The impact of galactic outflows on the baryon cycle of local dwarf galaxies

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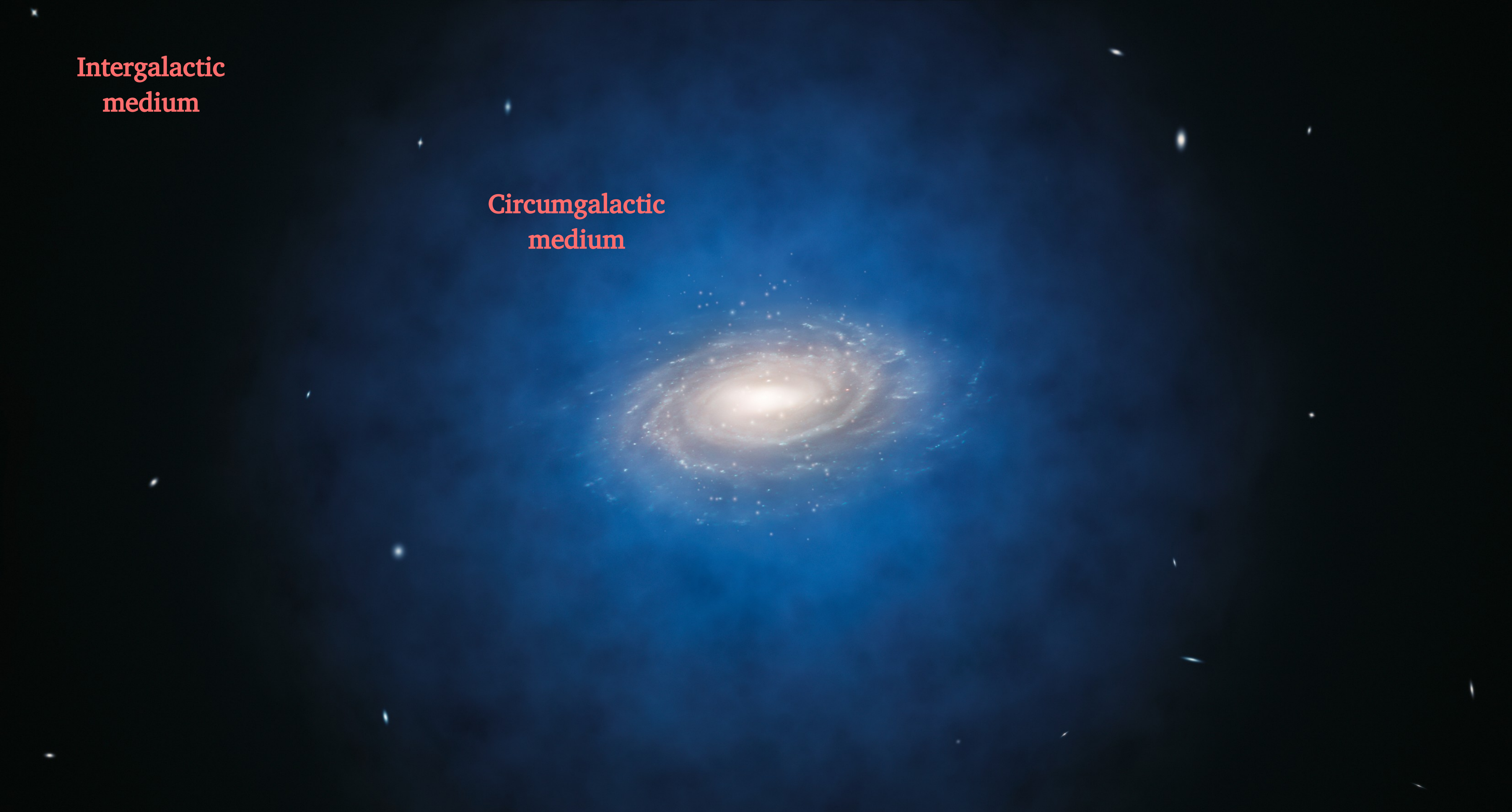
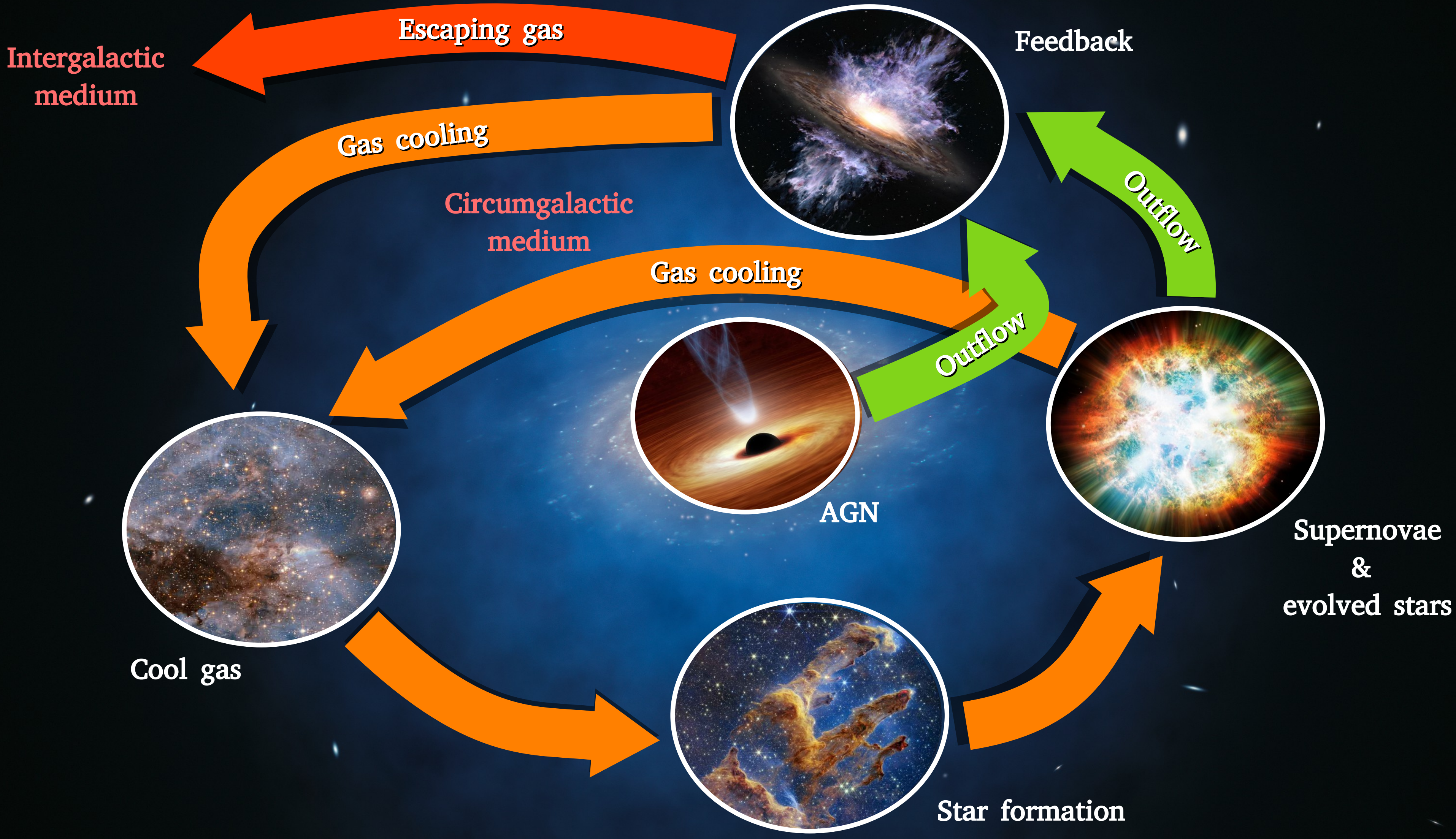

Intergalactic medium
Circumgalactic medium



Intergalactic medium

Escaping gas

Feedback

Gas cooling

Circumgalactic medium

Gas cooling

Outflow

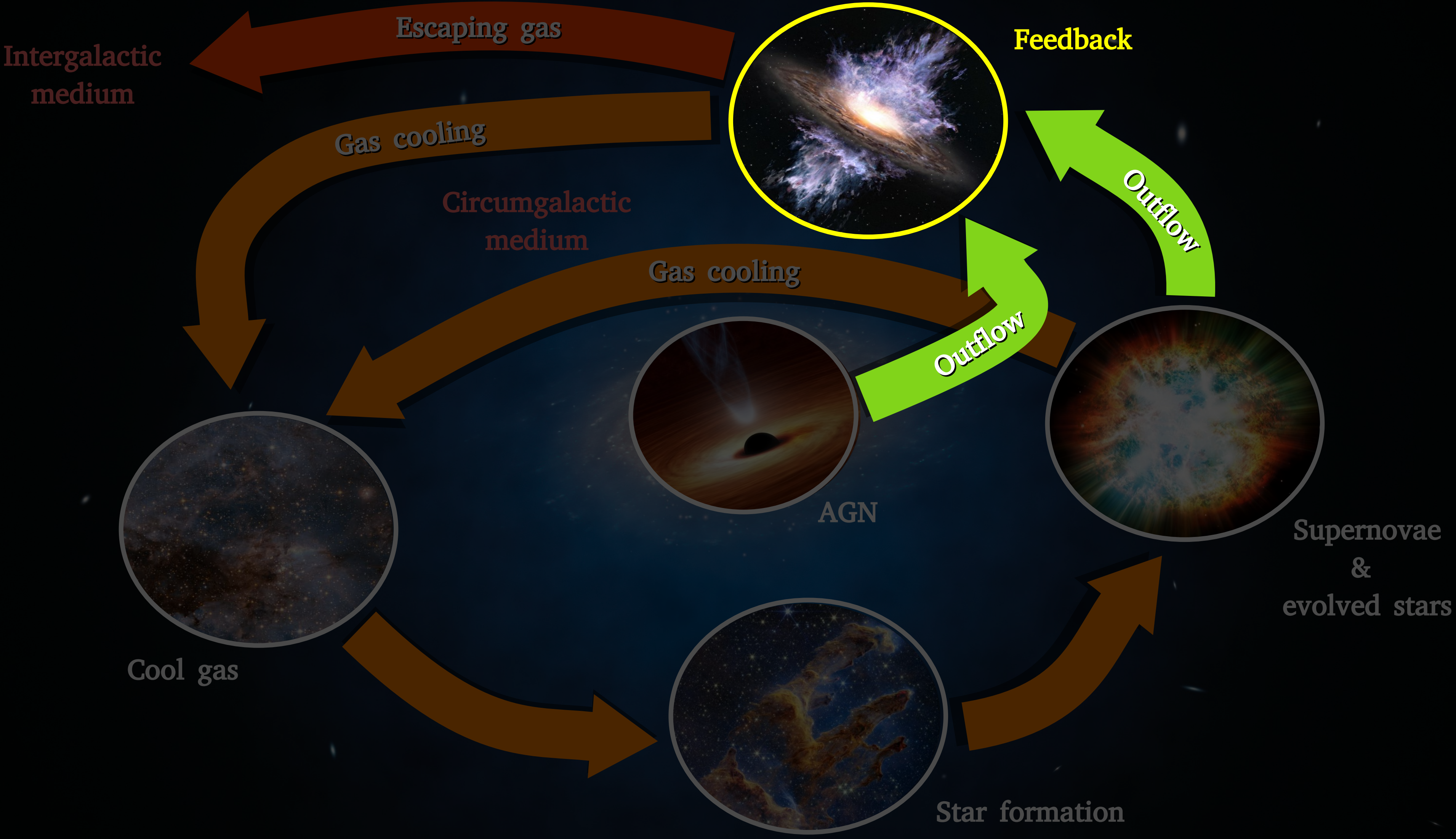
Outflow

AGN

Supernovae
&
evolved stars

Cool gas

Star formation


Escaping gas
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Star formation

General context

Efficient outflows are needed by chemical evolution models to reproduce the observations

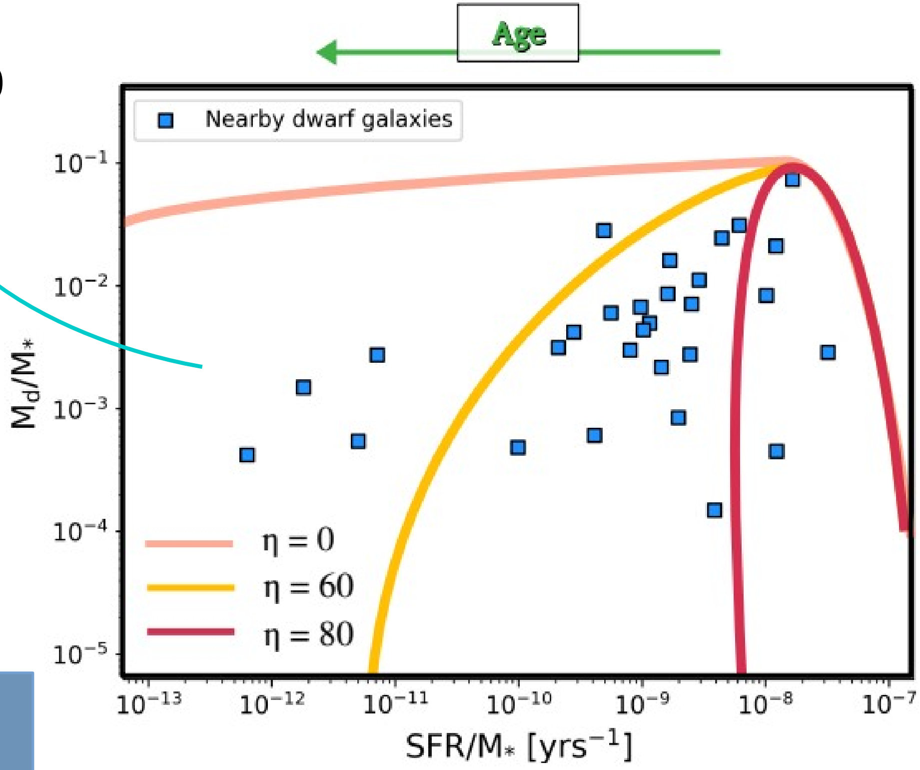
$$\eta \equiv \frac{\dot{M}_{out}}{SFR} \gg 1$$

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

Constraints on the mass-loading factor

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

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



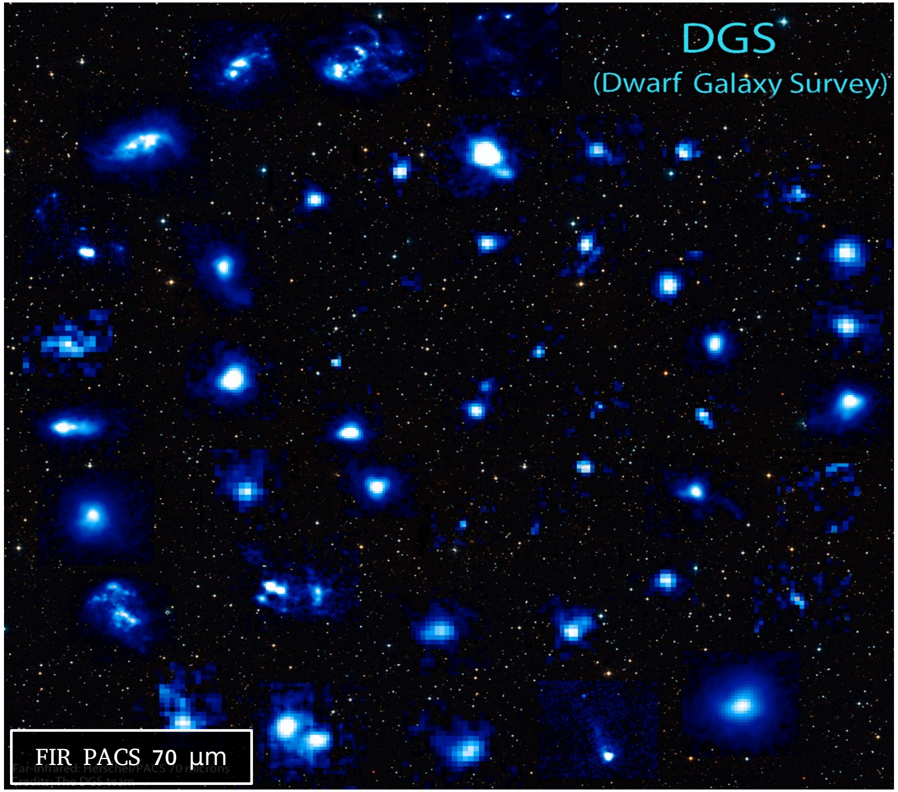
Based on Nanni et al. 2020

The sample

Physical properties

$12 + \log(O/H) \leq 8.4$
$D < 200$ Mpc
$\log(M/M_\odot) \sim 5 - 10$
$\log(SFR/M_\odot yr^{-1}) \sim -3 - 1$

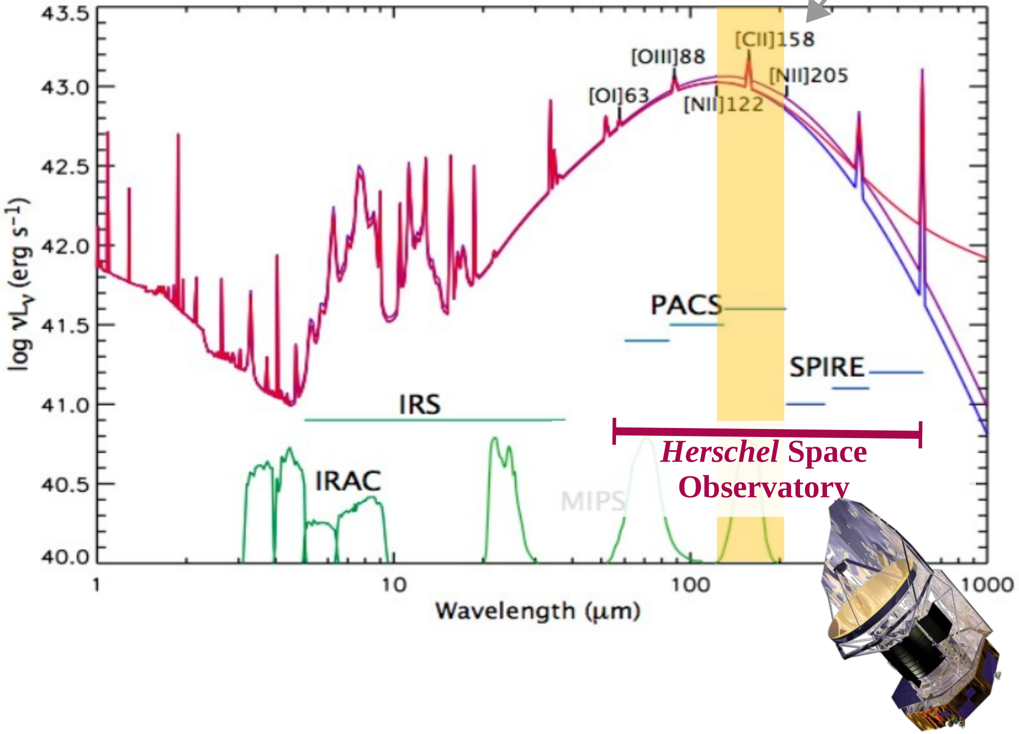
Credit: the DGS team



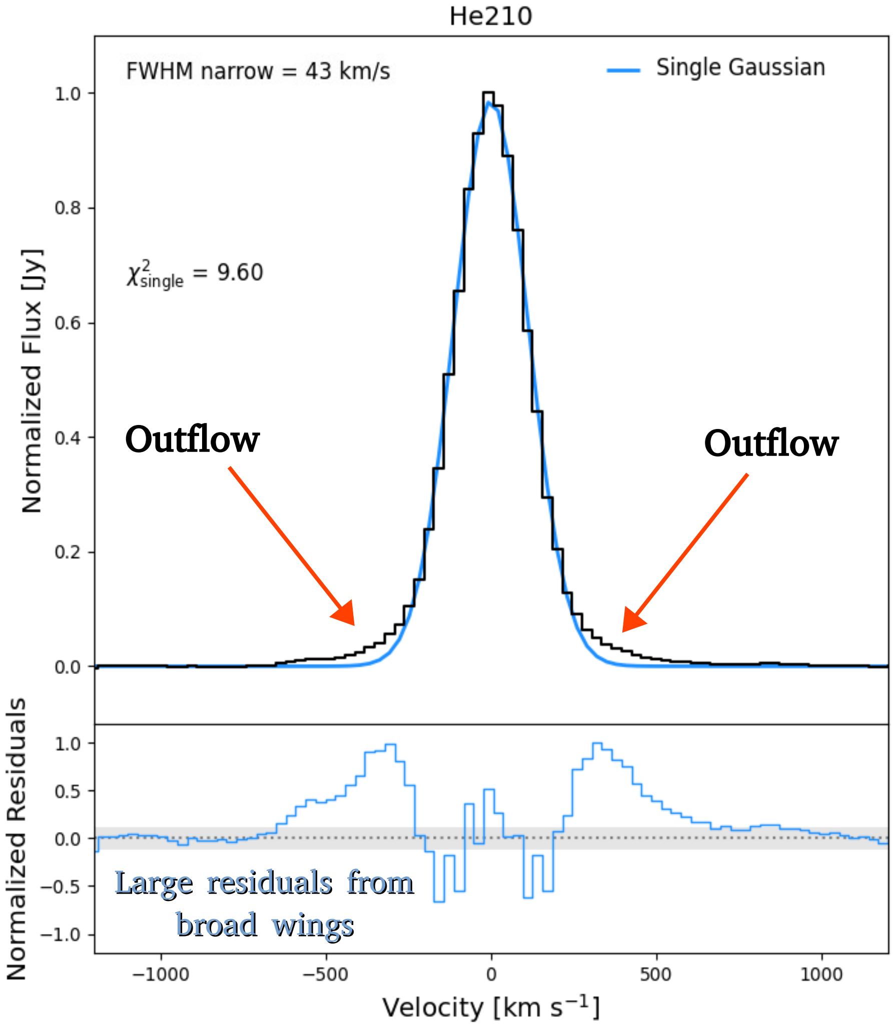
Why [CII] @ 158 µm?

- Good tracer of atomic gas
- One of the strongest line in the FIR
- Tracer of outflowing gas

Credit: Institute of Astronomy, University of Cambridge



The method: individual detections



Outflow

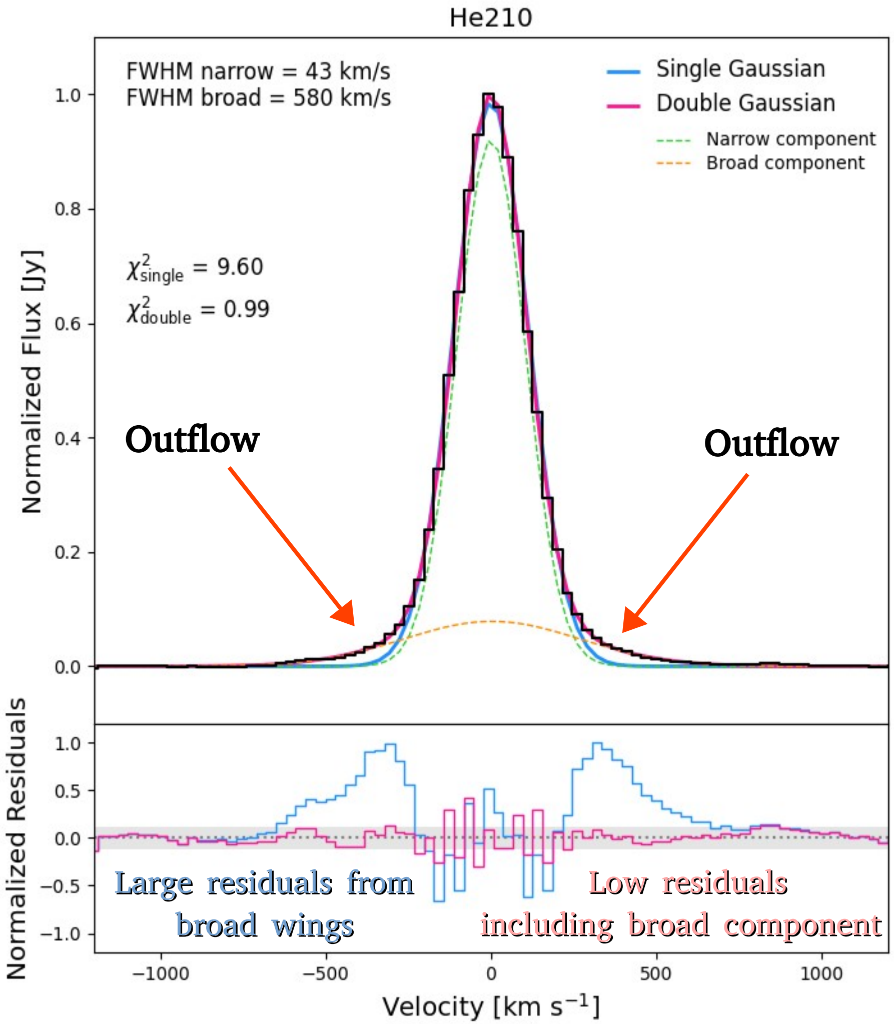
Outflow

Large residuals from broad wings

The method: individual detections

11/29 galaxies

with individual detection of atomic outflow



Outflow

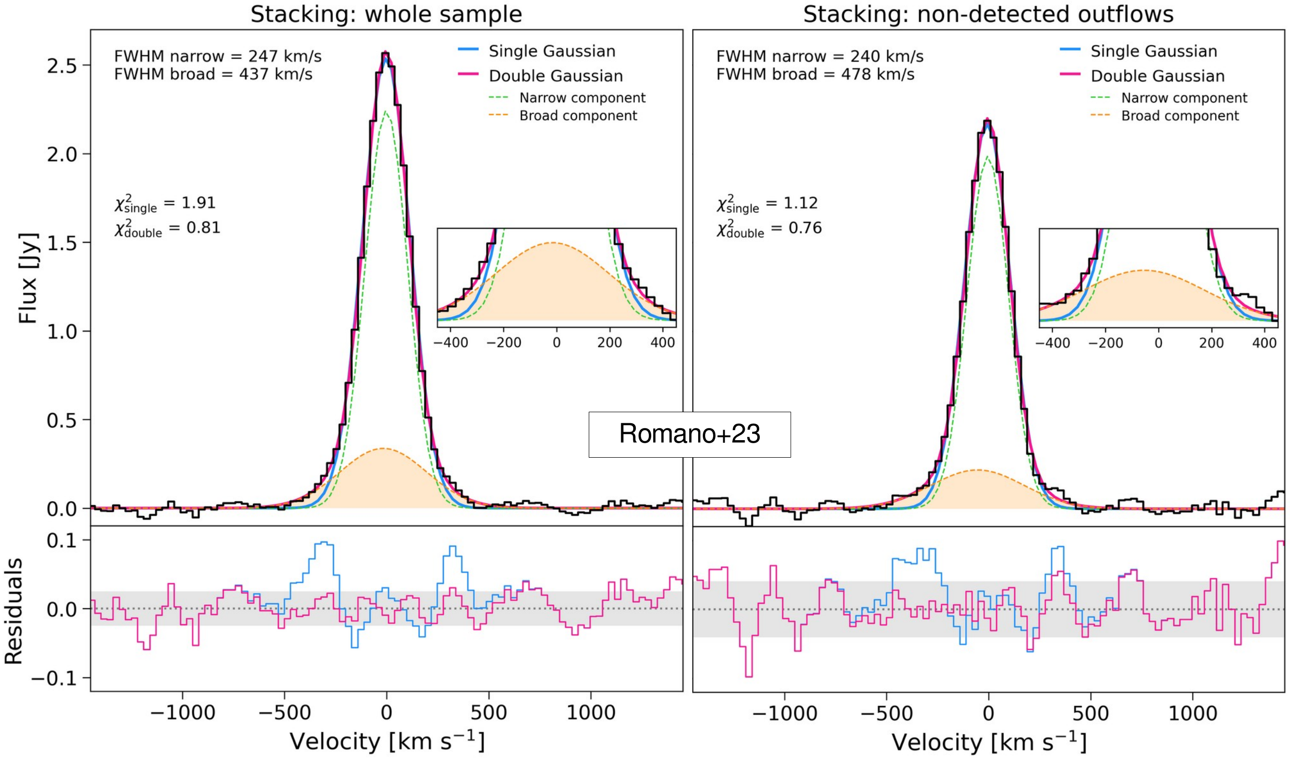
Outflow

Large residuals from broad wings

Low residuals including broad component

The method: spectral stacking

Average outflow properties for the whole galaxy population



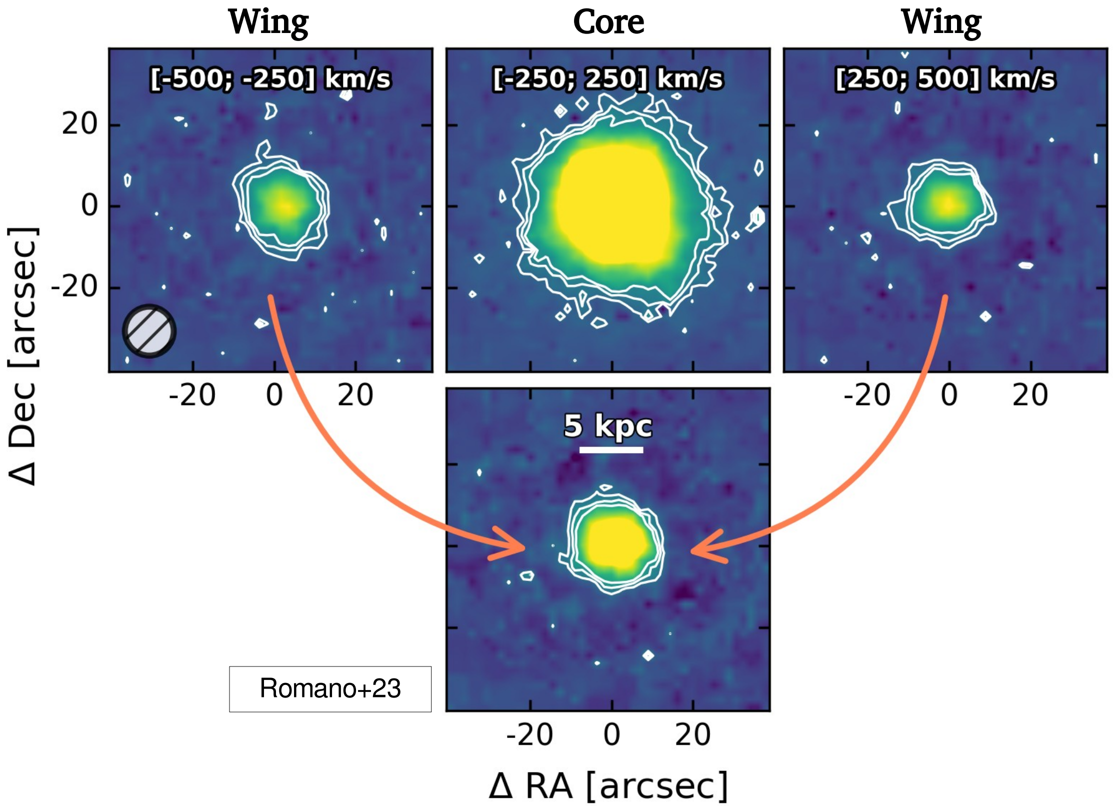
Romano+23

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

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

Both stacking of the whole sample and of the non-detection sub-sample show evidence for outflowing gas

The method: spatial stacking



Romano+23

R_{out} ~ 1 kpc

R_{core} ~ 1.5 kpc

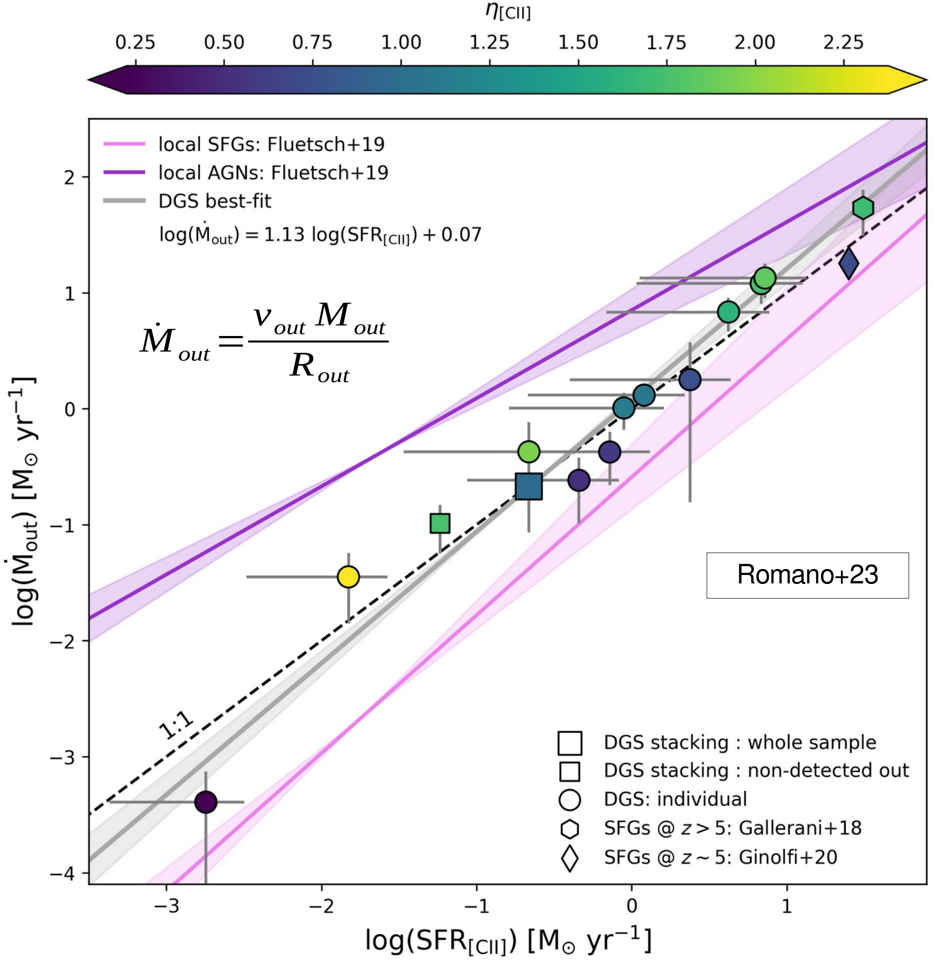
R_{UV} ~ 0.7 kpc

Possible evidence for [CII] halos around dwarf galaxies (Romano et al. in prep.)

Outflow efficiency: the mass-loading factor

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

Lower than predicted by chemical evolution models…



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

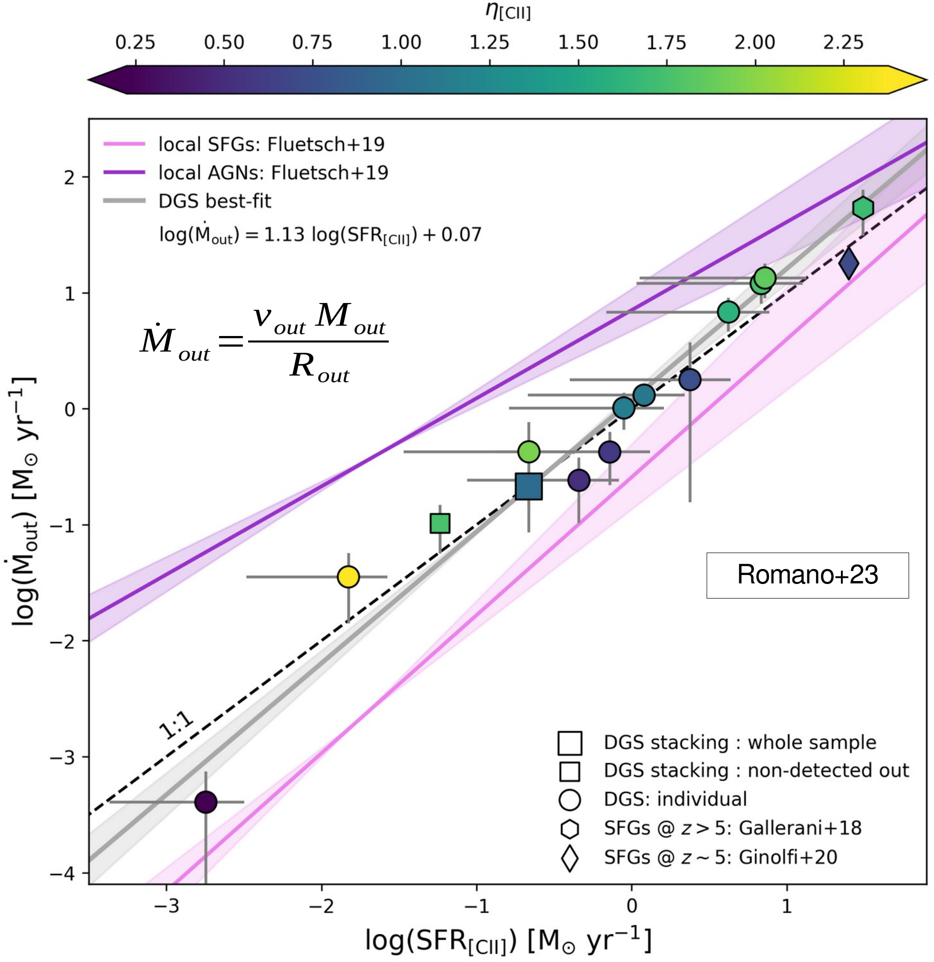
Outflow efficiency: the mass-loading factor

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

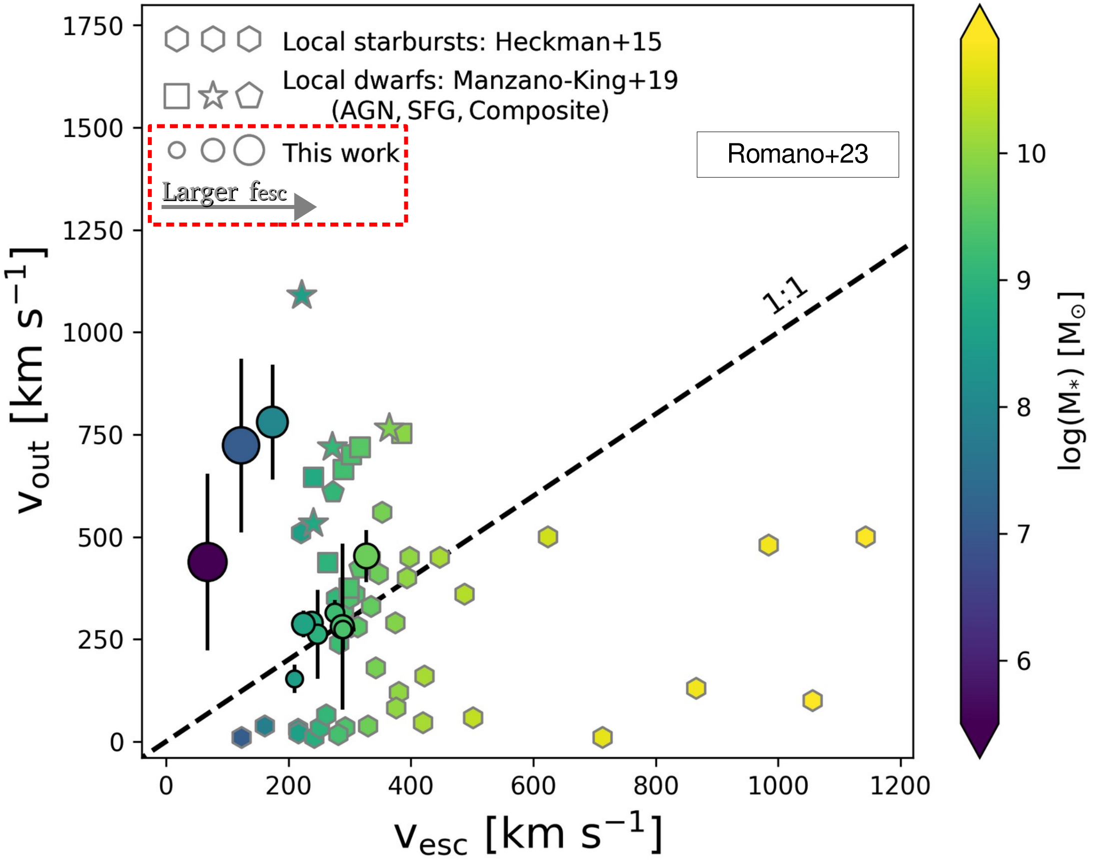
Lower than predicted by chemical evolution models…

Accounting for the multi-phase ISM

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



Chemical enrichment of the CGM/IGM



In most of the cases, the wind speed is comparable to (or larger than) that needed to escape the dark matter halo, with an average escape fraction

$$\langle f_{esc} \rangle = 40\,\%$$

Despite *low* efficiency ($\eta \sim 1$), outflows are able to significantly enrich the CGM/IGM around dwarf galaxies

Summary and future prospects

- We used [CII] emission to investigate the impact of feedback on a sample of 29 local dwarf galaxies drawn from the DGS survey
- 11/29 galaxies show clear signs of outflowing gas from the [CII] spectra; the remaining sources are likely hosts of weaker outflows that can be still detected in their stacked spectra
- The spatial stacking reveals an outflow radius of ~1 kpc, and a core [CII] emission more extended than the typical UV size of the galaxies
- On average, mass outflow rates are comparable to the SFRs of the galaxies, implying mass-loading factors of order of unity
- Outflow velocities are larger than (or comparable with) escape velocities, with an average fraction of 40% of atomic gas expelled outside of the galaxies

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- More observations to characterize the ionized and molecular phases of the outflows
- Use our findings as input for chemical evolution models, to constraint dust and metals production/destruction in the ISM (Nanni et al. in prep.)

Thank you for the attention!

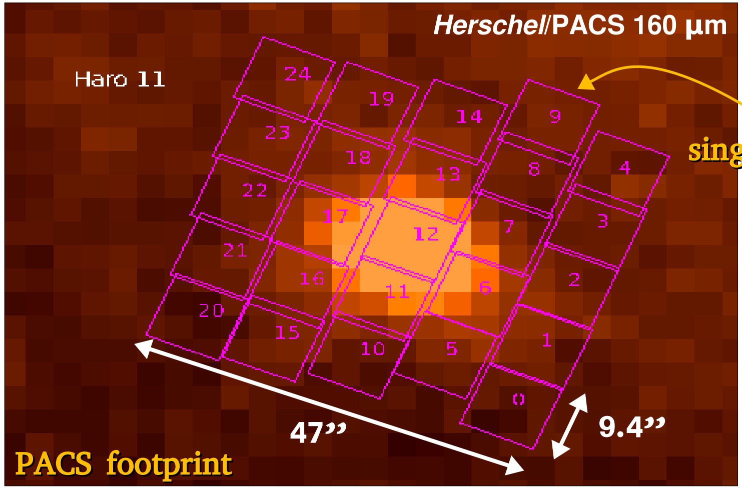
Based on:

Romano, M., et al. 2023, A&A, 677, A44

SCAN ME

EXTRAs

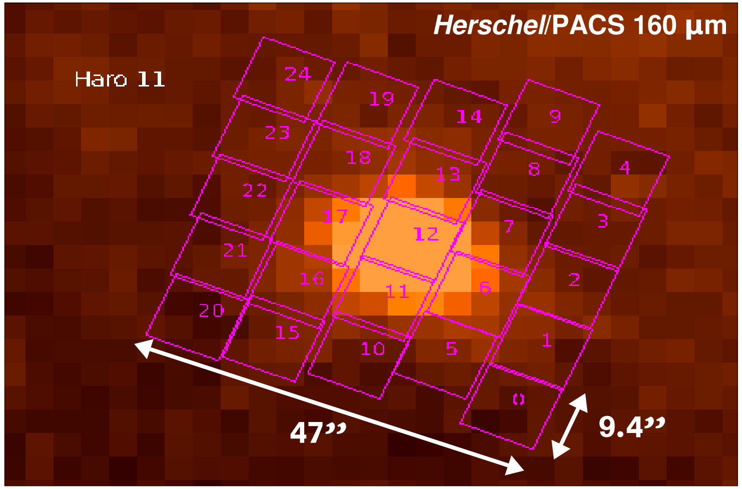
The method: spectra extraction

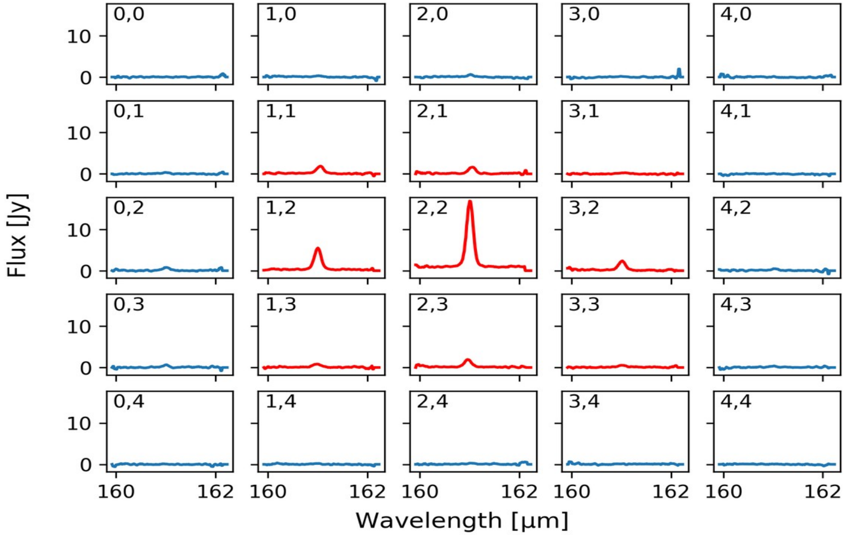


single spaxel

PACS footprint

The method: spectra extraction





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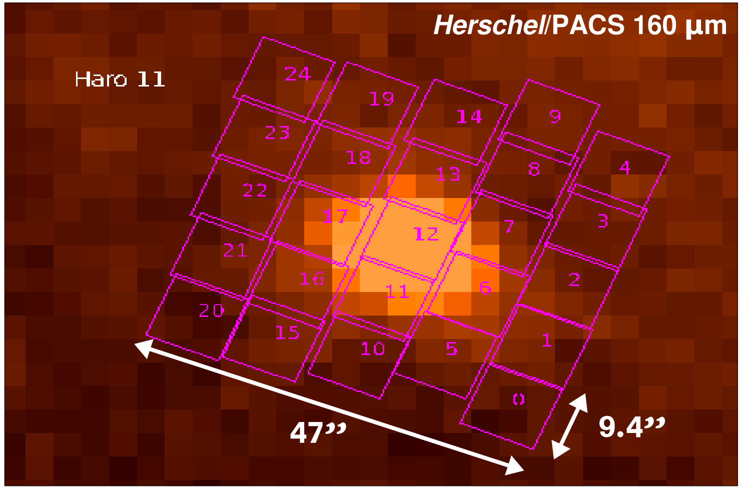

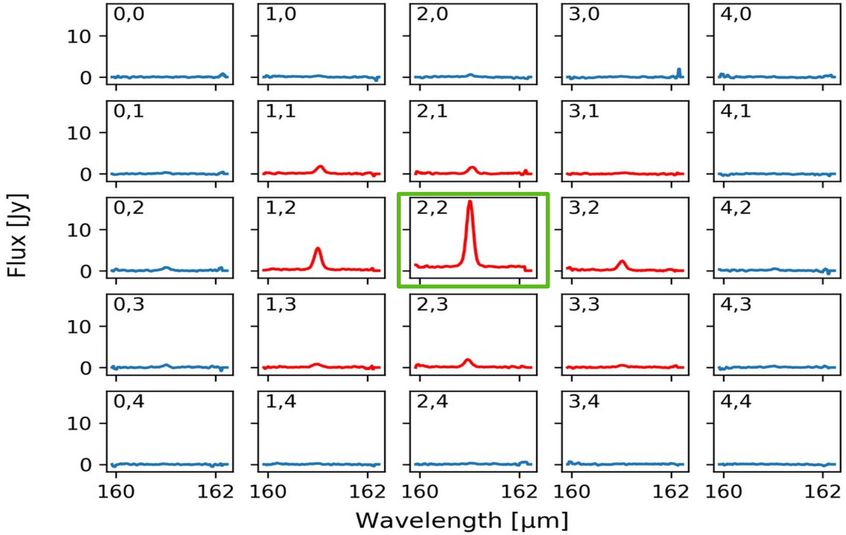

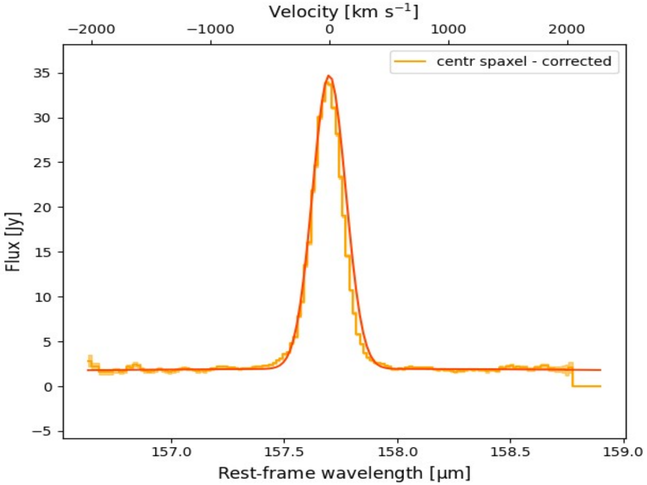

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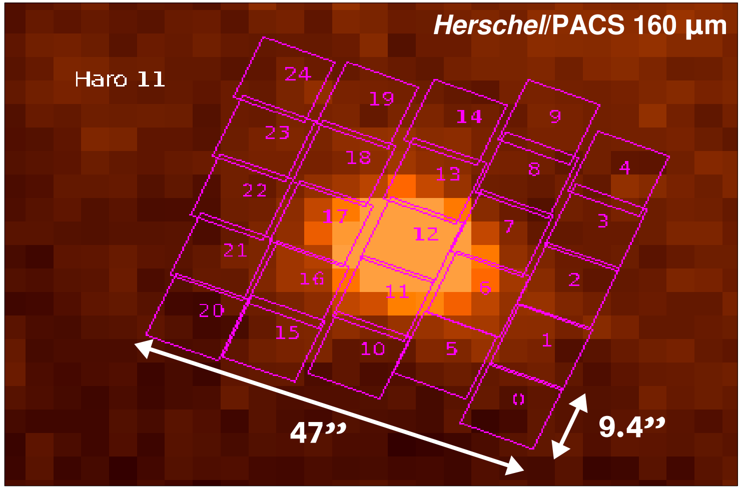

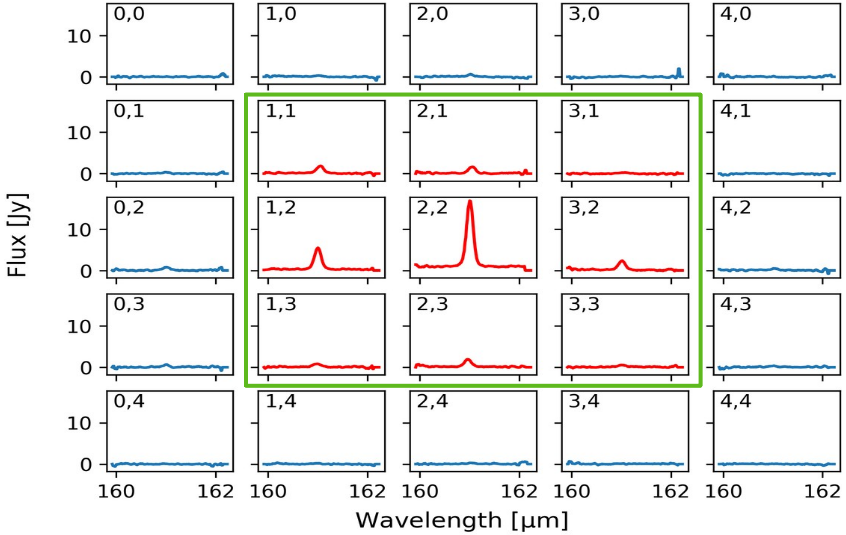

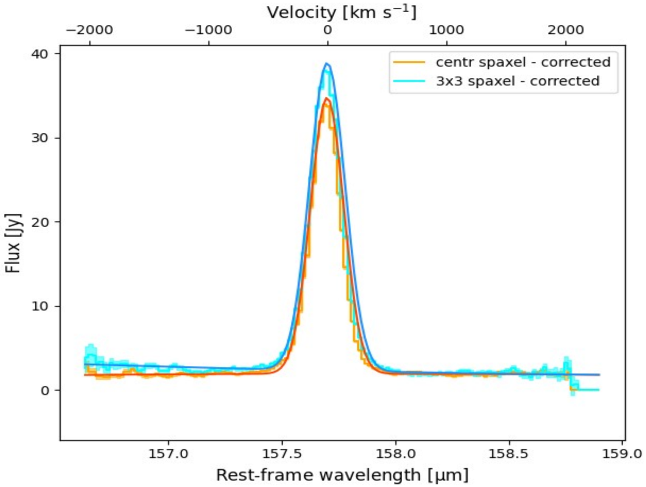

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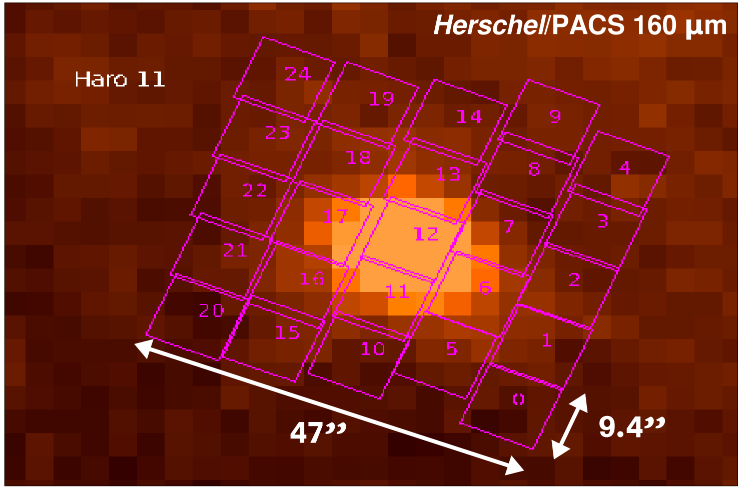

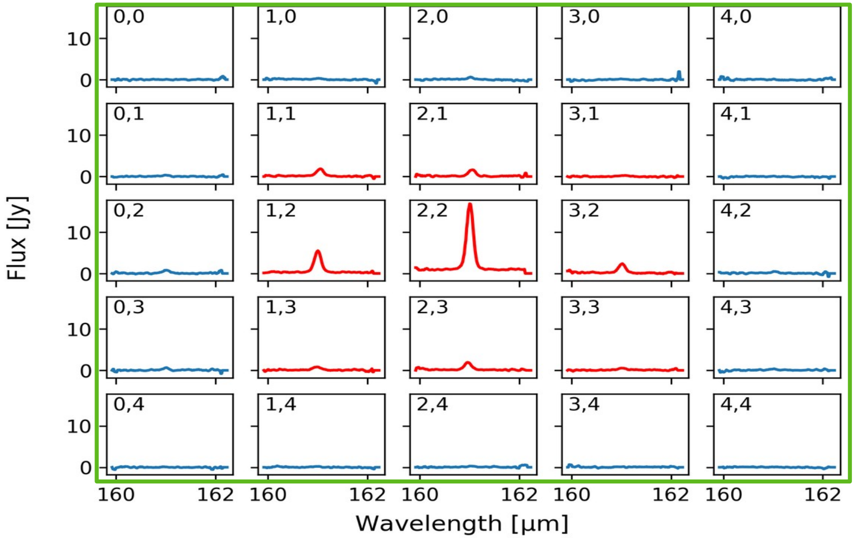

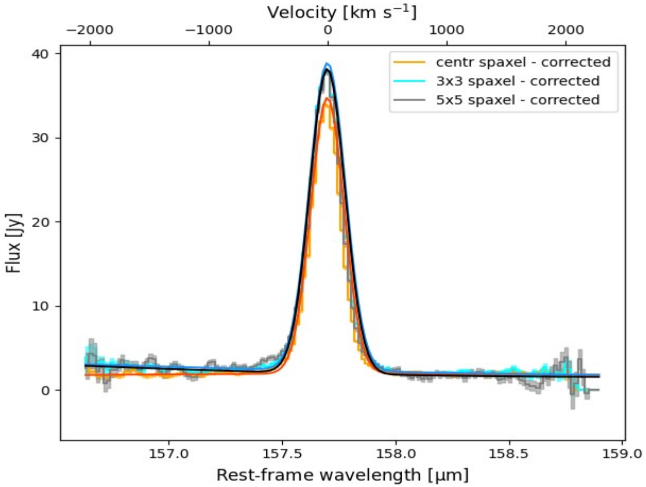

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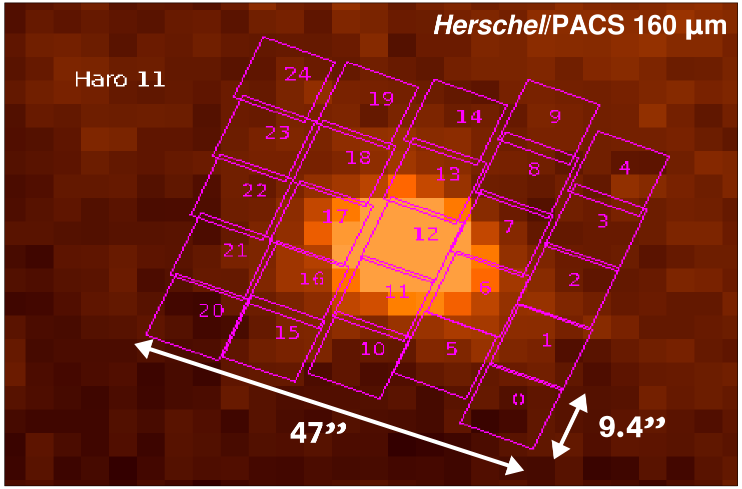
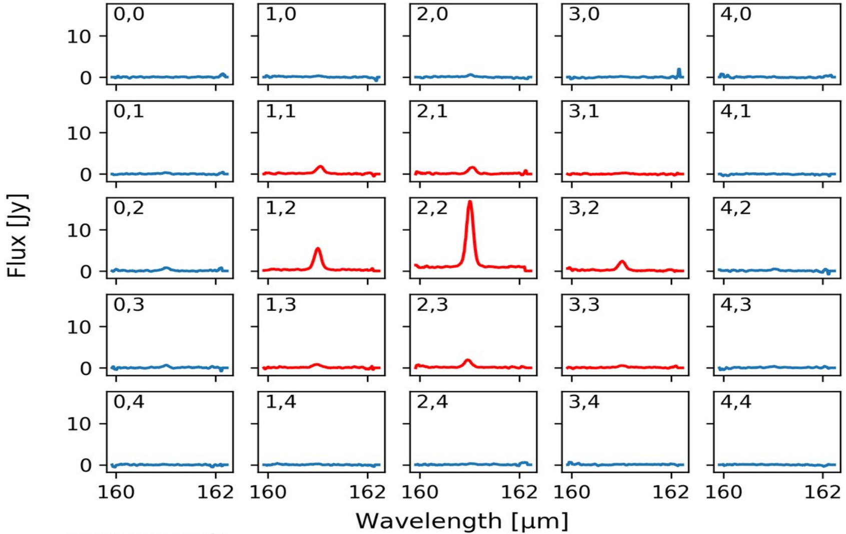
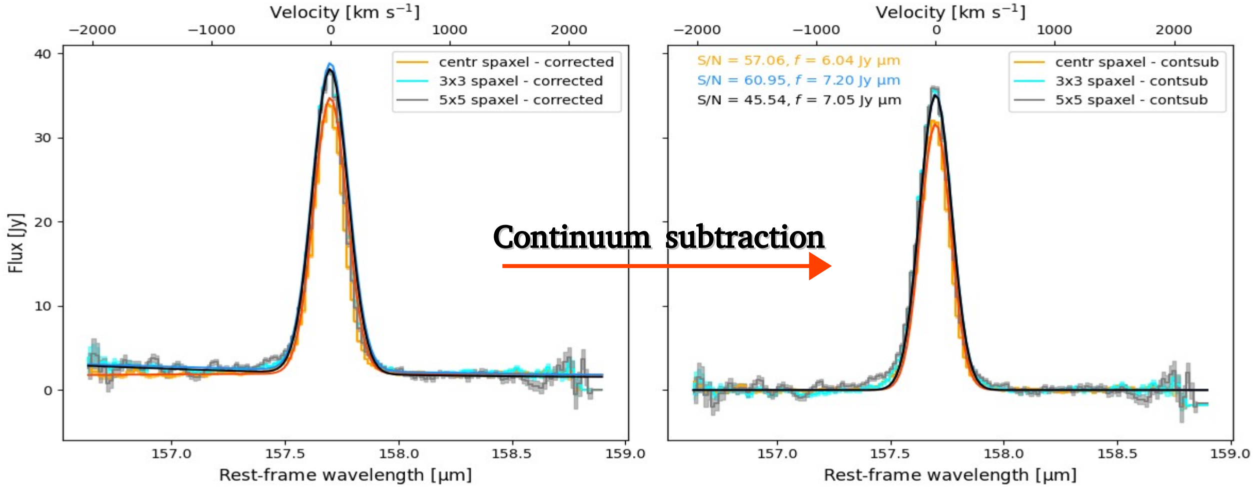




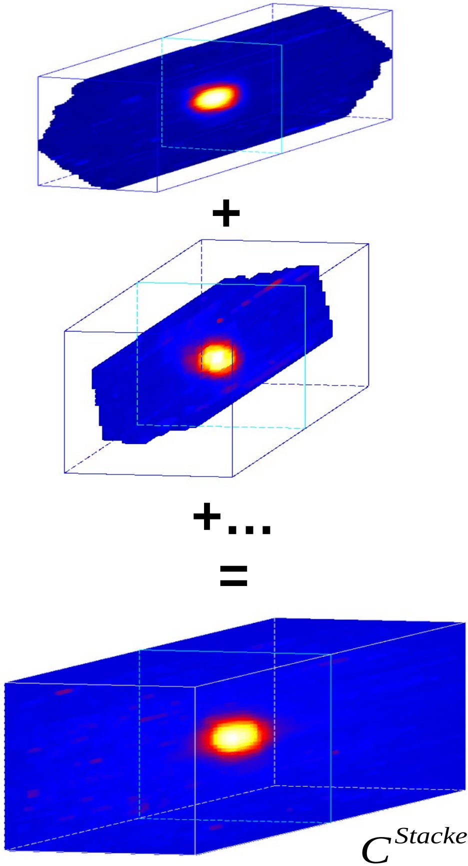


Continuum subtraction

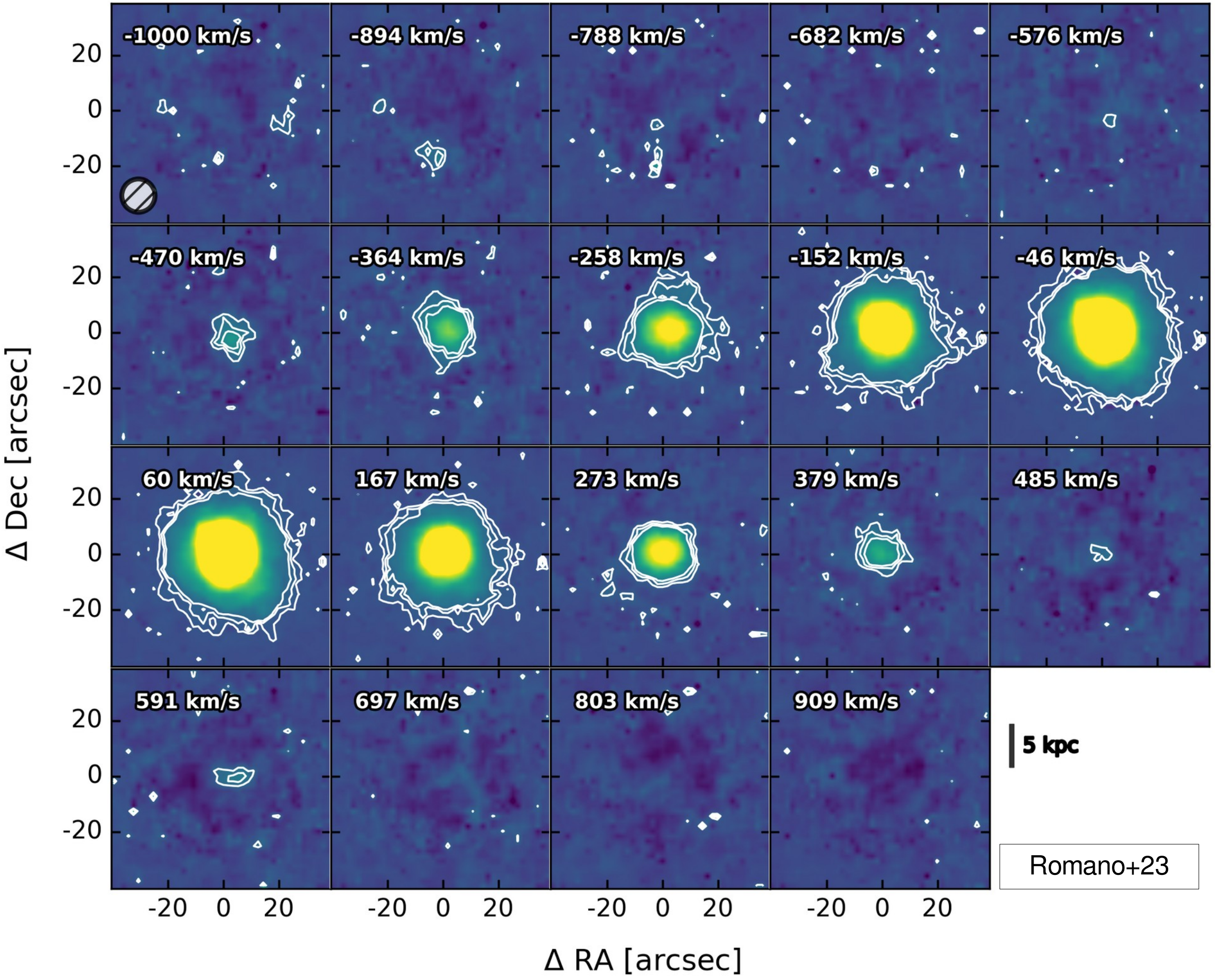
3x3 spectrum

Larger flux
Best S/N

Channel maps of the stacked [CII] emission



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



Romano+23

Mass-loading factor estimate

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

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

(De Looze+14)

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

- $$v_{out} = \frac{FWHM_{broad}}{2} + |v_{broad} - v_{narrow}|$$
- $$M_{out} = 0.77\left(\frac{0.7\,L_{[CII]}}{L_\odot}\right)\times\left(\frac{1.4\times10^{-4}}{X_{C^+}}\right)\times\frac{1+2e^{-91\,K/T}+n_{crit}/n}{2e^{-91\,K/T}}$$

  (Hailey-Dunsheath+10)
- $$R_{out} = \frac{a}{2}\sqrt{\frac{b}{a}}$$

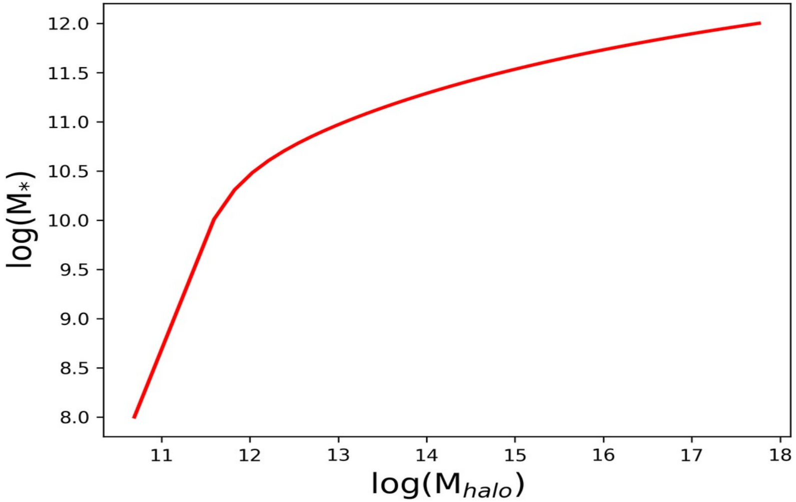
- 70% of the total [CII] luminosity contributes to atomic gas
- X_{c+} = 1.4e-4 → abundance of C per H atom
- T = 130 K → gas temperature
- n_{crit} = 2.8e3 cm^{-3} → critical density of [CII]
- n = 1e4 cm^{-3} → gas number density

Escape velocity estimate

(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)

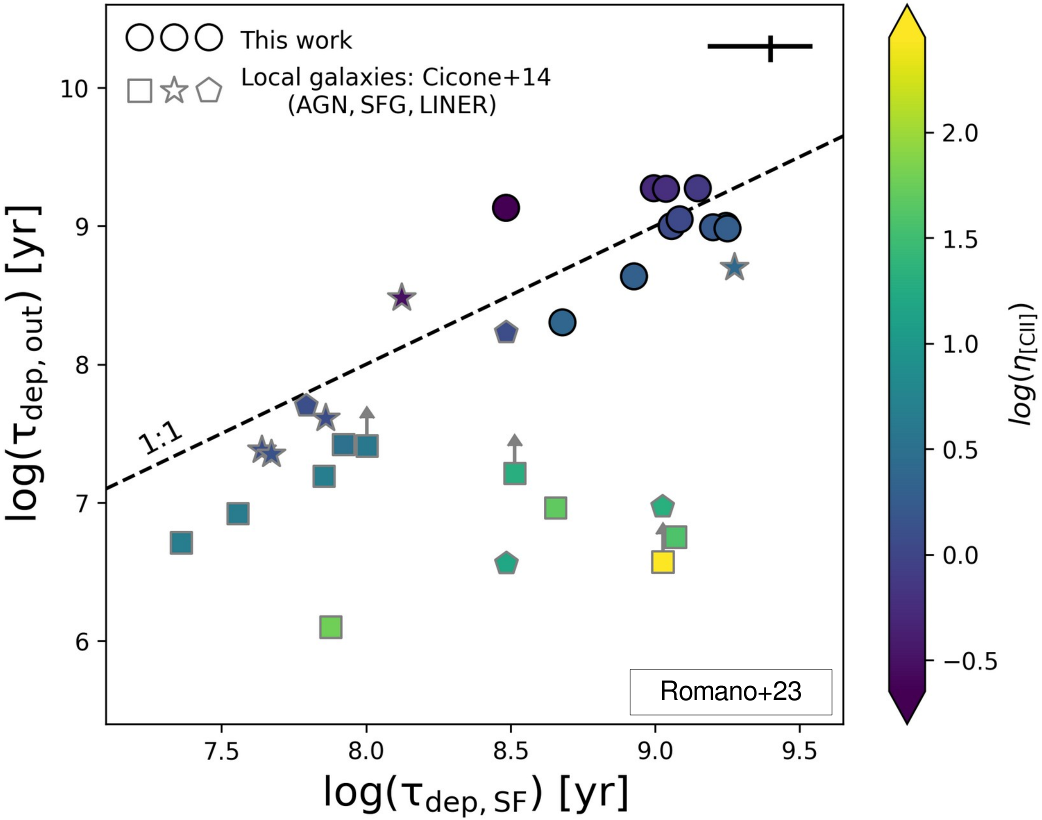
- $r_s = r_{halo}/c$ (Navarro, Frenk & White+95)

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

Depletion timescales

$$\tau_{dep,out} = M_{H2.TOT} / \dot{M}_{out} \quad \text{vs} \quad \tau_{dep,SF} = M_{H2.TOT} / SFR$$

Outflow depletion timescale ranges from
100 to **1000** Myrs

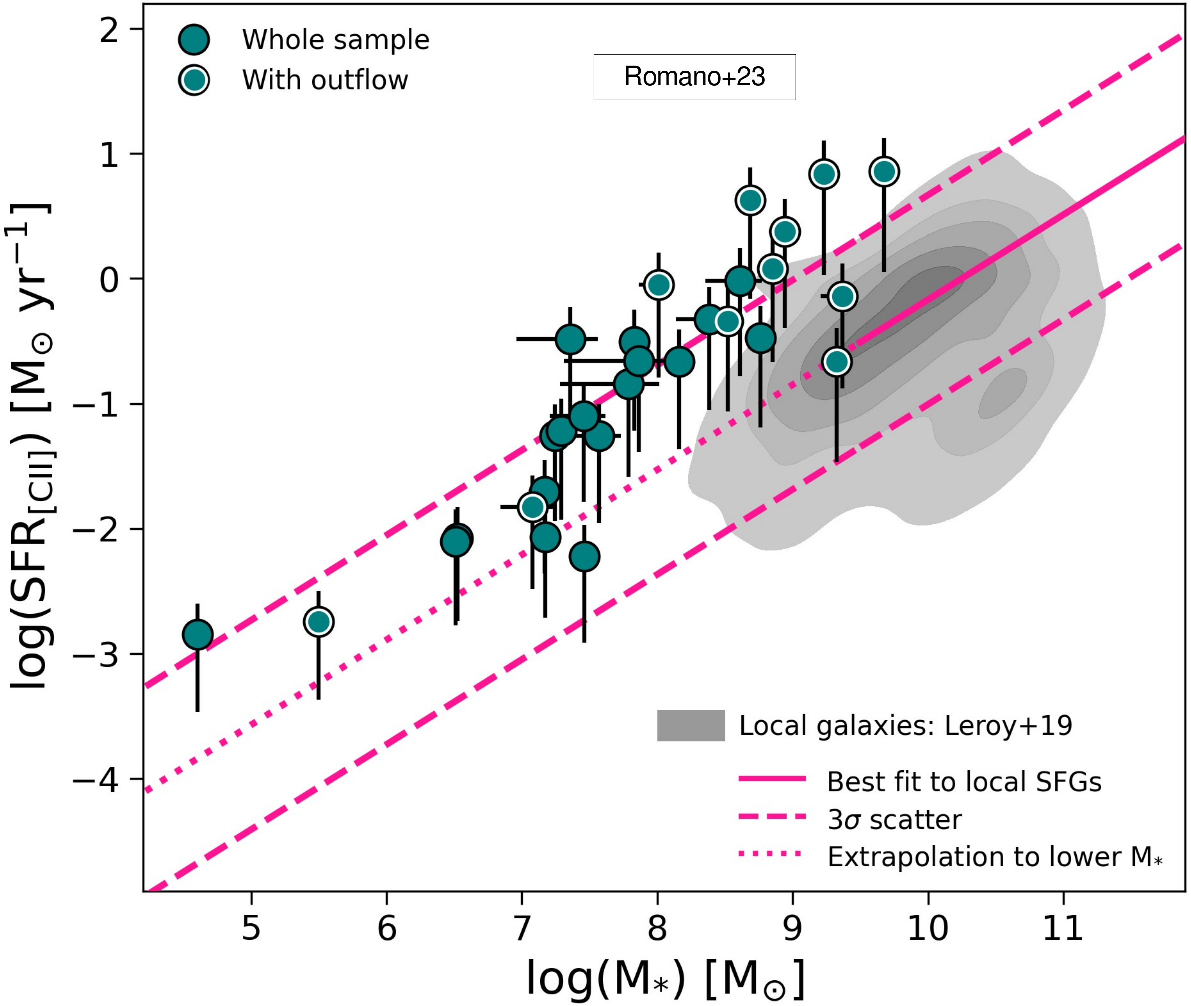


60-90% of the sample characterized by

$$\tau_{dep,out} < \tau_{dep,SF}$$

implying a significant role of galactic outflows in regulating star formation in dwarf galaxies

The sample

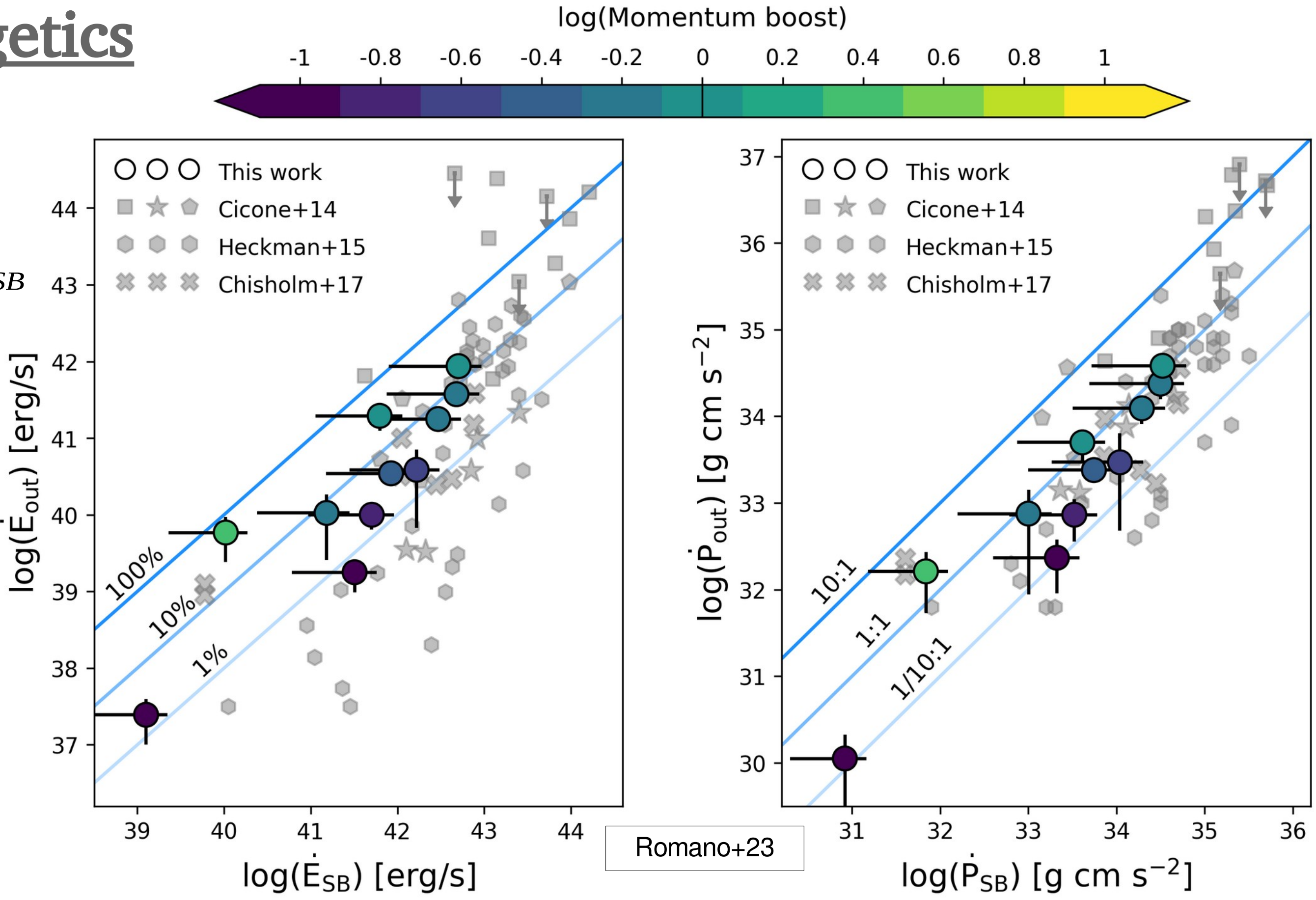


Whole sample
With outflow
Romano+23
Local galaxies: Leroy+19
Best fit to local SFGs
3σ scatter
Extrapolation to lower M*
log(SFR[CII]) [M⊙ yr⁻¹]
log(M*) [M⊙]
2
1
0
−1
−2
−3
−4
5
6
7
8
9
10
11

Outflow energetics

$$\dot{E}_{out} = \frac{1}{2}\dot{M}_{out}\, v_{out}^2$$
$$= (1-20\%)\,\dot{E}_{SB}$$

Coupling efficiency needed for kinetic power produced by SNe to drive the outflow



Romano+23

$$\dot{P}_{out} = \dot{M}_{out}\, v_{out}$$
$$\lesssim \dot{P}_{SB}$$

Momentum-driven outflow?

Most of our galaxies show momentum rates comparable to momentum supplied by starbursts:
radiation pressure onto dusty clouds in the ISM could possibly dominate the outflow driving mechanism