Journées SF2A, Nice, 15 Mai 2019

Explorer l'Univers à grand redshift avec ALMA

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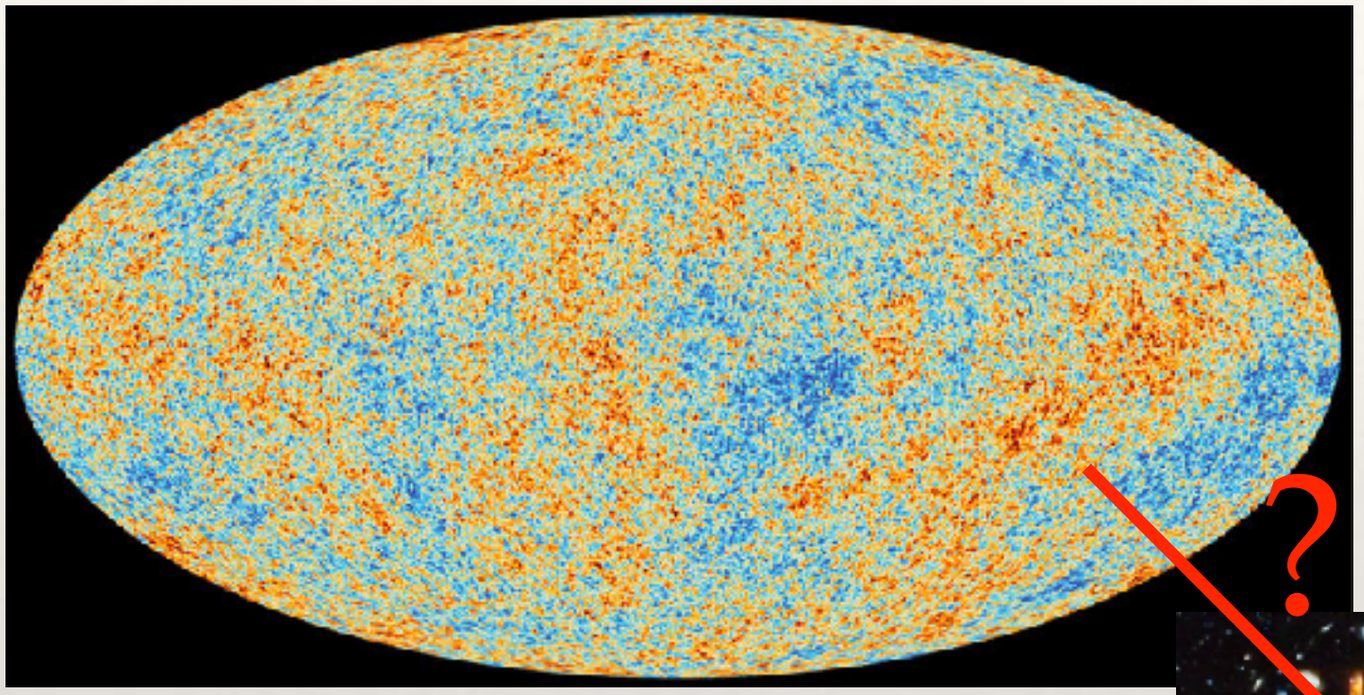
LAM

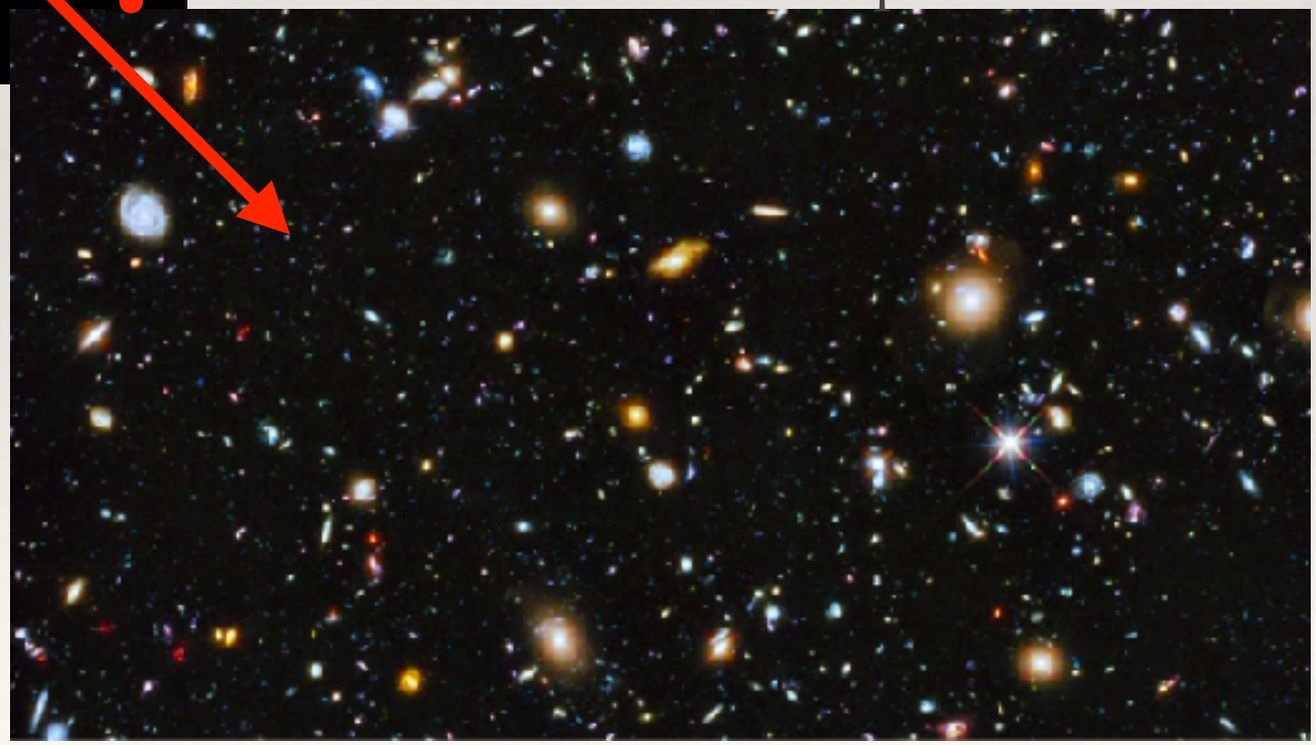
How did the Universe evolved from a quasi-homogeneity to its current impressive diversity?



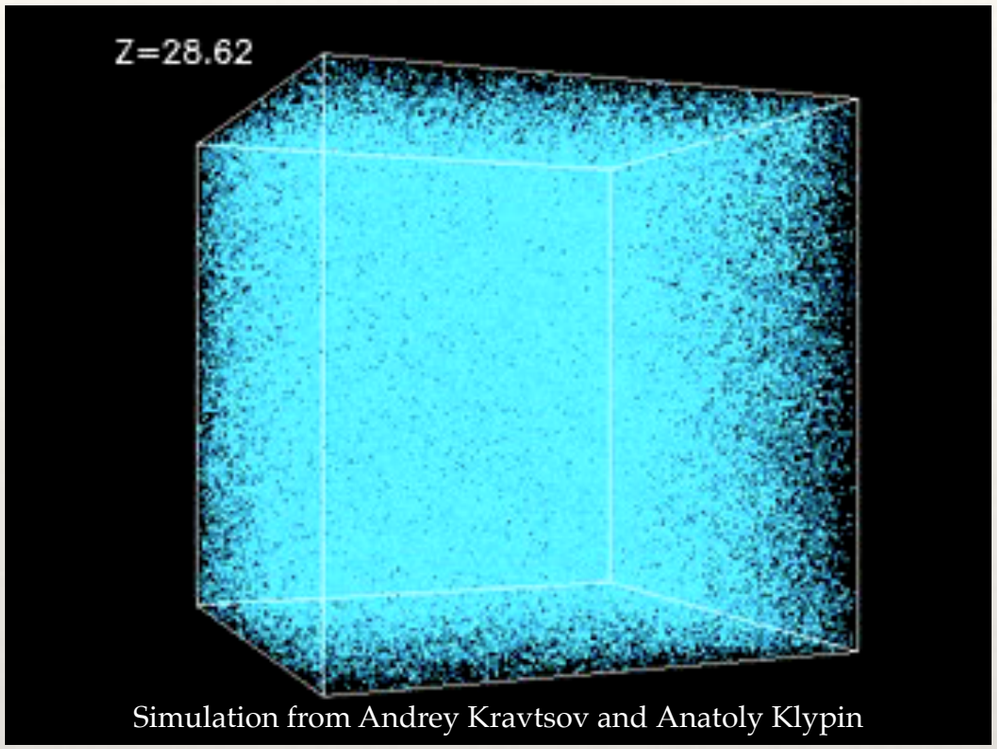
Cosmic microwave background from Planck

?

Hubble ultra deep field

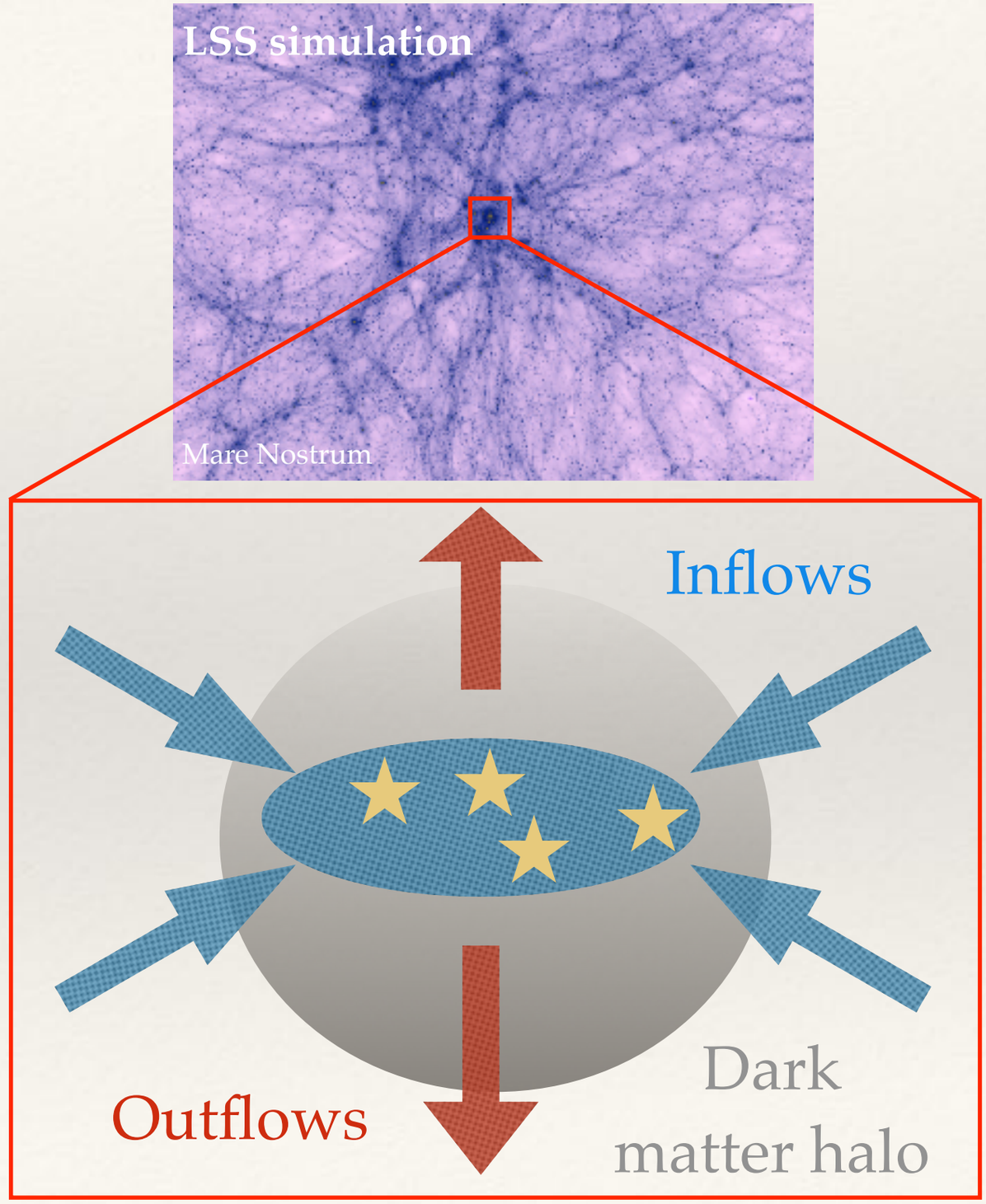


How does galaxies/stars form in the Universe?



- Large-scale structures (LSS): reasonably well understood

- Galaxies = complex systems (inflows, outflow, AGN and SN feedback…)



Why is ALMA important to understand high-z galaxies?

- Before forming stars, galaxies need cold gas reservoirs:

  Traced by cold dust emission, far-IR and, mm line in the ALMA frequency range at high z

- Early-assembled massive galaxies built up quickly lots of metals and dust:

  hard to detected them in optical/near-IR

  => ALMA probe the dust continuum close from their peak of emission

ALMA

- Collaboration ESO/NRAO/NAOJ
- 5000-m high in the Atacama to allow high-frequent observations (84-950 GHz)
- Main array: 50 antennae of 12-m with variable configuration (spatial resolution up to 20 mas)
- 12 antennae of 7-m for short-spacing + 4 total power antennae
- Order(s) of magnitude improvement compare with previous generation

NOEMA: extension of IRAM Plateau de Bure interferometer with 12 antennae of 15 meter
Important complement of ALMA in the northern hemisphere for the French community

Outline

- Dust-obscured star formation in the high-z Universe
- Cold interstellar medium at high redshift
- ALMA: a powerful tool to find galaxies and protoclusters in the early Universe

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- **Dust-obscured star formation in the high-z Universe**

- Cold interstellar medium at high redshift

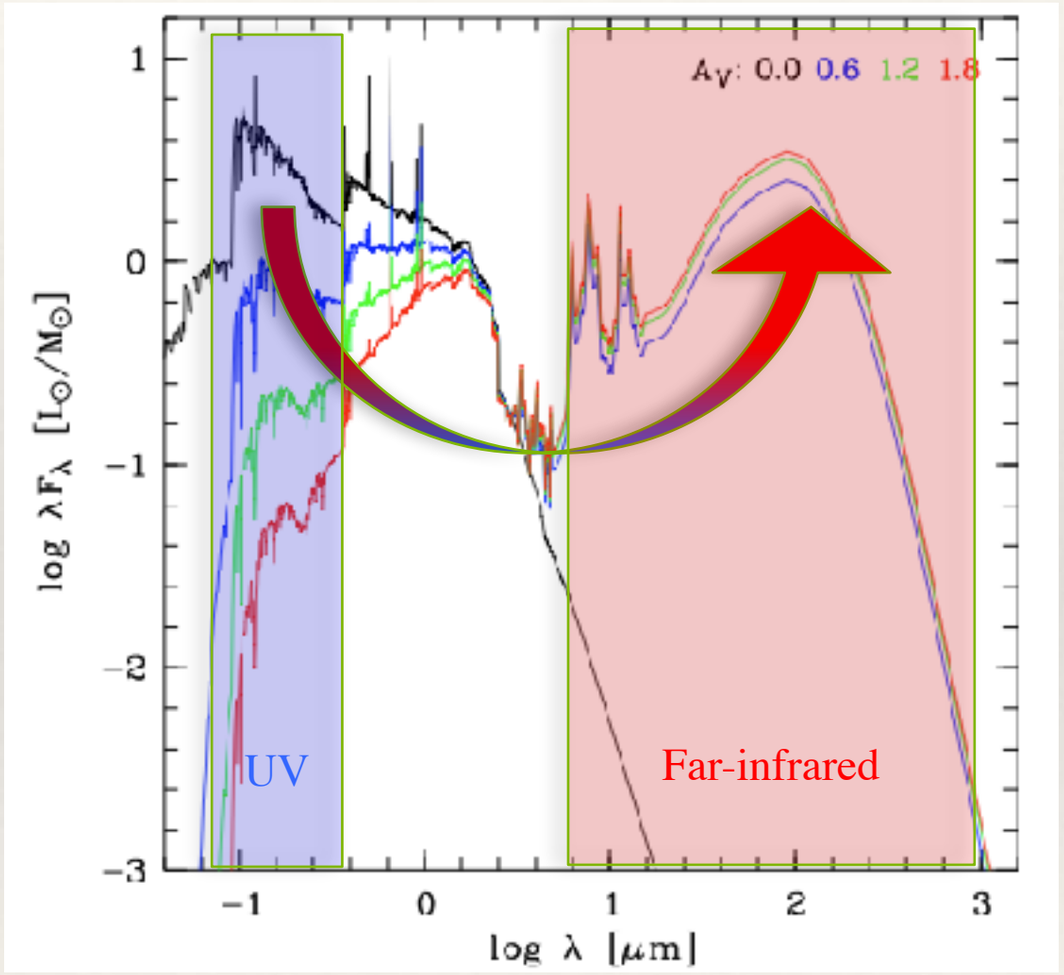
- ALMA: a powerful tool to find galaxies and protoclusters in the early Universe

Obscured star formation

- UV emissions of galaxies dominated by massive, hot, short-lived stars
  => tracer of recent star formation.

- PROBLEM: UV strongly absorbed by dust

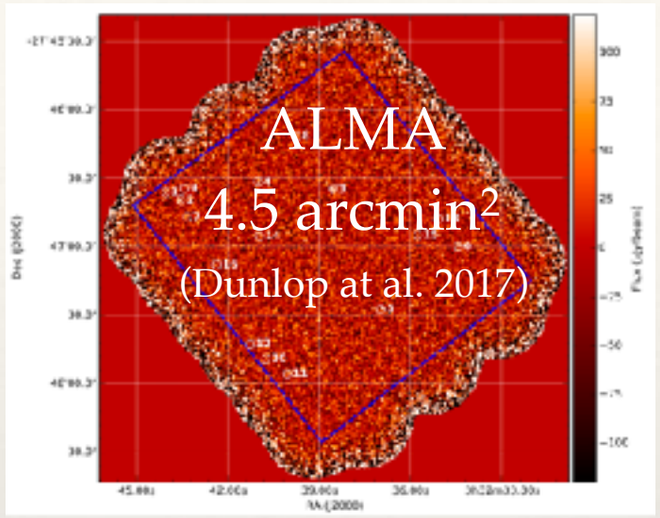
- Re-emission of UV by dust in far-IR = good tracer of reprocessed UV

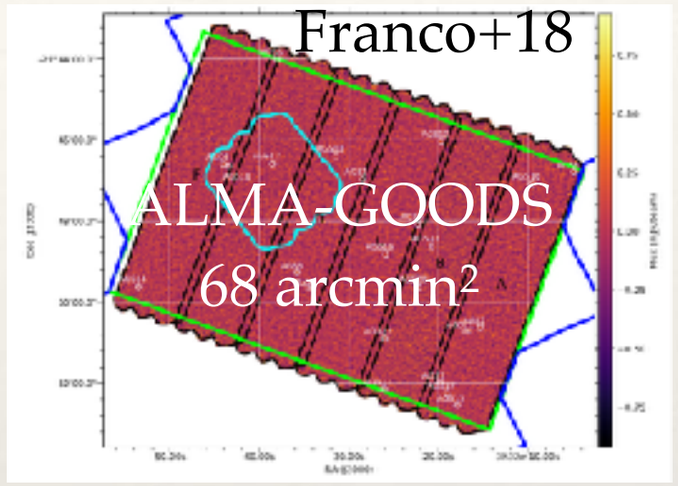


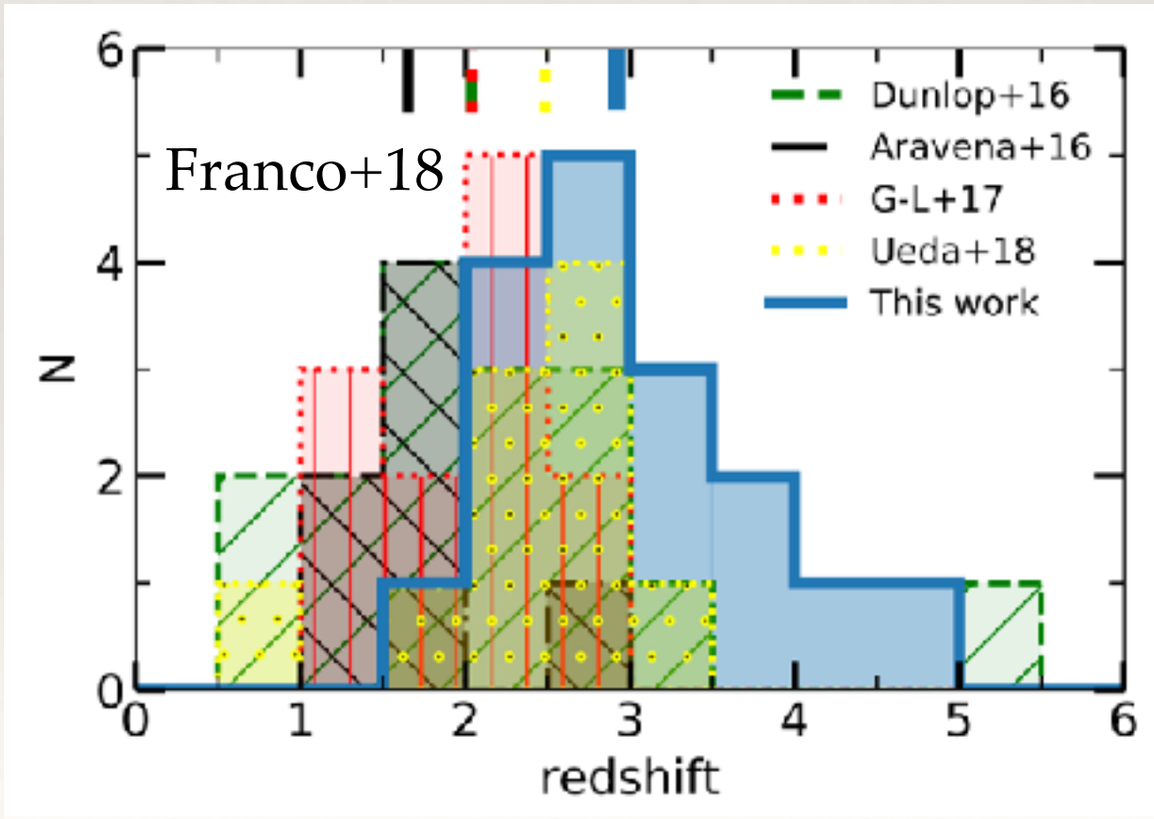
Spectral energy distribution of a galaxy (Noll+09)

Galaxy surveys with ALMA

- Single-dish surveys (*Herschel*, SCUBA2, NIKA2): map large area, but large beam (diffraction)
- ALMA: ultra deep, but field of view is the small (antenna primary beam)
- Current survey: ~1 source per hour
- Very few blind detections at z>4

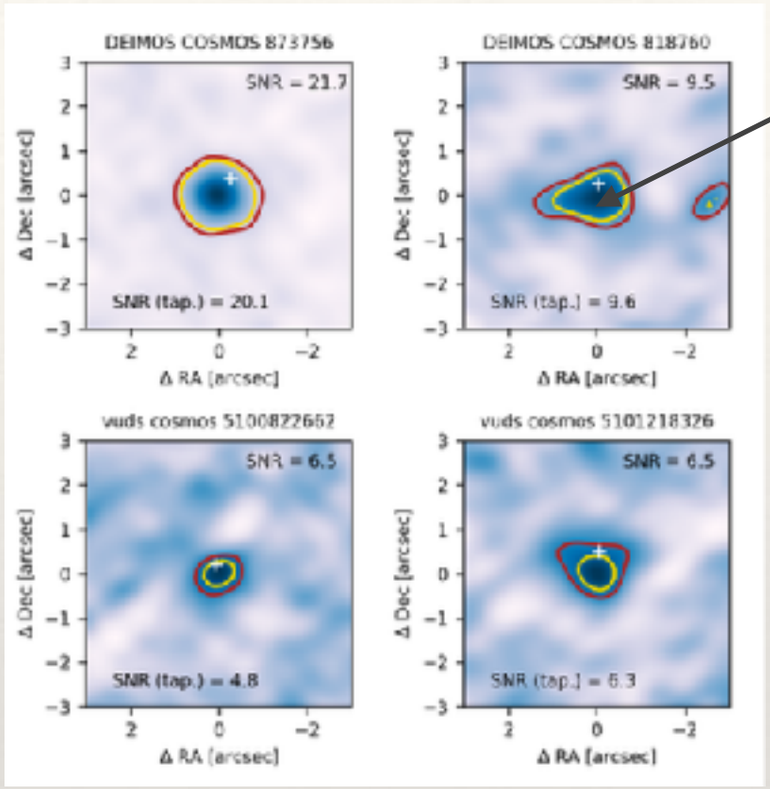






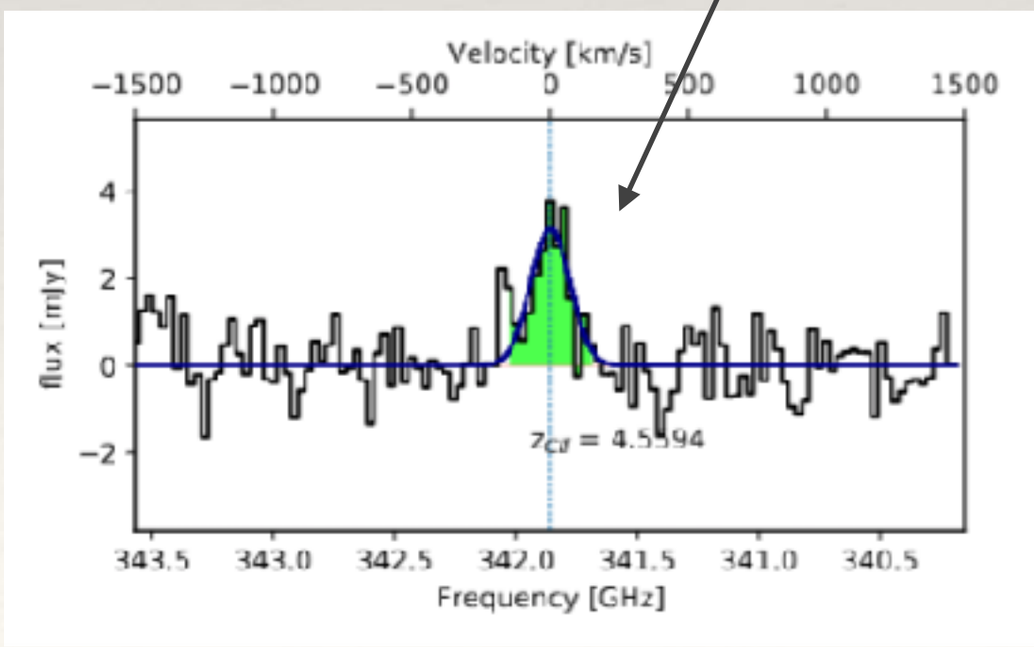
ALPINE: a sample of normal galaxies at 4<z<6

- ALPINE (PI: Le Fevre): ALMA large programme targeting [CII] and dust continuum in 122 4<z<6 normal galaxies
- Continuum: obscured SFR
  [CII]: 158um rest-frame line (dynamics, ISM prop.)
- 70h of ALMA time
- Data reduction almost finished (Béthermin+ in prep.)



Continuum detections

[CII] detection



ALPINE: obscured star formation at z>4

- Total star formation rate density: UV + ALMA
- ~150 um continuum: good tracer of obscured SFR
- Reconstruction of the IR SFRD from ALPINE sample
  (lower limit if populations fully missed by optical/near-IR)

PRELIMINARY

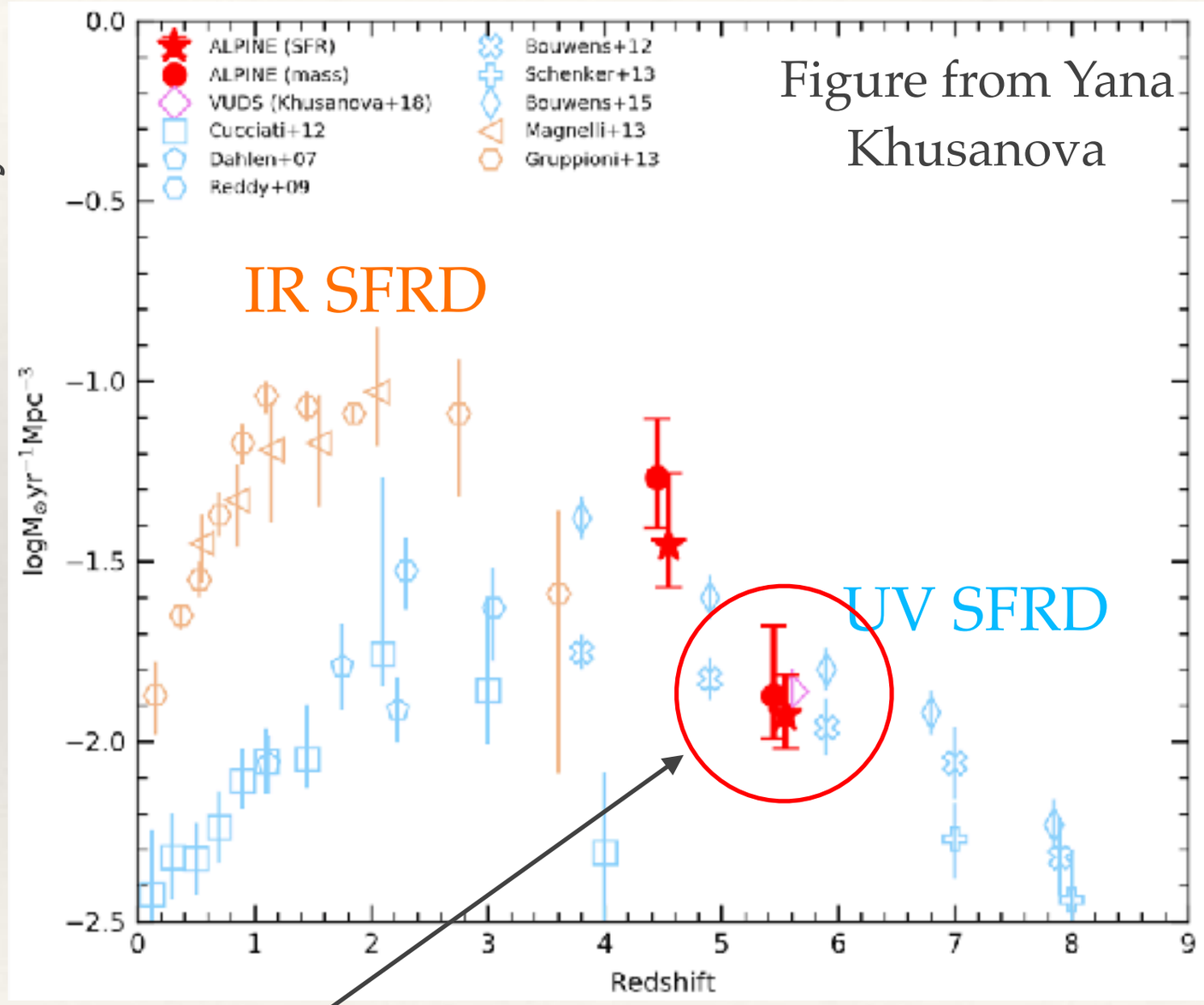


Figure from Yana Khusanova

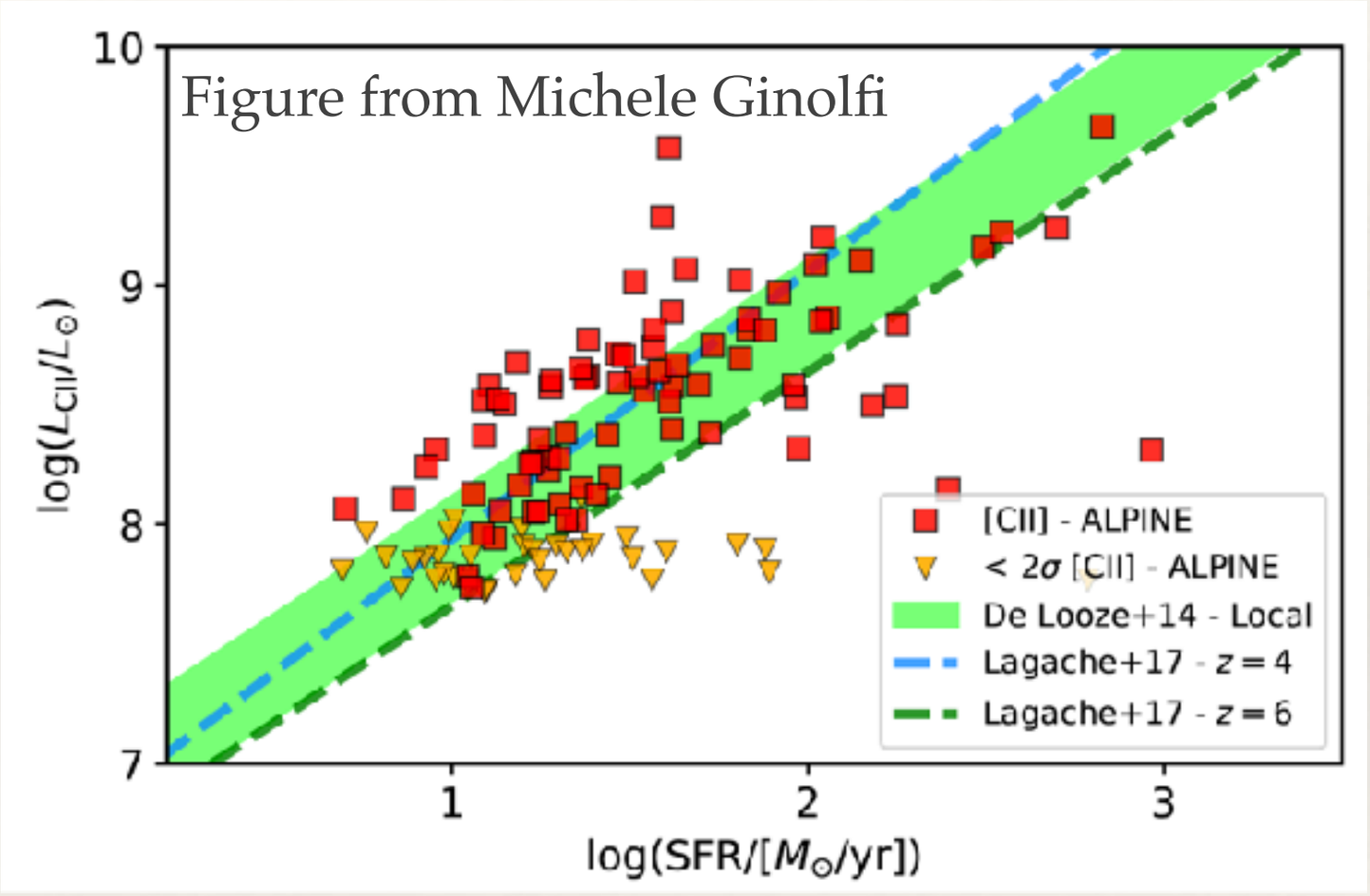
Redshift

At z=5.5, only half (or less) of the UV emitted by young stars escapes galaxies

ALPINE: [CII] in «normal» galaxies at 4<z<6

- [CII] at 158 microns is the brightest cooling line of galaxies
- Correlates with star formation, but deficit expected at high-z (e.g. Lagache+18)
- ALPINE: up to z=6, no average deficit of [CII]
- Confirm potential of [CII] intensity mapping to probe high-z large-scale structures (CONCERTO)

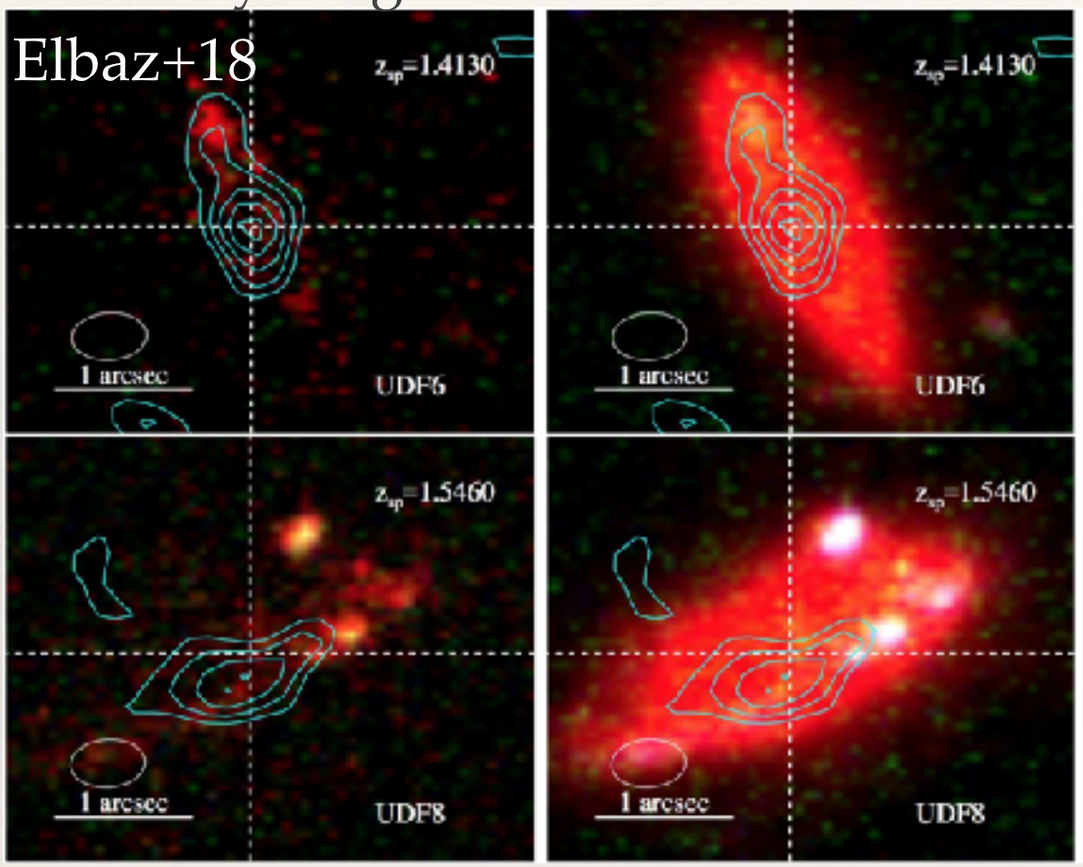
PRELIMINARY



ALMA morphologies: large contrast compared with optical/NIR

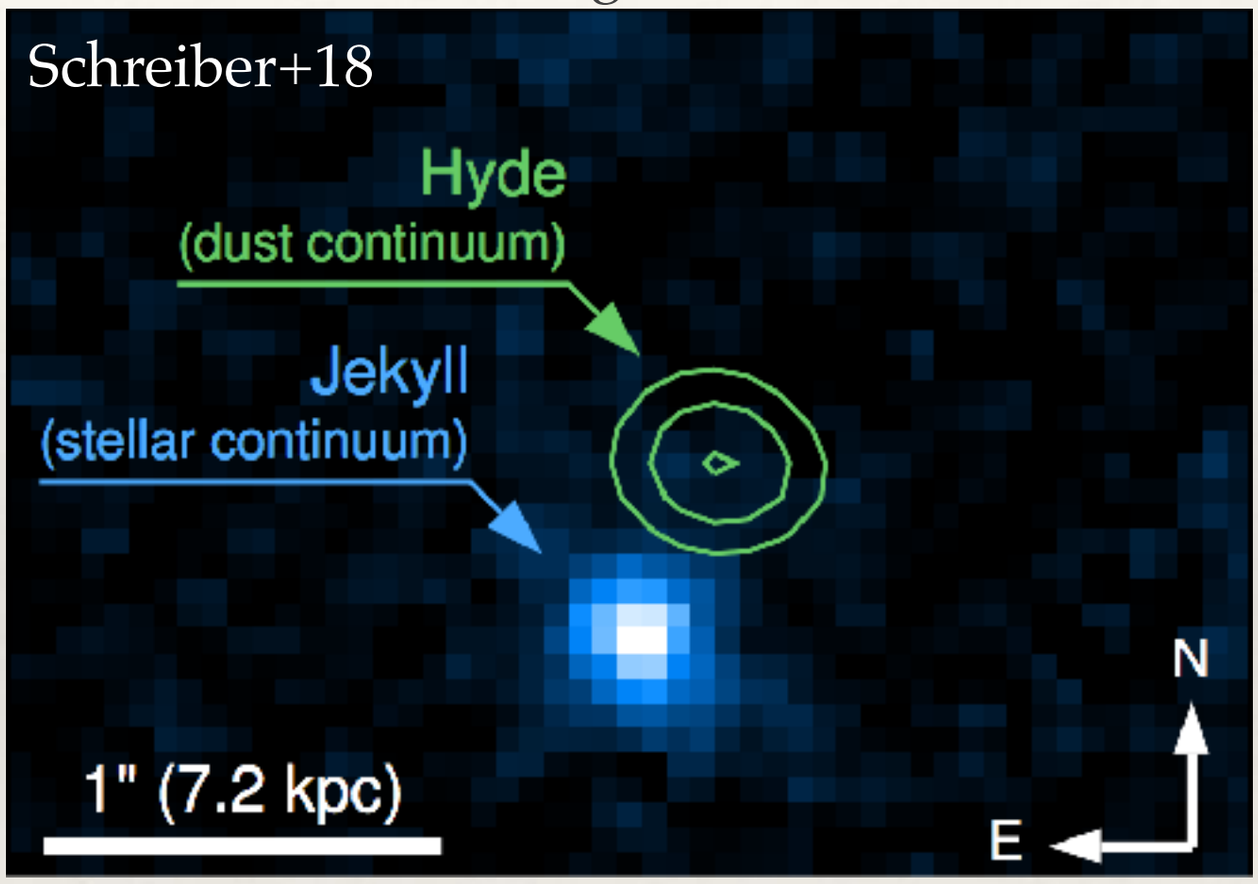
Unobscured rest-frame UV from young stars

Old stars seen in near-IR



Contours: ALMA

Extreme case with ALMA seeing a hidden neighbor



- Resolved ALMA observations to locate obscured star formation
- Huge difference found between ALMA and optical morphologies
- Lots of clumpy rotating structures identify

Outline

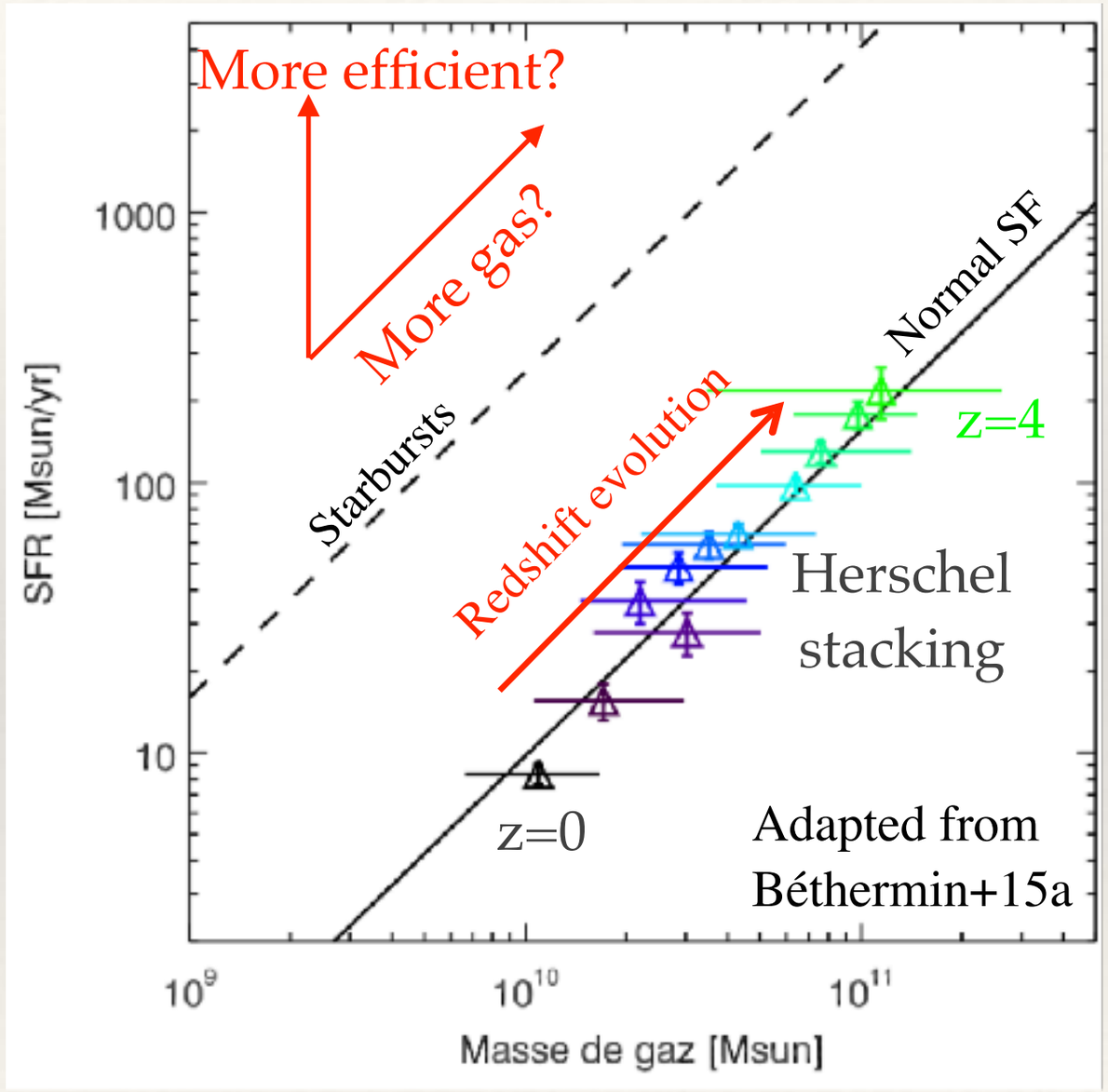
- Dust-obscured star formation in the high-z Universe

- **Cold interstellar medium at high redshift**

- ALMA: a powerful tool to find galaxies and protoclusters in the early Universe

Gas reservoirs and star formation at high z

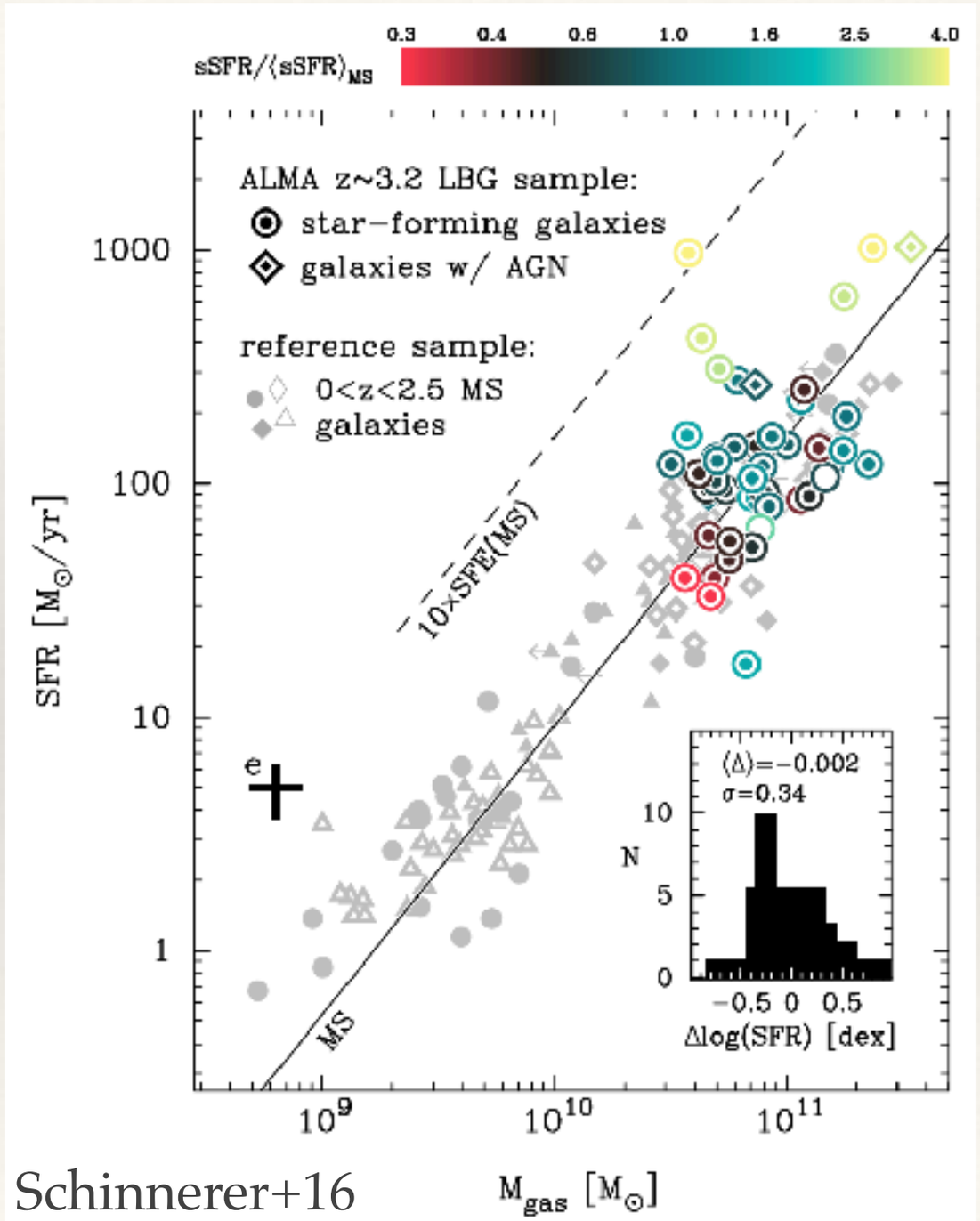
- Local Universe: high SFR usually associated to merger-driven starbursts
  => high SFE (=SFR/Mgas)
- High-z: more mergers, but also stronger diffuse accretion (i.e., larger gas reservoirs)
- What contributes the most to the impressive SFRs measured at high z?



Idea introduced in Daddi+10 and Genzel+10

ALMA: large gas reservoirs confirmed in high-z galaxies

- Cold dust continuum (>250 um rest-frame) can be used as a rough ISM mass tracer
- ALMA can quickly build samples targeting optically-selected samples
- ALMA confirms the important gas reservoirs causing the high SFR in «normal» objects

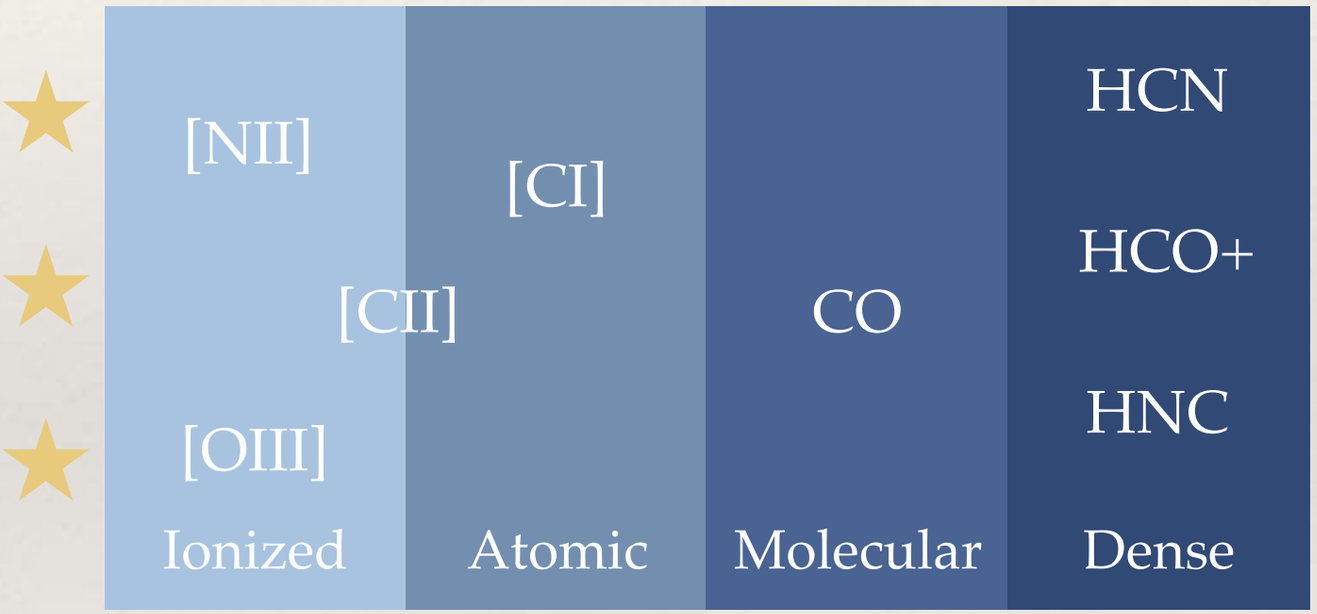


Schinnerer+16

See also, e.g., Magdis+12b, Tacconi+13, Dessauges-Zavadski+15, Scoville+17, Tacconi+18

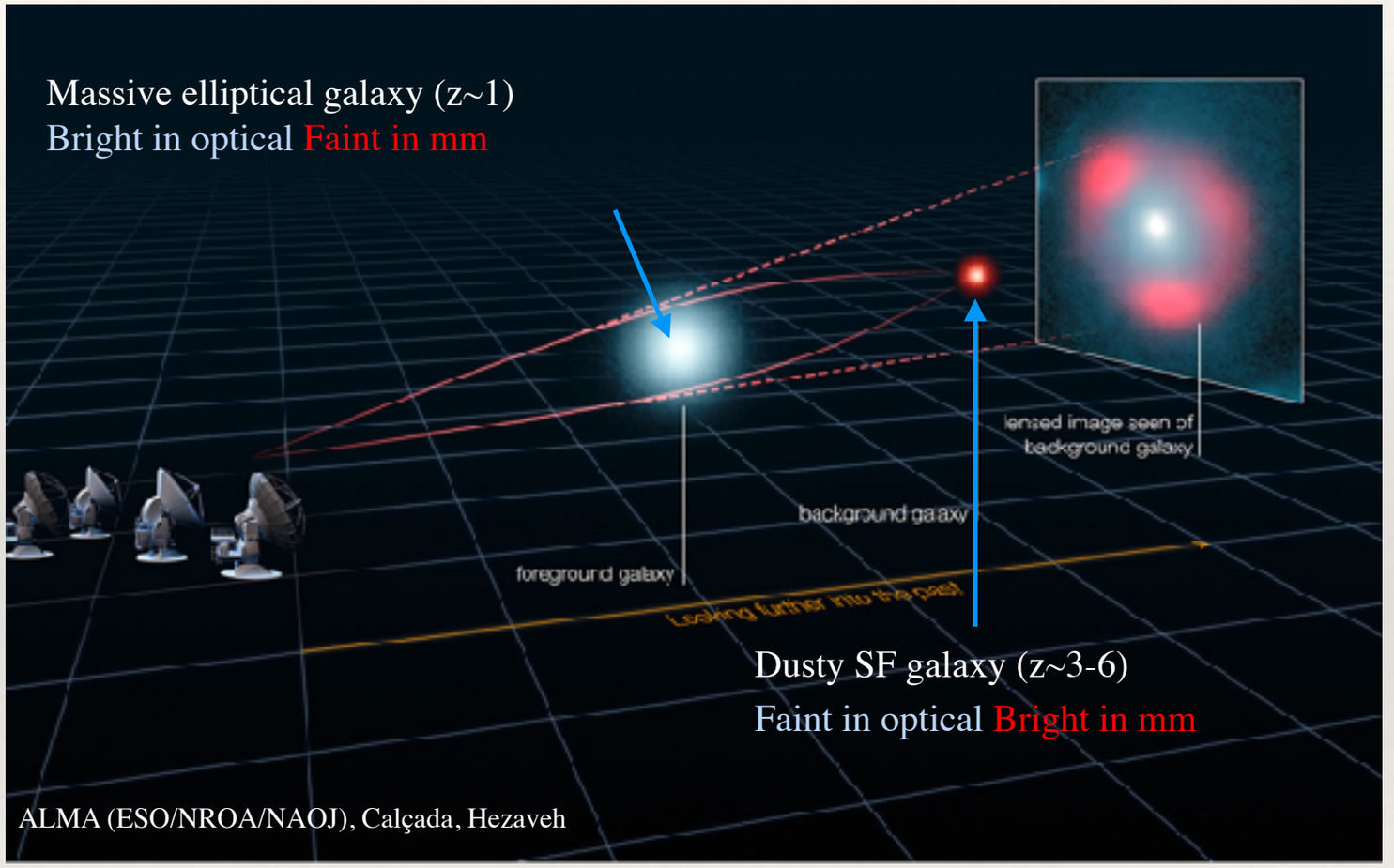
Probing the cold interstellar medium at high z

- Far-IR and millimeter lines allow us to probe the cold ISM
- Various lines probe various phases



Reaching higher z and/or fainter lines with lensing

- CO and [CII] are bright, but other lines might be much fainter
- Massive and bright galaxies are rare = unlikely to find them behind clusters
- Galaxy-galaxy lensing is our best solution
- Magnification ~10 => detection 100x faster



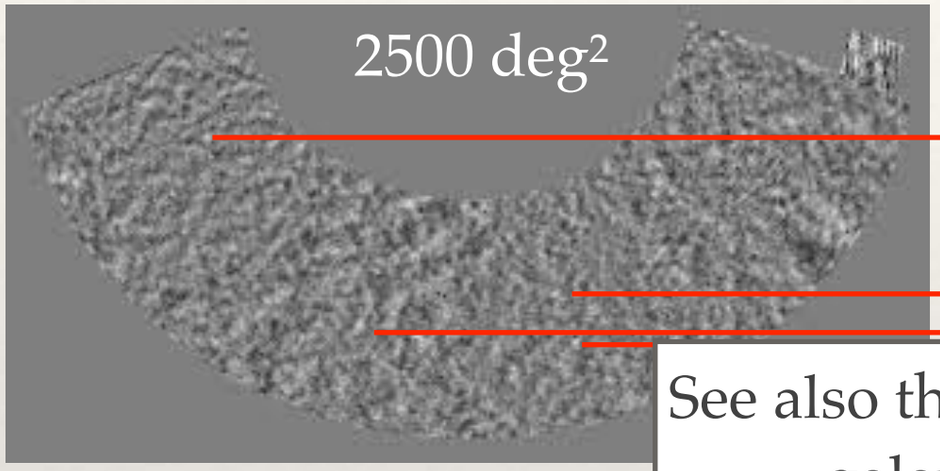
ALMA

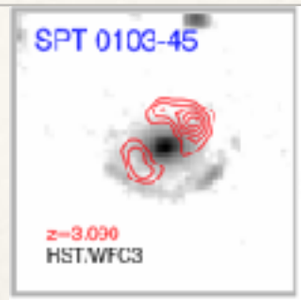
Natural telescope (gravitational lensing)

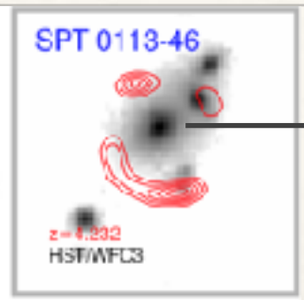
See, e.g., Negrello+09, Combes+12, Vieira+13

The SPT sample of lensed dusty galaxies

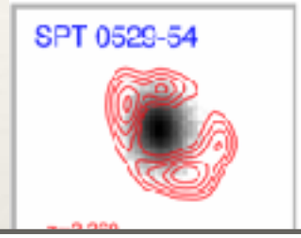
Large field, but low resolution (~1 arcmin)

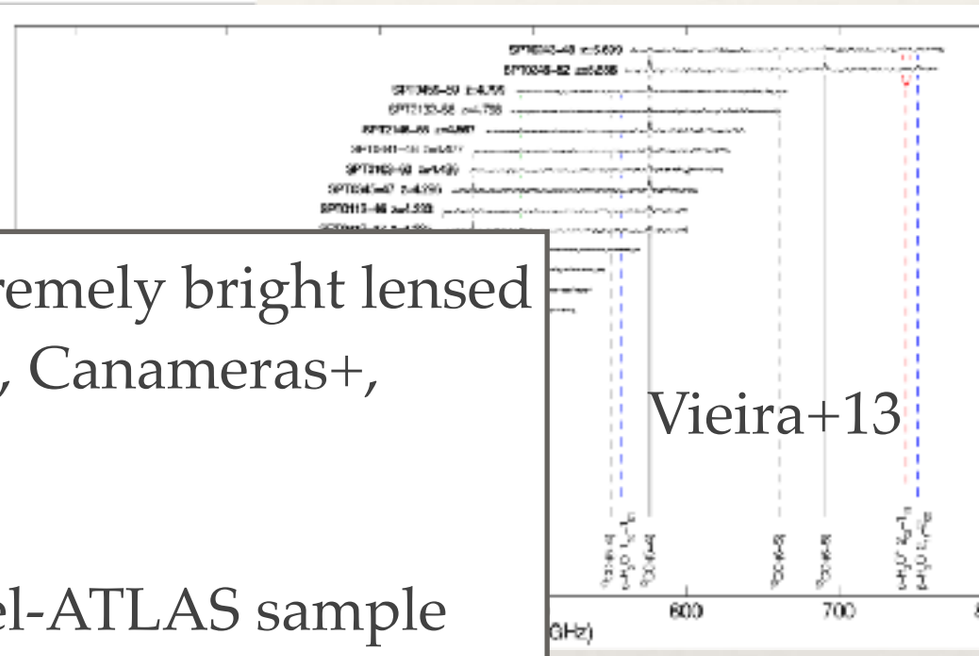






Confirmed as lensed objects

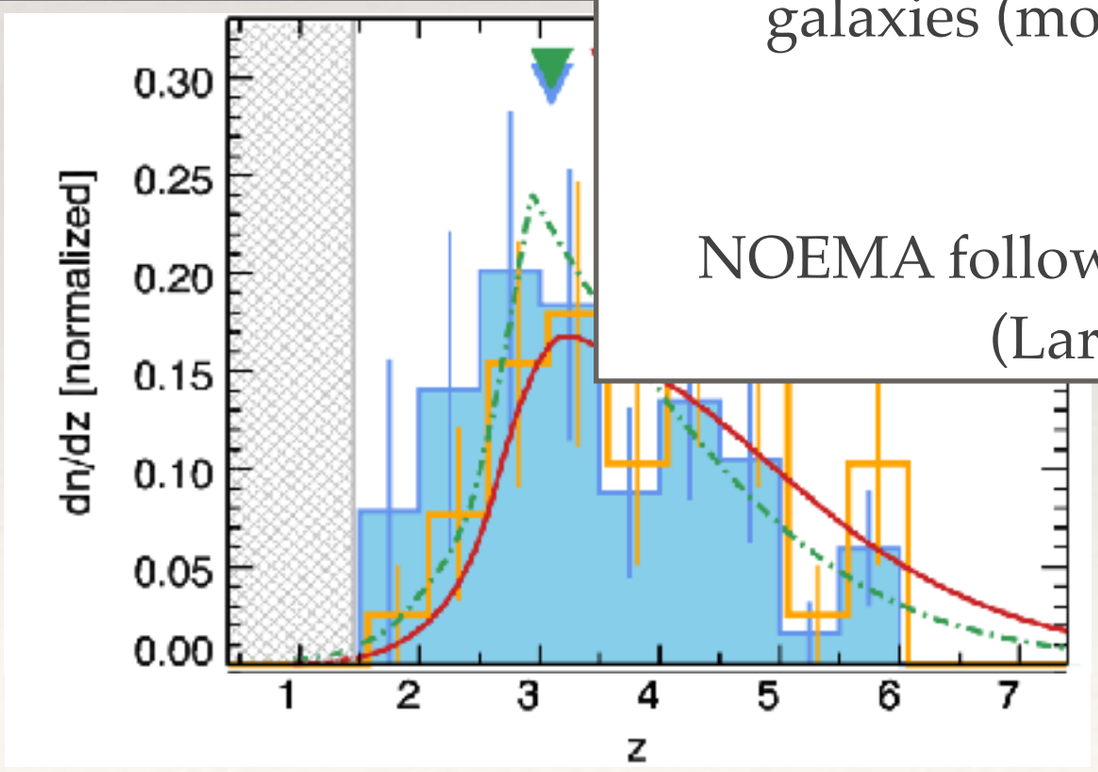




Vieira+13

See also the Planck sample of extremely bright lensed galaxies (mostly IRAM obs., Canameras+, Nesvadba+)

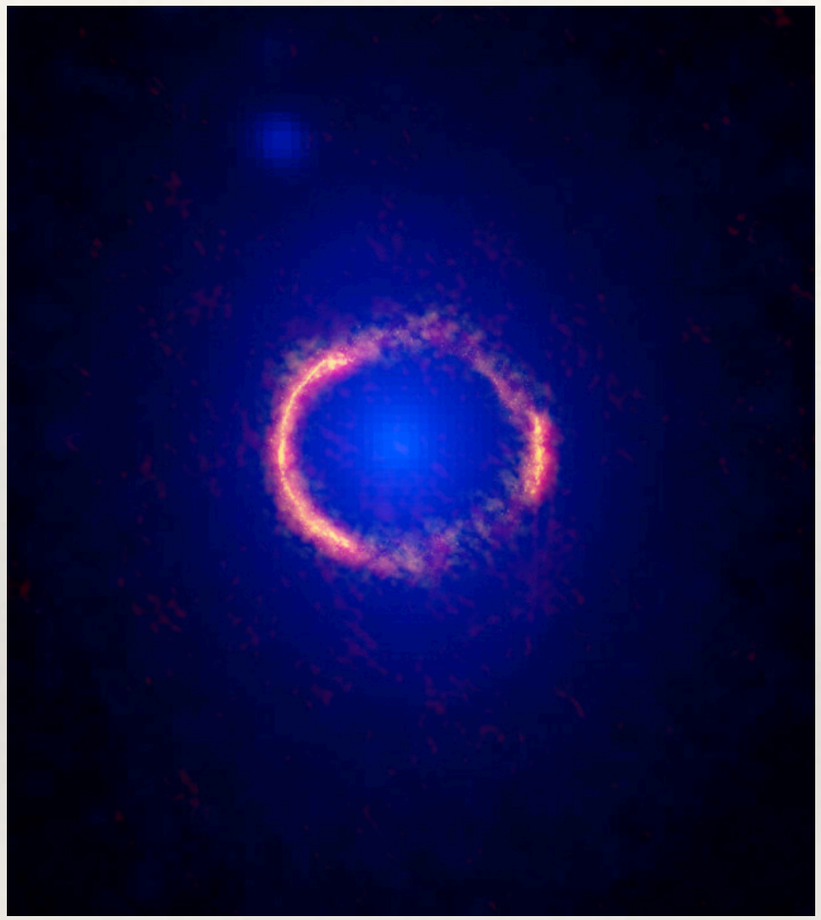
NOEMA follow up of Herschel-ATLAS sample (Large Program, PI: Cox)



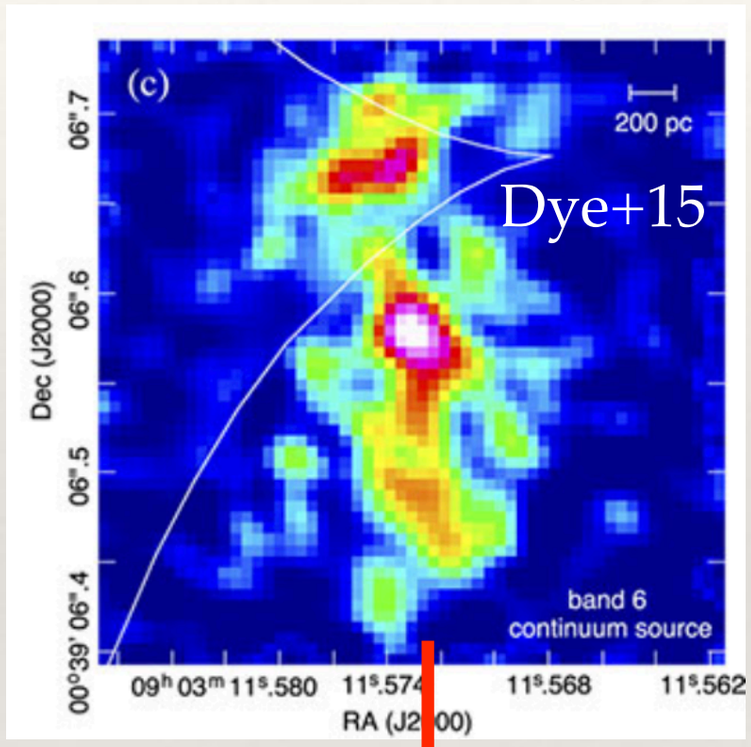
Spectroscopic redshift!

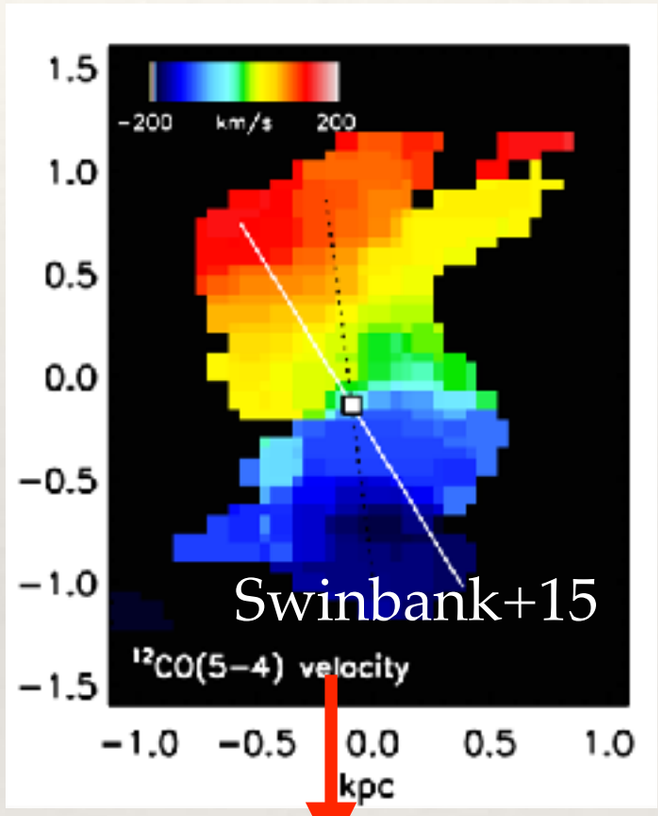
SDP.81: first high-resolution image of a lensed object

Red: Orange Blue: HST



Reconstructed image plane

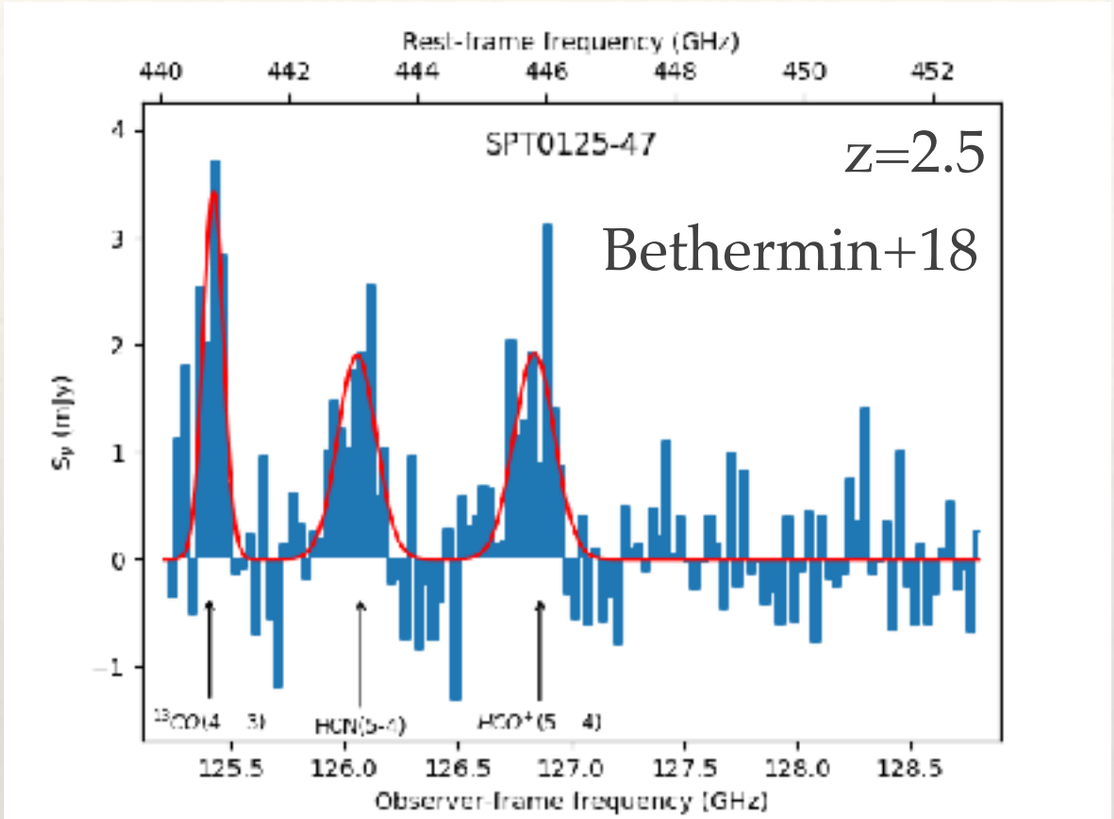


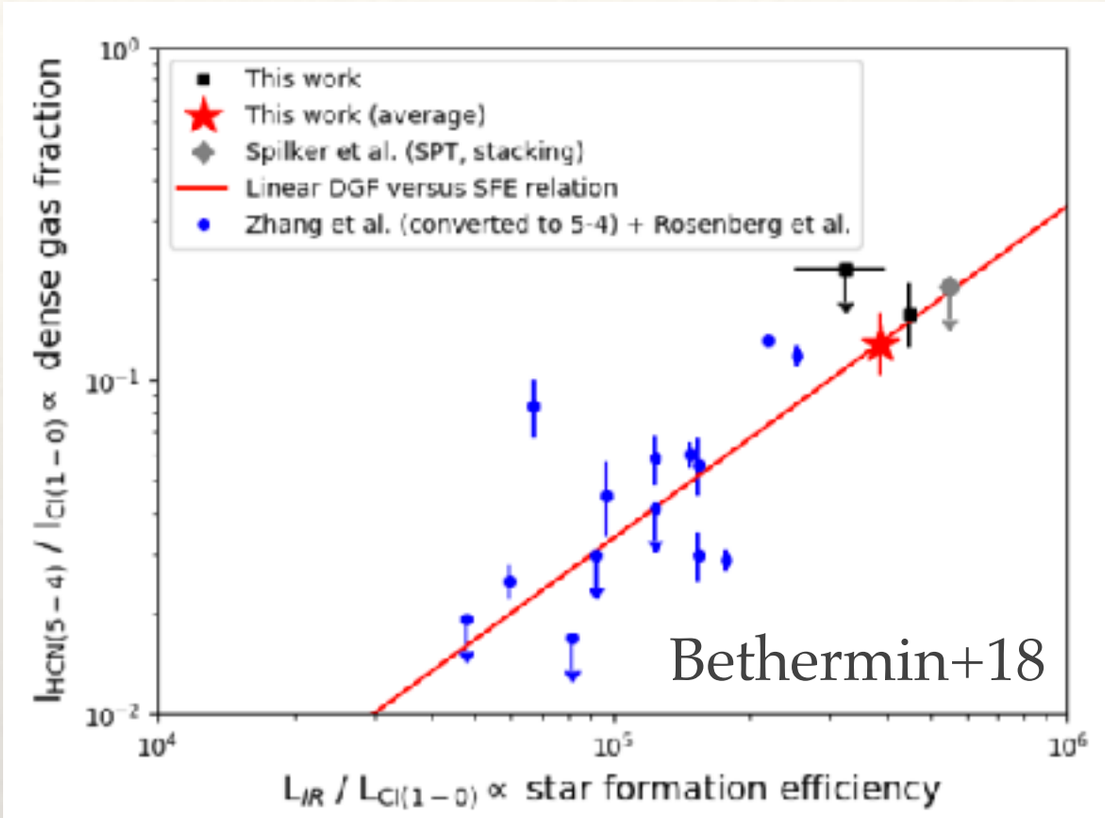


Clumpy rotating structure?

- First high-resolution (170 mas) image of a high-z lensed galaxy with ALMA
- Hints of a $10^{8.96\pm0.12}$ Msun sub-structure from strong-lensing modeling (Hezaveh+16)

Dense molecular gas in high-z monsters



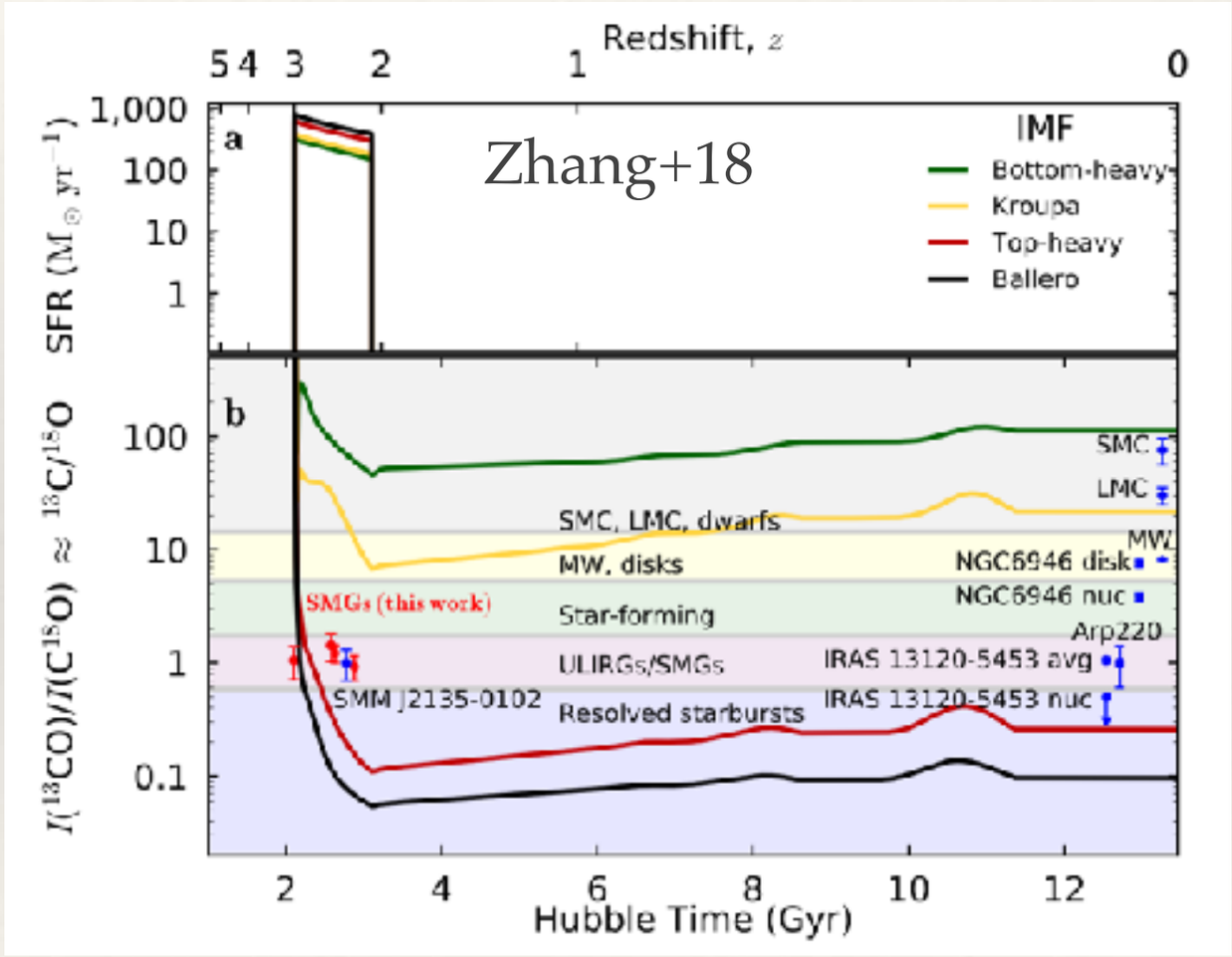


- HCN, HCO+, and HNC are tracers of the dense gas and can now be detected by ALMA
- Indications of high dense gas fraction associated to a high star formation efficiency in high-z dusty star-forming galaxies

See also Oteo+2017

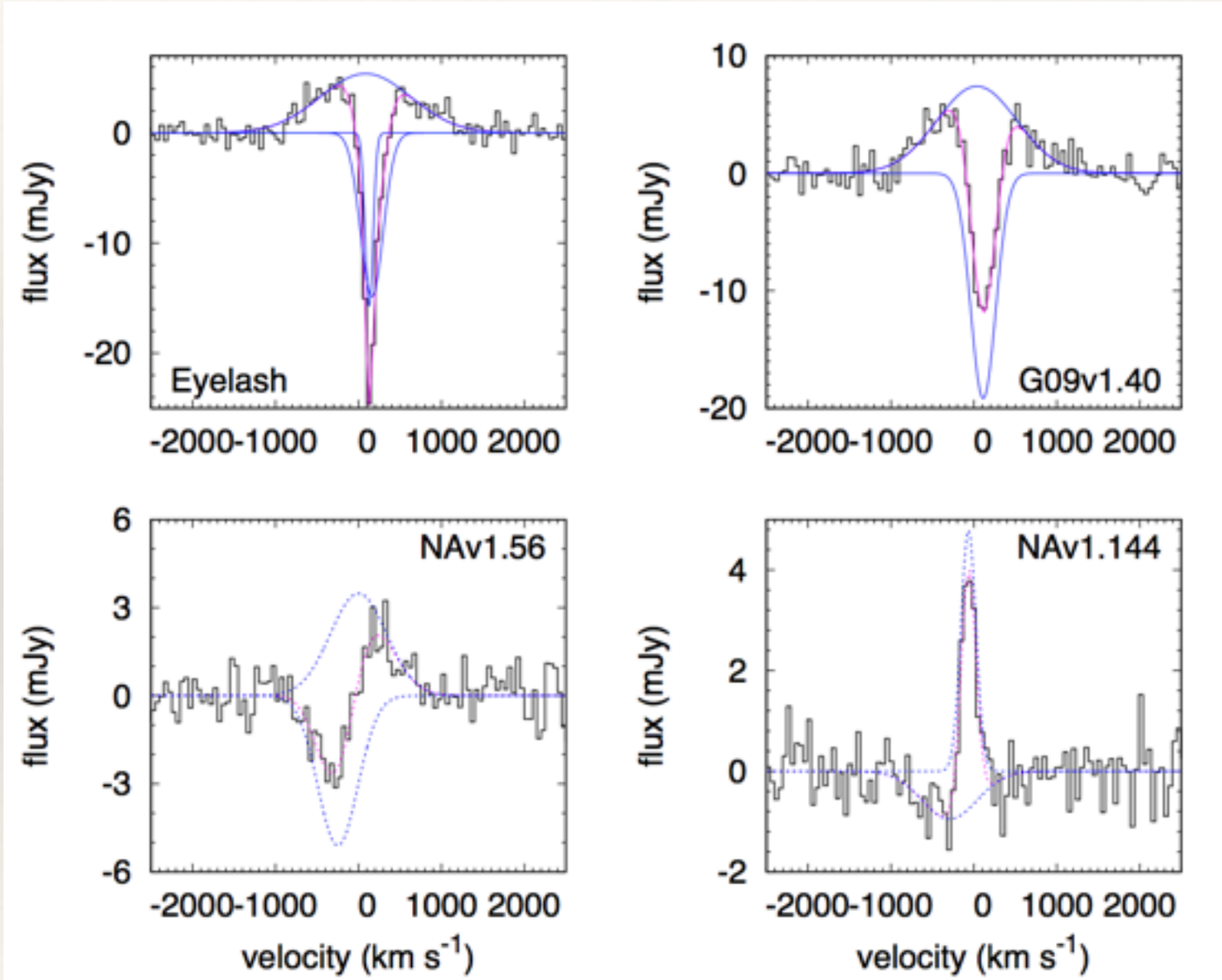
Testing the IMF at high redshift

- ^{13}CO / $C^{18}O$: proposed as a tracer of the IMF (Romano+17)
- Zhang+18: high-z starbursts compatible with top heavy IMF
- Seems in contradiction with the claim that old elliptical galaxies are bottom heavy (Cappellari+12, Canameras+17)



CH+: a probe a the turbulence at high-z

- CH+: emitted in high-density medium and absorbed at low density
- Observed by Falgarone+17 with ALMA
- Emission profile: dense shock wave induced by galactic winds
- Absorption: highly turbulent reservoirs extending far from the starburst core



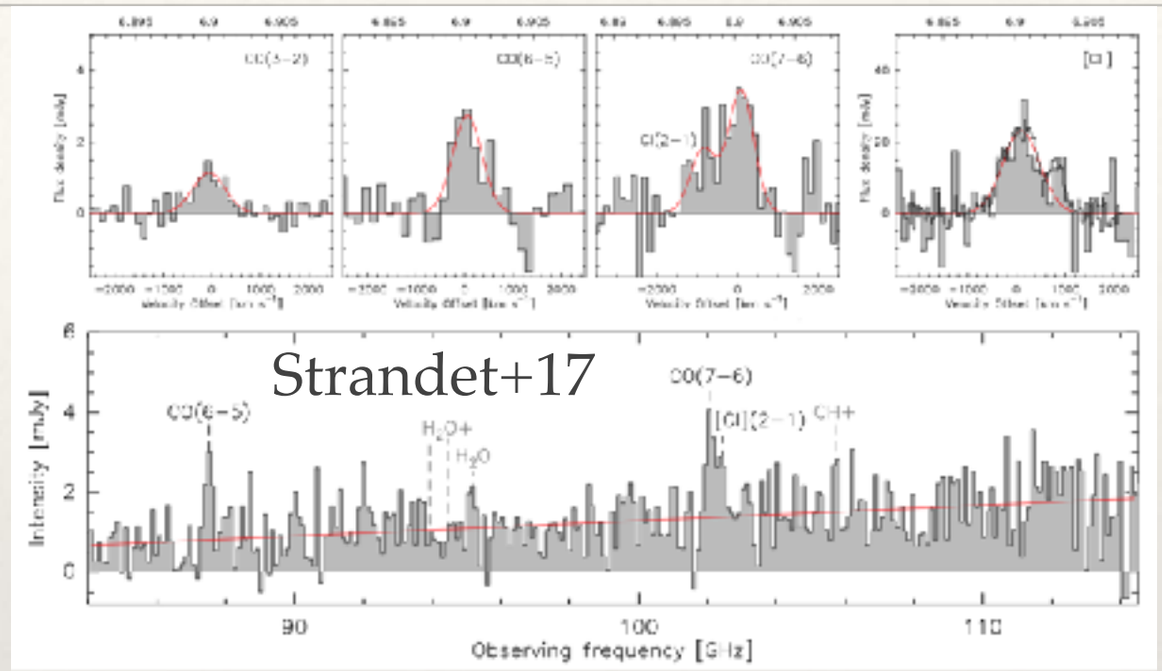
Falgarone+17

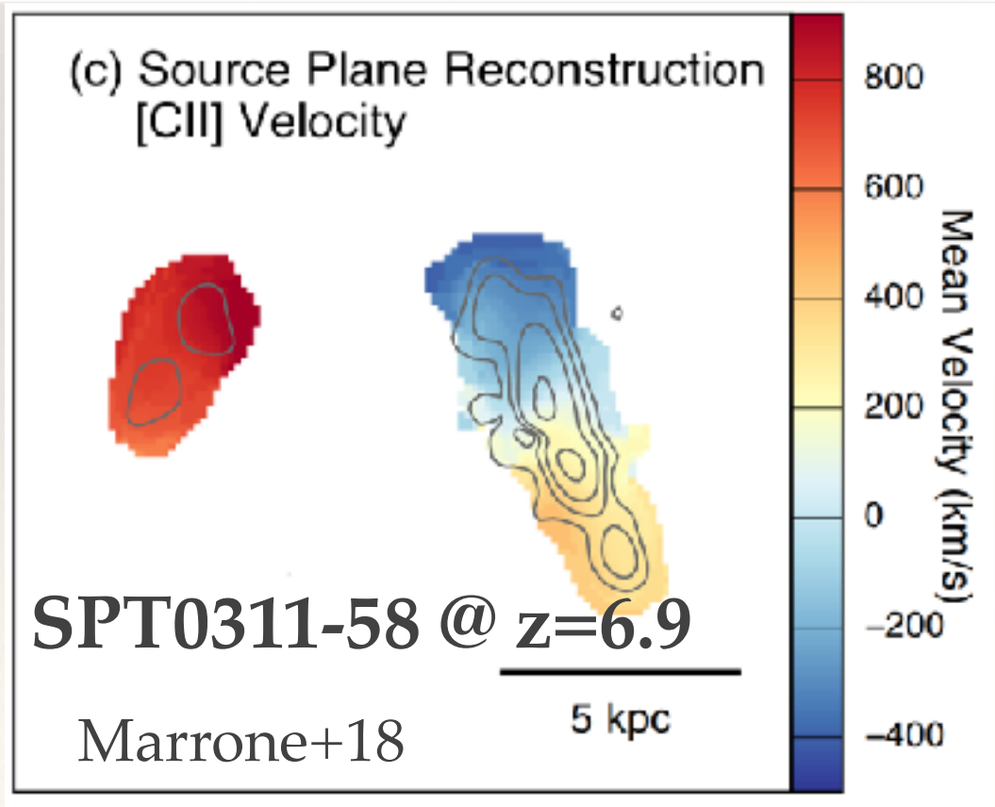
Outline

- Dust-obscured star formation in the high-z Universe
- Cold interstellar medium at high redshift
- **ALMA: a powerful tool to find galaxies and protoclusters in the early Universe**

Existence of massive dusty objects at z=7

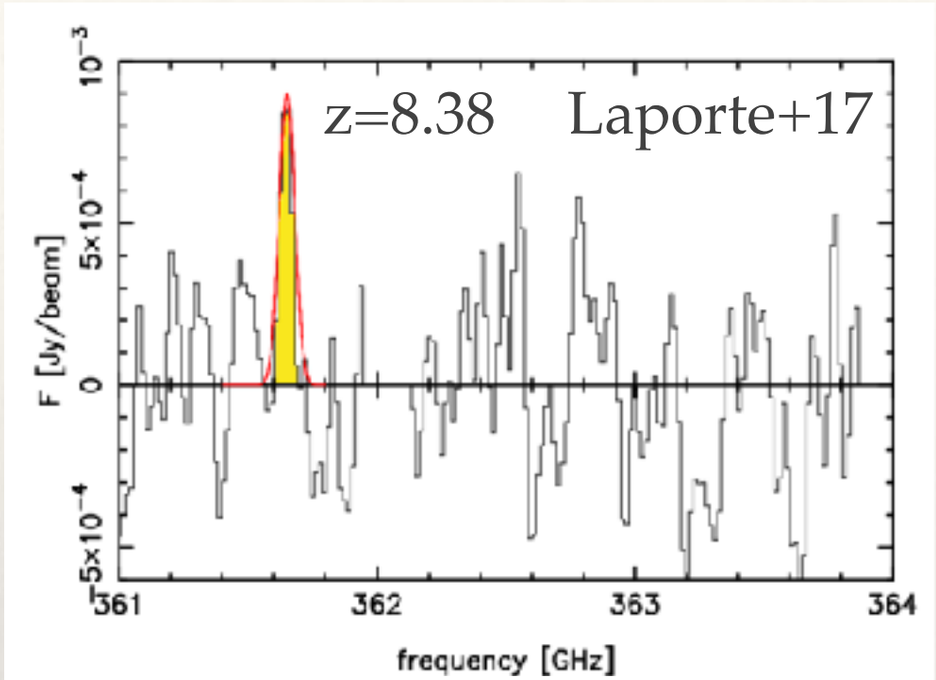
- Current record for a mm-selected galaxy: SPT0311-58 at z = 6.9
- [CII] is extremely bright and can be used to perform resolved kinematics, even at very high z
- SFR~2900 Msun/yr
  Mgas ~ 2.7 x 10^{11} Msun
  Est. Mhalo ~ a few 10^{12} Msun

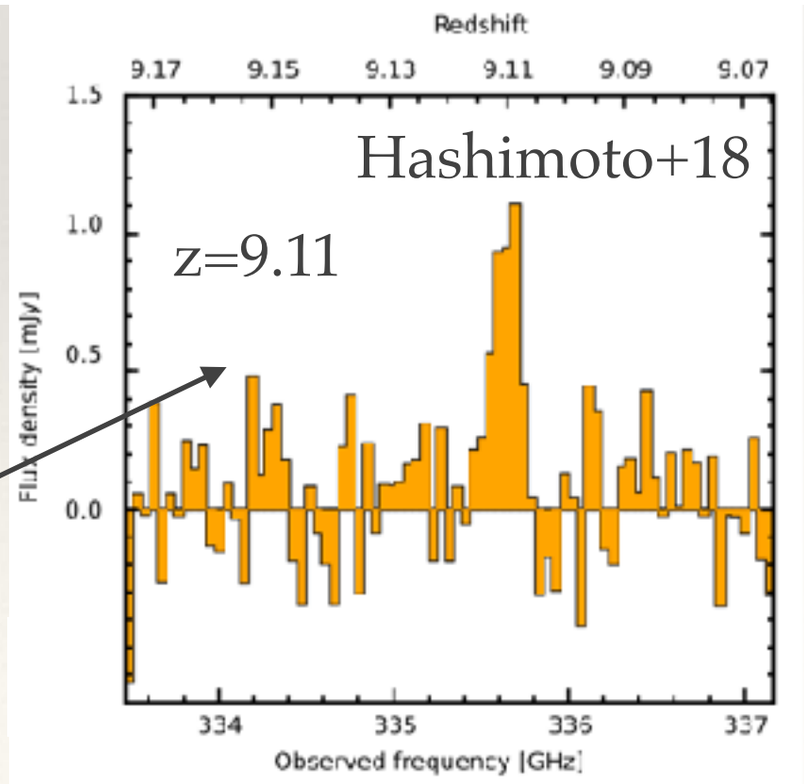




[OIII]: a new tool for the z>8 gold rush

- [OIII] (88 microns) redshifted to the millimeter atmospheric window at very high z
- [OIII] is expected to be brighter than [CII] in young high-z galaxies
- Before JWST, one of the best way to confirm z>7 candidate in spectroscopy

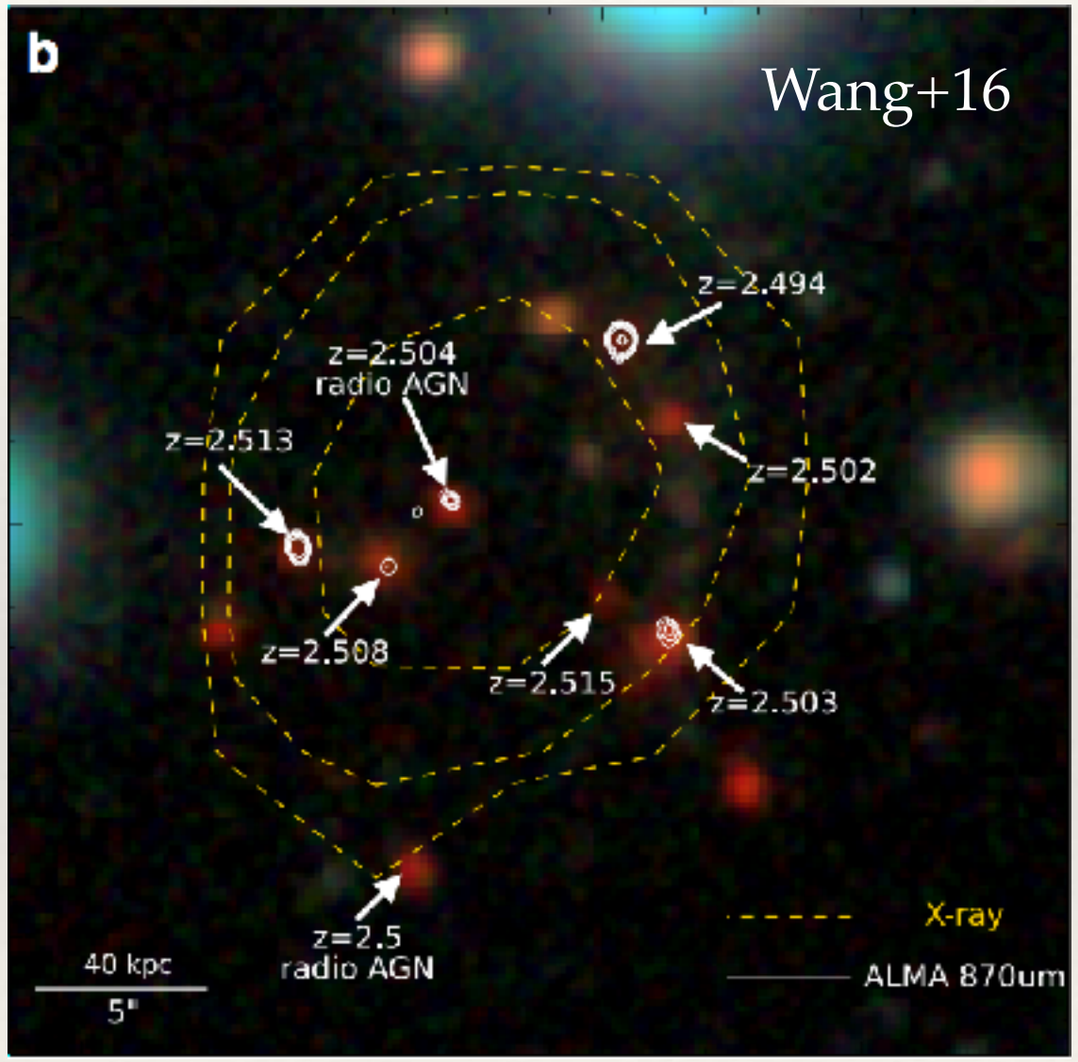




Highest spectroscopic redshift so far!

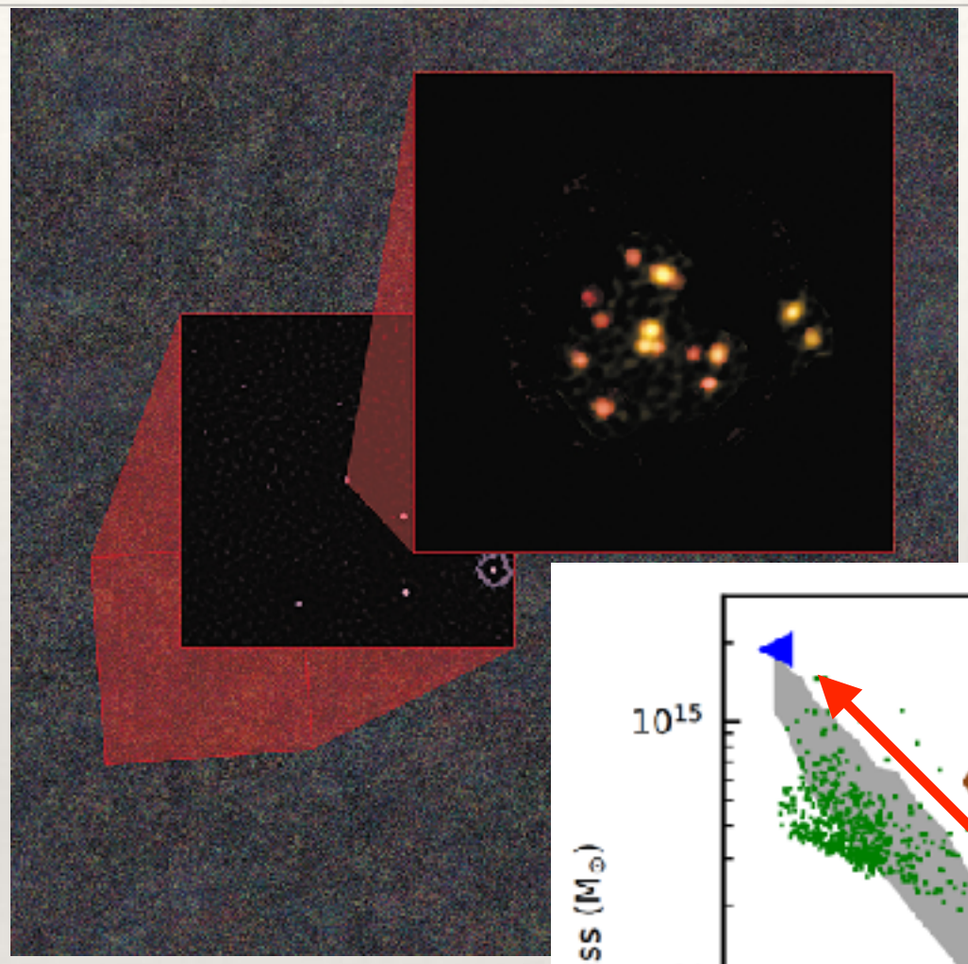
Overdensities at high-z hosting impressive star formation (1)

- Candidate cluster at z=2.5
- Detected in X-ray
- 11 of 17 members confirmed using the CO
- SFR~3400 Msun/yr in the core
- Estimated halo mass: $10^{13.9\pm0.2}$ Msun

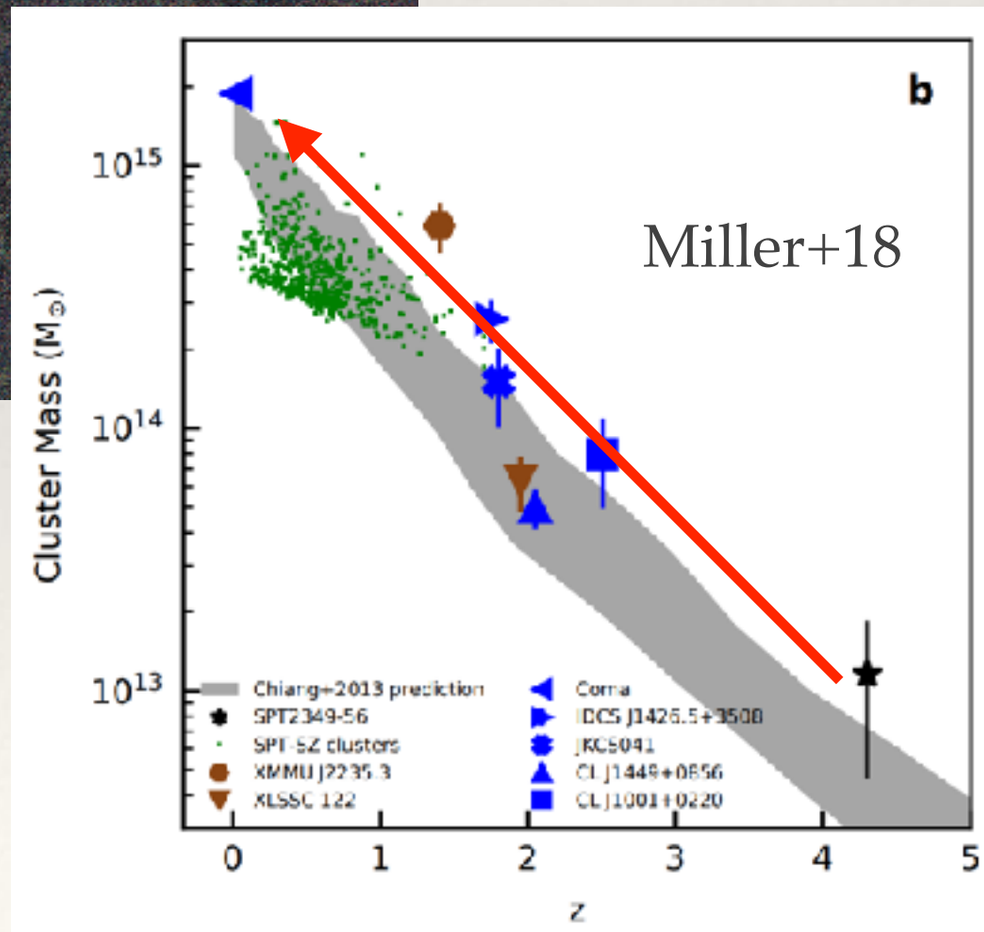


Overdensities at high-z hosting impressive star formation (2)

- Discovery of an impressive overdensity at z~4.3 in SPT unlensed sample



- 17 ALMA-confirmed members with SFR>100 Msun/yr
- Probably progenitor of a massive z=0 cluster



See also important effort to follow up Planck red sources led by IAS and IRAP (Planck papers, Kneissl+18, Martinache+19…)

Conclusion

- ALMA allows us to probe obscured star formation at high-redshift:
  - non-negligible contribution even above z=5
  - morphological differences compared with optical/near-IR
- ALMA combined with lensing is a powerful probe of cold ISM:
  - large gas reservoirs and large fraction of dense gas in the most extreme systems
  - top-heavy IMF?
- ALMA is a high-redshift machine:
  - record redshift for dusty and normal objects
  - identification and confirmation of high-z massive (proto)clusters

Merci de votre attention