The impact of star-formation driven outflows in chemical evolution models and circumgalactic enrichment of galaxies

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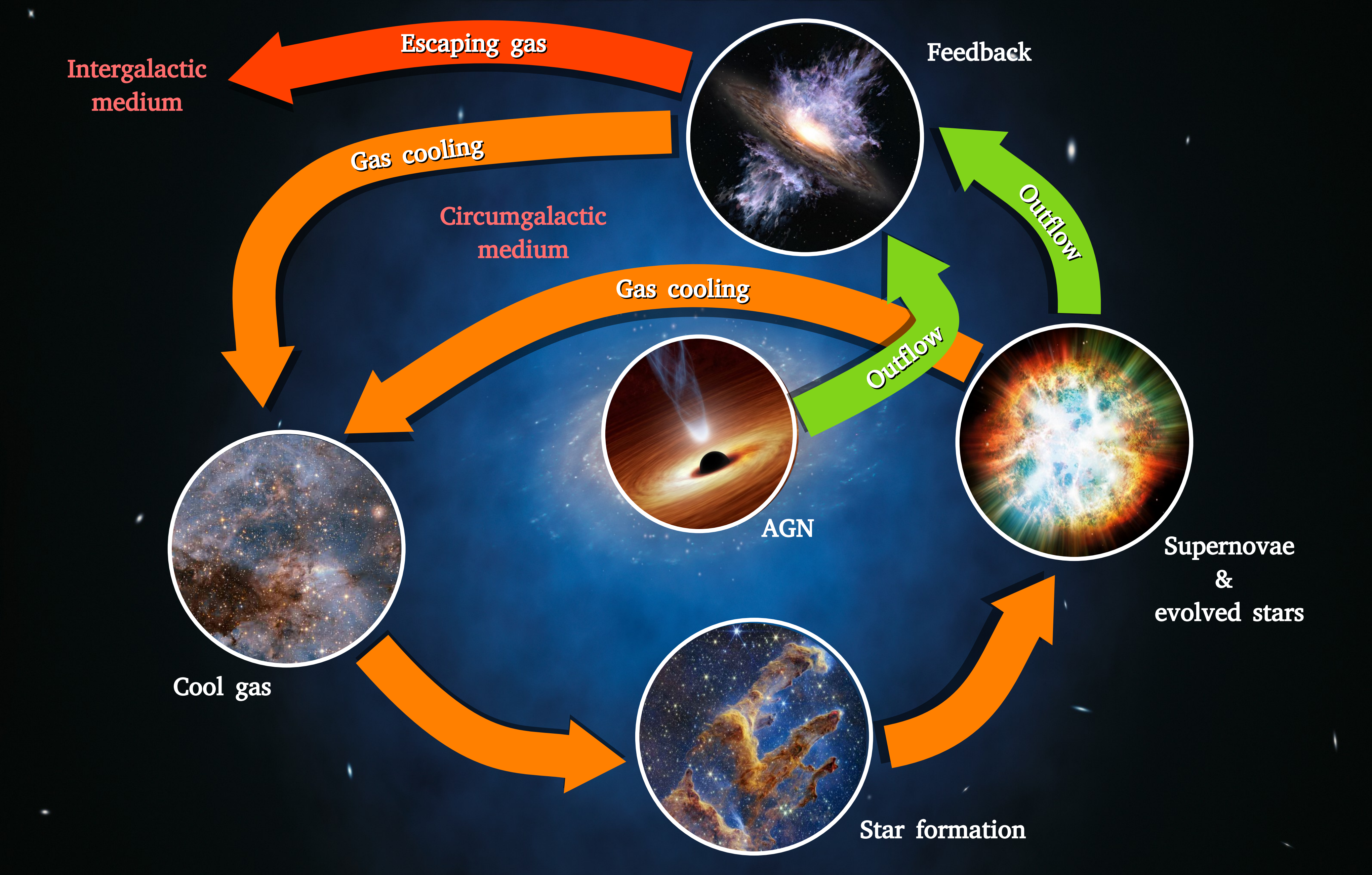
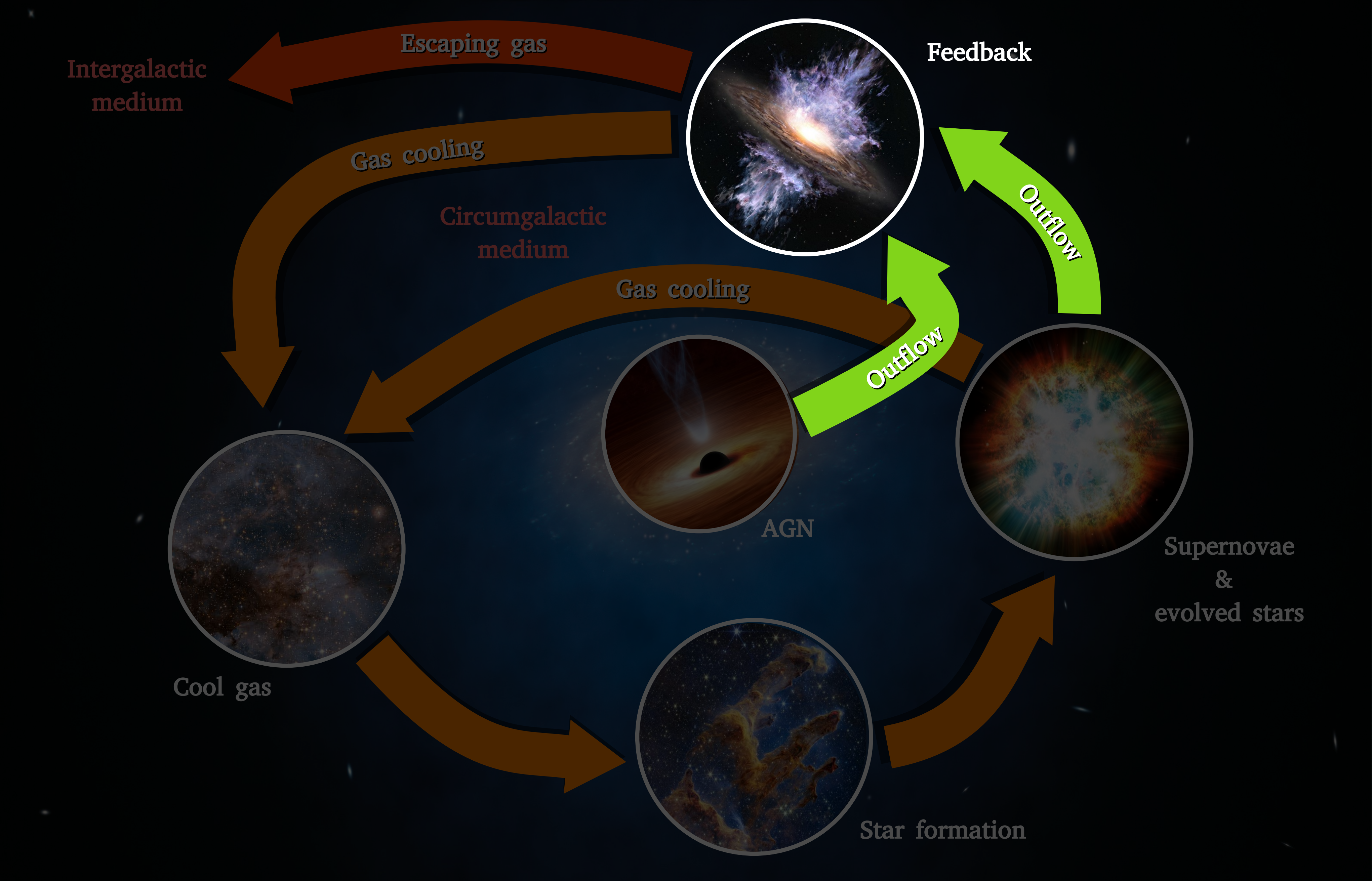
Outline

- **General Context**
- **The Dwarf Galaxy Survey (DGS): an overview**
- **Methodology**
- **Results**
  - Outflow efficiency
  - CGM/IGM enrichment
- **Summary and future prospects**


Intergalactic
medium
Circumgalactic
medium


Escaping gas
Intergalactic medium
Feedback
Gas cooling
Circumgalactic medium
Outflow
Gas cooling
Outflow
AGN
Supernovae & evolved stars
Cool gas
Star formation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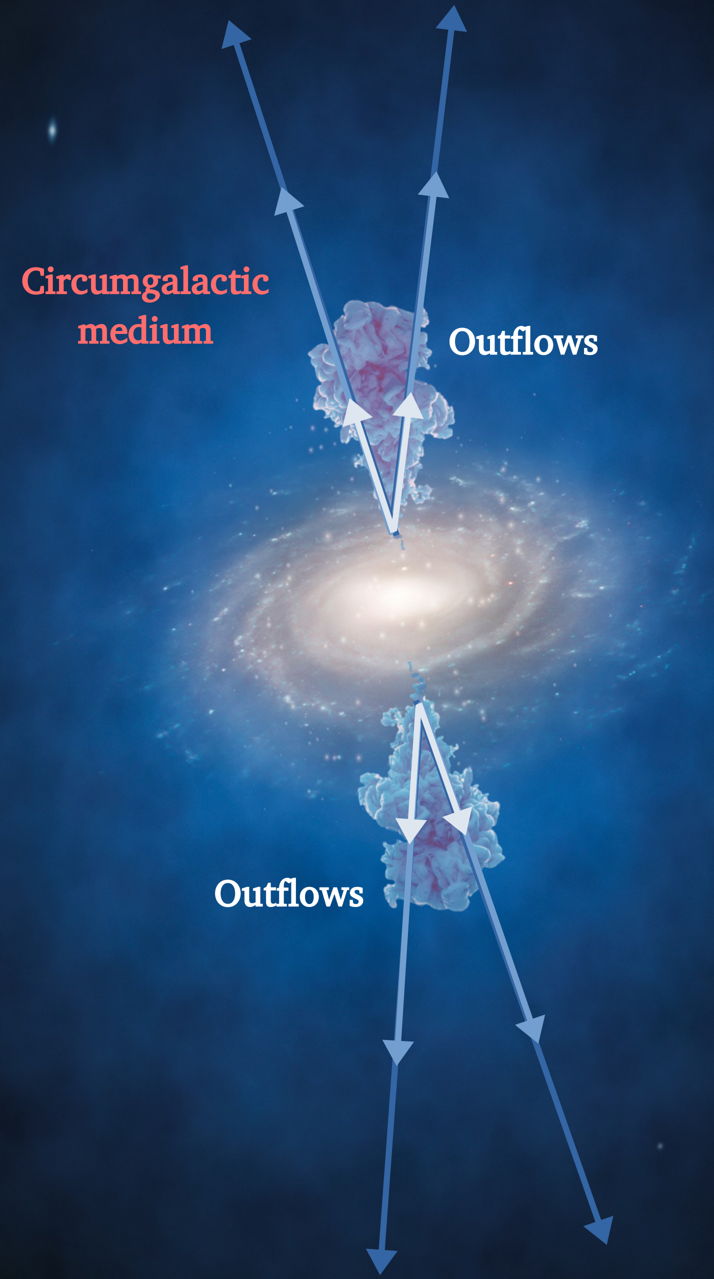
Intergalactic medium



Gas heating causing low star-formation efficiency

Needed to match the observed luminosity function with models

Quenching

Fine-tuning of chemical evolution models

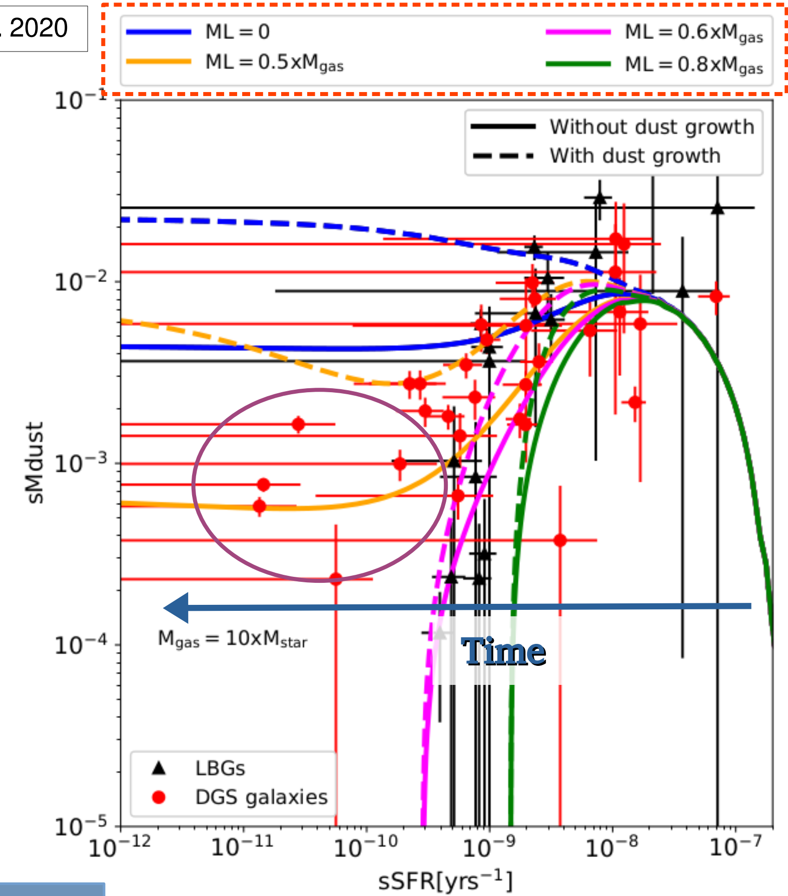
Expulsion of dust and metals out of the galaxy (CGM/IGM enrichment)

Outflow velocity

- Gas does not leave the galaxy
- CGM enrichment
- IGM enrichment

General context

Nanni et al. 2020



Efficient star-formation driven outflows are needed by models to reproduce the observations:

$$\eta \equiv \frac{\dot{M}_{out}}{SFR} \gg 1$$

$$\eta \approx 0 \rightarrow 80$$

$$\left.\begin{array}{c} \dfrac{dM_{gas}}{dt} \\ \dfrac{dM_{metal}}{dt} \\ \dfrac{dM_{dust}}{dt} \end{array}\right\} \propto \eta$$

Constraints on the mass-loading factor

Better description of dust/metals production and destruction in the ISM of galaxies

General context

Galactic outflows are ubiquitous in high-redshift (z > 1) starbursts and AGNs, and can be detected with different techniques:

1) Rest-frame UV/optical blue-shifted absorption lines (e.g., SiII), especially at z > 1

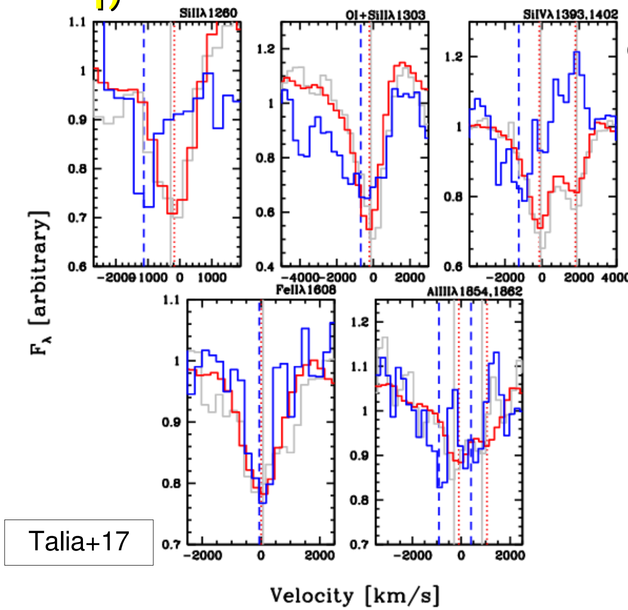
2) Nebular emission lines (e.g., Hα) in high-mass galaxies

3) FIR cooling lines (e.g., [CII]) at both low and high-z

4) Stacking, mostly for fainter or *normal* galaxies in the early Universe

1)

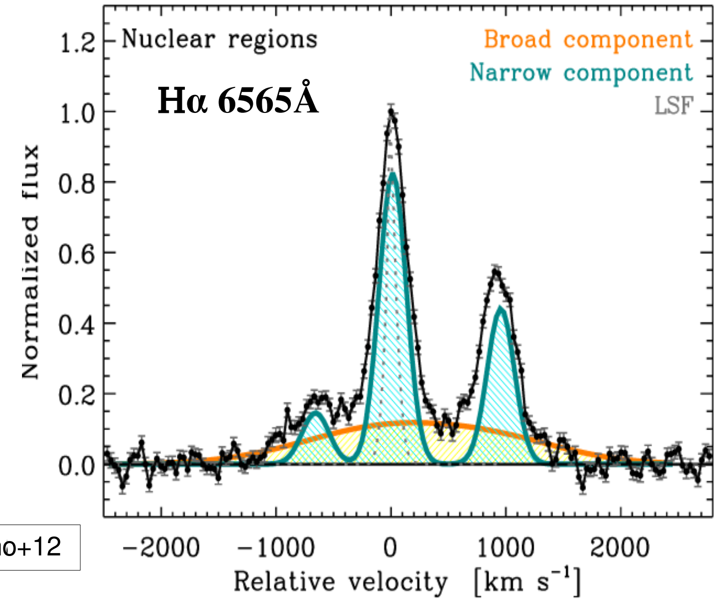
Blueshifted optical lines



Talia+17

2)

Förster-Schreiber+14



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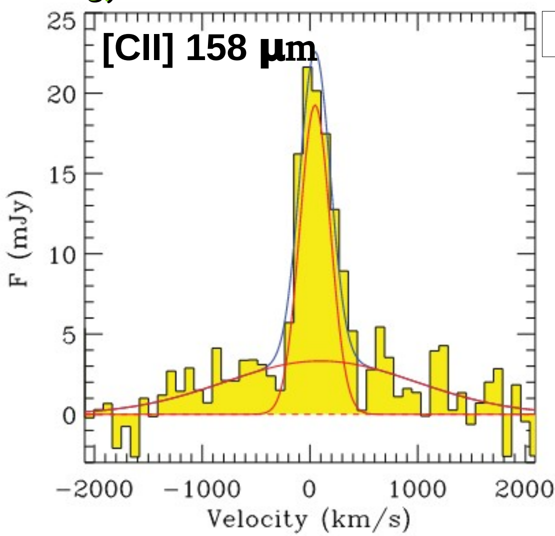
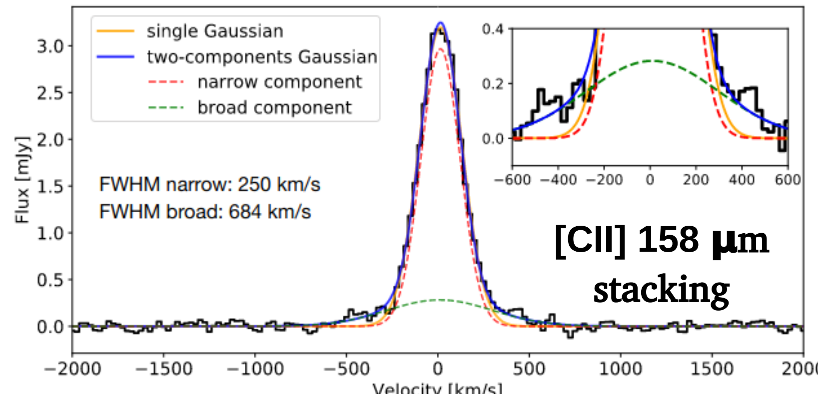


Maiolino+12

4)

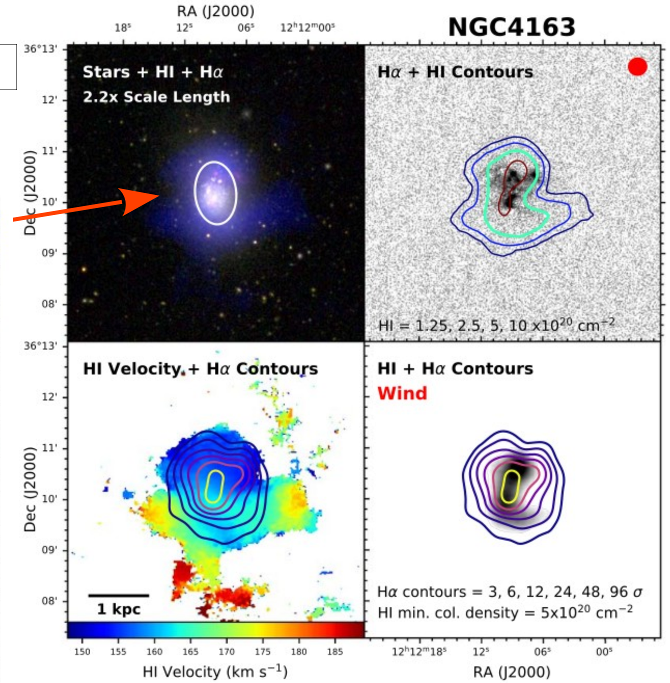


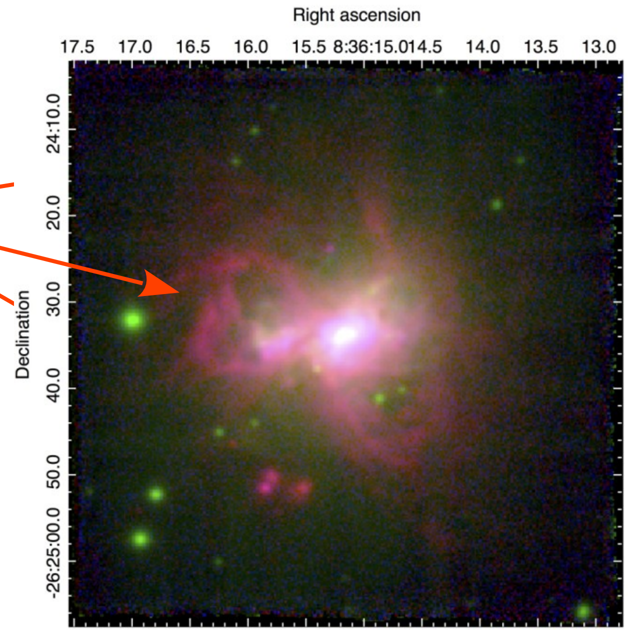
Ginolfi+20

General context

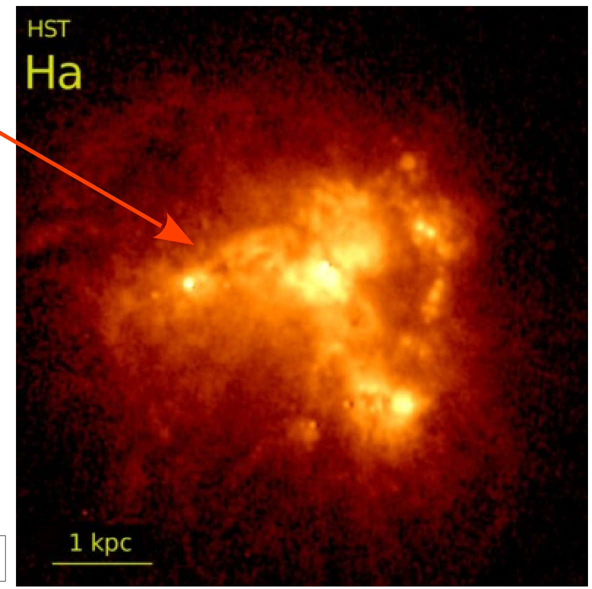
Nearby sources offer the best opportunity to study in detail galactic outflows and their impact on galaxy evolution.

McQuinn+19





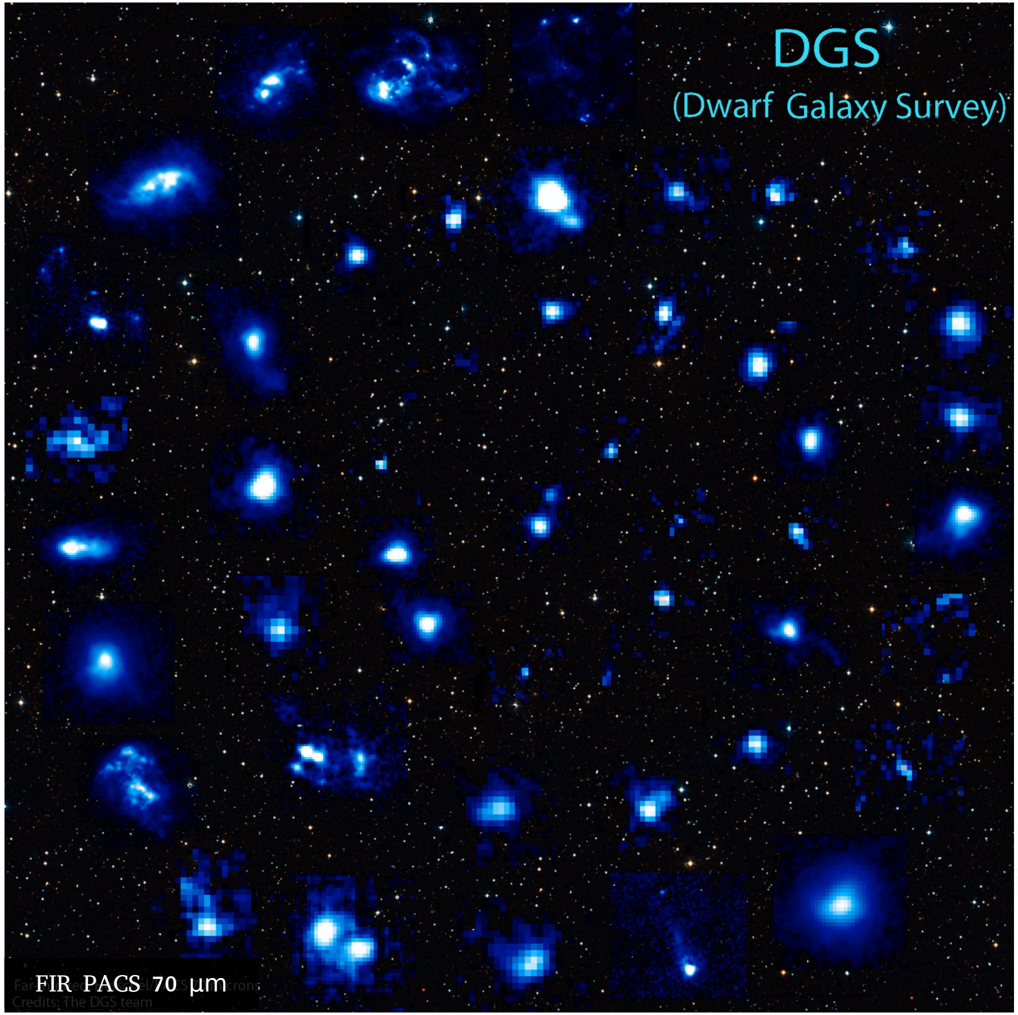
Cresci+17

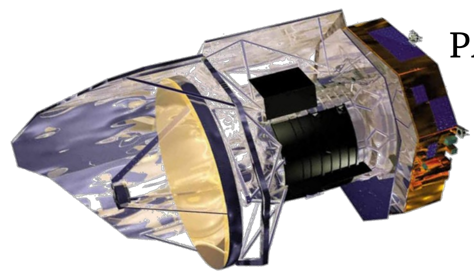


Menacho+19

Local dwarf galaxies are of particular interest for this kind of studies as they are much more sensitive to stellar feedback

Dwarf Galaxy Survey: an overview

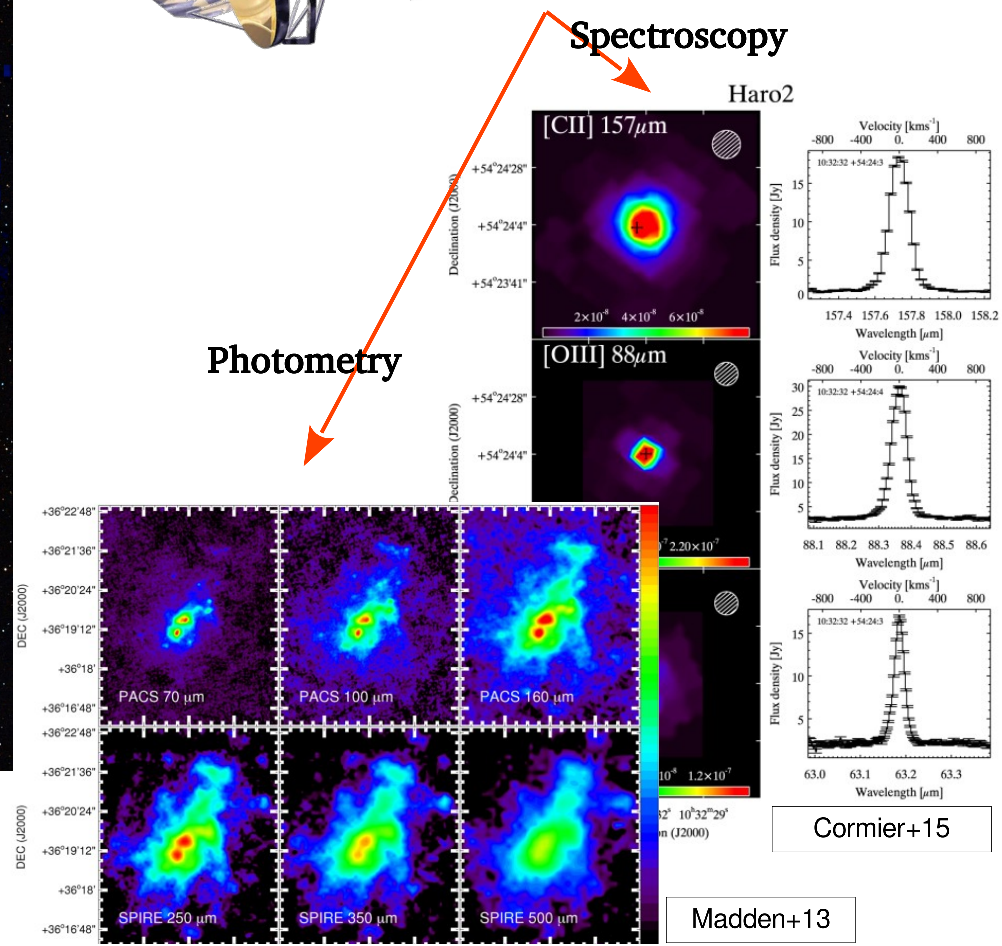




Herschel
PACS/SPIRE

Spectroscopy

Photometry



Cormier+15

Madden+13

Dwarf Galaxy Survey: an overview

DGS Sample properties:

- 48 dwarf galaxies
- 12 + log(O/H) ≤ 8.4
- D < 200 Mpc
- $\log(M_*/M_\odot) \sim 6 - 10$

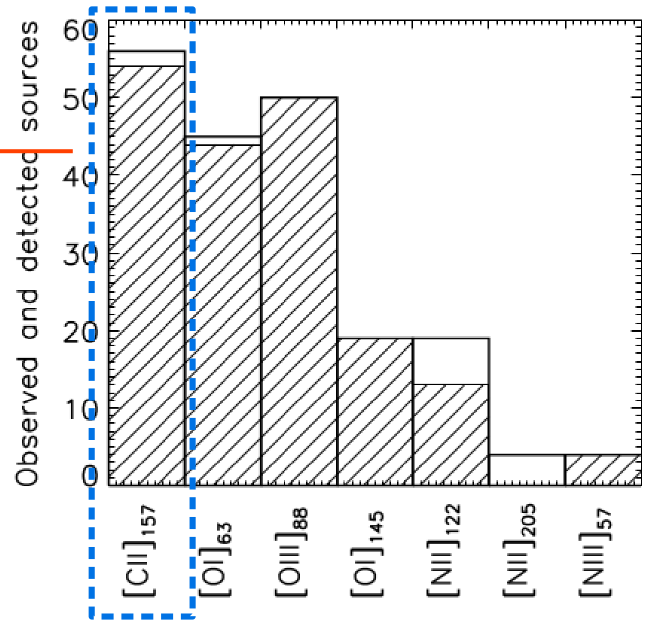
48 dwarf galaxies → 11 extended objects; 37 compact objects

37 compact objects →
- 2 faint objects not observed by PACS
- 6 sources with too noisy [CII] spectra

= 29 galaxies

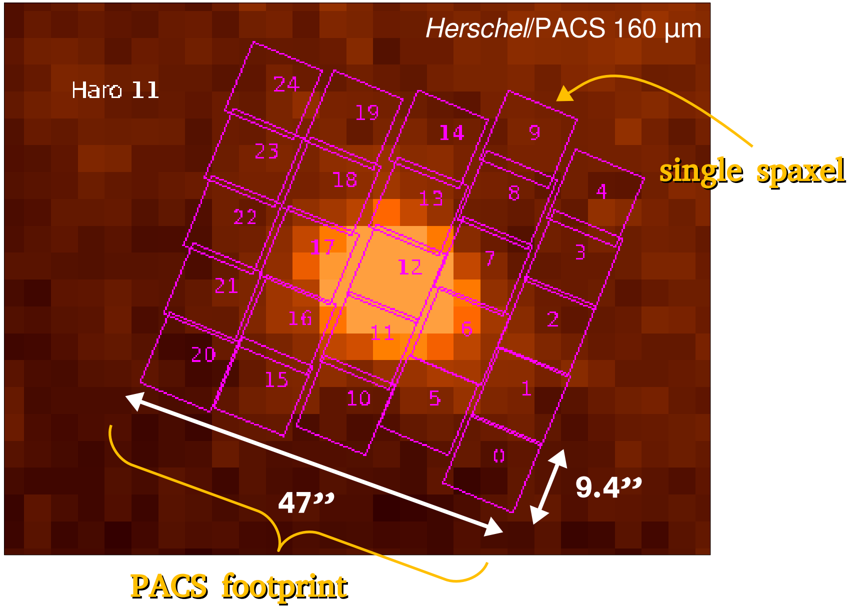
[CII] 158 μm rest-frame available for the whole sample

Tracer of atomic gas



Cormier+15

The method: data



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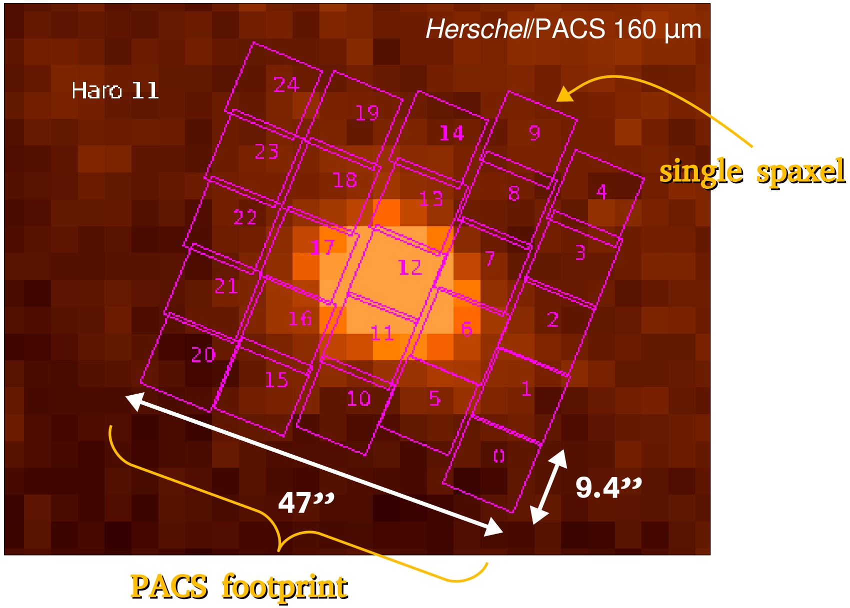

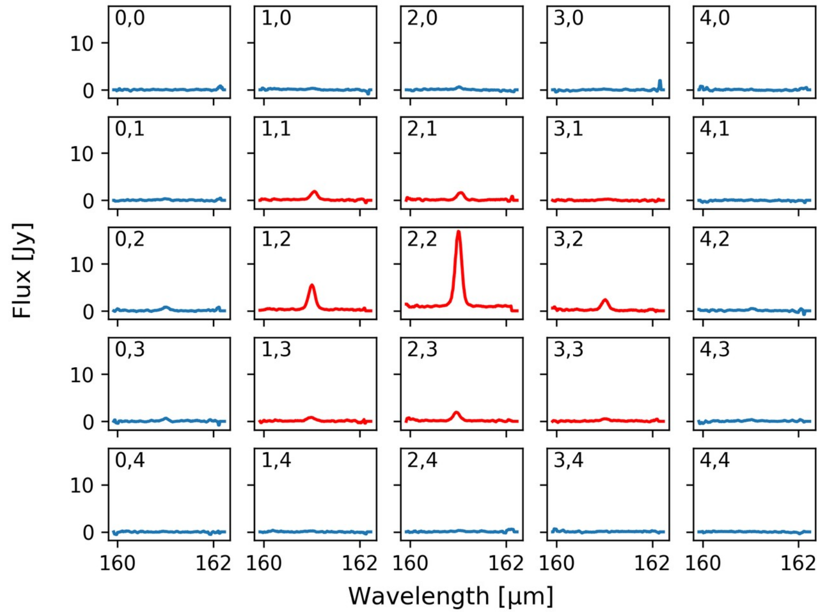

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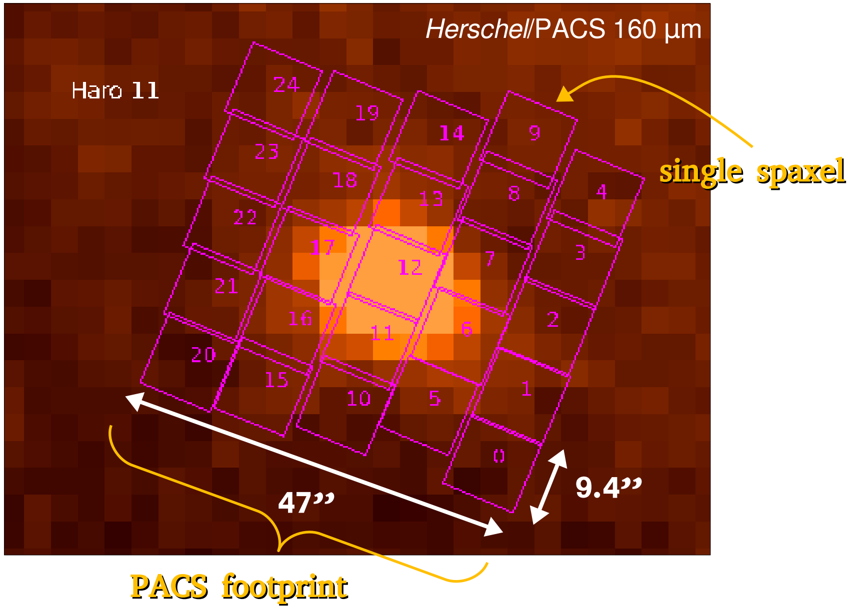

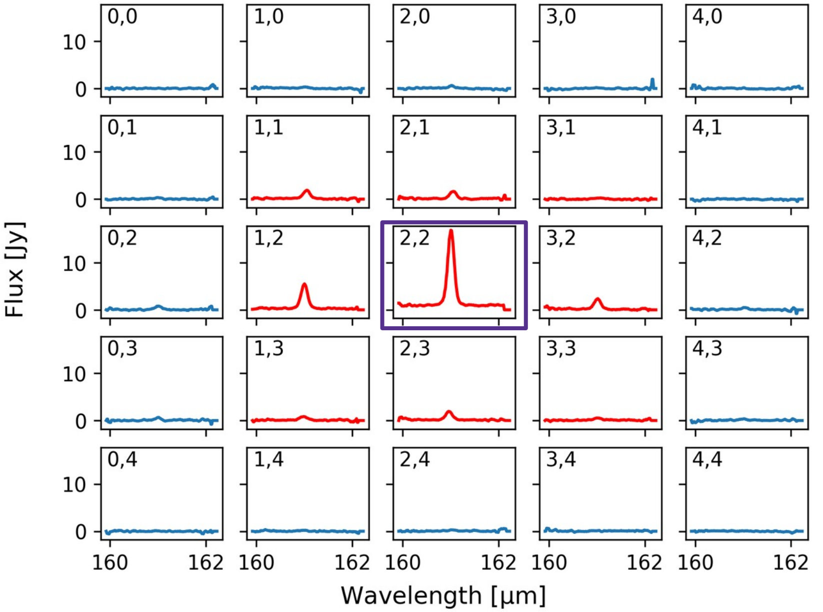

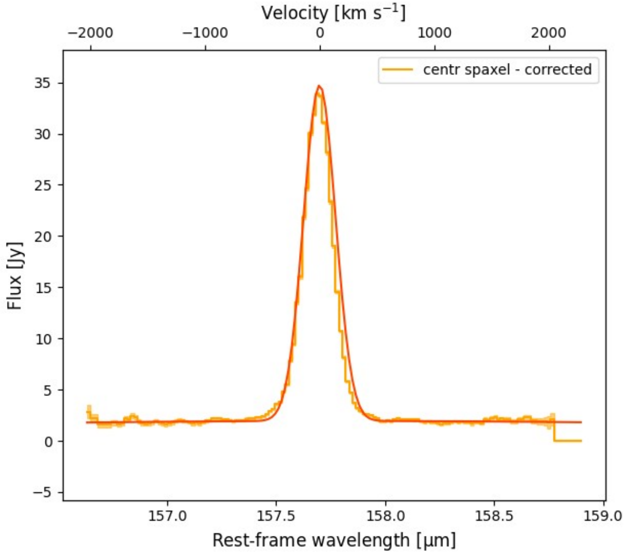

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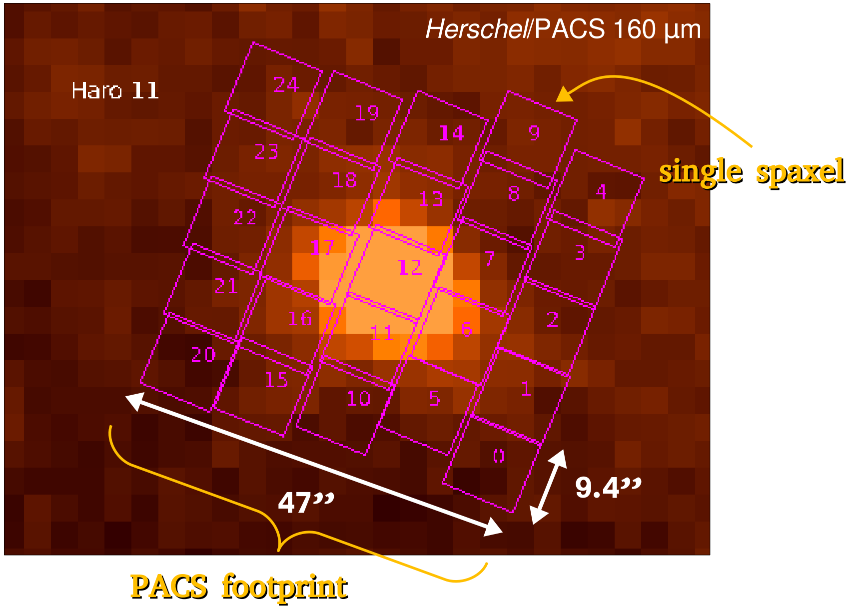

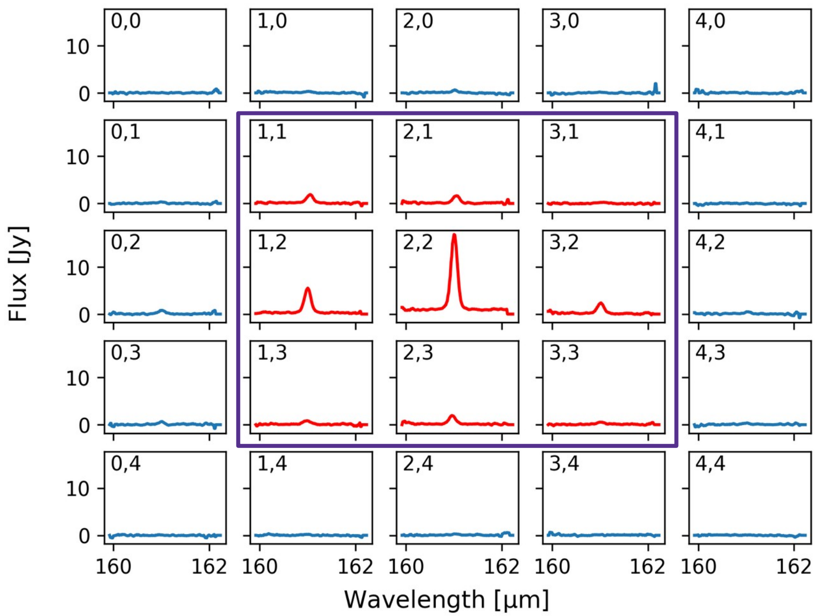

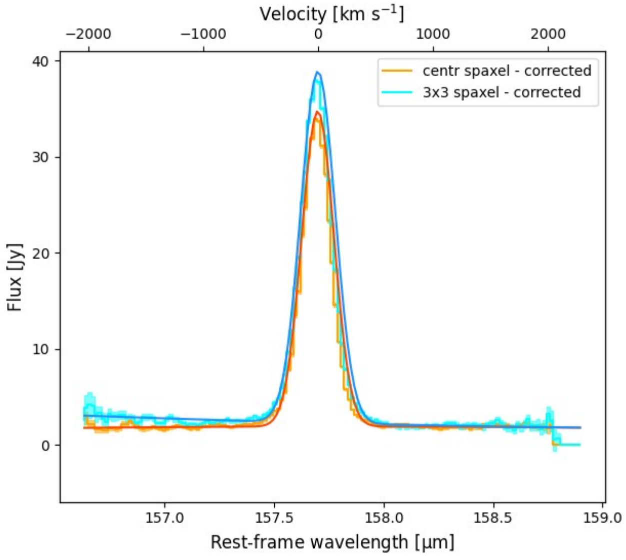

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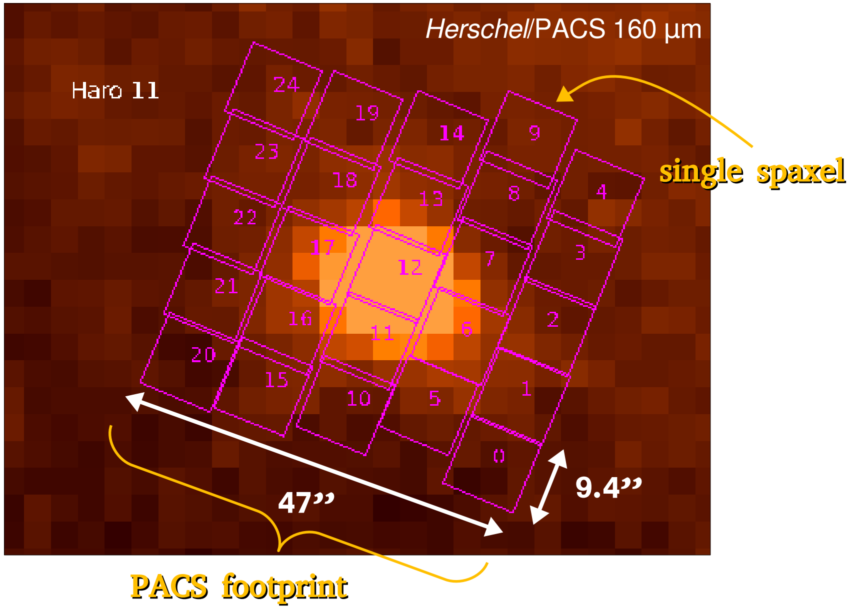

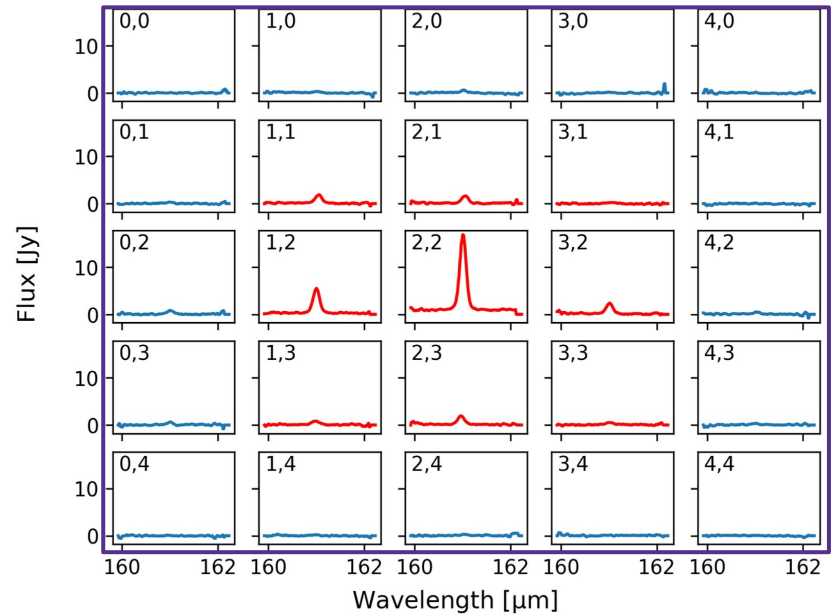

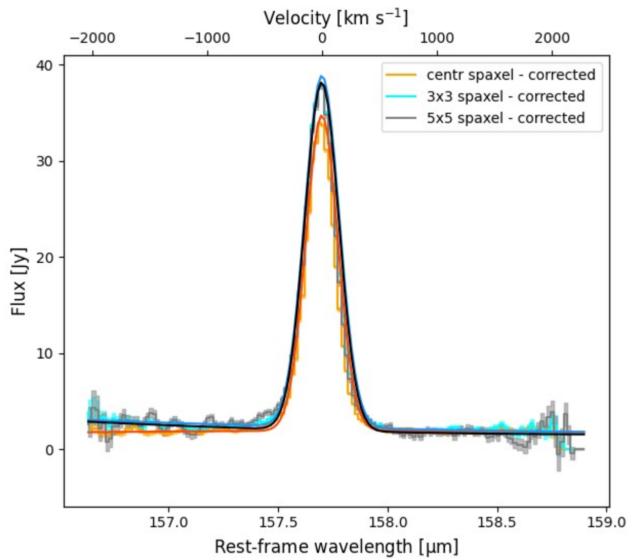

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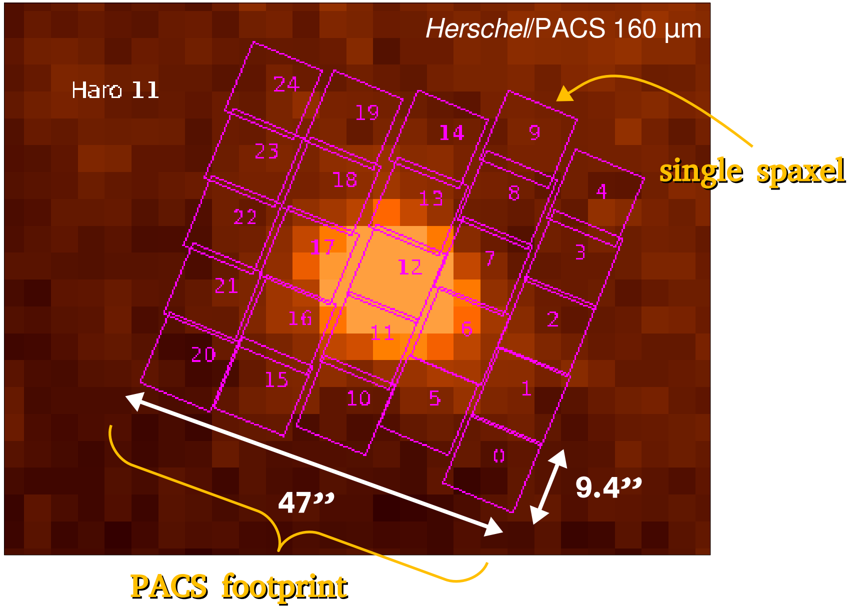
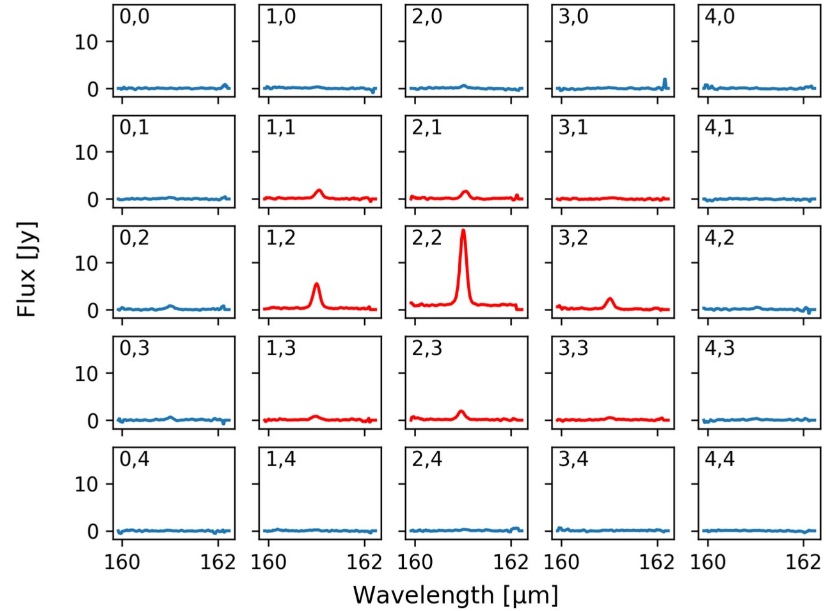
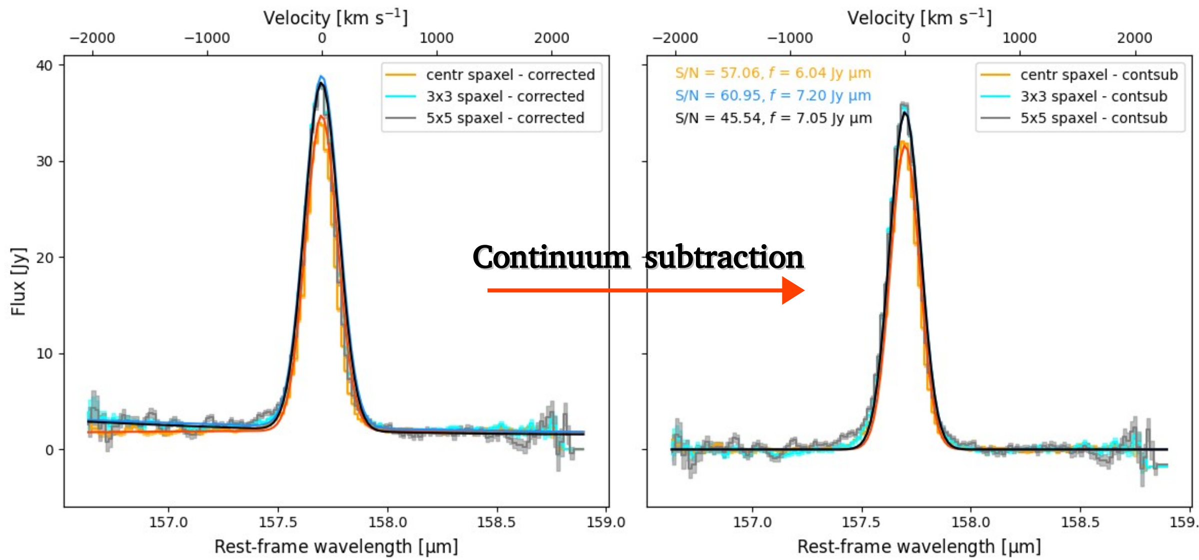


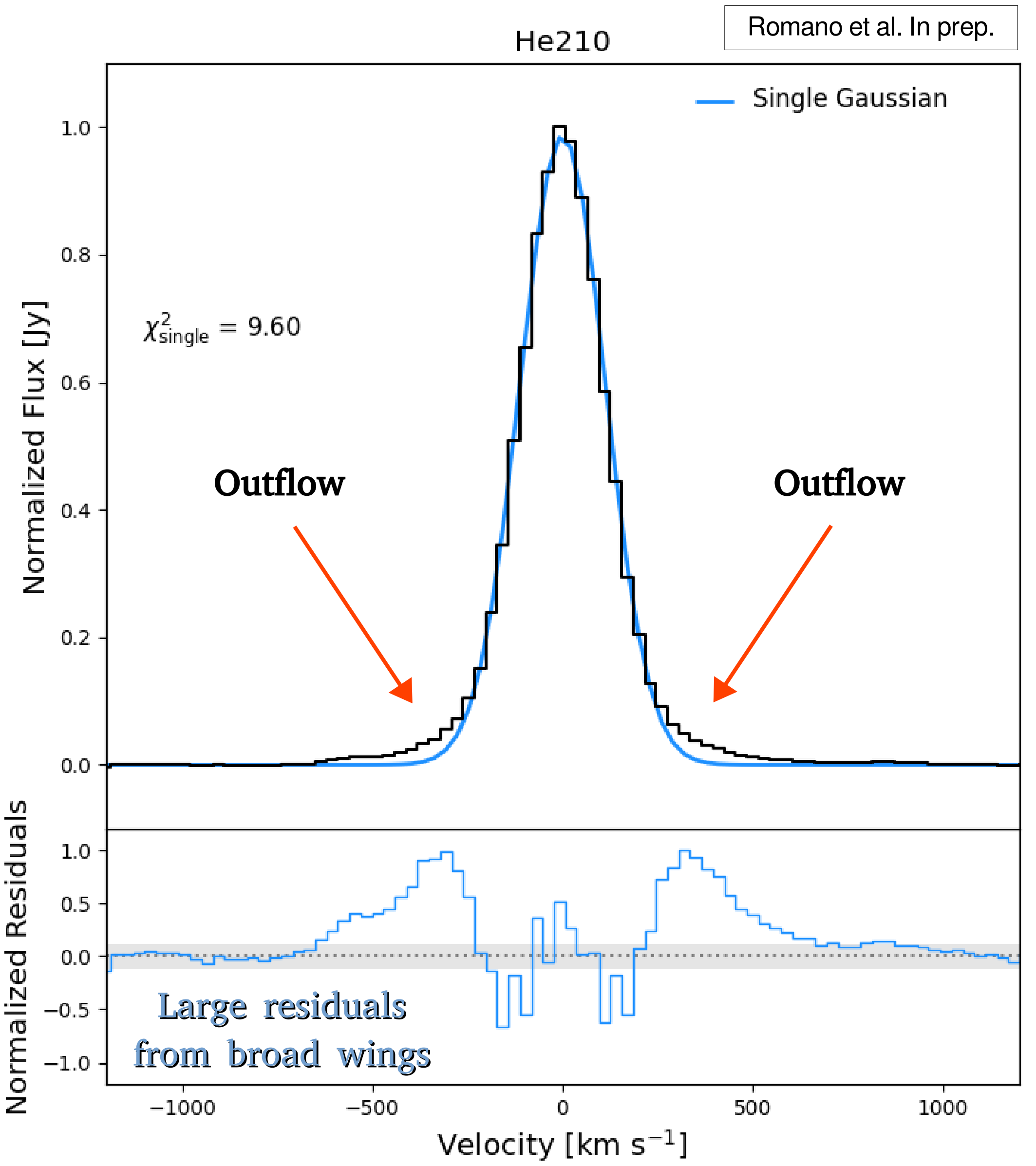




3x3 spectrum

Larger flux
Best S/N

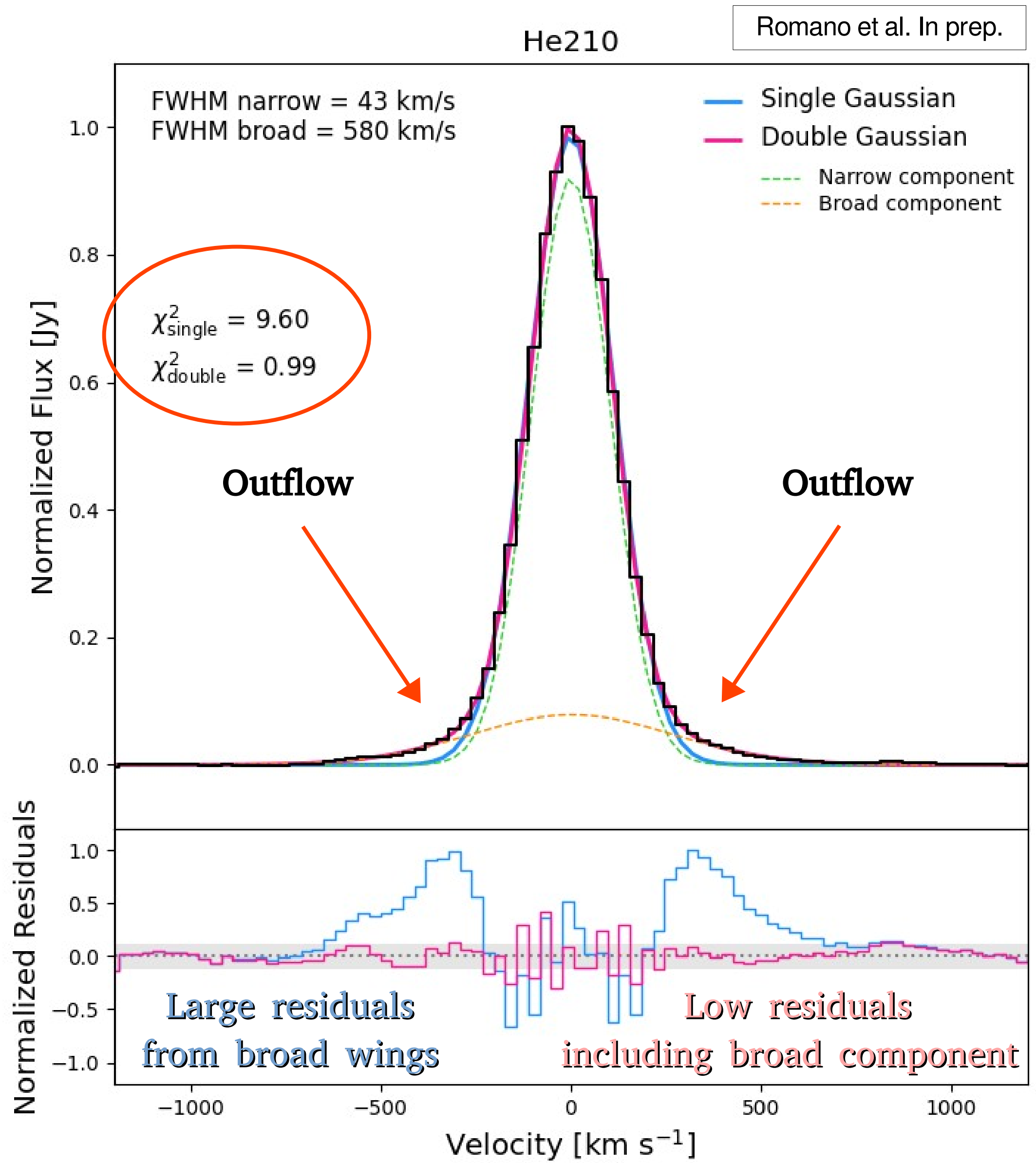
The method: individual detections



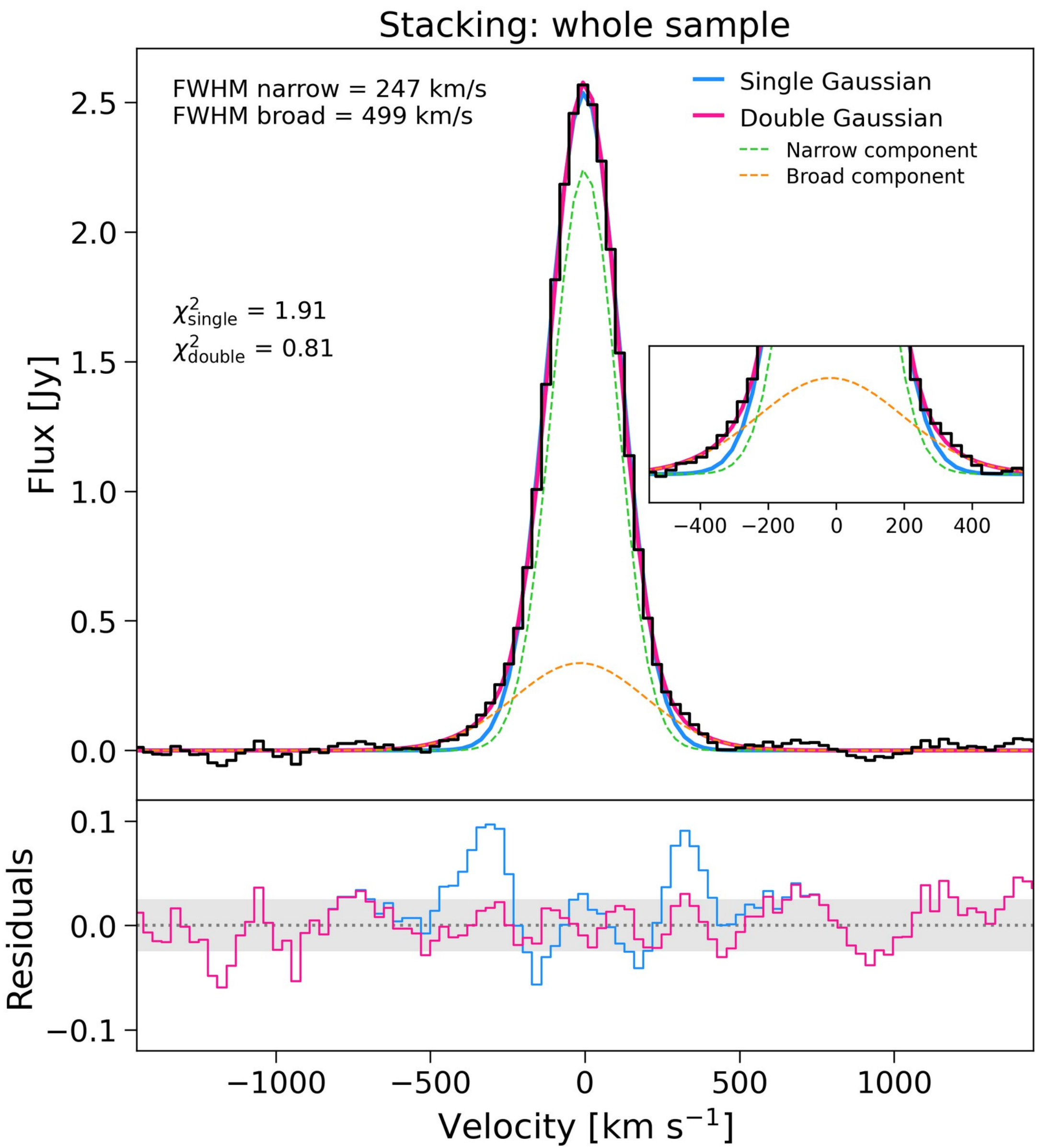
The method: individual detections

11 galaxies

with individual detection of atomic outflow



The method: spectral stacking



Romano et al. In prep.

Average outflow properties for the whole galaxy population

$$S^{Stacked} = \frac{\sum_{k=1}^{N} S_k \cdot w_k}{\sum_{k=1}^{N} w_k}$$

$$w_k = 1/\sigma_k^2$$

Outflow efficiency: the mass-loading factor

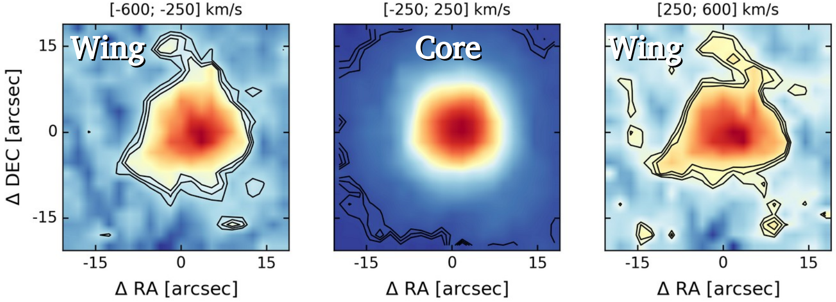
$$\eta \equiv \frac{\dot{M}_{out}}{SFR}$$

$$\dot{M}_{out} = \frac{v_{out} M_{out}}{R_{out}}$$

(De Looze+14)

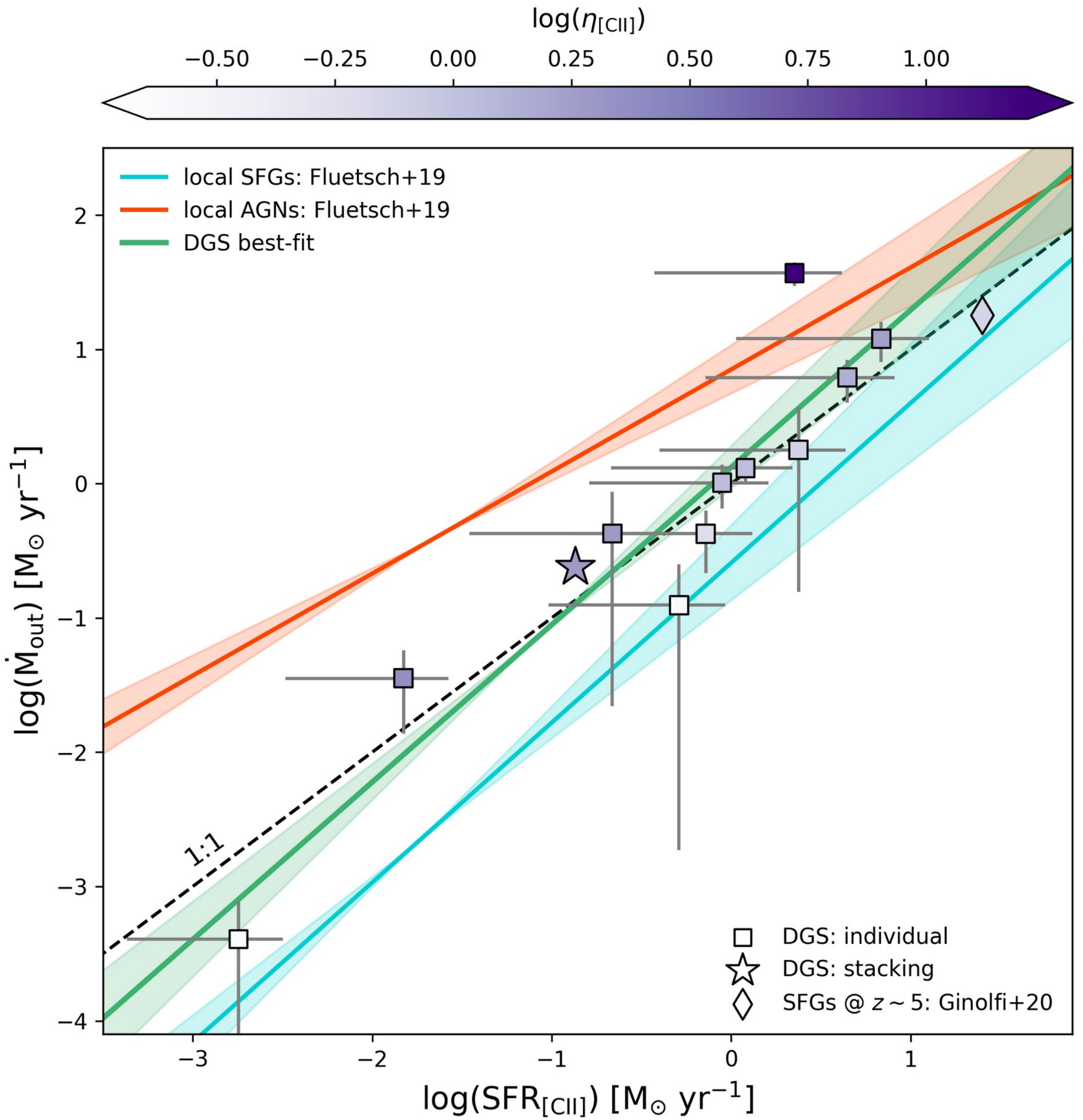
$$\log(SFR) = -5.73 + 0.80 \times \log(L_{[CII]})$$

- $$v_{out} = \frac{FWHM_{broad}}{2} + |v_{broad} - v_{narrow}|$$
- $$M_{out} = 0.77 \left(\frac{0.7\, L_{[CII]}}{L_\odot}\right) \times \left(\frac{1.4 \times 10^{-4}}{X_{C^+}}\right) \times \frac{1 + 2e^{-91\,K/T} + n_{crit}/n}{2e^{-91\,K/T}}$$ (Hailey-Dunsheath+10)
- $$R_{out} = \frac{a}{2}\sqrt{\frac{b}{a}}$$



- **70%** of the total [CII] luminosity contributes to atomic gas
- X_{c+} = **1.4e-4** → abundance of C per H atom
- T = **130** K → gas temperature
- n_{crit} = **2.8e3** cm^{-3} → critical density of [CII]
- n = **1e4** cm^{-3} → gas number density

Outflow efficiency: the mass-loading factor

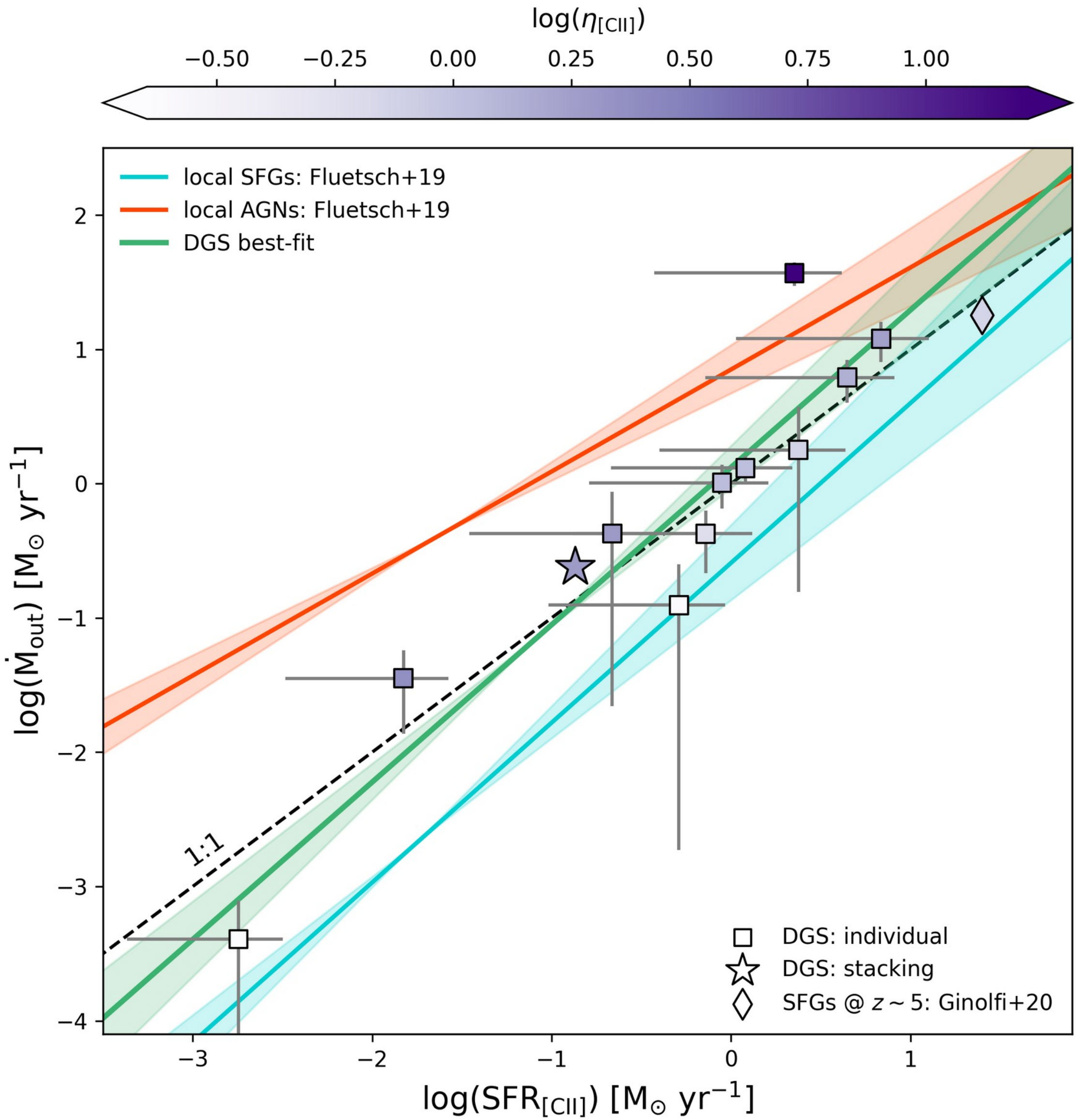


$$\eta_{[CII]} \sim 1-3$$

Lower than predicted by chemical evolution models..

Romano et al. In prep.

Outflow efficiency: the mass-loading factor



$$\eta_{[CII]} \sim 1-3$$

Lower than predicted by chemical evolution models..

Accounting for the multi-phase ISM

$$\eta_{TOT} \sim 3 \times \eta_{[CII]}$$

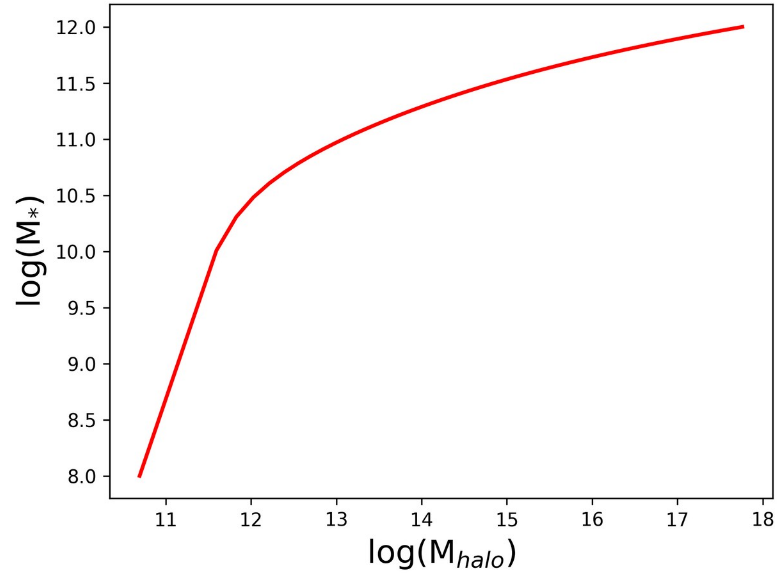
Romano et al. In prep.

Chemical enrichment of the CGM/IGM

(Fluetsch+19)

$$v_{esc,halo} \equiv \sqrt{2|\Phi(r)|} = \sqrt{\frac{2 M_{halo} G}{r_{halo}(\ln(1+c) - c/(1+c))} \ln(1 + r_{halo}/r_s)}$$

- M_{halo} from abundance-matching technique (Behroozi+10)



- $r_{halo} = \left[\frac{3 M_{halo}}{4\pi 200 \rho_{crit}}\right]^{1/3}$ (Huang+17)

- $r_s = r_{halo}/c$ (Navarro, Frenk & White+95)

- $\log(c) = 0.76 - 0.1 \log(M_{halo})$ (Duffy+08)

Chemical enrichment of the CGM/IGM

In most of the cases, the wind speed is comparable to (or above) that needed to escape the dark matter halo

Despite low efficiency (η ~ 1), outflows are able to enrich the IGM around dwarf galaxies

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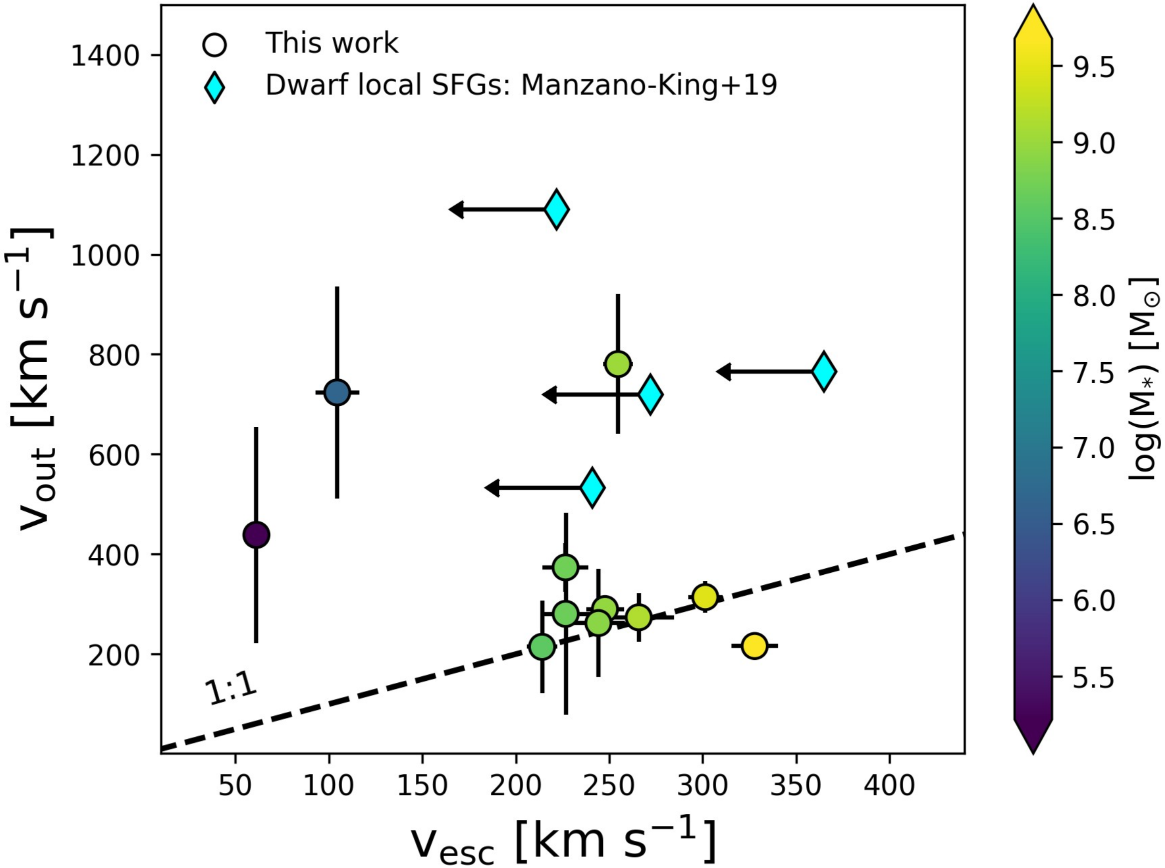

Summary and future prospects

- Local dwarf galaxies are characterized by **ubiquitous galactic outflows**

- Atomic gas is expelled out of the galaxies with a **rate proportional to (or slightly higher than) the SFR**
  - We found **$\eta \sim$ 1-3**, that is lower than expected from chemical evolution models

- **Our findings could be underestimated by a factor ~3** when inlcuding the other phases (ionized and molecular) of the ISM

- **Outflow velocities are typically larger than the escape velocities** from the galaxy dark matter halos:
  - Galactic outflows are thus **able to enrich the surrounding of the galaxies**, expelling material out into the IGM

Summary and future prospects

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Work in progress

→ [OIII] to characterize the ionized phase of the ISM

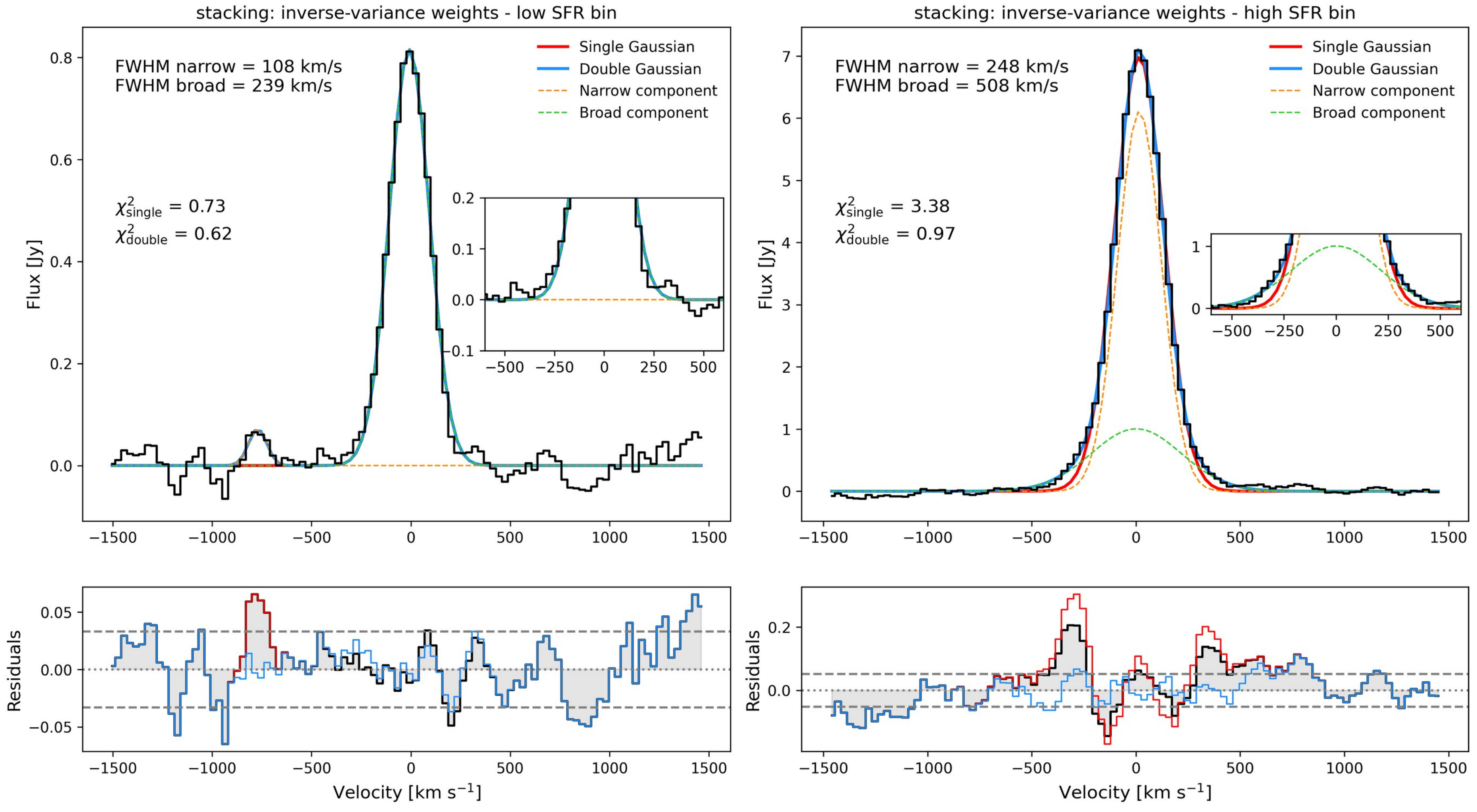
→ Applying for molecular observations to add to the few already available in the literature, to characterize the molecular phase of the ISM

→ Use our findings as input for chemical evolution models, to constraint dust and metals production/destruction in the ISM


Thank you for the attention!

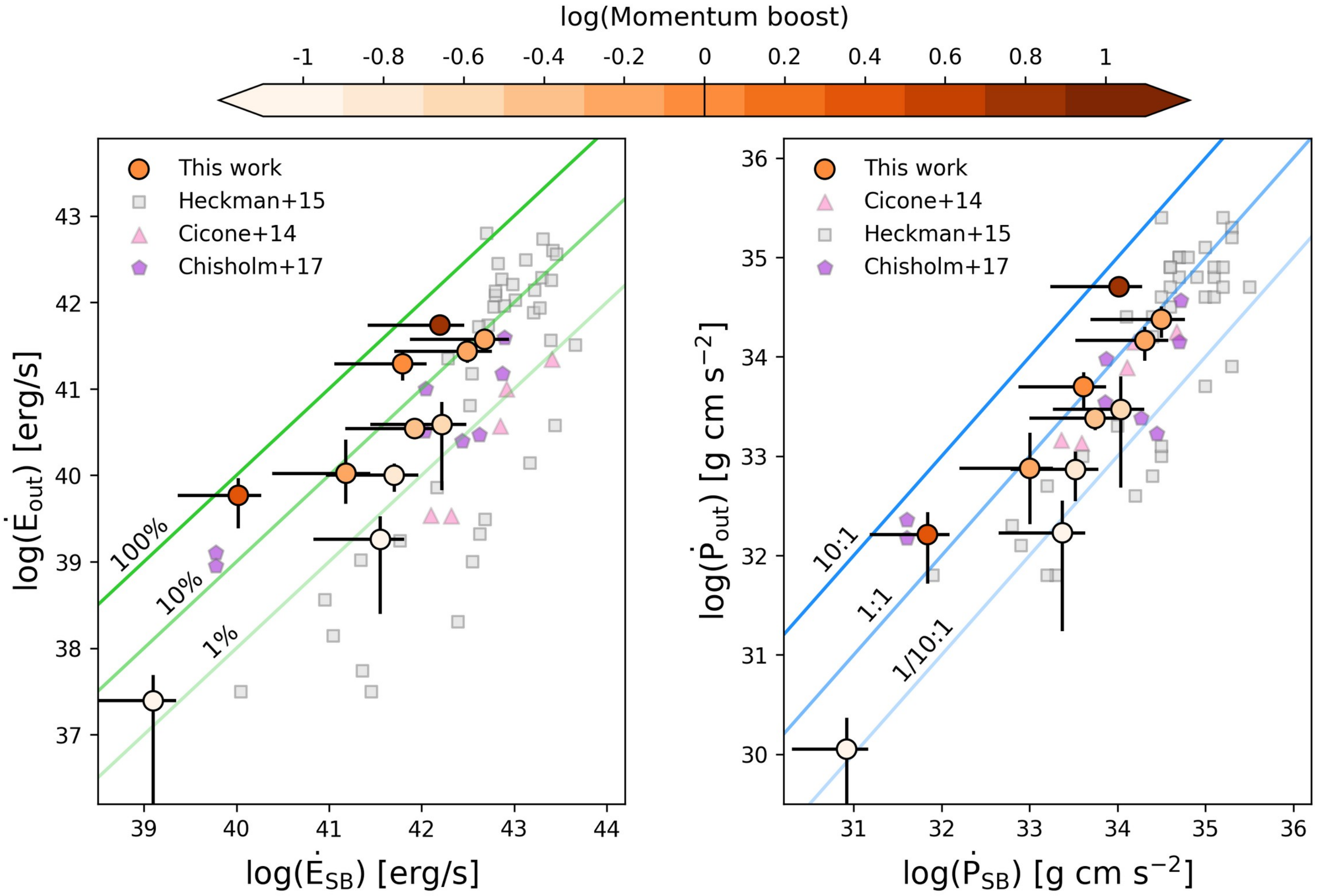
EXTRAs

Star-formation driven outflows

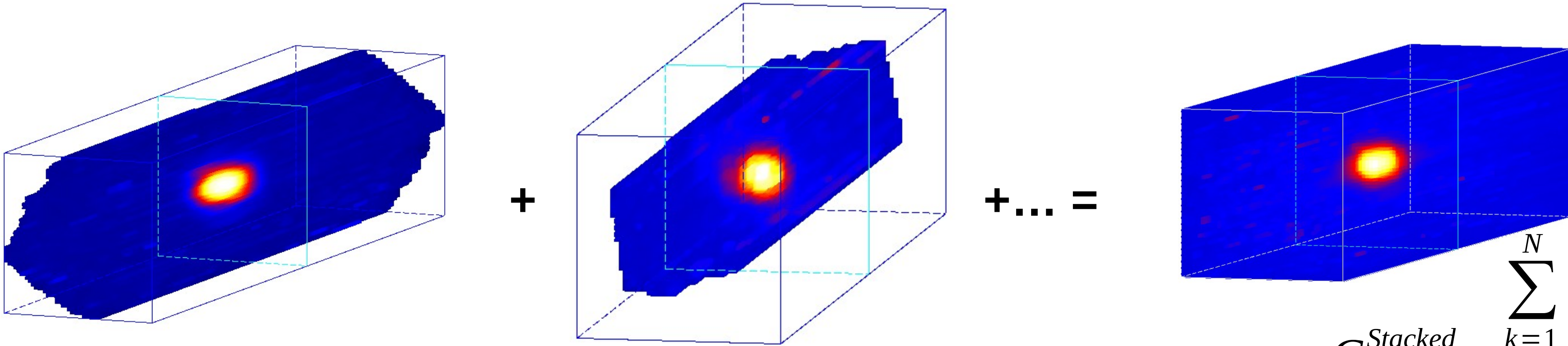


Outflow energetics

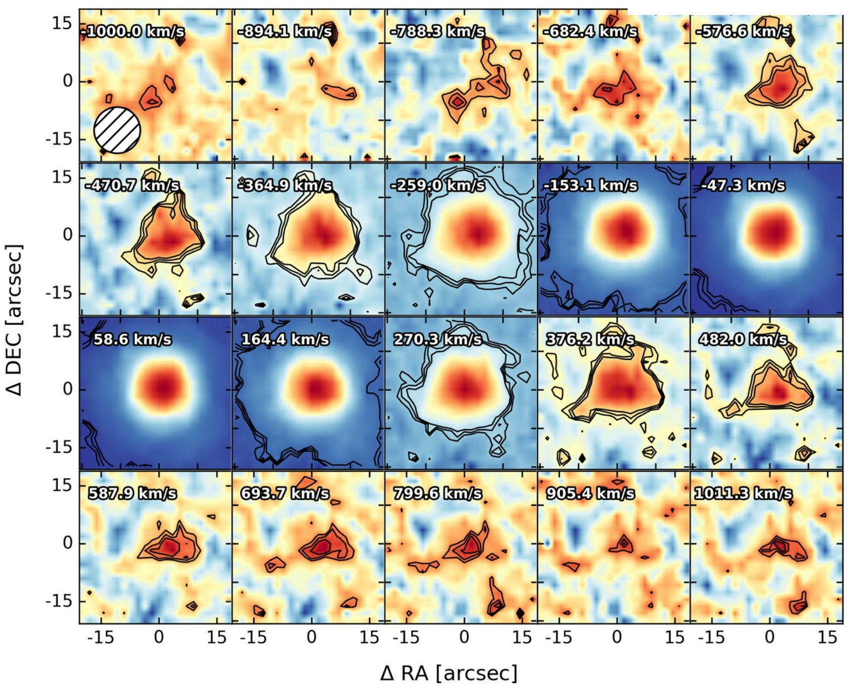
$$\begin{cases} \dot{E}_{out} = \frac{1}{2} \dot{M}_{out} v_{out}^2 \\ \dot{P}_{out} = \dot{M}_{out} v_{out} \end{cases}$$



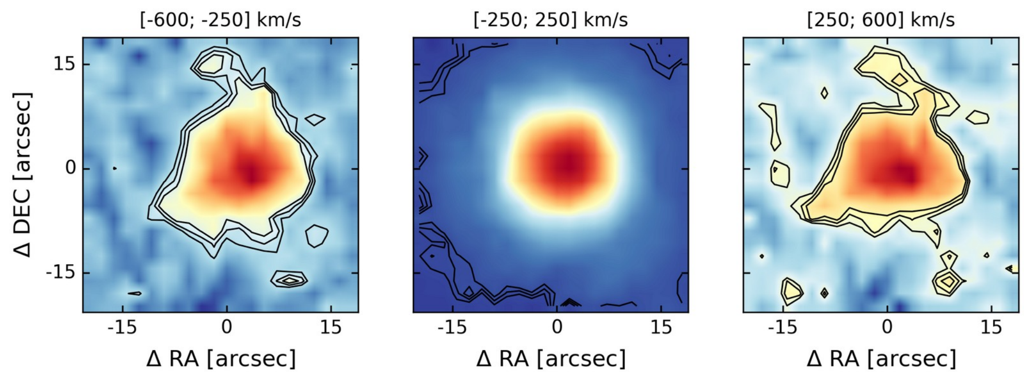
Outflow size estimation



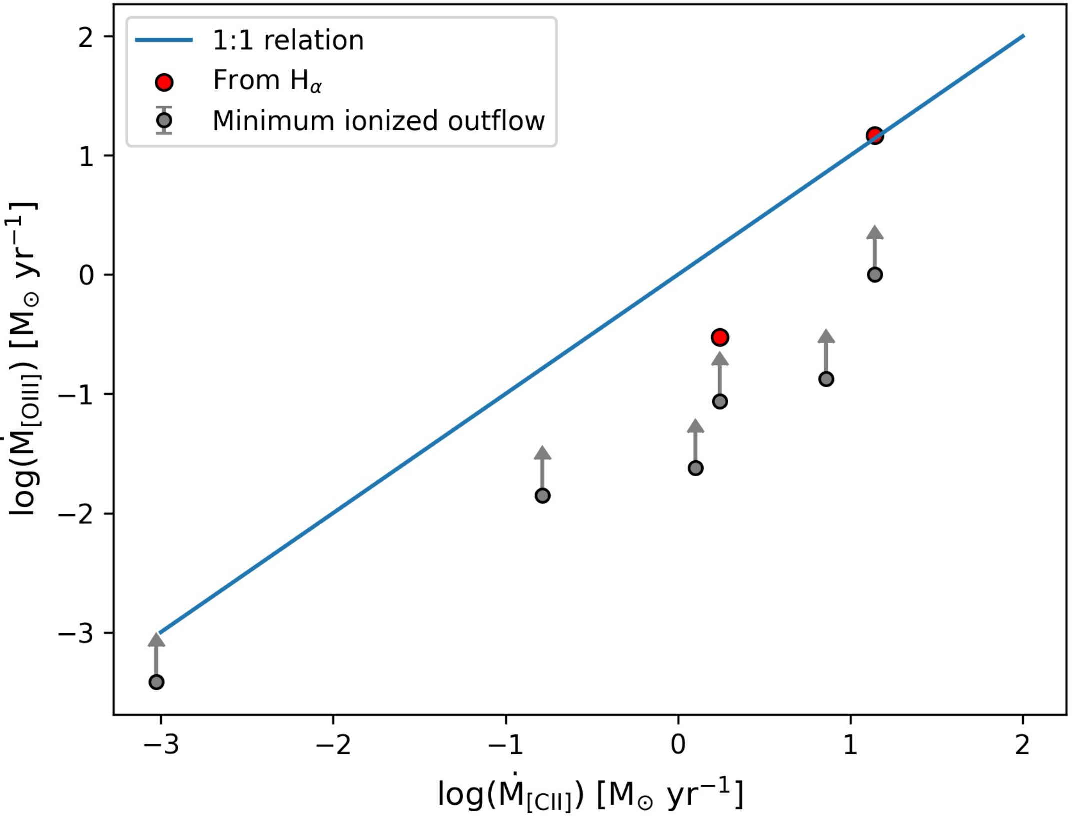
$$C^{Stacked} = \frac{\sum_{k=1}^{N} C_k \cdot w_k}{\sum_{k=1}^{N} w_k}$$



2D gaussian fit on mom-0 maps of the wings



Atomic vs ionized outflow



$$M_{min}^{H^+} = \frac{L_{[OIII]}}{\frac{g_l}{g_t} A_{ul} h \nu_{ul}} \frac{m_H}{\xi_{O^{++}}}$$

Some assumptions from the literature:

- mH = 1.6736e-27 Kg → H mass
- h = 6.626196e-27 erg/s → Planck constant
- Aul = 2.6e-5 s-1 → spontaneous emission coefficient
- νul = 3393.00624 Ghz → [OIII] rest-freq
- ξO++ = 5.9e-4 → O abundance
- gl = 3 → 2J+1
- gt = (g1/g0)exp(-ΔE/kT)
  - g0 = 1 → degenerate state in ground level
  - g1 = 3→ degenerate state in fist excitation level
  - ΔE = 163 K → energy relative to 88 μm
  - T = 1e4 → temperature of the ISM

Comparison between different SFR estimates