Far infra red emission lines in high redshift quasars and galaxies

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in collaboration with:

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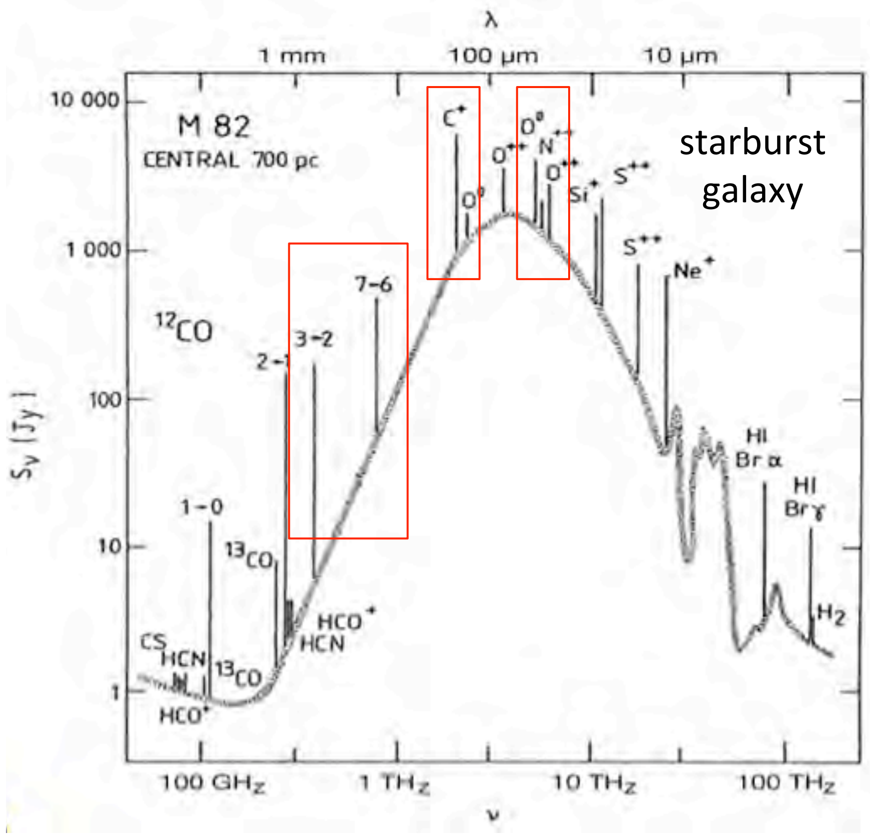
L. Vallini, A. Ferrara, S. Baek

Reionization in the Red Center, Uluru, 16th July 2013

Rest frame FIR emission lines

(e.g. [CII] ($^2P_{3/2}$-$^2P_{1/2}$) @158 μm; [NII] ($^3P_1$-$^3P_0$) @205 μm)



(e.g. Colbert et al. 1999)

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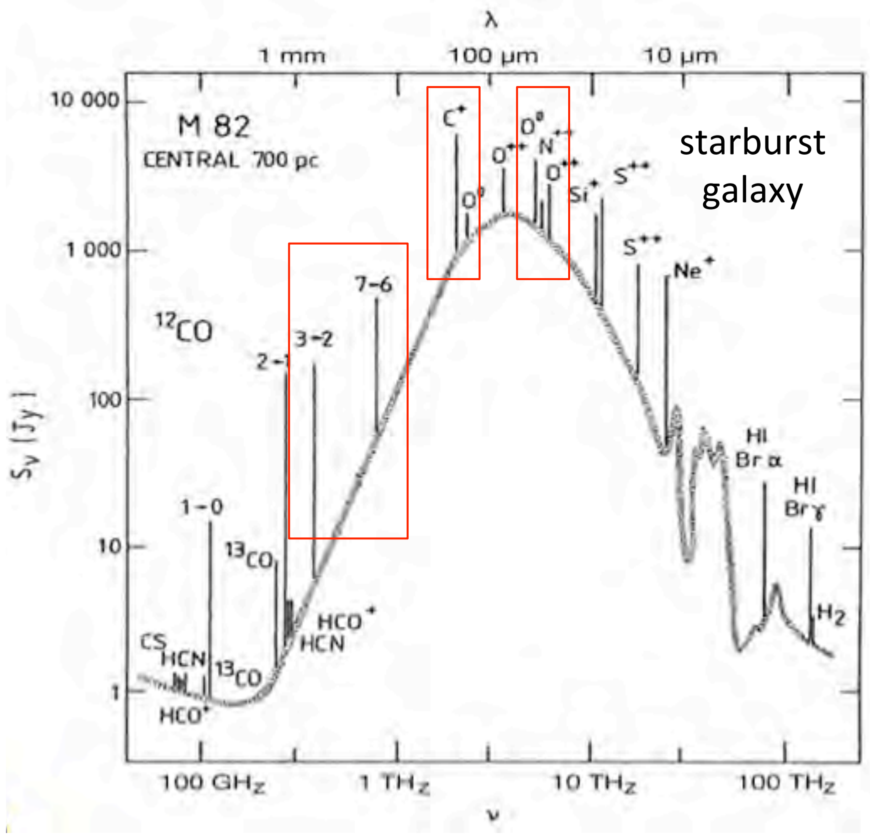
(e.g. [CII] ($^{2}P_{3/2}$-$^{2}P_{1/2}$) @158 μm; [NII] ($^{3}P_{1}$-$^{3}P_{0}$) @205 μm)

- Major coolants of the inter-stellar medium in star forming galaxies
- The strongest emission lines in most galaxies ($L_{[CII]}$ ~ 0.1-1% L_{FIR})



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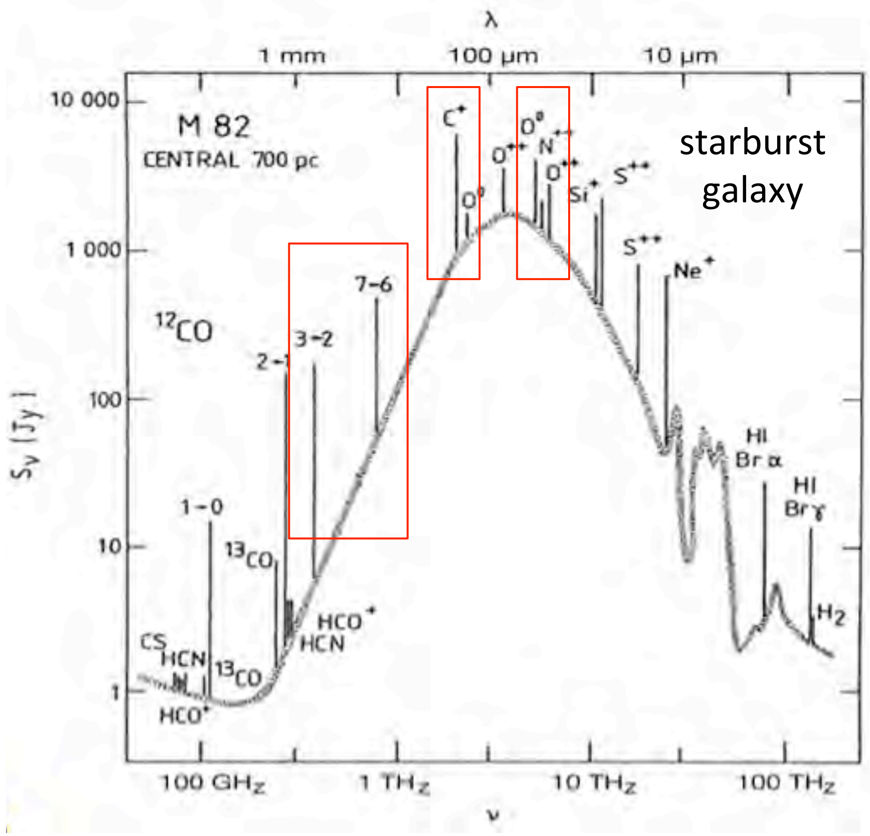

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Rest frame FIR emission lines

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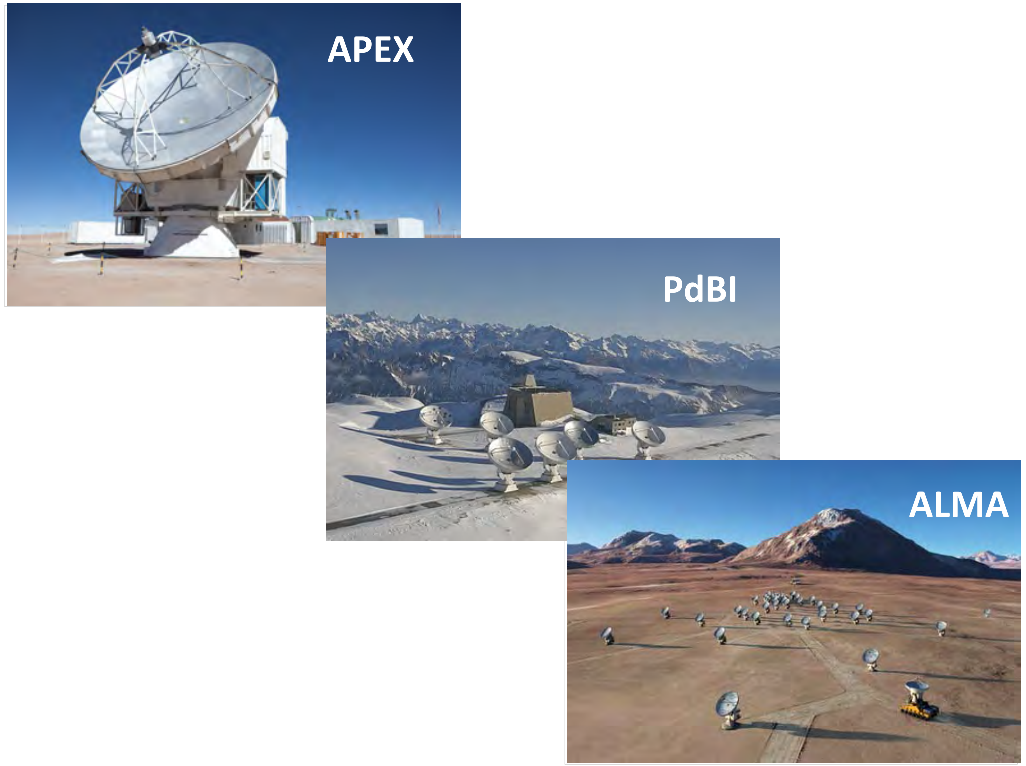
- Major coolants of the inter-stellar medium in star forming galaxies
- The strongest emission line in most galaxies ($L_{[CII]} \sim 0.1$-$1\% \ L_{FIR}$)
- Unaffected by dust extinction ($r_{dust} \leq 0.1$ μm)
- At z > 4 the [CII] emission line is redshifted into the mm



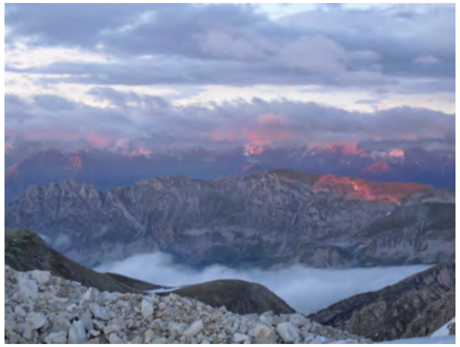
Thanks to current powerful millimeter facilities

(e.g. APEX, PdBI, ALMA)

they are considered promising tools

to detect high-z star forming galaxies and characterize their ISM

The Plateau de Bure Interferometer



Array of 6 antennas
15 m diameter
→
NOEMA 12 antennas
(2018)

located at 2550 m altitude
in the French Alps

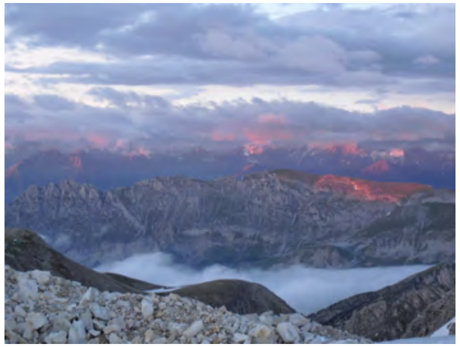
operated by IRAM
(Grenoble)

Technical properties:

WAVELENGTH COVERAGE
(0.8 mm < λ < 3 mm)
(370 GHz > ν > 80 GHz)

ANGULAR RESOLUTION
(0.35'' < R < 0.8'')

The Plateau de Bure Interferometer



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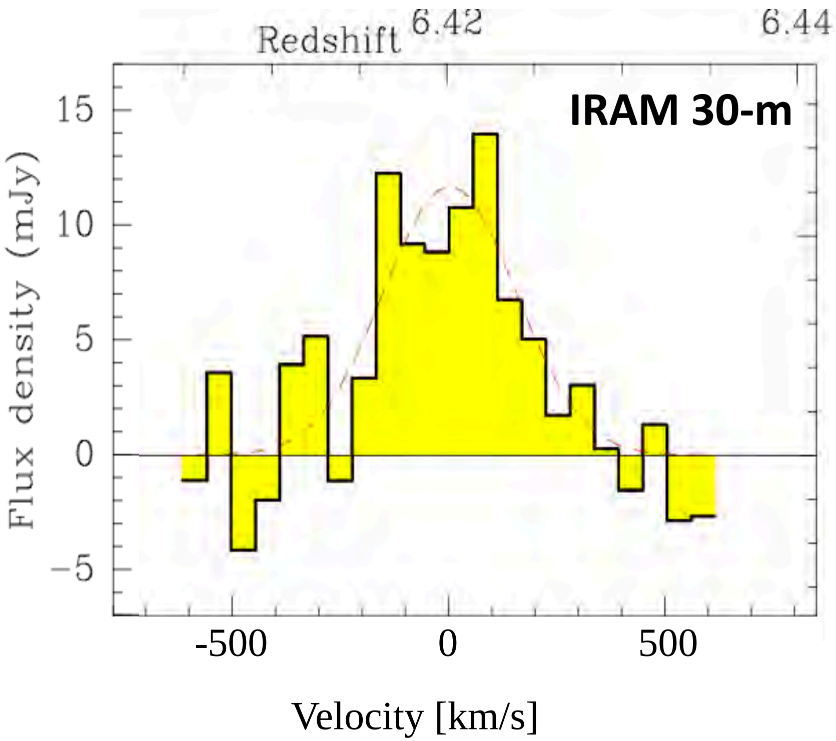
The case of:

SDSS 1148 at z=6.4

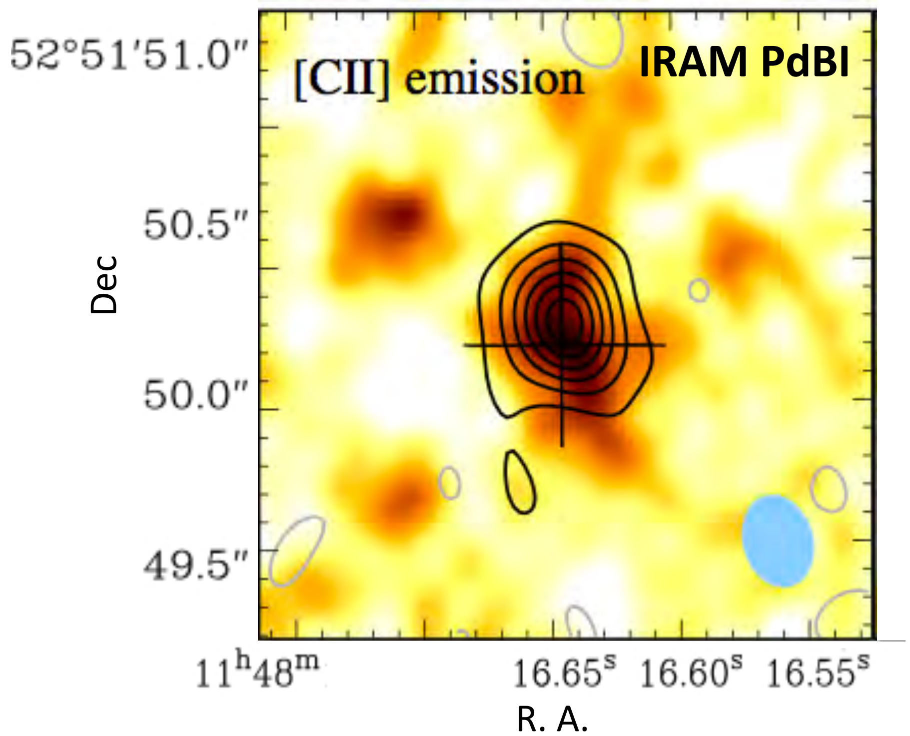
1" = 5.5 kpc @ z=6.4

[CII] emission in SDSS1148 at z=6.4



FIRST EVER DETECTION AT HIGH-z

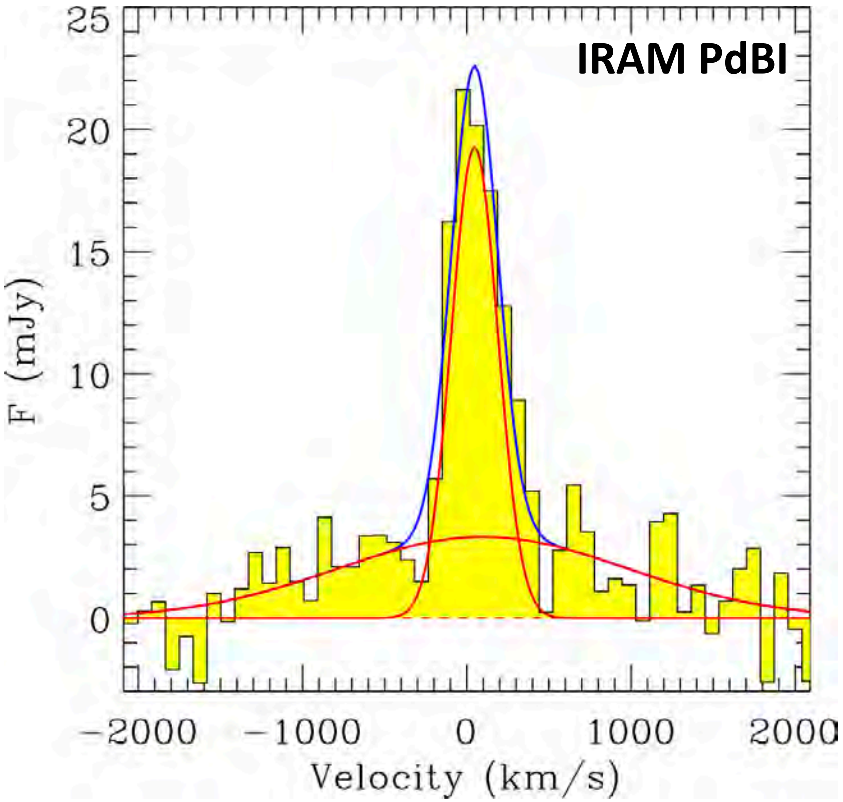
(Maiolino et al. 2005)



FIRST RESOLVED MAP AT HIGH-z

(Walter et al. 2004/2009)

Evidence of strong feedback at z≈6



The [CII] emission line has been fitted

with a **narrow** (FWHM=300 km/s)

and a **broad** (FWHM=2000 km/s) Gaussian.

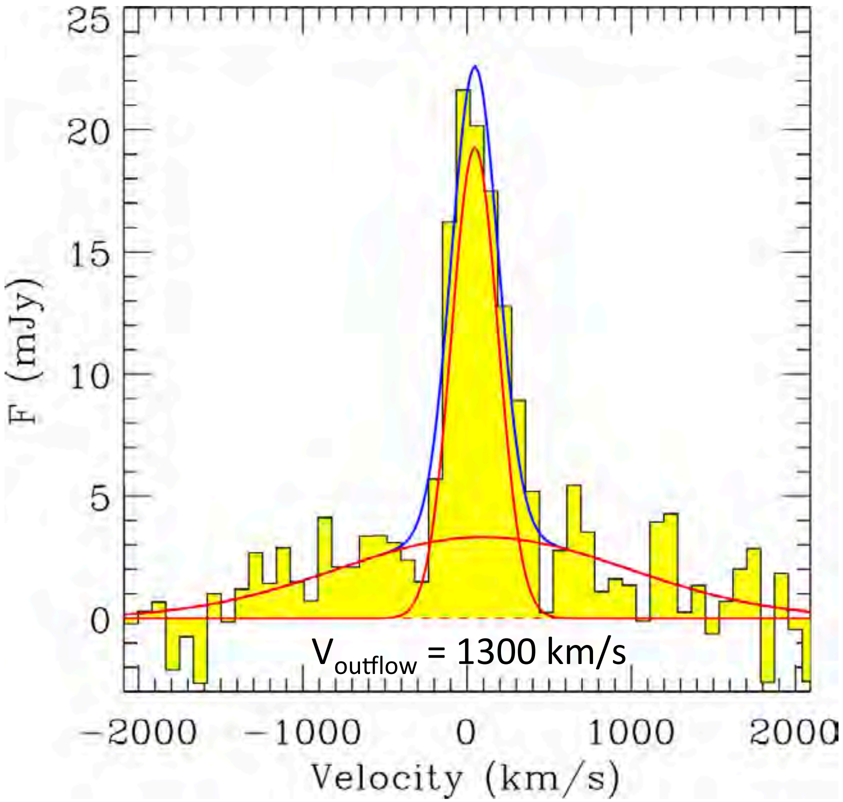
Maiolino, SG et al., (2012)

Broad wings extended up to about ± 1300 km/s

↓

indication of a powerful outflow

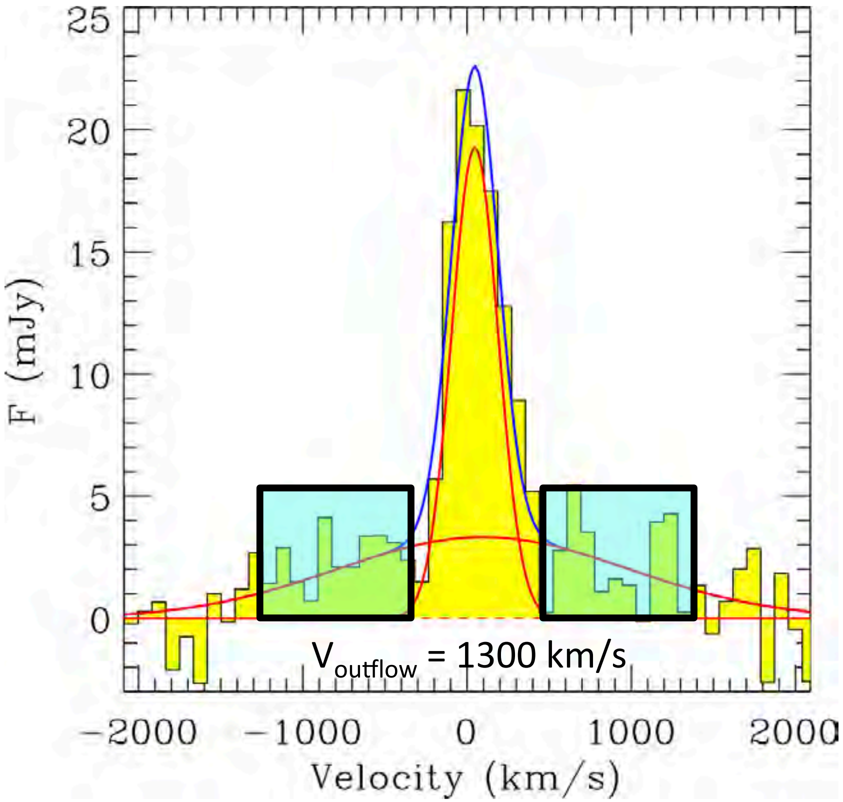
Strong feedback at z≈6: **outflow mass**

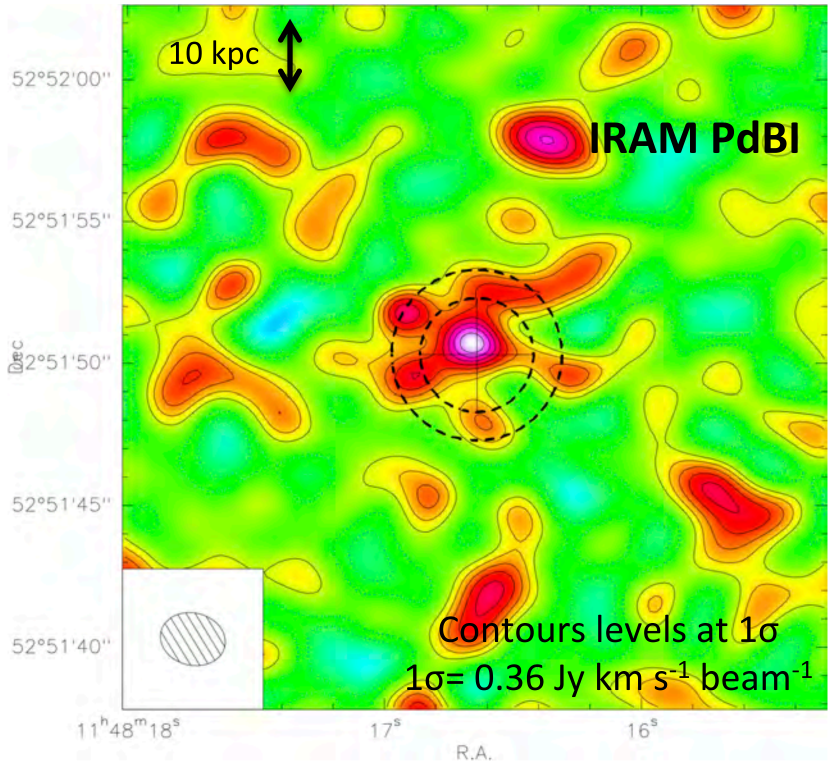


Under conservative assumptions

$L_{[CII]} = 7 \times 10^9 L_\odot \rightarrow M_{outflow} \geq 10^{10} M_\odot$

Strong feedback at z≈6: **outflow size**





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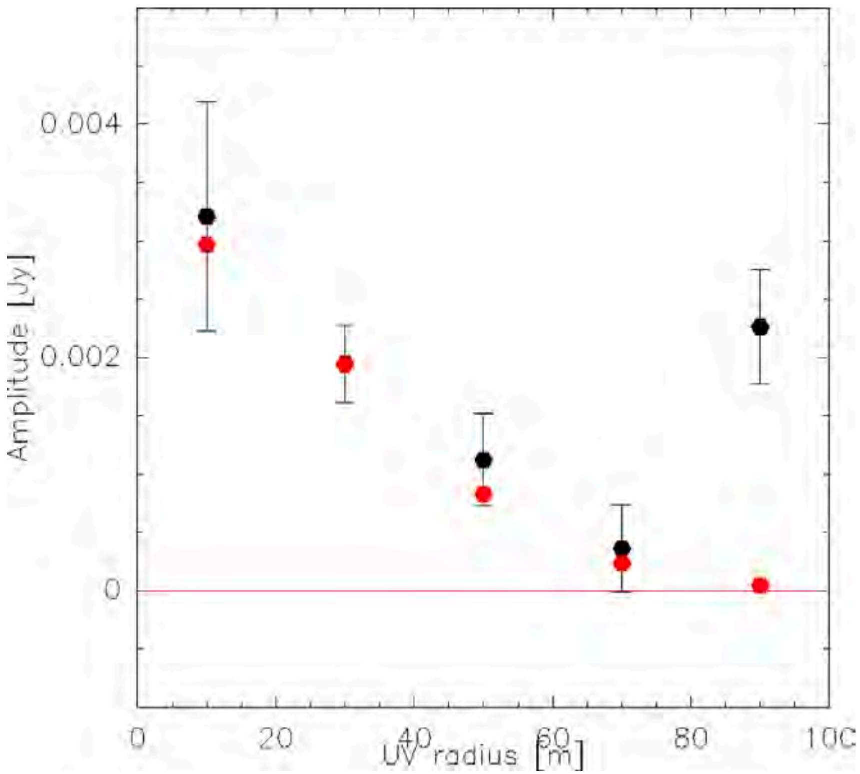
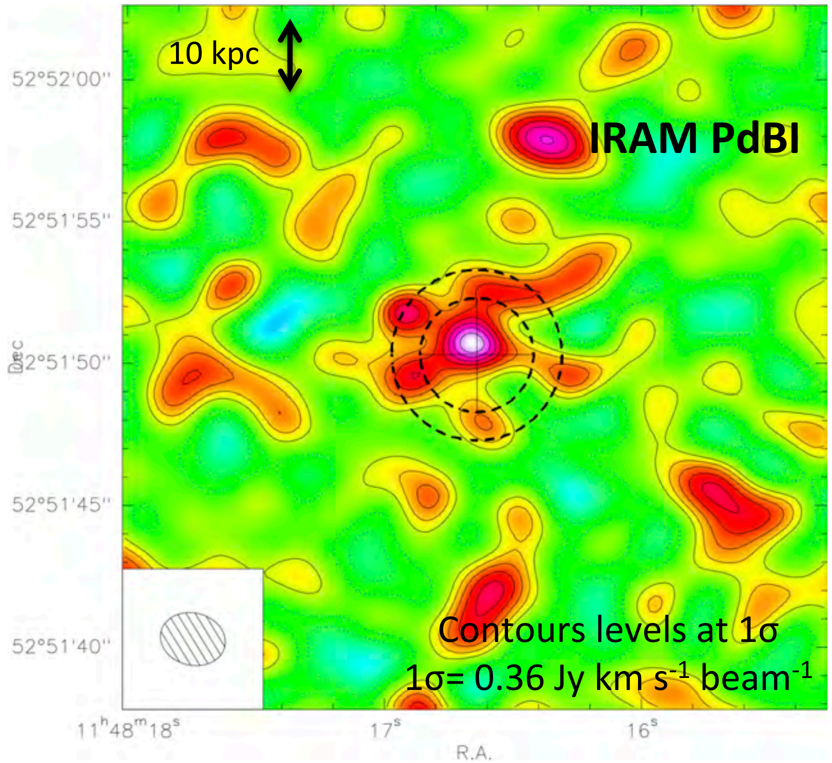
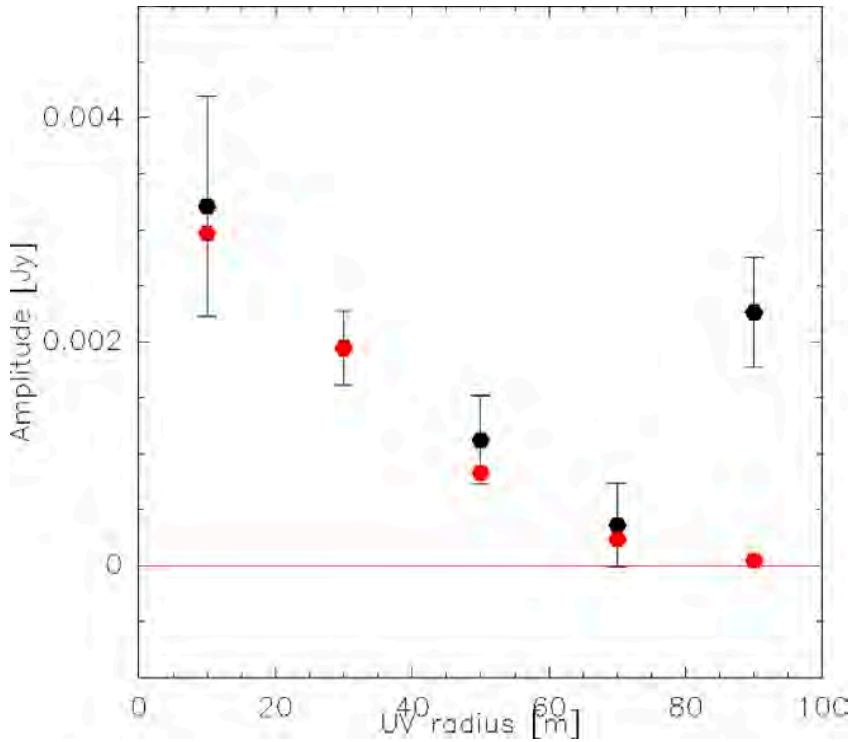




Maiolino, SG et al., (2012)

$R_{outflow}$ = 8 kpc

Strong feedback at z≈6: **outflow rate**



$V_{outflow}$ = 1300 km/s

$M_{outflow} \geq 10^{10}\ M_{\odot}$

$R_{outflow}$ = 8 kpc

$dM/dt \geq 3500\ M_{\odot}yr^{-1} > SFR = 3000\ M_{\odot}yr^{-1}$

(Walter et al. 2004/2009)

The outflow is quenching star formation

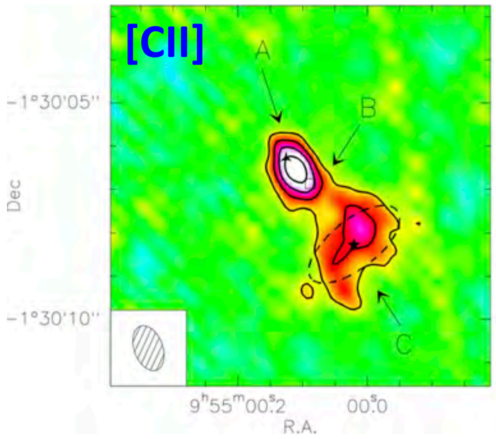
Mechanism required to explain the properties

of massive and passive galaxies at z≈2 ($t_H \approx$ 3 Gyr; $t_* >$ 2 Gyr)

(e.g. Cimatti et al. 2004, Grazian et al. 2007)

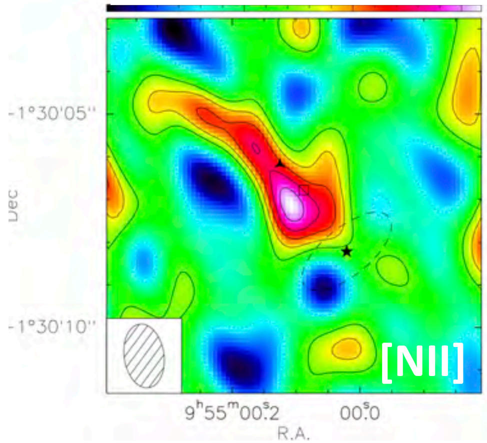
Observations of FIR emission lines in high redshift (extreme*) sources

Quasar at z=4.4



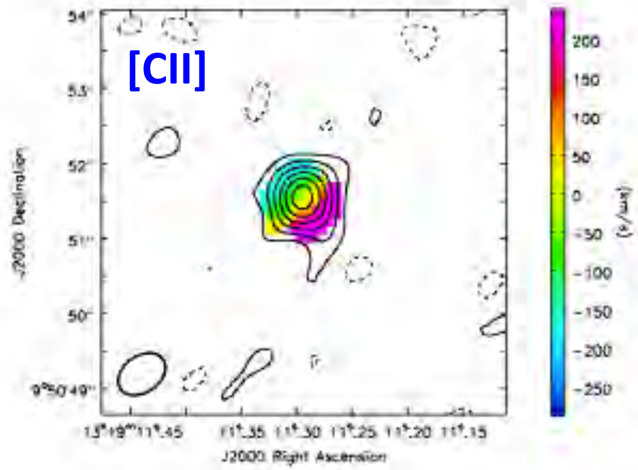
(Gallerani et al. 2012)

Quasar at z=4.4



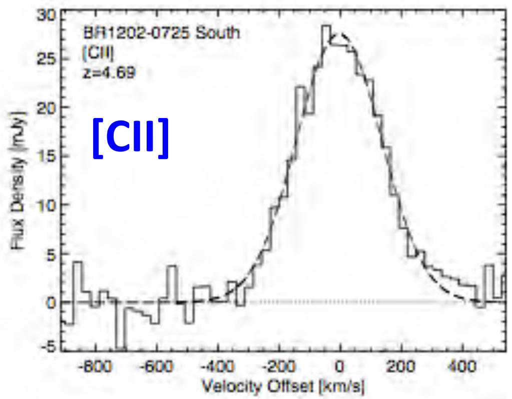
(Gallerani et al. 2013)

Quasar at z=6.1



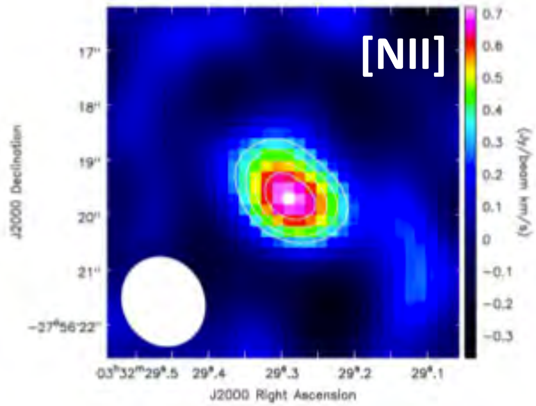
(Wang et al. 2012)

Quasar at z=4.7



(Wagg et al. 2012)

ULIRG at z=4.7

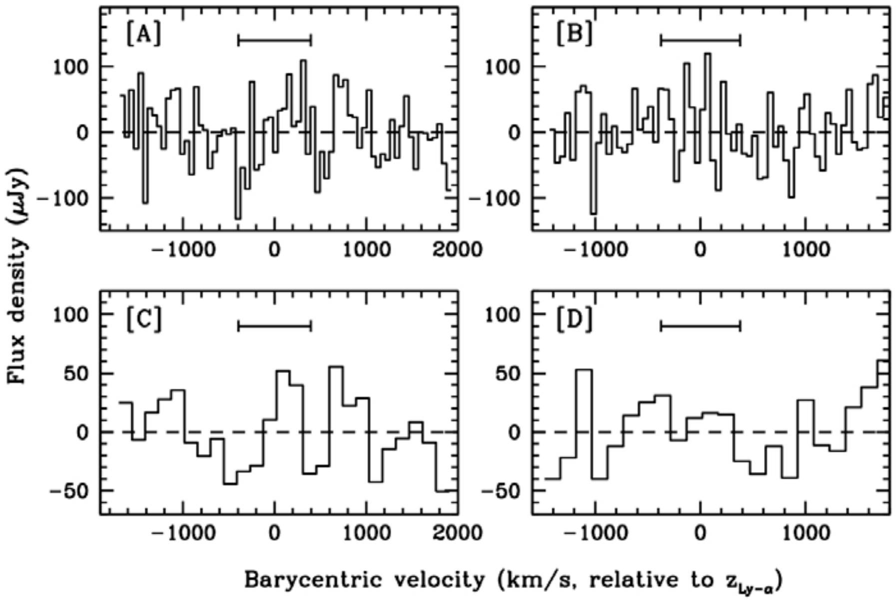


(Nagao et al. 2012)

(*100 ≤ SFR ≤ 1000 $M_{\odot} yr^{-1}$)

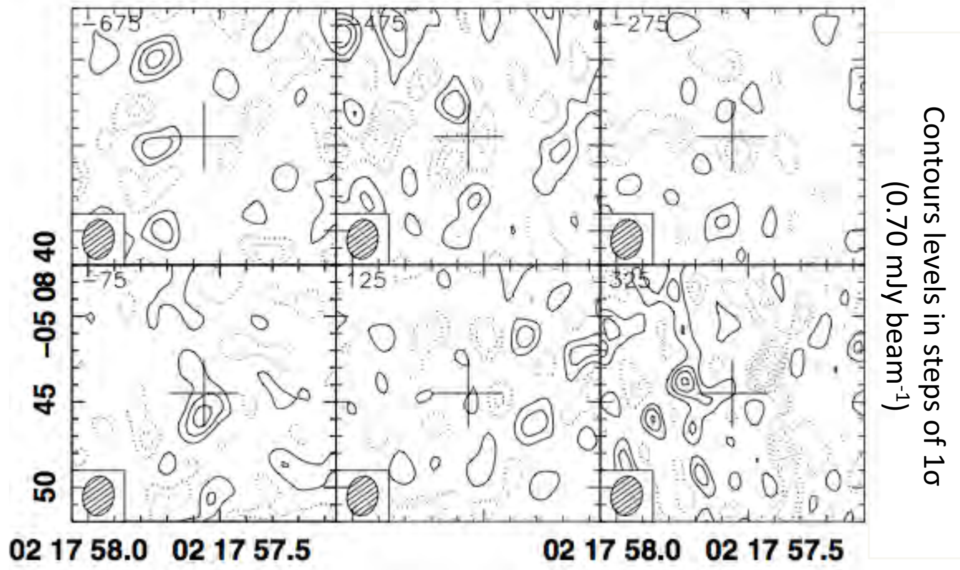
Searching for FIR emission lines in high redshift (normal*) galaxies

CO(1-0) in z > 6.5 LAEs with the GBT



Wagg et al. (2009)

[CII] in a z = 6.7 LAE with the PdBI



Walter et al. (2012)

(*$1 \leq SFR \leq 100\ M_{\odot} yr^{-1}$)

Searching for FIR emission lines in high redshift (normal*) galaxies

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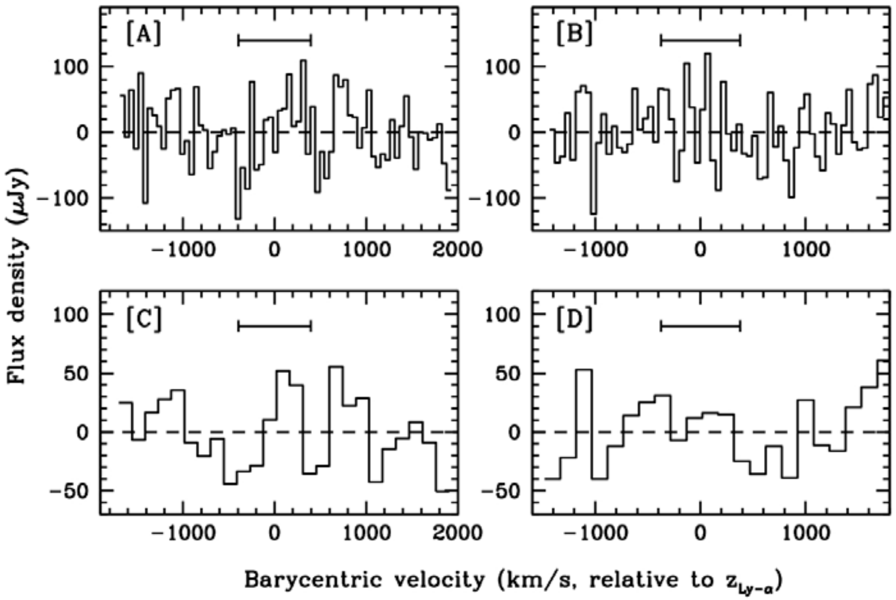

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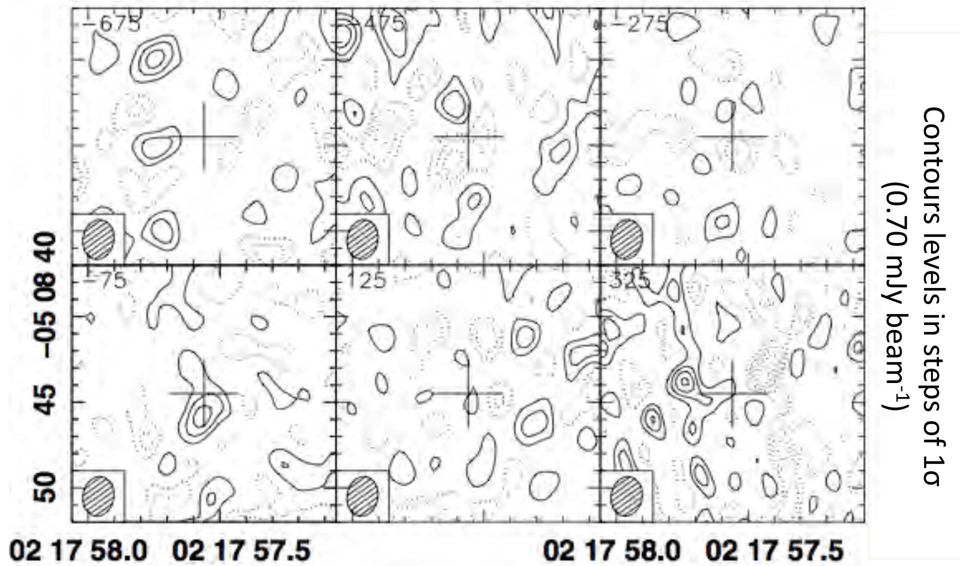
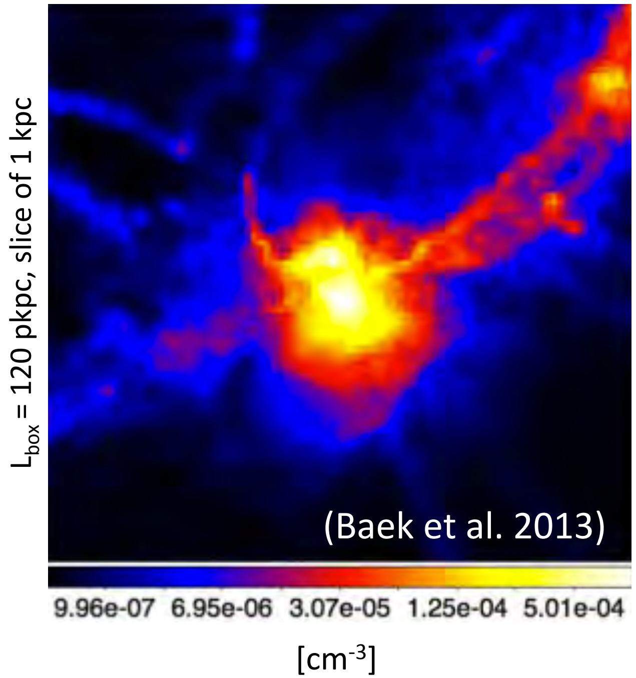


Walter et al. (2012)

NO DETECTION!

How bright are supposed to be FIR emission lines in high redshift normal galaxies?

Cosmological simulations of a z=6.7 galaxy



$L_{box} = 10\ h^{-1}$ Mpc

$M_{res} = 7 \times 10^5\ M_\odot$

$M_{halo} = 10^{11}\ M_\odot$

GADGET-2
(Springel 2005)

$L_{box} = 0.6\ h^{-1}$ Mpc

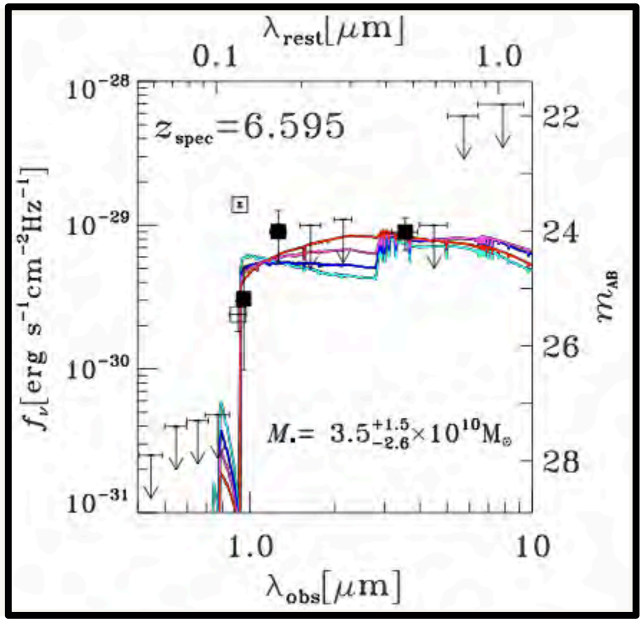
adaptive grid

$L_{min} \approx 0.6\ h^{-1}$ kpc

LICORICE
(Baek et al. 2009)

Radiative transfer simulations of a z=6.7 galaxy

Ouchi et al. (2009)



Salpeter IMF SFR = 10 $M_\odot$ yr^{-1} $Z = Z_\odot$

STRABURST99

Ionizing spectrum

L_{box} = 10 h^{-1} Mpc

M_{res} = 7 x 10^5 $M_\odot$

M_{halo} = 10^{11} $M_\odot$

GADGET-2
(Springel 2005)

L_{box} = 0.6 h^{-1} Mpc

adaptive grid

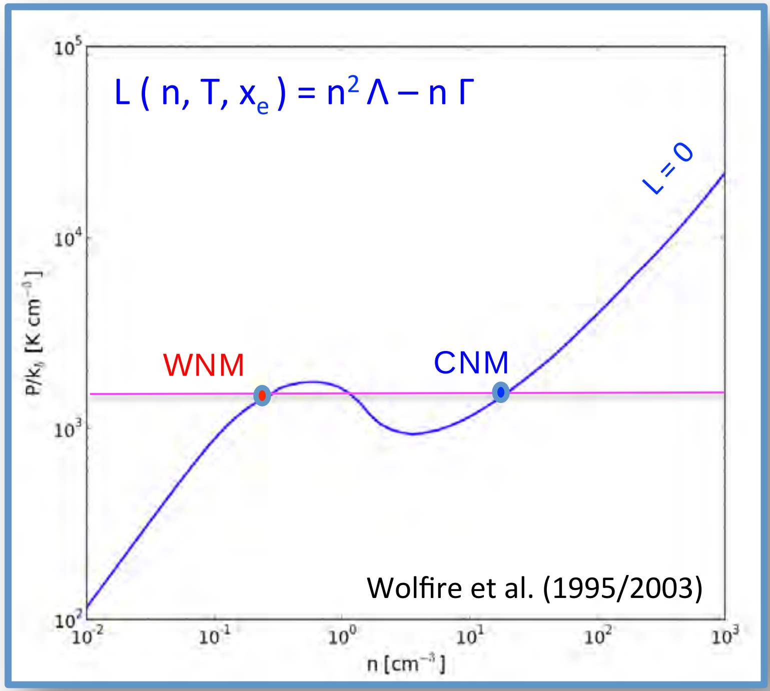
L_{min} ≈ 0.6 h^{-1} kpc

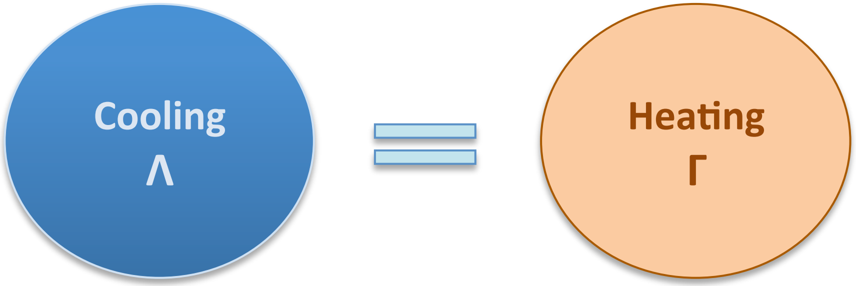
LICORICE
(Baek et al. 2009)

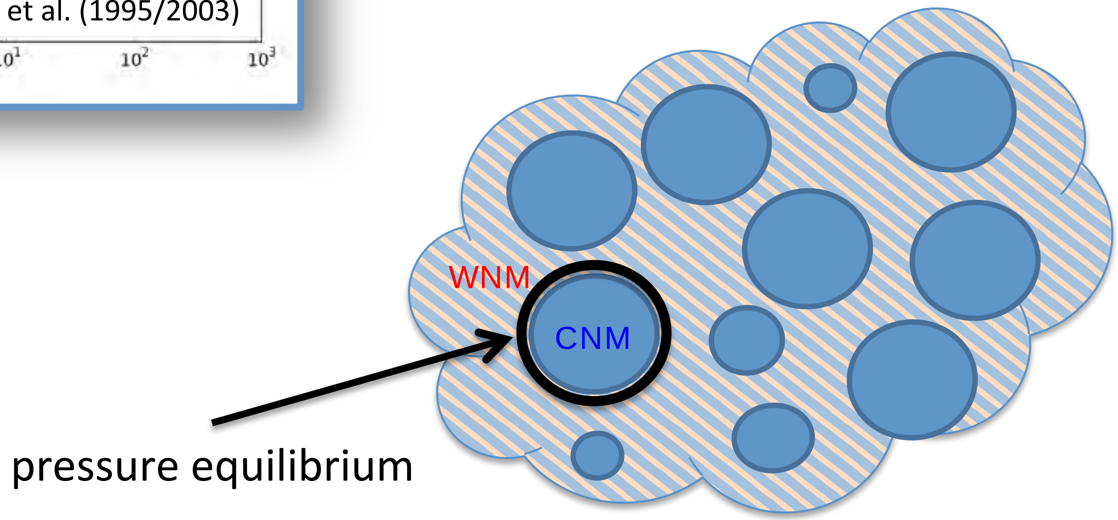
$x_e = x_e$ (x,z,y)

T = T (x,z,y)

Physics of multiphase ISM

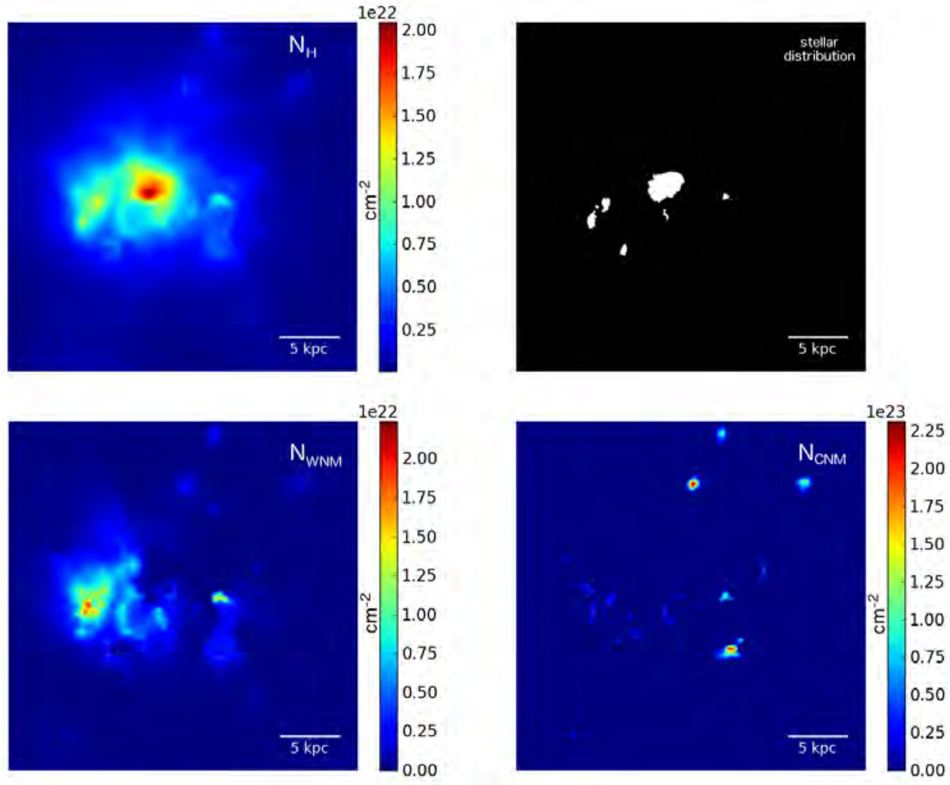






Warm and cold neutral medium

Vallini, SG, et al. (2013)

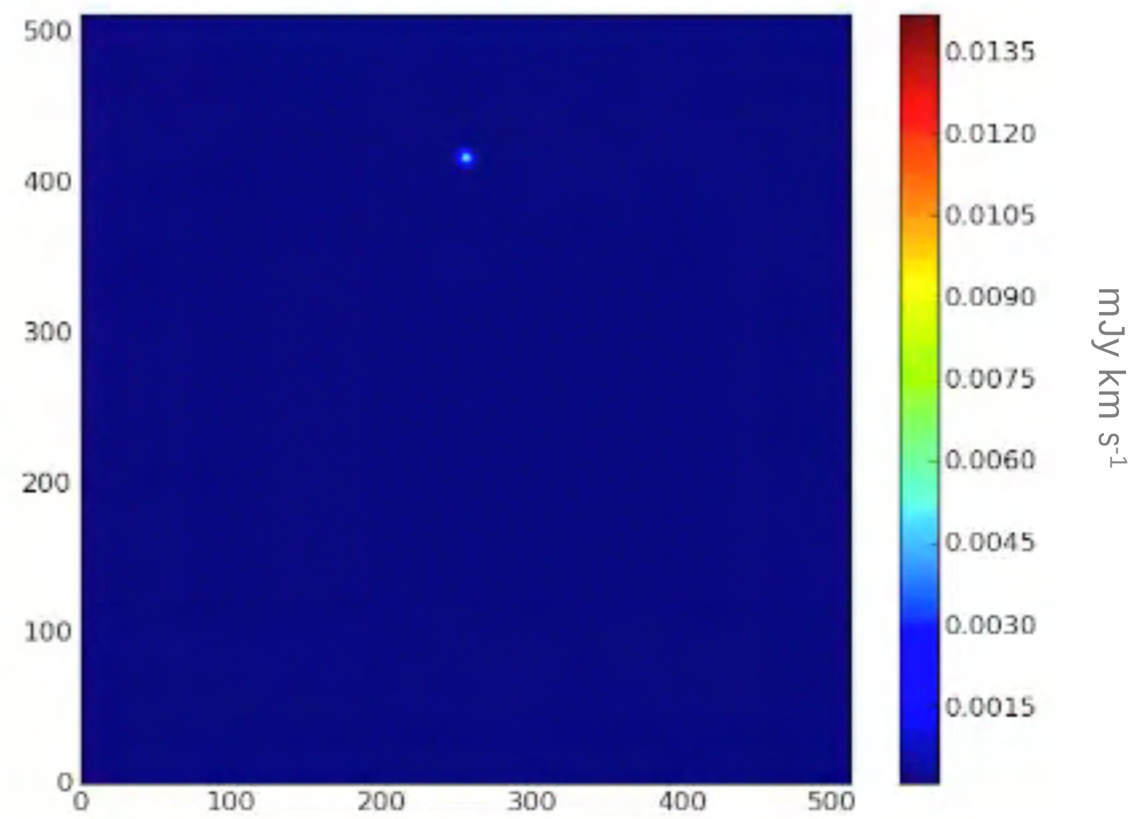


$$L_{[CII]} = V\,(\Lambda^H \chi_C n^2 + \Lambda^e \chi_C x_e n^2)$$

χ_C carbon abundance

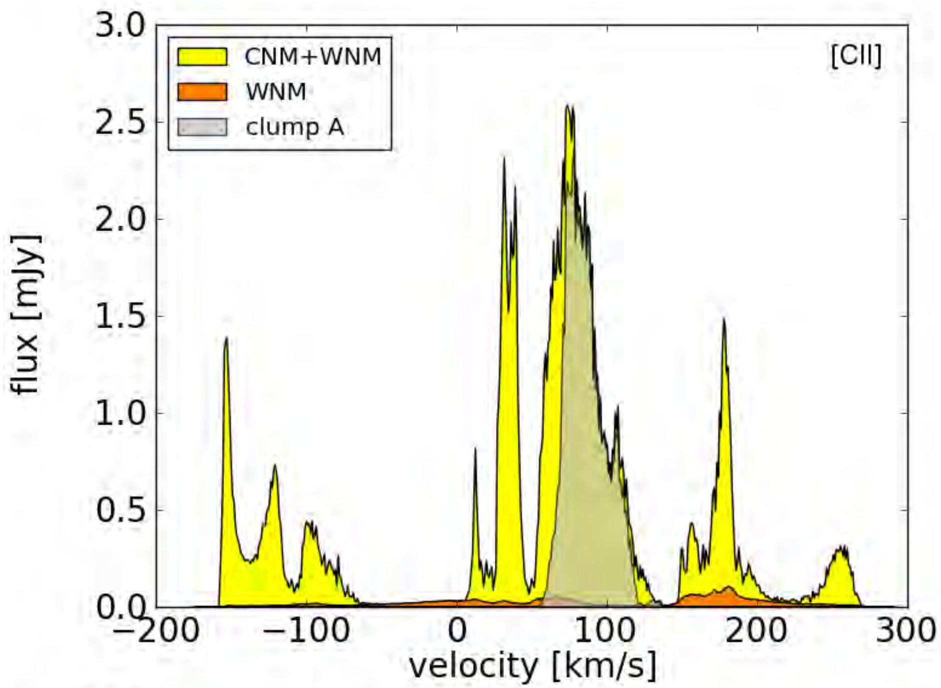
n cold / neutral medium density

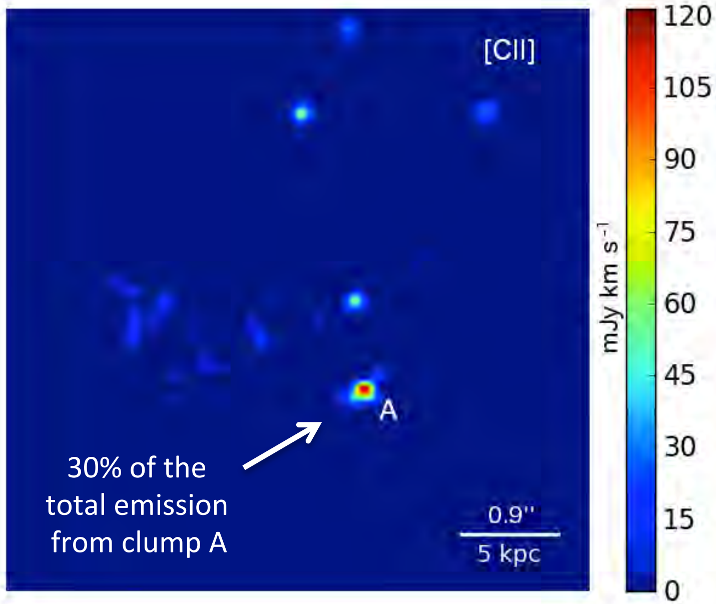
Λ^H / Λ^e cooling rate due to collision with H atoms / free electrons (Dalgarno & McCray 1972)



500
400
300
200
100
0
0
100
200
300
400
500
0.0135
0.0120
0.0105
0.0090
0.0075
0.0060
0.0045
0.0030
0.0015
mJy km s-1

Predictions for the [CII] emission in high-z galaxies

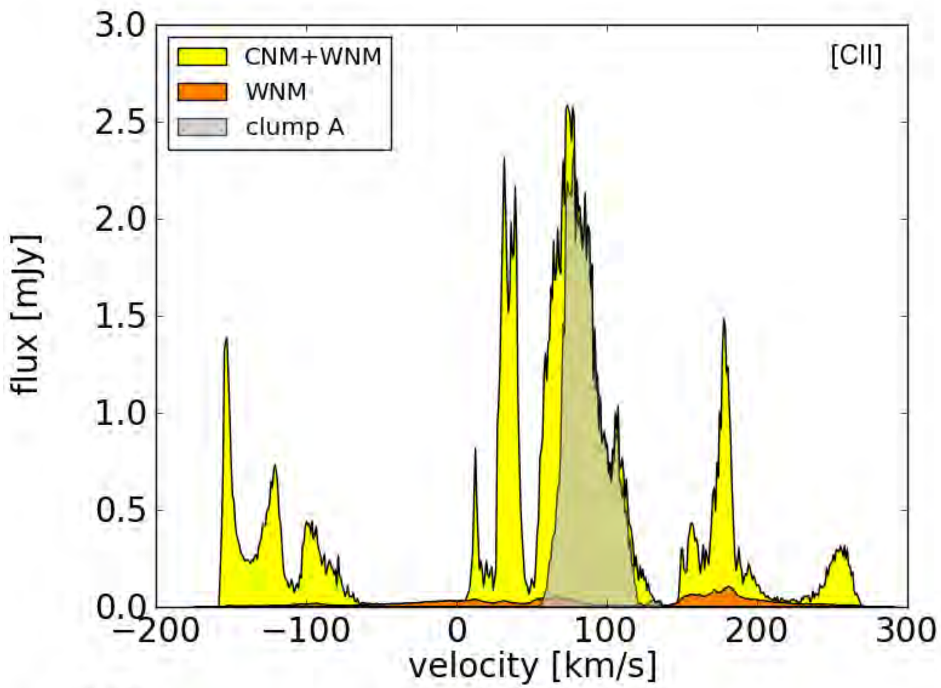


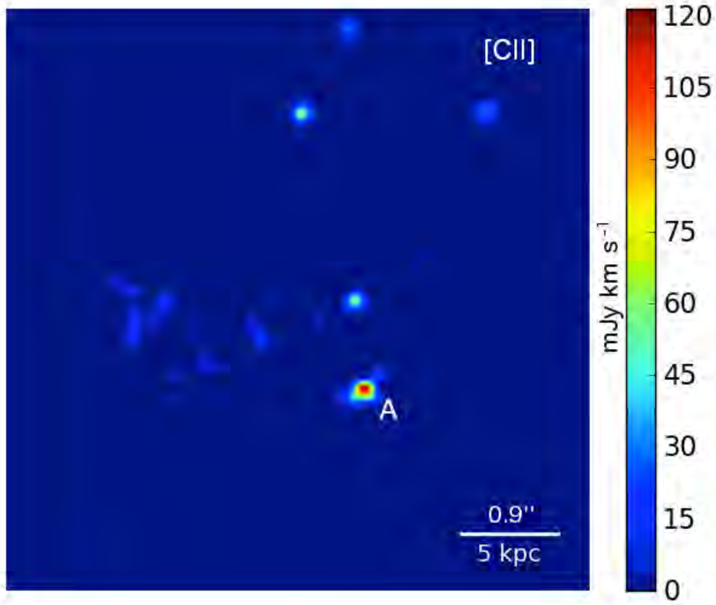


95% of the [CII] emission in the diffuse medium originates from the cold neutral medium

Vallini, SG, et al. (2013)

Predictions for the [CII] emission in high-z galaxies





Predictions for ALMA observations for $0.02 < Z < Z_{\odot}$

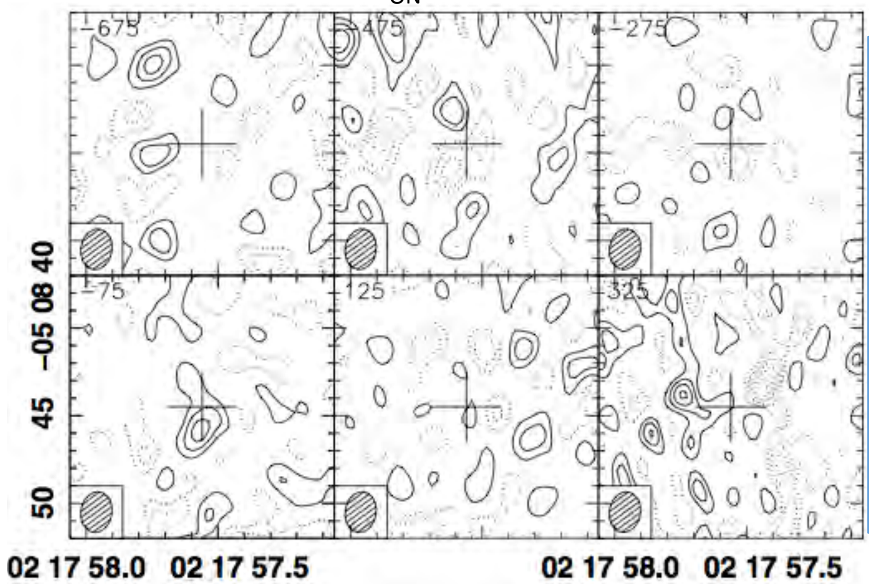
5σ detection
in 4 channels of 25 km s^{-1} → 1.9 h $< t_{ON} < 7.7$ h (full array)

Vallini, SG, et al. (2013)

PdBI observations of HIMIKO

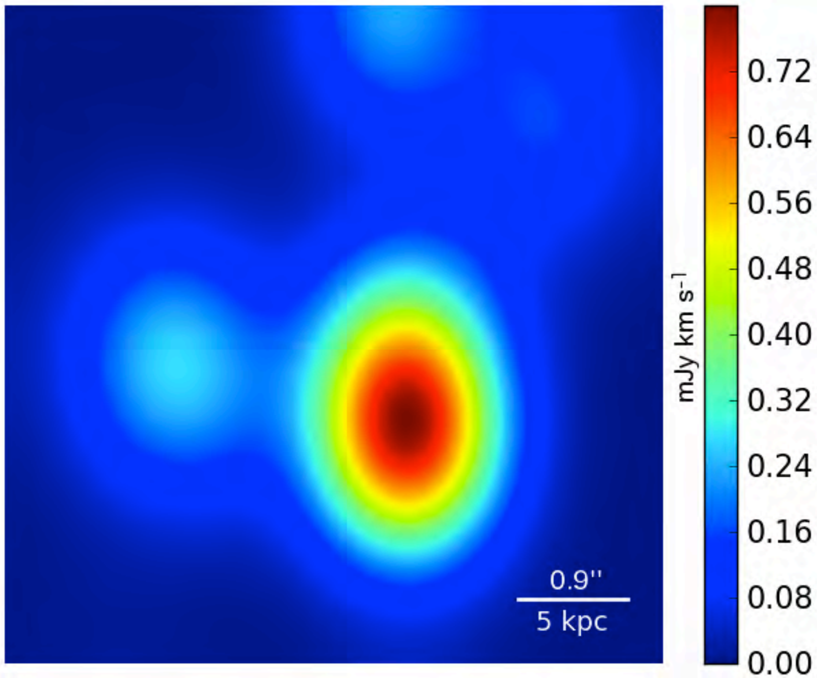
Undetected CII emission

Walter et al. (2012) t_{ON} = 11.5 h beam: 2.3'' x 1.7''

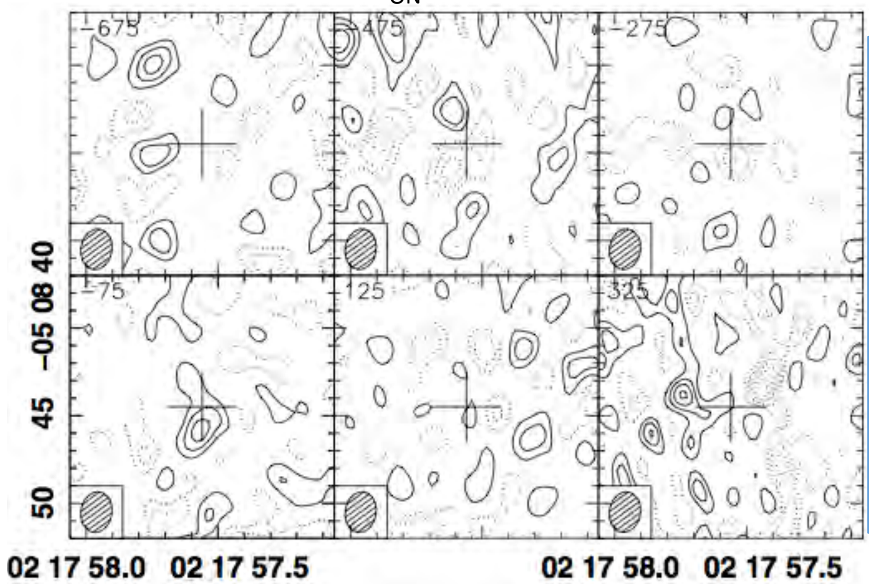


Contours levels in steps of 1σ (0.70 mJy beam^{-1})

Comparison with PdBI observations of HIMIKO



Walter et al. (2012) t_{ON} = 11.5 h beam: 2.3'' x 1.7''



Contours levels in steps of 1σ (0.70 mJy beam^{-1})

Constraints on the Himiko metallicity

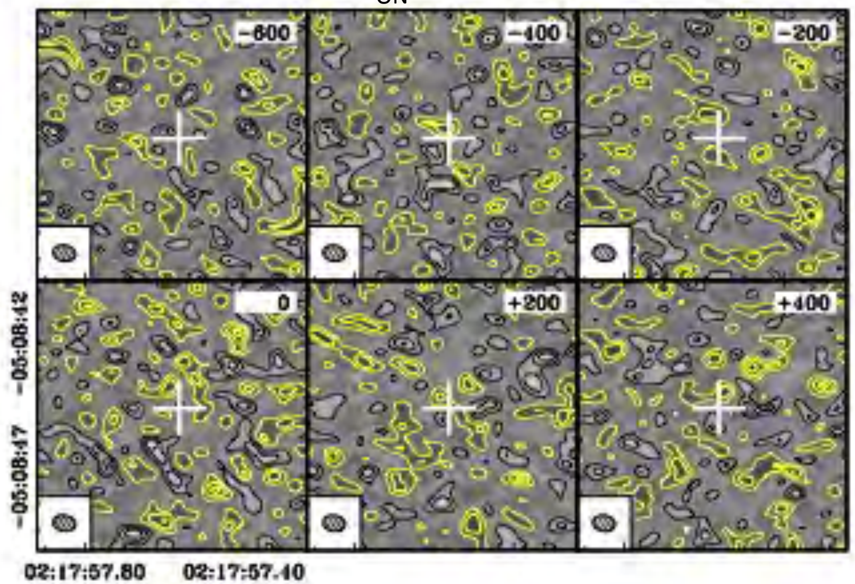
$$Z < Z_{\odot}$$

Vallini, SG, et al. (2013)

ALMA observations of HIMIKO

Undetected CII emission

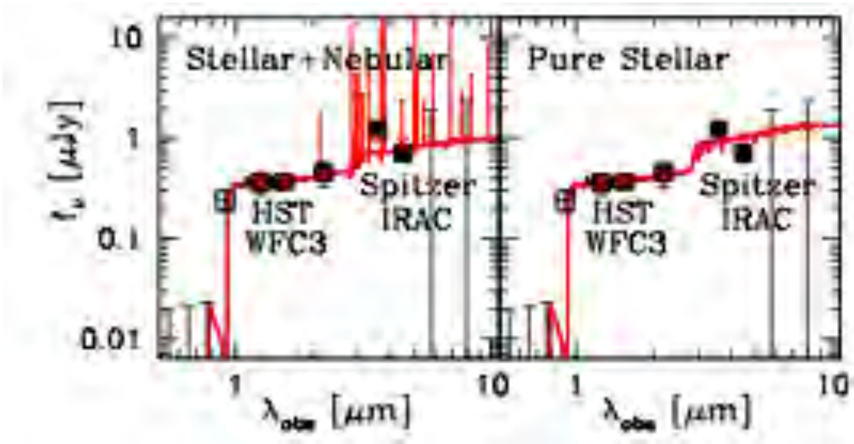
Ouchi et al. (2013) t_{ON} = 3.2 h beam: 0.8'' x 0.6''



Contours levels in steps of 1σ (0.08 mJy beam^{-1})

Comparison with ALMA observations of HIMIKO

SFR = 100 $M_\odot$ yr^{-1}



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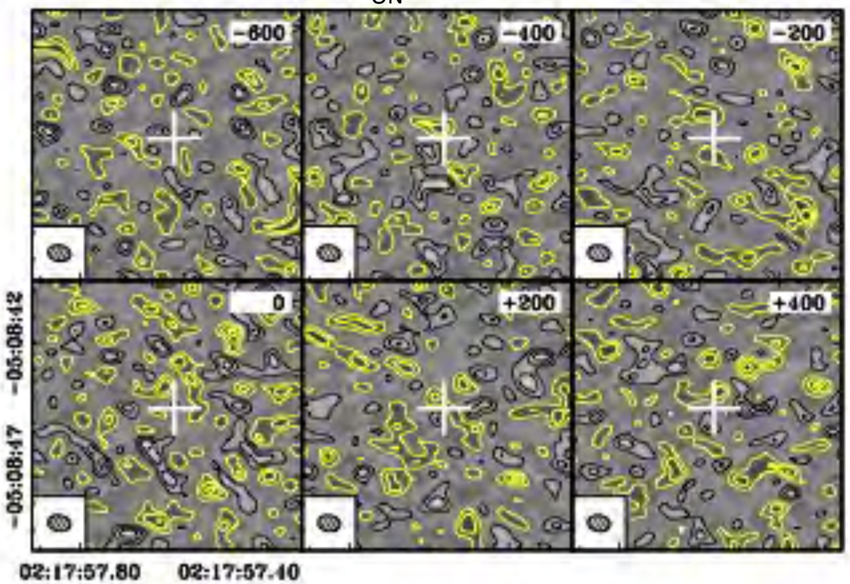

Contours levels in steps of 1σ (0.08 mJy $beam^{-1}$)

Stronger constraints on the Himiko metallicity

$Z < 0.02\, Z_\odot$ (Preliminary results)

FIR emission lines in high-z quasars and galaxies

Summary

- **SDSS 1148 at z=6.4**

  [CII] emission: evidence of a powerful quasar-driven outflow ($dM/dt \geq 3500\ M_{\odot} yr^{-1}$)

- **Himiko at z=6.7**

  [CII] emission: detection in $1.9 < t_{ON} < 7.7$ h with ALMA for $Z_{\odot} > Z > 0.02\ Z_{\odot}$

  constraint on the ISM metallicity: $Z < 0.02\ Z_{\odot}$

FIR emission lines in high-z quasars and galaxies

Summary and implications for cosmic reionization

- **SDSS 1148 at z=6.4**

  [CII] emission: evidence of a powerful quasar-driven outflow (dM/dt ≥ 3500 $M_\odot yr^{-1}$)

  Powerful outflows may enhance the escape fraction of ionizing photons.
  Are these kind of feedback processes ubiquitous?
  Any trend with redshift, SFR, M_*?

- **Himiko at z=6.7**

  [CII] emission: detection in $1.9 < t_{ON} < 7.7$ h with ALMA for $Z_\odot > Z > 0.02\ Z_\odot$

  constraint on the ISM metallicity: $Z < 0.02\ Z_\odot$

  Observations of several FIR lines may provide constraints on the SFR in LAEs,
  i.e. on their intrinsic Lyα emisson line,
  and therefore allow to improve constraints on the neutral hydrogen fraction.