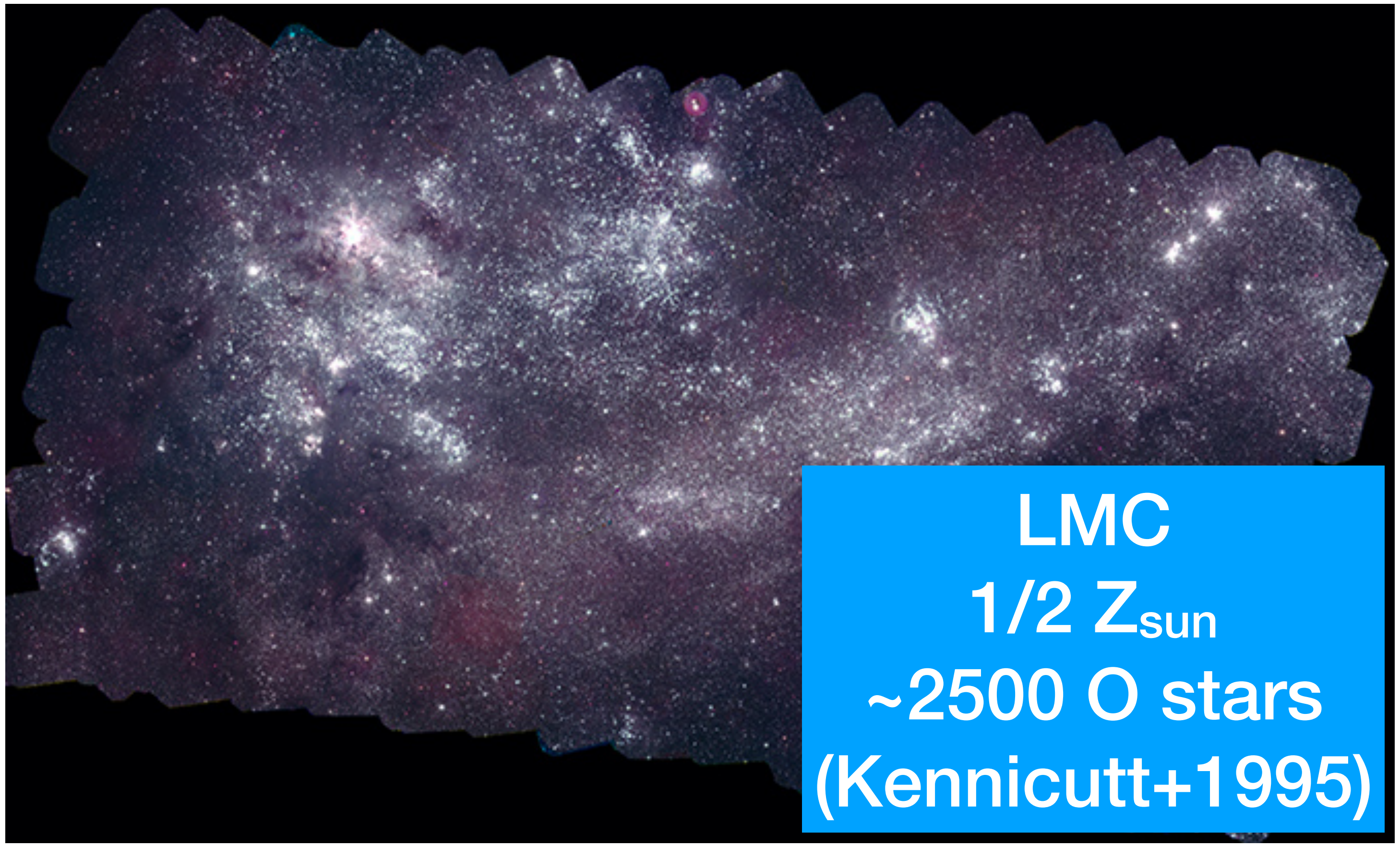
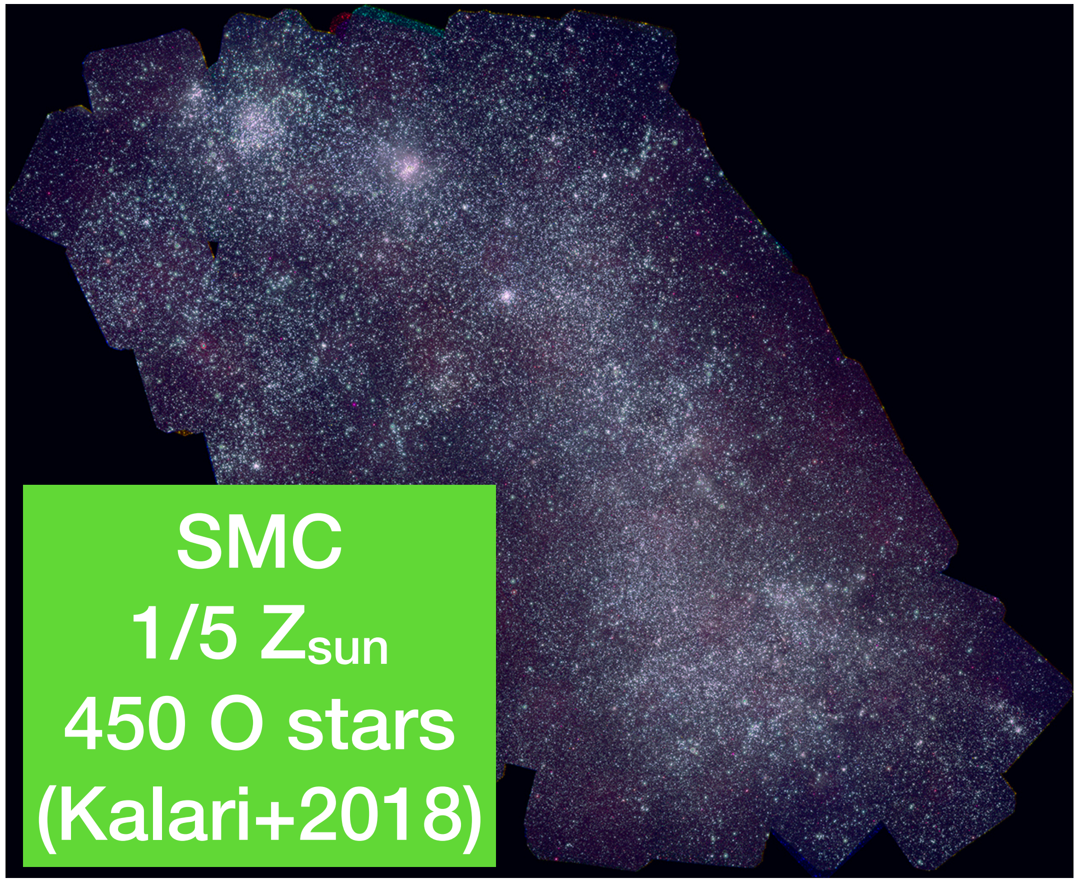
UV Diagnostics of Stellar Winds in Magellanic Cloud Massive Stars

The
University
Of
Sheffield.

Paul Crowther



LMC
1/2 Z_{sun}
~2500 O stars
(Kennicutt+1995)

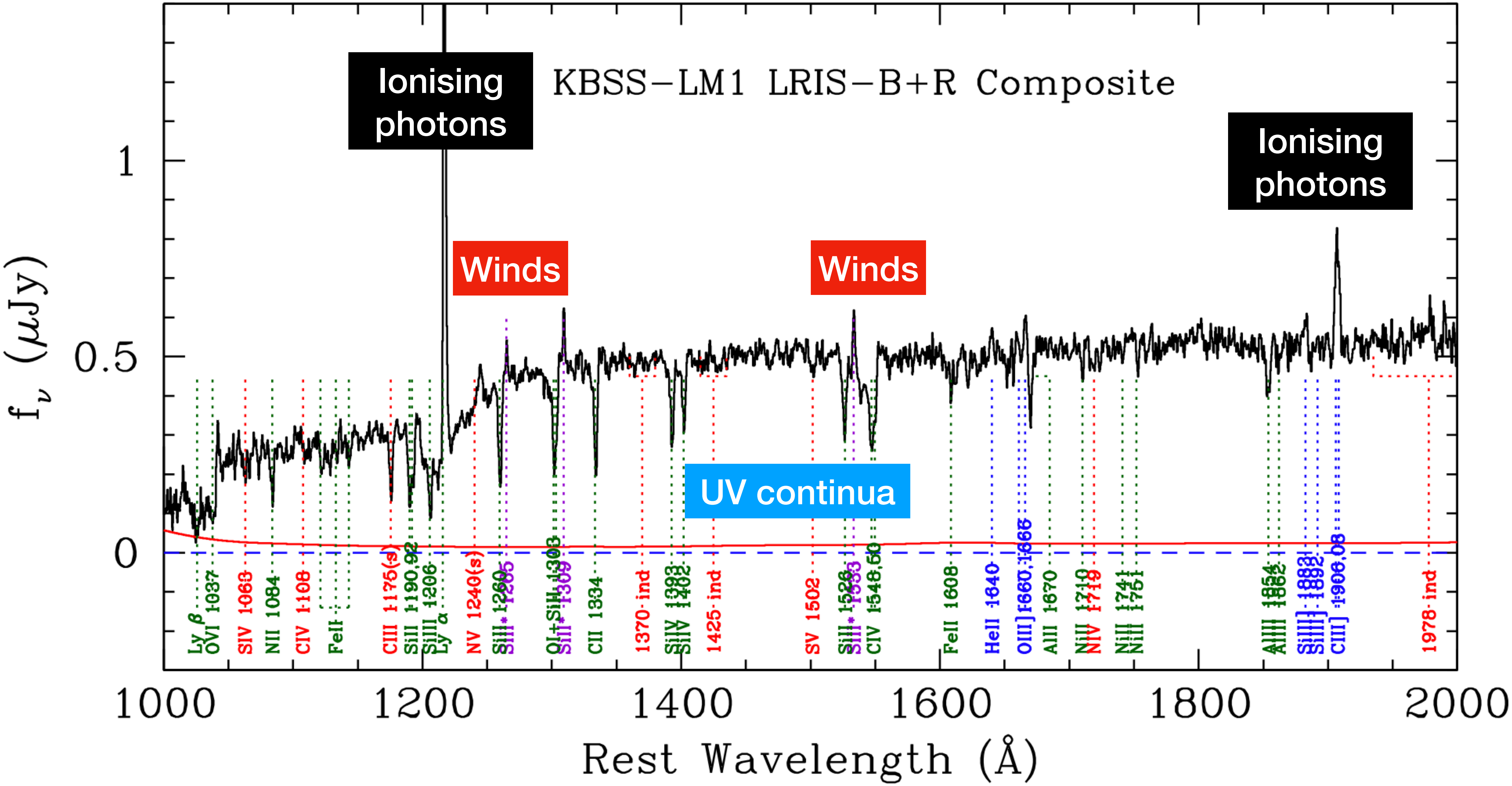


SMC
1/5 Z_{sun}
450 O stars
(Kalari+2018)

UVEX Community Workshop 2023: “Synergies and New Opportunities”

Massive stars at high-z

Stacked spectra of 30 Lyman-break galaxies at z=2.4 (Steidel+2016)



Ionising photons

Winds

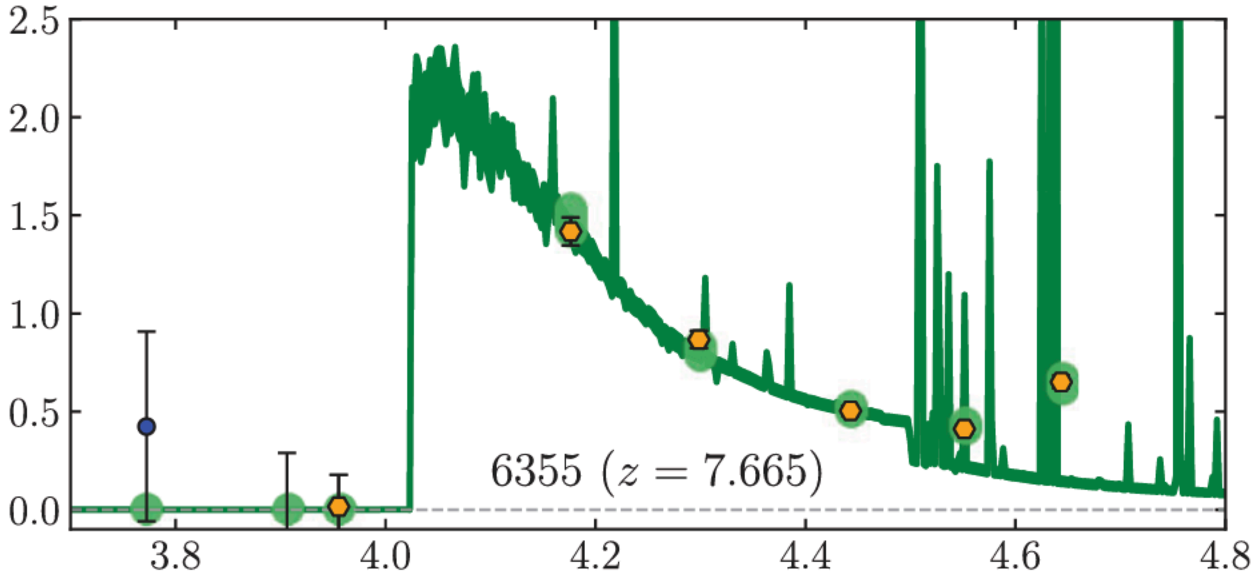
Winds

Ionising photons

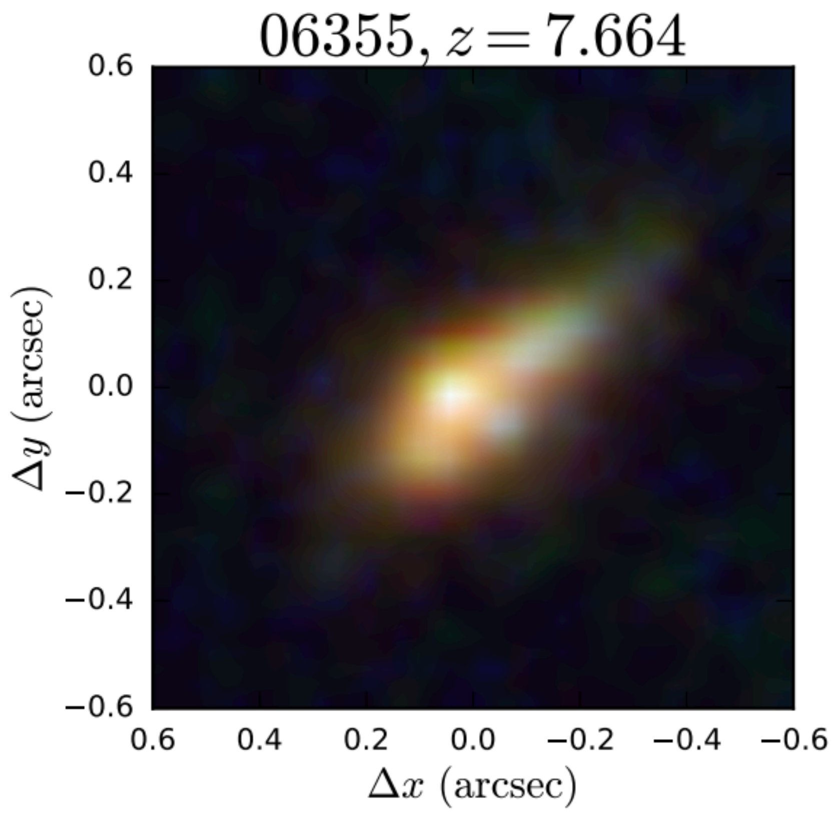
UV continua

Crowther: “UV diagnostics of stellar winds in Magellanic Cloud massive stars”

SMACS 0723 JWST high-z galaxies



Carnall+2023

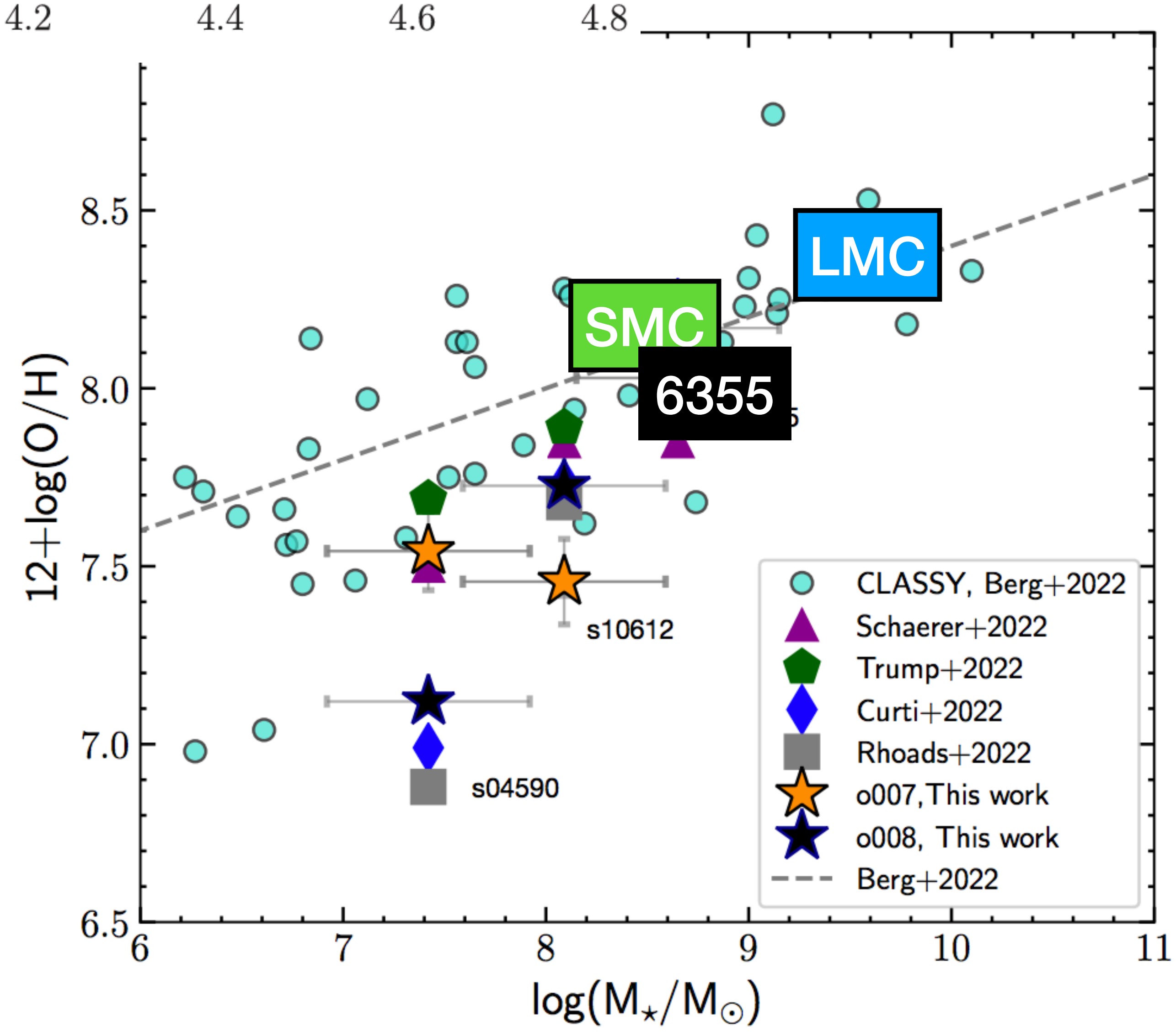


Trussler+2022

B: F090W (rest FUV),

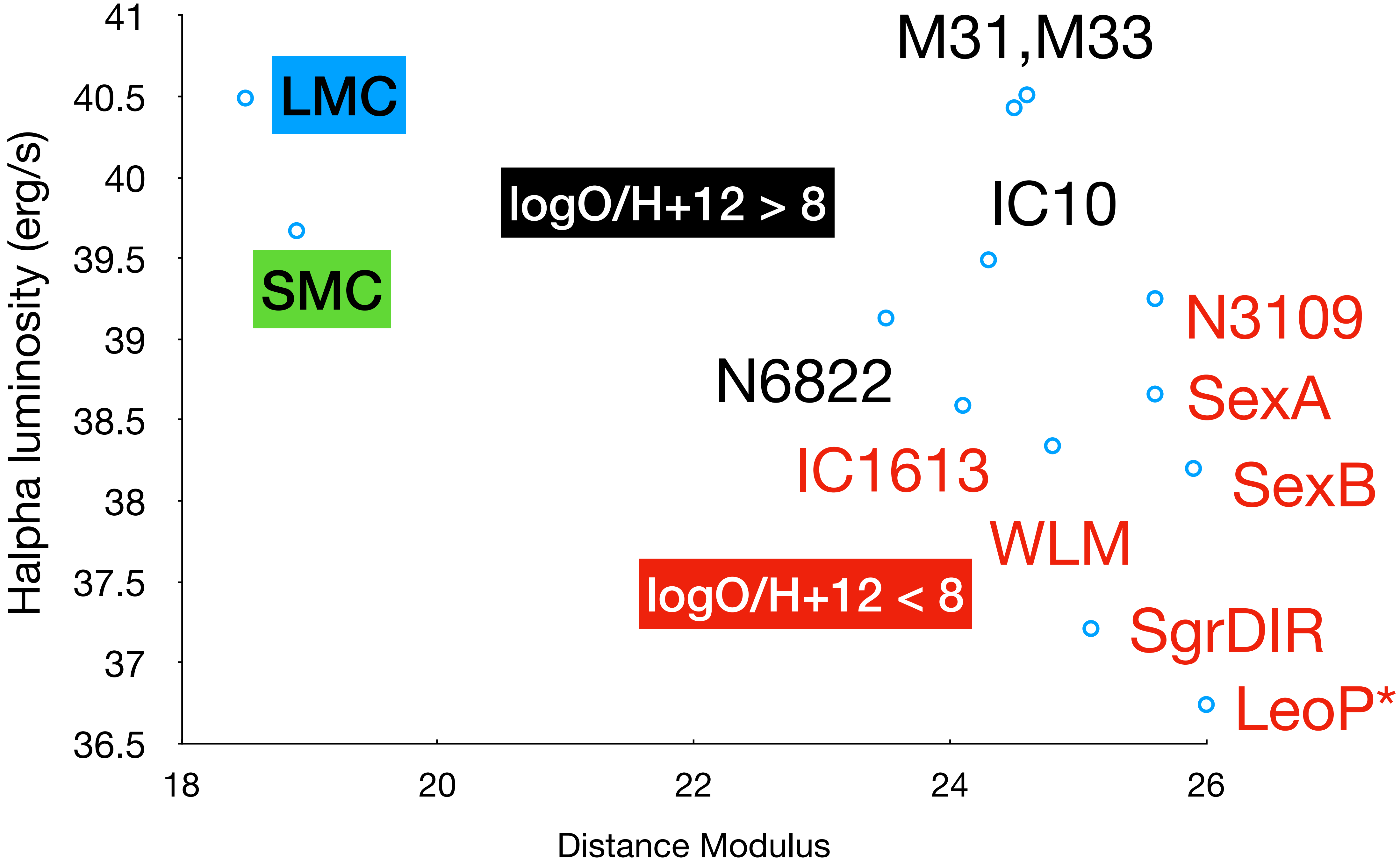
G:F200W+F277W (rest NUV),

R:F356W+F444W (rest blue)



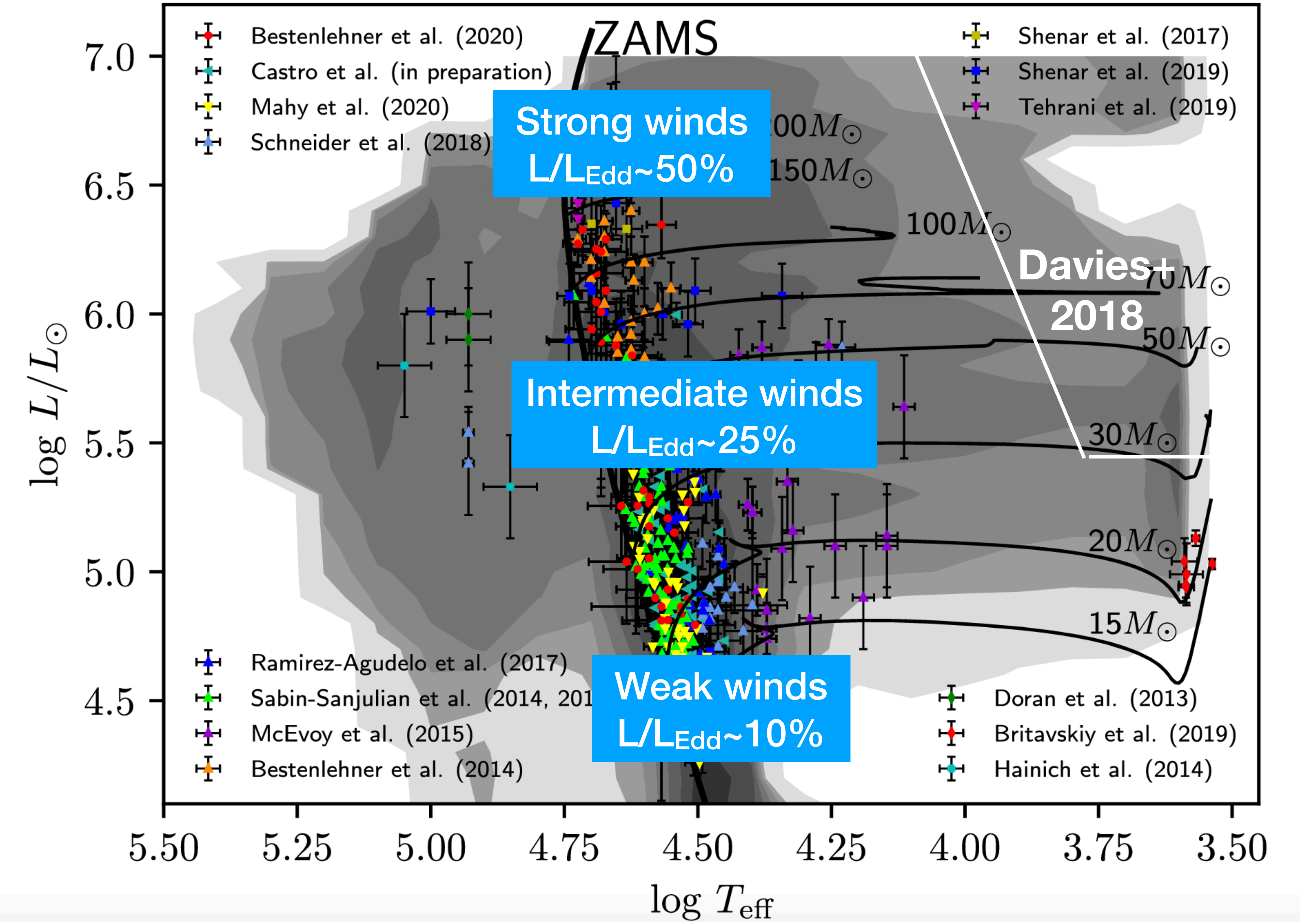
Arellano-Cordova+2022

Star formation in Local Group



Low star formation rates aside from M31, M33, LMC (Kennicutt+2008, *McQuinn+2015). High A_V for IC10

Evolution of metal-poor massive stars



- **Winds** (weaker at low metallicity)
- **Mixing** (traced via CNO abundances)
- **Binarity** (close binary evolution: Gotberg & Sana talks)

LMC Tarantula Nebula: Bestenlehner+2021

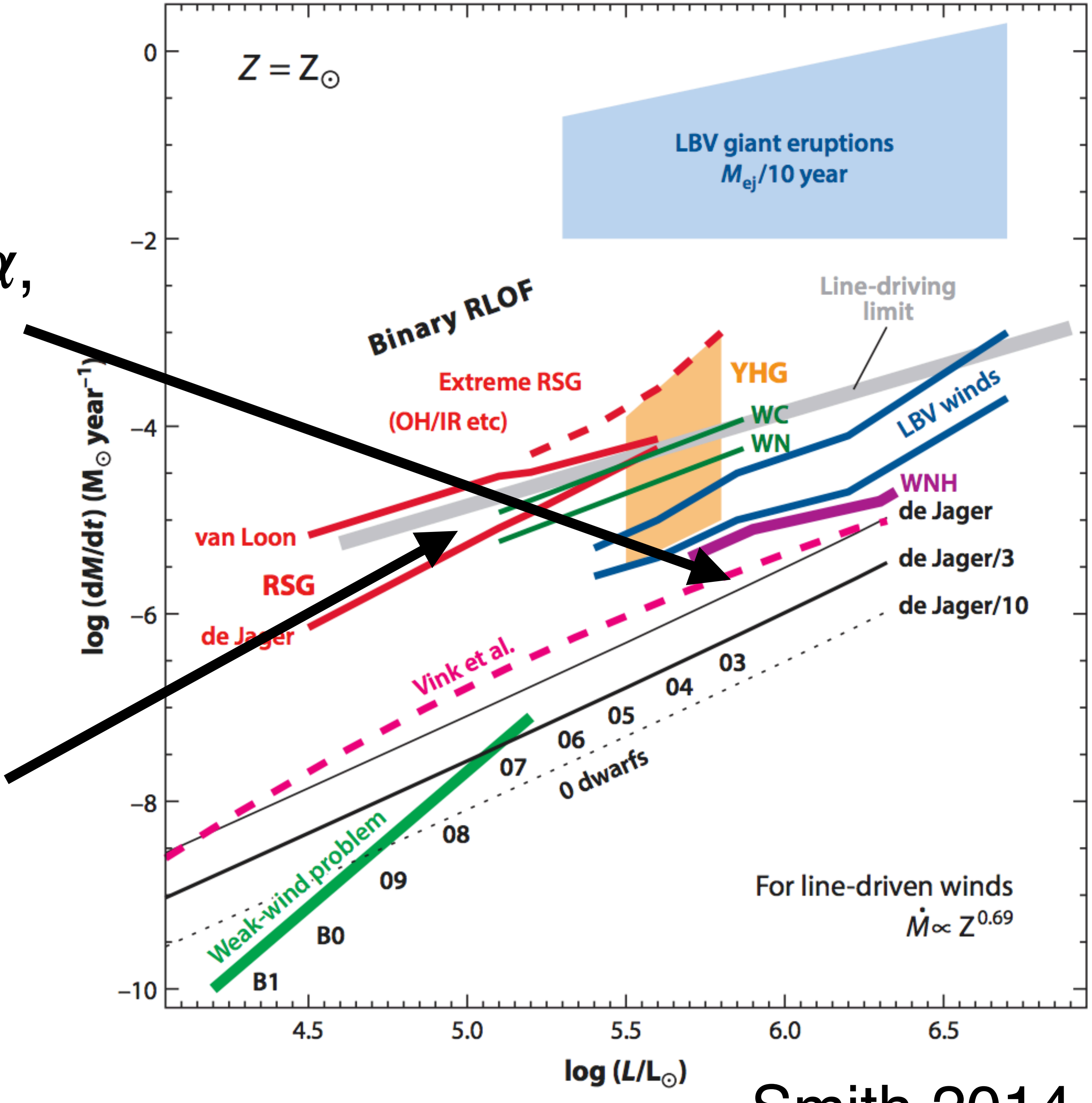
Wind Diagnostics

Fast winds from hot stars:

- Free-free excess (radio)
- Recombination lines (Hα, Pα). Radiative transfer
- **Resonance lines (far-UV). Radiative transfer**

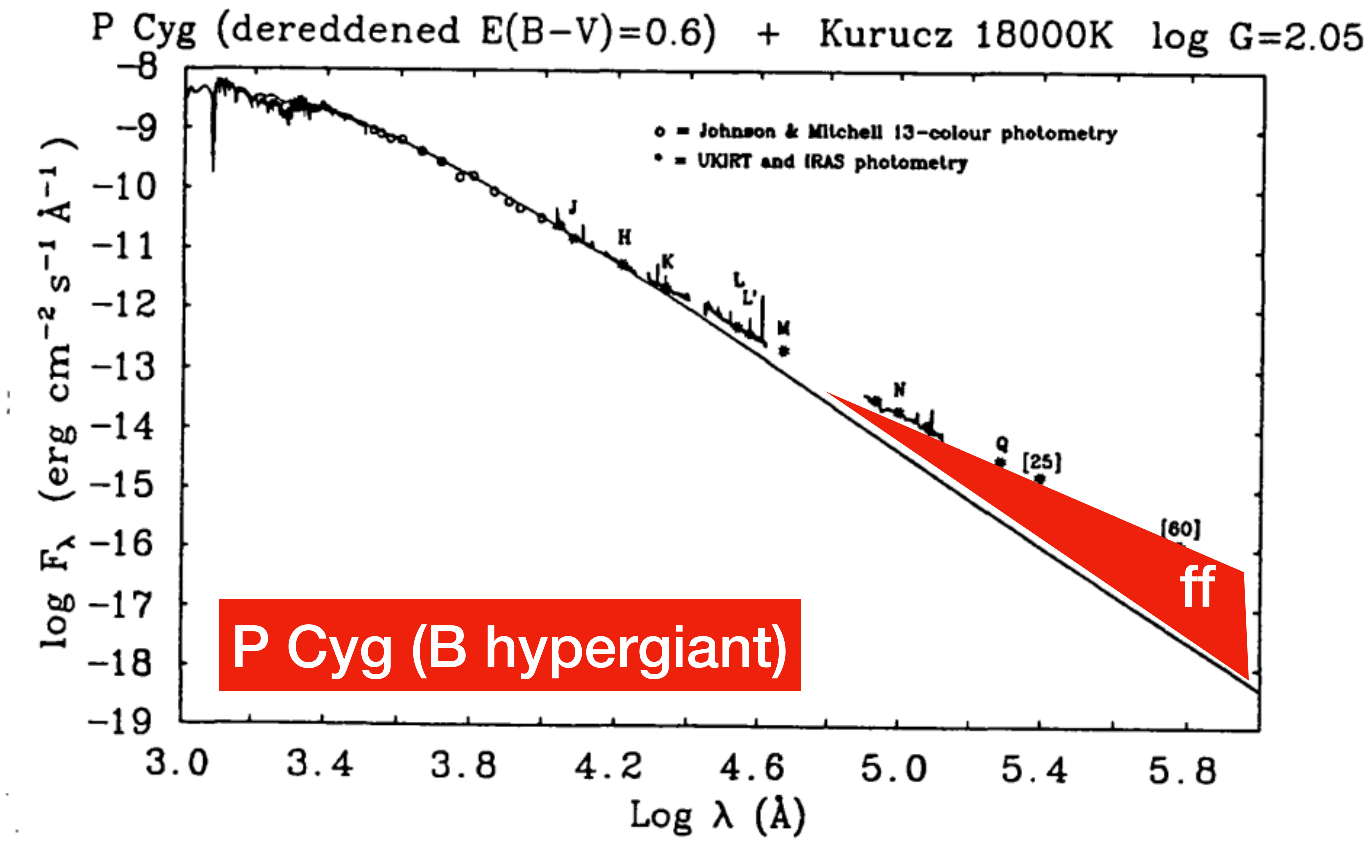
Slow winds from cool stars:

- Dust continuum (mid-IR). Dust-to-gas ratio?
- Molecular lines (mm). CO/H_2 ratio?

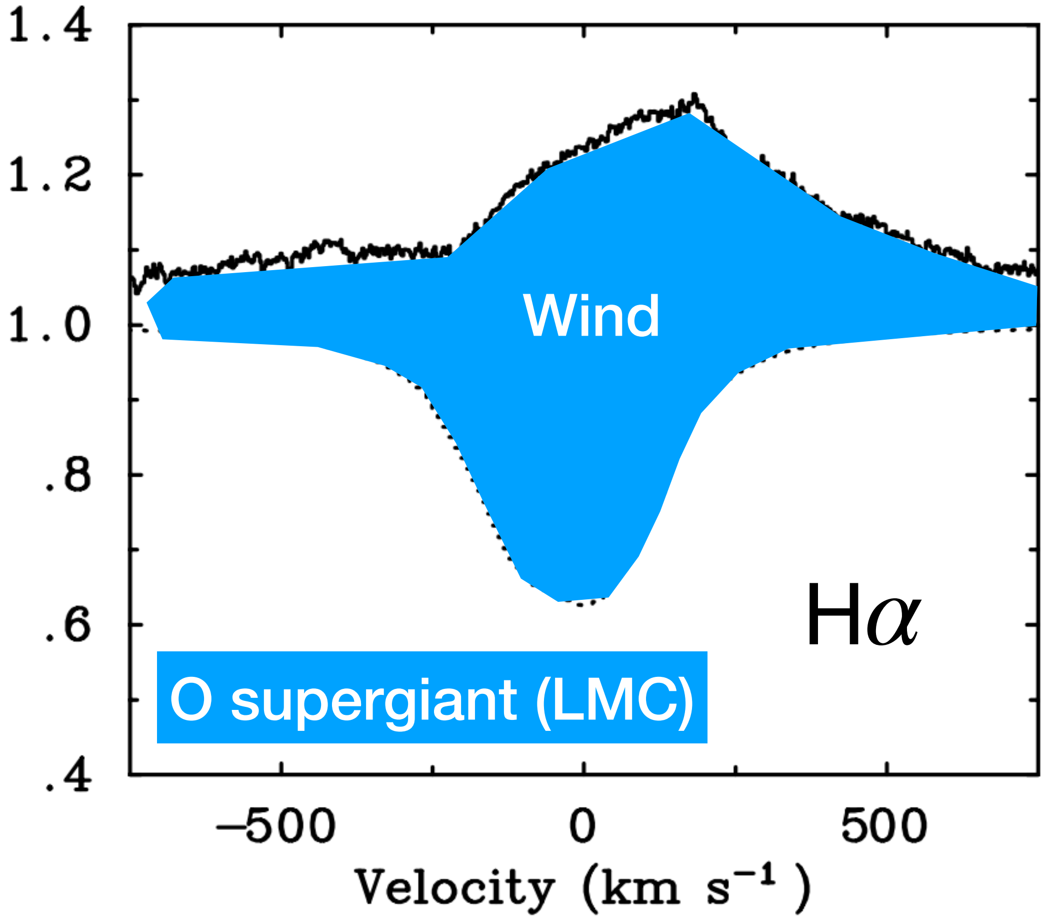


Smith 2014

Optical/IR wind diagnostics

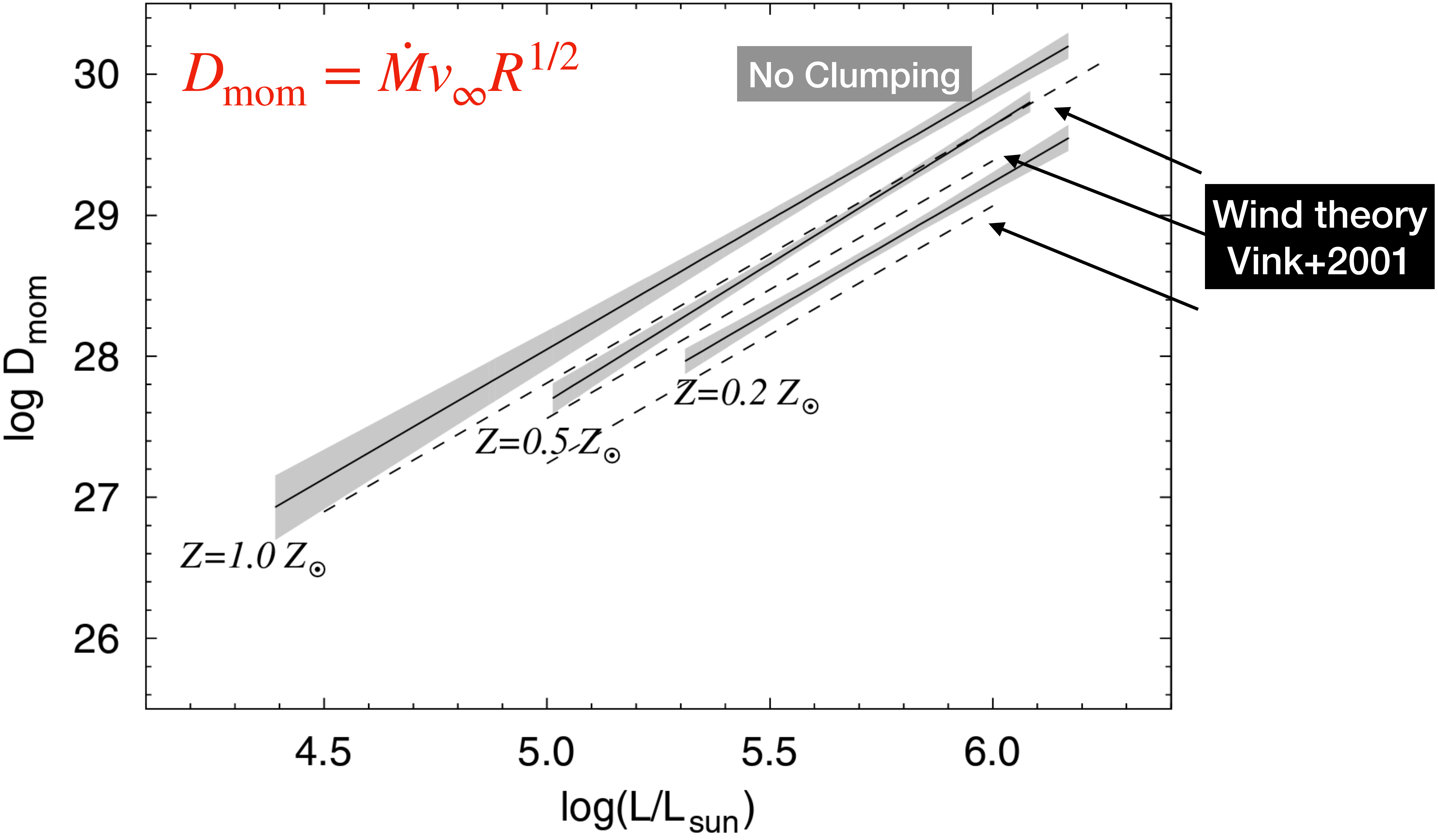


Free-free excess (Wright & Barlow 1975, Panagia & Felli 1975) Useful for Galactic OB stars, but sensitive to **wind clumping** (Rubio-Diez+2022)



Photospheric Hα profile (Lamers & Leitherer 1993) wind contaminated at high mass-loss rate. Radiative transfer & **wind clumping** dependent (Crowther+2002)

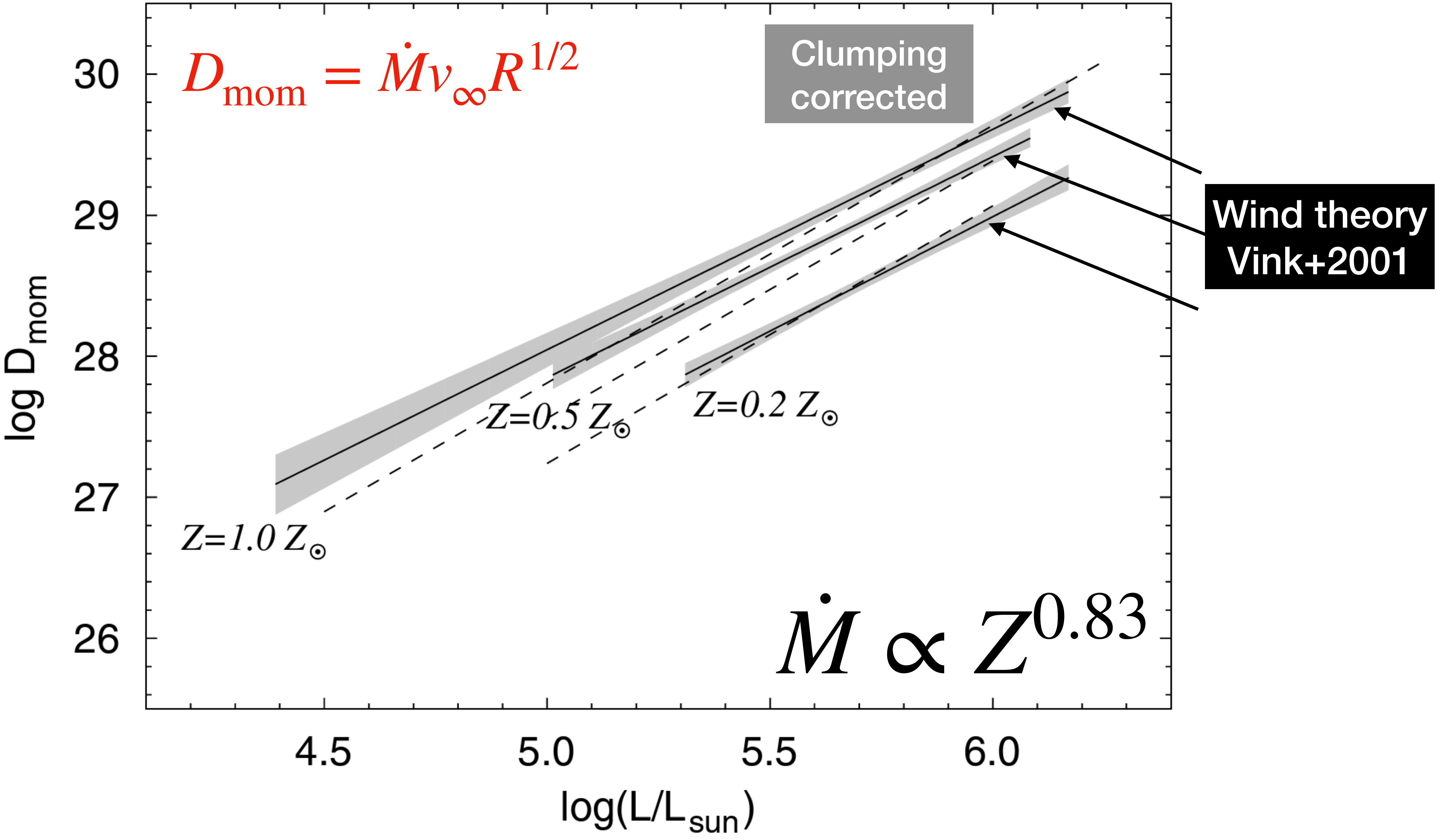
Metal-dependent OB winds



Wind theory
Vink+2001

Mokiem+2007 (Hα mass-loss rates of MW/LMC/SMC OB stars)

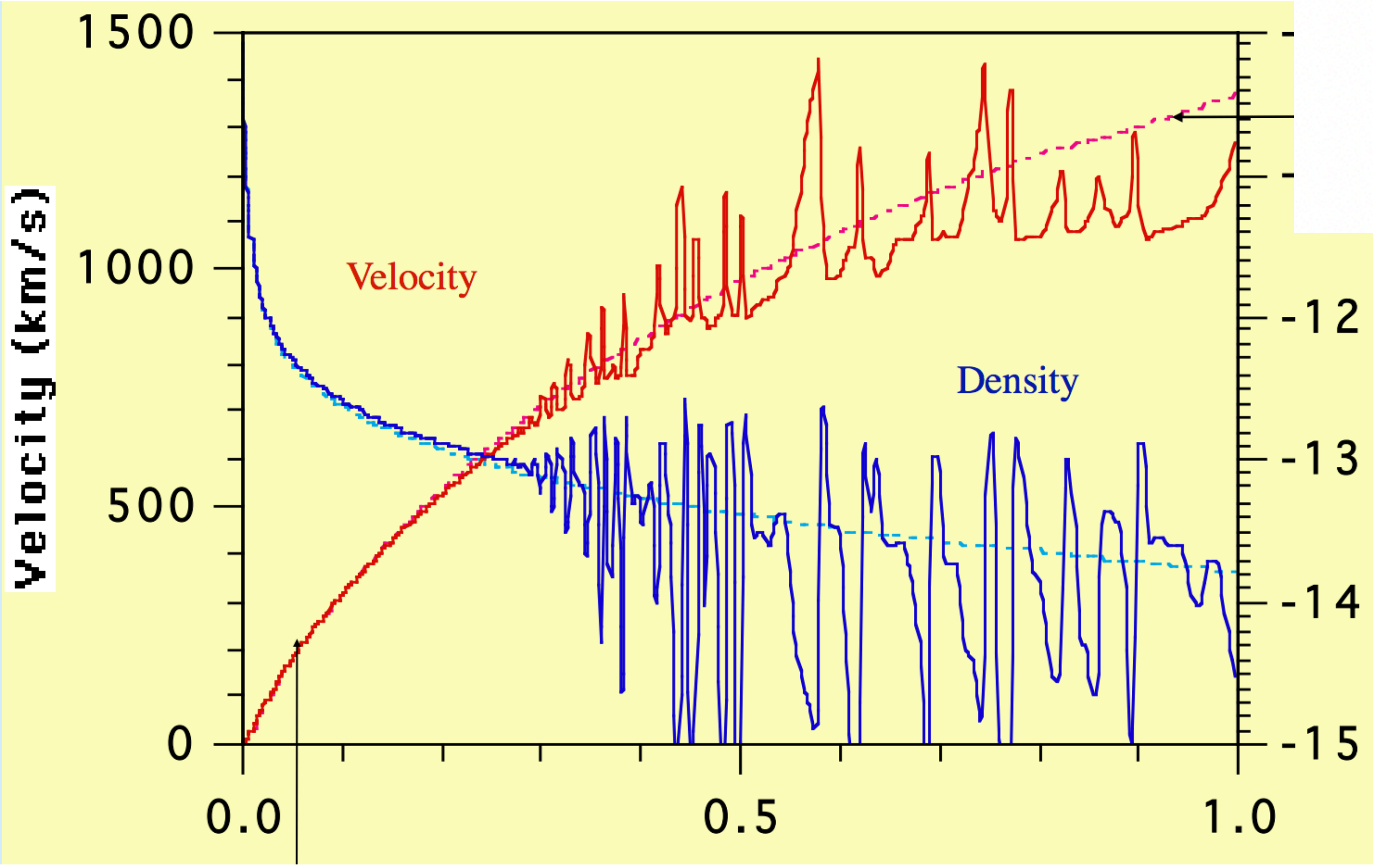
Metal-dependent OB winds

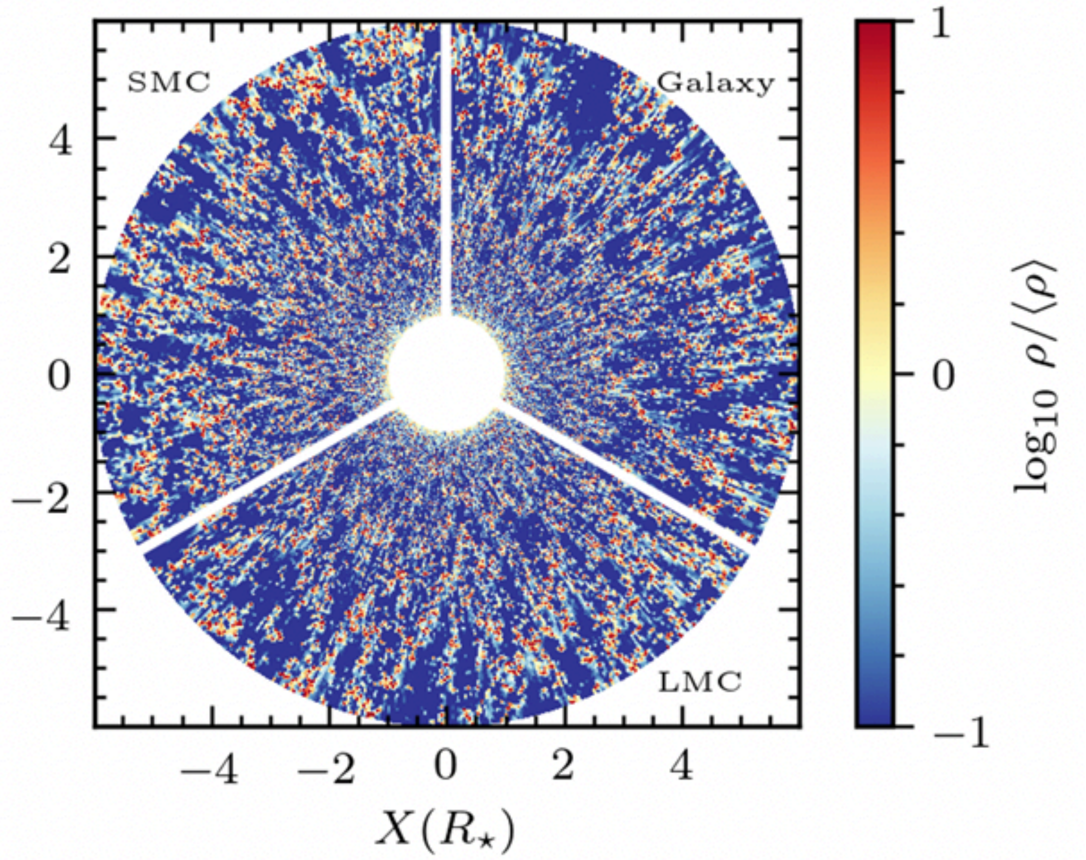


Mokiem+2007 (Hα mass-loss rates of MW/LMC/SMC OB stars)

Wind clumping

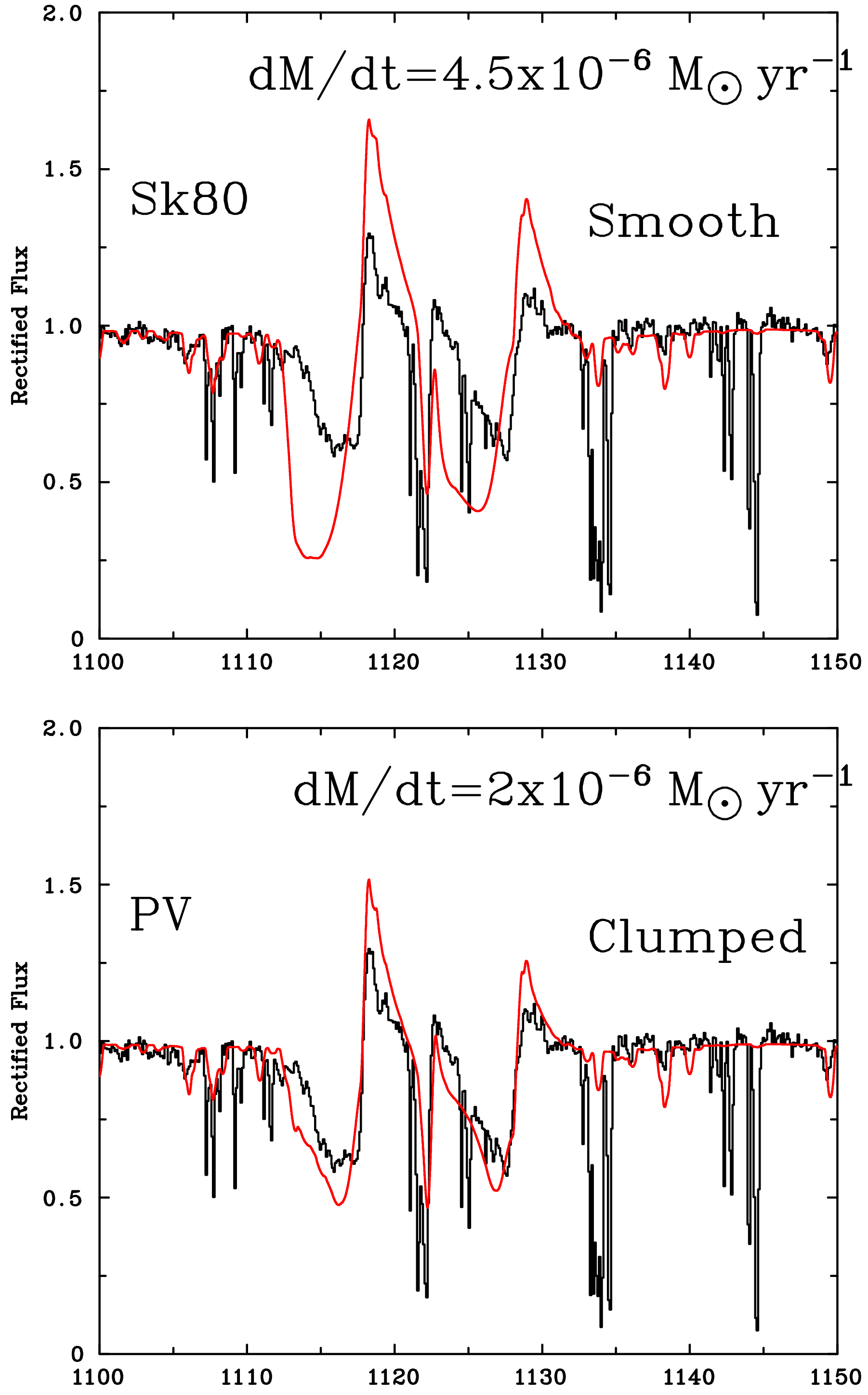
1D: Runacres & Owocki (2002)





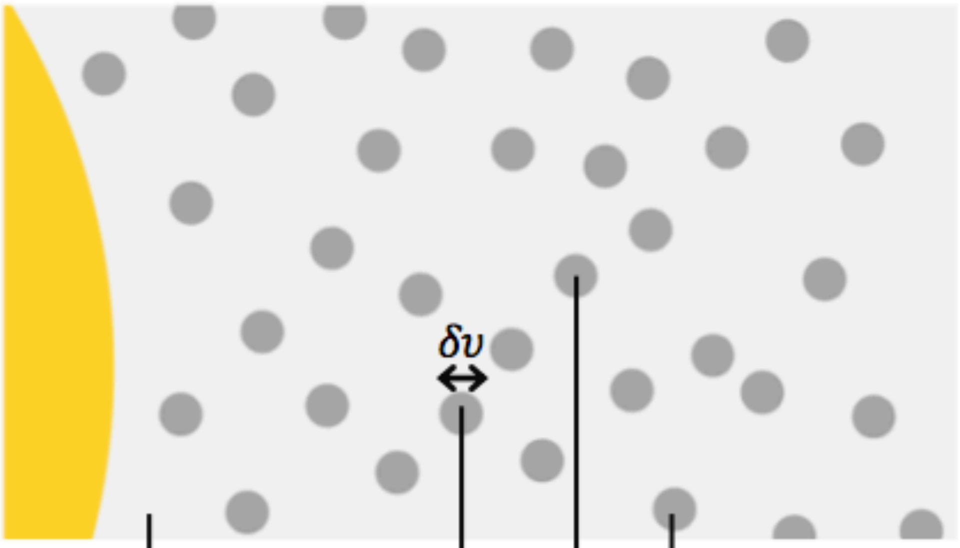
2D: Driessen+2022

UV wind diagnostics



Unsaturated resonance lines sensitive to wind clumping (Crowther+2002)

Clumps can become optically thick, especially in strong resonance lines.



$\rho_{\rm ic}$
Density of the interclump medium. A denser medium will absorb more light.

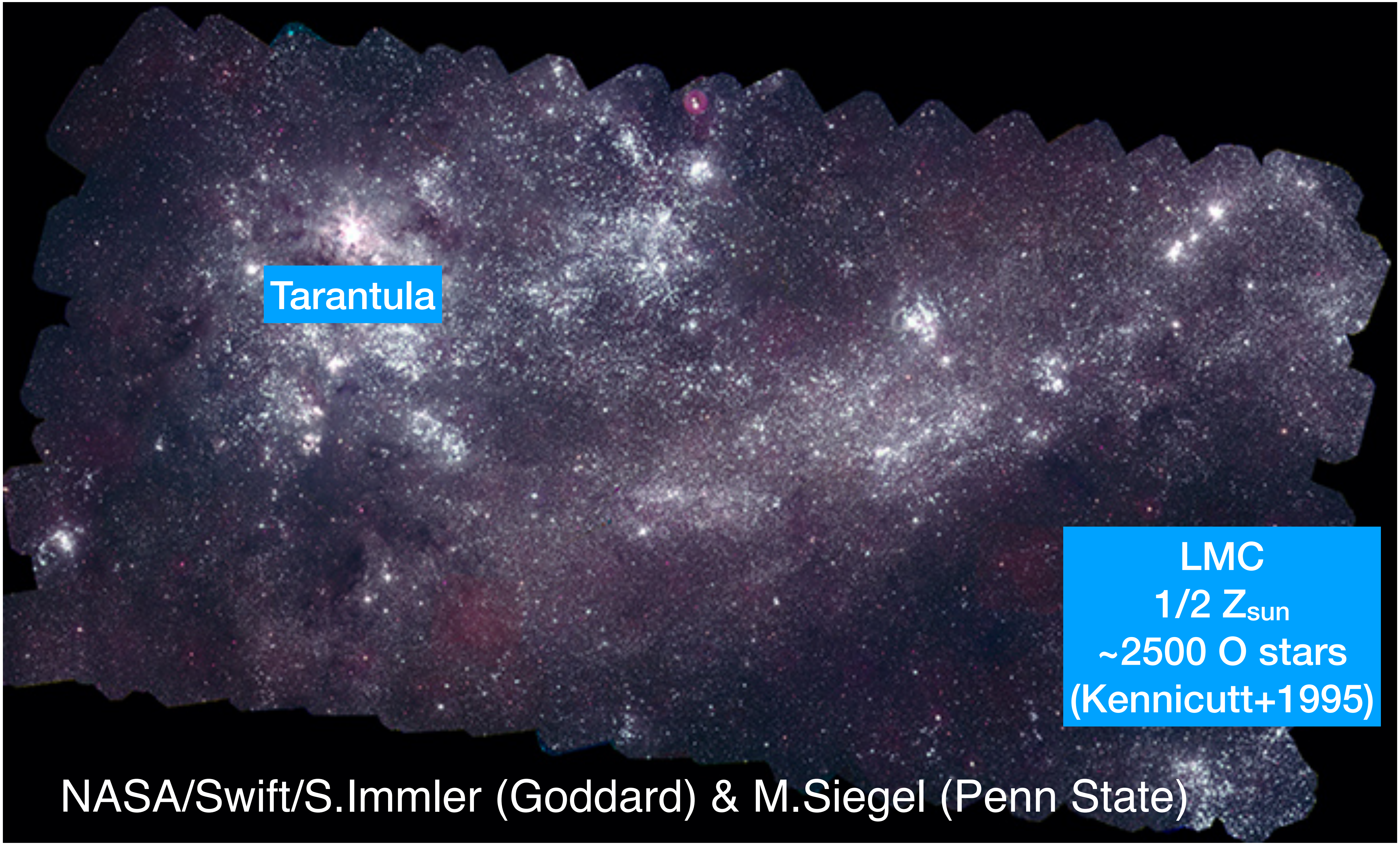
$\rho_{\rm cl}$
Density of the clumps. Affects the ionization state.

δv
The clumps span a certain velocity range δv, that can deviate from the underlying smooth field $\delta v_{\rm sm}$.

$f_{\rm vol}$
Fraction of the volume that is filled with clumps.

Clumping in 1D (Brands+2022)

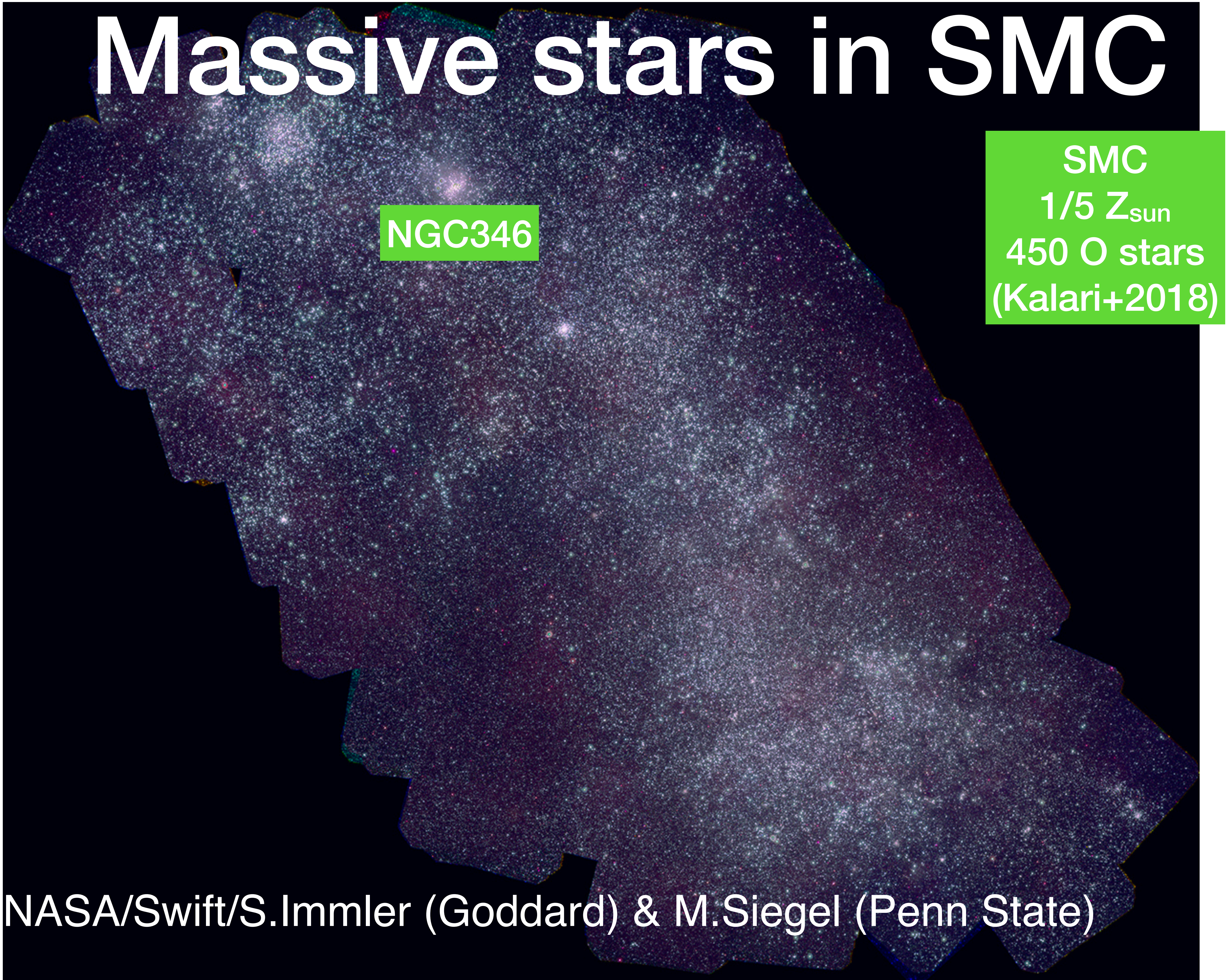
Massive stars in LMC



LMC
1/2 Z$_{sun}$
~2500 O stars
(Kennicutt+1995)

NASA/Swift/S.Immler (Goddard) & M.Siegel (Penn State)

Massive stars in SMC



SMC
1/5 Z_{sun}
450 O stars
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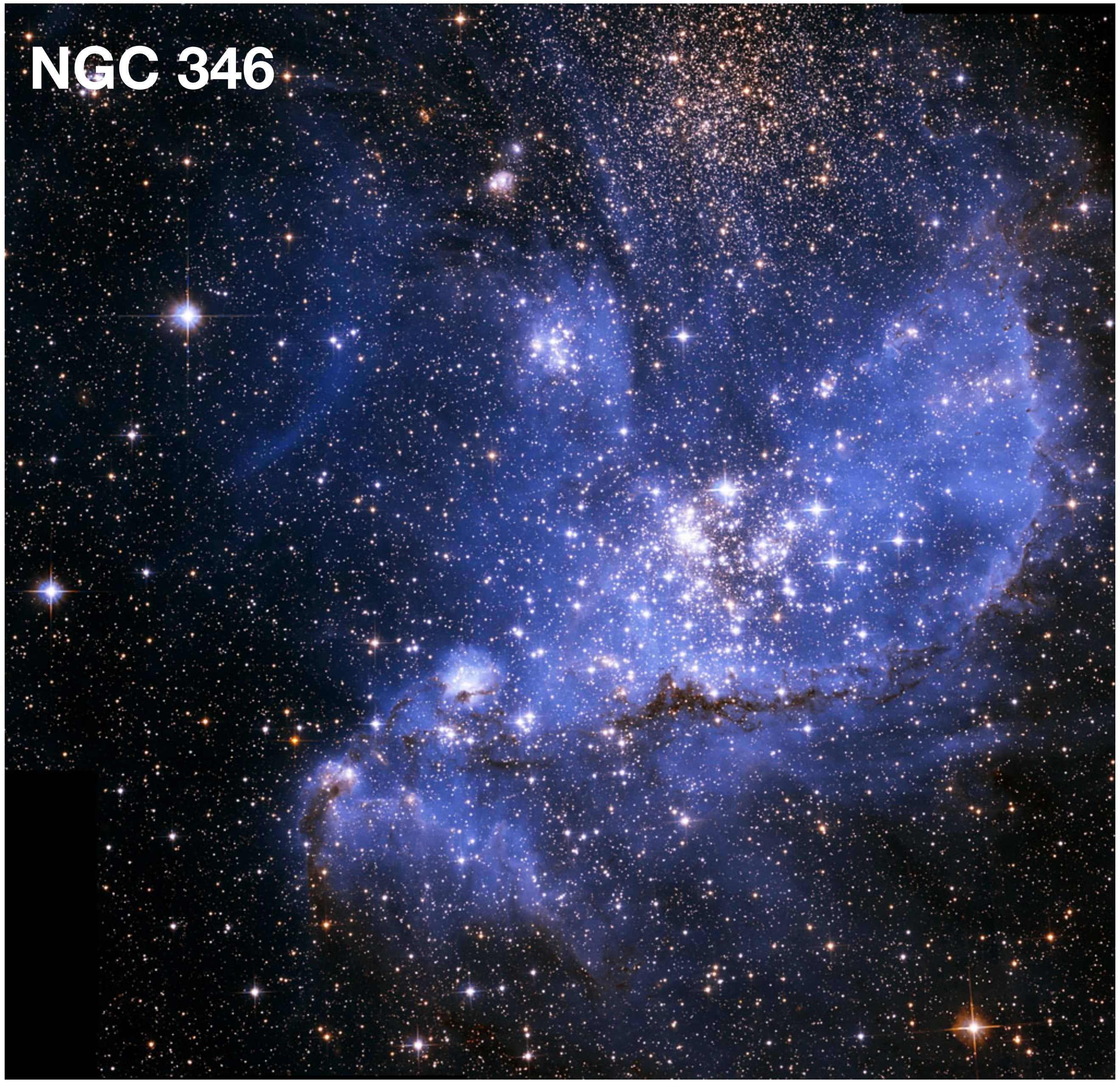
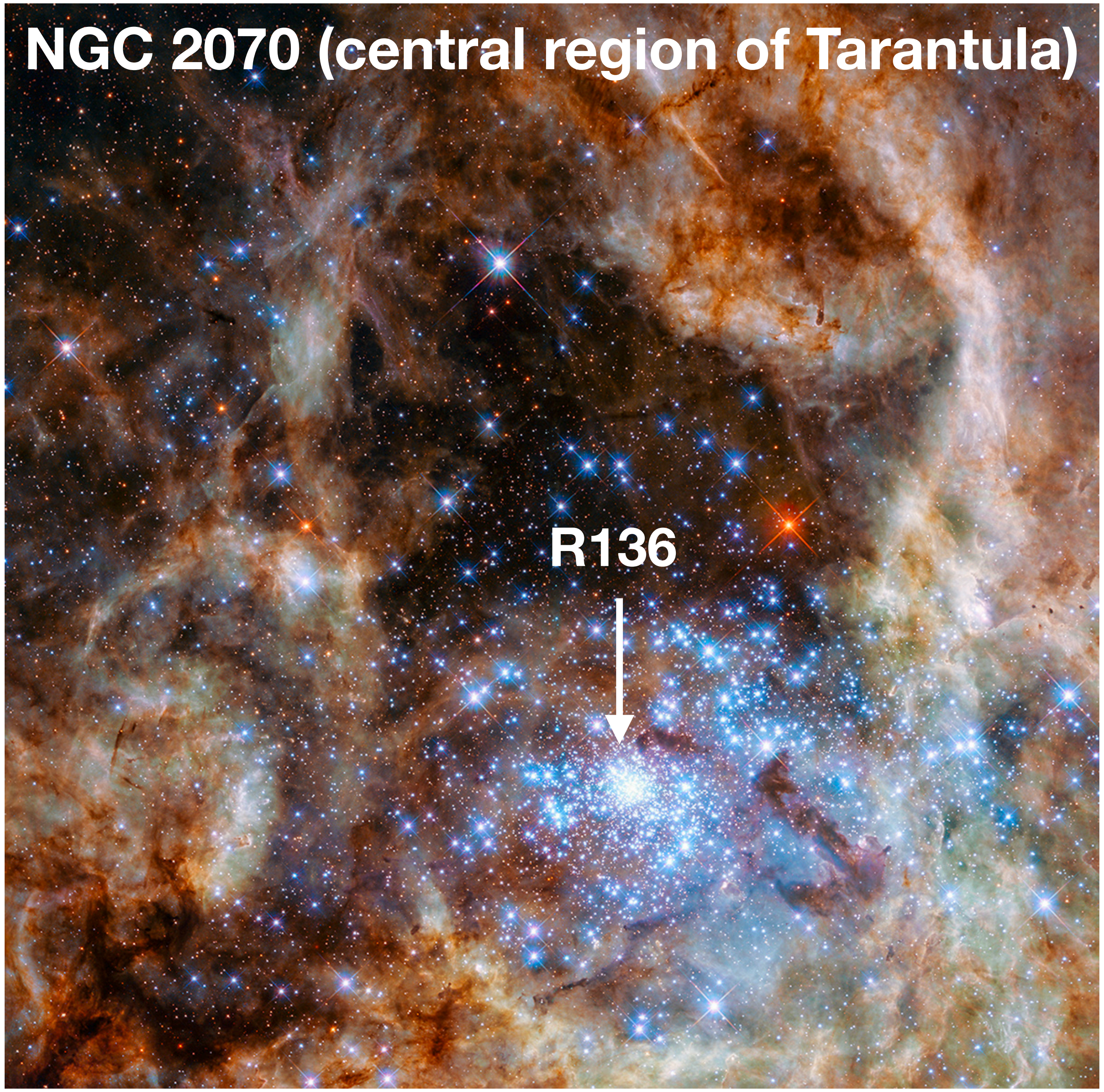
NASA/Swift/S.Immler (Goddard) & M.Siegel (Penn State)

SF regions in Mag Clouds

SMC
(1/5 Solar)



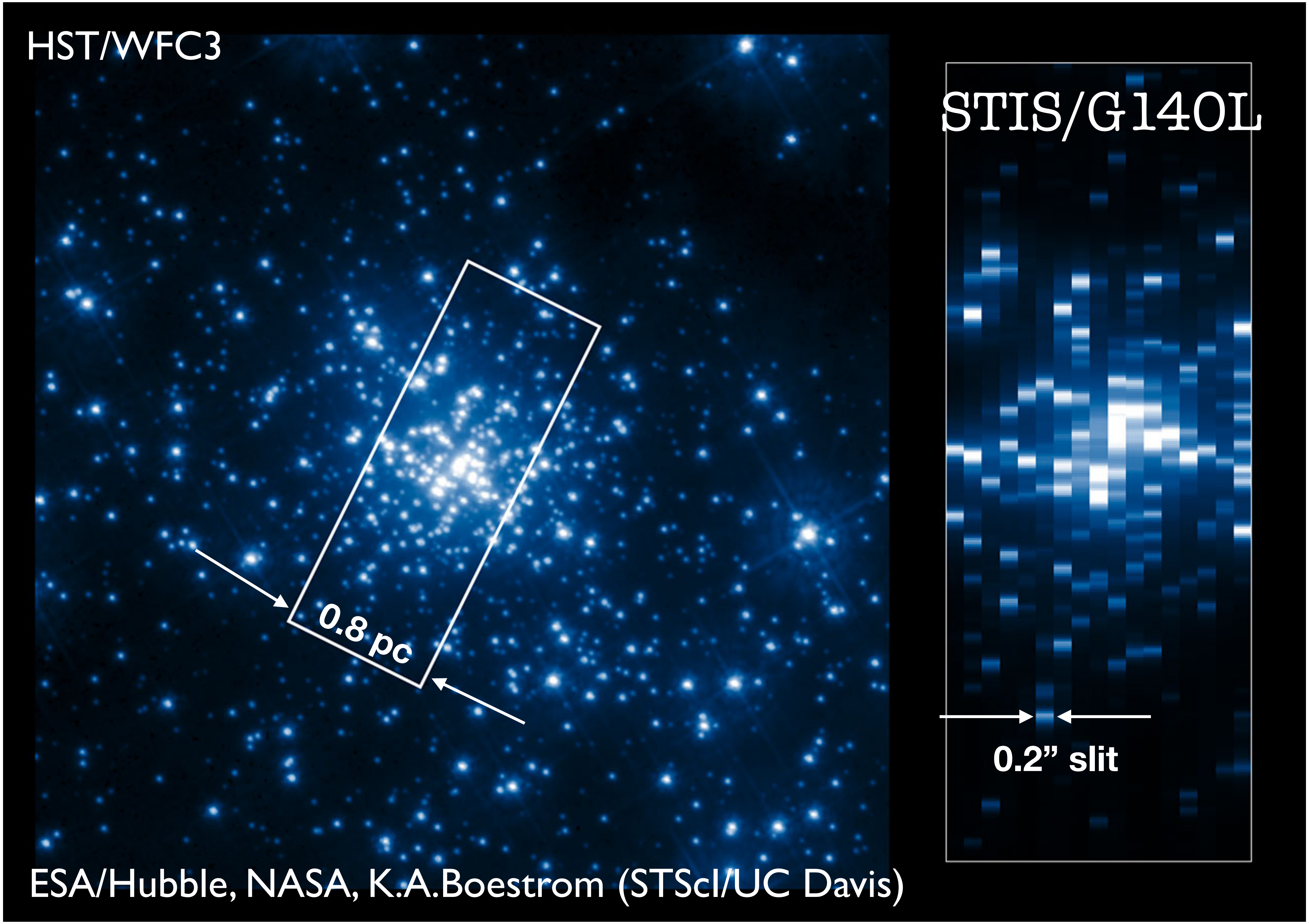


LMC
(1/2 Solar)

3.2’ (40pc @ 60kpc)

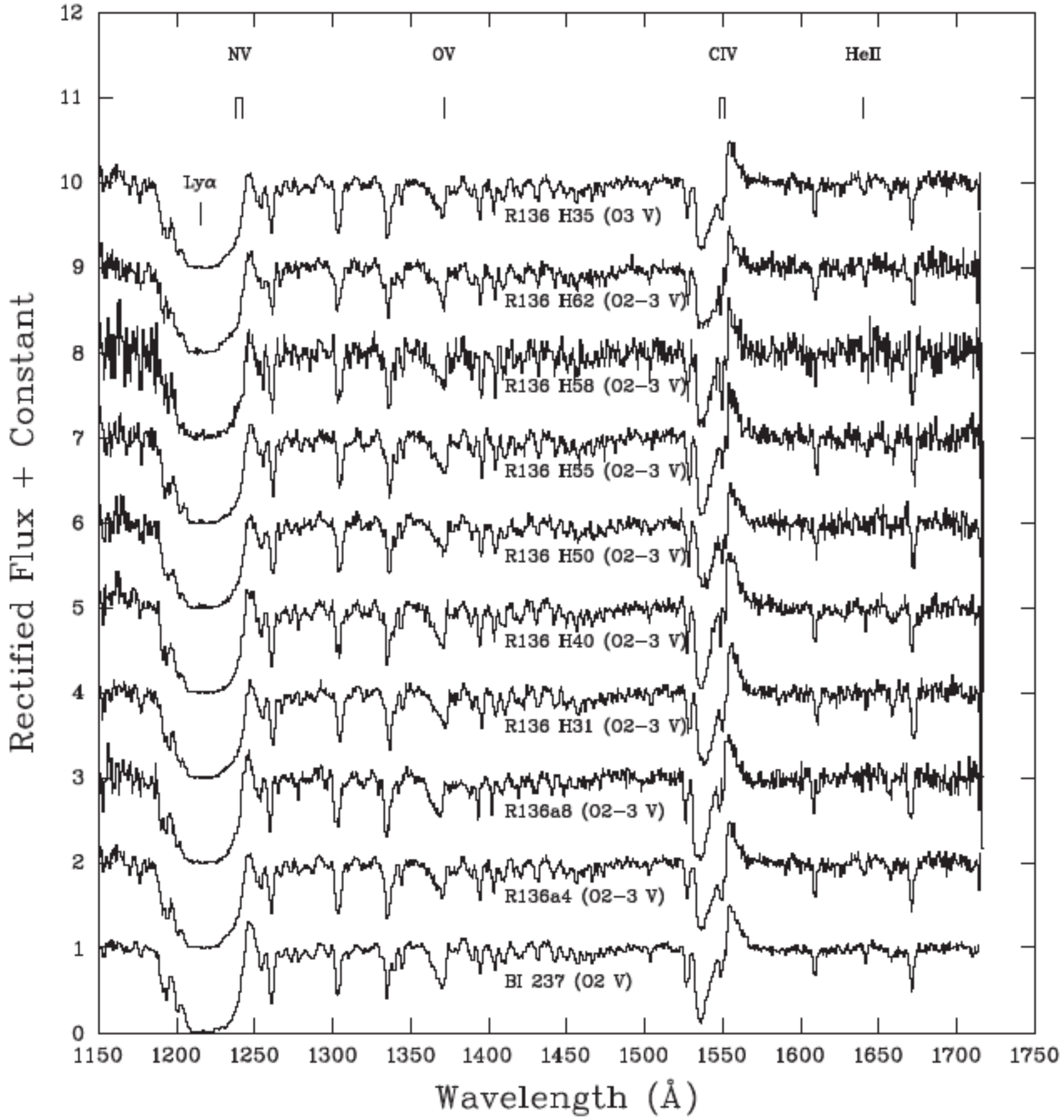
2.6’ (40pc @ 50kpc)

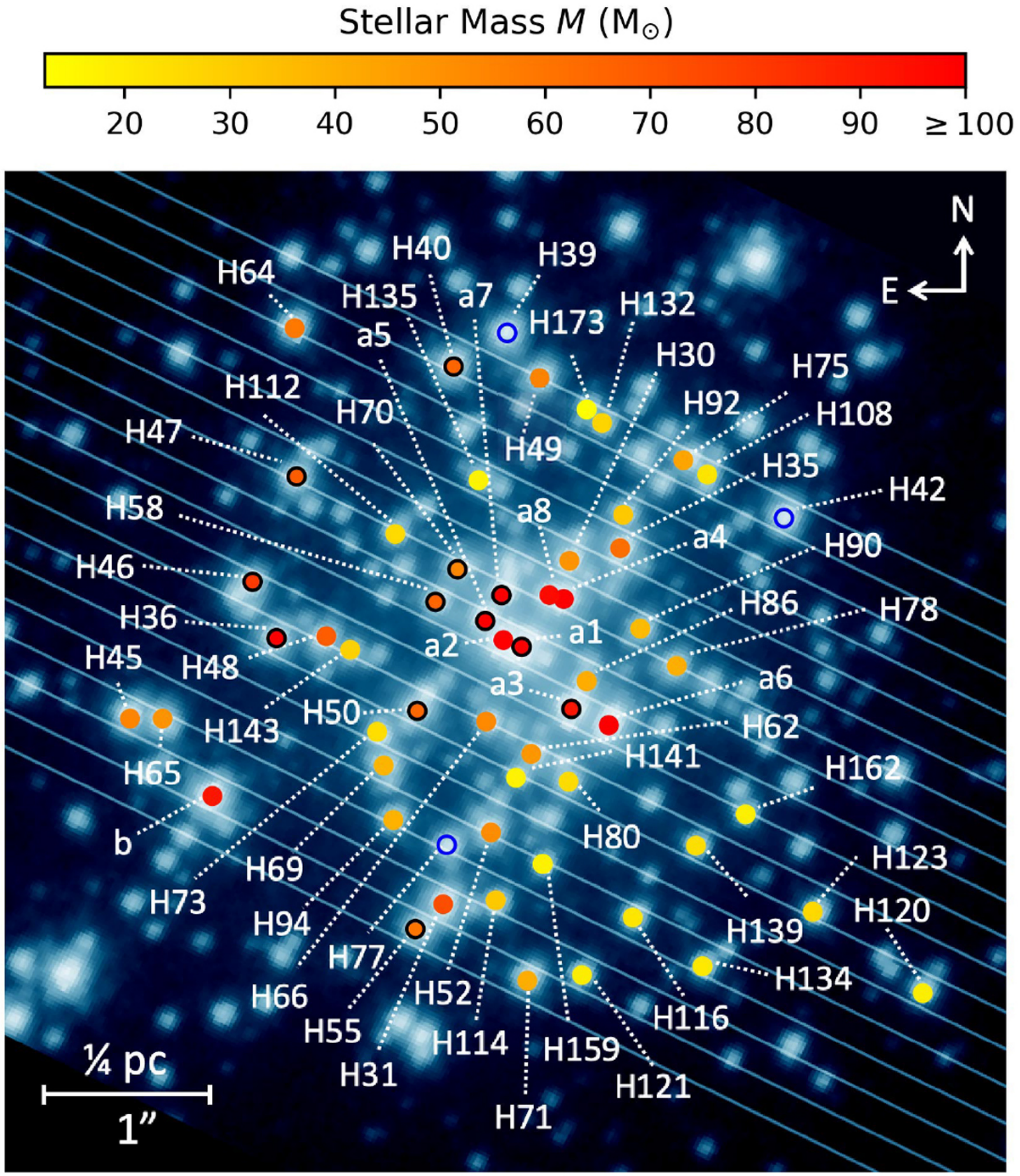
LMC: R136 resolved in UV



ESA/Hubble, NASA, K.A.Boestrom (STScI/UC Davis)

LMC: R136 resolved in UV



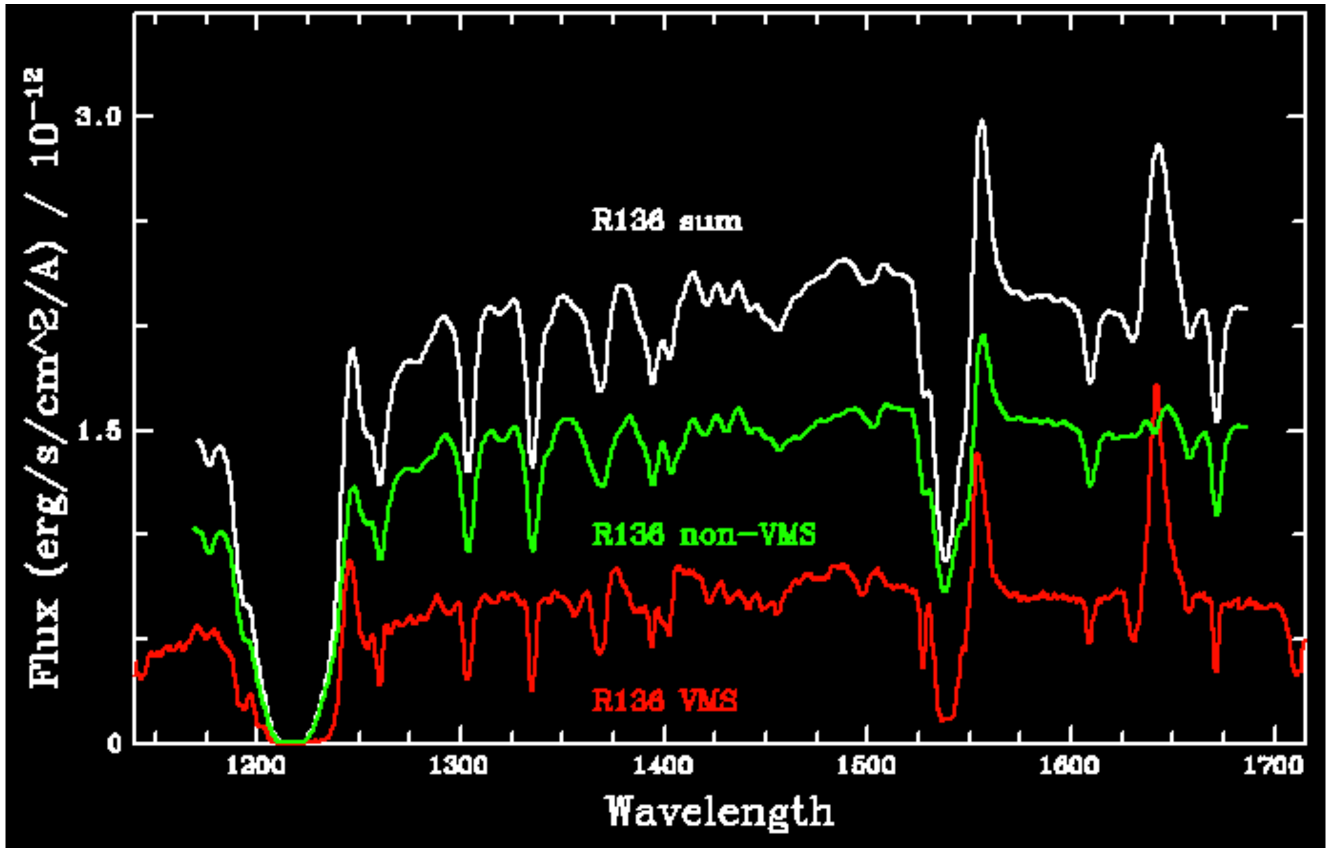


Lots of O2-3V stars

Massey & Hunter 1998;
Crowther+2016

Brands+2022

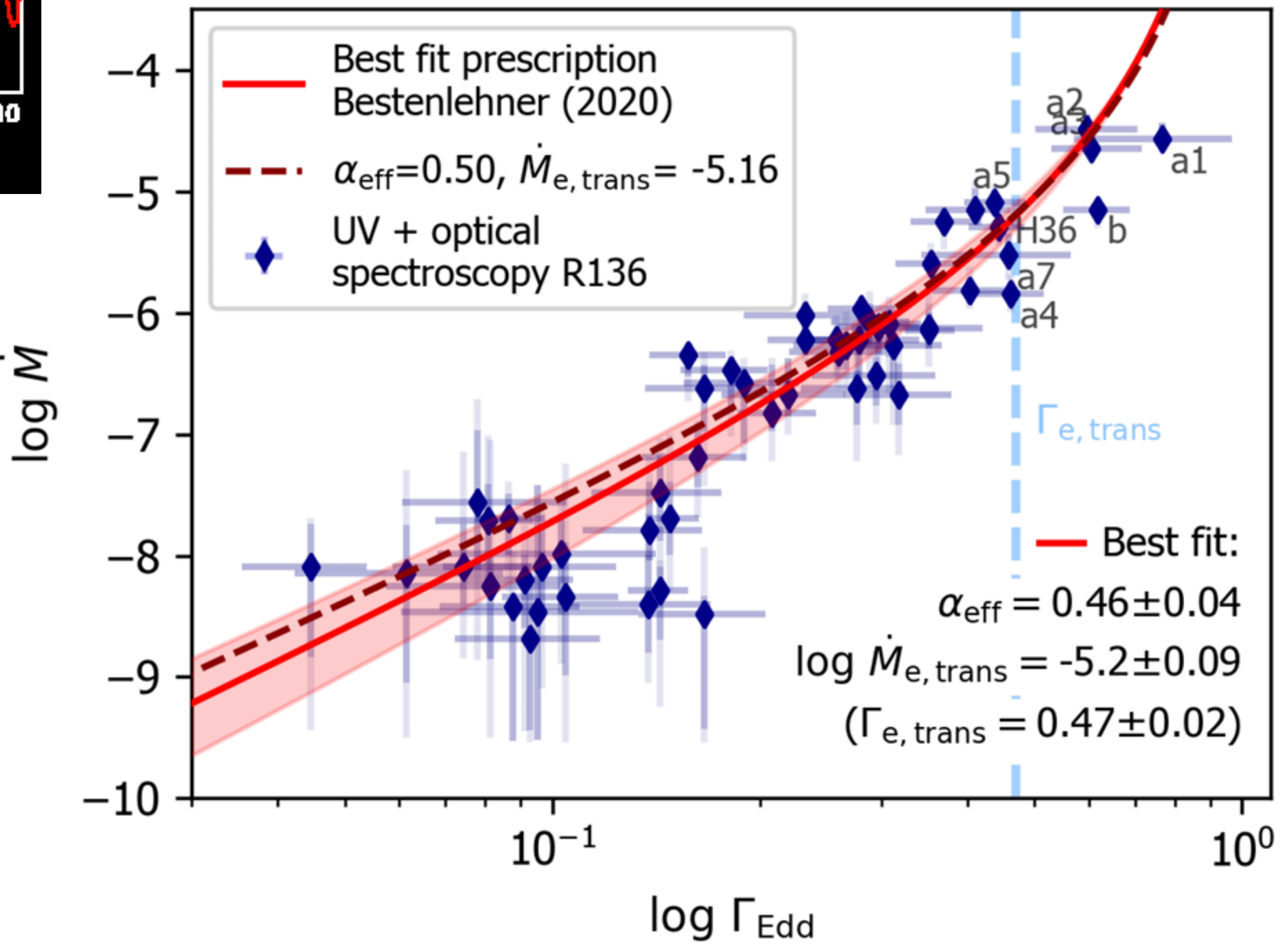
LMC: Mass-loss prescription



HST/STIS UV spectroscopy of R136 confirms youth (~1.5Myr). HeII 1640 emission from very massive stars (WR stars dominate at later ages)

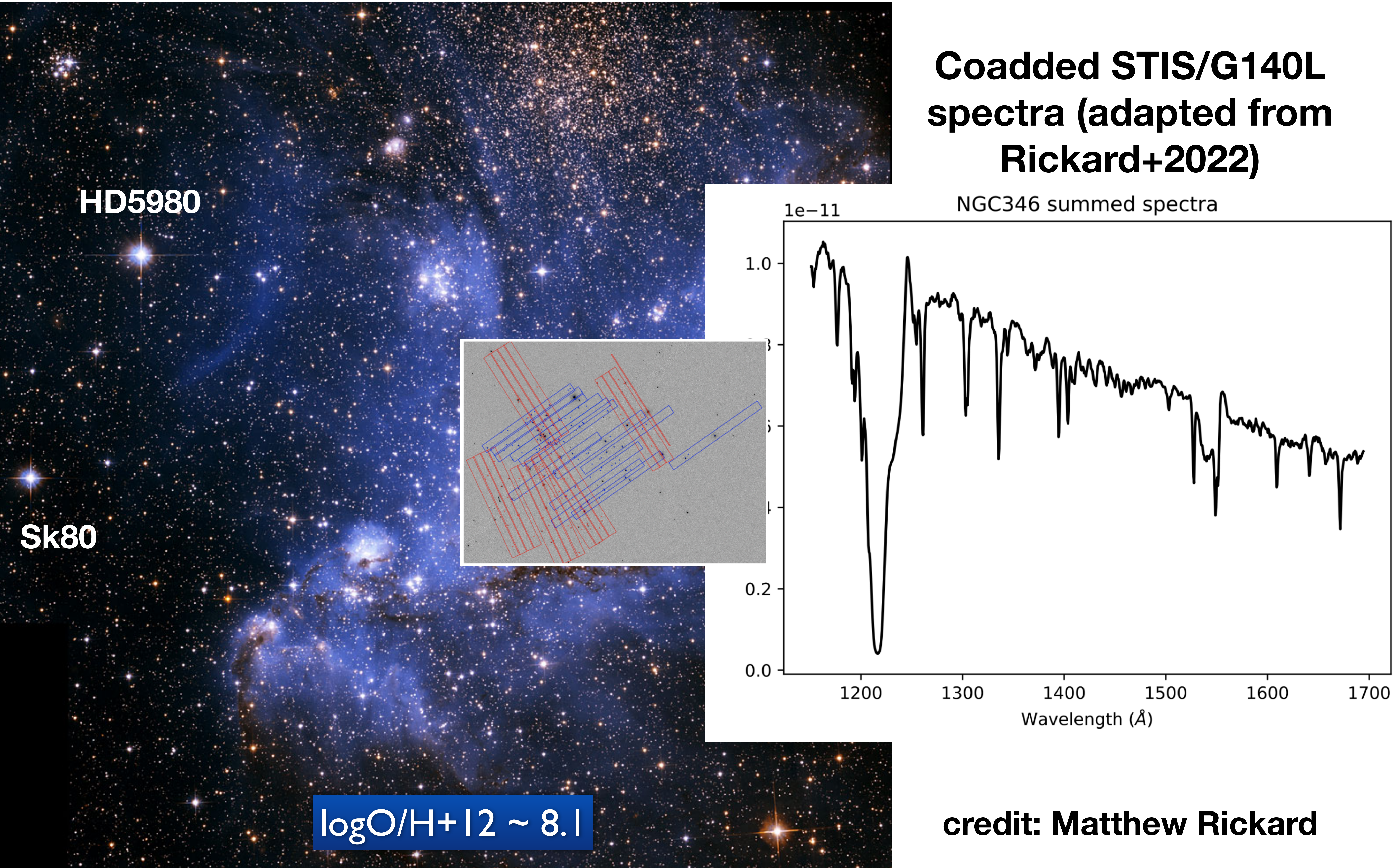
$$\boxed{\dot{M} = f(L, M, T, Z, v_{\rm rot})}$$

Sensitive to $L/L_{\rm Edd}$
Brands+2022



SMC: NGC 346 core resolved in UV

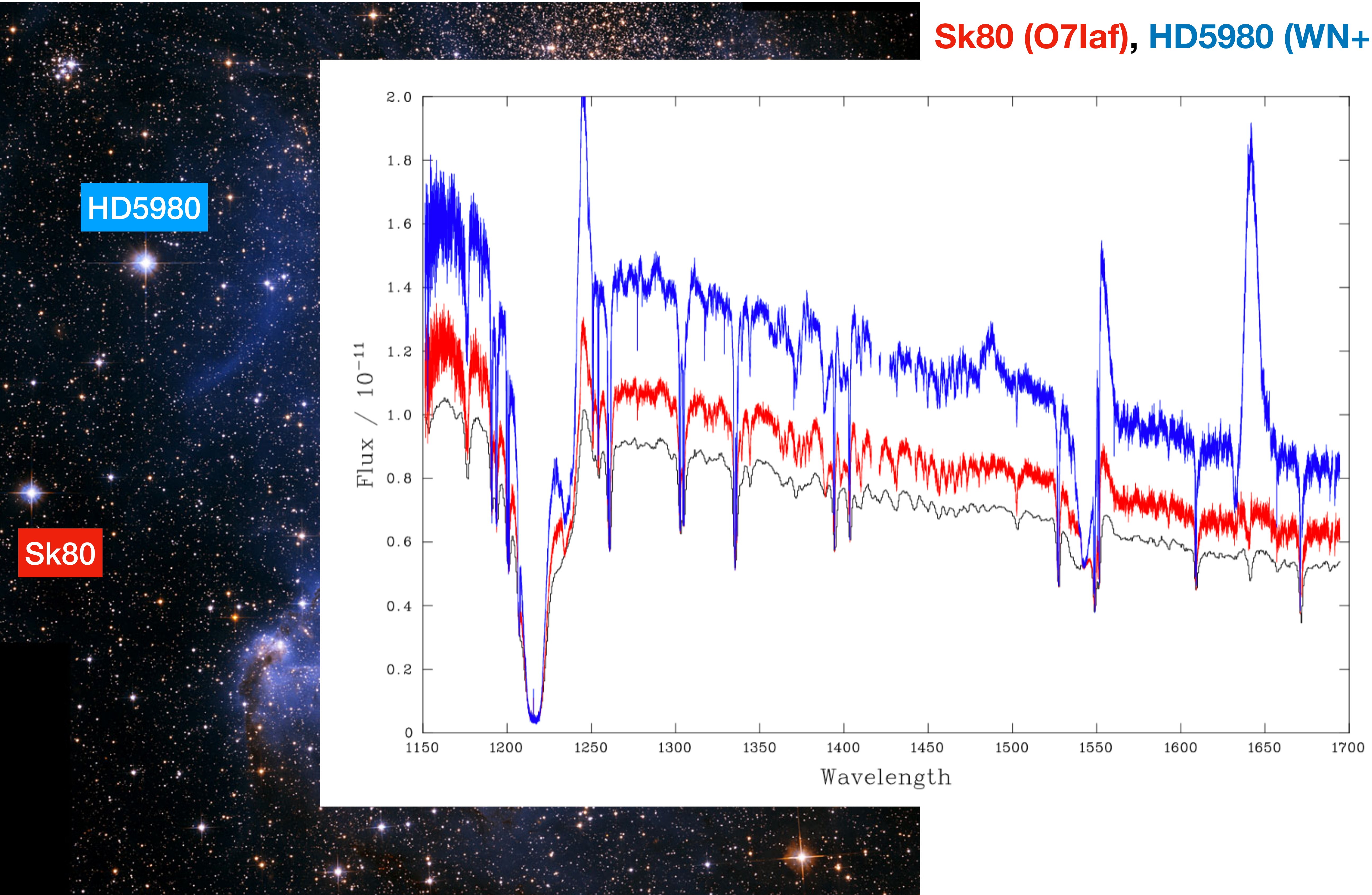
Coadded STIS/G140L spectra (adapted from Rickard+2022)



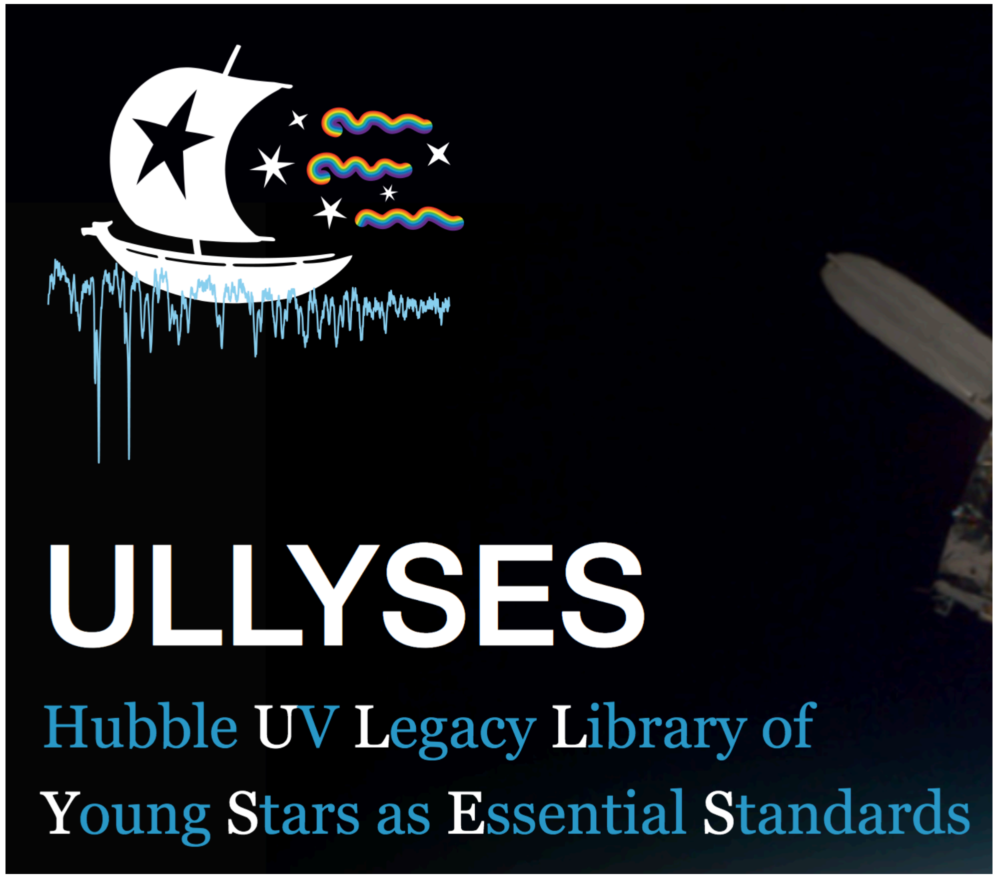
credit: Matthew Rickard

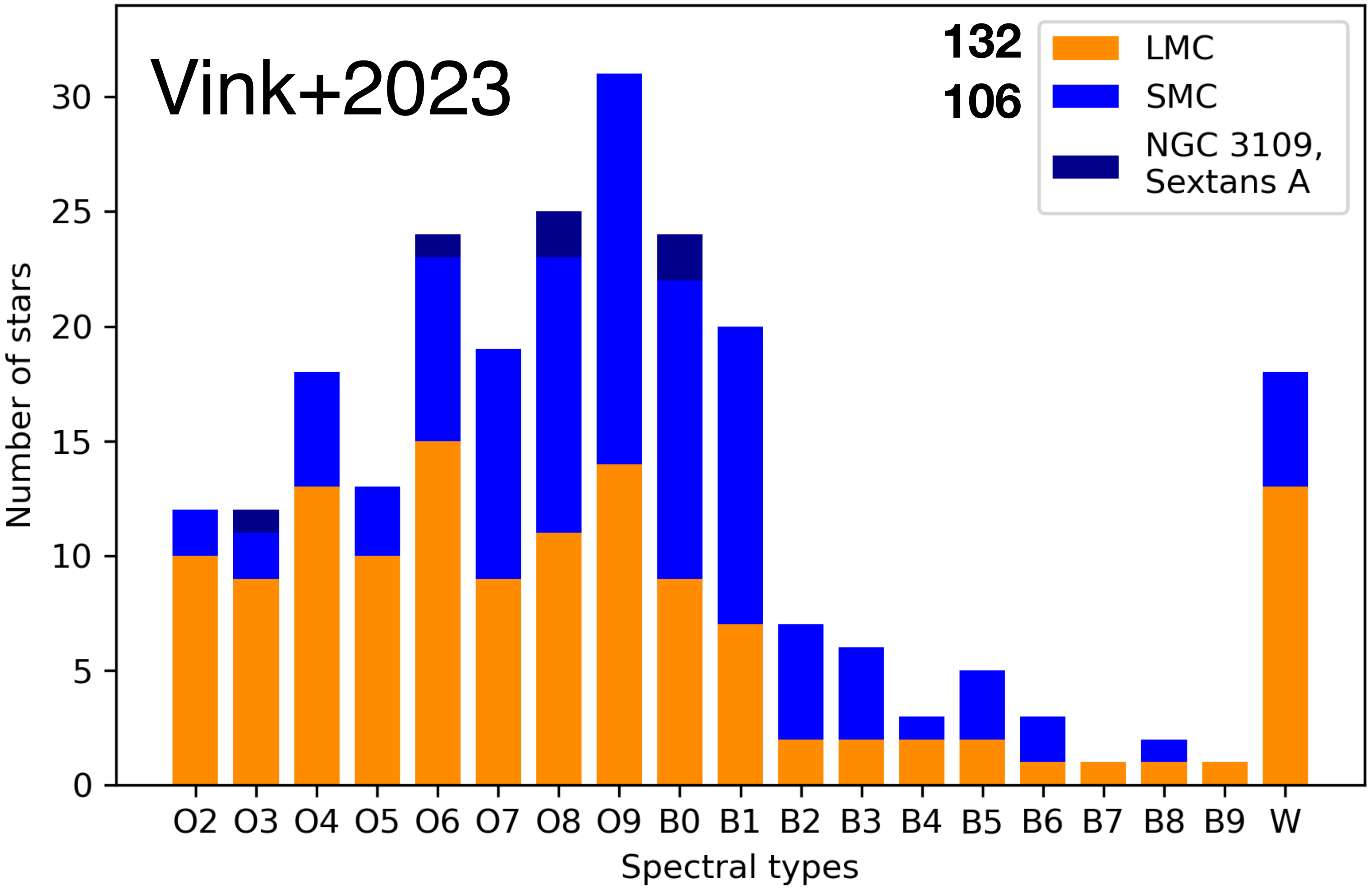
SMC: Weak winds excl. HD5980 (WN+..)

Sk80 (O7Iaf), HD5980 (WN+..)



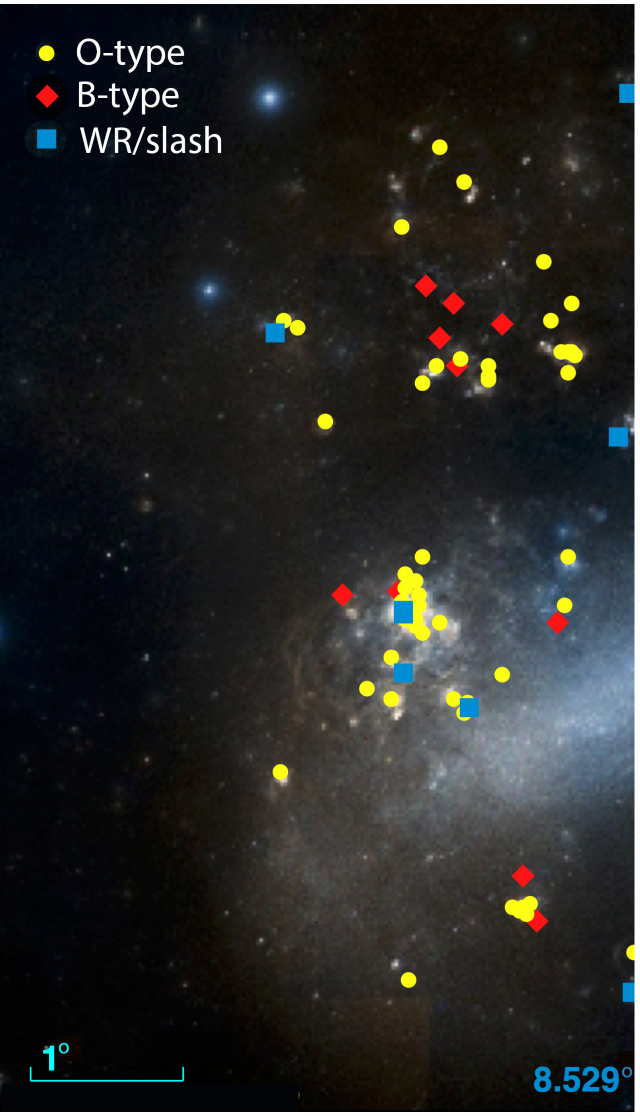
HST/ULLYSES



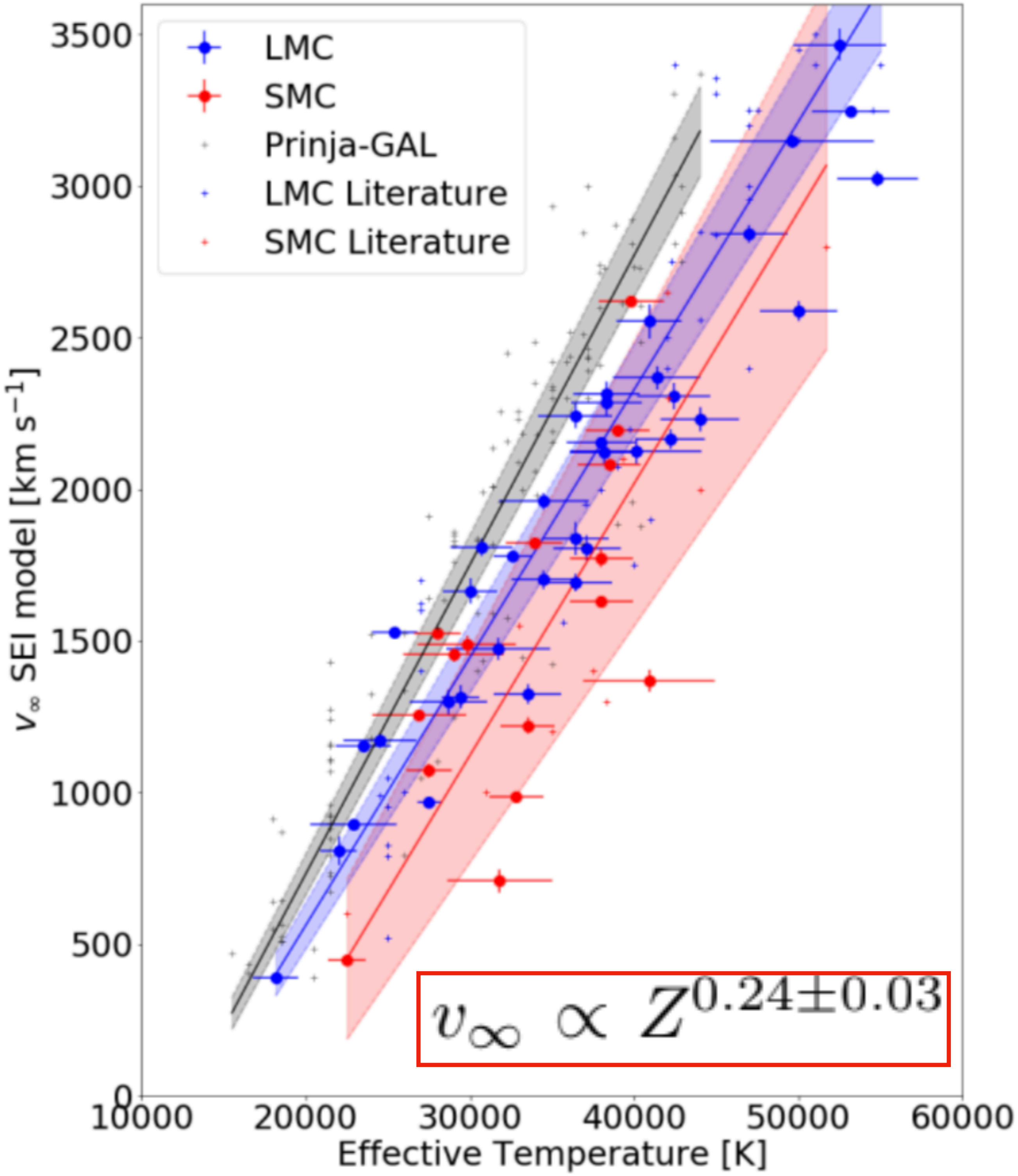


DDT initiative providing STIS/E140M or COS/G130M+G160M spectroscopy of >100 OB stars in each of Magellanic Clouds + STIS/E230M or COS/G190M for B supergiants (+ very metal-poor Local Group dwarf targets) plus selected Of/WN and WR stars

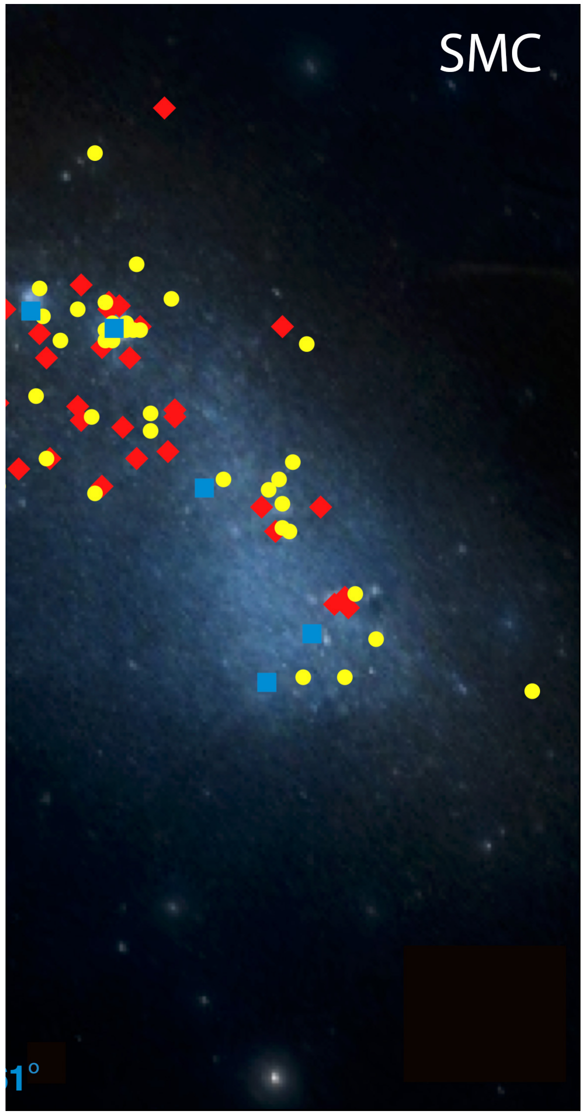
HST/ULLYSES



Vink+2023



$$v_\infty \propto Z^{0.24\pm0.03}$$



Hawcroft+2023

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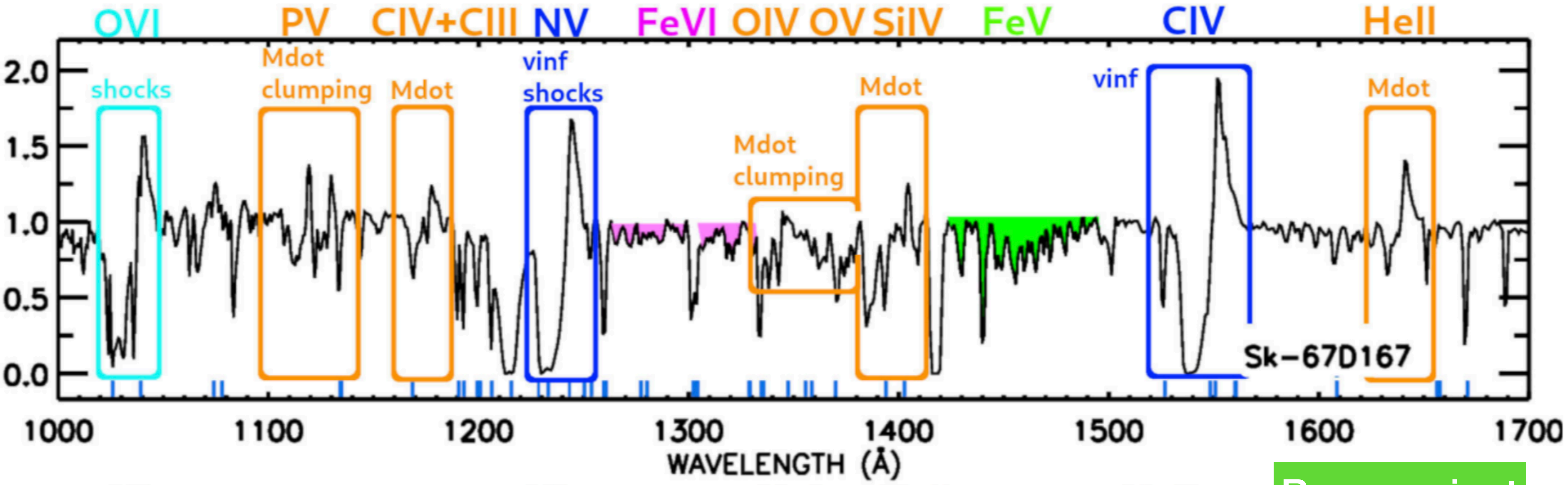
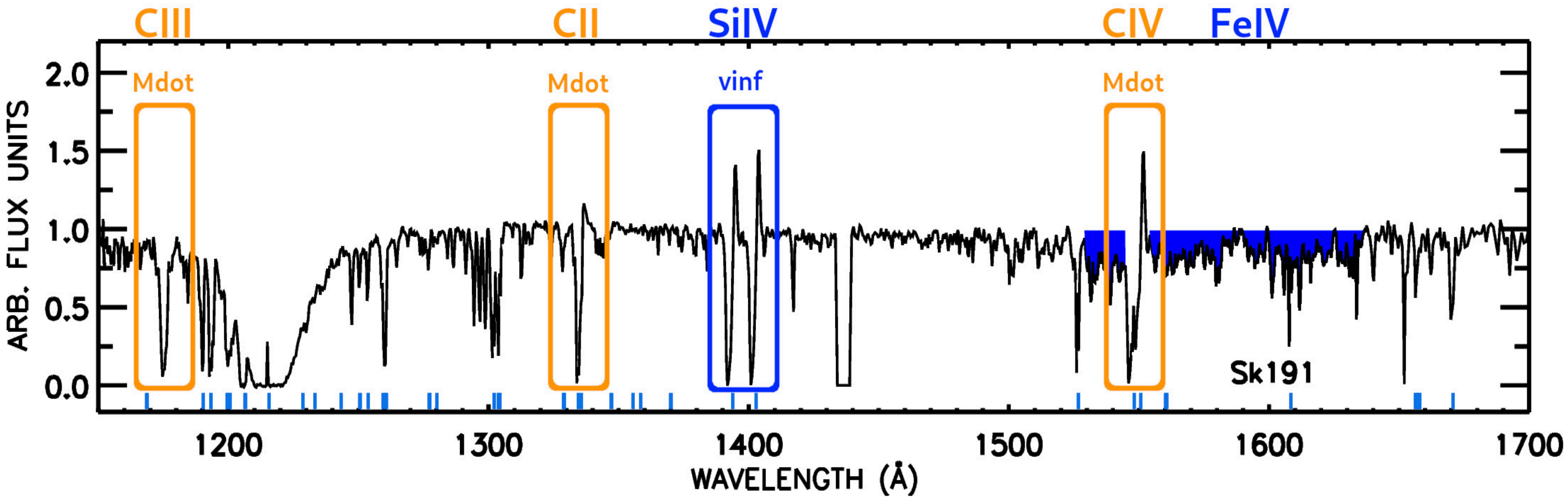
ULLYSES FUV

O supergiant



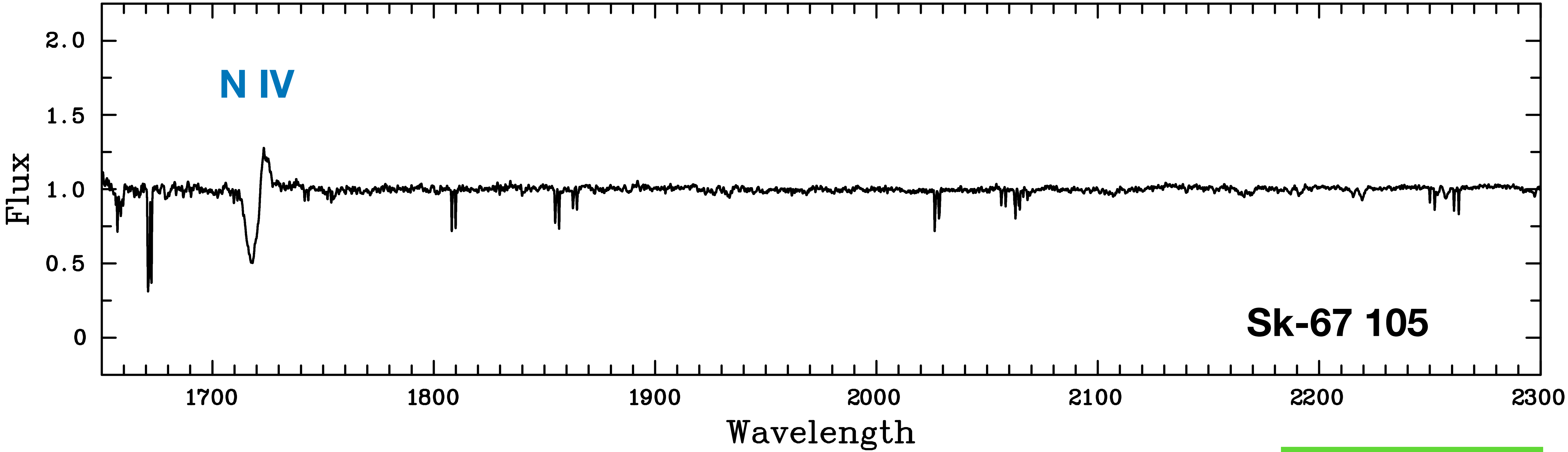
B supergiant



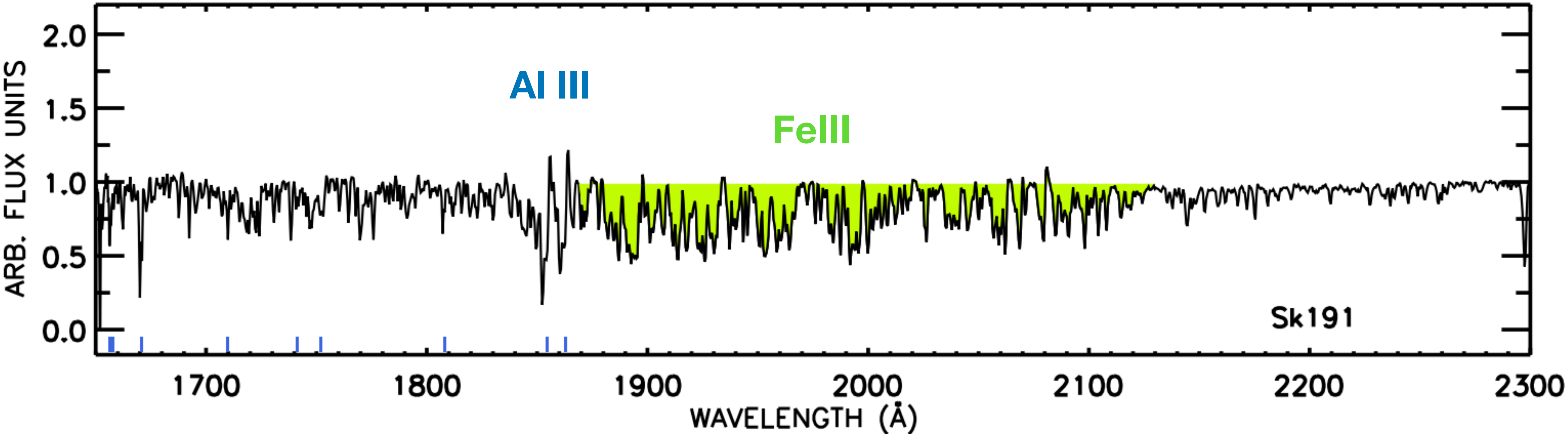
Vink+2023

ULLYSES NUV

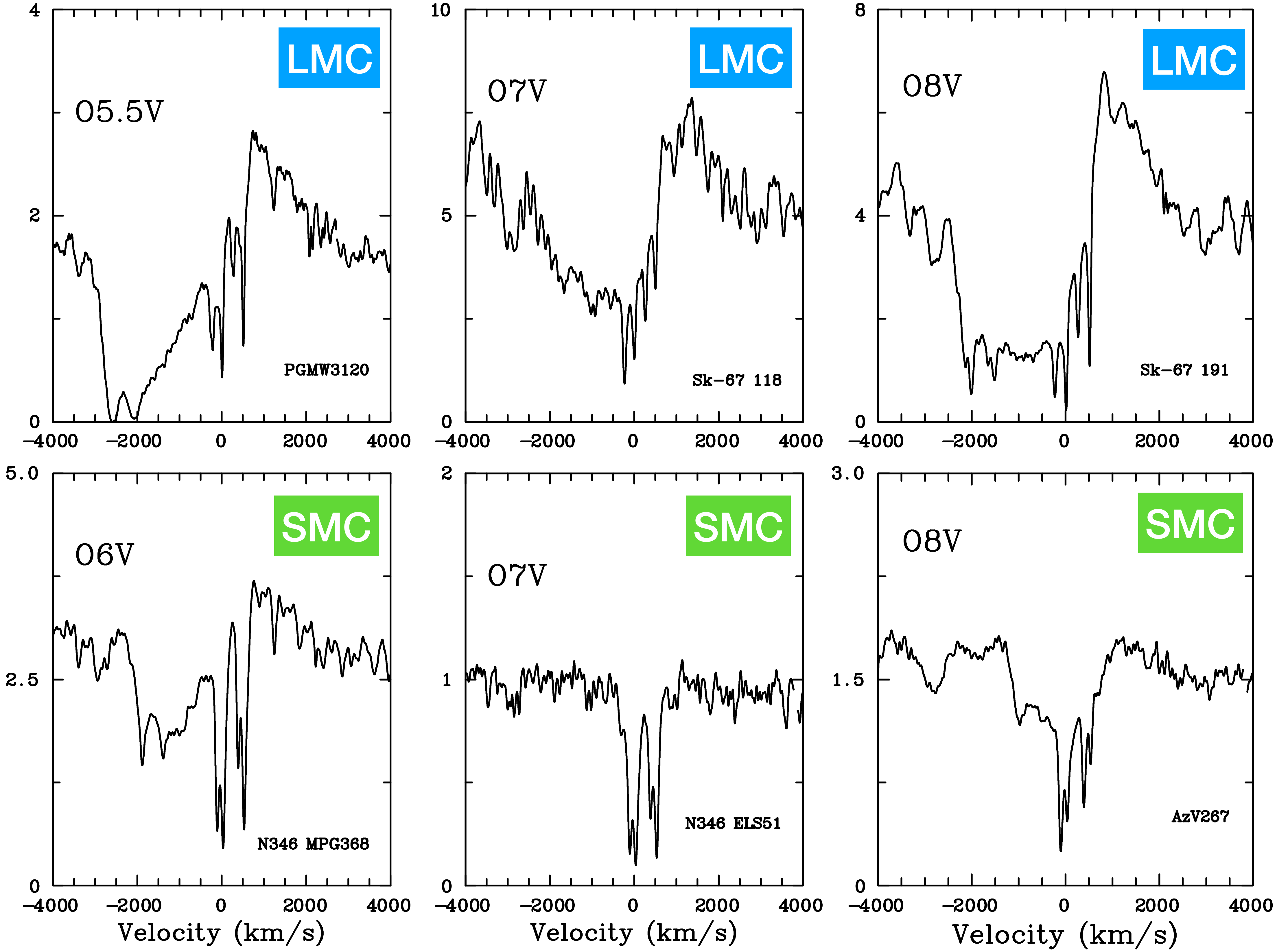
O supergiant



B supergiant

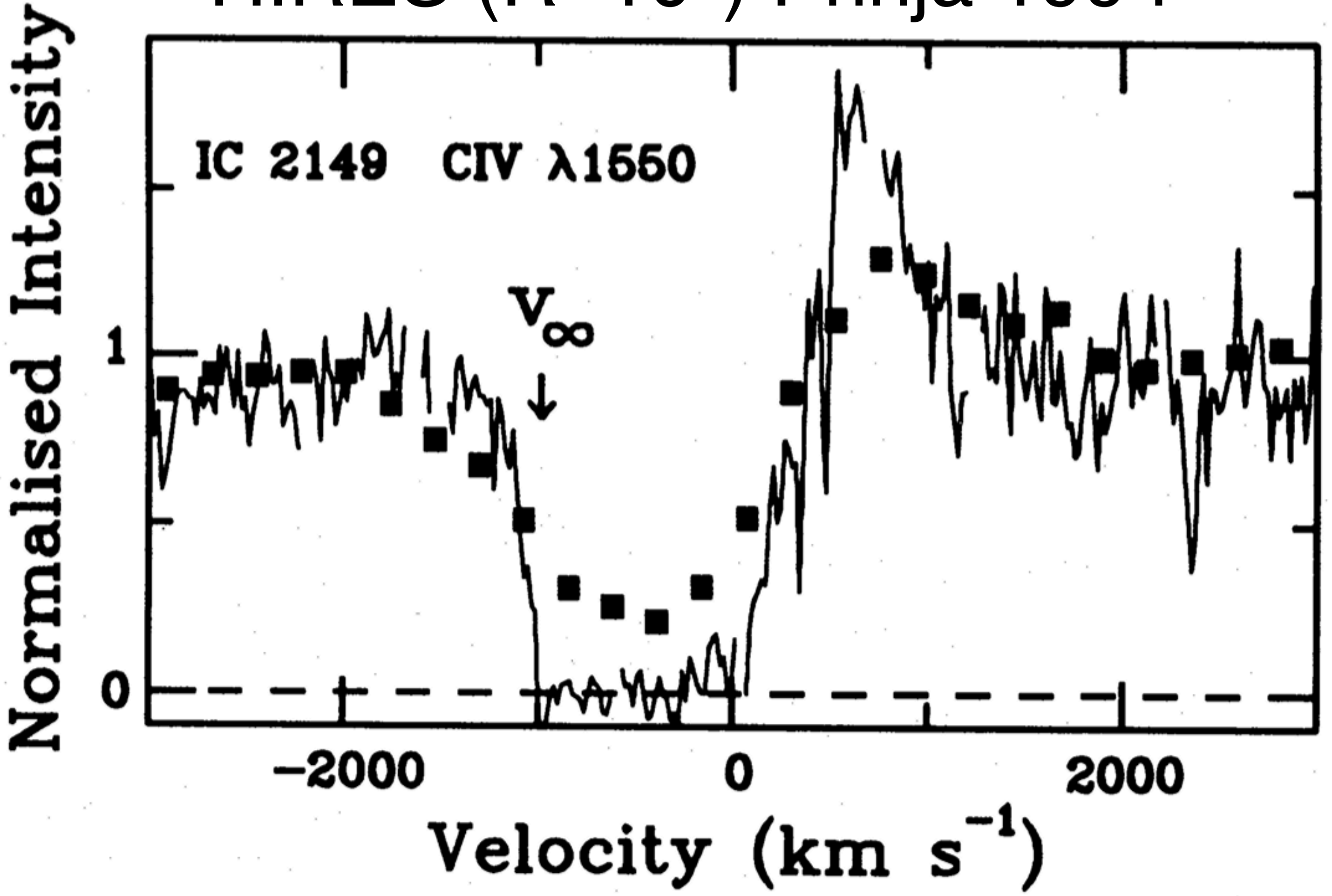


ULLYSES mid O dwarfs



UVEX

IUE/LORES (R=300) vs HIRES ($R=10^4$) Prinja 1994

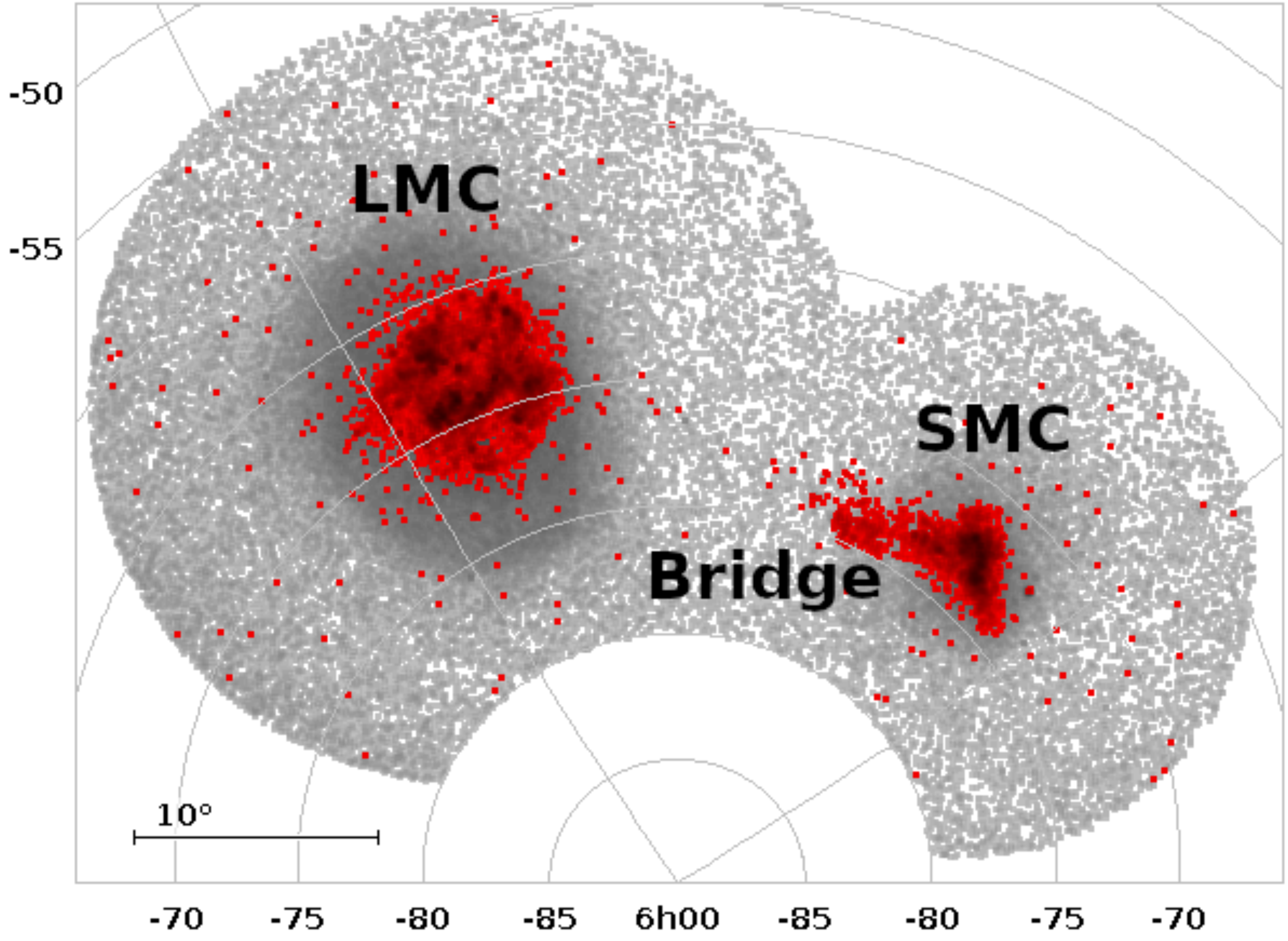


R~2000 for UVEX spectrograph well suited to wind velocities of O stars via CIV 1550 P Cygni profiles (recoverable for *wide* slit from IUE experience).

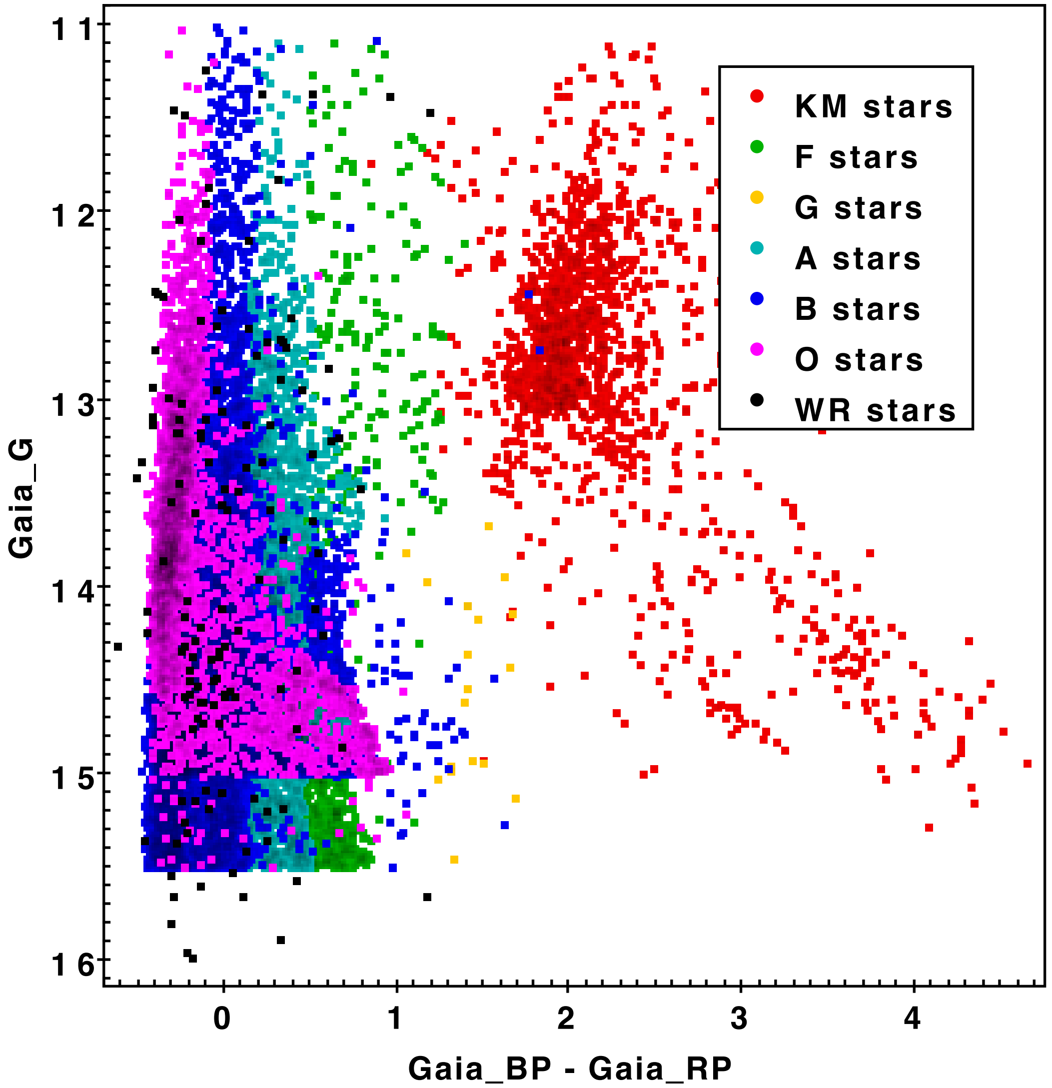
SMC O stars possess very weak wind signatures (very few of which exceed ~40 M_{sun}, Schootemeijer+2021), so UVEX better suited to comprehensive study of LMC OB population (large numbers exceeding ~40 M_{sun}, stronger winds).

UVEX + 4MOST/1001MC

Optical spectroscopy of ALL massive stars in Magellanic Clouds anticipated via 4MOST/1001MC survey (2024-2028).

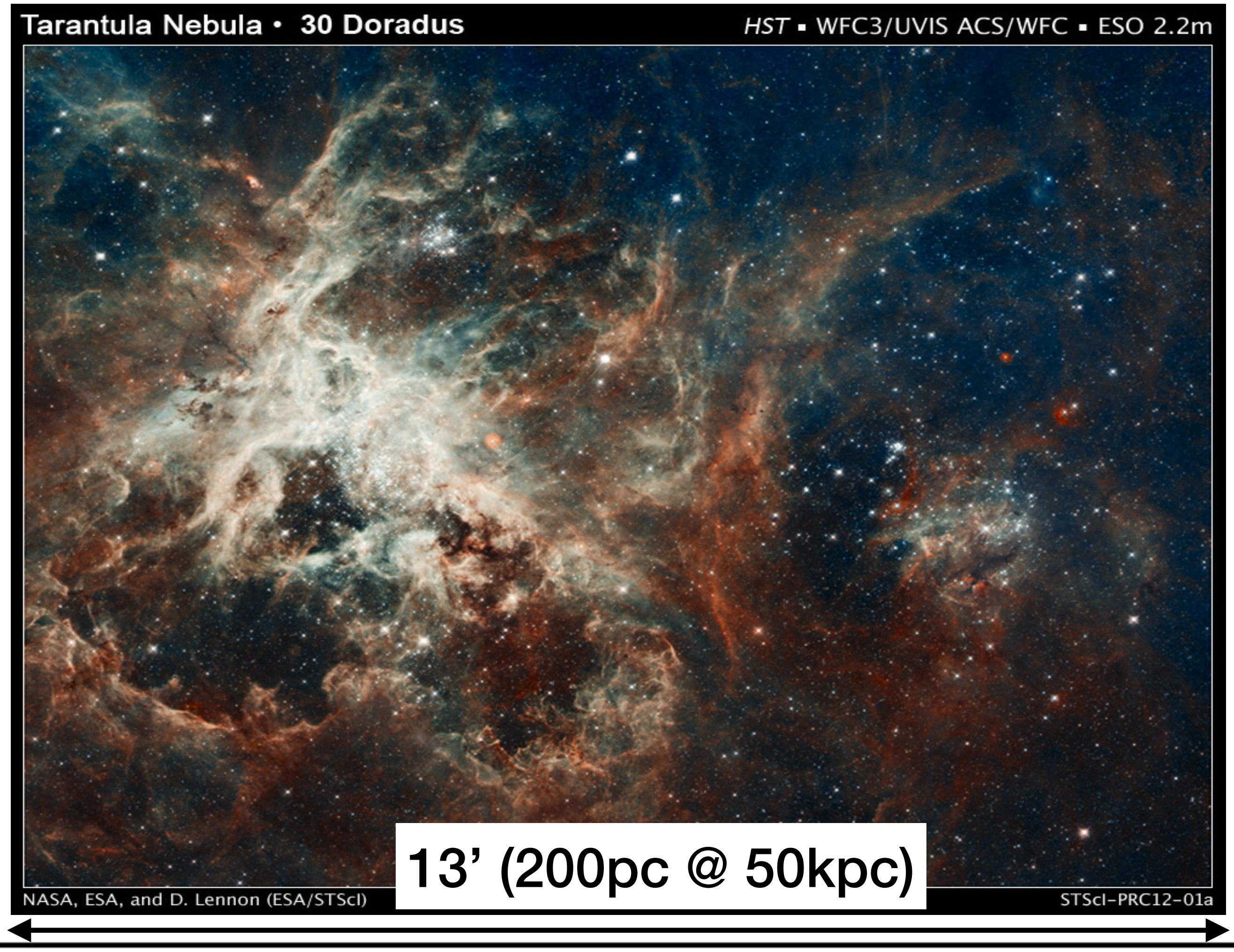


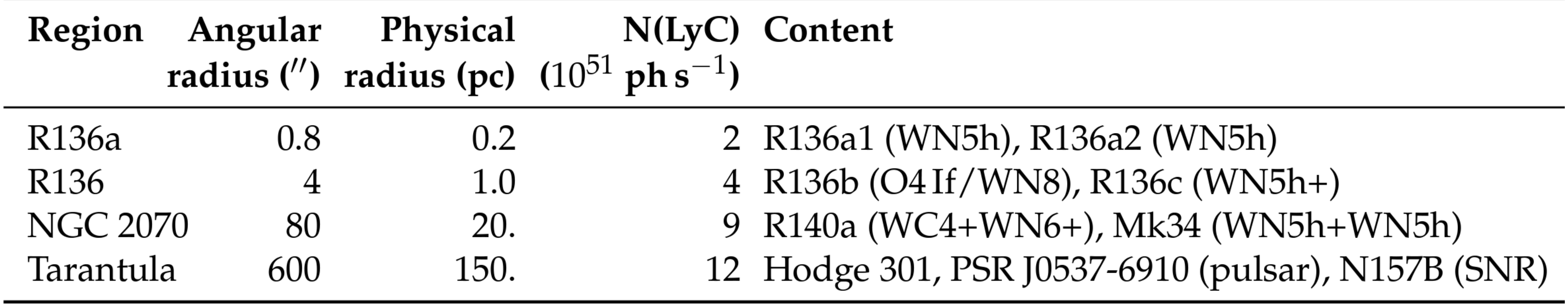
Cioni+2019



UVEX + Tarantula

- 60’ UVEX slit permits spatially resolved UV spectroscopy of extended star forming regions.
- Richest SF region within Magellanic Clouds is the Tarantula Nebula

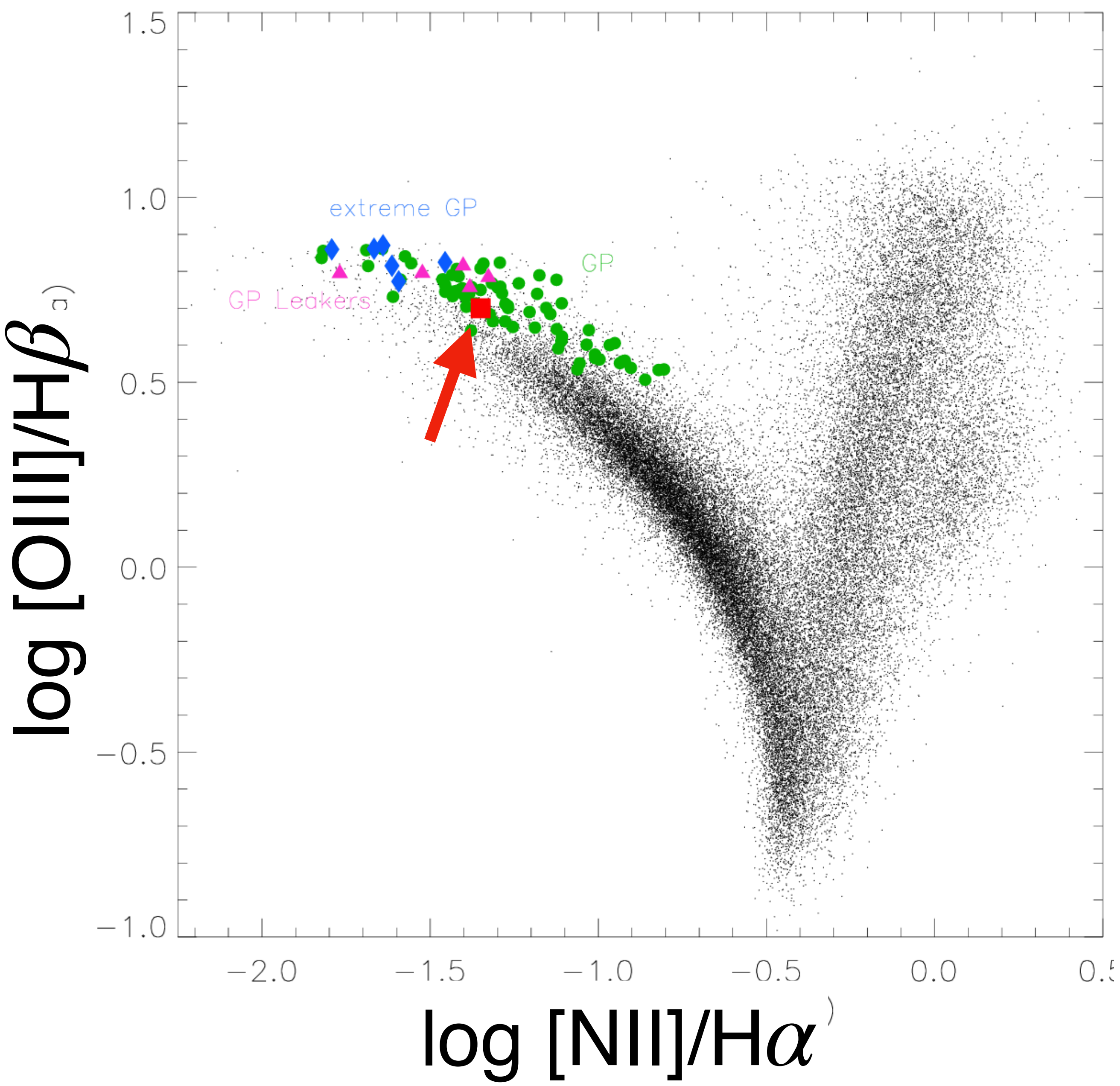


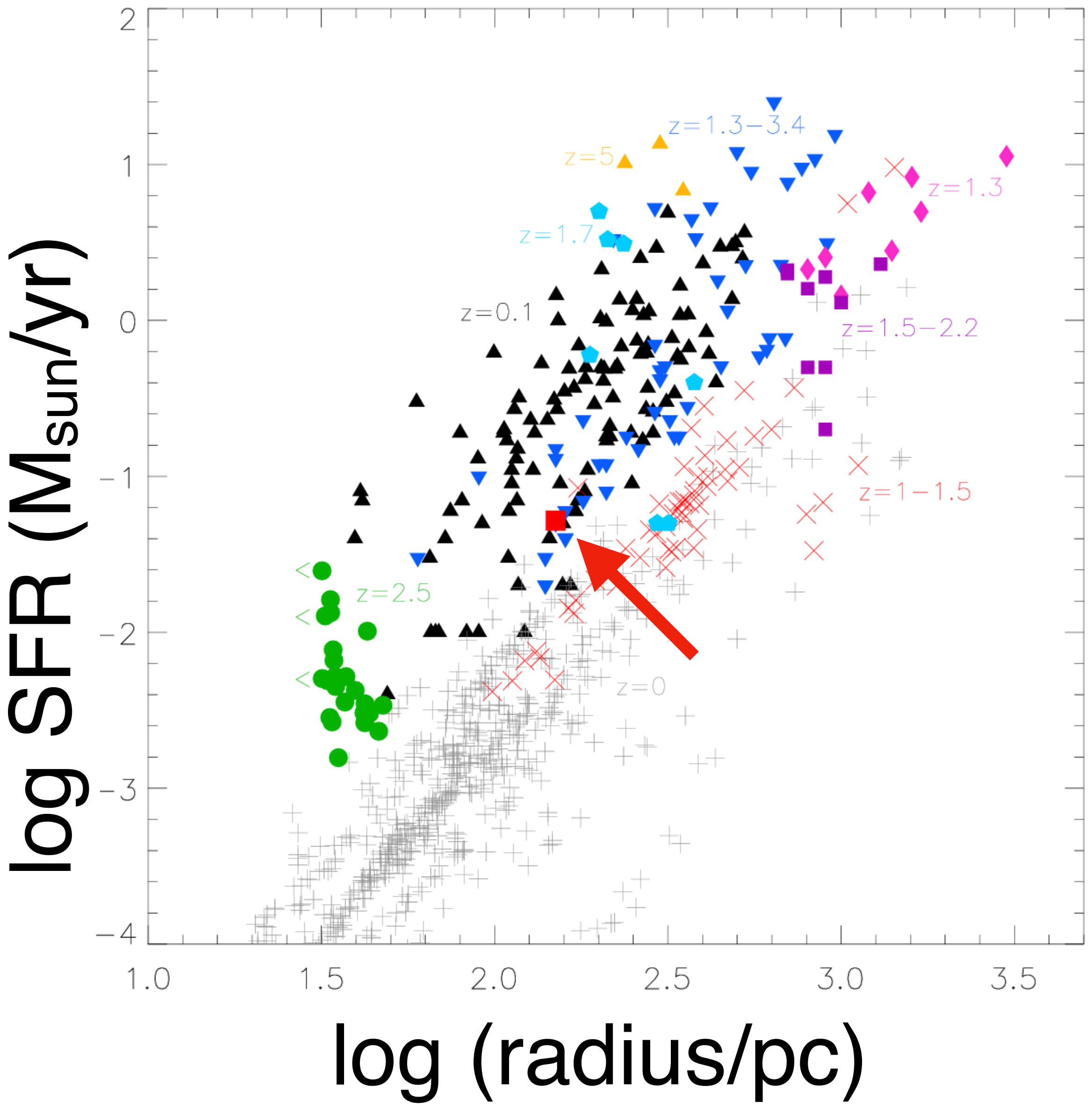


Region	Angular radius ($''$)	Physical radius (pc)	N(LyC) (10^{51} ph s^{-1})	Content
R136a	0.8	0.2	2	R136a1 (WN5h), R136a2 (WN5h)
R136	4	1.0	4	R136b (O4 If/WN8), R136c (WN5h+)
NGC 2070	80	20.	9	R140a (WC4+WN6+), Mk34 (WN5h+WN5h)
Tarantula	600	150.	12	Hodge 301, PSR J0537-6910 (pulsar), N157B (SNR)

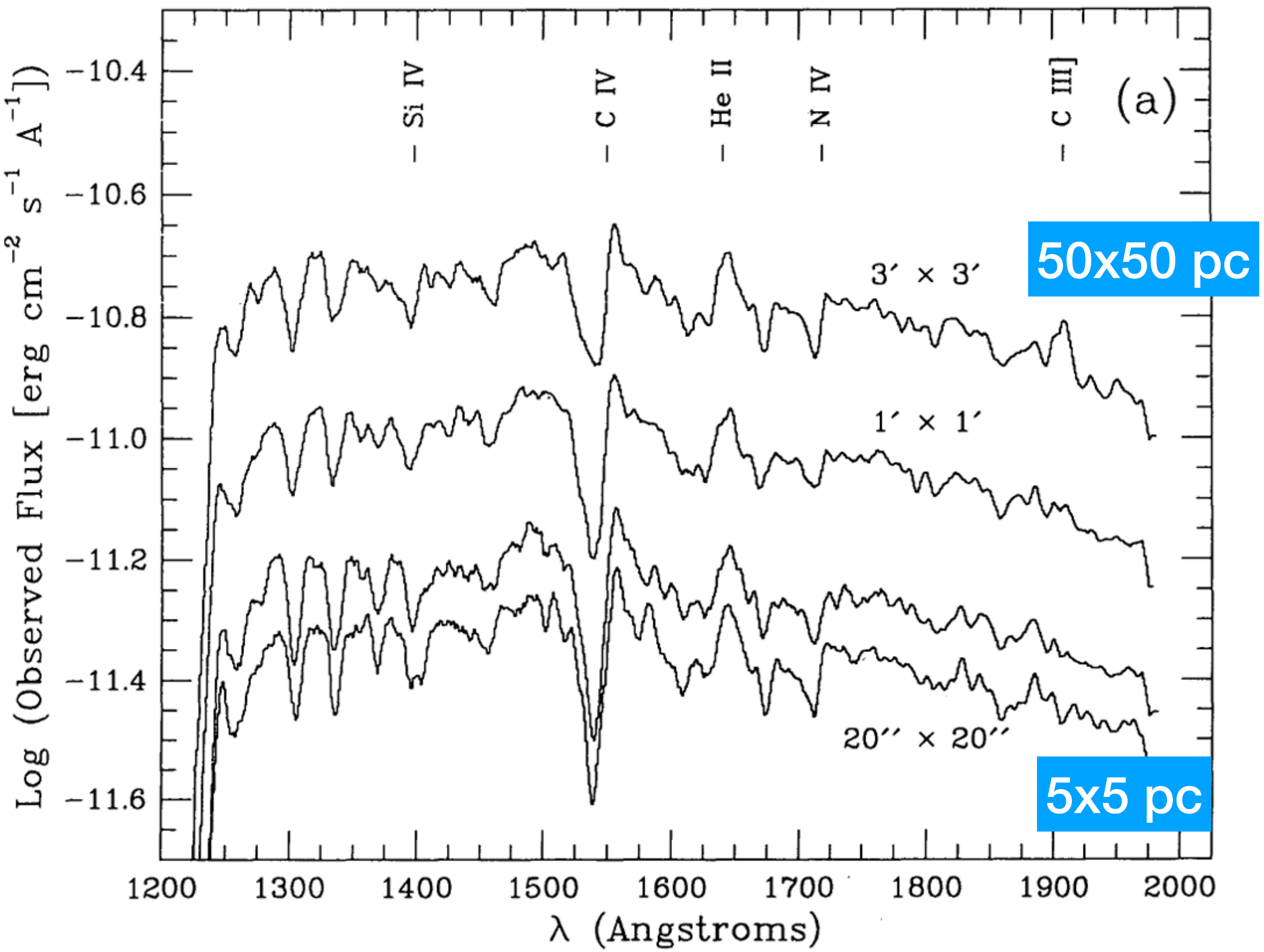
(Crowther 2019)

Tarantula (BPT, SFR)





Tarantula (UV)



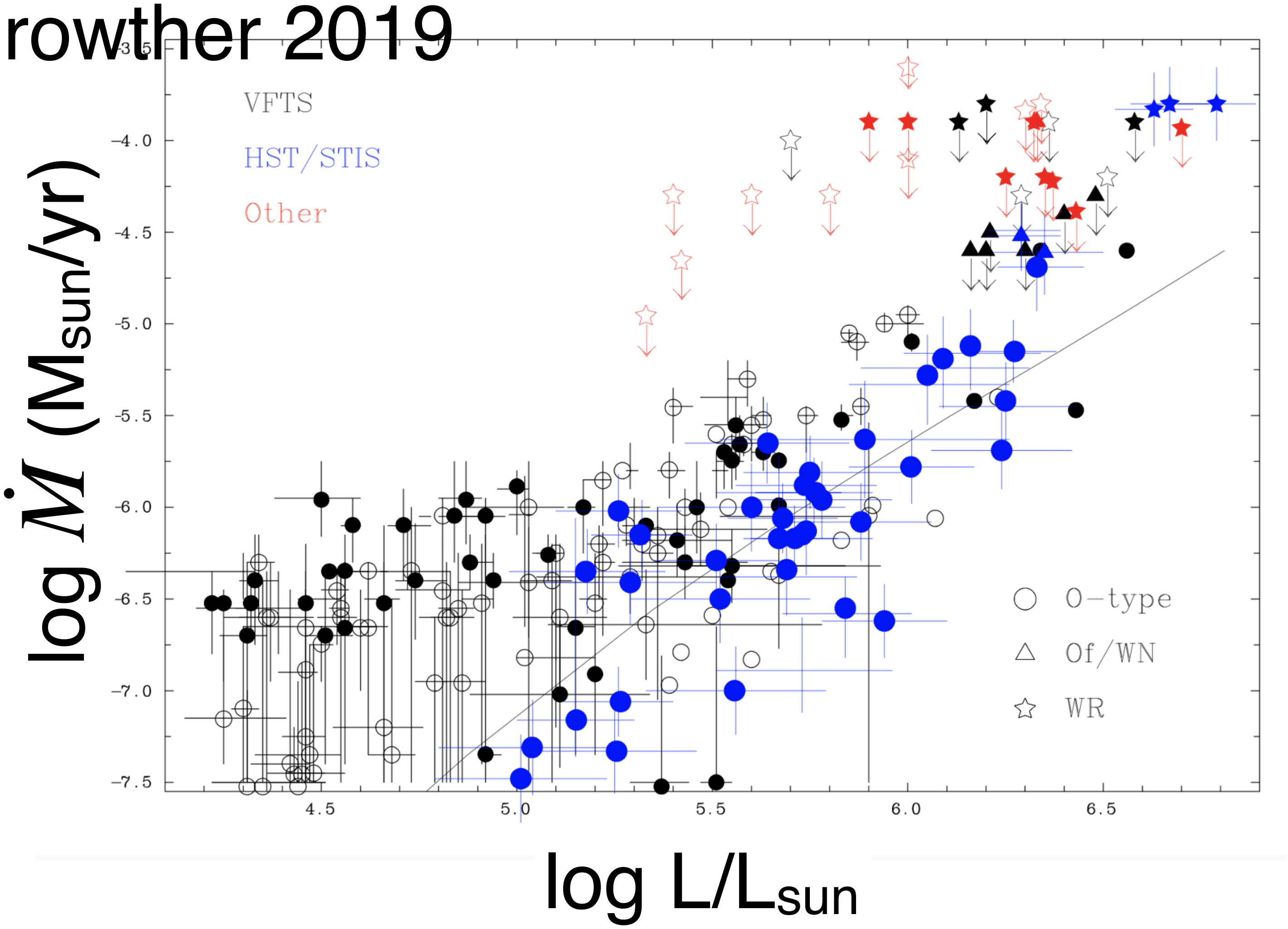
Integrated UV spectrum of core acquired with IUE (Vacca+1995)

Tarantula (content)

Telescope/inst	Target	N(O-type)	N(B-type)	N(WR)	N(Of/WN)	N(A+)
VLT/FLAMES	30 Dor	369	436	9	6	35
HST/STIS	R136	57	..	3	2	..
VLT/MUSE	NGC 2070	115	79	..	..	1
Other	30 Dor	29	8	16	..	5
Total	30 Dor	570	523	28	8	41

Crowther 2019

- Massive star population well studied optically (VFTS + follow up TMBM+BBC)
- >90% of OB stars lack UV spectroscopy so wind properties remain poorly constrained



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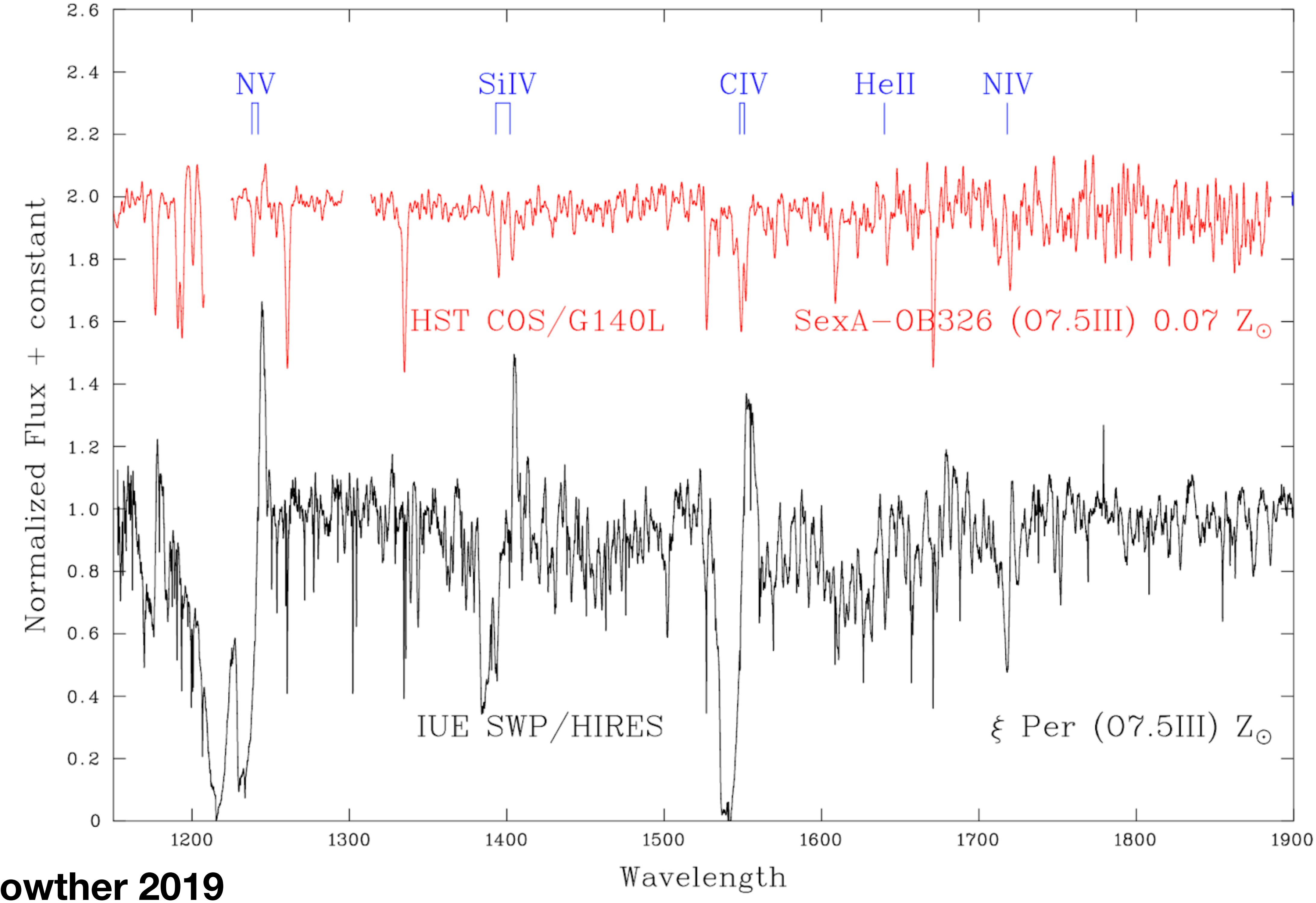
Very metal-poor templates

ξ Per (Walborn et al. 1985) and Sex A-OB326 (Garcia et al. 2017)



Oxygen abundance (not metallicity).

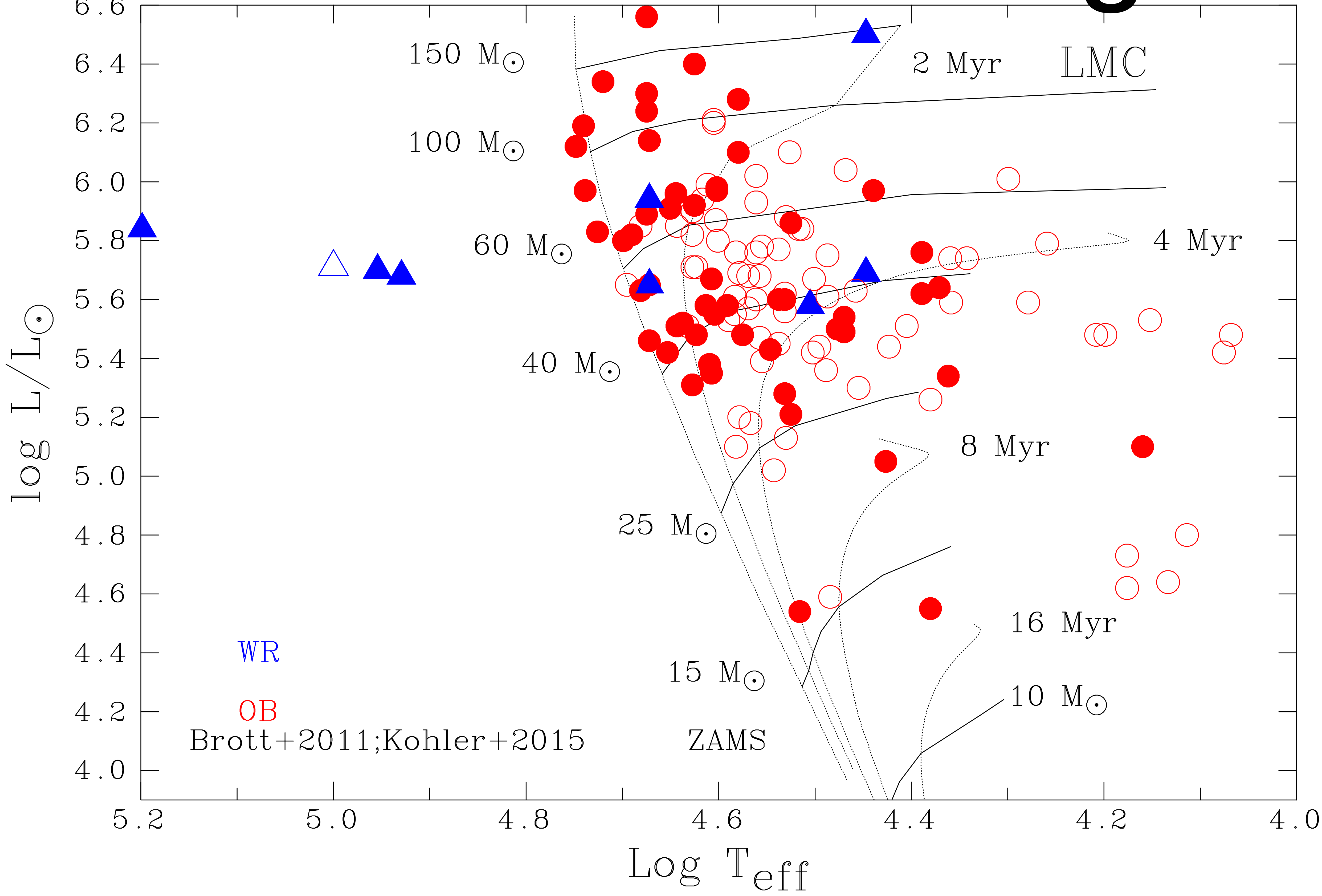
DM(Sex A) = DM(LMC) + 7 mag

Crowther 2019

Summary

- Similarities between high-z JWST Lyman break galaxies & Magellanic Clouds - latter provide detailed evolution of metal-poor massive stars (mass-loss, mixing, binarity)
- Evolution dominated by high mass-loss for ~100 M_{sun} stars (proximity to Eddington limit), much less so for weak winds of 10-20 M_{sun} stars (apart from blue and red supergiant phases), significance of mass-loss unclear for ~50 M_{sun} stars
- UV more sensitive to clumped mass-loss diagnostics in hot luminous stars than optical/IR, with high quality templates from HST/ULLYSES (~100 OB stars in each Magellanic Cloud)
- UVEX offers prospect of UV spectroscopy for 1000+ metal-poor OB stars, completing current spectroscopic surveys of Tarantula Nebula (VFTS) + upcoming surveys (4MOST/1001MC)

ULLYSES LMC HR diagram



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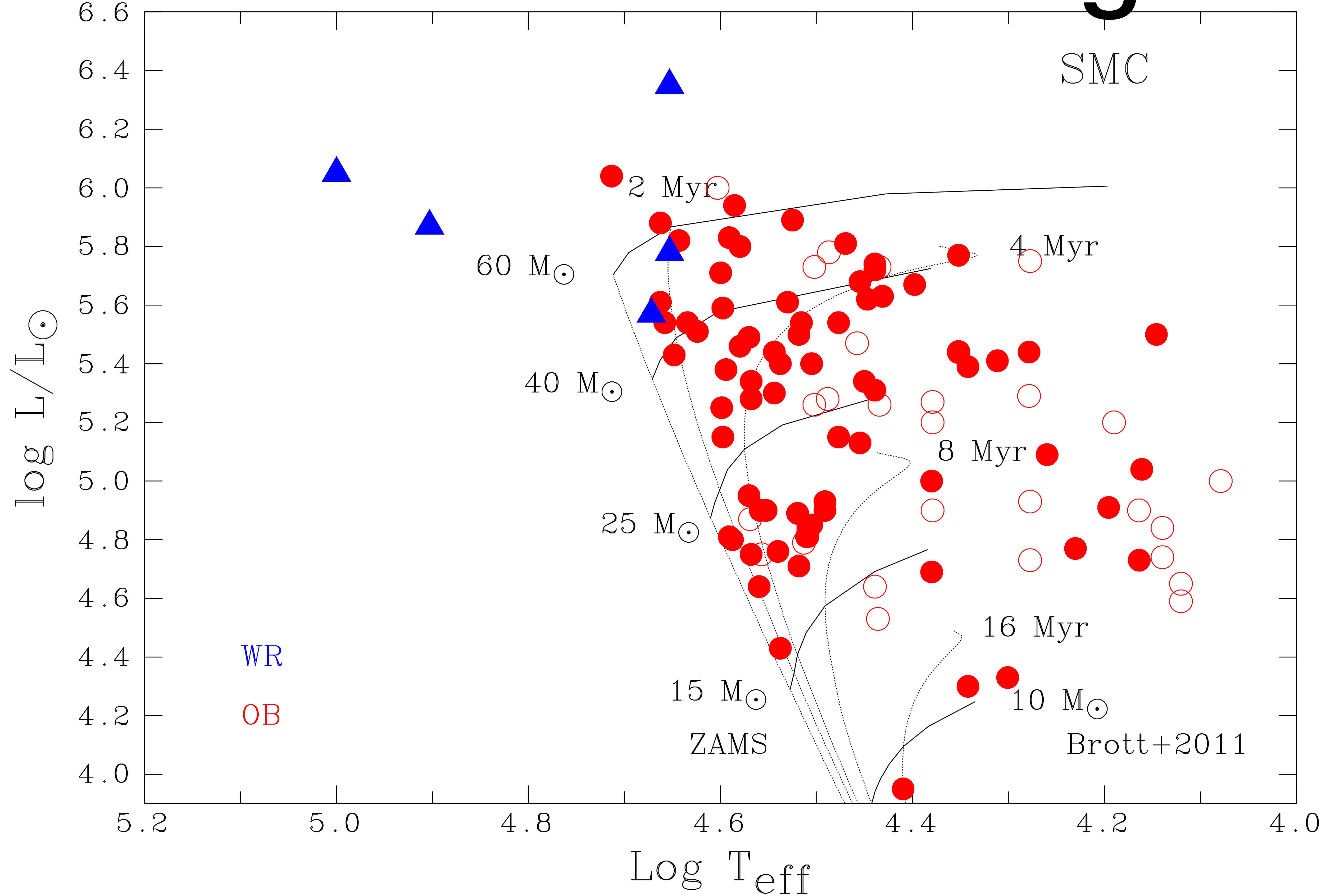
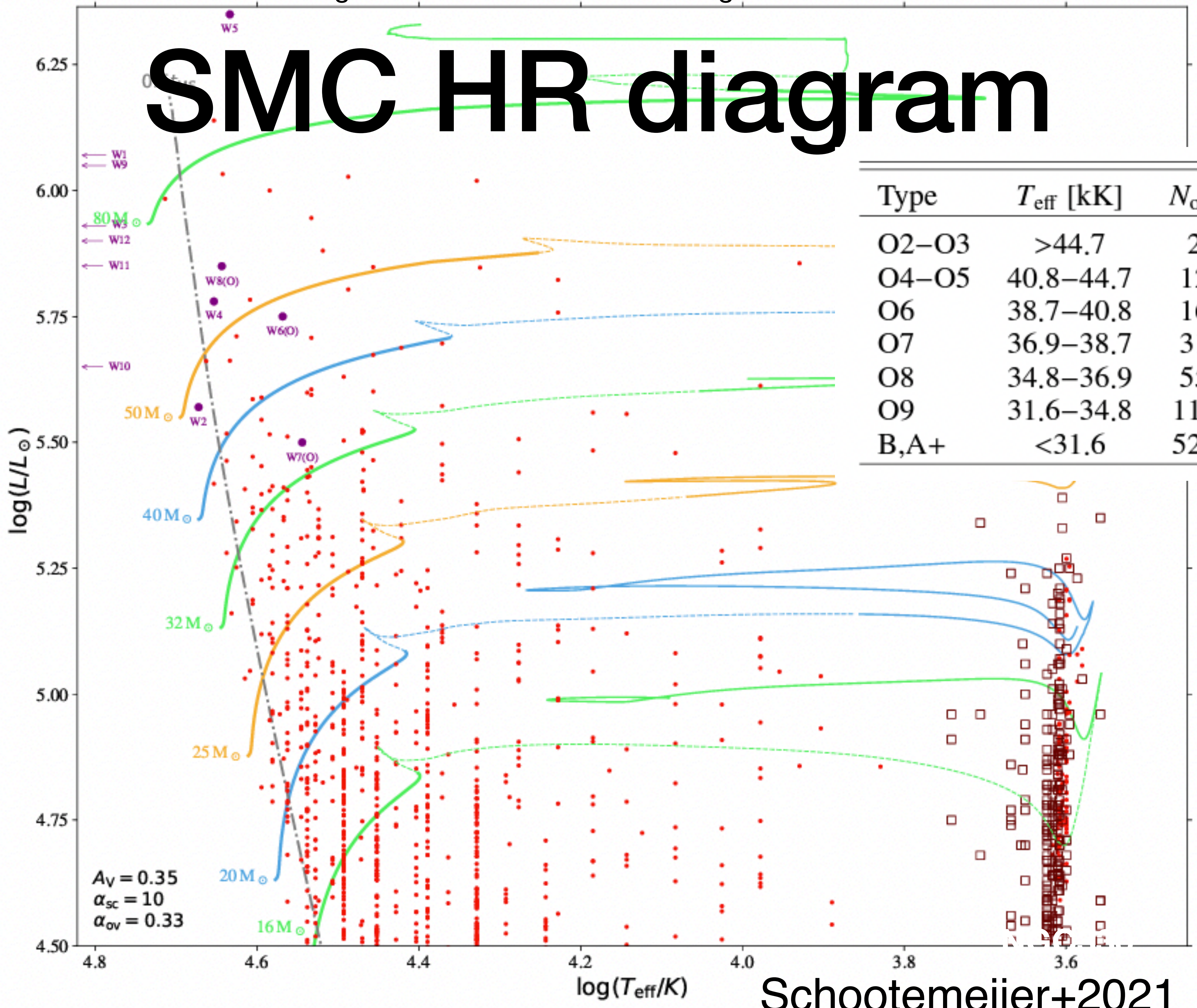
ULLYSES SMC HR diagram



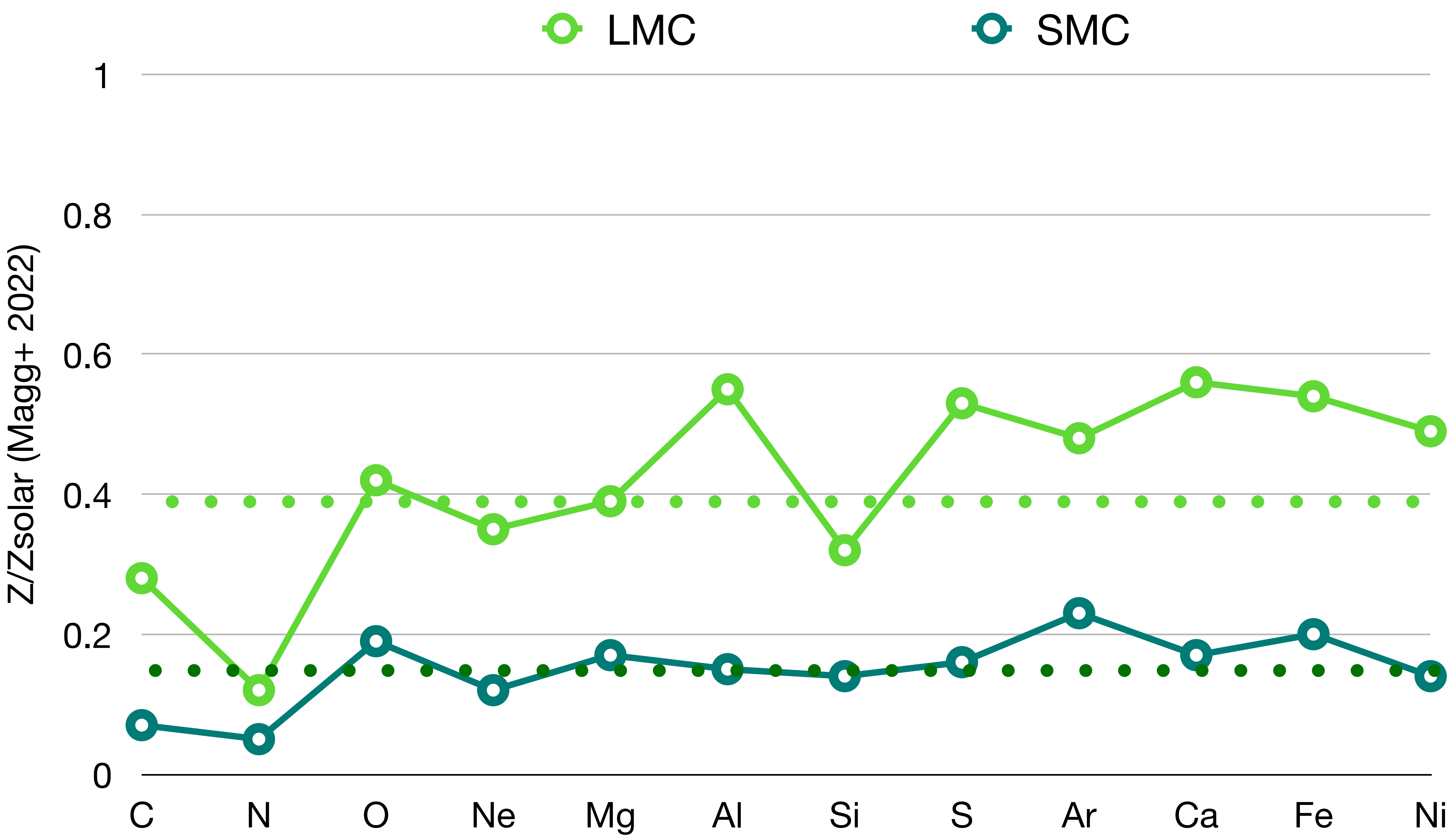
SMC HR diagram



Type	$T_{\rm eff}$ [kK]	$N_{\rm obs}$
O2–O3	>44.7	2
O4–O5	40.8–44.7	12
O6	38.7–40.8	16
O7	36.9–38.7	31
O8	34.8–36.9	55
O9	31.6–34.8	116
B,A+	<31.6	524

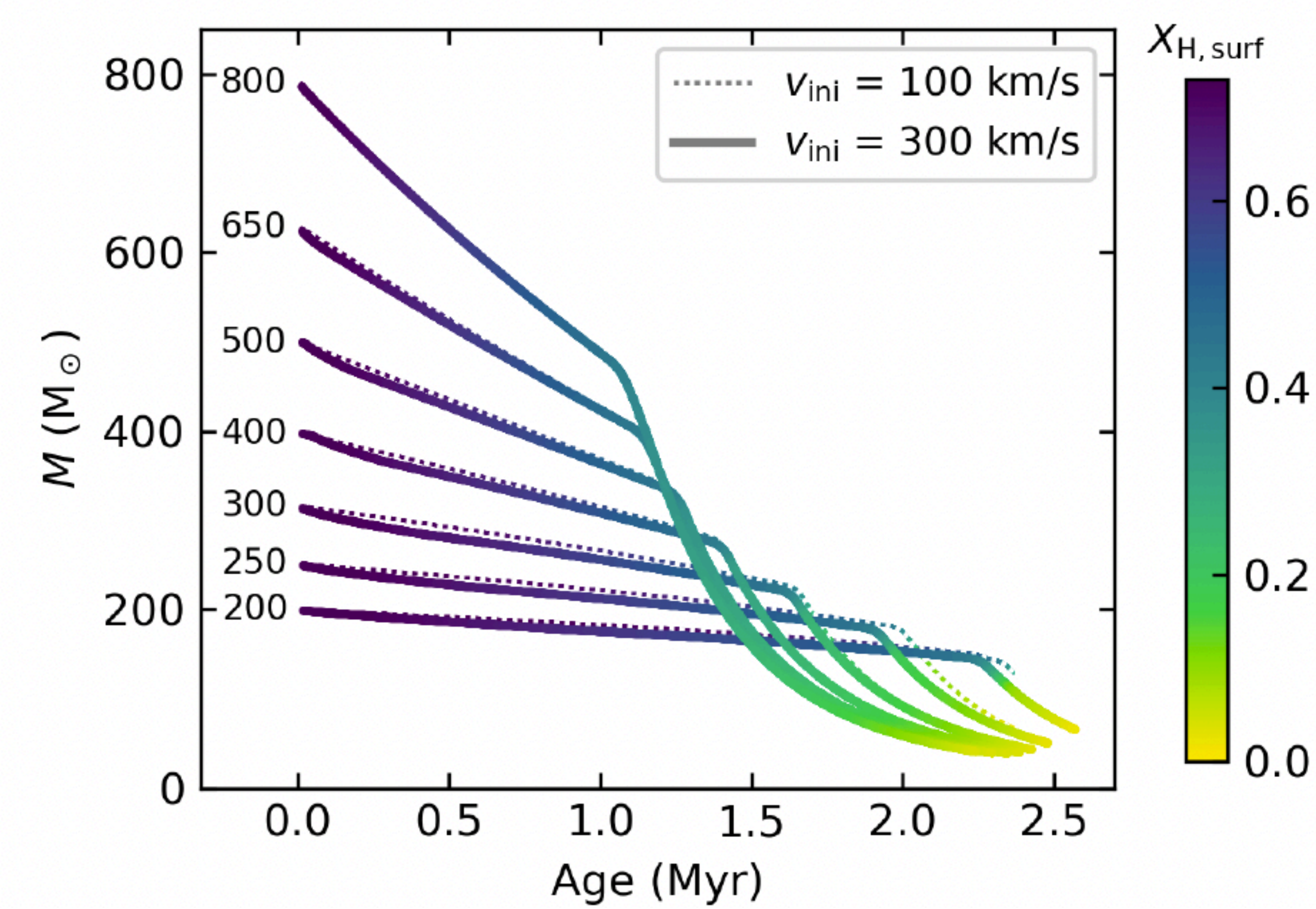
Schootemeijer+2021

Metallicity in Mag Clouds



HII regions (Kurt & Dufour 1998; Garnett 1999; Peimbert 2003; Tsamis+ 2003; Lebouteiller+ 2008; Toribio Sam Cipriano+ 2017). Stars (Hill+1995, 1997, 1999; Venn 1999; Korn+ 2000, 2005; Andreivsky+2001; Trundle+2007; Hunter+2007, 2009; Dufton+2018). SNR (Dopita+2019)

Mass-loss: Very massive stars



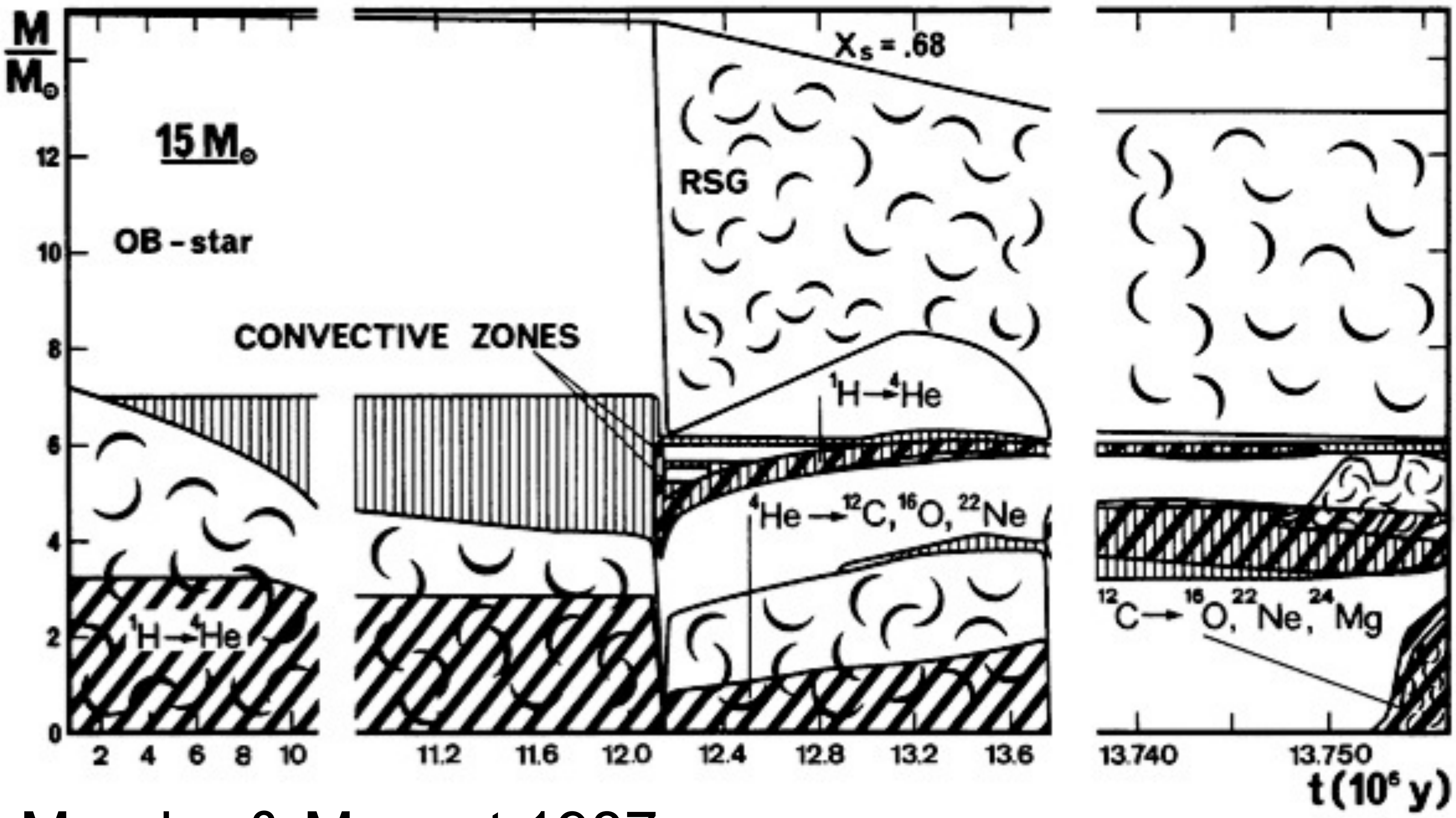
High Eddington parameter for very massive main sequence stars (Brands+2022) + WR prescription (Sander & Vink 2020) lead to modest final masses at LMC metallicity.

Mass-loss: Moderately massive stars

Main sequence:
Weak mass-loss
(Negligible impact on evolution)

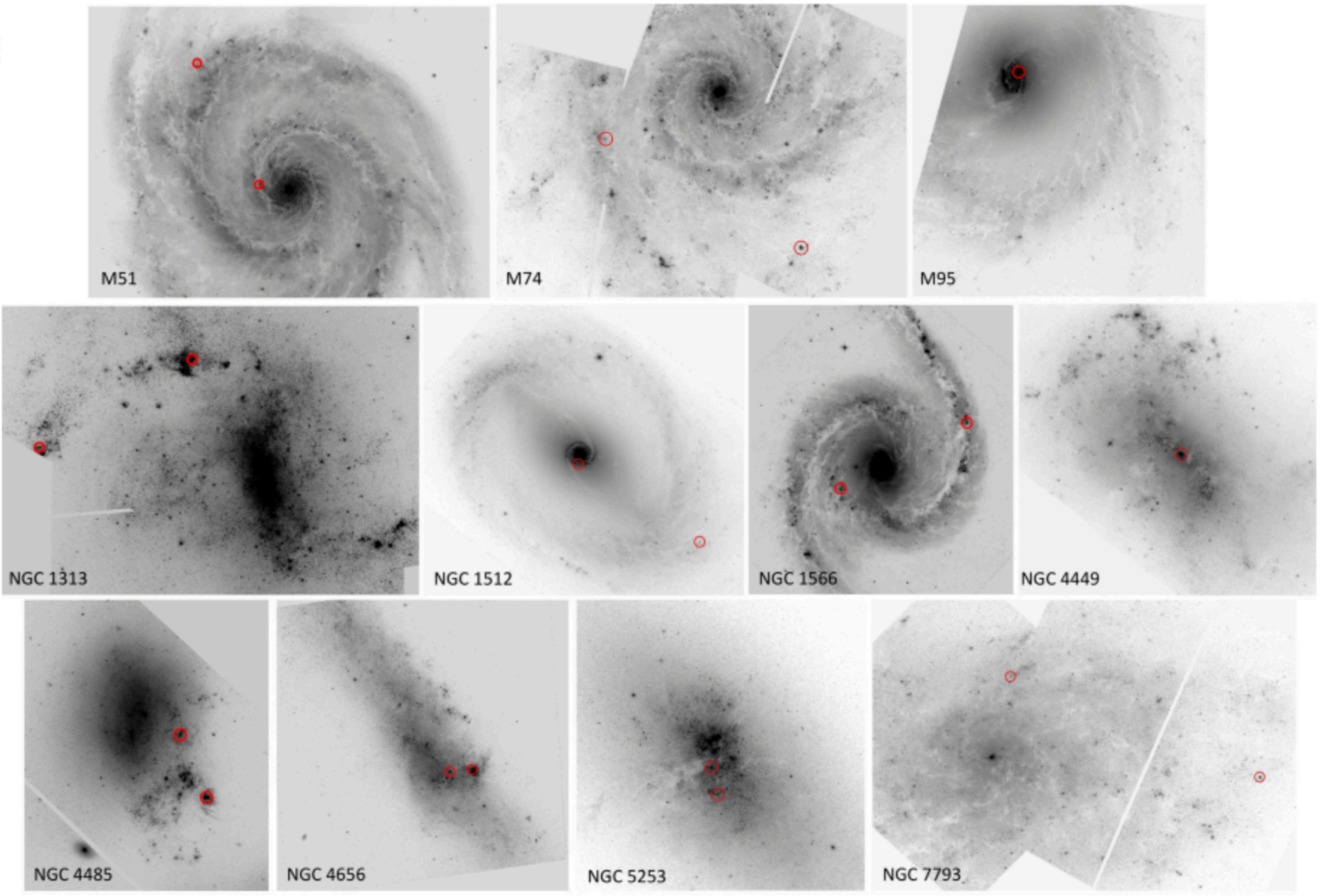
BSG: Uncertain mass-loss
(Potential impact on evolution)

RSG: Strong mass-loss
(impact on evolution)

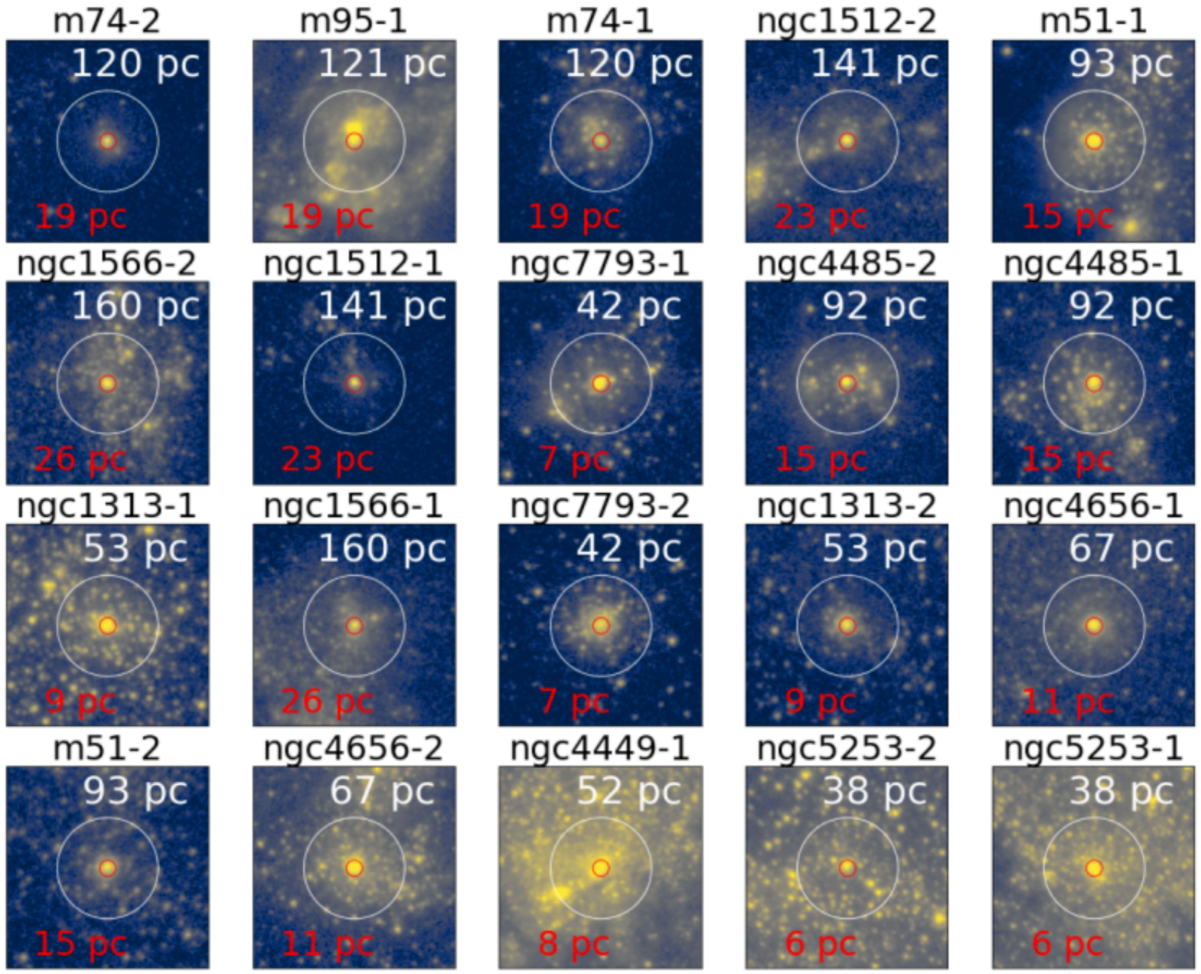


Maeder & Meynet 1987

Massive stars at low-z



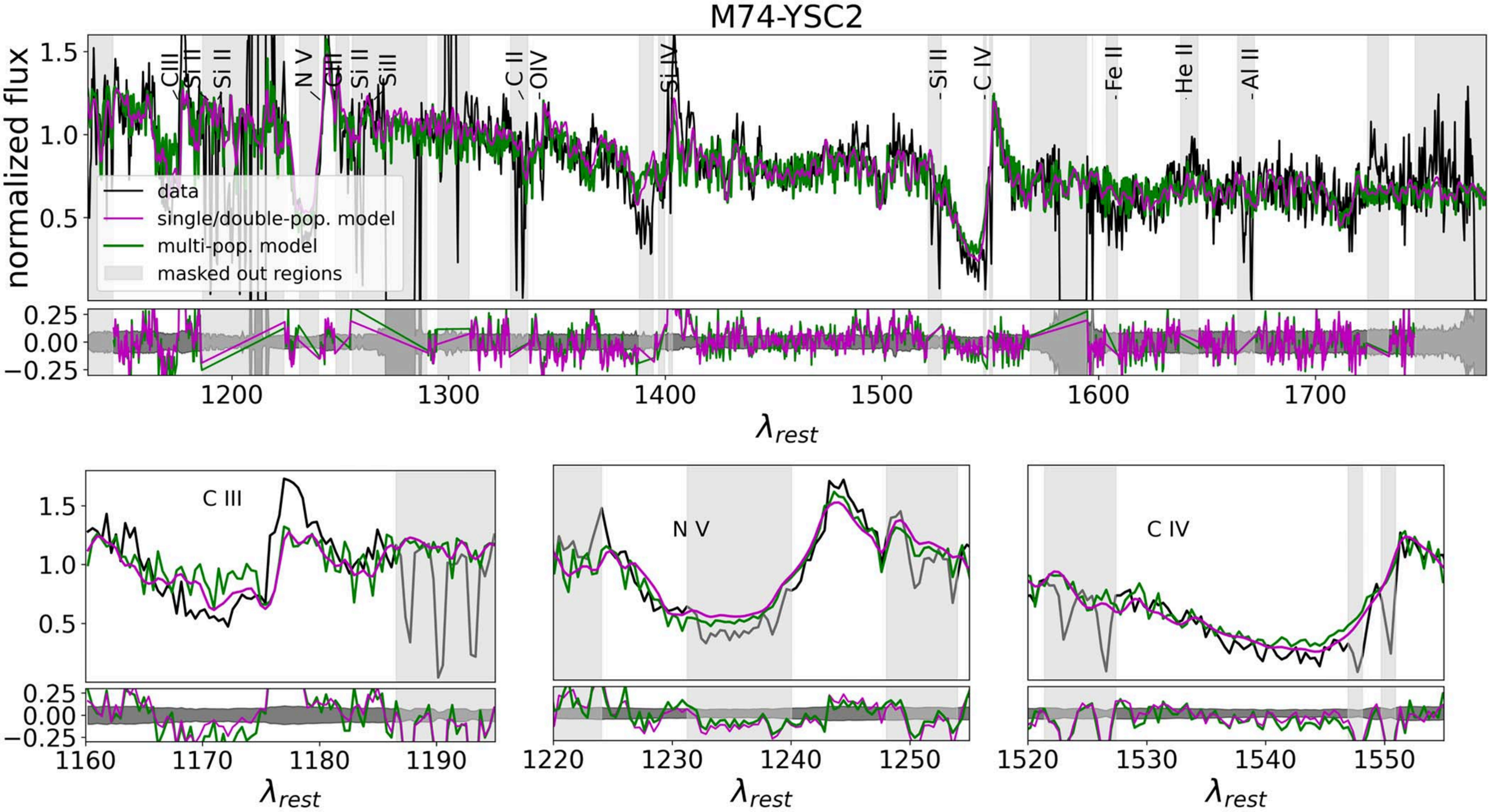
Target galaxies



Target star clusters

FUV survey of 20 young star clusters from LEGUS
"Clusters in the Uv as EngineS" (CLUES, Sirressi+2022)

Massive stars at low-z



M74-YSC2 (Sirressi+2022). See Chandar+2004, James+2014 for more UV spectroscopy of young massive clusters