Kinematics of the ionized gas in nearby galaxies
as diagnostics of the energy balance between ISM and massive stars

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Thanks to co-authors:

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SAI MSU: Tatiana Lozinskaya, Ivan Gerasimov, Anastasia Yarovova, Konstantin Vasiliev, Evgeniya Egorova

SAO RAS: Alexei Moiseev, Dmitry Oparin, Aleksandrina Smirnova

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Outline

Observational constraints on stellar feedback in ISM

1) Emission line profiles in nearby dwarf galaxies;
SIGMA-FPI database

2) Efficiency of mechanical stellar feedback
(PHANGS: MUSE+HST+JWST observations)

3) Future perspectives
(SDSS-V/LVM,
MUSE mapping of large
nearby galaxies etc.)

Stellar feedback and baryon cycle

Image credit: F.Santoro

Feedback from massive stars is a major regulator of a baryon cycle and evolution of galaxies
Via radiative, chemical, mechanical channels it:

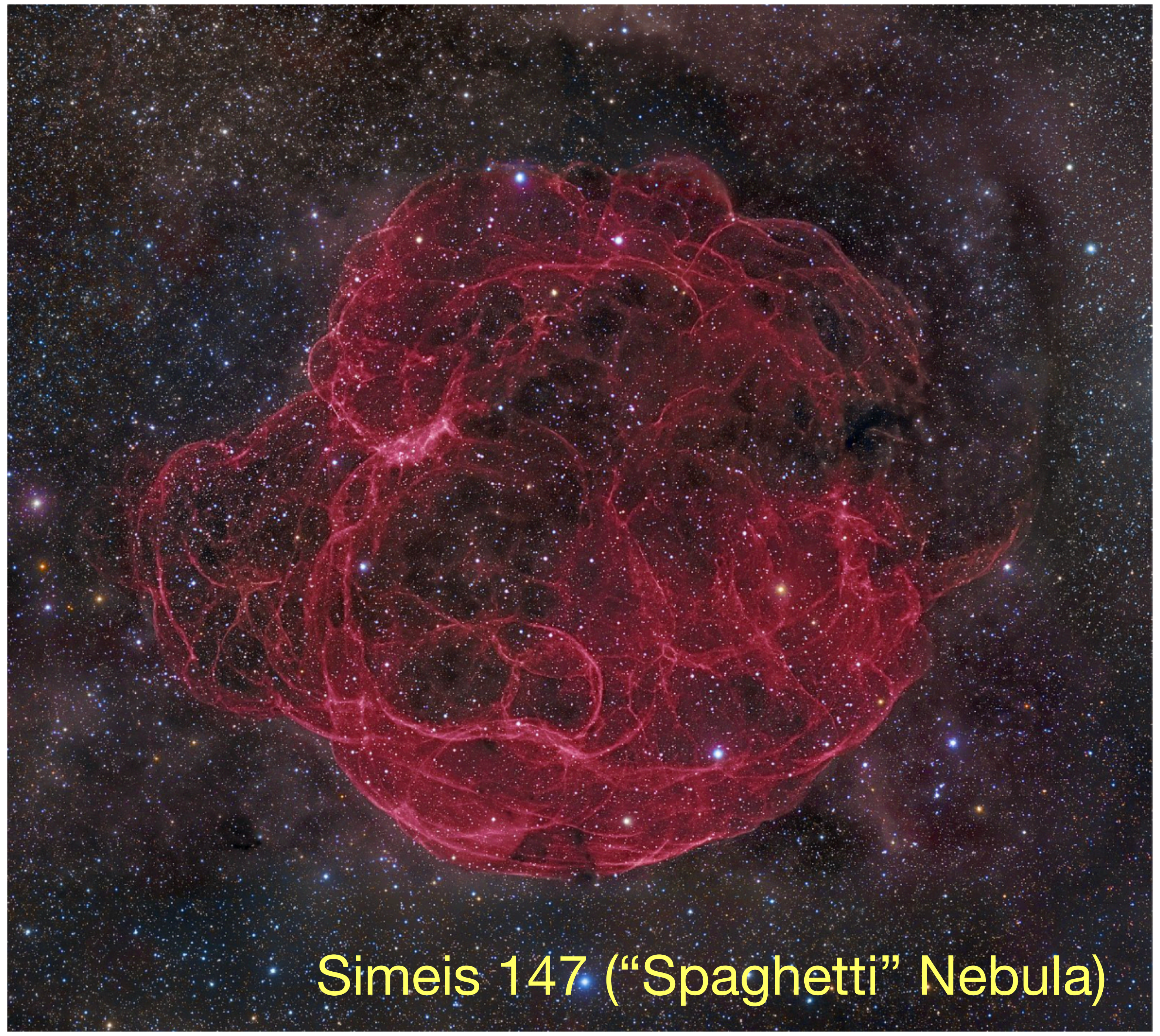
- Destroys/ionizes molecular clouds and dust
- Enriches the ISM and IGM with metals
- Shapes the ISM (shells/bubbles/outflows)
- Produces turbulence in the ISM
- Triggers star formation
- Supplies the DIG emission
- … Reionized the Universe

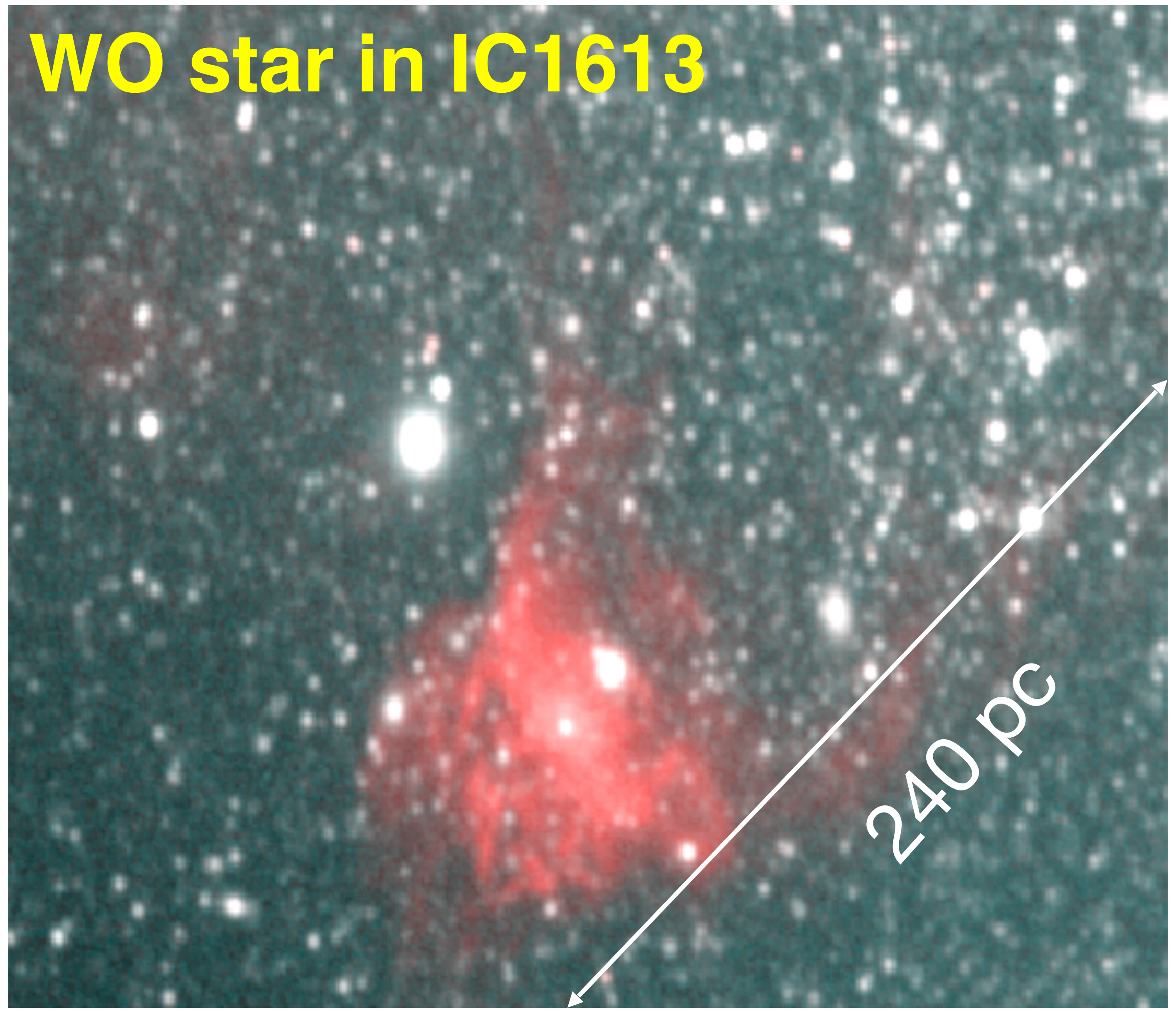
We need to understand how stellar feedback works at all scales in order to reproduce realistic galaxies in simulations (e.g. Hopkins et al. 2014)

Massive stars in the ISM

- Massive ($M>8M_{sun}$) stars inject mechanical energy and momentum into ISM through all their evolutionary stages via stellar wind (especially in the WR phase) and supernovae explosions

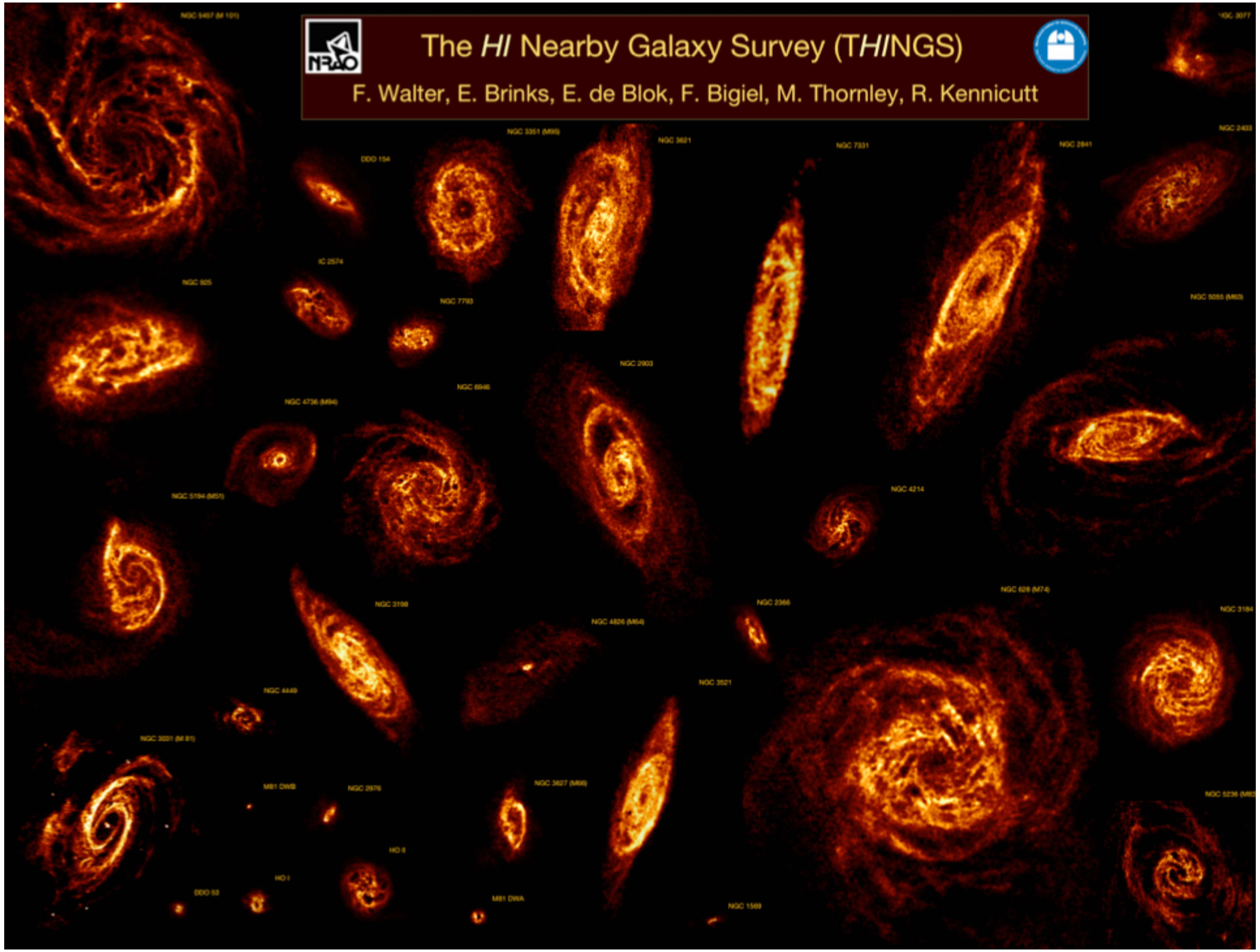
- Multiple bubbles around massive stars, up to tens of pc, but depends on the environment





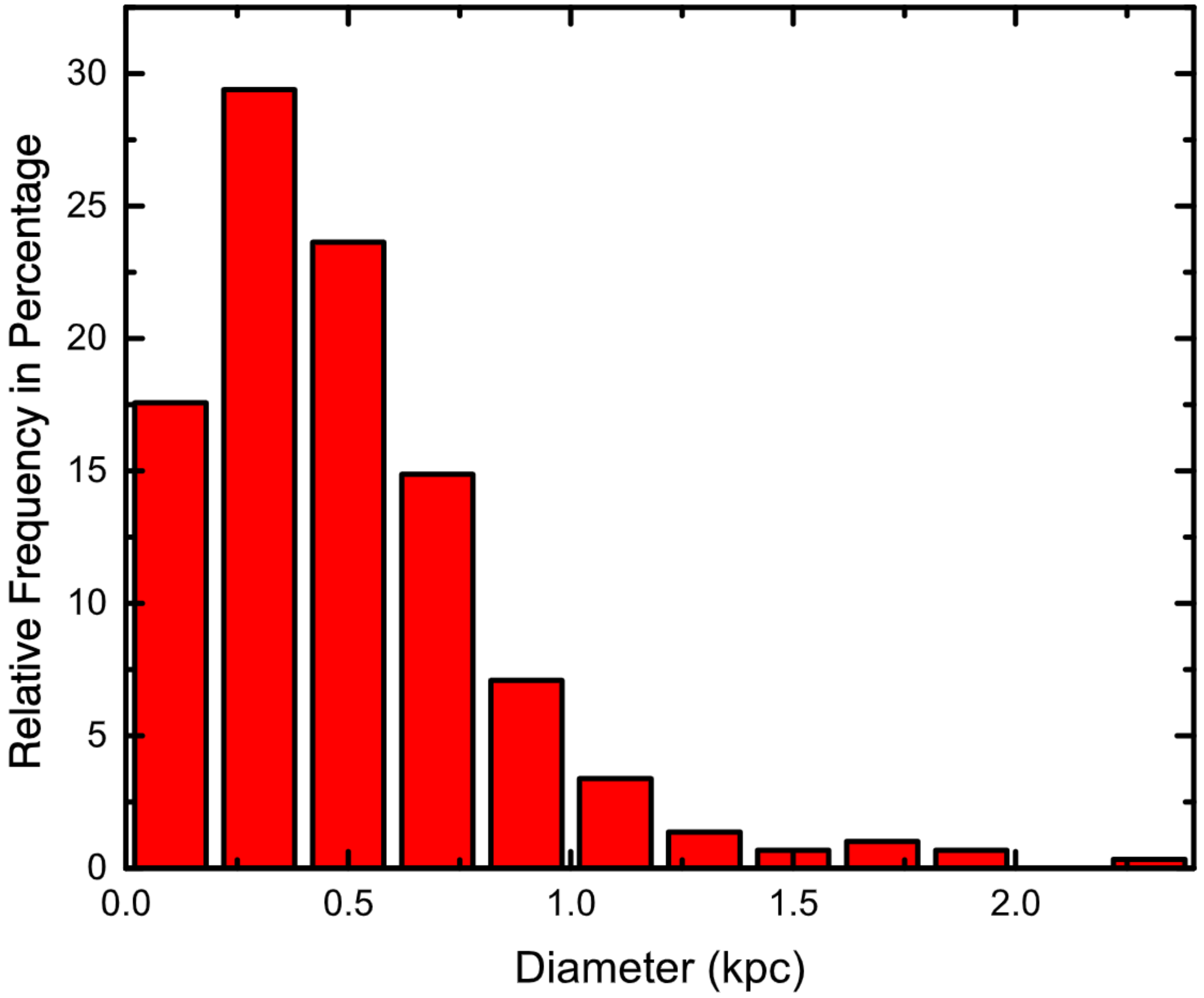
Afanasiev et al. (2000), Lozinskaya et al. (2001)

Stellar feedback shapes the ISM of the galaxies



Walter et al. (2008)

- **THINGS: About 1000 HI holes with sizes of 80-2600 pc (Bagetakos et al. 2011)**
- **LITTLE THINGS: 308 HI holes with sizes of 38 – 2300 pc in dwarf galaxies (Pokhrel et al. 2020)**



Pokhrel et al. (2020)

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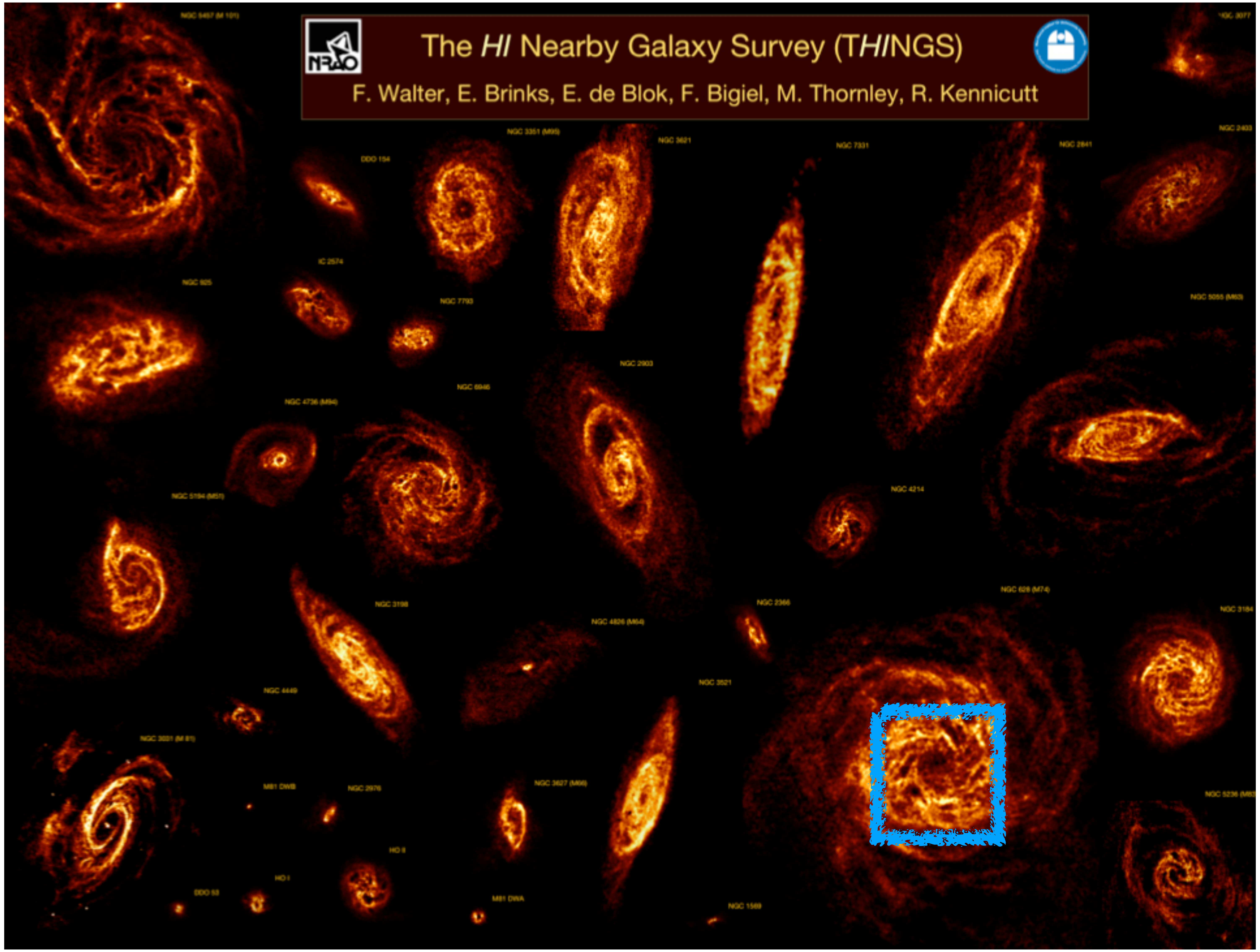

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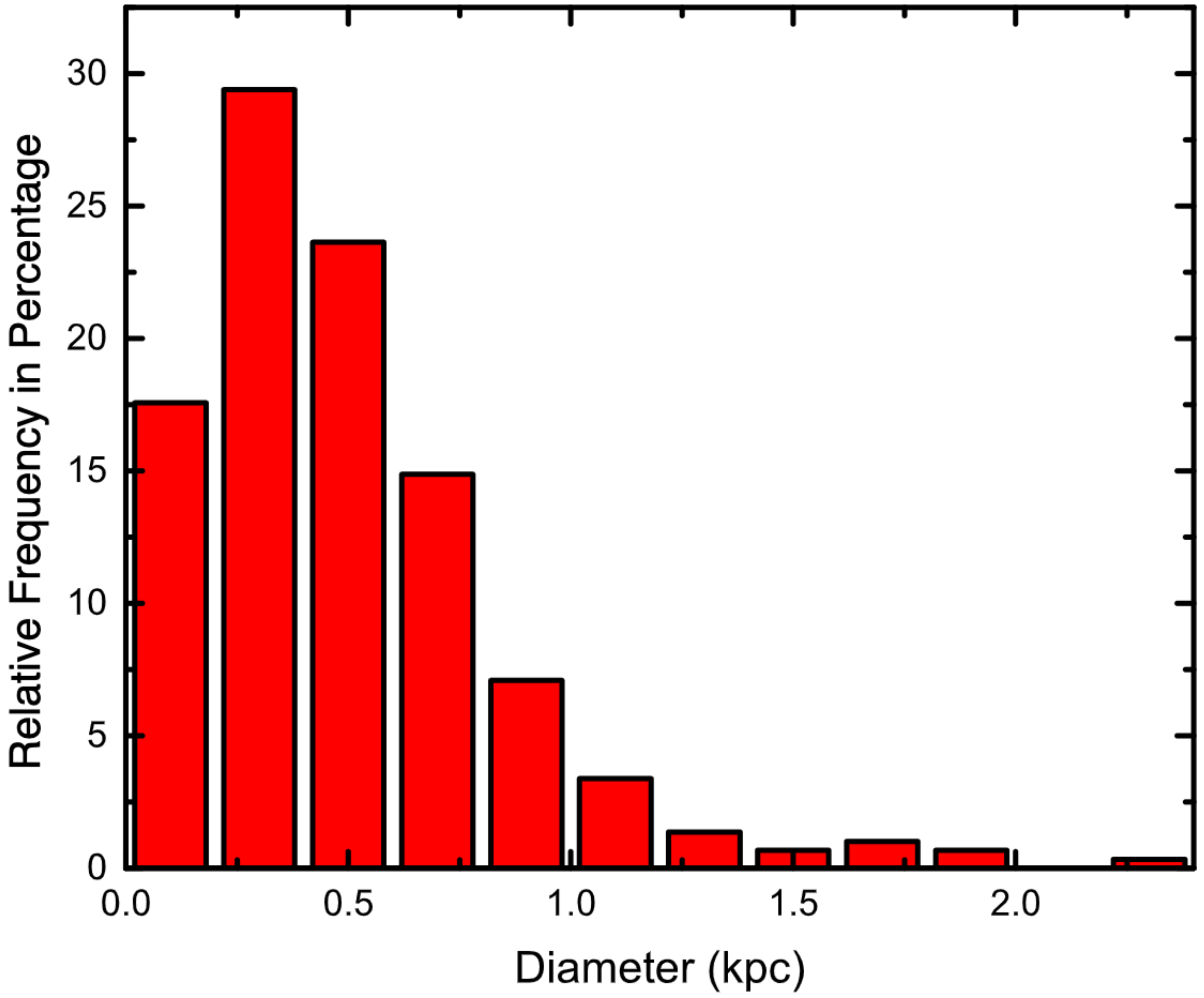

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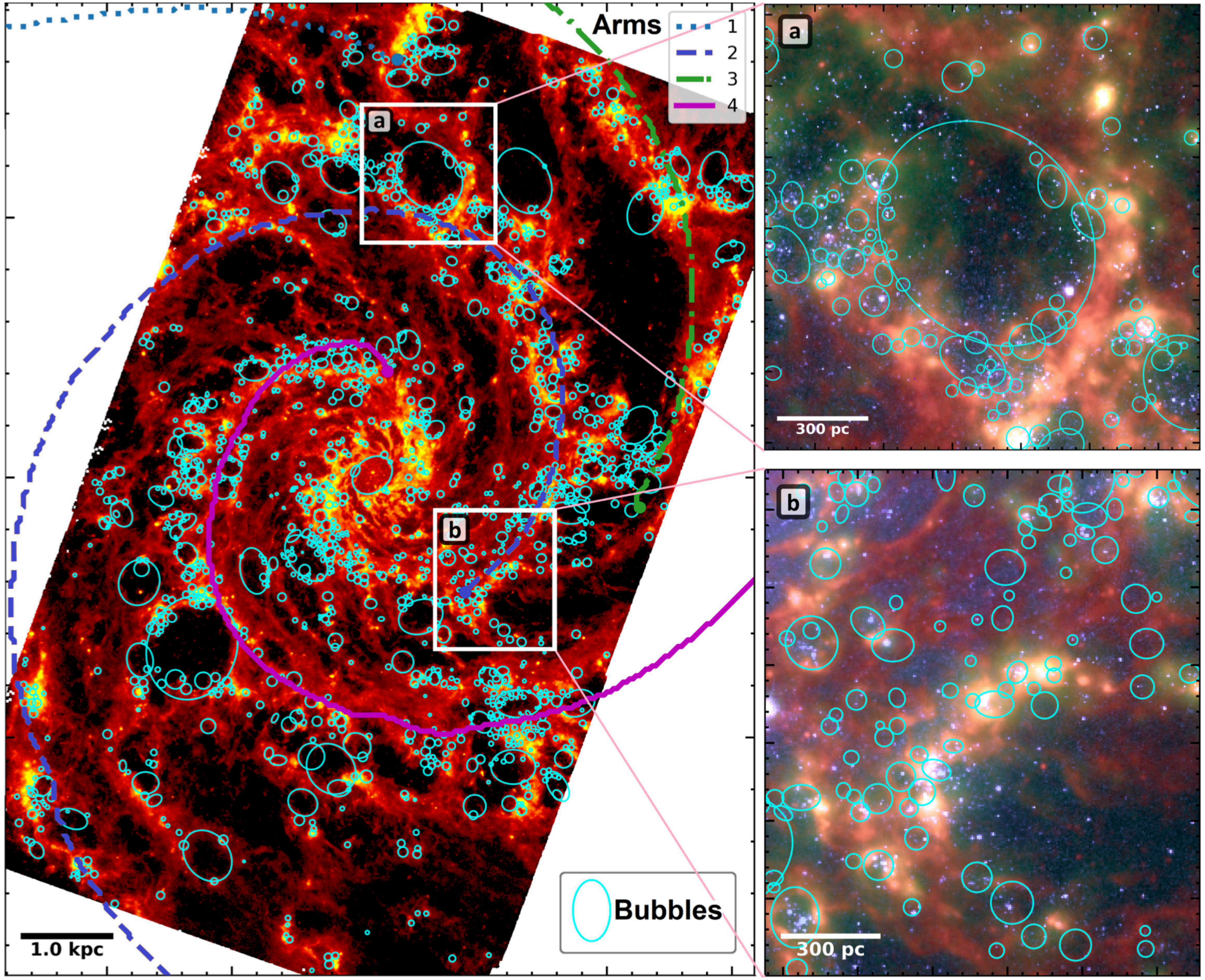
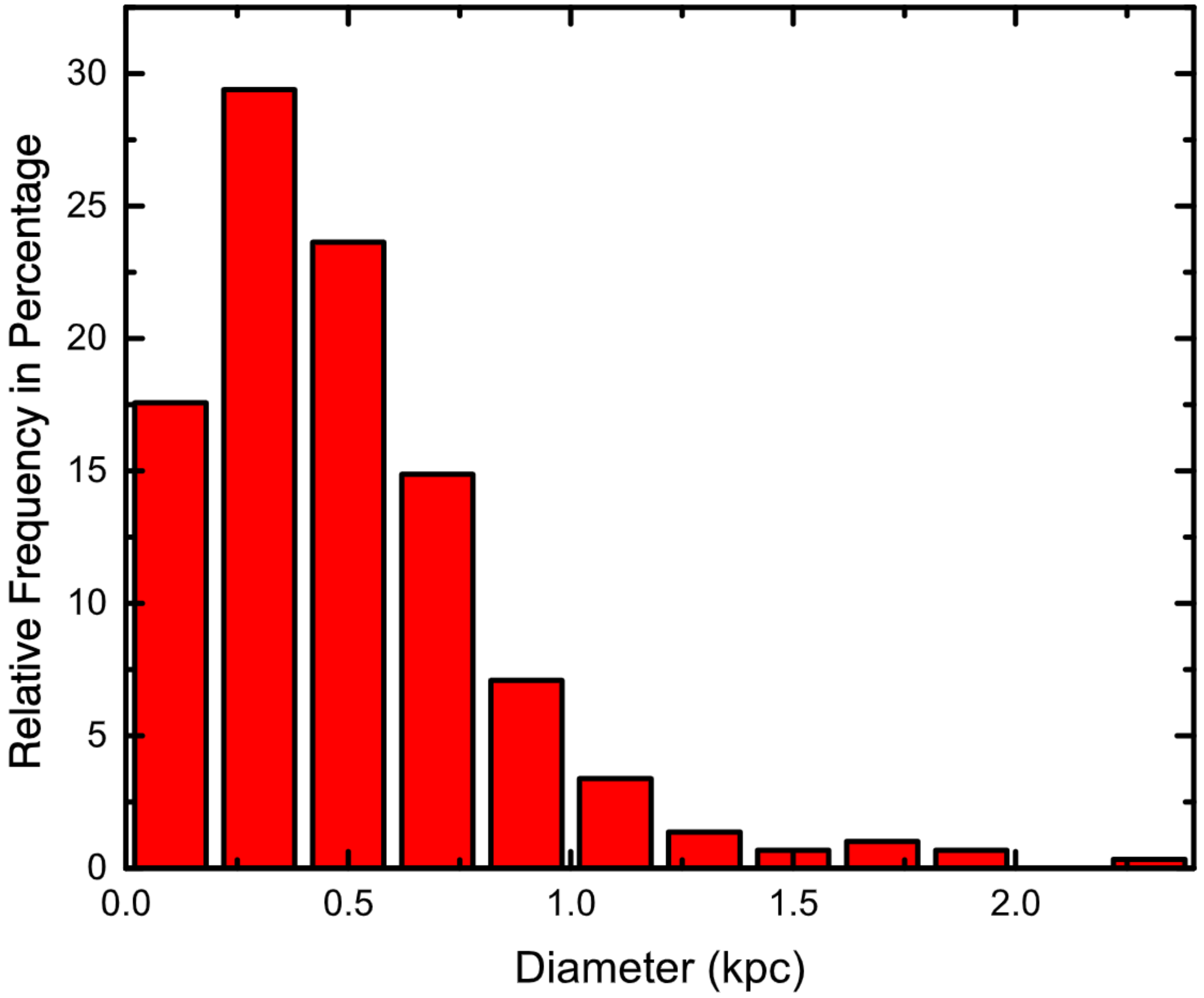


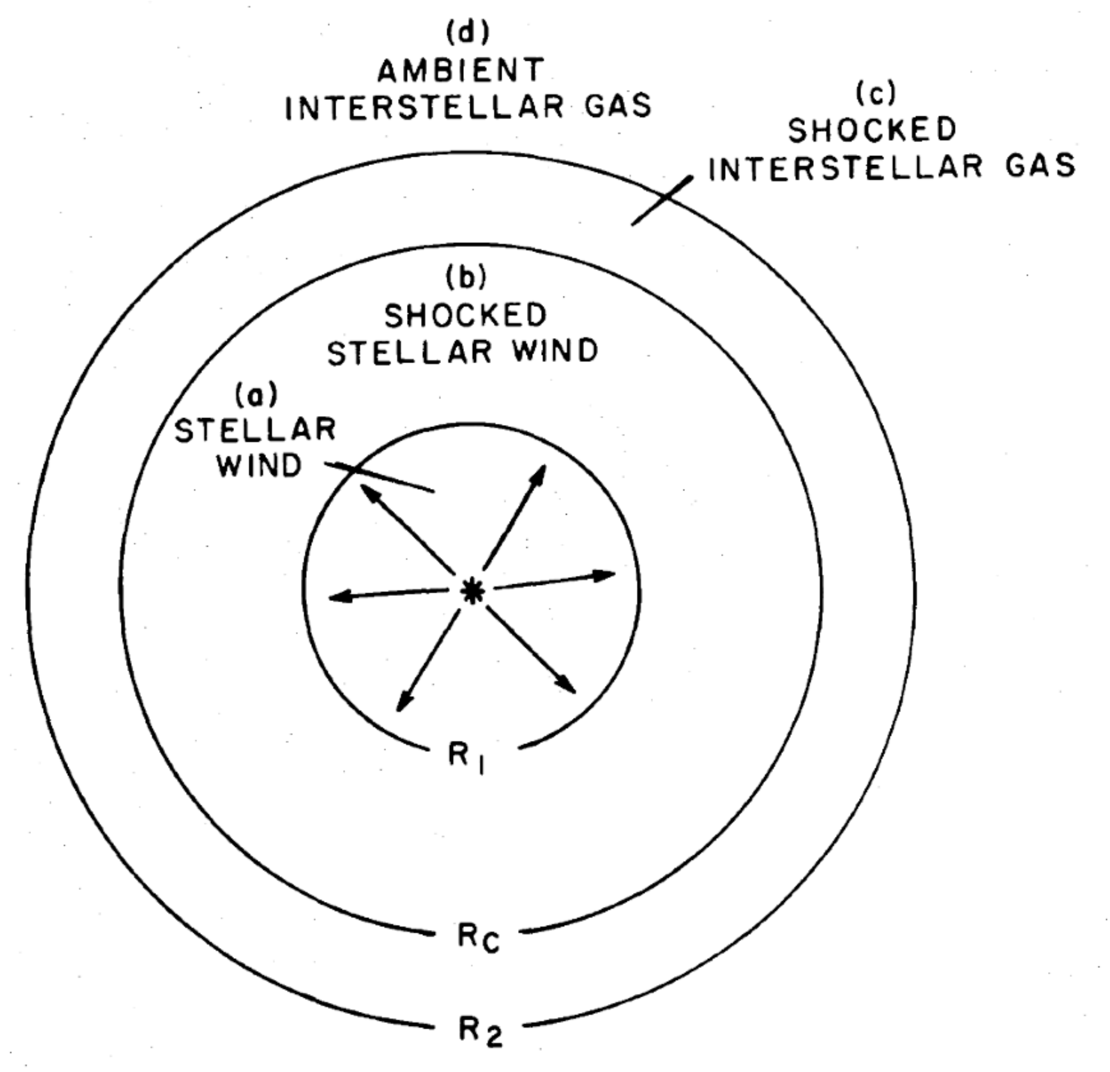
Watkins et al. +OE (2023)

- ➢THINGS: About 1000 HI holes with sizes of 80-2600 pc (Bagetakos et al. 2011)
- ➢LITTLE THINGS: 308 HI holes with sizes of 38 – 2300 pc in dwarf galaxies (Pokhrel et al. 2020)
- ➢PHANGS-JWST: 1694 superbubbles in the galaxy NGC 628 (Watkins et al, 2023)



Pokhrel et al. (2020)

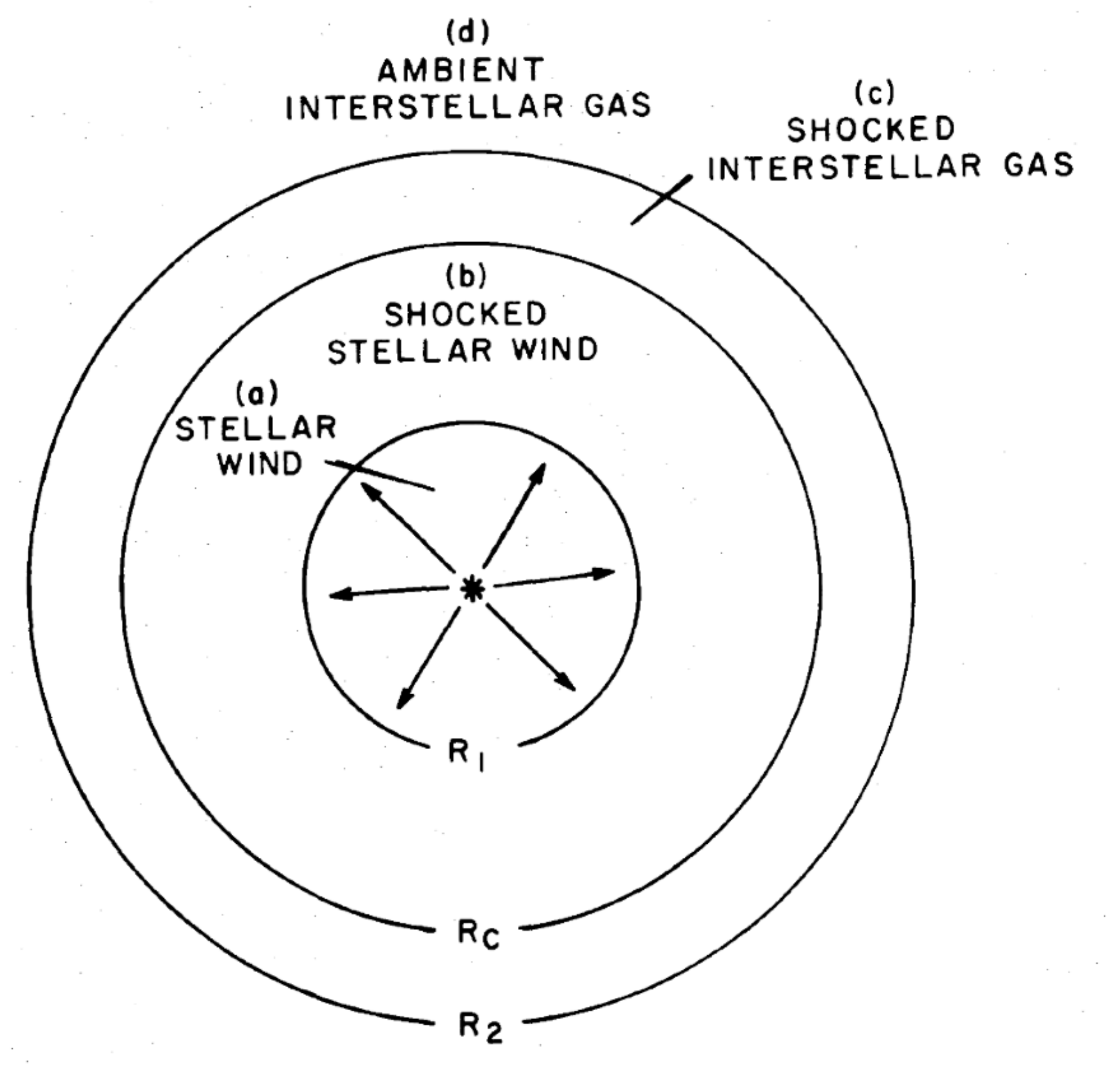
Evolution of the superbubbles in the ISM



Weaver et al. (1977)

- Qualitatively, the evolution of superbubbles is well described by the classical Weaver et al. (1977) model
- However, it doesn't agree well with observations quantitatively
- Only a small fraction of injected energy should retain in superbubble to support its expansion (*Sharma+2014; Krause&Diehl 2014; Vasiliev+2015; Yadav+2017*)
- Different models predict 1-40% efficiency of mechanical feedback driving the superbubbles expansion (depending on the density, clustering of SNe, age of the clusters, resolution of the simulations)

Evolution of the superbubbles in the ISM



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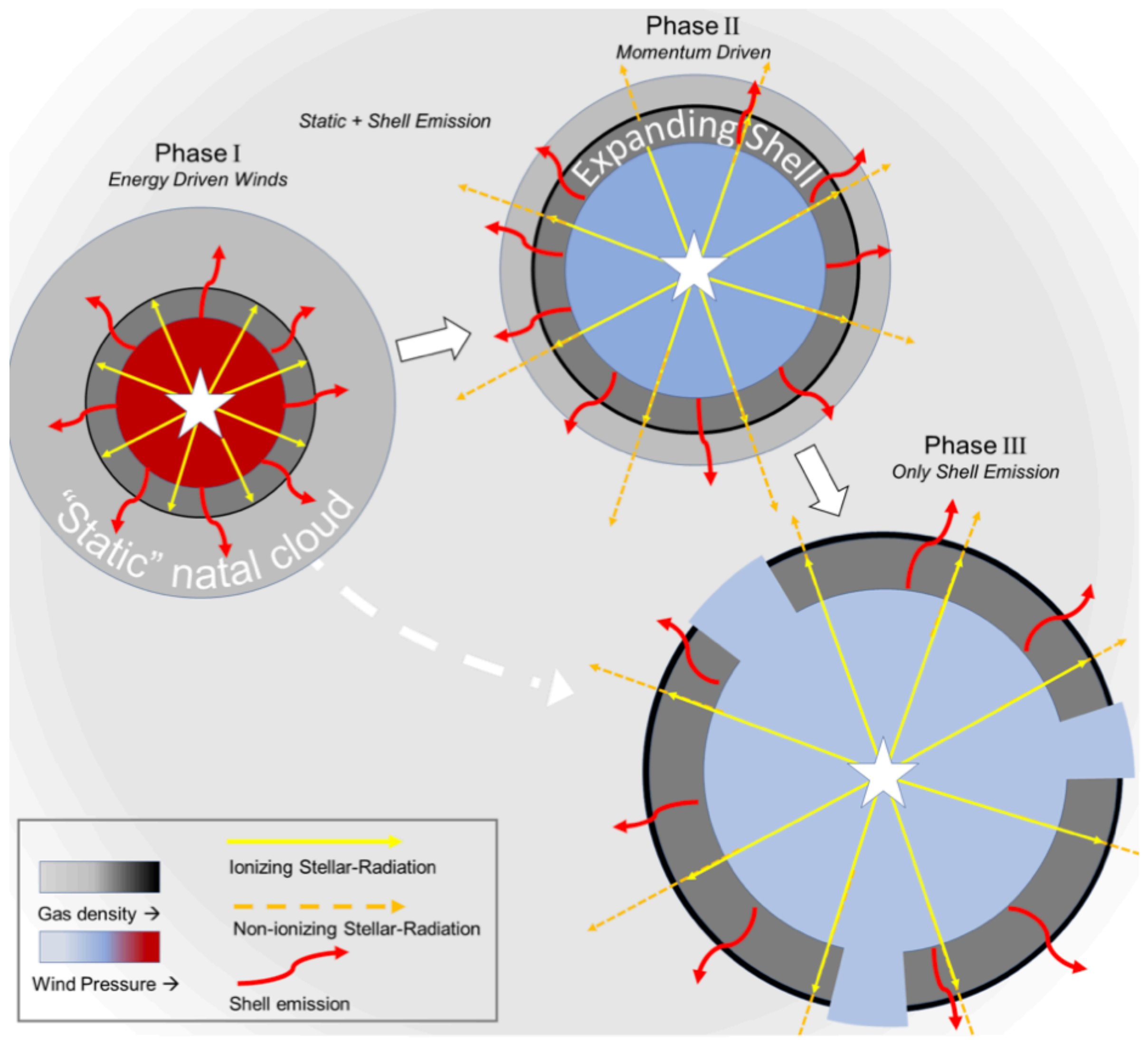
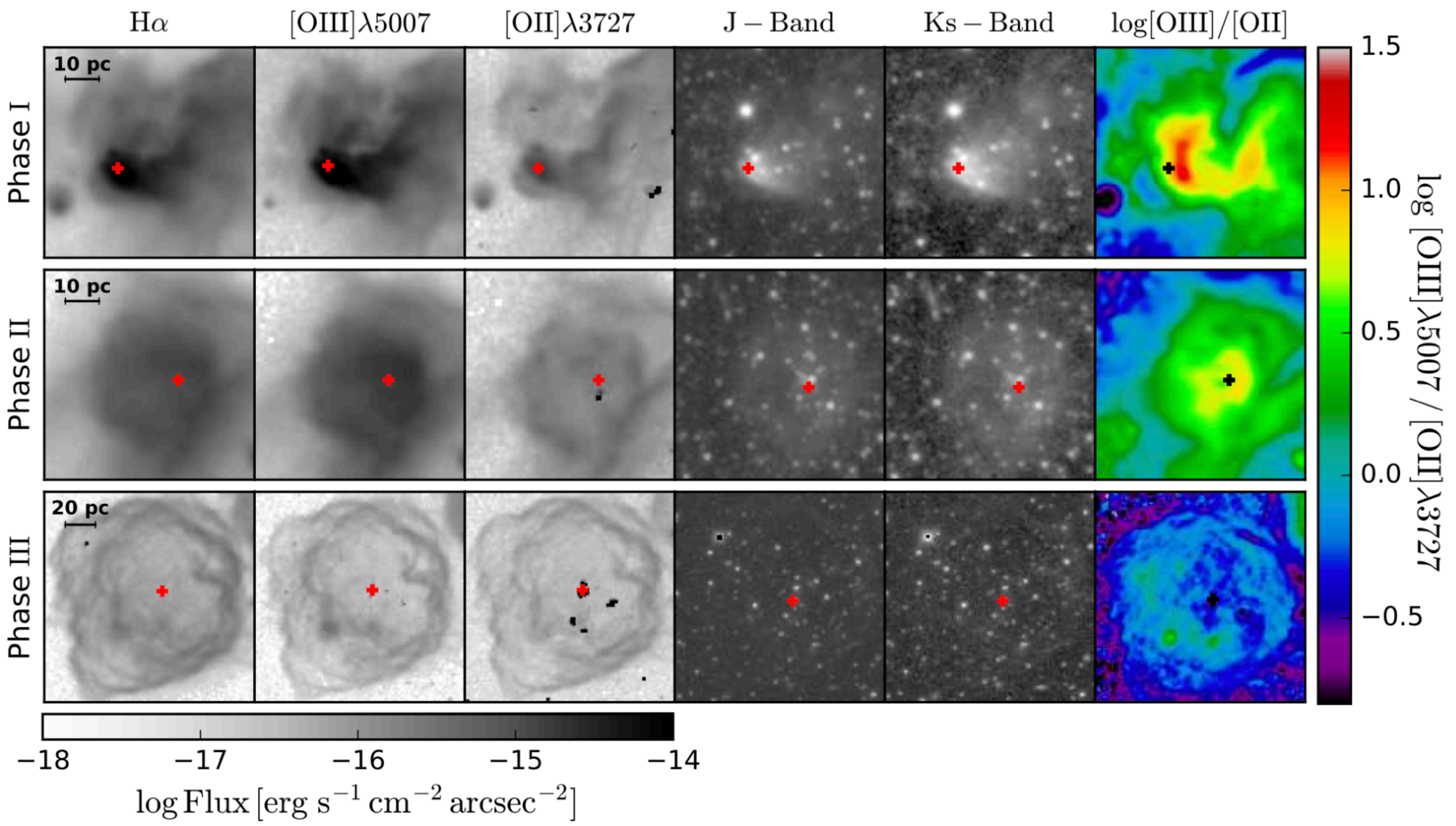
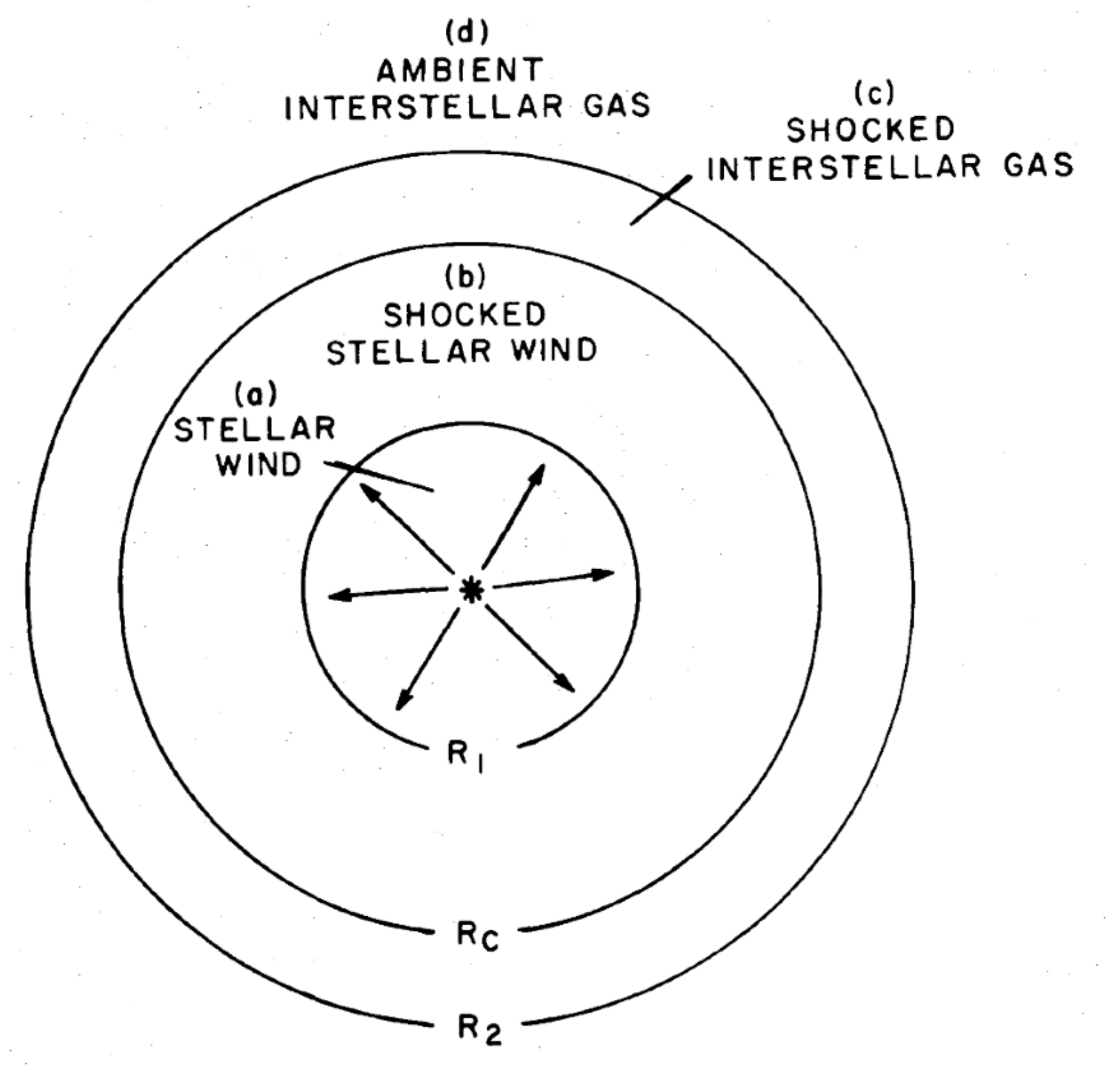




WARPFIELD-EMP: Pellegrini et al. (2020)

Evolution of the superbubbles in the ISM



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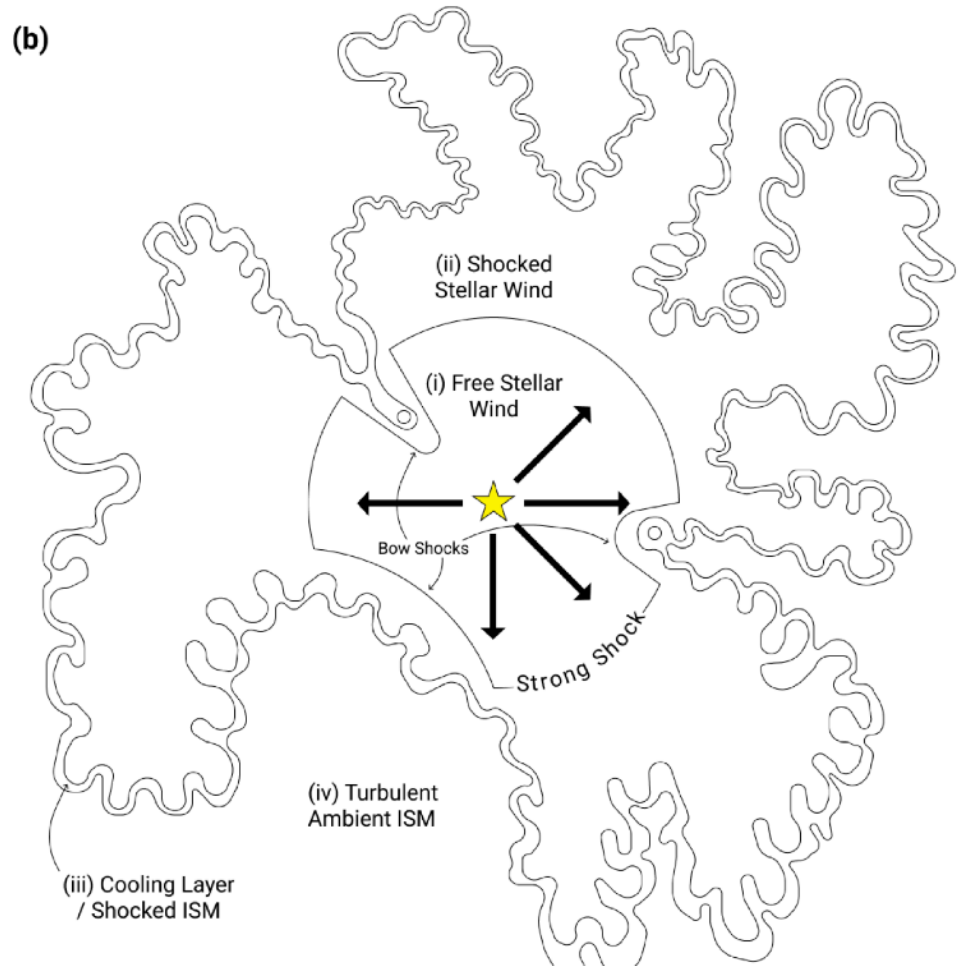
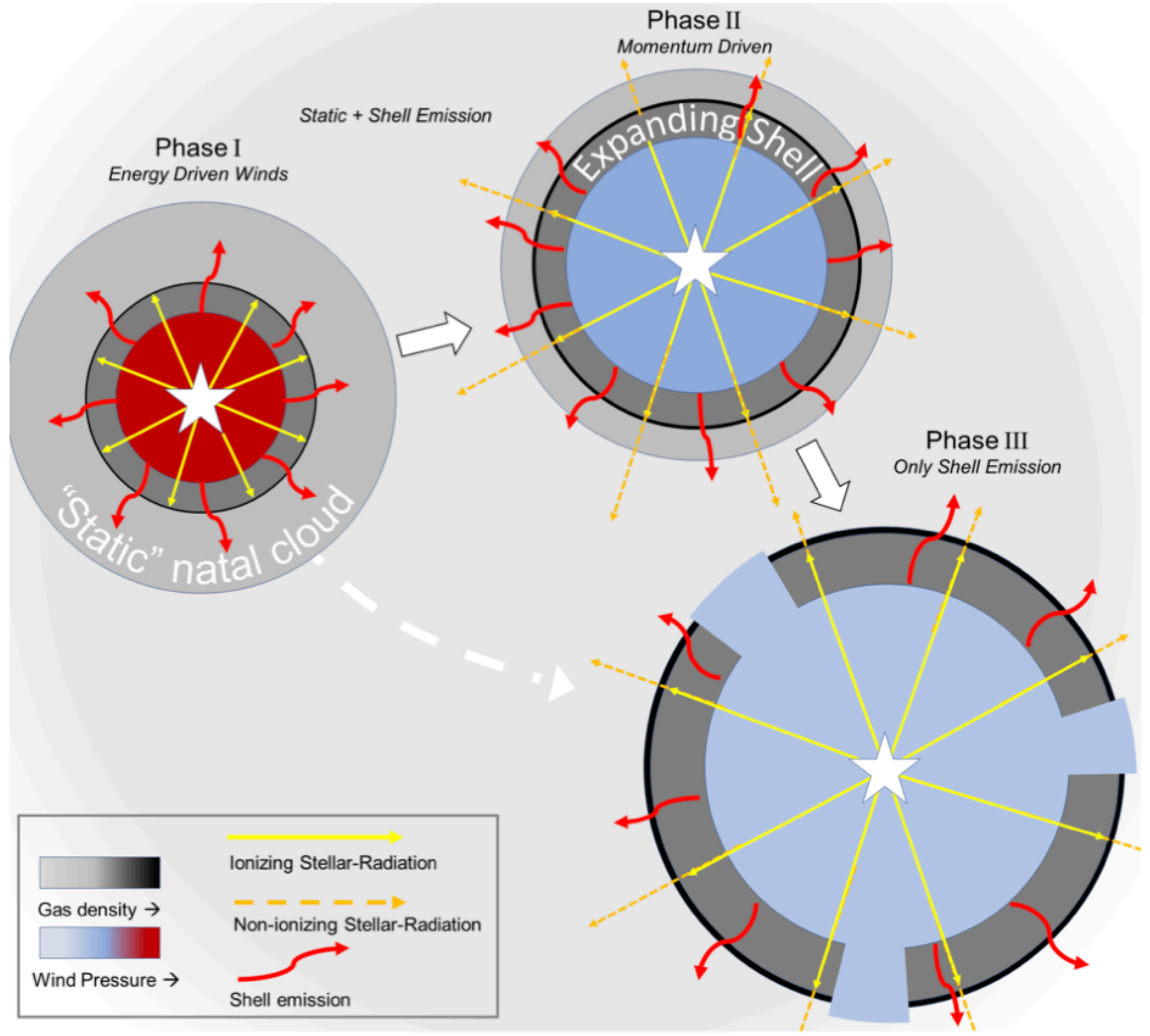
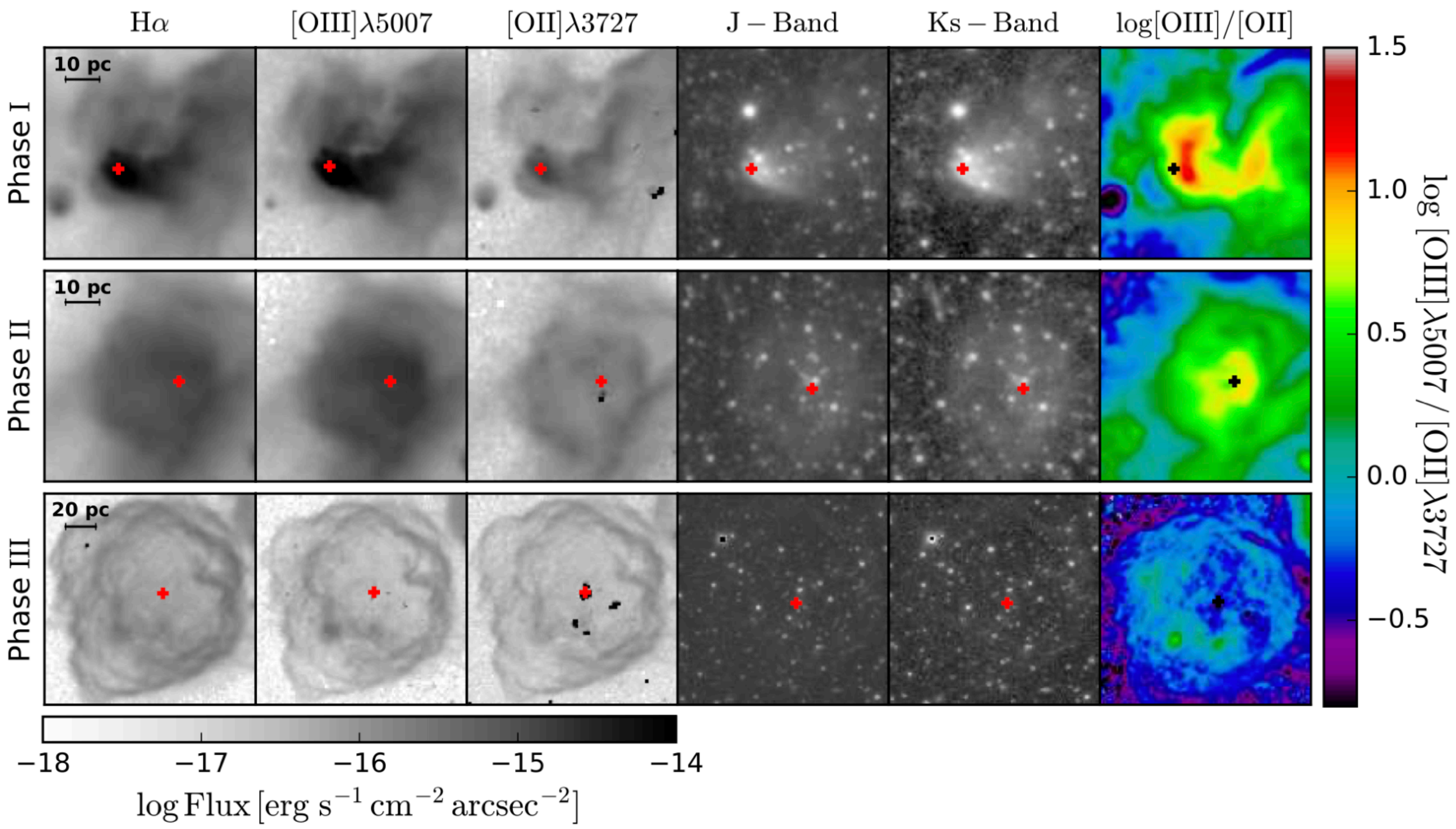


Lancaster et al. (2021)





WARPFIELD-EMP: Pellegrini et al. (2020)

Goal: establish the link between massive stars and ISM from observations

Find statistically significant sample of superbubbles/regions of supersonic gas motions in different environments

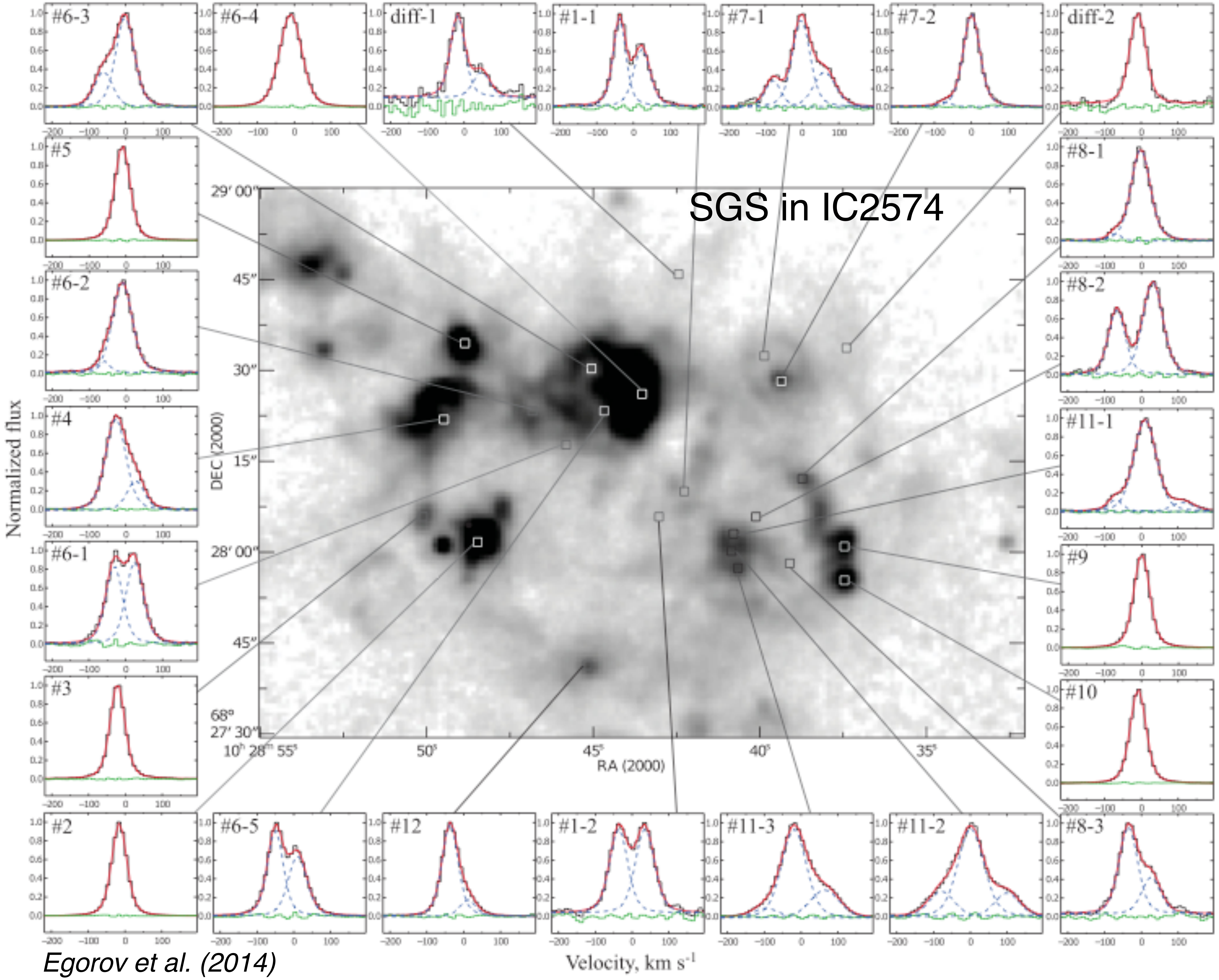
↓

Measure their energetics based on their gas mass and kinematics

↓

Identify and characterize the source of mechanical energy (young massive stars, supernova)

Spectral line shapes in star-forming regions



Egorov et al. (2014)

From line separation and/or velocity dispersion => velocities of the bubbles and gas turbulent motions => **constraints on the energetics of the ionized ISM**

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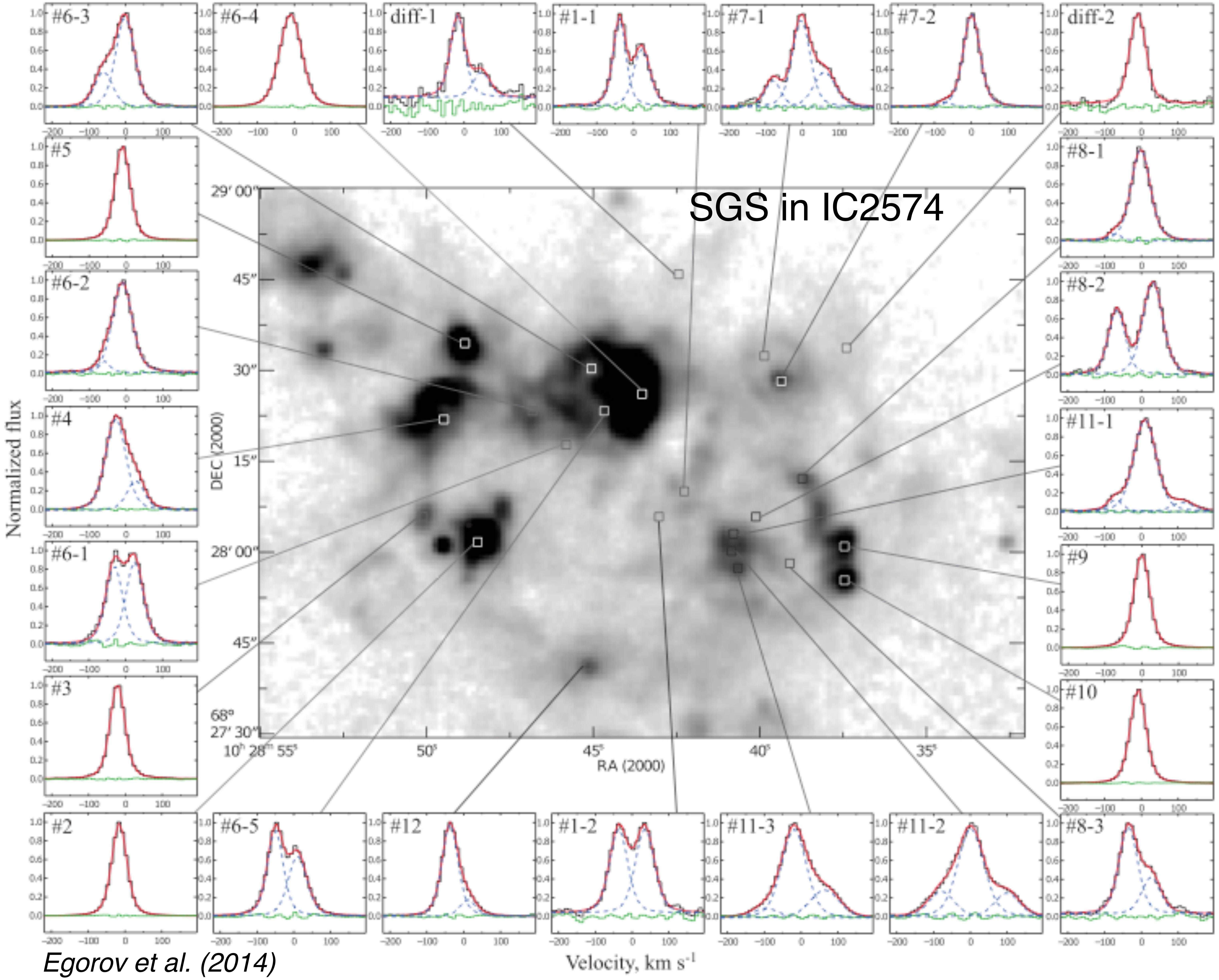

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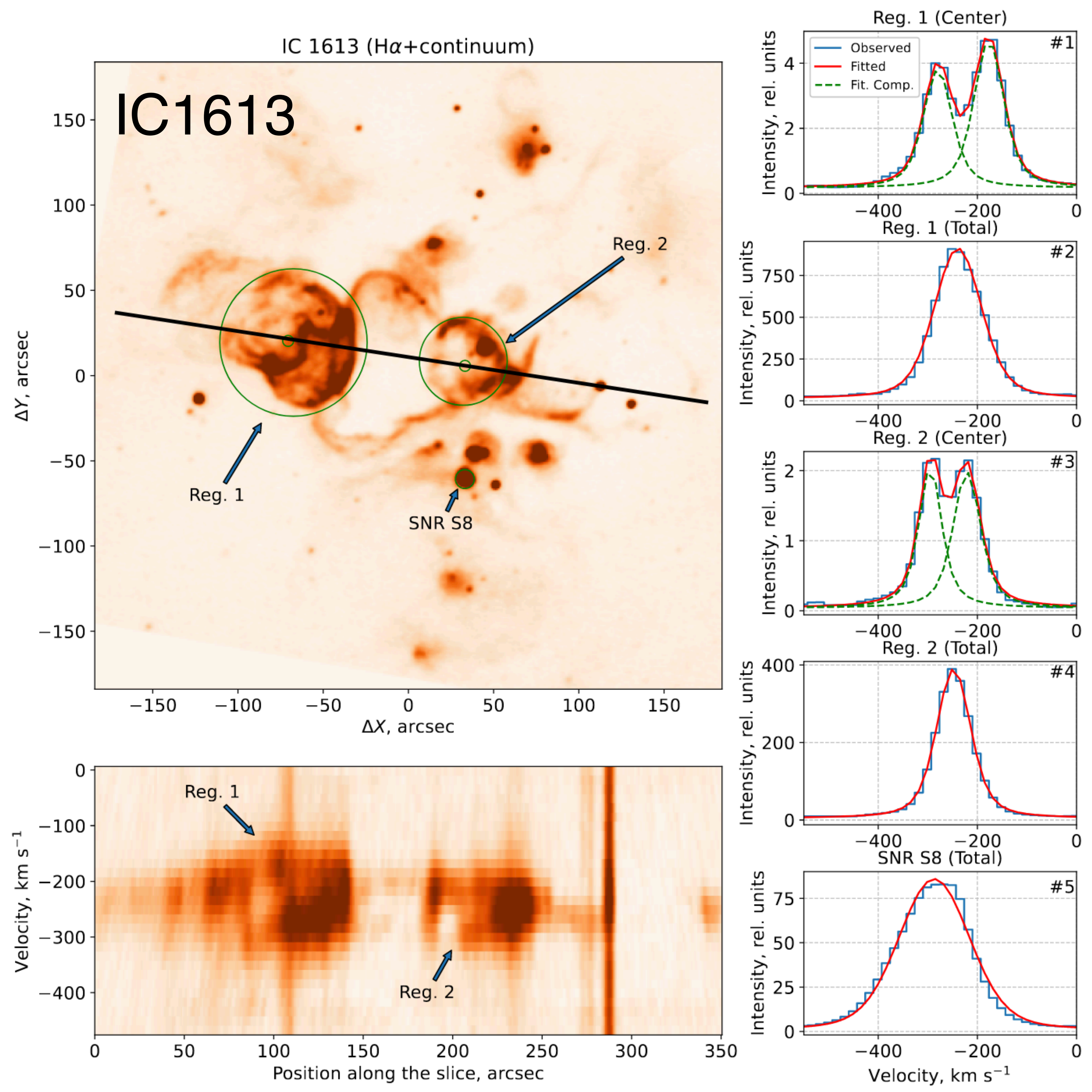

Smirnov-Pinchukov & Egorov (2021); see also Lozinskaya (2002)

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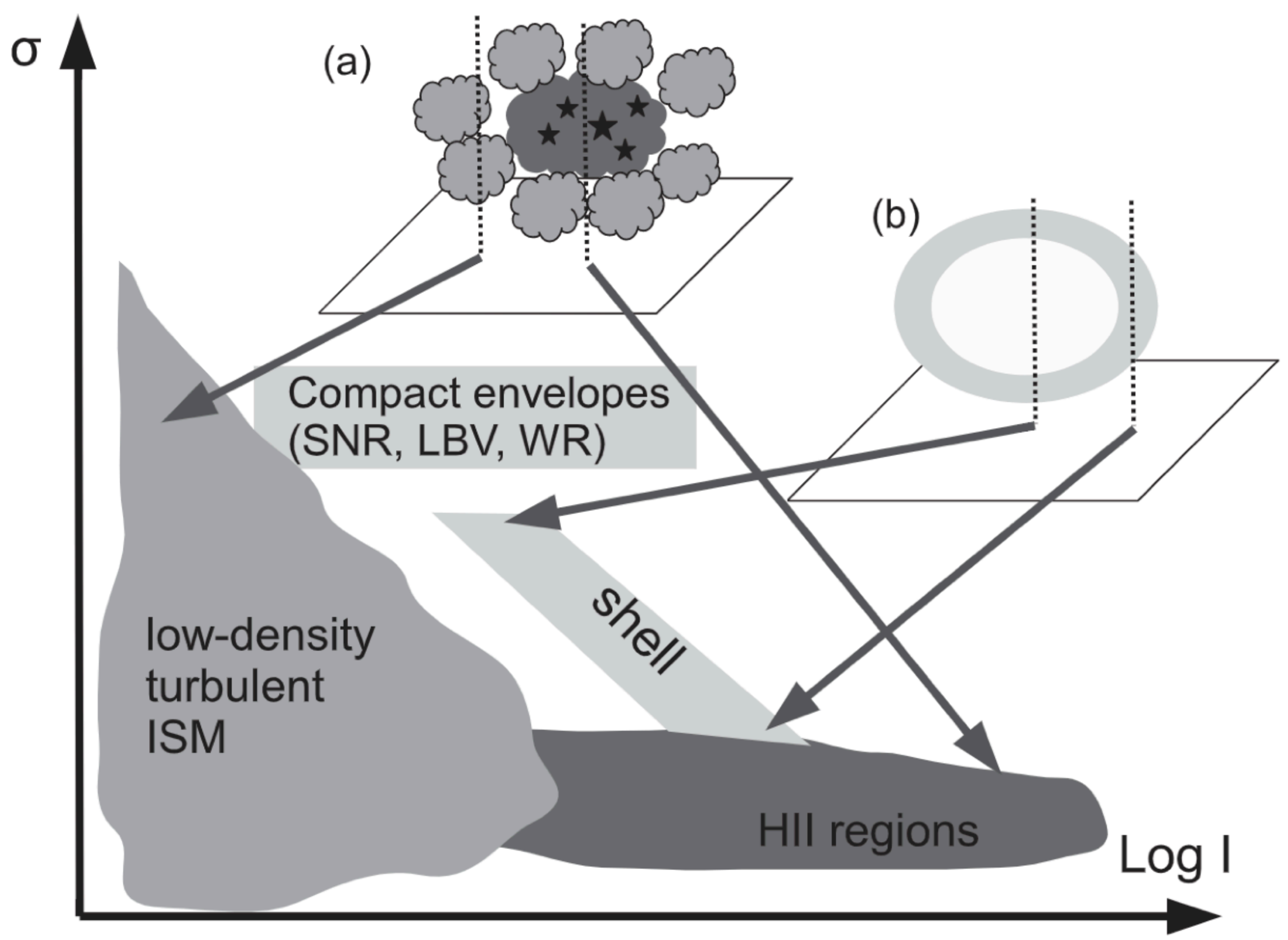
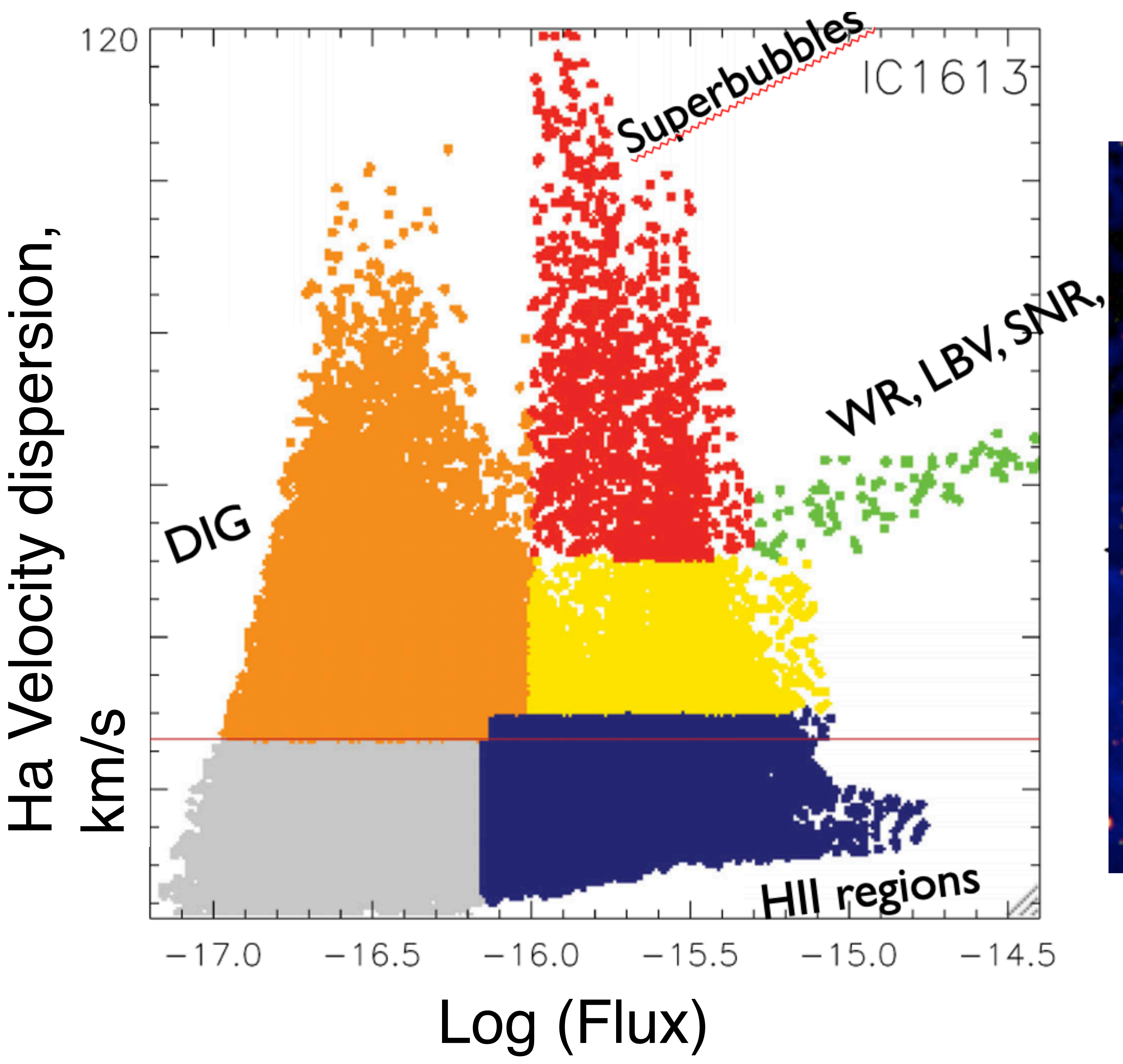
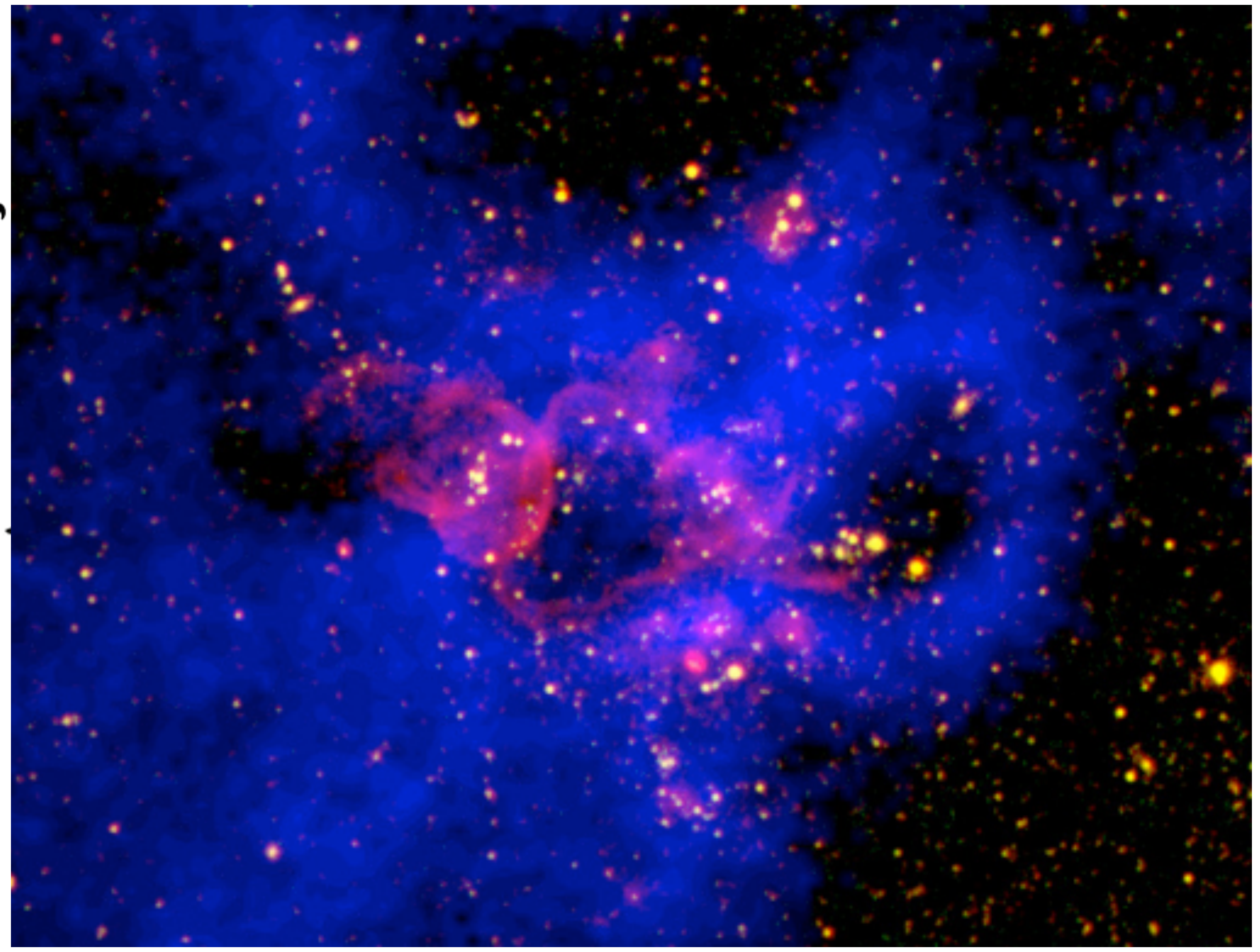
I-sigma diagram: diagnostics for the supersonic gas motions



Munoz-Tunon+ (1996)
Moiseev & Lozinskaya (2012)





HI 21cm Halpha

Moiseev & Lozinskaya (2012)
see also Egorov+(2017, 2018, 2021); Bresolin+(2020); Yarovova+OE (2023)

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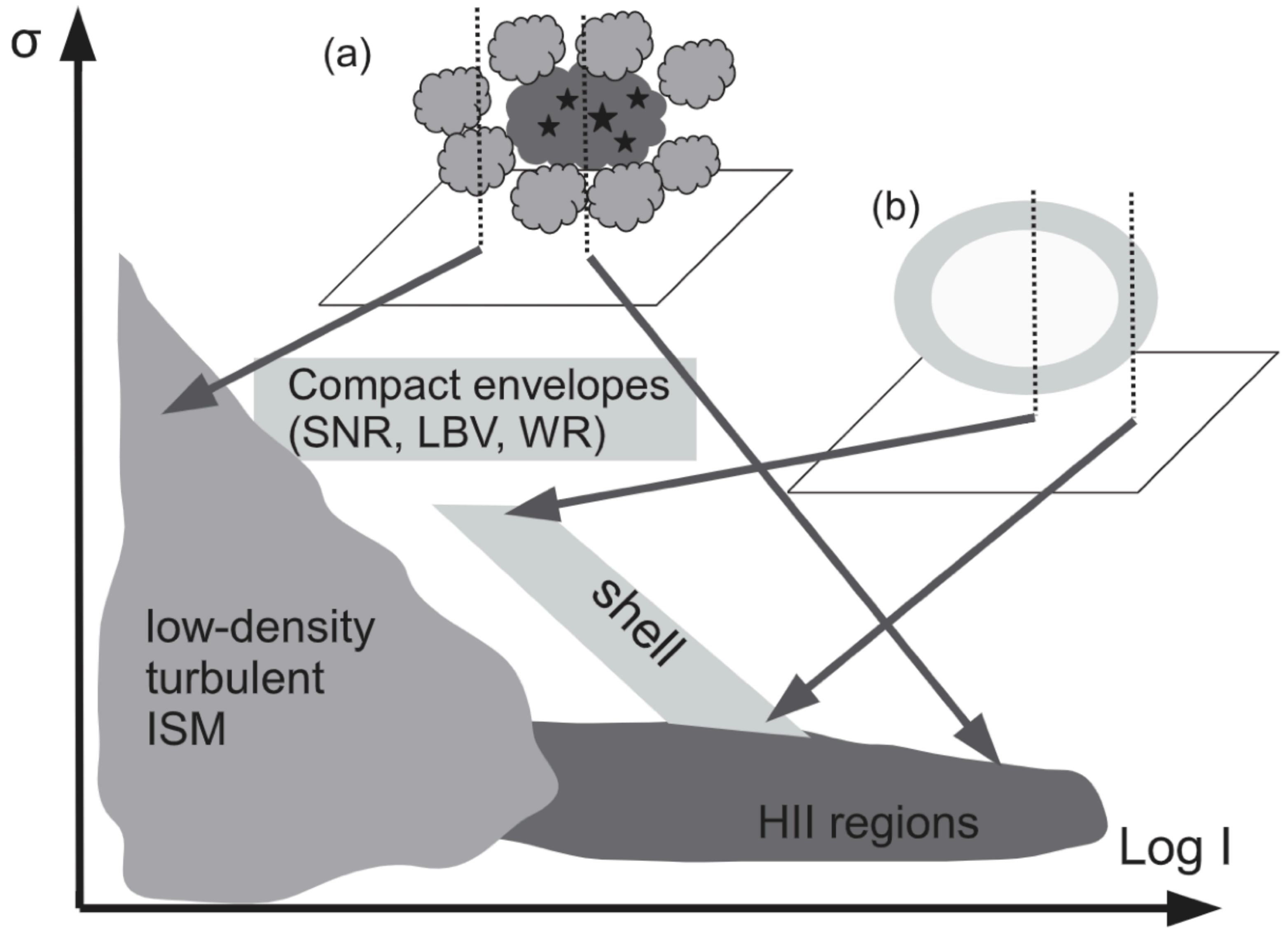

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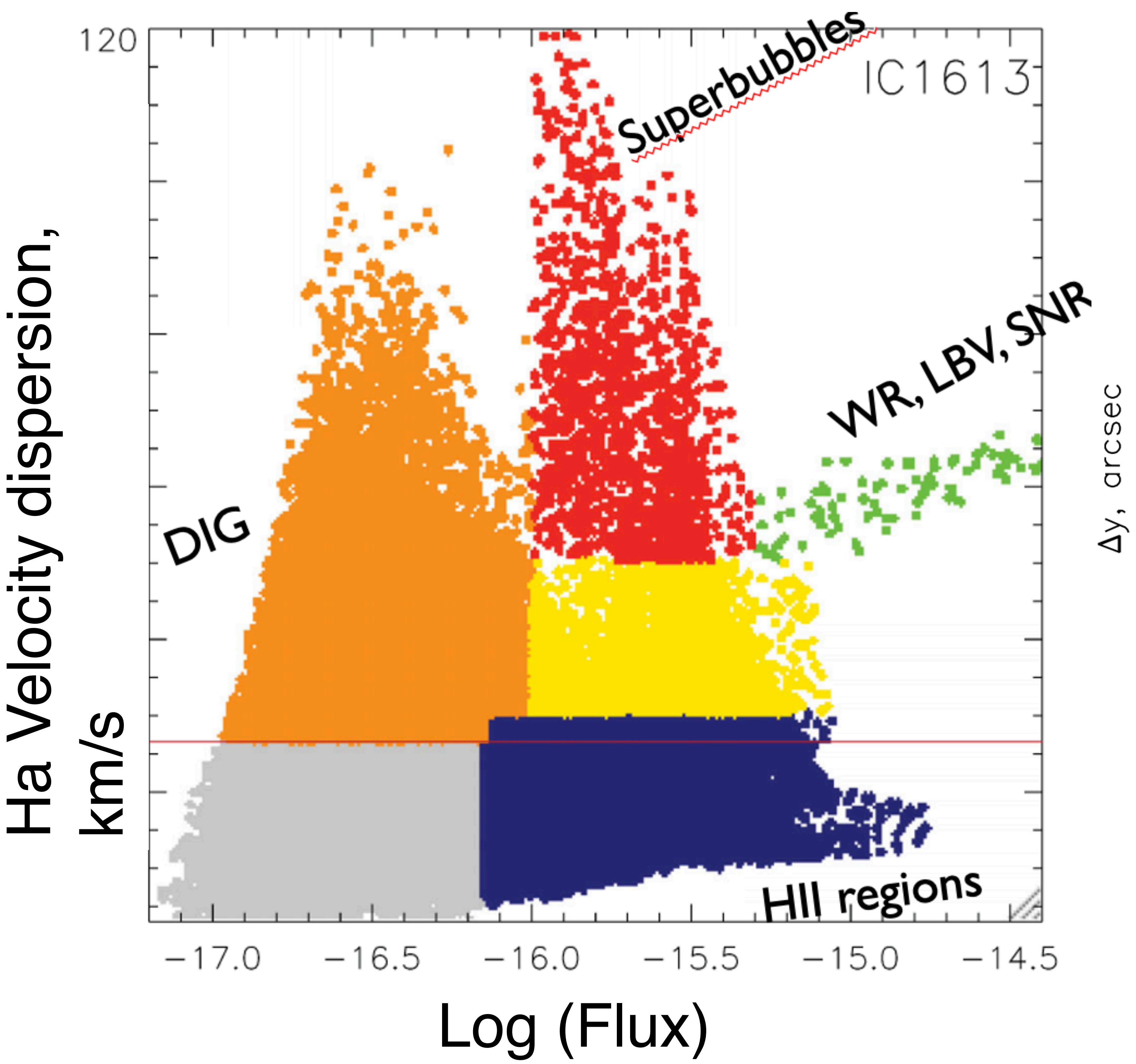
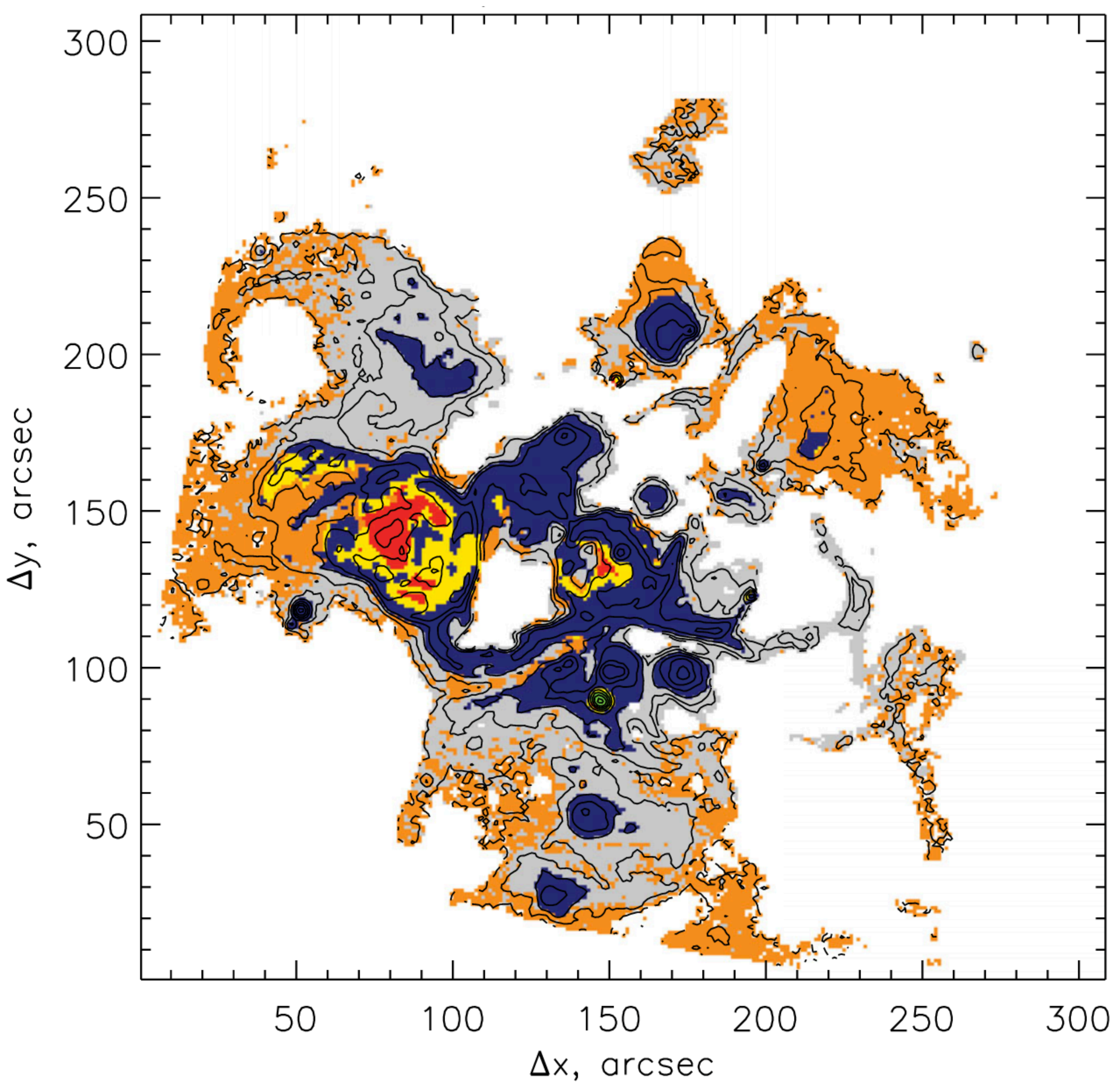
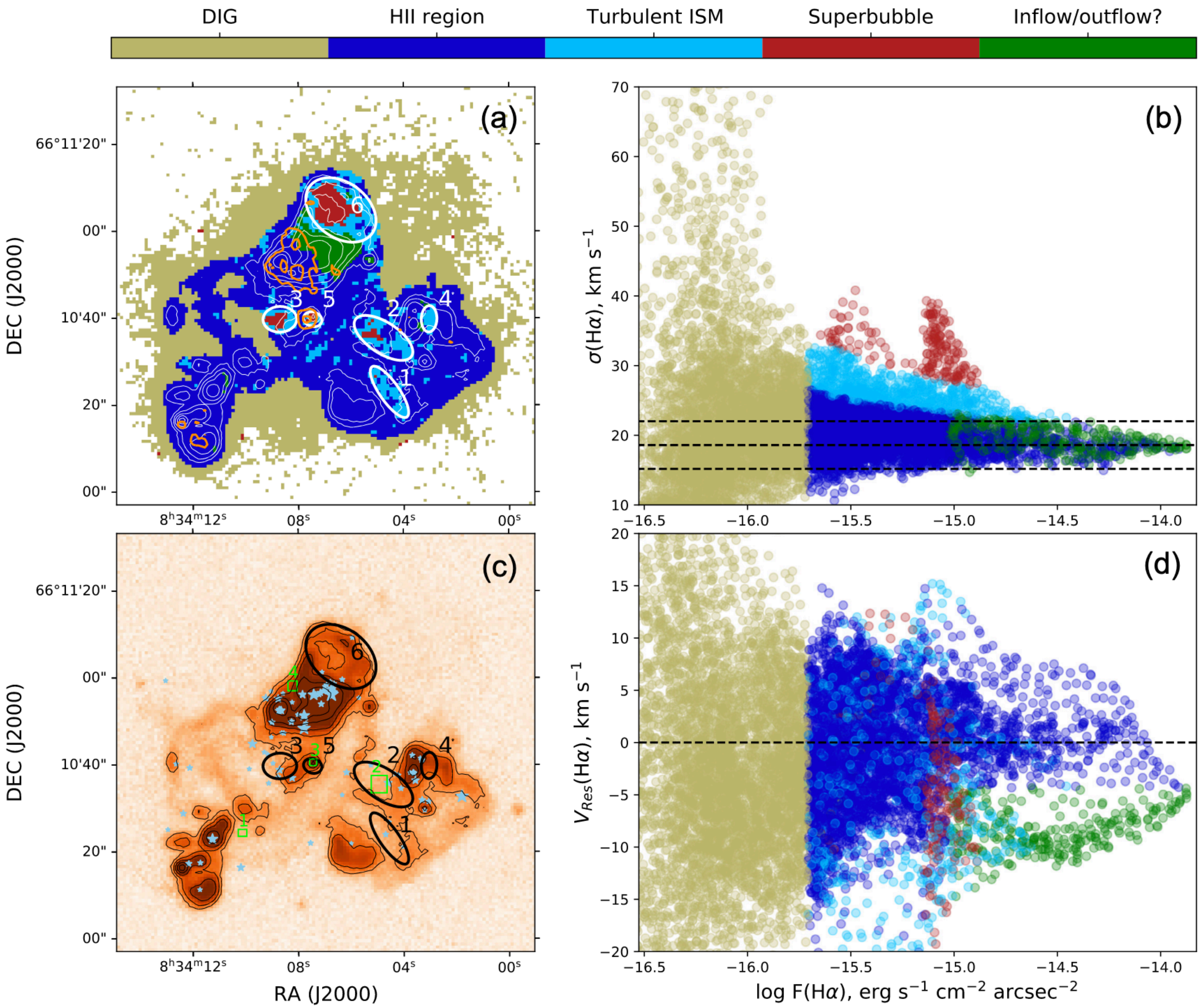




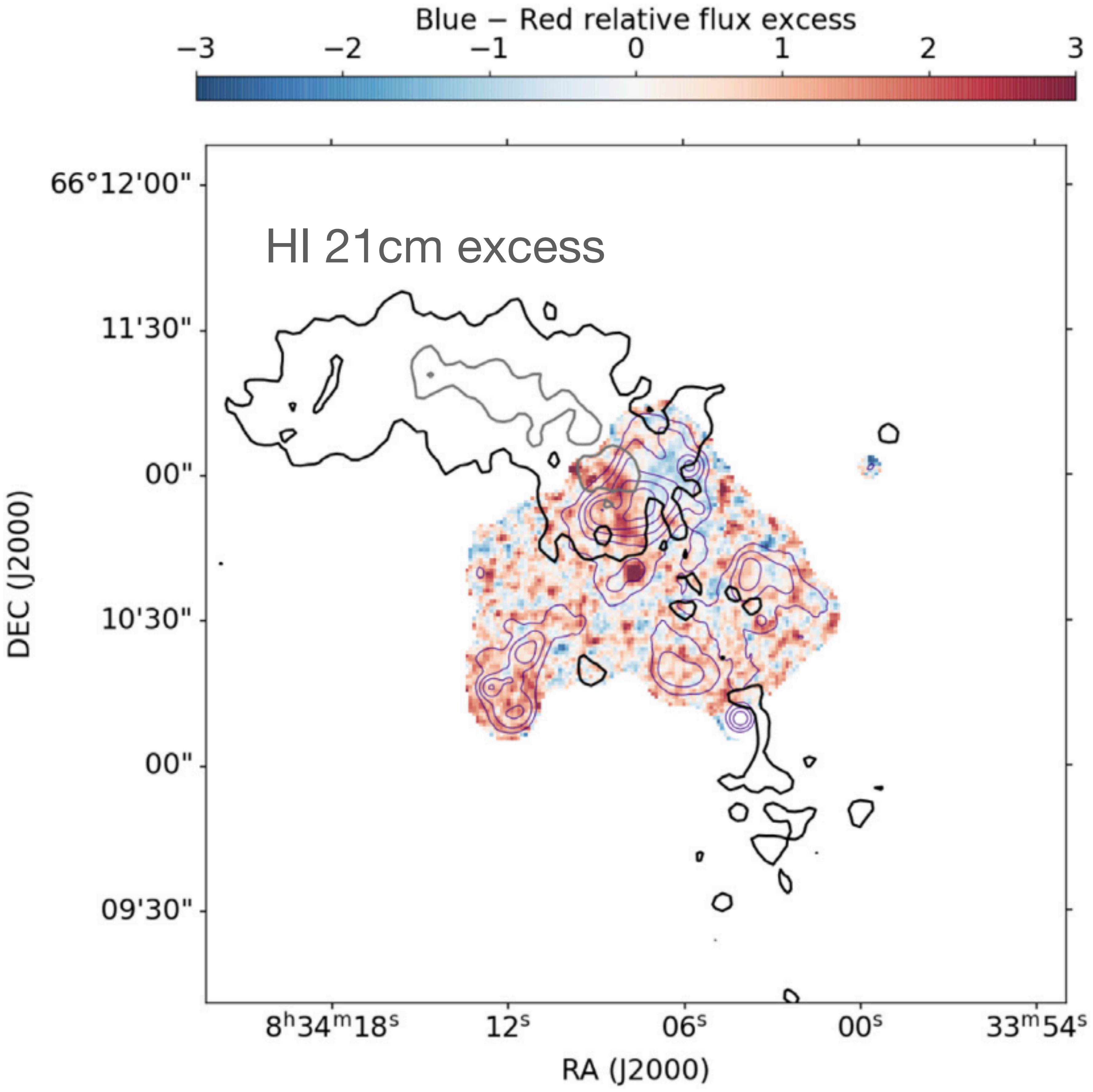
Moiseev & Lozinskaya (2012)
see also Egorov+(2017, 2018, 2021); Bresolin+(2020); Yarovova+OE (2023)

Around 200 expanding superbubble candidates were detected in the nearby (D < 5 Mpc) dwarf galaxies (Egorov+ in prep), which is almost an order of magnitude more than based on the visual morphological classification (Karachentsev et al. 2020)

I-sigma diagram: gas accretion and stellar feedback in DDO53



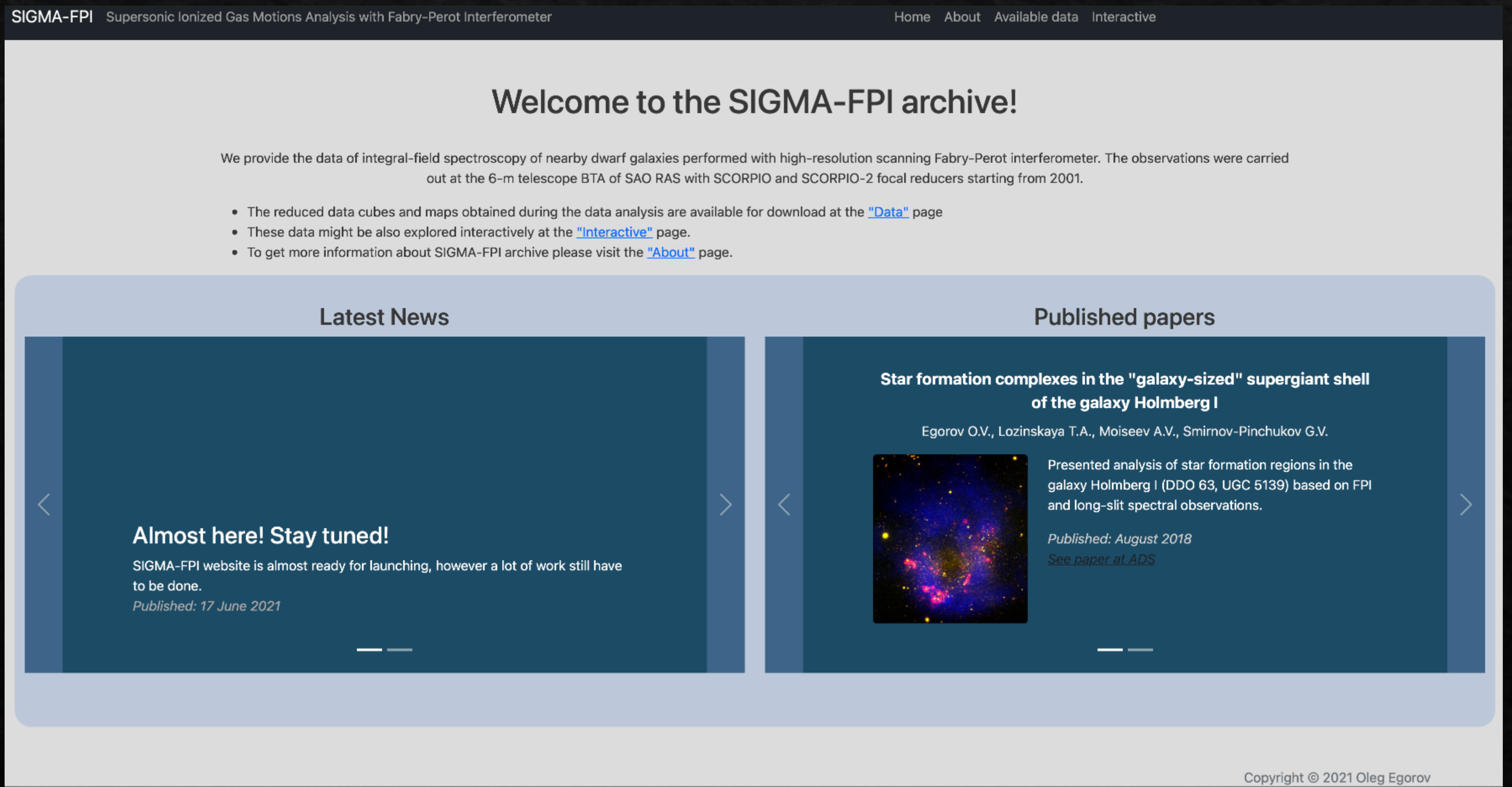
Egorov et al. (2021)



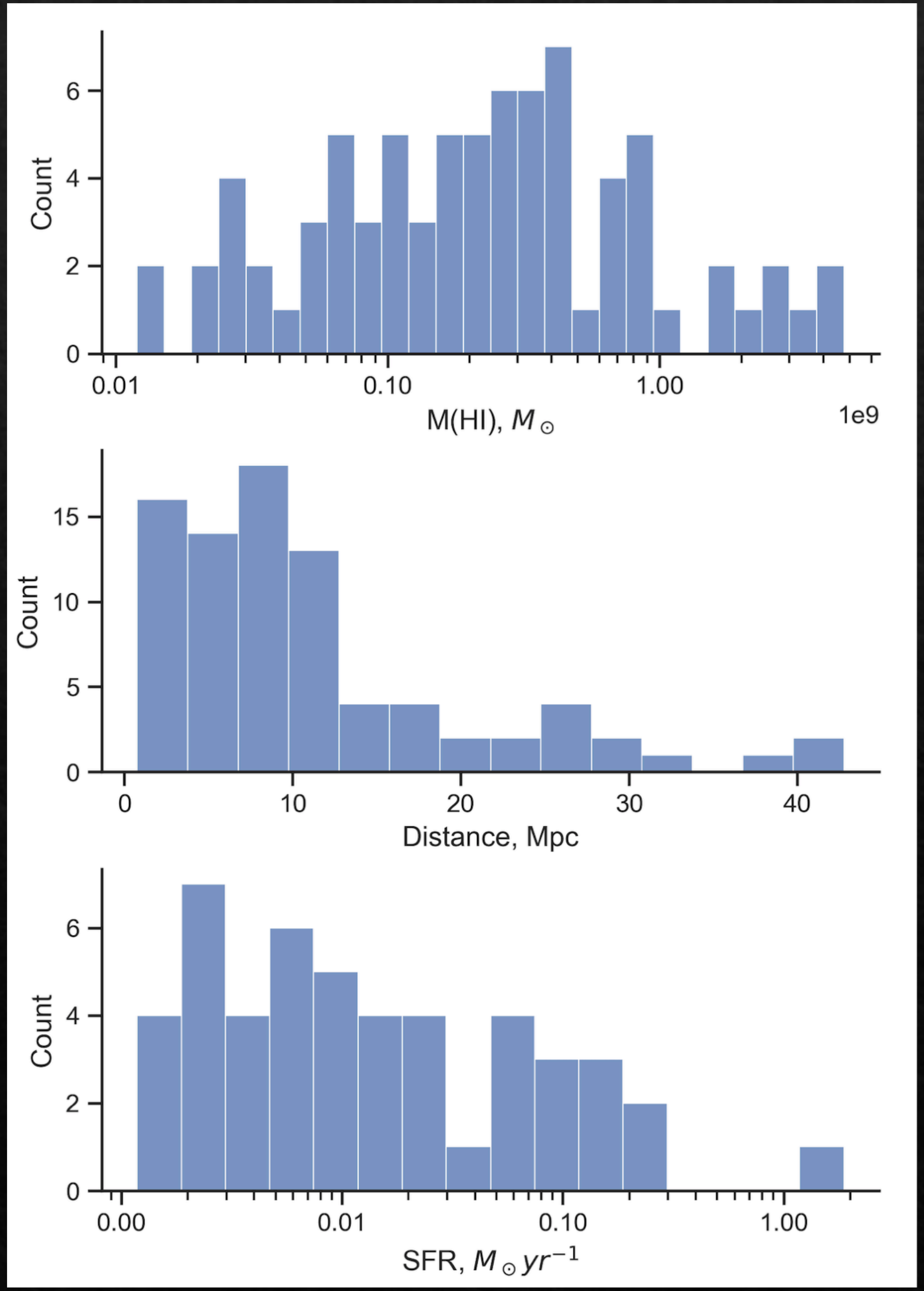
The analysis of Ha line shape an width, we are able to disentangle between the stellar feedback and external gas outflow

SIGMA-FPI

- **S**upersonic **I**onized **G**as **M**otions **A**nalysis with **F**abry-**P**erot **I**nterferometer
- Archive of the reduced FPI data cubes obtained with the 6-m telescope BTA and the results of their analysis:
  - Distribution of the flux in Halpha line ([OIII], [SII] in few cases)
  - Maps of the line-of-sight velocity & velocity dispersion
  - Tilted-rings models of velocity fields and the residuals (for limited sample)
  - Maps of asymmetries of the emission line profiles
  - I-sigma diagrams and catalogue of the superbubble candidates
- http://sigma.sai.msu.ru (partially released)

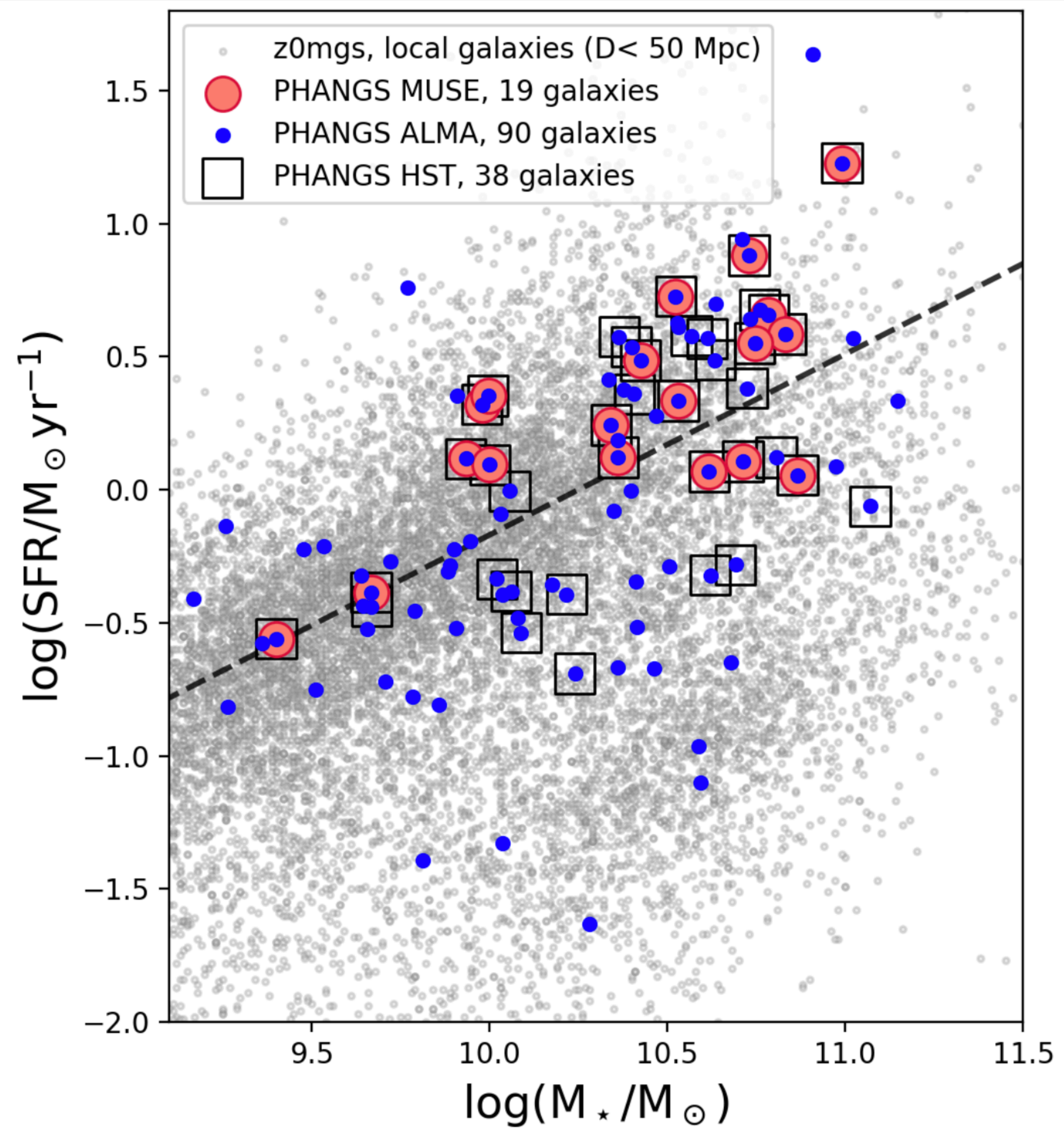


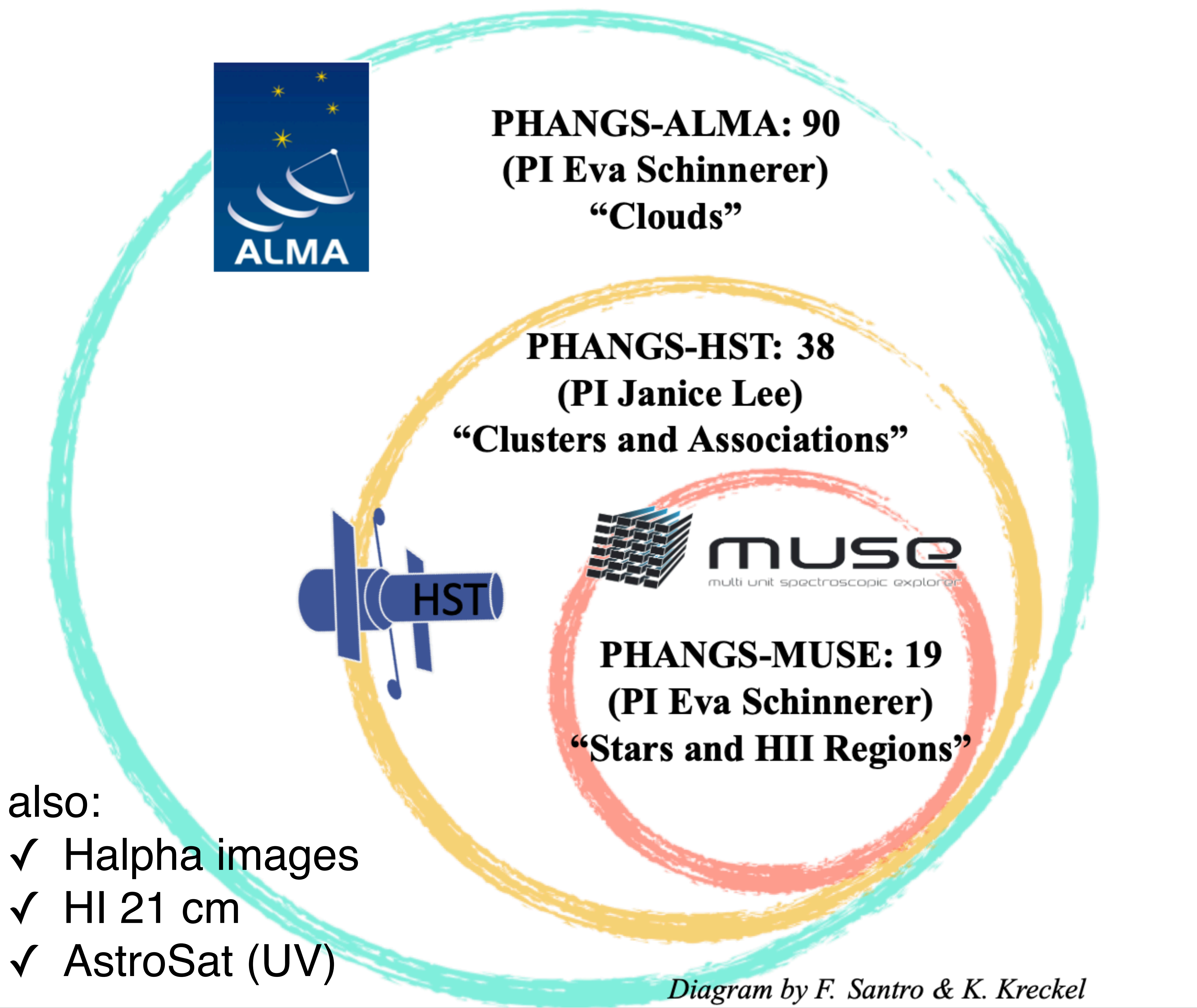
Currently in archive: 83 galaxies (+7 galaxies with D>45 Mpc)



Egorov et al. (in prep)

PHANGS: Physics at High Angular resolution in Nearby GalaxieS





Details in: Leroy et al. (2021) Lee et al. (2022) Emsellem et al. (2022) Lee et al. (2023)

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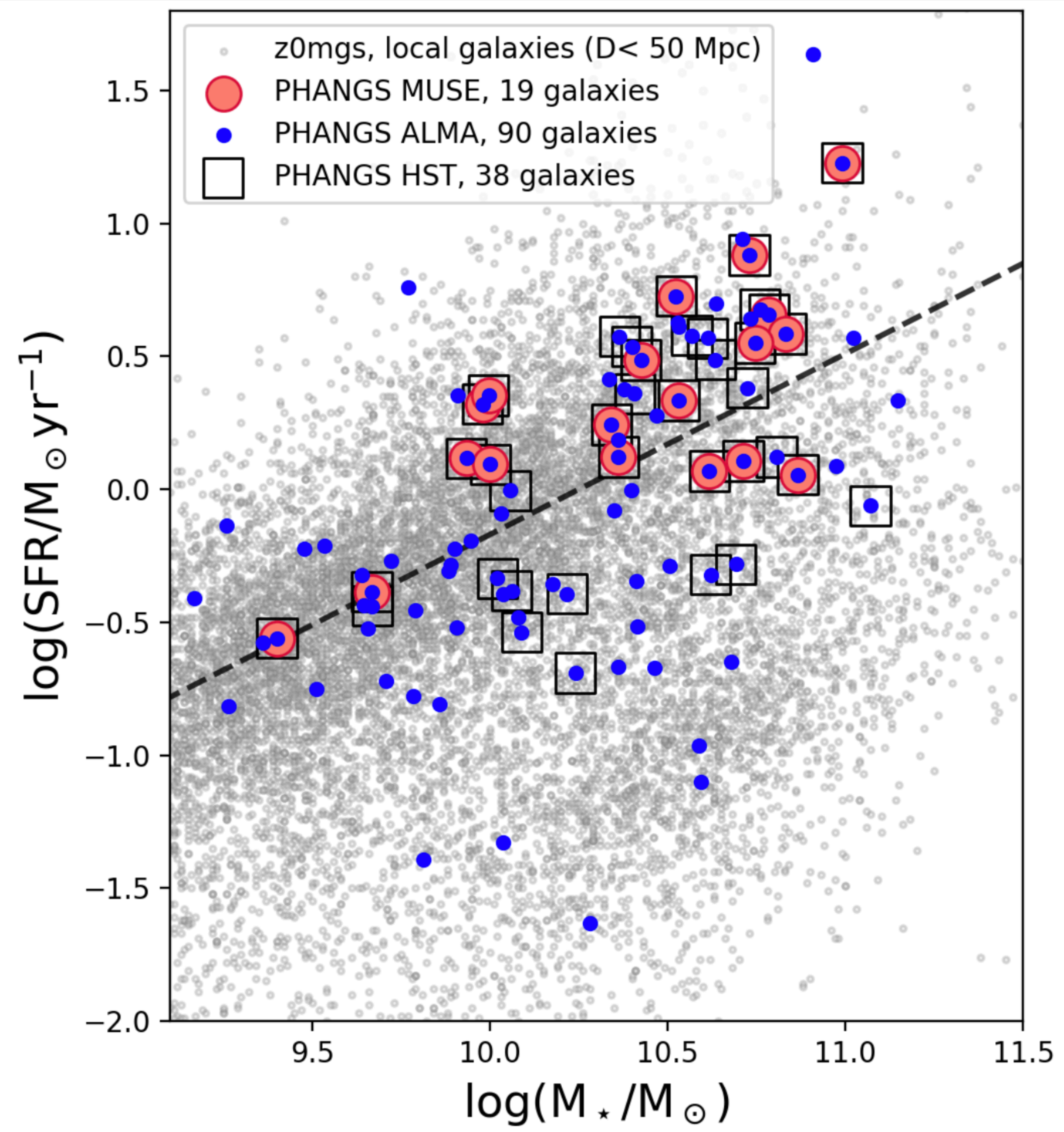
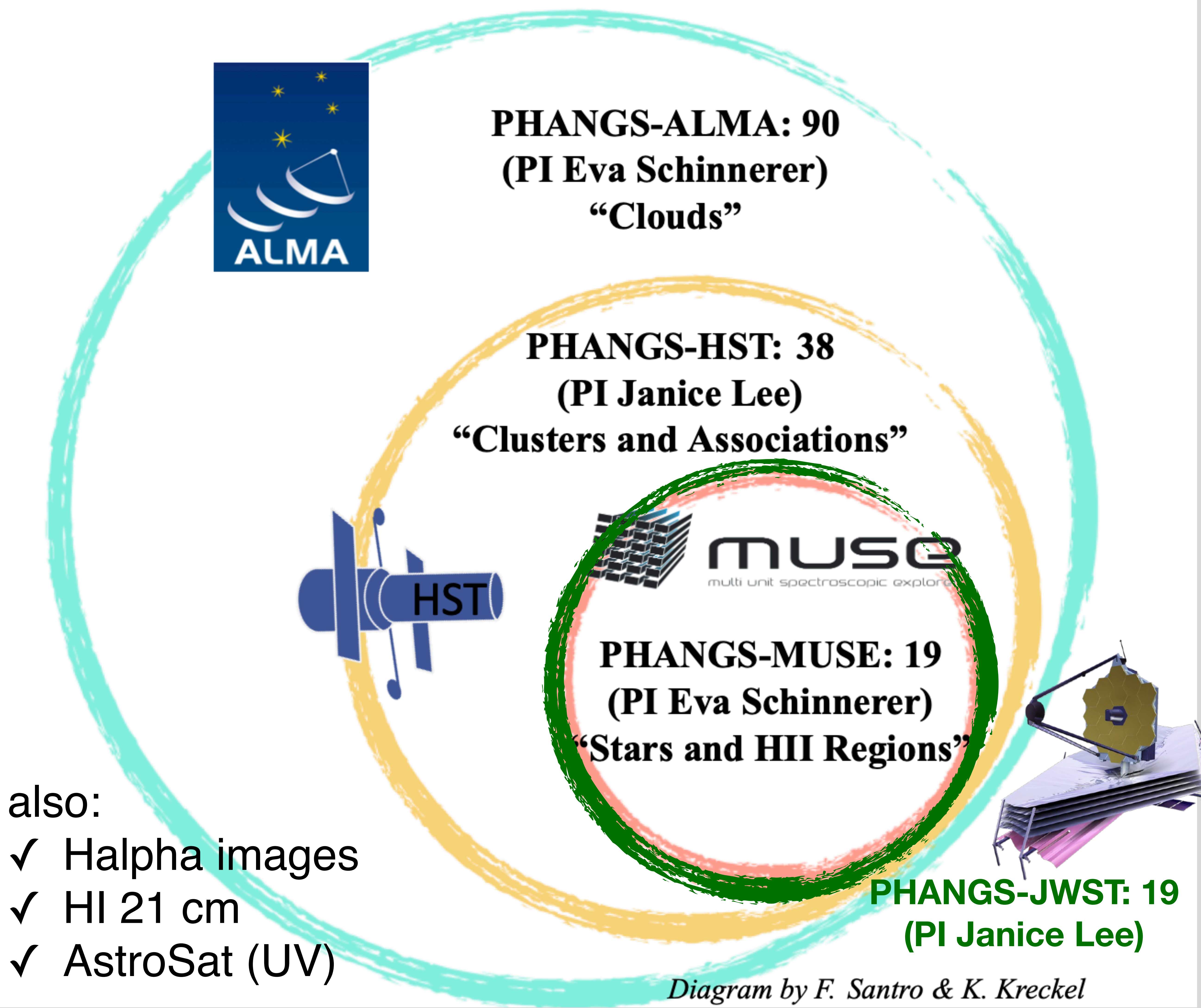




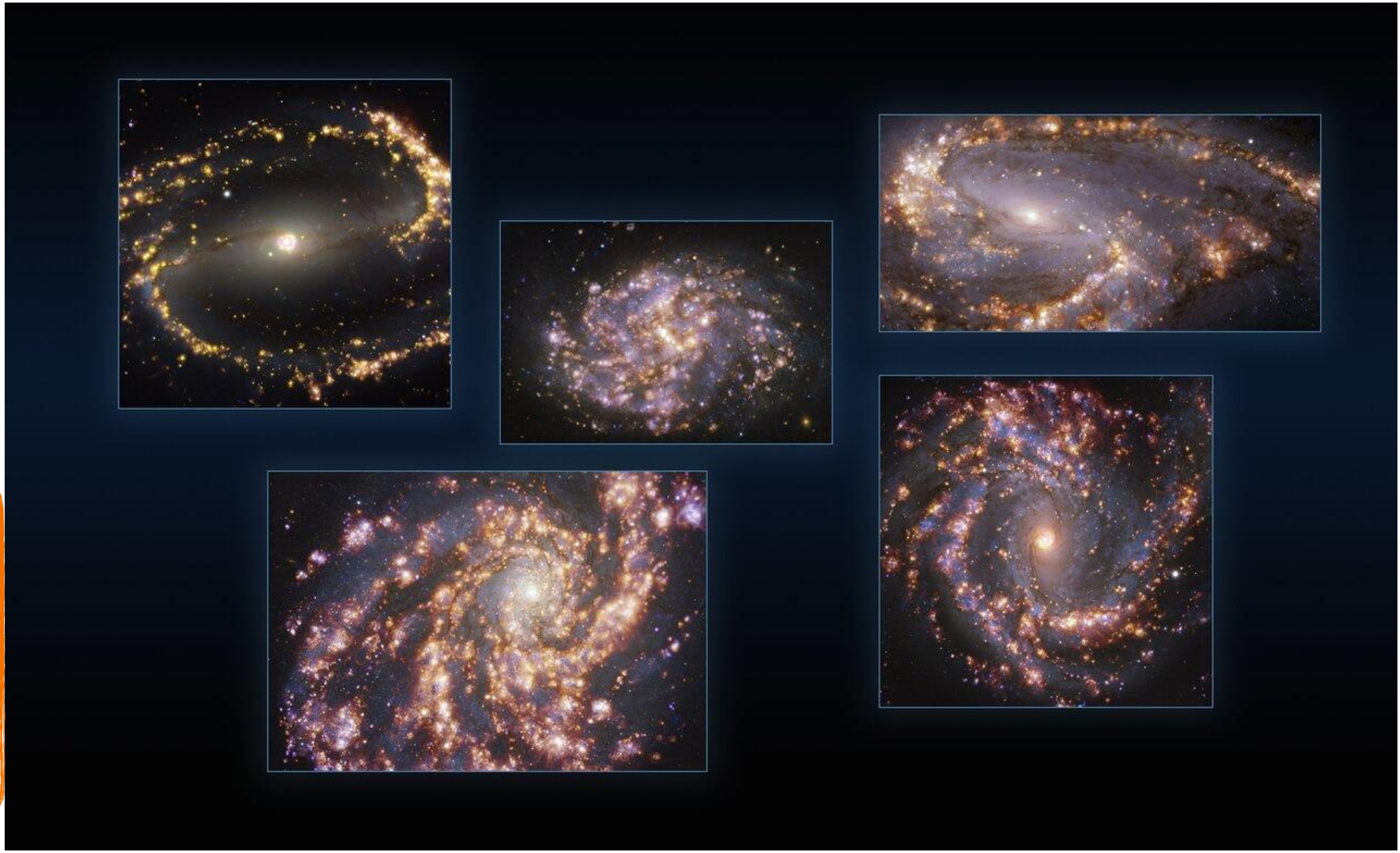
also:
- ✓ Halpha images
- ✓ HI 21 cm
- ✓ AstroSat (UV)

Details in: Leroy et al. (2021) Lee et al. (2022) Emsellem et al. (2022) Lee et al. (2023)

PHANGS-MUSE

- 19 spiral galaxies covered up to ~2R_e
- ***Distance:*** 5.2 – 19.6 Mpc
- ***Log(M^*/M_{sun}):*** 9.4 – 11
- ***Spatial resolution:*** *~50 pc*
- ***Spectral range:*** 4750 – 9350 A
- ***Spectral resolution:*** ~2.5A (σ~48 km/s in Hα line)

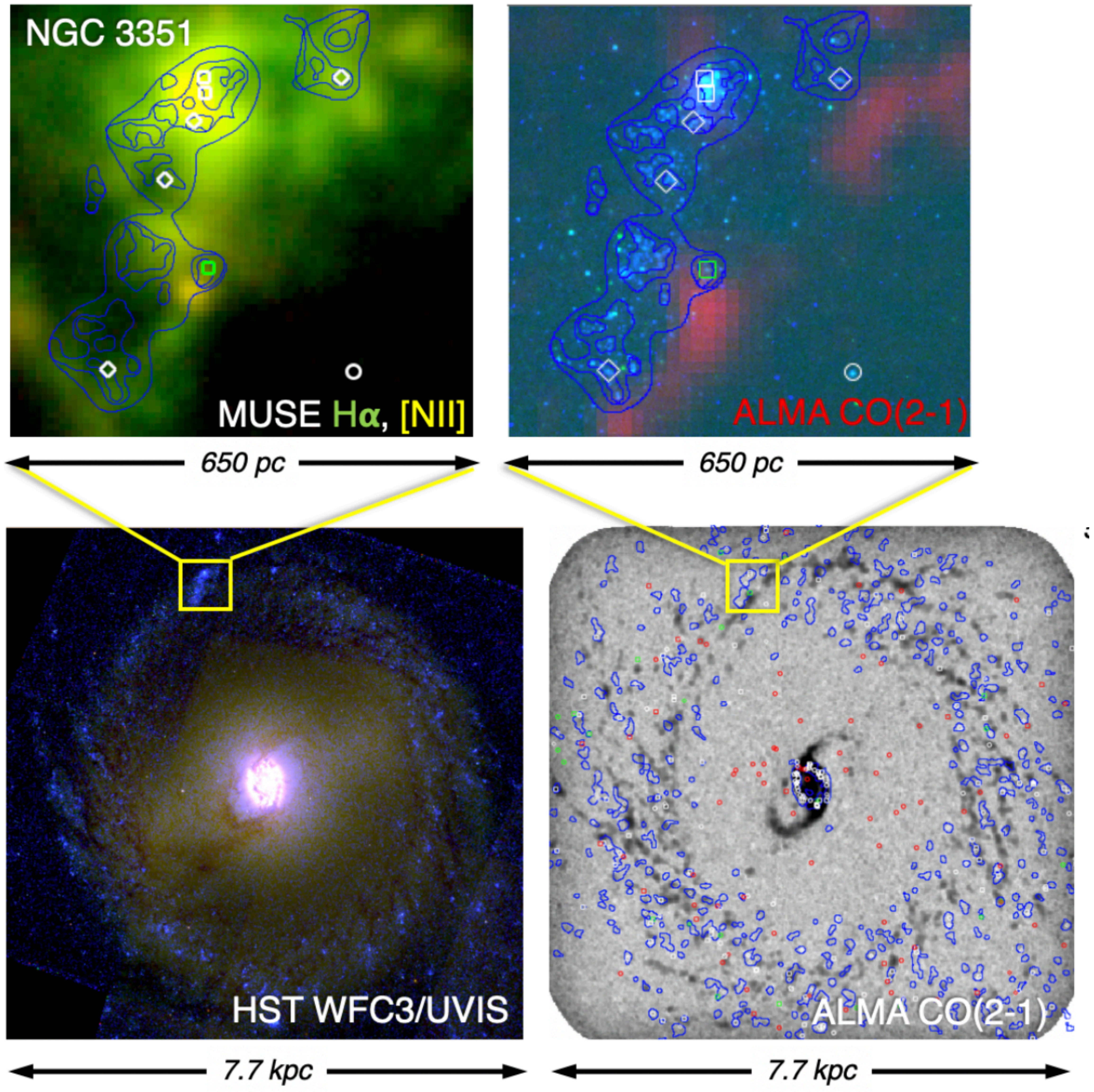
- **Data Products:**
- ***Emsellem et al. (2022):*** DR1 - data cubes; maps in emission lines and stellar population
- ***Groves et al. (2023):*** Catalogue of ~30 000 HII regions and their properties



Credit: ESO/PHANGS

Continuum in blue and white, [OIII]/[SII]/Ha composite in gold

PHANGS-HST



- 38 spiral galaxies including all PHANGS-MUSE
- ***Bands:*** NUV-U-B-V-I (WFC3 or ACS)
- ***Distance:*** 4 – 23 Mpc
- ***Log(M^*/M_{sun}):*** 9.4 – 11
- ***Angular resolution:*** *~0.08”*

- **Data Products:**
- ***Lee et al. (2022):*** DR1 - Multi-color images
- ***Anand et al. (2021)***: TRGB distances
- ***Whitmore et al. (2021); Thilker et al. (2022):*** Compact star clusters
- ***Larson et al. (2023)***: multi-scale stellar associations

~100 000 star clusters, associations

PHANGS-JWST

JWST imaging with MIRI and NIRCAM, Treasury programs

GO-2107, PI: Janice Lee (Cycle 1)

GO-3707, PI: Adam Leroy (Cycle 2)

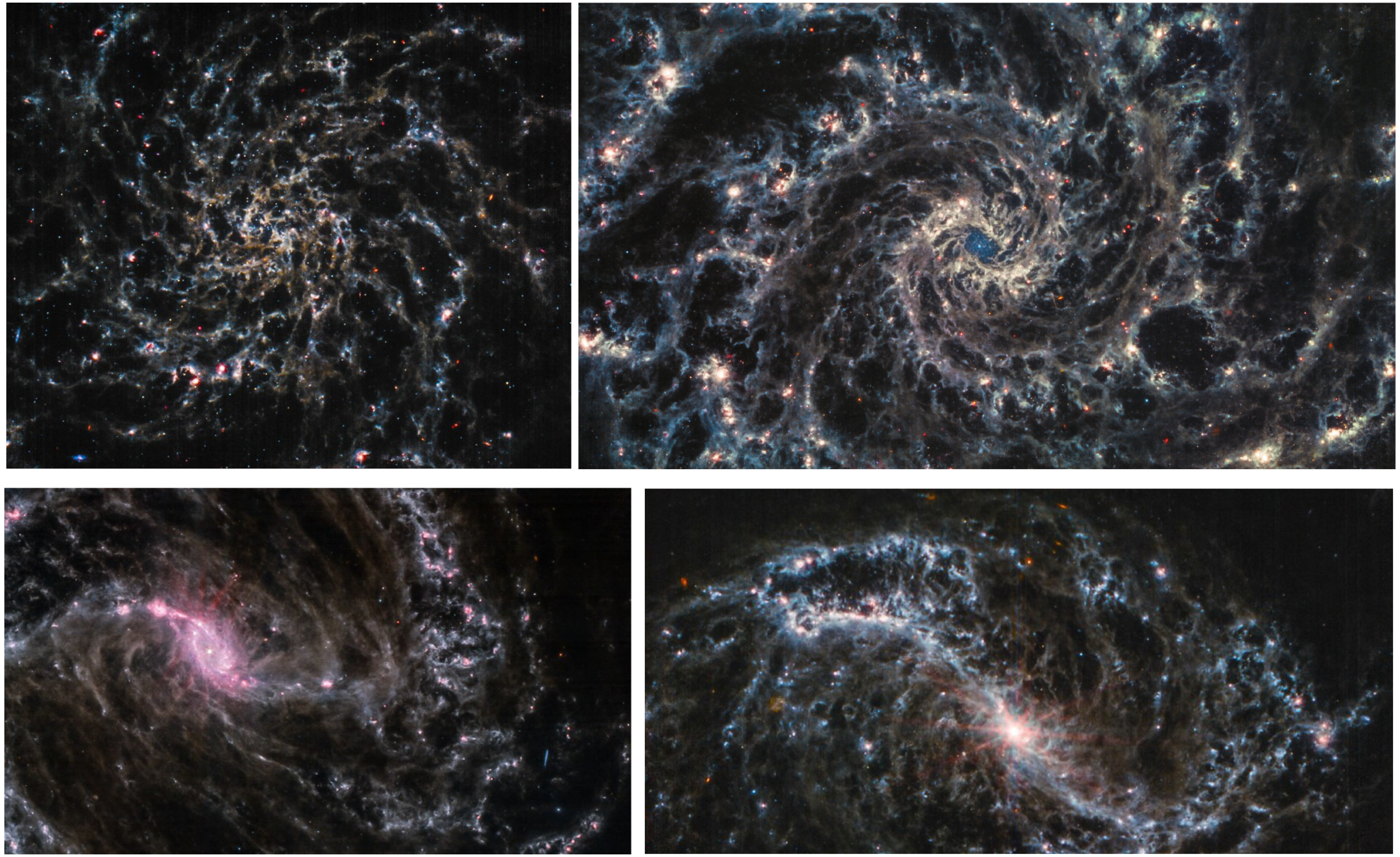
- 19 spiral galaxies, all from PHANGS-MUSE sample
- ***Bands:*** F200W, F300M, F335M, F360M,
  F770W, F1000W, F1130W, F2100W
- ***Distance:*** 5.2 – 19.6 Mpc
- ***Log(M^*/M_{sun}):*** 9.4 – 11
- ***Angular resolution:*** *0.25-0.67" in MIRI bands*

Data Products:

- ***Lee et al. (2023):*** Description of the survey, data reduction etc.

55 galaxies are expected in Cycle 2!

21μm 11.3μm 7.7μm 10μm



Credit: NASA/ESA,CSA; PHANGS, J. Schmidt & Lee et al. (2023)

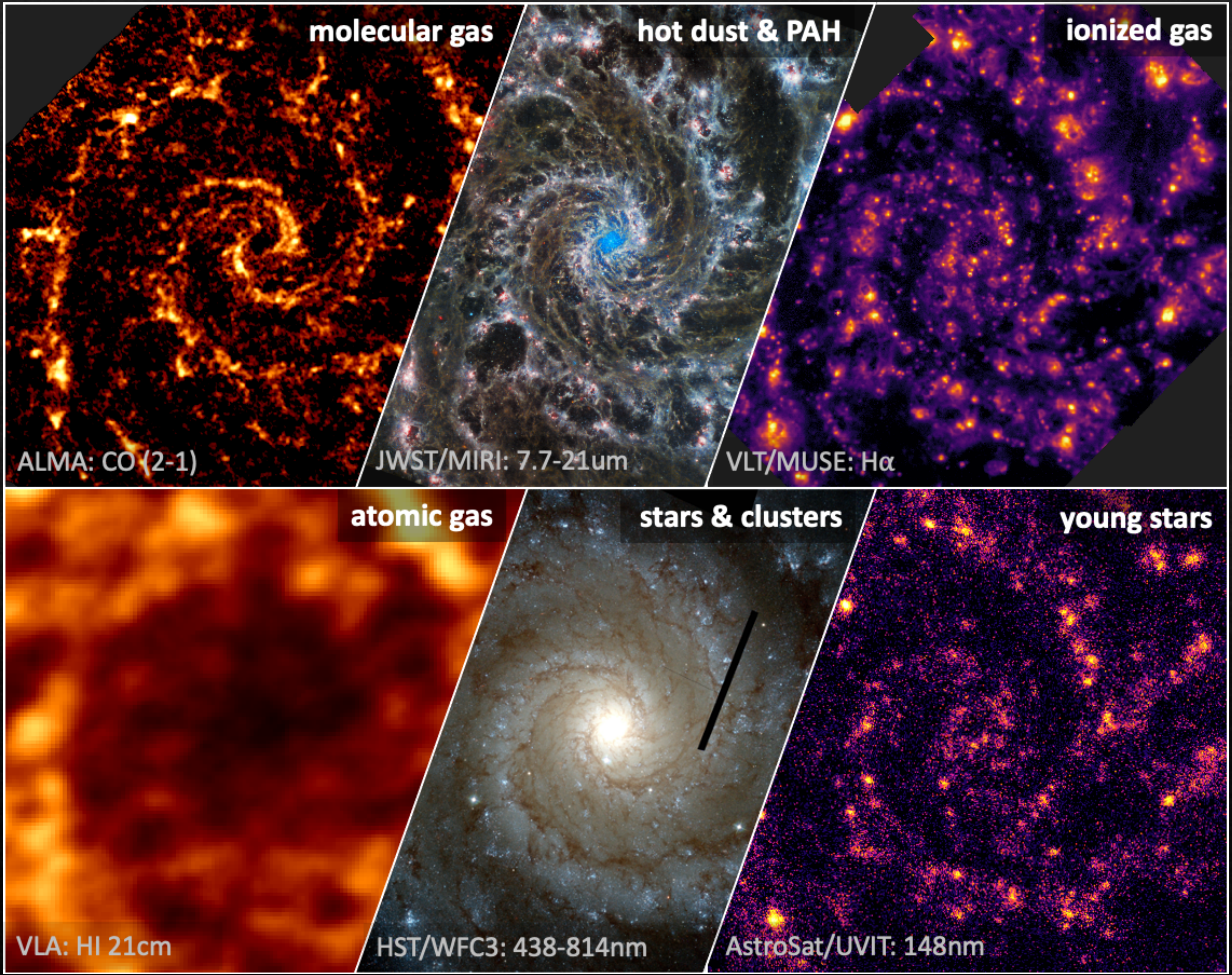
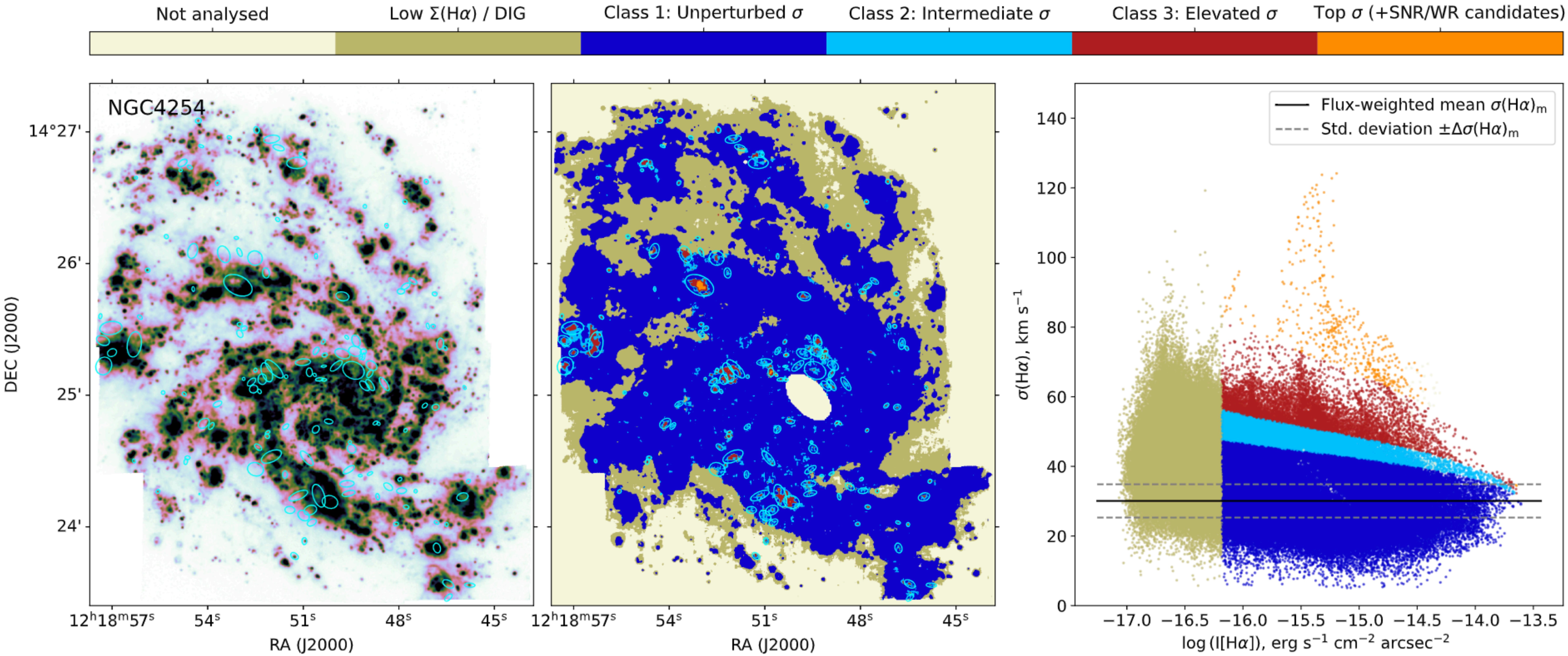


Image credit: J.Sun

I-sigma diagrams for PHANGS-MUSE galaxies

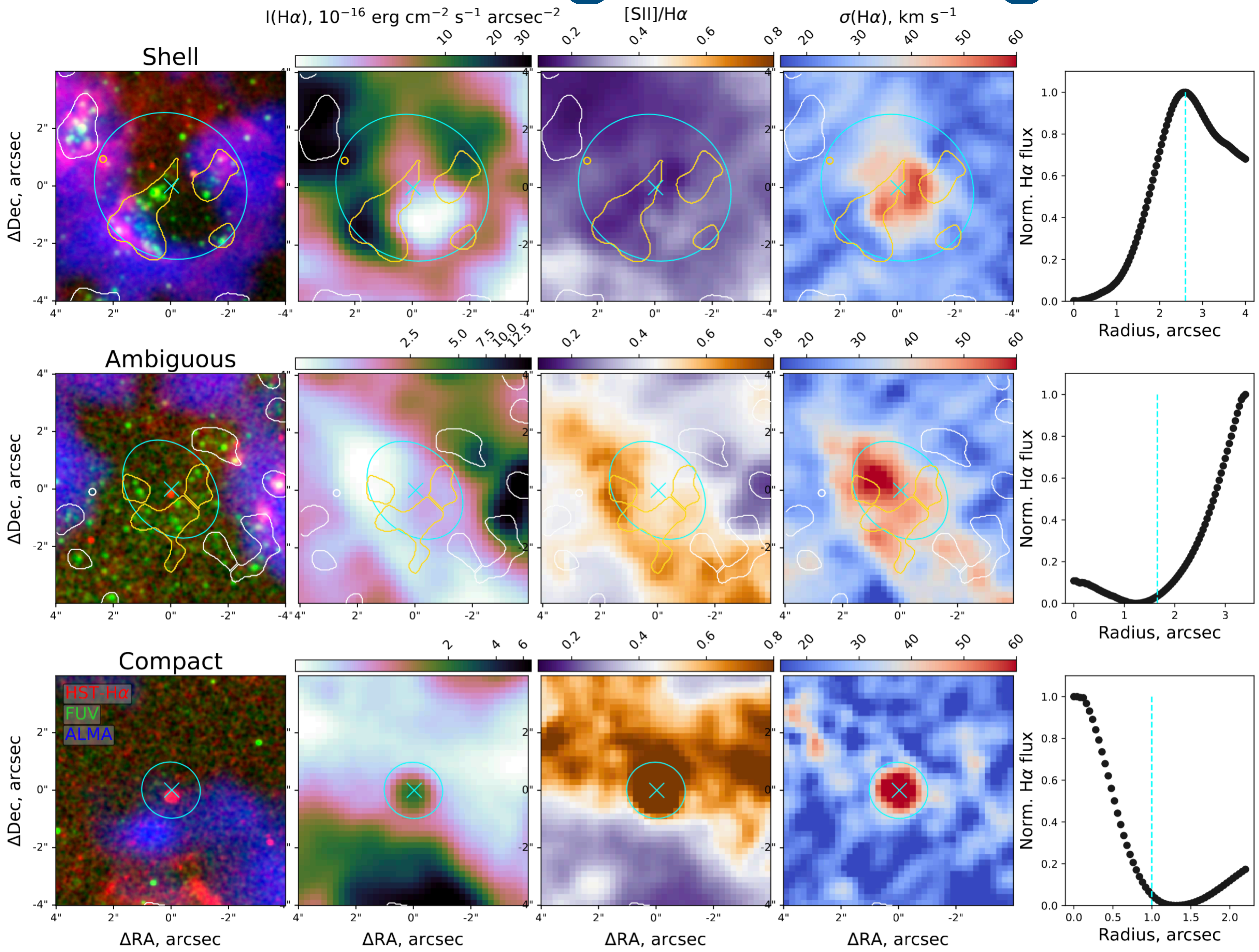


$$E_{\rm kin} \simeq E_{\rm turb} \simeq \frac{3}{2} M_{\rm ion}(\sigma({\rm H}\alpha)^2 - \sigma({\rm H}\alpha)^2_m)$$

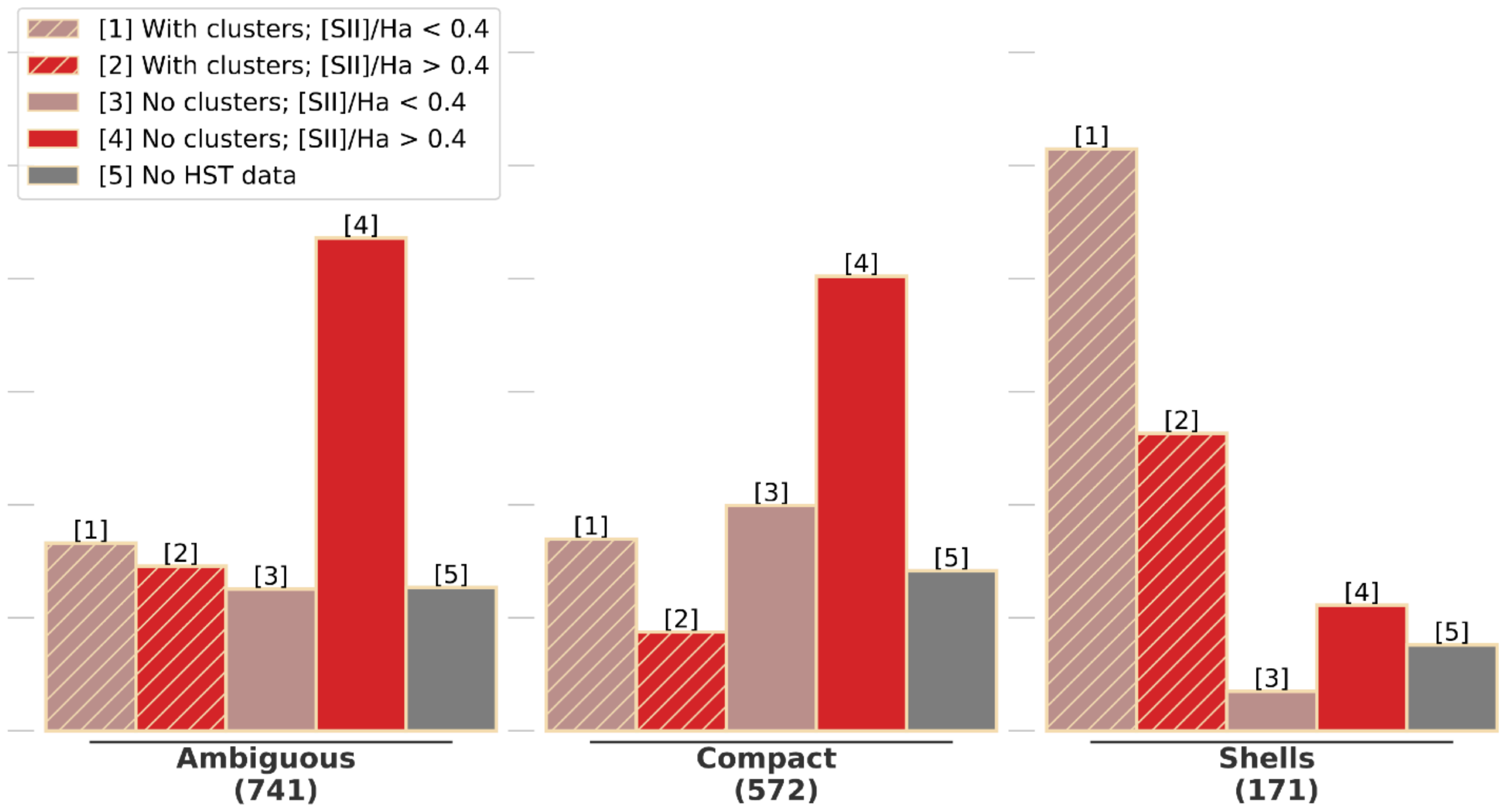
- ✓ Exclude bars, centers, and the regions affected by AGNs
- ✓ Typical velocity dispersion in the identified regions > 50 km/s, that exceeds MUSE resolution
- ✓ Use *astrodendro* on the classification map to select the regions of elevated velocity dispersion

Egorov et al. (2023, submitted)

Identified regions of high velocity dispersion



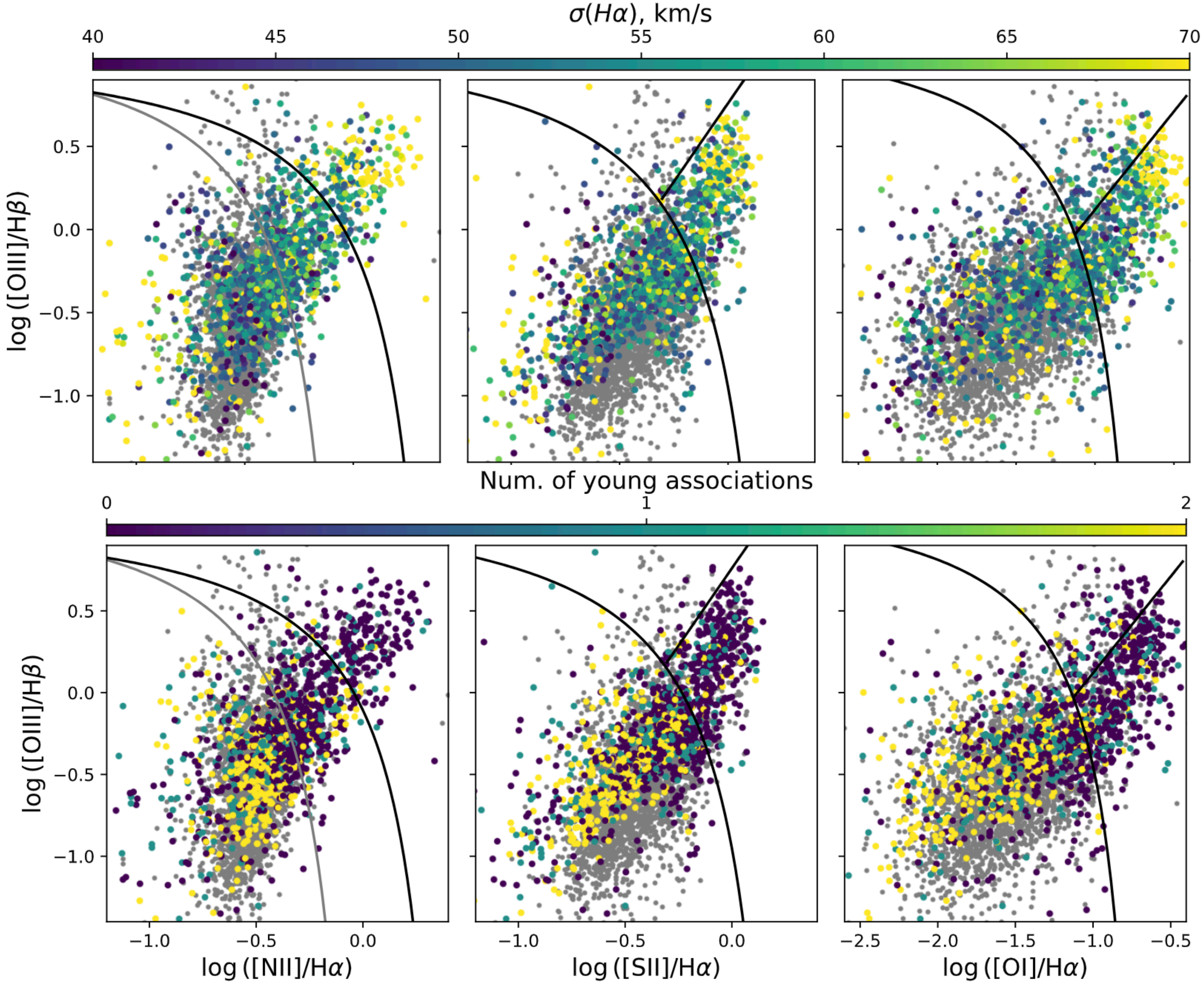
- 1484 regions of high-velocity dispersion in 19 PHANGS-MUSE galaxies (30-130 per galaxy)
- 511 regions are linked with at least one young stellar association
- 73% of the regions that are not linked with stellar associations are probable SNRs (based on optical emission lines ratios)



Egorov et al. (2023, submitted)

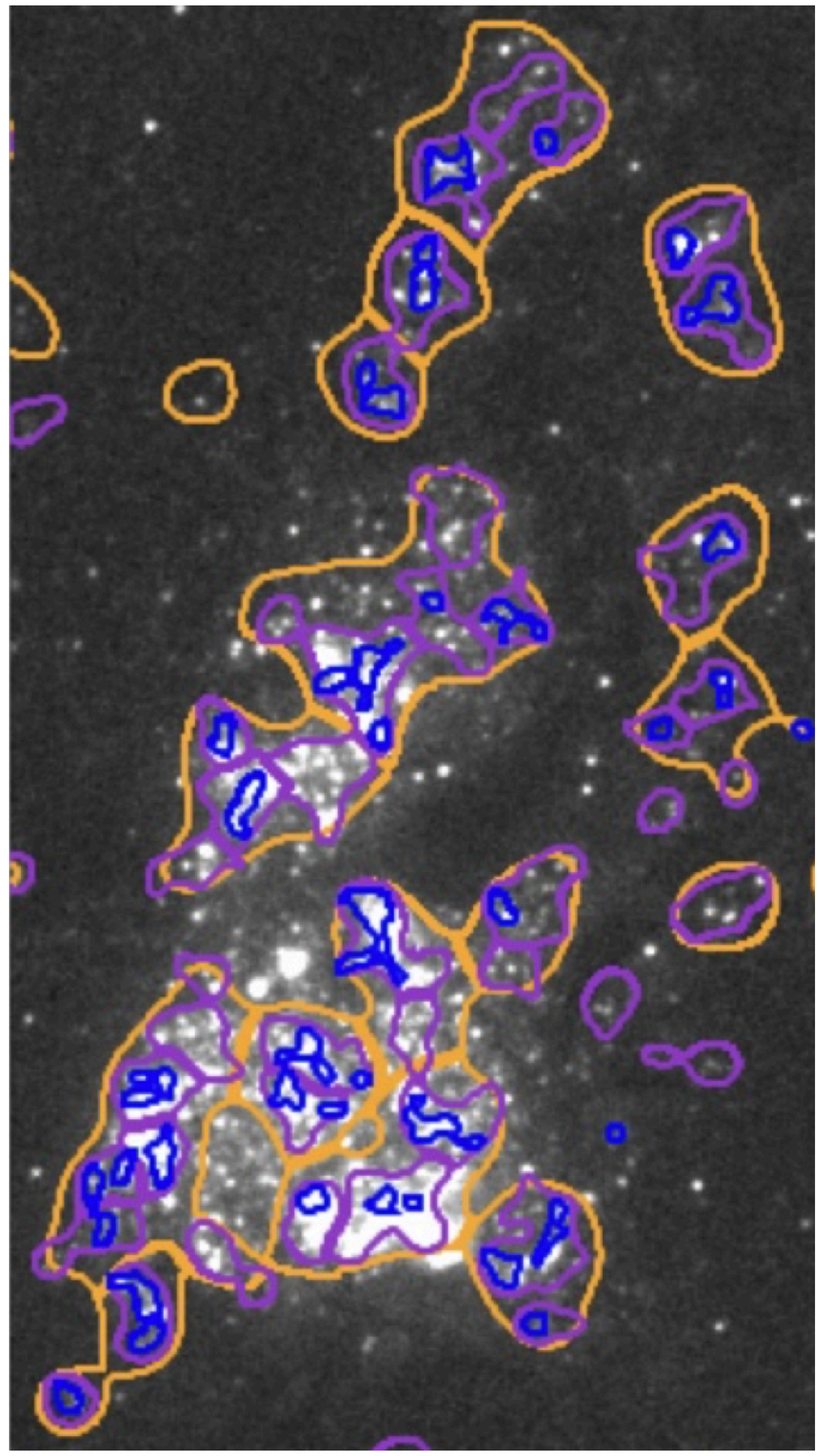
Diagnostics of the gas ionization state

- Most of the turbulent regions/superbubbles that are not linked with any star clusters show lines flux ratios characteristic for shock excitation
- Overall, position of the identified regions on BPT diagrams is consistent with BPT-sigma trends *(Oparin & Moiseev 2018; D'Augostino et al. 2019; Law et al. 2021)*



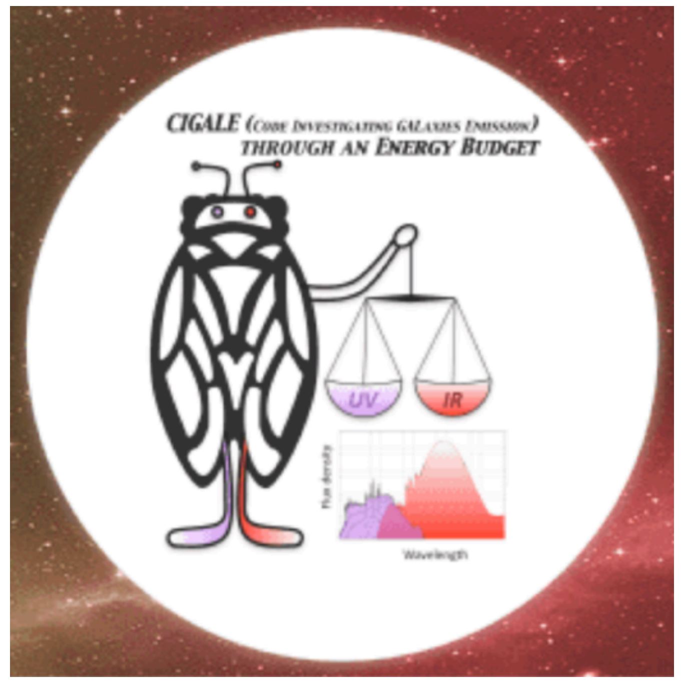
Egorov et al. (2023, submitted)

Quantifying mechanical energy input from stars



Larson et al. (2022)

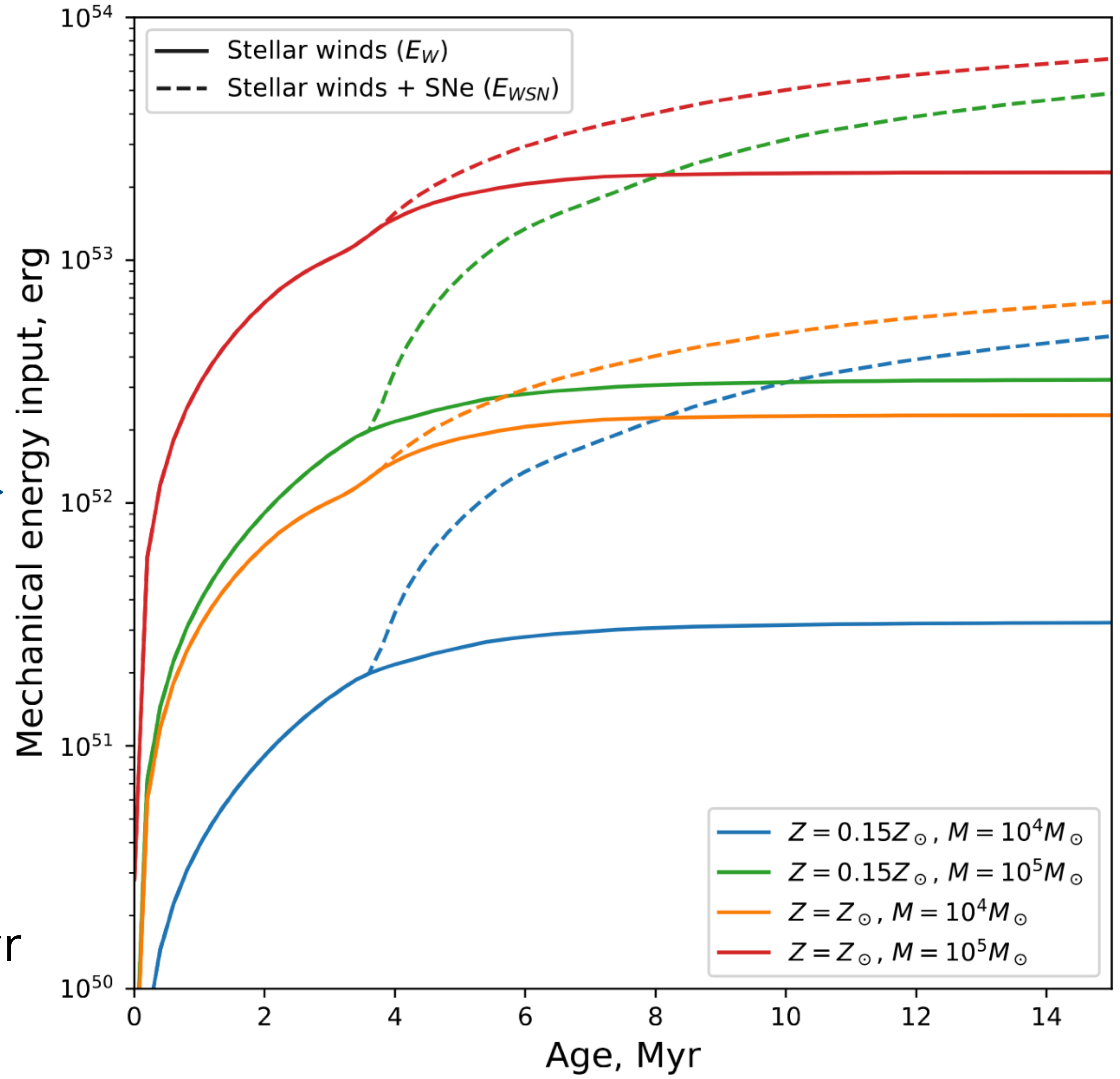
SED fitting with CIGALE



Boquien et al. (2019)

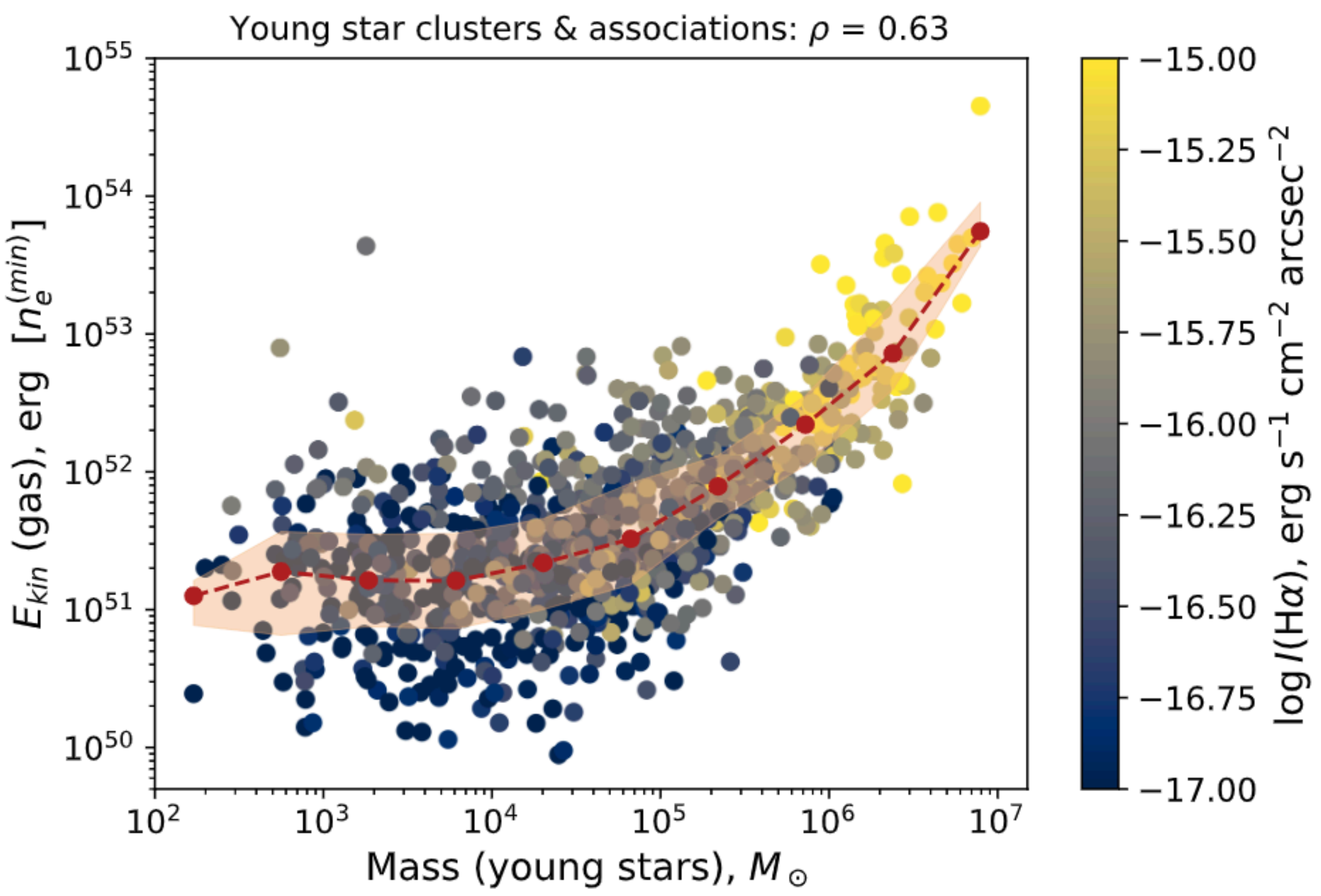
Age & Mass

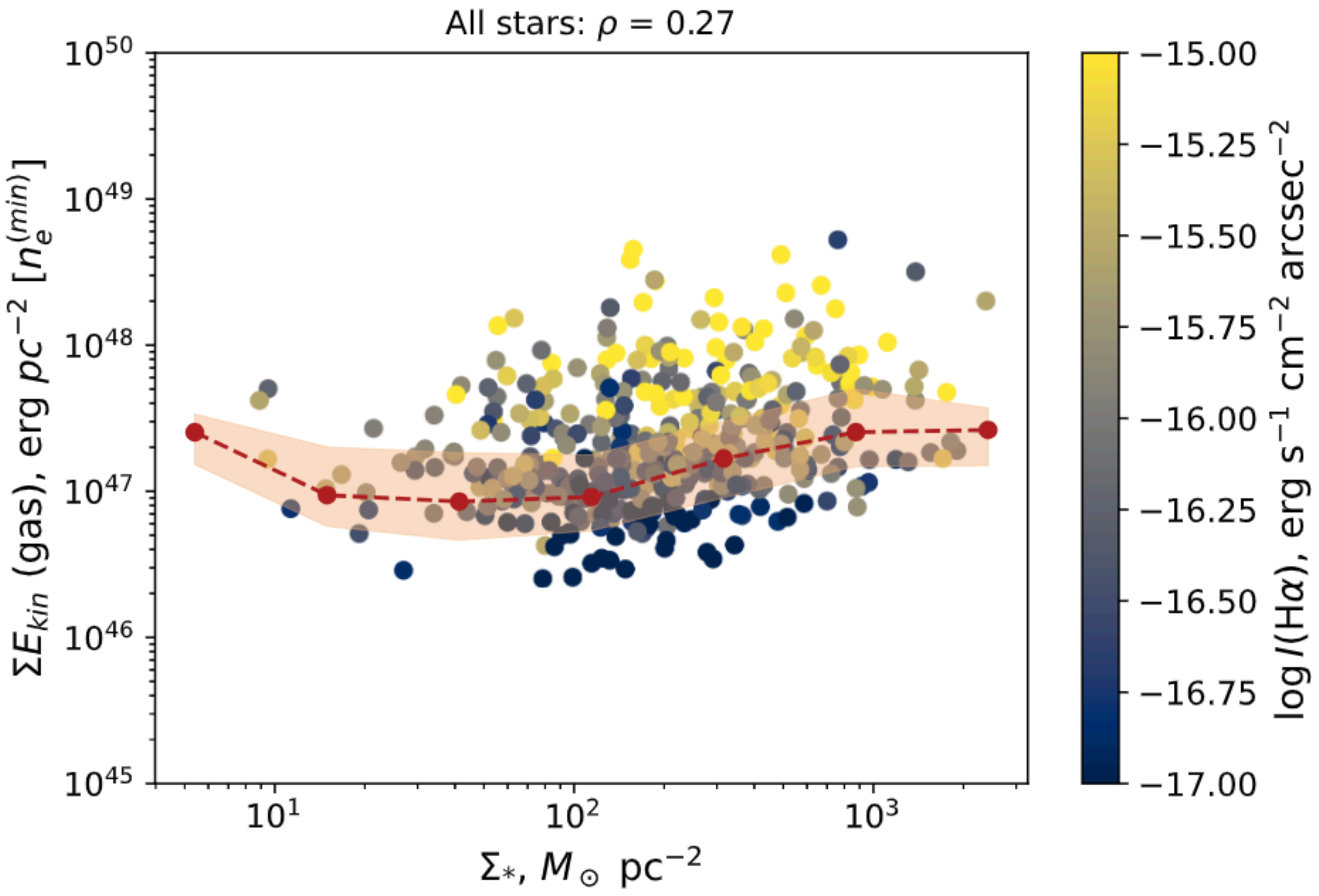
Starburst99 *(Leitherer et al. (1999, 2014)*



- Characteristic turbulence dissipation timescale ~10Myr *(Ostriker et al. 2001, Agertz et al. 2013)*
- Calculate contribution from stellar winds and SNe from all star clusters in the region during the last 10 Myr

Stellar feedback is a key driver of the small-scale supersonic motions



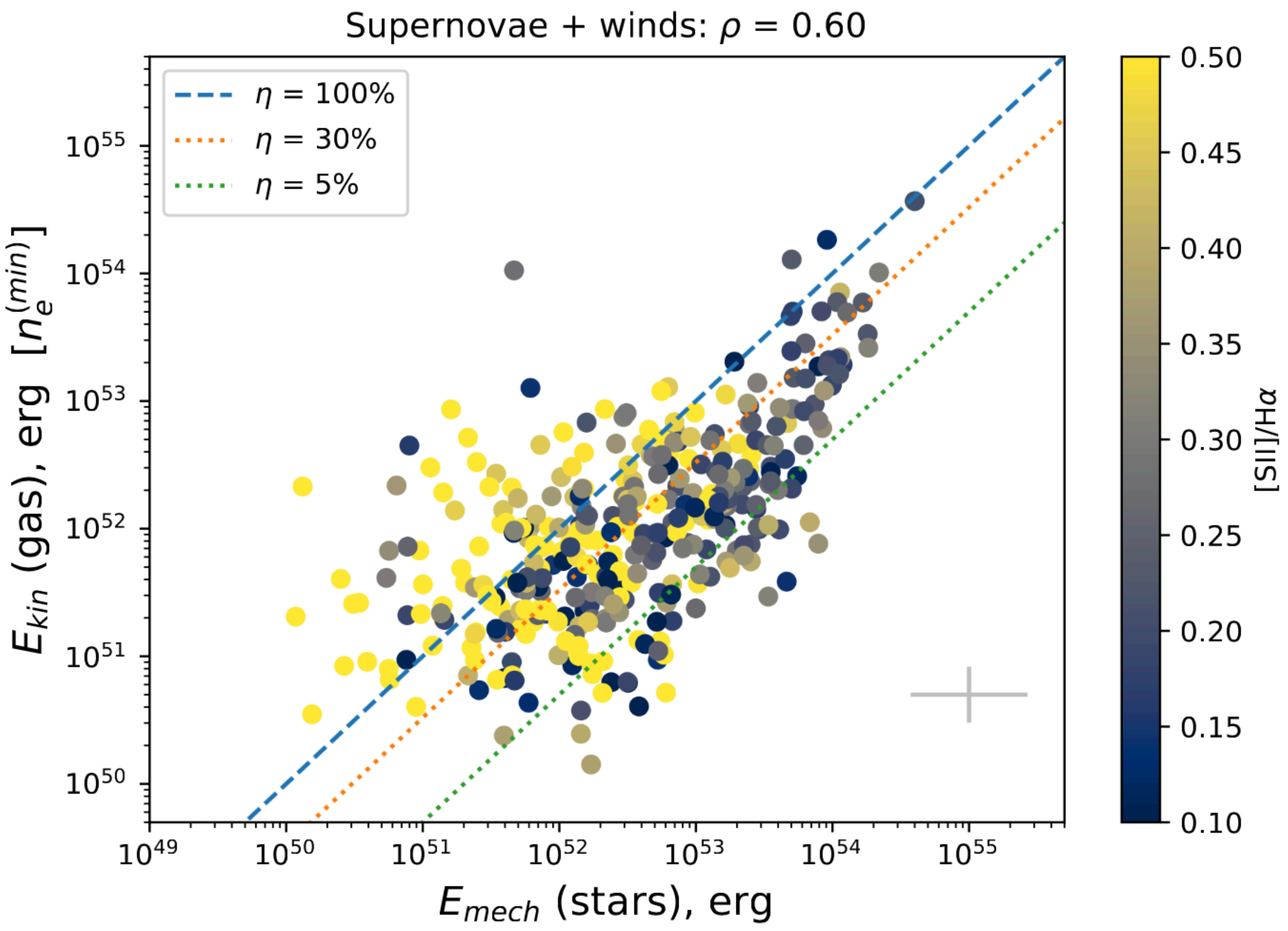


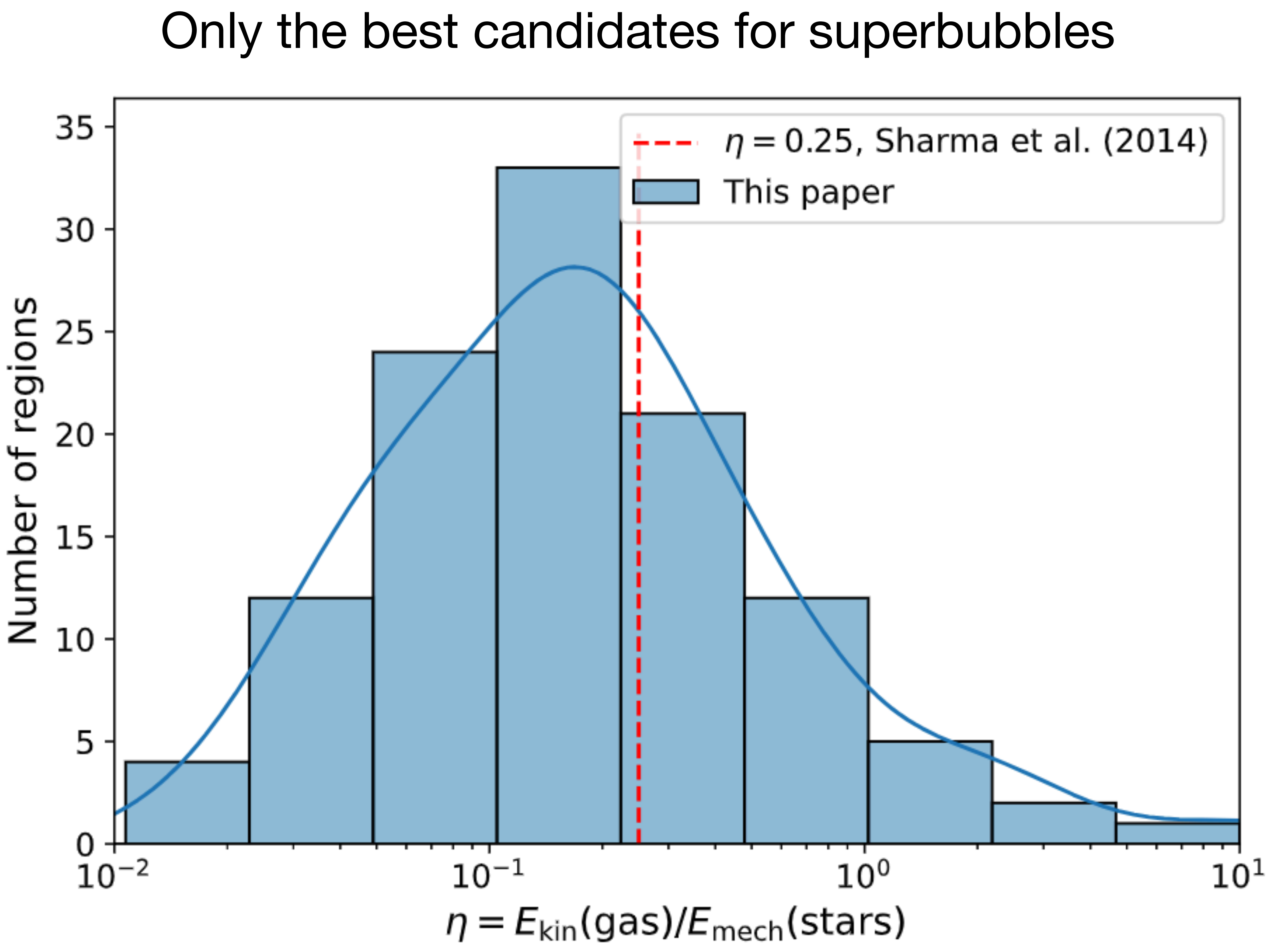
Strong correlation with the mass of the young star clusters and associations => feedback from massive stars is crucial

Only a weak correlation with the overall stellar surface density => gravitational potential is less important

Egorov et al. (2023, submitted)

Energy balance between turbulent ionized ISM and massive stars

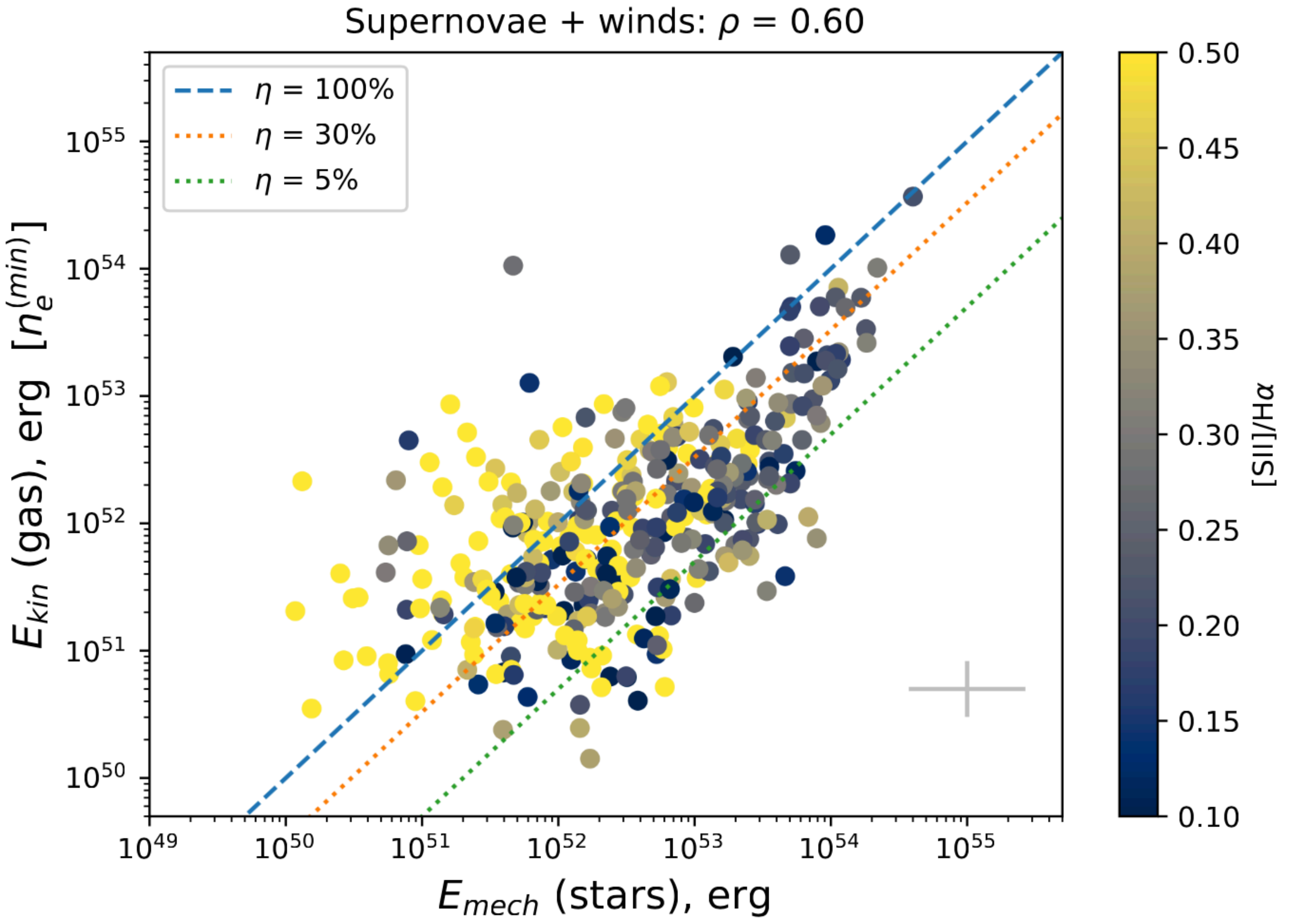


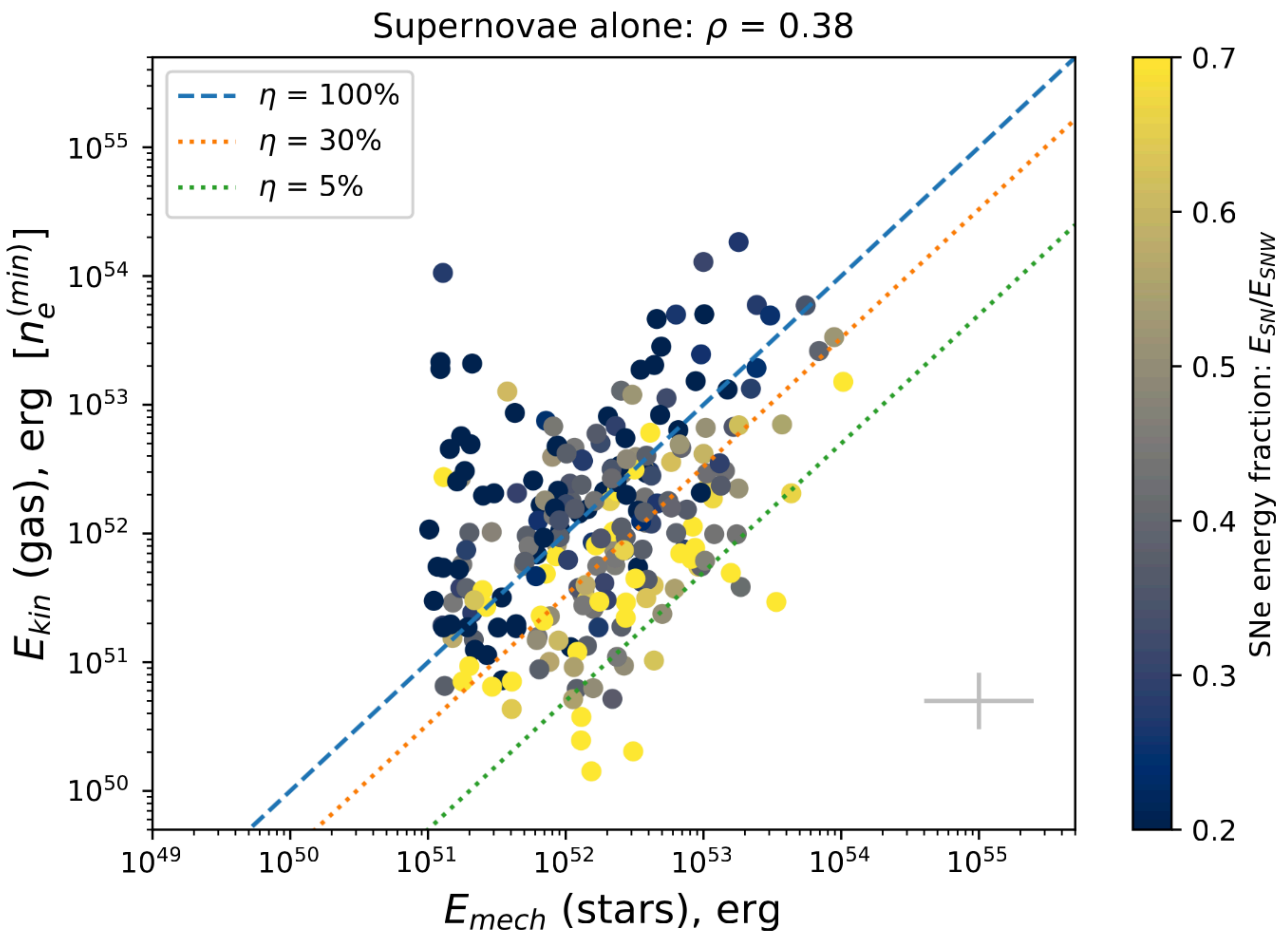


Our observational estimates show that 10-20% of the total mechanical energy injected by stars should retain in the superbubbles or turbulent ISM surrounding the stars.

Egorov et al. (2023, submitted)

Pre-supernova feedback is crucial component

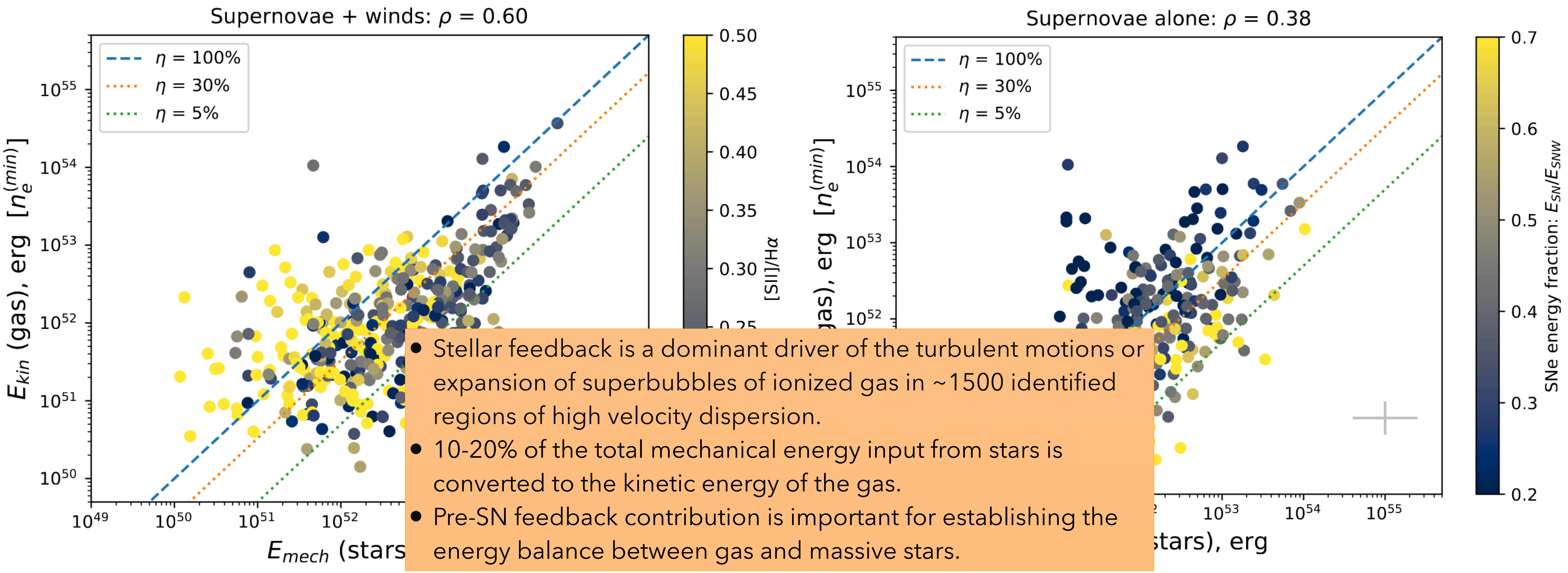




Supernovae alone do not produce sufficient mechanical energy to support the turbulent motions or superbubbles expansions for ~50% regions in our sample. Accounting for pre-SN feedback is crucial

Egorov et al. (2023, submitted)

Pre-supernova feedback is crucial component



- Stellar feedback is a dominant driver of the turbulent motions or expansion of superbubbles of ionized gas in ~1500 identified regions of high velocity dispersion.
- 10-20% of the total mechanical energy input from stars is converted to the kinetic energy of the gas.
- Pre-SN feedback contribution is important for establishing the energy balance between gas and massive stars.

Supernovae alone do not produce sufficient mechanical energy to support the turbulent motions or superbubbles expansions for ~50% regions in our sample.
Accounting for pre-SN feedback is crucial

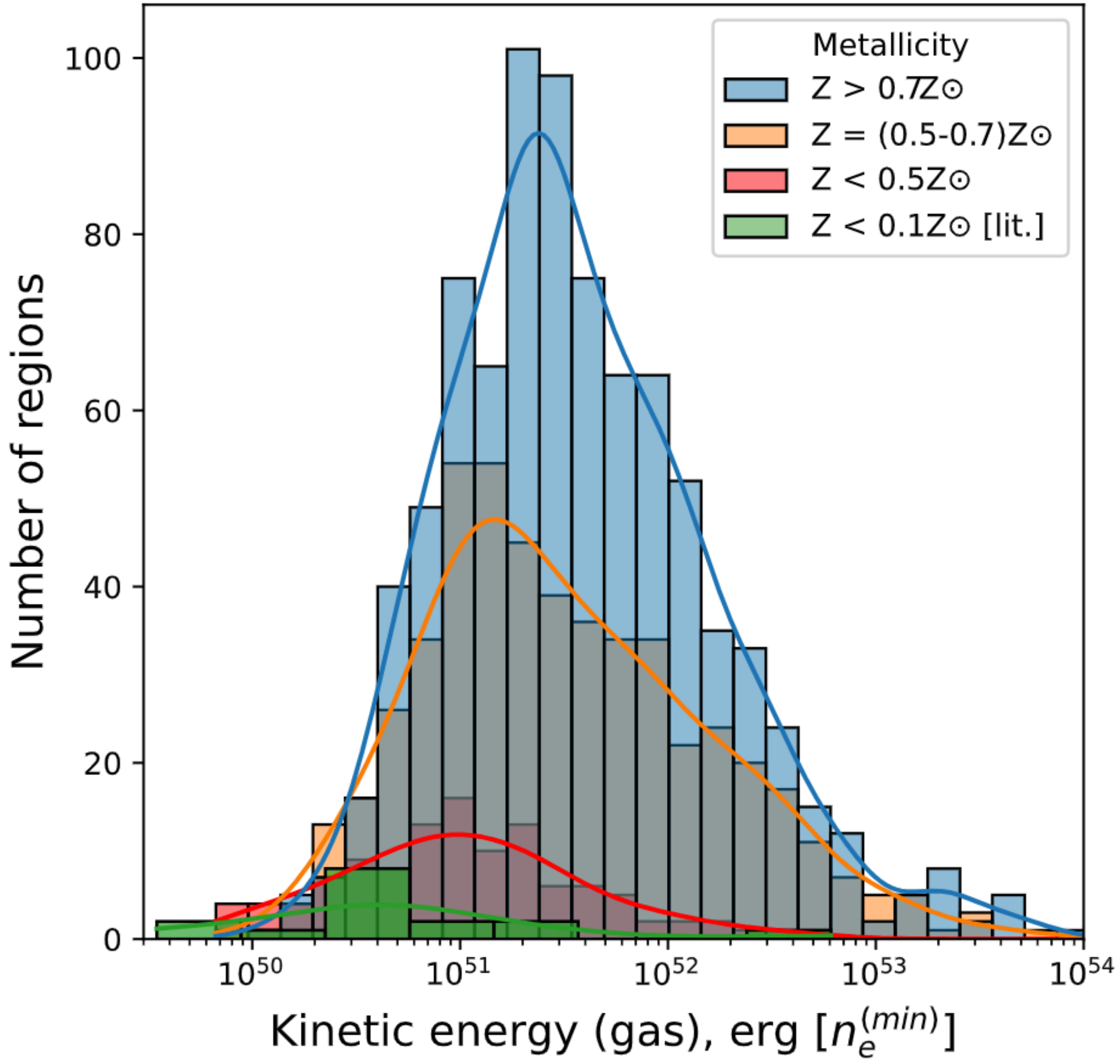
Egorov et al. (2023, submitted)

Energy of the turbulent ionized gas at different metallicities

- Based on PHANGS-MUSE observations, the energy of ionized gas in the regions of high velocity dispersion declines with metallicity

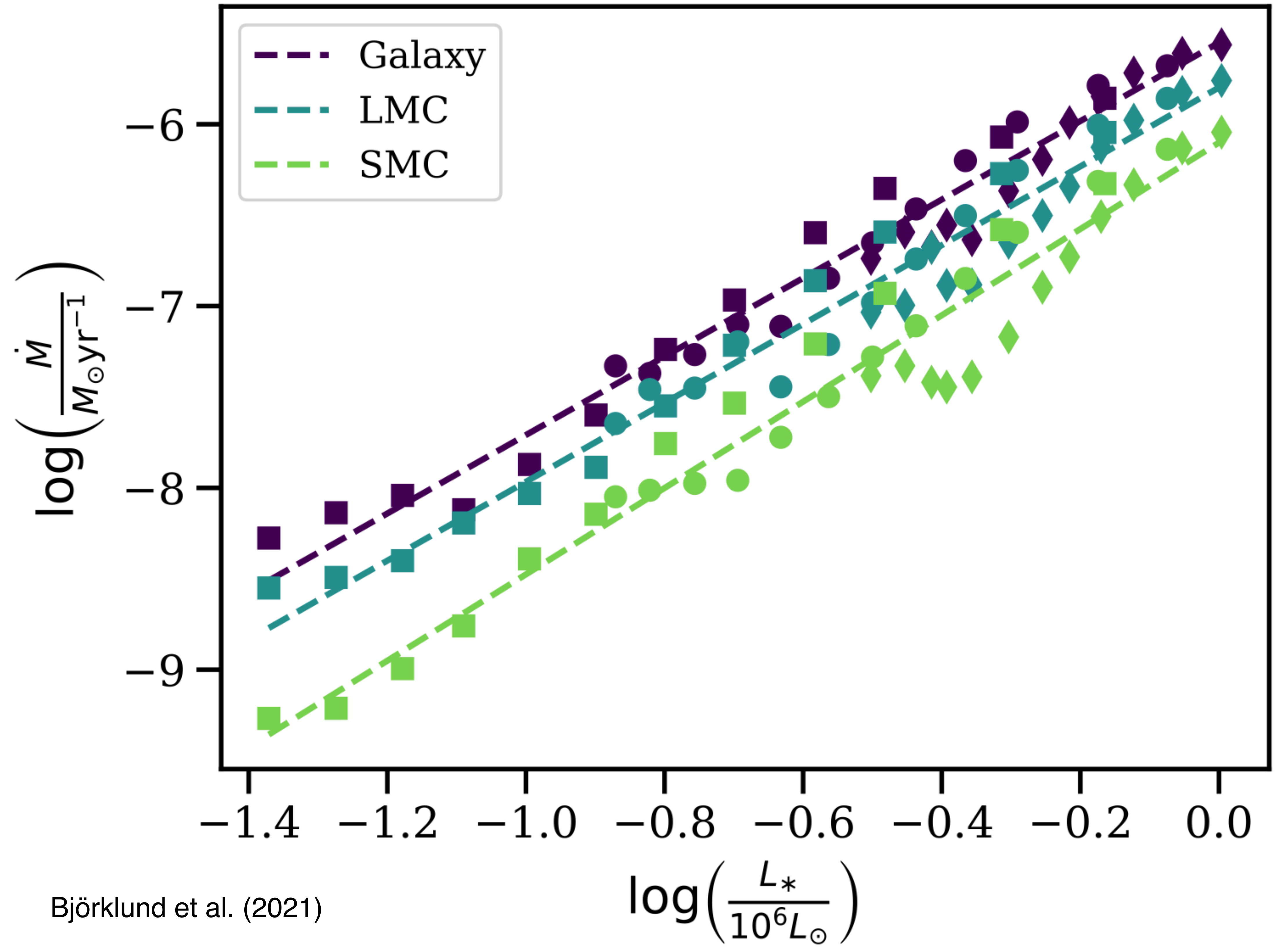
- FPI-based measurements made for ~15 ionized superbubbles from 2 nearby metal-poor (Z<0.1Zsun) dwarf galaxies follow the same trend:
  DDO53 (Egorov et al. 2021)
  Sextans A (Gerasimov, OE et al. 2022)

- Need more homogeneous data at low metallicity.

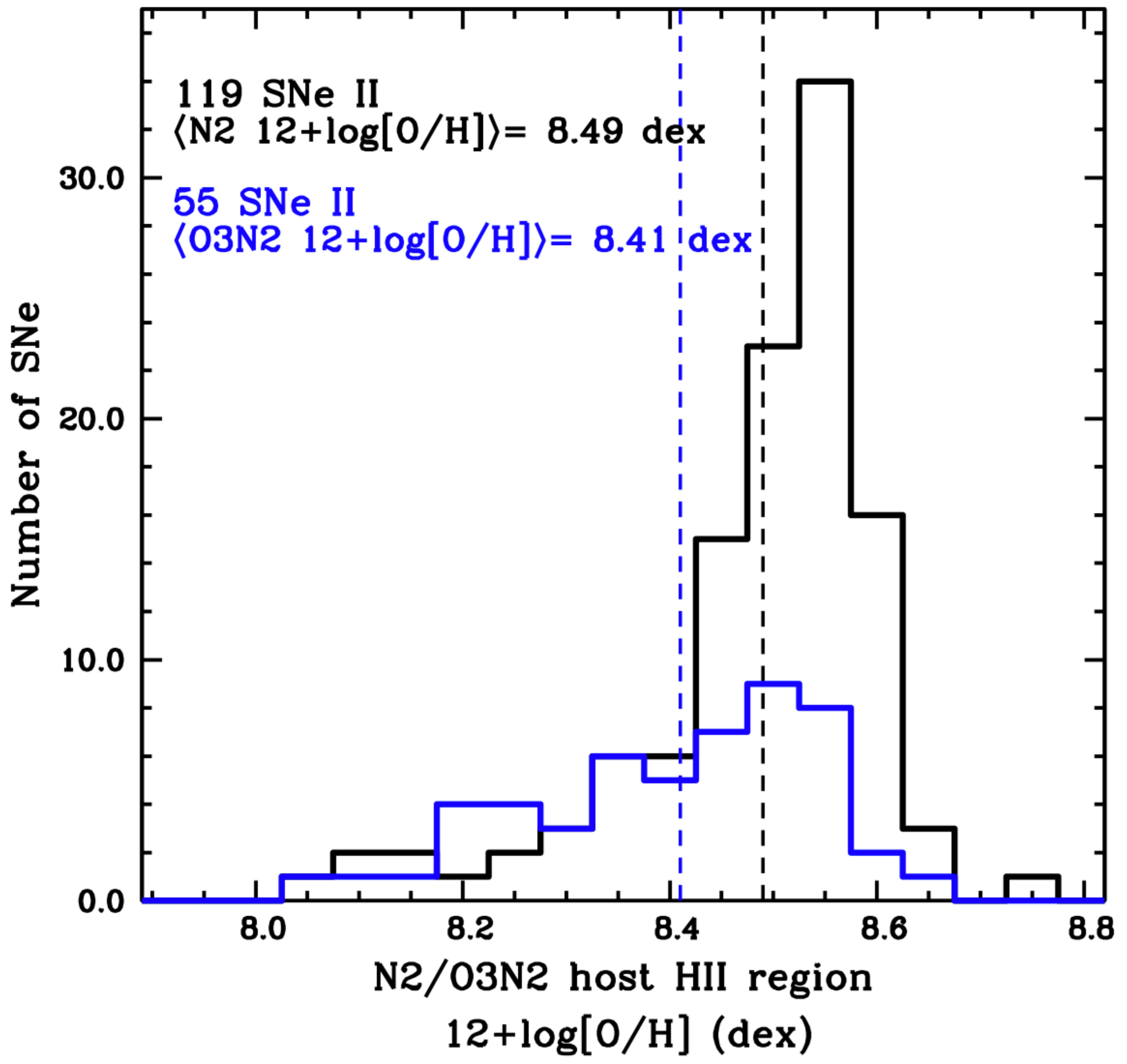


Egorov et al. (2023, submitted)

Stellar winds and SNe at low metallicity



Björklund et al. (2021)



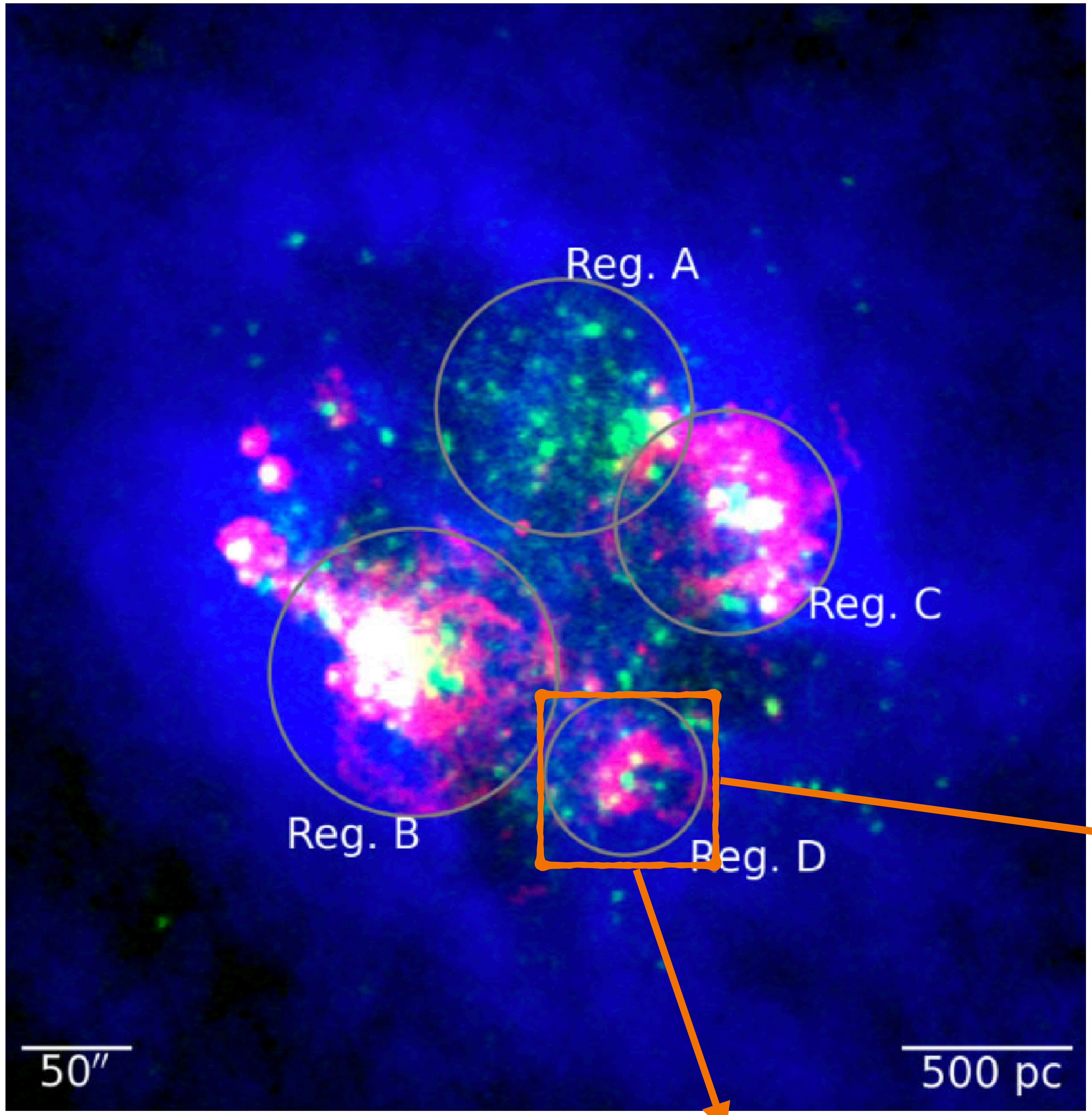
Vink et al. (2001, 2021): stellar wind is weaker in a low-metallicity environment

Stoll et al. (2013), Anderson et al. (2016): a smaller number of SNe II in a low-metallicity environment

The absolute effect of mechanical stellar feedback should decline with the metallicity

IFU studies of stellar feedback at low metallicity

Signatures of strong pre-SN feedback at very low metallicity (Z~0.05 Zsun)

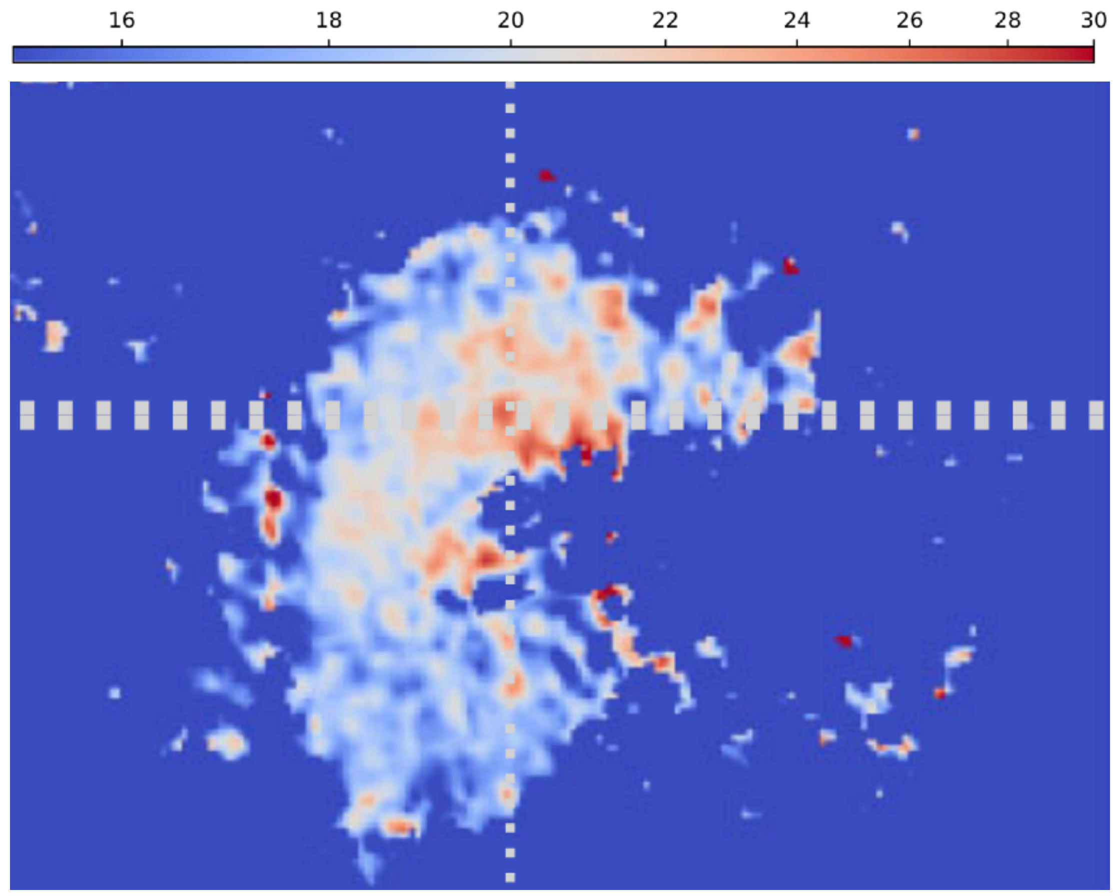


Garcia et al. (2019):
Most metal-poor stars in the Local Group

Ionized gas kinematics in Sextans A:

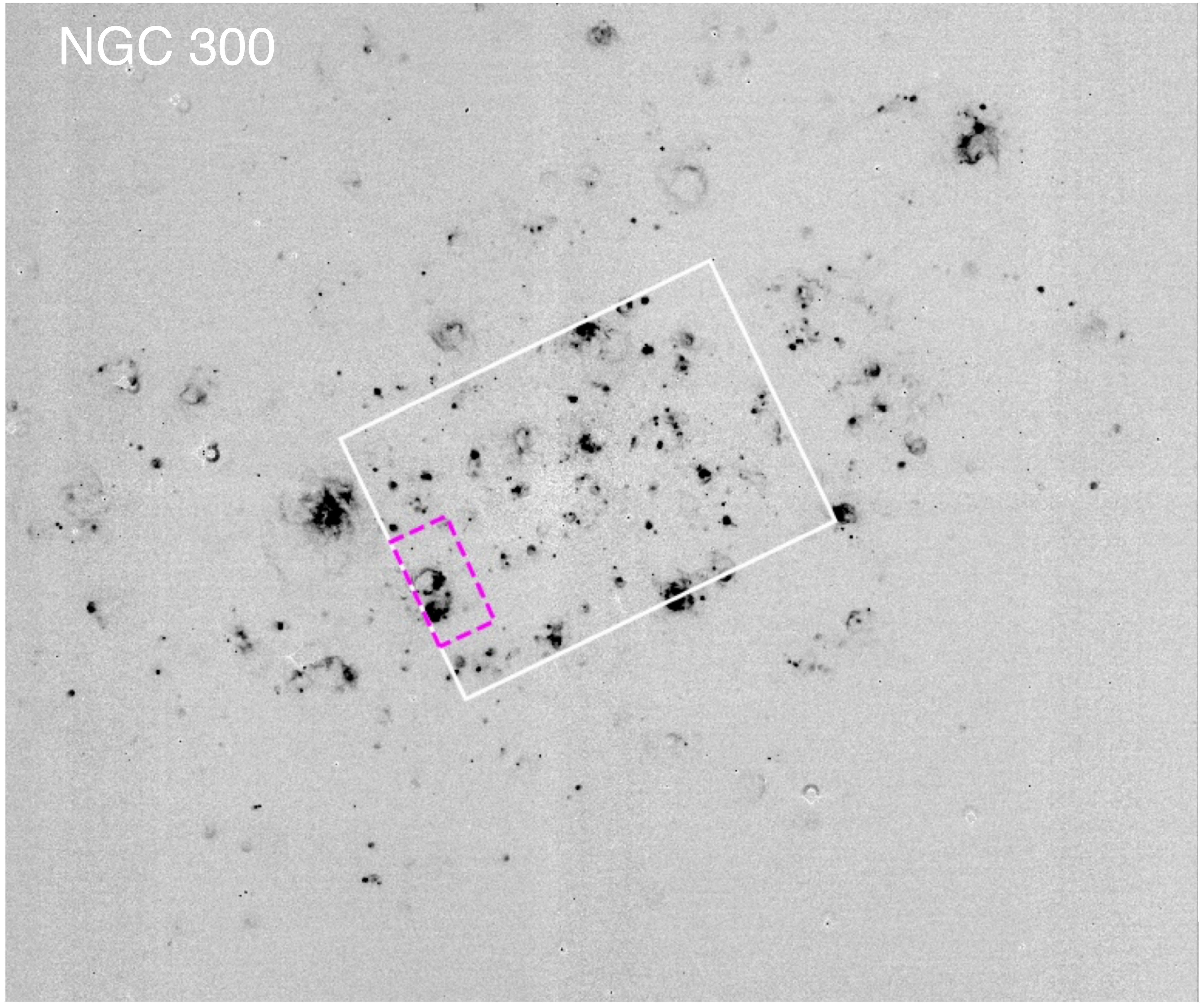
- 10 expanding young (~1-3 Myr) superbubbles in Sextans A.
- For most of them, pre-SN feedback alone can produce sufficient energy to drive their expansion, although signatures of SNe are observed

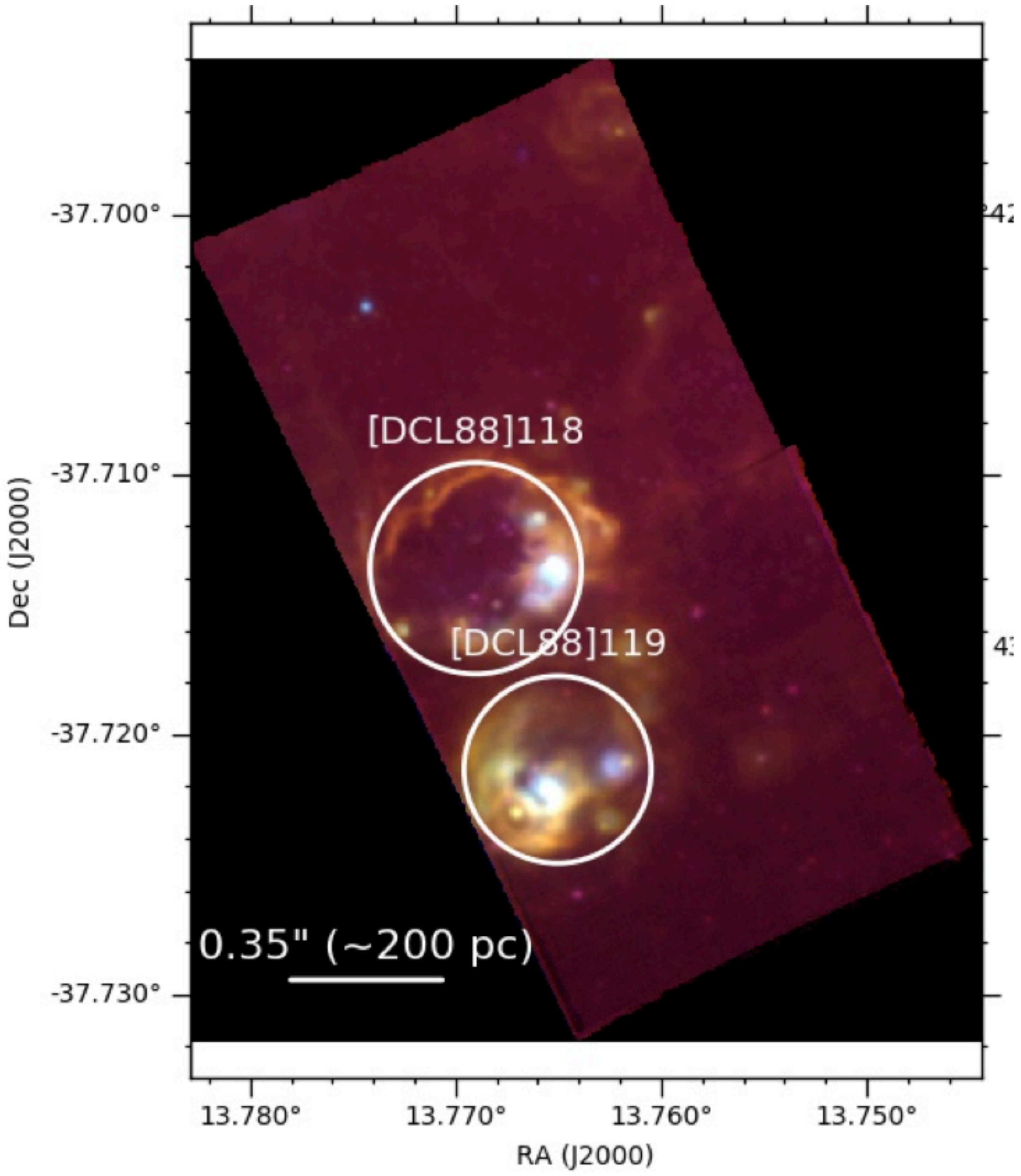
H-alpha velocity dispersion



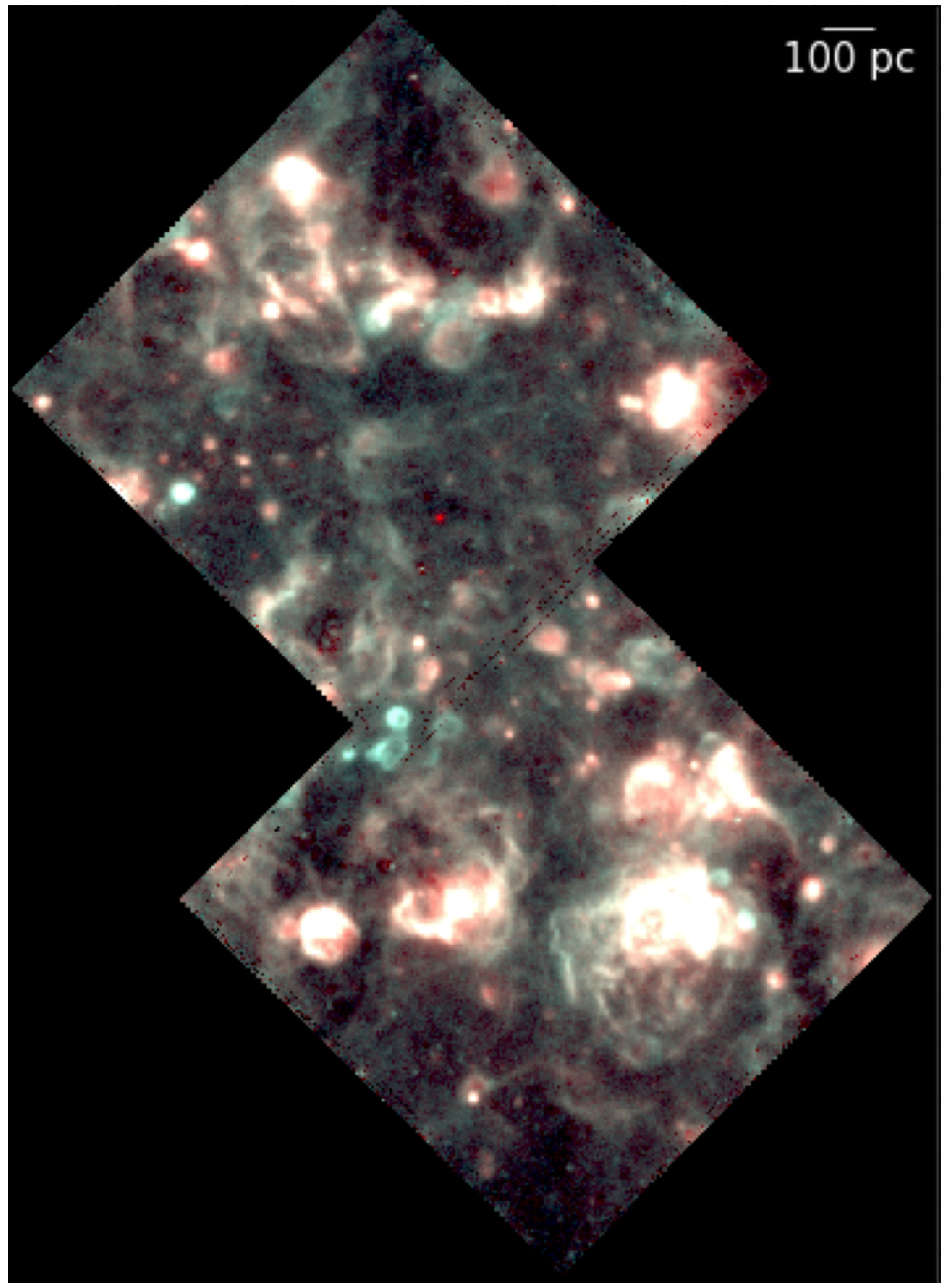
Gerasimov, OE et al. (2022)

IFU studies of stellar feedback at low metallicity





McLeod+ (2020)

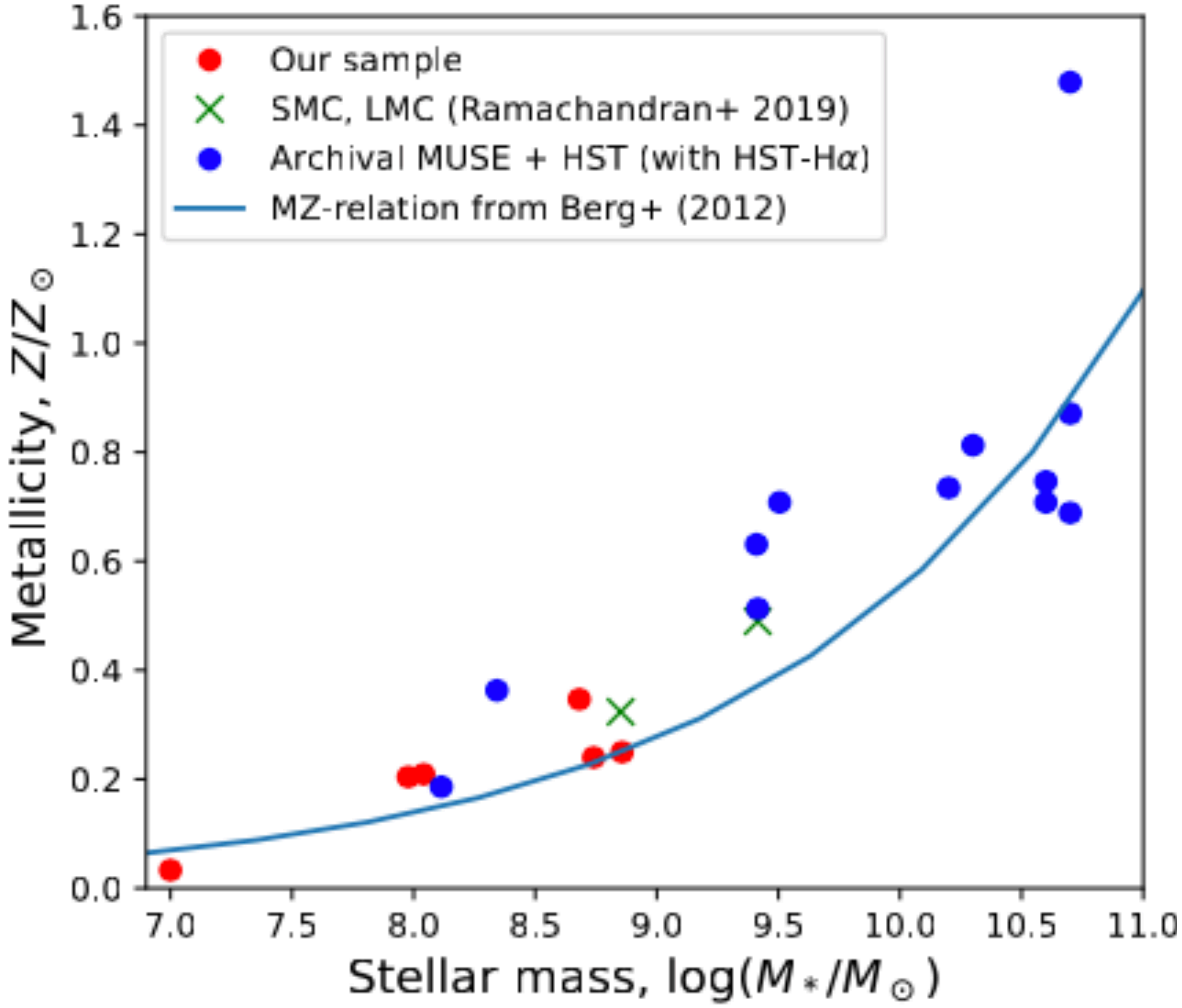


Della Bruna+ (2020, 2022)

See also Lopez+2014, Ramachandran+2019

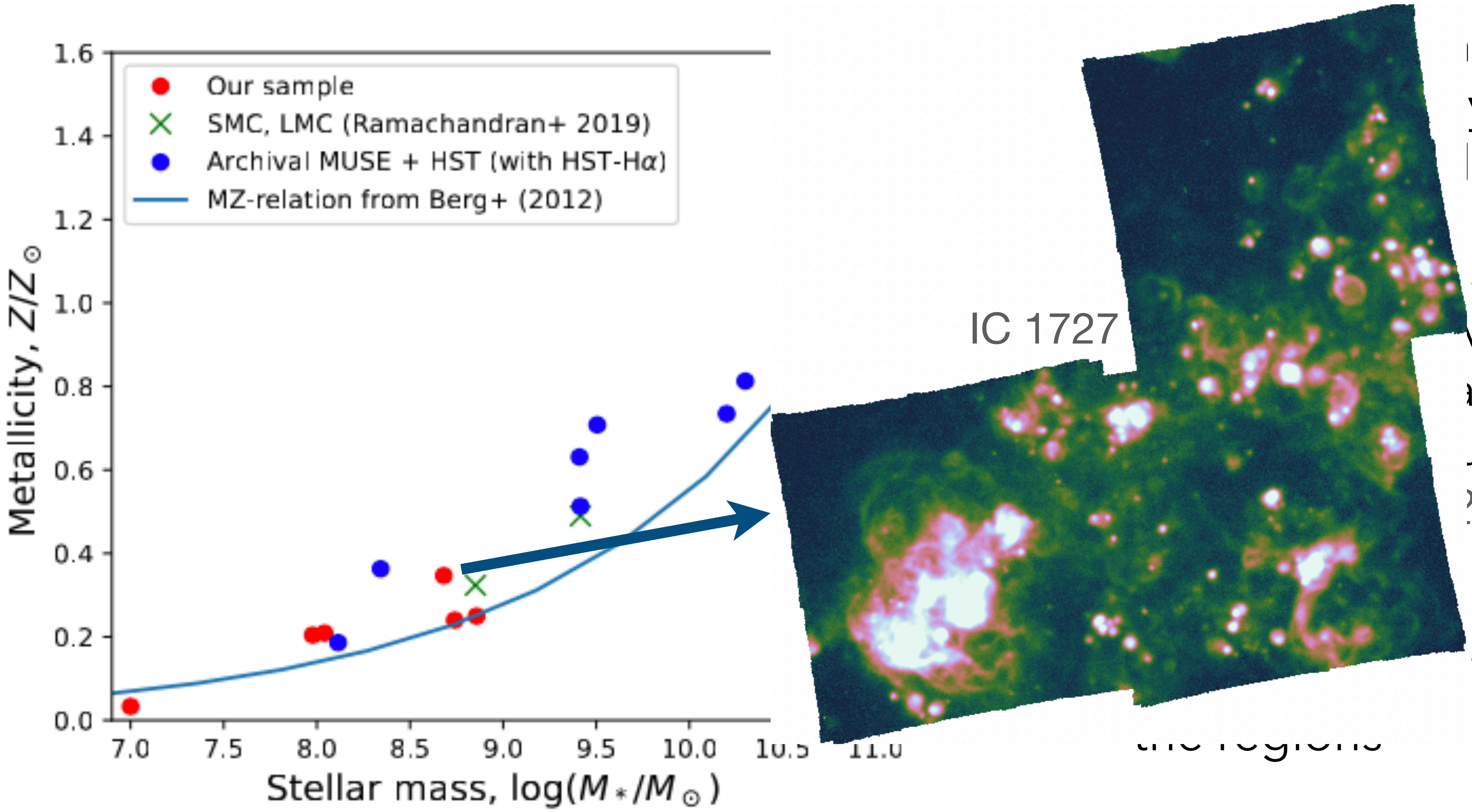
In HII regions, the contribution of different pressure terms is different in SMC, LMC and MW.

MUSE observations of dwarfs from LEGUS



- MUSE program «Quantifying feedback from young star clusters in low-mass galaxies» (PI: Egorov)
- 6 dwarf galaxies with metallicity $Z<\sim Z_{SMC}$ with available HST broadband images and star cluster catalogues from LEGUS *(Cook et al. 2022)*
- HST-Ha images are available for precise constraints of the sizes of the regions

MUSE observations of dwarfs from LEGUS



«Quantifying
young star clusters
axies» (PI: Egorov)

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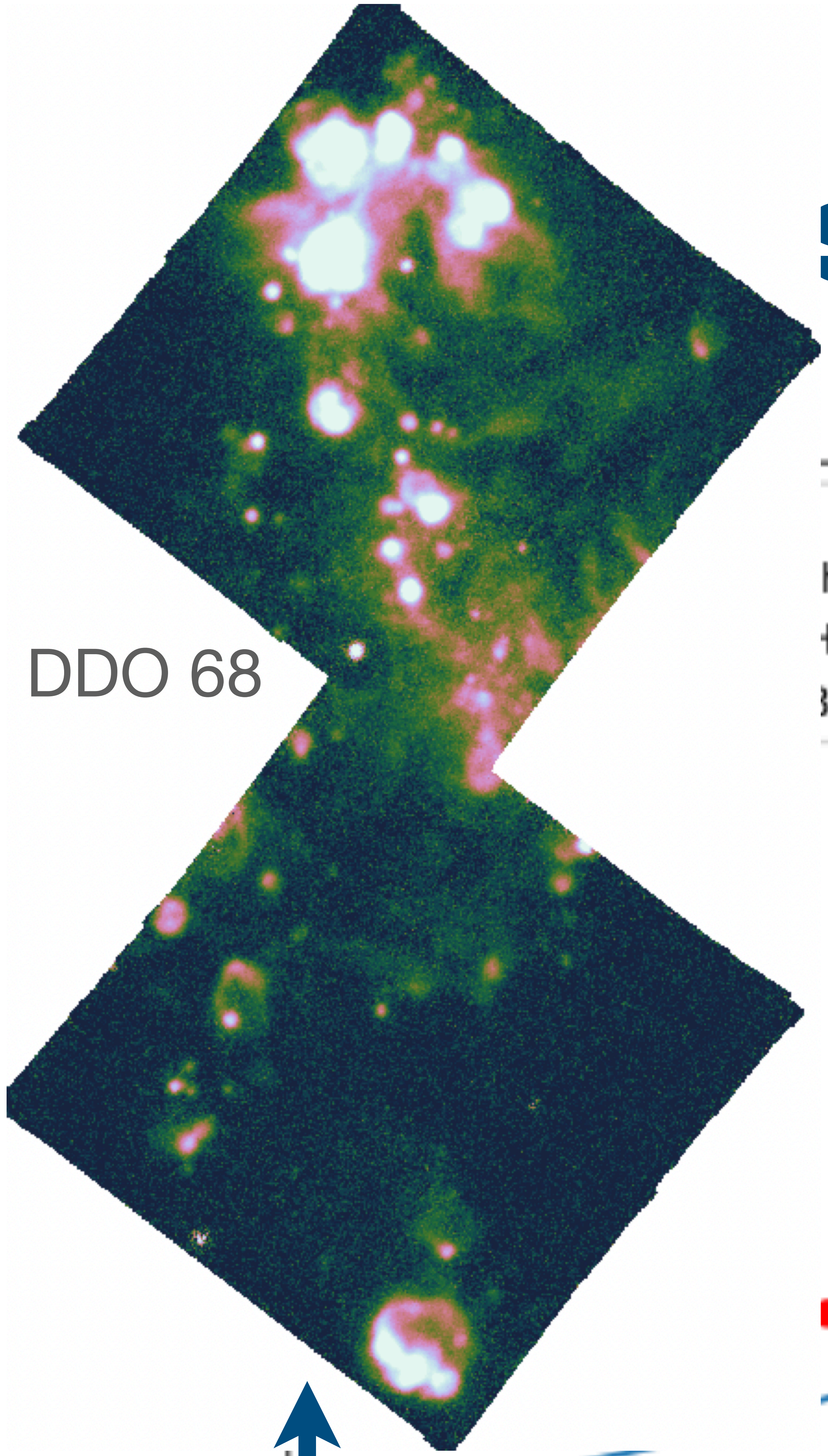
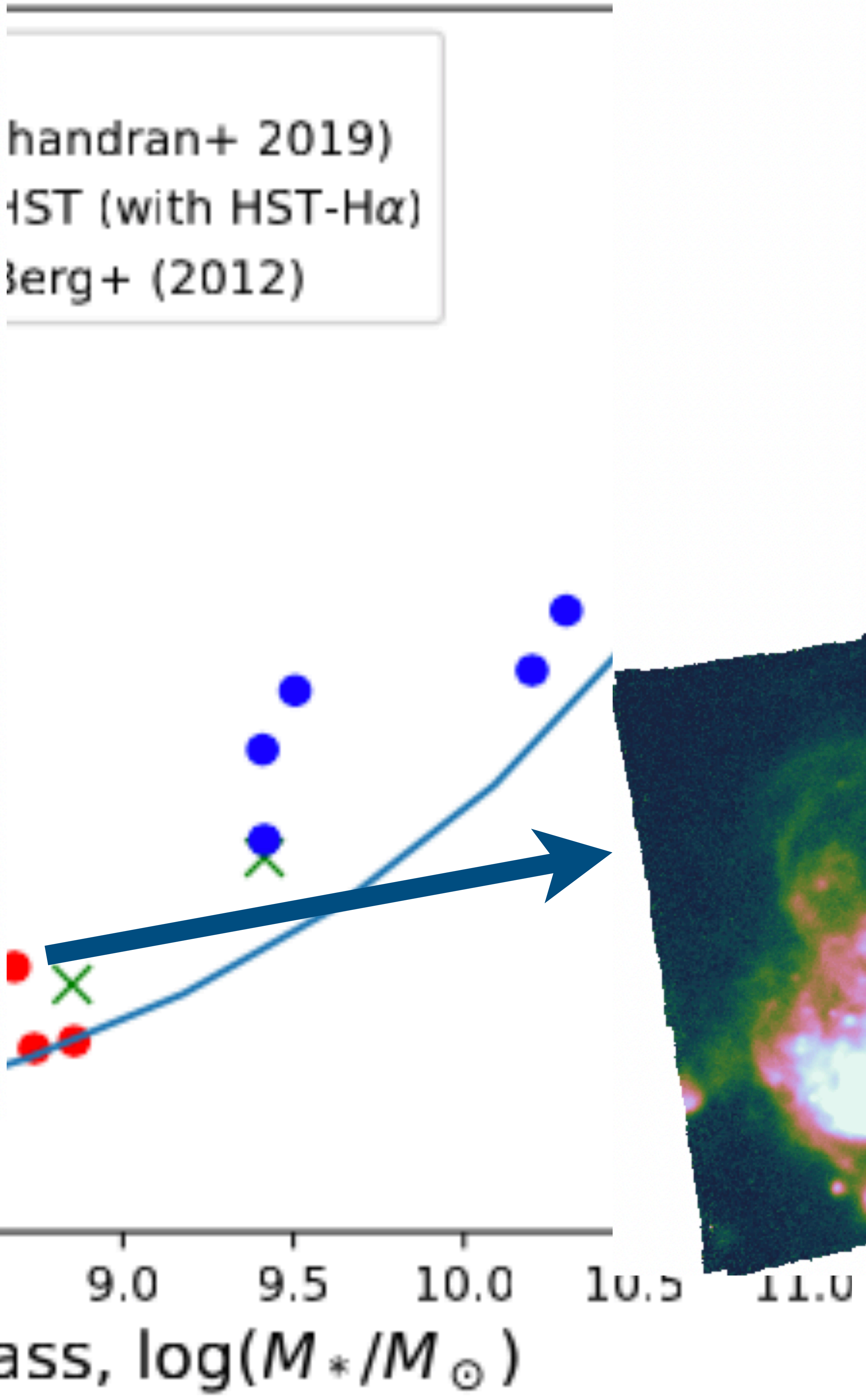
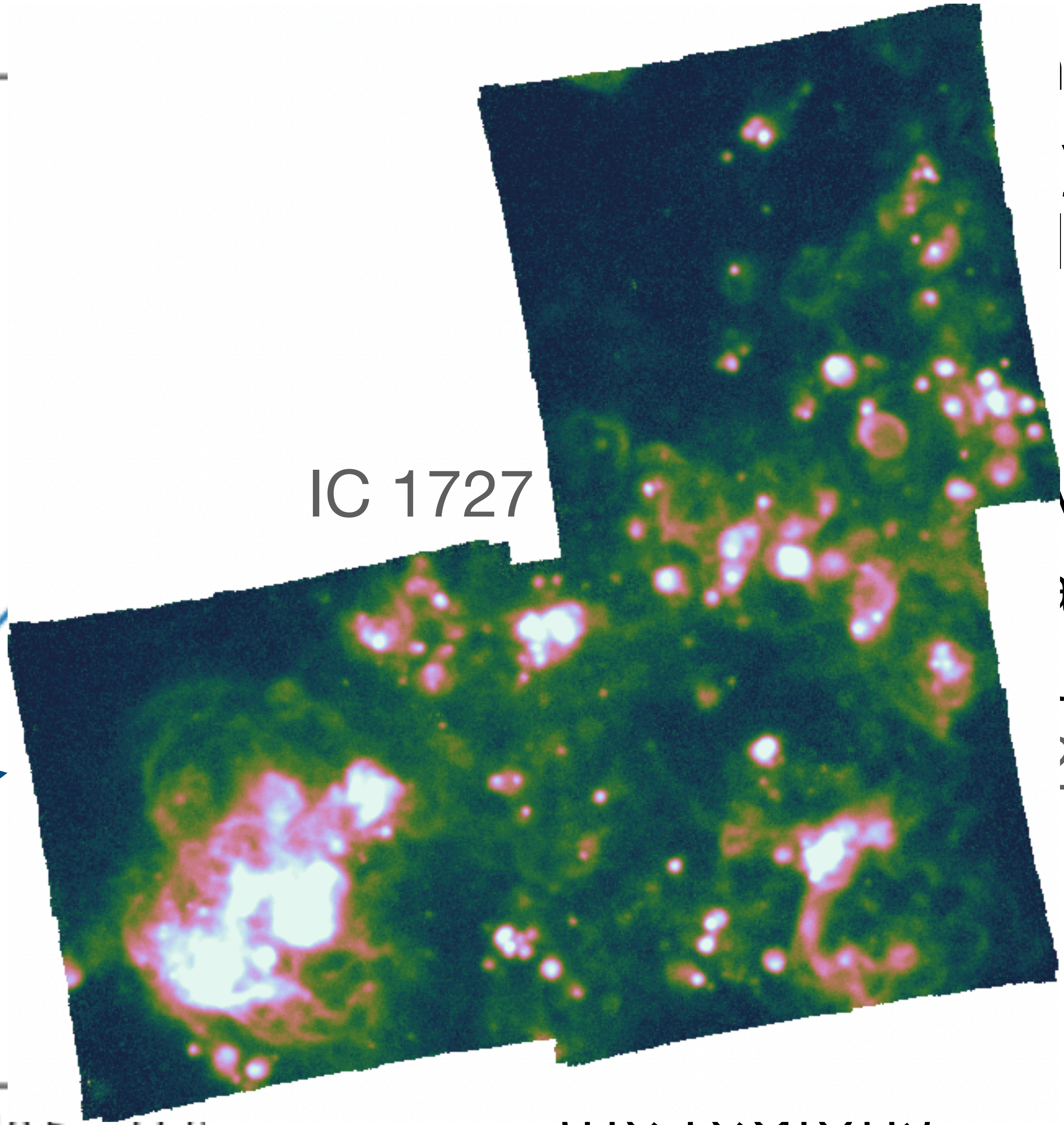
servations of dwarfs from LEGUS

DDO 68





IC 1727



«Quantifying
young star clusters
laxies» (PI: Egorov)

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2)

are available for
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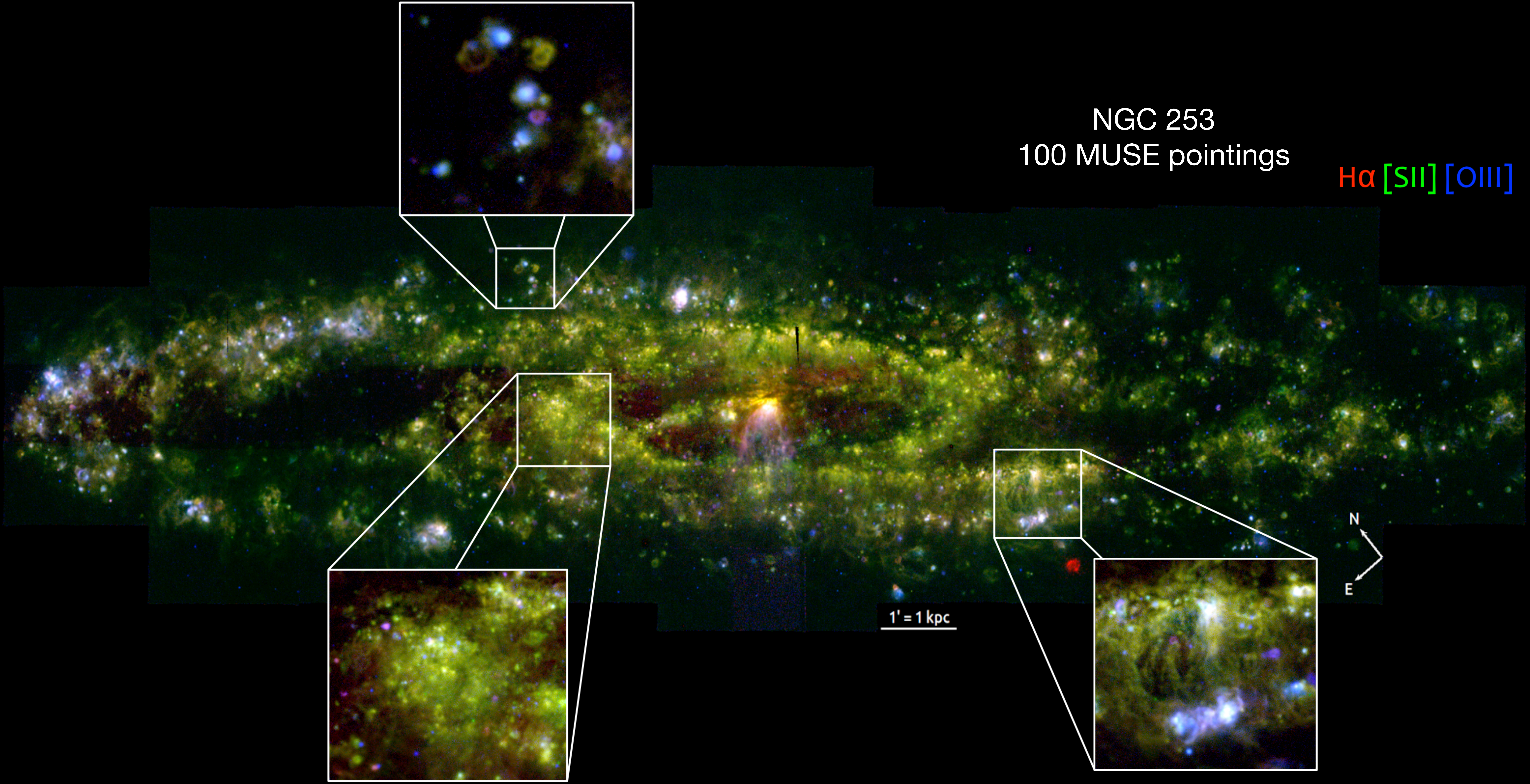
NGC 253
100 MUSE pointings

Hα [SII] [OIII]



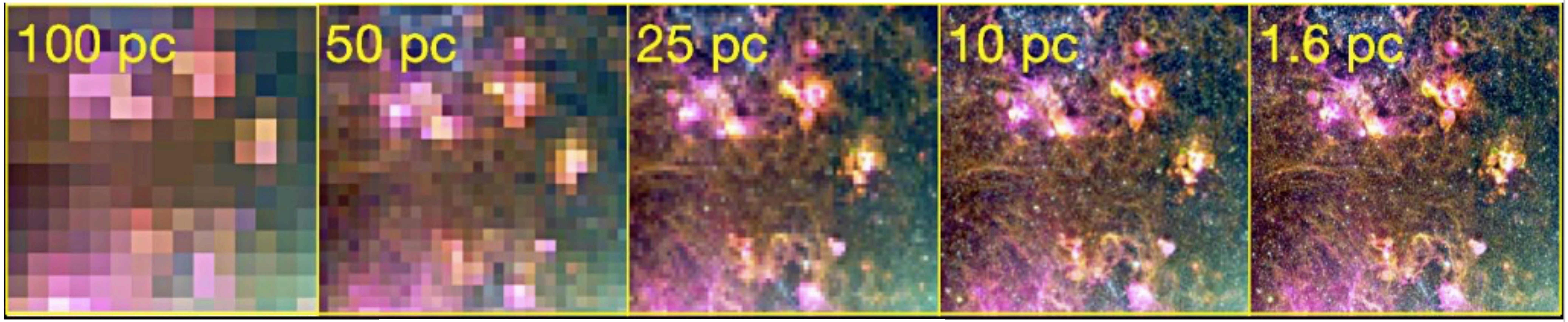
Congiu et al. (in prep)

See also M83 (Adamo et al.); NGC 300 (McLeod et al.)

SDSS-V

Local Volume Mapper

Resolving the Physics Driving Galaxy Formation

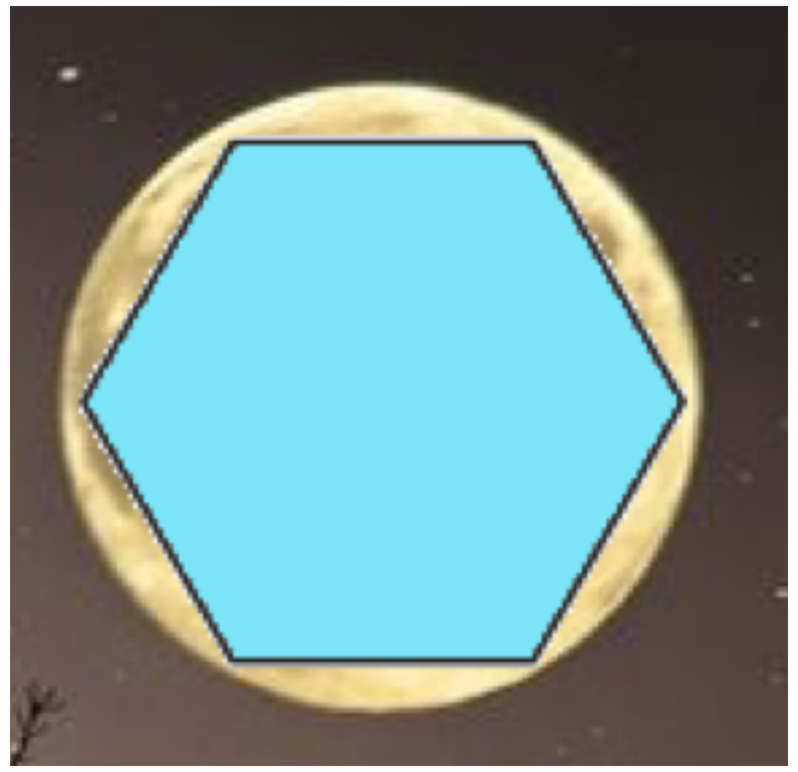


larger surveys

(PHANGS)

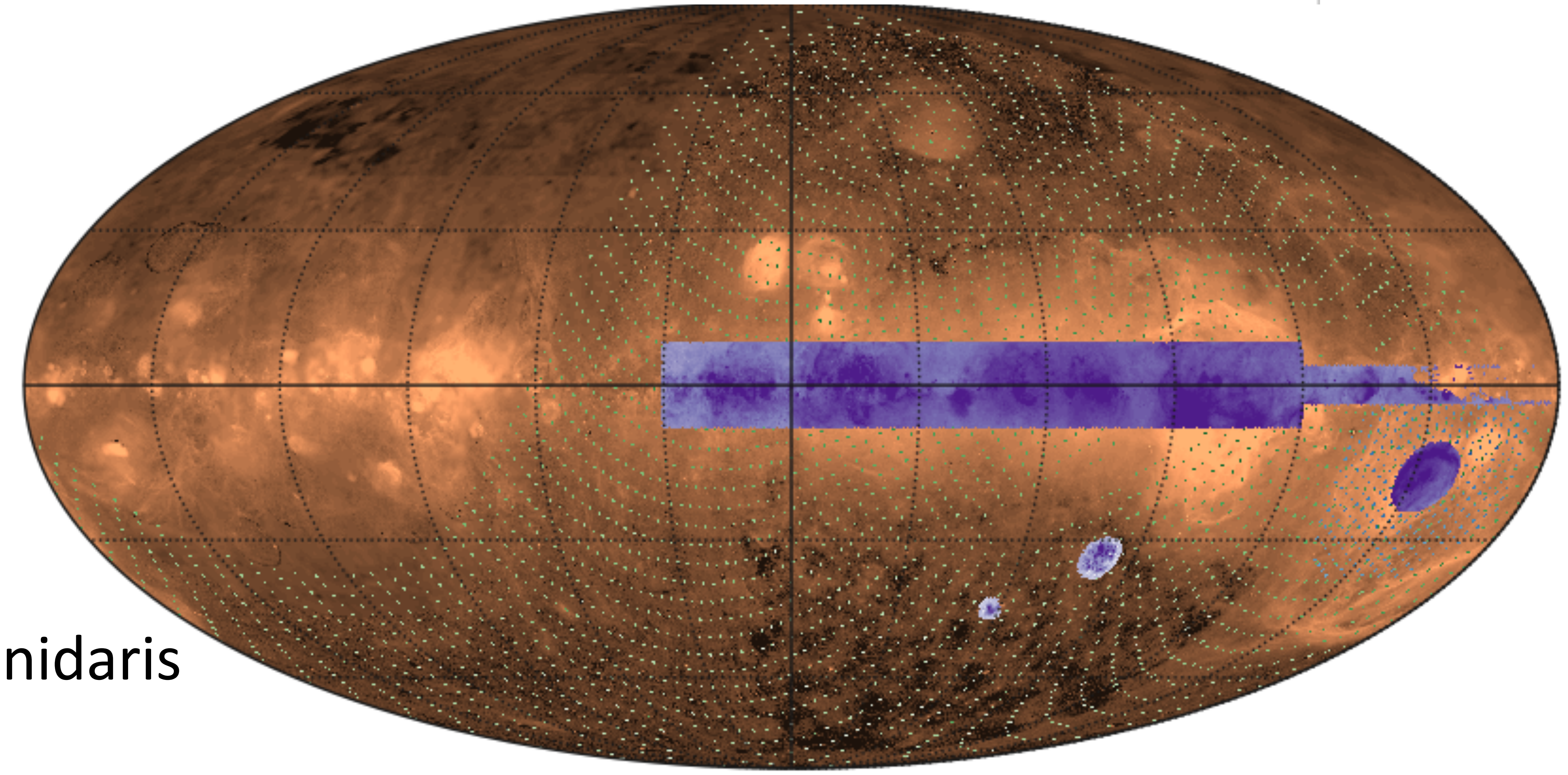
best IFU data

LVM in the Local Group

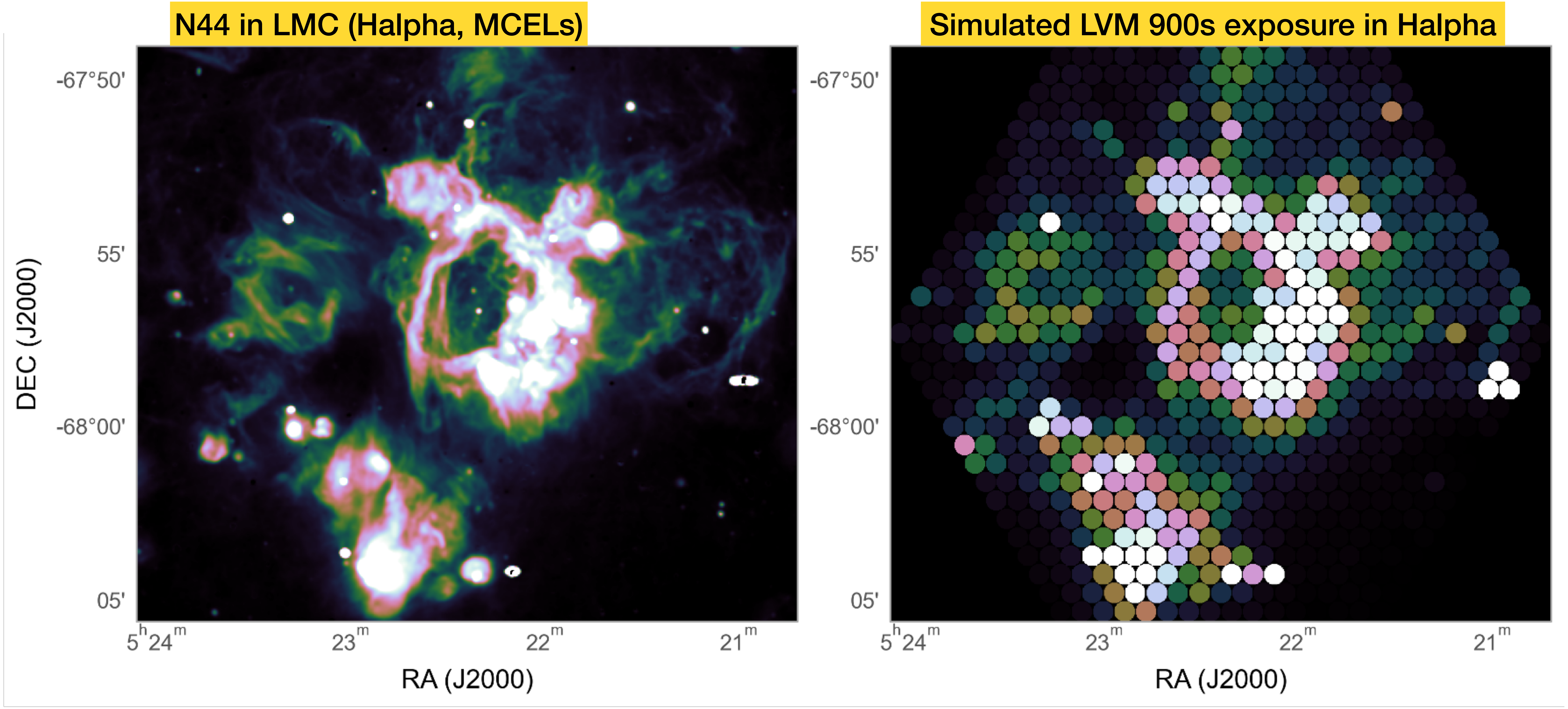


16cm telescopes @ LCO
3 DESI spectrographs:
3600 - 9800 A at R~4000
1800 x 35” fibers
~2-6x10^{-18} erg/s/cm^2/arcsec^2/A

Project head: N. Drory, Instrument lead: N. Konidaris
Survey scientists: K. Kreckel, G. Blanc



Commissioning - this summer!



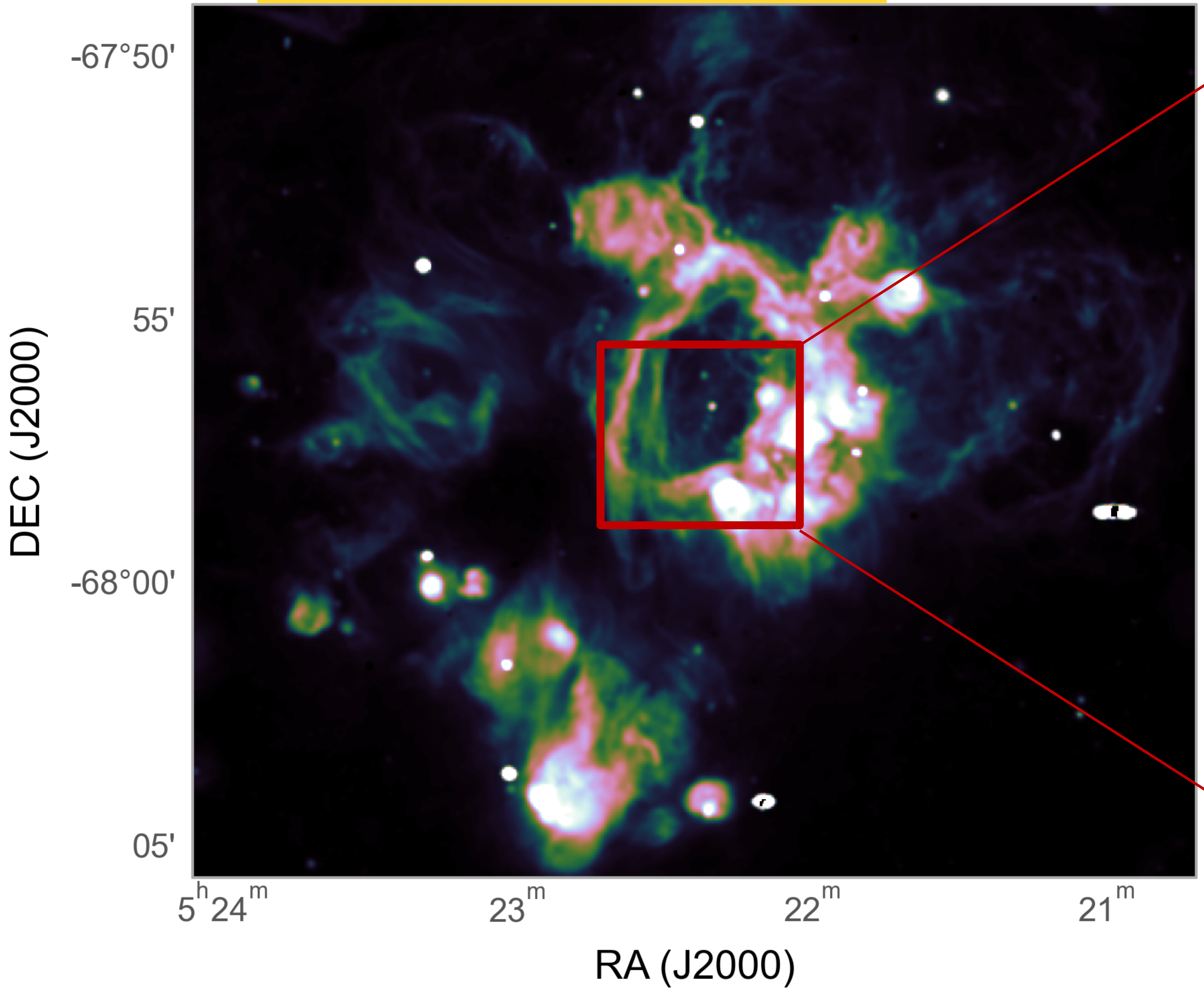
Produced with LVM data simulator
https://github.com/sdss/lvmdatasimulator (Egorov, Congiu et al., in prep)

SDSS-V

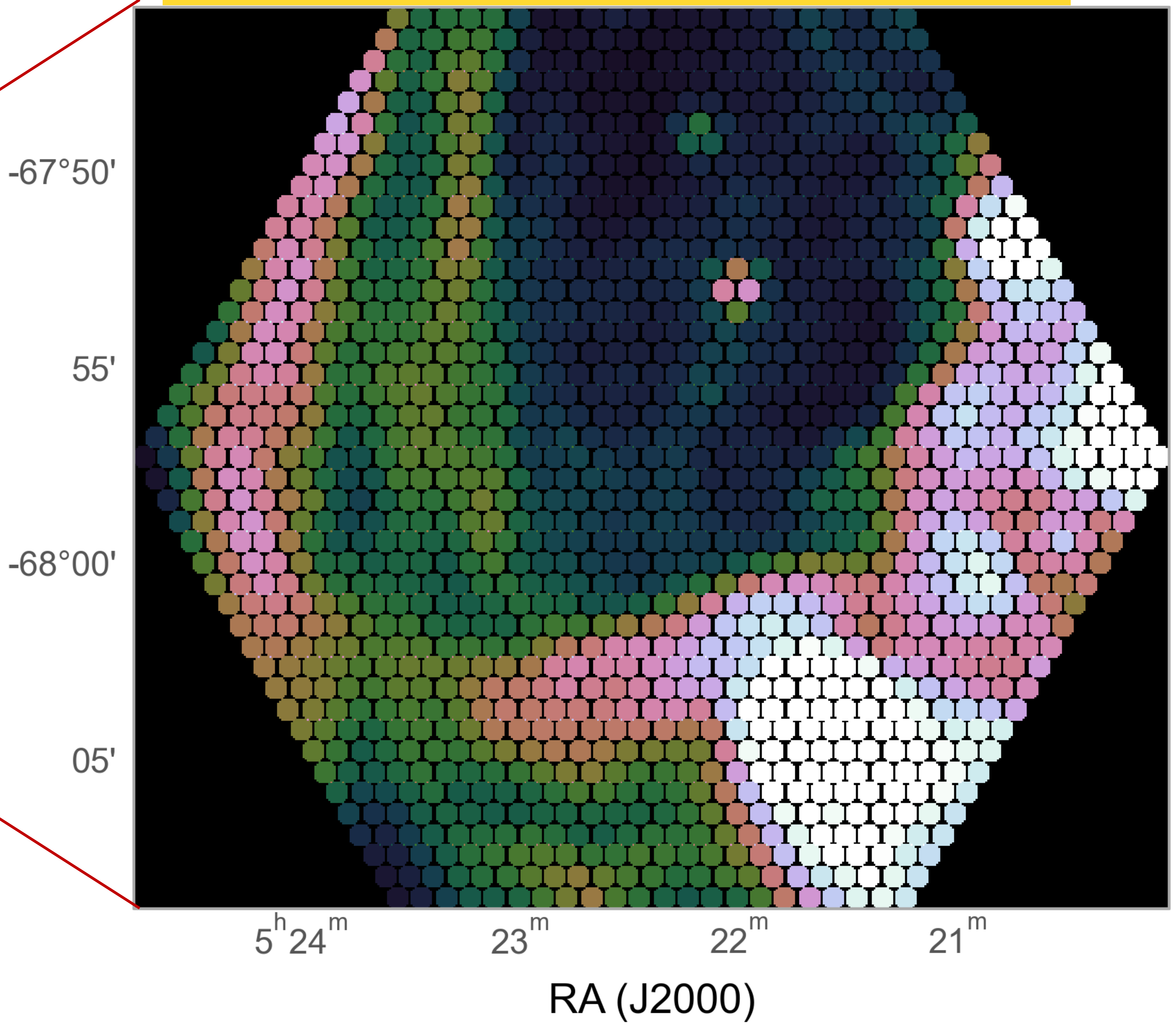
Local Volume Mapper

Resolving the Physics Driving Galaxy Formation

N44 in LMC (Halpha, MCELs)



Simulated LVM 900s exposure in Halpha
(if this region would be in MW)

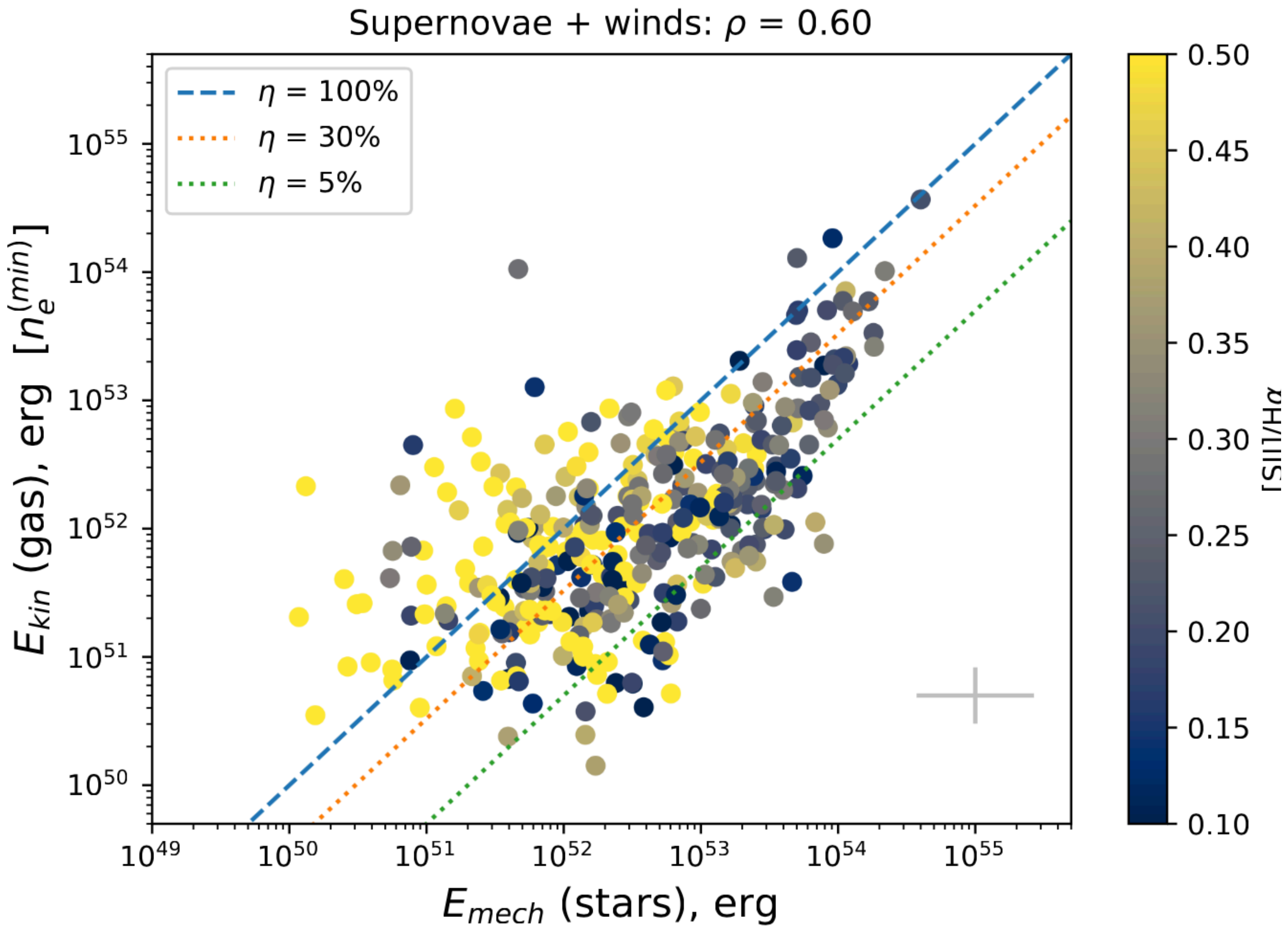


Produced with LVM data simulator
https://github.com/sdss/lvmdatasimulator (Egorov, Congiu et al., in prep)

Summary

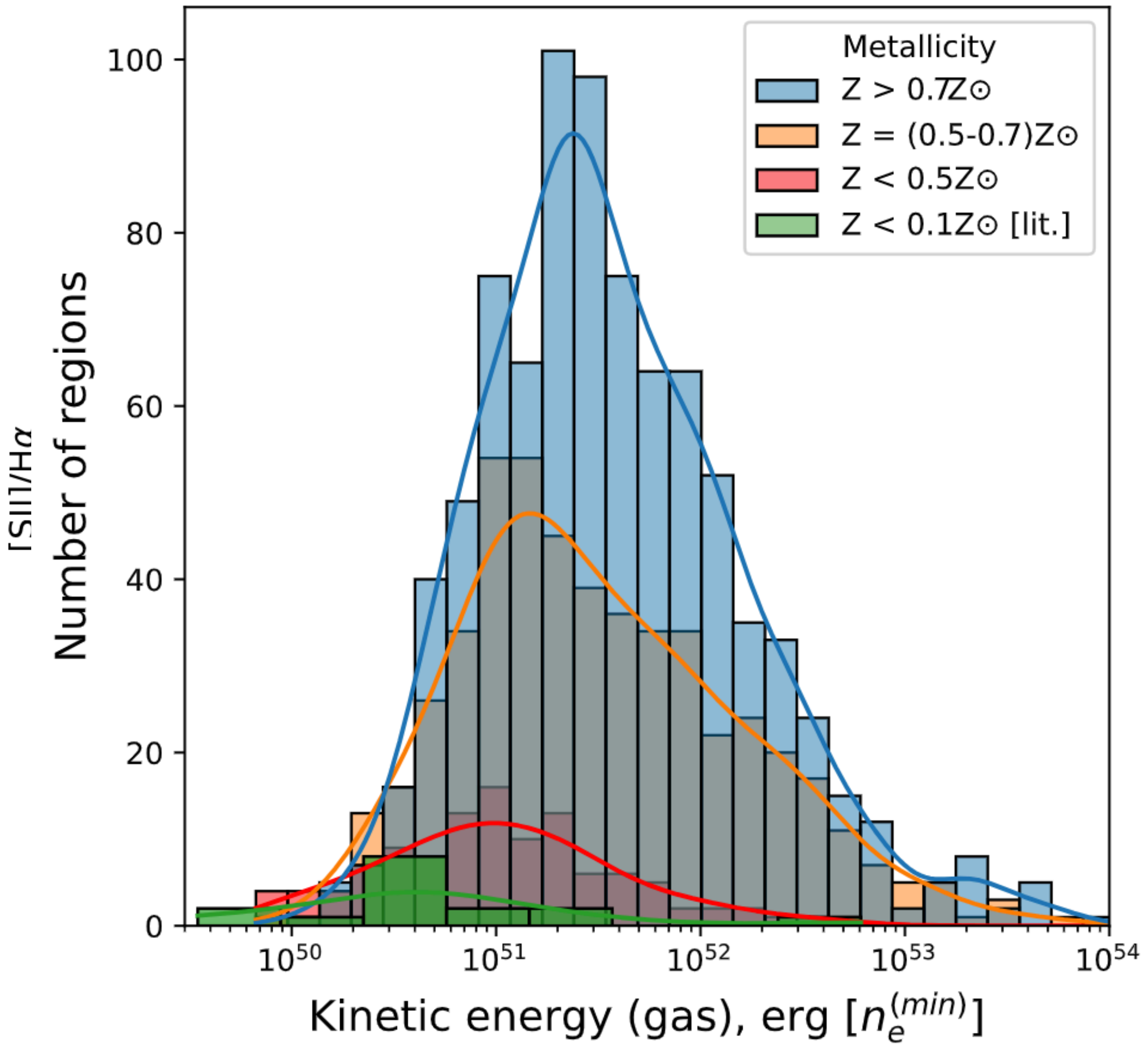
1) Energy balance between massive stars and small-scale supersonic motions of ionized gas in the ISM of 19 PHANGS galaxies with the efficiency of 10-20%

Acounting for pre-SN feedback impact is crucial



2) Kinetic energy of the turbulent ionized gas and superbubbles declines in the low-metallicity environment

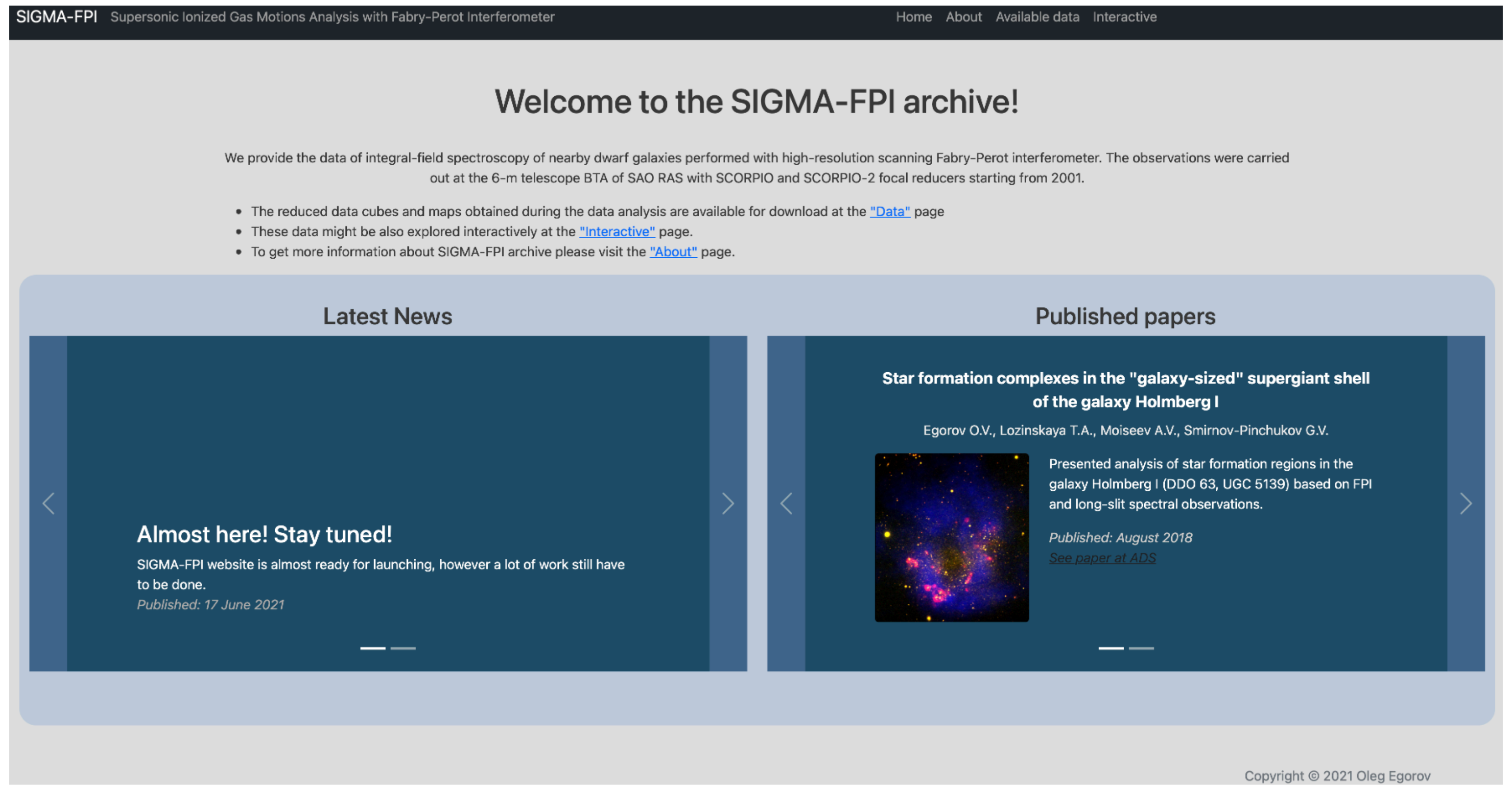
Nevertheless, the feedback-driven ionized gas motions are observed even in very metal-poor galaxies



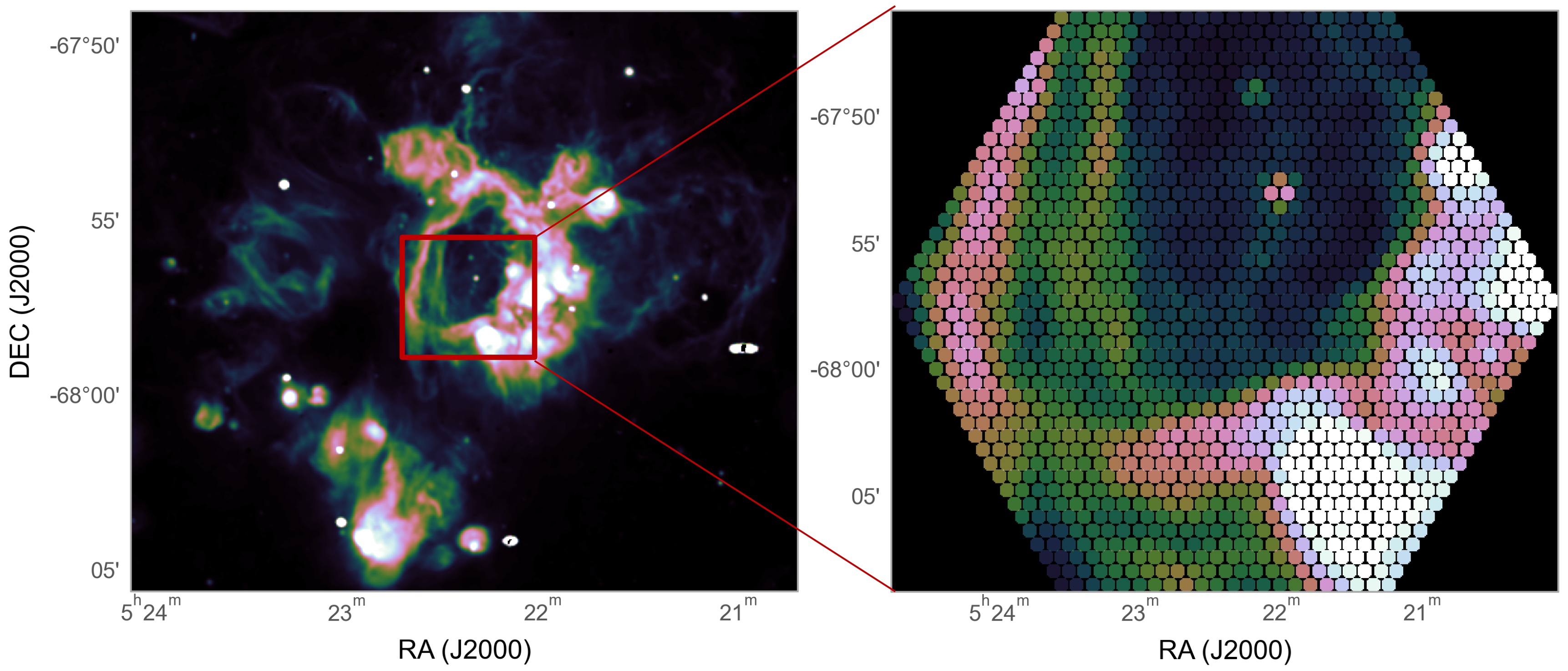
Egorov et al. (2023, submitted)

3) Resolved ionized gas kinematics is crucial to understand how stellar feedback shapes ISM of galaxies

Check out our SIGMA-FPI database



… and forthcoming amazing data from facilities like SDSS-V/LVM



Хвала вам на пажњи