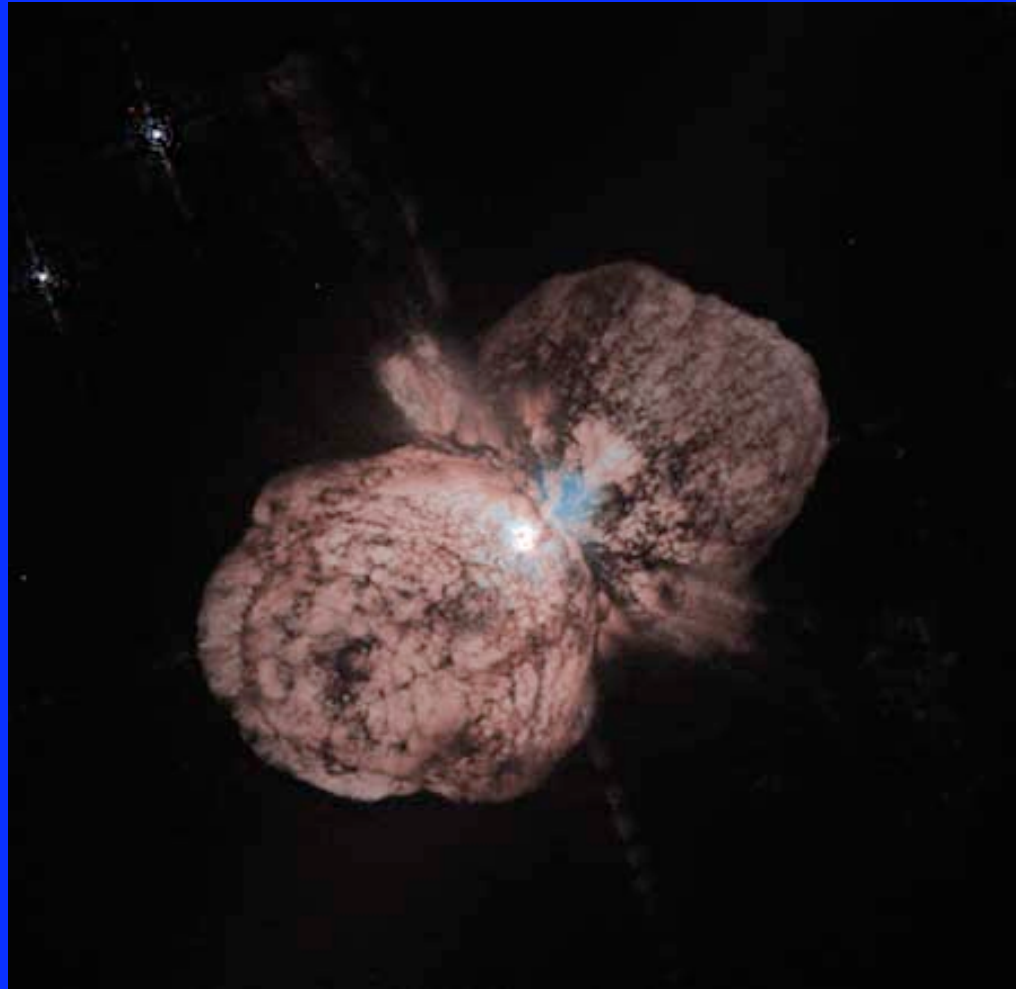


Yields as a function of Z

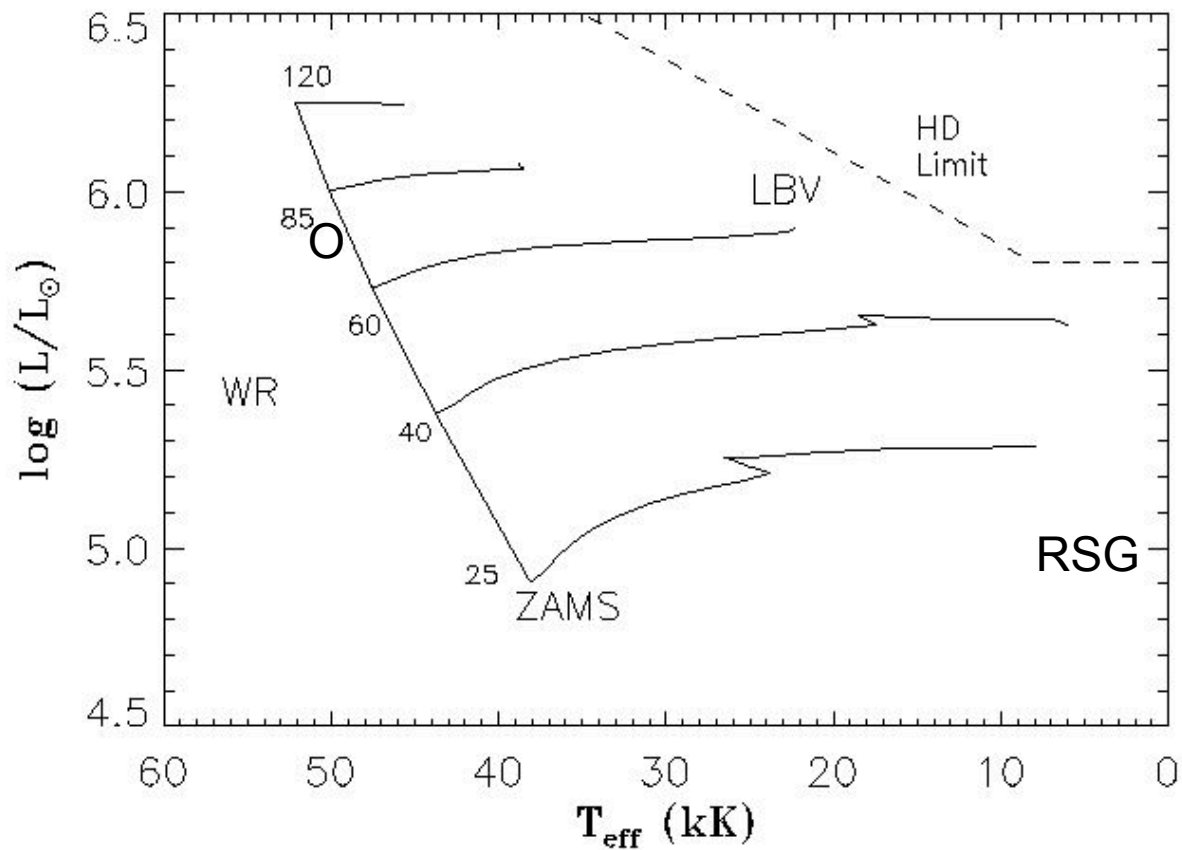


Jorick Vink (Armagh Observatory, UK)

Why massive stars?

- Rare but Bright
- Heavy metals
- Ionizing radiation
- kinetic energy input into ISM

Upper HRD- Massive Stars



Yields?

- Stellar wind mass loss
- SNe

Yields?

- Stellar wind mass loss
 - SNe
-
- Amount of weight loss
 - how do they die?

Metallicity (Z) effects

- $5 M_{\text{sun}} \rightarrow \text{AGB} \rightarrow \text{mass loss}$

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- $5 M_{\text{sun}} \rightarrow \text{AGB} \rightarrow \text{mass loss} \rightarrow Z?$
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- $60 M_{\text{sun}} \rightarrow \text{LBV} \rightarrow \text{WR} \rightarrow \text{SNe?}$

Metallicity (Z) effects

- 5 Msun \rightarrow AGB \rightarrow mass loss \rightarrow Z?
- 10 Msun \rightarrow RSG \rightarrow SNe
- 60 Msun \rightarrow LBV \rightarrow WR \rightarrow SNe?
- 60 Msun \rightarrow LBV \rightarrow SNe?
- Kotak & Vink (2006) Pastorello et al. (2007)

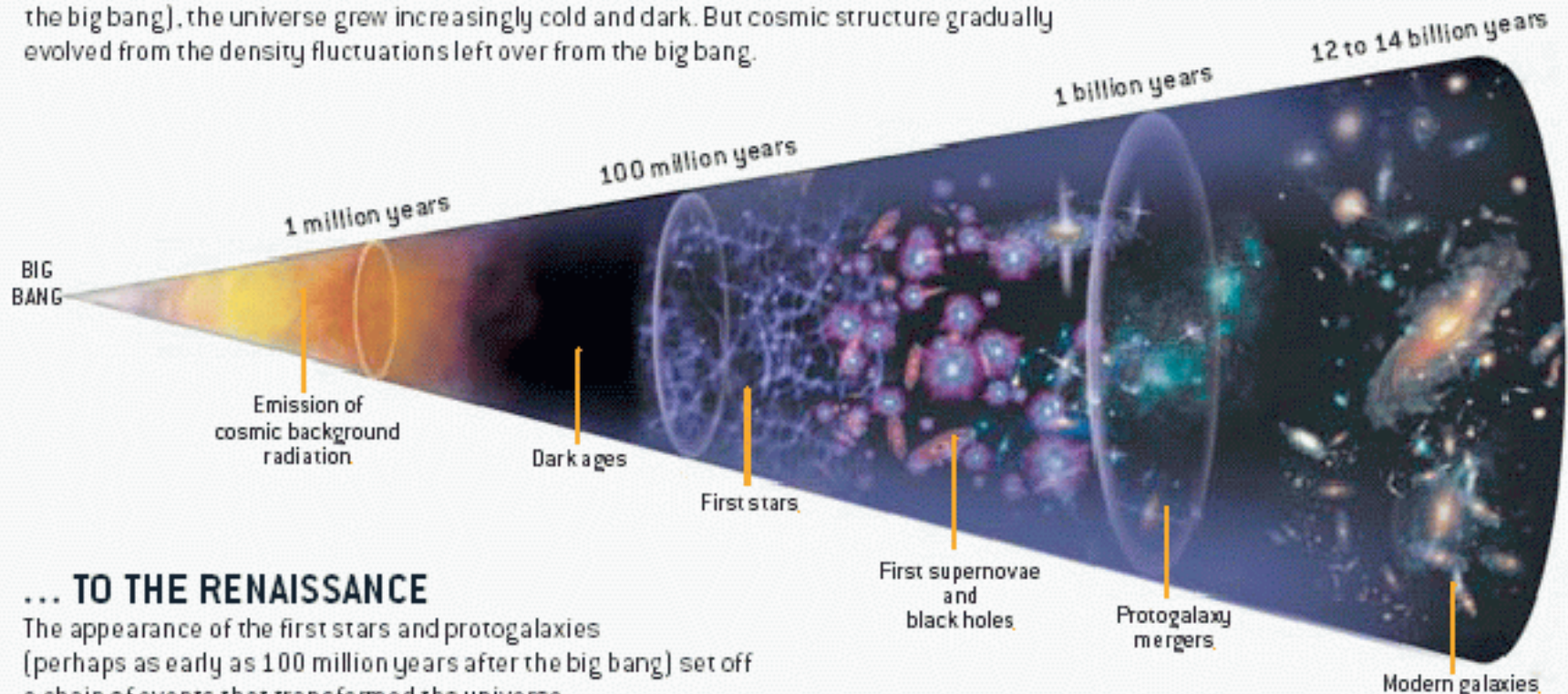
Metallicity (Z) effects

- $5 M_{\text{sun}} \rightarrow \text{AGB} \rightarrow \text{mass loss} \rightarrow Z?$
- $10 M_{\text{sun}} \rightarrow \text{RSG} \rightarrow \text{SNe}$
- $60 M_{\text{sun}} \rightarrow \text{LBV} \rightarrow \text{WR} \rightarrow \text{SNe?}$
- WILL be Z -dependent !

COSMIC TIMELINE

FROM THE DARK AGES ...

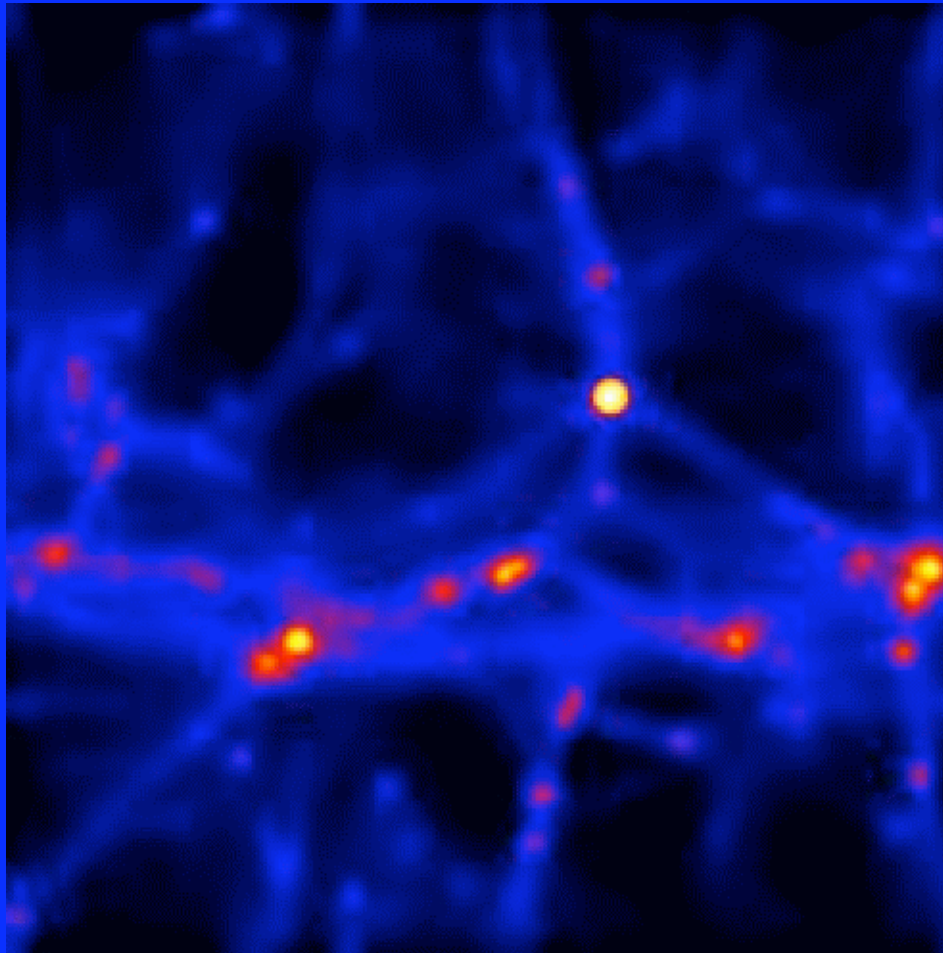
After the emission of the cosmic microwave background radiation (about 400,000 years after the big bang), the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left over from the big bang.



... TO THE RENAISSANCE

The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.

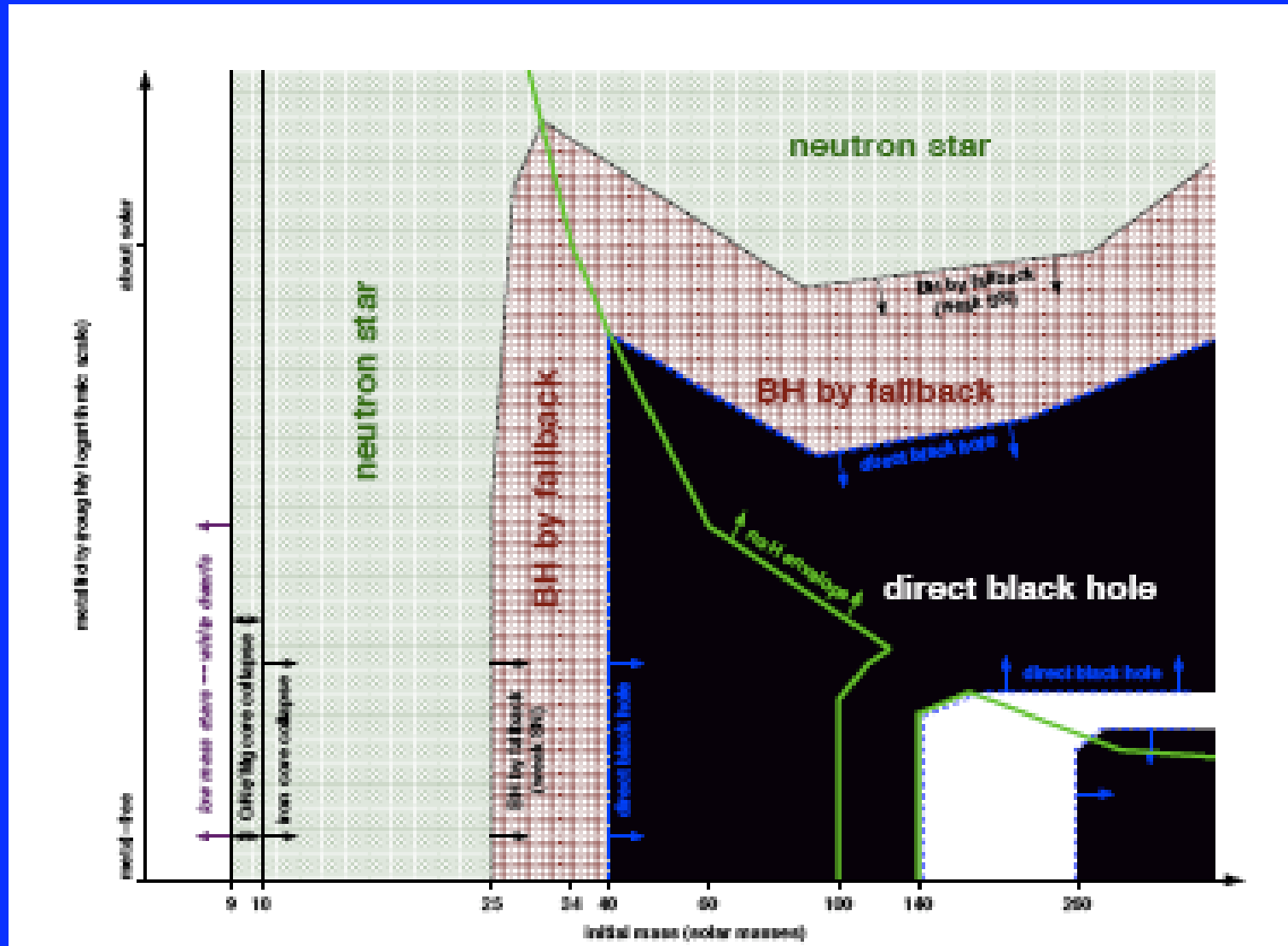
The First Stars at $Z = 0$



Credit: Volker Bromm

IMF Top Heavy?

How do massive stars die?



Heger et al. (2002)

140 - 260: PISNs!

Mass Loss and rotation

- Geneva models: rotational mixing: CNO enhanced \rightarrow more mass loss

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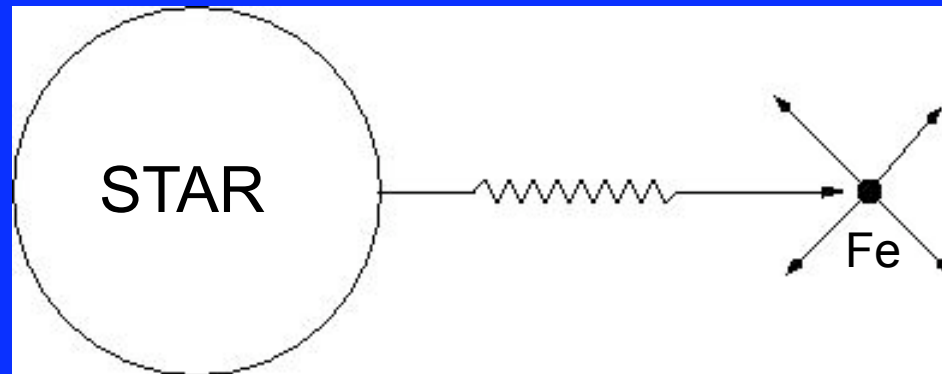
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- asymmetric mass loss!?

Mass Loss and rotation

- Geneva models: rotational mixing: CNO enhanced \rightarrow more mass loss
- GRBs - rotation to get a jet (1)
- mass loss removes H (2)
- asymmetric mass loss!?
- low Z !?

Radiation-driven wind by Lines

Lucy & Solomon (1970)



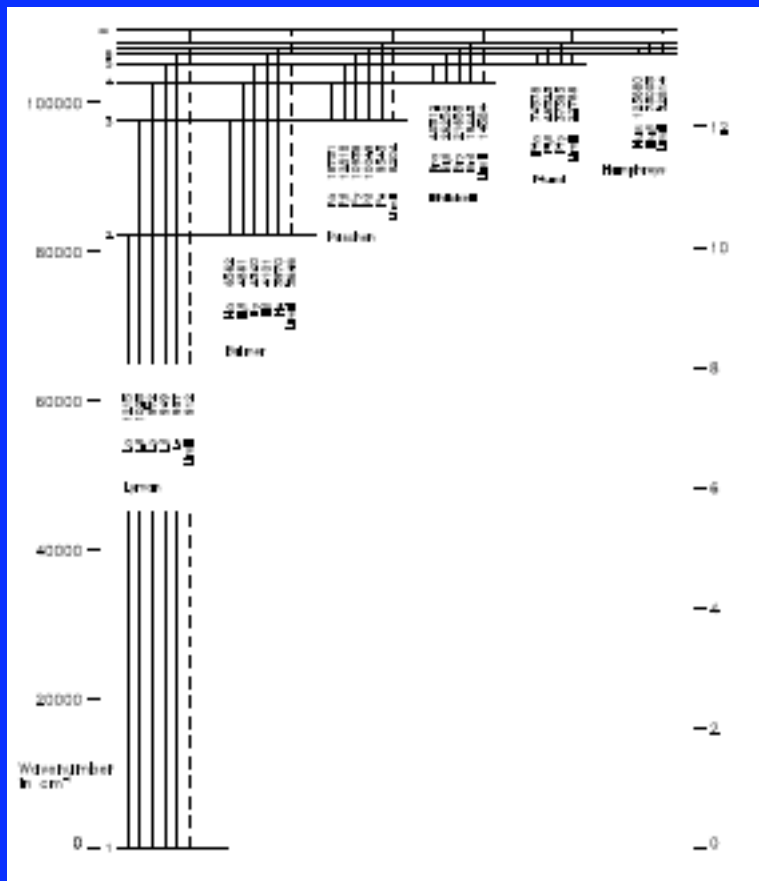
Outward Force \rightarrow Mass Loss

with $Z = (\text{C, N, O, Si, etc., Fe})$

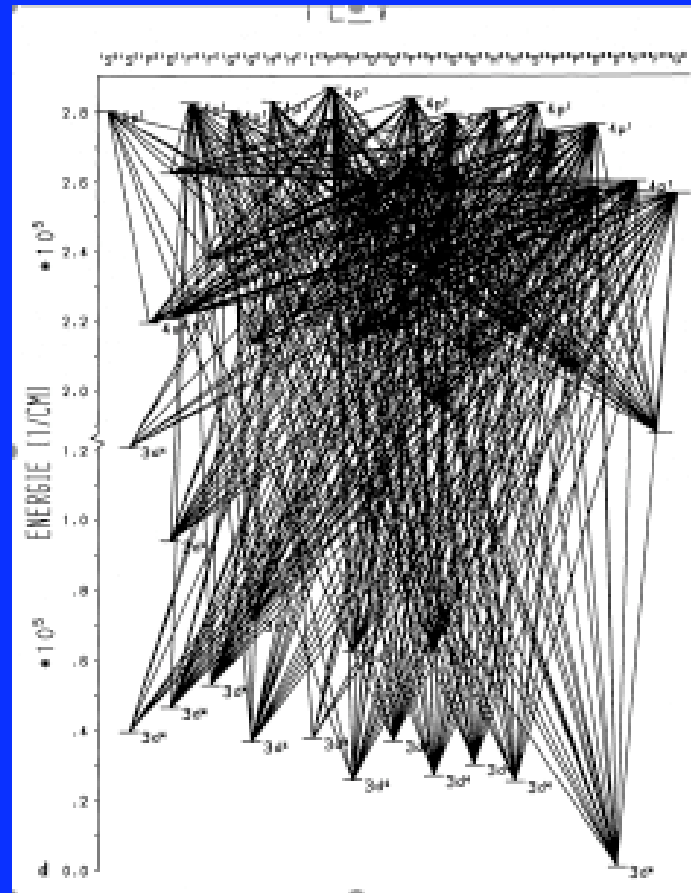
Which elements drive the wind?

abundance \times number of lines

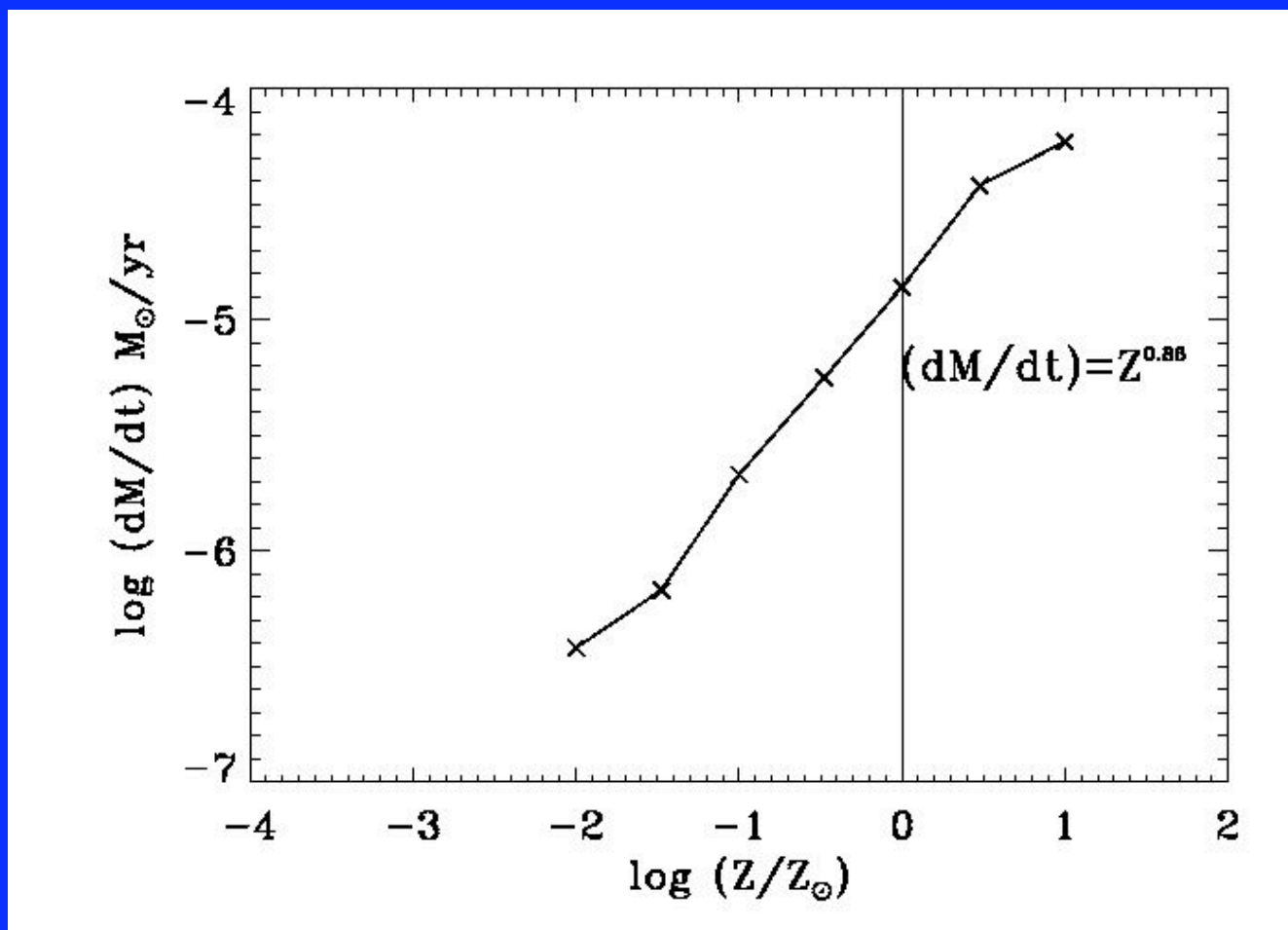
H atom



Fe V atom



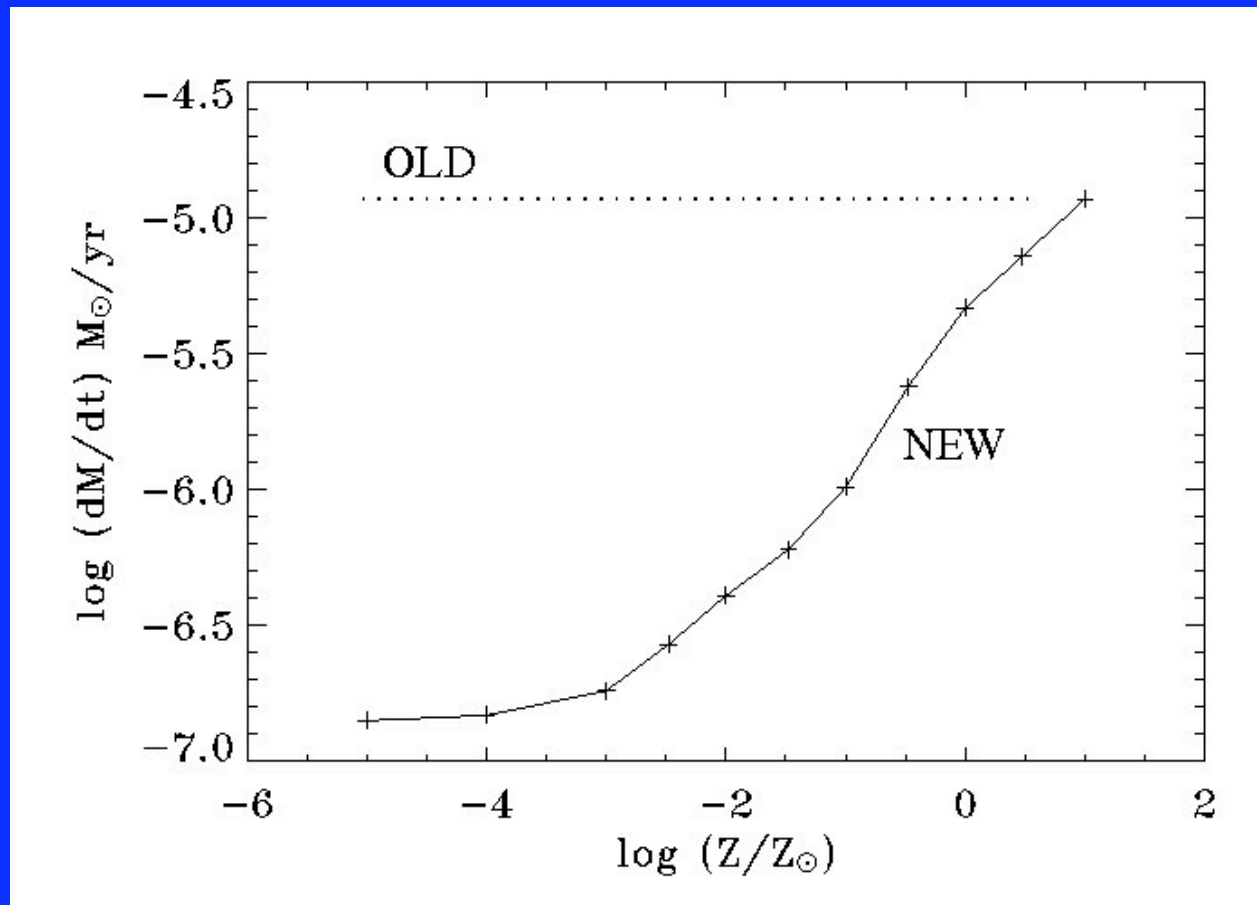
Mass-loss Z-dependence



Predictions: Vink et al. (2001)

Empirical: Mokiem et al. (2007)

Z-dependence of WR winds



Predictions: Vink & de Koter (2005)

Empirical: Crowther (2006)

Solution to GRB problem?

WR mass loss lower at low Z

→ less angular momentum loss

→ Long GRBs favoured at low Z

(Yoon & Langer 2005; Heger & Woosley 2006)

Polarimetry – asymmetry

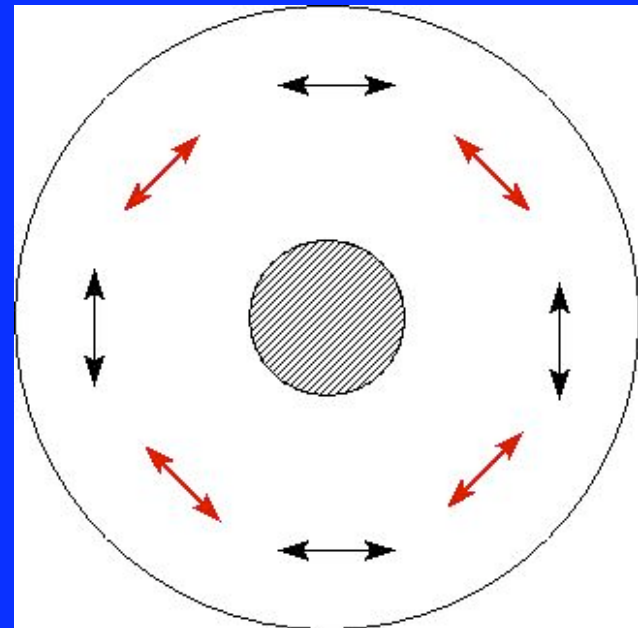
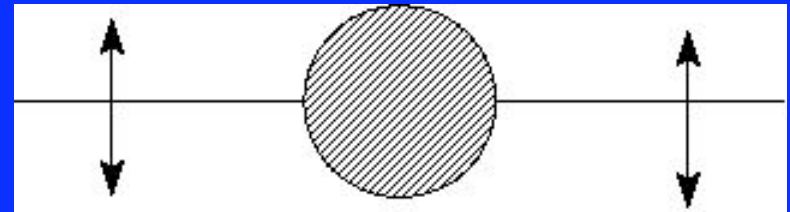
$$I$$

$$U = \begin{array}{c} \updownarrow \end{array} - \begin{array}{c} \longleftrightarrow \end{array}$$

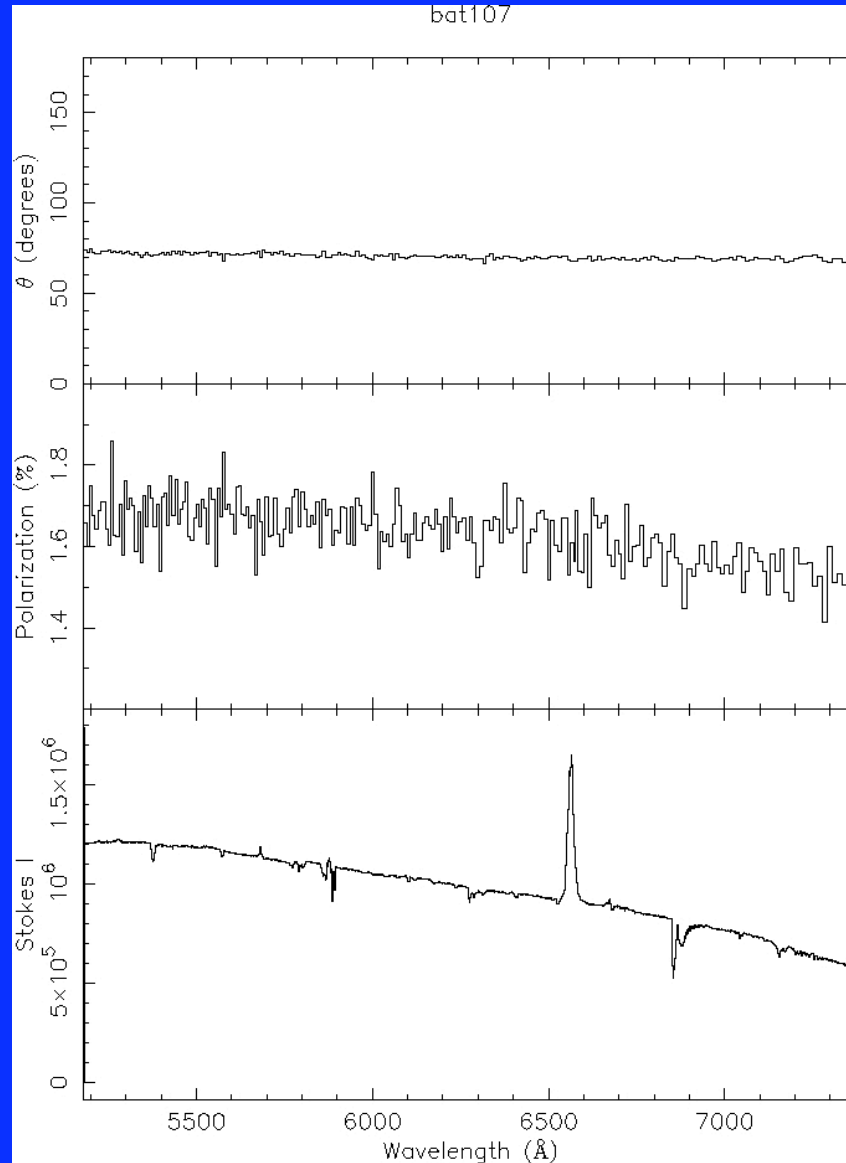
$$Q = \begin{array}{c} \nearrow \searrow \end{array} - \begin{array}{c} \nearrow \searrow \end{array}$$

$$P = \sqrt{U^2 + Q^2}$$

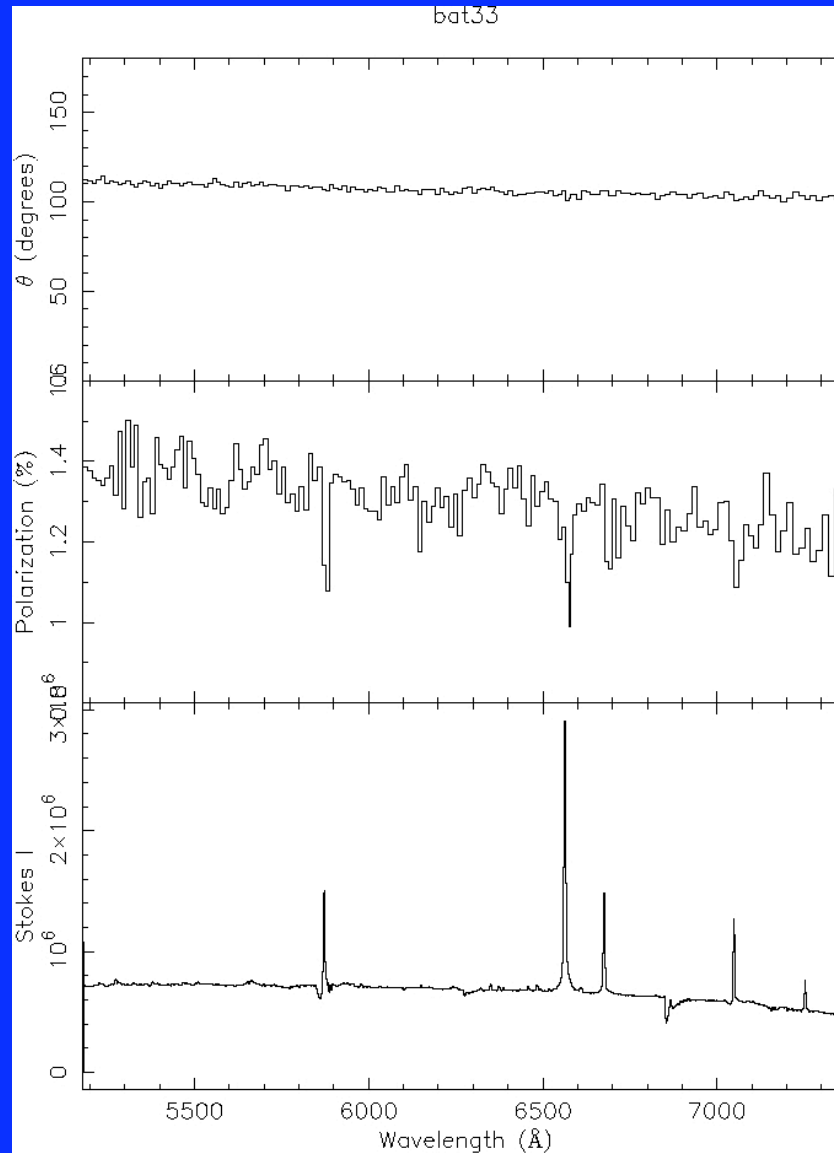
$$\theta = \frac{1}{2} \arctan\left(\frac{U}{Q}\right)$$



LMC WR spectropolarimetry



LMC WR spectropolarimetry



Statistics

- Be stars in galaxy: 60% line effects
- WR stars in galaxy 15-20%
Harries et al. (1998)
- WR stars in LMC: 2/13 i.e. 15%
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- GRB upper threshold Z of 40-50% solar

E-ELT

- WR spectropolarimetry at low Z SMC metallicity
- Interplay between rotation and mass loss
- Which and how many massive stars make SNe, HNe, GRBs, PISNs, etc.