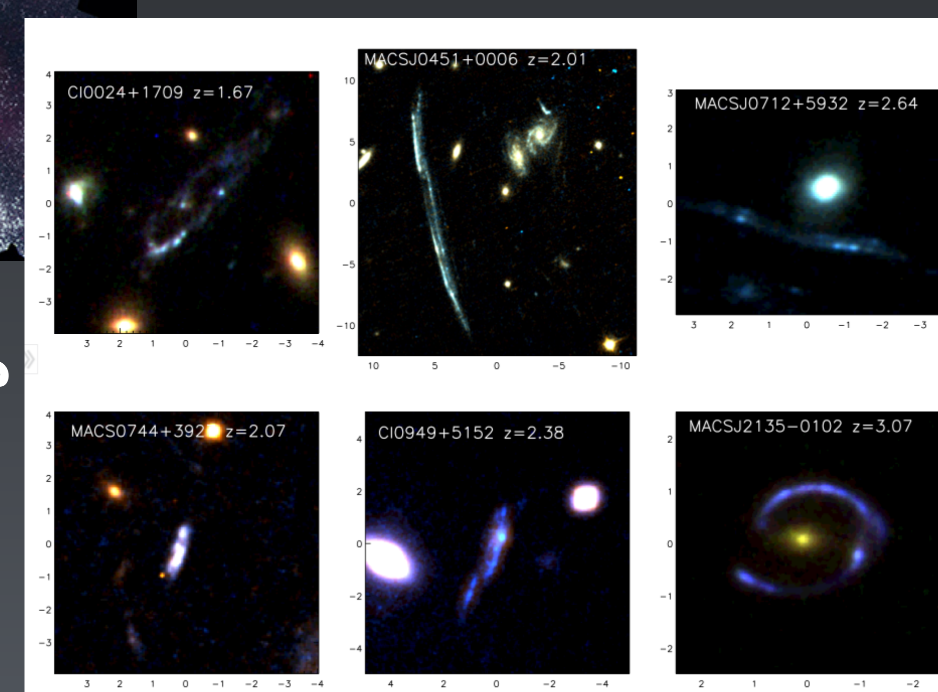
Lyman continuum production from single stars, binaries and stellar populations



Paul Crowther

The University Of Sheffield.

Summary (version for jet lagged audience)

Q. Where do LyC photons in non-active galaxies originate?

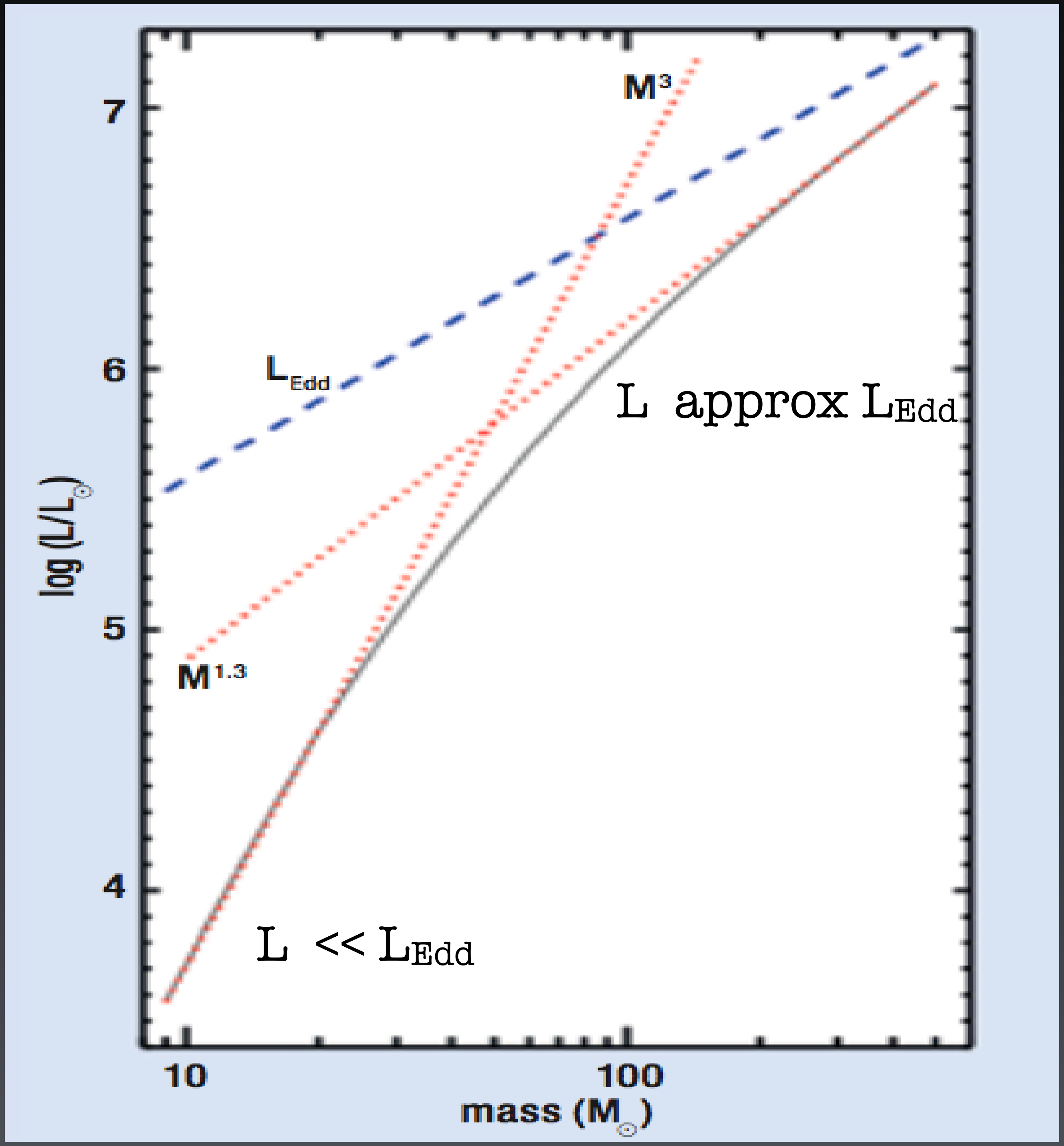
A. Really hot stars

Q. Really?

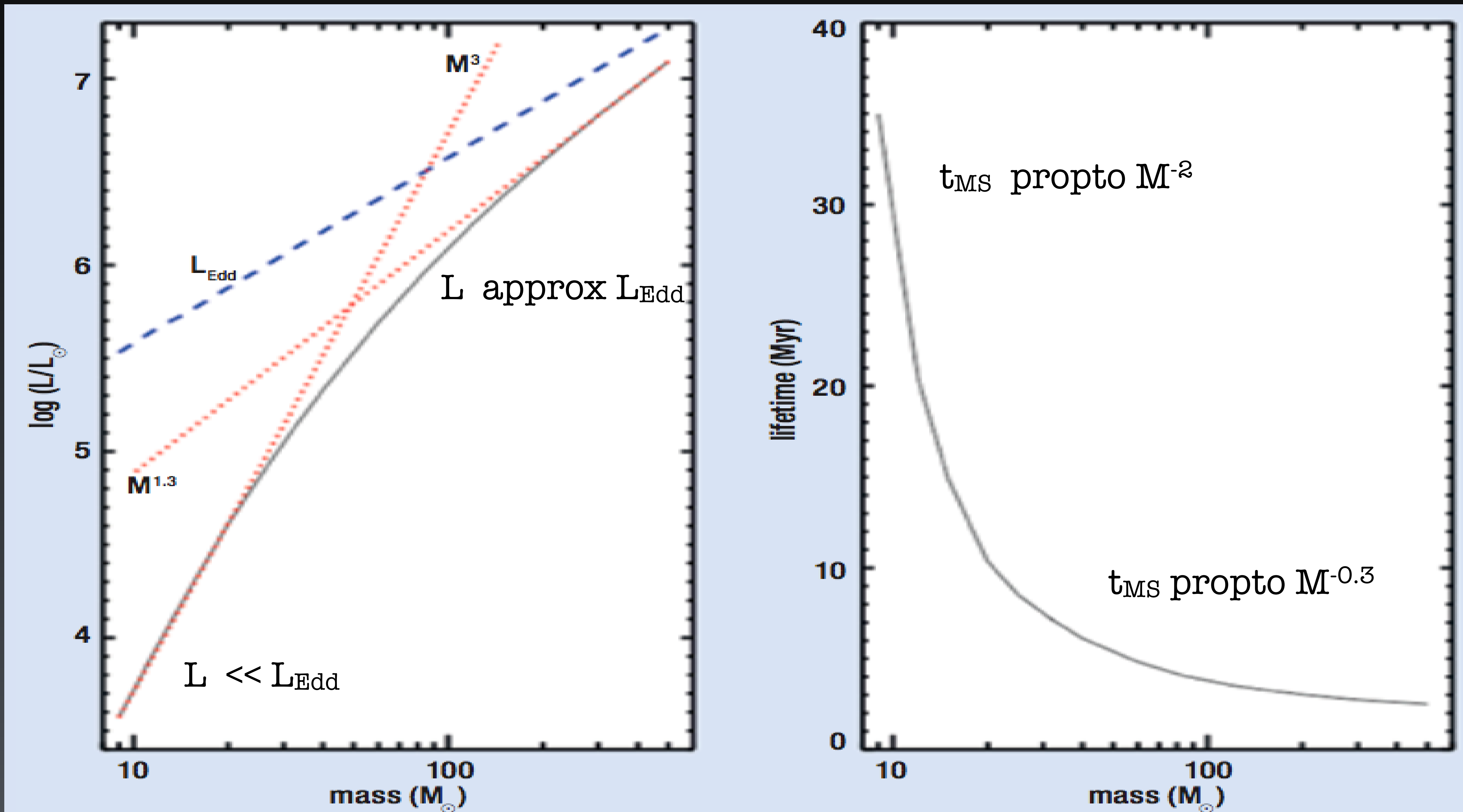
A. Yes, really luminous hot stars (some due to binary evolution)

OB STARS

Massive Stars?



Massive Stars?



Crowther (2012)

O stars dominate LyC production

TLUSTY (nonLTE; Lanz & Hubeny (2003)

T=55 kK

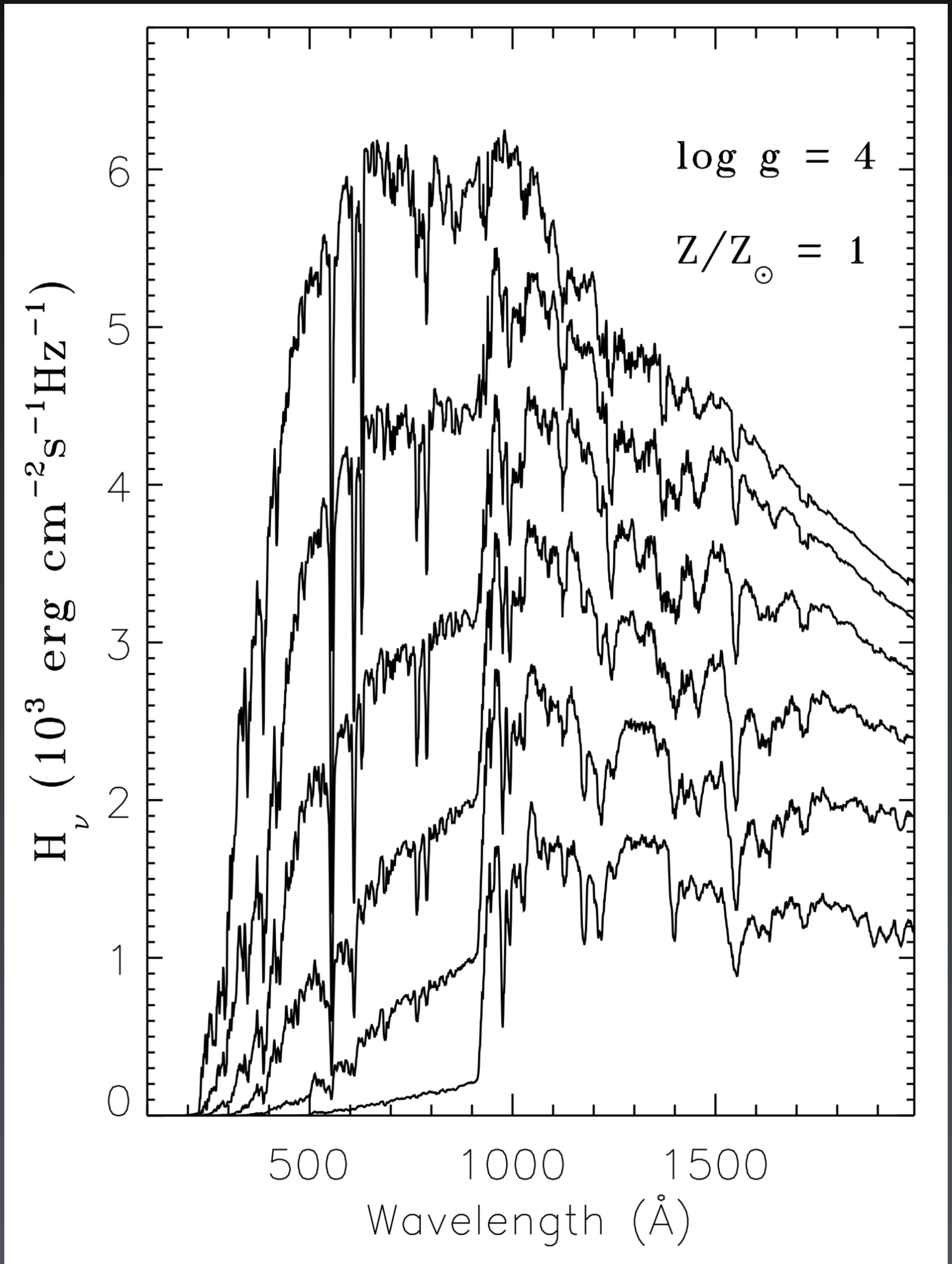
T=50 kK

T=45 kK

T=40 kK

T=35 kK

T=30 kK



$L_{EUV}/L_{Bol} = 0.72$

$L_{EUV}/L_{Bol} = 0.66$

$L_{EUV}/L_{Bol} = 0.52$

$L_{EUV}/L_{Bol} = 0.38$

$L_{EUV}/L_{Bol} = 0.19$

$L_{EUV}/L_{Bol} = 0.03$

O stars dominate LyC production

TLUSTY (nonLTE; Lanz & Hubeny (2003)

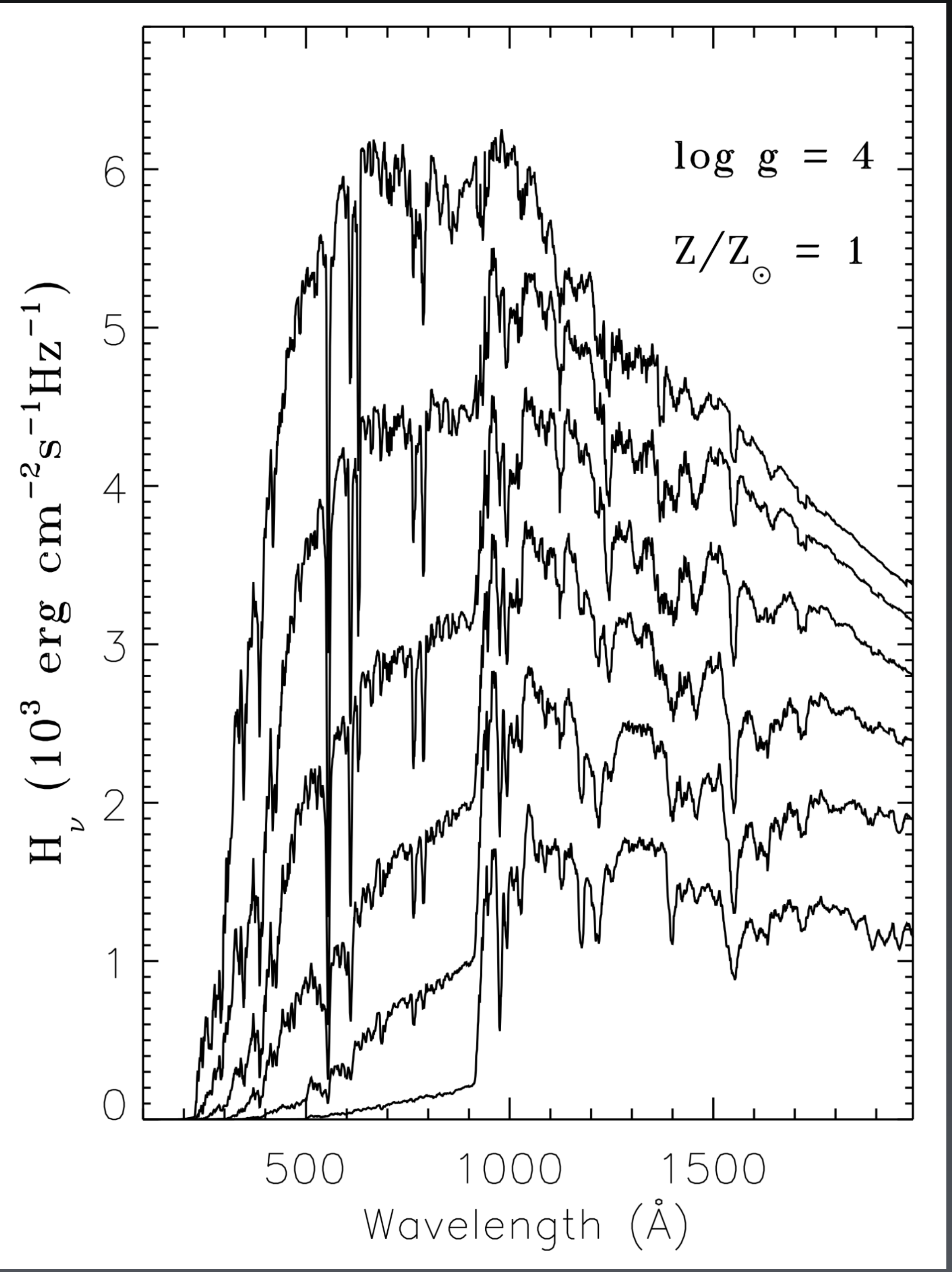
M=100 M_{sun}

M=70 M_{sun}

M=45 M_{sun}

M=30 M_{sun}

M=20 M_{sun}



log L_{Bol} = 6.0

log L_{Bol} = 5.8

log L_{Bol} = 5.5

log L_{Bol} = 5.1

log L_{Bol} = 4.6

OB stars

m(cluster)=4000 Msun + Salpeter IMF (log N(LyC)=50.1)

Spectral Type	<Mass> (Msun)	N	τ_{MS} (Myr)	% of N(LyC)
O3V	70	1	4	37%
O6V	40	2	5	30%
O5V	50	2	6	17%
O8V	32	3	7	9%
O9V	25	4	8.5	5%
B0V	20	4	10	0.8%
B1V	15	12	15	0.2%
B2V	9	42	35	0.01%

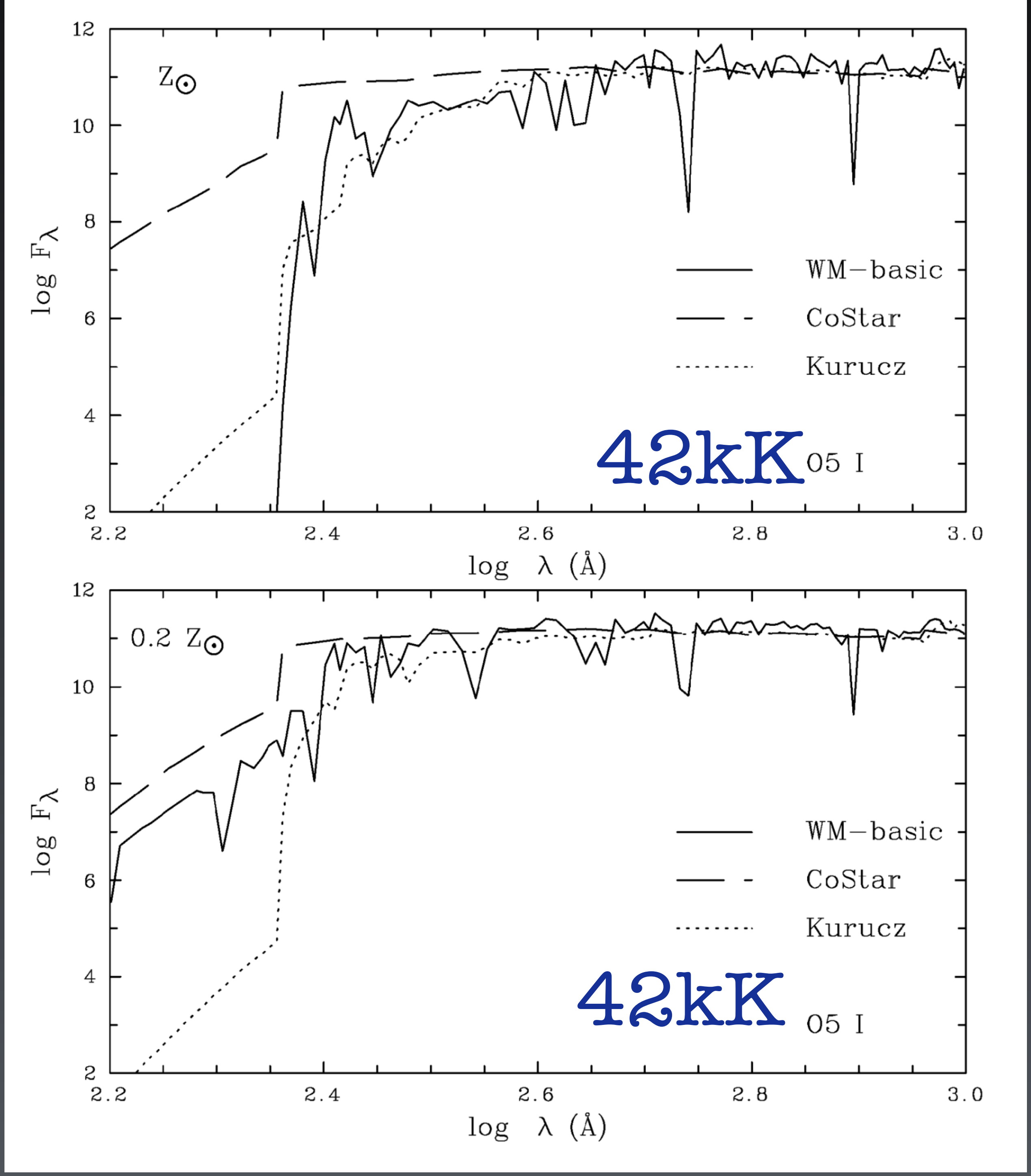
Ionizing output of s.f. galaxies are dominated by rare, short-lived O-type stars (>20 M_{sun}), not their more numerous B-type cousins

OB star model atmospheres

Smith, Norris & Crowther (2002)

Zsun

0.2 Zsun

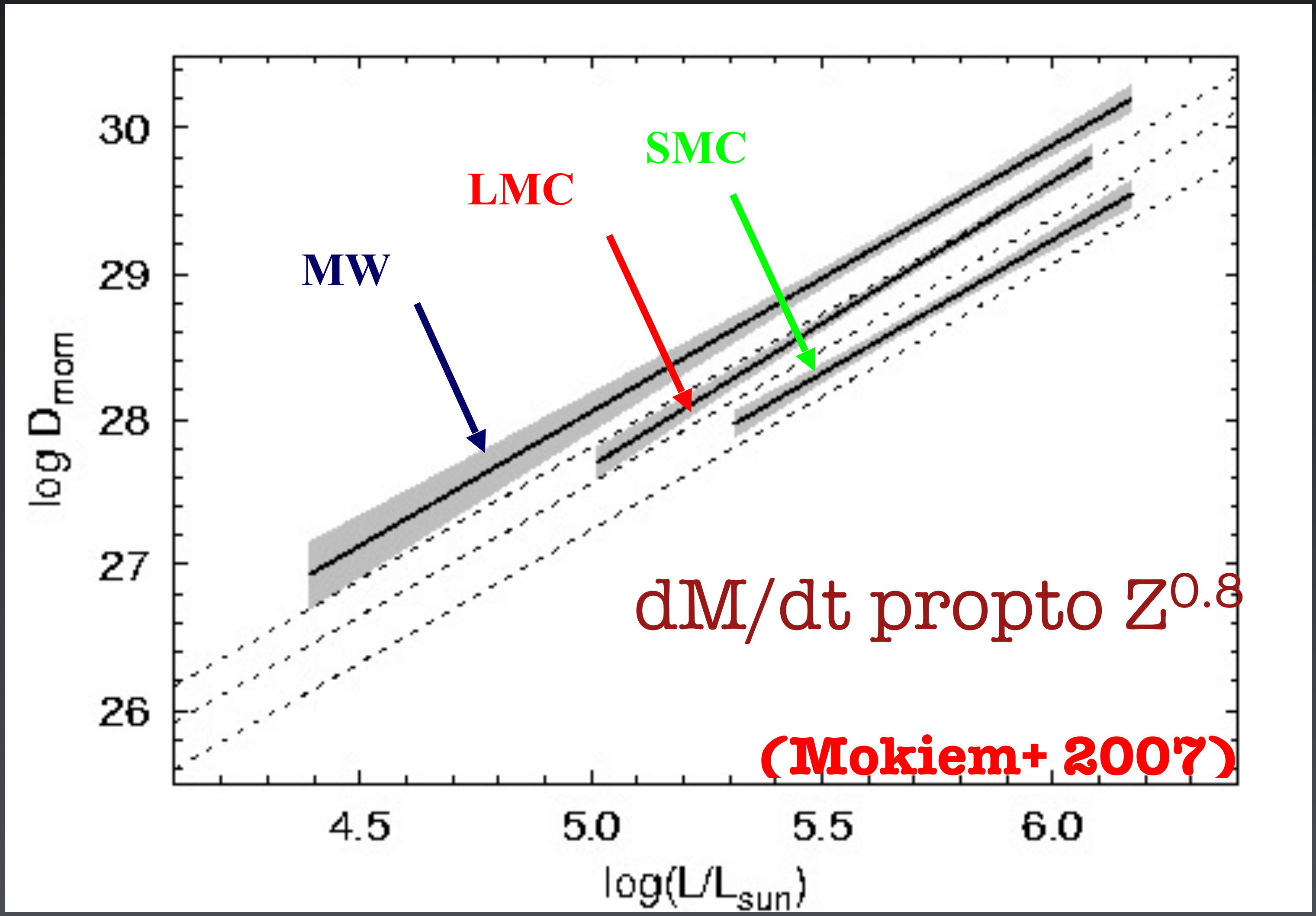


LTE plane parallel: ATLAS (Kurucz)
nonLTE plane parallel: TLUSTY (Hubeny & Lanz)
Spherical geometry: WM-basic (Pauldrach), CMFGEN (Hillier), FASTWIND (Puls) & PoWR (Hamann)

Indirect role of metallicity

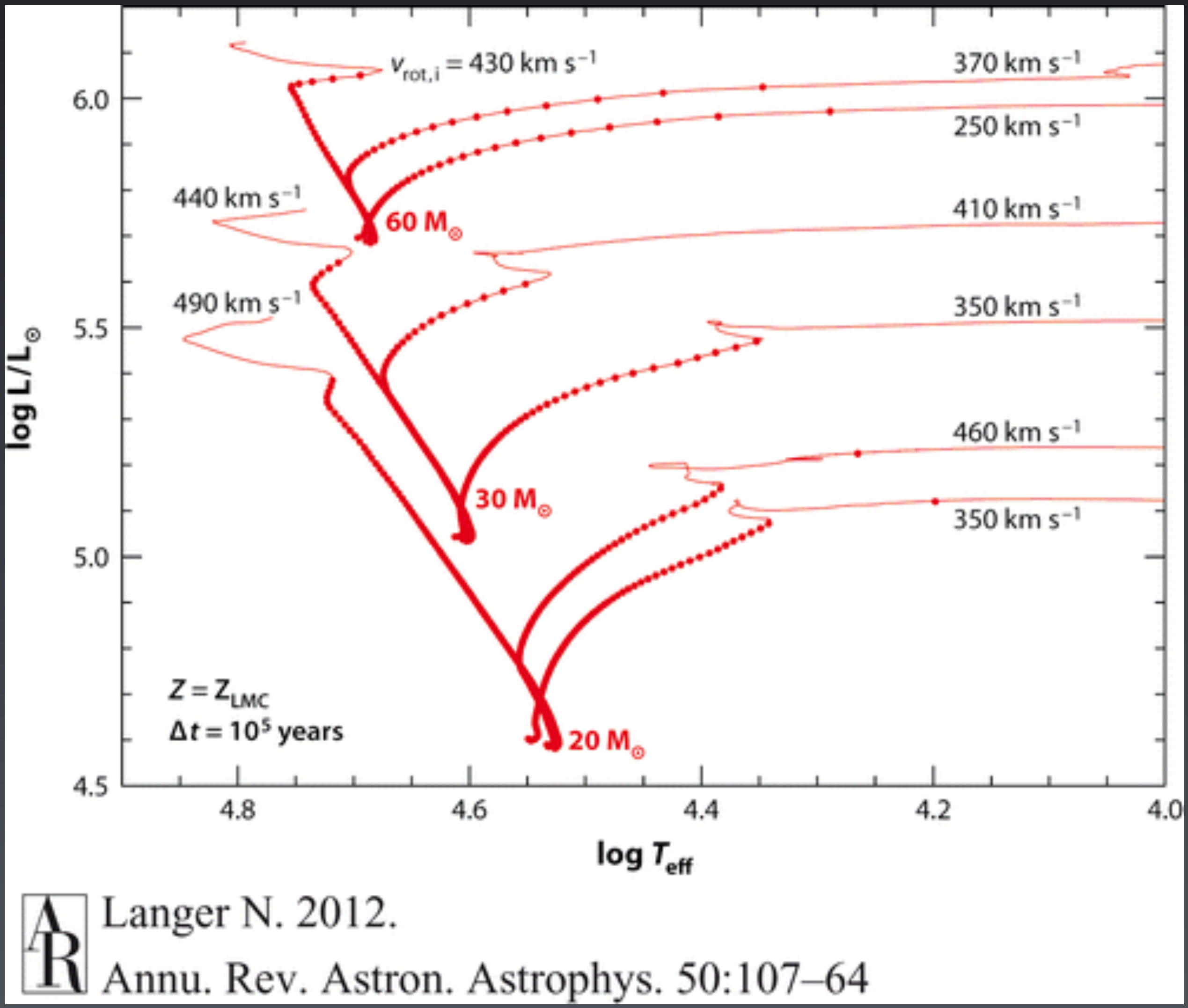
D_{mom} = dM/dt * v_{inf} * sqrt(R)

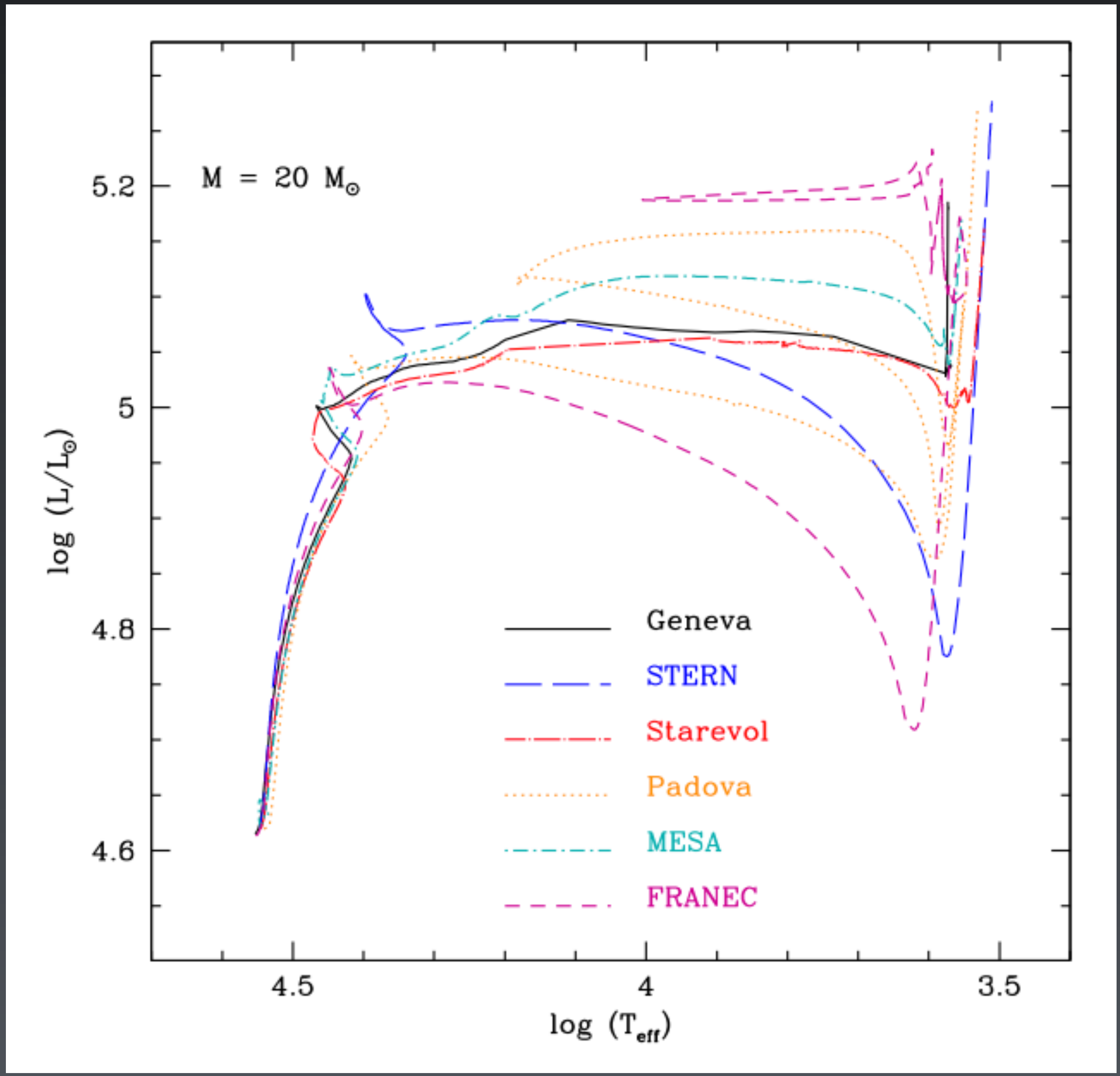
Weaker O star winds at low Z (owing to metal line-driven winds) influences evolution.



Evolutionary models & N(LyC)

No significant enhancement of LyC production from evolutionary models unless very high rotation rates ("homogeneous evolution") although significant differences between codes.

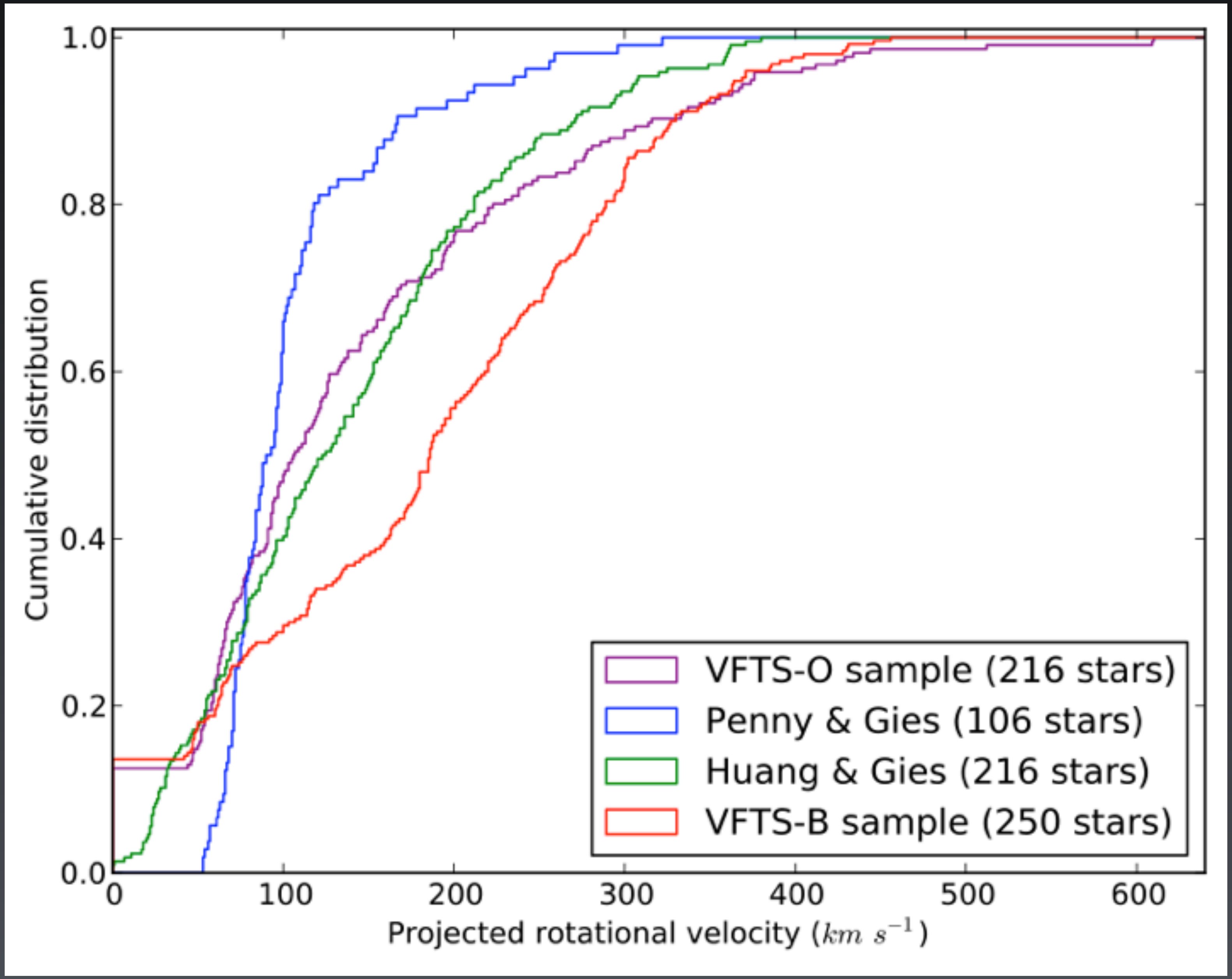




Martins & Palacios 2013

Rapid rotation in OB stars?

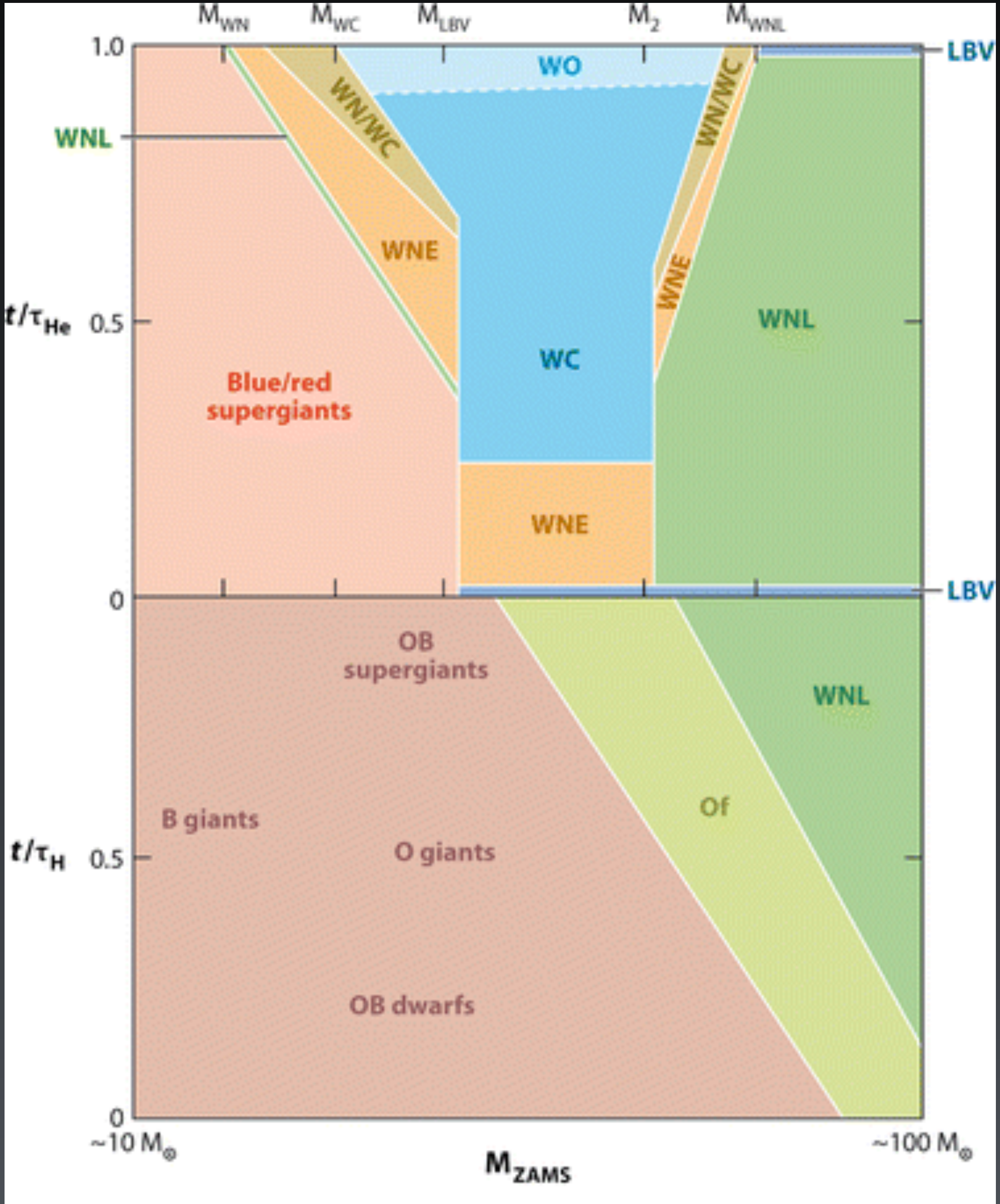
Quasi-homogeneous evolution restricted to fastest rotators (>400 km/s) which involves only a few % of O stars in Milky Way, LMC (e.g. VFTS Ramirez+ 2013)



Wolf-Rayet Stars

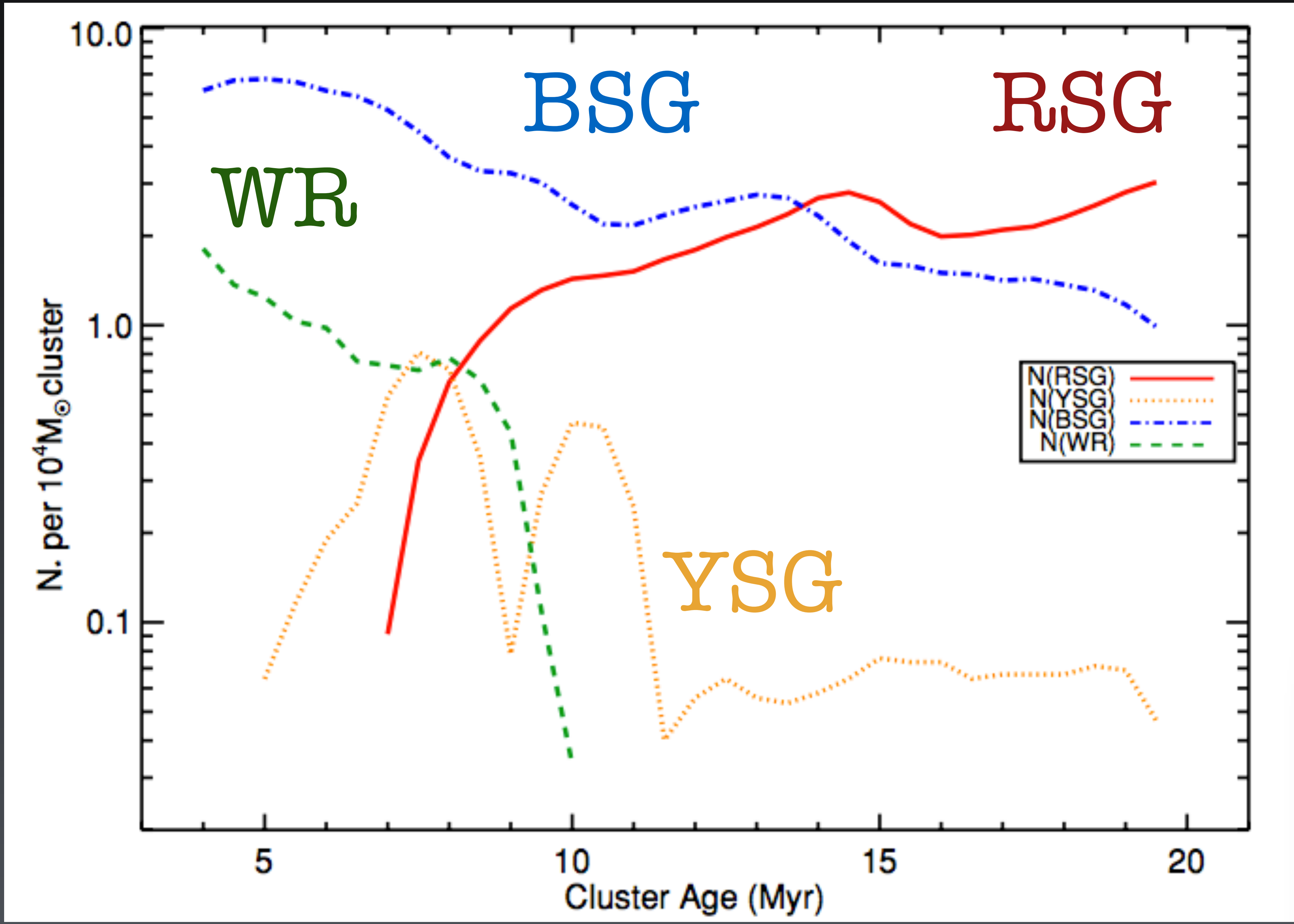
Wolf-Rayet stars

- Classical WR stars arise from stripping of envelopes of massive O star progenitors (>20-25 Msun) to reveal naked cores. Two primary flavours: WN (He, N rich), WC (C, O, He).
- Luminous H-rich WN stars are main sequence very massive stars (>100 Msun)
- Some HII galaxies show WR features in integrated light ("WR galaxies")



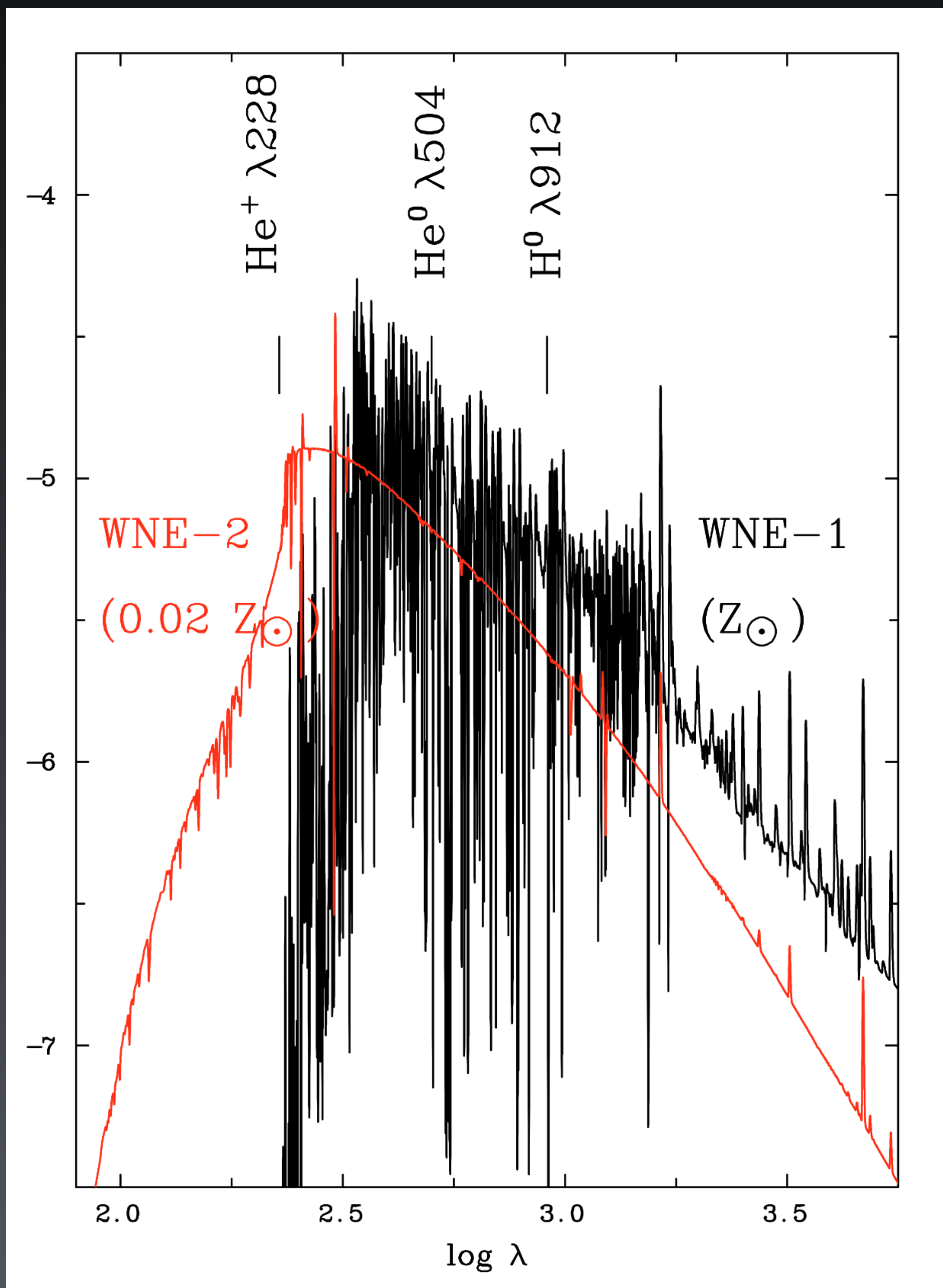
Langer N. 2012.
Annu. Rev. Astron. Astrophys. 50:107–64

Age sensitive massive star populations

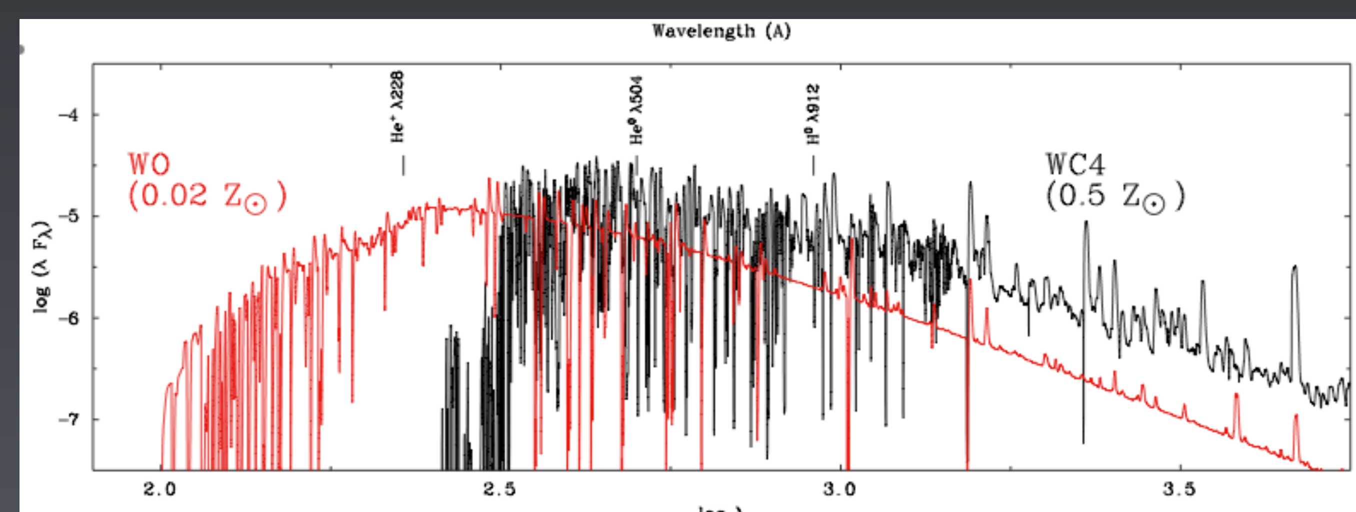


Davies+ 2009

Role of metallicity for WR stars?



WR stars produce copious N(LyC) fluxes, although at high Z, their winds suppress extreme UV ionizing output (harder EUV flux at low Z owing to weaker winds)

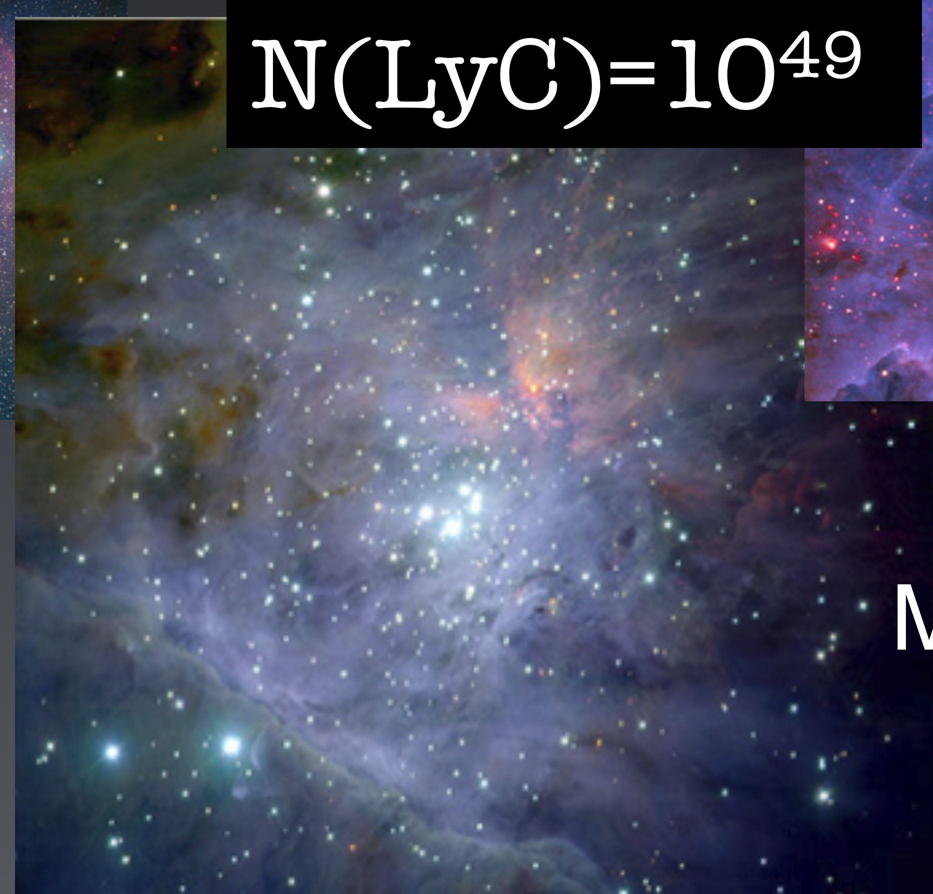


Crowther & Hadfield 2006

Young stellar populations

Massive star forming regions?

Upper "cluster" mass limit is truncated in galaxies with low star formation intensities (Gieles 2009; Cook+ 2012)



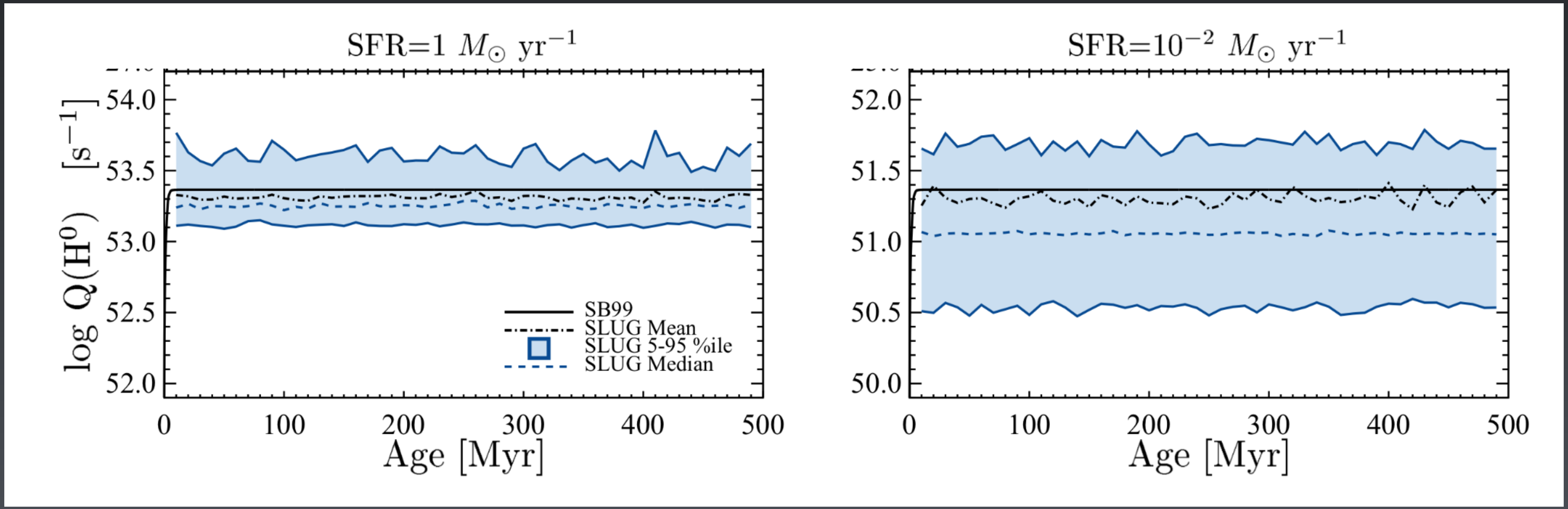
ONC (2×10^3 M_o)
M_{max}~35 M_o (θ^1C Ori)
N(LyC)=10^{49}

ρ Oph (10^2 M_o)
M_{max}~8 M_o (ρ Oph)
N(LyC)=10^{45}

NGC 3603 (10^4 M_o)
M_{max}~170 M_o (3603-B)
N(LyC)=10^{51}

Population synthesis (& stochasticity)

Stochastic effects become important for star clusters with masses below a few 10^4 Msun. Da Silva+ 2011 have developed SLUG (pop synthesis + Monte Carlo) to reflect stochasticity for low global s.f. Rates



Da Silva+ 2011

Very massive stars?

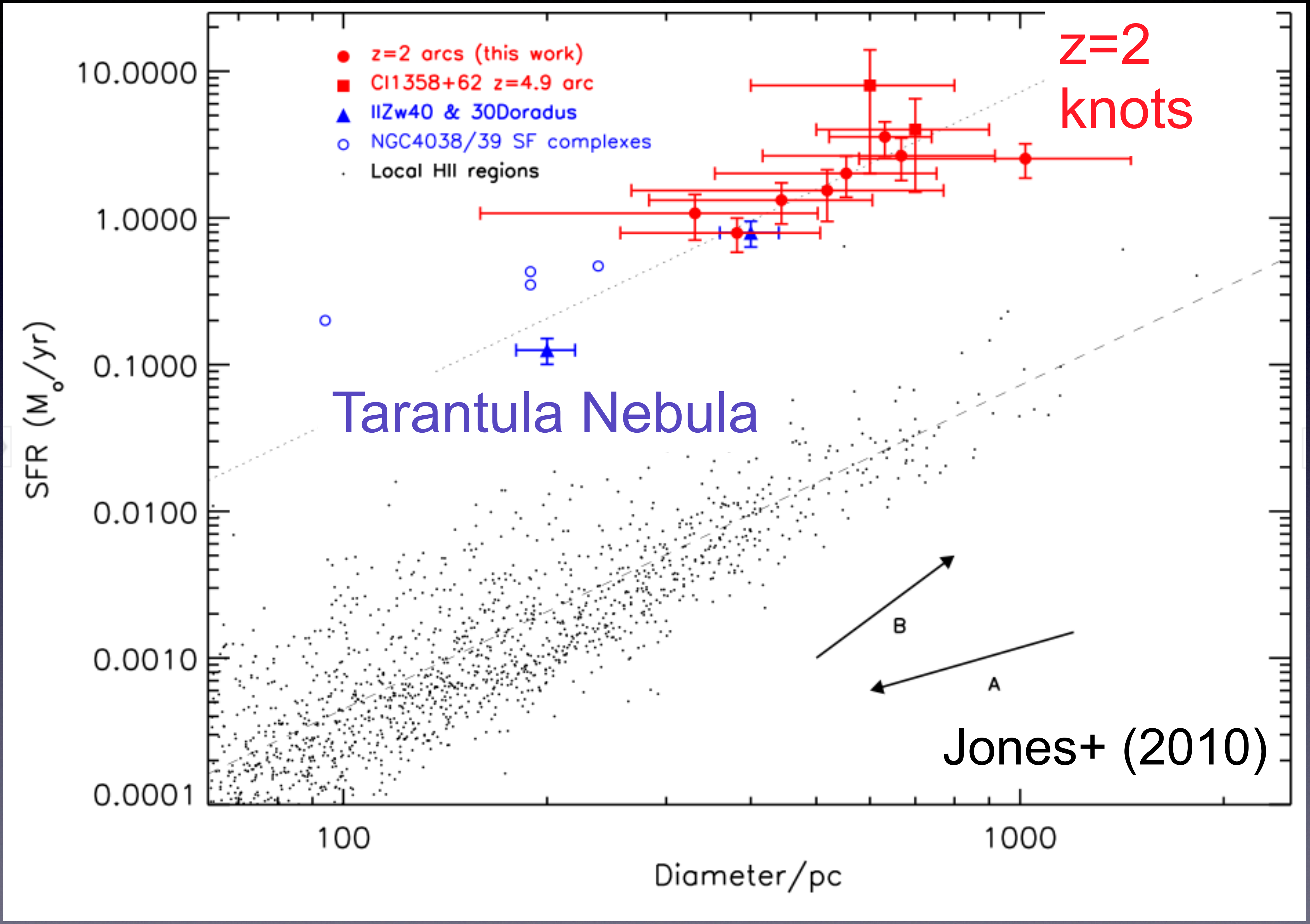
Population synthesis models usually set upper mass limit of 100 Msun. VMS absent from scaled OB associations (Cyg OB2) present in high s.f. intensity regions (e.g. R136 in 30 Dor)

$N(>100\ M_{sun})=0$ (Herrero+ 2002)

$M(CygOB2) \sim 5.10^4\ M_{sun}$

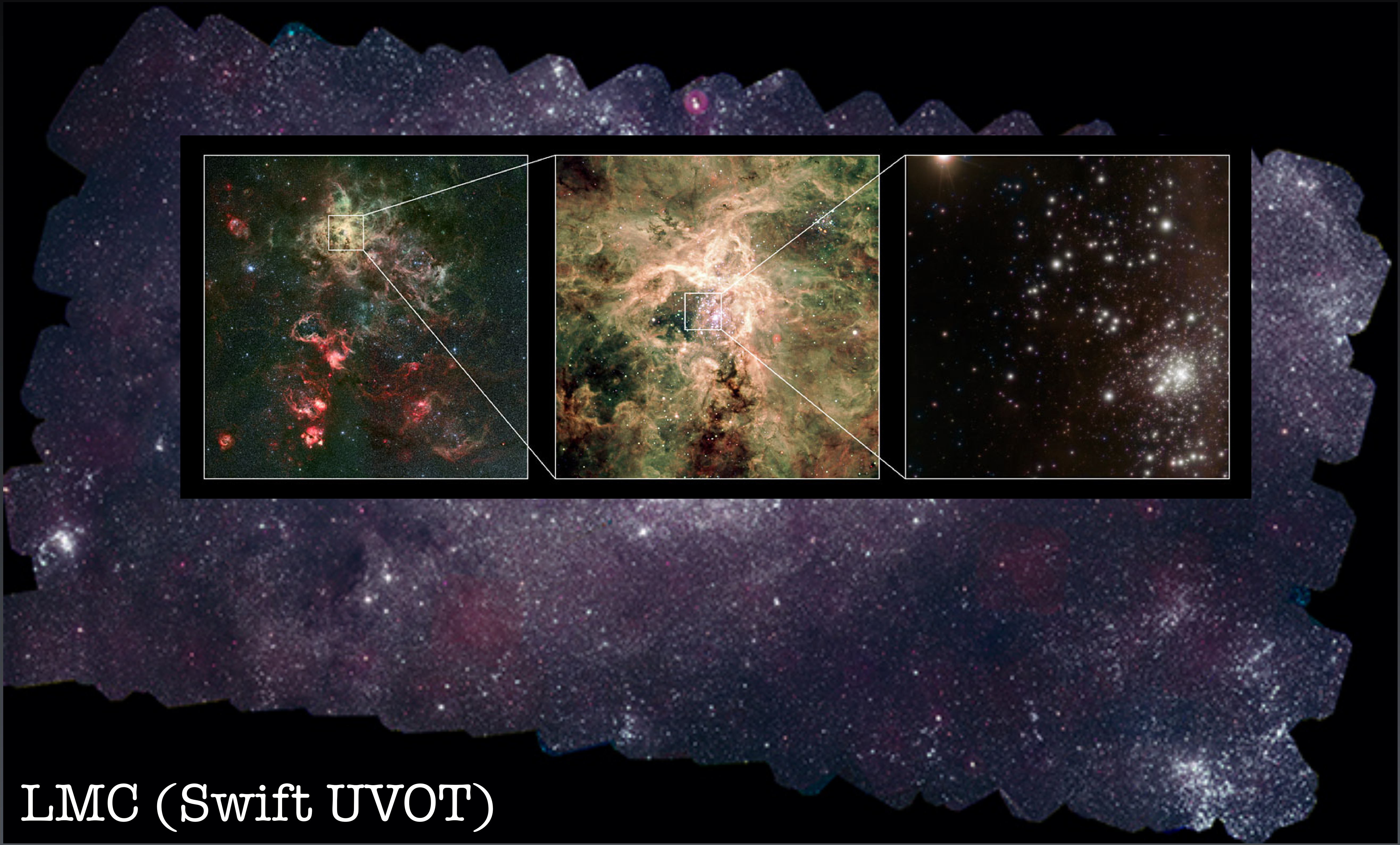
$N(>100\ M_{sun}) \sim 30$ (Crowther+ 2016)

$M(30\ Dor) \sim 10^5\ M_{sun}$



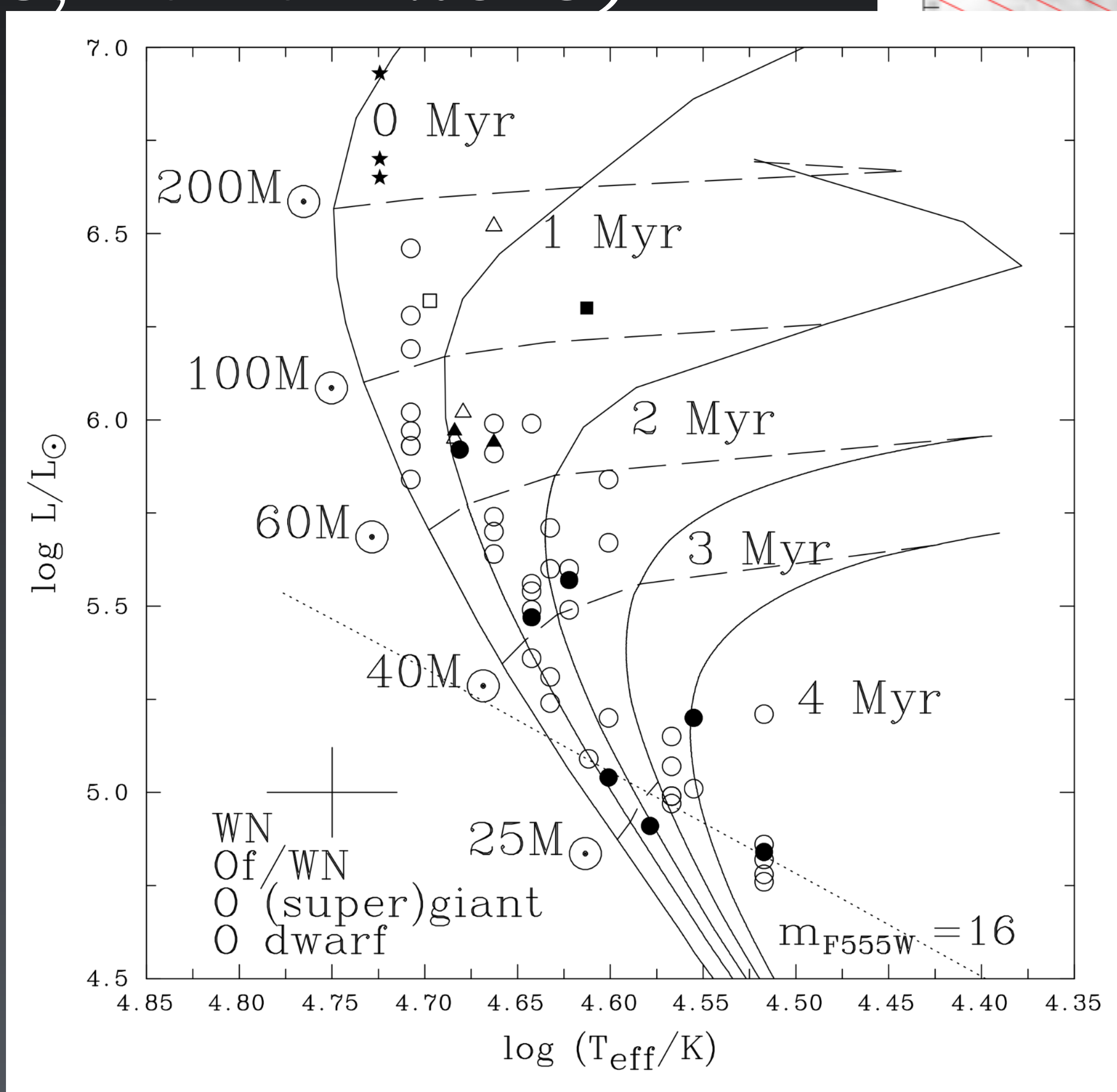
z=2 arcs (this work)
Cl1358+62 z=4.9 arc
IIZw40 & 30Doradus
NGC4038/39 SF complexes
Local HII regions
10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
SFR (M☉/yr)
100
1000
Diameter/pc
B
A
z=2
knots
Tarantula Nebula
Jones+ (2010)

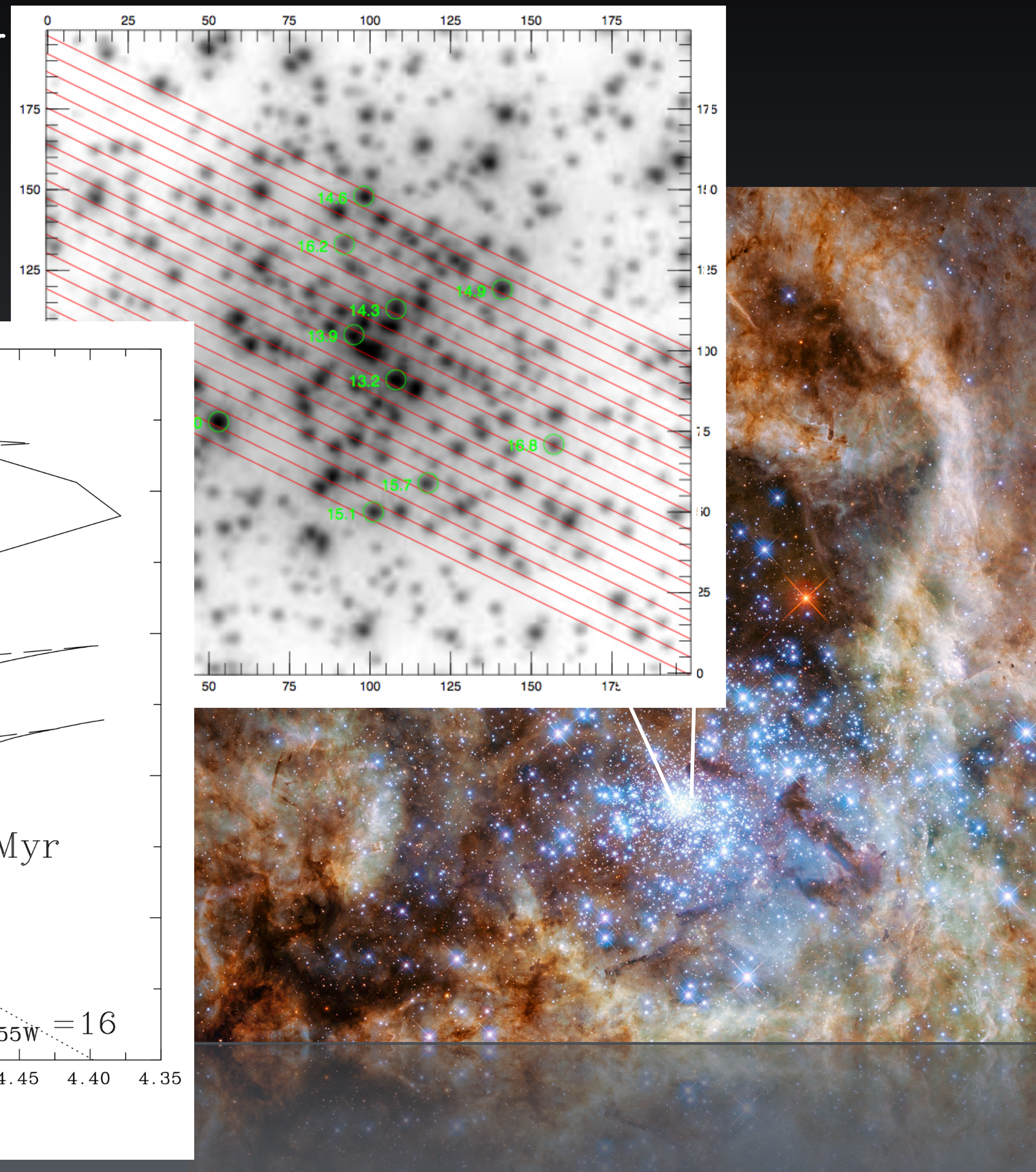
Starburst regions: Tarantula Nebula



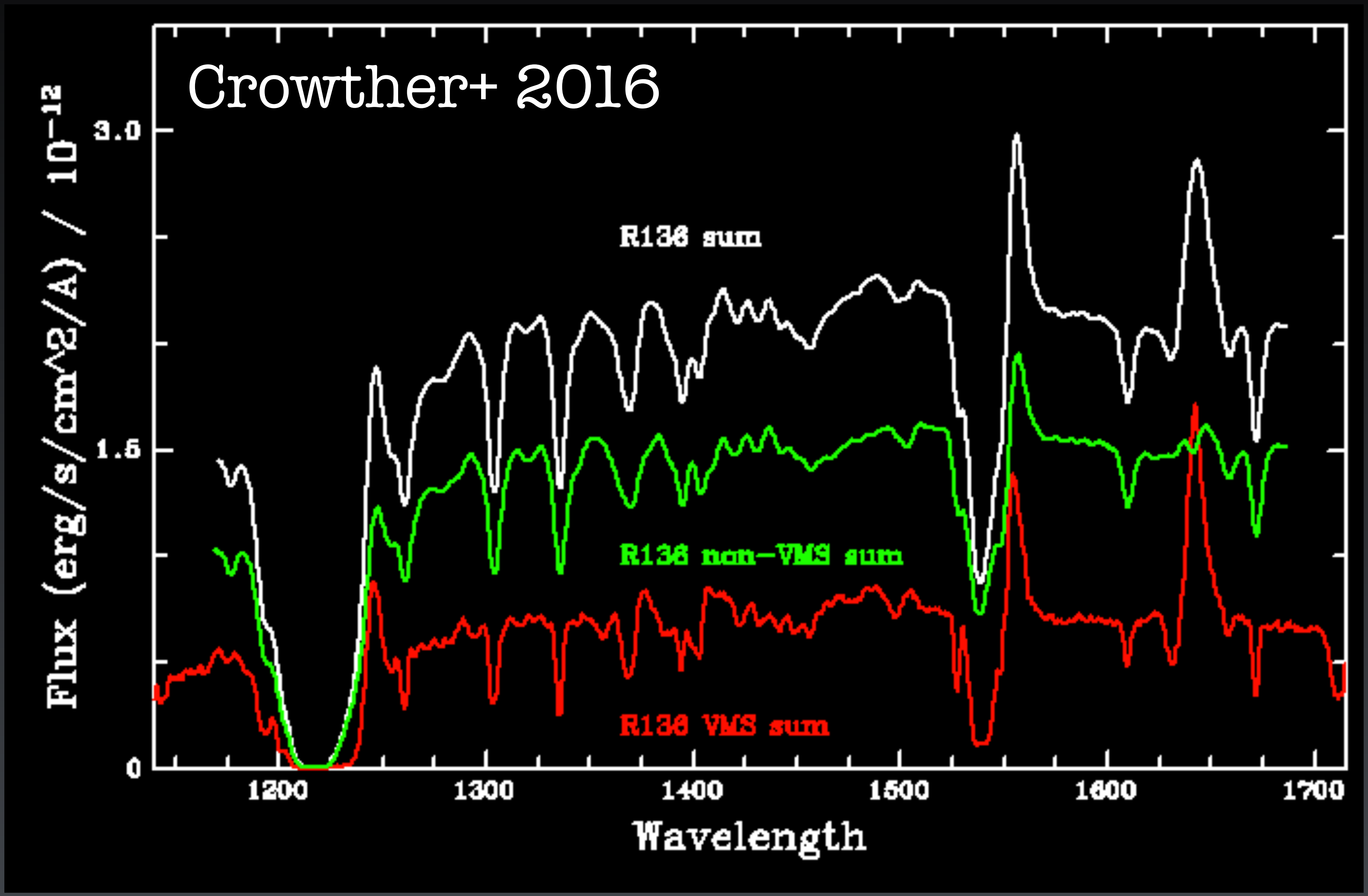
“My God.. its full of stars!”

STIS spectroscopy of every UV bright star in R136 (Crowther+ 2016). Models by (models by Yusof+ 2013; Kohler+ 2015)





R136 cluster dissected

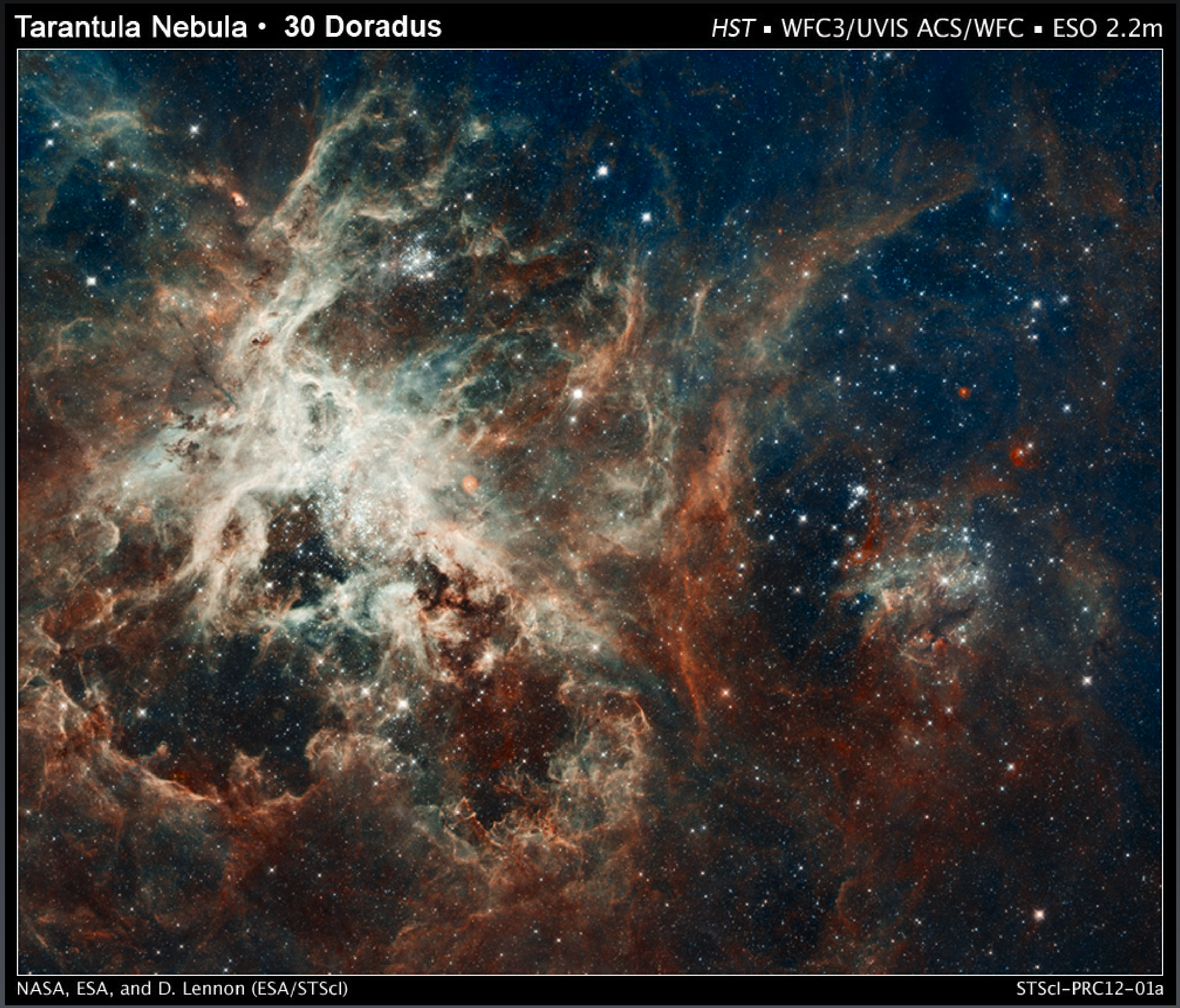


Composite FUV spectrum of R136 reveals that very massive stars (VMS) contributes 1/3 of integrated FUV flux. Individual VMS provide up to N(LyC) = 6.10^{50} ph/s (Crowther+ 2010)

Very Massive Stars in Tarantula

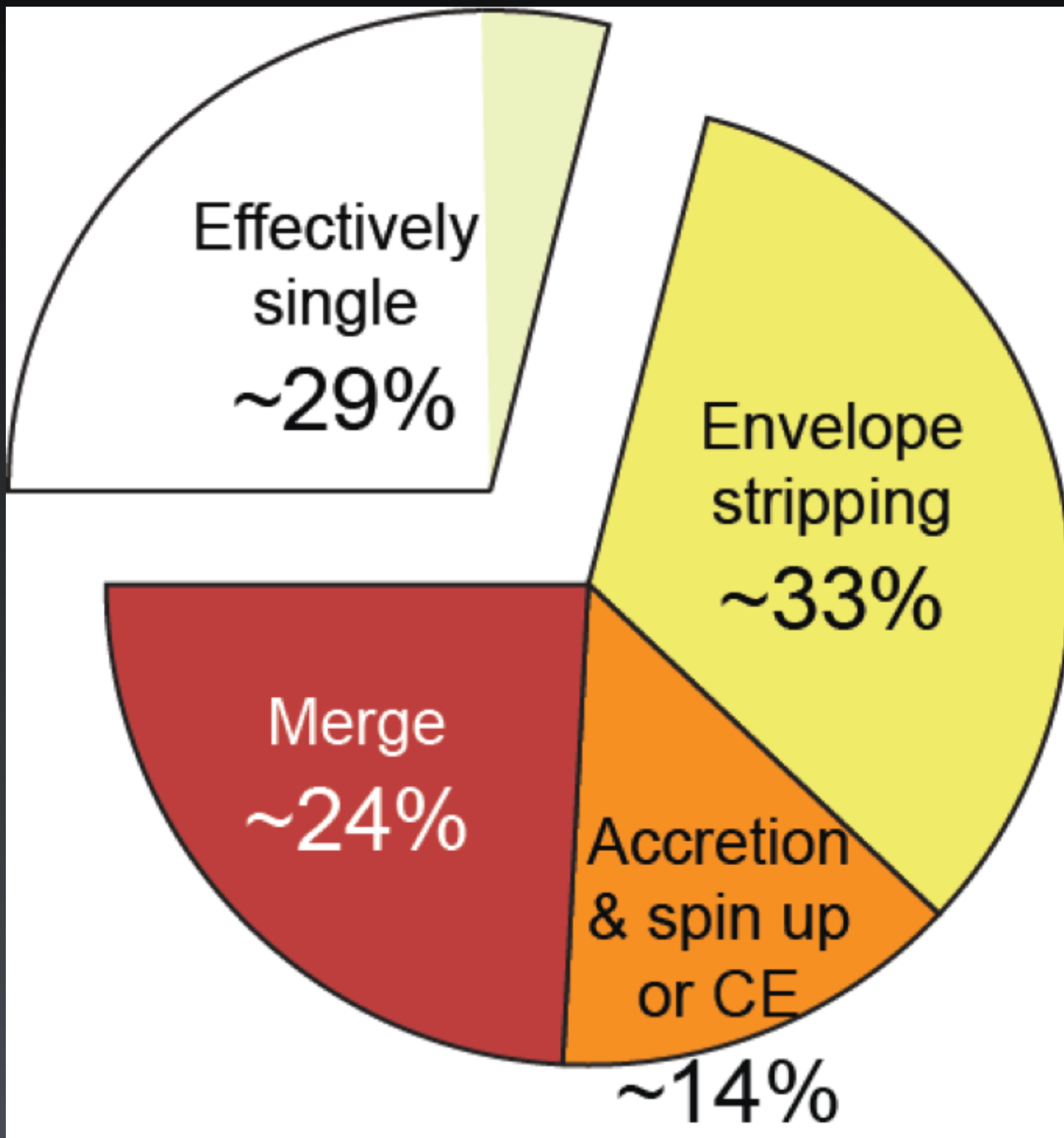
Census of 1000 brightest massive stars in Tarantula nebula reveals that the 10 most massive stars provide 1/4 of the global Lyman continuum flux (Doran+ 2013).

Approx 30 VMS cumulatively increase NLyC by 50% (Stanway +16 models find similar results)

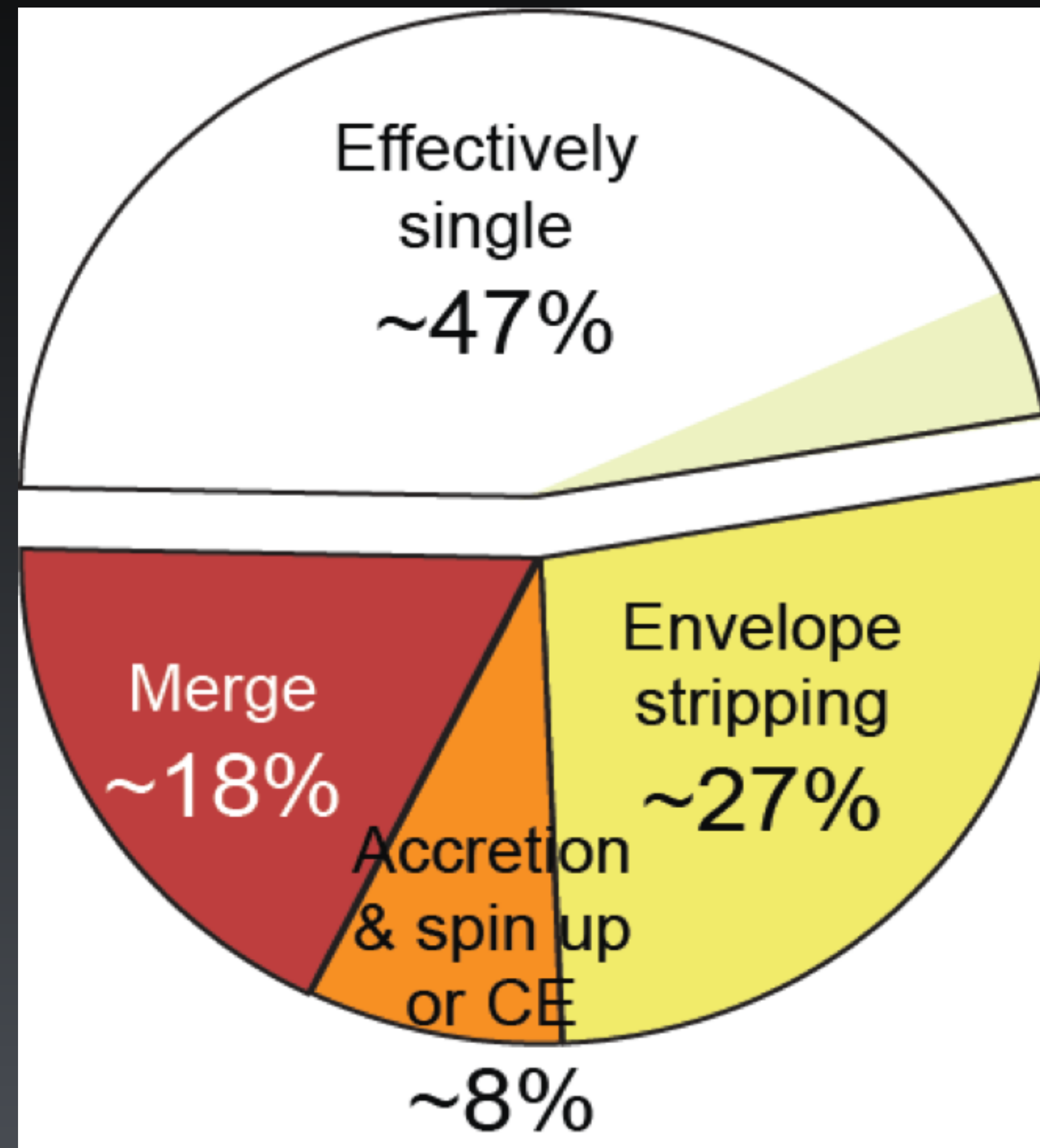


BINARIES

Massive Binaries



Sana+ (2012 Galactic clusters)

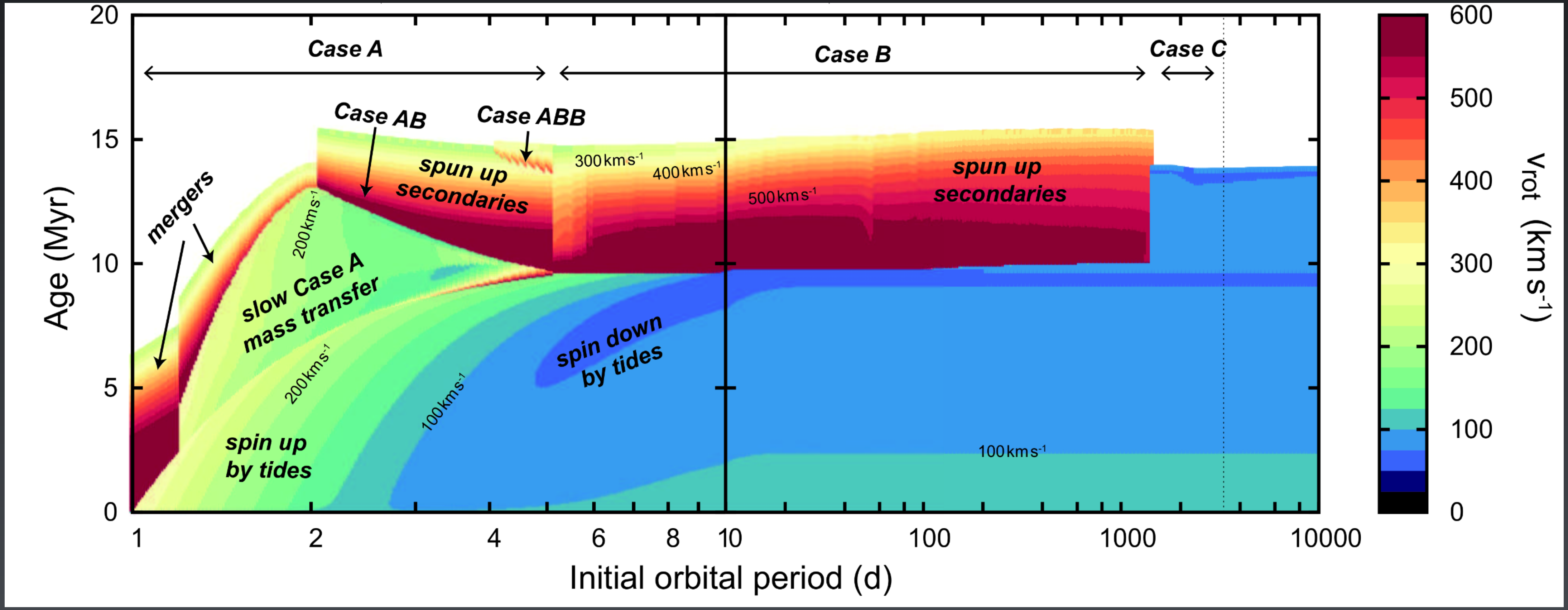


Sana+ (2013, VFTS:30 Dor)

Mass transfer in binaries

Mass transfer in binaries & ionizing fluxes: Secondary

Secondary (mass gainer) is rejuvenated, spun up, extending main sequence lifetime & duration of LyC production.



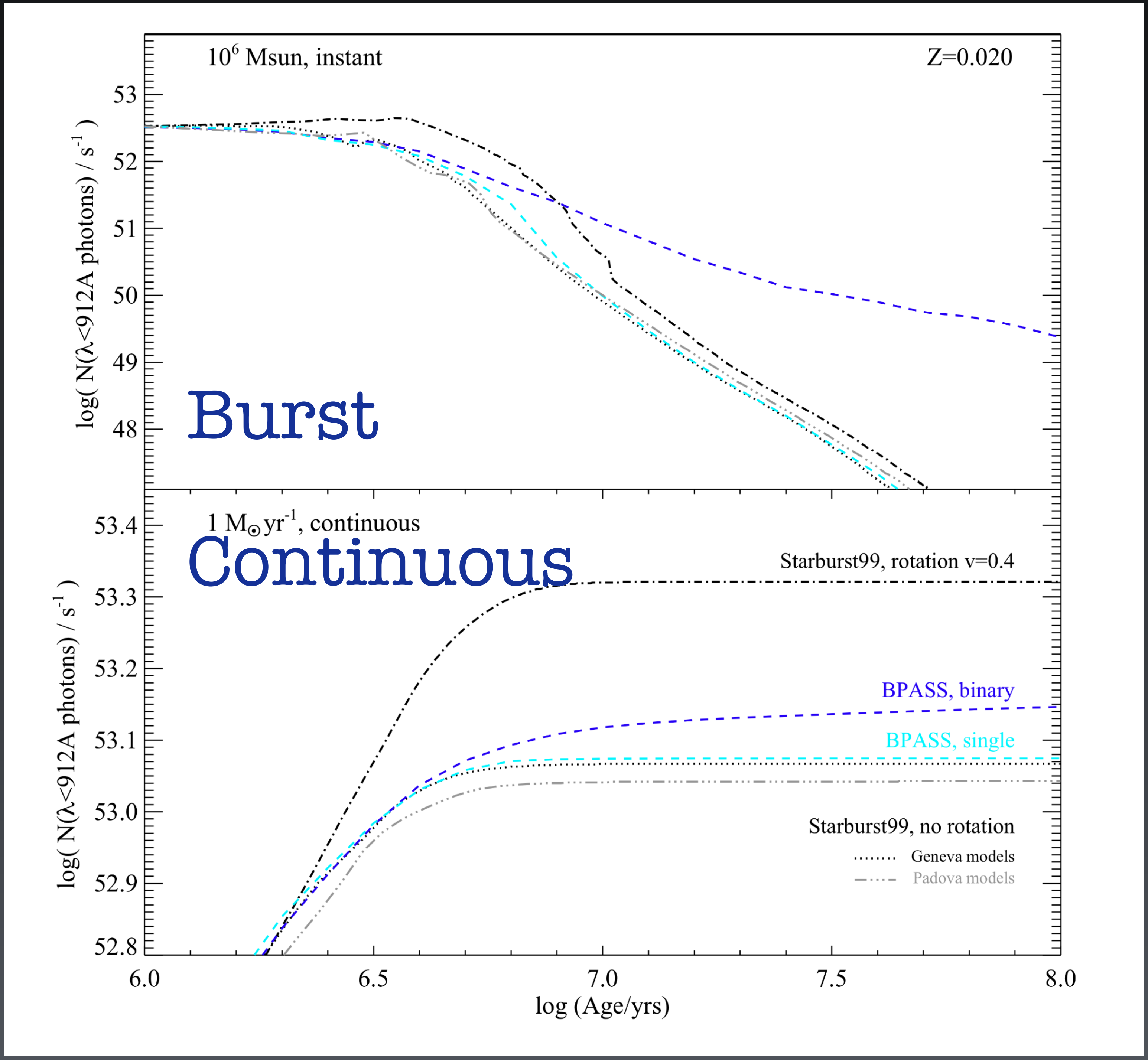
de Mink+ 2013

Rapid rotation in single star models also enhances ionizing output (e.g. SB99 + Geneva rotating tracks, Levesque+2012)

Mass transfer in binaries & ionizing fluxes: Primary

Primary (mass donor) in close binary reveals bare Helium core, adding to LyC ionisation radiation compared to single stellar populations.

Effect becomes apparent in burst models beyond 0.01 Gyr and very significant at 0.1Gyr

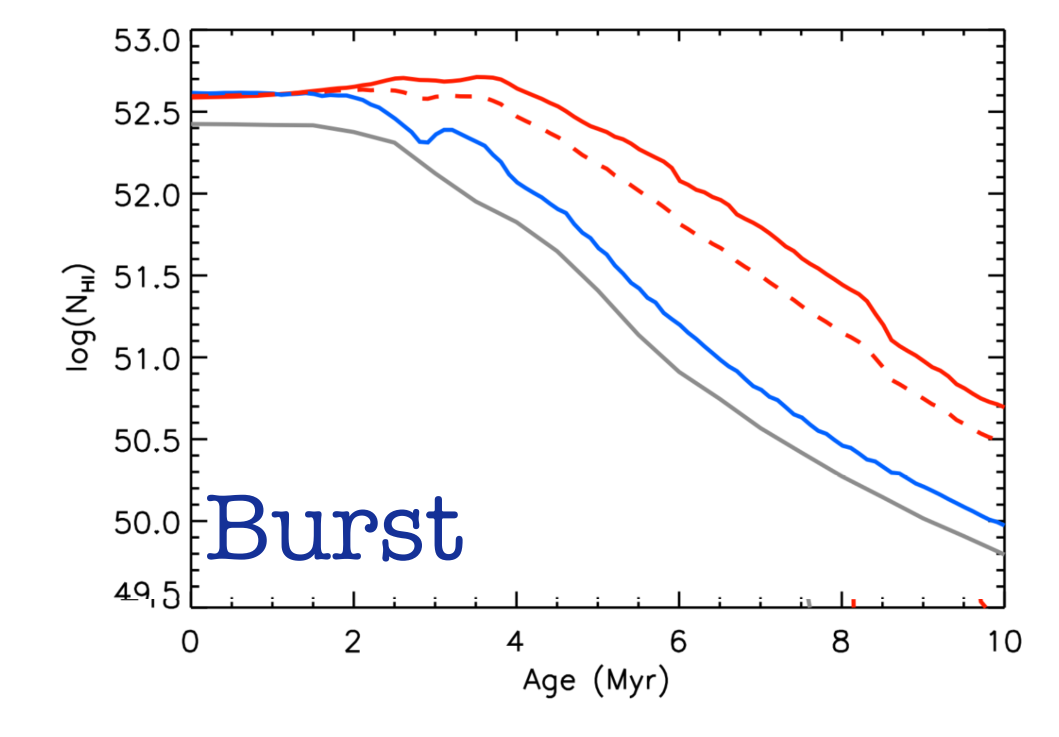


Stanway, Eldridge & Becker 2016

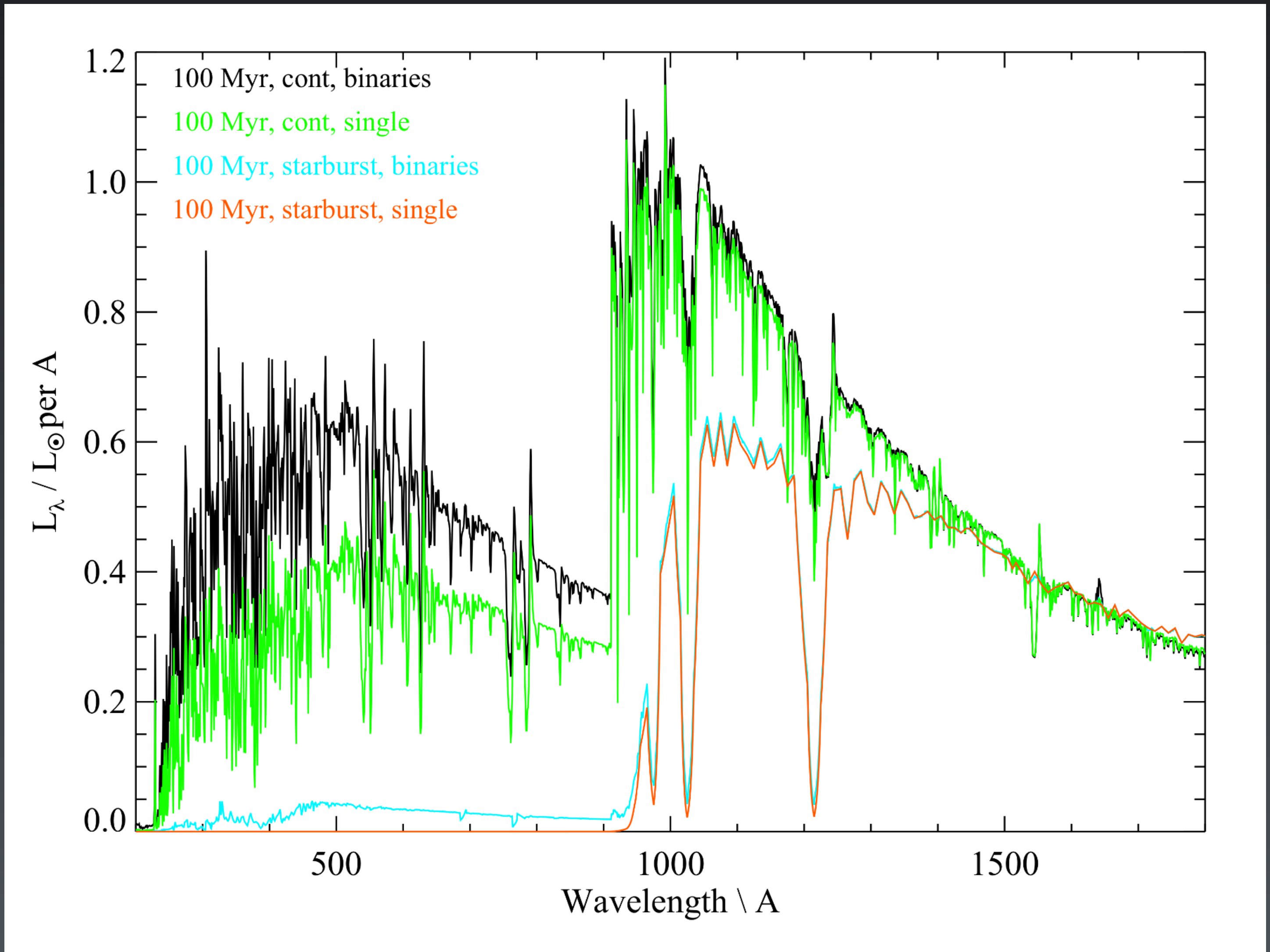
Single/binary pop synthesis

Starburst99 incorporates realistic OB and WR stellar models (WM-Basic & CMFGEN) and advanced stellar evolutionary models for single stars - Geneva rotating (red) vs non-rotating (blue, grey)

BPASS uses WM-Basic and PoWR models for O and WR stars, less sophisticated evolutionary models (STARS) but does incorporate both single & binary populations.



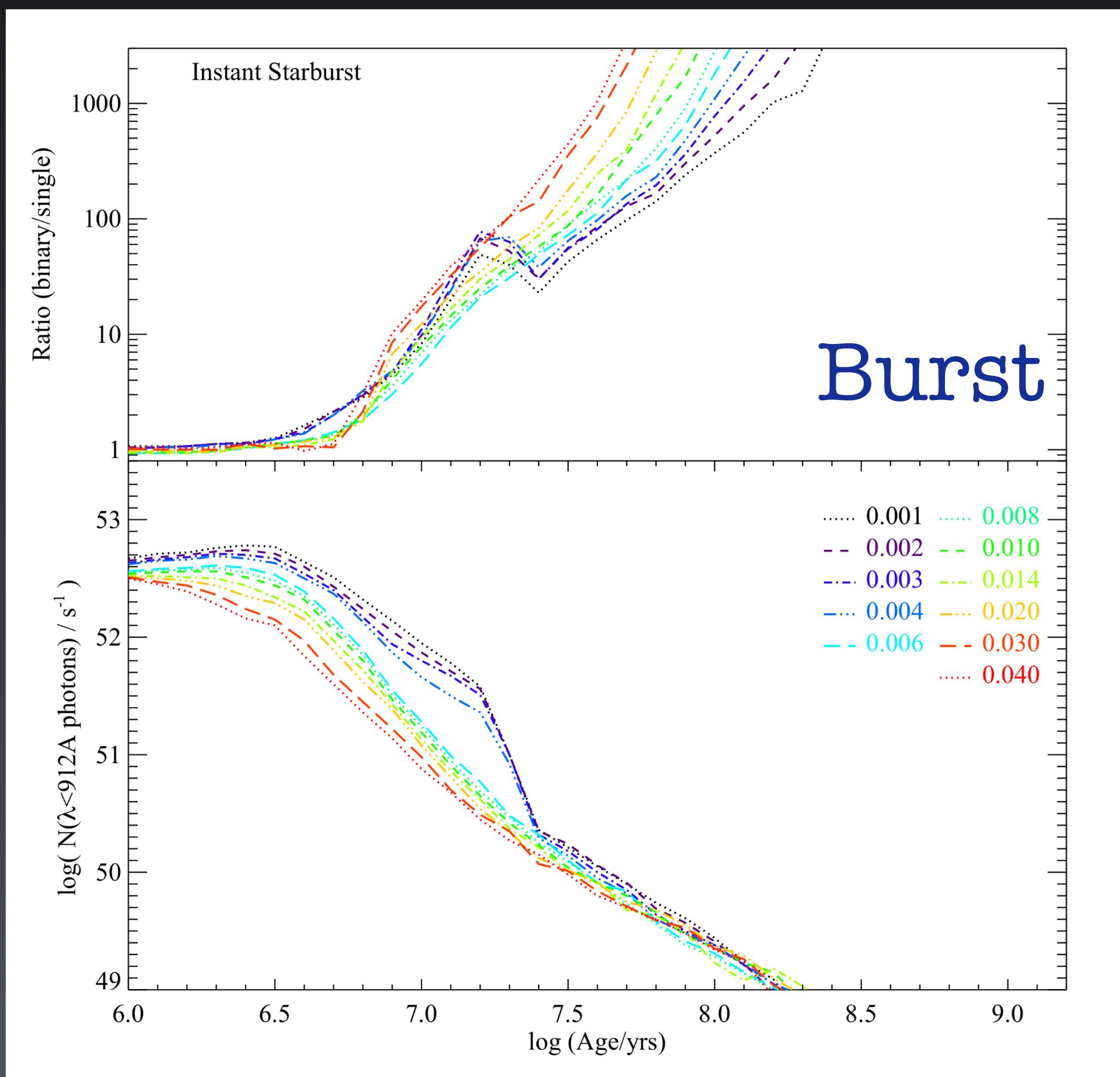
Levesque+ 2012

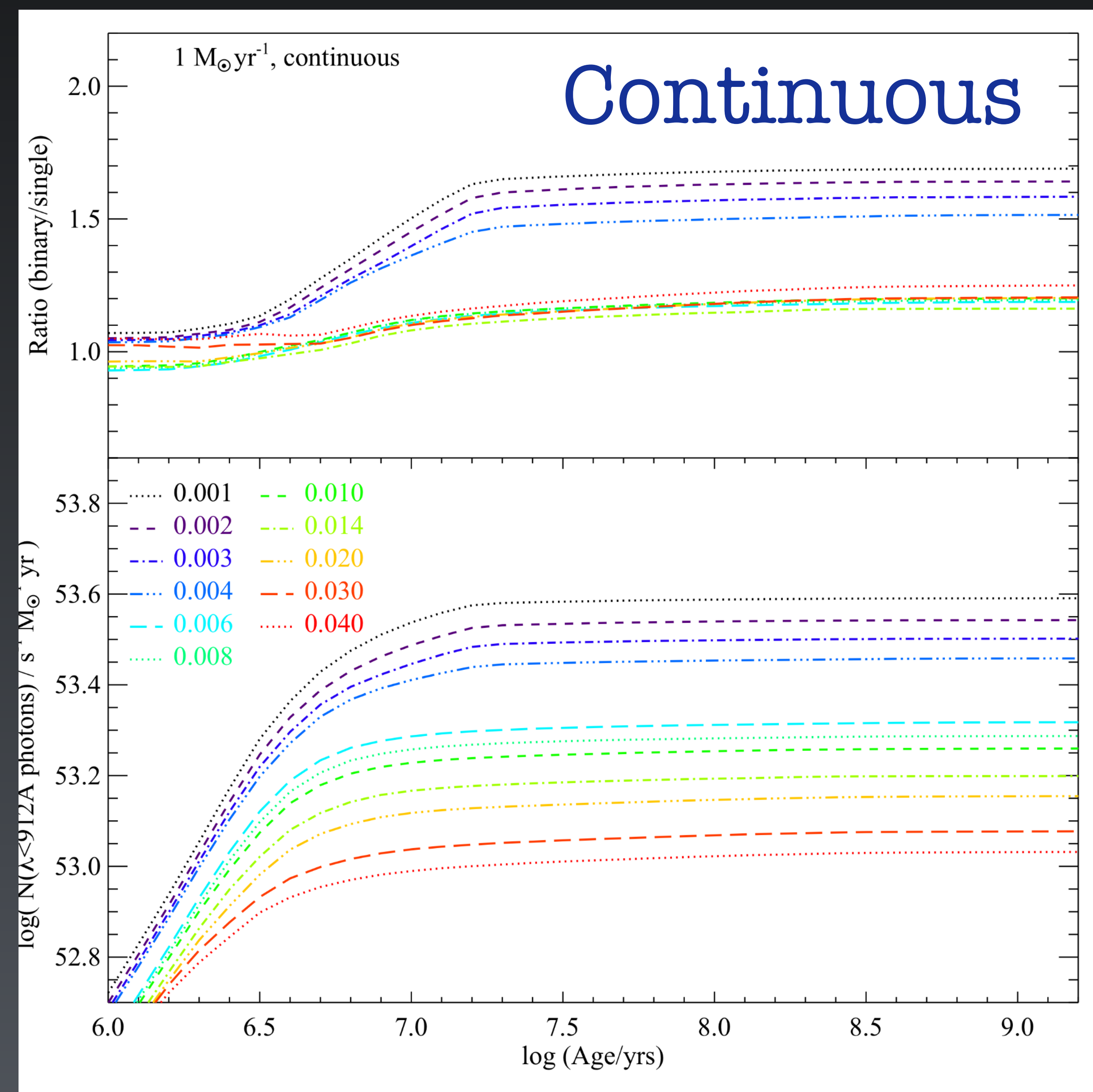


Stanway, Eldridge & Becker 2016

Excess of N(LyC) from binaries

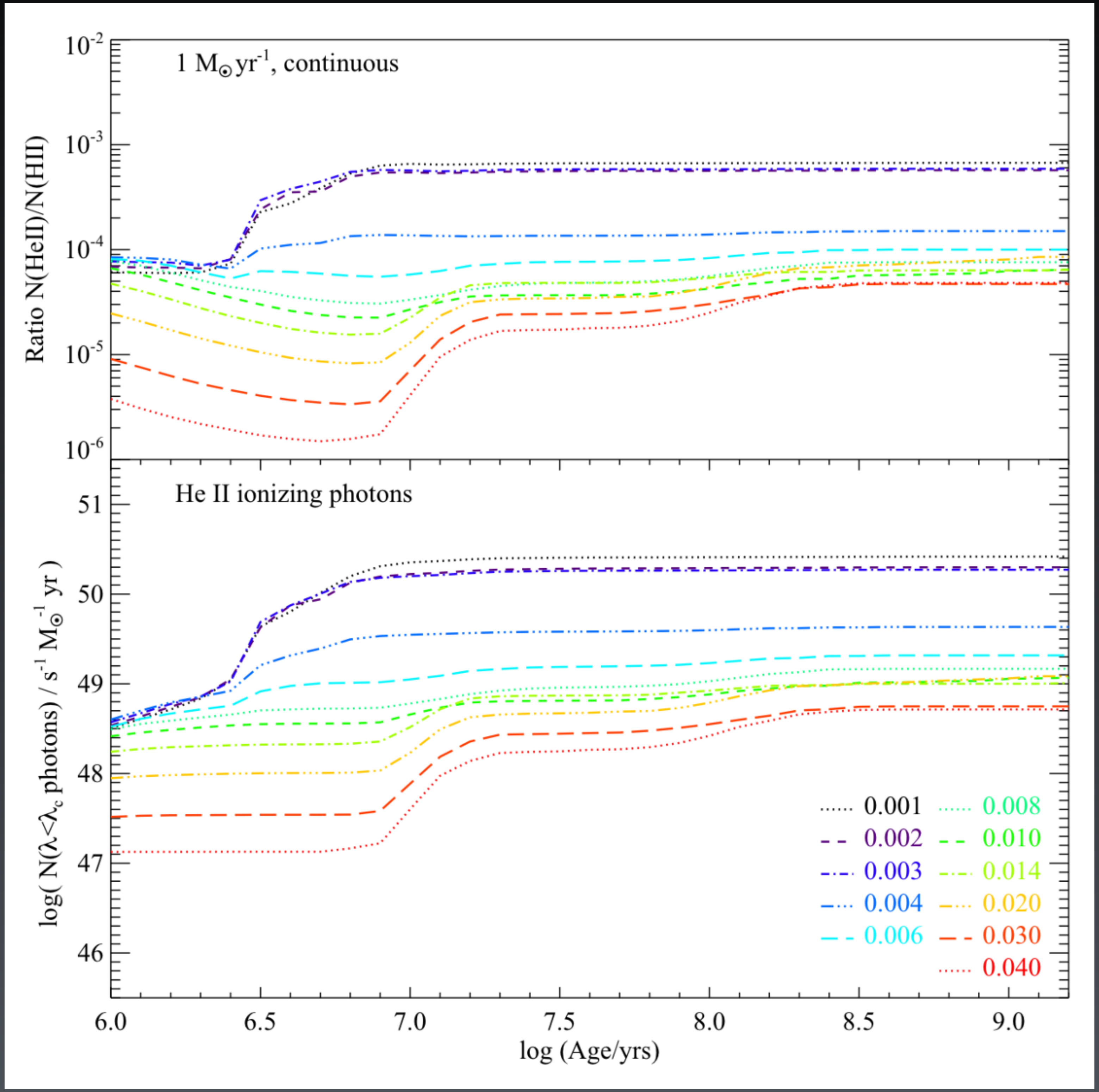
Excess N(LyC) resulting from He stars in binaries ranges from factor of 1000 for a starburst after 100 Myr (Stanway+ 2016) to 20-60% for continuous s.f.





Excess of N(HeII LyC) from binaries

Helium stars are compact so emit large numbers of N(HeII LyC) photons, especially for metal poor populations (weak winds)

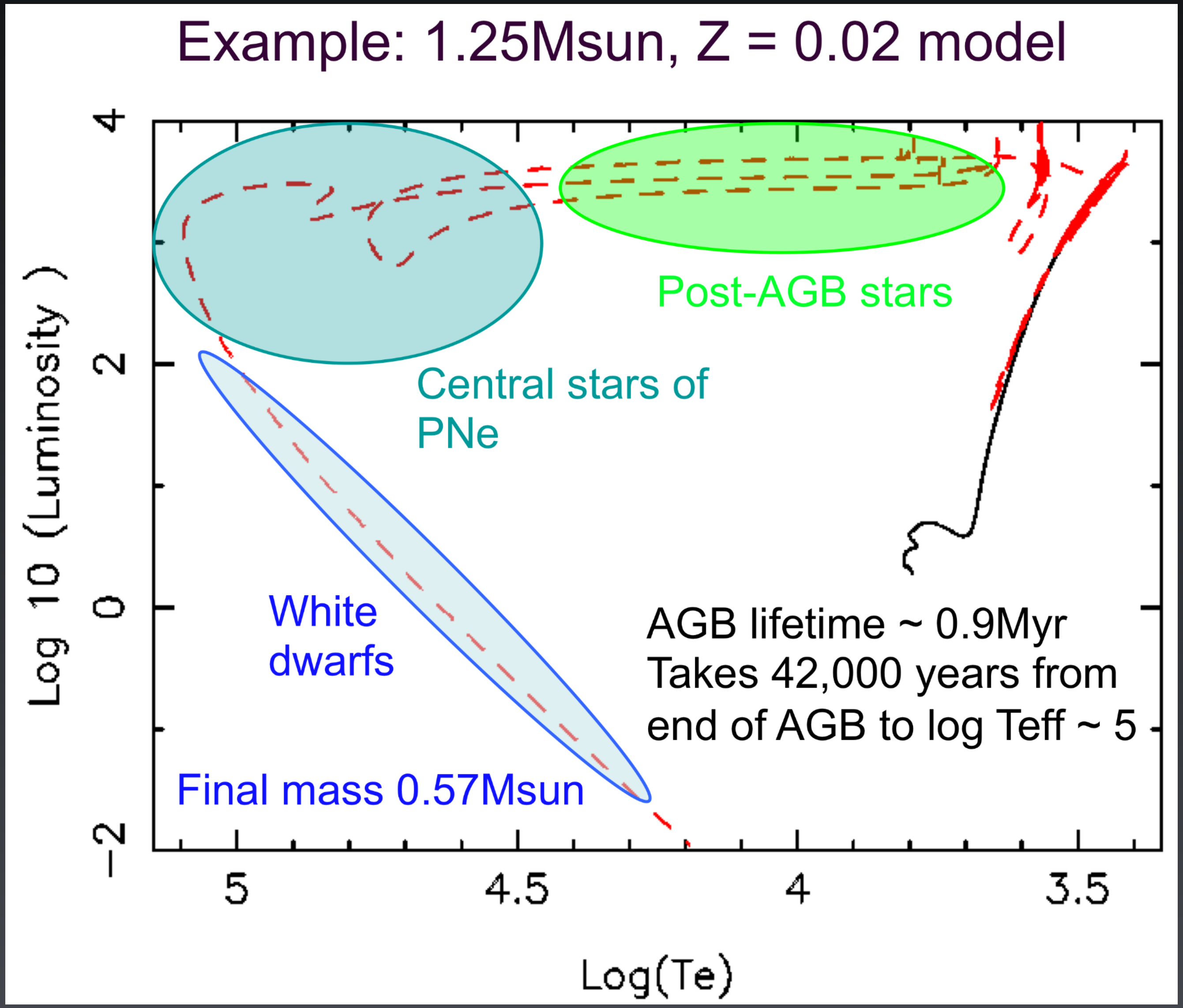


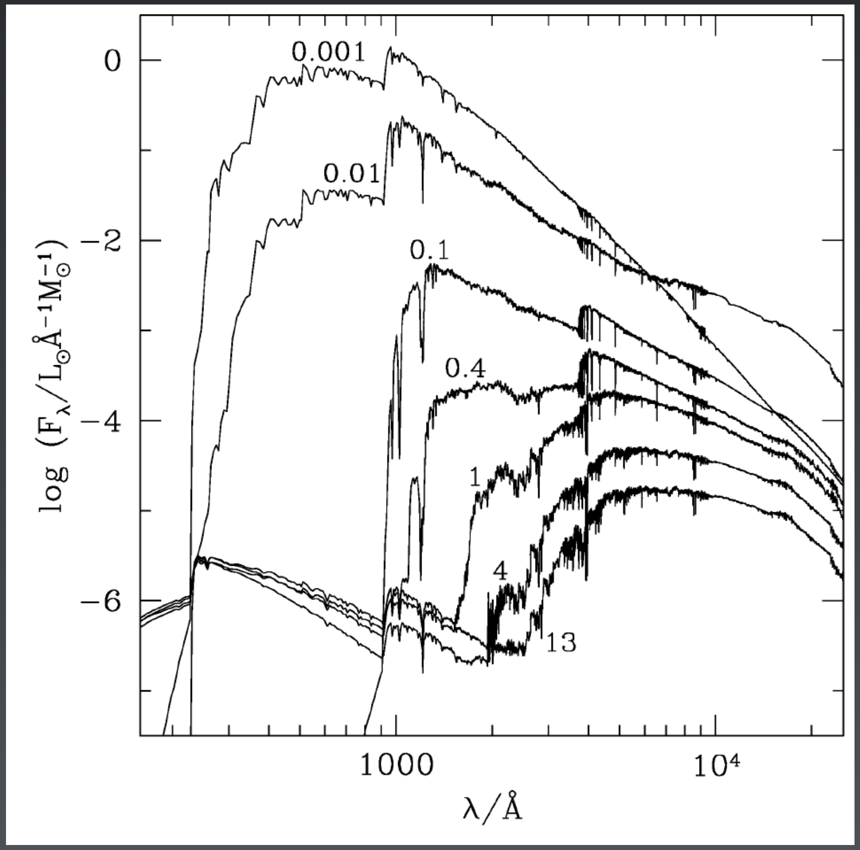
Stanway+ 2016

Post AGB stars

Post AGB stars/CSPNe

At late times (following single and binary evolution of massive stars), key players are intermediate and low mass post-AGB, pre-WD stars (CSPNe)





Herwig (2005)

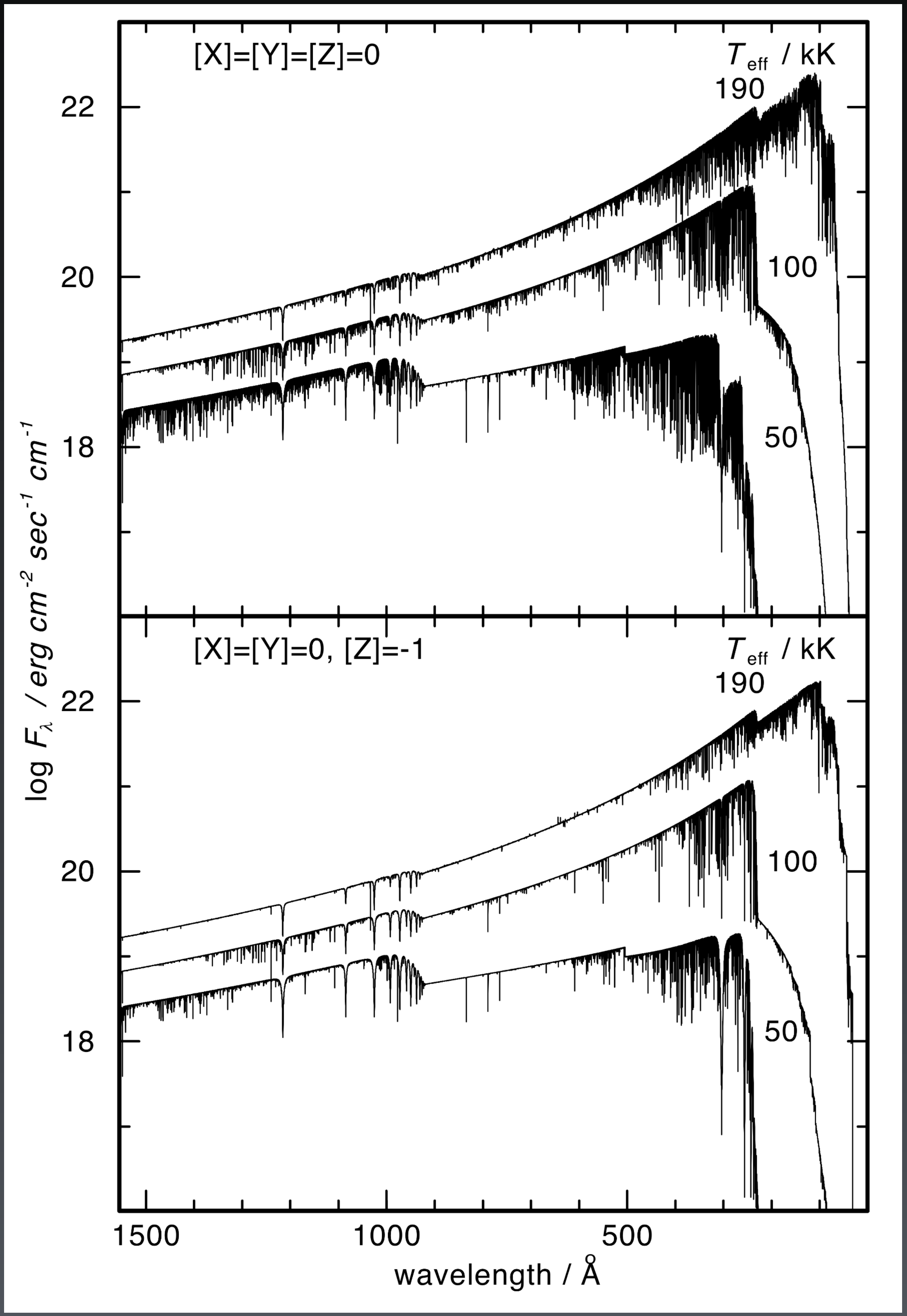
Bruzual & Charlot (2003)

Stellar atmospheres

- Standard atmospheric models for hot stars (LTE Kurucz/ATLAS; non-LTE, Hubeny & Lanz/TLUSTY) are designed for T=10-50kK

- Bruzual & Charlot (2003) employ TMAP non-LTE models (Werner & Rauch) hot post-AGB stars (T>50kK).

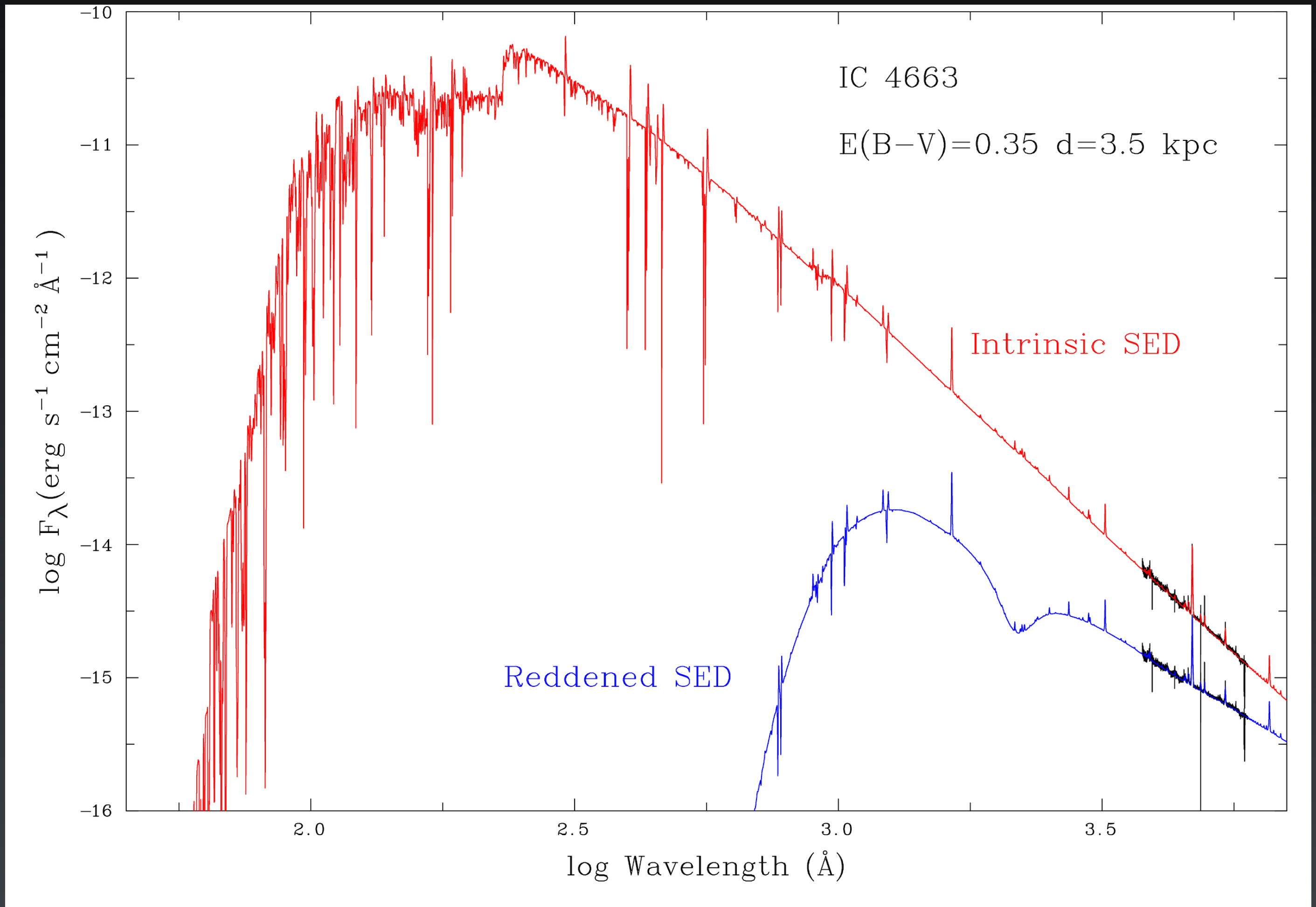
- Rauch (2003) provide grids of post-AGB models for solar (top) and 1/10 solar (bottom) compositions.



CSPNe with winds

- Low mass post-AGB stars have 5,000 Lsun, so N(LyC) are a few 10^{47} photons/s
- CMFGEN or PoWR suited to hot post-AGB stars with strong winds (e.g. IC4663 [WN3])
- T approx 100kK so N(HeII LyC) are a few 10^{46} photons/s

Miszalski, Crowther+ 2013



Biggest issue for old stellar populations involves the AGB phase of stellar models (mostly simple 1D single stellar evolution)

Binaries?

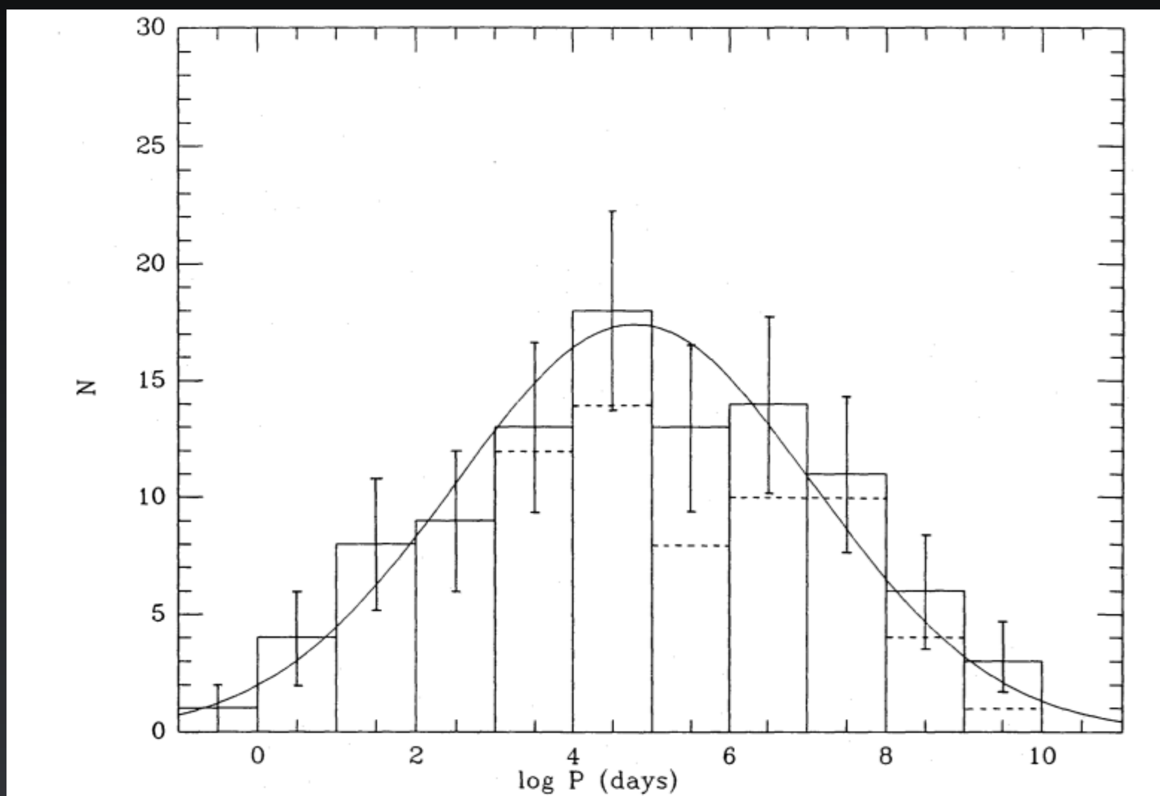
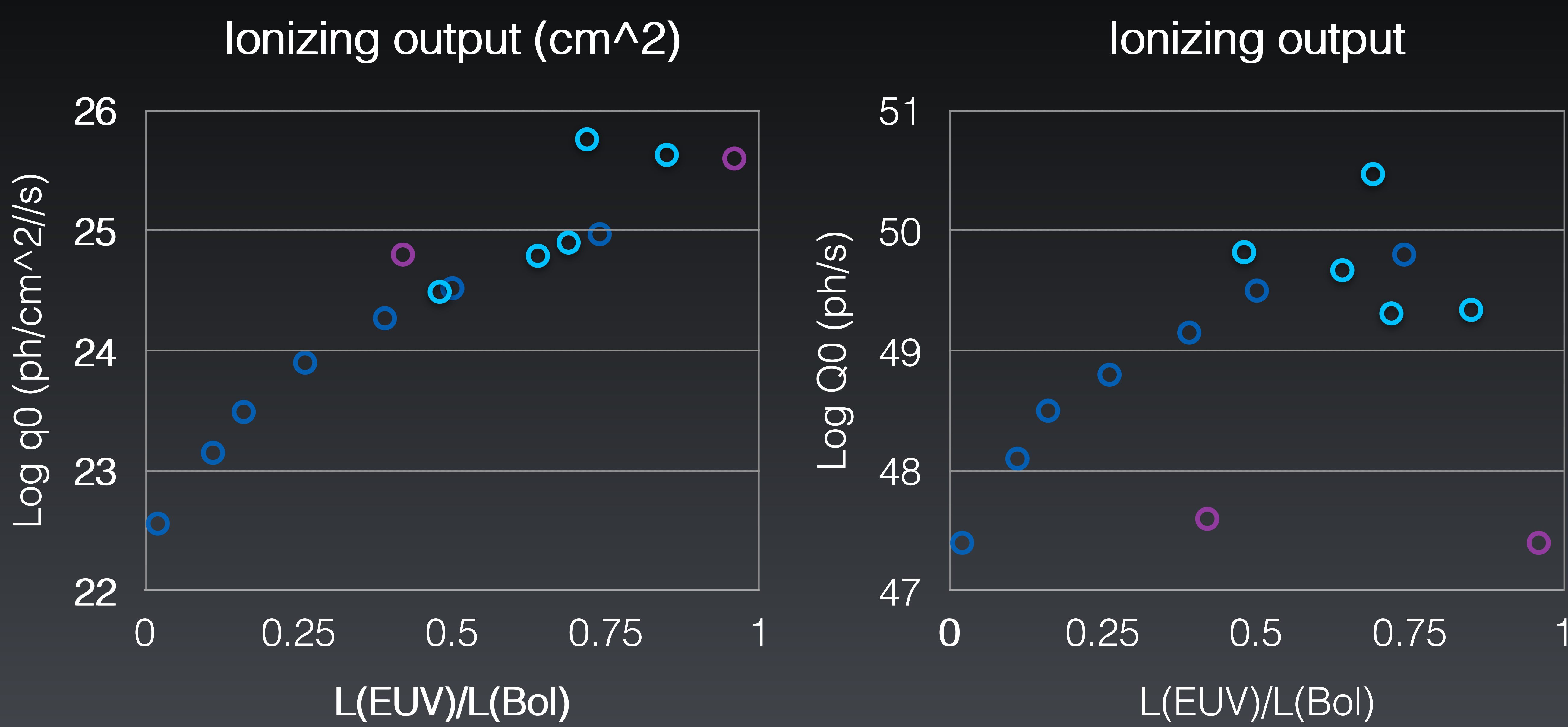


Fig. 7. Period distribution in the complete nearby G-dwarf sample, without (dashed line) and with (continuous line) correction for detection biases. A Gaussian-like curve is represented whose parameters are given in the text

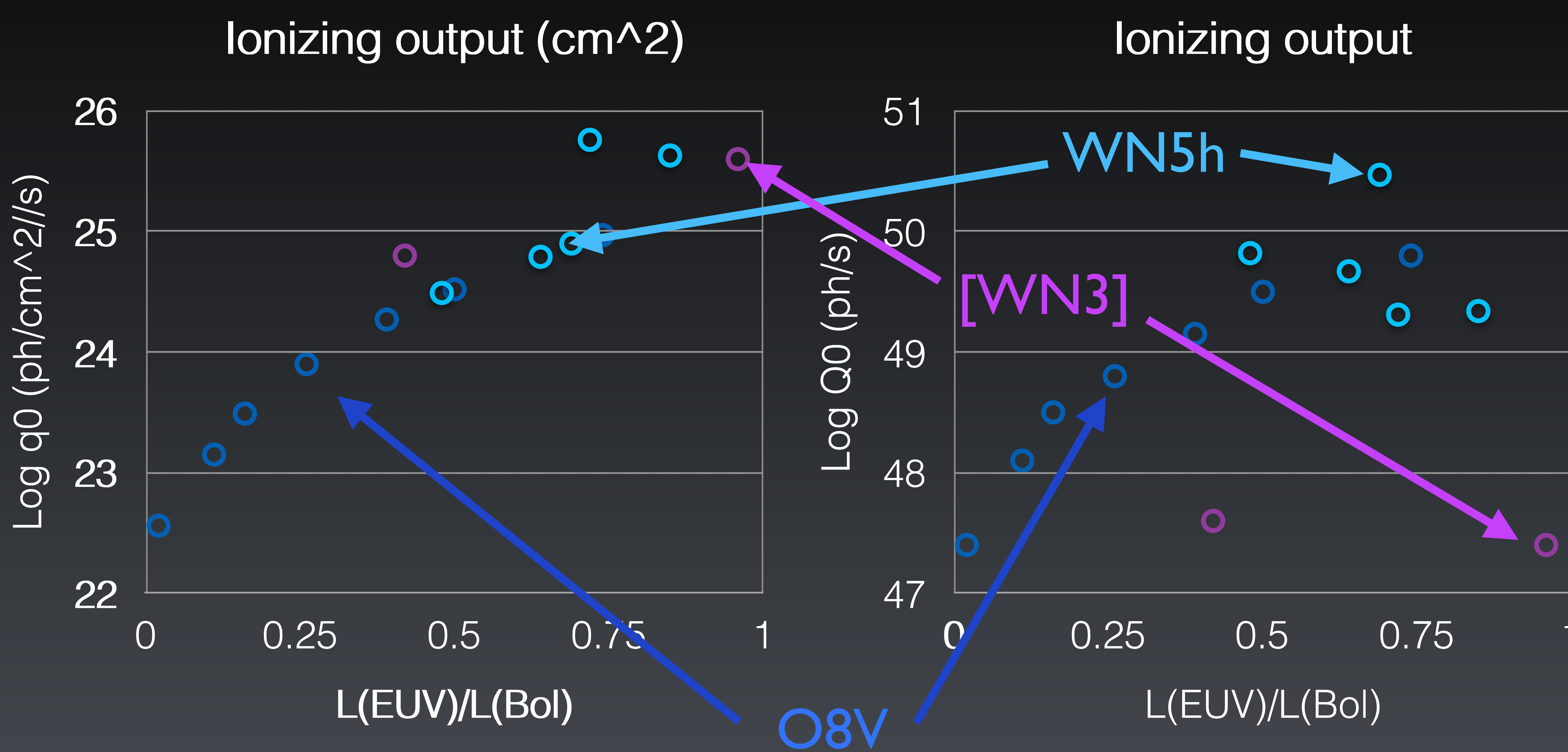
Most stars are born in binary systems, although low/intermediate stars have larger period distribution than for massive stars (so fewer interact during lifetimes)

Binarity add to complexity but many phenomena relating to low and intermediate mass require binary evolution (e.g. asymmetric planetary nebulae; Novae, type Ia SNe)

OB dwarfs; WR stars; PN central stars

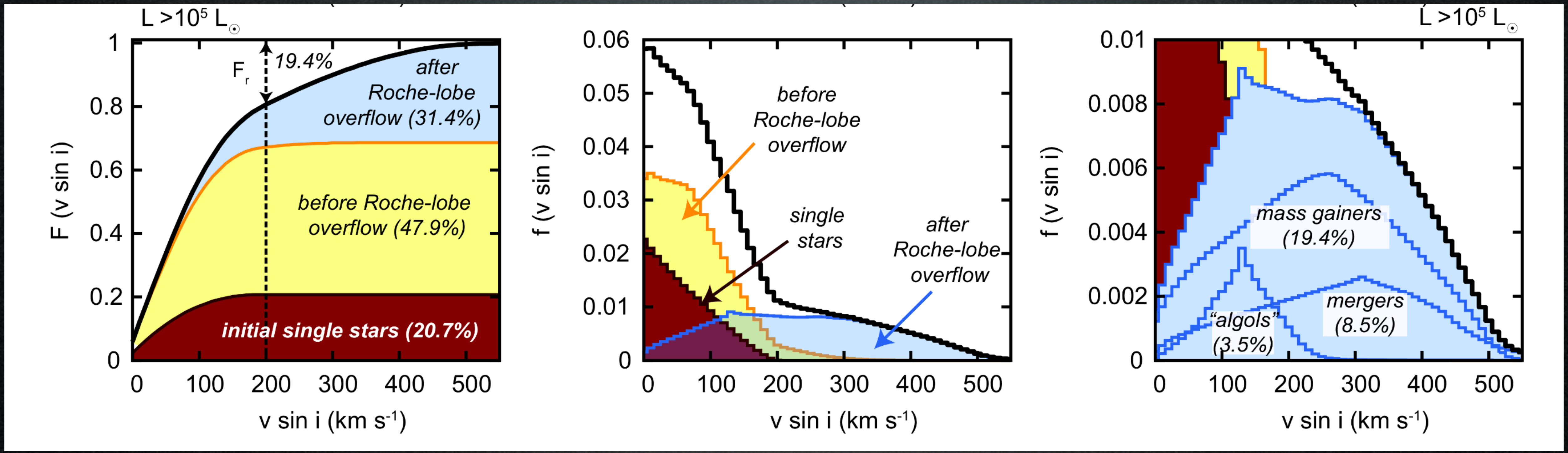


OB dwarfs; WR stars; PN central stars



Summary

- Lyman Continuum output from synthesis models assuming ...
  - ..continuous s.f. need modest upward revision to account for close binary evolution and upward revision for high s.f. intensity owing to presence of very massive stars
  - ..a burst of s.f. may require significant (several orders of magnitude) upward at late times to account for He stars resulting from close binary evolution
- binary influence untested for post-AGB phase of low/intermediate mass stars



L >10^5 L☉
F_r
19.4%
after Roche-lobe overflow (31.4%)
before Roche-lobe overflow (47.9%)
initial single stars (20.7%)
F (v sin i)
v sin i (km s^-1)
before Roche-lobe overflow
single stars
after Roche-lobe overflow
f (v sin i)
v sin i (km s^-1)
L >10^5 L☉
mass gainers (19.4%)
mergers (8.5%)
"algols" (3.5%)
f (v sin i)
v sin i (km s^-1)