# Massive stars

Wofford[1]+

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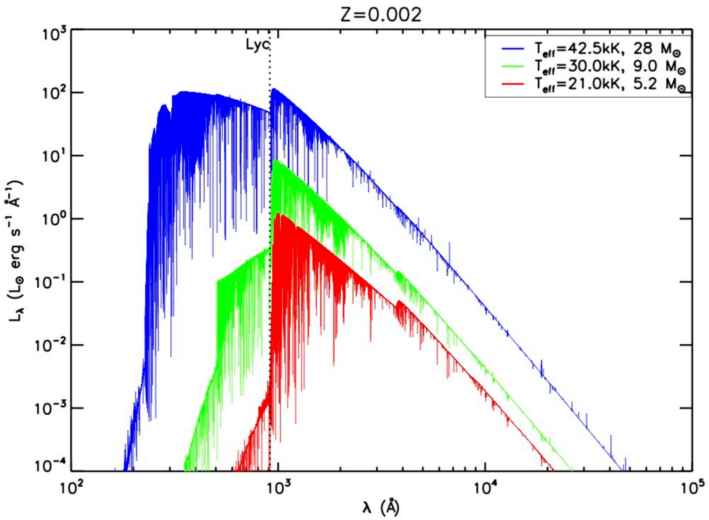



1. **~8-120 $M_\odot$**(ignite C non-degenerately)
2. rare by number, ~0.26%; ~23% by mass
   (assuming Kroupa IMF over 0.1-120 $M_\odot$)
3. non-negligible in terms of feedback
   - $10^4$-$10^6$ $L_\odot$ (hot $T_{eff}$~$10^4$ K)
   - inject momentum via winds, explosions
   - production sites of elements essential to life

5\. peak luminosity in UV, sources of ionizing photons

6\. short lifetimes (<50 Myr)

7\. progenitors of type II and Ib/c SNe

8\. possible progenitors of $\gamma$-ray bursts

9\. produce stellar BH

10\. produce dust (via type II SN, WC stars)

11\. good for determining distances via spectroscopic binaries

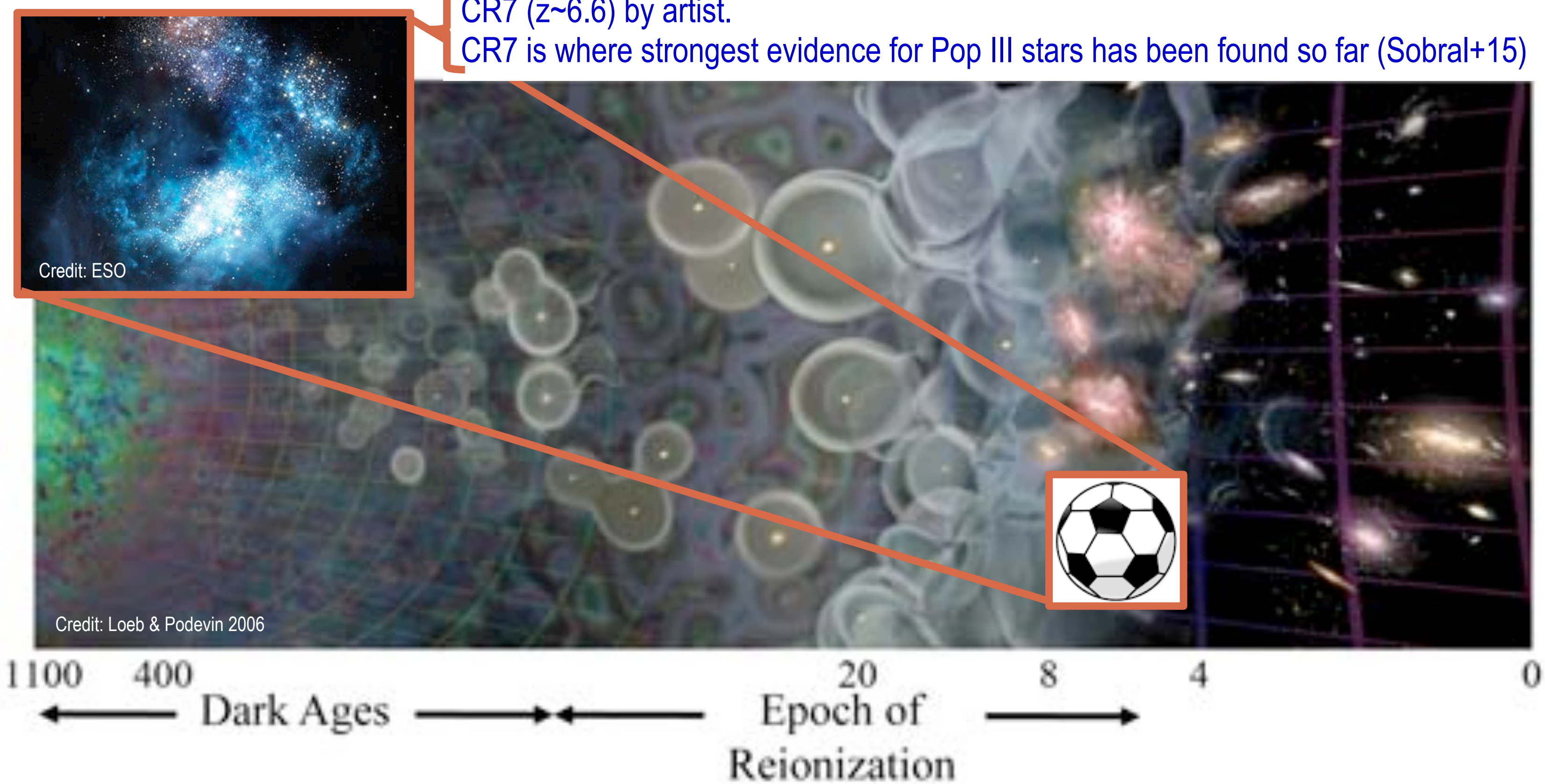
# Massive stars: why do we care?

Improving our understanding of massive stars is crucial for addressing fundamental questions in at least 3 areas…

# Area #1

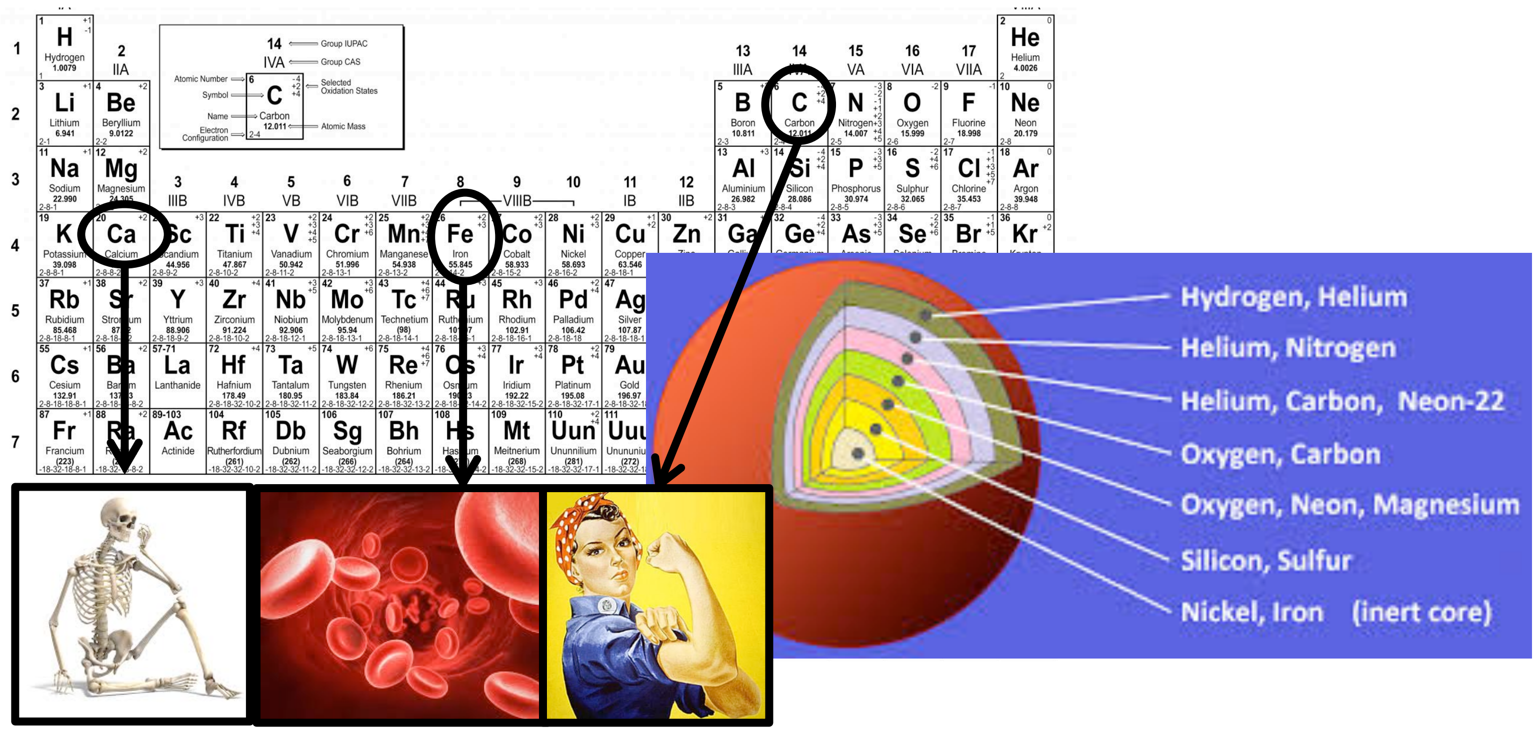
When did the **first stars** in the universe form and how did they influence their environments? First stars were massive (~ 30-300 $M_\odot$); first stars contributed to **reionization.**

CR7 (z~6.6) by artist.
CR7 is where strongest evidence for Pop III stars has been found so far (Sobral+15)



# Area #2

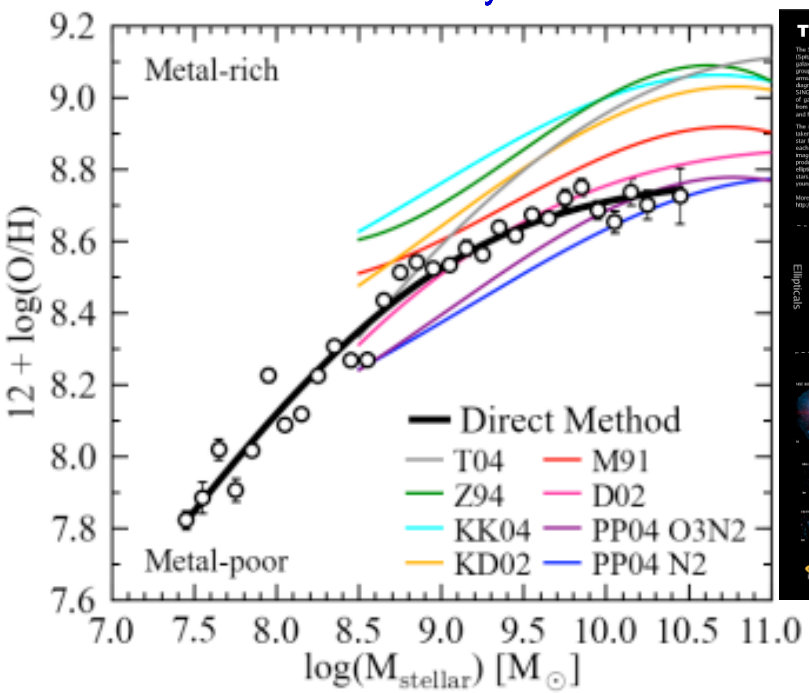
What are the cosmic origins of **chemical elements**, particularly those fundamental to **life**? Massive stars: cosmic production sites of bulk of $\alpha$-elements (O, …, Ca); produce some C, N, some Fe & Fe-peak elem.



# Area #3

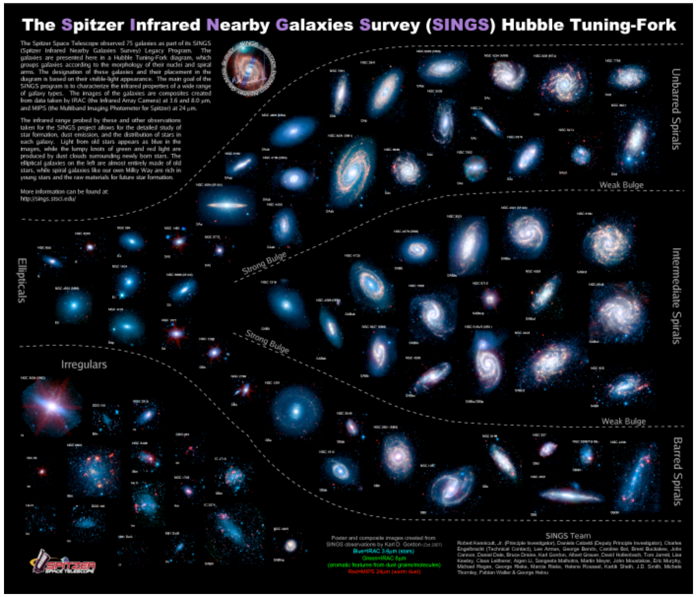
How exchanges of mass and momentum between massive stars and the environment shape the origin and **evolution of galaxies**?

Mass-metallicity relation




Credit: Andrews & Martini (2013)

Hubble sequence




Credit: SPITZER

# What should we do next?

We build our science case around where the largest uncertainties are, i.e.

- extinction by dust
- stellar evolution

# Summary of what we need

1) Extragalactic UV+optical **extinction curves** along many more sightlines in the Magellanic Clouds and beyond for recovering intrinsic light

2) R~$10^4$ UV spectroscopy of **statistically significant samples** of individual massive stars and their descendants in order to pin down their evolution and final fates

3) R~$10^3$ UV spectroscopy of stars in **extreme environments** (very low Z, high SFR) that build the bridge to higher redshifts results

4) Abundances & physical parameters of large samples of wind bubbles, SNRs, H II regions sampling a wide range of conditions in order to constrain stellar nucleosynthesis and feedback

# Extragalactic extinction curves

# Extinction curves: what is required?

Standard technique to derive extinction curves is to observe stellar pairs of identical spectral types, one member heavily reddened and the other unreddened, and to compare their SEDs.

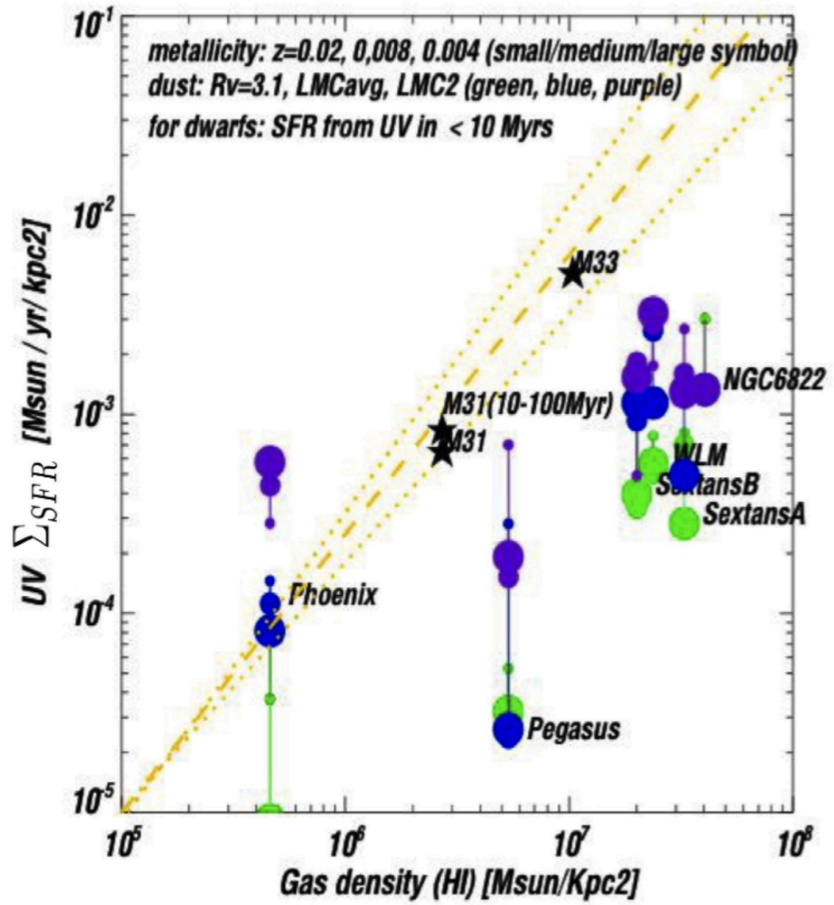
What is required:

- 912 - 3000 Å coverage (includes the dust bump 2175 Å)
- co-spatial optical coverage
- low resolution SEDs and/or
- panchromatic photometry of resolved stars

# Consequences of uncertain extinction laws

Our scarce knowledge of extragalactic UV extinction translates into large systematic uncertainties in

- **cluster masses** (~factor of a few; Calzetti+, subm.)
- **star formation rates** (~an order of magnitude; Bianchi+11).




Credit: Bianchi+11

## Statistically significant samples of individual massive and their evolved descendants

(supergiants, Wolf-Rayet stars, Luminous Blue Variables)

# Stellar evolution affects

- nuclear reaction rates
- ionizing rates
- duration of evolutionary stages
- final fates of massive stars

# Large samples of individual stars are needed in order to…

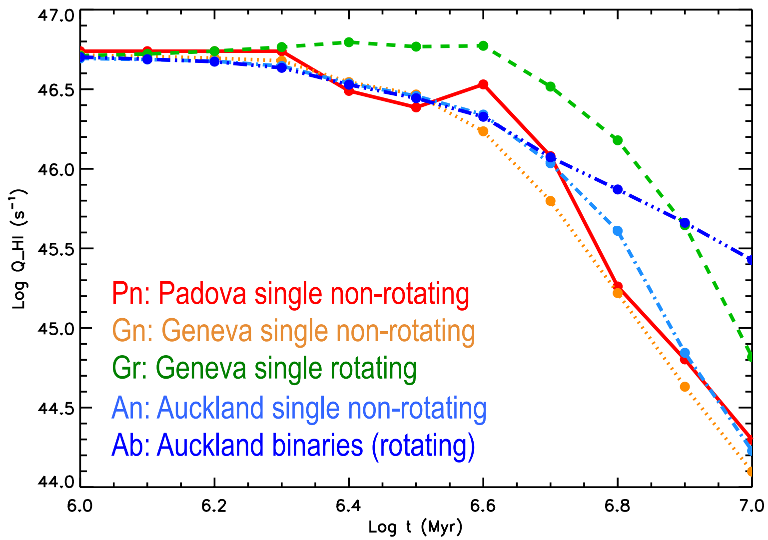
1. Separate the many competing factors that influence the **stellar evolution** and observed properties of massive stars:
   - mass
   - chemical composition
   - convection
   - mass-loss
   - rotation
   - binarity (mass transfer & tidal interactions)
   - magnetic fields

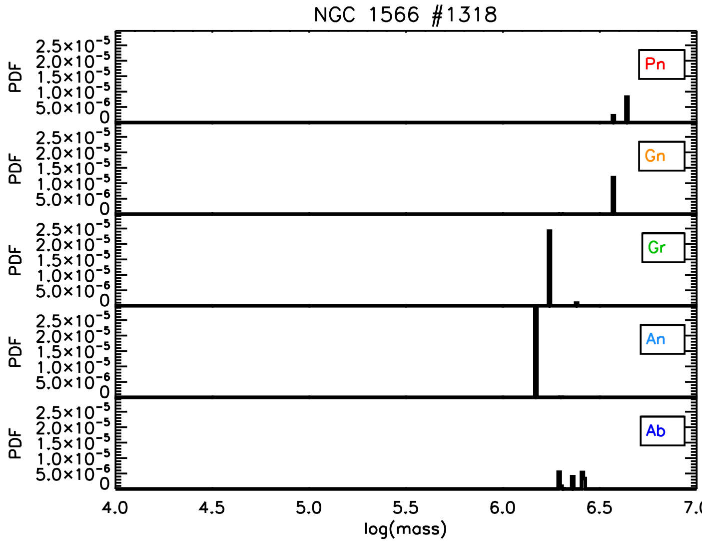
Credit: HST.
Nebula around Wolf-Rayet star 124

2. Identify the **progenitors of core-collapse SNe** at masses $\geq 30\ M_{\odot}$

# Consequences of uncertain evolution

- **[Higher H I ionizing rates by a factor of 5]** for population synthesis models dominated by O stars that include rotation versus non-rotating ones (Leitherer+14)
- **[Cluster ages and masses off by a factor of 2]** if determined with state-of-the-art models that account for different important astrophysics (Wofford+)

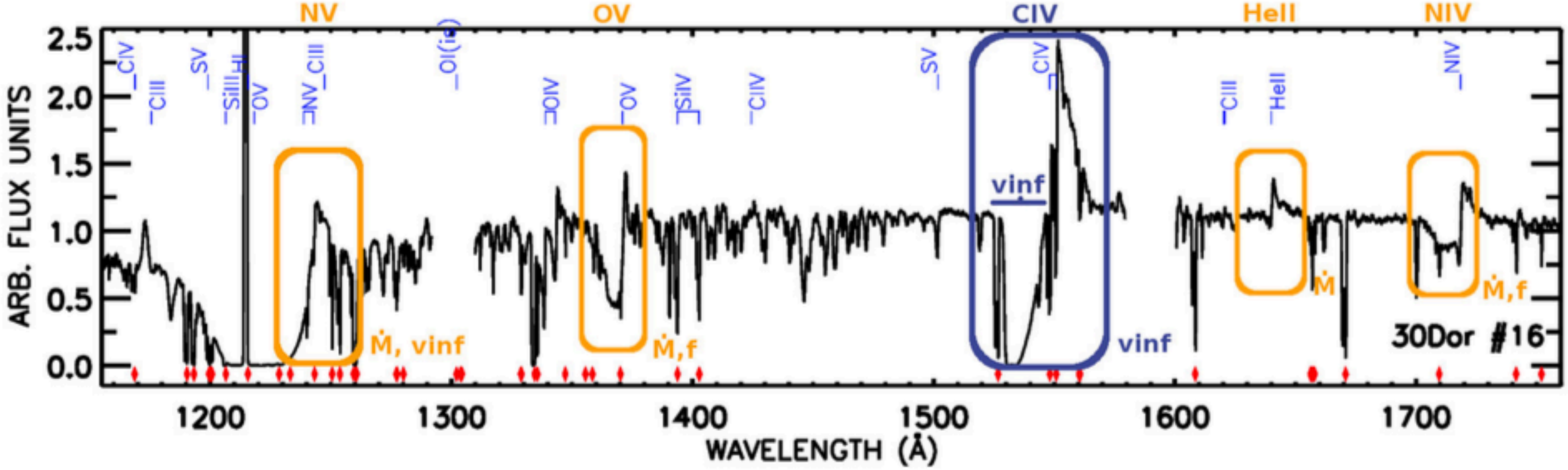


# Why the UV?

~1200-1900 Å spectroscopy is how the main photospheric and wind parameters of massive stars are determined

- mass
- bolometric luminosity
- mass loss
- wind terminal velocity
- clumping
- iron content (metallicity)



# Past work

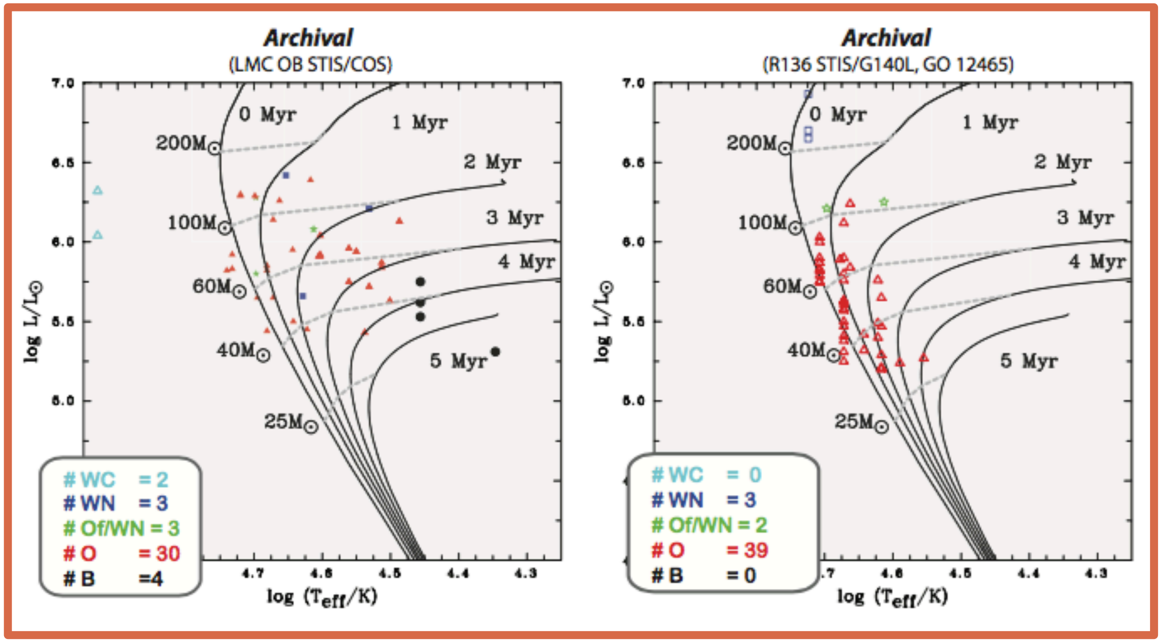
The designs of past and current UV satellites were not optimized to

- spectroscopically observe large samples of massive stars at R~$10^3$-$10^4$ in the 1200-1900 Å range in Local Group galaxies
- spectroscopically observe massive stars at lower resolution in galaxies beyond the Local Group (@>2 Mpc)

E.g., figure shows existing sample of stars with masses ≥20 $M_\odot$ observed with HST STIS or COS, in LMC. This is not a statistically significant sample considering the zoo of peculiar objects, extent of binary parameter space, etc. Credit: Sana.

LMC

- 1/2 solar
- ~50 kpc



# Extreme environments

# What are extreme environments?

They are environments found beyond the Local Group with:

- **very low metallicity** (1/30 solar; approaching primeval conditions) or
- **clusters of $\geq 10^5$ $M_\odot$** (reminiscent of high SFR galaxies at z~3; Swinbank+15)

Examples are:

- DDO 068 (~7.9 Mpc)
- I Zw 18 (~18 Mpc)
- Antennae (21.5 Mpc)

Very metal poor galaxy I Zw 18

Antennae galaxies host very massive clusters, hypergiants

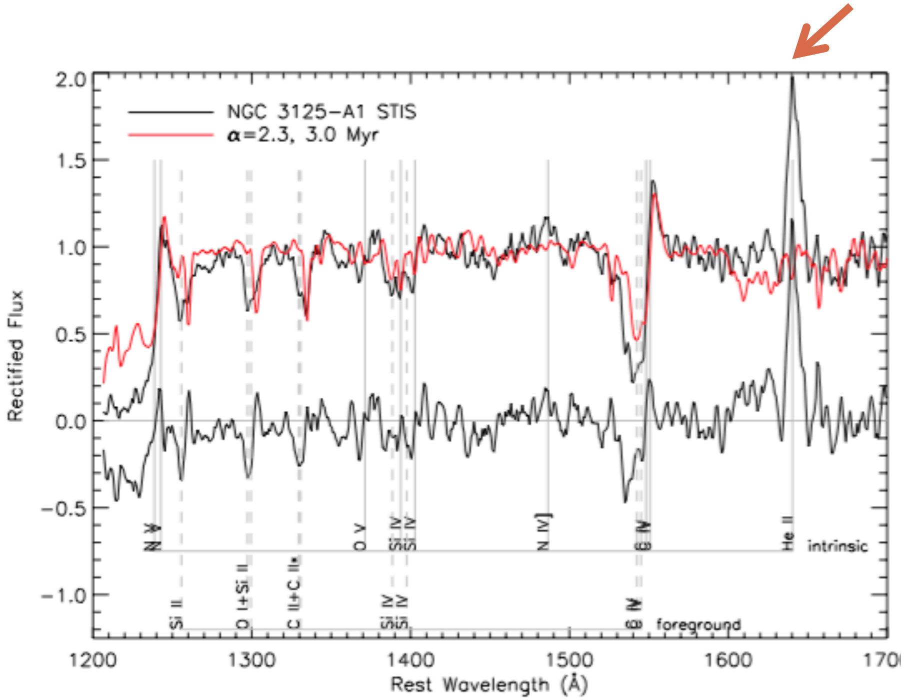
# Why do we care about low metallicity?

1. The dependency of stellar parameters with metallicity has hardly been addressed in part because we are limited by distance. It affects: IMF, stellar mass-luminosity relation, mass loss, …
2. Studies of IC1613 (1/7 solar) by García+14 and Bouret+15 show **higher Fe** content in stellar atmospheres **than expected** by scaling Fe based on oxygen from the ISM. This has consequences for the mass-metallicity relation.
3. Low metallicity galaxies show narrow He II emission at many redshifts, which is suggestive of the presence of **very massive stars (>120 $M_\odot$)** (Kherig+15; Gräfner & Vink 2015), binary products, or binaries at play (Eldridge+).

# Why do we care about high mass clusters?

1. High mass clusters could also contain **very massive stars**
2. **Dynamics** in massive clusters could play a role in stellar evolution.

E.g., population synthesis models with nominal stellar upper mass limits fail to reproduce He II 1640 Å in super star cluster NGC 3125-A1 (1/2 solar, ~11.5 Mpc, ~$10^5$ $M_\odot$). An unrealistically flat IMF is required, or very massive stars.




From Wofford+14.

# What instruments on flagship?

1. Wide field imager

- 912-10,000 Å wavelength coverage
- sub-arcsec spatial resolution
- wide range of narrow to wide-band filters

2. Multi-object FUV + optical spectrograph

- high sensitivity
- medium ($R{\sim}10^4$) and lower ($R{\sim}10^3$) resolution


**Fig. 6** Portion of the Magellanic Bridge seen at optical wavelengths (DSS) and in the UV (GALEX FUV, NUV), illustrating the sensitivity of UV to hot stars. FUV imaging only exists for the periphery of LMC and SMC and portions of the Magellanic Bridge, the main stellar body of these galaxies was too bright for GALEX detectors

Bianchi, L., in "From the Realm of Nebulae to the Society of Galaxies" , eds. M. D'Onofrio et al., Springer, in press .

# What we would get…

1. Complete color-magnitude diagrams of massive-star populations down to 1 $M_\odot$ in wide range of environments.

2. Co-spatial UV+optical medium-resolution spectroscopy for ~100 massive stars in one exposure in Local Group galaxies.

3. Multiple exposures to improve S/N, address stellar variability, monitor SN progenitor candidates and $\gamma$-ray bursts

4. Low-resolution SEDs of individual stars and emission and absorption spectra of the ISM in galaxies covering a wide range of conditions

5. Detailed UV+optical extinction maps in the Magellanic Clouds and beyond via
   – low resolution spectra
   – panchromatic photometry of resolved star

Thank you!