Massive Stars and Their Environment

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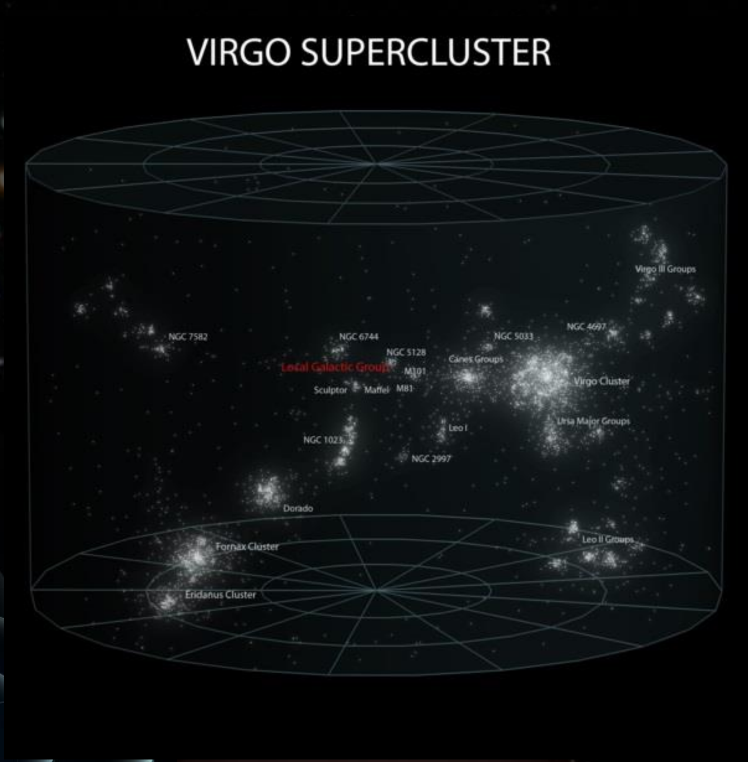
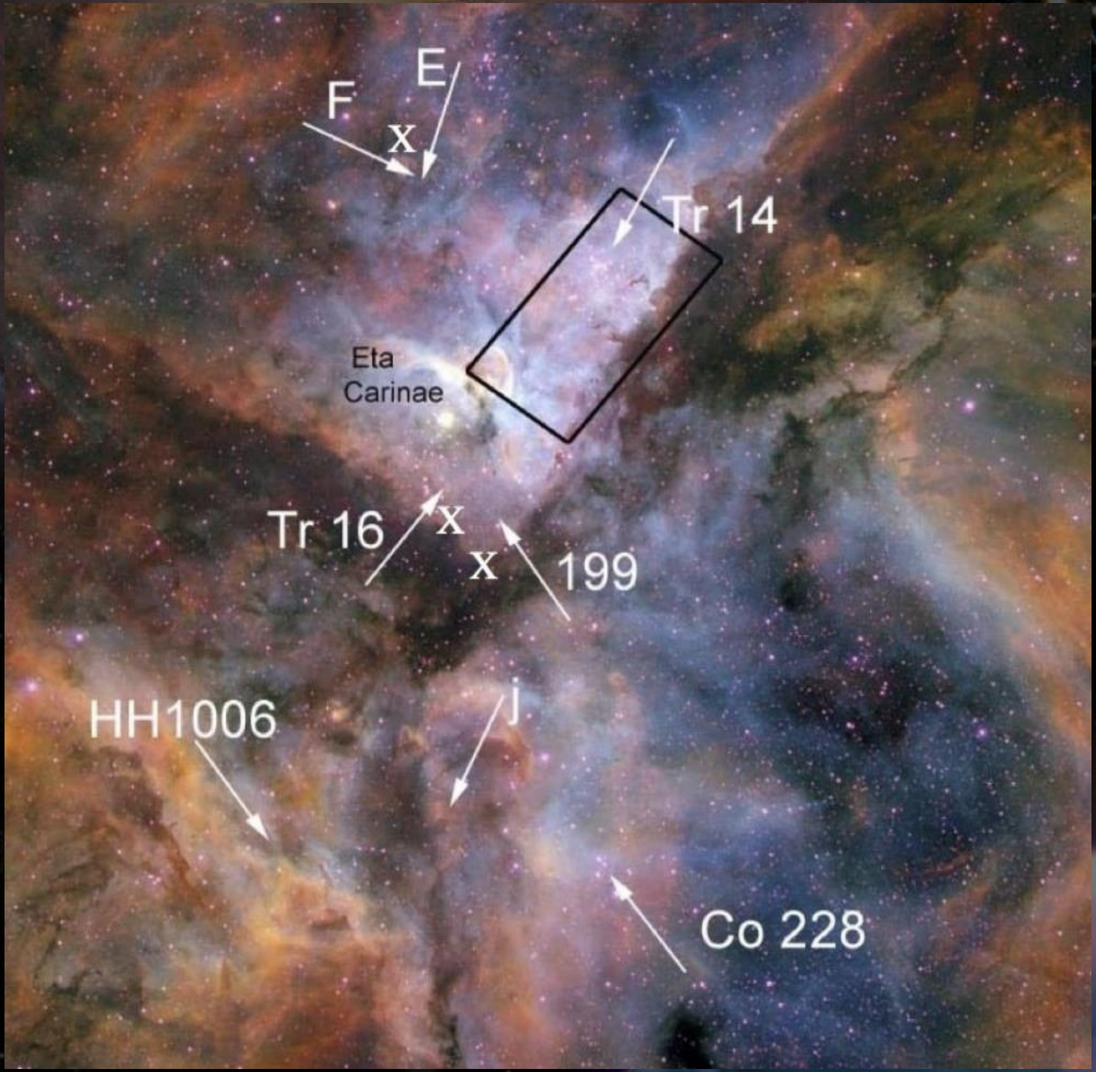
- IMF (including super-massive stars)
- Feedback (radiation, momentum, matter)
- Ionizing photon output and escape
- Metallicity of the host galaxy
- Cluster versus global galactic properties



The Galaxy

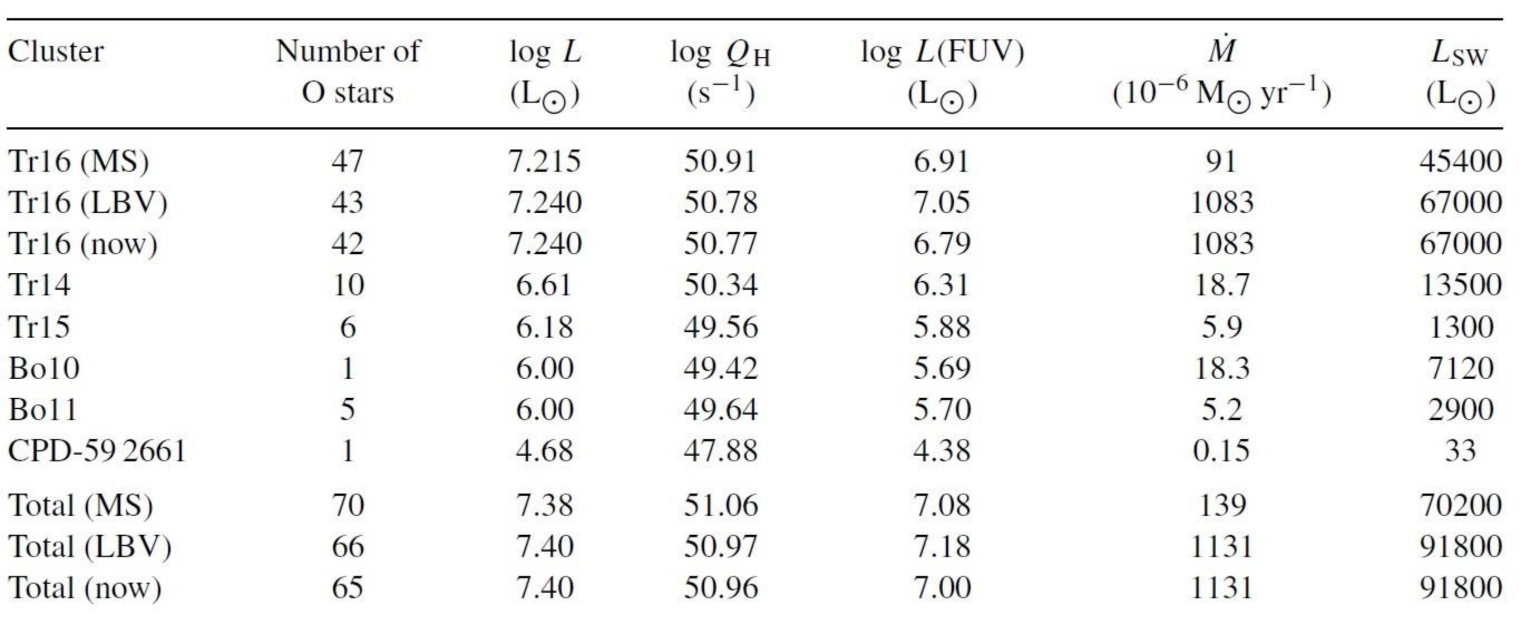
- Carina Nebula (Trumpler 14 &16)
- NGC 3603
- Other young clusters harboring massive stars

- Haikala et al. (2017): the Carina Nebula and its ionizing stars



- Trumpler 14, 16: some of the most massive stars known in the Galaxy
- η Carinae
- HD 93129A (O2 If*); Morrell, Walborn & Arias (2005)

Smith (2006); Smith & Brooks (2007): stellar and nebular properties



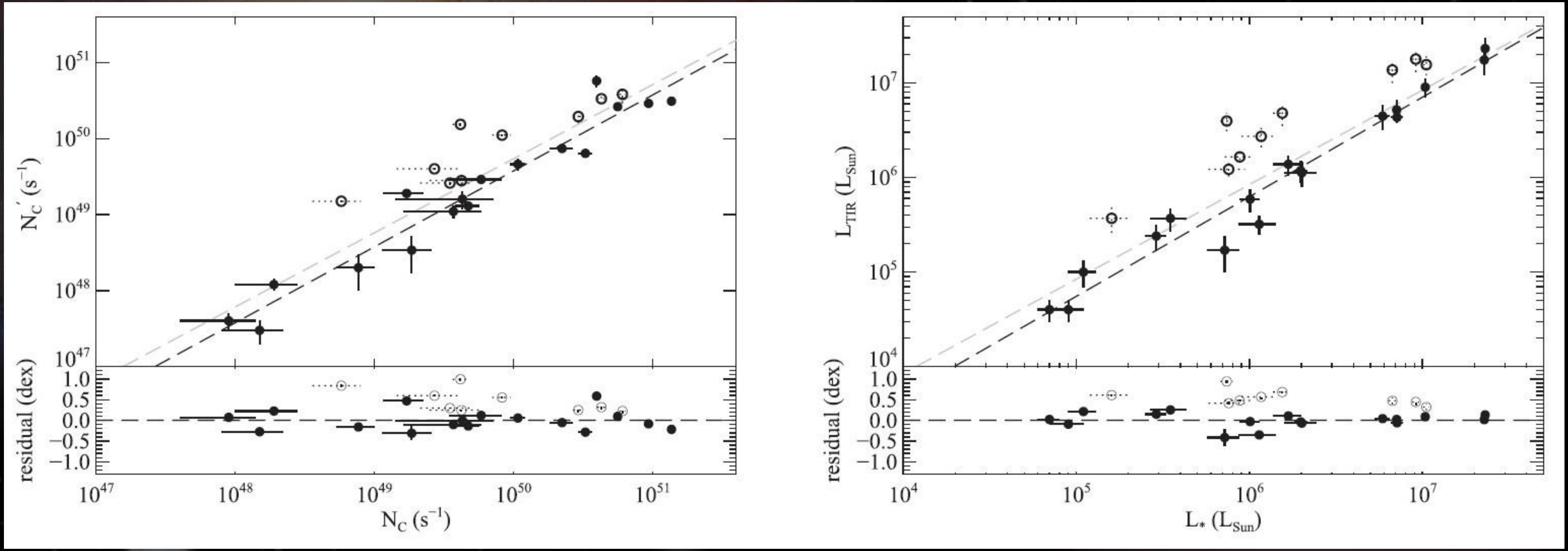
Cluster	Number of O stars	log L ($L_\odot$)	log Q_H (s^{-1})	log L(FUV) ($L_\odot$)	$\dot{M}$ (10^{-6} $M_\odot$ yr^{-1})	L_{SW} ($L_\odot$)
Tr16 (MS)	47	7.215	50.91	6.91	91	45400
Tr16 (LBV)	43	7.240	50.78	7.05	1083	67000
Tr16 (now)	42	7.240	50.77	6.79	1083	67000
Tr14	10	6.61	50.34	6.31	18.7	13500
Tr15	6	6.18	49.56	5.88	5.9	1300
Bo10	1	6.00	49.42	5.69	18.3	7120
Bo11	5	6.00	49.64	5.70	5.2	2900
CPD-59 2661	1	4.68	47.88	4.38	0.15	33
Total (MS)	70	7.38	51.06	7.08	139	70200
Total (LBV)	66	7.40	50.97	7.18	1131	91800
Total (now)	65	7.40	50.96	7.00	1131	91800

- η Car currently not important but would contribute 25% of Q_H if closer to ZAMS
- O star mass-loss rates not clumping corrected
- Nebular Hα is ~70% of the stellar ionizing flux
- Kinetic energy of the nebula is ~30% of the stellar-wind energy
- Supernova input is small (t = 3 Myr)

NGC 3603; $d = 6.9$ kpc

- Crowther & Dessart (1998): photon and energy budget
- $Q_H = 1.3 \times 10^{51}$ s^{-1}; $L_w = 5.5 \times 10^{38}$ erg s^{-1}
- W-R are 10% of O numbers but provide 20% of Q_H and 60% of L_w

Binder & Povich (2018): census of 28 Galactic clusters

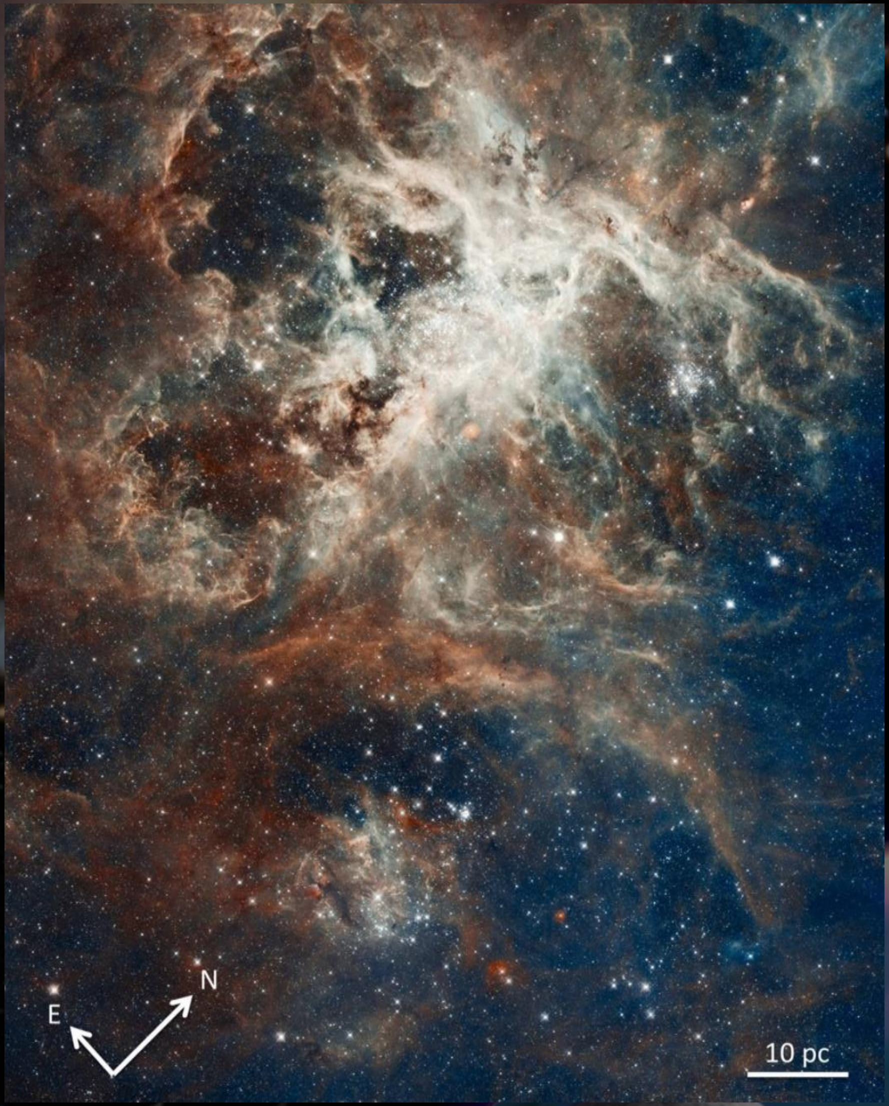


- Left: comparison of stellar (horizontal) vs. nebular (vertical) Q_H
- Right: comparison of stellar (horizontal) vs. dust (vertical) L_{bol}
- 34% of Lyman photons are absorbed by dust before ionization of gas
- 68% of the stellar L_{bol} is absorbed and reprocessed by dust
- Sample includes Tr 14/16 and NGC 3603: excellent agreement

The Local Group

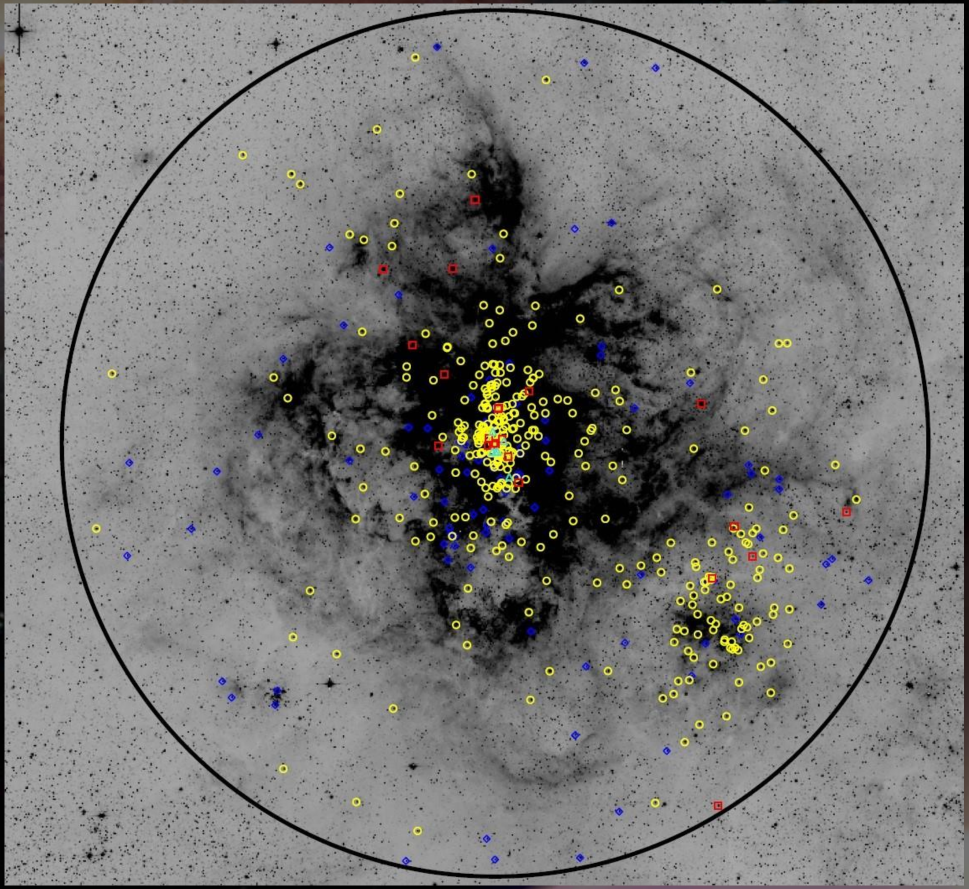
- Large Magellanic Cloud
- Small Magellanic Cloud
- M31

Sabbi et al. 2013: HTTP (Hubble Tarantula Treasury Project)



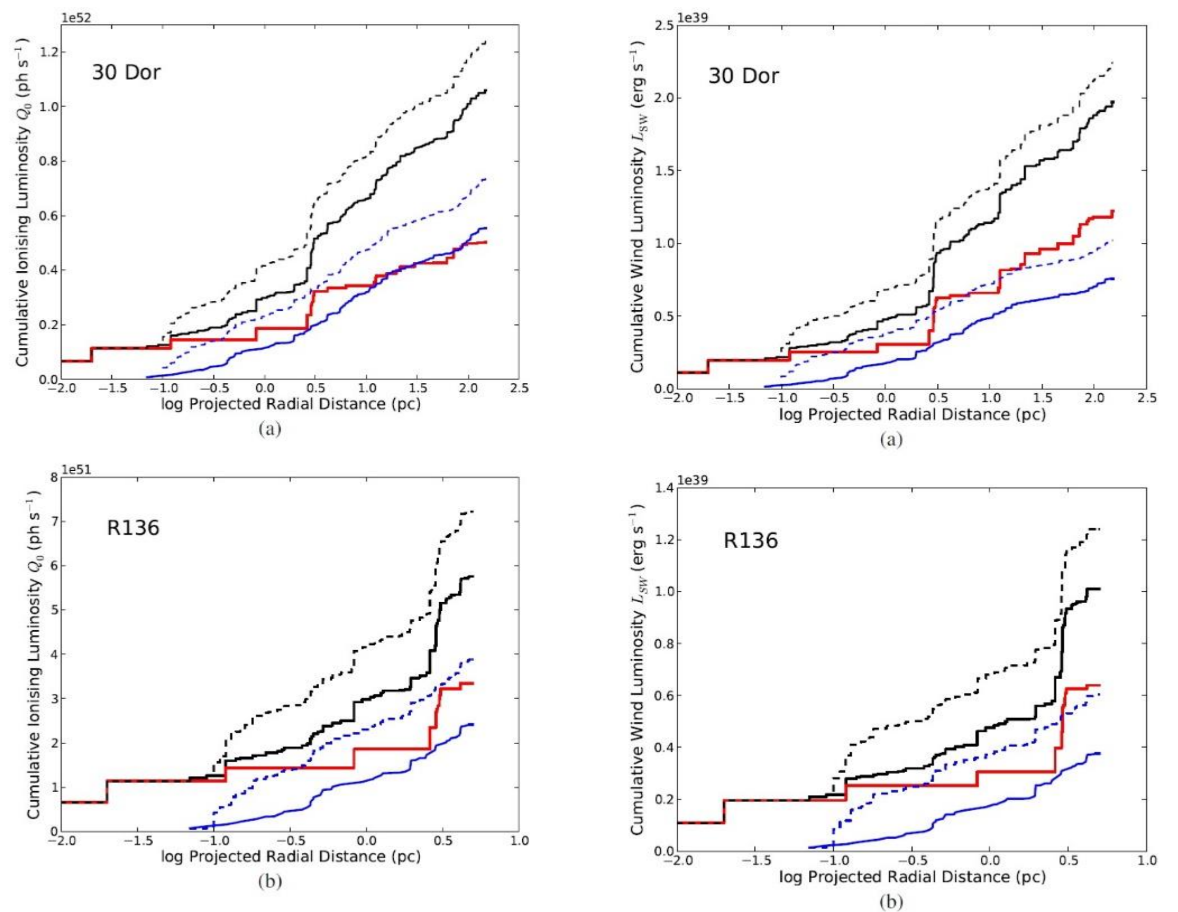
- 30 Dor: giant H II region
- NGC 2070: ionizing cluster
- R136: central core

Doran et al. (2013): massive star inventory in 30 Dor



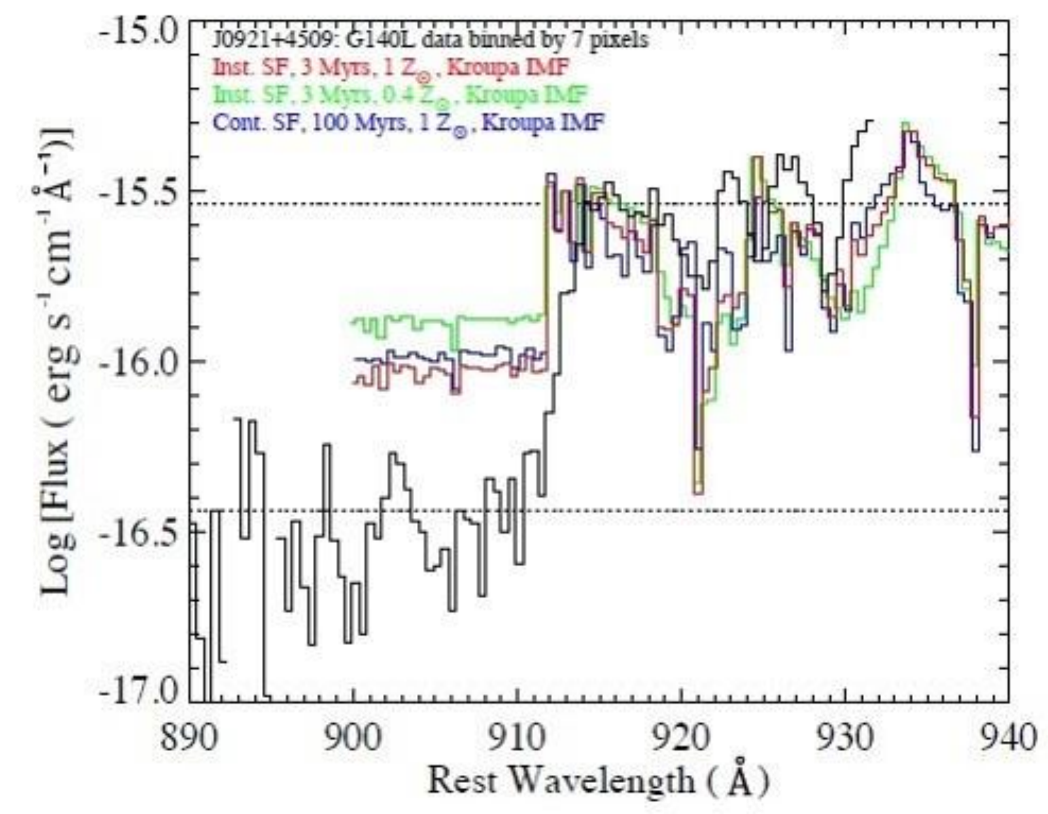
- Location of massive stars with spectroscopy
- Yellow: O stars; blue: B stars; red: W-R stars

Cumulative ionizing (left) and wind (right) luminosity for 30 Dor and R136



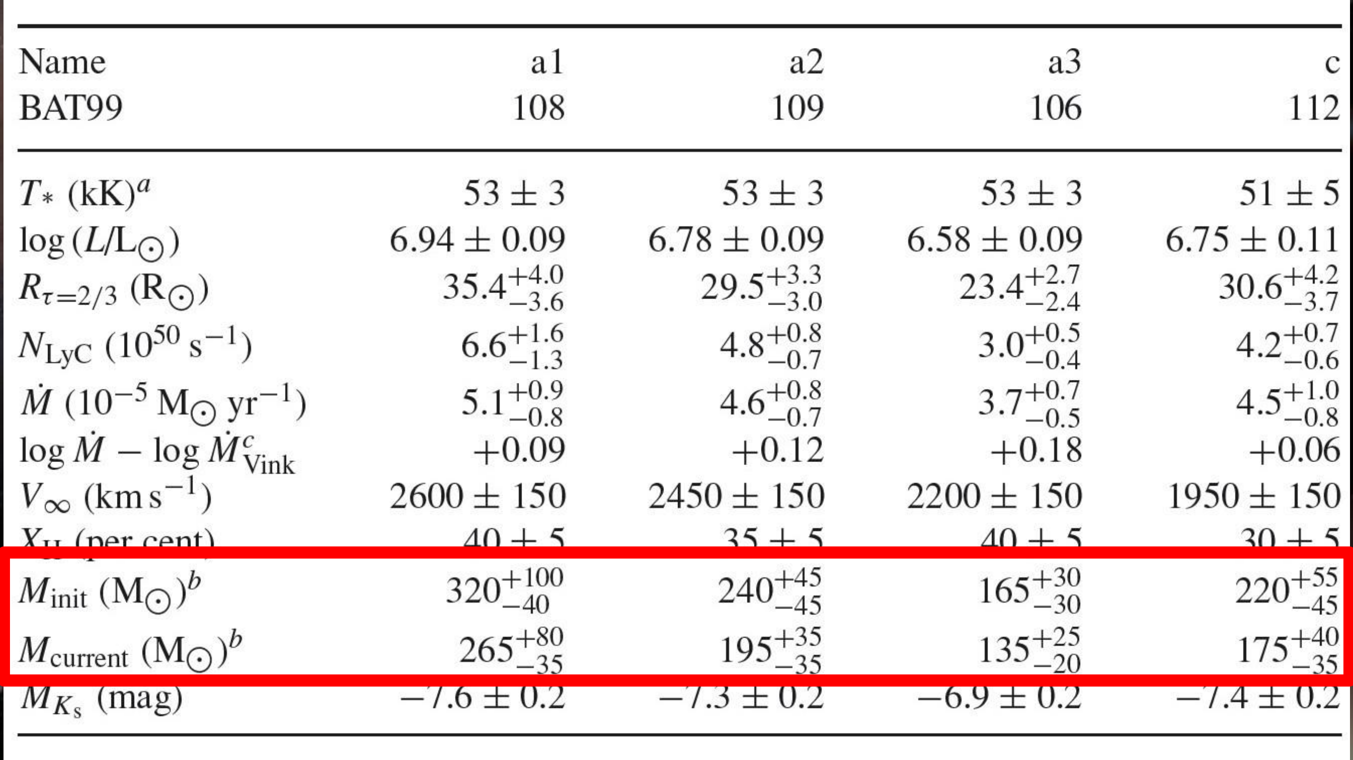
- $L_W = 2.2 \times 10^{39}$ erg s^{-1} (cf. NGC 3603)
- $Q_H = 1.2 \times 10^{52}$ s^{-1}; 70% → gas; 20% → dust; 10% → escape
- Photon leakage?

Borthakur et al. (2014): direct detection of Lyman escape at z ≈ 0.3



- Also: Izotov et al. (2016a, b; 2018)…..

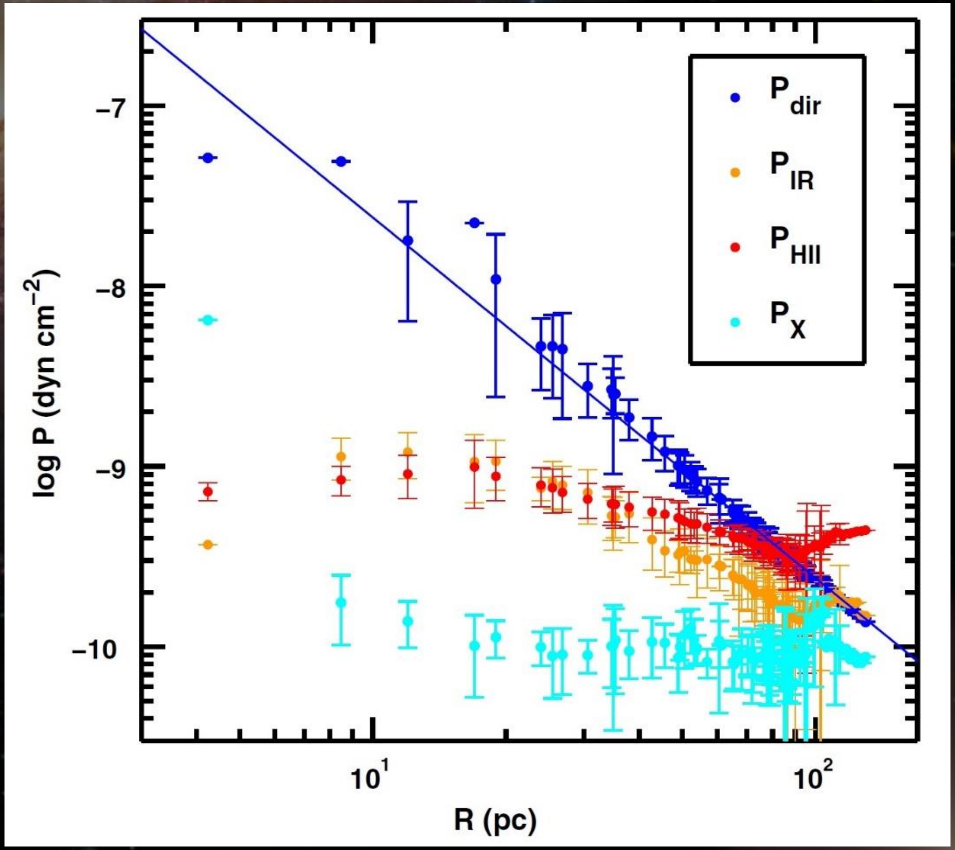
Crowther et al. (2010): R136 host stars with masses > 200 $\mathrm{M}_\odot$



Name	a1	a2	a3	c
BAT99	108	109	106	112
T_* (kK)[a]	53 ± 3	53 ± 3	53 ± 3	51 ± 5
$\log (L/\mathrm{L}_\odot)$	6.94 ± 0.09	6.78 ± 0.09	6.58 ± 0.09	6.75 ± 0.11
$R_{\tau=2/3}$ ($\mathrm{R}_\odot$)	$35.4^{+4.0}_{-3.6}$	$29.5^{+3.3}_{-3.0}$	$23.4^{+2.7}_{-2.4}$	$30.6^{+4.2}_{-3.7}$
N_{LyC} (10^{50} s^{-1})	$6.6^{+1.6}_{-1.3}$	$4.8^{+0.8}_{-0.7}$	$3.0^{+0.5}_{-0.4}$	$4.2^{+0.7}_{-0.6}$
$\dot{M}$ (10^{-5} $\mathrm{M}_\odot$ yr^{-1})	$5.1^{+0.9}_{-0.8}$	$4.6^{+0.8}_{-0.7}$	$3.7^{+0.7}_{-0.5}$	$4.5^{+1.0}_{-0.8}$
$\log \dot{M} - \log \dot{M}^{c}_{\mathrm{Vink}}$	+0.09	+0.12	+0.18	+0.06
V_∞ (km s^{-1})	2600 ± 150	2450 ± 150	2200 ± 150	1950 ± 150
X_{H} (per cent)	40 ± 5	35 ± 5	40 ± 5	30 ± 5
M_{init} ($\mathrm{M}_\odot$)[b]	320^{+100}_{-40}	240^{+45}_{-45}	165^{+30}_{-30}	220^{+55}_{-45}
M_{current} ($\mathrm{M}_\odot$)[b]	265^{+80}_{-35}	195^{+35}_{-35}	135^{+25}_{-20}	175^{+40}_{-35}
M_{K_s} (mag)	-7.6 ± 0.2	-7.3 ± 0.2	-6.9 ± 0.2	-7.4 ± 0.2

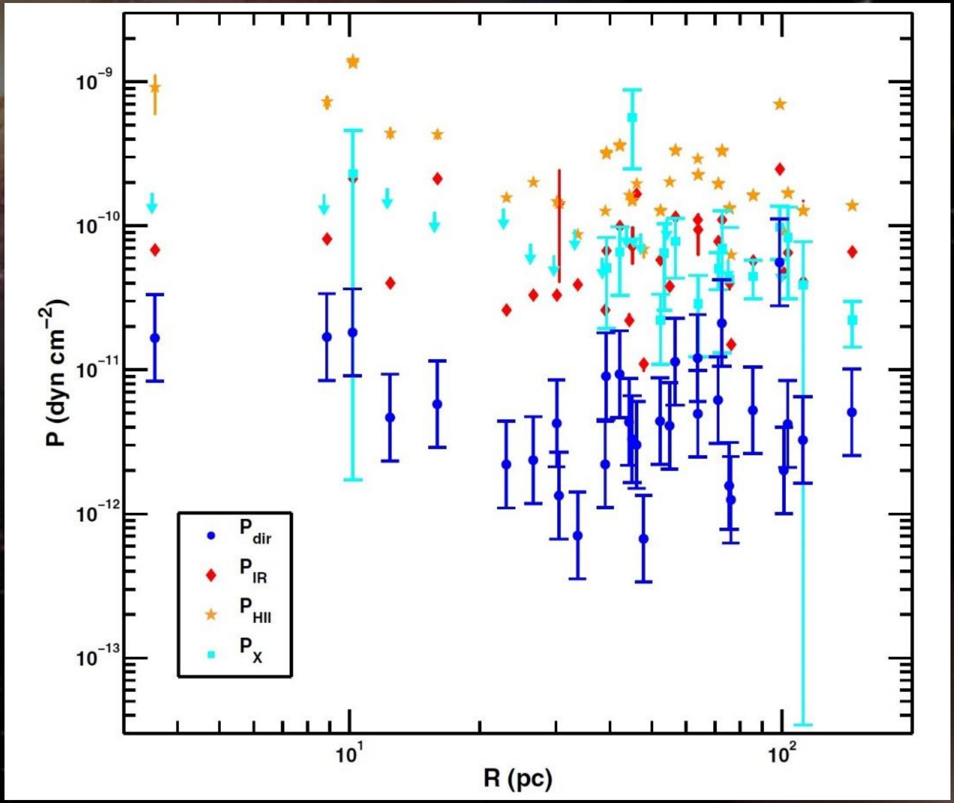
- Very massive stars significantly affect the photon budget
- Important for IMF
- 30 Dor IMF has excess of very massive stars (Schneider et al. 2018)

Lopez et al. (2011): comparing pressure components in 30 Dor



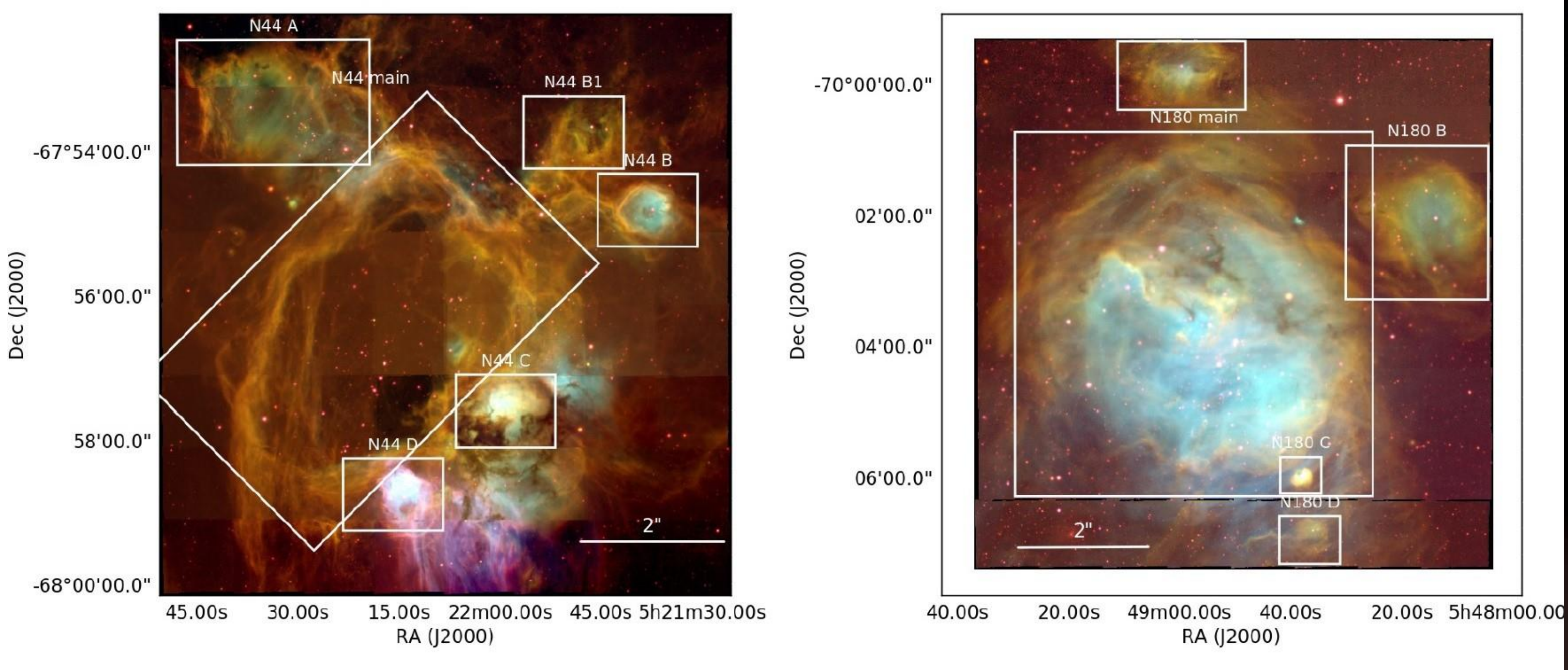
- Mapping pressures in radio, IR, UV/optical, X-rays
- Dust-processed radiation pressure and hot gas pressure are not important
- Radiation pressure dominates within 75 pc of R136
- H II gas pressure dominates at larger radii.

Lopez et al. (2014): generalize prior study to 32 LMC and SMC H II regions



- Radiation pressure no longer dominant
- No signatures to indicate that shocks are an important source of ionization
- Well described by photoionization from the central clusters where the ionizing continuum is dominated by the most massive O stars

McLeod et al. (2018): VLT/MUSE observations of N44 and N180



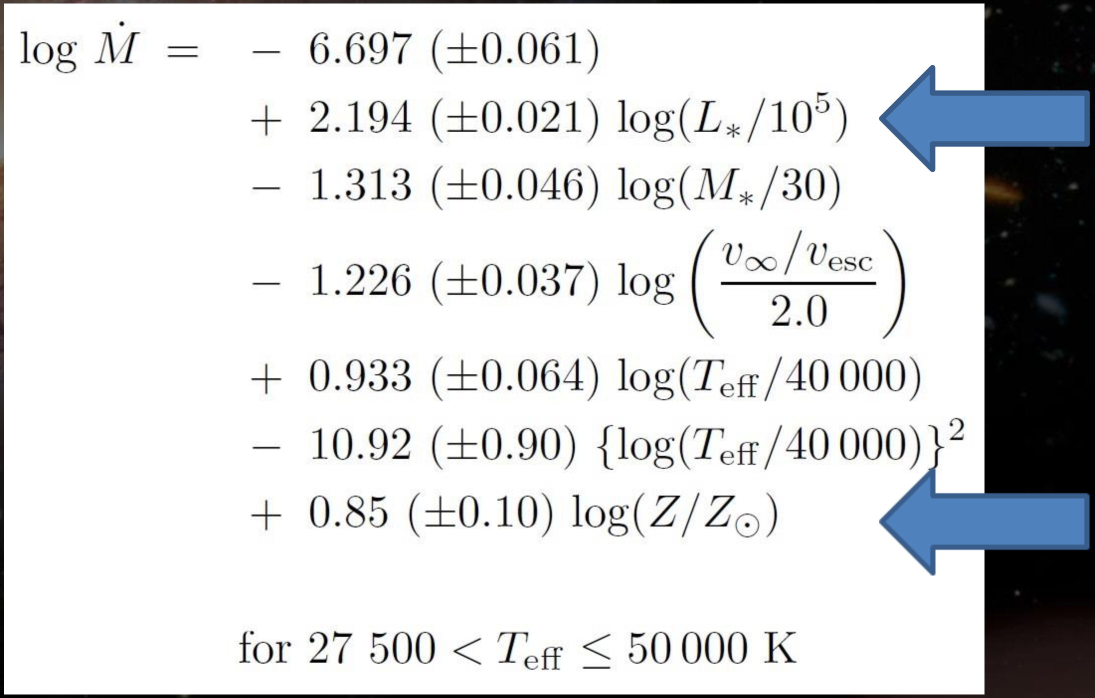
- MUSE: IFU with 1 arcmin FOV; 8 by 8 mosaic
- Obtain spectra of gas and all ionizing stars at the same time

$$P_{\rm dir} = \frac{Q_{0,\star}\langle h\nu\rangle}{4\pi R^2 c}$$

$$P_w \simeq 2.3 \times 10^{-12}\left(\frac{L_w}{10^{36}\ {\rm erg}\ s^{-1}}\right)^{2/5}\left(\frac{{\rm n}_0}{0.25\ {\rm cm}^{-3}}\right)^{3/5} \left(\frac{10^6\ {\rm yr}}{t}\right)^{4/5} \qquad {\rm dyn\ cm}^{-2}$$

$$P_{\rm ion} = (n_{\rm e} + n_{\rm H} + n_{\rm He})kT_{\rm e} \approx 2n_{\rm e}kT_{\rm e}$$

- Feedback from the massive stellar population in individual subregions
- Direct radiation pressure $P_{\rm dir}$
- Pressure from stellar winds $P_{\rm w}$
- Pressure of the warm ionized gas $P_{\rm ion}$
- The warm ionized gas and winds drive the expansion of the H II regions

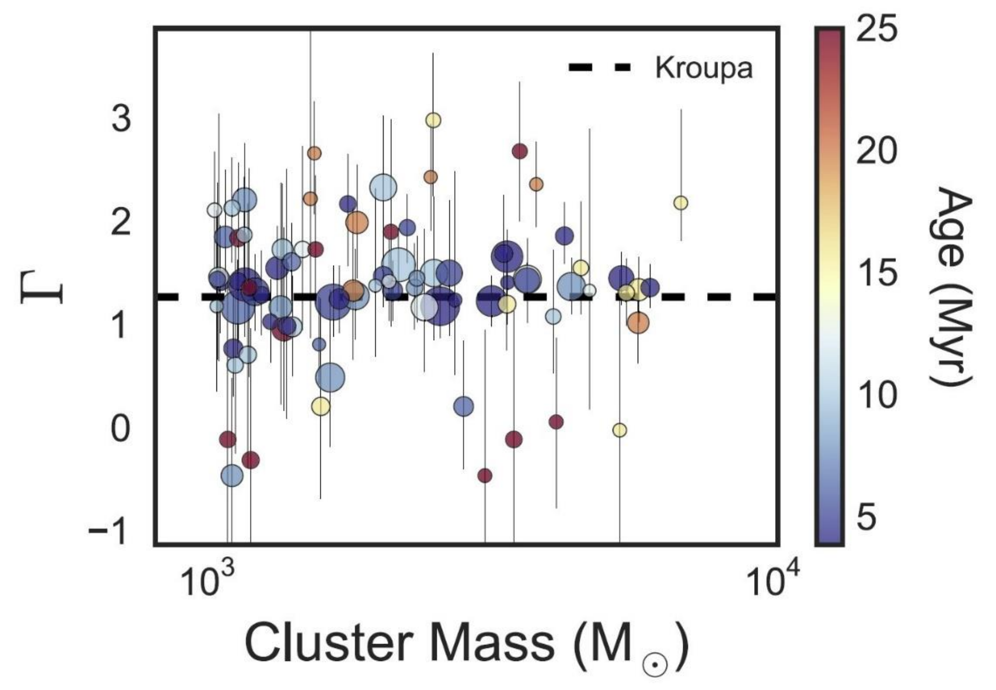


$$
\begin{aligned}
\log \dot{M} \;=\; & -\; 6.697\ (\pm 0.061) \\
& +\; 2.194\ (\pm 0.021)\ \log(L_*/10^5) \\
& -\; 1.313\ (\pm 0.046)\ \log(M_*/30) \\
& -\; 1.226\ (\pm 0.037)\ \log\left(\frac{v_\infty/v_{\rm esc}}{2.0}\right) \\
& +\; 0.933\ (\pm 0.064)\ \log(T_{\rm eff}/40\,000) \\
& -\; 10.92\ (\pm 0.90)\ \{\log(T_{\rm eff}/40\,000)\}^2 \\
& +\; 0.85\ (\pm 0.10)\ \log(Z/Z_\odot)
\end{aligned}
$$

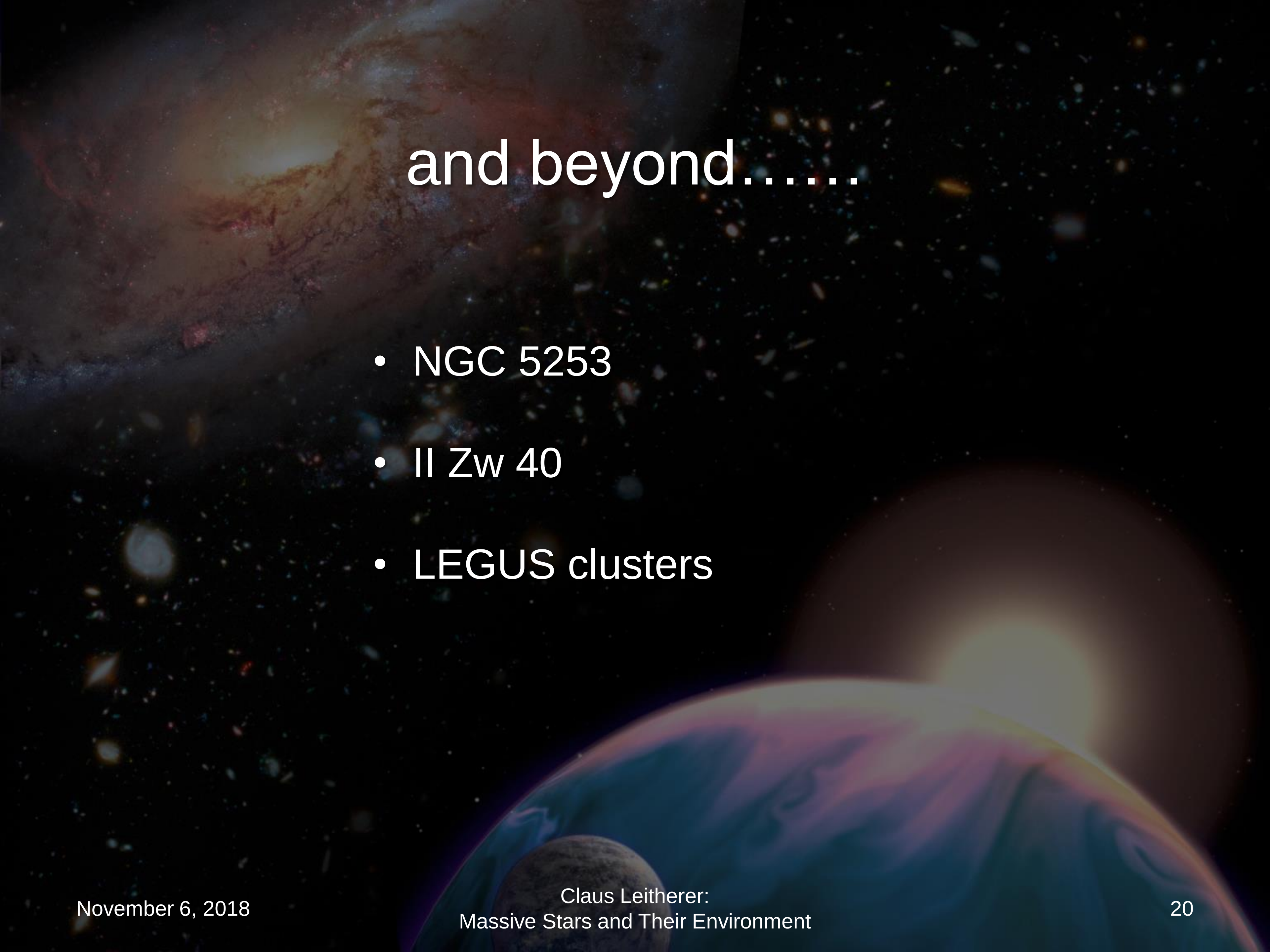
for $27\,500 < T_{\rm eff} \leq 50\,000$ K

- Wind input may have been overestimated
- Assumed solar abundances for mass-loss rates
- Mass-loss rates scale with heavy-element abundances (Vink et al. (2001)
- Generally supported by data in the LMC and SMC
- Weak wind features in spectra of extremely metal-deficient galaxies
- Difficult to disentangle from uncertainties in *L*

Weisz et al. (2015): PHAT (Panchromatic Hubble Andromeda Treasury)



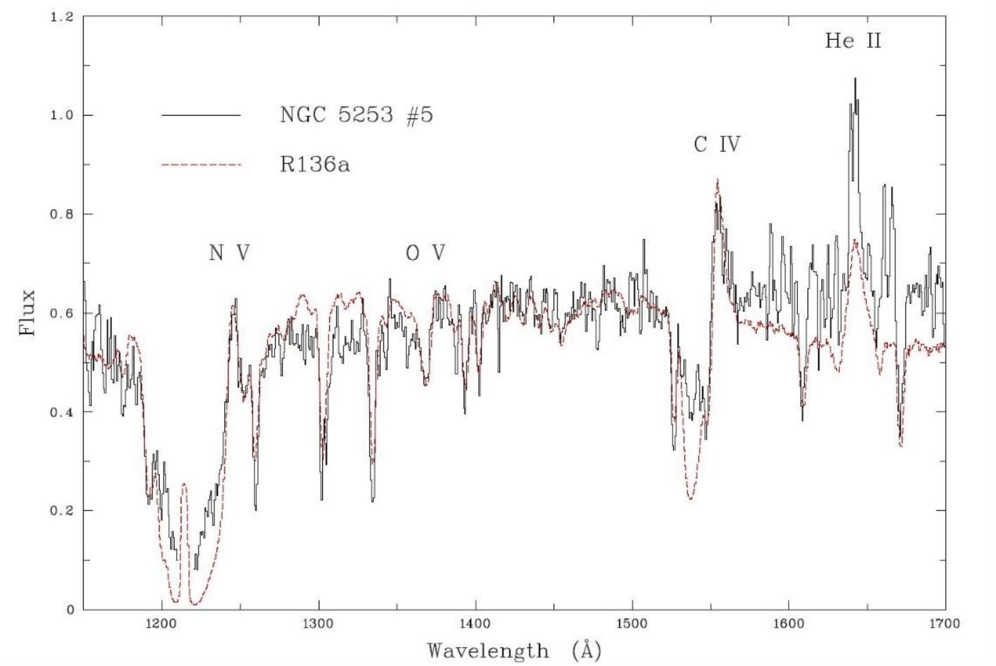
- IMF determination in young M31 clusters
- Slope at the upper end close to Kroupa (2002)
- No significant dependence on environment and other cluster properties
- Caveat: exclusively based on photometry



and beyond……

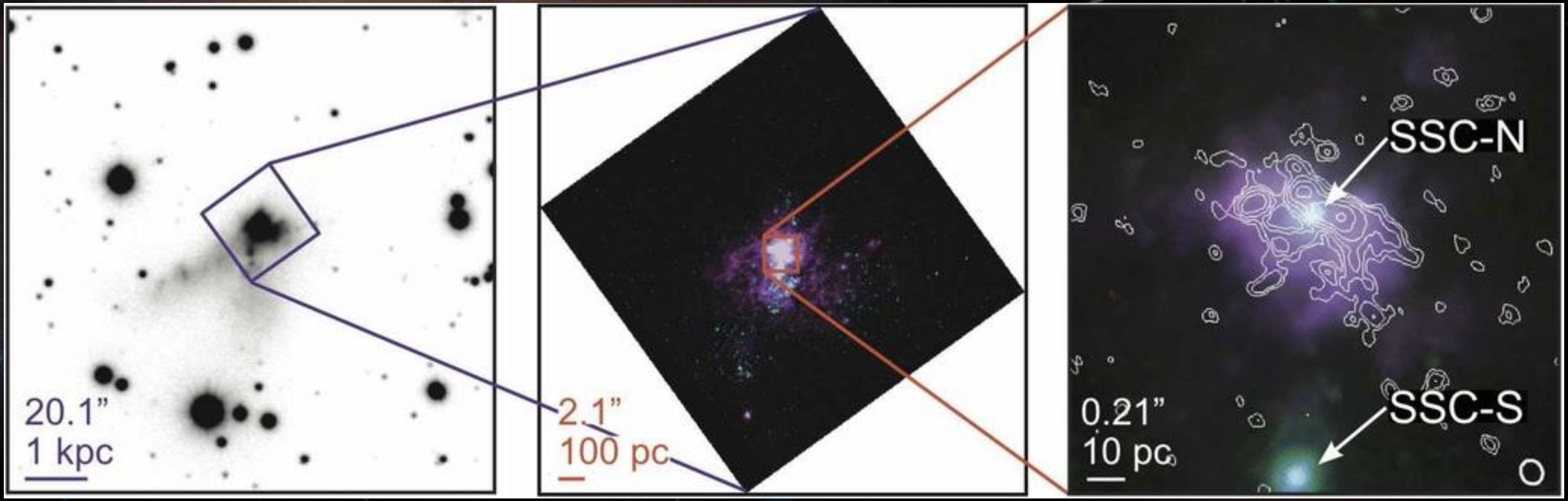
- NGC 5253
- II Zw 40
- LEGUS clusters

Smith et al. (2016): HST COS spectroscopy of a massive cluster in NGC 5253



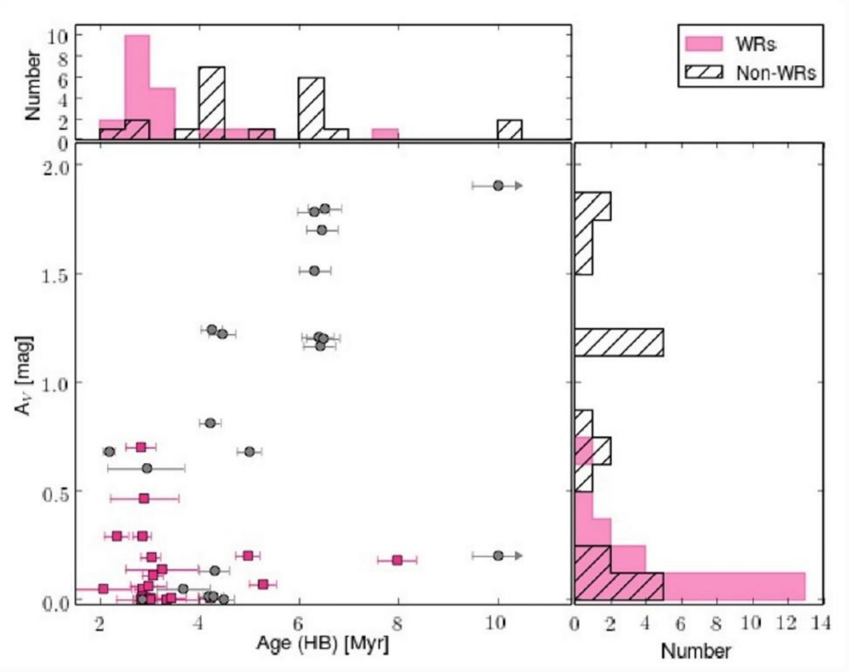
- $M = 3 \times 10^5$ $M_\odot$
- $t < 2$ Myr
- Spectrum strikingly similar to that of central stars of NGC 2070
- Presence of very massive stars is likely

Kepley et al. (2014): thermal radio emission in II Zw 40



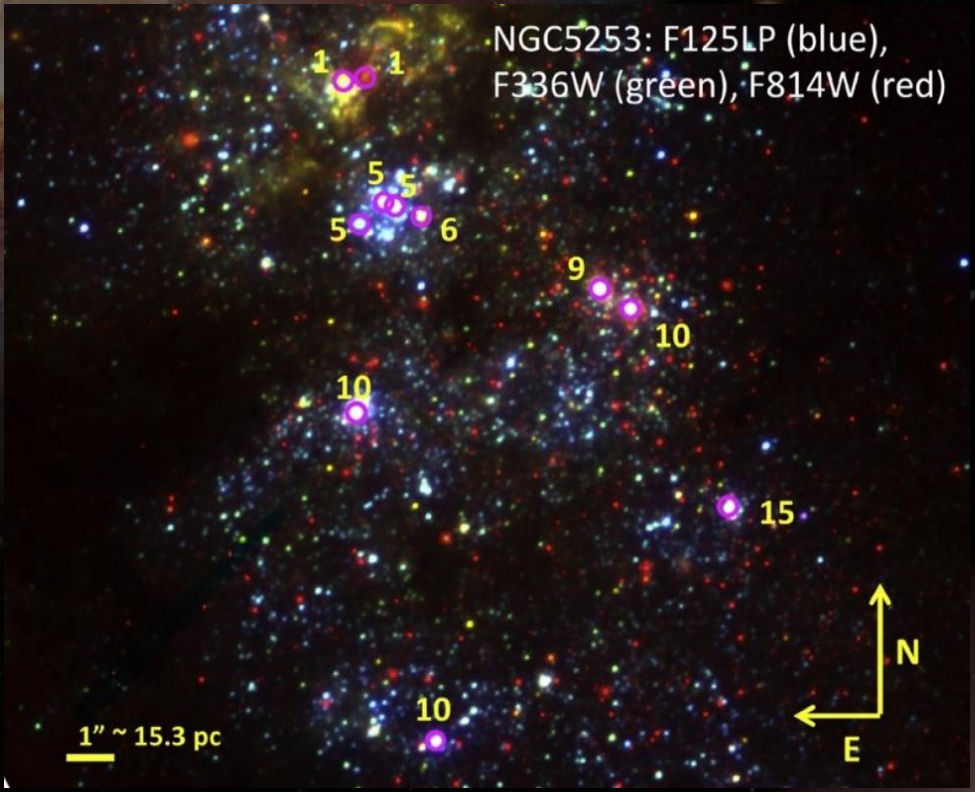
- II Zw 40: original “extragalactic HII region” (Searle & Sargent 1971)
- O/H+12 =8.09; D=11.1 Mpc; $M_{\rm dyn}$= 6 × 10^9 $M_\odot$
- Dominated by one ionizing cluster “SSC-N” and associated giant H II region
- $M = 9 \times 10^5\ M_\odot$, $L_{\rm Bol} = 1.1 \times 10^9$ erg s^{-1},$Q_{\rm H} = 6 \times 10^{52}$ s^{-1}, $t = 2.8$ Myr
- Order of magnitude more massive and luminous than 30 Dor (Leitherer et al. 2018)

Sokal et al. (2016): emerging star clusters with W-R features



- Star clusters selected as thermal radio emitters and embedded in dust
- W-R features commonly detected at ages as young as 2 Myr
- Birth material cleared out by W-R winds
- Genuine W-R stars not predicted by evolution models at this age

Calzetti et al. (2015): HST LEGUS (Legacy Extragalactic UV Survey)



- Panchromatic UV to near-IR imaging of NGC 5253
- Labels indicate ages in Myr; Cluster #5 is at the very top
- Age gradient → propagating star formation
- H I tail → interaction with M83 and infall of gas (López-Sánchez et al. 2012)

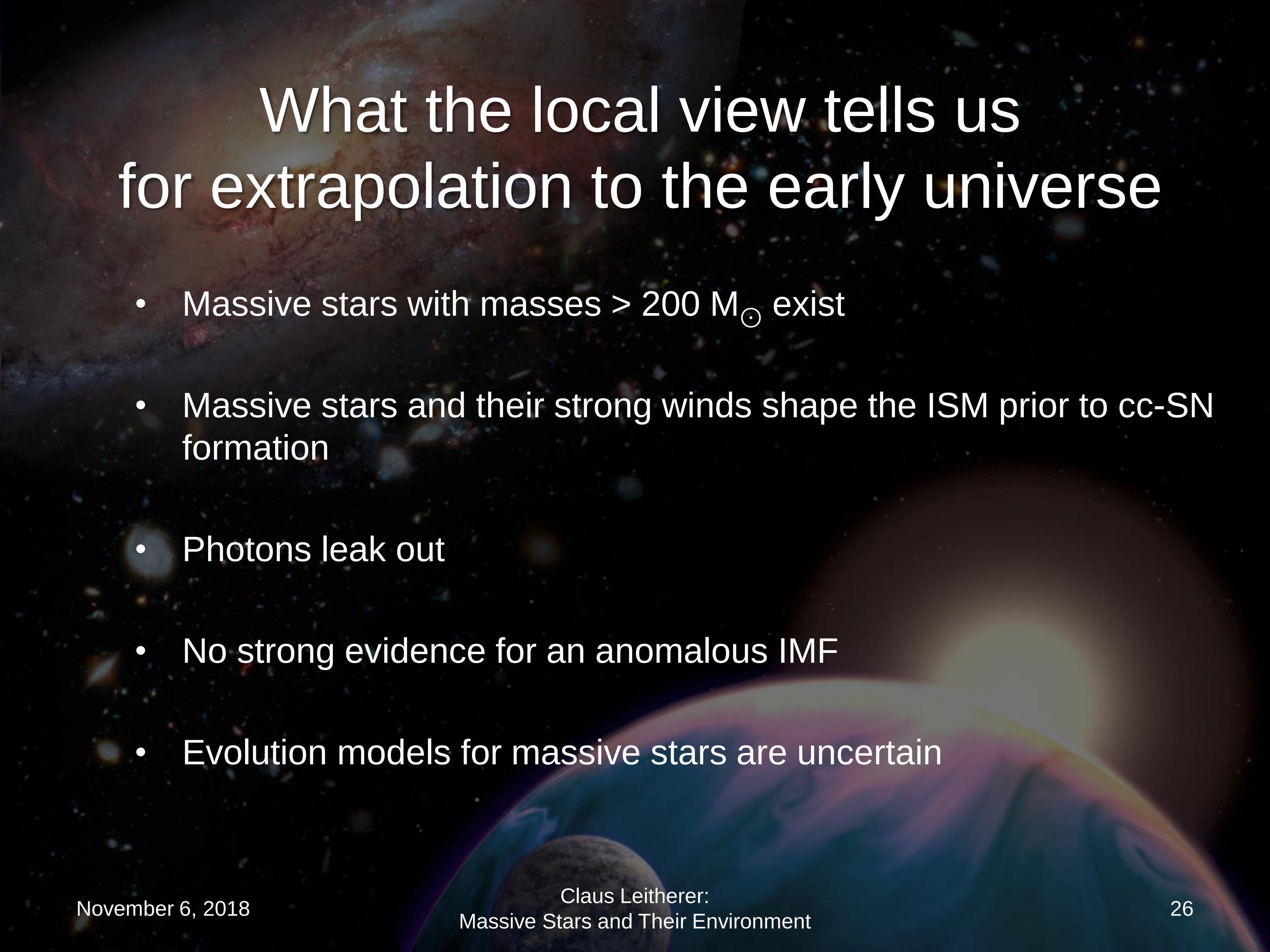
Hunter et al. (2018): environmental effects in LEGUS galaxies

- Star clusters characterized by concentrations, masses, and formation rates

- Compared to surrounding galactic pressure, stellar mass density, H I surface density, and star formation rate surface density

- No trend of cluster characteristics with environmental properties

- Rapid dynamical evolution may erase any memory of the initial conditions.



What the local view tells us for extrapolation to the early universe

- Massive stars with masses > 200 $M_\odot$ exist
- Massive stars and their strong winds shape the ISM prior to cc-SN formation
- Photons leak out
- No strong evidence for an anomalous IMF
- Evolution models for massive stars are uncertain