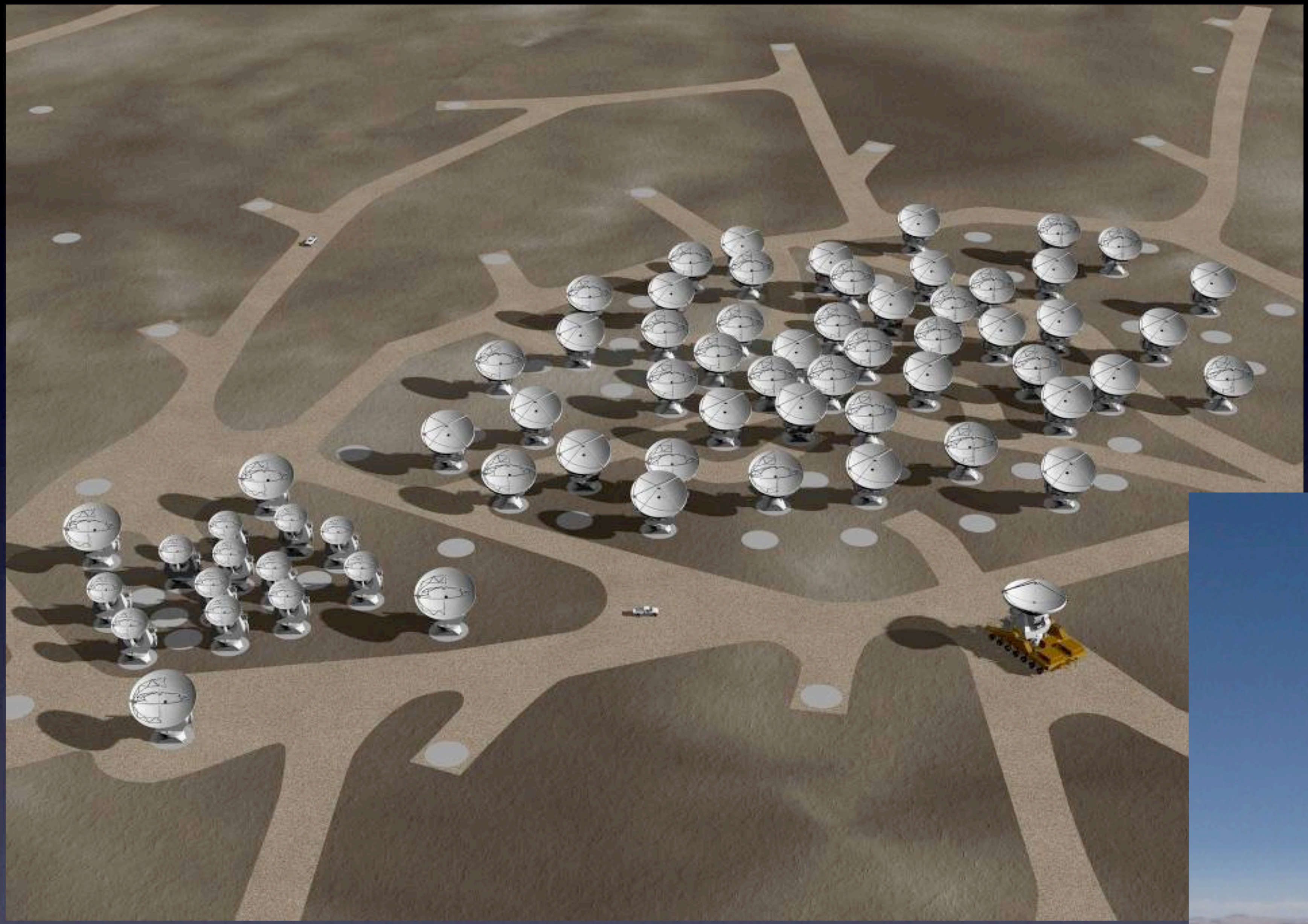
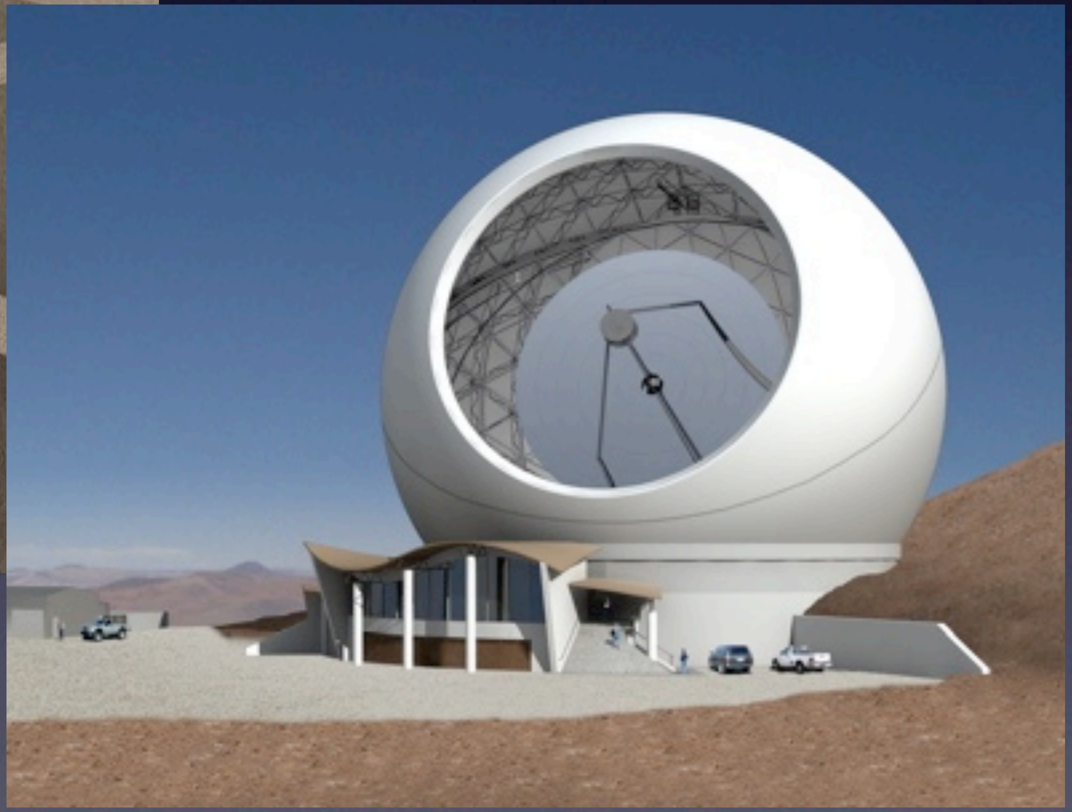
Some additional comments on

SZ Observations with ALMA / CCAT

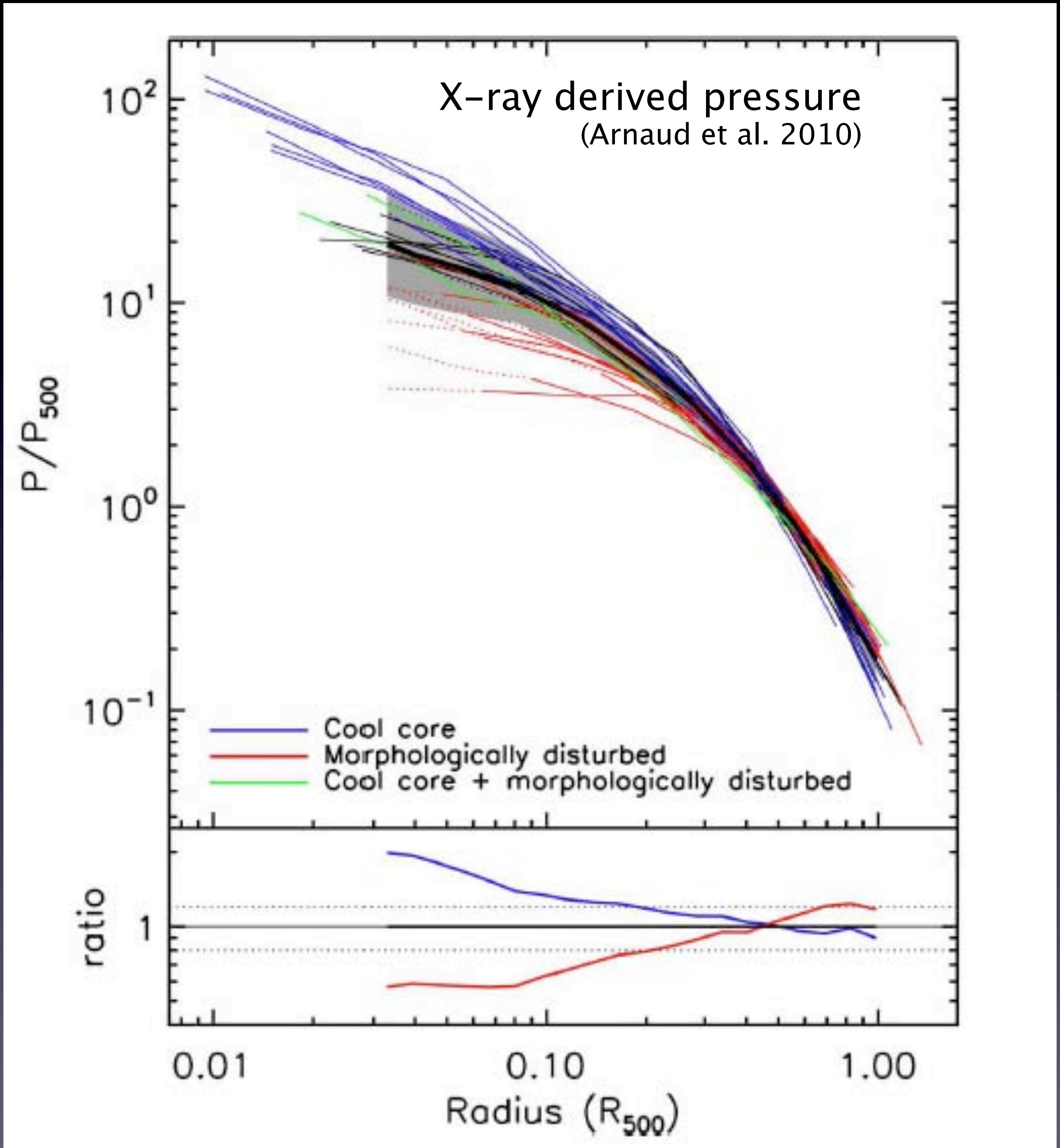




Kaustuv moni Basu, **Frank Bertoldi**

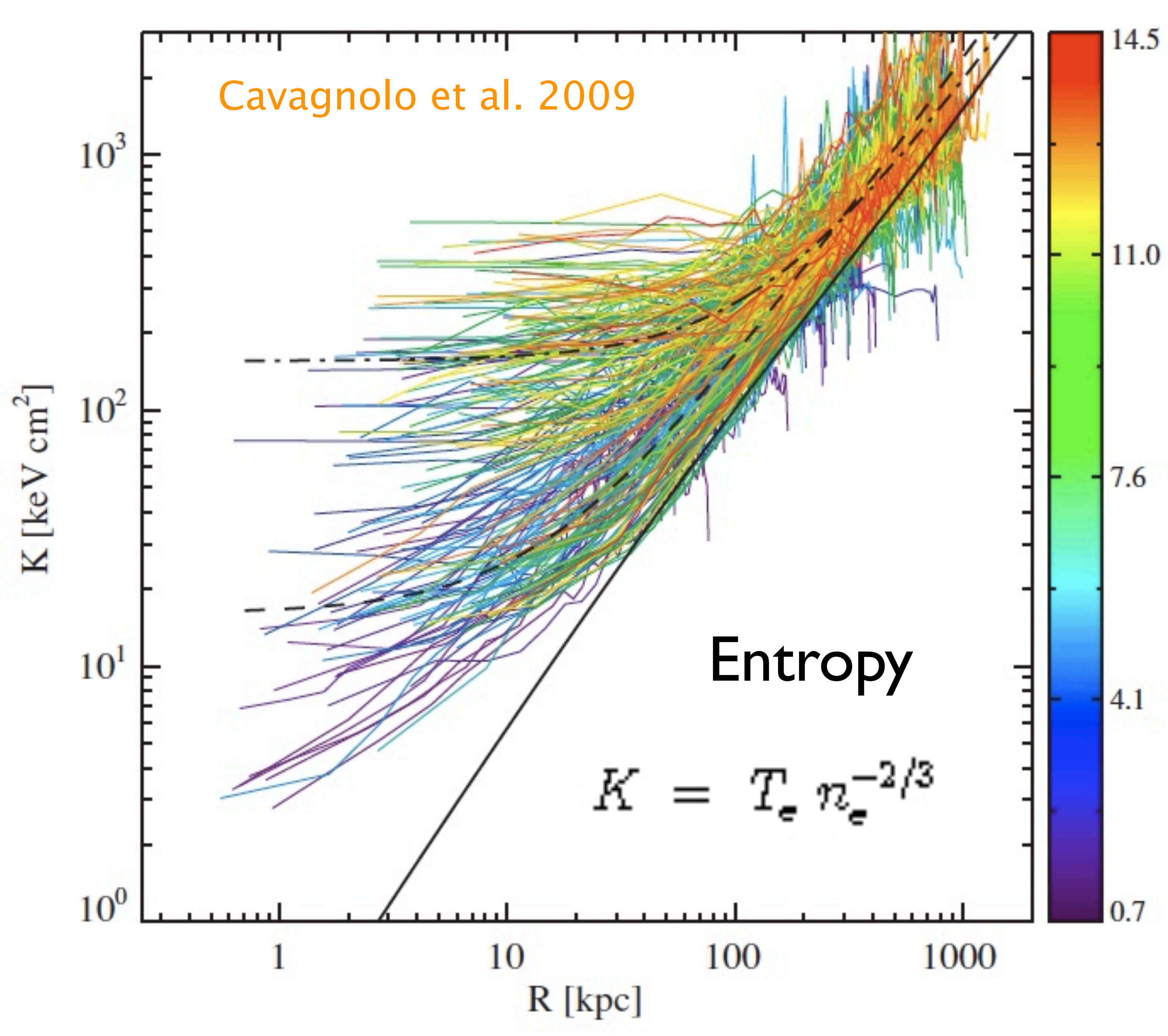
APEX-SZ collaboration

SZ with CCAT : Modeling cluster cores



- Recent X-ray analyses have shown that pressure profiles vary strongly with cluster morphology near the center
- Need SZ observations (X-ray spectral measurements can be biased)
- Steeply rising pressure profile near the center for cool core clusters can produce a bias in SZ cluster surveys, needs to be understood for precision cosmology.
- Understanding deviations from self-similar profile important to constrain role of AGN feedback and energy transport mechanisms near cluster cores

SZ with CCAT : Modeling cluster cores



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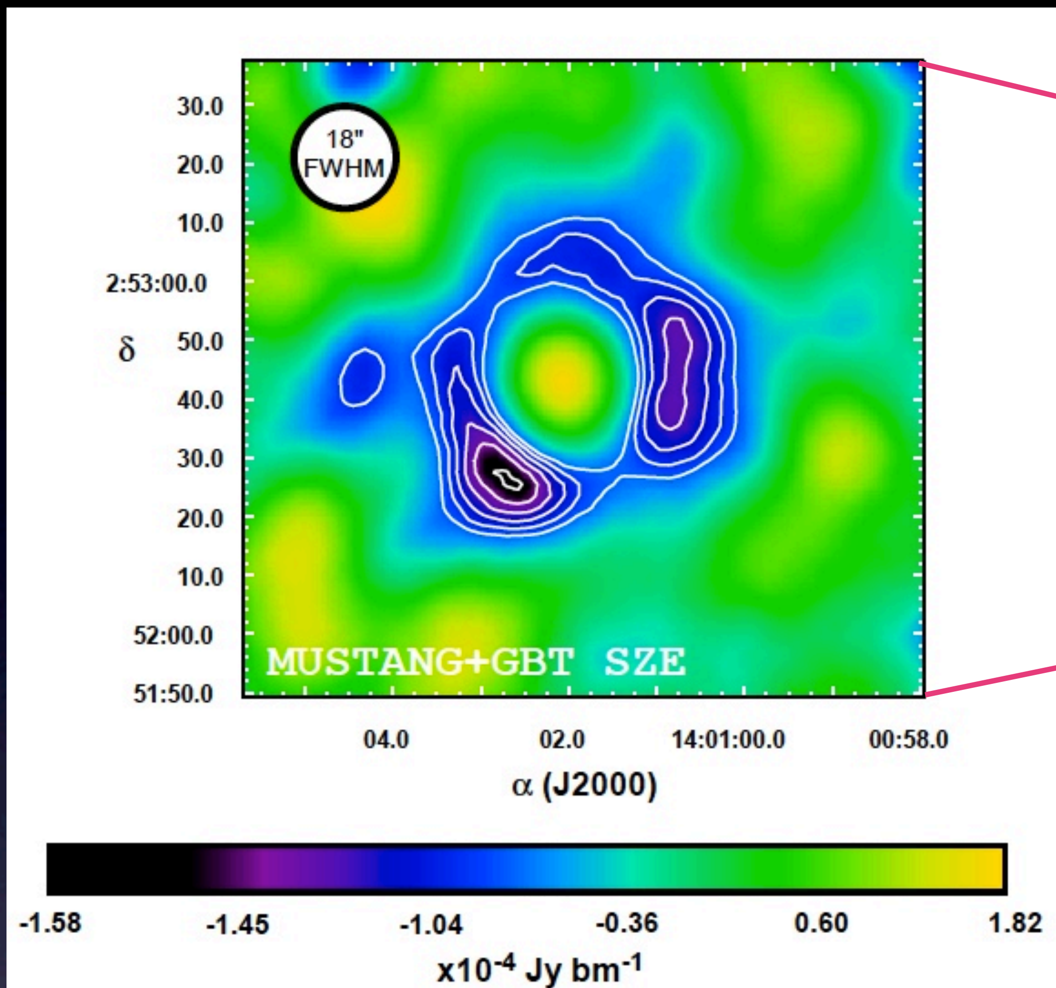
SZ with CCAT : Modeling cluster cores

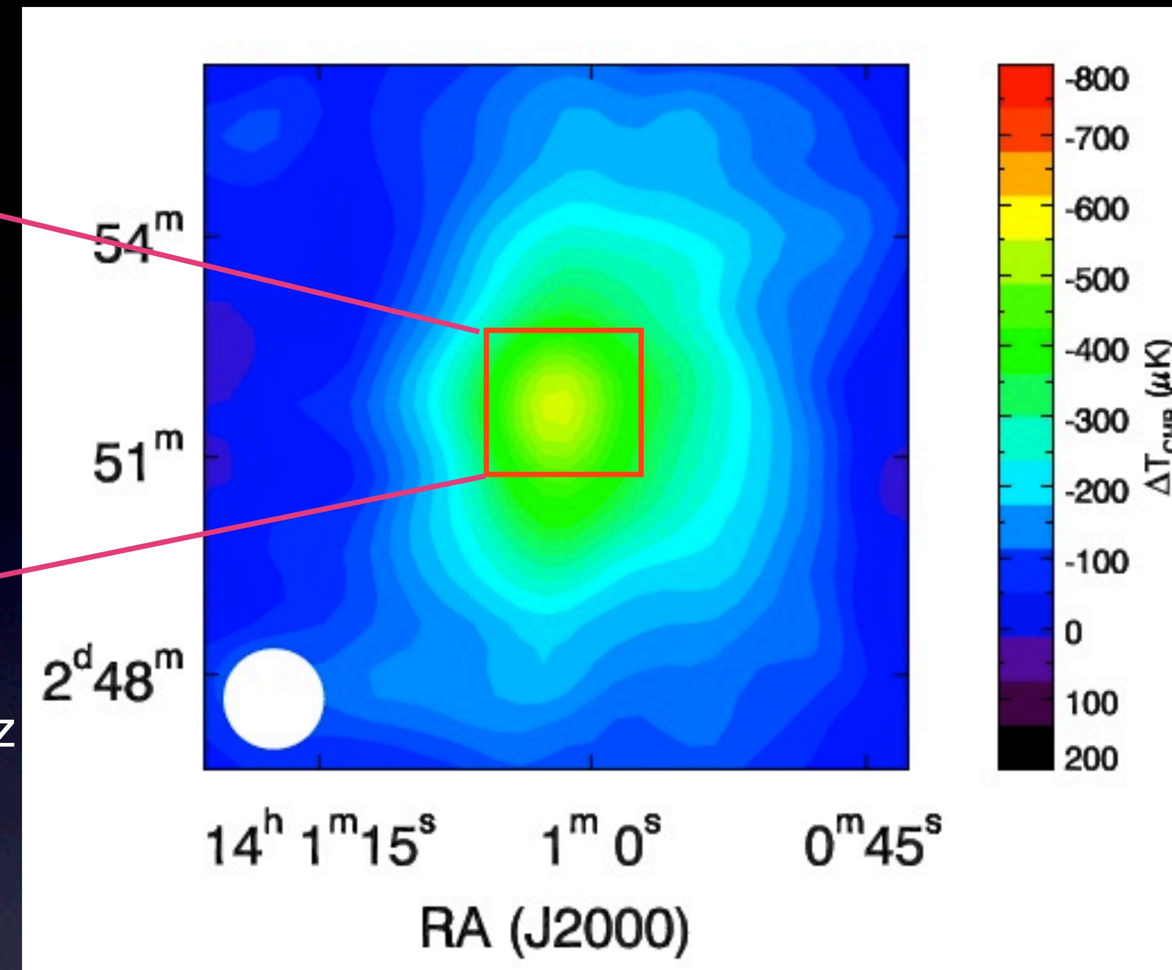


Korngut et al. 2010

Abell 1835
(CC cluster)

MUSTANG 90 GHz high resolution but only 42'' FoV

BOLOCAM 150 GHz 8' FoV with 1' FWHM beam (deconvolved image)

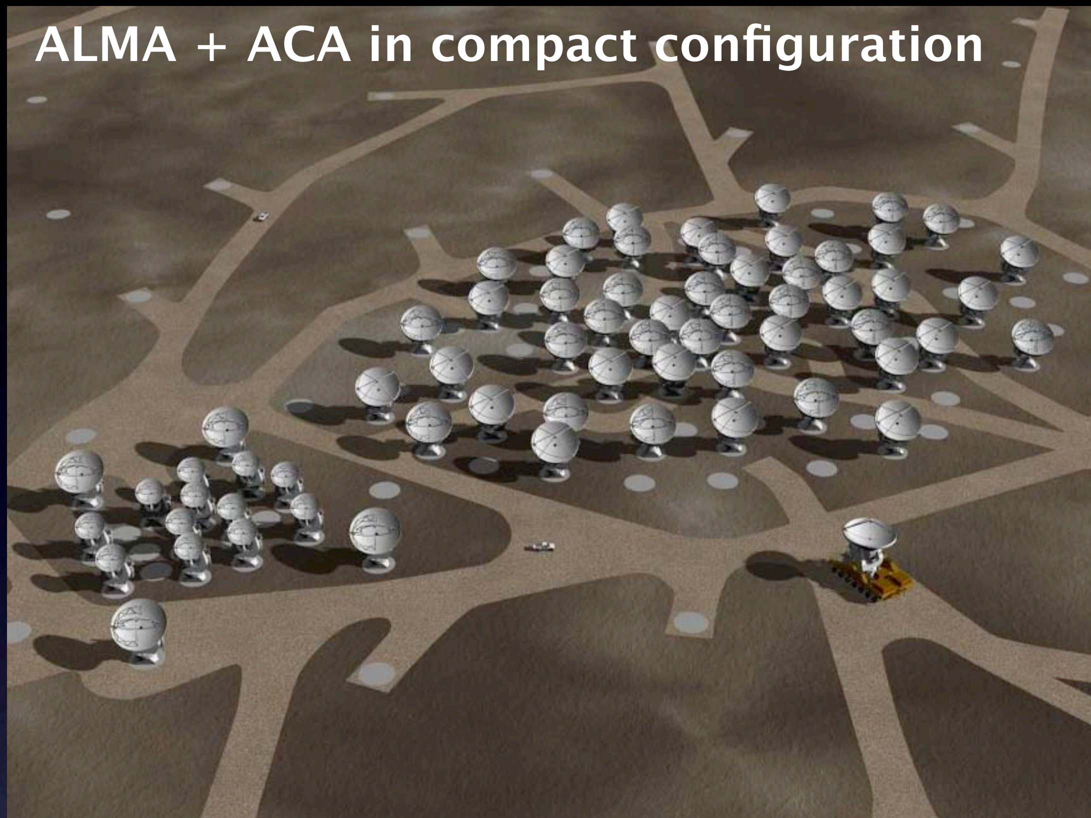


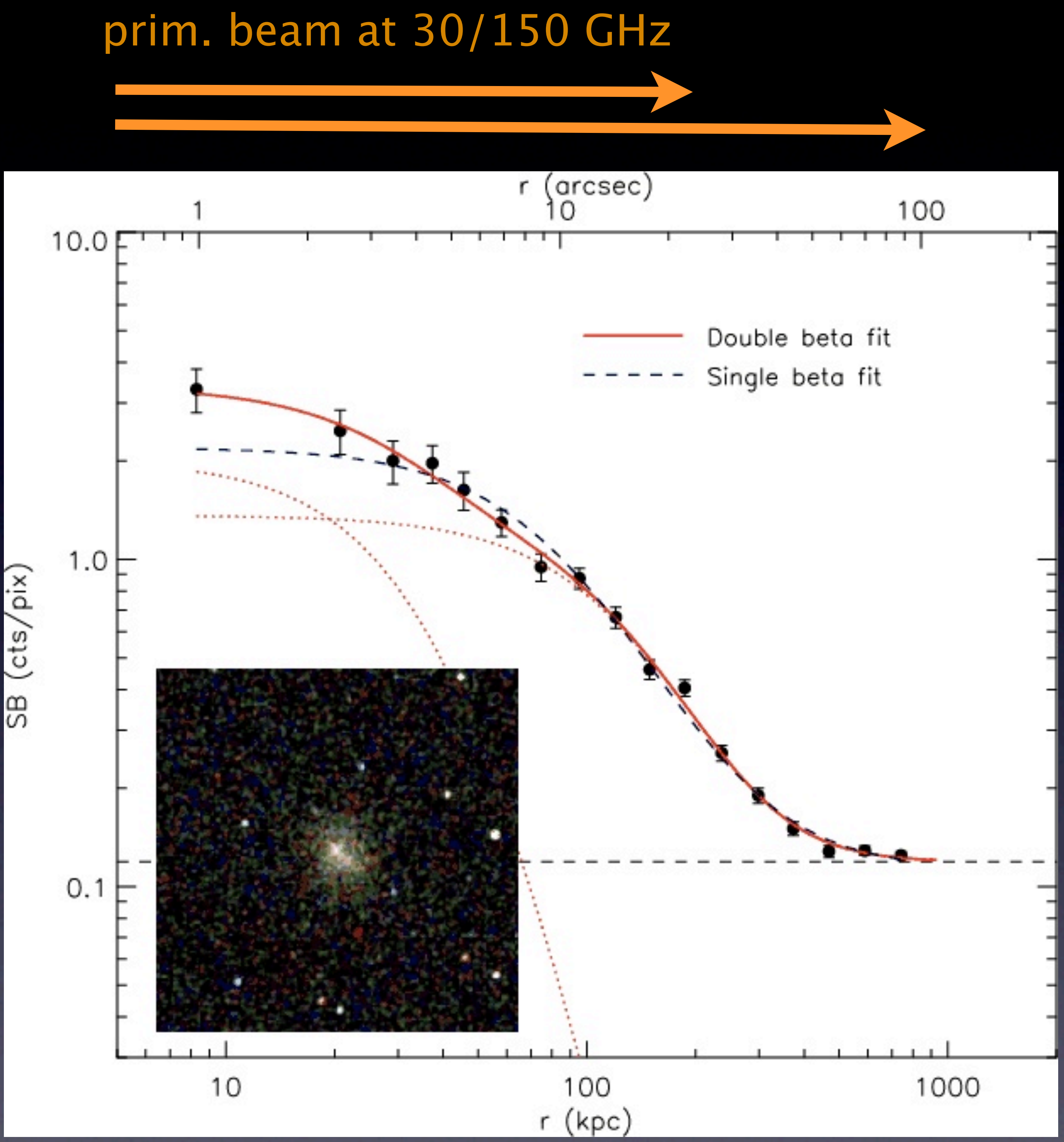
Sayers et al. 2010

We are currently attempting to combine APEX-SZ and MUSTANG data sets (Basu, Mroczkowski et al.), but this is non-trivial (more so if frequencies don't match)

CCAT with arcsec resolution and >20 arcmin FoV will easily overcome this problem!

SZ with CCAT : Complementing ALMA

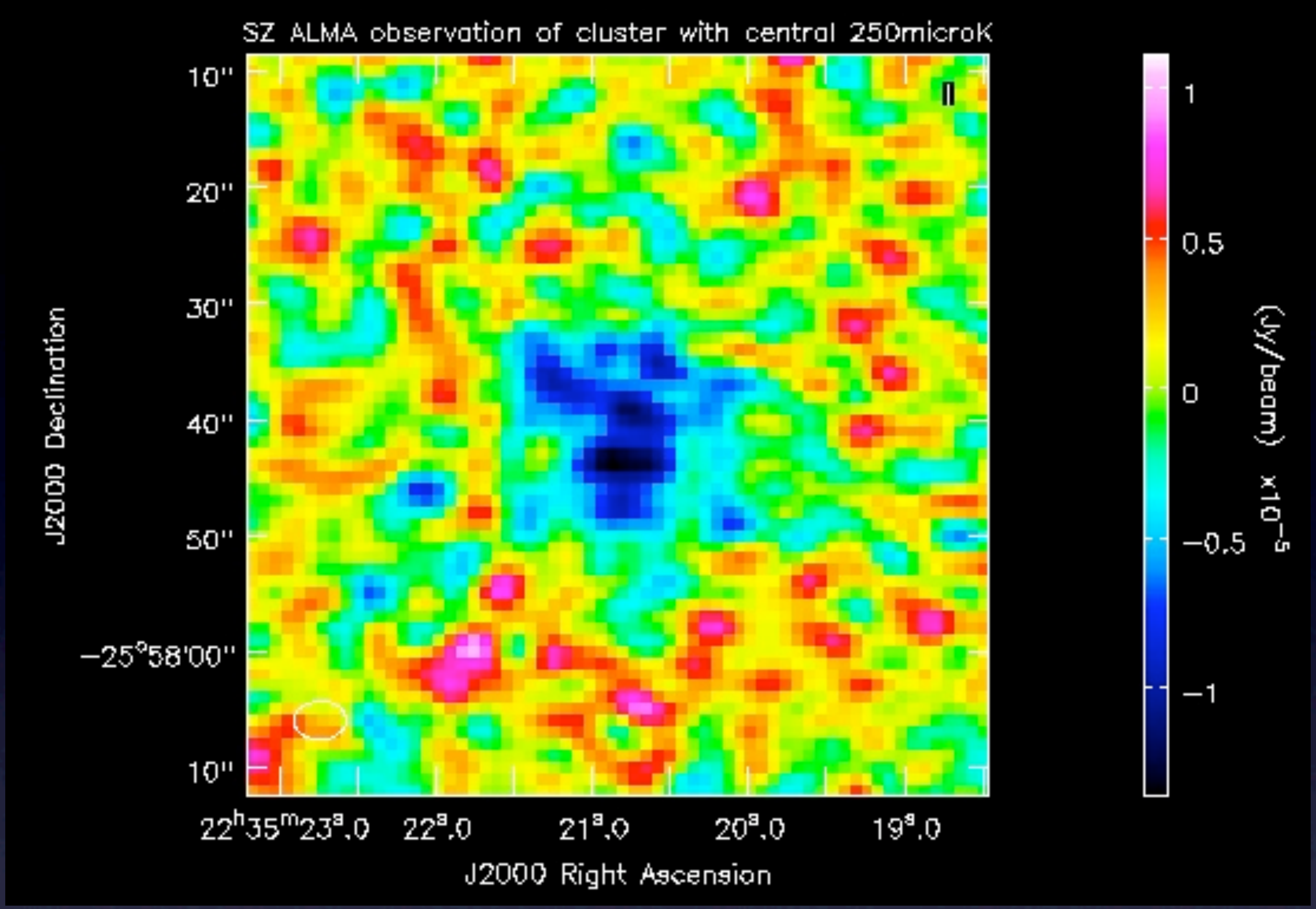


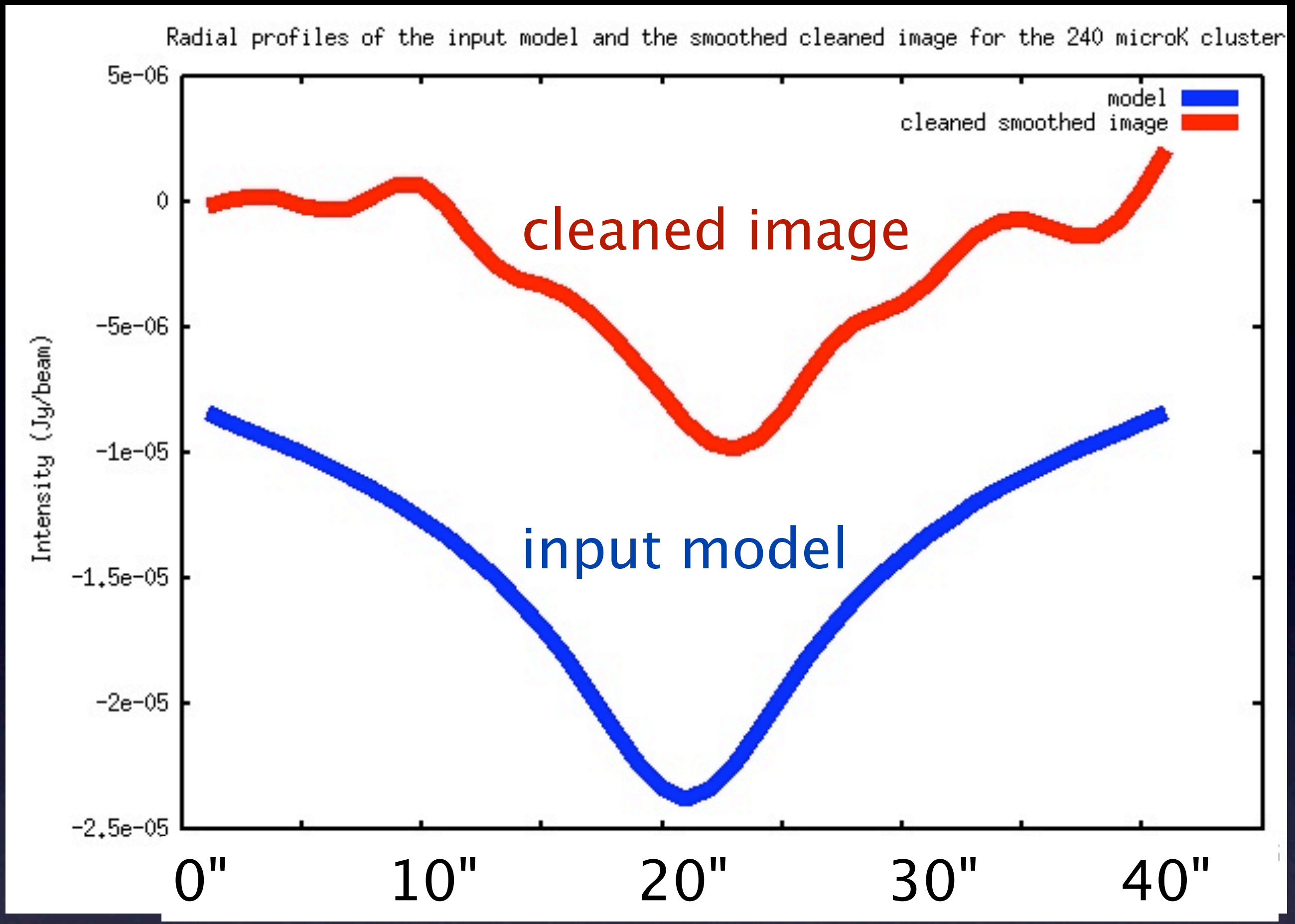


Clusters are extended objects, so even for the high-z compact ones zero-spacing information will be necessary

XMM J2235.3-2557 (z=1.39)
Rosati et al. 2009

SZ with CCAT : Complementing ALMA





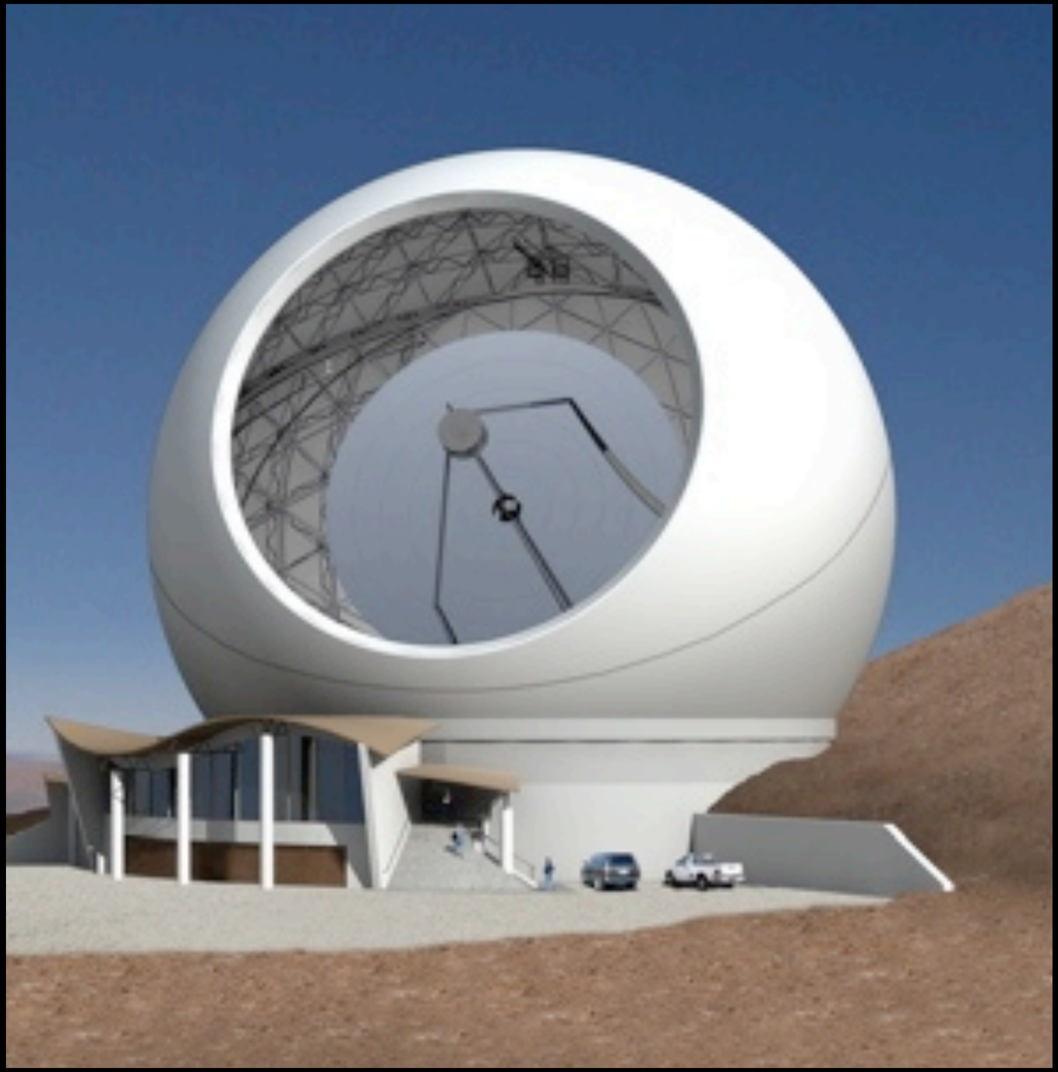
Simulated ALMA observation of XMMJ2235 at z=1.39 (Basu, Burkutean et al., in prep)
The cluster image at 110 GHz (left) and radial cut (right). Need of zero-spacing is evident!

SZ zero-spacing with bolometers is practicable, since the spectral shape of the SZ signal inside the bolometer band is known

CCAT will be the ideal choice for complementing ALMA!

The most distant Galaxies: CCAT and ALMA

Frank Bertoldi
Bonn University

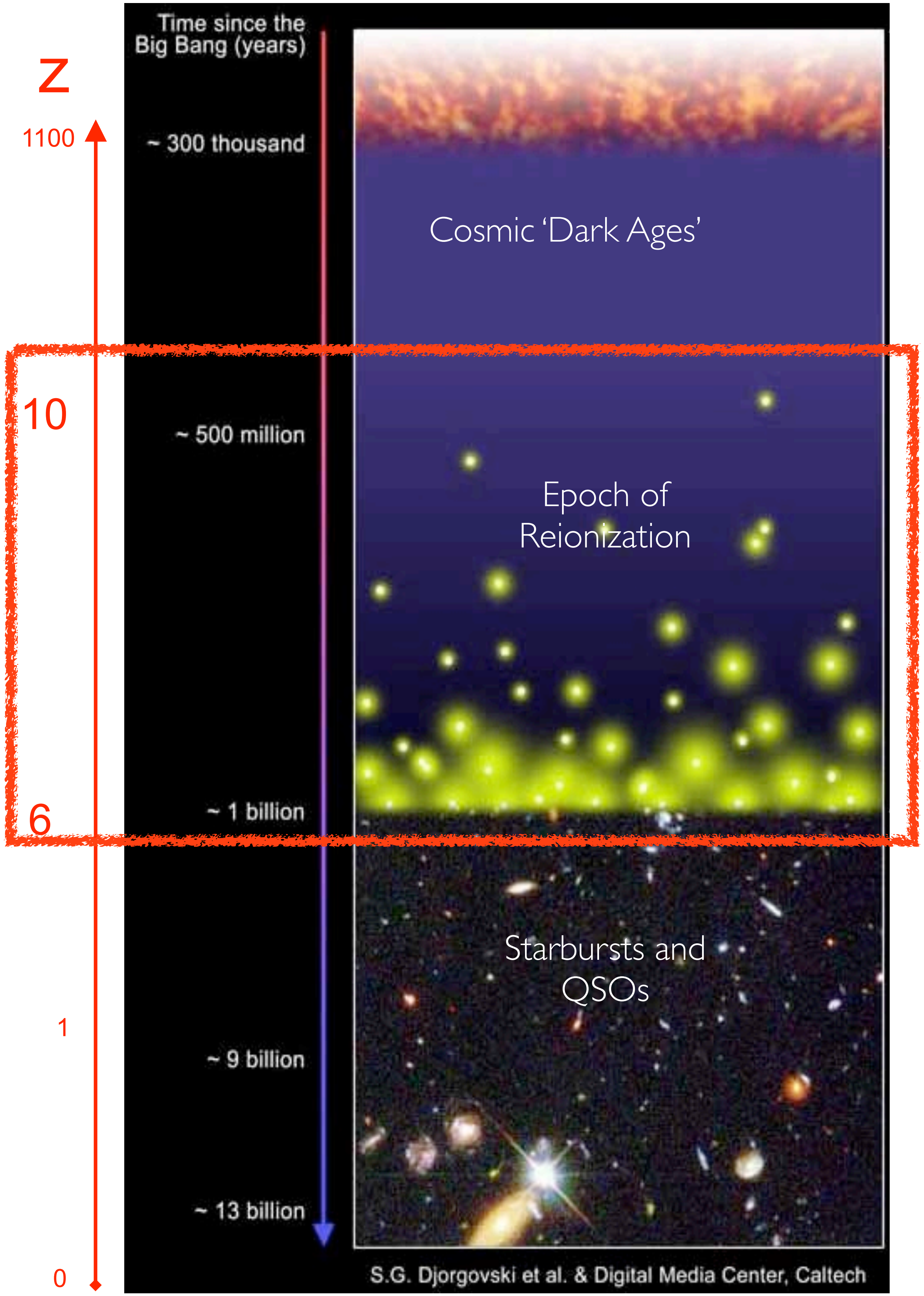


with thanks to:
Fabian Walter, Roberto Maiolino, Kirsten Knudsen, Chris Carilli, Dominik Riechers, Pierre Cox, Roberto Neri, Ran Wang, Axel Weiss, Xiaohui Fan, Thomas Greve, a.m.o.

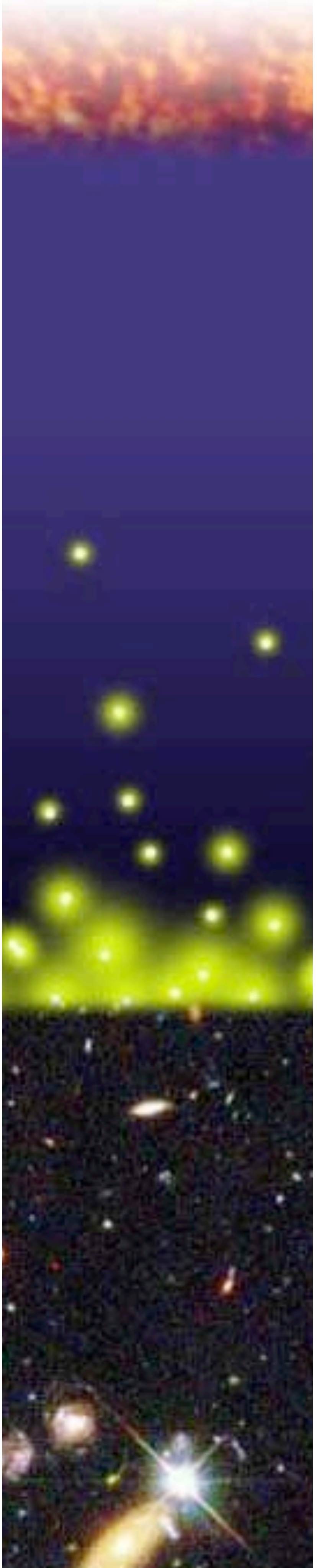
Most star formation later in the early Universe, but let's focus on

Epoch of Reionization

key benchmark in cosmic structure formation



- CMB polarization suggests ionization to z=11±3 (Page '06)
- complex process, variance in space & time (Fan '06)
- Gunn-Peterson absorption at z>6
  ➠ optically obscure



Studies of z>6 Sources: Why care?

Sources responsible for <u>reionization</u>
SMBH, Fe/α high, rapid <u>enrichment</u>

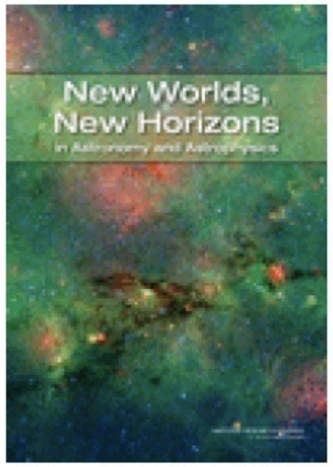
Constrain: SFR (contribution to reionization)
M_{gas} (fuel for SF & evol. state)
M_{dyn} (hierarchical models, M-σ)

Probe the state of the <u>IGM</u>!

<u>Galaxies</u> now detected to z=7.0,8.2 (500 Myr after Big Bang)

We ***know*** that they must have formed <u>stars at z>8</u>
z=8 ⇨ z=10: 150 Myr

Key waveband: submm (FIR ISM cooling lines, molecules, dust)



New Worlds, New Horizons in Astronomy and Astrophysics

Committee for a Decadal Survey of Astronomy and Astrophysics; National Research Council

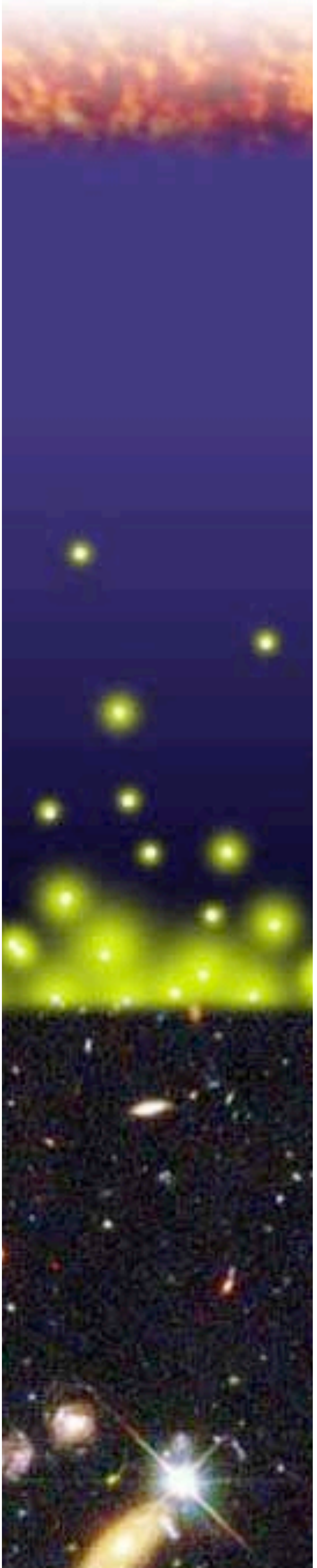
ISBN: 0-309-15800-1, 270 pages, 7 x 10, (2010)

Cosmic Dawn: Searching for the First Stars, Galaxies, and Black Holes

Box 7.1 Implementing a Cosmic Dawn Science Plan

- Carry out simulations and theoretical calculations to motivate and interpret observations aimed at understanding our cosmic dawn.
- Find and explore the epoch of reionization using hydrogen line observations starting with the **HERA** telescopes that are already under construction.
- Use **CCAT** to identify the best candidate young galaxies for study with submillimeter observations.
- Study these galaxies in detail using **ALMA**; in particular, monitor how fast the gas that they contain is being converted into stars.
- Use **JWST** to measure the rate at which stars are being formed out of gas, and understand their role in reionizing the universe.
- Use **GSMT** to study the early evolution of infant galaxies using optical and infrared spectroscopy.
- Use **GSMT** and **IXO** to monitor the exchange of gas between the galaxies and the surrounding intergalactic medium.
- Study the rate of formation and growth of black holes in the nuclei of young galaxies using **IXO** and **WFIRST**.
- Employ **LISA** to measure the rate at which young galaxies merge through observing powerful bursts of gravitational radiation produced during the mergers of the nuclear black holes.
- Study the oldest stars in nearby galaxies using **GSMT**.

ALMA, Atacama Large Millimeter/submillimeter Array; CCAT, Cerro Chajnantor Atacama Telescope; GSMT, Giant Segmented Mirror Telescope; HERA, Hydrogen Epoch of Reionization Array; IXO , International X-Ray Observatory; JWST, James Webb Space Telescope; LISA, Laser Interferometer Space Antenna; and WFIRST, Wide-Field Infrared Space Telescope.



z>6 Sources: How to find them?

Broad band searches:

SDSS: ~dozen z~6 QSOs [7000 sq.deg.] [Fan et al. 06]

QSO record holder: J1148+5251 at z=6.42

UKIDDS/VISTA

PanSTARRS

Submm

Narrow band searches:

Lyα emitters: - z~6.6, [~30, 1/4 sq.deg.] - SFR~30 M_{sun}/yr

[Taniguchi et al. 05]

- z=5.7 in COSMOS [Muraya et al. 07]

Carilli et al. '07: radio (100) & mm (10) stacking

- z=6.98 [Iye et al. 06]

- z=8.8 non-det. [Cuby et al. 06]

Hα emitter: z~9.8 w/ IRS/Spitzer [Lacy et al. 06]

GRBs : already up to z=8.2 !

ALMA : (FOV: 1') will not be a survey machine

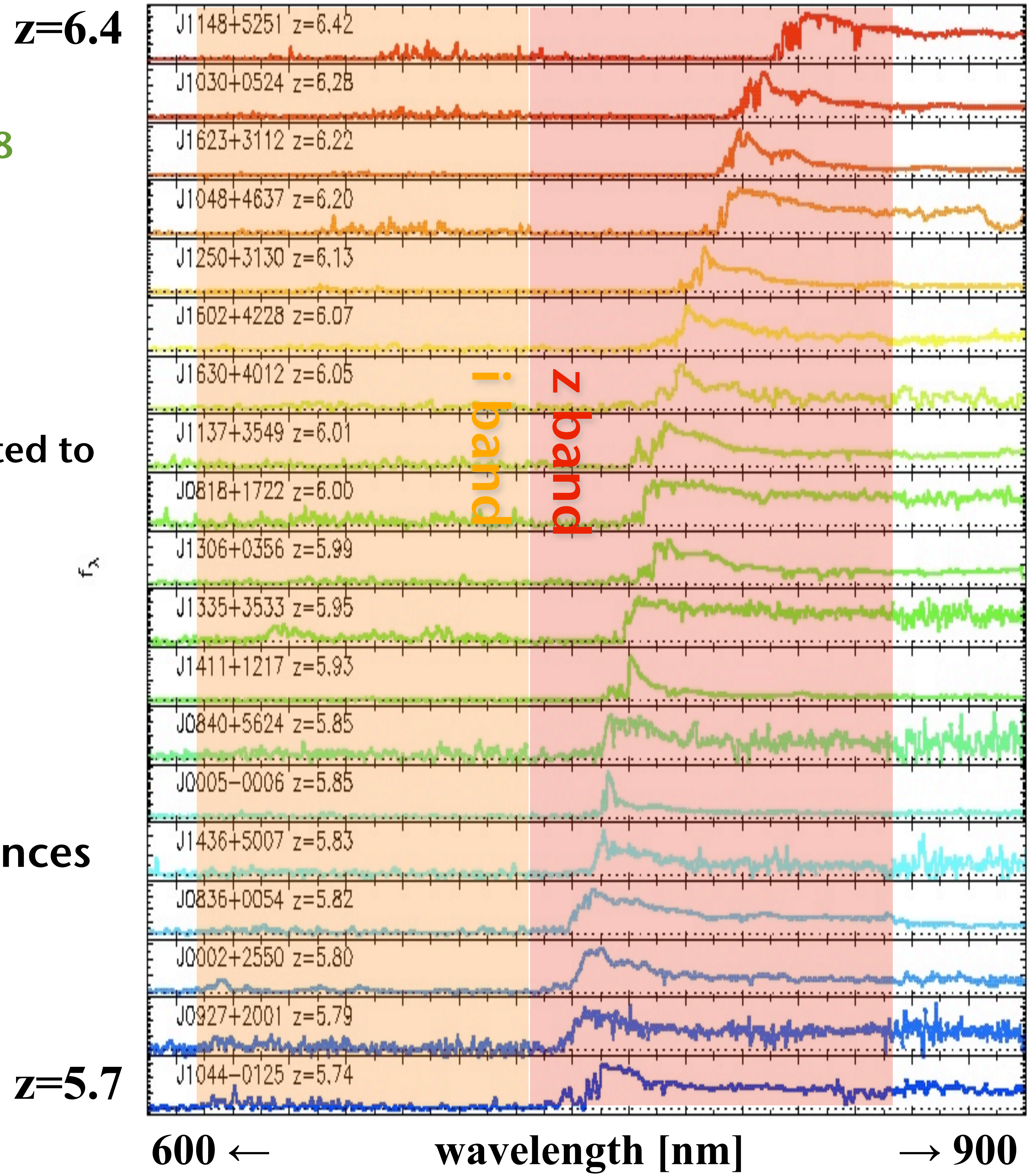
z~6 SDSS QSOs

Fan et al. 200N, N=3,4,5,6,8
see also CFHT z~6 quasars (Willott et al. 07, 09)

- GP effect

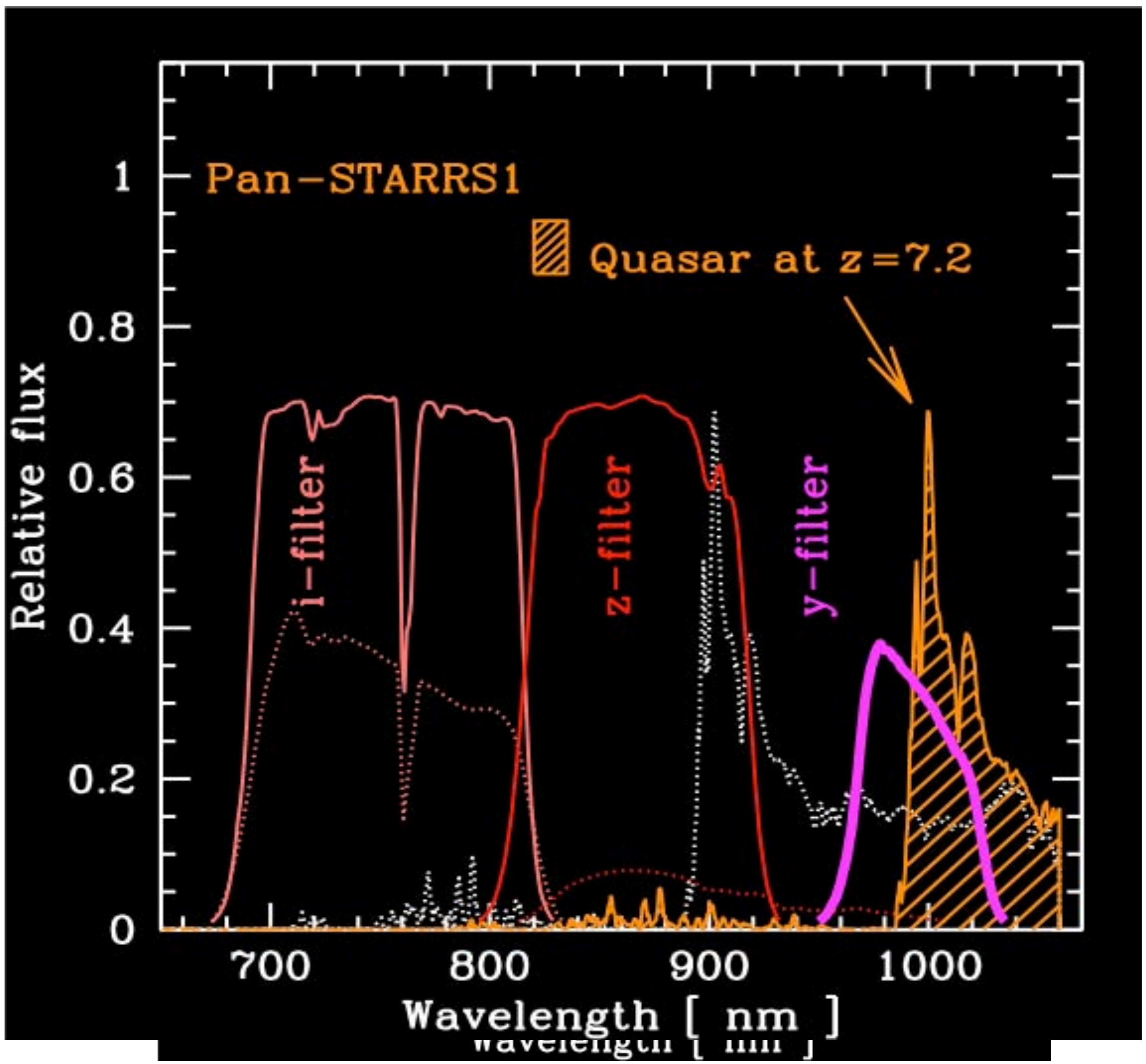
  study of 'first light' restricted to λ_{obs} > 1μm

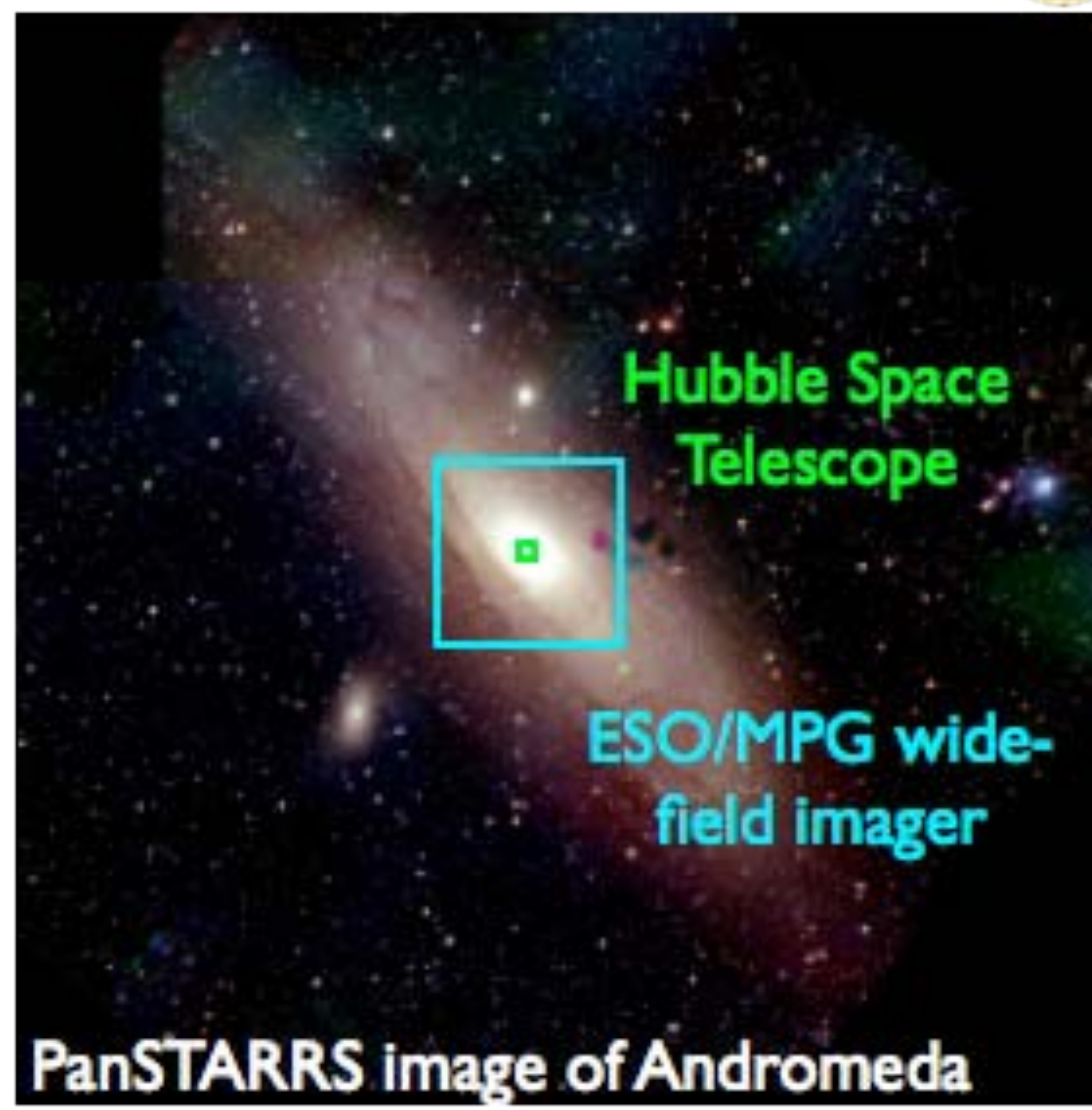
- NIR follow-up:
  - M_{BH}: ~10^9 M_o
  - Fe/α: ~solar abundances



redder filter than SDSS

→ search out to z=7.5

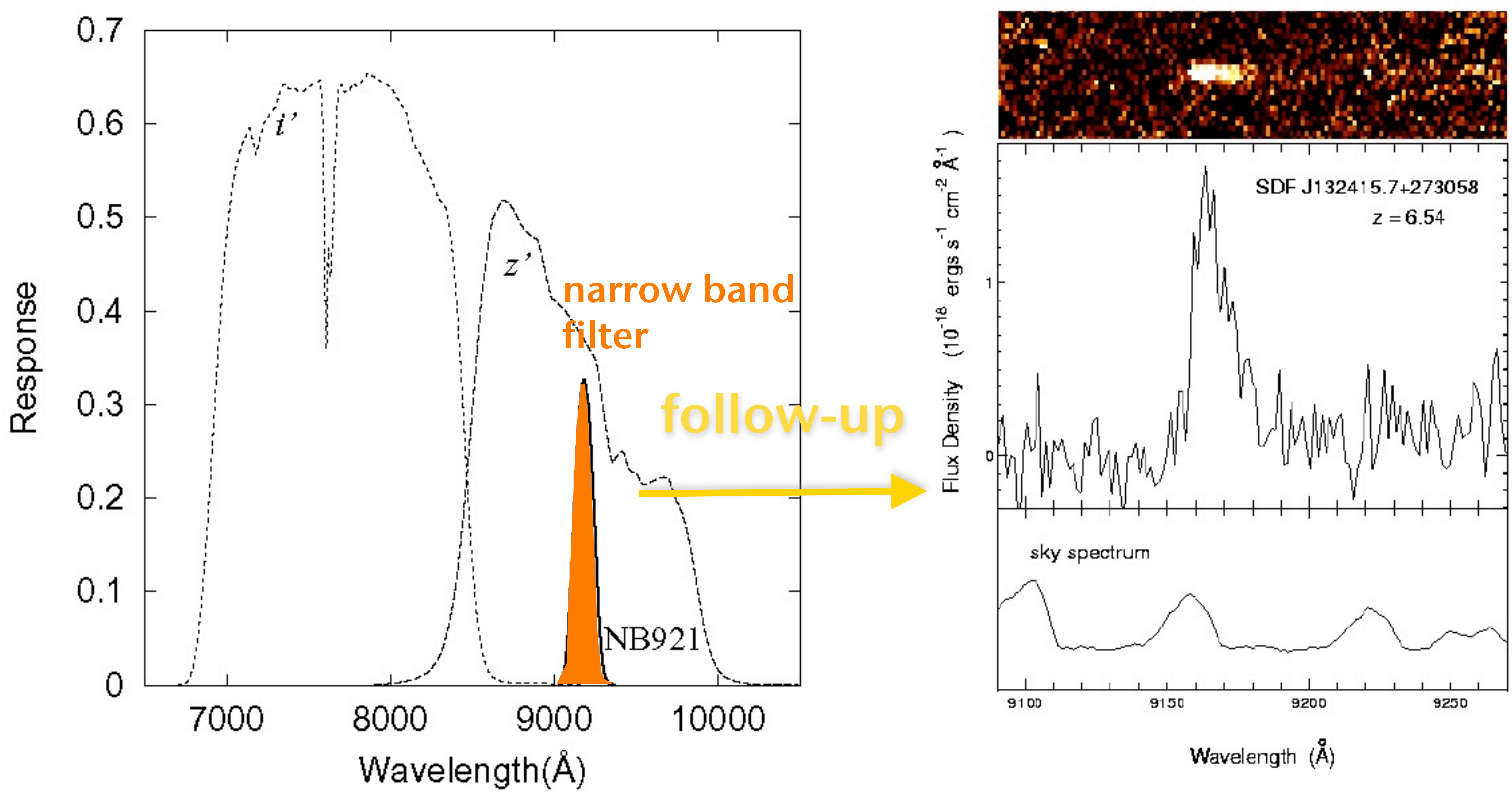




survey started May 2010

z=6-7 Narrow-band Lyman α searches

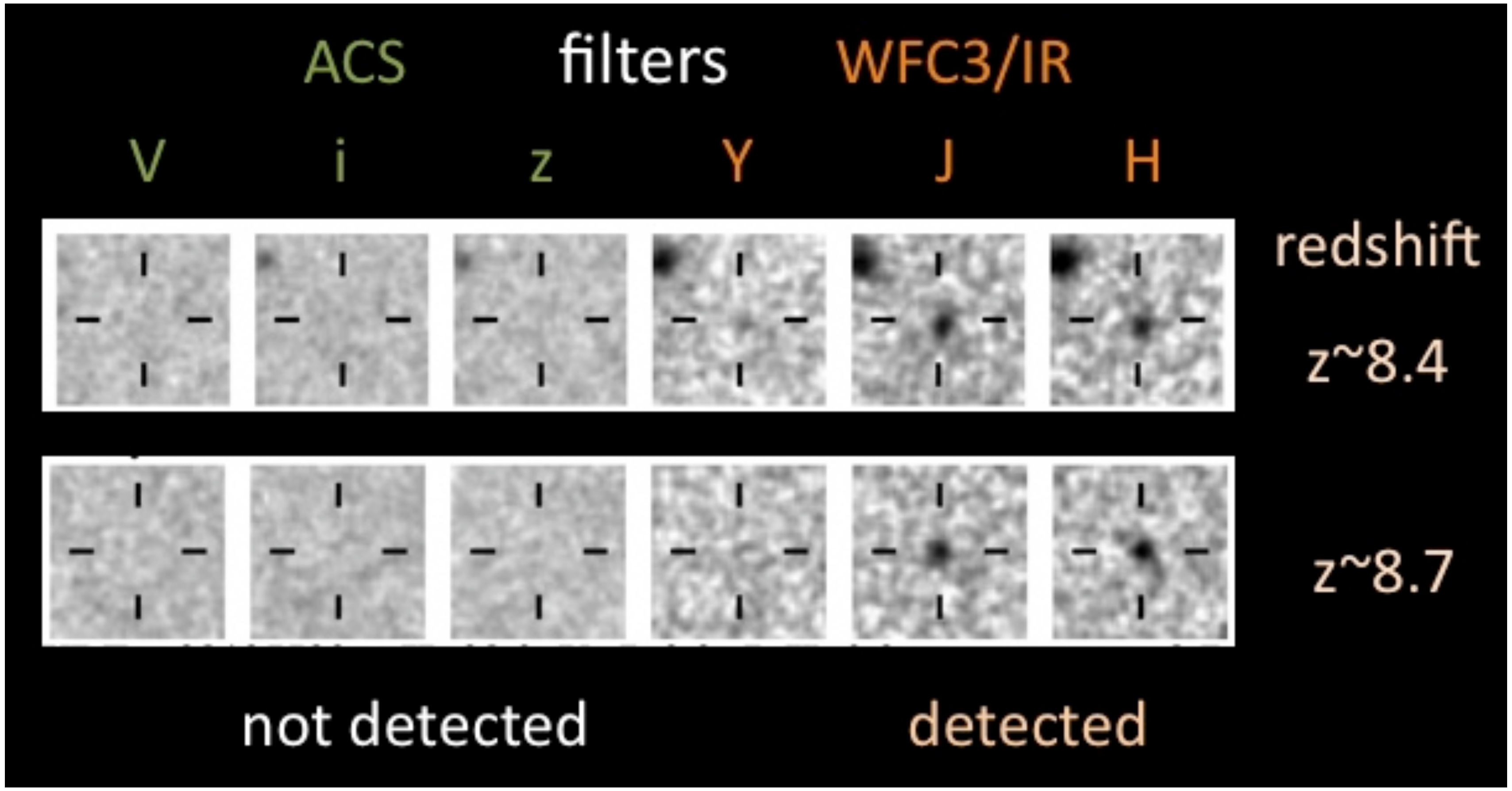
e.g., Subaru Deep Field (Taniguchi ea. 2005) - SFR: 10-60 M_{sun} yr^{-1}



2 prominent sources: Himiko z=6.6 (Ouchi et al. 09)
IOK-1 z=6.98 (Iye et al. 08)

WFC3 observations of z~8 galaxies

e.g., Bouwens ea. 2009, 2010



Y band dropouts

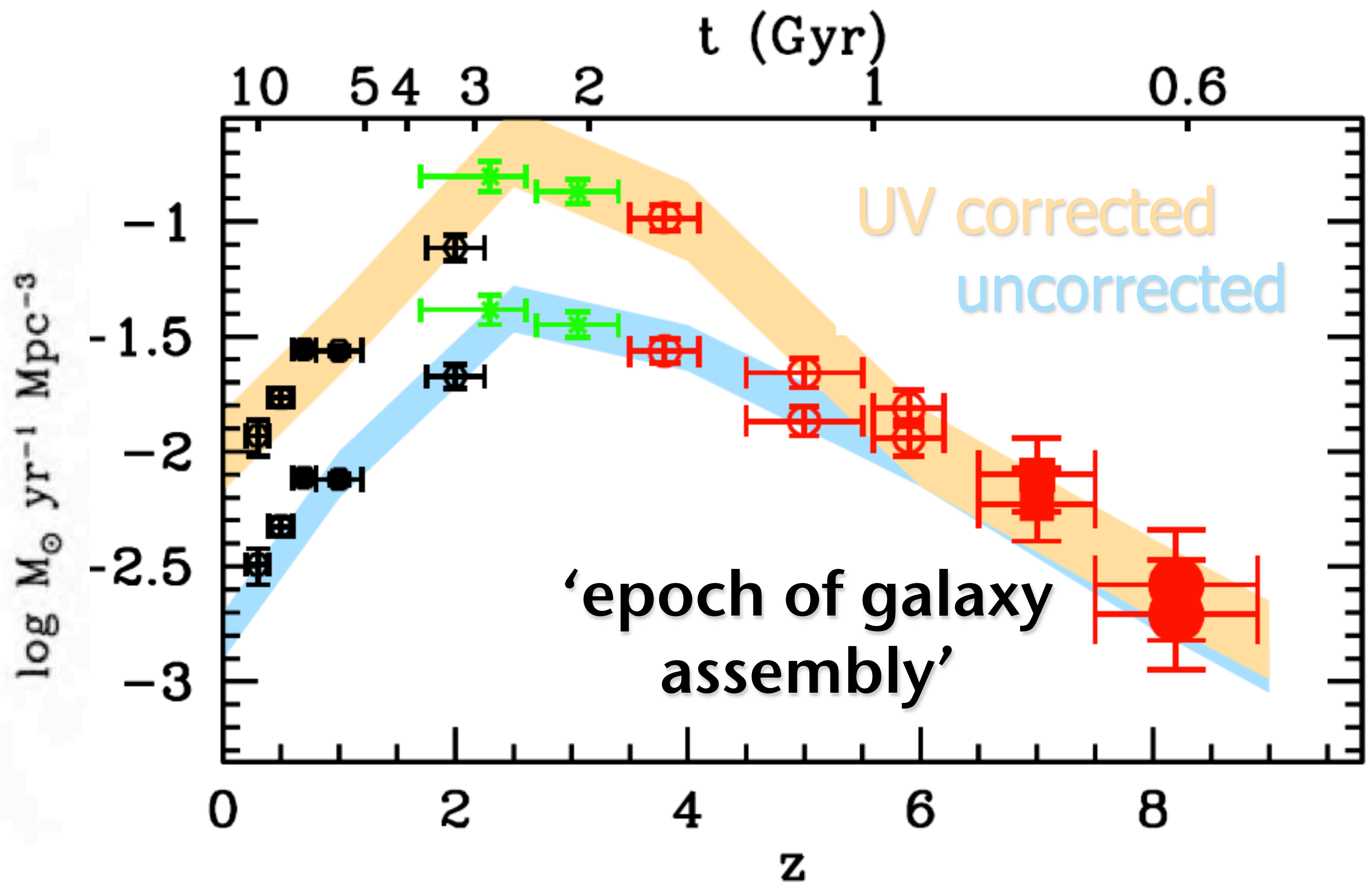
→ z=8-8.5

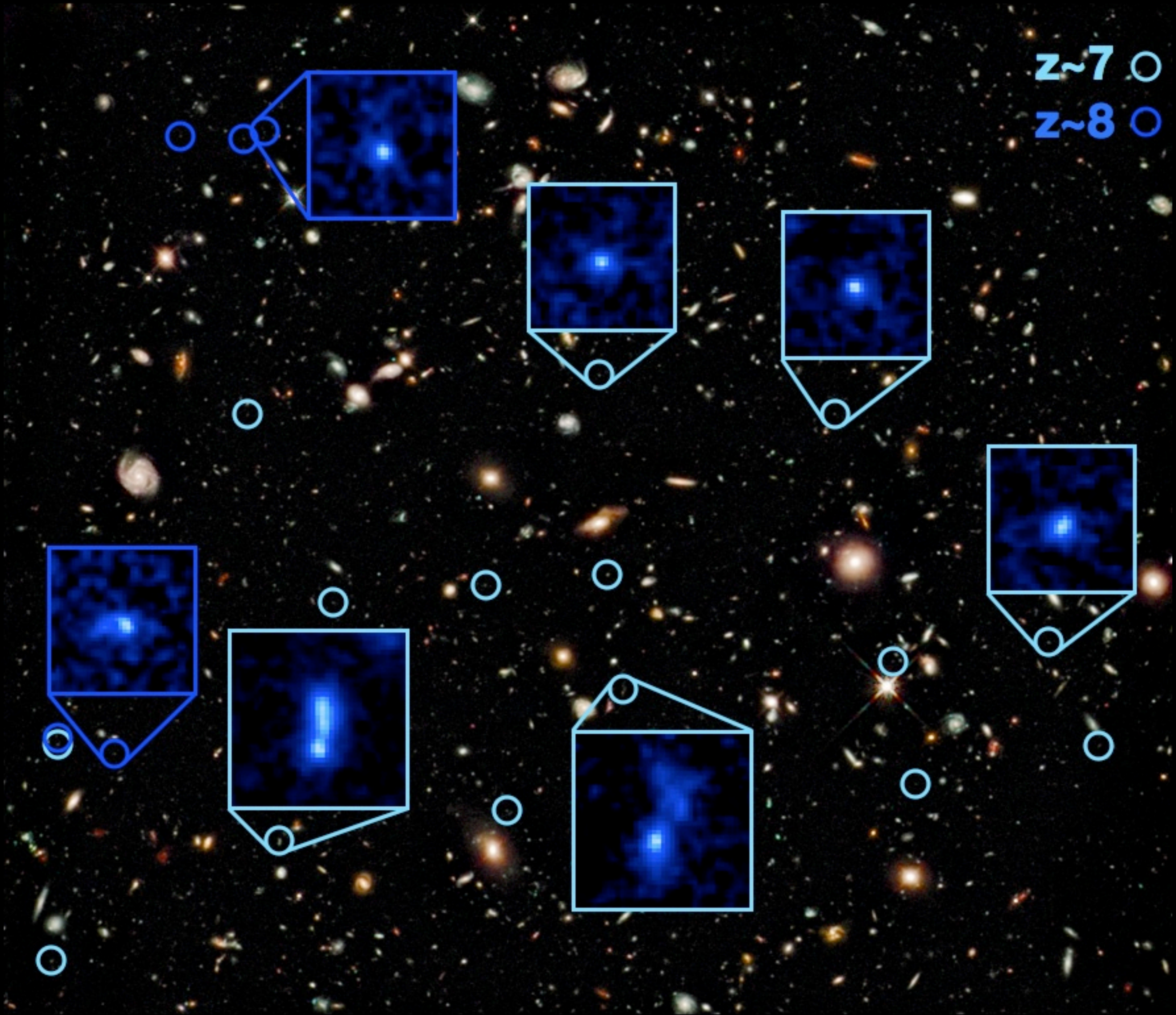
600 Myr after recombination

H mag ~28.5 (!!)

[cf. Quasars: 19-20]

SFR~1-10 $M_{sun}\ yr^{-1}$



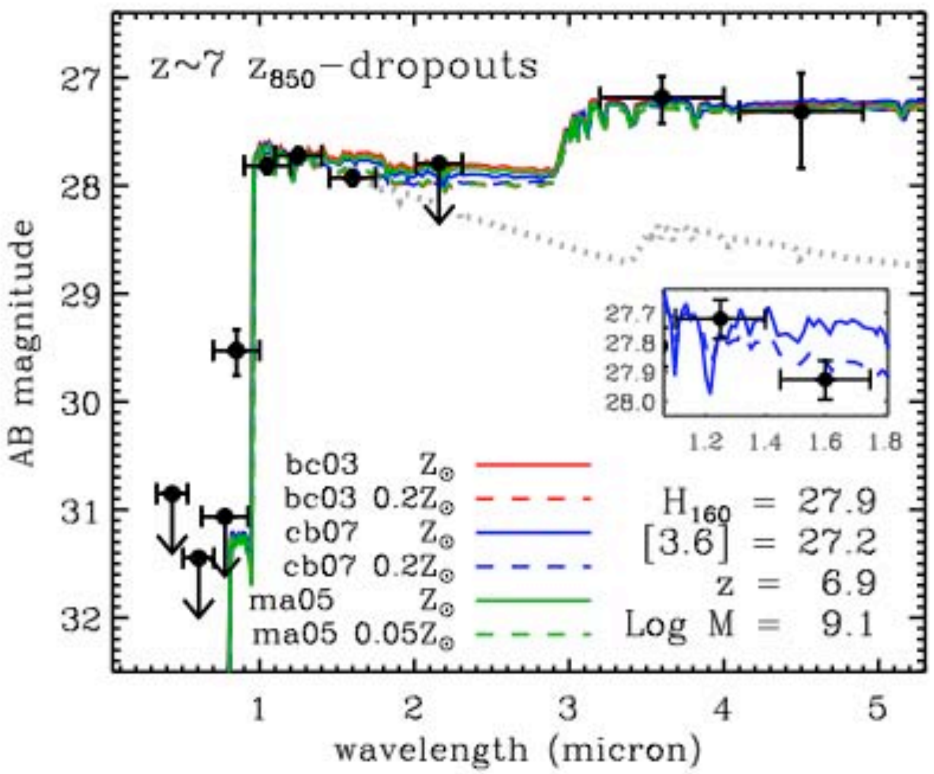


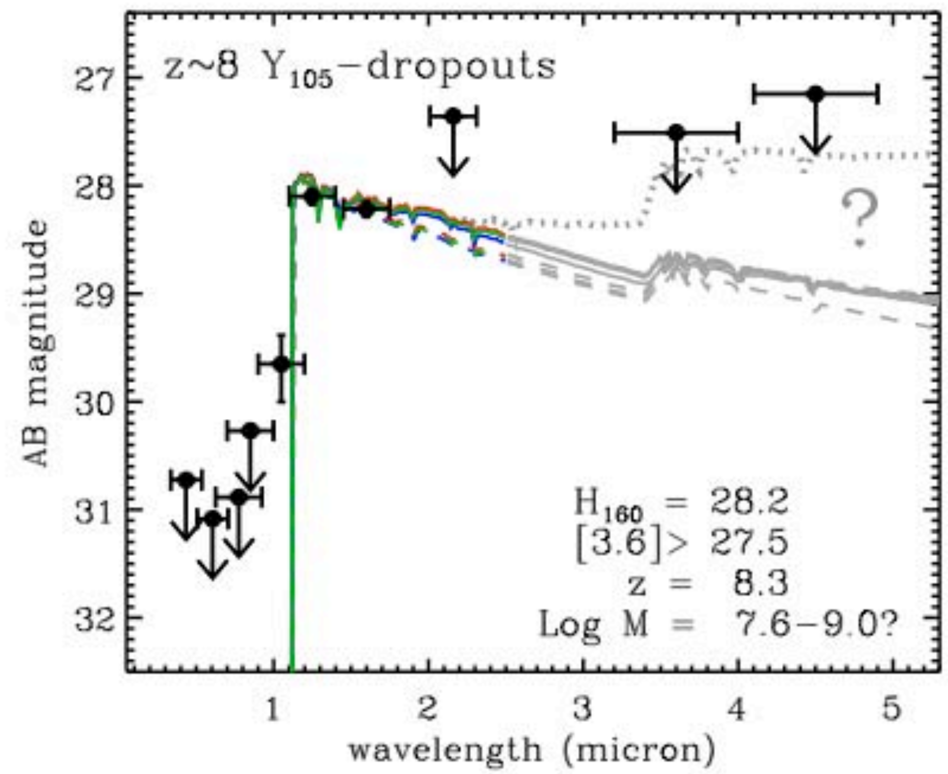
HUDF09 WFC3/IR Image with z~7 and z~8 Galaxies

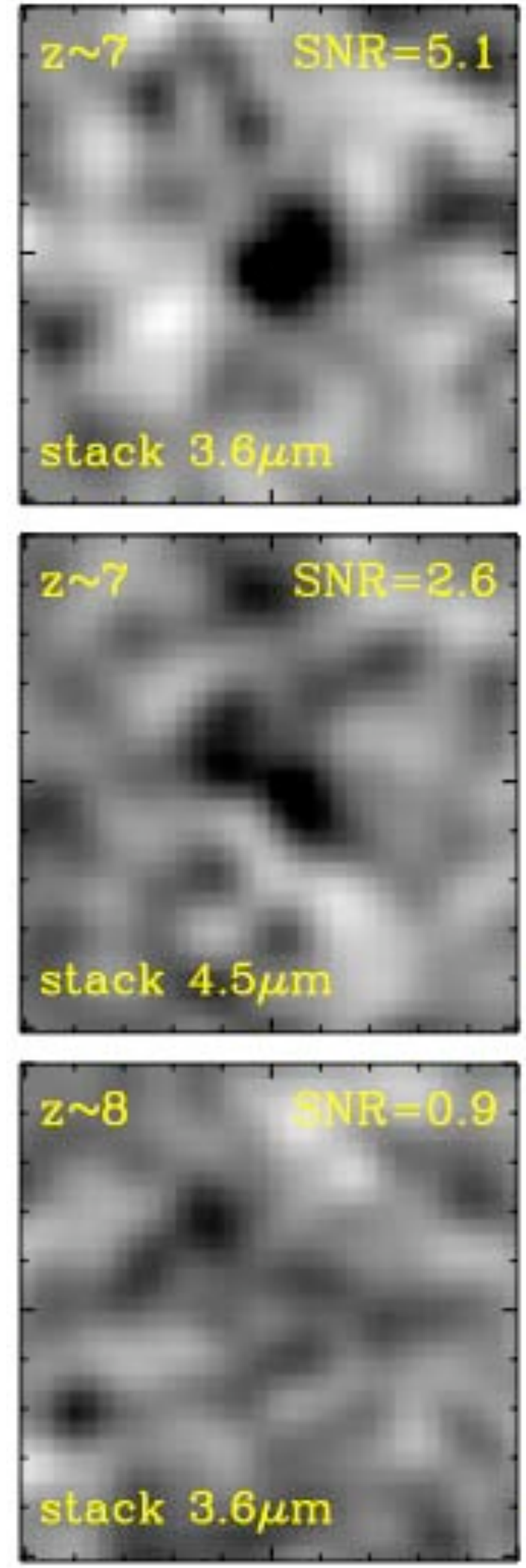
Credit: NASA, ESA, G. Illingworth, R. Bouwens (University of California, Santa Cruz), and the HUDF09 Team.

IRAC stacking of z=7, 8 samples

in IRAC 3.6 and 4.5 μm bands:
50 und 45 nJy







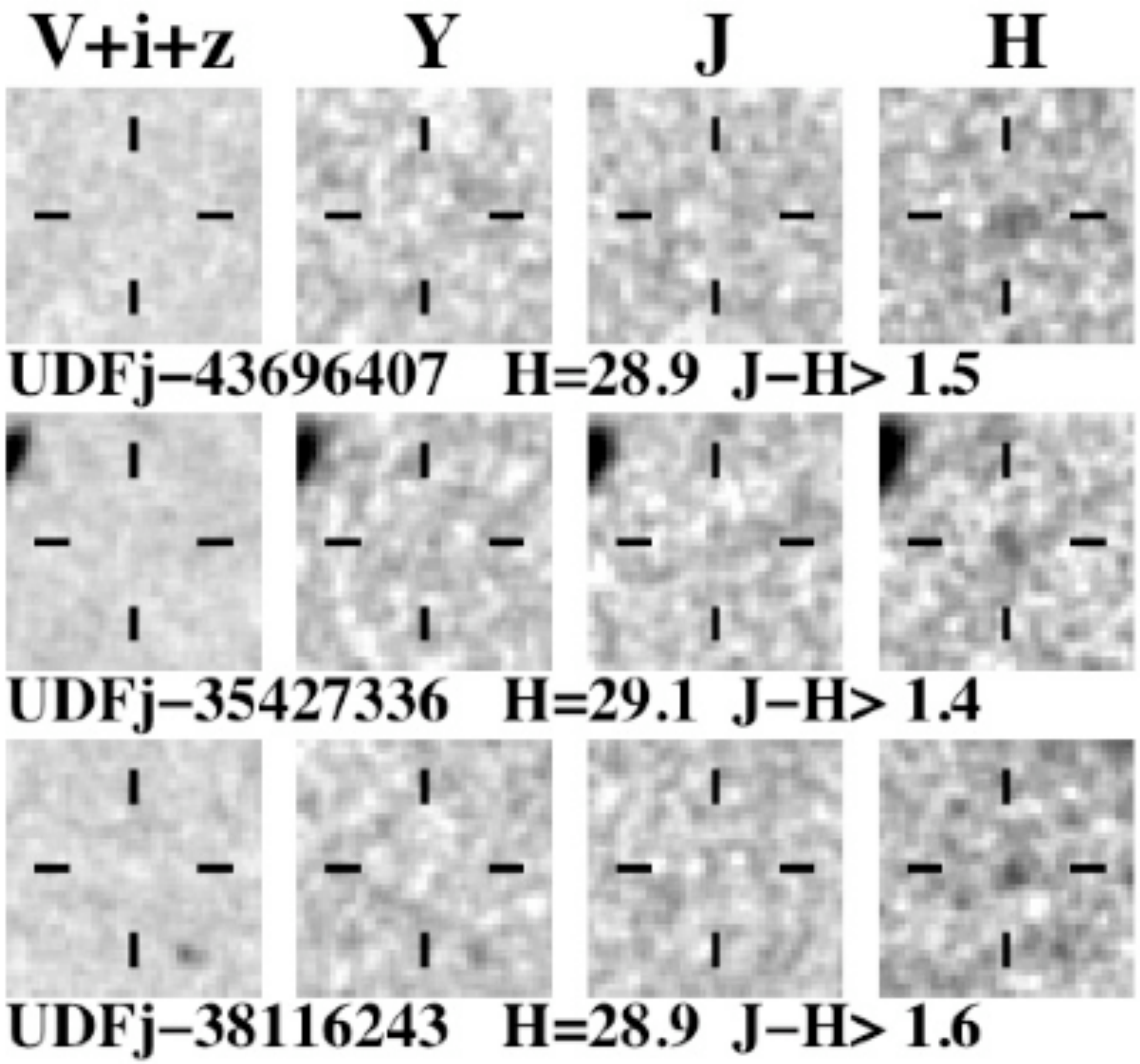
25 hours in each band

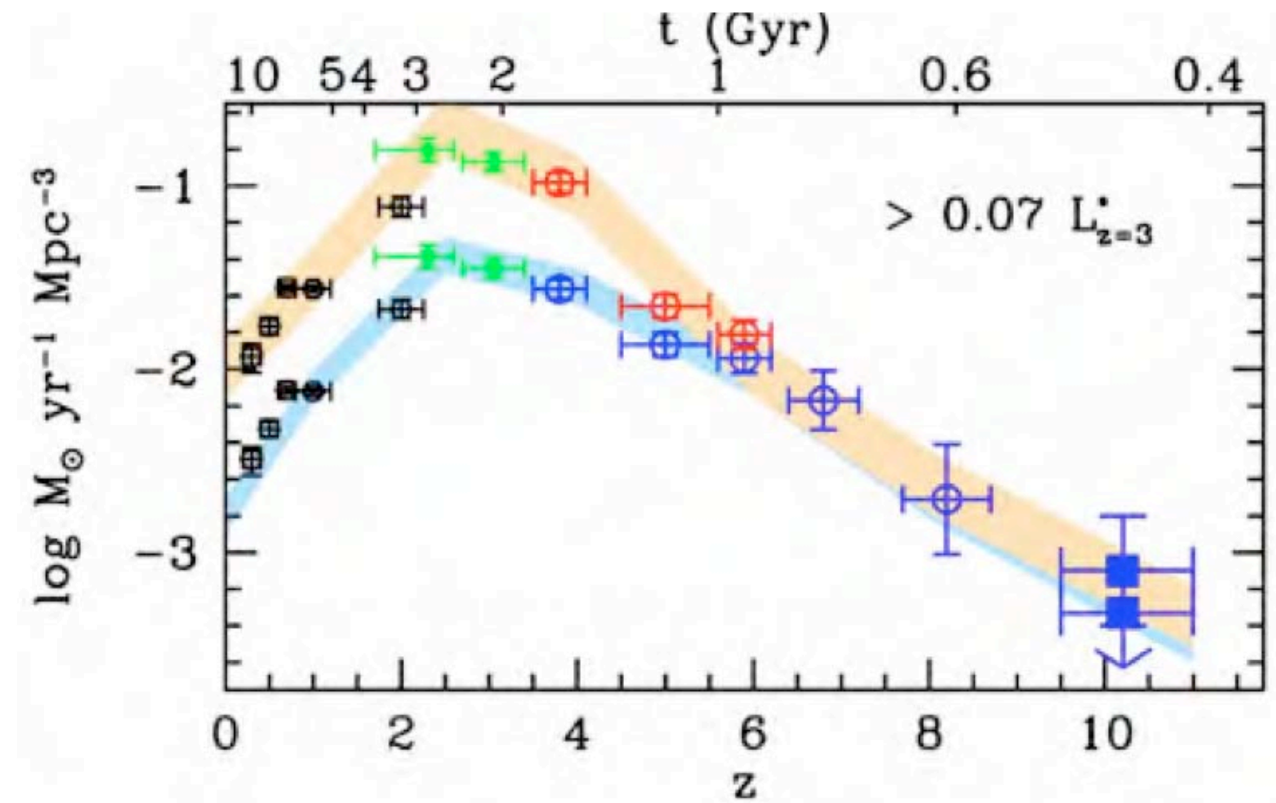
Labbe et al. 2010

5h per source with JWST/MIRI (5-28μm) at 5σ
(NIRCam much faster)

Three z=10 candidates

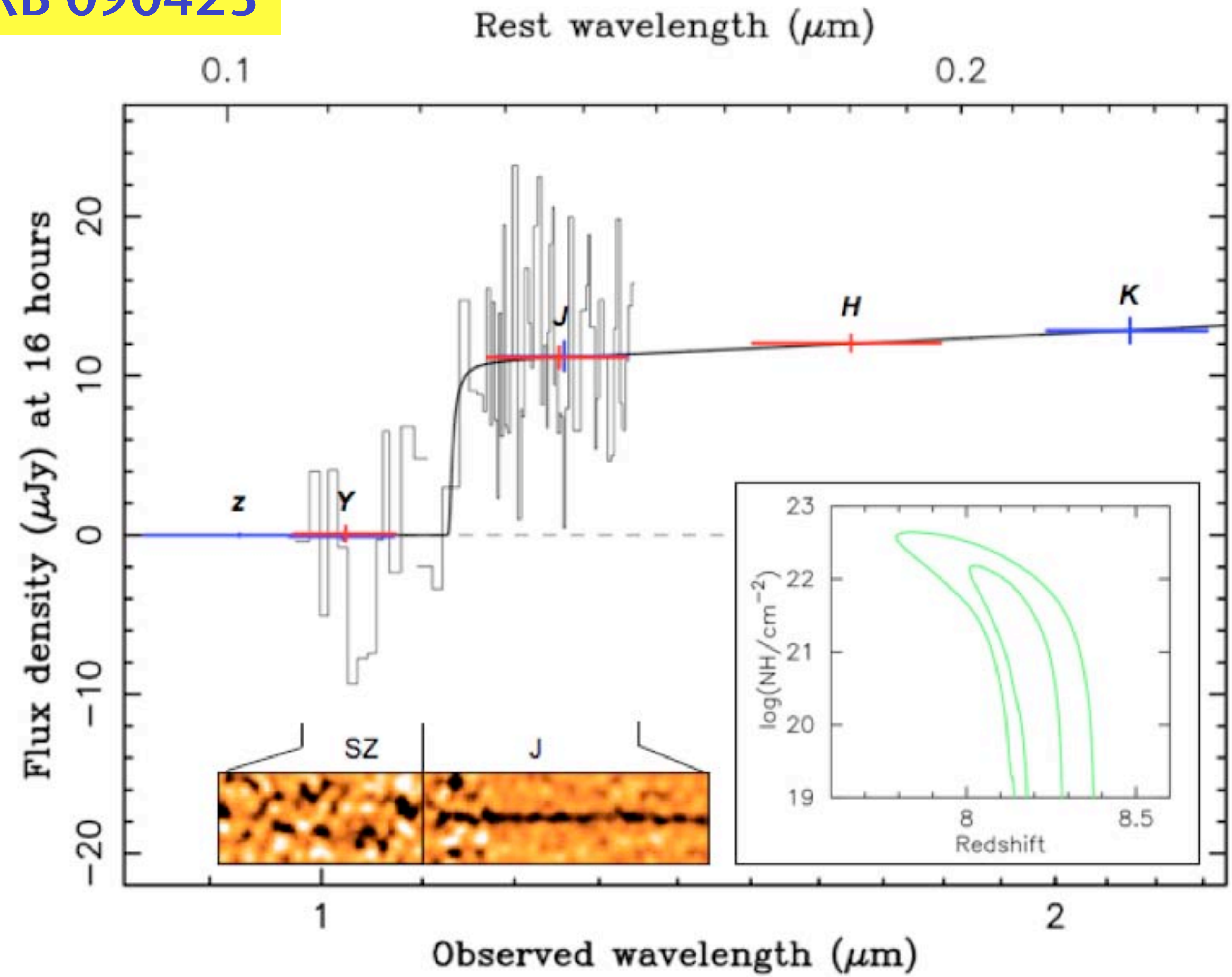
UDF, 4.7 arcmin^2, 60 orbits, WFC3, 1 pointing





e.g., Bouwens ea. 2009, 2010

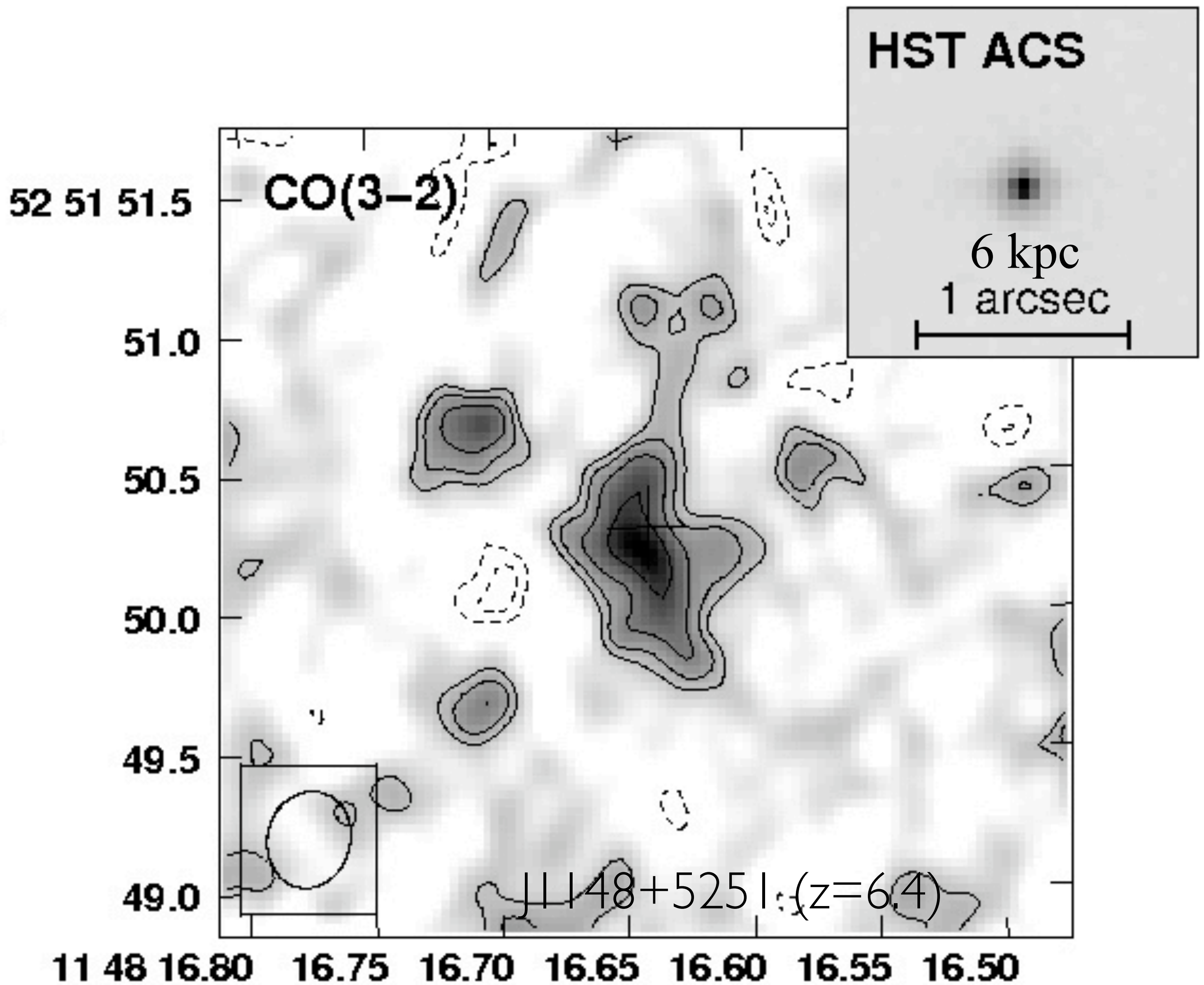
z=8.2 GRB 090423



Tanvir et al. 2010

Star-forming dense gas observations at high z: state of the art

Spatially resolved gas in z=6.4 QSO host



Walter ea. 2004

- 870 Myr after BB, in EoR
- *host* galaxy
- $M_{H2} = 2\ 10^{10}\ M_{sun}$

  ...using low α_{CO}

Mass in C&O: $3 \times 10^{7}\ M_{sun}$

i.e., need to produce, cool, condense, distribute metals

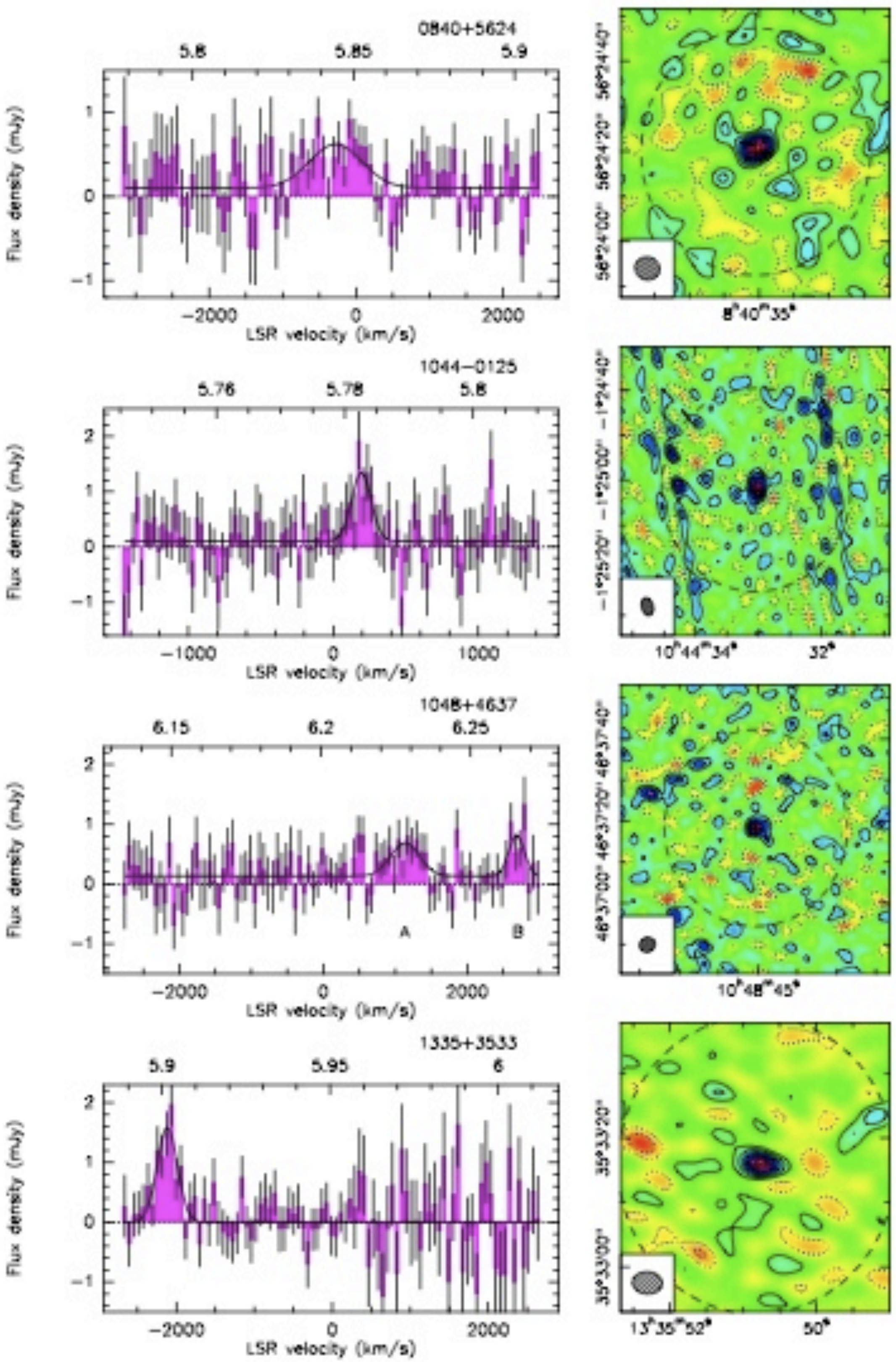
- $M_{gas} = 2 \times 10^{10}\ M_{sun}$
- $M_{dyn} \sim 6 \times 10^{10}\ M_{sun}$
- $M_{BH} = 3 \times 10^{9}\ M_{sun}$

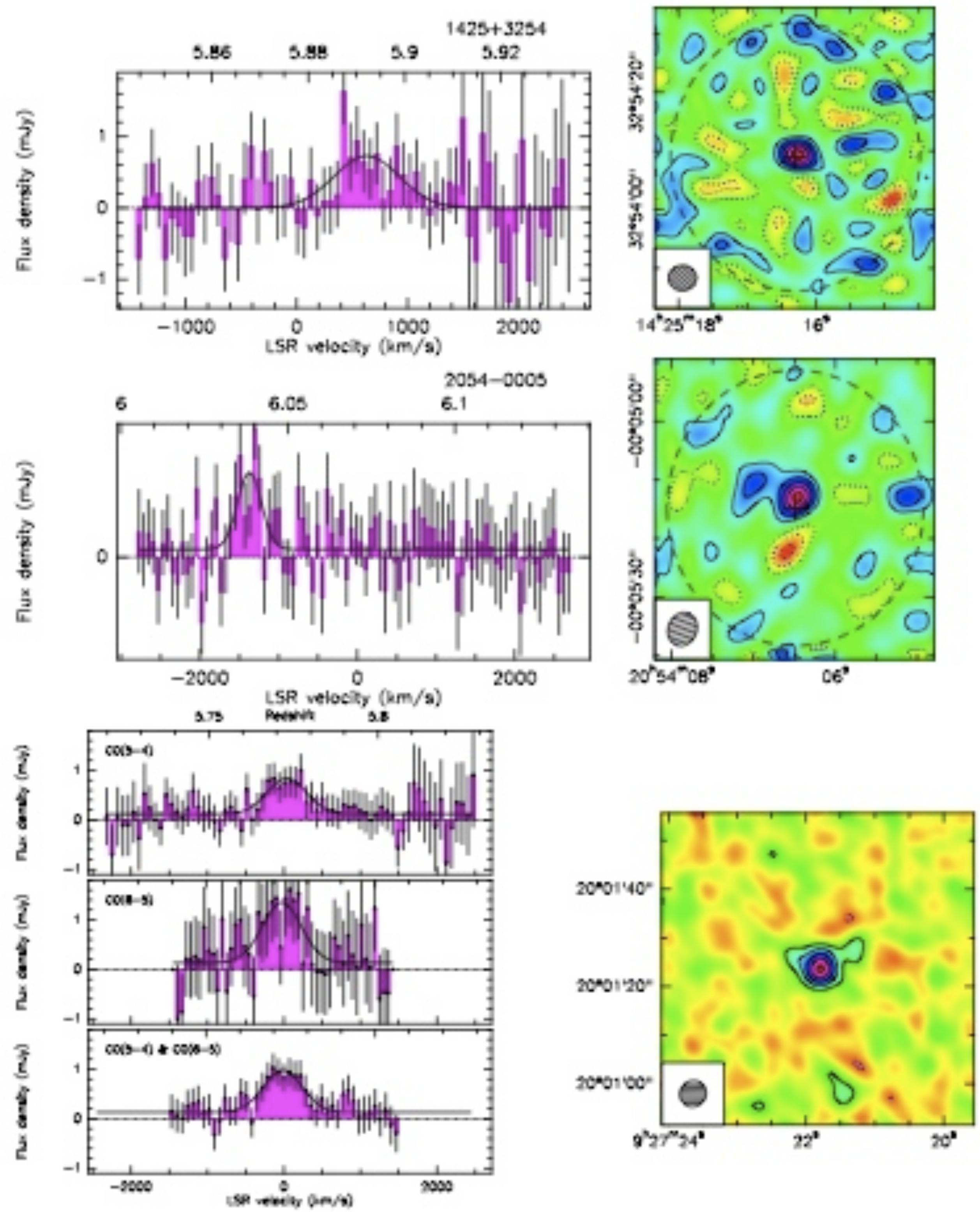
$M_{dyn} \sim M_{gas}$

$M_{dyn} = 20\ M_{BH}$

6 years later: 8 z=6 CO detections

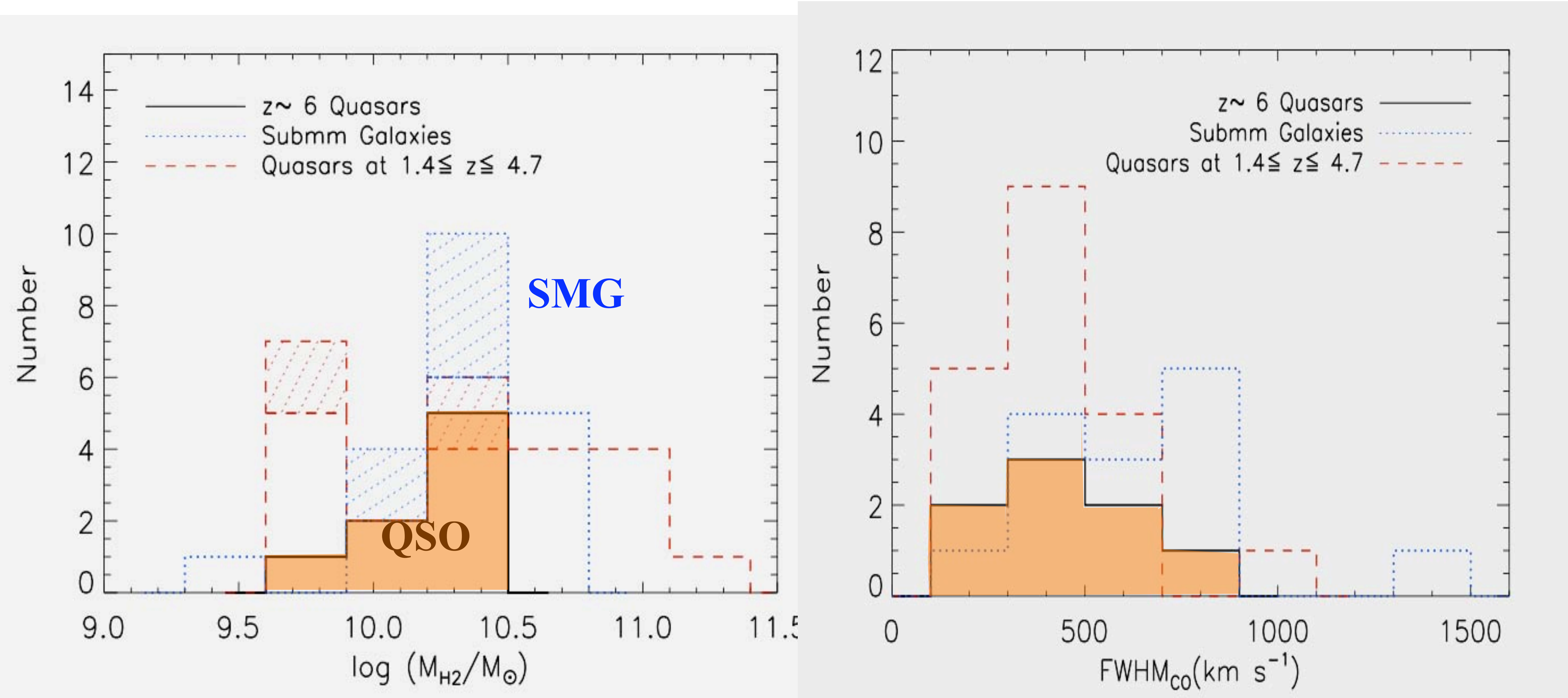
Wang et al 2010





z=6 QSOs vs. low z QSOs and SMGs

Wang et al 2010

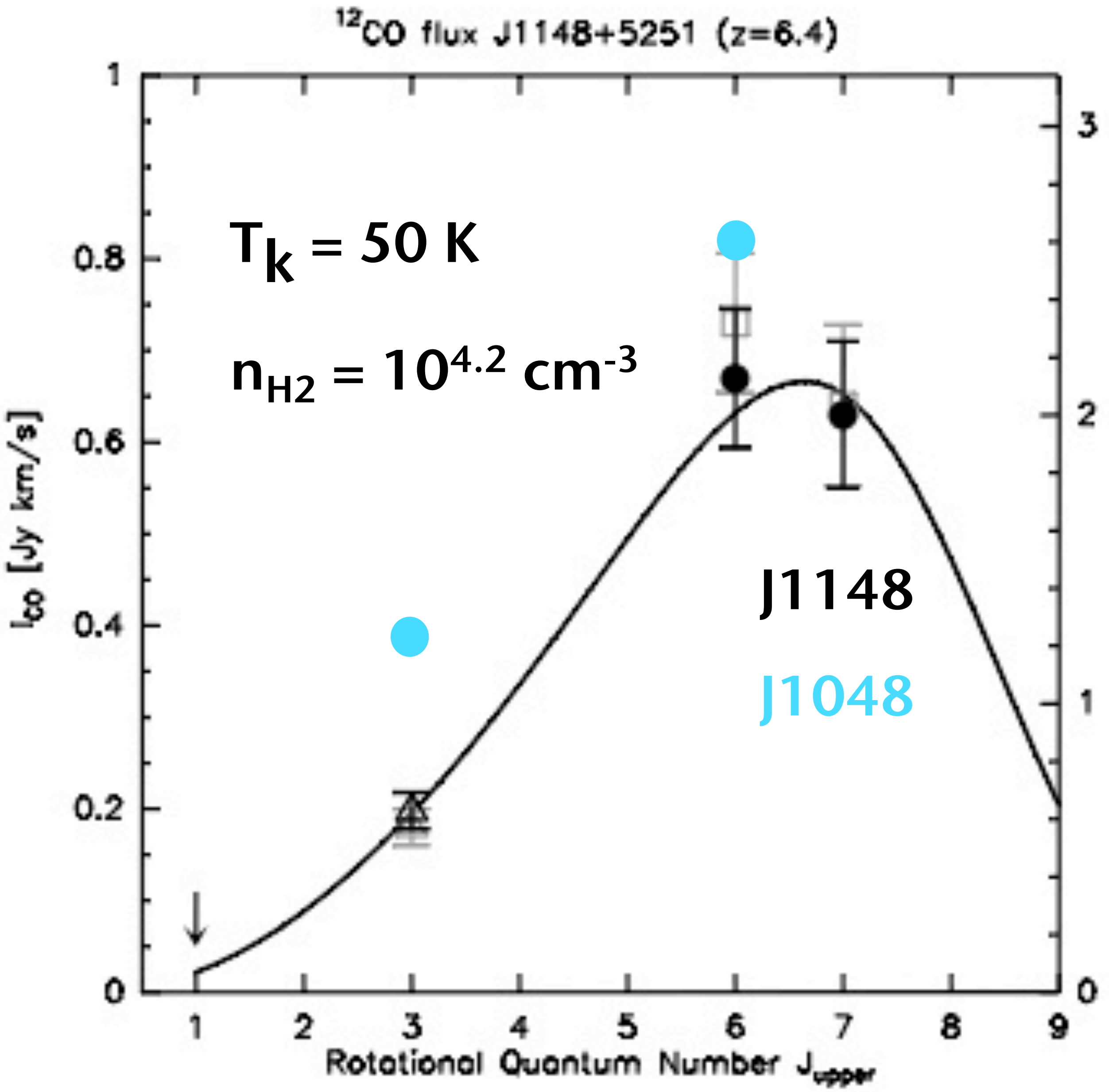


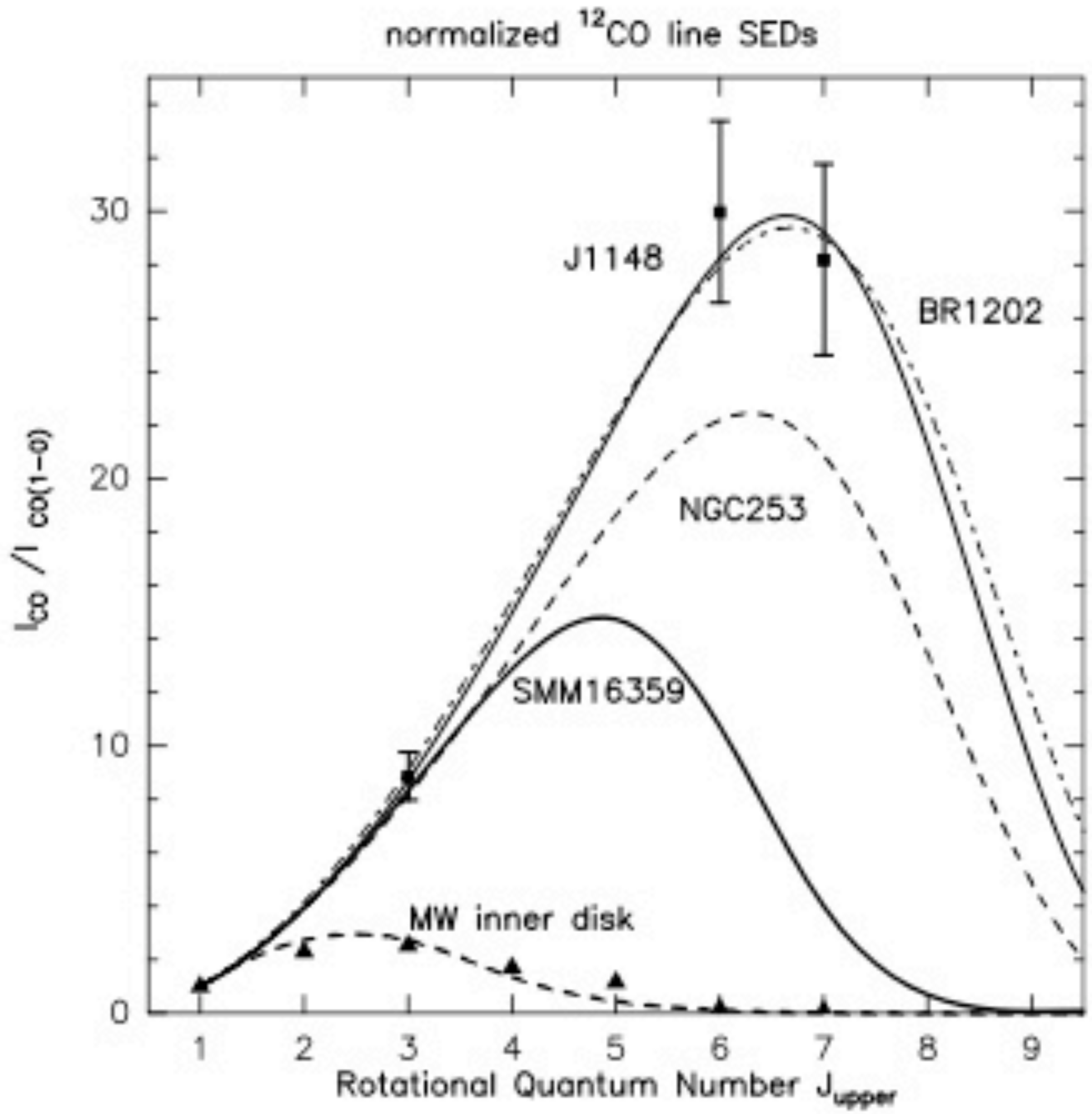
- **Quasars:** $M_{med} = 3\ 10^{10}\ M_o$ FWHM$_{med}$ = 413 km s^{-1}

  dense gas mass — line width

- **SMG (z~2.3):** $M_{med} = 2\ 10^{10}\ M_o$ FWHM$_{med}$ = 565 km s^{-1}

CO excitation: Dense, warm gas

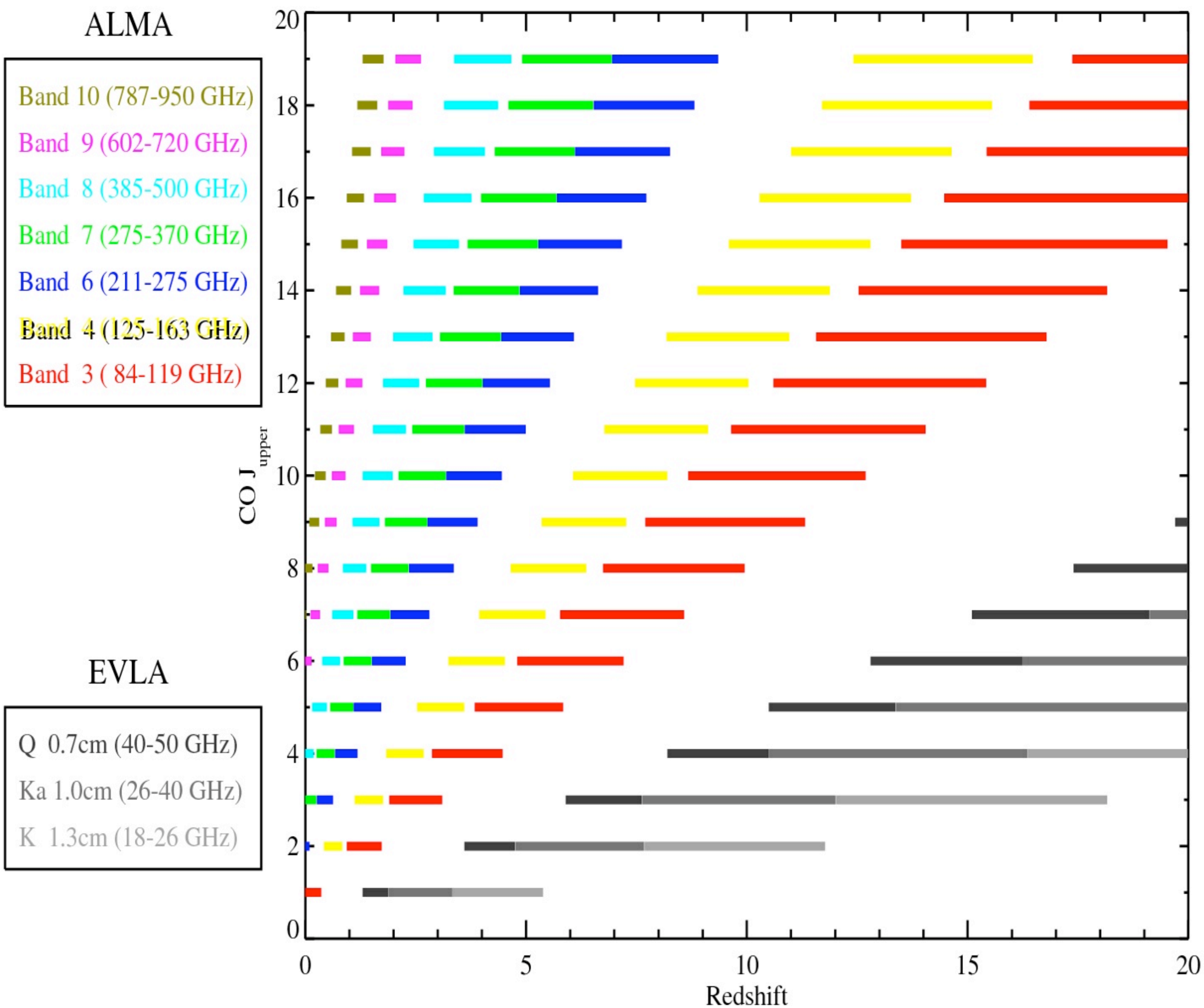




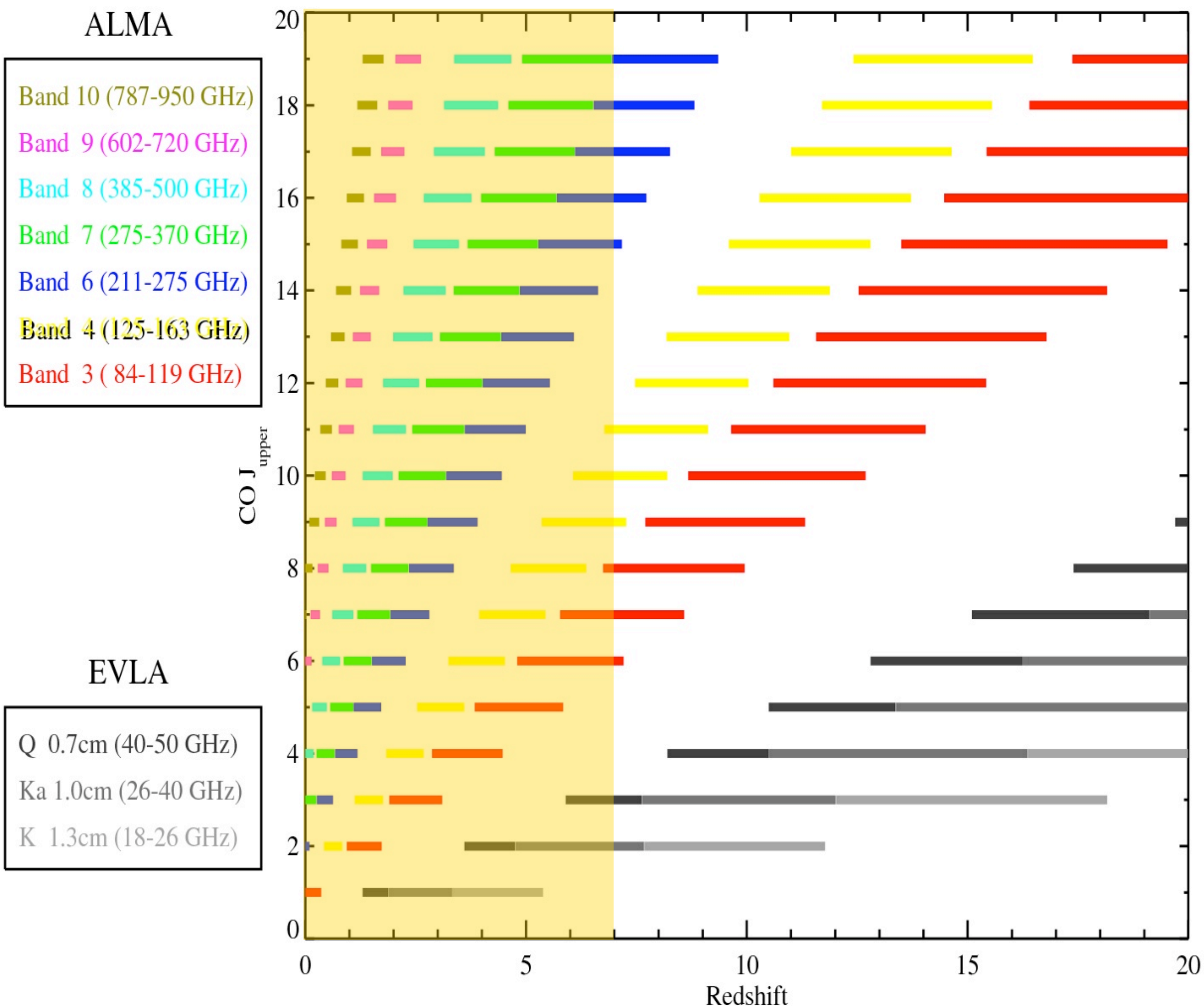
Compare with:
GMC (50pc) ~ 100 to 2000 cm^{-3}
GMC cores (<1pc) > 10^4 cm^{-3}

So far few objects!
Prospects for ALMA and eVLA?

CO discovery space



z>7 Sources: CO discovery space



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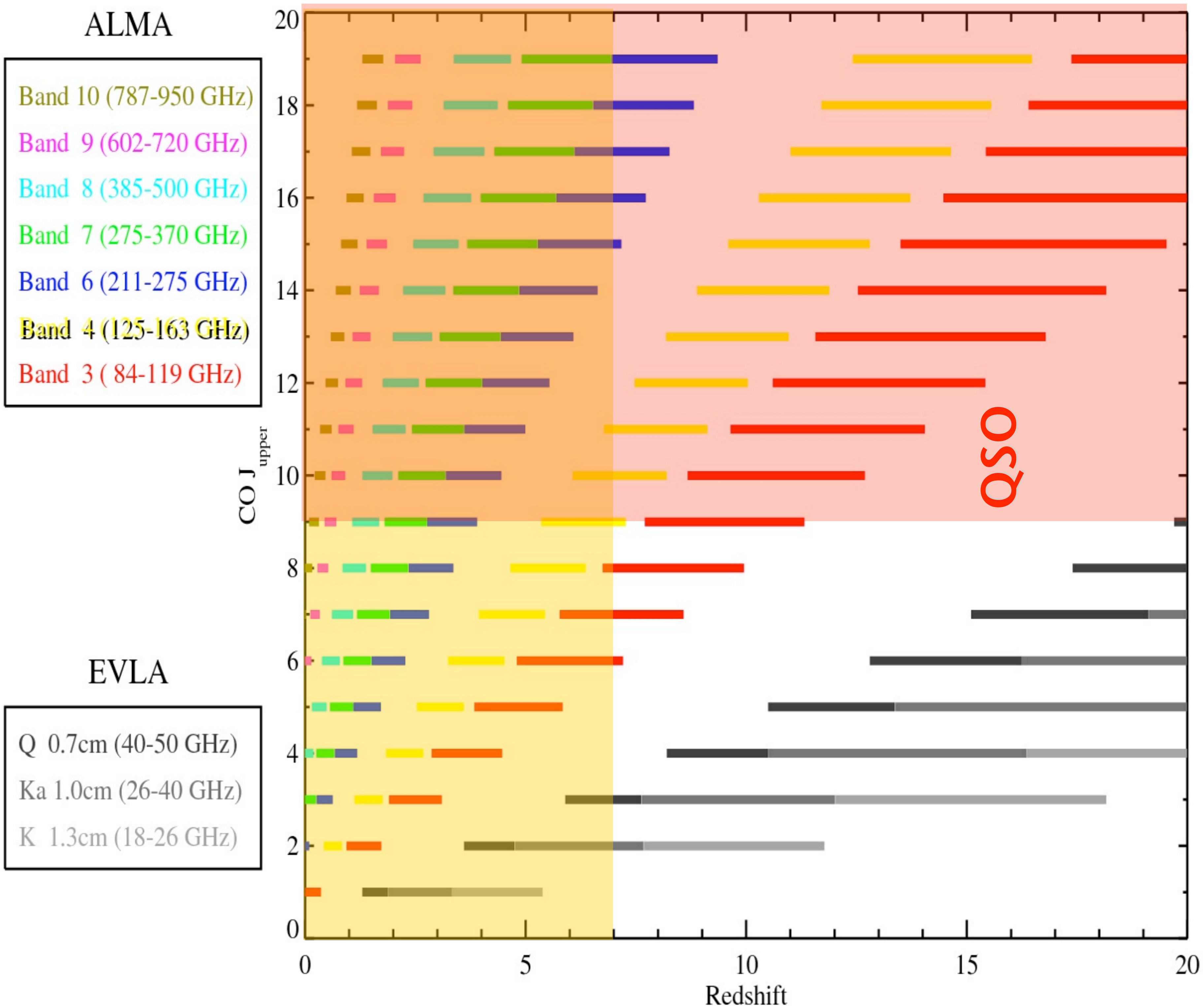
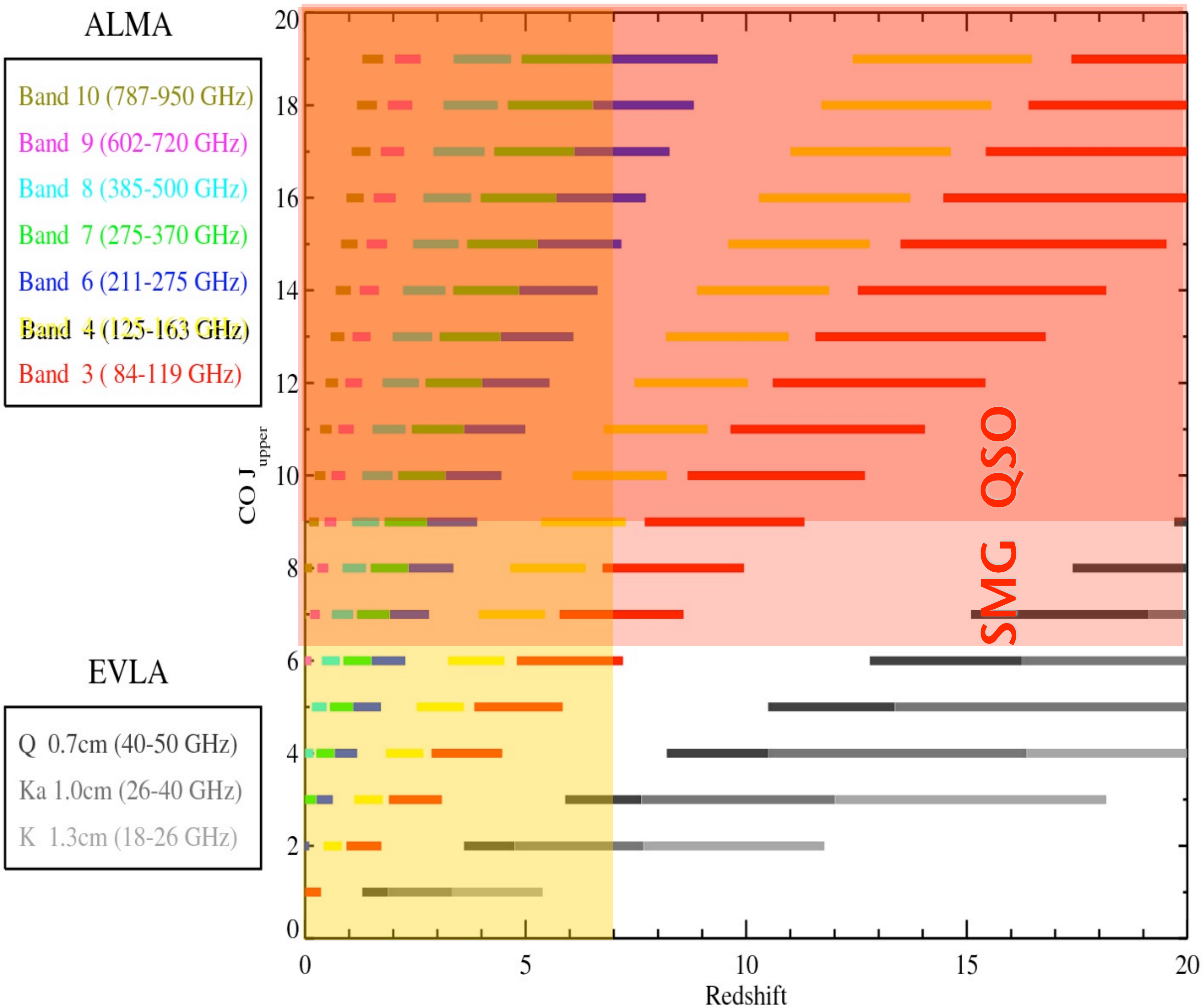


z>7 Sources: CO discovery space



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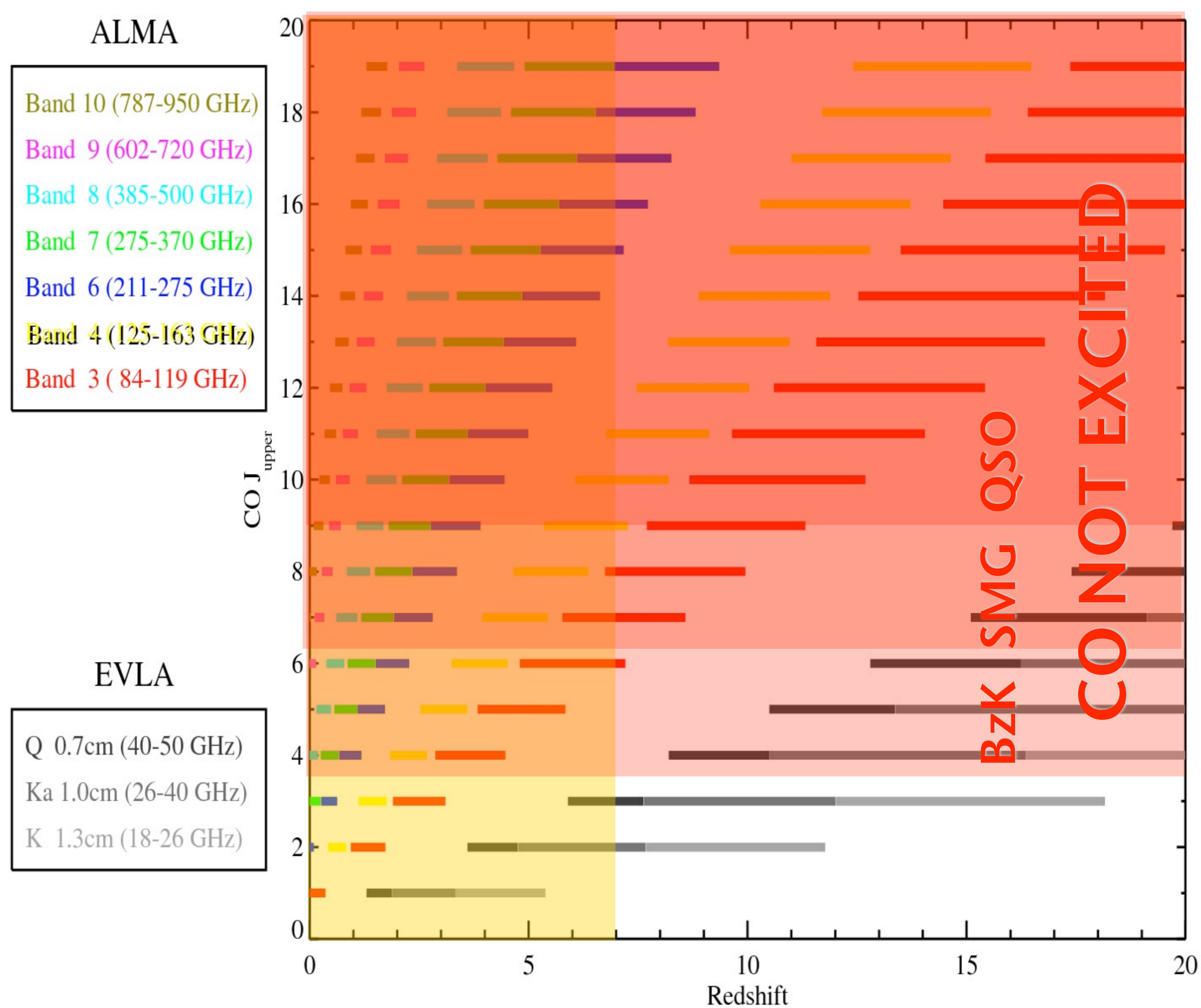
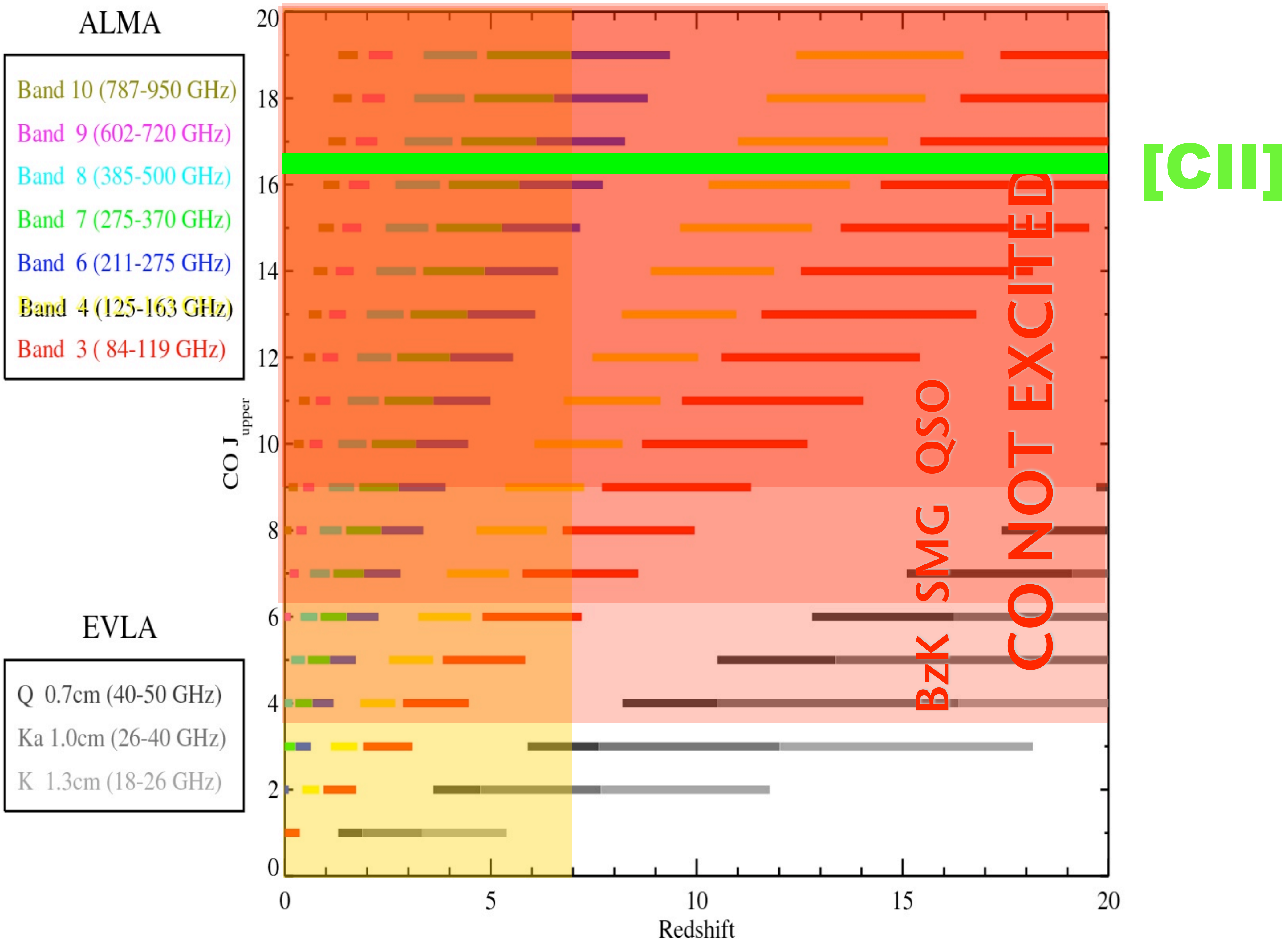
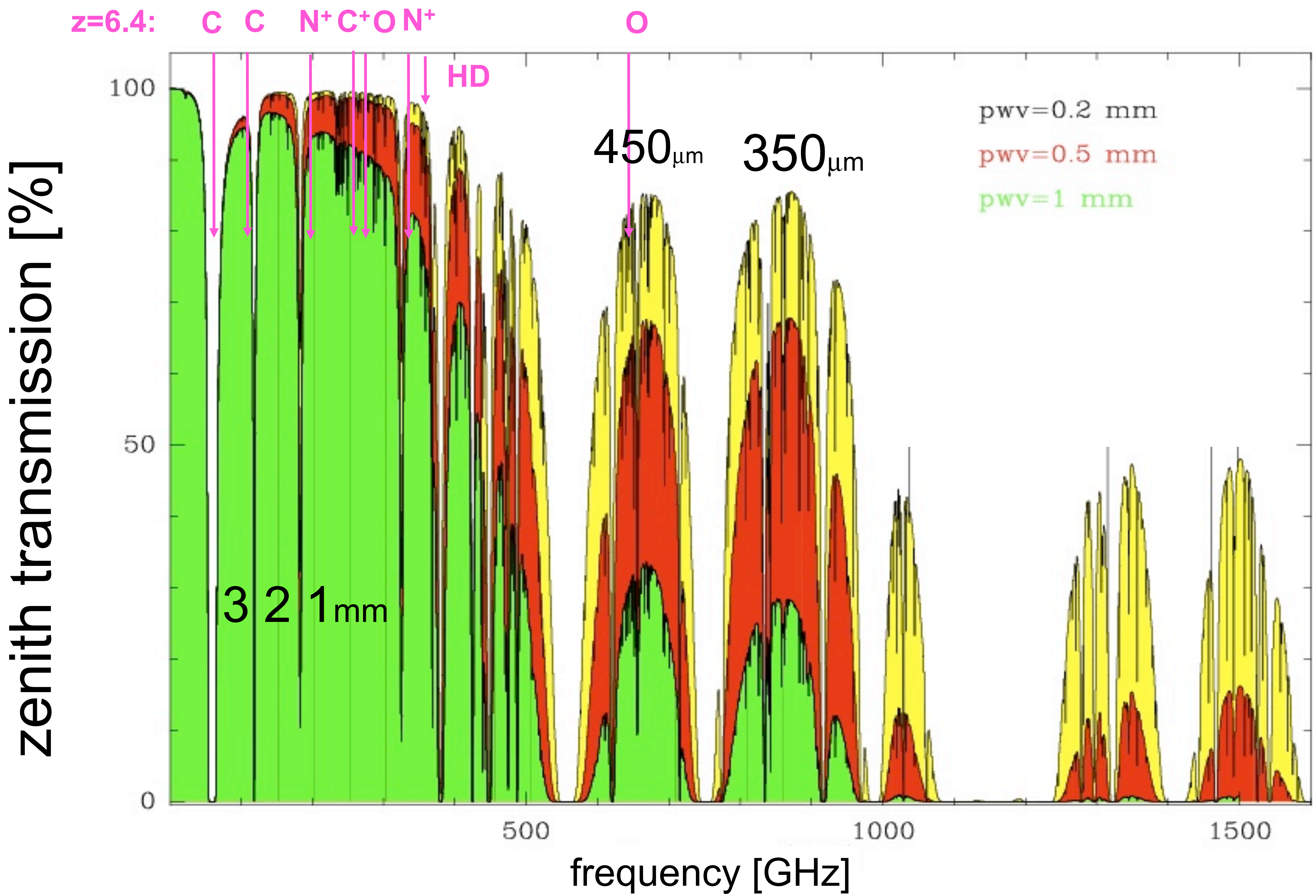


[CII] to the rescue

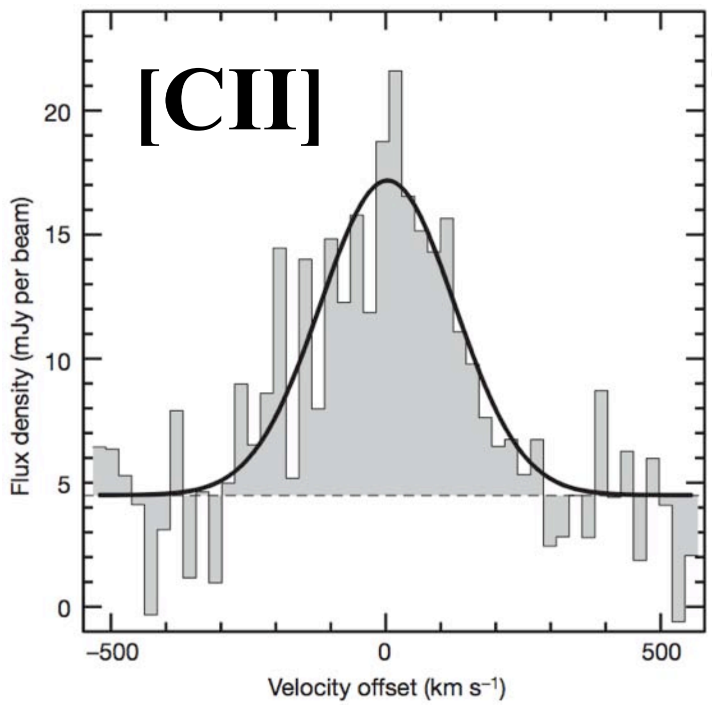


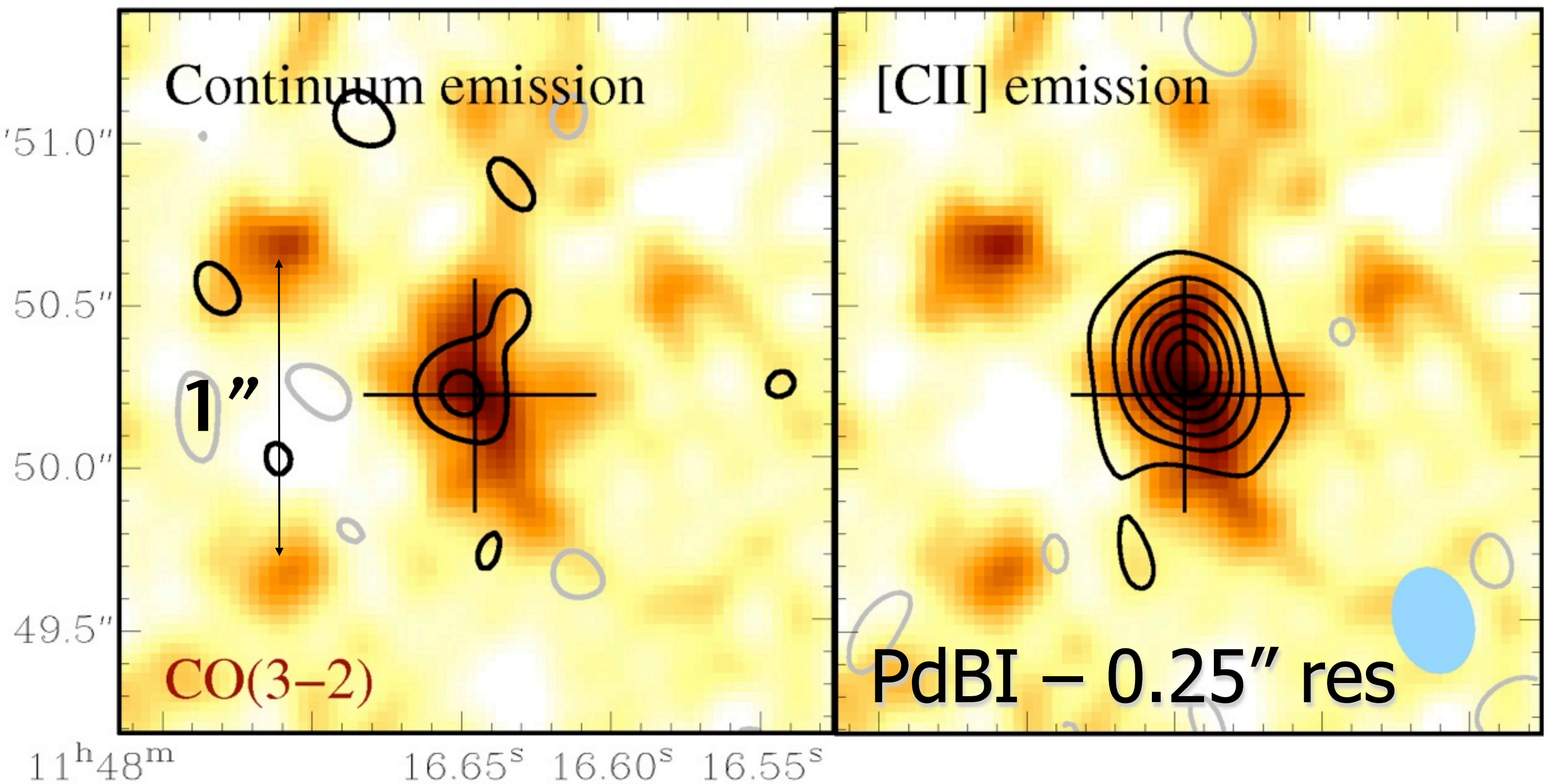
Far-IR Cooling lines at high z shifted into observable windows



Resolved [CII] : Maximum Starburst @z=6.4

Maiolino+05
Walter+09





FIR continuum [CII]

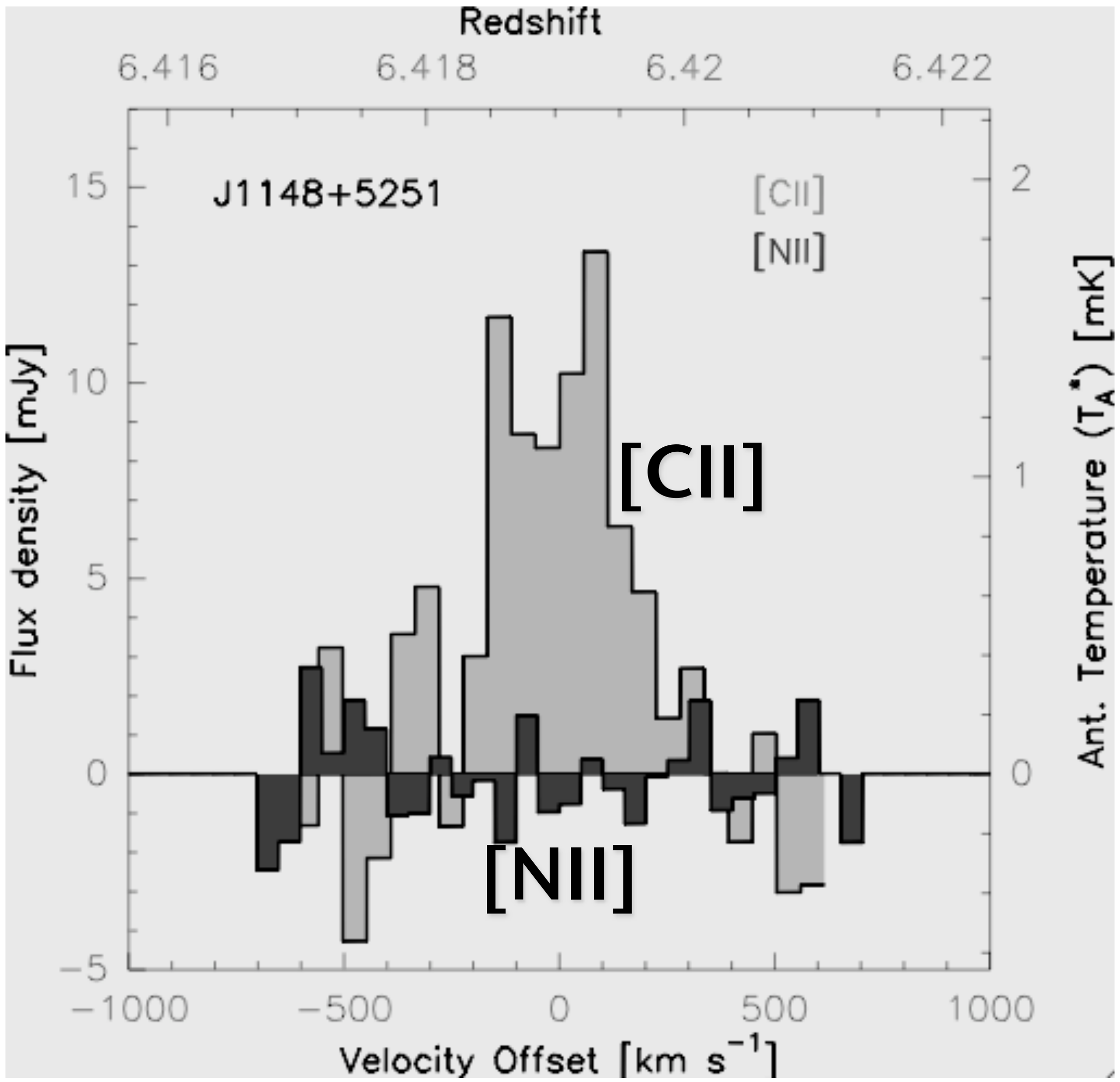
SFR ~ $10^{-5.2}$ $L_{[CII]}$ ~ 3000 M_o/yr

[CII] size ~ 1.5 kpc ⇒ SFR/area ~ 1000 M_o yr^{-1} kpc^{-2}

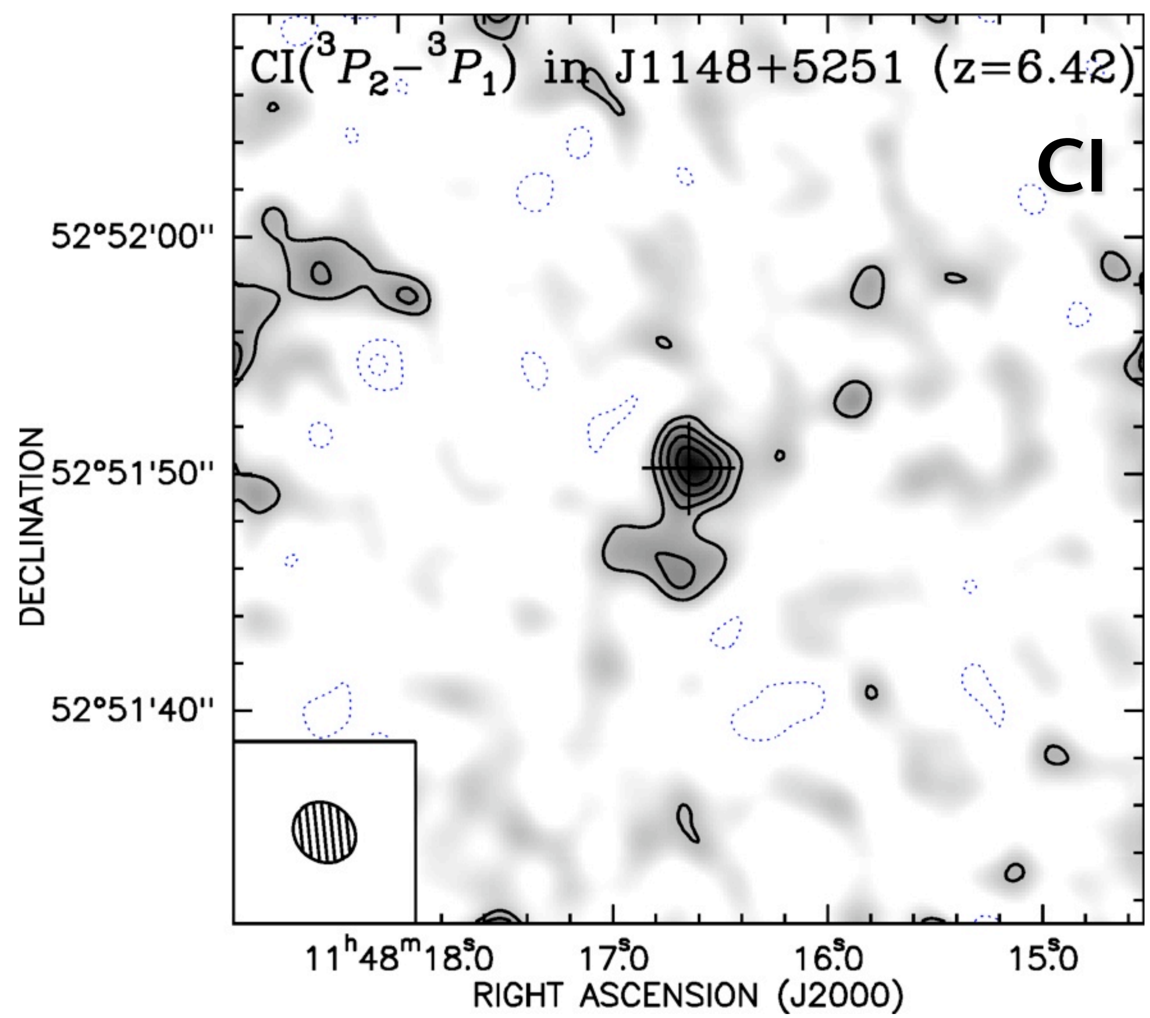
Maximal starburst: (Thompson, Quataert, Murray 2005)

- Self-gravitating gas disk with vertical support through radiation pressure
- 'Eddington limited' SFR/area ~ 1000 M_o yr^{-1} kpc^{-2}

Other Atomic Lines: [NII]205μm and [CI]609μm at z=6.4



Walter ea. 2009b



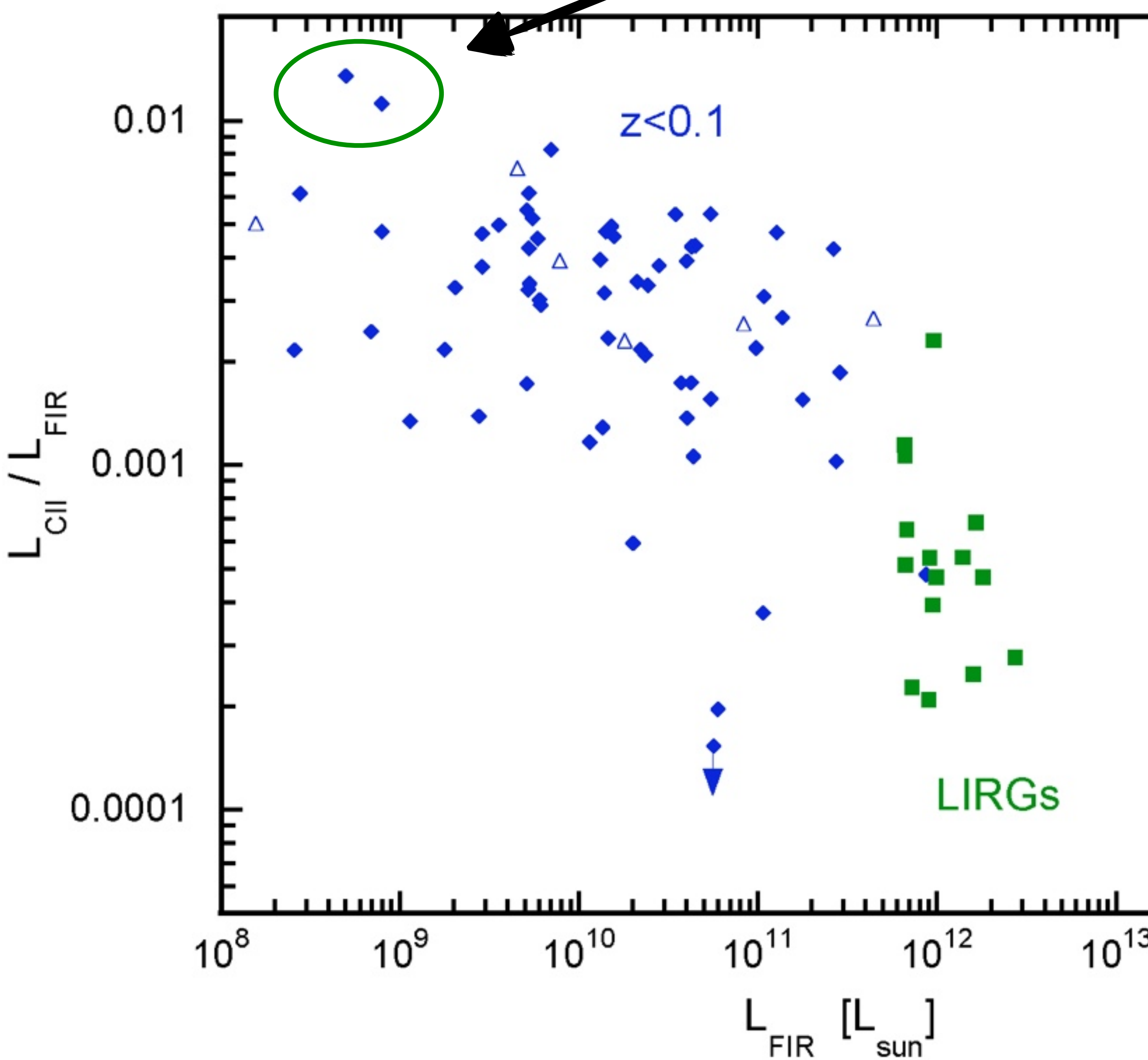
Riechers ea. 2009

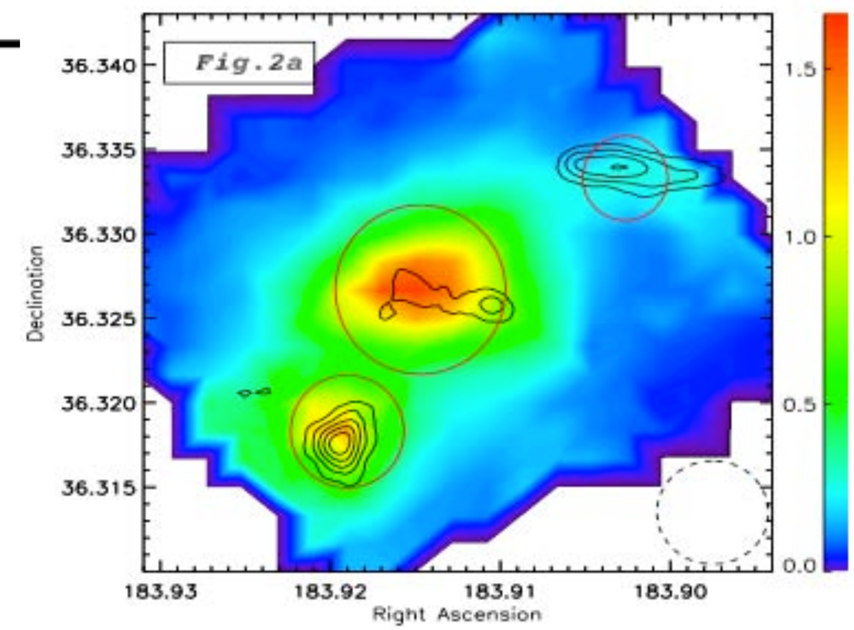
$L_{[CII]} = 4 \times 10^9 L_o$

$L_{[NII]} < 10\% \; L_{[CII]}$

$L_{CI} \sim 2\% \; L_{[CII]}$

may be easier to detect fainter, low metallicity sources?

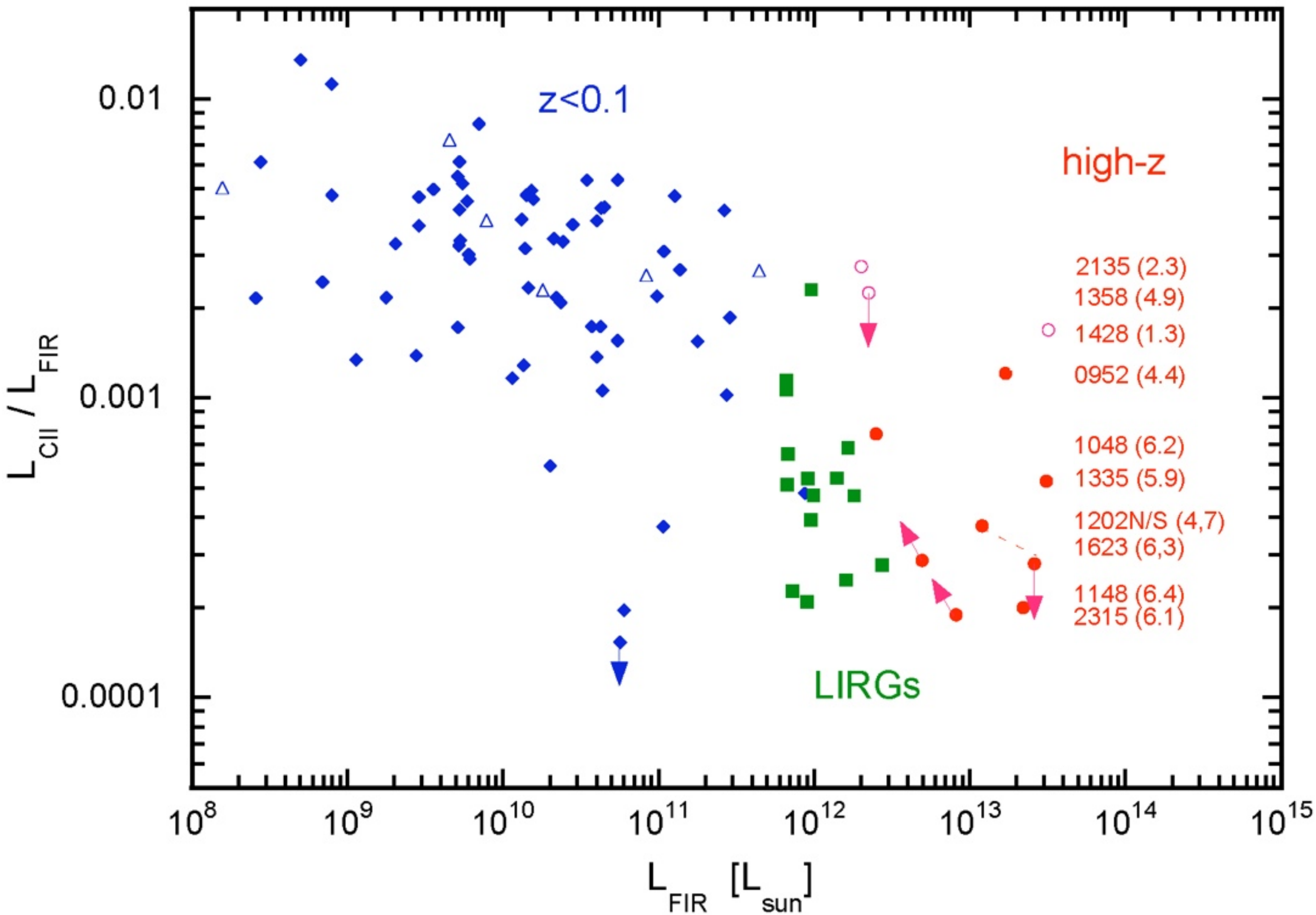


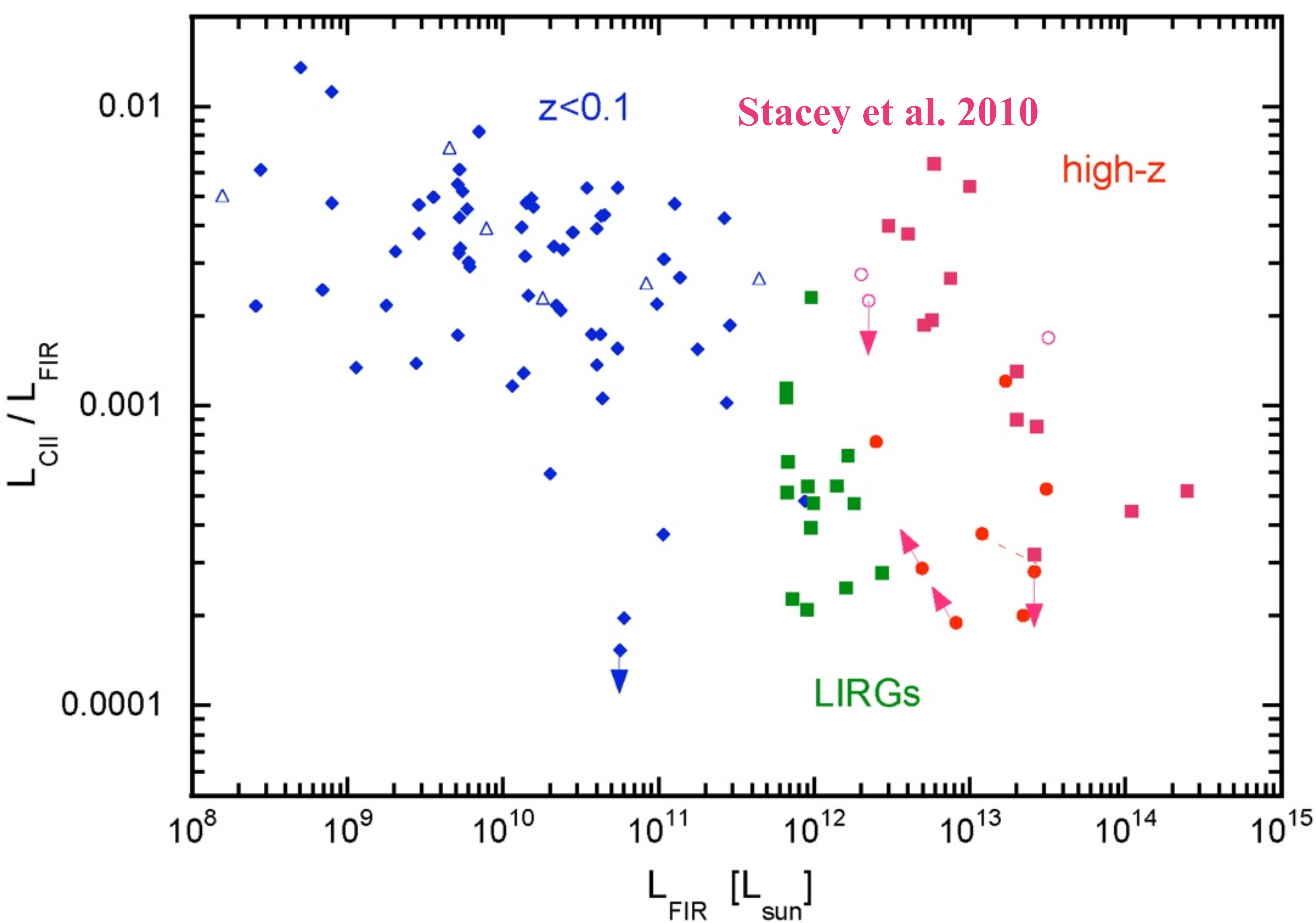


[CII] Herschel-PACS image of NGC 4214 ($Z \sim 0.3 Z_{\odot}$)

[CII]/FIR ~ 0.01
[CII]/CO ~ 50000 !

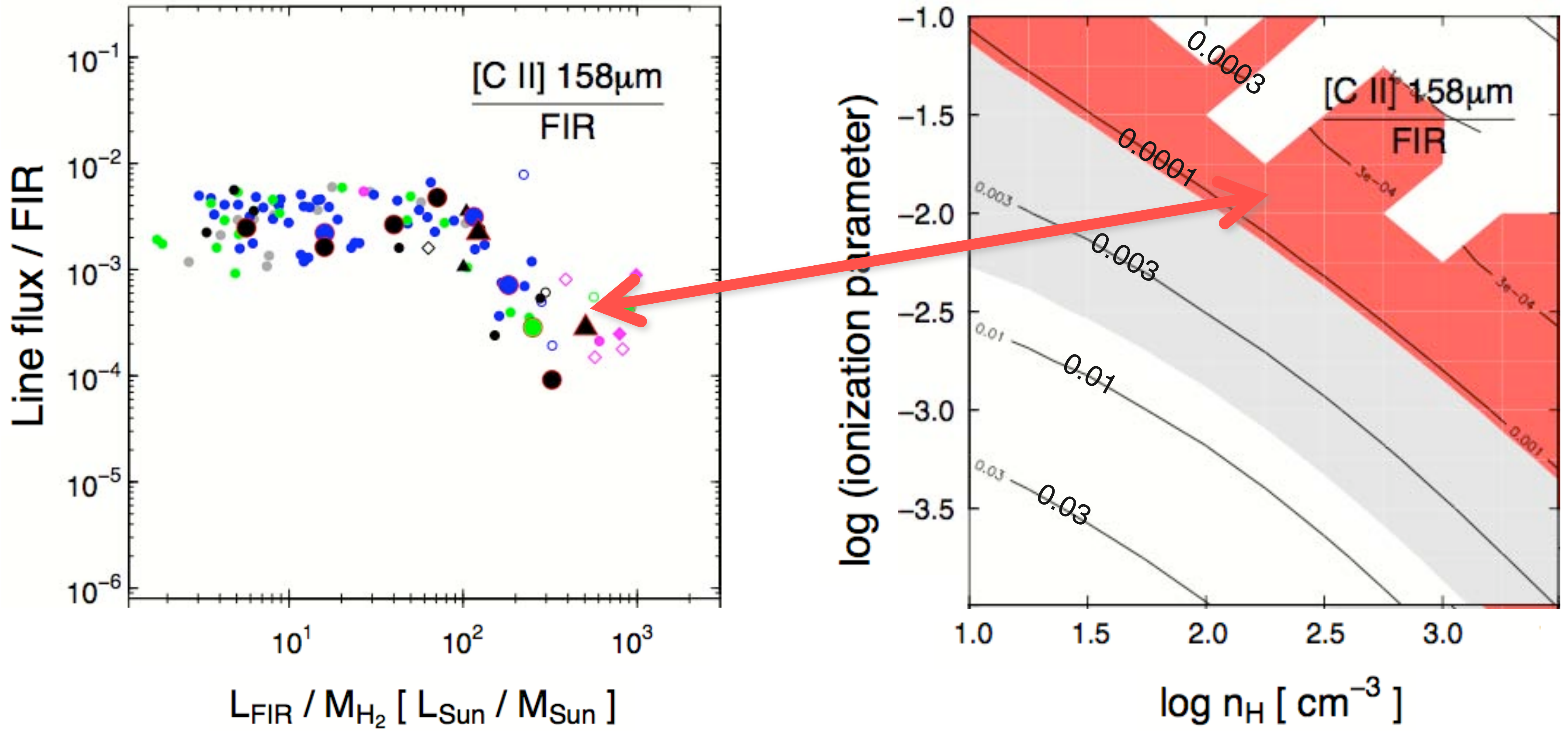
5 - 10 times stronger than CO !





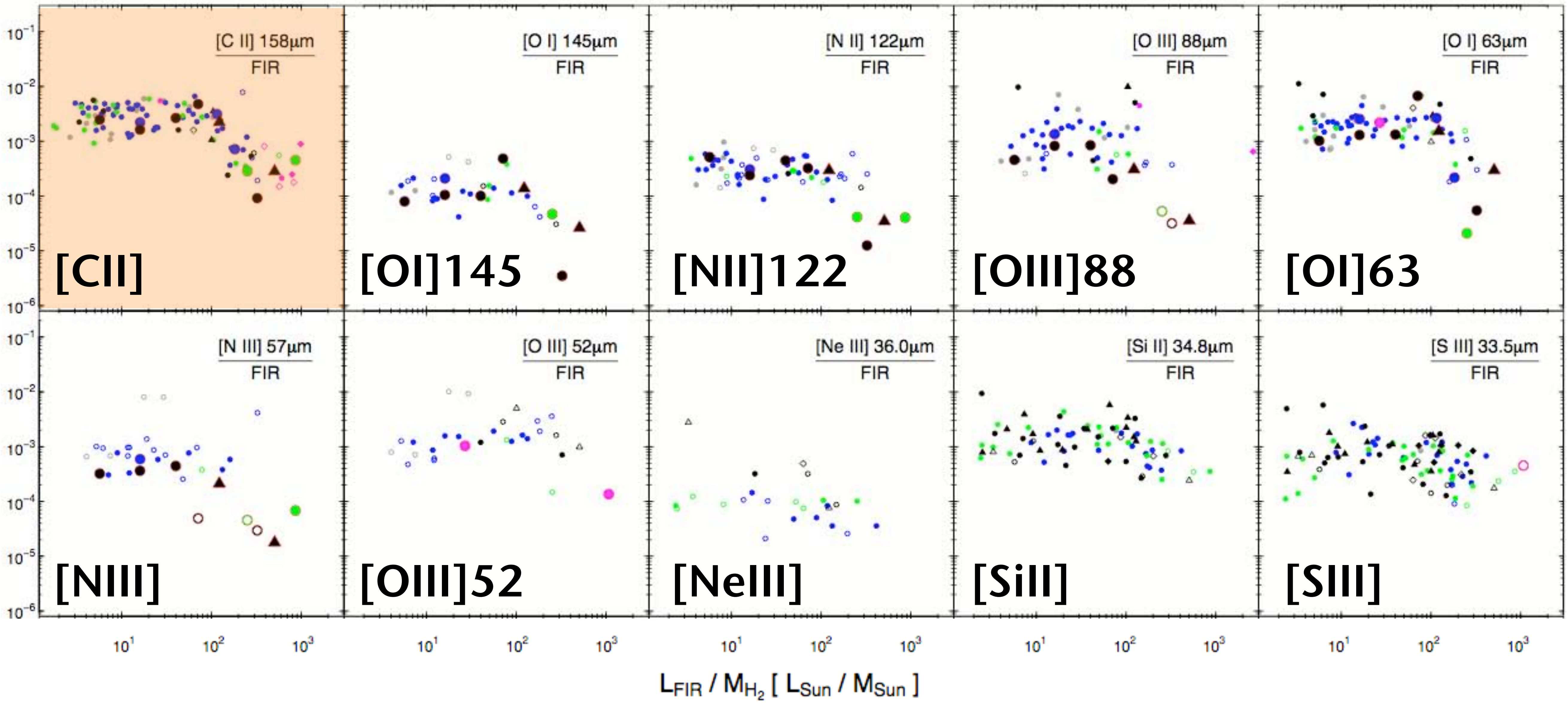
z<0.1
Stacey et al. 2010
high-z
LIRGs
0.01
0.001
0.0001
L_{CII} / L_{FIR}
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
L_{FIR} [L_{sun}]

PDR models



Black symbols: AGNs (circles: Seyfert 2, triangles: Seyfert 1, diamonds: QSOs);
green: LINERs; blue: HII galaxies; grey: unclassified; magenta: high z.

Gracia-Carpio et SHINING 2010

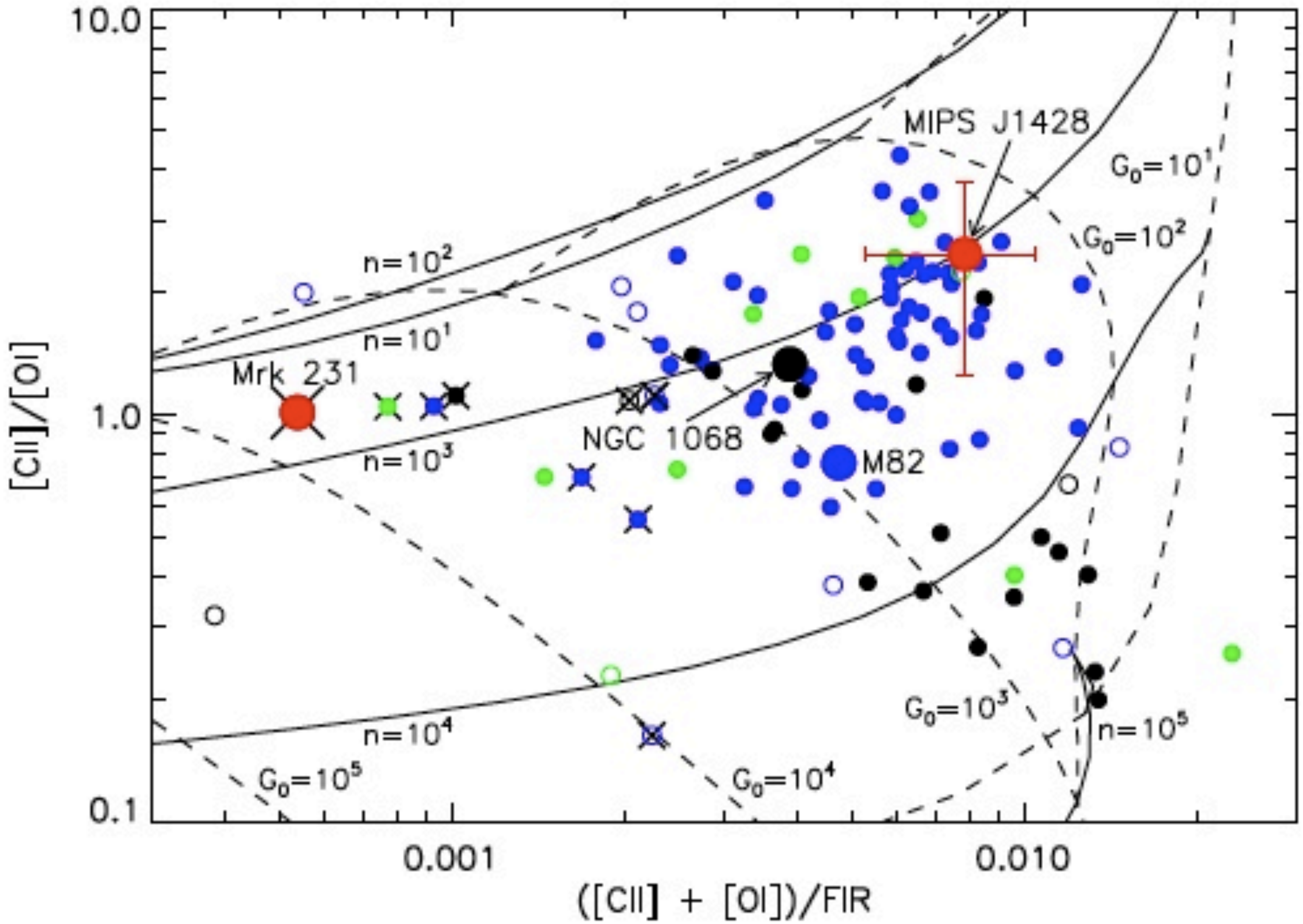


No [CII] deficiency

→ most FS lines show a decline ....

Gracia-Carpio et SHINING 2010

.... that can be modeled in framework of PDRs:



Sturm et al. 2010

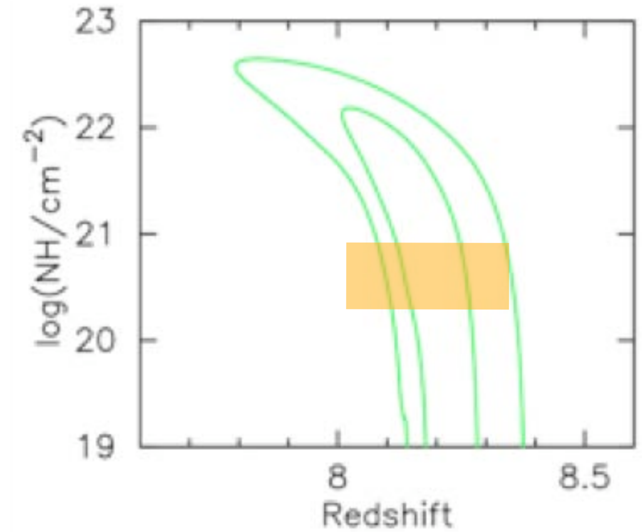
Fig. 4. [C II]/[O I] vs. ([C II]+[O I])/FIR. PDR models of Kaufman et al. (1999) are used. The position of MIPS J1428 is indicated, using [C II] from Hailey-Dunsheath et al. (2010). Symbols as in Figure 2, sources with $L_{IR} \geq 10^{12} L_\odot$ are marked with a cross. Open symbols correspond to [O I] non-detections. The Mrk 231 data are from Fischer et al. (2010).

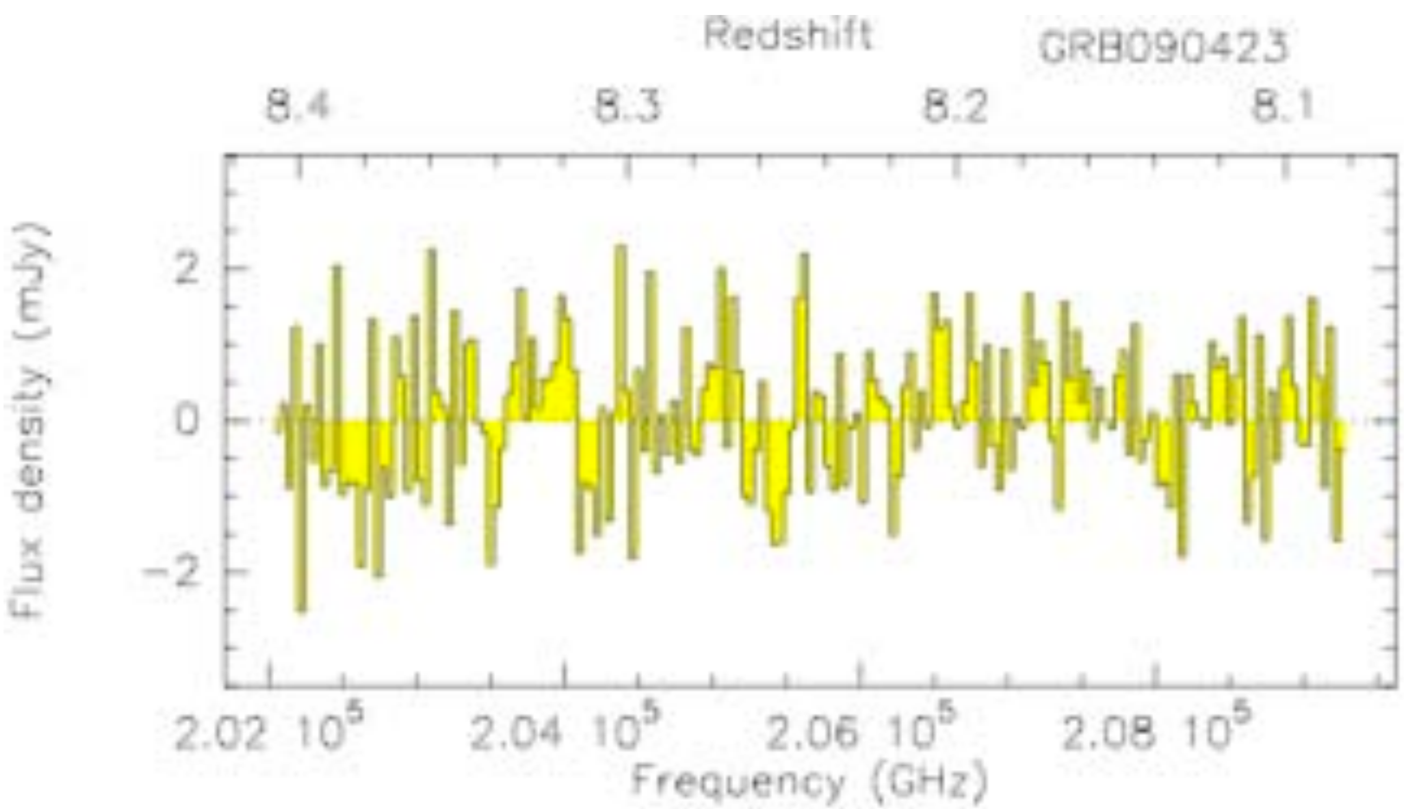
[CII] at z=8.2?

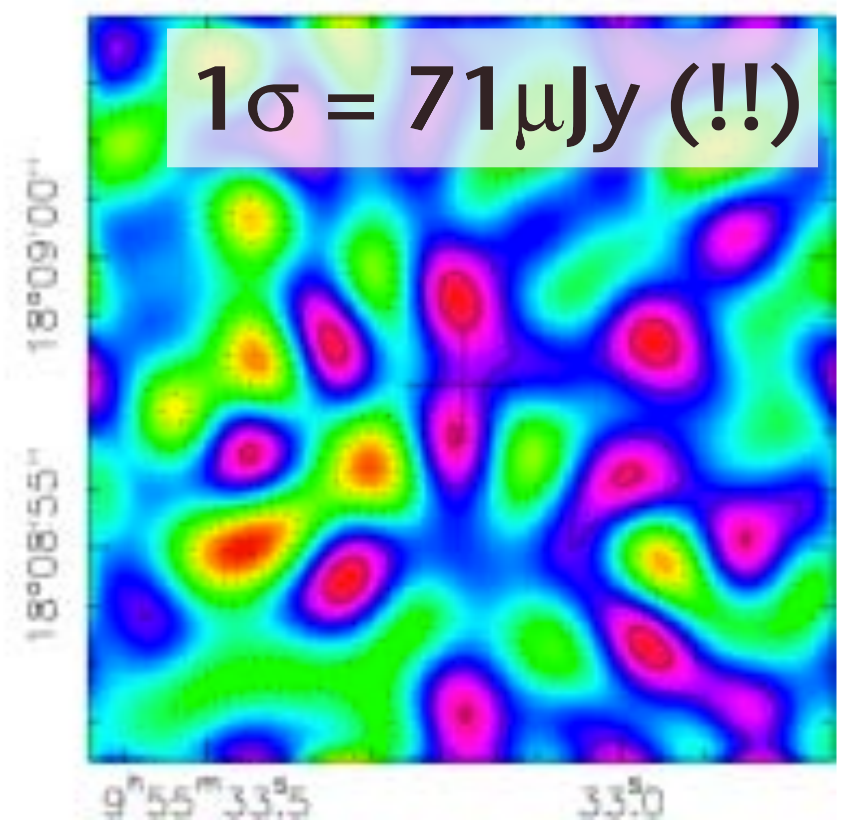
nope…

High-z studies mostly limited to extreme objects

observations with Widex!

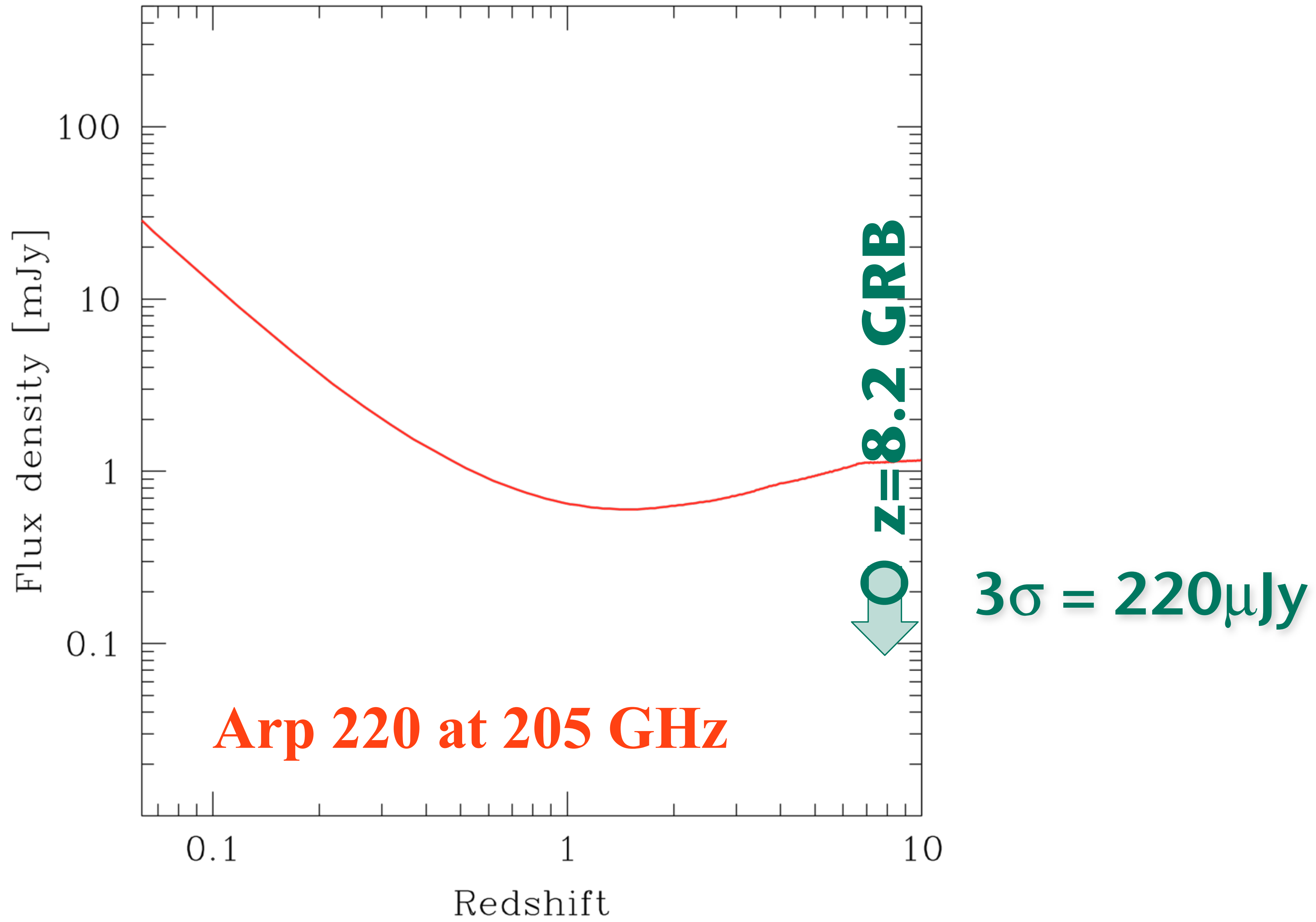






5 sigma limit: 0.75 Jy km/s, z=8.2 (D_L=85Gpc): L_{CII}<1.2 10^9
assuming L_{CII}/L_{FIR}=300 → L_{FIR}<1.2 10^{11} (LIRG)

Continuum Limit z=8.2 GRB

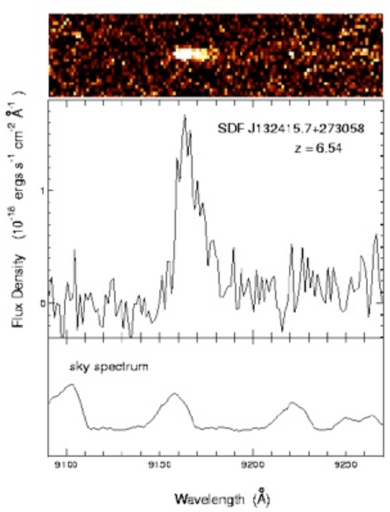


$L_{FIR} < 3\ 10^{11}\ L_{sun}$ (3σ, β=1.5, T=35K) → SFR < 50 $M_{sun}\ yr^{-1}$

High-z studies mostly limited to extreme objects

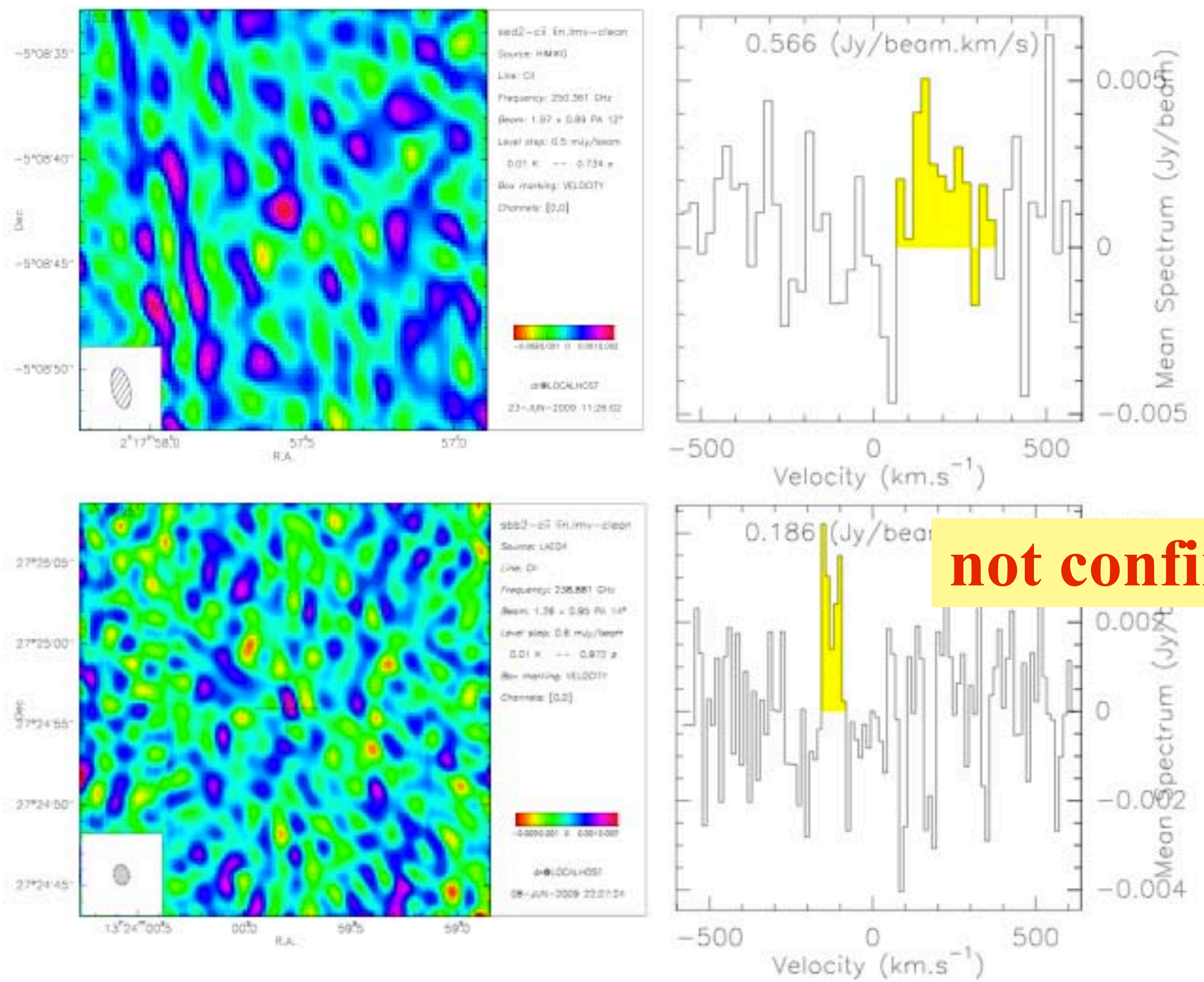
More typical galaxies: [CII] @ z=6.6-7.0

not yet…



Himiko – z=6.58

IOK-1– z=6.98

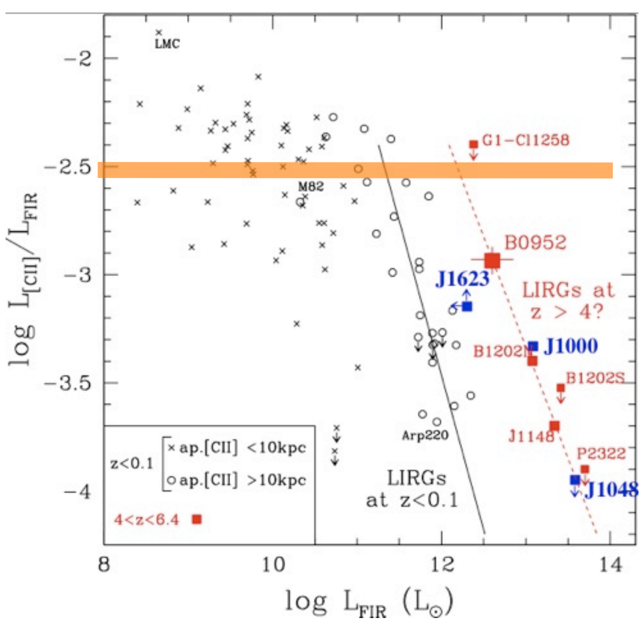


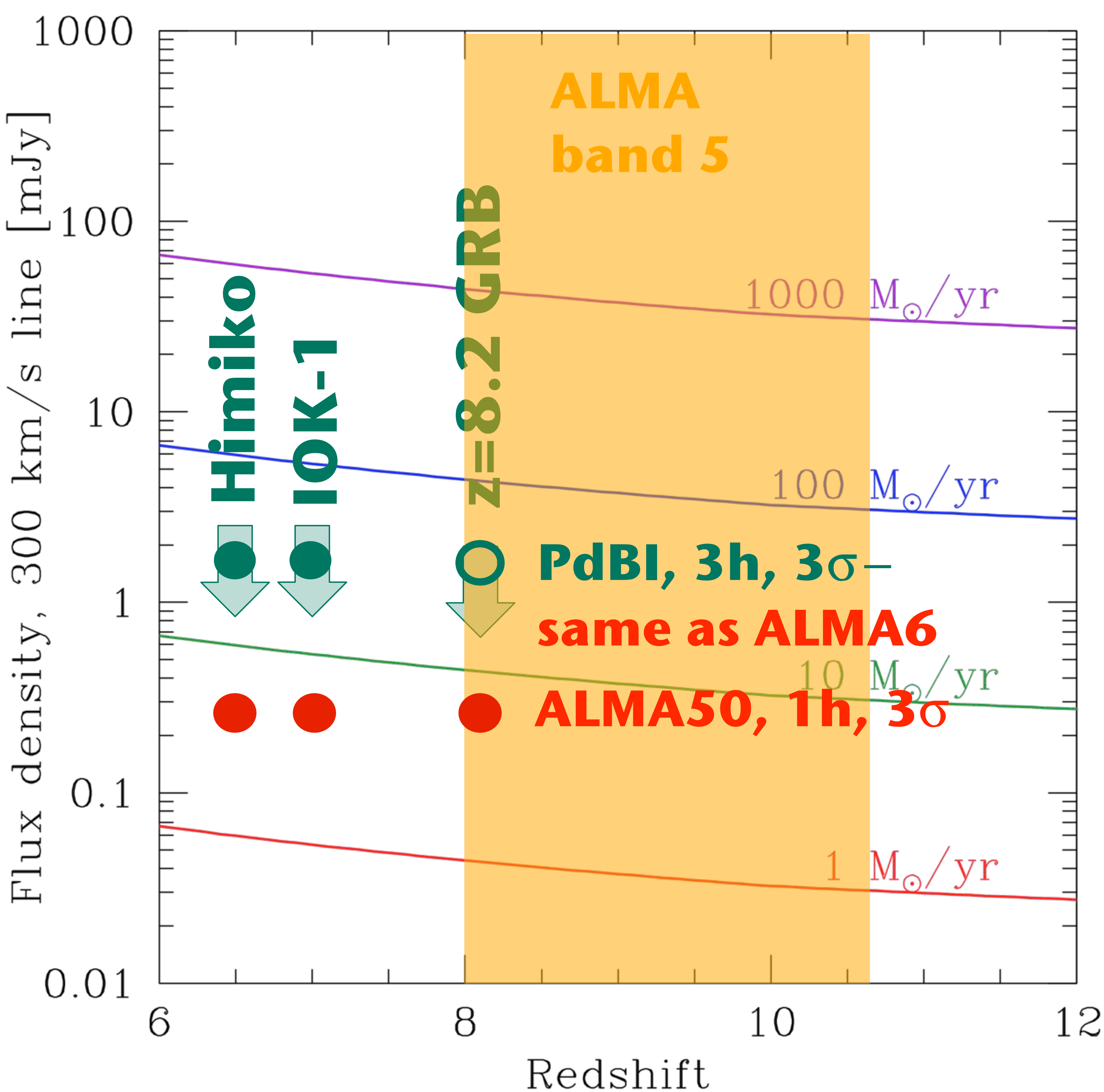
Walter etal in progress

not confirmed

VERY tentative line strengths are close to expectations

Expected [CII] line strength

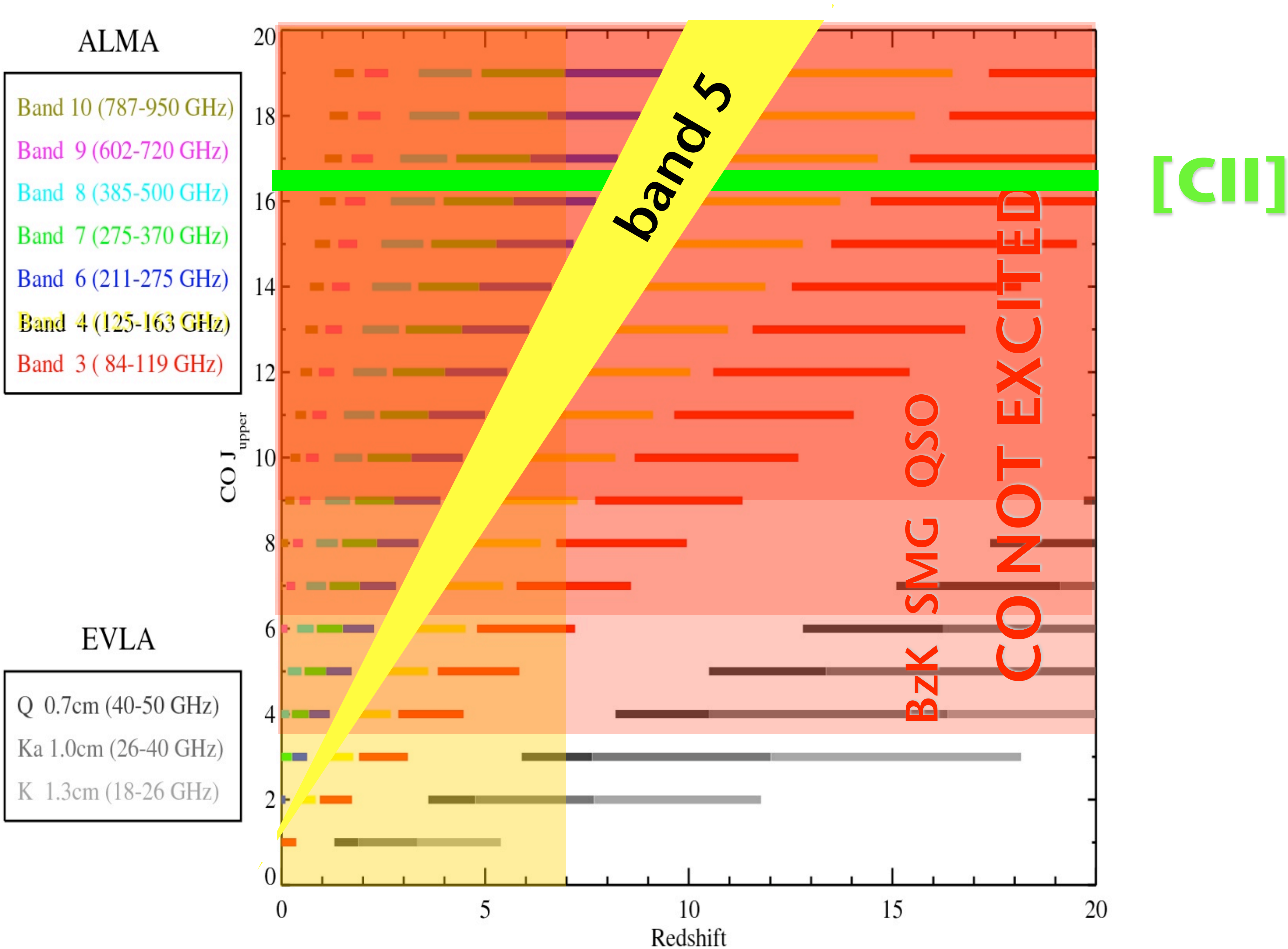




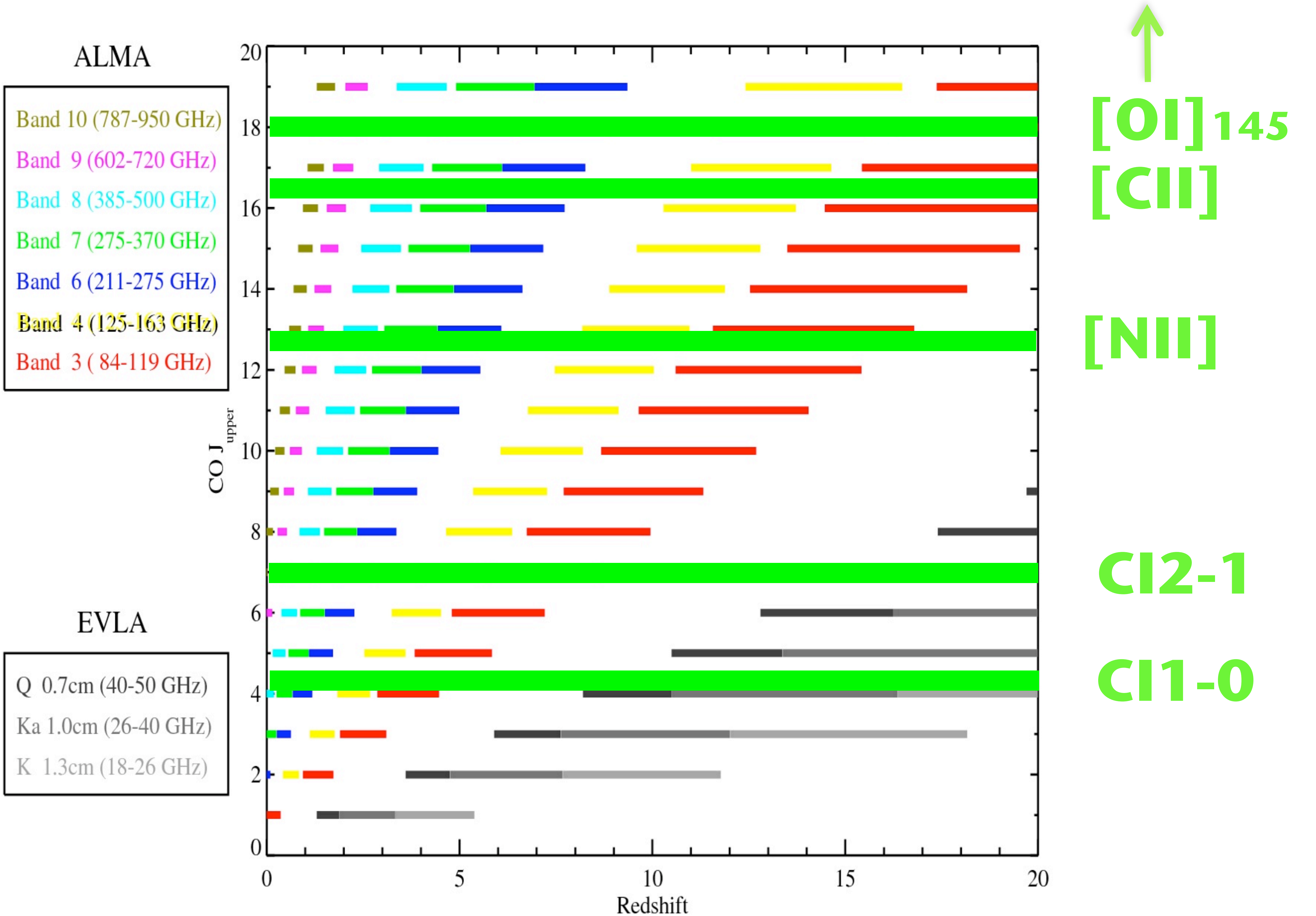
Assumptions:

L_{CII}/L_{FIR}=0.003
line width: 300 km s^{-1}
SFR = 1.8 10^{-10} $L_{FIR}(L_{sun})$

[CII] to the rescue? Need band 5!



other lines to the rescue ?



Lyman α and [CII]

band 4: 125-163 GHz

[CII]: 10.6<z<14.2

Ly α @ 1417-1848 nm

band 5: 163-211 GHz

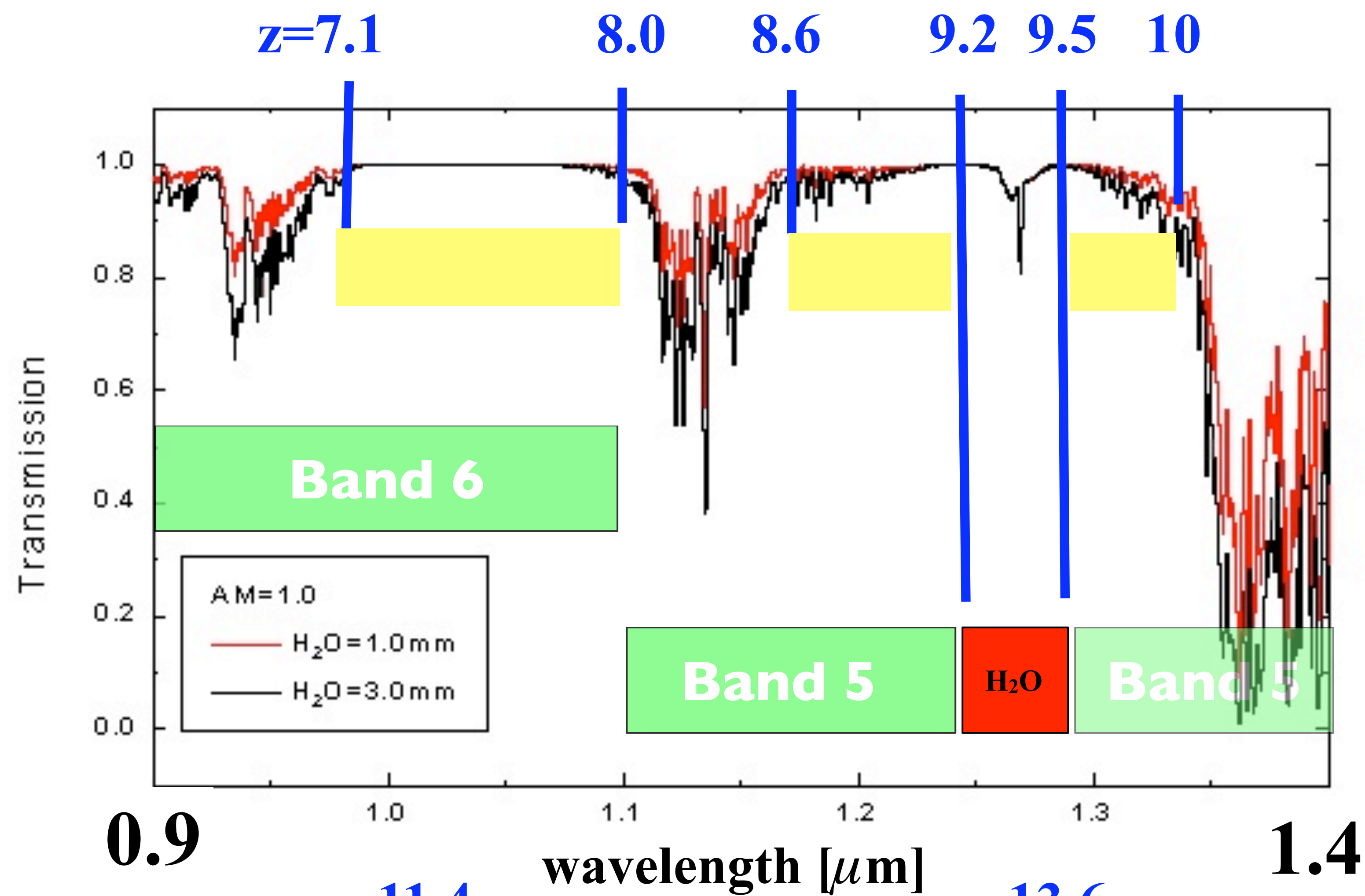
[CII]: 8.00<z<10.6

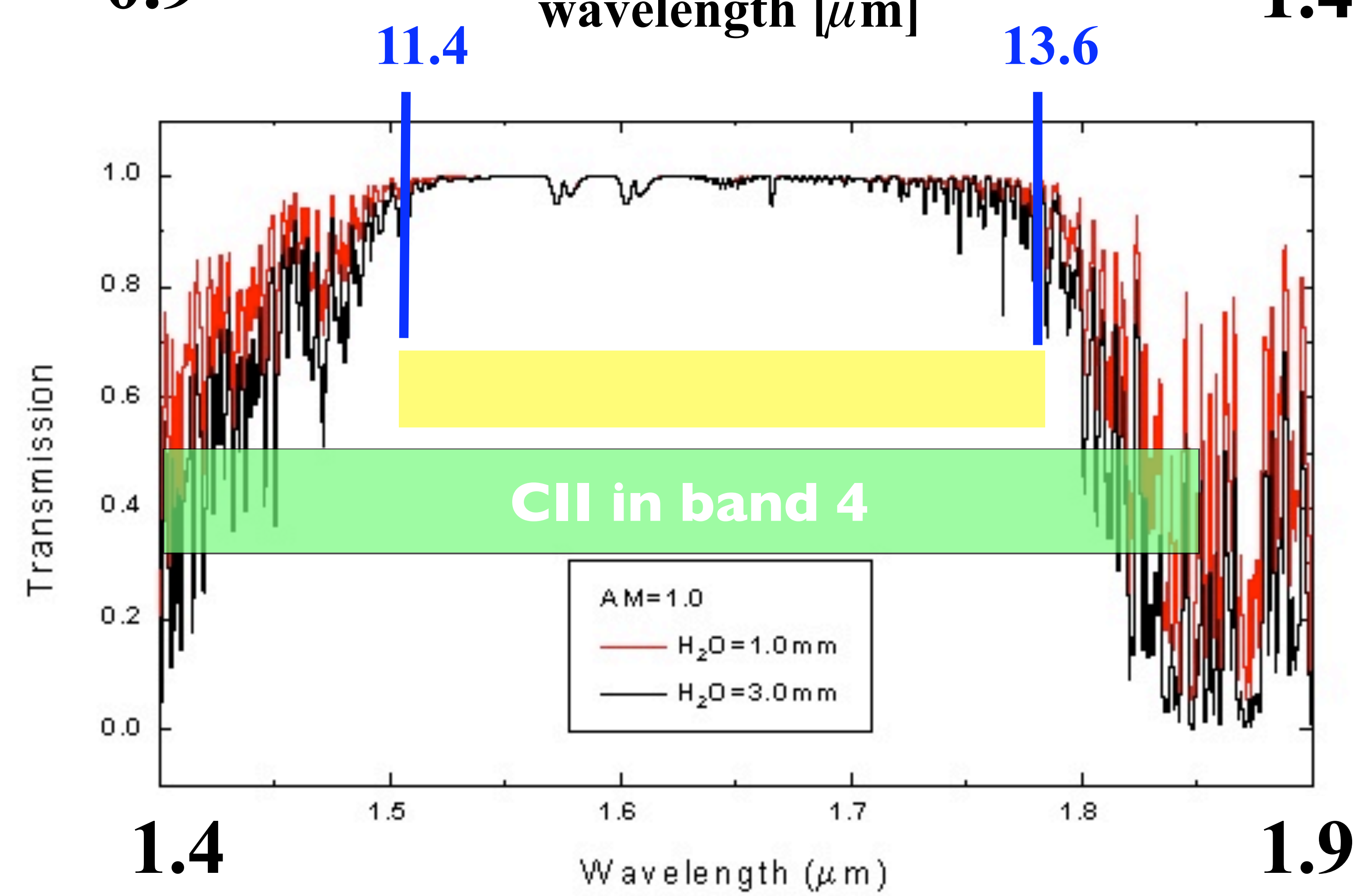
Ly α @ 1094-1417 nm

band 6: 211-275 GHz

[CII]: 5.9<z<8.00

Ly α @ 839-1094 nm



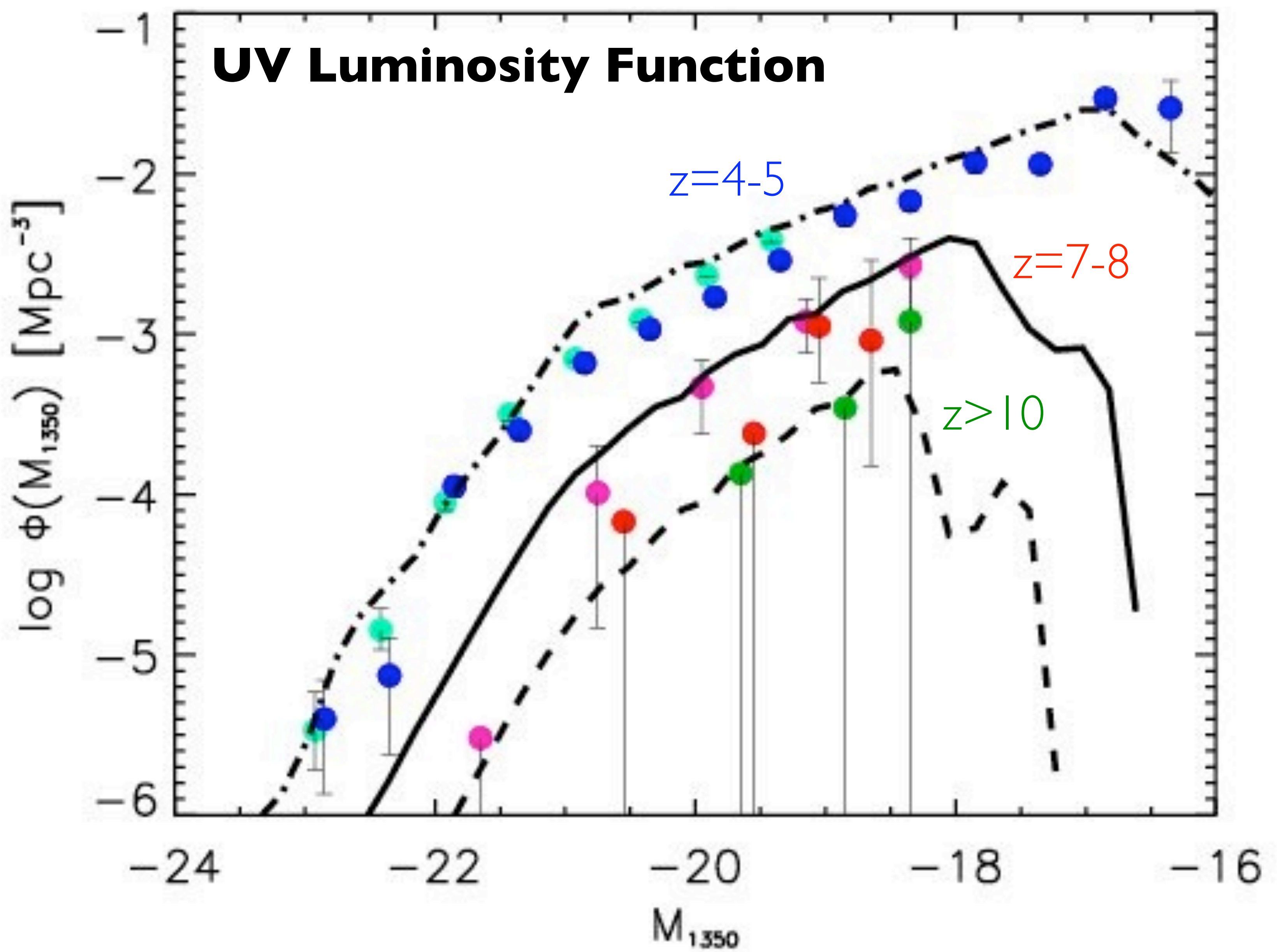


How many galaxies at z>8 expected detectable through [CII]?

Is ALMA a redshift machine or for followup?

Maiolino & de Zotti:

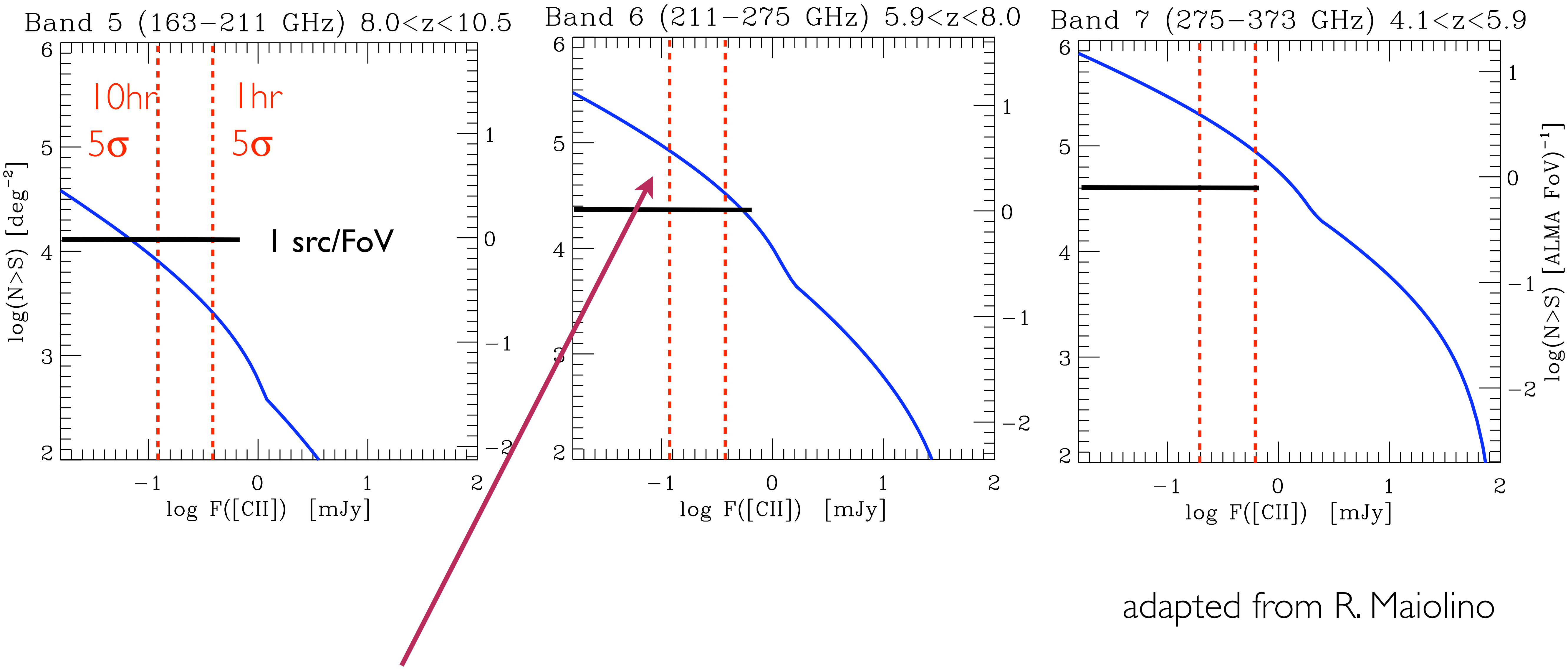
Use current WFC3 and Hawk-I constraints on z>7 populations (m$_{AB}$~28.5 dropouts)
Use models to interpolate and extrapolate data (Mao+07, Blaizot+10)



Convert SFR into [CII] luminosity through fit to the FIR-[CII] global relation

Assume FWHM[CII] ~ 150 km/s (conservative)

Integrated Number Counts



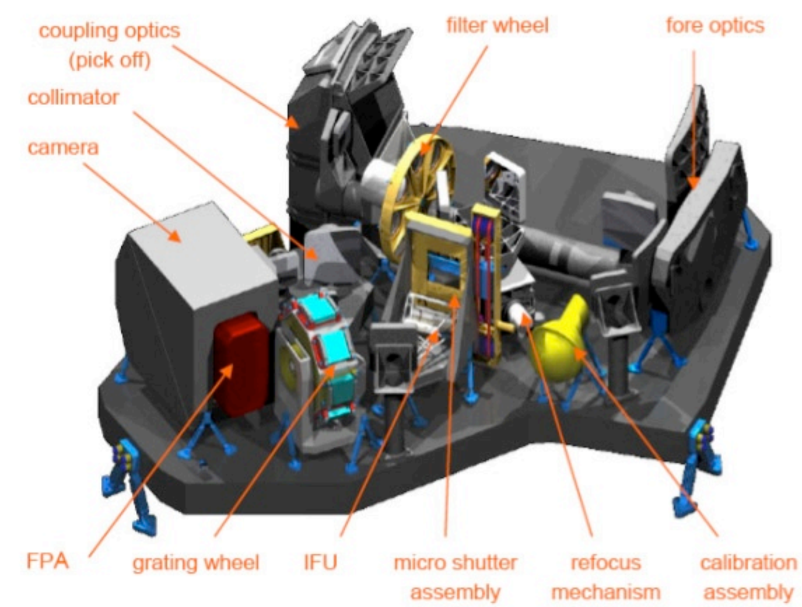
adapted from R. Maiolino

Several sources per FoV in 10 hr of integration.
Requires multiple frequency settings.

Focus on redshift ranges of specific interest
or IF spectrometer on CCAT!

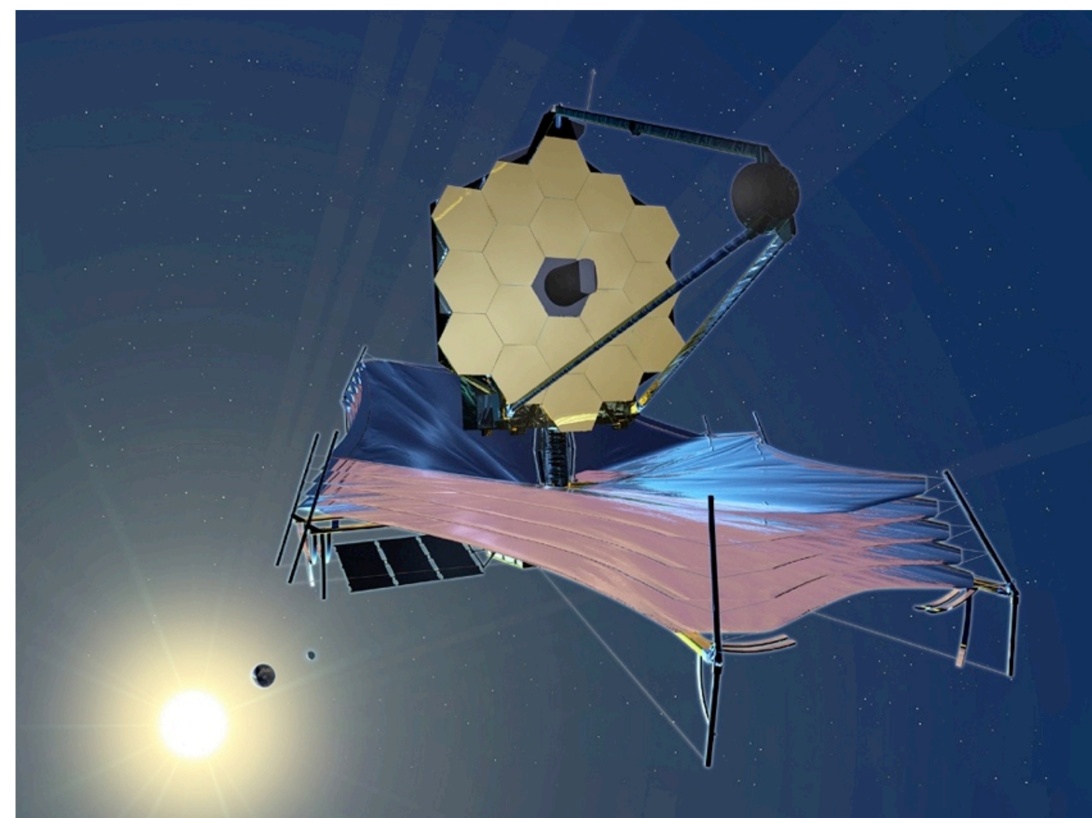
Or target z>8 sources identified by other facilities, e.g. JWST

NIRSpec sensitivity well matched to ALMA



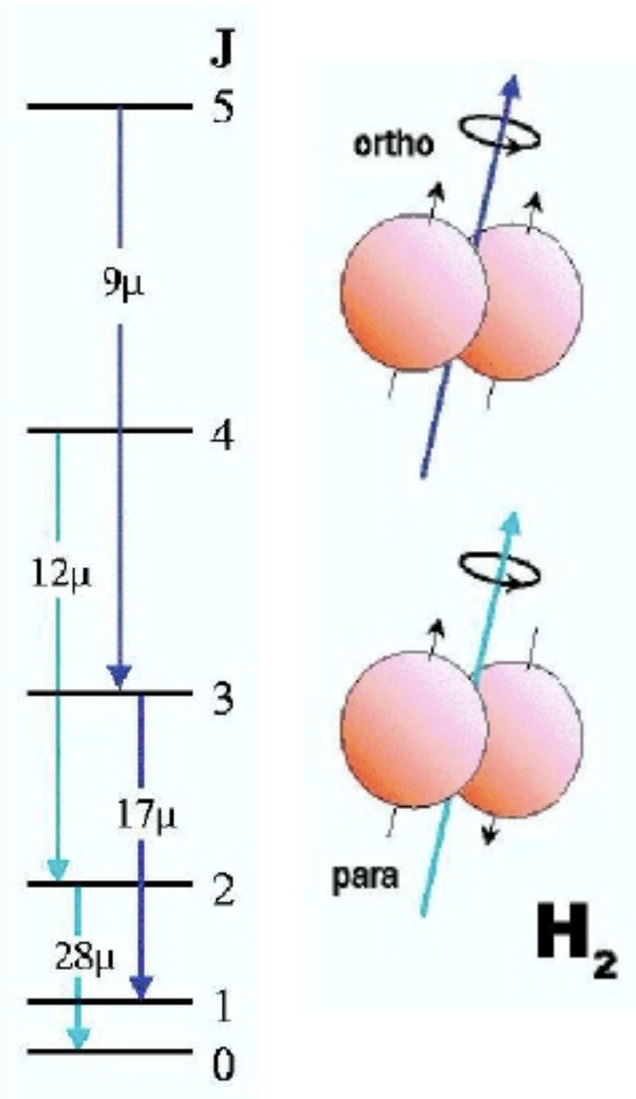
Plan for first two NIRSpec deep observations (~4x3 arcmin^2):
~10 sources at z>8 down to AB~28.5

→ $F_{[CII]}$~0.2 mJy

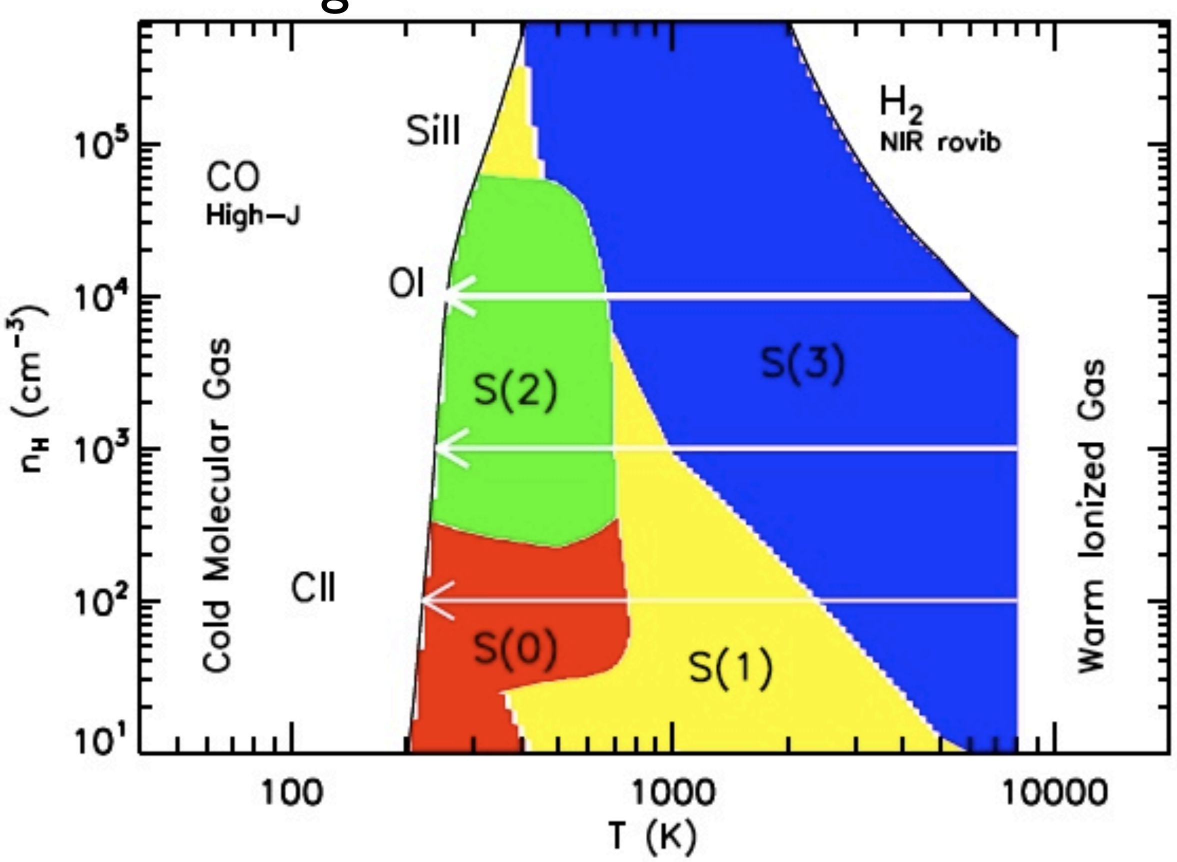


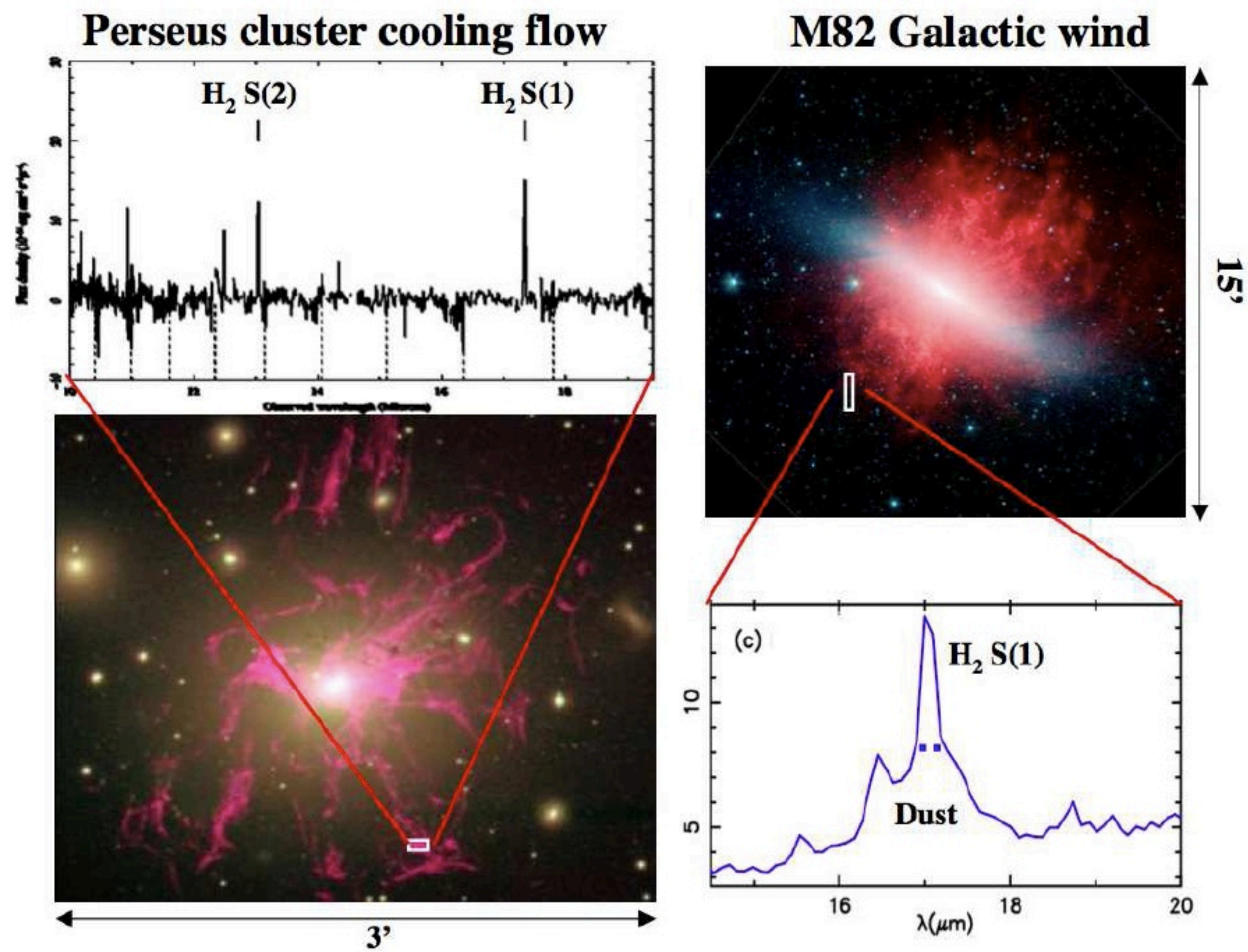
expected to deliver
several z>8 galaxies
with good spectroscopic redshifts

But: problem with too compact or low surface brightness sources.
No resolved spectral imaging, need ALMA

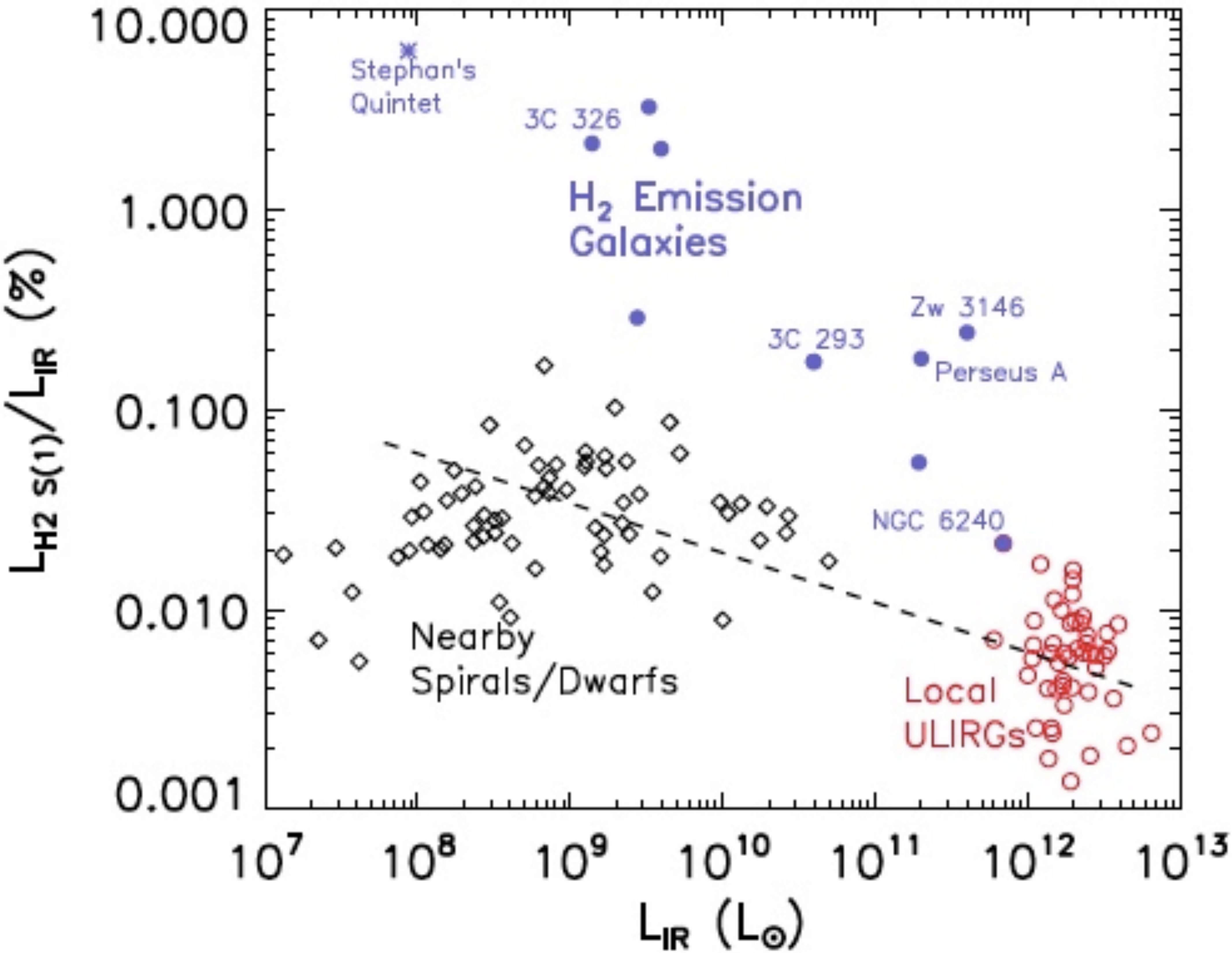


Boulanger et al. 2008





- H_2 prominent coolant in transition regions
- star forming region PDRs
- intergalactic medium
- Early Universe



Stephan's Quintet
3C 326
H_2 Emission Galaxies
Zw 3146
3C 293
Perseus A
NGC 6240
Nearby Spirals/Dwarfs
Local ULIRGs
$L_{H2\ S(1)}/L_{IR}$ (%)
L_{IR} ($L_\odot$)
10.000
1.000
0.100
0.010
0.001
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}

H_2 with ALMA Band 10 & 11a,b

0-0 S(0) 28.2 μm, 10.1 THz
z= 5.5-6.0, 6.3-7.1

0-0 S(1) 17.0 μm, 17.6 THz
z= 10.2-11.2 (no Ly-α but CII in B5-6)
1570-1440 GHZ

Here 0-0 S(0) at 831-903 GHz

(Band 10: 787-950 GHz)

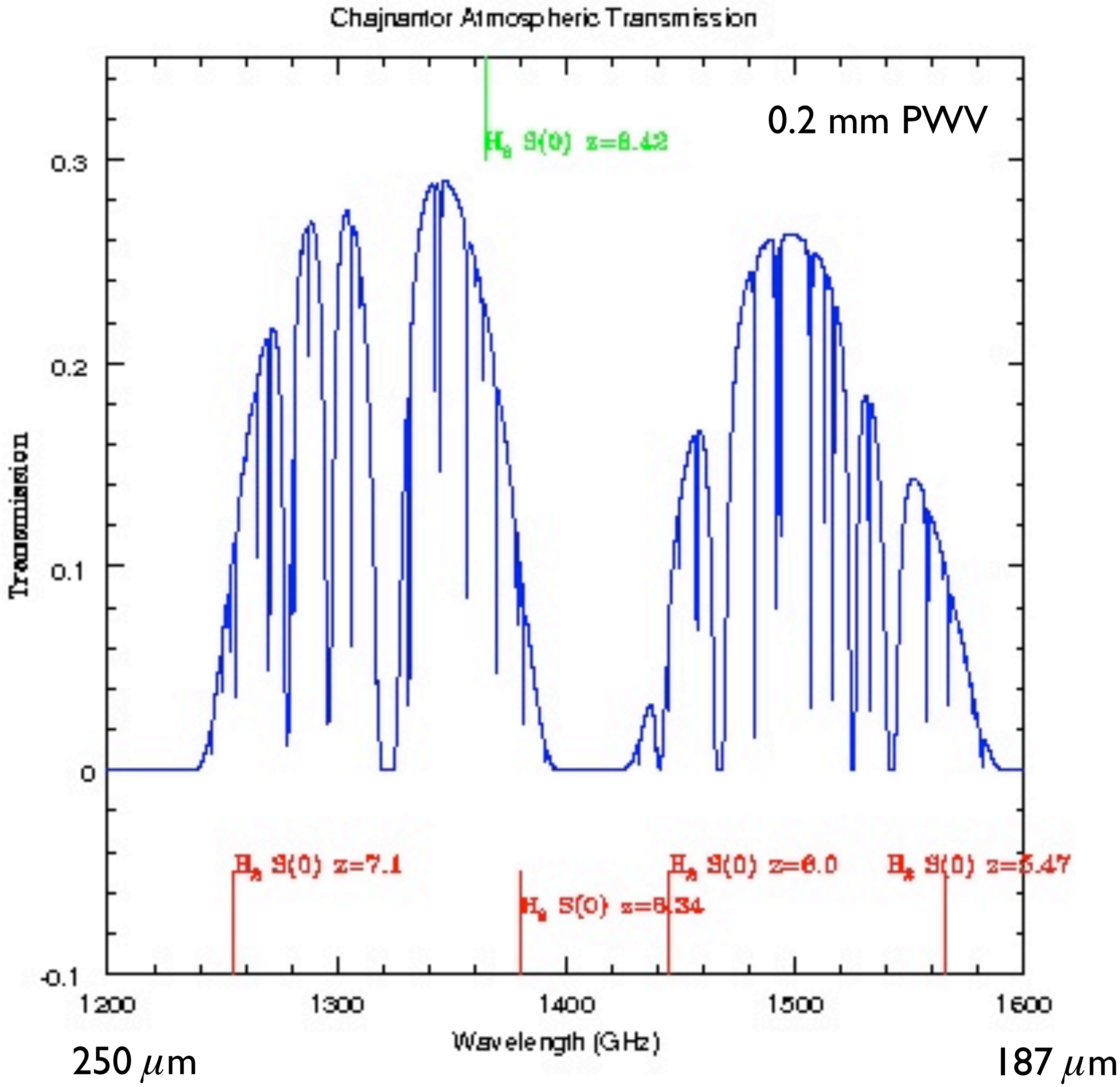
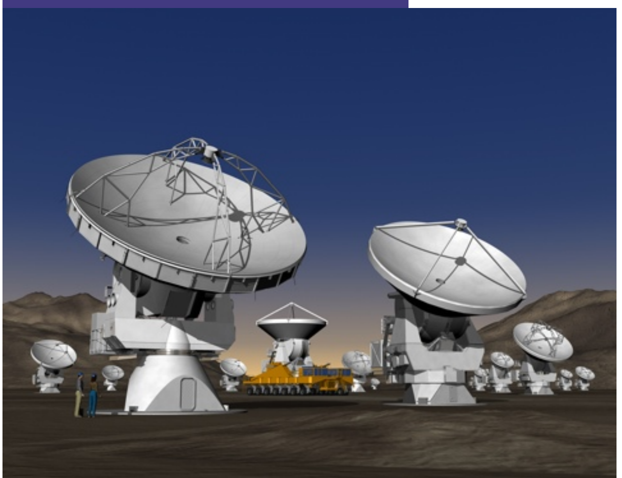


Figure from Al Wooten

Summary



- Epoch of Reionization: The final frontier
- HST reveals population of z=8-10 galaxies. next step: JWST
- (sub)mm observations give unique information
  M_{gas}, M_{dyn}, SFR, [CII] will be key line for z>6 studies
- ALMA: can't do CO (excitation) *and* [CII] for z=8-10.6
  Need Band 5!
- state of art: close to detecting [CII] in z>6 'normal' galaxies
- blind spectral surveys not with ALMA or JWST - need CCAT