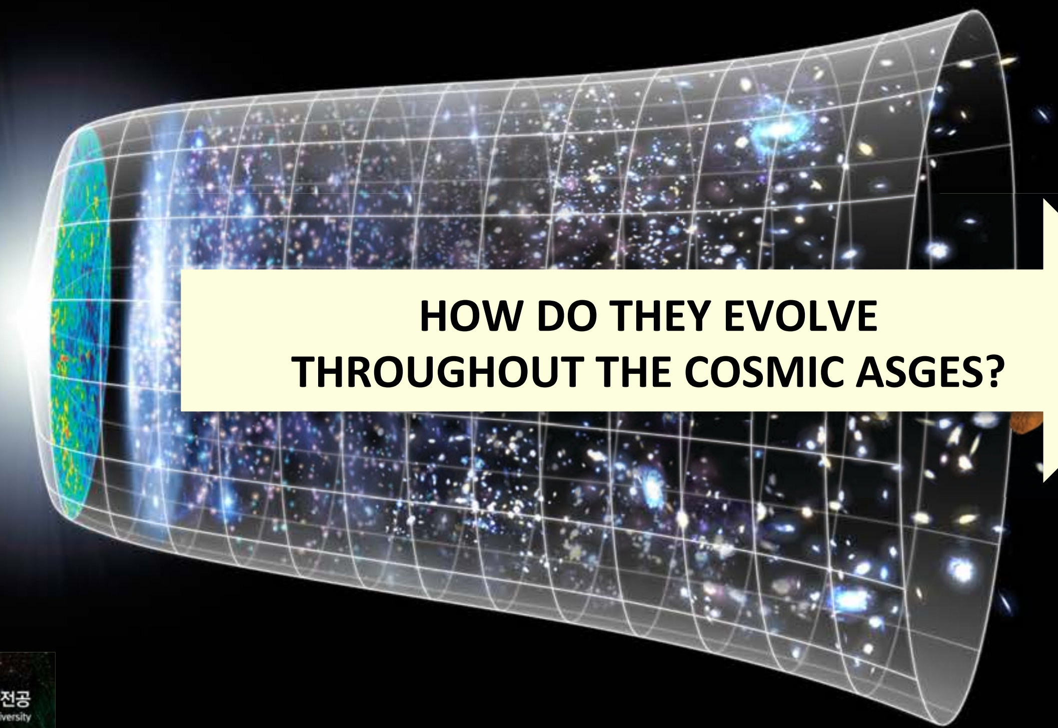
PRE-SUPERNOVA EVOLUTION OF MASSIVE STARS



HOW DO THEY EVOLVE THROUGHOUT THE COSMIC ASGES?

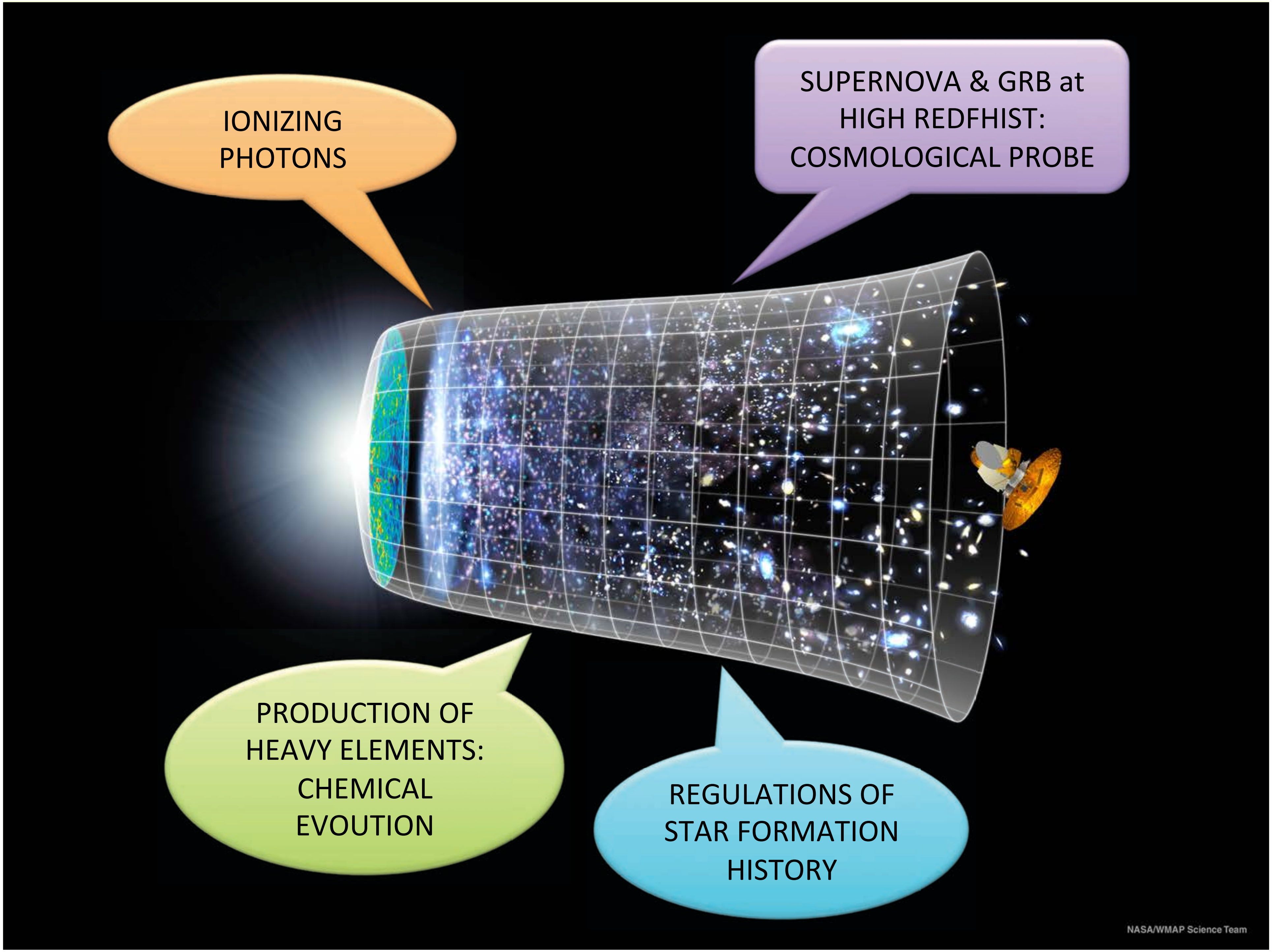
Sung-Chul Yoon

(Seoul National University)

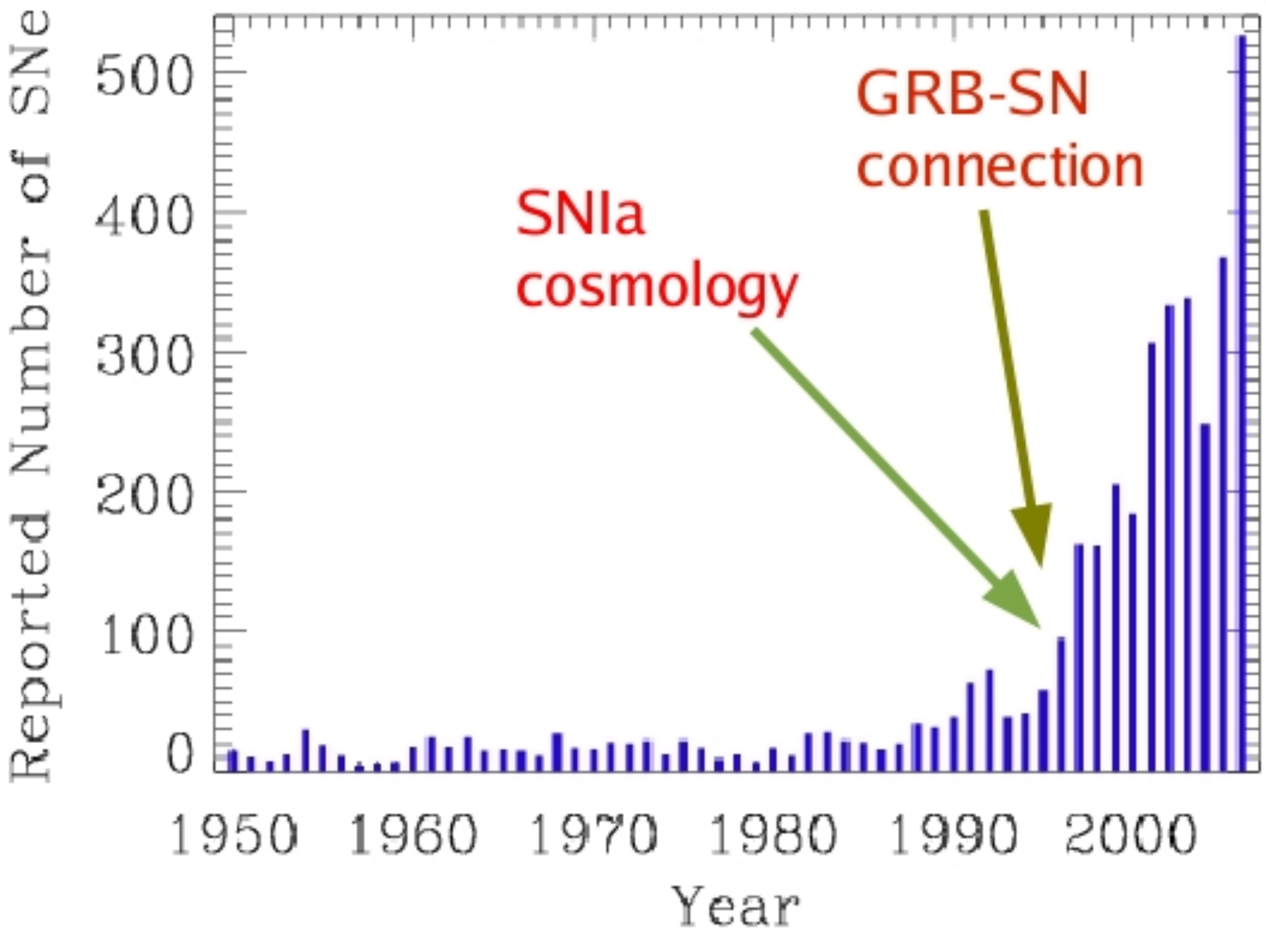
EAST ASIAN YOUNG ASTRONOMERS MEETNG

Taipei, February 11 , 2015

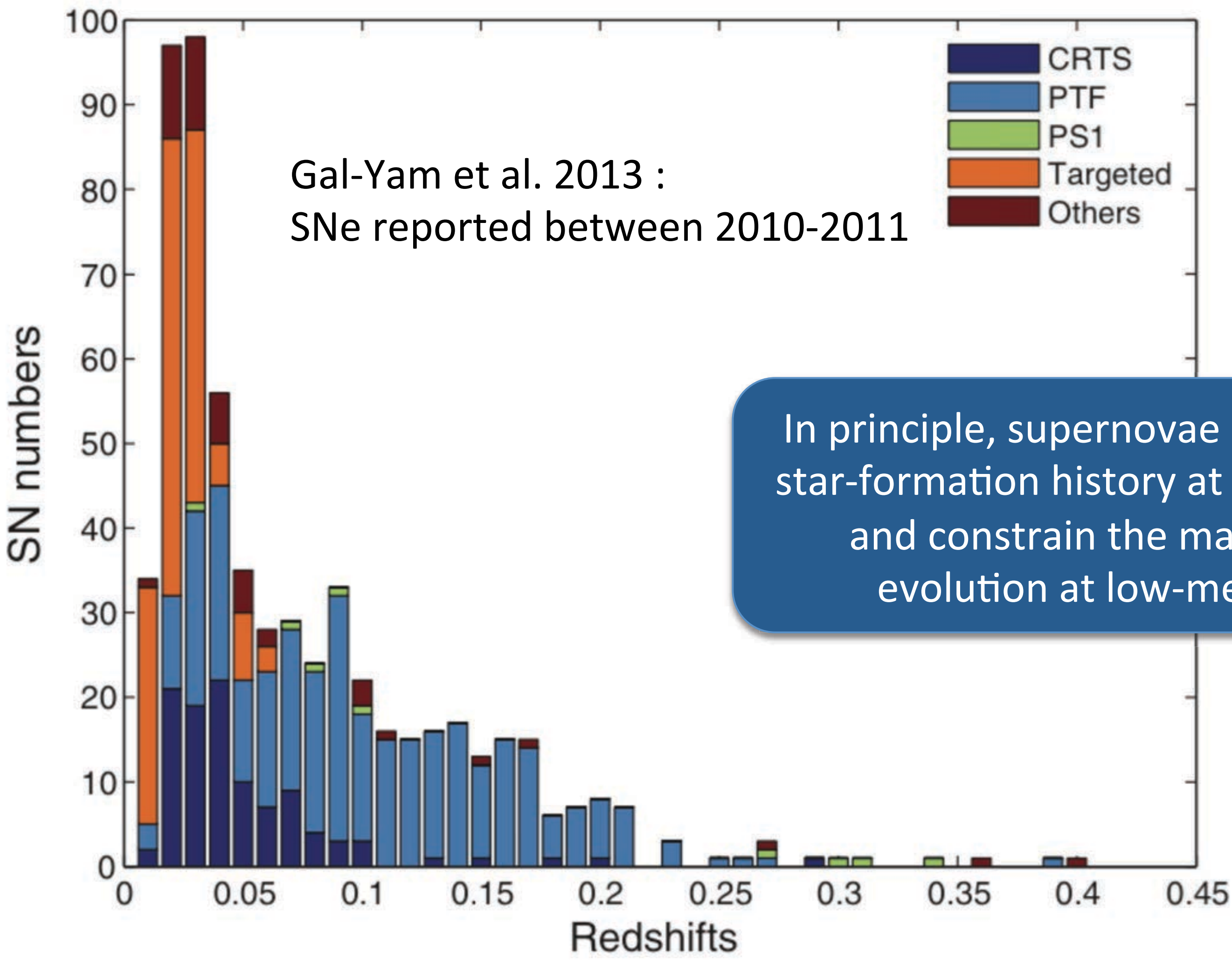
NASA/WMAP Science Team


IONIZING PHOTONS
SUPERNOVA & GRB at HIGH REDFHIST: COSMOLOGICAL PROBE
PRODUCTION OF HEAVY ELEMENTS: CHEMICAL EVOUTION
REGULATIONS OF STAR FORMATION HISTORY
NASA/WMAP Science Team

Supernovae :
Excellent probes for massive star evolution

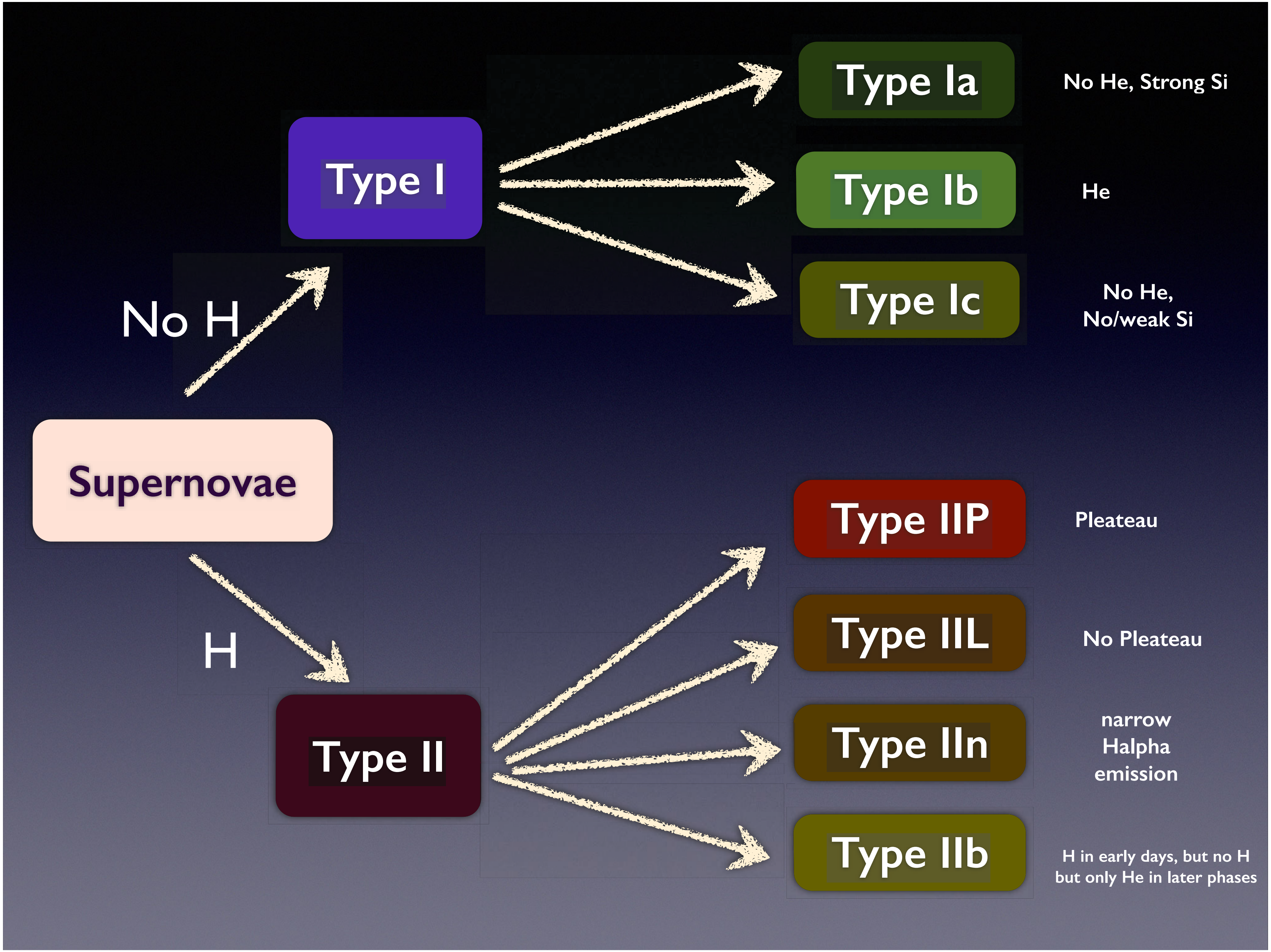


Supernovae :
Excellent probes for massive star evolution



Gal-Yam et al. 2013 :
SNe reported between 2010-2011

In principle, supernovae can trace the star-formation history at high-redshift, and constrain the massive star evolution at low-metallicity

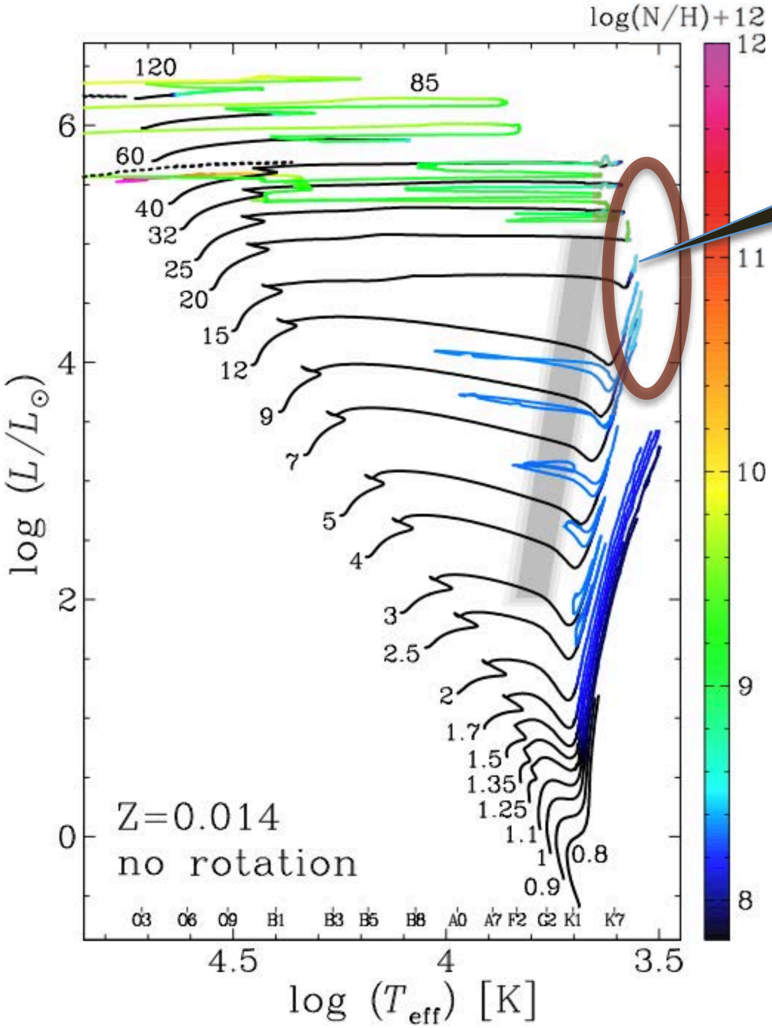

Supernovae
No H
H
Type I
Type II
Type Ia
No He, Strong Si
Type Ib
He
Type Ic
No He,
No/weak Si
Type IIP
Pleateau
Type IIL
No Pleateau
Type IIn
narrow
Halpha
emission
Type IIb
H in early days, but no H
but only He in later phases

Standard scenario of massive star evolution

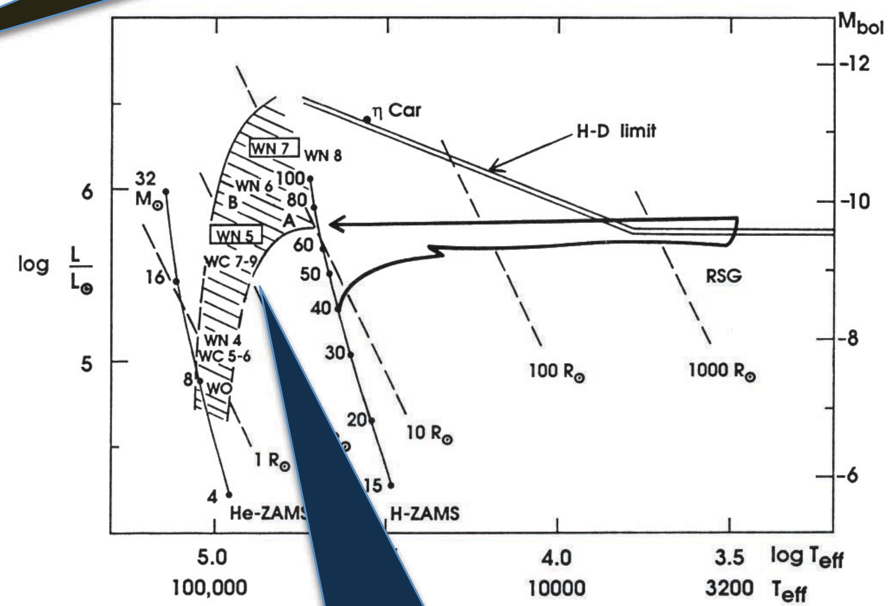
$$L \propto M^{\alpha}, \ \alpha = 1.0 - 3.8$$

$$\dot{M}_{\rm wind} \propto L^{1.5} Z^{0.7}$$

Standard scenario of massive star evolution



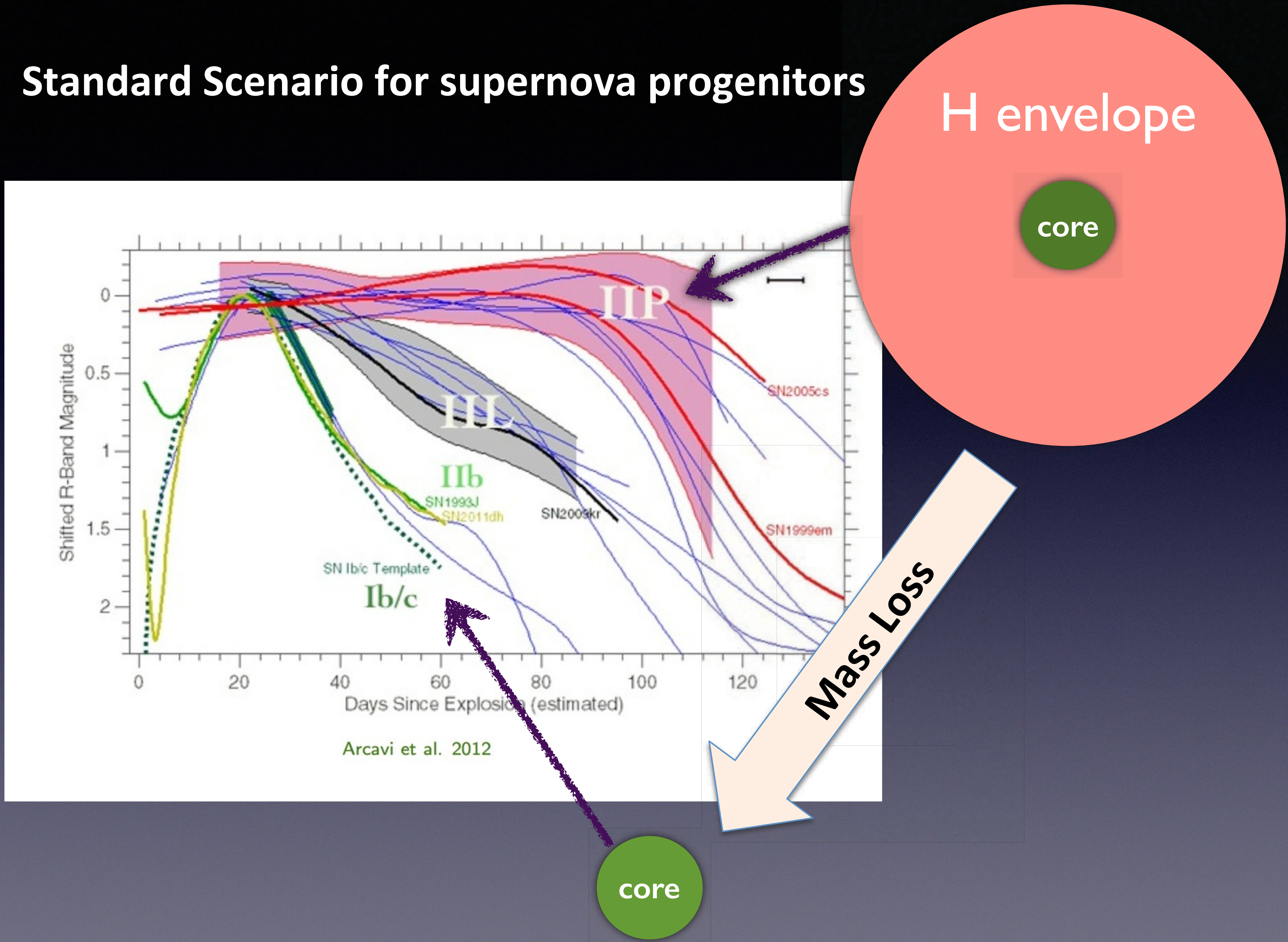
Type IIP, IIL, IIb supernovae
from 8 < M < 25 - 30 Msun

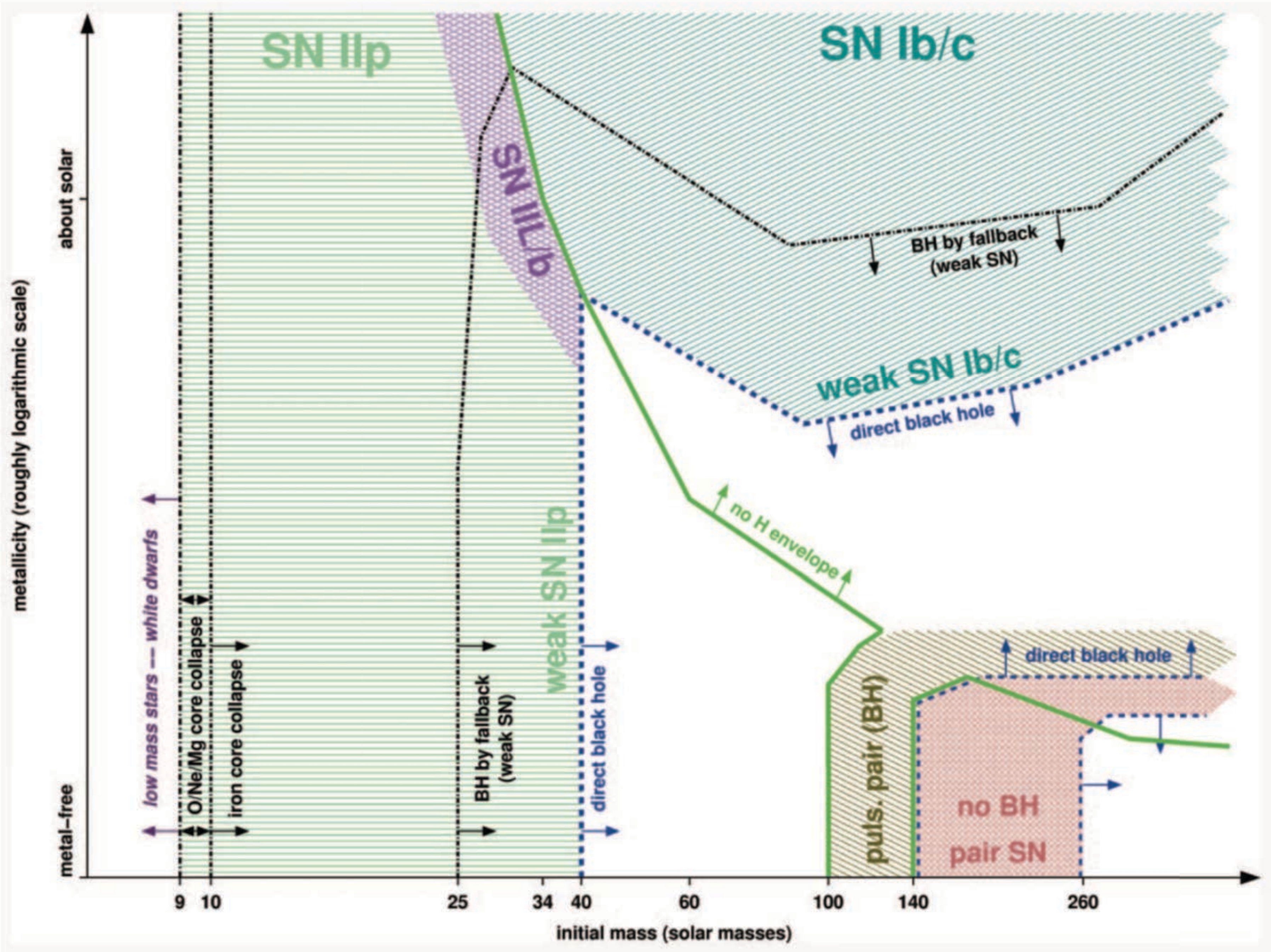


Type Ib/c supernovae
from M > 25 - 30 Msun

Ekstroem et al. 2012

Standard Scenario for supernova progenitors

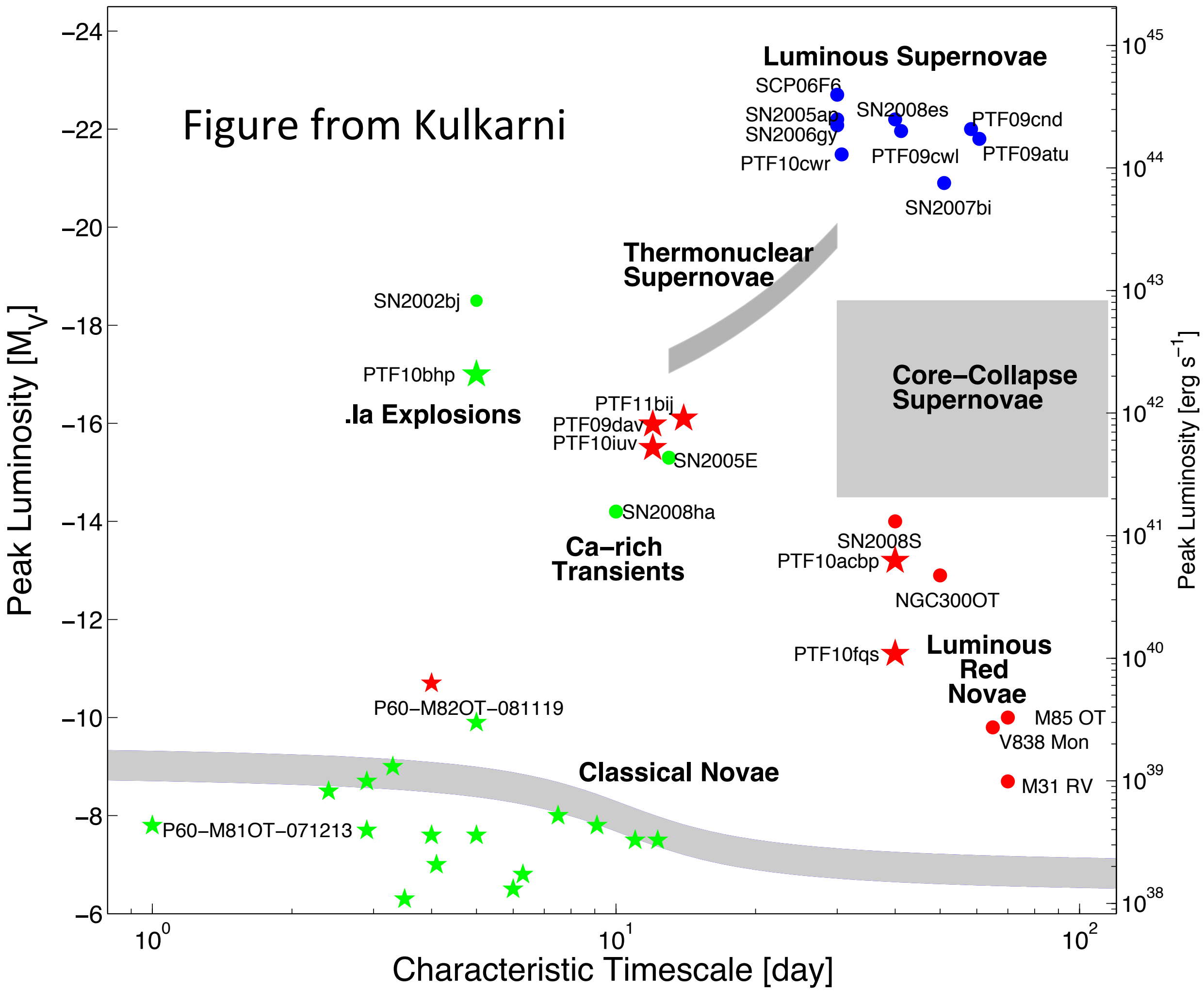




Heger et al. 2003

Supernova Diversity

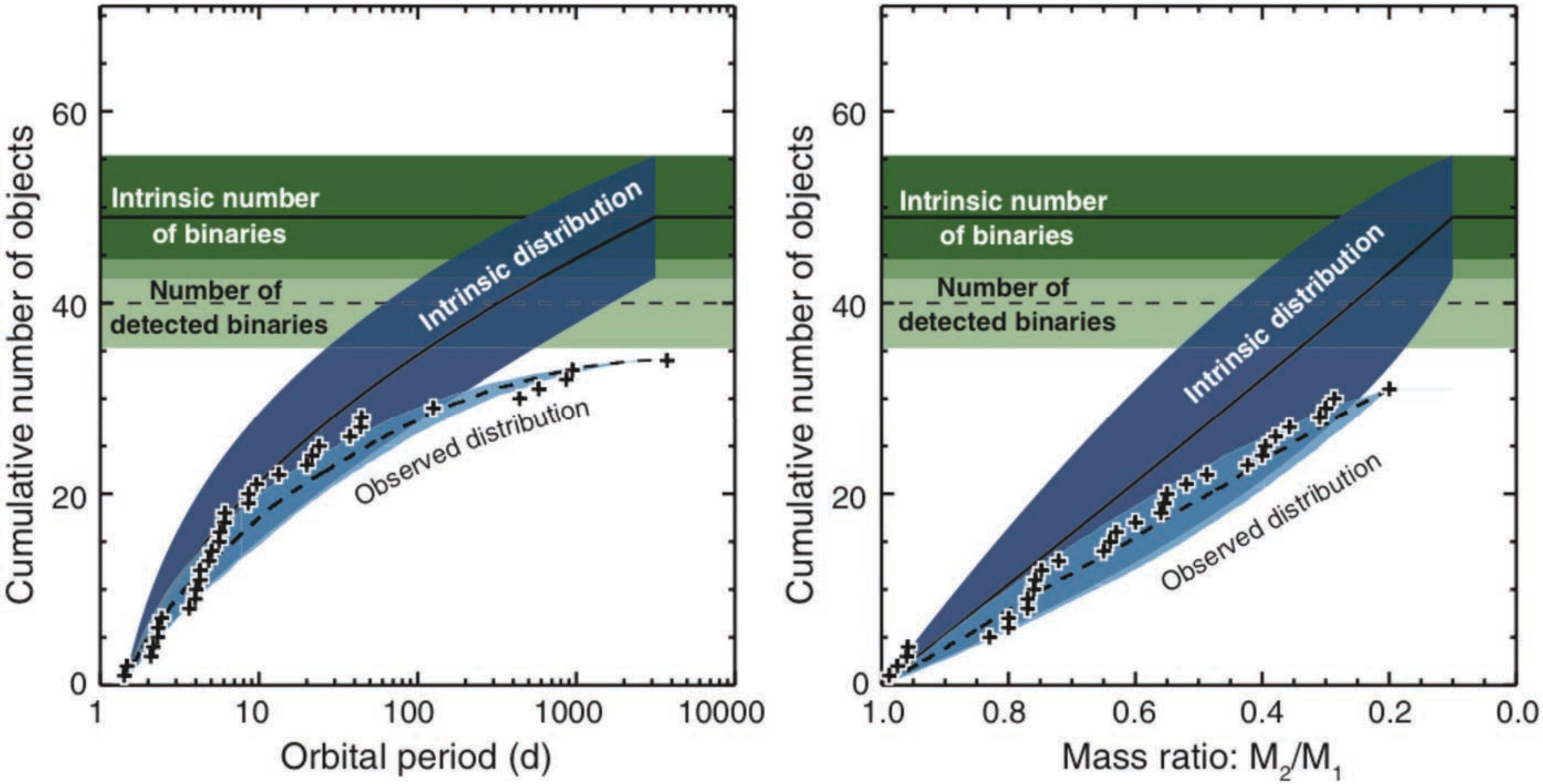
The standard scenario based on single star models cannot explain this large diversity.



Recent Paradigm Shift:

the majority of massive stars are in close binary systems

About 70% of massive stars undergo binary interactions: Sana et al. 2012



Massive binary systems and Type Ib/c supernovae

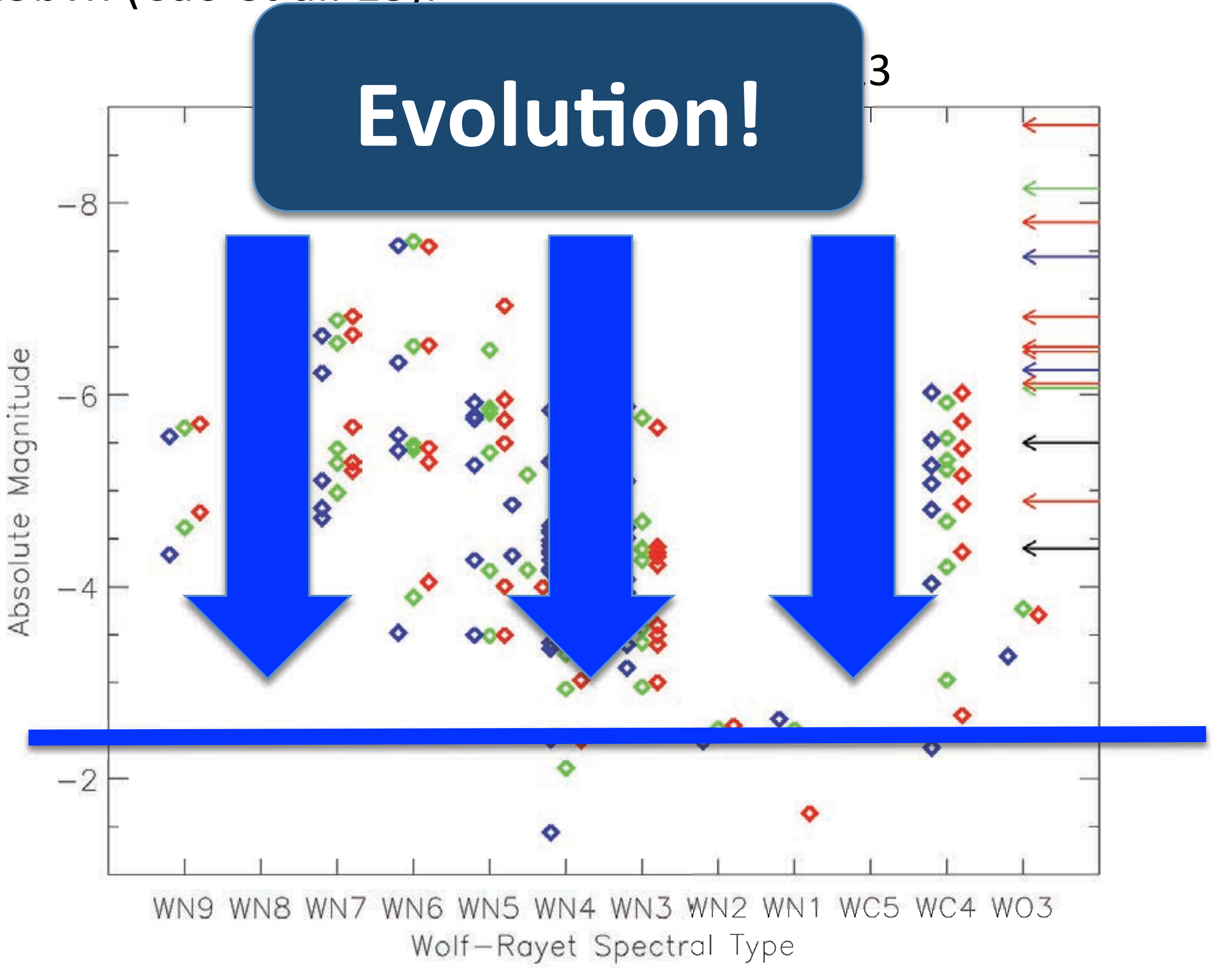
SN Ibc from hydrogen-deficient progenitors
Single or Binary Origin?

- **No or little hydrogen is found in SN Ibc:**
  - ✓ the hydrogen envelope is stripped off from the progenitor.

- **mass loss by stellar winds :** high metallicity
- **binary interactions :** any metallicity – but for SN Ibc, high-Z is still preferred (at low Z, SN IIb would be more frequently produced).

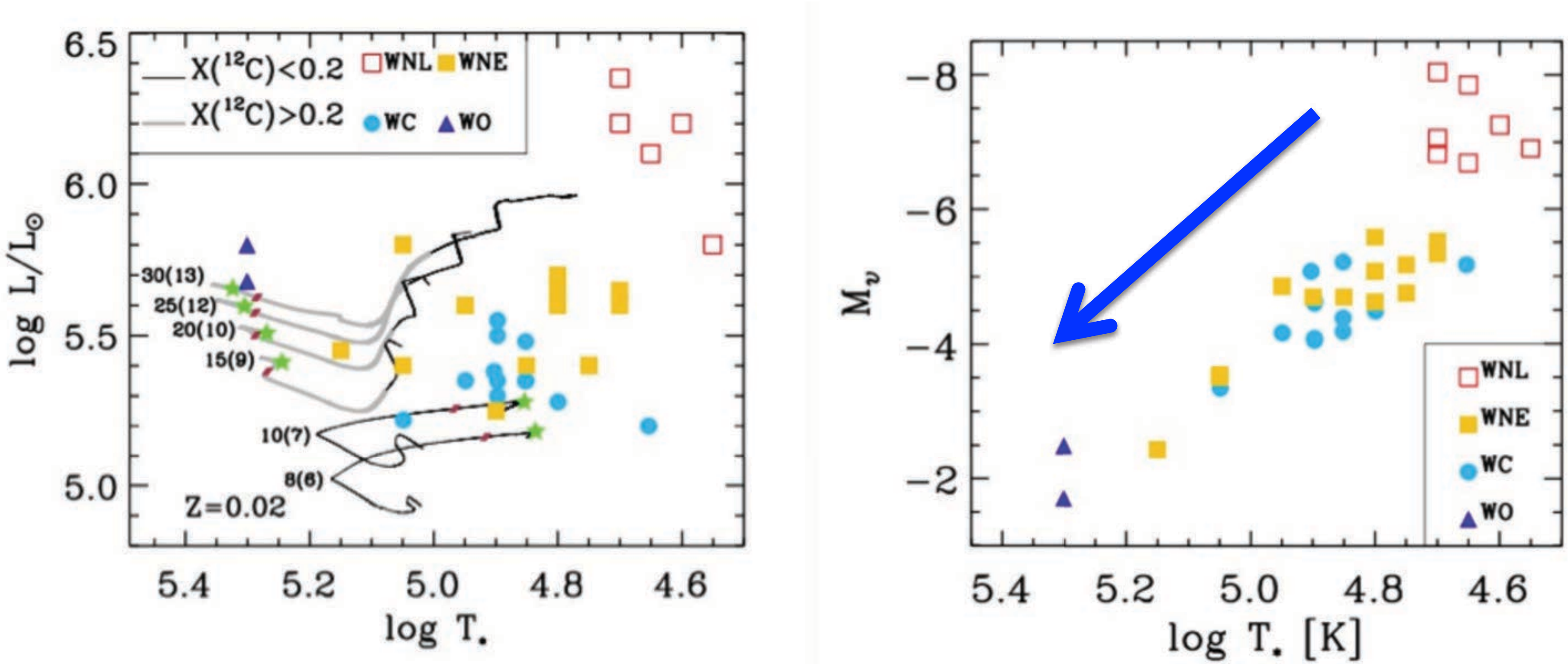
Single Wolf-Rayet stars : SN Ibc progenitors?

WR stars are generally very bright, but all attempts to directly identify SN Ibc progenitors have failed so far (Smith 09; Eldridge et al. 13), except the tentative case with iPFT13bvn (Cao et al. 13).



WR stars as SN Ibc progenitors

Galactic WR stars, which are luminous in the optical, may not represent SN Ib/c progenitors at the pre-supernova stage, and their direct identification in pre-supernova images may be very difficult.



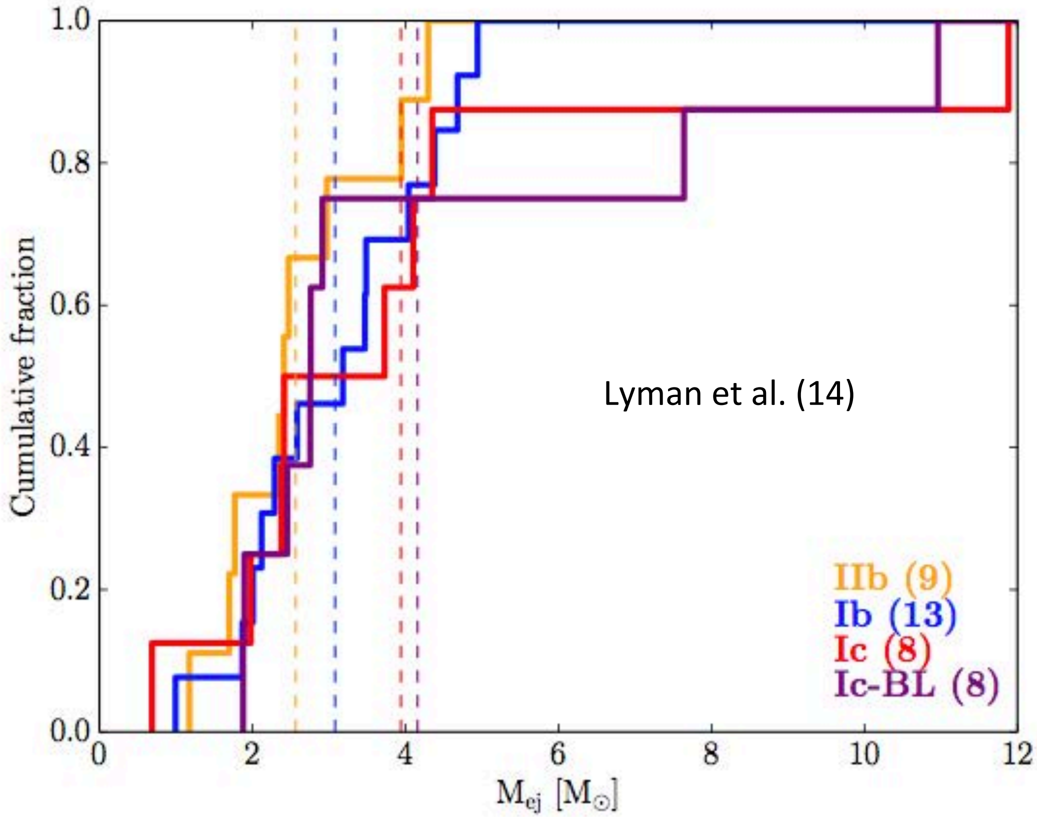
Yoon et al. 2012; WR data from Sander et al. 12

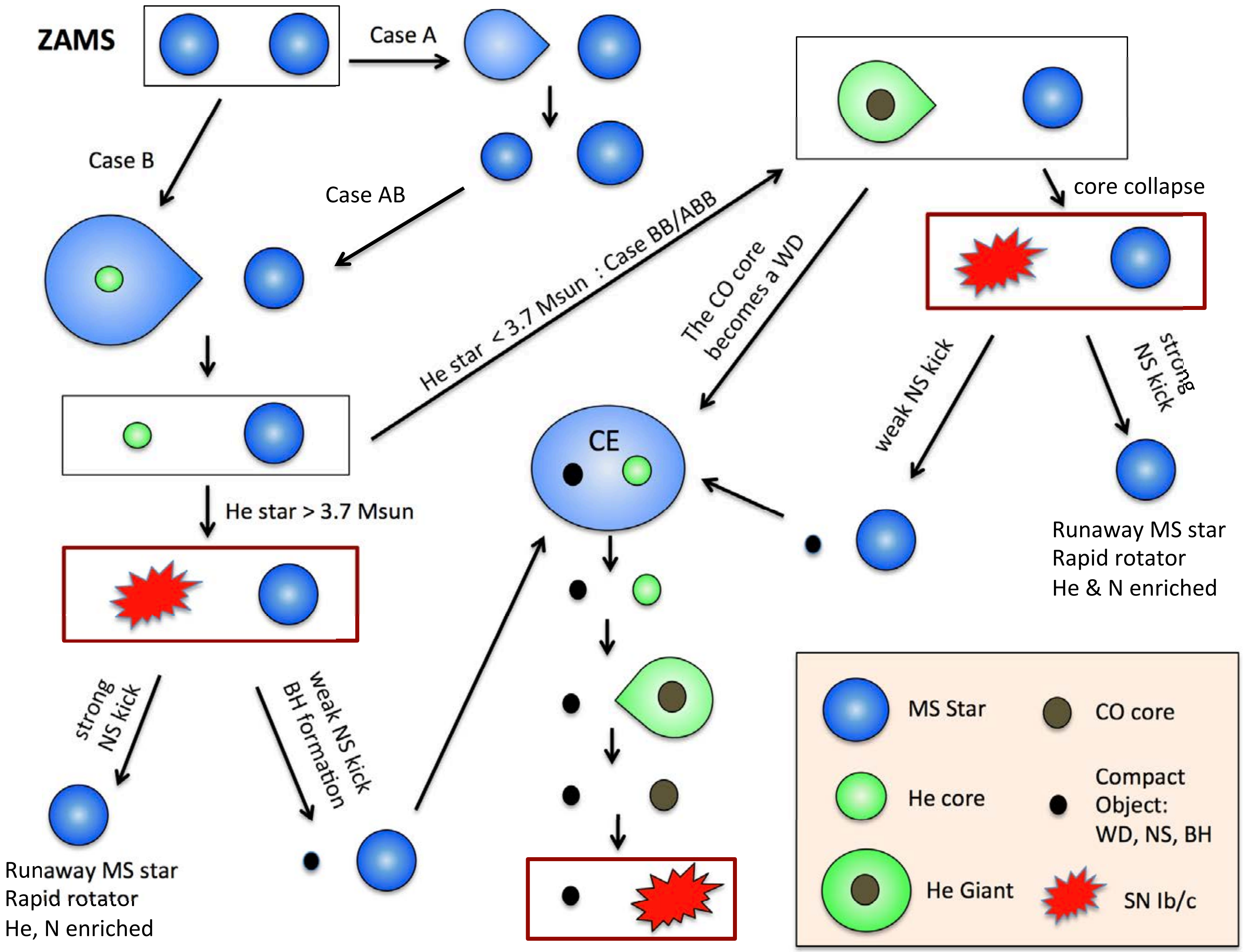
Some recent observational constraints

- **Most of ordinary SNe Ibc have an ejecta mass of about 2 – 3 Msun.** (e.g., Drout et al. 11, Dessart et al. 11, Cano13, Lyman et al. 14, Bernsten 14, Fremling 14), in favor of the binary scenario.

- Some cases seem to support WR progenitors;
  - ✓ e.g., PTF10vgv – compact progenitor like WR stars (Corsi et al. 12)

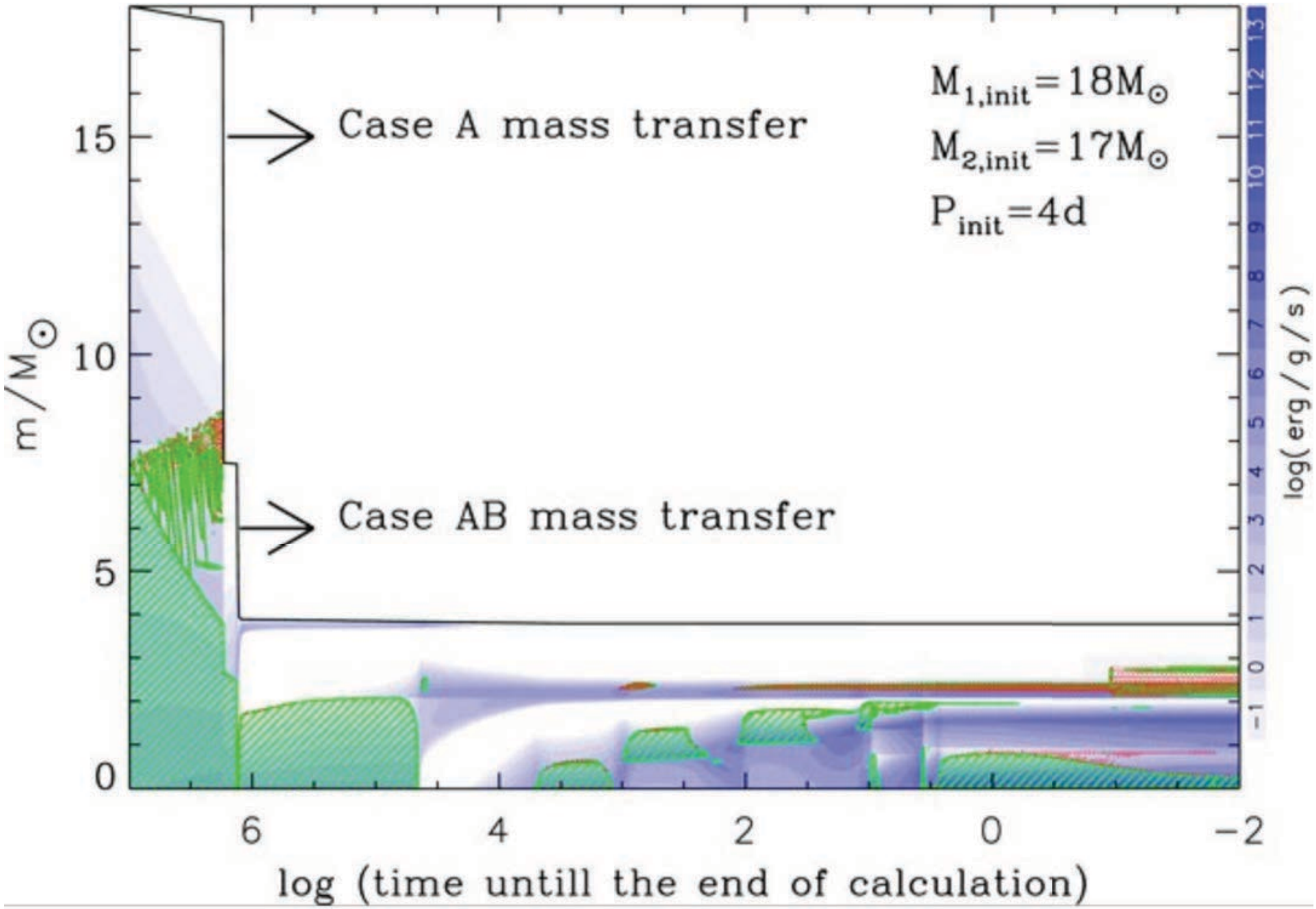
- Broad-lined SNe Ic might have a single star origin, having systematically higher ejecta masses.




ZAMS
Case A
Case B
Case AB
He star < 3.7 Msun : Case BB/ABB
The CO core becomes a WD
core collapse
weak NS kick
strong NS kick
CE
He star > 3.7 Msun
strong NS kick
weak NS kick BH formation
Runaway MS star
Rapid rotator
He & N enriched
Runaway MS star
Rapid rotator
He, N enriched
MS Star
CO core
He core
Compact Object: WD, NS, BH
He Giant
SN Ib/c

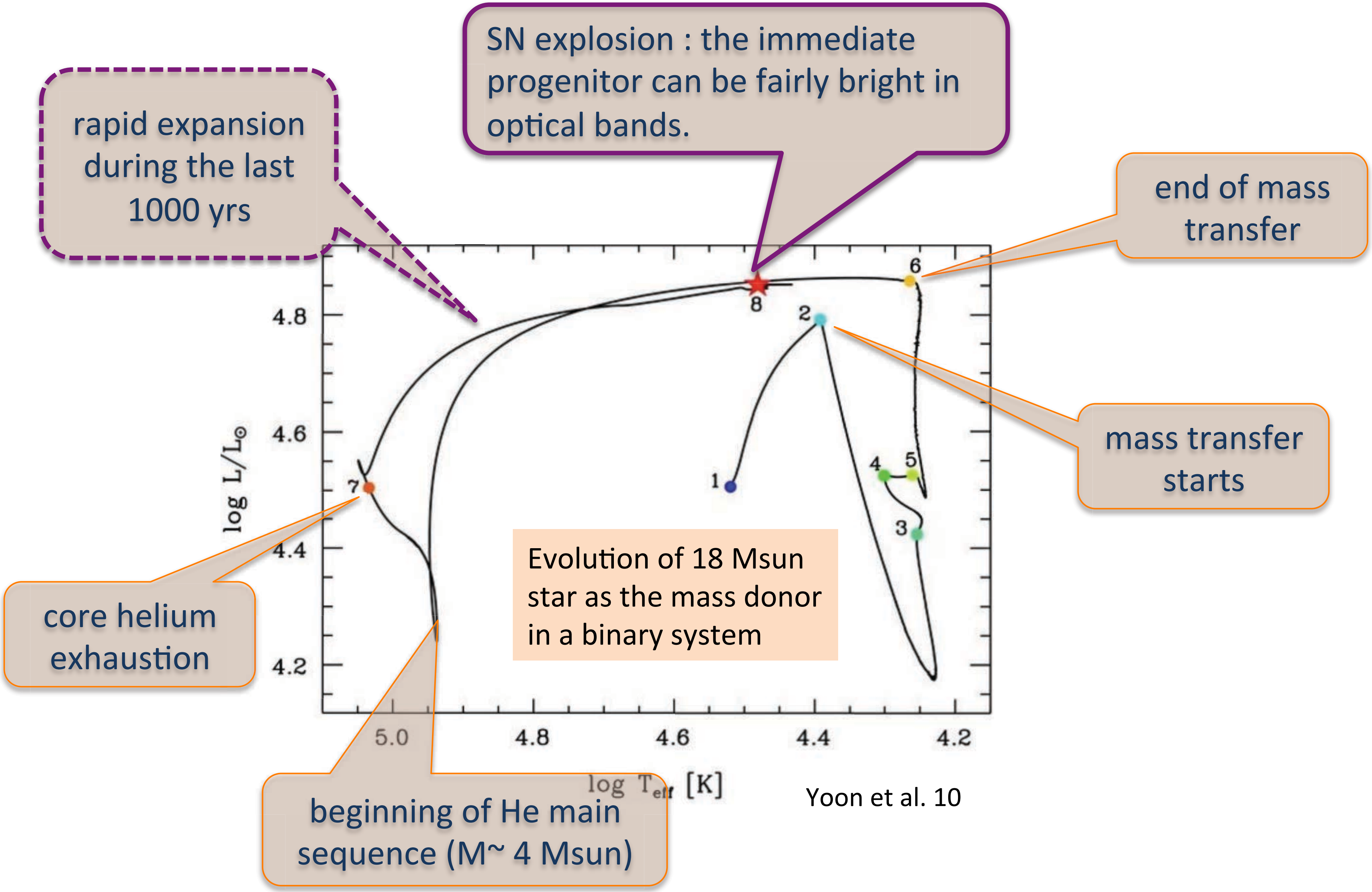
Yoon 2015

Binary stars as SN Ibc progenitors



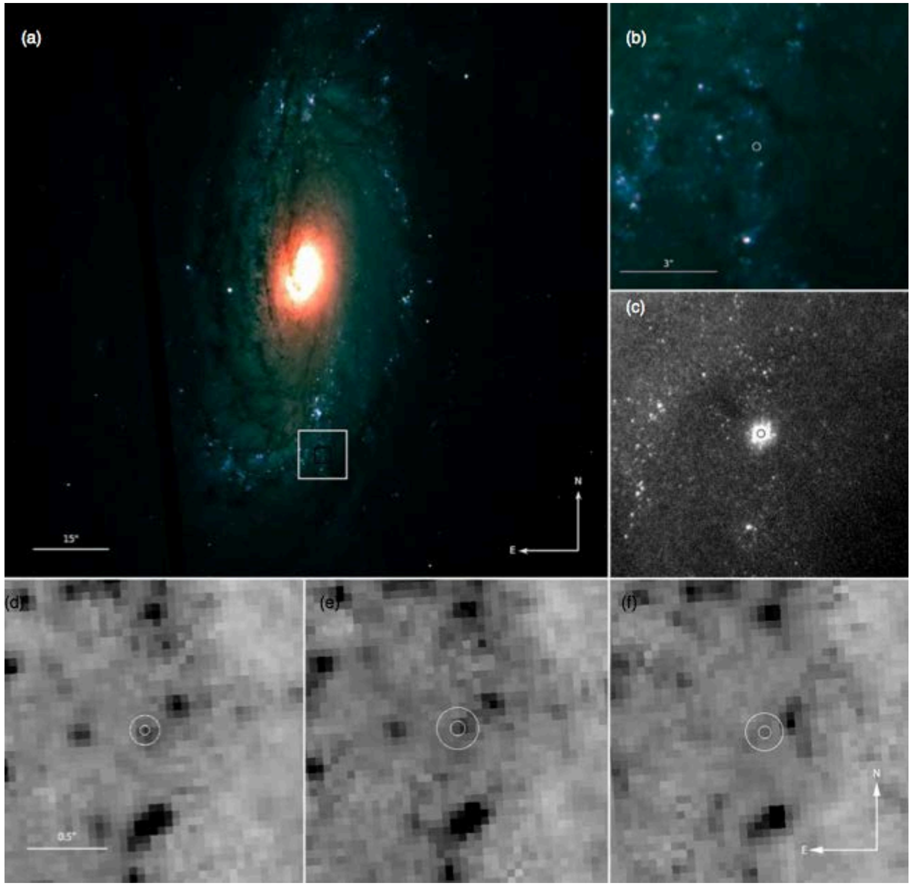
Yoon et al. 2010

Binary stars as SN Ibc progenitors



Yoon et al. 10

iPTF13bvn: *binary or single star progenitors?*



F435W F555W F814W

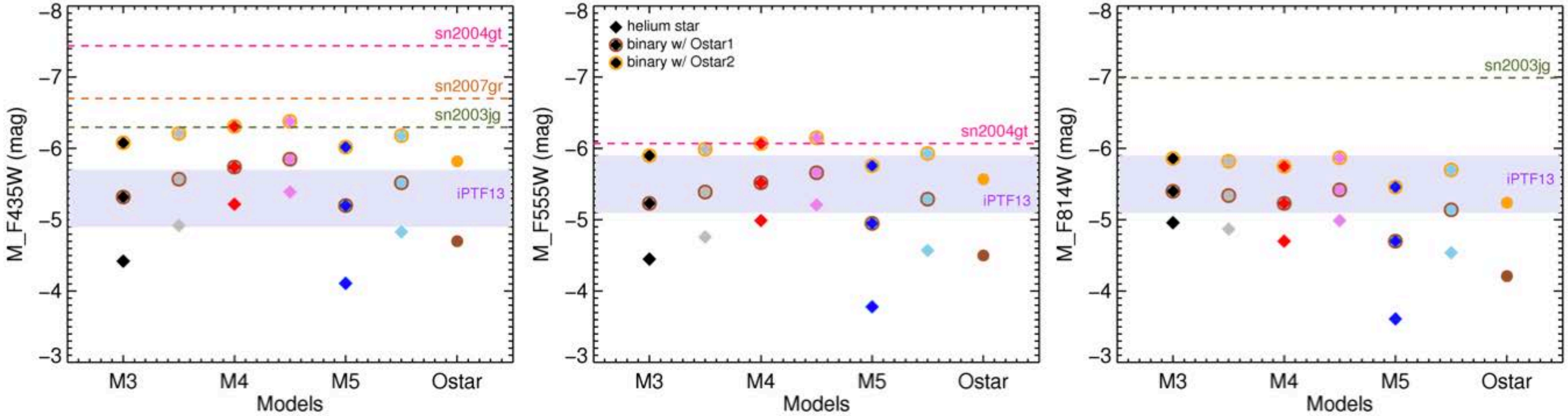
Cao et al. 13 found a progenitor candidate for SN Ib iPTF13bvn:

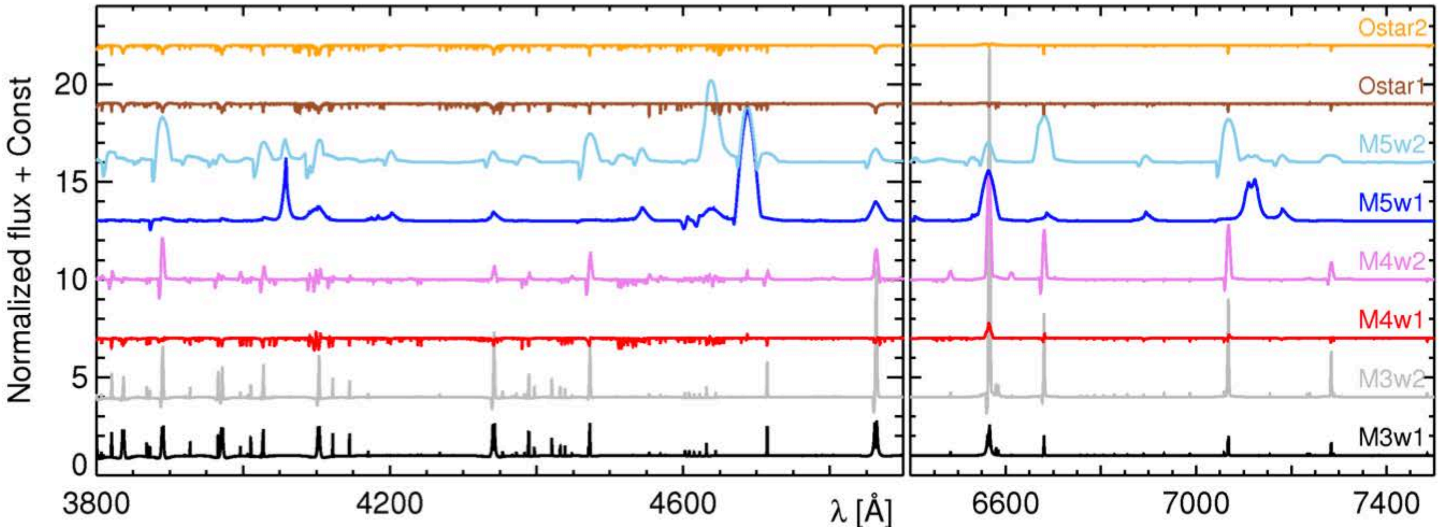
✓ M_V = -5.55 ~ - 6.5

✓ Bersten et al. (14), Fremling et al. (14), Lyman et al. (14) estimate the ejecta mass of only about 2 Msun.

iPTF13bvn: binary or single star progenitors?

The iPTF13 can be well explained by a binary system of 3~4 Msun He star + 20~30 Msun O-type star (Bernsten 2014, Eldridge et al. 2014, Lymann et al. 2014, Kim et al. 2015)





CFGEM calculation of binary SN Ibc progenitor models:

H.-J. Kim et al. 2014

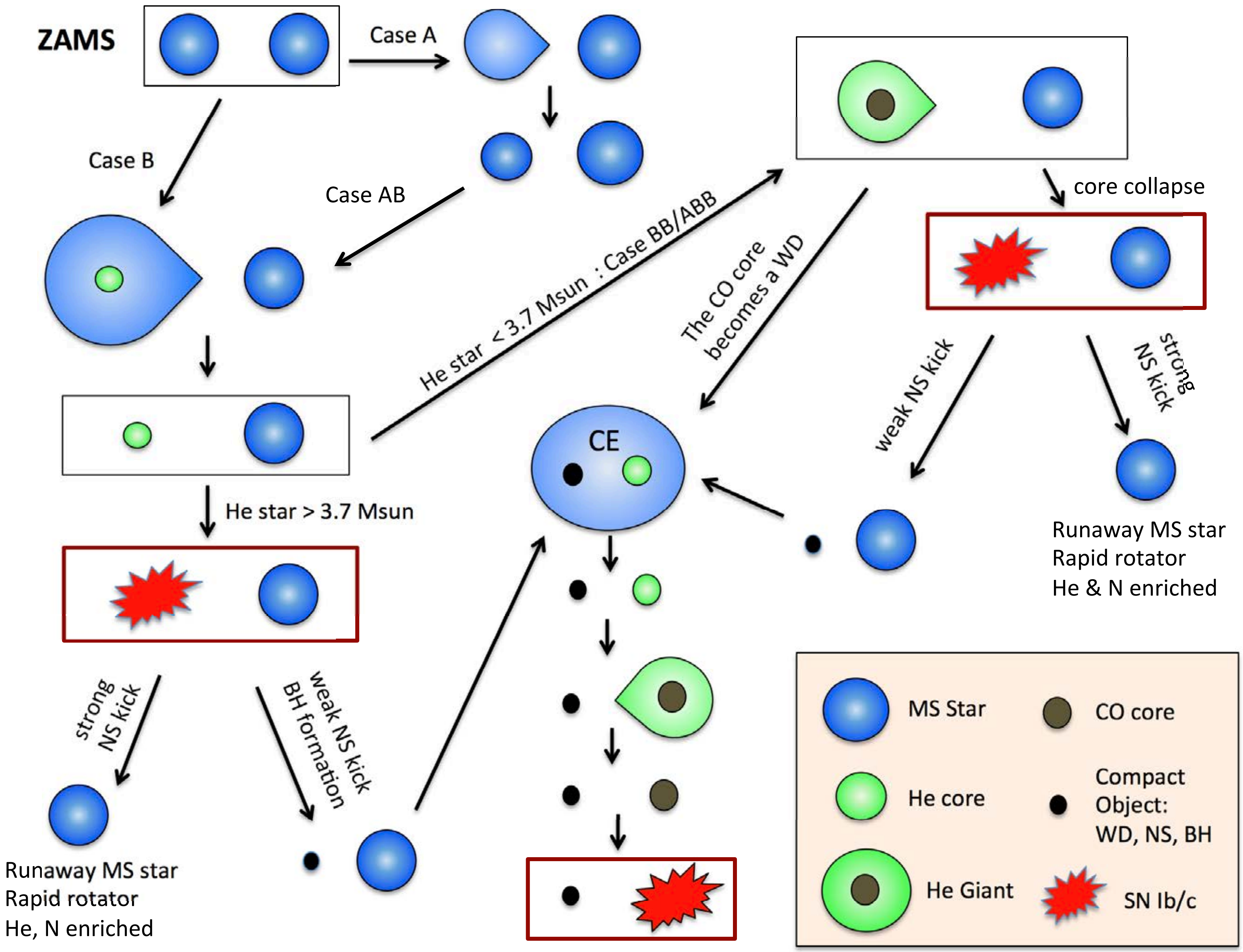
Observational counterparts of SN Ib/c progenitors in binary systems?

Helium stars of 3 Msun ~ 6 Msun.

Some possible candidates:

- **qWR stars (quasi-WR stars) – HD 45166, WR 7a : He main sequence stars (~ 4 Msun)?**
- **υ Sgr, KS Per, LSS 4300 – Evolved helium stars of about 3 Msun?**

Peculiar Supernovae from massive binary systems


ZAMS
Case A
Case B
Case AB
He star < 3.7 Msun : Case BB/ABB
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He & N enriched
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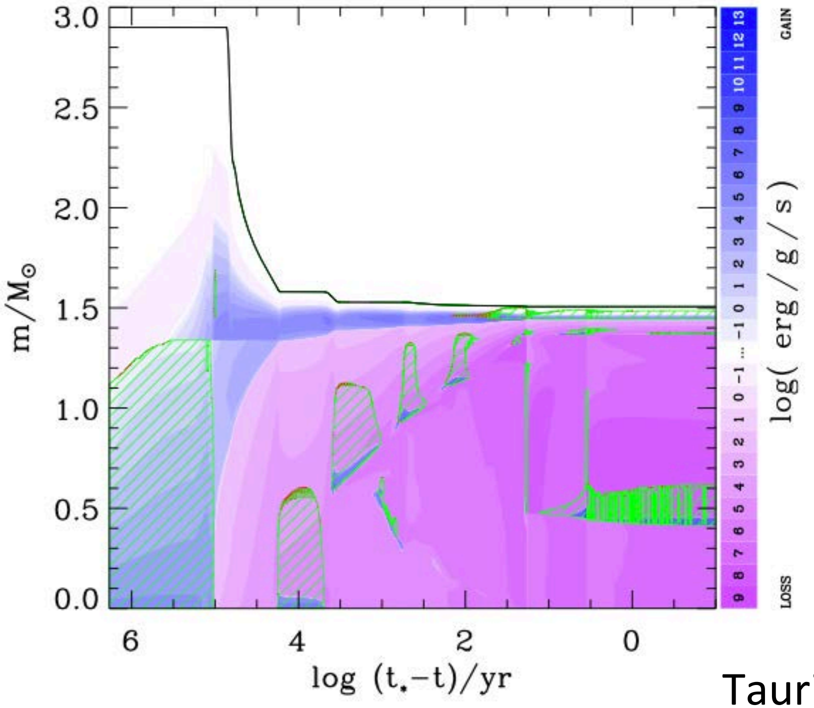
strong NS kick
weak NS kick BH formation
Runaway MS star
Rapid rotator
He, N enriched
MS Star
CO core
He core
Compact Object: WD, NS, BH
He Giant
SN Ib/c

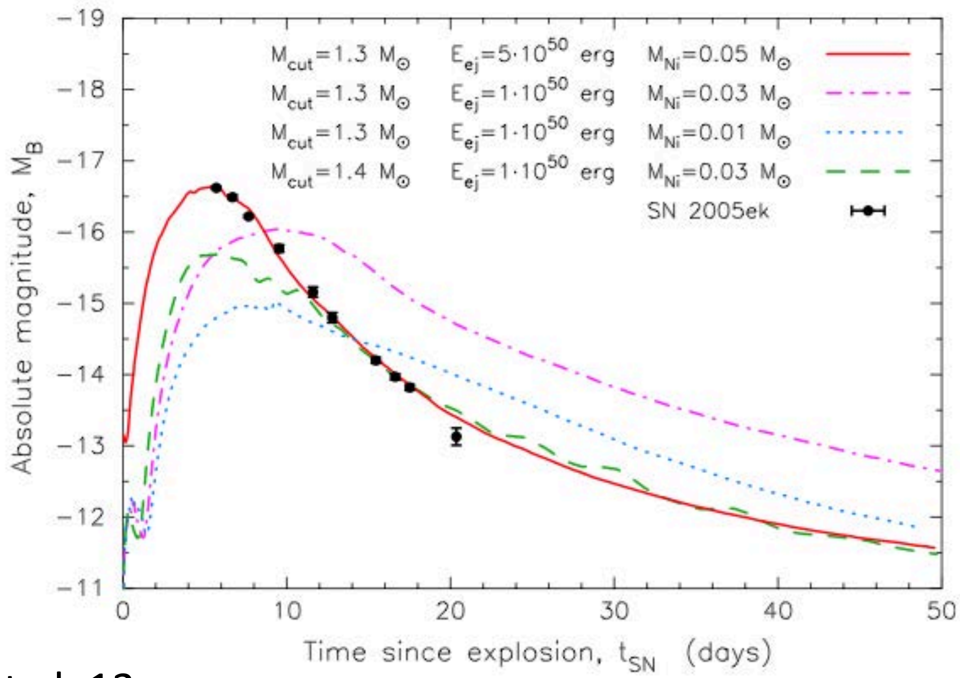
Yoon 2015

Ultra-faint Type Ic progenitors from binaries

He stars with M < ~ 3 Msun become giants after core He exhaustion:

- ✓ rapid mass transfer from He star to its companion (in particular compact object) can lead to formation of He-deficient, very compact progenitor of SN Ic with final masses of 1.5 ~ 2 Msun.





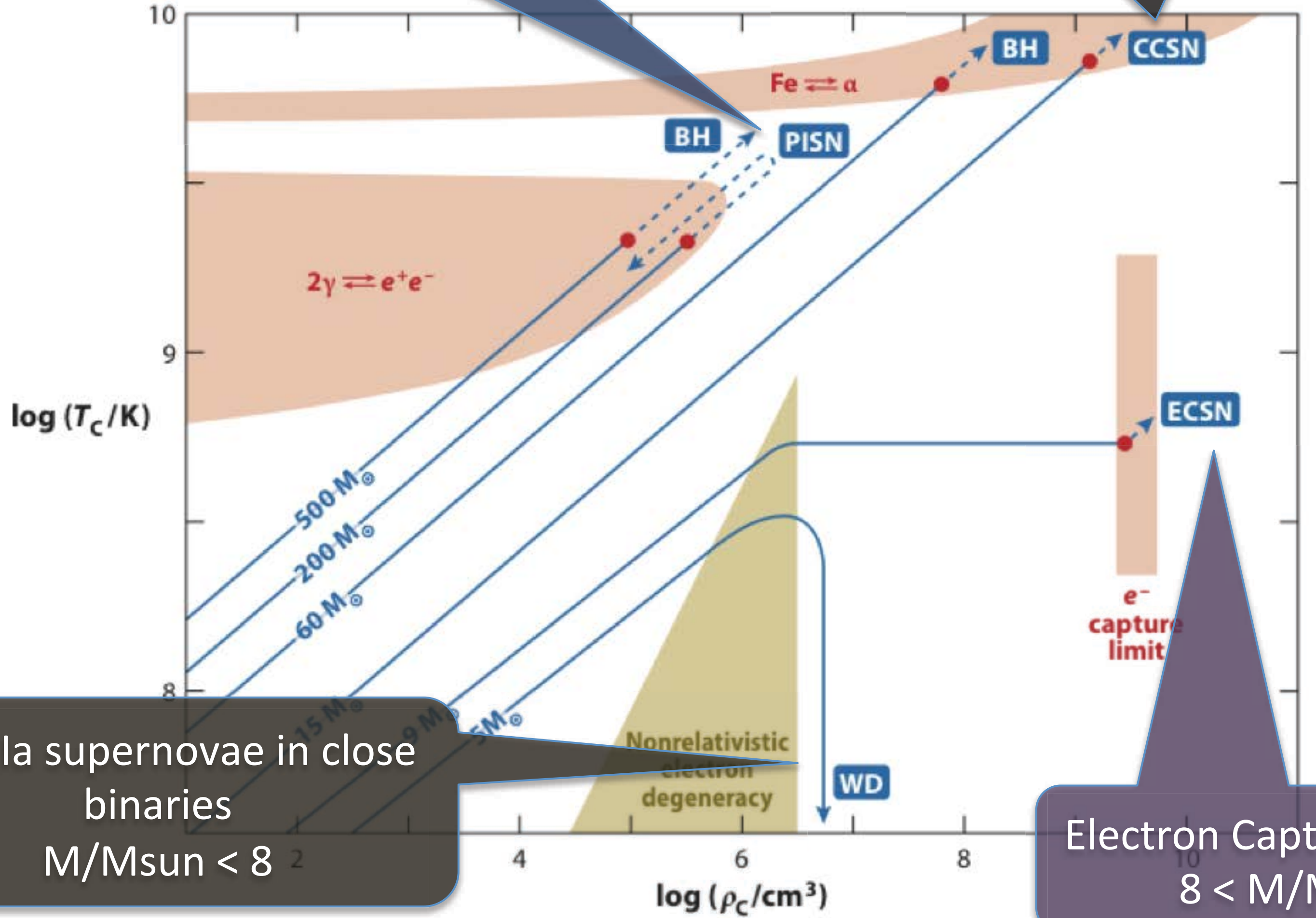
Tauris et al. 13

Pair-Instability Supernovae in the Local Universe?

Explosion mechanisms according to the initial mass

Pair Instability Supernovae
160 < M/Msun < 300 (at low Z)

Core collapse supernovae
10 < M/Msun < 25



Type Ia supernovae in close binaries
M/Msun < 8

Electron Capture Supernovae
8 < M/Msun < 10

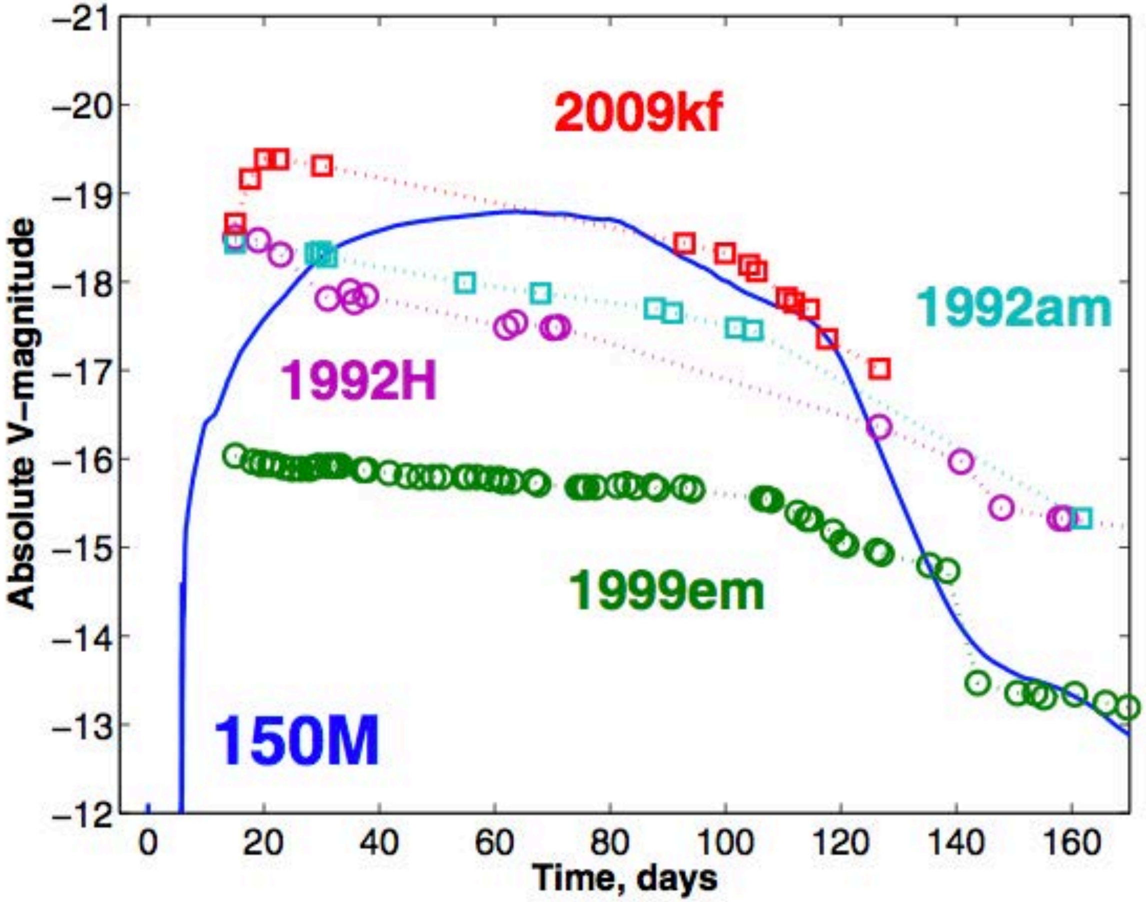
Very massive stars in the local Universe

- R136a1: 265 Msun (LMC)
- R136a2: 195 Msun (LMC)
- VFTS 682 : 150 Msun (LMC)
- R136a3 : 135 Msun (LMC)
- NCG 3603-B: 132 Msun
- Eta Carinae A: 120 Msun

.....

Some of these stars might produce pair-instability supernovae.

Pair Instability Supernova Models



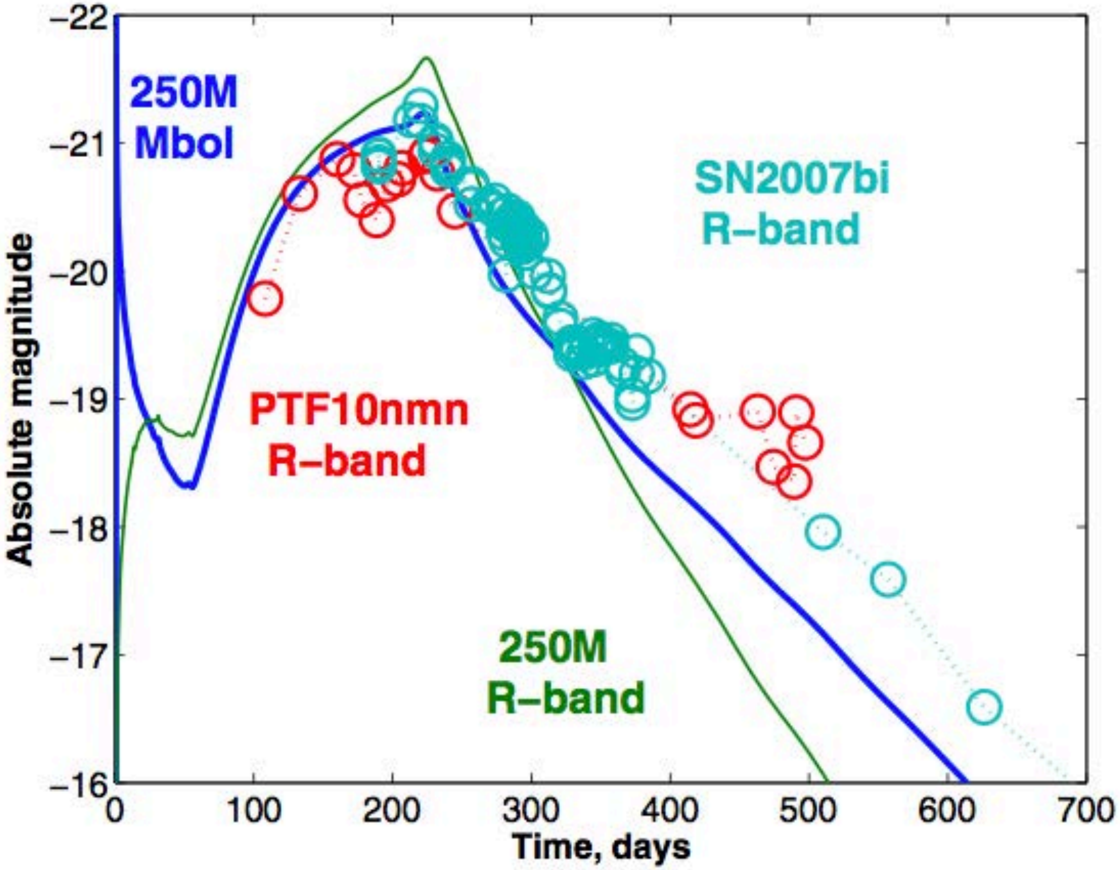
150 Msun star at Z = 0.001.

This star ends its life as a red-supergiant, and explodes by pair-instability in the oxygen core.

Many of local pair-instability supernovae would look like very luminous Type IIP supernovae.

Kozyreva et al. 2014

Pair Instability Supernova Models



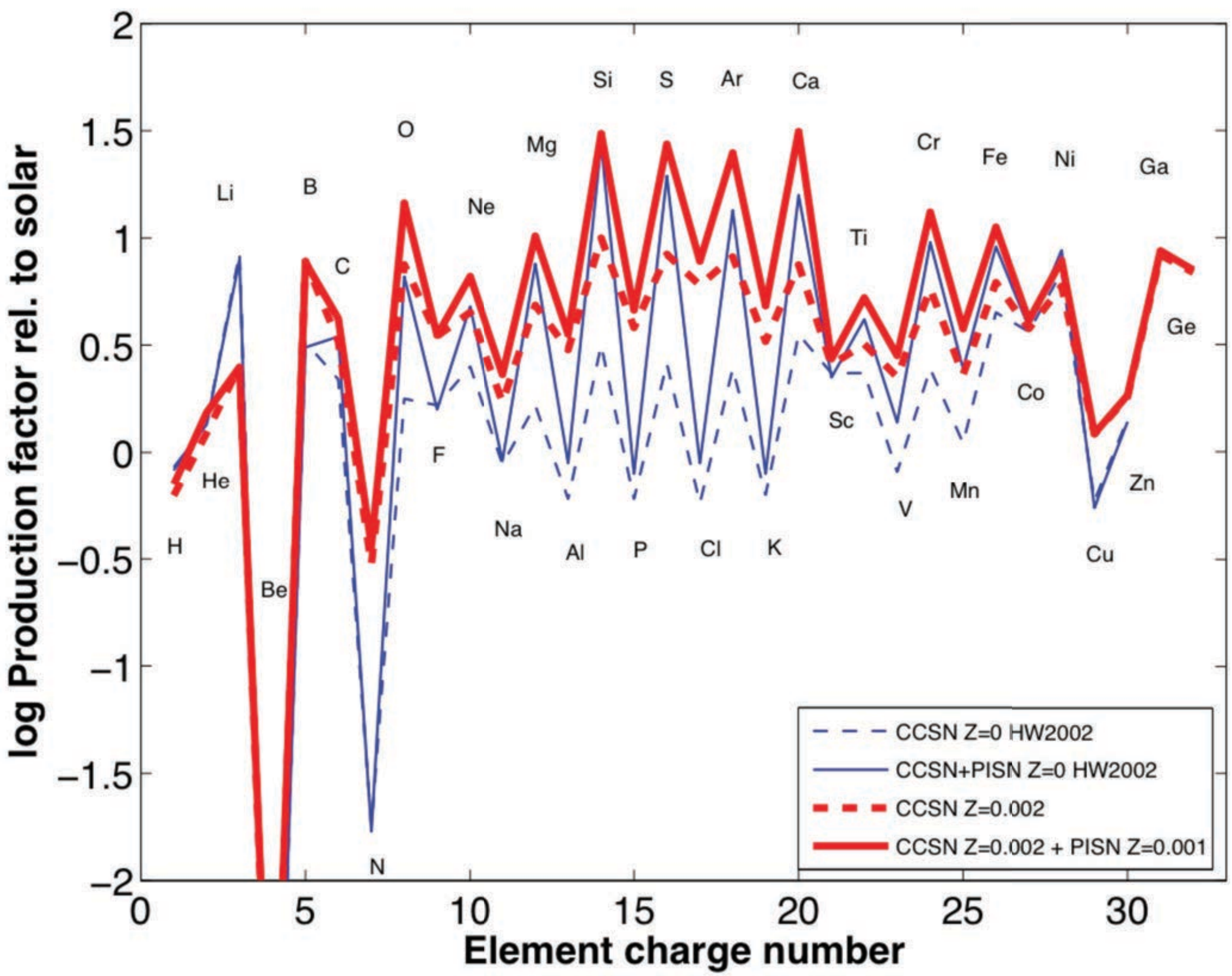
Kozyreva et al. 2014

Pair-instability supernovae from very massive stars (M > 200 Msun) would be strongly powered by radioactive nickel, which resemble the super-luminous SN2007bi.

This might explain some of the super-luminous supernovae in the local Universe.

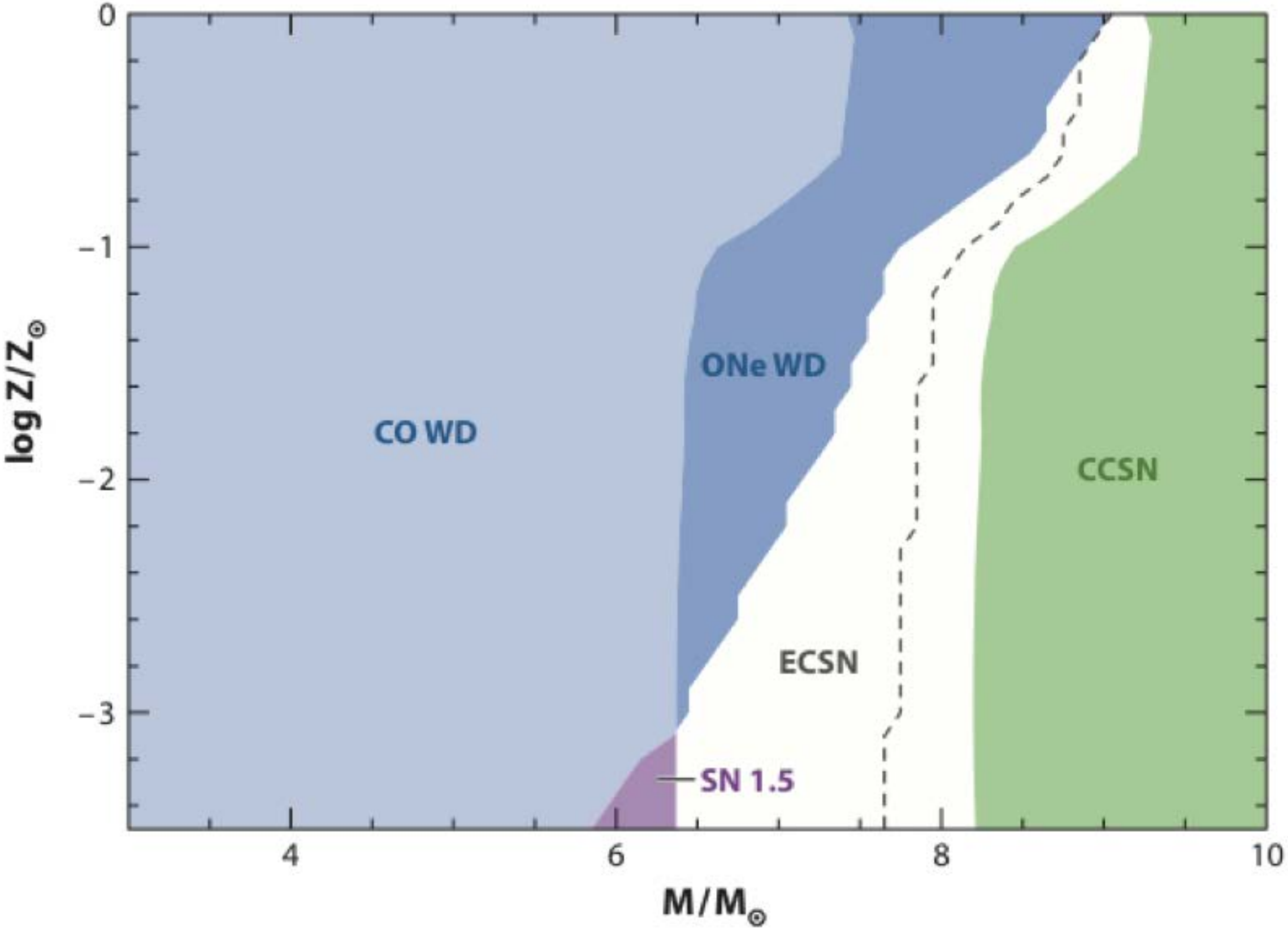
Pair Instability Supernovae and nucleosynthesis

Stong Odd-Even effect: Kozyreva et al. 2014, Heger & Woosley 2002



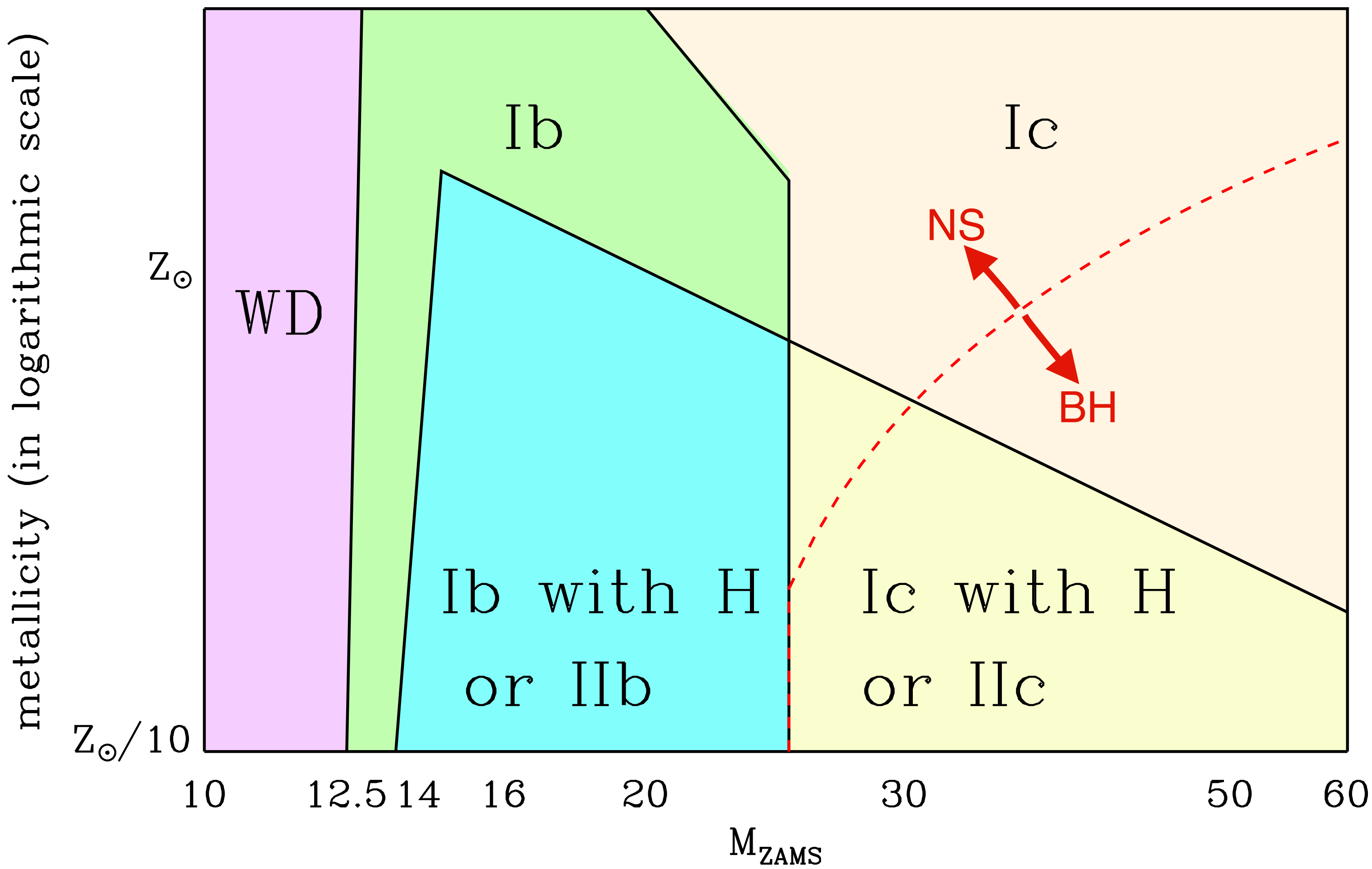
Metallicity Dependence of Massive Star Evolution and Implications for SNe from High Redshift

Dominance of electron-capture supernovae at low-metallicity, for single stars?



Langer 2012, Poelarends et al. 2008

Supernova types from binary systems as a function of metallicity



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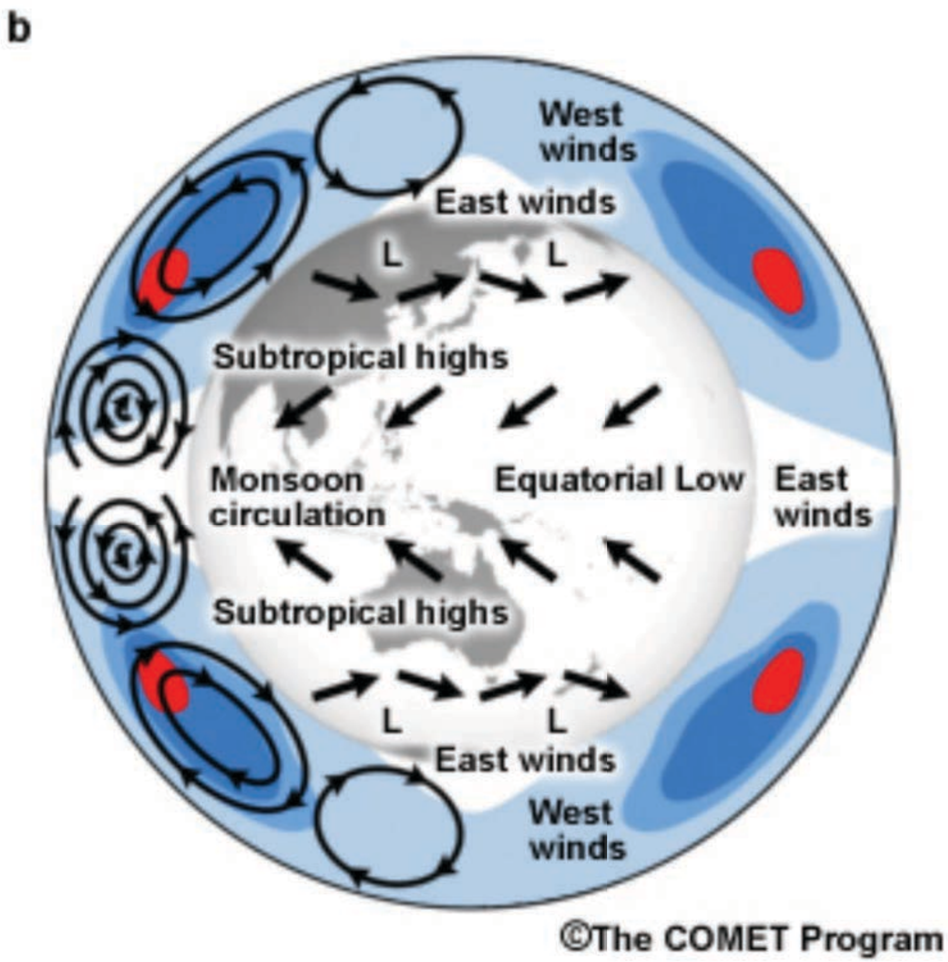
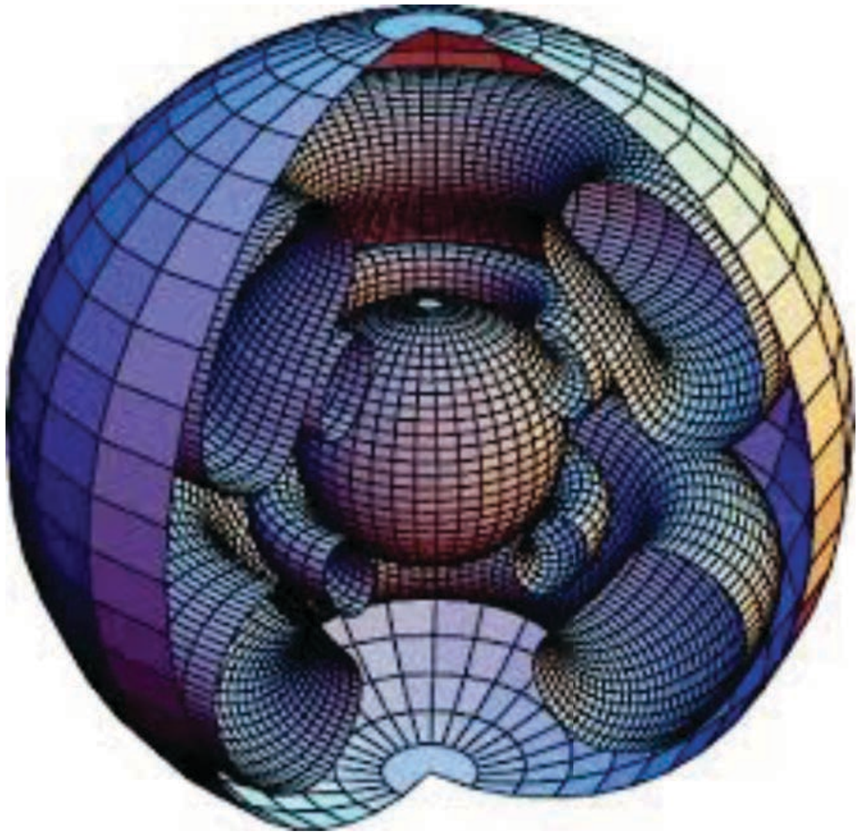
Critical Role of Rotation at low metallicity

High Metallicity	Low Metallicity
Strong winds resulting from metal lines	Weaker line-driven winds
Unstable for many times	Relatively stable? (cf. Baraffe et al. 2001)
Strong mass loss	Weak mass loss
The evolution of massive stars is dominated by "mass loss"	The evolution of massive stars is dominated by "rotation" (i.e., rotational mixing and centrifugally driven winds)

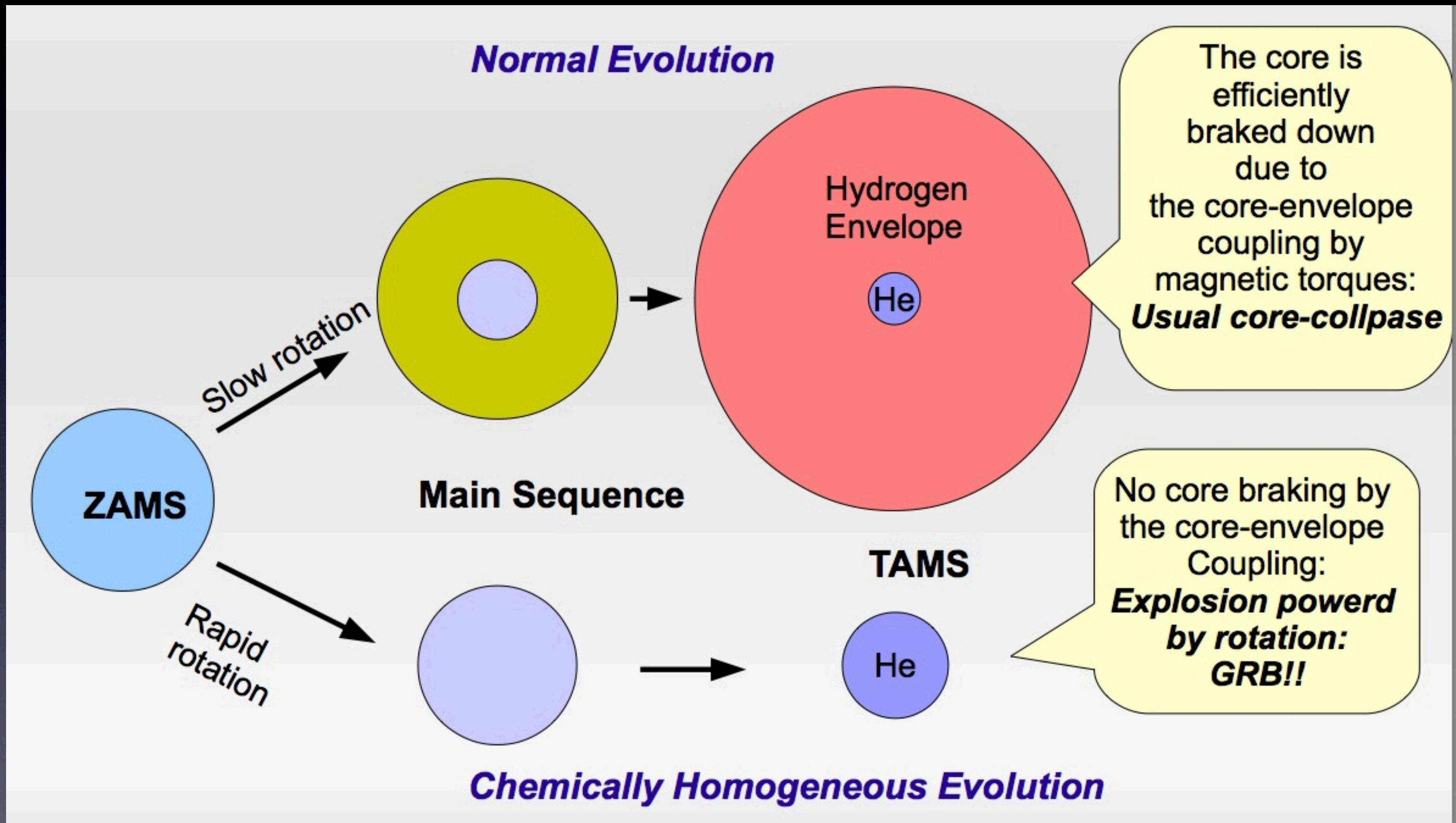
Rotationally induced chemical mixing



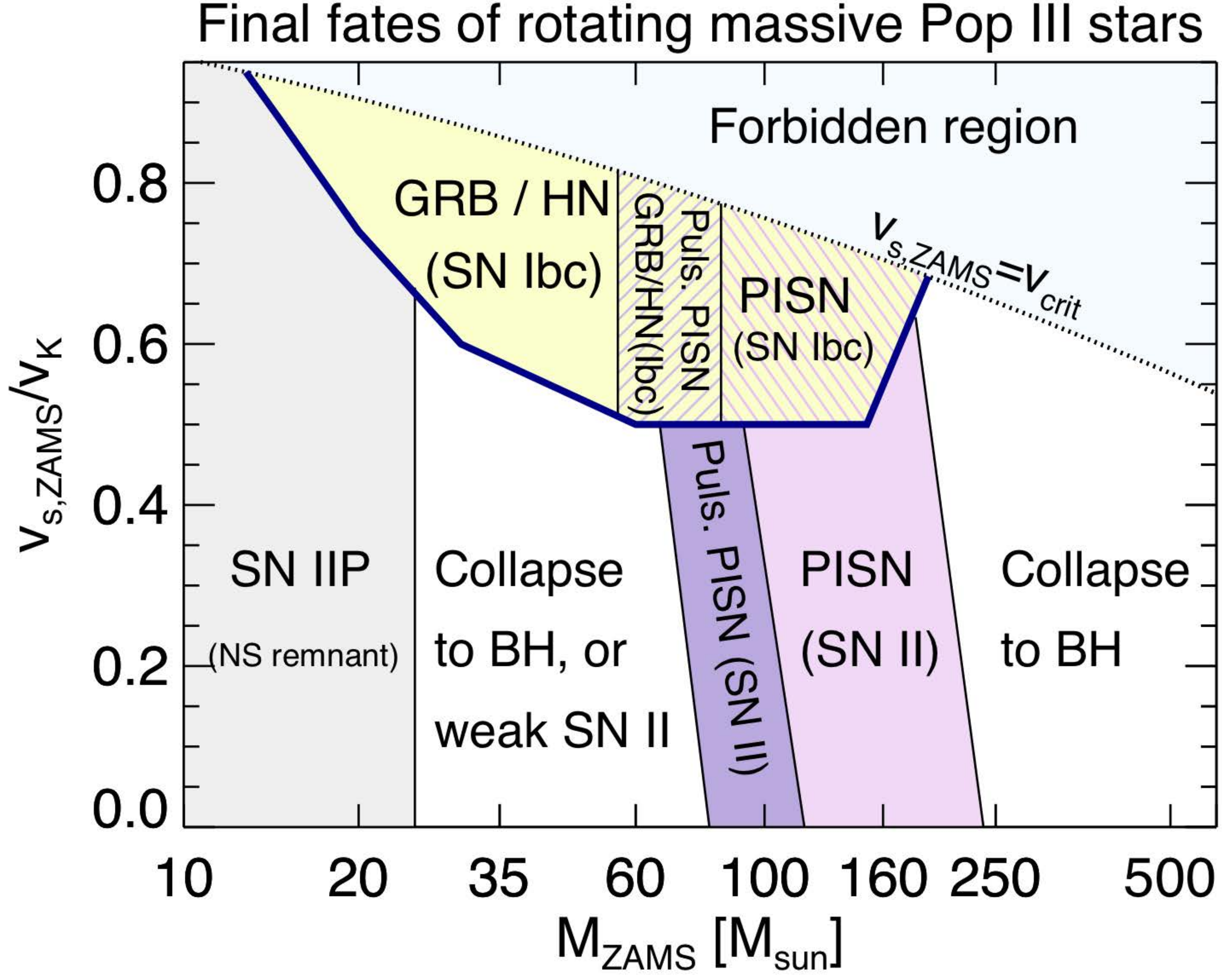


Meridional circulations on Earth **in Stars**

Bifurcation of massive star evolution at low-metallicity



Yoon & Langer 05, Yoon et al. 06, Woosley & Heger 06, Yoon et al. 12



Yoon et al. 2012

Supernova Surveys in the GMT/TMT/ELT era

- LSST (Optical) /PanSTARRS-4: 100,000 SNe per year : z up to about 1.0
- Euclid: 1.2m, NIR survey, z up to about 1.5
- WFIRST (from 2024, IR, very high-z SN)
- etc, etc, etc