Massive stars at low Z

Grids of CMFGEN models

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140 anos
Observatório
do Valongo

UFRJ
UNIVERSIDADE FEDERAL
DO RIO DE JANEIRO

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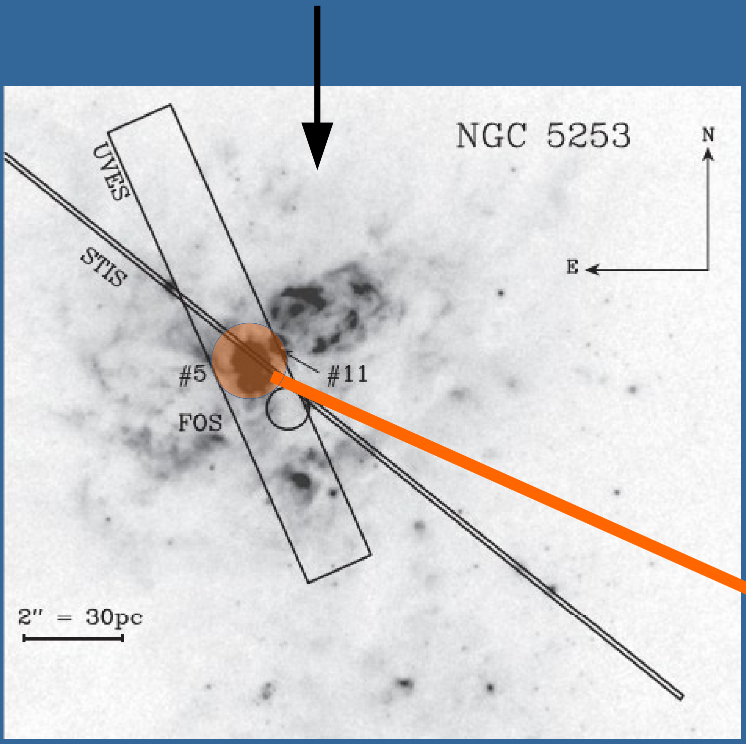
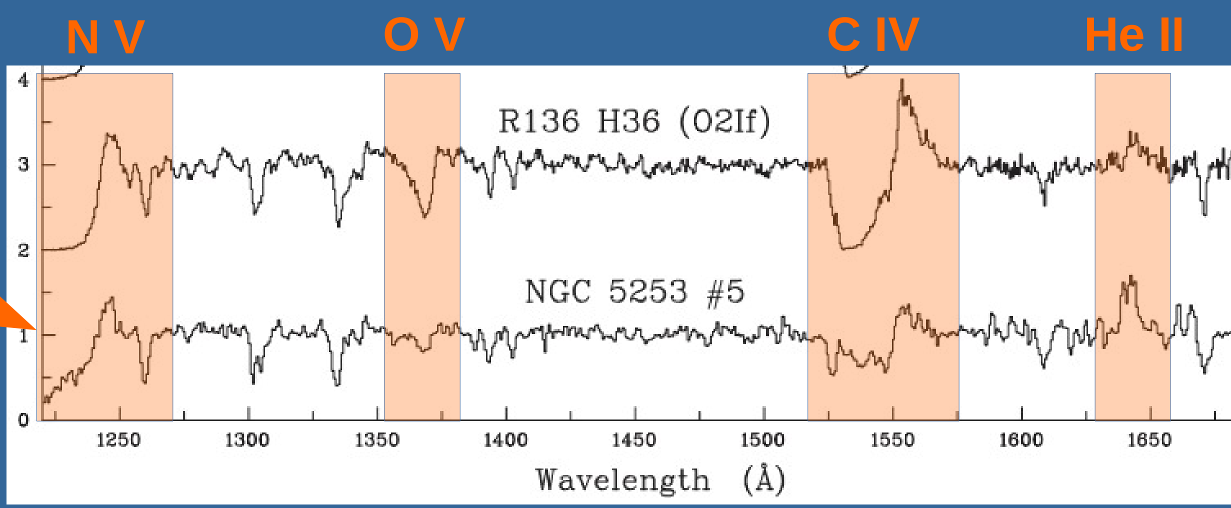
+ **Tapirapé Group (Helio Jaques + Gustavo F. P. de Mello + Luan Ghezzi + students)**

Massive stars

- Mass M > 9 $M_{\odot}$
- Extremely rare (IMF)
- High luminosities (10^4 – 10^6 $L_{\odot}$) and high temperatures (T_{eff} ~ 20 000 – 50 000 K)
- Intense stellar winds
- Big impact on the their host galaxies



Blue compact dwarf galaxy ~ 3 Mpc (Smith+16)



Massive stars and their winds

Massive Stars

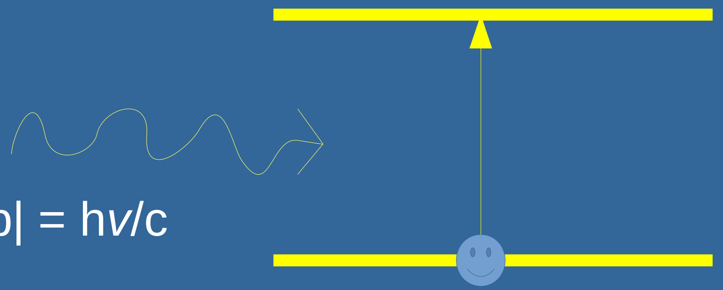
- Mass-loss rates $10^{-9} - 10^{-5}\ M_{\odot}$/yr; wind speeds ~ 1000 – 3000 km s^{-1}
- Evolution severely impacted (see e.g., Ekström+12)
- Nature of the outflow:

Line driven winds – metals (CNO+Fe+Si, etc.)

$$\rho \frac{d\vec{v}}{dt} = -\nabla p - \frac{GM\rho}{r^2}\hat{r} + \sum_i \vec{F}_i = -\nabla p - \frac{GM\rho}{r^2}\hat{r} + \vec{f}_{rad}$$

Several thousands of transitions absorbing UV radiation

Momentum transfer of the radiation field to the gas



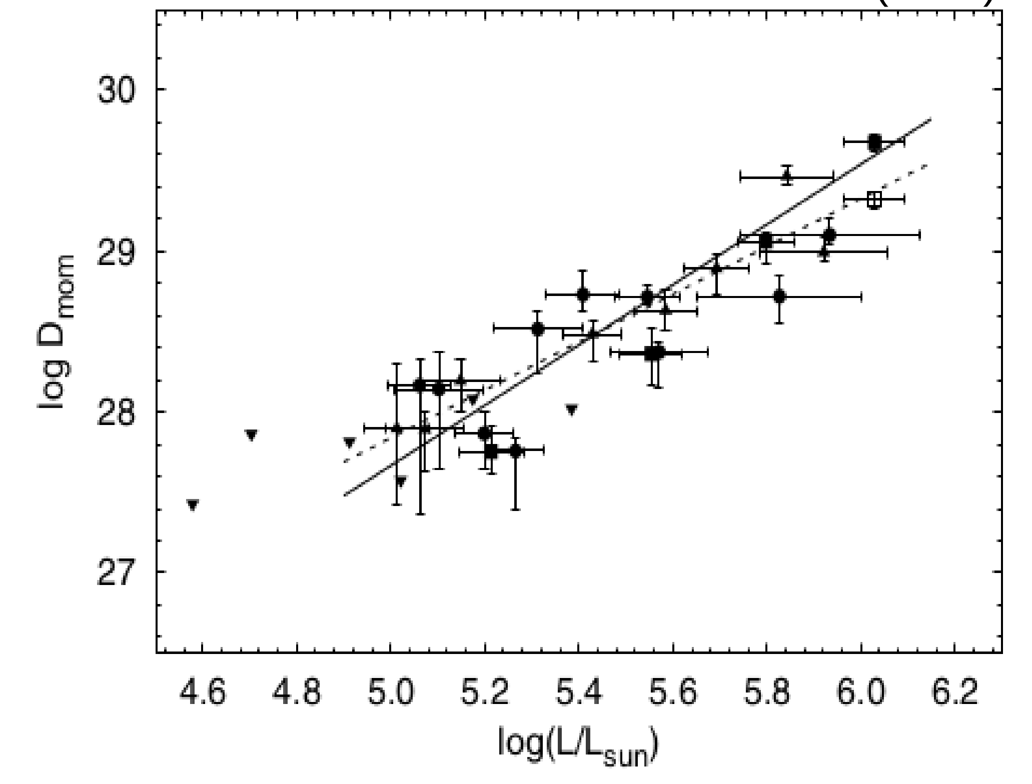
$|p| = h\nu/c$

Radiation $\xrightarrow{\text{momentum}}$ Gas

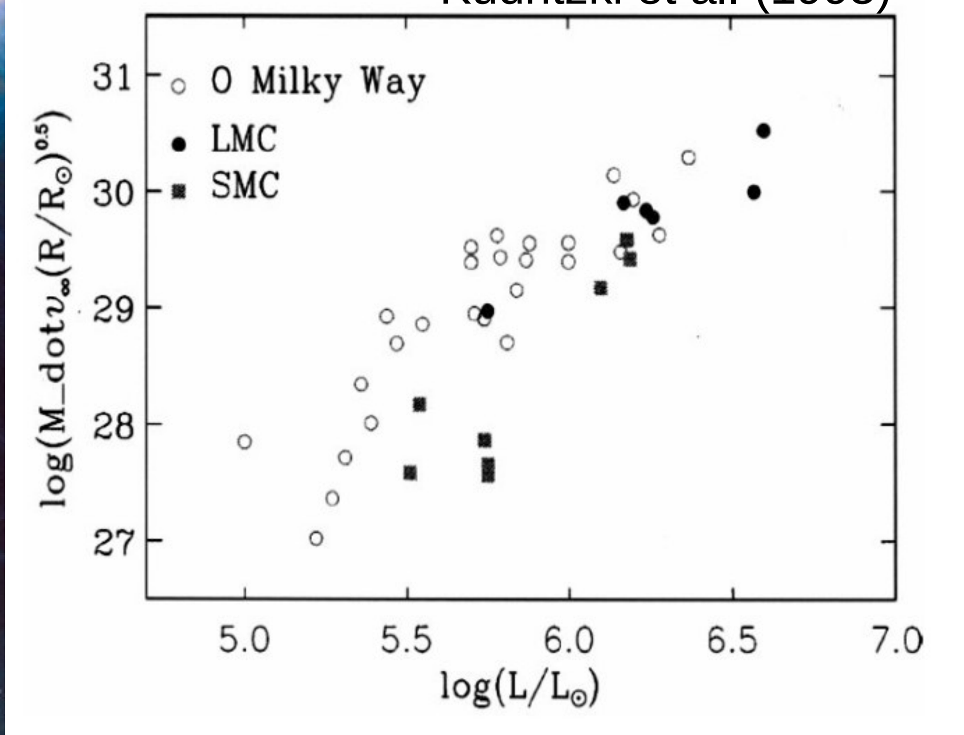
$$\rho\frac{d\vec{v}}{dt} = -\nabla p - \frac{GM\rho}{r^2}\hat{r} + \sum_i \vec{F}_i = -\nabla p - \frac{GM\rho}{r^2}\hat{r} + \vec{f}_{rad}$$

wind intensity (D) correlates with luminosity, depends on Z (metal line-driven)

Mokiem et al. (2007)



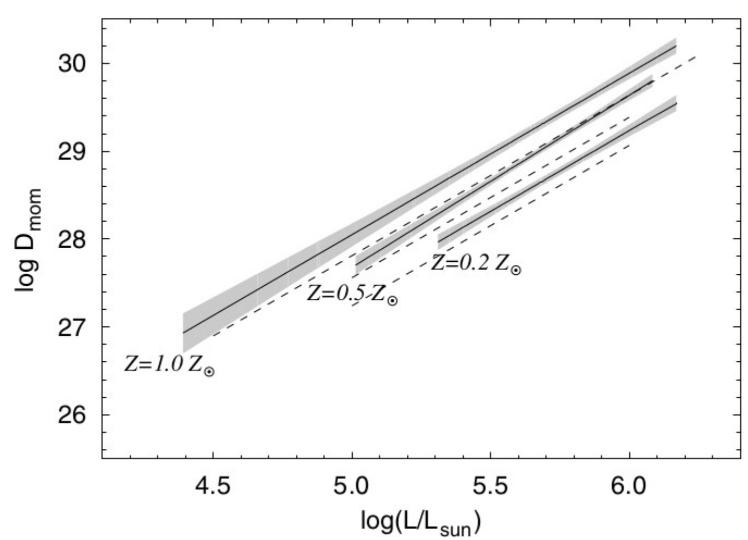
Kudritzki et al. (1995)



We need to understand f(Z)!

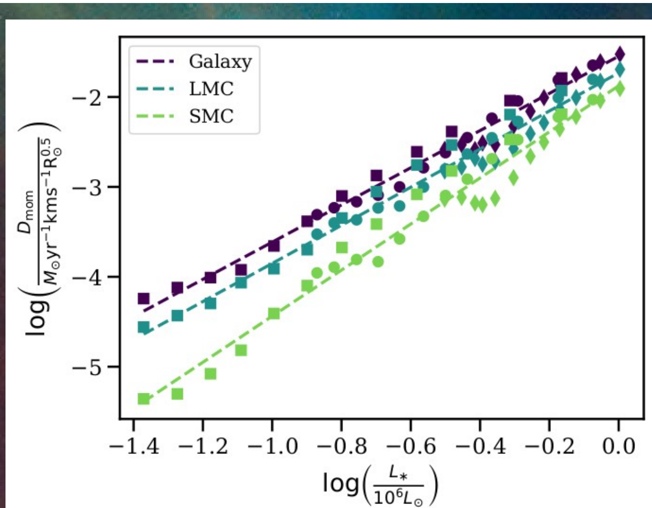
Some Z dependence works:

$V_\infty \propto Z^{0.13}$
theory (Leitherer+92)

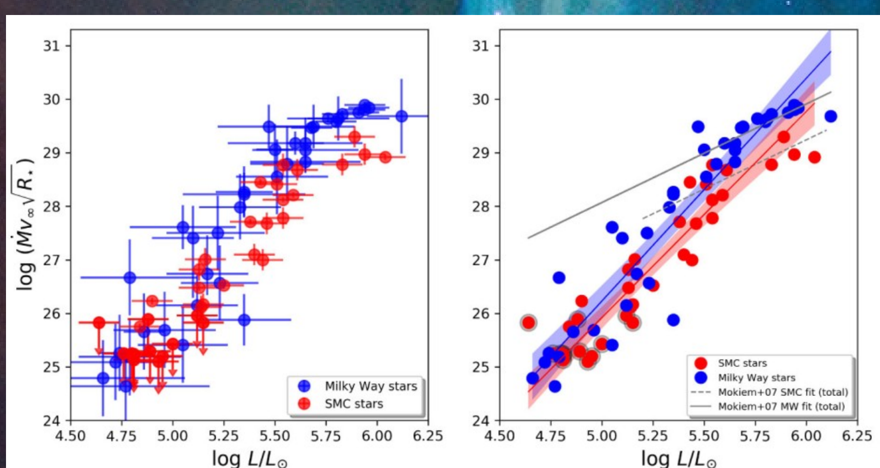


$\dot{M} \propto Z^{0.69}$
theory (Vink et al. 2001)

$\dot{M} \propto Z^{0.83}$
observations - Mokiem et al. (2007)



$\dot{M} \propto Z^{0.95}$
theory - Bjorklund et al. (2020)



$\dot{M} \propto Z^{0.5\text{-}0.8}$
observations (bright objects only)
Marcolino et al. (2022)

There are many other references
(Vink & Sander 2021; Krtička & Kubat 2017; 2018; Brands et al. 2022; etc.)

Understand details about the Z dependence is a big deal!

It is crucial to understand stellar evolution, populations and feedback in the local and far Universe.

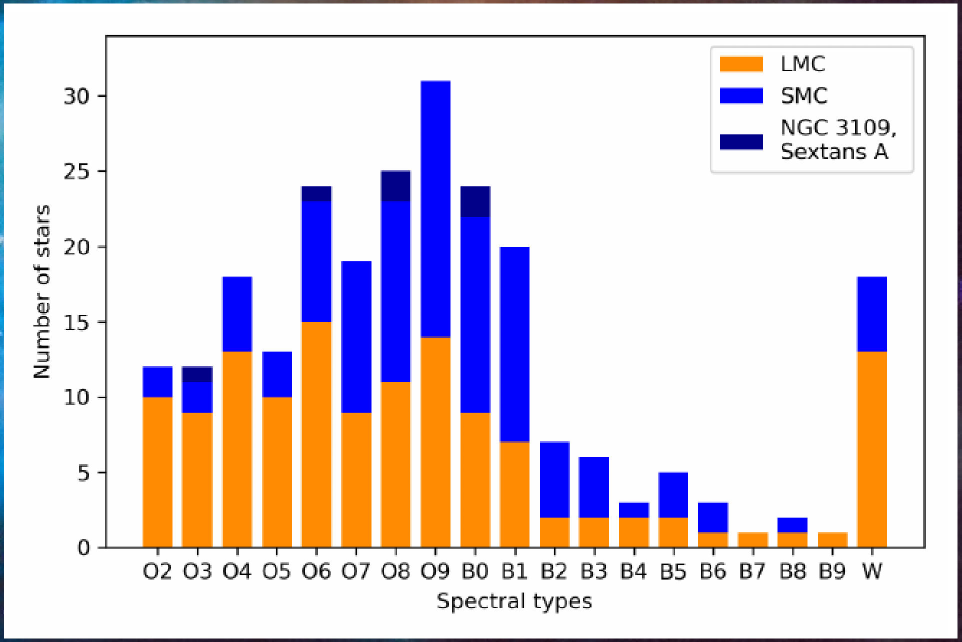
Efforts on f(Z)

- ULLYSES program with Hubble (STIS/COS)

500 orbits dedicated to massive stars

~250 OB stars at low Z
(LMC, SMC, Sextans A, NGC 3109).

(Roman-Duval+20)

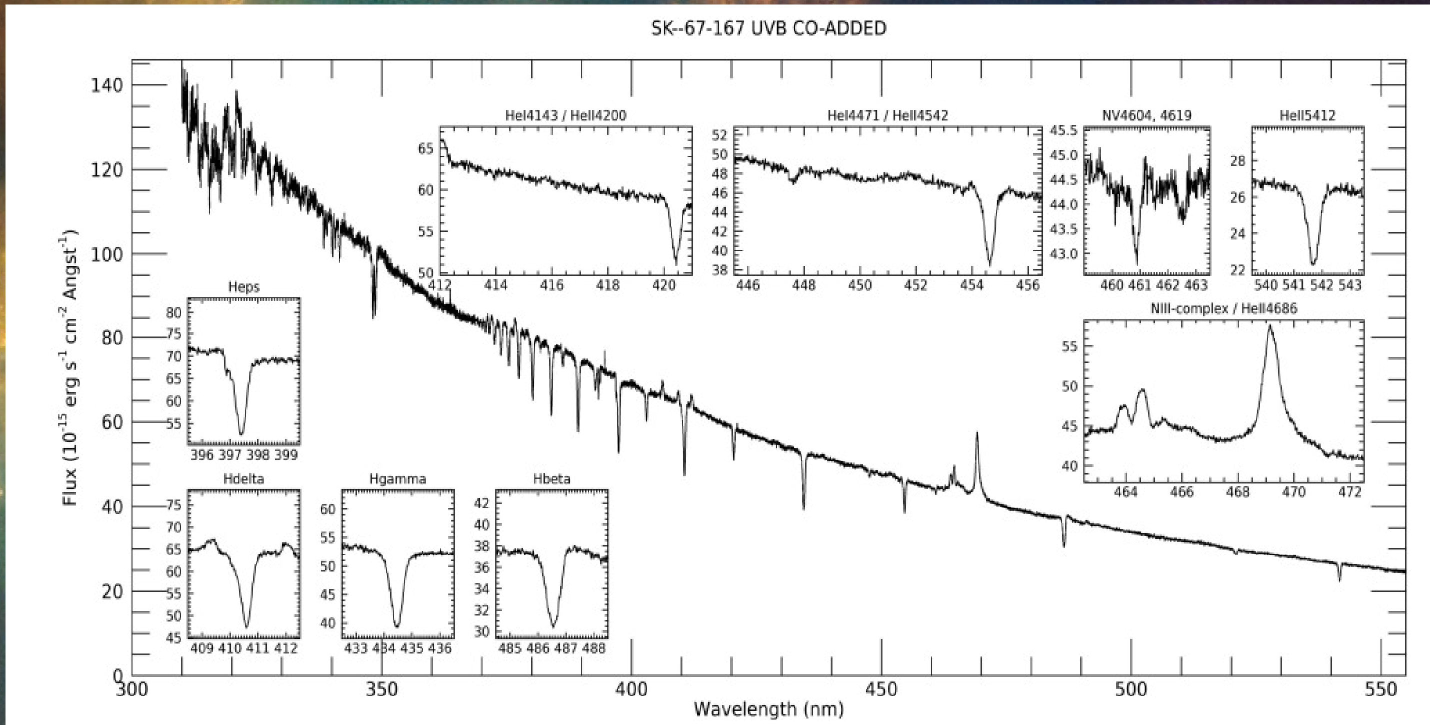


- XShootU Collaboration - "X-Shooting ULLYSES"

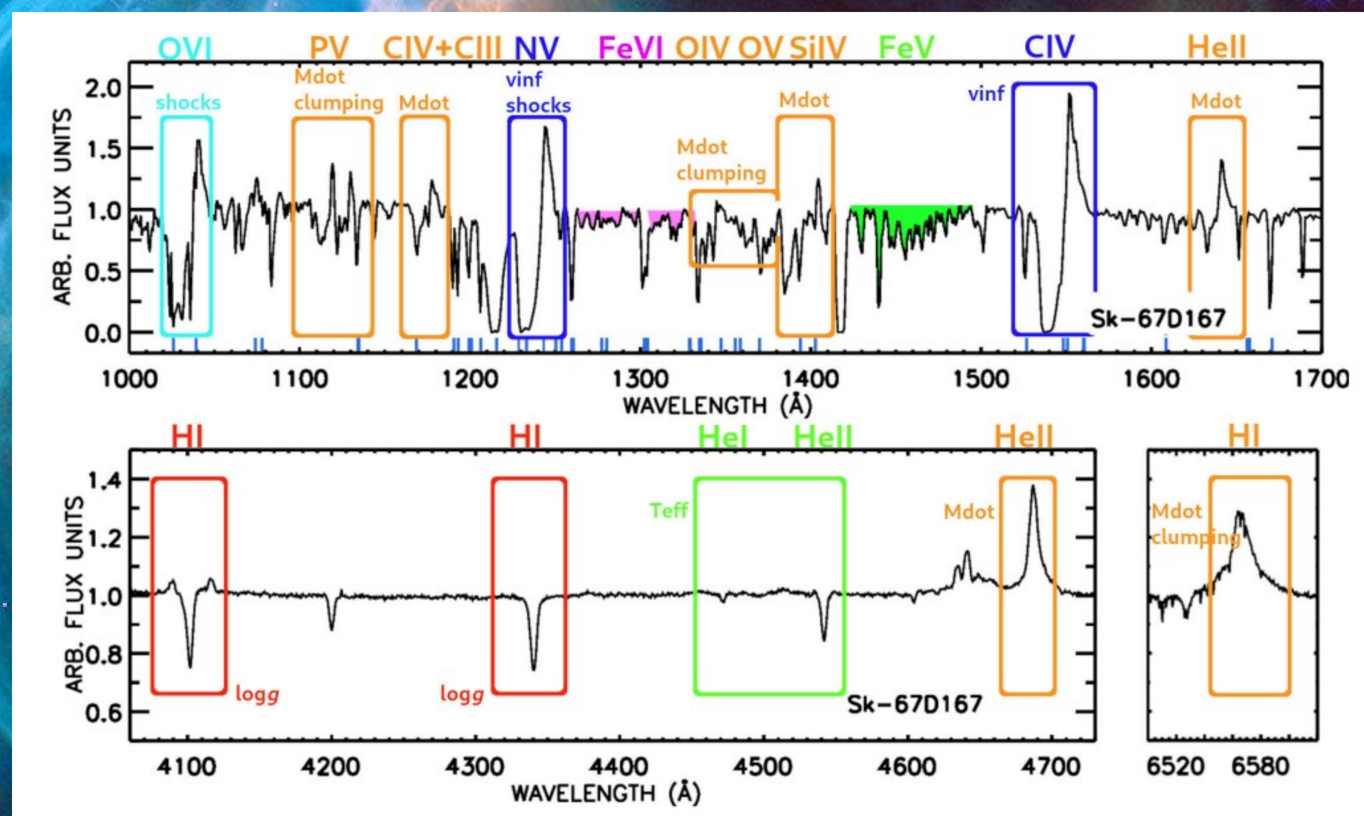
Optical spectra of HST targets with Xshooter - VLT/ESO

near UV – near IR
UVB arm: 300 – 500 nm
VIS arm: 500 – 1000 nm
NIR arm: 1000 – 2500 nm
(R ~ 5000-10000)

(see Vink+23)


SK--67-167 UVB CO-ADDED
Flux (10^-15 erg s^-1 cm^-2 Angst^-1)
Wavelength (nm)
HeI4143 / HeII4200
HeI4471 / HeII4542
NV4604, 4619
HeII5412
NIII-complex / HeII4686
Heps
Hdelta
Hgamma
Hbeta

Vink+23


OVI
PV
CIV+CIII
NV
FeVI
OIV
OV
SiIV
FeV
CIV
HeII
shocks
Mdot
clumping
vinf
Sk-67D167
ARB. FLUX UNITS
WAVELENGTH (Å)
HI
HeI
HeII
logg
Teff
Mdot clumping

Observations of massive stars in the Local Group

- Hundreds of high-resolution spectra available being /waiting to be analyzed by different tools/atmosphere models (e.g., PoWR, FASTWIND, CMFGEN)
- Analysis is complex; models are computationally expensive (NLTE+winds).
- Tailored and automatic analyses (e.g., Brands+22)

GRIDS at low Z are WELCOME!

Grids of CMFGEN models at low Z

Marcolino, Bouret, Martins & Hillier (to be submitted)

Grids of CMFGEN models at low Z

Marcolino, Bouret, Martins & Hillier (to be submitted)

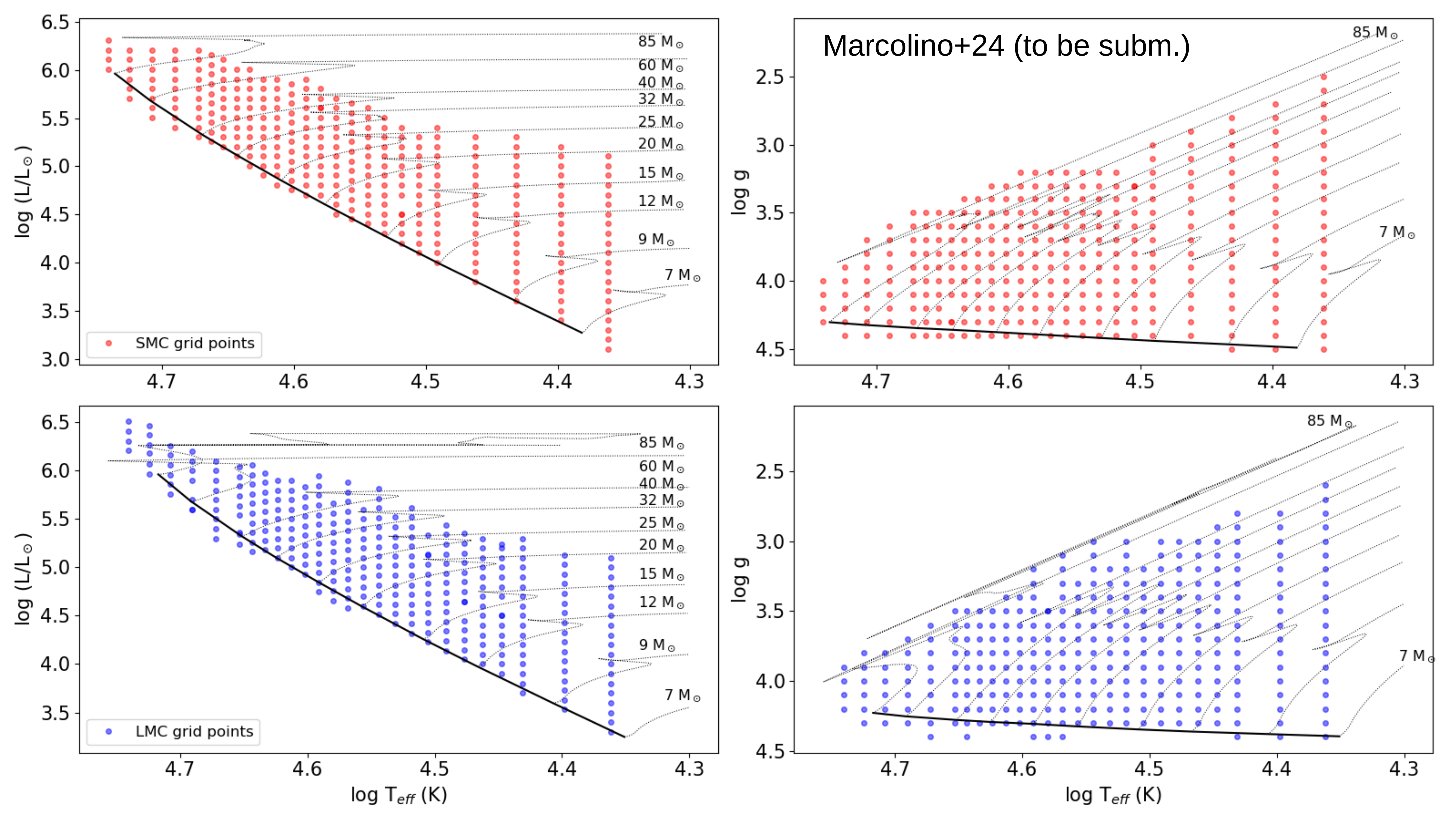
Aims:

- Expedite multiwavelength analysis of massives stars in low Z environments
- Provide models to the massive star community (spectra and structure)

Methods:

- CMFGEN (Hillier & Miller 1998) + LMC and SMC metallicities (1/2 and 1/5)
  NLTE, line-blanket, expanding atmosphere models
- Compute detailed spectra from EUV to mid-IR (continuum and lines)
- Use the spectra to compute important subproducts (log Q's, M_λ's, BC_λ's)

Grid setup (tracks from Georgy+13 and Eggenberger+21)



He/H = 0.085 (solar by number)
other elements: solar scaled 1/2 and 1/5 solar (Asplund+09)
Teff = 23 – 55 kK (steps: 1000K for 27 – 45kK and 2000K 23 – 27kK)
various log g's for each Teff (0.1 dex steps) – use of clusters in Marseille/Montpellier

Grid setup (other assumptions)

microturbulence: fixed at 10 km s^{-1}

β-law: fixed at 1.0

Mass-loss rates:
computed according to the Vink formula (Vink+01)
adopting V_∞/V_{esc} = 3.0 (Martins & Palacios 2021)

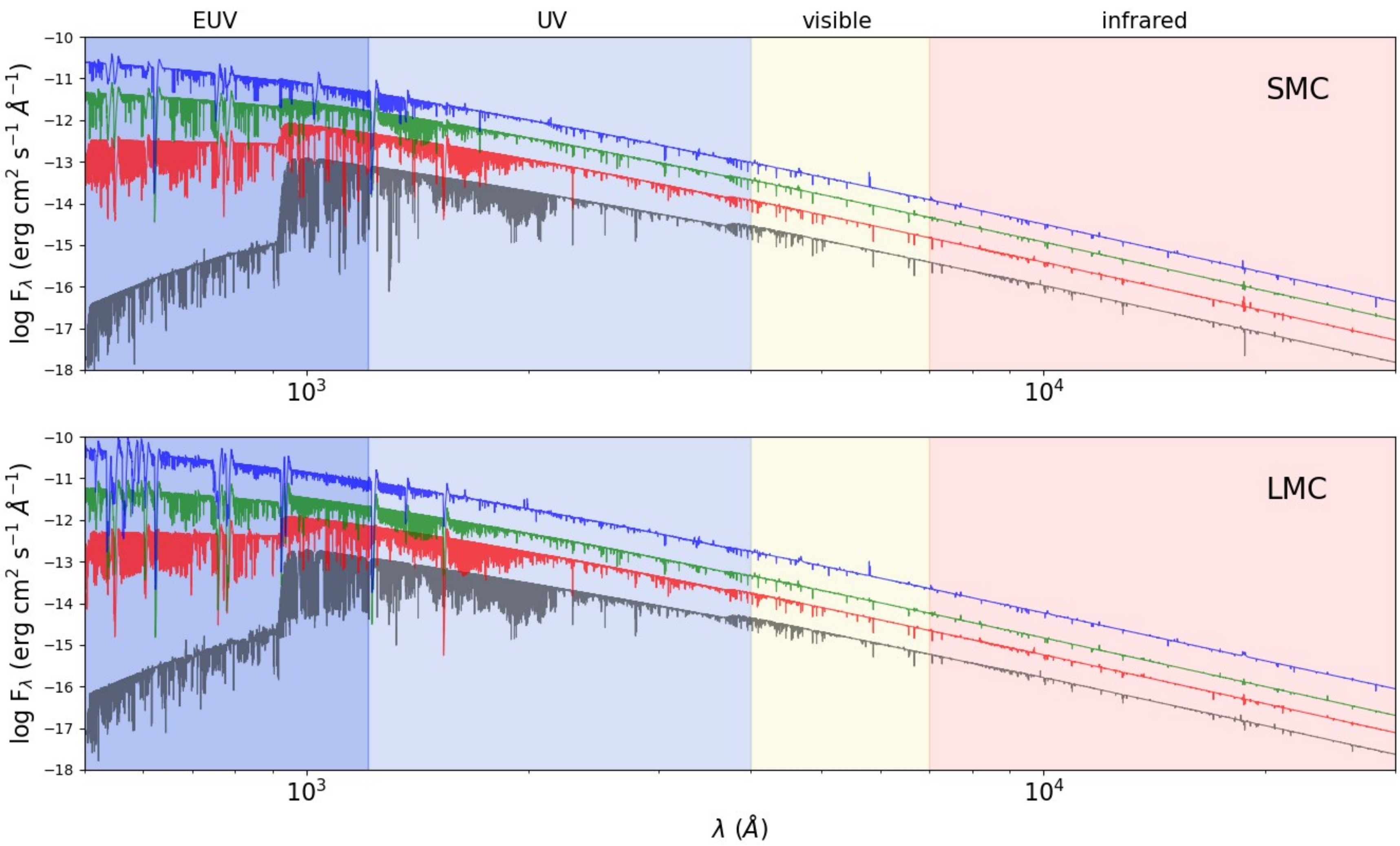
Atomic data:
complete as possible →

- 9178 levels (2046 SLs): hundreds of thousands of transitions
- appropriate amount of metal-line blanketing
- computationally feasible (hours-days/each model if converge)
- able to reproduce the rich UV spectra of OB stars

Total number of models: 606 (300 LMC + 306 SMC)
(may be extended in the near future)

Ion	# super-levels	# levels
H I	30	30
He I	69	69
He II	30	30
C II*	92	322
C III	99	243
C IV	64	64
N II*	59	105
N III	57	287
N IV	44	70
N V	41	49
O II*	155	274
O III	36	104
O IV	30	64
O V	32	56
O VI*	9	15
Ne II	14	48
Ne III	23	71
Ne IV	17	52
Ne V	37	166
Mg II	36	44
Si II*	27	53
Si III	50	50
Si IV	66	66
S III	39	78
S IV	40	108
S V	37	144
S VI*	28	58
Ar III	24	138
Ar IV	30	102
Ar V	14	29
Ar VI*	21	81
Ca III	29	88
Ca IV	19	72
Ca V*	10	613
Fe II*	24	295
Fe III	65	607
Fe IV	100	1000
Fe V	139	1000
Fe VI	59	1000
Fe VII*	41	252
Ni II*	27	158
Ni III	24	150
Ni IV	36	200
Ni V	46	183
Ni VI	40	182
Ni VII*	37	308

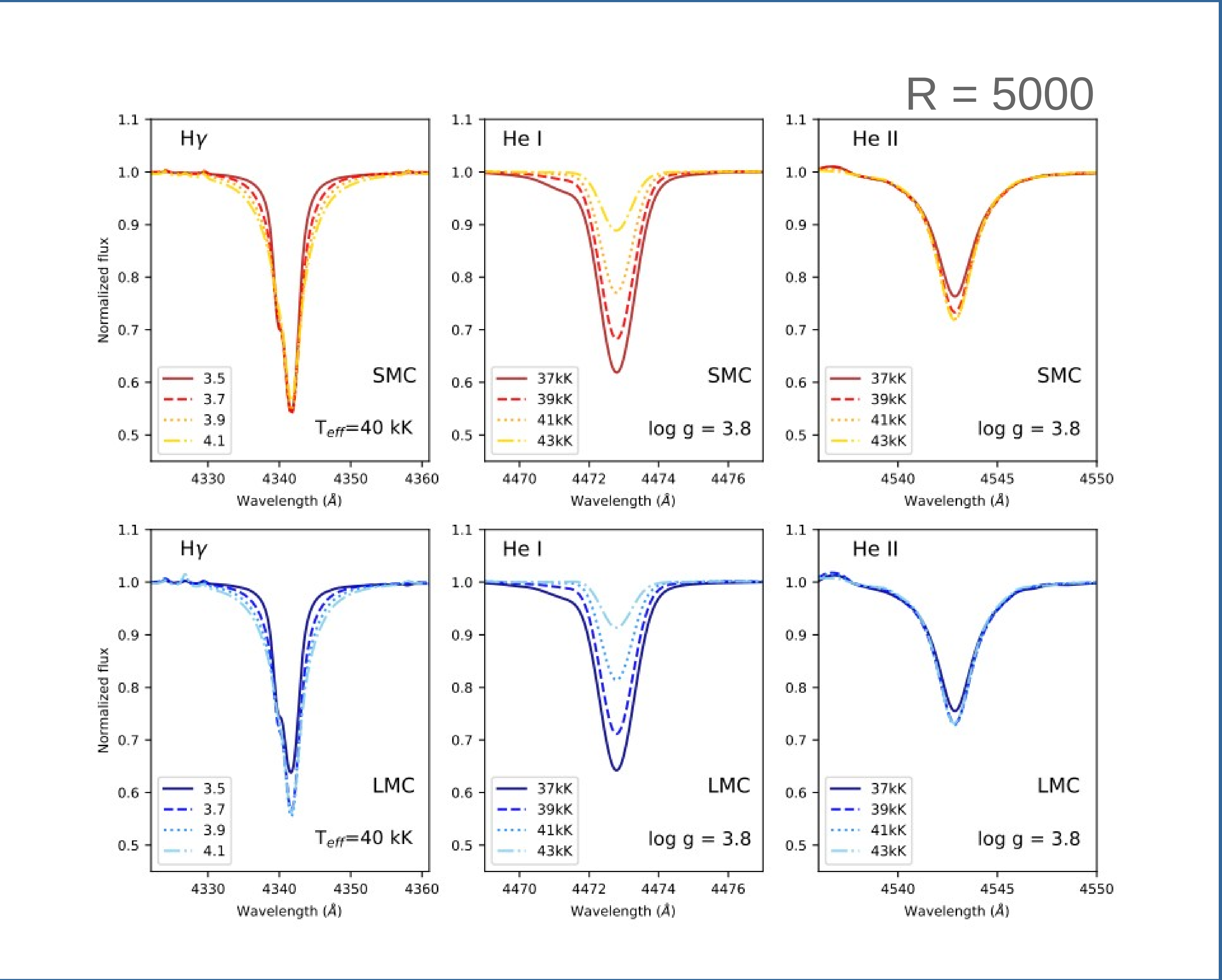
Example of spectra: 500-30000Å



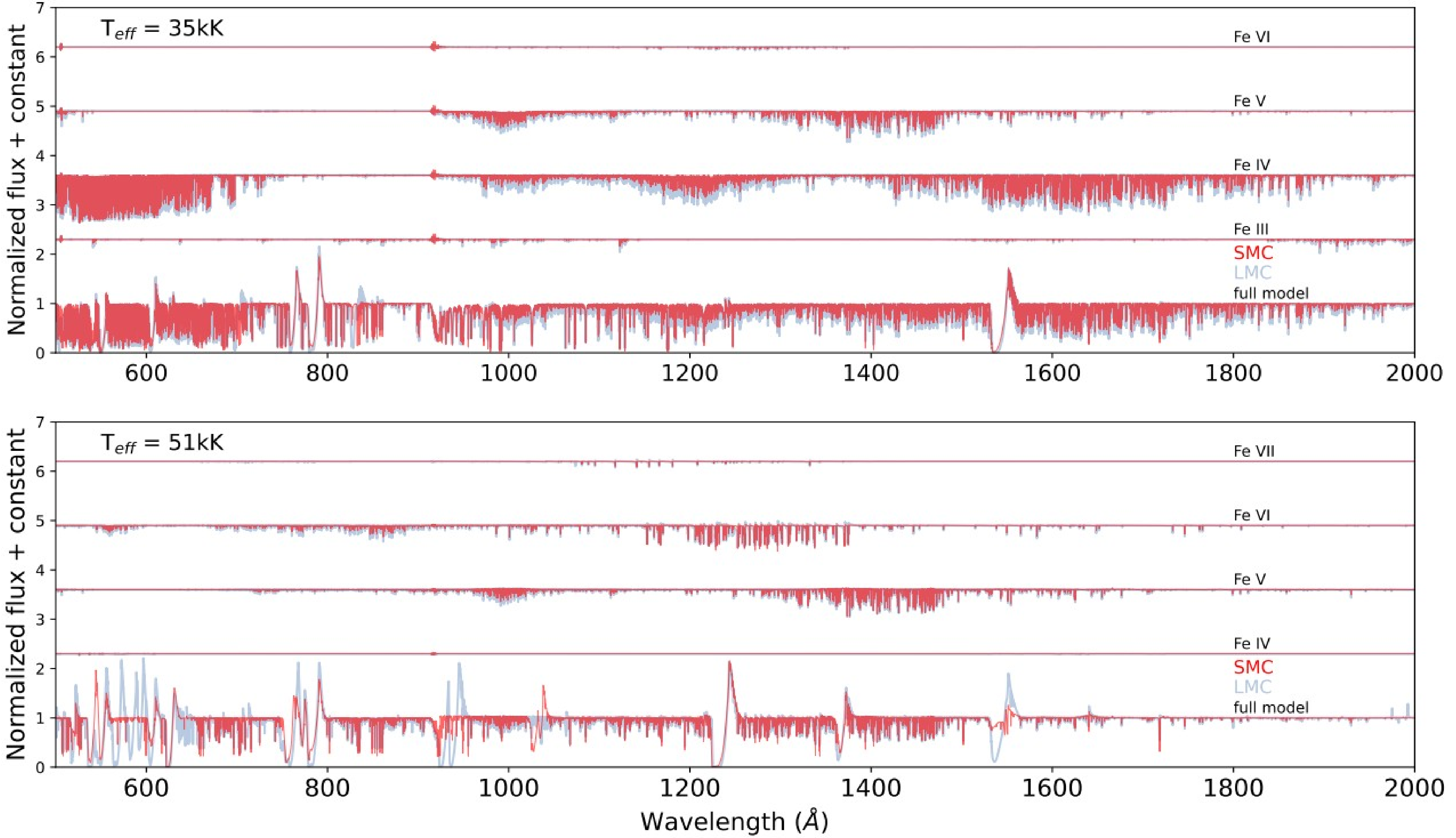
T_{eff}'s: 25000, 35000, 45000, and 55000 K ; log g = 4.0

(roughly an early B, late O, mid-O and early O typer star)

Optical spectra and line sensitivity

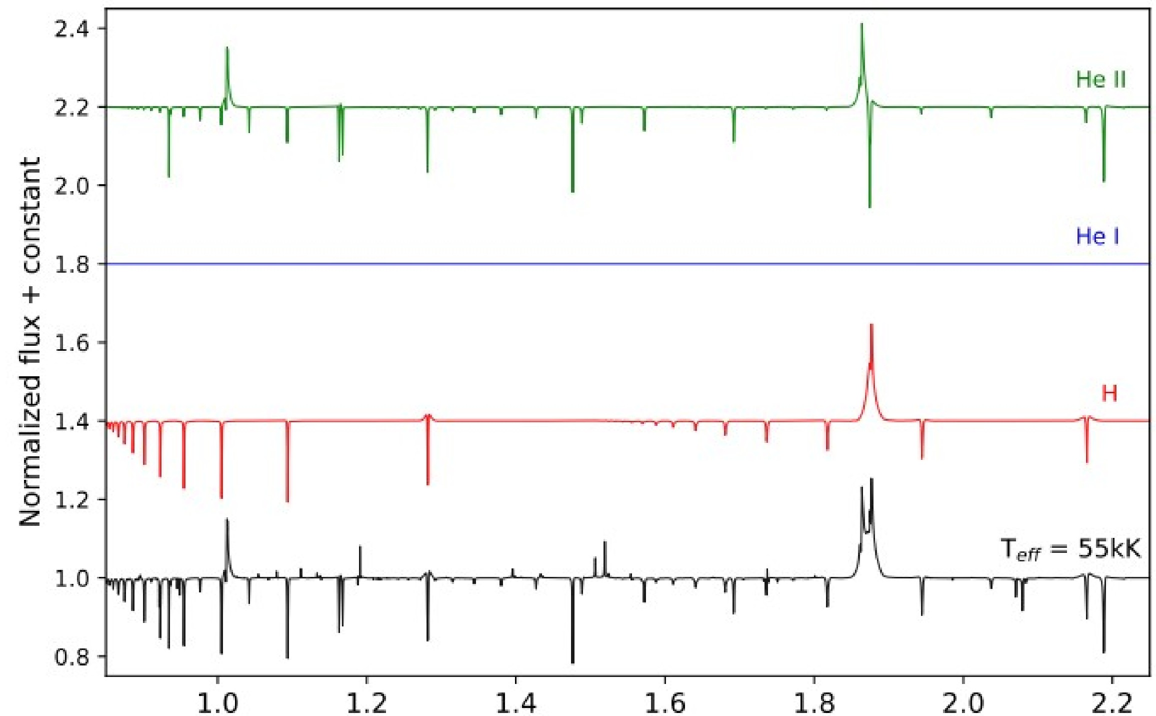


UV spectra and line sensitivity

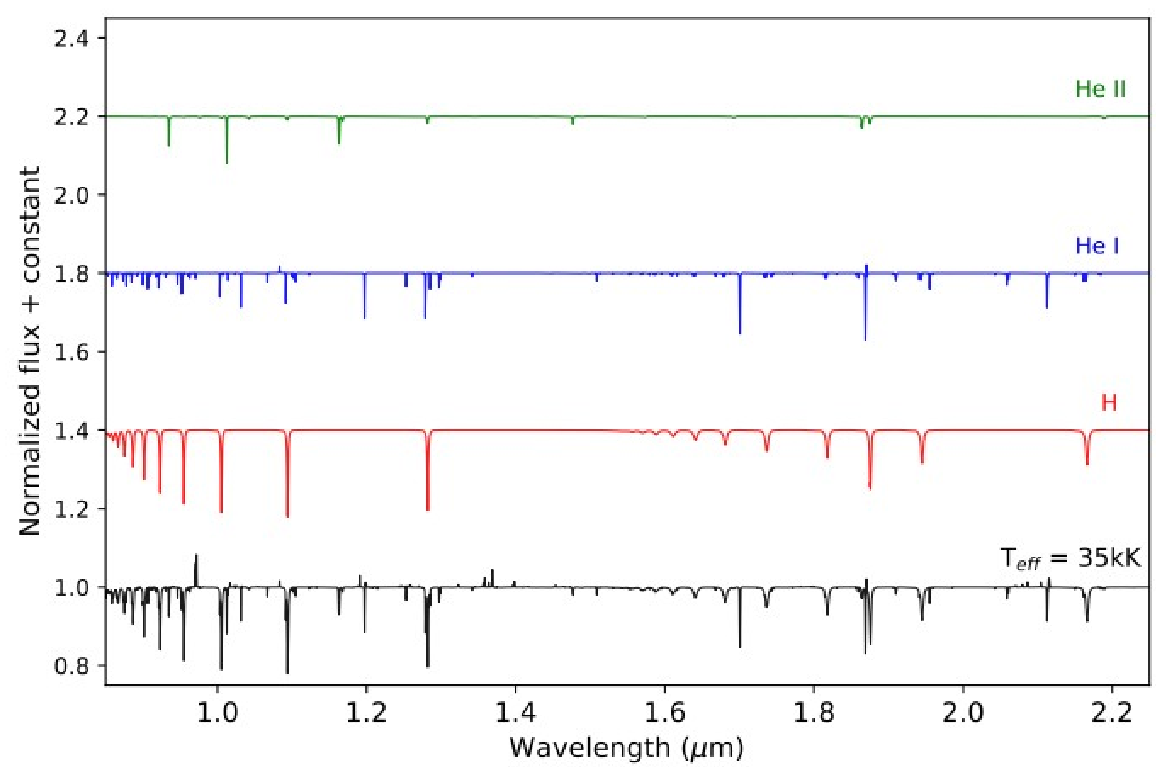


IR spectra
(R=2700; Z_{LMC})

55kK



35kK



Spectra appropriate to analyze, e.g., JWST NIRcam data

Synthetic Photometry

- The vast wavelength interval allows the computation of absolute magnitudes, BC's and other subproducts.

- We chose the bands:

    - UBVRIJHK – classical Johnson, Cousins, Bessel
    - GAIA G
    - JWST wide filters – F070W, F090W, F115W, F150W, and F200W
    - LSST ugrizy

- PYPHOT package + incursions on the SVO to obtain the filters transmissions
  (Morgan Fouesneau – github) (e.g., svo.get_pyphot_astropy_filter("LSST/LSST.r"))

model

$$M_\lambda = -2.5 \times log \int F_\lambda B_\lambda d\lambda + const.$$

filter

Bolometric corrections

$$BC_\lambda = M_\odot^{bol} - M_\lambda - 2.5 \times log \frac{L}{L_\odot}$$

Sun
(4.75 IAU 1999)

model

Synthetic Photometry

- The vast wavelength interval allows the computation of absolute magnitudes, BC's and other subproducts.

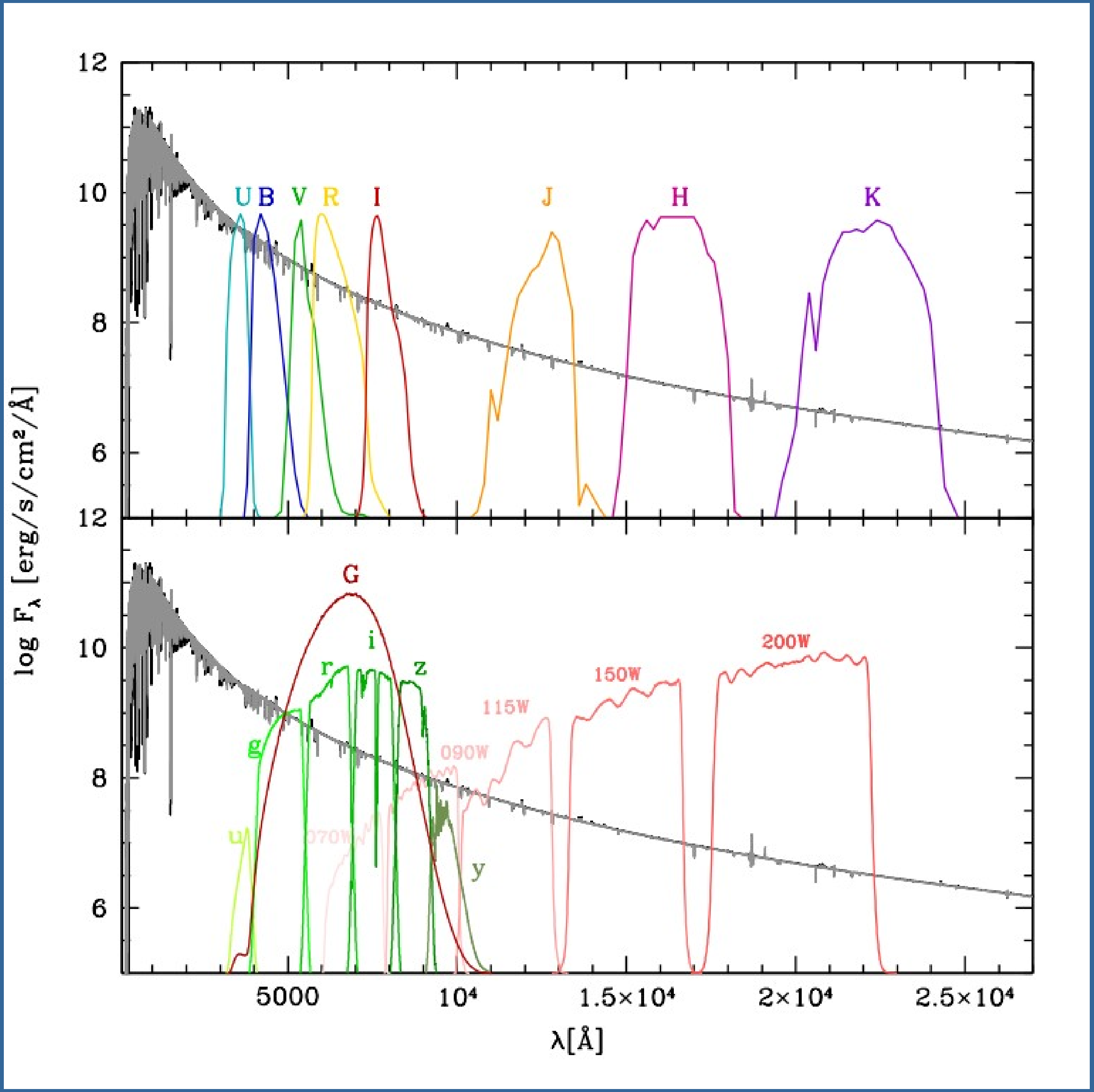
- We chose the bands:

    - UBVRIJHK
    - GAIA G
    - JWST wide filters
    - LSST ugrizy

- Pyphot package
  (Morgan Fouesneau - github)

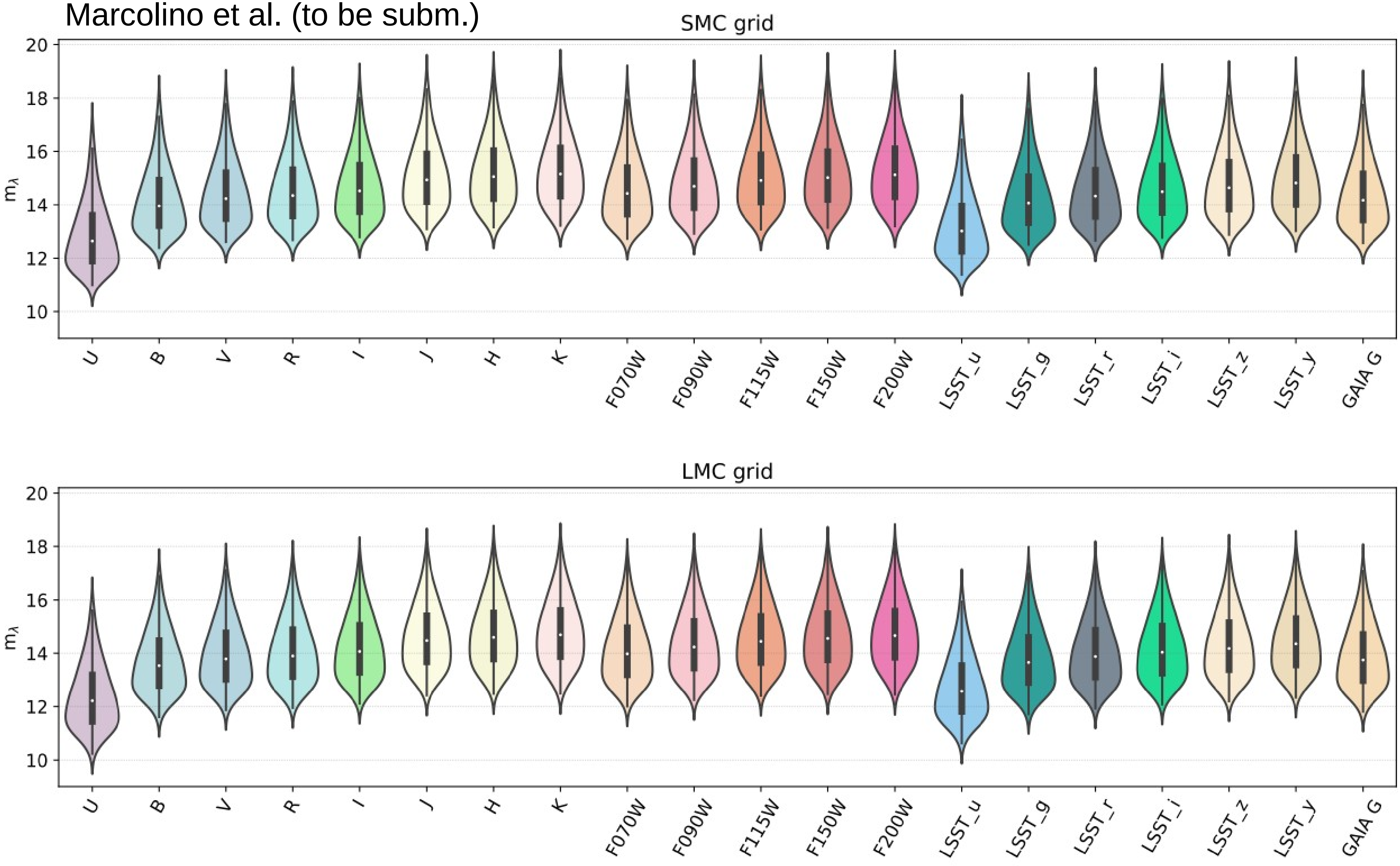
$$M_\lambda = -2.5 \times log \int F_\lambda B_\lambda d\lambda + const.$$

$$BC_\lambda = M_\odot^{bol} - M_\lambda - 2.5 \times log \frac{L}{L_\odot}$$

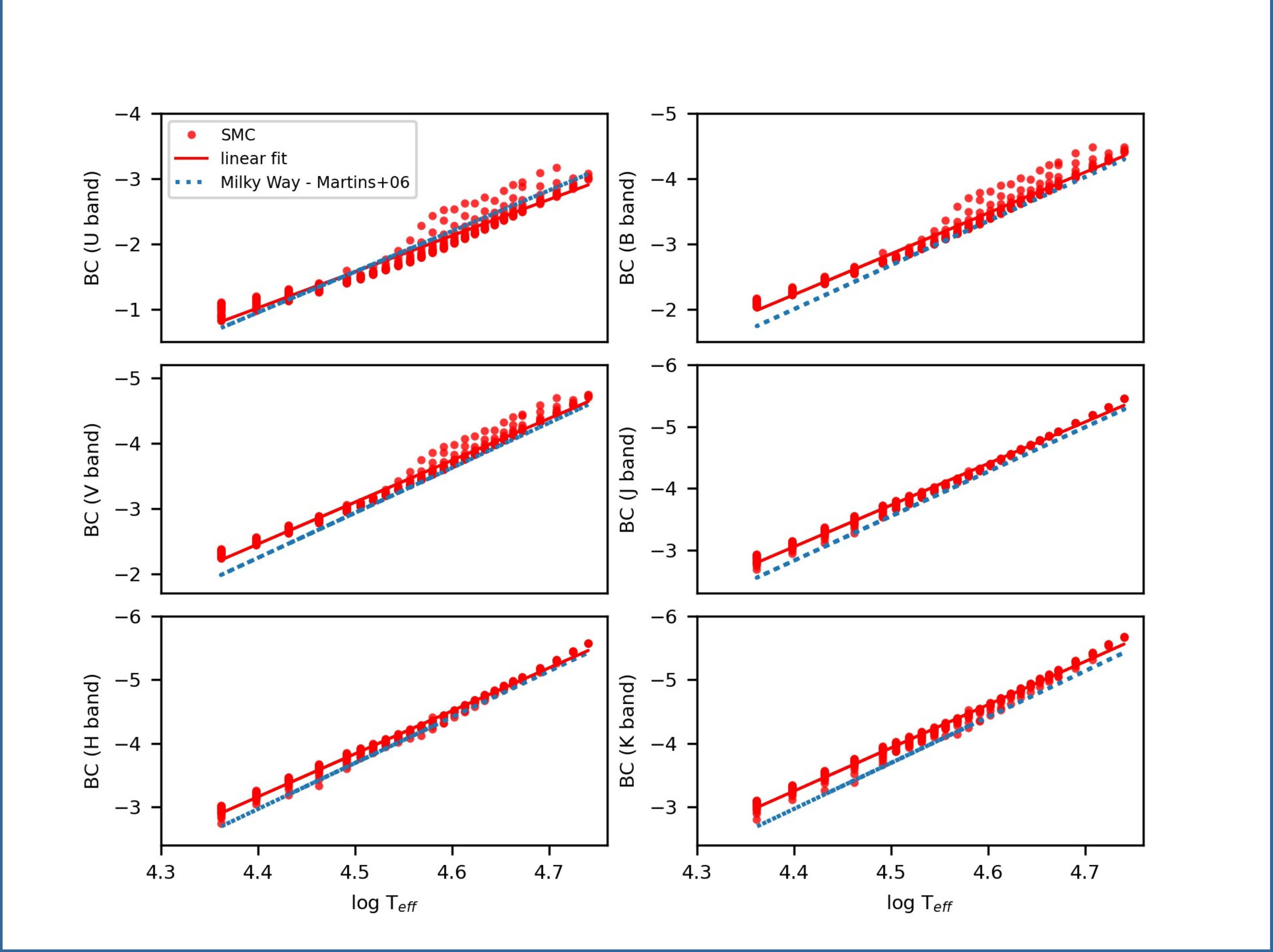


Synthetic Photometry

Marcolino et al. (to be subm.)



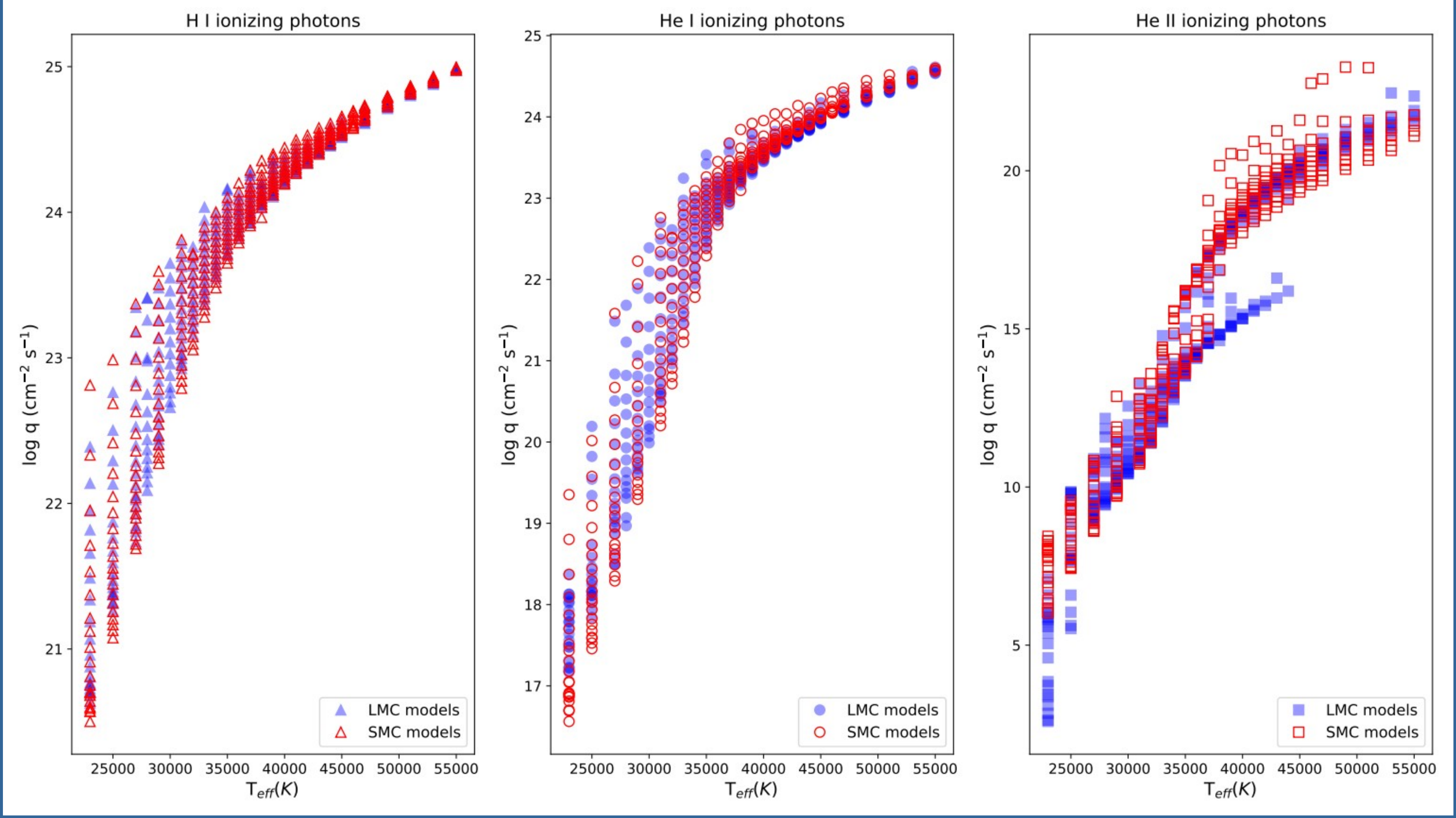
Bolometric Corrections - UBVJHK



mild Z effect on the BC's

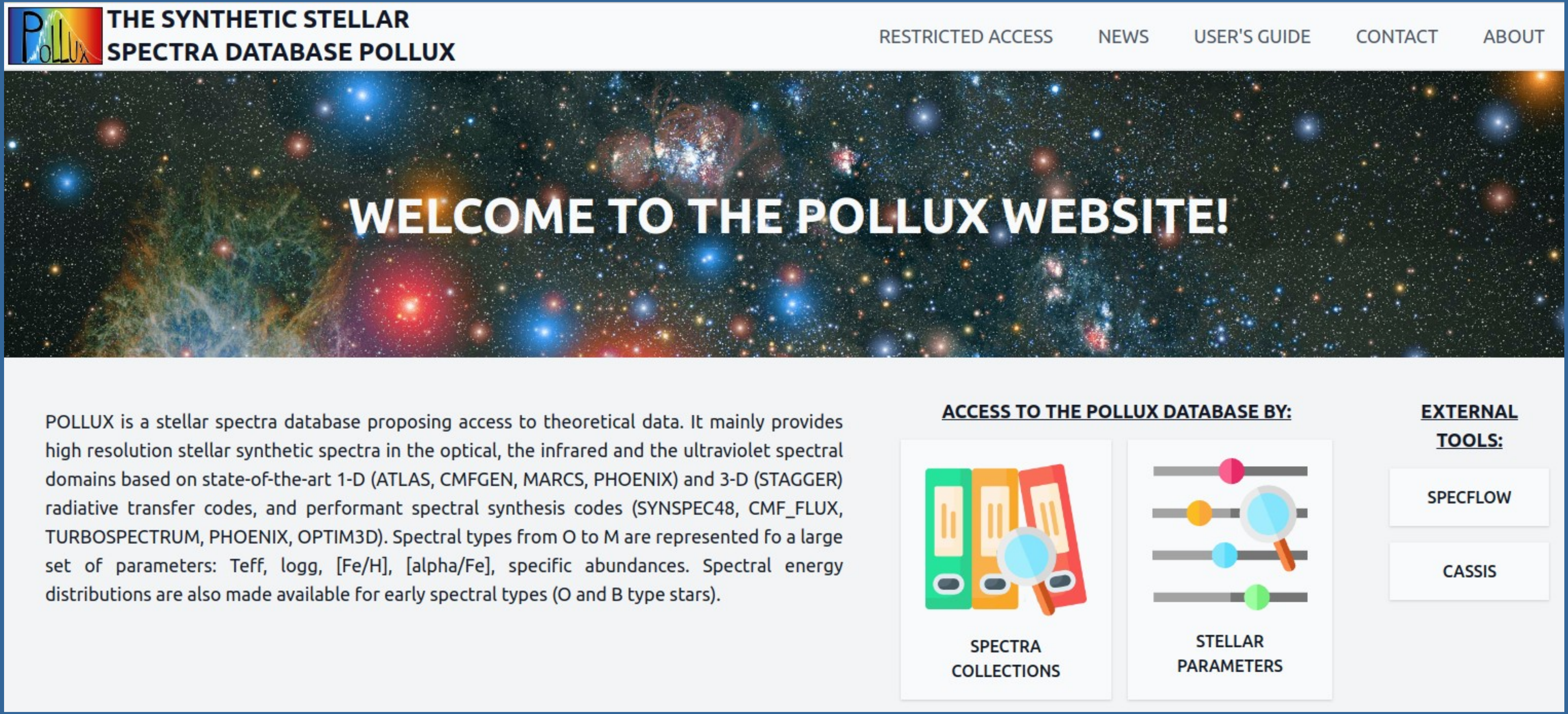
Ionizing fluxes – log Q's

- Spectra computed from ~30 Å to 5 μm: $$Q = \int_{\nu_o}^{+\infty} \frac{L_\nu}{h\nu} d\nu,$$
- Q(He II) behavior is complex - depends largely on He II opacity/ground state population



GRID availability

- The spectra can be found at https://pollux.oreme.org/ (Palacios+10)
- Individual models can be made available by request
- A catalog at Vizier with all subproducts is also planned
  (absolute magnitudes, bolometric corrections, log Q's, etc.)



Conclusions

- ➔ We provide two grids of NLTE expanding atmosphere models appropriate to investigate OB stars at low metallicities (LMC and SMC).
- ➔ We computed spectra from the EUV to the mid-IR (606 models).
  Z-effect on several spectral bands is conspicuous
- ➔ Absolute magnitudes and BC_λ's were computed in several bands.
  LSST, GAIA and JWST for the first time; BC's x T_{eff} show mild Z effect
- ➔ Ionizing fluxes of H I, He I and He II were calculated.
  Q(HI) and Q(HeI) do not reveal a metallicity dependence; Q(HeII) behavior is complex
- ➔ The models can be made available upon request (soon).
- ➔ The spectra can be dowloaded at the Pollux database.
  https://pollux.oreme.org/
- ➔ We hope to improve the both grids in the near future.
- ➔ Our models will expedite the analysis of massive stars in low Z environments.

Thanks