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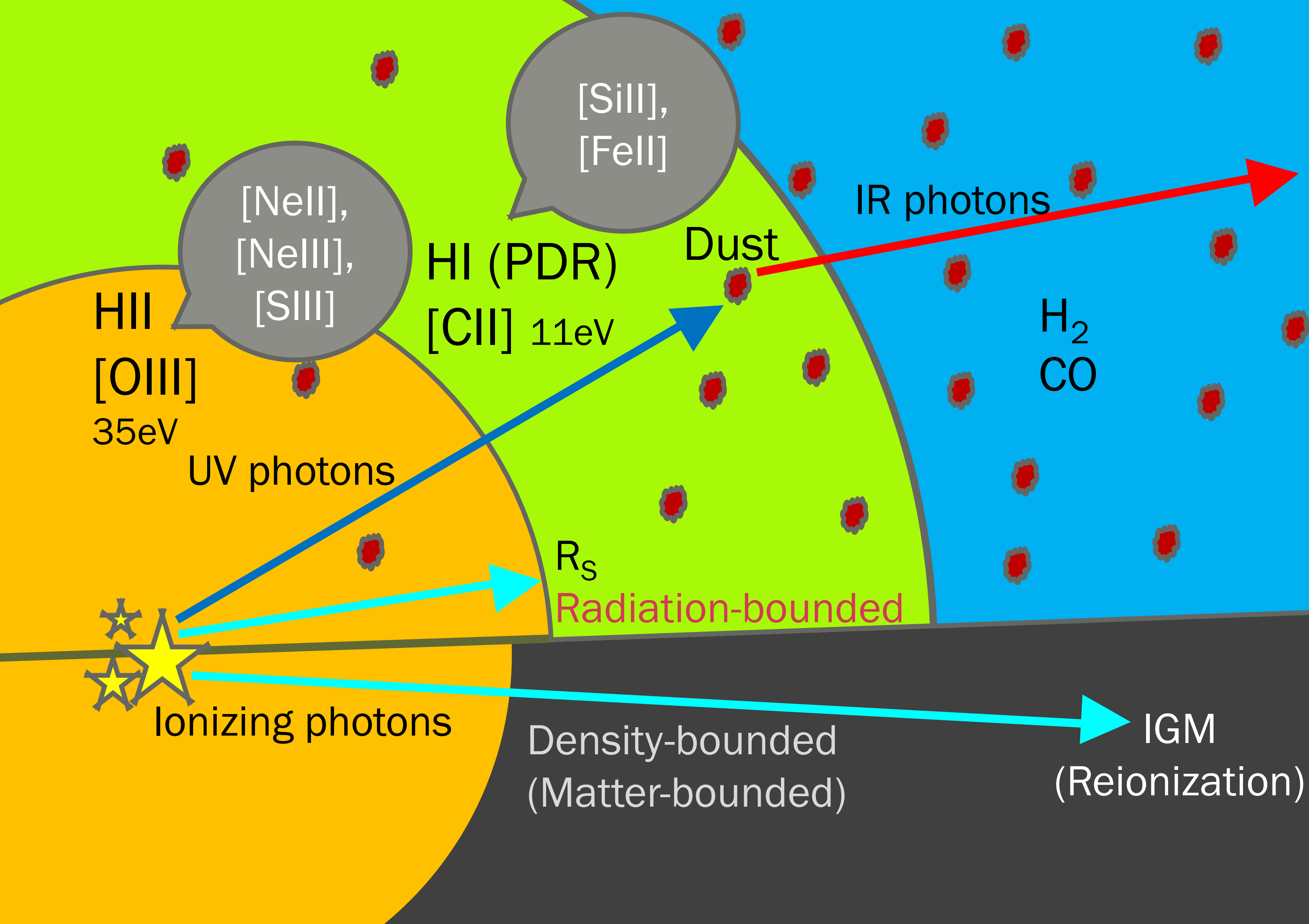
FIR FINE-STRUCTURE LINES AND DUST AT HIGH-Z: ALMA TO SPICA

Contents

- ALMA observations in the reionization era
  - *FIR fine structure lines*
  - *Dust*
- SPICA


[SiII],
[FeII]
[NeII],
[NeIII],
[SIII]
HI (PDR)
[CII] 11eV
Dust
IR photons
HII
[OIII]
35eV
UV photons
H_2
CO
R_S
Radiation-bounded
Ionizing photons
Density-bounded
(Matter-bounded)
IGM
(Reionization)

ALMA observations at z>7

	Object	Redshift	Features	References
1	M*****	*.*****	[OIII]88, No dust	Hashimoto+18a
2	A2744_YD4	8.382	[OIII]88 off, Dust	Laporte+17
3	M*****	8.*****	[OIII]88, Dust	Tamura+18
4	ID27	7.575	[CII]158 off, Dust	Aravena+16
-	Z8-GND-5296	7.508	No [CII]158, No dust	Schaerer+15
5	ID31	7.494	[CII]158 off, Dust	Aravena+16
6	IDX34	7.491 ?	[CII]158 ?, No dust ?	Aravena+16
7	SXDF-NB1006-2	7.2120	[OIII]88, No [CII]158, No dust	Inoue+16
8	B14-65666	7.1518	[OIII]88, [CII]158, Dust	Hashimoto+18b
9	COSMOS13679	7.1416	[CII]158, No dust	Pentericci+16
10	******	7.*****	[CII]158, Dust	*****+
11	BDF-3299 III ?	7.108 ?	[OIII]88 ?, No dust ?	Carniani+17
12	BDF-3299 II ?	7.106 ?	[OIII]88 ?, No dust ?	Carniani+17
13	BDF-3299 I	7.097	[OIII]88 off, [CII]158 off, No dust	Carniani+17
-	BDF-521	7.008	No [CII]158, No dust	Maiolino+15

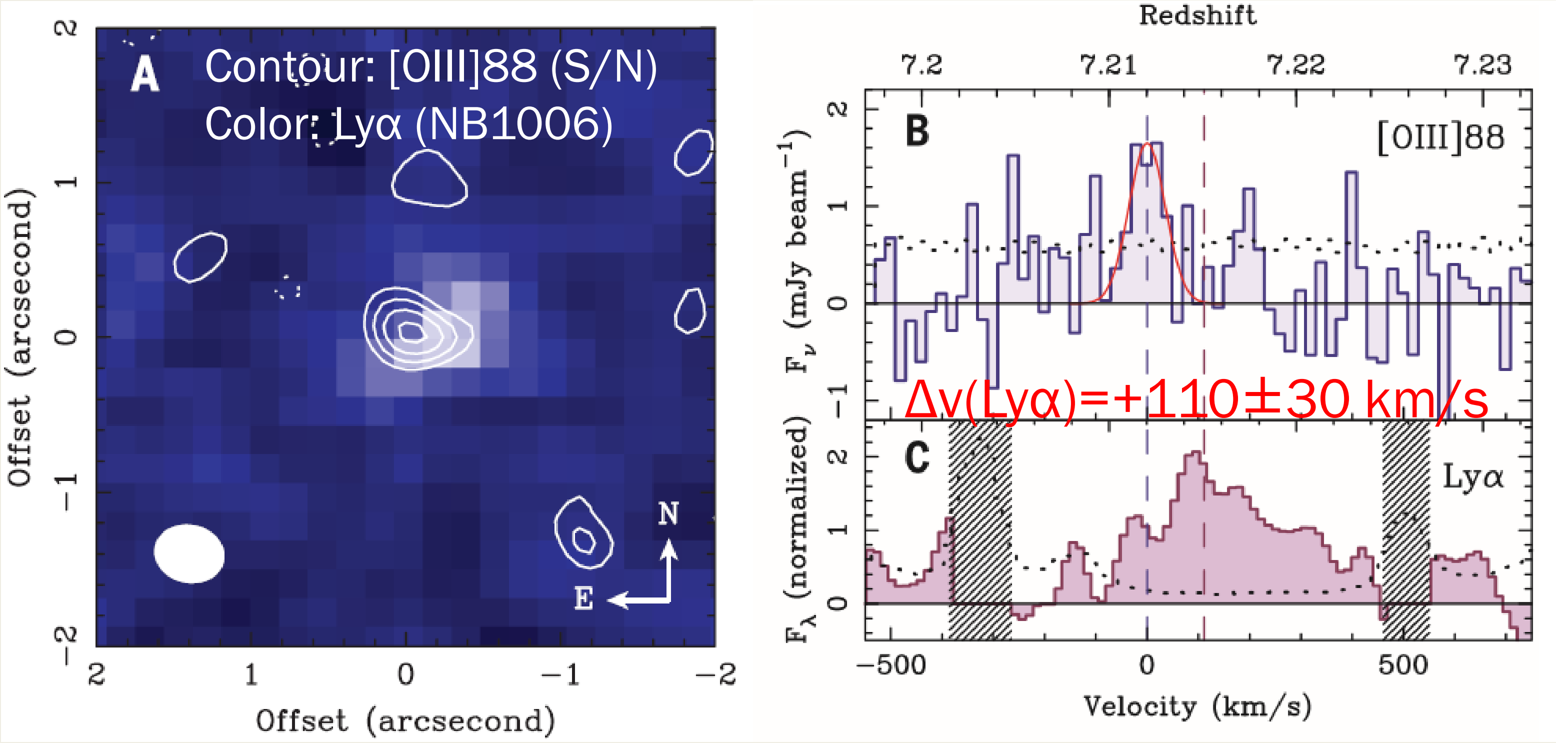
Implication from ALMA

- The [OIII]88 line is always (6 out of 6!) detected but the [CII]158 line is not always.
  - *Lines from HII regions are simply correlated with UV (i.e. SFR).*
  - *Lines from PDRs are not simply but anti-correlated with Lyα.*
- Lines sometimes show spatial offsets.
  - *Spectral mapping (or IFU) is essentially important.*
- Dust shows a huge diversity.
  - *ISM growth/destruction processes.*

SXDF-NB1006-2

Inoue+16, Science

- [OIII] 88 μm line was detected (5.3σ).
  - *z([OIII])=7.2120 The most distant oxygen ever found! (in 2016)*



SXDF-NB1006-2

Inoue+16, Science

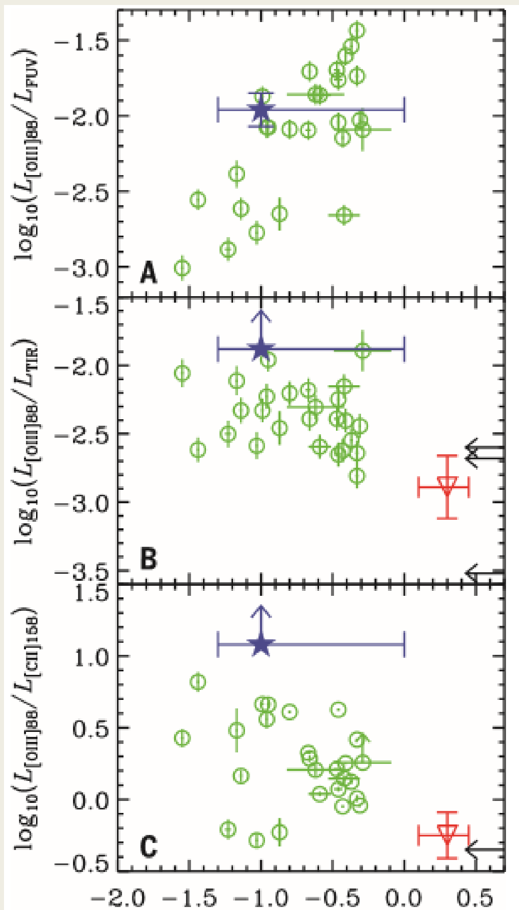
- No [CII] 158 μm at the [OIII] position.
- No dust continuum in the two bands.

Logarithmic values

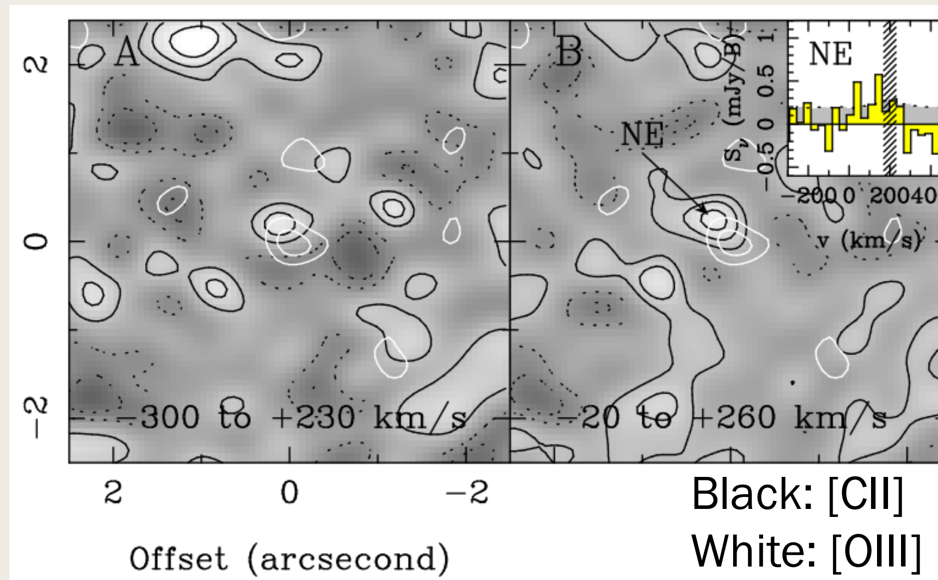
[OIII]/UV

[OIII]/IR

[OIII]/[CII]



[O/H]



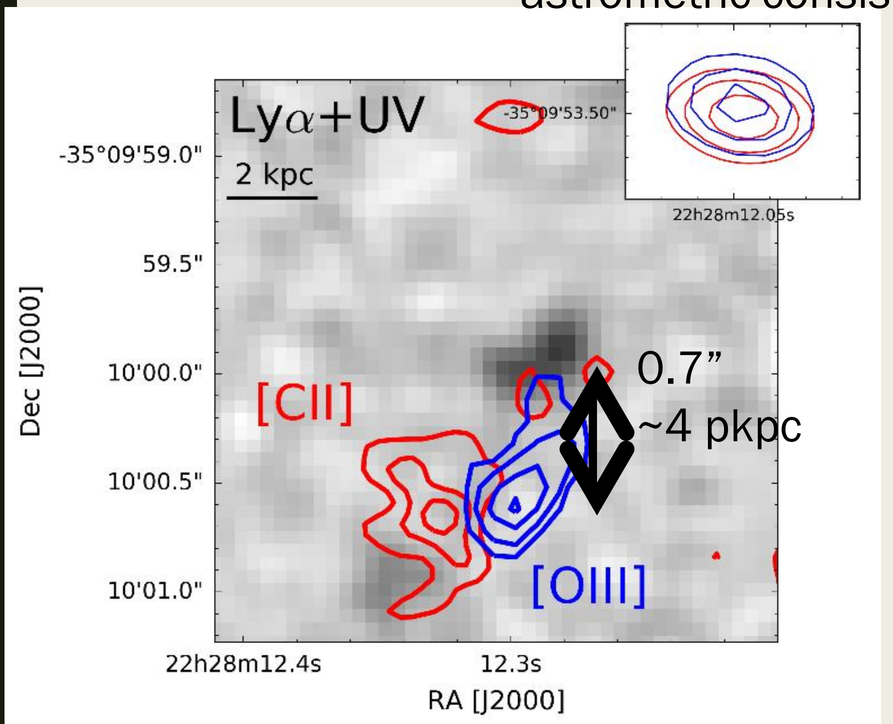
Black: [CII]
White: [OIII]

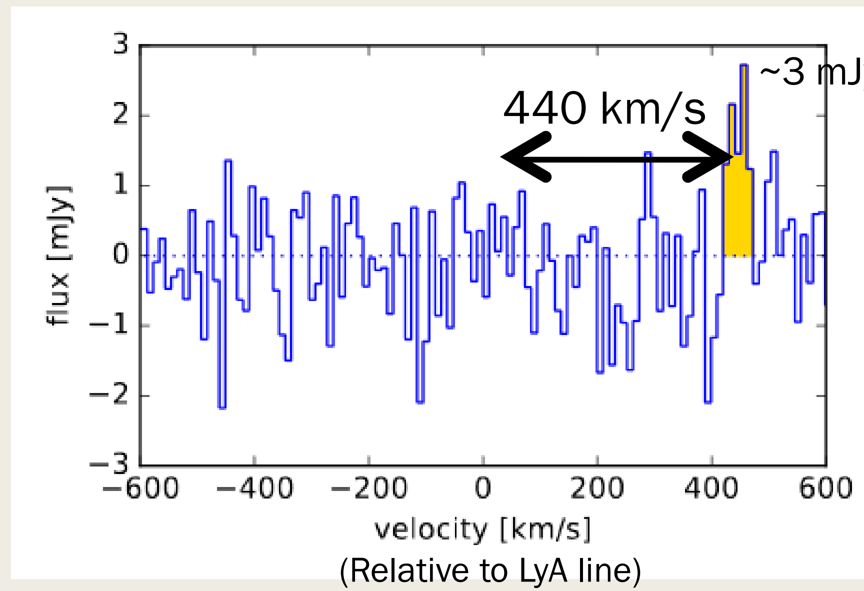
BDF-3299

Carniani+17/Maiolino+15

- Spatially offset [OIII]88 and [CII]158 lines

ALMA Bands 6 and 8
astrometric consistency

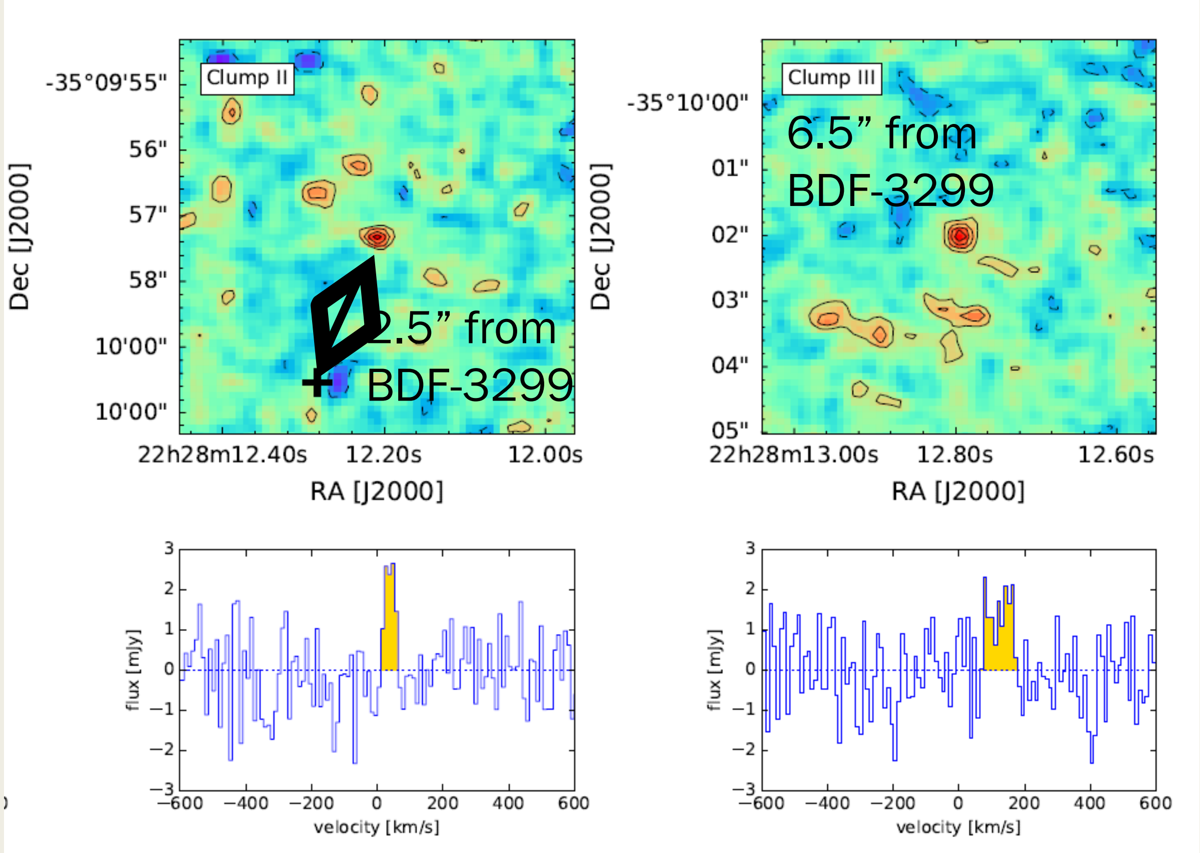




BDF-3299

Carniani+16

- [OIII]88 lines w/o continuum counterparts?
  - *This galaxy is in an overdensity.* (Castellano+16)

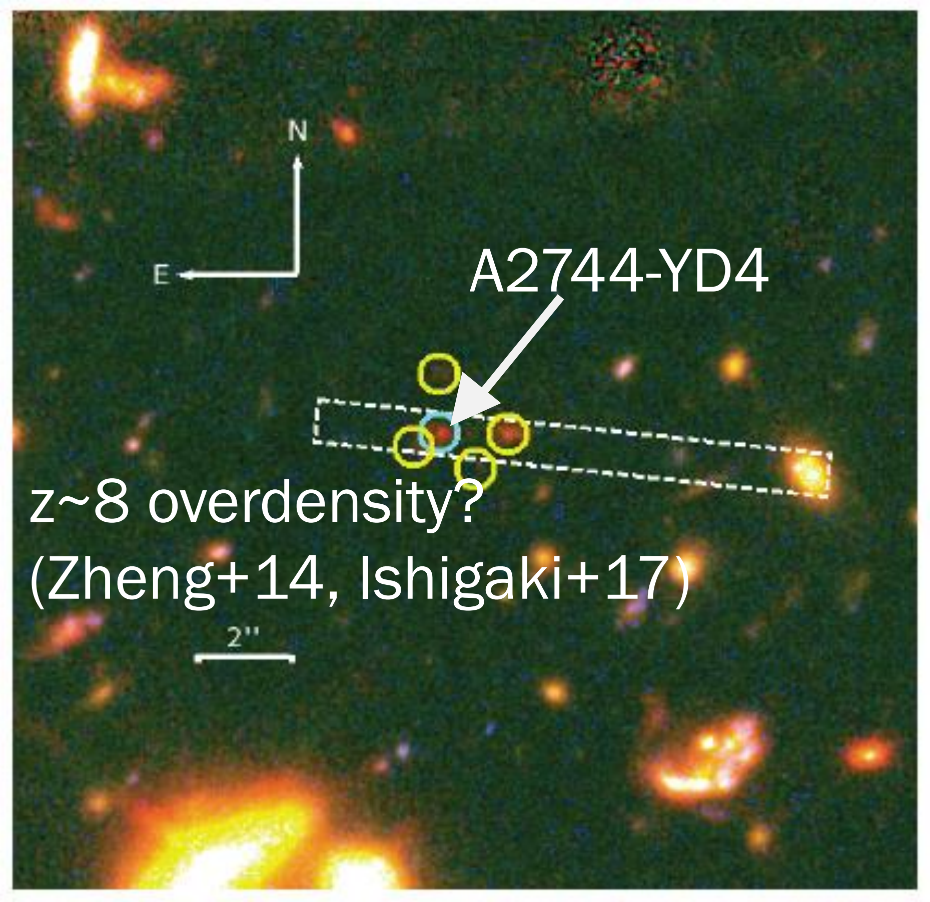


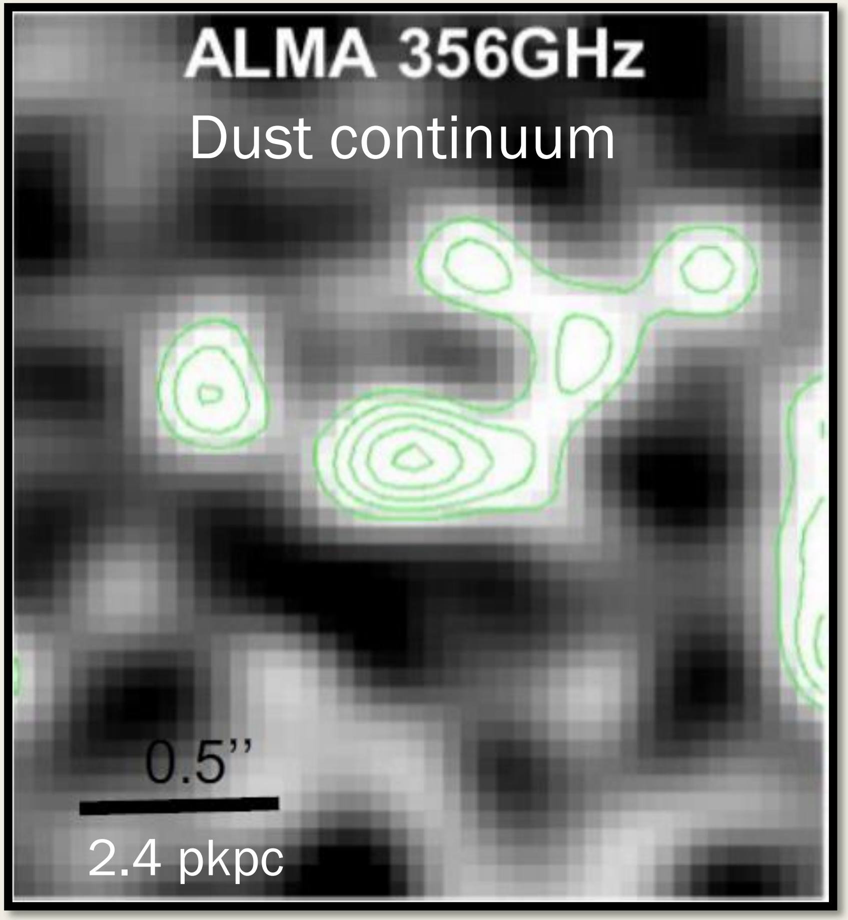
1"~5 pkpc

A2744_YD4

Laporte+17

- Redshift z=8.38: [OIII], Lyα, & dust





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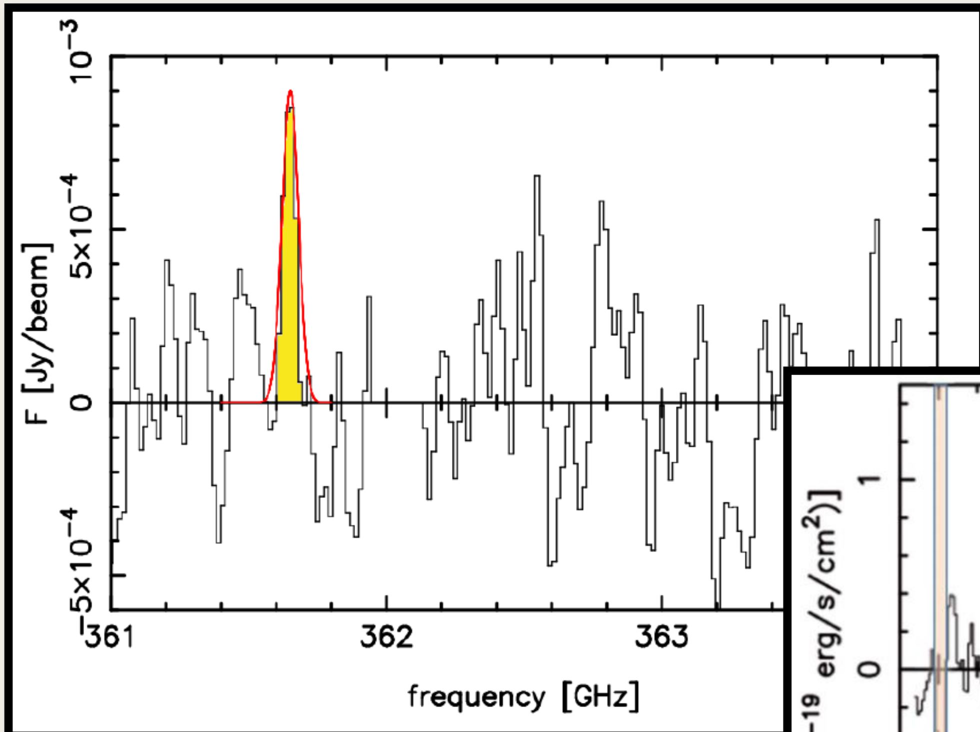
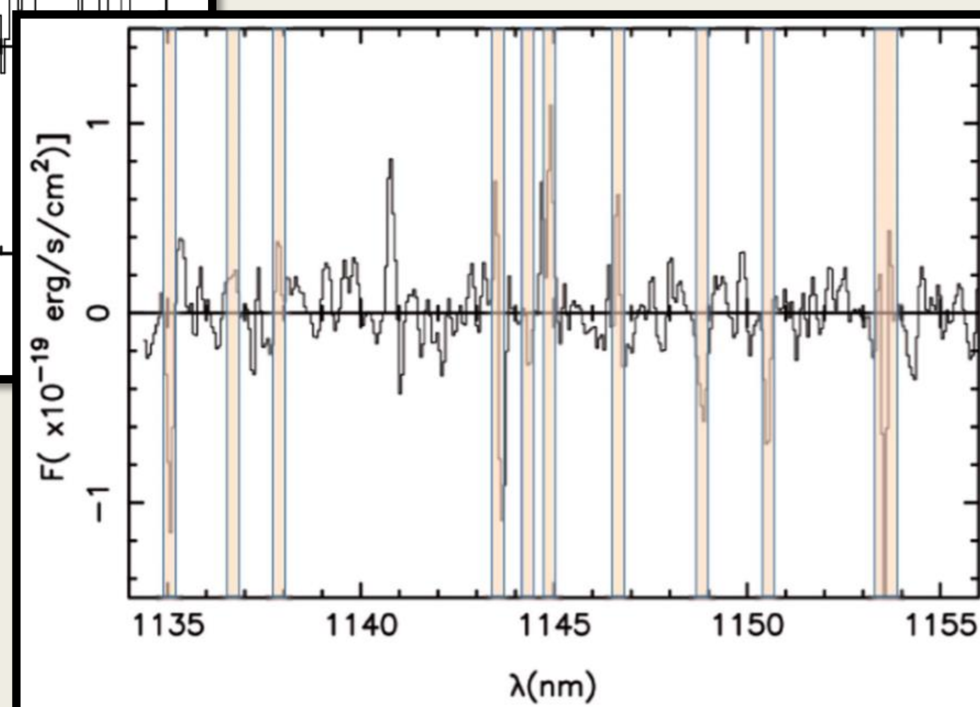


[OIII]88 line at z=8.382 (4σ)
FWHM~50 km/s

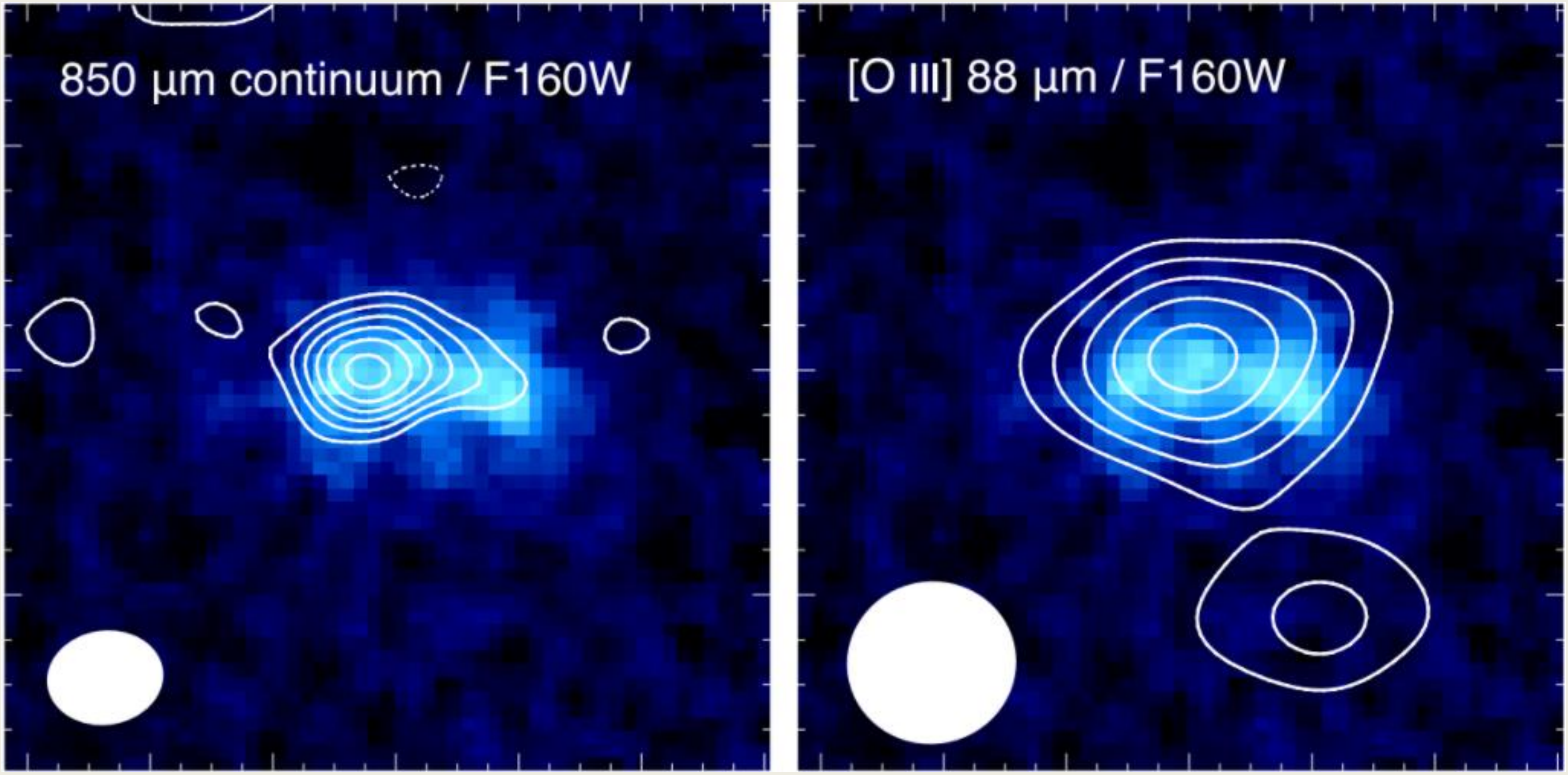


Lyα line at z=8.384 (4σ)
FWHM~20 km/s
Δv(Lyα)~+70 km/s

M*****

Tamura+18

- Another z>8 [OIII]88 and dust!



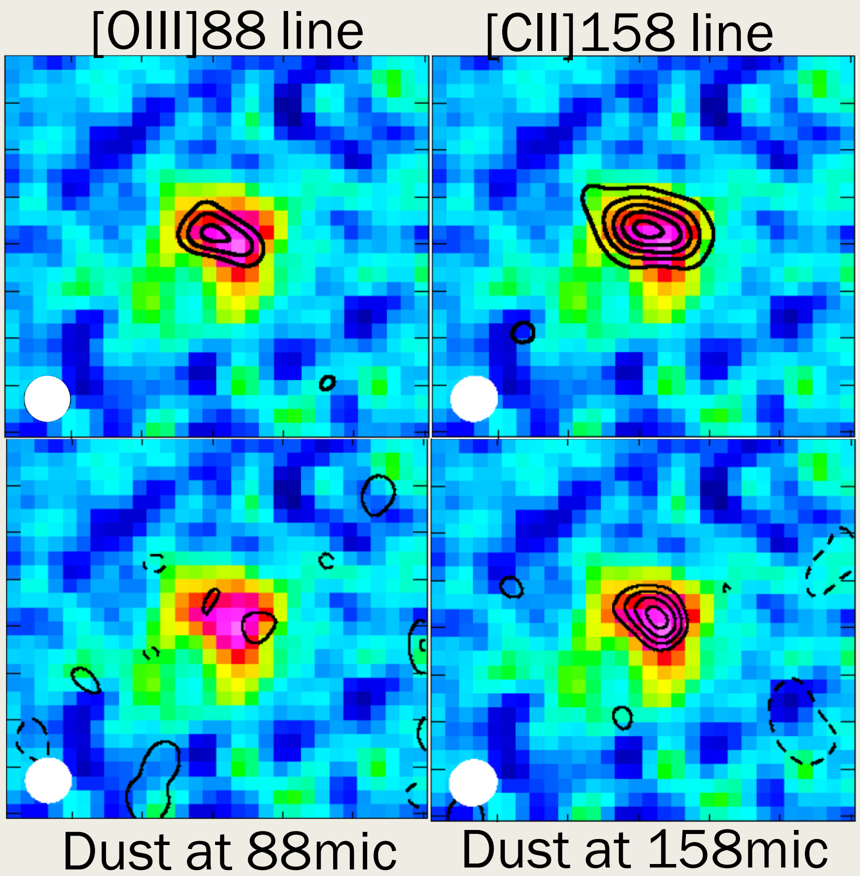
Contour: +2, +3, …, +7σ

B14-65666

Hashimoto+18b

- The first complete set of [OIII], [CII] & dust!
  - *z(Lyα)=7.1702*
  - *z[OIII]=7.1517*
  - *z[CII]=7.1518*
  - *Dust (Band6)*

[OIII]/[CII]=2.1
Δv(LyA)=+677 km/s
→High N(HI)
→ low fesc

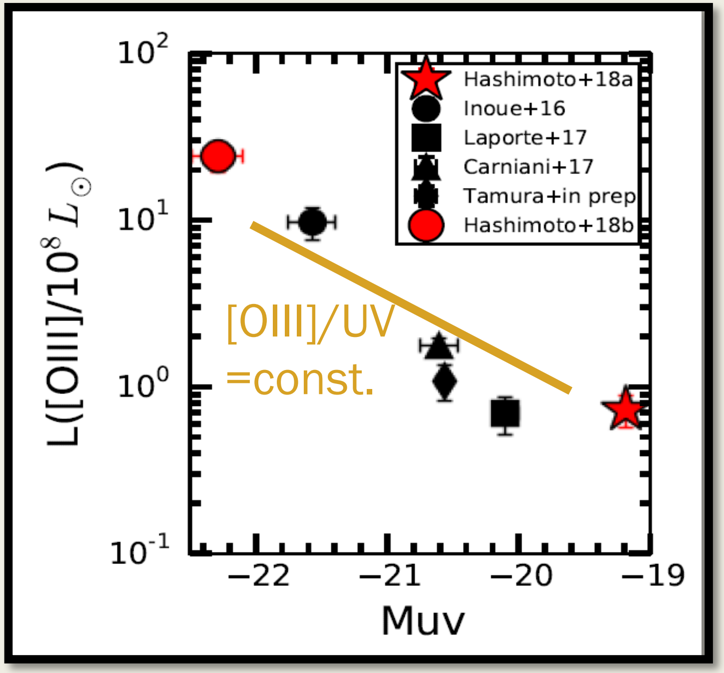


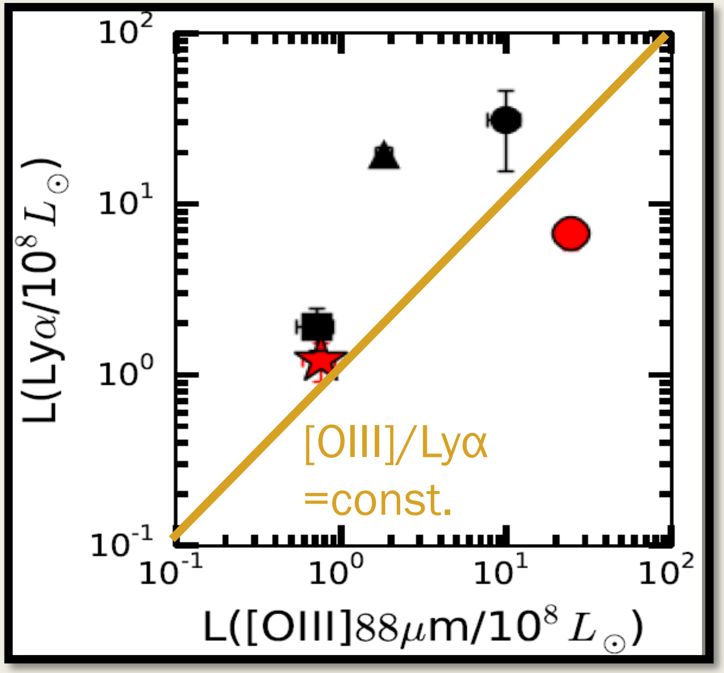
Contour:
ALMA lines 3, 4, 5, …xσ
ALMA continua 2, 3, 4, …xσ
Background: UVISTA H-band

[OIII]-UV-Lyα correlation

Hashimoto+18c

- Nice correlations → Well predictable
- Some deviations → ISM conditions?
  - *Ionization parameter, metallicity, depletion, etc.*

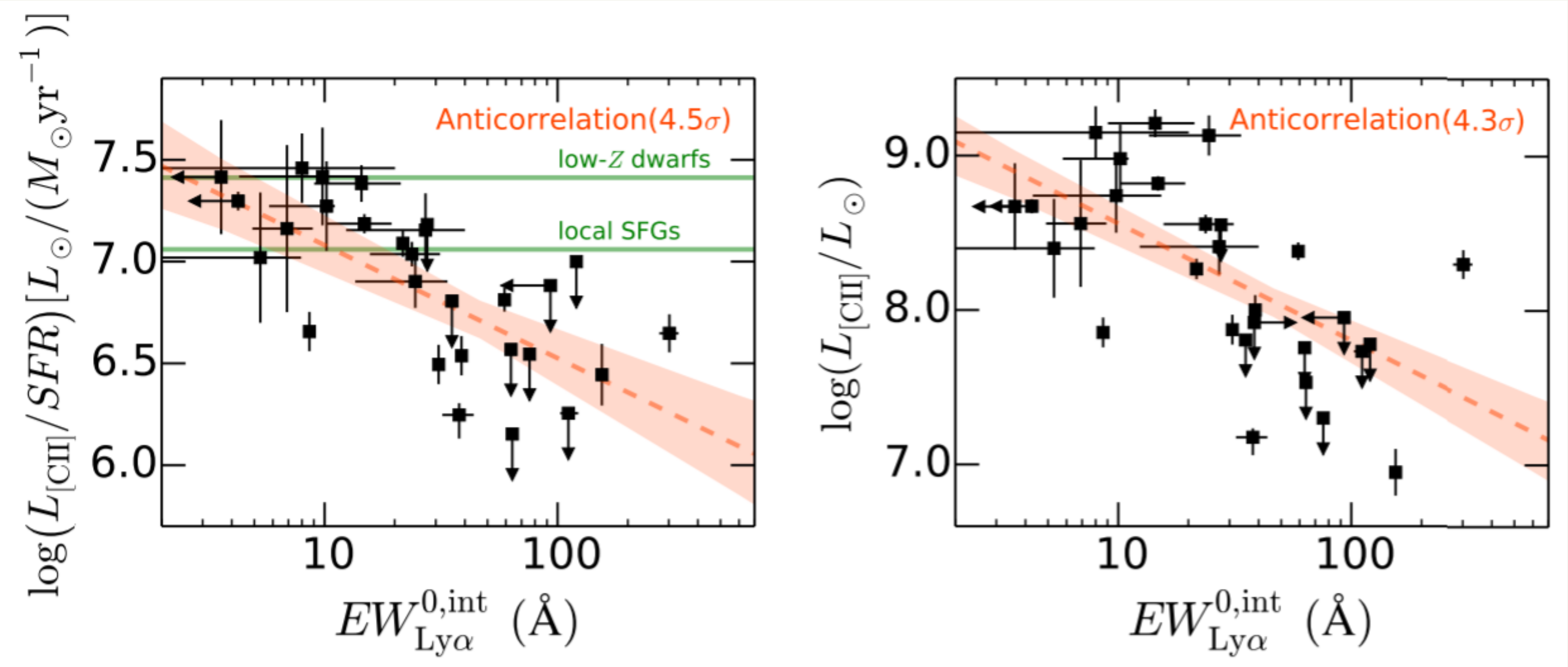




[CII]-Lyα anti-correlation

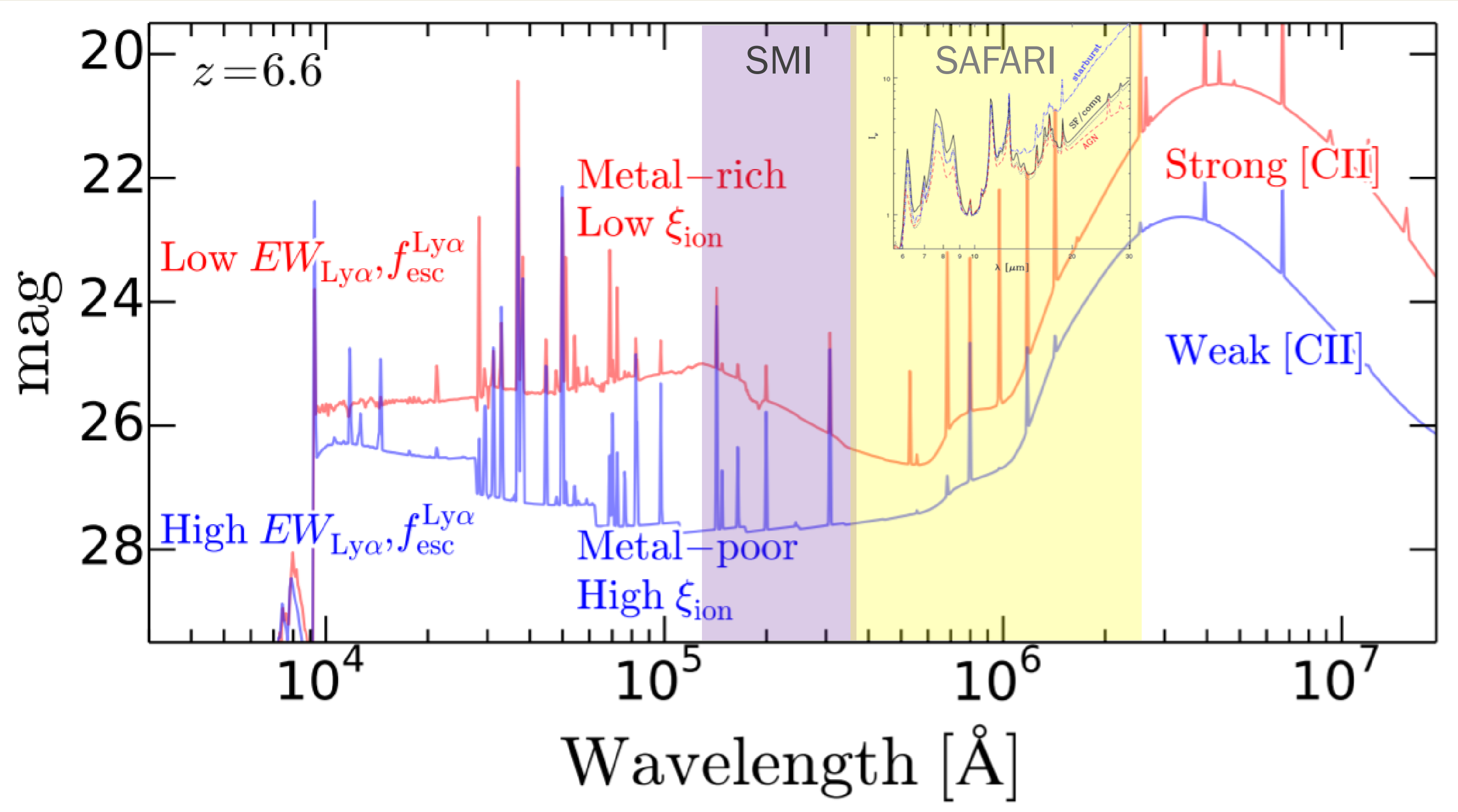
Harikane+17

- PDR (HI) and Lyα anti-correlation
  - *Ionization parameter (or G_0), metallicity, depletion, etc.*



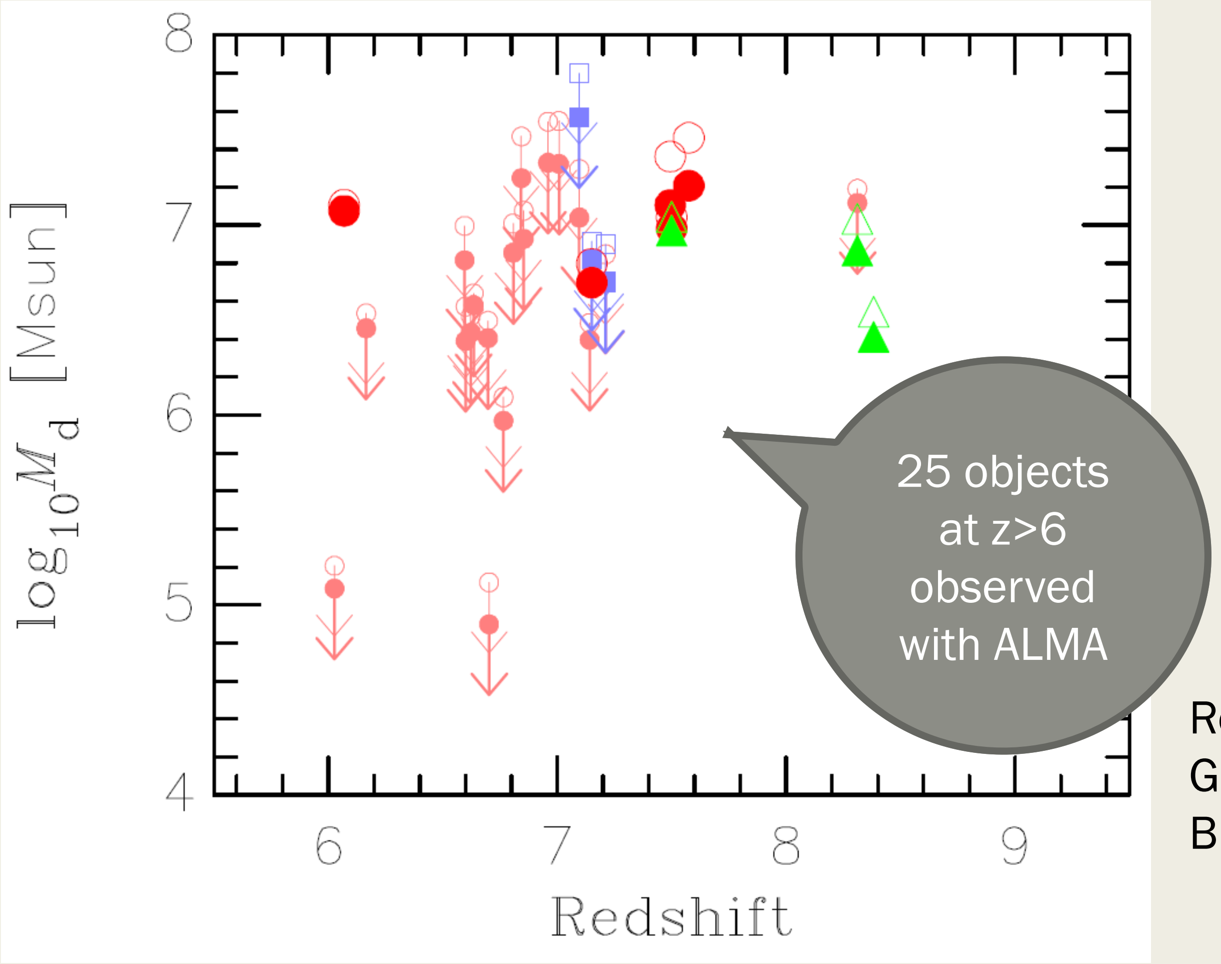
[CII]-Lyα anti-correlation

Harikane+17



Dust mass

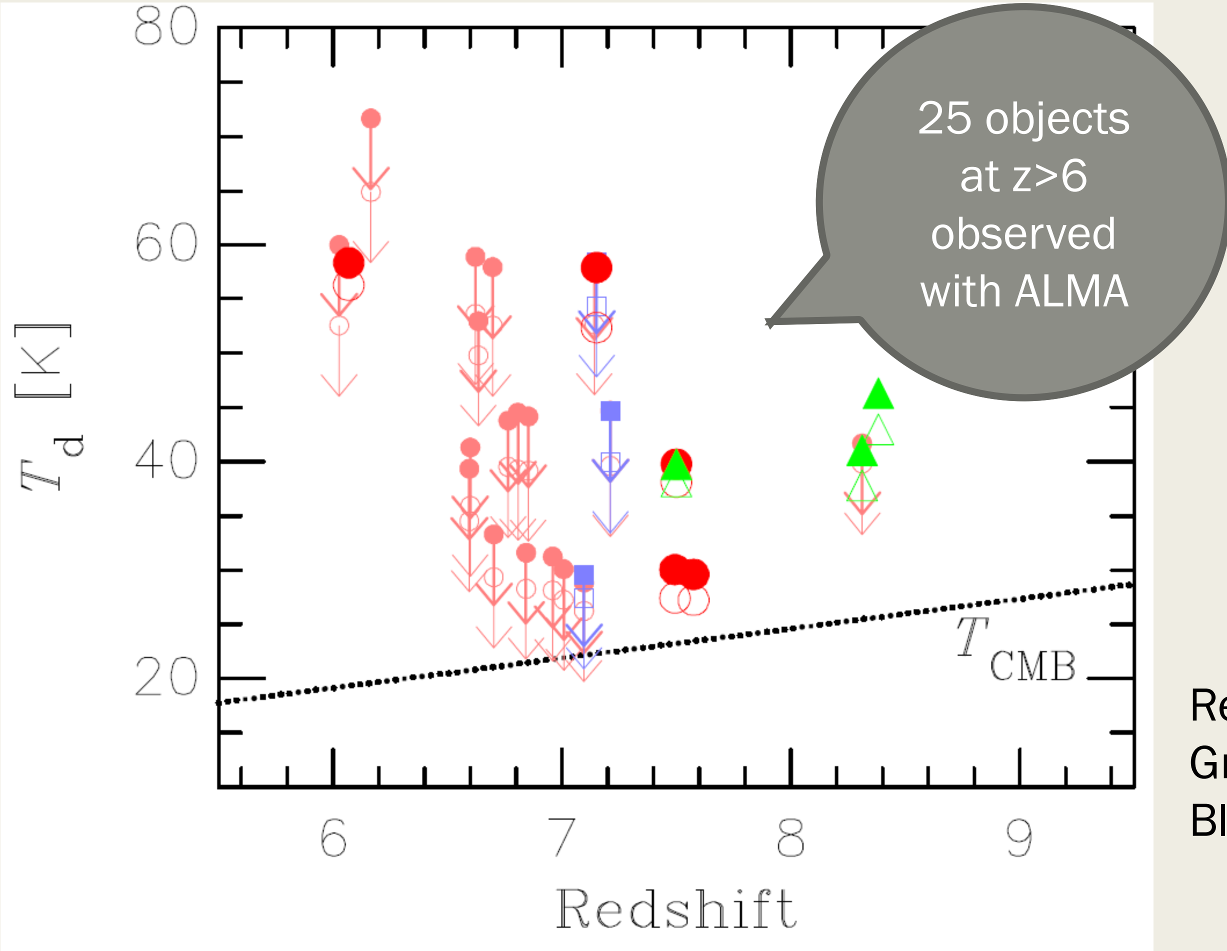
- A huge diversity!
  - *More than two orders of magnitude!*



Red: Band 6
Green: Band 7
Blue: Band 8

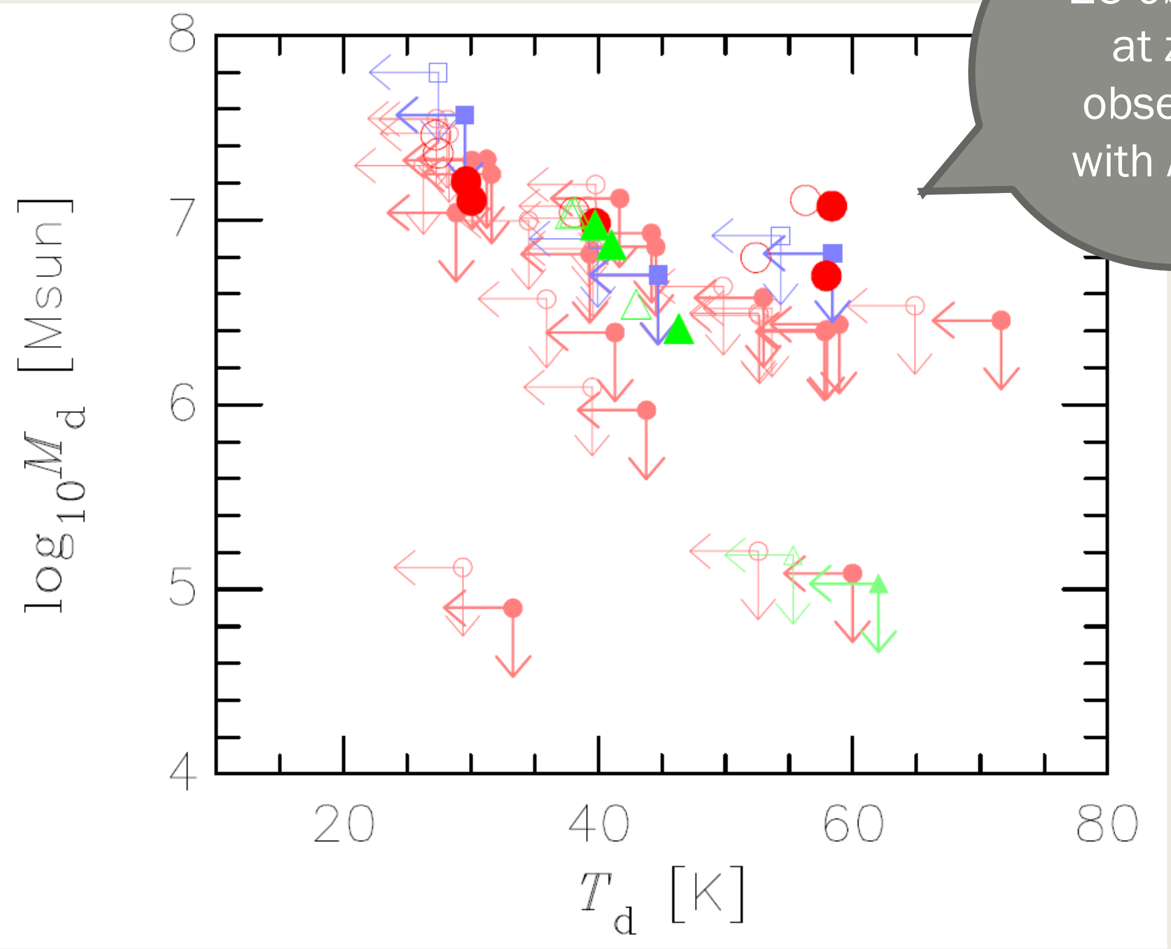
Dust temperature

- A huge diversity!
  - *But need a precise size measurement.*



Red: Band 6
Green: Band 7
Blue: Band 8

Mass vs. Temperature

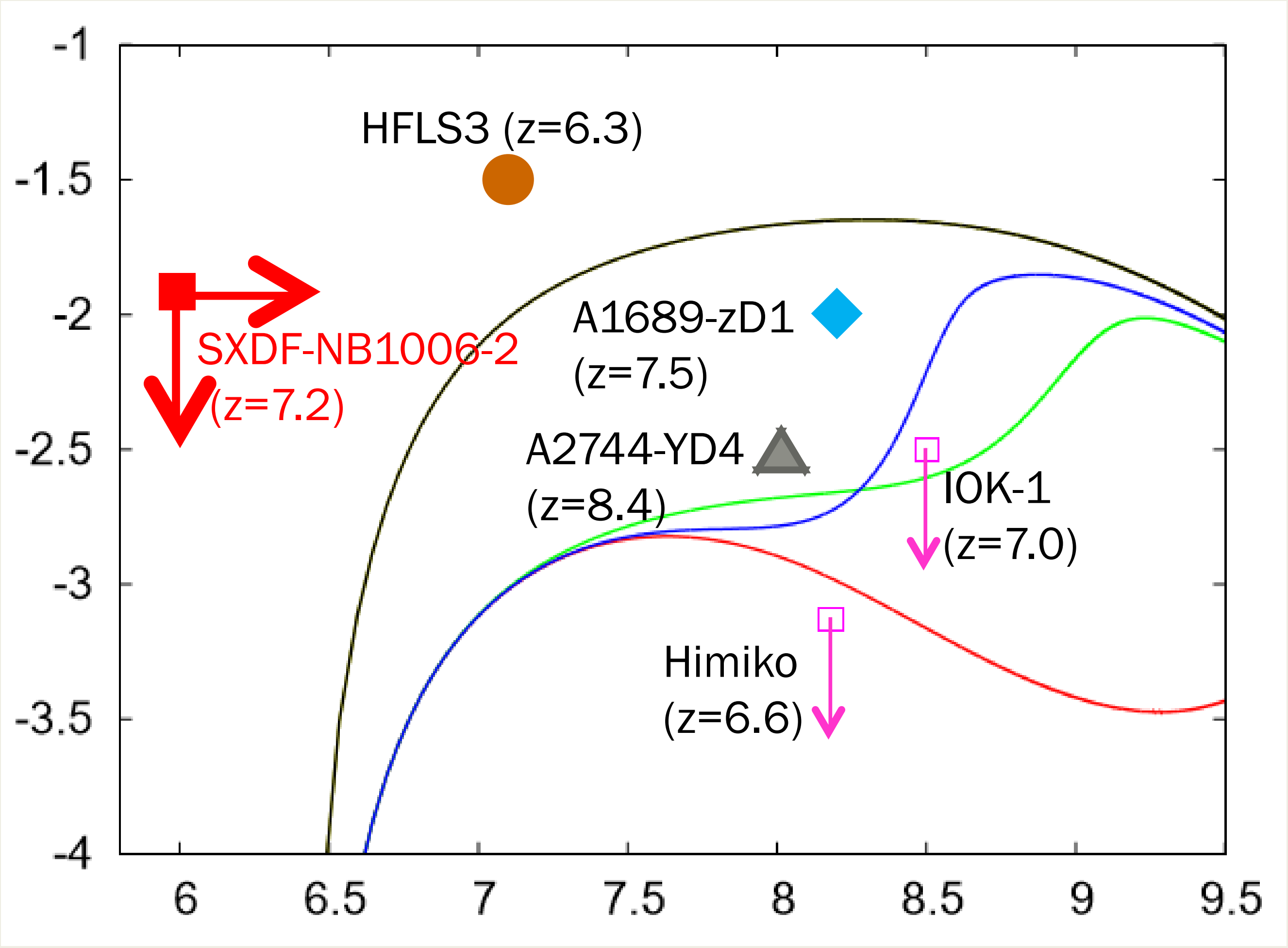


25 objects at z>6 observed with ALMA

Red: Band 6
Green: Band 7
Blue: Band 8

Origin of the dust content diversity

- Dust growth/destruction in the ISM?



log10(Mstar/SFR) [yr] ~ SF age

Black line: M_Z/Mstar (max dust)
Red line: Efficient destruction
Green line: Inefficient destruction
Blue line: Efficient growth

Implication from ALMA (Reused)

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  - *Lines from HII regions are simply correlated with UV (i.e. SFR).*
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- Lines sometimes show spatial offsets.
  - *Spectral mapping (or IFU) is essentially important.*
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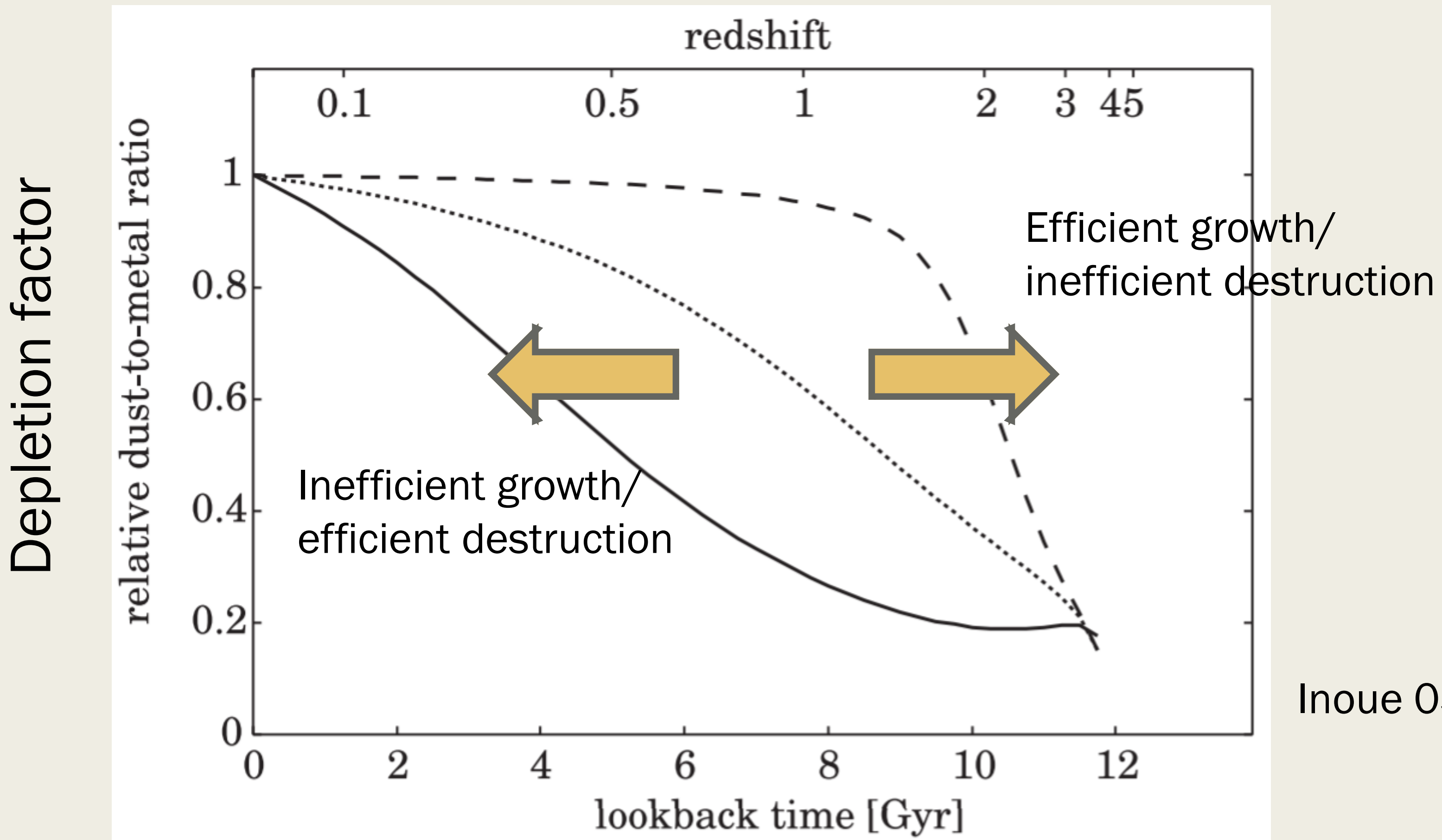
  - *ISM growth/destruction processes.*

Cosmic evolution of the "depletion"

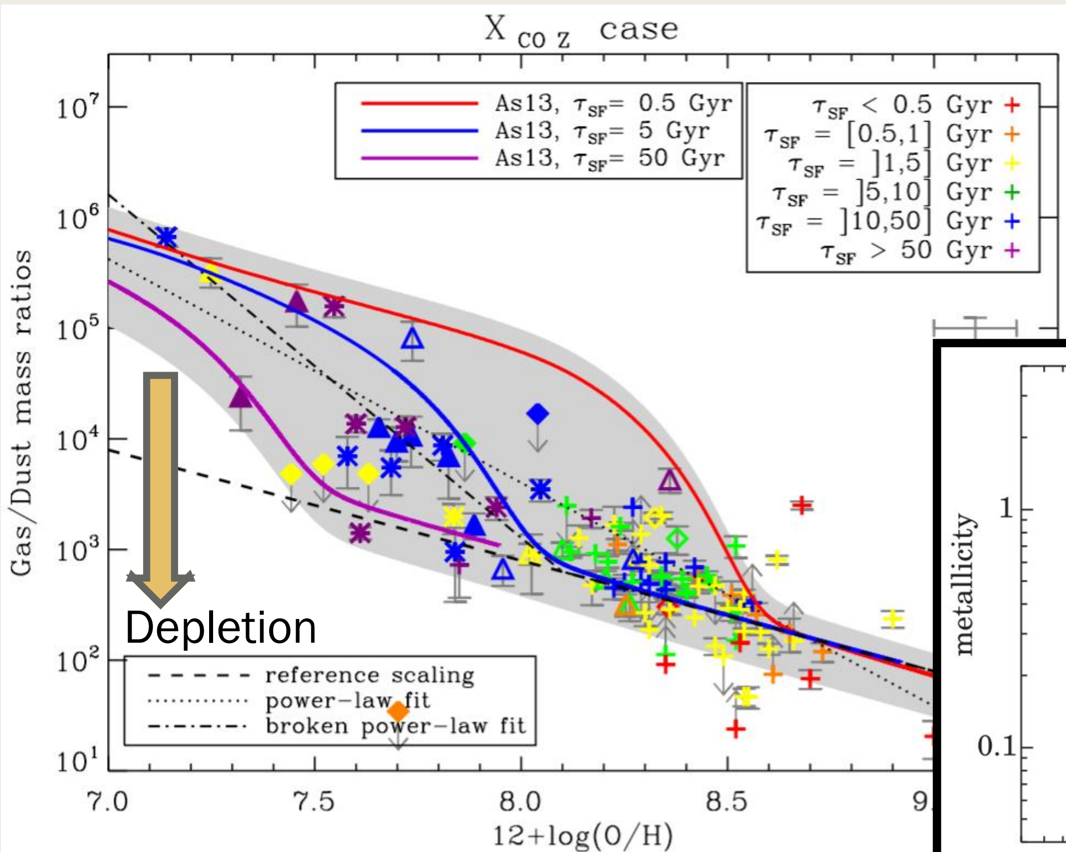
- Dust growth/destruction in the ISM cause an evolution of the dust/metal ratio.



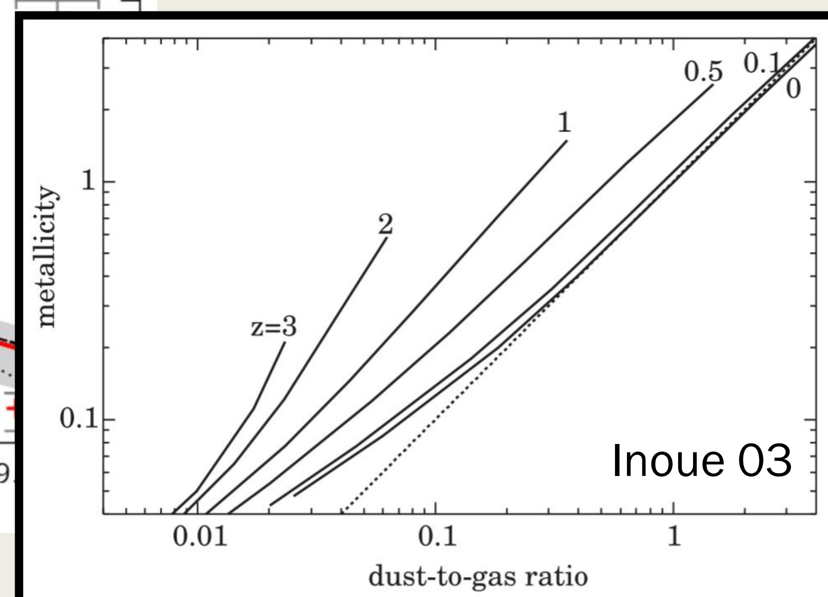
Inoue 03

Cosmic evolution of the "depletion"

- Dust growth/destruction in the ISM cause an evolution of the dust/metal ratio.



Remy-Ruyer+14
(z=0)



Cosmic evolution of the "depletion"

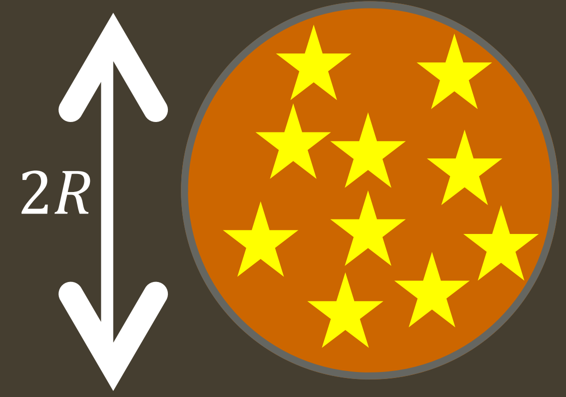
- Metallicity measurements
  - *E.g., [NeII], [NeIII], [SII], [SIII]*
- Depletion measurements
  - *E.g., [SiII] (but this comes from PDRs)*

→ Constraints on dust growth/destruction

Dust mass & temperature estimates

$$L_{UV}^{abs} + L_{CMB}^{abs} = L_{IR}^{dust}(T_d)$$

$$L_{UV}^{abs} = L_{UV}^{obs} \times \frac{1 - P_{esc}(\tau_{UV})}{P_{esc(\tau_{UV})}}$$



Spherical homogeneous

Spherical homogeneous:

$$\tau_{UV} = \frac{9 M_d Q_{UV}}{16 \pi a \rho_g R^2}$$

$$P_{esc}(\tau) = \frac{3}{4\tau}\left(1 - \frac{1}{2\tau^2} + \left(\frac{1}{\tau} + \frac{1}{2\tau^2}\right) e^{-2\tau}\right)$$


Spherical shell

Spherical shell:

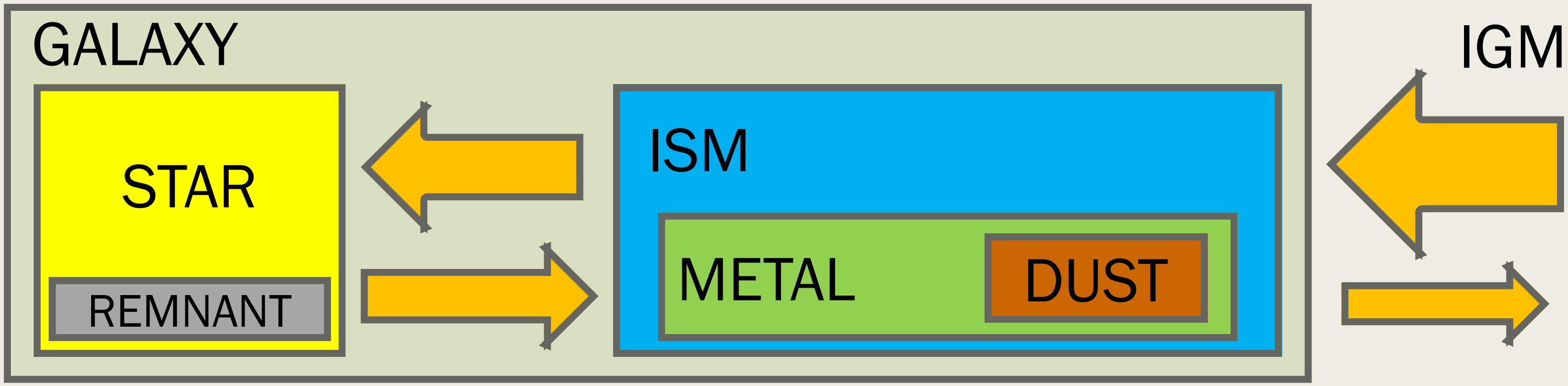
$$\tau_{UV} = \frac{3 M_d Q_{UV}}{16 \pi a \rho_g R^2}$$

$$P_{esc}(\tau) = e^{-\tau}$$

Dust mass evolution model

Dwek 80, 98
Hirashita 00

- A galaxy as a non-linear open system



STAR $$\frac{dM_*}{dt} = S - R$$

ISM $$\frac{dM_{\rm ISM}}{dt} = -S + R + I - O$$

METAL $$\frac{dM_{\rm Z}}{dt} = -ZS + Y_{\rm Z} + I_{\rm Z} - O_{\rm Z}$$

DUST $$\frac{dM_{\rm d}}{dt} = -Z_{\rm d}S + Y_{\rm d} - \frac{M_{\rm d}}{\tau_{\rm SN}} + \frac{M_{\rm d}}{\tau_{\rm ac}} + I_{\rm d} + O_{\rm d}$$

Dust supply by stars ($+Y_{\rm d}$)

Destruction by SN shock ($-\frac{M_{\rm d}}{\tau_{\rm SN}}$)

Dust mass growth in ISM ($+\frac{M_{\rm d}}{\tau_{\rm ac}}$)