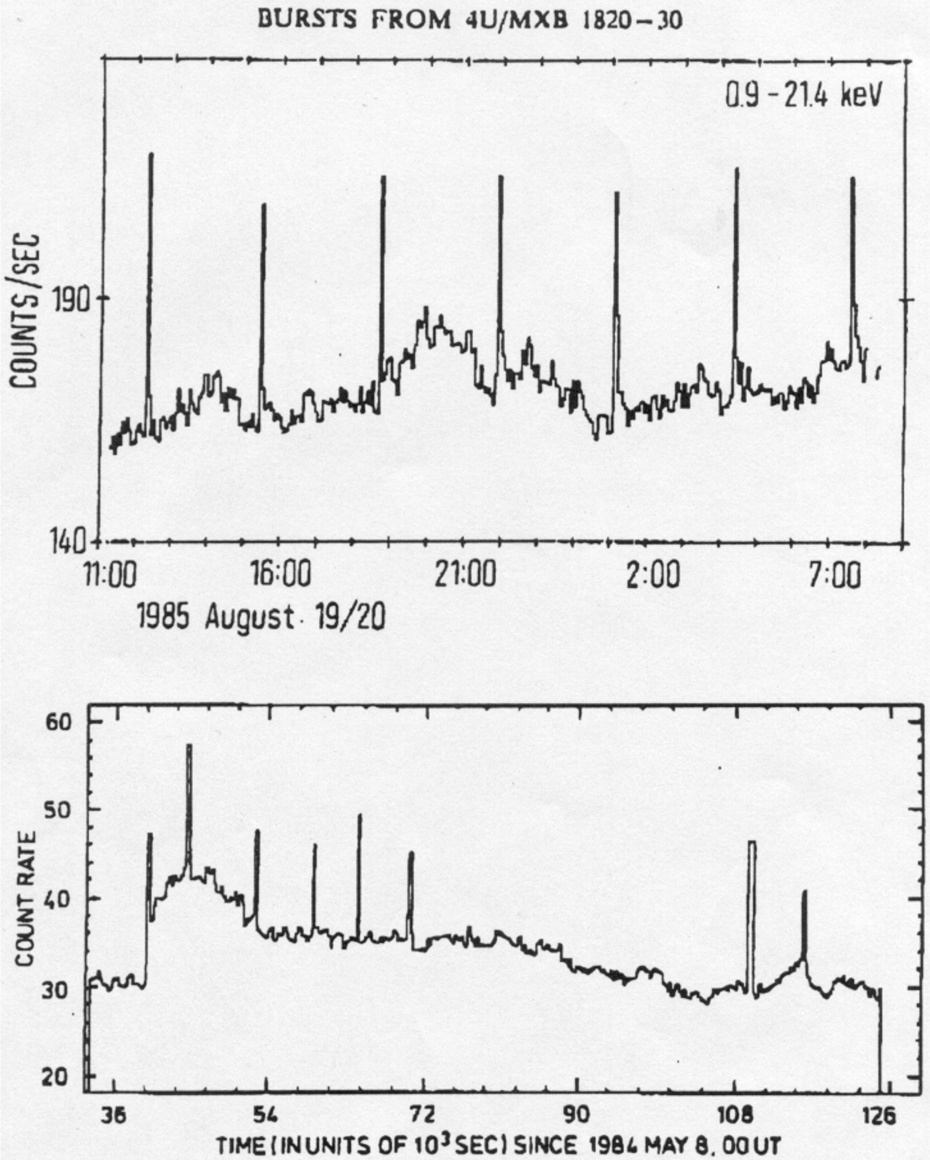


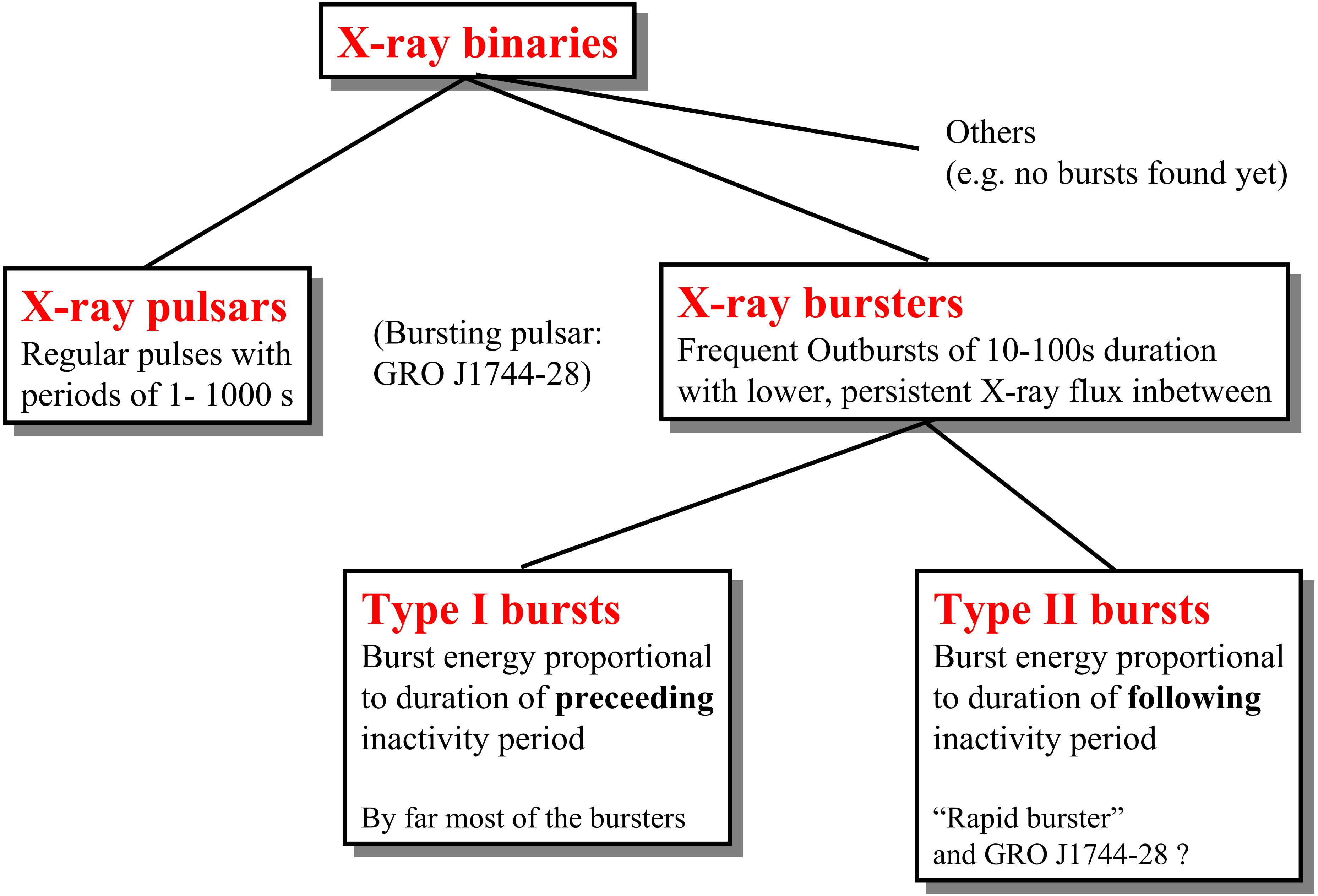
Fig. 3.14. (a) Example of a very regular burst recurrence pattern, observed for 1820–303 (from Haberl *et al.* 1987). (b) Irregular burst recurrence, observed from 1636–536 (from Sztajno *et al.* 1985).

## Typical X-ray bursts:

- $10^{36}$-$10^{38}$ erg/s
- duration 10 s – 100s
- recurrence: hours-days
- regular or irregular

Frequent and very bright phenomenon !

(stars $10^{33}$-$10^{35}$ erg/s)



**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

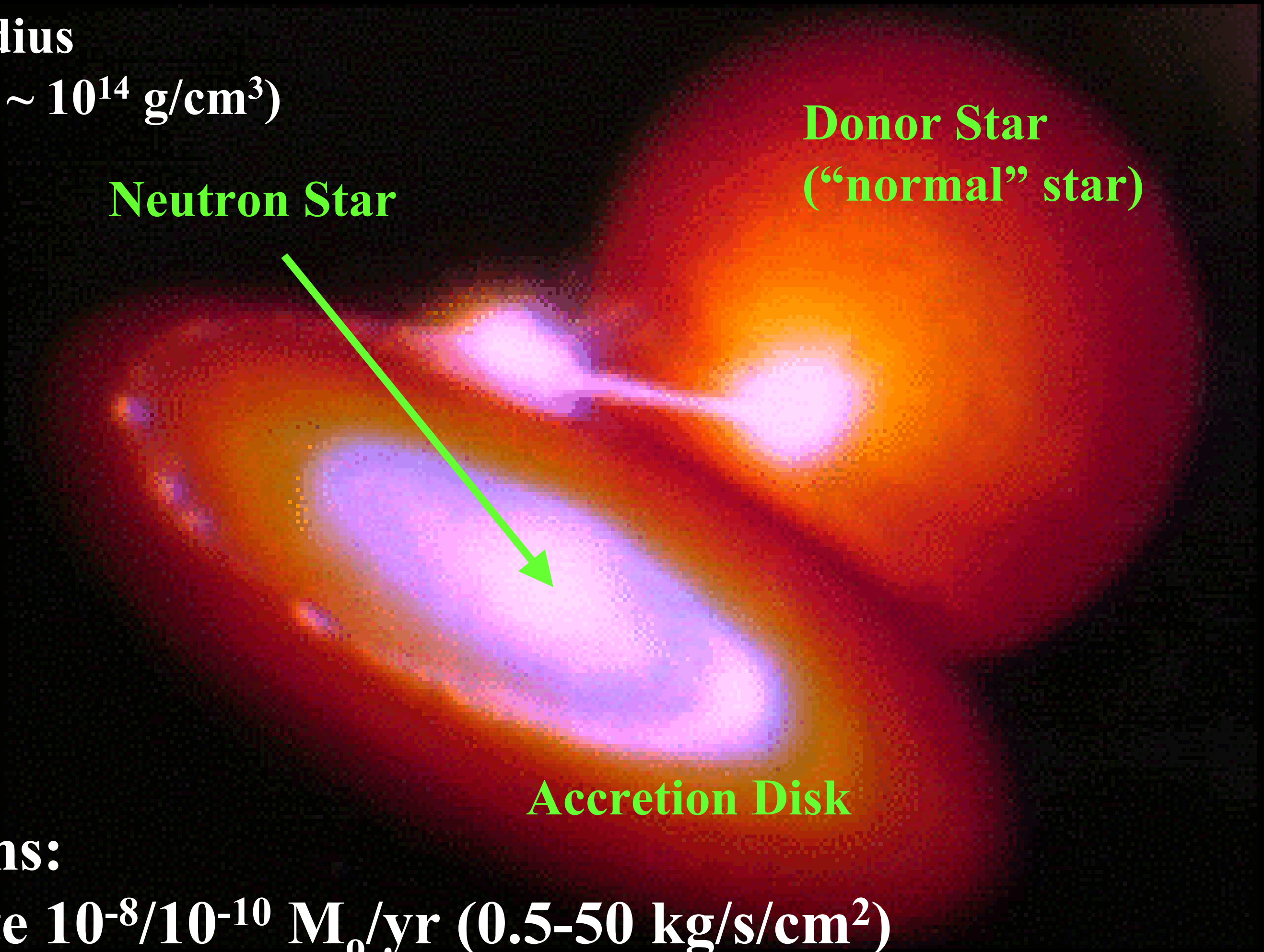
By far most of the bursters

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

“Rapid burster”
and GRO J1744-28 ?

# The Model

**Neutron stars:**
**1.4 $M_o$, 10 km radius**
**(average density: ~ $10^{14}$ g/cm$^3$)**



**Typical systems:**

- **accretion rate $10^{-8}/10^{-10}$ $M_o$/yr (0.5-50 kg/s/cm$^2$)**
- **orbital periods 0.01-100 days**
- **orbital separations 0.001-1 AU's**

# Mass transfer by Roche Lobe Overflow

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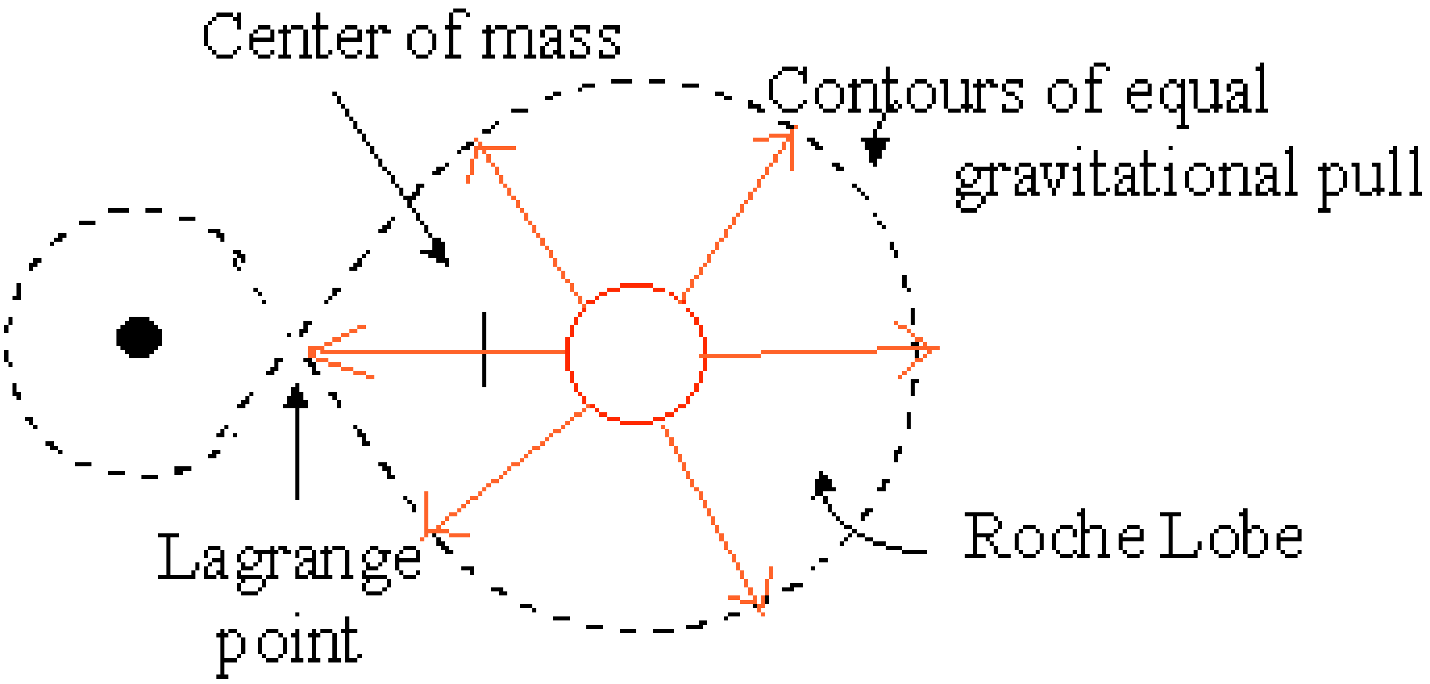
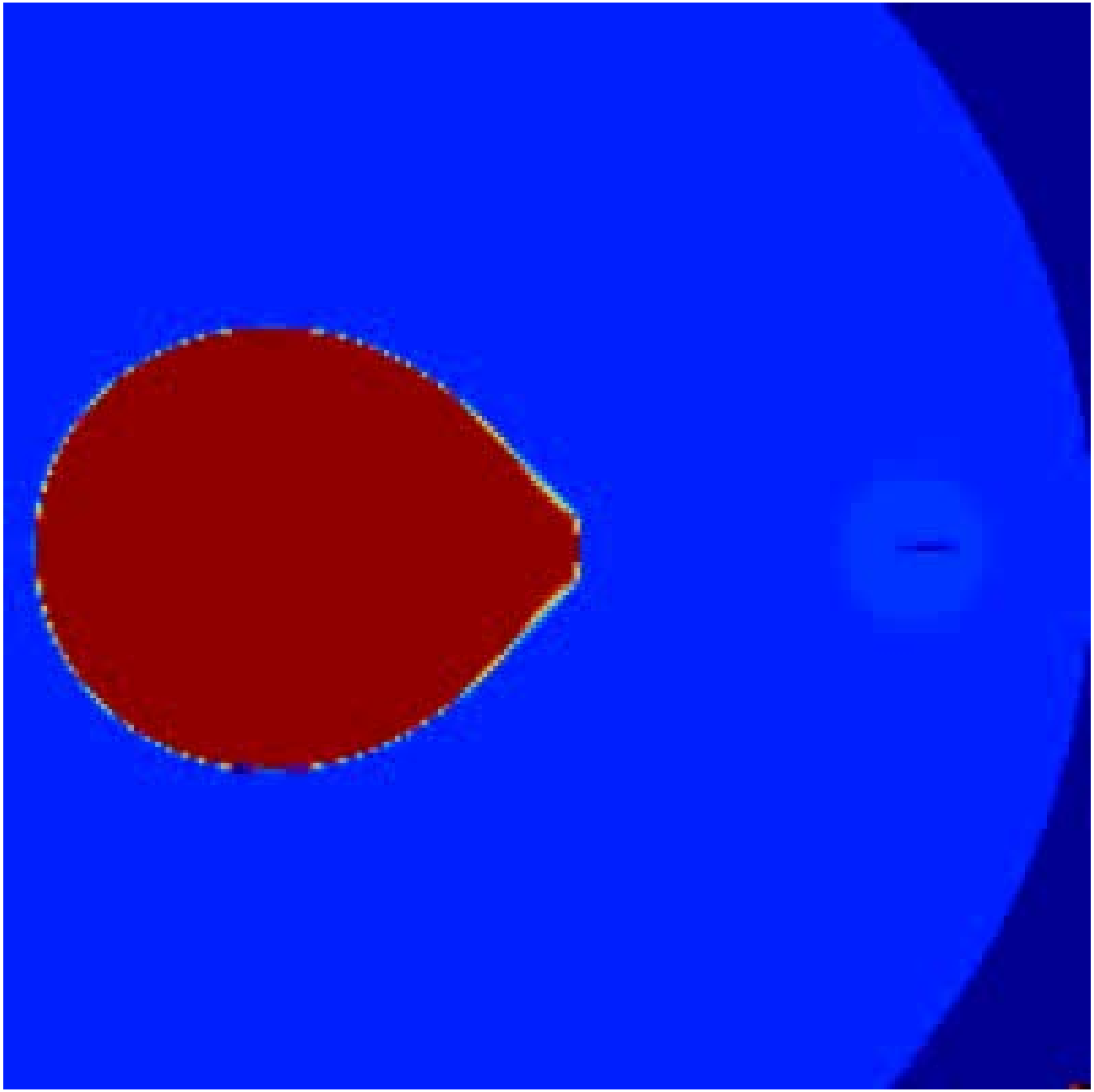


Star expands on main sequence.
when it fills its Roche Lobe mass transfer happens
through the L1 Lagrangian point



John Blondin, NC State, http://wonka.physics.ncsu.edu/~blondin/AAS/

## Energy generation: thermonuclear energy

$4\mathrm{H} \longrightarrow {}^{4}\mathrm{He}$ 6.7 MeV/u

$3\,{}^{4}\mathrm{He} \longrightarrow {}^{12}\mathrm{C}$ 0.6 MeV/u (“triple alpha”)

$5\,{}^{4}\mathrm{He} + 84\,\mathrm{H} \longrightarrow {}^{104}\mathrm{Pd}$ 6.9 MeV/u (rp process)

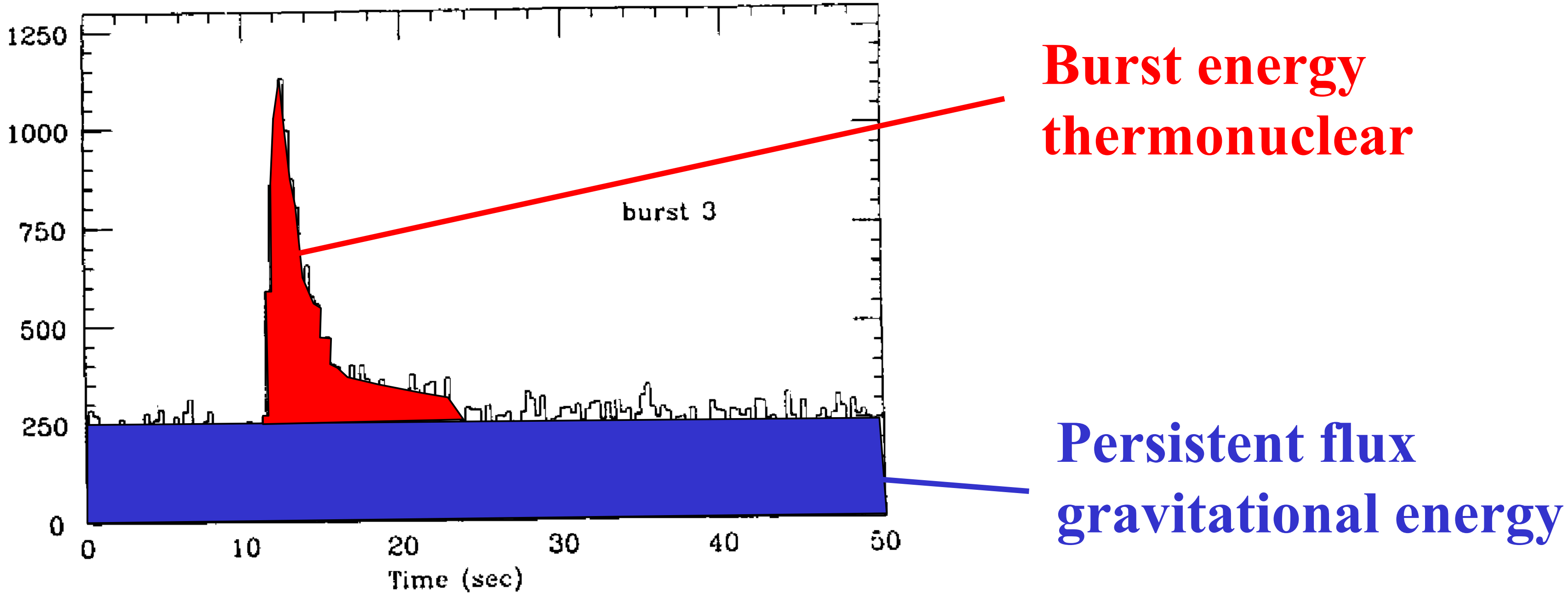
## Energy generation: gravitational energy

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

**Ratio gravitation/thermonuclear ~ 30 - 40**

# Observation of thermonuclear energy:

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



# Ignition and thermonuclear runaway

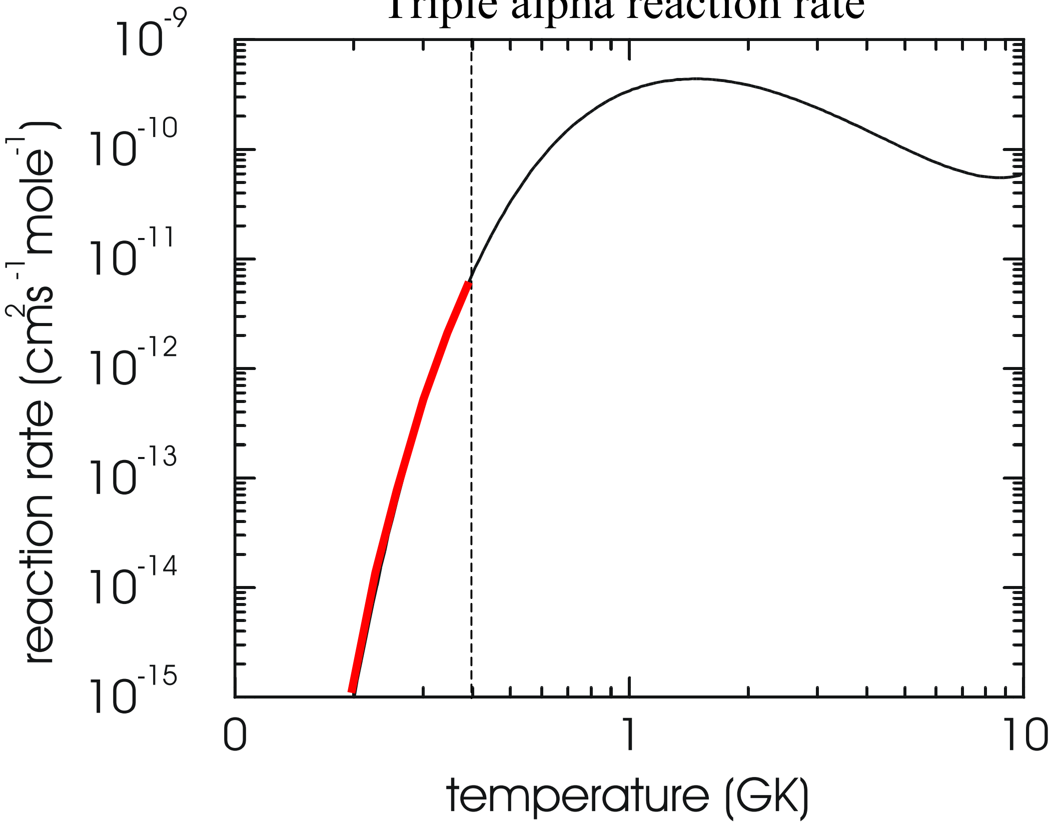
Burst trigger rate is "triple alpha reaction" $3\,{}^4\mathrm{He} \longrightarrow {}^{12}\mathrm{C}$

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

$\varepsilon_{nuc}$ Nuclear energy generation rate

$\varepsilon_{cool} \sim T^4$ Cooling rate

Triple alpha reaction rate



**Ignition < 0.4 GK:**

unstable **runaway**
(increase in T increases
$\varepsilon_{nuc}$ 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 $L = \sigma A\ T^4_{eff}$ gives typical neutron star radii
- Maximum luminosities consistent with Eddington luminosity
  for a neutron star (radiation pressure balances gravity)

$$L_{edd} = 4\pi cGM/\kappa = 2.5 \text{ x } 10^{38}(M/M_\odot)(1+X)^{-1} \text{ erg/s}$$

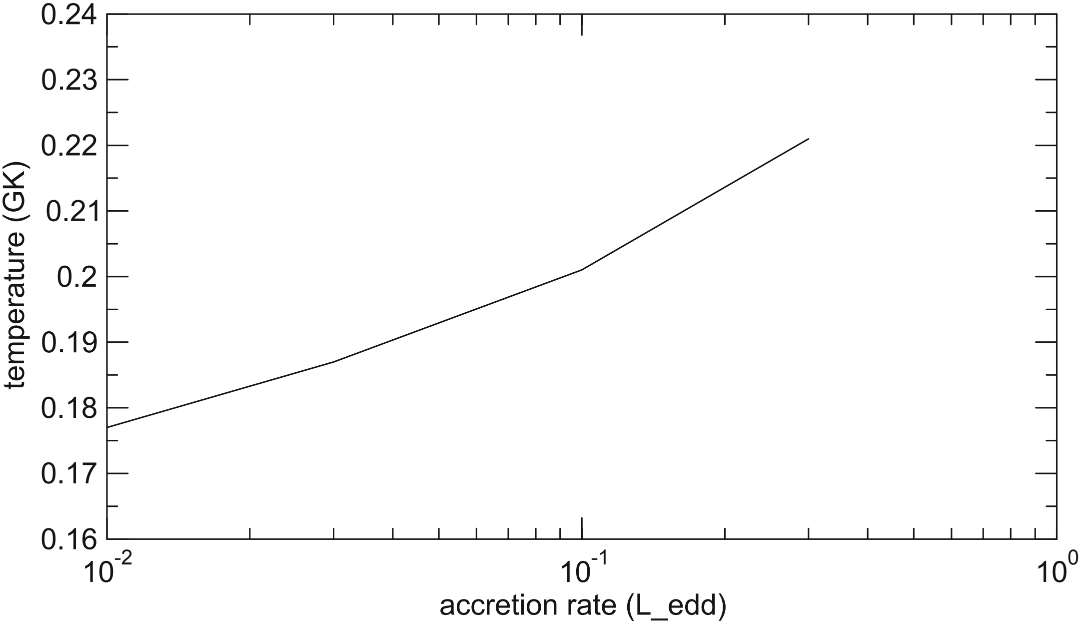
(this is non relativistic – relativistic corrections need to be applied)

$\kappa$=opacity, X=hydrogen mass fraction

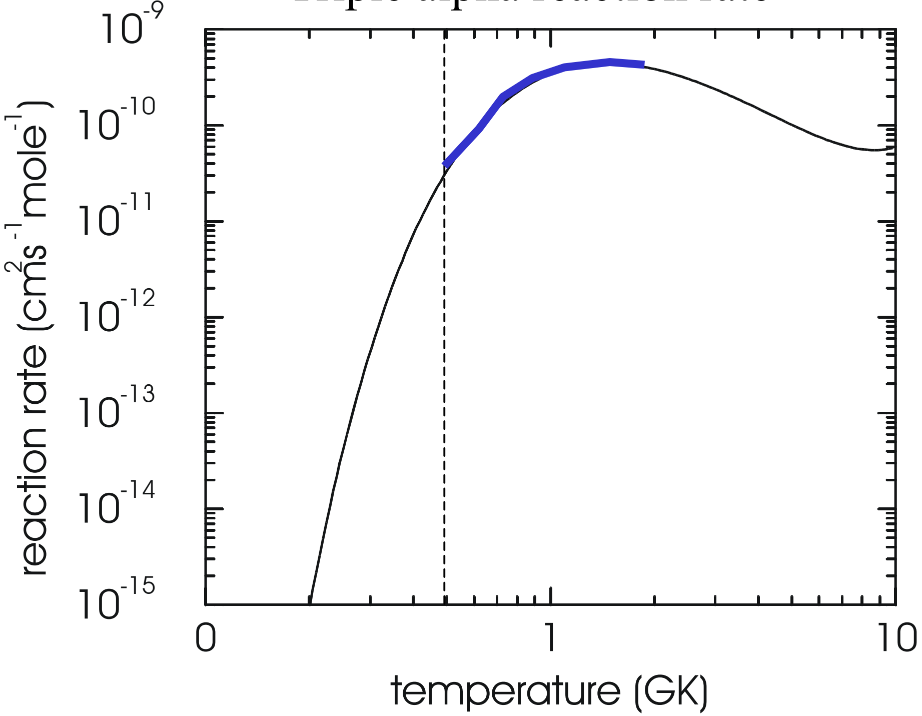
# What happens if “ignition temperature” > 0.4 GK

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

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

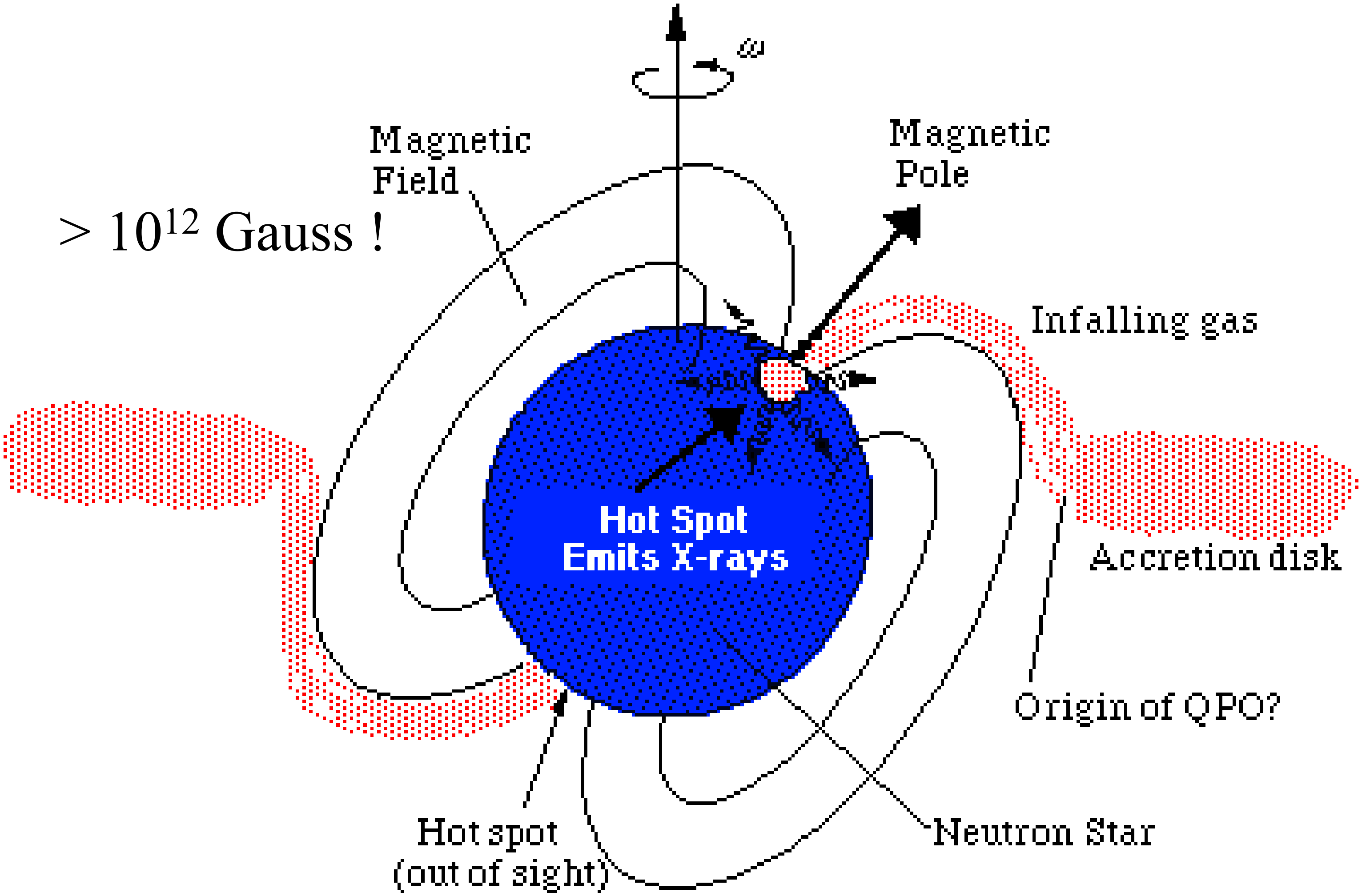


Triple alpha reaction rate



**Stable nuclear burning**

# X-ray pulsar



> $10^{12}$ Gauss !

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

# Why do we care about X-ray binaries ?

- Basic model seems to work but many open questions

- Unique laboratories to probe neutron stars:
    - Over larger mass range as they get heavier
    - Over larger spin range as they get spun up
    - Over larger temperature range as they get heated

# Some current open questions

- **Burst timescale variations**

  why do they vary from ~10 s to ~100 s
- **Superbursts (rare, 1000x stronger and longer bursts)**

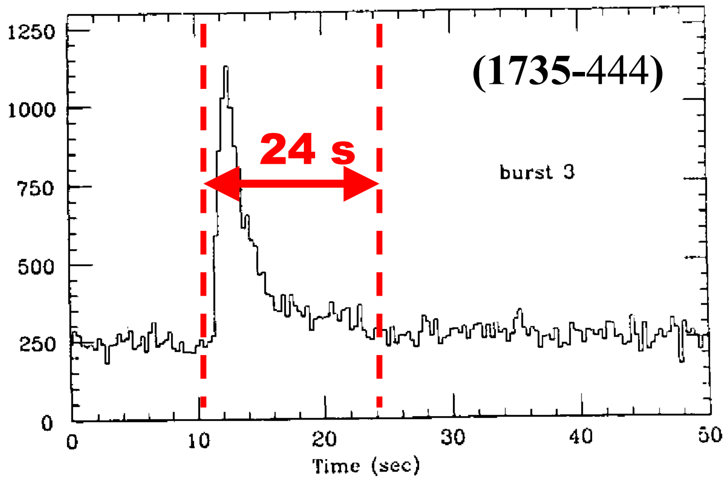
  what is their origin ?
- **Contribution of X-ray bursts to galactic nucleosynthesis ?**
- **NCO's (300-600Hz oscillations during bursts, rising by ~Hz)**

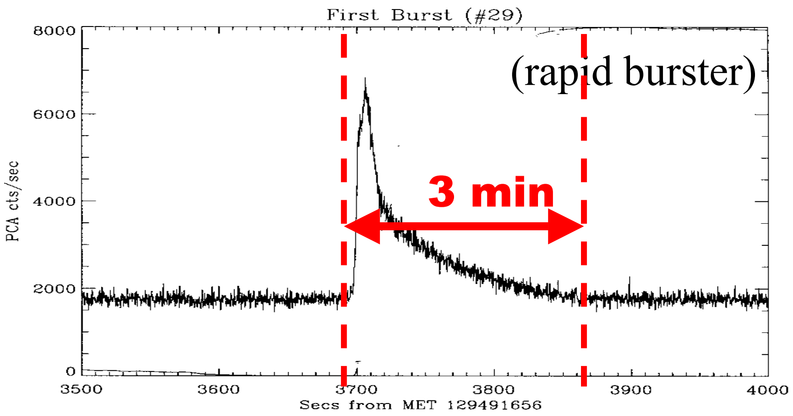
  what is their origin ?
- **Crust composition – what is made by nuclear burning ?**
  - Magnetic field evolution ?

    (why are there bursters and pulsars)
  - Thermal structure ?

    (what does observed thermal radiation tell us ?)
  - Detectable gravitatioal wave emission ?

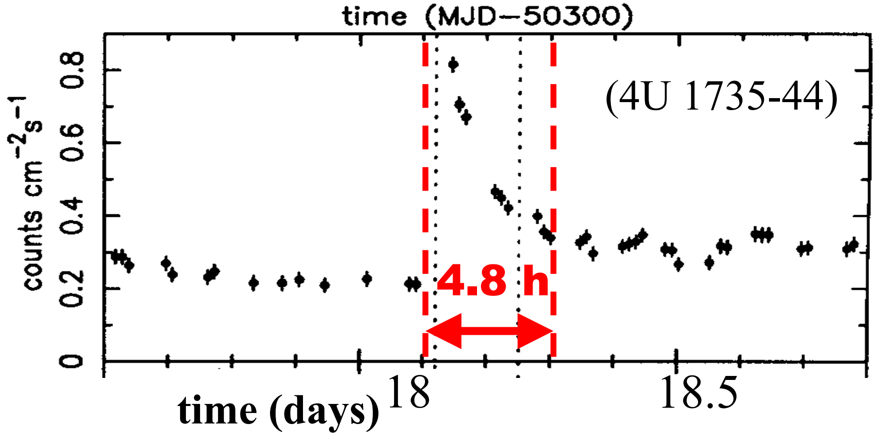
    (can crust reactions deform the crust so that the spinning neutron star emits gravitational waves ?)





## Normal type I bursts:

- duration 10-100 s
- ~$10^{39}$ erg



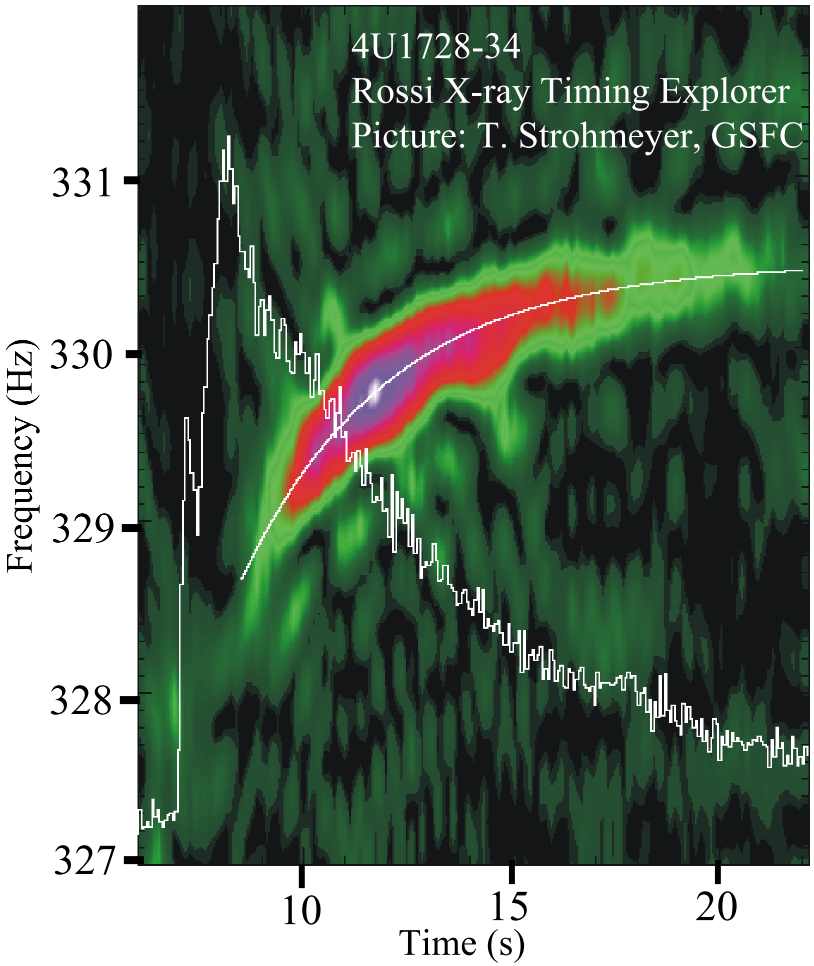
## Superbursts:

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

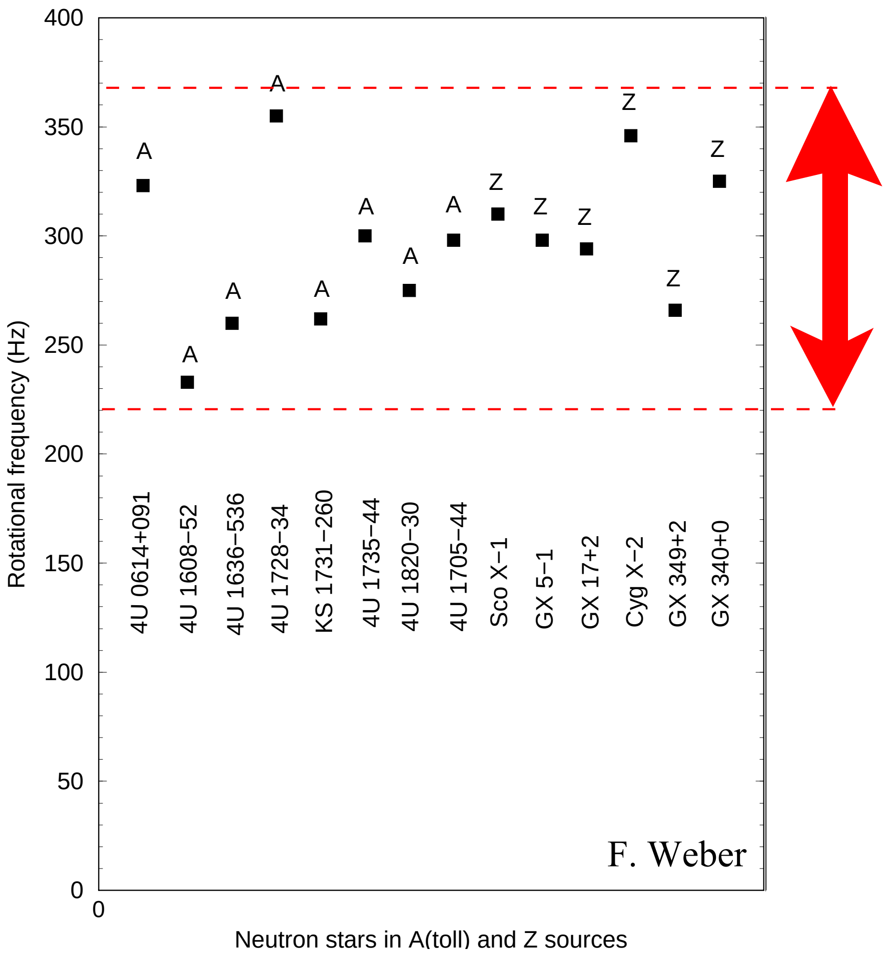
- duration …
- ~$10^{43}$ erg
- rare (every 3.5 yr ?)

# Spin up of neutron stars in X-ray binaries

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



4U1728-34
Rossi X-ray Timing Explorer
Picture: T. Strohmeyer, GSFC

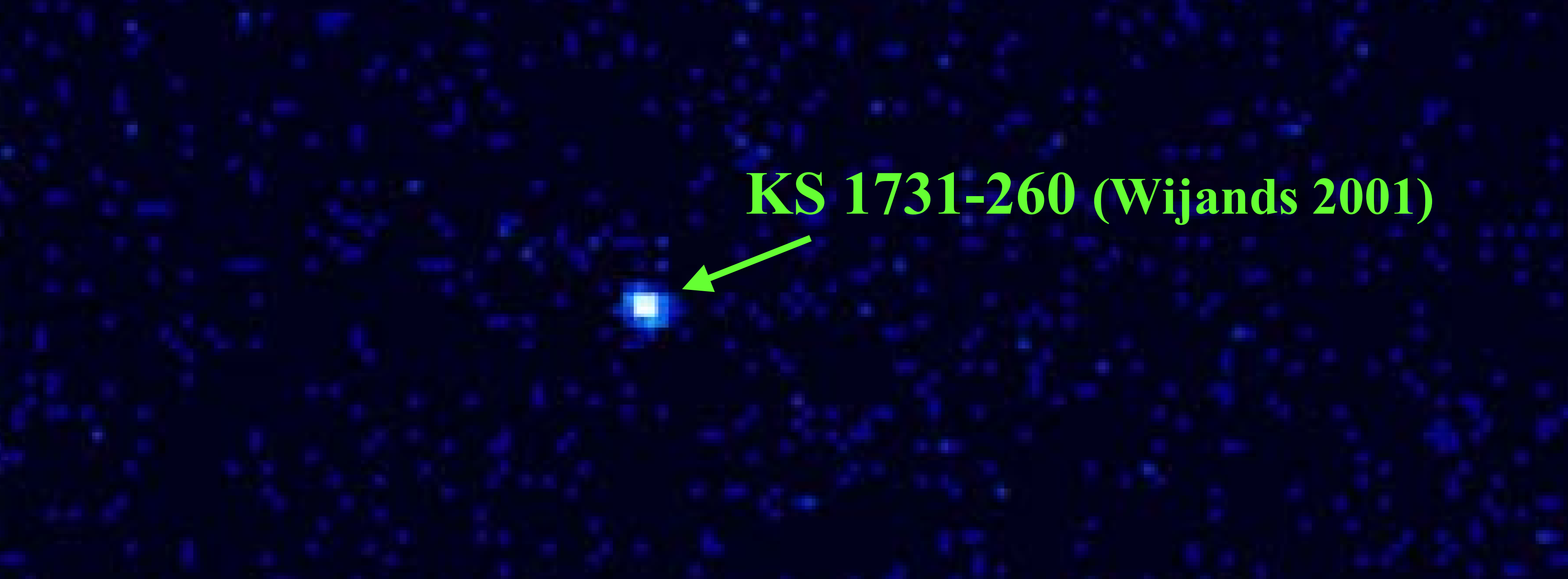


F. Weber

Spin periods lie in a surprisinly narrow range!

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

# Chandra observations of transients



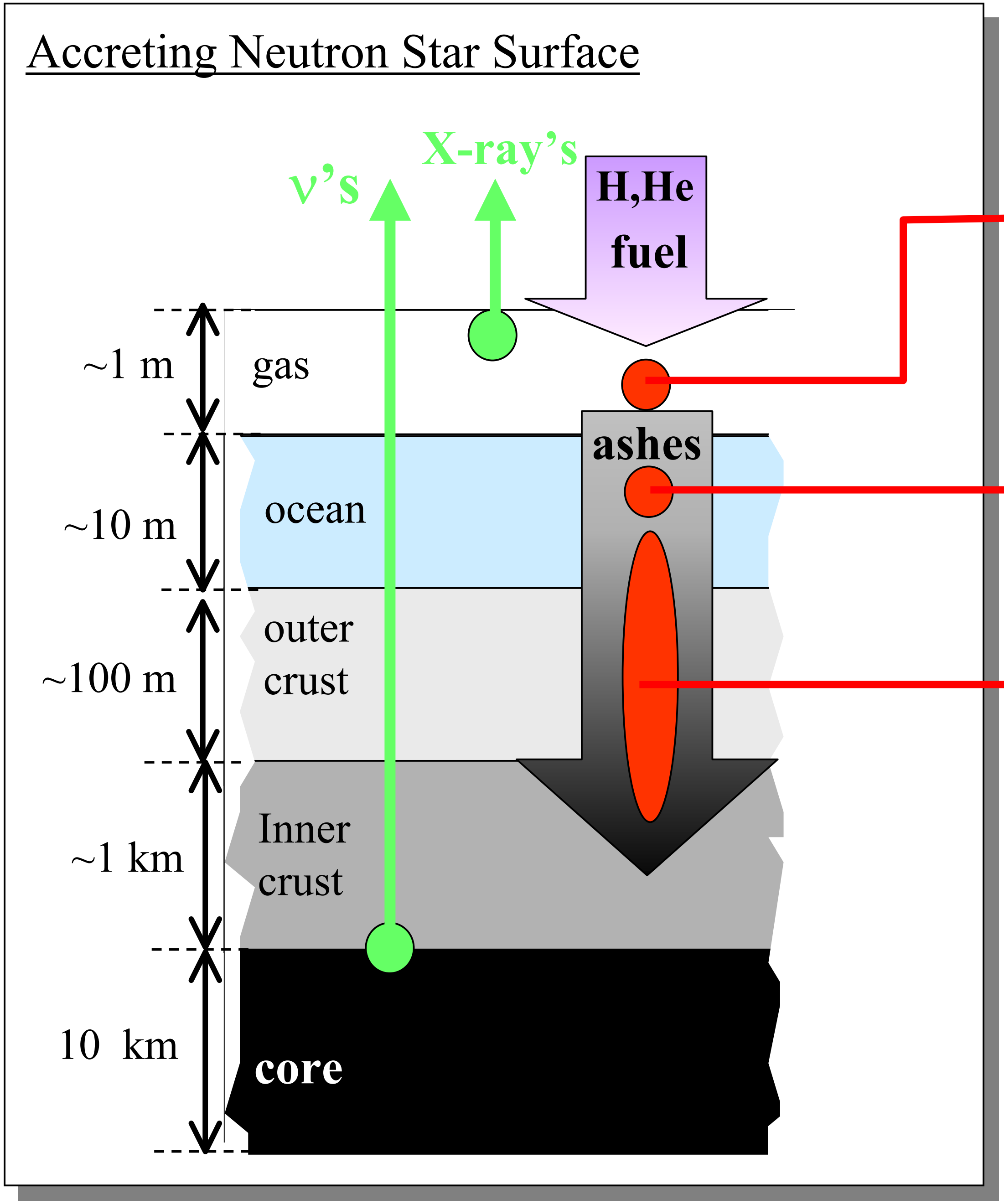
KS 1731-260 (Wijands 2001)

**Bright X-ray burster from 1988 -early 2001**
**Accretion shut off early 2001**

**Detect thermal X-ray flux from cooling crust:**

- **Too cold ! (only 3 mio K)**
- **Constraints on duration of previous quiescent phase**
- **Constraints on neutron star cooling mechanisms**

# Nuclear physics overview



Thermonuclear H+He burning
(rp process)

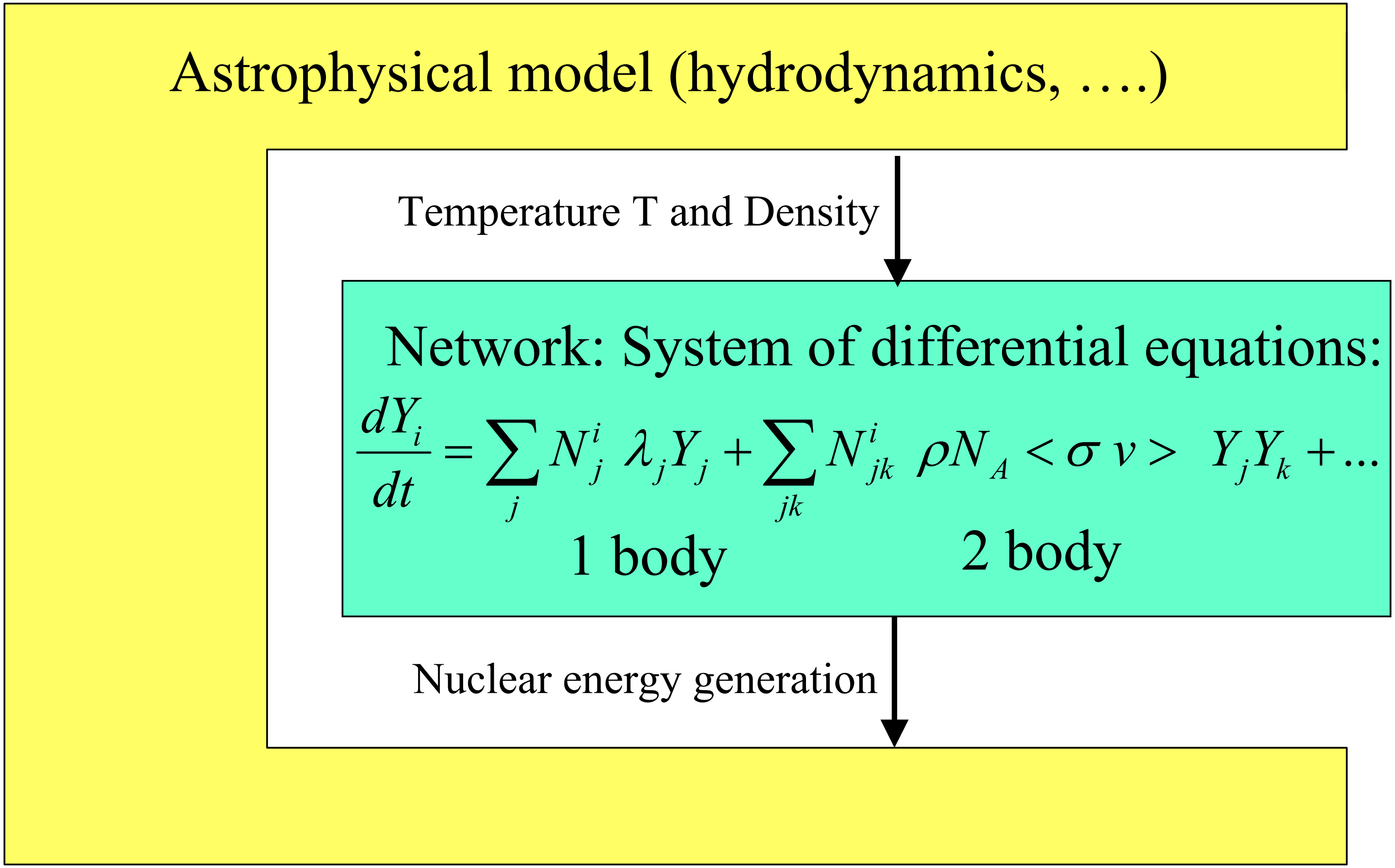
Deep burning
(EC on H, C-flash)

Crust processes
(EC, pycnonuclear fusion)

# Nuclear reaction networks

| | |
|---|---|
| Mass fraction of nuclear species | $X$ |
| Abundance | $Y = X/A$ (A=mass number) |
| Number density | $n = \rho N_A Y$ ($\rho$=mass density, $N_A$=Avogadro) |

(note $N_A$ is really $1/m_u$ – works only in CGS units)



Astrophysical model (hydrodynamics, ….)

Temperature T and Density

Network: System of differential equations:

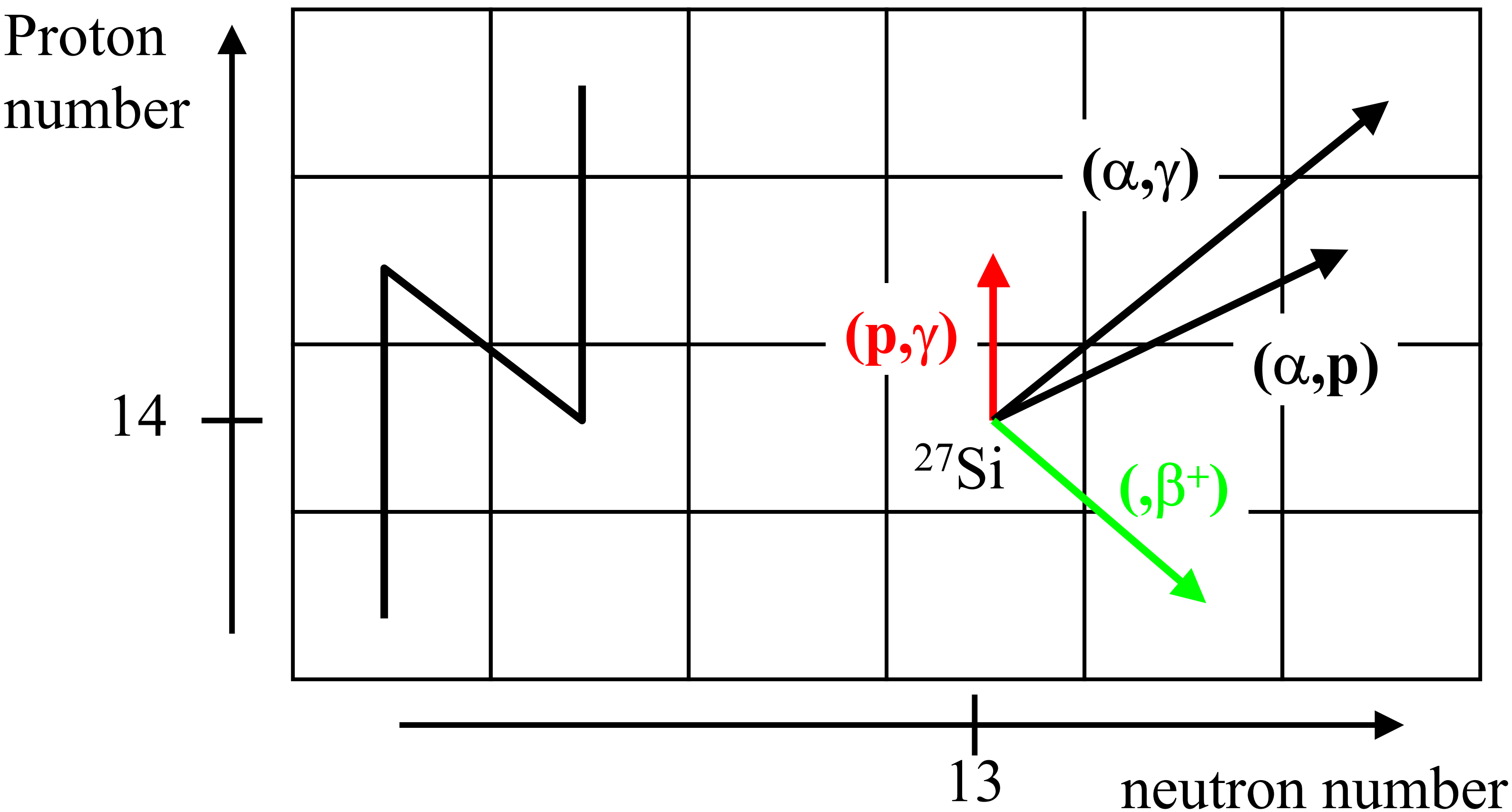
$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{jk} N^i_{jk} \rho N_A < \sigma v > Y_j Y_k + \ldots$$

1 body 2 body

Nuclear energy generation

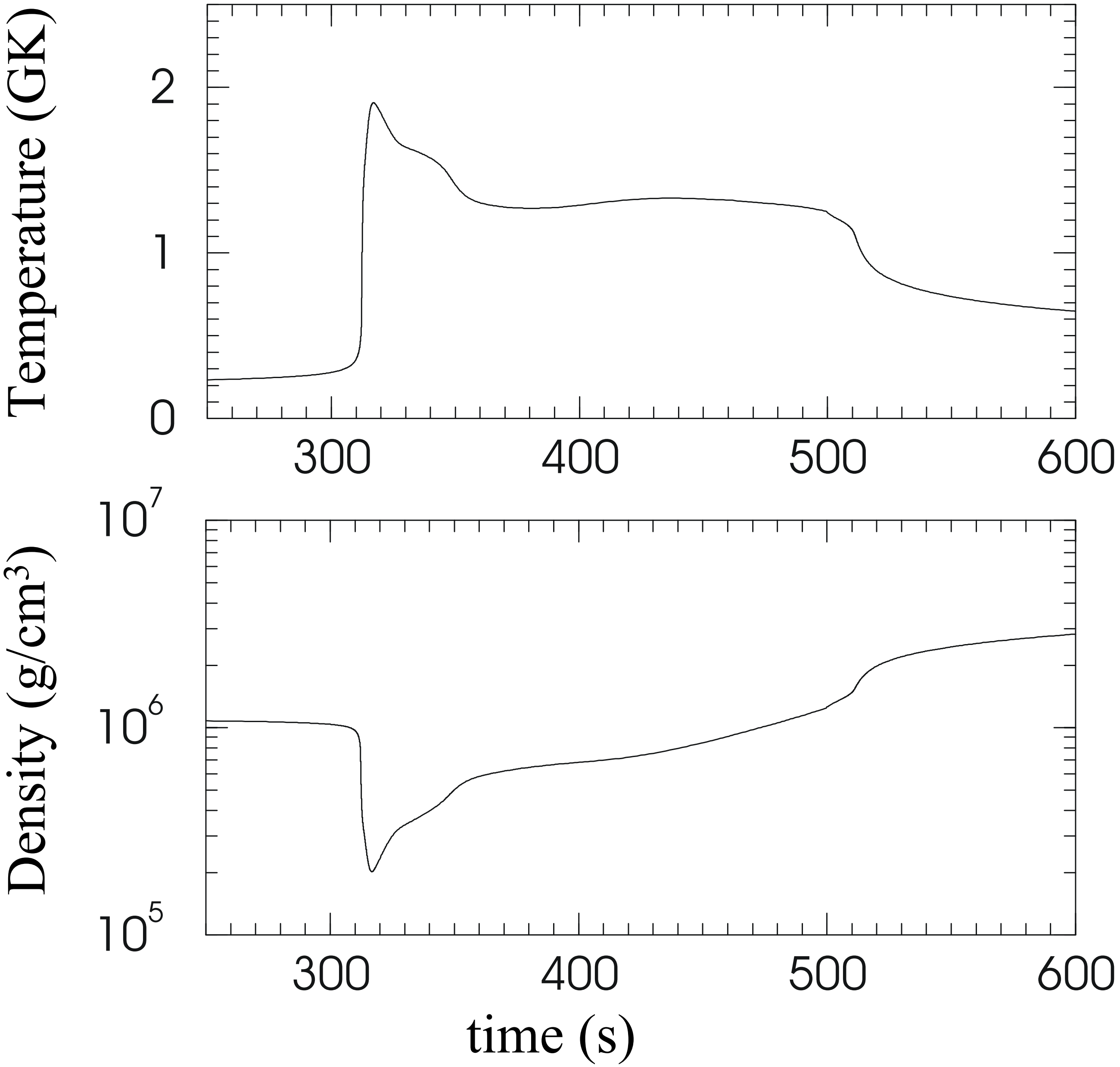
$N^i_{\ldots}$: number of nuclei of species I produced (positive) or destroyed (negative) per reaction

# Visualizing reaction network solutions

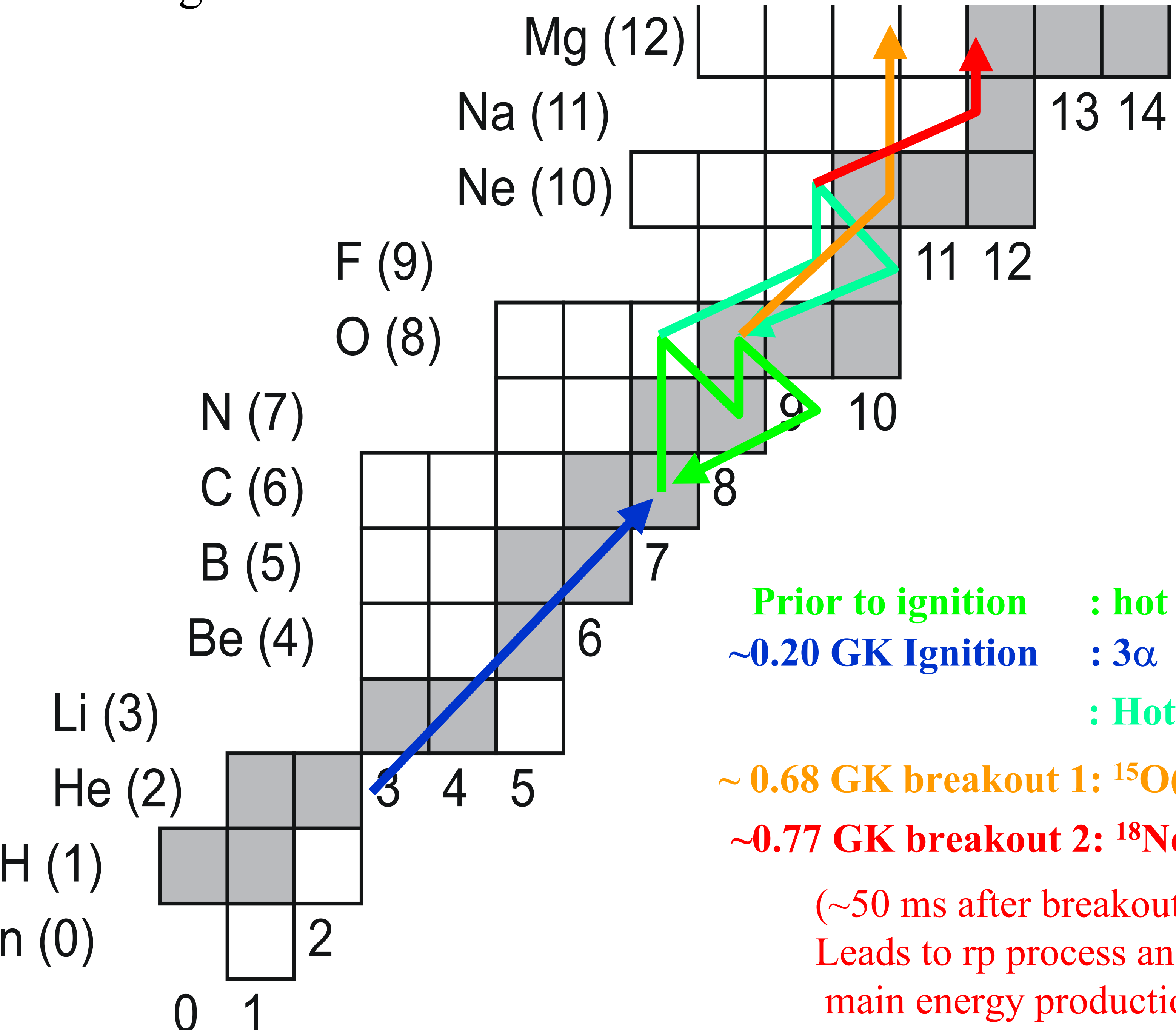


$$\text{Lines} = \text{Flow} = \quad F_{i,j} = \int \left[ \frac{dY_i}{dt}_{\,i->j} - \frac{dY_j}{dt}_{\,j->i} \right] dt$$

# 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

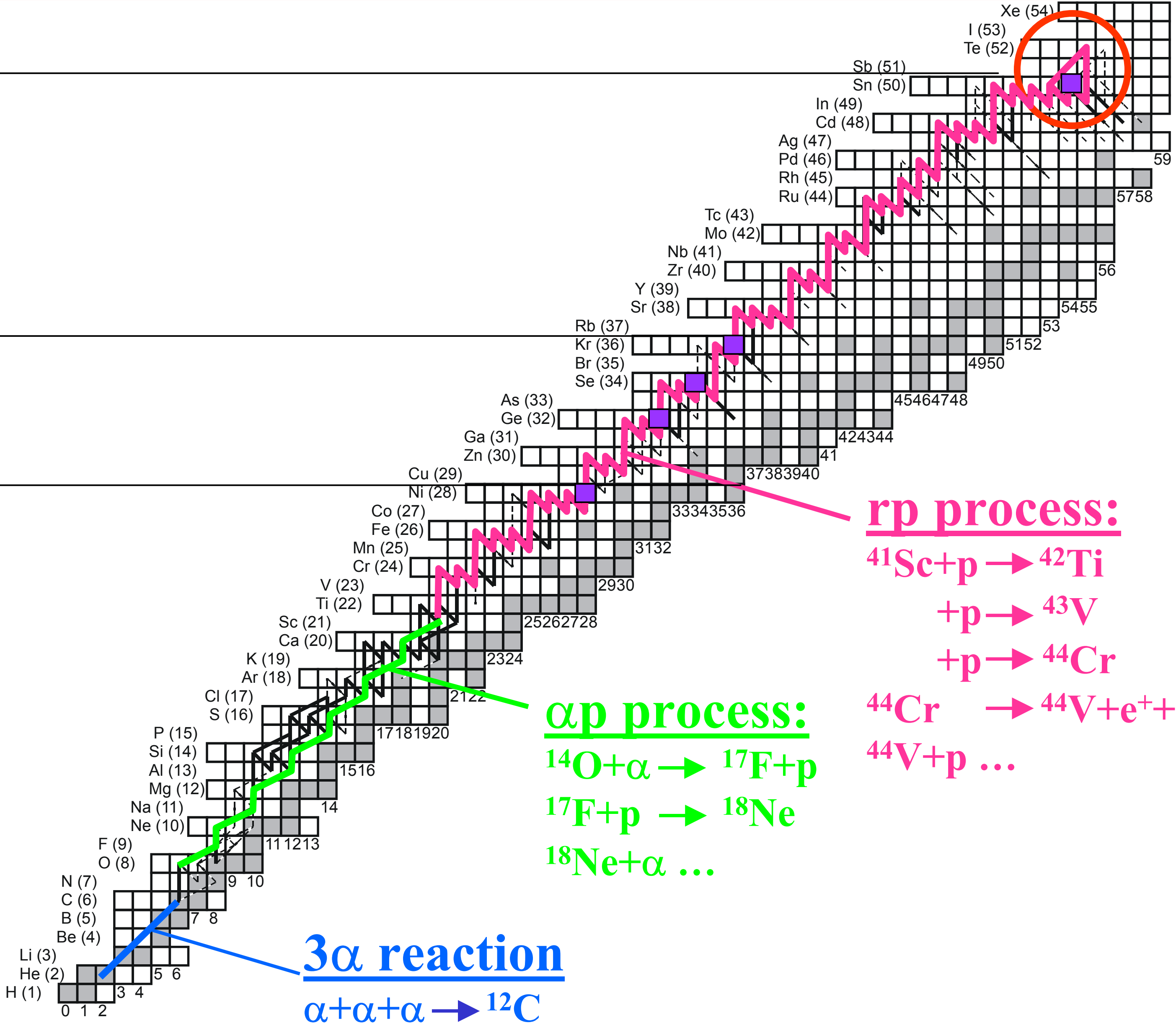
# Models: Typical reaction flows

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:**

$^{41}$Sc+p → $^{42}$Ti

+p → $^{43}$V

+p → $^{44}$Cr

$^{44}$Cr → $^{44}$V+e$^{+}$+$\nu_e$

$^{44}$V+p …

**αp process:**

$^{14}$O+α → $^{17}$F+p

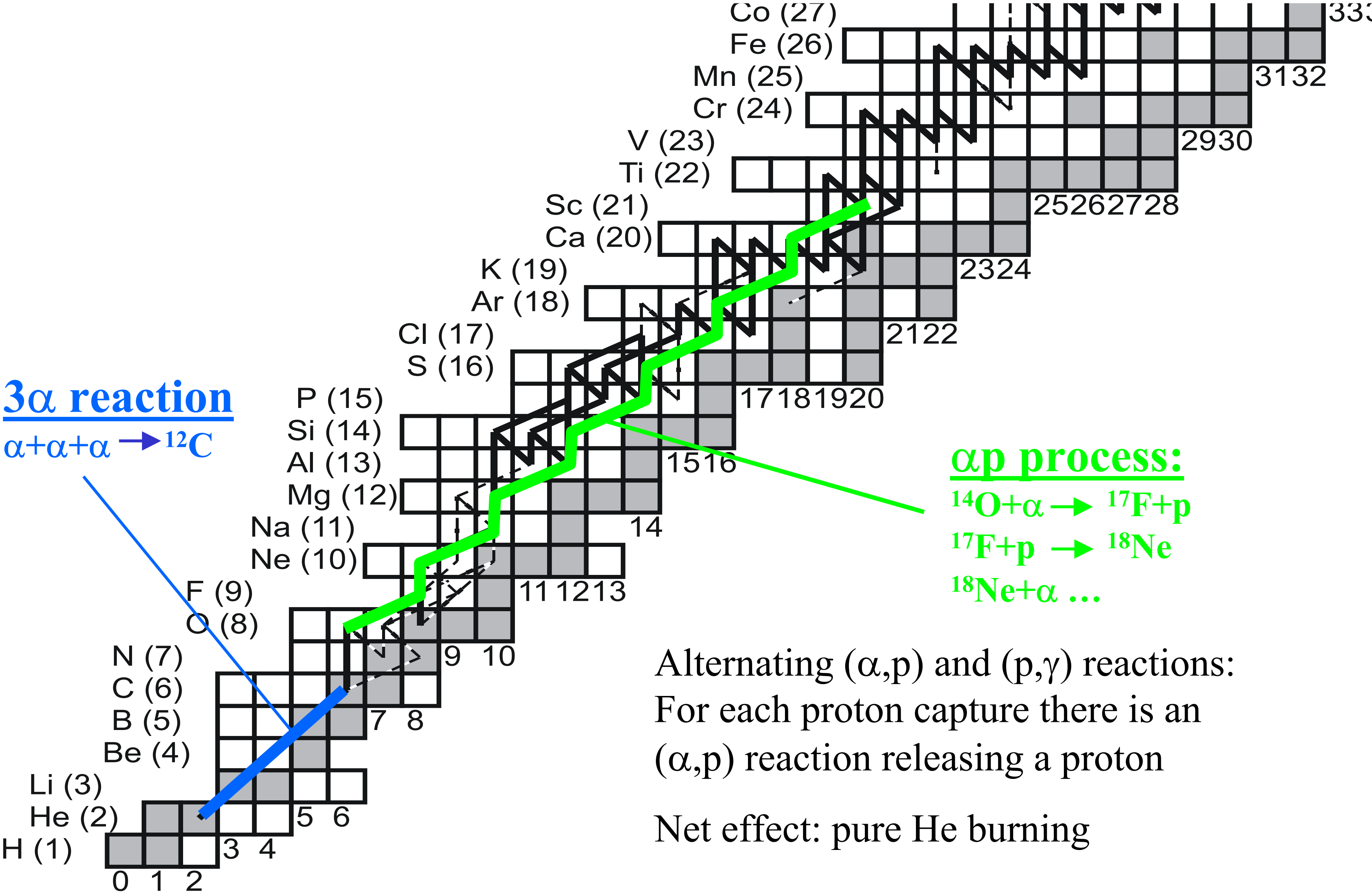
$^{17}$F+p → $^{18}$Ne

$^{18}$Ne+α …

**3α reaction**

α+α+α → $^{12}$C

# In detail: αp process



**3α reaction**

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

**αp process:**

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

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

${}^{18}Ne+\alpha$ …

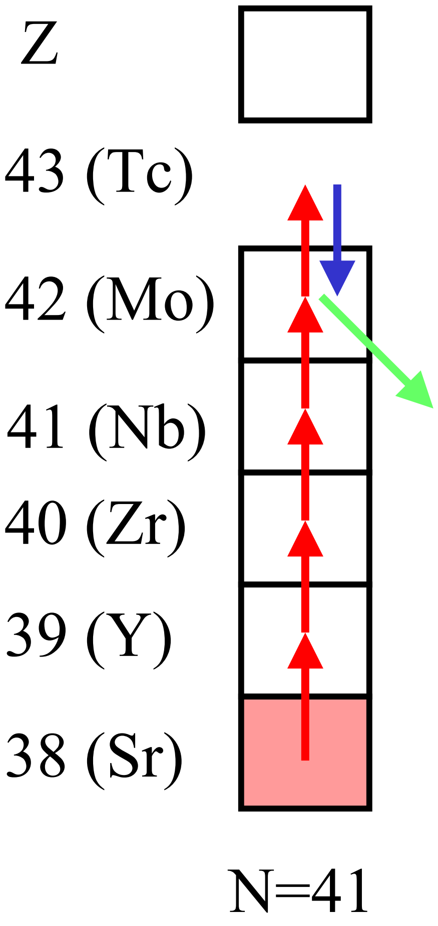
Alternating (α,p) and (p,γ) reactions:
For each proton capture there is an (α,p) reaction releasing a proton

Net effect: pure He burning

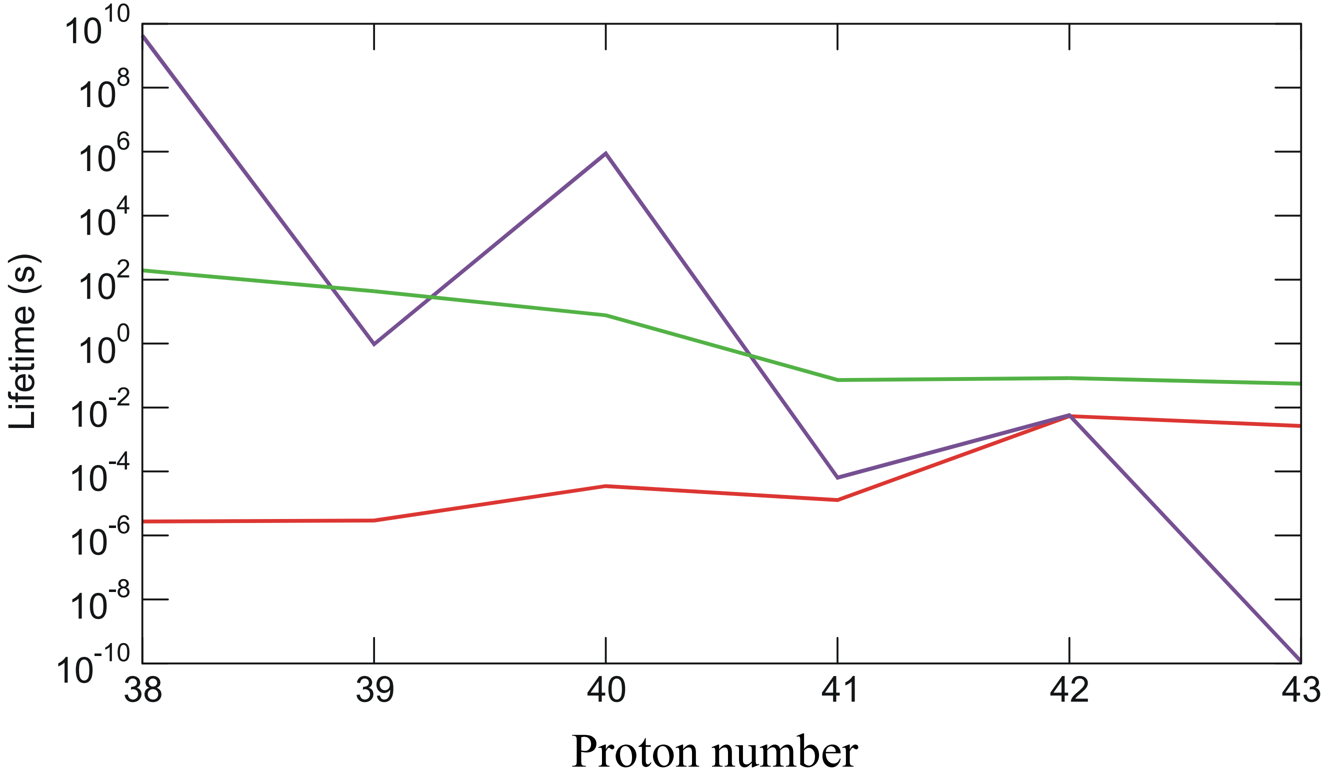
# In detail: rp process

Nuclear lifetimes: (average time between a …)

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



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

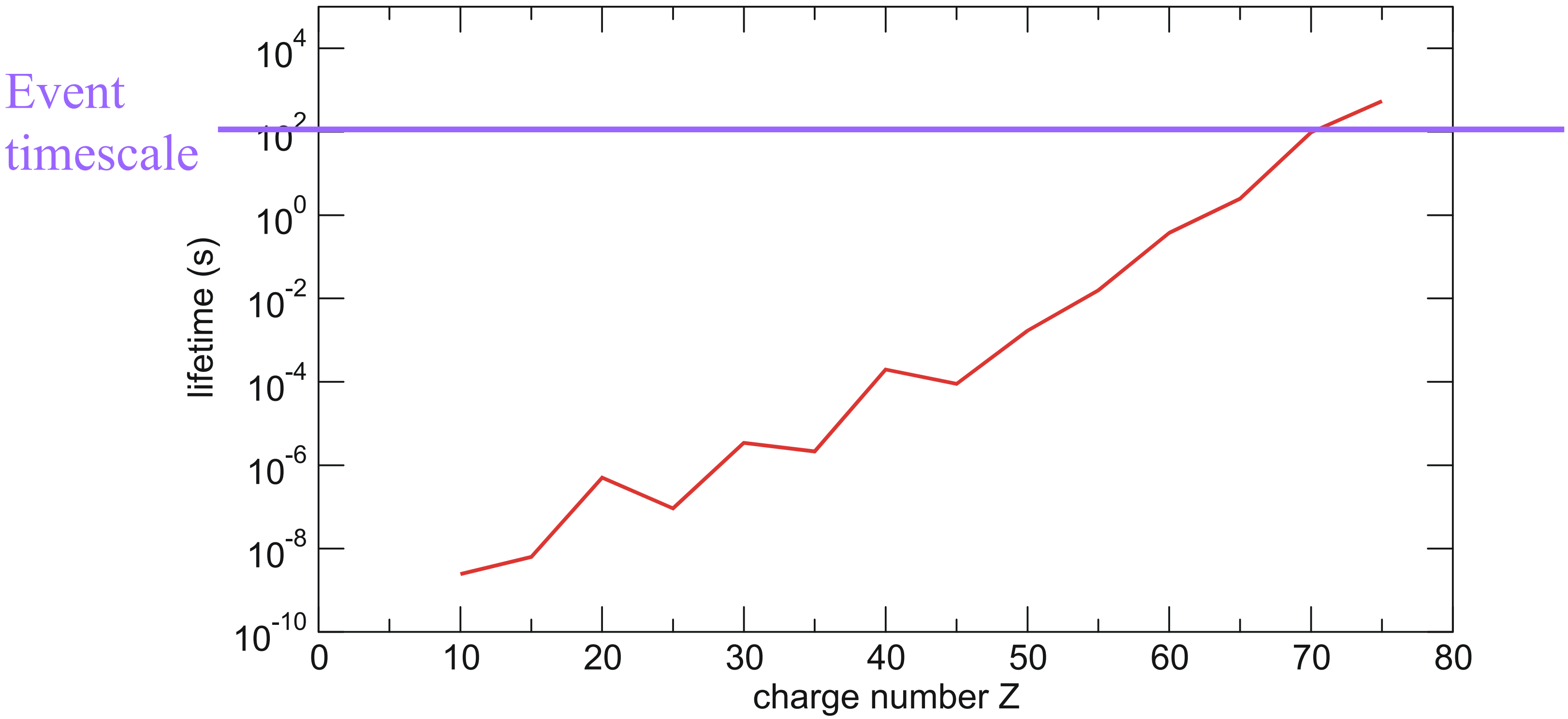


# The endpoint of the rp process

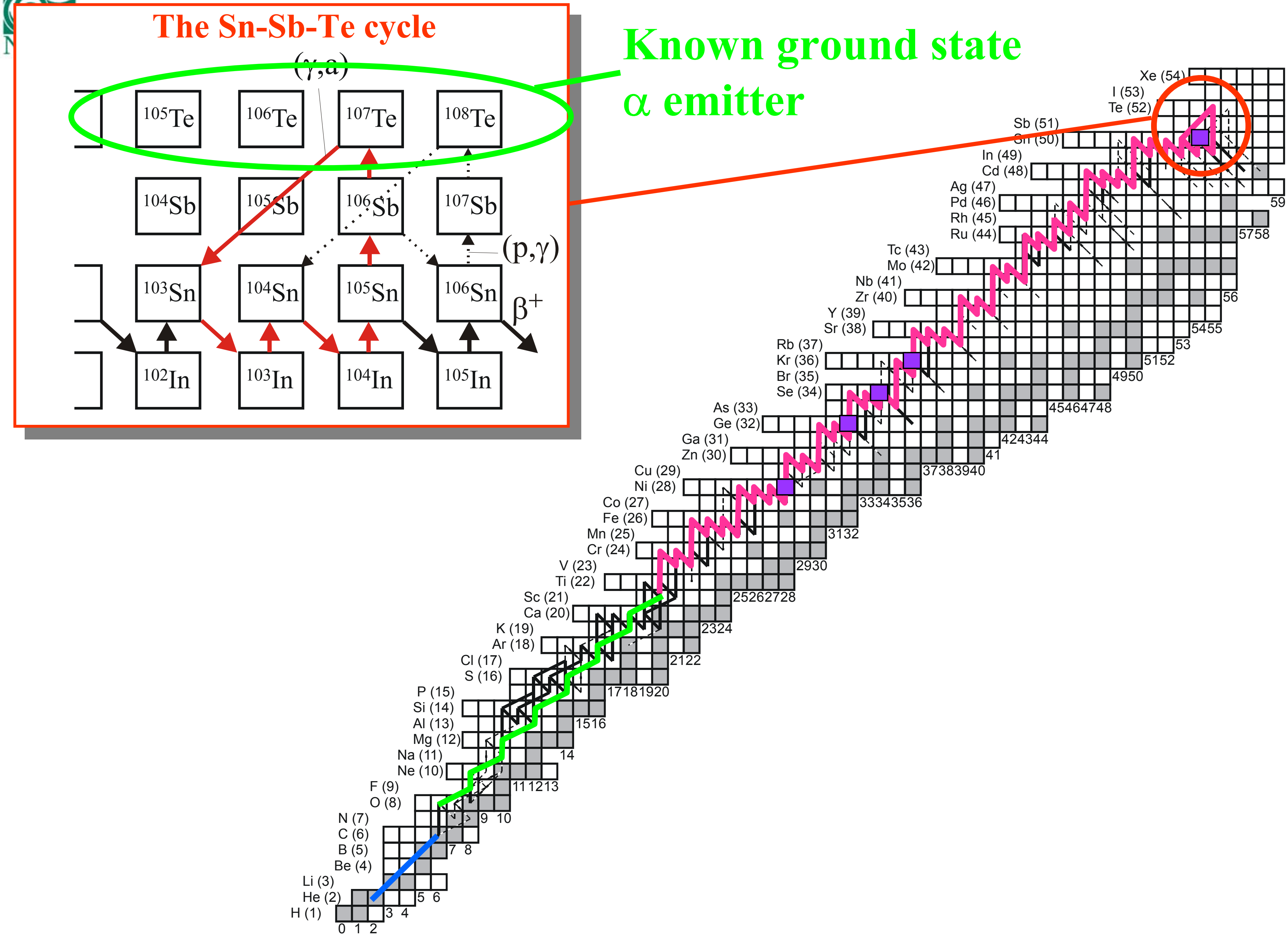
Possibilities:

- 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 -> $^{41}$Sc

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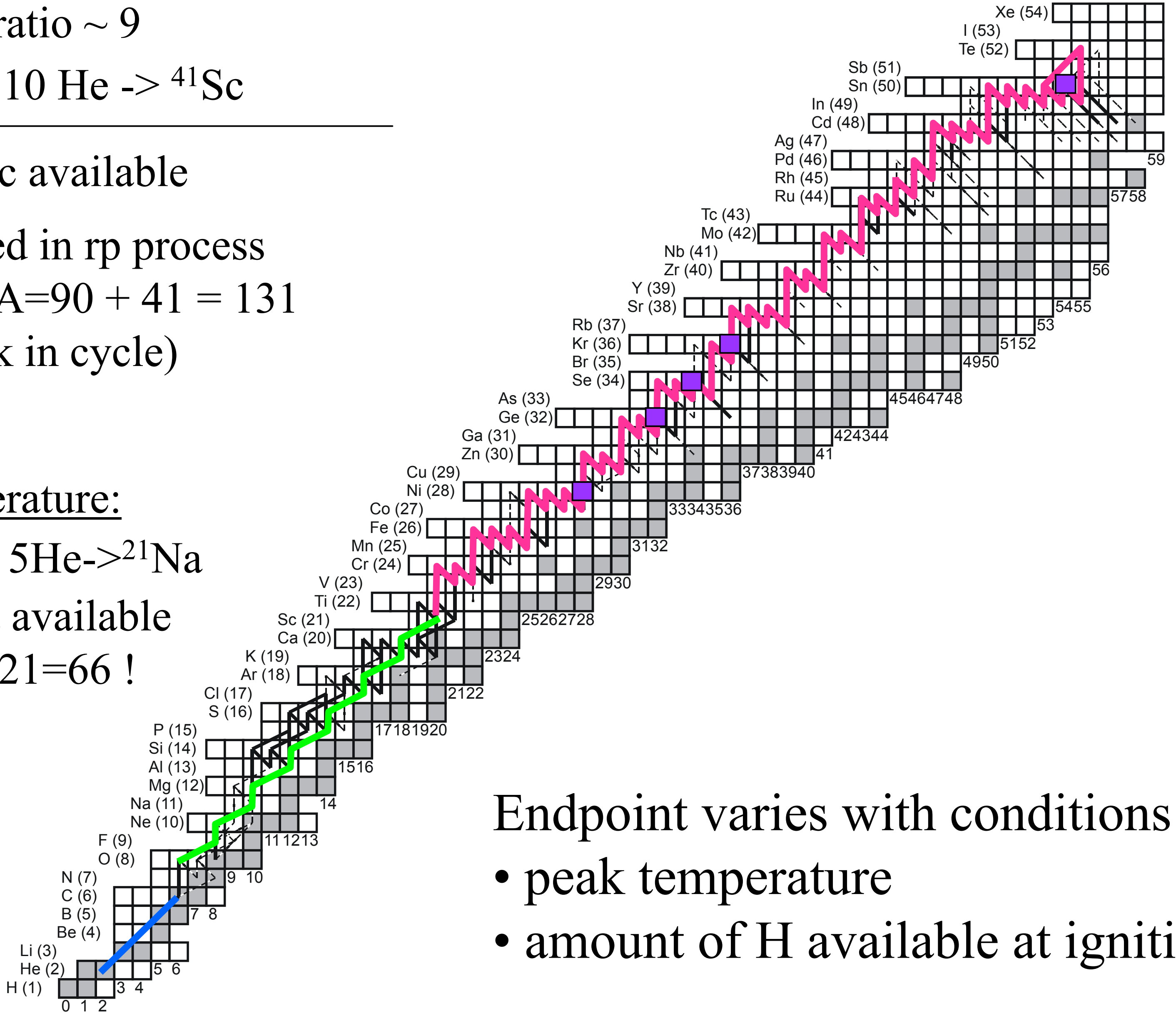
90 H per $^{41}$Sc available

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

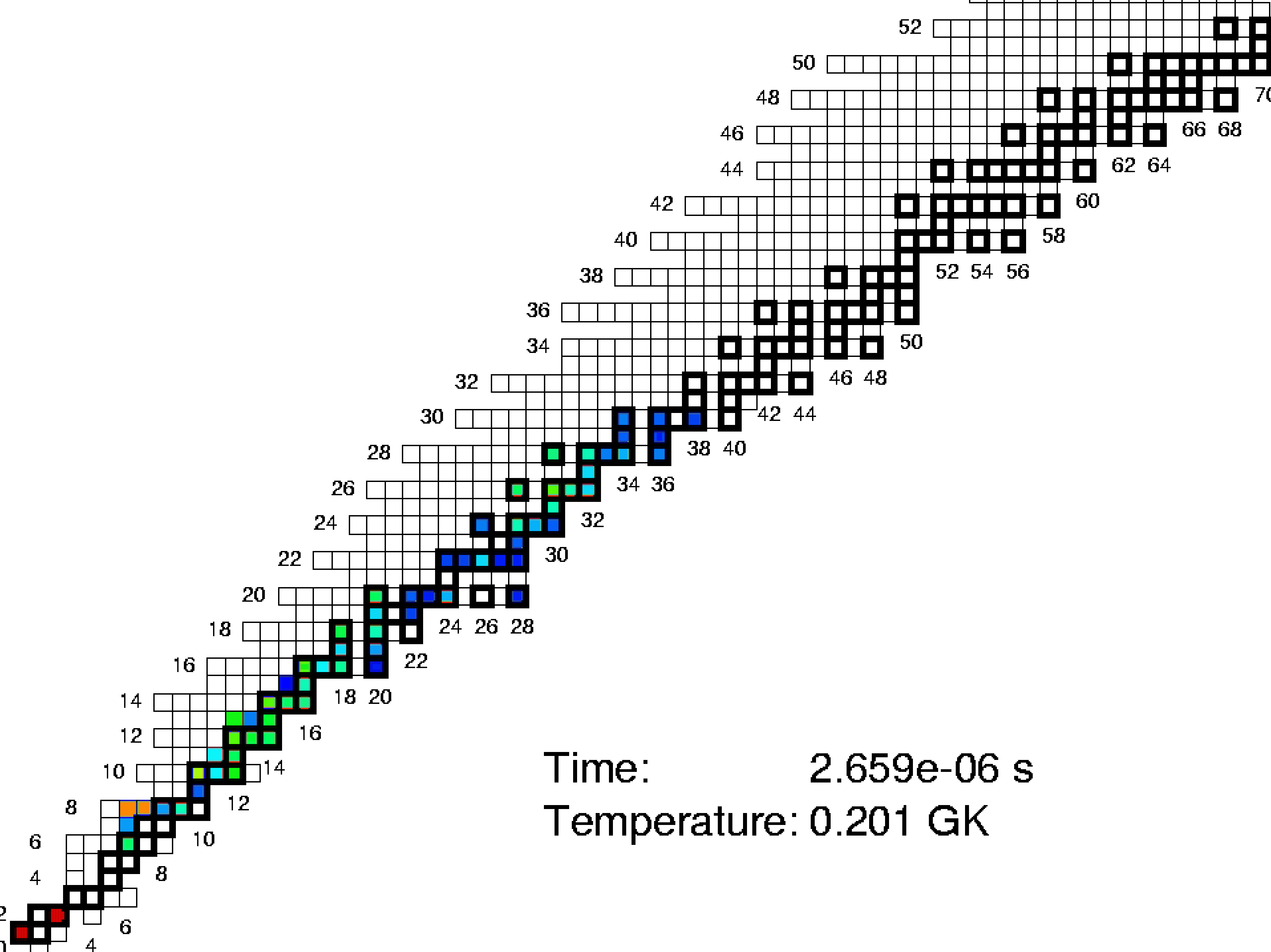


## Lower temperature:

Assume only 5He->$^{21}$Na
45H per $^{21}$Na available
reach A=45+21=66 !

Endpoint varies with conditions:
- peak temperature
- amount of H available at ignition

# Production of nuclei in the rp process – waiting points

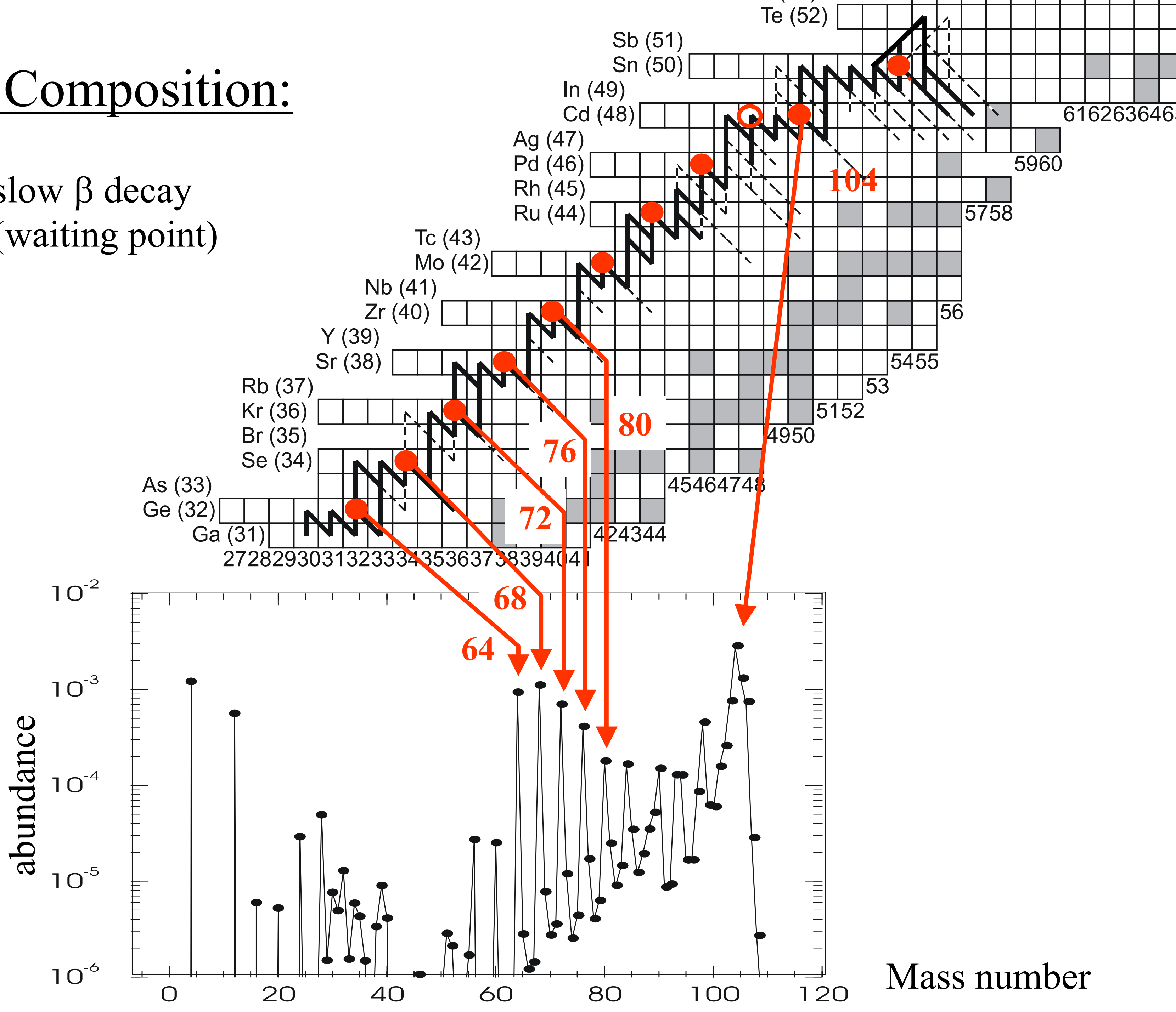


Time: 2.659e-06 s

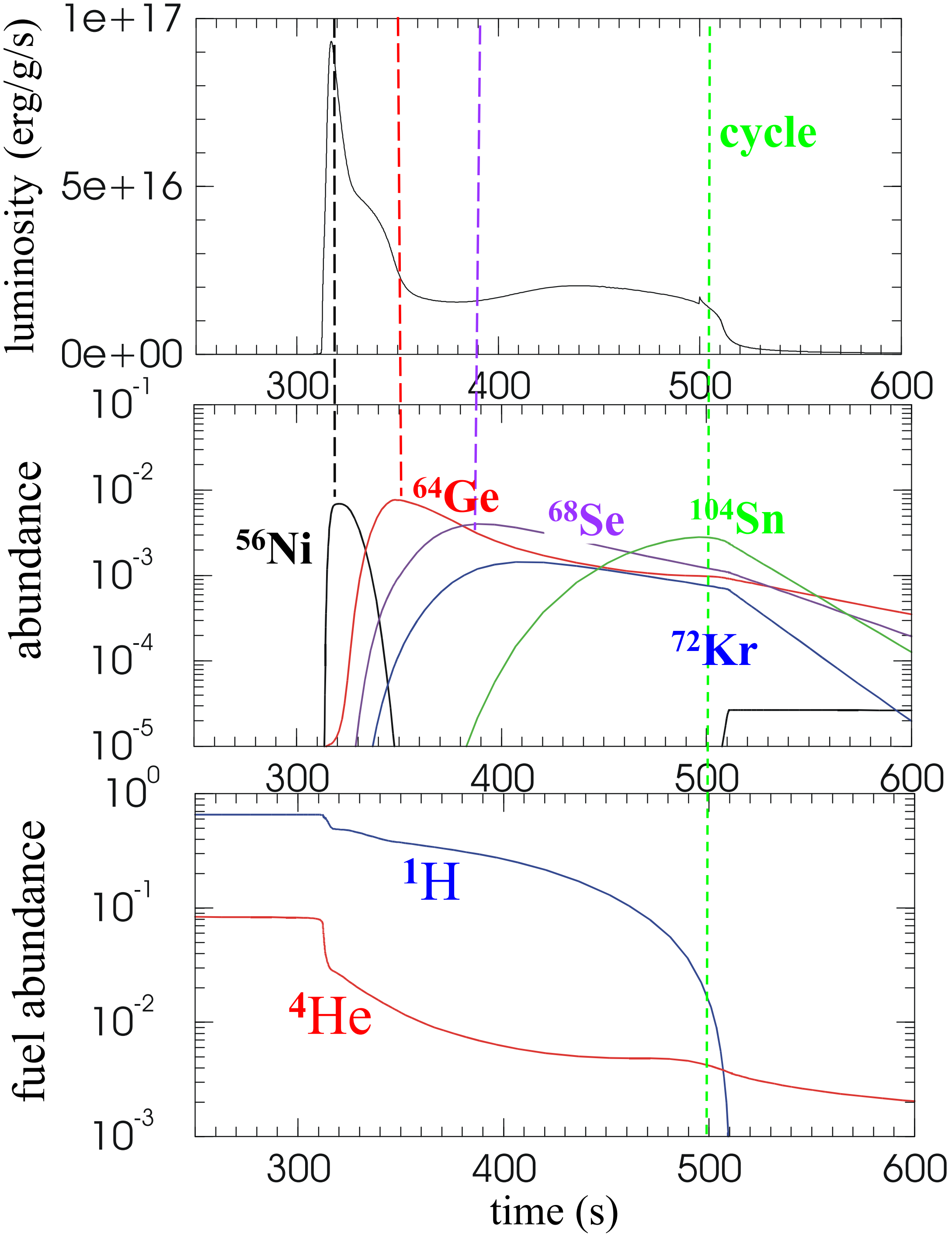
Temperature: 0.201 GK

# Final Composition:

● slow β decay
(waiting point)



# X-ray burst:



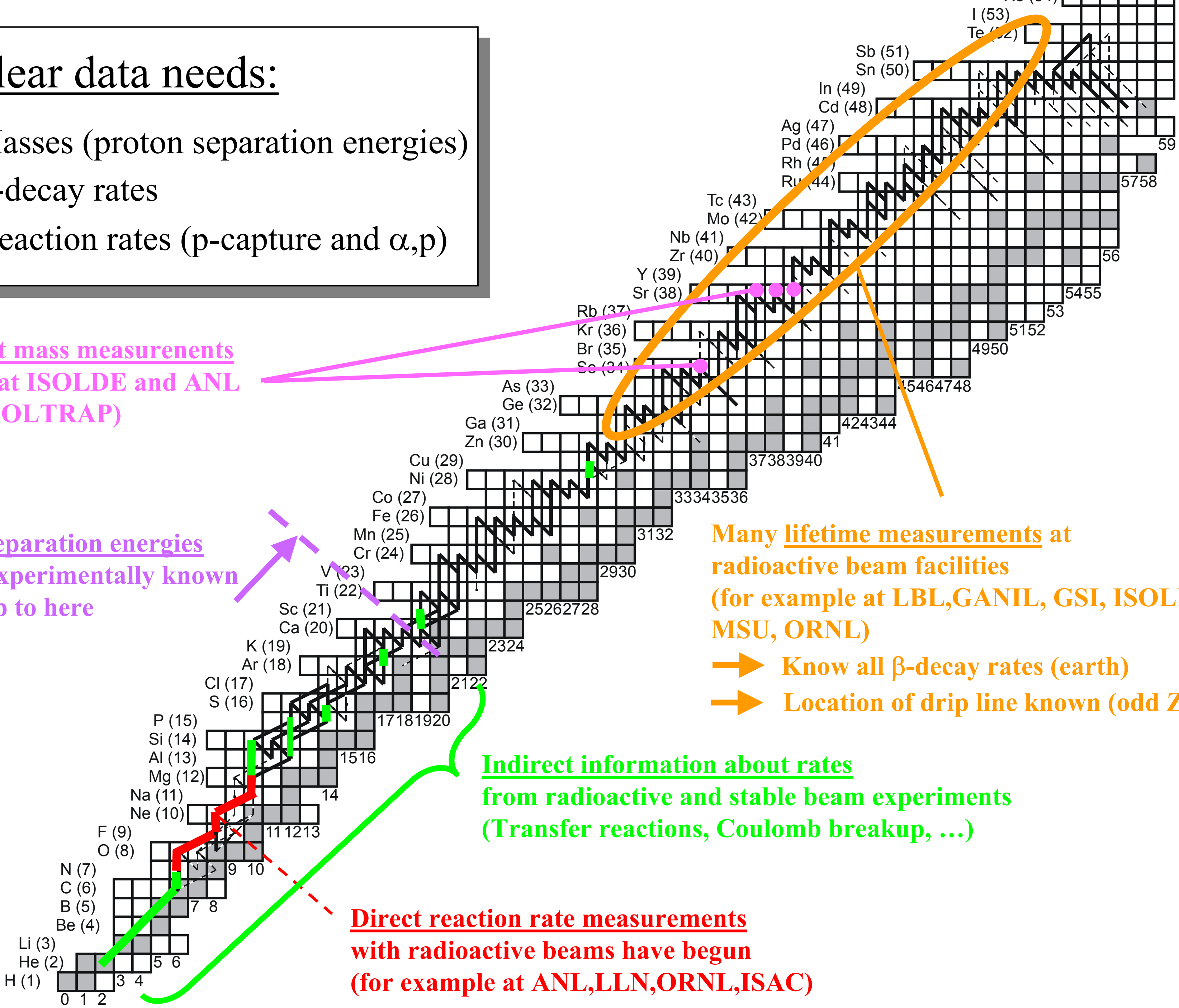
- Luminosity:

- Abundances of waiting points

- H, He abundance

# 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)