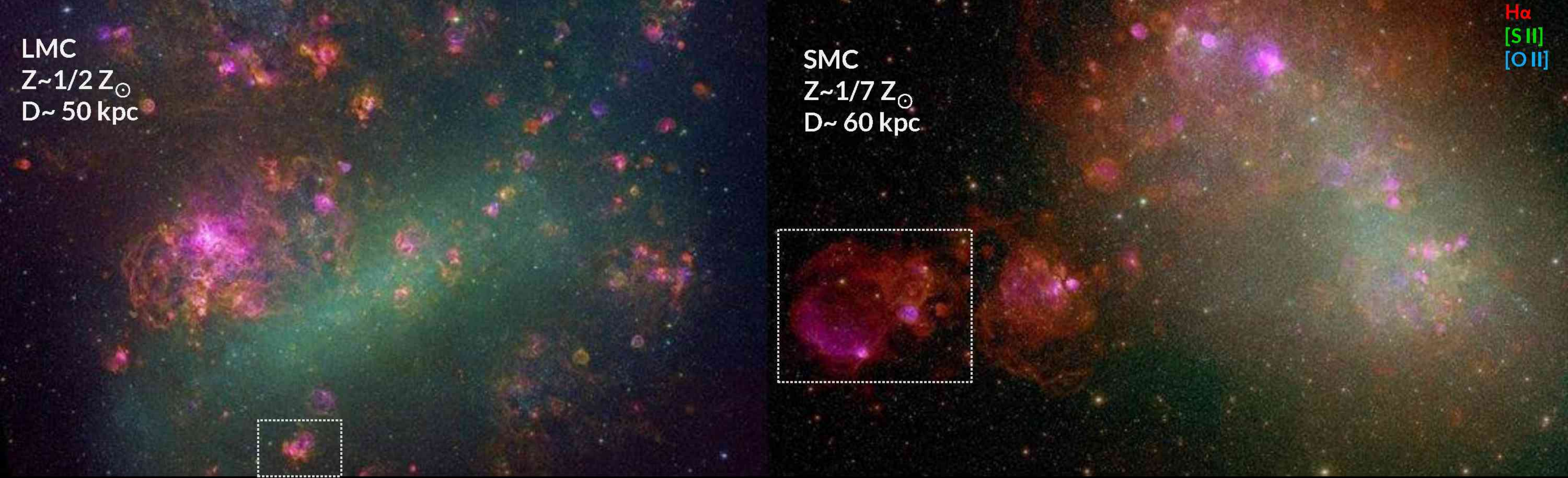

Stellar feedback powering star-forming complexes in the Magellanic Clouds

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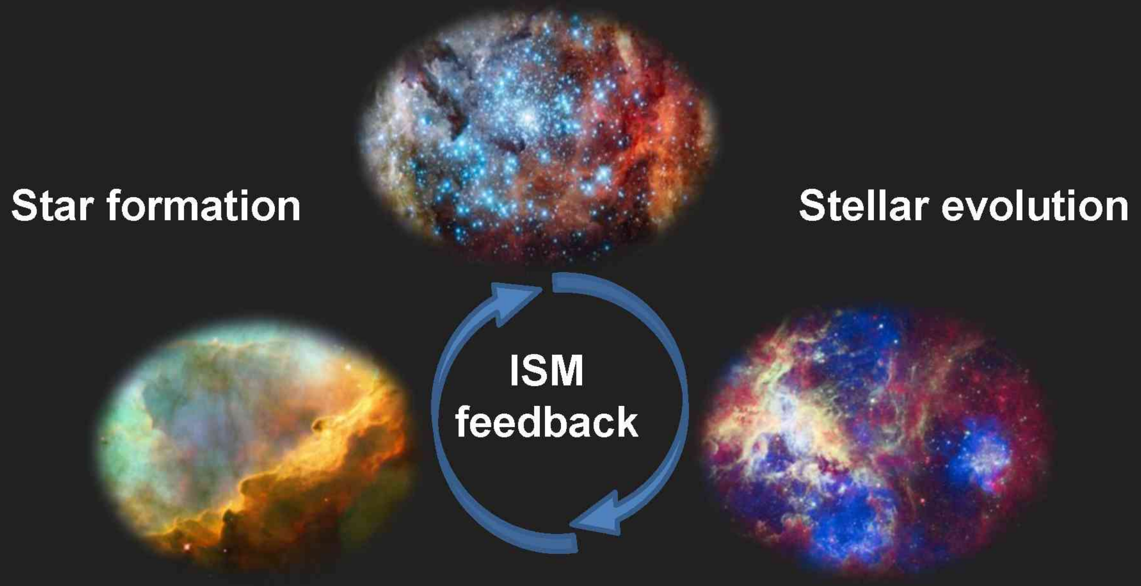
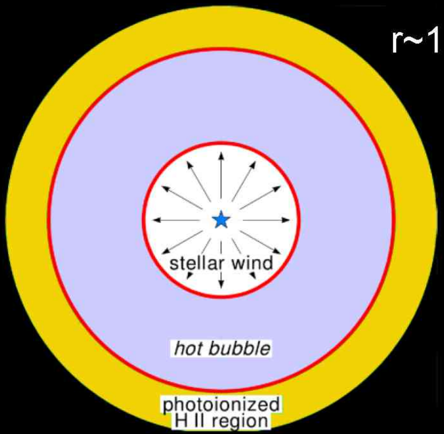

Star formation
Stellar evolution
ISM
feedback

Is stellar feedback sufficient to explain the large-scale ISM structures?

- Quantify stellar feedback
- Key feedback agents
- Energy budget
- Impact of metallicity

- Formation and evolution of superbubbles and supergiant shells
- Mode of star formation

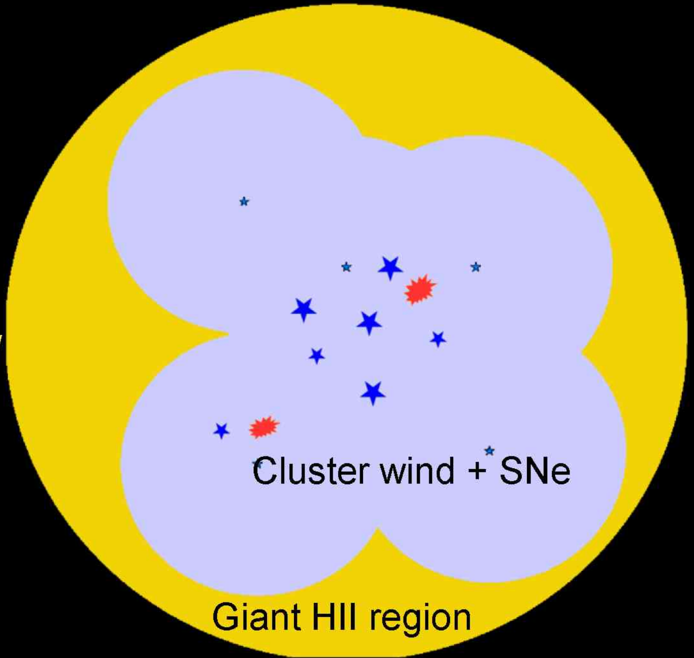


r~10 pc

Bubbles around single stars

r~100 pc

Superbubble/ giant shell



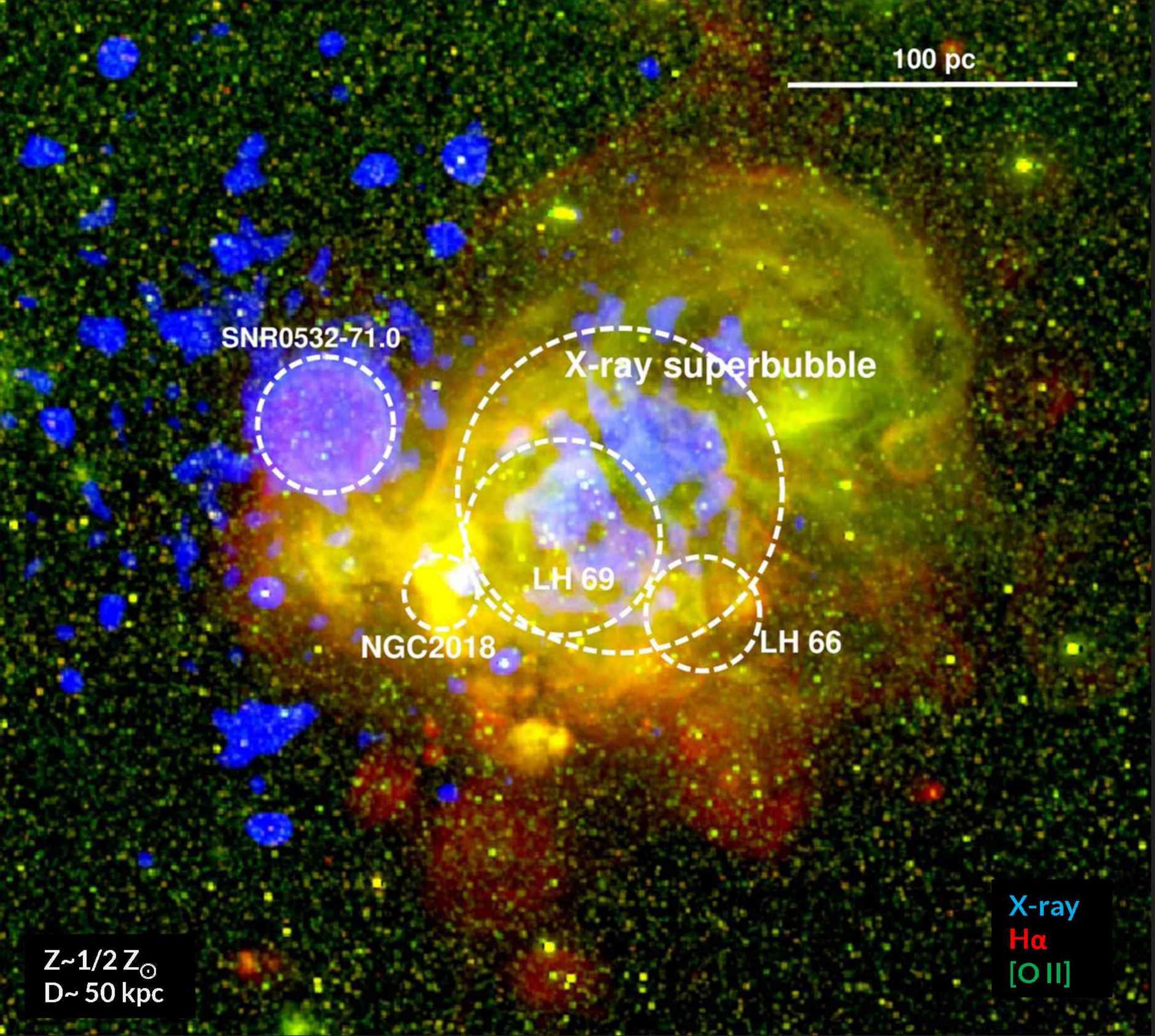
LMC
$Z \sim 1/2\ Z_{\odot}$
D~ 50 kpc

Towards lower metallicities

Milky Way
$Z = Z_{\odot}$

SMC
$Z \sim 1/7\ Z_{\odot}$
D~ 60 kpc

Magellanic Clouds as a template to study low-metallicity massive stars & ISM in the early Universe



The LMC-N206 Complex

(Ramachandran et al. 2018a, b)

Cavity filled with X-rays
Surrounding H II region

Young clusters / associations

Active star-formation at the rim of superbubble

X-ray analysis by Kavanagh et al. (2012)

VLT-FLAMES spectroscopy in LMC-N206

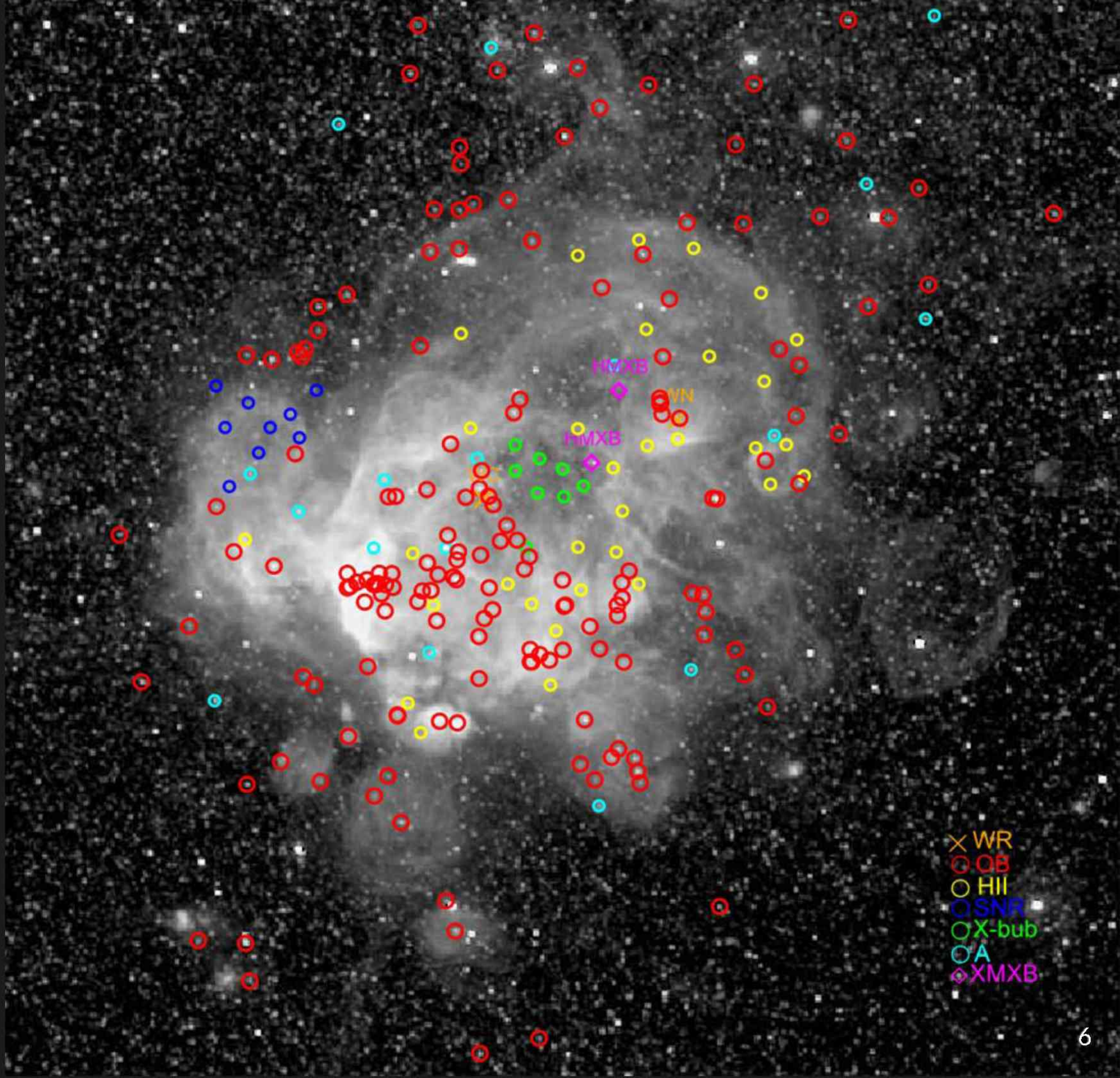
blue hot stars(> B2V):
B − V < 0.20 and V < 16 mag

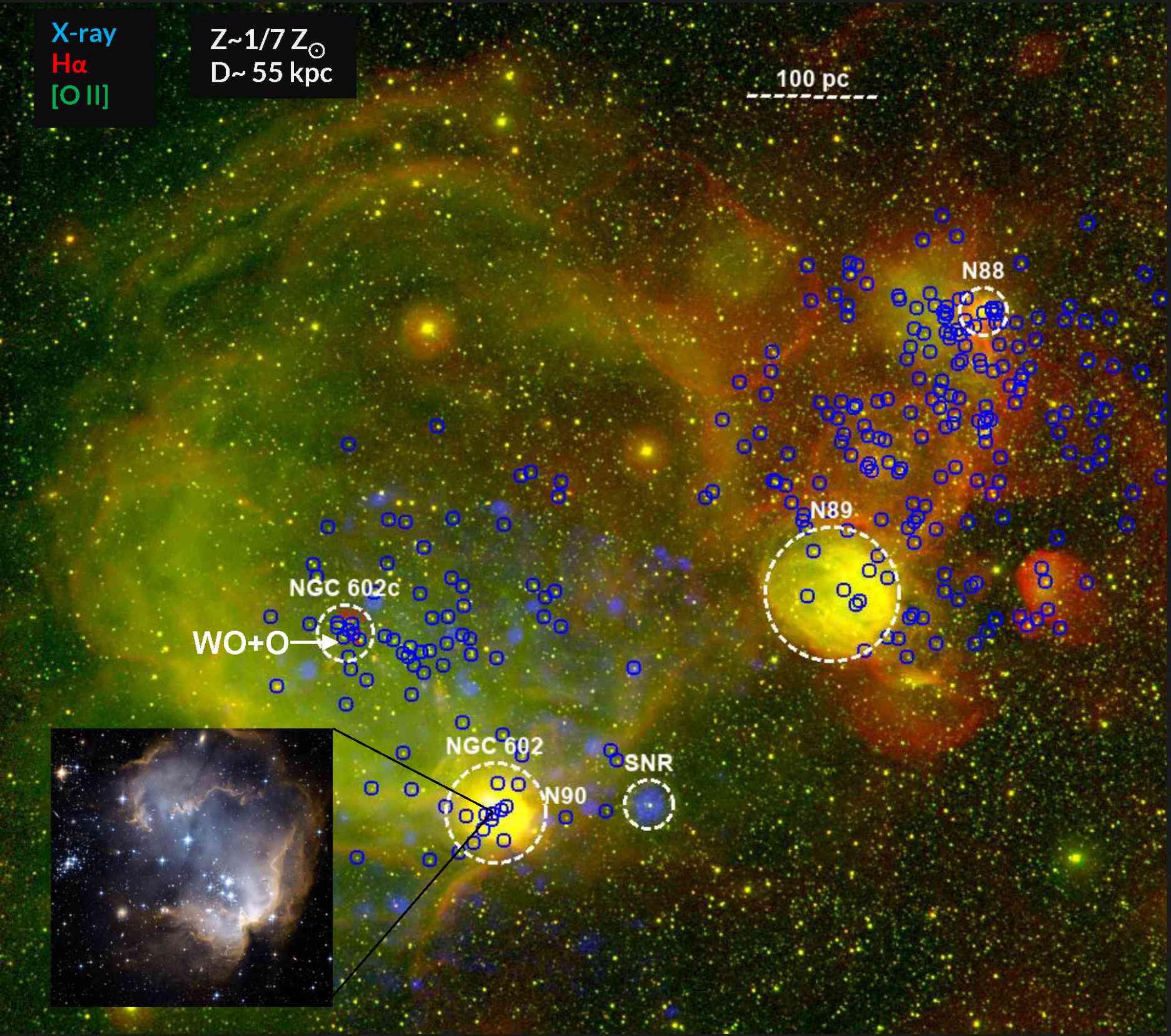
λ: 3960-5071Å (R~7000),
6442-6817Å (R~19000)

S/N > 50

Massive stars :
WN star (1)
WC star (1)
OB stars (164)

Ionized gas :
HII region (32)
X-ray bubble (8)
SNR (9)





The supergiant shell SMC-SGS1

(Ramachandran et al. 2019)

- Low density, low metallicity
- r_{SGS}~ 300 pc, complex ~1 kpc
- Several nebular regions & clusters
- No diffuse X-ray in the SGS
- Associated with H I supershell

VLT-FLAMES spectra of 320 OB stars

λ: 3960-5071Å (R~7000),
6442-6817Å (R~19000)

V < 17 mag; S/N > 50

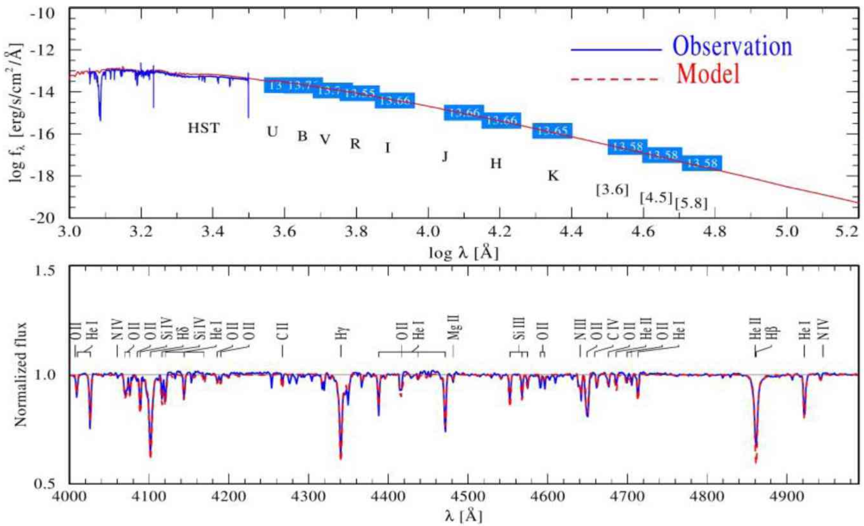
PoWR - The Potsdam Wolf-Rayet Models

PoWR models from the web: SEDs, spectra, ionizing fluxes: http://www.astro.physik.uni-potsdam.de/PoWR/

OB model grids | WR model grids

LMC | SMC | Galaxy

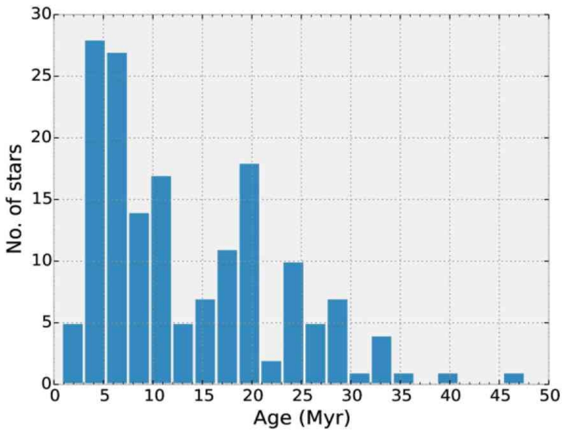
Spectral analysis

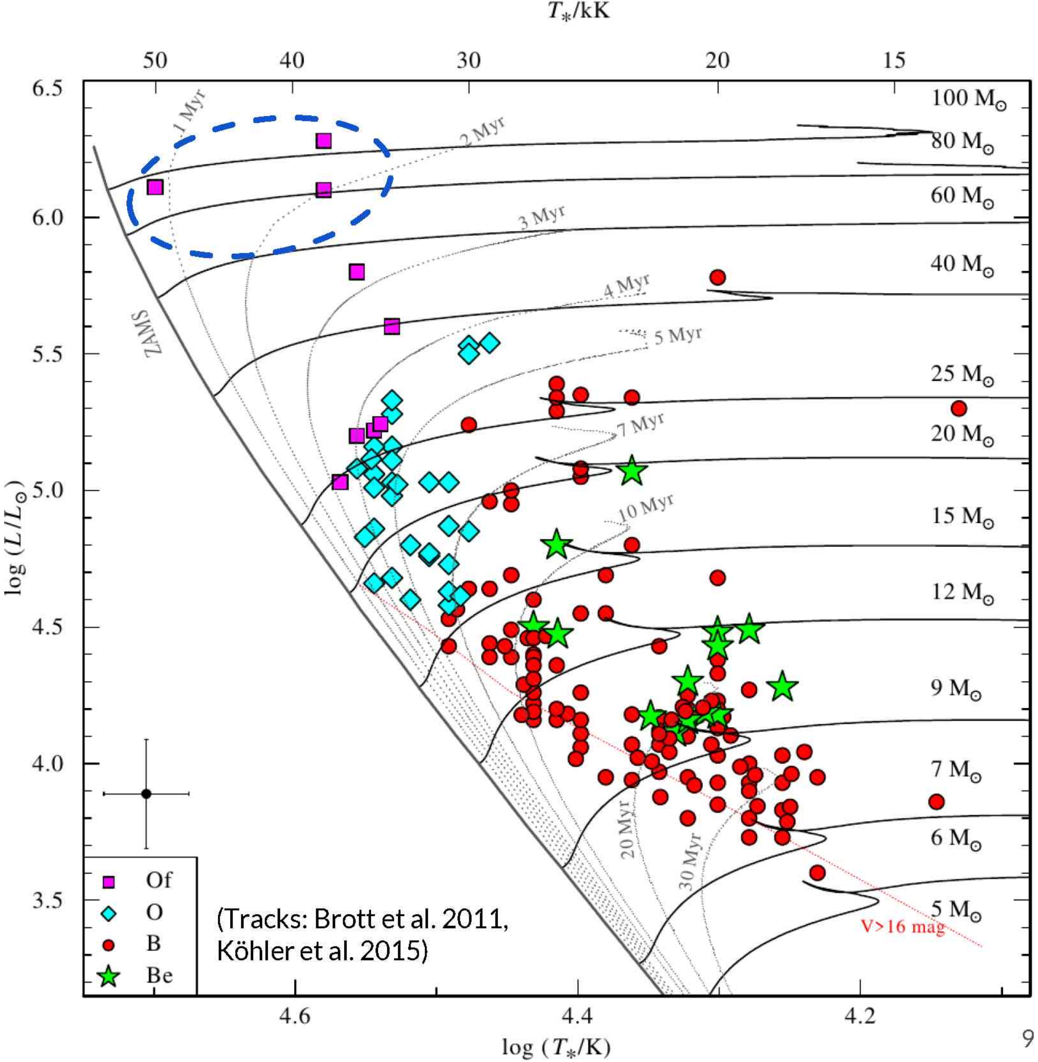


- Temperature
- Surface gravity
- Luminosity
- Color excess
- Stellar radius
- Stellar mass
- Mass-loss rate
- Terminal wind velocity
- Radial velocity
- Projected rotational velocity
- Ionizing photons

HRD of massive star population in LMC-N206

- Ages spread from 0 - 30 Myr
- Massive stars are not co-eval
- 3 Of stars with log L > 6 are the youngest (<2 Myr) and most massive (70 -100 $M_\odot$) stars!
- SFR ~ 0.03 $M_\odot$ yr^{-1} kpc^{-2}





Massive stars/ cluster (older generation)

↓

Emergence of superbubble

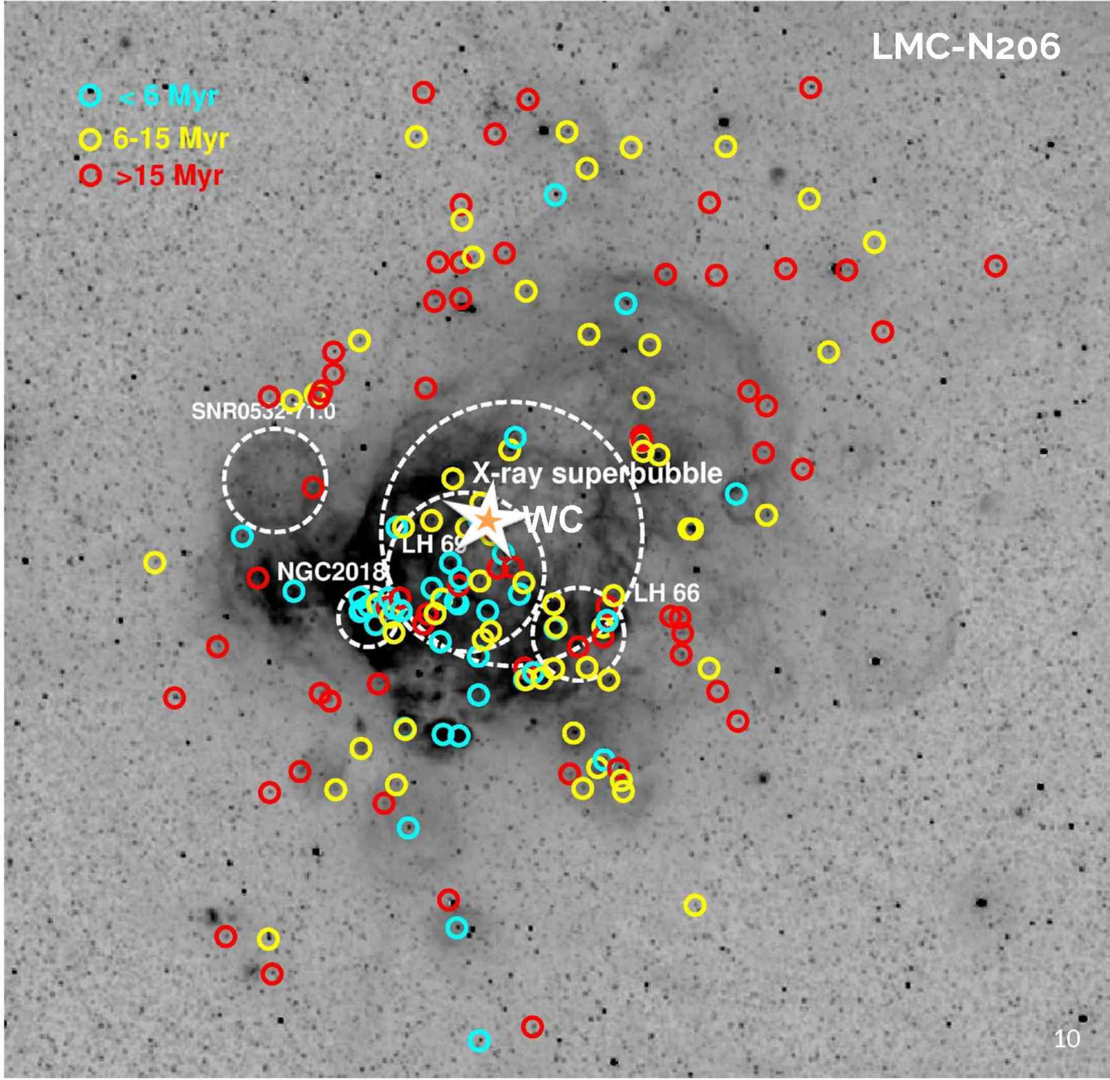
↓

Expansion of superbubble

↓

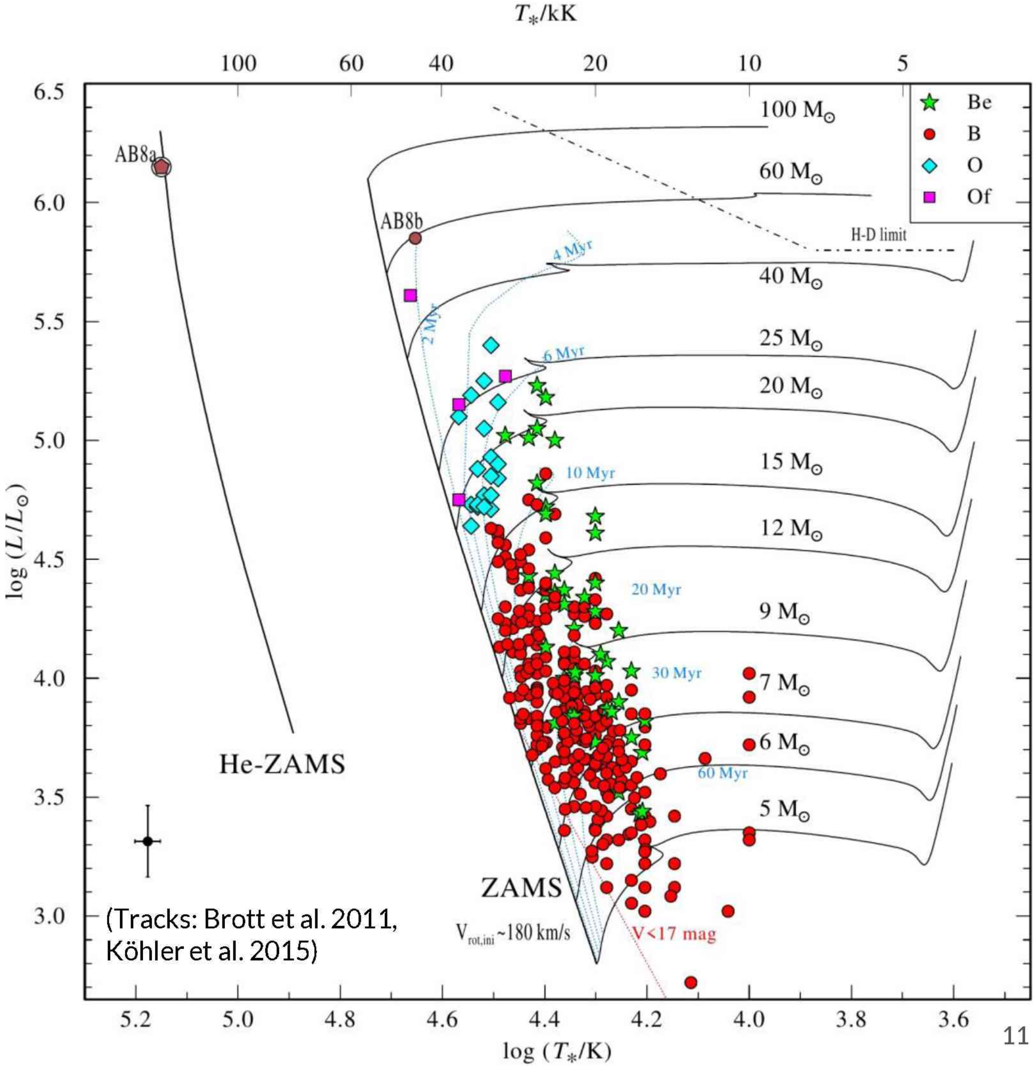
Trigger formation of Massive stars/ cluster at the rim

Older generation O stars → evolved/SNe
B stars → migrated outwards

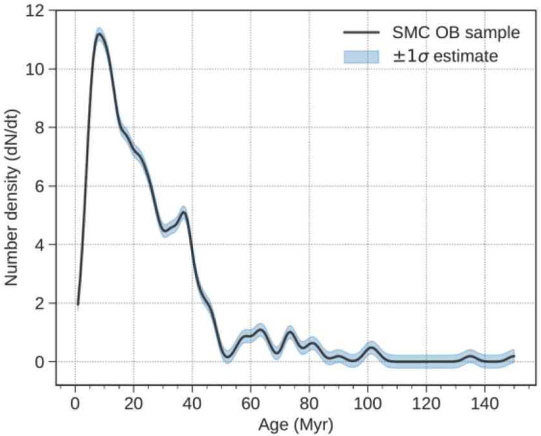


HRD of massive star population in SMC-SGS1

- Evolutionary masses ~5–50 $M_\odot$
- The earliest (O3) massive star with M~47 $M_\odot$ & age < 2Myr
- Massive binary WO+O4 with M_{ini}~200 $M_\odot$ and age ~3 Myr (Shenar et al. 2016)
- Wide MS; age spread in the complex ~ 0 - 100 Myr
- SFR surface density ≈ 4 × 10^{-3} $M_\odot$ yr^{-1} kpc^{-2}



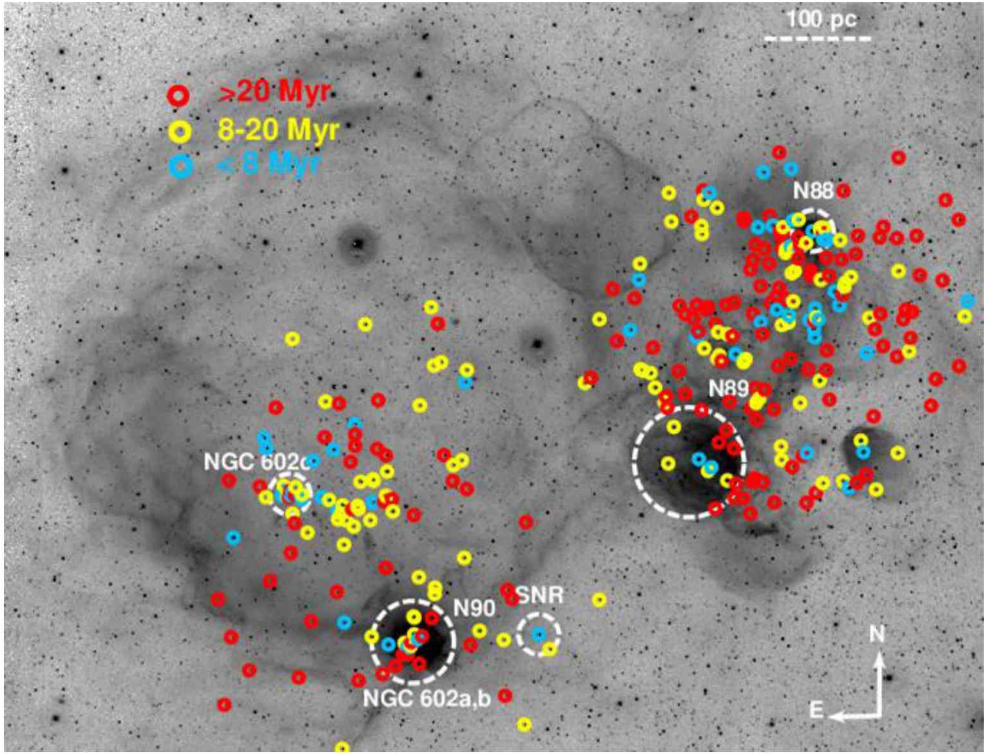
Stochastic mode of star formation in SMC-SGS1



Persistent star formation since more than 100 Myr across ~ 1 kpc

SFR ~0.004 $M_{\odot}$ yr^{-1} kpc^{-2}

Hα not a good proxy for SFR?



Spatial distribution of ages of OB stars ⇒ nullifies SGS induced star formation at the rim; supports a stochastic mode of star formation!

LMC-N206
Ionizing feedback

Rate of hydrogen ionizing photons Q

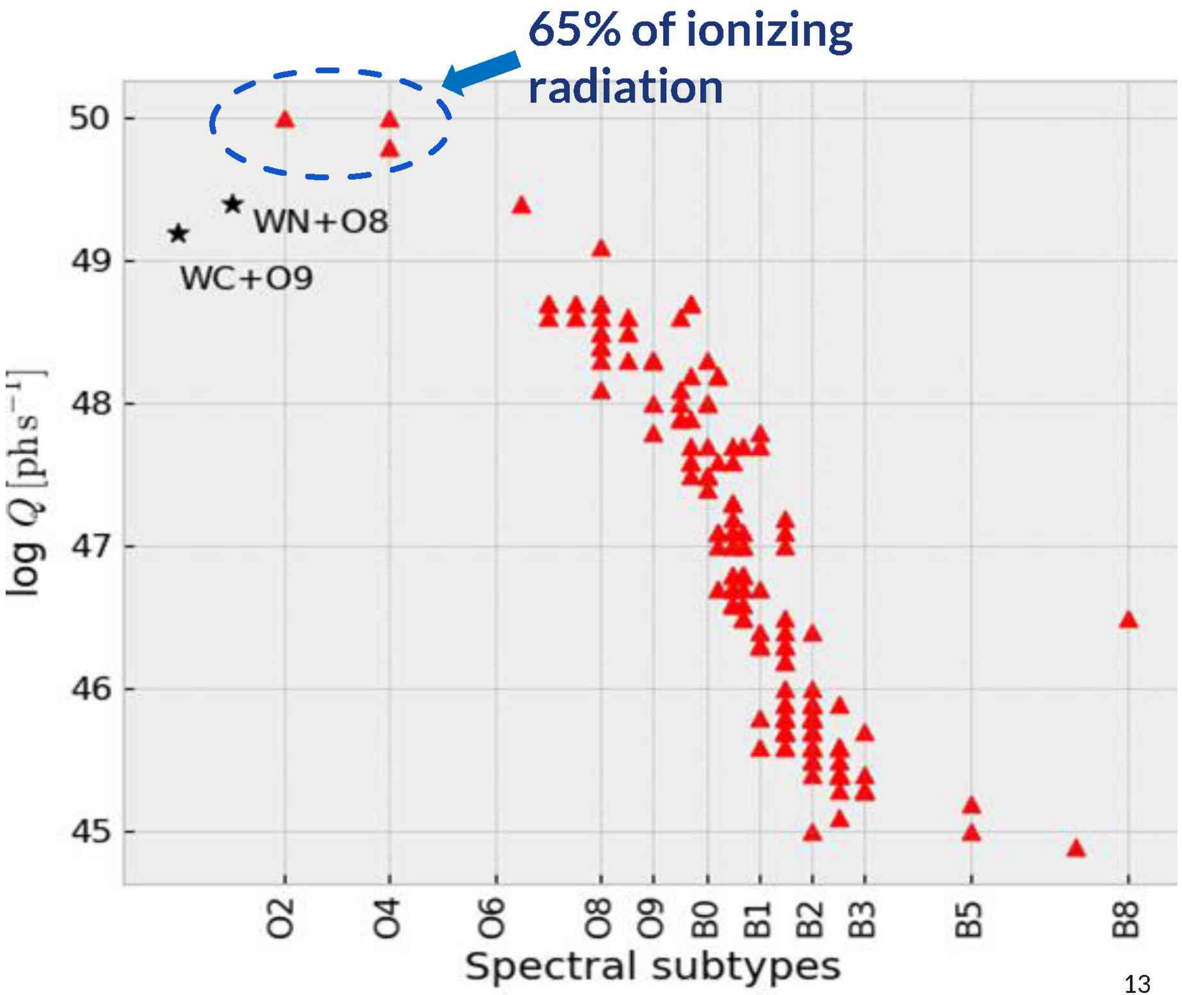
Dominated by 3 massive O stars

OB : $\Sigma Q \approx 4 \times 10^{50}\,s^{-1}$

WR : $\Sigma Q \approx 5 \times 10^{49}\,s^{-1}$

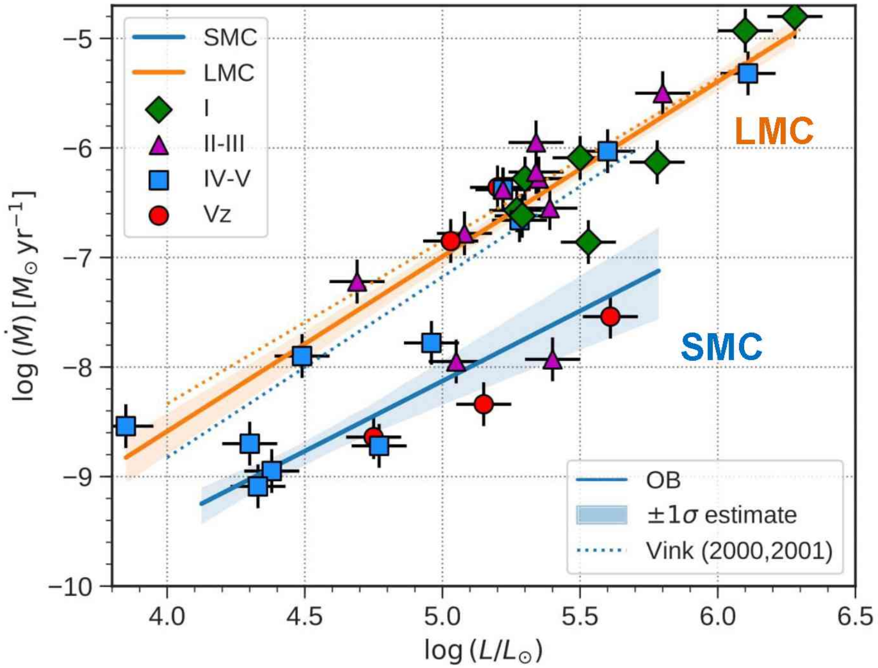
Q (H α) ≈ $2.7 \times 10^{50}\,s^{-1}$

→ 40 % photon leakage



Winds of massive stars at low metallicity

- OB stars with UV + optical spectra
- SMC OB stars have very weak winds!
  - an order of magnitude systematic offset compared to theoretical predictions
- A steeper relation between $\dot{M}$ and Z?



LMC-N206
Stellar wind feedback

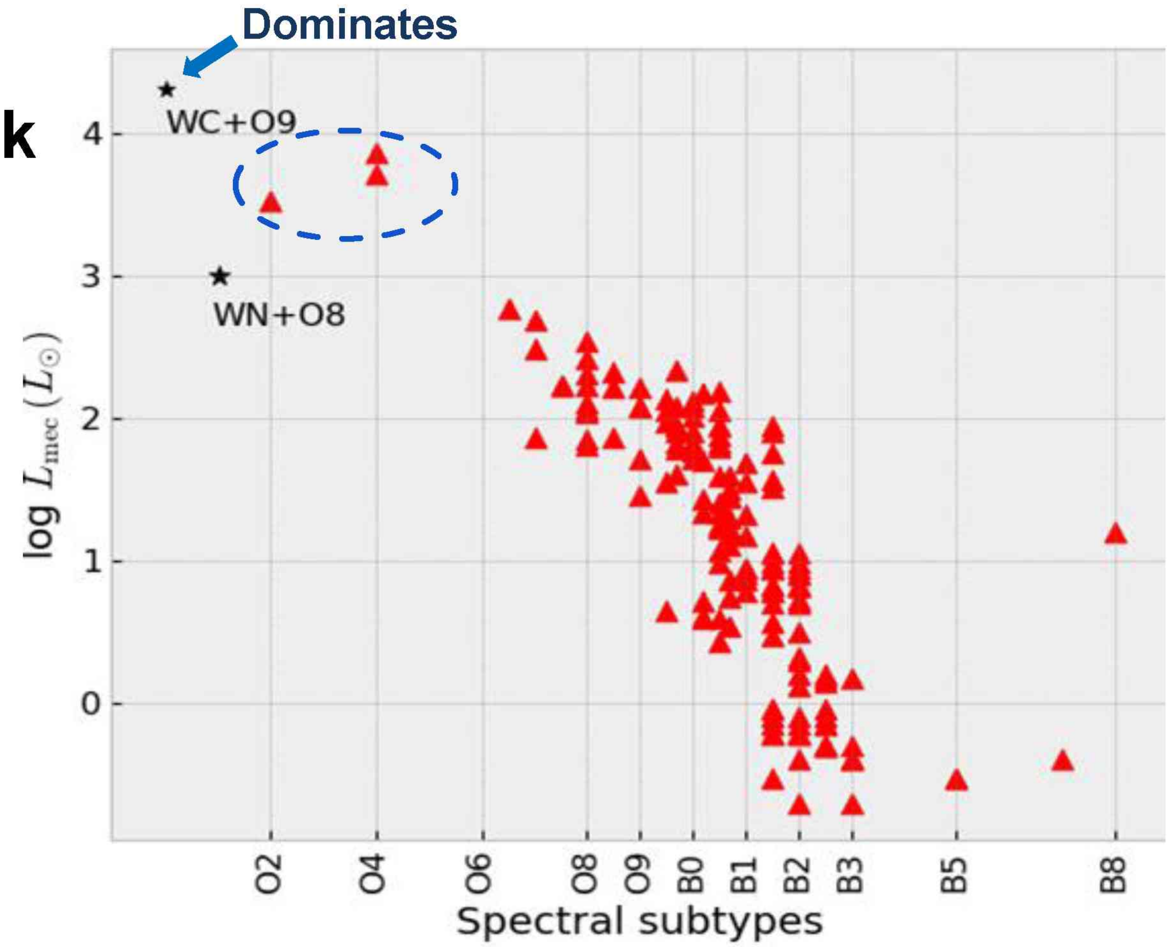
Mechanical luminosity
$L_{mec} = 0.5 \dot{M} v_{\infty}$

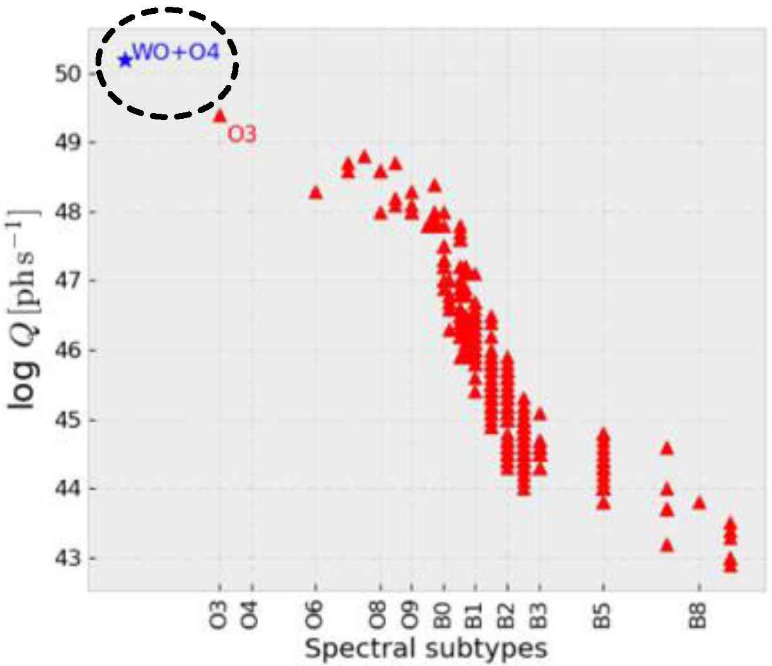
30% from 3 massive O stars

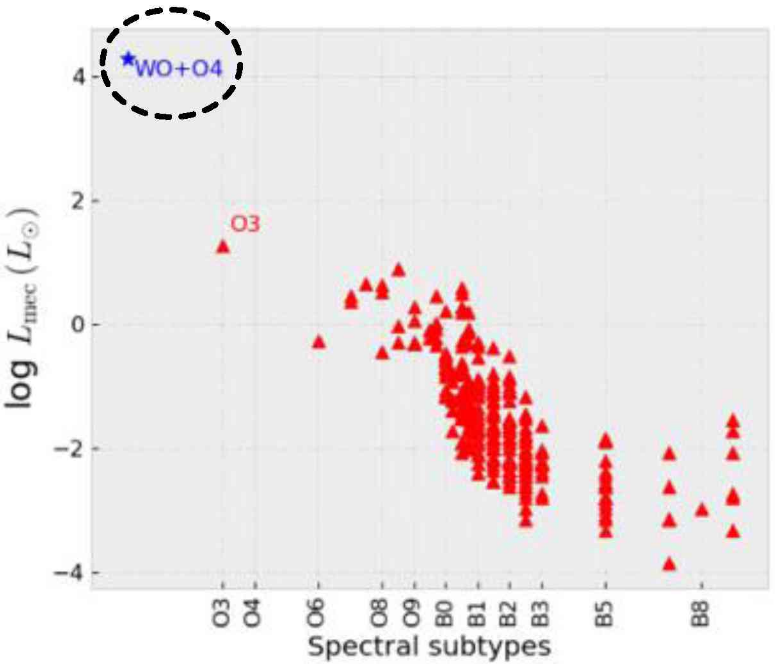
OB stars vs. WR binaries
50-50 !

Comparison with X-ray
(Kavanagh et al. 2012)

$\sum L_{mec}$ (WR+OB) >> $L_{X\text{-ray superbubble}}$
factor of 250 larger !







A WO+O system dominates the radiative feedback and current mechanical luminosity of the SGS-SMS1 ⇒ other 300+ OB stars have no impact!

Total Mechanical feedback

Wind + Supernovae

Mechanical energy stored over time E_{mec}

$= \sum \int_0^{\tau} \frac{1}{2} \dot{M} v_{\infty}^2 + \sum E_{SN}$

Supernovae rate in the complex ~ 2…3 per Myr

Stellar winds vs. Supernovae

	LMC-N206	SMC-SGS1
Total E_{mec}	2.3×10^{52} erg	1.2×10^{52} erg
OB	43%	0.5%
WR	9%	16%
SNe	48%	83%

$E_{wind} \approx E_{SNe}$

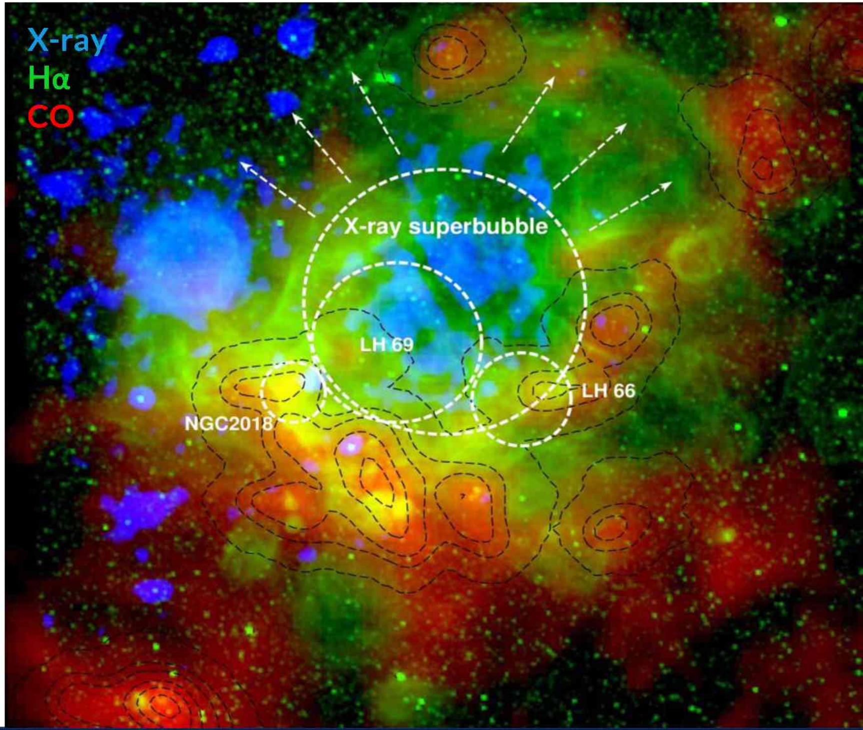
SNe dominate

Metallicity decides the key feedback agents!

LMC-N206: Energy budget

Input		Output
Stars		**ISM**
Mechanical energy $\gtrsim 2 \times 10^{52}$ erg	**>**	**Hot gas + expansion of superbubble** $\sim 5 \times 10^{51}$ erg
$Q_{LyC} \approx 4.5 \times 10^{50}\ s^{-1}$	**>**	$Q_{H\alpha} \approx 2.7 \times 10^{50}\ s^{-1}$

Missing energy & photons!



Stellar feedback is more than sufficient to create superbubble + giant HII region $\Rightarrow$ Most of the energy is leaking from the complex!

SMC-SGS1: Energy budget

Input		Output
Stars		**ISM**
		(HI supershell)
Momentum		**Momentum**
$\sim 5 \times 10^{45}$ g cm s^{-1}	$\approx$	$\leq 6 \times 10^{45}$ g cm s^{-1}
Mechanical energy		**Kinetic energy**
$\gtrsim 10^{52}$ erg	>	$\sim 6 \times 10^{51}$ erg
$Q_{LyC} \approx 2.3 \times 10^{50}$ s^{-1}	>	$Q_{H\alpha} \approx 10^{50}$ s^{-1}

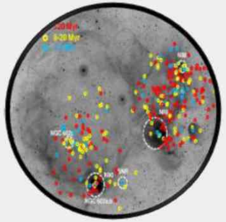
Missing energy & photons!

Stellar feedback over past 30 Myr fully capable of producing the SMC supergiant shell

Summary

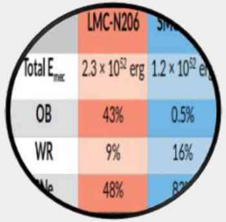
Ramachandran et al. 2018 a, b, 2019

Quantitative spectroscopy of massive stars in the Magellanic Clouds →
Star formation and feedback at low metallicity



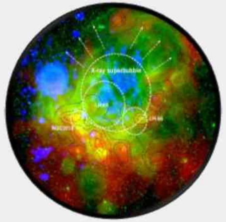
Metallicity and density of the ISM decide on mode & duration of SF

- Higher Z & gas density ⇒ sequential star formation, high SFR, short bursts
- At low Z & low density: stochastic & persistent star formation



Metallicity decides the key feedback agents Winds vs. SNe

- At LMC metallicity or higher: strong winds, stellar wind feedback ~ supernovae
- At low Z: very weak winds, supernovae dominate the feedback



Stellar feedback >> observed energy content

- Stellar feedback is more than sufficient to create large-scale ISM structures even at low Z
- Most of the energy and radiation are leaking out