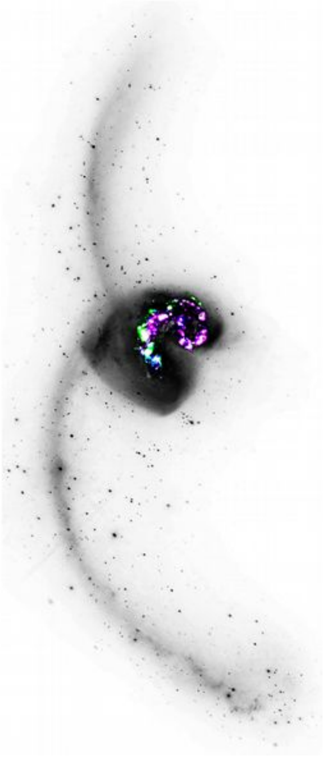
AIP

muse
multi unit spectroscopic explorer

Evidence for Lyman-continuum escape from HII regions in the



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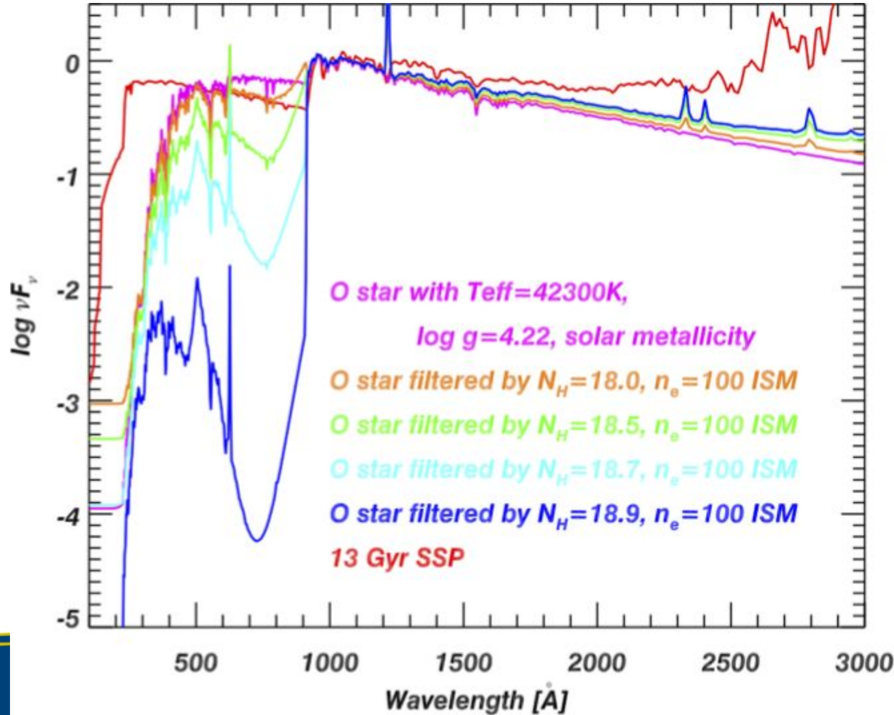
and the *MUSE Collaboration*

based on Weilbacher et al. 2018 A&A 611, A95
(arXiv:1712.04450)

Diffuse Ionized Gas (**DIG**)

- Ionized gas emission between HII regions
  - fainter surface brightness
  - but no clear definition!
- Typically has high [SII]/Hα and [OI]/Hα ratios
  → different UV radiation field? (Reynolds 1985, Mathis 2000, ...)
- Where does it come from?
  - Leaking HII regions? (Zurita et al. 2002, Hoopes & Walterbos 2003)
  - Shocks? (Dopita & Sutherland 1995)
  - Dimmed SN remnants? (Roth et al. 2018)
  - Old stellar populations? (Gomes et al. 2016, Zhang et al. 2017)
  - Cosmic rays? (Dahlem et al. 1994, Collins et al. 2000)

Zhang et al. 2017



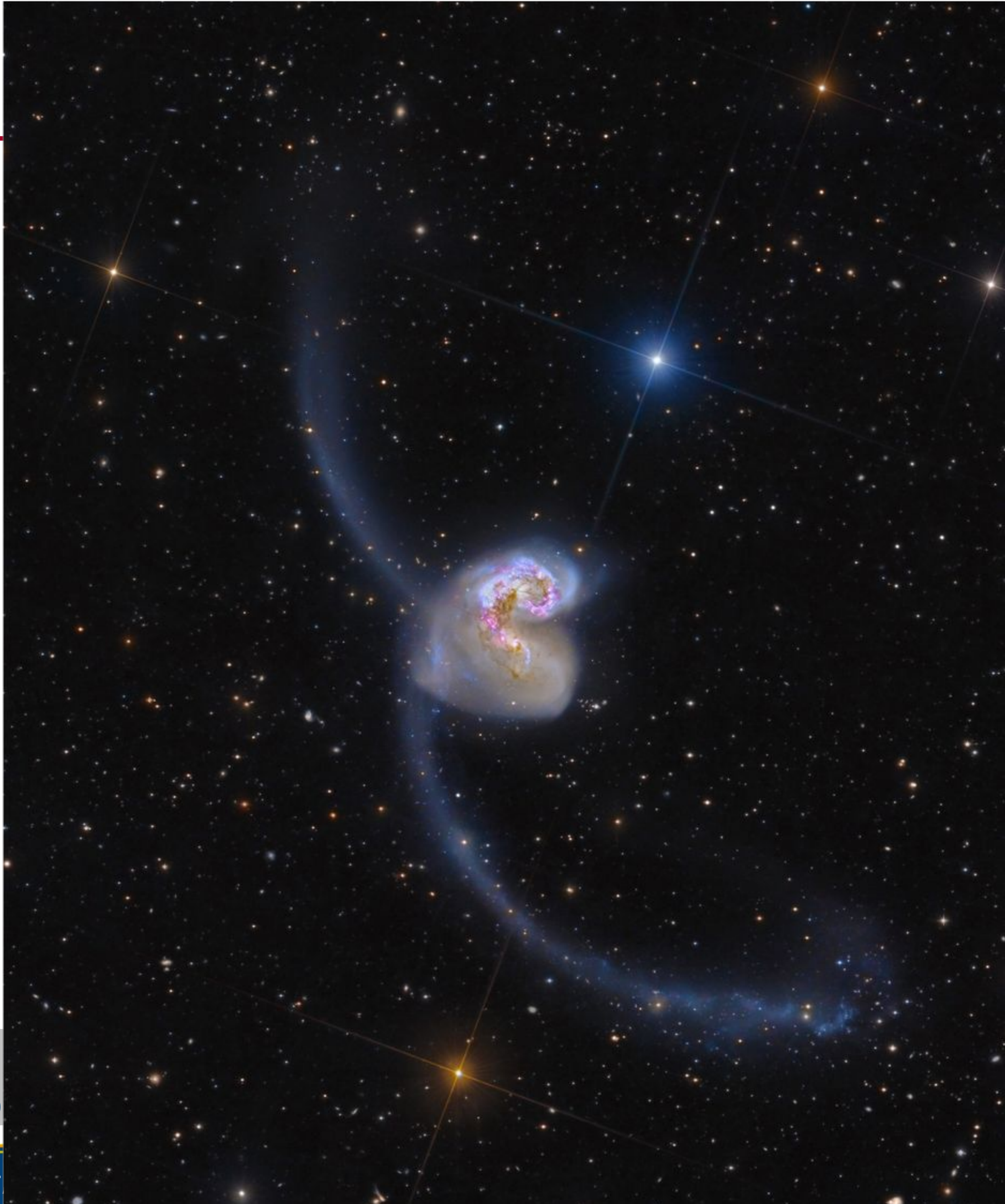
Lyman-continuum escape

- Keeping the universe ionized since high-z
- LyC escape from local galaxies recently detected
  - typically a few percent (Leitherer et al., Izotov et al., ...)
- Escape from HII regions
  - observed in the LG (Voges et al. 2008, Pellegrini et al. 2012)
  - escape from 20-30% of HII regions
  - f_{esc} up to 50% and more!
- Only escape galaxy, if not absorbed in ISM, CGM

→ compare DIG strength and LyC rates

The Antennae

NGC 4038/39
Arp 244



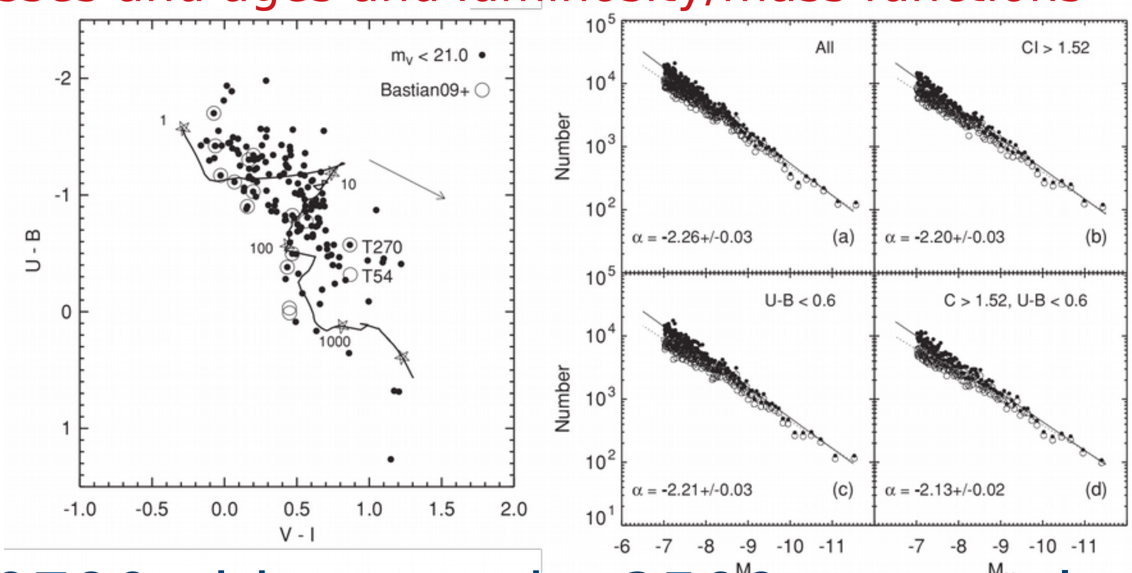
Peliccia & Olsen
(various instruments)

Antennae Properties

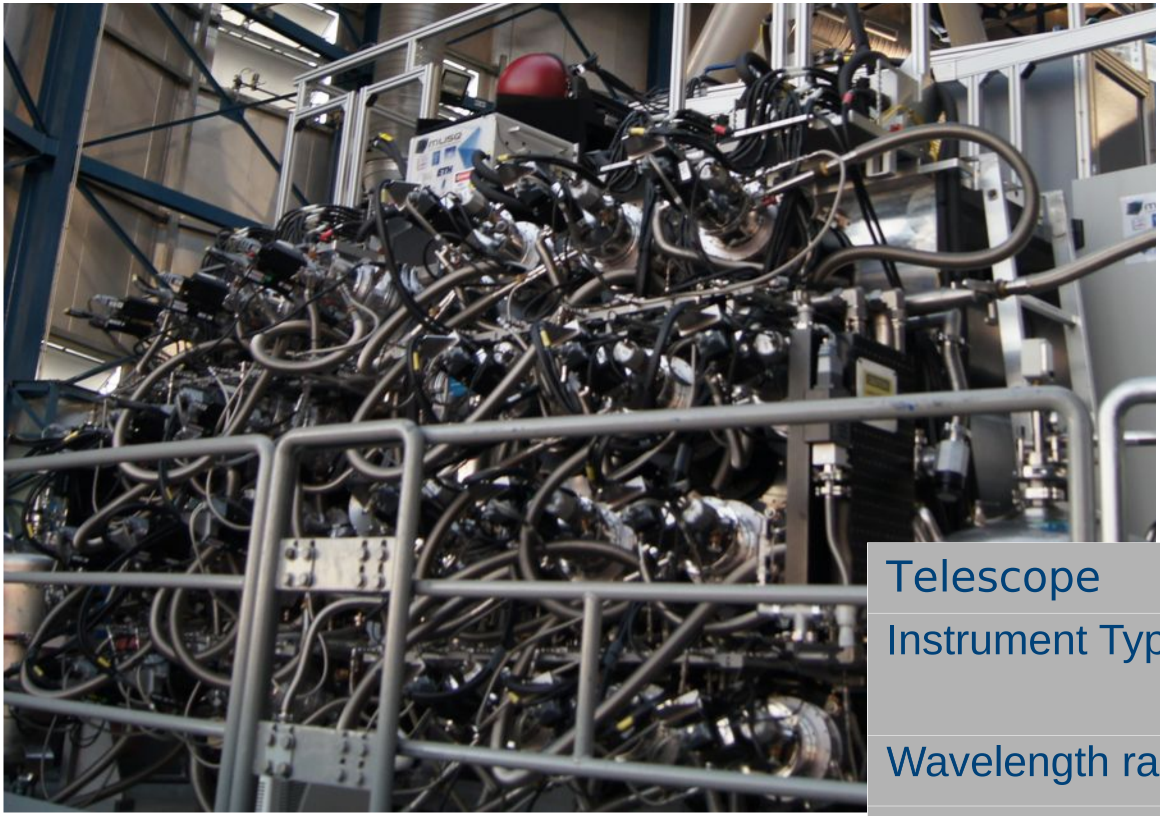
- „Youngest“ member of the „Toomre sequence“ (Toomre 1977)
  - D=22±3 Mpc (Schweizer et al. 2008, SN Ia and TRGB)
    → scale 106.6 pc/''
  - distance between nuclei: ~7 kpc
  - distance to tip of tails: S ~60 kpc, N ~50 kpc
  - two spiral progenitors (Privon et al. 2013, Lahén et al. 2018)
- L_{IR}~7.2 10^{10} $L_\odot$ (Sanders et al. 2003, below LIRG limit)
- SFR ~20 $M_\odot$/yr (Zhang et al. 2001, multi-λ compilation)
- M_{mol} ~ 1.5 10^{10} $M_\odot$ (Gao et al. 2001, NRAO 12 m telescope)
  → gas consumption in ~750 Myr
- M_{HI} ~ 5 10^9 $M_\odot$ (Hibbard et al. 2001, VLA)
- No AGN in either nucleus (Brandl et al. 2009)

Super Star Clusters

- HST data of Whitmore et al.
  - 1995: find 700 pointlike blue objects
  - 1999: first iconic highres HST color picture
    → measure cluster sizes and ages
  - 2010: even deeper B,V,I,Hα (+U & NIR) imaging
    → cluster masses and ages and luminosity/mass functions

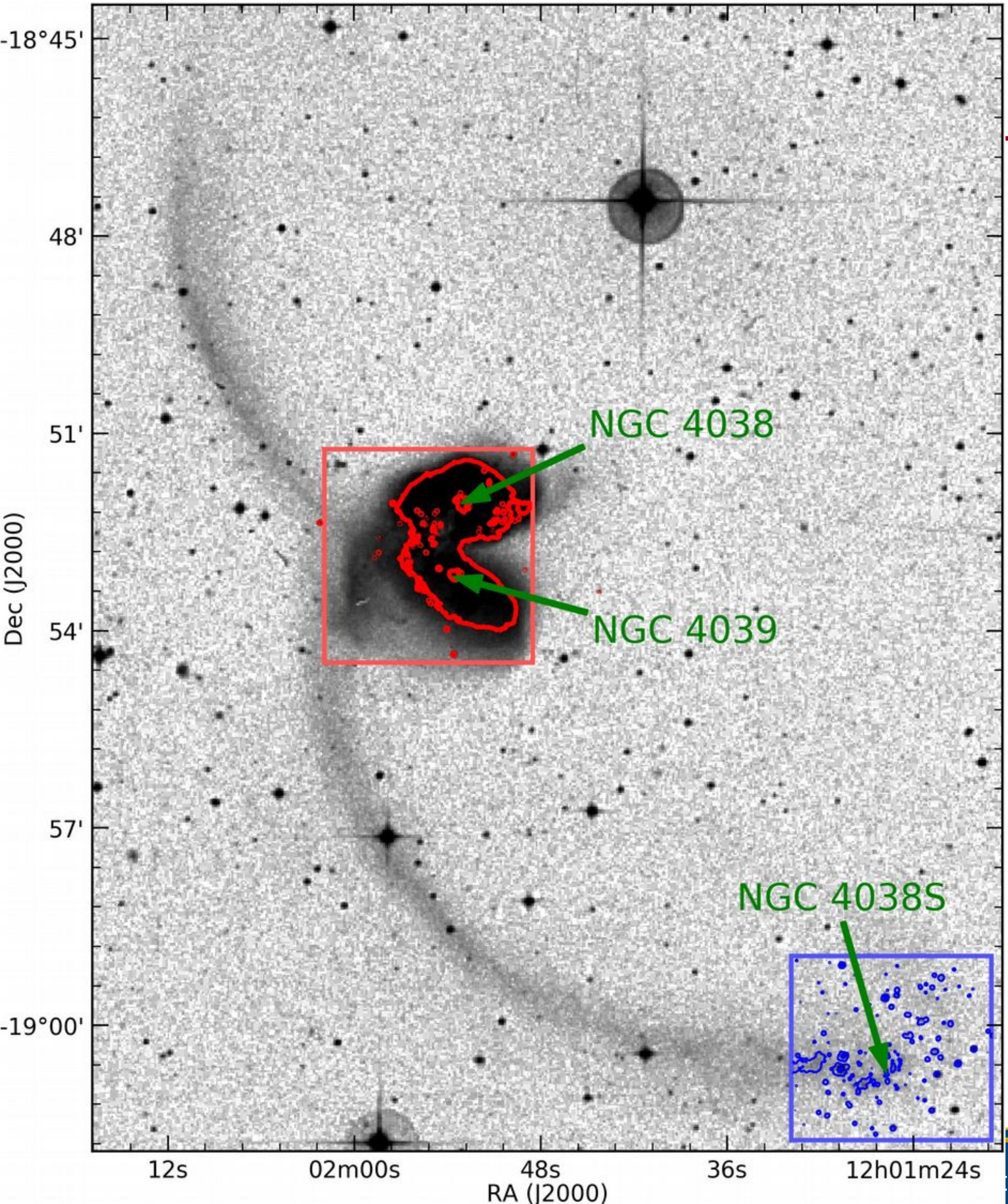


- Catalog of 60790 objects and ~2500 young clusters

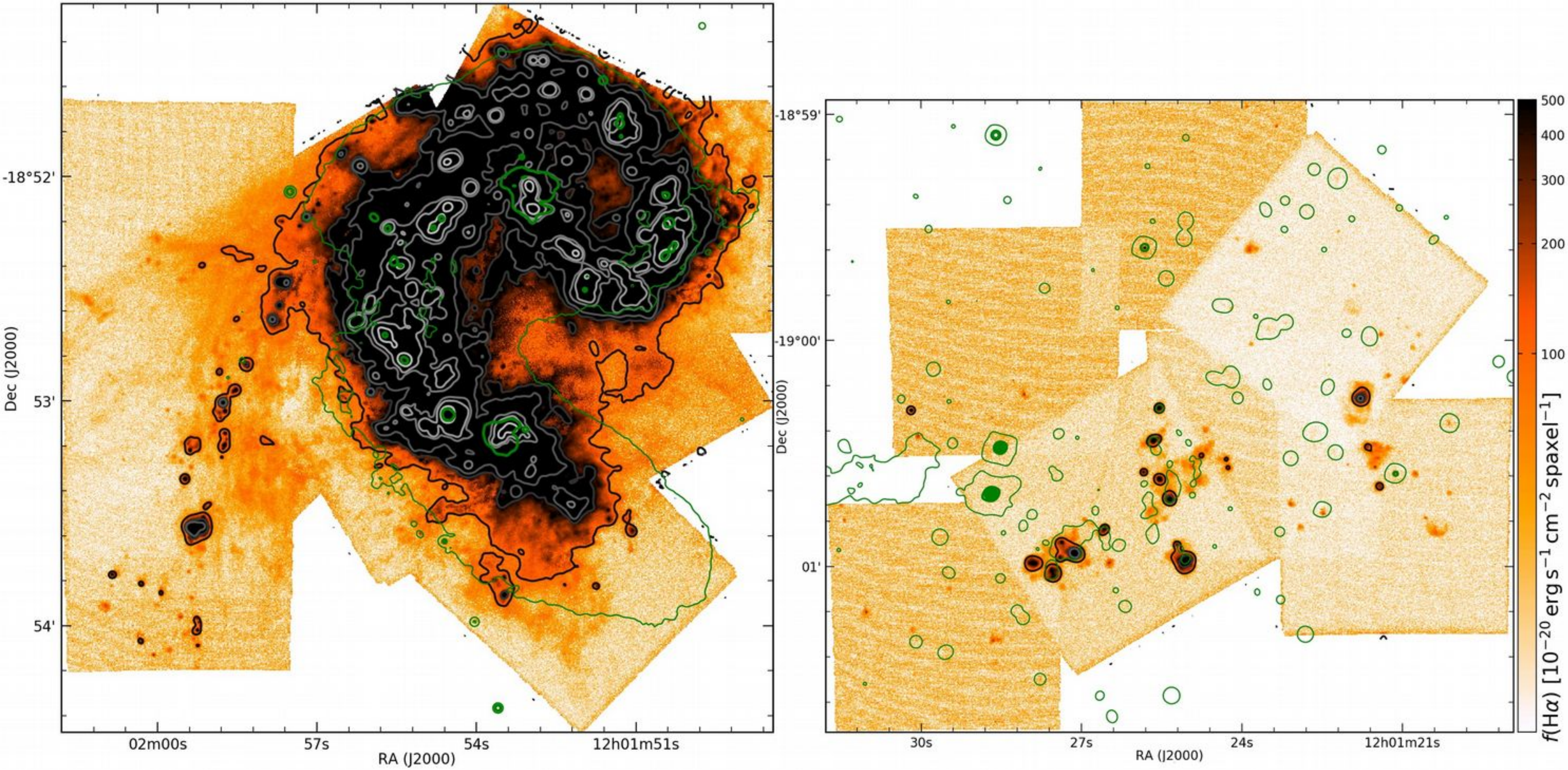


Telescope	VLT UT4 Yepun
Instrument Type	Optical Integral Field Spectrograph
Wavelength range	(4650)4800 – 9300 Å
Resolution	R ~ 1800 – 3600
Field of view	contiguous 1' x 1' (WFM)
Detectors	24 deep depletion CCDs (e2v), 4k x 4k
Sampling	0.2'' x 0.2'' x 1.25 Å
Throughput	35% (14% at extreme wavelengths)

MUSE data locations



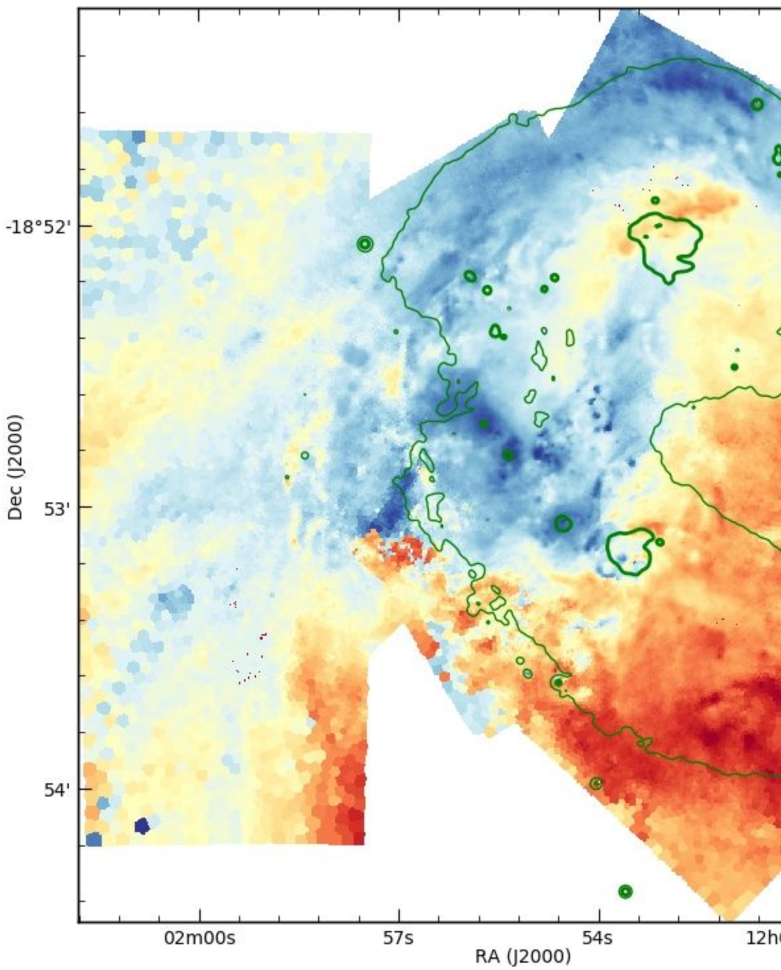
MUSE Hα maps

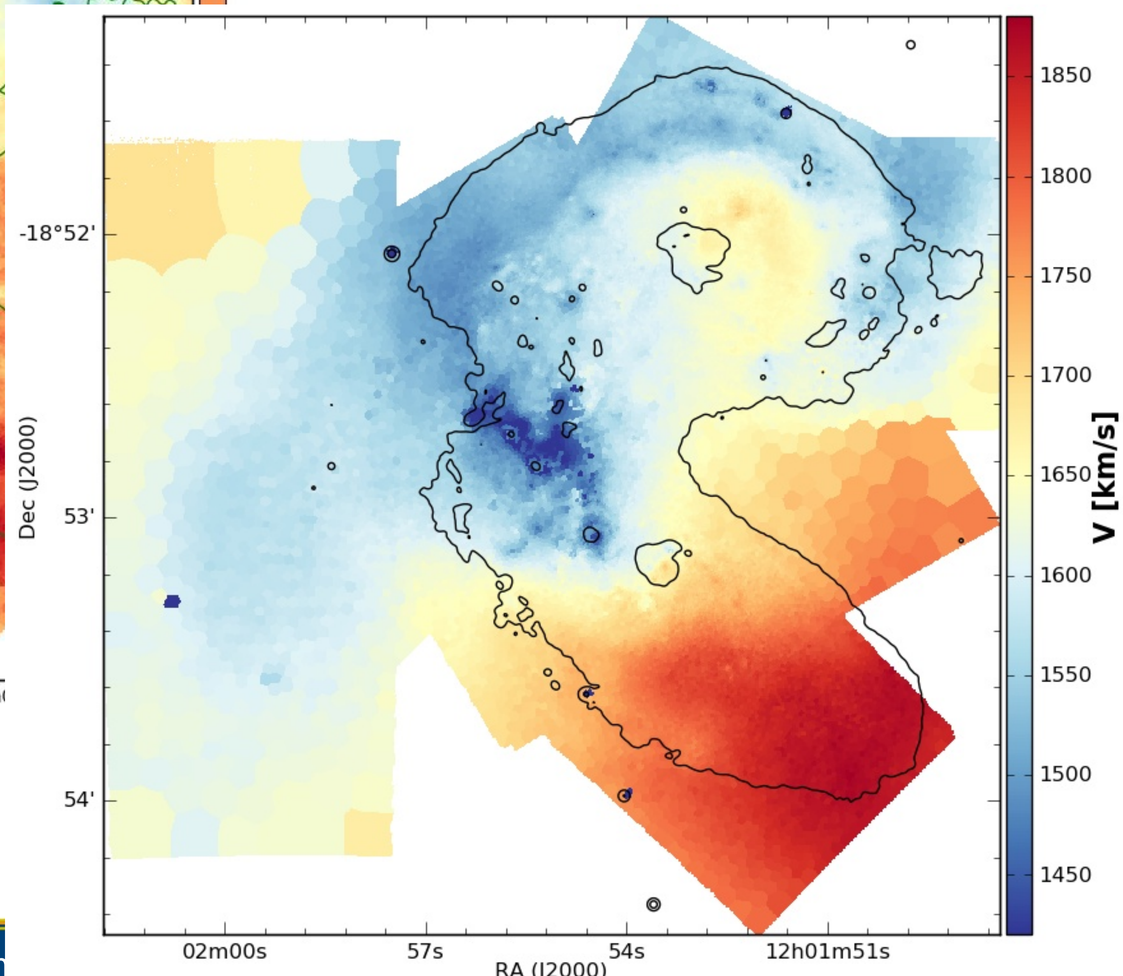


~1.5h depth → $1\sigma \approx 3\times10^{-20}$ erg $s^{-1}cm^{-2}pix^{-1}$

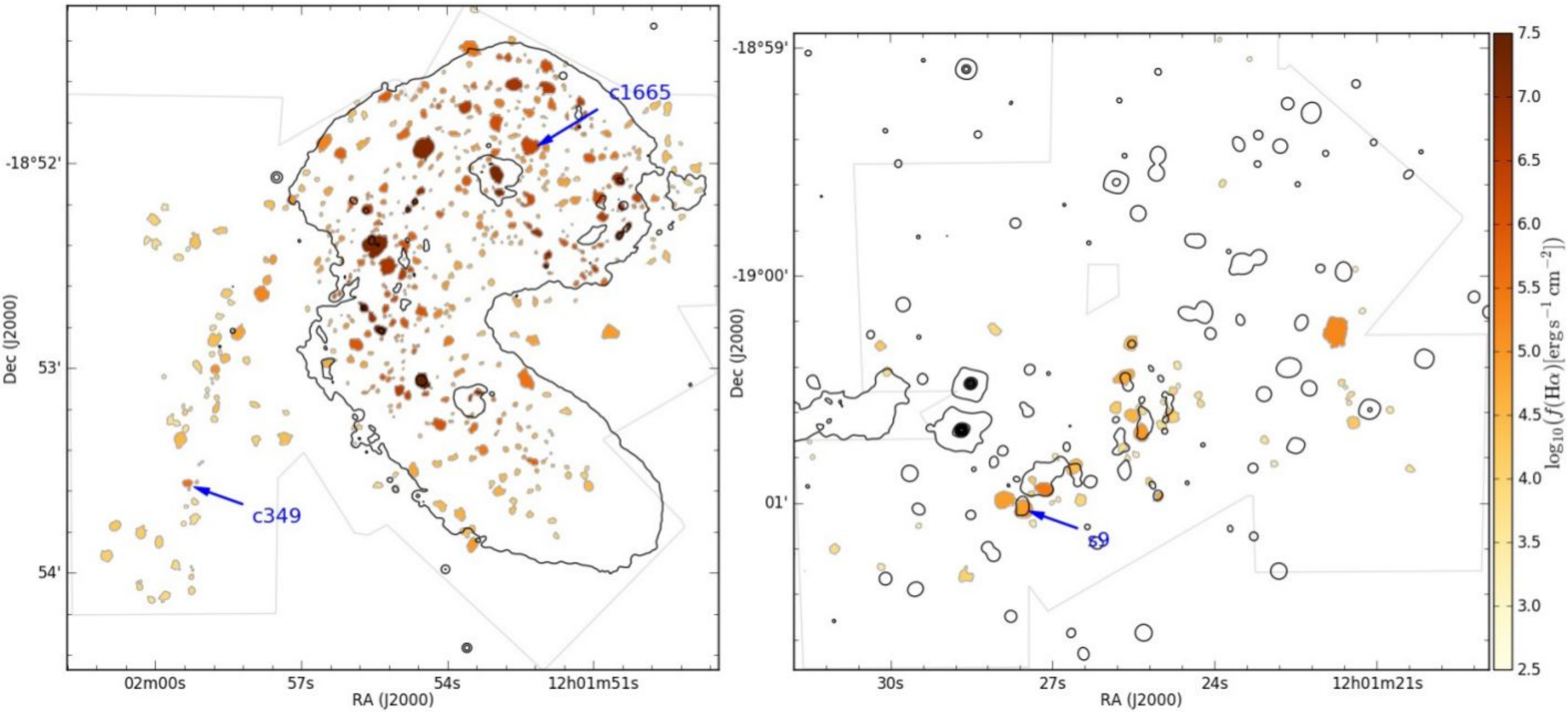
$=7.5\times10^{-19}$ erg $s^{-1}cm^{-2}$□''

Velocities


1800
-18°52'
53'
54'
Dec (J2000)
02m00s
57s
54s
RA (J2000)

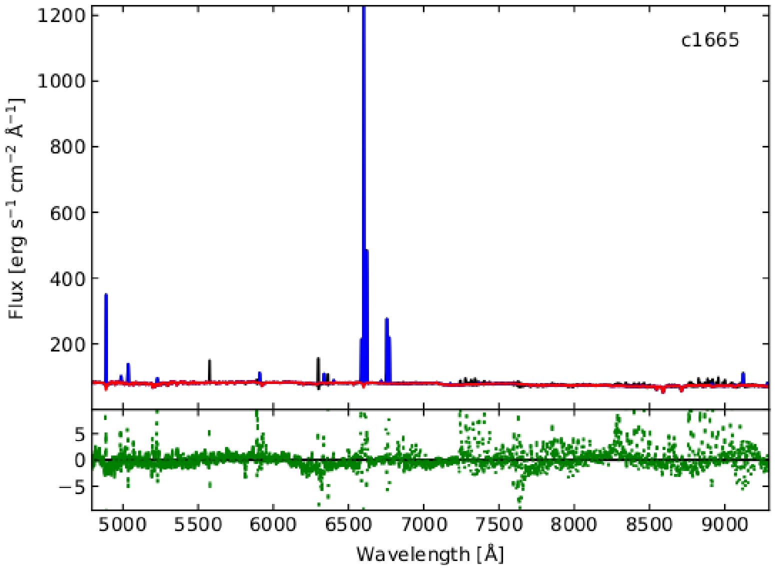

1850
1800
1750
1700
1650
1600
1550
1500
1450
V [km/s]
-18°52'
53'
54'
Dec (J2000)
02m00s
57s
54s
12h01m51s
RA (J2000)

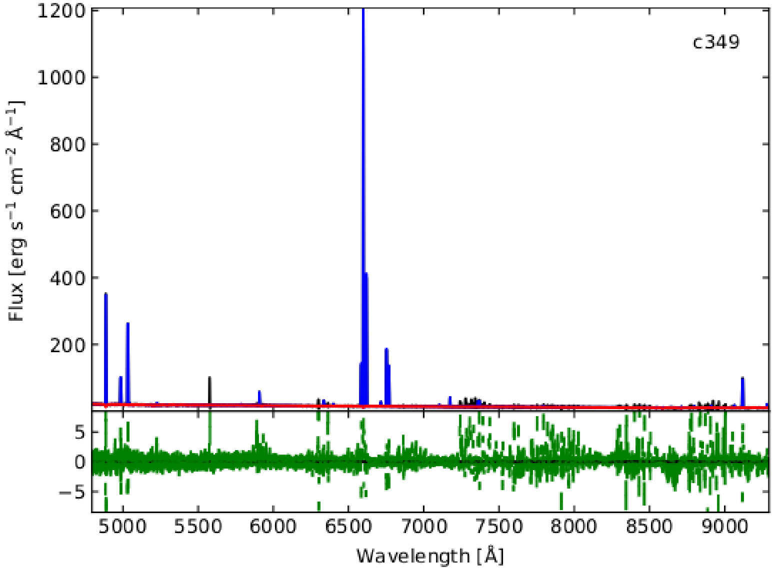
HII regions

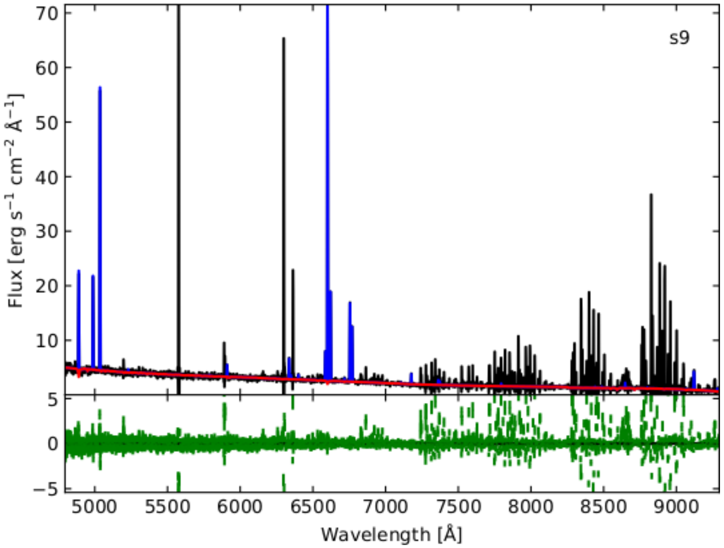


- astrodendro (Goodman et al. 2009, Robitaille et al.)
  `http://dendrograms.org/` → `https://dendrograms.readthedocs.io/`
- detect HII regions as peaks in Hα image

HII region spectra







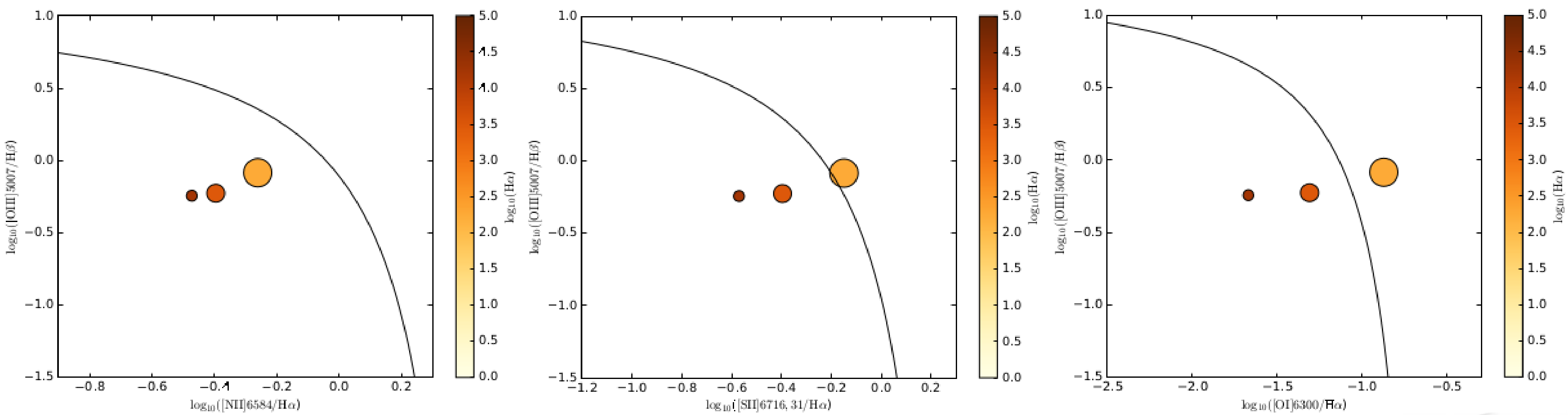
DIG in/around the Antenna

- Integrate spectra *around* HII regions:
  - bright
  - intermediate
  - faint
- compute line ratios and properties

$A_V \approx 0.1$mag

	$c_{H\beta}$	n_e [cm^{-3}]	T_e [K]
Bright	0.043	53^{+38}_{-32}	7940^{+130}_{-120}
Intermediate	0.066	21^{+9}_{-8}	9290^{+90}_{-60}
Faint	0.000	14^{+14}_{-11}	$11\,560^{+710}_{-760}$

$A_V \approx 0.14$mag



[NII] [SII] [OI]

Hα Diffuse Fraction

Fluxes of the components in erg s^{-1} cm^{-2}

estimate	total	HII	DIG	f_{DIG}
	Center			
masking	8.35×10^{-12}	3.33×10^{-12}	5.02×10^{-12}	60.2%
spectral	9.36×10^{-12}	3.79×10^{-12}	5.57×10^{-12}	59.5%
speccor	1.33×10^{-11}	7.31×10^{-12}	6.02×10^{-12}	45.2%
specsub	[spectral]	2.75×10^{-12}	[6.61×10^{-12}]	[70.7%]
	South			
	total	HII	DIG	f_{DIG}
masking	1.71×10^{-14}	1.53×10^{-14}	1.78×10^{-15}	10.5%
spectral	[1.39×10^{-14}]	1.22×10^{-14}	[masking]	[12.8%]
speccor	[1.42×10^{-14}]	1.25×10^{-14}	[masking]	[12.5%]
specsub	[1.39×10^{-14}]	1.01×10^{-14}	[3.82×10^{-15}]	[27.4%]

NB continuum subtraction

pPXF continuum subtracted

attenuation corrected

with annular bg subtraction

- typical diffuse fractions in spiral galaxies are 40-50% (M51/NGC 5195 and M81, Greenawalt et al. 1998)
- or even 59+/-19% (SINGG, Oey et al. 2007)

HII regions, LyC escape

- HII region flux

  → $Q(\mathrm{H}^0,\mathrm{HIIreg}) = 7.31\times10^{11}\,L(\mathrm{H}\alpha)$
- Whitmore et al. HST cluster catalog
  - contains cluster mass and age
- use matching stellar populations (GALEV, SB99, BC03, or BPASS)

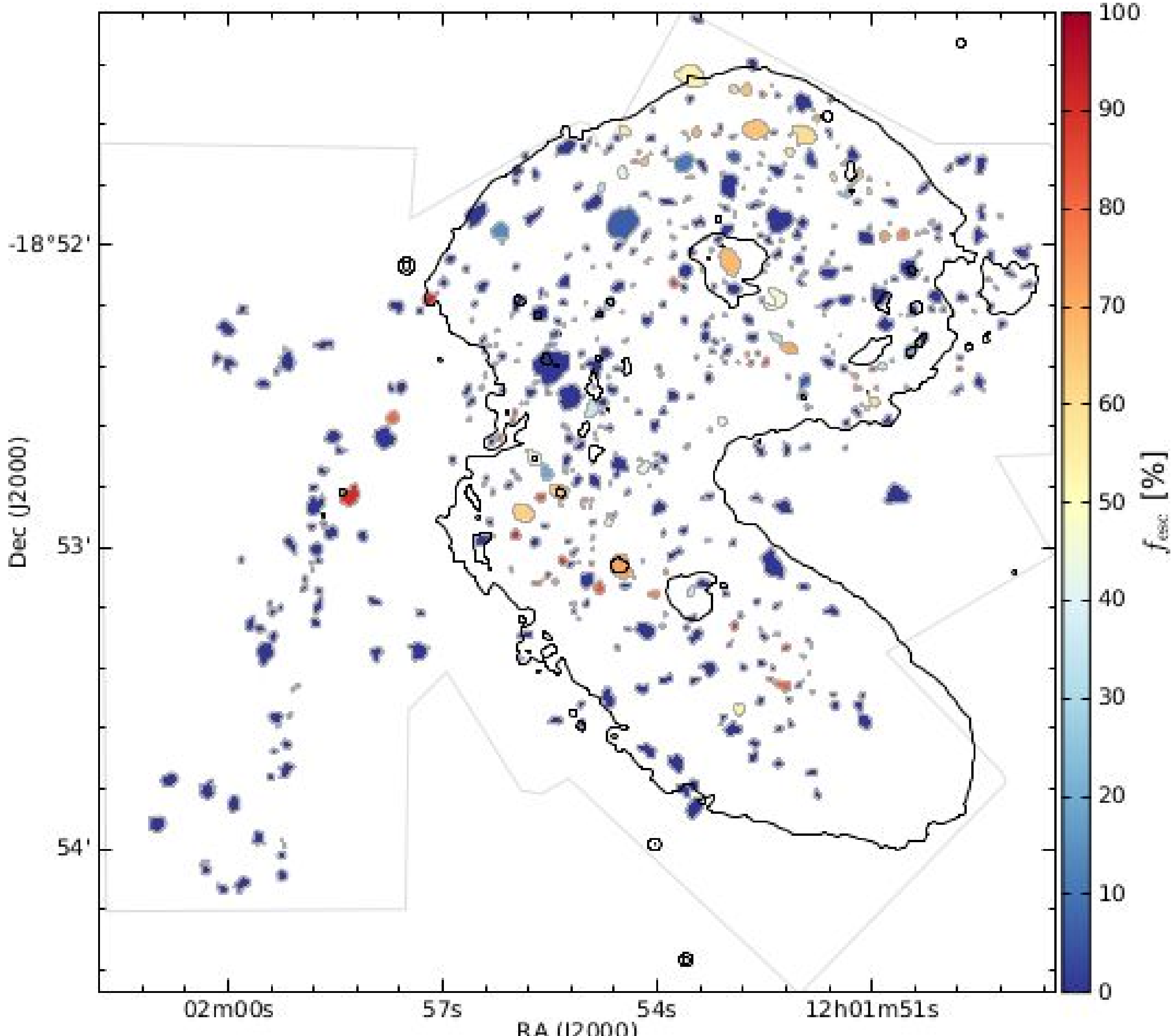
  → $Q(\mathrm{H}^0,\mathrm{YSC})$ from stellar population model

→ $f_{esc} = 1 – Q(\mathrm{H}^0,\mathrm{HIIreg}) \,/\, Q(\mathrm{H}^0,\mathrm{YSC})$

LyC photon budget, Center

- 60790 objects in Brad Whitmore's full catalog
- 2162 young massive clusters (6.0..7.8 logage, mass>0, valid *UBI*)
- 551 HII regions total
- 98 leaking HII regions

HII regions, LyC escape



LyC photon budget, Center

- 60790 objects in Brad Whitmore's full catalog
- 2162 young massive clusters (6.0..7.8 logage, mass>0, valid *UBI*)
- 551 HII regions total
- 98 leaking HII regions → **$Q(H^0,\mathrm{leak})=2.7\times10^{53}\ \mathrm{s}^{-1}$** (GALEV)

  (SB99, BC03, BPASS or bg subtraction give higher estimates!)

- we need

  $f(H\alpha,\mathrm{DIG})\approx5.02\times10^{-12}$ erg s^{-1} cm^{-2} → **$Q(H^0,\mathrm{DIG})=2.13\times10^{53}\ \mathrm{s}^{-1}$**

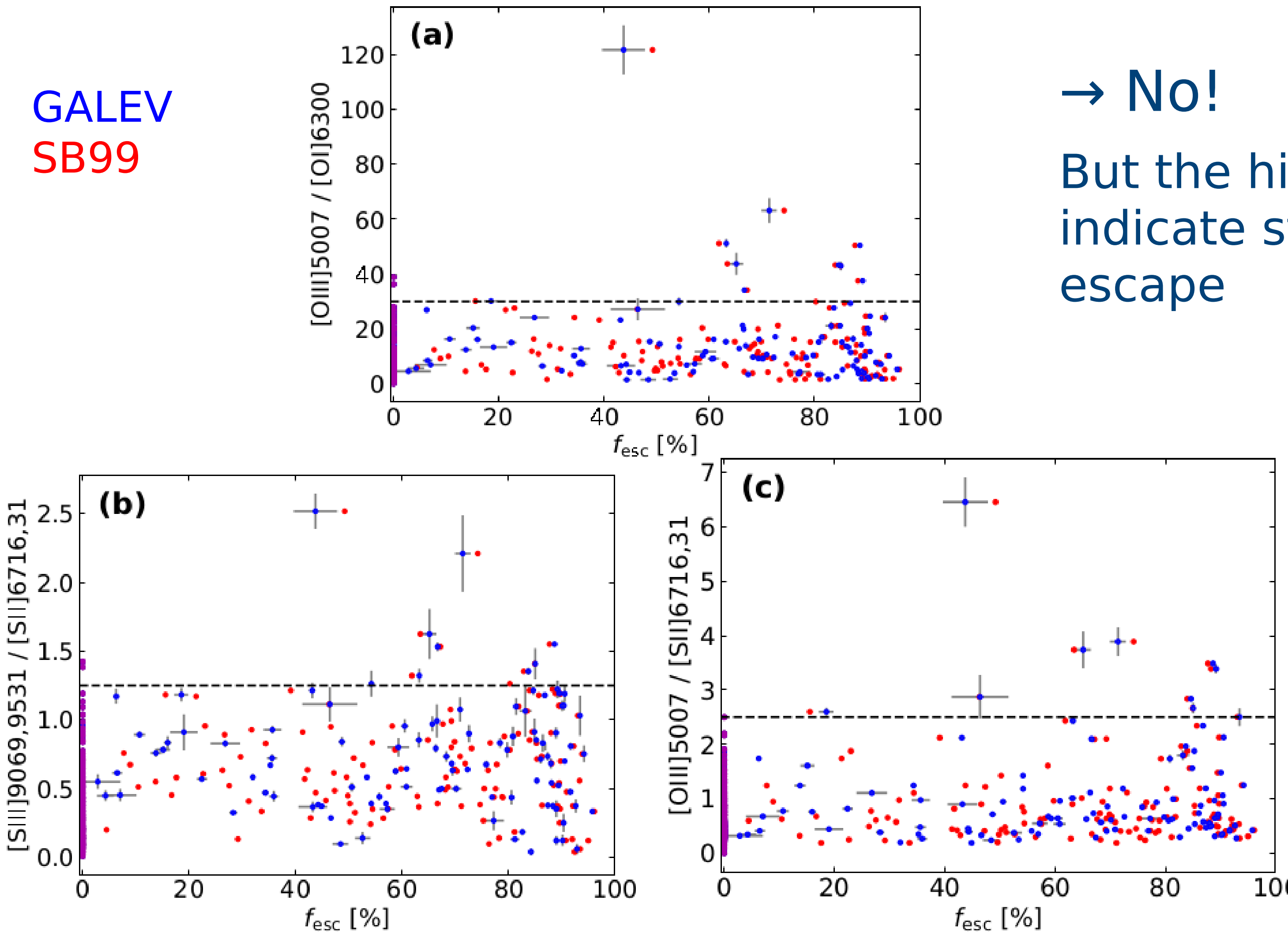
→ enough LyC photons leak from HII regions to explain the DIG in the central Antennae

HII regions

- high ionization parameter: indicative of low opacity
- track such regions with line ratios of different ionization energy:
  - [OIII] / [OII] → not with MUSE in nearby galaxies!
  - [OIII] / [SII]
  - [SIII] / [SII]
  - [OIII] / [OI]
- popular especially at intermediate to high redshifts

Correlation?

GALEV
SB99



→ No!

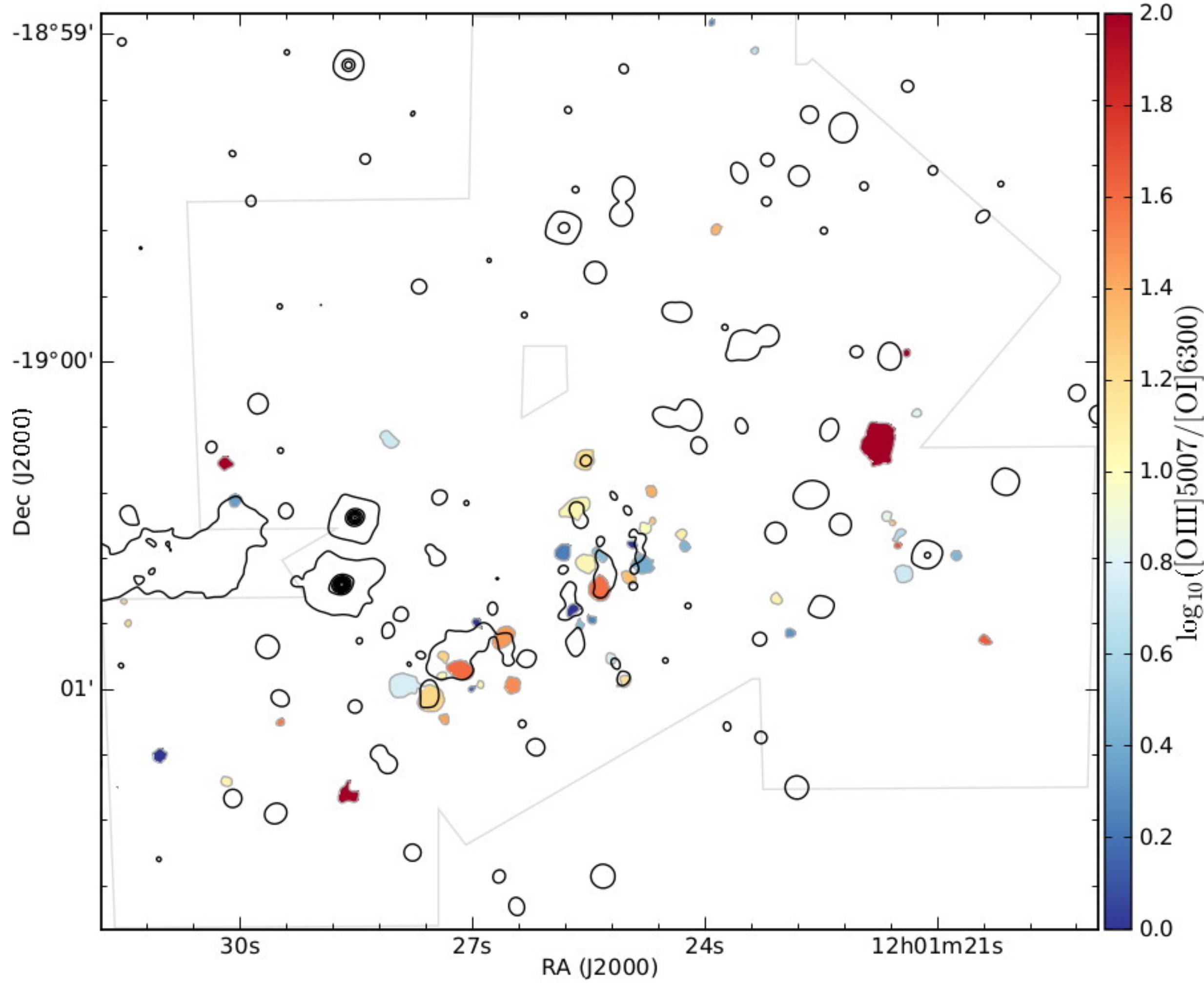
But the highest ratios indicate strong LyC escape

LyC photon budget, South

- no HST cluster catalog
- from DIG estimate: $\mathbf{Q(H^0)=7.55\times10^{49}\ s^{-1}}$ needed

- average f_{esc}~7% for regions with $\log_{10}L(H\alpha)\leq38.25$
  → $\mathbf{Q(H^0)=3.7\times10^{49}\ s^{-1}}$ available

Line ratios, South



LyC photon budget, South

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  → **$Q(H^0)=3.7\times10^{49}$ s^{-1}** available

- 5 regions with [OIII]/[OI]>30
  → can fill the gap with only 23.3% escape fraction

Energy sources

- Available LyC photons and Balmer emission from HII regions + DIG are approximately in balance
- Other energy sources exist:
  - hidden SF, IR and ALMA data (Mirabel et al. 1998, Herrera et al. 2011-2017, Johnson et al. 2015)
  - SNe (Schweizer et al. 2008)
  - stellar winds, WRs! (Bastian et al. 2006)
  - shocks (Baldi et al. 2006, Ueda et al. 2014)
  - ...

→ The Antennae is a likely LyC emitter.

Summary

- (Diffuse) ionized gas exists everywhere in the central merger
  - diffuse fraction ~60%
  - Lower diffuse fraction in southern field (~10%)
- Comparison to HST clusters (central region):
  - enough LyC leakage to excite both the *nebular* and the *diffuse* gas
  - *Very* high ionization parameter sensitive ratios: good indicator of density bounded HII regions
- Southern region: enough LyC escape to explain DIG
- The Antennae overall likely leaks LyC photons.