The Massive Star Content of the Magellanic Clouds

Image credit: Kathryn Neugent

Philip Massey
Lowell Observatory

The Team

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John Hillier

Maria Drout

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Georges Meynet

Sylvia Ekström

Cyril Georgy

And of course…
Nidia!

Why Study Massive Stars in the Magellanic Clouds?

We’d like to understand massive star evolution as a function of metallicity. Mass-loss affects the evolution of massive stars via stellar winds, which is metallicity dependent.

Magellanic Clouds Are Our Ideal Laboratories

1) They're nearby!

Image credit: ESO/S. Brunier - ESO

2) Metallicities differ!

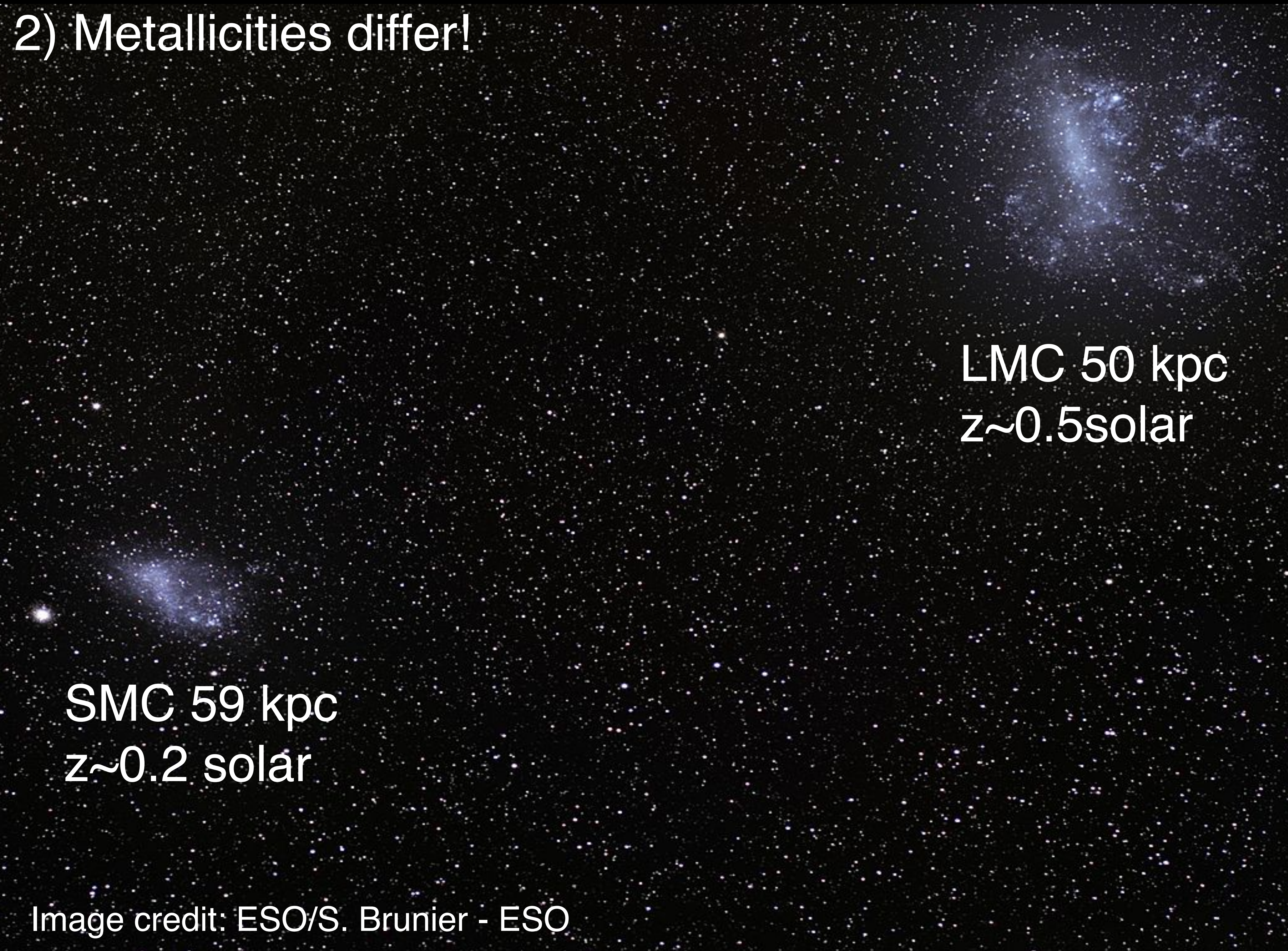


Image credit: ESO/S. Brunier - ESO

3) Lots of massive stars!

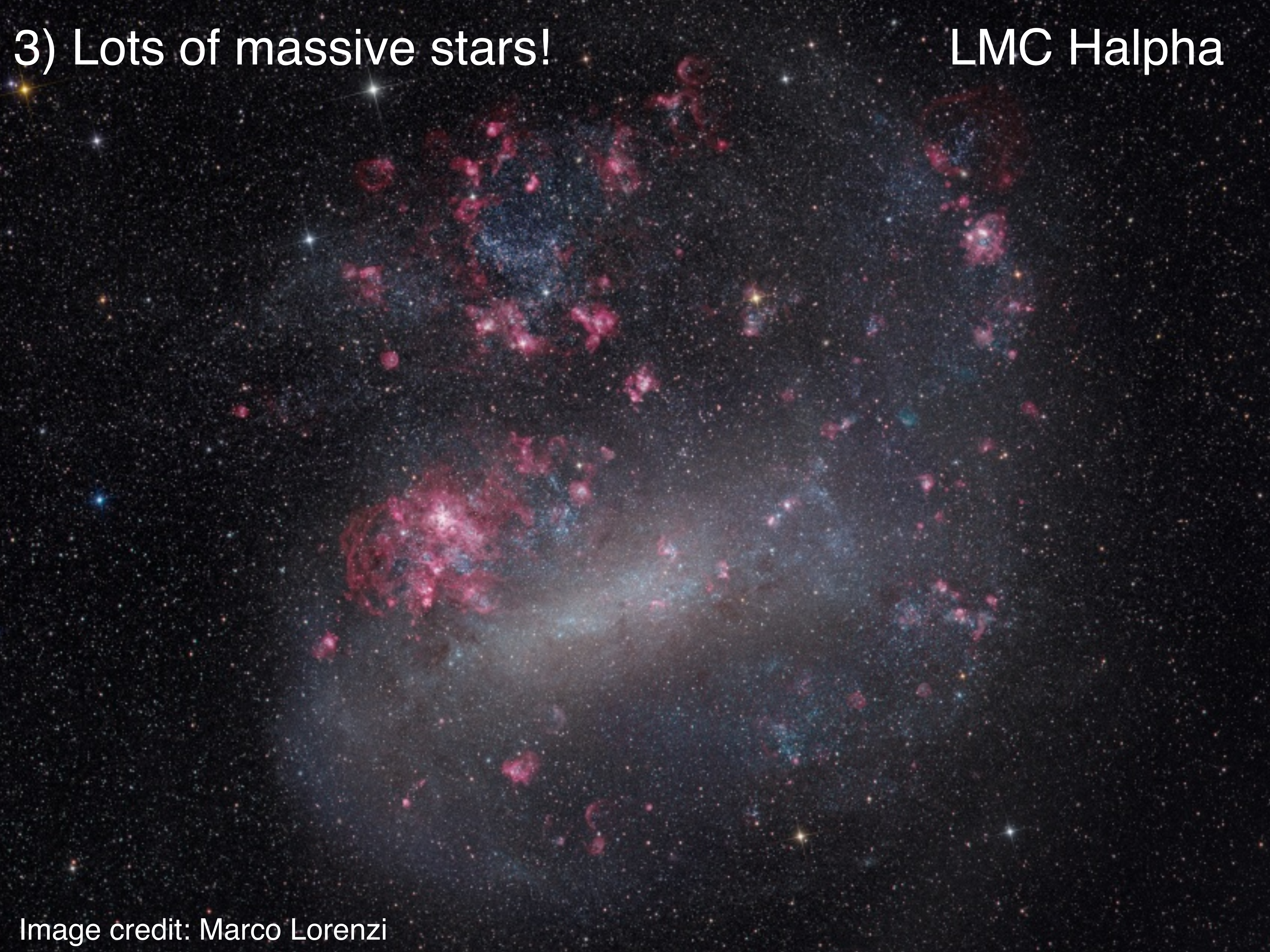


Image credit: Marco Lorenzi

3) Lots of massive stars!

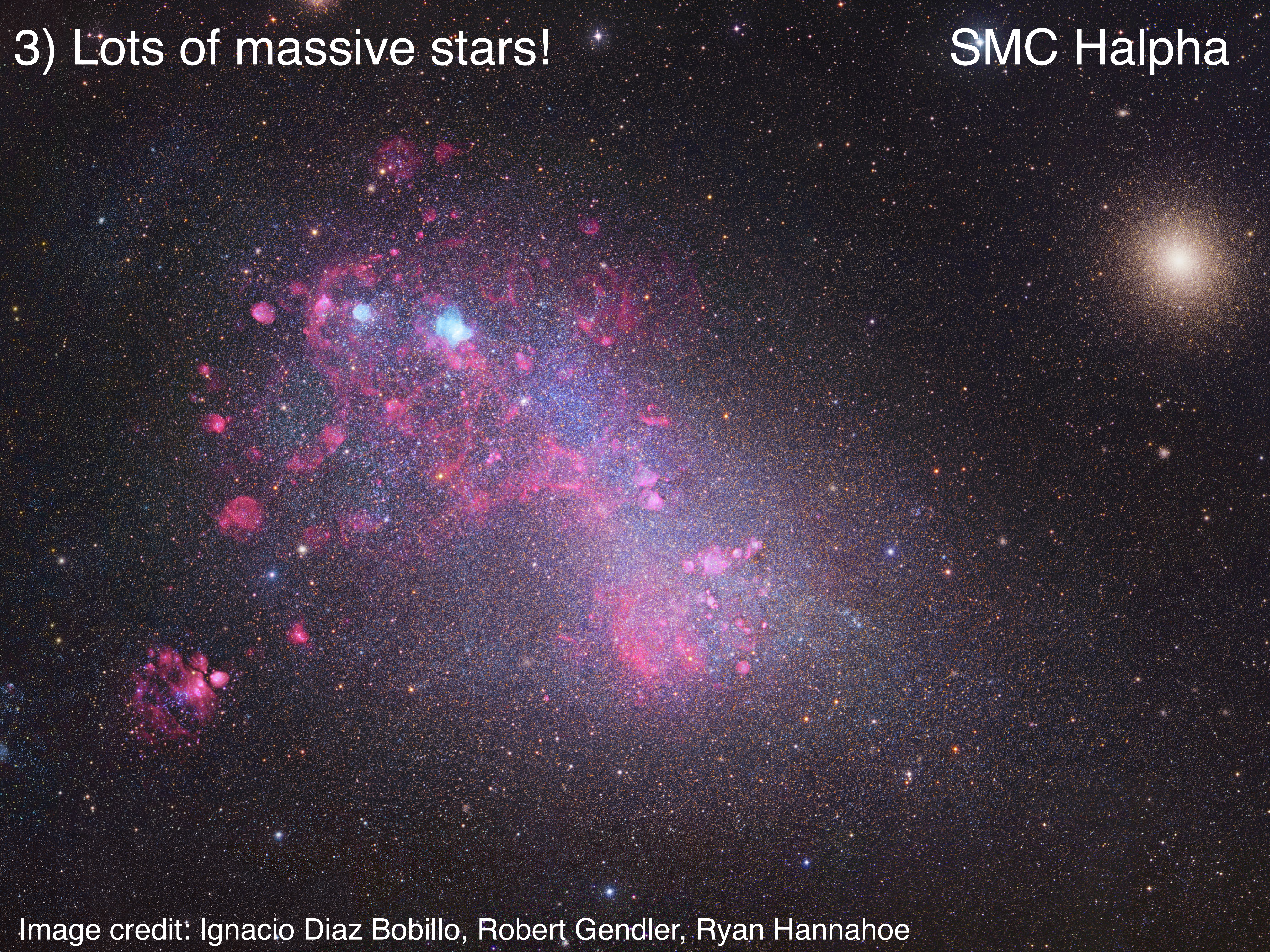
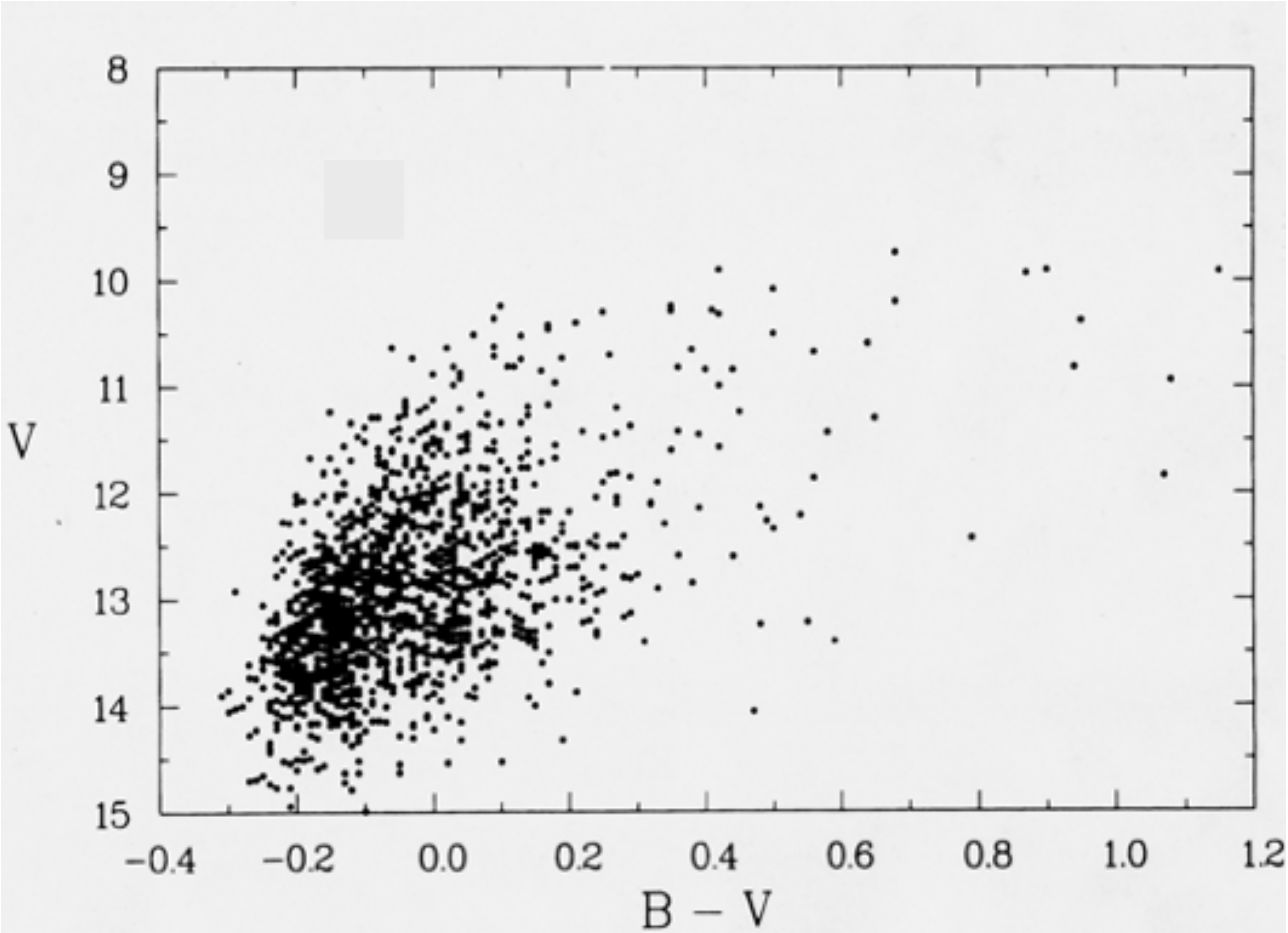


Image credit: Ignacio Diaz Bobillo, Robert Gendler, Ryan Hannahoe

The LMC CMD in 1990

LMC

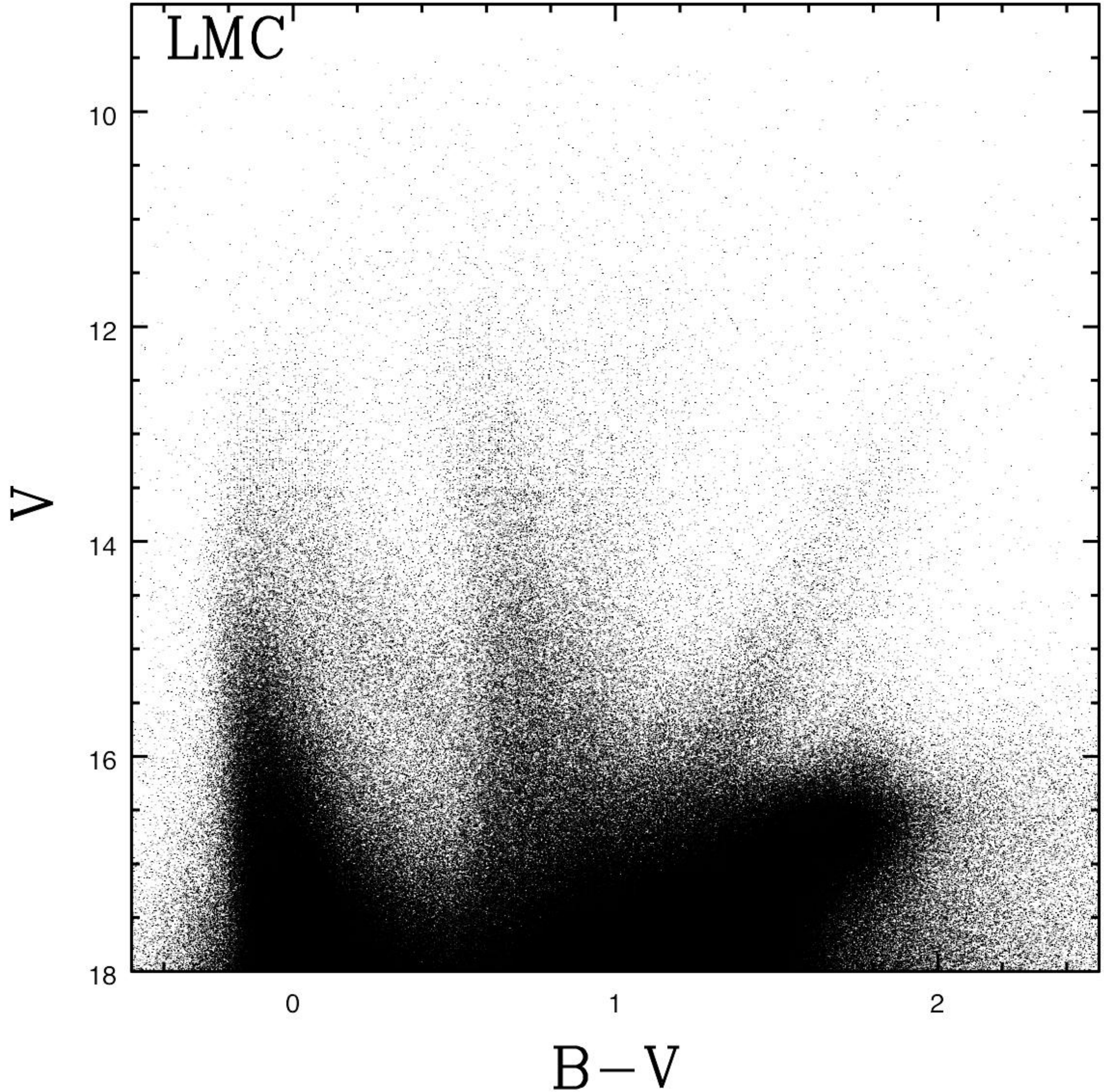
From Fitzpatrick & Garmany (1990)



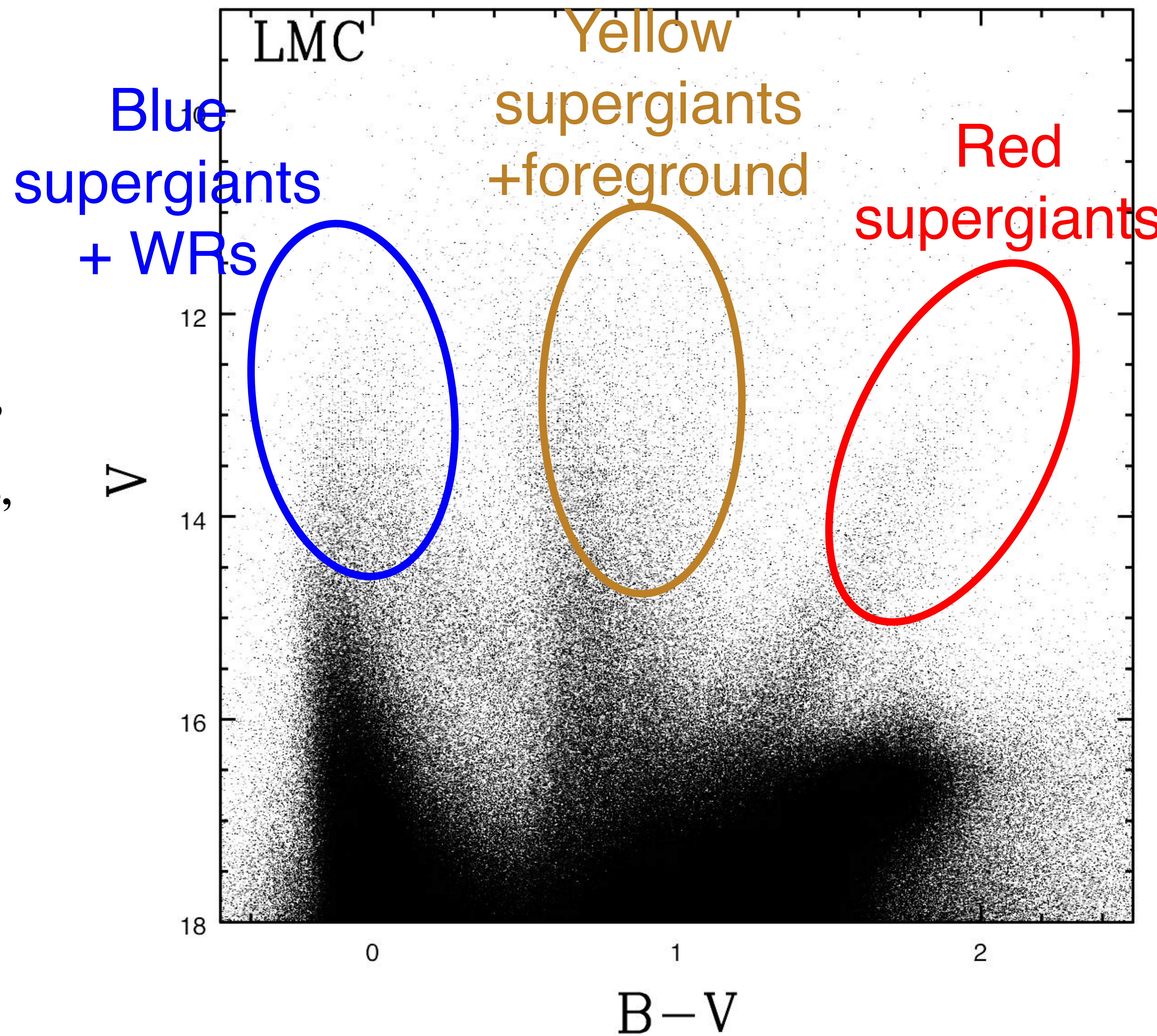
The LMC CMD today

LMC

Photometry from Zaritsky et al (2004, AJ, 128, 1605) and Massey (2002, ApJS, 141, 81)

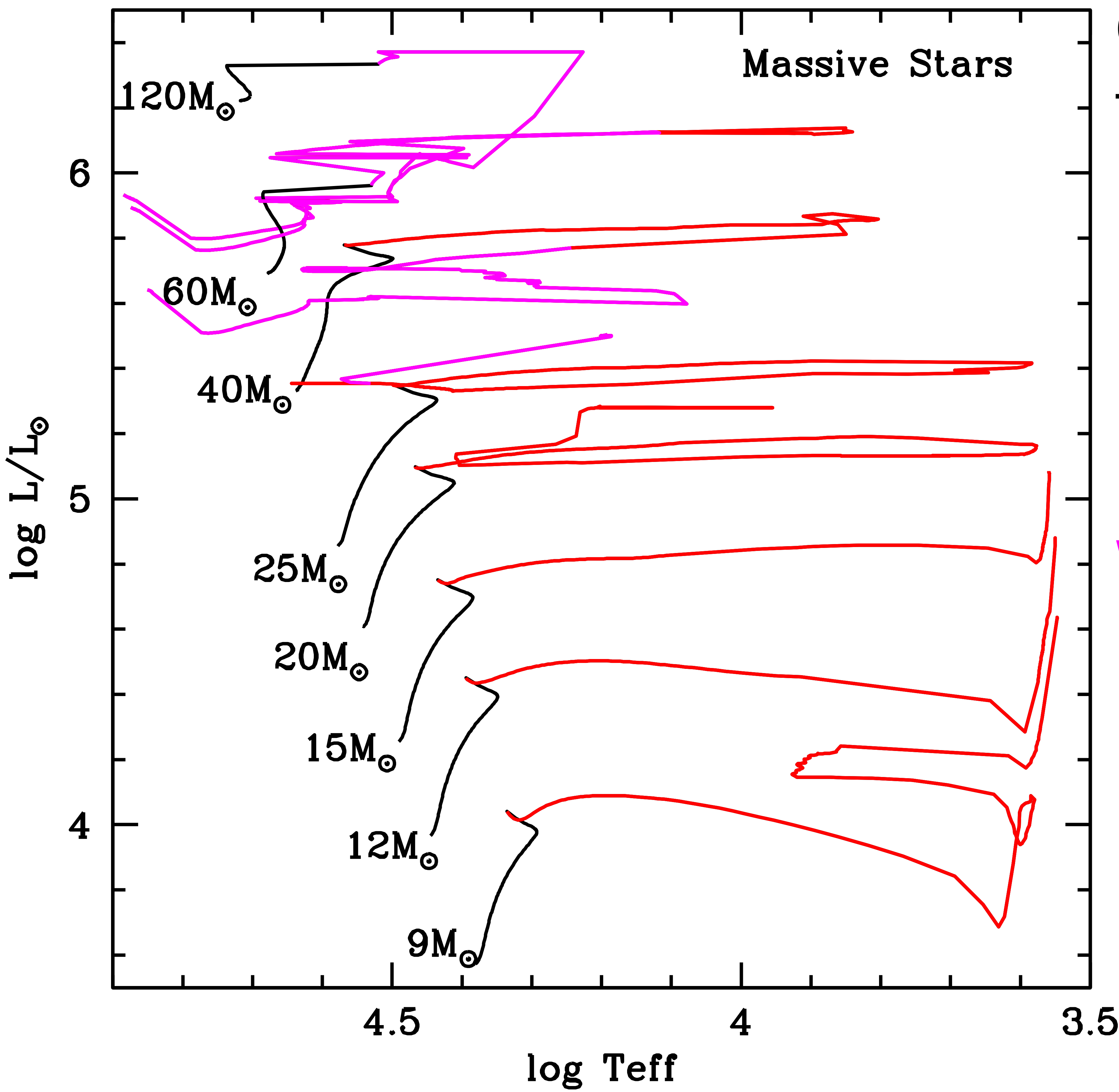


The LMC CMD today



LMC

Photometry from Zaritsky et al (2004, AJ, 128, 1605) and Massey (2002, ApJS, 141, 81)

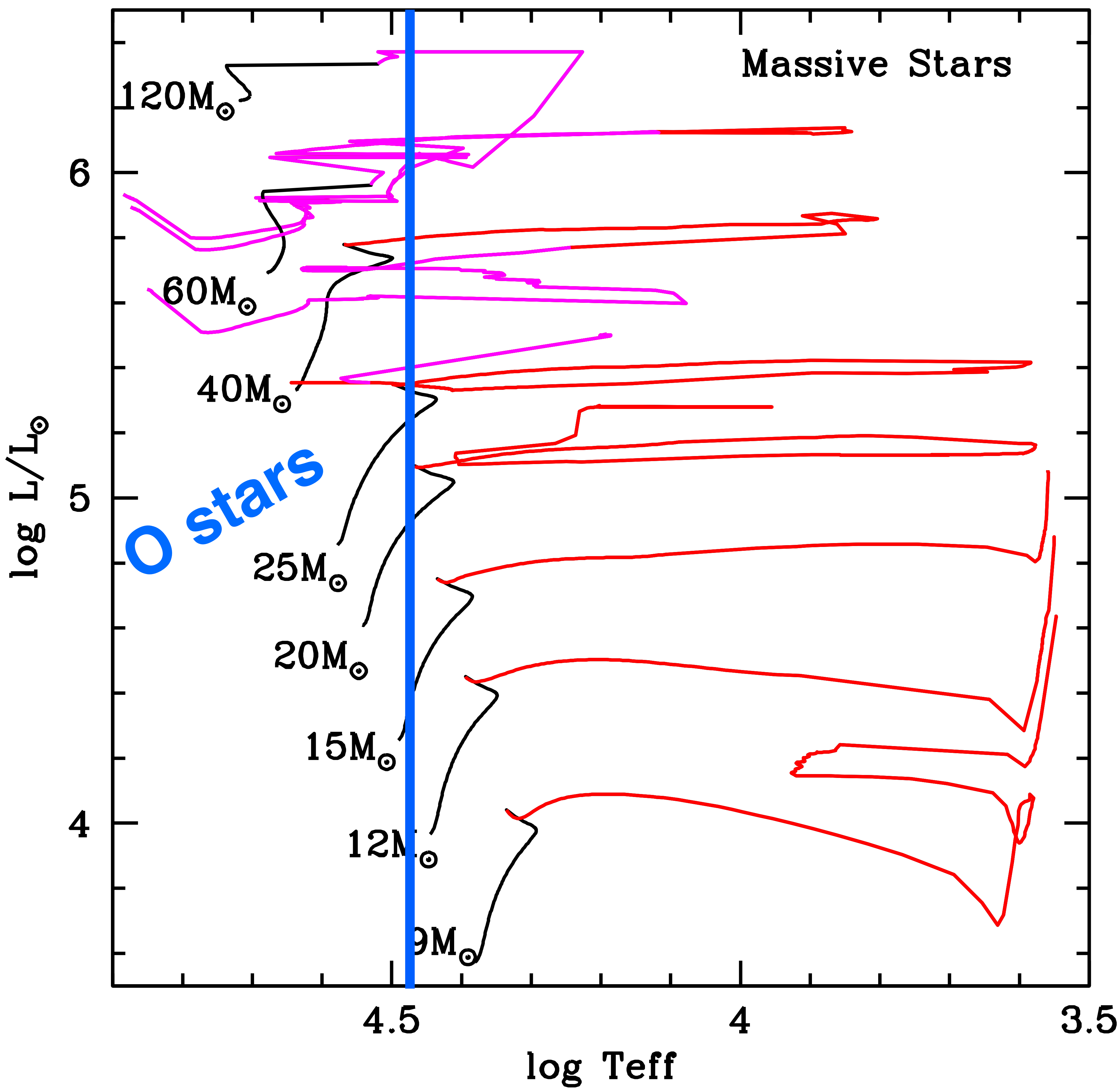


Geneva tracks
Ekstrom et al (2012)

H-burning
He-burning
Wolf-Rayet

What's What: O-type Stars

O-type stars: Defined spectrosopically as luminous stars that show H and He II absorption in the optical. Modeling shows that these stars have Teff > 30,000 K.


Massive Stars
120M⊙
60M⊙
40M⊙
25M⊙
20M⊙
15M⊙
12M⊙
9M⊙
O stars
6
5
4
log L/L⊙
4.5
4
3.5
log Teff

What's What: O-type Stars

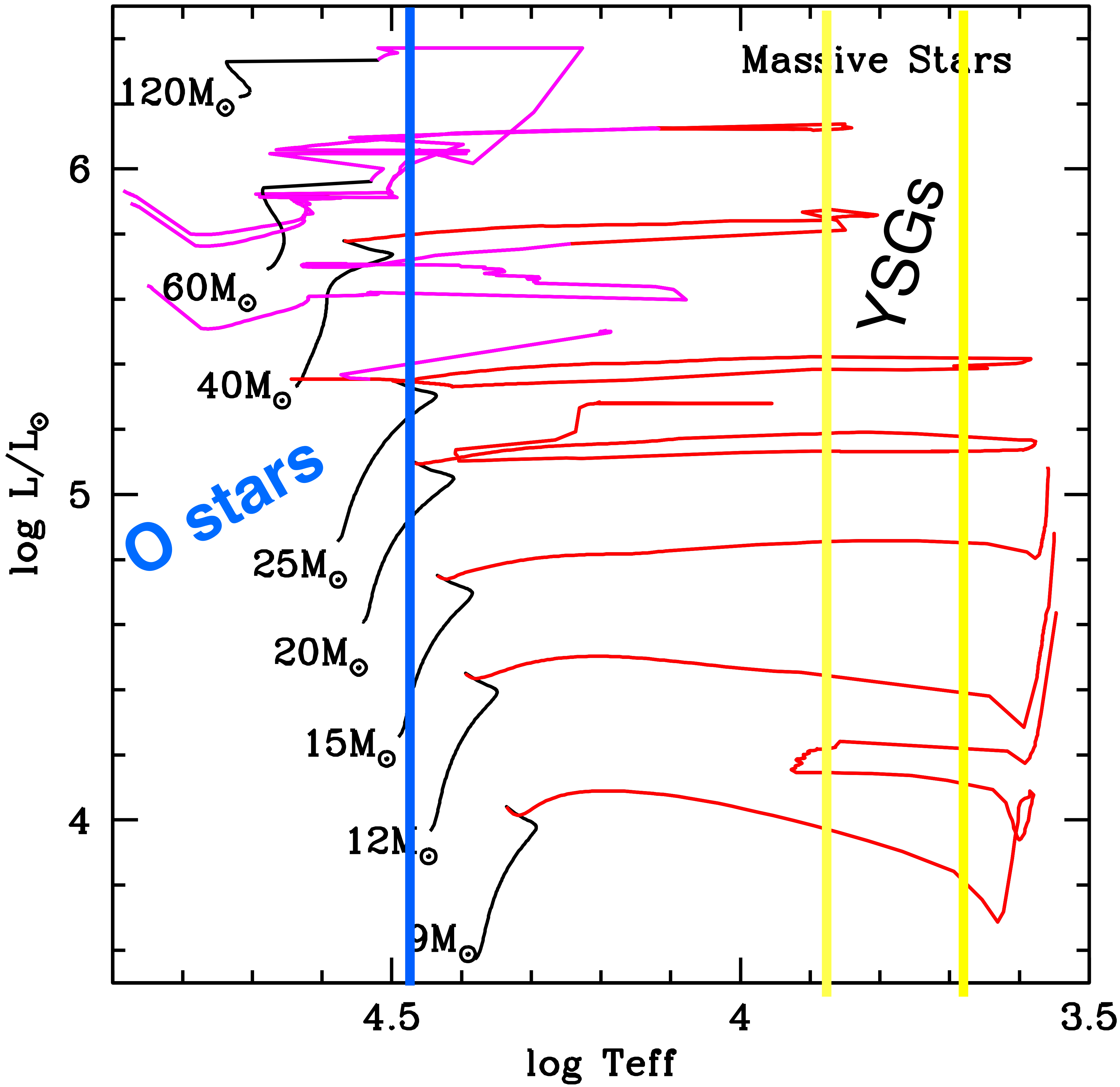
From an evolutionary point of view, O-type stars are relatively unevolved.

- ✳All 25Mo and above main-sequence stars are O-type. Thus, the highest mass stars spend most of their lives as O-type stars.

- ✳That said, "O-type stars" is not synomonous with "highest mass stars." Some late-type O stars are as low in mass as 15Mo.

What's What:
Yellow Supergiants

Yellow Supergiants (YSGs): F- and G-type with 7500 K> Teff > 4800 K.

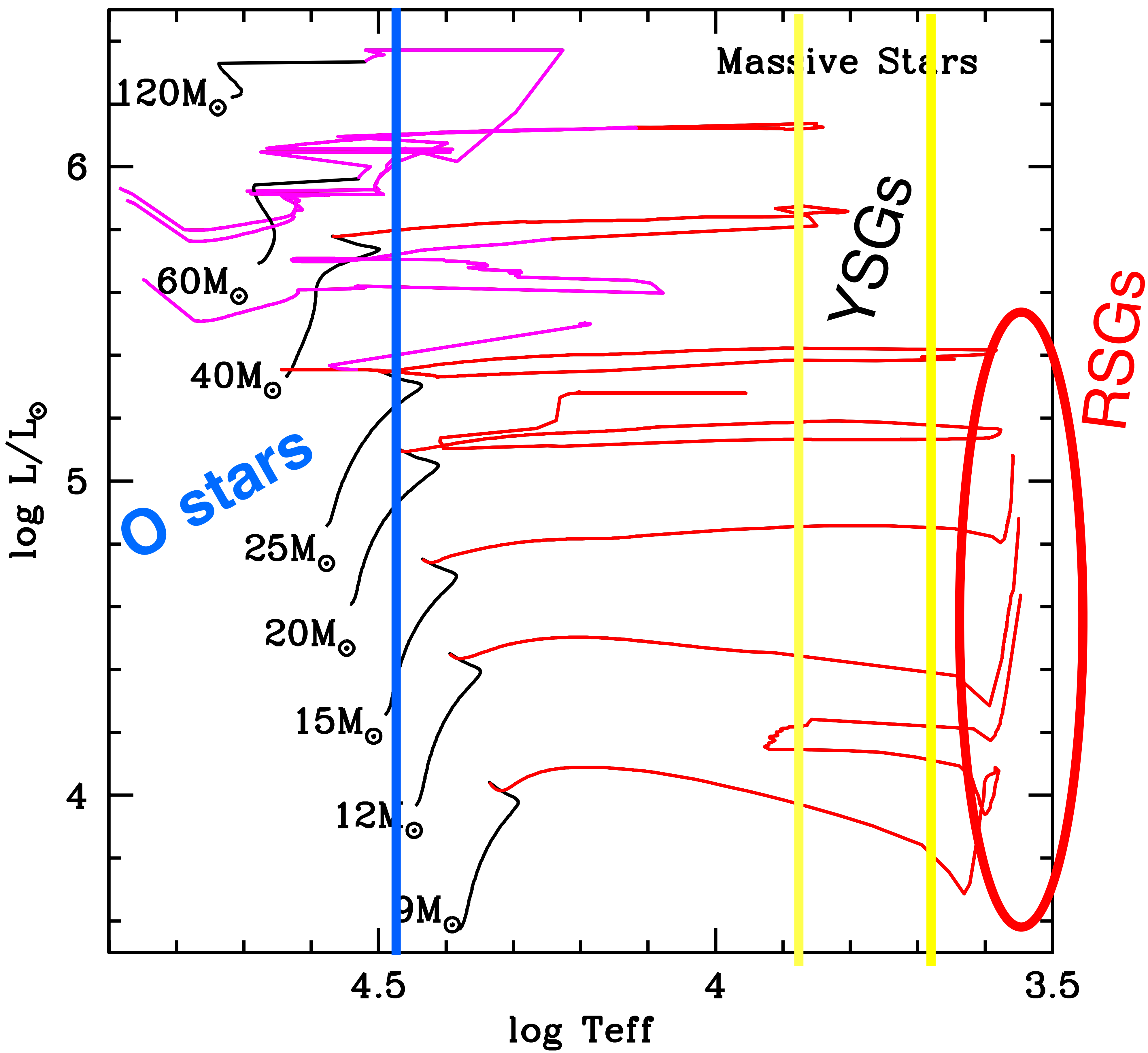

Massive Stars
YSGs
O stars
120M⊙
60M⊙
40M⊙
25M⊙
20M⊙
15M⊙
12M⊙
9M⊙
log L/L⊙
6
5
4
log Teff
4.5
4
3.5

What's What: Yellow Supergiants

From an evolutionary point of view, YSGs are very short-lived (10,000 years) transitional phase.

What’s What:
Red Supergiants

Red supergiants (RSGs): These are K- and M-type with Teff < 4800 K extending down to ~3700 K

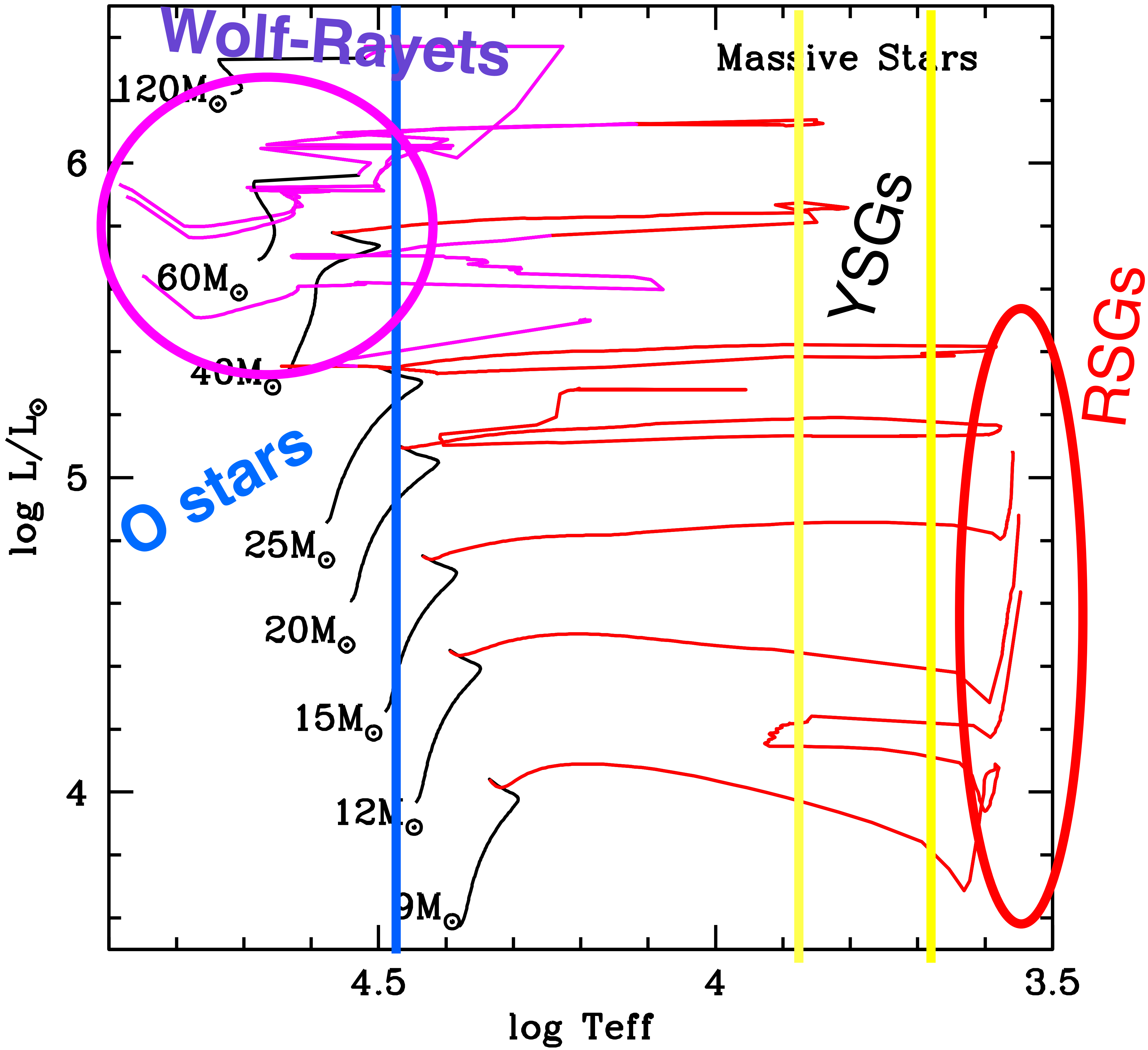

Massive Stars
120M⊙
60M⊙
40M⊙
25M⊙
20M⊙
15M⊙
12M⊙
9M⊙
O stars
YSGs
RSGs
6
5
4
log L/L⊙
4.5
4
3.5
log Teff

What's What: Red Supergiants

From a stellar evolution point of view, we expect RSGs to be the "retirement" home for most massive stars. This is the phase they will have for most of their He-burning lives. The highest mass to make it to the RSG phase is model-dependent, but something like 30Mo. Most RSGs have initial masses of 15Mo and below.

What's What: Wolf-Rayet Stars

Wolf-Rayet stars: These are spectroscopically identified as luminous stars having broad, strong emission lines of He and N (WN-type) or He, C, and O (WC/WO-types). Modeling shows that their temperatures are high (>50,000K). Their H abundances are low (H/He < 1), and their N or C abundances large.



Wolf-Rayets
Massive Stars
120M⊙
60M⊙
40M⊙
25M⊙
20M⊙
15M⊙
12M⊙
9M⊙
O stars
YSGs
RSGs
6
5
4
log L/L⊙
4.5
4
3.5
log Teff

What's What: Wolf-Rayet Stars

From an evolutionary point of view, WRs are the stripped "bare cores" of high mass stars, with either the products of CNO-cycle H-burning (WN) or triple-alpha He-burning (WC) revealed at their surfaces. The stripping may take place either by stellar winds or other processes (LBV phase or binary interactions).

Let's Start with the Evolved Massive Stars of the MCs

These evolved stages act as a "sort of magnifying glass, revealing relentlessly the faults of calculations of earlier phases" (Kippenhahn & Weigert 1991).

Let's Start with the Evolved Massive Stars of the MCs

Fun tests include:

Luminosity distribution of YSGs.

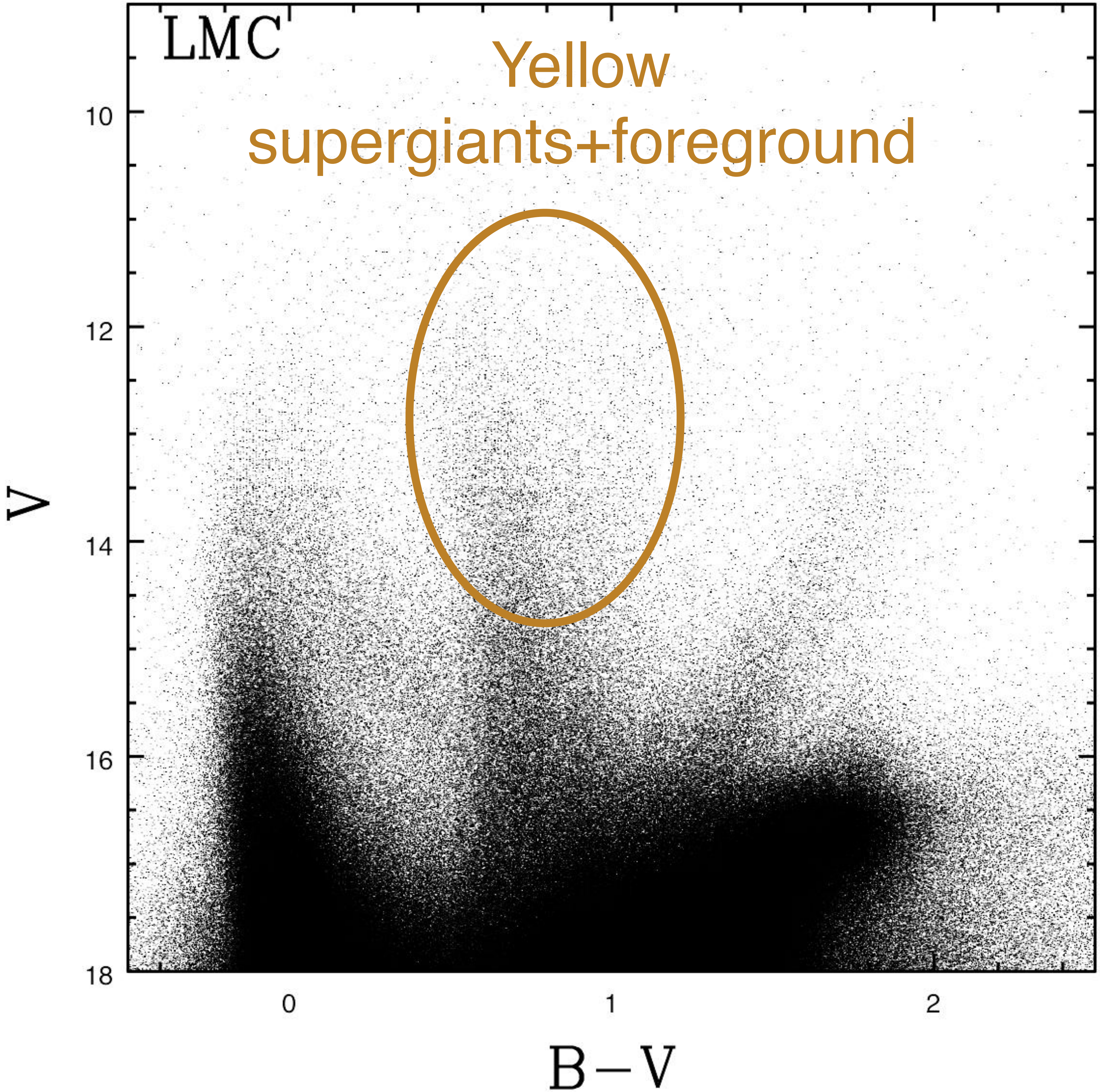
Relative numbers of WRs and RSGs.

Relative numbers of WRs and O-type stars.

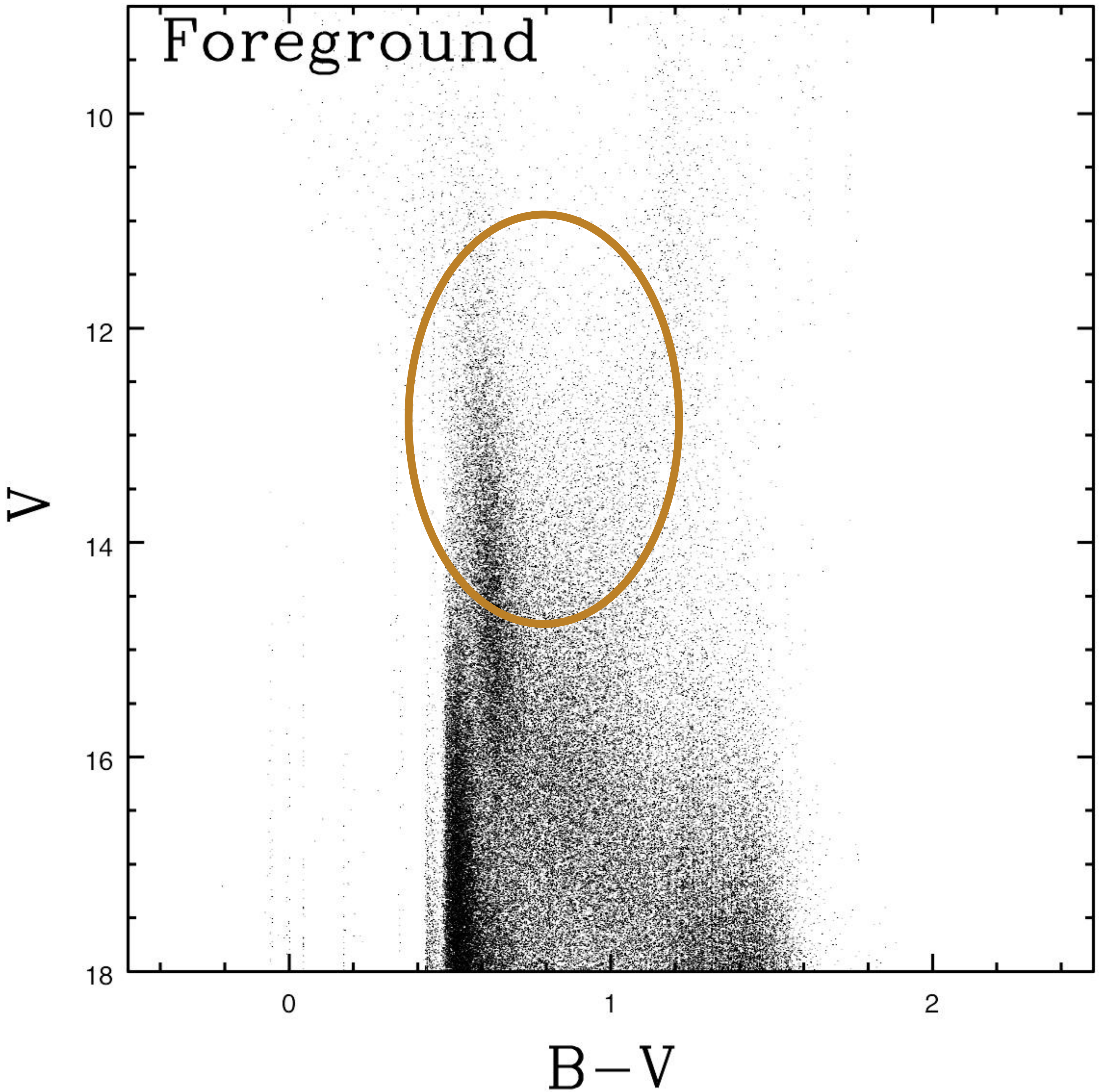
Let’s Start with the Evolved Massive Stars of the MCs

However, these tests mostly require *complete* samples to be identified, with foreground contamination removed.

Searching for Yellow Supergiants



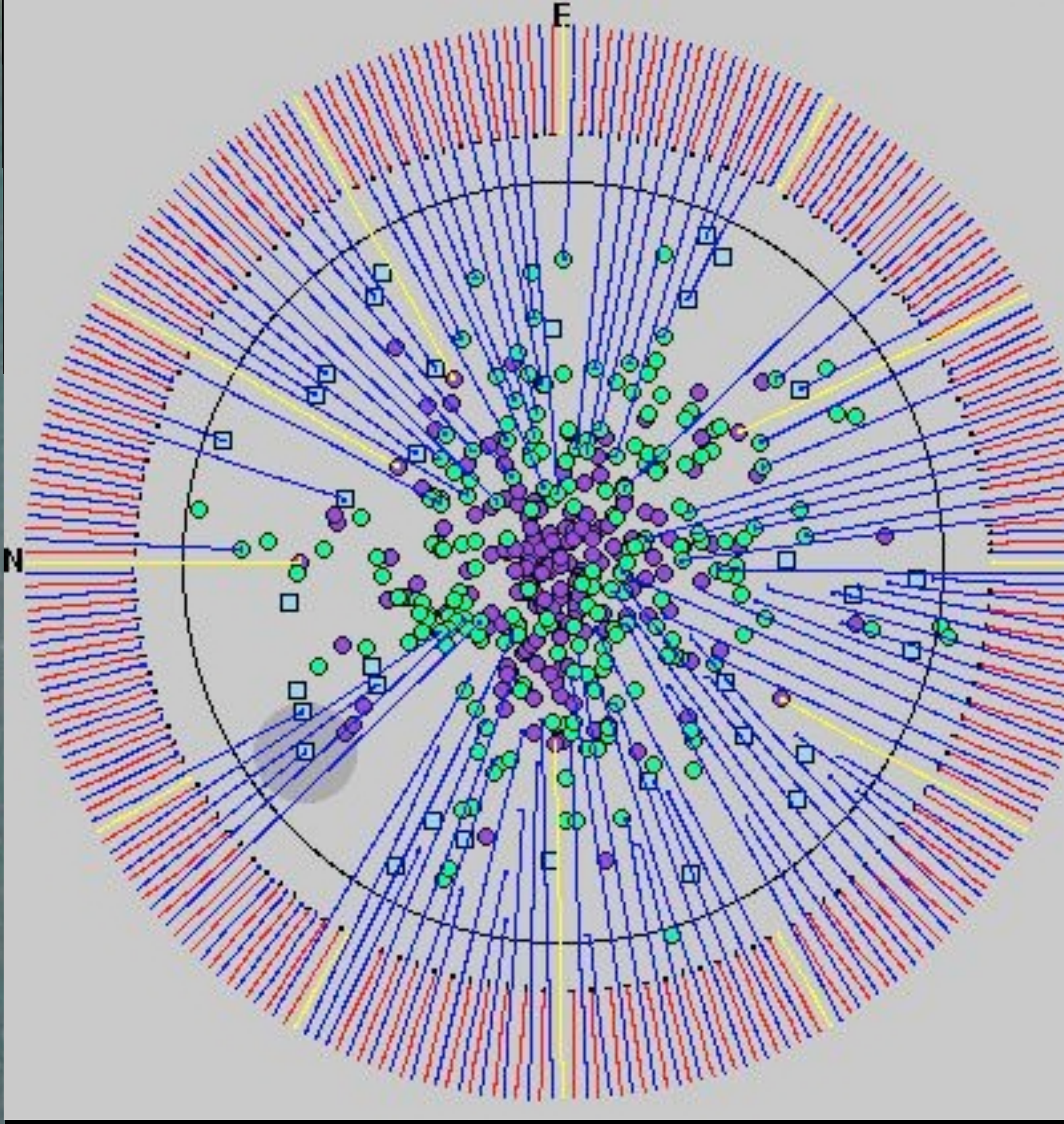
LMC
Yellow
supergiants+foreground
V
10
12
14
16
18
0
1
2
B−V


Foreground
V
10
12
14
16
18
0
1
2
B−V

Looking through the MW

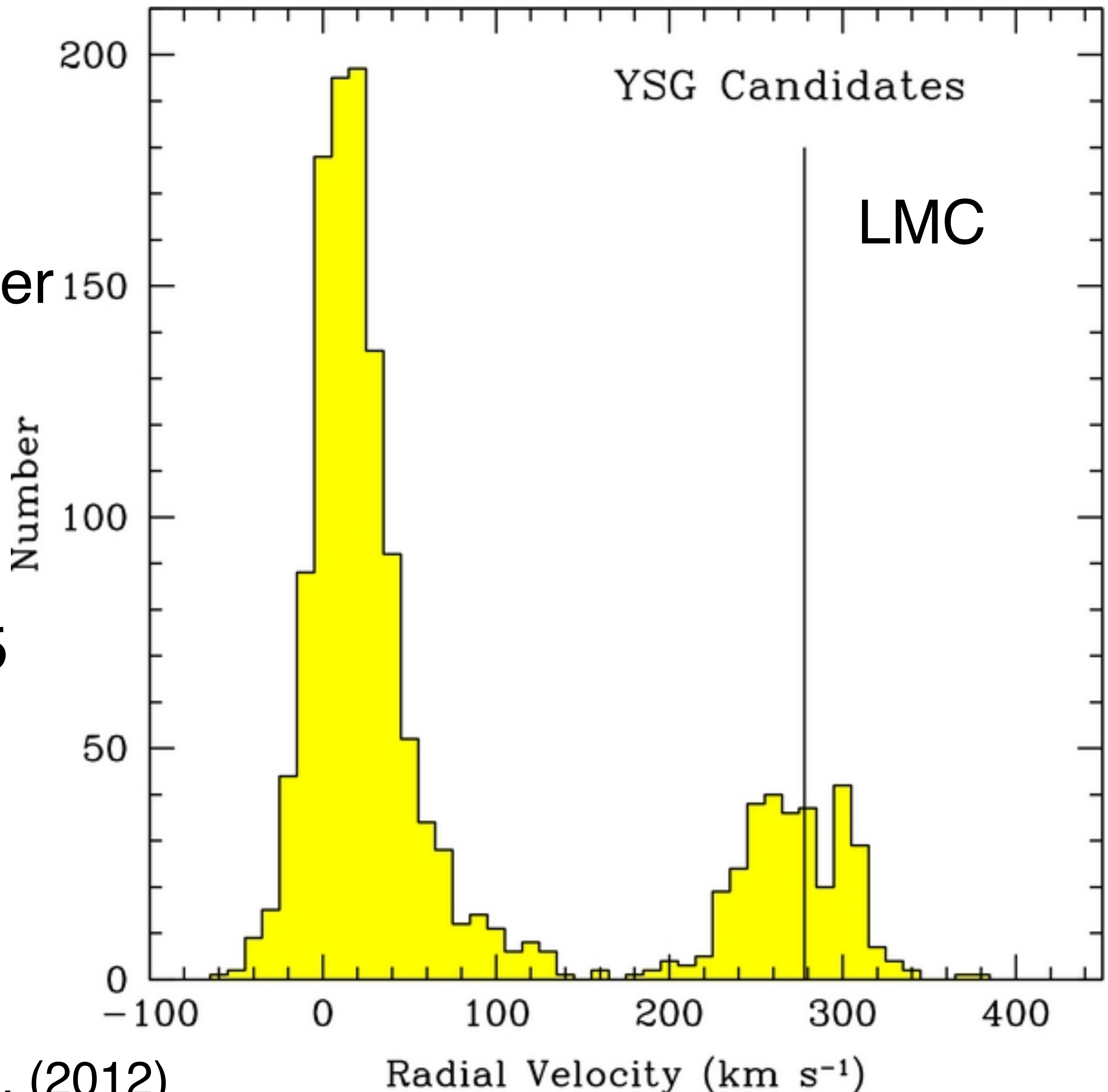
Eliminating foreground stars

- In the olden days (pre-DR2) one needed to take spectra of thousands of stars in each galaxy to obtain radial velocities.
- Practical thanks to multi-object fiber positioners.



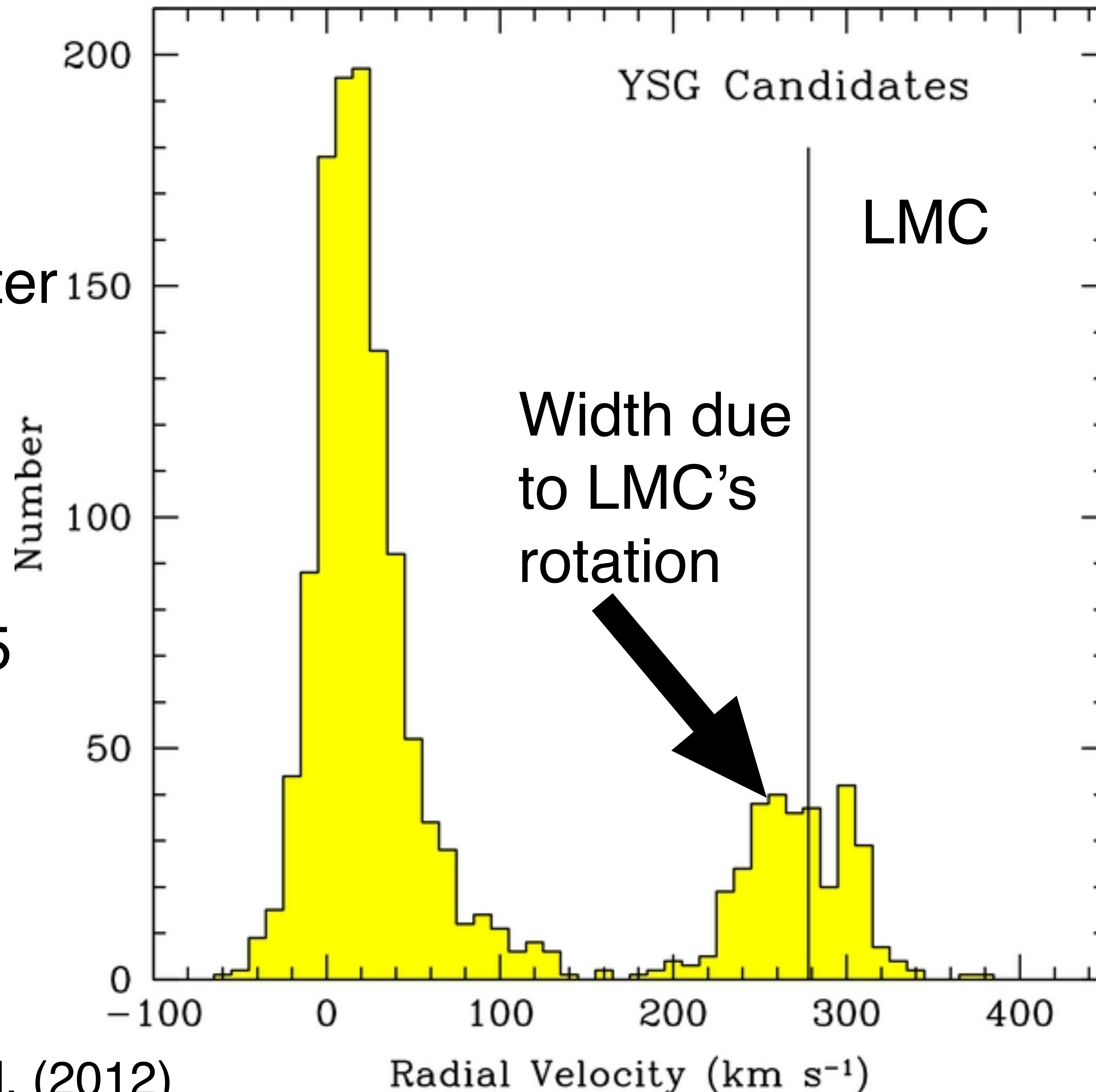
Hydra and CTIO 4-m for Magellanic Clouds

Sample selection after excluding stars with absolute proper motions >15 mas /year.



Neugent et al. (2012)

Sample selection after excluding stars with absolute proper motions >15 mas /year.

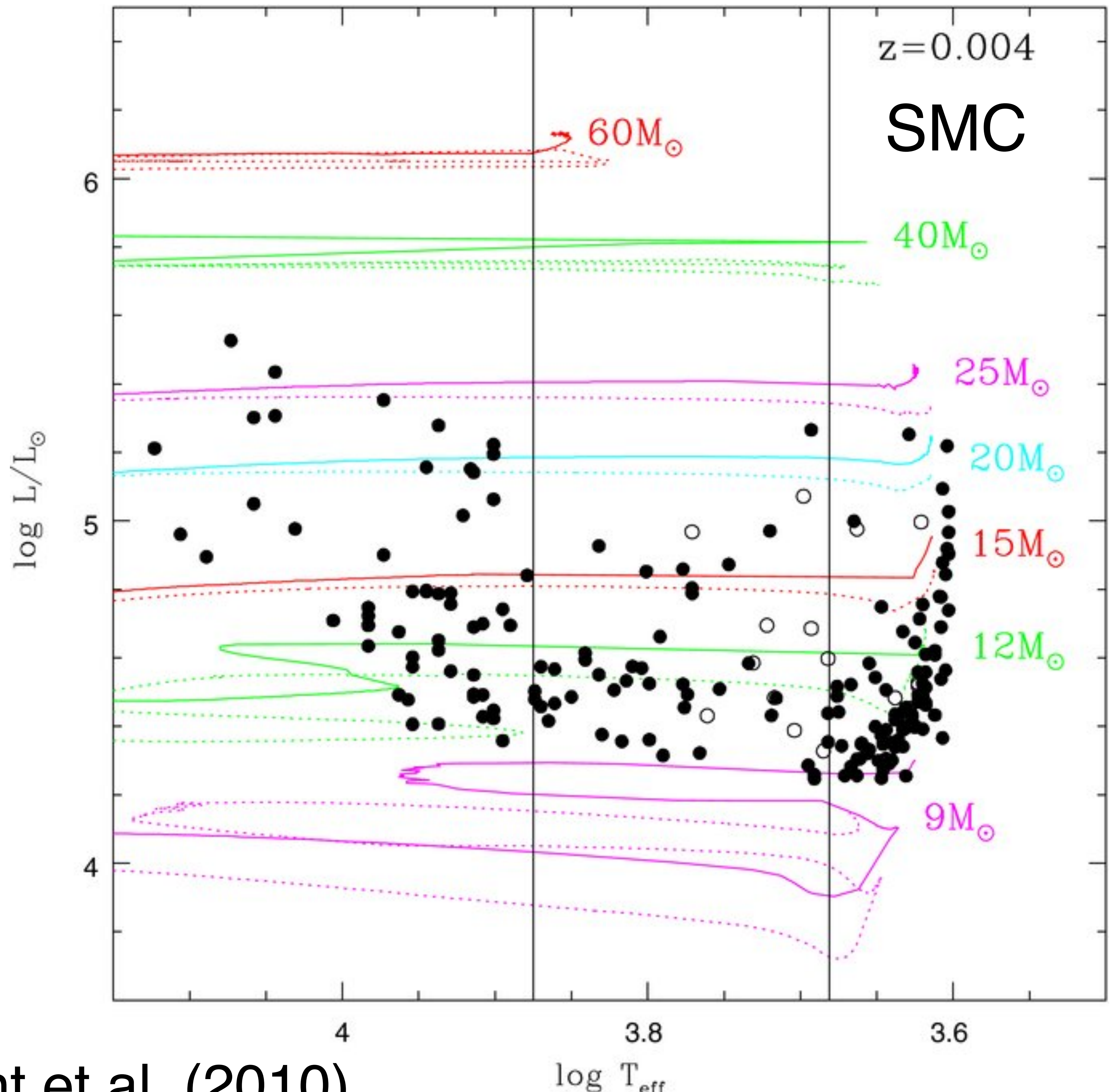


Neugent et al. (2012)

What Did We Learn from This?

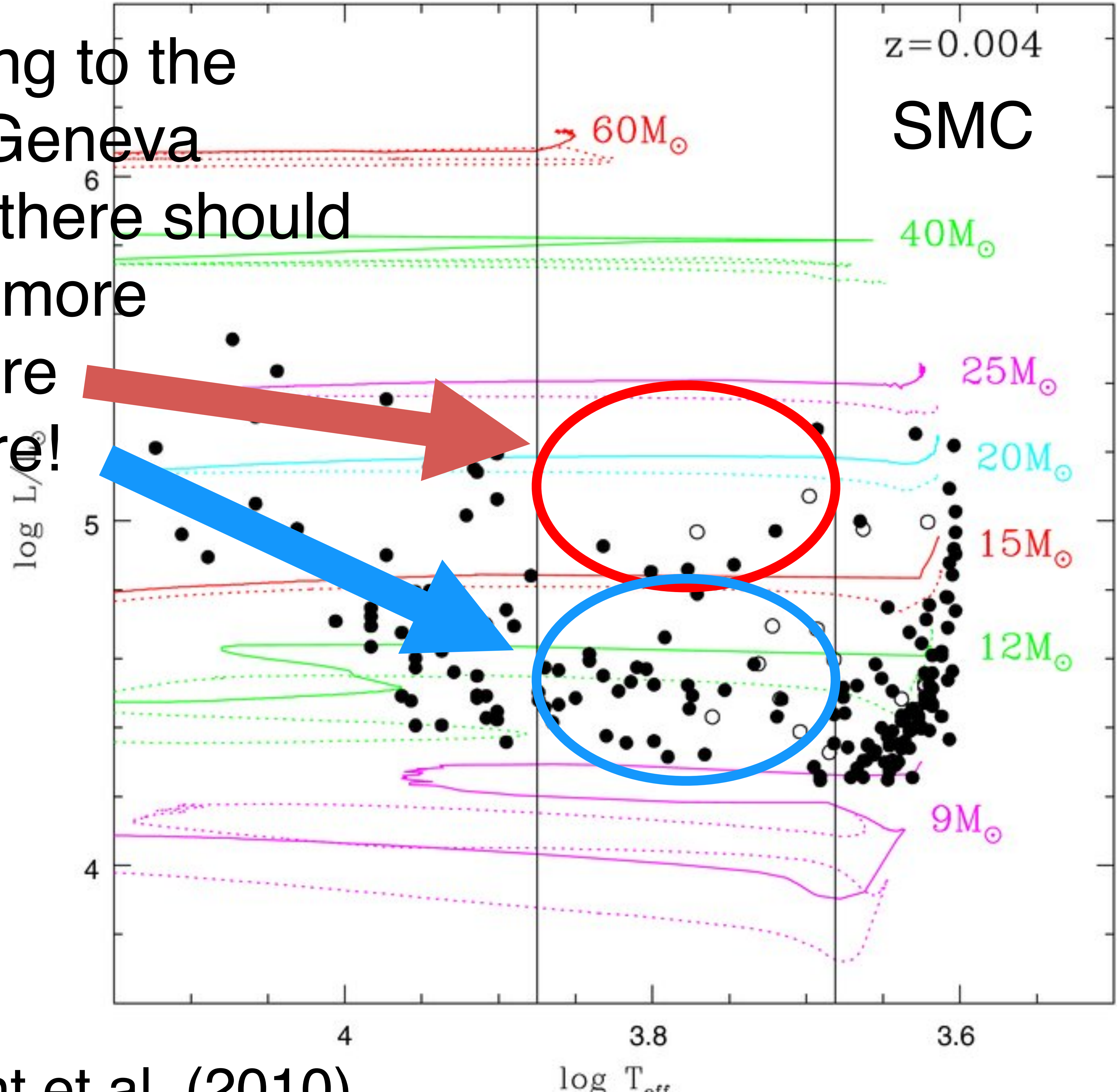
- Drout et al. (2009) had analyzed the YSG content of M31, and found that the older Geneva models failed to predict the relative numbers of YSG as a function of luminosity: the lifetimes of the highest luminosity YSGs were too long.

- Neugent et al. (2010) repeated this test for SMC, to see if the problem was metallicity (mass-loss) related. It wasn't.



Neugent et al. (2010)

According to the (older) Geneva models there should be 1.6x more stars here than here!



Neugent et al. (2010)

What Did We Learn from This?

When we got to the LMC, the Geneva group had made significant improvements to their models!

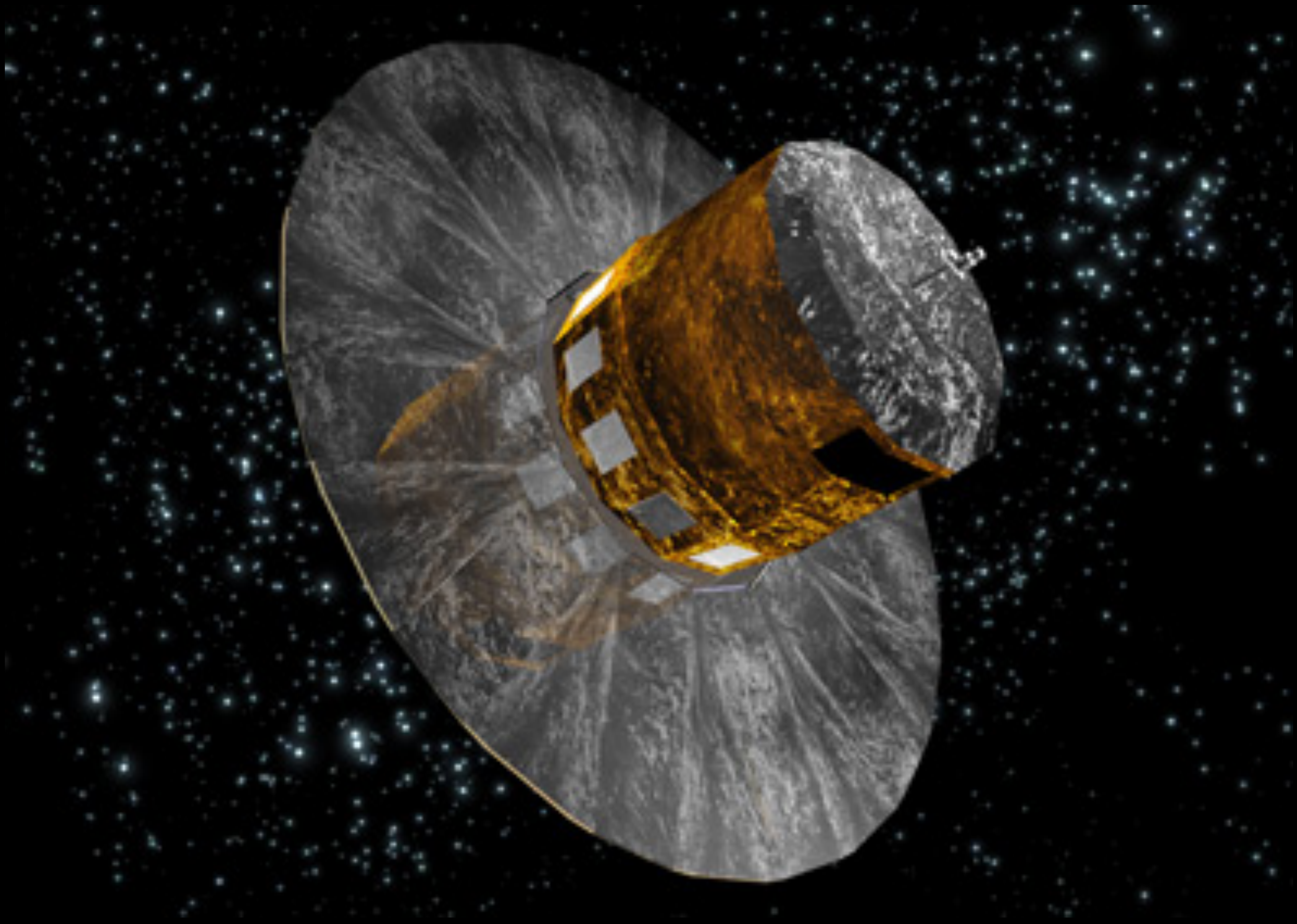
YSGs Relative Lifetimes Weighted by IMF

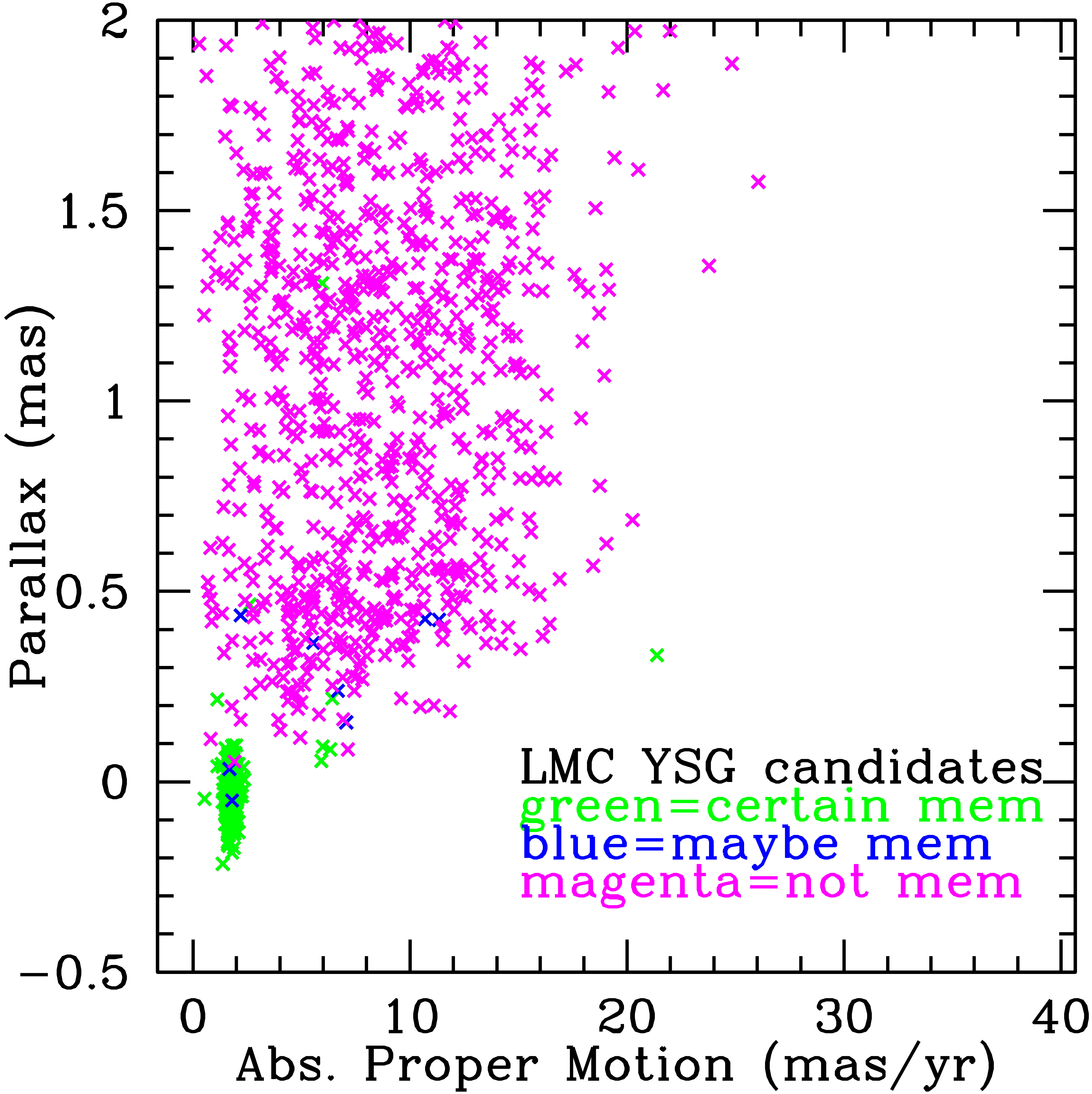
LMC Number of YSGs normalized to 12-15Mo

Masses	Obs	Models
12-15Mo	1	1
15-20Mo	0.54	0.58
20-25M	0.29	0.20
25-40M	0.12	0.15

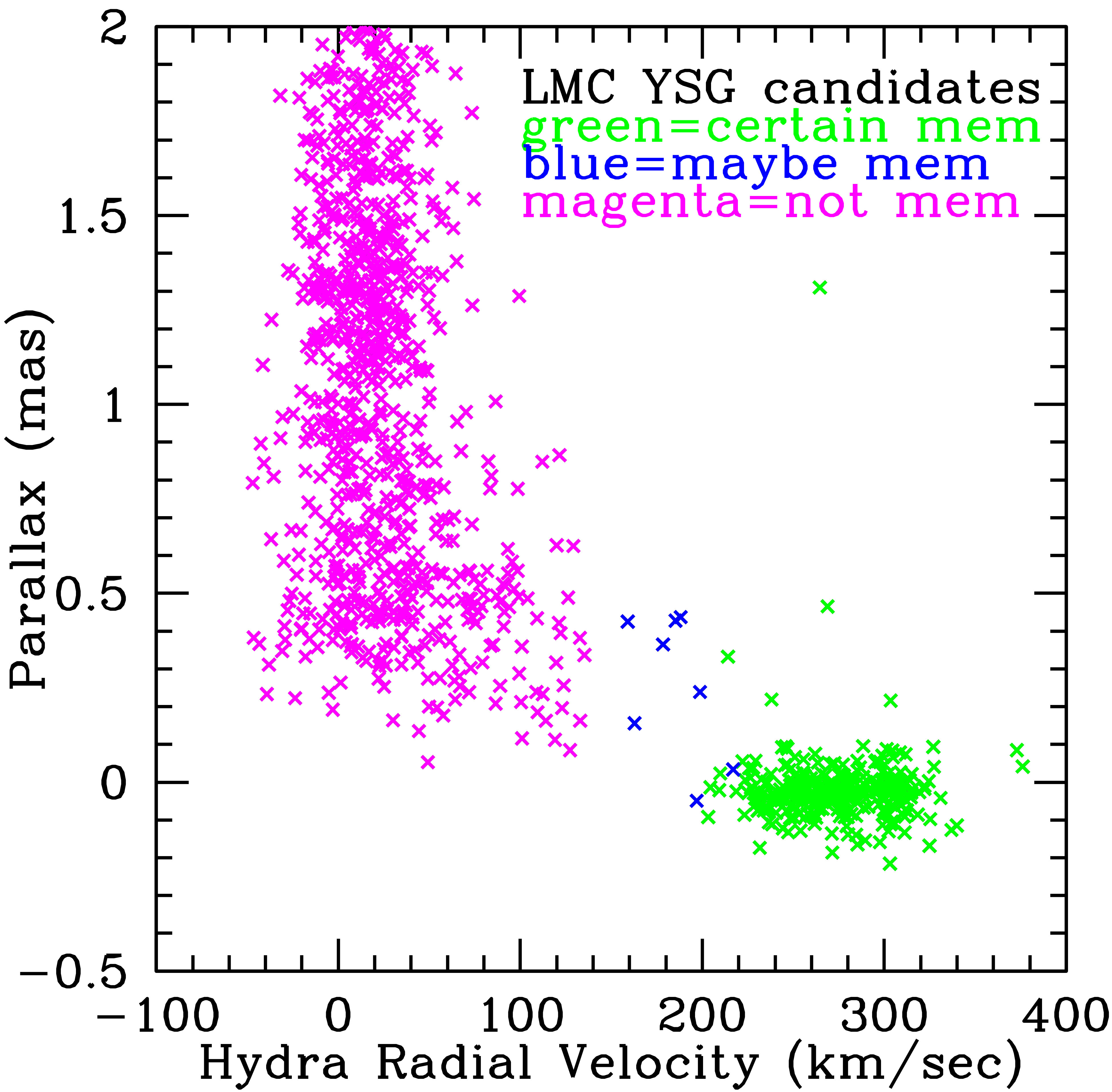
From Neugent et al. (2012)

Does Gaia/DR2 Confirm Our Results?



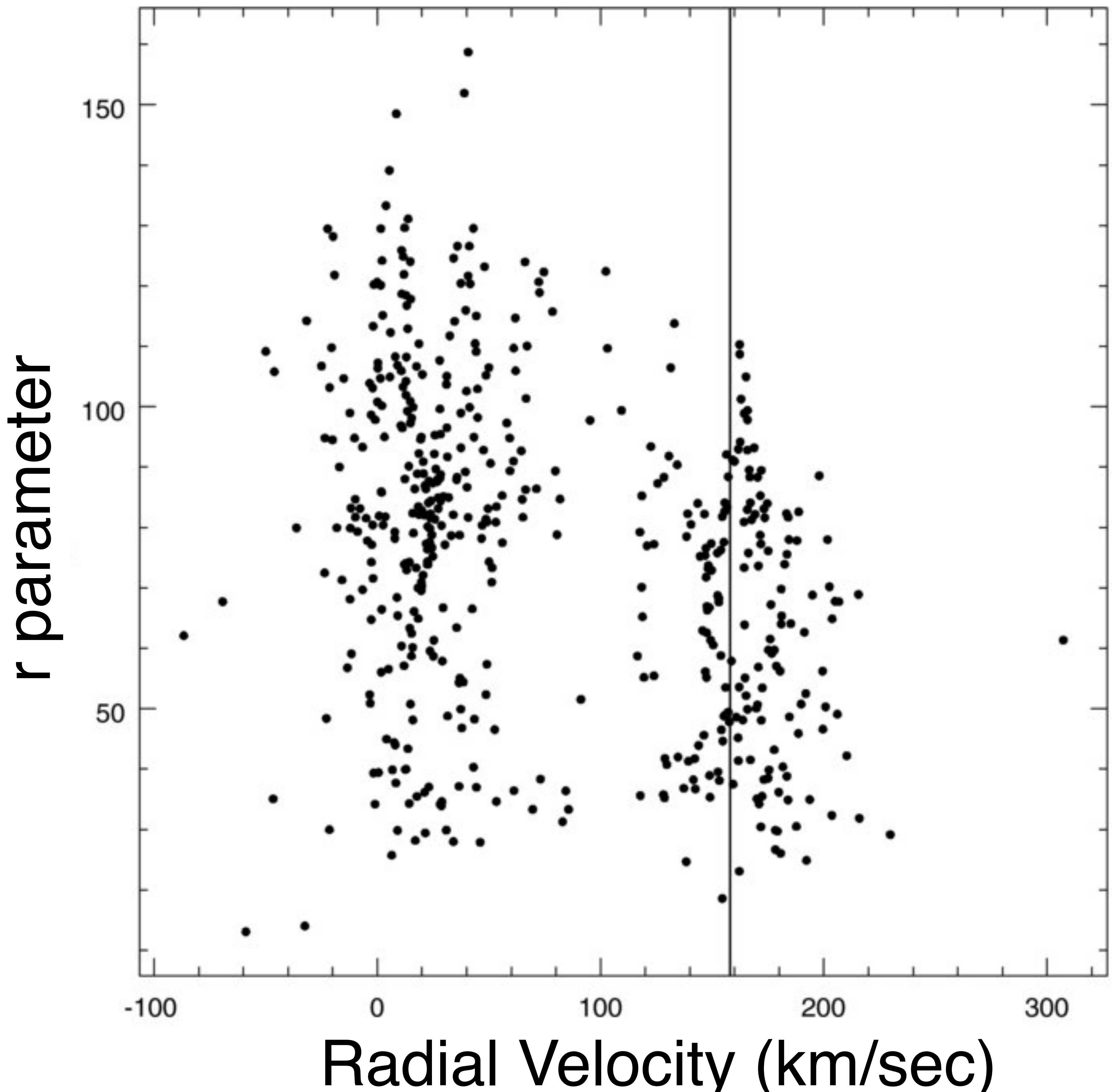


LMC YSG candidates
green=certain mem
blue=maybe mem
magenta=not mem
Parallax (mas)
Abs. Proper Motion (mas/yr)
2
1.5
1
0.5
0
−0.5
0
10
20
30
40

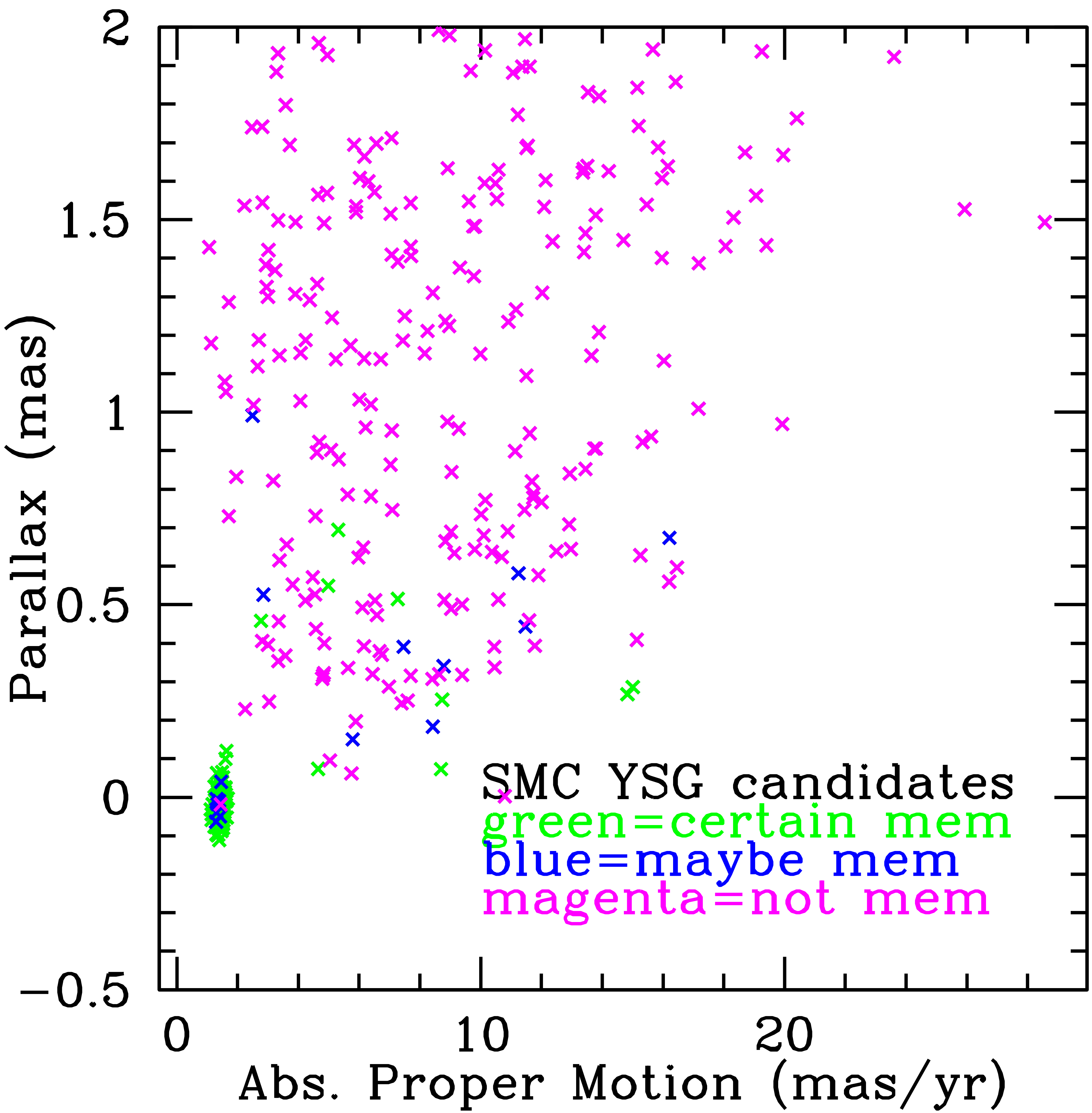

LMC YSG candidates
green=certain mem
blue=maybe mem
magenta=not mem
Parallax (mas)
Hydra Radial Velocity (km/sec)
2
1.5
1
0.5
0
−0.5
−100
0
100
200
300
400

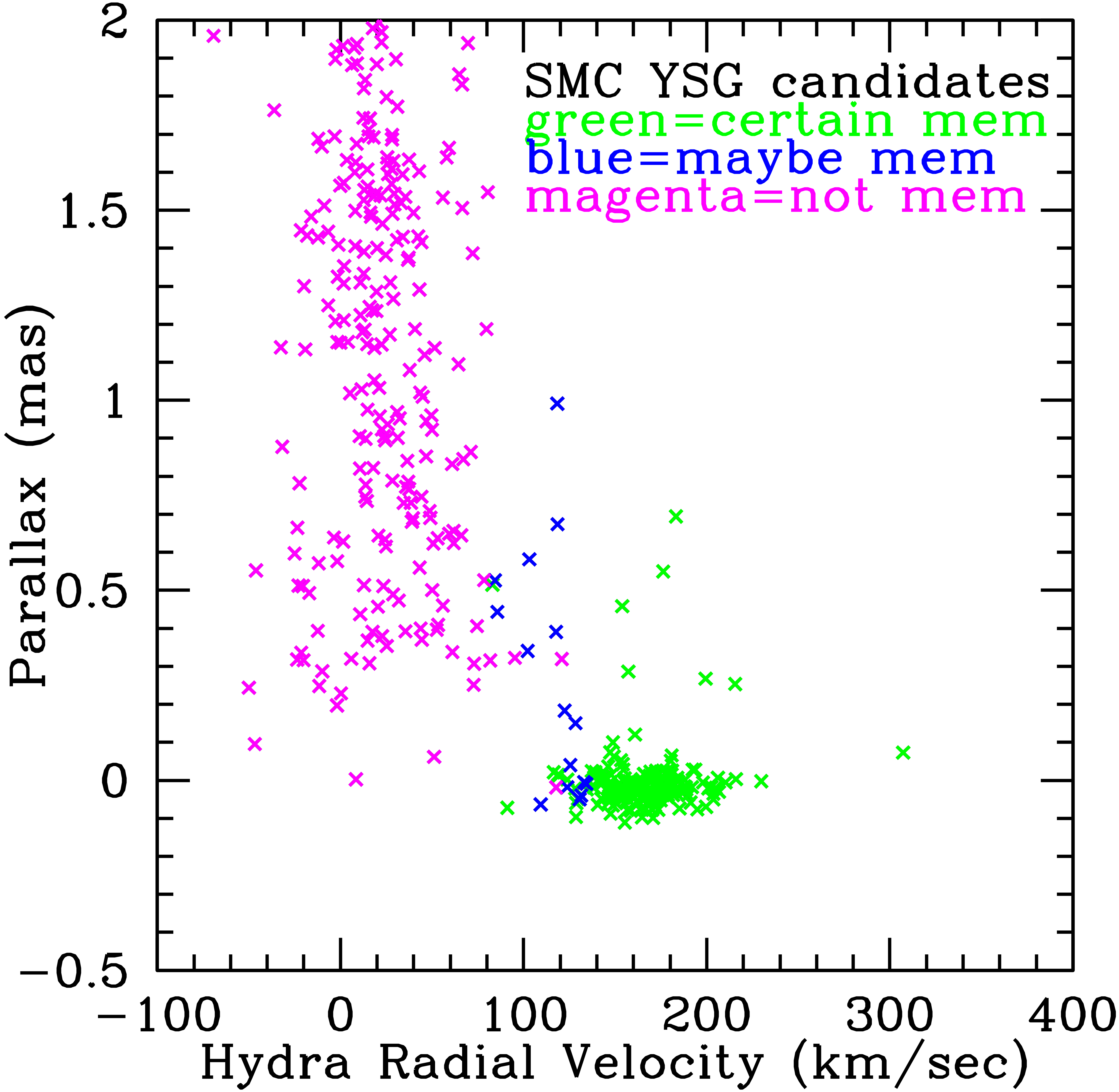
Does Gaia/DR2 Confirm Our Results?

- Absolutely and whole-heartedly YES for the LMC!
- What about the SMC? It’s a bit tougher case…



Neugent et al. (2010)


SMC YSG candidates
green=certain mem
blue=maybe mem
magenta=not mem
Parallax (mas)
Abs. Proper Motion (mas/yr)
2
1.5
1
0.5
0
−0.5
0
10
20



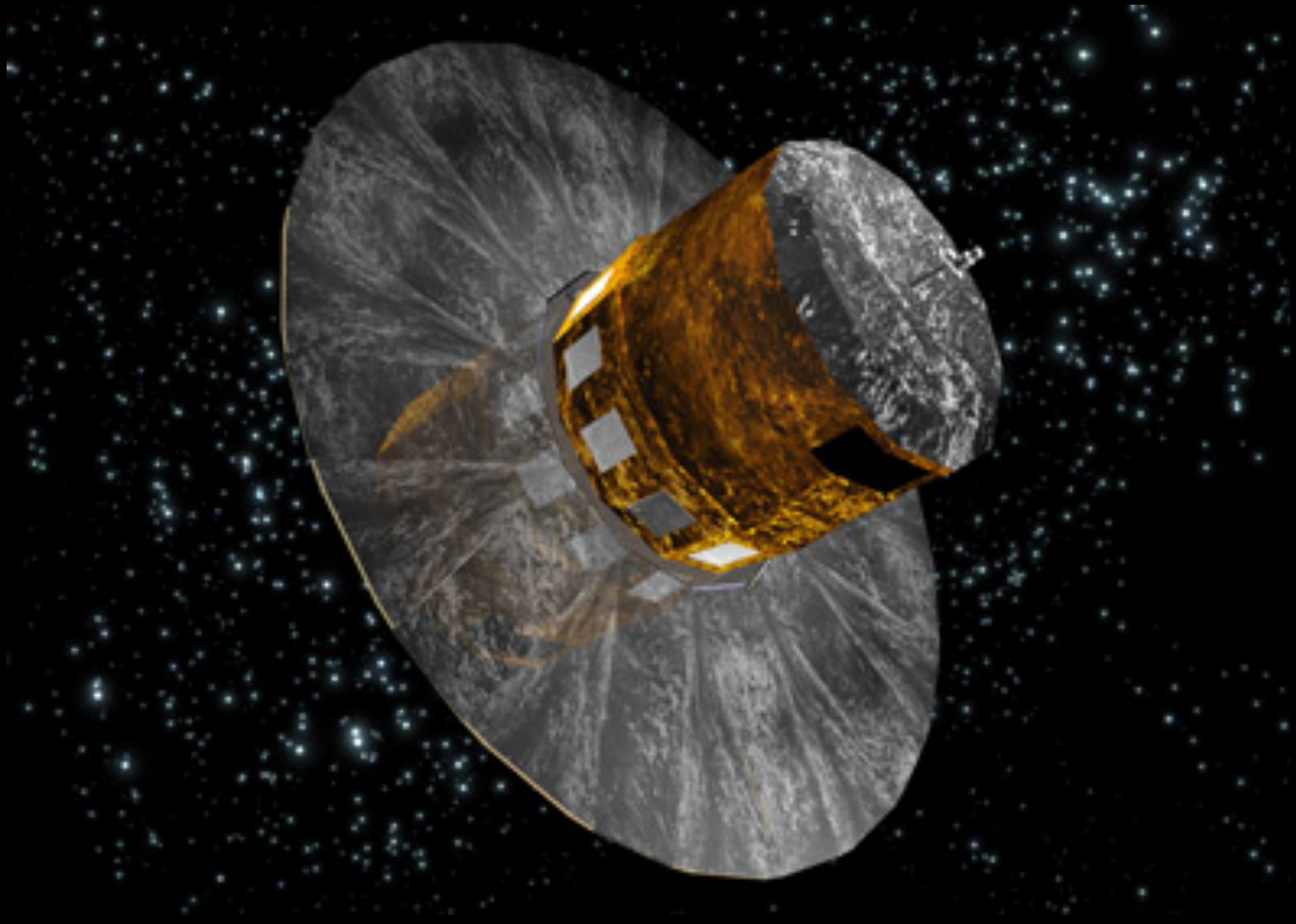
SMC YSG candidates
green=certain mem
blue=maybe mem
magenta=not mem
Parallax (mas)
Hydra Radial Velocity (km/sec)
2
1.5
1
0.5
0
−0.5
−100
0
100
200
300
400

Does Gaia/DR2 Confirm Our Results?

- Absolutely and whole-heartedly YES for the LMC!
- And a resounding YES for the SMC!

Gaia Can help Us In Other Ways!

- What is the total number of YSGs in the SMC and LMC?



Total number of YSGs Vetted through Gaia

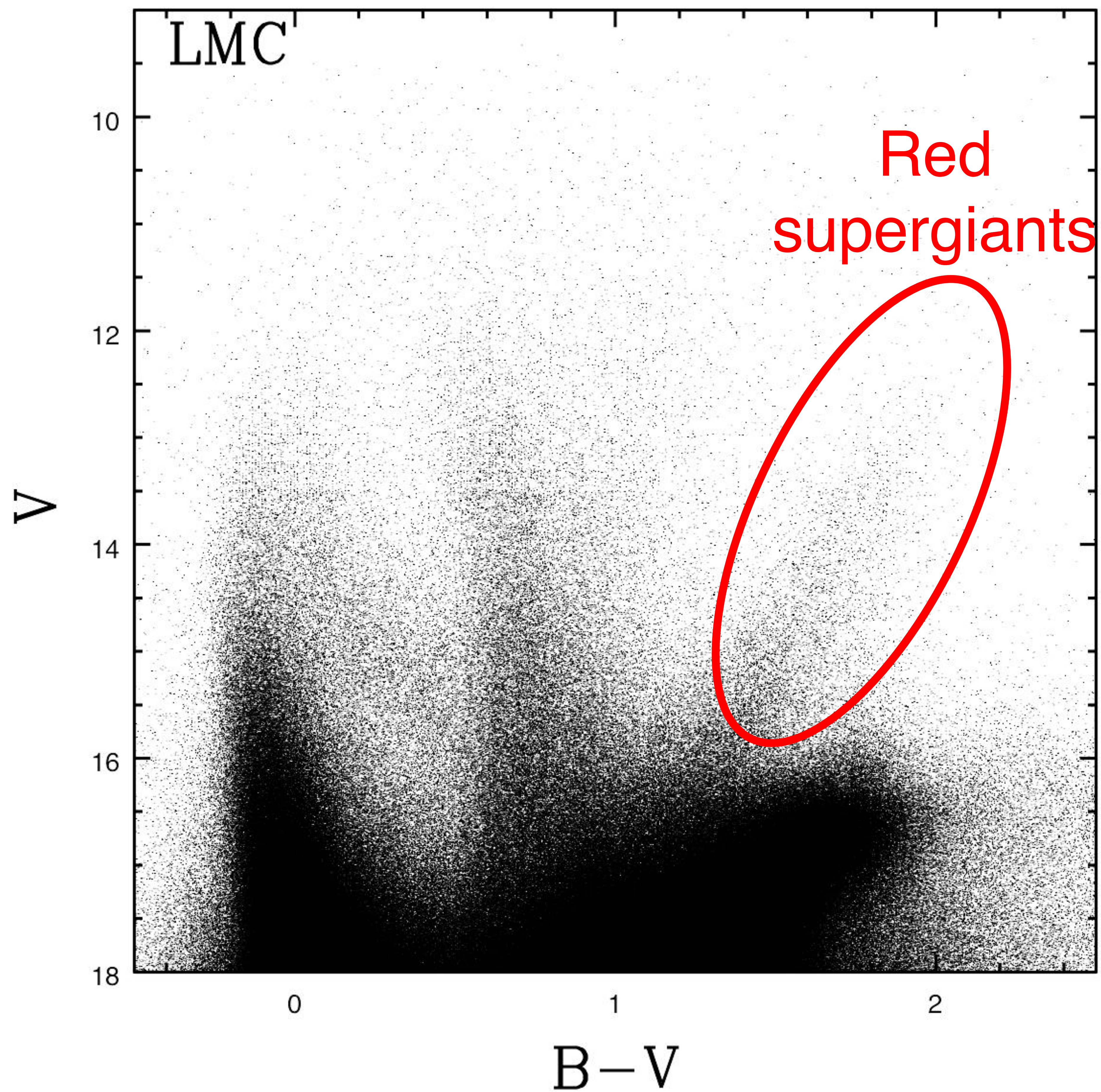
SMC: 182 YSGs out of 3580 candidates (95% contamination)

LMC: 337 YSGs out of 4701 candidates (93% contamination)

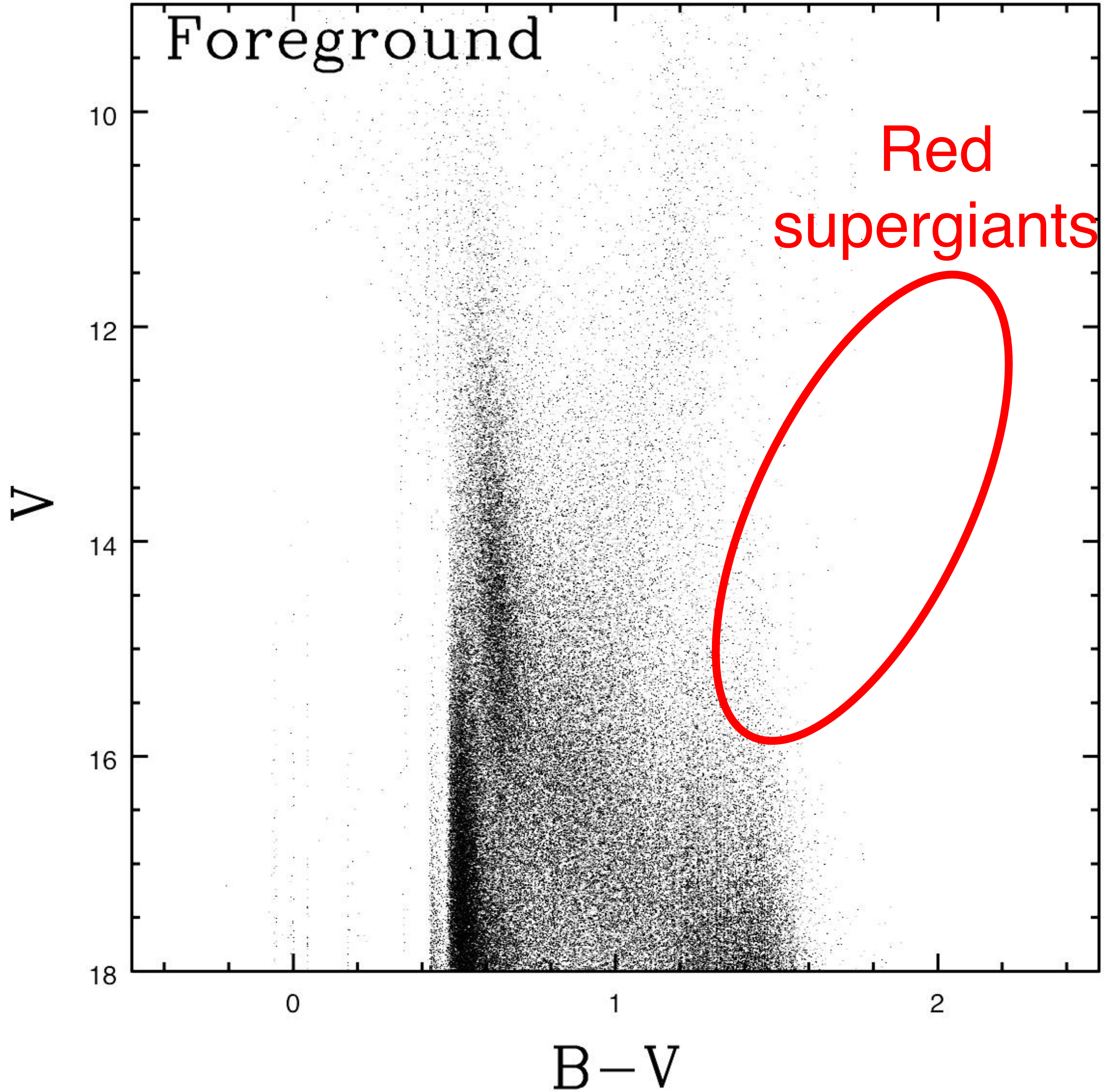
Mass range	SMC	LMC
>9Mo	182	337
>12Mo	43	127
>15Mo	10	46
>20Mo	2	18
>25Mo	0	6

Searching for Red Supergiants

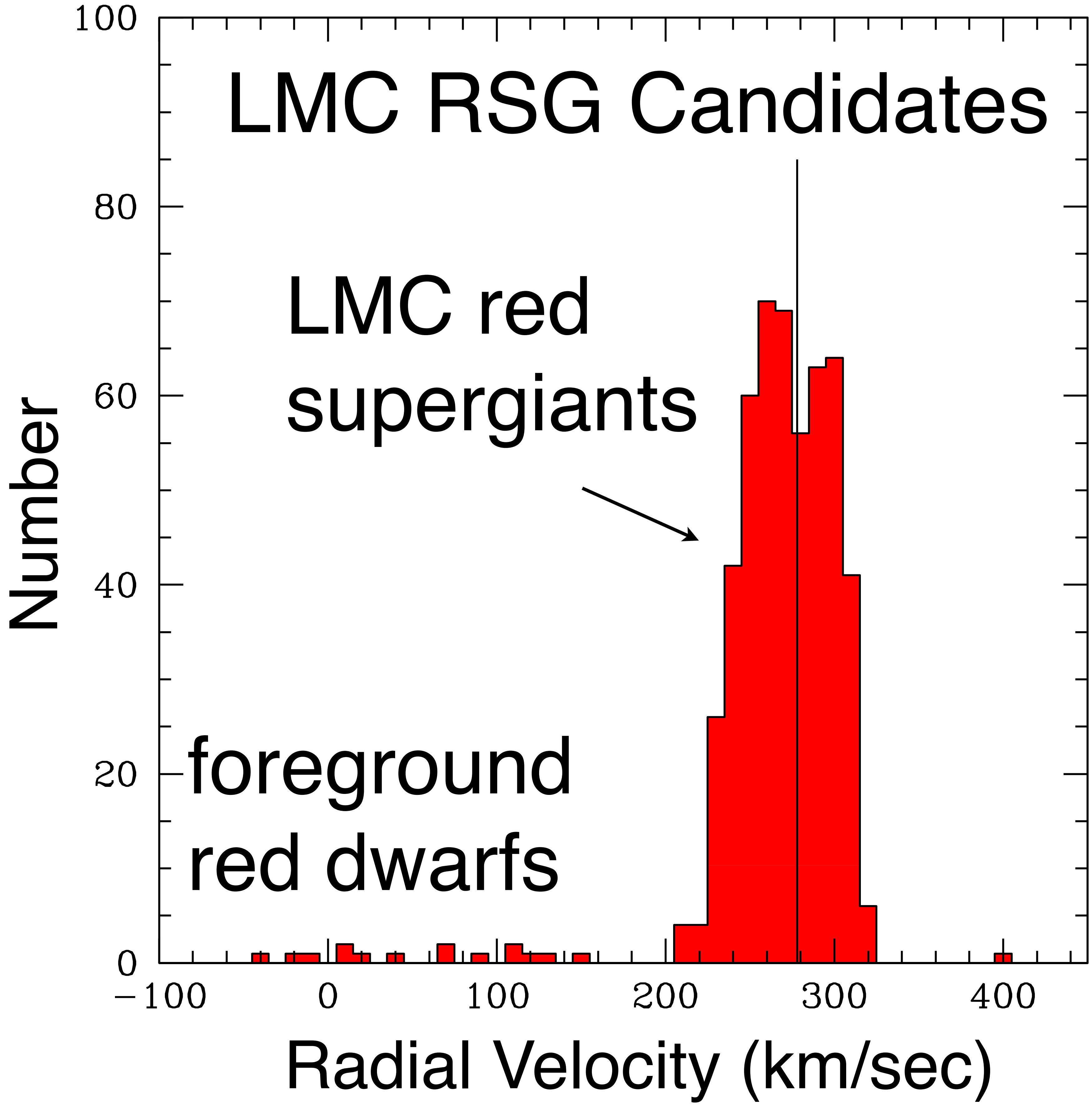
Foreground contamination is a lot smaller



LMC
Red supergiants
V
10
12
14
16
18
0
1
2
B−V



Foreground
Red supergiants
V
10
12
14
16
18
0
1
2
B−V



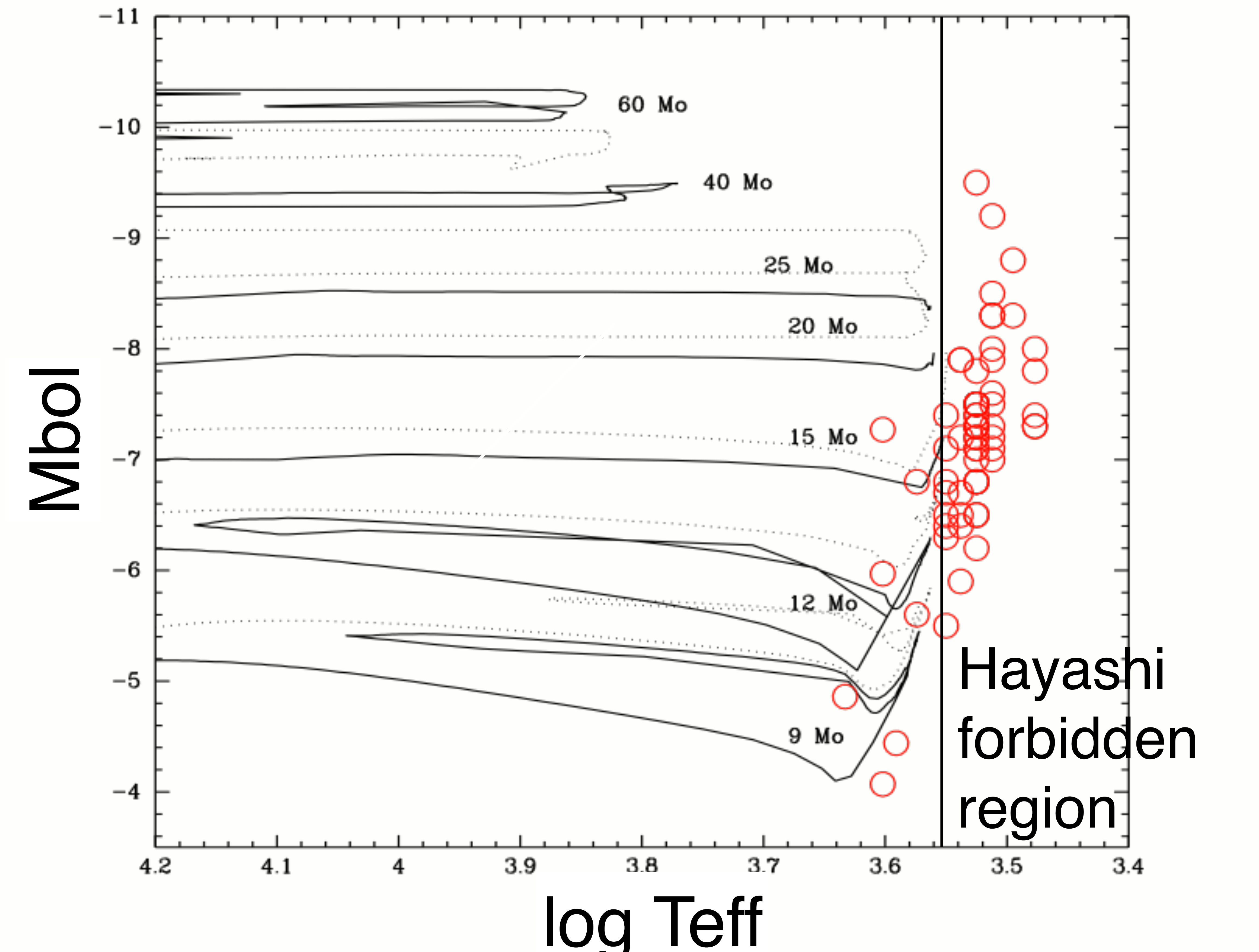
Sample selection after excluding stars with absolute proper motions >15 mas /year.

Neugent et al. 2012, ApJ, 749, 177

Motivation is two-fold

(1) To characterize the physical properties of RSGs.

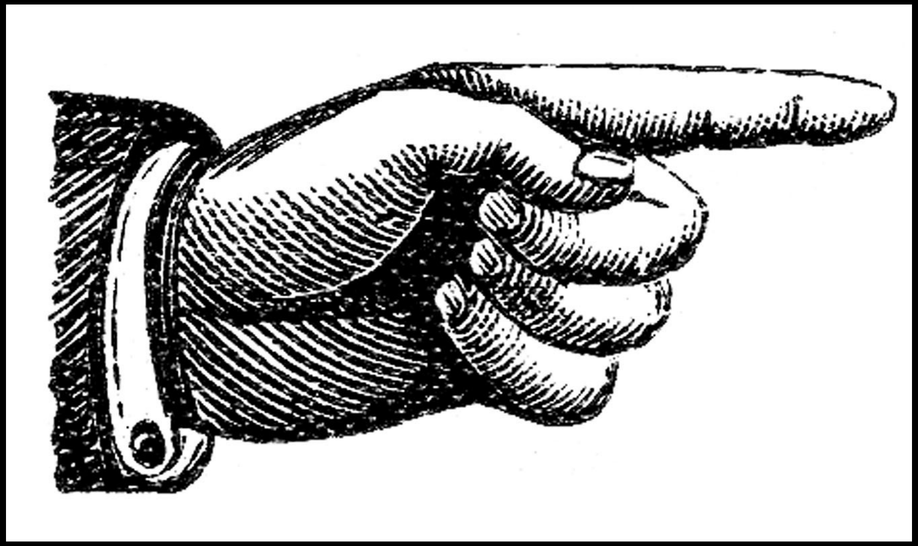
(2) To compare their numbers with those of other massive stars.



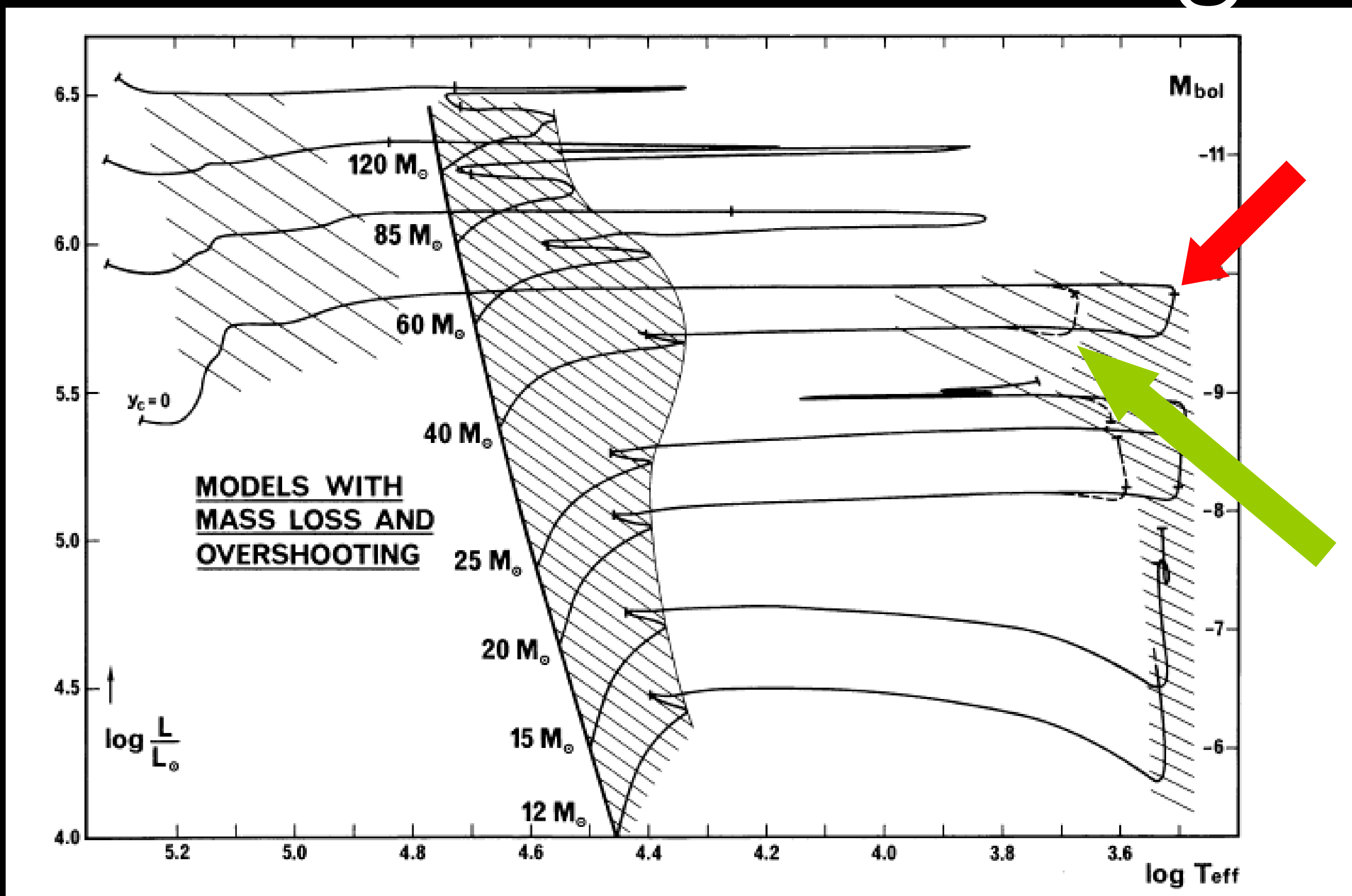
Mbol
log Teff
60 Mo
40 Mo
25 Mo
20 Mo
15 Mo
12 Mo
9 Mo
Hayashi
forbidden
region
-11
-10
-9
-8
-7
-6
-5
-4
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4

Usually when theory and observation disagree, we point our finger at the theorists....

Usually when theory and observation disagree, we point our finger at the theorists....



Tracks *are* sensitive to treatment of convection and mixing



Conventional mixing length proportional to pressure scale height

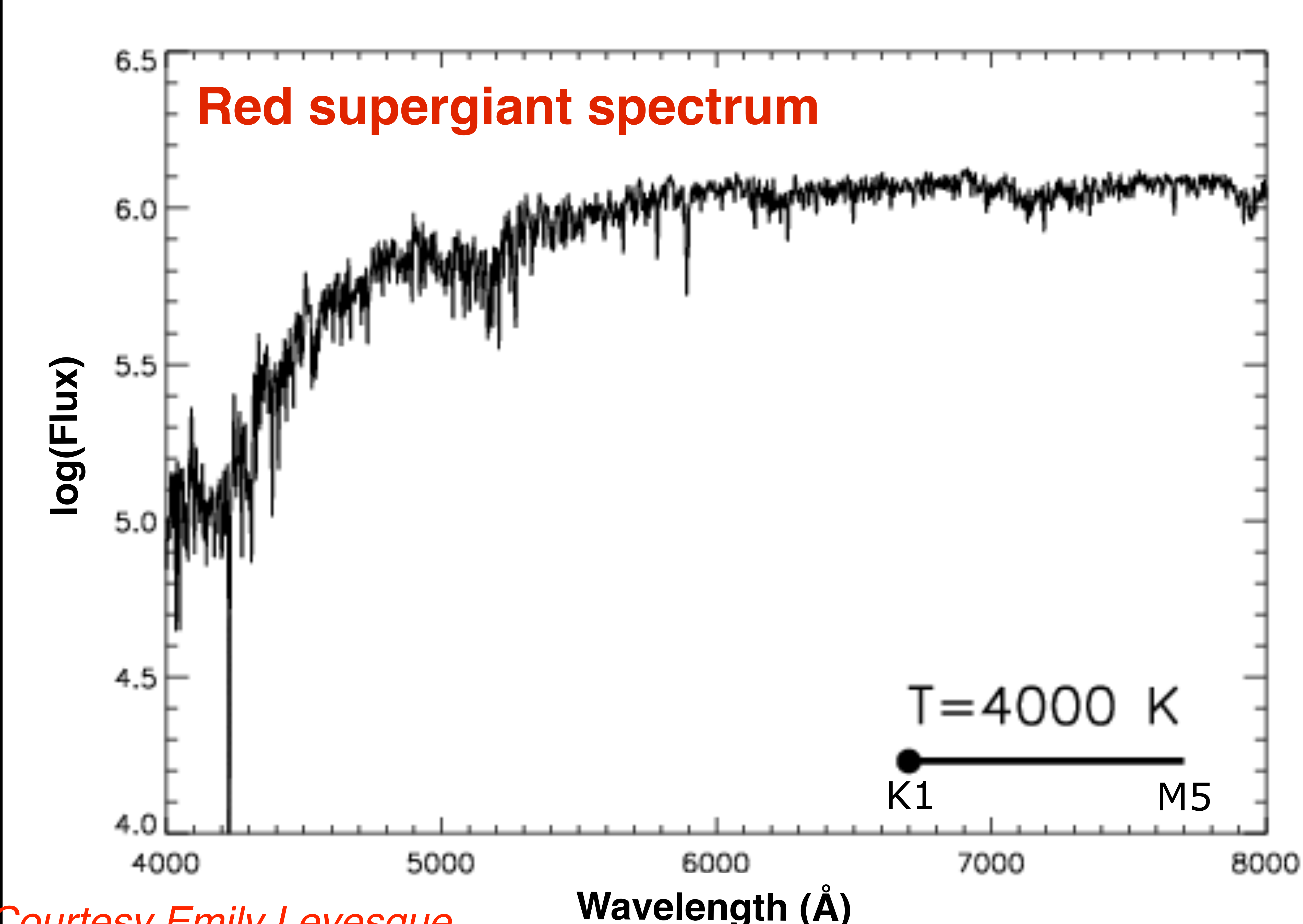
Mixing length proportional to density scale height.

From Maeder & Meynet 1987 A&A 182, 243

But what if "observations" were wrong???

We don't "observe" temperatures and luminosities; instead, we obtain photometry and spectral types and convert these to effective temperatures and bolometric luminosities.

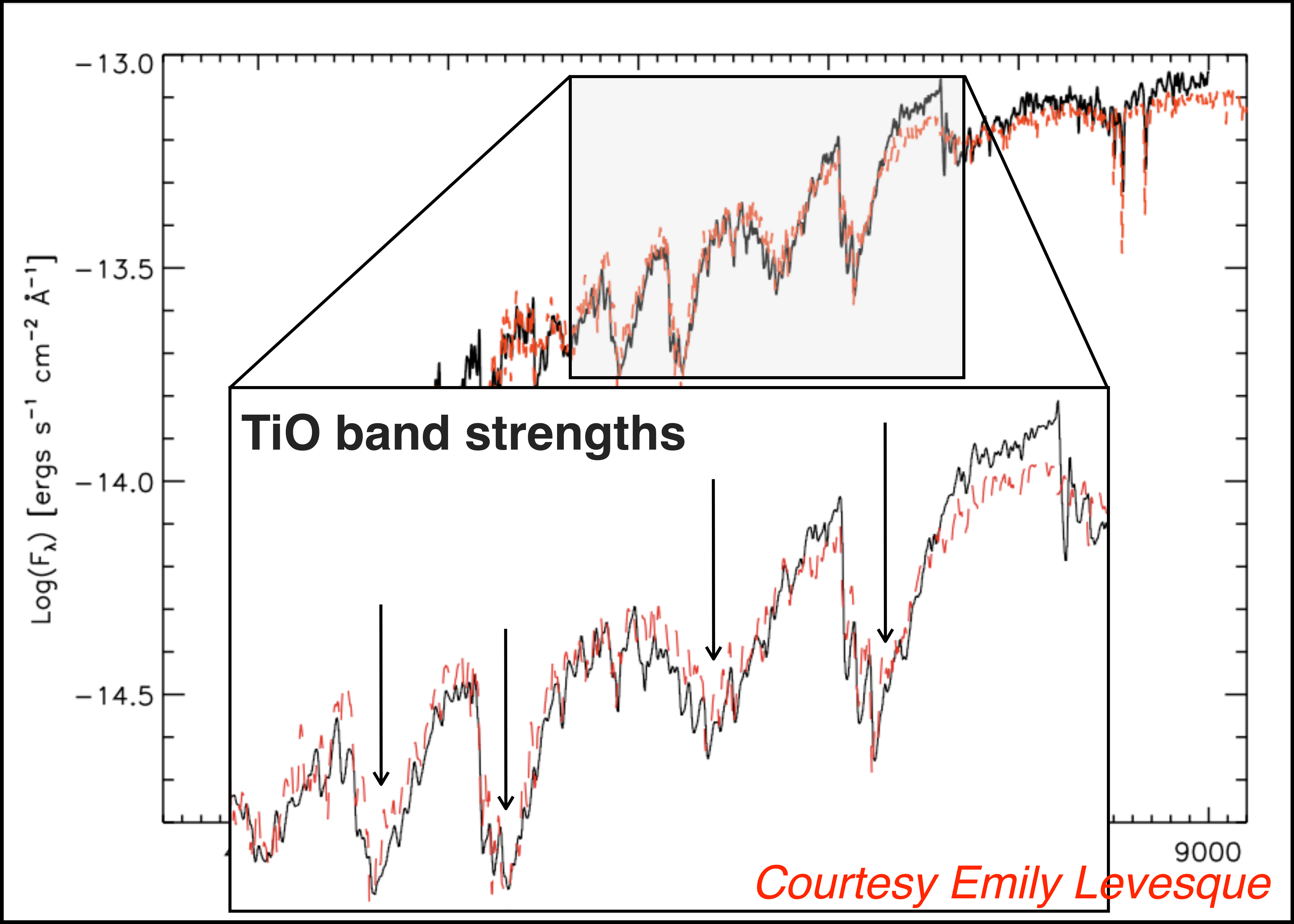
RSG spectra very sensitive to temperature



Courtesy Emily Levesque

New Observations of RSGs

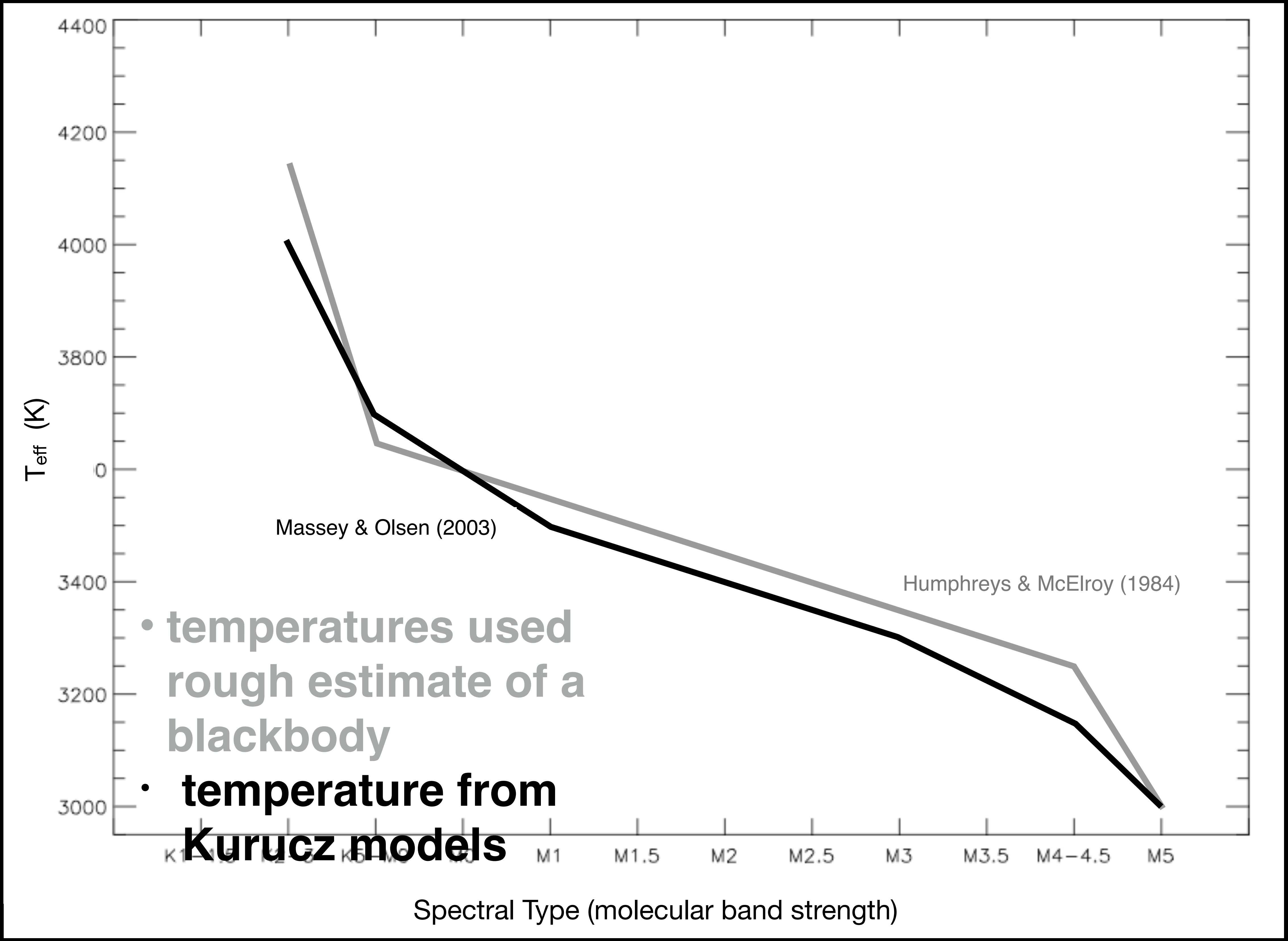
Fitting the spectra



Courtesy Emily Levesque

MIT undergrad Emily Levesque at the controls...

Effective Temperature Scale of RSGs

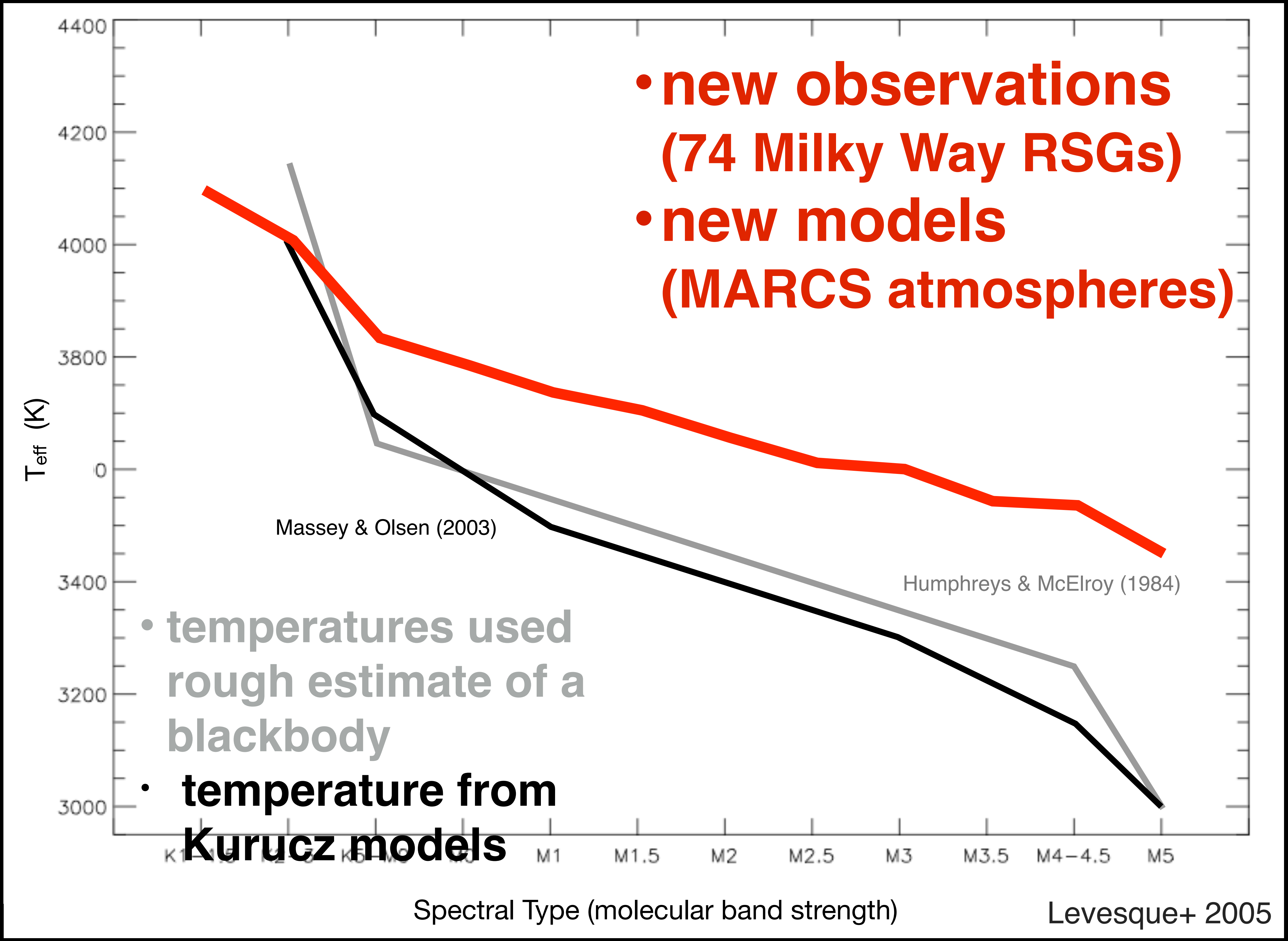


- temperatures used rough estimate of a blackbody
- **temperature from Kurucz models**

Levesque et al (2005, ApJ, 628, 973)

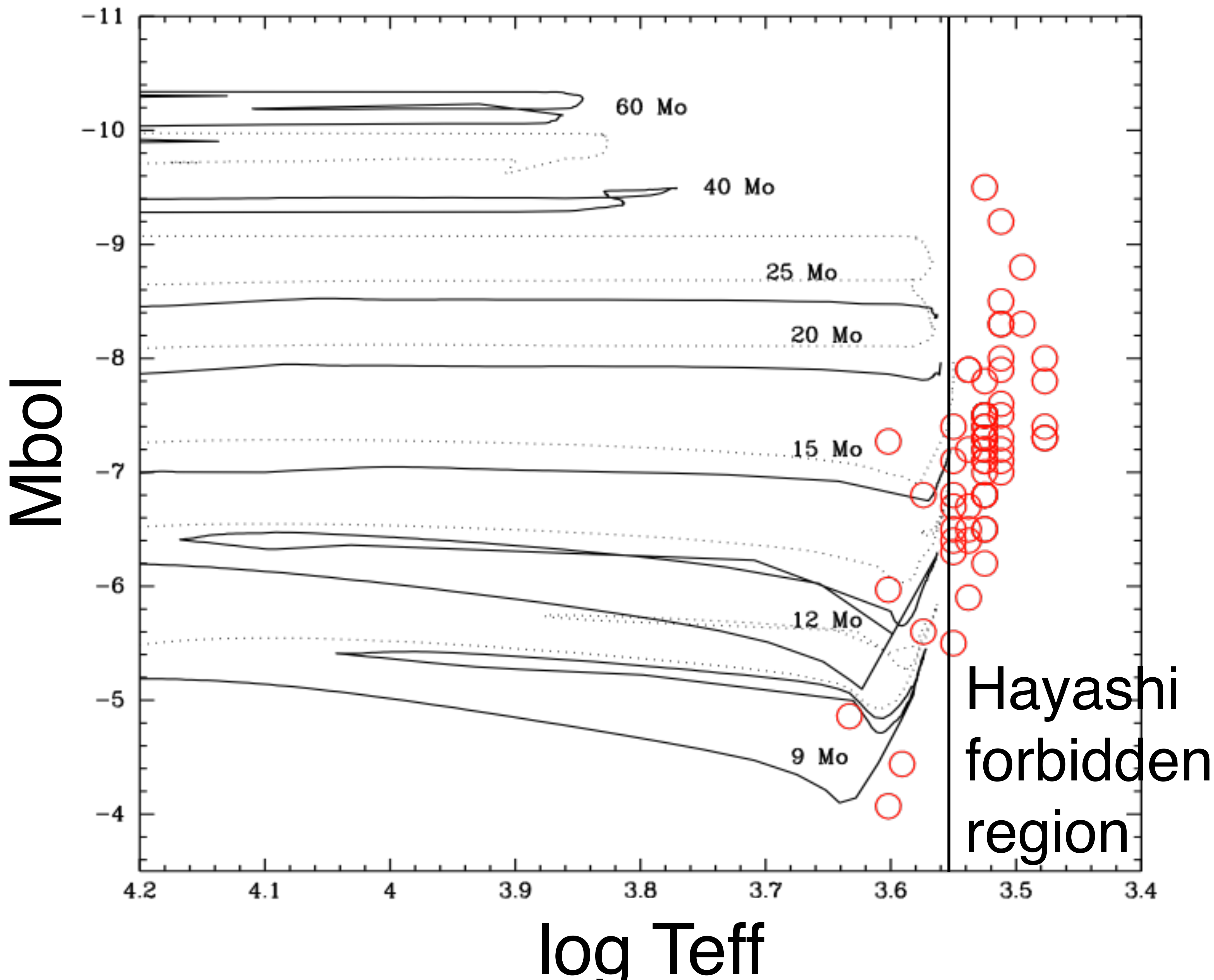
Courtesy Emily Levesque

Effective Temperature Scale of RSGs



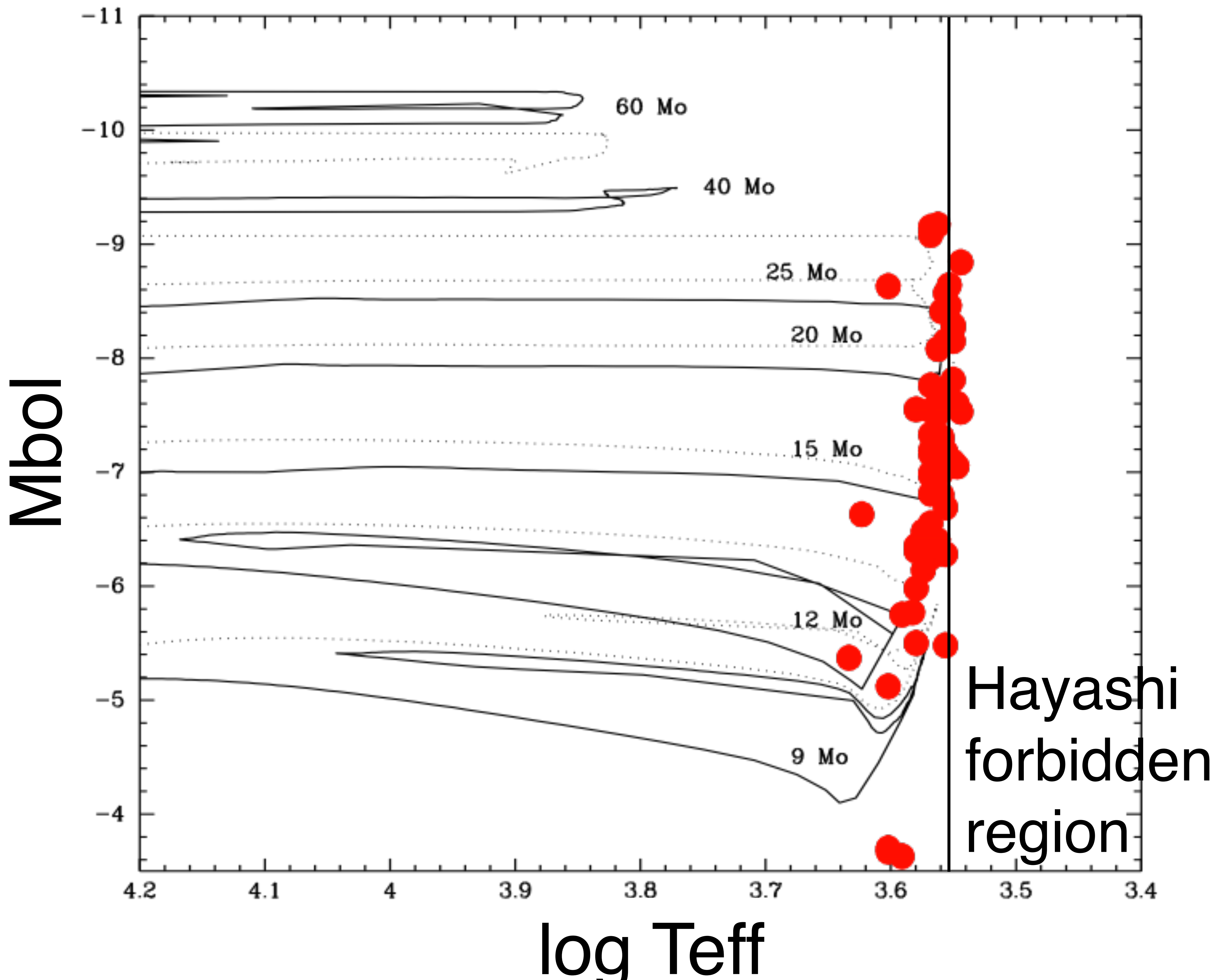
Levesque et al (2005, ApJ, 628, 973) *Courtesy Emily Levesque*

OLD



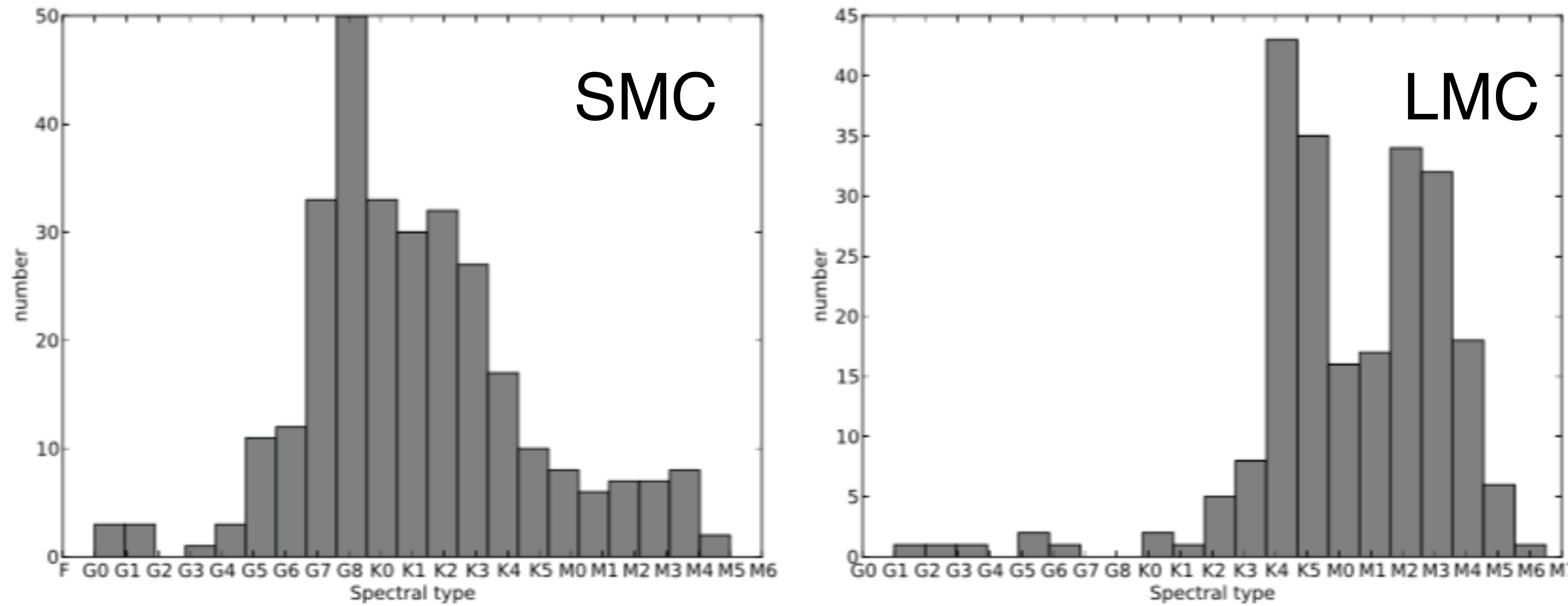
60 Mo
40 Mo
25 Mo
20 Mo
15 Mo
12 Mo
9 Mo
Hayashi forbidden region
Mbol
log Teff
−11
−10
−9
−8
−7
−6
−5
−4
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4

NEW



60 Mo
40 Mo
25 Mo
20 Mo
15 Mo
12 Mo
9 Mo
Hayashi forbidden region
Mbol
log Teff
−11
−10
−9
−8
−7
−6
−5
−4
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4

Average spectral type depends upon metallicity



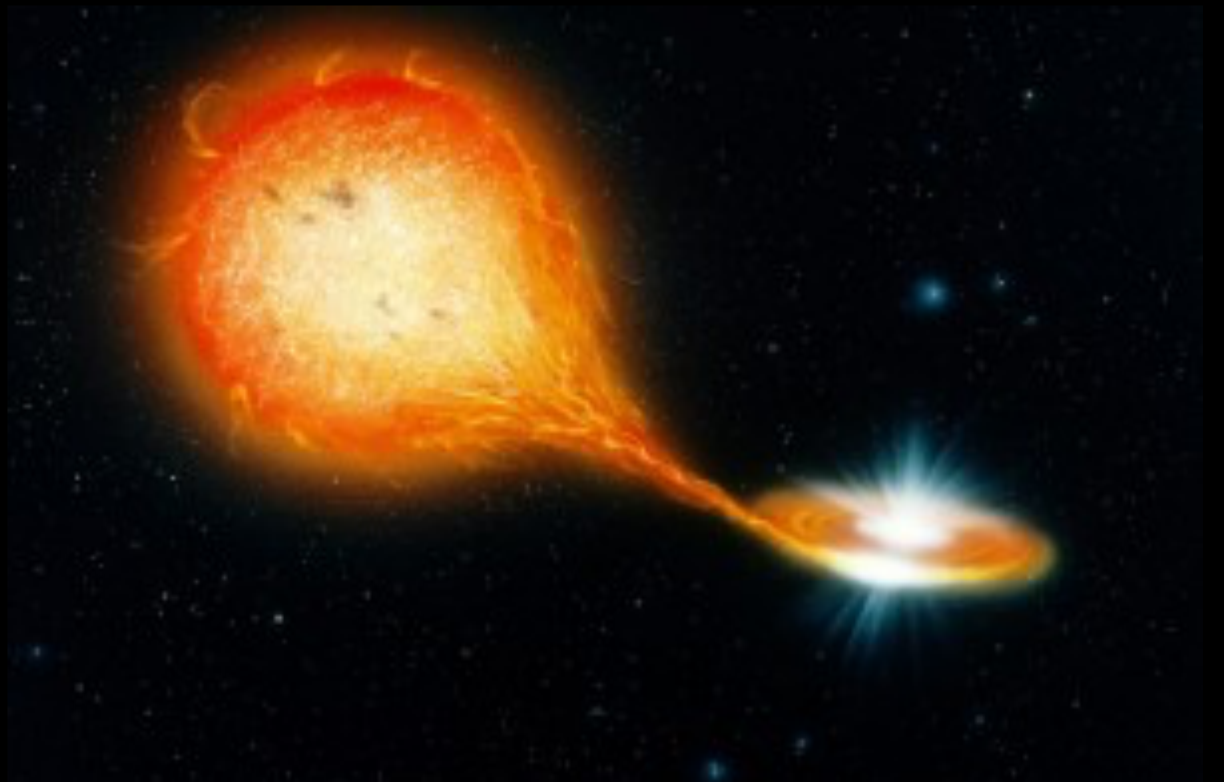
Spectral types shift towards earlier types at lower metallcity, same as expected from Hayashi limit

From Dorda et al. (2016) A&A, 592, A16.

Other Cool Things We've Found

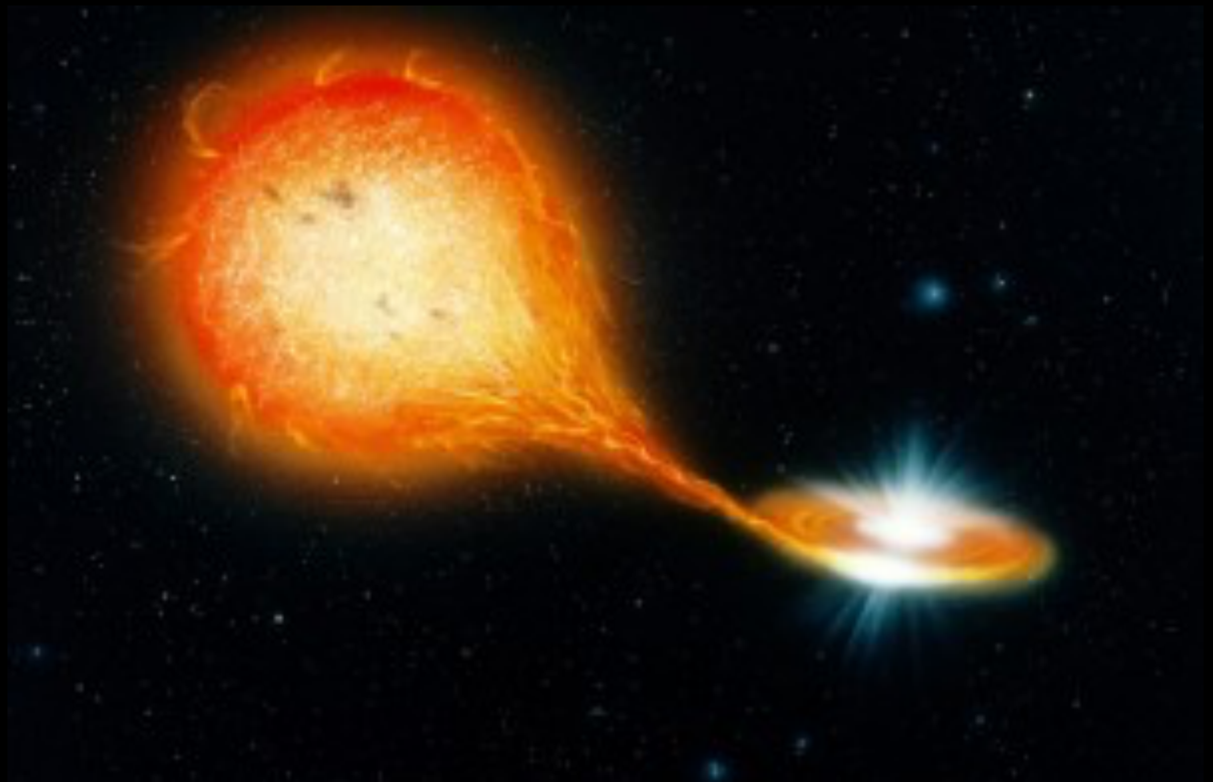
TZO Candidate

This led to Levesque et al's (2014) identification of HV 2112 (in the SMC) as a likely Thorne-Zytkow object, the result of a RSG merger with a neutron star.



TZO Candidate

"I don't know what it is, but I know I like it!" —Nidia at Magellan upon doing the quick-look reduction of the spectrum at Magellan

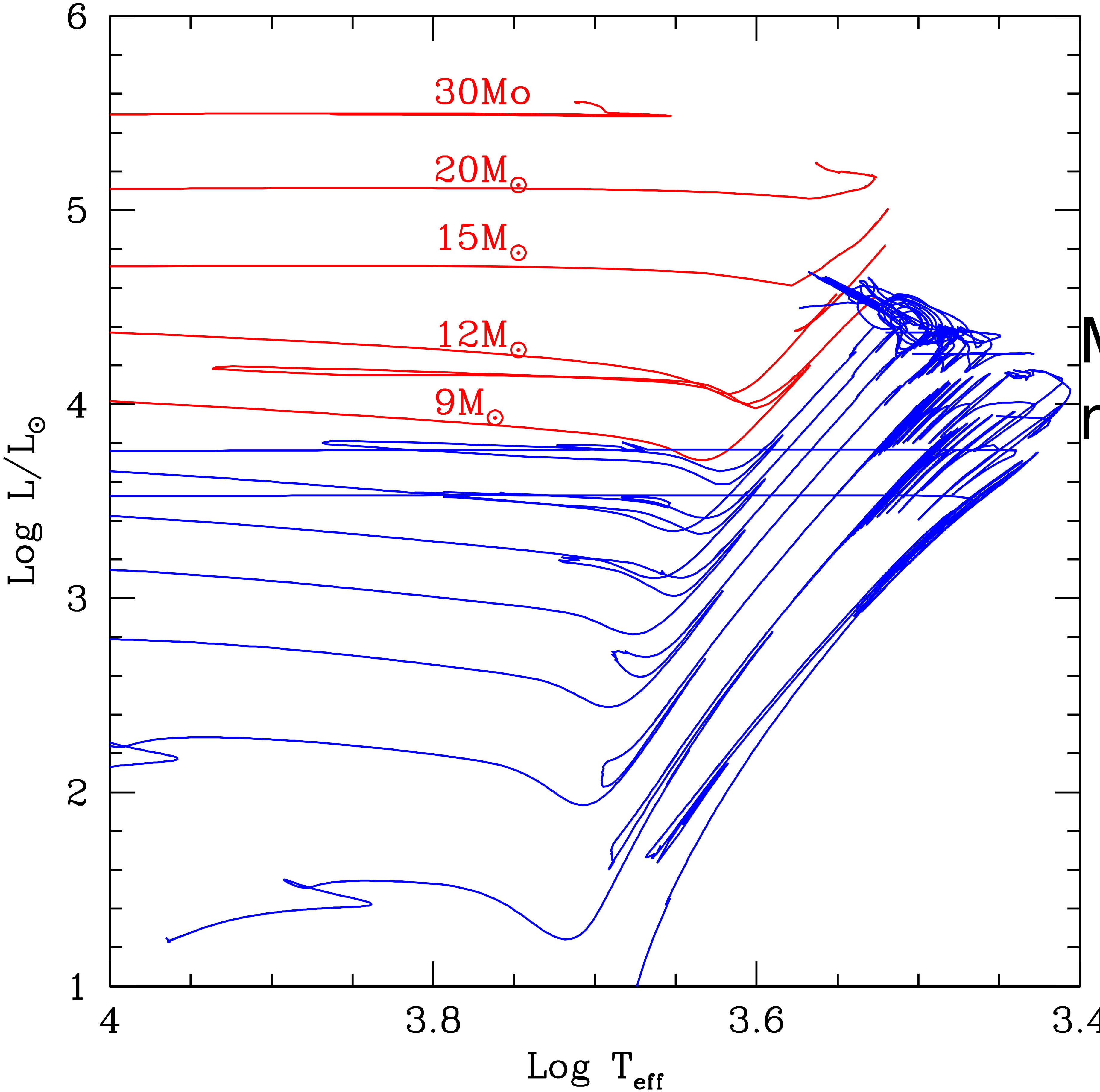


Total Number of RSGs

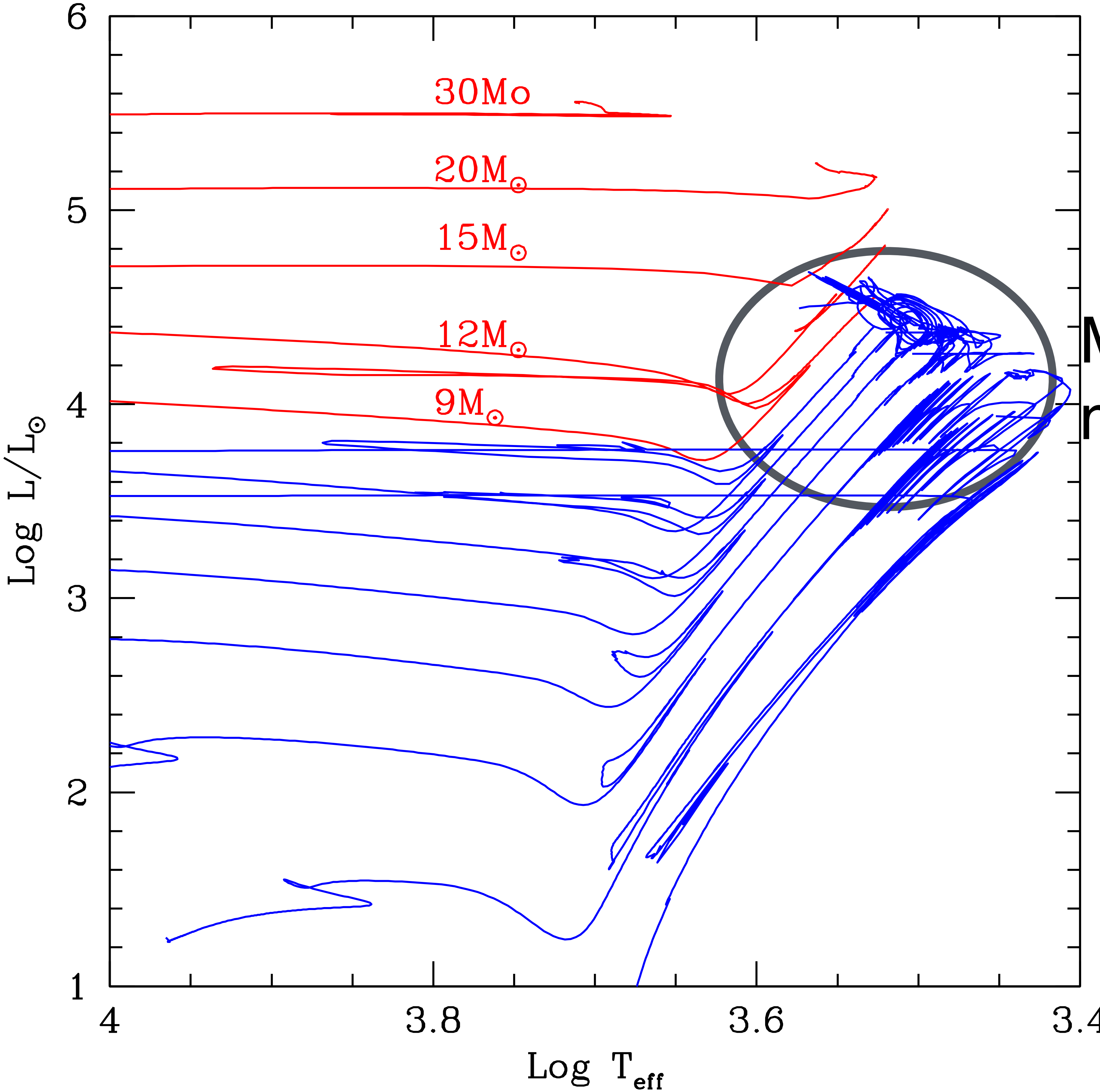
- Although foreground contamination is not a huge issue, there is another type of contamination which is: AGBs!
- (And potentially “super-AGB stars”—see Carolyn Doherty’s talk.)

Total Number of RSGs

- AGBs are the late-stage evolutionary phase of solar-mass stars.
- How bad is it?



MIST/MESA
models



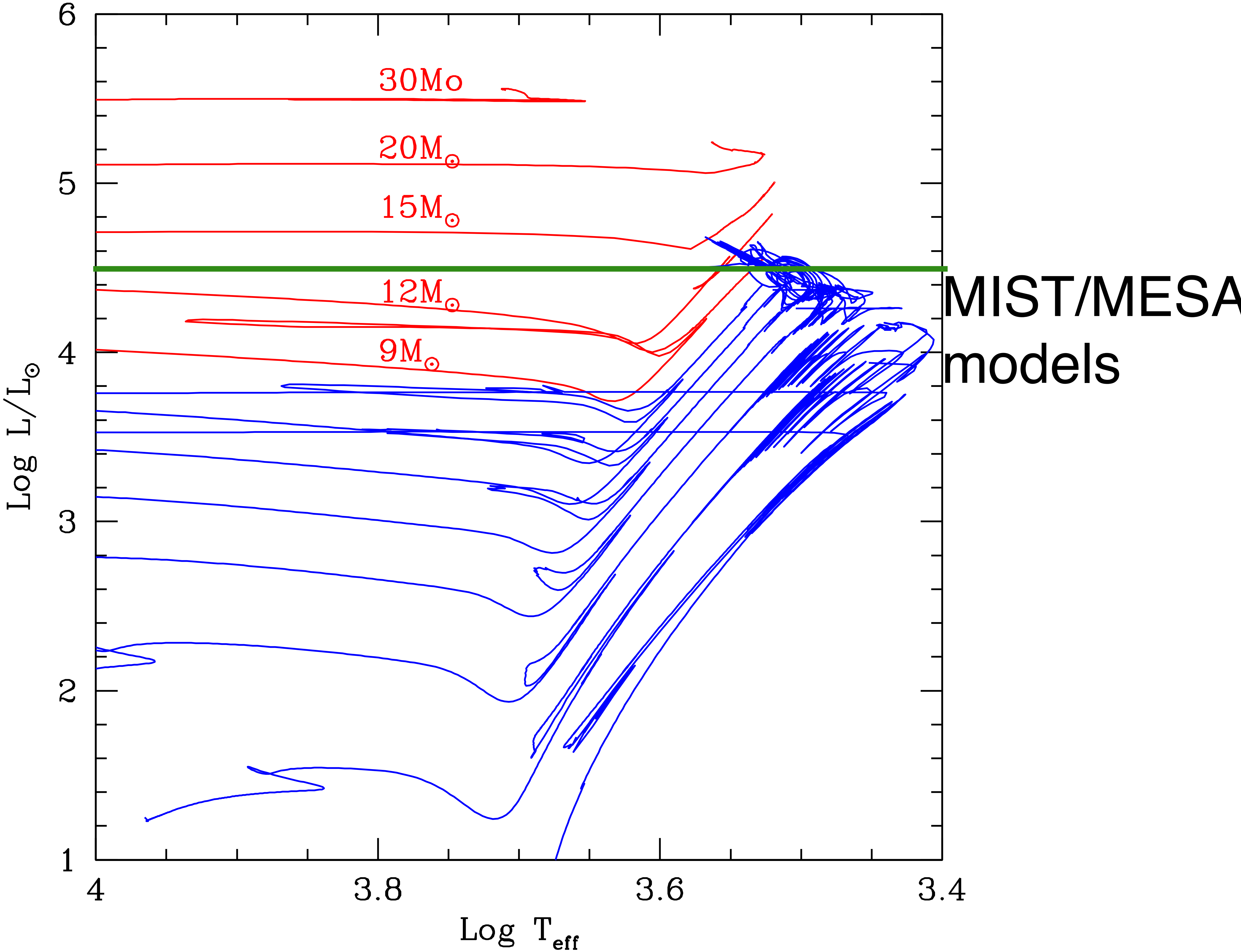
MIST/MESA
models

Total Number of RSGs

```
Log L/Lo>=   4.0 Percent contam by <=8Mo:  26.90
Log L/Lo>=   4.1 Percent contam by <=8Mo:  19.66
Log L/Lo>=   4.2 Percent contam by <=8Mo:  13.78
Log L/Lo>=   4.3 Percent contam by <=8Mo:   7.20
Log L/Lo>=   4.4 Percent contam by <=8Mo:   2.96
Log L/Lo>=   4.5 Percent contam by <=8Mo:   1.73
Log L/Lo>=   4.6 Percent contam by <=8Mo:   1.04
Log L/Lo>=   4.7 Percent contam by <=8Mo:   0.55
Log L/Lo>=   4.8 Percent contam by <=8Mo:   0.13
Log L/Lo>=   4.9 Percent contam by <=8Mo:   0.00
```

Total Number of RSGs

```
Log L/Lo>=   4.0 Percent contam by <=8Mo:  26.90
Log L/Lo>=   4.1 Percent contam by <=8Mo:  19.66
Log L/Lo>=   4.2 Percent contam by <=8Mo:  13.78
Log L/Lo>=   4.3 Percent contam by <=8Mo:   7.20
Log L/Lo>=   4.4 Percent contam by <=8Mo:   2.06
Log L/Lo>=   4.5 Percent contam by <=8Mo:   1.73
Log L/Lo>=   4.6 Percent contam by <=8Mo:   1.04
Log L/Lo>=   4.7 Percent contam by <=8Mo:   0.55
Log L/Lo>=   4.8 Percent contam by <=8Mo:   0.13
Log L/Lo>=   4.9 Percent contam by <=8Mo:   0.00
```


30Mo
20M⊙
15M⊙
12M⊙
9M⊙
Log L/L⊙
Log Teff
6
5
4
3
2
1
4
3.8
3.6
3.4
MIST/MESA models

How Many RSGs Are There in the MCs?

- SMC
  - ➡ log L/Lo>4.5: 246
- LMC
  - ➡ log L/Lo>4.5: 675

Wolf-Rayet Stars

Image credit: Kathryn Neugent

Wolf-Rayet Stars

Stay tuned for Kathryn Neugent's talk!

LMC: 154
SMC: 12

Neugent, Massey & Morrell (2018)

Wolf-Rayet Stars

We expect that the relative number of RSGs to WRs will be highly metallicity dependent if stellar winds (rather than binary stripping) dominates the evolution of WRs (Maeder et al. 1980), with proportionally fewer WRs at low metallicity.

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Using only the “uncontaminated” sample for the RSGs (log L/Lo>4.5):

Ratios of RSGs/WRs:

LMC: 675 / 154 = 4.4

SMC: 246/12 = 20.5

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WOW!

Searching for the O Stars

Image credit: Kathryn Neugent

Searching for the O Stars

How Hard Can It Be to Find the Most Luminous Stars?

…..With apologies to Pat Morris,

Searching for the O Stars

How Hard Can It Be to Find the Most Luminous Stars?

…..With apologies to Pat Morris,

DARN HARD!

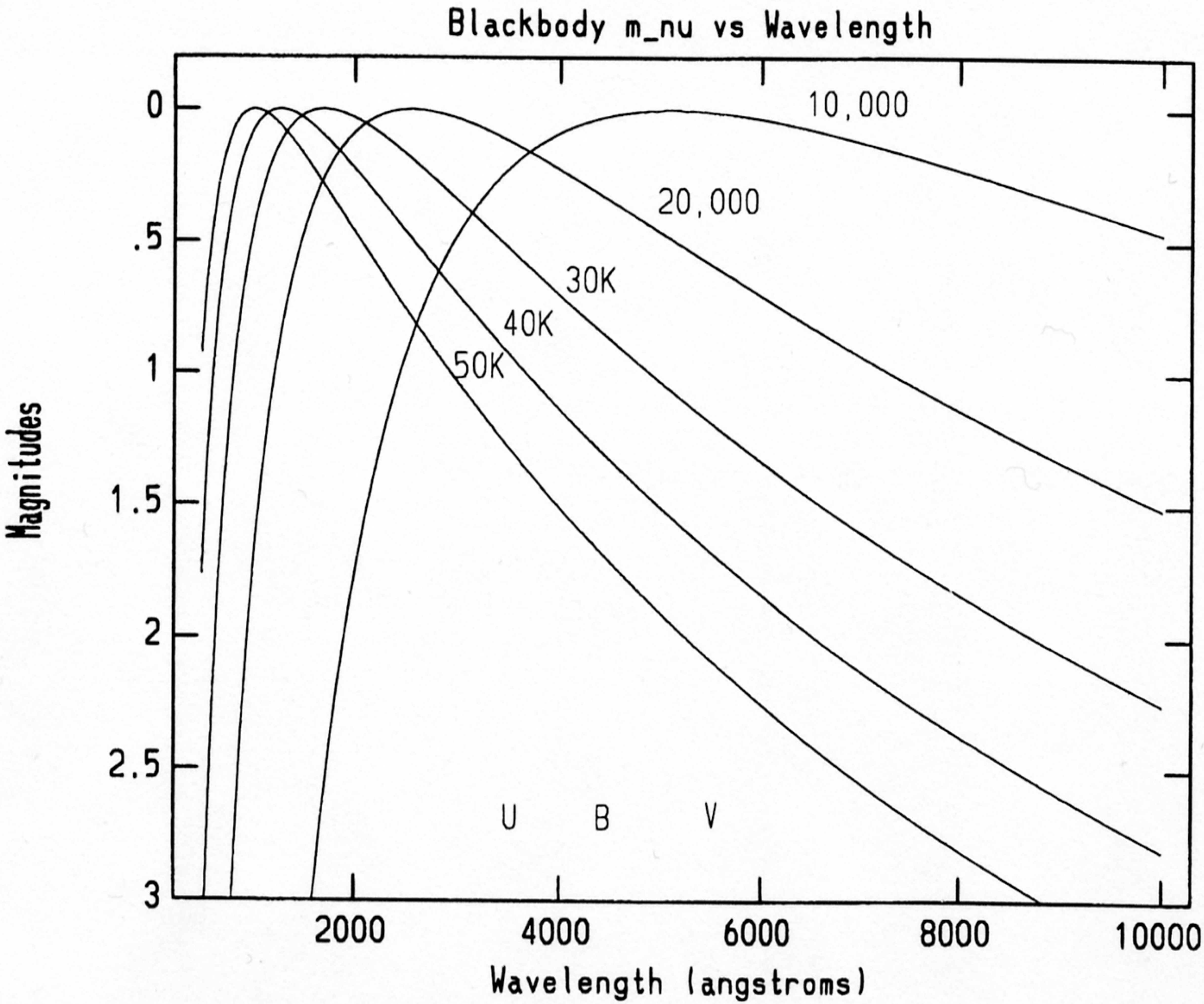
Searching for the O Stars

Three problems, all related to their high effective temperatures:

(1) Converting their visual brightness to luminosities (and hence masses) requires accurate knowledge of temperature. (BC steep function of Teff.)

(2) Can't get accurate knowledge of temperatures without spectroscopy.

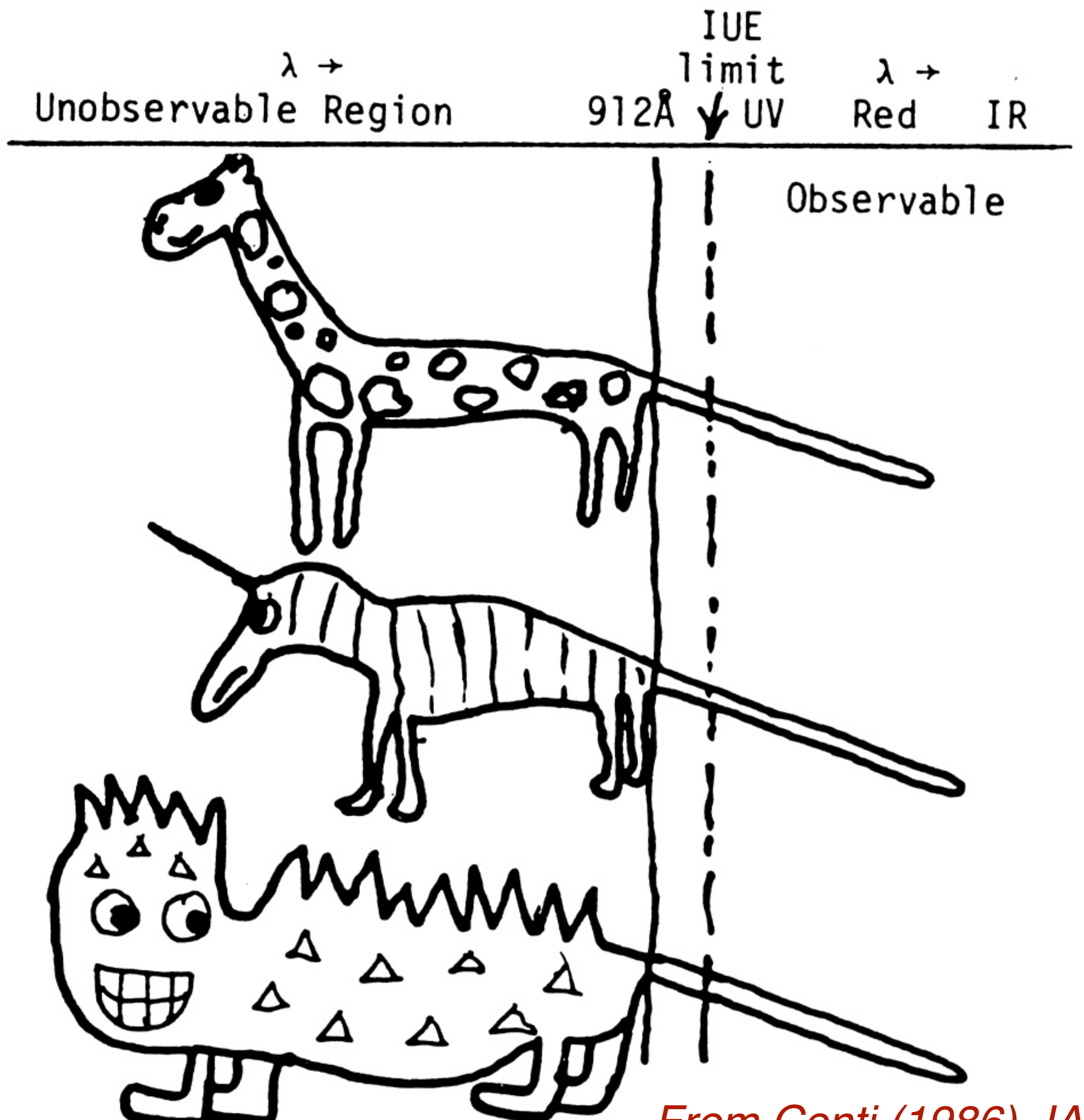
(3) Most luminous stars are not the visually brightest stars.



Blackbody m_nu vs Wavelength
Magnitudes
0
.5
1
1.5
2
2.5
3
10,000
20,000
30K
40K
50K
U
B
V
2000
4000
6000
8000
10000
Wavelength (angstroms)

PROBLEMS WITH CONTINUUM MEASURES
OF HOT STARS ...

(with apologies to H.J.G.L.M.L.)



From Conti (1986), IAU Symp. 116

Searching for the O Stars

Spectroscopy has been focused on a few star-forming regions, e.g., NGC 346 in the SMC, 30 Dor in the LMC.

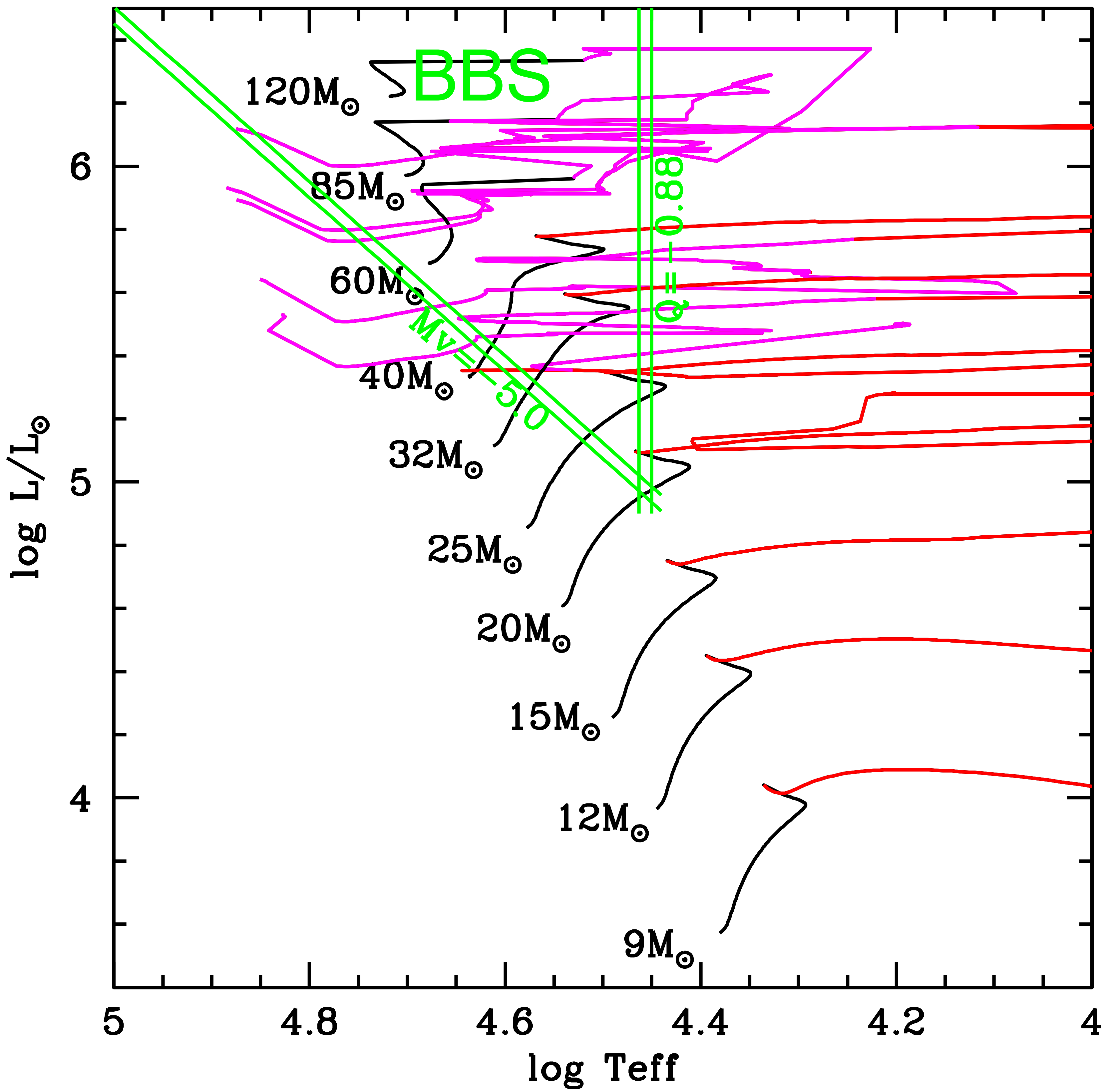
Every time we survey another OB association in the Clouds, we identify dozens of previously unknown O stars.

Searching for the O Stars

Basically we can't identify "O stars" from photometry alone. So is it hopeless? No!

We really don't just want "O stars." We'd like to identify the *most massive unevolved stars.* And that we CAN do from photometry.

BBS: Neugent et al. (2018) and Aadland et al. (2018+) use the Zaritsky et al. (2002, 2004) photometry to define a sample of "Bright Blue Stars," with $M_V < -5.0$ and reddening-free color criteria ($Q<-0.88$).



BBS
120M⊙
85M⊙
60M⊙
40M⊙
32M⊙
25M⊙
20M⊙
15M⊙
12M⊙
9M⊙
Mv = -5.0
Q = -0.88
log L/L⊙
log Teff
6
5
4
5
4.8
4.6
4.4
4.2
4

BBS: Who's In and Who's Out?

If you weight by a Saltpeter IMF and the length of time spent between M_V<-5 and Q<-0.88, then NO stars with masses 20Mo and below.

7.5% 20-25Mo

Over half will have masses above 40Mo.

How Many BBS Are there in the MCs?

LMC: 688 stars (excluding 30 Dor region)

SMC: 135

Ratio of number of stars to WRs

If mass-loss mechanisms for forming WRs are metallicity dependent, then we expect the ratio of BBS to WRs to be smaller in the LMC than in the SMC:

Ratio of number of stars to WRs

If mass-loss mechanisms for forming WRs are metallicity dependent, then we expect the ratio of BBS to WRs to be smaller in the LMC than in the SMC:

BBS/WR ratios:

LMC: 688 / 117 (excluding 30 Dor) = 5.9

SMC: 135 / 12 = 11.2

How Well Do We Know the O Star Content of the MCs?

- Of the 135 BBS in the SMC, ~80% have types, the vast majority of those are early B-types supergiants.
- Of the 688 BBS in the LMC, ~40% have types, of which half are O types, and half are early B supergiants.

The Future

The majority of the highest mass stars in the Magellanic Clouds still lack spectroscopy!!!

Image credit: Kathryn Neugent

Still a lot of work ahead for Nidia!