THE EVOLUTION OF RED SUPERGIANTS TO SUPERNOVA

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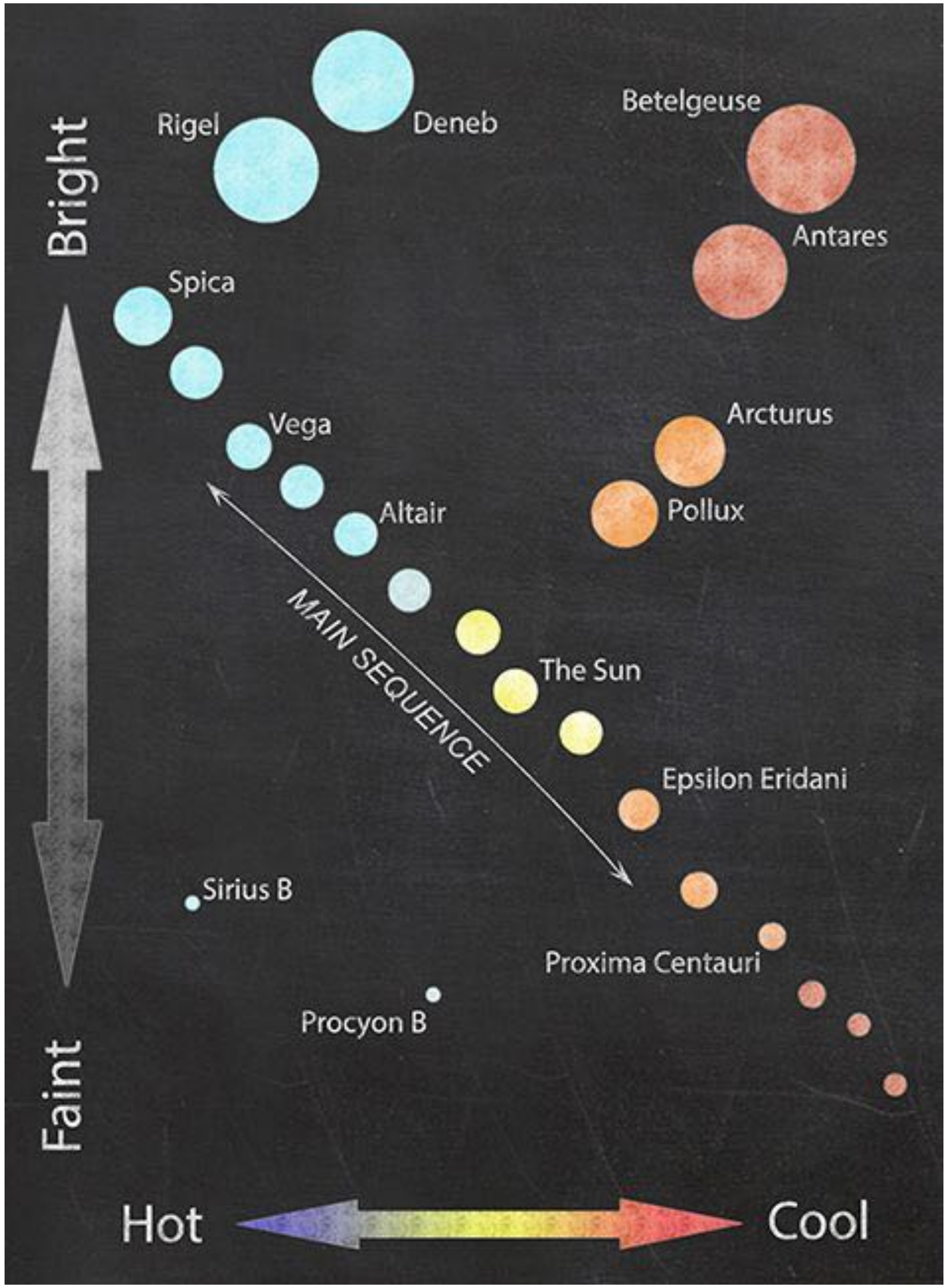
SOFIA Tele-talk, July 15th 2020

Outline

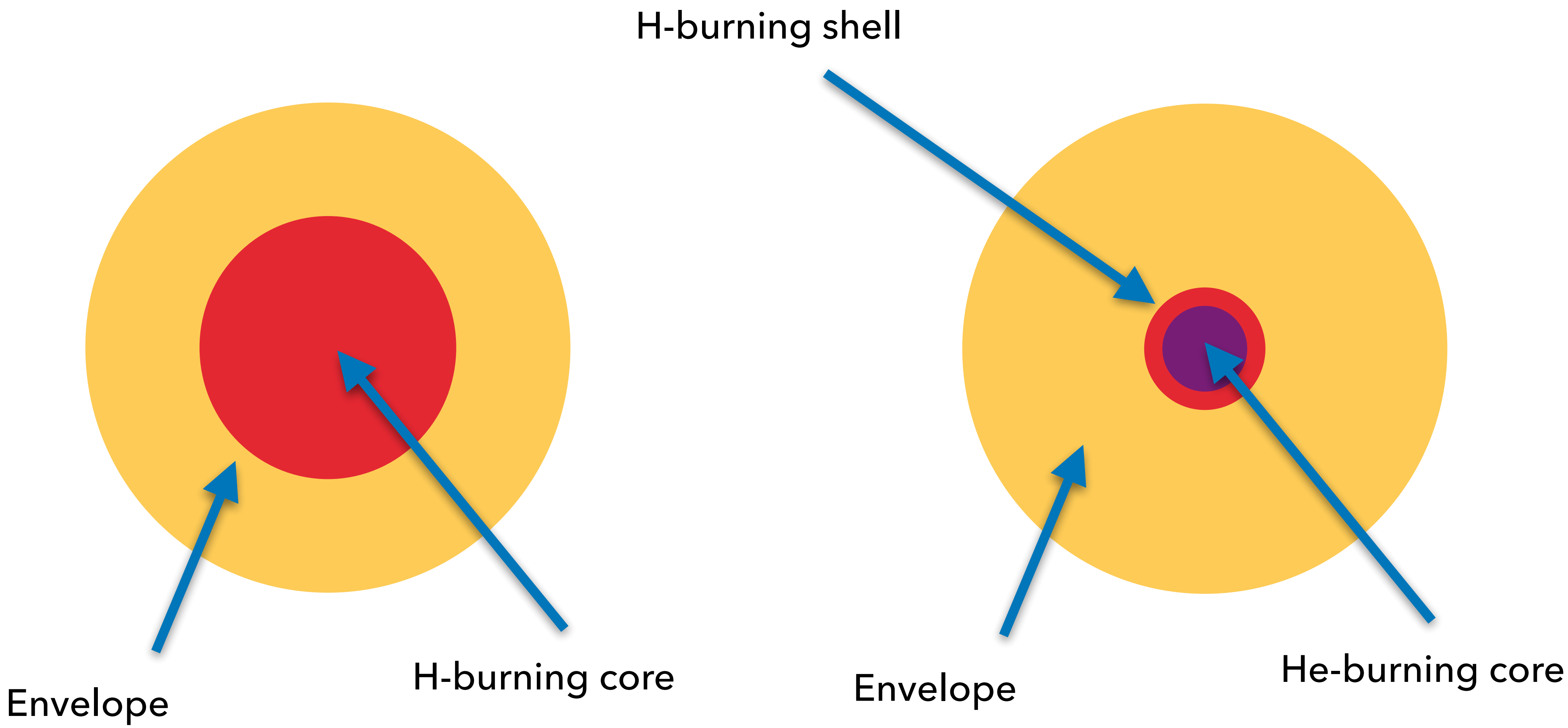
- Introduction to RSGs
- Evolution of RSGs to SN
- Mass-loss
- Age determinations
- Summary

RED SUPERGIANTS

- Evolved massive stars (8-25 $M_{\odot}$)
- Direct progenitors to Type II SN - ***powerful test of stellar evolutionary theory***

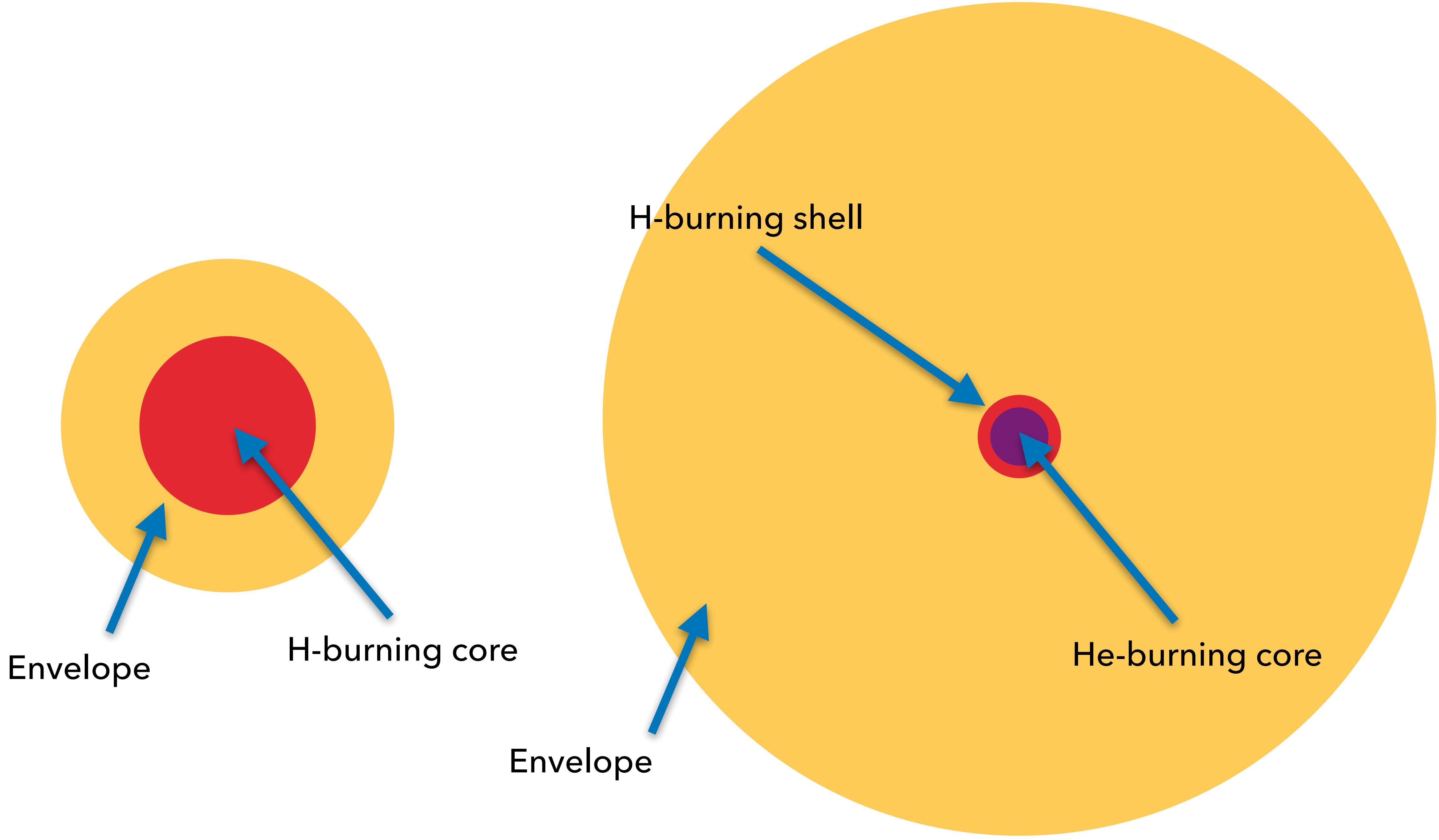


EVOLUTION OF A 15M$_\odot$ STAR



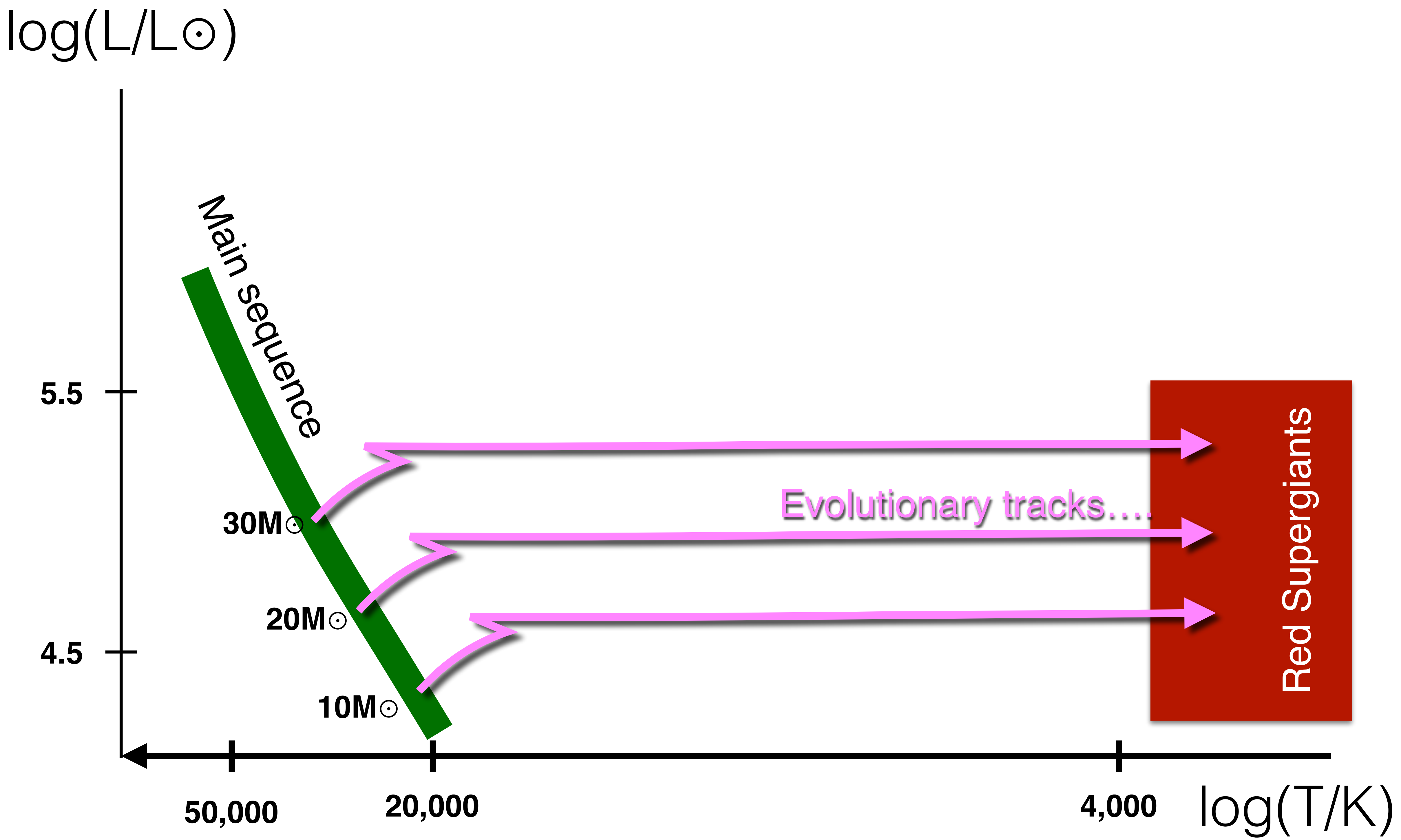
Core contracts… star swells up

EVOLUTION OF A 15$M_{\odot}$ STAR



Core contracts, star swells up.
Lots of convection in the envelope

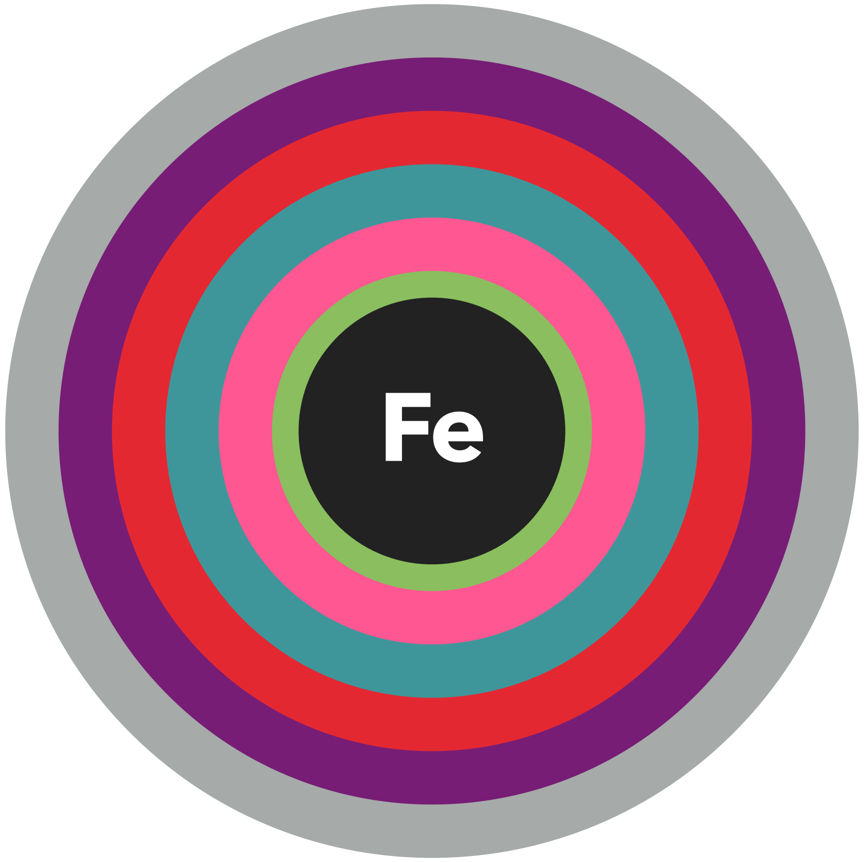
EVOLUTION TO RSG PHASE

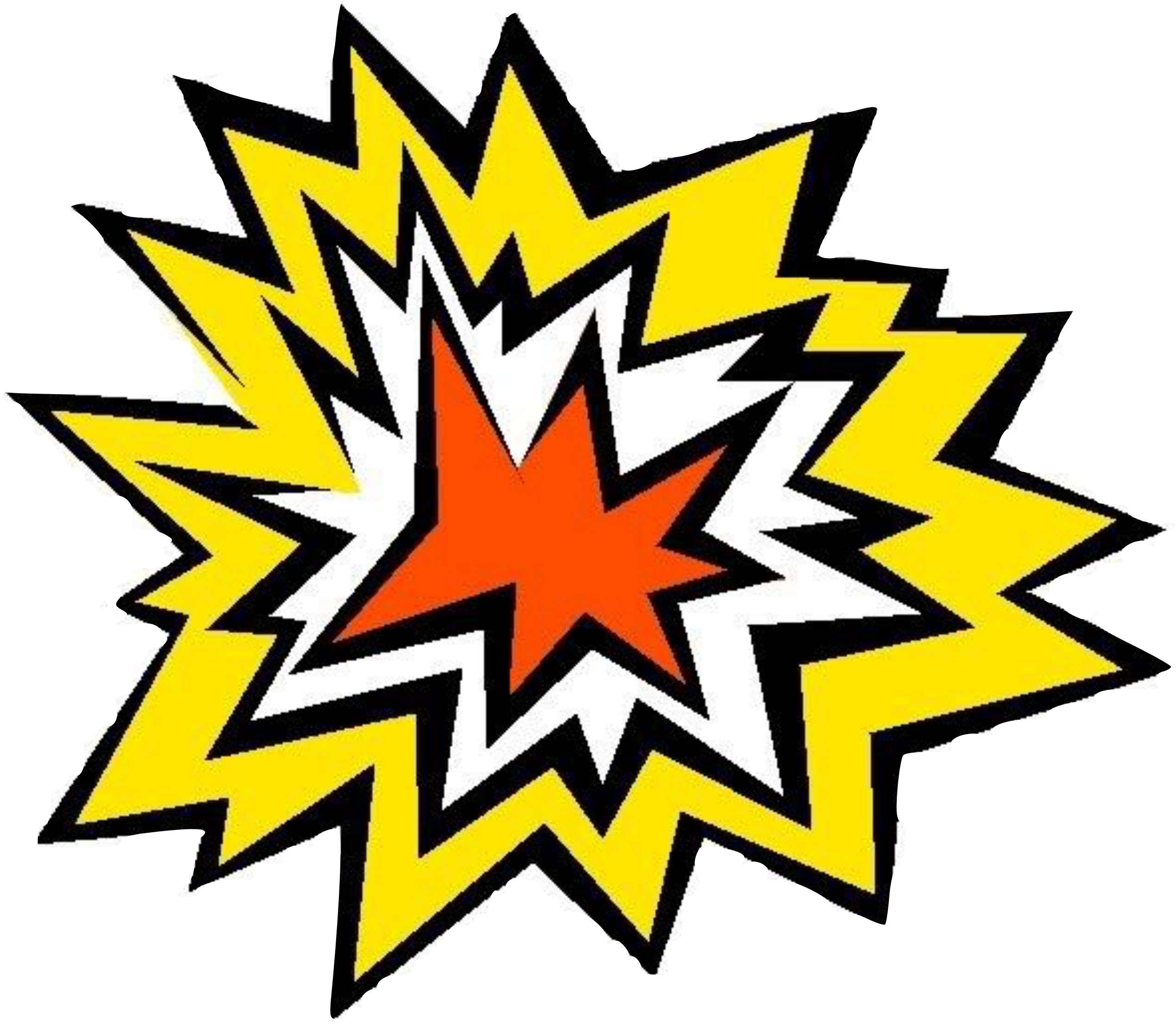


credit: Ben Davies

THE PATH TO SUPERNOVA

- He-core gets exhausted, fuses into carbon core, which fuses into oxygen, which fuses into neon…
- Core gets heavier and heavier
- No more nuclear reactions
- Star collapses onto the core…

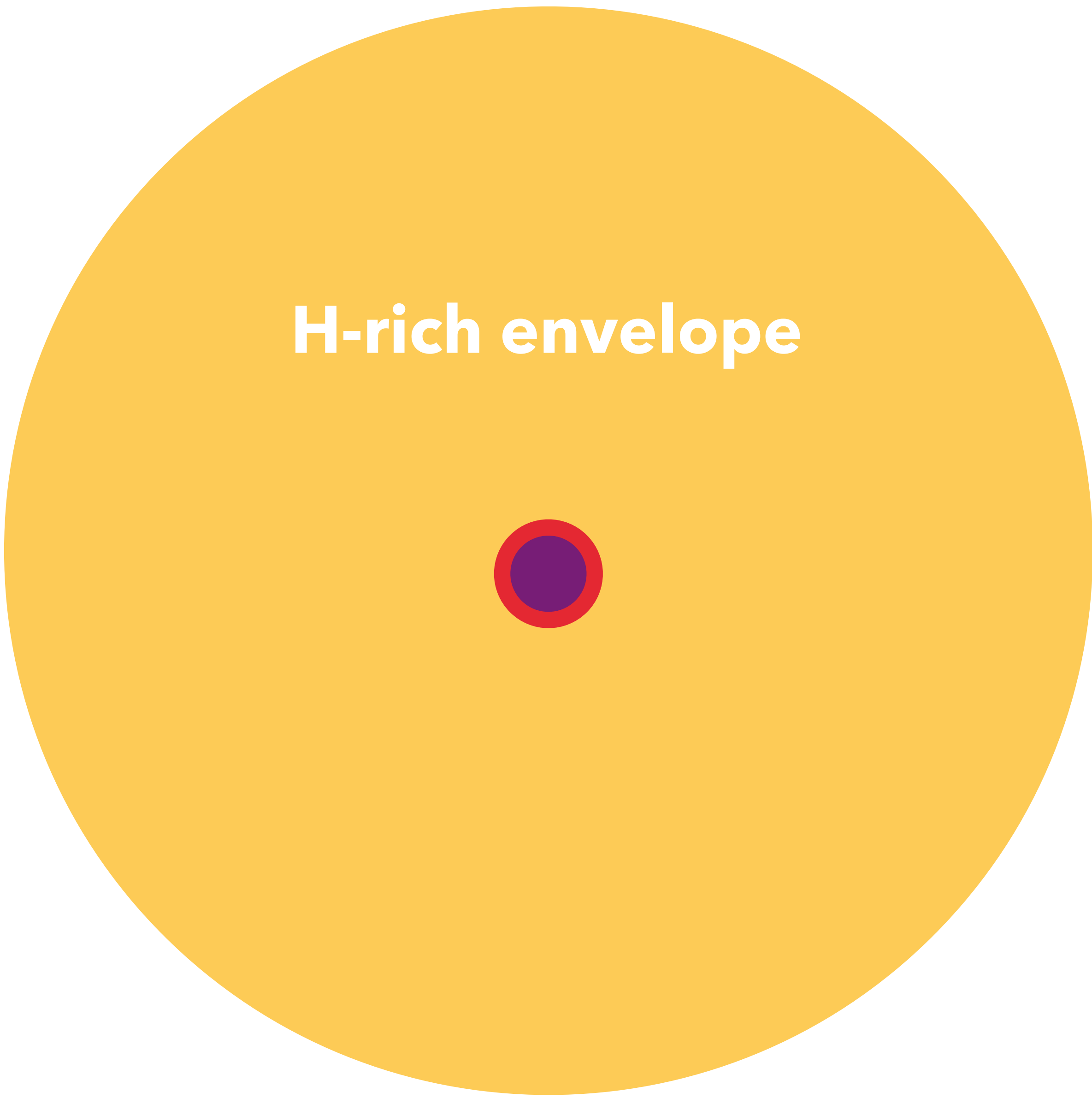




Core-collapse supernovae

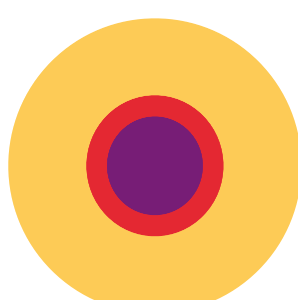
THE PATH TO SUPERNOVA

- What kind of SN depends on the appearance of the progenitor at core collapse
- Strong winds peel away envelope
- RSGs live ~10^6 yrs, mass-loss timescale (M/Mdot) is about the same
- Whole envelope can be peeled off through lifetime

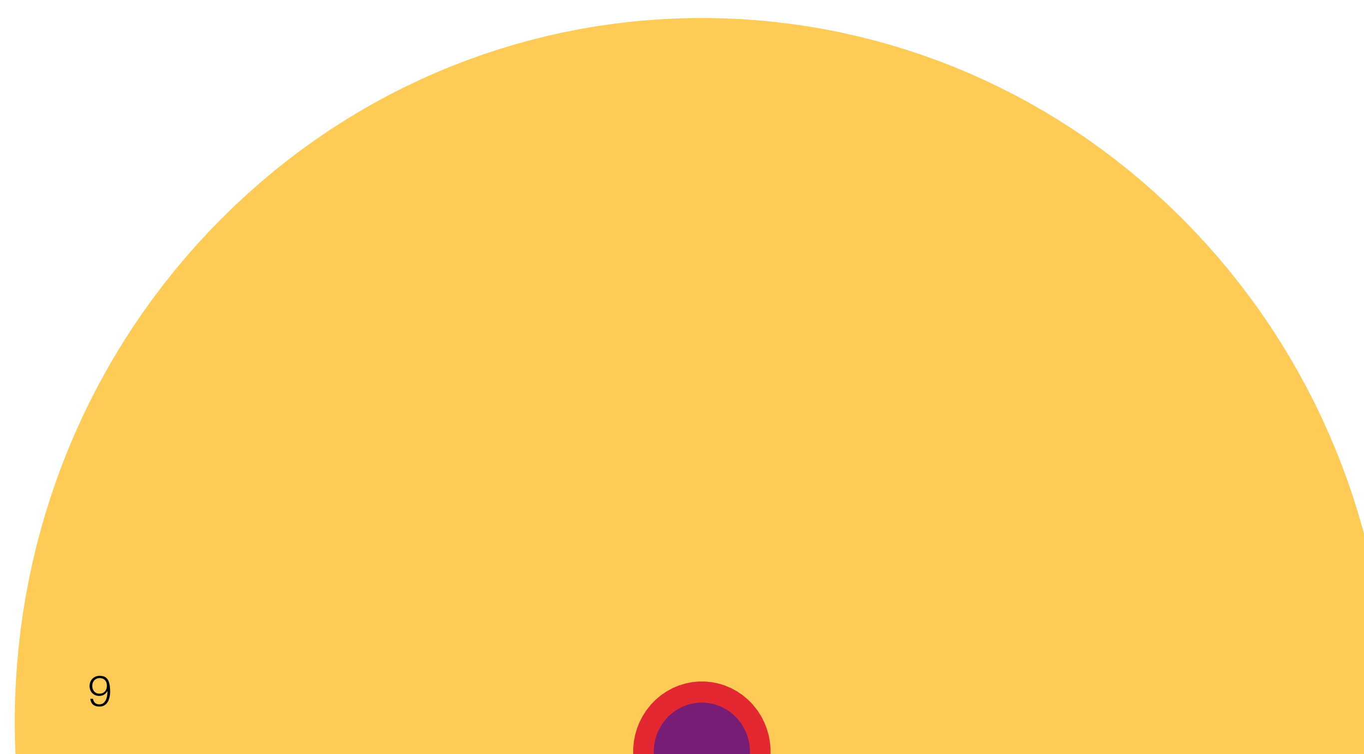


TWO OPTIONS…

- ‘Wolf-Rayet’ (hot progenitor)
- Stripped/H-poor SN (type Ibc)



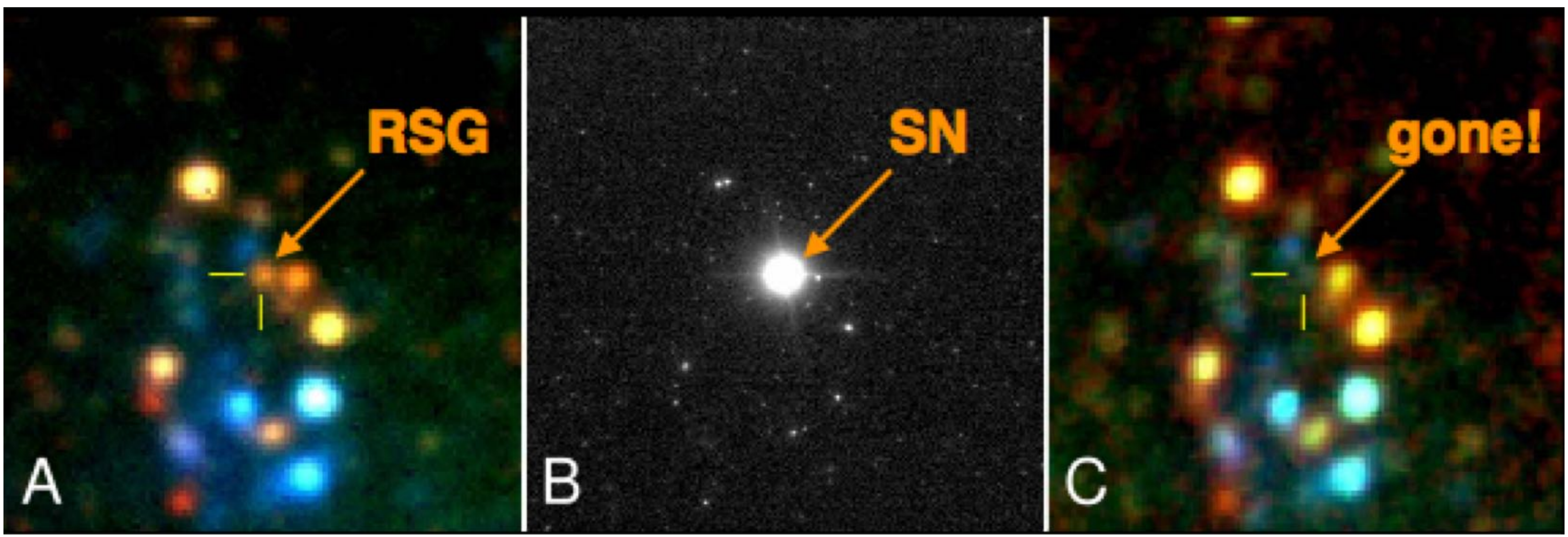
- RSG/YSG progenitor
- H-rich envelope intact
- Unstripped SN (Type II)



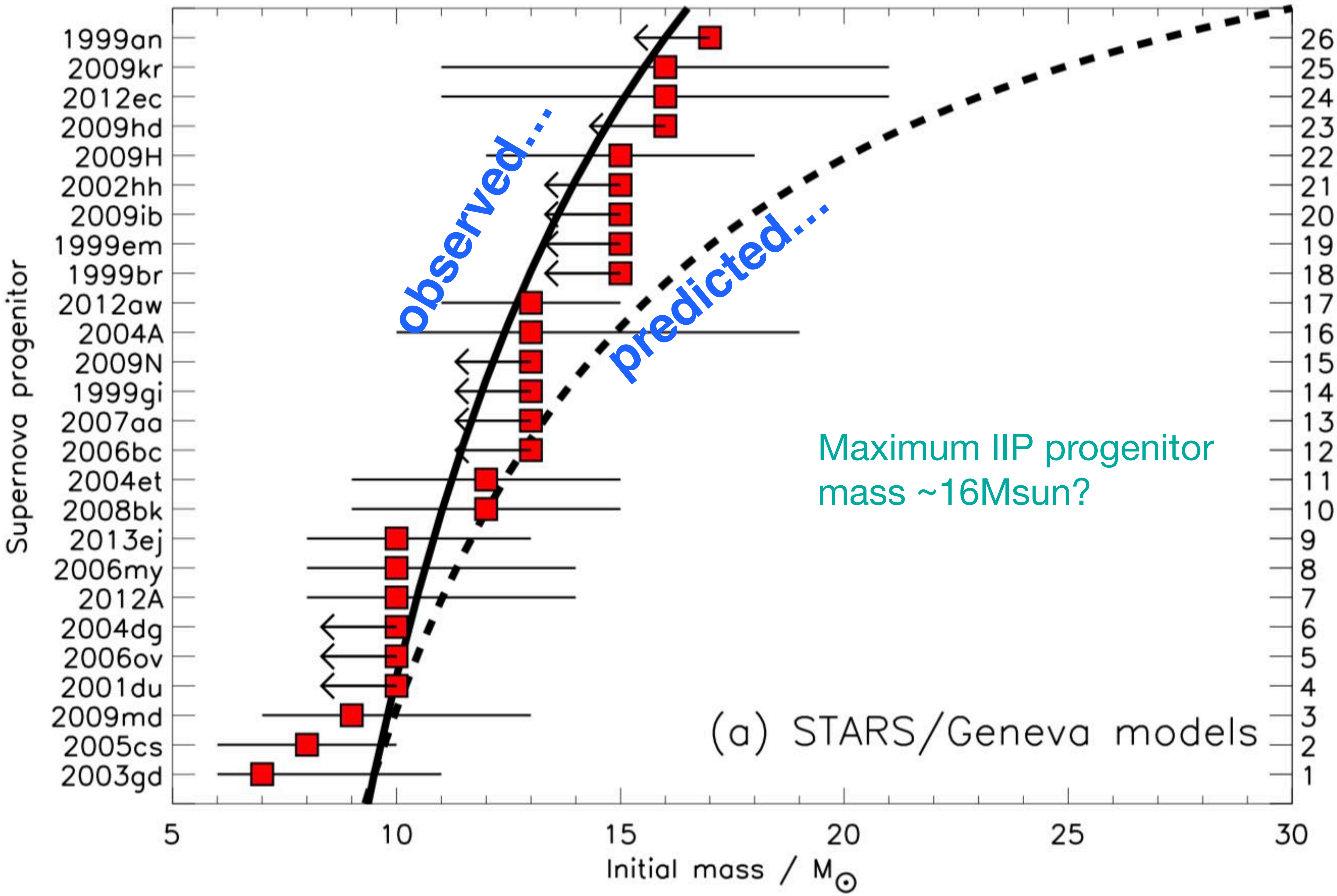
We know RSGs explode as II-P SNe

SN —> check archival images —> identify progenitor

Pre-explosion photometry + *some* assumptions allow us to find the terminal luminosity of the progenitor and infer a mass

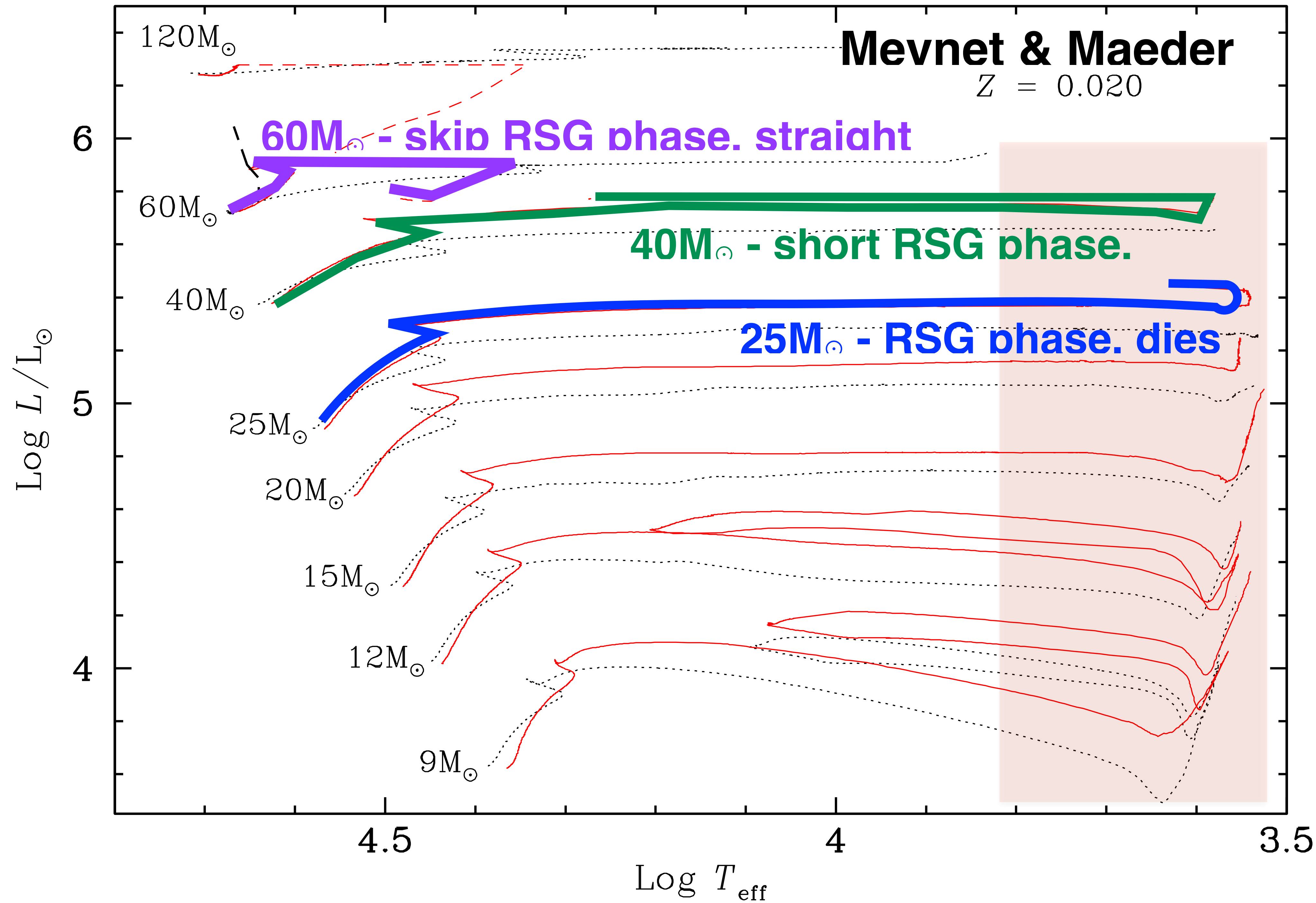


Red supergiant problem…

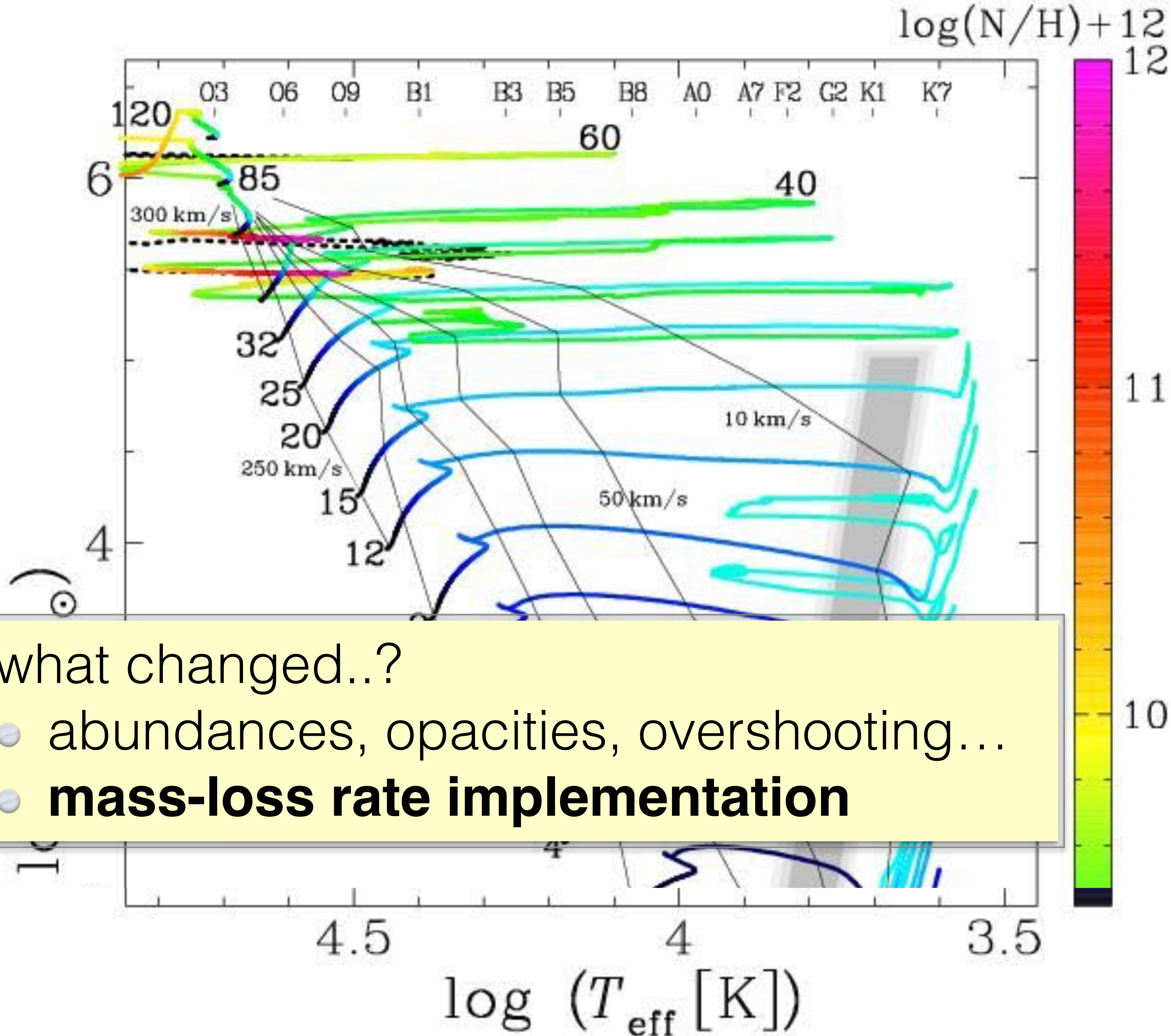


Smartt et al. 2009, updated in Smartt 2015

EVOLUTION FROM MS TO RSG



...MODEL DEPENDENT



what changed..?

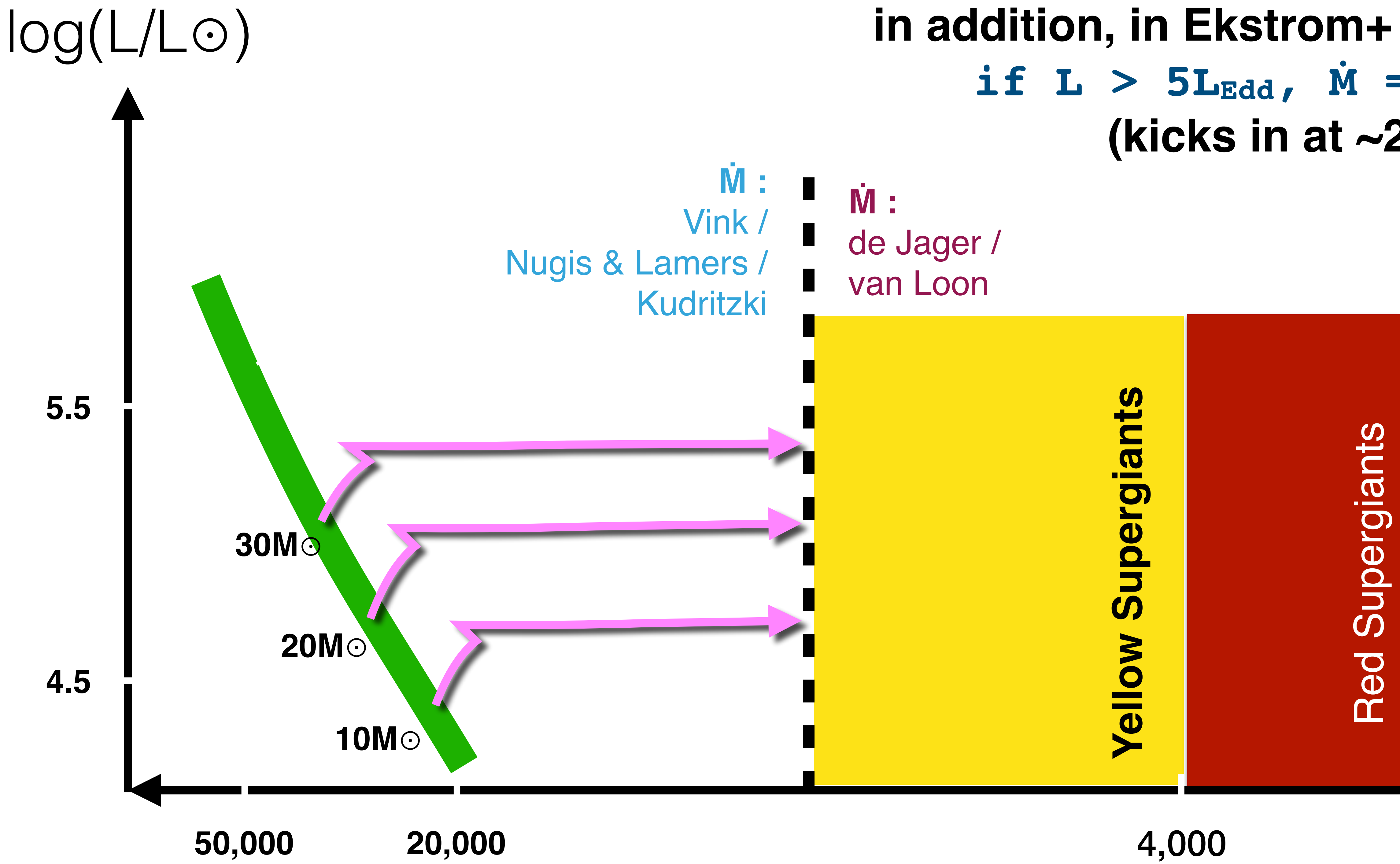
- abundances, opacities, overshooting…
- **mass-loss rate implementation**

MASS-LOSS RATE IMPLEMENTATION

in addition, in Ekstrom+ 2012:

`if L > 5L_Edd, Ṁ = Ṁx3`

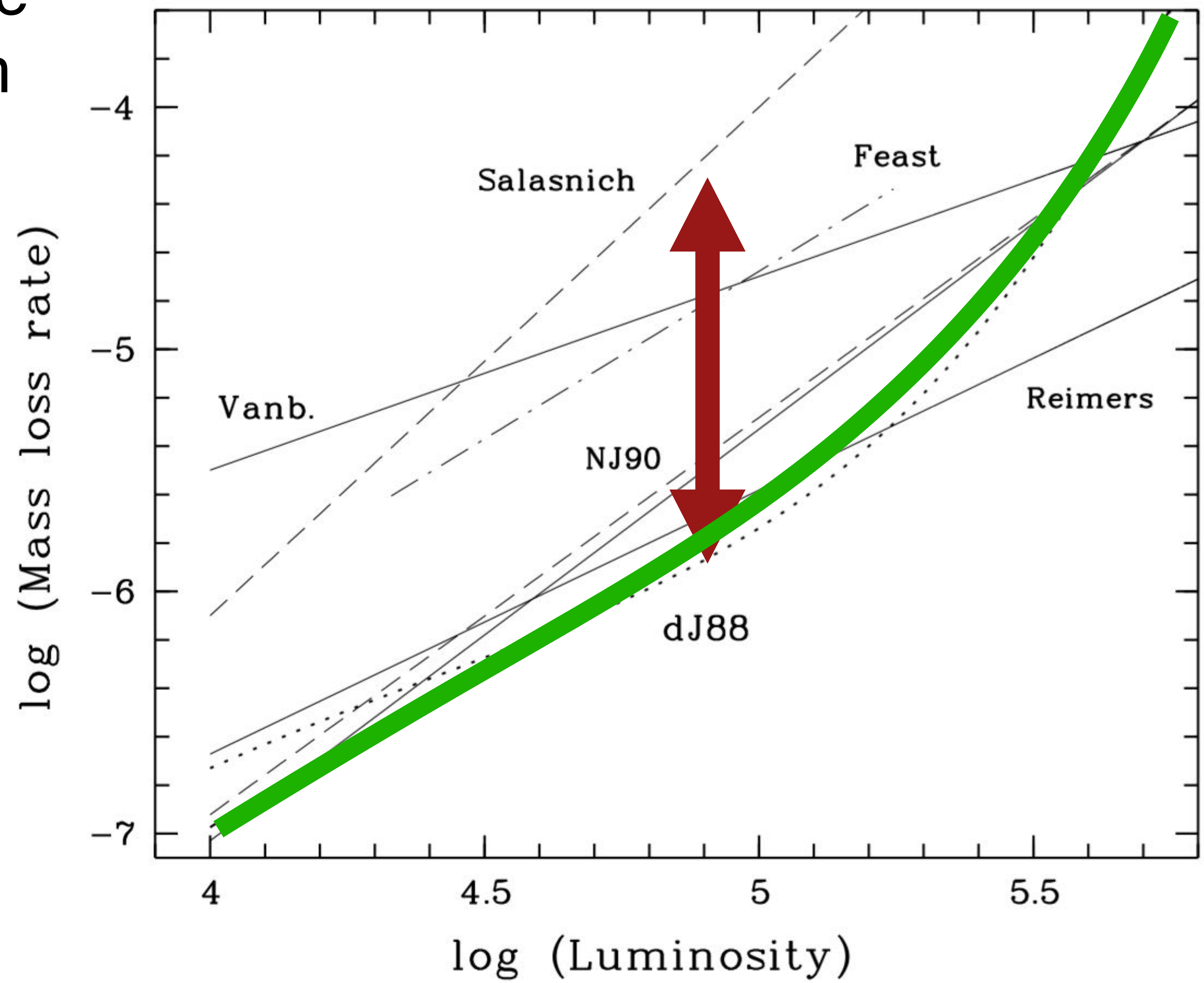
(kicks in at ~20M⊙)



credit: Ben Davies

EMPIRICAL MASS-LOSS RELATIONS

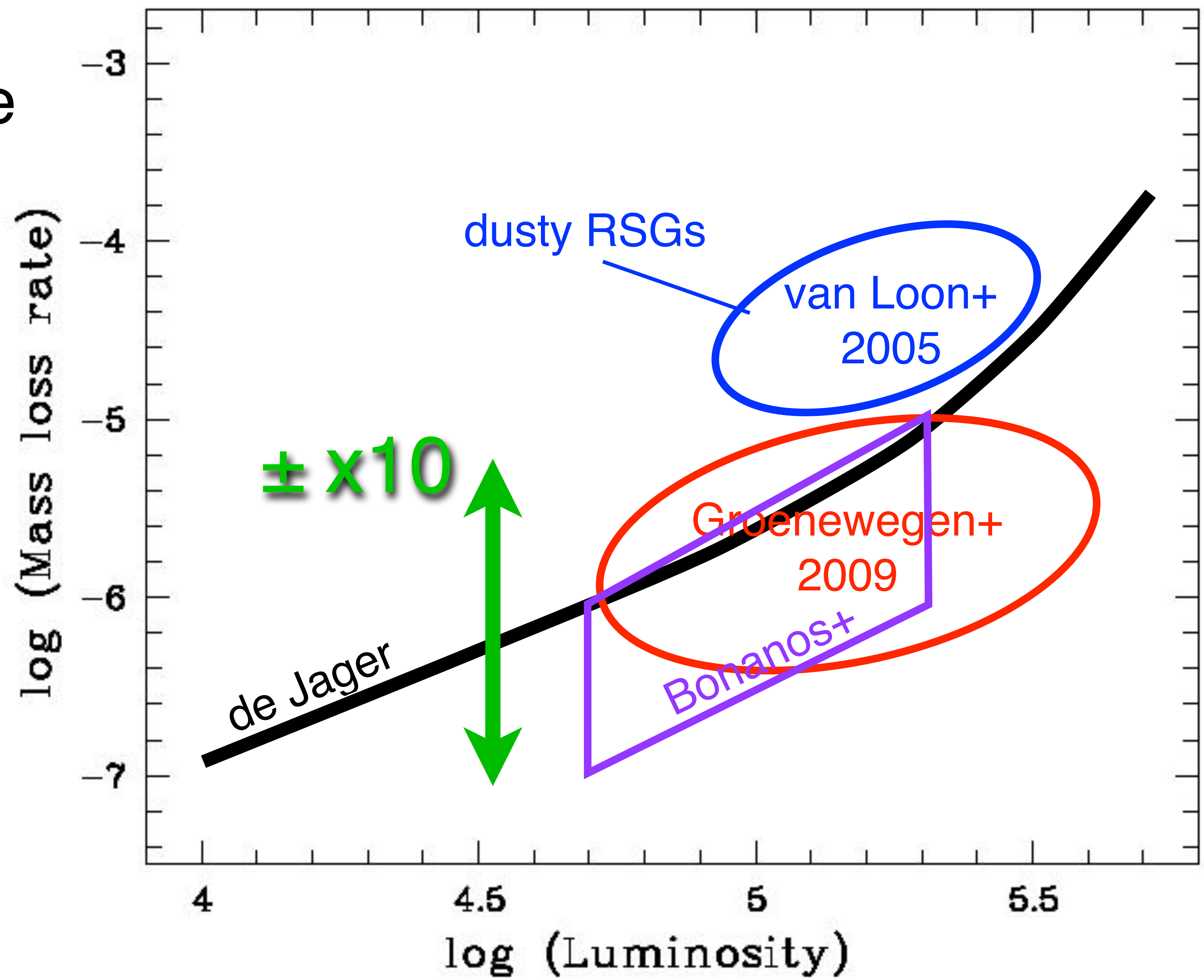
- Mass-loss rates are *not* calculated from first principles



Mauron & Josselin 2010

EMPIRICAL MASS-LOSS RELATIONS

- Mass-loss rates are *not* calculated from first principles
- Lots of internal scatter



Mass loss rates in the Hertzsprung-Russell diagram

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([1]) Laboratory for Space Research, Beneluxlaan 21, 3527 HS Utrecht, The Netherlands
([2]) Astronomical Institute, University of Utrecht, Utrecht, The Netherlands

Received January 19, accepted June 19, 1987

Needs a bit of an update…

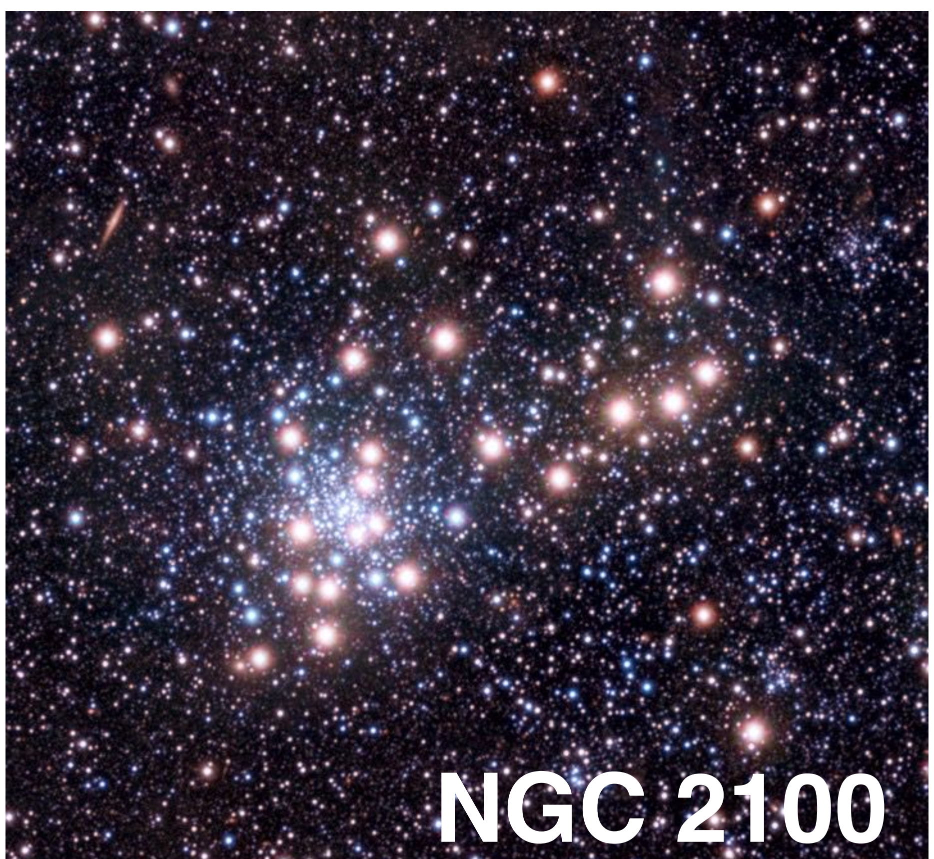
Summary. — From the literature we collected values for the rate of mass loss for 271 stars, nearly all of population I, and of spectral types O through M. Rates of stellar mass loss determined according to six different methods were compared

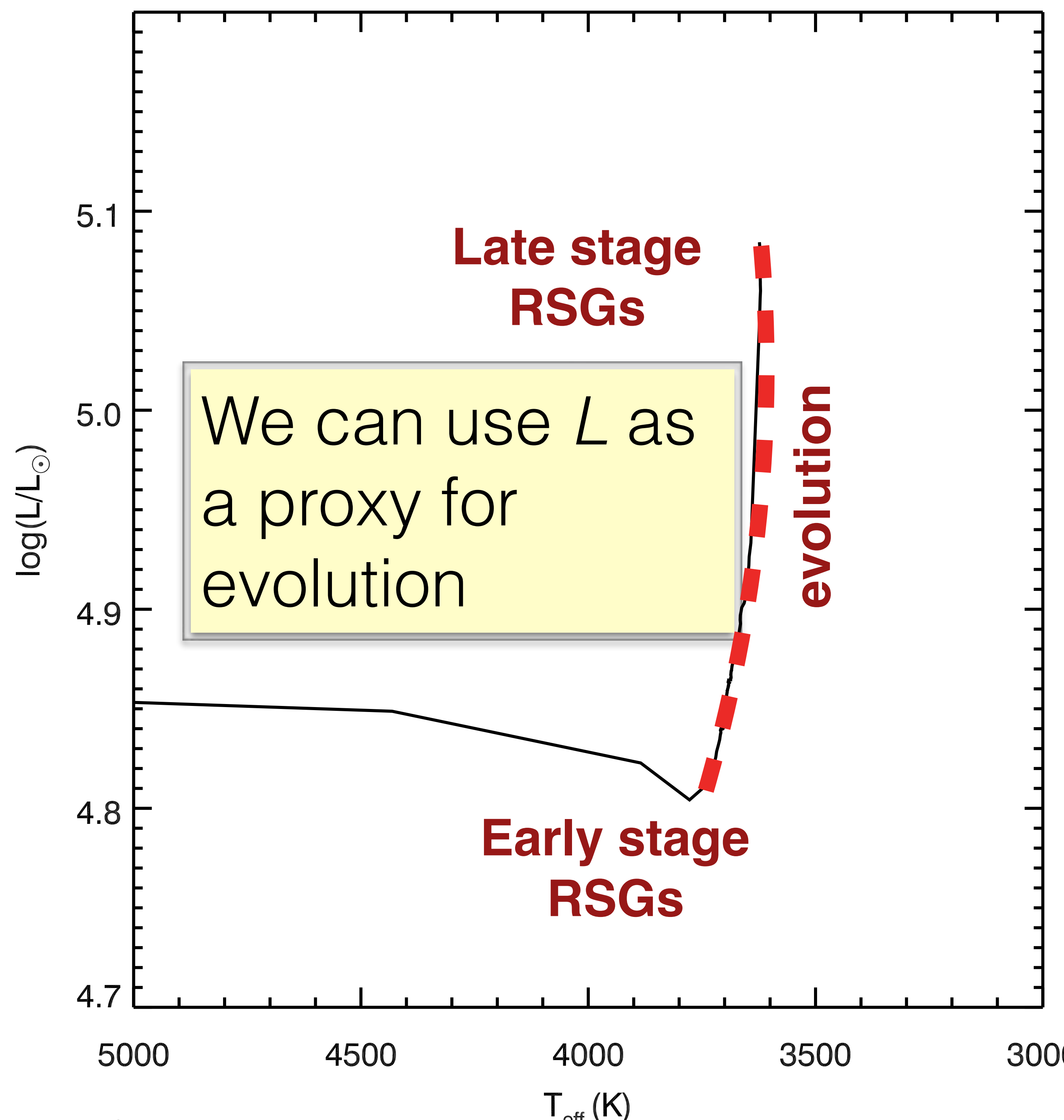
- ★ Highly heterogeneous sample (masses, metallicities…)
- ★ Highly heterogeneous methodologies (mid-IR excesses, abs line analysis, radio…)
- ★ No longer used for OBA

U : from ultraviolet spectra, mainly from far UV resonance line profiles ;
V : from spectral lines in the visual and near ultraviolet spectral ranges, mainly subordinate lines such as H_α, but in some cases also from other lines, including the H and K lines ;
I : from broad-band infrared photometric data, assuming the flux to be due to free-free emission ;
C : from infrared data on C-molecular compounds ;
M : from maser lines in the microwave range ;
R : from radio continuum data : radiofluxes due to free-free emission, i.e. excluding data of stars for which the radio emission is assumed to be synchrotron radiation (cf. e.g. Underhill, 1984a).

REAPPRAISAL OF RSG MASS-LOSS

- By targeting RSGs in clusters, we can assume all RSGs are the same Z and same M_{ini}





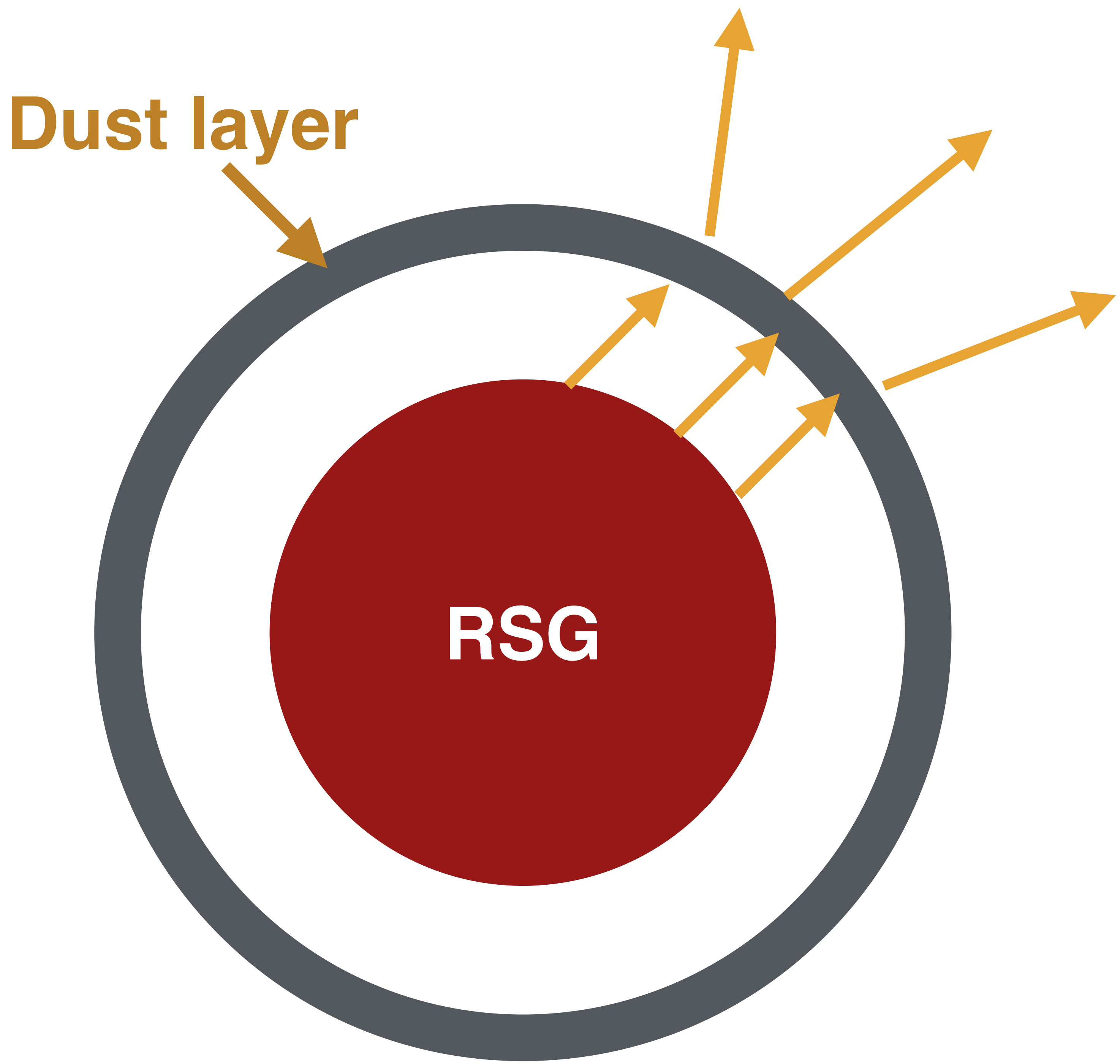

SOFIA - new data (PI N Smith)
NASA
DLR


WISE - archival


SPITZER - archival

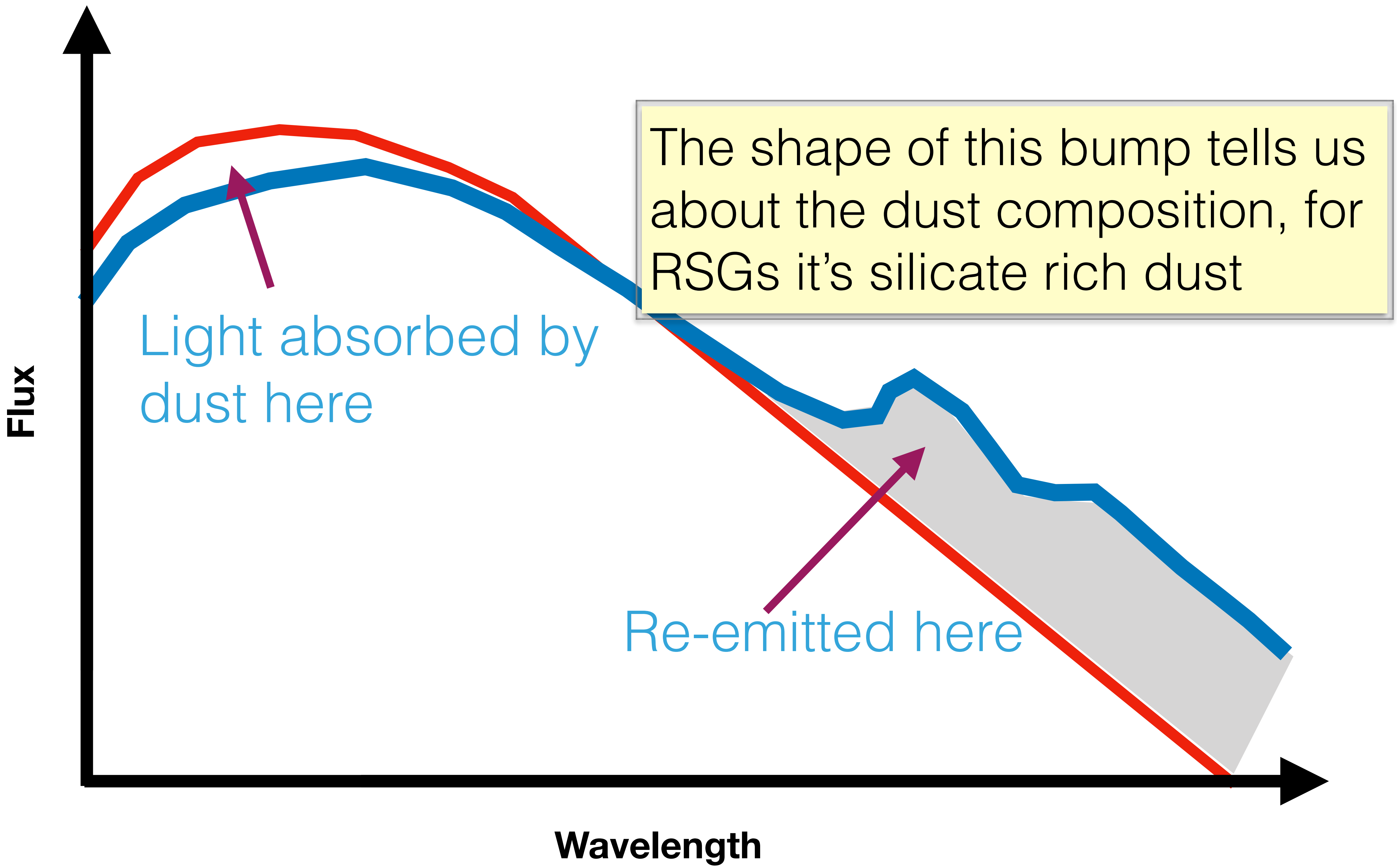

MSX - archival

HOW DO WE MEASURE MASS-LOSS RATES?



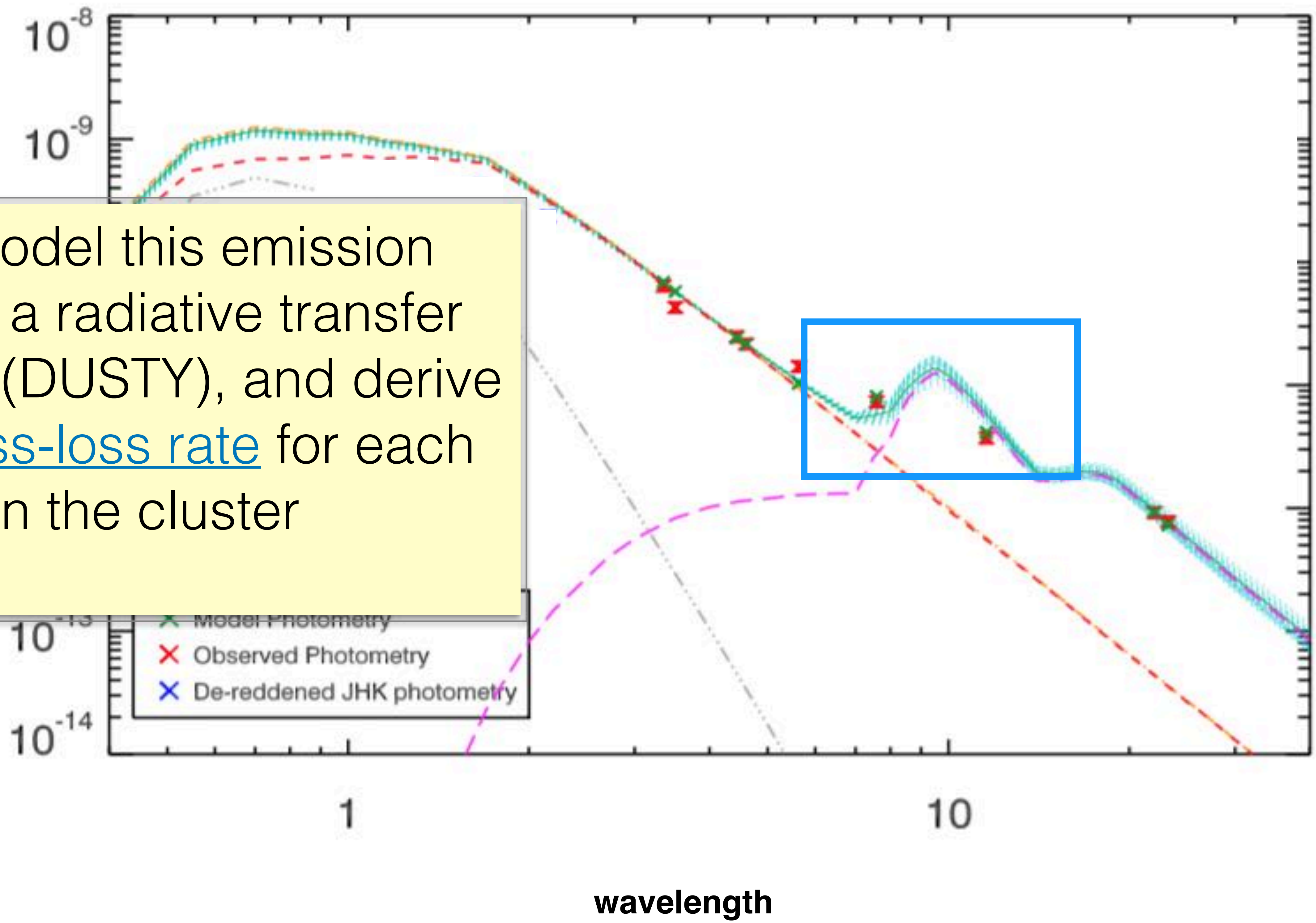
- Dust layer absorbs and re-emits photons
- Mass-loss can be measured by modeling mid-IR excess

HOW DO WE MEASURE MASS-LOSS RATES?



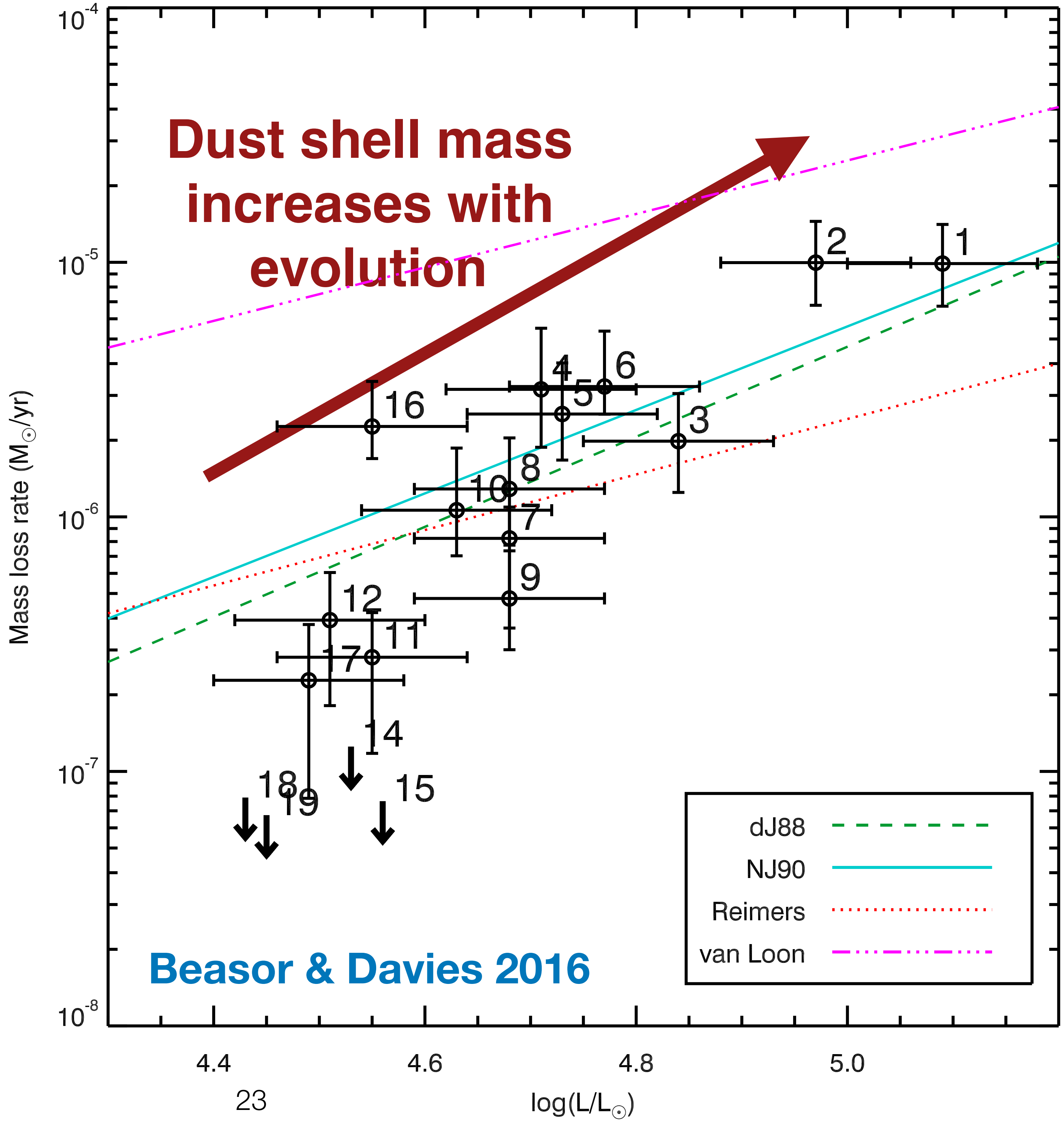
HOW DO WE MEASURE MASS-LOSS RATES?

We model this emission using a radiative transfer code (DUSTY), and derive a mass-loss rate for each RSG in the cluster

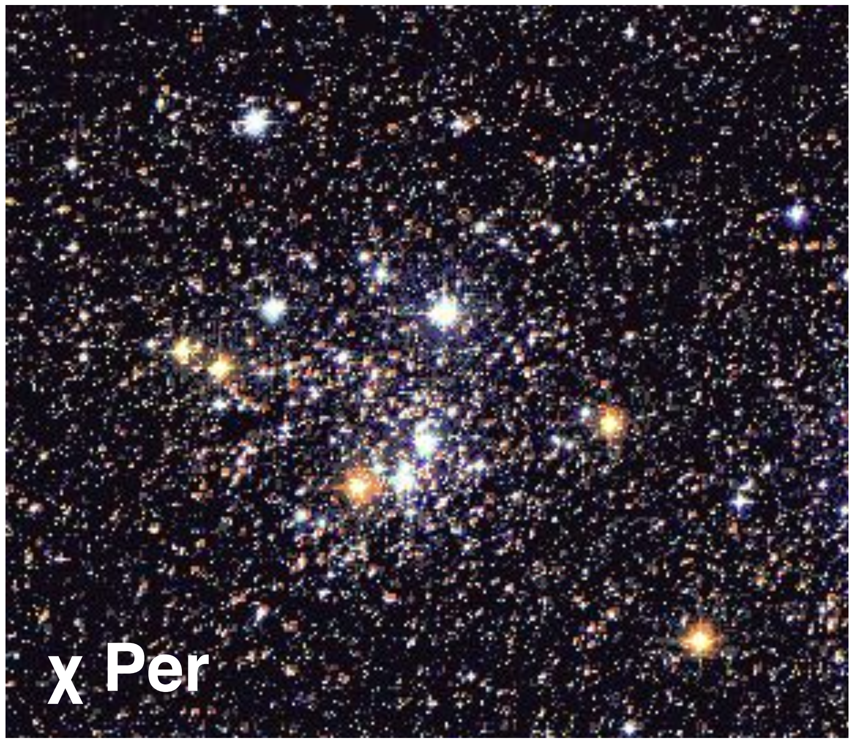


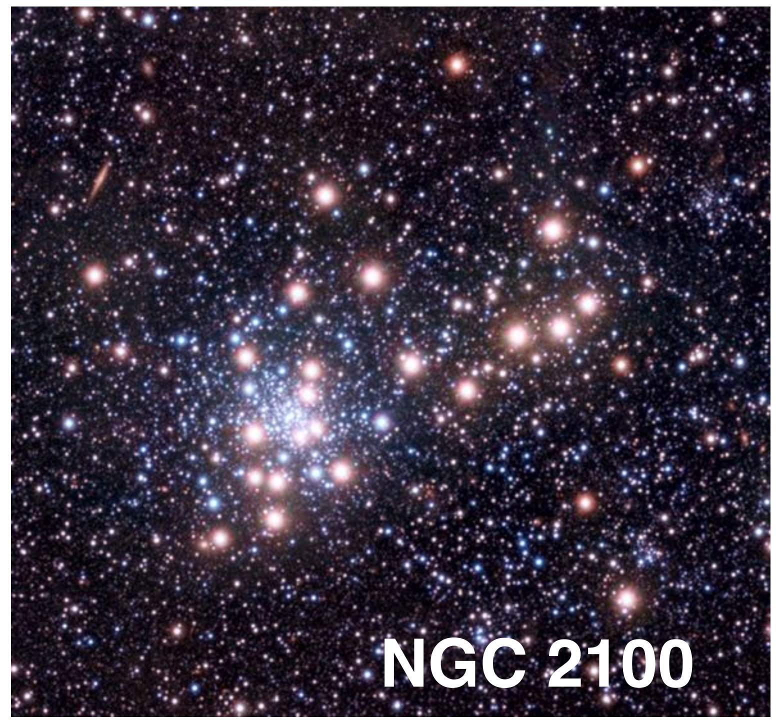
NGC2100

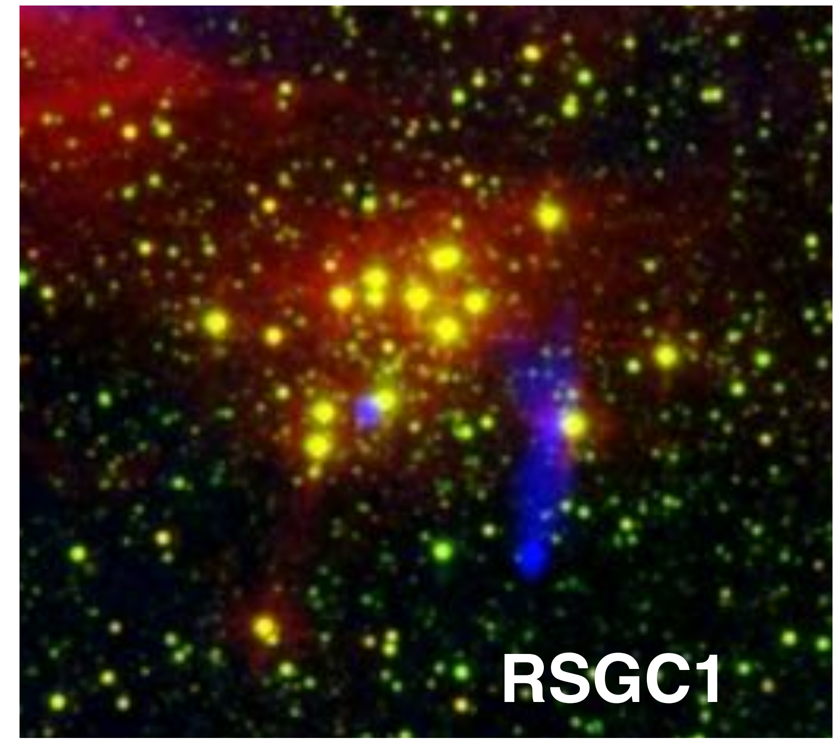
- Tight correlation…
- Fixed initial mass and Z



HOW DO MASS-LOSS RATES CHANGE WITH INITIAL MASS?

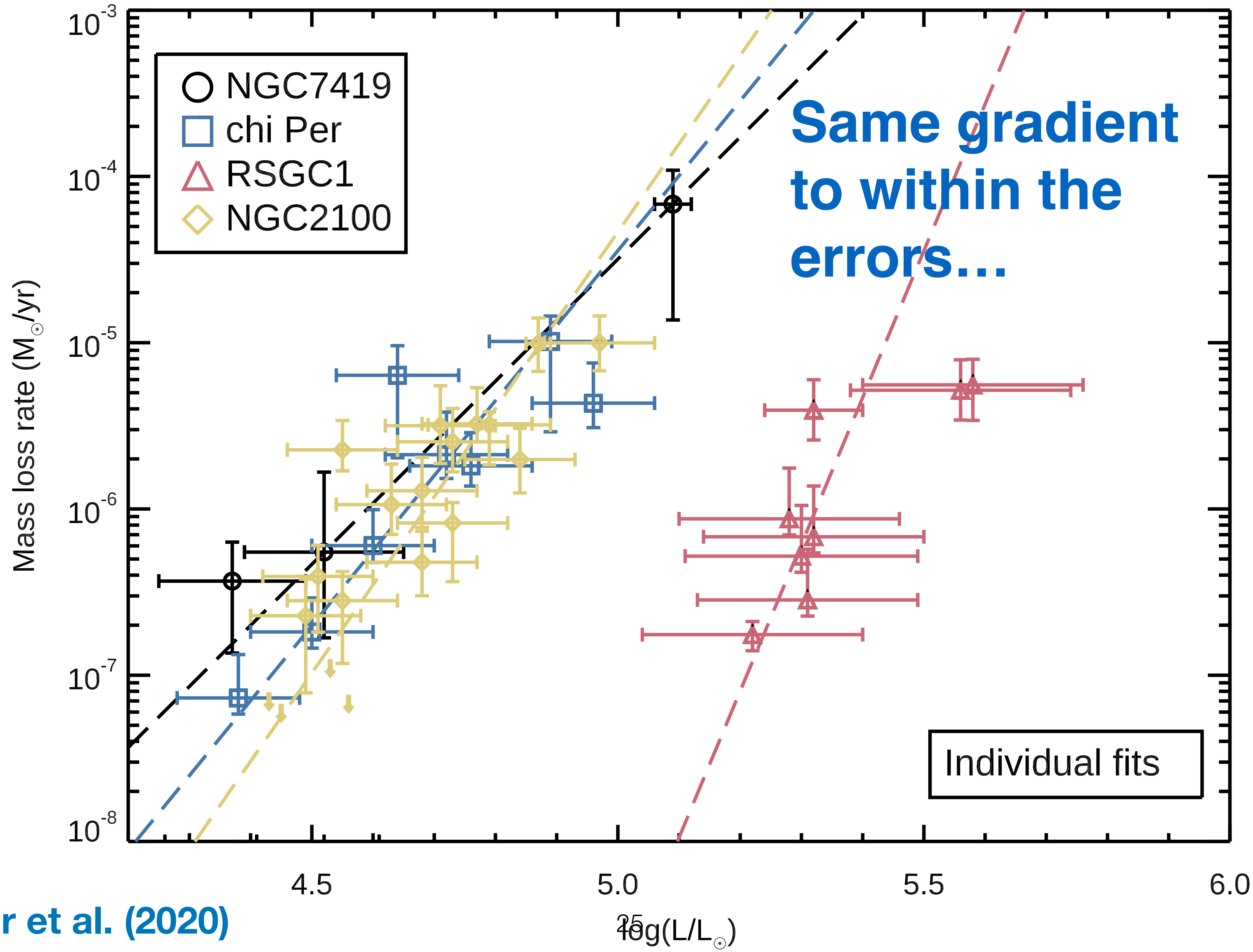






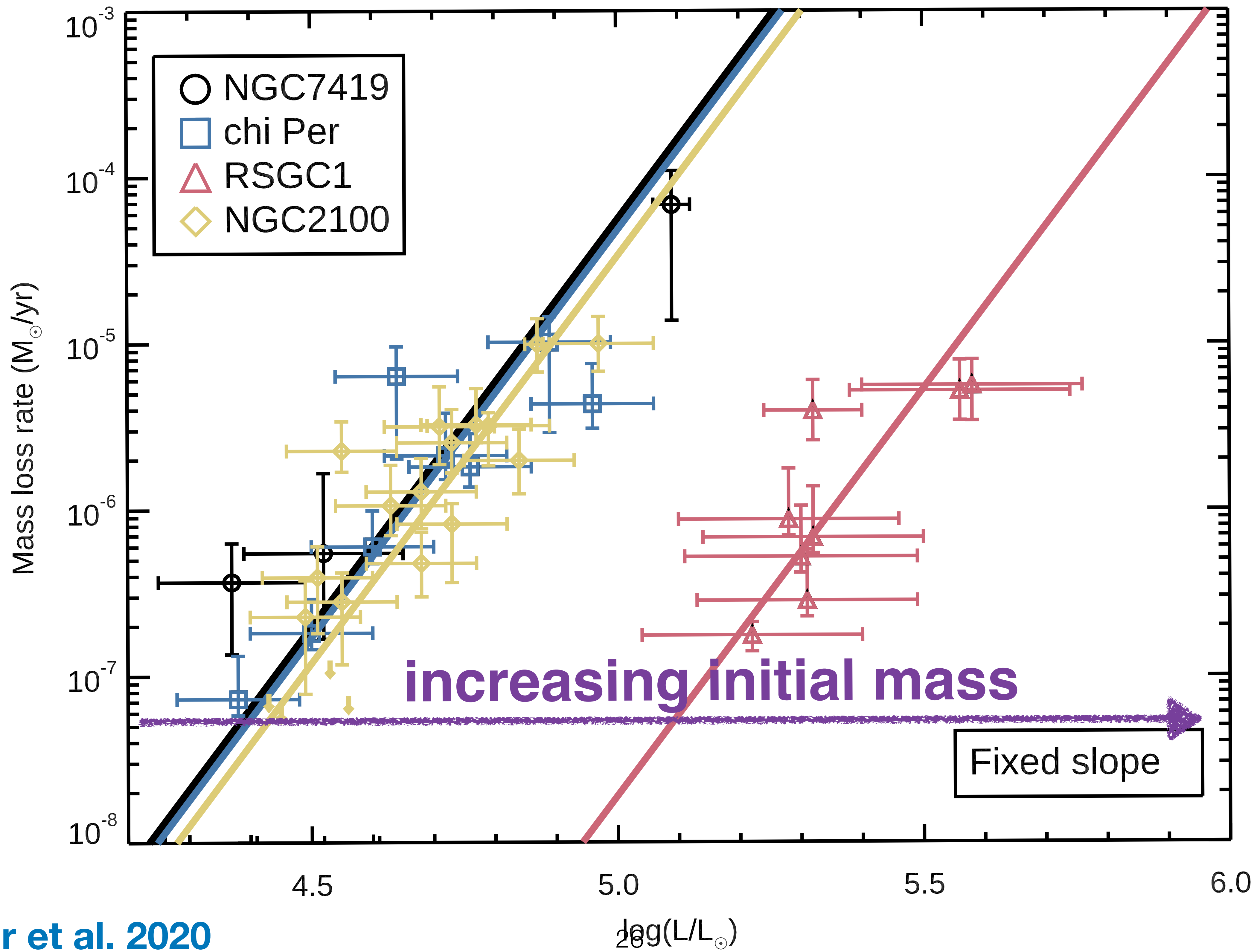
- Repeat for clusters of different ages (and hence RSGs of different initial masses..)

A MASS-DEPENDENT MASS-LOSS RATE PRESCRIPTION



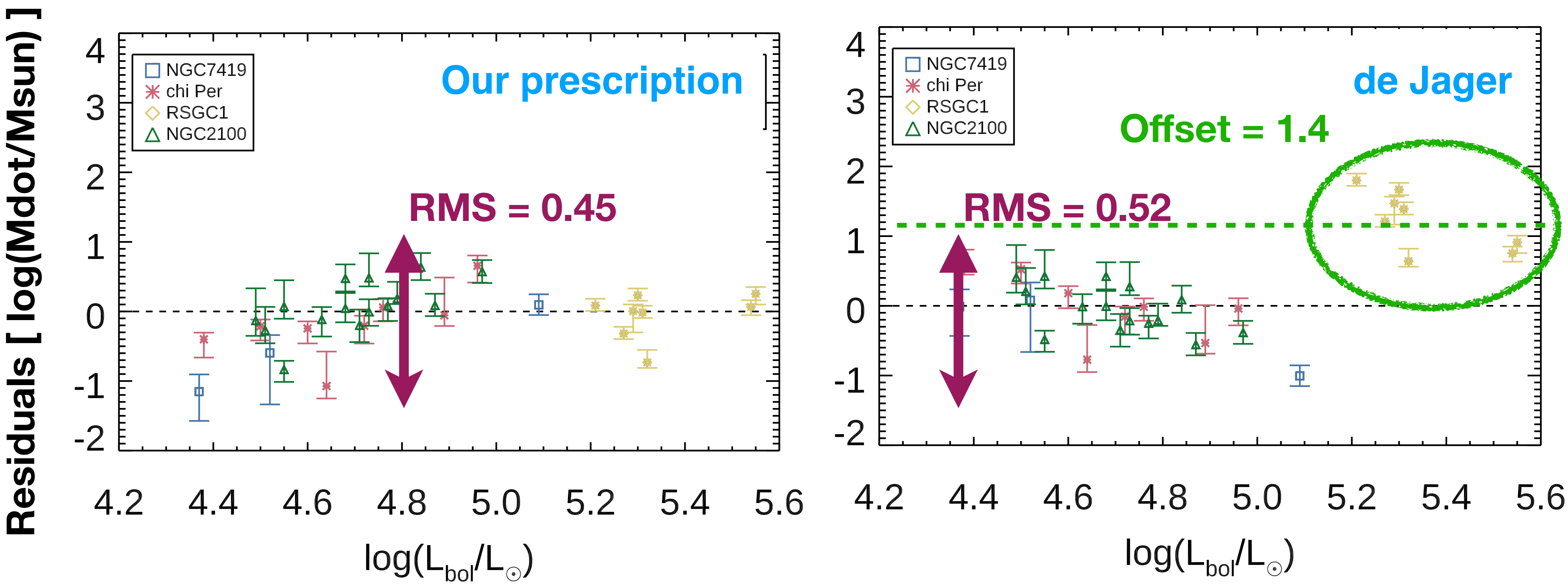
Beasor et al. (2020)

A MASS-DEPENDENT MASS-LOSS RATE PRESCRIPTION



Beasor et al. 2020

COMPARISON TO OTHER PRESCRIPTIONS

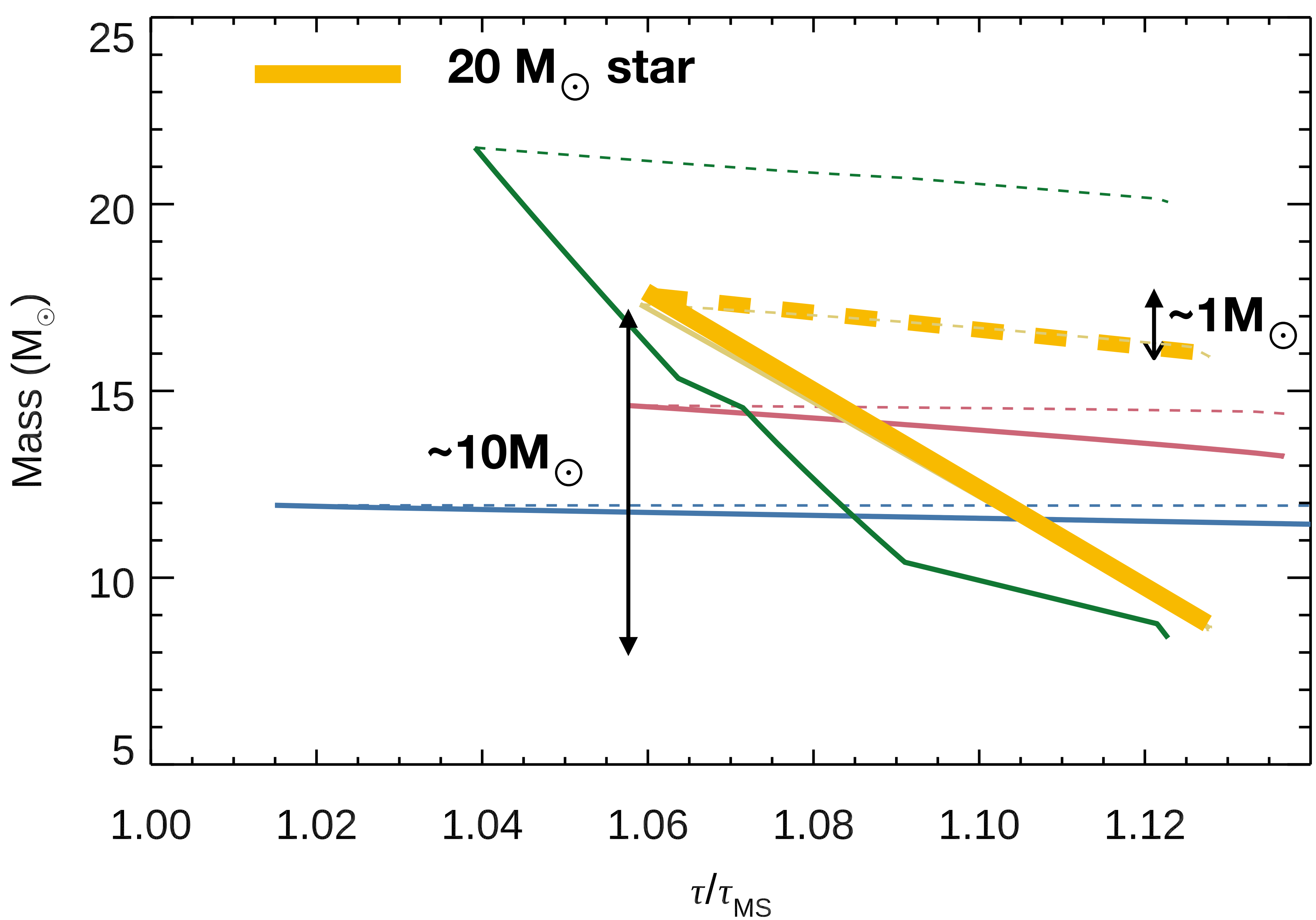


- Lower scatter
- No offset

- Scatter slightly higher
- Avg offset = 0.13
- BUT much worse for higher luminosity stars…

Beasor et al. 2020

COMPARISON TO EVOLUTIONARY MODELS



- Solid line - current implementation
- Dashed line - our prescription
- Quiescent mass-loss *cannot* remove the H envelope….

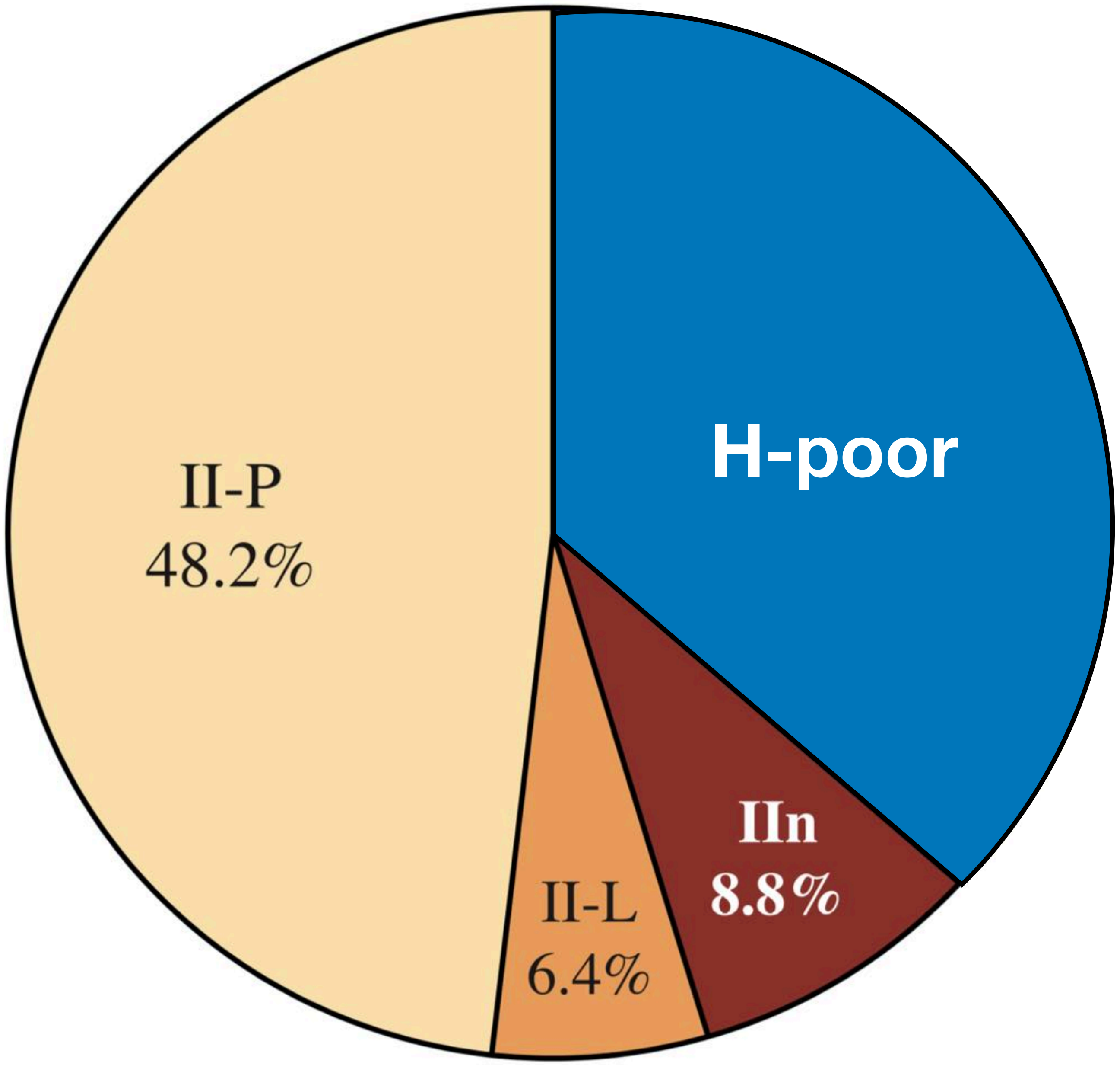
Beasor et al. 2020

What does it all mean…

- Observed H-poor SN fraction ~ 1/3
- Back of the envelope IMF calculation…

% stars 8-30M$_\odot$ ~ 85%

% stars >30M$_\odot$ ~ 15%



Core-Collapse SN Fractions

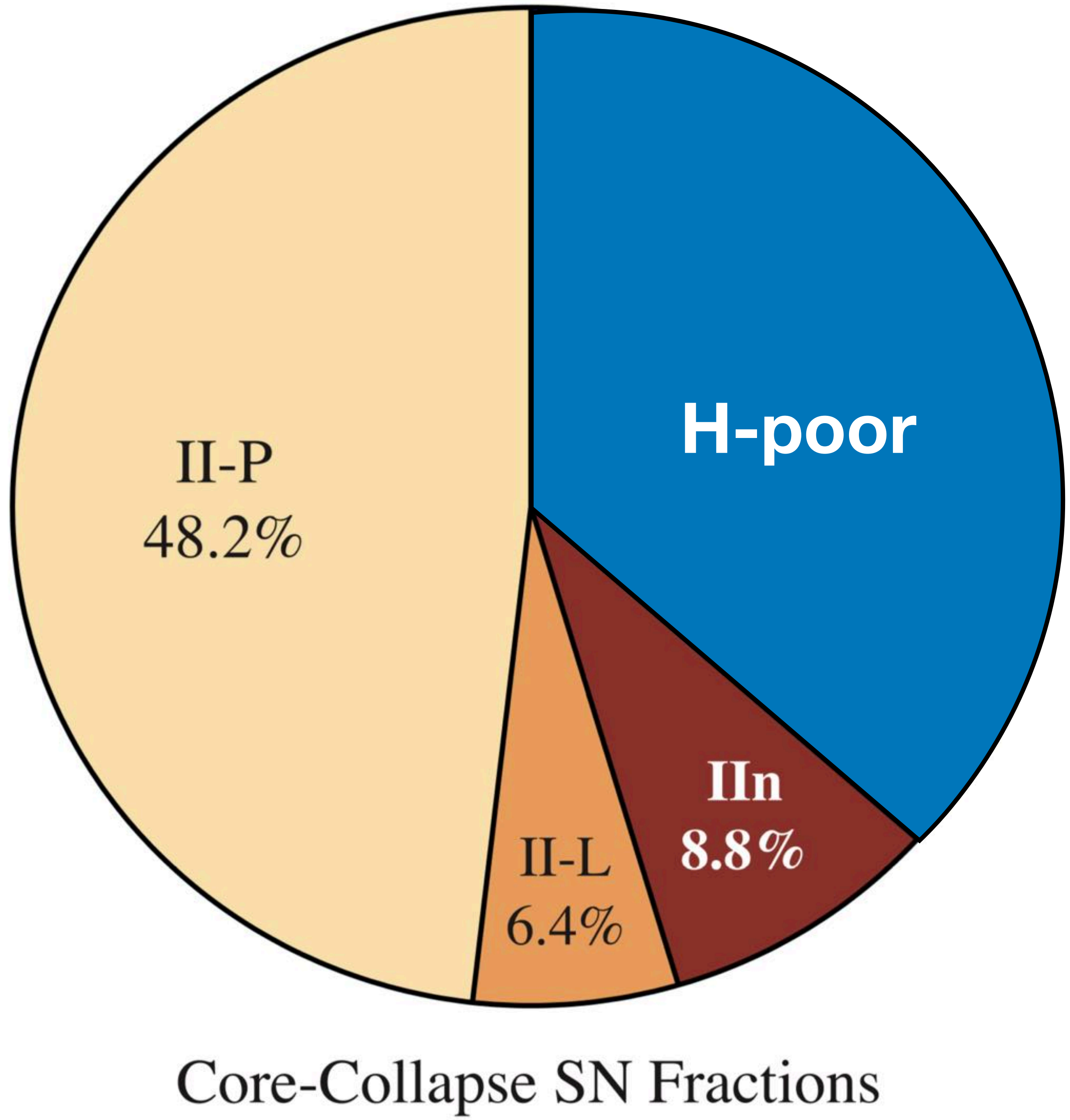
Smith et al. 2011

What does it all mean…

- If mass-loss rates were higher… could explain this discrepancy

% stars 8-16$M_\odot$ ~ 60%

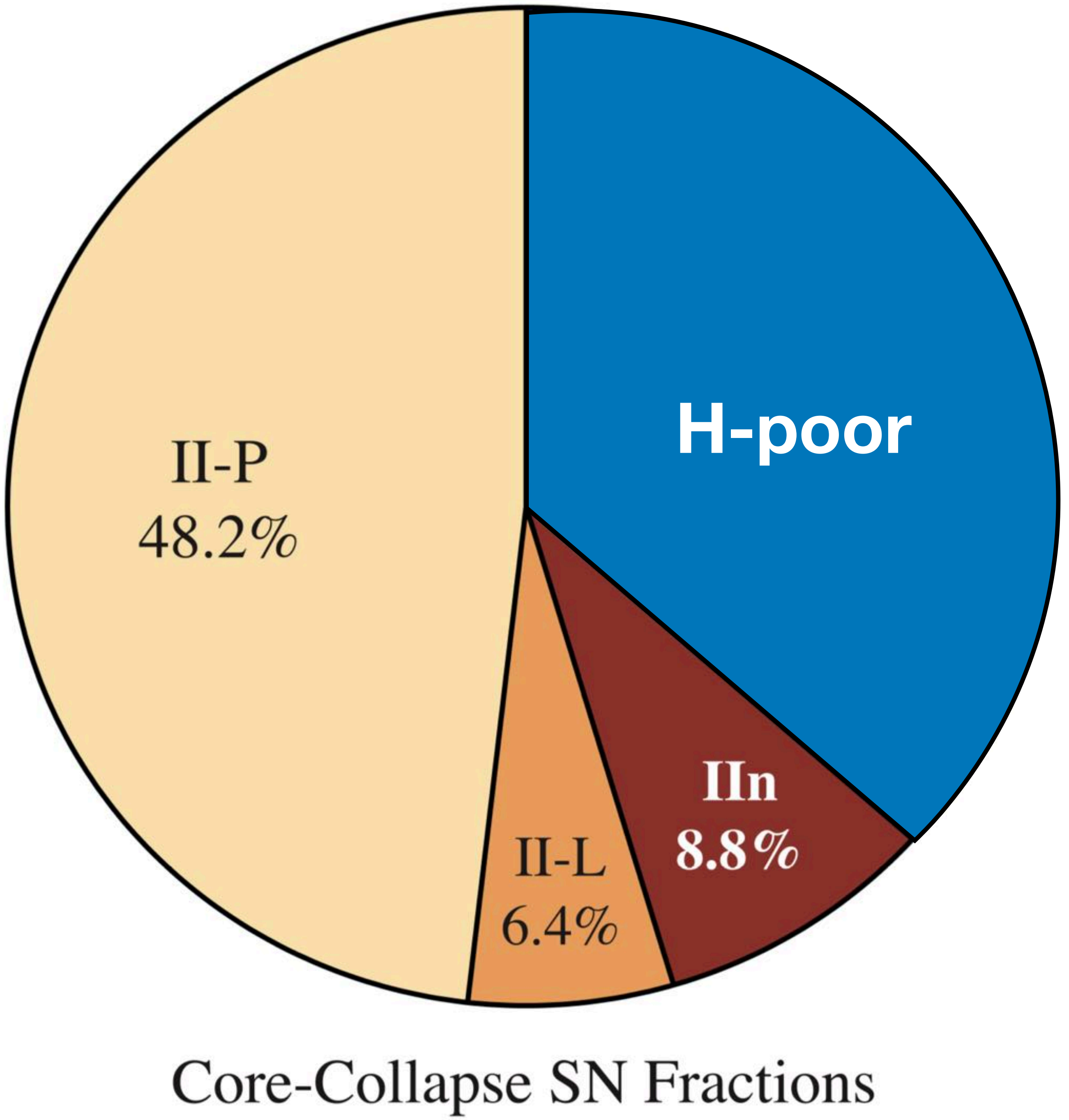
% stars >16$_\odot$ ~ 40%



Smith et al. 2011

What does it all mean…

- But, mass-loss rates are **lower**
- Single star evolution cannot explain the observed SN rate
- Strong evidence for **most H-poor SN being the products of binary interaction**

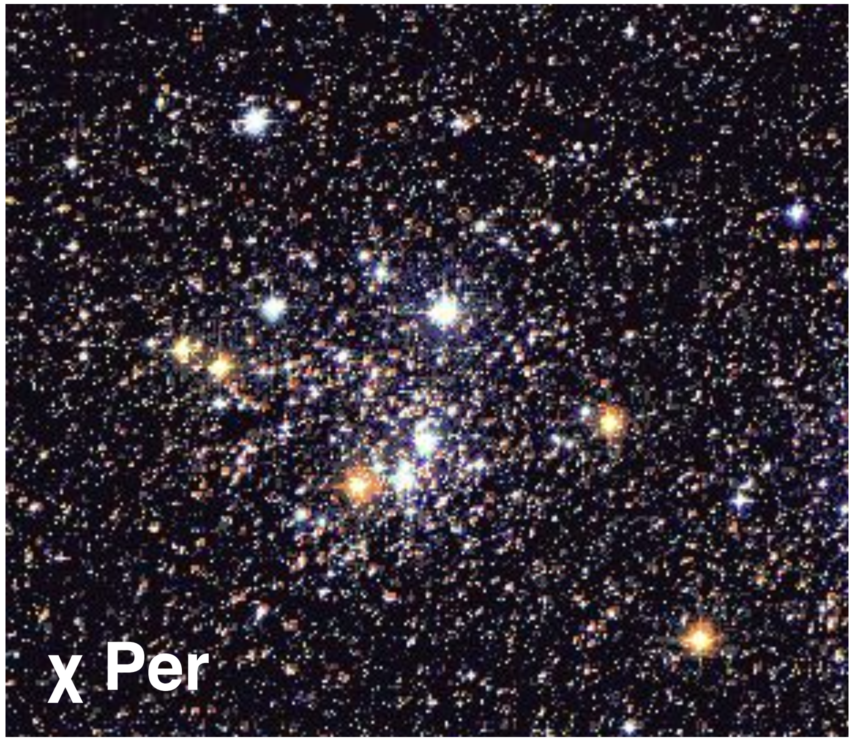


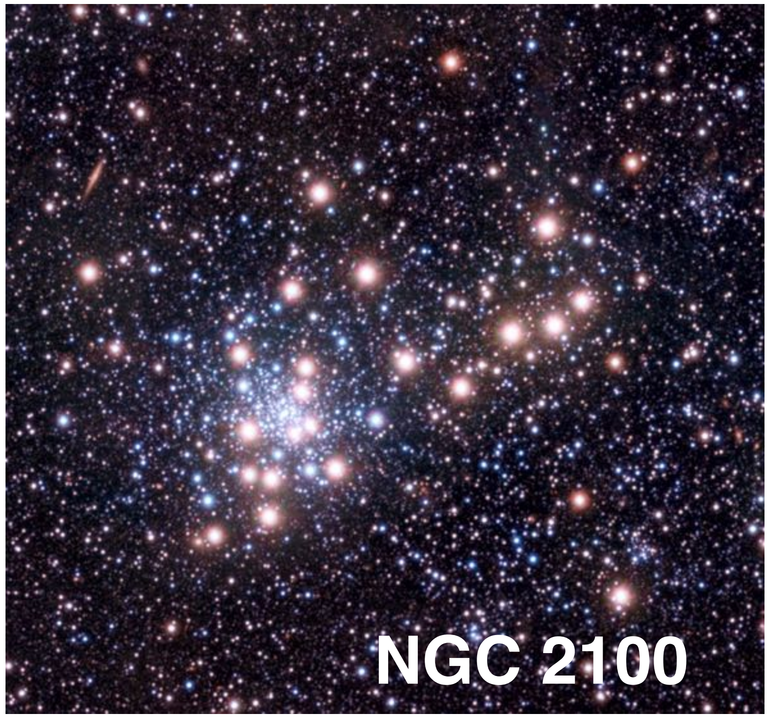
Smith et al. 2011

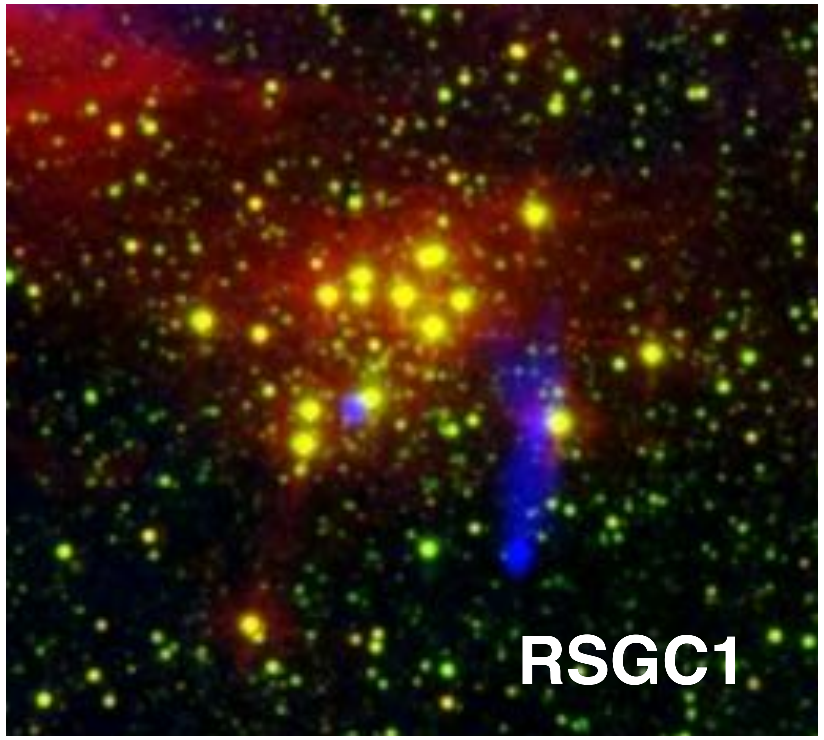
CONCLUSIONS: Part 1

- There is no observationally motivated reason to increase mass-loss by factors of 3 or more in stellar evolution models
- RSGs that evolve as single stars *do not* shed their envelope via quiescent mass loss
- Single stars between 20-30$M_{\odot}$ *do not* lose enough mass to evolve blueward
- The relative number of stripped/unstripped SN events predicted by single star models is way off
- Something else (binaries??) is removing the envelope

HOW WELL DO WE KNOW CLUSTER AGES?

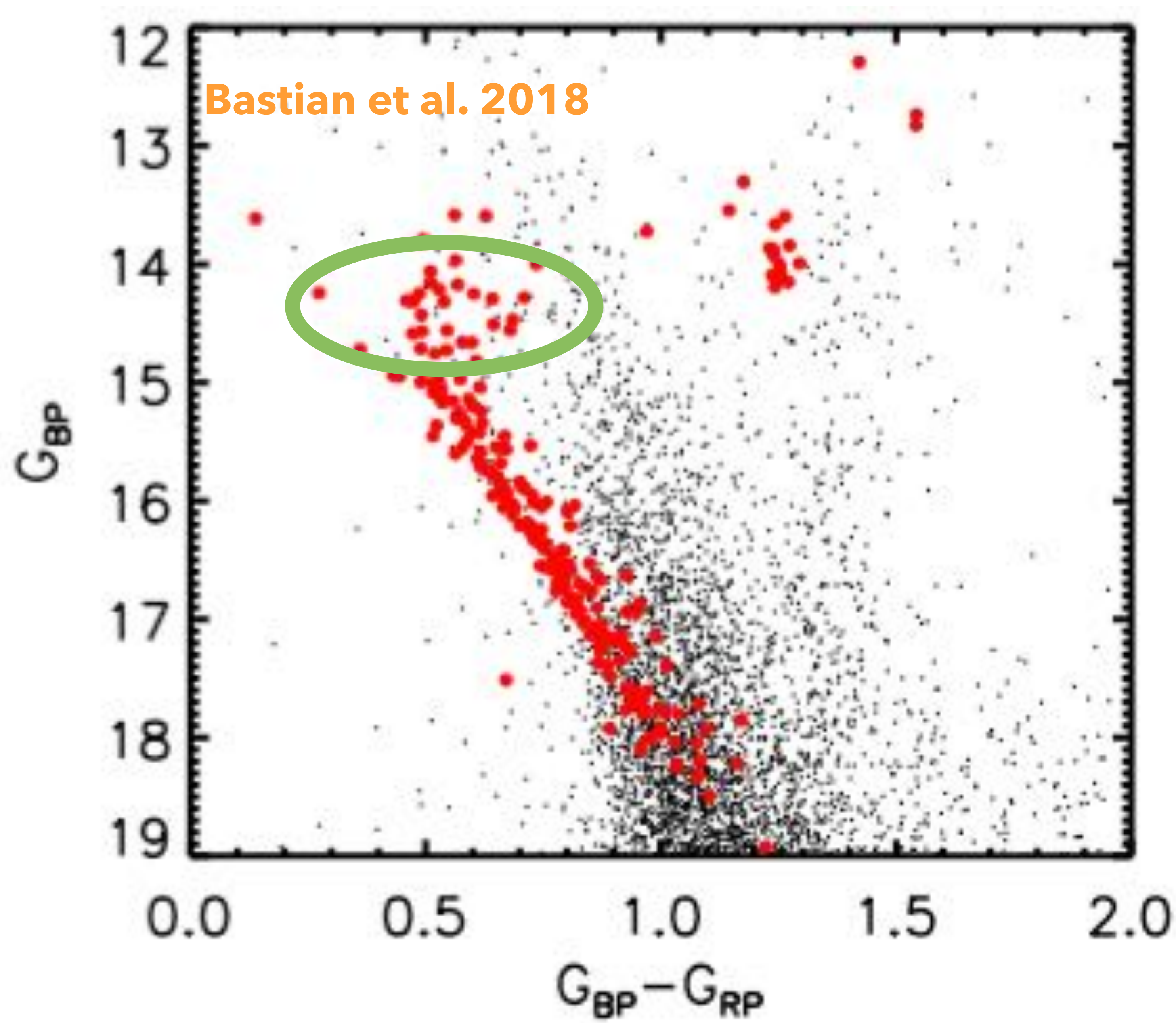




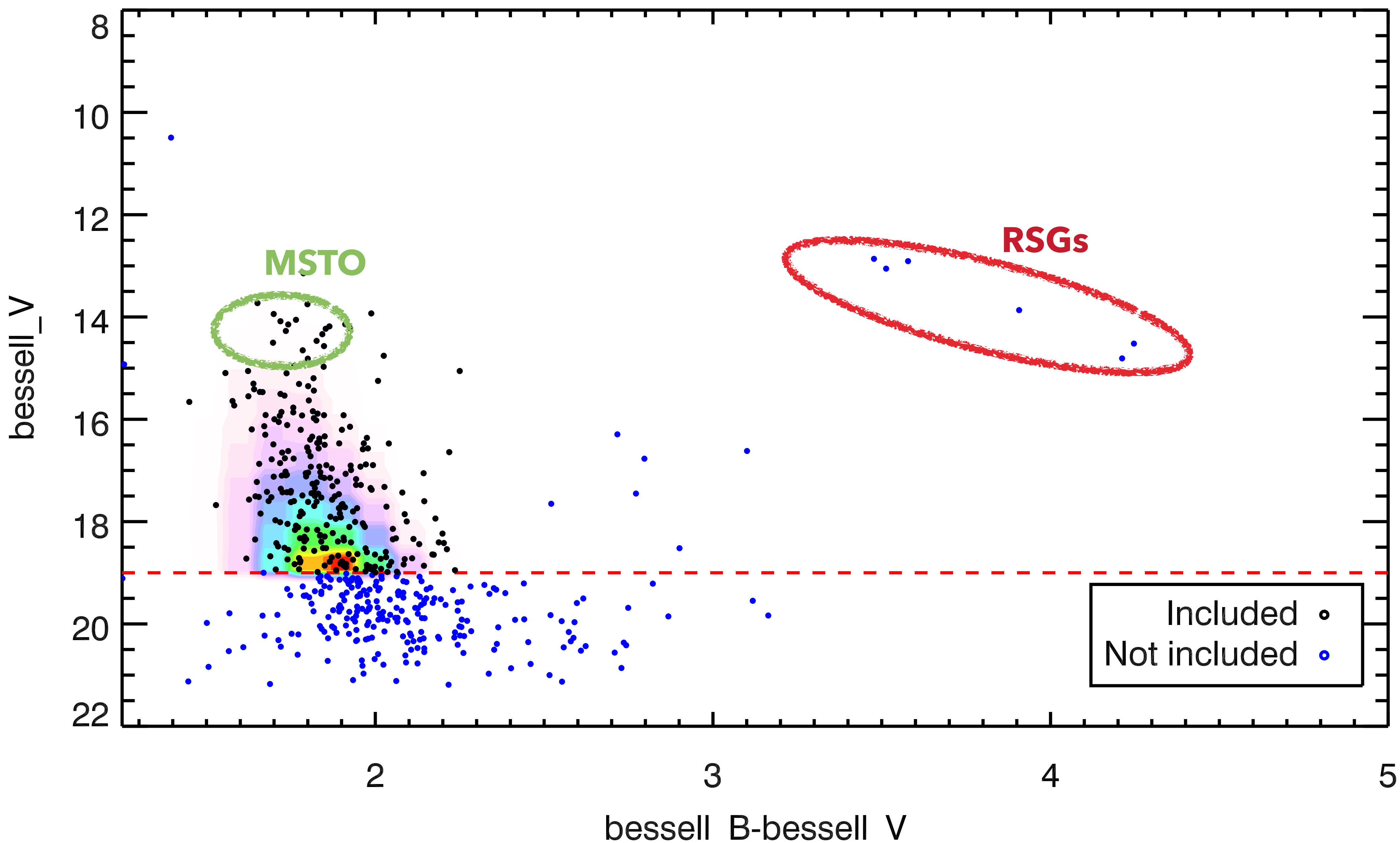


USING THE CMD

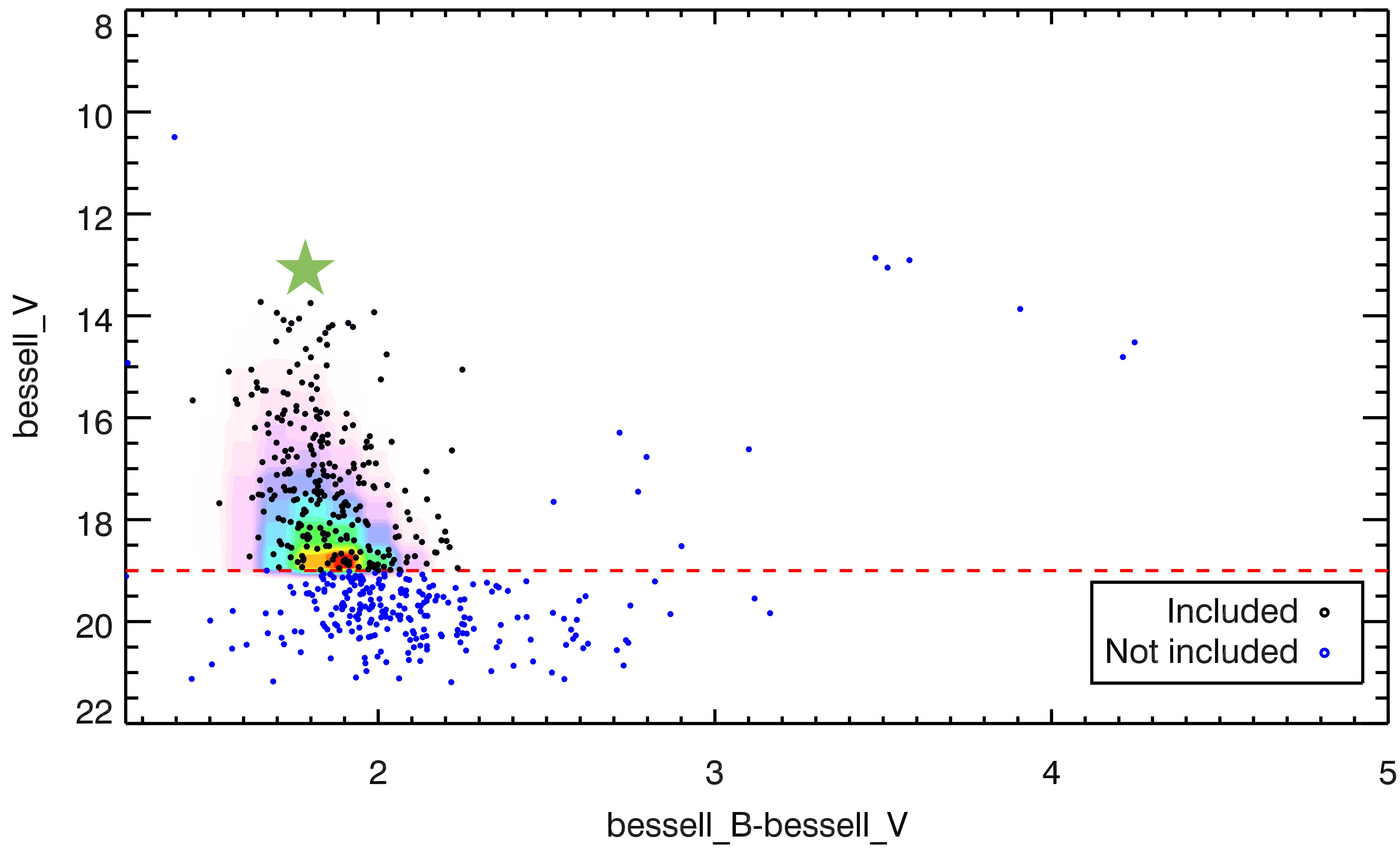
- For old and intermediate age clusters (>50Myr), many observational effects can't be explain by SSP…
- e.g. blue stragglers



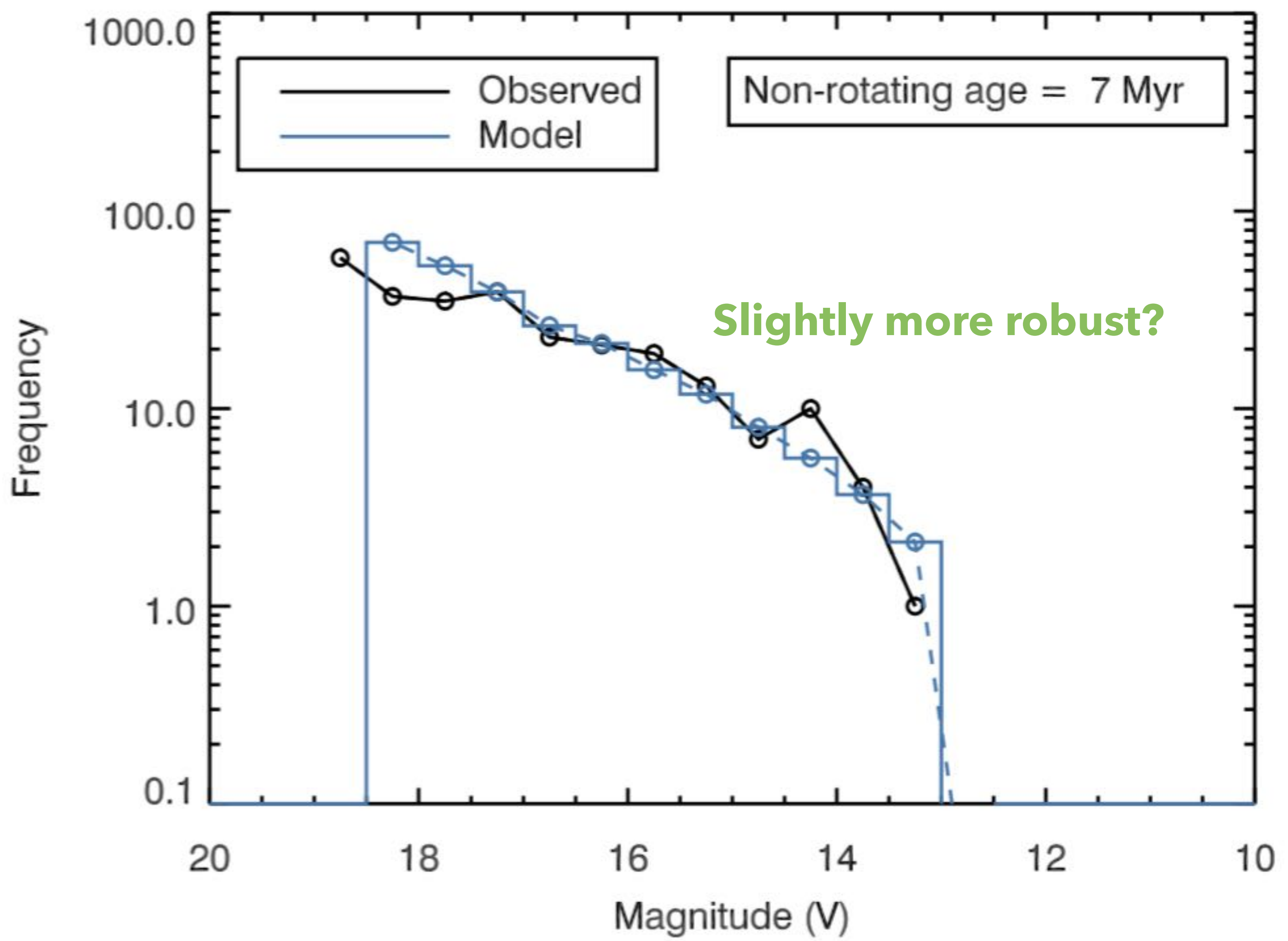
CMD of NGC 7419



METHOD 1: brightest TO star

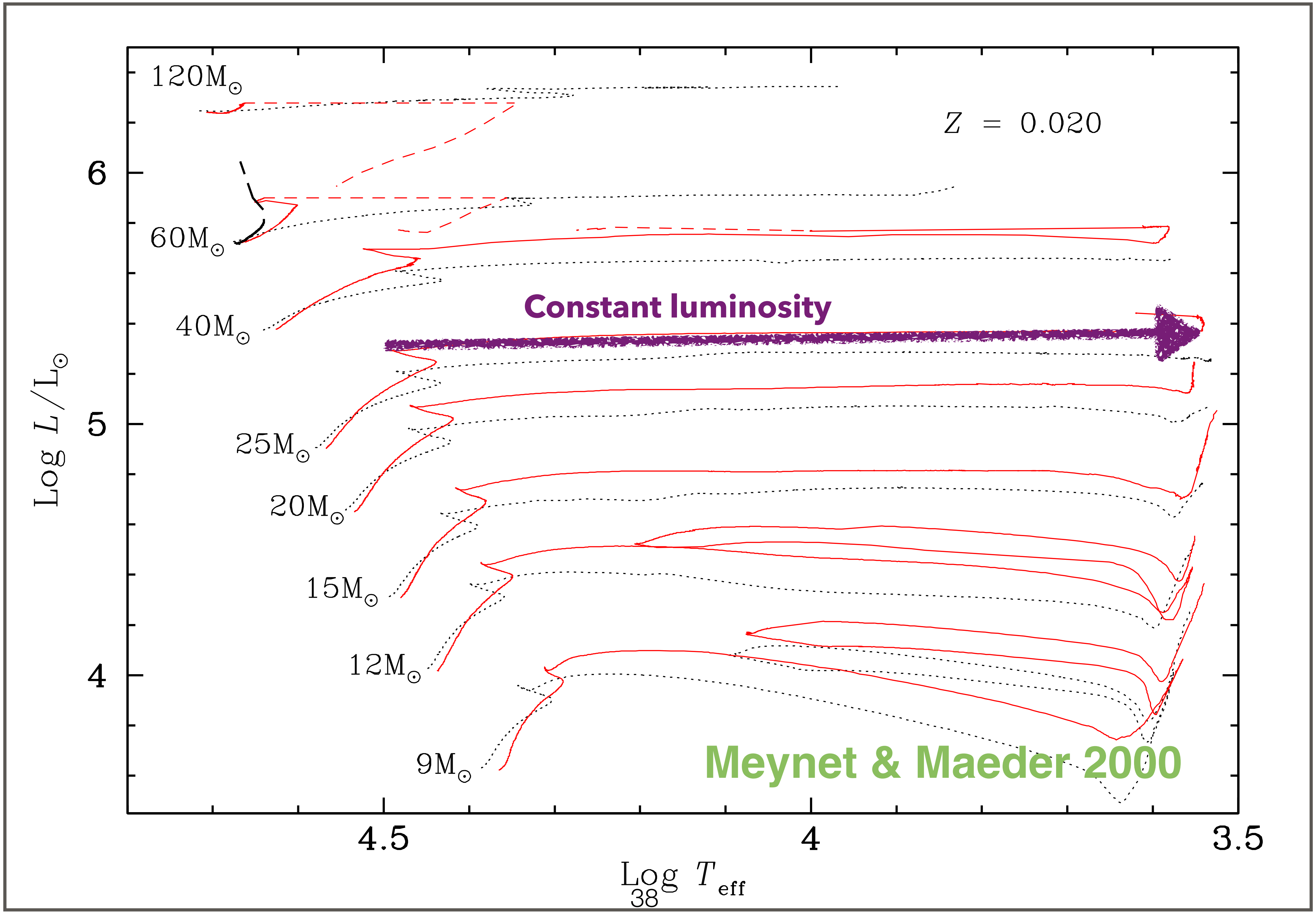


METHOD 2: luminosity function of the TO

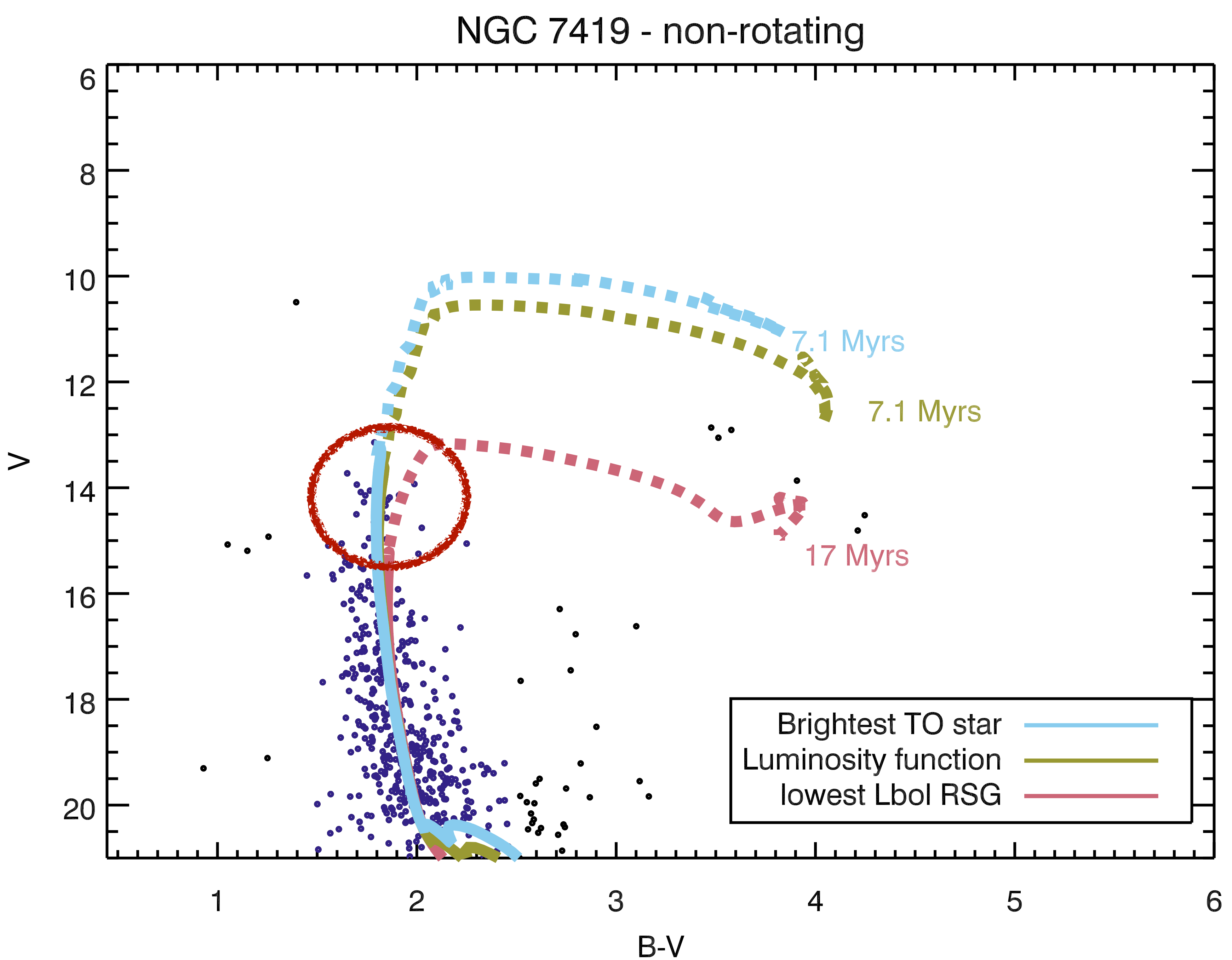


Slightly more robust?

METHOD 3: lowest luminosity RSG



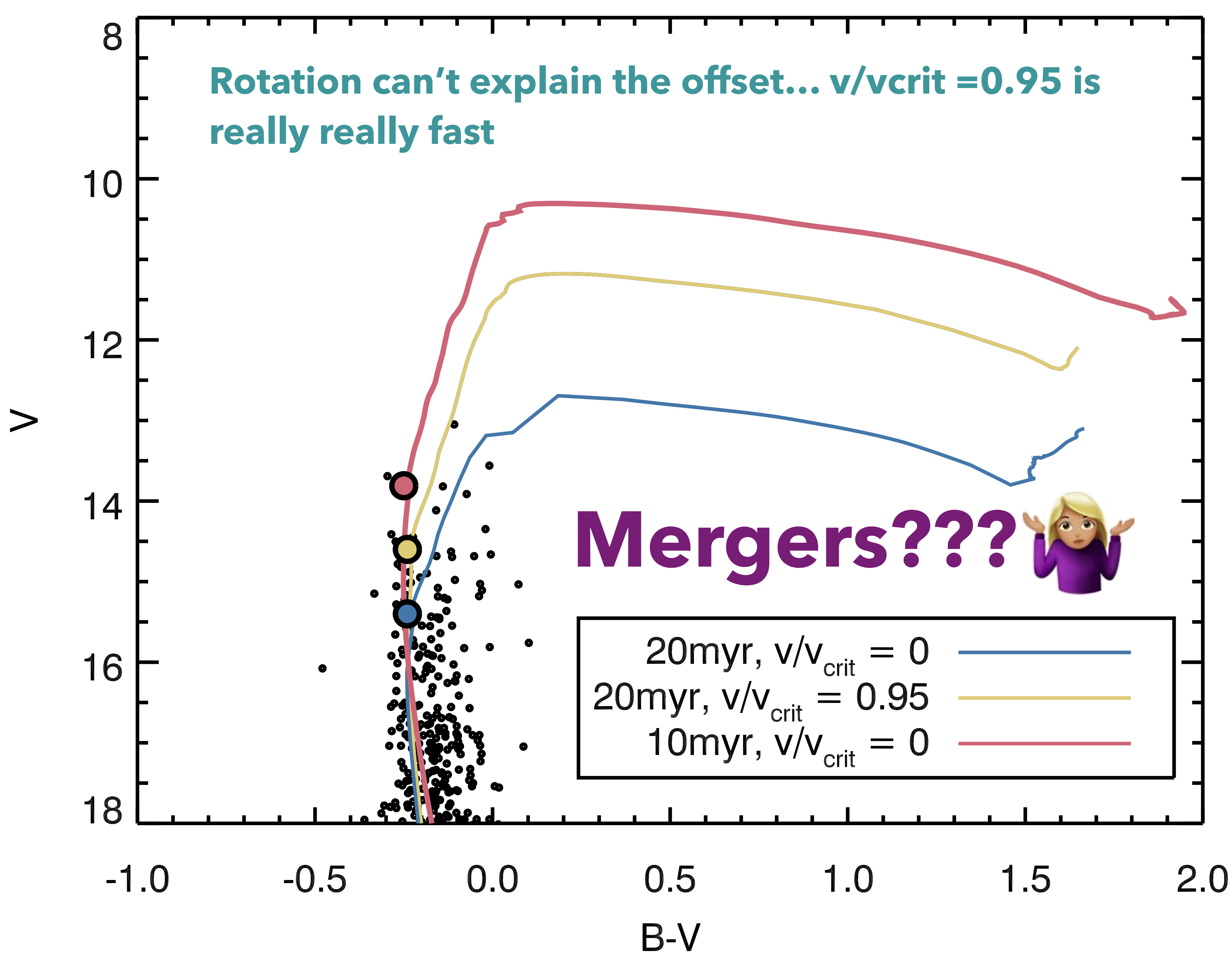
Results...



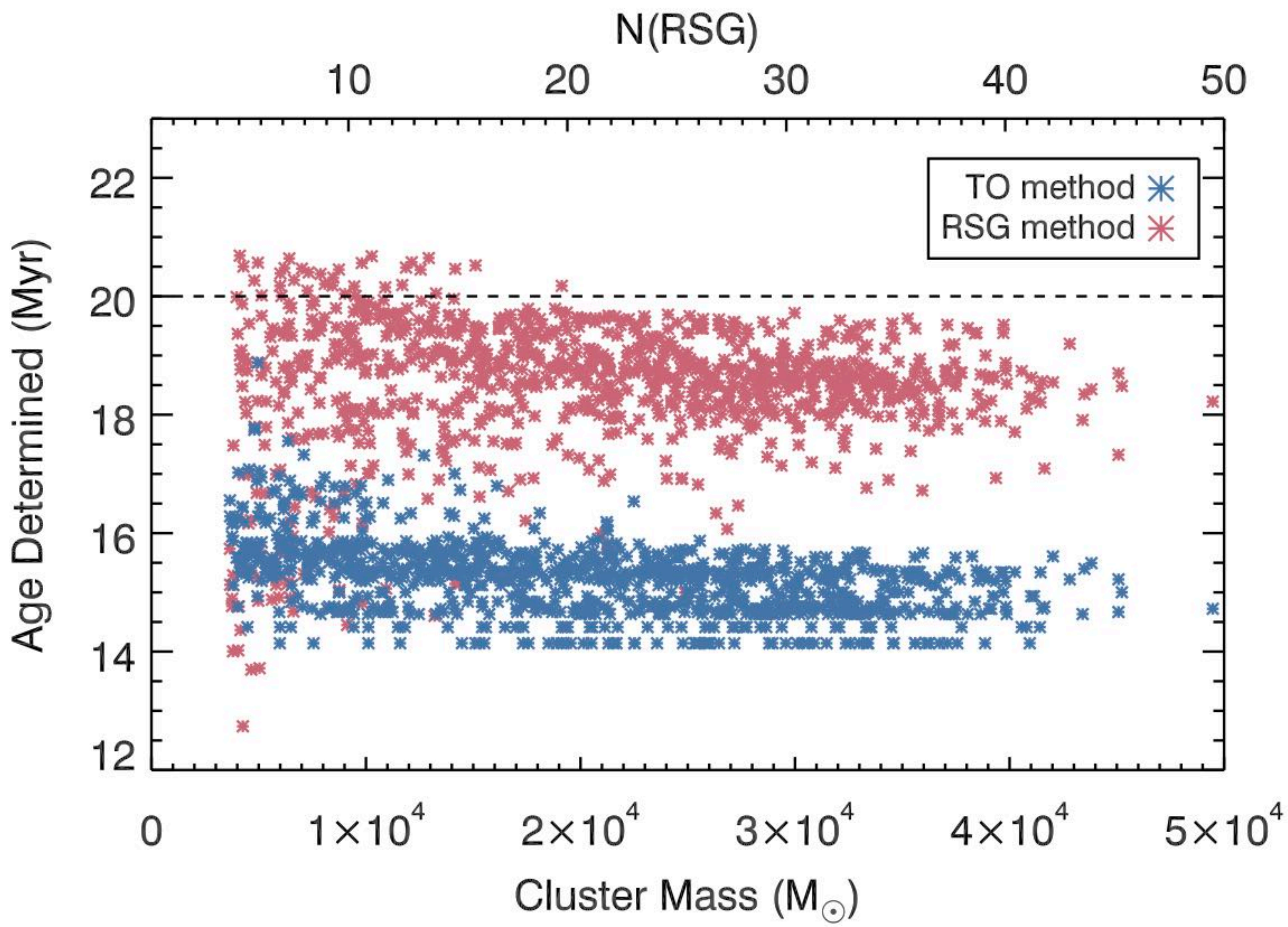
Big disagreement in ages between the methods

This is seen for **all** clusters in our sample

What's going on..?

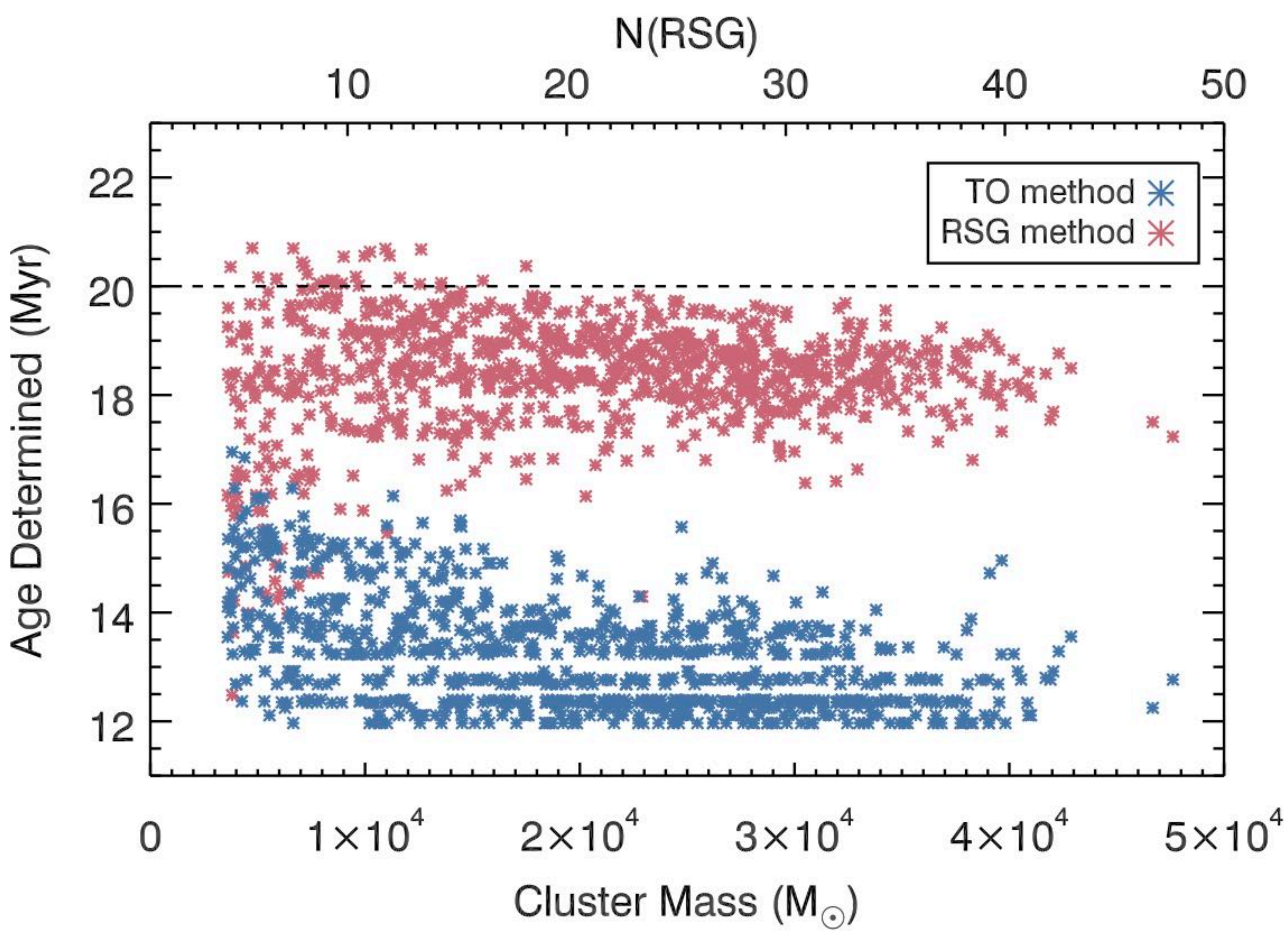


Testing with synthetic clusters… - single stars



Single stars only. TO method underestimates the age by quite a lot

Testing with synthetic clusters…
- binary fraction of 50%

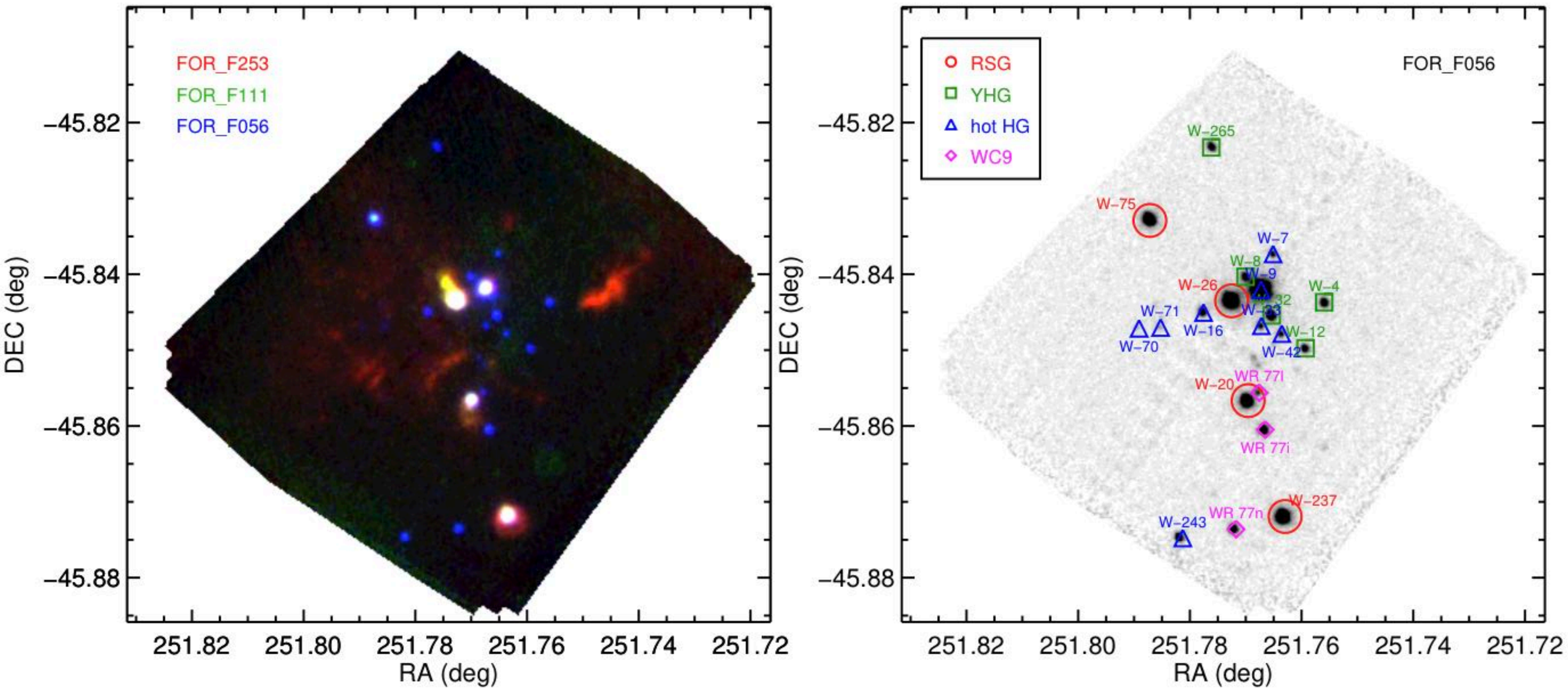


Binary fraction of 50%.

Even worse for TO…

RSGs do better.

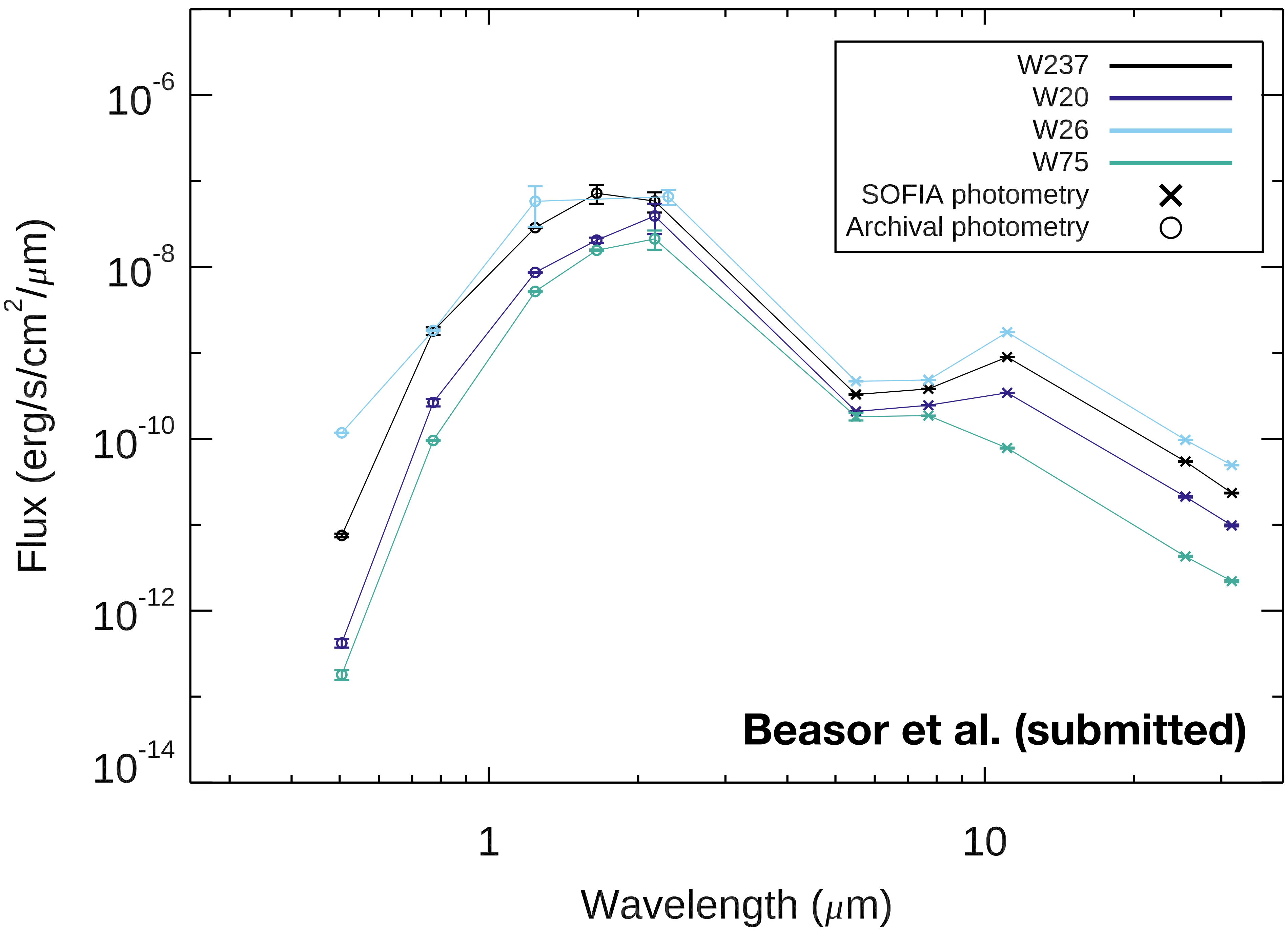
CASE STUDY: Westerlund 1



Beasor et al. (submitted)

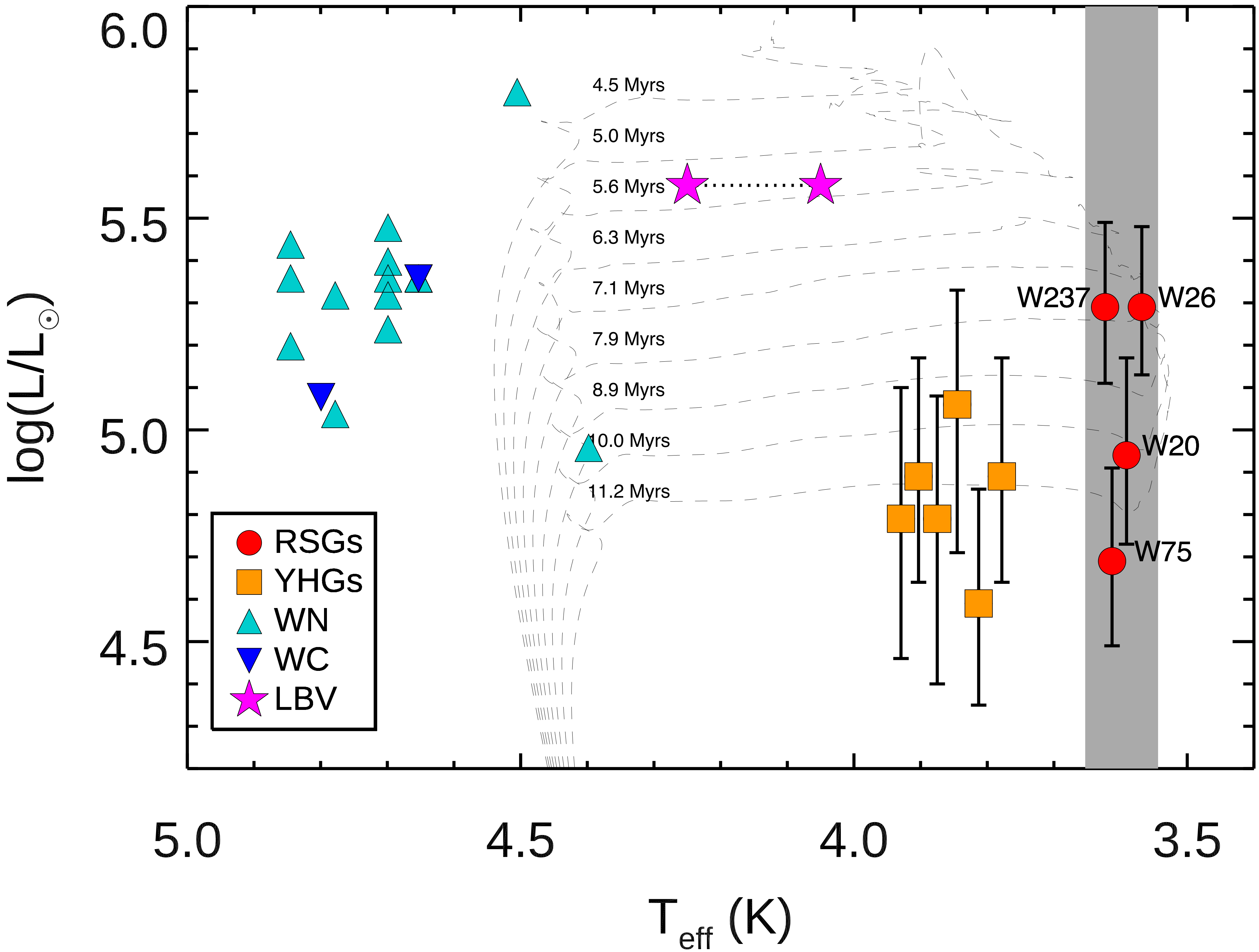
Supposedly a very young Galactic cluster (~4Myr), and massive (10^5 Msun).

CASE STUDY: Westerlund 1



First time we've been able to attempt a bolometric luminosity for these RSGs…

CASE STUDY: Westerlund 1



Beasor et al. (submitted)

CONCLUSIONS: Part 2

- Using the cluster turn-off to estimate age will cause ages to be *underestimated*
- Using red supergiants allows a *binary independent* age to be determined
- There could be lots of mergers/mass transfer systems in young clusters
- Westerlund 1 probably isn't as young as people first thought