Massive Stars: Key Players in the Early Universe

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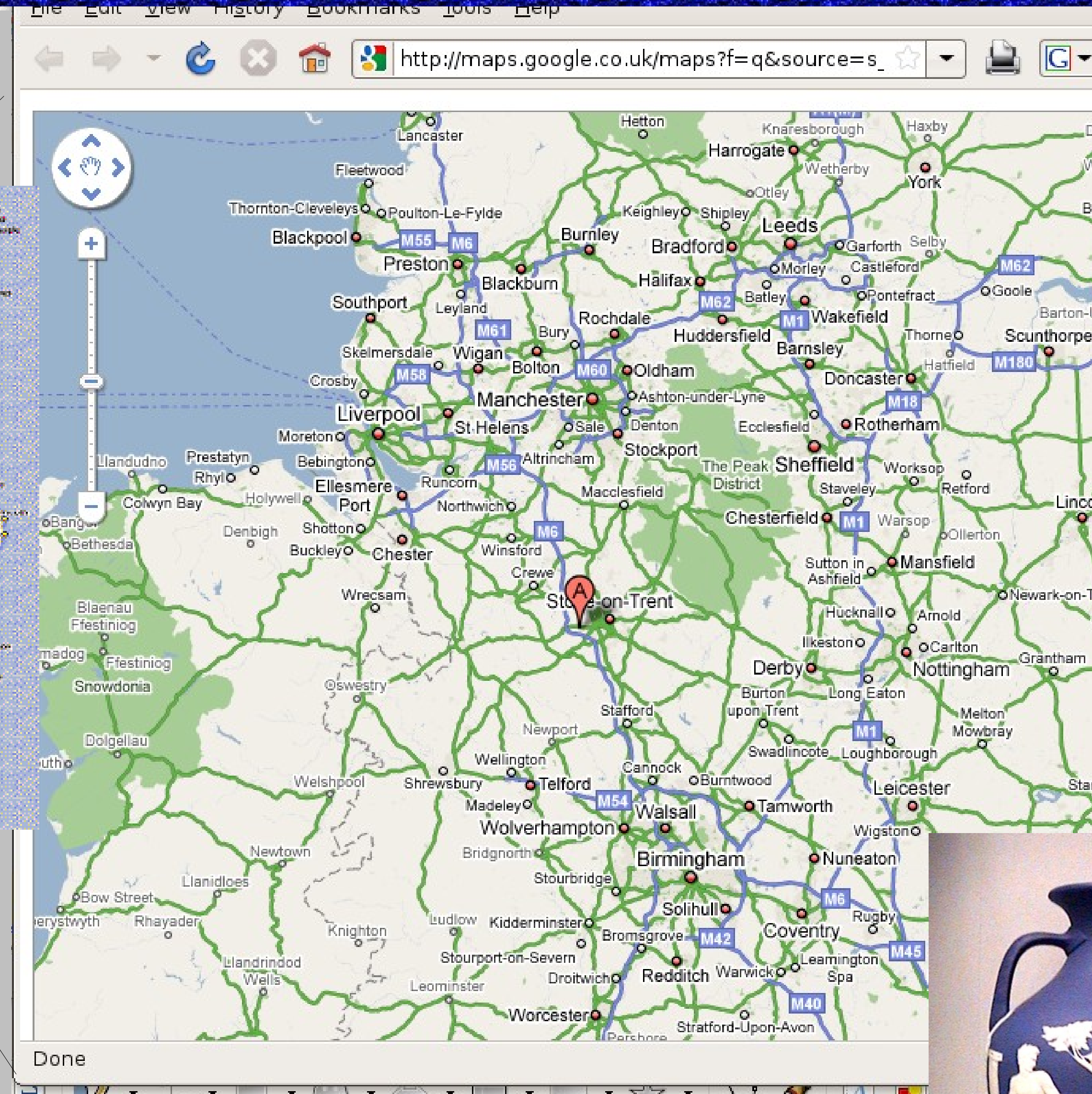
West Midlands:



Keele area

is famous for pottery: Wedgwood, ...

Plan

Introduction

Solar metallicity models including rotation

Metallicity dependence

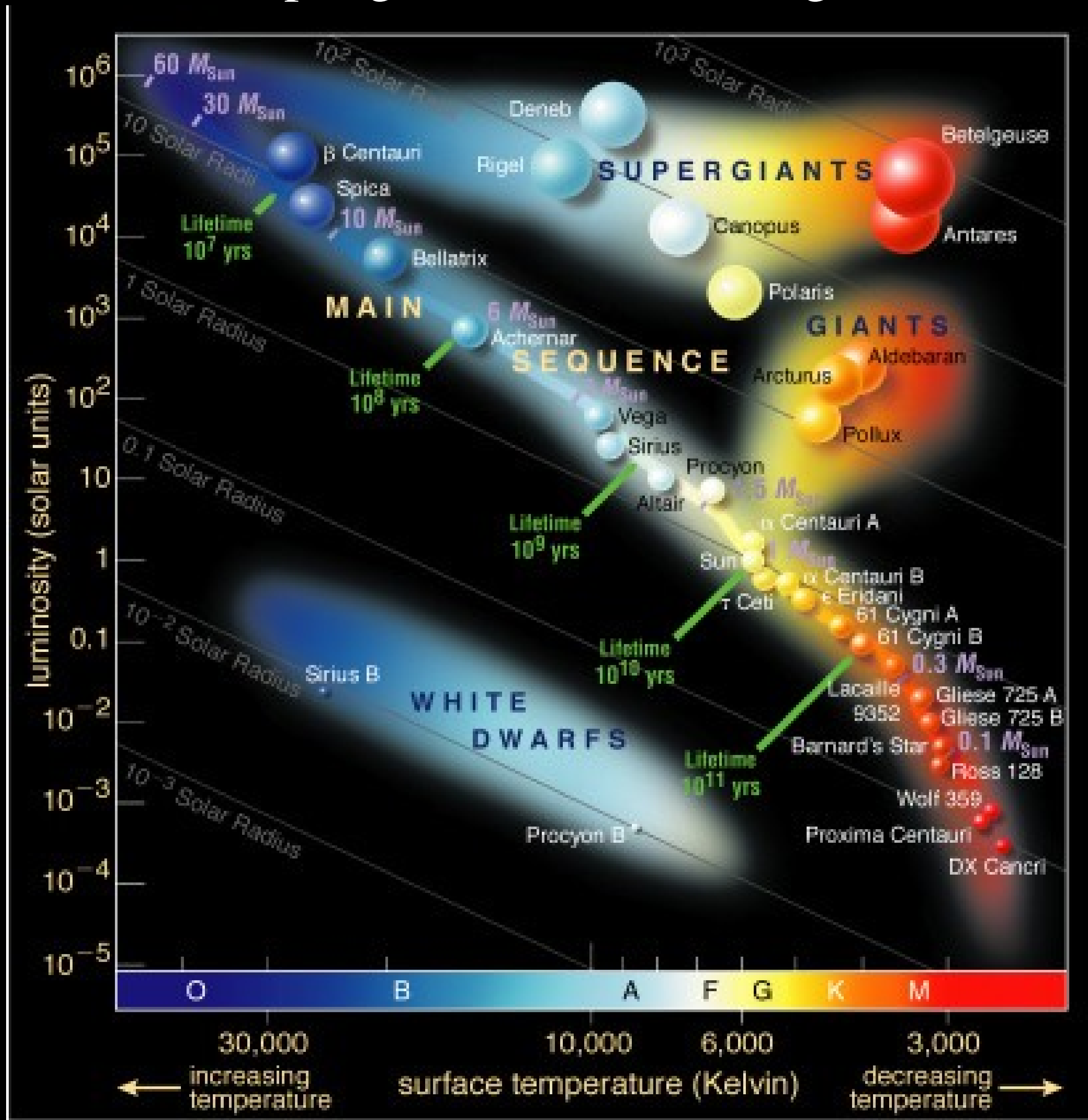
First Stellar generations

GRB-SN connections

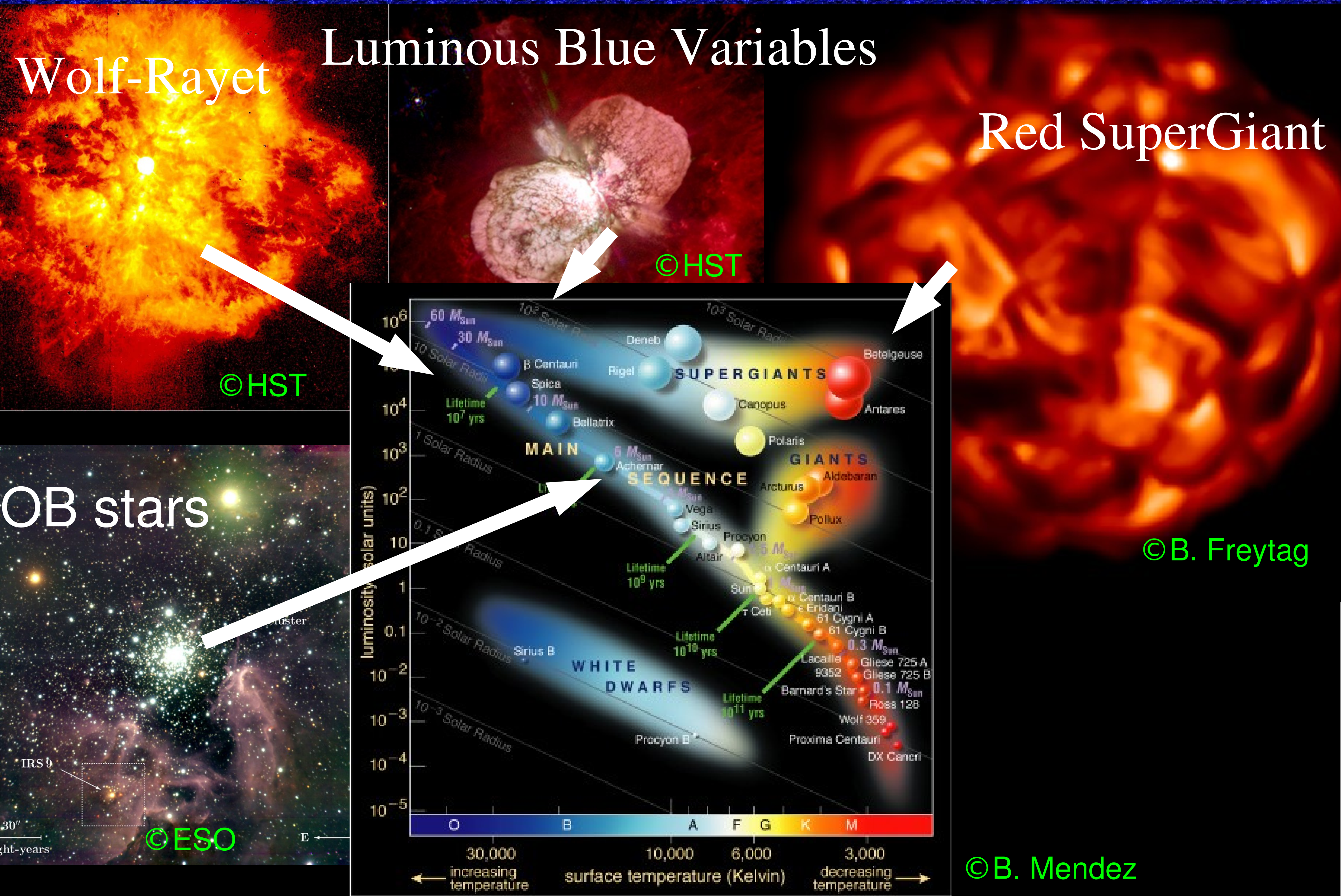
Conclusions & outlook

Massive Stars: Importance as Stellar Objects

Hertzsrpung-Russell (HR) Diagram:



Massive Stars: Importance as Stellar Objects



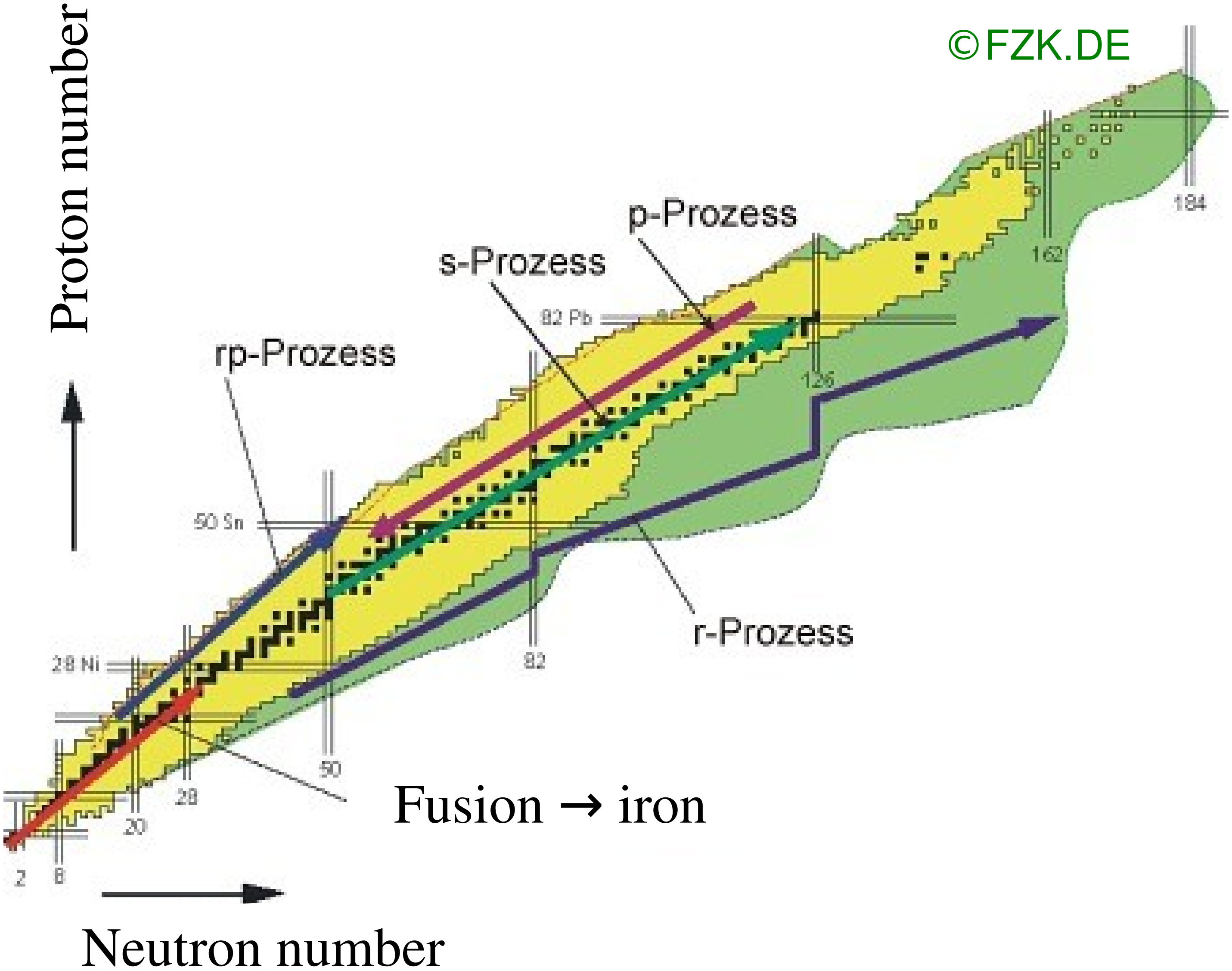
Massive Stars: Importance as Progenitors

Supernovae

Neutron Stars

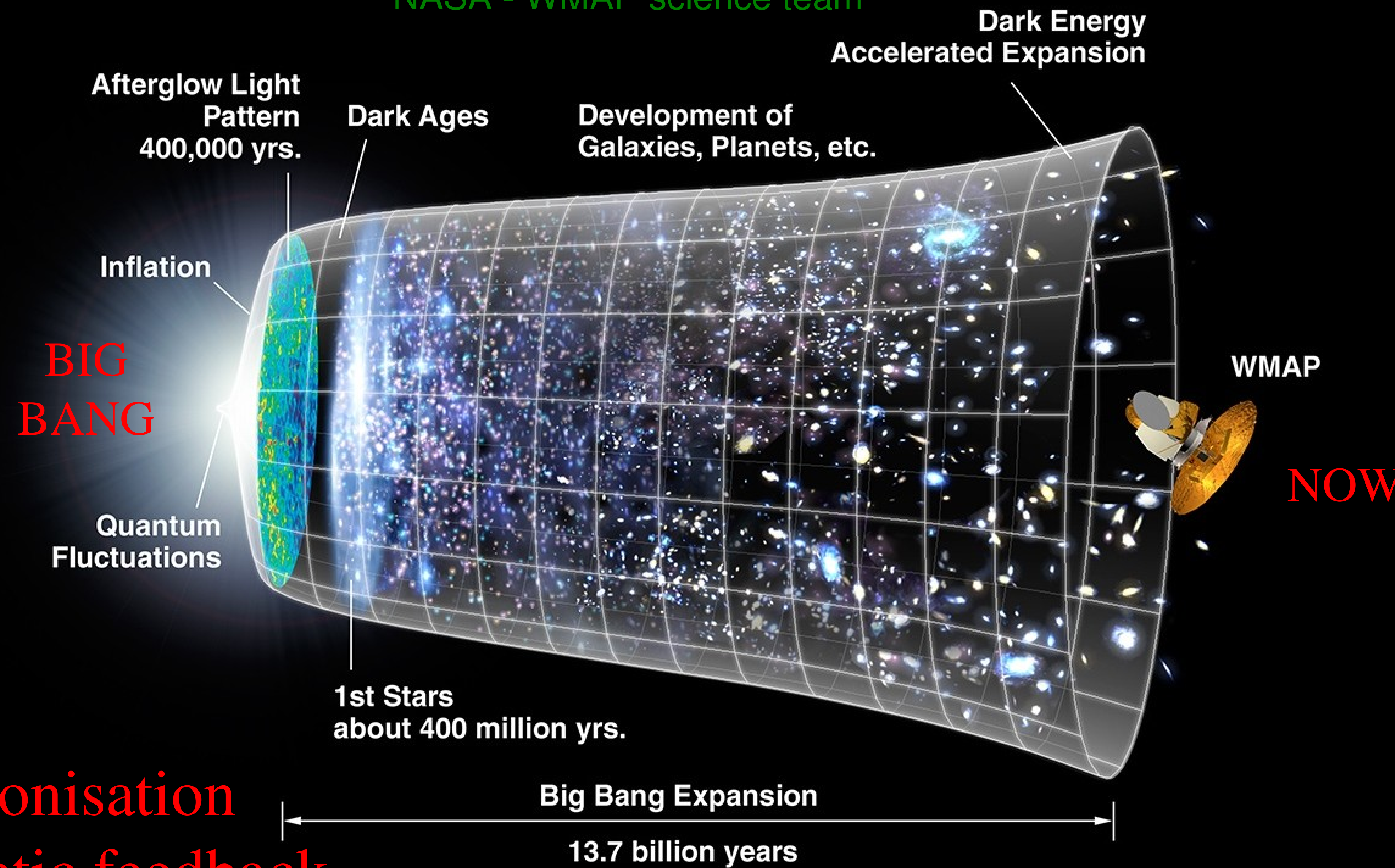
Black Holes

Massive Stars: Importance for Nucleosynthesis



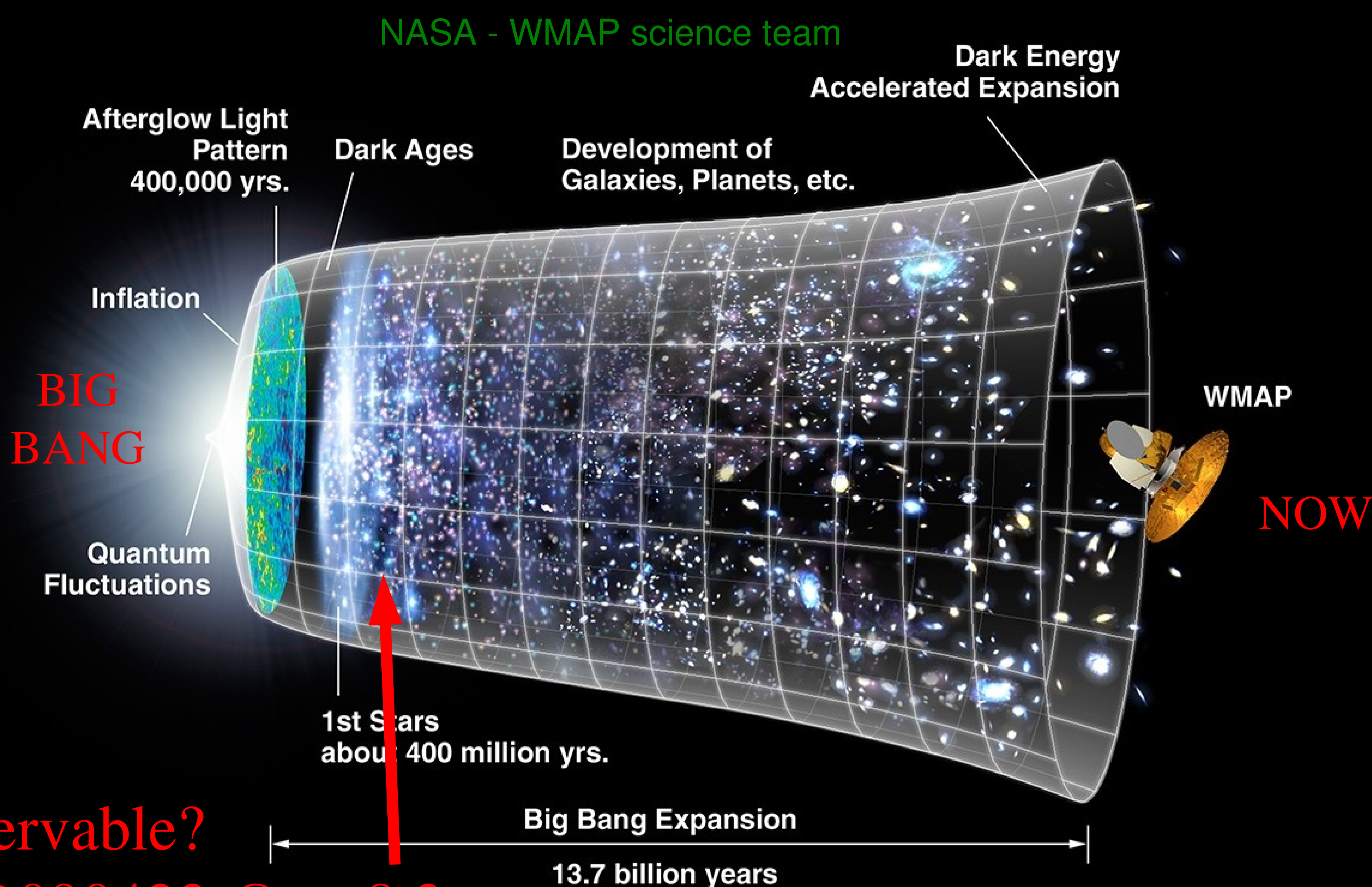
First Stellar Generations: Importance

NASA - WMAP science team



- Re-ionisation
- Kinetic feedback
- Chemical feedback observed in EMP stars

First Stellar Generations: Importance



- Observable?
- GRB090423 @ z=8.3

Universe age ~ 600 Myr (Tanvir et al 09: arXiv:0906.1577)

Massive Stars

Massive stars: M > ~10 solar masses

Main sequence:

hydrogen burning

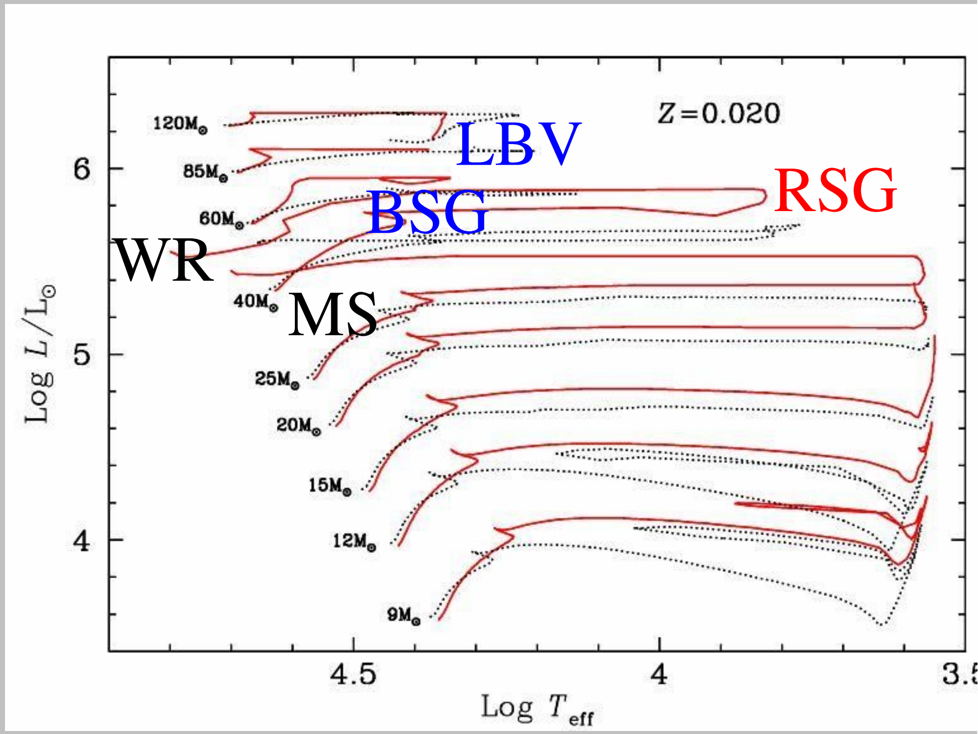
After Main Sequence:

Helium burning

Supergiant stage (red or blue)

Wolf-Rayet (WR): M > 20-25 M_o

WR without RSG: M > 40 M_o



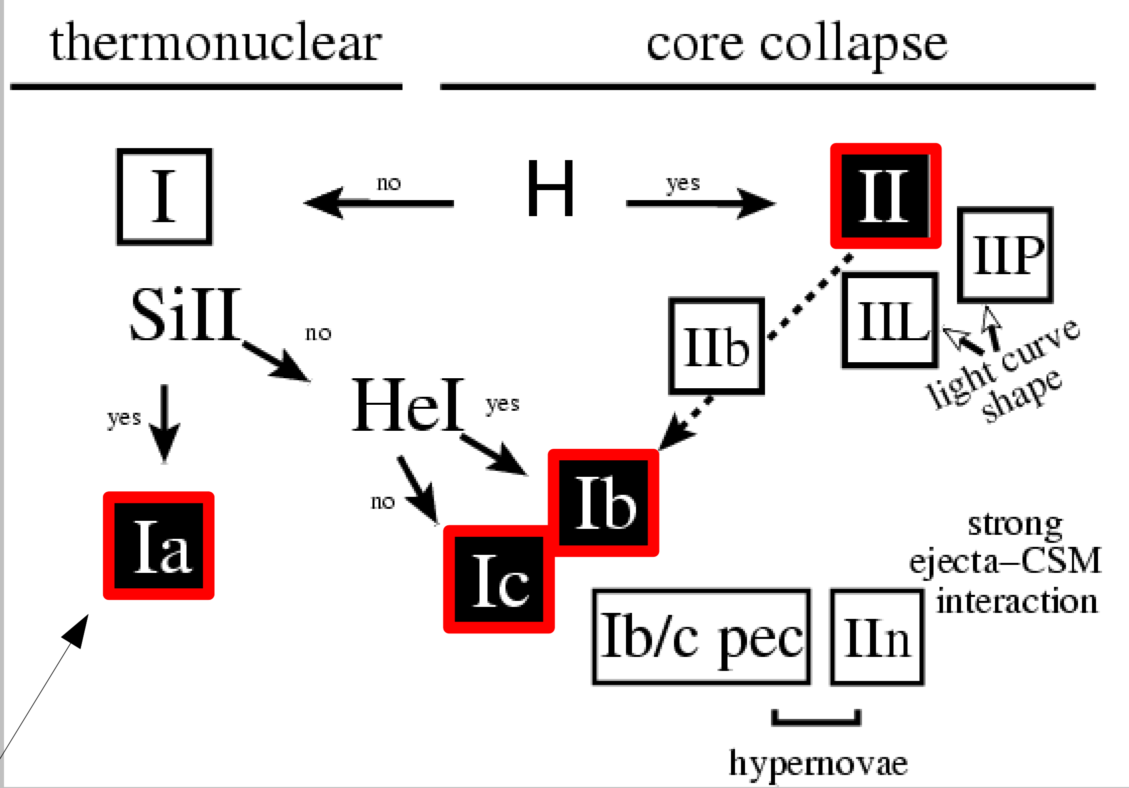
Advanced stages:

carbon, neon, oxygen, silicon burning → iron core

Core collapse → bounce → supernova explosion

Supernova Explosion Types

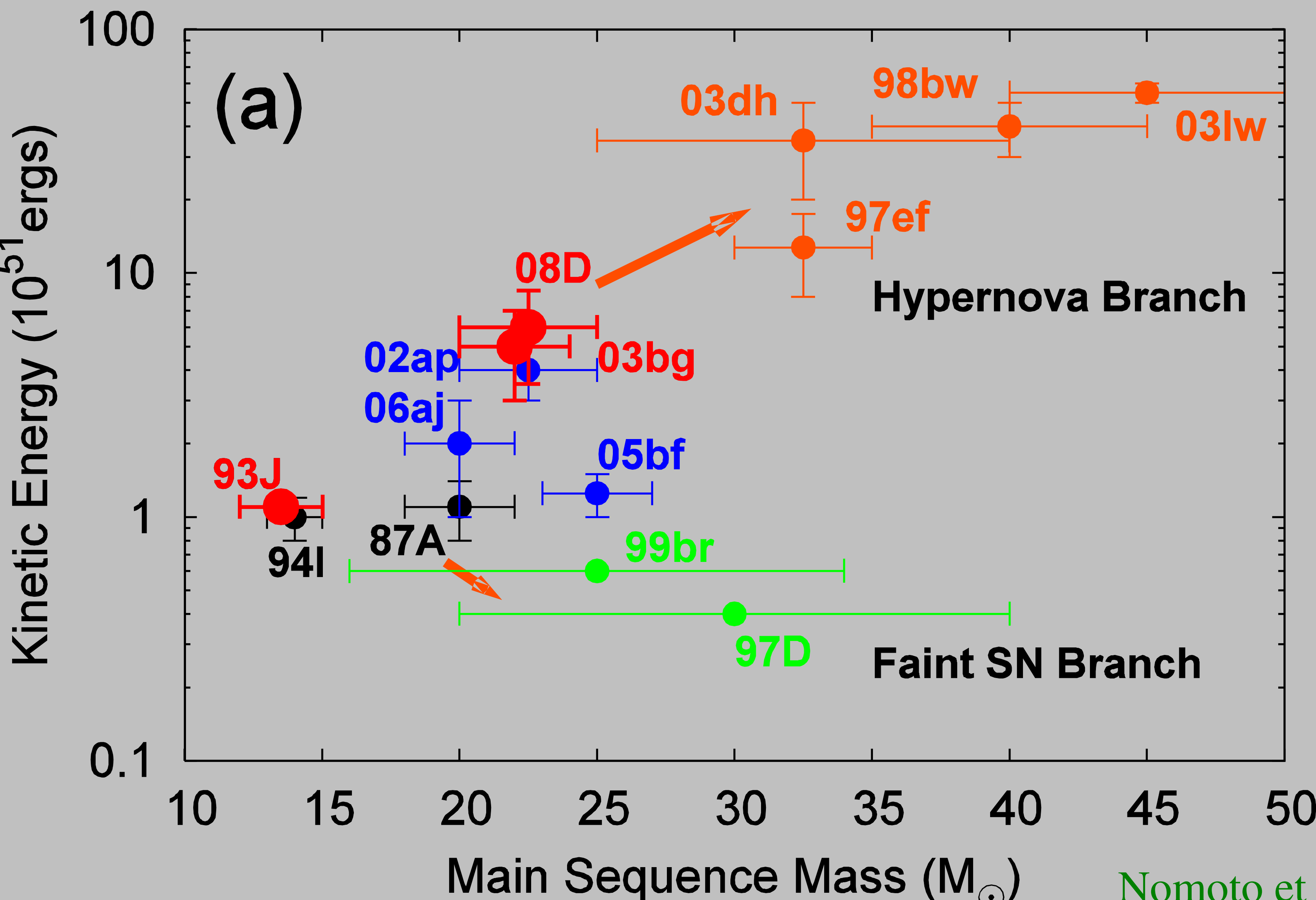
Massive stars: → SN II (H envelope),
Ib (no H), Ic (no H & He) ← WR



White dwarfs (WD): in binary systems (Turatto 03)

Accretion → Chandrasekhar mass → SN Ia

Supernova Explosion Types



Fast
Rotating
Stars

Slow/non
Rotating
Stars

Nomoto et al

Geneva Stellar Evolution Code

1.5D hydrostatic code

Mass loss α Z & Ω (Vink et al 00,05,06)

Rotation: (Maeder & Meynet)

Centrifugal force

Mixing: meridional circ. & shear

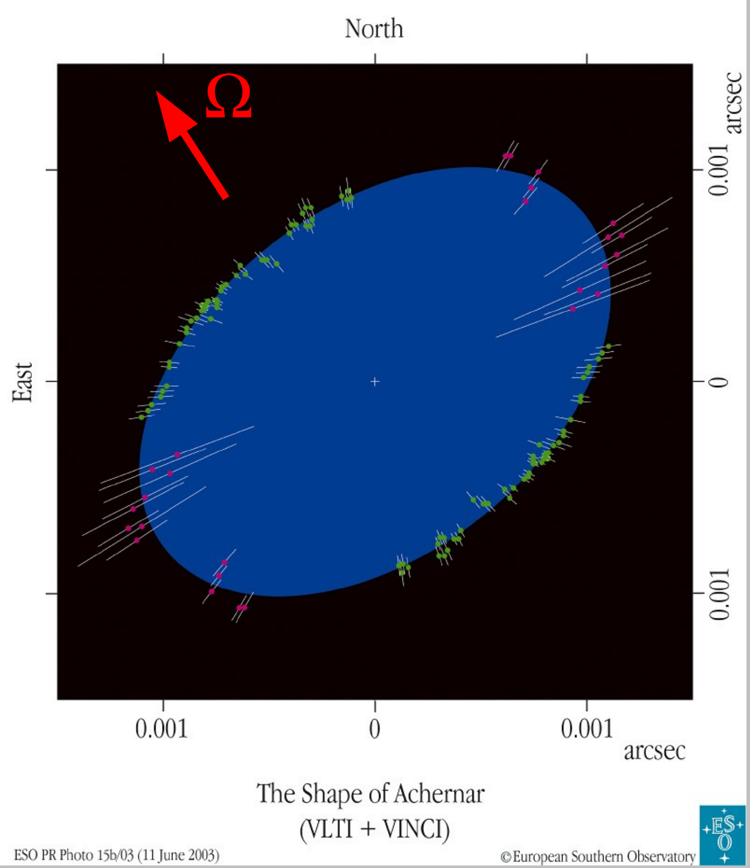
Mass loss: enhanced and anisotropic

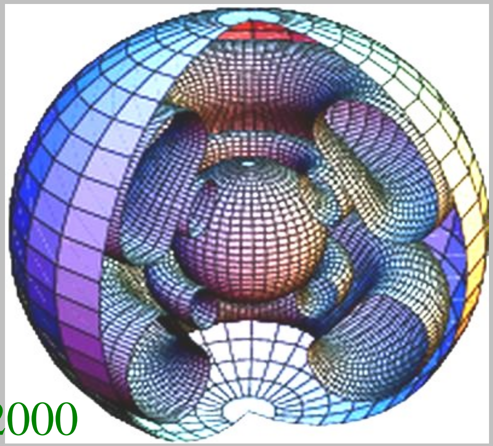
Convection: Schwarzschild + 0.1 H_P

Nuclear reaction rates: NACRE/Reaclib

B-fields (Spruit 02, Maeder 05)

Models ZAMS until Silicon burning





Meynet & Maeder 2000

Massive Stars: Evolution of the chemical composition

Burning stages (lifetime [yr]):

Hydrogen ($10^{6\text{-}7}$): $^{1}H \rightarrow {}^{4}He$

& ^{12}C, $^{16}O \rightarrow {}^{14}N$

Helium ($10^{5\text{-}6}$): $^{4}He \rightarrow {}^{12}C$, ^{16}O

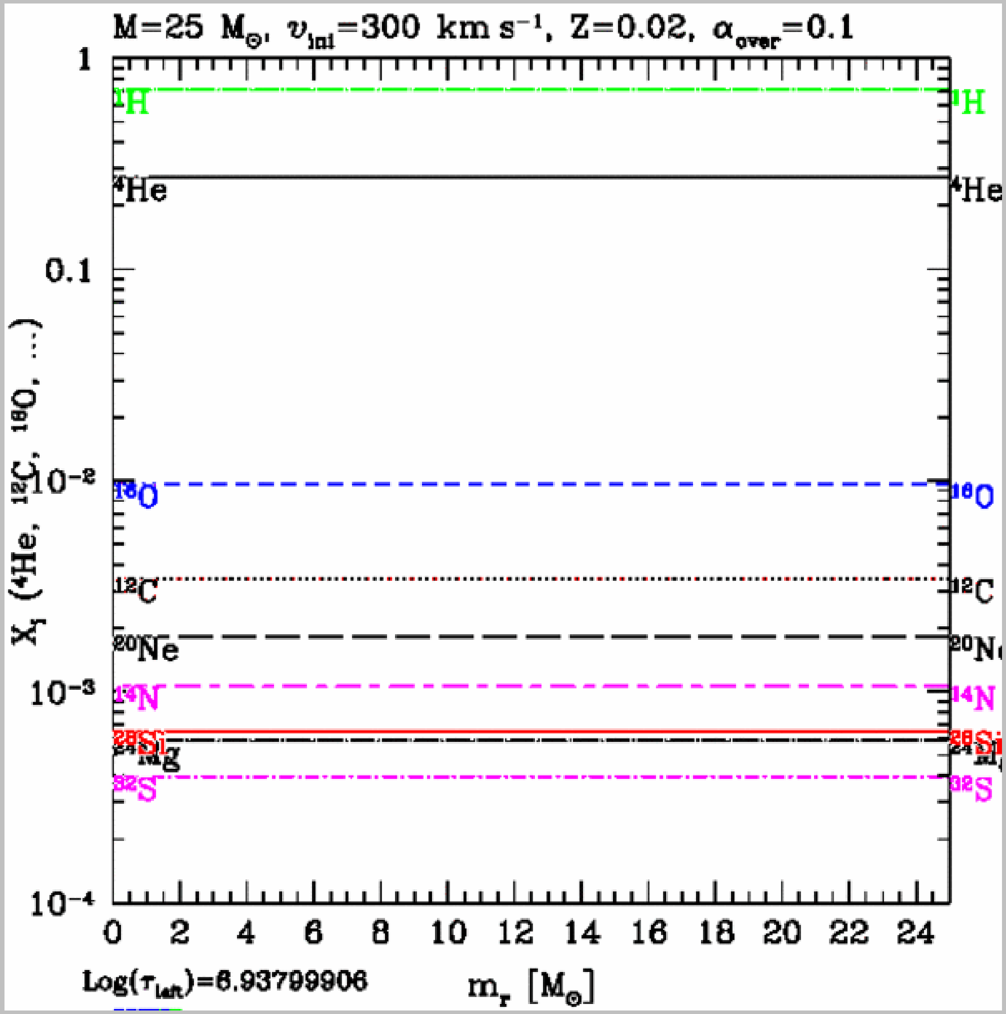
& $^{14}N \rightarrow {}^{18}O \rightarrow {}^{22}Ne$

Carbon ($10^{2\text{-}3}$): $^{12}C \rightarrow {}^{20}Ne$, ^{24}Mg

Neon (0.1-1): $^{20}Ne \rightarrow {}^{16}O$, ^{24}Mg

Oxygen (0.1-1): $^{16}O \rightarrow {}^{28}Si$, ^{32}S

Silicon (10^{-3}): ^{28}Si, $^{32}S \rightarrow {}^{56}Ni$

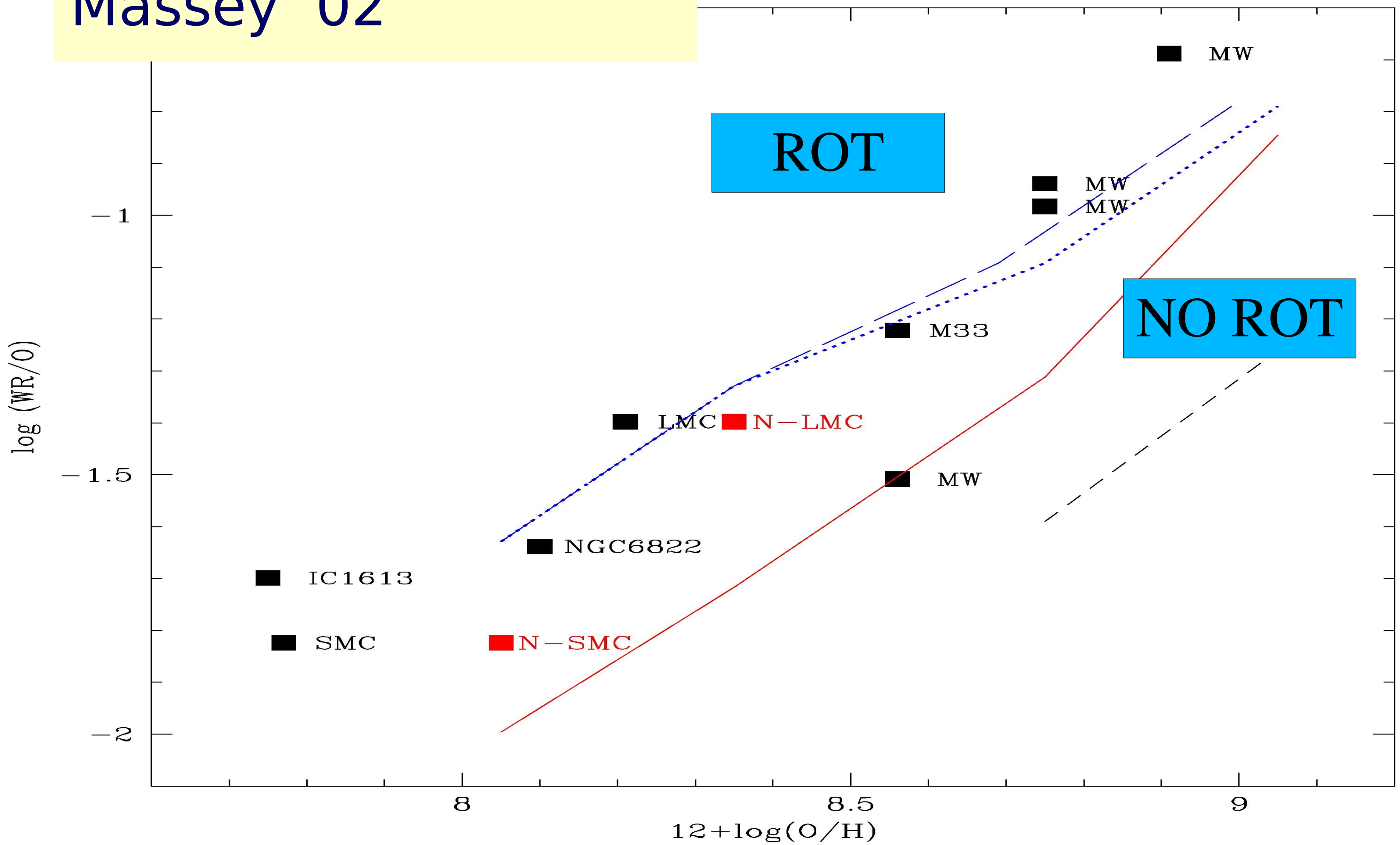


http://www.astro.keele.ac.uk/~hirschi/animation/anim.html

WR / O Ratio

Data from

Conti & Maeder’94; Massey ‘02

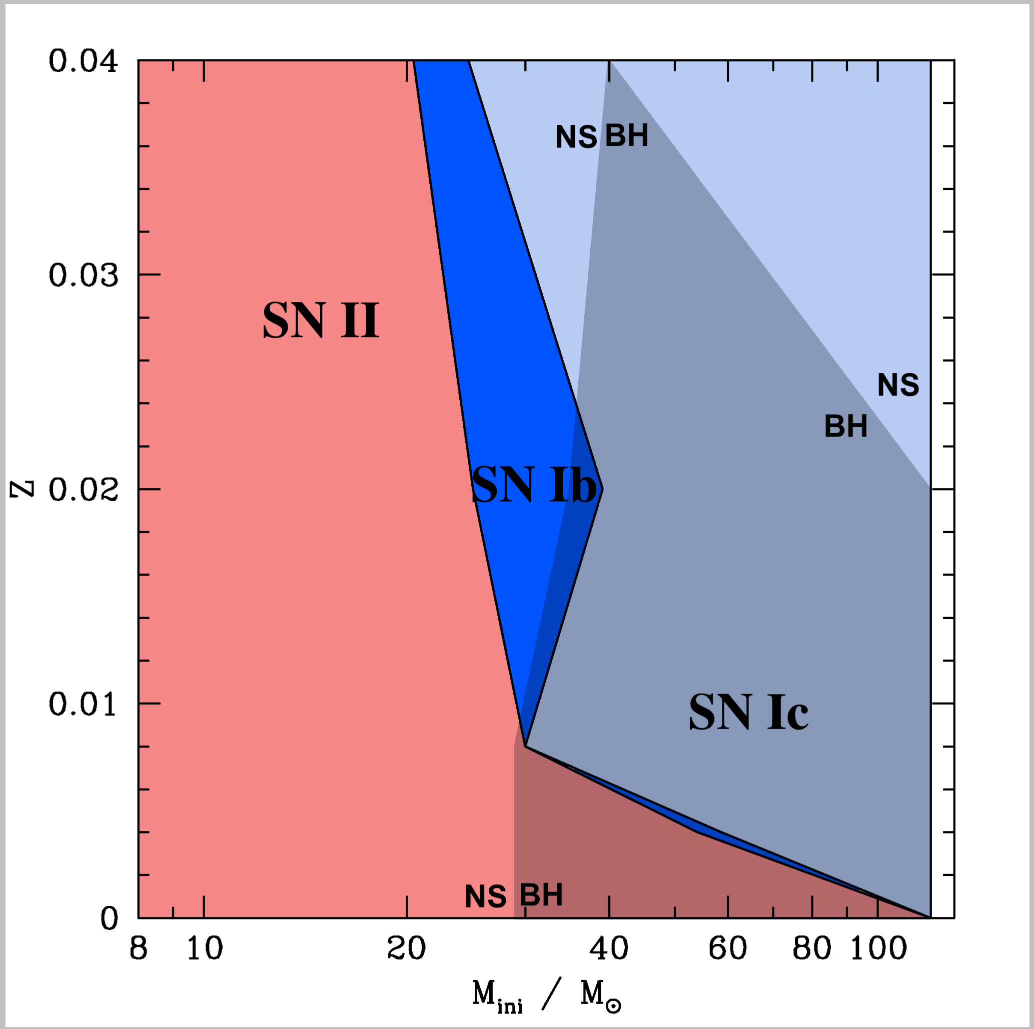


Vazquez et al 07

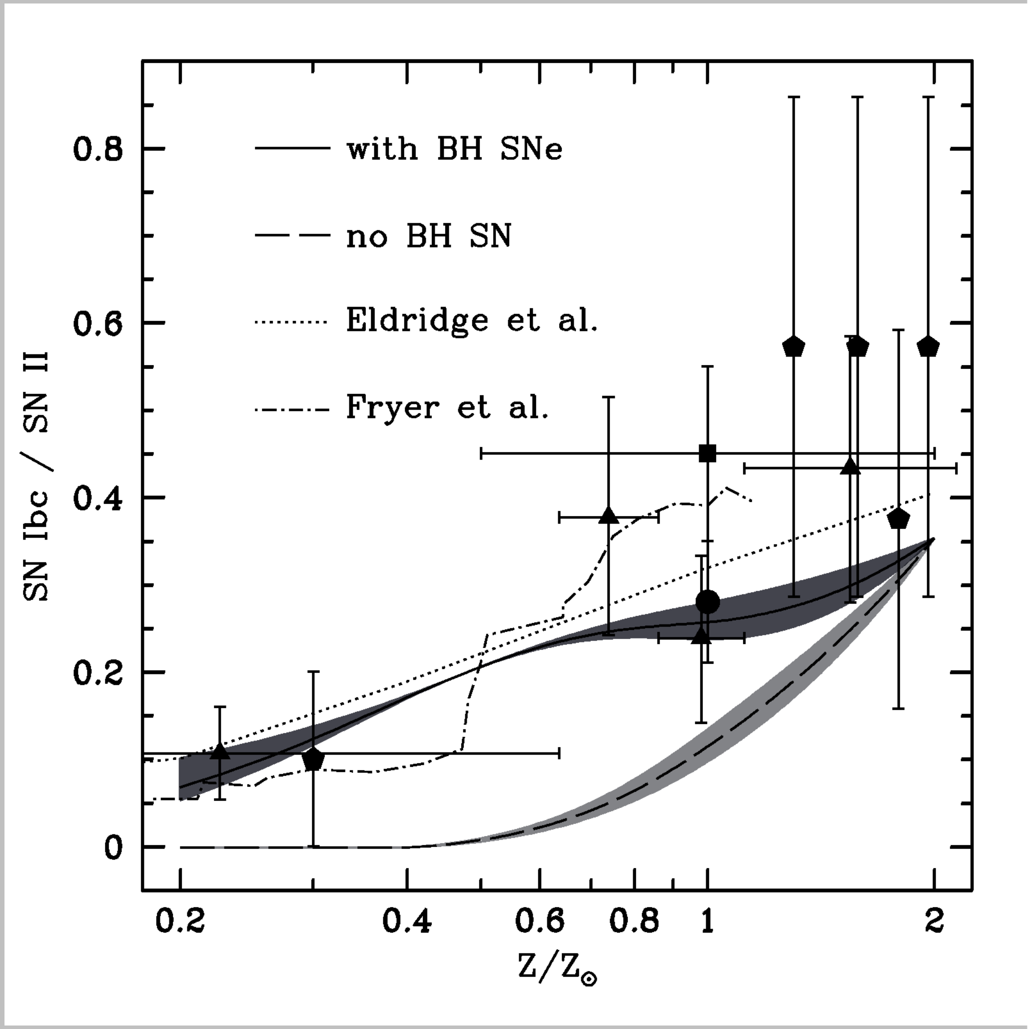
Foellmi et al. 2003ab
SMC → only 40% of WR in binaries

Final stages & SN type

Ratio SNIbc/SNII: tests final type



Georgy et al 09



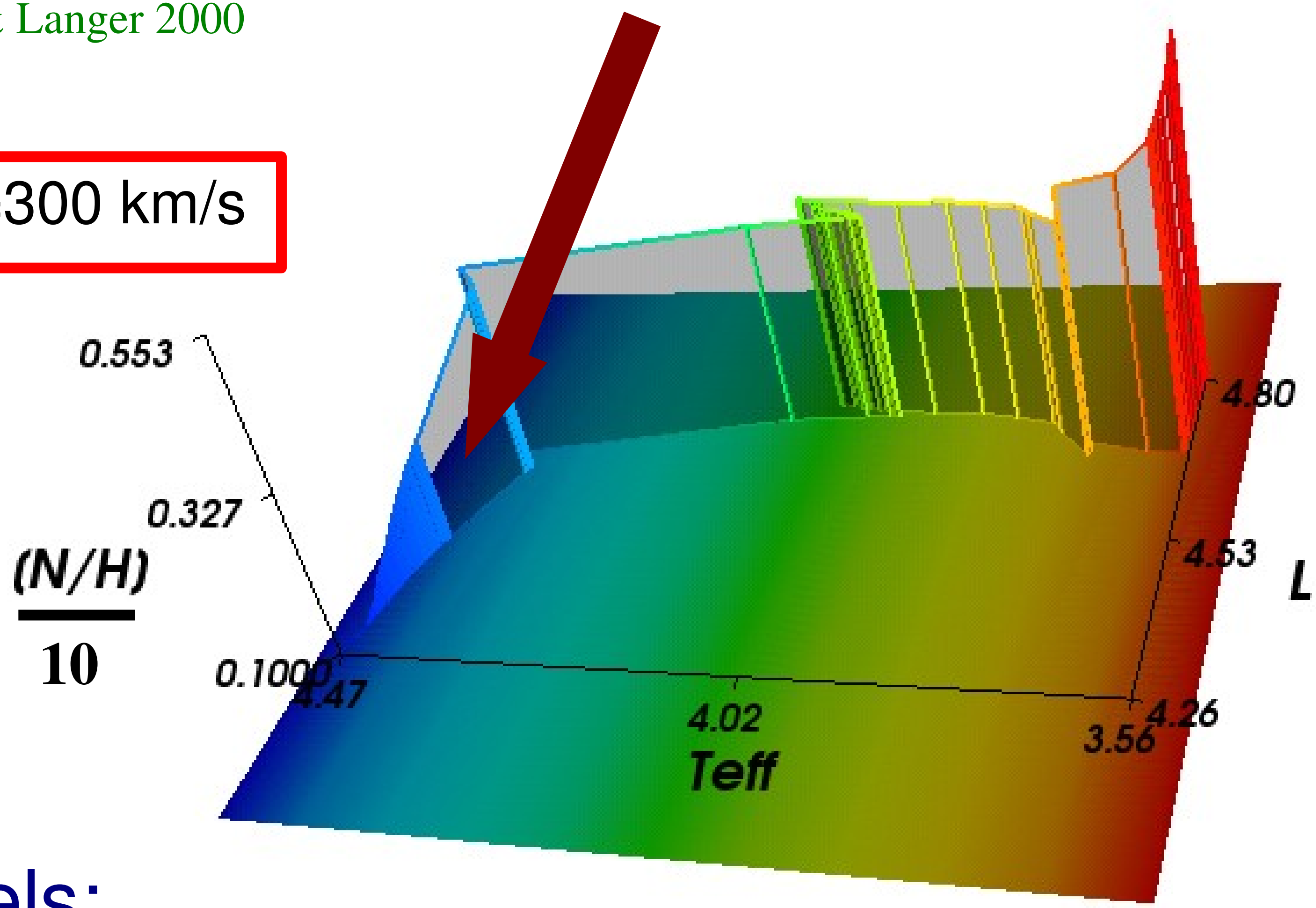
- THEORY: Georgy et al 09 (solid line)
  binaries: Eldridge etal 08 (dotted)
- OBS: Prantzos & Boissier 03 (triangles)
  Prieto etal 08 (pentagons)

Nitrogen Surface Enrichment

Rotating models: enrichment starts during MS

Meynet & Maeder 2000, Heger & Langer 2000

15 $M_\odot$ model with υ_{ini}=300 km/s



Non-rotating models:

no enrichment before 1st dredge up (RSG)

Nitrogen Surface Enrichment

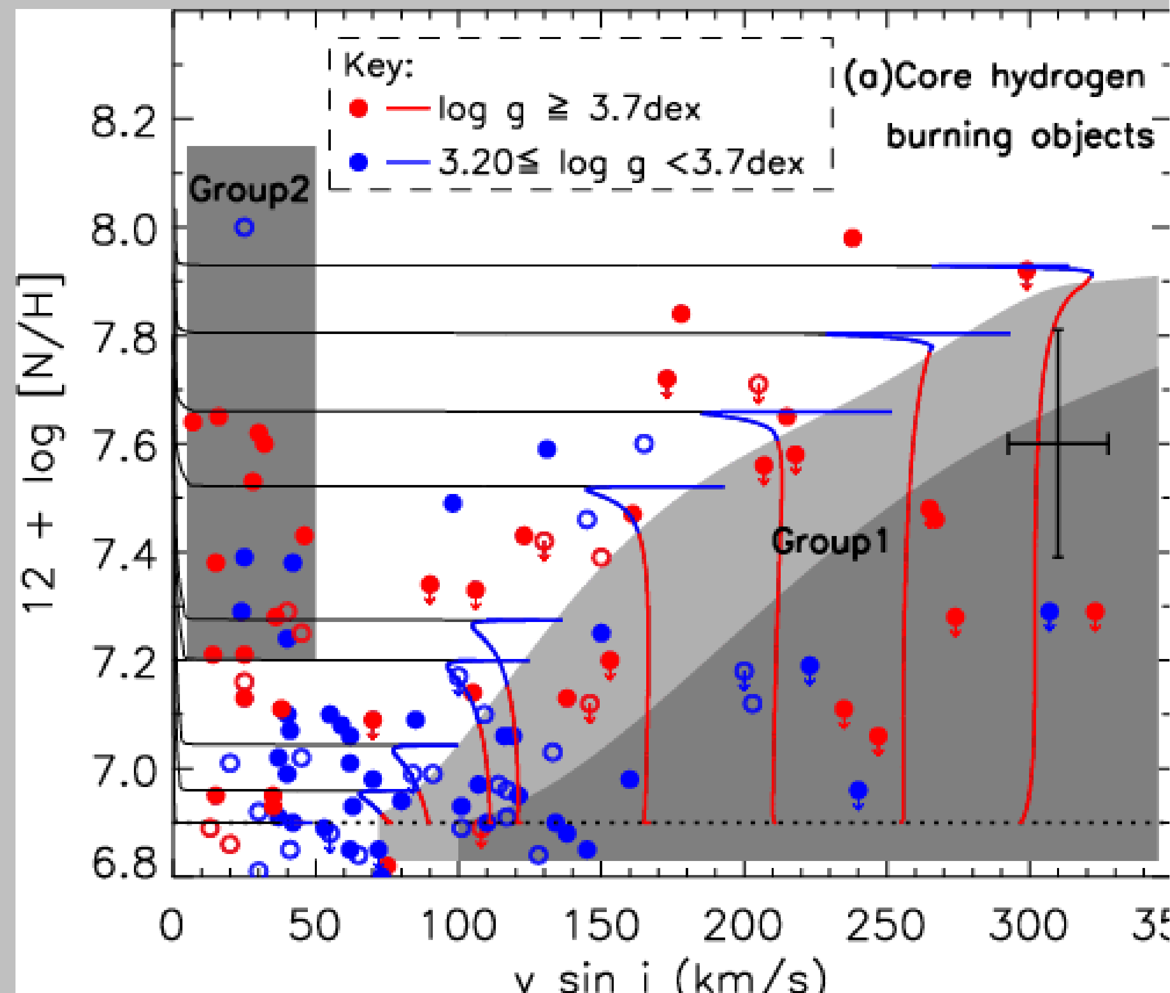
Flames survey: majority of stars explained BUT

Explanations:

Single stars:

G1: less evolved/
lower mass

G2: pole-on / B-f?



Binary stars:(Langer etal 08)

G1: N-poor matter accr.

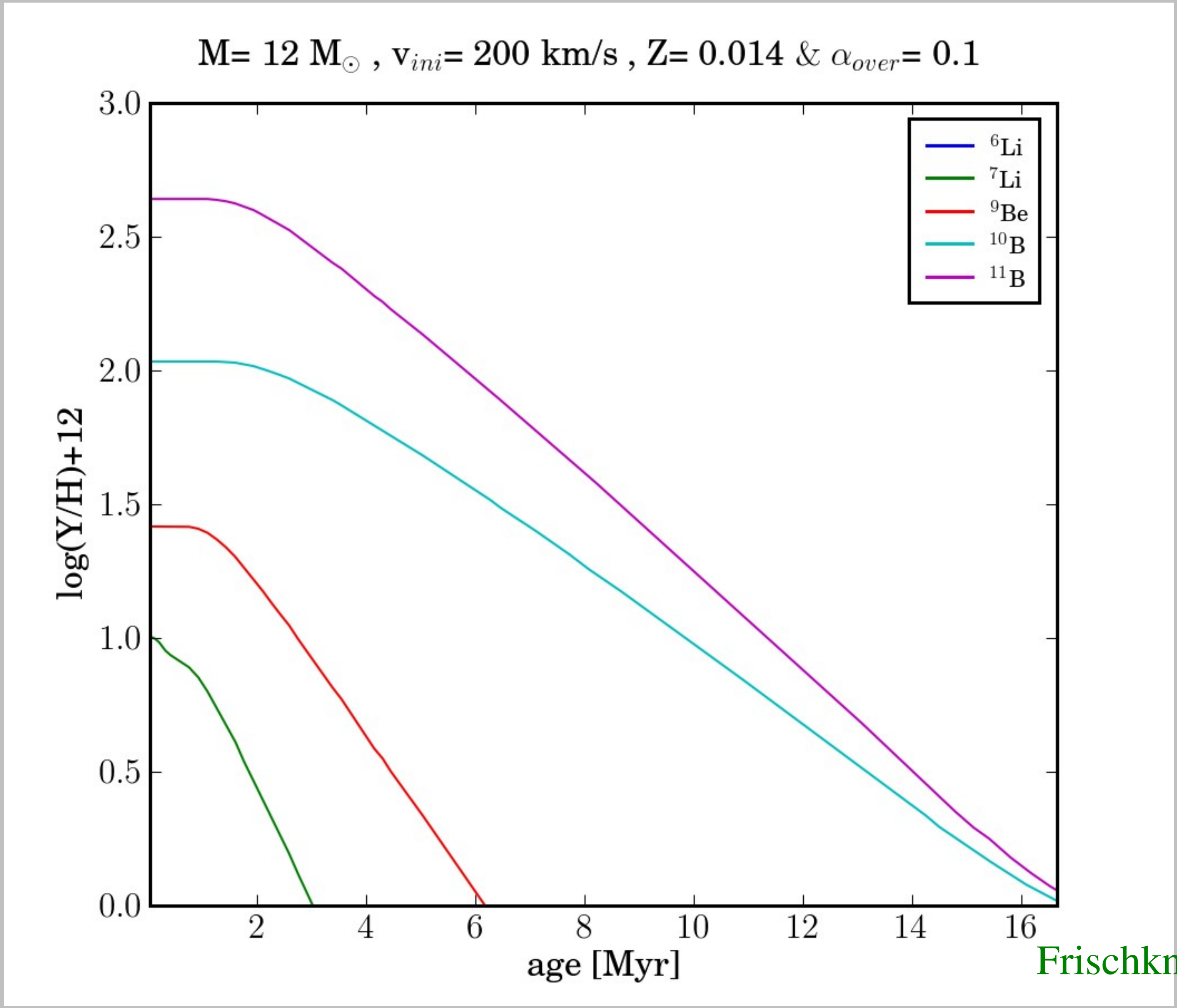
G2: * slowed down / B-f?

Other issues: Initial composition, overshooting, enriched blue supergiants

Boron can help distinguish between rotation and binarity (Brott etal 08, Langer etal)

Boron Surface Depletion: models

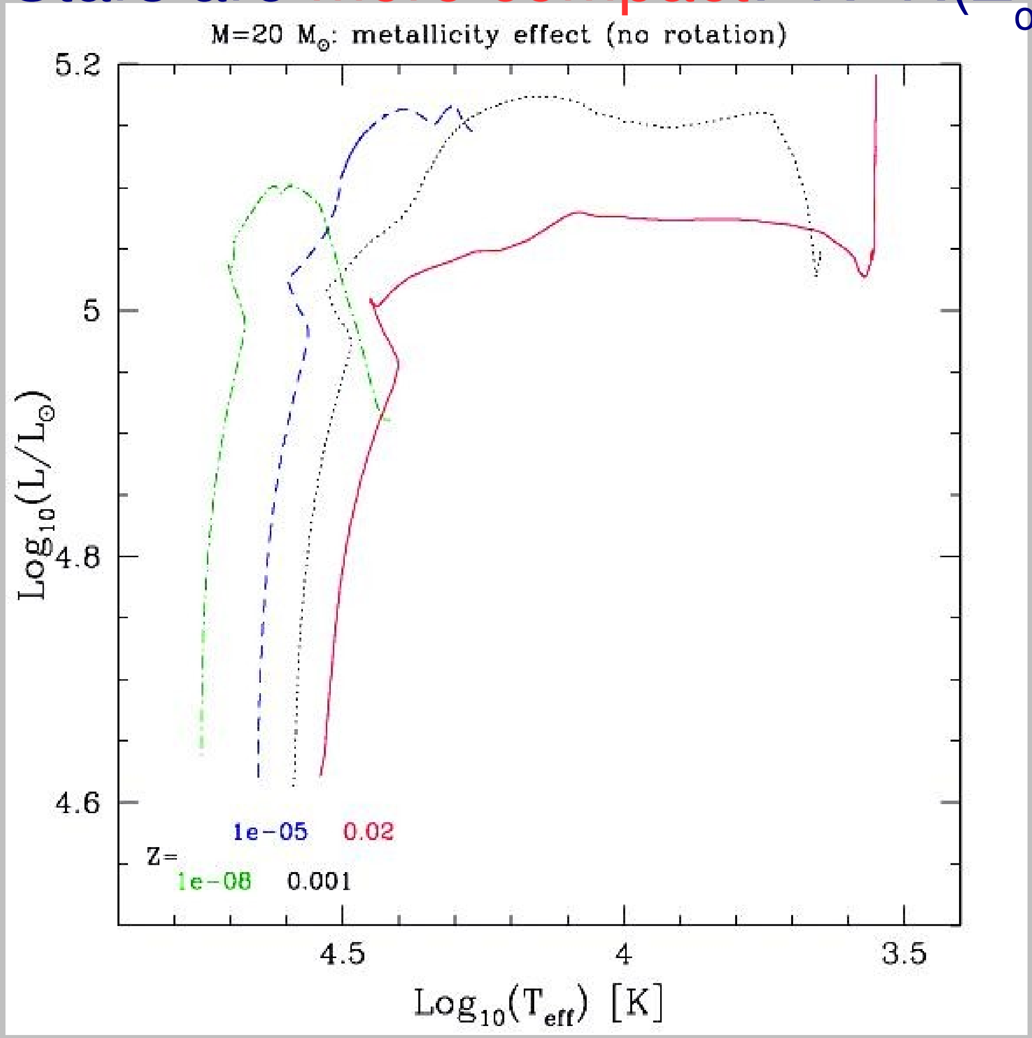
Rotational mixing -> surface boron depletion



Frischknecht et al in prep

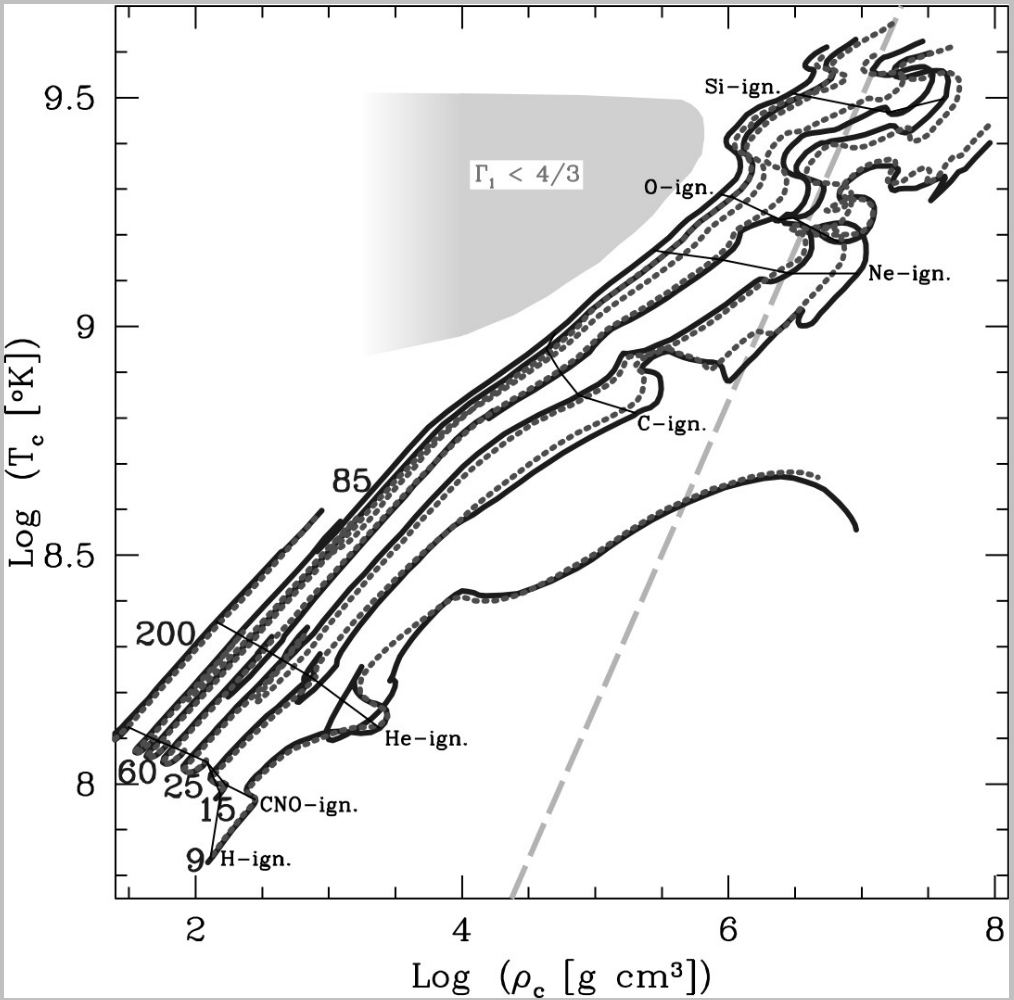
Physics @ Low Metallicity (Z)

Stars are more compact: $R \sim R(Z_o)/4$ (lower opacities)



(Hirschi 07, A&A, 461, 571)

(Ekström et al 2008)



Z=0 ($<10^{-10}$): only pp chains; no CNO cycle at start

Physics @ Low Metallicity (Z)

Mass loss ~ $Z^{(0.5-0.86)}$ => weaker winds

- Main contributors: CNO, Fe? Mdot ~ (CNO+Fe)**0.5 assumed

Vink & De Koter 2005, Vink, de Koter & Lammers 2001, Kudritzki 2002, Van Loon 05

O* & WR: Z dep. / Fe dom. & plateau at low Z for WR (Vink et al 05)

CNO-driven wind at low Z for WR? Graefener & Hamann 08

RSG (and LBV?): no Z-dep.; CNO (Van Loon 05)

Higher initial masses? <M>10 ~100 M_o? (Bromm & Larson ARAA 04)

<M> ~1 & ~100 M_o? (Nakamura & Umemura 01)

<M> ~1000 M_o? (Okhubo et al 09)

El Eid et al 1983; Chiosi et al 1983; Ober et al 1983; Bond et al 1984; Klapp 1984; Arnett 1996, Woosley & Weaver 1995 ; Siess et al. 2002; Herwig 2002; Picardi et al. 2004; Gil-Pons et al. 2005

First Generations: Fate of Non-Rotating Stars

Z~0:

M<25 Mo: SNII

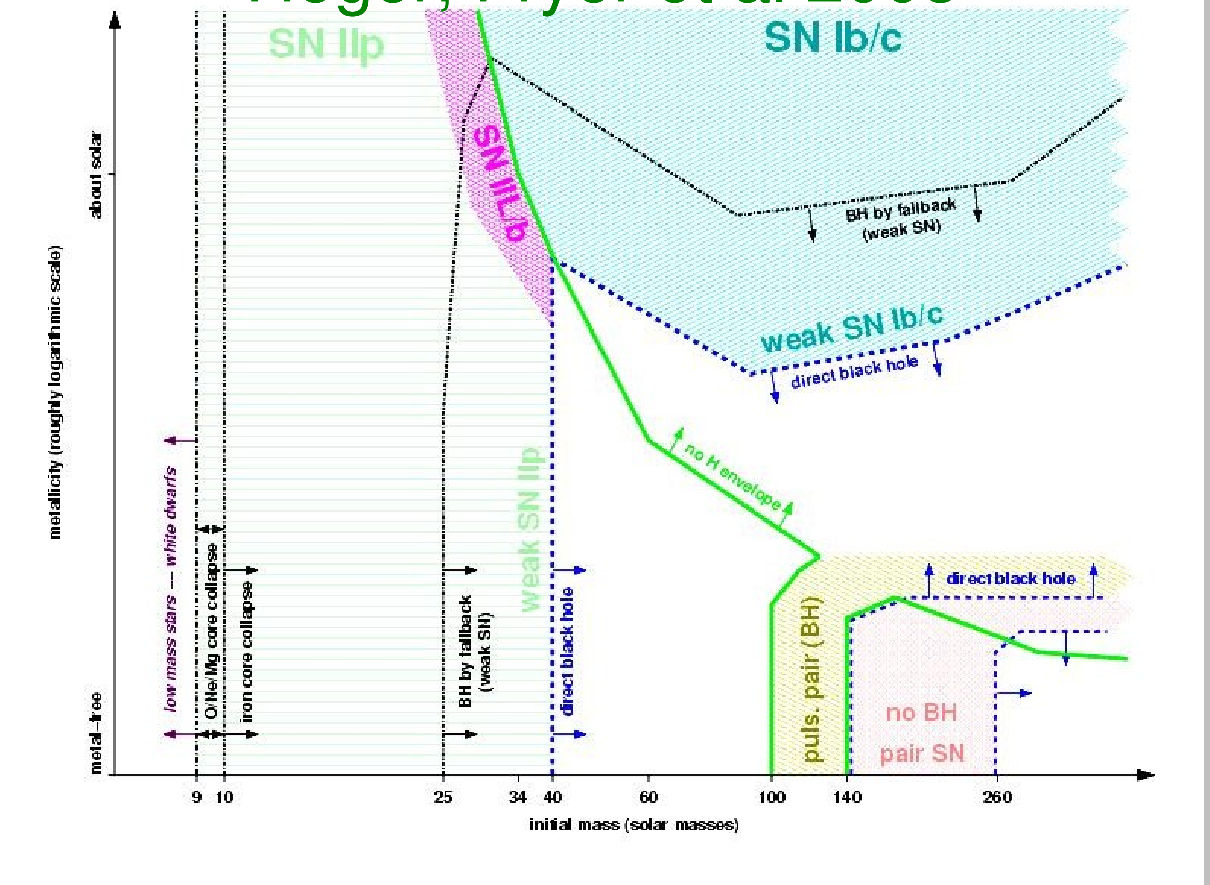
25-40: weak SNII

40-140:BH, no SN

140-260: PCSN

260-?: BH, no SN

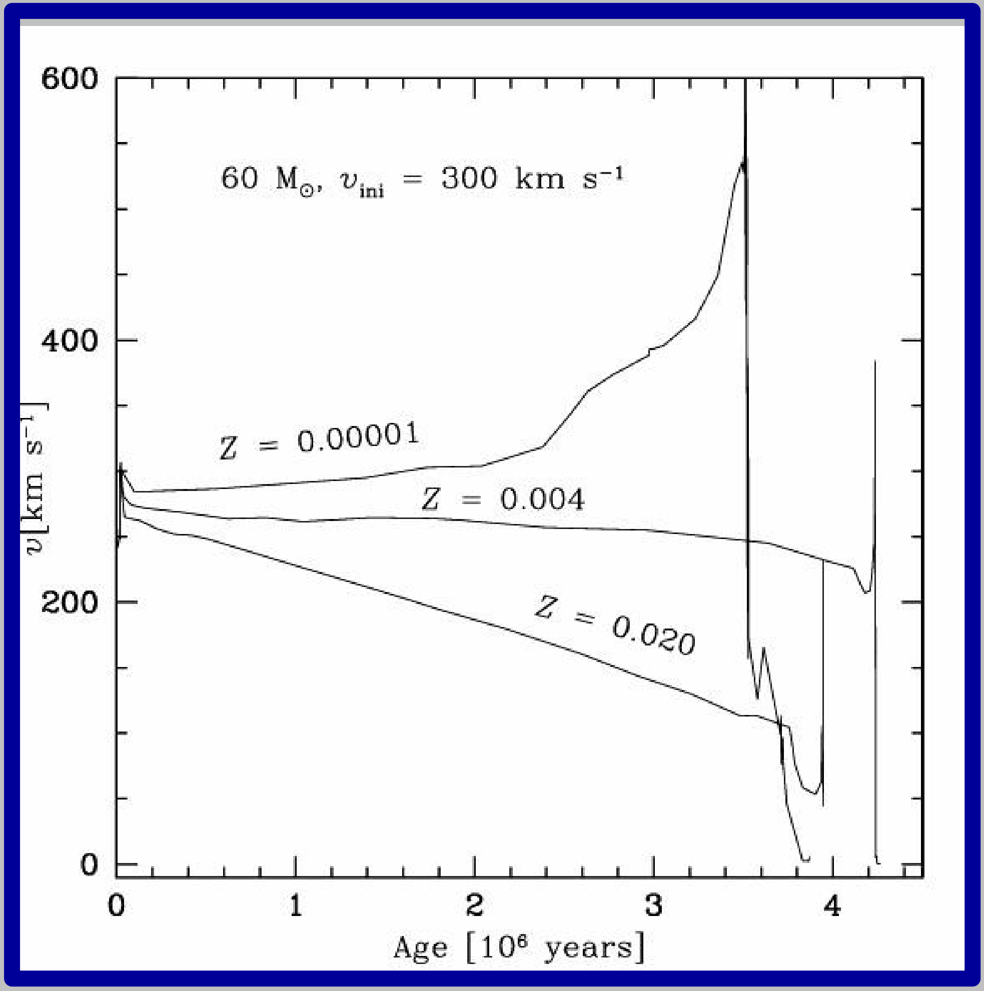
Heger, Fryer et al 2003



Pair Creation SN (M:140-260 Mo) (Heger and Woosley 02, Scannapieco et al 05):

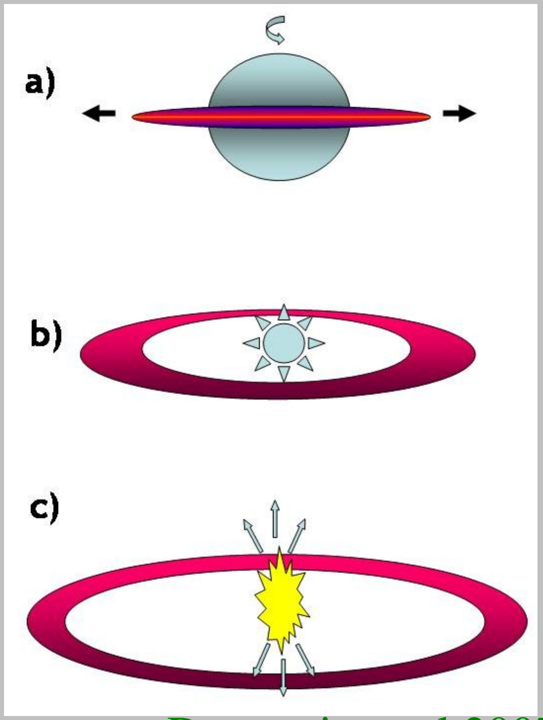
- Chemical signature of PCSN not observed in EMP stars
  (Umeda and Nomoto 02,03,05, Chieffi and Limongi 00,02,04)
- Due to strong mass loss? Ekström et al 2008
- 2006gy might be a PCSN (Smith et al 07, Langer et al 07, Heger et al 07)

Rotation @ Low Z



Break-up often reached

Mass loss at critical rotation:



Decressin et al 2007

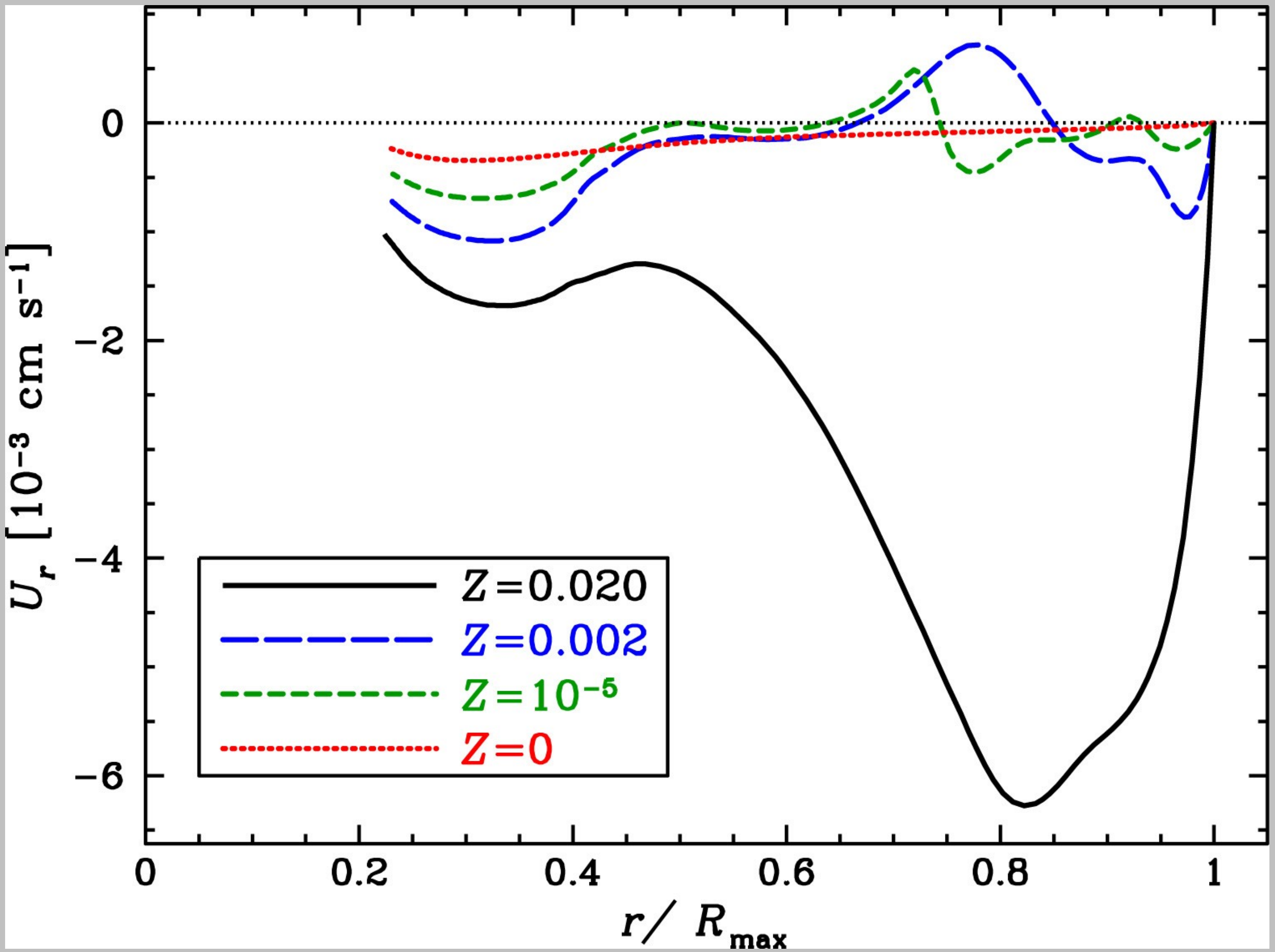
Stronger shear mixing (t_{mix}~R^2/D) (Meynet et al 02,05)

→ Stronger effects of rotation at low Z

Rotation Powered SNe @ Z=0?

Stars are more compact: meridional circulation is less efficient

Ekström et al 08

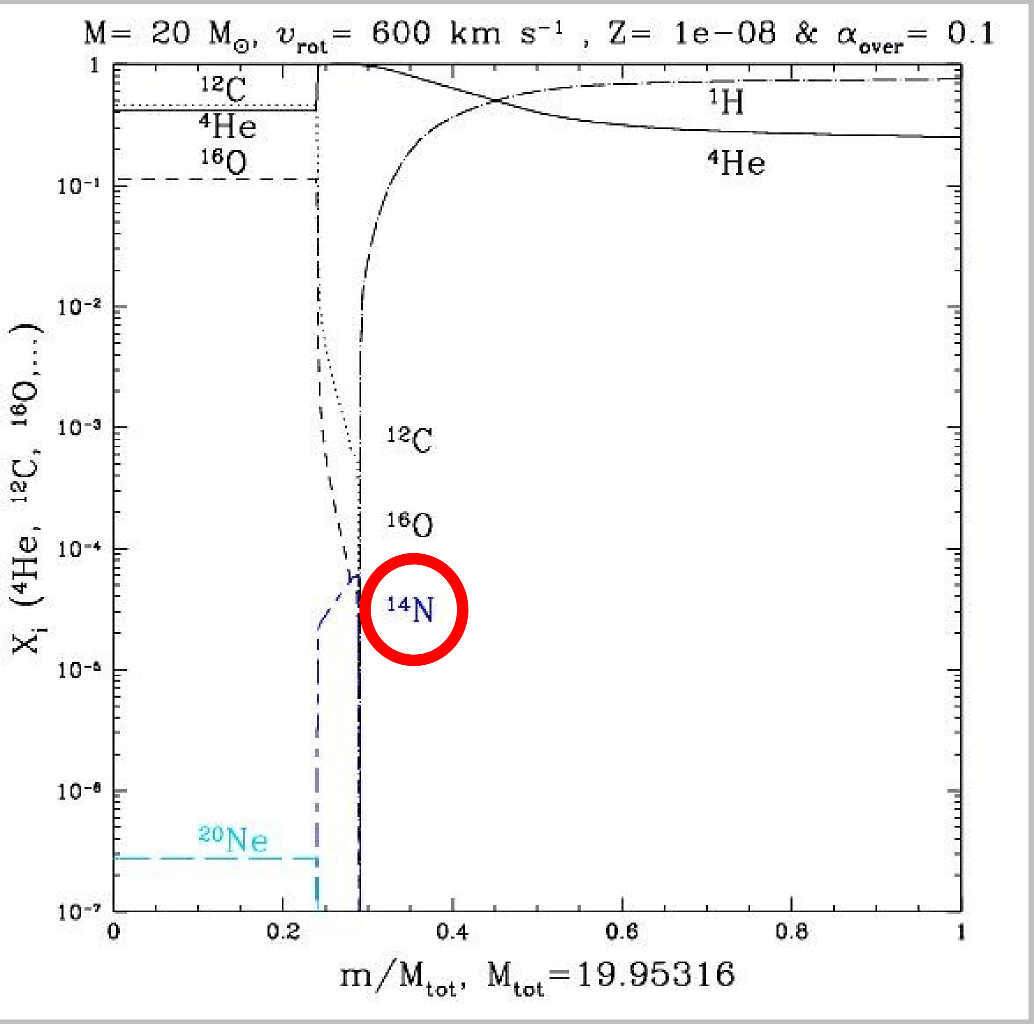


→ less transport of angular momentum

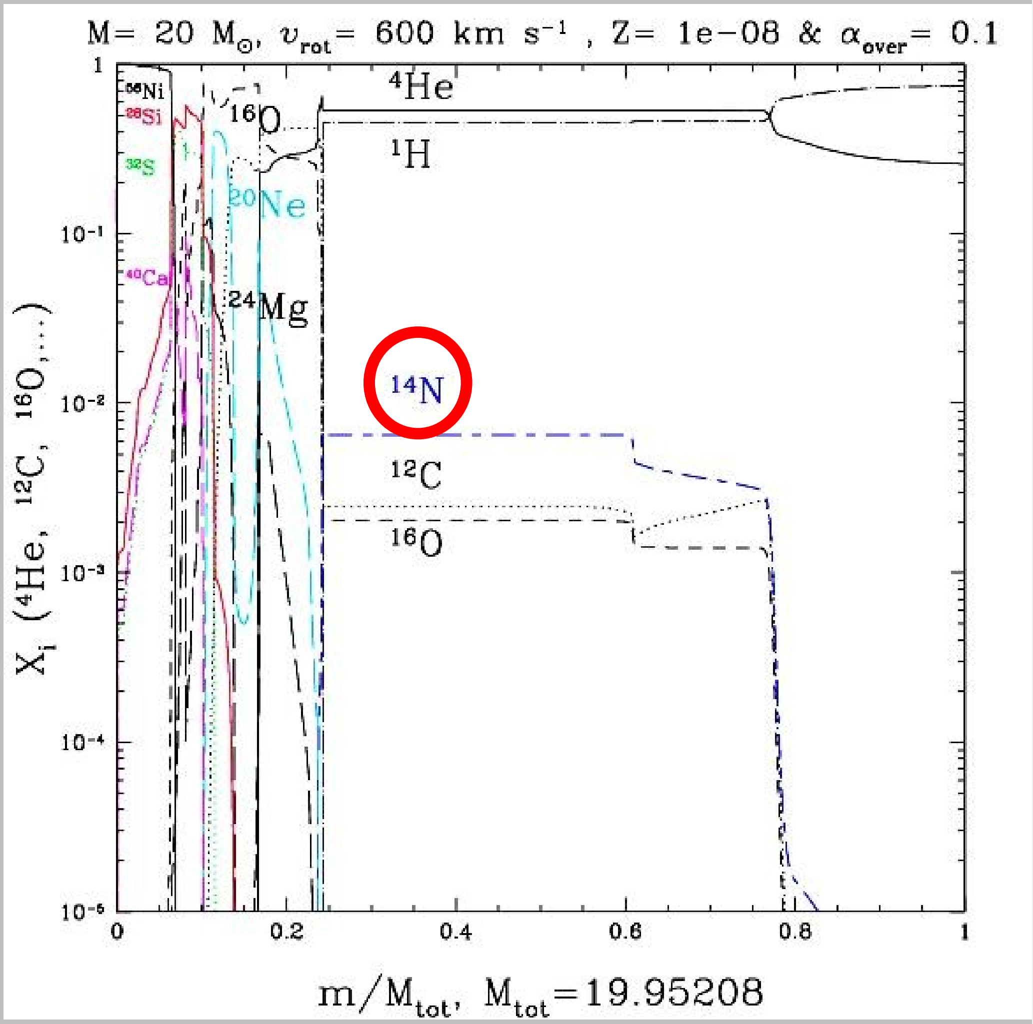
If B=0: Rotation powered explosion @ Z=0!!

Rotation induced mixing @ low Z

Before H-shell boost



Pre-SN stage



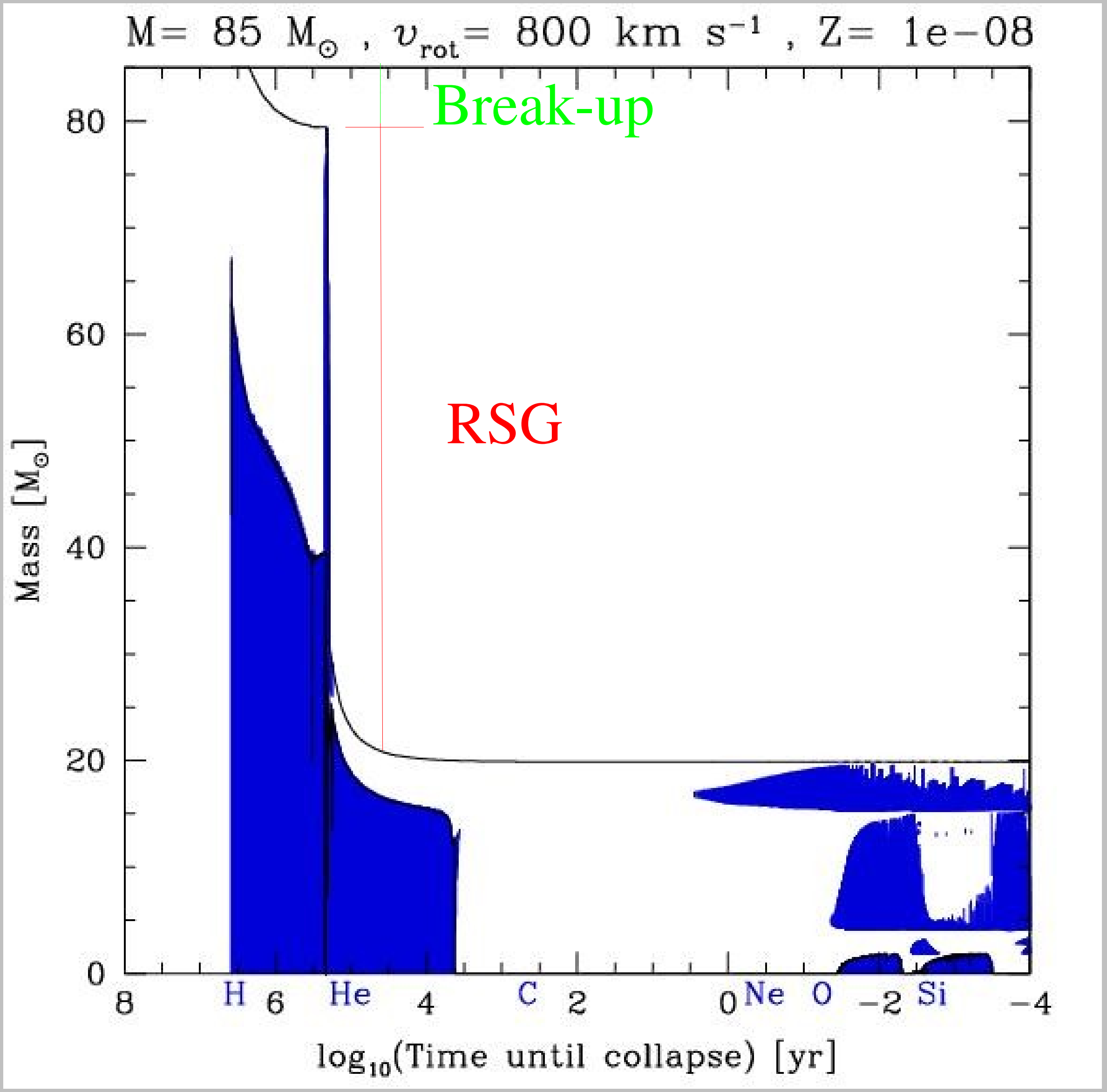
Mass Loss @ Very Low Z?

Strong mass loss during RSG stage (M_{ini} >~60 M_o):

Meynet et al 06, Hirschi 07

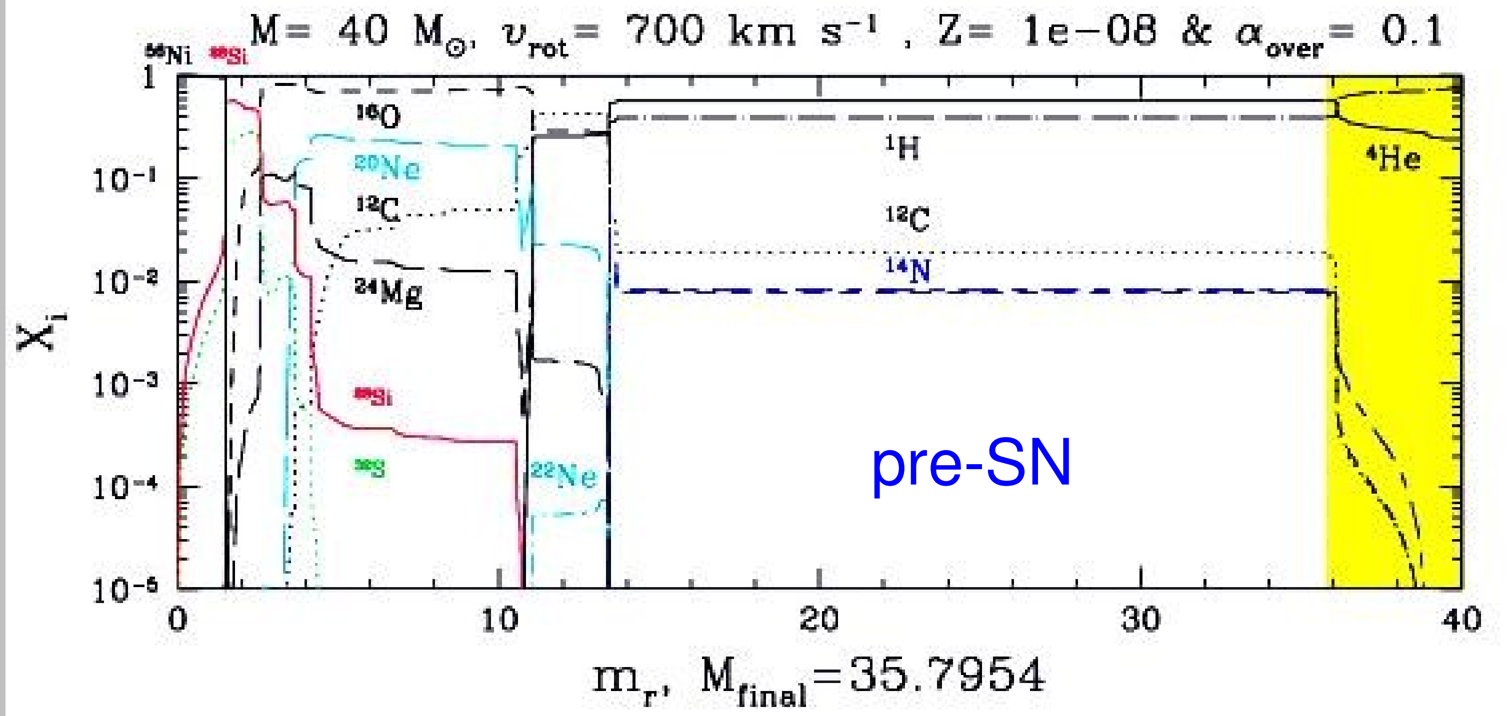
← Mixing of CNO

into envelope after MS



$M \leq 40\ M_o$:

- SN/HN only



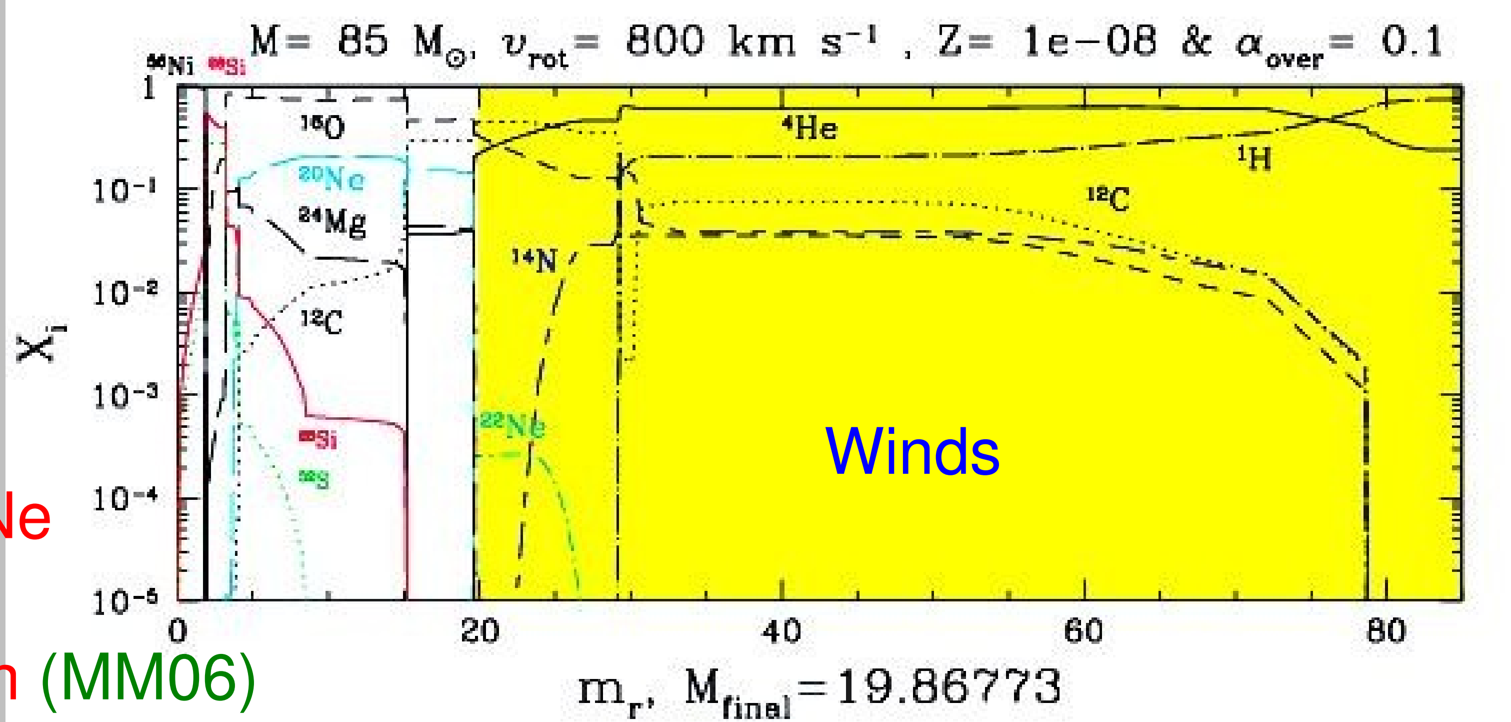
$40\ M_o \leq M \leq 60\ M_o$:

- Winds only?

$Z=10^{-8}$: M_{min}(WR & SNIb,c) ~ 60 M_o

$M \geq 60\ M_o$:

- Strong winds & possible SN or GRB



Winds:

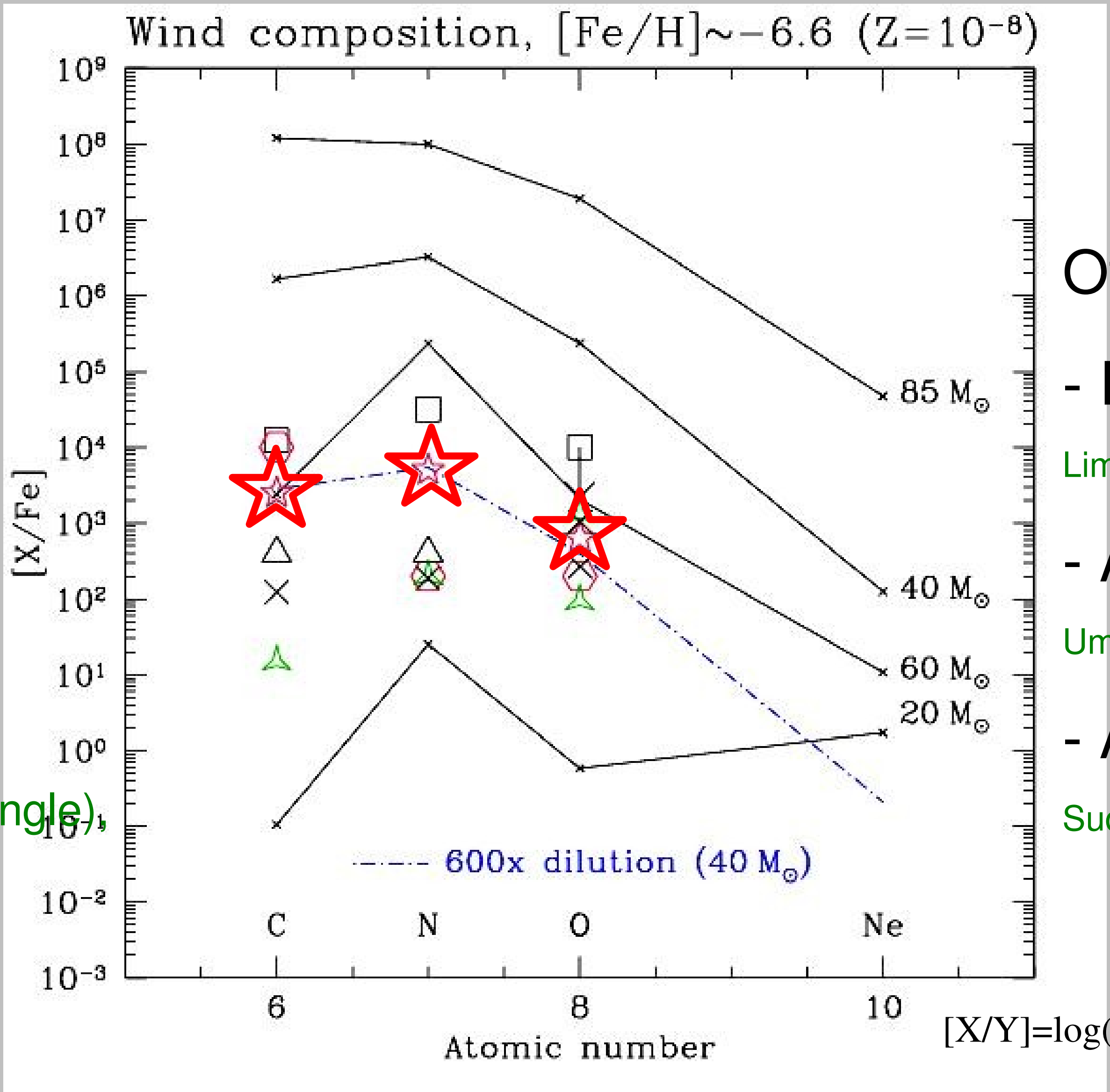
- Rich in ^{13}C, ^{14}N & ^{22}Ne
- Poor in ^{7}Li
- Rich in ^{4}He → ω Cen (MM06)

CEMP Star: HE 1327-2326 (Frebel)

(Carbon-rich Extremely Metal Poor stars)

Ejecta from winds match observed abundance pattern

Meynet et al 06, Hirschi 05, 07



Observations:

Frebel et al 04 &
Aoki et al 05 (stars),
Plez & Cohen 05 (triangle),
Christlieb et al 04,
Norris et al 04,
Depagne et al 02

Other models:

- Pop III

Limongi et al 2003

- Asym. Expl.

Umeda & Nomoto 2003

- AGBs

Suda et al 2004

$[X/Y]=\log(X/Y)-\log(X_o/Y_o)$

Galactic Chemical Evolution: Primary ^{14}N

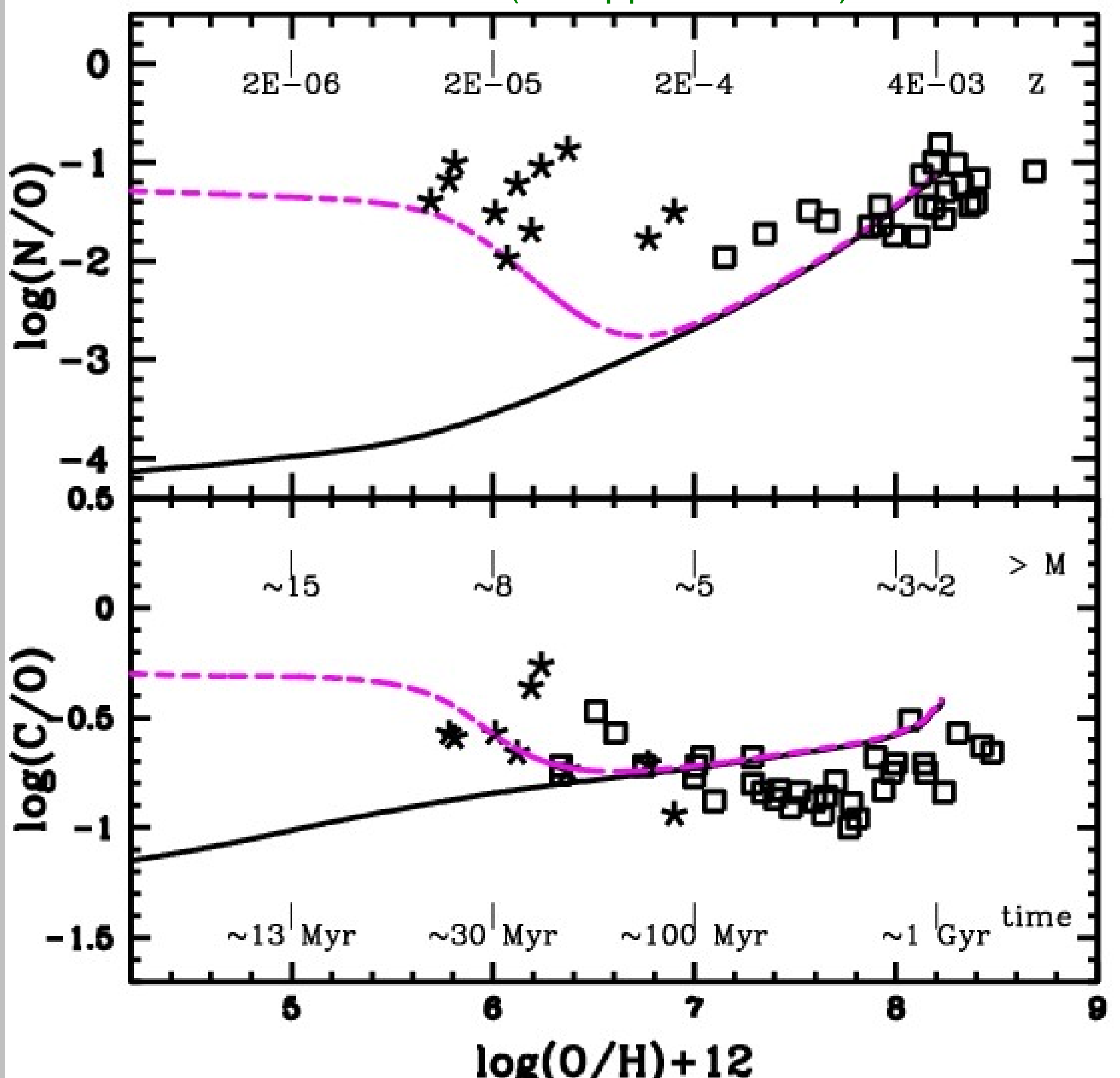
Evolution of [N/O]

reproduced

← using $Z=10^{-8}$ yields

Hirschi 07: - - - - - - - -

(Chiappini et al 06)



Upturn of [C/O]

Observations:

Spite et al 2004 (asterisks)

Israelian et al 2004 (squares)

Fabbian et al 2008

DLAs Pettini et al 2008

Long soft GRB-SN Ic connection: GRB060218/SN2006aj

Cusumano et al 2006, ...

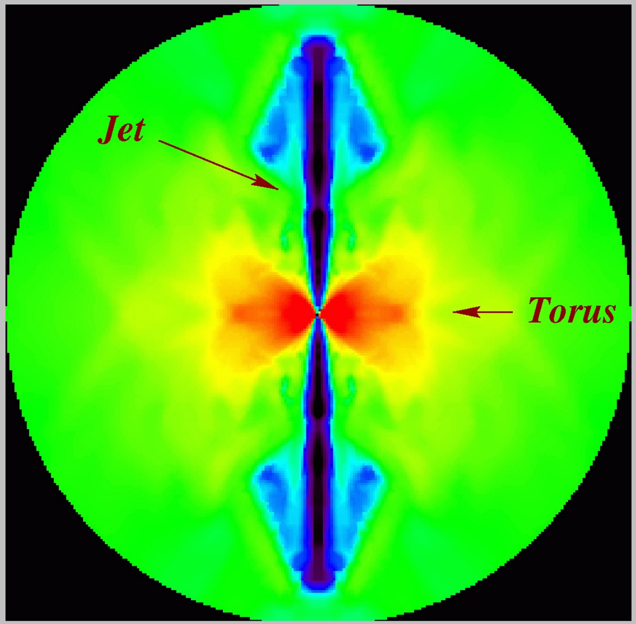
GRB 031203-SN 2003lw / GRB 030329-SN 2003dh / GRB 980425-SN 1998bw, ...
Tagliaferri, G et al 2004 / Matheson 2003, ... / Iwamoto, K. 1999, ...

Collapsar progenitors must: (Woosley 1993, A. Mc Fadyen)

Form a BH

Lose their H-rich envelope → WR star

Core w. enough angular momentum



(simulation by Mc Fadyen)

Observational info:

Z of close-by GRBs is lower than solar

~ Z (Magellanic clouds)

(Stanek et al 06, Le Floc'h er al 2003, Fruchter et al 2006)

Theoretical GRB rates (without B-fields)

Obs: R(GRB)=$3x10^{-6}$ to $6x10^{-4}$ & R(SNII,Ib,c)~$7x10^{-3}$ [yr^{-1}]

Podsiadlowski et al 04

GRB from all WR types:

Too many

GRB from WO (SN Ic):

OK with obs.

Hirschi et al A&A, 443, 581, 2005

	Z_{SMC}	Z_{LMC}	Z_o	Z_{GC}
M_{GRB}^{min}(WR)	32	25	22	21
M_{GRB}^{max}(WR)	95	95	75	55
R_{GRB}^{max}(WR)	1.15E-03	1.74E-03	2.01E-03	1.92E-03
M_{GRB}^{min}(WO)	50	45	-	-
M_{GRB}^{max}(WO)	95	95	-	-
R_{GRB}^{max}(WO)	4.74E-04	5.99E-04	-	-

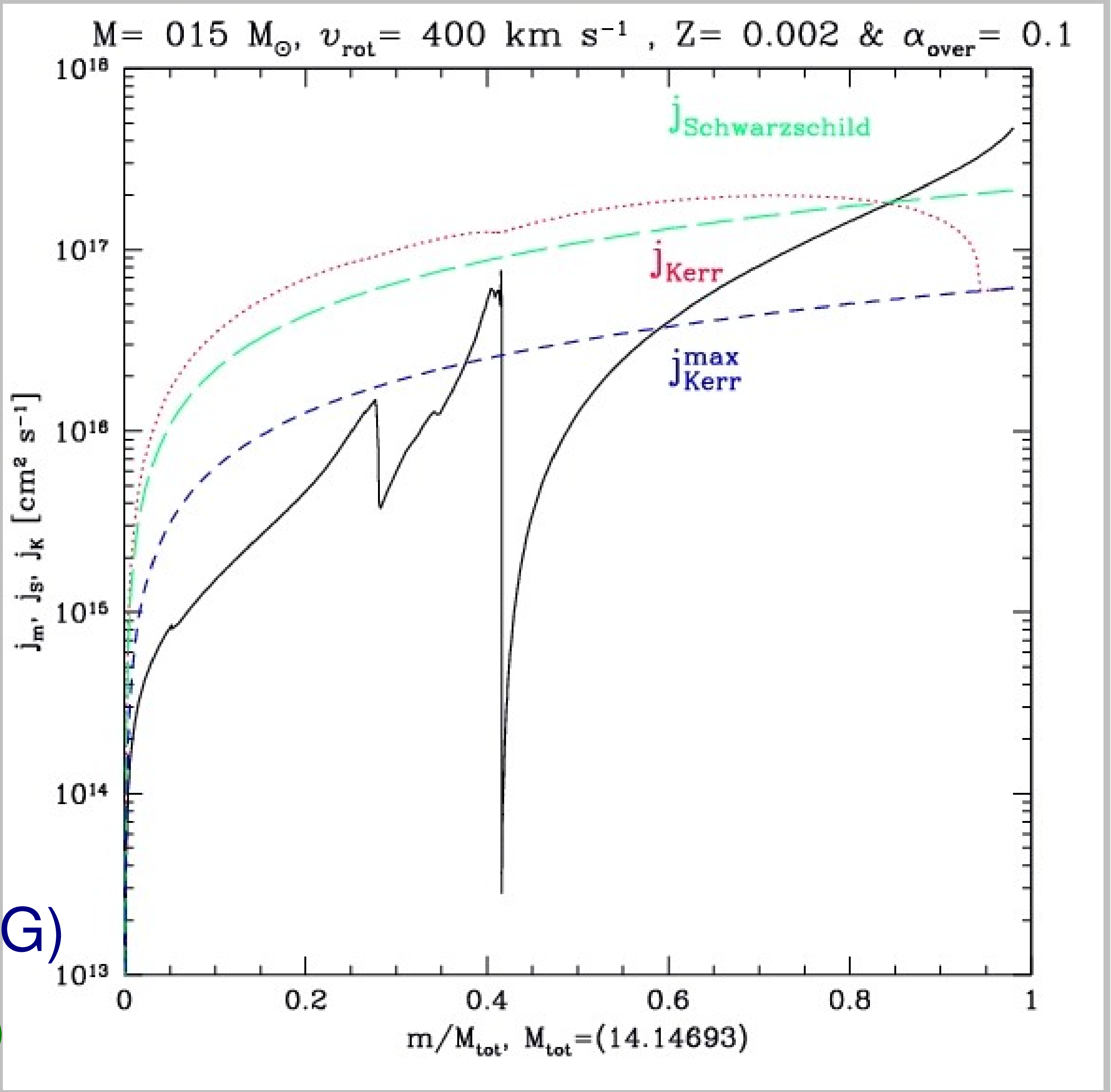
GRB favoured at low Z, maybe also very low Z (85 Mo)

Magnetic Fields: Masive Stars

Taylor-Spruit dynamo (Spruit 02, Maeder & Meynet 05) :

Better for pulsar periods

(Heger et al 2005)



GRBs/MHD explosions?

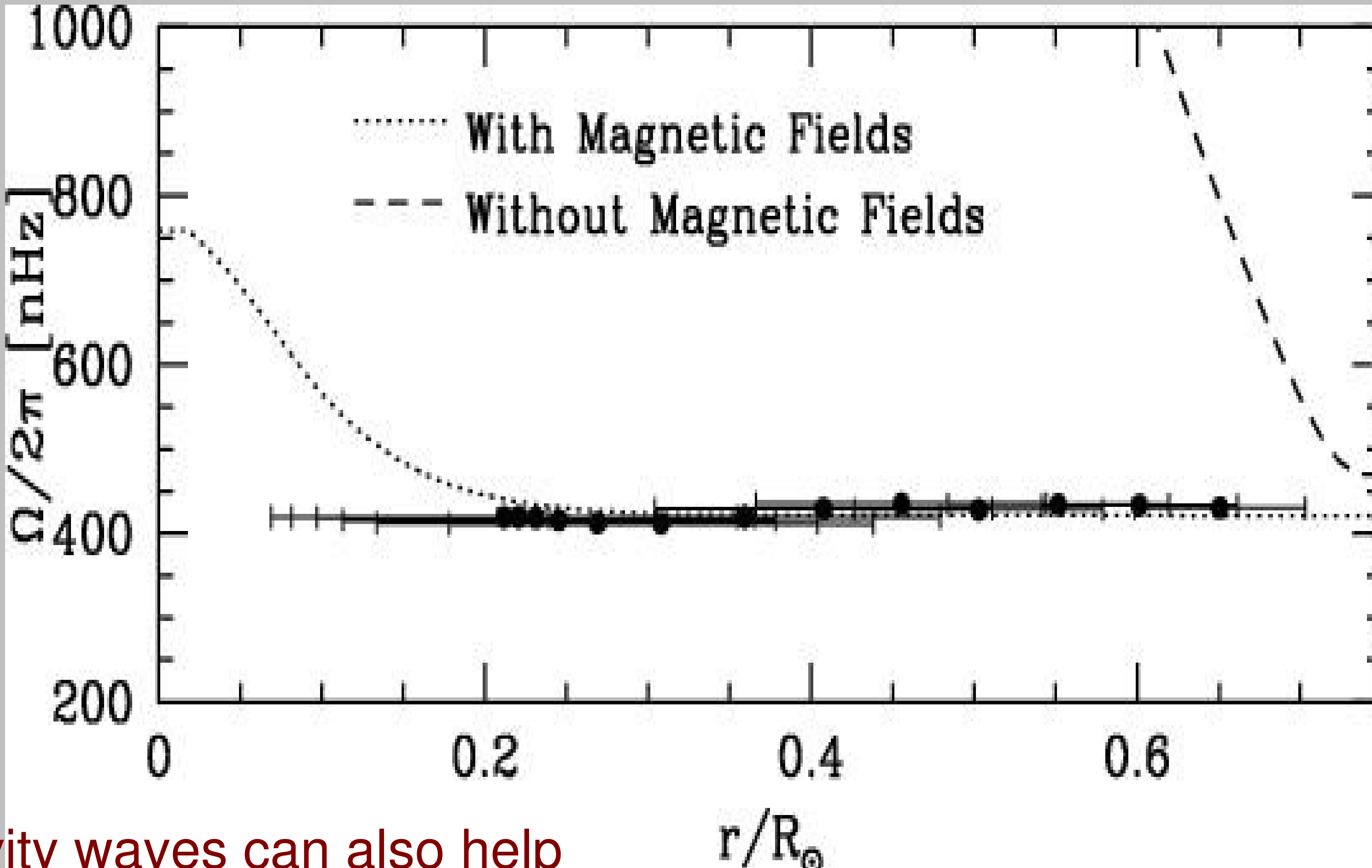
← Quasi chemically-homog.

evol. of fast rot. stars (avoid RSG)

(Yoon et al 06,07, Woosley & Heger 2006)

Sun rotation profile compatible with helioseismology

(Eggenberger et al 2005)



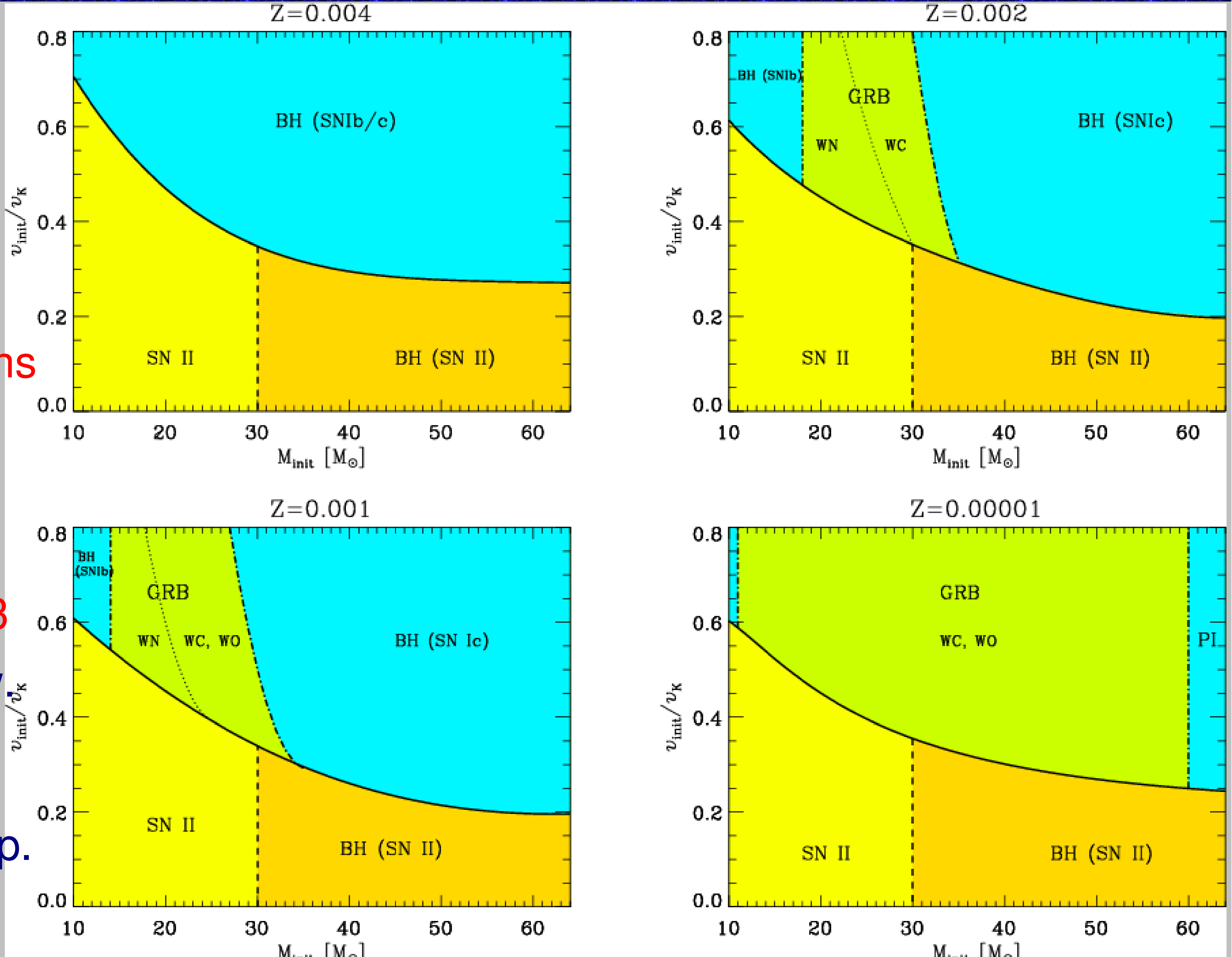
Gravity waves can also help

(Charbonnel & Talon 2005, Arnett & Maekin 2006)

GRB progenitors with B-Fields

Yoon, Langer & Norman 06

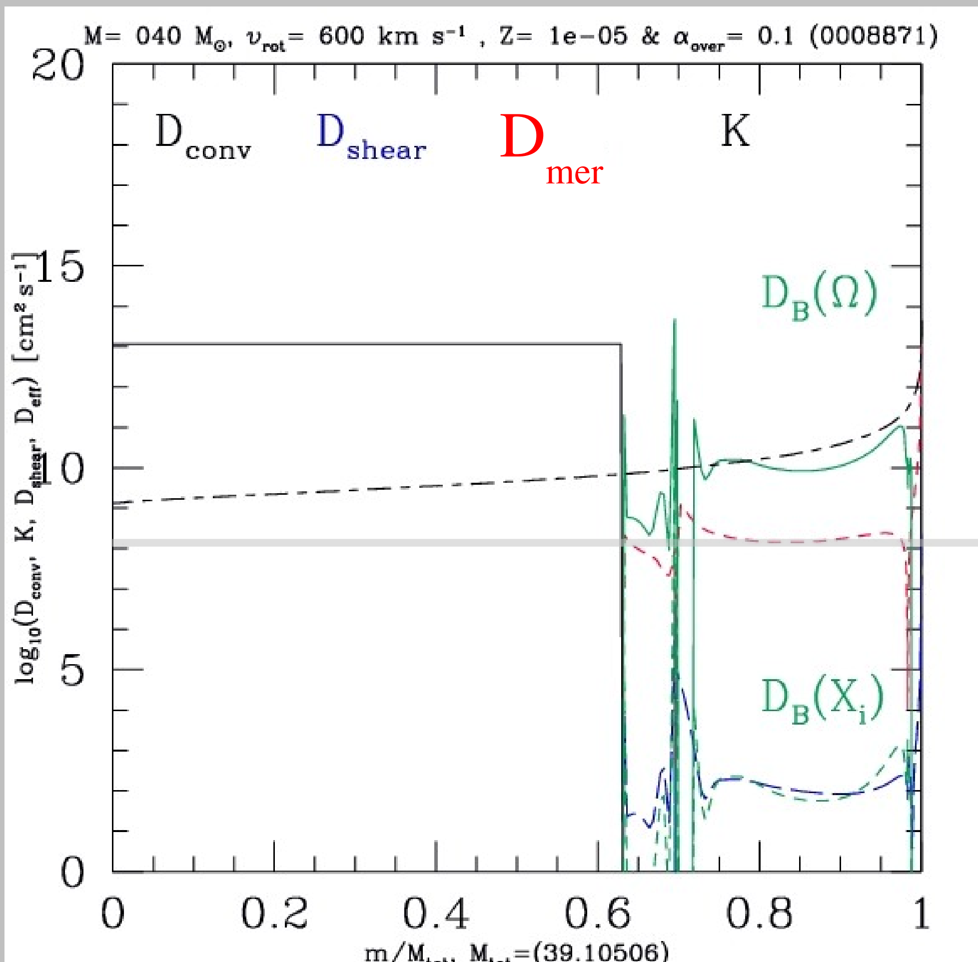
Rates compatible with observations



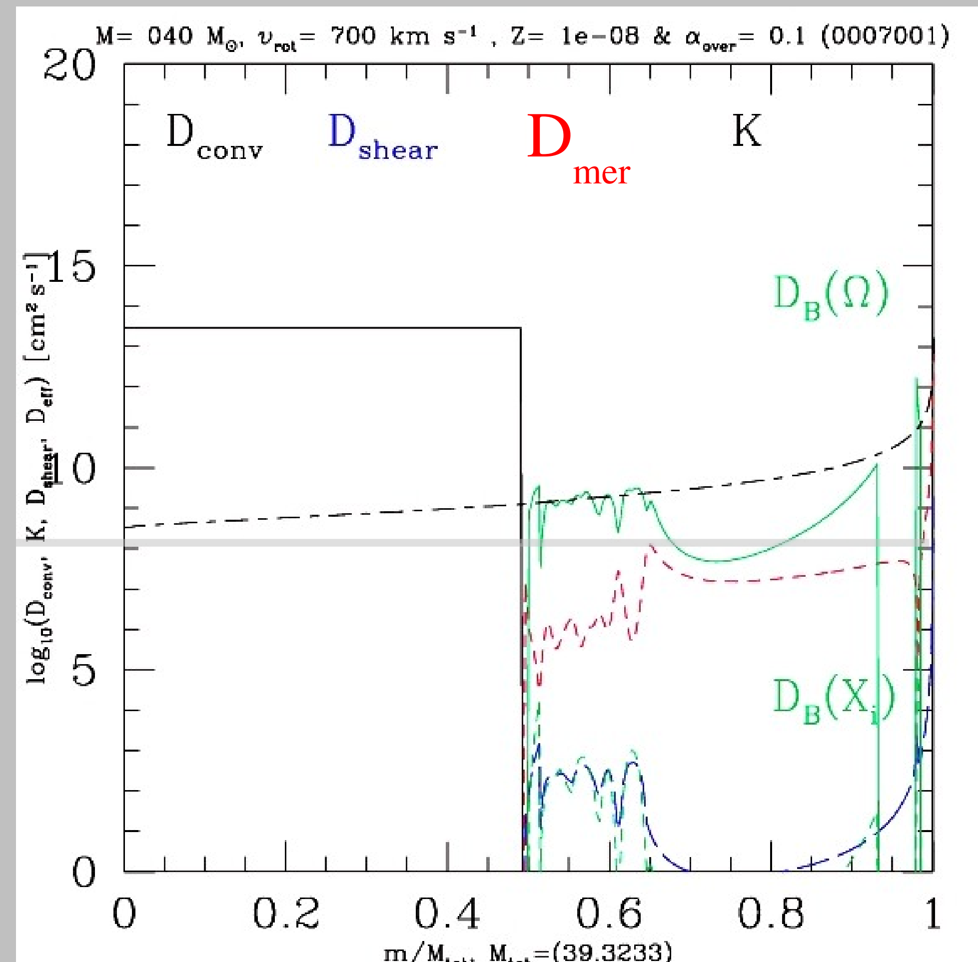
Z_{max} ~0.003 is a bit low. Dep. on Mdot & Solar comp.

Quasi-Chem. Evol. @ very low Z? 40M_o models

Z=1e-5, v_{ini}=600 km/s (v_{ini}/v_{crit} =0.59)



Z=1e-8, v_{ini}=700 km/s (v_{ini}/v_{crit} =0.55)



Diff. Coeff. Smaller --> Quasi-Chem. Evol. harder for the first stellar generations

Conclusions

PCSN not found in EMP stars (very low Z) but poss. @ low Z

Rotation changes evolution @ low Z:

Strong mixing between helium & hydrogen burning zones

Rotation powered SNe @ Z=0 (no B-field) → GW signal?

Strong mass loss during RSG phase

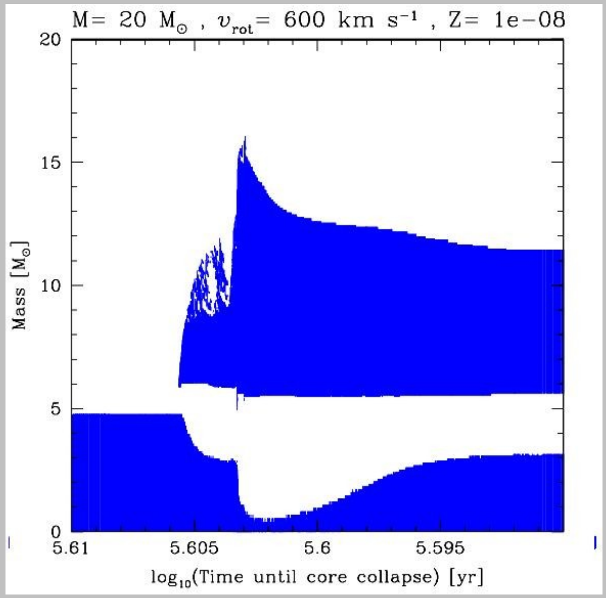
Large s process, primary ^{14}N,^{13}C prod. over large Z:1e-8 - 1e-6

GRB progenitors: quasi-chem. Hom. Evol.

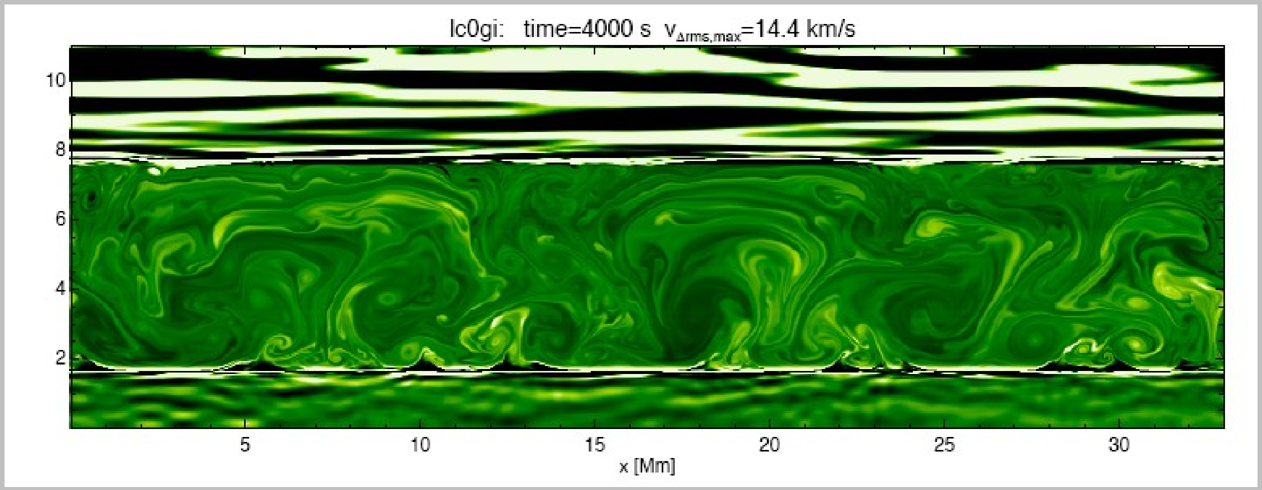
Fast rotators (GRBs) ok @ low Z but not all * become GRBs

3D – 1D link

Multi-D simulations: burning & mixing



Hirschi 07



Herwig et al 06

Determine effective diffusion (advection?) coefficient

Outlook

SEGUE, OZ surveys of EMP stars

Swift & GLAST satellites for SNe & GRBs

VLT FLAMES survey of massive stars

Interactions between rotation, magnetic fields, binarity & mass loss & Mass loss in RSG and LBV stages need to be studied in more details

LMC/SMC: excellent Z for tests of models

Grids of models over large Z range (Z: 0 – 2*solar)

Comprehensive nucleosynthesis