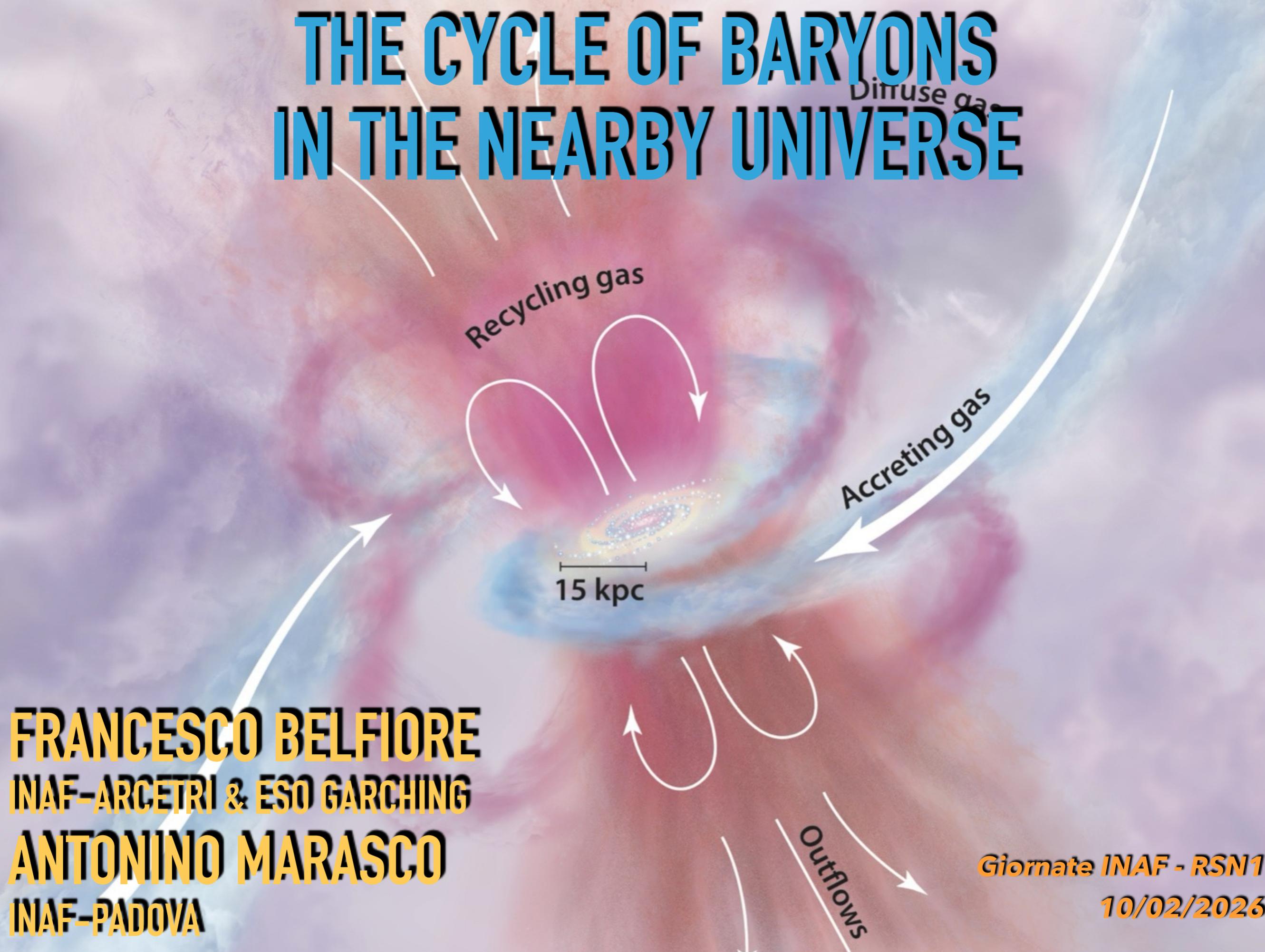


# THE CYCLE OF BARYONS IN THE NEARBY UNIVERSE



**FRANCESCO BELFIORE**  
INAF-ARCETRI & ESO GARCHING  
**ANTONINO MARASCO**  
INAF-PADOVA

*Giornate INAF - RSN1*  
**10/02/2026**

# The galaxy-halo gas circulation

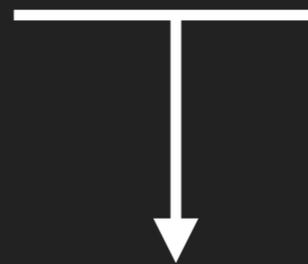
# Gas accretion & galaxy evolution

Gas consumption timescale in nearby galaxies is of a few Gyr. It gets shorter at higher  $z$ .

*Kennicutt 98, Bigiel+11, Leroy+13  
Saintonge+13, Tacconi+18*

Star forming galaxies in the field have  $\sim$  flat or slowly declining SFH at least up to  $z=1$

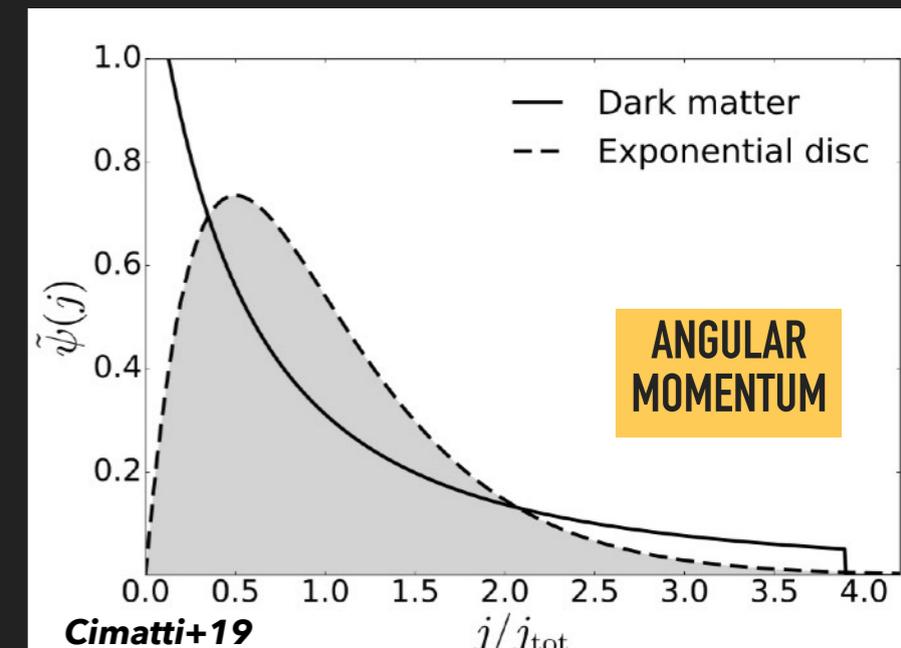
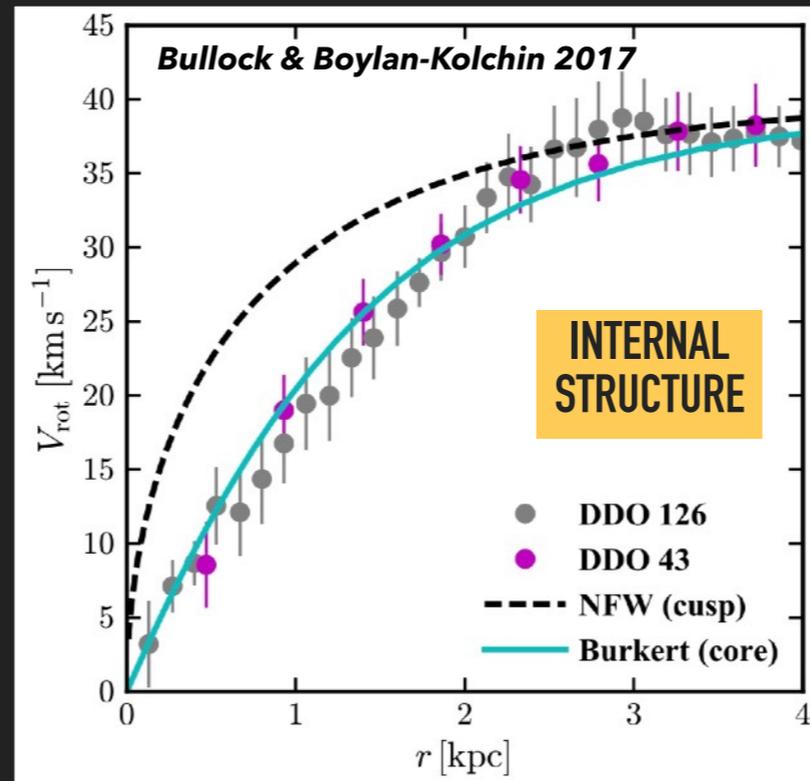
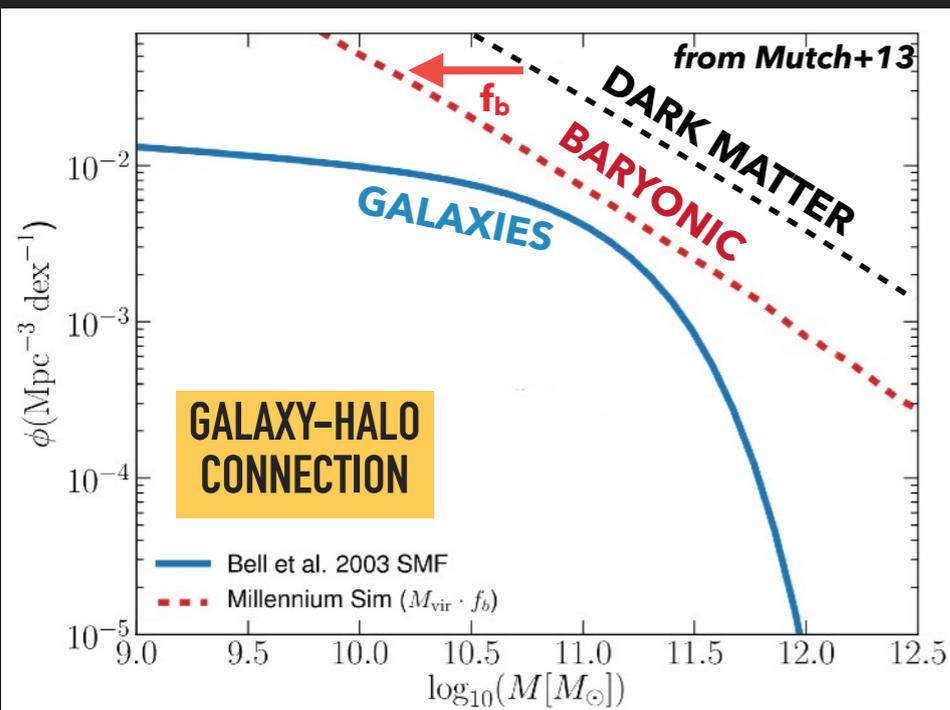
*e.g., Aumer & Binney 2009, [Guglielmo+15](#)*



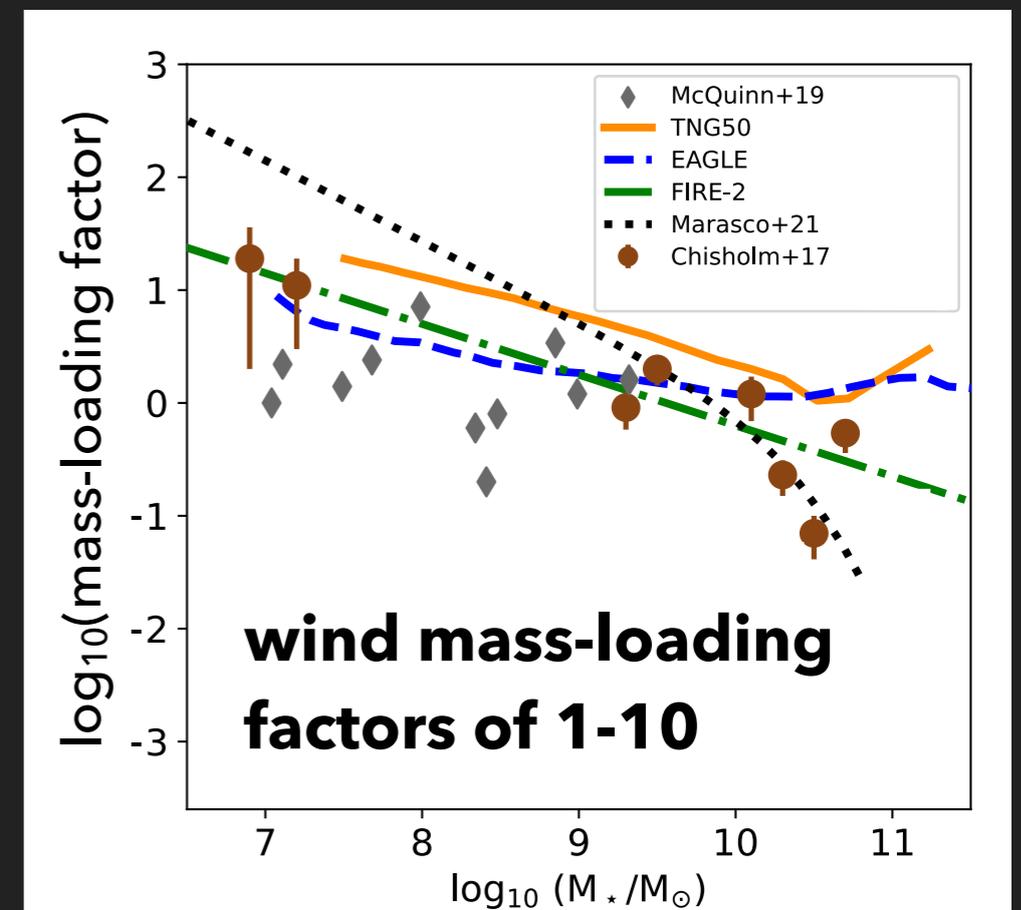
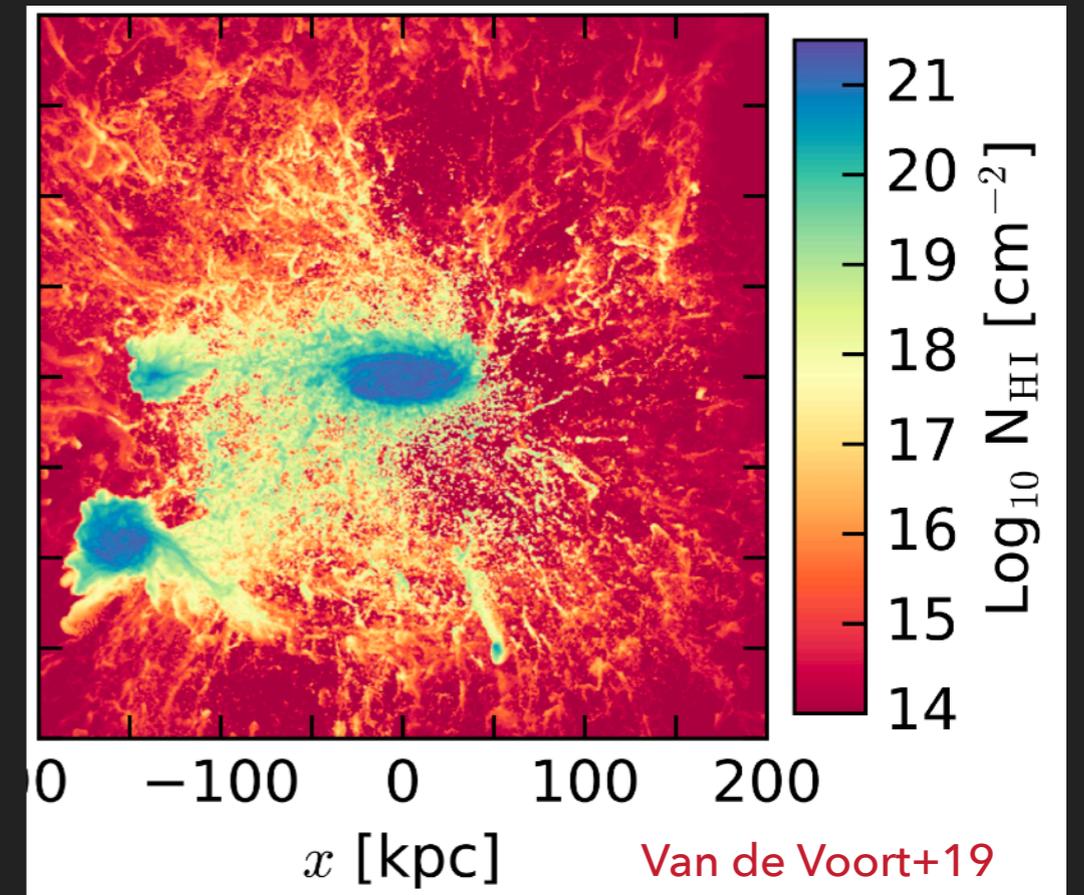
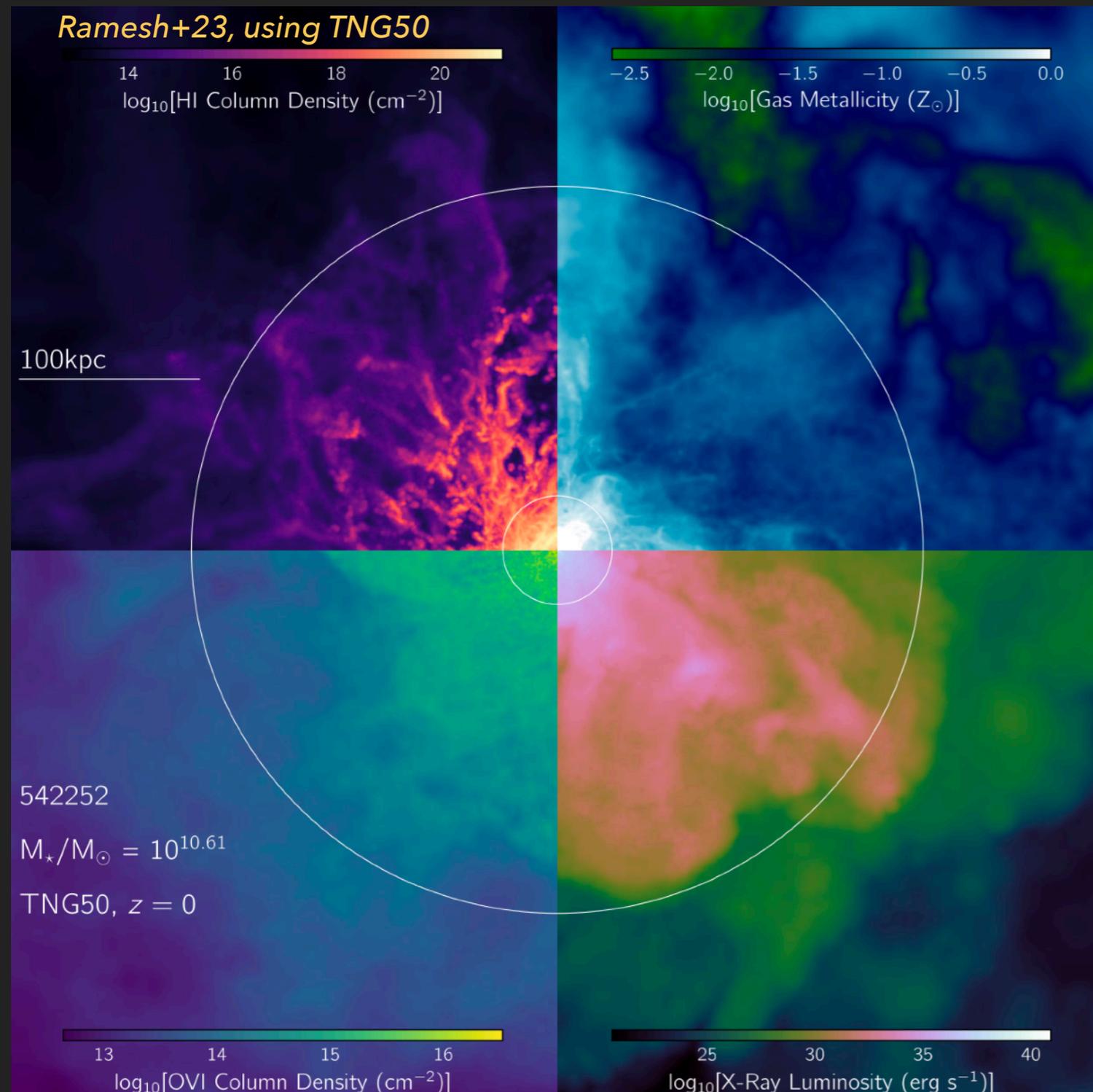
Galaxies continuously replenish the fuel used for star formation

# Gas outflows & galaxy evolution

Winds are thought to be key to address small-scale problems of  $\Lambda$ CDM



# Predictions from cosmological hydro simulations



filamentary / clumpy gas distribution up to hundreds of kpc from galaxy discs

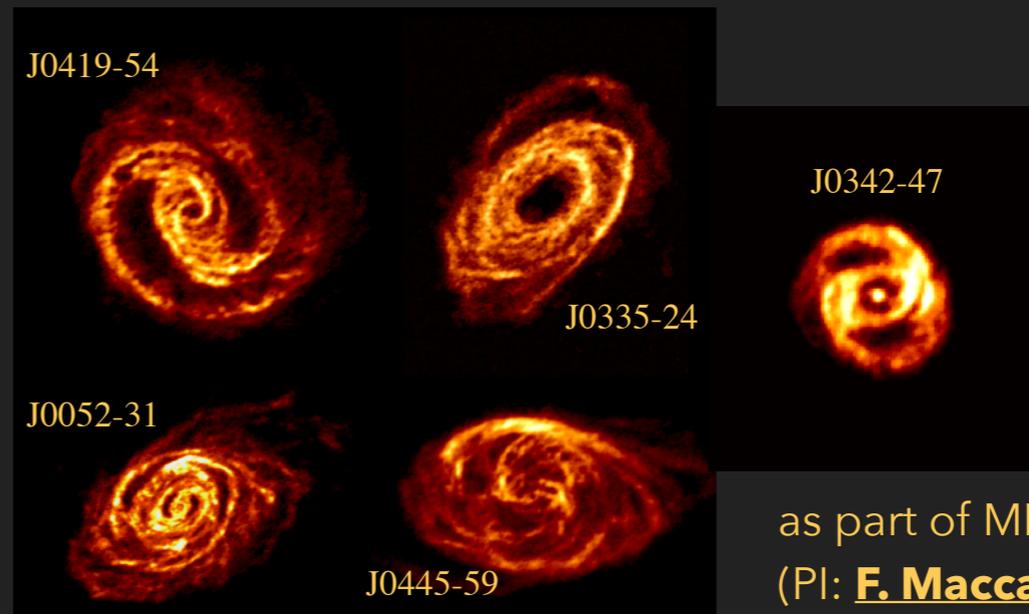
**Challenging this picture**

**A gentle gas cycle in and around galaxies**

# HI in and around observed and simulated galaxy discs (Marasco+25)

## HI observations with MeerKAT (n=5)

- ▶ MW-like stellar mass
- ▶  $D \sim 20$  Mpc
- ▶ FoV  $\sim 1$  deg  $\rightarrow R_{\text{max}} \sim 200$  kpc
- ▶ res 20" (HR), 60" (LR)  $\rightarrow 2$  and 6 kpc
- ▶ min  $N_{\text{HI}} \sim 5 \times 10^{18} \text{ cm}^{-2}$  (HR),  $10^{18} \text{ cm}^{-2}$  (LR)



**MHONGOOSE**  $\leftarrow$   
(de Blok+24)

as part of MKT-20202 project  
(PI: **F. Maccagni**)

## synthetic HI observations from cosmological simulations

### TNG-50 (n=15)

*Pillepich+19; Nelson+19*

- ▶ AREPO moving-mesh code
- ▶  $(50 \text{ Mpc})^3$  box
- ▶ res  $\sim 70$  pc,  $8.5 \times 10^4 M_{\odot}$
- ▶ equation of state for cold gas

### FIRE-2 (n=5)

*Hopkins+18; Wetzel+23*

- ▶ GIZMO, meshless finite-mass
- ▶ zoom-in
- ▶ res  $\sim 1$  pc,  $7.1 \times 10^3 M_{\odot}$
- ▶ No AGN physics

Parameter	Unit	HR	LR
Field of view <sup>(a)</sup>	$^{\circ}$	$\sim 1$	$\sim 1$
	kpc	$\sim 350$	$\sim 350$
Beam size <sup>(b)</sup>	"	$26.4 \times 18.2$	$65.3 \times 64.0$
	kpc	$2.6 \times 1.8$	$6.3 \times 6.2$
Beam PA	$^{\circ}$	136	92
Pixel size	"	5	20
	kpc	0.5	1.9
Velocity range	$\text{km s}^{-1}$	$\pm 500$	$\pm 500$
Channel width <sup>(c)</sup>	$\text{km s}^{-1}$	1.4	1.4
$\sigma_{\text{rms}}$ per channel	$\text{mJy beam}^{-1}$	0.15	0.25
Minimum $N_{\text{HI}}$ <sup>(d)</sup>	$\text{cm}^{-2}$	$5 \times 10^{18}$	$1 \times 10^{18}$

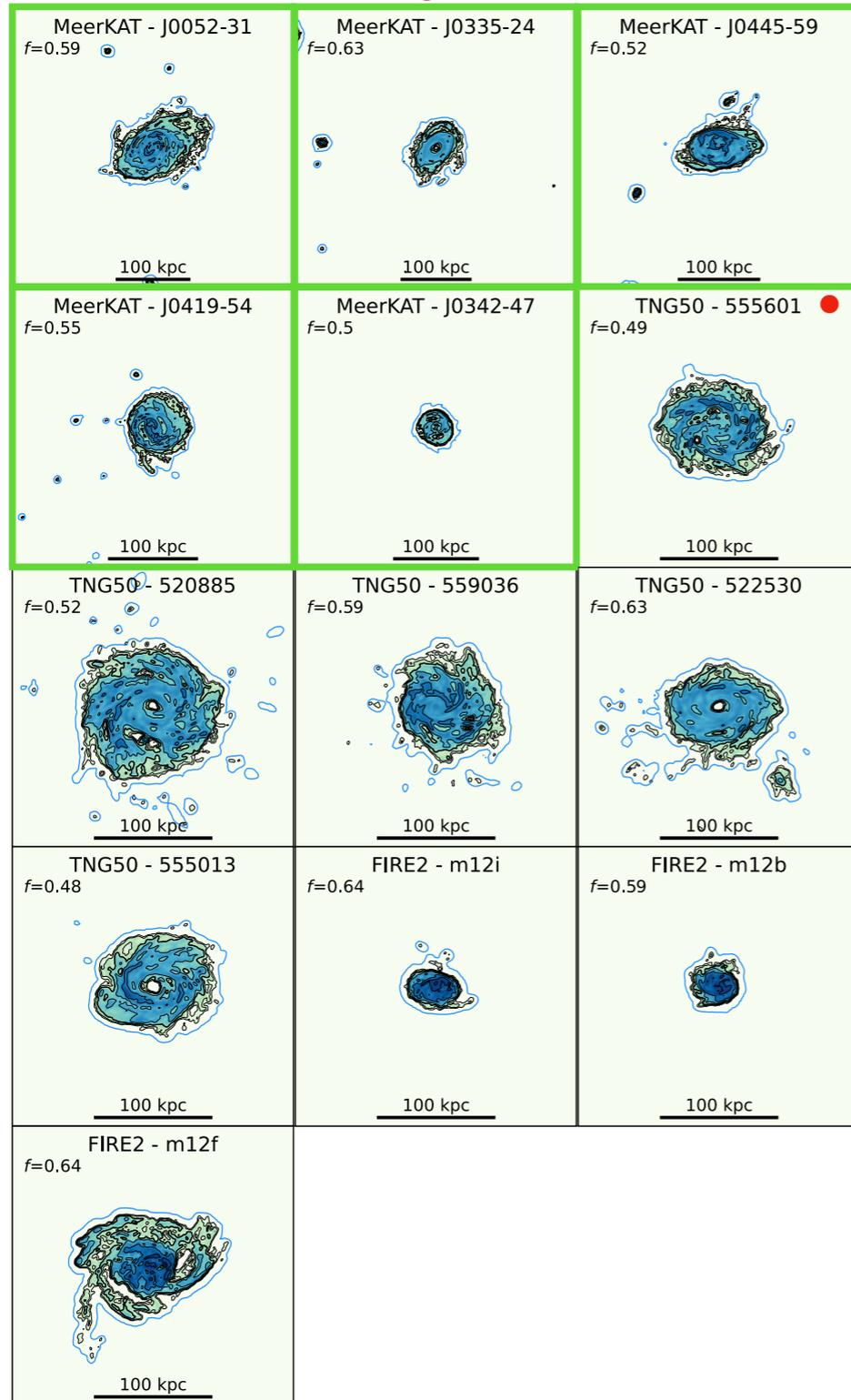
# Regular and irregular systems

Galaxies dominated by high- $N_{\text{HI}}$  spaxels ( $>10^{20} \text{ cm}^{-2}$ )

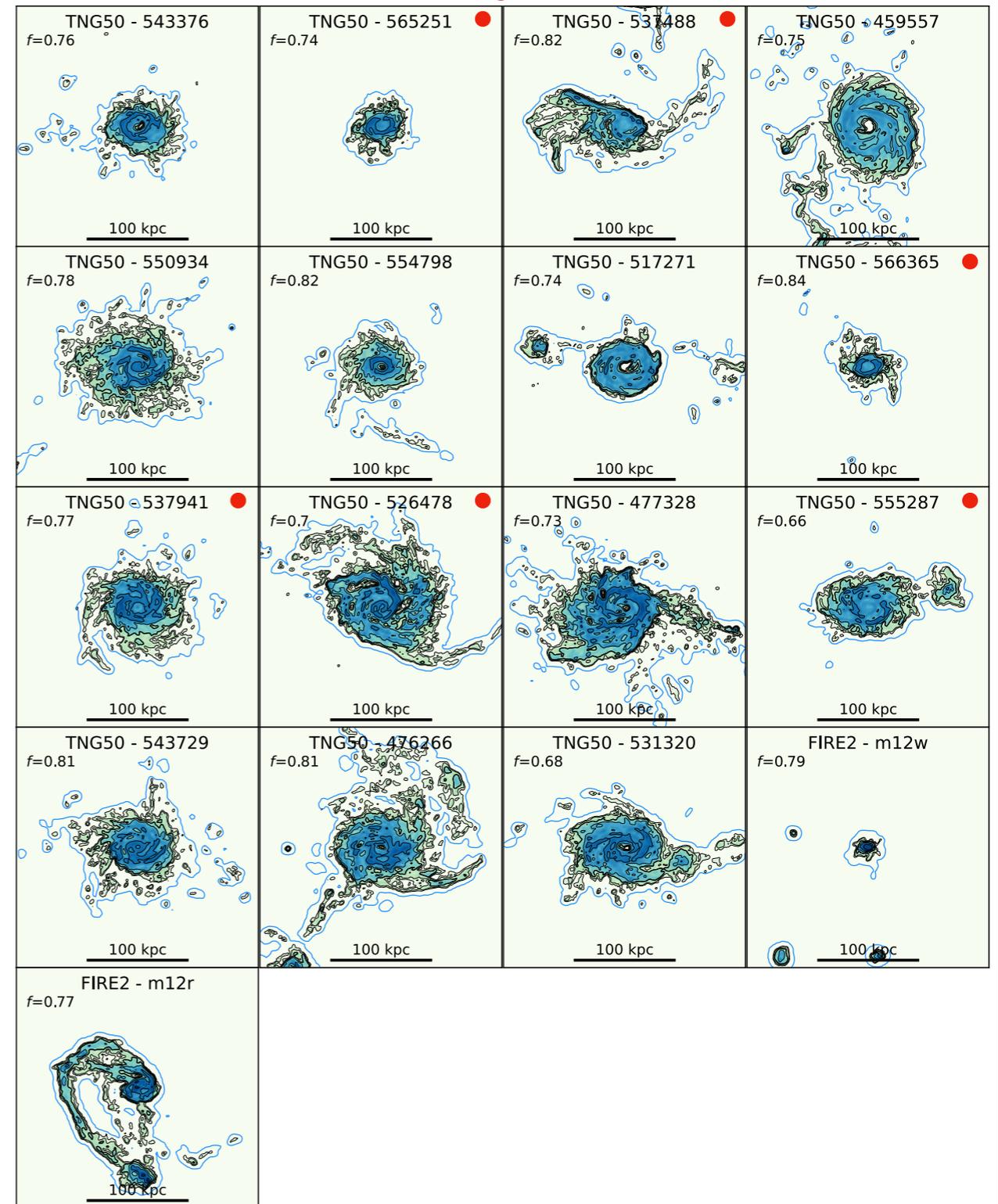
Galaxies dominated by low- $N_{\text{HI}}$  spaxels ( $<10^{20} \text{ cm}^{-2}$ )



## Regular



## Irregular



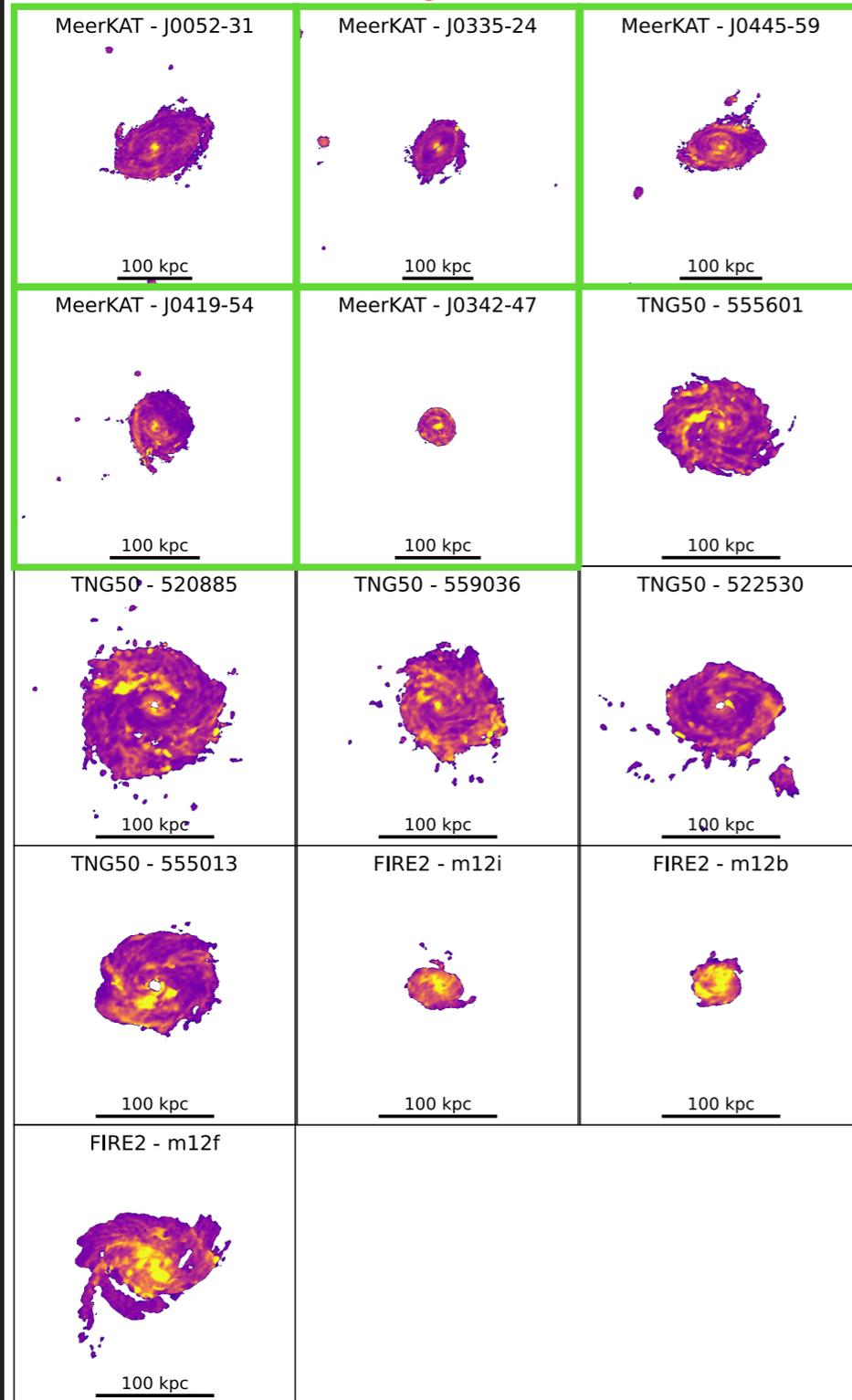
# Regular and irregular systems

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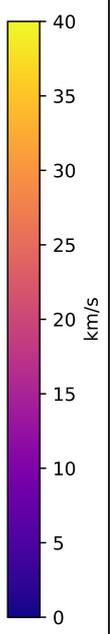
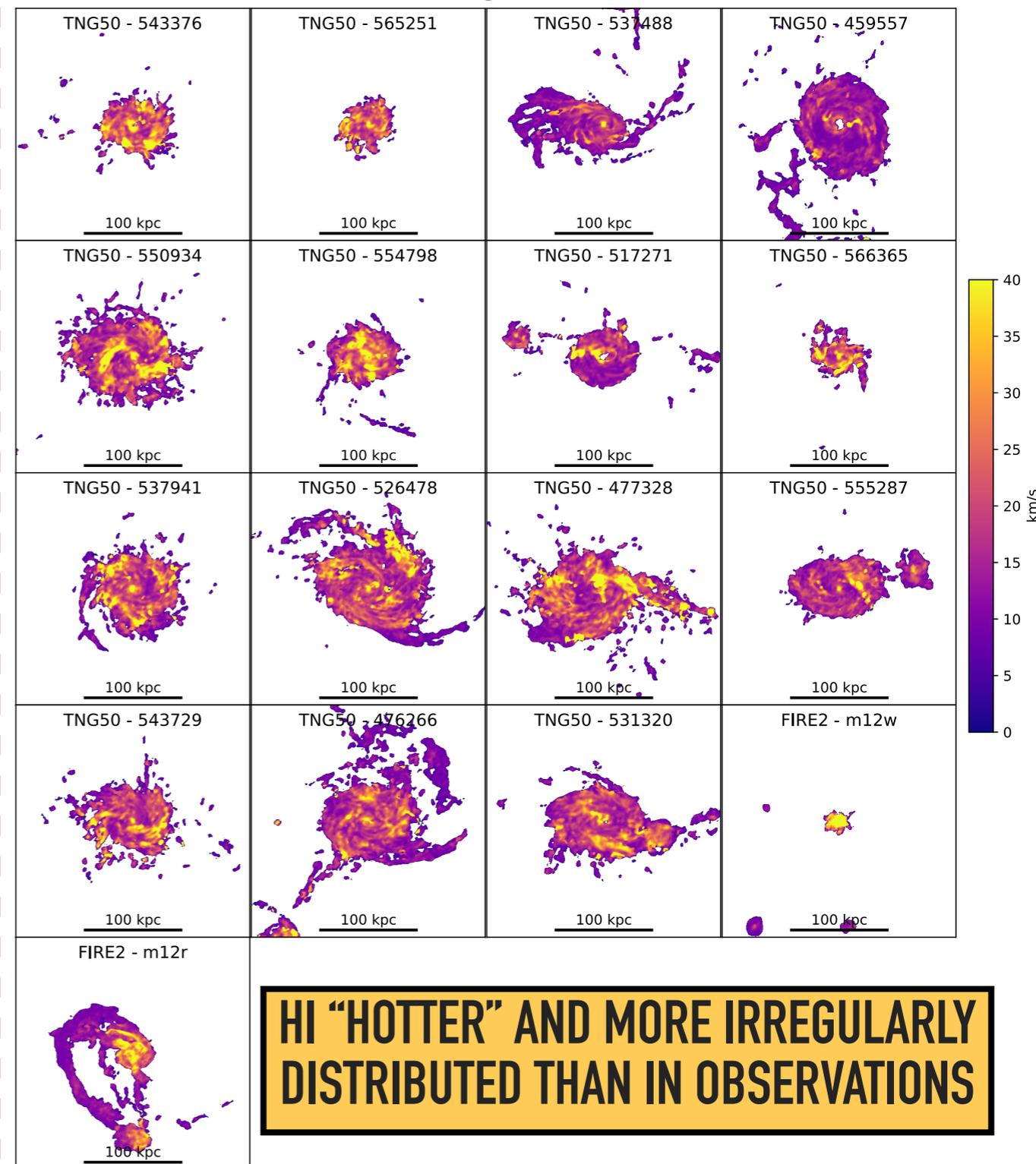
Galaxies dominated by low- $N_{\text{HI}}$  spaxels ( $<10^{20} \text{ cm}^{-2}$ )



## Regular

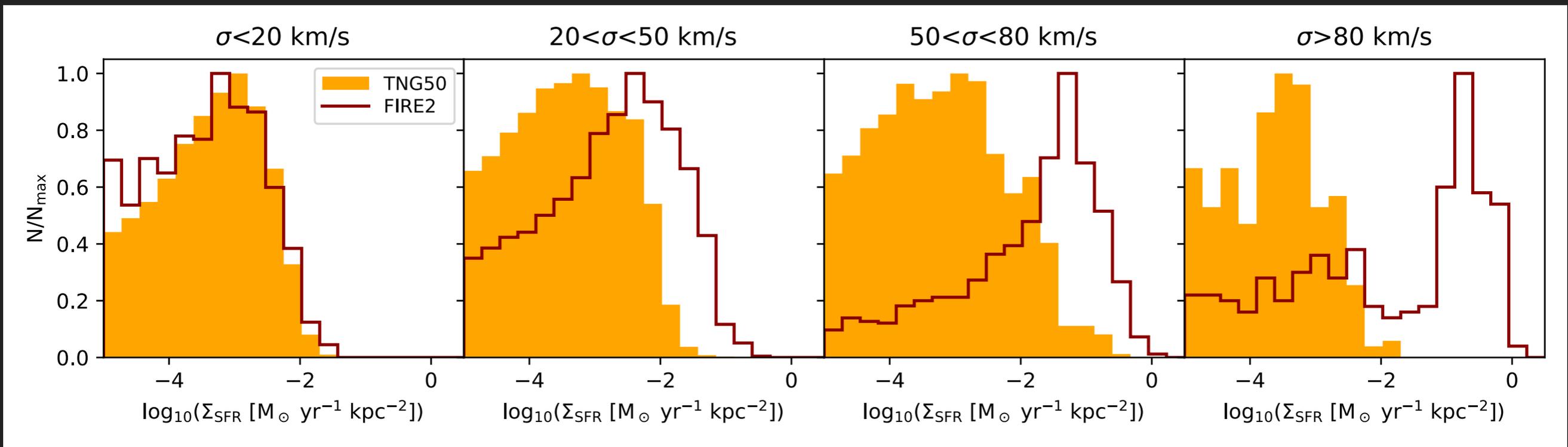


## Irregular



# Origin of irregular, high- $\sigma$ HI

## Stellar Feedback?

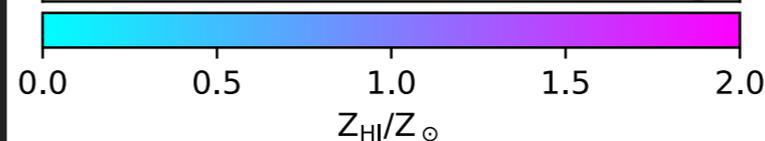
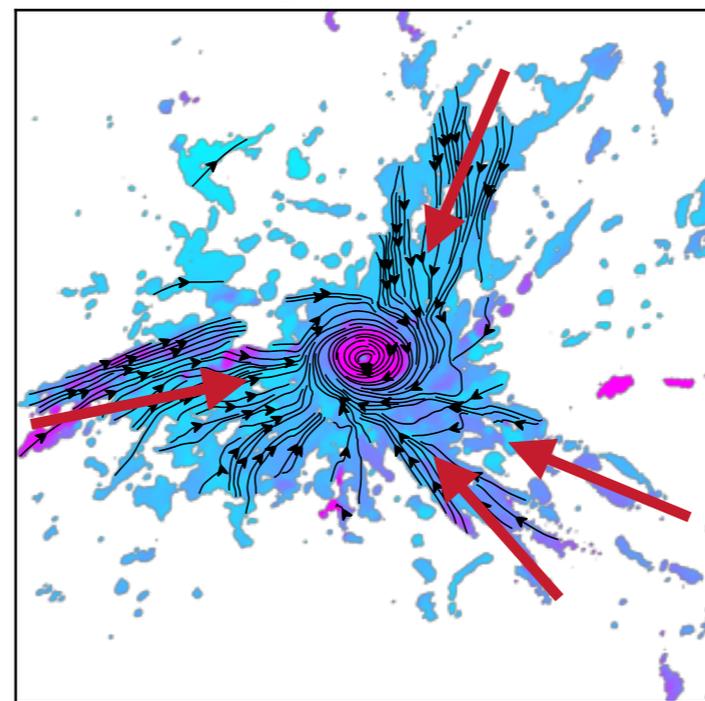


$\Sigma_{\text{SFR}}$  and  $\sigma$  highly correlated in FIRE2. What about TNG?

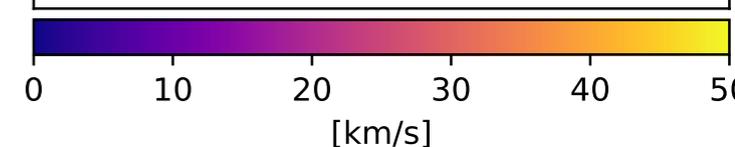
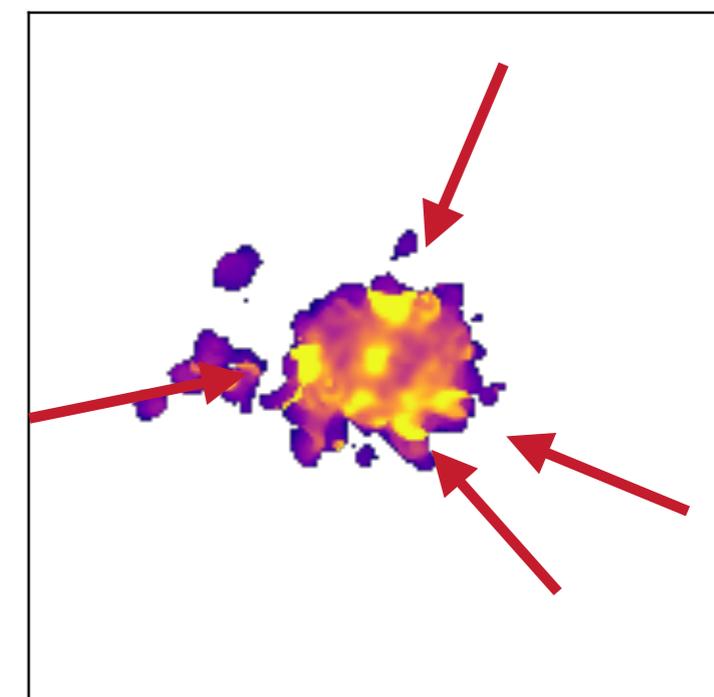
## Cold gas accretion

**STELLAR FEEDBACK (FIRE2)  
& GAS ACCRETION (TNG50)  
ARE TOO "VIGOROUS" IN THE SIMS**

HI metallicity + vel. vector field



moment-2

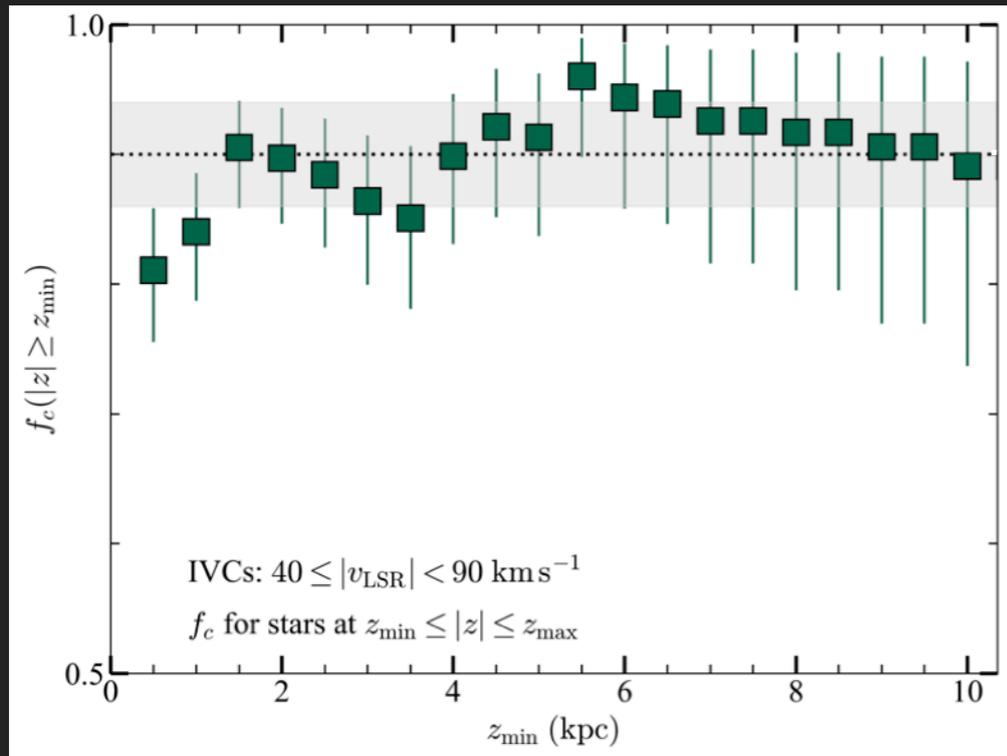


# Observing the Galactic CGM in absorption

Lehner, Howk, Marasco & Fraternali 2022

## $f_c$ vs $z$

IVCs



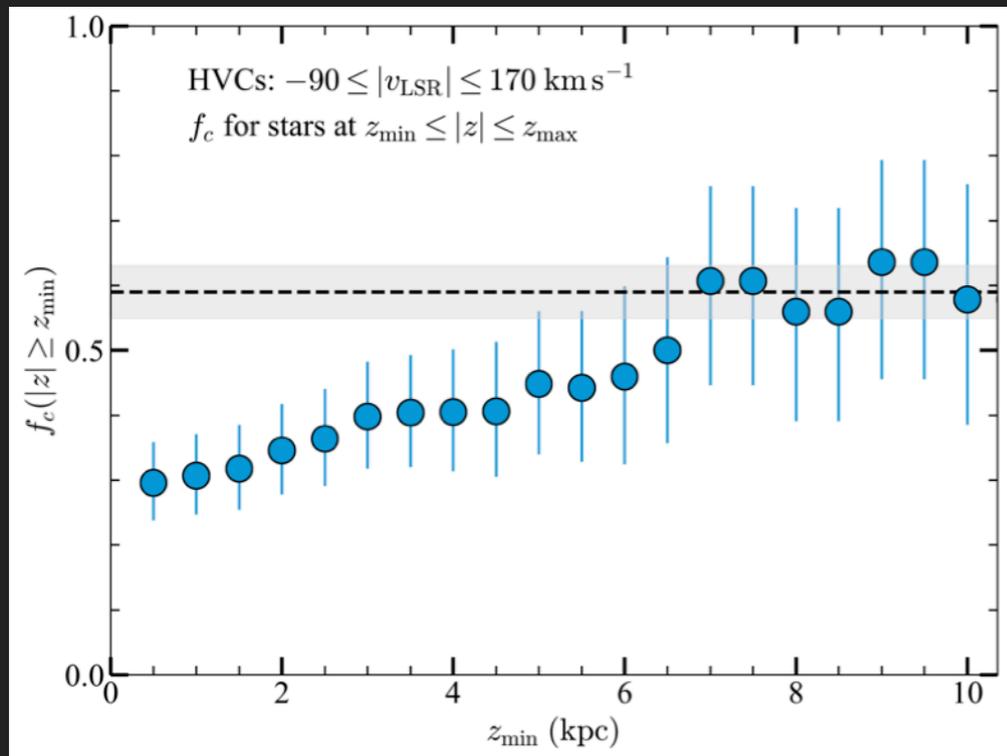
f<sub>c</sub> towards QSOs

covering fraction  
towards distant stars  
 $\cong$   
covering fraction  
towards QSOs



**All IVCs and HVCs up to  
170 km/s confined  
within  $|z| < 7-10$  kpc**

HVCs (up to 170 km/s)



f<sub>c</sub> towards QSOs

QSOs do not probe  
additional material

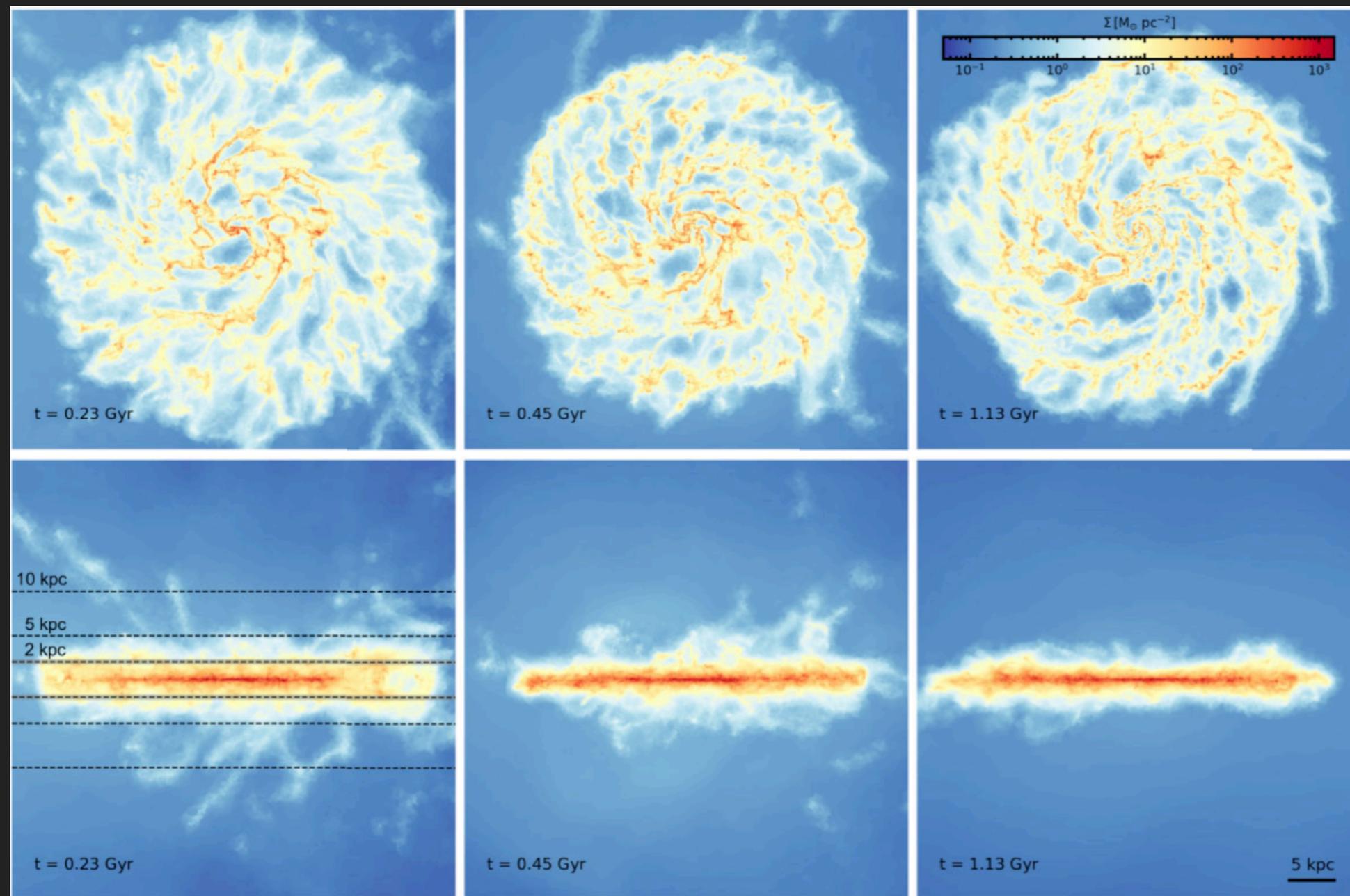
VHVCs are located at  
larger distances

(but typically associated with Magellanic  
Stream or Fermi Bubble)

# Linking stellar feedback and gas accretion

F. Barbani+23, +25

- ▶ Sets of controlled hydrodynamical simulations of MW-like galaxies
- ▶ AREPO code + SMUGGLE sub-grid model for a multiphase ISM (Marinacci+19)
- ▶ isolated galaxy embedded within a cosmological hot corona

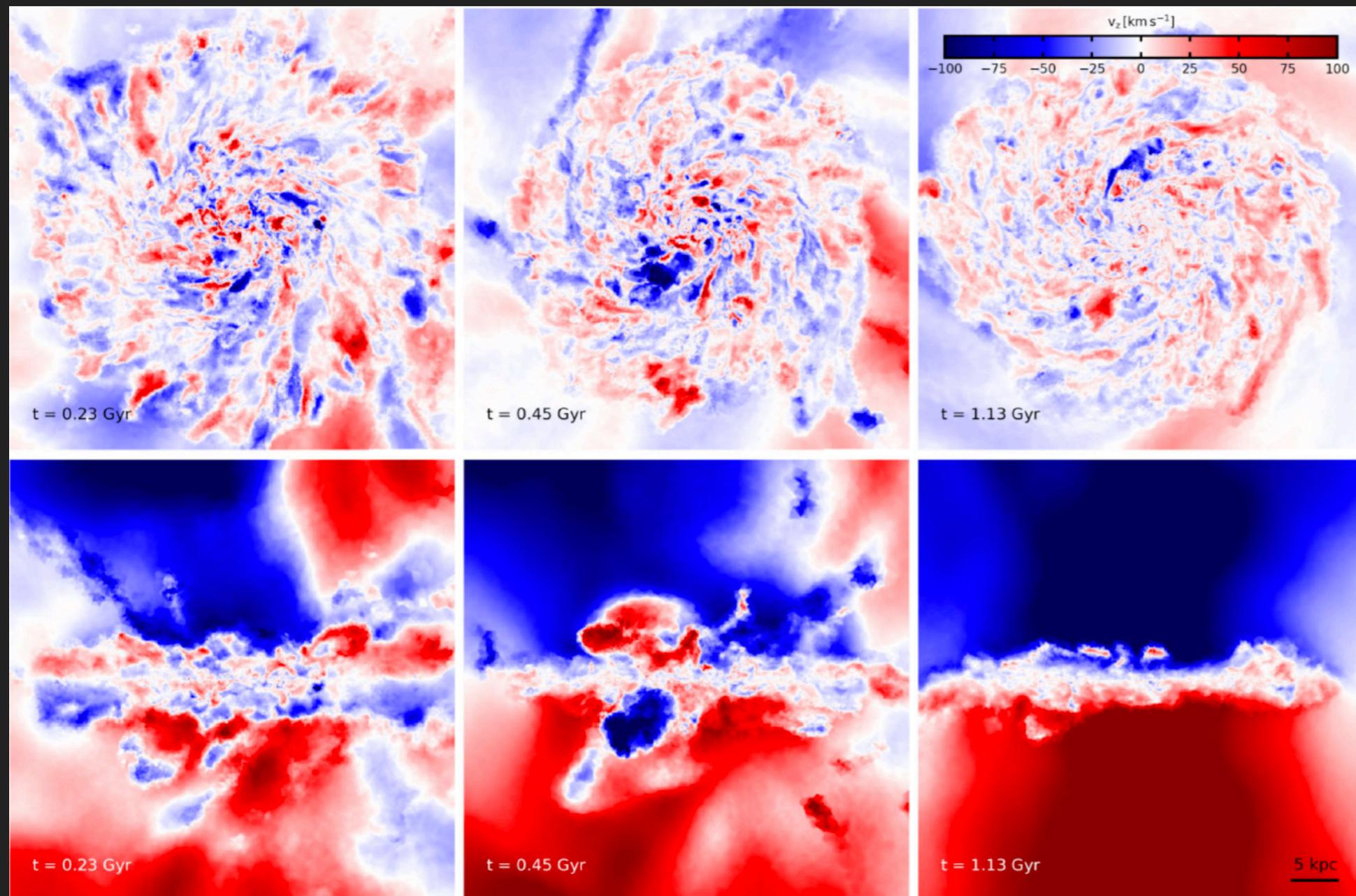


Dense gas is confined within  $\sim 5$ -10 kpc from the midplane.

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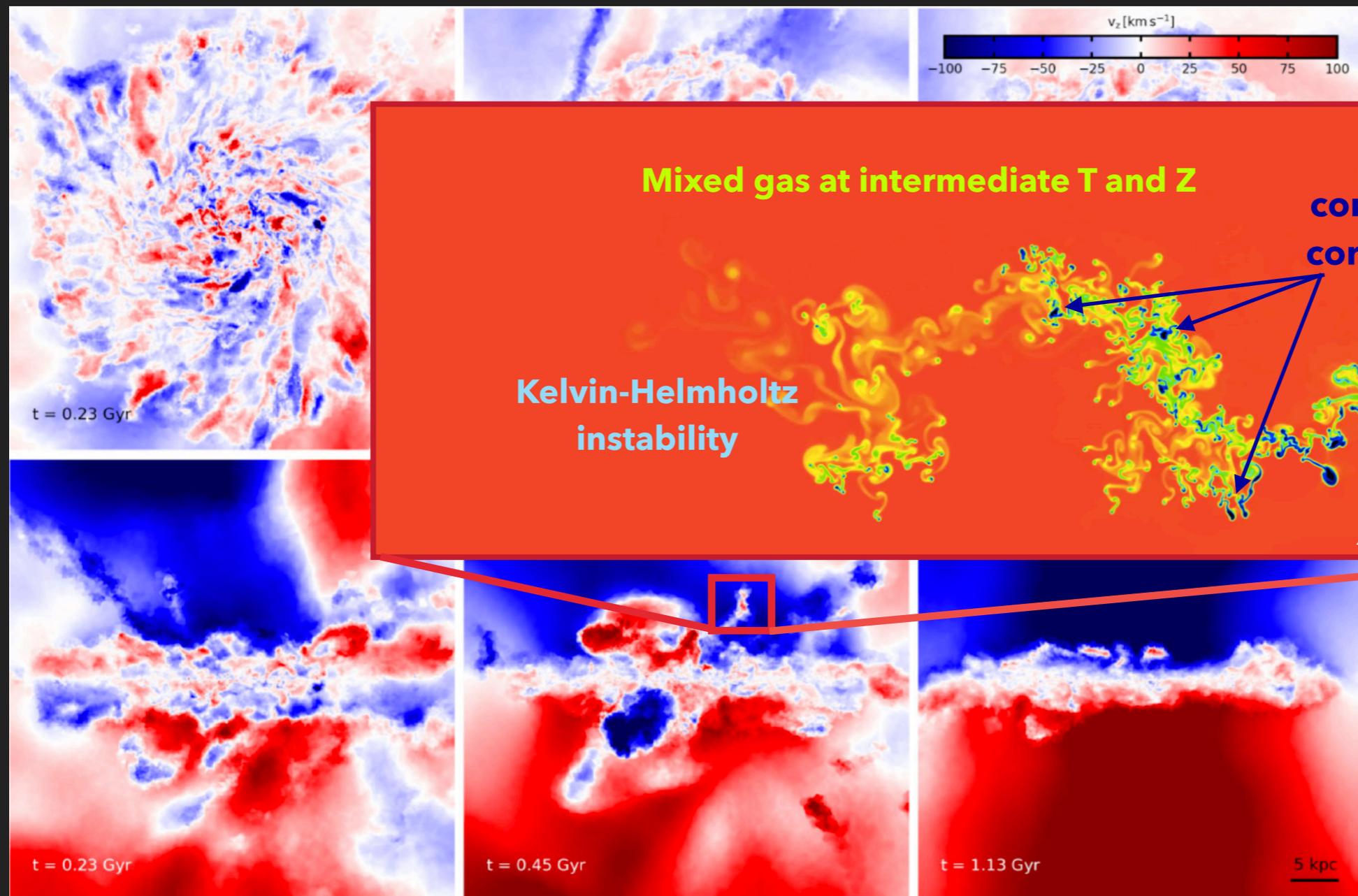
Vertical speeds  $< 100$  km/s

**feedback triggers a (gentle) galactic fountain**

# Linking stellar feedback and gas accretion

F. Barbani+23, +25

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Dense gas is confined  
~ 5-10 kpc from the  
midplane.  
speeds < 100 km/s

feedback triggers a  
) galactic fountain

galactic fountain  
stimulates gas accretion  
by promoting the cooling  
of the coronal gas

# Linking stellar feedback and gas accretion

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- ▶ Sets of controlled hydrodynamical simulations of MW-like galaxies
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- ▶ isolated galaxy embedded within a cosmological hot corona



Mixed gas at intermediate T and Z

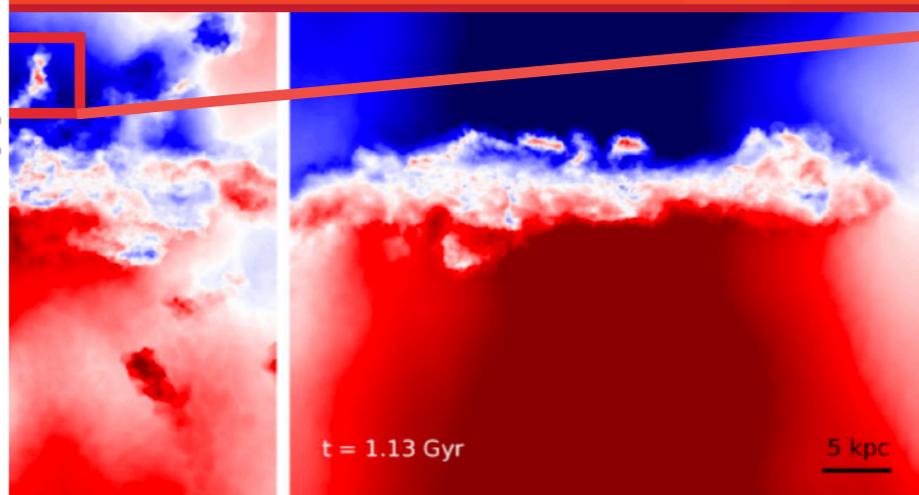
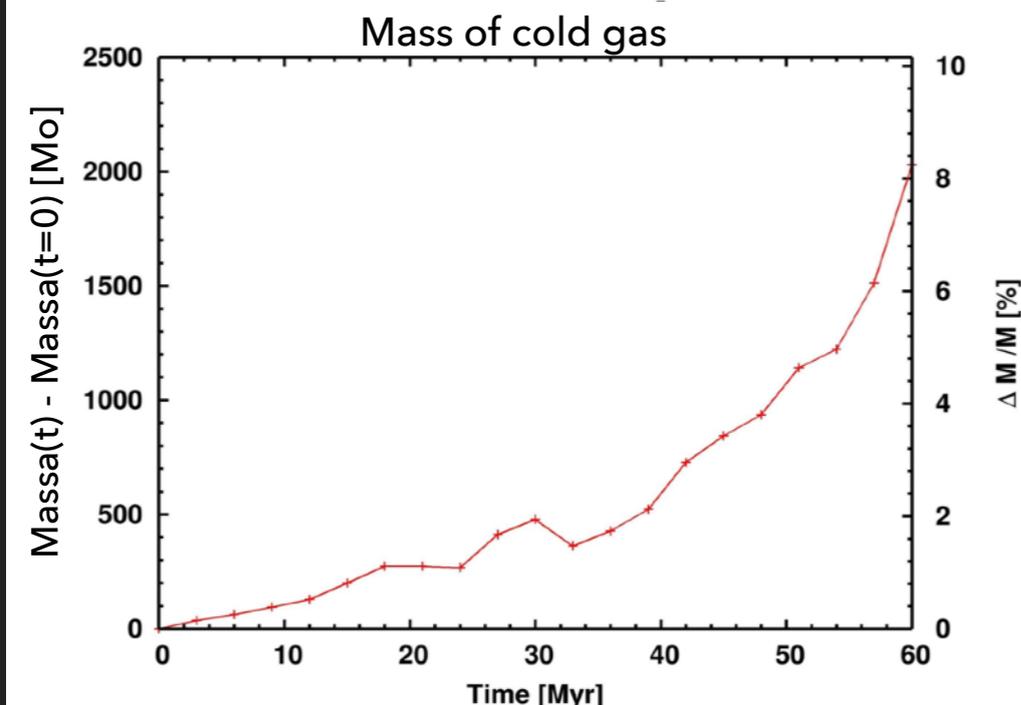
condensed coronal gas

Kelvin-Helmholtz instability

Armillotta+16

Dense gas is confined  
~ 5-10 kpc from the  
midplane.  
speeds < 100 km/s

feedback triggers a  
) galactic fountain

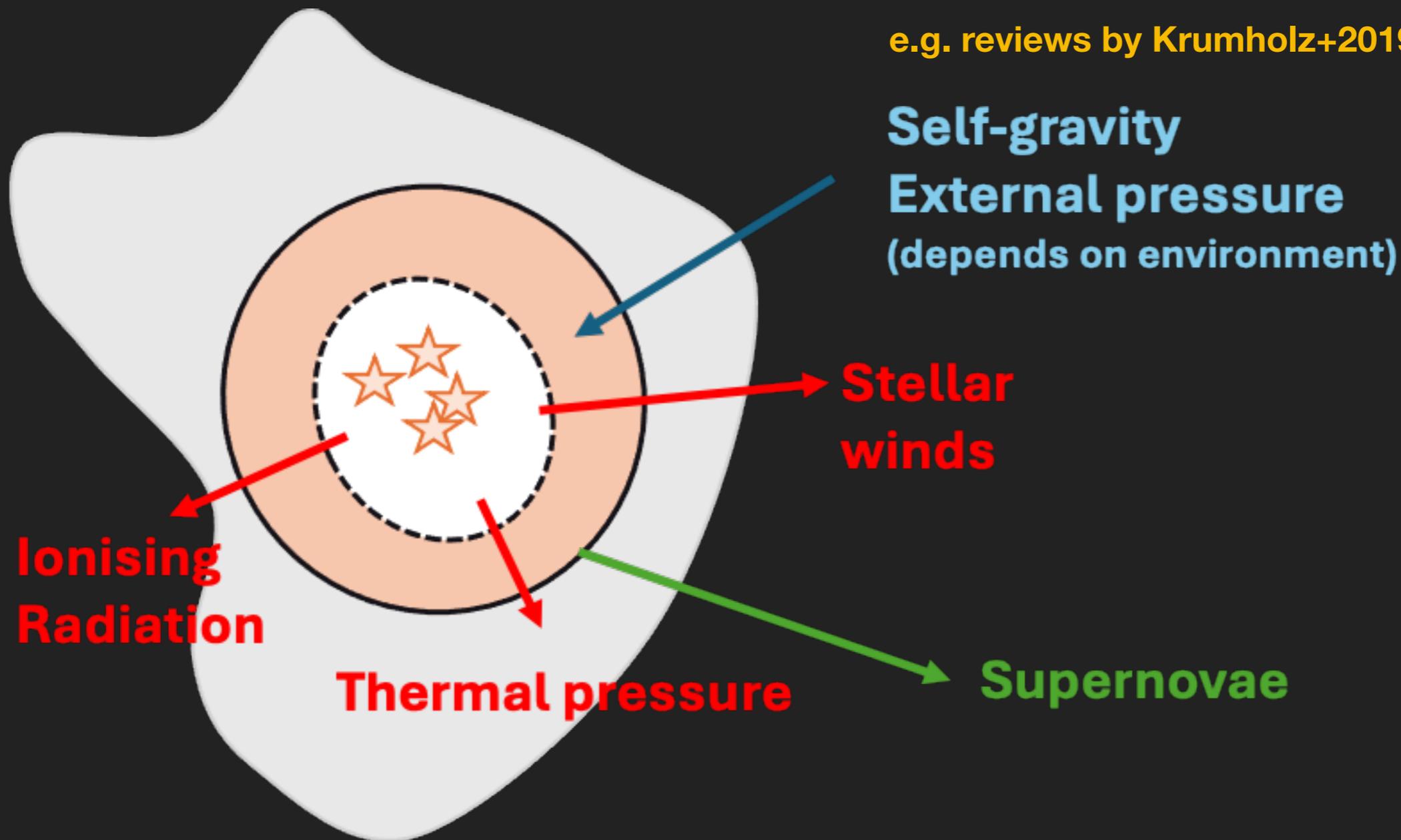


galactic fountain  
stimulates gas accretion  
by promoting the cooling  
of the coronal gas

# The small-scale matter cycle

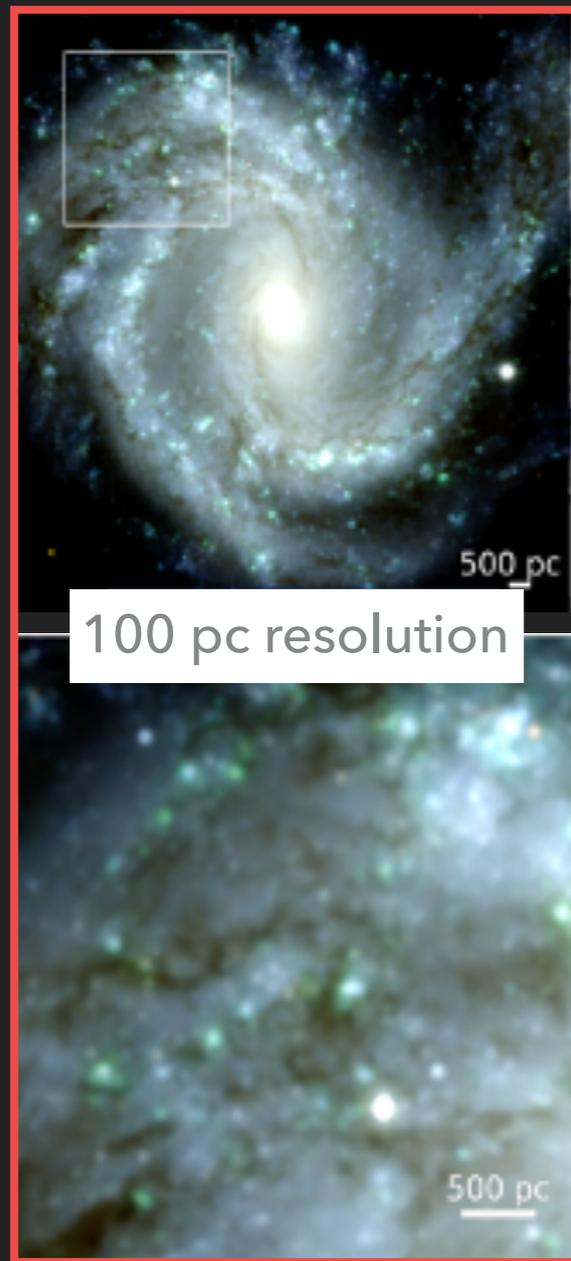
# The physics of stellar feedback

e.g. reviews by Krumholz+2019, Chevance+2020

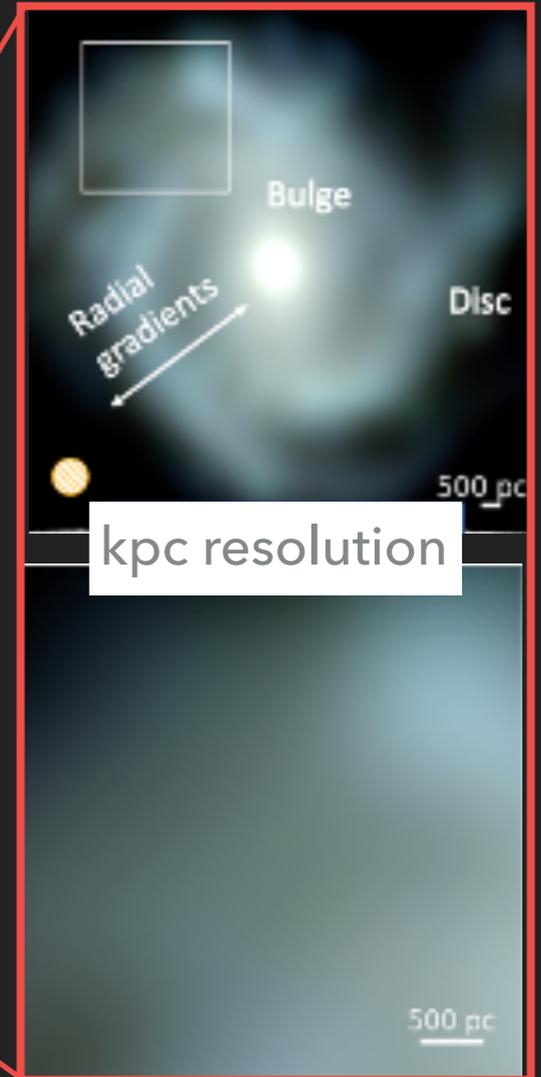


- ▶ Which feedback mechanisms dominate (as a function of physical conditions/redshift)?
- ▶ How do ionising photons shape the ISM?
- ▶ How does local dynamical environment affect SFE?

# On observer's perspective on the small-scale matter cycle



LEGUS,  
PHANGS

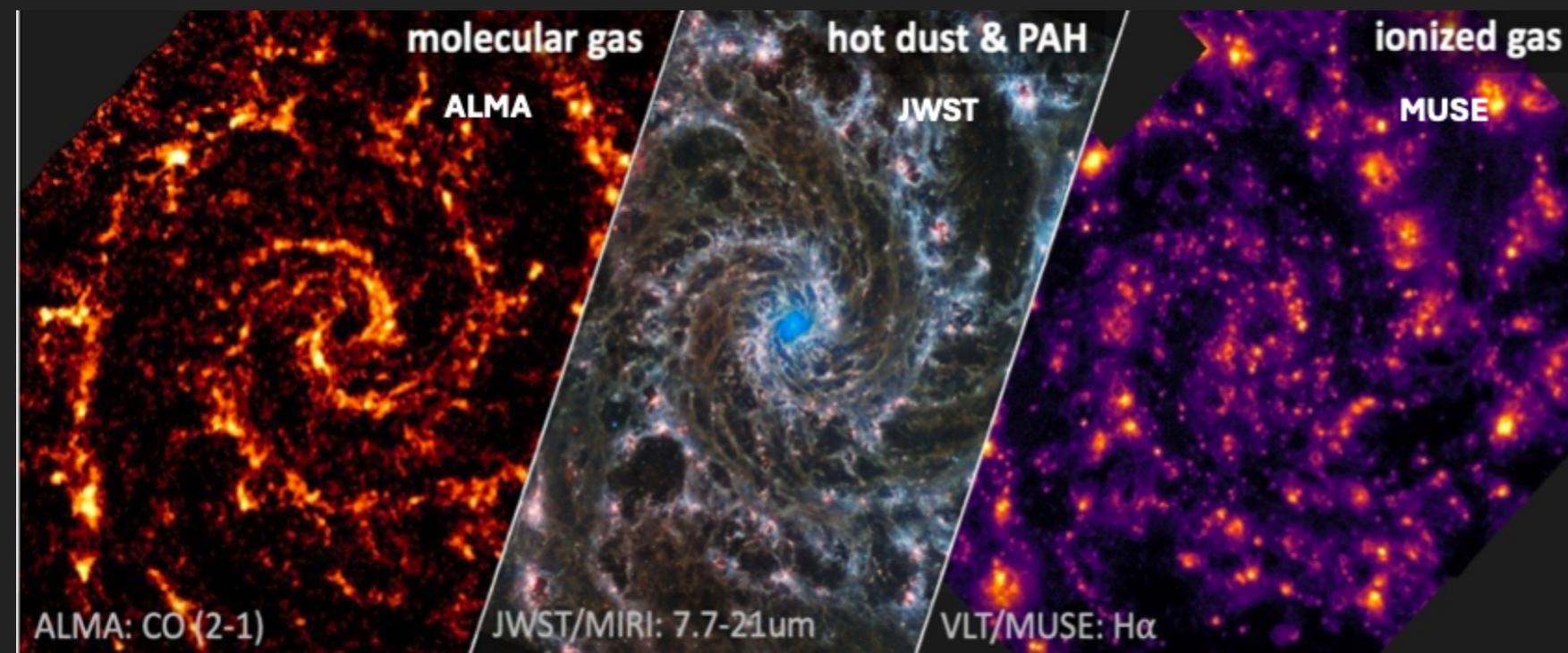


CALIFA  
(EDGE),  
Dustpedia,  
MaNGA +  
KILOGAS



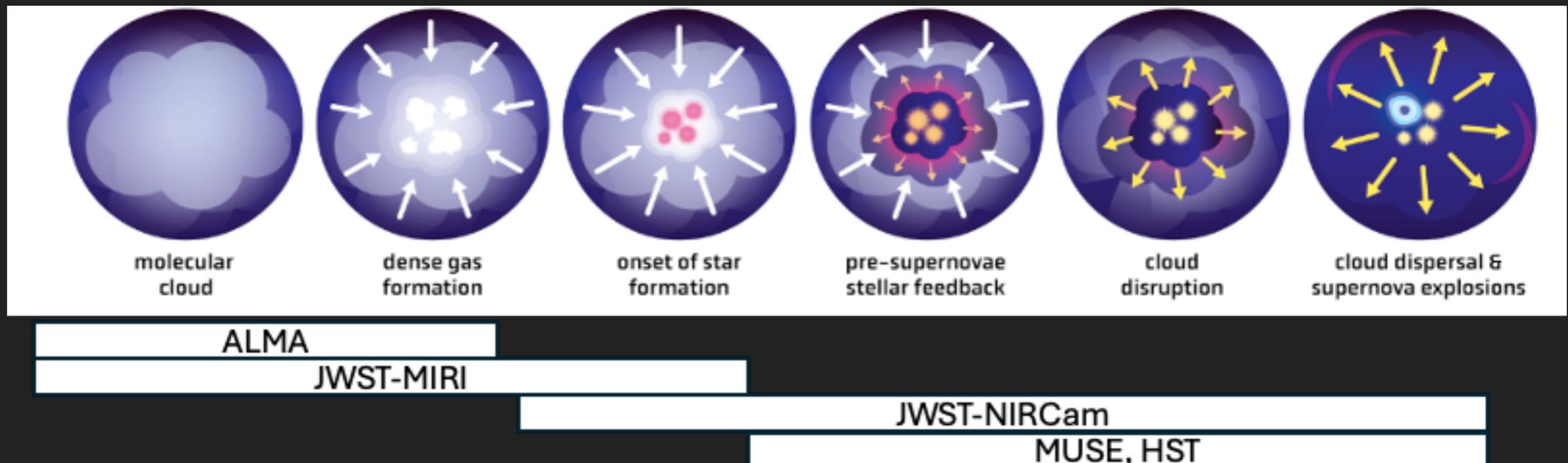
SDSS V LVM

# A high-resolution view of the small-scale matter cycle



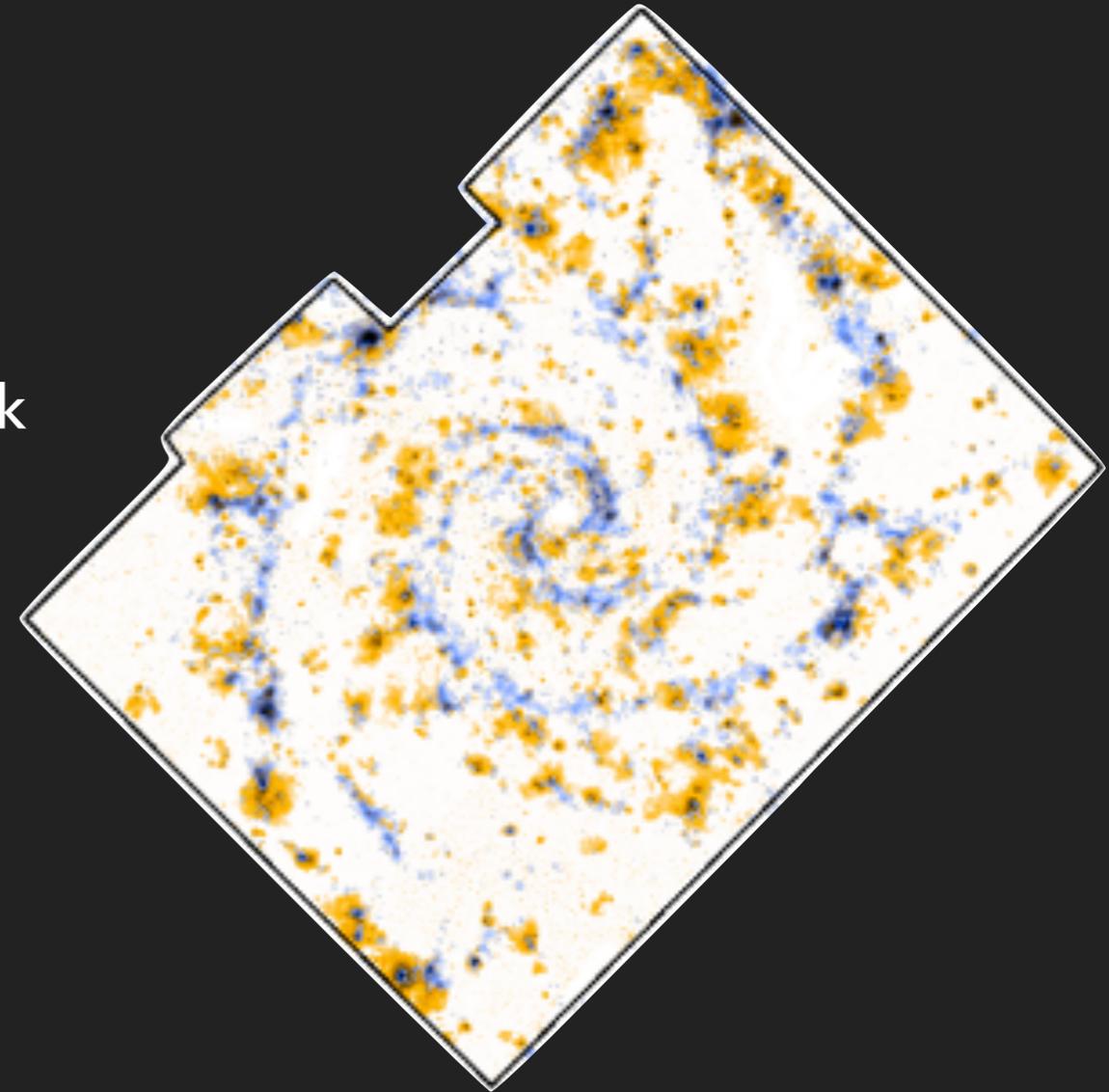
Resolve the fundamental units of the star formation cycle at cloud scales (100 pc): **GMCs, HII regions, star clusters**

The PHANGS survey studies ~100 nearby galaxies with ALMA, HST, JWST and MUSE



# The multi-phase ISM at cloud-scale resolution

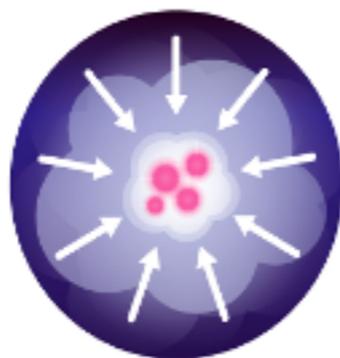
- The **spatial decorrelation** between CO and H $\alpha$  traces the timescales of feedback
- Star formation in individual clouds is disrupted by early (**pre-supernova**) feedback



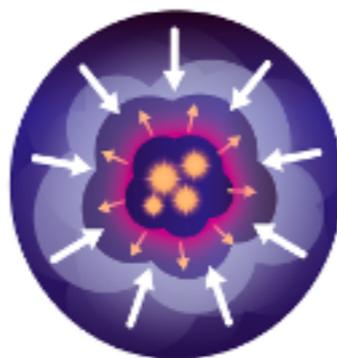
GMC timescale      Feedback phase  
4-20 Myr              1-6 Myr



molecular cloud



onset of star formation

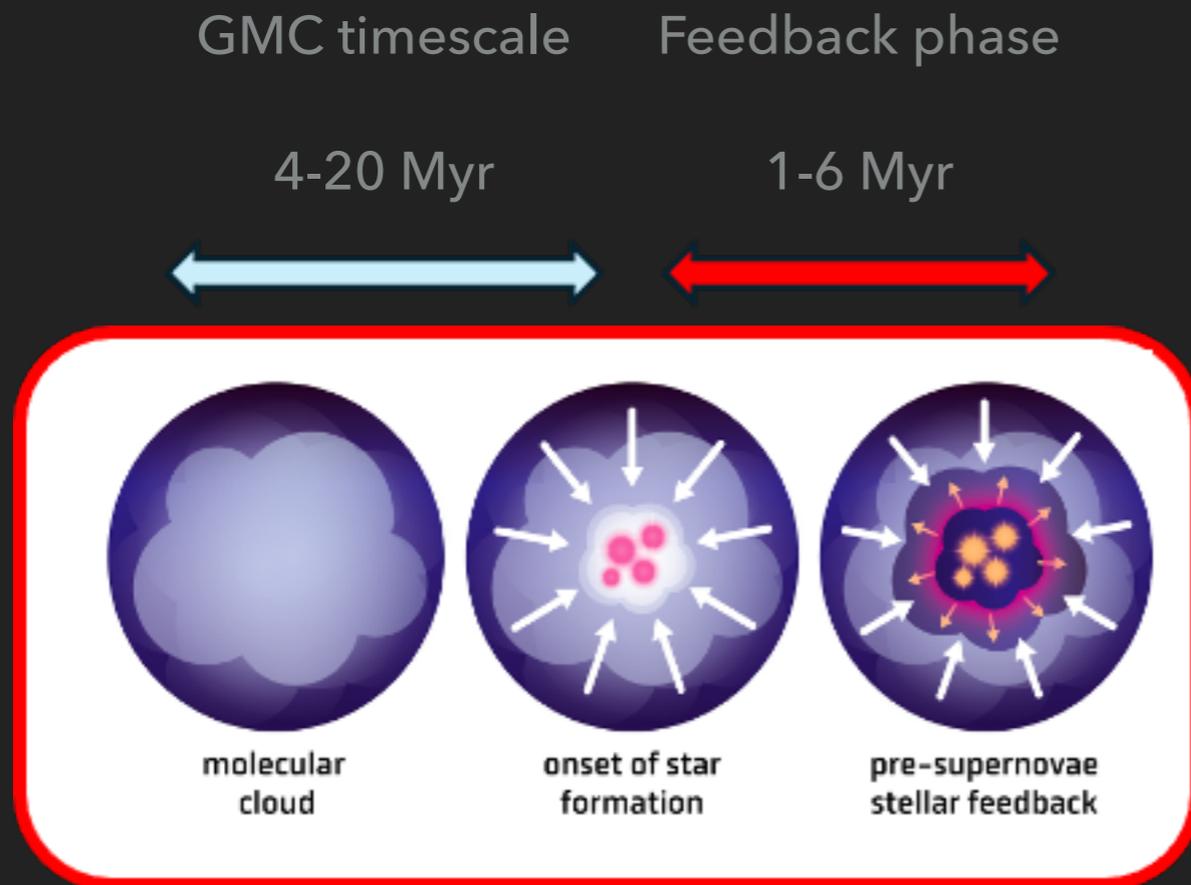


pre-supernovae stellar feedback

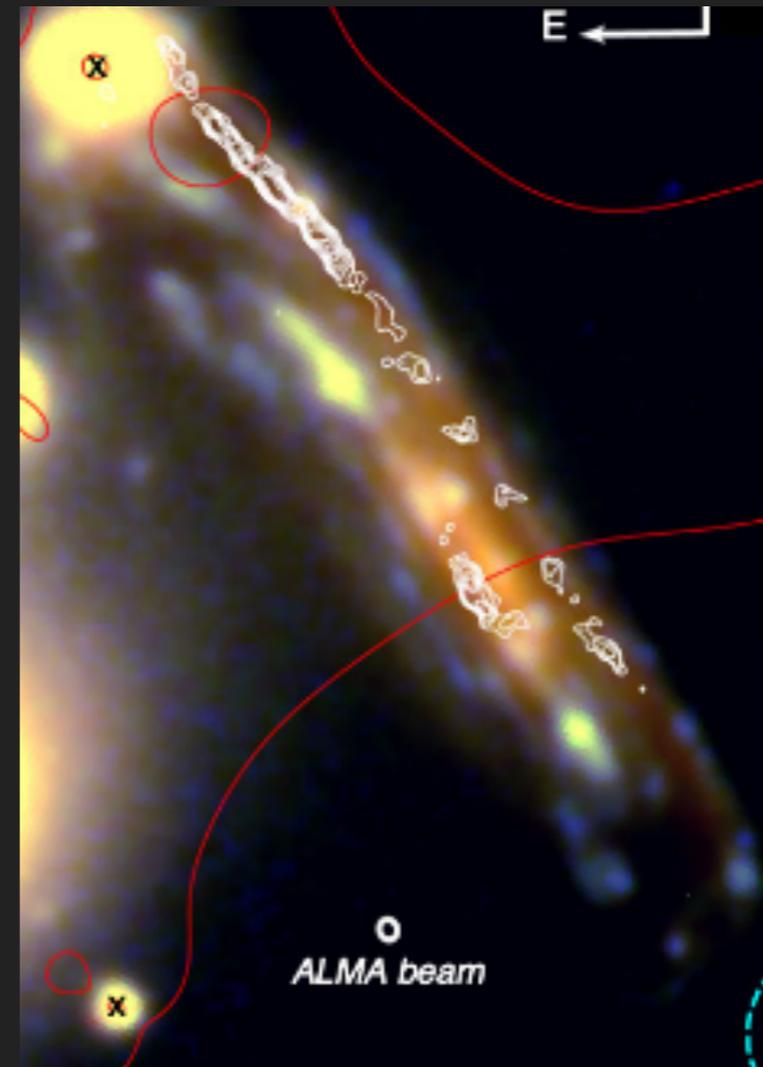
Kawamura+2009, [Corbelli+2017](#),  
Schinnerer+2019, [Chevance+2020](#), [Kim+2022](#)

# The multi-phase ISM at cloud-scale resolution

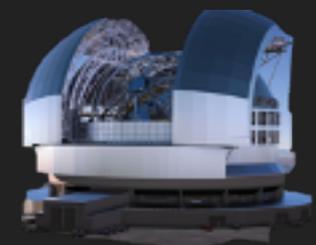
- The **spatial decorrelation** between CO and  $H\alpha$  traces the timescales of feedback
- Star formation in individual clouds is disrupted by early (**pre-supernova**) feedback



Pushing towards GMC resolution at  $z\sim 1$  with ALMA and lensing



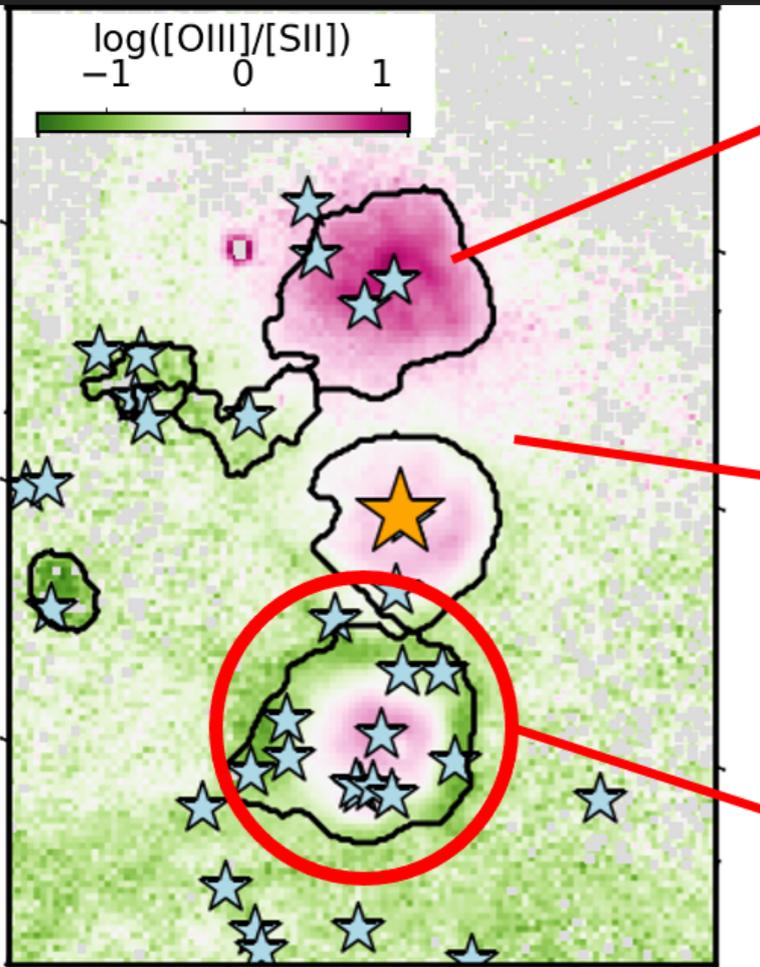
Dessagues-Zavadsky+23



ETL's diffraction limit  $z\sim 2 = 100\text{pc}$

# A diversity of ISM conditions

Three HII regions in M33 observed with MUSE



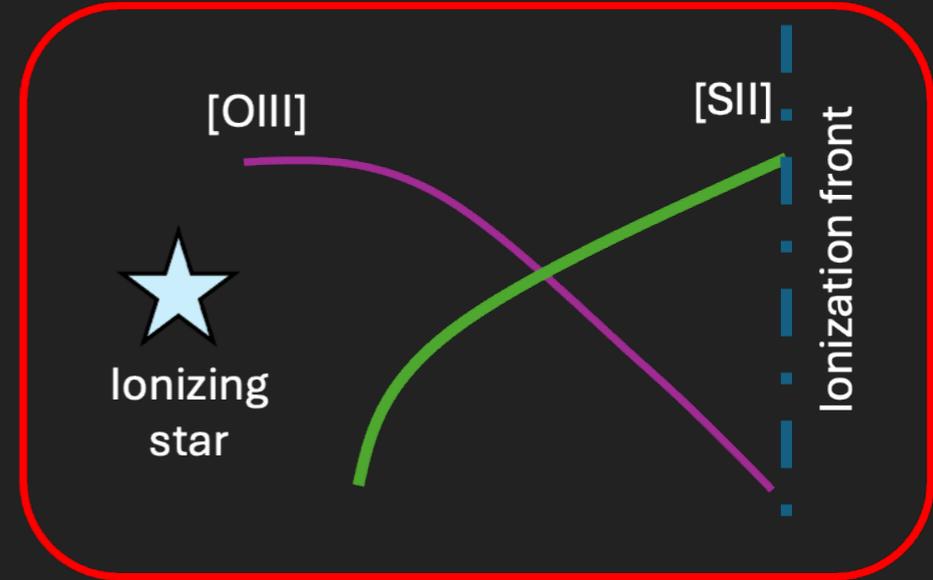
**Matter-bounded HII regions:** no clear ionization front  
 → escaping photons ionize the DIG

**A Wolf-Rayet star:** harder ionization field, local enrichment?

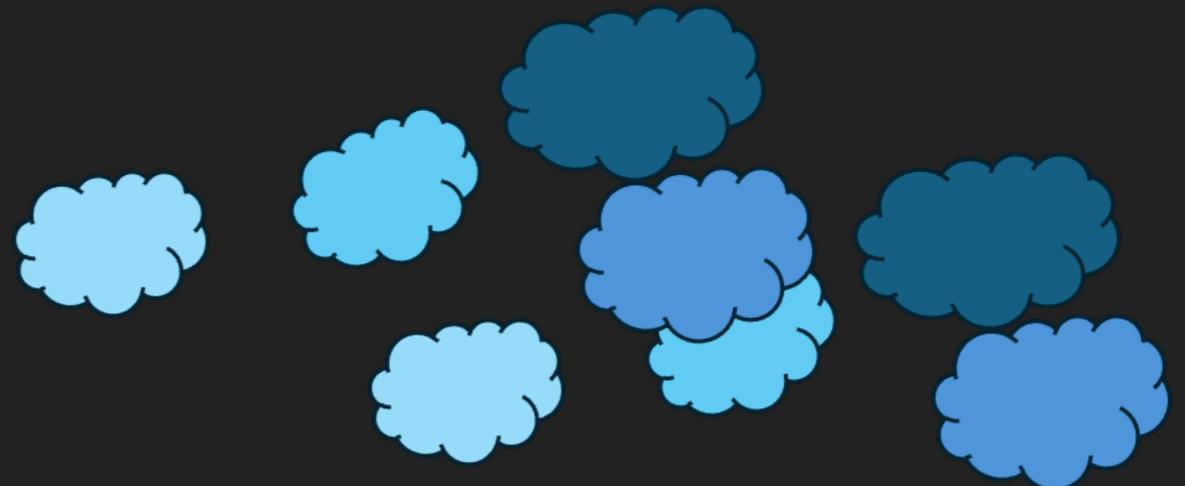
**A classical, ionization-bounded HII region**

Feltre+25

Photoionization cartoon



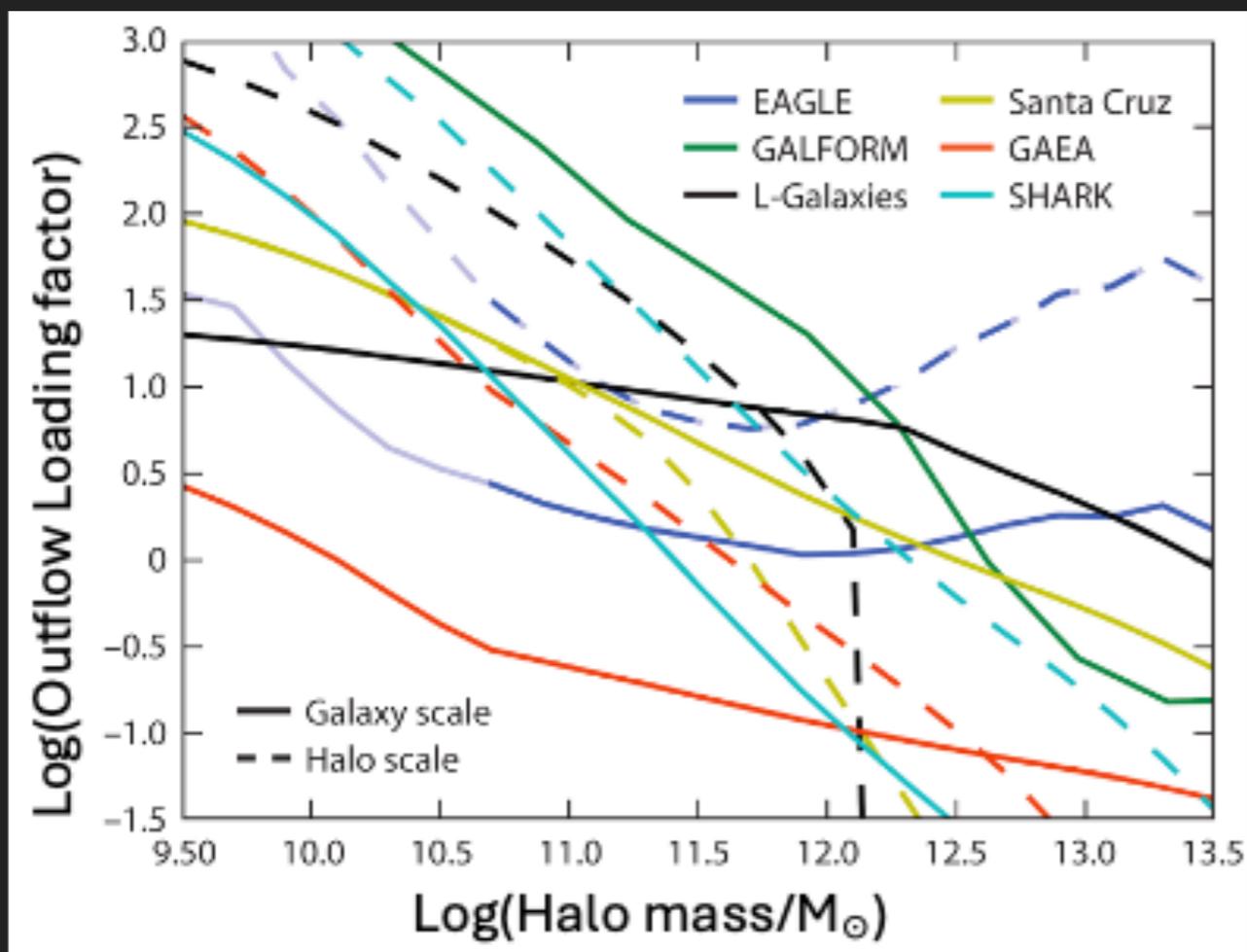
$$= \sum_{i=0}^n$$



Marconi+24, Moreschini+25

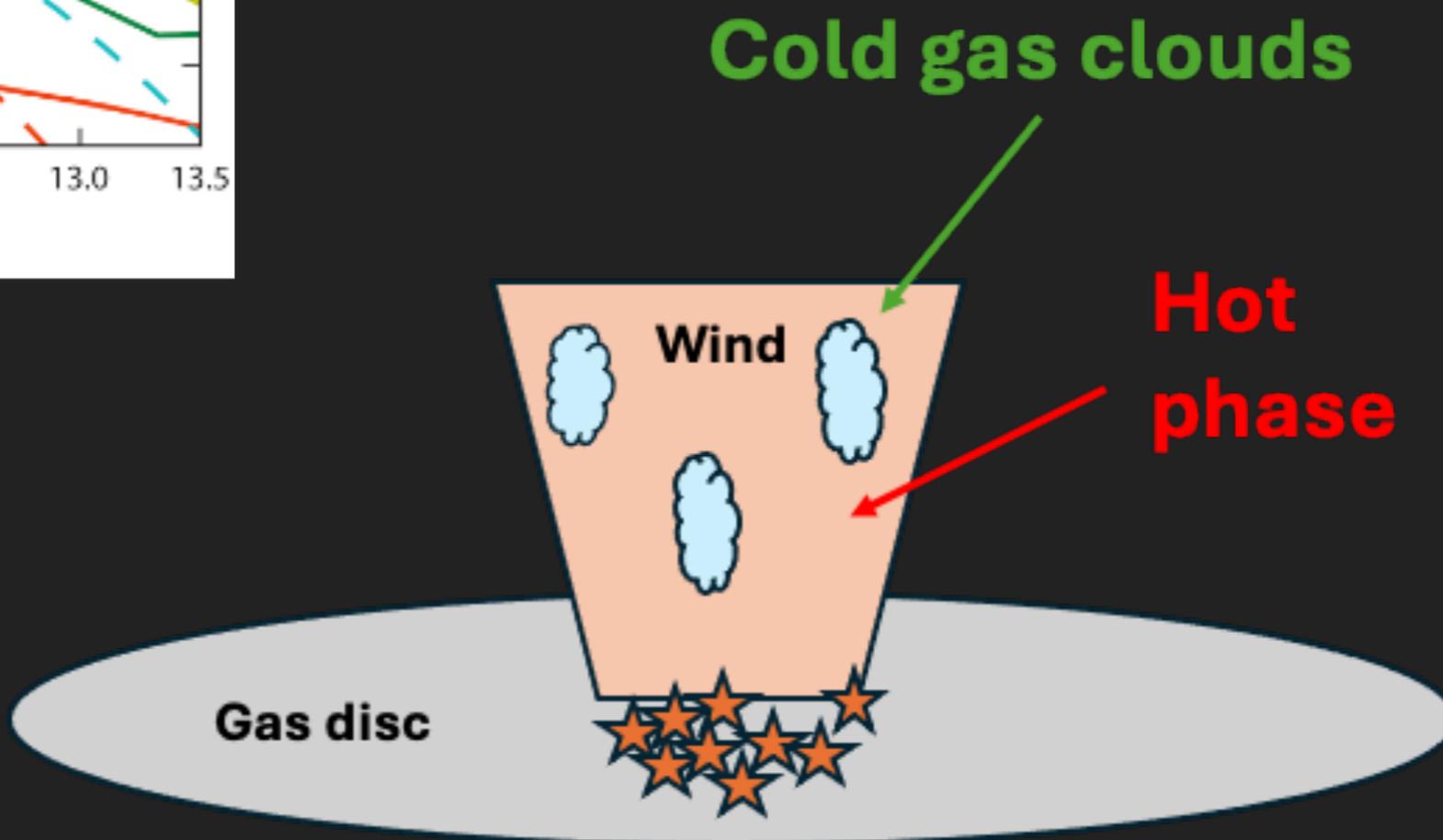
# The physics of galactic winds

e.g. review by Faucher-Giguere & Oh 2023



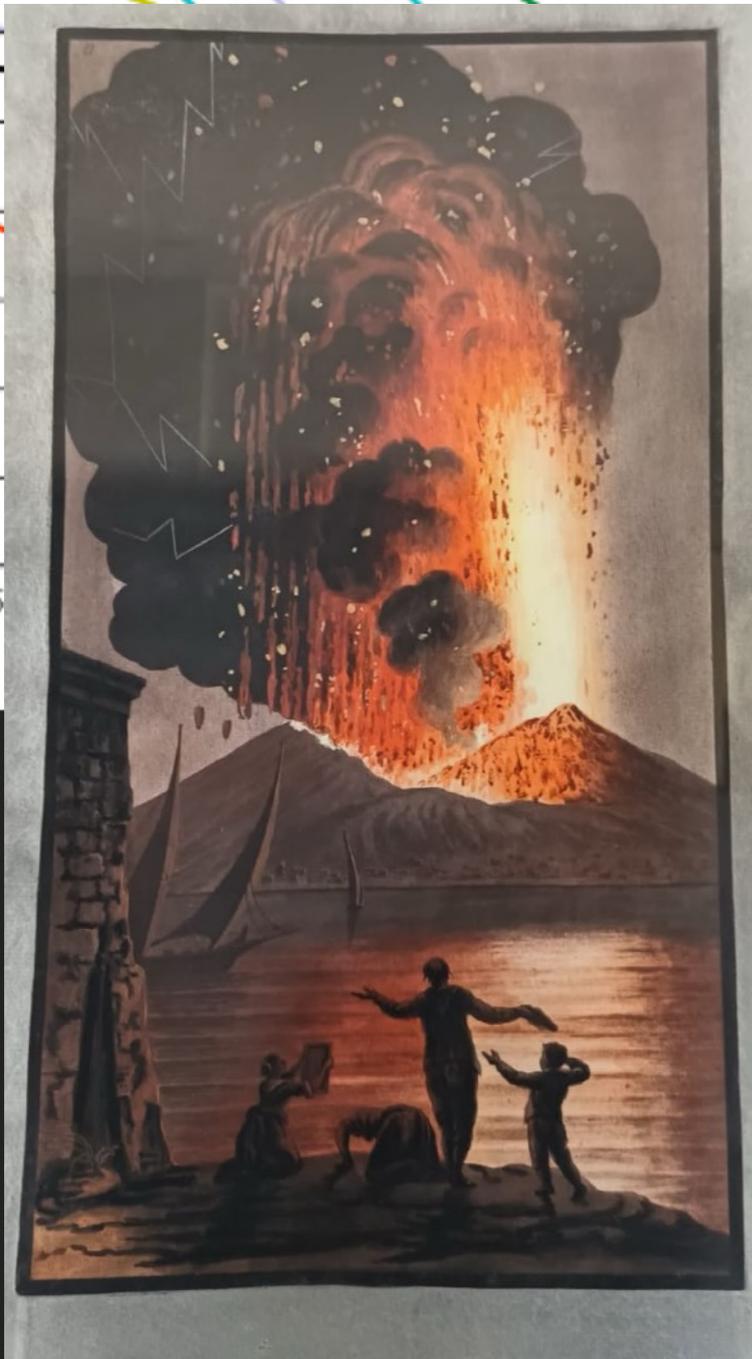
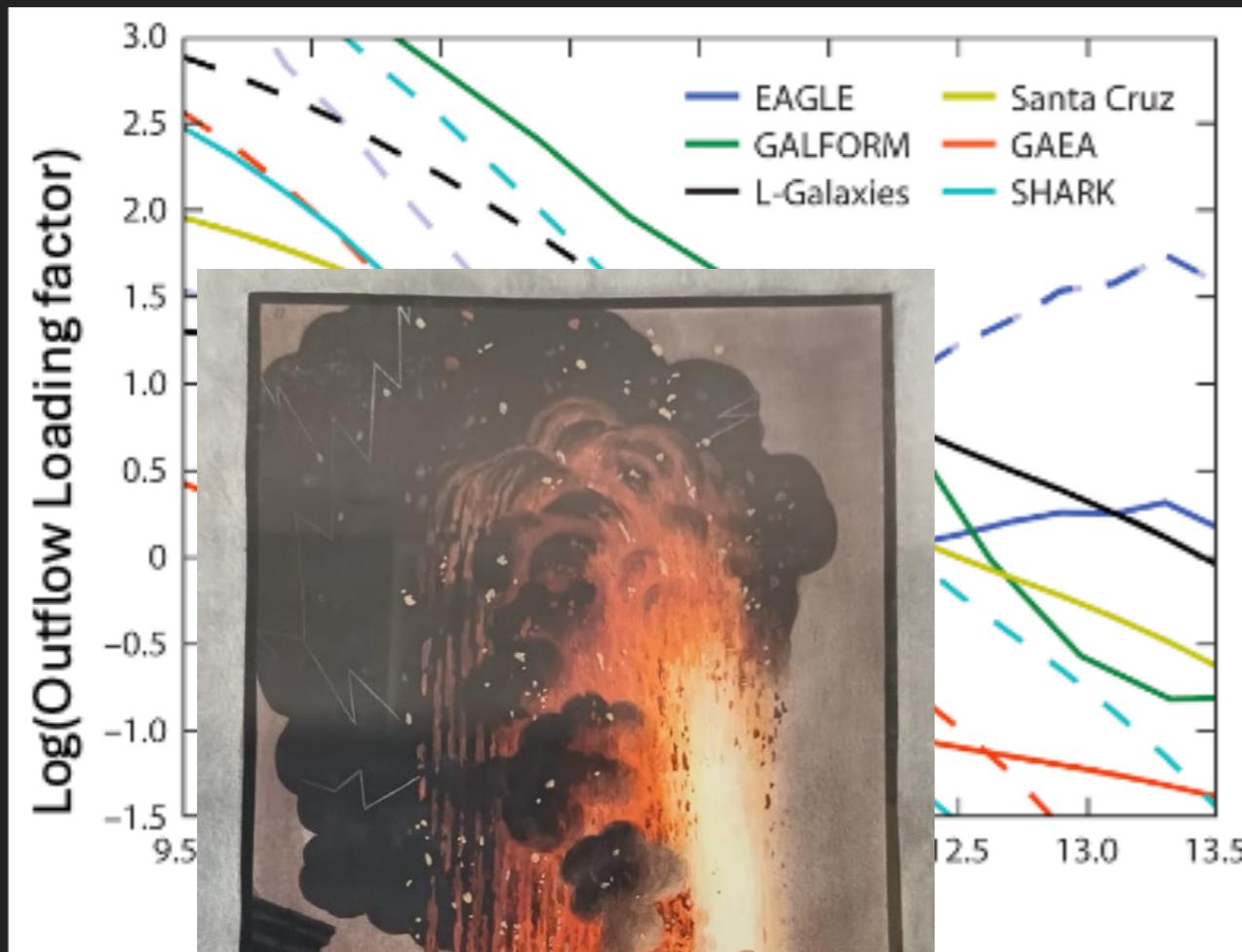
Thompson & Heckman 24

- ▶ Entrainment of cold gas?
- ▶ Role of radiation pressure?
- ▶ Cosmic Ray feedback?

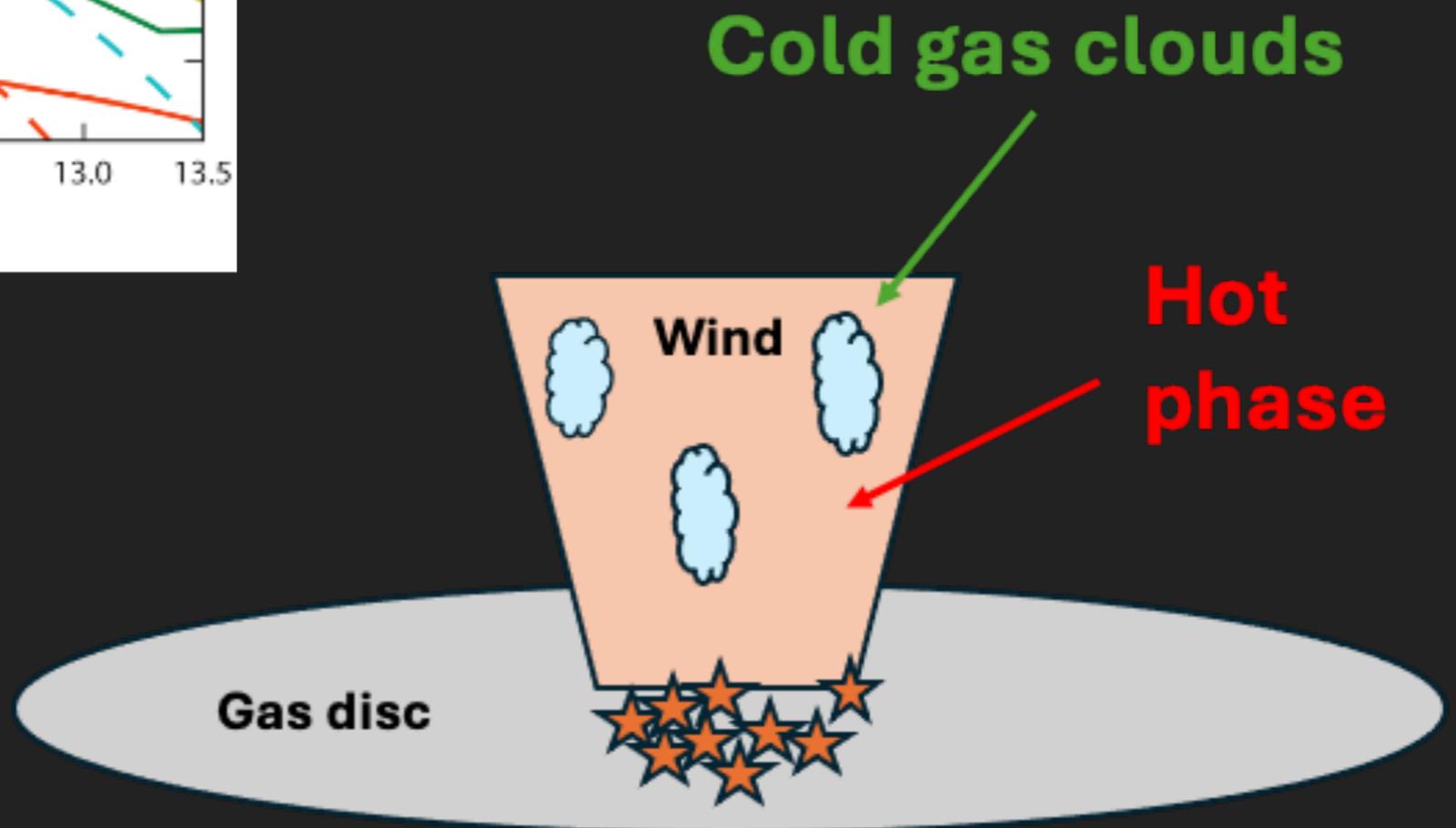


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e.g. review by Faucher-Giguere & Oh 2023



- ▶ Entrainment of cold gas?
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# Ionised gas outflows in nearby starburst dwarfs

Marasco+23

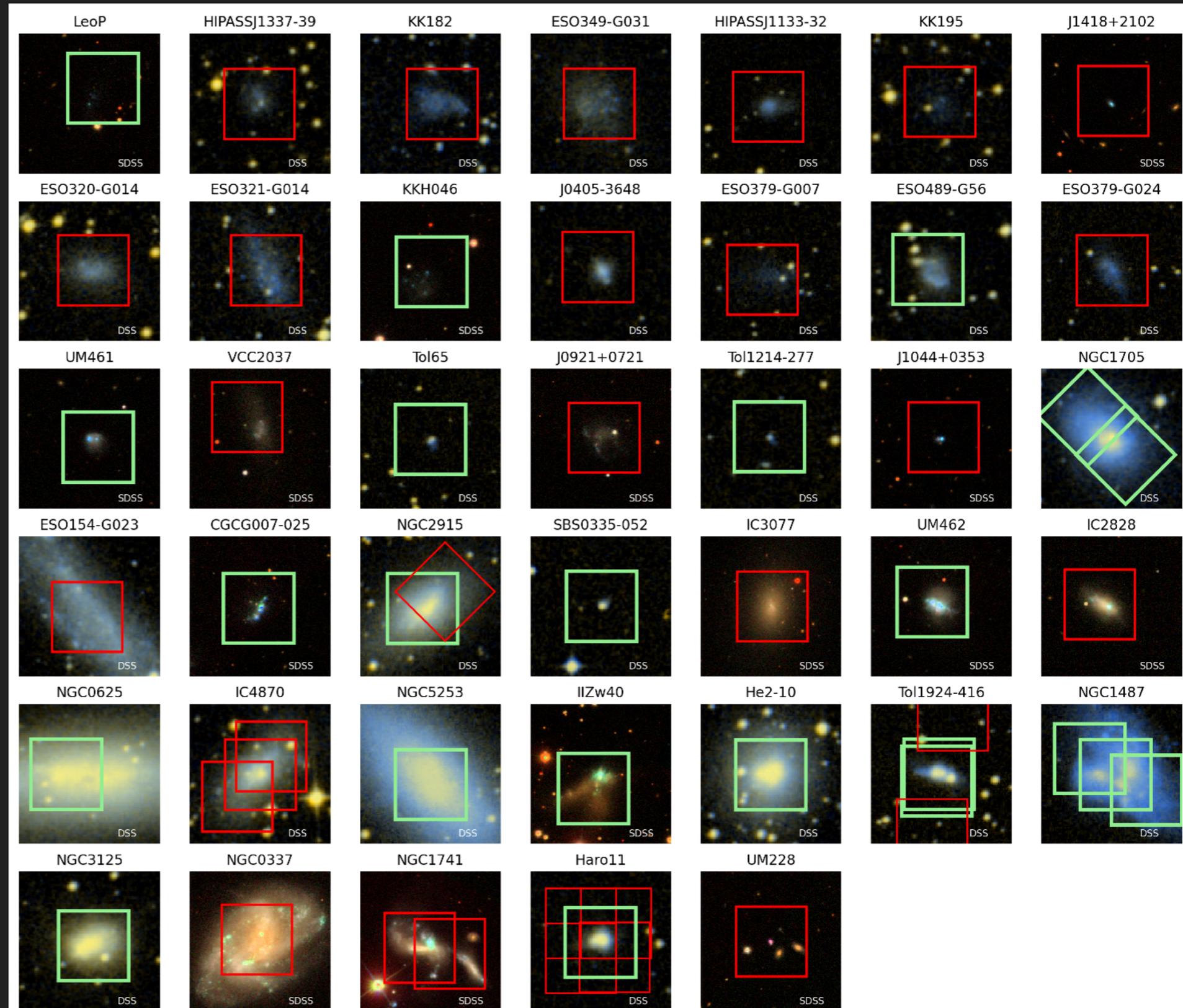
**D**Warf galaxies  
**A**rchival  
**L**ocal survey for  
**I**nterstellar medium  
**i**nvestigation **N**

*From either*

Herschel Dwarf Galaxy Survey  
(Cormier+15)

Local volume galaxy catalogue  
( $D < 11$  Mpc,  $M_{\star} < 10^9 M_{\odot}$ )  
(Karachentsev+13)

+ archival MUSE data



# Ionised gas outflows in nearby starburst dwarfs

Marasco+23

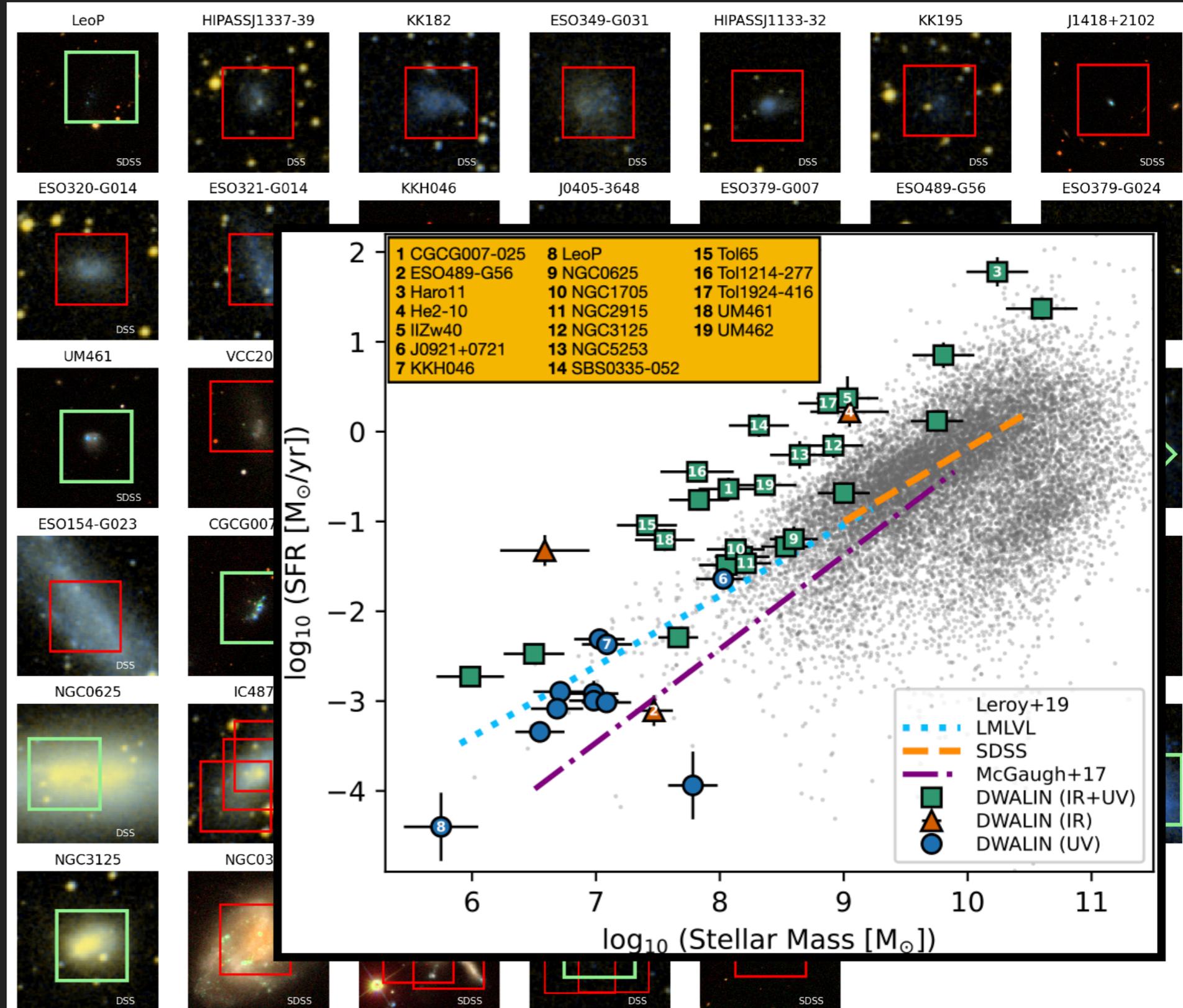
Dwarf galaxies  
Archival  
Local survey for  
Interstellar medium  
investigation

From either

Herschel Dwarf Galaxy Survey  
(Cormier+15)

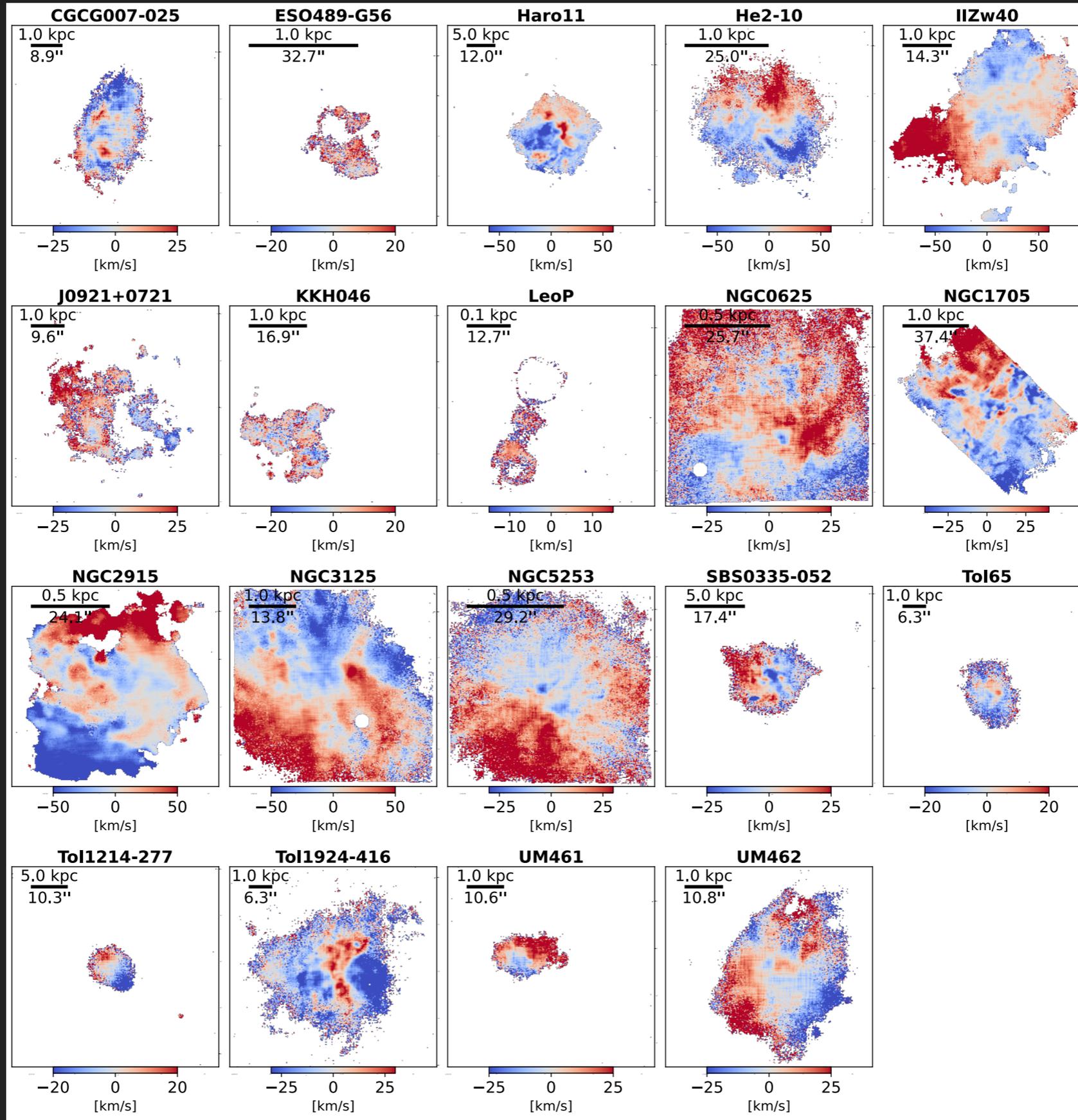
Local volume galaxy catalogue  
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(Karachentsev+13)

+ archival MUSE data



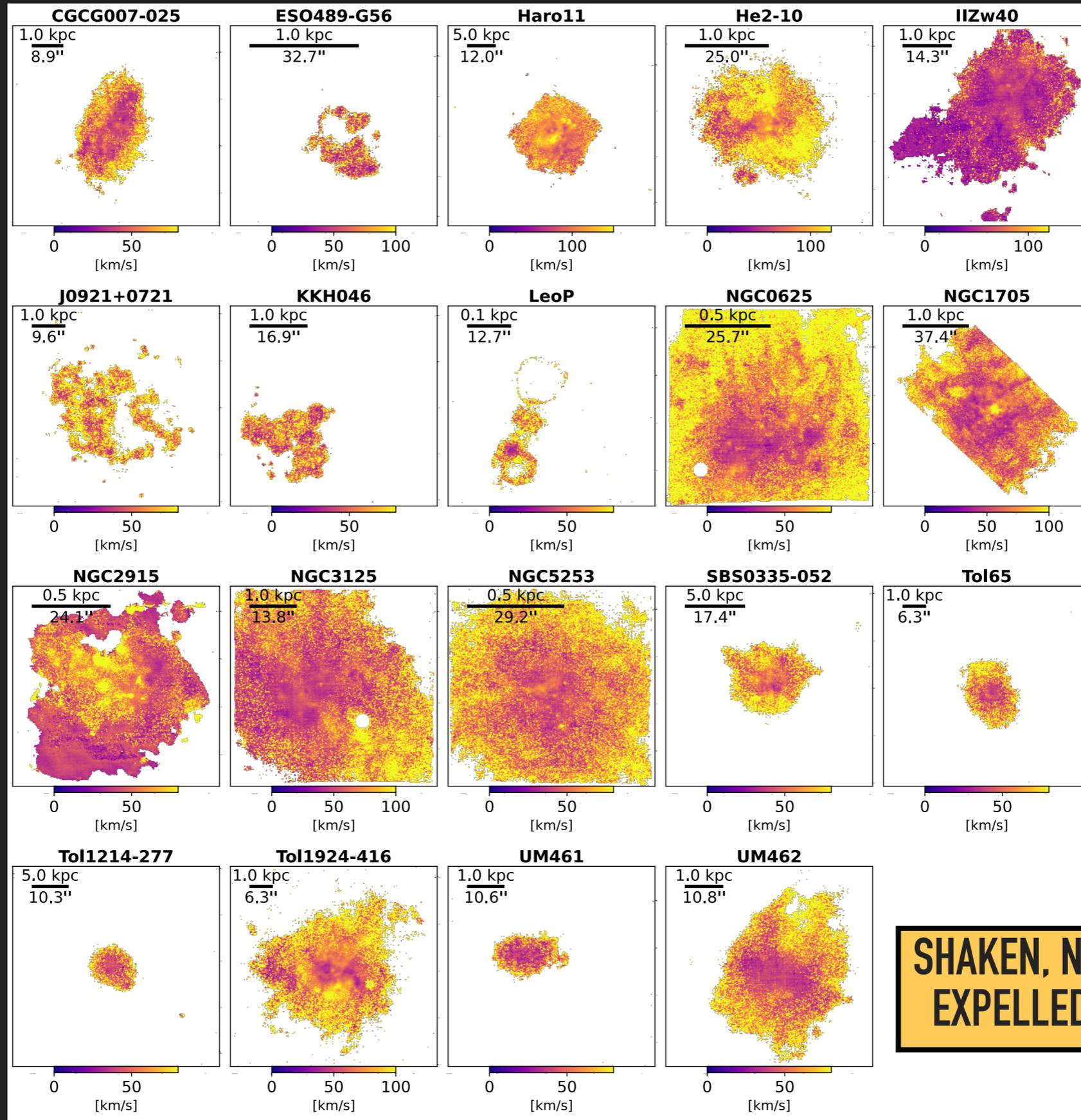
# ionised gas kinematics

## DWALIN - velocity fields



# ionised gas kinematics

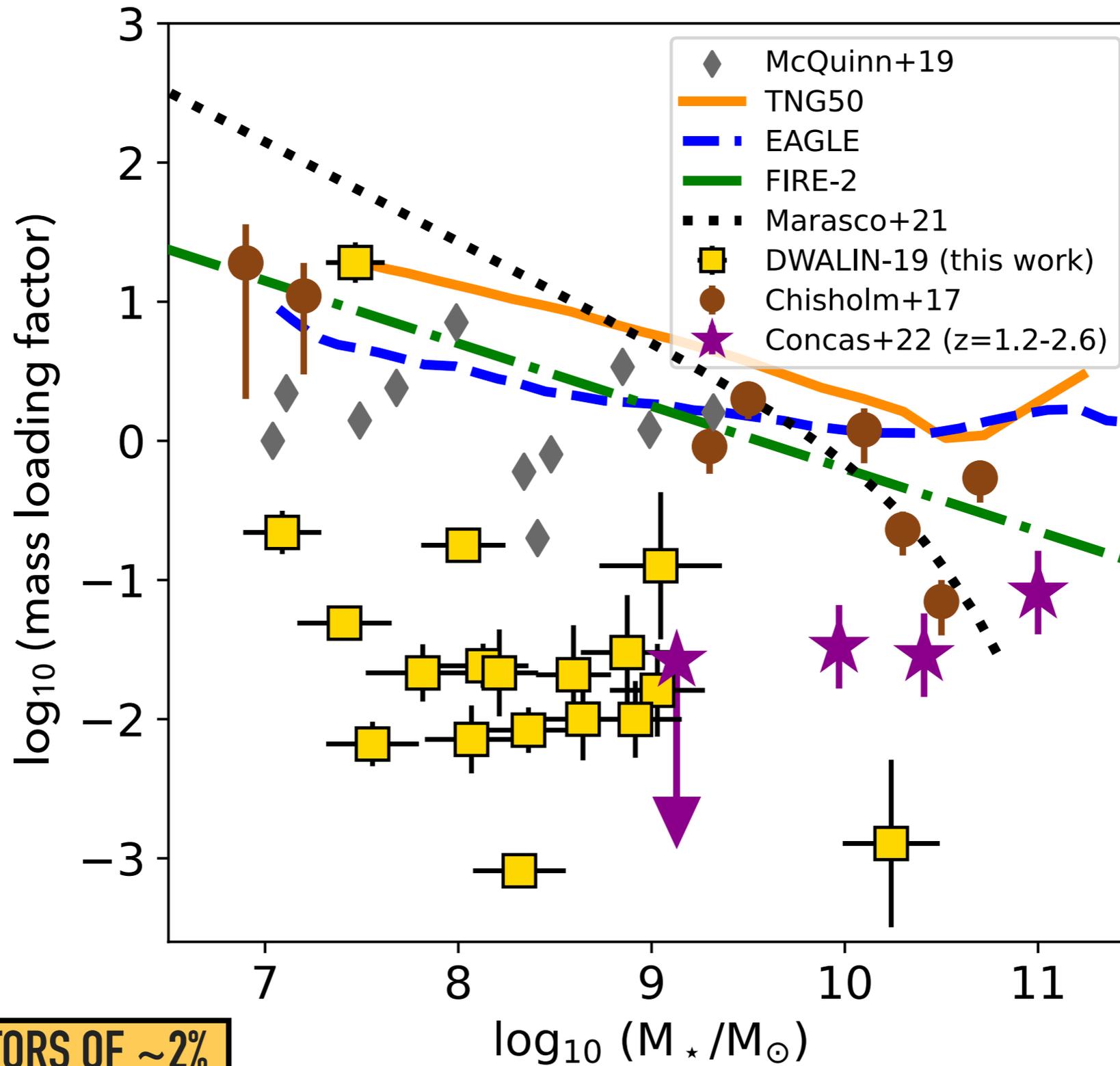
*DWALIN - velocity dispersion maps*



**SHAKEN, NOT  
EXPELLED!**

# Ionised gas outflows in nearby starburst dwarfs

Marasco+23

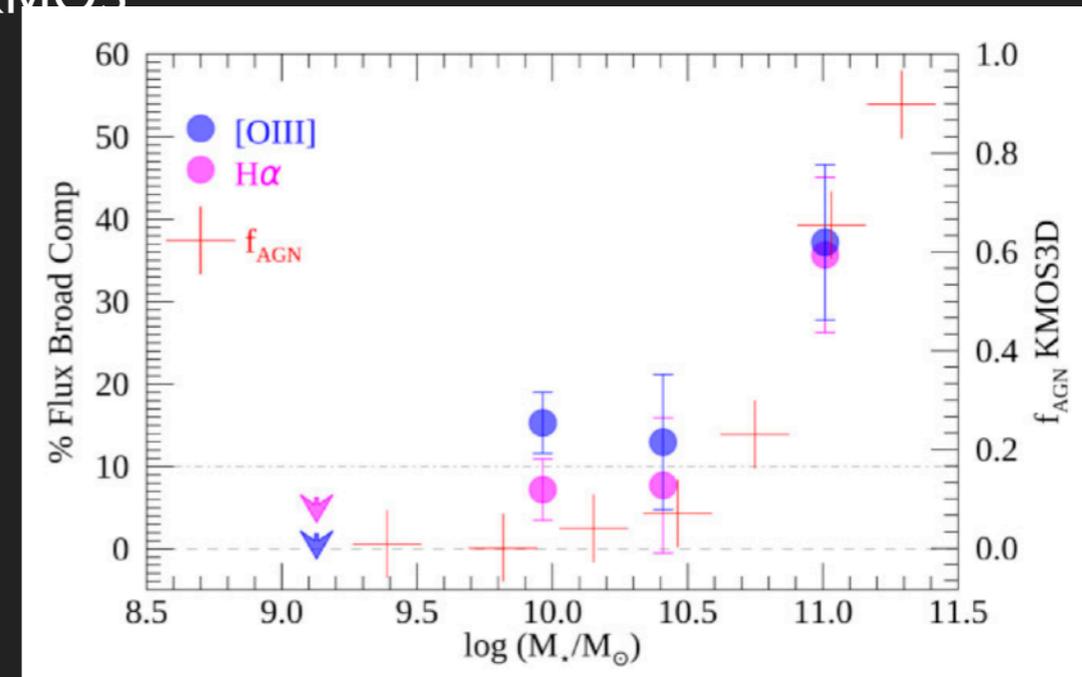
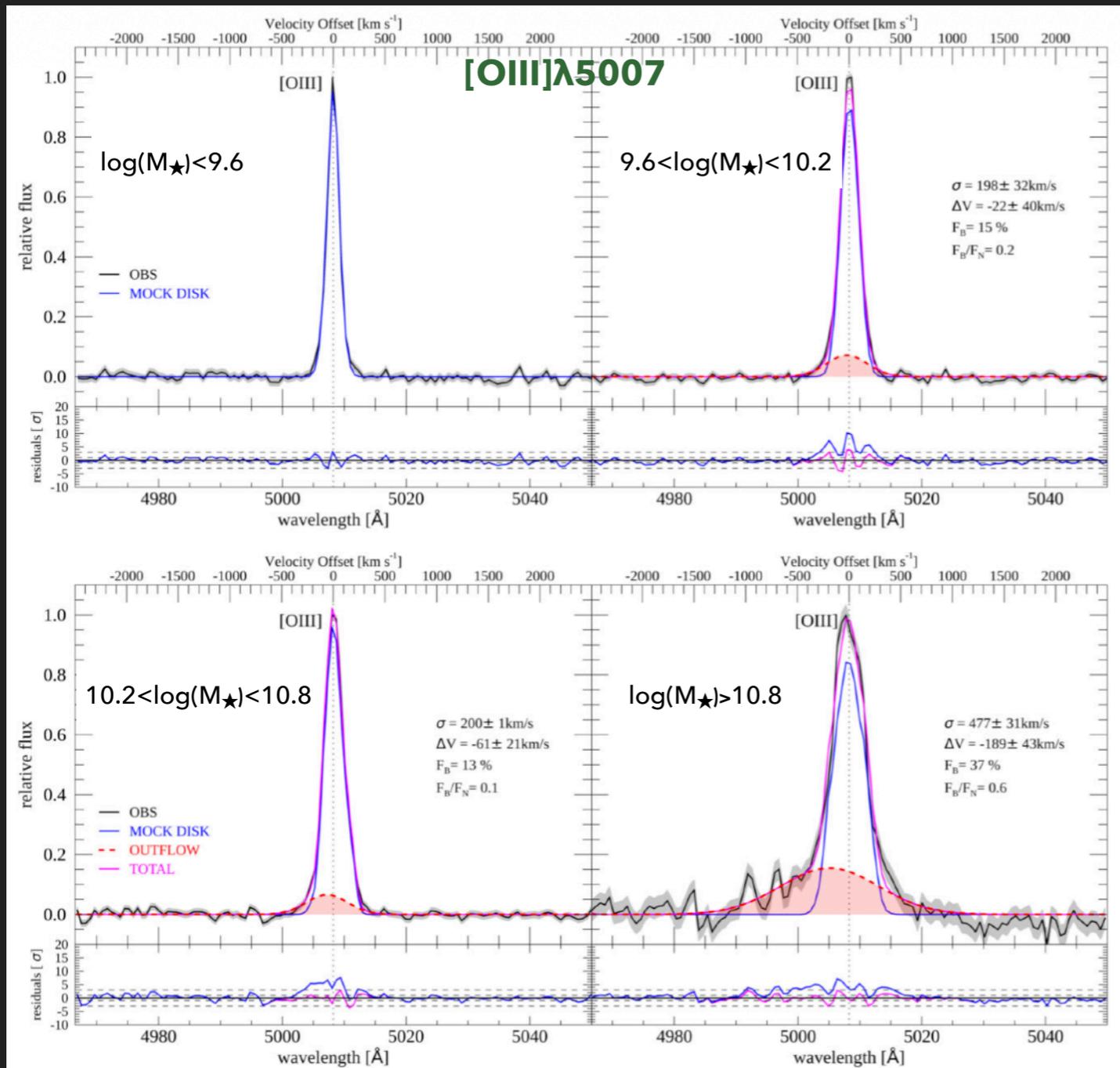


**MASS LOADING FACTORS OF  $\sim 2\%$   
-> 2 DEX LOWER THAN SIMS**

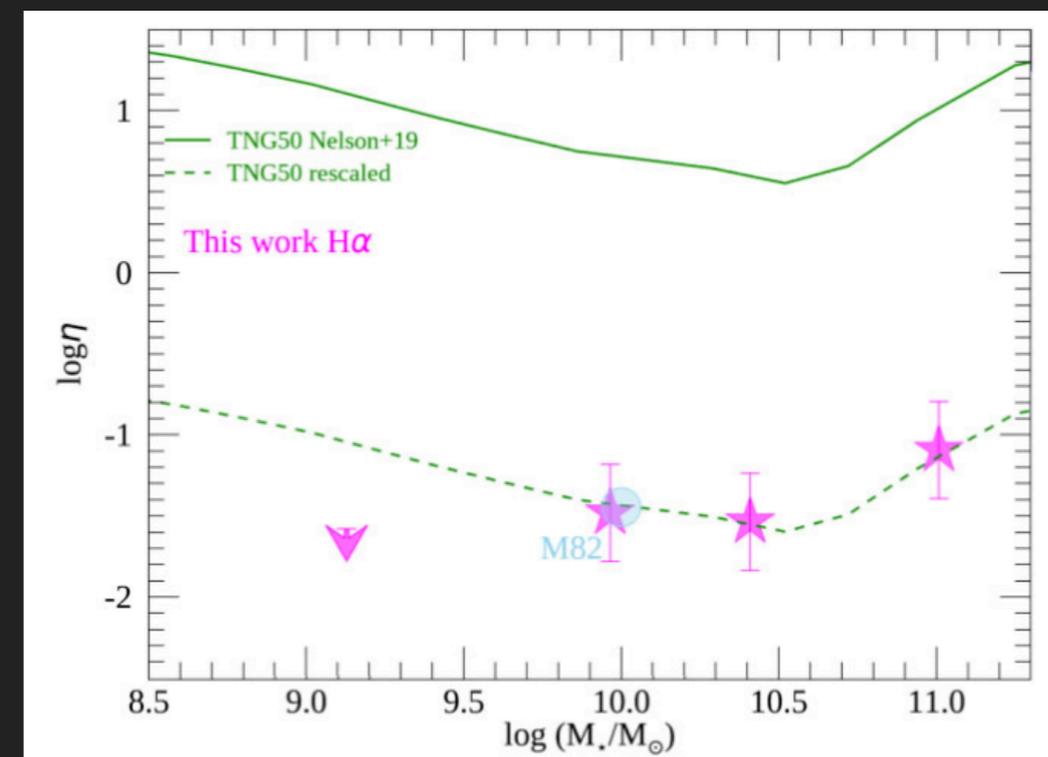
# Ionised gas outflows in MS galaxies at $z \sim 2$

Concas+22

- ▶ KLEVER Survey: 141 MS galaxies at  $1.2 < z < 2.6$  observed with KMOS
- ▶ Fraction of lensed systems to push down to low stellar masses
- ▶ emission line stacking + modelling using rotating disk



**WINDS ARE PRESENT MAINLY AT HIGH  $M_{\star}$ , AGN-DRIVEN**

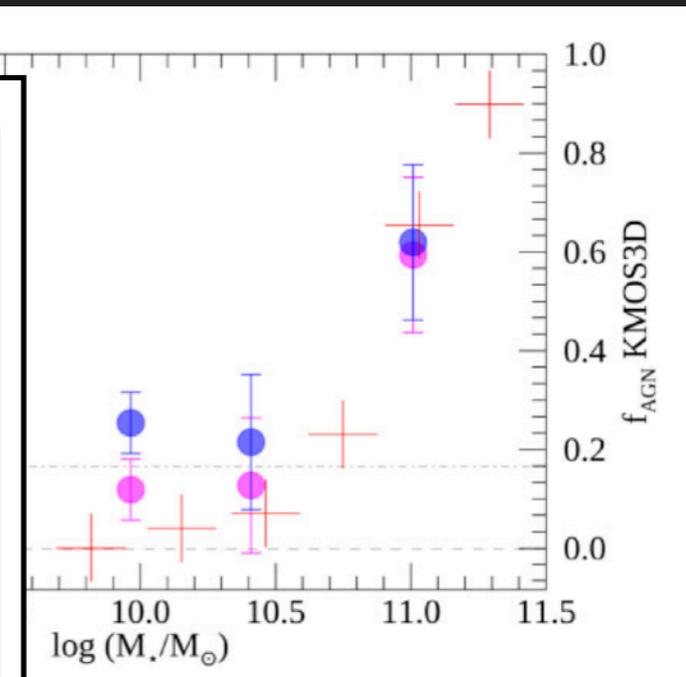
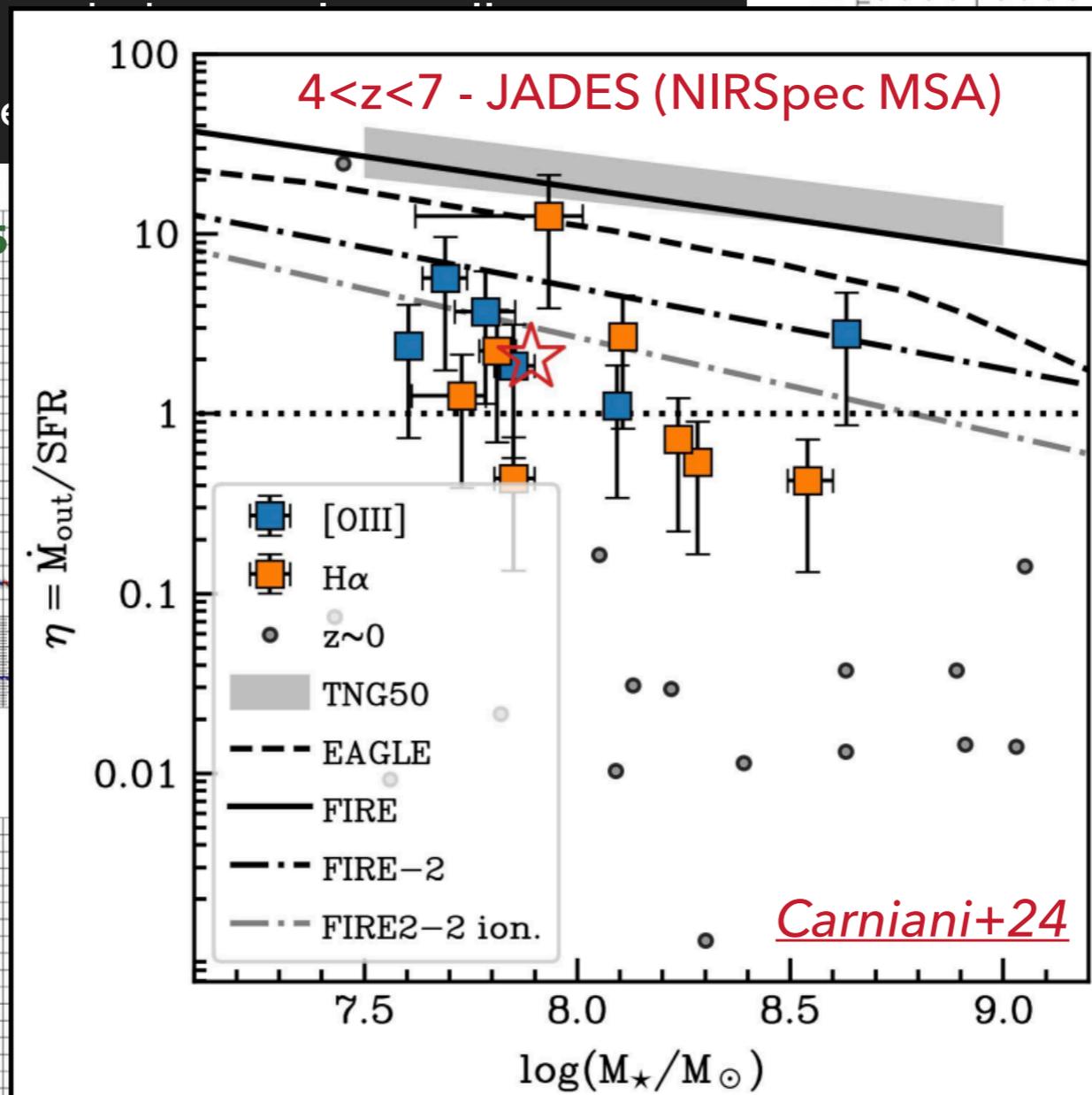
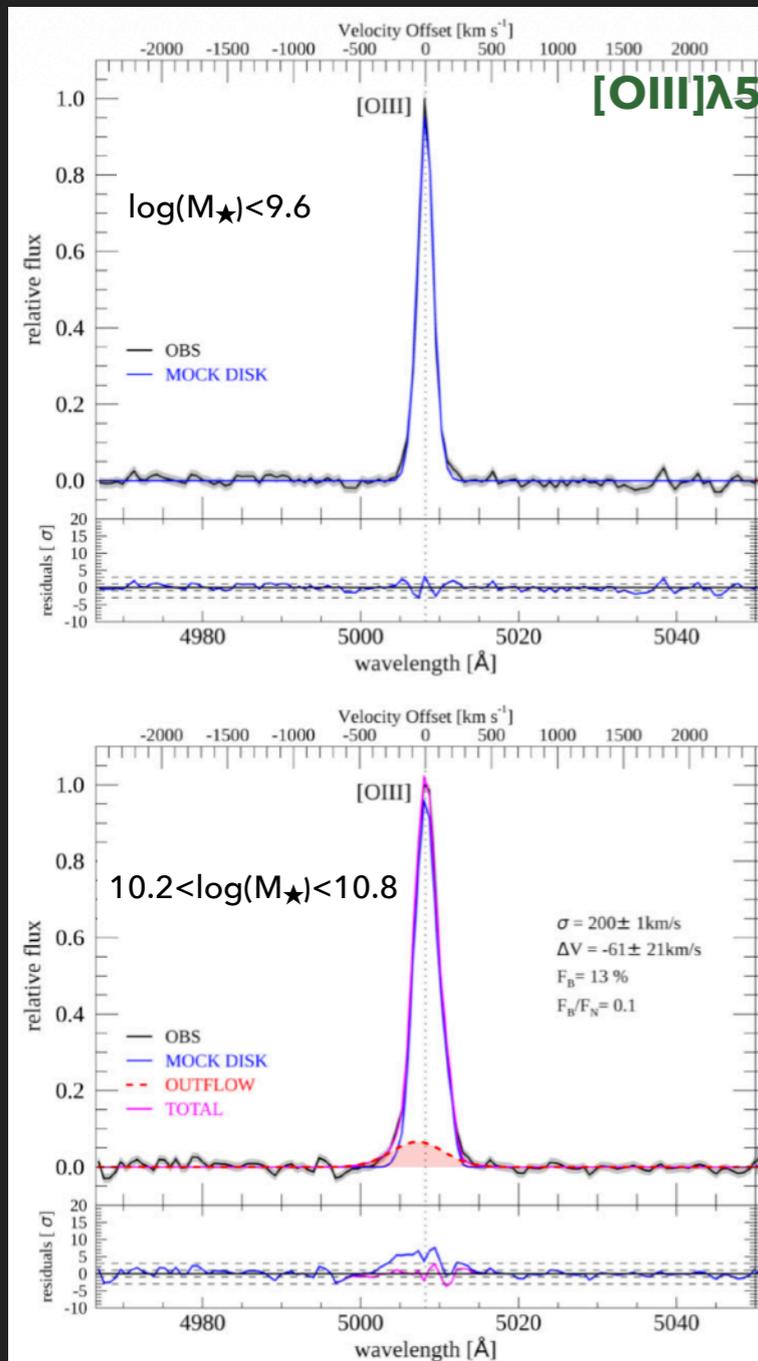


**MASS LOADING FACTORS OF A FEW %**

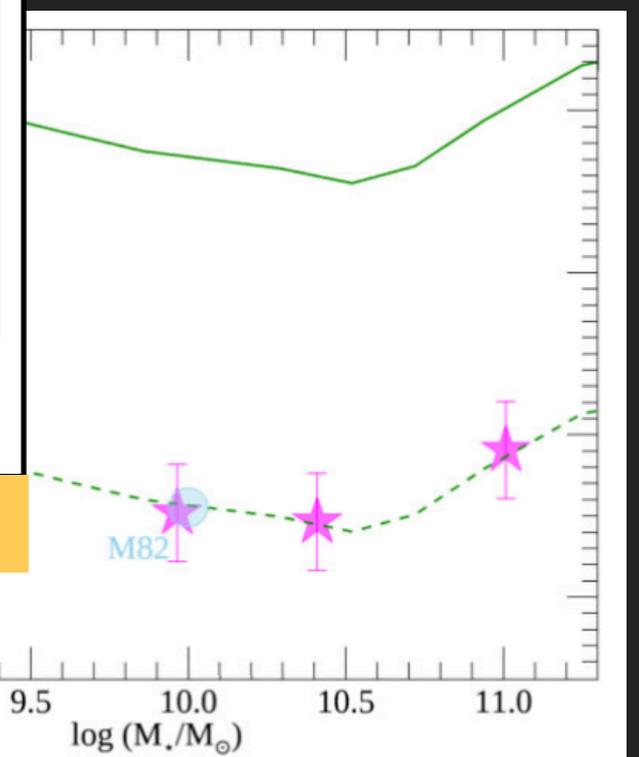
# Ionised gas outflows in MS galaxies at $z \sim 2$

Concas+22

- ▶ KLEVER Survey: 141 MS galaxies at  $1.2 < z < 2.6$  observed with KMOS
- ▶ Fraction of lensed systems to emission line stacking + model



MAINLY AT HIGH M<sub>★</sub>, AGN-DRIVEN



SITUATION AT HIGH REDSHIFT IS QUITE DEBATED

MASS LOADING FACTORS OF A FEW %

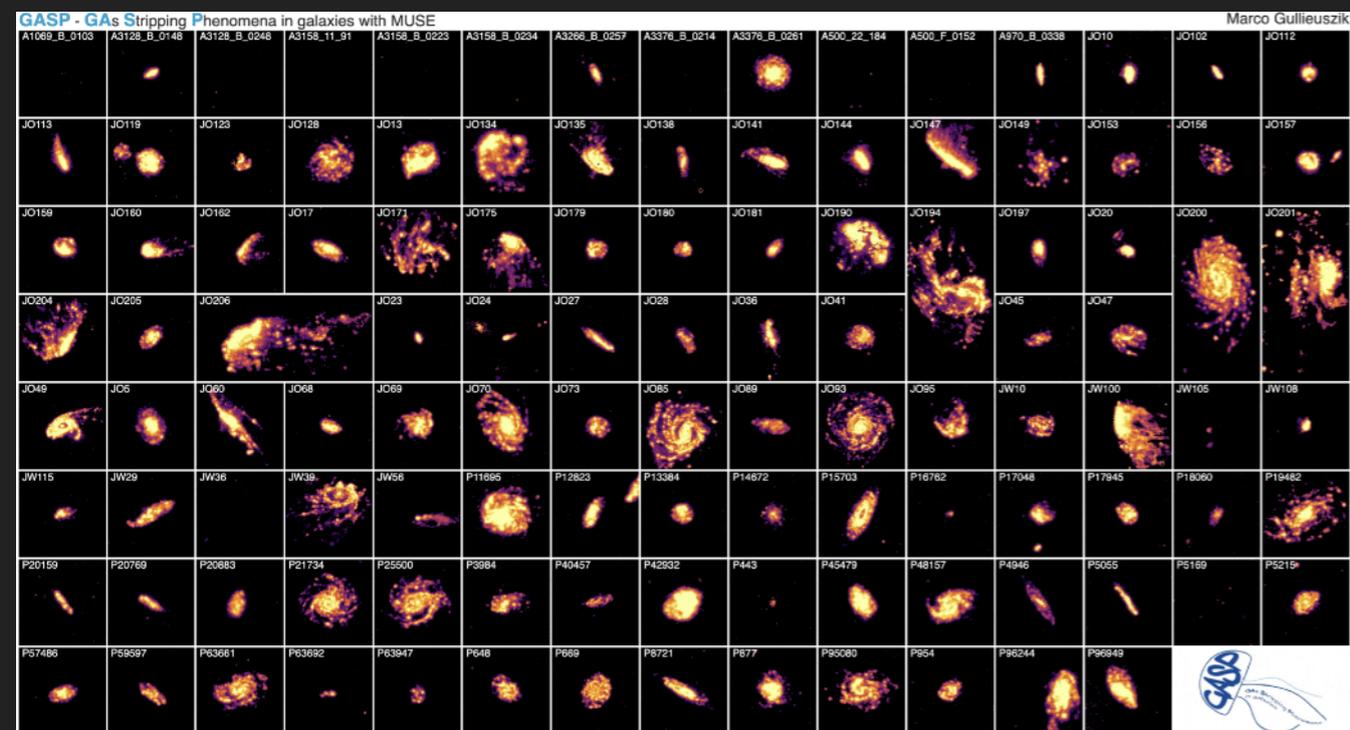
# The full story is more complicated, if one accounts for... environment

## GAs Stripping Phenomena in galaxies



- ▶ MUSE study of 114 galaxies in local clusters + field
- ▶ Additional data (ancillary or follow-up) from HST, ALMA, LOFAR, MeerKAT, UVIT for multi- $\lambda$  coverage
- ▶ joint observational + theoretical efforts
- ▶ More than 80 papers since 2017!

*B. Poggianti, B. Vulcani, A. Moretti, M. Gullieuszik [...]*



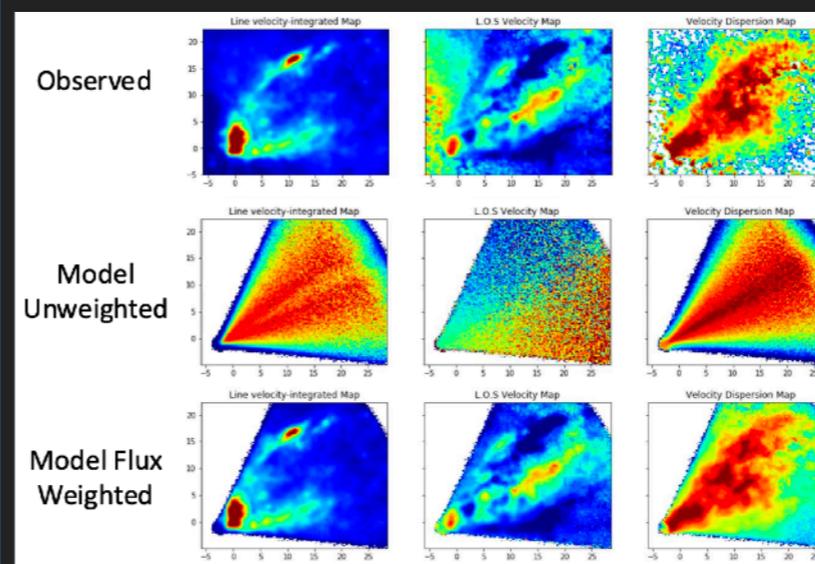
credits: *M. Gullieuszik*

## AGNs

### Measuring Active Galactic Nuclei Under MUSE Microscope

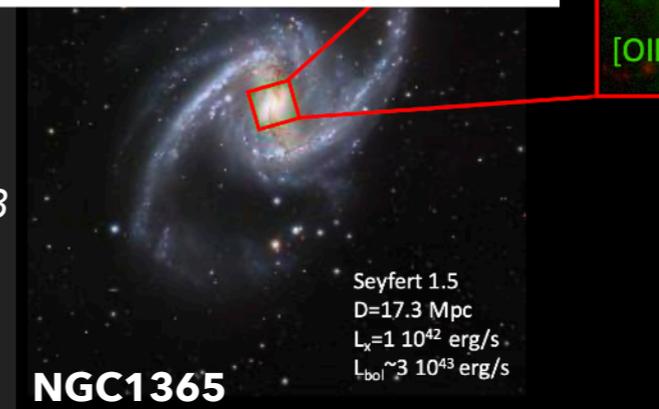
- ▶ MUSE study of nearby (<50 Mpc) AGNs
- ▶ Ancillary data from several facilities + ALMA & MIRI follow up
- ▶ detailed study of the physics of galaxy nuclei
- ▶ dedicated kinematic & photo-ionisation modelling

*G. Cresci, A. Marconi, G. Venturi, M. Mingozzi [...]*



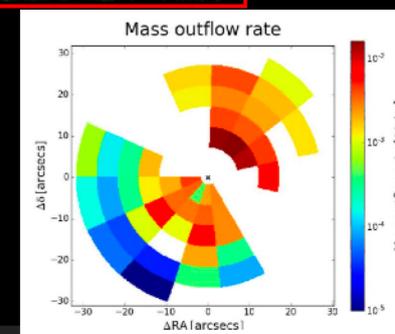
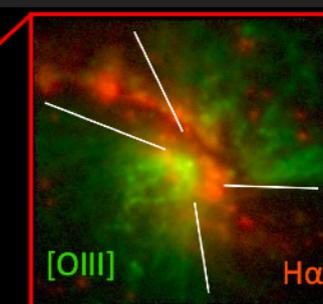
*Marconcini+23 (MOKA3D)*

*Venturi+18*



Seyfert 1.5  
 $D=17.3$  Mpc  
 $L_x=1 \cdot 10^{42}$  erg/s  
 $L_{bol} \sim 3 \cdot 10^{43}$  erg/s

**NGC1365**



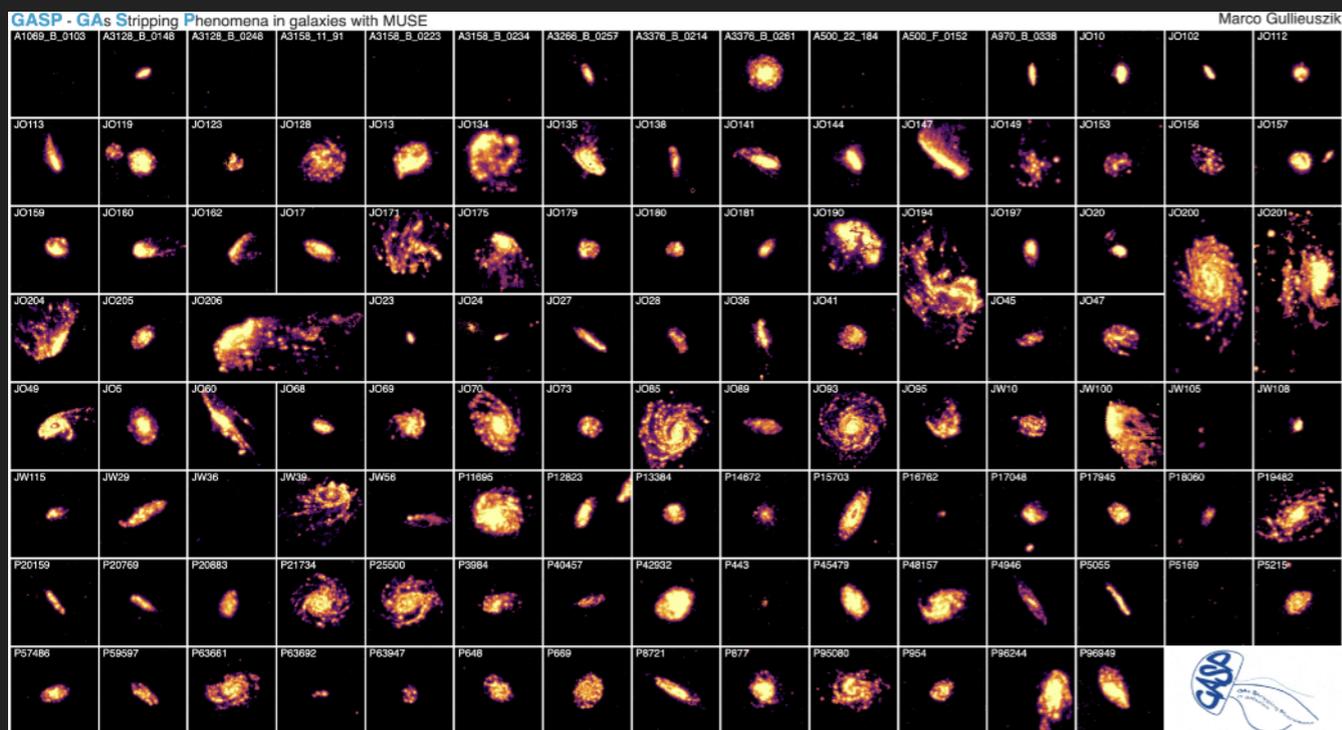
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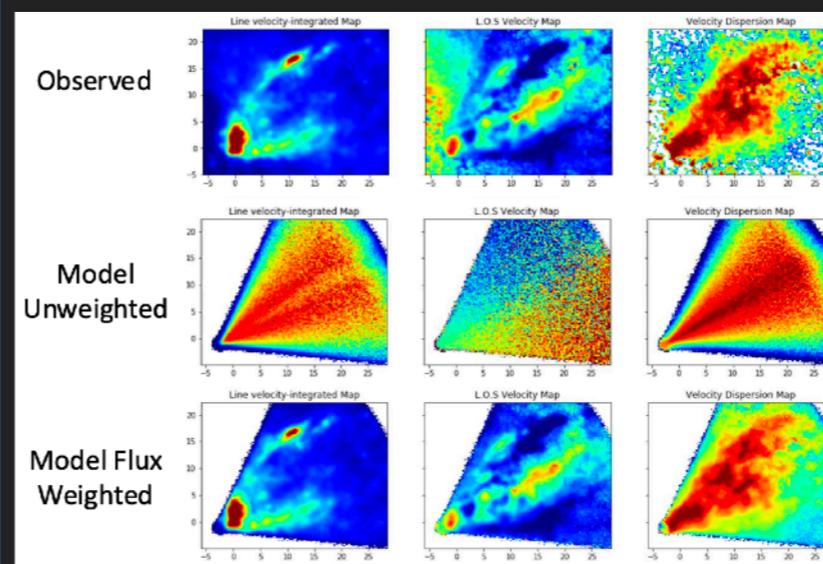
credits: *M. Gullieuszik*

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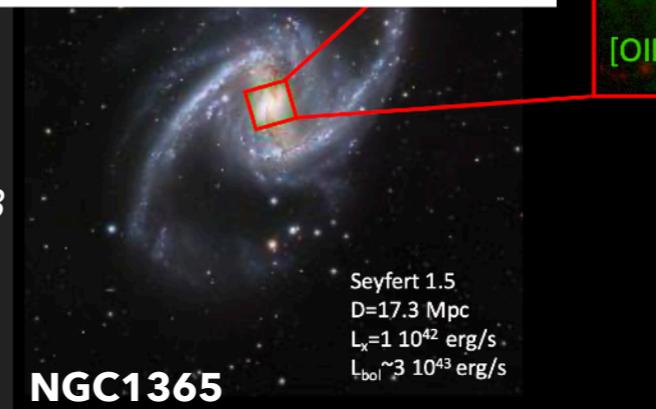
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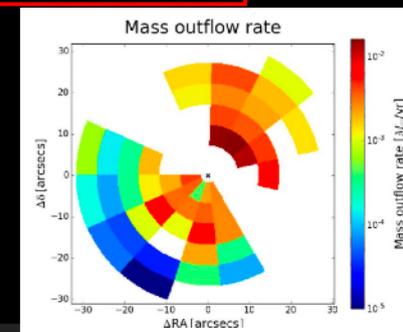
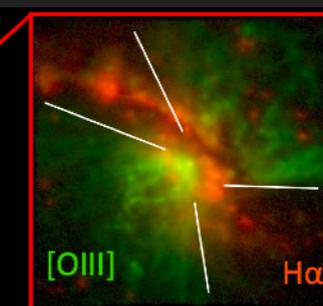


*Marconcini+23 (MOKA3D)*

*Venturi+18*



**NGC1365**



# Future perspectives

## Observational side

- ▶ The **disc-halo interface** is complex and multi-phase, requiring high-quality, multi- $\lambda$ , spatially resolved data. MeerKAT / MUSE / ALMA now, SKA / WST / ALMA2030 in the future?
- ▶ The **small-scale matter cycle** will start be explored statistically at low with with SKA/ WST and at comparable 'cloud-scale' resolution at high-redshift with the ELT

QUALITY OVER QUANTITY



THE FUTURE IS BIG DATA



Let's discuss

# Future perspectives

Deep wide-field imaging

Euclid

Vera Rubin (LSST)

Roman Space Telescope

The radio sky

Meerkat, SKA

The ELT

MORFEO/MICADO, HARMONI, ANDES, MOSAIC

The VLT 2030 landscape

MAVIS, BlueMUSE

Habitable World Observatory (?)

ESO expanding horizons

# The VLT in the 2030s

All UT allocations of **future instruments** are purely for visualization purposes and do not correspond to ESO's final choice



**UT2**  
FLAMES  
CUBES  
UVES

**UT3**  
SPHERE  
X-SHOOTER  
CRIRES+

**UT4**  
MAVIS  
MUSE  
ERIS

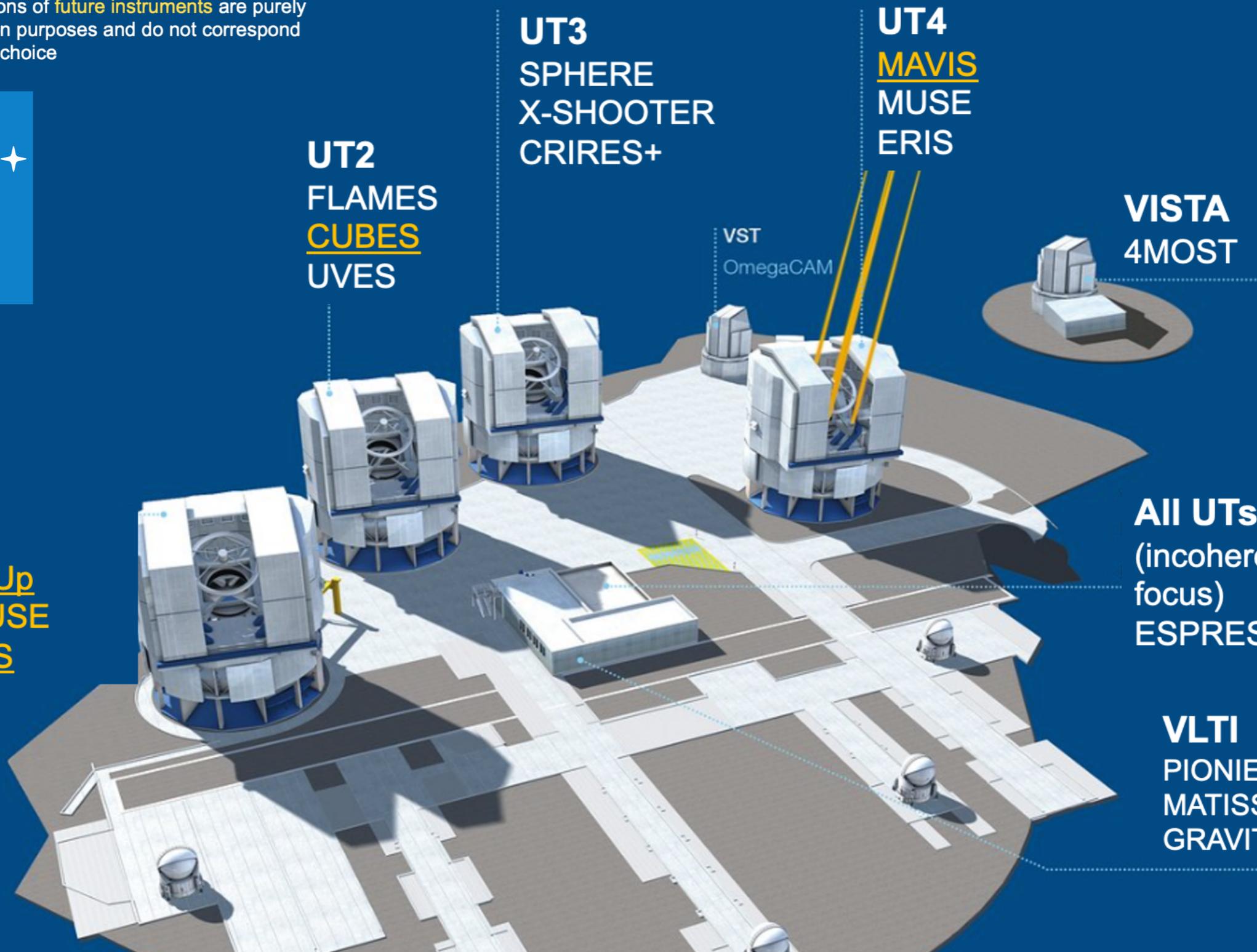
**VISTA**  
4MOST

VST  
OmegaCAM

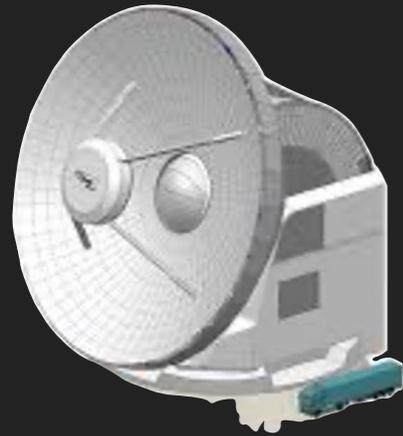
**UT1**  
FORS-Up  
BlueMUSE  
MOONS

**All UTs**  
(incoherent focus)  
ESPRESSO

**VLT1**  
PIONIER  
MATISSE  
GRAVITY+



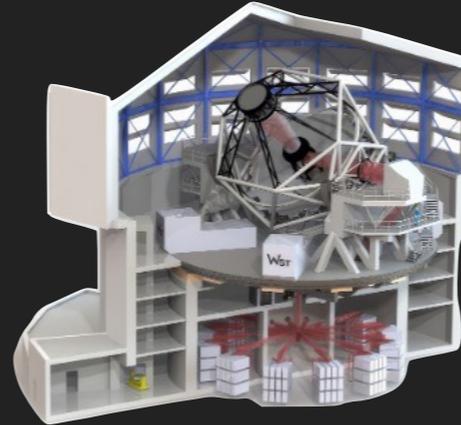
# ESO in the 2040s: Expanding Horizons



## AtLAST

- Large 50m single dish sub-mm telescope
- Large FoV ( $>1 \text{ deg}^2$ )
- Highly multiplexed instruments

[Kampen+24, Lee+24, Liu+24](#)



## WST

- 12m optical telescope
- Large FoV ( $3 \text{ deg}^2$ )
- MOS (30k) + SuperMUSE ( $3' \times 3'$ )
- Possible upgrade to GLAO (IFU) + IR MOS

[Mainieri+24, Fahrion+25](#)



## ALMA 2040

- Radical upgrade to ALMA
- Increased sensitivity and baselines (TBD)

[https://  
www.euroalma2040.com/](https://www.euroalma2040.com/)

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- ▶ The **small-scale matter cycle** will start be explored statistically at low with with SKA/ WST and at comparable 'cloud-scale' resolution at high-redshift with the ELT

## Theoretical side

- ▶ **Multi-scale feedback** physics that grant consistencies across all spatial scales
- ▶ Tighter connection between observations and simulations: systematic production of **mock data** from the latter to derive useful predictions for the former
- ▶ One simulation is not enough!

**The true challenge consists in bridging theory and observations**