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The challenge of studying the interstellar medium in z~7 galaxies

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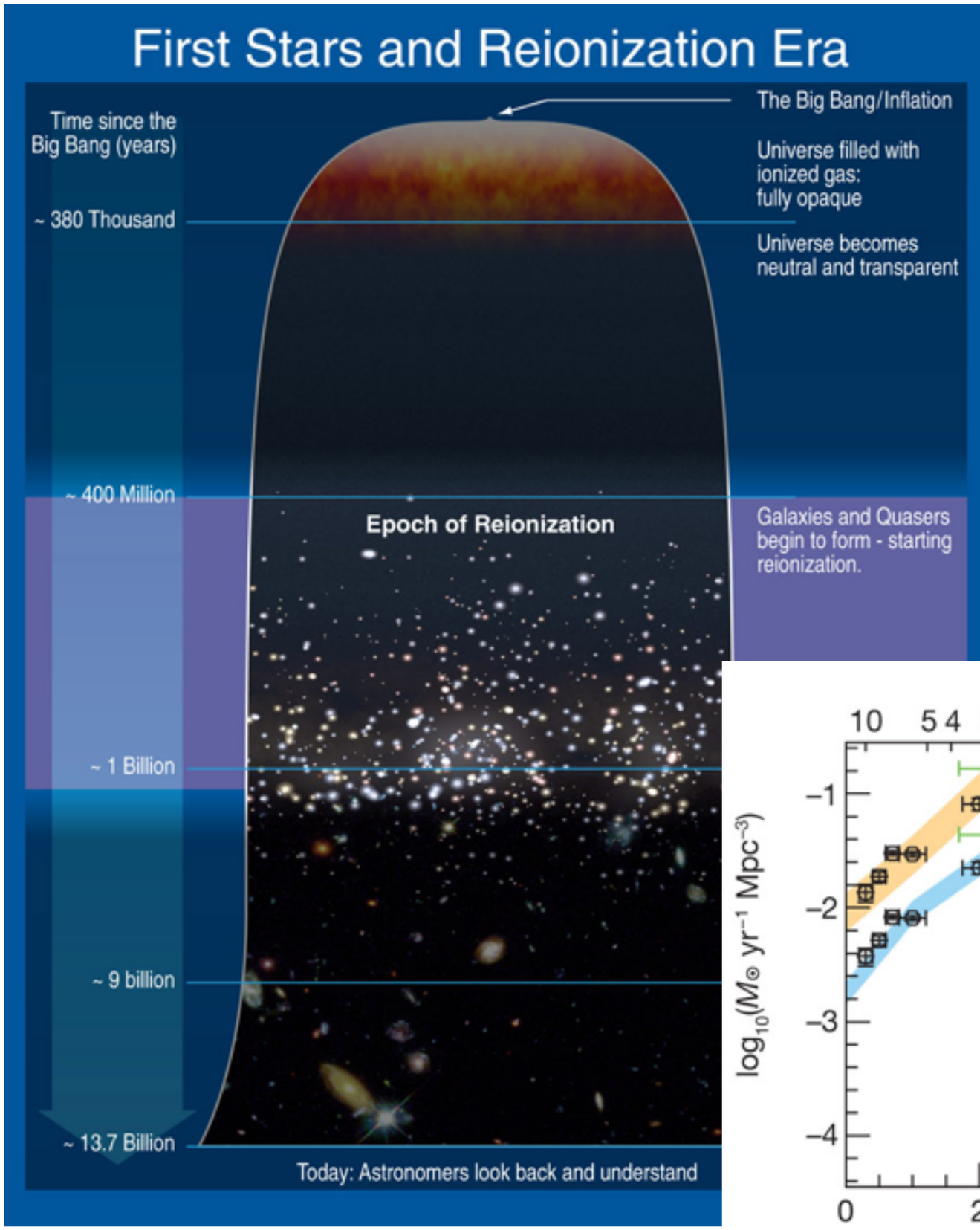
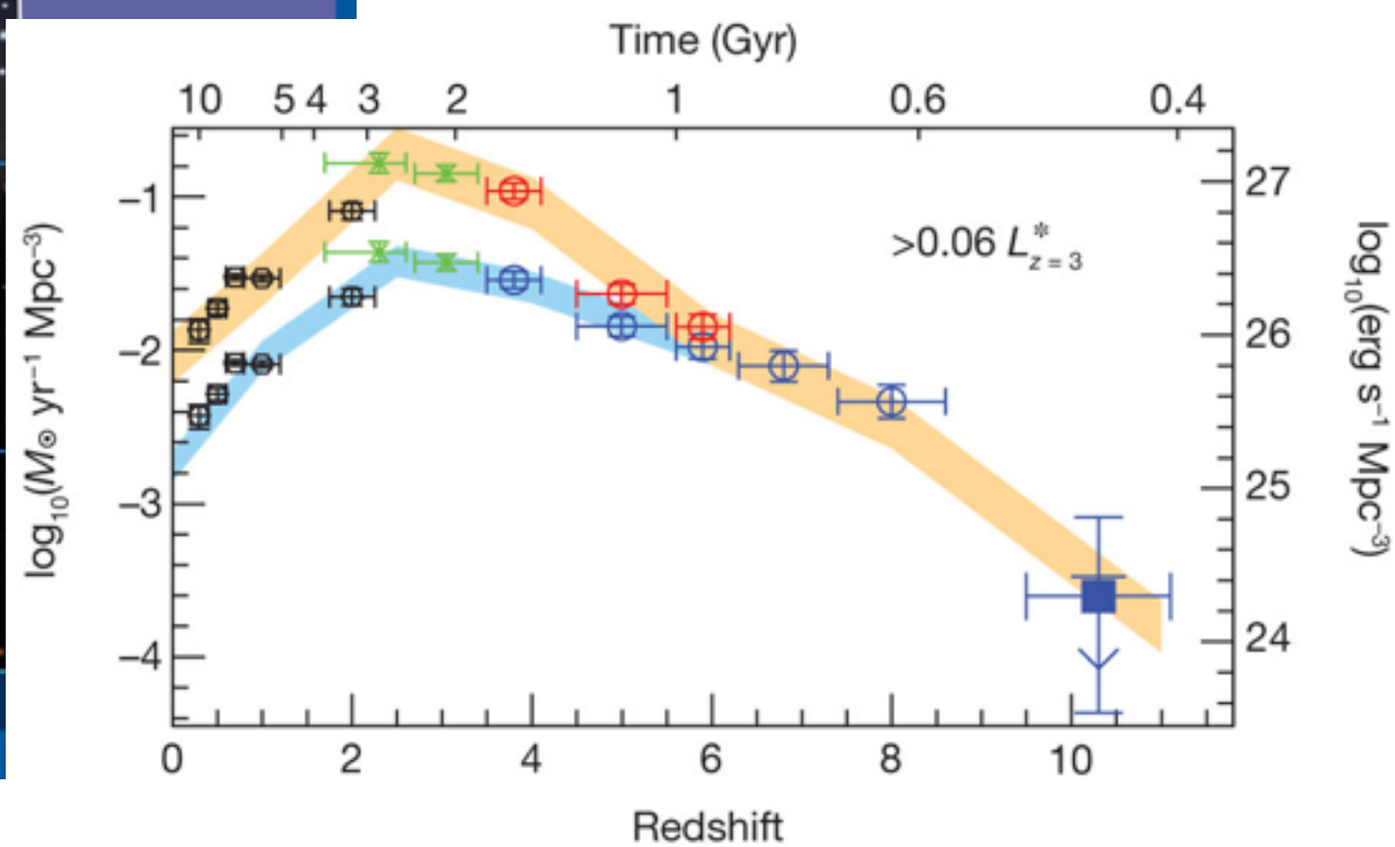
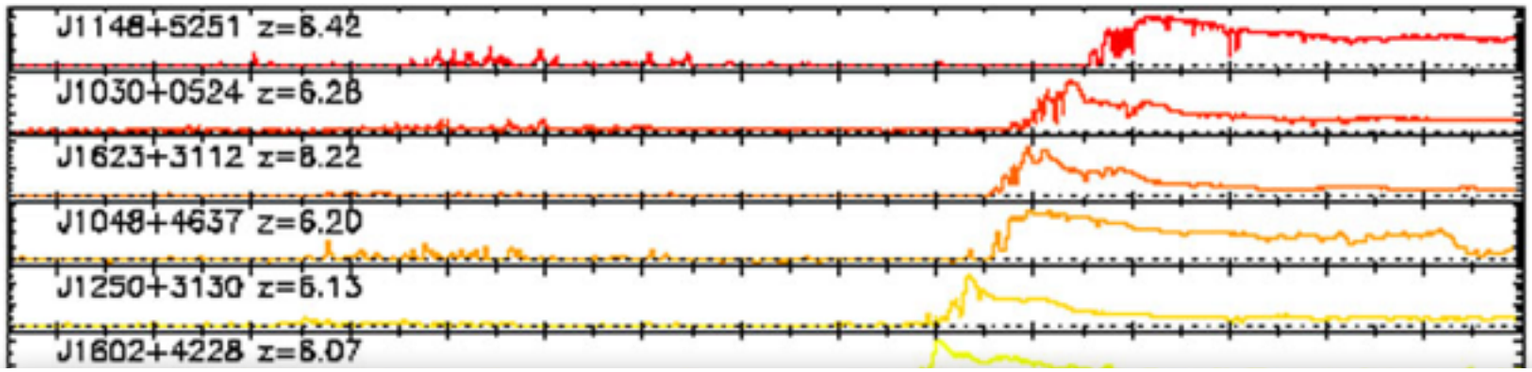
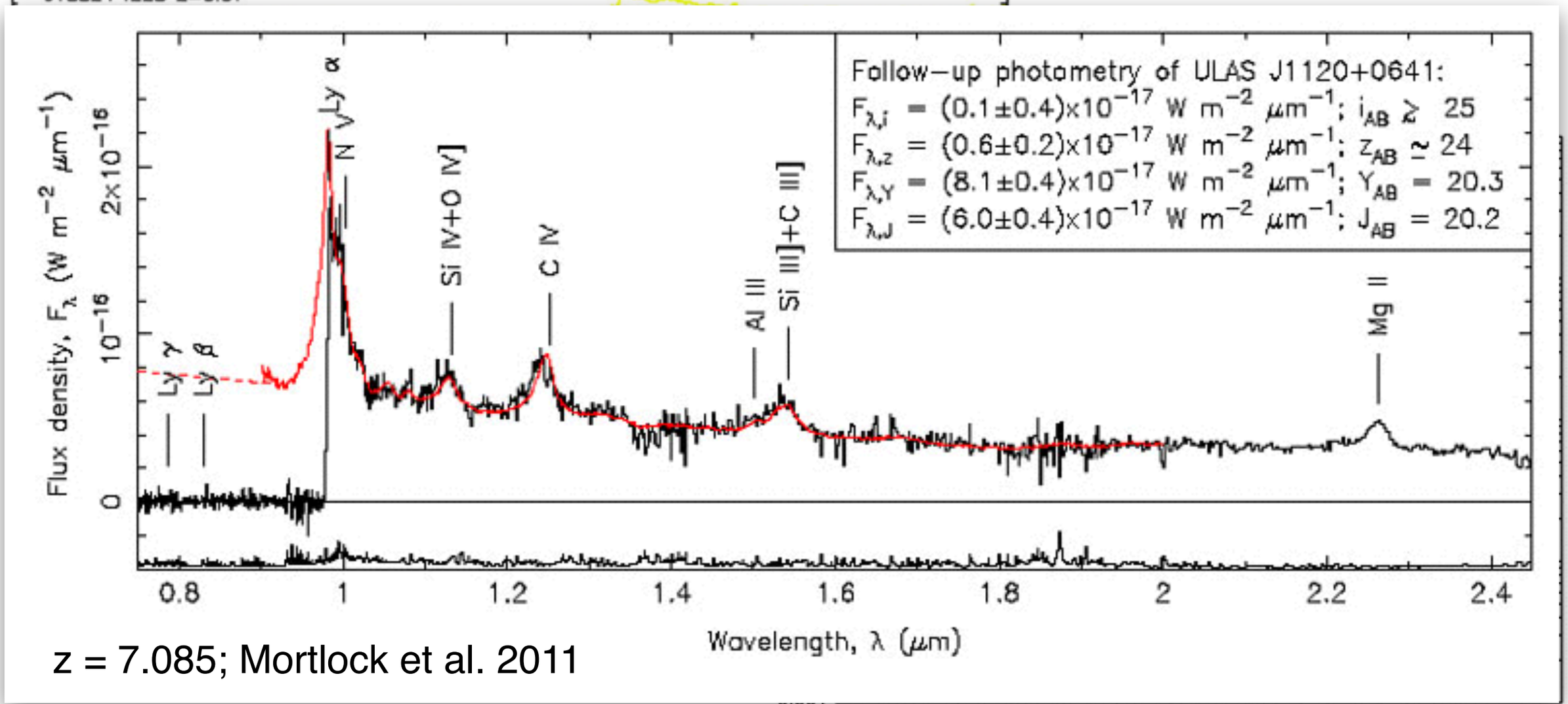




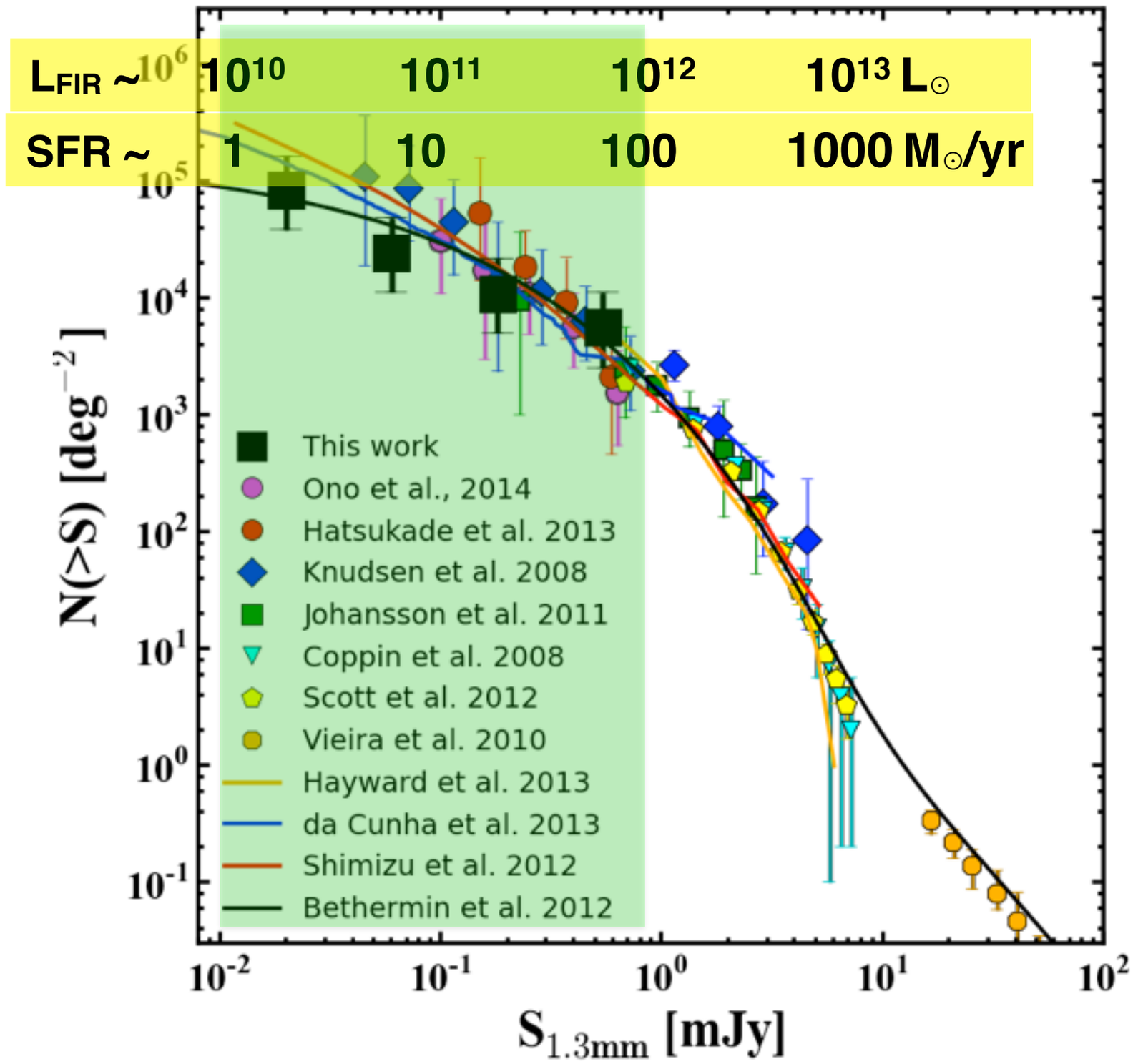
e.g. Bouwens et al. 2011





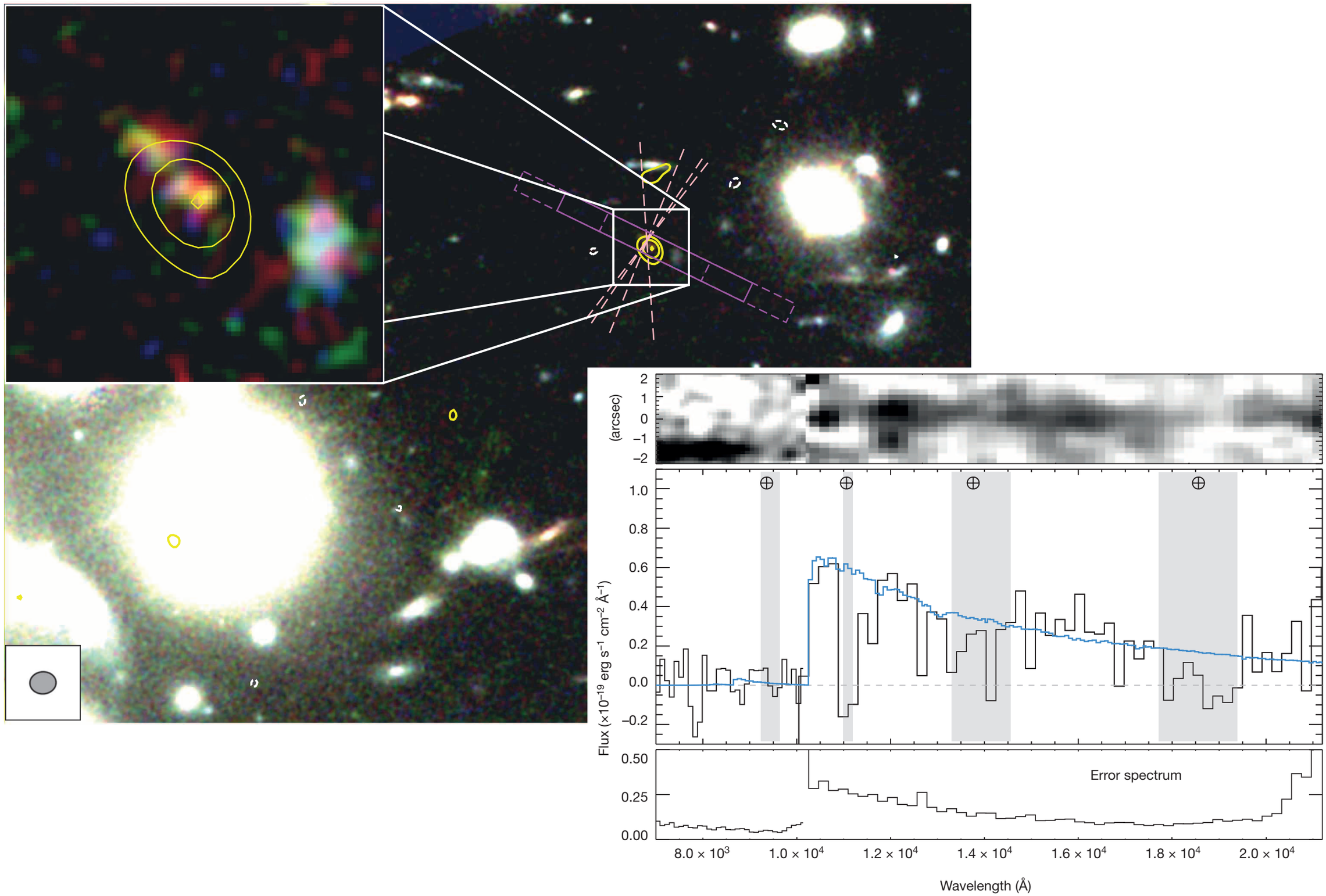
z = 7.085; Mortlock et al. 2011

Fan X, et al. 2006.
Annu. Rev. Astron. Astrophys. 44:415–62


L_{FIR} ~ 10^{10} 10^{11} 10^{12} 10^{13} $L_\odot$
SFR ~ 1 10 100 1000 $M_\odot$/yr
This work
Ono et al., 2014
Hatsukade et al. 2013
Knudsen et al. 2008
Johansson et al. 2011
Coppin et al. 2008
Scott et al. 2012
Vieira et al. 2010
Hayward et al. 2013
da Cunha et al. 2013
Shimizu et al. 2012
Bethermin et al. 2012
N(>S) [deg^{-2}]
$S_{1.3mm}$ [mJy]

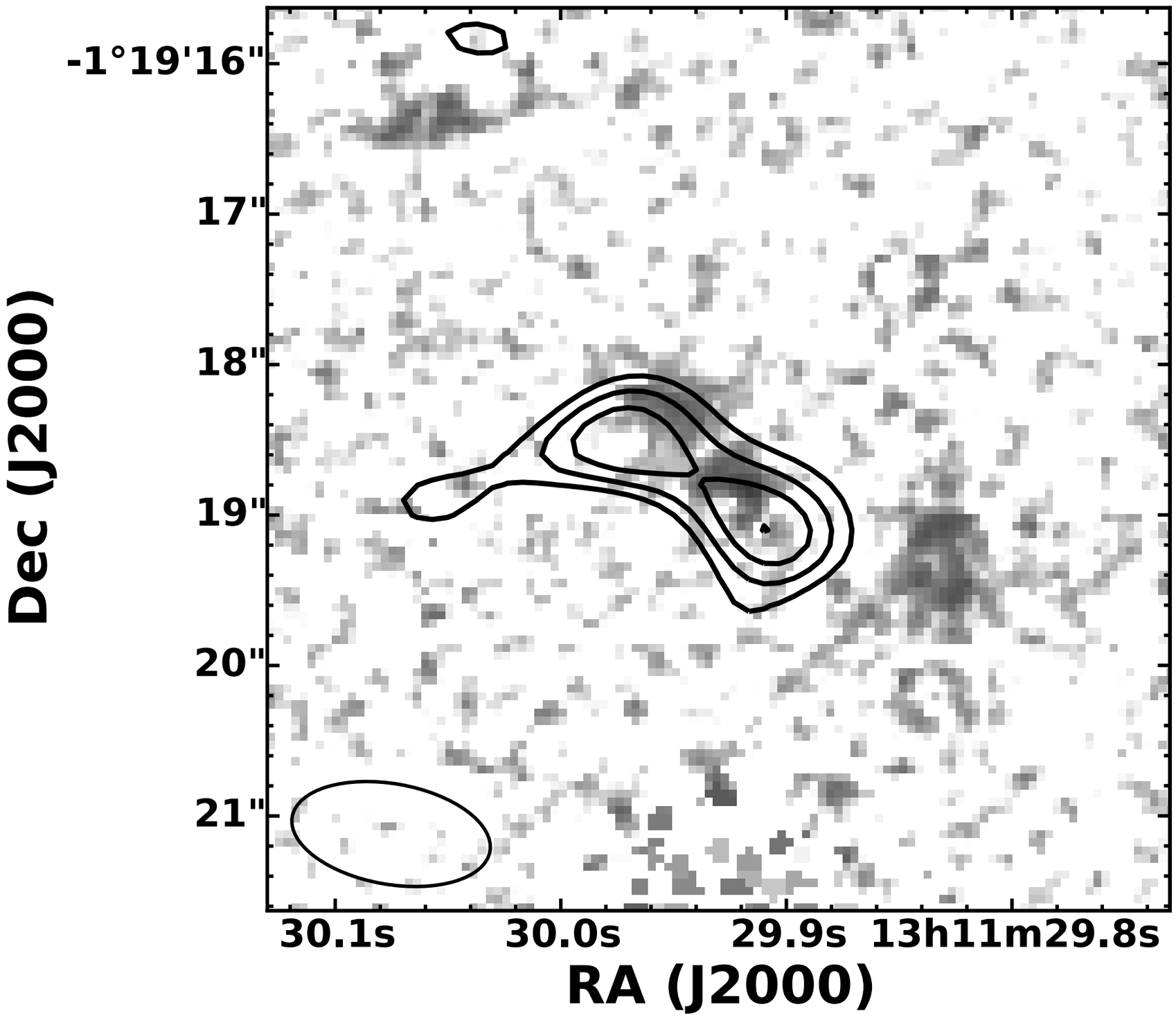
Galaxy cluster field A1689

A1689-zD1: Dust at *z* ~ 7.5



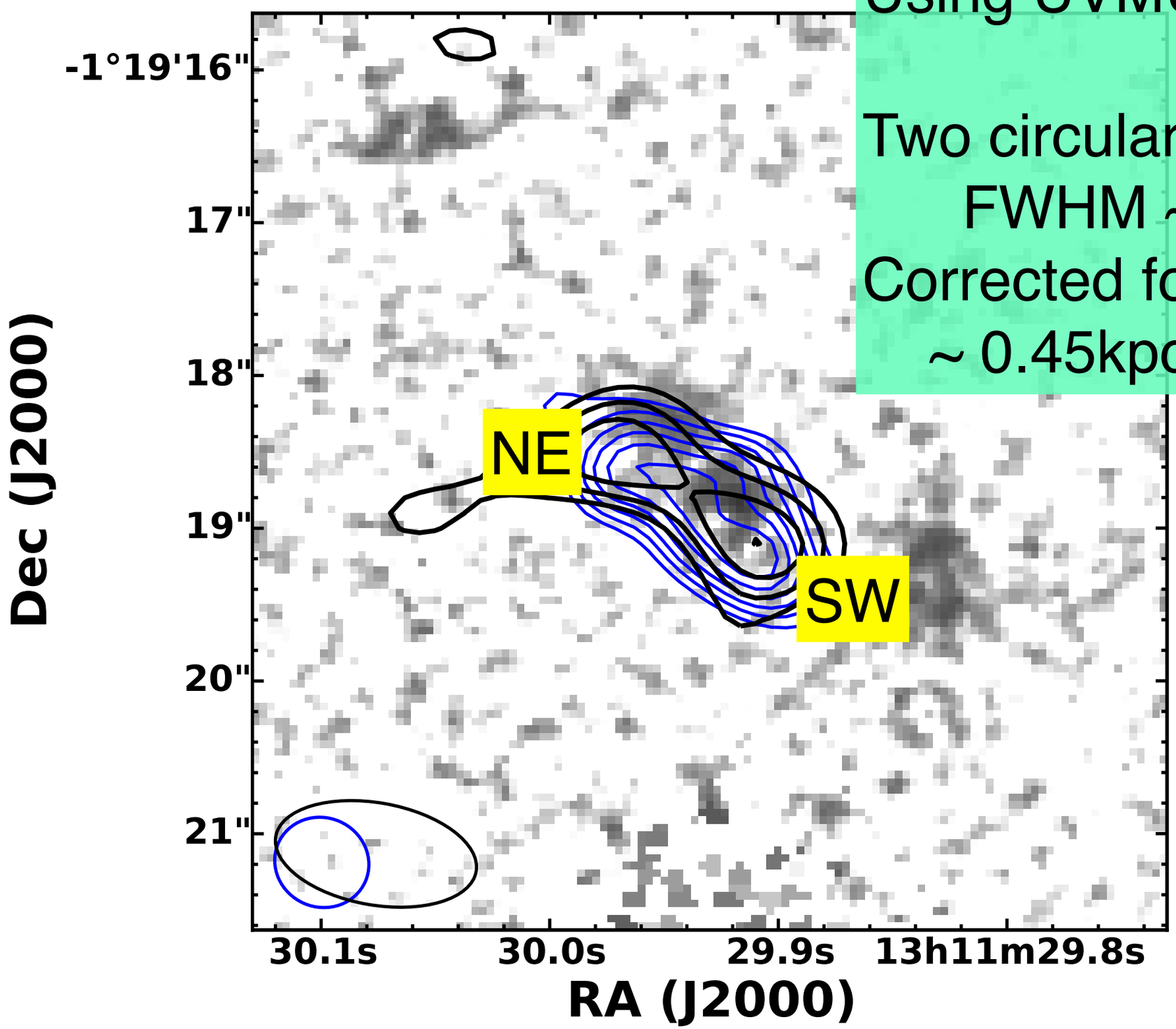
Watson, Christensen, Knudsen *et al.* 2015, Nature

More ALMA data: structure - merger or proto-disc?



Knudsen, et al, 2017

More ALMA data: structure - merger or proto-disc?

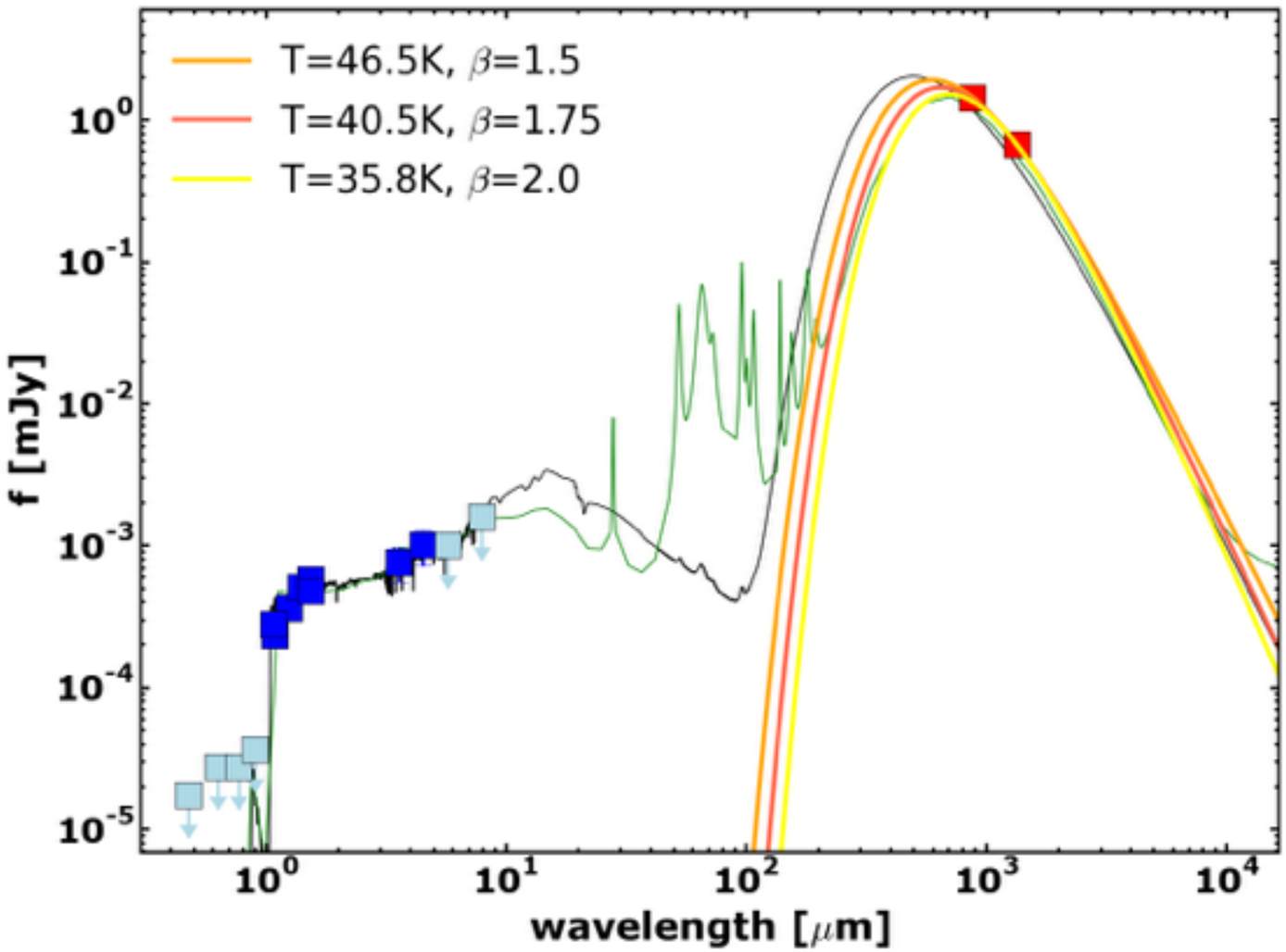


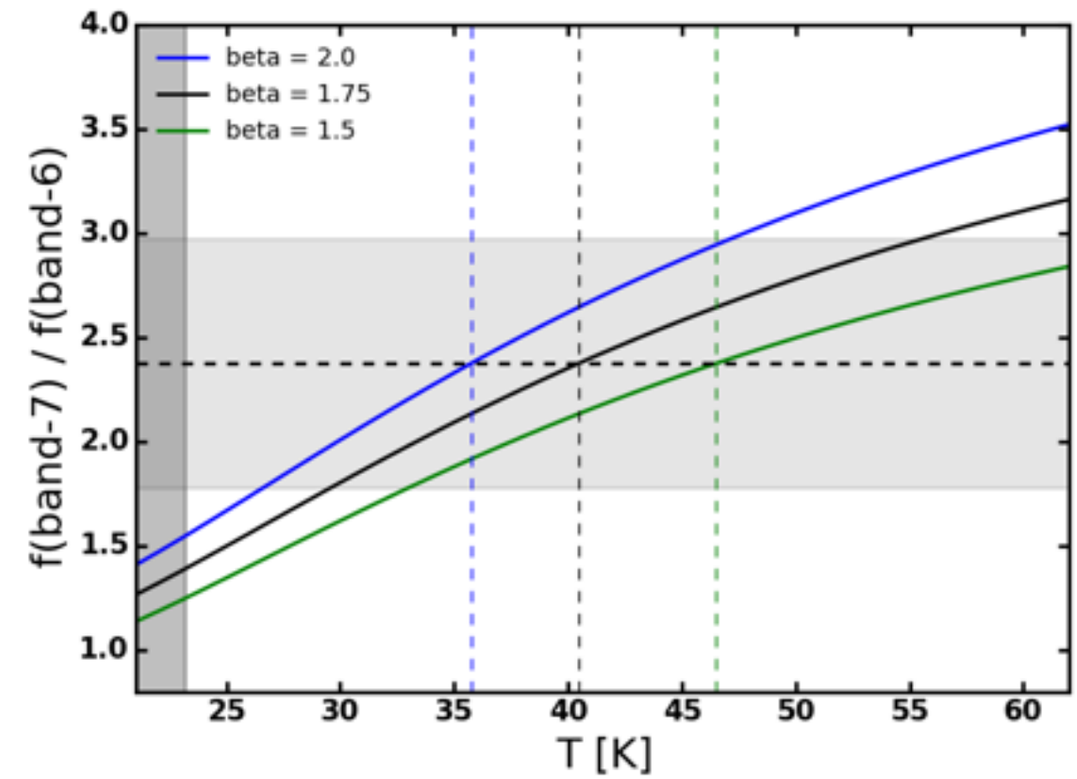
Using UVMULTIFIT:

Two circular Gaussians
FWHM ~ 0.5"-0.6"
Corrected for lensing:
~ 0.45kpc x 1.9kpc

Knudsen, et al, 2017

A1689-zD1: SED





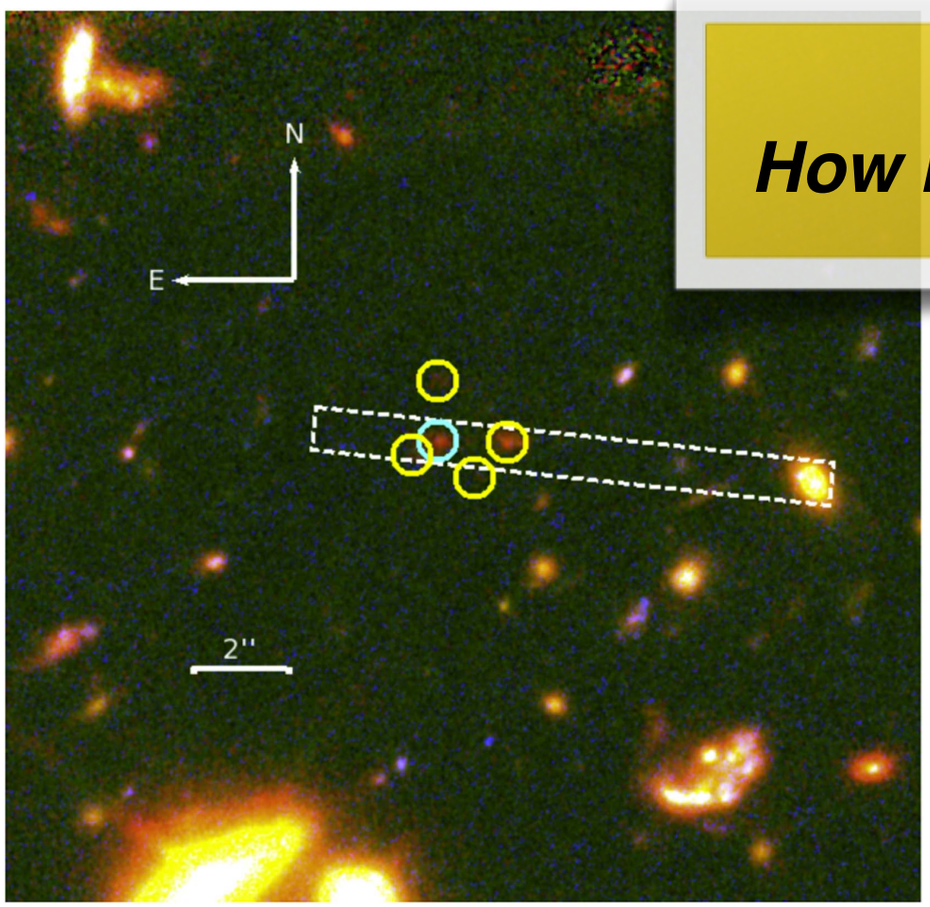
CMB effects: T~40K, beta=1.75:
Band 7: 8% , Band 6: 17%

$L_{FIR} \sim 1.8 \times 10^{11}\ L_o$
SFR(total) ~ 13 M_o/yr
$\log(M_{stellar}/M_o) \sim 9.3$ (+/– 0.13)
$\log(M_{dust}/M_o) \sim 7.2$-$7.6$

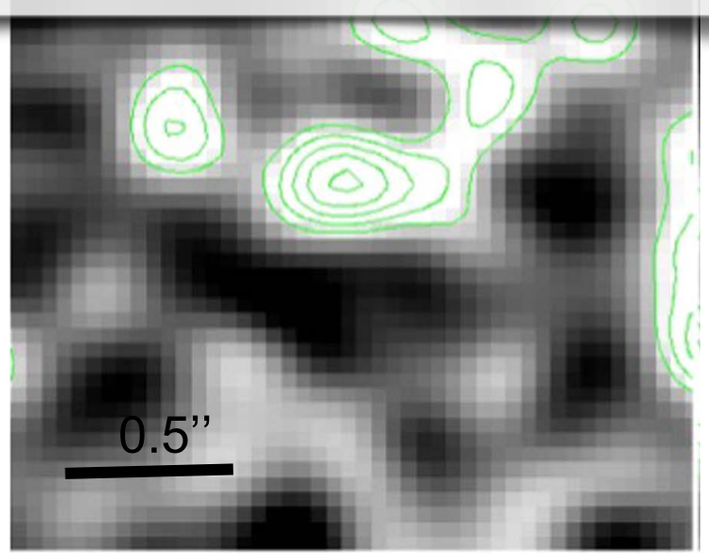
Knudsen et al, 2017

A2744_YD4: pushing to even higher redshift

z = 8.38



How many more of such systems??



SFR(total) ~ 20 M_o/yr

$M_{stellar}$ ~ $2x10^9$ M_o

M_{dust} ~ $6x10^6$ M_o

Laporte et al. 2017

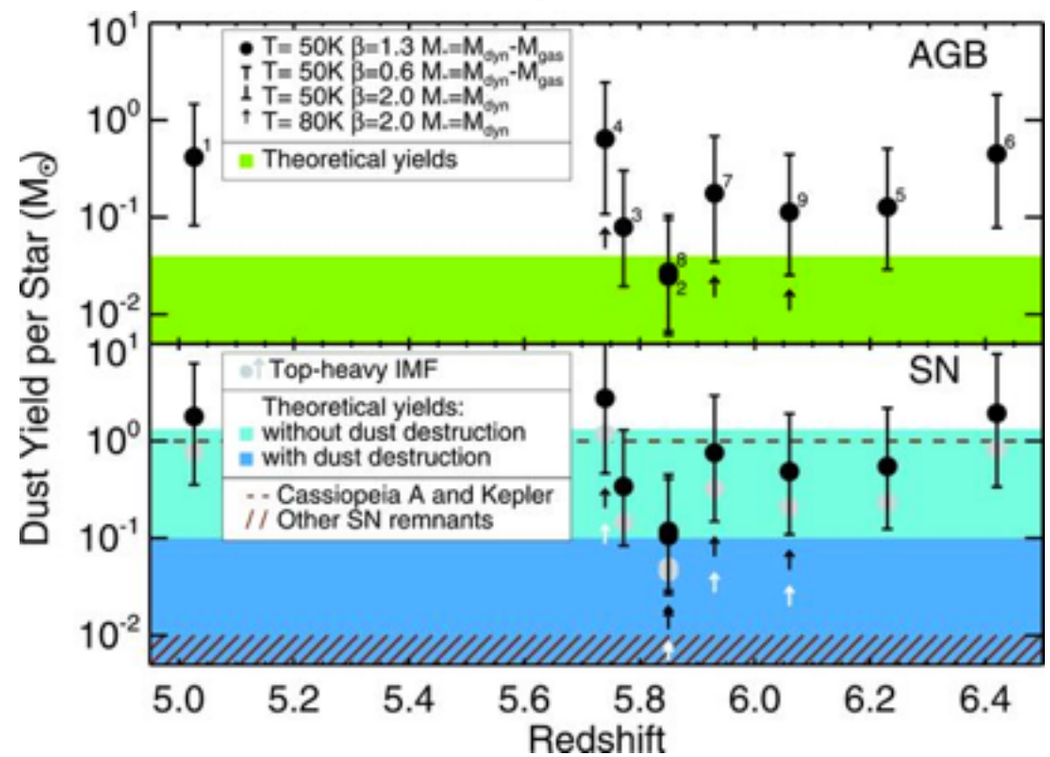
Questions: the dust masses and interstellar medium properties of galaxies during the first one billion years

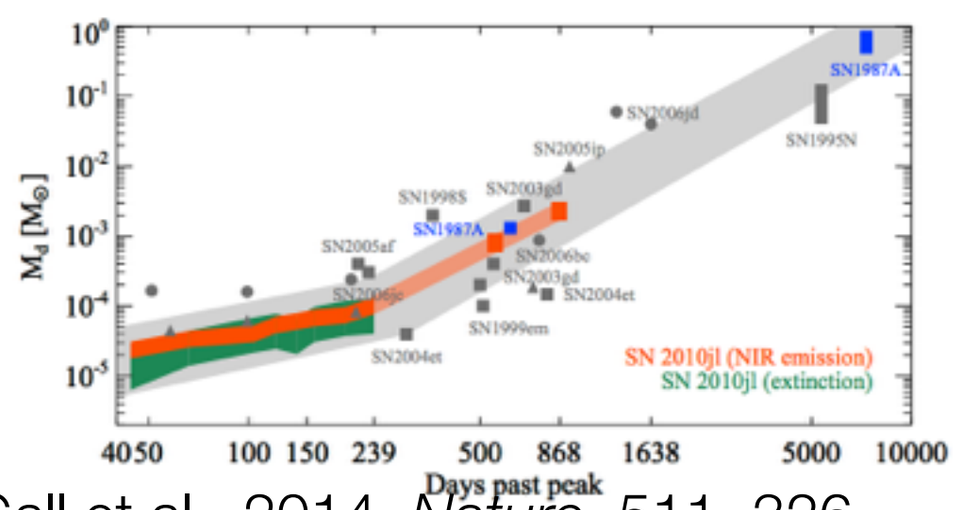
- The dust grain growth:
  - Where does all the dust come from on such a relatively short time scale?
  - Grain growth in the ISM vs return from massive stars?
- How is the star formation affected by the conditions at this early epochs?
  - Do the conditions of the ISM and the (neutral) IGM play a role?
  - Early phases of galaxy evollution.
- Are the ISM properties different?
  - Massive, bright-end galaxies do not appear to be very different in line properties. What about the less extreme galaxies?

Implications for high-*z* dust formation

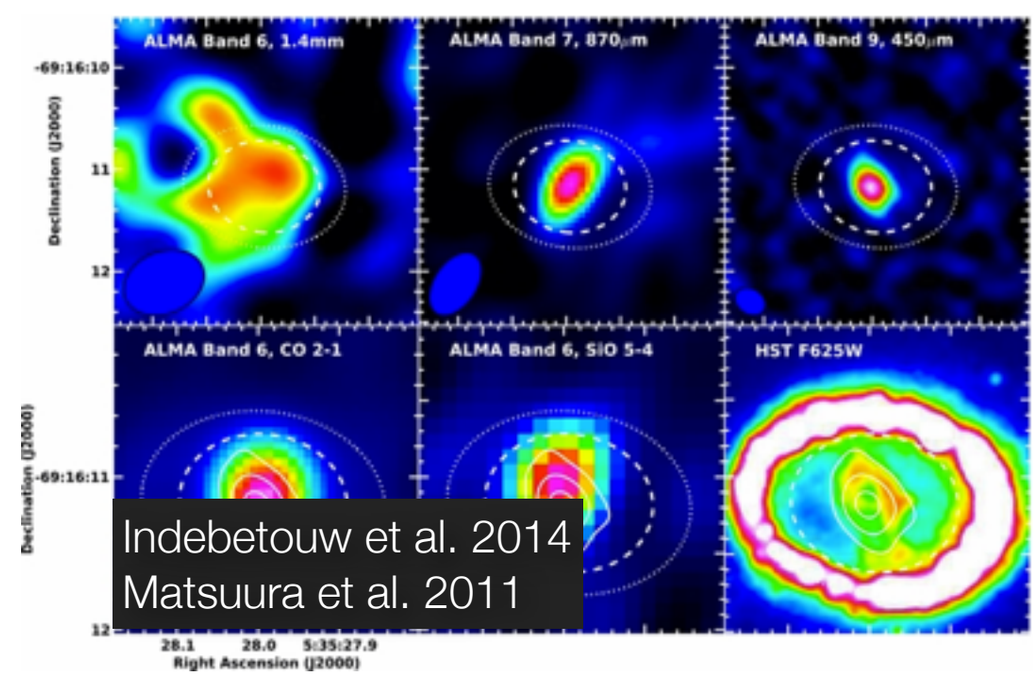
- Where does dust form? – AGB stars, SNe, ISM grain growth
- Earliest direct hard limit on dust formation timescale: <~500Myr from beginning of SF in the universe. Dust formation must be fast
- Already have a good idea that dust formation is quick => AGB stars cannot dominate SF at these redshifts (or any redshift?)
- CCSNe produce the metals that form the dust: should be a maximum dust-to-stellar mass ratio.

e.g. Michalowski et al. 2010





Gall et al., 2014, *Nature*, 511, 326



Indebetouw et al. 2014
Matsuura et al. 2011

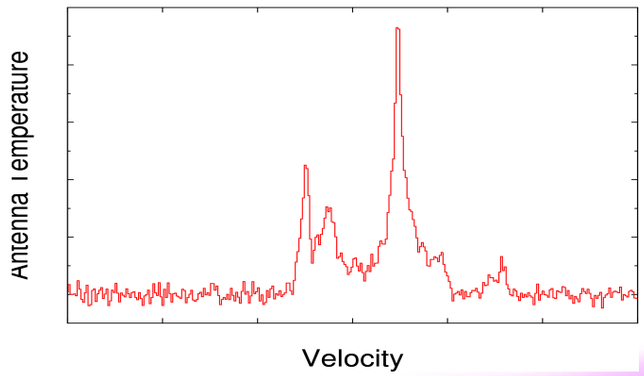
Table 1. Characteristics of the PACS FIR fine-structure cooling lines.

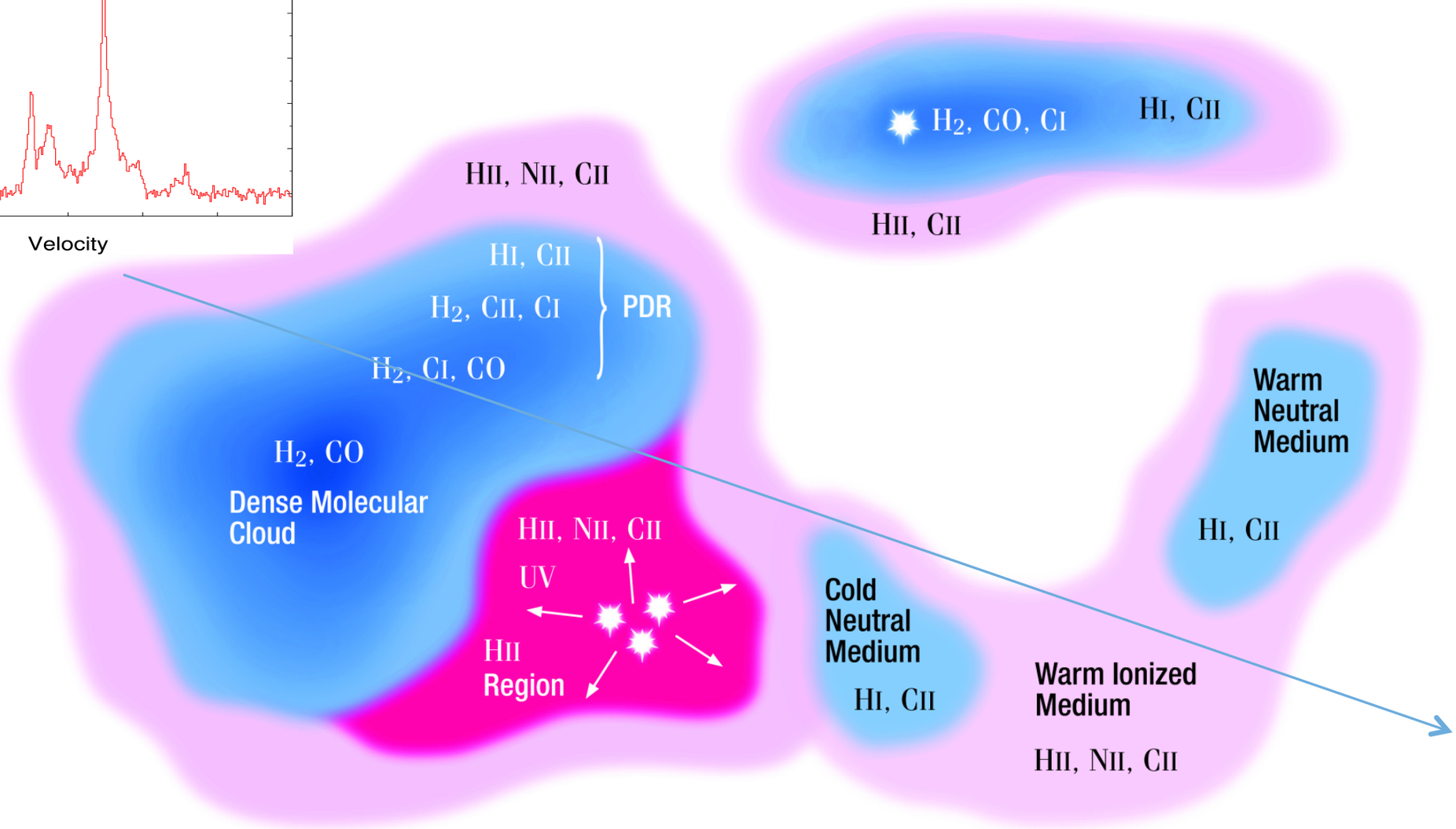
Species	λ [μm]	Transition	IP [eV]	$\Delta E/k^a$ [K]	$n_{\rm crit}$ [cm^{-3}]
[C II]	157.7	$^2P_{3/2}$–$^2P_{1/2}$	11.3	91	50^b , 2.8×10^3
[N II]	121.9	$^3P_2$–$^3P_1$	14.5	188	310
[N II]	205.2	$^3P_1$–$^3P_0$	14.5	70	48
[N III]	57.3	$^3P_{3/2}$–$^3P_{1/2}$	29.6	251	3.0×10^3
[O I]	63.2	$^3P_1$–$^3P_2$	–	228	4.7×10^5
[O I]	145.5	$^3P_0$–$^3P_1$	–	327	9.5×10^4
[O III]	88.4	$^3P_1$–$^3P_0$	35.1	163	510

Notes. Values taken from Madden et al. (2013). The IP for [O II] is 13.62 eV. $^{(a)}$ Excitation temperature $\Delta E/k$ required to populate the transition level from the ground state. $^{(b)}$ Critical density for collisions with electrons.

From Cormier et al. 2015

[CII] traces the different phases of the ISM





[CII] can be excited by collisions with:

- Electrons.
- Atomic Hydrogen.
- Molecular Hydrogen (dense or diffuse).

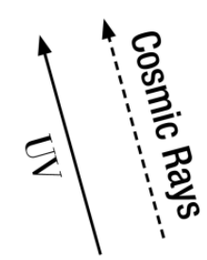
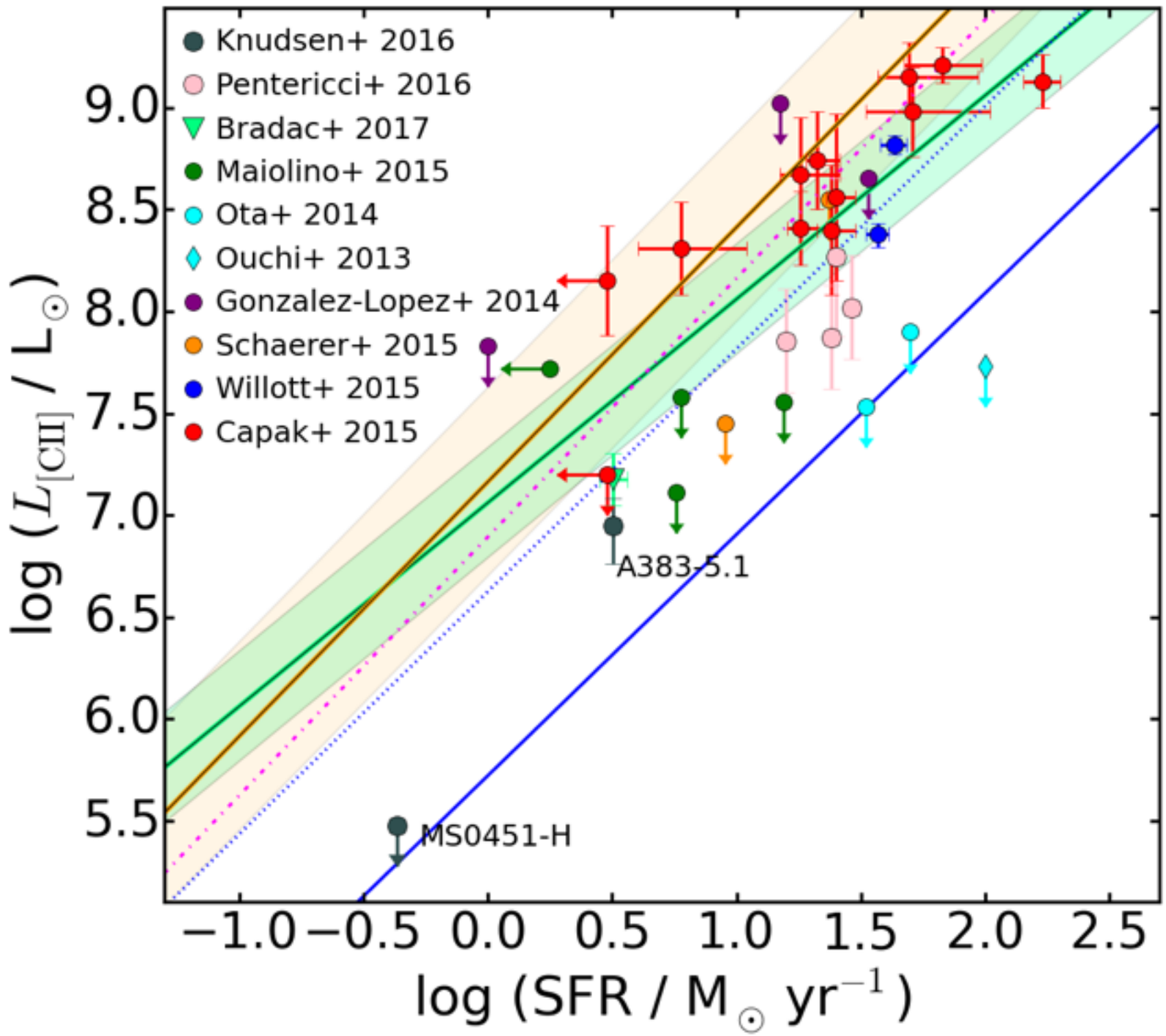
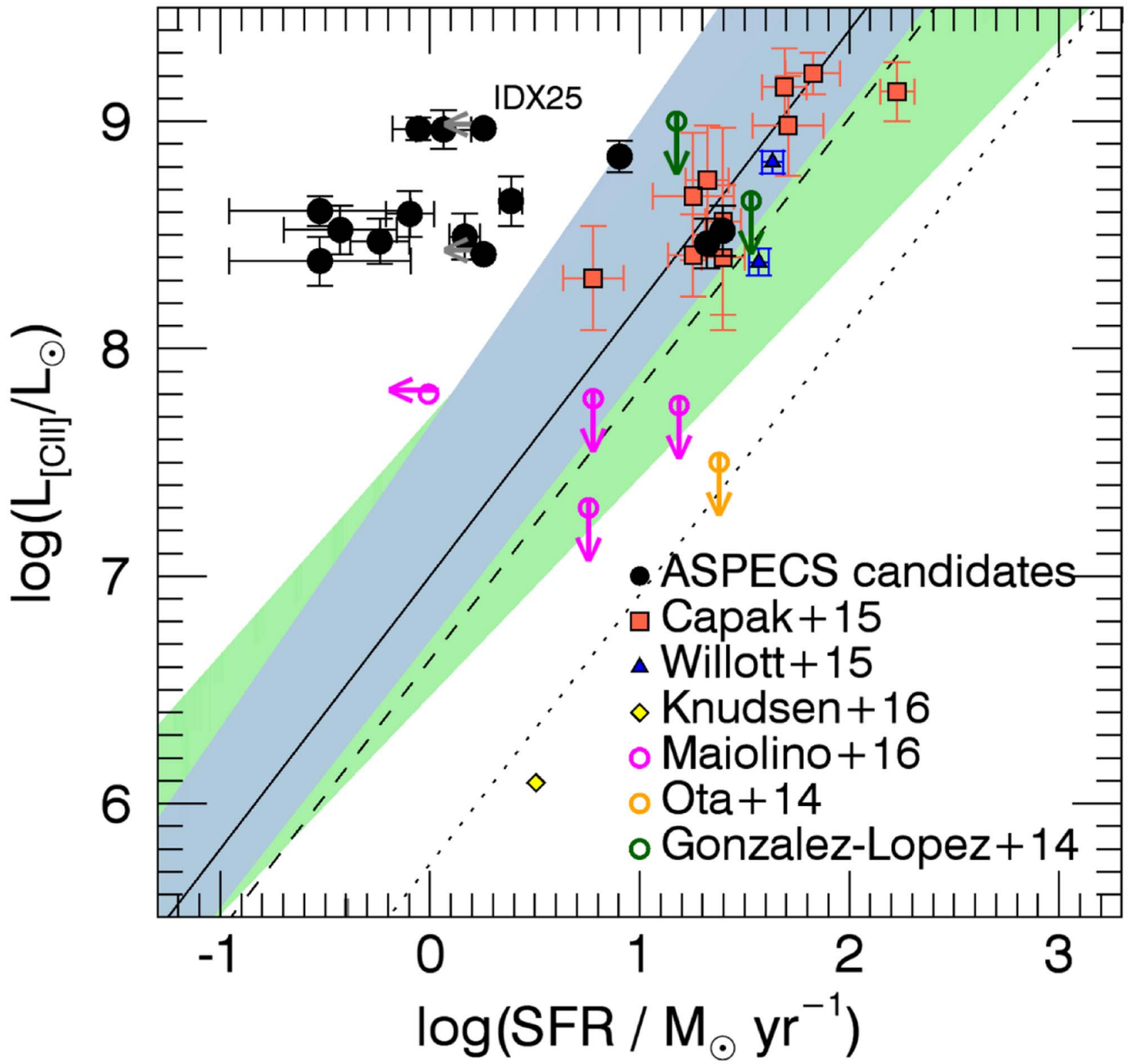


Illustration from: Pineda et al.



updated from **Knudsen, Richard, Kneib et al. 2016a, MNRAS**

From “blind" searches (ASPECS):



Aravena et al. 2016

Why is it sometimes difficult to see C^+ at $z > 6$?

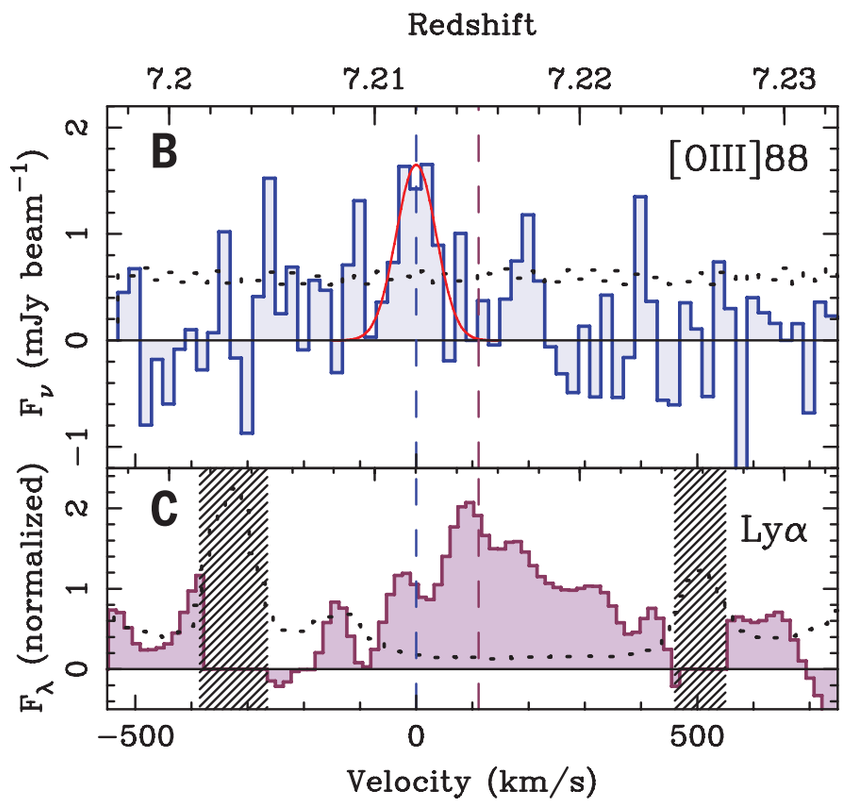
- Metallicity?
  - If low, $L_{[CII]}$ decreases, but not dramatically compared to e.g. CO
- Density?
  - $n > n_{crit}$ - collisional de-excitation
  - C bound in CO
- Temperature?
  - Other tracers, which are more luminous?
- SFR, $M_{stellar}$, etc estimates?
  - Maybe the uncertainties are larger than expected, the stellar populations are different during the first few 10^8 yrs
  - If using Ly-alpha, then maybe excitation is due to shocks and infalling gas in DM halos.
- Radiation field?
  - A harder radiation field (increase (far-)UV emission) would C^+ -> C^{++}

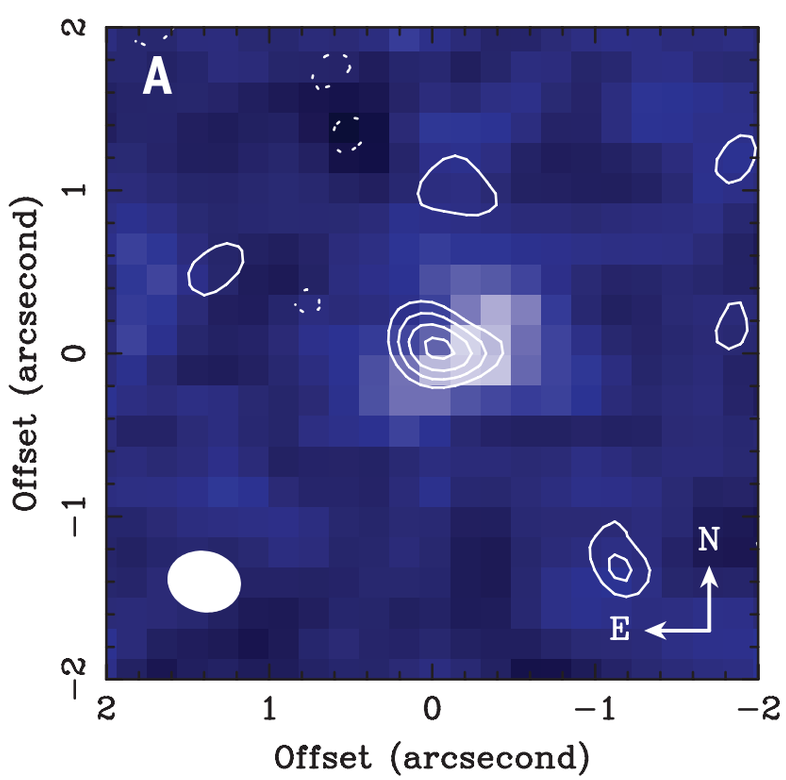
Why is it sometimes difficult to see C^+ at $z > 6$?

- Selection biases?
  - Ly-alpha emitters vs Lyman-alpha break galaxies? Dust selected? Mass selected?

- Other lines? Better tracers?
  - What do we know from local galaxies?
- [NII]?
  - Tracing ionized gas only - but weaker
- [OI], [OII], [OIII]?
  - [OI] and [OII] likely weaker, however, [OIII] could have comparable strength depending on the gas conditions.
  - [OIII] 88μm, observable with ALMA band 8-10.

[OIII] 88μm at z = 7.2 - ALMA results





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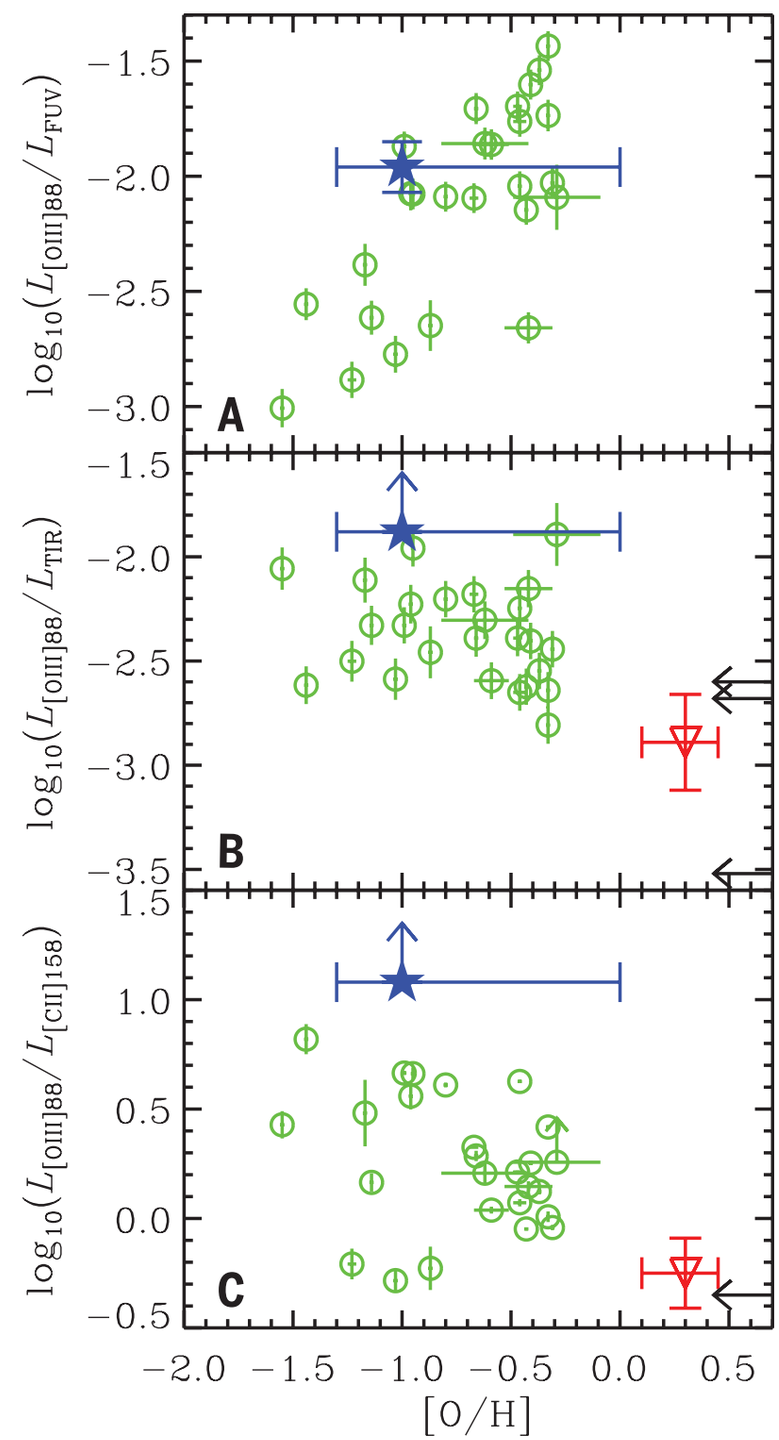


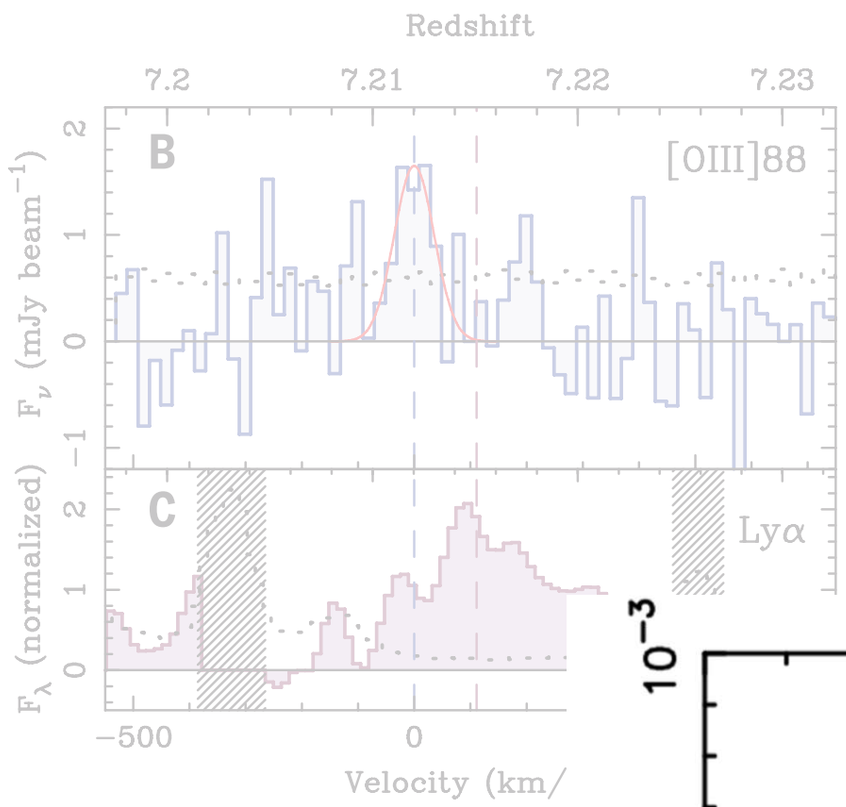
[OIII] / F_{FUV}

[OIII] / L_{IR}

[OIII] / [CII]

Inoue et al. 2016, Science

[OIII] 88μm at z = 7.2 - ALMA results



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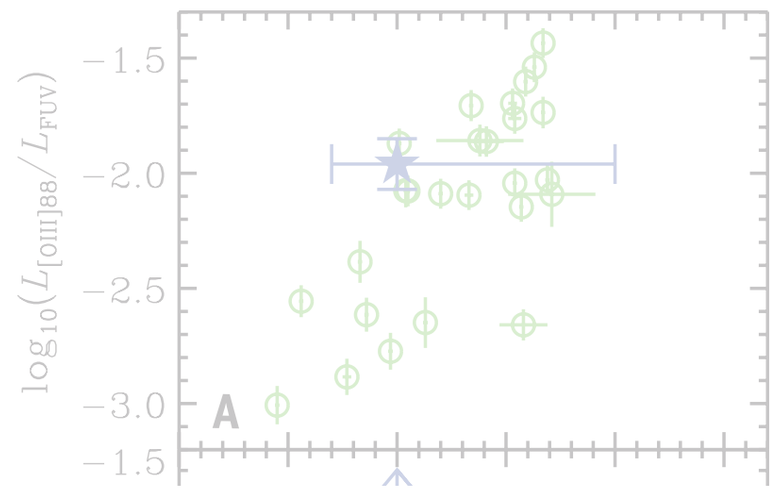
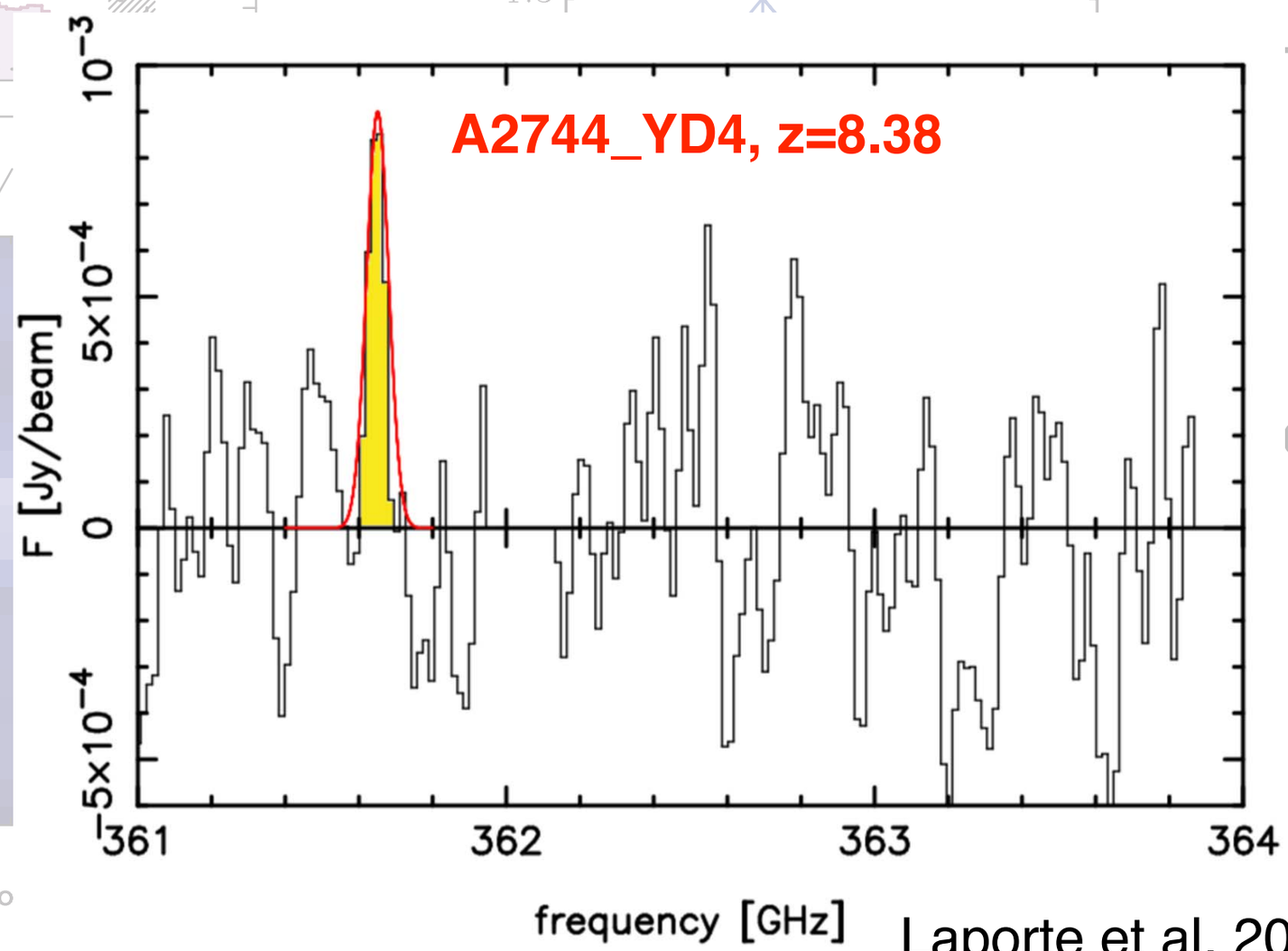


[OIII] / F_{FUV}

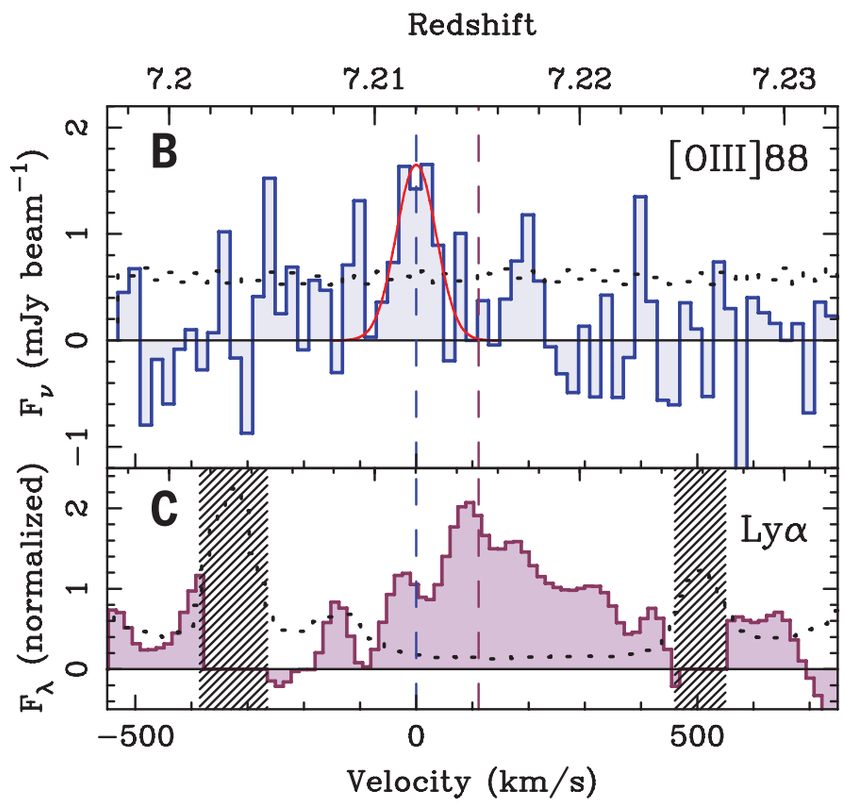
-IR

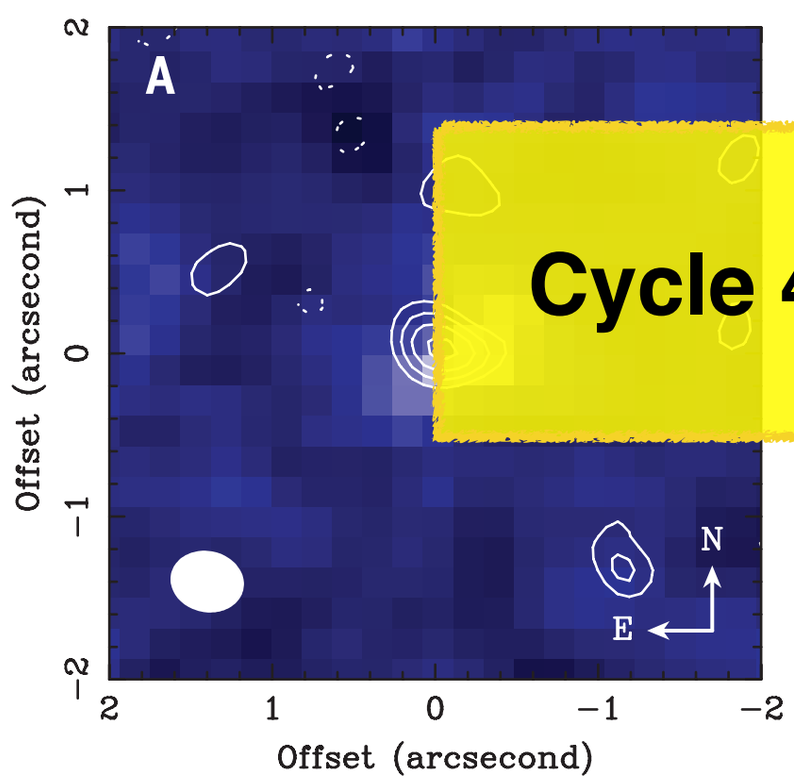


CII]

Laporte et al. 2017

[OIII] 88μm at z = 7.2 - ALMA results





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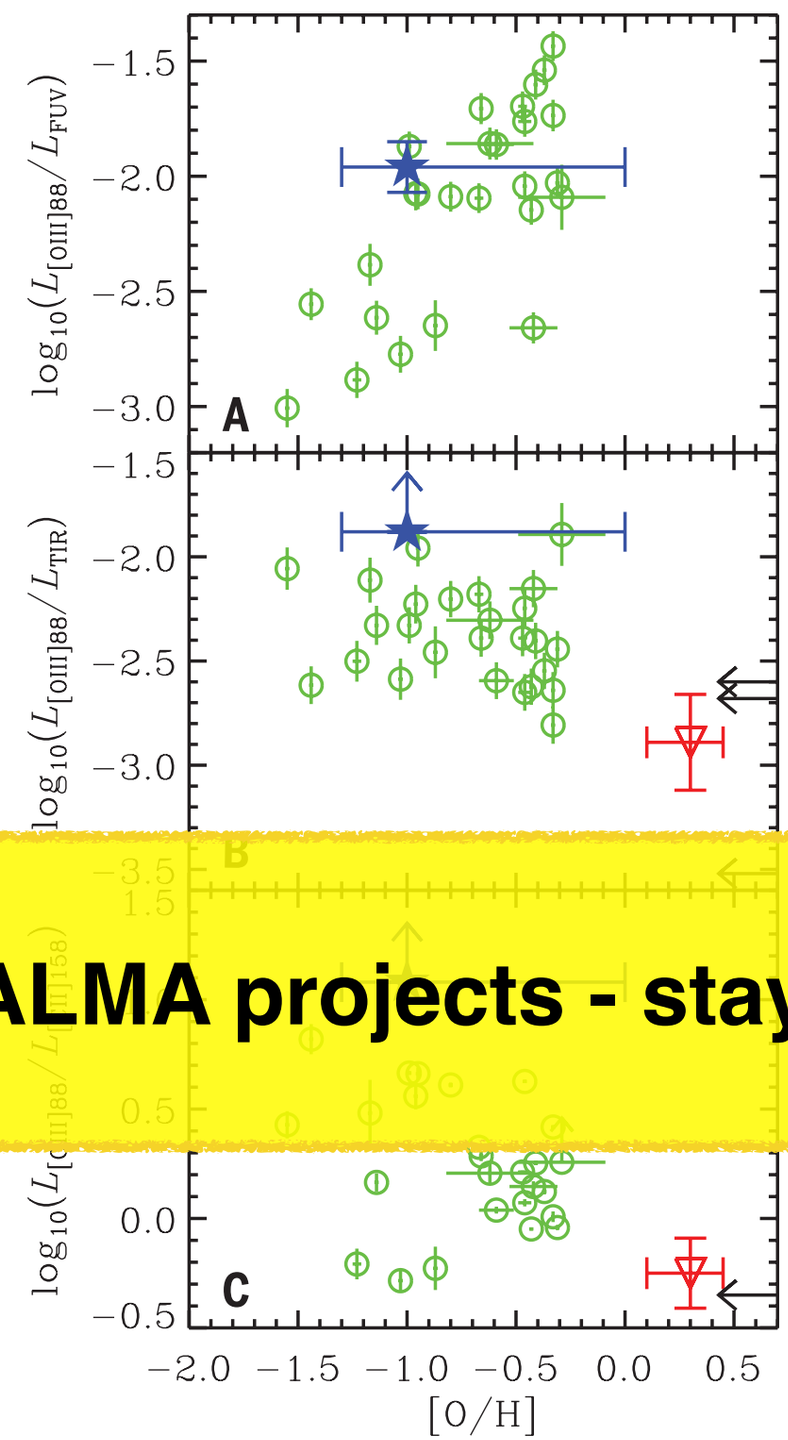


[OIII] / F_{FUV}

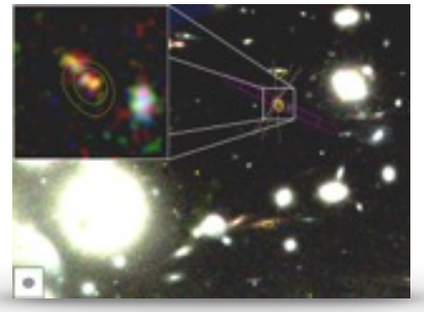
[OIII] / L_{IR}

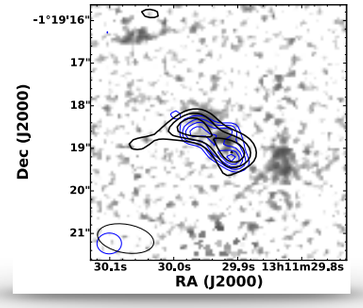
[OIII] / [CII]

Cycle 4-5 ALMA projects - stay tuned

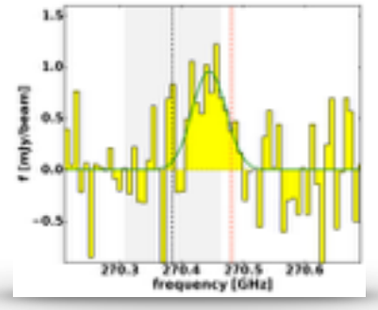
Inoue et al. 2016, Science

Summary....

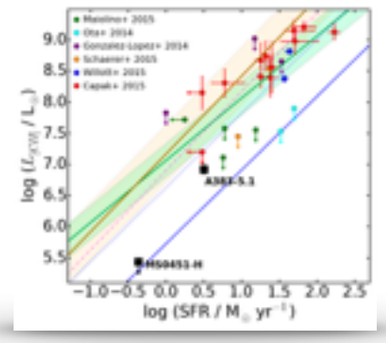




- ★ Finding extended dust emission at redshift $z > 7$
- ★ Detections of [CII] at z > 6, but also a large number of non-detections
- ★ Using lensing to push the sensitivity.



- ★ What does this mean of design of future (cluster/ lensed/blank field) z>6 surveys with ALMA?



- ★ [CII] vs other tracers: [OIII] ?