CO Intensity Mapping: Science Requirements

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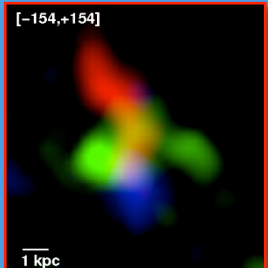
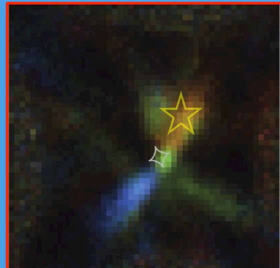
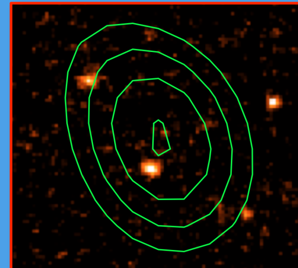
with thanks to Chris Carilli

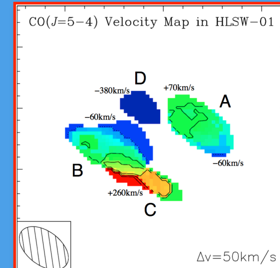
KISS Workshop "The First Billion Years"
August 22, 2011

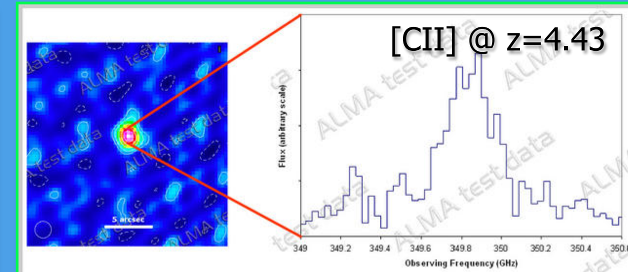
(y)our instrument here?





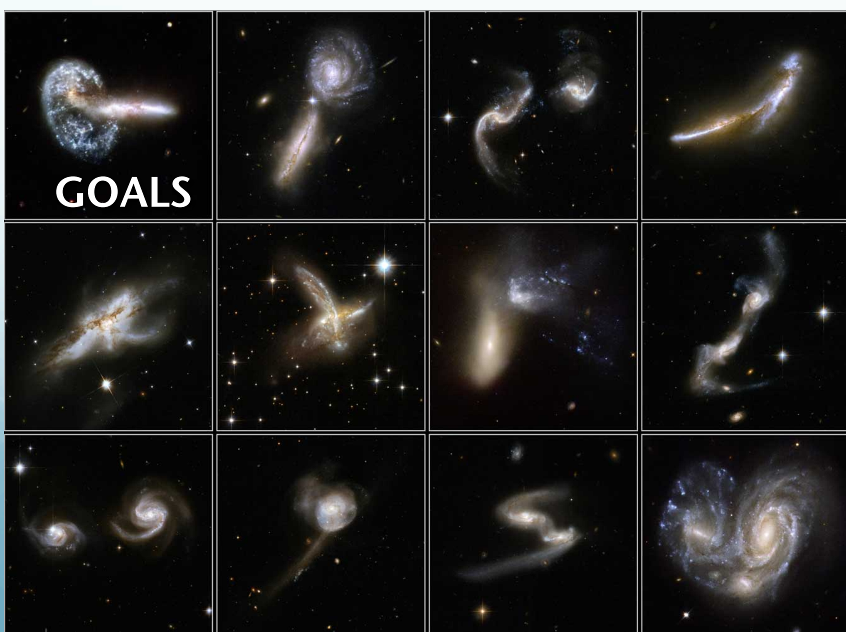


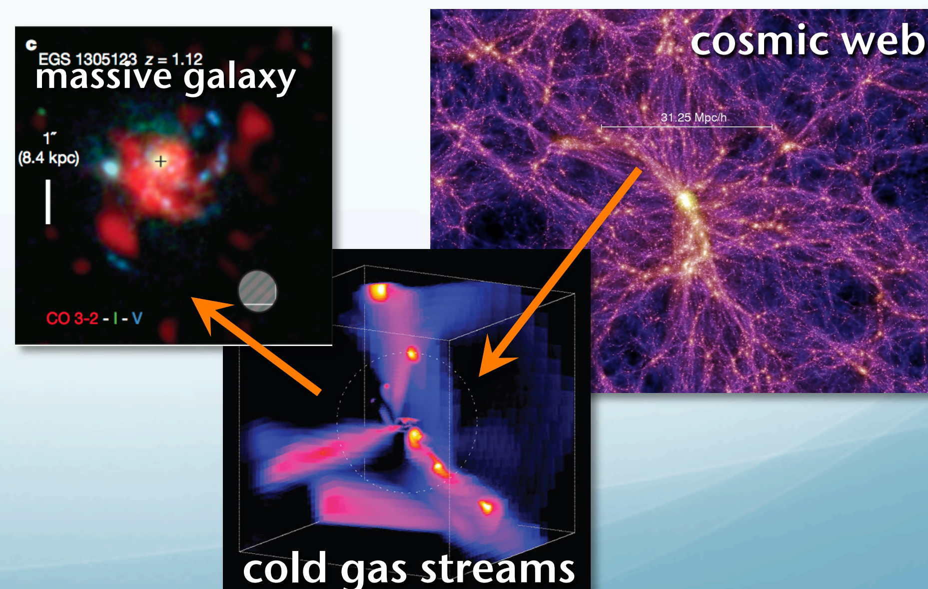




Outstanding Major Issues in Galaxy Evolution

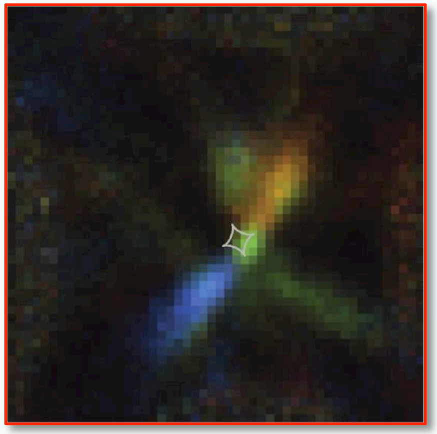
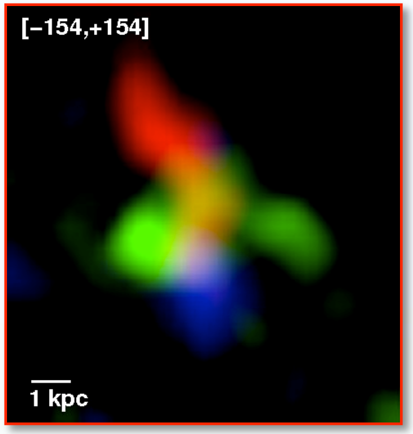
- Does star formation/M_* buildup at early cosmic times occur dominantly through major mergers, minor mergers, steady 'cold mode' accretion?
- How do high-z galaxies get their gas? What are their gas mass fractions?
- What are the physical/chemical properties, distribution, and dynamics of the gas in high-z galaxies that set the initial conditions for star formation?

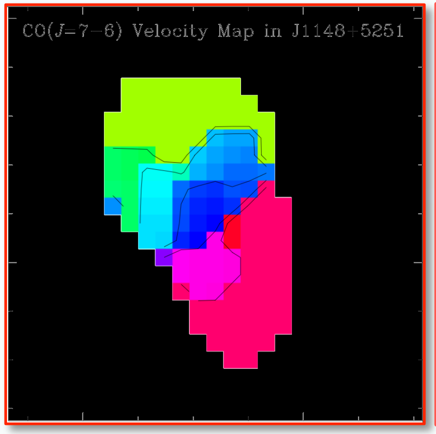


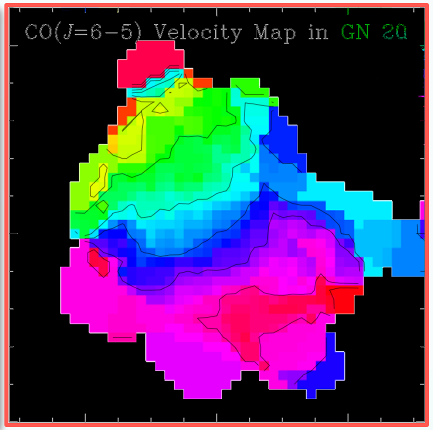


Images: Springel, Dekel, Tacconi

Critical element: molecular gas in galaxies





Requirements:

(1) Detailed studies of molecular gas in individual high-z galaxies

⇒ **need to dynamically resolve few 100pc/cloud scales to study mechanism for SF and determine robust rotation curves/3D merger structure**

⇒ **need to dynamically calibrate gas mass/dispersions for star-forming clumps**

⇒ **robust gas masses, gas fractions, merger fractions, dynamical drivers of SF**

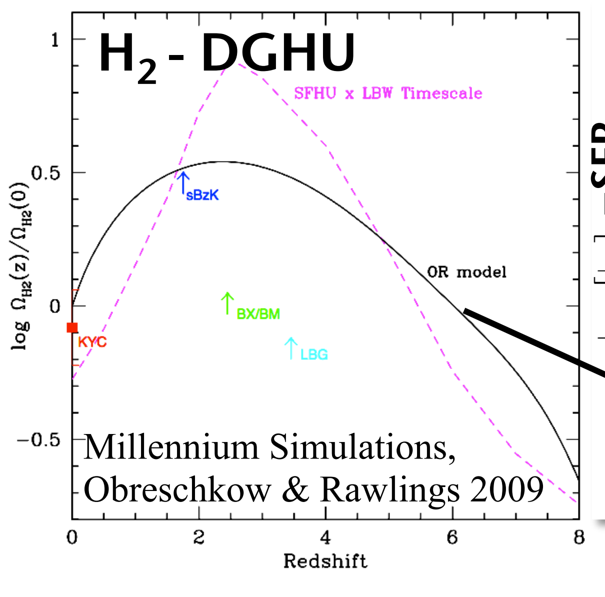
⇒ **need to study multiple molecular gas tracers and their excitation properties**

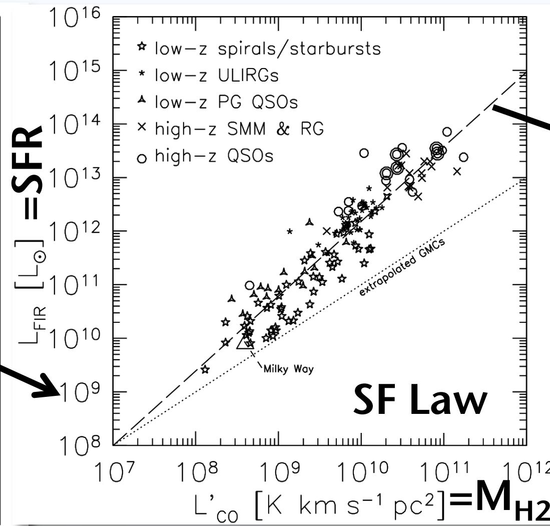
(2) Systematic studies of molecular gas in *all* high-z galaxy populations

⇒ Dense gas history of the universe, "blind" CO Deep Field & **intensity mapping**

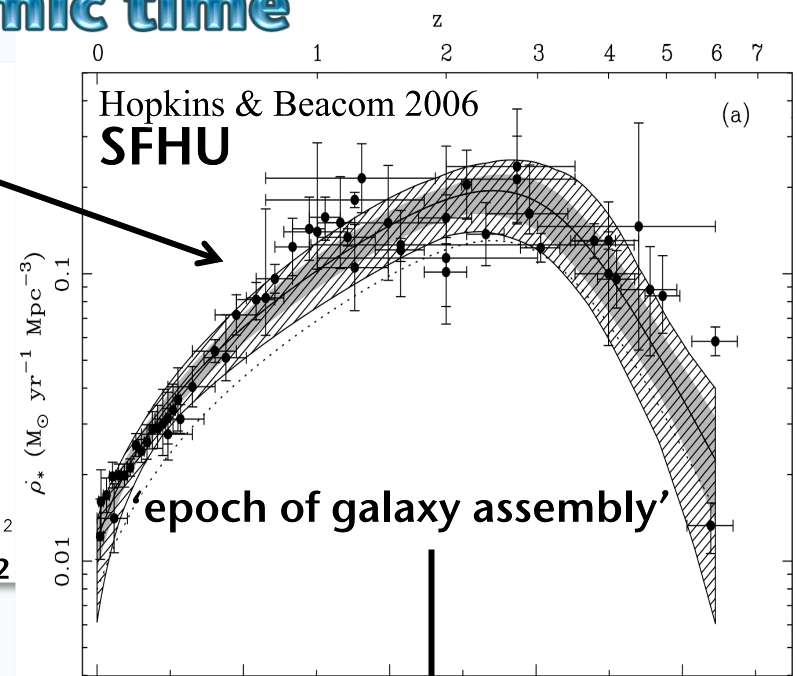
Images: Riechers ea. 2008a, 2008b, 2009; Carilli ea. 2010

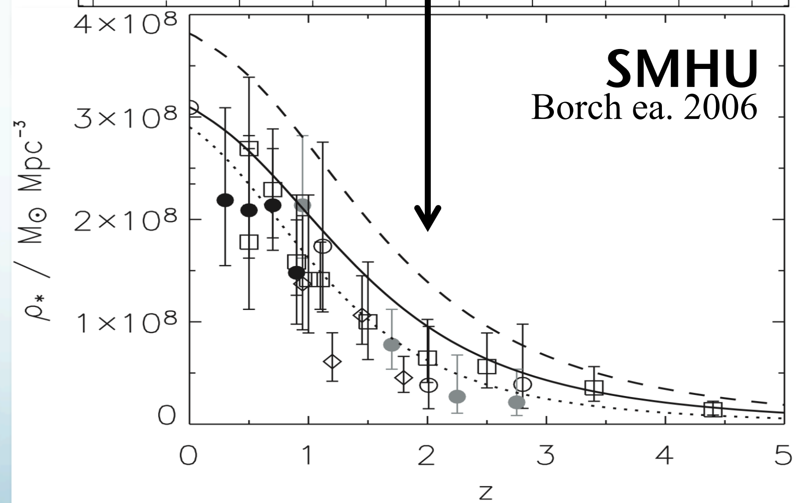
Dense gas history of the Universe → Tracing the fuel for galaxy formation over cosmic time





Riechers ea. 2006





Dense Gas -> SF Law -> Star Formation -> Stars

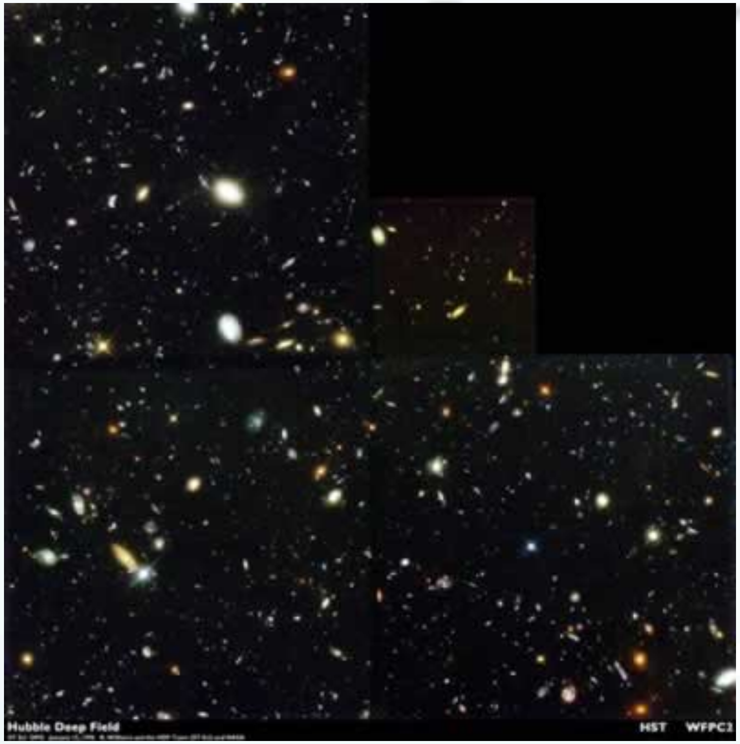
~50% present day M_* produced @z~1-3

Formation History:

- **past: M_* ('effect')**
- **current: SFR**
- **future: M_{gas} ('cause')**

⇒ DGHU is critical next step for a complete picture of galaxy formation

H_2 Mass Function: CO Deep Field Study

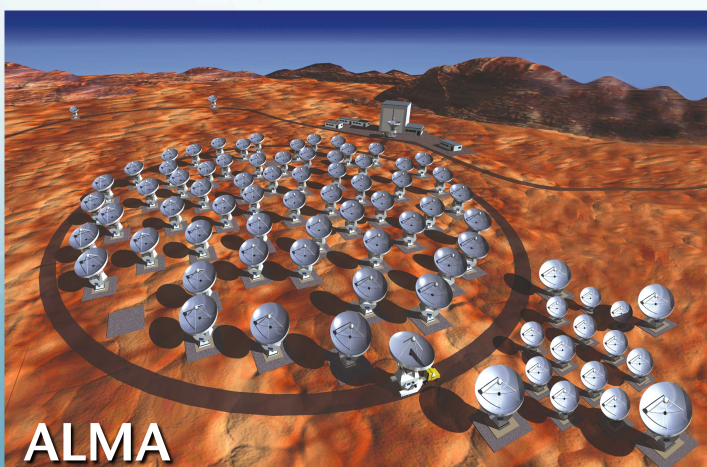


Problem:

CO studies at high z are highly selected
(optical/FIR/radio brightness, spectral features)

Method to overcome selection bias:

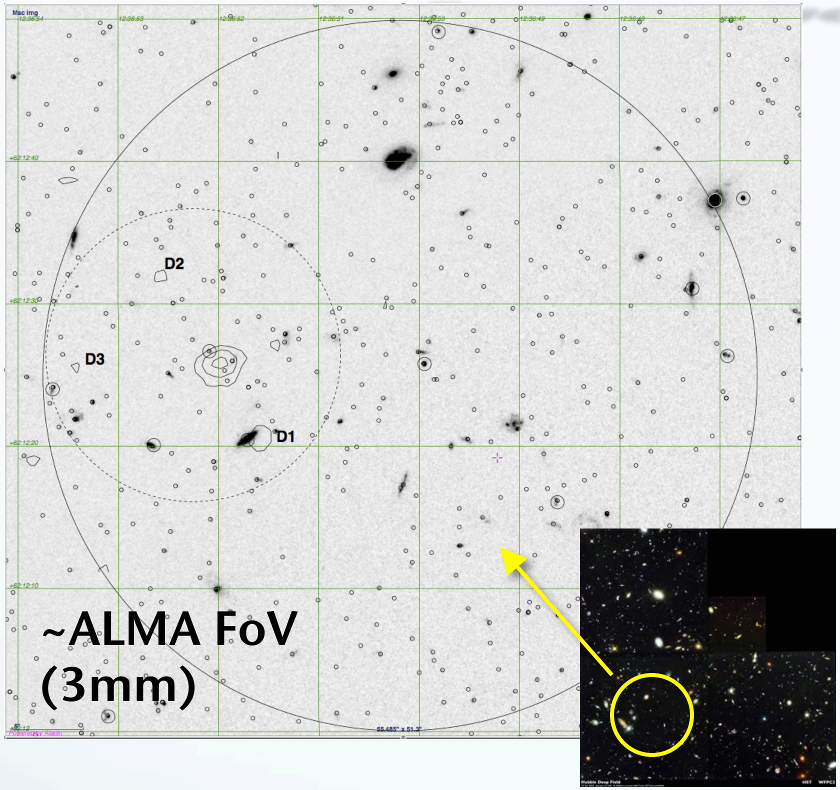
⇒ select *directly* in CO!
⇒ like early SFRD studies: do 'Deep Field'
⇒ ideal: CO data cube contains redshifts



Requirements:

⇒ disentangle galaxy populations based on CO (CO -> H_2)
⇒ direct, 'blind' CO redshift selection
⇒ continuous redshift coverage (=volume)

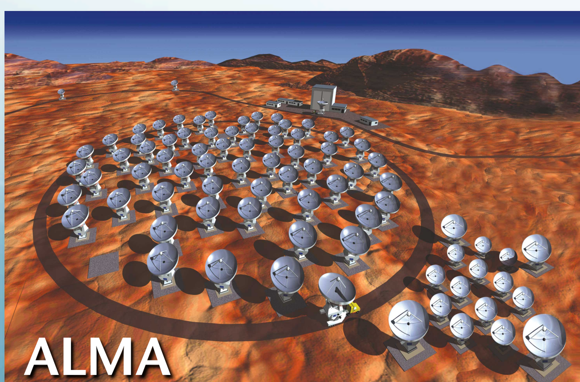
H_2 Mass Function: CO Deep Field Study



z~2 'normal' gas-rich SF galaxies:
- few per arcmin^2
  => common, HDF-size region ok
  (same as initial SFRD by Madau/Lilly)

- ALMA can get 'blind' CO redshifts
  => no optical/UV or FIR bias,
  large cosmic volume (*all* z>1)

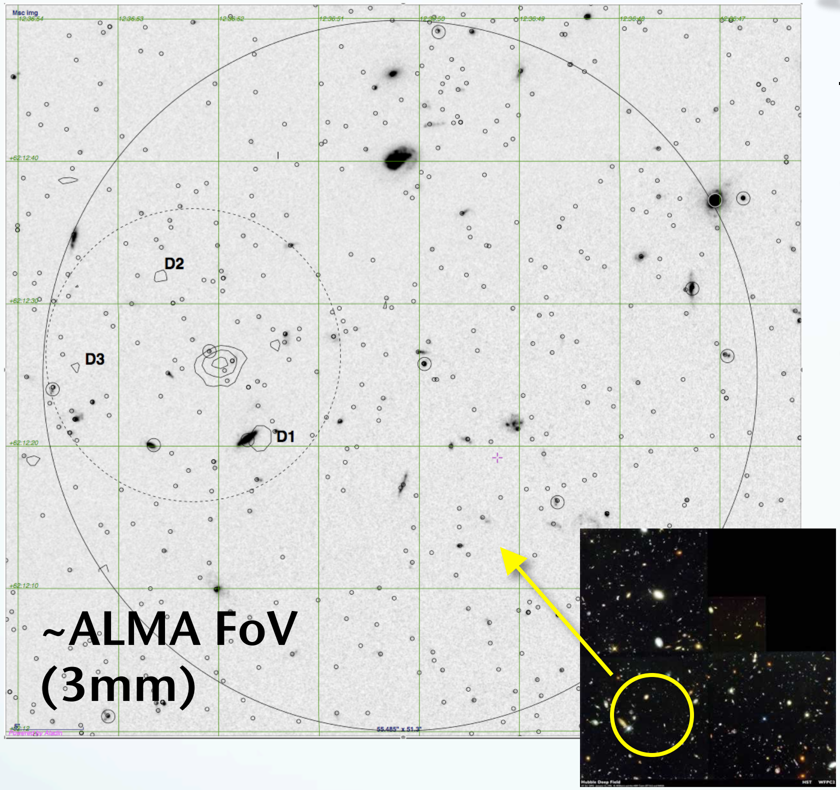
- ALMA: down to >~10^9 M_0 in M_{gas}
  over HDF-size region feasible
  => comparable to typ. high-z M_* limits
  => below 'knee' of H_2 mass function

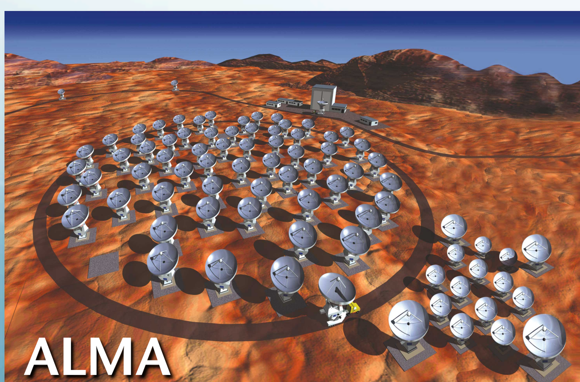


<u>CO Deep Field</u>: 10' scales, 2" resolution

- ideal probe of **individual galaxies**
- study **galaxy physics** & **evolution**

CO Deep Field: Limitations





Limitations:

- low-mass galaxies & systems with low gas fraction will require line stacking (z_{spec})

- will still miss the bulk of very numerous, but very faint, low-mass galaxies

- 3.5’x3.5’ field needs 500-1000hr w/ ALMA

⇒ can never overcome cosmic variance

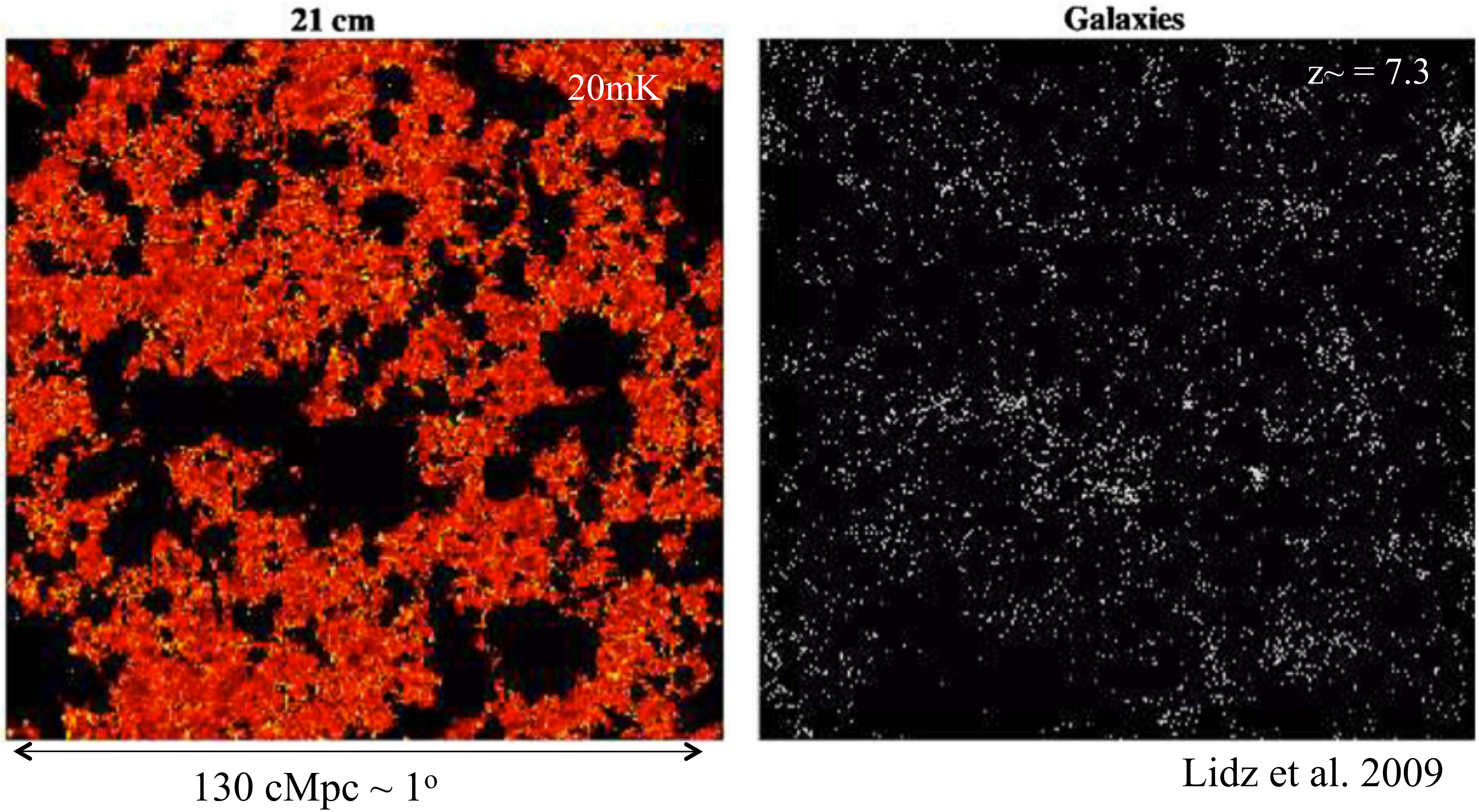
⇒ “SDSS-size” high-z surveys not feasible

⇒ incompleteness & limited size disallows to constrain structure of reionization

But: will constrain astrophysics for any large scale approach (=**COIM**)

‘Inverse’ views of evolution of large scale structure during reionization

- Neutral intergalactic medium via HI 21cm line observations = consequence
- Galaxies which drive reionization = sources



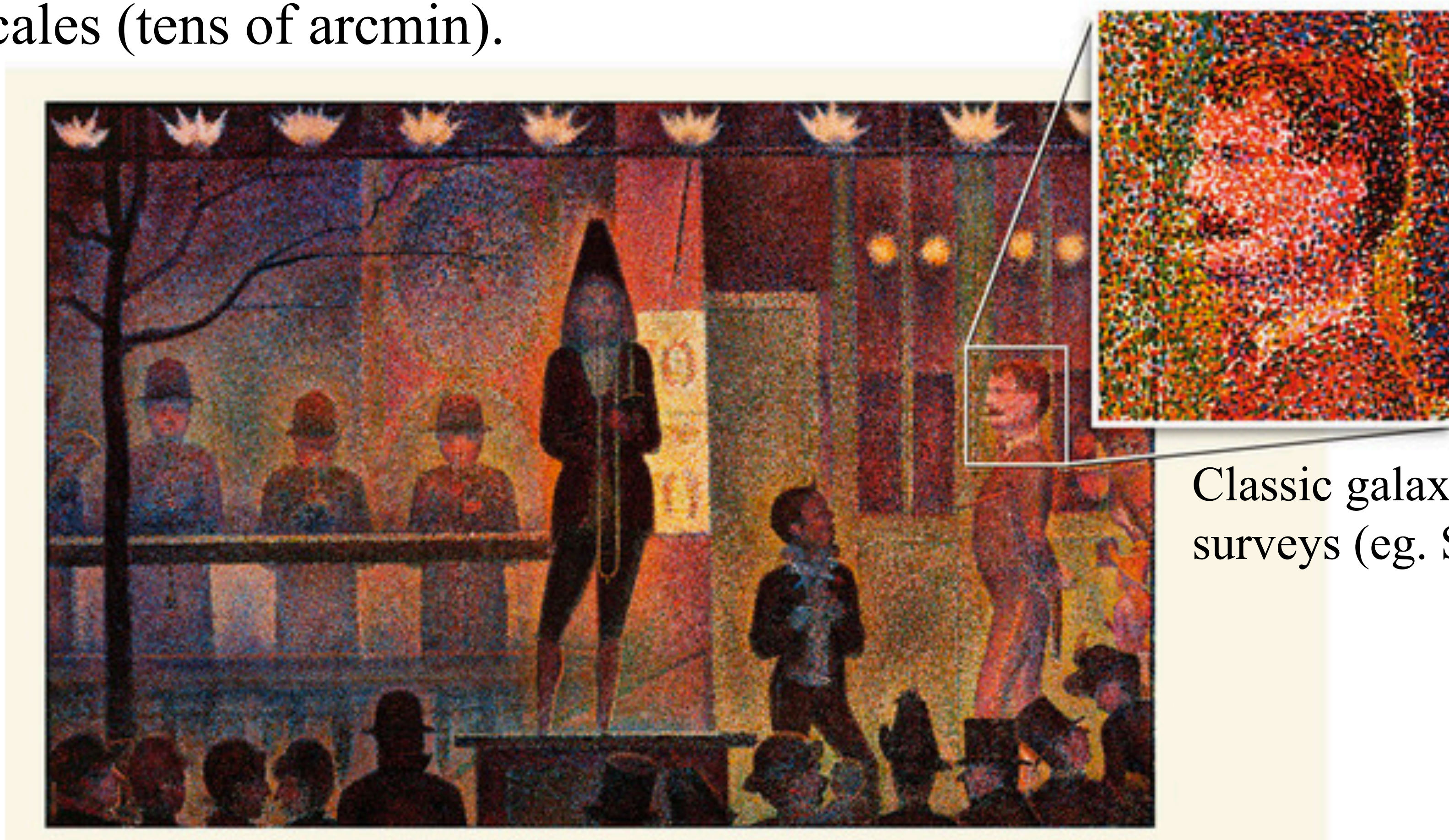
Lidz et al. 2009

Inverse Views of the Universe: Neutral IGM vs. galaxies

- Power
  - ➢ Complete view of physics: sources of reionization and their impact on the IGM
  - ➢ Cross correlation of HI 21cm signal with galaxy distribution mitigates large (but independent) systematic errors (eg. foregrounds) in each measurement (Lidz ea)
- Challenge: Problematic to match very (very) large scale of HI measurements with classical galaxy surveys
  - ➢ HI 21cm experiments cover 100 to 1000 deg^2 and z range ~ 6 to 10
  - ➢ $z>6$ galaxy surveys by JWST/ALMA have FoV ~ arcmin, $dz < 0.5$
- Solution: Intensity mapping of the aggregate CO emission from the galaxies that reionize the Universe

Galaxy distribution

- Classical method: one galaxy at time, eg. SDSS 2e7 galaxies
- Intensity mapping: low spatial and spectral resolution imaging of summed signal from aggregates of thousands of galaxies on Mpc scales (tens of arcmin).

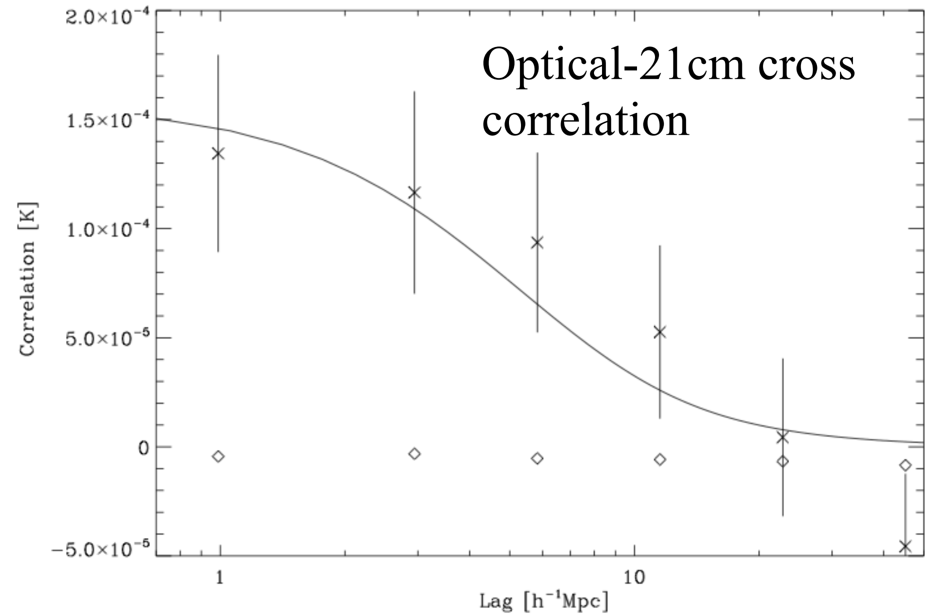


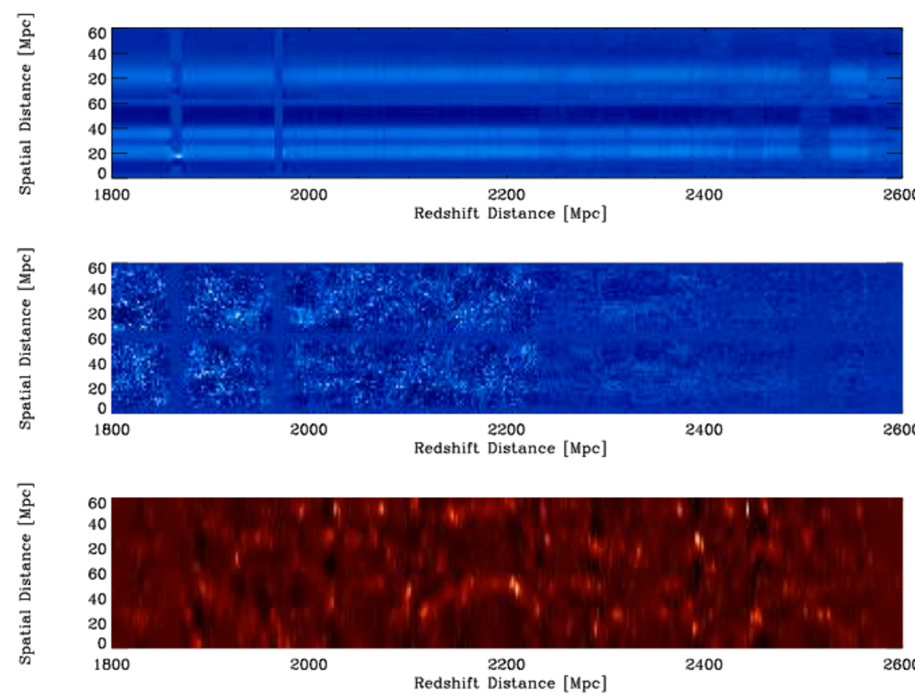
Classic galaxy surveys (eg. SDSS)

Intensity mapping

GBT IM of LSS in HI at z ~ 1
Chang ea 2010, Nature

- 850MHz, 15’ res, 1000 km/s/ch
- Cross correlation with DEEP2 galaxy survey => Detection! = aggregate HI signal from galaxies on Mpc scales.
- First detection of HI 21cm emission at substantial redshift => confirms DLA HI mass density
- Promise of mapping large scale structure at high redshift, such as the Baryon Acoustic Oscillations





CO Intensity Mapping: Science Goals

Map LSS thru fluctuations of emission lines from galaxies to:

- constrain <u>tomography of reionization</u> in redshift slices
  - if SF activity follows merging history, CO should trace similar clustering pattern
  - photoionization heating during reionization changes <u>min. mass</u> of halos that host galaxies, i.e., can estimate ionizing flux from faint galaxies & look for sharp change in signal as f(z) due to change in M_{min}
- constrain early formation of GMCs & subsequent process of metal <u>enrichment</u> of the IGM throughout cosmic times & <u>clustering properties</u> of enriched regions
- constrain evolution of metallicity, SFR, bias & duty cycles of faint, <u>individually undetectable</u> galaxies as f(z) at z>6 (=information missing from "traditional" galaxy surveys)
- get <u>clustering signal</u> from *all* galaxies, not just bright ones

CO IM: Measured Signal

- **Epoch of interest: z=6-10 -> CO 1-0 & 2-1 ideal:**

⇒ **measurable at 10-40 GHz, region w/ little line confusion**

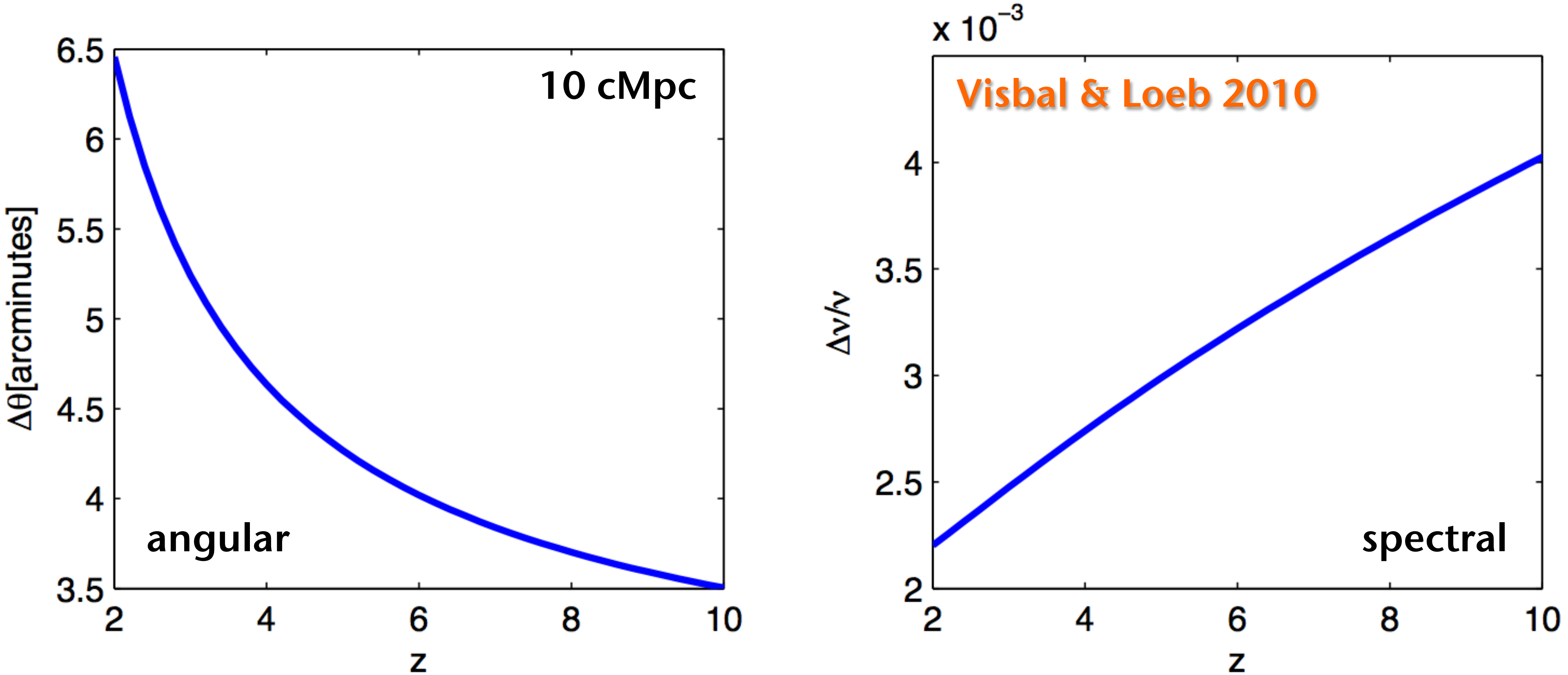
⇒ **can be covered easily from the ground**

⇒ **have highest contribution on T_b scale relative to CMB, Milky Way, radio & dust continuum foregrounds**

<u>Issue:</u>

- **Line confusion, so measure <u>line cross power spectrum</u> between CO 1-0 & 2-1 (and HI_{21cm}, $[CII]_{158\mu m}$) anisotropies (power spectrum of CO foreground fluctuations) to statistically isolate signal at a certain redshift**
- **cross PS = cosmic matter PS * avg. signal from pair of lines * luminosity-weighted bias of source galaxies**

CO IM: Critical Scales

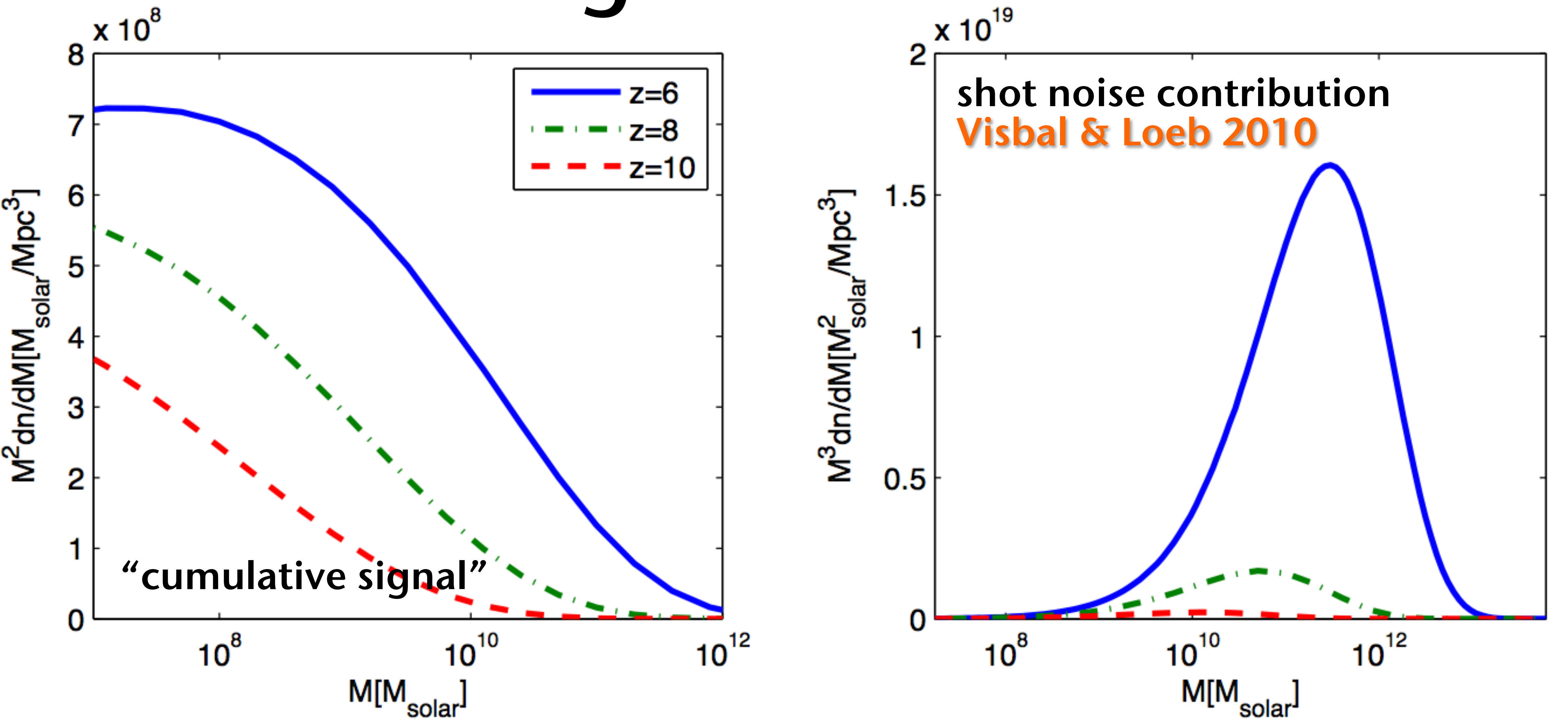


- measured most efficiently on scales of bubble sizes
- larger than individual halos, average out f_{gas} variance

⇒ resolve 1-10 comoving Mpc (cMpc)

⇒ 3’-5’ spatial resolution, 1e-3 frequency res (=10-40 MHz)

CO IM: Signal Contributions

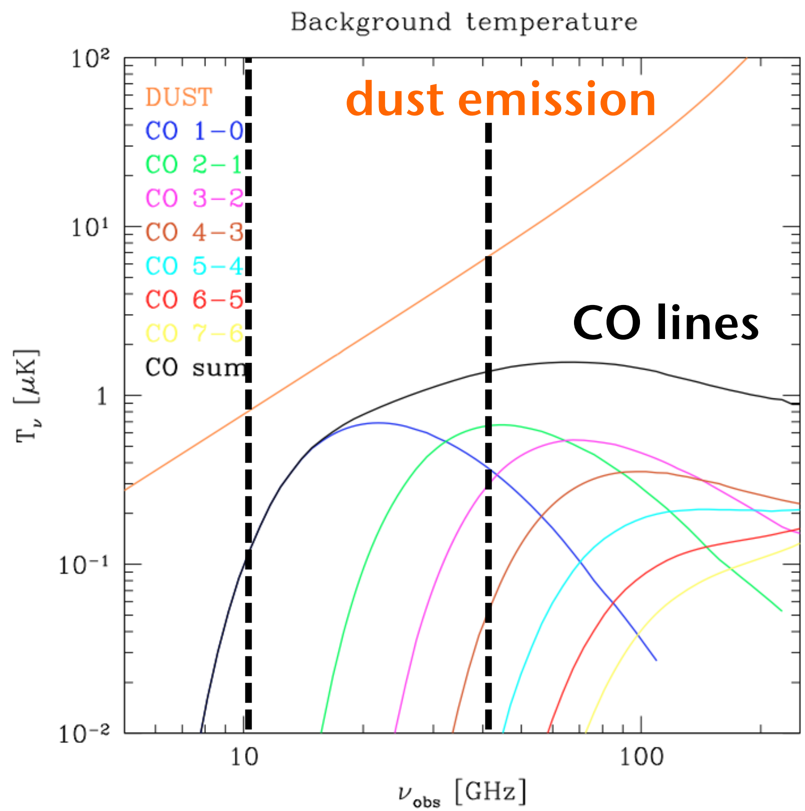


Clustering PS has 2 terms:

- poisson fluct. #/halos = shot noise (dominated by most massive halos)
- correlation with DM density field (dominated by low-mass halos)

⇒ the *faintest* galaxies produce the most line signal per log mass interval

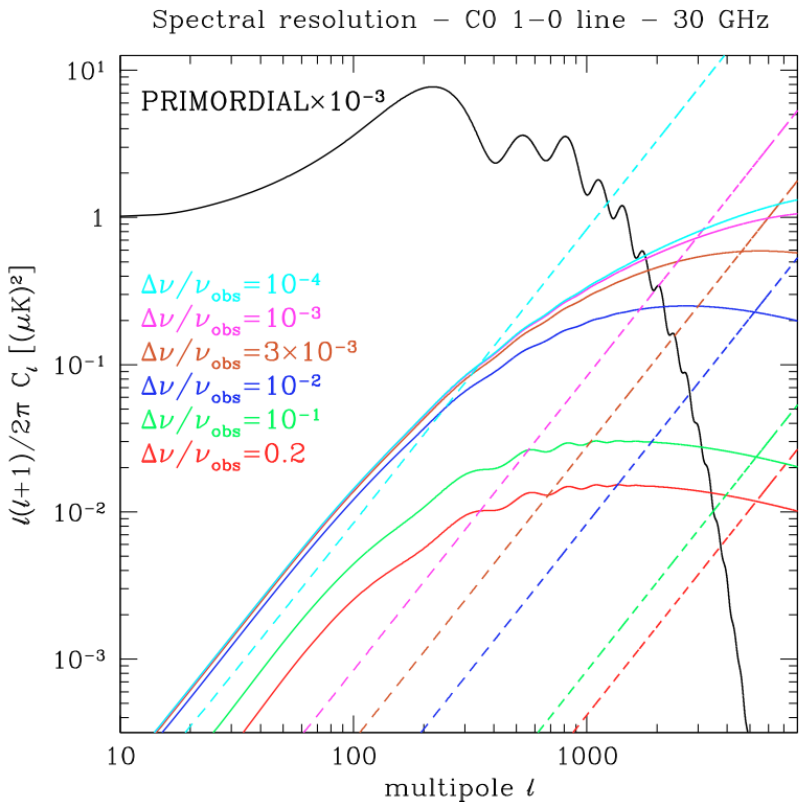
CO IM: Relative Signal Strength



- expected CO signal few-100x weaker than dust continuum
- best contrast for CO 1-0 & 2-1

Righi ea. 2008

CO IM: Relative Signal Strength



<u>solid:</u> correlation
<u>dashed:</u> Poisson term

- Poisson term dominates on small scales, down to typical galaxy sizes (few kpc)

- expected CO signal amplitude >1e3-1e6x weaker than CMB
- best contrast for spectral resolution of ~1e-3 "saturates" on these scales (corresp. to few-10 cMpc)
- relative importance of Poisson vs. correlation terms depends on spec. res.

Measurement of the Cross Power Spectrum

1) Reject continuum foregrounds (Galactic dust/ synchrotron,free-free, low-z galaxies) & CMB

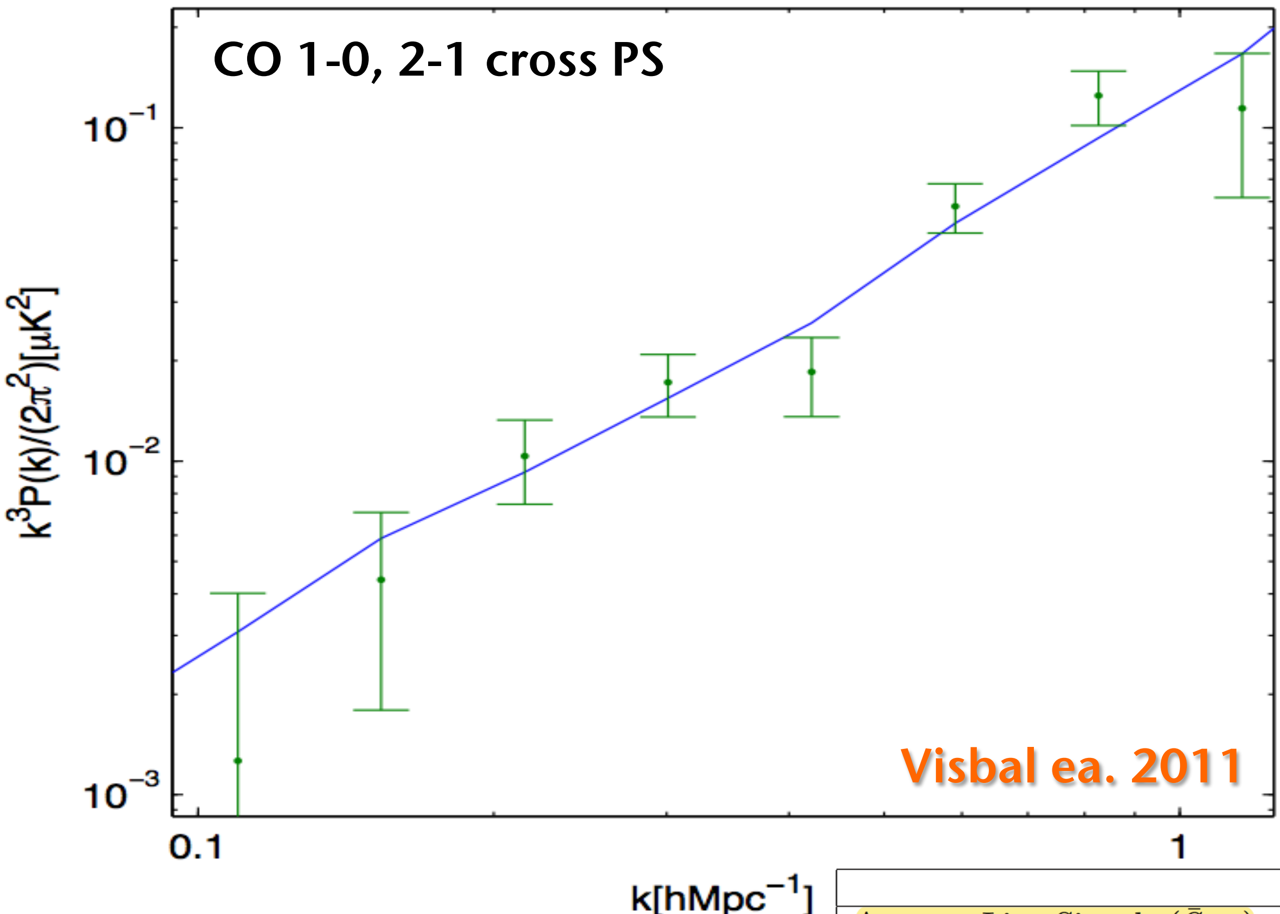
⇒ Fit & subtract smooth function in frequency to each resolution element

2) Mask out bright interloper lines and bright "point sources" that dominate the Poisson term

⇒ Reject corresponding *k*-modes

3) Measure PS from Fourier modes, average into spherical shells in *k*-space to get different scales

Measurement of the Cross Power Spectrum



Simulation for:

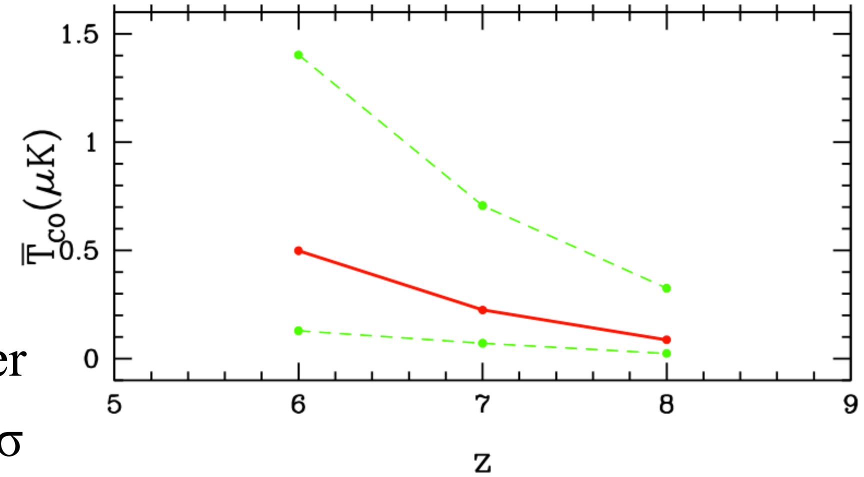
z=7.5+/-0.9
T_{sys}=30K
T_{int}~1yr (dual pol)
$\Delta\nu/\nu$=1e-3
FoV=3deg^2 @ 3.5'-5' res

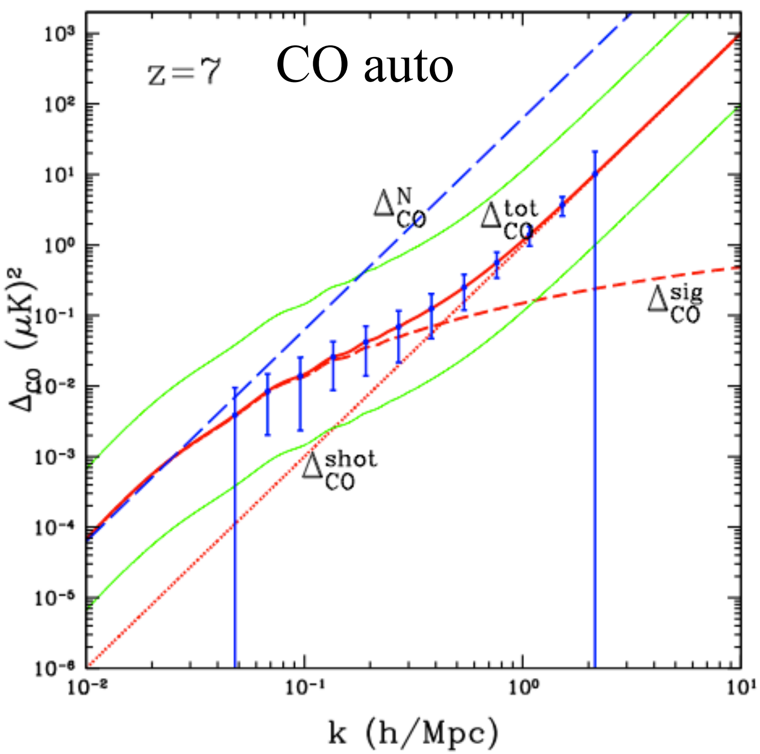
(Input: DM simulations)

	CO(1-0)	CO(2-1)
Average Line Signals ($\bar{S}_{\rm line}$)	0.1μK	0.094μK
Fraction of Voxels Masked	0.0	0.015
RMS Detector Noise	1.0μK	0.7μK
Bad line Power/Noise Power ($k = 0.1h^{-1}$Mpc)	0.0	7.0
Bad line Power/Noise Power ($k = 0.3h^{-1}$Mpc)	0.0	1.5
Bad line Power/Noise Power ($k = 0.8h^{-1}$Mpc)	0.0	0.5
Cross Power S/N per k-mode ($k = 0.1h^{-1}$Mpc)	0.24	
Cross Power S/N per k-mode ($k = 0.3h^{-1}$Mpc)	0.12	
Cross Power S/N per k-mode ($k = 0.8h^{-1}$Mpc)	0.05	

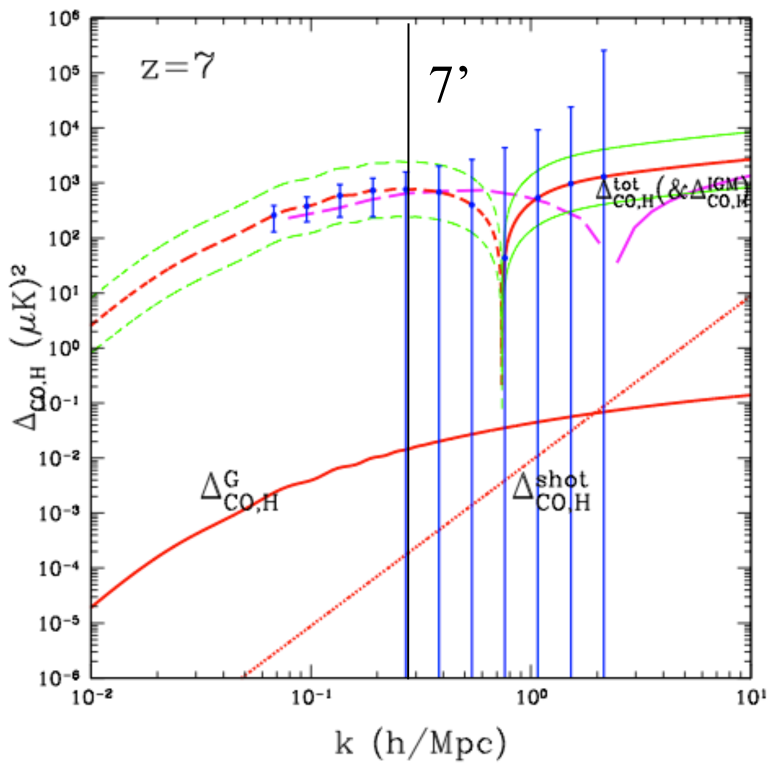
Gong et al.: numerical prediction of T_B

- Obreschkow & Rawlings CO galaxy catalog based on Millenium simulations
- $<T_B>_{z=7}$ = 0.1 and 0.7uK
- Fluctuations on 10' scales are factor few smaller
- CO auto-power spectrum can be detected at 40σ
- CO-HI cross power spectrum: errors dominated by HI measurements!





HI-CO cross



CO intensity mapping: dominant tracer of molecular gas in galaxies (Carilli 2011)

Predicted mean sky brightness temperature in 3 simple steps

1. Cosmic star formation rate density required to reionize the IGM using mean baryon density (Haardt & Madau, Bunker et al.)

$$\dot{\rho}_{SFR}^{reion} \equiv \mathrm{SFR/Volume} = 0.005\ f_{esc}^{-1}\ [\frac{(1+z)}{8}]^3\ (C/5)X\ \mathrm{M_\odot\ yr^{-1}\ Mpc^{-3}}$$

- f_{esc}^{uv} = ionizing photon escape fraction ~ 0.06 (MW), up to 0.2 for z~3 LBGs
- C = IGM clumping factor (recombinations) = 5 to 30 (simulations)
- Strong increase with z due to increase in mean cosmic baryon density

2. Conversion of star formation rate to IR luminosity based on known properties of galaxies (eg. Kennicutt 1998 and many others)

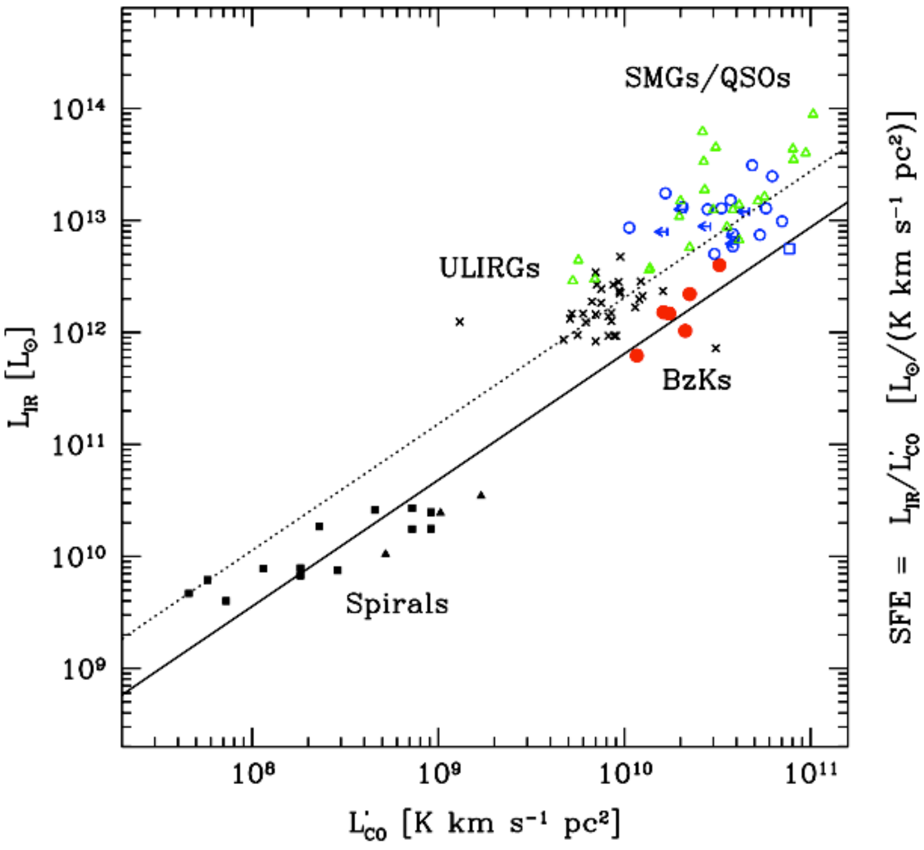
$$L_{FIR} = 1.1 \times 10^{10}\ \mathrm{SFR\ L_\odot}$$

Predicted Mean CO Brightness Temperature

3. Conversion of IR luminosity to CO luminosity based on known properties of galaxies ('K-S law'; Daddi et al. 2010)

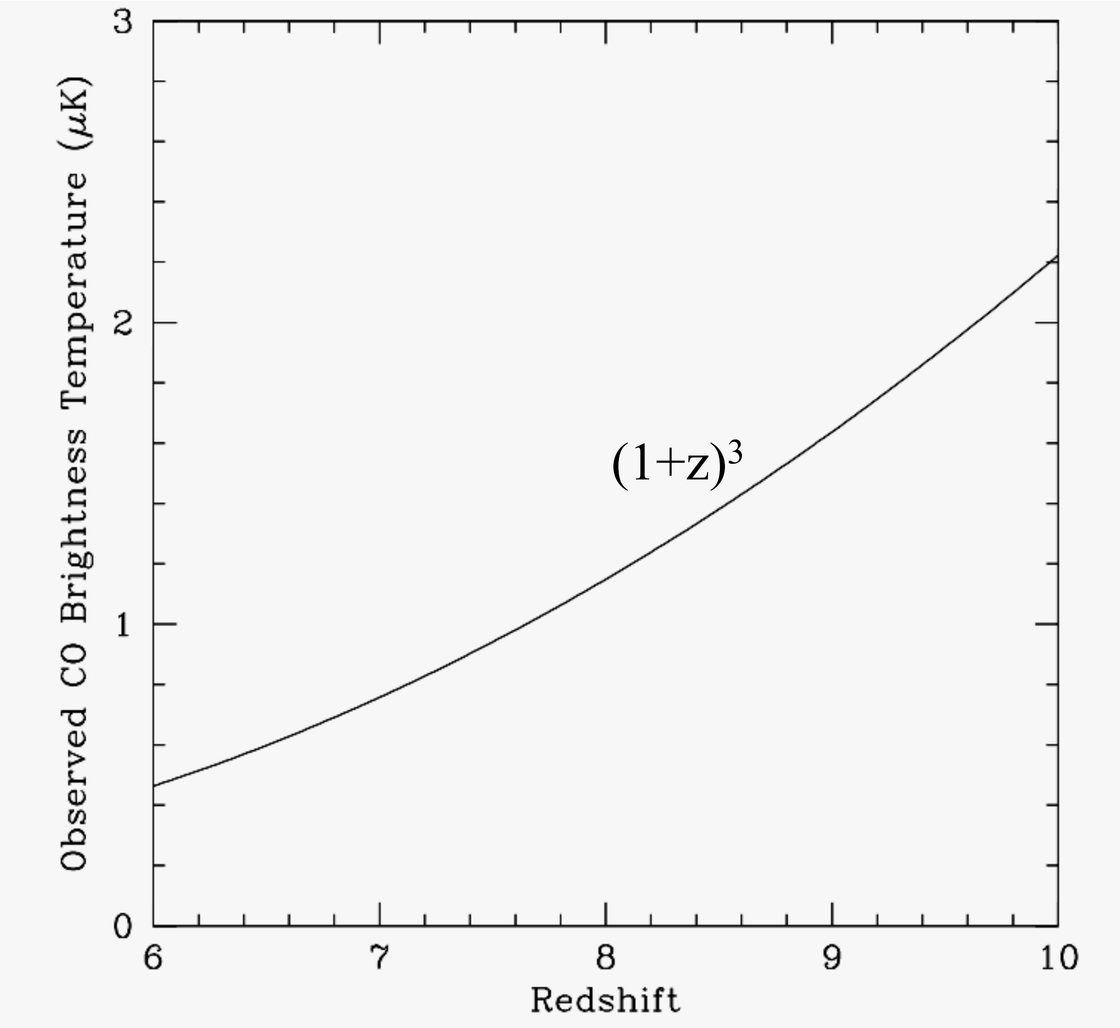
$$L'_{CO} = 0.02 L_{FIR} \text{ K km s}^{-1}\text{ pc}^2$$

- ➢ Roughly linear relationship between L'_{CO} and L_{FIR} for disk galaxies at low and high z
- ➢ Similar slope for merger driven starbursts, with different normalization
- ➢ Disks likely dominate cosmic star formation rate density



Doing some cosmic algebra => mean brightness temperature of CO emission from the galaxies that reionize the neutral IGM at a given redshift

$$\langle T_B^{sky} \rangle_{z=8} = 1.1\ (0.1/f_{esc})^{-1}\ (C/5)\ \text{uK}$$



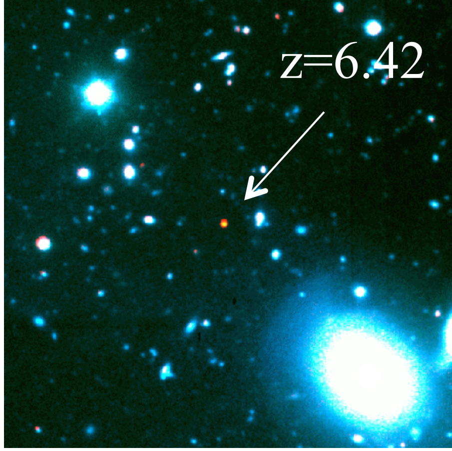
[Not what we expect to see at all redshifts, but what is required to have reionization occur at that redshift.]

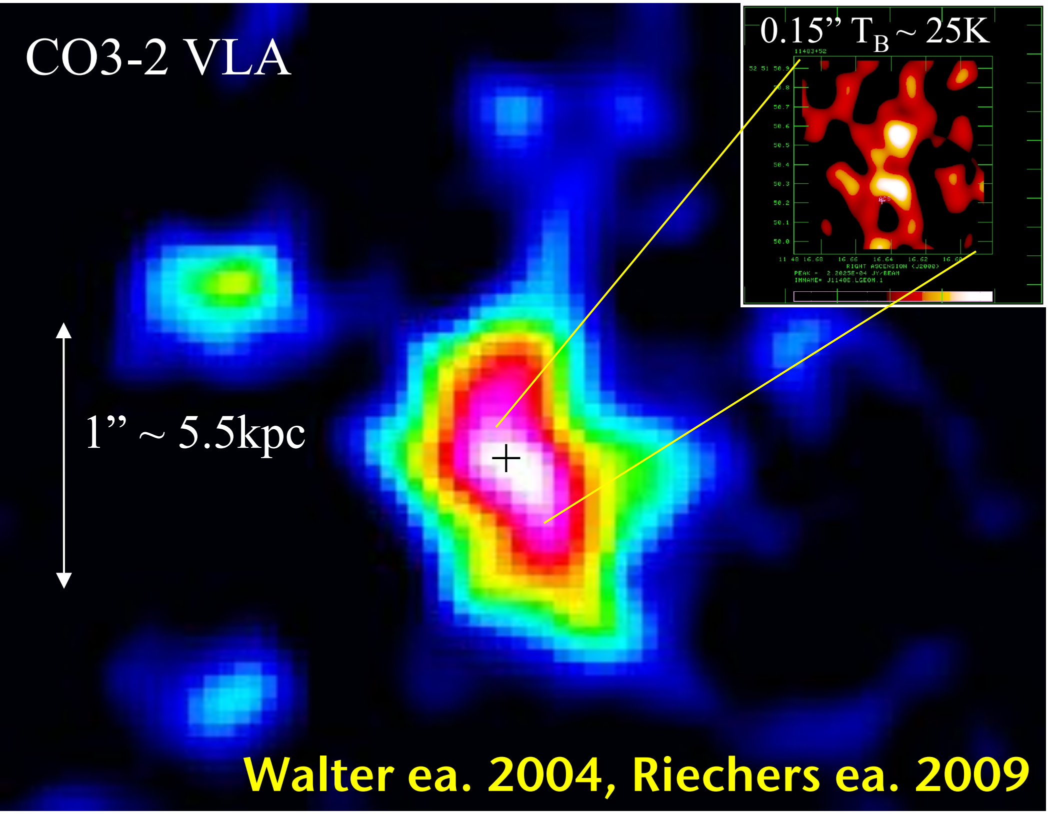
Major uncertainties:

- f_{esc} – calibrated with JWST observations of 1[st] galaxies
- *C* – get handle via HI 21m observations (21cm forest absorption?)
- Line confusion (30GHz = CO 2-1 z=6.7 or 1-0 at z=2.8): requires dual frequency, cross correlation experiment (eg. 15 and 30GHz). Cross correlation with 21cm will also help (Gong, Visbal)
- Early production of CO and dust (SFR – FIR – L'CO relationships)

Early production of dust + CO: detections of 12 quasar host galaxies at z~6

M(dust) ~ $10^8 M_o$, M(H_2) ~ 10^{10} M_o





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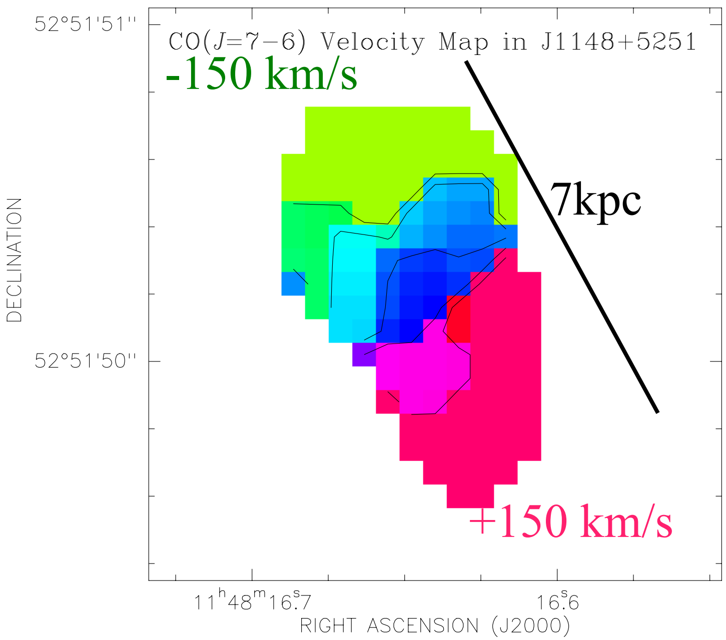
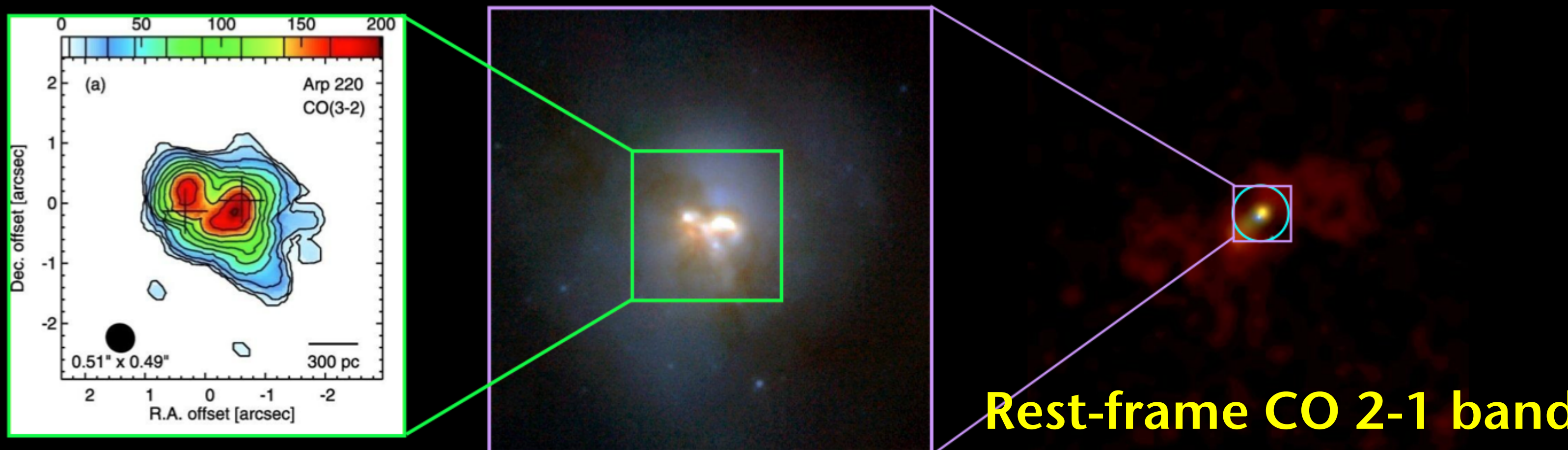


SFR – FIR – L'_{CO} relationships can be calibrated with ALMA/EVLA/JWST observations of representative z>6 galaxy samples.

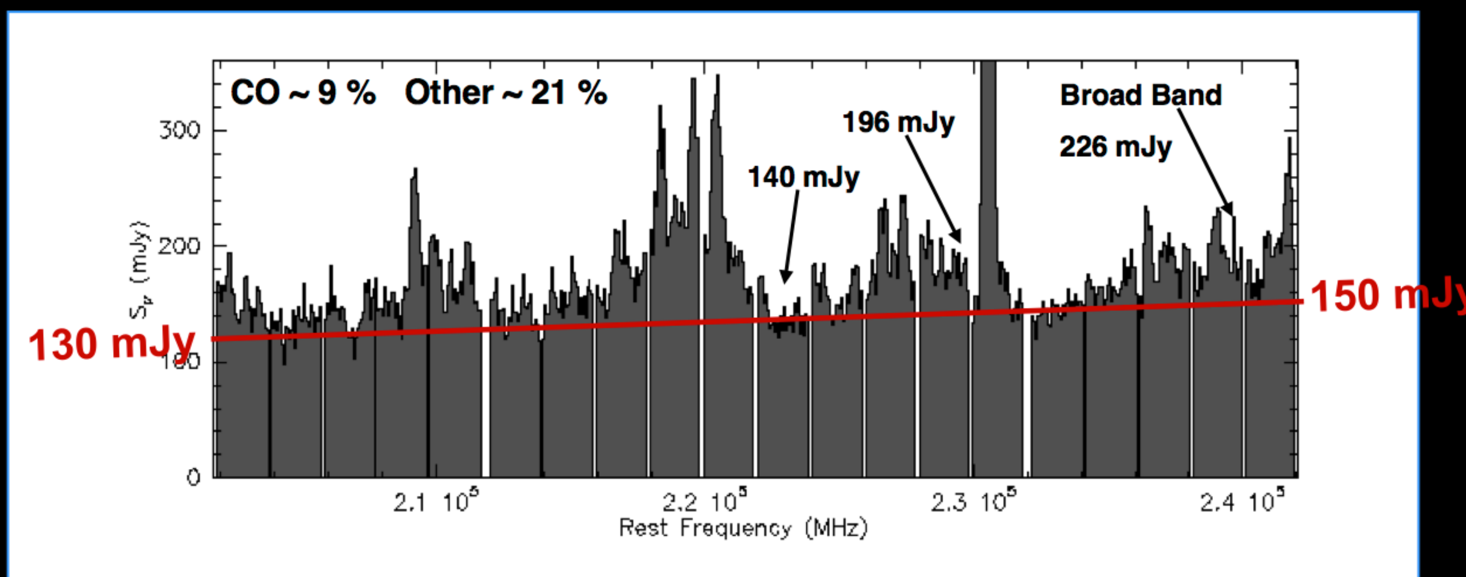
Remaining issues: more detailed treatment of line confusion

The SMA 1.3 mm line survey of the ULIRG Arp 220 shows the future ALMA/EVLA surveys at high redshift



850um – SMA | NIR – HST | X Rays – CHANDRA

Sakamoto et al. 2008 | Scoville et al. 1998 | Mc Dowell et al. 2002



Remaining issues: more detailed treatment of line confusion

The SMA 1.3 mm line survey of the ULIRG Arp 220 shows the future ALMA/EVLA surveys at high redshift

202 – 242 GHz

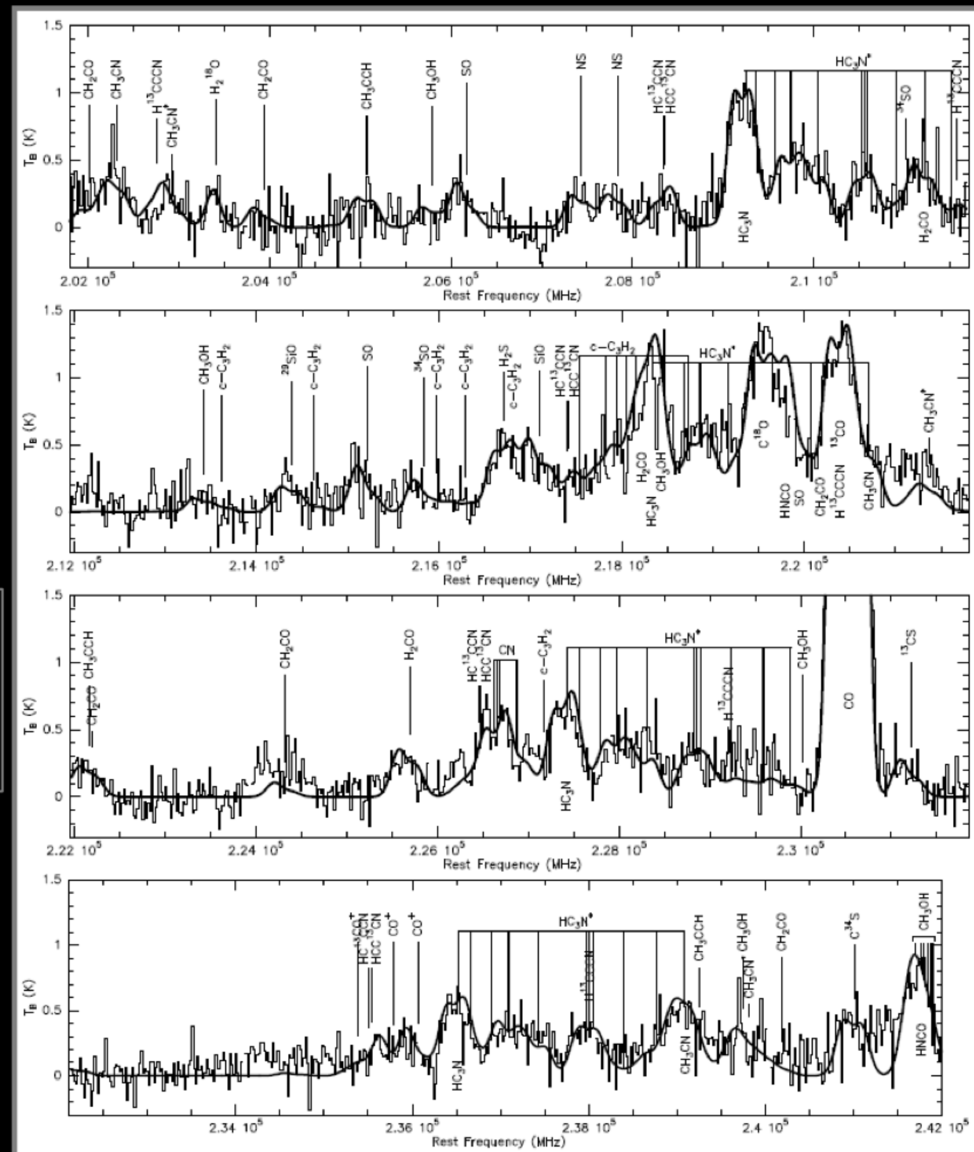
70 individual spectral features

15 species + 6 isotopologues

1.8 lines/Ghz = Partially confusion limited

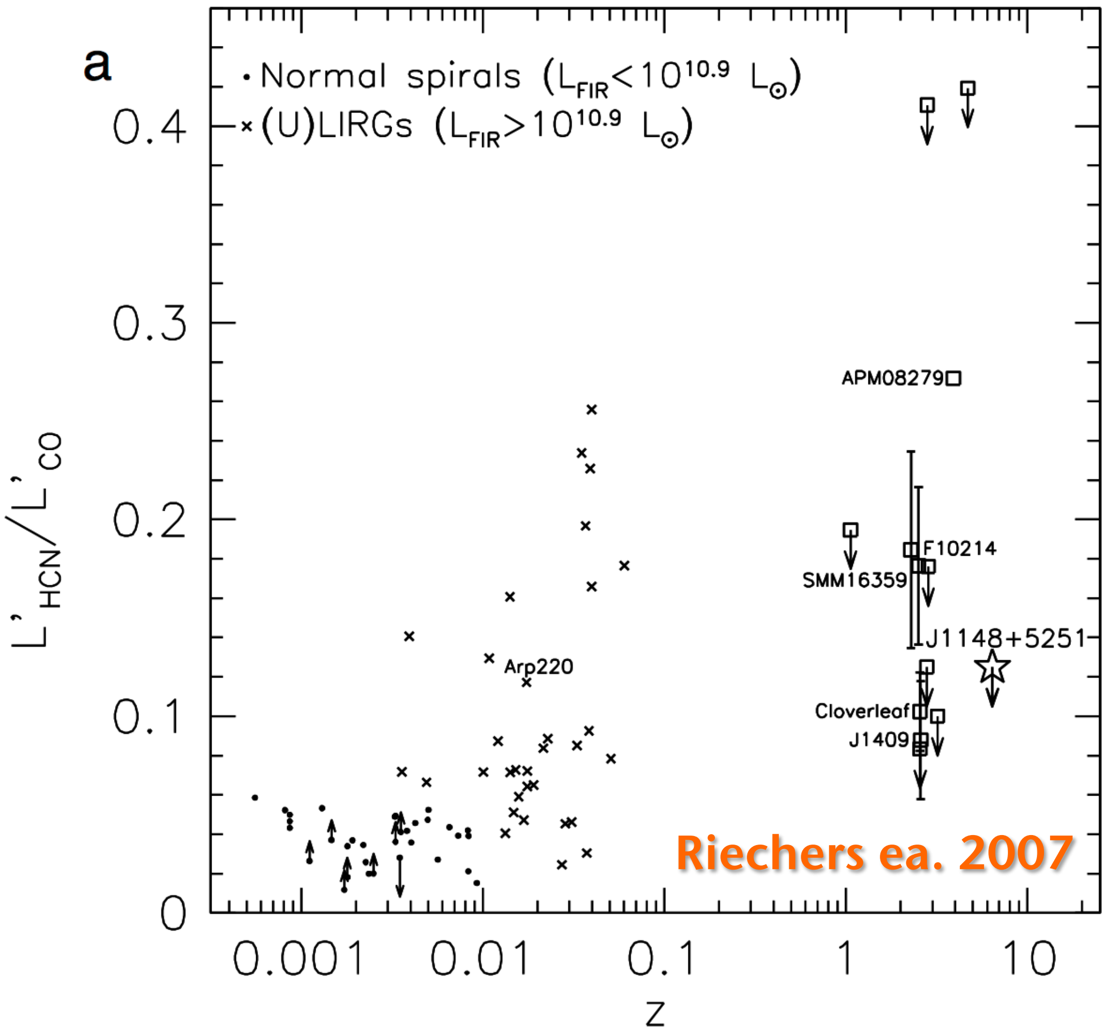
LTE analysis:

Fitting of synthetic spectra of individual molecules



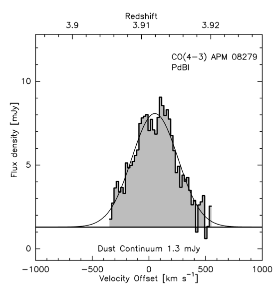
(Martin et al. 2011)

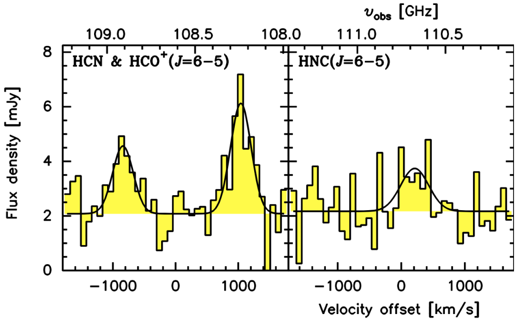
Remaining issues: more detailed treatment of line confusion



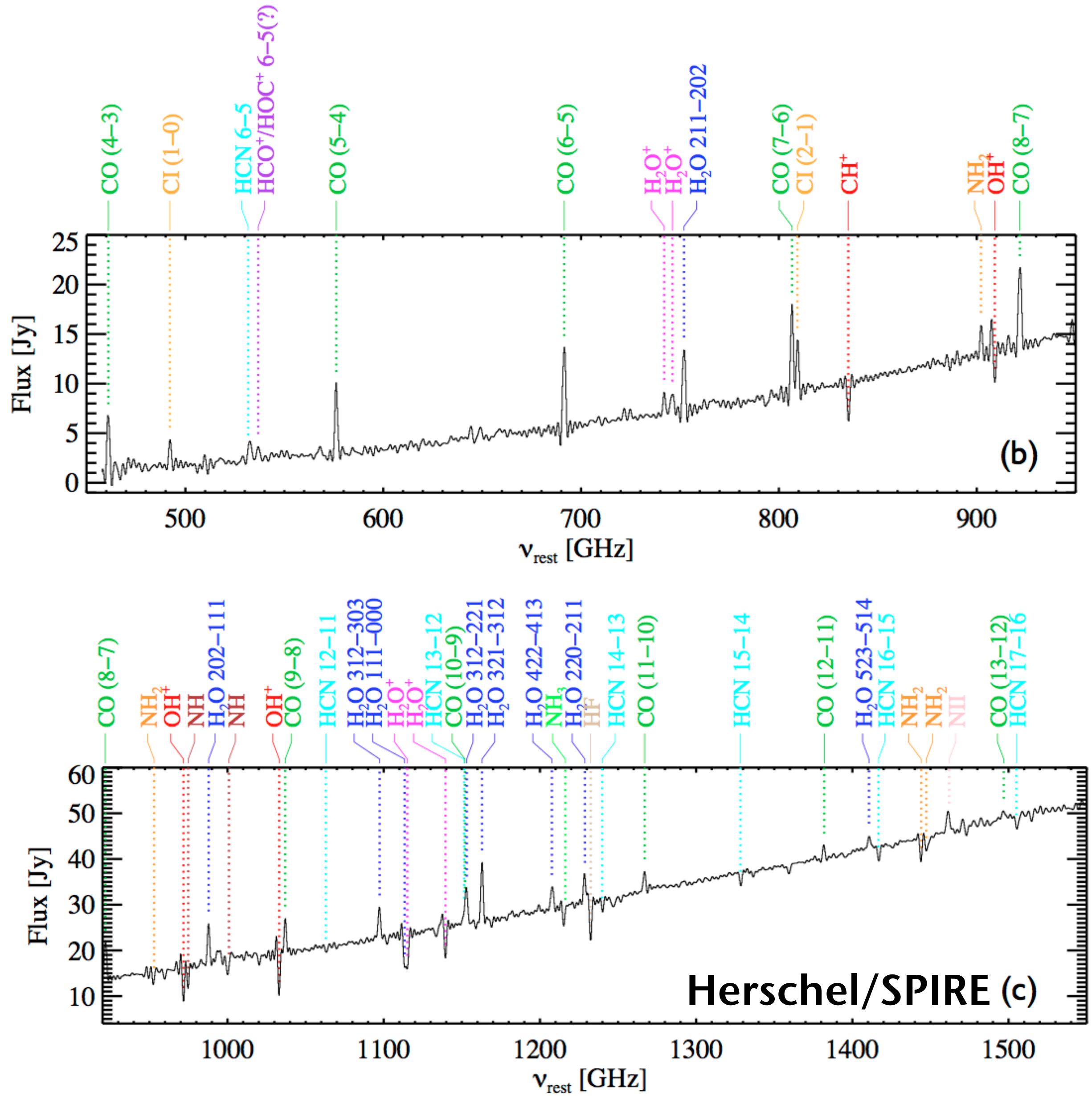
- individual line ratios low for "normal" galaxies
- but: can be 10%-15% CO flux
- Also: bright HCN/HCO+/HNC within 2 GHz rest-frame (250 MHz @z=8)

⇒ can contribute >30%-40% on some "smoothing" scales?





Remaining issues: more detailed treatment of line confusion



Arp220:

H_2O lines as bright as mid-J CO lines

Rangwala ea. 2011

Summary: CO IM - Science Goals

Map LSS thru fluctuations of emission lines from galaxies to:

- **constrain tomography of reionization in redshift slices**
  - if SF activity follows merging history, CO should trace similar clustering pattern
  - photoionization heating during reionization changes min. mass of halos that host galaxies, i.e., can estimate ionizing flux from faint galaxies & look for sharp change in signal as f(z) due to change in M_{min}
- **constrain early formation of GMCs & subsequent process of metal enrichment of the IGM throughout cosmic times & clustering properties of enriched regions**
- **constrain evolution of metallicity, SFR, bias & duty cycles of faint, individually undetectable galaxies as f(z) at z>6 (=information missing from "traditional" galaxy surveys)**
- **get clustering signal from *all* galaxies, not just bright ones**