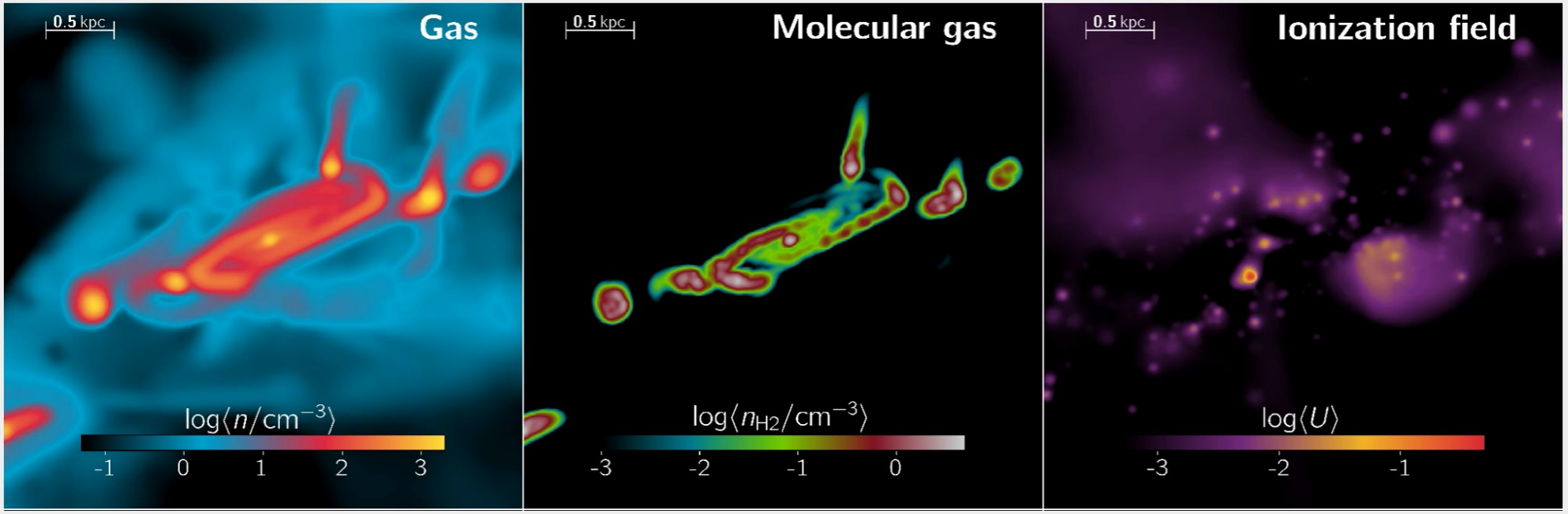
Key Questions:

- Which are the differences between local and high-redshift galaxies?
- What are the properties of galaxies in the Epoch of Reionization?
- How can we infer information via line/continuum observations?



CENTRO FERMI Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi

Scuola Normale Superiore

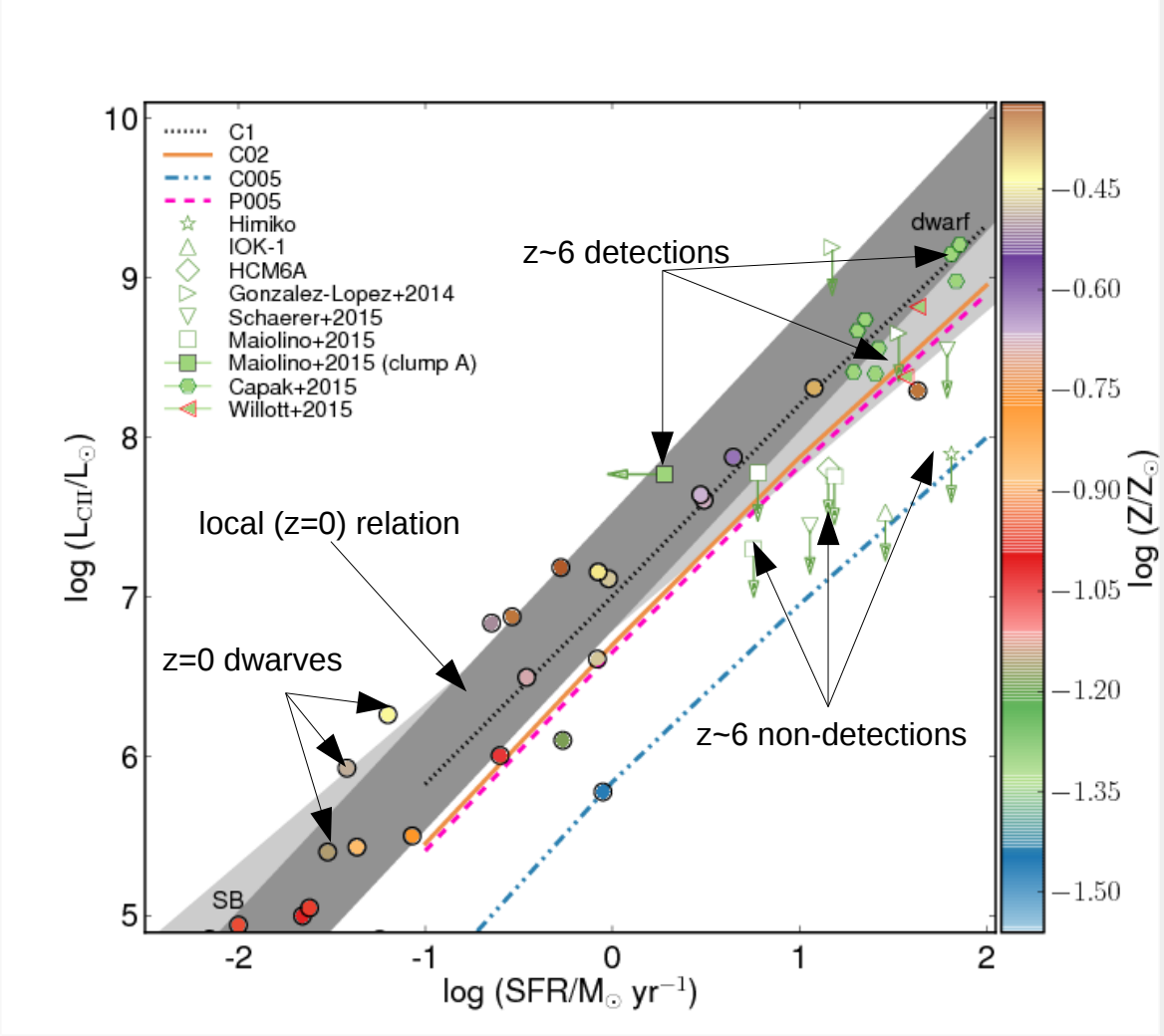
Andrea Pallottini

serra

in collaboration with:
A. Ferrara, S. Gallerani, L. Vallini, C. Behrens, S. Carniani, D. Decataldo,
R. Maiolino, M. Kohandel, T.K.D. Leung, S. Bovino, S. Salvadori, V. D'Odorico, C. Feruglio, ...

The [CII]-SFR relation: local vs high-redshift galaxies

Vallini+15



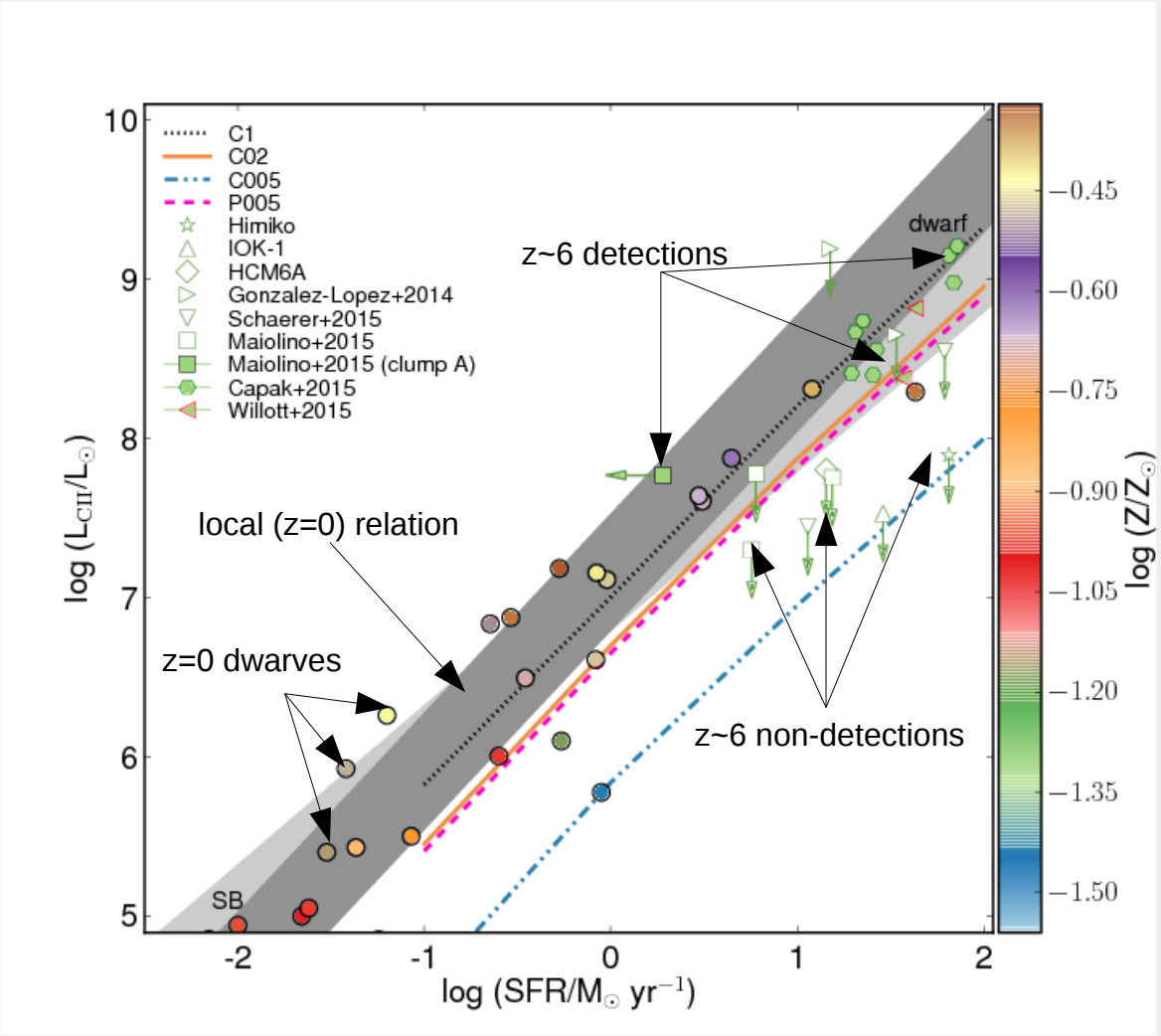
[CII]-SFR affected by metallicity, CMB, photoionization, ...

see Vallini+13,+17, Pallottini+15, Olsen+17, Katz+17, Lupi+19, Decataldo+19

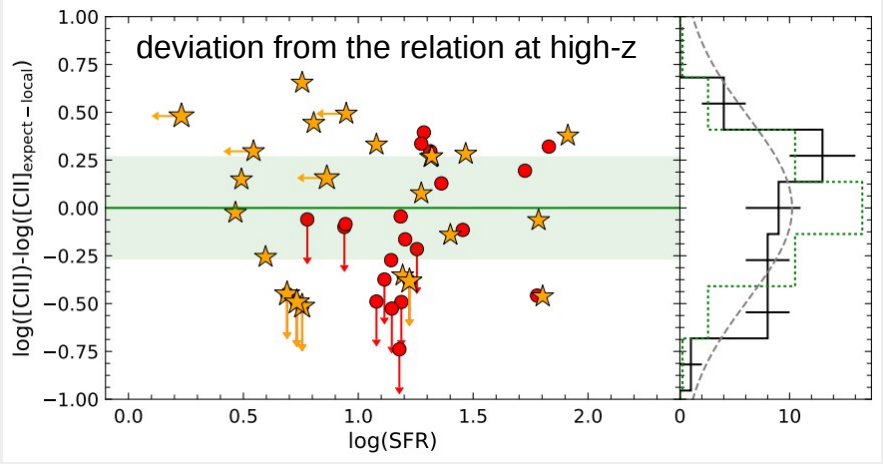
local relation observations: De Looze+14, Herrera-Camus+15

The [CII]-SFR relation: local vs high-redshift galaxies

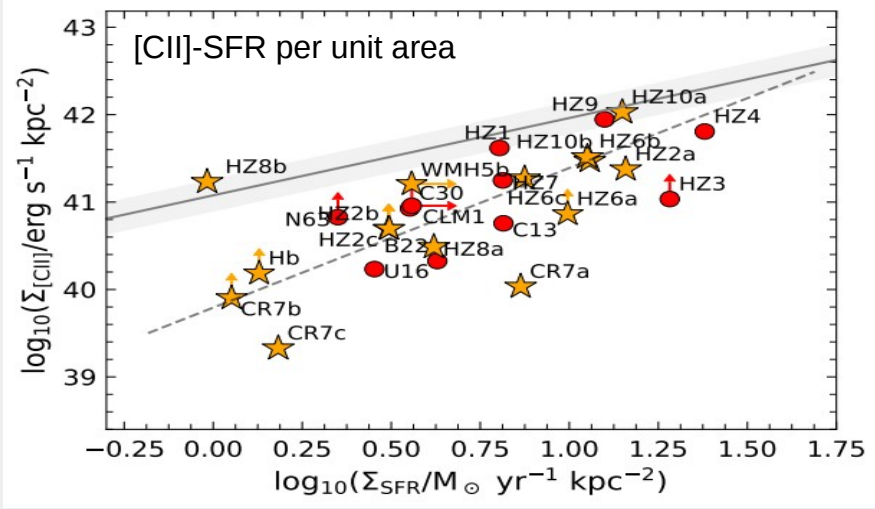
Vallini+15



Carniani+17b



indication of a wider spread of ISM properties



[CII]-SFR affected by metallicity, CMB, photoionization, ...

does the relation hold at high-z?

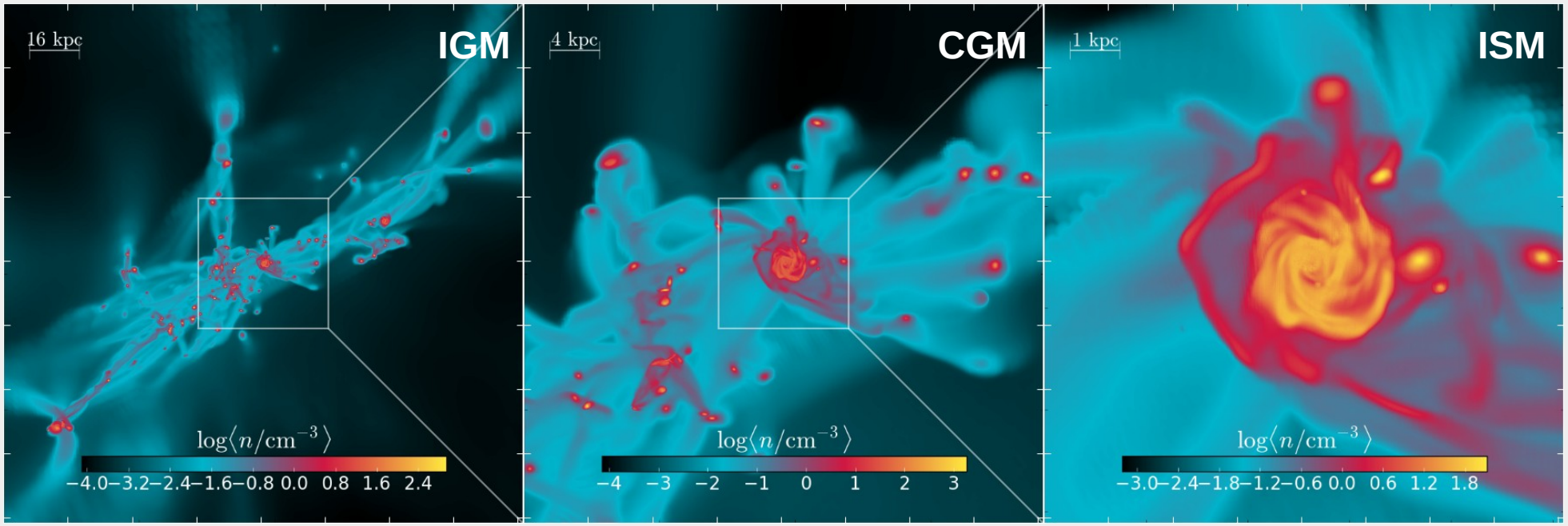
see Vallini+13,+17, Pallottini+15, Olsen+17, Katz+17, Lupi+19, Decataldo+19

local relation observations: De Looze+14, Herrera-Camus+15

Zooming-in high-z galaxies

Dahlia

Pallottini+17a



Resolution	
gas mass	$m_g \simeq 10^4\,\mathrm{M}_\odot$
AMR	$\sim 80 - 0.1\,\mathrm{ckpc/h}$
at $z = 6$	$\Delta x \simeq 30\,\mathrm{pc}$

Target LGB characteristics (at z=6)		
dark matter	$M_{\rm dm} \sim 10^{11}\mathrm{M}_\odot$	
size	$r_{\rm vir} \simeq 15\,\mathrm{kpc}$	$r_{\rm eff} \simeq 0.5\,\mathrm{kpc}$
stars	$SFR \sim 100\,\mathrm{M}_\odot/\mathrm{yr}$	$M_\star \sim 10^{10}\mathrm{M}_\odot$
gas	$M_H \sim 10^{10}\mathrm{M}_\odot$	$M_{\rm H2} \sim 10^8\mathrm{M}_\odot$
metals	$Z \simeq 0.5\,\mathrm{Z}_\odot$	$M_D \sim 10^7\mathrm{M}_\odot$

serra

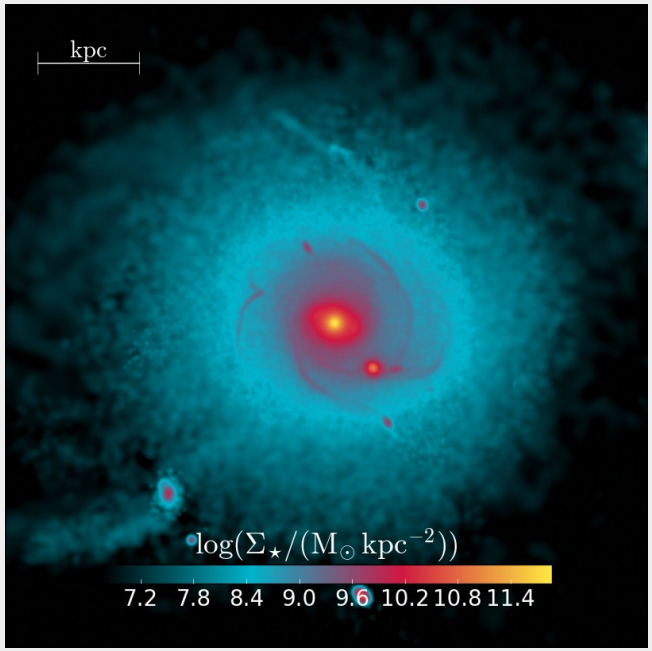
from cosmological to molecular cloud scales

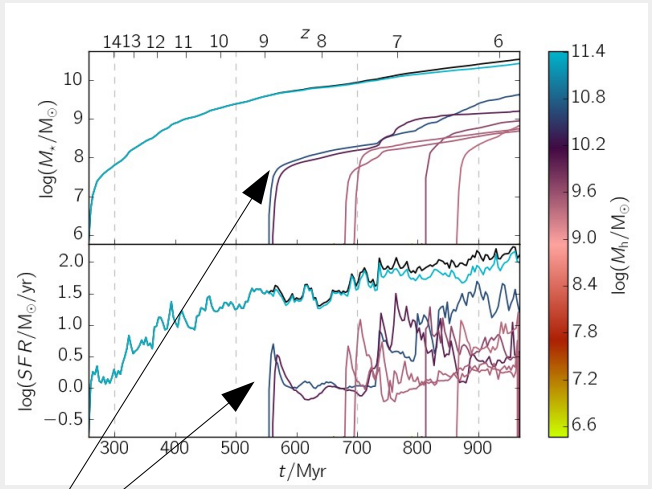
Model main features	
AMR code RAMSES Teyssier 2002	zoom-in IC MUSIC Hahn 2011
H_2 based star formation (SK relation) Krumholz+09	Stellar tracks from STARBURST99 Leitherer+10
Thermal and kinetic energy (e.g. Agertz&Kravtsov 2015)	
GRACKLE 2.1 cooling module Bryan+14	Kinetic energy dissipation Mac Low 1999; Teyssier+13
SN explosions, OB/AGB winds & radiation pressure (e.g. Agertz+13, Hopkins+14)	
Subgrid modelling for blastwaves Ostriker&McKee 1988	

Stellar component properties

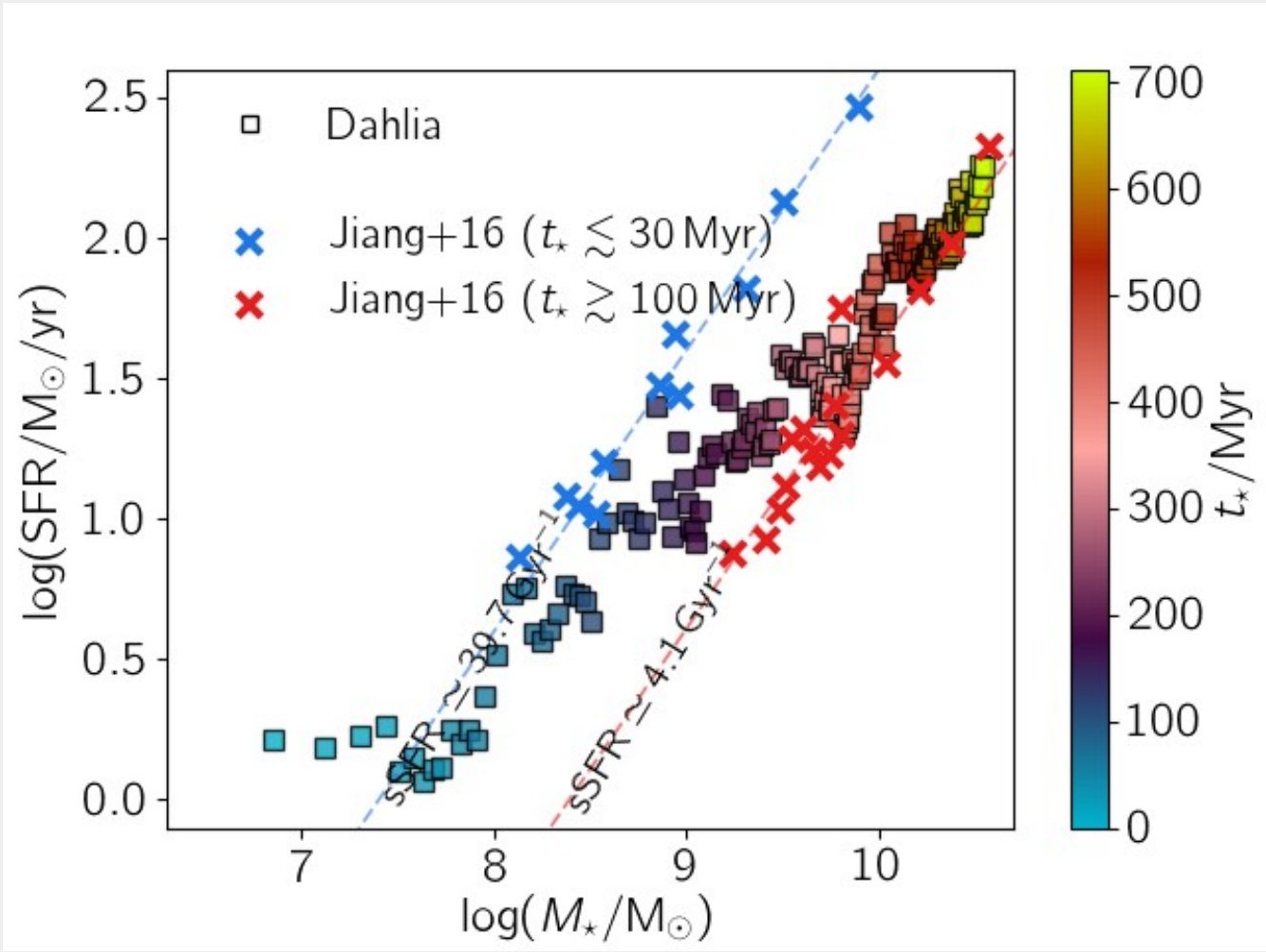
Dahlia

Pallottini+17a,b





other galaxies in the field

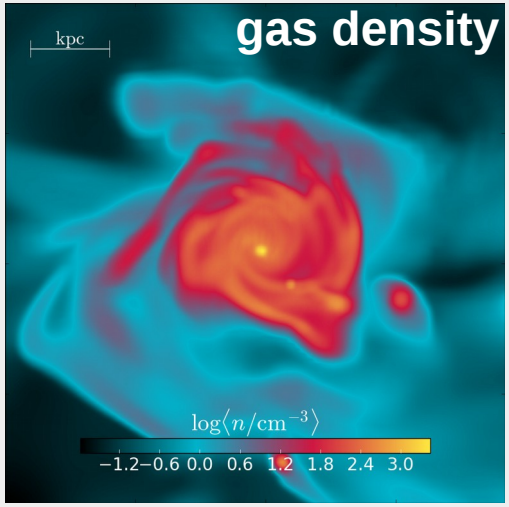


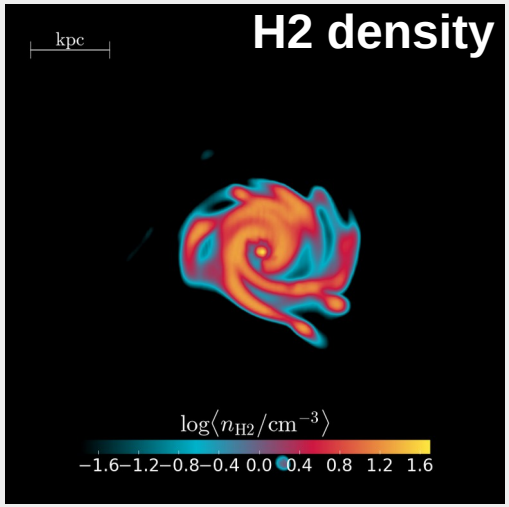
star formation increasing with time
frequent bursts due to merger/gas inflows
about 4–40 times higher sSFR w.r.t. the low-z MS
intense feedback is expected

Molecular gas properties

Althæa

Pallottini+17b,Vallini+18, Leung+19



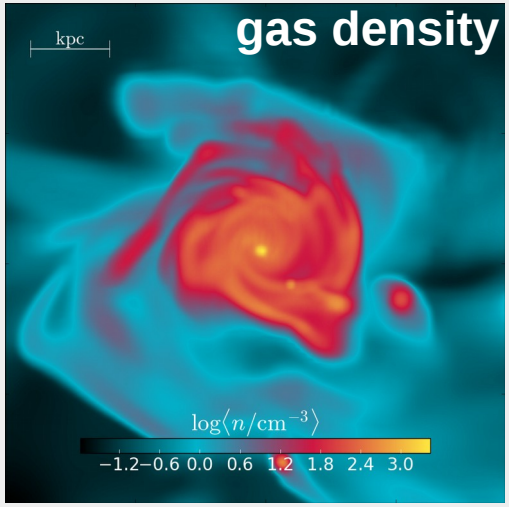


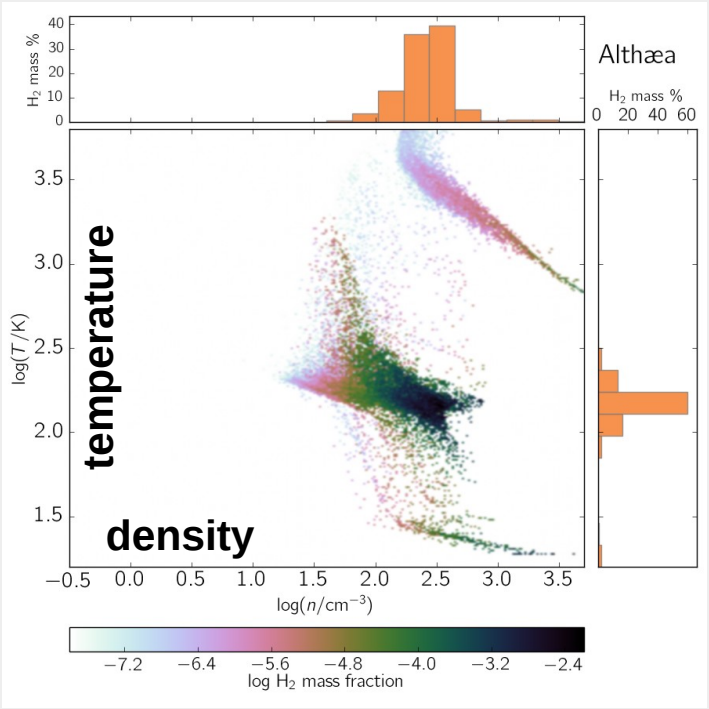
clumpy and concentrated in the galactic disk

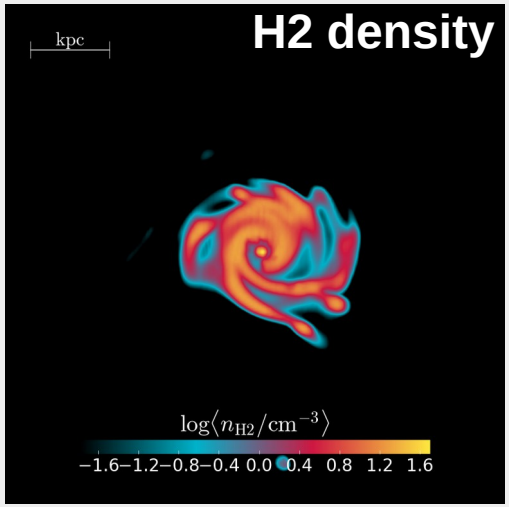
Molecular gas properties

Althæa

Pallottini+17b,Vallini+18, Leung+19





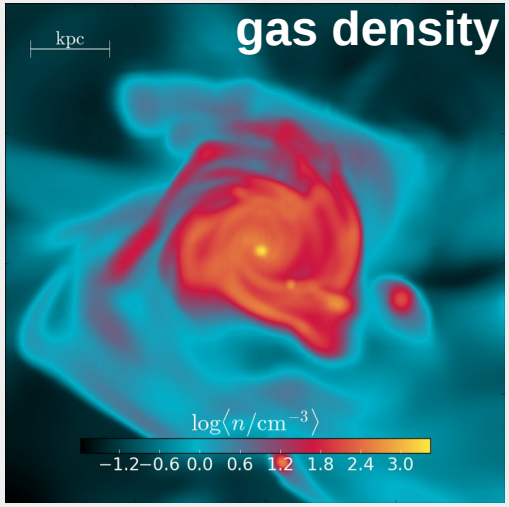


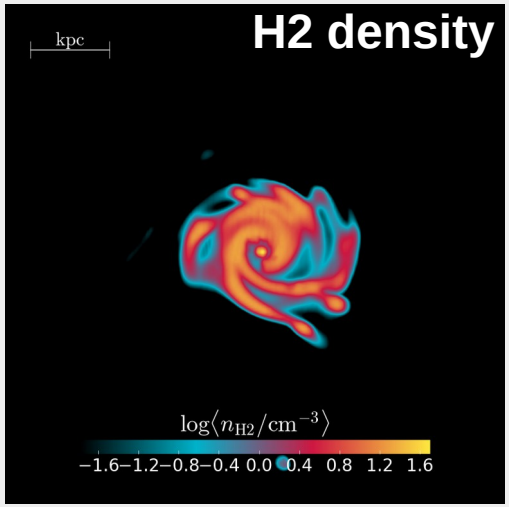
clumpy and concentrated in the galactic disk
relatively denser and hotter w.r.t. the MW

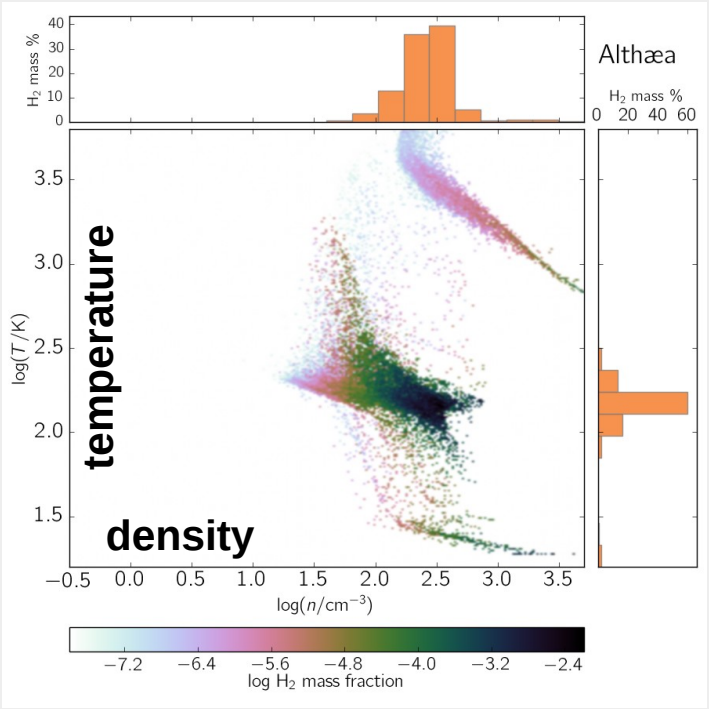
Molecular gas properties

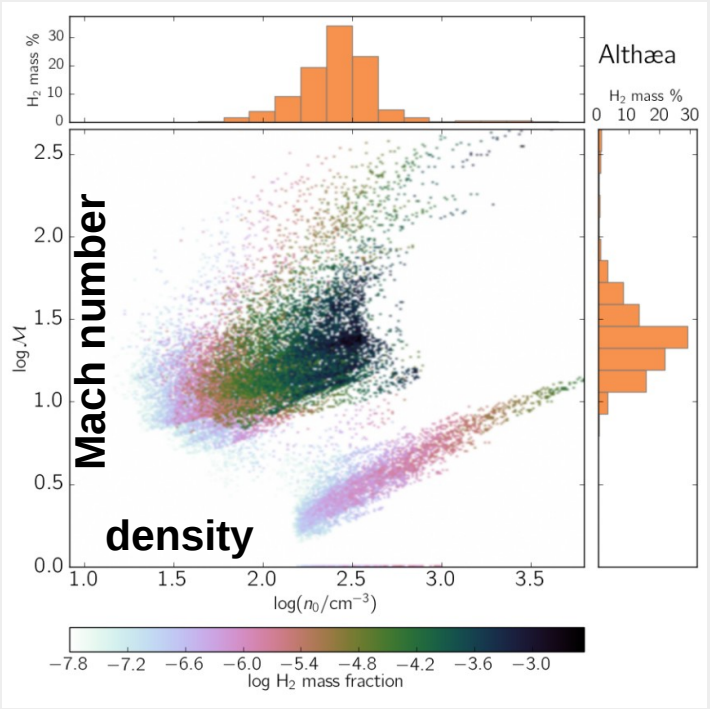
Althæa

Pallottini+17b,Vallini+18, Leung+19







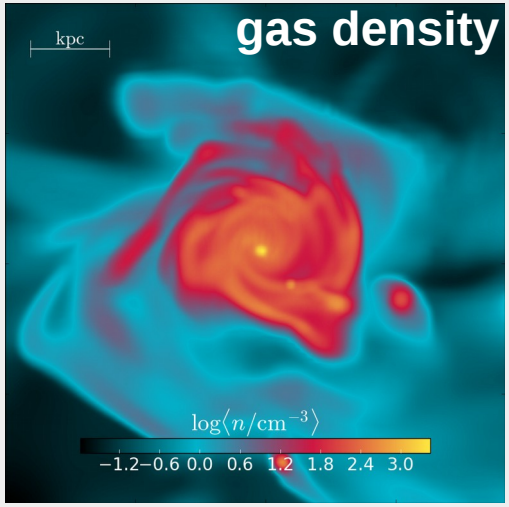


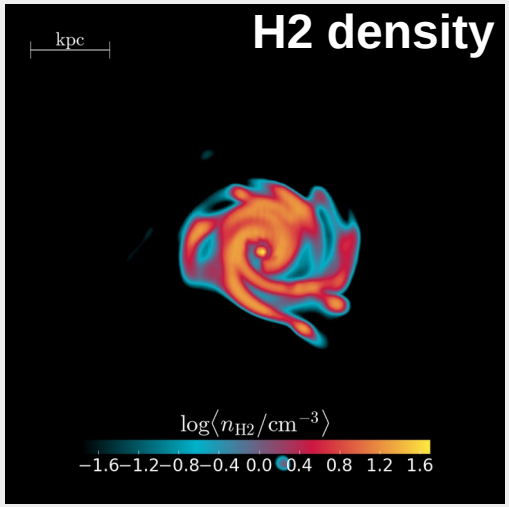
clumpy and concentrated in the galactic disk
relatively denser and hotter w.r.t. the MW
higher turbulence, as a consequence of feedback

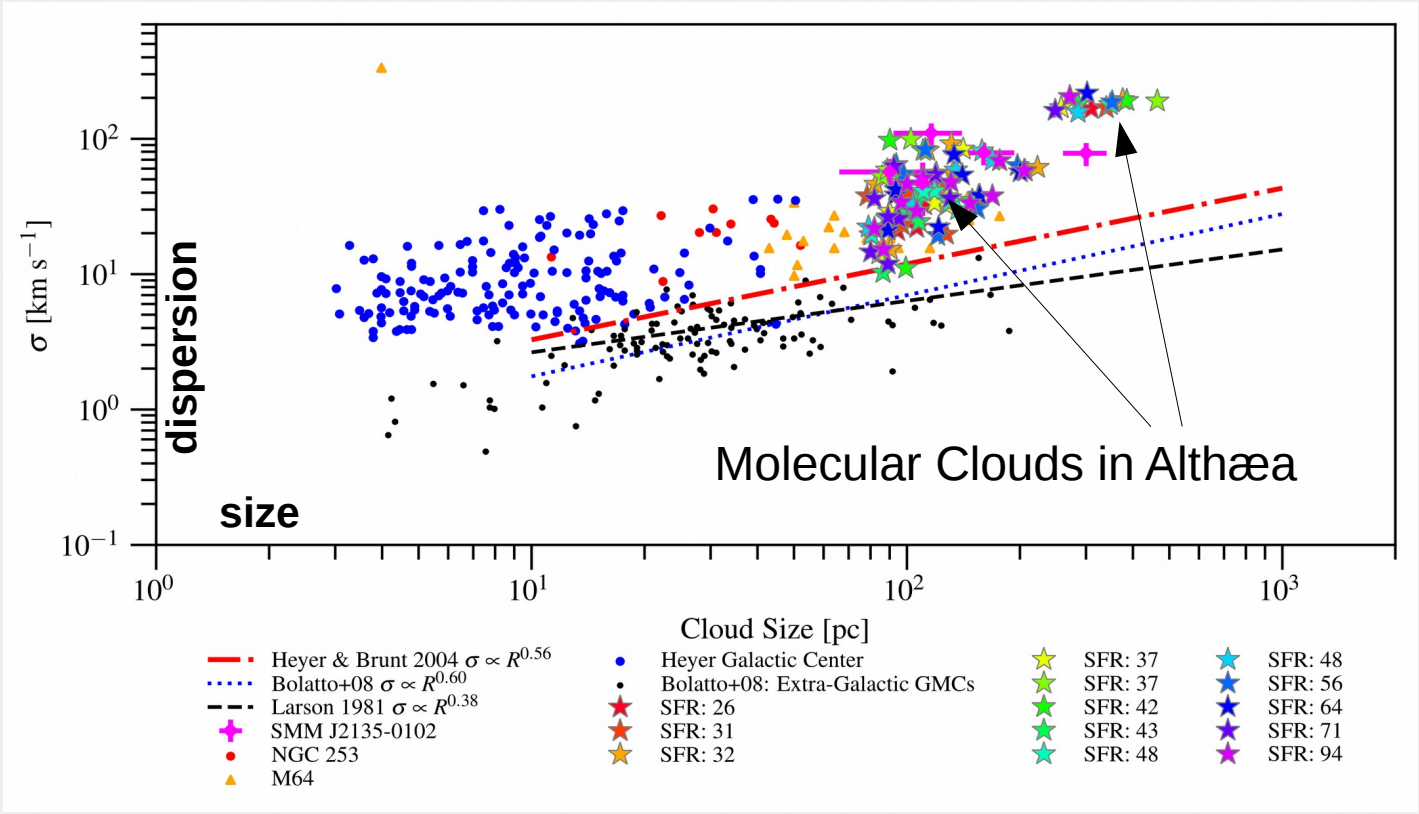
Molecular gas properties

Althæa

Pallottini+17b,Vallini+18, Leung+19



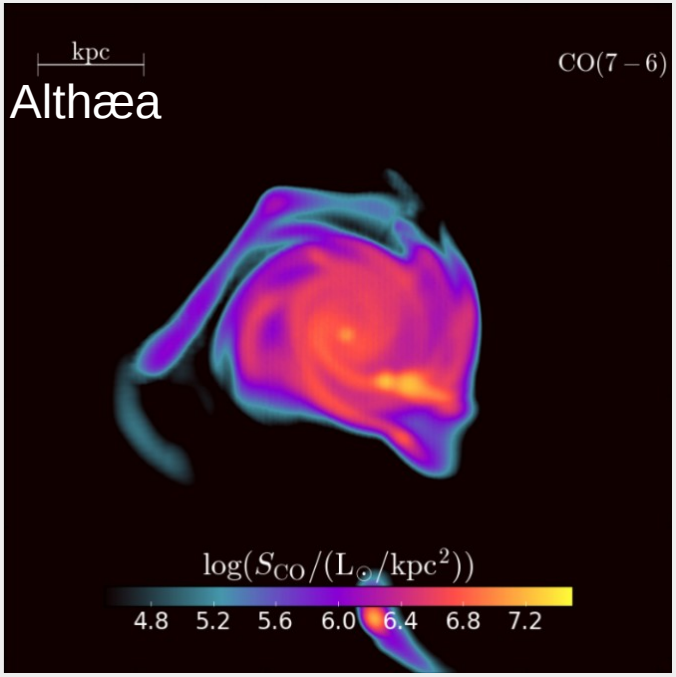


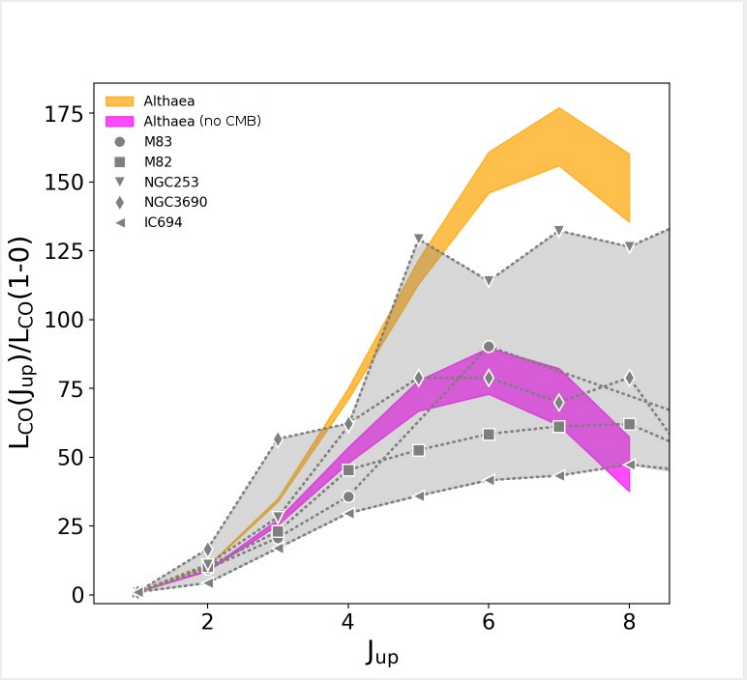


clumpy and concentrated in the galactic disk
relatively denser and hotter w.r.t. the MW
higher turbulence, as a consequence of feedback

Observing molecular gas at high-z: CO

Pallottini+17b, Vallini+18

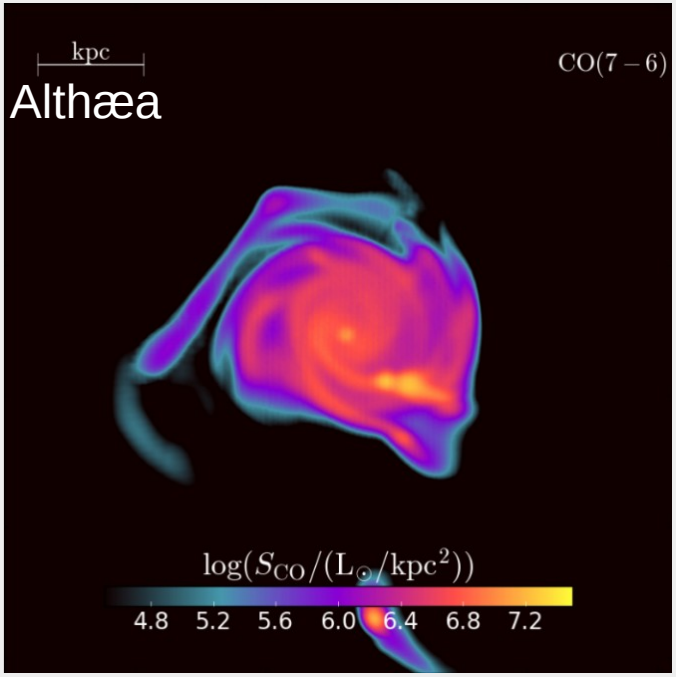


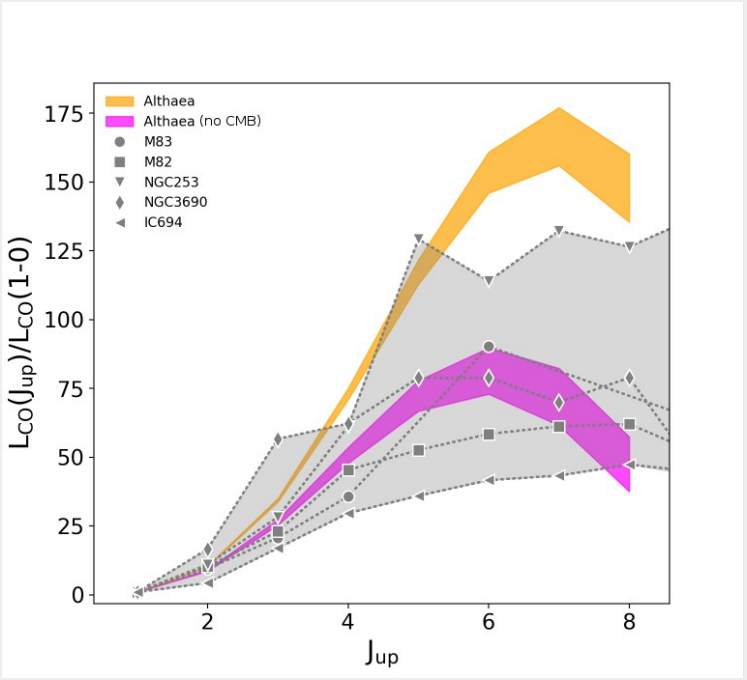


SLED peak at J=7 as MCs are denser, hotter, and more turbulent

Observing molecular gas at high-z: CO

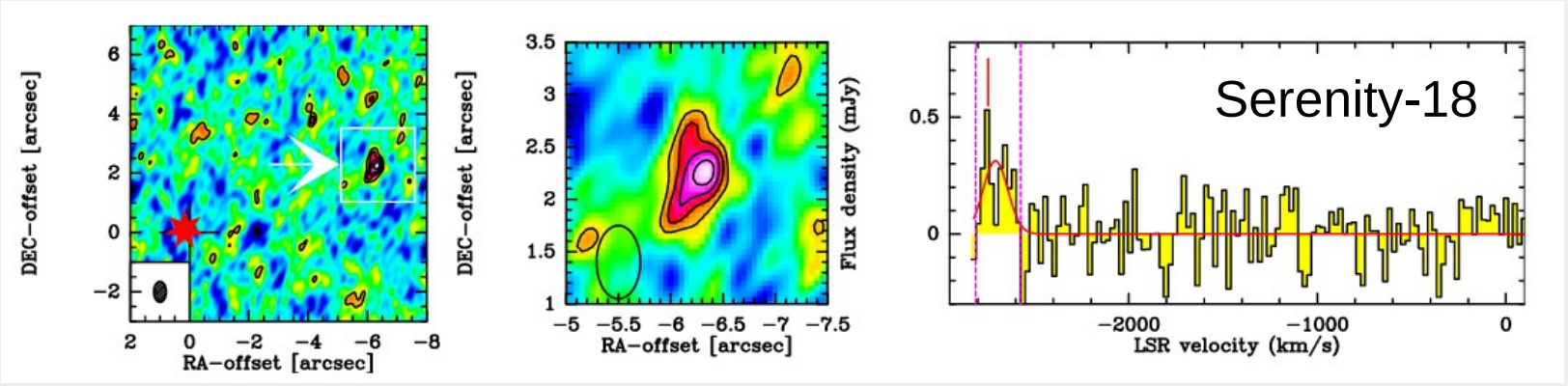
Pallottini+17b, Vallini+18





SLED peak at J=7 as MCs are denser, hotter, and more turbulent
observations are challenging: ~10h detection with ALMA

only CO detection available in a normal star forming galaxy at high-z:

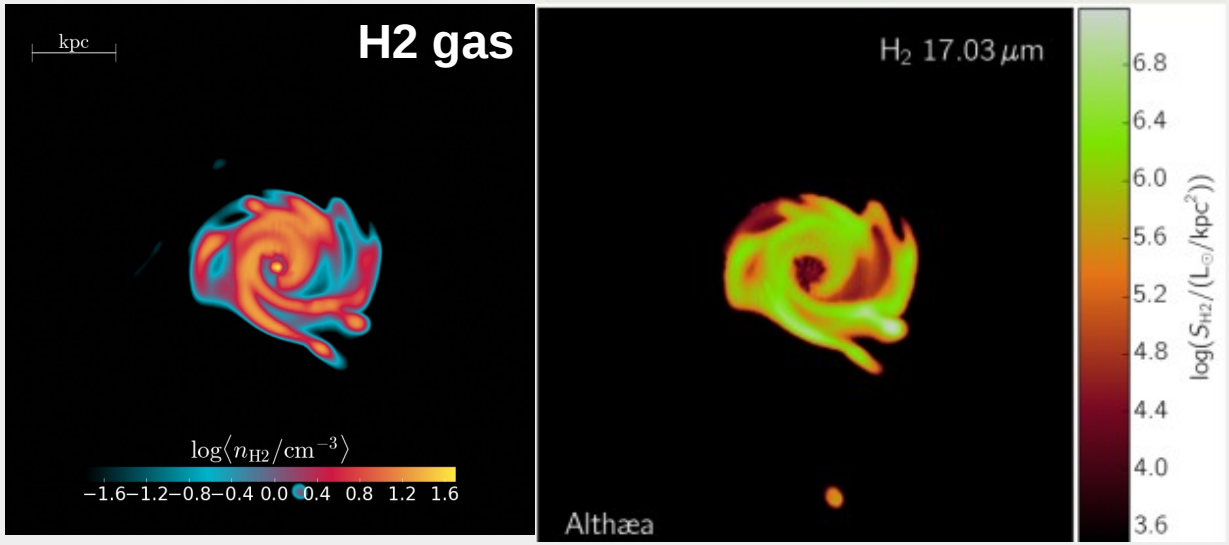


Feruglio+18
D'Odorico+18

Observing molecular gas at high-z: which lines should we use?

Althæa

Pallottini+17b, Spinoglio+17, Vallini+18, Egami+18, Kohandel+19

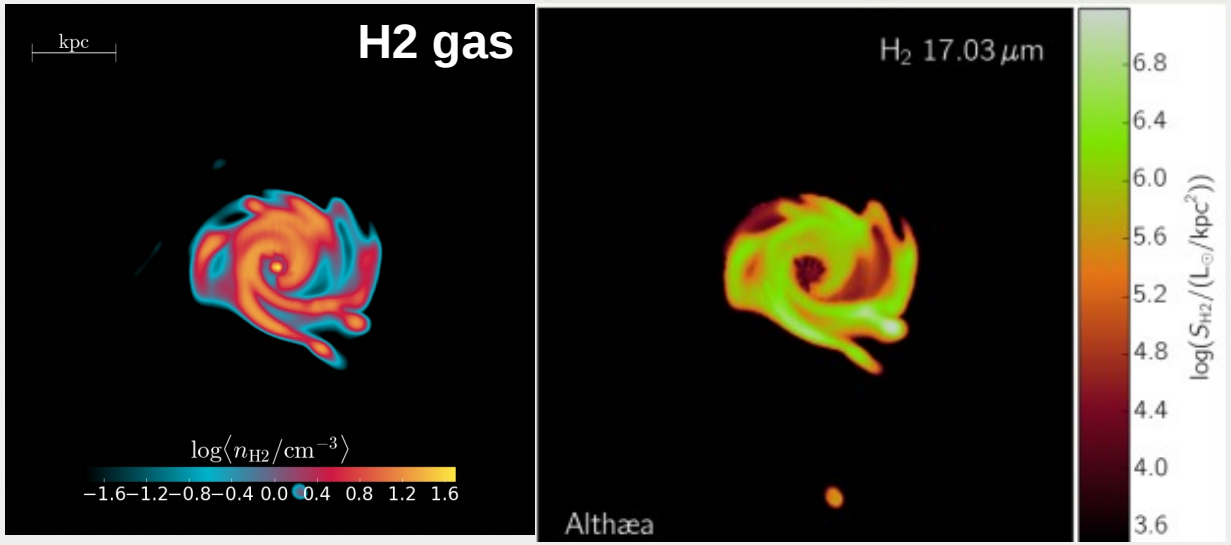


H2 not directly accessible, we have to wait for SPICA

Observing molecular gas at high-z: which lines should we use?

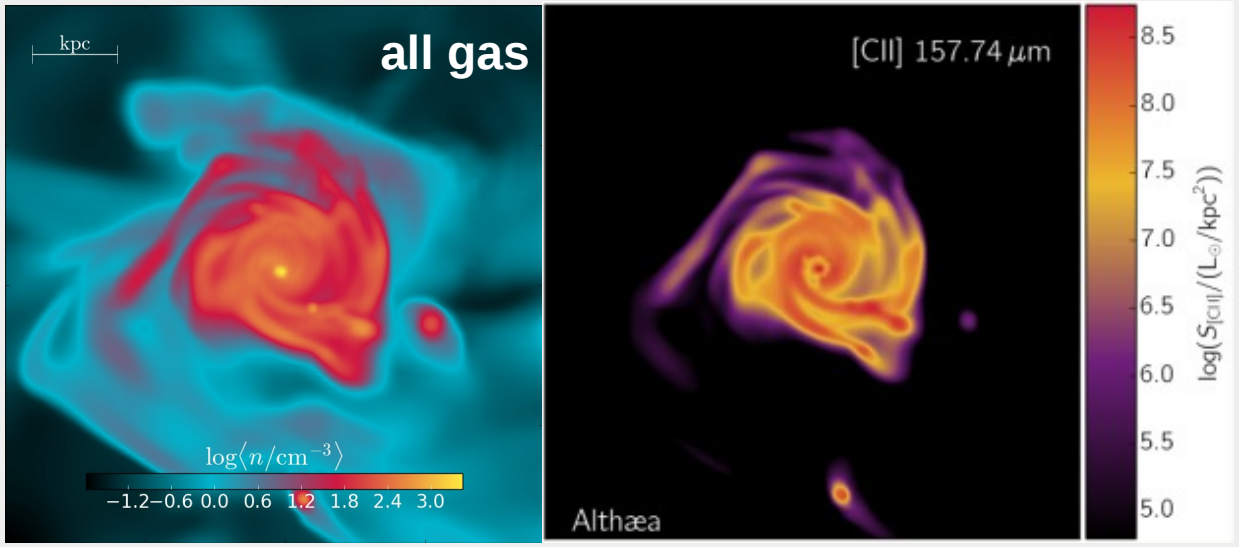
Althæa

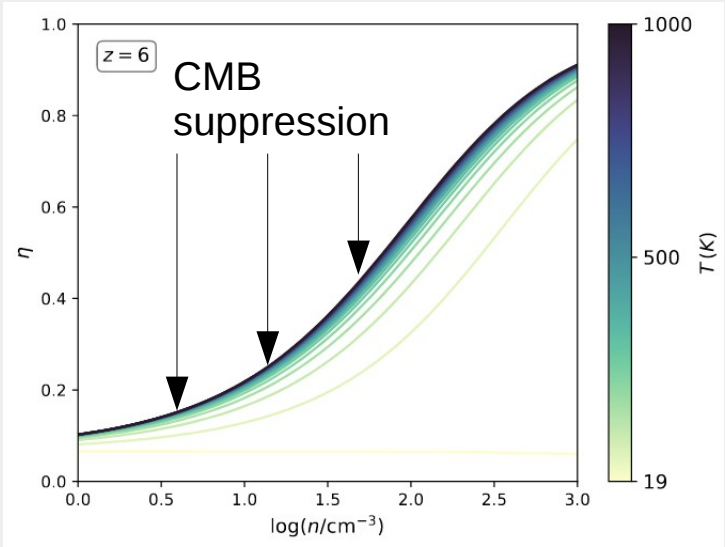
Pallottini+17b, Spinoglio+17, Vallini+18, Egami+18, Kohandel+19



H2 not directly accessible, we have to wait for SPICA

95% of the [CII] emission co-located with the dense molecular gas

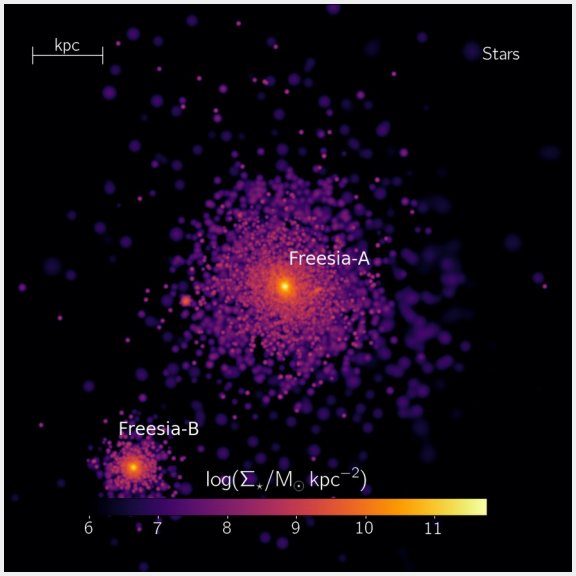


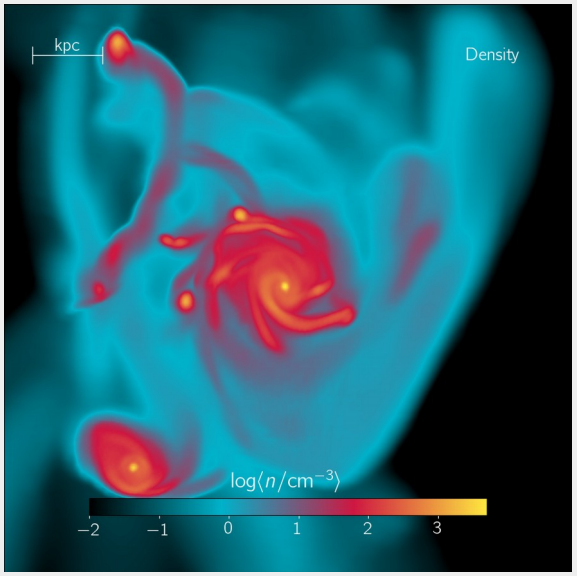


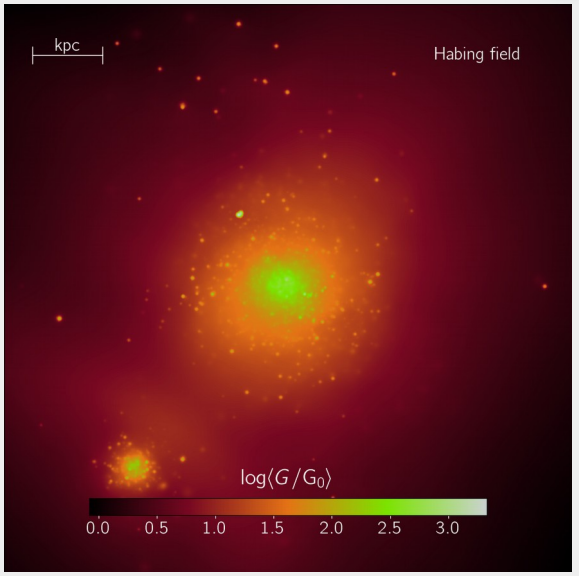
see also Vallini+13,+15, Pallottini+15, Olsen+17, Katz+19, Zanella+19

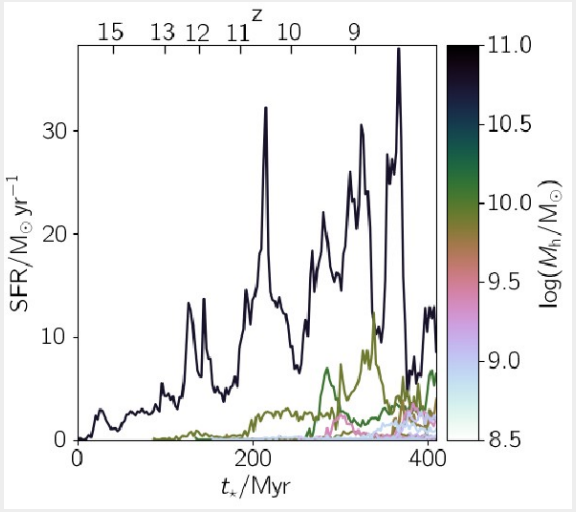
Toward the [CII]-SFR: introducing Freesia

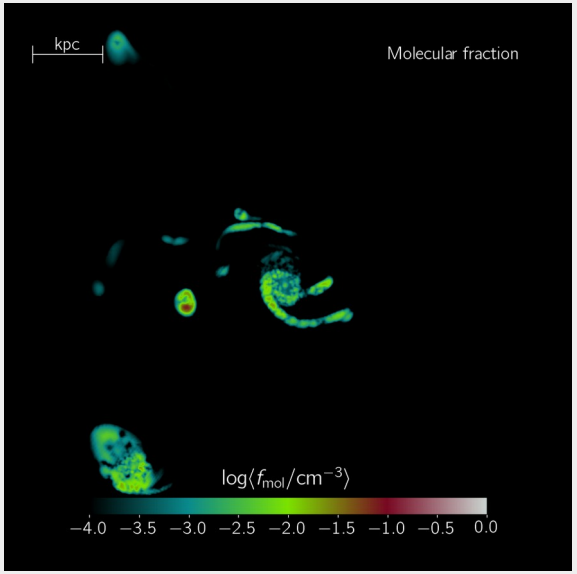
Pallottini+19

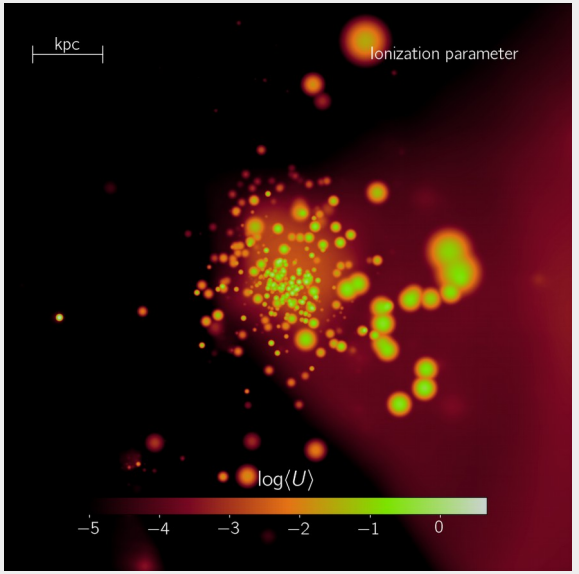












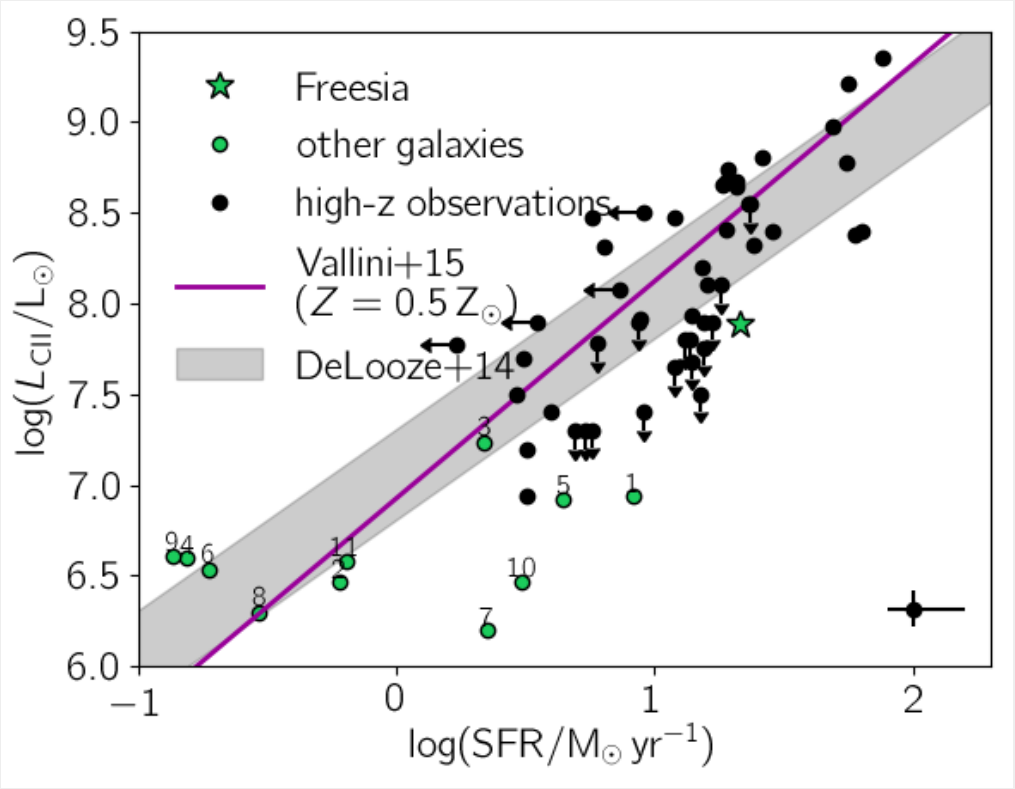
Fresia at z=8:
two-component system
caught after a starburst

for radiation model see Rosdahl+13, Decataldo+19
for chemical model see Grassi+14, Bovino+15, Pallottini+17b
for SN/winds model see Ostriker+1988, Teyssier+13, Agertz+13,+15, Pallottini+17a

The [CII]-SFR relation at high-z

Pallottini+19

[CII]-SFR



observations from: Barisic+17, Bradac+17, Capak+15, Carniani+17,+18, Matthee+17, Jones+17, Inoue+16, Ota+14, Schaerer+15, Smit+18, Willott+15, Kanekar+13, Knudsen+16

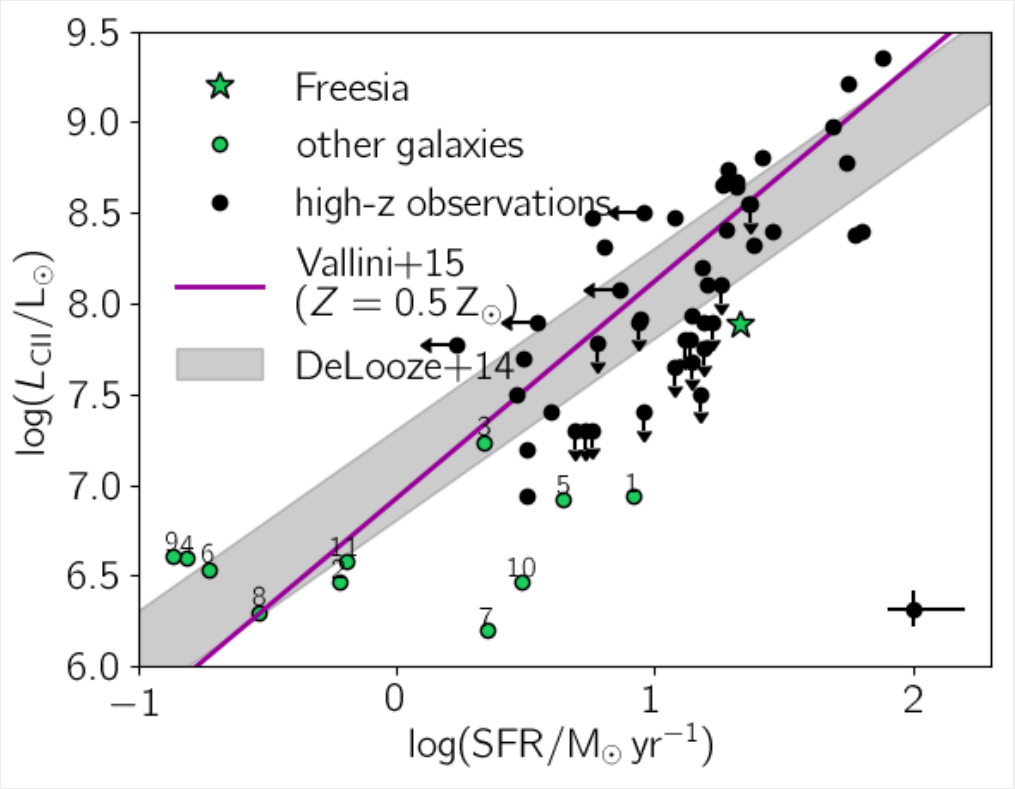
metallicity not low enough to explain the deviation

see also Vallini+13,+15+17, Pallottini+15,+17,a,b, Olsen+17, Katz+19, Ferrara+19

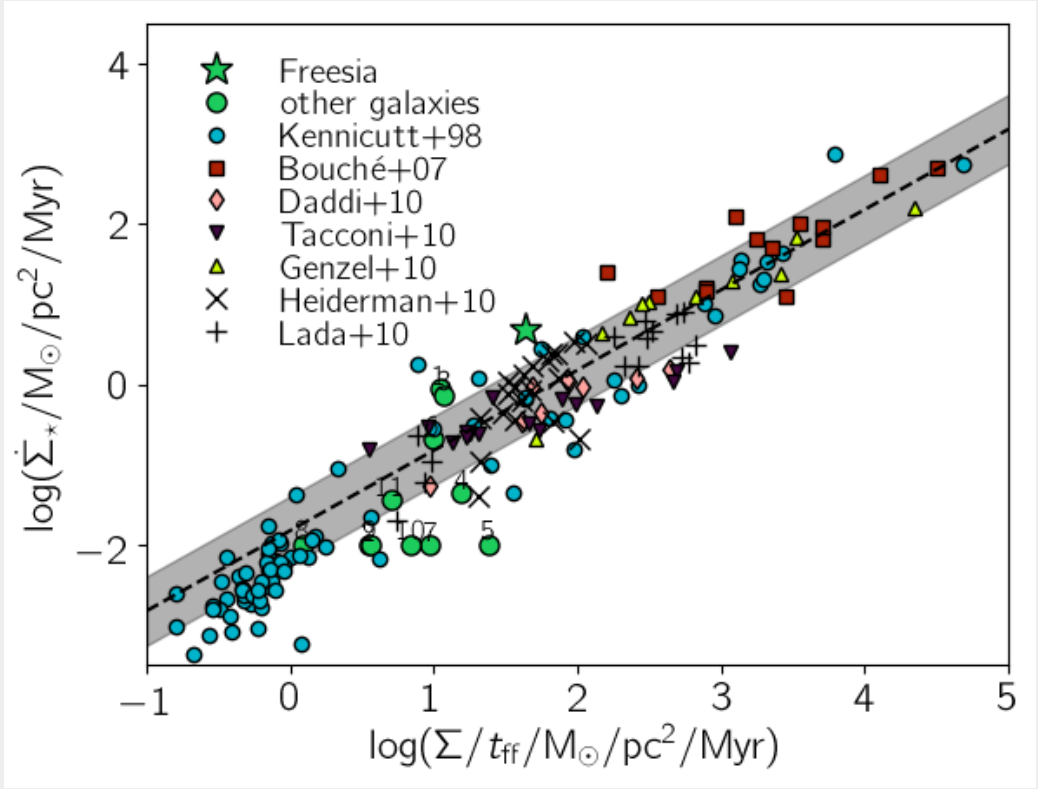
The [CII]-SFR relation at high-z

Pallottini+19

[CII]-SFR



Kennicut-Schmidt



observations from: Barisic+17, Bradac+17, Capak+15, Carniani+17,+18, Matthee+17, Jones+17, Inoue+16, Ota+14, Schaerer+15, Smit+18, Willott+15, Kanekar+13, Knudsen+16

above the Kennicutt-Schmidt (within 2σ)
below the [CII]-SFR (within 2σ)

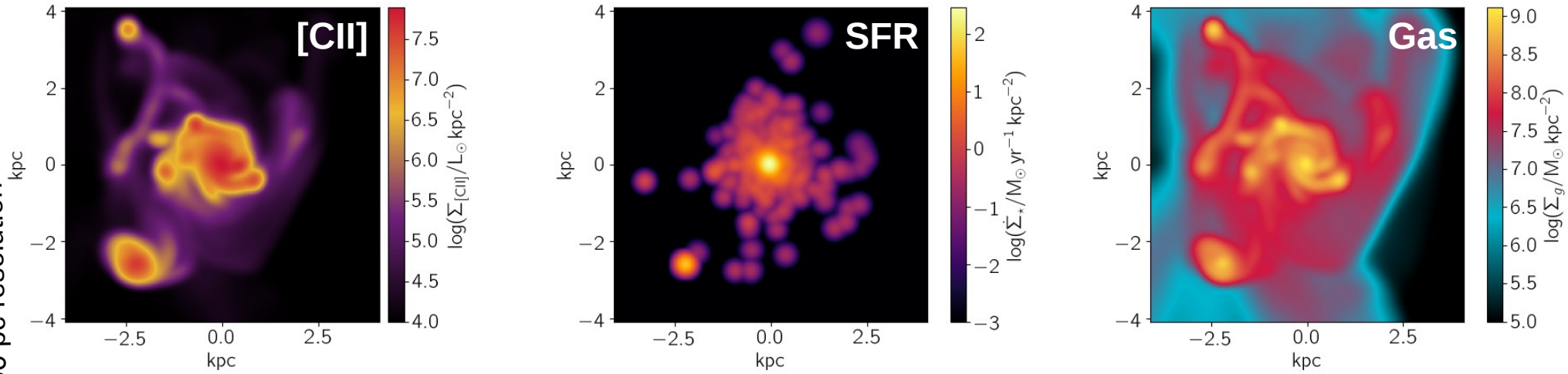
metallicity not low enough
to explain the deviation

see also Vallini+13,+15+17, Pallottini+15,+17,a,b, Olsen+17, Katz+19, Ferrara+19

The [CII]-SFR and Kennicutt-Schmidt connection

Pallottini+19

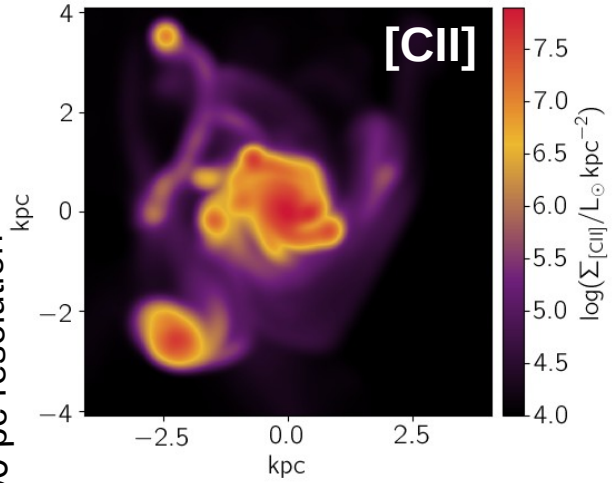
maps at 100 pc resolution

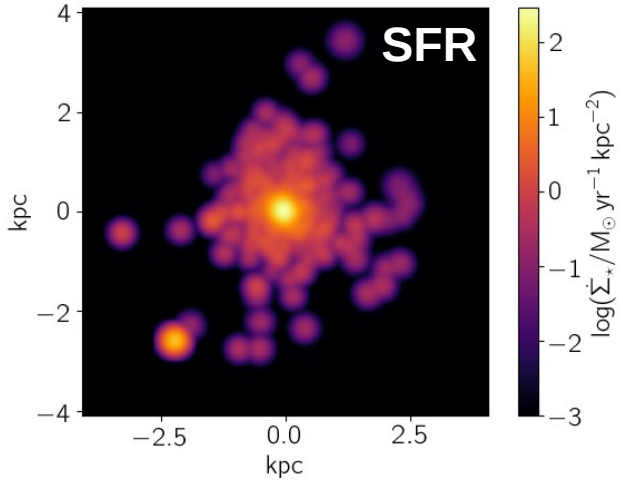


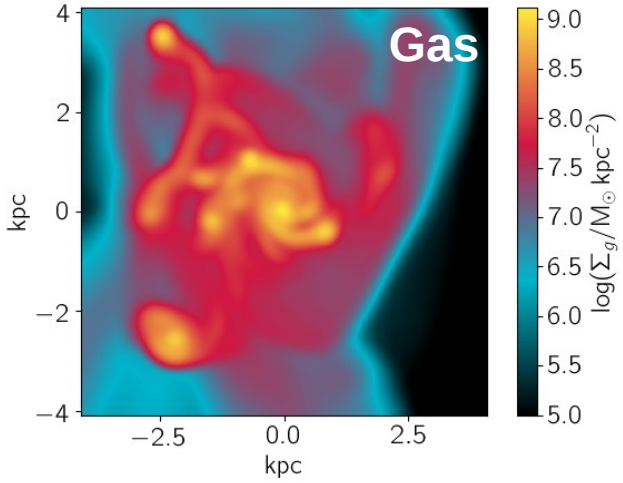
The [CII]-SFR and Kennicutt-Schmidt connection

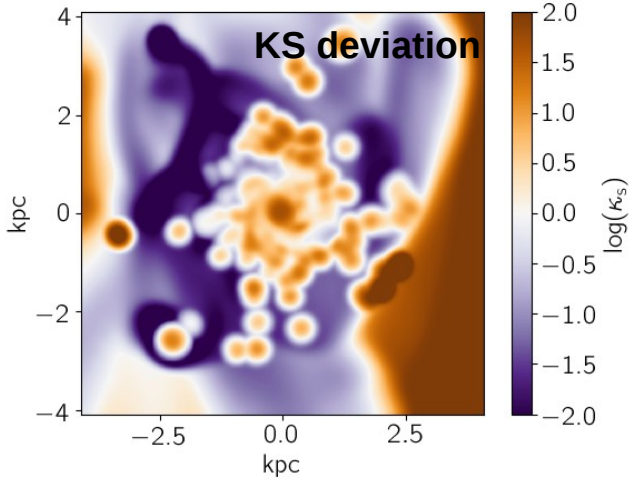
Pallottini+19

maps at 100 pc resolution





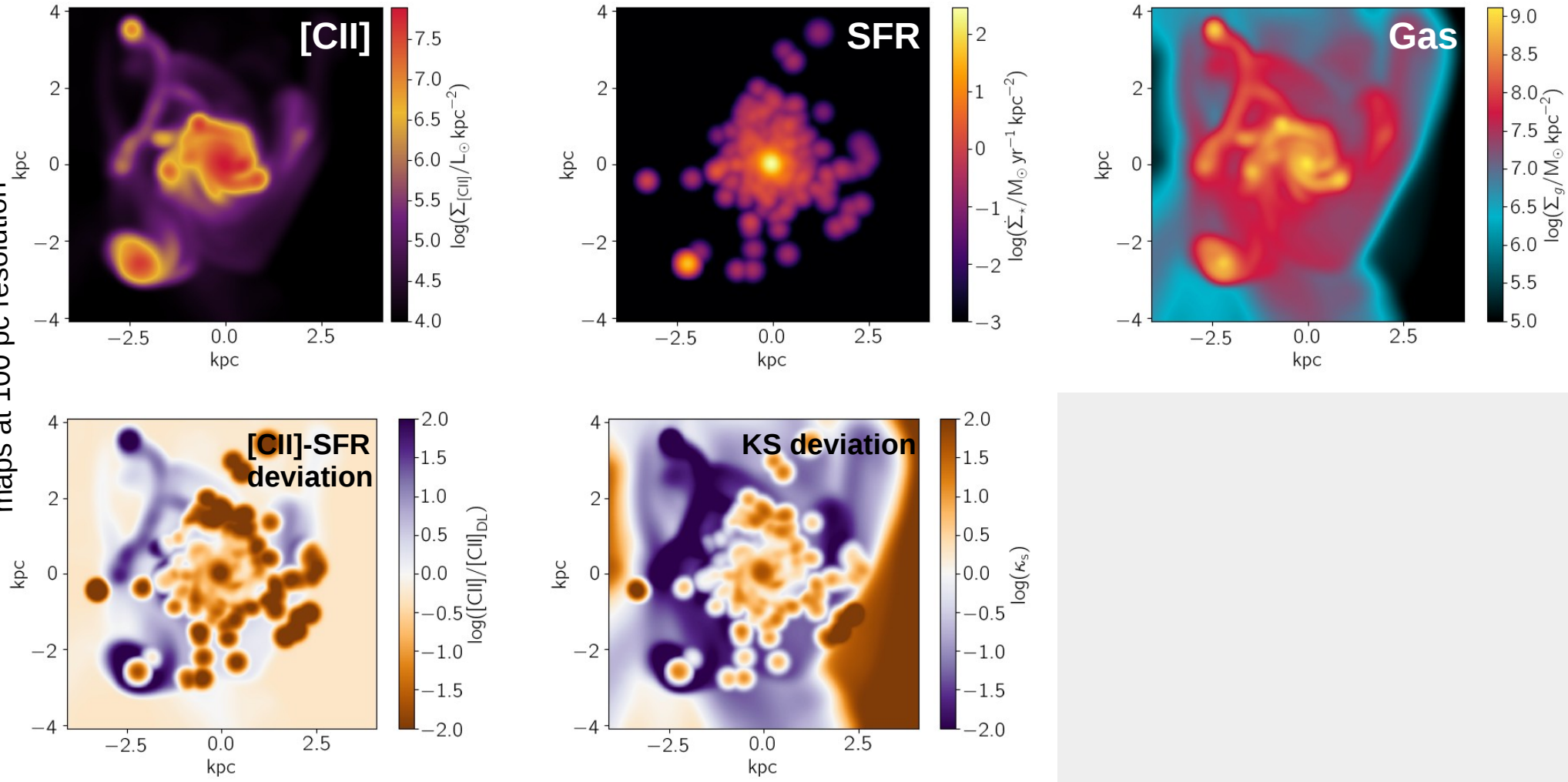




The [CII]-SFR and Kennicutt-Schmidt connection

Pallottini+19

maps at 100 pc resolution

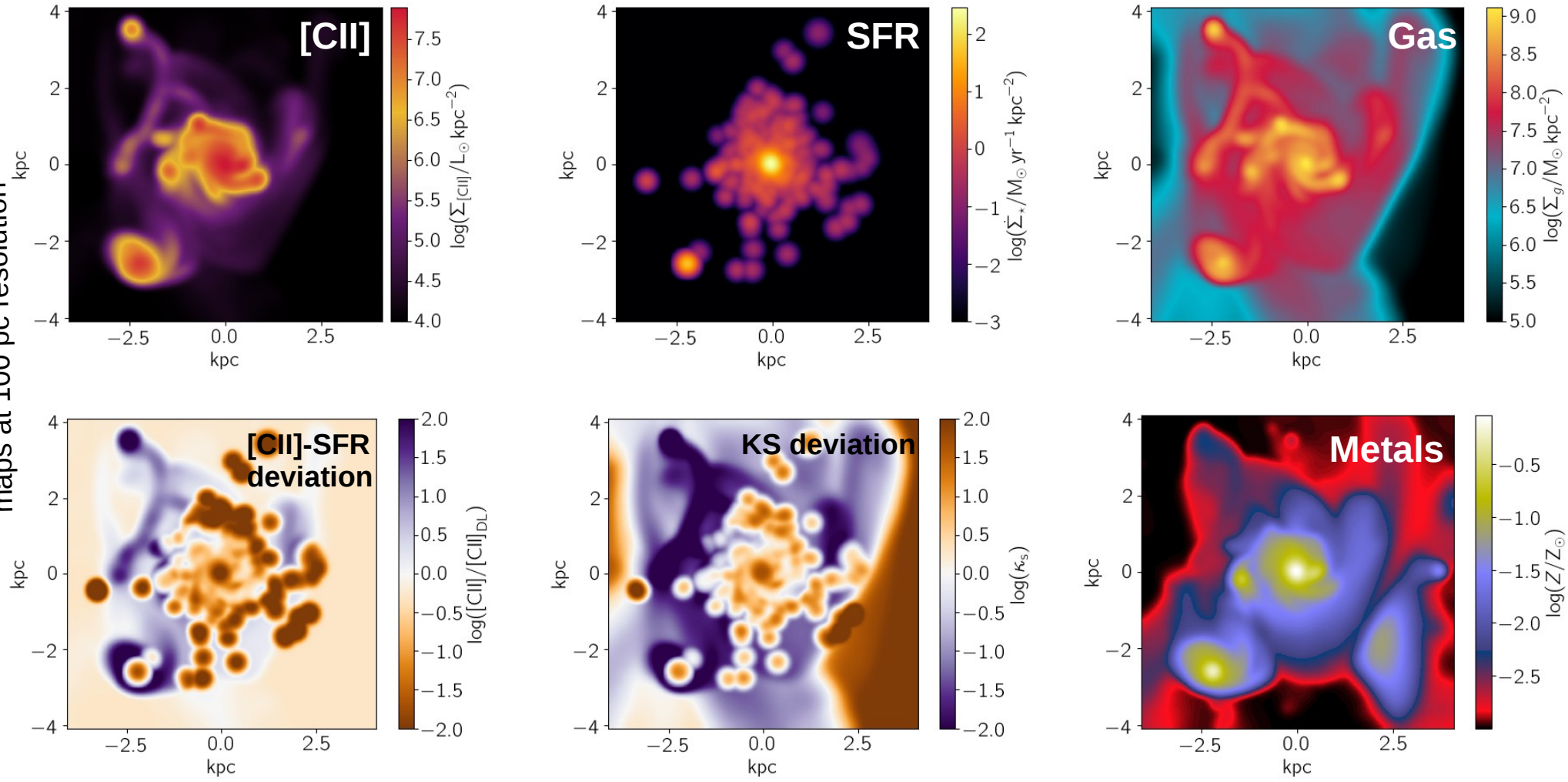


in most of the cases
being above (below) the KS implies
being below (above) the [CII]-SFR

The [CII]-SFR and Kennicutt-Schmidt connection

Pallottini+19

maps at 100 pc resolution



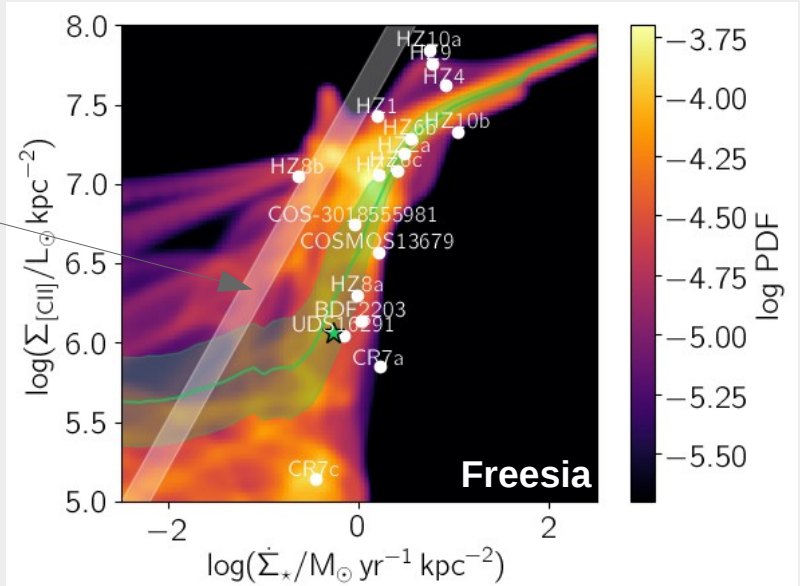
in most of the cases
being above (below) the KS implies
being below (above) the [CII]-SFR

- metal content plays a secondary role
- can be important for extremely metal poor systems

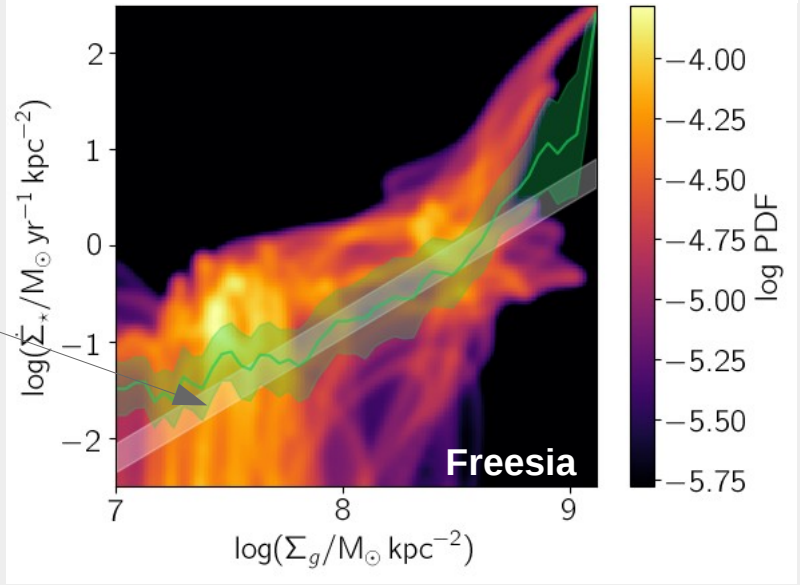
[CII]-SFR: a summary of the physical model

Pallottini+19

[CII]-SFR
Delooze+14



Kennicutt-Schmidt
Heiderman+10



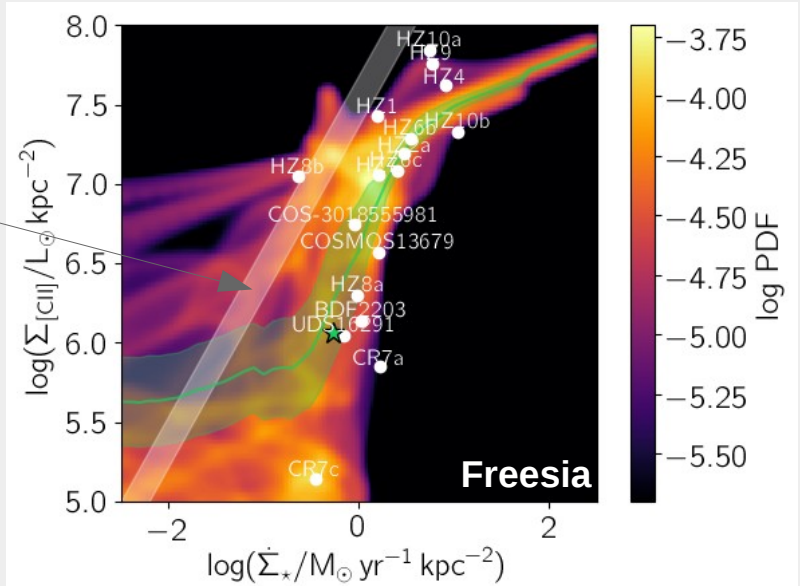
bulk of the observed galaxies have [CII]-SFR similar to Freesia

[CII] data: Ouchi+13, Capak+15, Carniani+18, Willott+15, Maiolino+15, Jones+17, Pentericci+16

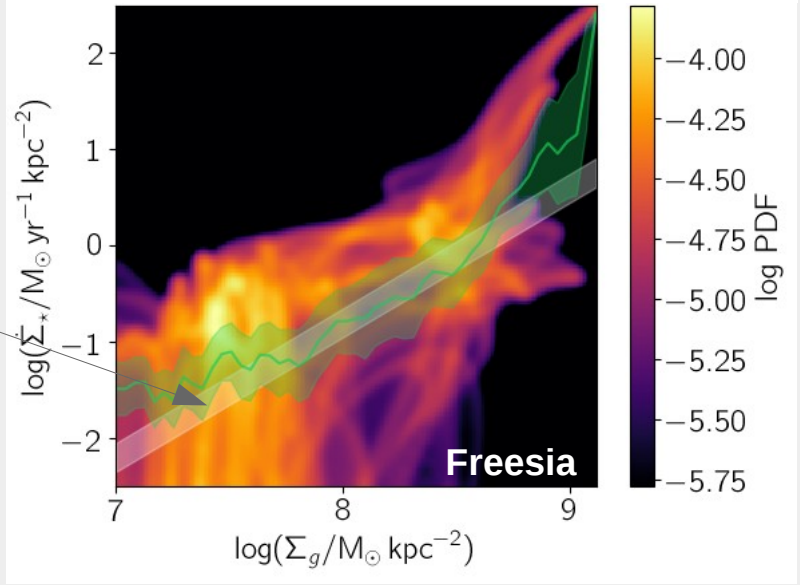
[CII]-SFR: a summary of the physical model

Pallottini+19

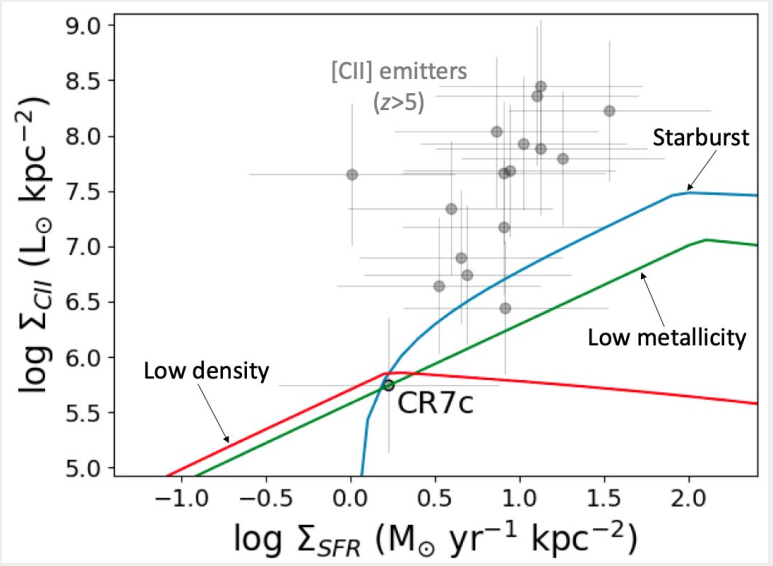
[CII]-SFR
Delooze+14



Kennicutt-Schmidt
Heiderman+10



Ferrara+19



bulk of the observed galaxies have [CII]-SFR similar to Freesia

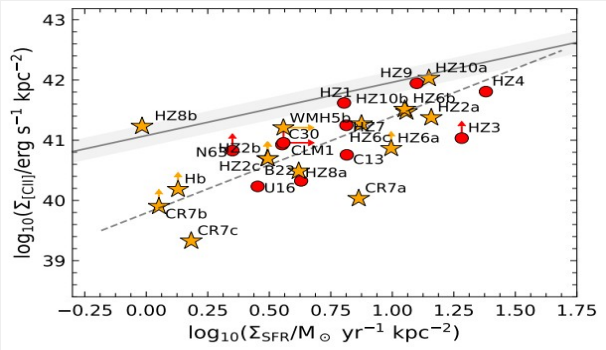
for some extreme objects (e.g. CR7c) the [CII] deficit can have other cause

additional lines (e.g. [OIII], CIII]) are needed to remove the degeneracy

[CII] data: Ouchi+13, Capak+15, Carniani+18, Willott+15, Maiolino+15, Jones+17, Pentericci+16

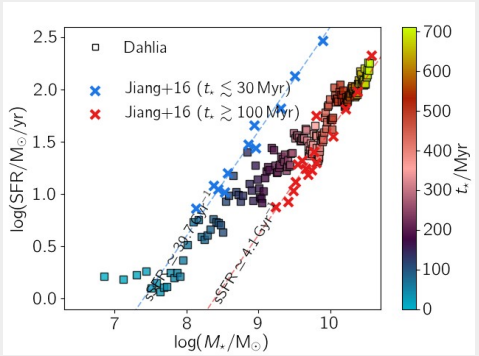
Summary:

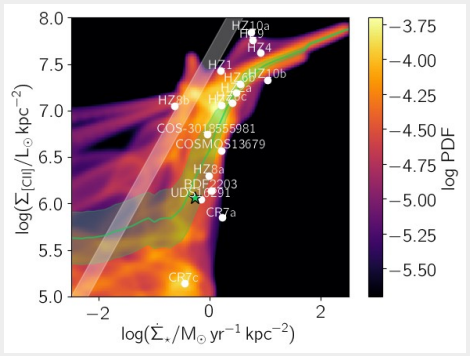
we are starting to have a more complete picture of the properties of galaxies in the EoR

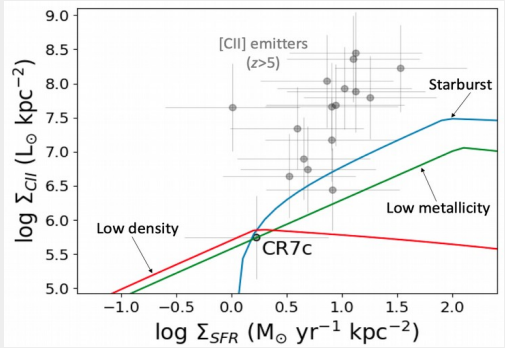


new data is coming very soon

from the theoretical side, some of ISM/ISFR properties are reasonably well understood and match current observations







more and deeper observations are needed in order to better constrain our model and thus further our physical understanding