Full of Orions?

Dissecting the extreme star-formation in the early Universe

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Dusty star-forming galaxies (DSFGs)

The star-forming activity of the Universe peaked between 9-13 billion years ago (redshift z=2-5). At this epoch, up to 50% of all stars lived in dusty star-forming galaxies[1] (DSFGs), which were forming stars at rates higher than any present-day galaxy. DSFGs thus provide a unique window into the physics of extreme star formation.

What are the physical conditions inside the DSFGs?

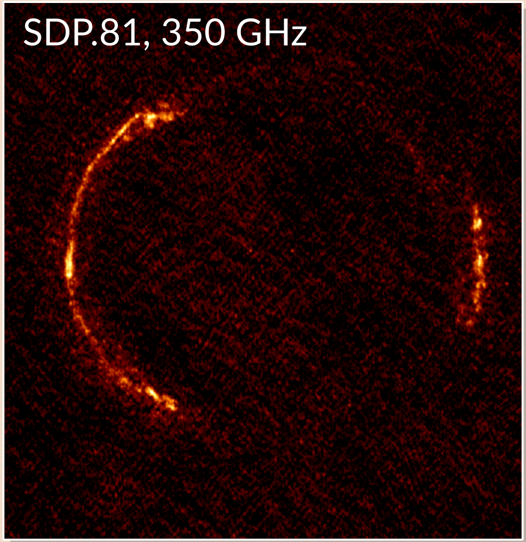
To understand the physical processed inside DSFGs and how they impact the newborn stars, we need to study the thermodynamics of their molecular gas (density, far-UV radiation, temperature ...).

But: studies of DSFG thermodynamics have been restricted to mostly unresolved observations[3,4,5]. The physical conditions inferred from this unresolved data might be severely biased as different tracers (dust, [CII], low/mid/high-J CO lines) are not necessarily co-spatial[6,7].

Our approach:

- Resolve DSFGs in multiple emission lines and continuum.
- Use gravitational lensing for extra resolution.
- Map the physical conditions in ~100 pc scales.

[1] Swinbank+2014, MNRAS 438 • [2] Tielens & Hollenbach, 1985, ApJ 291 • [3] Stacey+ 2010, ApJ 724 • [4] Gullberg+2015, MNRAS 449 • [5] Wardlow+ 2017, ApJ 837 • [6]Calistro-Rivera+2018, ApJ 863 • [7] Rybak+ 2019, ApJ 876 • [8]Negrello+ 2010, Science 330 • [9]ALMA Partnership+ 2015, ApJL 808 • [10]Rybak+ 2015, MNRAS 451

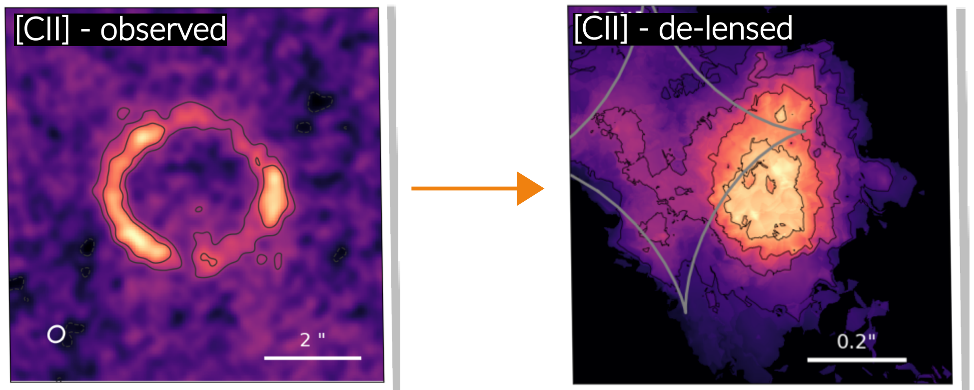


Our target: SDP.81 (z=3.042)

SDP.81 is a spectacular, strongly gravitationally lensed DSFG discovered by the H-ATLAS survey[8]. We use the data from the ALMA Long Baseline Campaign[9] – Bands 4, 6 and 7 far-IR continuum, CO(5-4), (8-7) and (10-9) lines, and complement them with new CO(3-2), [CII] and Band 8 continuum observations: a total of 40 hr of ALMA high-resolution observations.

De-lensing:

We remove the gravitational lensing effect using the technique of Rybak+2015a, which directly fits the observed visibilities rather than post-processed images. This allows us to reconstruct the background galaxy with high fidelity and resolution.



SDP.81 – what does it look like?

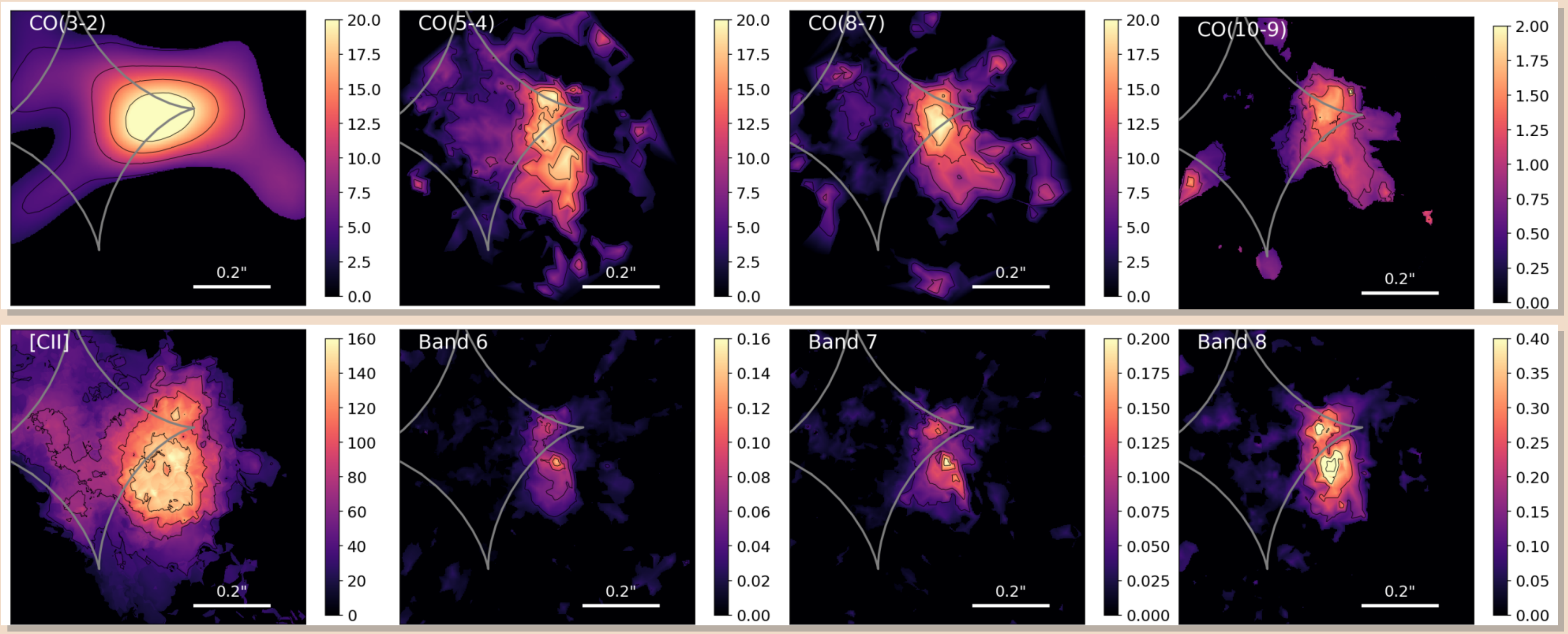
Reconstructed source – lensing effect removed

SDP.81 deciphered

This is how SDP.81 looks like in different lines and continuum Bands after de-lensing.

CO lines vs. far-IR continuum

The CO lines look very different from each other: CO(5-4) correlates closely with the far-IR continuum (dust), but the higher-excitation CO(8-7) and (10-9) lines look very different: an evidence for varying gas temperature.



Units: CO/[CII] - mJy km/s kpc^2, continuum: mJy/kpc^2

[CII] emission emission is very different from CO or [CII] - itactually dips in the areas with most star formation. In these areas, CO accounts for more than 25% of the gas cooling!

Far-IR continuum (dust) is concentrated in 2-3 clumps. The continuum does not vary much between the three ALMA Bands – the dust temperature does not change significantly.

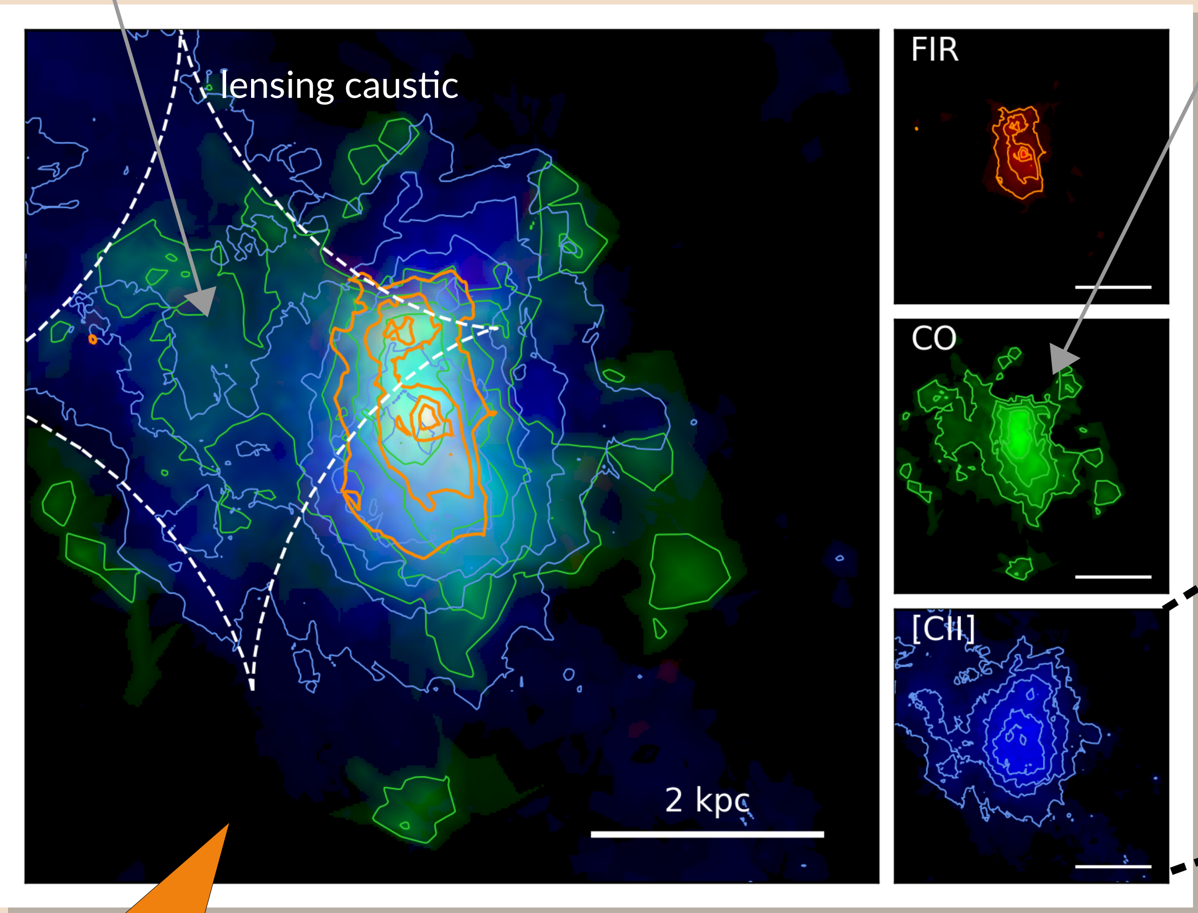
All reconstructions publicly available: sdp81.strw.leidenuniv.nl

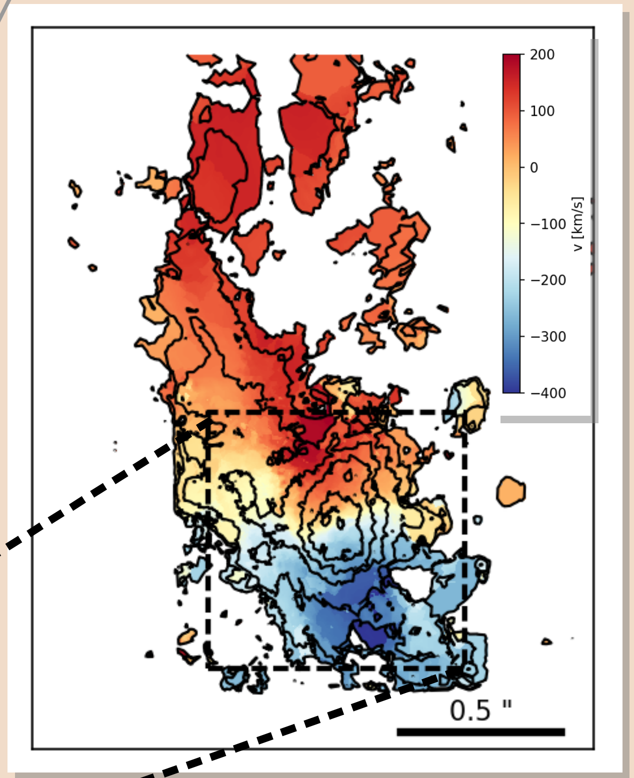
SDP.81 – what does it look like?

Reconstructed source – lensing effect removed

Lots of gas, little dust
This region is very faint in dust continuum, but bright in [CII] and CO lines. The star-formation is very limited here.

CO vs [CII] cooling
Under normal conditions, [CII] line dominates the gas cooling. But in the central part of SDP.81, CO lines account for >25% of the total cooling – an indication of very dense, warm gas.



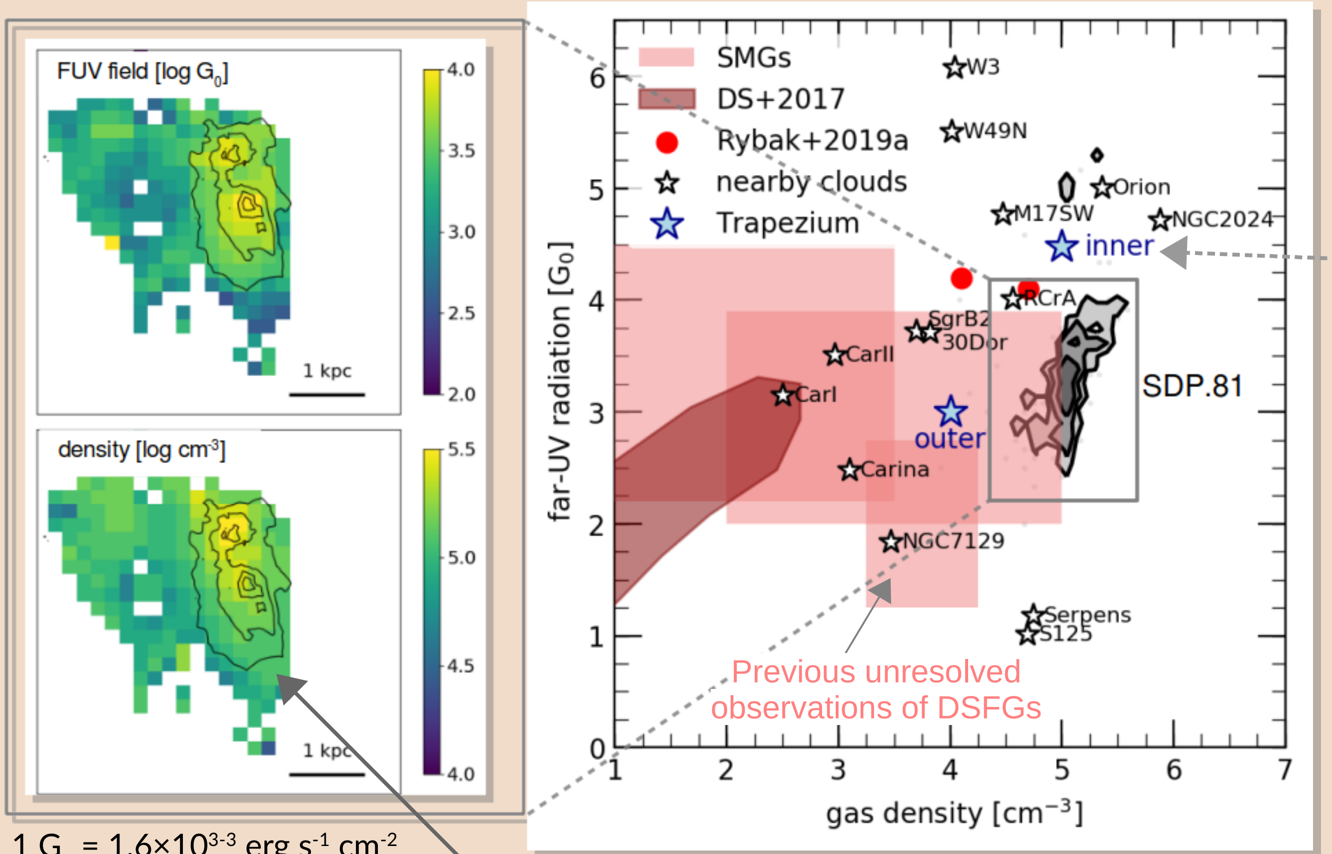


Mean resolution: 200 pc!

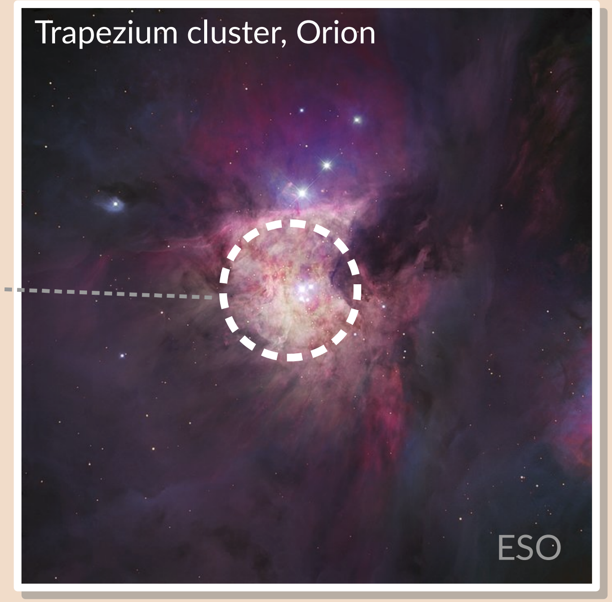
Spectacularly extended [CII]
The [CII] emission is much more extended than dust or CO: it forms a massive structure >10 kpc long. SDP.81 is an on-going merger: the extended [CII] emission is likely a tidal tail.

SDP.81 versus Orion

The first resolved view of gas thermodynamics in a high-redshift galaxy



1 G_0 = $1.6 \times 10^{3-3}$ erg s^{-1} cm^{-2}



Resolving the physical conditions in SDP.81
We use the **PDRToolbox**[1,2] radiative transfer models to infer the under-lying gas density, far-UV irradiation and temperature for **each pixel**, using all the lines, continuum and upper limits.Somewhat surprisingly, the **data is well-reproduced by the simple models**.
This is because even with ~40 hours of ALMA data, our error budget still includes considerable systematics. Our new data will help us reduce them!

Full of Orions?
Here we compare the resolved conditions in SDP.81 to other high-redshift galaxies and nearby star-forming regions[3]. On 200-pc scales, the physical conditions in SDP.81 are similar to the **Trapezium cluster** in Orion[4].
But the star-forming regions in SDP.81 are likely more extreme at higher resolution. There are true monsters lurking in there!

[1] Kaufman+2006, ApJ 644 • [2] Pound & Wolfire, 2008, ASPCS 394 • [3] Oberst+2011, ApJ 739 • [4] Goicoechea+2015, ApJ 812