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Modeling of Type I X-Ray Bursts

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Some superburst models were born as GRB models ~40 yr ago...

Nature Vol. 263 September 9 1976 101

articles

γ-ray bursts from thermonuclear explosions on neutron stars

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It is proposed that γ-ray bursts originate from carbon detonations initiated by the accretion of matter on to the surface of a neutron star. The observations are interpreted in terms of this theory. Possible implications for the nuclear powered model of giant X-ray pulses are discussed briefly.

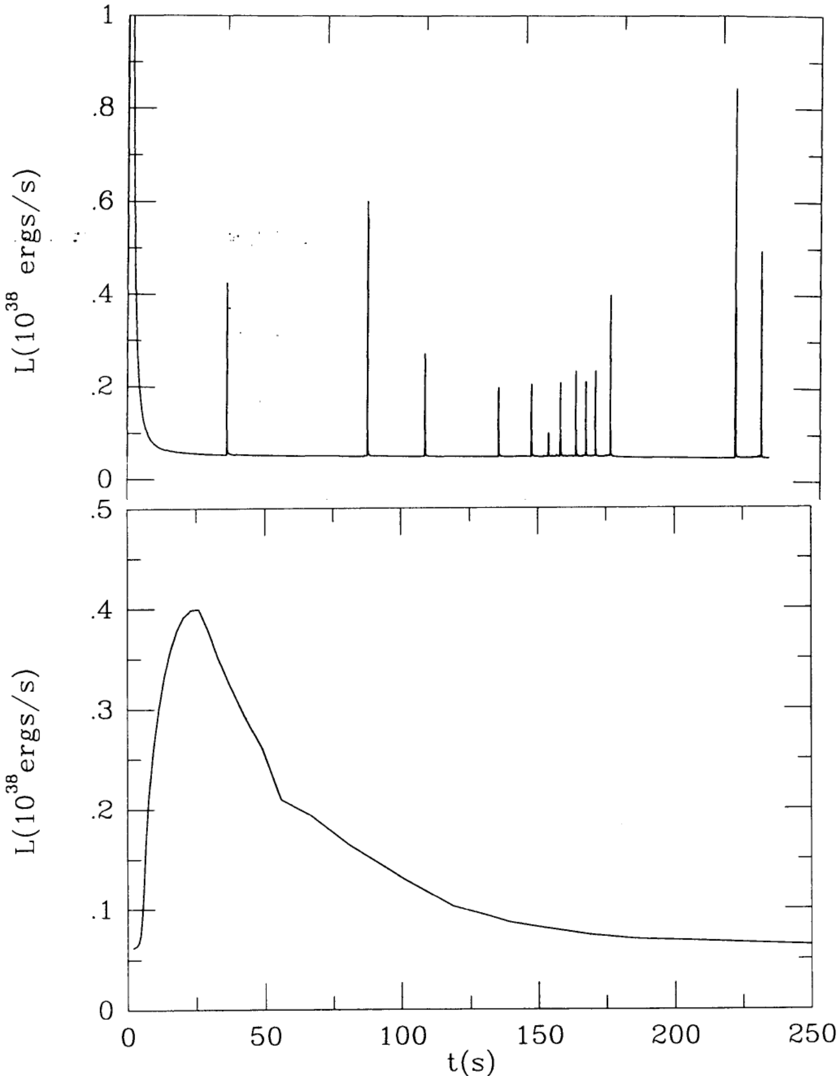
- H/He accretion on NS, burning to C layer cooled by neutrinos
- Column depth ~3×10^{9} g cm^{-3}, 10^{22} g carbon layer
- Recurrence time of ~1 yr
- Possible detonation within < 1 ms, radiate ~5×10^{39} erg
- Cooling time ~10^{3} – 10^{4} s
- Fine structure from “hot bubbles” < 1 s

[End of their Conclusions]

The fact that the time between bursts is longer for the more energetic bursts is an observed attribute of certain X-ray burst sources[23]. Clearly a large range and diversity of nuclear outbursts of various energies and time scales are possible for the possible spread of accretion rates, neutron star masses, and magnetic field configurations. The subject is ripe for continuing experimental investigations and serious theoretical examination, and hopefully this somewhat speculative paper will encourage both. We especially urge that known γ-ray burst sites be continously monitored for giant X-ray pulses and vice versa.

Early XRB Simulations I

(Woosley & Wever 1984;
Taam, Woosley, Lamb, Weaver 1993)



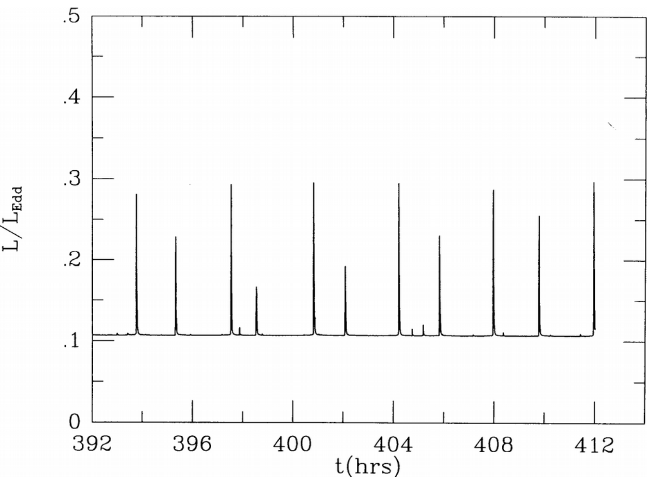
- Use RPROX approximate *r*-process network with 19 isotopes
- Light curves are already quite similar to current ones
- Find very irregular bursting for low metallicity and high heat flux from the crust
- Limitations in transition from hot to cold burning cause H left behind that causes subsequent bursts (*irregular behaviour*)

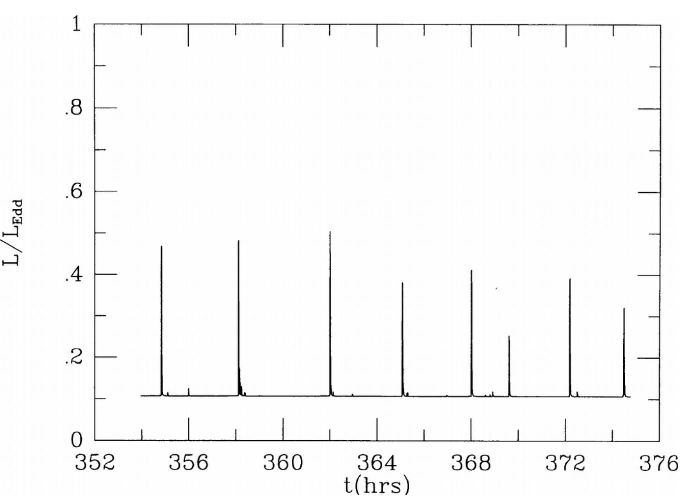
Early XRB Simulations II

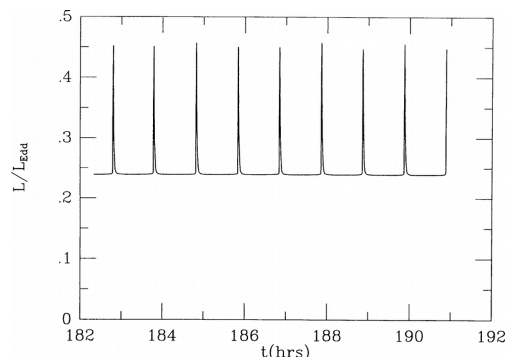
(Taam, Woosley, Lamb 1996)

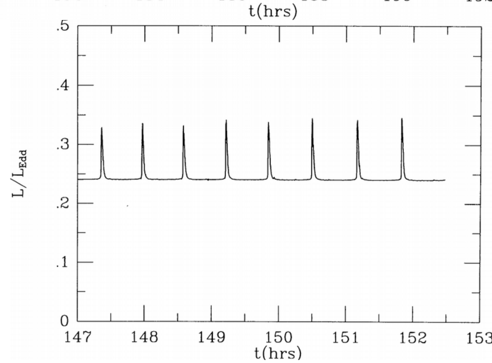
- Continue use RPROX network
  => irregular busts in some regimes

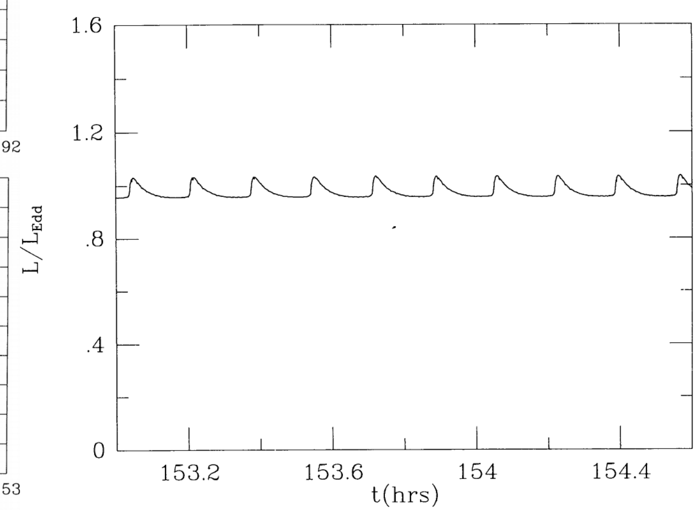
- Find transition to QPOs at high accretion rates – but at L_{edd} as today



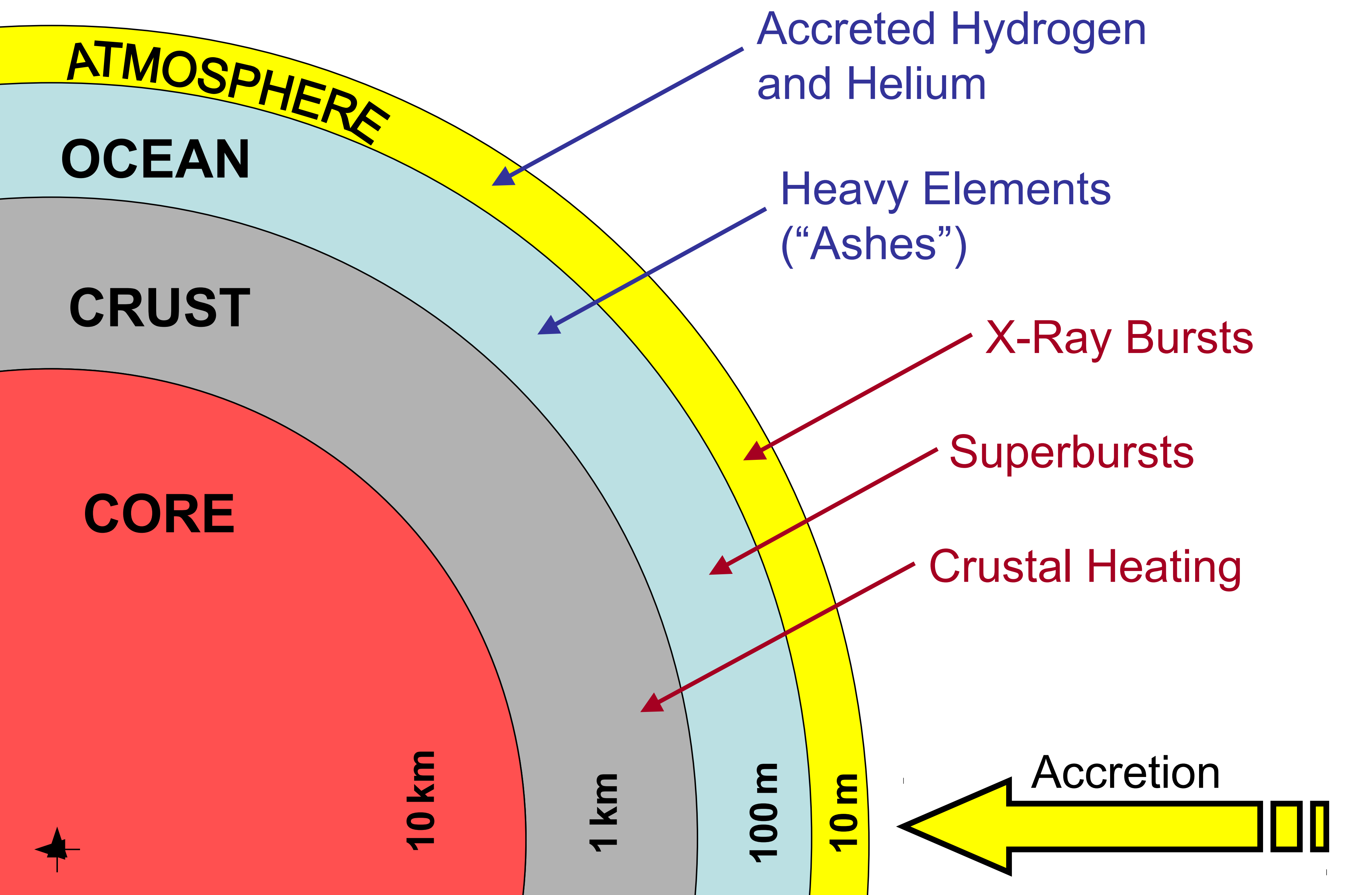




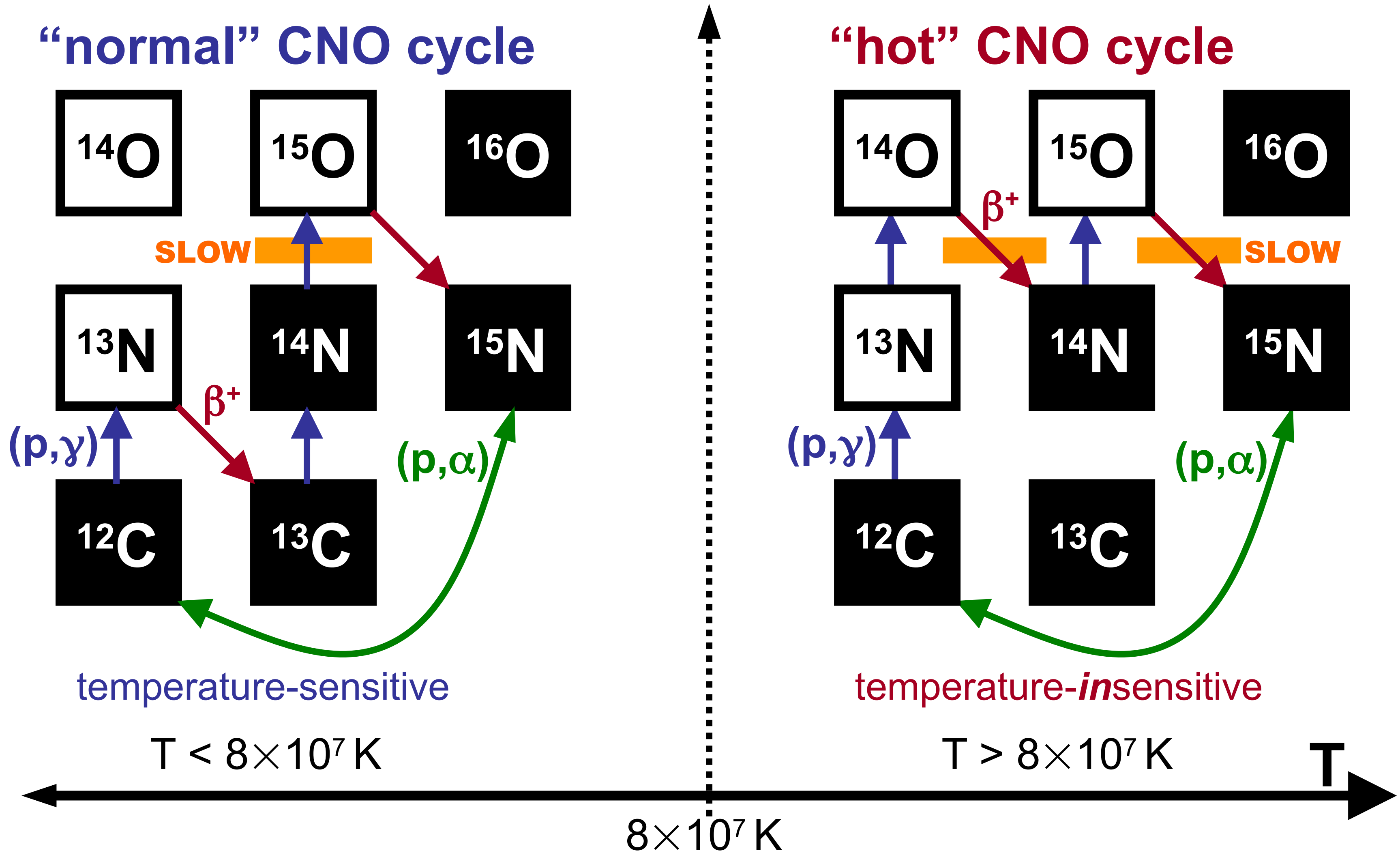




Structure of an Accreting Neutron Star



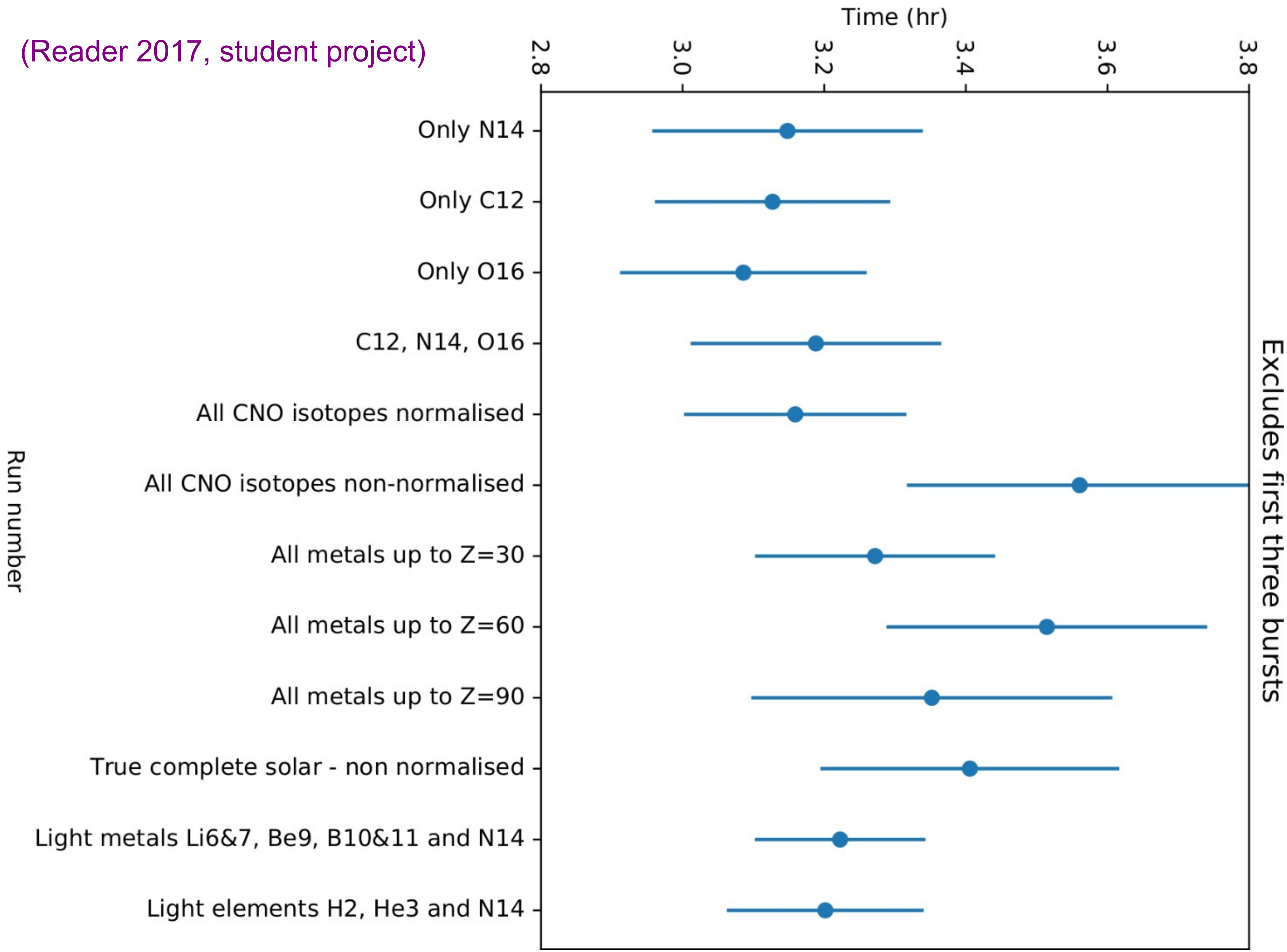
Hydrogen Burning by CNO Cycle

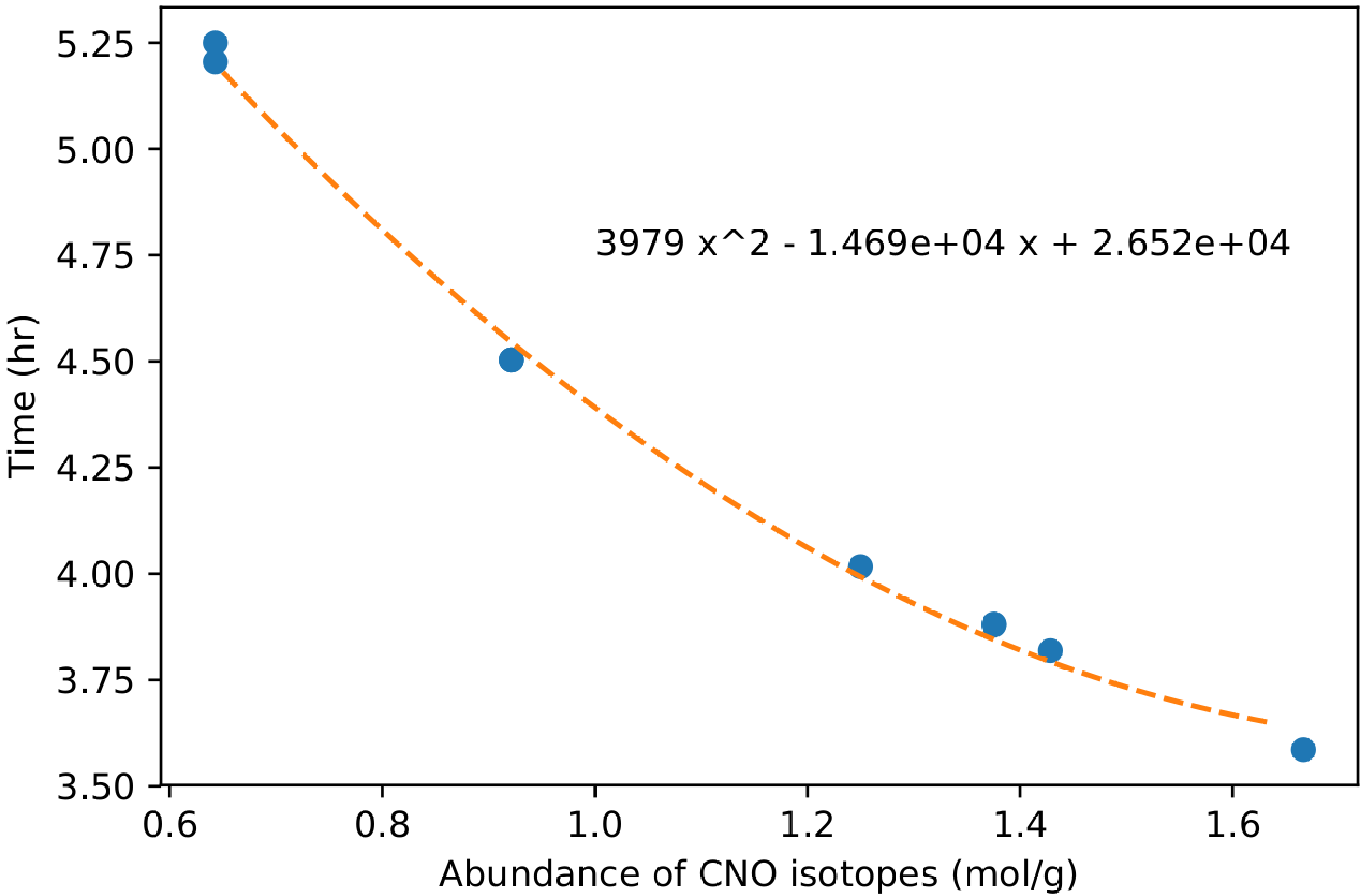


time for an eddy to burn its hydrogen content by **hot** CNO cycle

$$\tau_H = 11\ \text{h} \left(\frac{0.02}{Z}\right)\left(\frac{X_0}{0.7}\right)$$

(Reader 2017, student project)



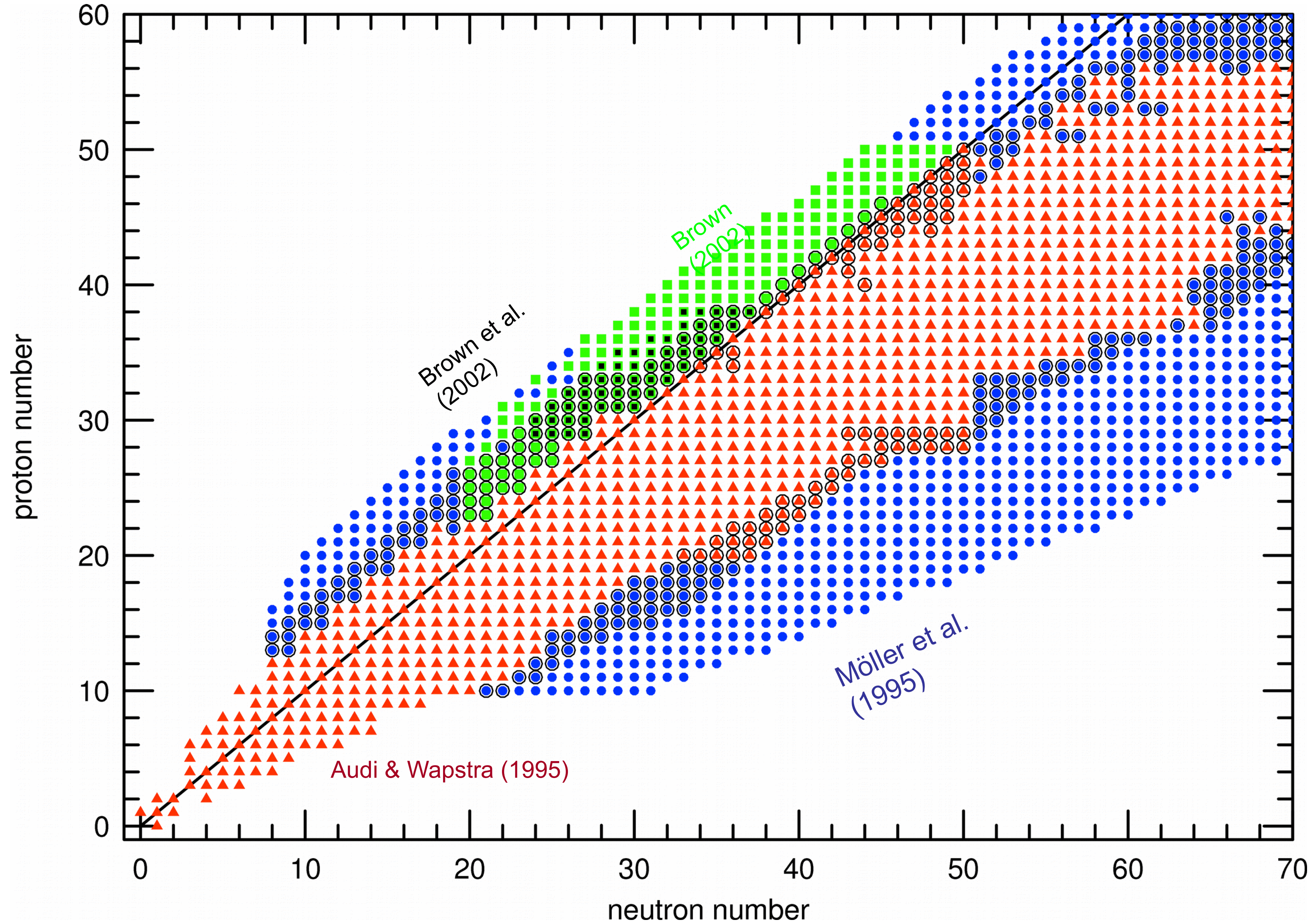


(Reader 2017, student project)

Numerical Method

- Stellar evolution code **KEPLER** (Weaver, Zimmerman, & Woosley 1978)
- Extended nuclear reaction library from neutron to proton drip line and from H though Po
  (Rauscher et al. 2003; Brown et al. 2002; Audi & Wapstra 1995; Möller et al. 1995)
- Implicit coupling of large reaction network to stellar structure solver (energy generation, density (X,Ye), opacity)
- Adaptive reaction network adds all isotopes needed by problem (and removes those no longer needed - save time)
- Include thermal and weak decay neutrino losses
  (Petr Vogel, priv. comm.)
- Carry up to 1000 zones (or more in some cases!)

Mass excess data excerpt relevant for XRBs



Standard Problem Setup

- Layer thickness (~few m) $\ll$ neutron star radius (~few km)
  -> locally in layer use Newtonian approximation
  (results have to be corrected for GR effects to translate into observer frame)

- Use R = 10 km, M = 1.4 Msun, g = 1.9x10^{14} cm/s^2 (Newtonian) (similar to Schatz et al. 2001) (the same g is obtained in GR for a NS radius of ~11.2 km and same gravitating mass)

- Accrete zones to surface of star (typically ~2x10^{19} g)

- Assume substrate luminosity of 0.15 MeV per accreted nucleon (Schatz et al. 2001)

- 10^{25} g of substrate (carried on grid) relaxed to thermal equilibrium before accretion is started

- No rotation, no magnetic field

Current Problem Updates

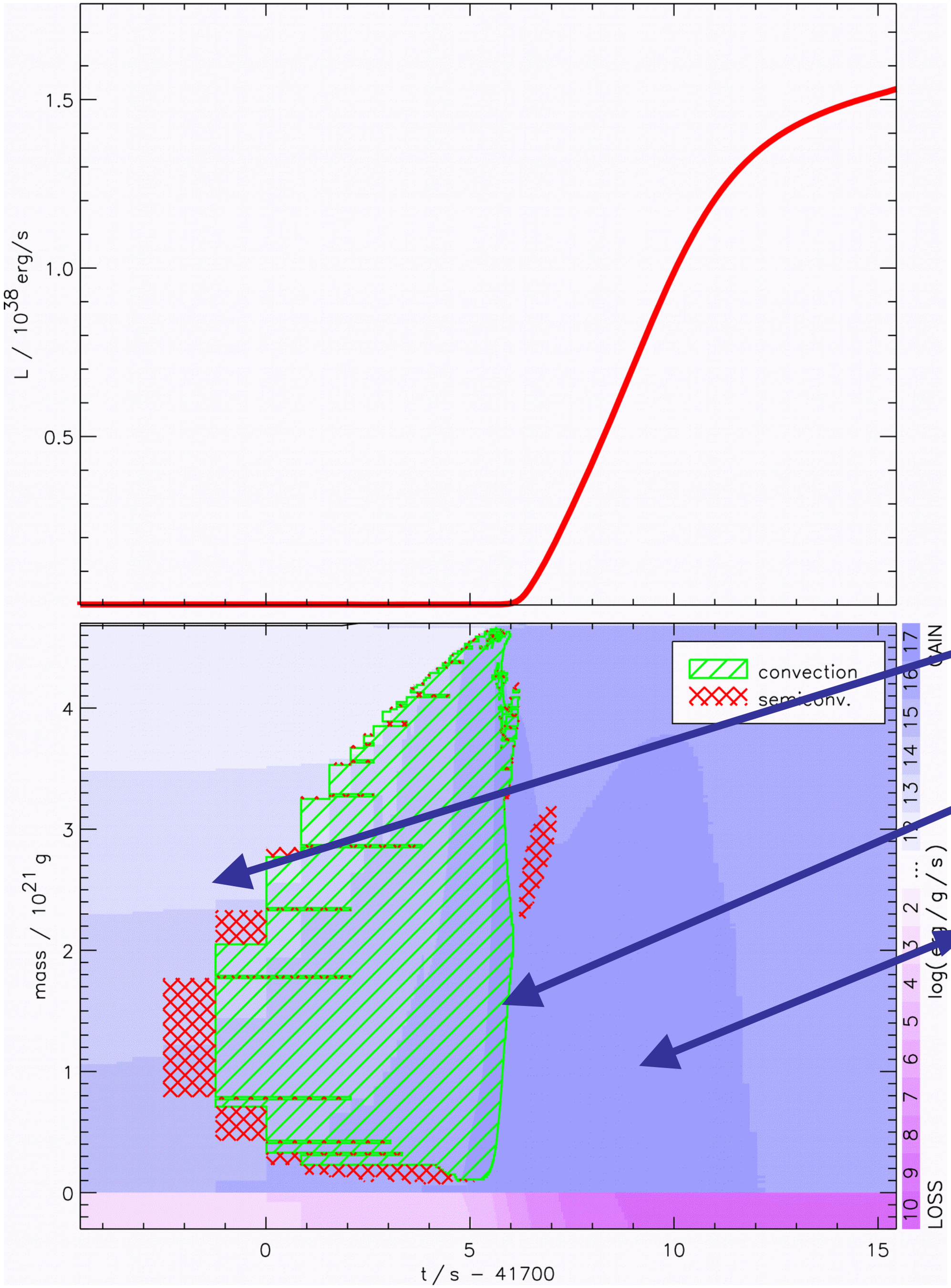
- Allow fine surface zoning with essentially arbitrary fine zones
  → Setup for PRE burst studies
- Allow advection relative to grid
- Include energy terms from advection – heating/cooling
- Include decretion of mass at the bottom of grid → fixed domain
- Time-dependent heating and acccretion rates
- Heating due to angular momentum transport (dependent of process – hydrodynamic / magnetic fields)
- Many updates on nuclear reaction rates (Cyburt – JINA lib)

Low Metallicity + High Accretion Rate

hydrogen/helium ignition bursts

STRUCTURE

Start of first burst

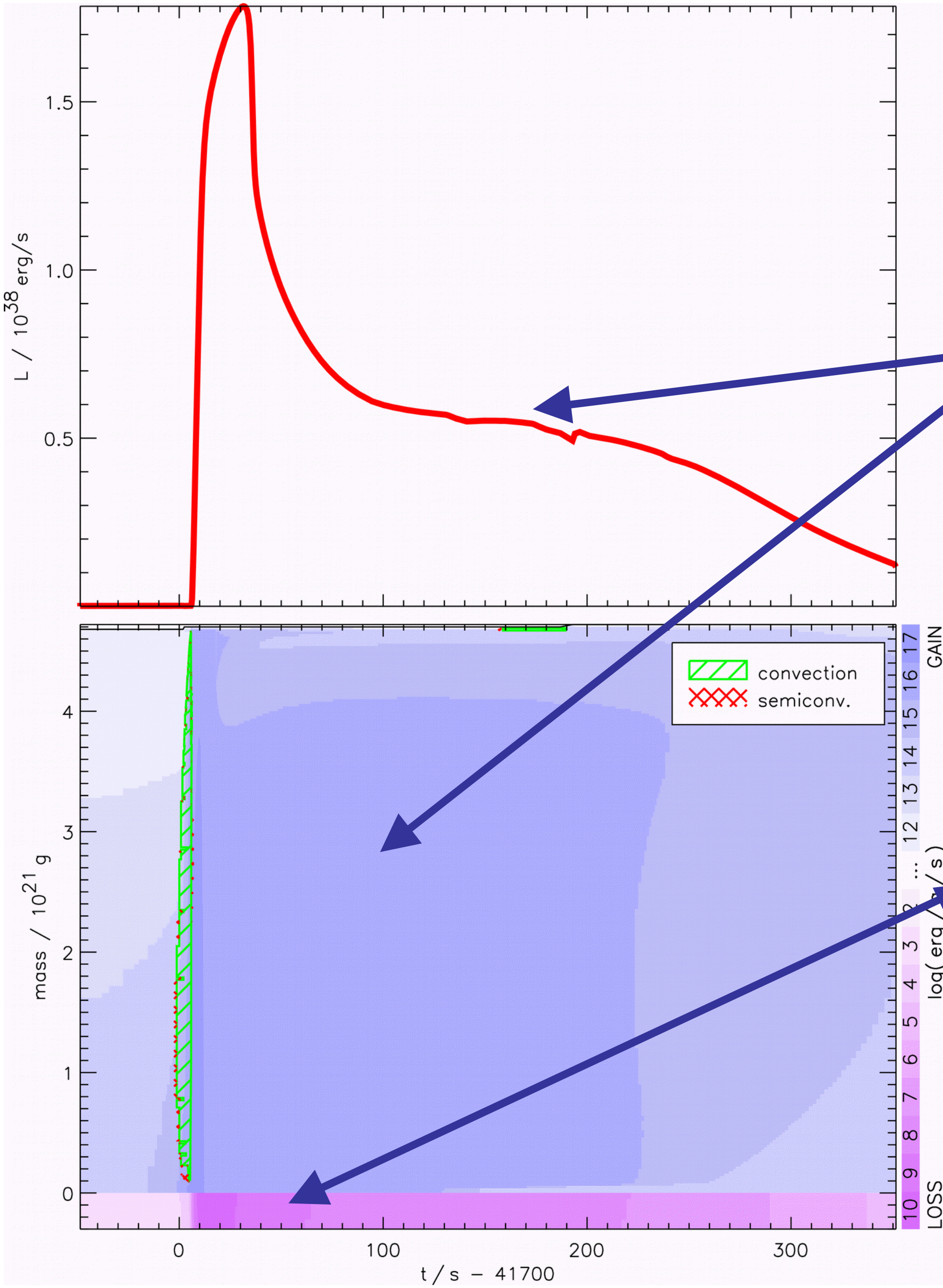


Convection starts and terminates before rise of light curve

Significant burning after layers have become convectively stable

zM

Long time evolution of first burst



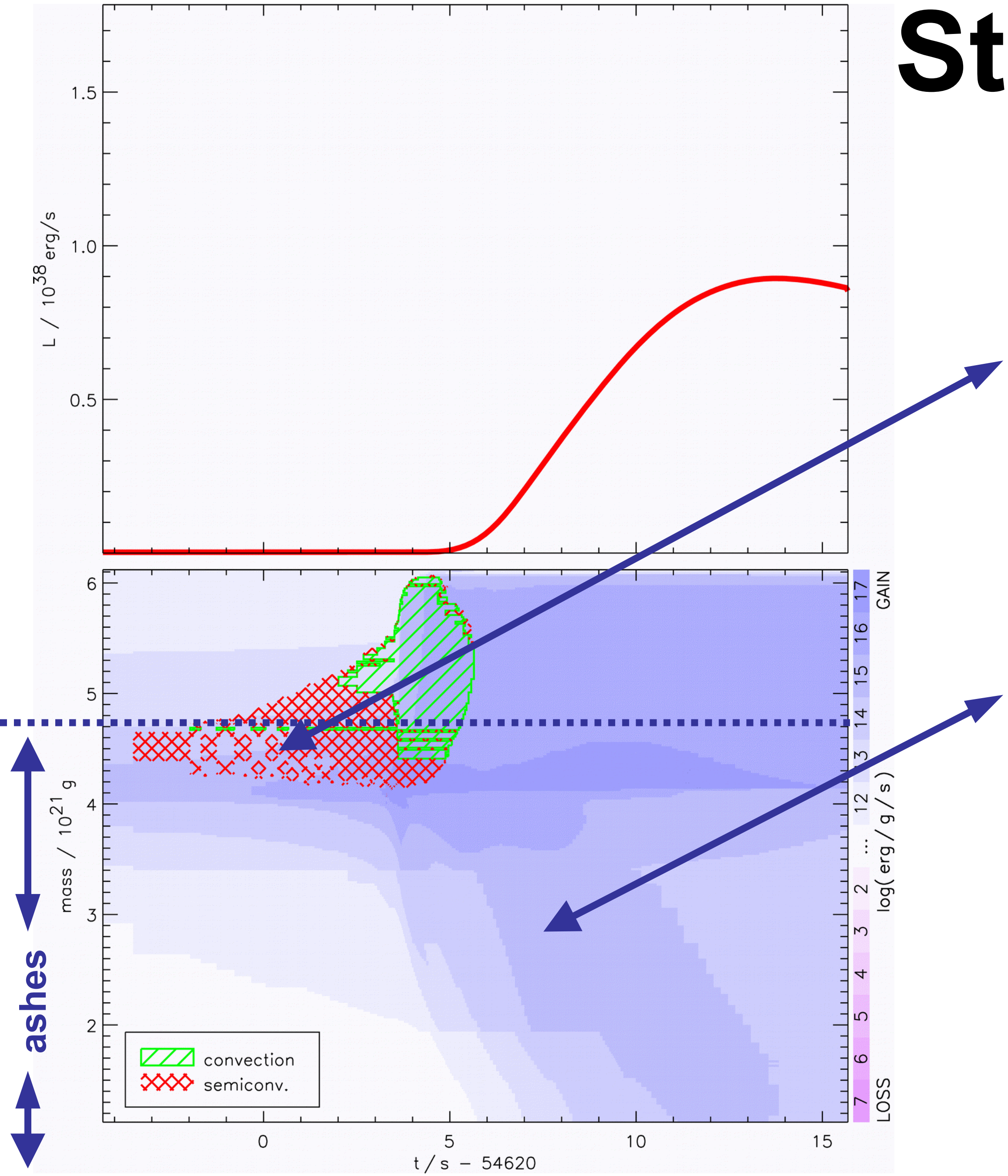
Tail of light curve (~200 s) while rp-process is proceeding

Heating of substrate by energy from burst

(here: visible by causing thermal neutrino losses)

zM

Start of Burst



Ignition of burst in/by ashes layer of previous burst

➔ **compositional inertia**

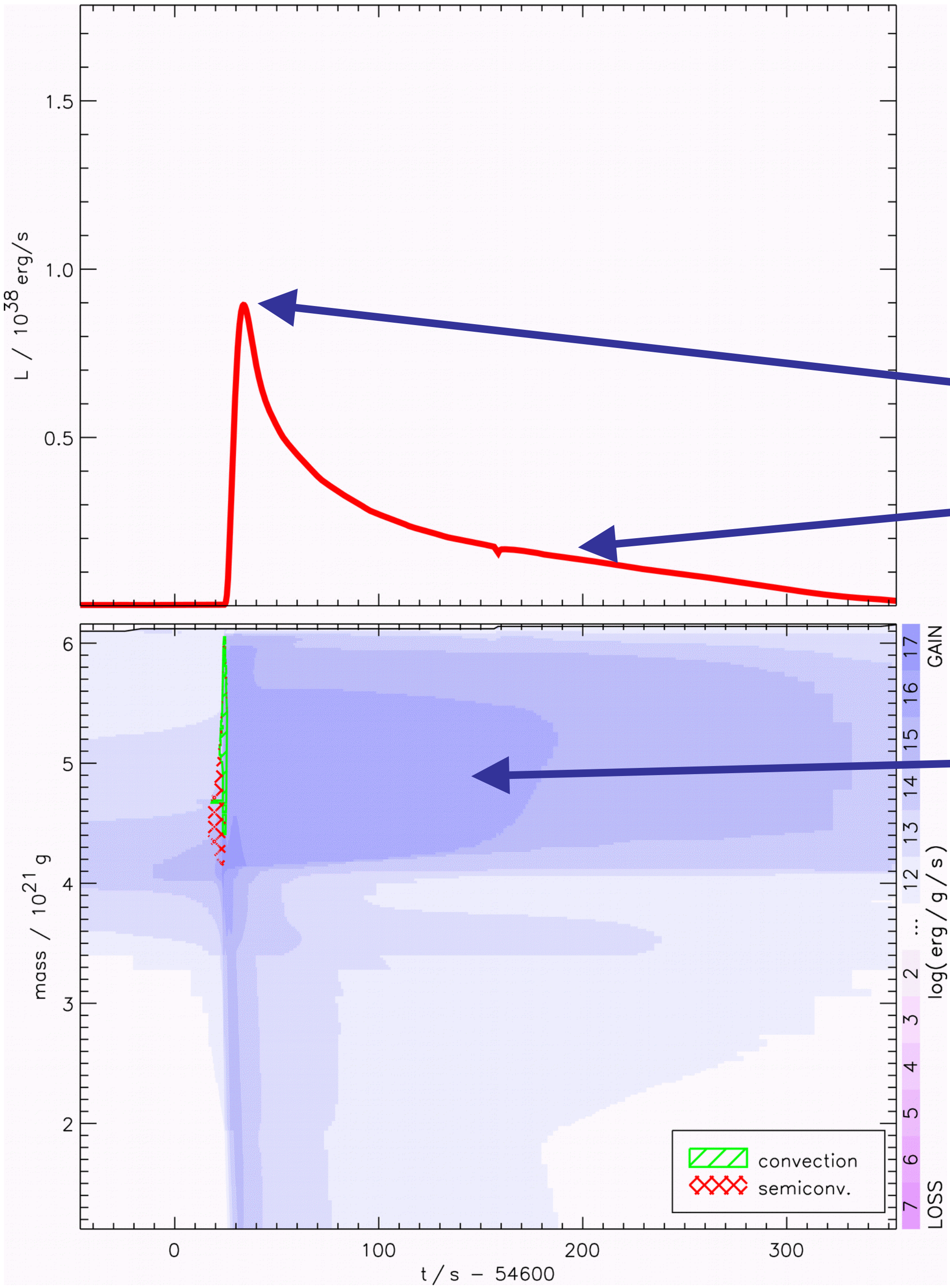
Heating of substrate by energy from burst

➔ burning of ^{4}He

➔ destruction of ^{12}C

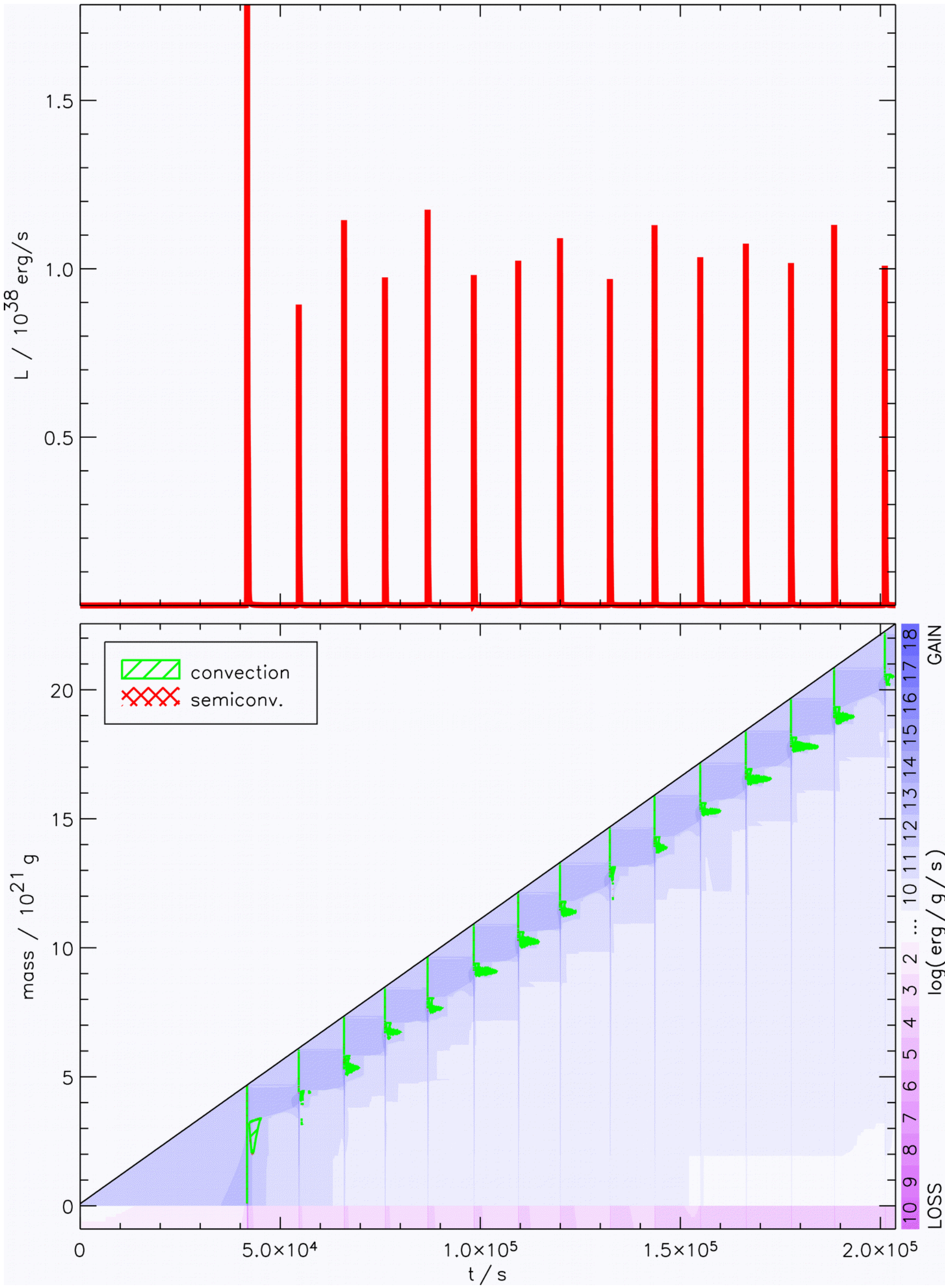
(at low He abundance the $^{12}C(\alpha,\gamma)$ rate dominates over the 3α rate)

Long-Time Evolution



Peak of light curve less luminous and tail decays faster

rp-process continues for some time, but some H remains



A sequence 15 bursts

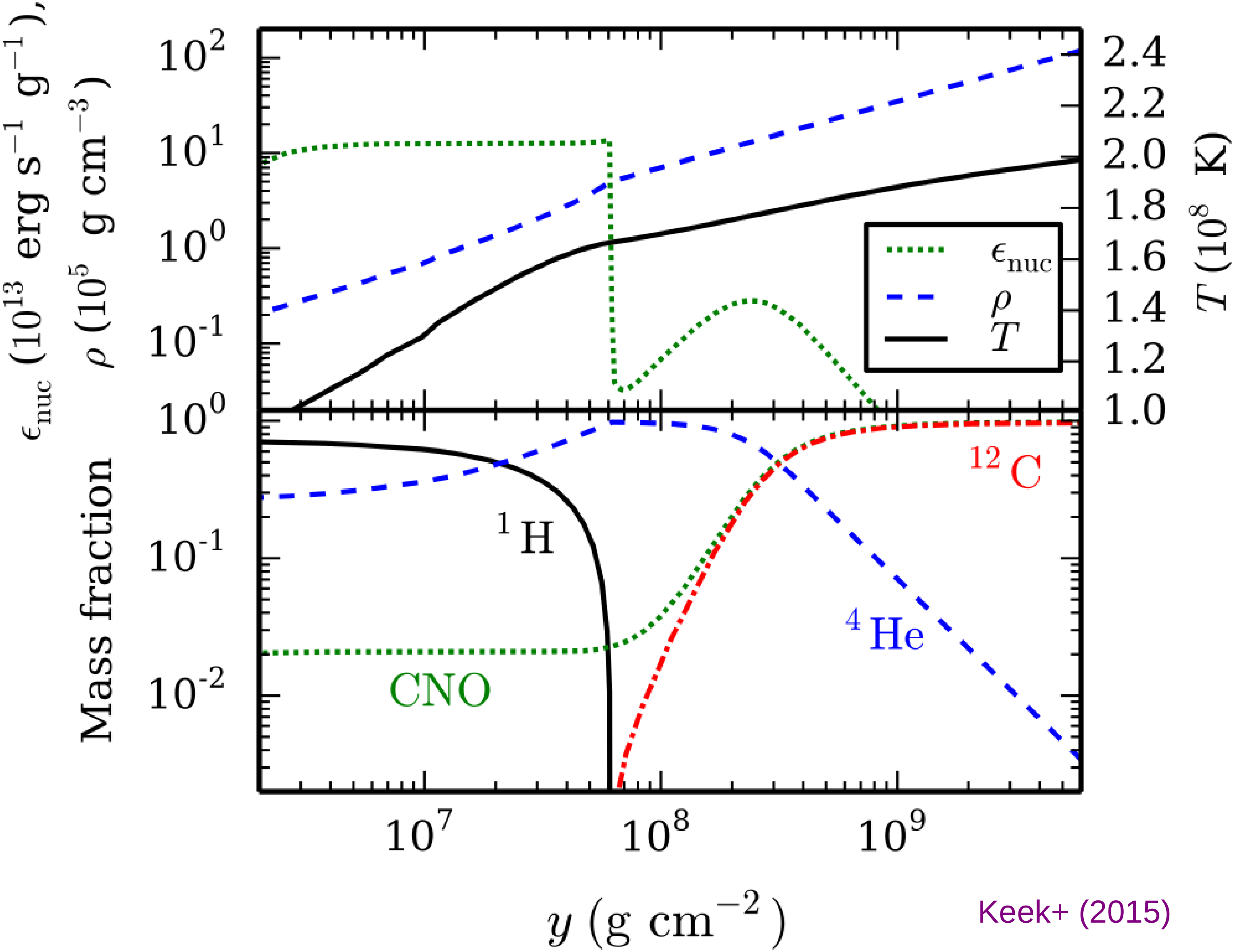
- Except for first burst, all burst have peak similar luminosity and light curves
- The structure of subsequent bursts is very similar

zM

A New Steady Burning Regime


Burning Regimes
Increasing accretion rate
flash
Stable burning
H+He
Deep H burst, burns He
H+He
He
Shallow H flash and
deep He flash
Beta-limited CNO
H+He
He
Stable H burn and
He flash
H+He
He
C
Stable H burn and
stable He burning
H+He
Mixed H+He bursts
Stable CNO breakout
Marginally stable H+He burning
H+He
Stable H+He burning

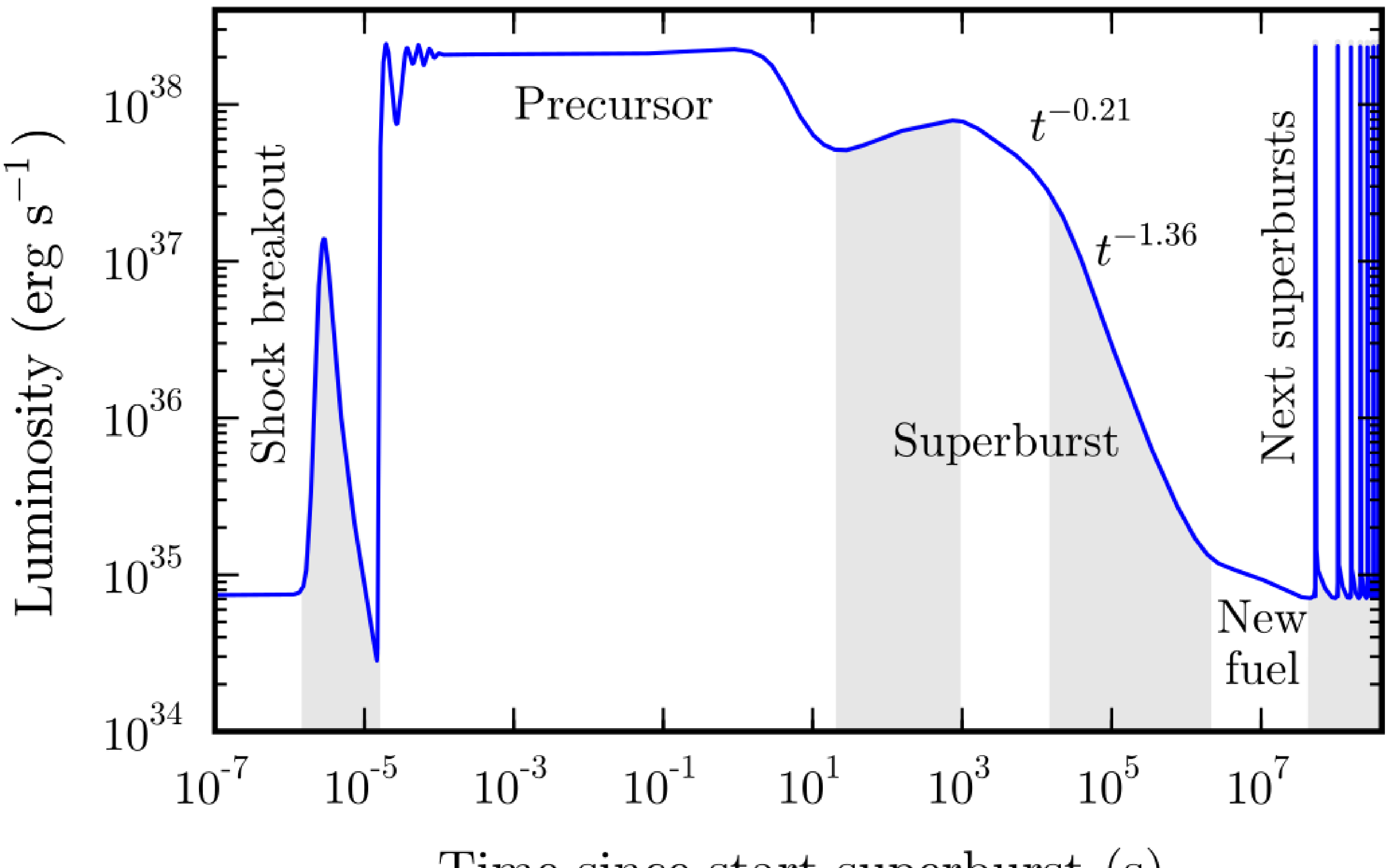
A New Steady Burning regime



Keek+ (2015)

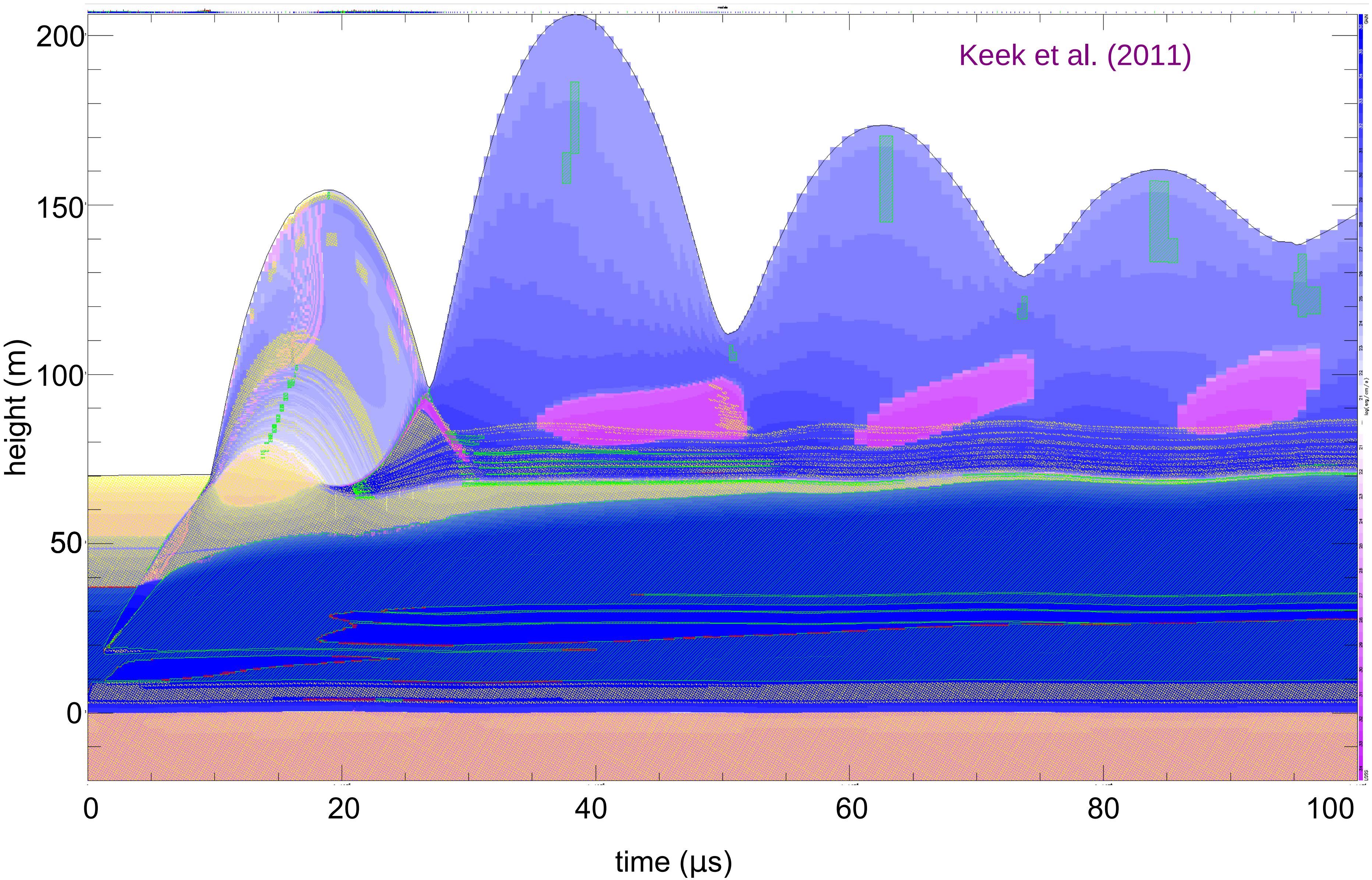
Superbursts

Superburst Phases

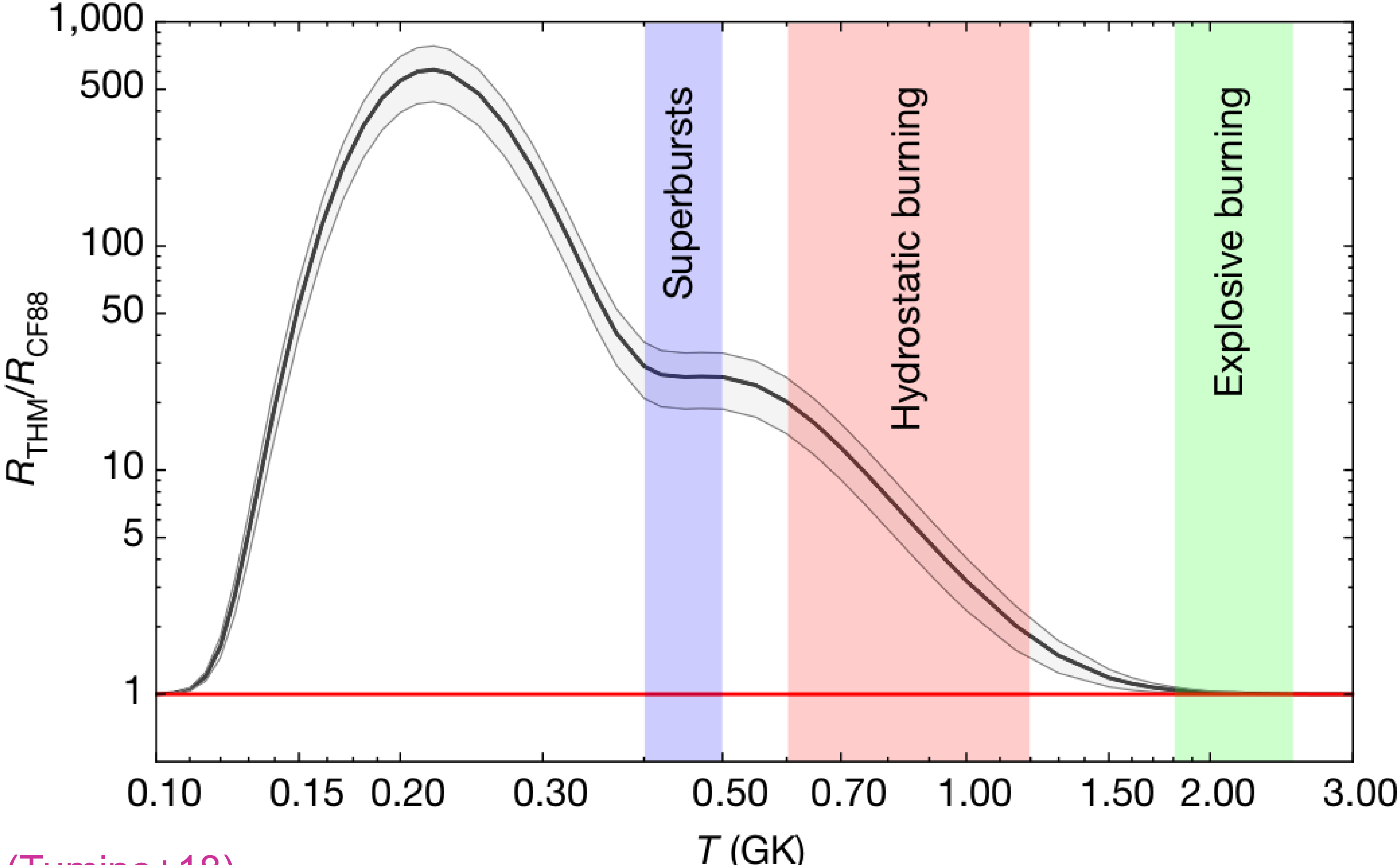


Keek et al. (2011)

Superburst Breakout



New $^{12}C+^{12}C$ Rate



(Tumino+18)

Question

How will this affect superburst ignition?

Could this allow a new burning regime for steady state C burning in some regimes?

Summary

- Can do full-network 1D simulations, but still have many limitations from input physics, including nuclear data

- WANTED – nuclear data for reaction rates, for me EC rates from p-rich to n-rich nuclei, masses and energy levels and the weak rates and nu loss rates to combine current burst to consistent heating and cooling.