Ionized Carbon
[Forbidden]

Low Dust and High [C II] Emission in Galaxies at z~5-6

Authors: P. L. **Capak** et. al.
2015

Presenters

Jiyun Di, **Xiangyu Huang**, and **Ben Levine**

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Tuesday, February 21, 2023; 13:15-13:45

158 µm [CII] Line as Estimate for Star Formation Rate

- Hardly affected by dust extinction (FIR)
- Very bright!
- High $L_{[CII]}/L_{FIR}$ ratio selects star forming galaxies
- $L_{[CII]}/L_{FIR}$ ratio and $L_{[CII]}/L_{(CO(1\text{-}0))}$ ratio is the same between star forming galaxy samples and nearby starburst galaxies → star forming galaxies at higher redshift is the “scaled up” version of starbursts near us
- [CII] line is then a good tracer for the star formation in distant galaxies!
- Can also be used to determine source redshift

arXiv:1009.4216

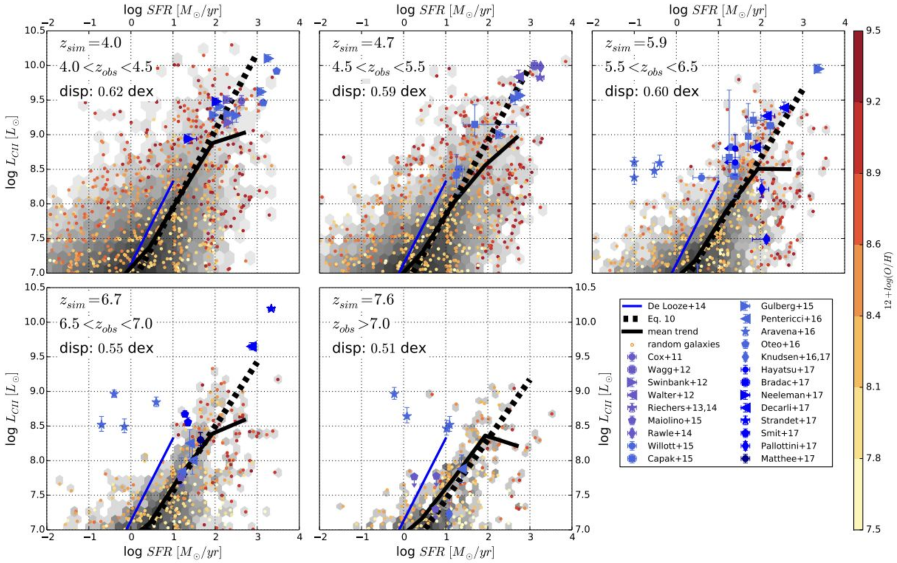
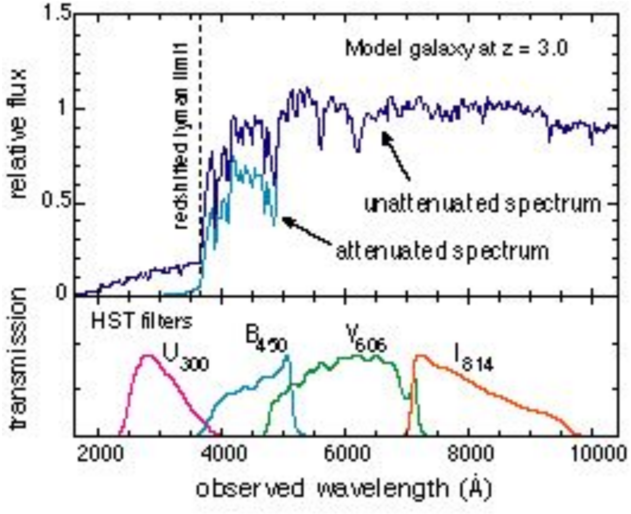


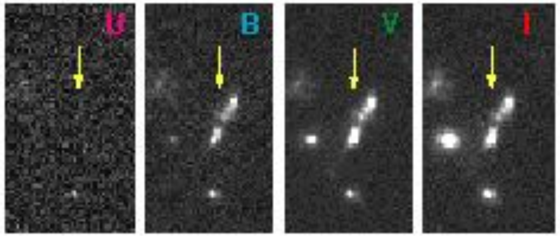
Fig. 7. $L_{[CII]}$–SFR relation. Predictions from our model are shown for a set of redshifts from z = 4 to z = 7.6. In each panel the whole sample of G.A.S. galaxies is shown in grey scale. The average relation is plotted with a solid black line. The black dashed line shows the relation given in Eq. 10. Yellow to red coloured points mark the gas metallicity of a randomly selected sample of simulated galaxies (note that the observed tendency of high-metallicity galaxies to fall either above or below the mean trend, i.e. making an “envelop”, is only a trick of the eye caused by the plotting; galaxies with high metallicities (Z_g > 8.8) are spread over the whole area, with a higher density of objects at high SFR). Our predictions are compared to a large sample of observational data that are detailed in Table B.1. Amplification corrections on luminosity and SFR, when available, are applied. For dusty star forming galaxies, SFR are converted directly from L_{IR} using the Kennicutt (1998) conversion factor assuming a Chabrier (2003) IMF where SFR ($M_\odot\,yr^{-1}$)= $1.0\times10^{-10}\,L_{IR}(L_\odot)$. The blue solid line shows the De Looze et al. (2014) relation for the local dwarf galaxy sample.

arXiv:1711.00798

Sample: Lyman Break Galaxies (LBGs)

- Star forming galaxies at high redshift
- In star forming regions of galaxies, radiation bluer than the Lyman limit (912 Angstrom) are absorbed by neutral gas
- Use multiple filters to identify them
- Sources need to be at high redshift to be detected as LBGs





arXiv:astro-ph/9807287

https://en.wikipedia.org/wiki/Lyman-break_galaxy

Infrared-Excess to UV-Slope (IRX-β) relation

- UV-Slope: UV continuum spectrum parameterized as

$$f_\lambda \propto \lambda^\beta$$

  Typical value ~-2

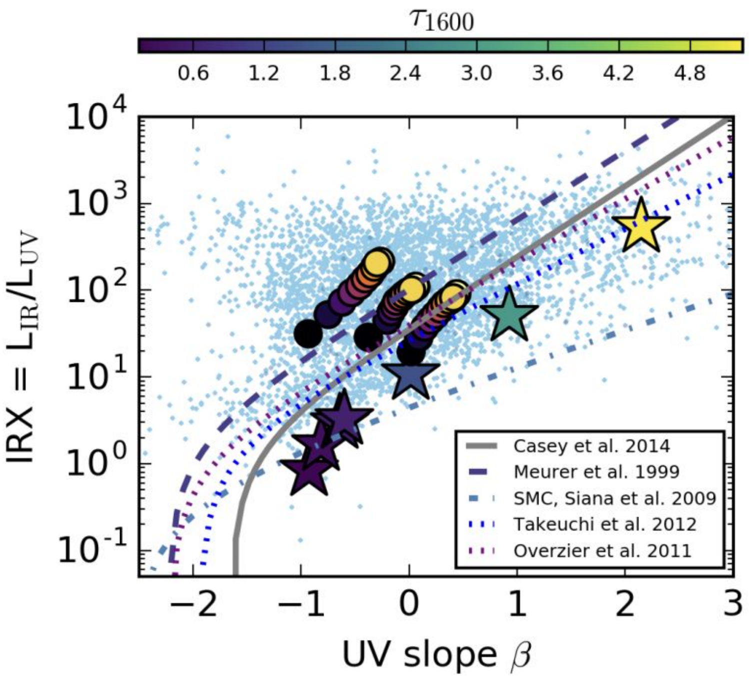
  Closely related to dust: more positive → redder,

  More negative → bluer

  Sensitive to metallicity

- IRX-β relation: dust-attenuation relation

  Sensitive to both dust properties and column densities



arXiv:1705.05858

Dynamical Mass of Galaxies

- The mass of a galaxy inferred from dynamical equilibrium:

$$\langle T \rangle = -\frac{1}{2} \langle U \rangle$$

$$M_{\text{dynamical}} \propto \frac{r < v^2 >}{G}$$

Overview of Measurements

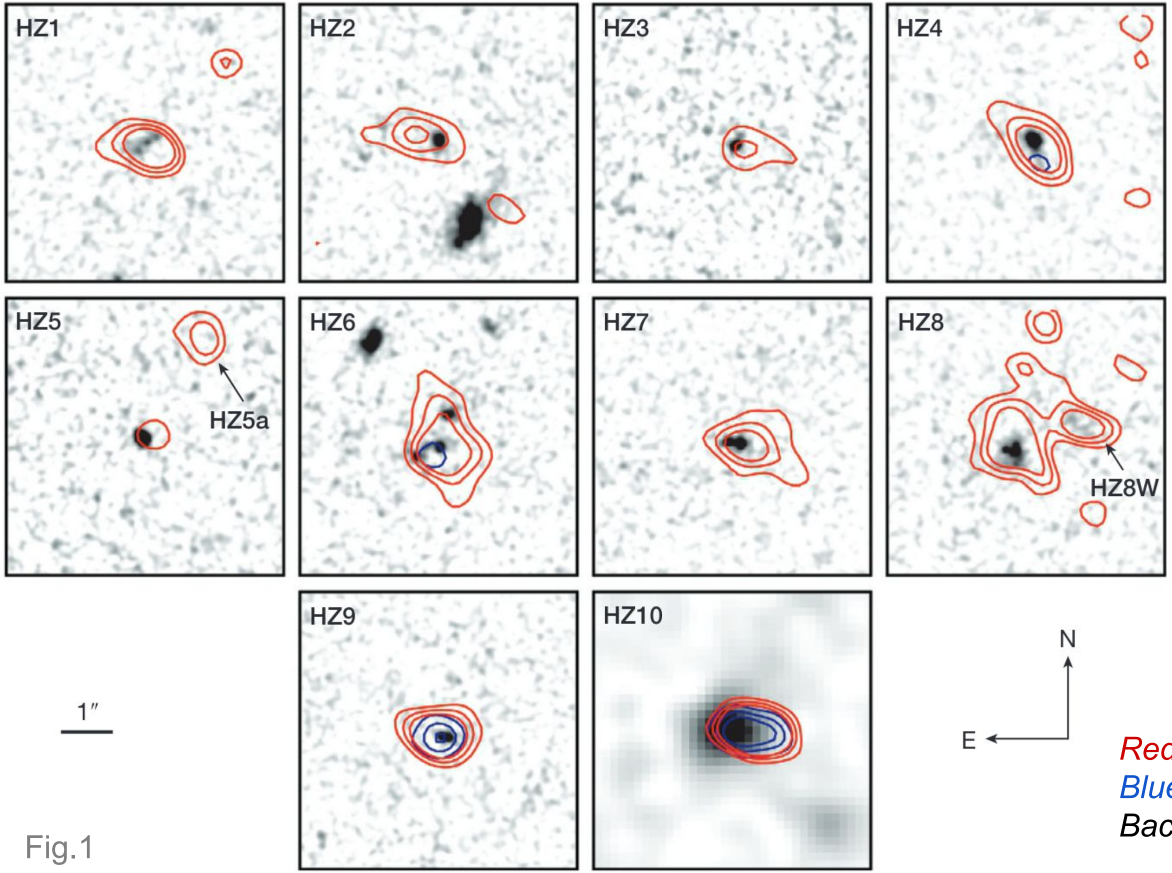


Fig.1

- 10+2 Lyman break galaxies selected from COSMOS
- Observed with ALMA (millimeter); HST, HSC, Spitzer (NIR/optical)
  - Optical: morphology
  - ALMA: [CII] (neutral gas), FIR continuum (dust emission)

*Red: [CII] (traces __**neutral gas**__)*
*Blue: FIR continuum (traces __**dust**__)*
Background: UV imaging

[CII] Emission

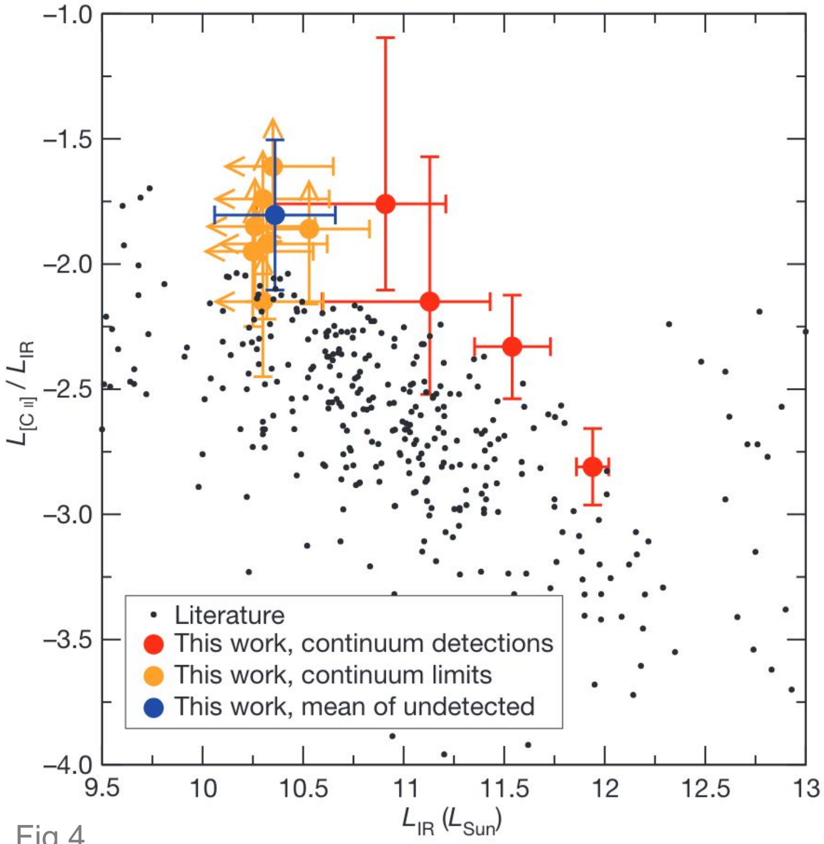


Fig.4

- Enhanced emission compared to 0<z<3
- Similar to low-z metal-poor systems
  - Lower dust/gas ratio allows UV radiation to energize a larger volume of neutral gas (main hypothesis)
  - Evolution of metallicity?
  - Evolution of dust properties?
  - Evolution of dust geometry?
- Not detected in other studies
  - [CII] is fainter than predicted by some models, so you really have to be looking for it!

Dust Properties

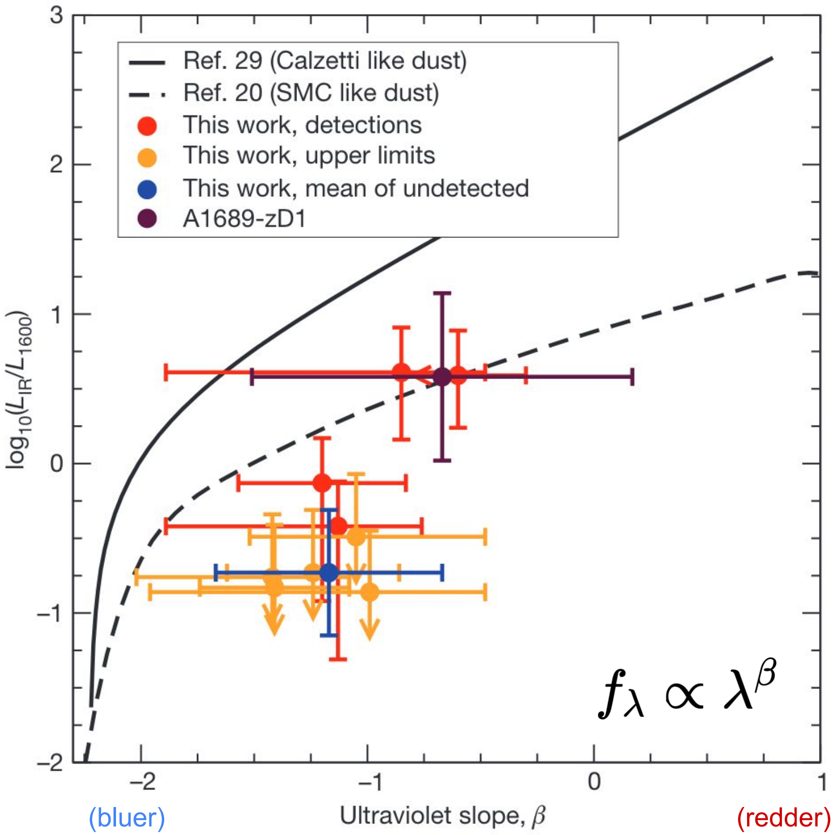


Fig.2

- Compare fiducial Meurer model with low-metallicity model
    - Meurer is generally consistent for z<3
- Here, low-metallicity model fits better

Main Takeaway: these ("representative") systems are most similar to low-metallicity/low-dust systems at low z (such as the SMC)

[CII] Line Profiles

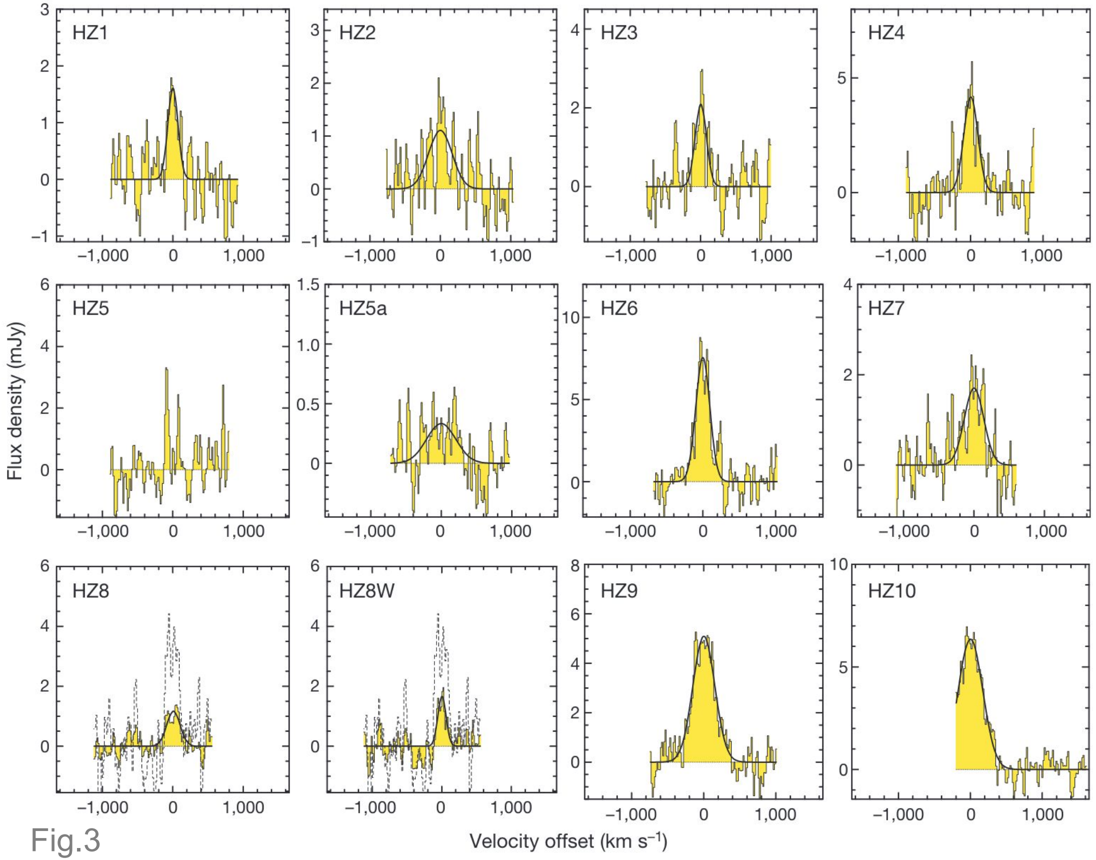


Fig.3

- Line profiles yield velocity dispersions → masses
- High uncertainty
  - How do you measure physical extent and inclination??

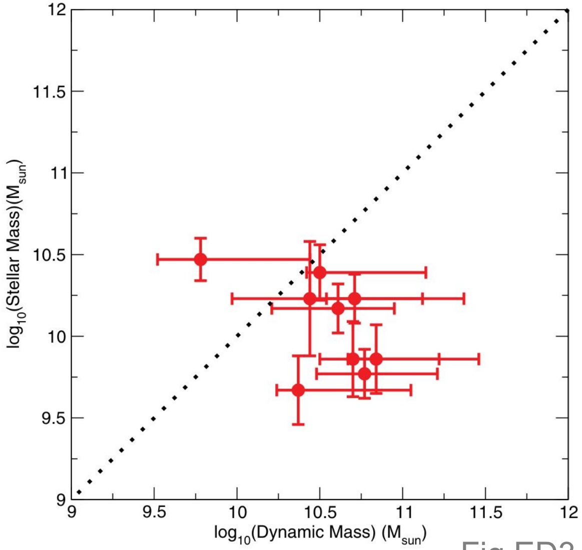


Fig.ED3

Star-Formation Rates

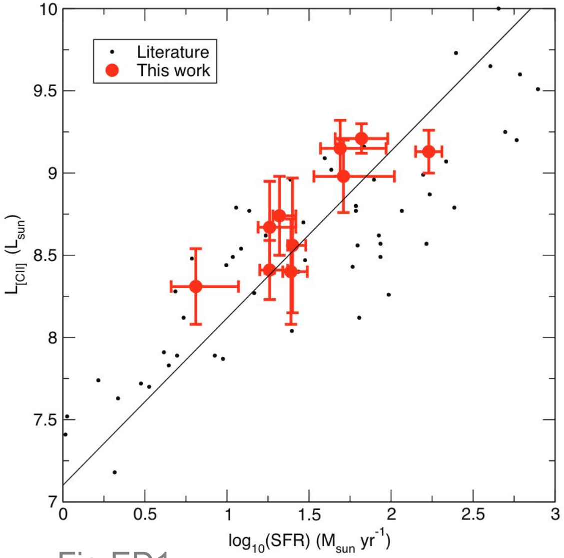


Fig.ED1

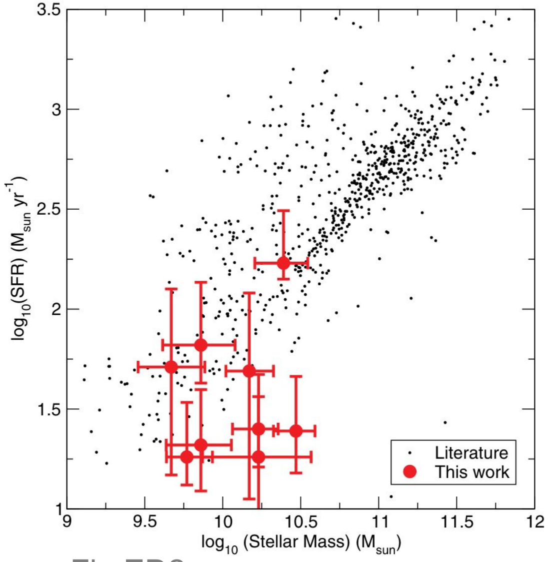
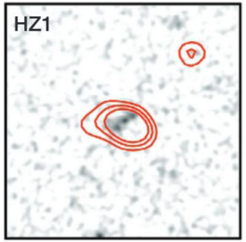


Fig.ED2

- Compute SFR using UV and FIR emission
- Consistent with low-z [CII]/SFR relation
- Kind of consistent with z~5-6 M/SFR relation
    - Three objects are more massive than expected, but one of them may be wrong because it is poorly-resolved

This one is poorly-resolved



Star Formation Histories

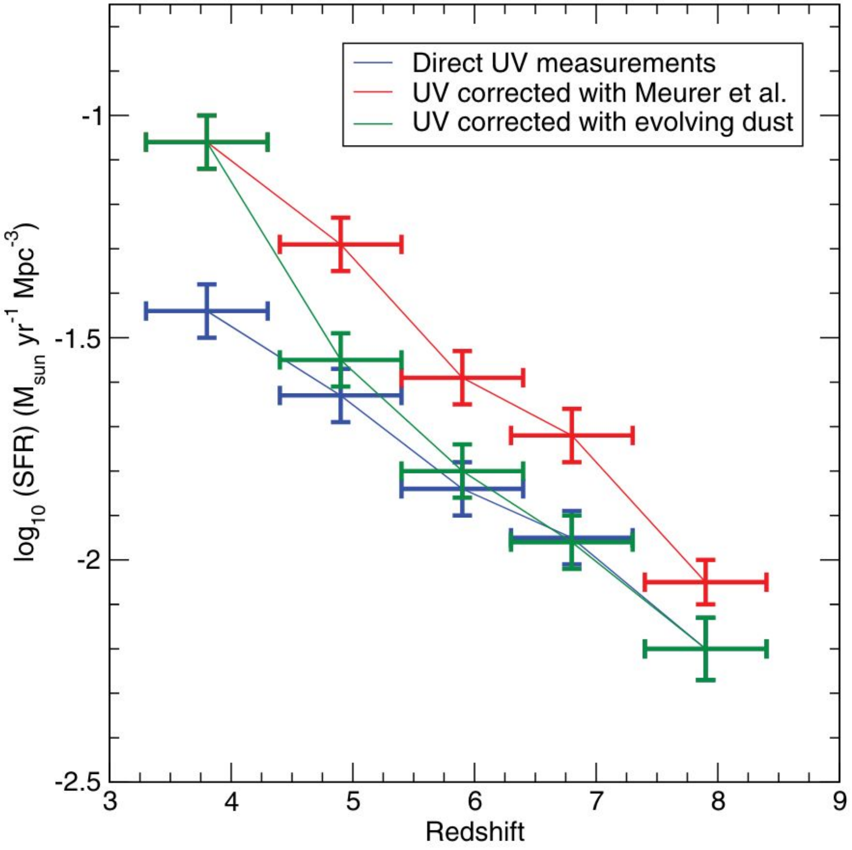


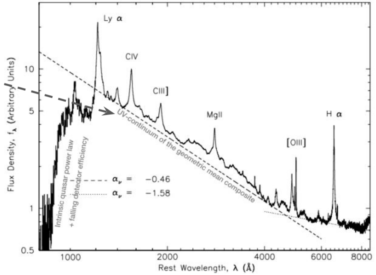
Fig.ED4

- SFH for universe assuming early galaxies behave like this sample and later galaxies behave like Meurer model
- Come up with a dust correction that begins at measured value, transitions to SMC-like model at z~5, and ends at Meurer model at z~4
  - Physically representative of evolving dust characteristics

Main Takeaway: ~35% less star formation at z=6 compared to fiducial model

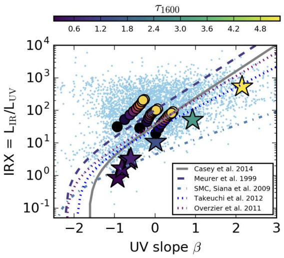
Blue: no dust correction
Red: Meurer correction (shown to be inconsistent)
Green: ~evolving~ dust

Possible Future Work



- More galaxies at higher redshifts
  - Optical (*HST*, Subaru) → **UV slope β**, but not easy. (max. z=11, 6)
  - ALMA band coverages: 300μm (z=1) - 8600μm (z=53)

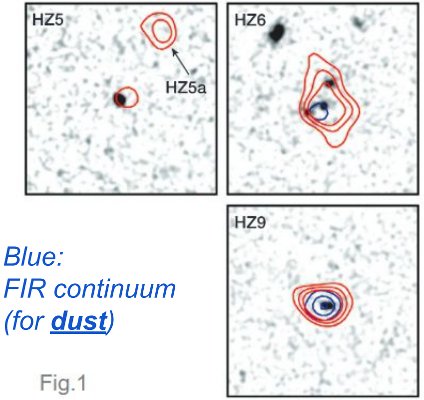
    → Narrower bandwidth available to get more accurate FIR continuum.
  - Need a **deep enough** survey to map out FIR emission:
    - Integration: < 20% of the star formation is leading to FIR emission at z~5.
    - Redshift: take spectra of candidate galaxies to get accurate spec redshifts.



HST

Subaru

ALMA

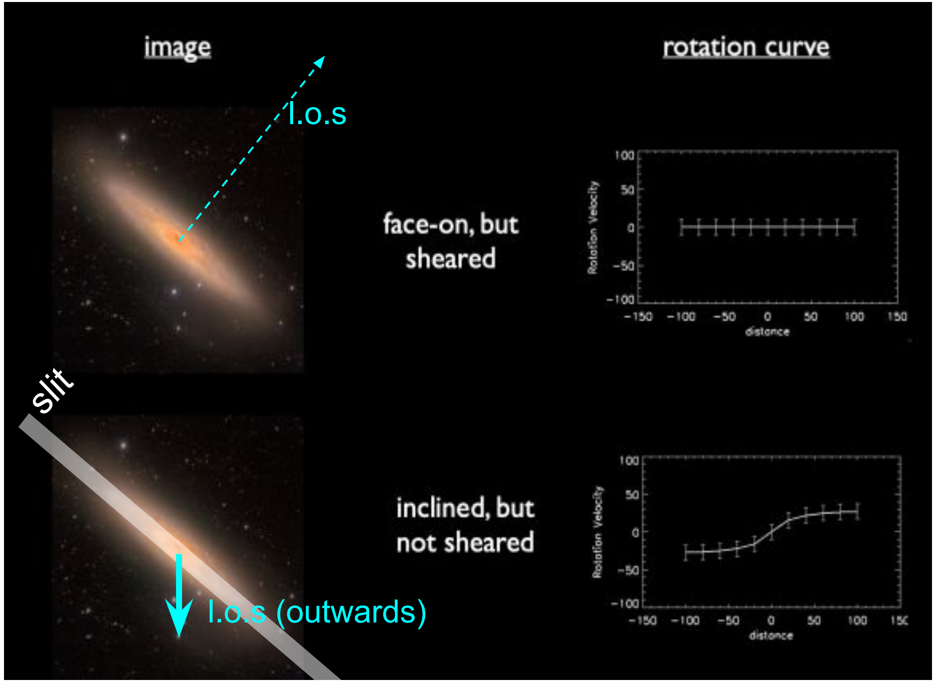


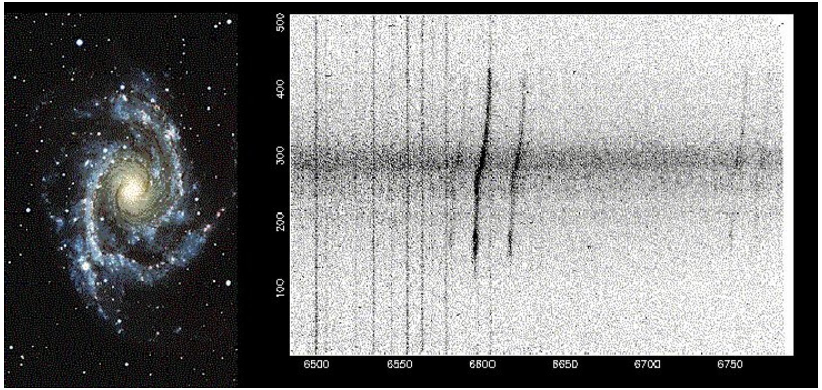
Blue:
FIR continuum
*(for **dust**)*

Fig.1

Possible Future Work

- Galaxy Morphology
  - Inclination i
    - Take spectrum to see vertical spirals





Possible Future Work

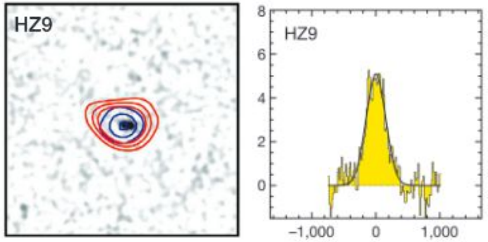
- Galaxy Morphology
  - Dynamical Mass & Inclination i
    - Take spectrum to see vertical spirals "S"
    - Get intrinsic galaxy shape
    - Correct velocity distribution σ
    - Face-on → no spectral spiral

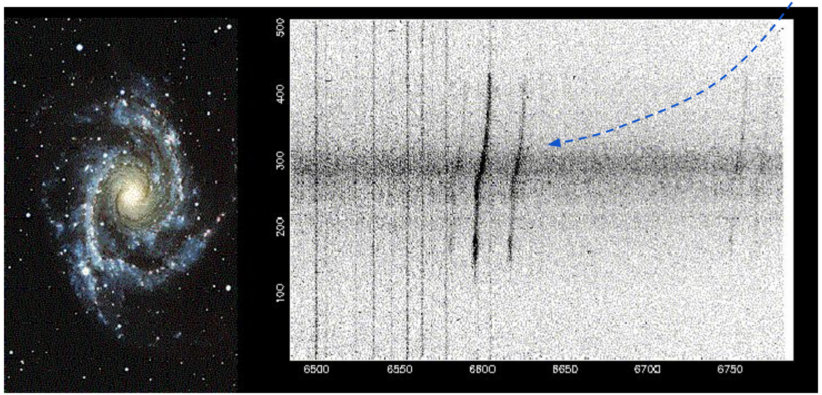
      (Xu et al. 2023)

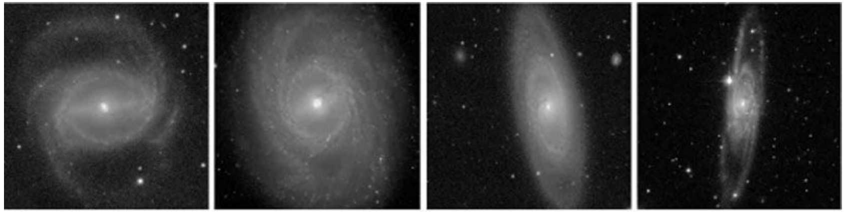
$$M_{\rm dyn} = 1.16 \times 10^5\, V_{\rm cir}{}^2\, D$$

$$V_{\rm cir} = 1.763\, \sigma_{[\rm C\ II]}/\sin(i)$$

Red: [CII] (for gas)
Blue: FIR continuum (for dust)
BG: Emitted UV or observed ~9000A







33° 49° 71° 81°

More researchers can help

- Evolution has been started very early at the epoch of reionization. More redshift-dependent trends.
- Current models estimating [C II] excess still remain unclear. (Need more data!)
- The [CII] emission can be also inferred once **knowing SFR** and the relation (De Looze et al. 2014)
- ALMA high resolution imaging is not satisfying (**~1''**; Lambert et al. 2023)
- *JWST* best resolution: **0.1''**
- NOrthern Extended Millimeter Array (IRAM/NOEMA, **0.1''**)

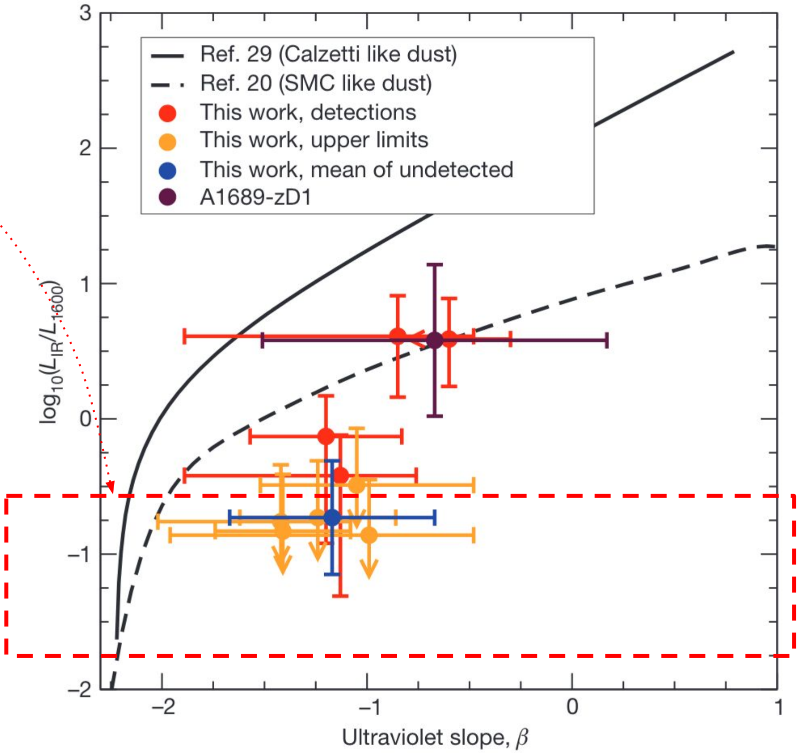
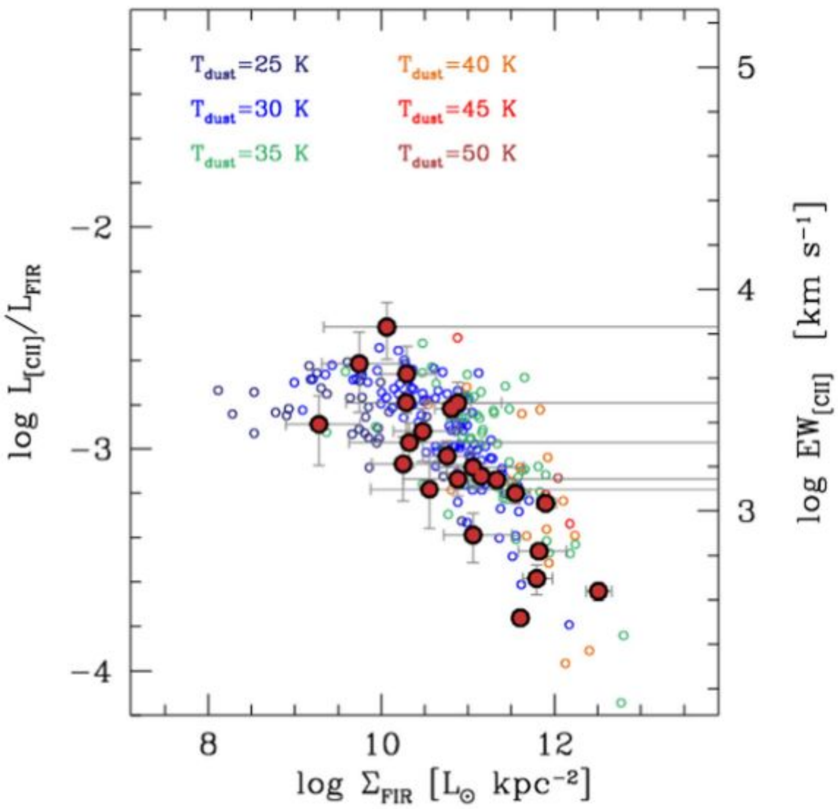


Fig.2

More researchers can help (Optional)

- Quasars at high redshifts can also be good proxies (they are the most luminous objects at high-z).
- Other correlations are undiscovered and may correspond to physical properties!
    - Various dust temperatures in quasar host galaxies.
    - Increasing dust temperature at decreasing [C II]/FIR. (Decarli et al. 2018)



Exploring the obscured star formation and interstellar medium

Information from

- The dust continuum emission
- Some relevant **FIR emission lines** ([C II] 158 μm, [O III] 88 μm, and CO) from various rotational levels (Pizzati et al. 2023)

→

Galaxy internal properties

- Assembly history
- **ISM thermal structure**
- **Gas dynamics**
- Dust/metal enrichment
- Interstellar radiation field

Main Paper

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Appendix 1 - Some unsure thoughts, if radio spectrum is not doable

- Galaxy Morphology
  - Velocity Dispersion σ
    - Take spectrum to see flux vs. wavelength curve
    - Measure the width of other lines and analogous to [C II]
    - This yields to a very precise velocity dispersion

      → improves dynamical mass calculations

      → also benefits stellar masses (SED model fits emission)

$$M_{\rm dyn} = 1.16 \times 10^5 \, V_{\rm cir}{}^2 \, D$$

$$V_{\rm cir} = 1.763 \, \sigma_{[\rm C\,II]}/\sin(i)$$

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