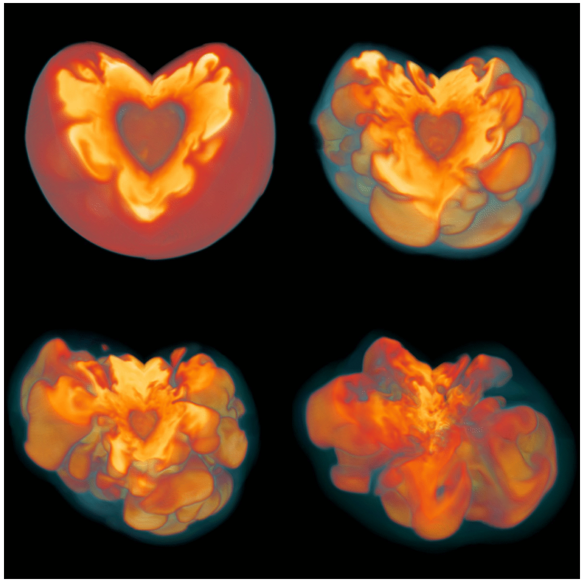
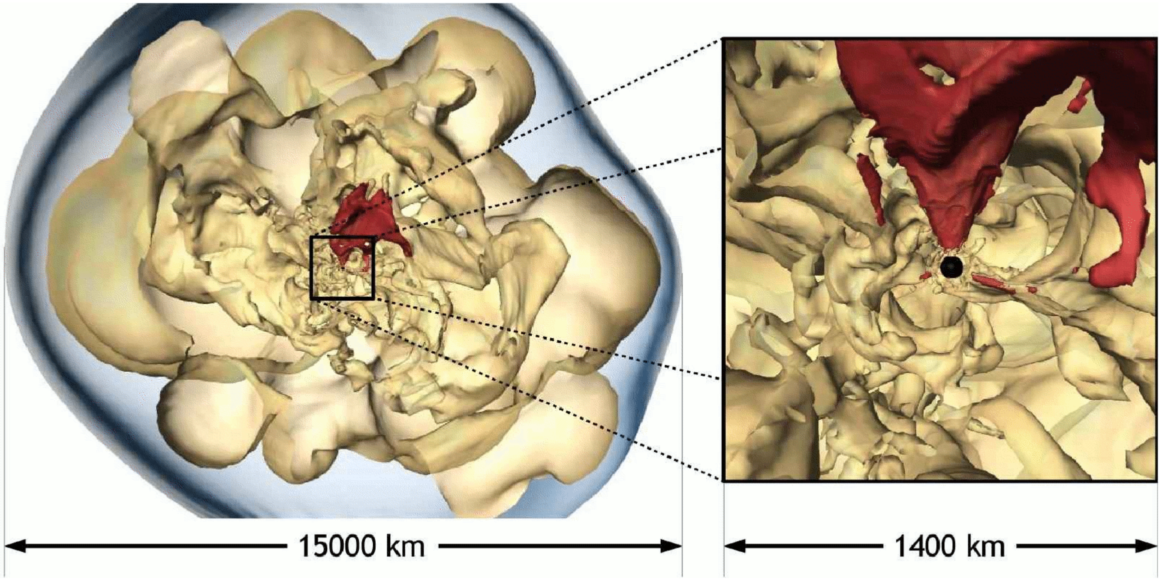
Core Collapse Supernovae – 3D

Cold inflow and **hot outflow** in 3D simulations ➔ similar to dipolar flow pattern observed in 2D rotationally symmetric simulations



(Scheck, Janka, *et al.* 2006)



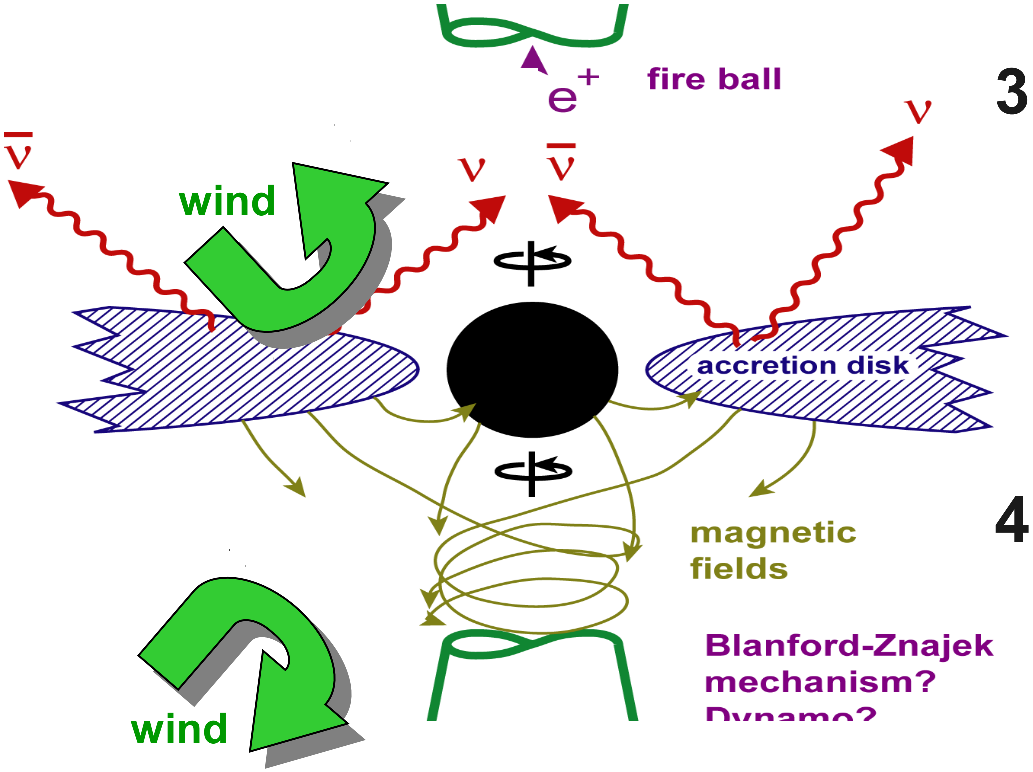
(Janka *et al.* 2005)

How else can massive stars explode?

$25M_\odot < M < 100M_\odot$,

$M > 250M_\odot$

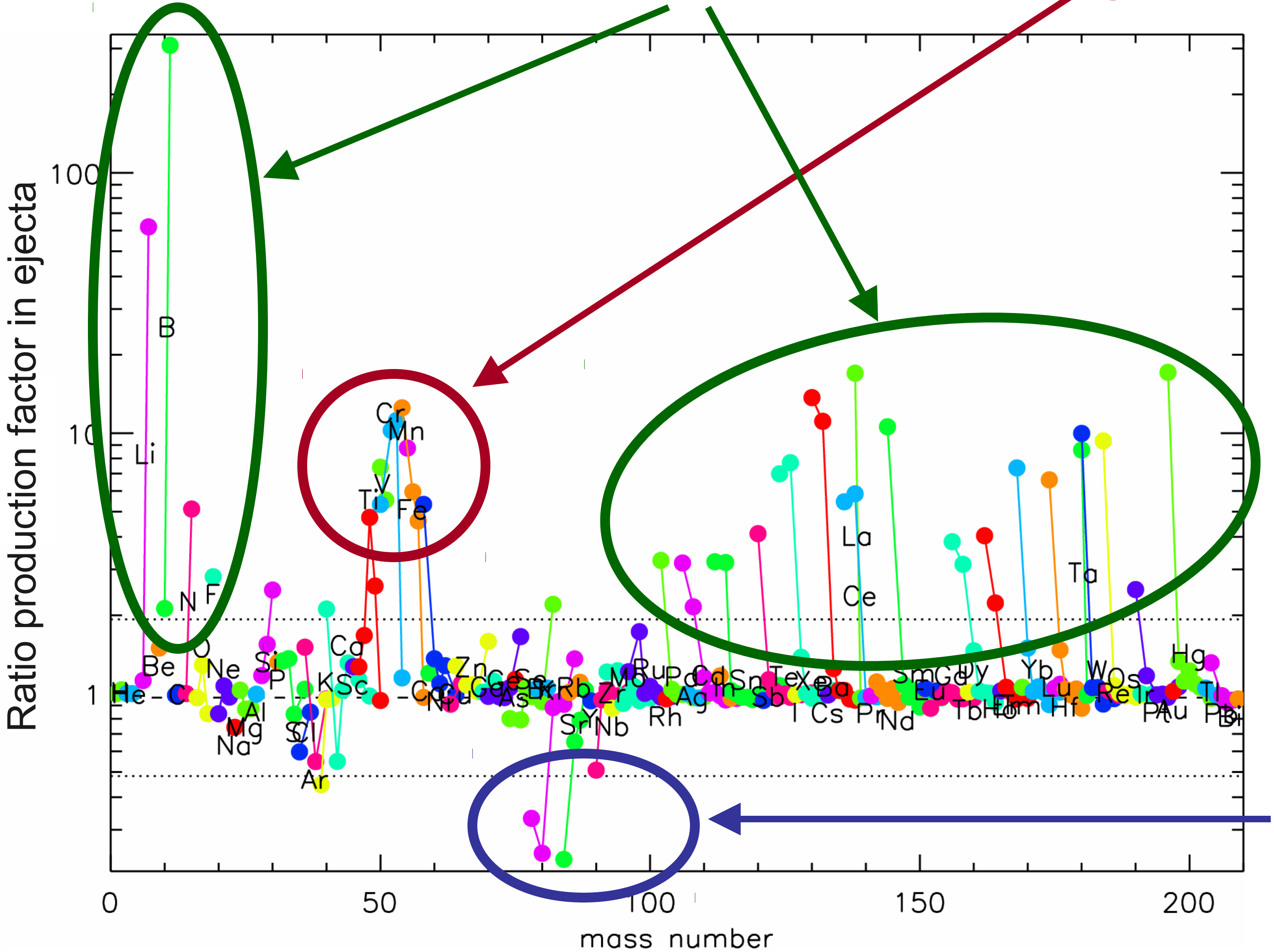
The "Collapsar Engine"



1. black hole forms inside the collapsing star
2. The infalling matter forms and accretion disk
3. The accretion disk releases gravitational energy (up to 42.3% of rest mass for Kerr BH)
4. Part of the released energy or winds off the hot disk explode the star

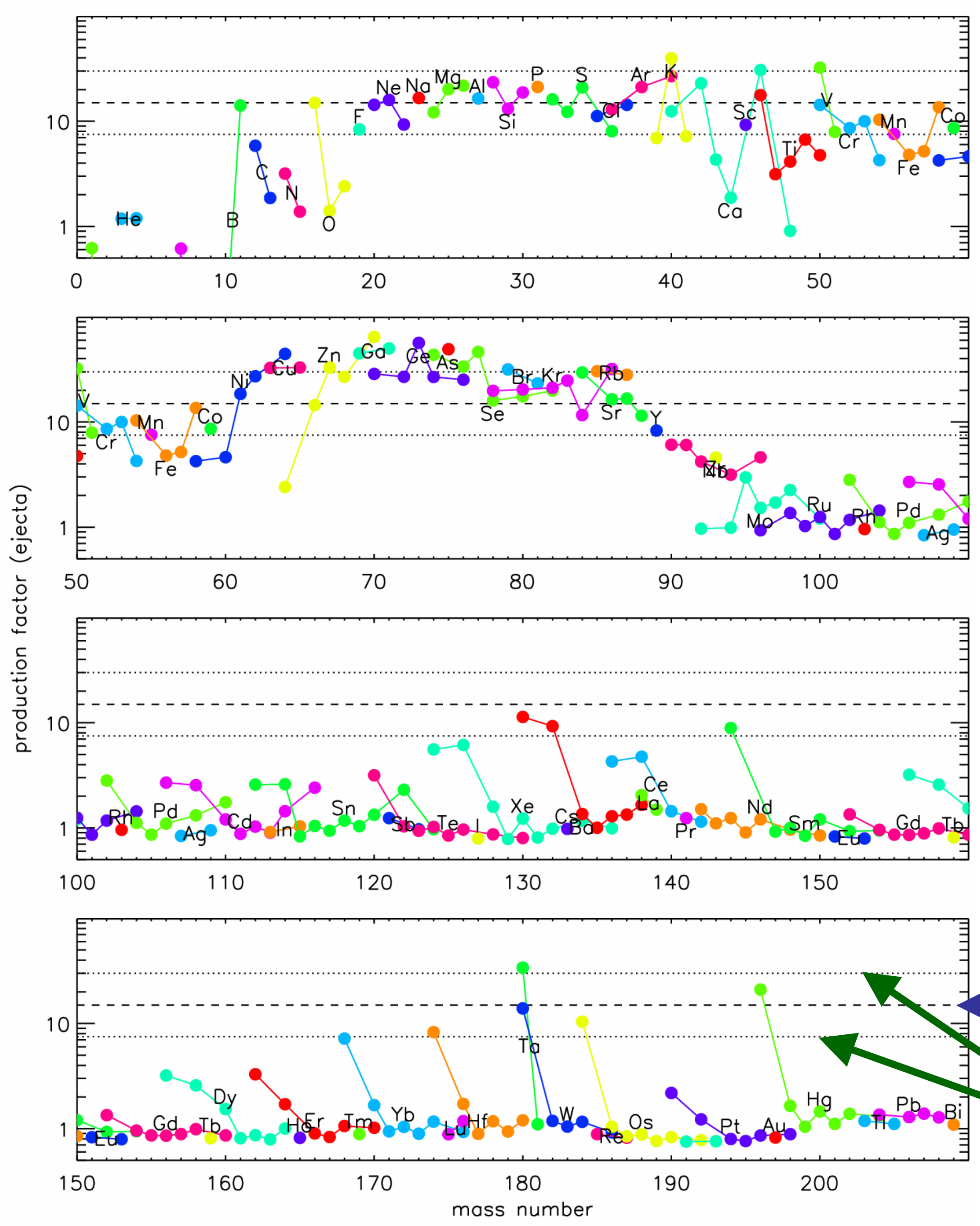
Explosive Nucleosynthesis contribution

→production of p-process and iron group



25 M_o star

some destruction



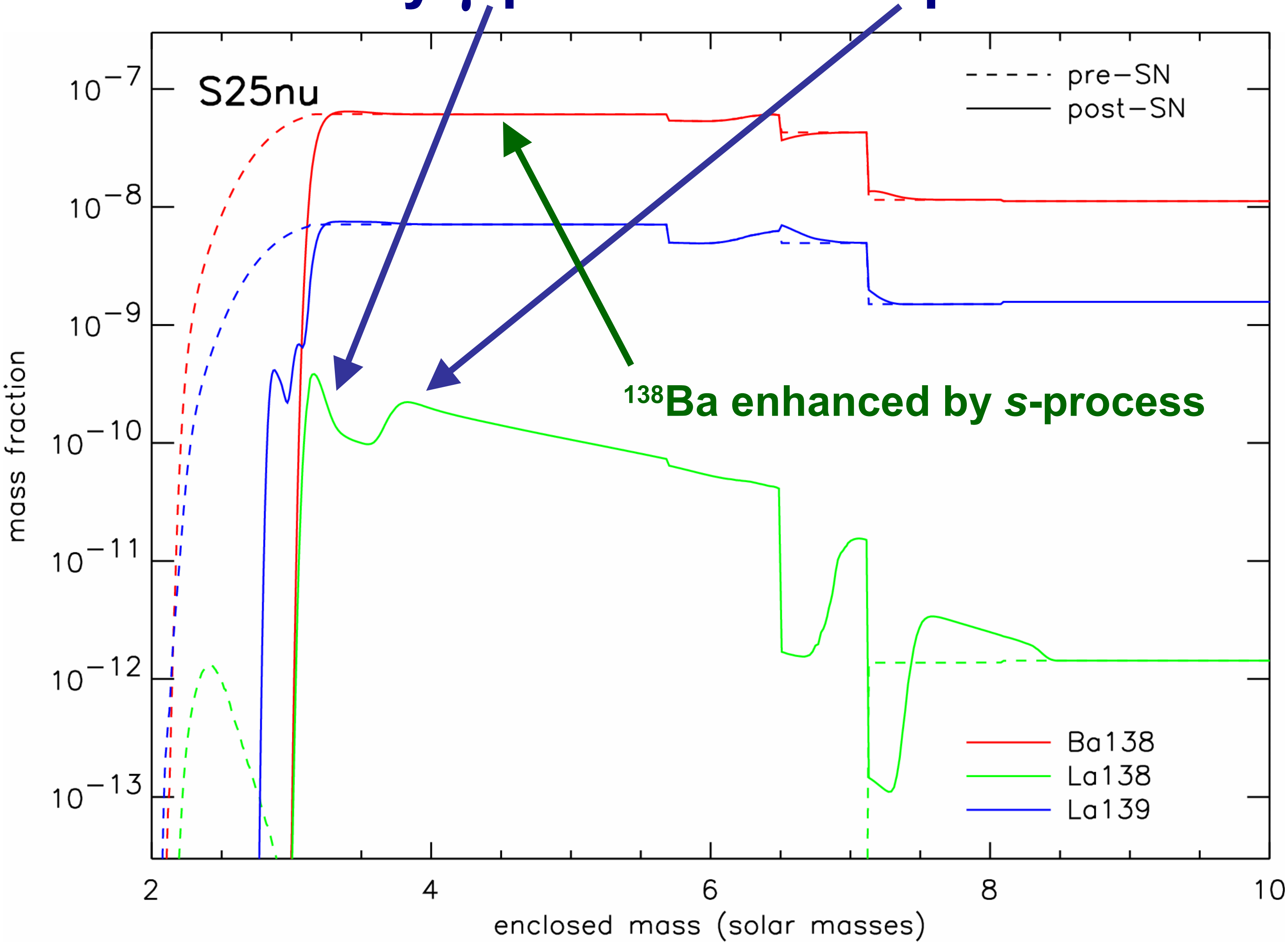
25 $M_{\odot}$ star

Production factors relative to solar composition

"band of acceptable co-production" defined by ^{16}O production (± a factor 2)

The Production of ^{138}La

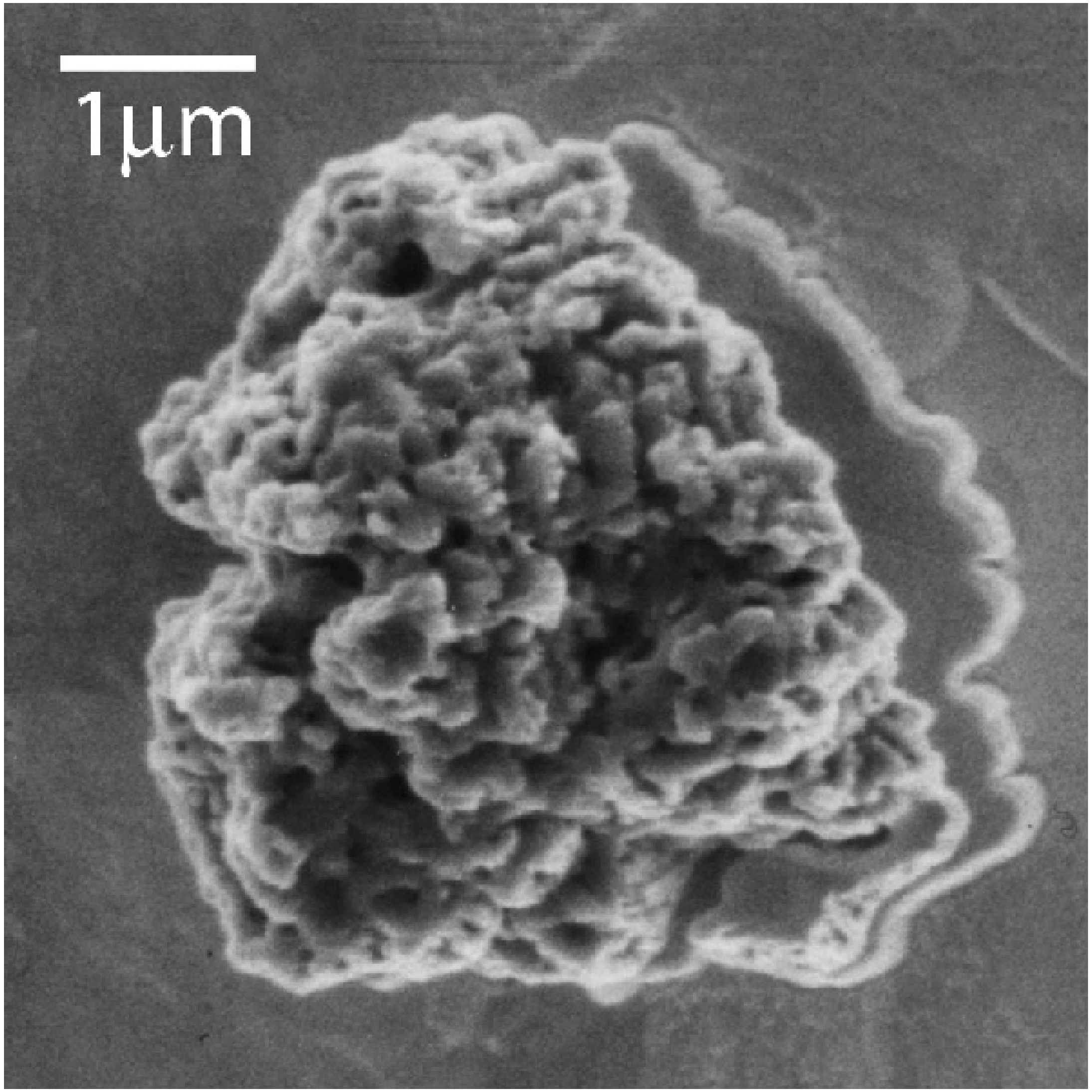
by γ-process and ν-process



^{138}Ba enhanced by *s*-process

Presolar grains

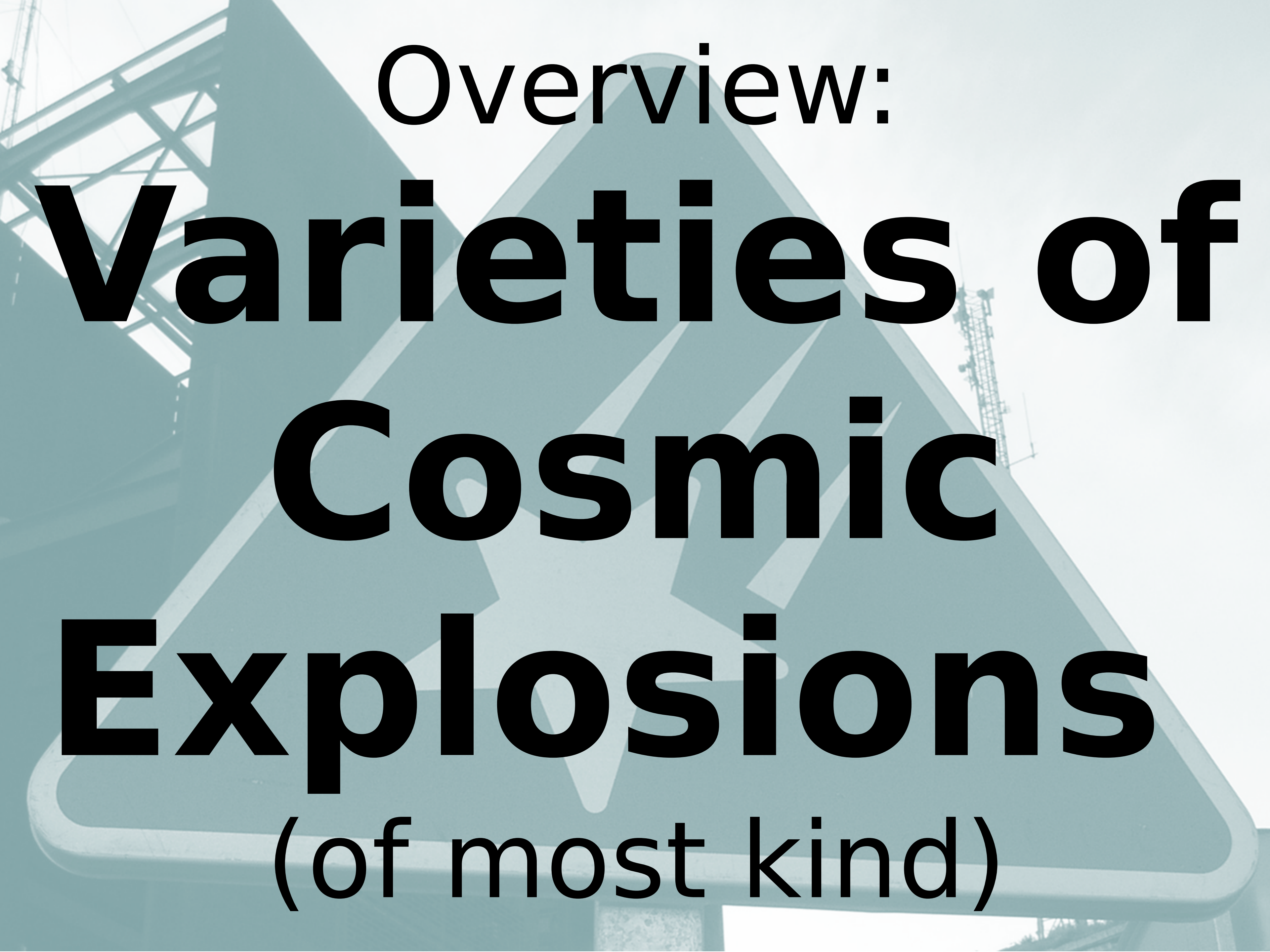
Direct access to pristine SN nucleosynthesis?



However:
need to understand

- chemistry
- condensation
- SN mixing
- implantation

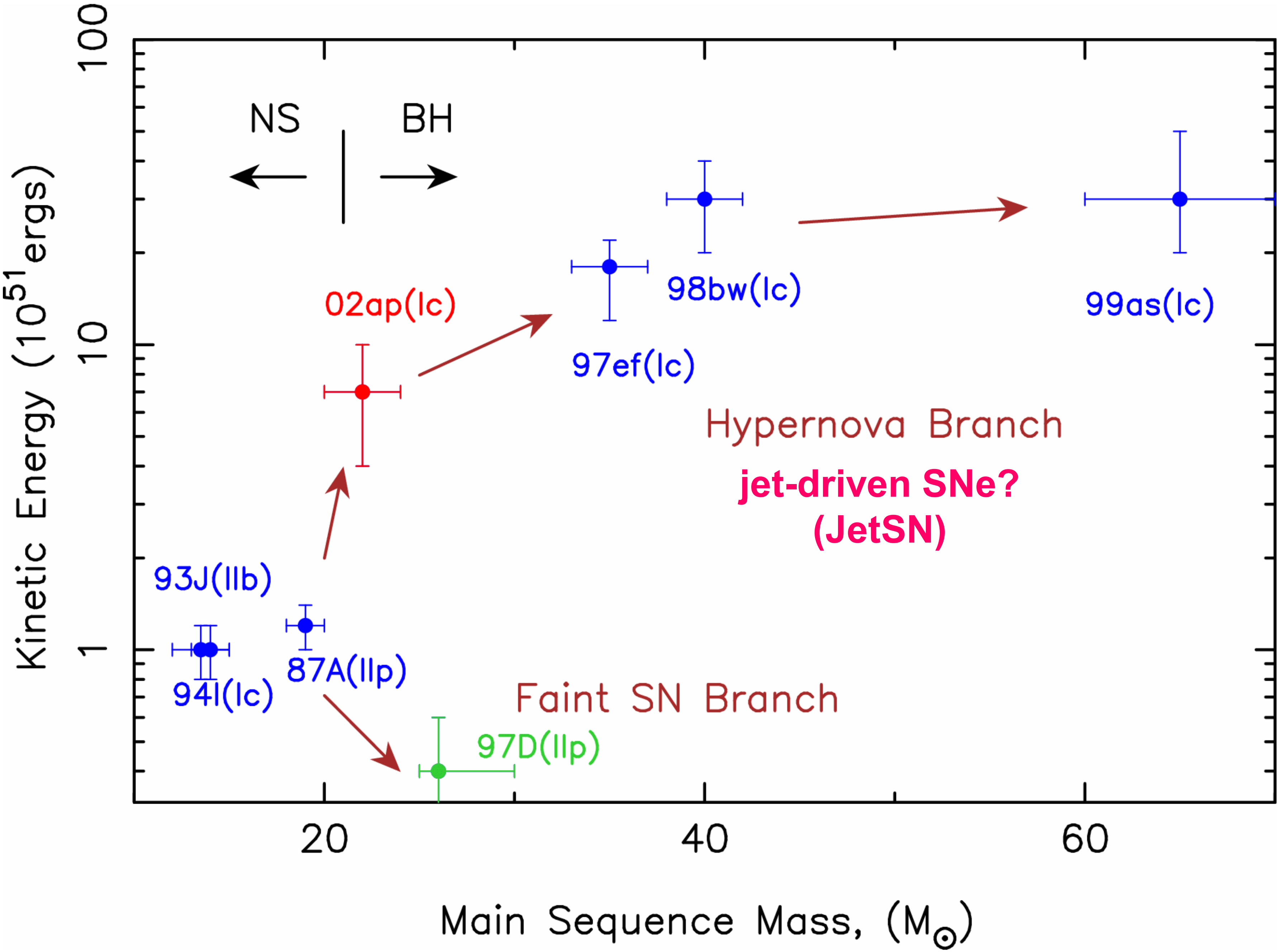
see Denault, Clayton & Heger (2003)



Overview:

Varieties of Cosmic Explosions

(of most kind)



jet-driven SNe?
(JetSN)

(Nomoto 2002, priv. com.)

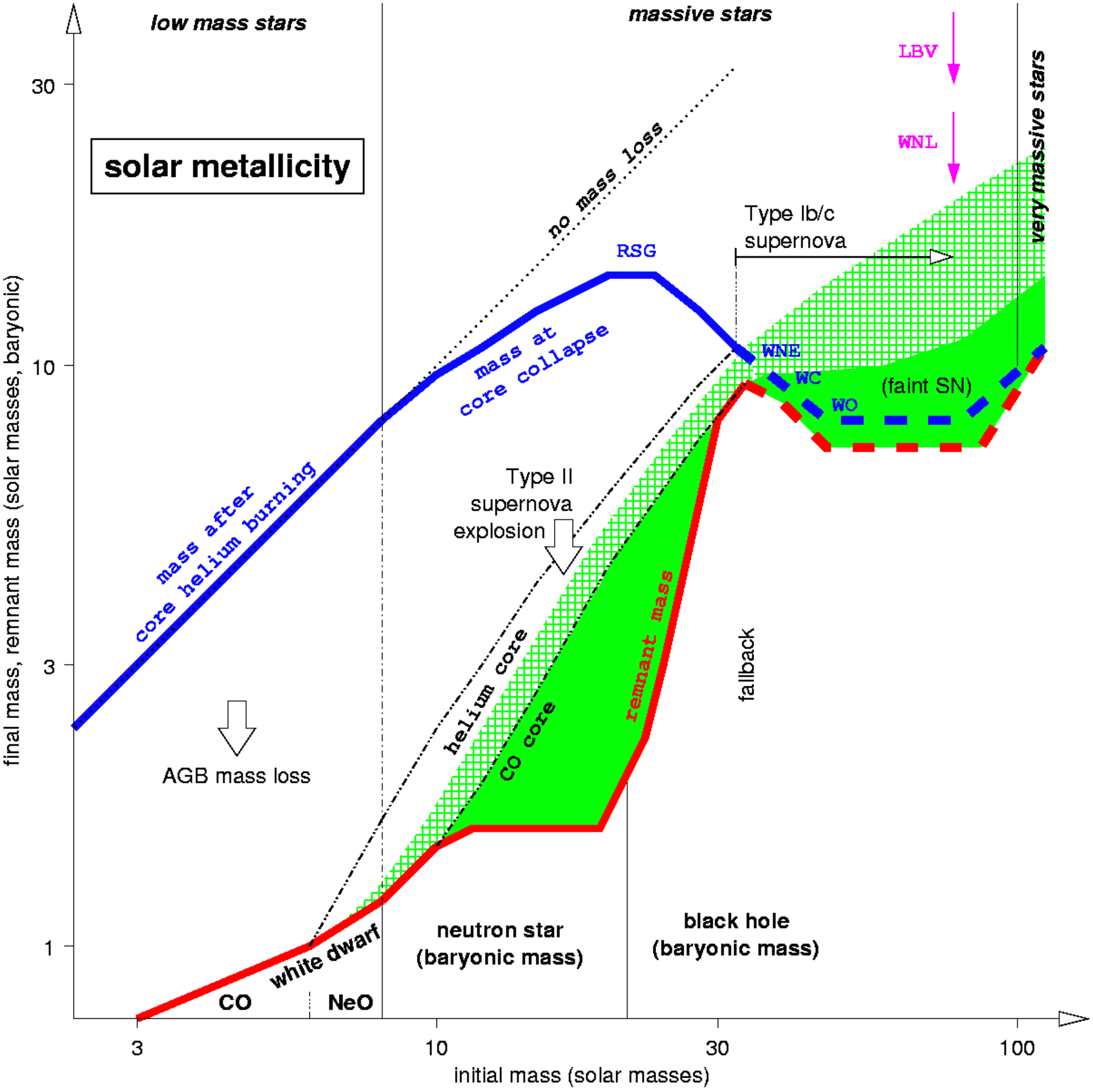
Energy Scales

Log E	Explosion	Thermonuclear
39	X-ray Bursts	√
40	Long-Duration He Bursts	√
41		
42	X-ray Superbursts	√
43		
44		
45	Classical Novae	√
46		
48	Faint SN (visible LC?)	
49	SN (visible LC)	
50	Bright SN (LC?)	
51	SN (kinetic)	SN Type Ia total
52	Hypernova? GRB?	Pair-SN total (low-mass end)
53	SN (neutrinos – several 10^{53}erg)	Pair-SN total (upper limit)
54	*(a lot of energy - 0.5* $M_\odot c^2$*)*	
55	GR He SN	GR He SN (upper limit)
56	GR H SN, $Z > 0$ (Fuller *et al.* 1986)	√

Massive Star Fates as Function of Initial Mass

(solar metallicity)

Ejected “metals”



Advanced Topics

The First Stars

in the Universe

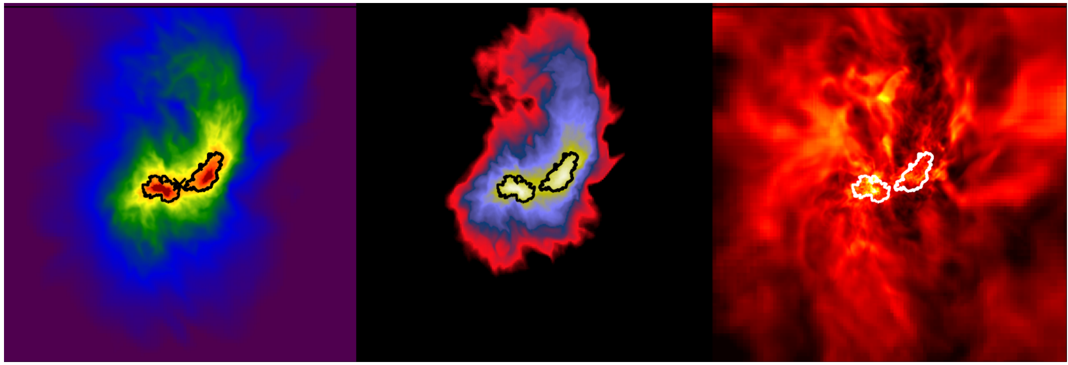
Formation and Mass of the First Stars

No metals ➔ no metal cooling ➔ more massive stars

(Bromm, Coppi, & Larson 1999, 2002; Abel, Bryan, & Norman 2000, 2002;Nakamura & Umemura 2001; O'Shea & Norman 2006,...)

➔ typical mass scale ~10...300 $M_{\odot}$?

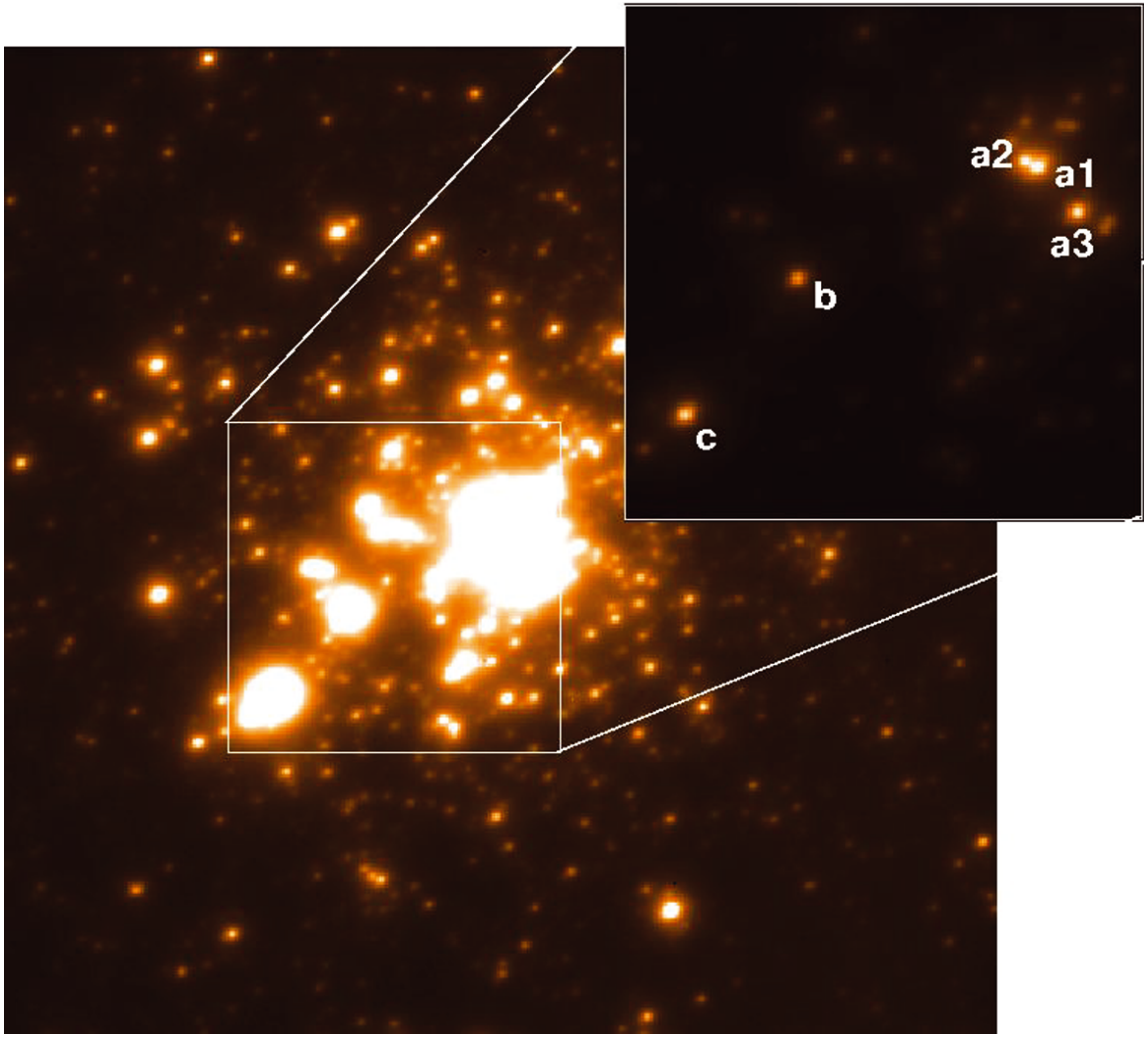
- ***Now*** simulations indicate binaries may exist



(Turk, Abel, O'Shea 2010)

- **But ...**
  We still don't have a really strong constrain on Pop III star masses in general

The Most Massive Stars Today



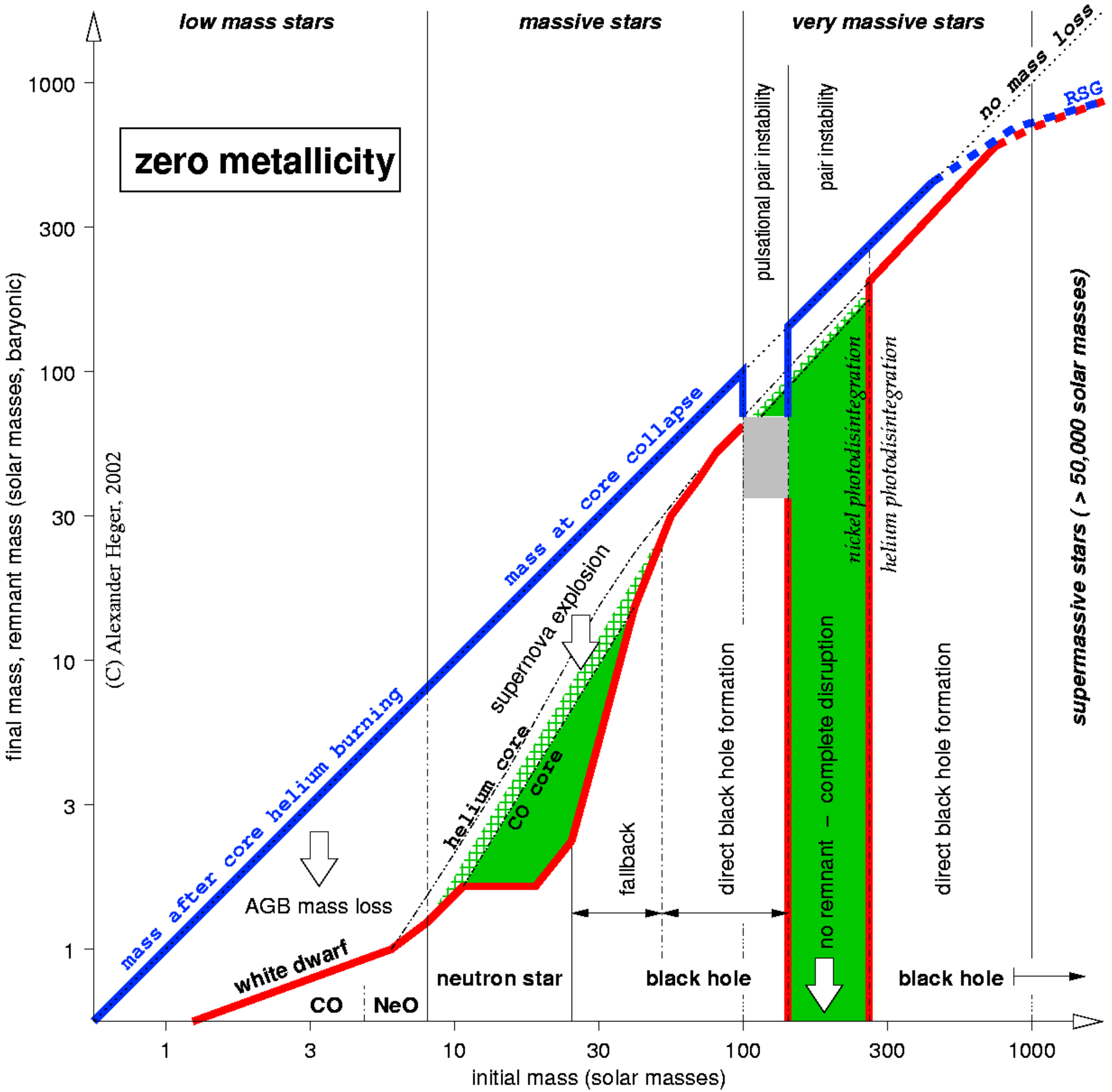
R136

- young massive star cluster
- Age around 1.5 Myr
- Star “a1”: maybe 200 $M_{\odot}$ initial mass

(Crother et al. 2010)

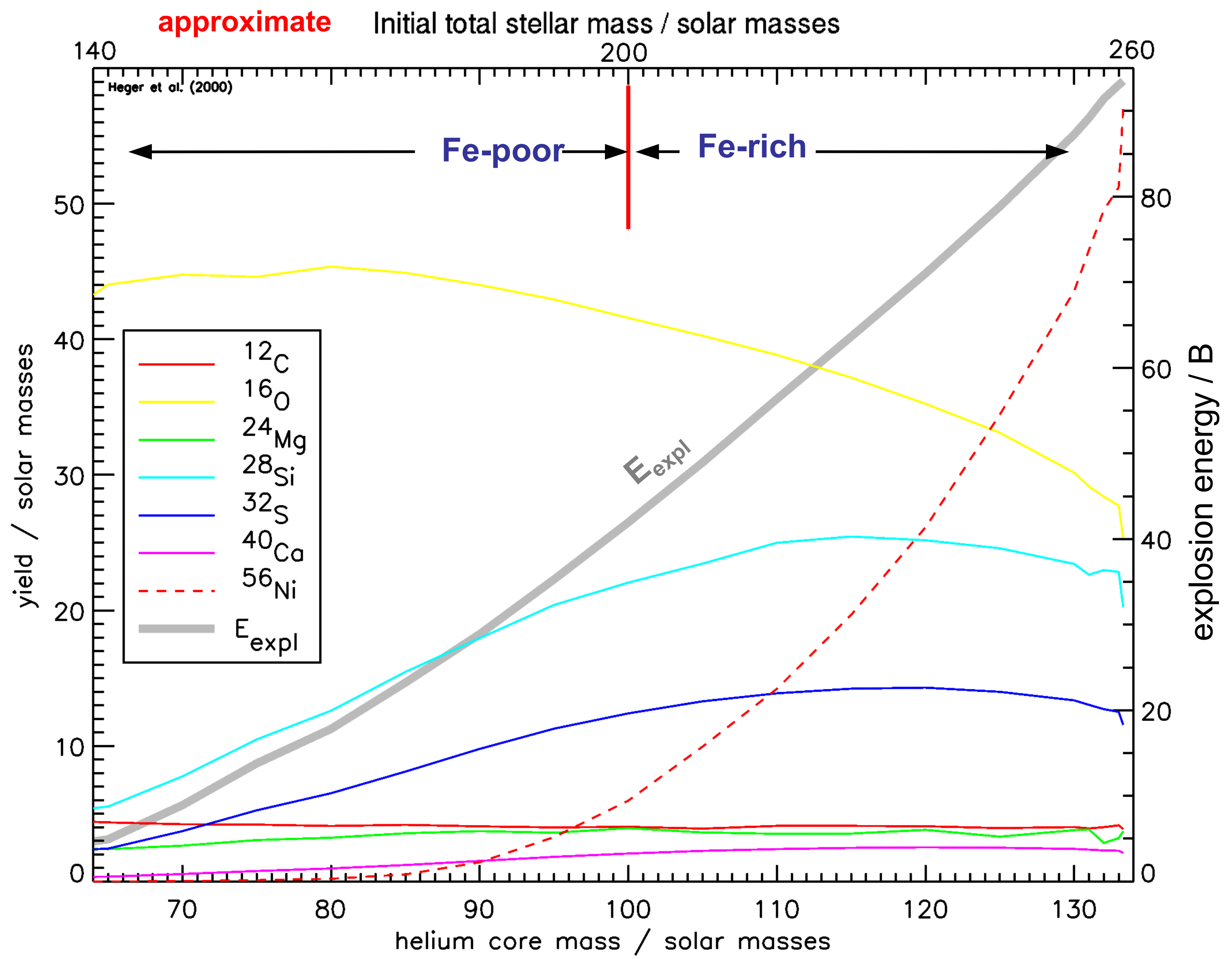
Nuclear Burning Stages

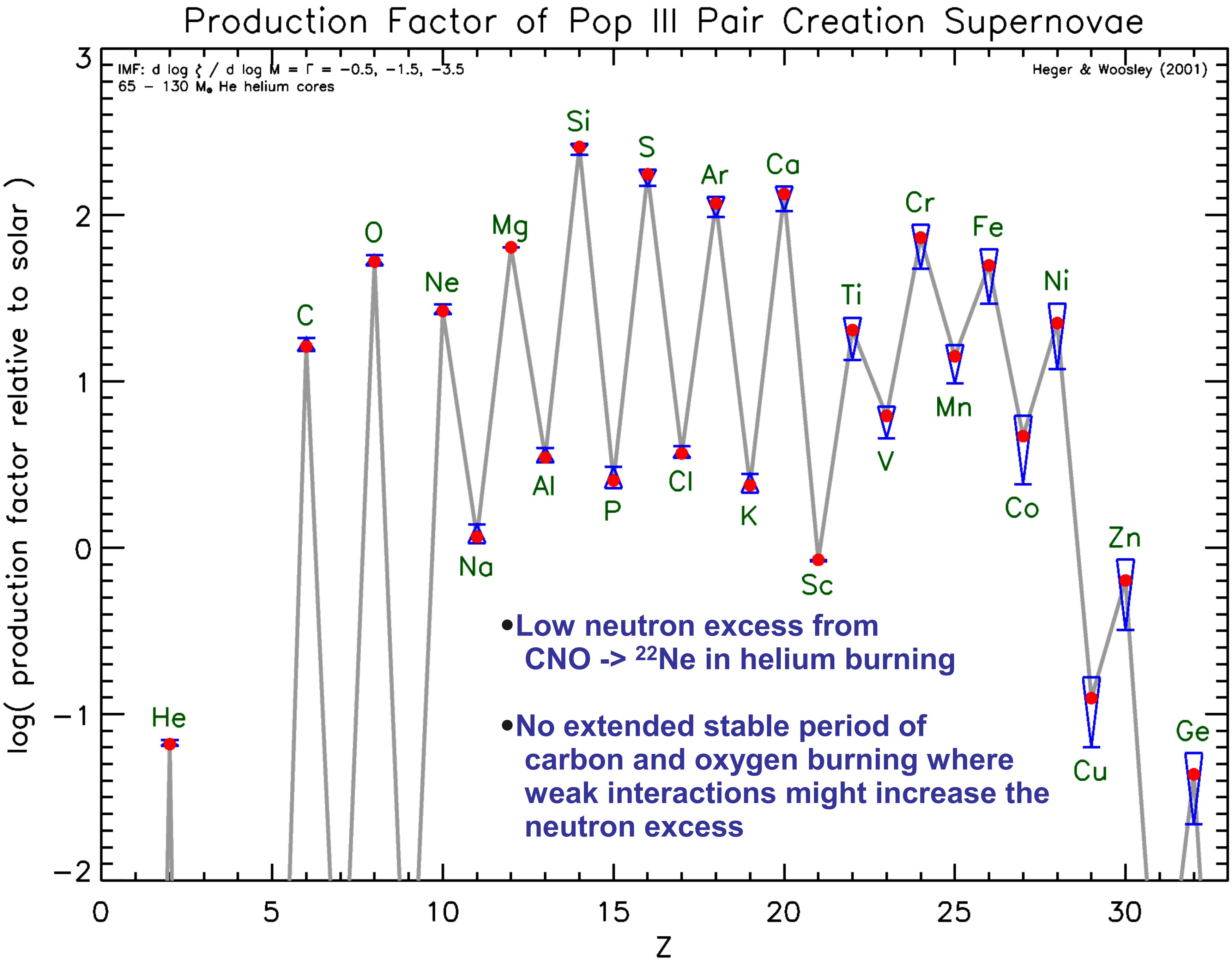
Burning stages		20 $M_\odot$ Star		200 $M_\odot$ Star	
Fuel	Main Product	T (10^9 K)	Time (yr)	T (10^9 K)	Time (yr)
H	He	0.02	10^7	0.1	2×10^6
He	O, C	0.2	10^6	0.3	2×10^5
C	Ne, Mg	0.8	10^3	1.2	10
Ne	O, Mg	1.5	3	2.5	3×10^{-6}
O	Si, S	2.0	0.8	3.0	2×10^{-6}
Si	Fe	3.5	0.02	4.5	3×10^{-7}



Ejected "metals"

Nucleosynthesis
in
Pair-Instability
Supernovae


approximate
Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
Fe-poor
Fe-rich
E_{expl}
^{12}C
^{16}O
^{24}Mg
^{28}Si
^{32}S
^{40}Ca
^{56}Ni
E_{expl}
yield / solar masses
0
10
20
30
40
50
explosion energy / B
0
20
40
60
80
70
80
90
100
110
120
130
helium core mass / solar masses

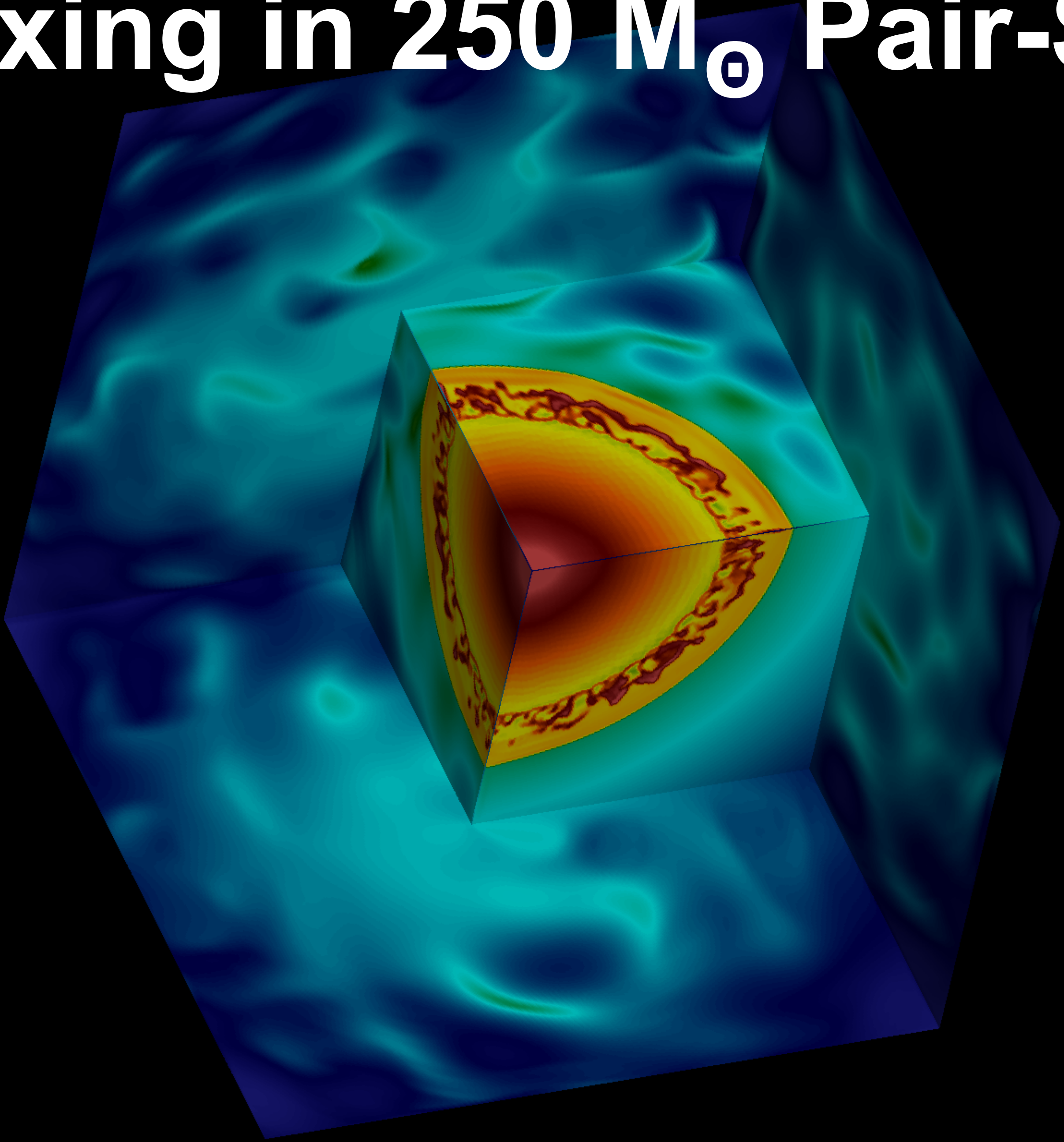


- **Low neutron excess from CNO -> ^{22}Ne in helium burning**
- **No extended stable period of carbon and oxygen burning where weak interactions might increase the neutron excess**

➔Problem

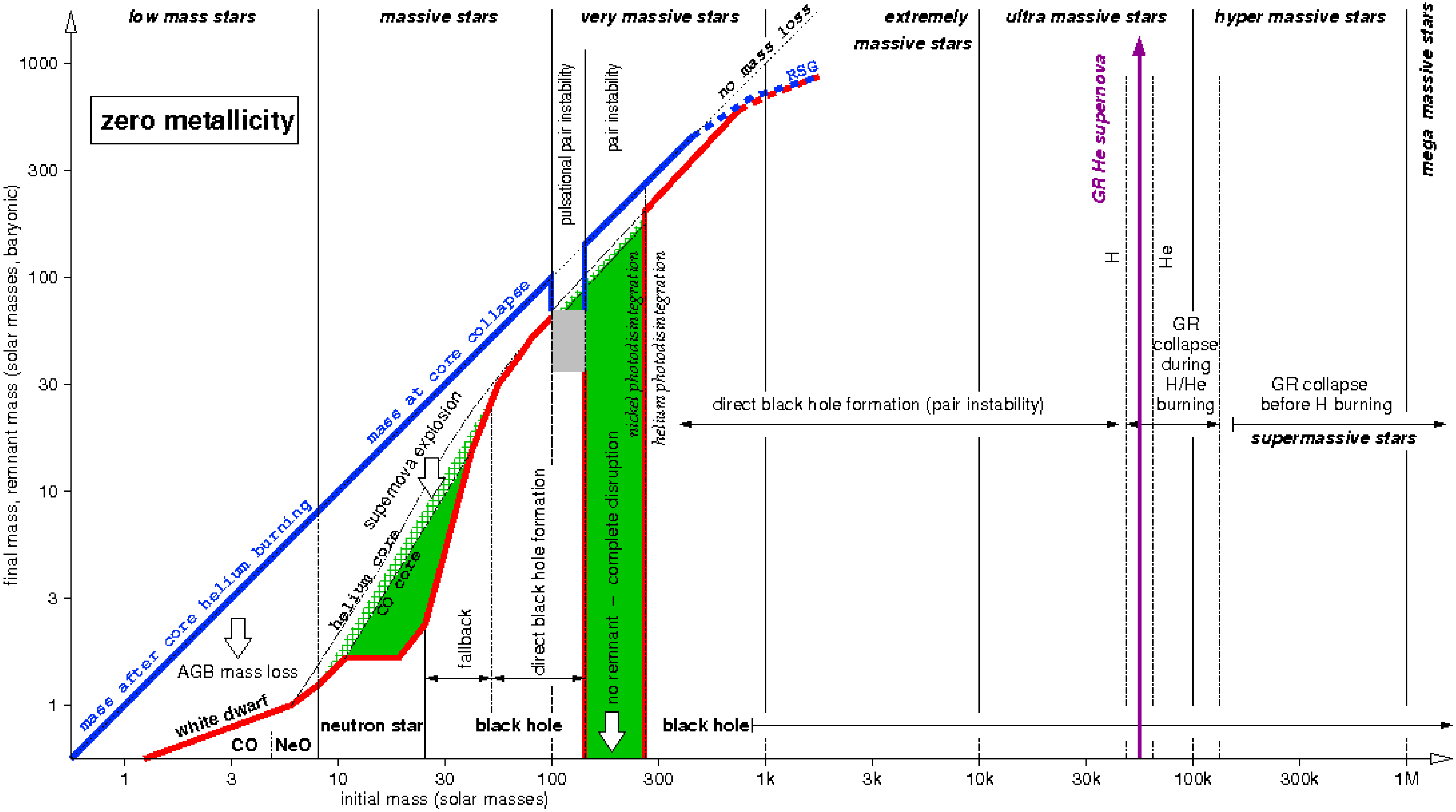
Pair-Instability Supernovae do not reproduce the abundances as observed in very metal poor halo stars!

Mixing in 250 $M_\odot$ Pair-SN

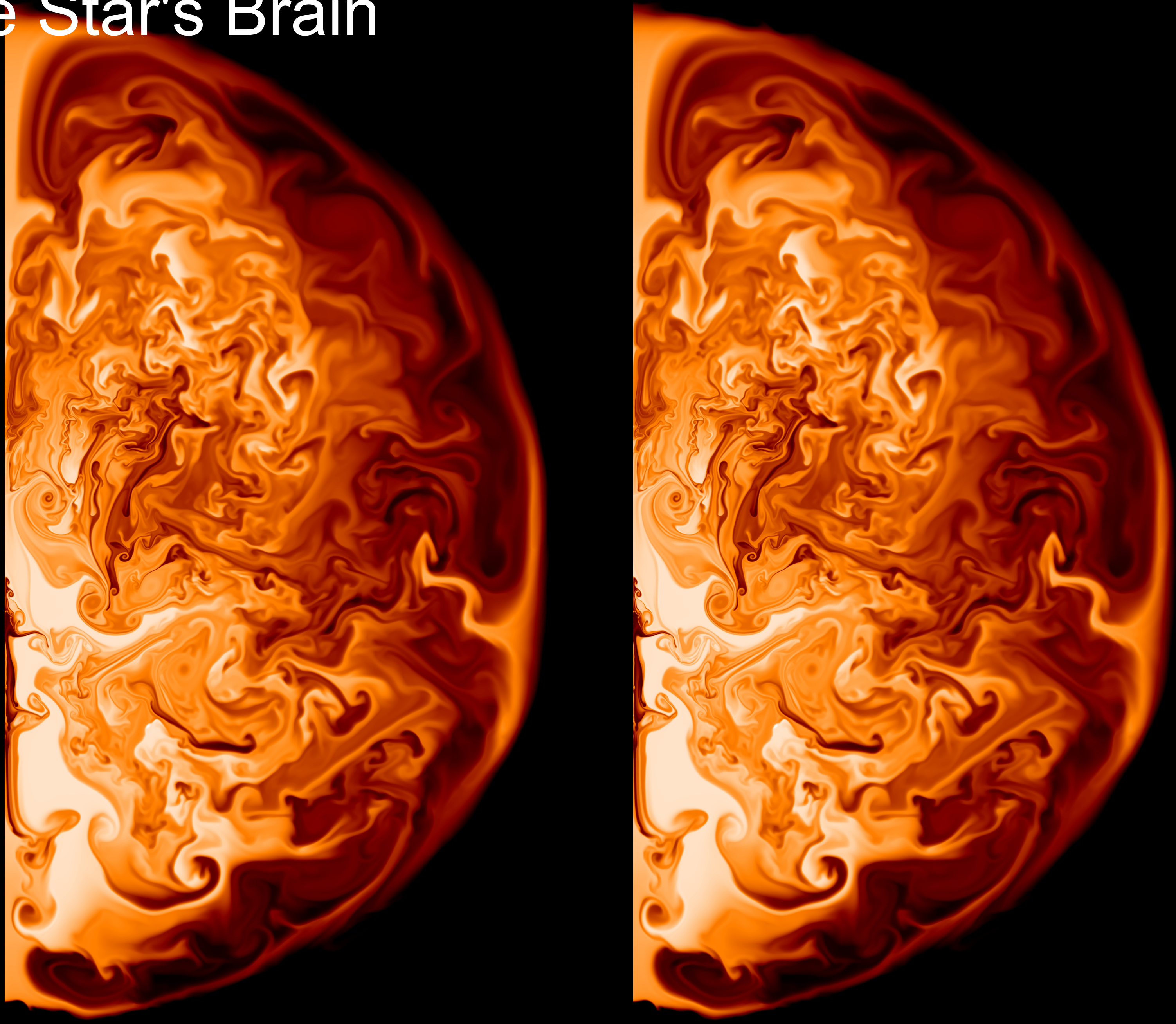


(Ken Chen 2011)

Supermassive Stars



The Star's Brain

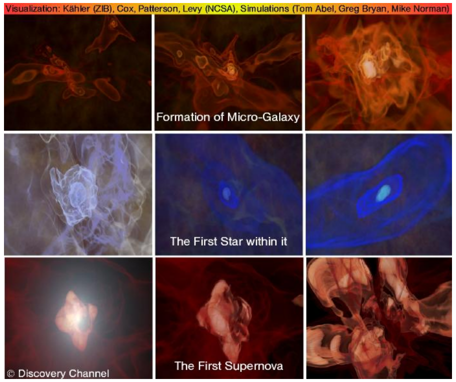


55,500 $M_\odot$ Star exploding at 10^{55} erg

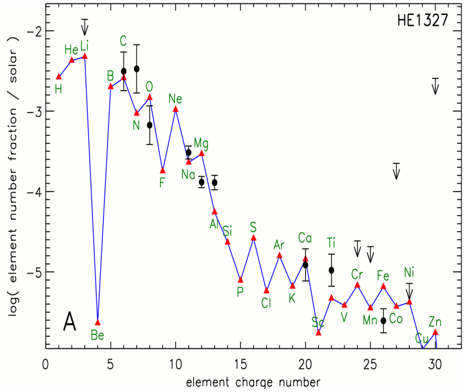
(Ken Chen 2011)

Nucleosynthesis
in
Massive Pop III
Stars

Reconstruction of the Pop III IMF



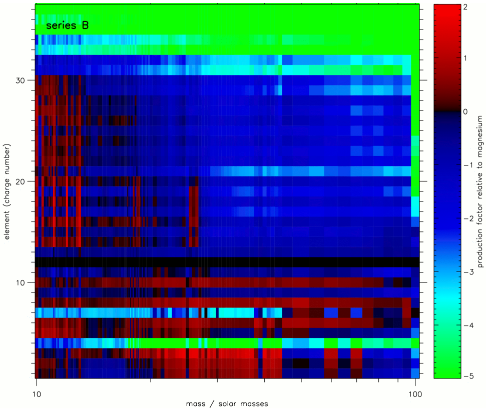
primordial stars form, nucleosynthesis ejected



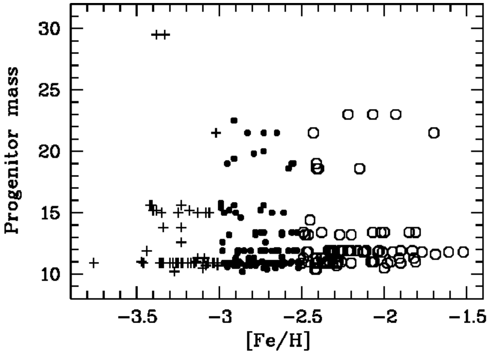
ejecta incorporated in low-Z halo stars

find low-Z halo stars (HERES, SEGUE, …)

measure abundances (VLT, KECK, …)



compare abundances to primordial star nucleosynthesis library

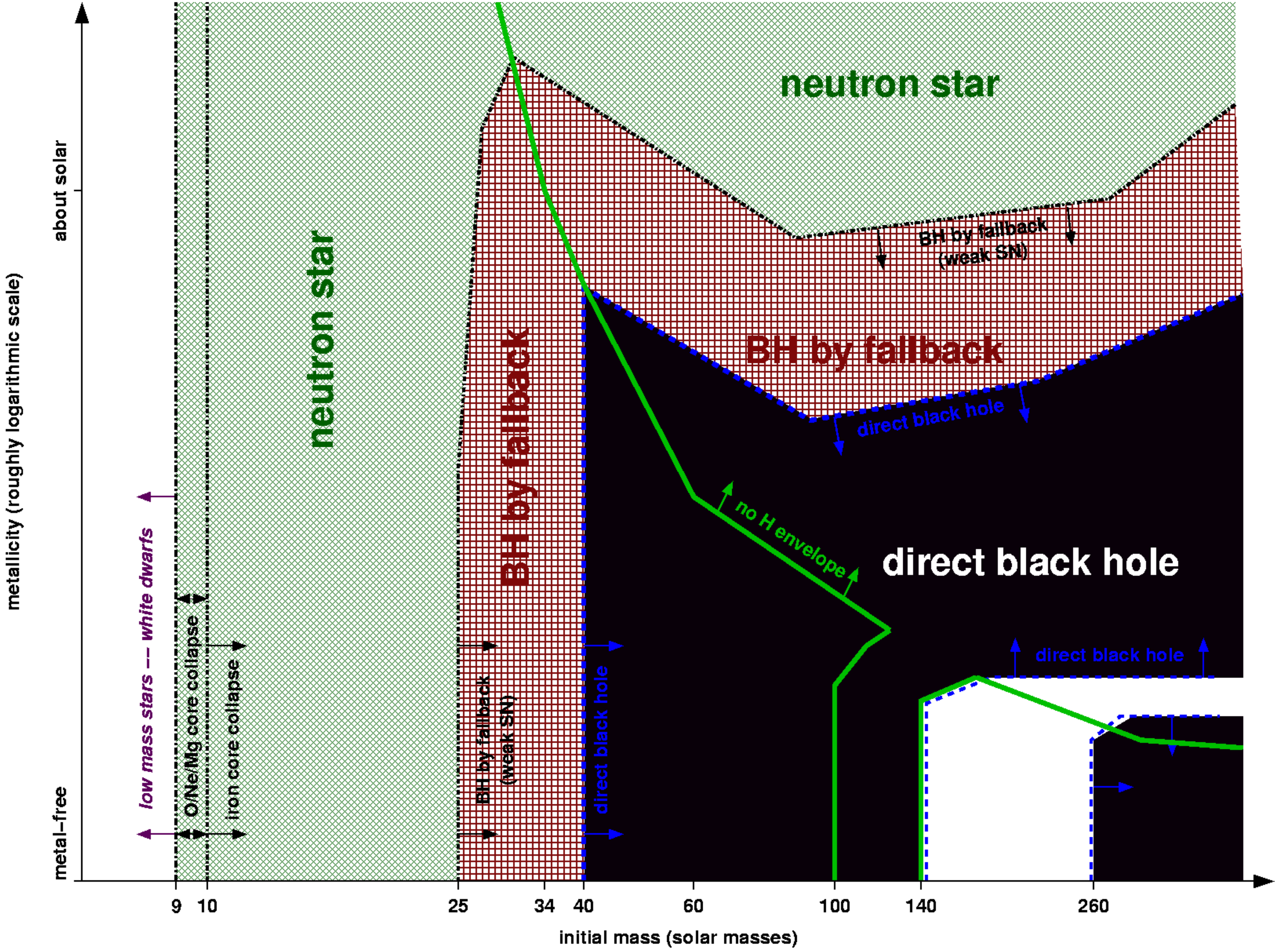


obtain IMF of population of progenitor stars

Frebel, priv. com. (2007)

Massive Star Fates as Function of Mass and Metallicity

(single stars)


neutron star
neutron star
BH by fallback
BH by fallback
BH by fallback (weak SN)
BH by fallback (weak SN)
direct black hole
direct black hole
direct black hole
direct black hole
no H envelope
low mass stars -- white dwarfs
O/Ne/Mg core collapse
iron core collapse
about solar
metal-free
metallicity (roughly logarithmic scale)
9
10
25
34
40
60
100
140
260
initial mass (solar masses)

Things that blow up

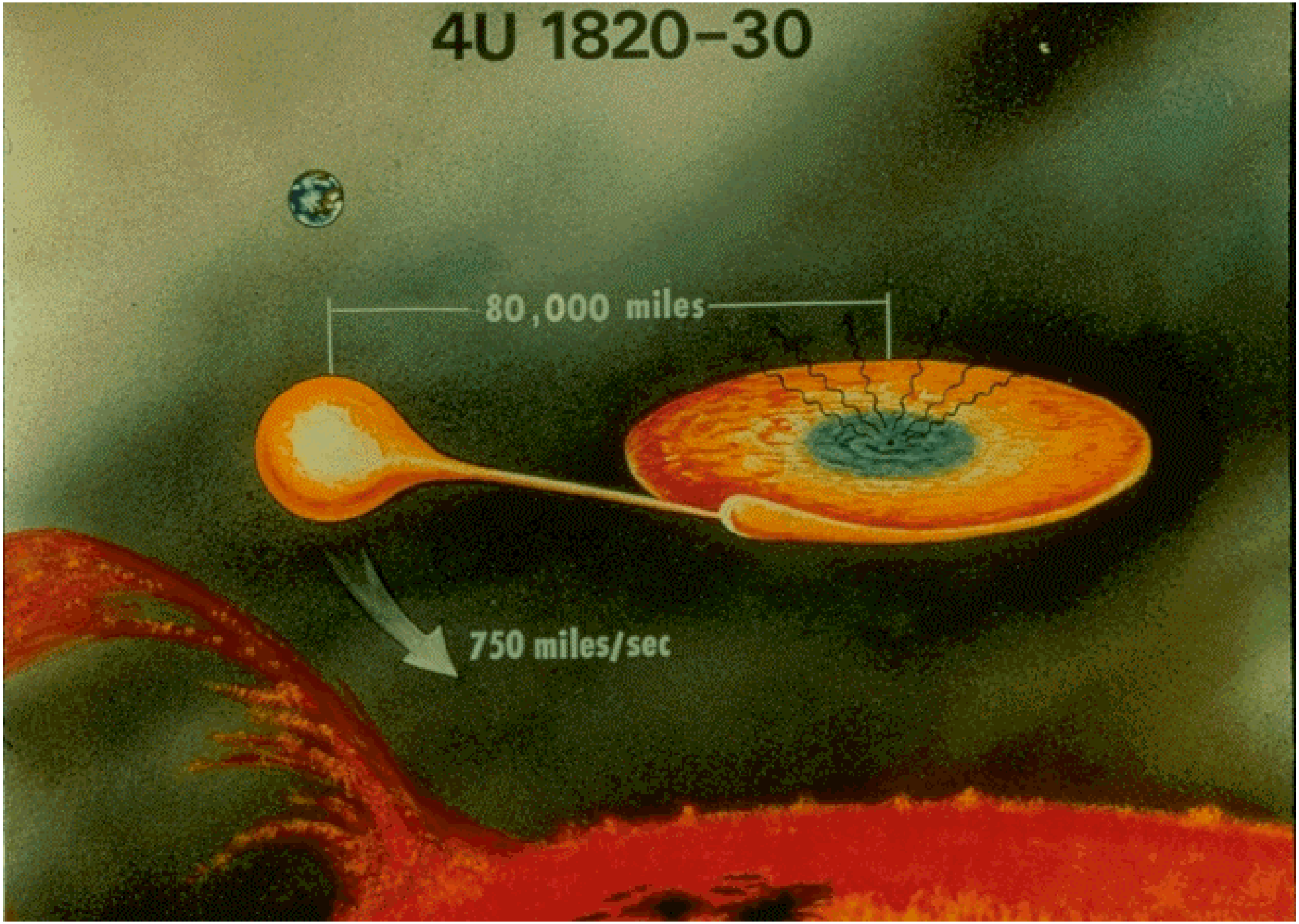
supernovae

1B=10^{51} erg

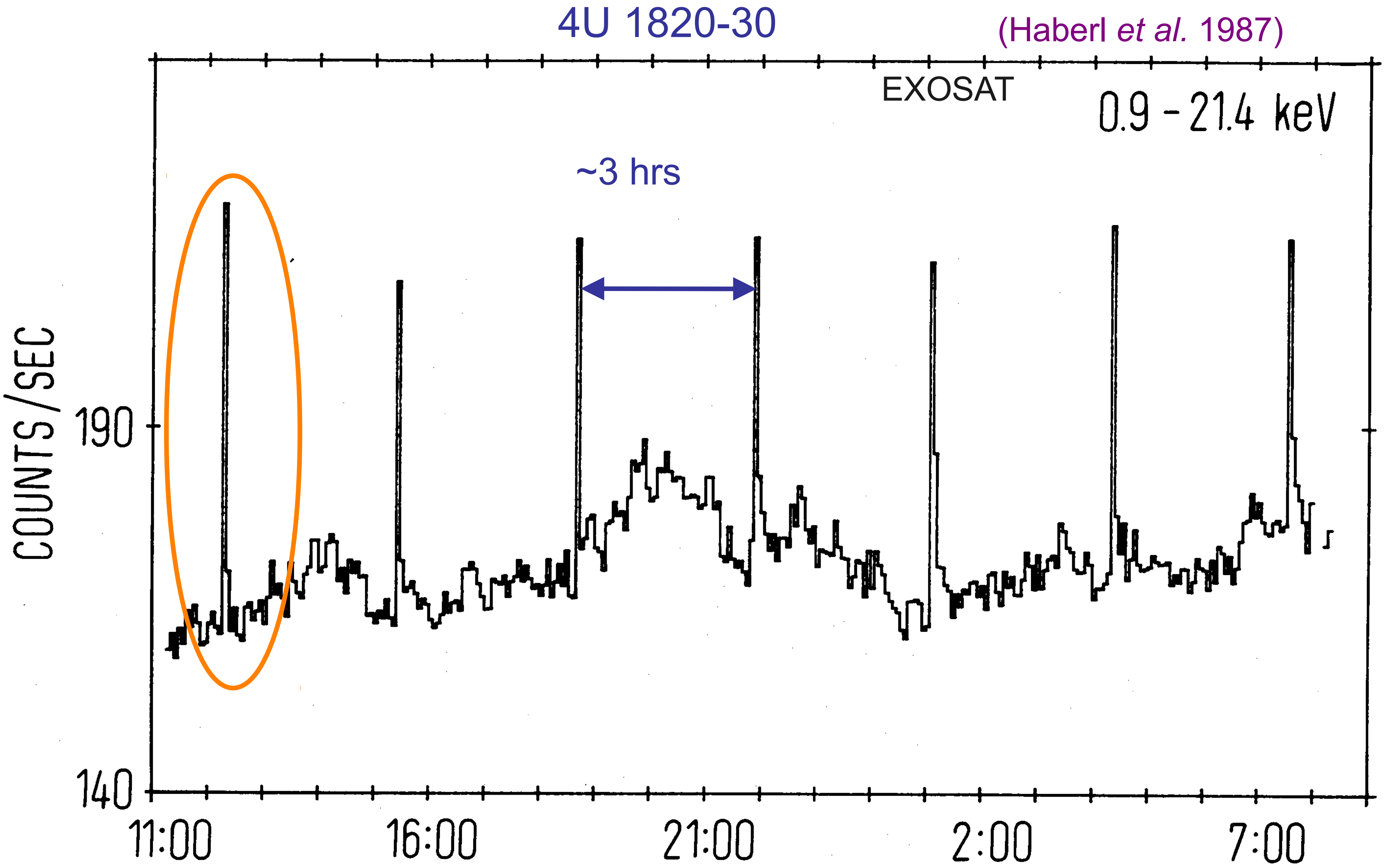
MASS

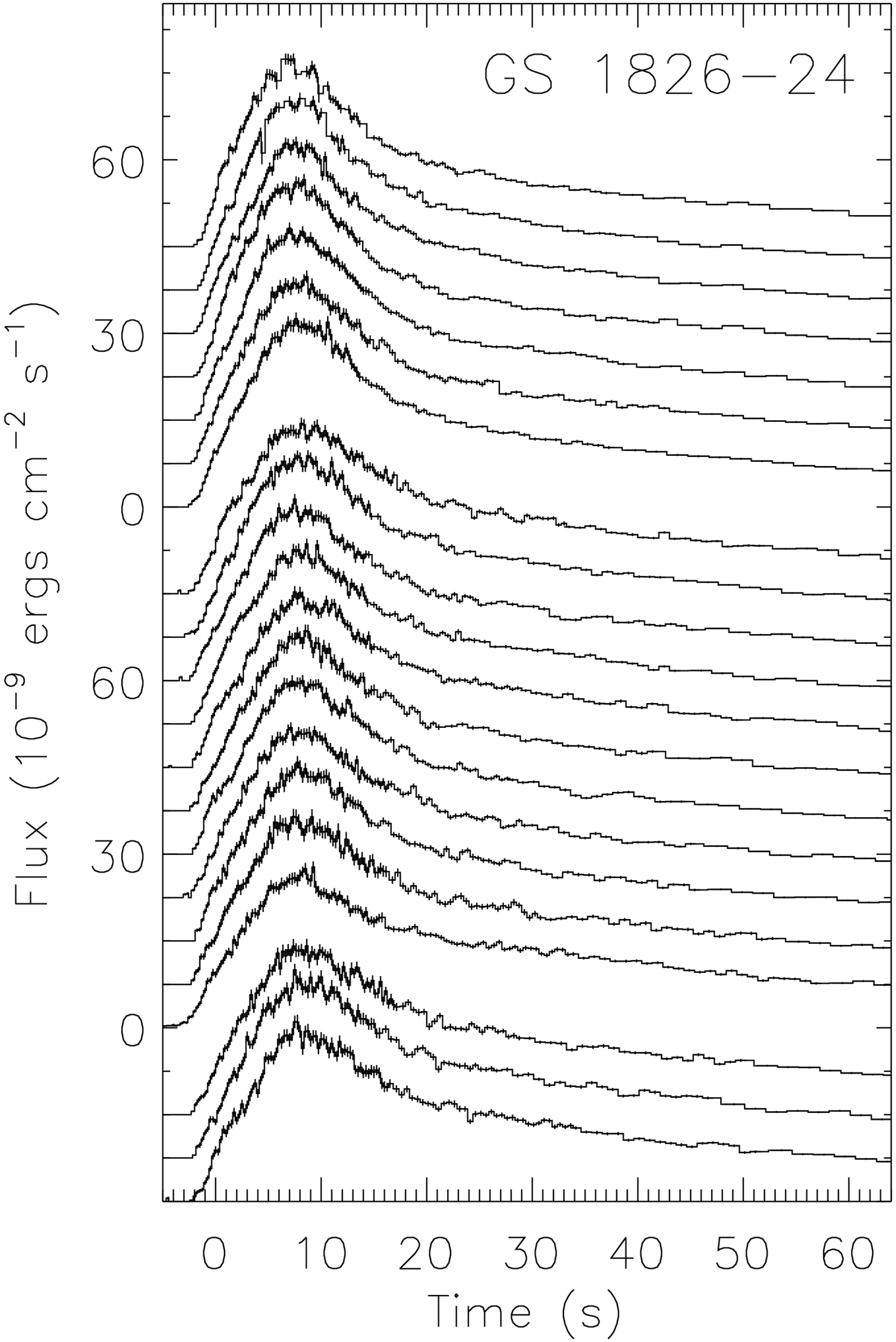
- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- "SAGB" star (AGB, then SN) ➔ EC SN
- "normal" SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- "Collapsar", GRB ➔ broad line Ib/a SN, "hypernova"
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B (1B=10^{51} erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- GR He instability ➔ >100 B SN+SMBH, or 10,000 B
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

Type I X-Ray Bursts



Thermonuclear Origin of X-ray Bursts



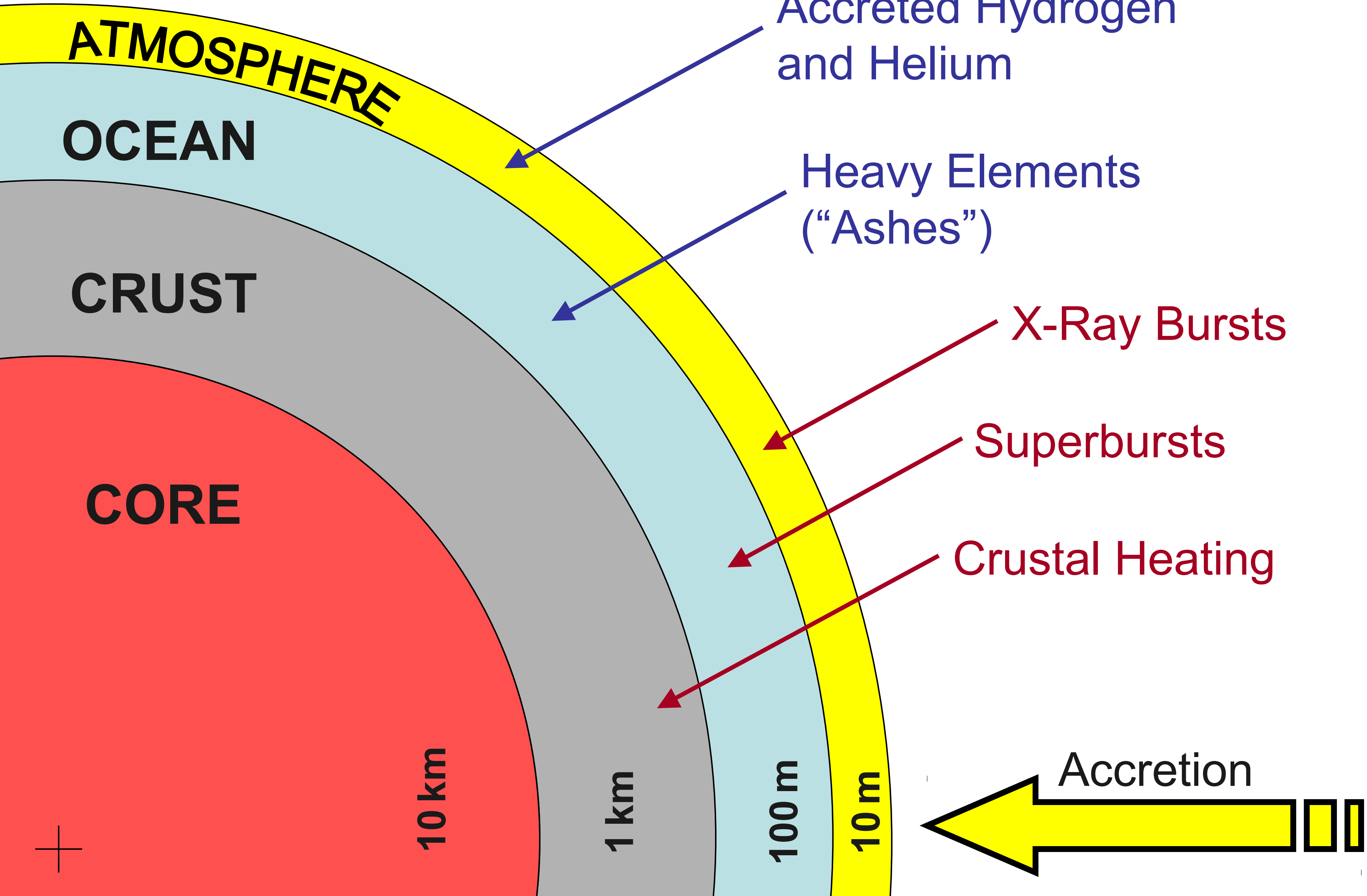


XRB Observations

- Repeated burst of X-rays
- tens of seconds duration
- repeat time hours to days
- inferred luminosity close to Eddington

***The* most common thermonuclear explosion in nature!**

Structure of an Accreting Neutron Star



Accreted Hydrogen and Helium

Heavy Elements (“Ashes”)

X-Ray Bursts

Superbursts

Crustal Heating

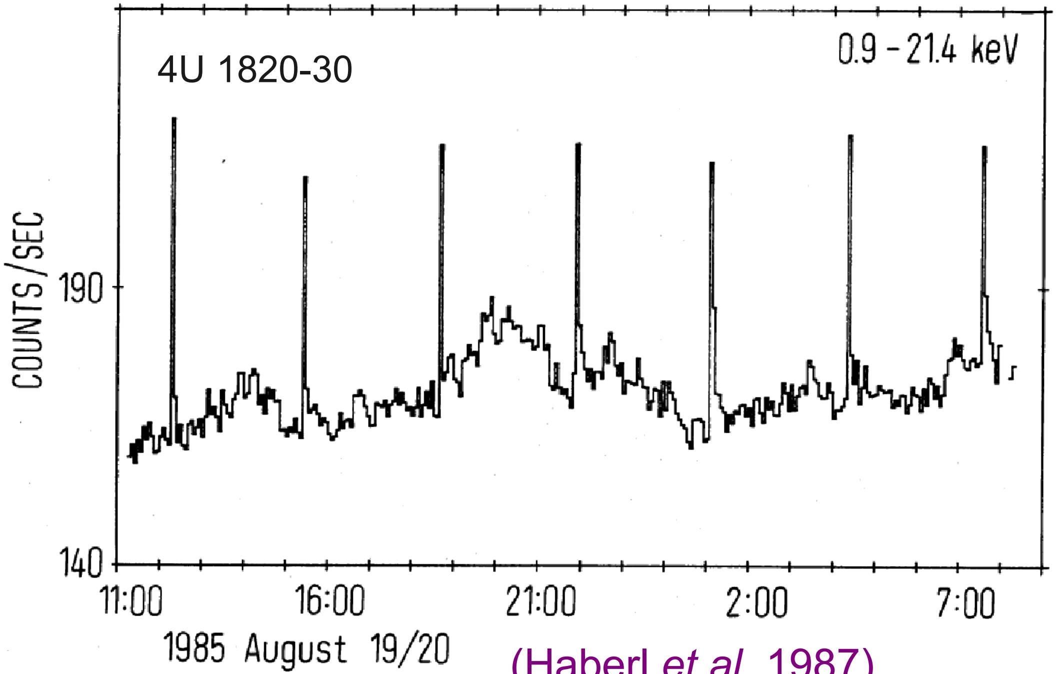
Accretion

Energetics of Bursts

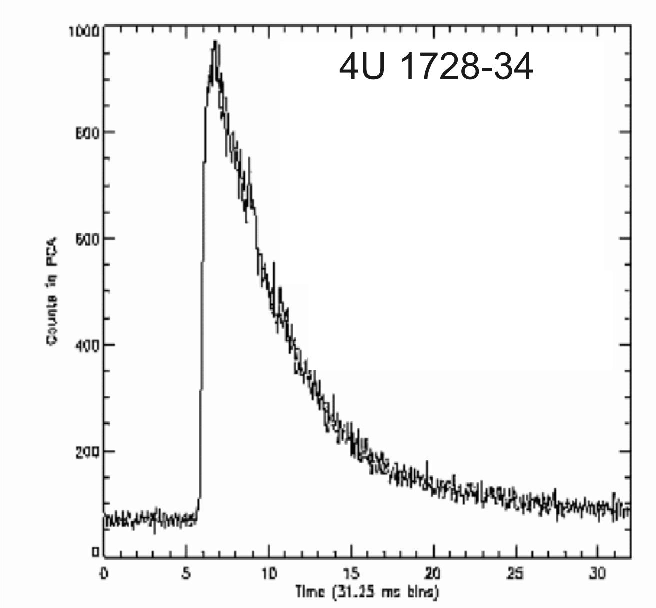
nuclear energy release $Q_{nuc} \approx (1\text{-}5)\ \mathrm{MeV} / \mathrm{nucleon}$

gravitational energy release $\dfrac{GM}{R} \approx 200\ \mathrm{MeV} / \mathrm{nucleon}$

ratio of energies $\alpha = \dfrac{\int F_p dt}{\int F_b dt} \approx \dfrac{GM/R}{Q_{nuc}} \approx 40 - 100$

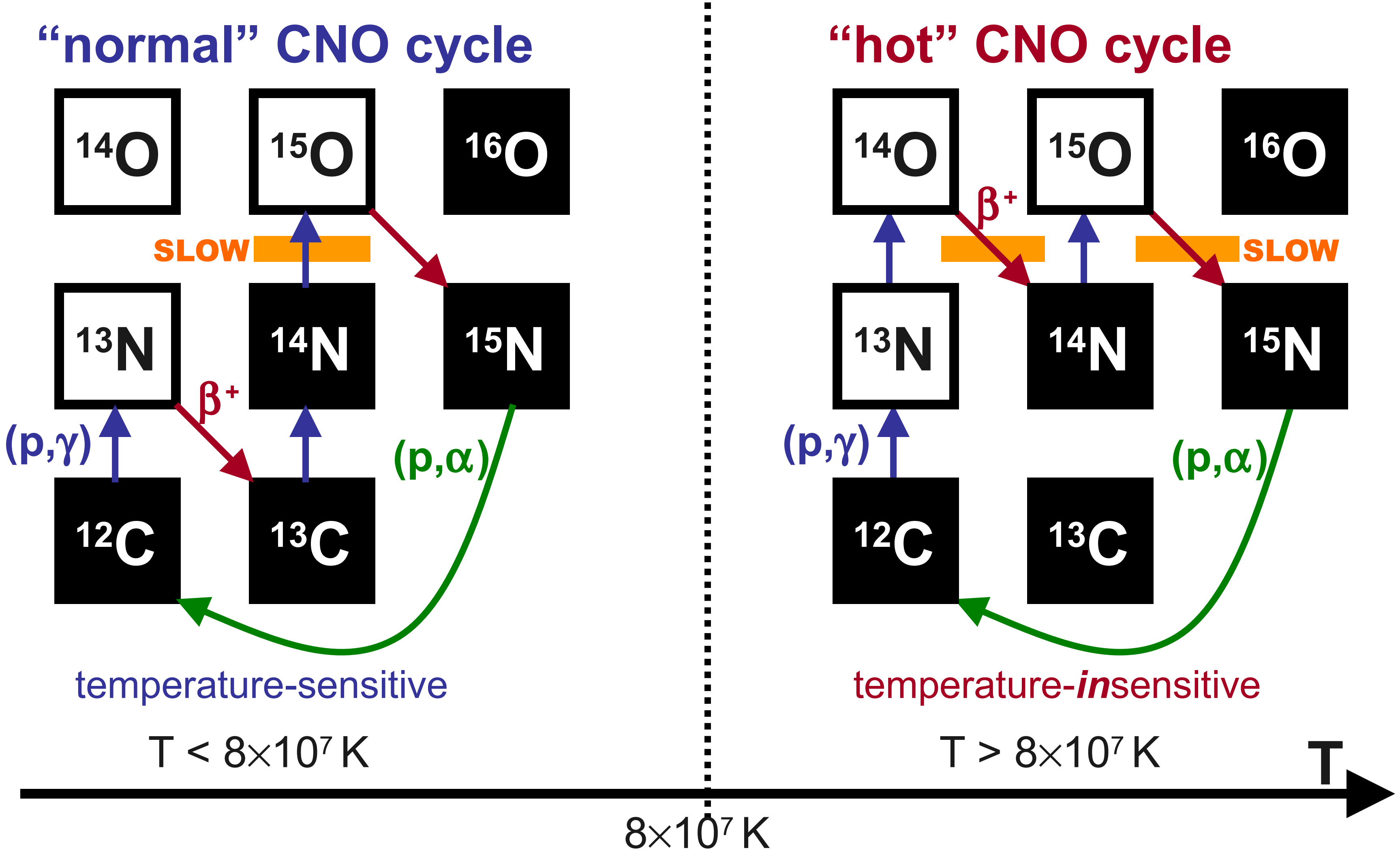


(Haberl *et al.* 1987)



(Strohmayer *et al.* 1996)

Hydrogen Burning by CNO Cycle



“normal” CNO cycle

^{14}O ^{15}O ^{16}O

^{13}N ^{14}N ^{15}N

^{12}C ^{13}C

SLOW

β^+

(p,γ)

(p,α)

temperature-sensitive

T < 8×10^7 K

“hot” CNO cycle

^{14}O ^{15}O ^{16}O

^{13}N ^{14}N ^{15}N

^{12}C ^{13}C

β^+

SLOW

(p,γ)

(p,α)

temperature-*in*sensitive

T > 8×10^7 K

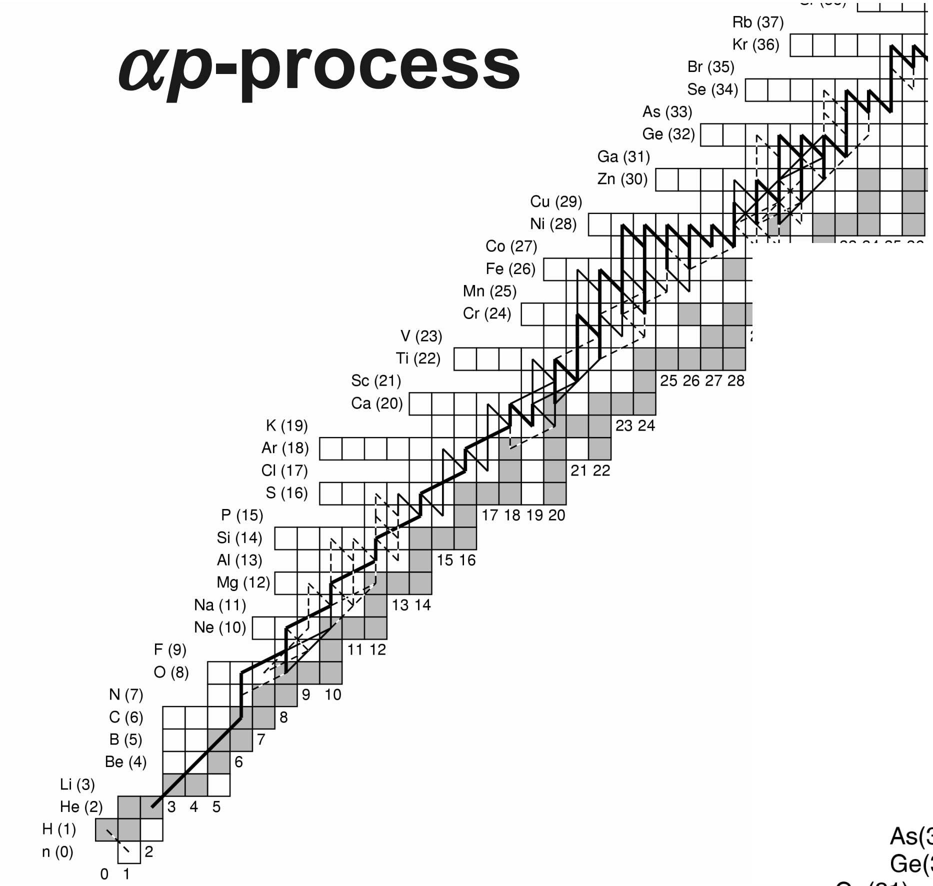
T

8×10^7 K

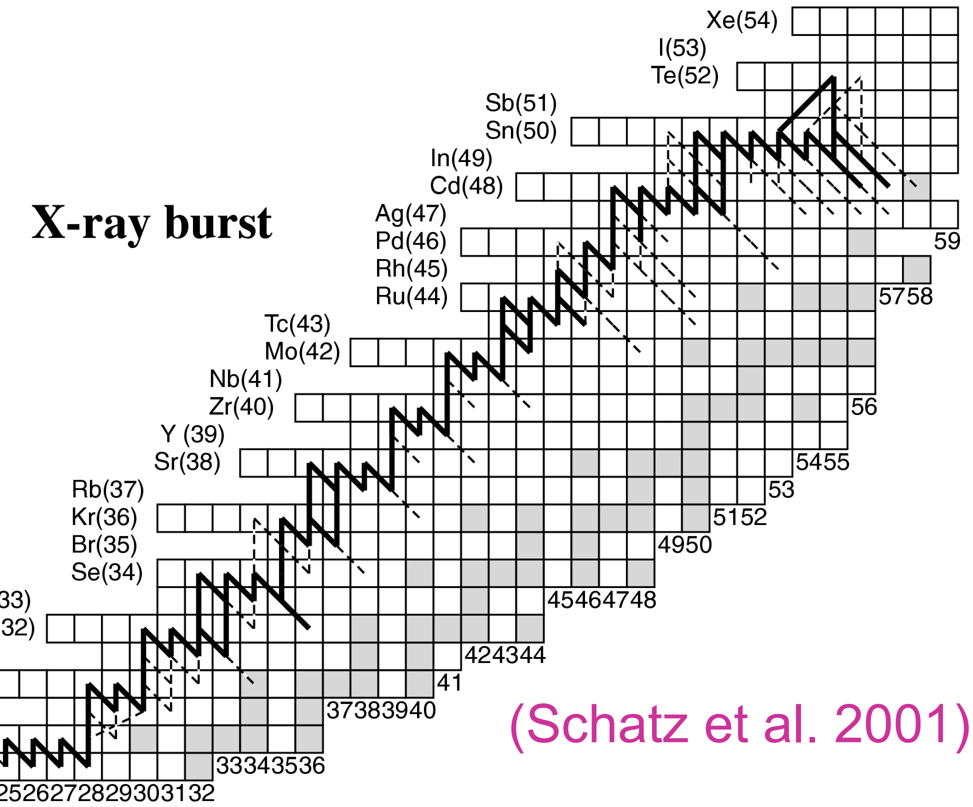
time for an eddy to burn its hydrogen content by **hot** CNO cycle

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

αp- and *rp*-Process Paths

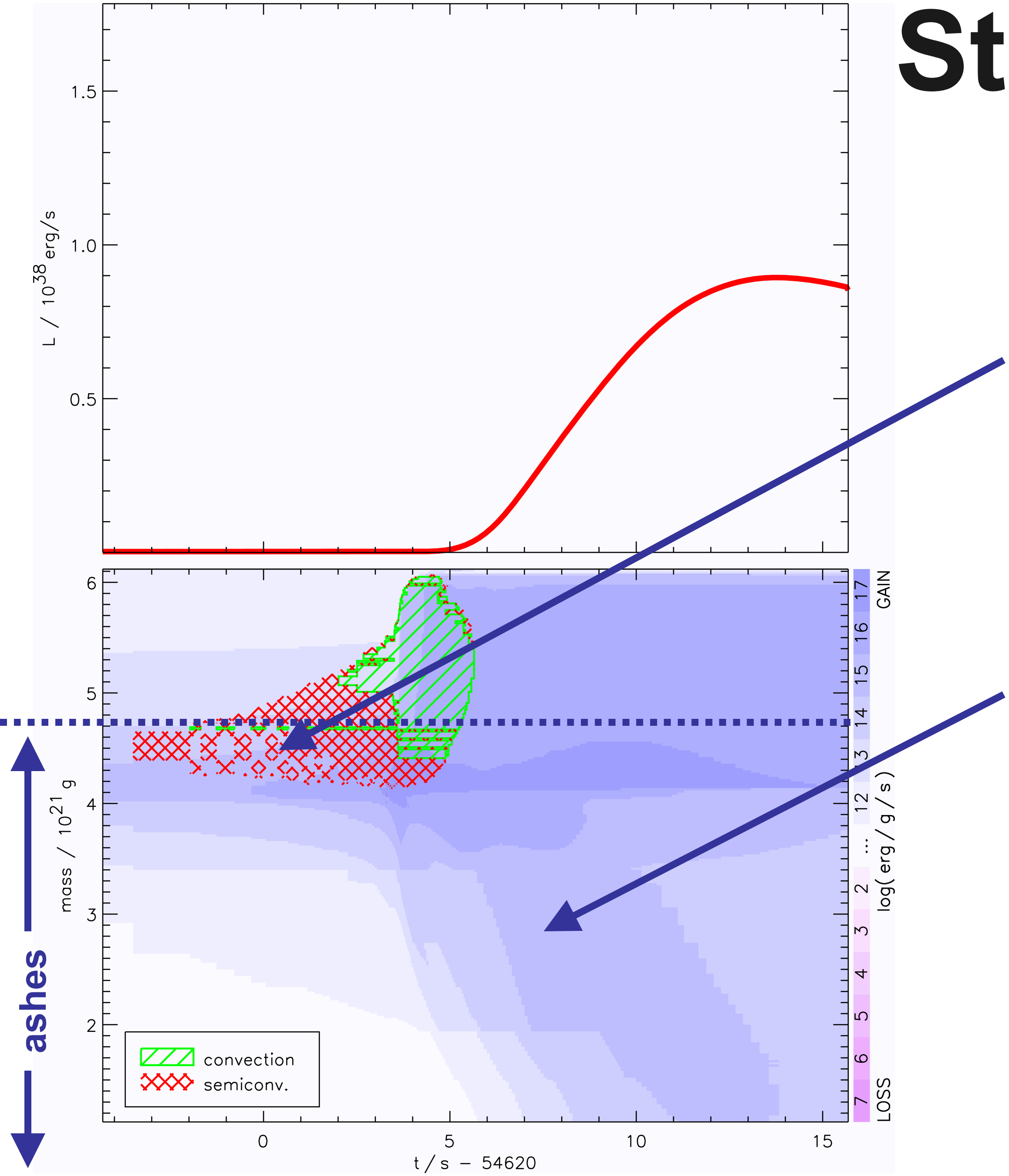


(Schatz, Bildsten,
& Cumming 1999)



(Schatz et al. 2001)

Start of Burst



Ignition of burst in/by ashes layer of previous burst

➔ **compositional inertia**

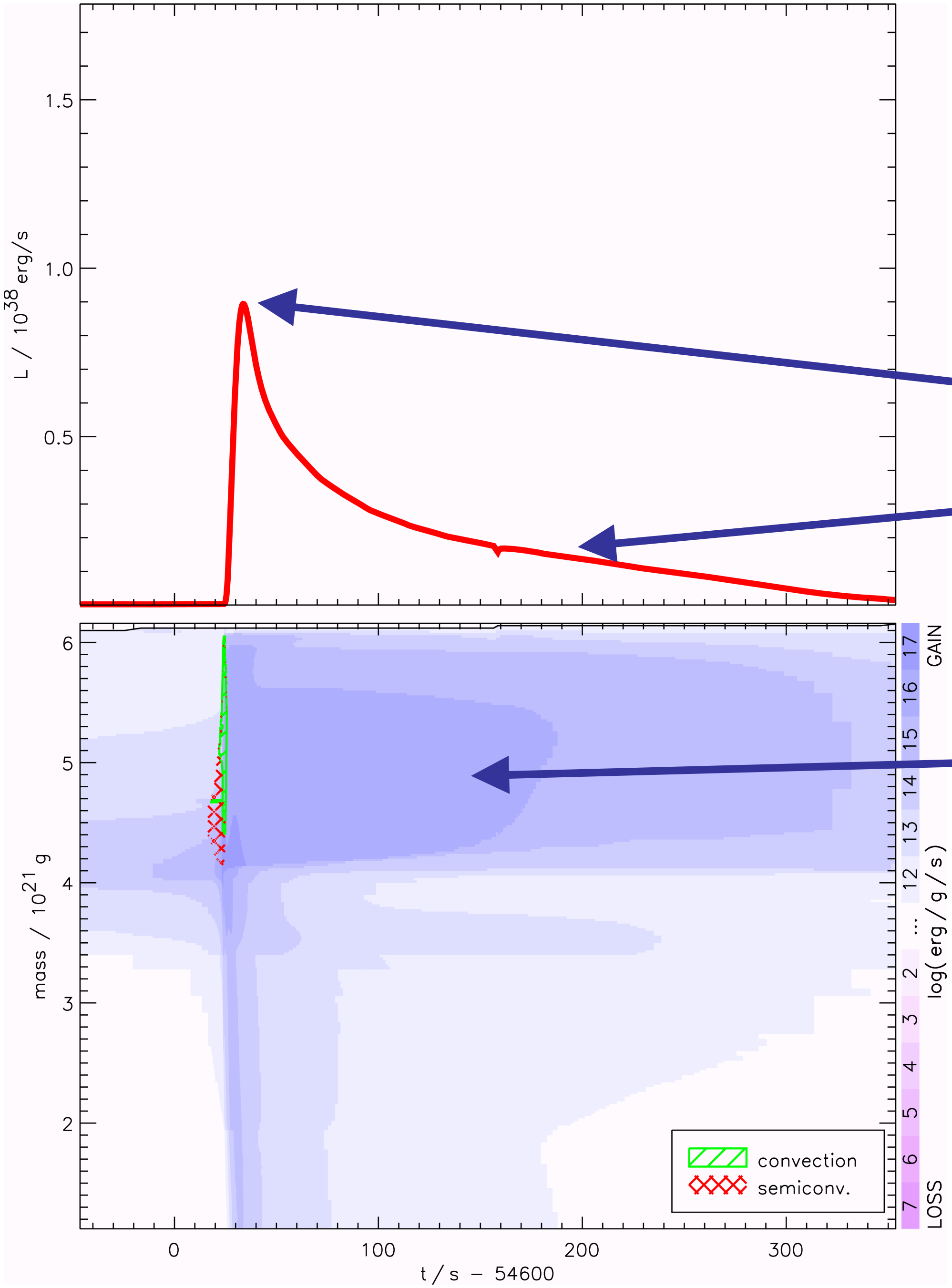
Heating of substrate by energy from burst

➔ burning of ^{4}He

➔ destruction of ^{12}C

(at low He abundance the ^{12}C(α,γ) rate dominates over the 3α rate)

Long-Time Evolution



Peak of light curve less luminous and tail decays faster

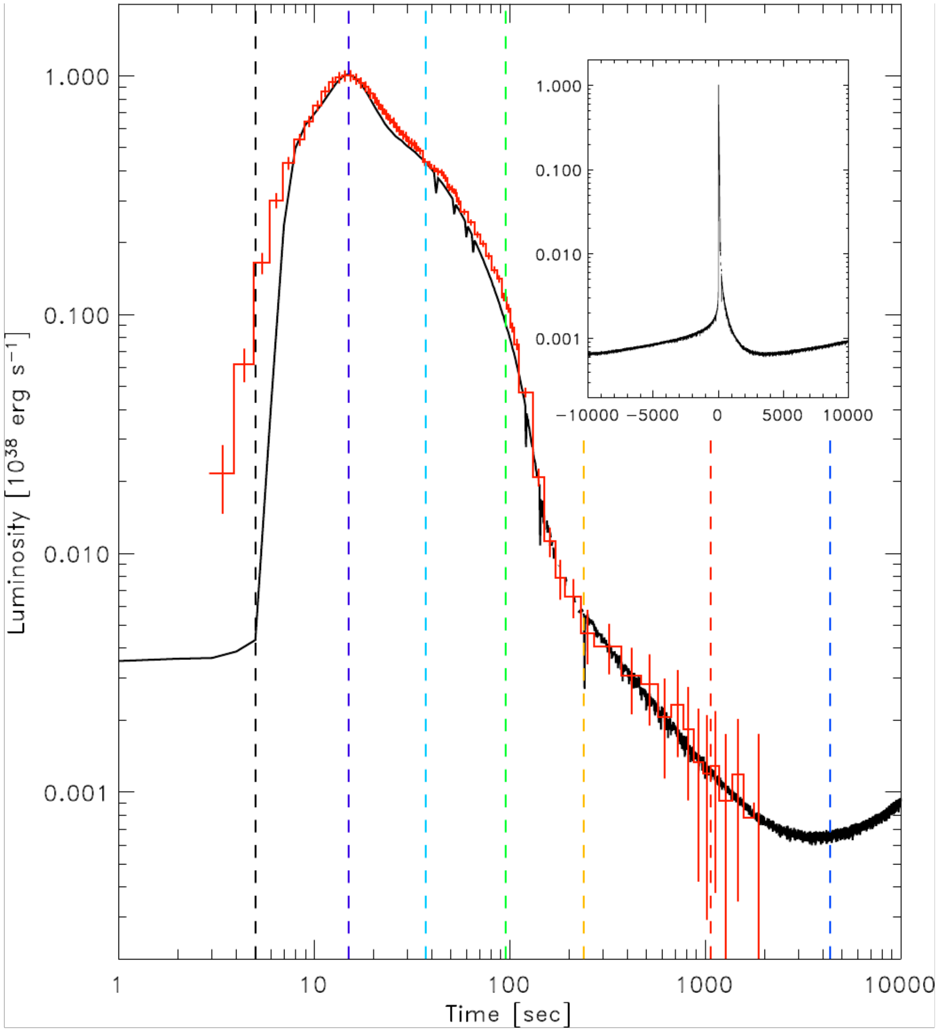
rp-process continues for some time, but some H remains

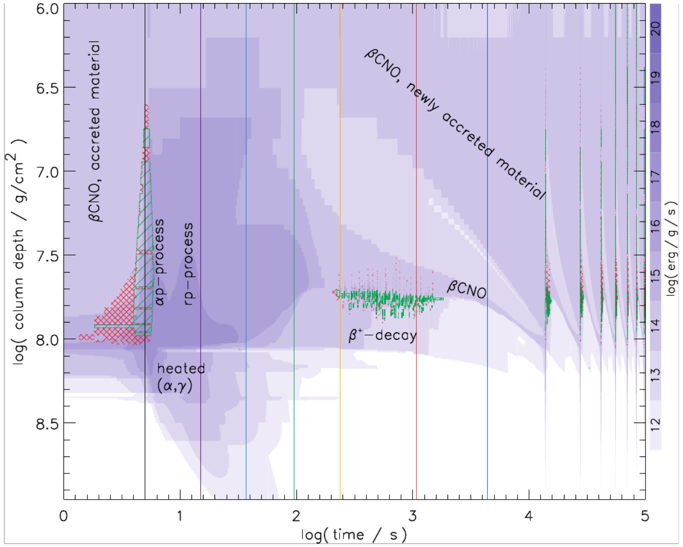
Comparison of *light curve* with Models

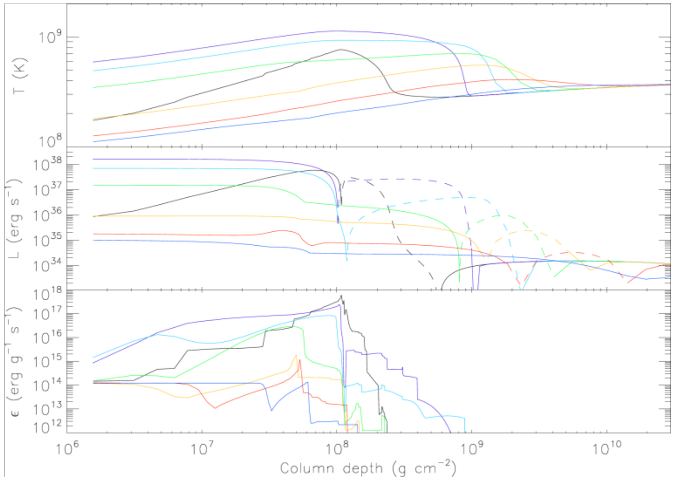
(solar metallicity, 0.1 Eddington accretion; corrected for GR effects)

with averaged observed data for GS 1826-24

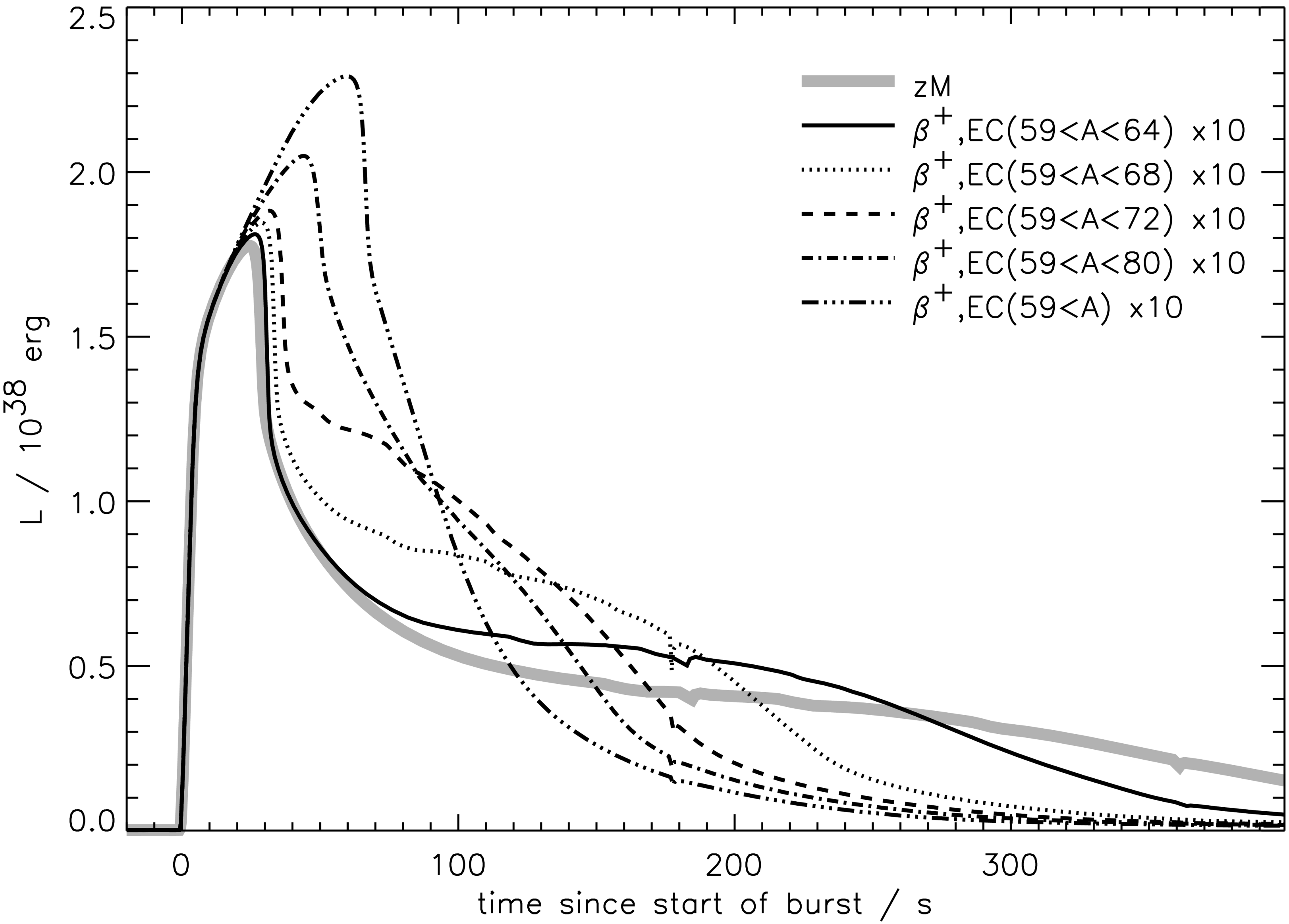
(J.J. In’t Zand *et al.* 2009)





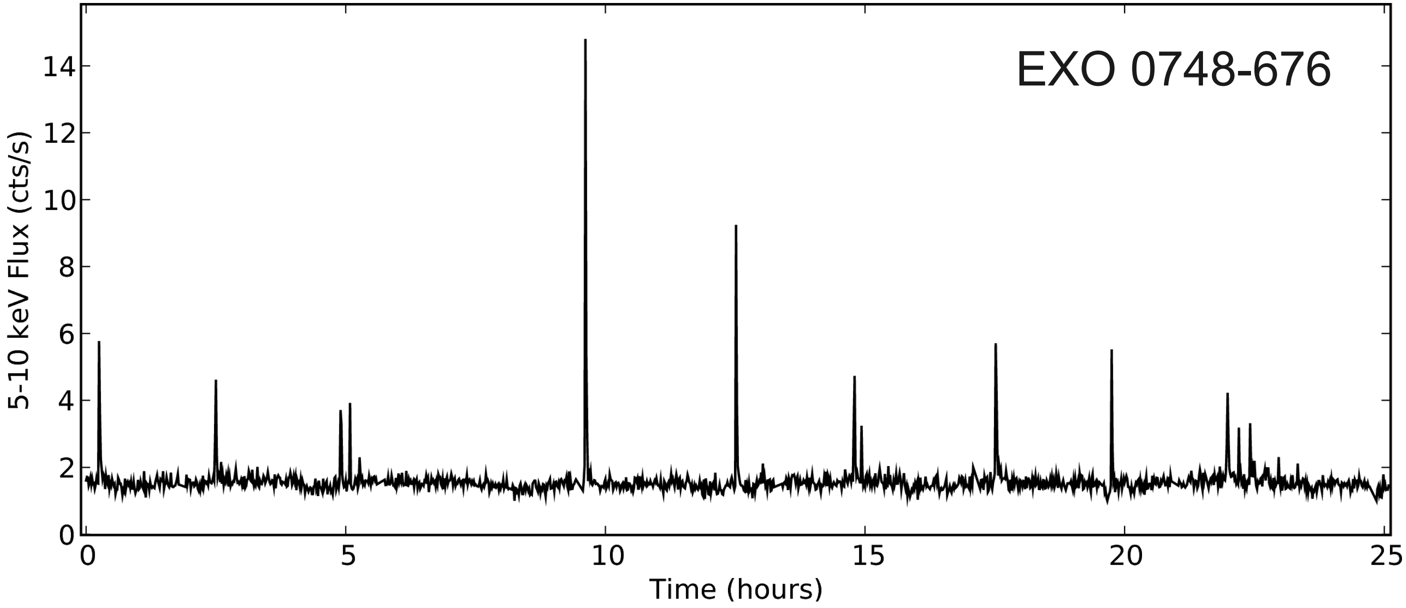


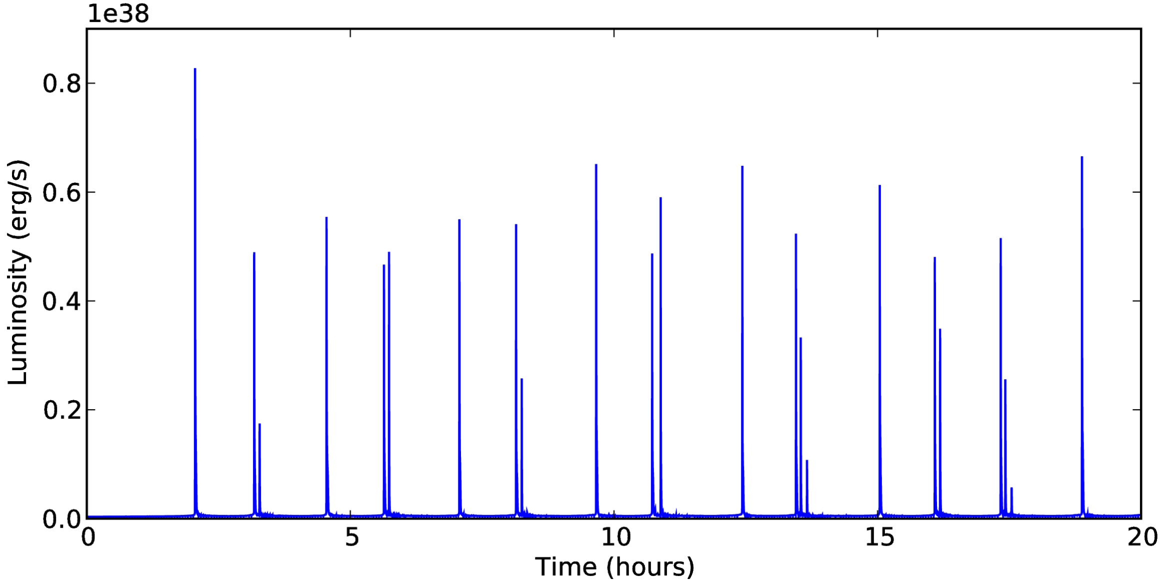
Sensitivity of the XRB Light Curve to Variation at the *r*-Process Waiting Points



zM

Short Recurrence Time Bursts



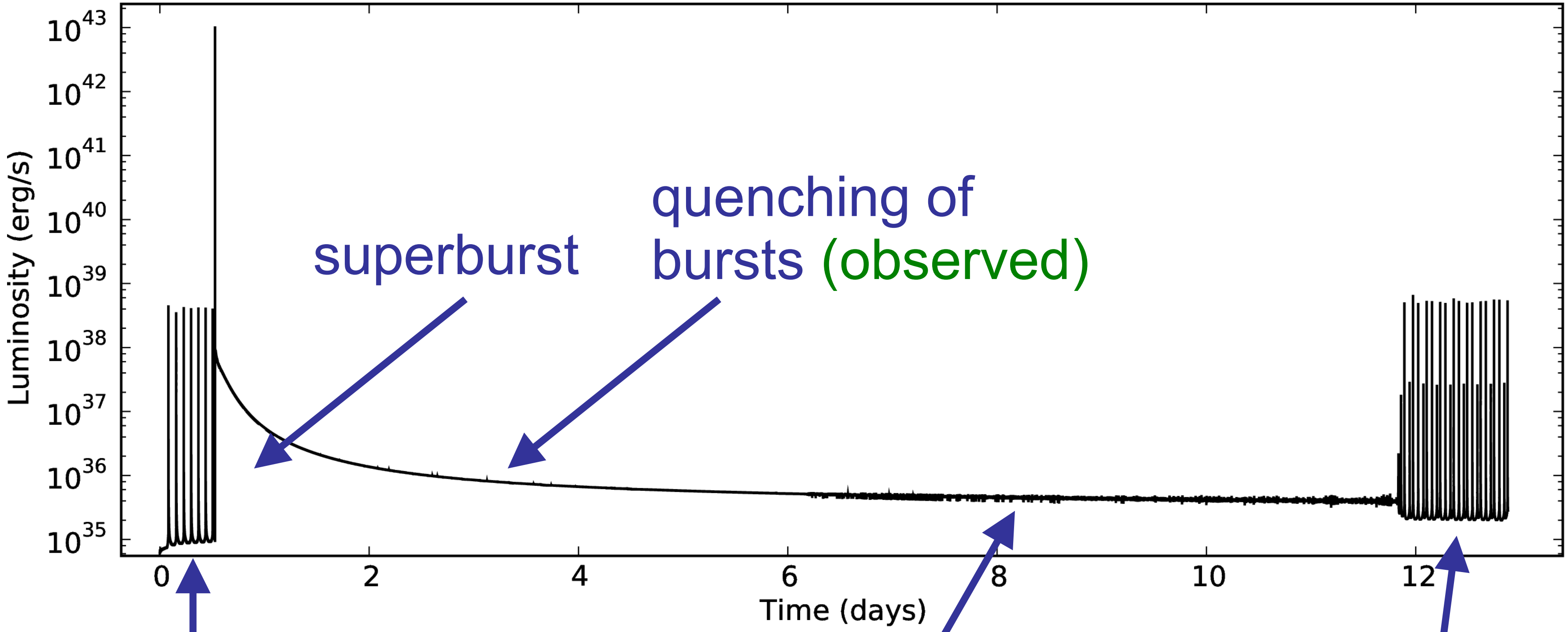


numerical model

(no accretion luminosity included in light curve)

requires high heat flux from crust!

A Full Superburst



superburst

quenching of bursts (observed)

bursts before superburst

oscillatory burning (new)

bursts resume (observed but we predict time scale)

Superburst Breakout