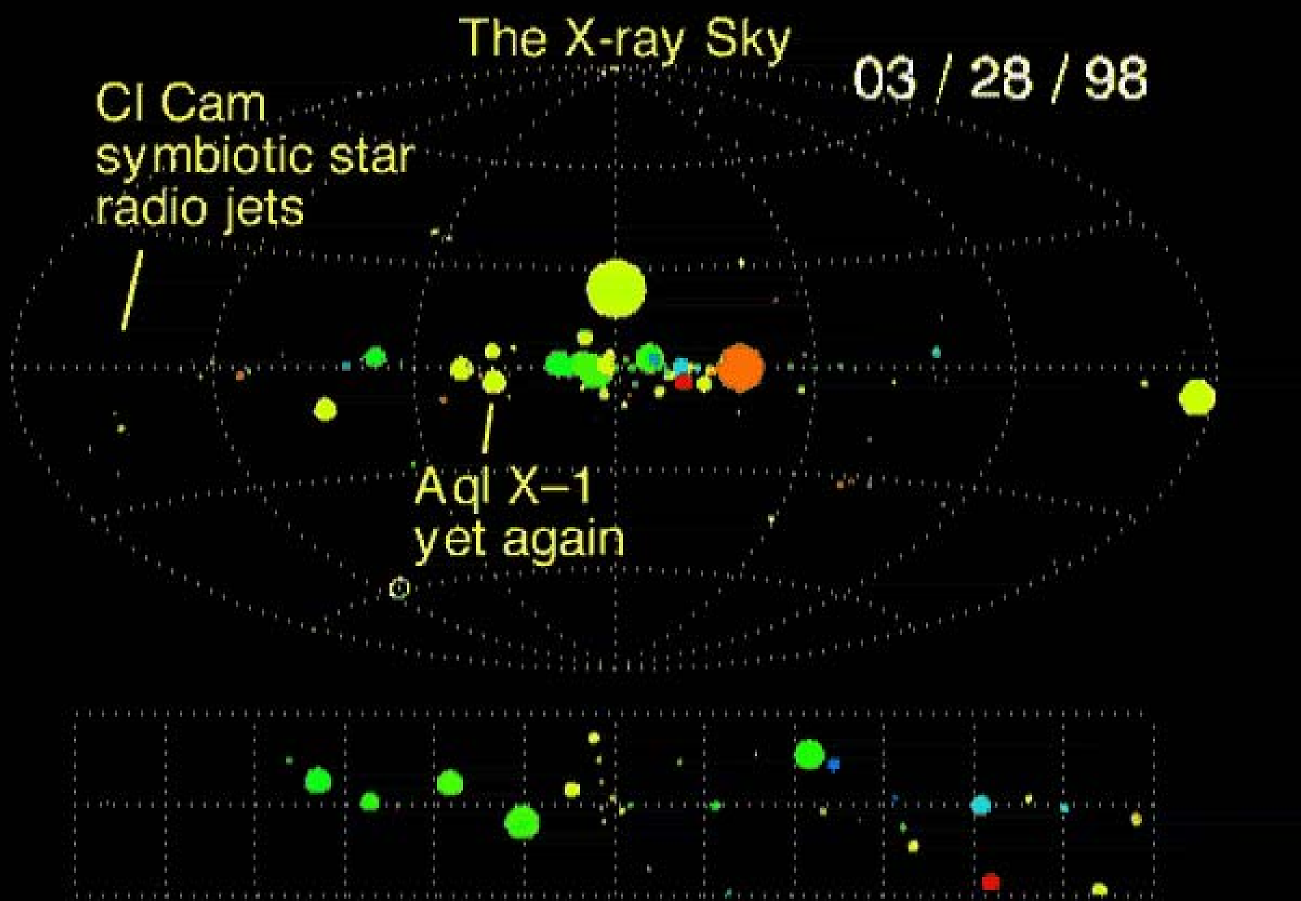
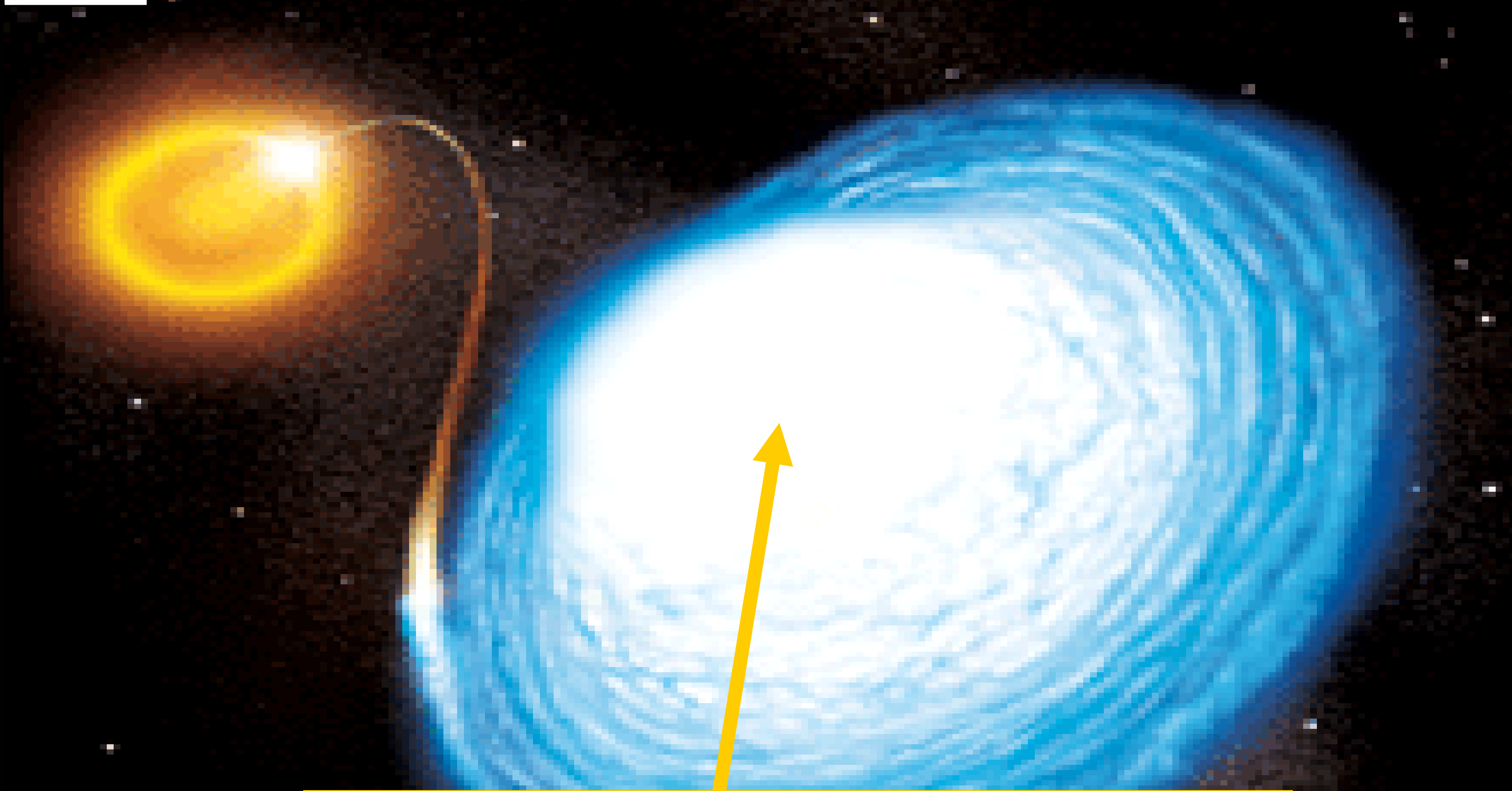
Nuclear physics of X-ray bursts and dense nuclear matter

H. Schatz, MSU & Joint Instutute for Nuclear Astrophysics



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

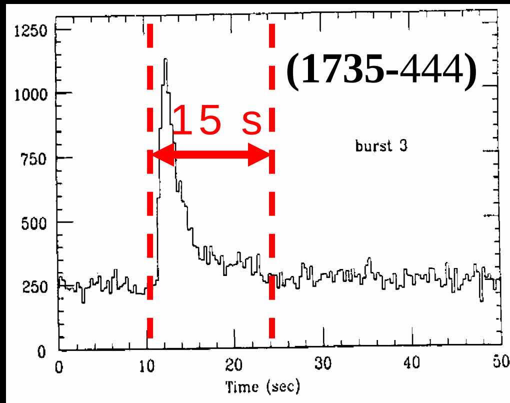
Accreting neutron stars



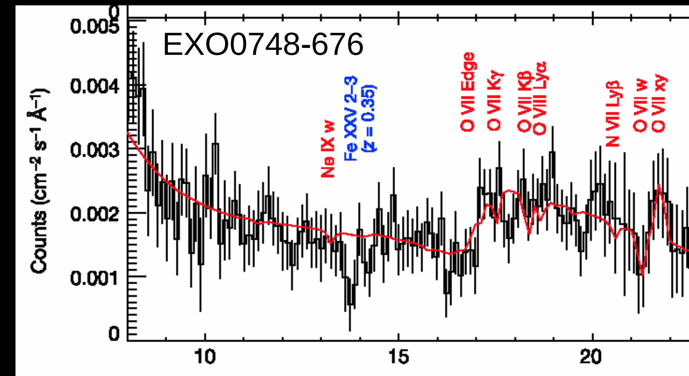
<u>Open new parameter space as probes for dense matter</u>

- spin up
- heated (in transients heating and cooling alternates)
- mass increase

X-ray bursts → cooling



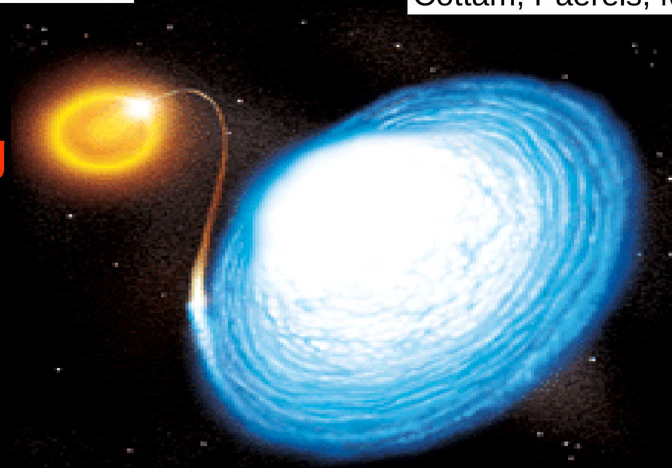
Lines during bursts → M,R



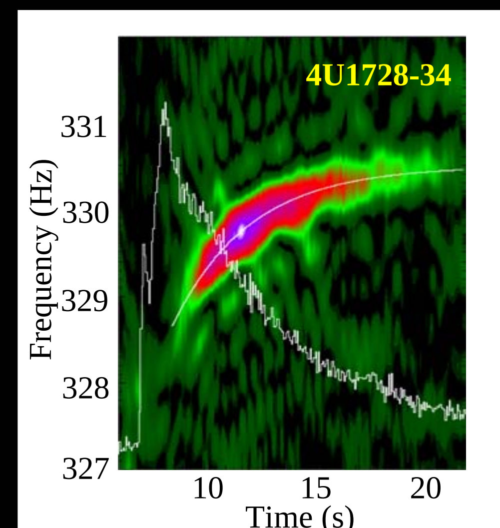
Cottam, Paerels, Mendez 2002

Off-state Lum. → cooling

NASA/Chandra/Wijnands et al.

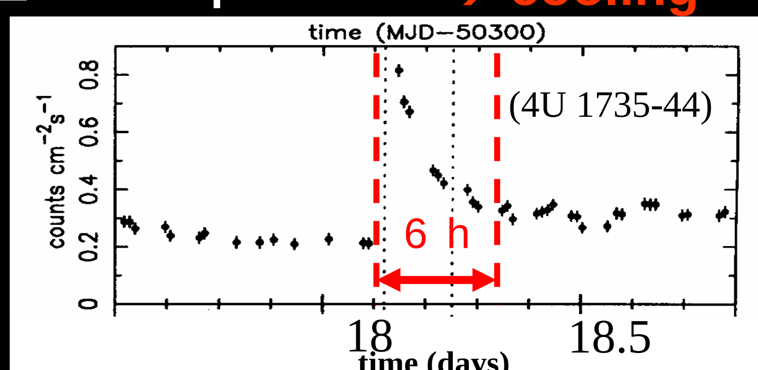


ms burst oscillations → M,R

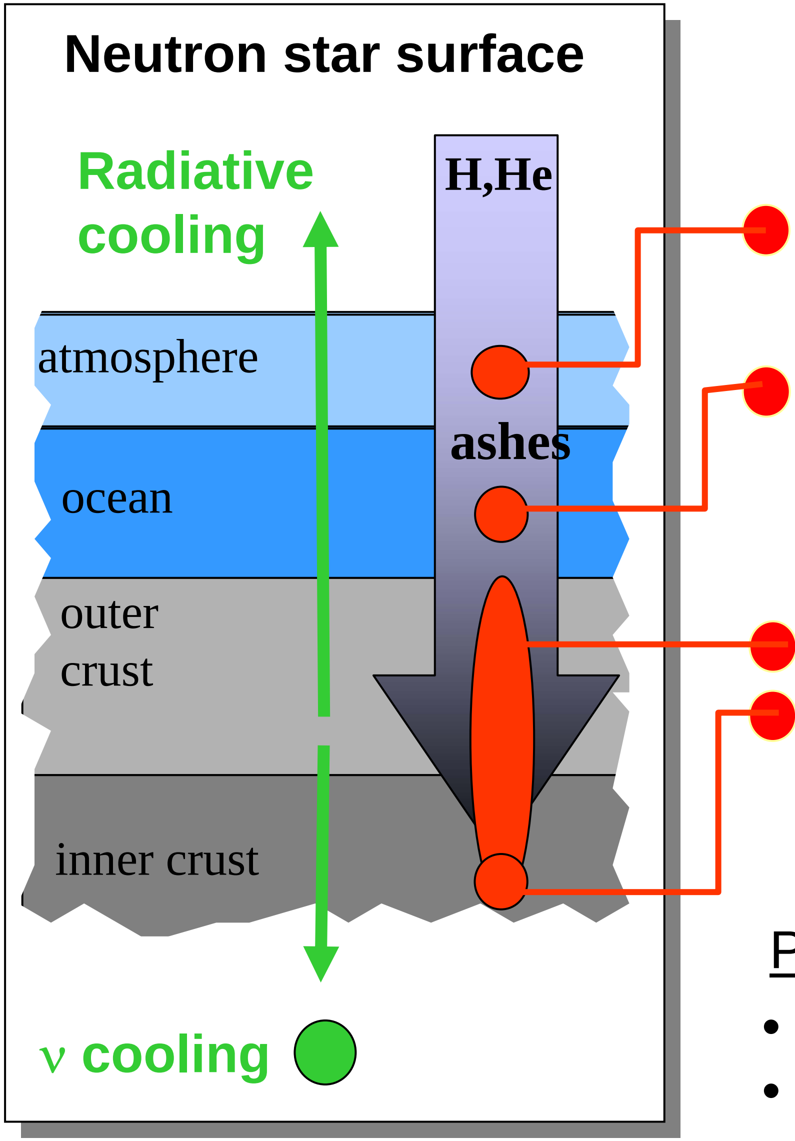


Strohmayer
Bhattacharyya et al. 2004

Superbursts → cooling



Probing the thermal structure of accreting neutron stars



Bursts: H, He burning (rp-process)

Superbursts: deep burning ?

Need burst physics

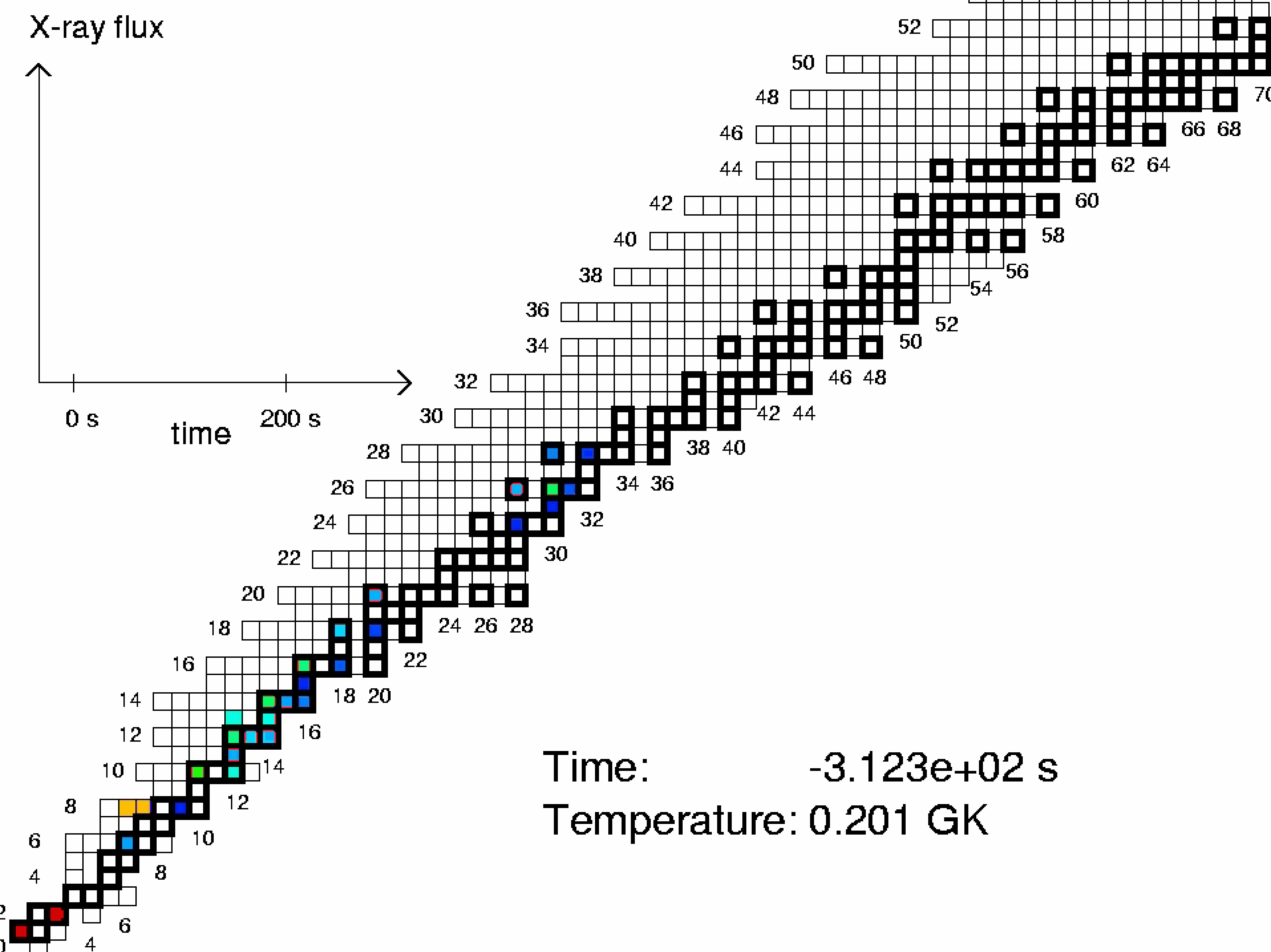
Probes
Crust composition

electron capture
pycnonuclear fusion

Crust heating

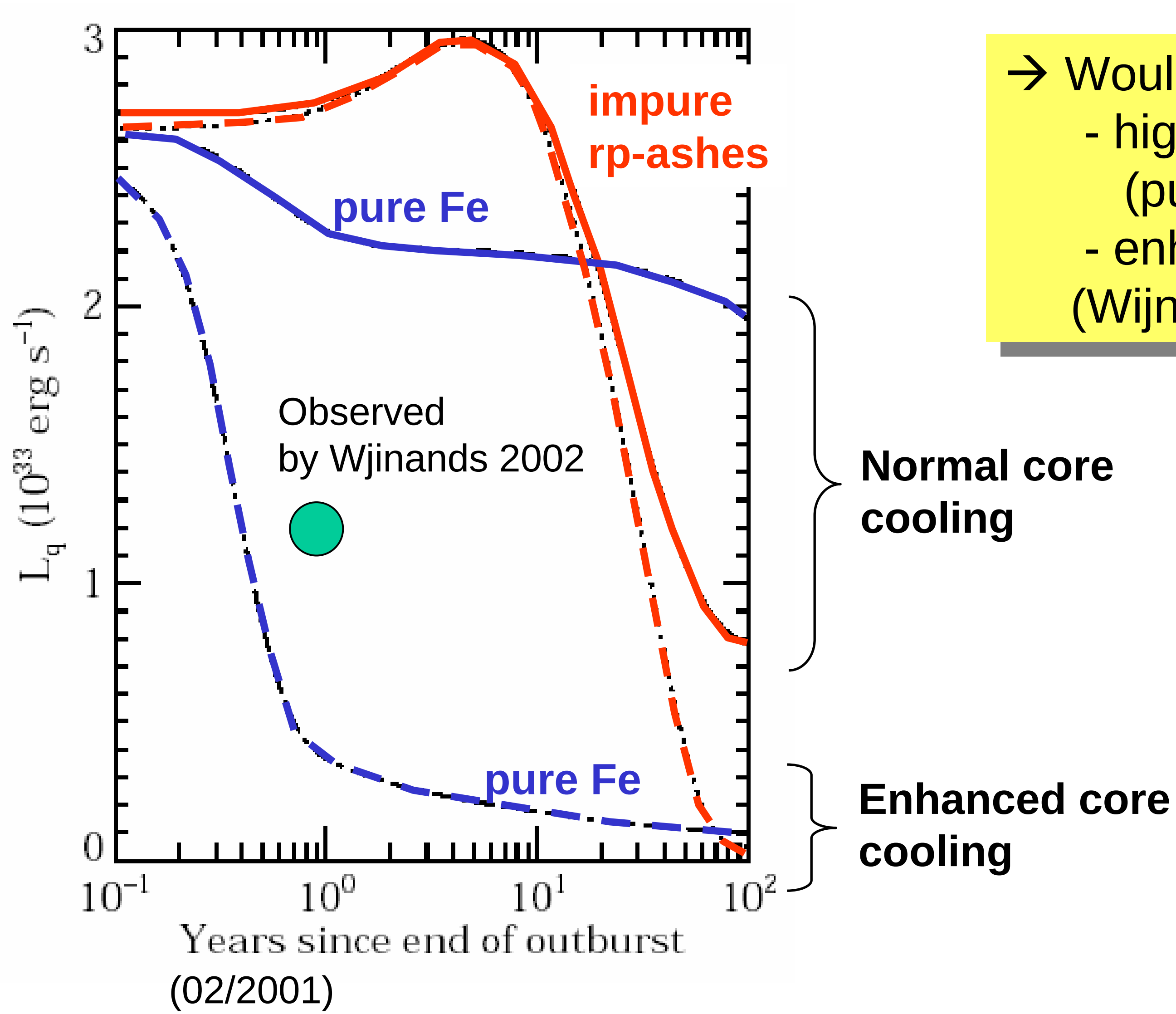
Probes for cooling:

- radiative cooling observable during off-state
- Burst behavior


X-ray flux
0 s
time
200 s
Time: -3.123e+02 s
Temperature: 0.201 GK

Example: Consequences of rp-process crust composition

Rutledge et al. 2002 ApJ 580, 413 (for KS 1731-260)

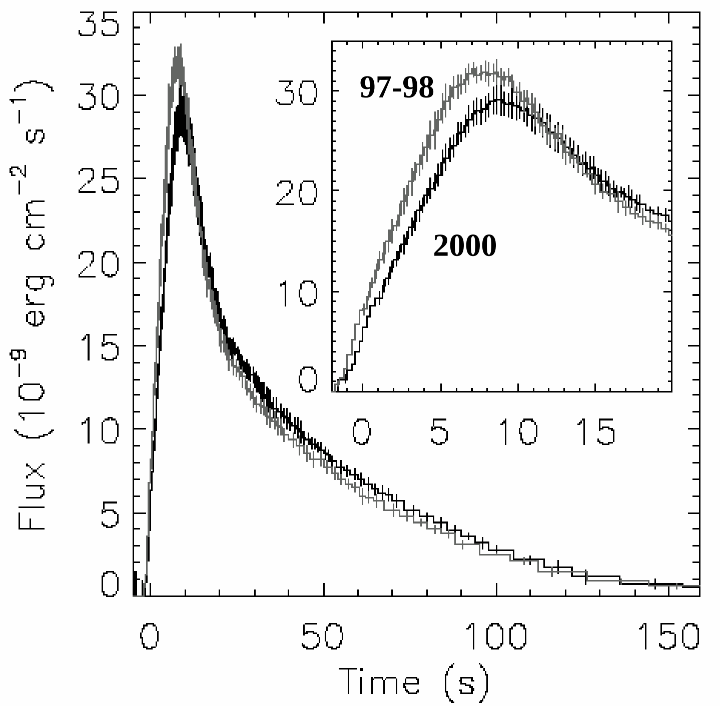


→ Would require:
- high conductivity
  (pure Fe lattice)
- enhanced core cooling
  (Wijnands et al. 2002)

Reality check: Burst comparison with observations

Precision X-ray observations

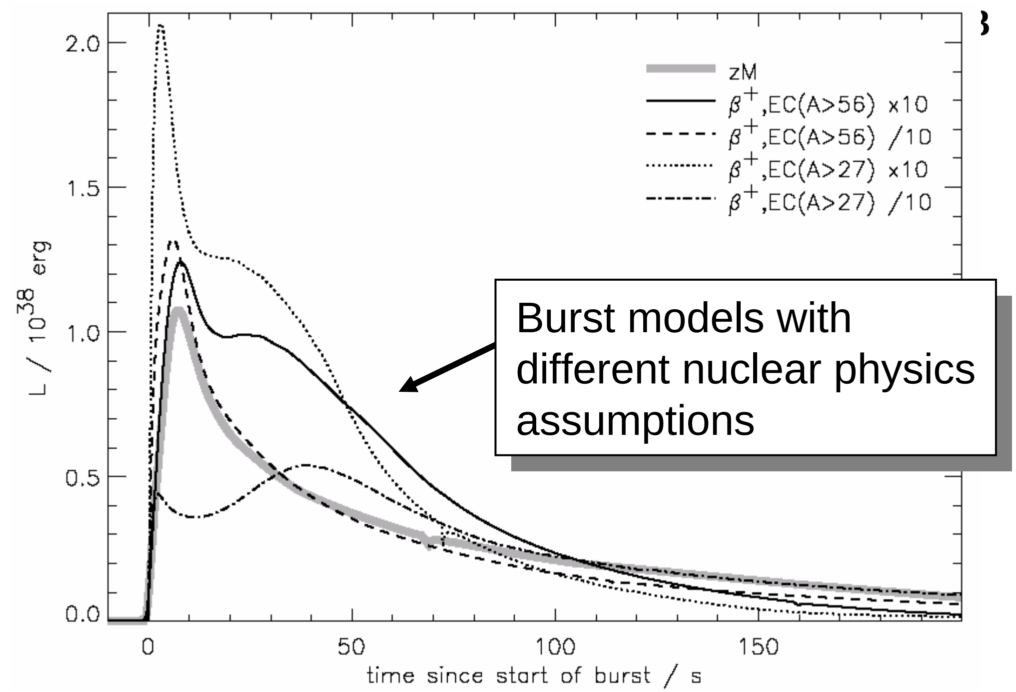
(NASA's RXTE)



→ GS 1826-24 burst shape changes !

(Galloway 2003 astro/ph 0308122)

Uncertain models due to nuclear physics



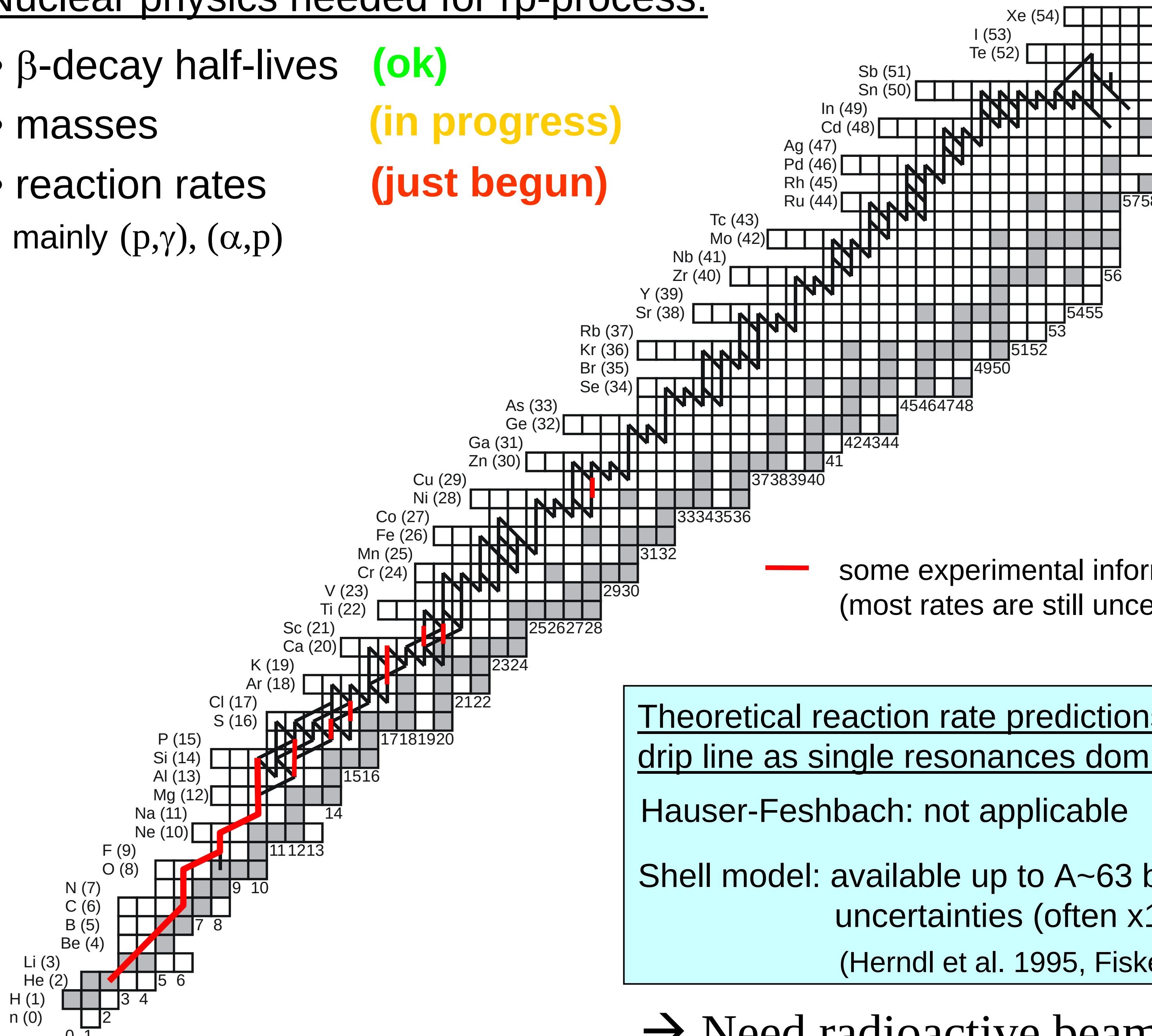
Woosley et al. 2003 astro/ph 0307425

- Need much more precise nuclear data to make full use of high quality observational data

Nuclear physics needed for rp-process:

- β-decay half-lives **(ok)**
- masses **(in progress)**
- reaction rates **(just begun)**

  mainly (p,γ), (α,p)



some experimental information available
(most rates are still uncertain)

<u>Theoretical reaction rate predictions difficult near drip line as single resonances dominate rate:</u>

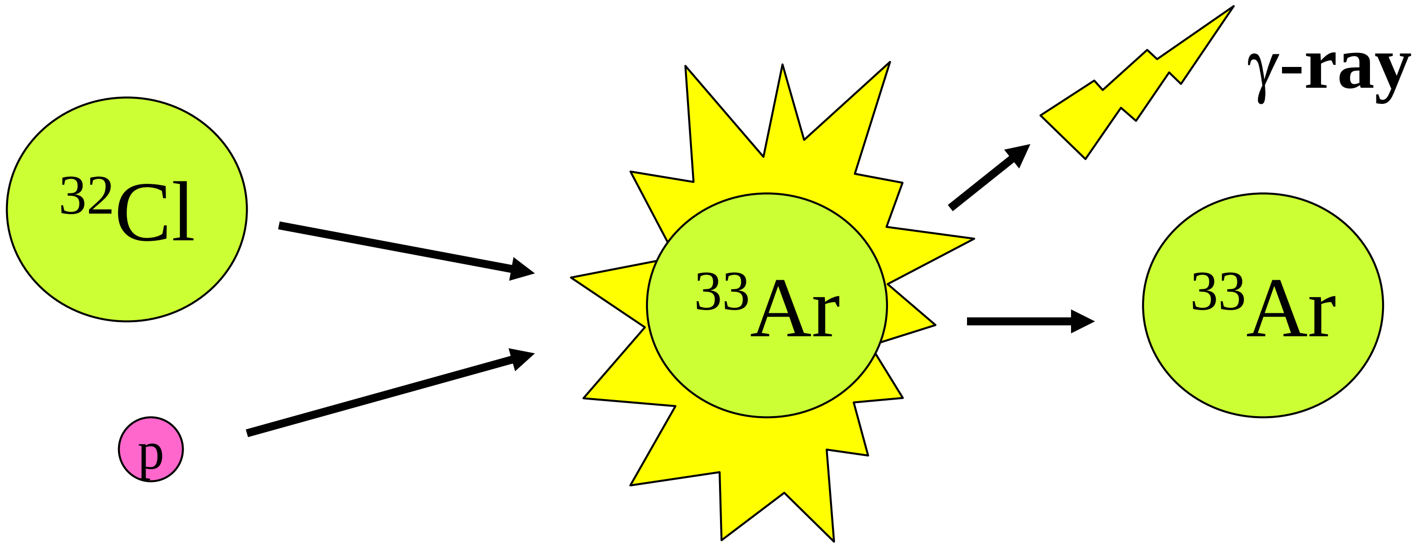
Hauser-Feshbach: not applicable

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

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

→ Need radioactive beams

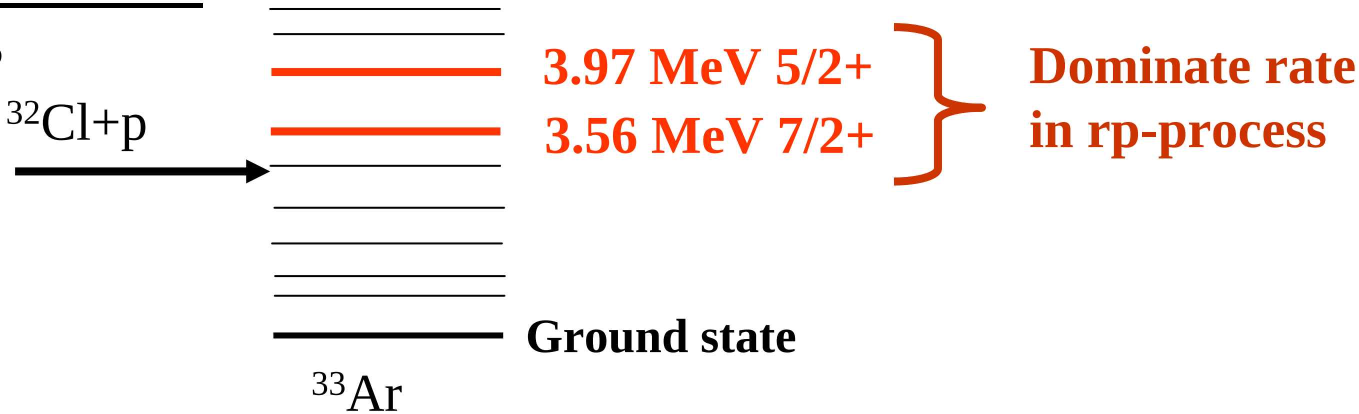
New experimental techniques at NSCL: ^{32}Cl(p,g)^{33}Ar



Resonant enhancement of rate due to 33Ar excited states at the right excitation energy ?

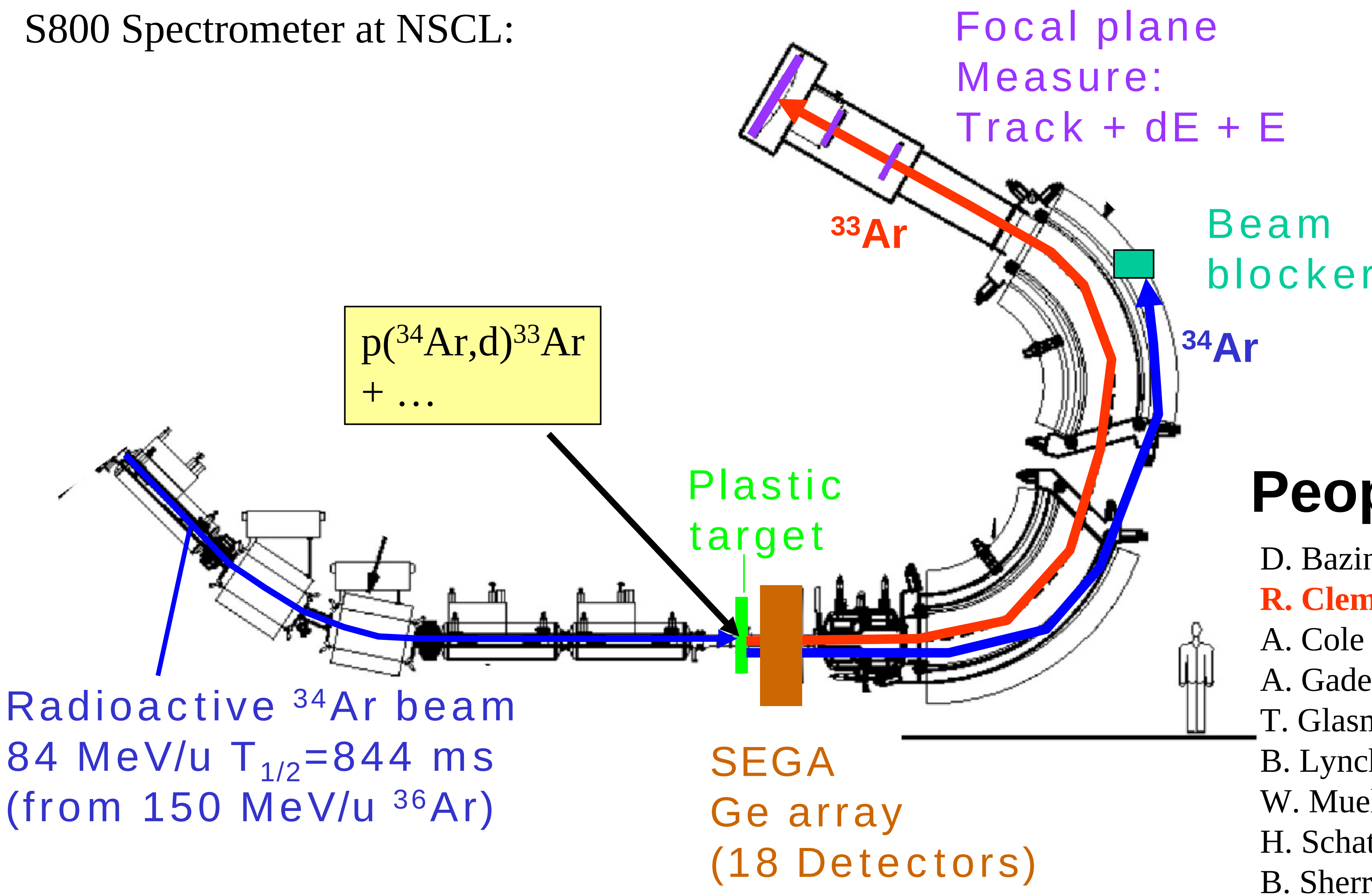
Shell model calculation:

Herndl et al. 1995



Setup

S800 Spectrometer at NSCL:



People:

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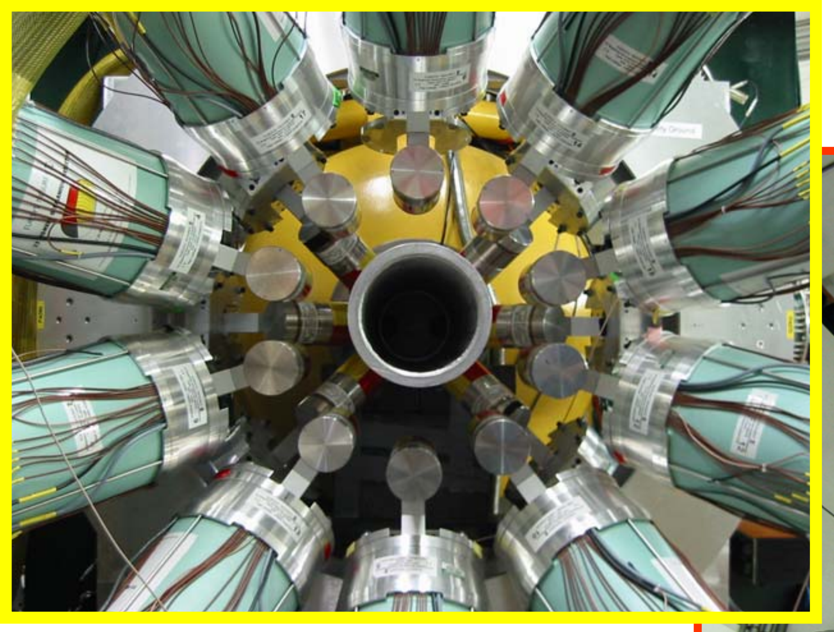


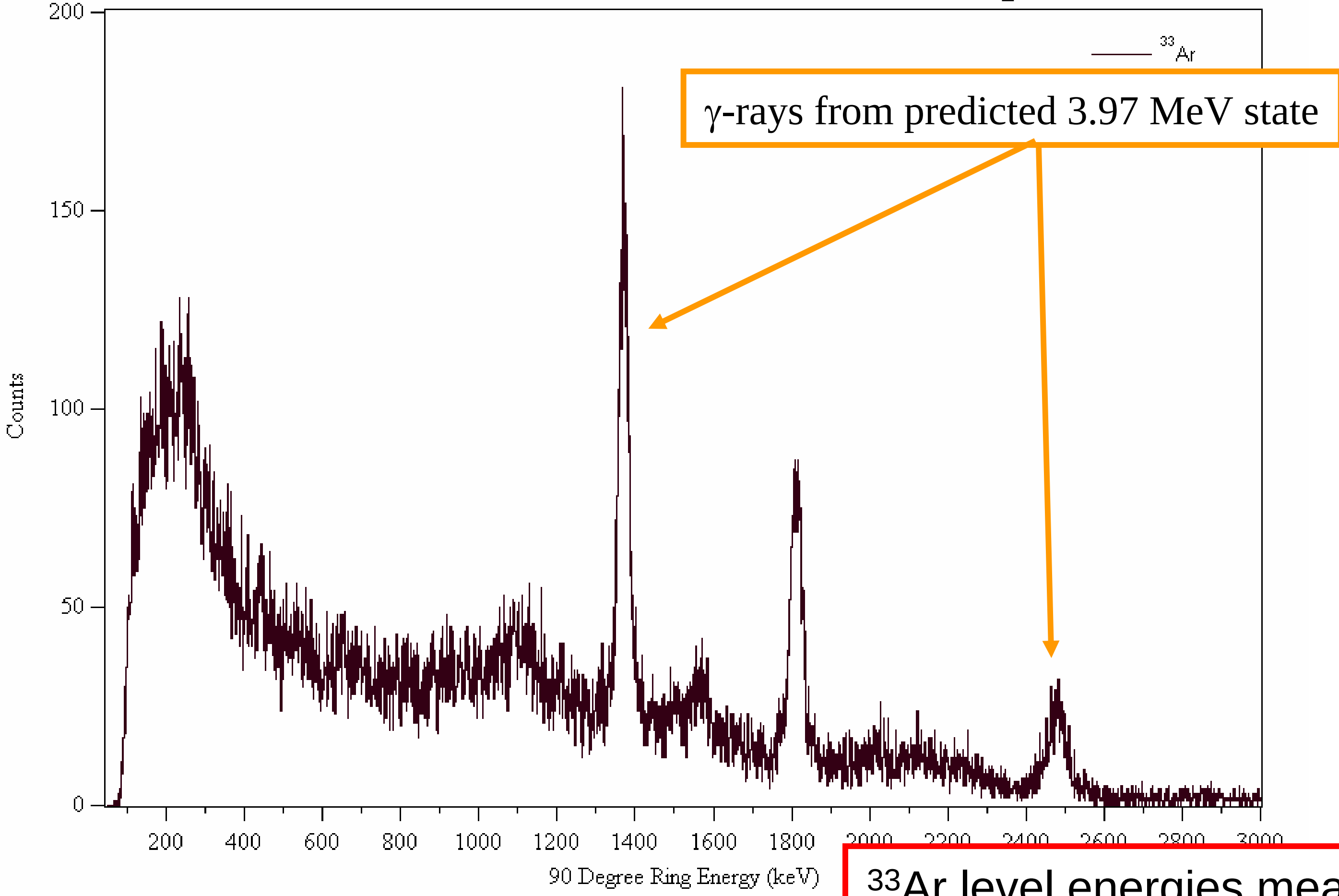
SEGA Ge-array

S800 Spectrometer

NSCL

Results

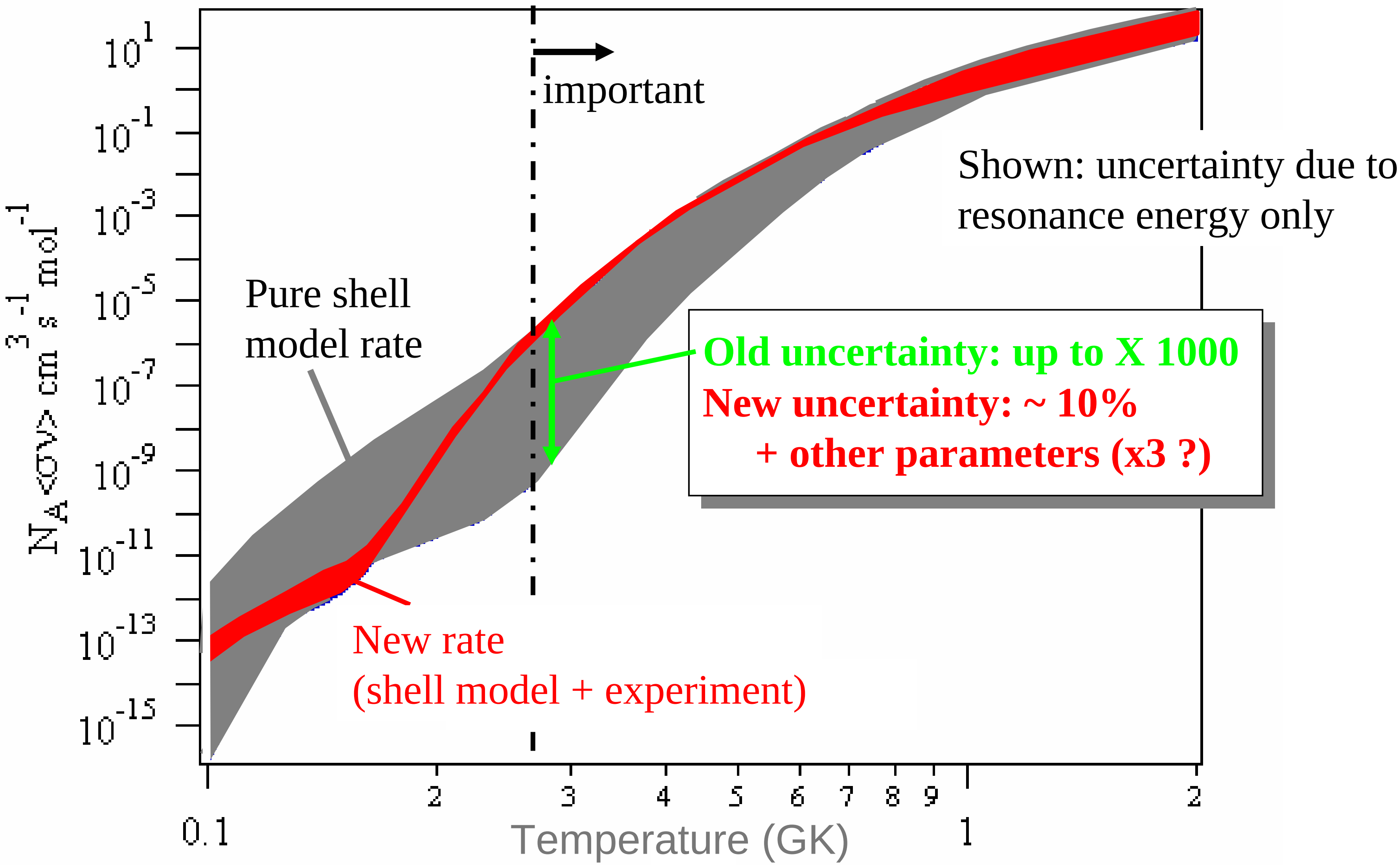
Doppler corrected γ-rays in coincidence with 33Ar in S800 focal plane:



^{33}Ar level energies measured:

3819(4) keV (150 keV lower than predicted)
3456(6) keV (104 keV lower than predicted)

New $^{32}Cl(p,g)^{33}Ar$ rate – Clement et al. PRL 92 (2004) 2502



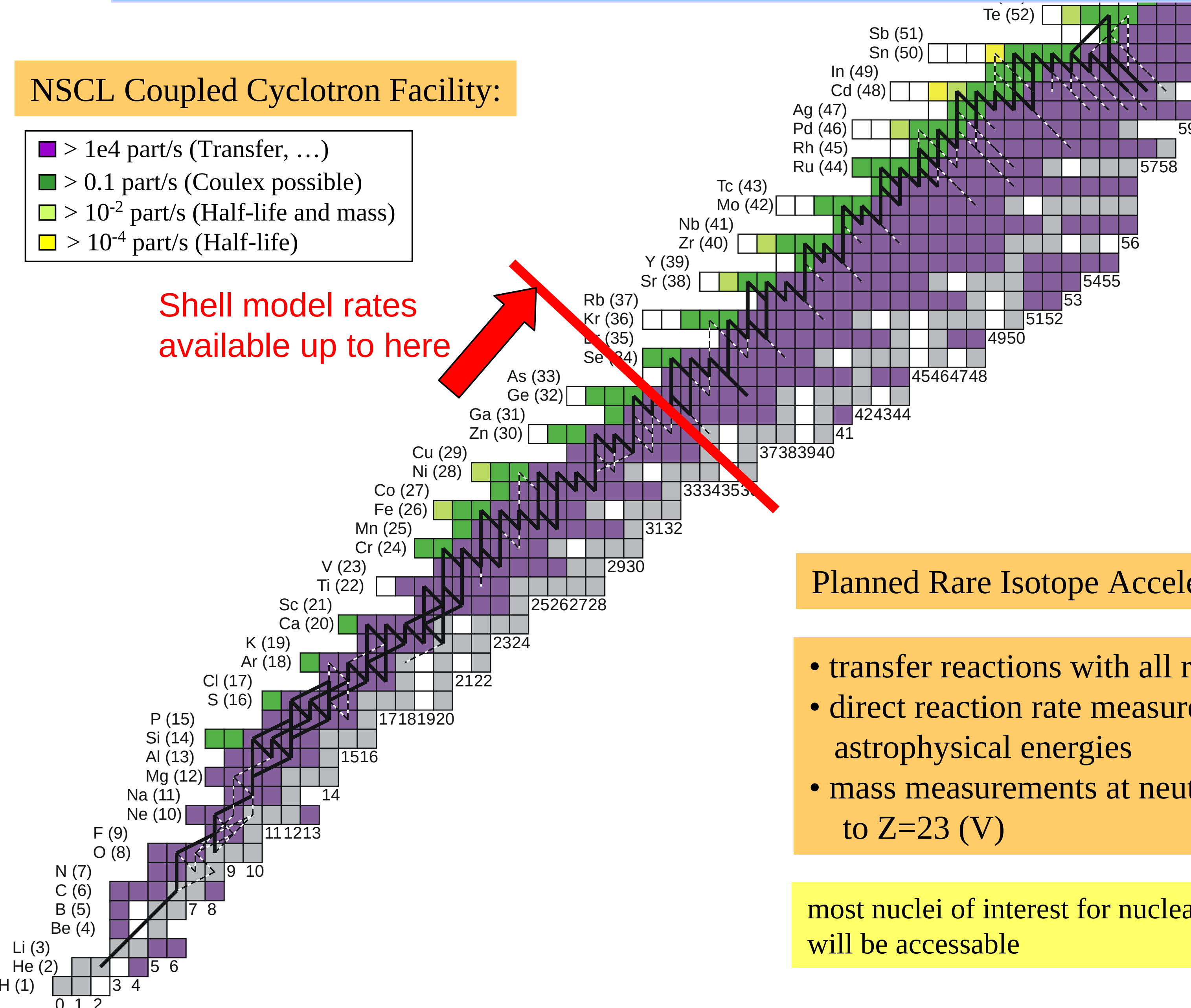
All rp-process nuclei up to A~73 accessable at NSCL

H. Schatz

Future perspectives

NSCL Coupled Cyclotron Facility:

- > 1e4 part/s (Transfer, …)
- > 0.1 part/s (Coulex possible)
- > 10^{-2} part/s (Half-life and mass)
- > 10^{-4} part/s (Half-life)



Planned Rare Isotope Accelerator (RIA):

- transfer reactions with all rp-process nuclei
- direct reaction rate measurements at low astrophysical energies
- mass measurements at neutron drip up to Z=23 (V)

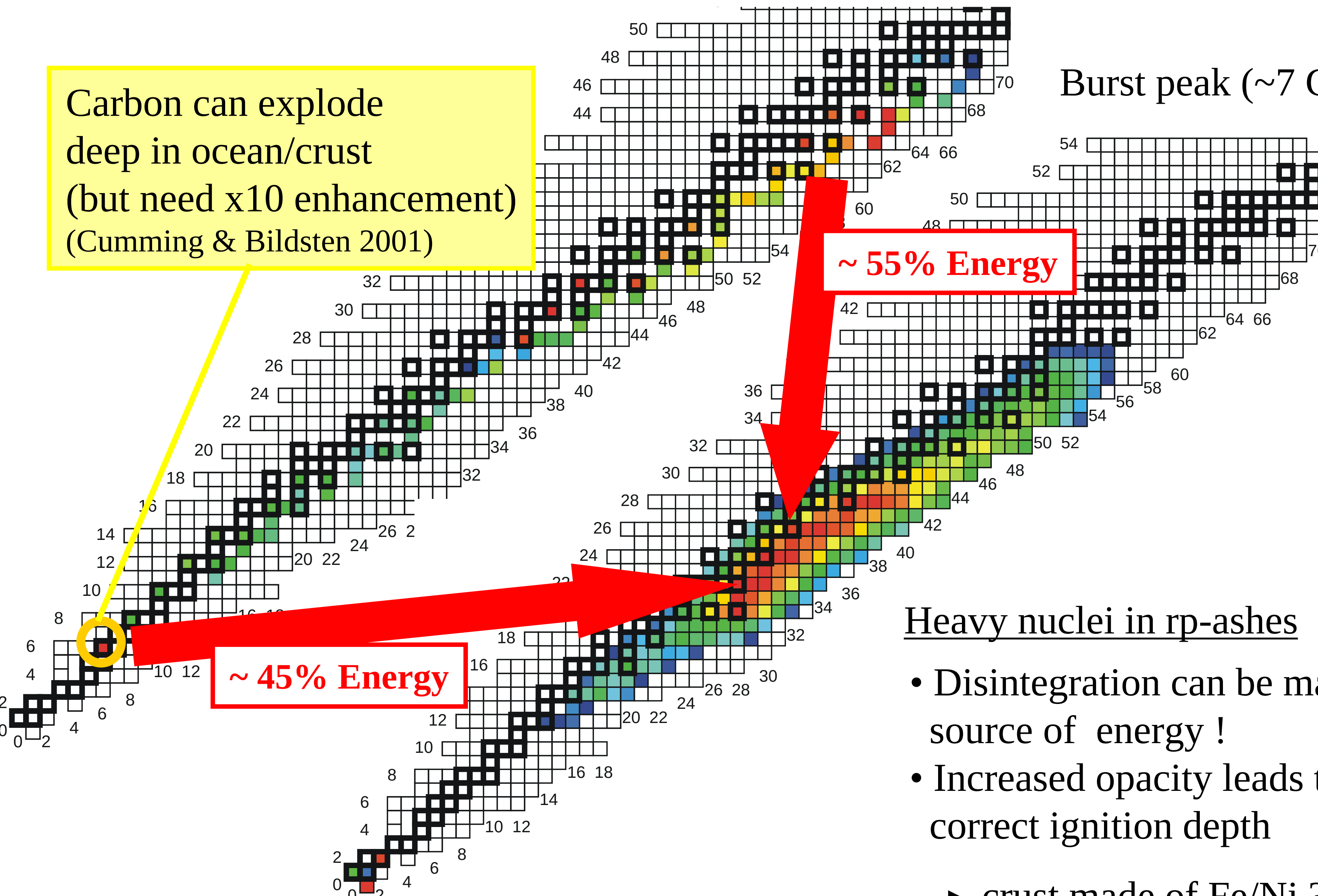
most nuclei of interest for nuclear astrophysics will be accessable

H. Schatz

Ashes to ashes – the origin of superbursts ?

Carbon can explode
deep in ocean/crust
(but need x10 enhancement)
(Cumming & Bildsten 2001)

Burst peak (~7 GK)



Heavy nuclei in rp-ashes

- Disintegration can be main source of energy !
- Increased opacity leads to correct ignition depth

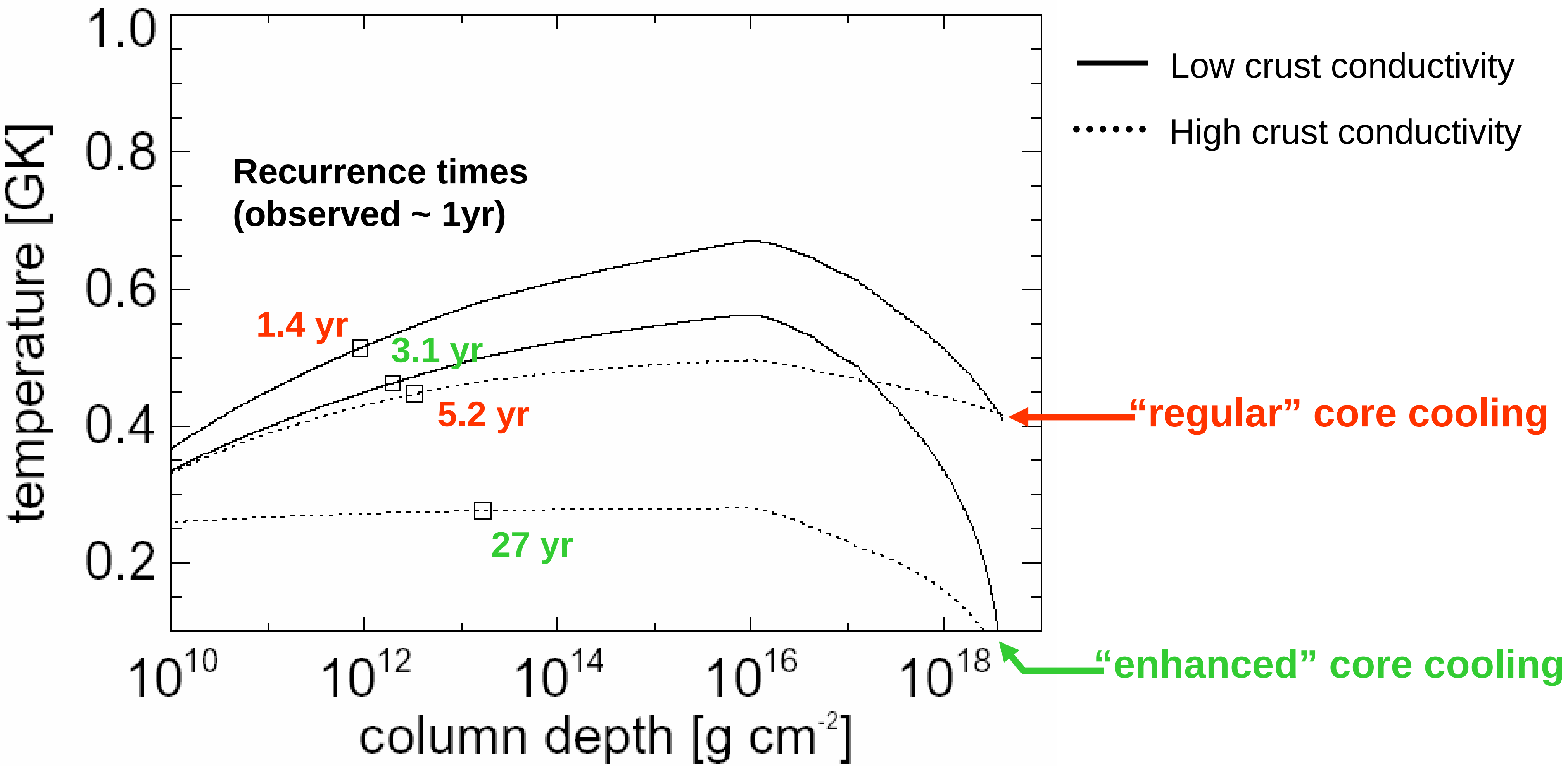
→ crust made of Fe/Ni ?

(Schatz, Bildsten, Cumming, ApJ Lett. 583(2003)L87

Superbursts as probes for NS cooling

Superburst ignition depth (Ed Brown, to be published)

(for accretion rate of 3e17 g/s and X(12C)=0.1)



→ Recurrence time depends on crust conductivity and core cooling

→ Observations require LOW conductivity and no enhanced cooling (incl. KS1731-260)

Summary

- Accreting neutron stars are great laboratories for dense matter
- There are many ways to extract information on NS properties
  - M, R from lines, oscillations during bursts
  - Determine thermal properties:

    From off state luminosity in transients
    From Superbursts
- Need accurate X-ray burst calculations with accurate nuclear physics
  - To X-ray bursts as probes for system parameters
  - To determine the composition of the crust → conductivity
  - To calculate superburst fuel → use superbursts as thermal probes
- New facilities like NSCL will be able to much improve rp-process physics
- Future facilities like RIA needed to “wrap up” the nuclear physics issues
- JINA: www.jinaweb.org