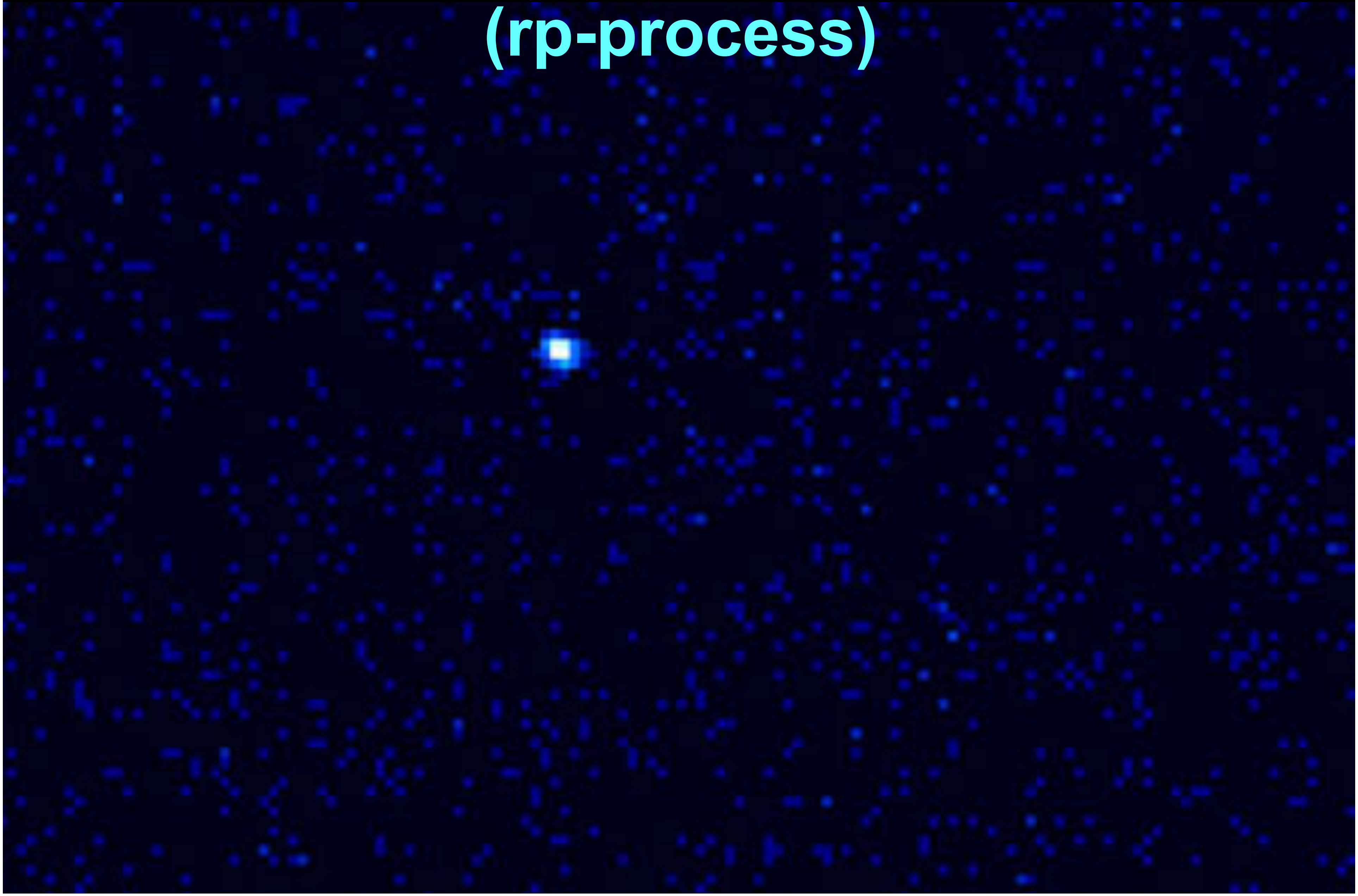
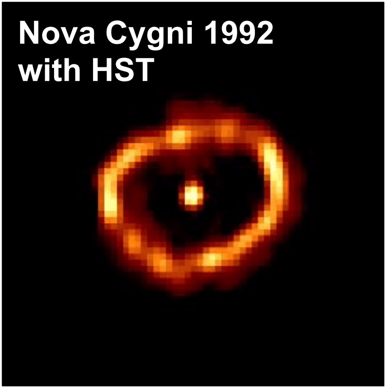
The rapid proton capture process (rp-process)



Sites of the rp-process

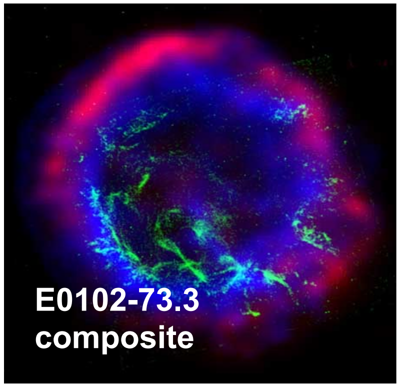
This lecture

Novae



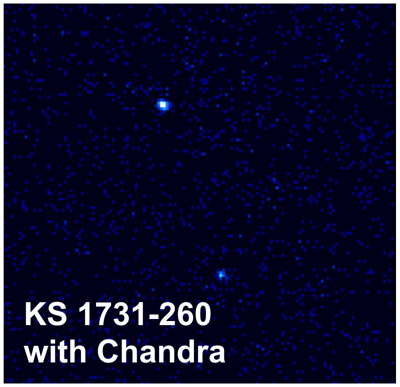
- "r"p-process (not really a full rp-process)
- makes maybe ^{26}Al

ν-wind in supernovae ?

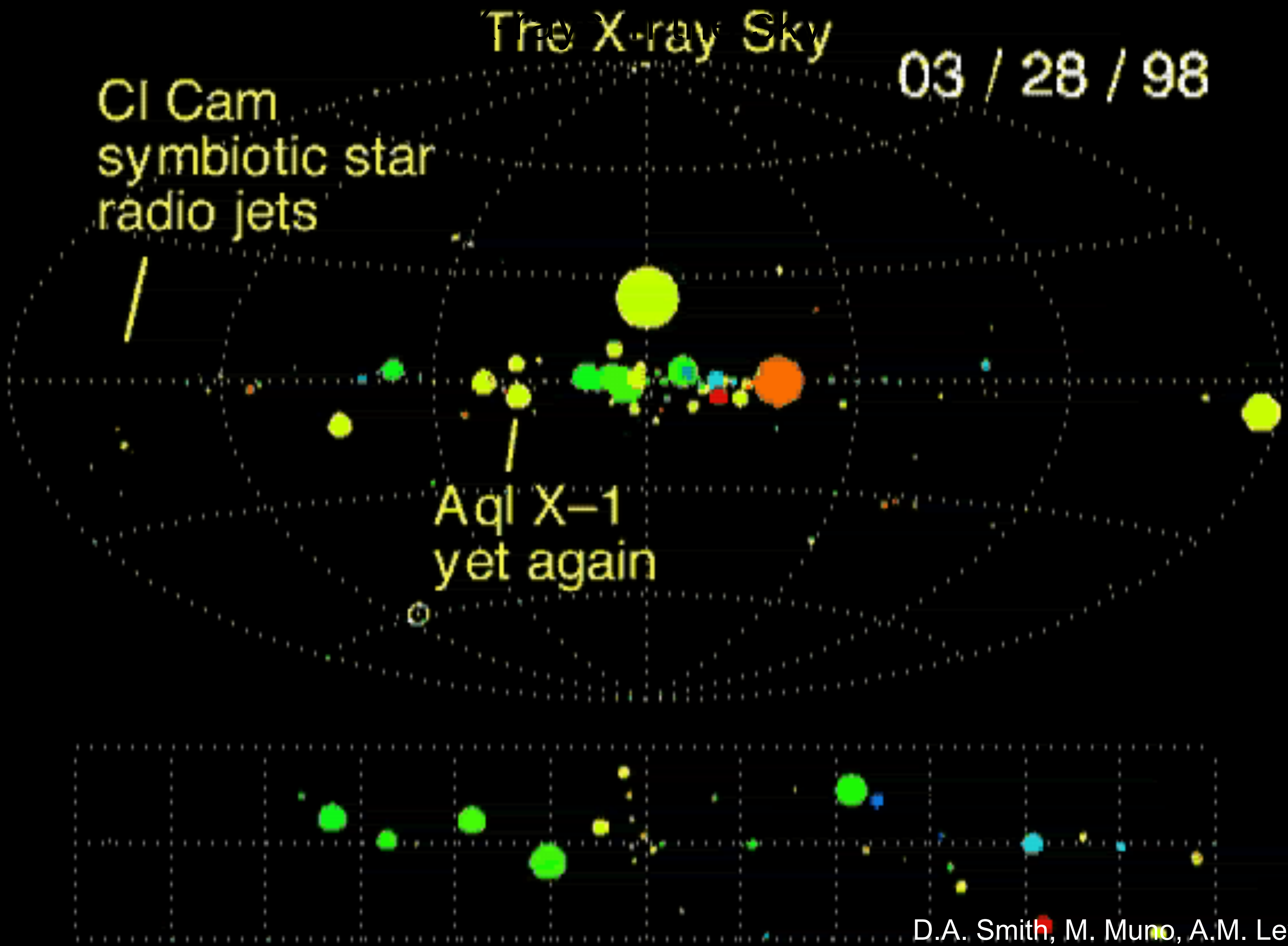


- makes maybe ^{45}Sc and ^{49}Ti
- if n accelerated (ν interactions) maybe a major nucleosynthesis process?

X-ray binaries

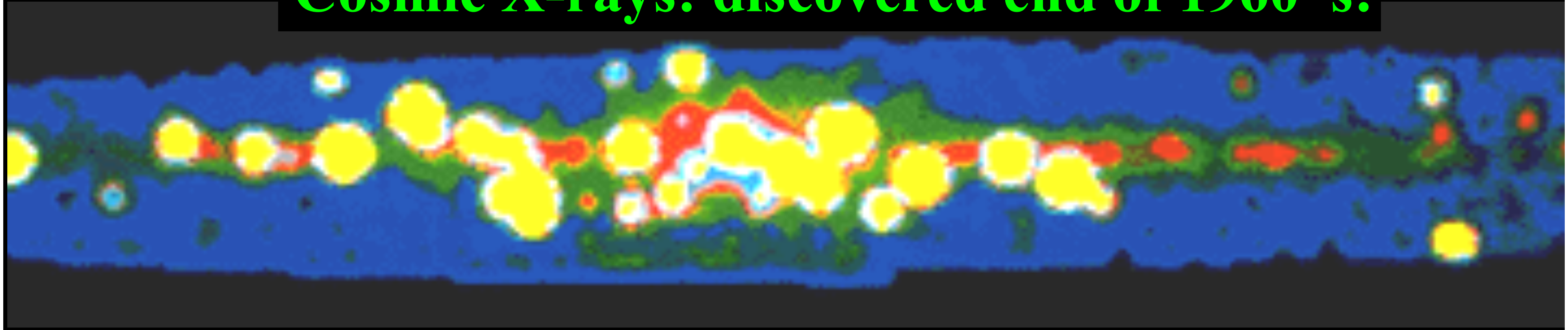


- full rp-process
- unlikely to contribute to nucleosynthesis



D.A. Smith, M. Muno, A.M. Levine,
R. Remillard, H. Bradt 2002
(RXTE All Sky Monitor)

Cosmic X-rays: discovered end of 1960's:

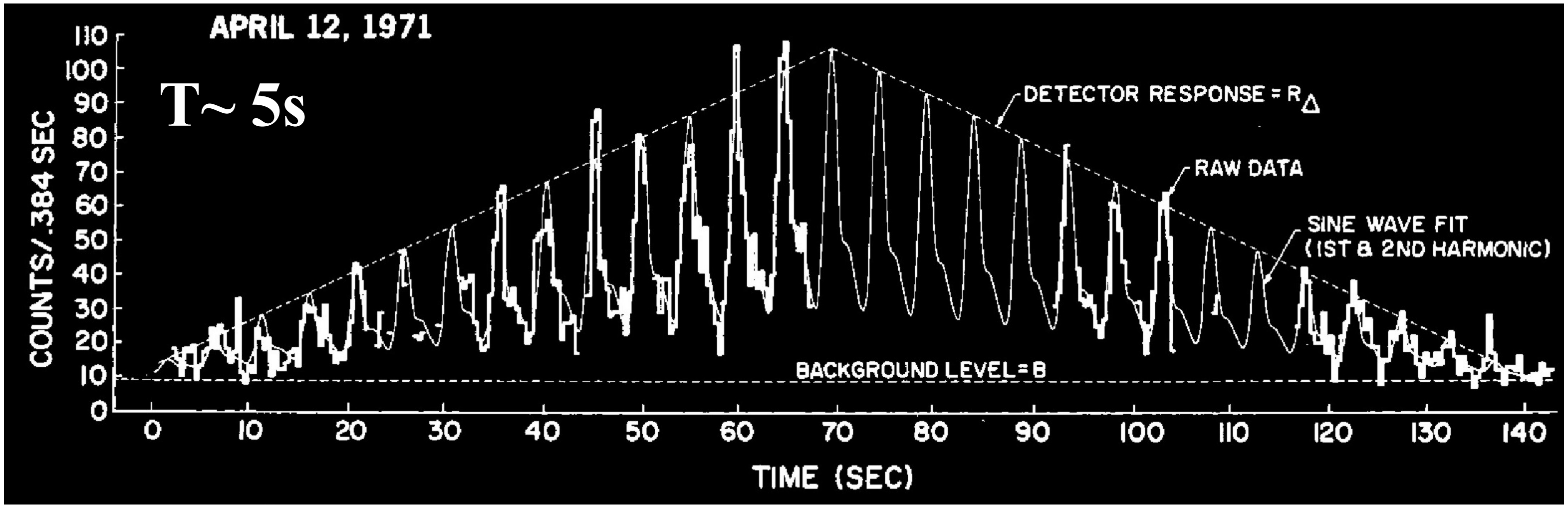


0.5-5 keV (T=E/k=6-60 x 10^6 K)

Nobel Price in Physics 2002
for Riccardo Giacconi

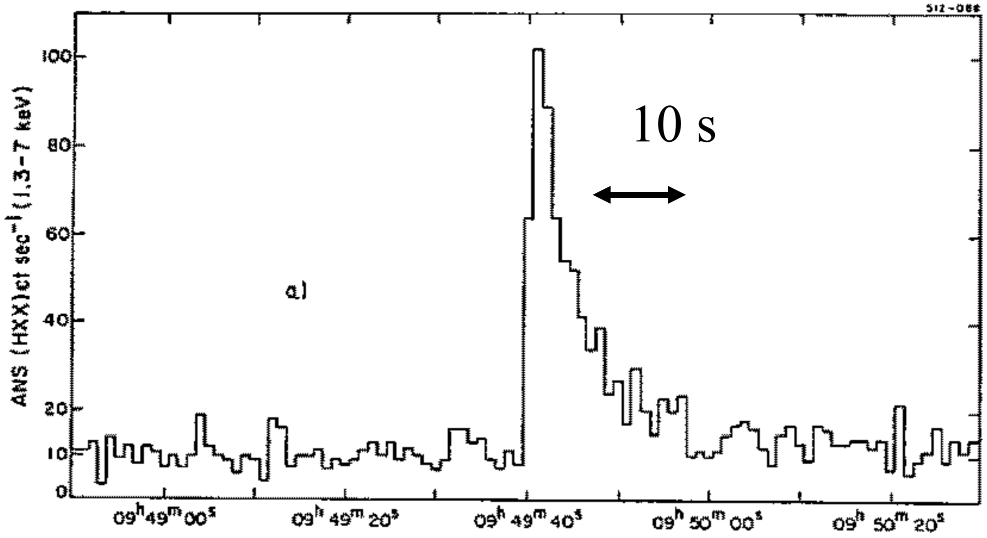
Discovery of X-ray bursts and pulsars

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:
~70 burst sources out of 160 LMXB's

Total ~230 X-ray binaries known

Burst characteristics

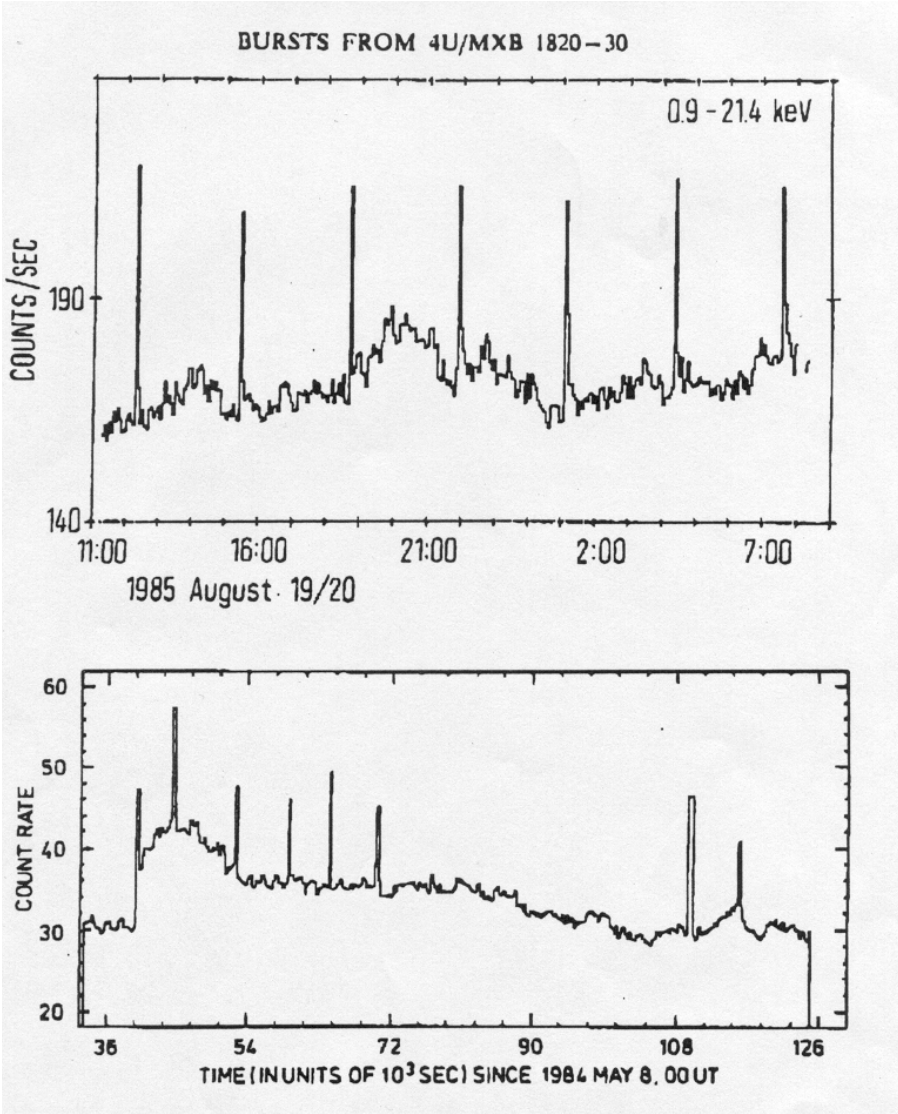


Fig. 3.14. (a) Example of a very regular burst recurrence pattern, observed for 1820–303 (from Haberl *et al.* 1987). (b) Irregular burst recurrence, observed from 1636–536 (from Sztajno *et al.* 1985).

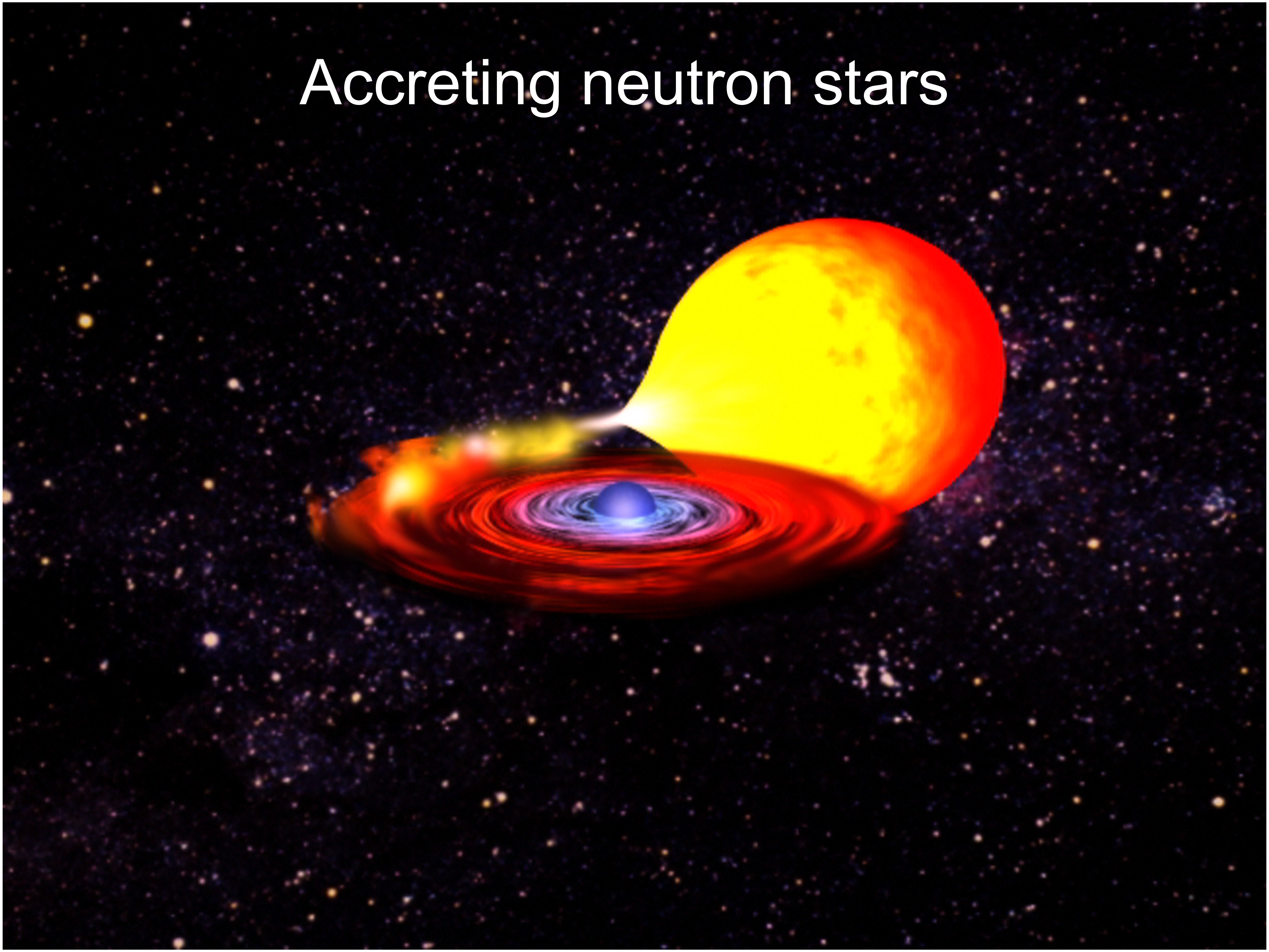
Typical X-ray bursts:

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

Frequent and very bright phenomenon !

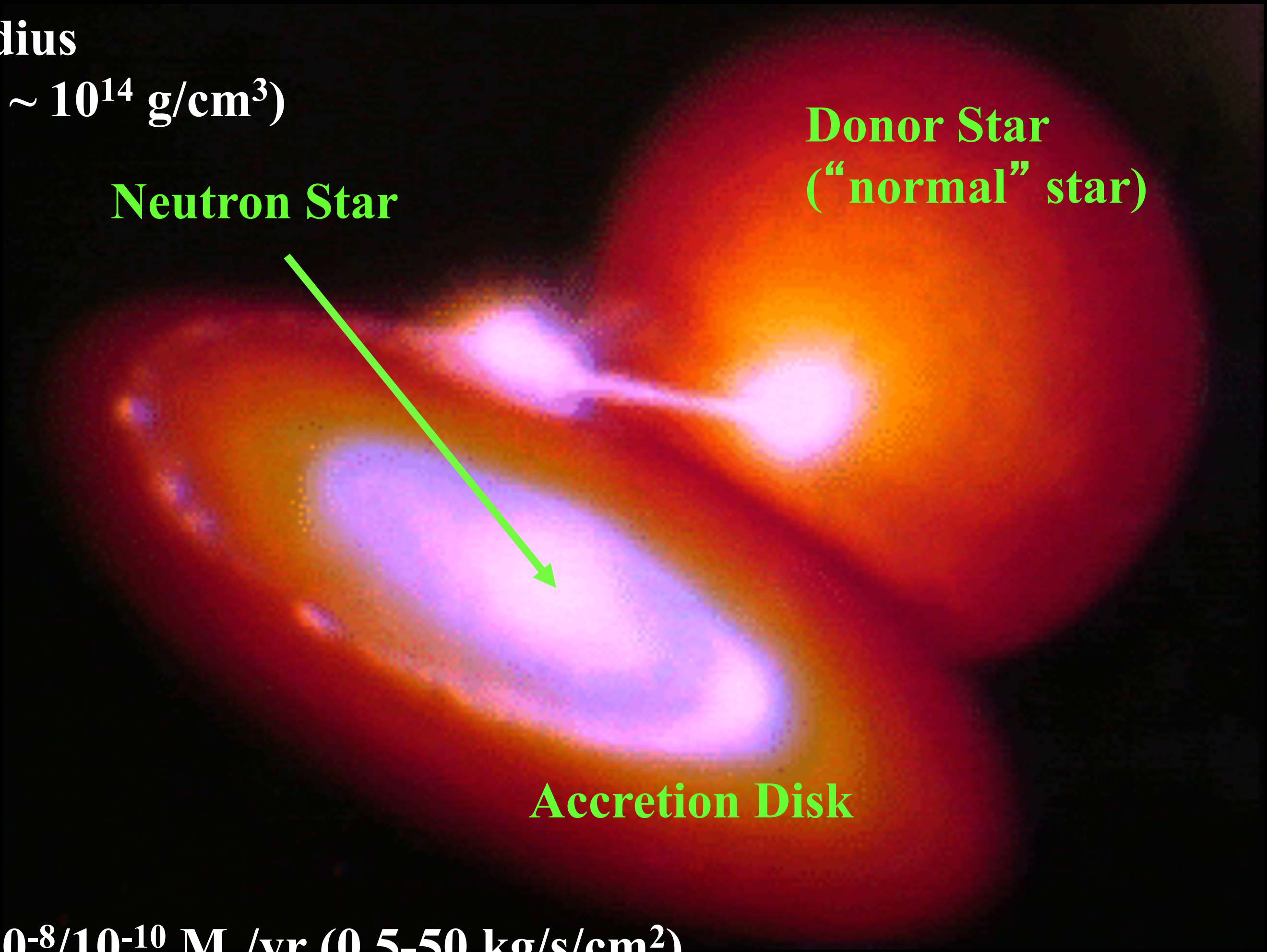
(stars 10^{33}-10^{35} erg/s)

Accreting neutron stars



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**

Energy sources

Energy generation: thermonuclear energy

$4H \longrightarrow {}^{4}He$	6.7 MeV/u	
$3\ {}^{4}He \longrightarrow {}^{12}C$	0.6 MeV/u	("triple alpha")
$5\ {}^{4}He + 84\ H \longrightarrow {}^{104}Pd$	6.9 MeV/u	(rp process)

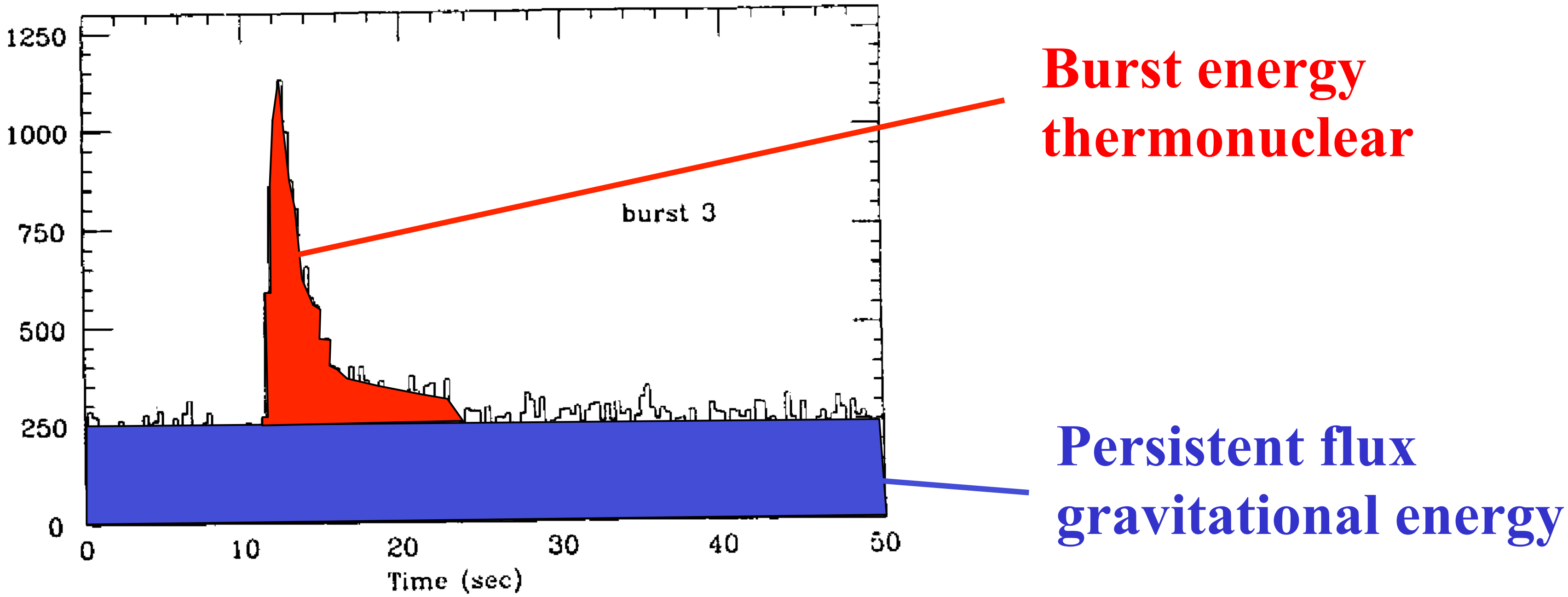
Energy generation: gravitational energy

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

Ratio gravitation/thermonuclear ~ 30 – 40 (called α)

Observation of thermonuclear energy

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



Burst energy thermonuclear

Persistent flux gravitational energy

Burst ignition

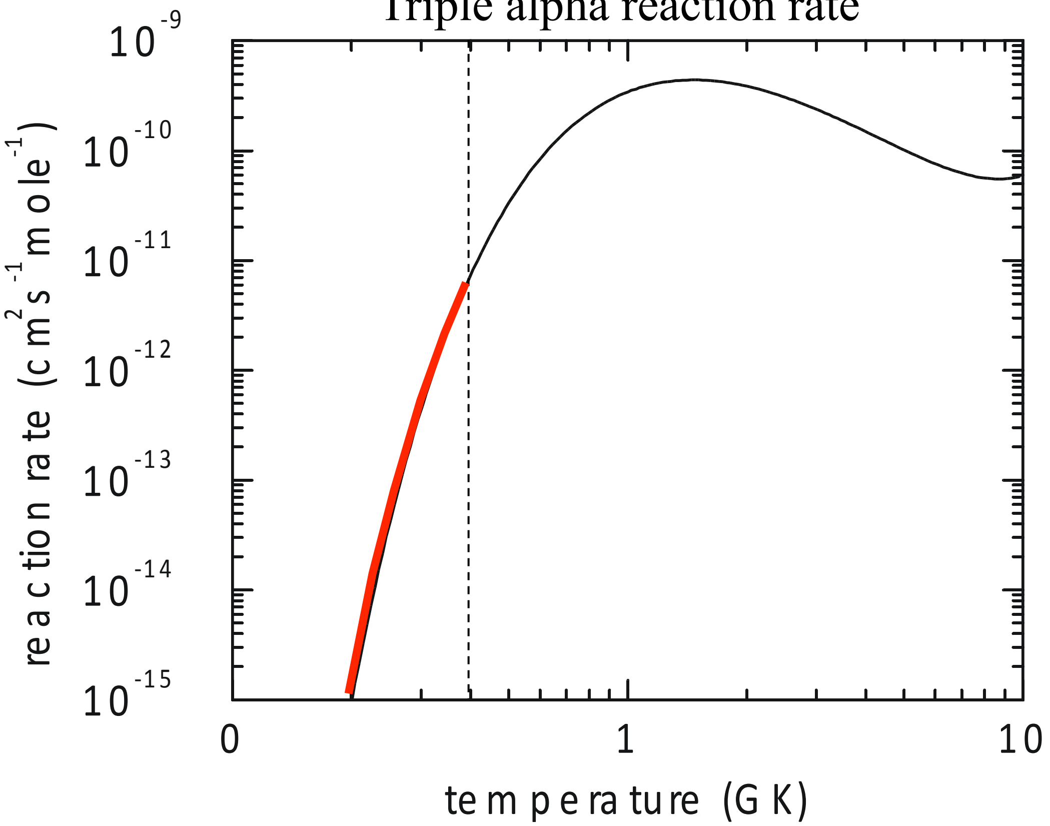
Burst trigger rate is “triple alpha reaction” $3\ {}^4\mathrm{He} \longrightarrow {}^{12}\mathrm{C}$

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

ε_{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
ε_{nuc} that increases T …)

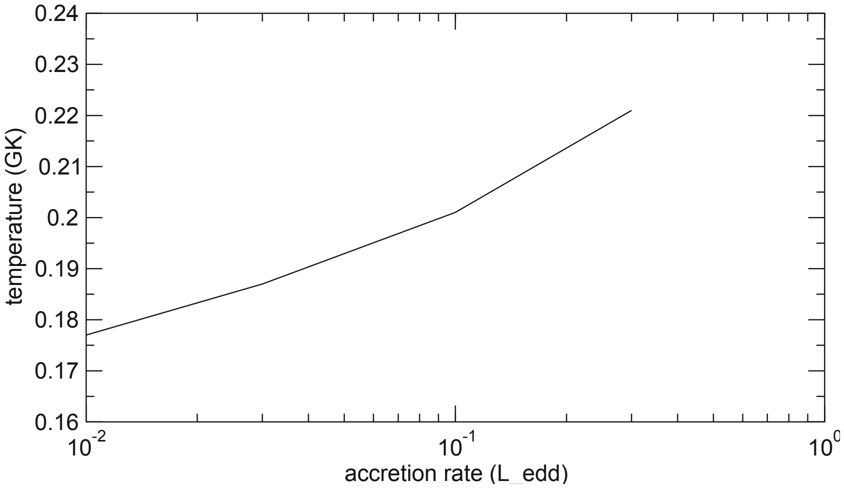
degenerate e-gas helps !

BUT: energy release dominated by subsequent reactions !

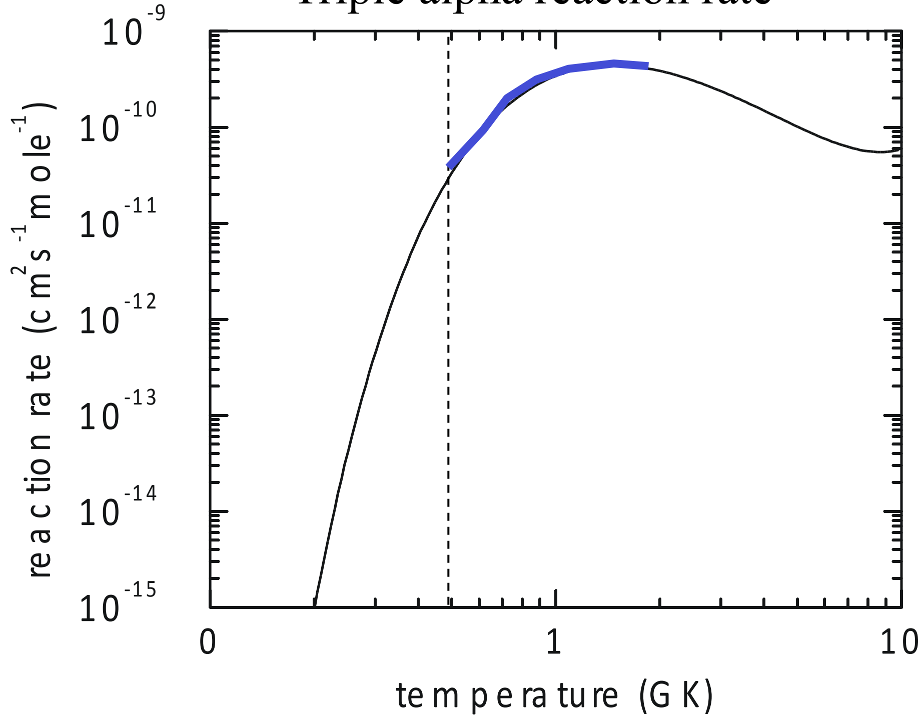
At large (local) accretion rates

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

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



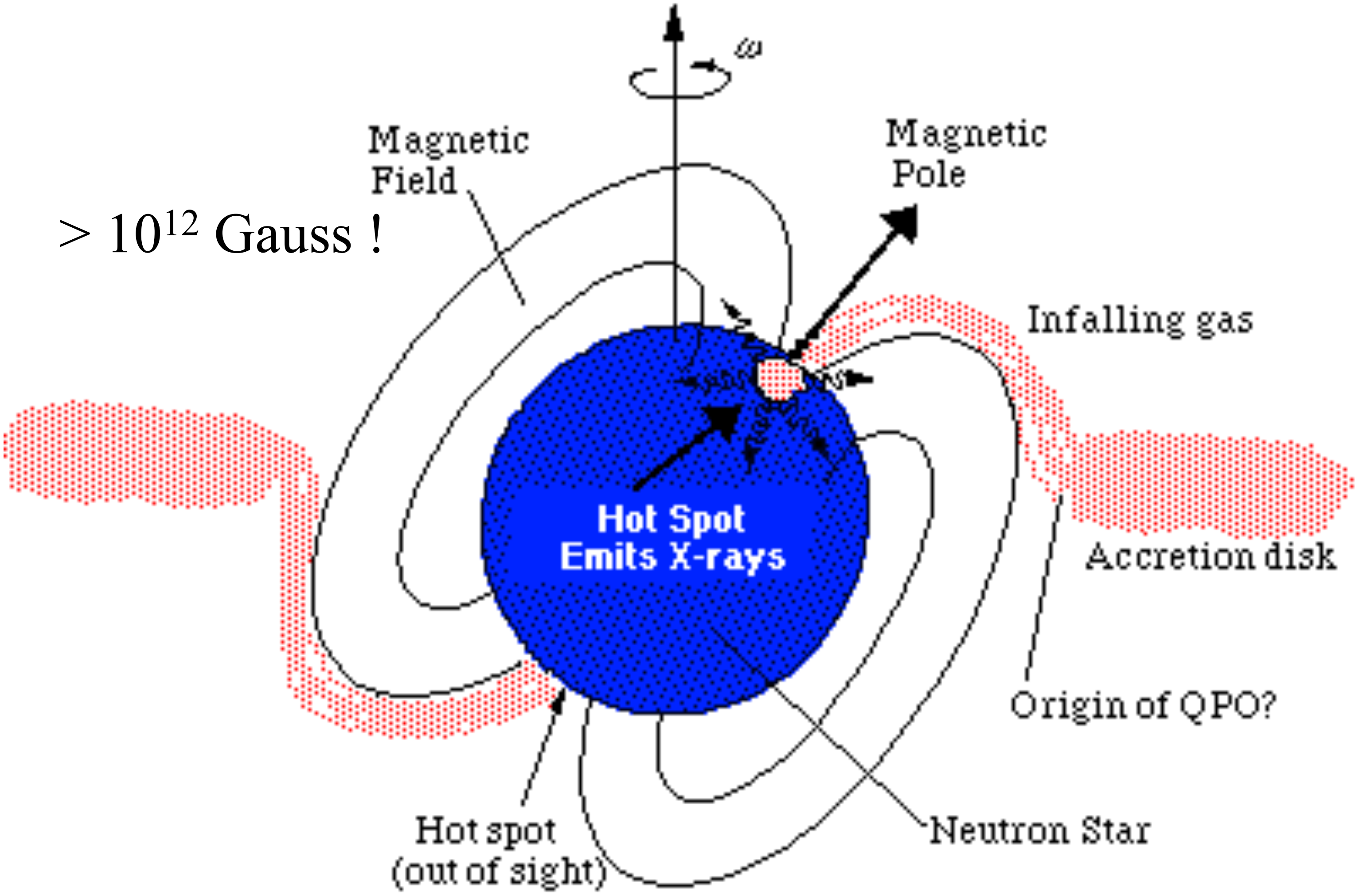
Triple alpha reaction rate



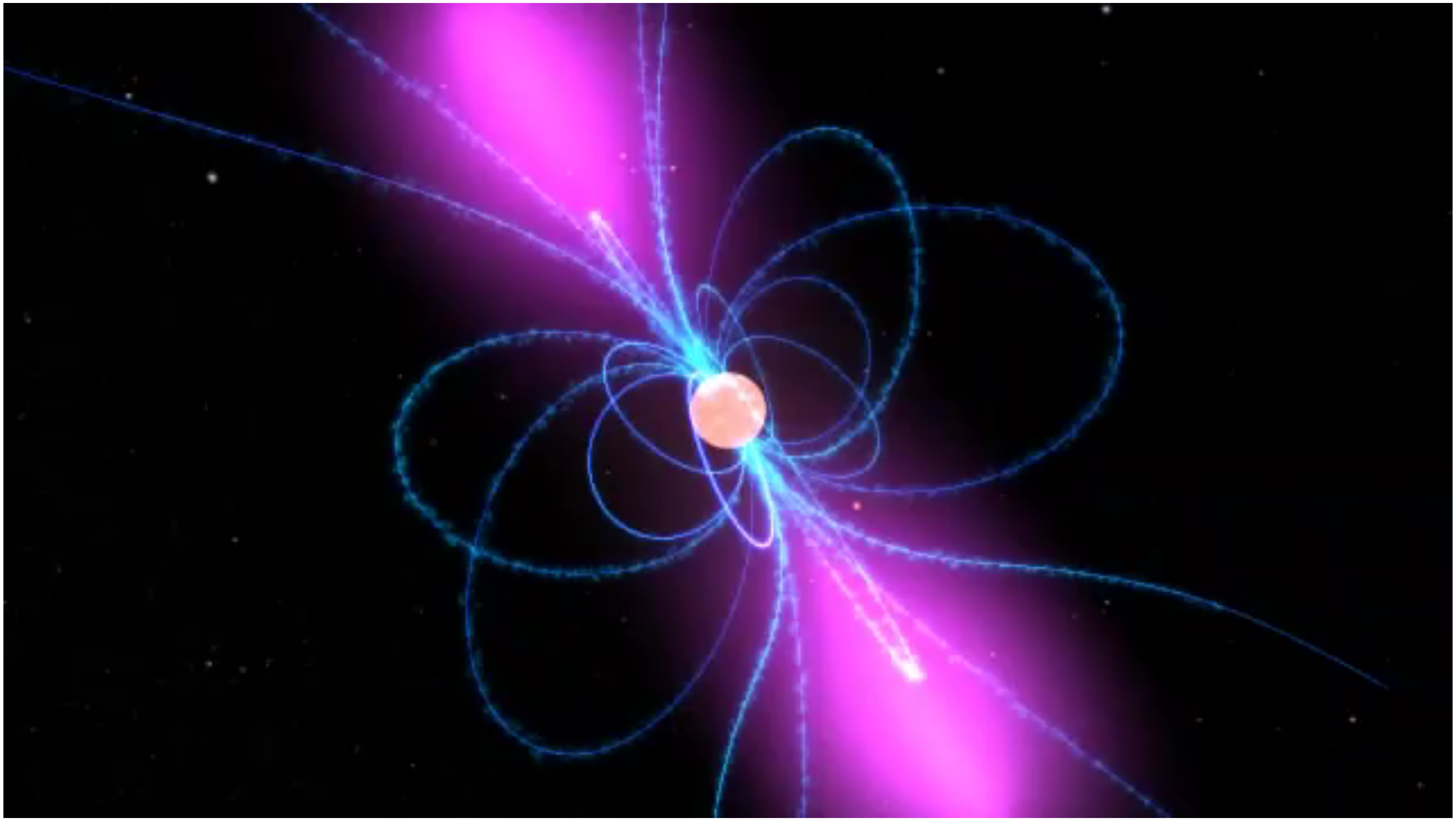
Stable nuclear burning

X-ray pulsar

> 10^{12} Gauss !



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

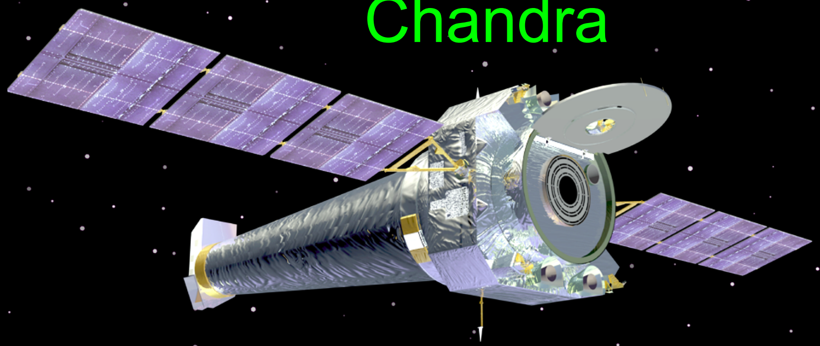


http://www.gsfc.nasa.gov/topstory/2003/0702pulsarspeed.html http://www.gsfc.nasa.gov/topstory/2003/0702pulsarspeed.html

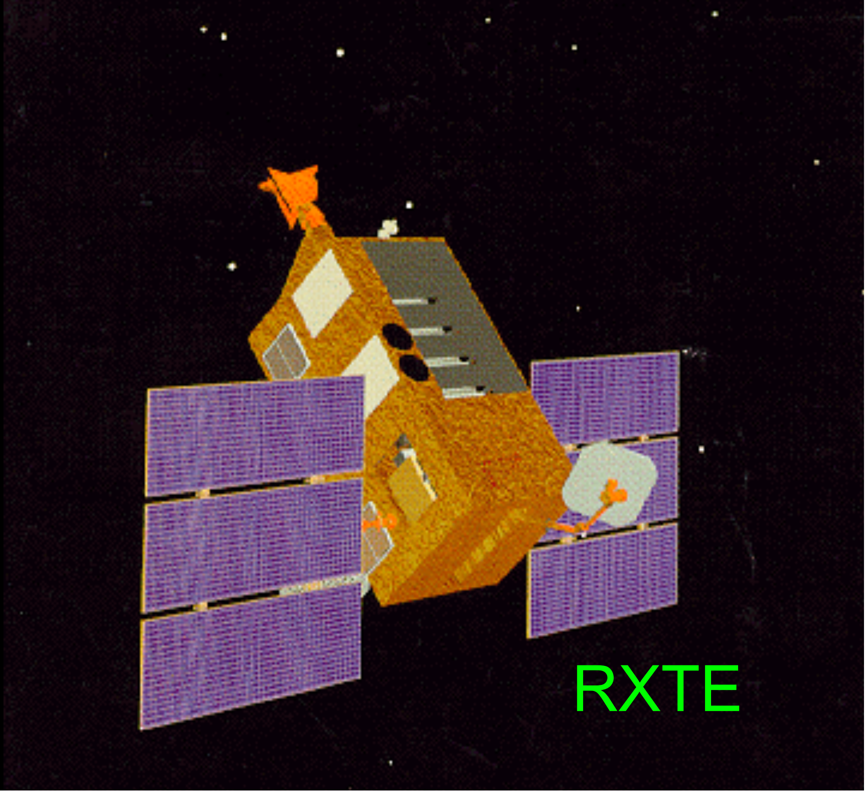
Golden Age for X-ray Astronomy ?

Constellation X

XMM Newton



Chandra

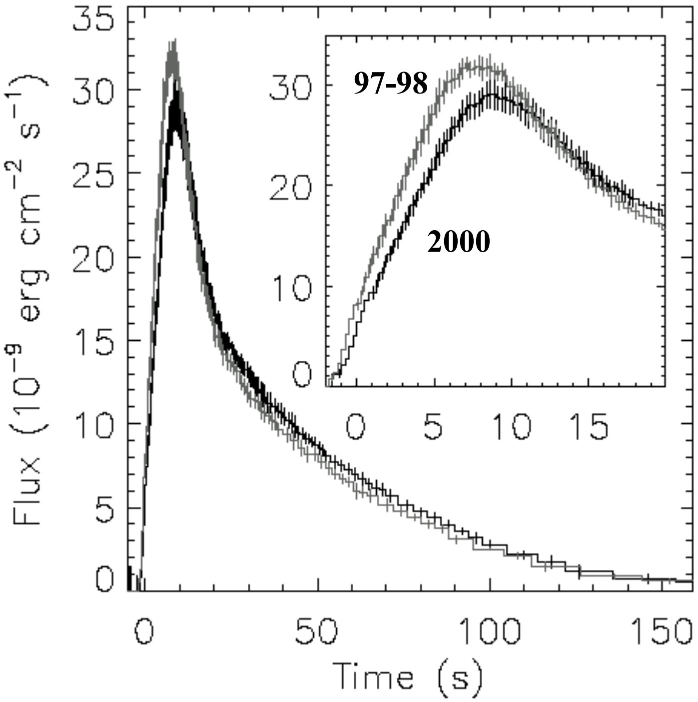


RXTE

New era of precision astrophysics

Precision X-ray observations

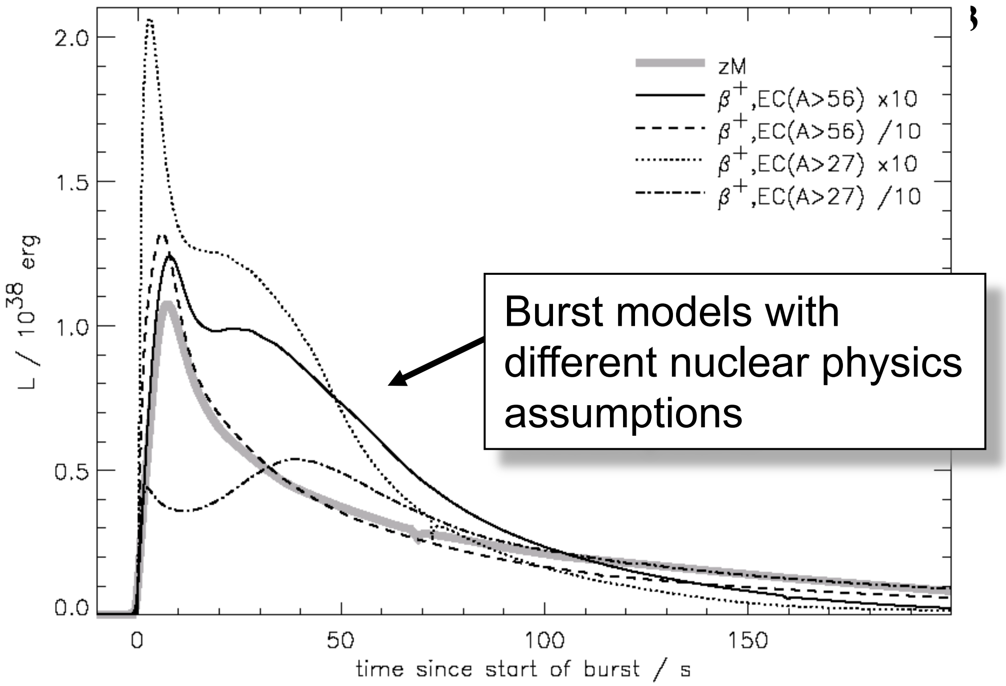
(NASA’s RXTE)



→ GS 1826-24 burst shape changes !

(Galloway 2003 astro/ph 0308122)

Uncertain models due to nuclear physics



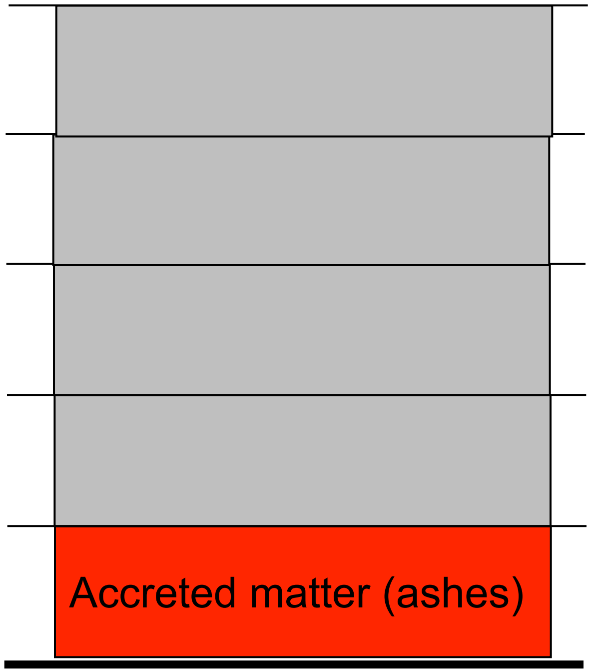
Burst models with different nuclear physics assumptions

Woosley et al. 2003 astro/ph 0307425

But only with precision nuclear physics

Fate of matter accreted onto a neutron star

accretion rate: ~10 kg/s/cm^2



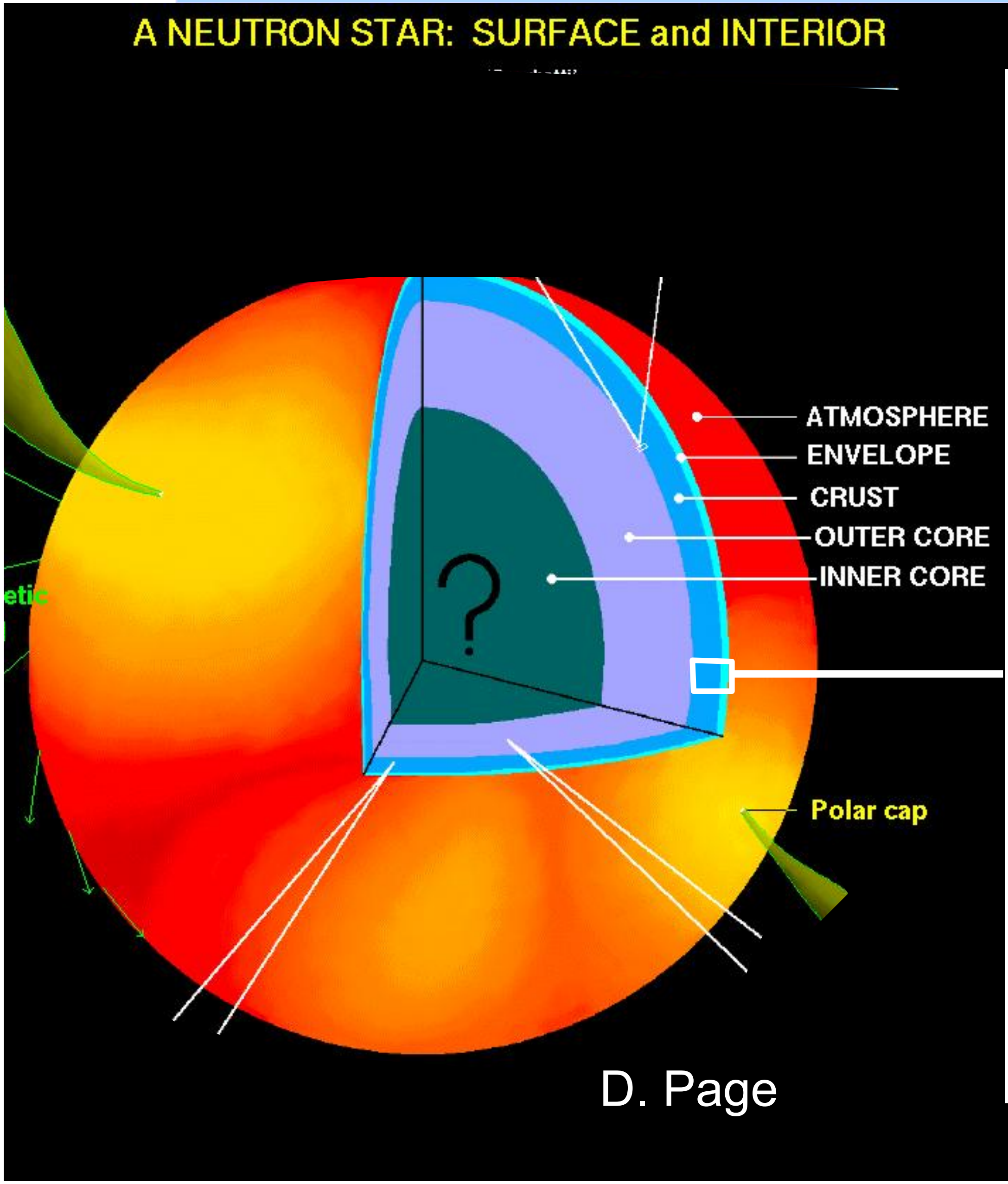
Neutron star surface

Accreted matter (ashes)

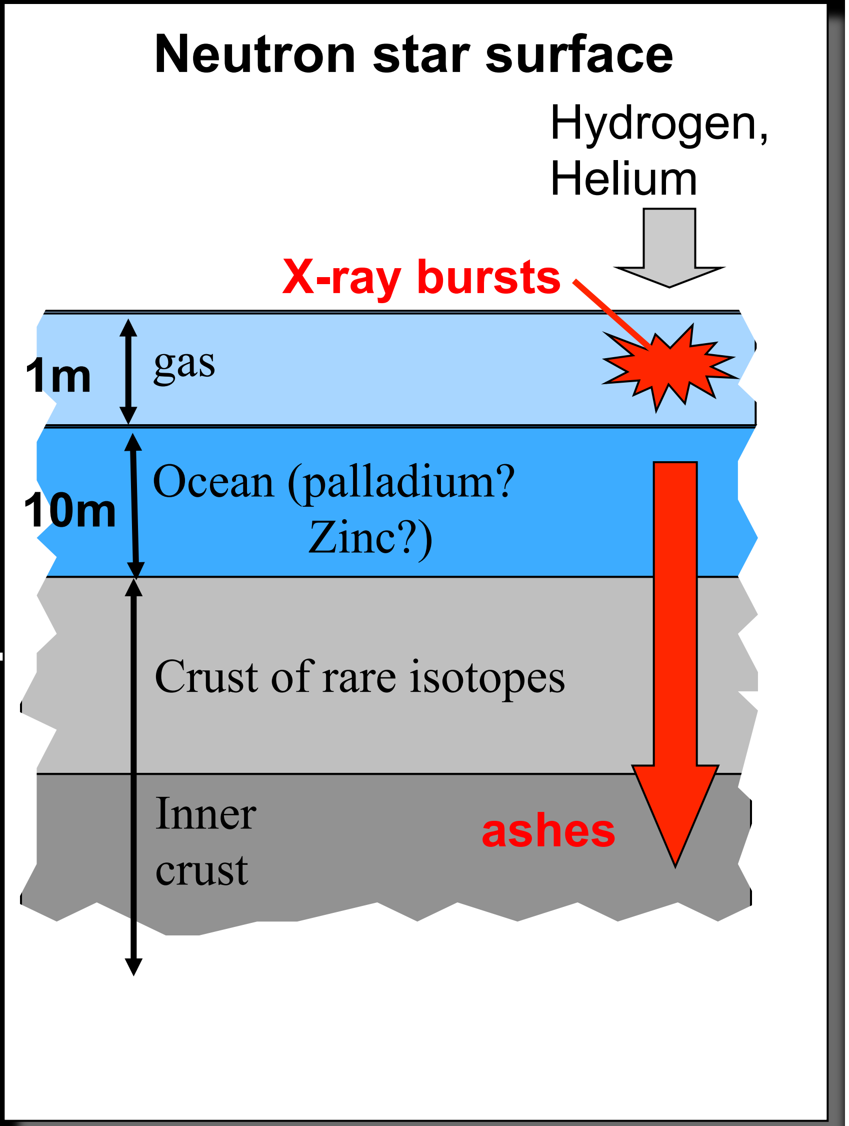
→ Accreted matter is incorporated deeper into the neutron star

→ As the density increases interesting things happen

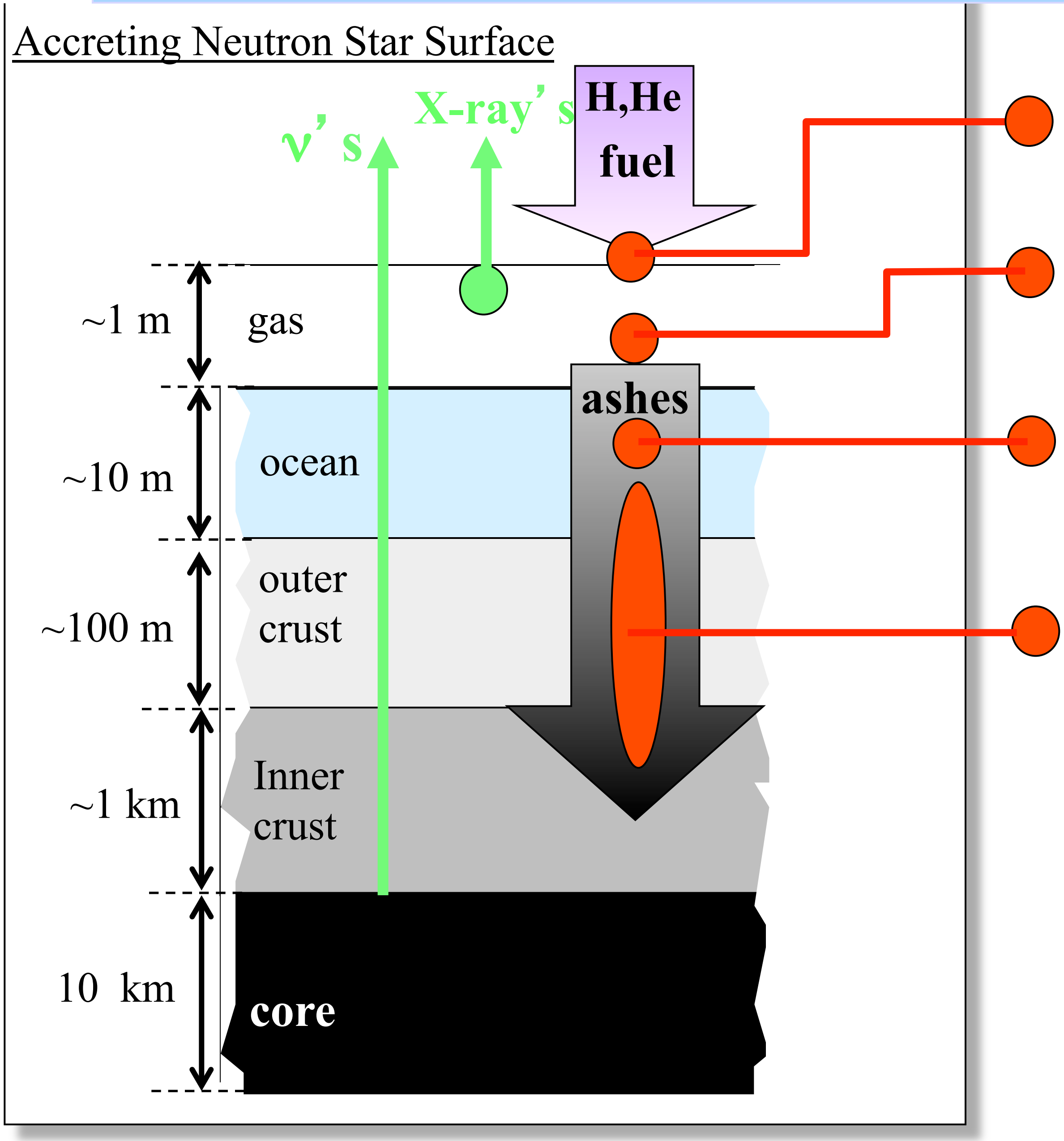
Surface of accreting neutron stars



D. Page



Nuclear physics overview


Accreting Neutron Star Surface

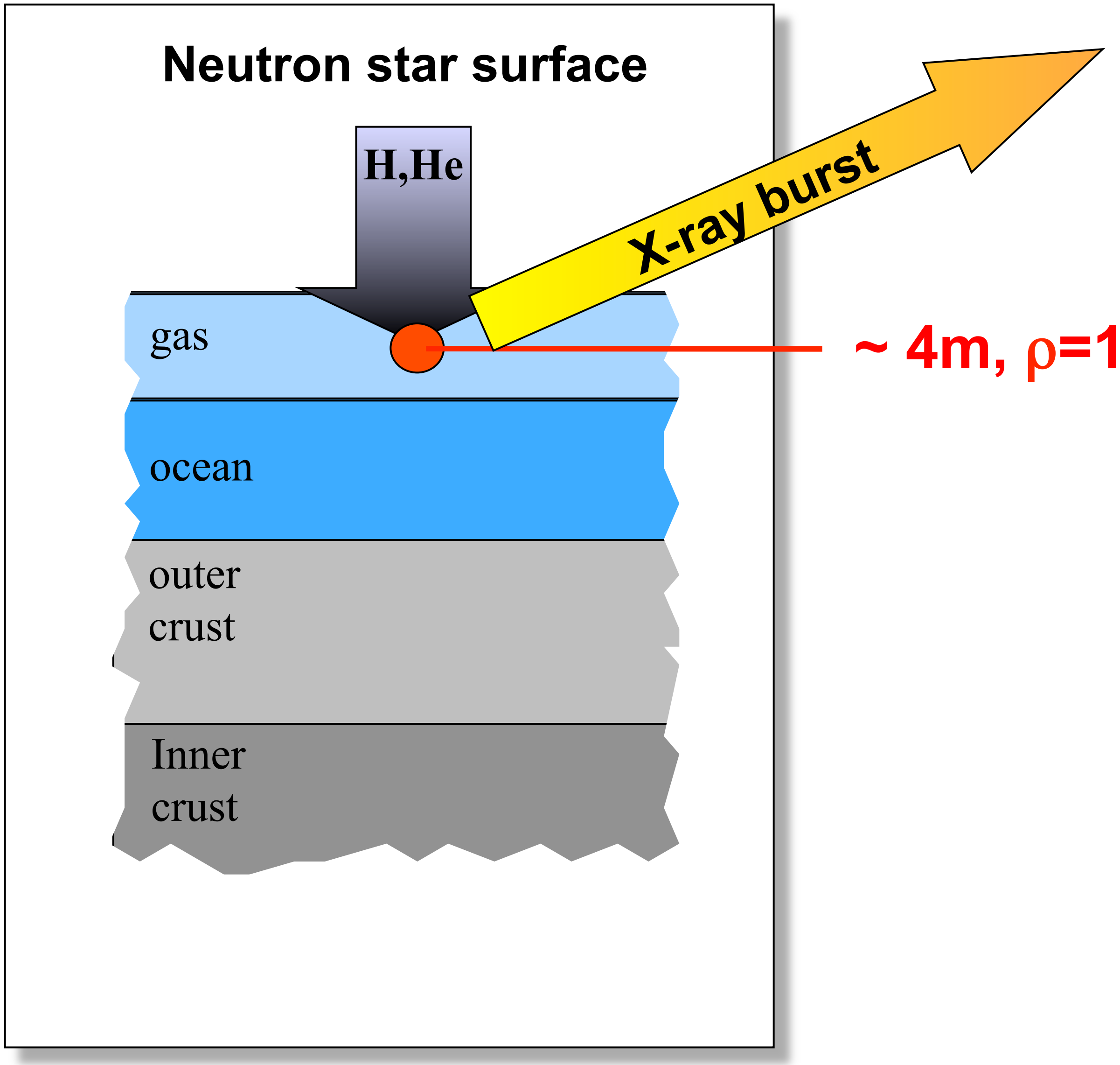
Spallation of heavy nuclei ?

Thermonuclear H+He burning
(rp process) → X-ray bursts

Deep burning ?
→ superbursts

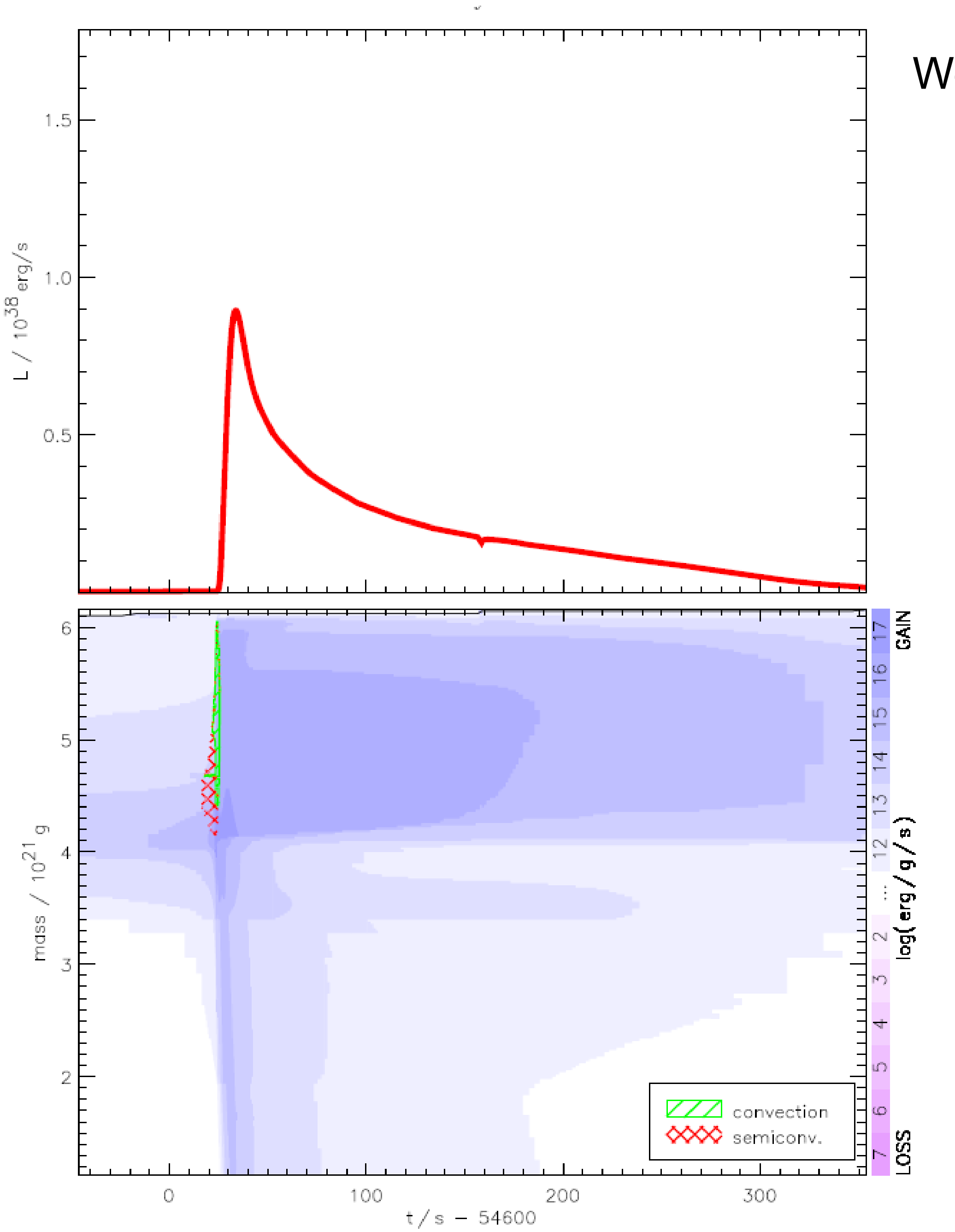
Crust processes
(EC, pycnonuclear fusion)
→crust heating
→crust conductivity

Step 1: Thermonuclear burning in atmosphere



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

Woosley et al. 2003

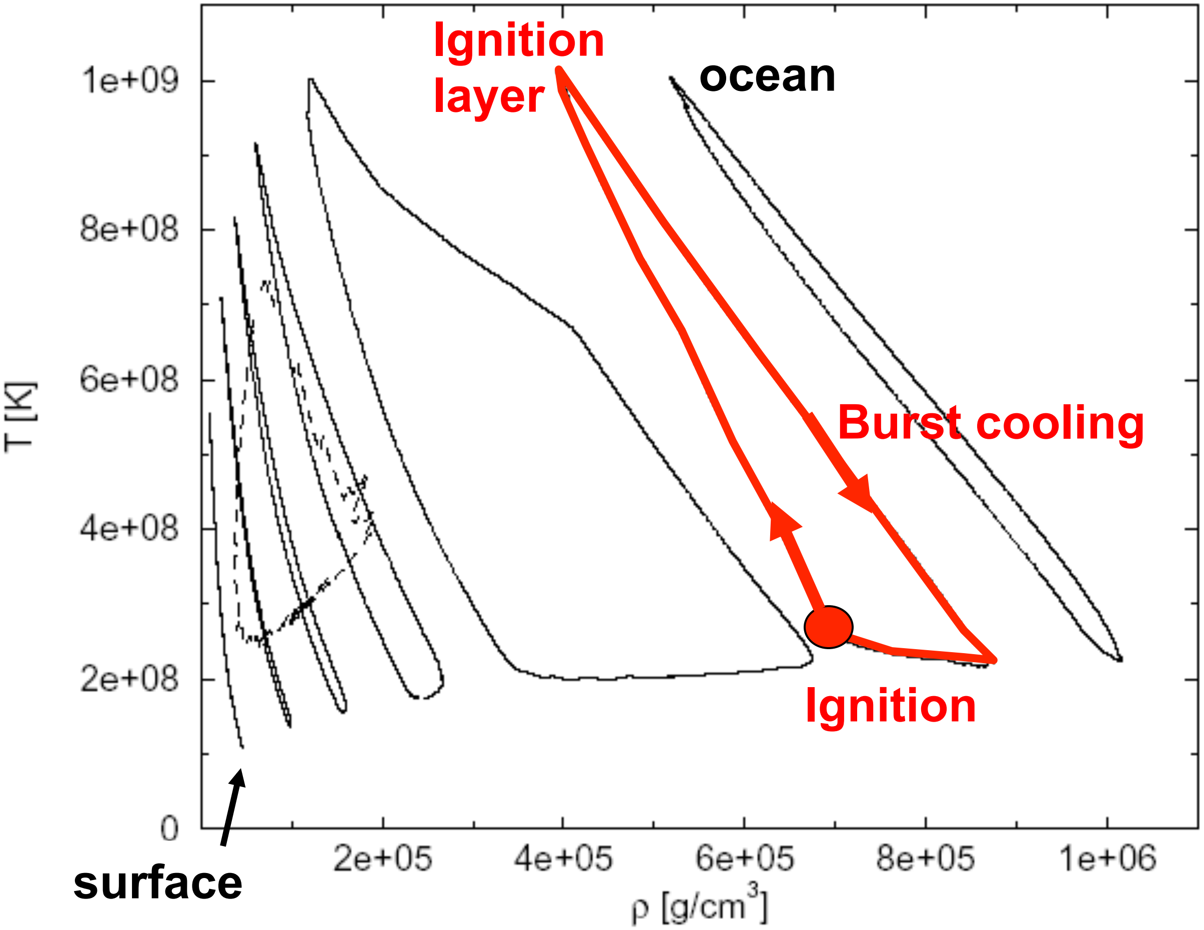


Kippenhahn diagram

depth

time

Conditions during an X-ray burst



J. Fisker Thesis (Basel, 2004)

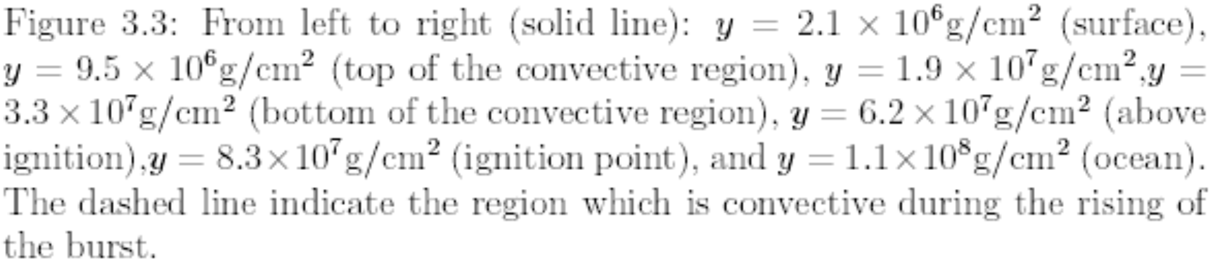
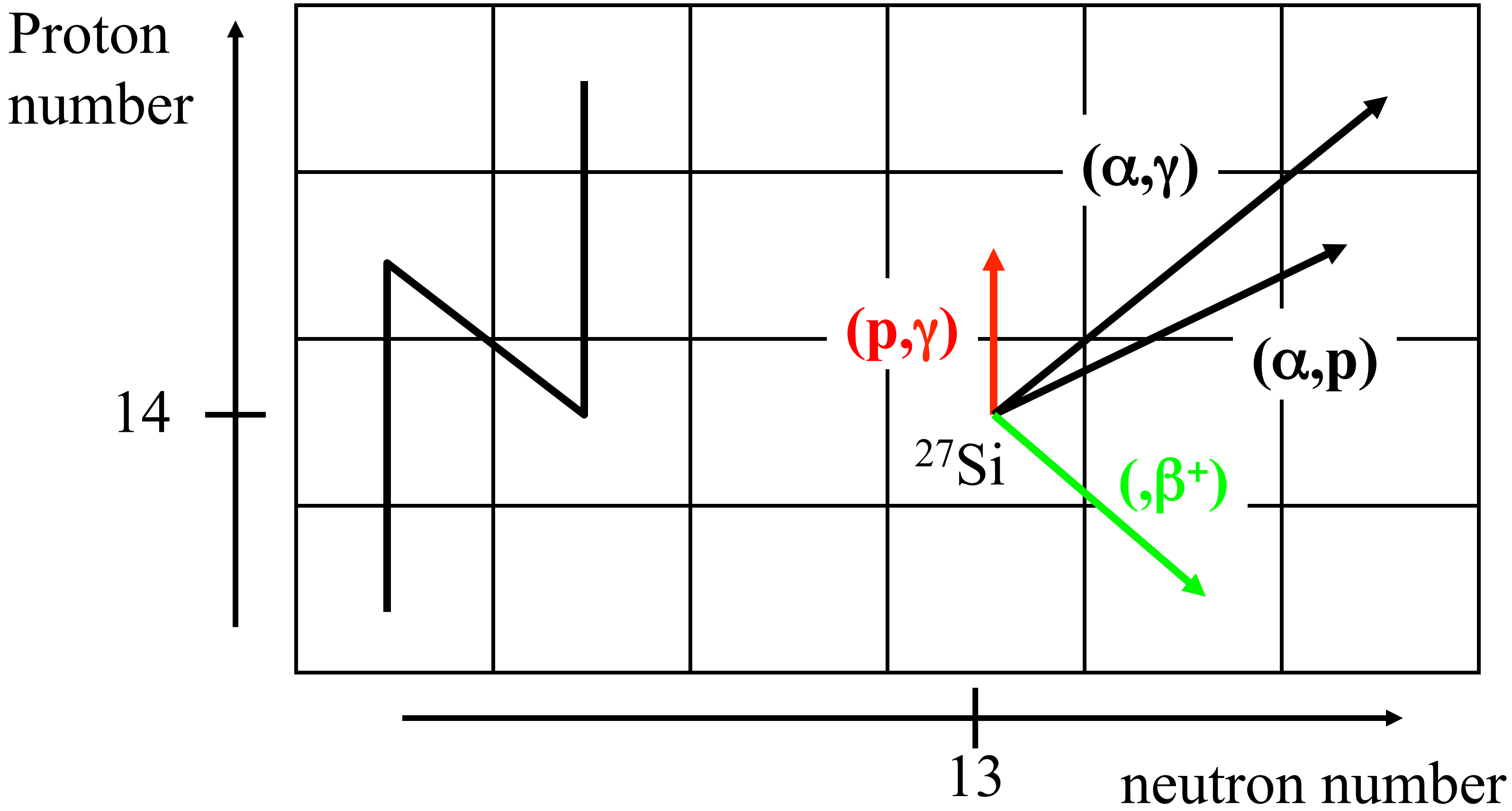


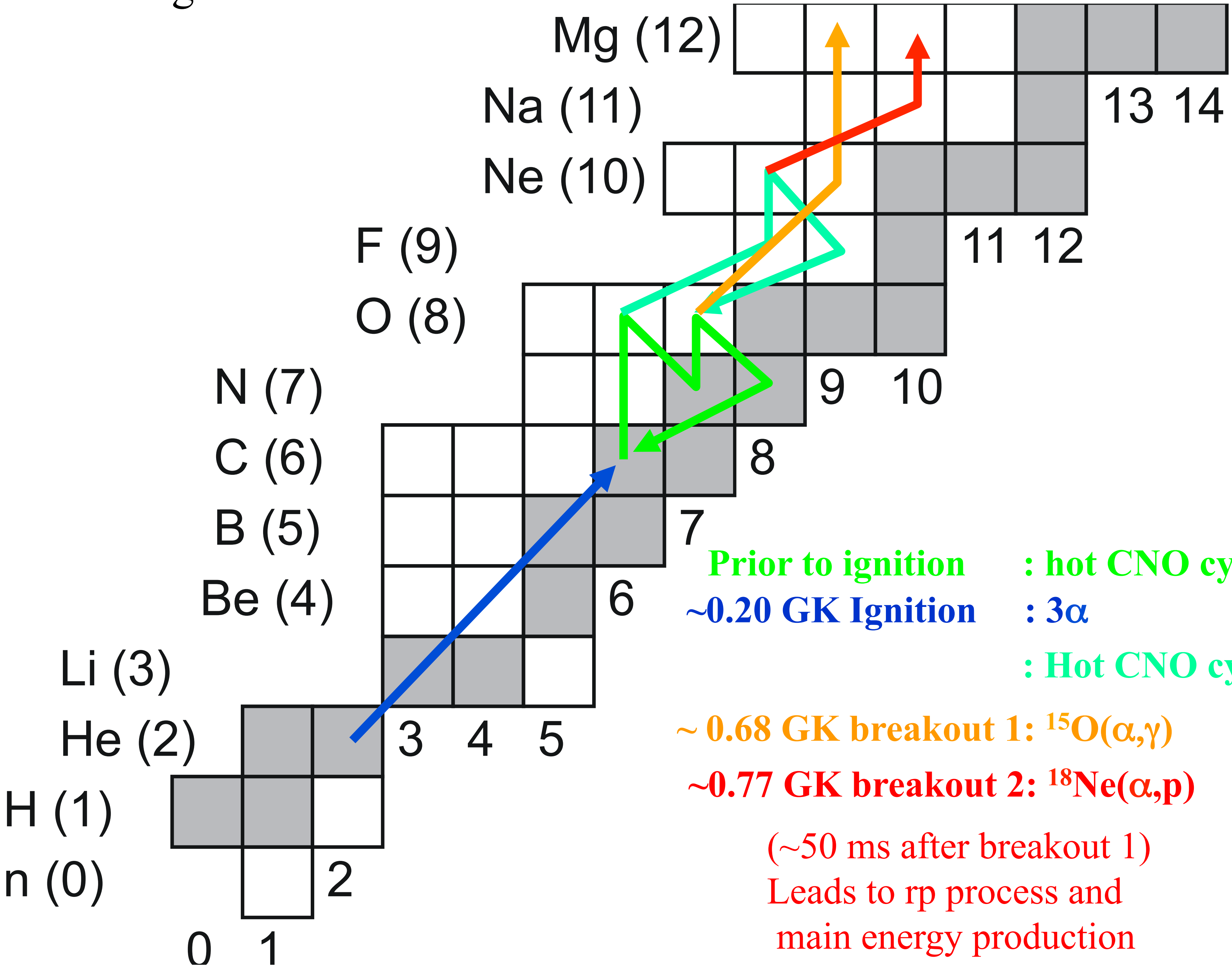
Figure 3.3: From left to right (solid line): $y = 2.1 \times 10^6 \mathrm{g/cm^2}$ (surface), $y = 9.5 \times 10^6 \mathrm{g/cm^2}$ (top of the convective region), $y = 1.9 \times 10^7 \mathrm{g/cm^2}$,$y = 3.3 \times 10^7 \mathrm{g/cm^2}$ (bottom of the convective region), $y = 6.2 \times 10^7 \mathrm{g/cm^2}$ (above ignition),$y = 8.3 \times 10^7 \mathrm{g/cm^2}$ (ignition point), and $y = 1.1 \times 10^8 \mathrm{g/cm^2}$ (ocean). The dashed line indicate the region which is convective during the rising of the burst.

Visualizing reaction networks



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

Burst Ignition:



Prior to ignition : hot CNO cycle

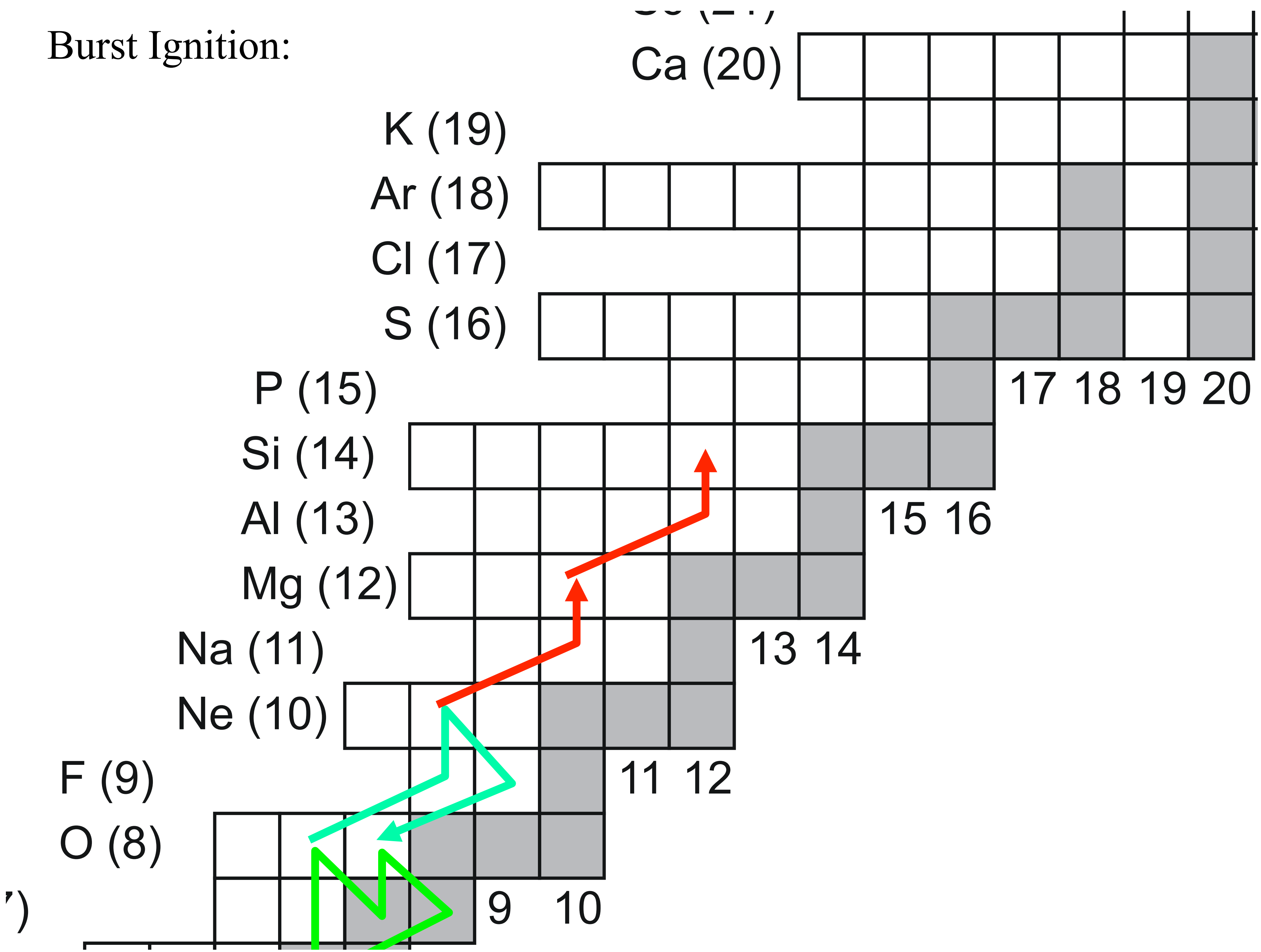
~0.20 GK Ignition : 3α

: Hot CNO cycle II

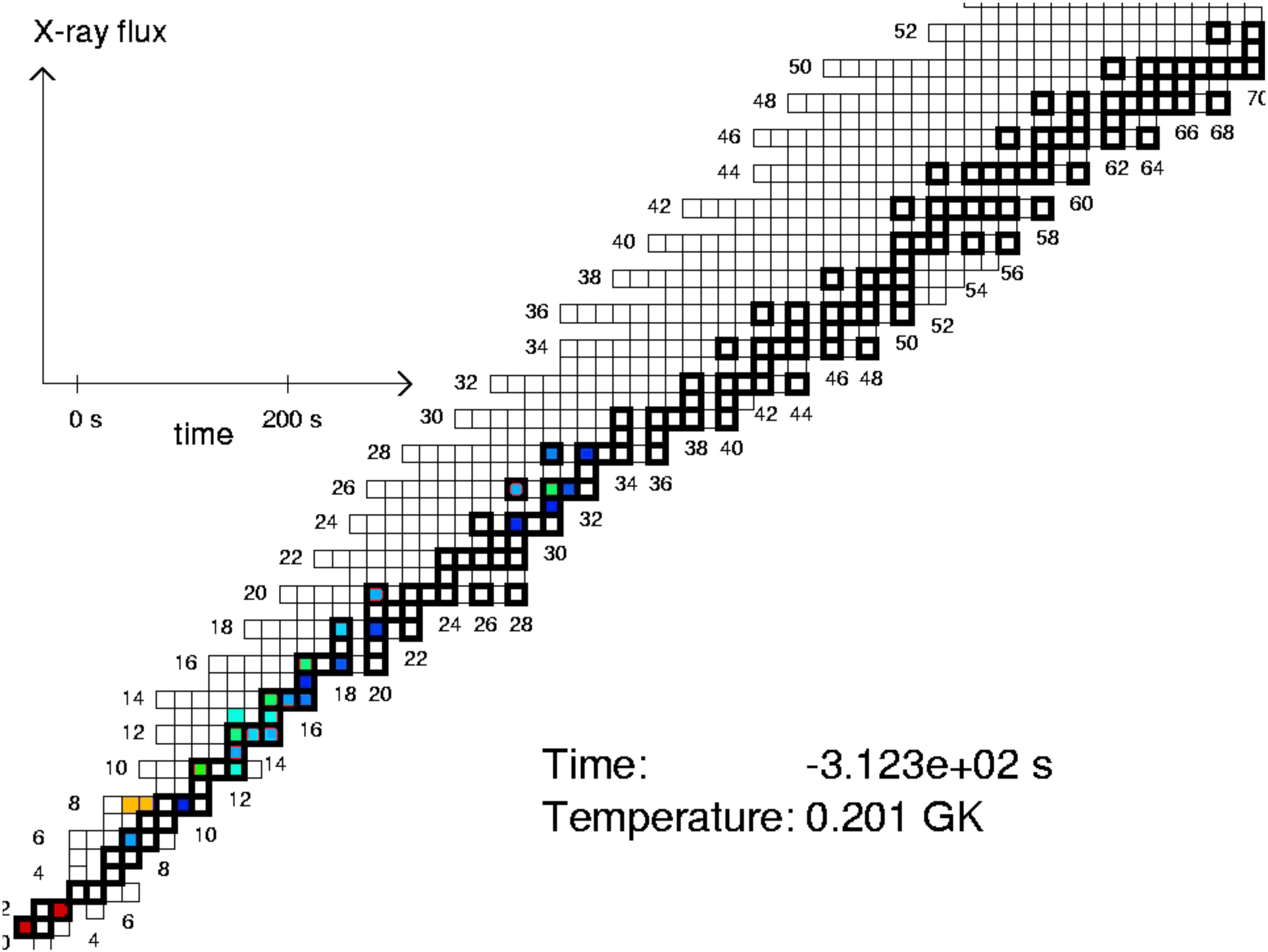
~ 0.68 GK breakout 1: $^{15}O(\alpha,\gamma)$

~0.77 GK breakout 2: $^{18}Ne(\alpha,p)$

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



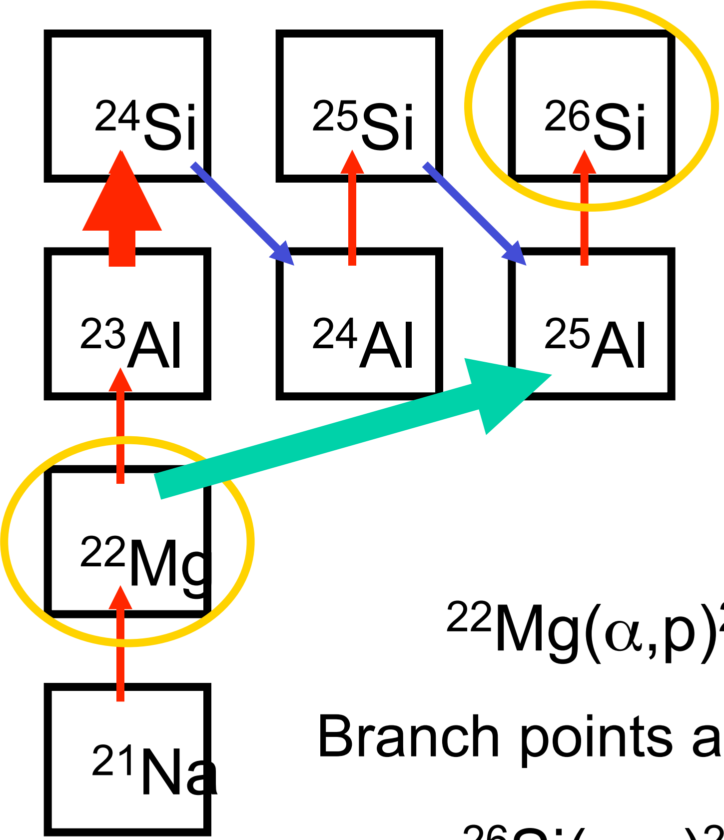
Burst Ignition:



Time: -3.123e+02 s

Temperature: 0.201 GK

Competition between αp- & rp- processes



- ^{22}Mg is branching point
- (p,γ) and (α,p) compete
- rp-process eats p's
- αp-process eats α's

^{22}Mg(α,p)^{25}Al vs ^{23}Al(p,γ)^{24}Si

Branch points also appear at ^{26}Si, ^{30}S & ^{34}Ar

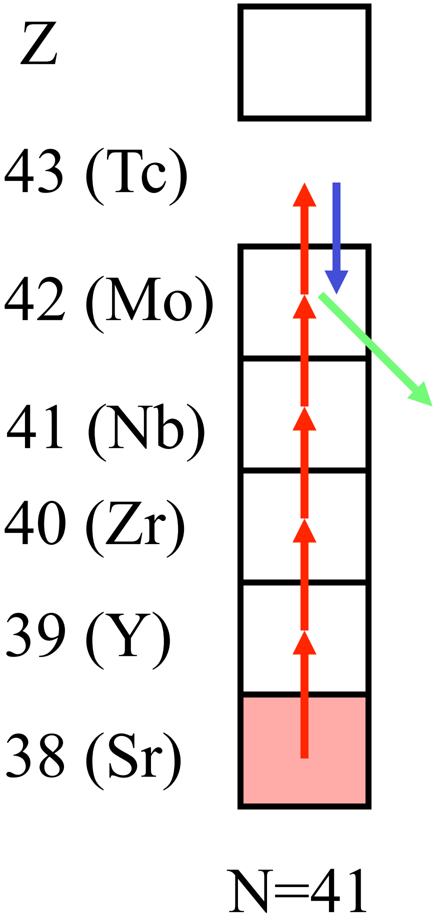
^{26}Si(α,p)^{29}P	vs	^{27}P(p,γ)^{28}S
^{30}S(α,p)^{33}Cl	vs	^{31}Cl(p,γ)^{32}Ar
^{34}Ar(α,p)^{37}K	vs	^{35}K(p,γ)^{36}Ca

H. Schatz

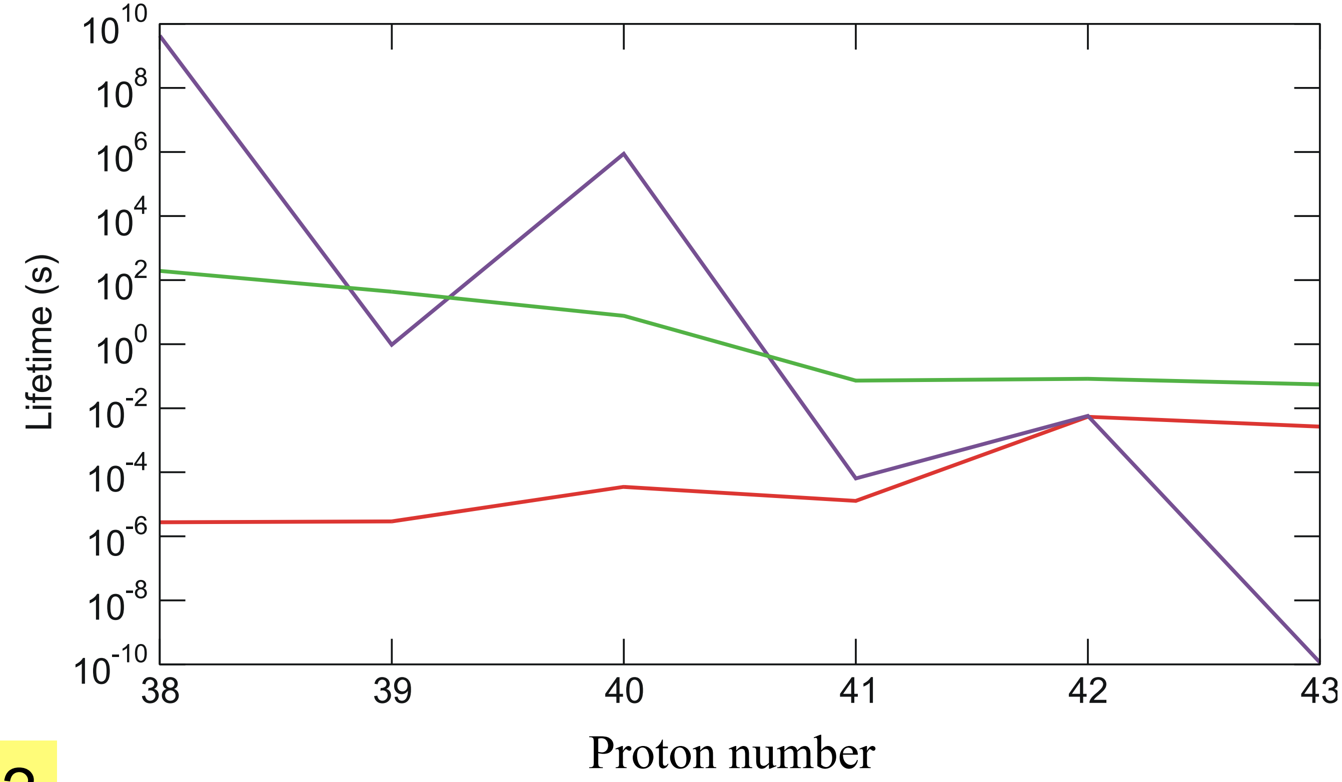
How the rp-process works

Nuclear lifetimes: (average time between a …)

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



(for $\rho=10^6$ g/cm^3, Yp=0.7, T=1.5 GK)

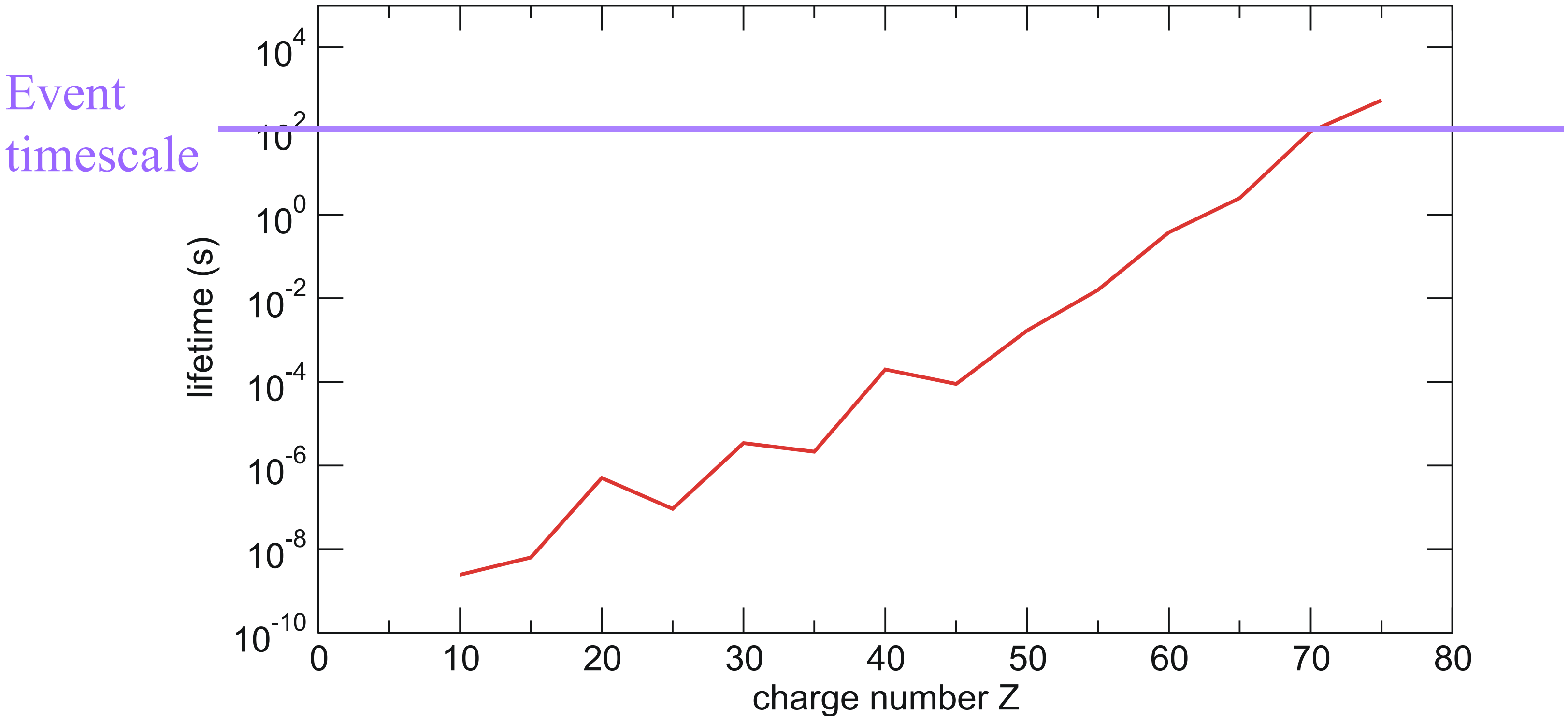


→ Endpoint ?

The endpoint of the rp-process

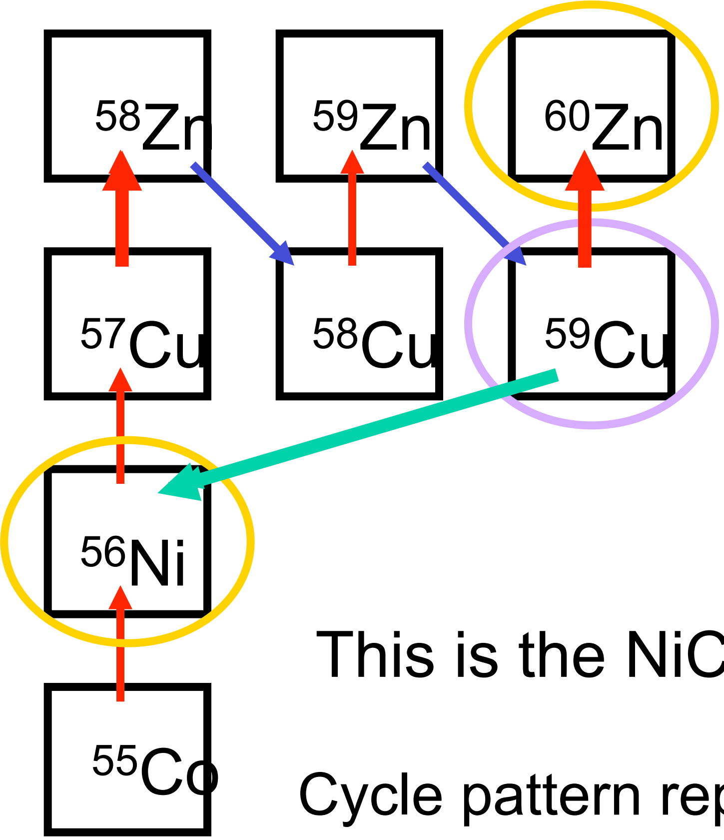
<u>Possibilities:</u>

- 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

Development of Cycles



- ^{56}Ni is doubly magic
- ^{59}Cu is branch point
- Either rp-continues
- or (p,α) back to ^{56}Ni

This is the NiCu cycle

Cycle pattern repeats for ^{60}Zn

This is the ZnGa cycle

Cycle 1 rxns

- ^{57}Cu(p,γ)^{58}Zn
- ^{59}Cu(p,γ)^{60}Zn
- ^{59}Cu(p,α)^{56}Ni

Cycle 2 rxns

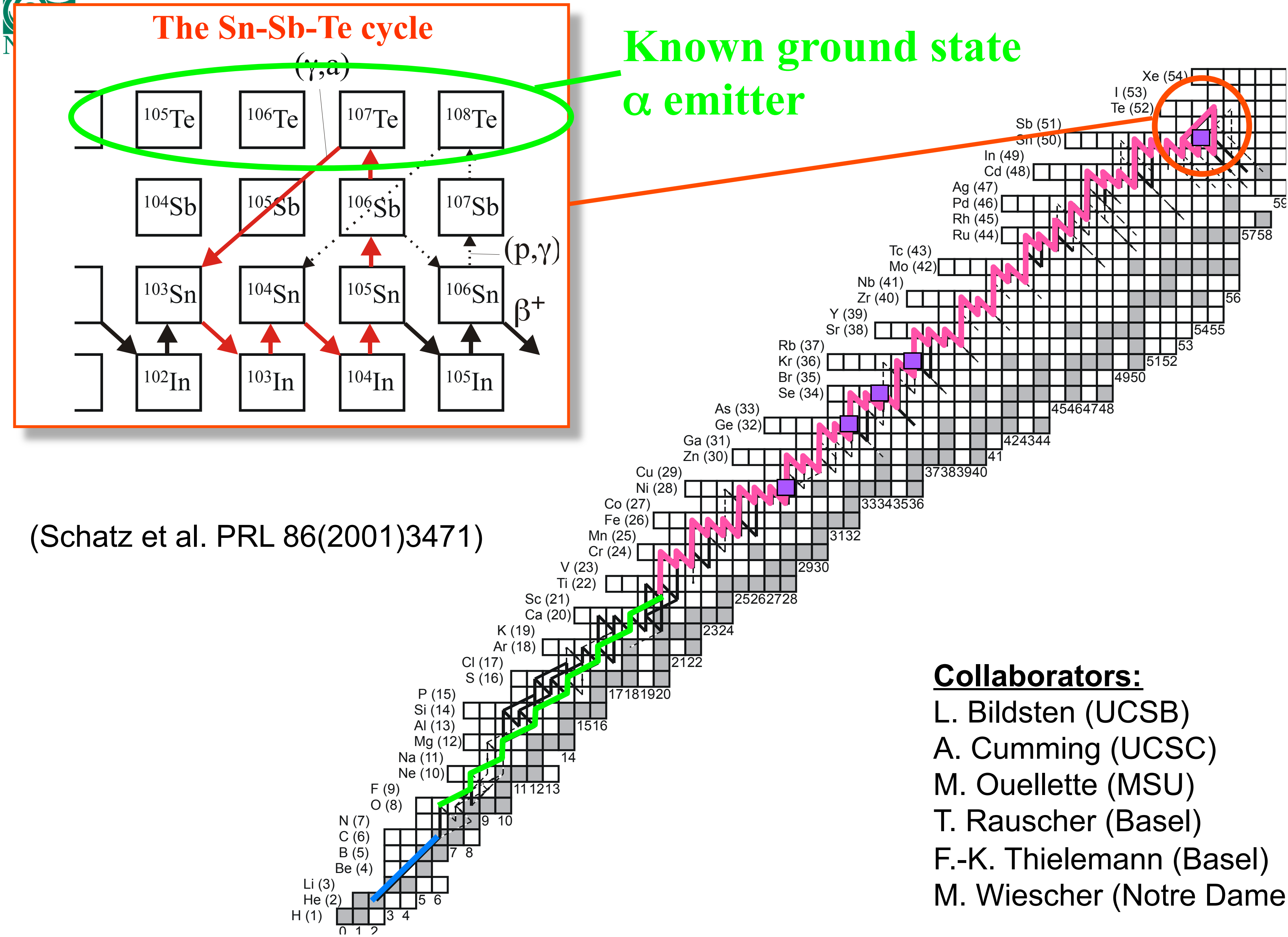
- ^{61}Ga(p,γ)^{62}Ge
- ^{63}Ga(p,γ)^{64}Ge
- ^{63}Ga(p,α)^{60}Zn

Waiting points

Slow reactions → extend energy generation
→ abundance accumulation
(steady flow approximation λY=const
or $Y \sim 1/\lambda$)

Critical “wating points” can be easily identified in abundance movie

Endpoint: Limiting factor I – SnSbTe Cycle



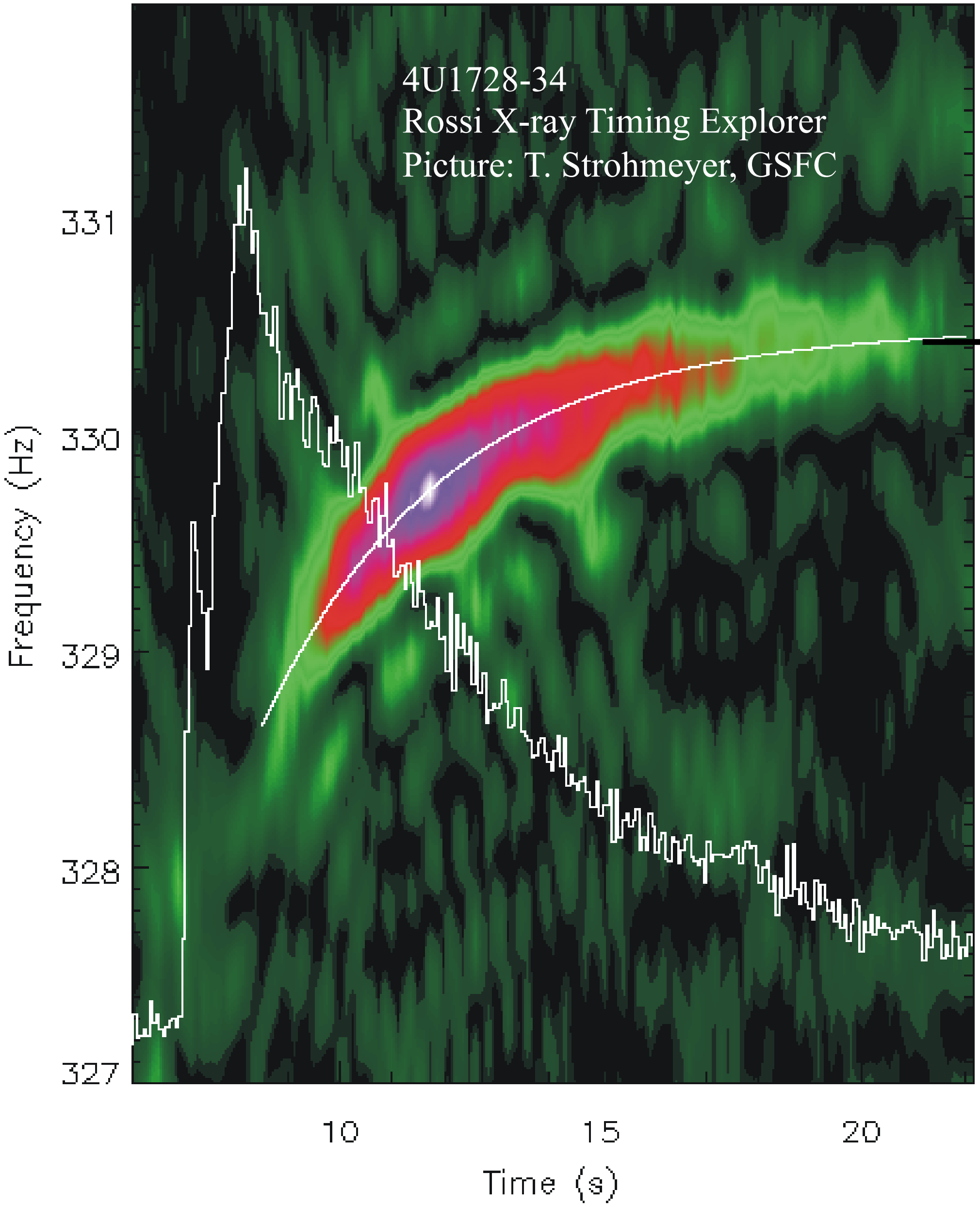
Known ground state α emitter

(Schatz et al. PRL 86(2001)3471)

Collaborators:

L. Bildsten (UCSB)
A. Cumming (UCSC)
M. Ouellette (MSU)
T. Rauscher (Basel)
F.-K. Thielemann (Basel)
M. Wiescher (Notre Dame)

Open question I: ms oscillations



Neutron Star spin frequency

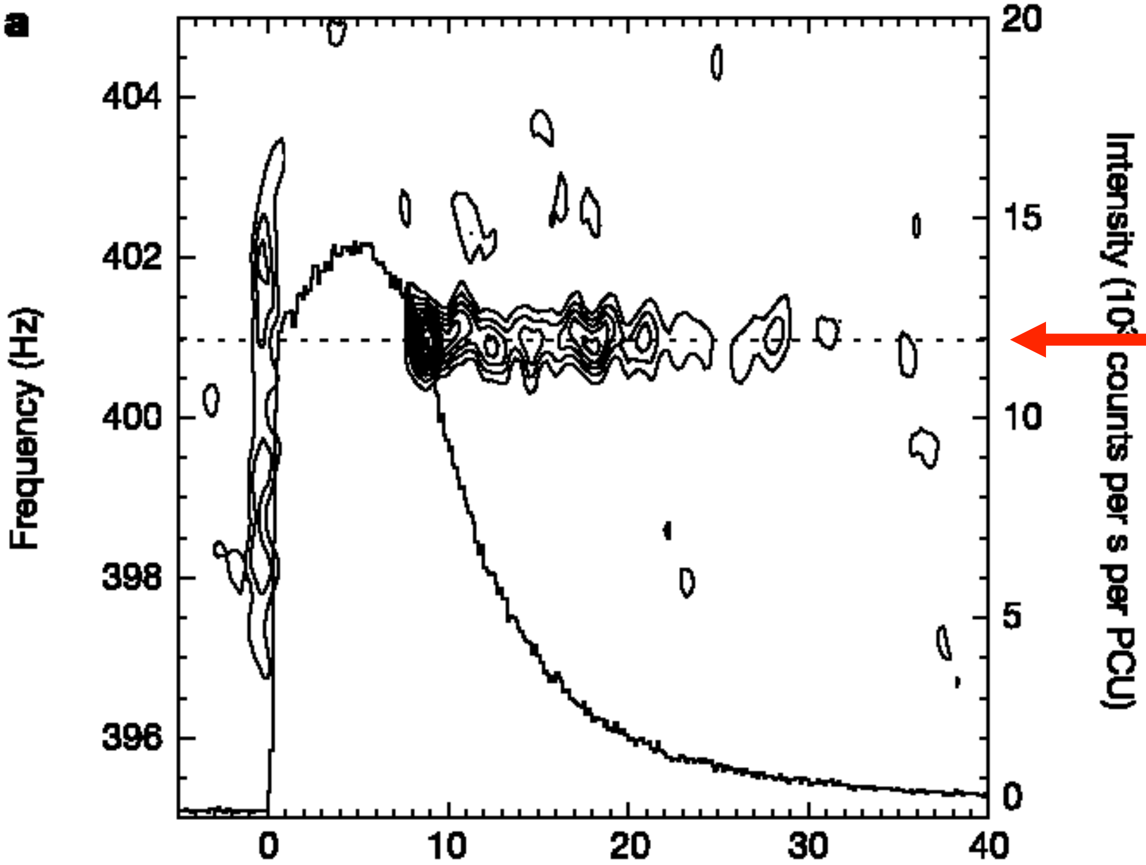
Now proof from 2 bursting pulsars

(SAX J1808.4-3658, XTE J1814-338)
(Chakrabarty et al. Nature 424 (2003) 42
Strohmayer et al. ApJ 596 (2003)67)

- Origin of oscillations ?
- Why frequency drift ?

The bursting pulsar

SAX J1808.4-3658



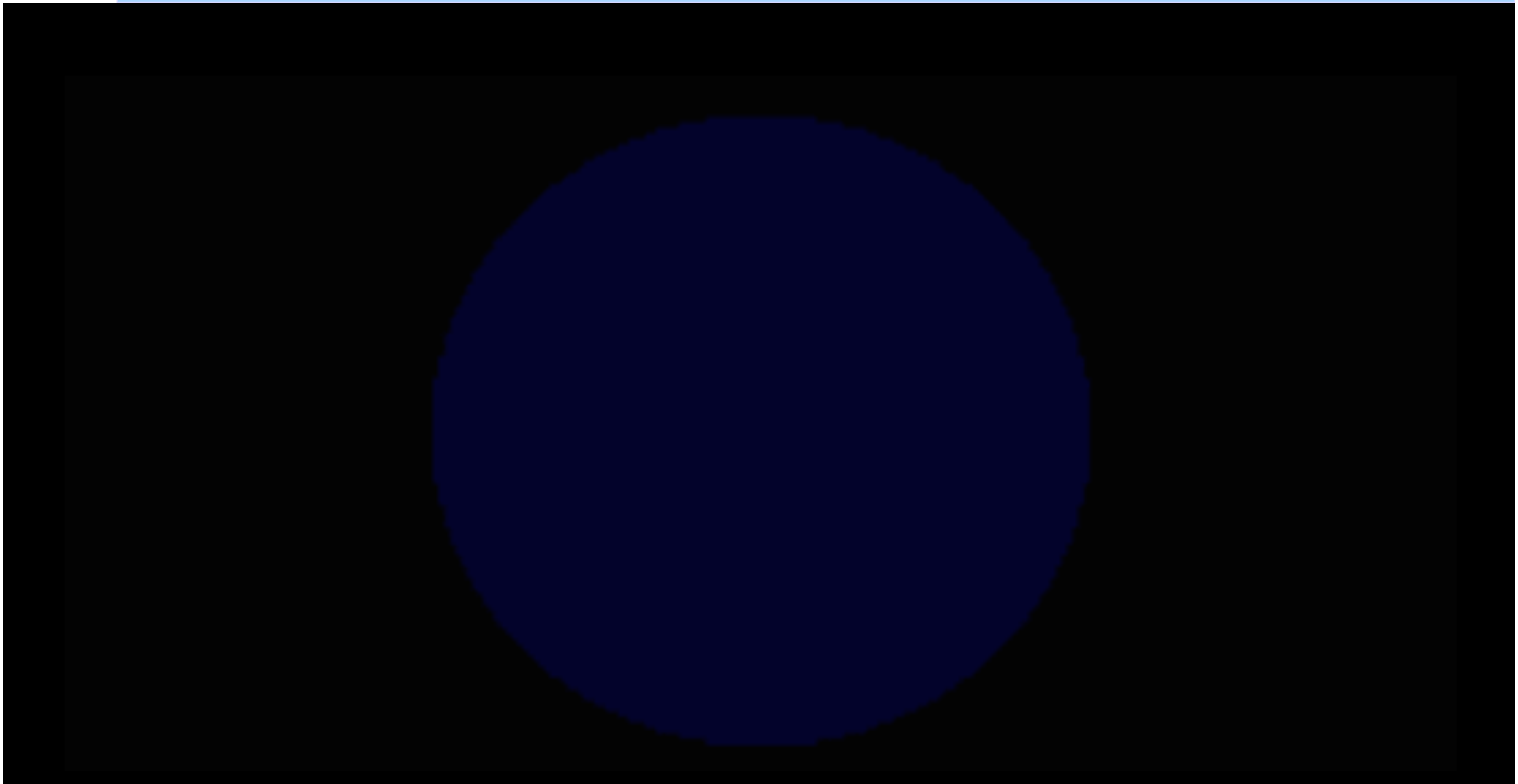
Seconds since burst

D. Chakrabarty et al.
Nature 424 (2003) 42

Pulsar
Frequency

Origin of frequency drift in normal bursting systems ???
(rotational decoupling ? Surface pulsation modes ?)

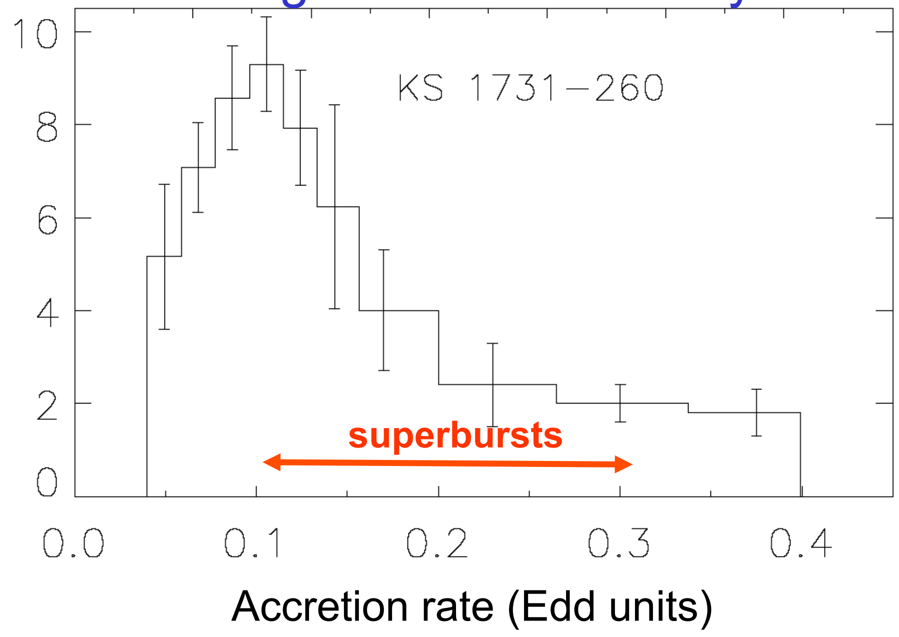
Open question II: ignition and flame propagation



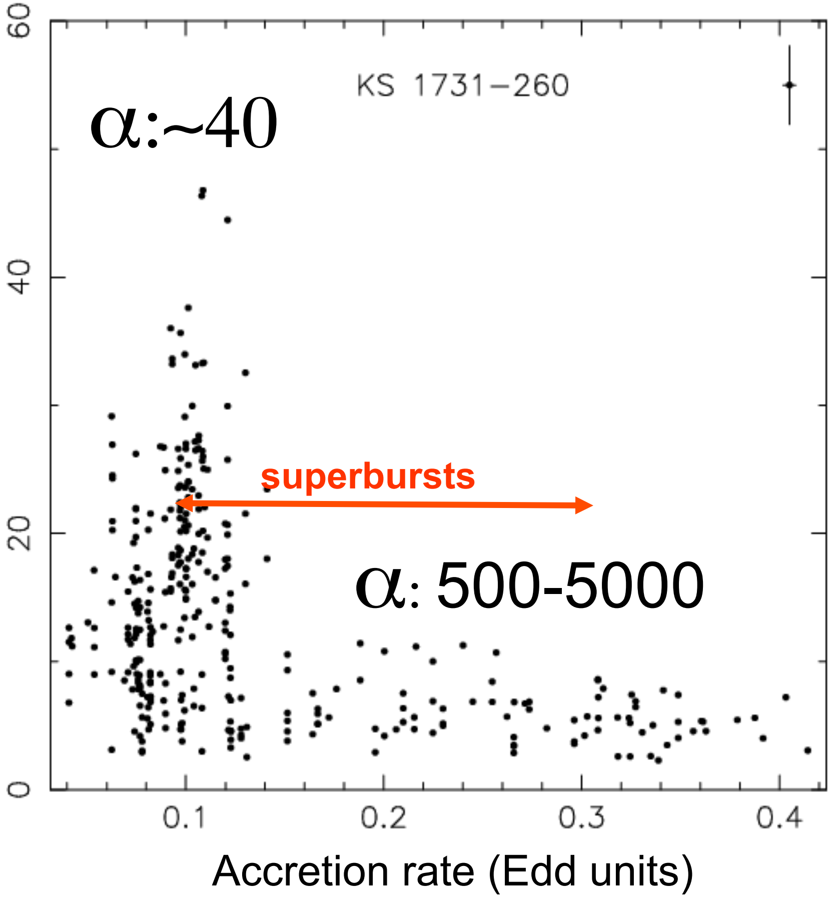
Anatoly Spitkovsky (Berkeley)

Open question III: burst behavior at large accretion rates

Regular burst rate /day

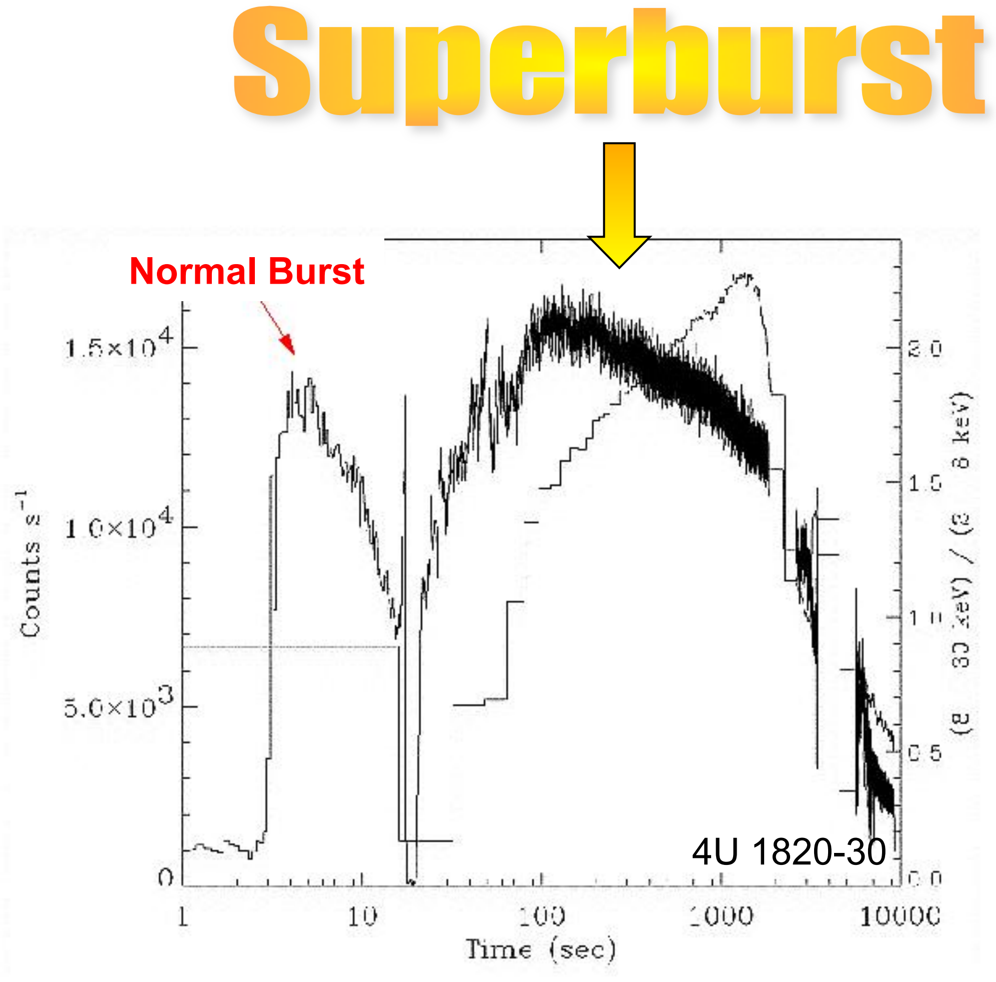


Regular burst duration (s)



Cornelisse et al. 2003

Open question IV: superbursts



4U 1820-30
Strohmayer & Brown (2001)

X 1000 duration
(can last ½ day)

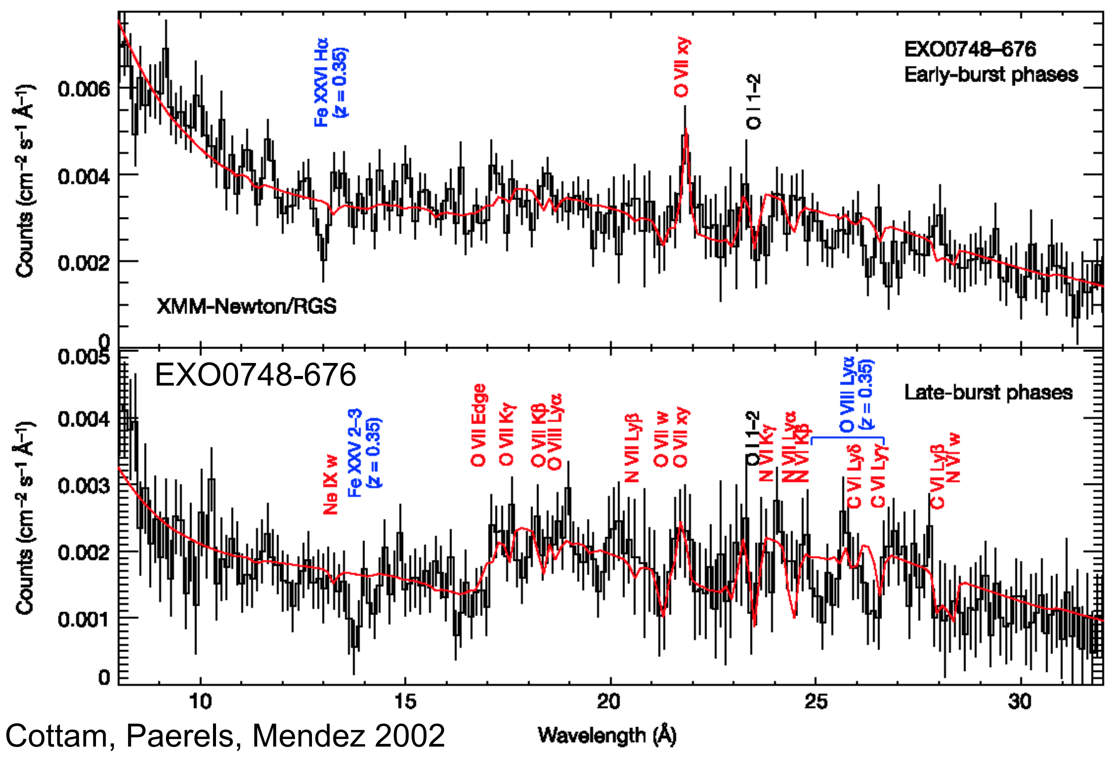
X 1000 energy

11 seen in 9 sources

Recurrence ~1 yr ?

Often preceeded by
regular burst

Open question V: abundance observations ?



Cottam, Paerels, Mendez 2002