THE ISM OF HIGH REDSHIFT GALAXIES
HINTS FROM EMISSION LINES

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THE ISM
**INTERNAL PROPERTIES OF HIGH-Z GALAXIES**

"DAHLIA", A LBG @ $z = 6$

**Pallottini+17a**

**AMR simulation (RAMSES)**
- Spatial res = 10 pc
- $\text{H}_2$- based SFR prescription
- Updated SN feedback model
- Radiation pressure (on dust)

Over-dense accreting filaments

Dahlia’s bipolar outflow

Molecular/stellar disk

$M_h = 1.8 \times 10^{11} \, M_{\odot}$

$M_\ast = 1.6 \times 10^{10} \, M_{\odot}$

$\Sigma_\ast = 15 \, M_{\odot} \, yr^{-1} \, kpc^{-2}$

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DAHLIA: STELLAR COMPONENT

Stellar build-up

SF history

Halo mass

INTERNAL PROPERTIES OF HIGH-Z GALAXIES

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\[
\text{Total } [\text{CII}] \text{ Luminosity } L_{\text{CII}} = 3.5 \times 10^7 \, L_\odot
\]

\(\frac{1}{3}\) of CII mass in diffuse, low-Z, weakly emitting gas (invisible due to CMB)

95% of emission co-located with H\(_2\) disk
**[CII]-SFR Relation**

**ALMA [CII] detection**
- $5 \times$ Lensed LAE @ $z=6.765$
- $L_{\text{CII}} = 1.4 \times 10^7 \ L_\odot$
- Low [CII]-Ly$\alpha$ shift = 20 km/s

**Best fit relation (Yue+15)**

$$\log L_{\text{CII}} = 7.0 + 1.2 \log (\text{SFR}) + 0.021 \log Z + 0.012 \log (\text{SFR}) \log Z - 0.74 \log^2 Z$$

**Diagram**

- HST composite
- Dahlia
- Bradac+17
- Vallini+15, $Z=Z_\odot$
- Vallini+15, 5% $Z_\odot$
H$_2$ forms at much higher density ($\approx 300$ vs $30$ cm$^{-3}$); ISM becomes more clumpy boosting (by $7\times$) [CII] line emission.
CO AT HIGH REDSHIFT?

High gas surface density
+ 
Large Mach number ($\mathcal{M} \approx 30$)
+ 
Warm GMCs ($T_k \approx 45K$)

CO SLED peaks @ $J = 7$

Low $\alpha_{CO} = \frac{1}{3} \alpha_{CO}$ (Milky Way)

CO(7–6) line @ $5\sigma$ with ALMA detected (resolved) in 13 (38) hr
Stacked residuals after gaussian subtraction for the 9 \([\text{CII}]\) emitters in Capak+15 sample

Flux excess due to \([\text{CII}]\) line wings

\( M = 65 \, M\odot \, yr^{-1} \).

Dahlia’s outflow
[CII]-detected high-z LBGs in Capak+15 sample show FIR deficit, i.e. they are “infrared dark”

They show a marked deviation from the local infrared excess, \( \text{IRX} \) (8-1000 \( \mu \text{m} \)), vs. UV slope (\( \beta \), defined in 1600-2500 Å) relation

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**A POSSIBLE SCENARIO**

- UV emission by stars
- IR radiation re-emitted by dust
- Molecular clouds
- Diffuse medium

\[ \text{hot} \approx 45 \text{ K} \equiv T_{\text{CMB}} \]

\[ \text{cold} \approx 20-25 \text{ K} \]
DUST AND IRX RELATION

\[ \mu = \frac{M_{\text{H}_2}}{M_{\text{gas}}} \]

IRX – UV SLOPE RELATION

Tracer of (high?) molecular content of high-z galaxies. Consistent with simulations

Capak+15 sample

Points: LBGs @ \( z=5-6 \)

SMC extinction curve
FROM OBSERVABLES TO PHYSICS

IFU data (MUSE, JWST, ALMA..)

Observed

Simulated

Spaxel (emission lines)

A Supervised Machine Learning code to extract physical properties from emission line spectra

EMISSION LINES WITH JWST

Ucci+17a,b

Physical fields (density, metallicity, ionization..)
HENIZE 2-10 @ 8.23 Mpc

MUSE IFU  Hα Image (PI: Cresci)

A HIGH-Z GALAXY ANALOG?

320 x 320 spaxels (spatial resolution 0.2’’)

He 2-10 has size, SFR, dynamics similar to those inferred/predicted for high-z galaxies (e.g. Dahlia). A testbed to interpret JWST observations.

64” = 2.56 kpc

100,000 spectra from 4650-9300 A (R=1750-3750)
Henize 2-10 physical maps from GAME

Gas density
High (> 500 cm$^{-3}$) central density

Metallicity
Supersolar $Z$

Ionization parameter
High in the external regions

Radial profiles
Little is known about the internal properties and ISM of high redshift galaxies.

Progress made by combining FIR (ALMA), NIR (JWST) spectra + dust continuum.

ALMA detections + hi-res simulations show that $z > 5$ galaxies:
- Are compact and have large reservoirs of dense gas
- Are considerably metal/dust enriched and possibly obscured in SF regions
- Have large SFR/area and strong interstellar radiation fields and outflows
- Are detectable in high-$J$ CO lines

Supervised Machine Learning approaches (GAME) to IFU optical/FIR data very successful when applied to local galaxy studies.

Strong potential of SML for JWST and ALMA applications at high-$z$.