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?

Andrea Pallottini

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

[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

does the relation hold at high-z?

Carniani+17b

indication of a wider spread of ISM properties

deviation from the relation at high-z
Zooming-in high-z galaxies

Dahlia

Pallottini+17a

Resolution

- Gas mass: $m_g \approx 10^4 M_\odot$
- AMR: $\sim 80 - 0.1$ ckpc/h
- At $z = 6$: $\Delta x \approx 30$ pc

Target LGB characteristics (at $z=6$)

- DM: $M_{\text{dm}} \sim 10^{11} M_\odot$
- Virial radius: $r_{\text{vir}} \approx 15$ kpc
- Effective radius: $r_{\text{eff}} \approx 0.5$ kpc
- SFR: $SFR \sim 100 M_\odot/\text{yr}$
- Stellar mass: $M_\ast \sim 10^{10} M_\odot$
- Gas mass: $M_H \sim 10^{10} M_\odot$
- H$_2$ mass: $M_{\text{H}_2} \sim 10^8 M_\odot$
- Metallicity: $Z \approx 0.5 Z_\odot$

Model main features

- AMR code: RAMSES Tytler 2002
- Star formation: H$_2$ based (SK relation) Krummhoib-09
- Thermal and kinetic energy: e.g. Agertz & Kravtsov 2015
- Cooling: GRACKLE 2.1
- SN explosions, OB/AGB winds & radiation pressure: Bryan 14
- Subgrid modelling for blastwaves: Ostriker & McKee 1988

from cosmological to molecular cloud scales
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

Althœa

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

SLED peak at J=7 as MCs are denser, hotter, and more turbulent
Observing molecular gas at high-z: CO

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

H₂ not directly accessible, we have to wait for SPICA
Observing molecular gas at high-z: which lines should we use?

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

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

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 $\text{[CII]}$-SFR and Kennicutt-Schmidt connection

Pallottini+19

Maps at 100 pc resolution
The [CII]-SFR and Kennicutt-Schmidt connection

Pallottini+19
The [CII]-SFR and Kennicutt-Schmidt connection

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

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

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

Ferrara+19

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

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

new data is coming very soon