EXTRA CREDIT

Find as many mistakes as you can and correct them!

Cite your source for the lyrics and
astronomical data.
Show any math/conversions explicitly.

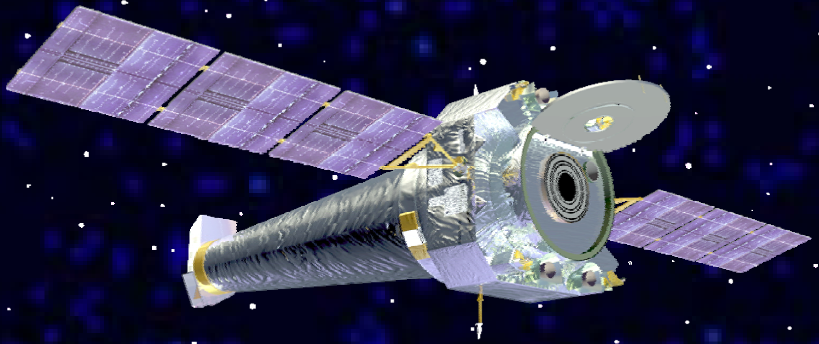
Due: Last day of classes, May 1

Room Change

Monday April 20, 2009
BioChem room 111

X-ray binaries – nuclear physics at the extremes

Outline

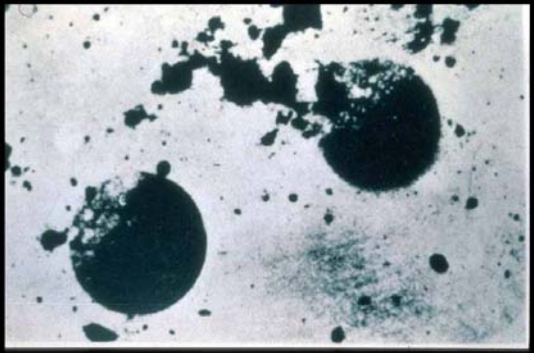


1. **Observations**
2. **X-ray Burst Model**
3. **Nuclear Physics – the rp process**
4. **Open Questions**

X-rays

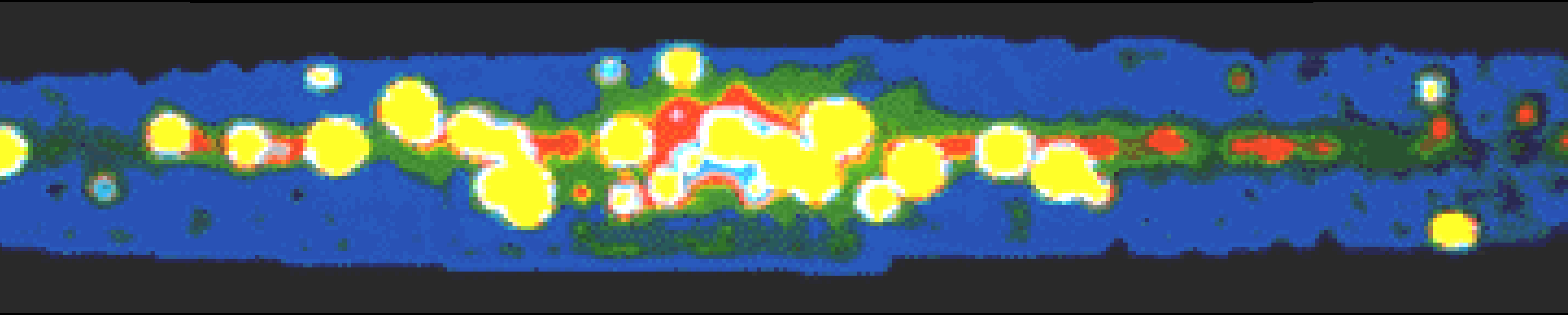
Wilhelm Konrad Roentgen, First Nobel Price 1901 for discovery of X-rays 1895

Ms Roentgen’s hand, 1895



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

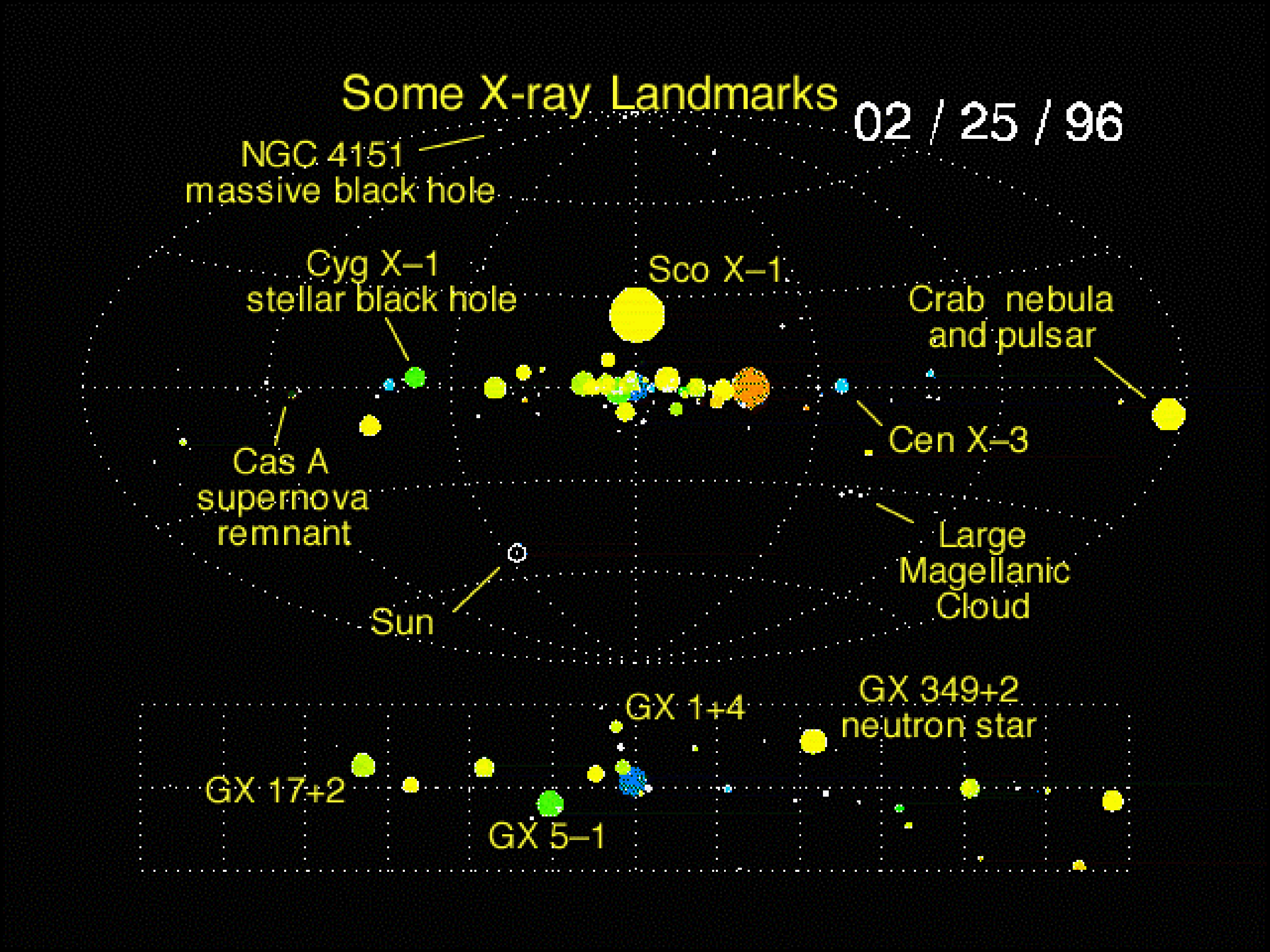
Cosmic X-rays: discovered end of 1960's:



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

Again Nobel Price in Physics 2002
for Riccardo Giacconi

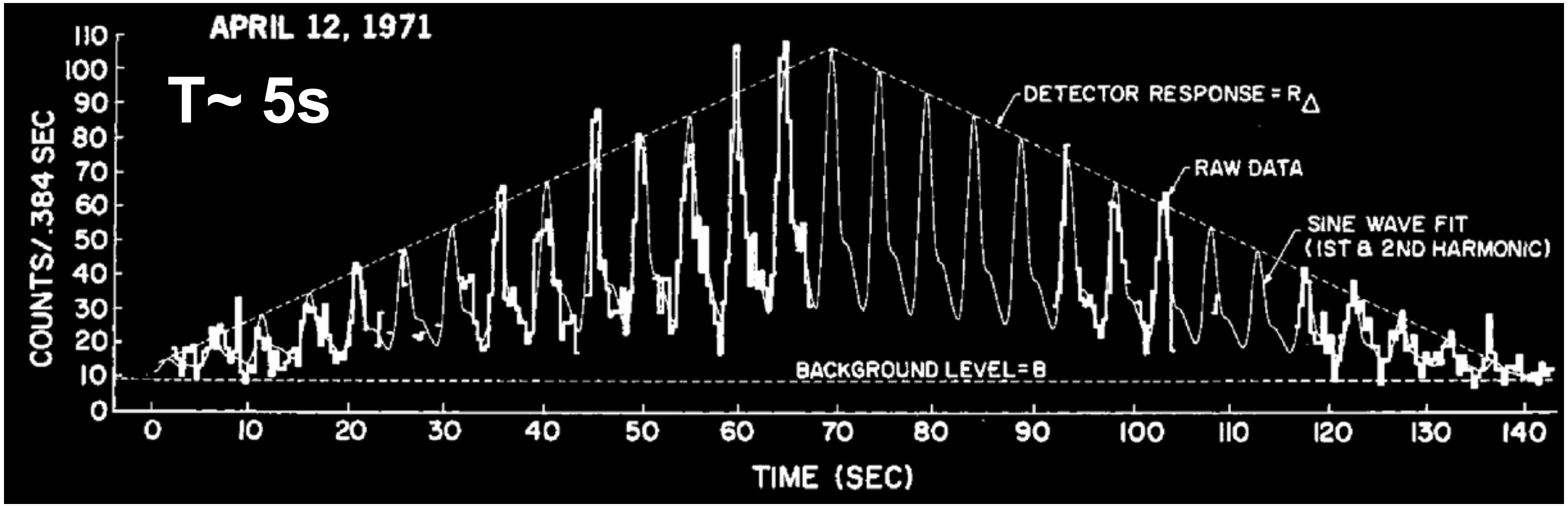
X-rays in the sky



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

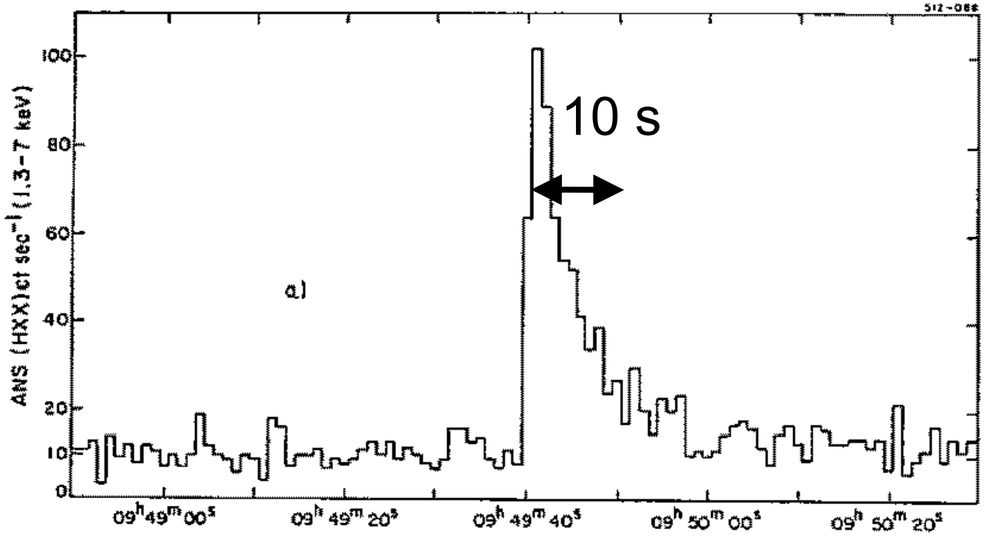
Discovery of X-ray bursts and pulsars

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

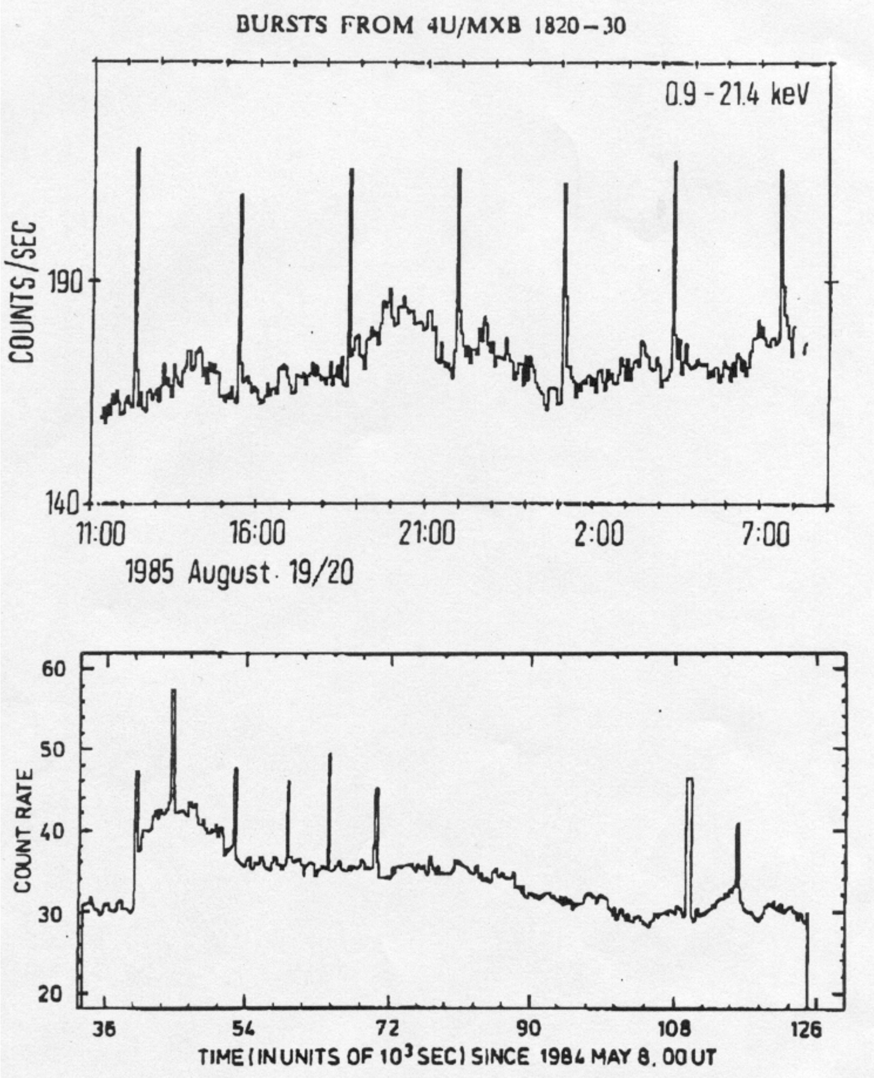


Fig. 3.14. (a) Example of a very regular burst recurrence pattern, observed for 1820–303 (from Haberl *et al.* 1987). (b) Irregular burst recurrence, observed from 1636–536 (from Sztajno *et al.* 1985).

Typical X-ray bursts:

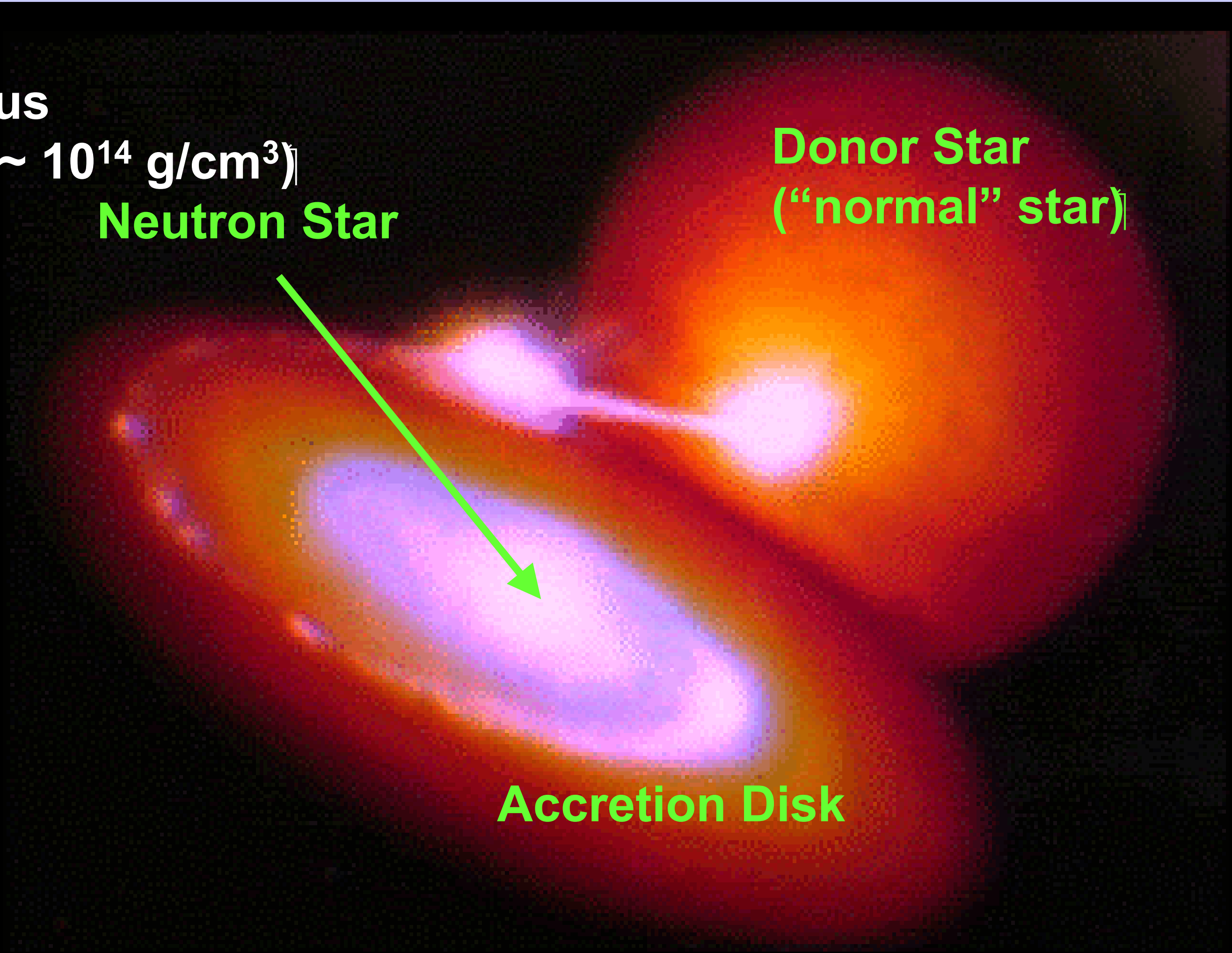
- 10^{36}-10^{38} erg/s
- duration 10 s – 100s
- recurrence: hours-days
- regular or irregular

Frequent and very bright phenomenon !

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

The model

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

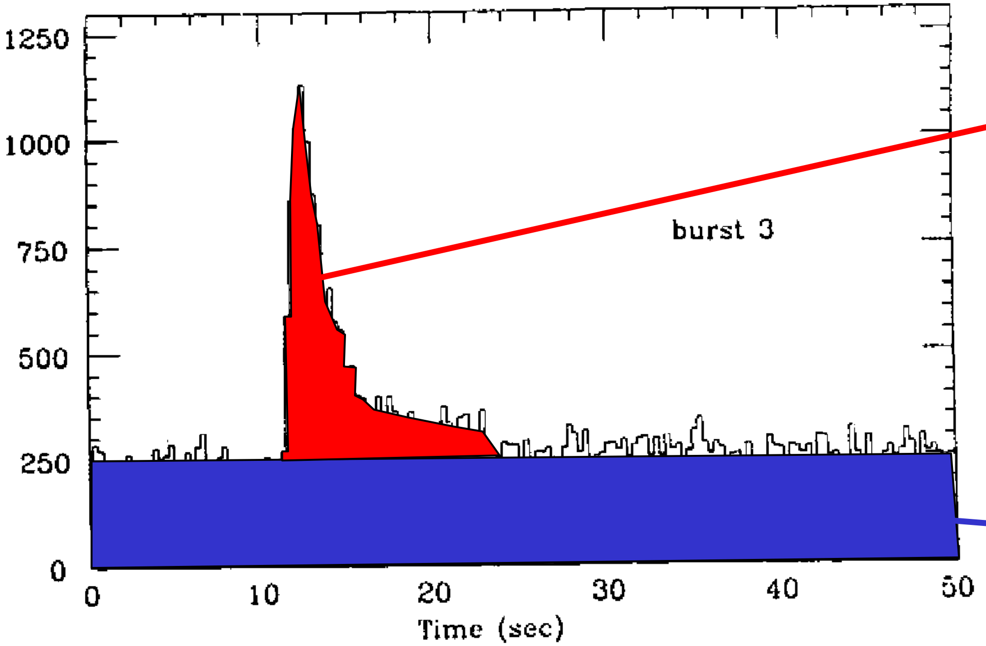


Typical systems:

- **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**
- **surface density ~ 10^6 g/cm^3**

Observation of thermonuclear energy

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



Burst energy thermonuclear

Persistent flux gravitational energy

Energy sources

Energy generation: thermonuclear energy

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

Energy generation: gravitational energy

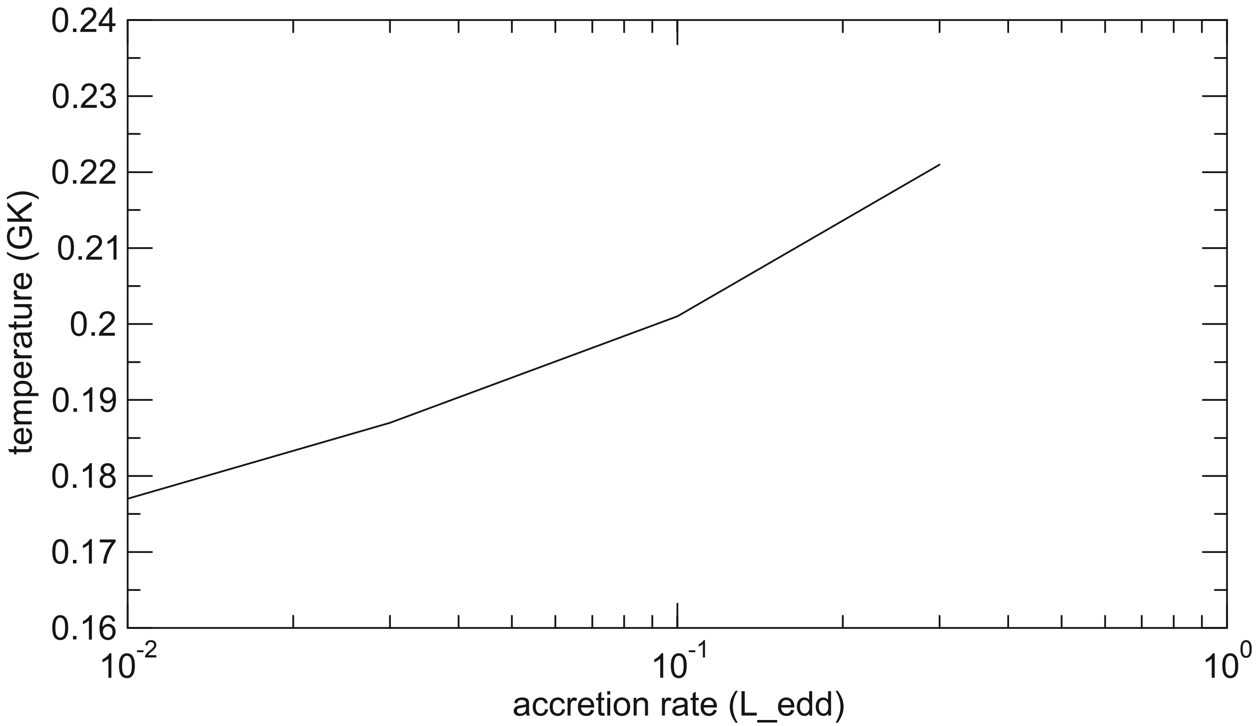
$$E = \frac{G\,M\,m_u}{R} = 200\ \text{MeV/u}$$

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

Initial Conditions

- Accreting material loses energy via X-ray emission
  - Gravitational energy

- Surface temperature related to accretion rate
  - Kinetic energy



Burst ignition at “low” accretion rates

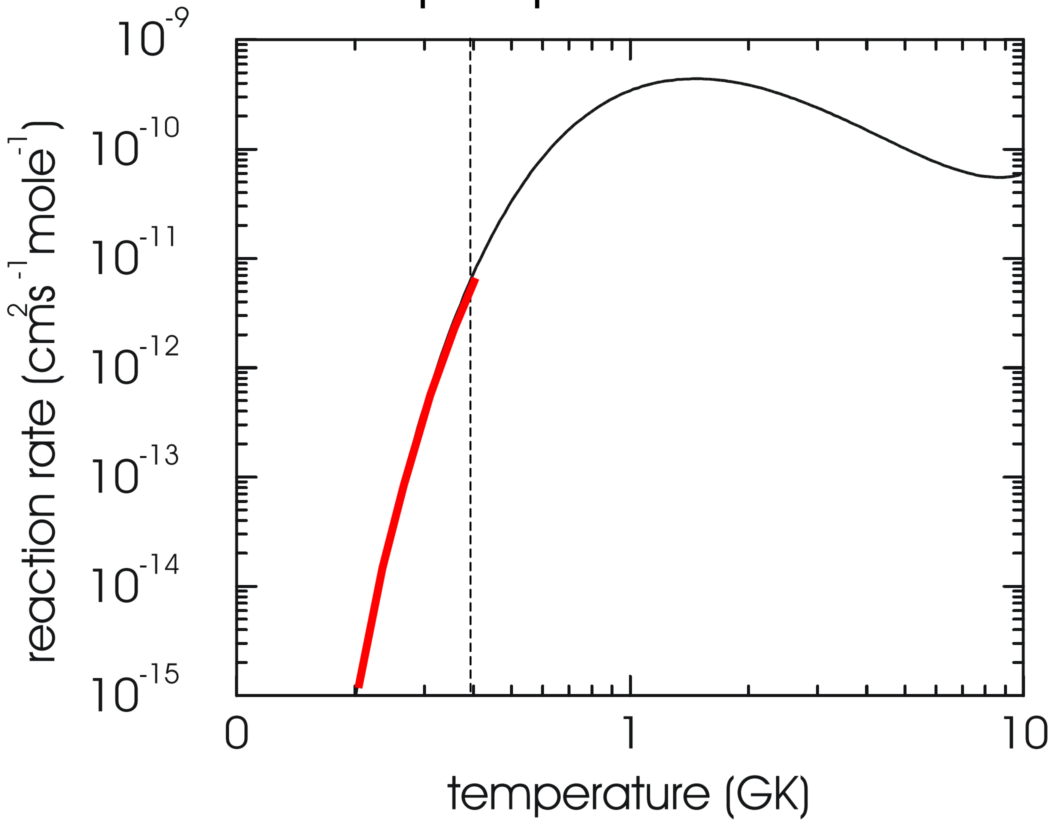
Burst trigger rate is “triple alpha reaction” $3\,^{4}He \longrightarrow {}^{12}C$

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

ε_{nuc} Nuclear energy generation rate

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

Triple alpha reaction rate



Ignition < 0.4 GK:

unstable **runaway**

- heat added increases T
- higher T increases ε_{nuc}
- larger ε_{nuc} increase T more

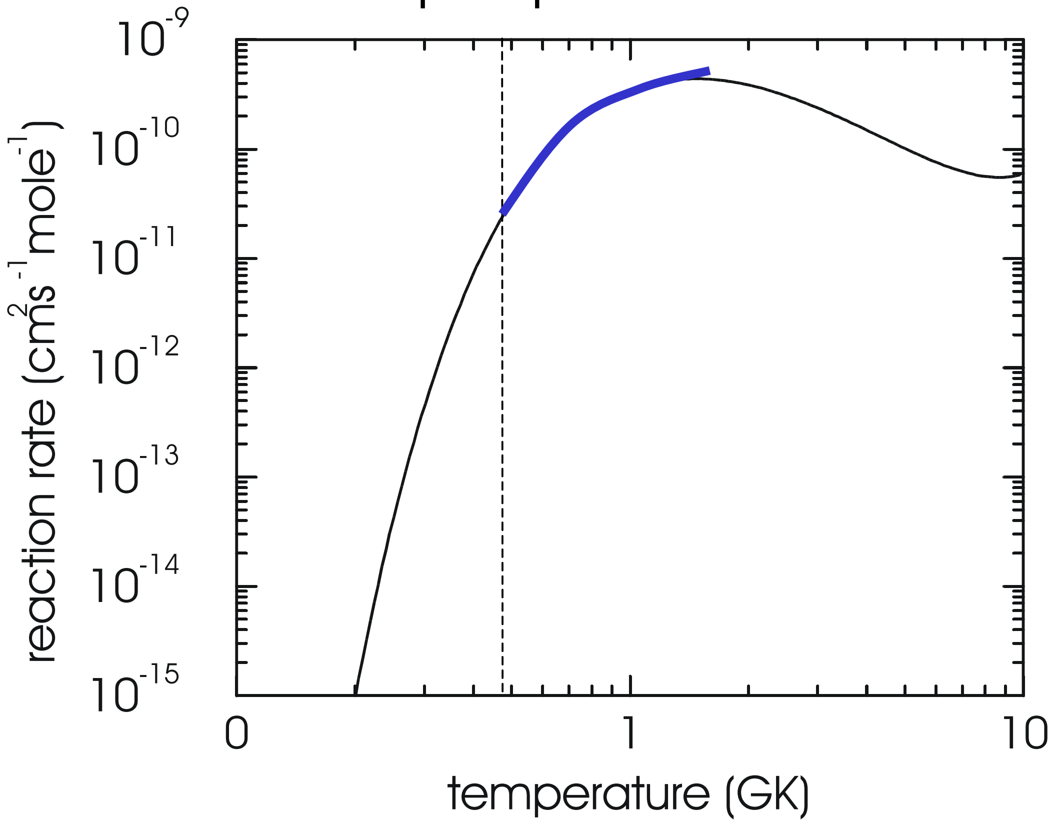
Stable burning at “high” accretion rates

Stable Burning: $\left|\frac{d\varepsilon_{nuc}}{dT}\right| < \left|\frac{d\varepsilon_{cool}}{dT}\right|$

ε_{nuc} Nuclear energy generation rate

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

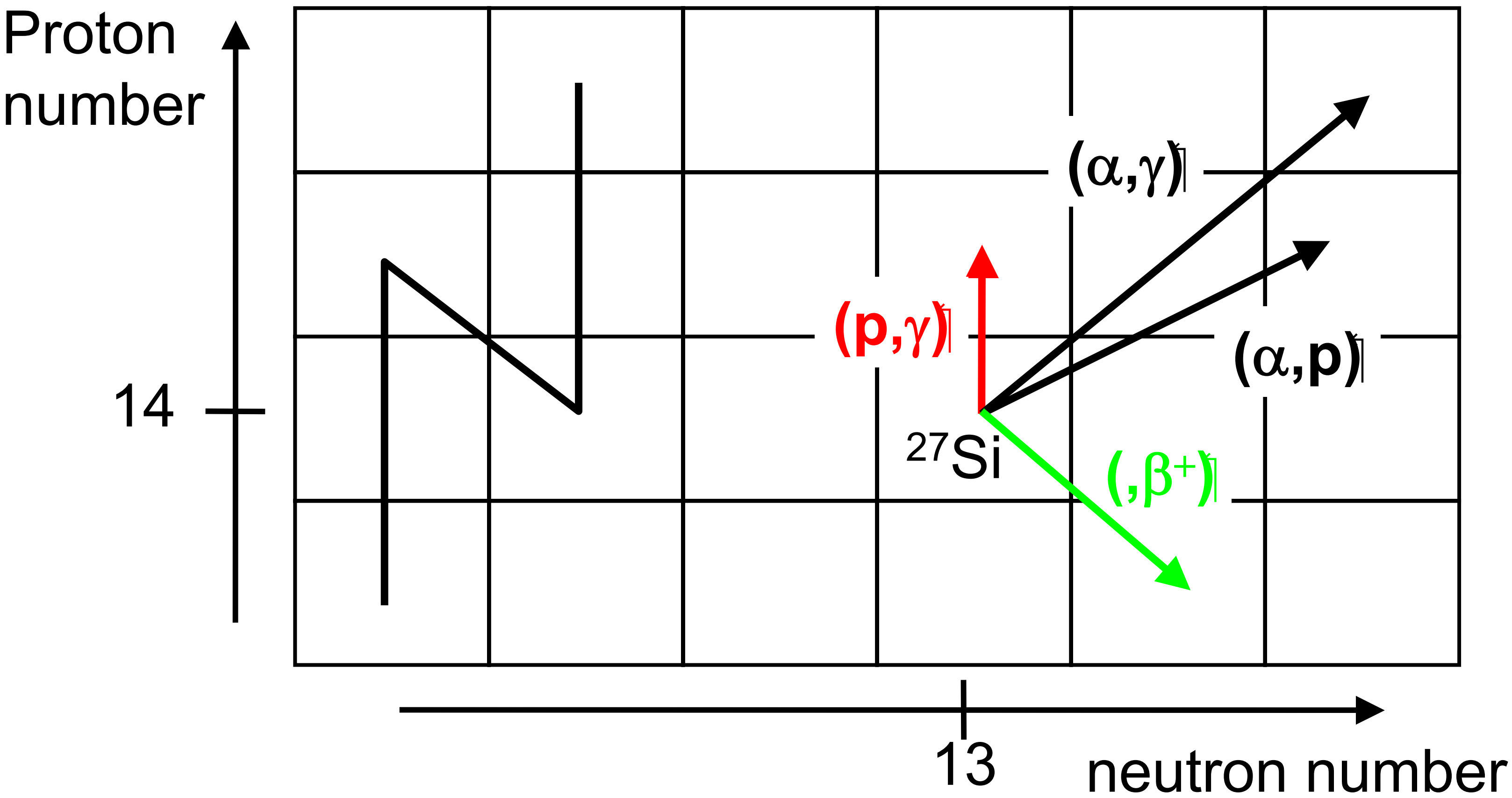
Triple alpha reaction rate



Stable Burning > 0.5 GK:

- heat added efficiently cooled
- T doesn’t change dramatically
- NO X-Ray Bursting!!

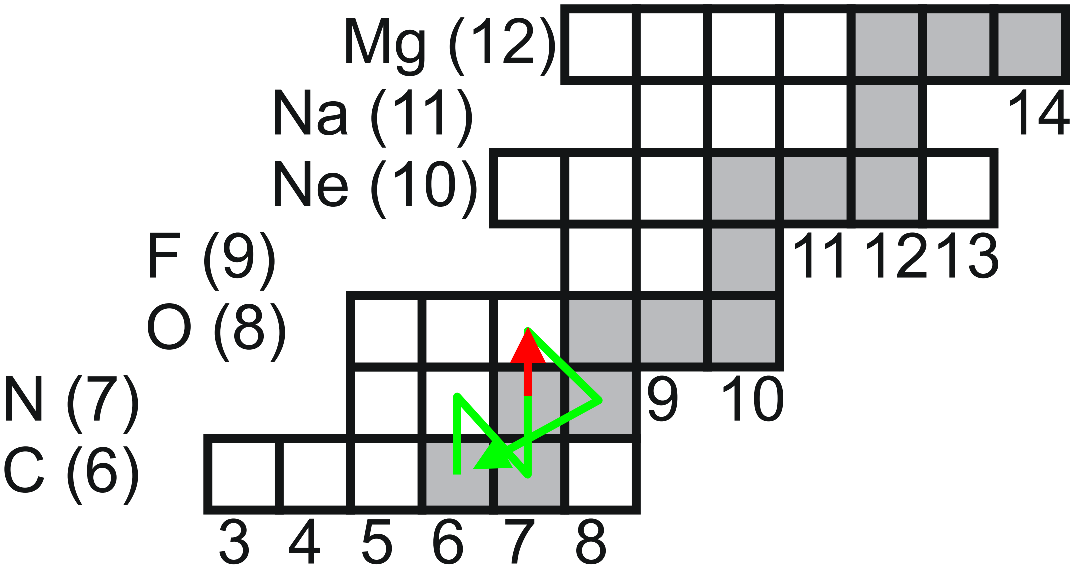
Visualizing reaction networks



“Cold” CN(O)-Cycle $T_9 < 0.08$

Energy production rate:

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



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

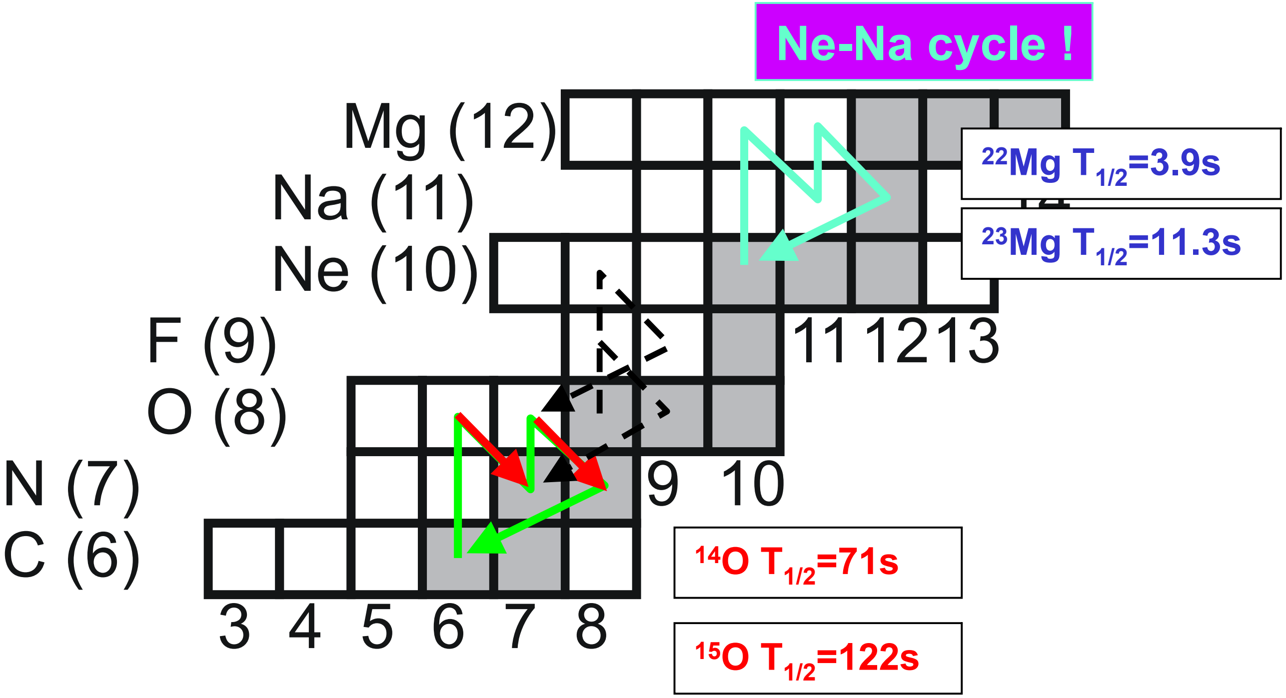
“beta limited CNO cycle”

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

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

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

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



Ne-Na cycle !

^{22}Mg $T_{1/2}$=3.9s

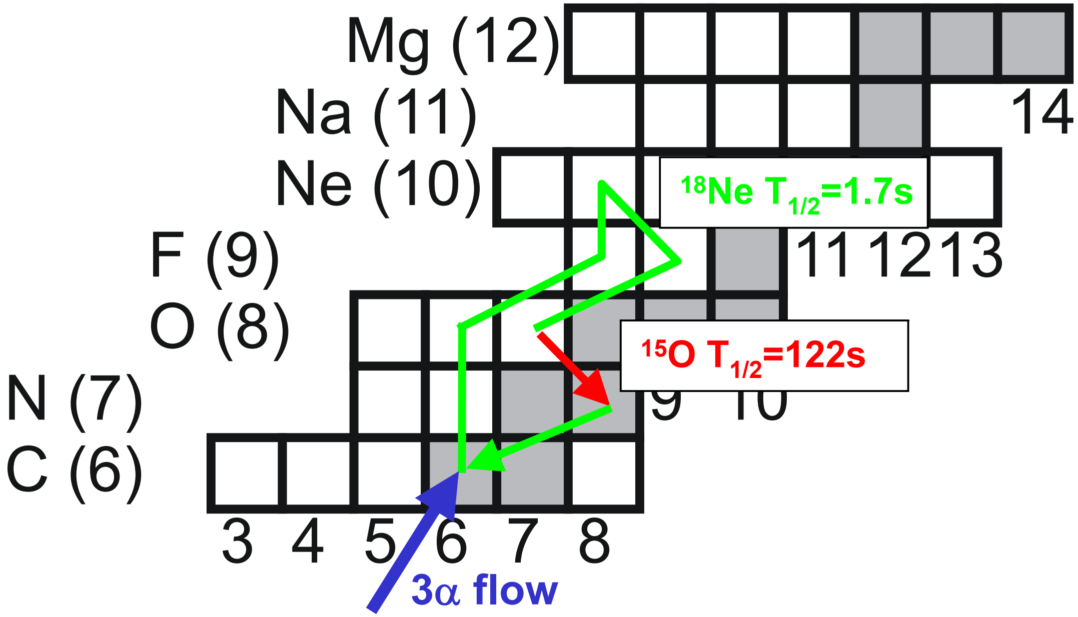
^{23}Mg $T_{1/2}$=11.3s

^{14}O $T_{1/2}$=71s

^{15}O $T_{1/2}$=122s

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

still “beta limited”

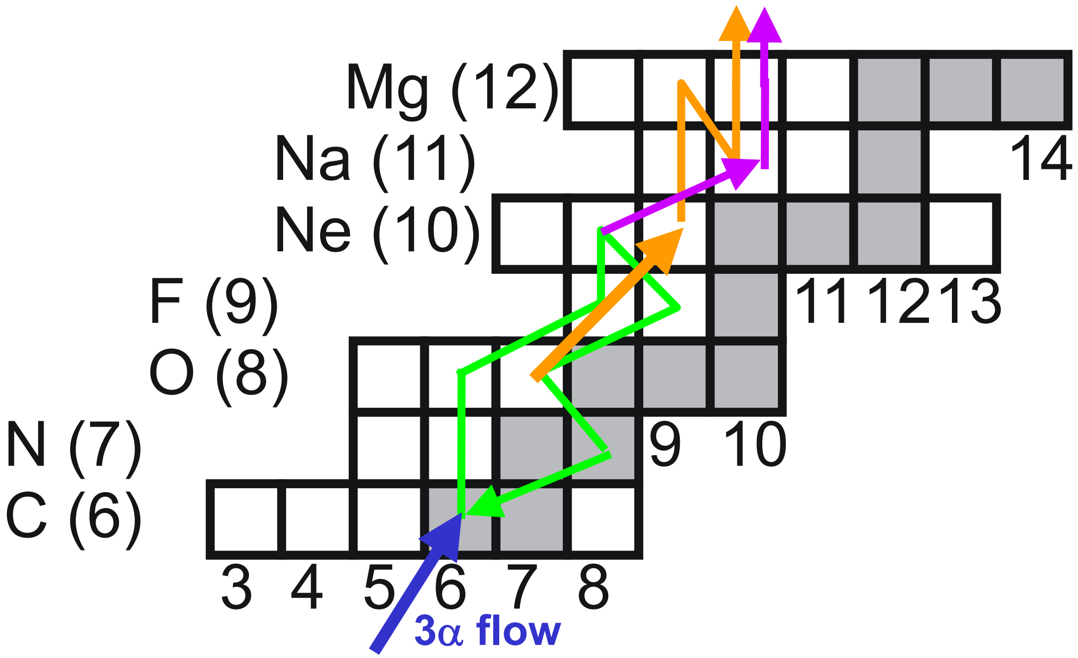


Breakout

processing beyond CNO cycle
after breakout via:

$T_9 > 0.36$ $^{15}O(\alpha,\gamma)^{19}Ne$

$T_9 > 0.62$ $^{18}Ne(\alpha,p)^{21}Na$

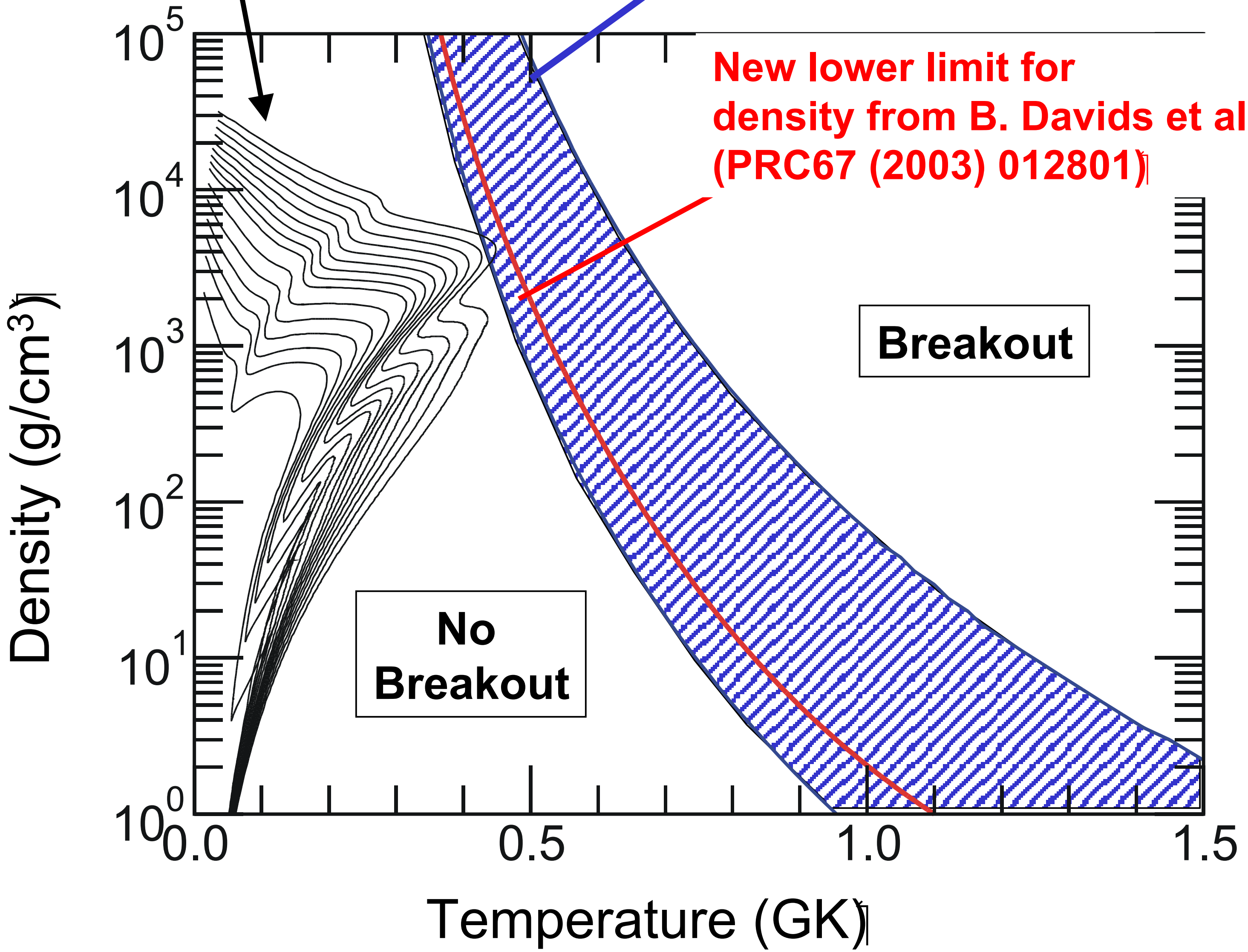


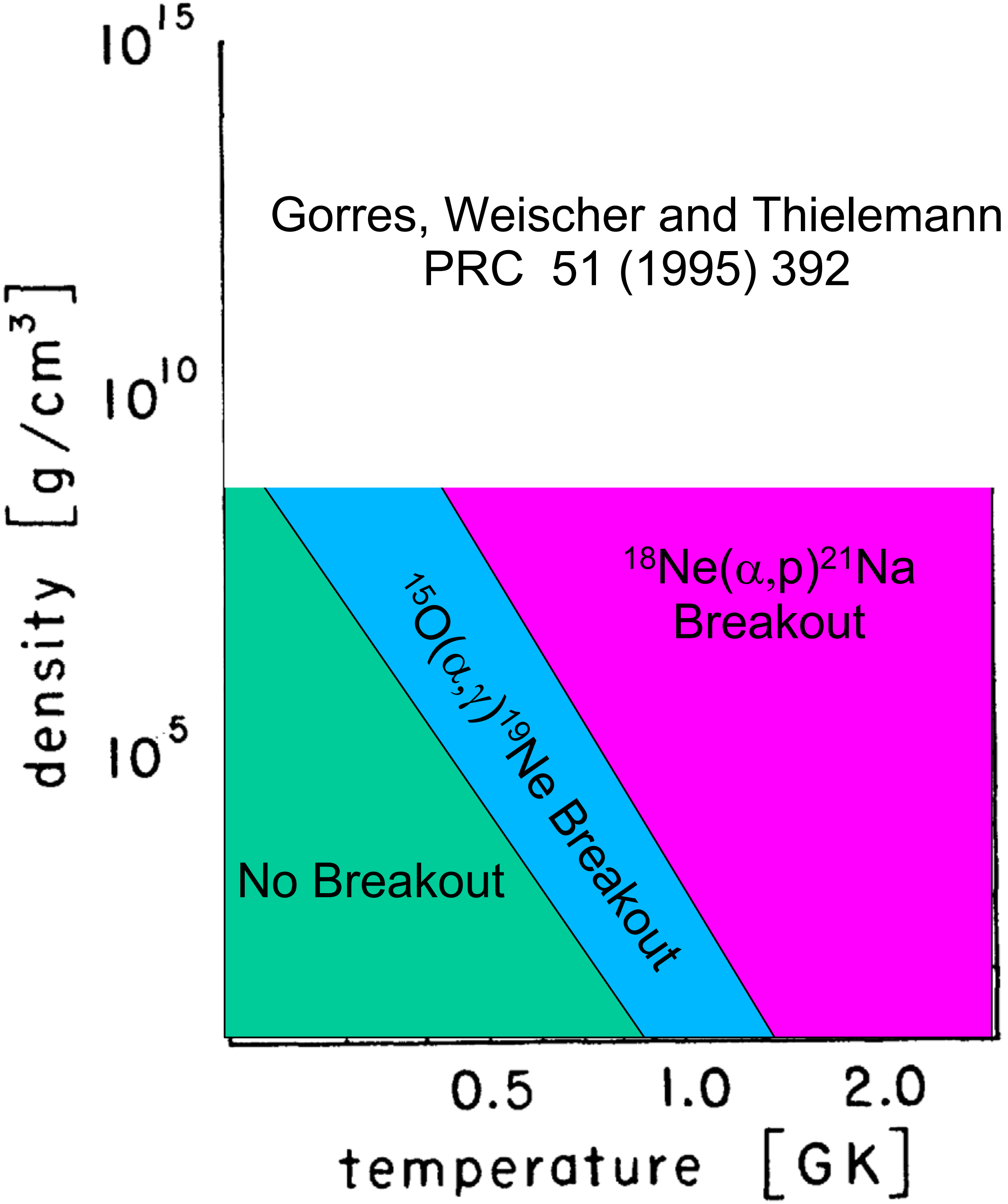
How do we calc?

Multizone Nova model
(Starrfield 2001)

Current ^{15}O(a,γ) Rate
with X10 variation

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





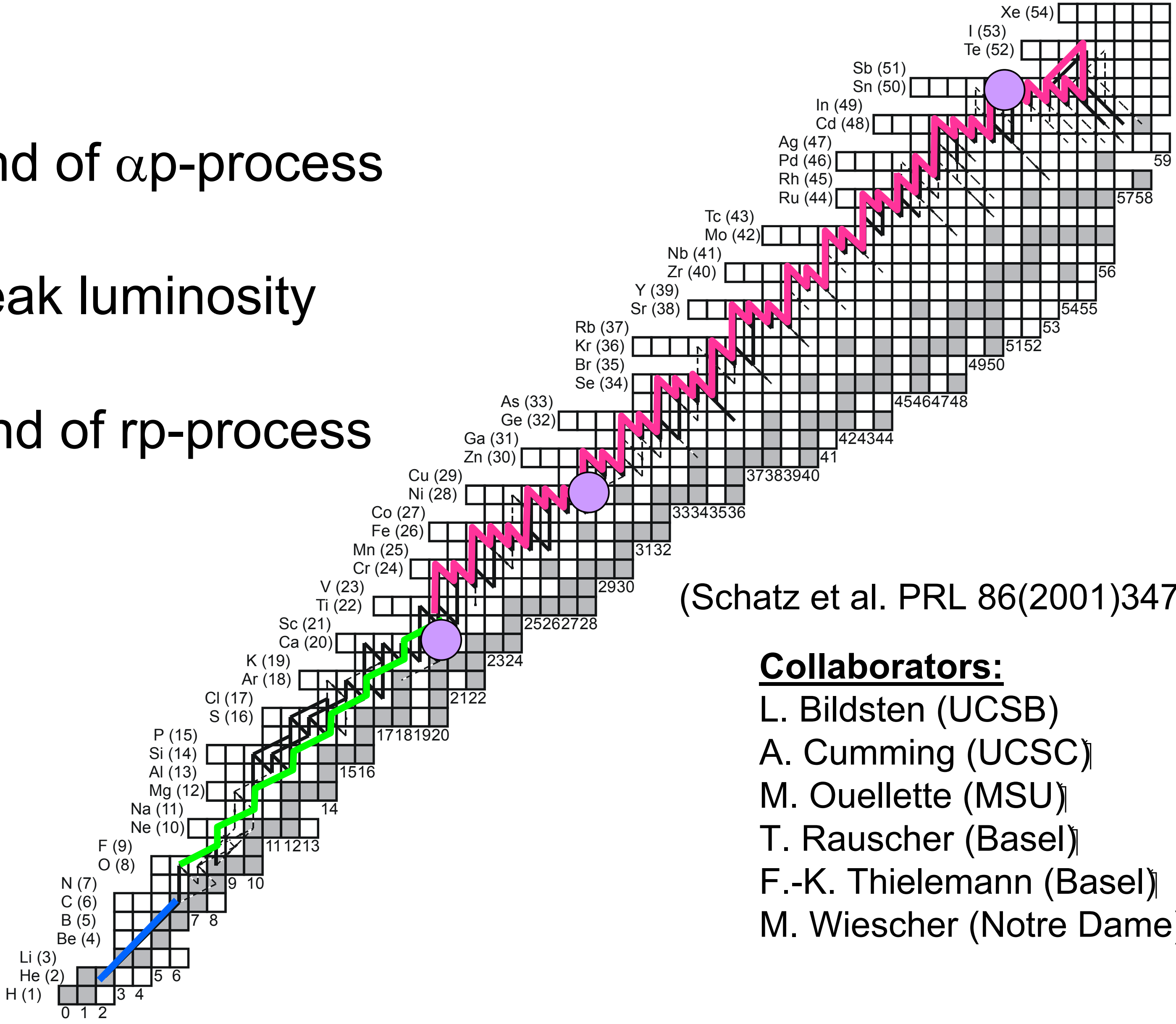
Gorres, Weischer and Thielemann
PRC 51 (1995) 392

Doubly Magic Nuclei influence nucleosynthesis

^{40}Ca – end of αp-process

^{56}Ni – peak luminosity

^{100}Sn – end of rp-process



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

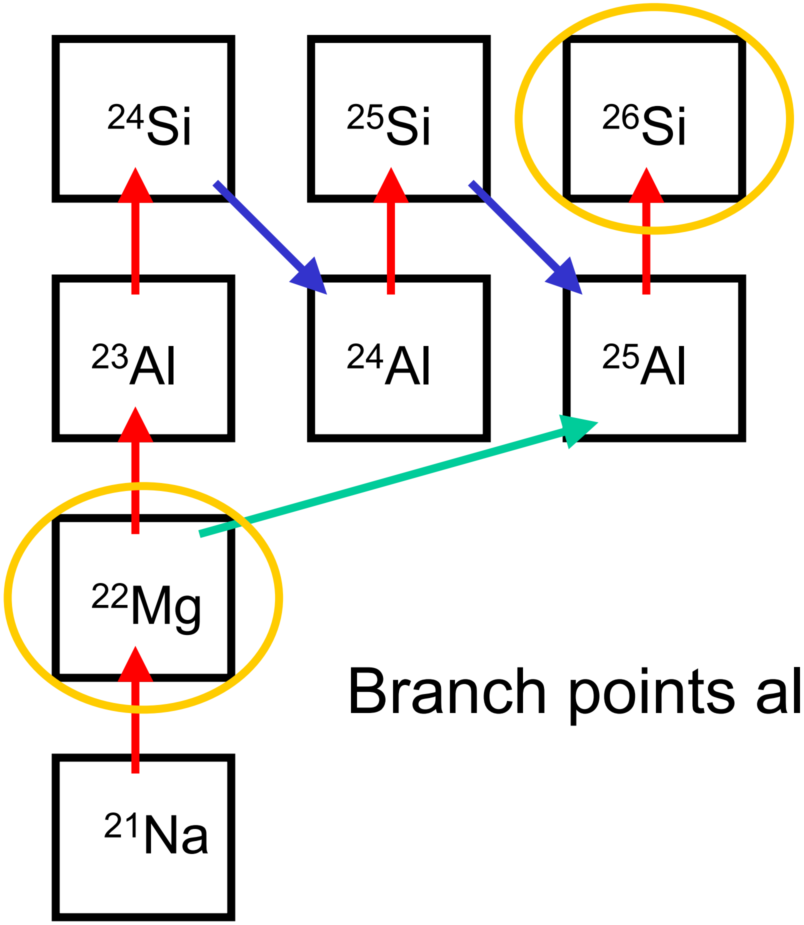
Collaborators:

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

After Breakout

- αp & rp competition
  - Important branching points
- past ^{40}Ca, α-induced reactions inhibited
  - rp-process continues
- Most energy generated near ^{56}Ni
  - Can develop cycles
  - Heavy α-nuclei are waiting points
- ^{100}Sn region natural endpoint

Competition between αp- & rp- processes



^{24}Si

^{25}Si

^{26}Si

^{23}Al

^{24}Al

^{25}Al

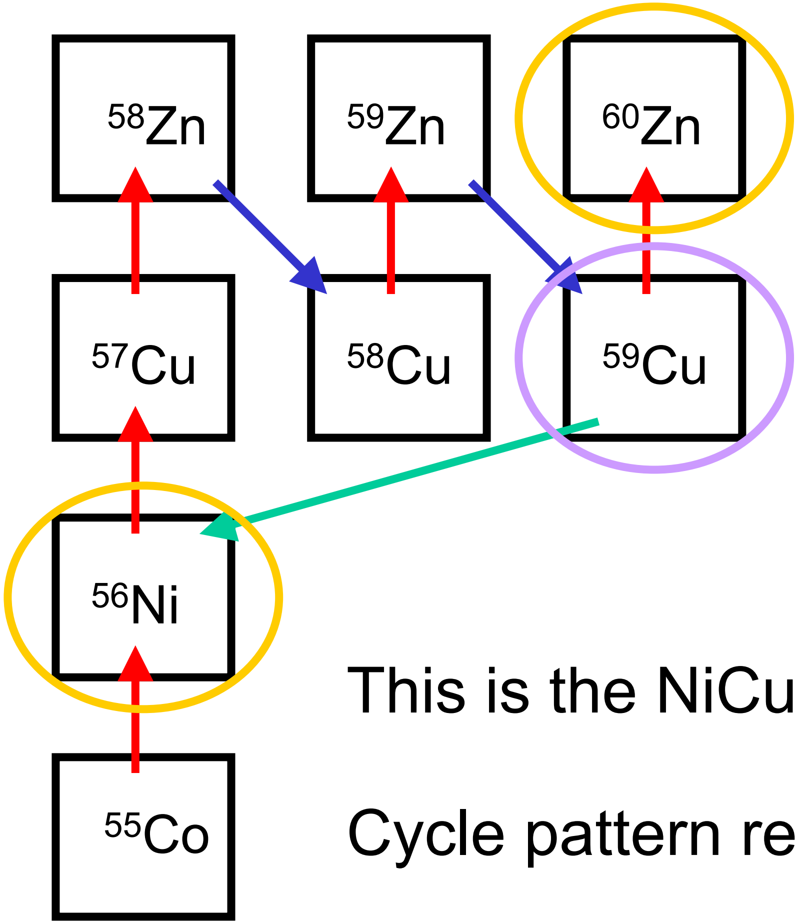
^{22}Mg

^{21}Na

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

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

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

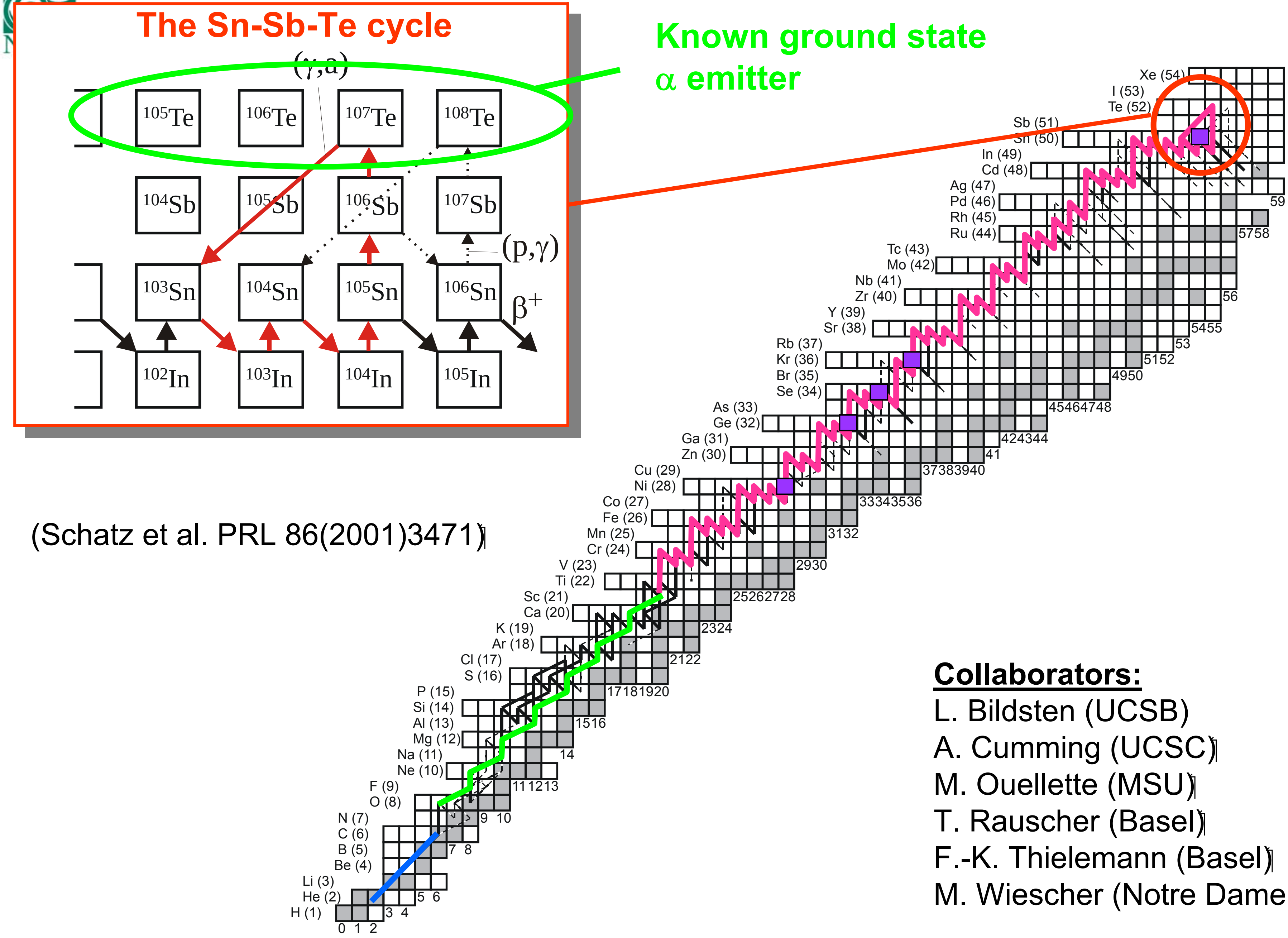
Waiting points

Slow reactions → extend energy generation
→ abundance accumulation

(steady flow approximation $\lambda Y = \text{const}$ or $Y \sim 1/\lambda$)

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

Endpoint: Limiting factor I – SnSbTe Cycle



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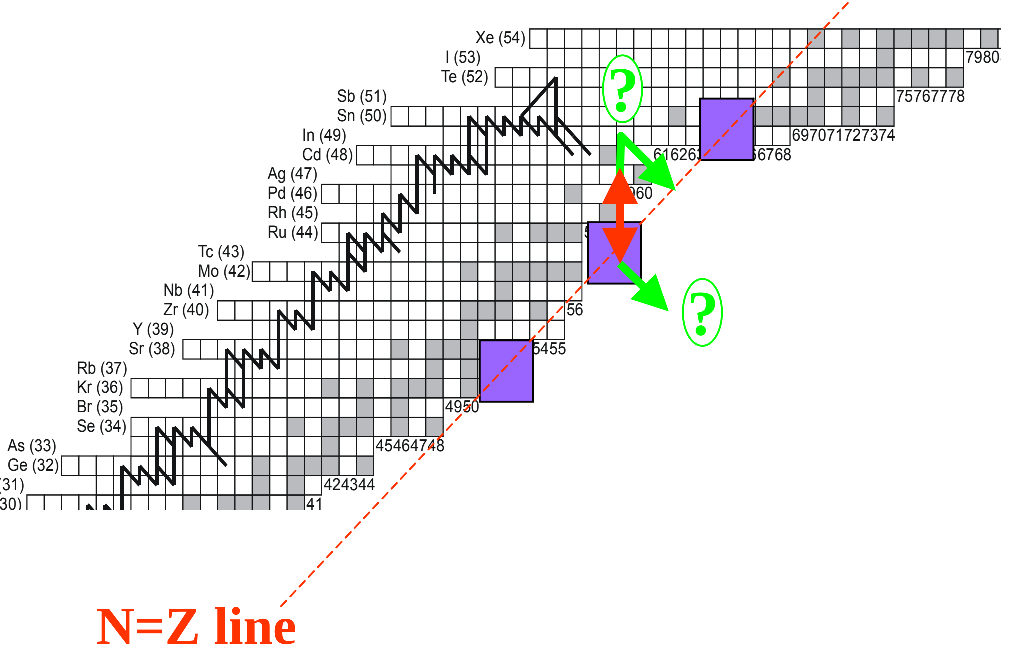
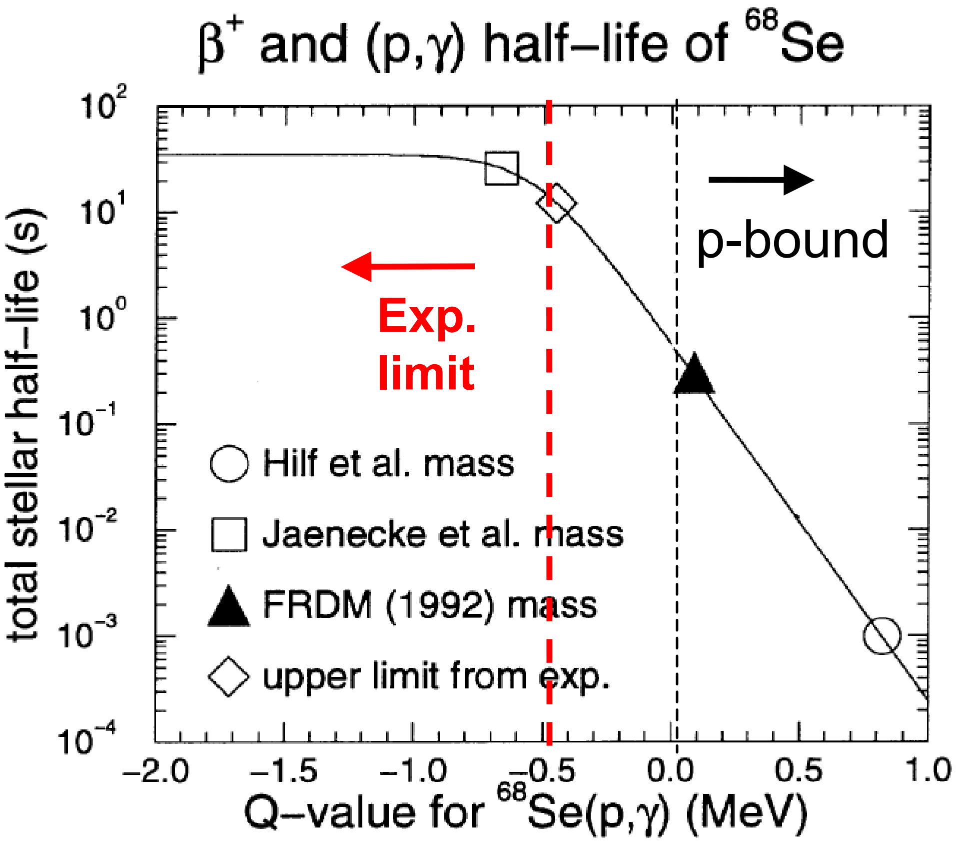
Experiments in the rp-process

Henrique Bertulani

Data needs for rp process





Schatz et al.
Phys. Rep. 294(1998)167

→ Key nuclear physics parameters:

- Proton separation energies (masses)
- β-decay half-lives
- proton capture rates

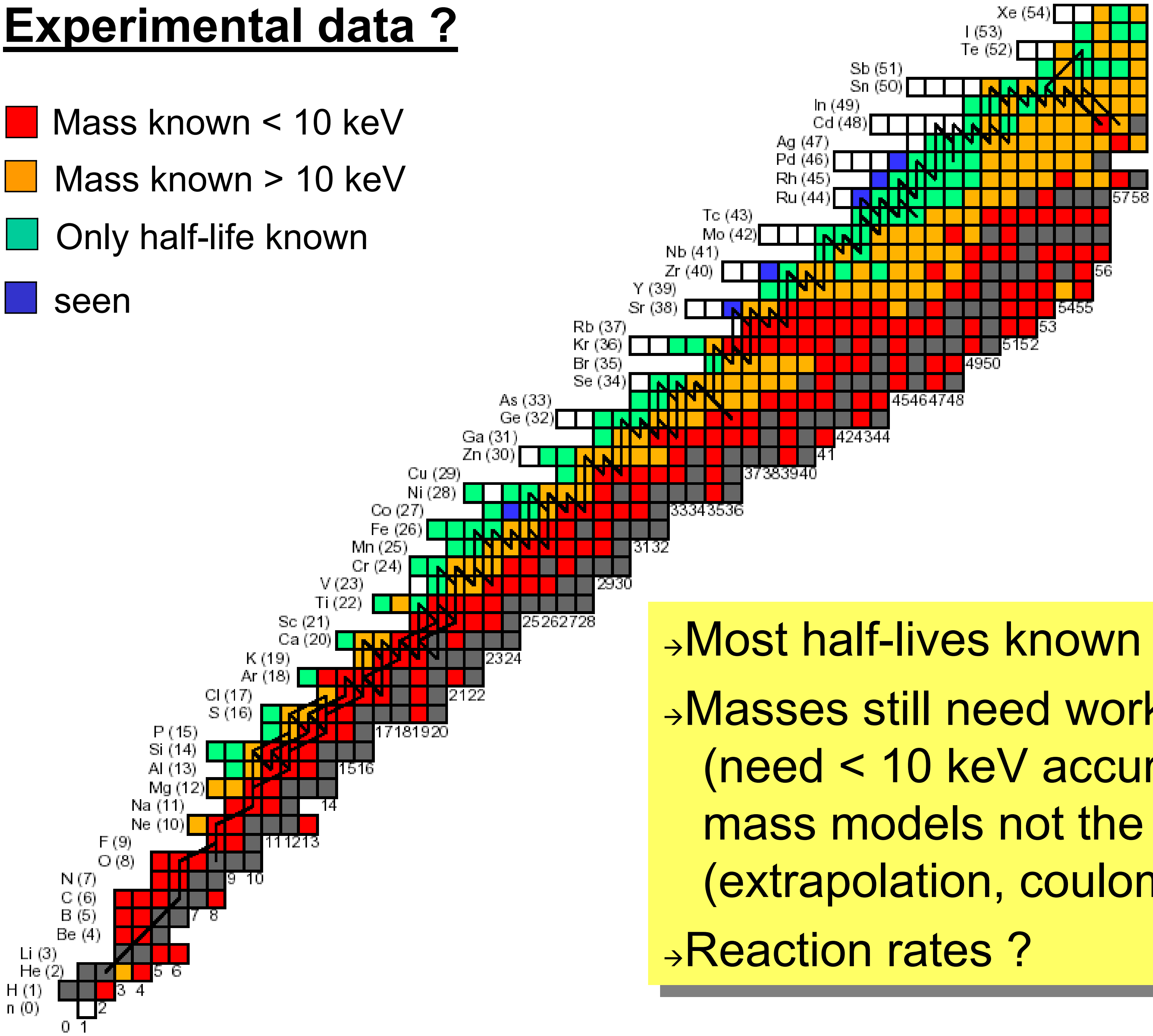
Experimental data ?

🟥 Mass known < 10 keV

🟧 Mass known > 10 keV

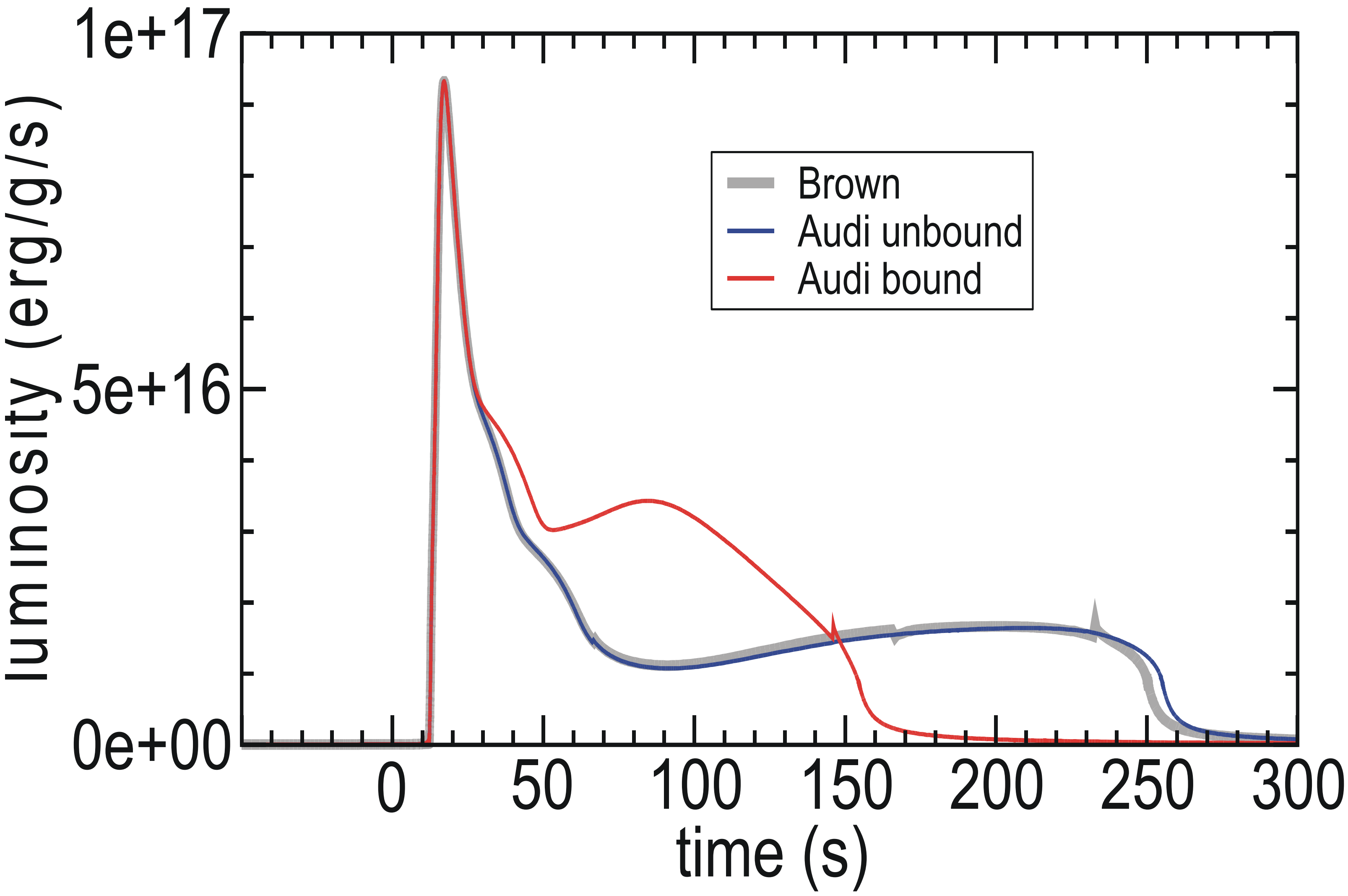
🟩 Only half-life known

🟦 seen



- →Most half-lives known
- →Masses still need work
  (need < 10 keV accuracy)
  mass models not the issue
  (extrapolation, coulomb shift)
- →Reaction rates ?

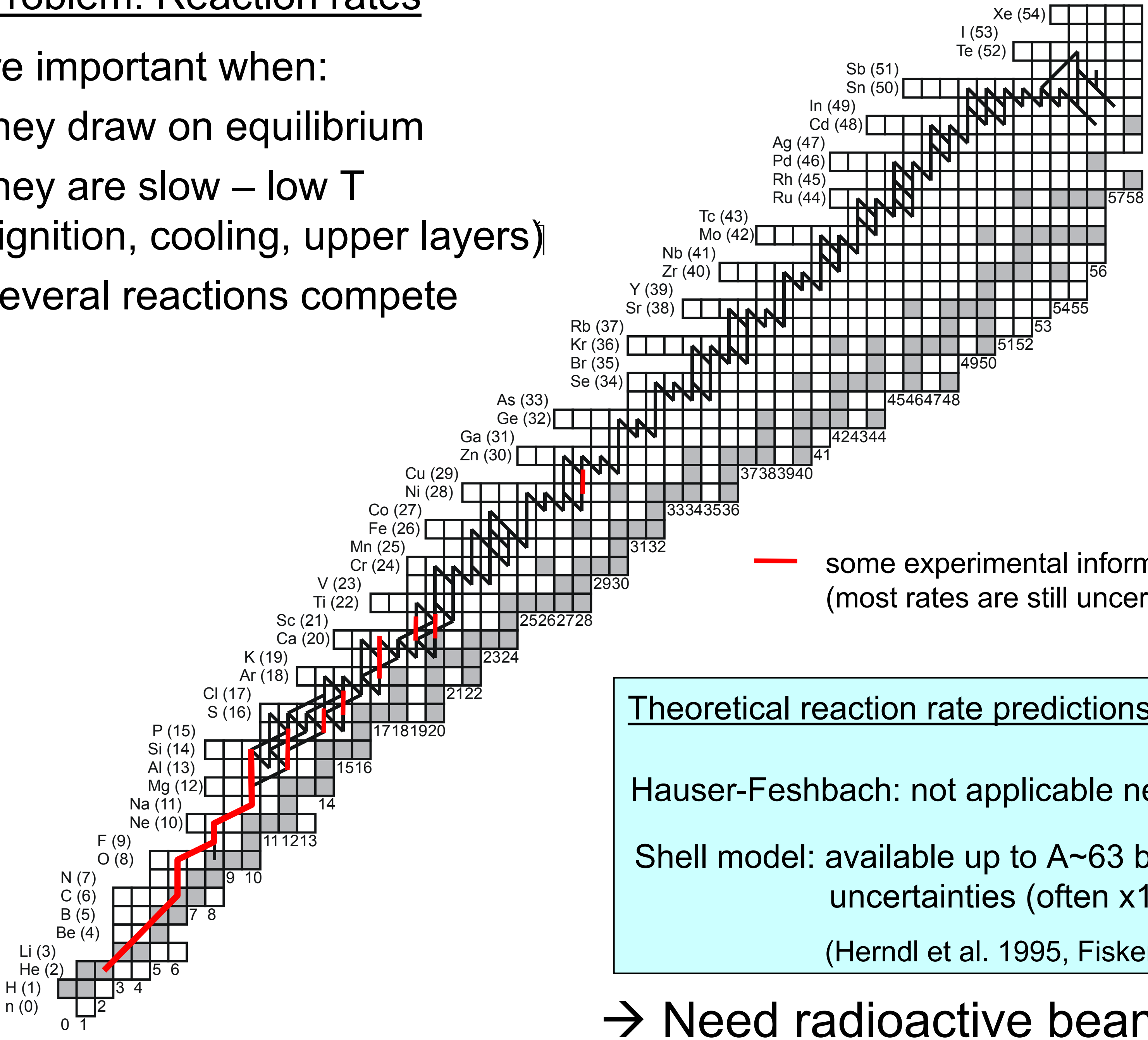
Influence of masses on X-ray burst models



Problem: Reaction rates

Are important when:

- they draw on equilibrium
- they are slow – low T
  (ignition, cooling, upper layers)
- several reactions compete



some experimental information available
(most rates are still uncertain)

Theoretical reaction rate predictions:

Hauser-Feshbach: not applicable near drip line

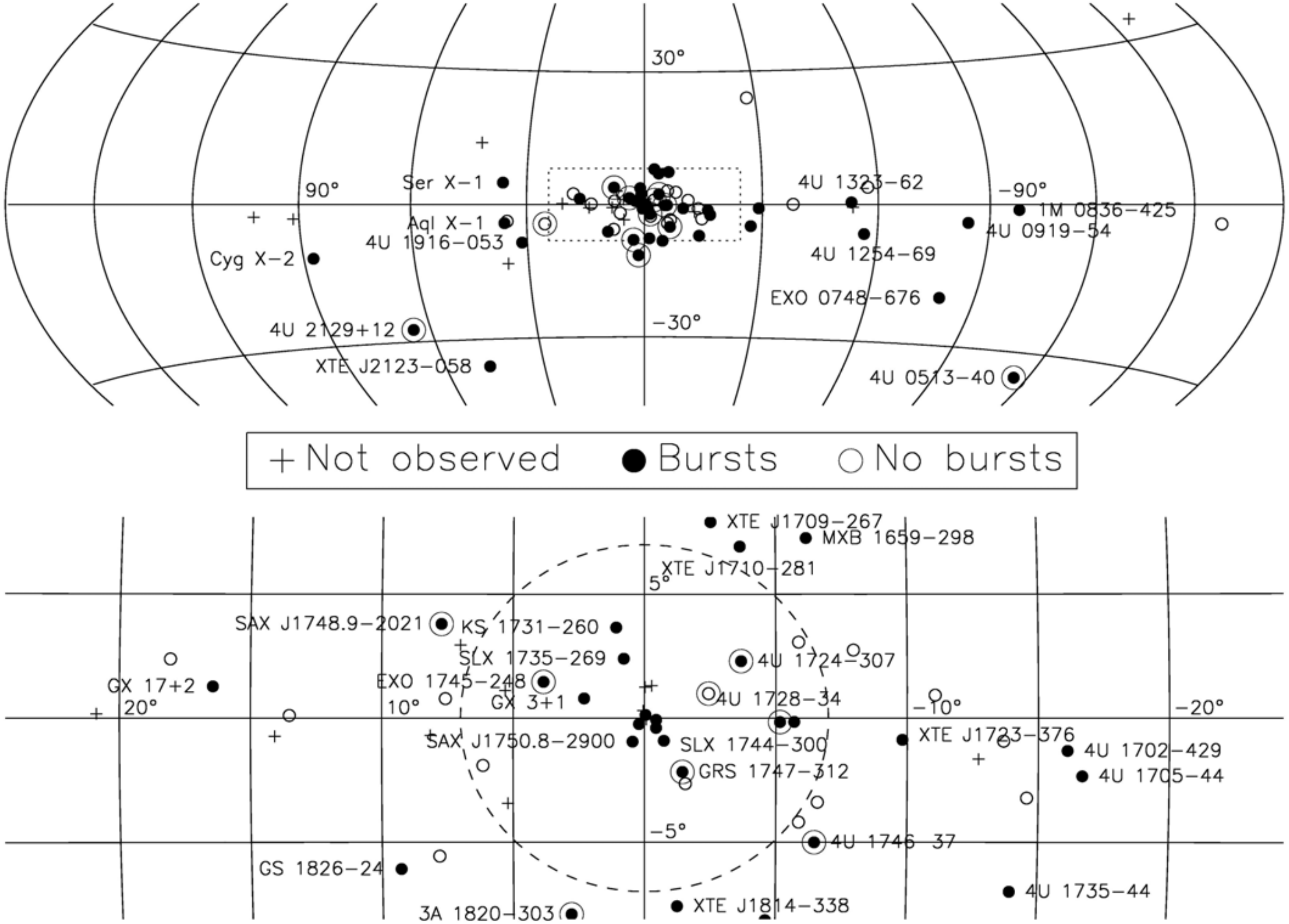
Shell model: available up to A~63 but large uncertainties (often x1000 - x10000)

(Herndl et al. 1995, Fisker et al. 2001)

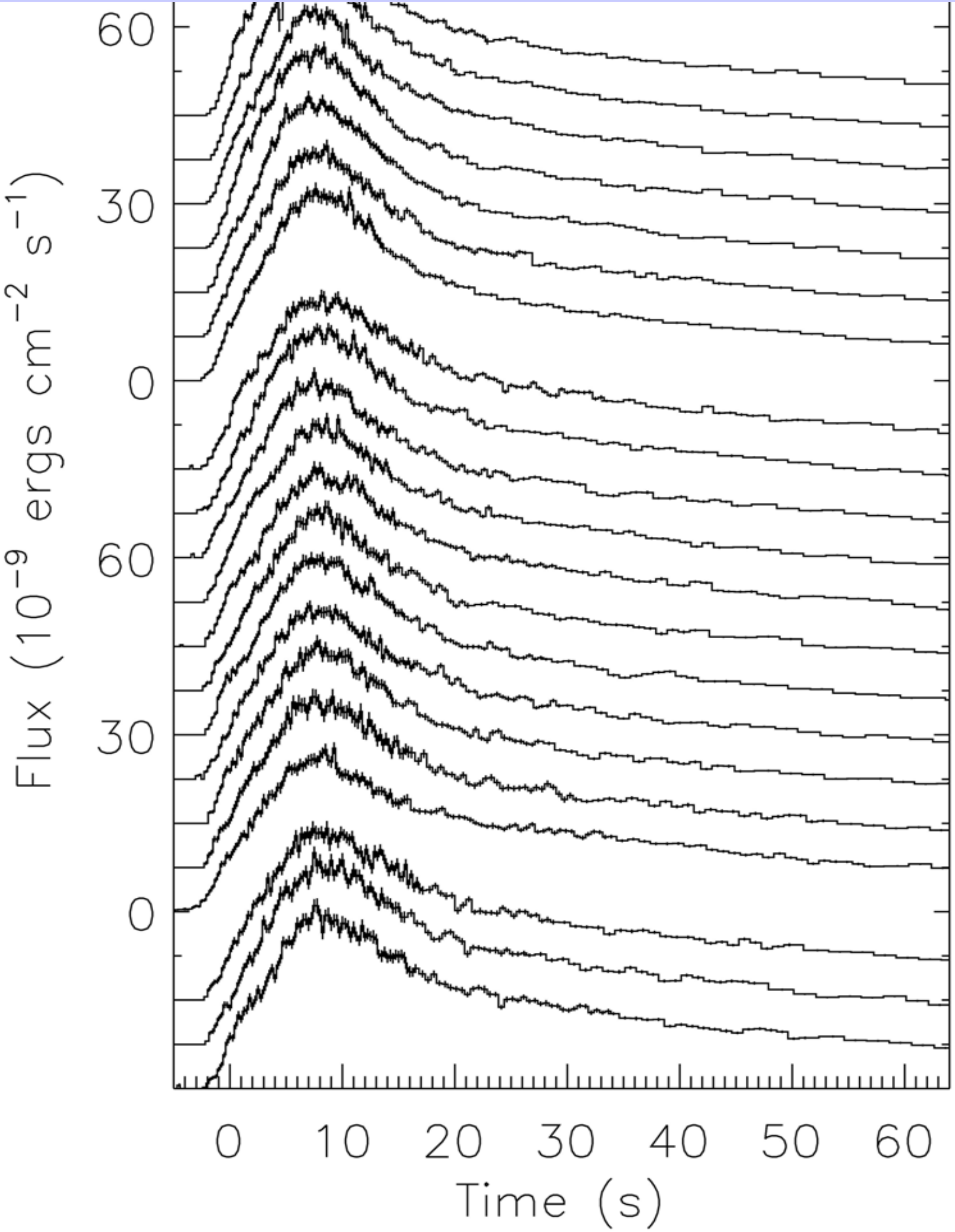
→ Need radioactive beams

Comparison to Observations

Galloway et al ApJS 179 (2007) 360



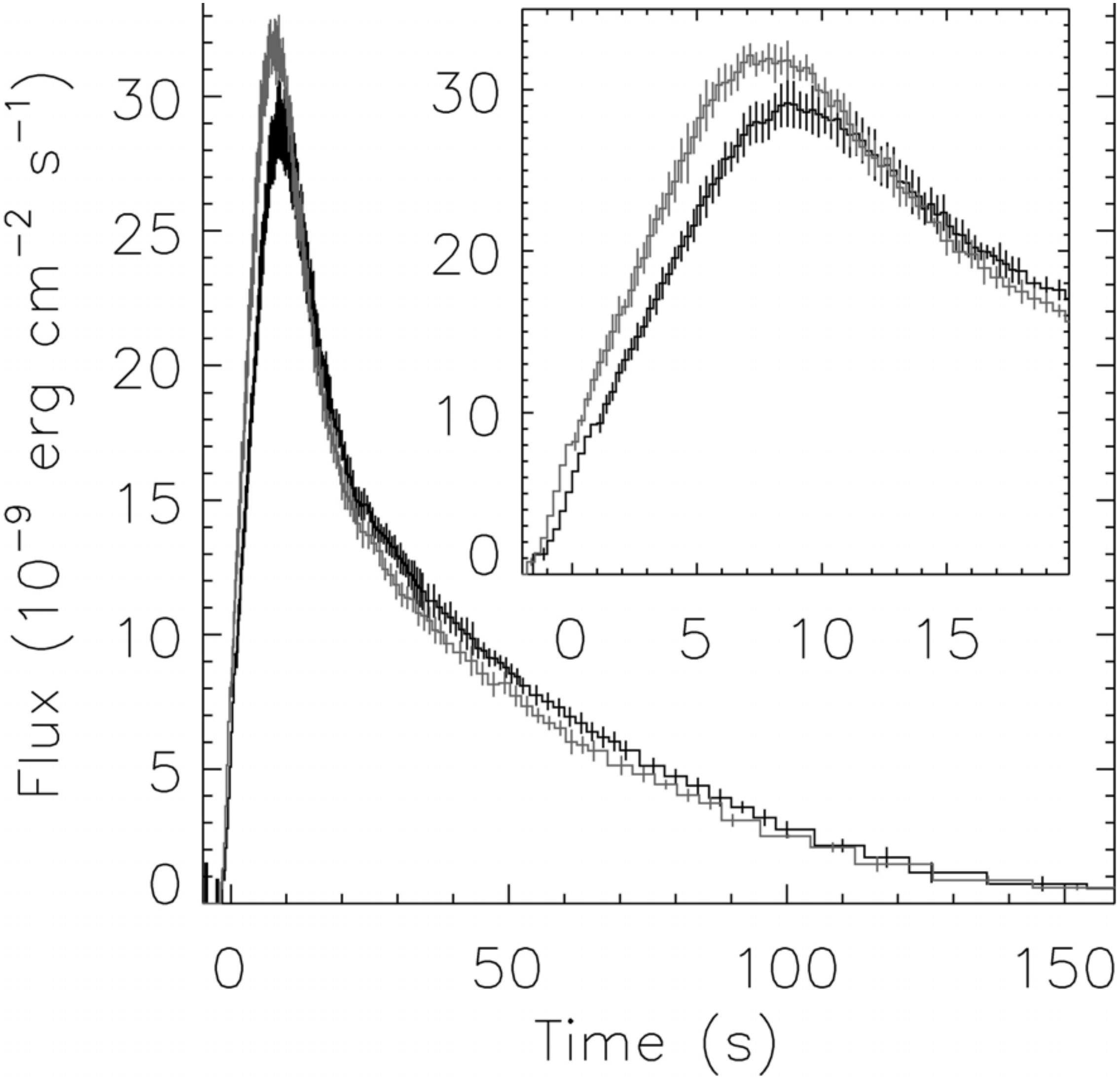
Repeated Observations of GS 1828 24



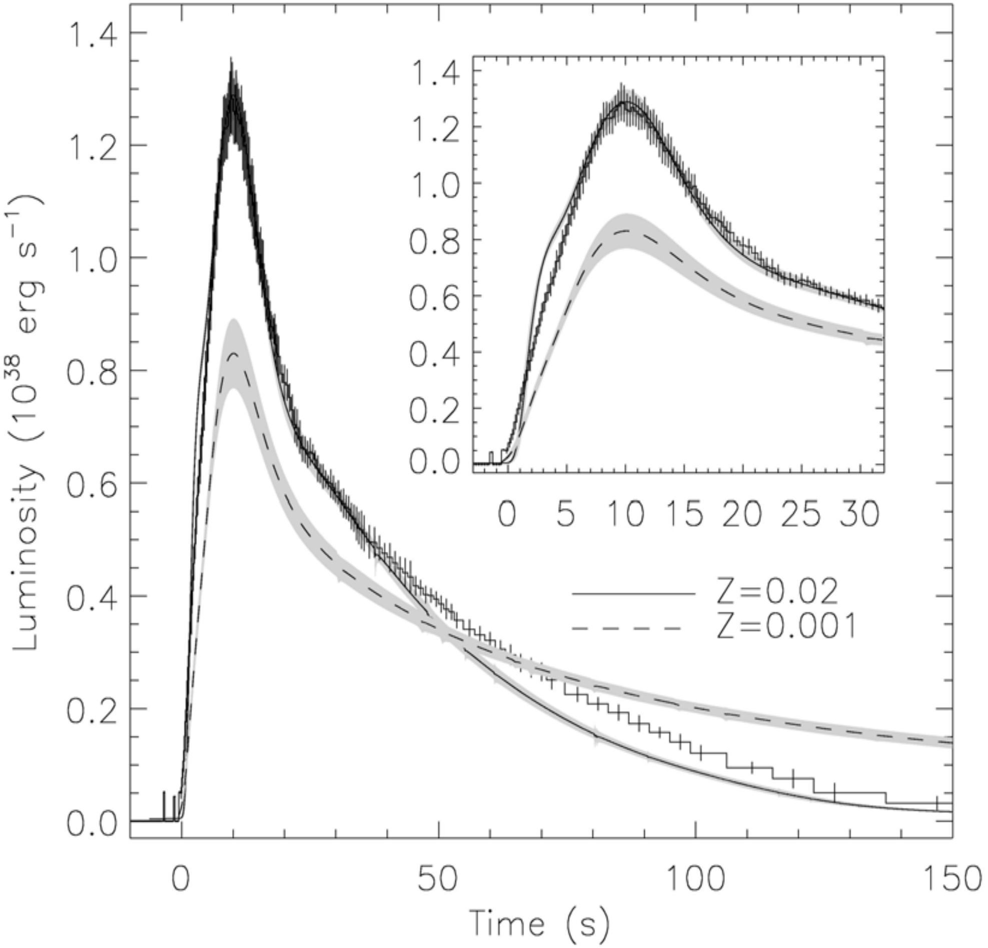
Galloway et al ApJ 601 (2004) 466

Average XRB Light Curve

Galloway et al ApJ 601 (2004) 466



Model Comparisons



Heger et al ApJL 671 (2007) 141

Summary

- rp-process is important to understand
  - X-ray bursts
  - crusts of accreting neutron stars/ transients
  - neutron stars !

- need radioactive beam experiments
  - much within reach at existing facilities
  - with RIA and FAIR precision tests possible

- lots of open question – much work to do
  - modelling
  - nuclear physics (predict instabilities ?)
  - observations