ALMA Observatory and Galaxy Science

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ALMA

In search of our cosmic origins

⋆ What is ALMA?

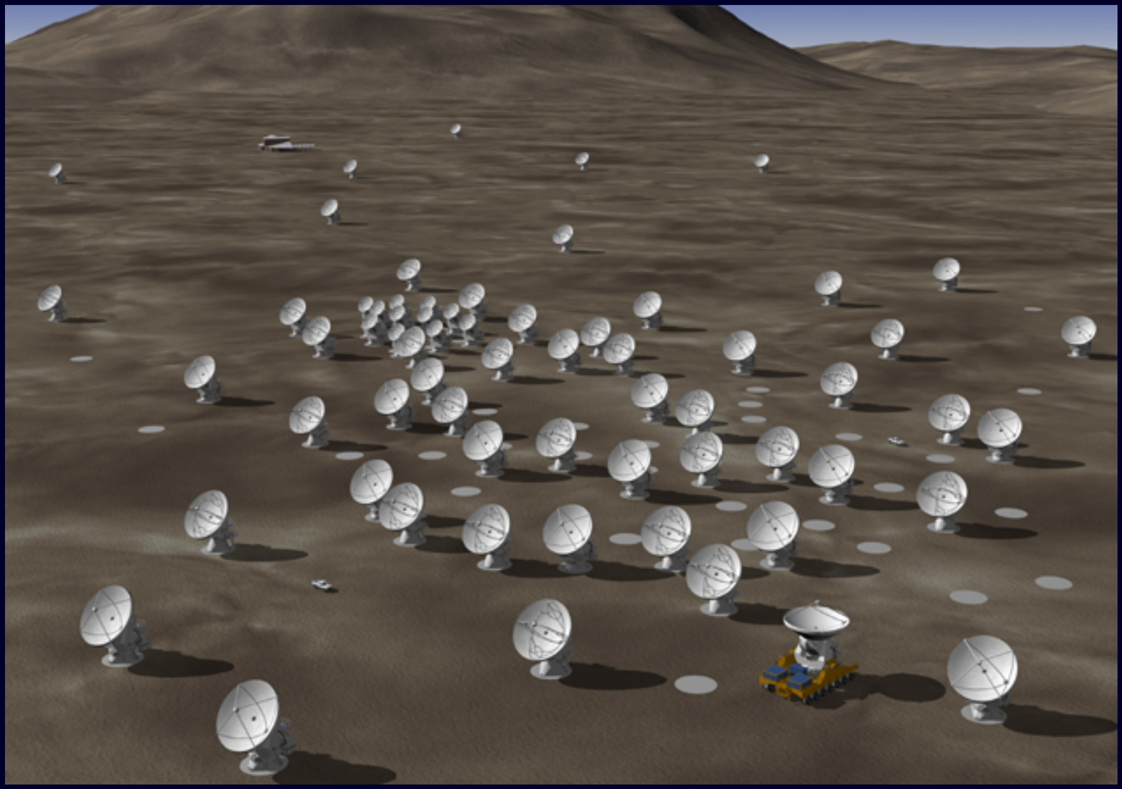
The **Atacama Large Millimeter Array** (ALMA) is an interferometer made up of 66 antennas:

12-m array ➔ 50 x 12 m

ACA ➔ 12 x 7 m + 4 x 12 m

All antennas can work together as a single telescope with a total diameter of up to 16 km and a collecting area of 6500 m^2.

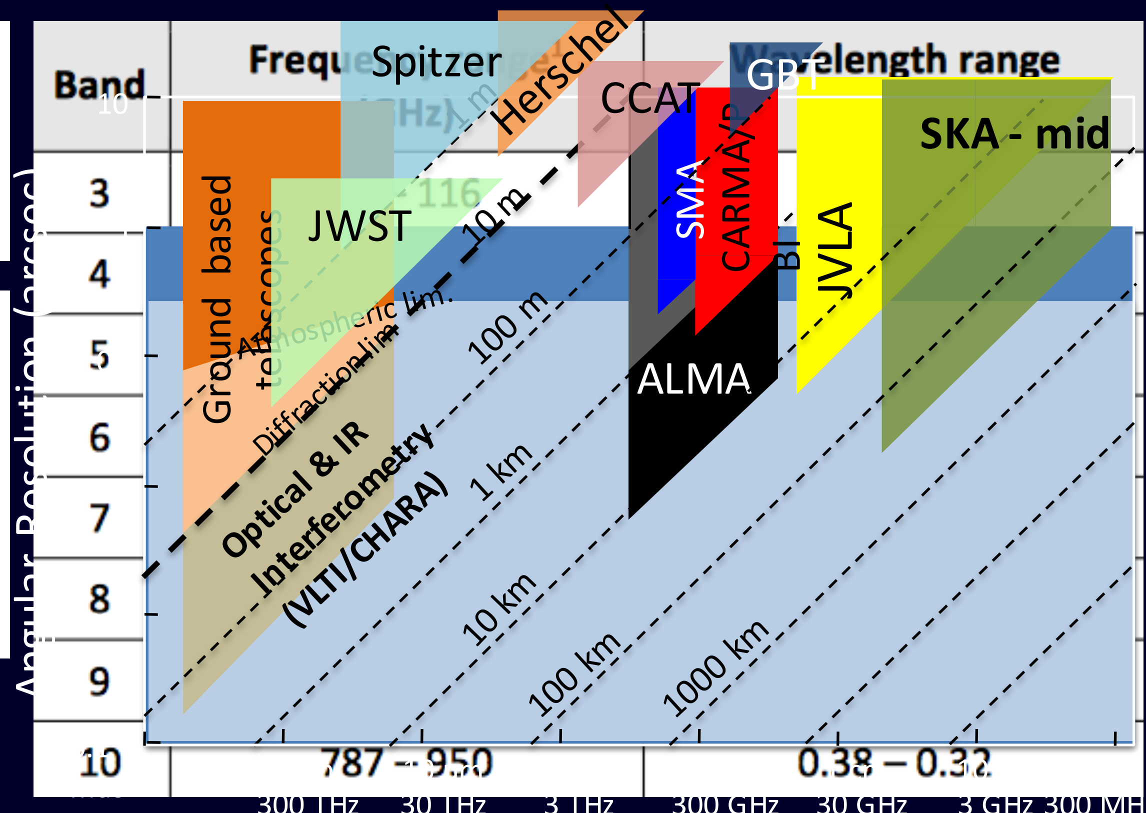
ALMA is fully operational since September 2015 (Cycle 3)



⋆ What is ALMA?

ALMA operates at millimeter and sub-millimeter wavelengths:
8 spectral bands spread over 0.3–3 mm (i.e. 84–950 GHz)

At these wavelengths together with the 16 km baselines, ALMA reaches an unprecedented angular resolution below 0.01'' (θ ~ λ/D), beating all current and near-future facilities.



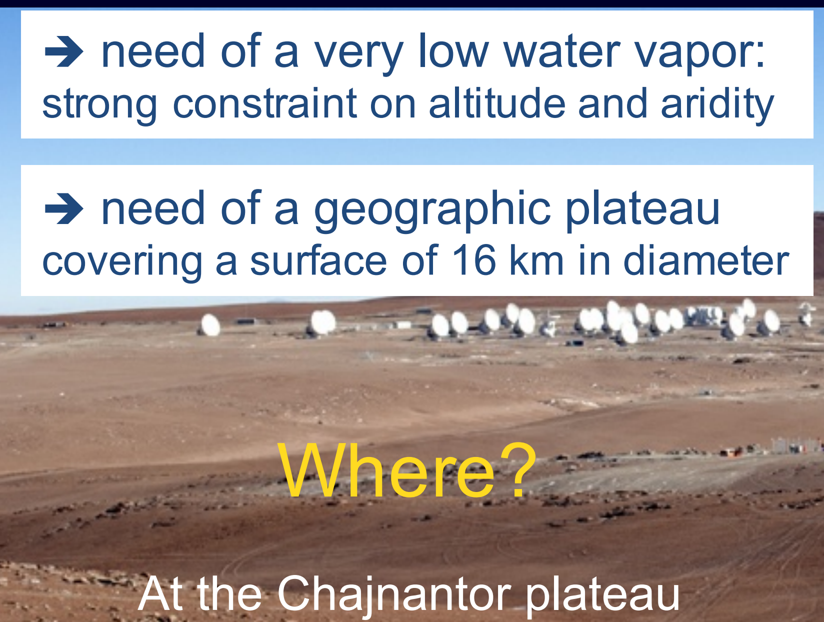
The objective is to have two additional receivers (bands 1 and 2) working up to 10 mm (31 GHz).

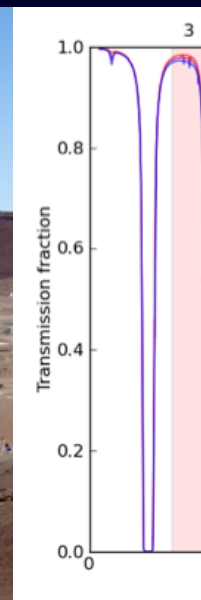
⋆ Why is ALMA so powerful?

To satisfy ALMA's specifications, the quality of the site plays a crucial role.

➔ need of a very low water vapor:
strong constraint on altitude and aridity

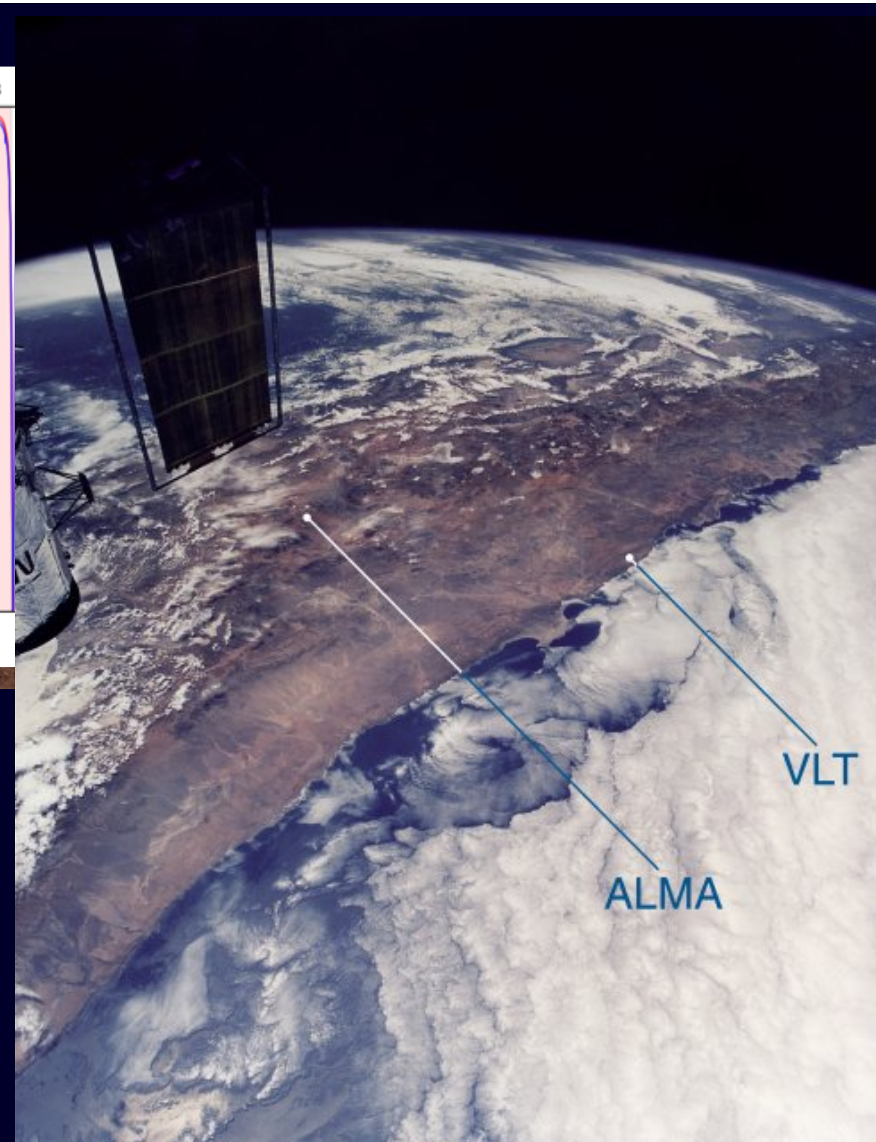
➔ need of a geographic plateau
covering a surface of 16 km in diameter





Where?

At the Chajnantor plateau
located at 5000 m above sea level
in the Atacama desert (Chile).



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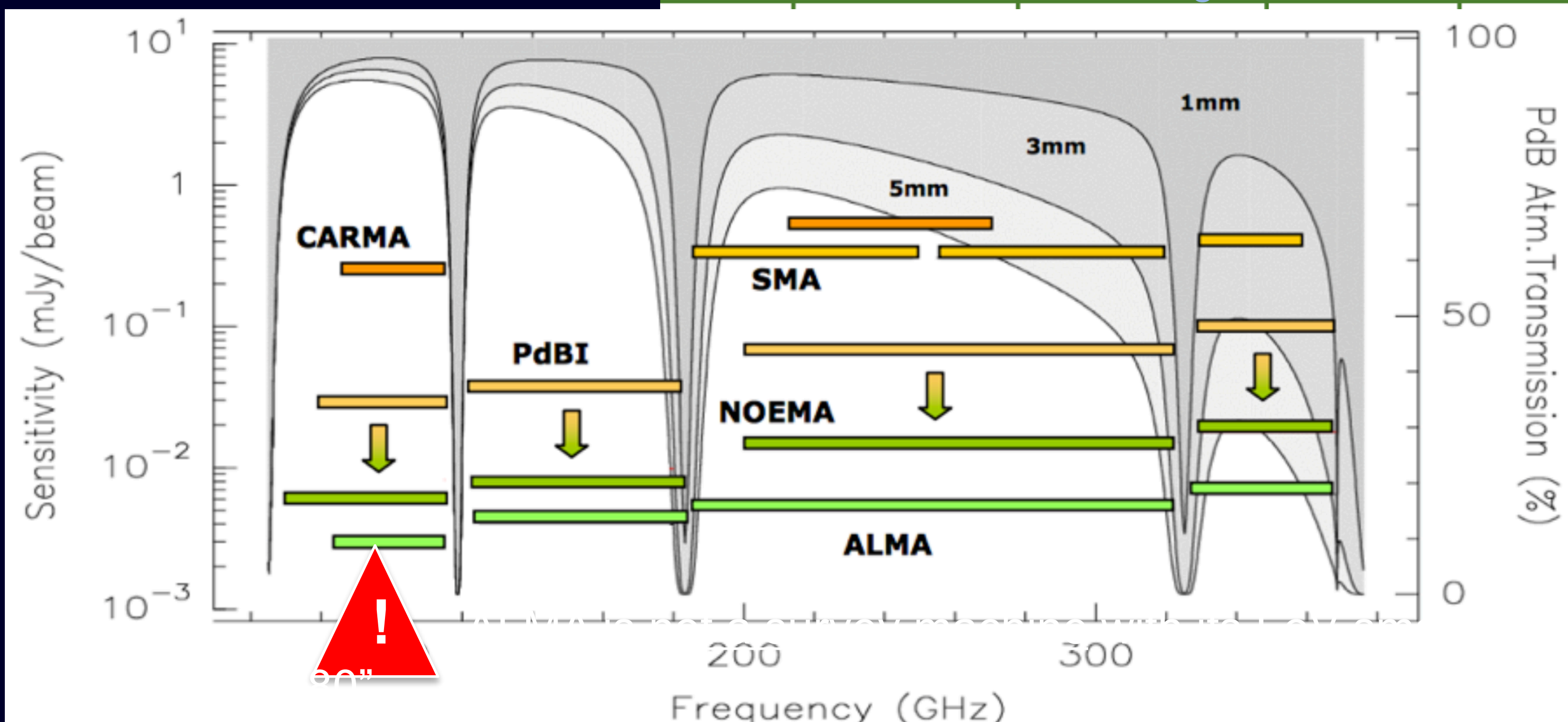
⋆ ALMA sensitivity

Sensitivities in the continuum obtained after 60 s of integration time and a bandwidth of 7.5 GHz.

ALMA clearly dominates all other existing millimeter facilities.

Band	Frequency (GHz)	Wavelength (mm)	Primary Beam (FOV; ")	Continuum Sensitivity (mJy/ beam)
3	84-116	2.6-3.6	73-53	0.088
4	125-163	1.8-2.4	49-38	0.12
[illegible]	[illegible]	[illegible]	[illegible]	12
[illegible]	[illegible]	[illegible]	[illegible]	12
[illegible]	[illegible]	[illegible]	[illegible]	22
[illegible]	[illegible]	[illegible]	[illegible]	42
[illegible]	[illegible]	[illegible]	[illegible]	0
[illegible]	[illegible]	[illegible]	[illegible]	6

In 8h of integration time



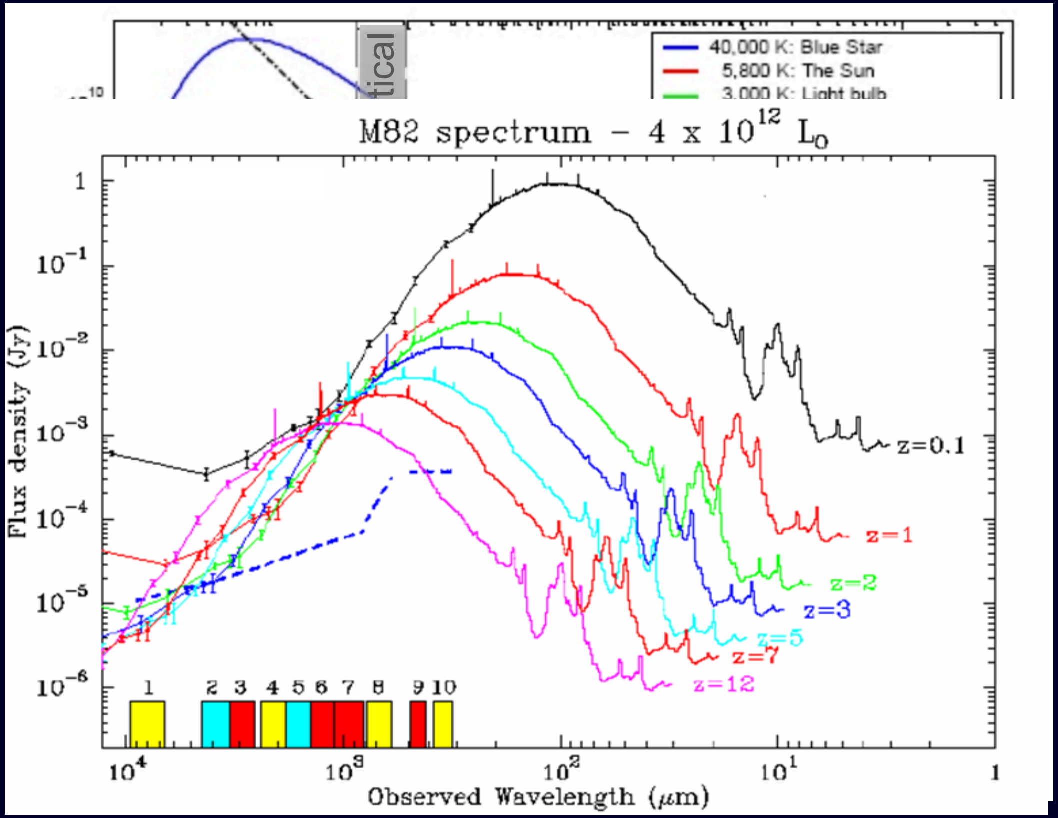
⋆ What do we see at mm wavelengths?

Any radiation below 100 K

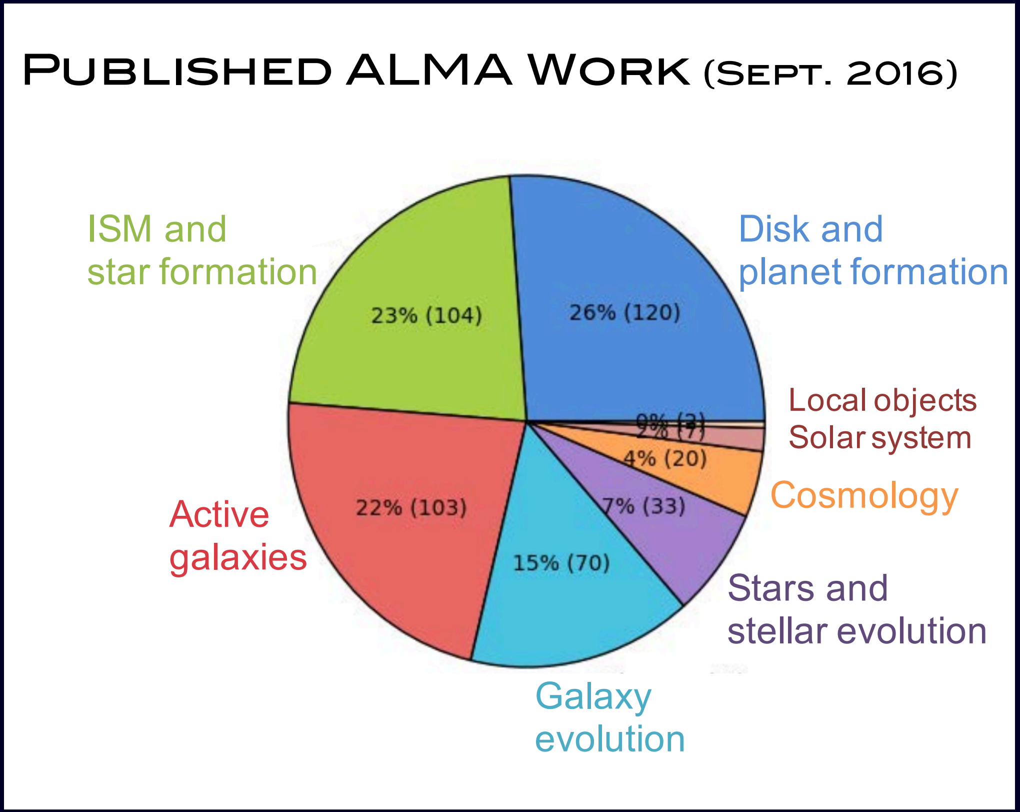
- CMB radiation
- Optically thin cold dust emission
- Rotational molecular transitions from CO to complex species

At high redshifts

- SED peak (inverse K-correction)
- Fine-structure lines emitted by PDR or star-forming (HII) regions



★ The science ALMA is doing is overwhelming



→ Cosmology

→ Galaxy evolution

⋆Cosmology and Galaxy evolution − Motivations

z~1000
300'000 yr

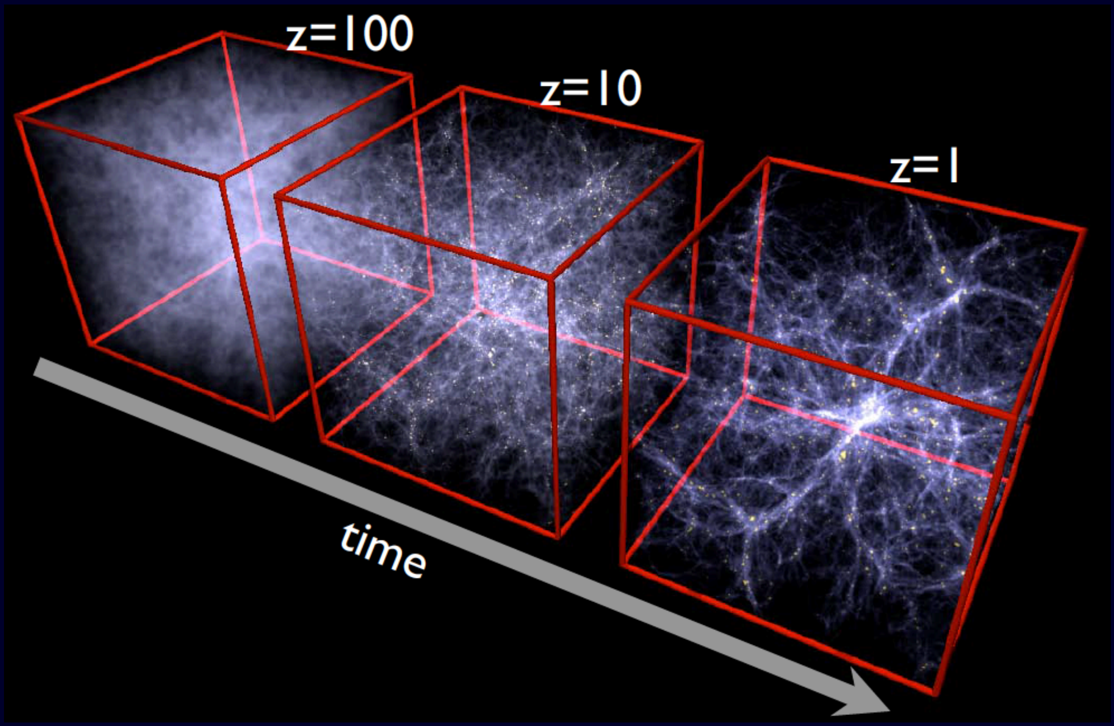
z~15–1000
300'000 yr – 0.3 Gyr

z~8–15
0.3–1 Gyr

z<8
>1 Gyr

z~0
13.7 Gyr

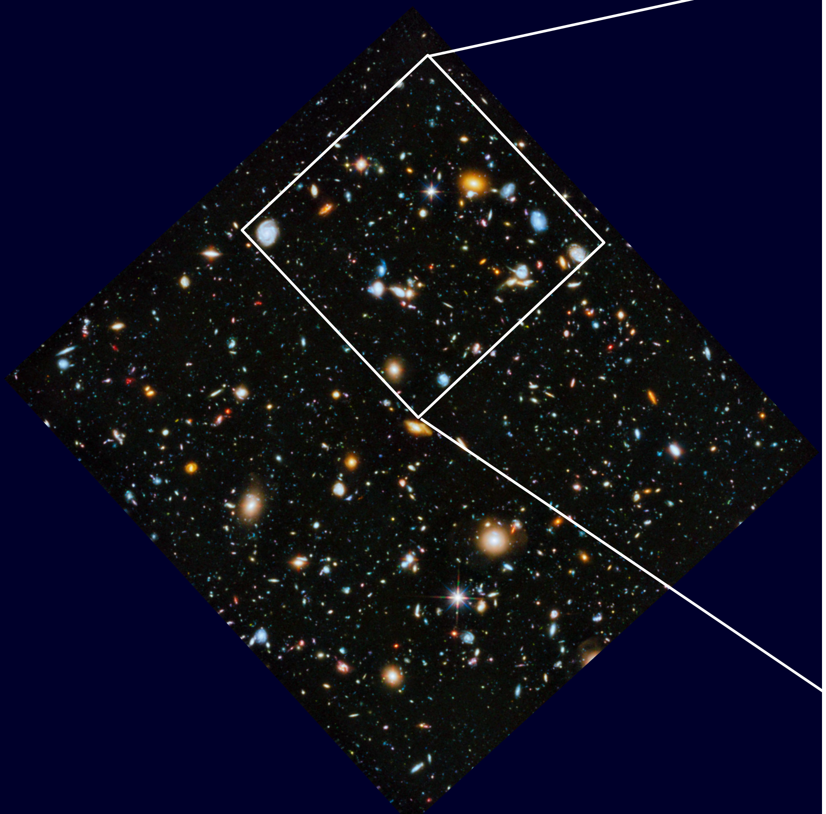
Hydrodynamical simulations of structure formation

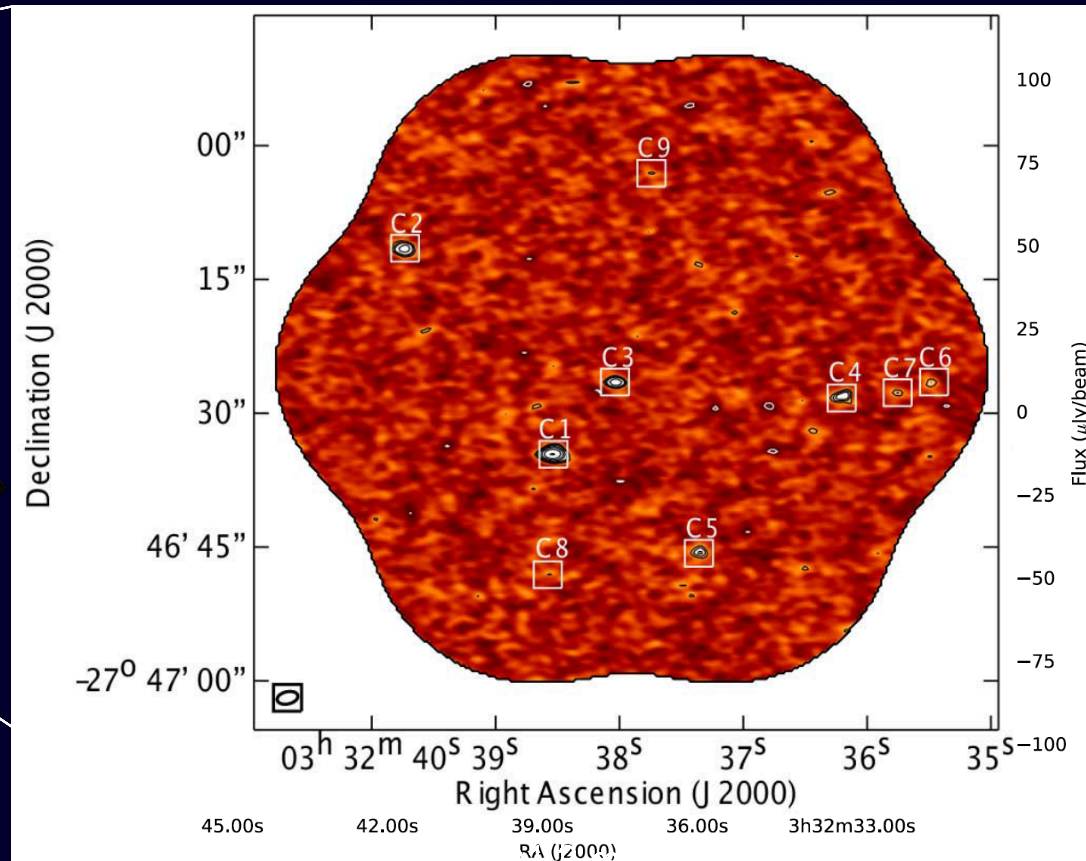


Galaxies grow through gas accretion, <u>but</u> this gas supply and early galaxy growth is largely unconstrained observationally.

⋆ Current ALMA view of HUDF

Why the Hubble Ultra Deep Field?
deepest multi-wavelength field with thousands of well-characterized galaxies (z~0-10)





Achieved sensitivity: 35 μJy @1.3mm and 0.7” resolution (20h):
16 sources detected in continuum
(Dunlop+16)

9 sources detected in continuum (5x times more)
(Walter+16; Aravena+16)

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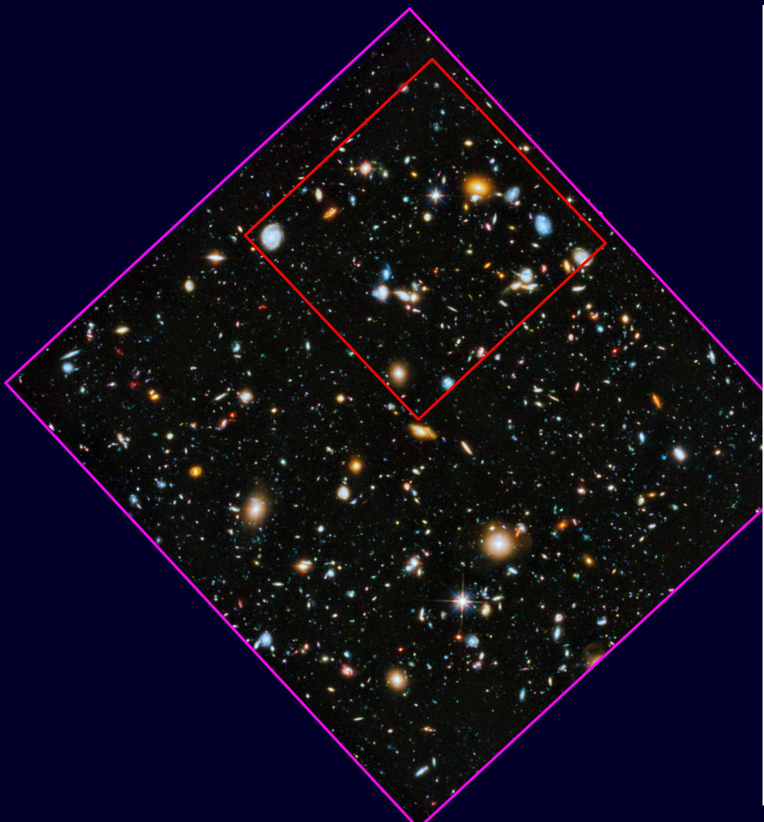
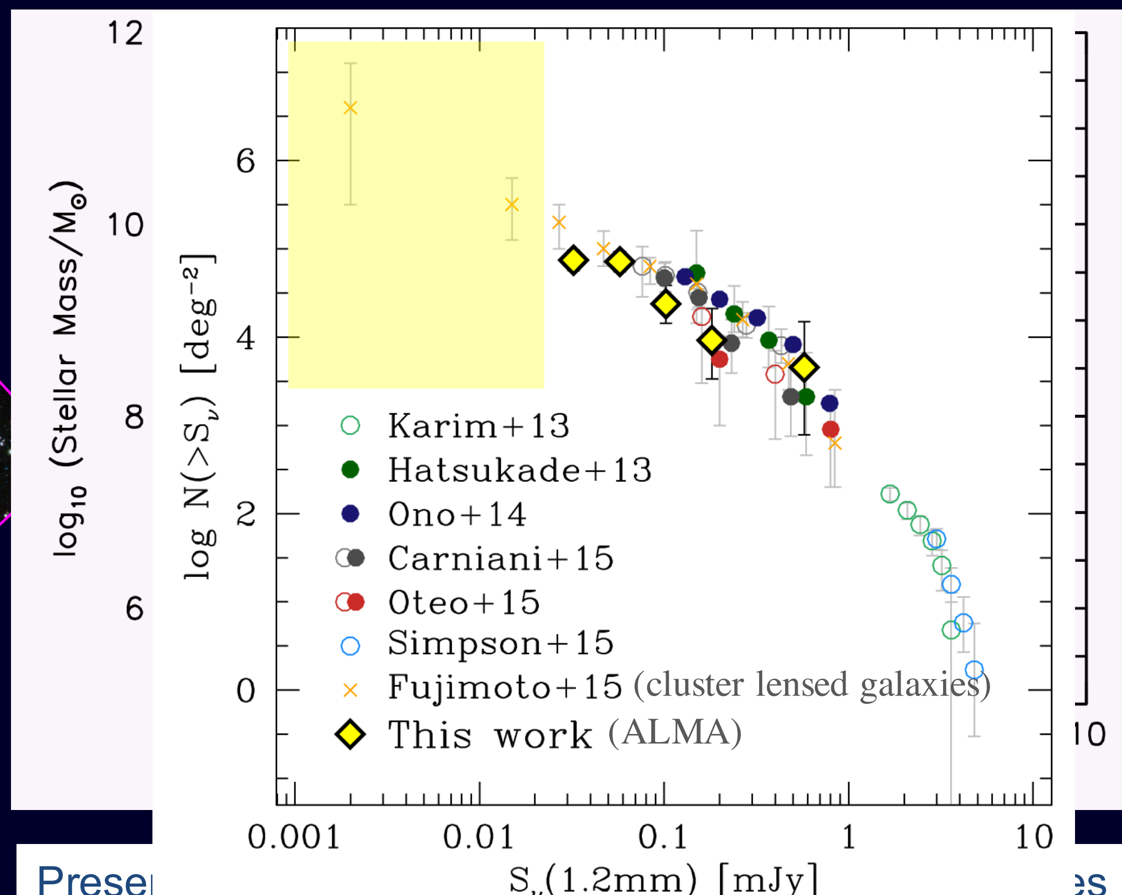




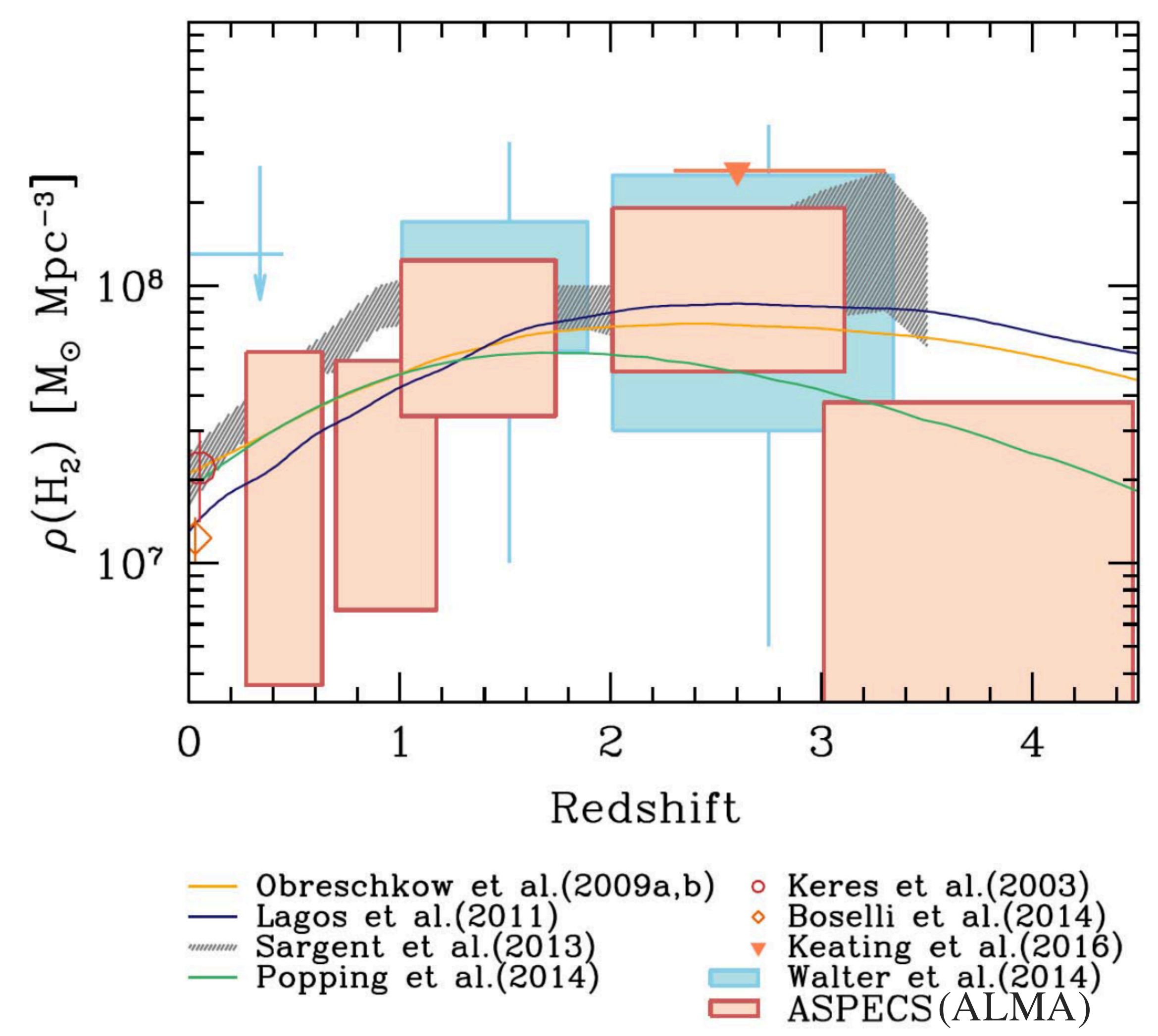
Prese… …es
at high stellar mass and high SFR end at z<3 !!!

Number counts of ALMA 1.2 mm continuum sources agree with literature values.

⋆ Current ALMA view of HUDF

Blind CO search at 3 and 1 mm (ALMA bands 3 and 6)

CO detections up to z=4.5

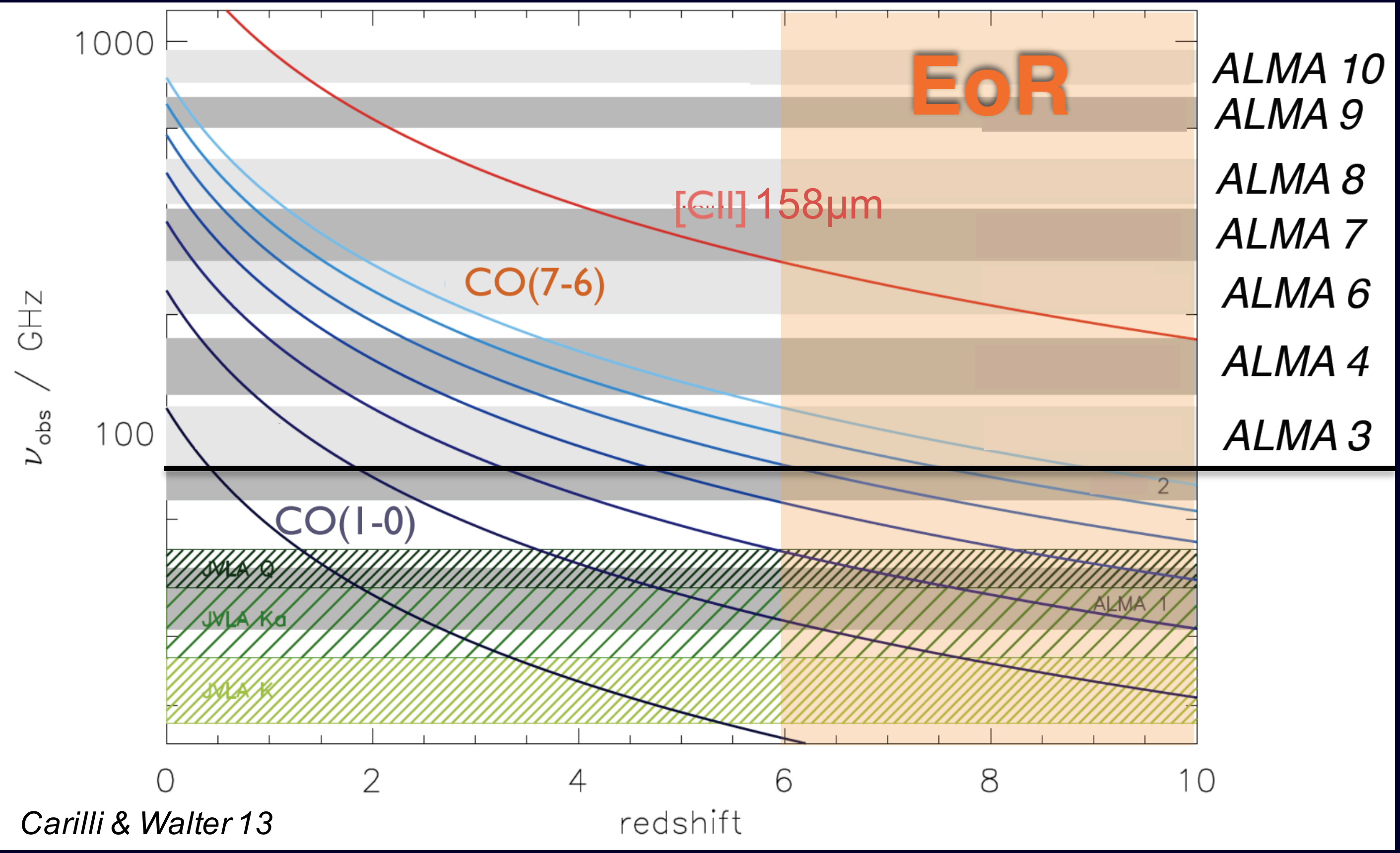


Evolution of the Cosmic mass density of molecular gas

- decline from z=2 → 0 slower than the SFR density?
- rapid decline at z>4?
- error bars admittedly large

Walter+16; Decarli+16

⋆ The promise of ALMA in EoR galaxies



Carilli & Walter 13

Redshift dependence of CO + [CII] frequencies

CO not a good tracer of galaxies at EoR [CO(7-6) transitions and above not excited in normal star-forming galaxies]

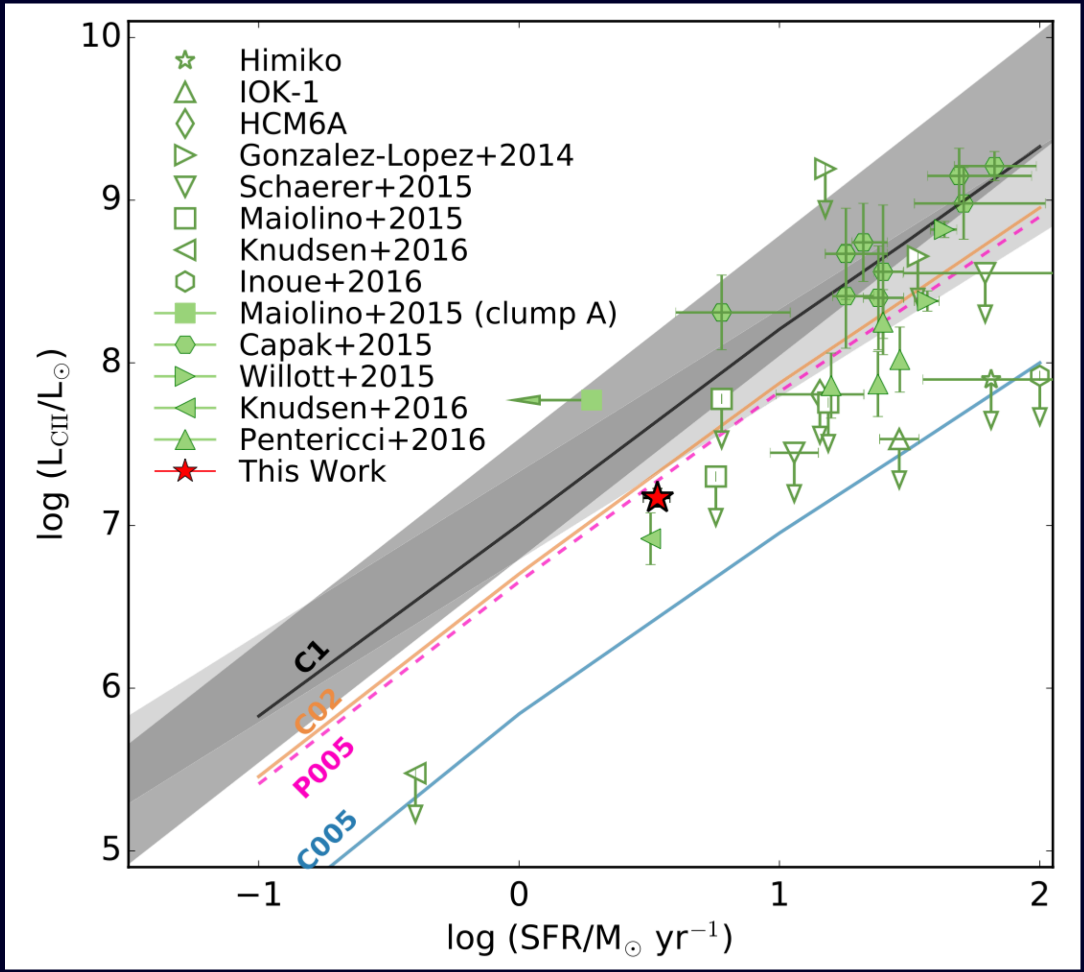
⇓

[CII] to the rescue at z>6

[CII] 158µm benefits:

1. strongest cooling line of the ISM
2. not subject to the neutral hydrogen absorption becoming important near EoR
3. direct tracer of SFR *(de Looze+14; Herrera-Camus+15)*
4. probes the systemic redshift of galaxies
5. probes the ISM gas mass

⋆ The promise of ALMA in EoR galaxies



Bradac+17

Current status of [CII] detections

Up to z~5.5-6:

- [CII] detected in many LAEs/LBGs
- local L([CII])−SFR relation satisfied

(Capak+15; Willott+15; Knudsen+16)

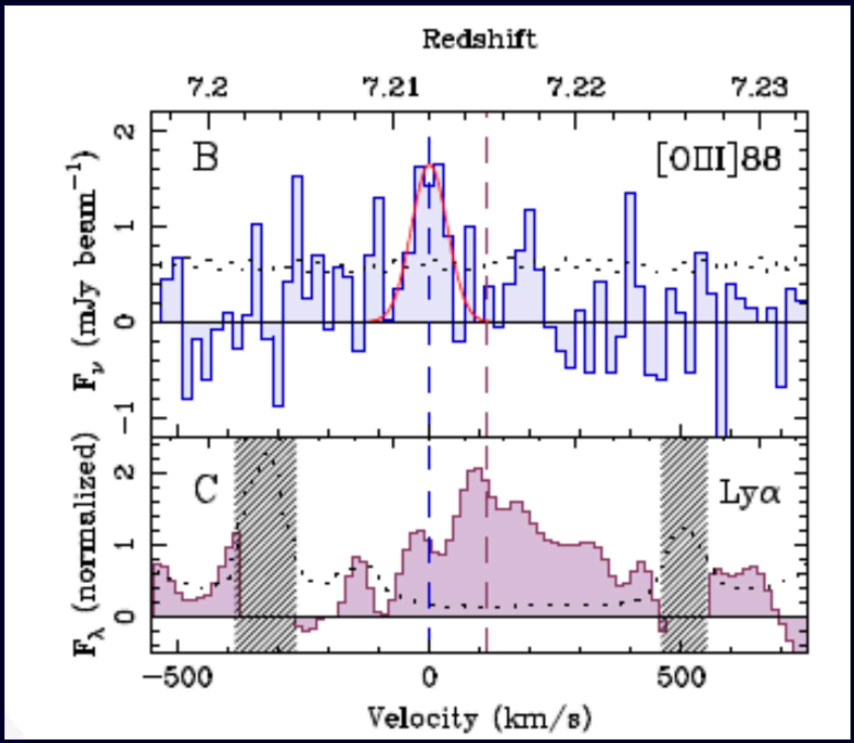
Above z~6.5:

- many [CII] non-detections!!!
- possible trends for [CII] detections
  - ✧ [CII] deficit with SFR
    lower metallicities? *(Vallini+15)*
  - ✧ spatial offset between [CII] and rest-frame UV emissions
    [CII] arises from external accreting/satellite clumps of neutral gas? *(Maiolino+15)*

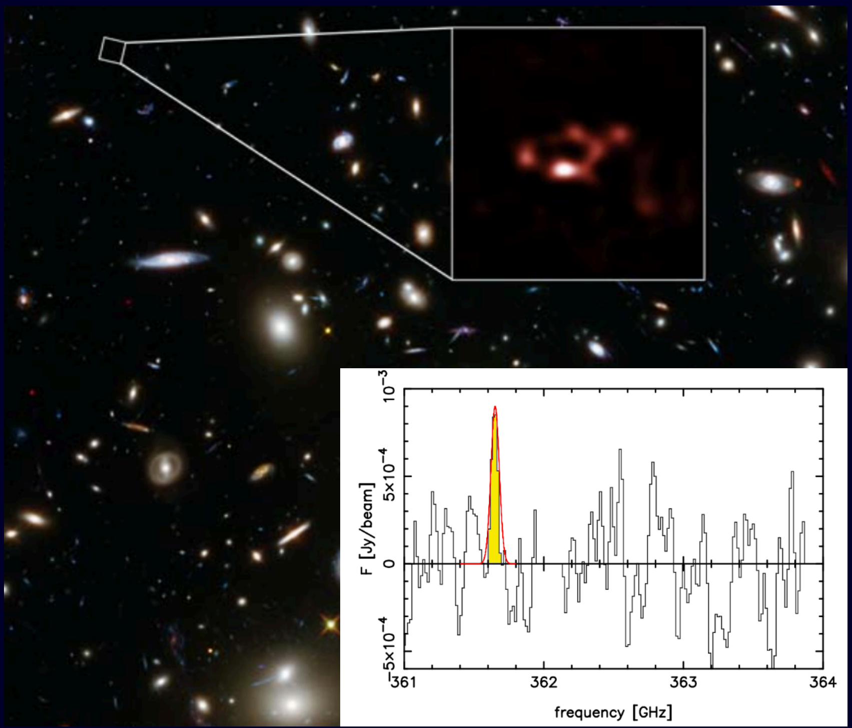
⋆ The promise of ALMA in EoR galaxies

100% of detection rate of the [OIII] 88μm line at z>7, emitted in HII regions

@ z=7.21 *Inoue+16*



@ z=8.38 *Laporte+17*



This is the youngest galaxy that ALMA has ever seen

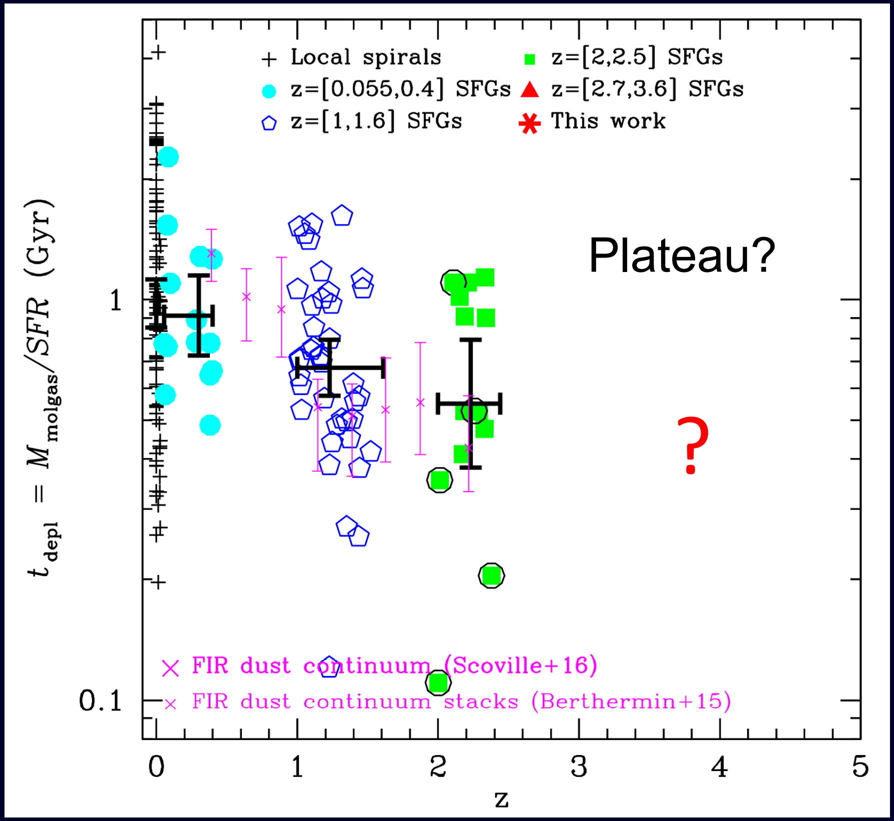
Detection of [OIII] and dust continuum @356 GHz

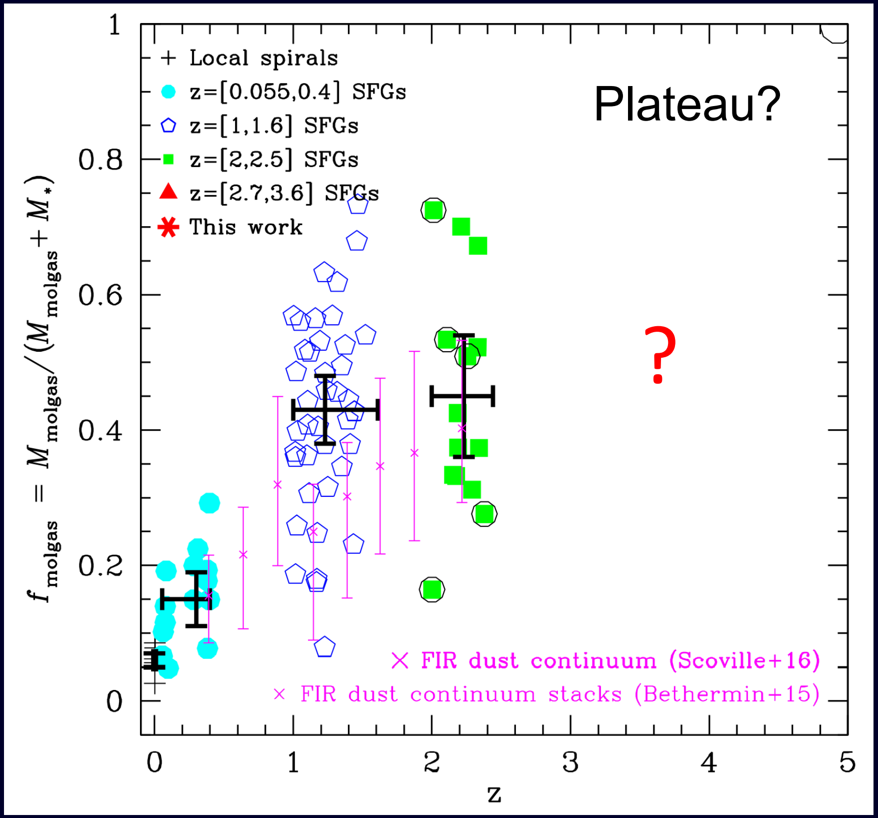
M_{stars} ~ 2×10^9 $M_\odot$ / SFR = 20 $M_\odot$/yr

M_{dust} ~ 6×10^6 $M_\odot$ → formation of such a dust mass only ~200 Myr after the onset of cosmic reionization → strong constraints on the first SNe

⋆ Galaxy evolution traced by ALMA

The observed evolution of the molecular gas depletion timescale and the molecular gas fraction in normal star-forming galaxies provides insights on how star formation proceeds over cosmic time.





The depletion timescale describes how long a galaxy could sustain star formation at the current rate before running out of fuel, assuming that the gas reservoir is not replenished.

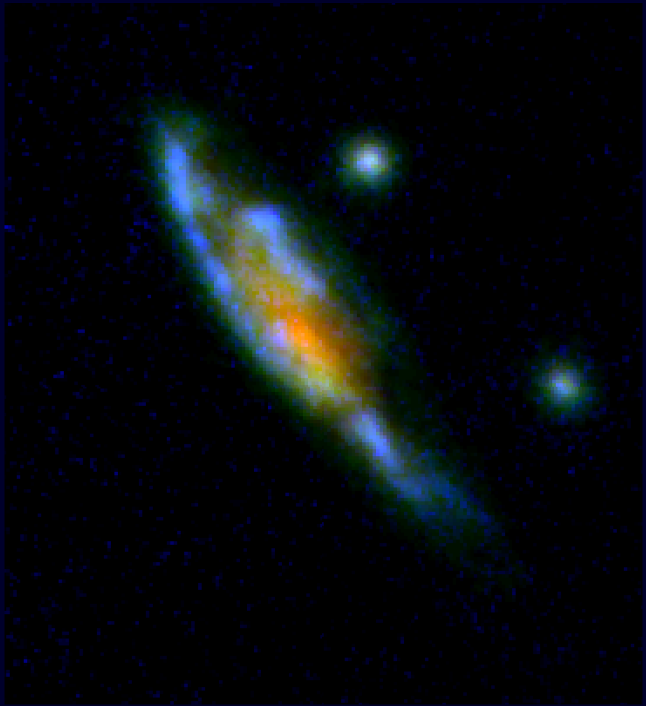
→ If the plateau is confirmed for both $t_{depl}(z)$ and $f_{molgas}(z)$, by definition the specific SFR has also to flatten at z>3

→ The evolution in the SFR density at z>3 is then driven by the number density of star-forming galaxies and not a change of the gas reservoir available.

Combes+13; Tacconi+13,17; Sargent+14; Genzel+15; Dessauges-Zavadsky+15,17; Scoville+16; Schinnerer+16

⋆ Typical clumpy galaxy seen under the gravitational and ALMA telescope

Clumpy galaxies at z>1 are common.
Dominant interpretation of their origin: disk fragmentation resulting from the gravitational instability maintained by cold gas accretion, high velocity dispersion, and high molecular gas fraction.



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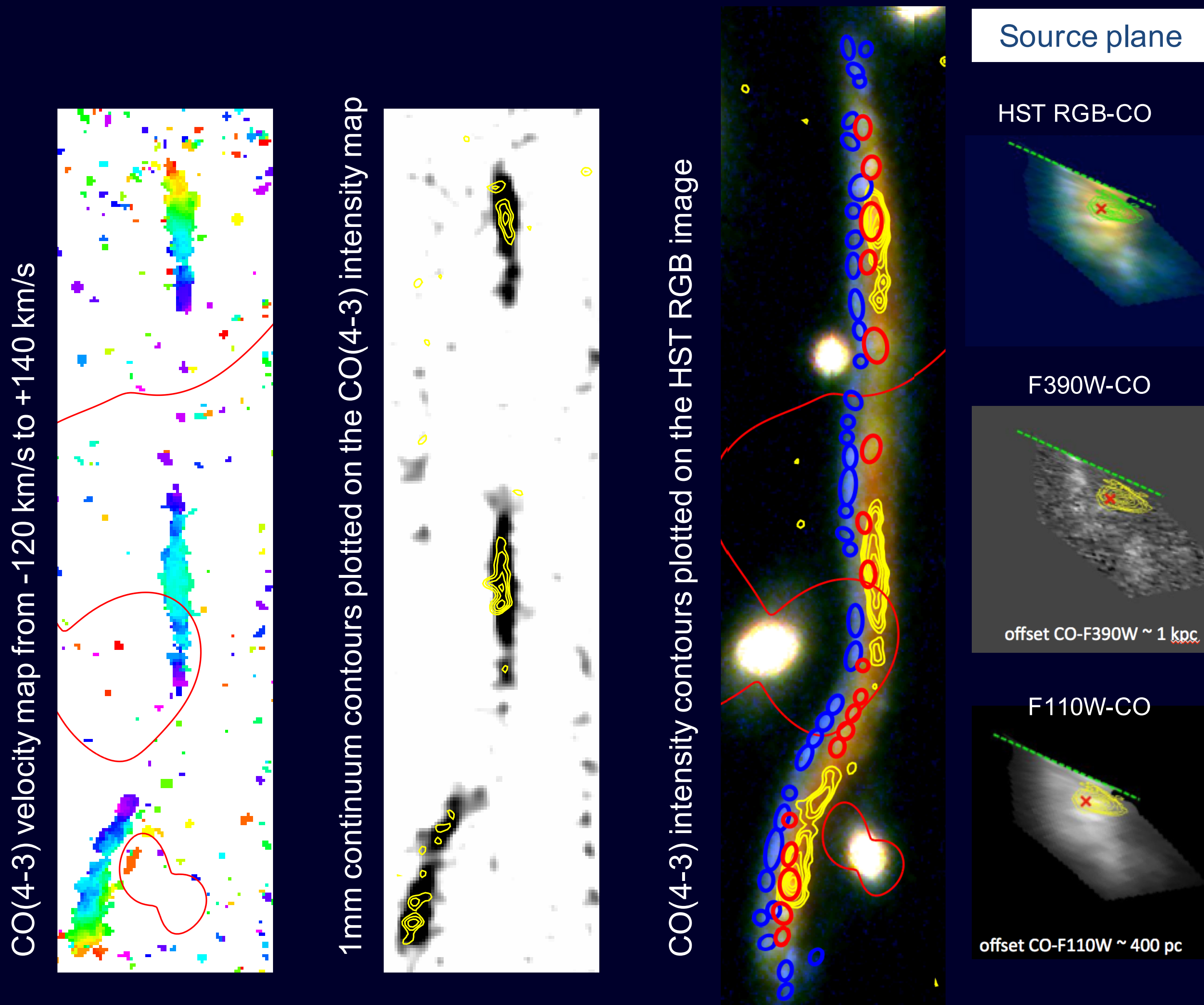
Unique
strongly lensed galaxy at
z~1
the “Cosmic Snake”
(amplified by a factor larger than 100)

⋆ Typical clumpy galaxy seen under the gravitational and ALMA telescope

Amazing high-quality ALMA data

They reveal:

- a disk in rotation
- clumpy dust continuum
- spatial offset of 0.4−1 kpc between CO+dust and rest-frame UV+optical



Dessauges-Zavadsky, Schaerer, Cava, Richard, in prep.

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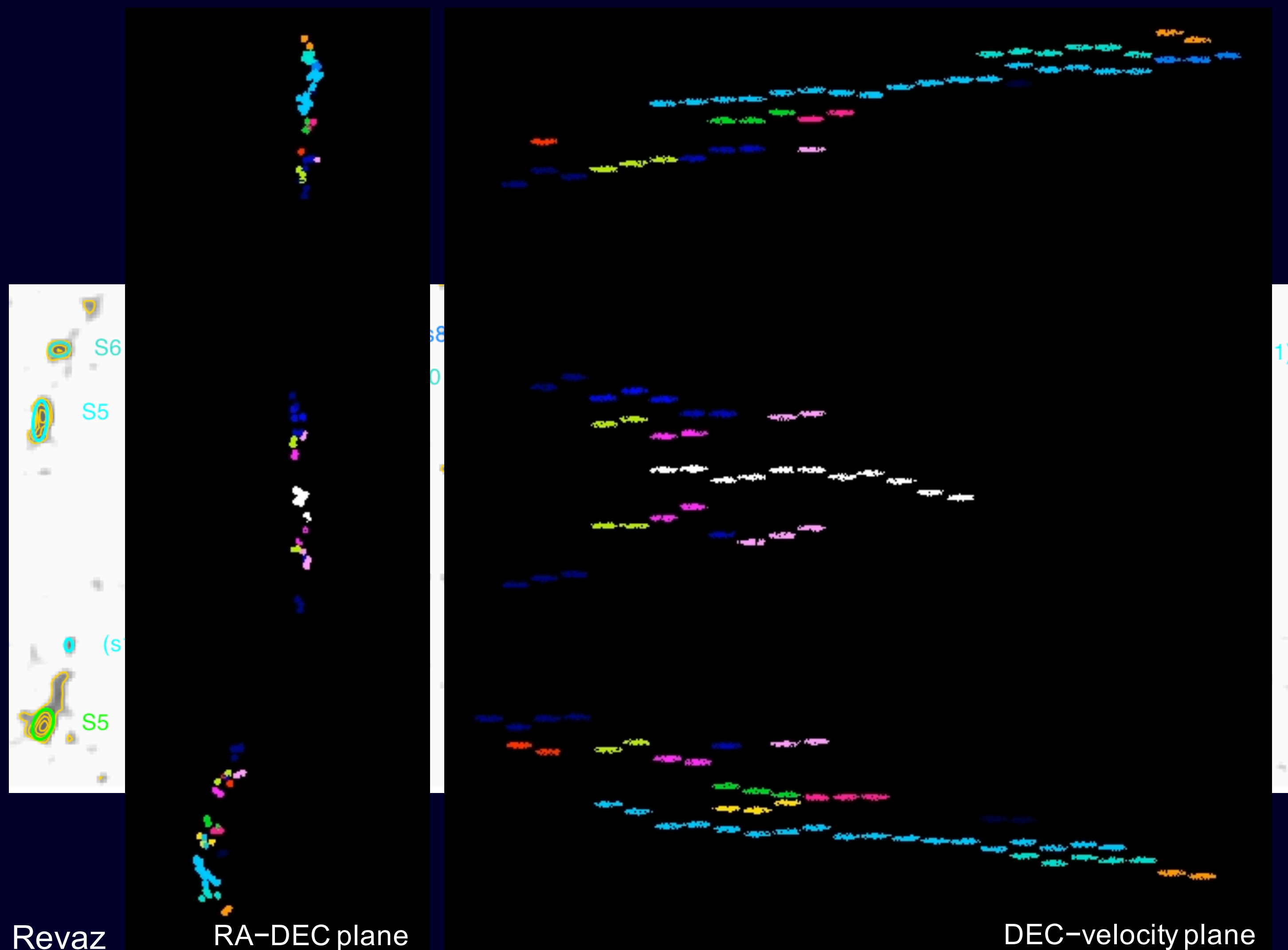
- individual giant molecular clouds

Giant molecular cloud (GMC) identification and projections



Credit: Y. Revaz

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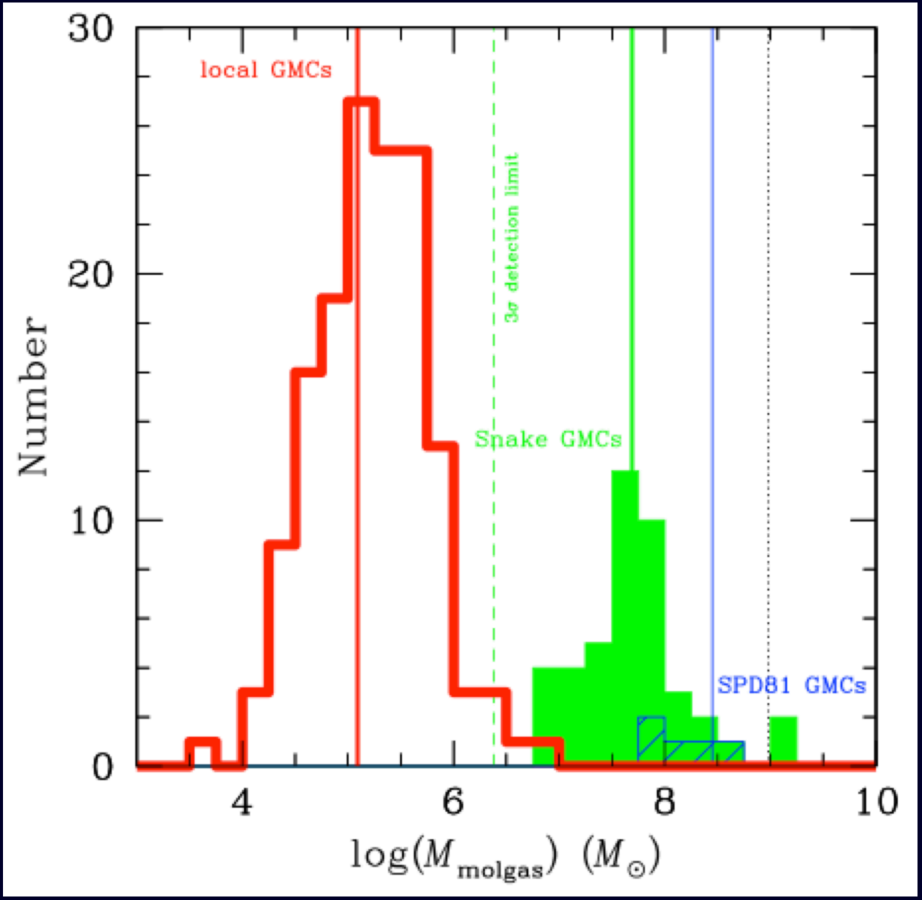
They reveal:

- a disk in rotation
- clumpy dust continuum
- spatial offset of 0.4−1 kpc between CO+dust and rest-frame UV+optical
- individual giant molecular clouds
- high-redshift GMCs more massive than



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