Chemical enrichment in local galaxies as probed by star-formation driven outflows

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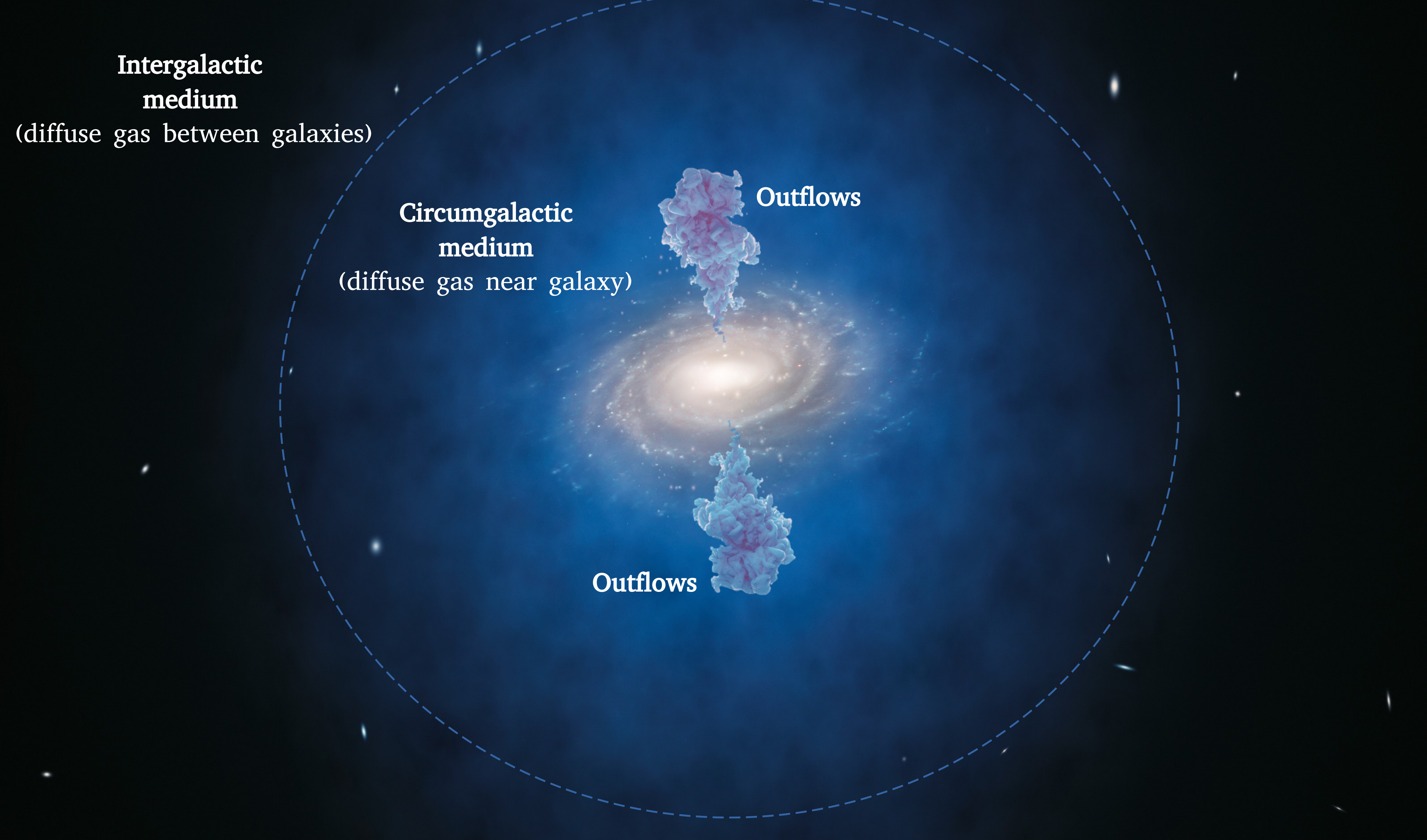
Outline

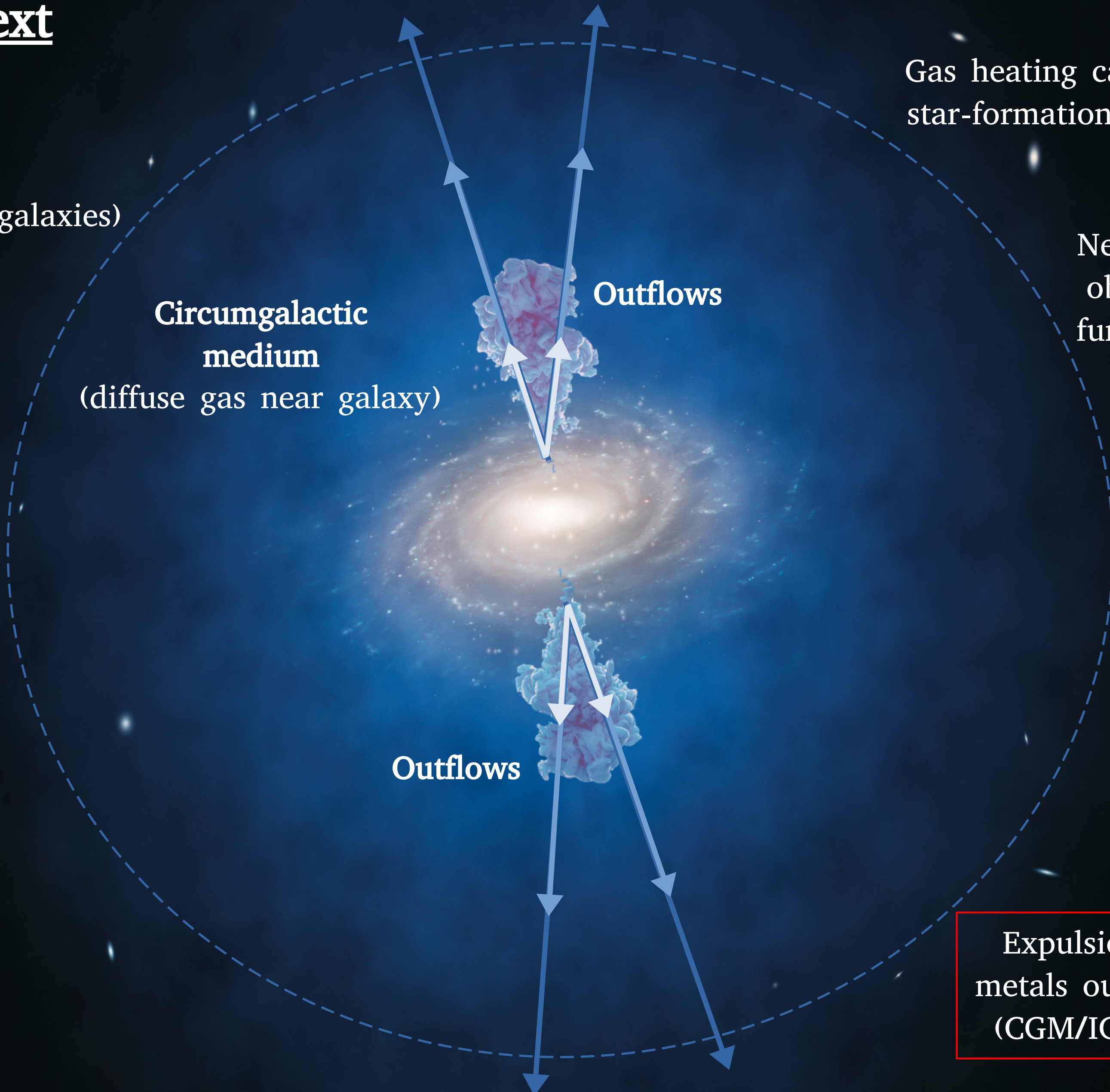
- General Context
  - Why galactic outflows are important in this context?
- The Dwarf Galaxy Survey (DGS): an overview
- Methodology
- Results:
  - Outflow efficiency
  - CGM/IGM enrichment
- Conclusions and future prospects

General context



General context

Intergalactic medium
(diffuse gas between galaxies)



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

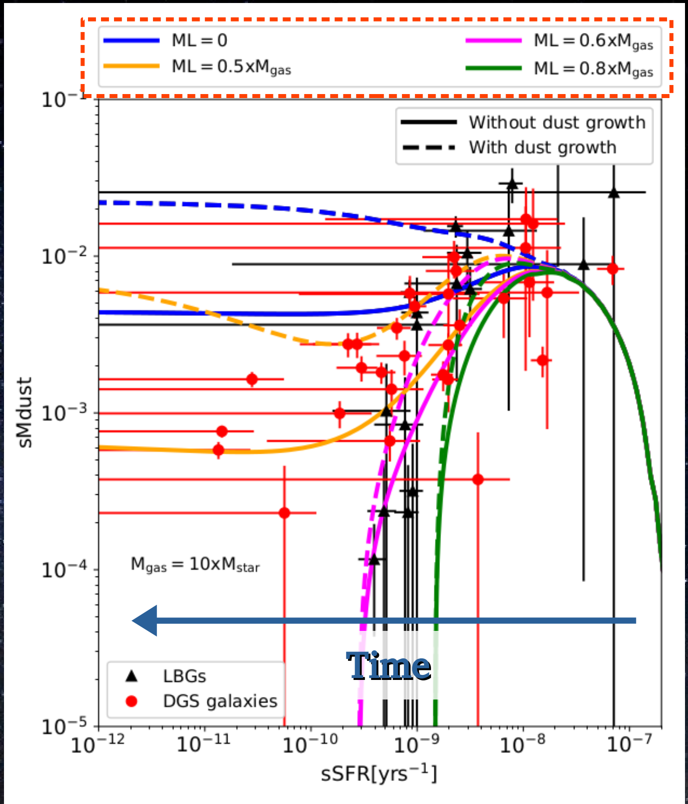
- Gas does not leave the galaxy
- CGM enrichment
- IGM enrichment

General context

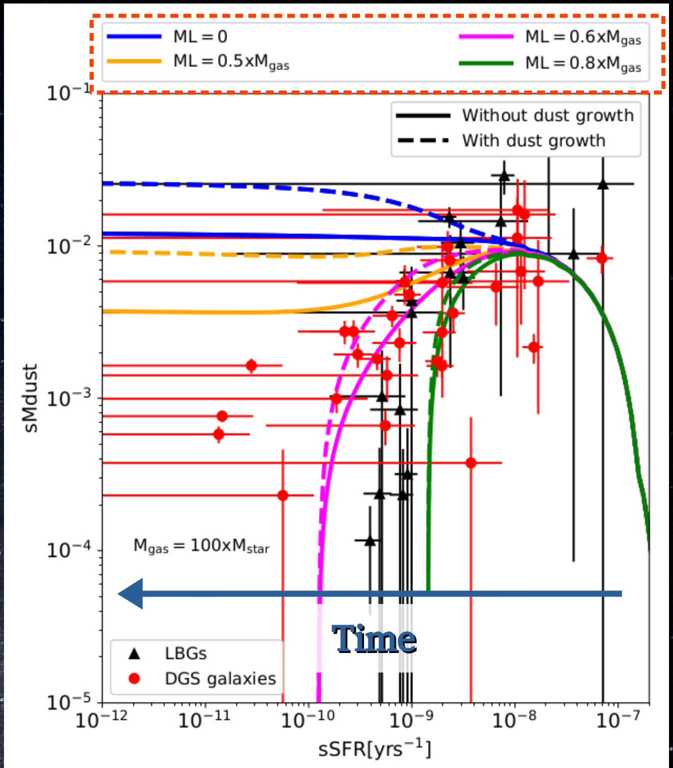
Efficient star-formation driven outflows are needed by models to reproduce the observations:

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

Nanni et al. 2020



Nanni et al. 2020



$$\left.\begin{array}{l} \dfrac{dM_{gas}}{dt} \\[2ex] \dfrac{dM_{metal}}{dt} \\[2ex] \dfrac{dM_{dust}}{dt} \end{array}\right\} \propto \eta$$

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:

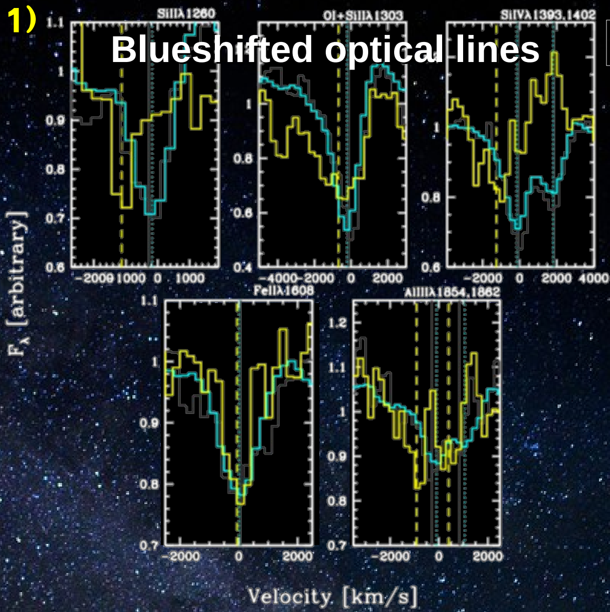
1) Rest-frame UV/optical blue-shifted absorption lines (e.g., SiII), especially at z > 1

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

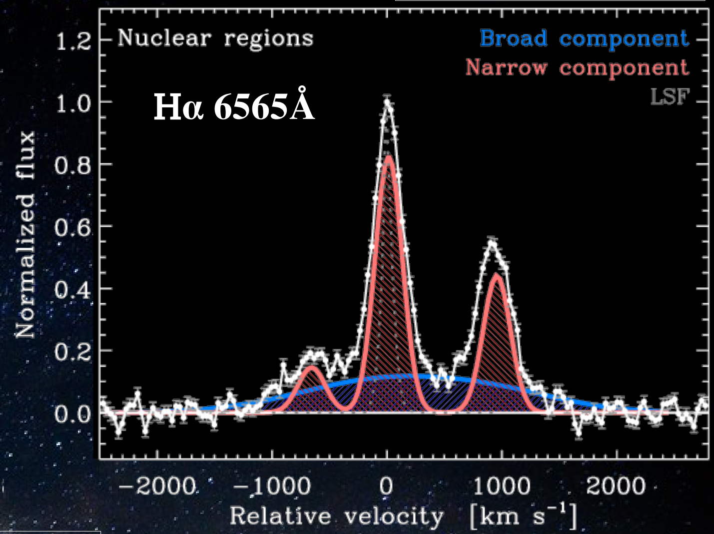
1)



Talia+17

2)

Förster-Schreiber+14



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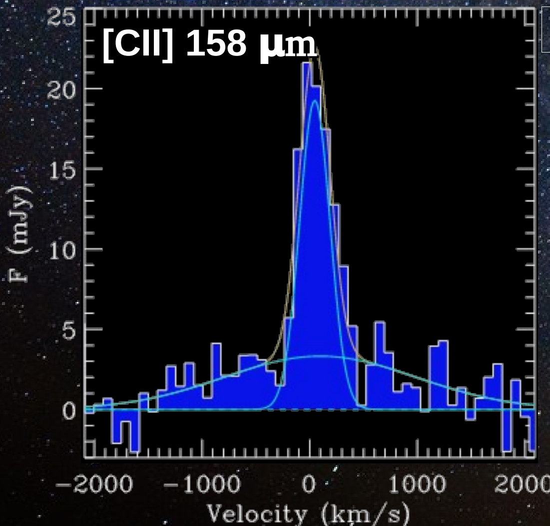
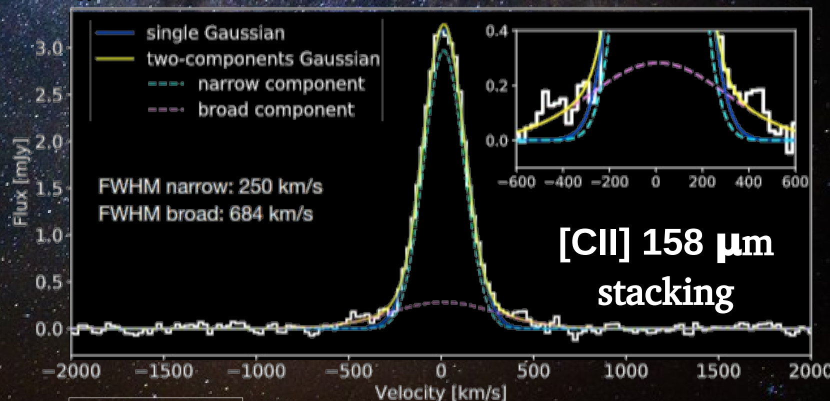


Maiolino+12

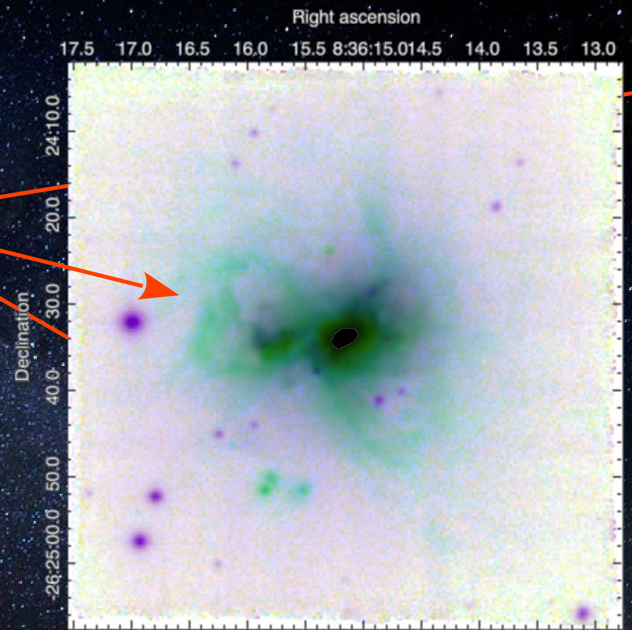
4)



Ginolfi+20

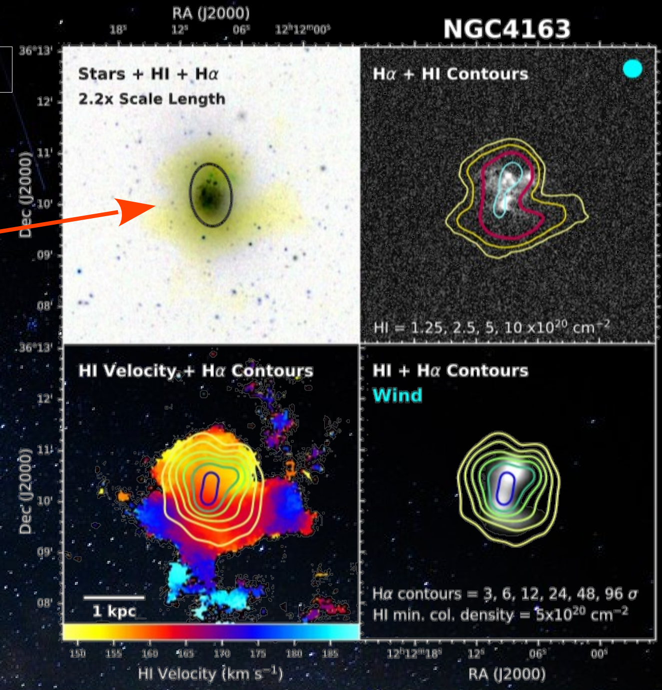
General context

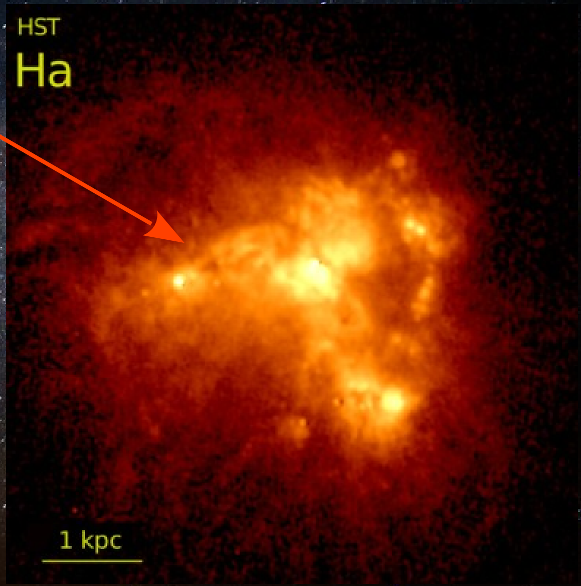
Nearby sources offer the best opportunity to study in detail galactic outflows and their impact on galaxy evolution.



Cresci+17

McQuinn+19





Menacho+19

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

The Dwarf Galaxy Survey (DGS): an overview

Madden+13

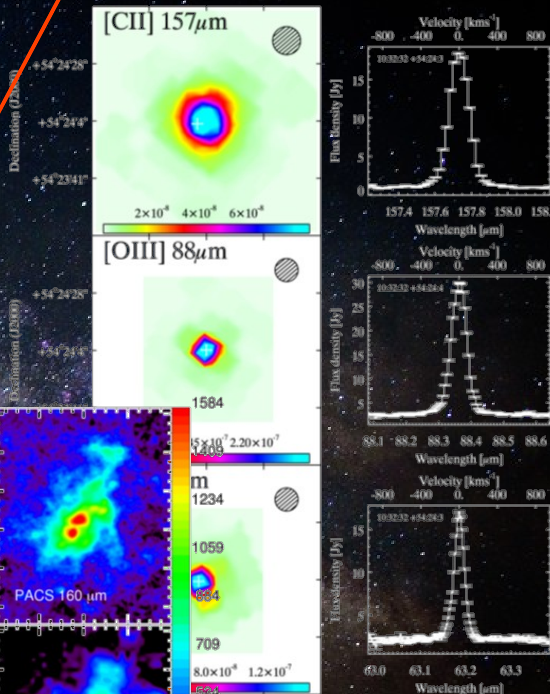
FIR *Herschel*/PACS 70 µm

The DGS team

Herschel

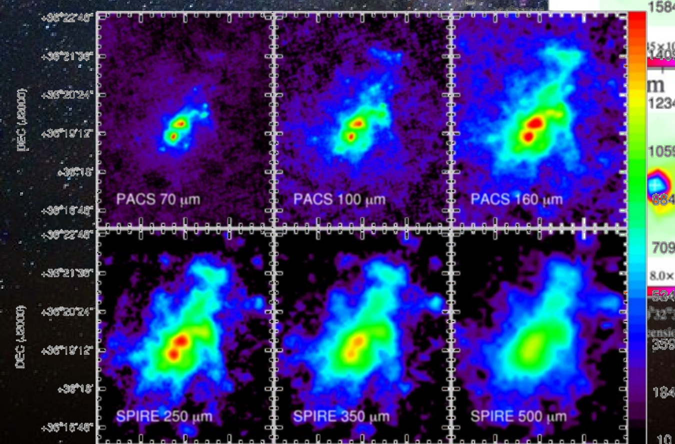
PACS/SPIRE

Spectroscopy



Cormier+15

Photometry



Madden+13

The Dwarf Galaxy Survey (DGS): an overview

Madden+13

DGS Sample properties:

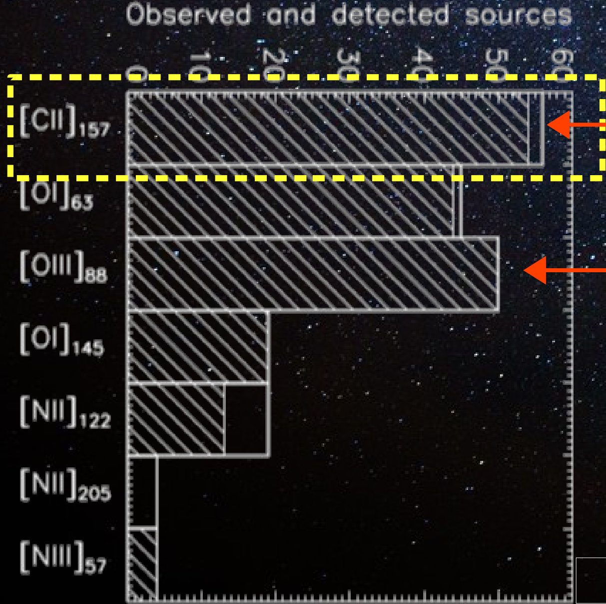
- 48 dwarf galaxies
- $12 + \log(O/H) \leq 8.4$
- D < 200 Mpc
- $\log(M_*/M_\odot) \sim 6 - 10$

11 extended objects

37 compact objects

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

= **29 galaxies**



Cormier+15

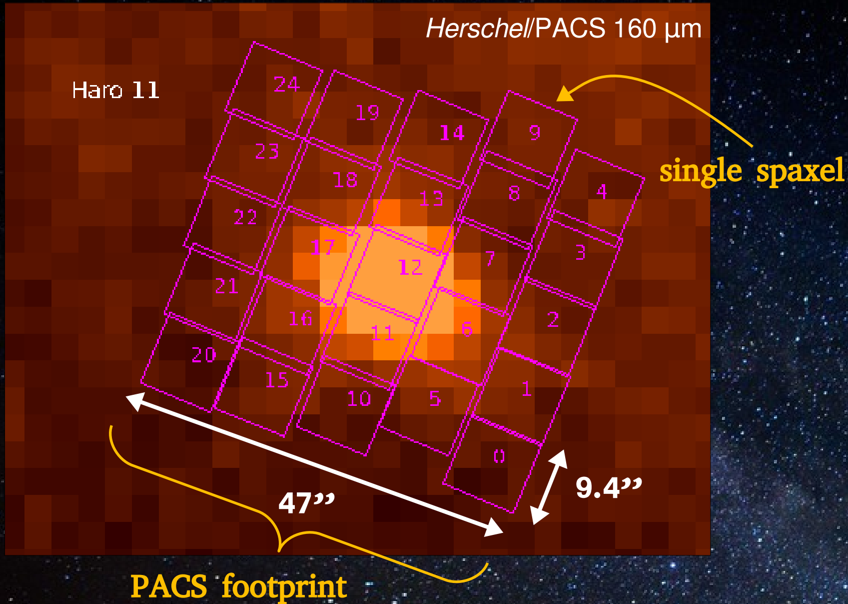
[CII] 158 µm rest-frame available for the whole sample

Tracer of atomic gas

[OIII] 88 µm rest-frame available for ~1/3 of the sample

Tracer of ionized gas

The method: data



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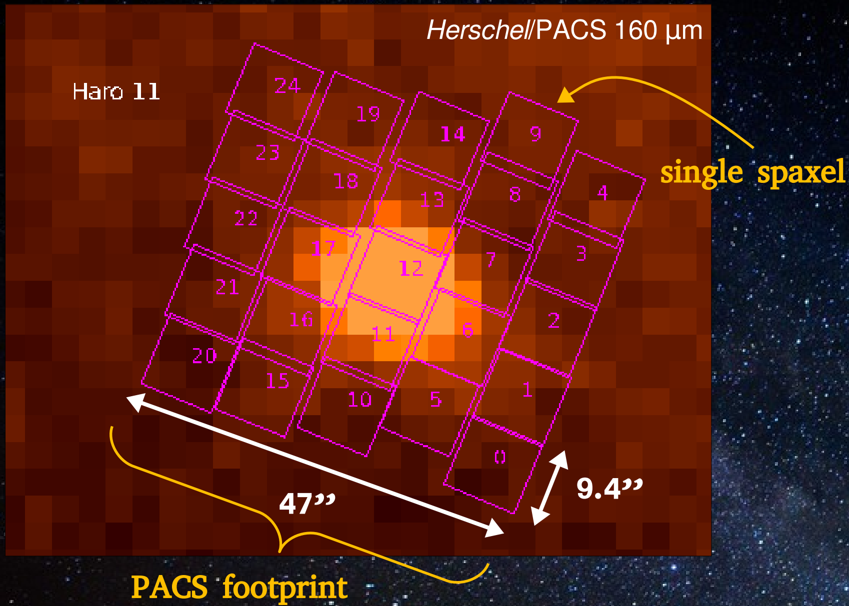

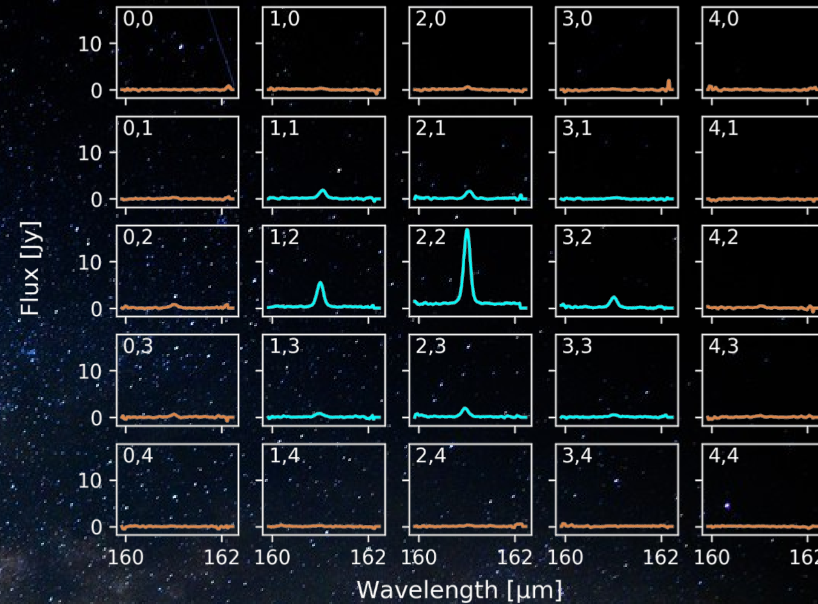

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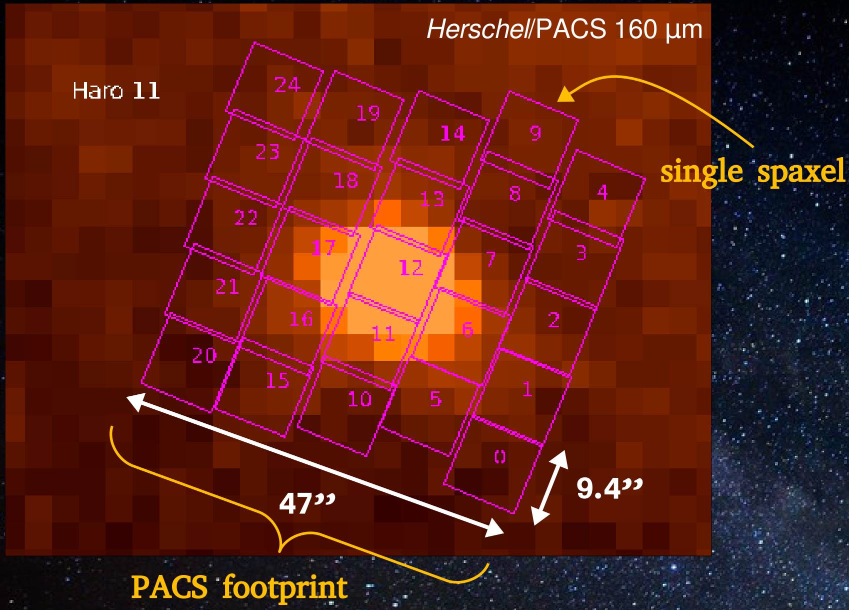

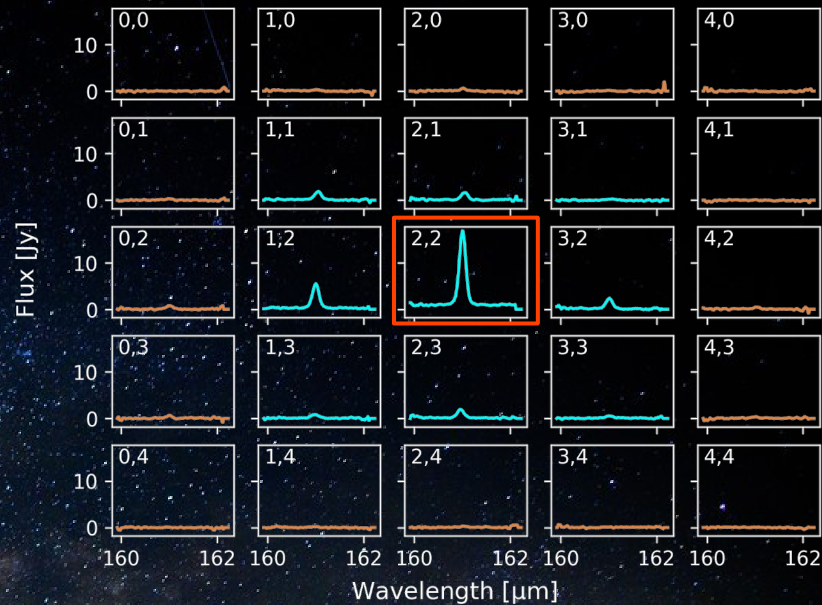

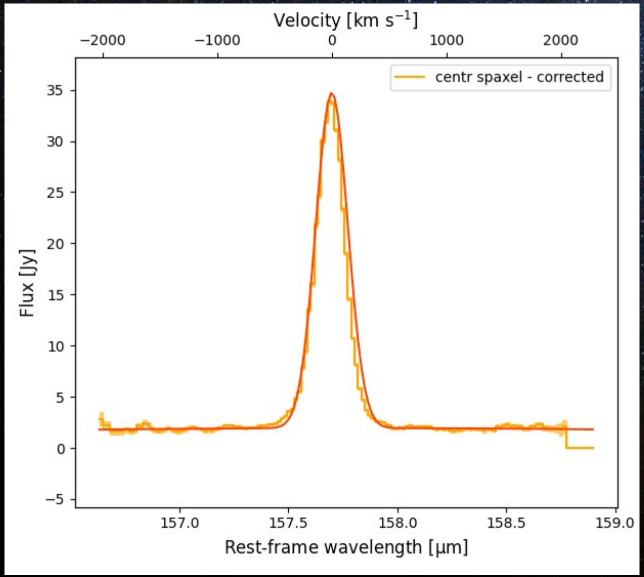

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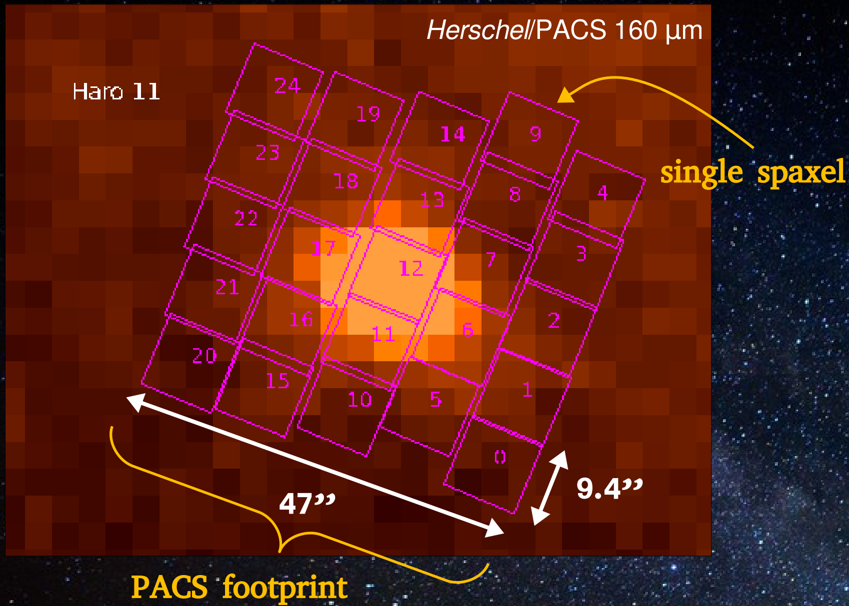

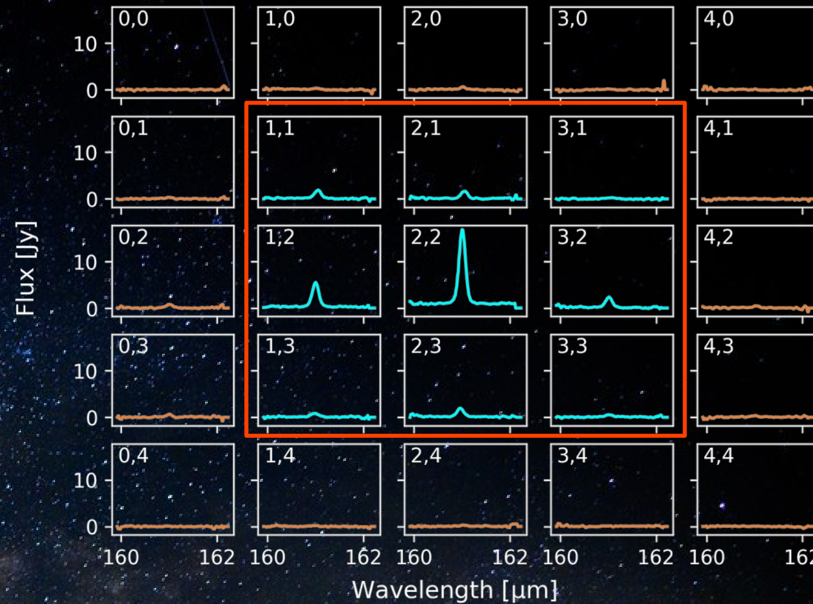

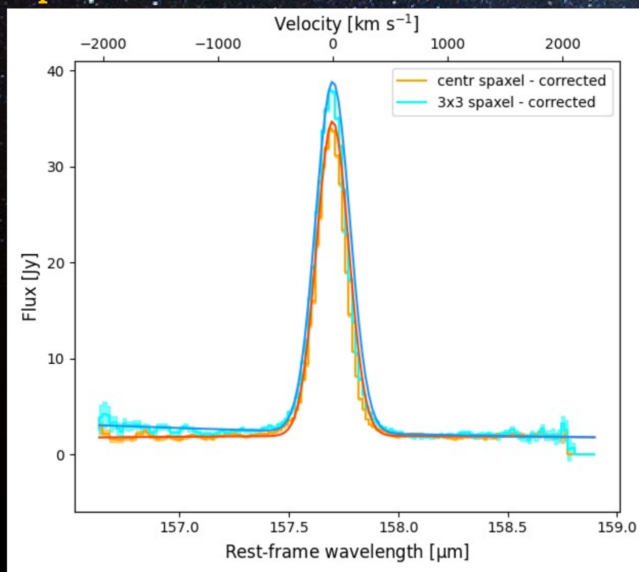

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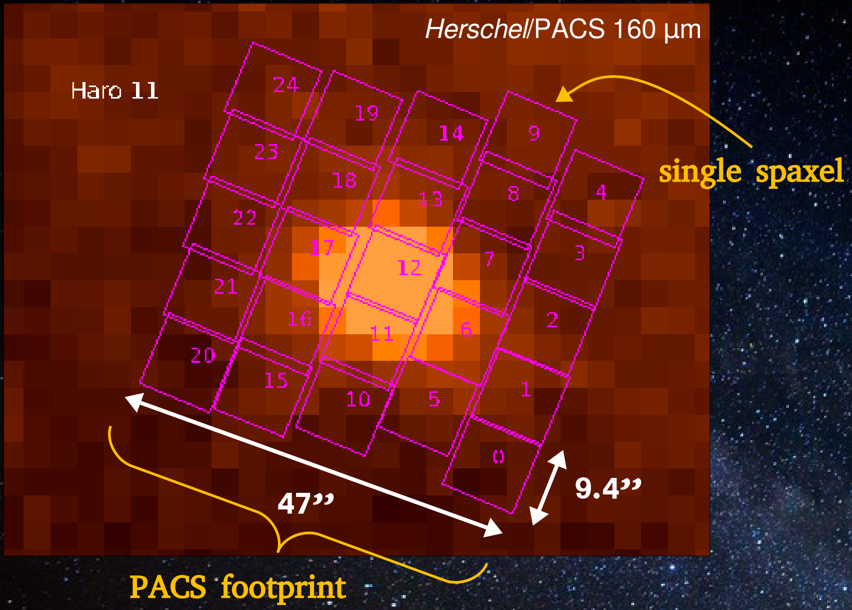

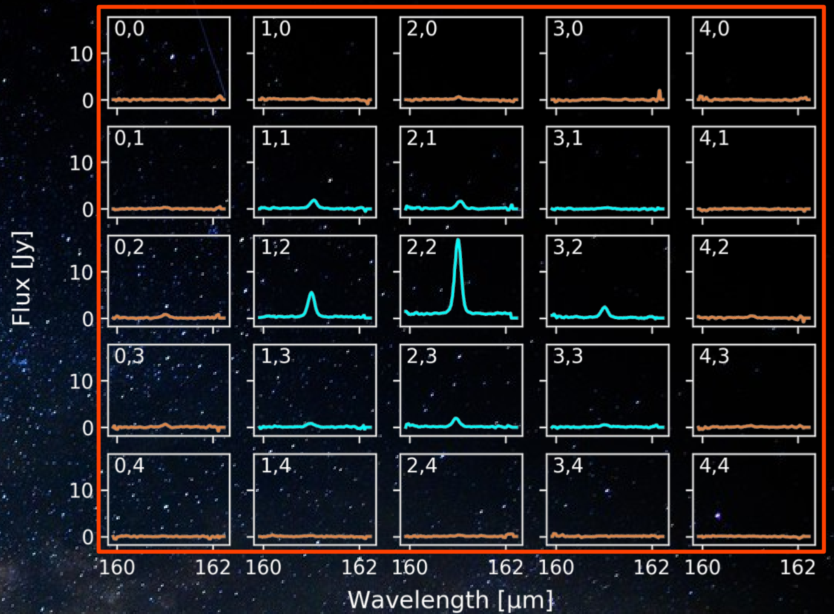

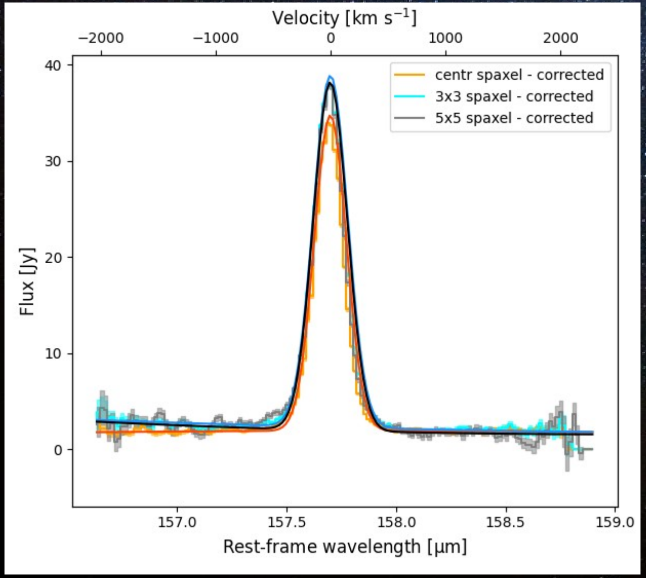

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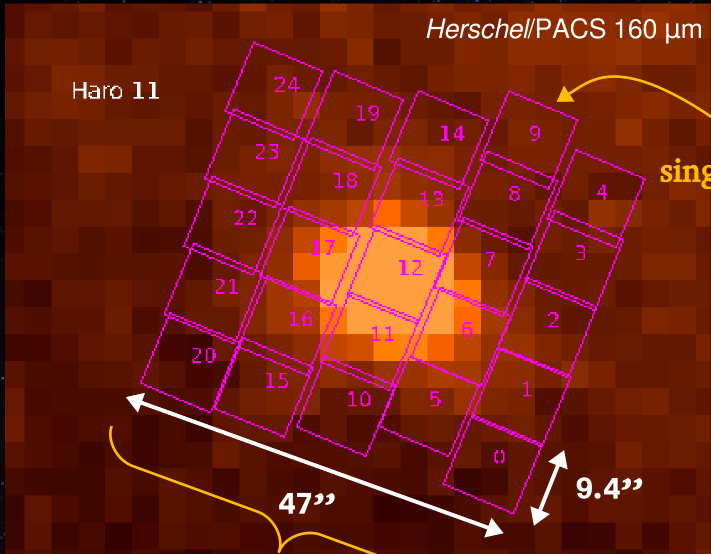
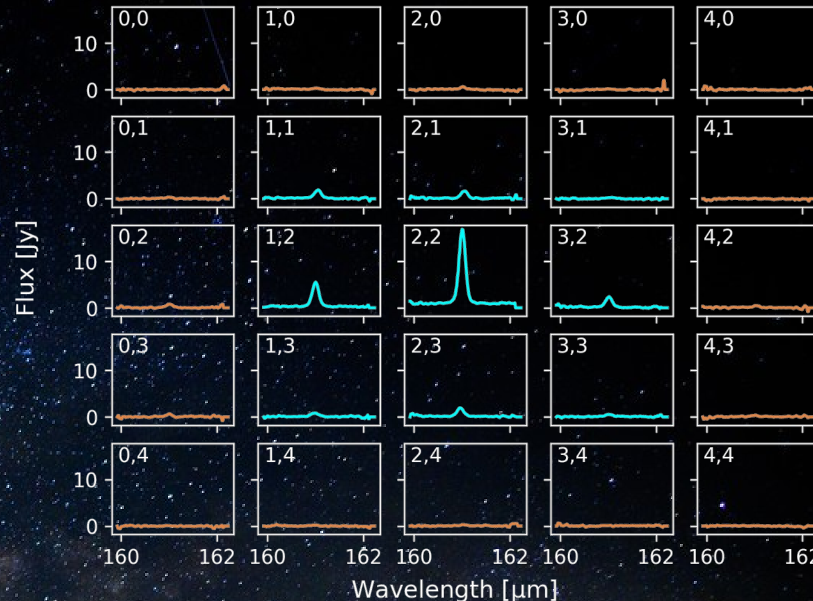
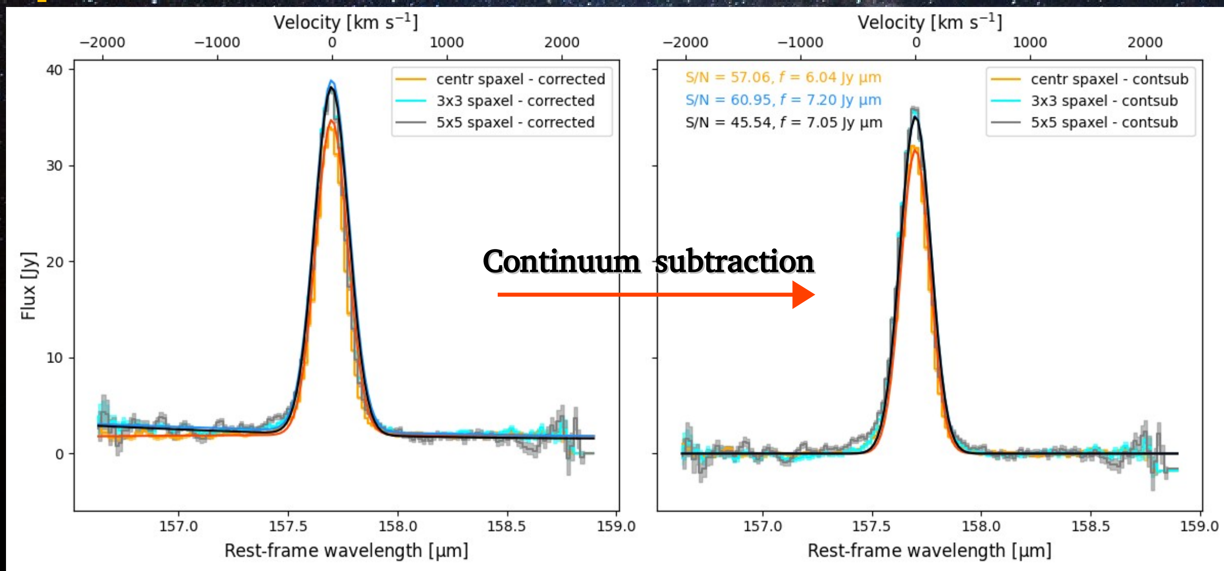


single spaxel

PACS footprint

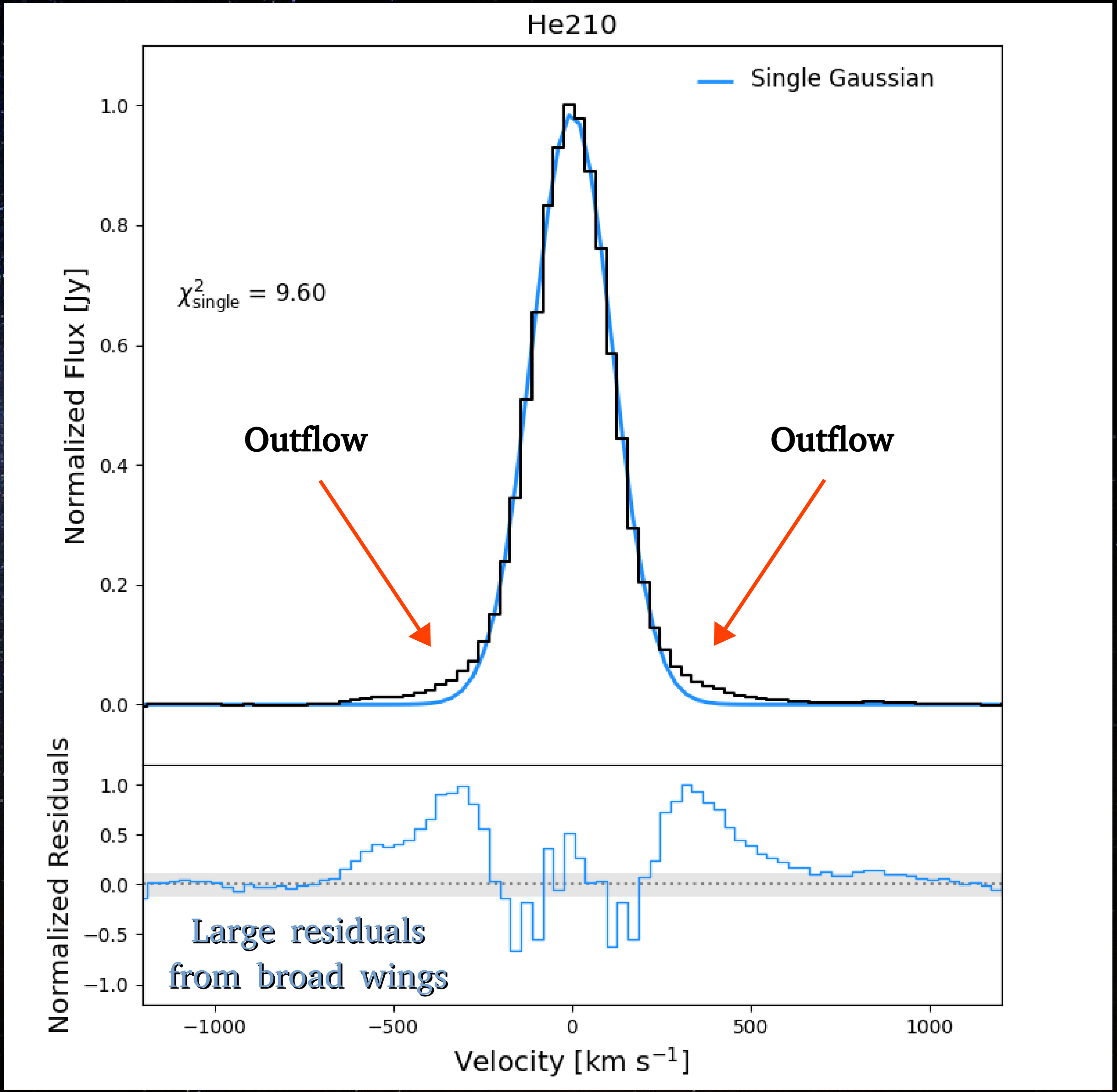




3x3 spectrum

Larger flux
Best S/N

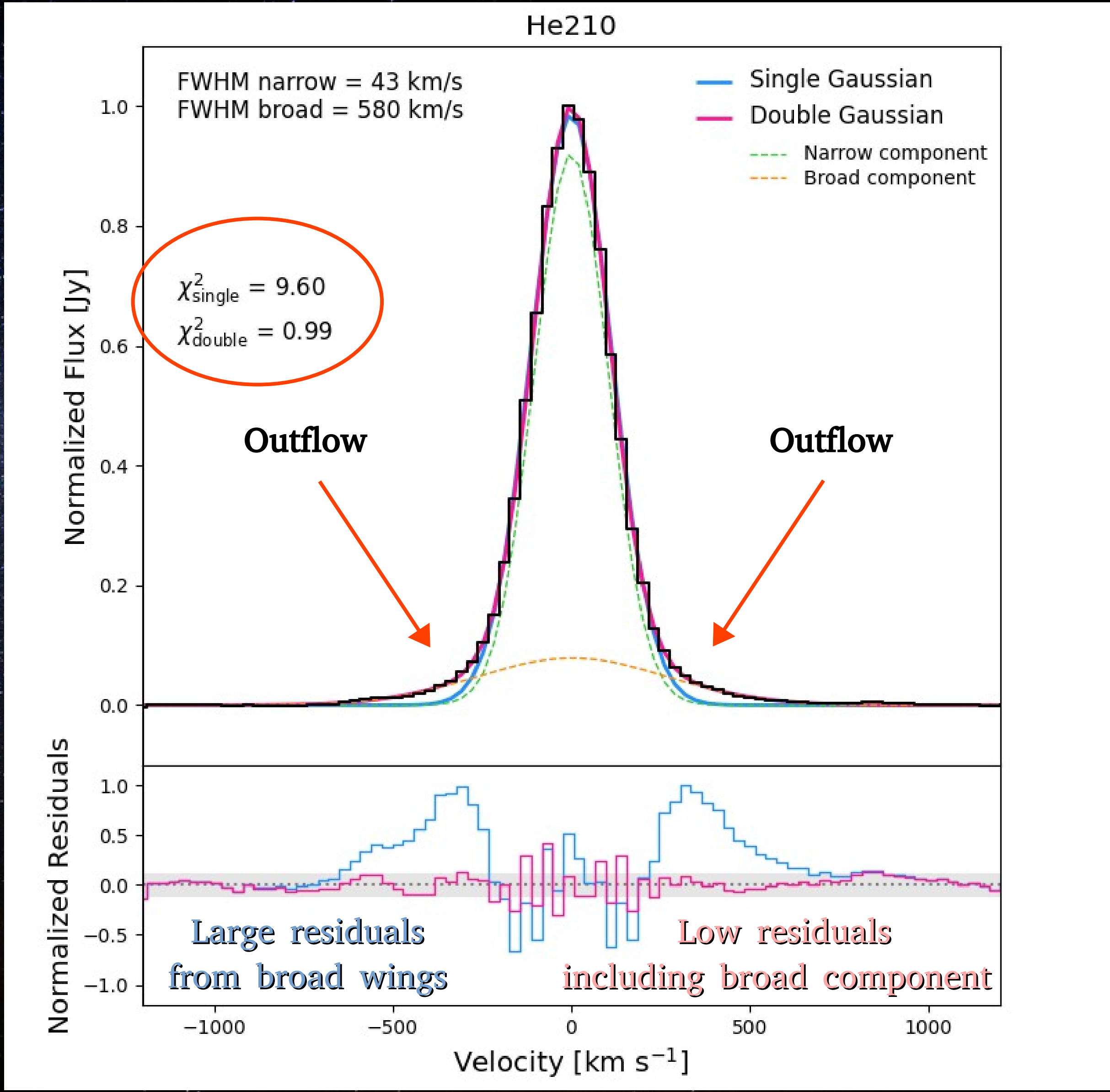
The method: individual detections



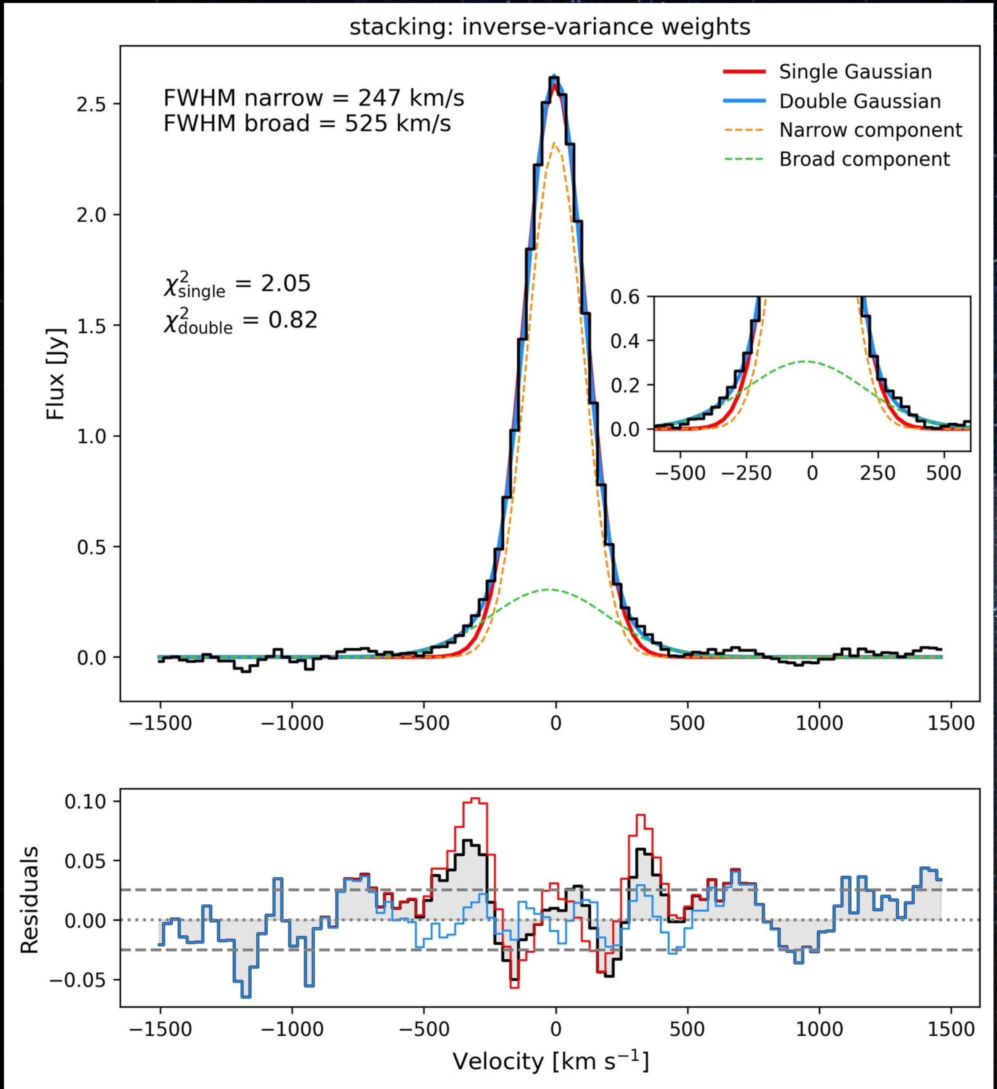
The method: individual detections

10 galaxies

with individual detection of atomic outflow



The method: spectral stacking



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

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

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

From $L_{[CII]}$

(Rupke+05)

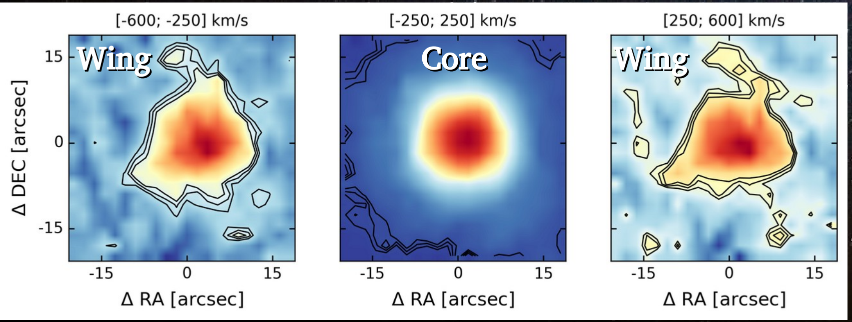
$$v_{out} = \frac{FWHM_{broad}}{2} + |v_{broad} - v_{narrow}|$$

$$M_{out} = 0.77 \left(\frac{0.7\, L_{[CII]}}{L_{\odot}} \right) \times \left(\frac{1.4 \times 10^{-4}}{X_{C^{+}}} \right) \times \frac{1 + 2e^{-91\,K/T} + n_{crit}/n}{2\,e^{-91\,K/T}}$$

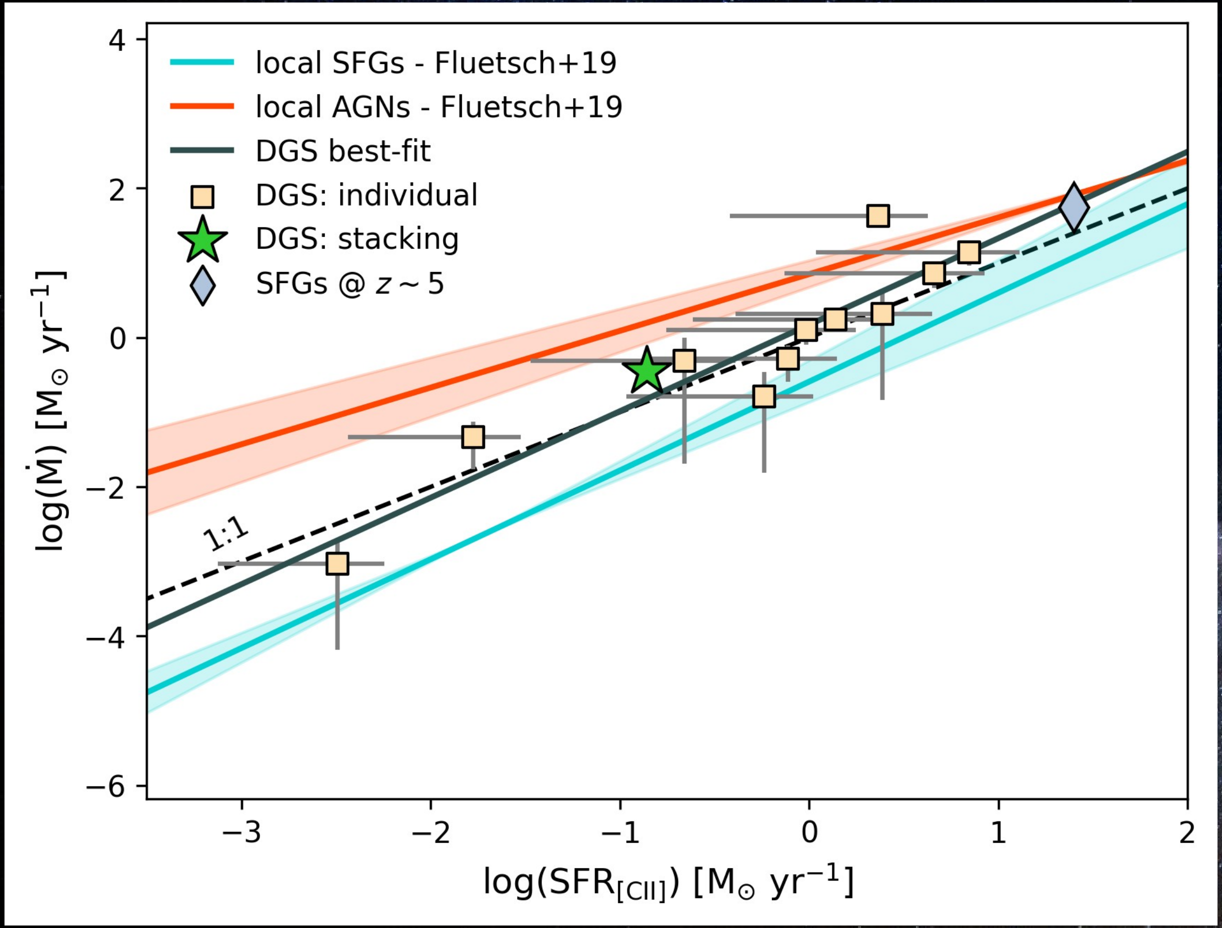
(Hailey-Dunsheath+10)

- 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

$$R_{out} = \frac{a}{2}\sqrt{\frac{b}{a}}$$



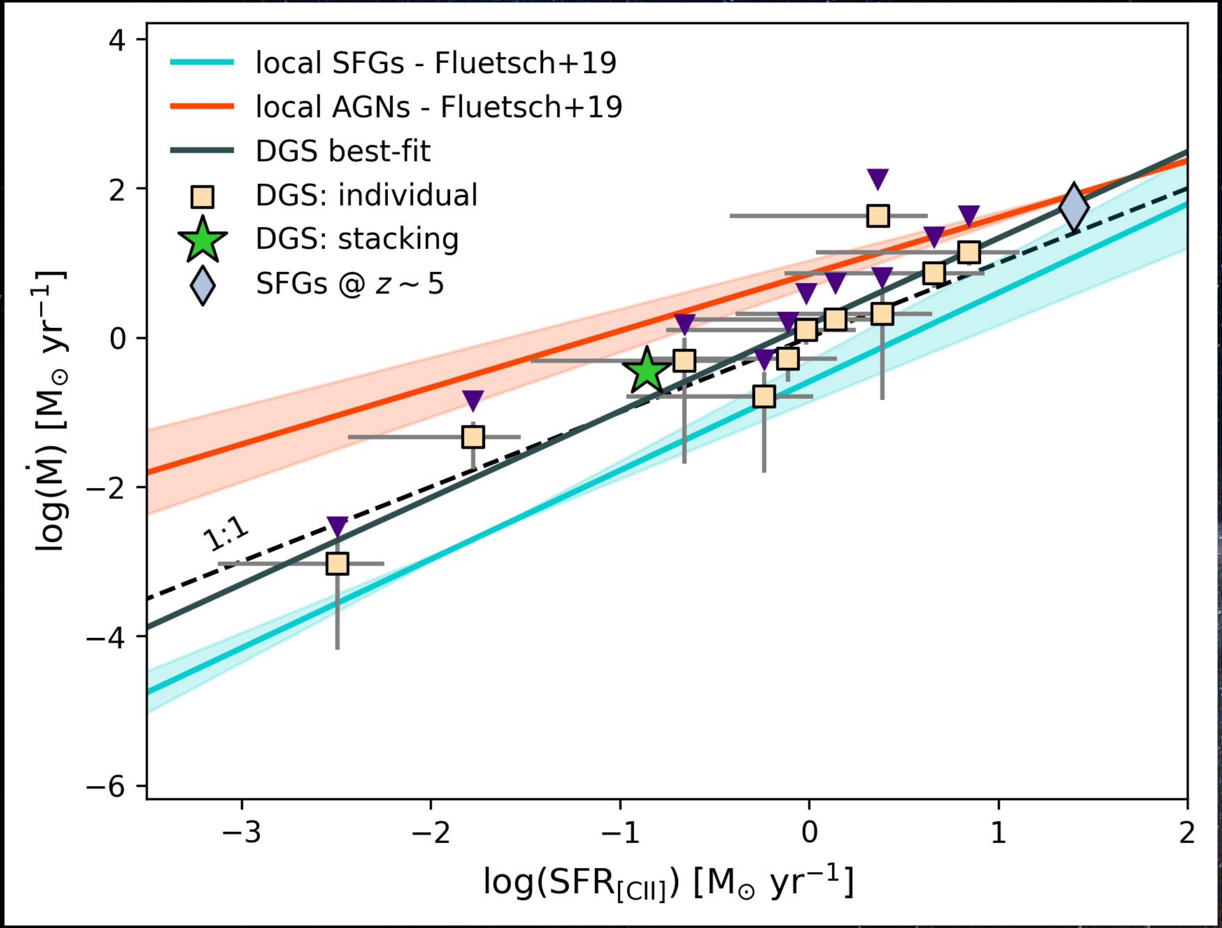
Outflow efficiency: the mass-loading factor



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

Lower than predicted by chemical evolution models..

Outflow efficiency: the mass-loading factor



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

Lower than predicted by chemical evolution models..

Accounting for the multi-phase ISM

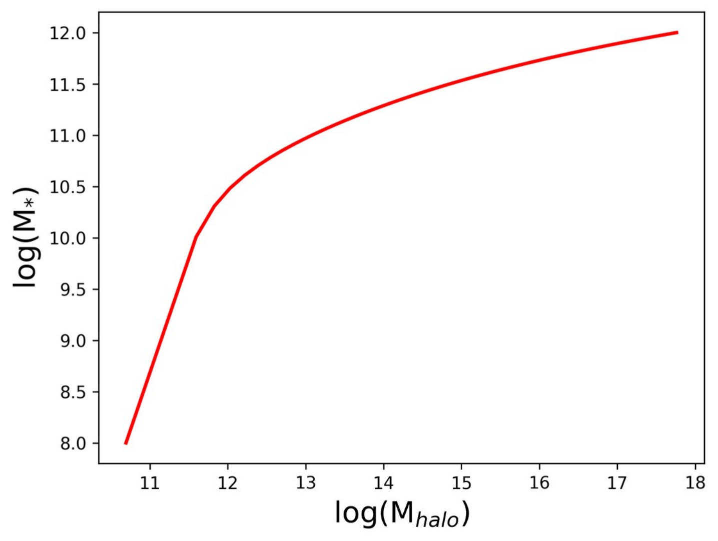
$$\eta_{TOT} \sim 3 \times \eta_{[CII]}$$

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)

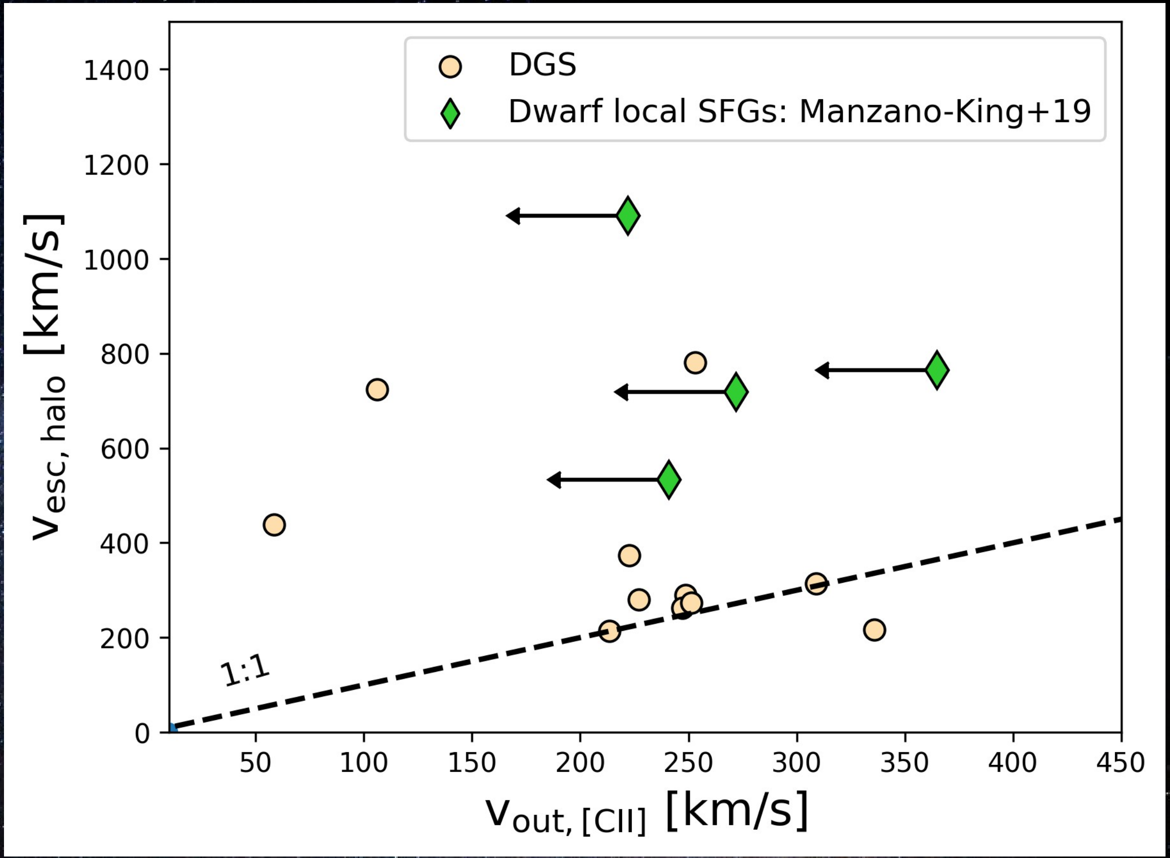
$$r_s = r_{halo}/c$$ (Navarro, Frenk & White+95)

$$\log(c) = 0.76 - 0.1 \log(M_{halo})$$ (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 ($\eta \sim 1$), outflows are able to enrich the IGM around dwarf galaxies



Conclusions and future prospects

1) Local dwarf galaxies are characterized by **ubiquitous galactic outflows**

2) 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

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

4) **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

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Work in progress

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

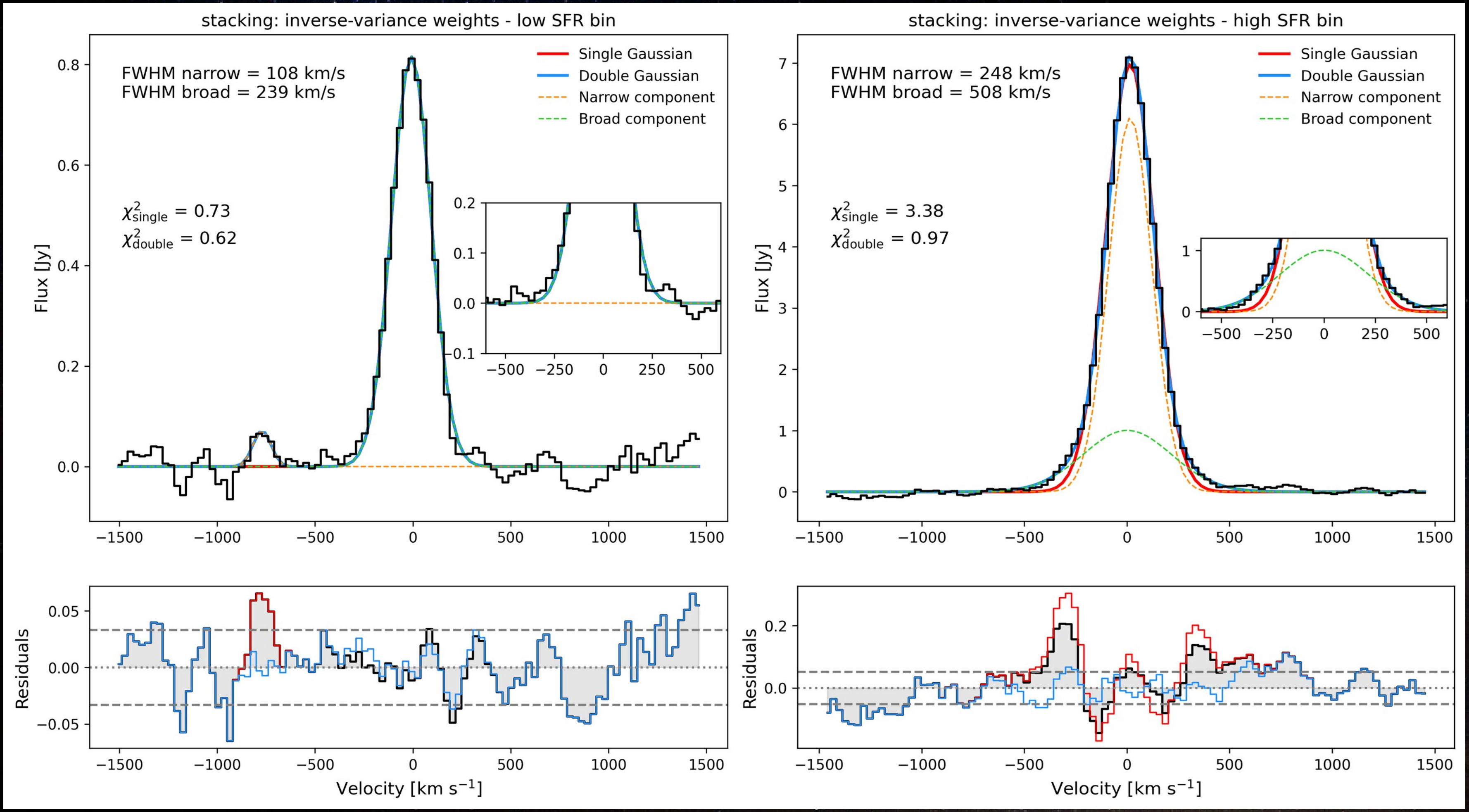
→ Applying for molecular observations to add to the few already available in the literature, to characterize the **molecular phase** of the ISM

→ 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



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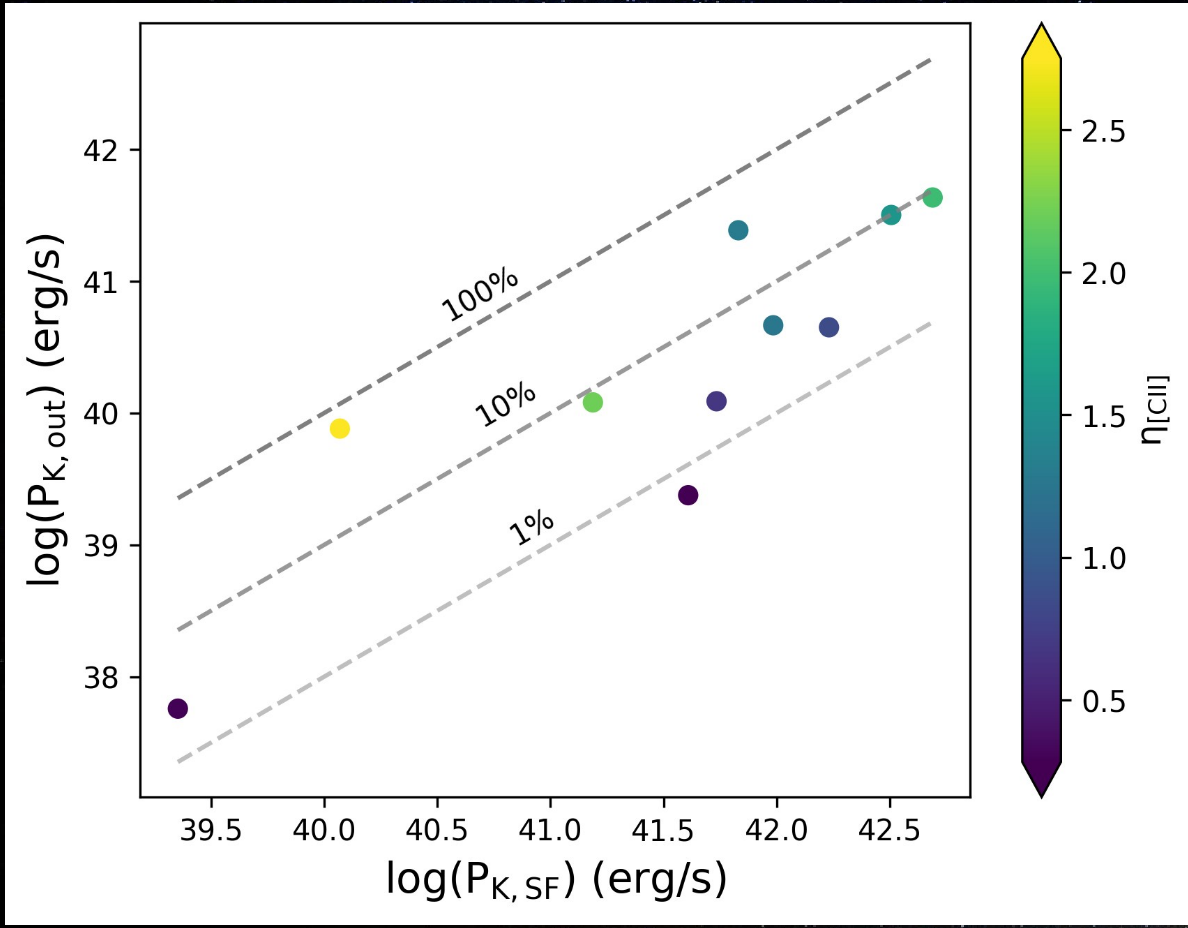
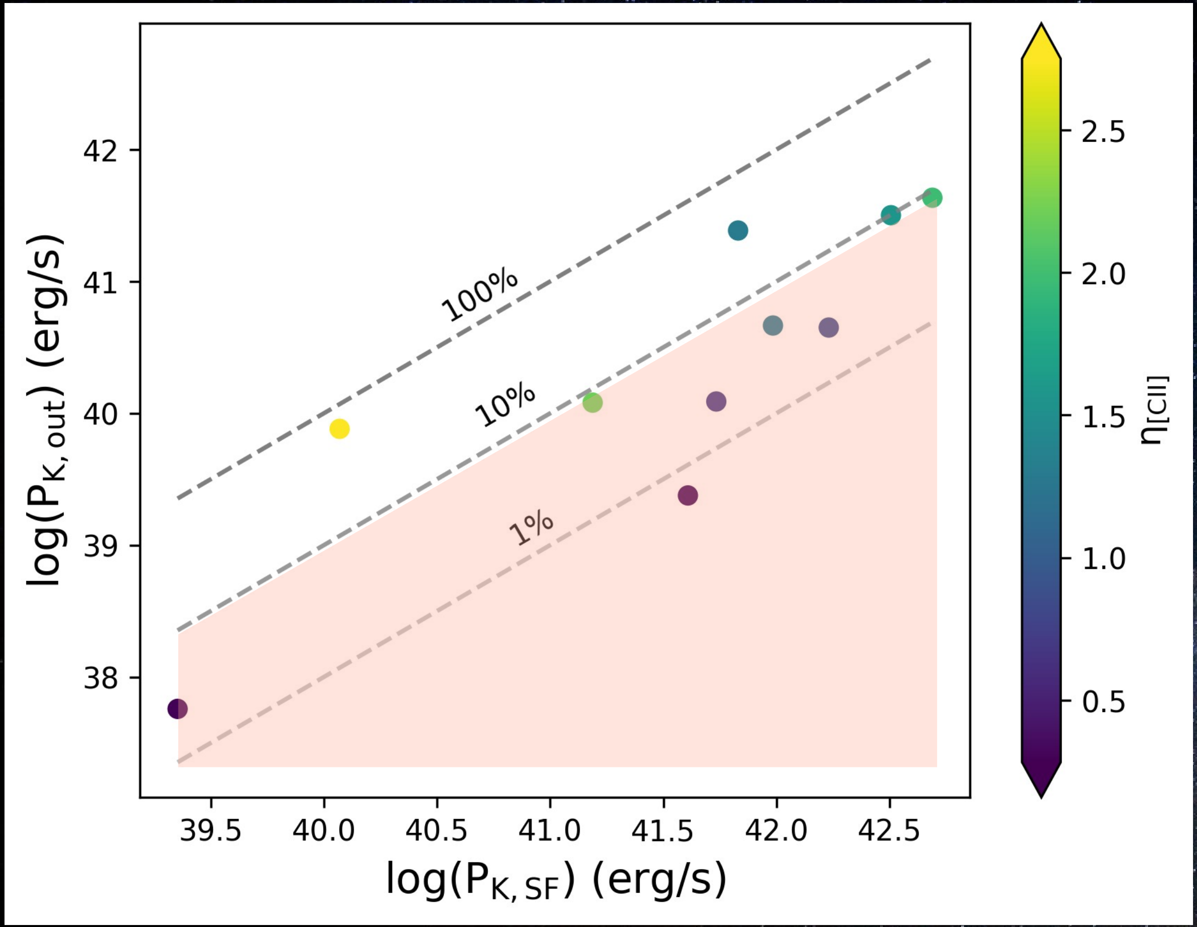


$$P_{K,out} = \frac{1}{2}\dot{M}_{out} v_{out}^2$$

$$P_{K,SF} = 7 \times 10^{41} SFR$$

(Veilleux, Cecil & Bland-Hawthorn+05)

Star-formation driven outflows



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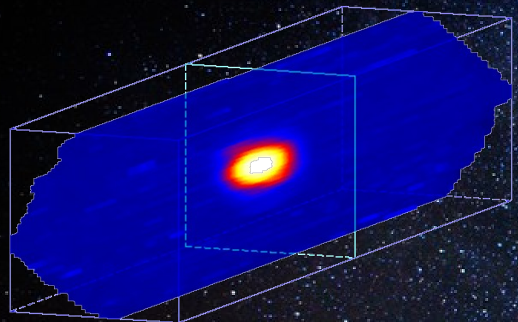
(Veilleux, Cecil & Bland-Hawthorn+05)

The kinetic power of most sources can be explained by SNe assuming a coupling efficiency below **10%**

Outflow size estimation



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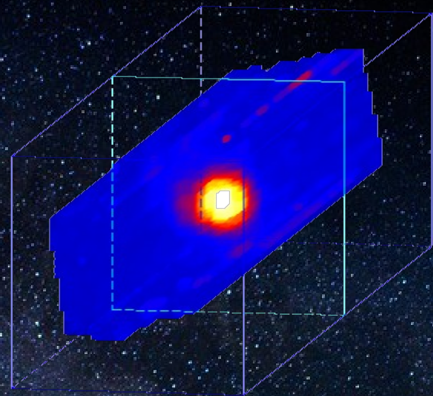
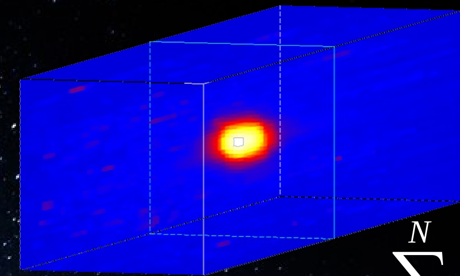
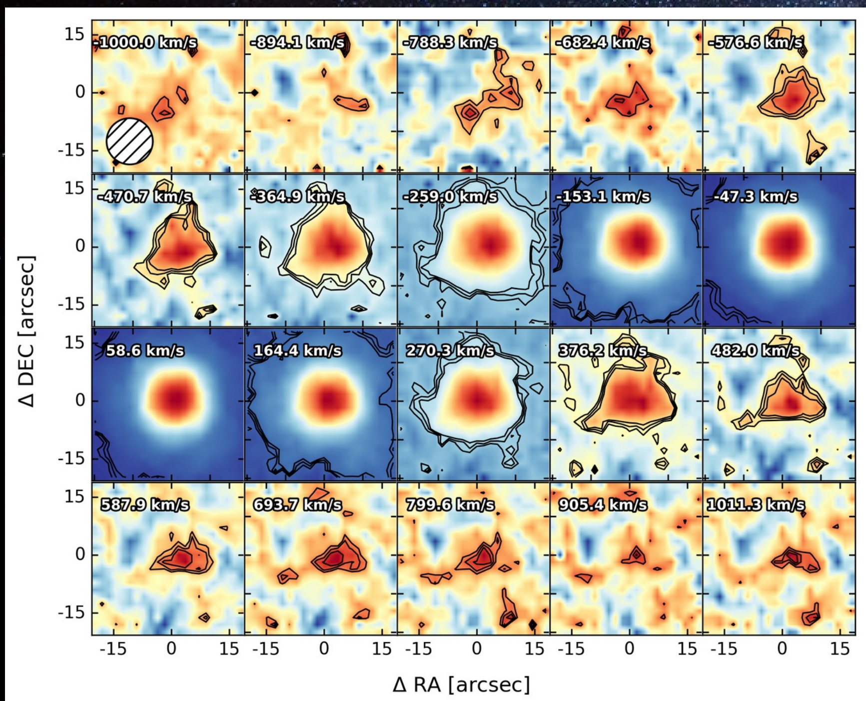


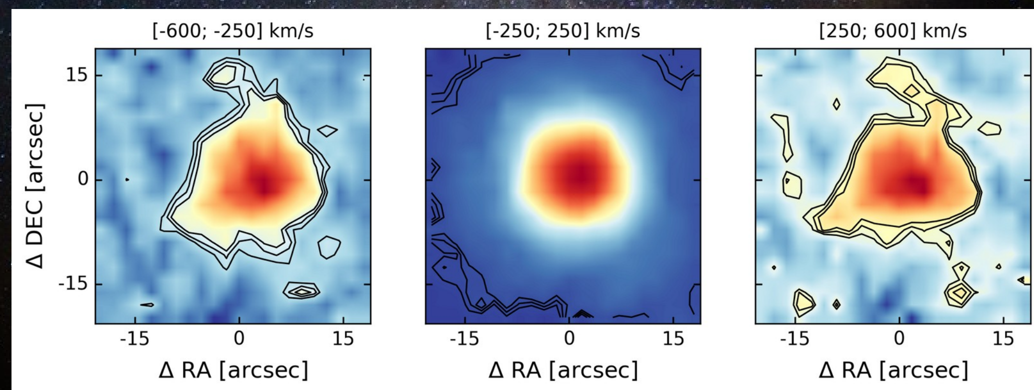
+... =



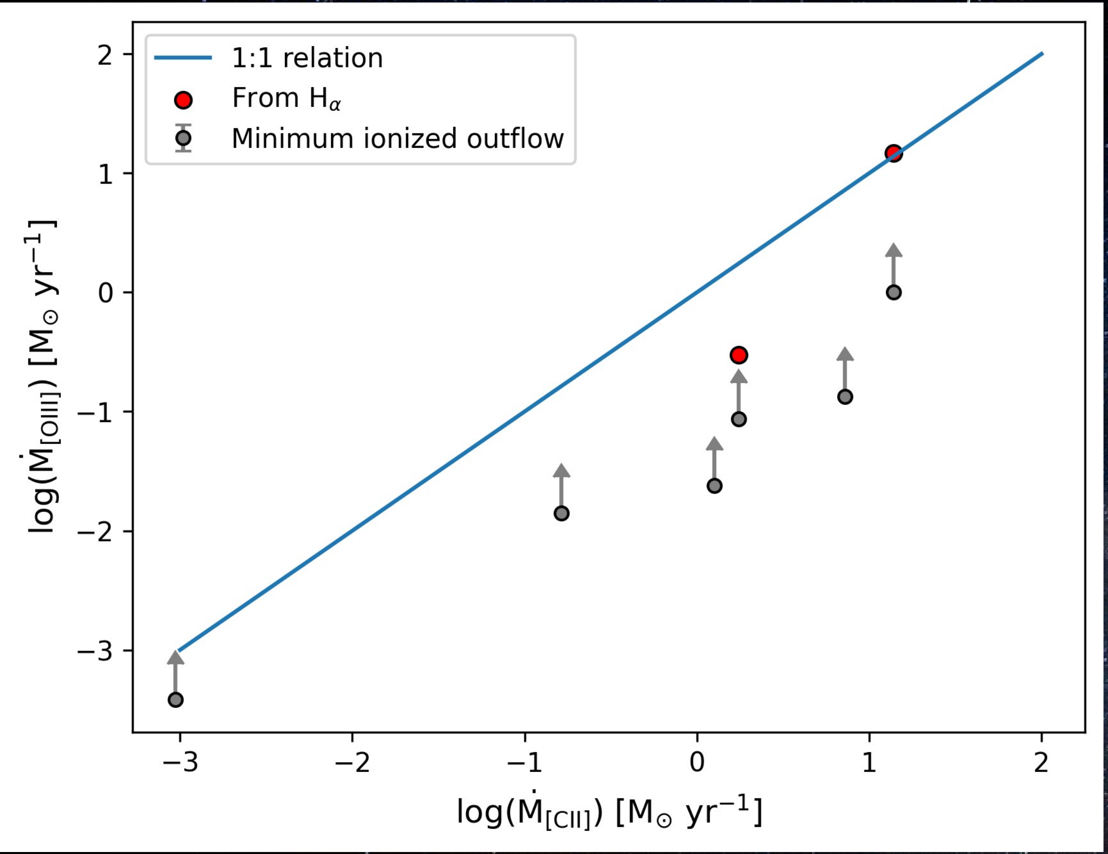
$$C^{Stacked} = \frac{\sum_{k=1}^{N} C_k \cdot w_k}{\sum_{k=1}^{N} w_k}$$



2D gaussian fit on mom-0 maps including the outflow



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 estimators