Galaxy Formation: The Radio Decade

(Dense Gas History of the Universe)

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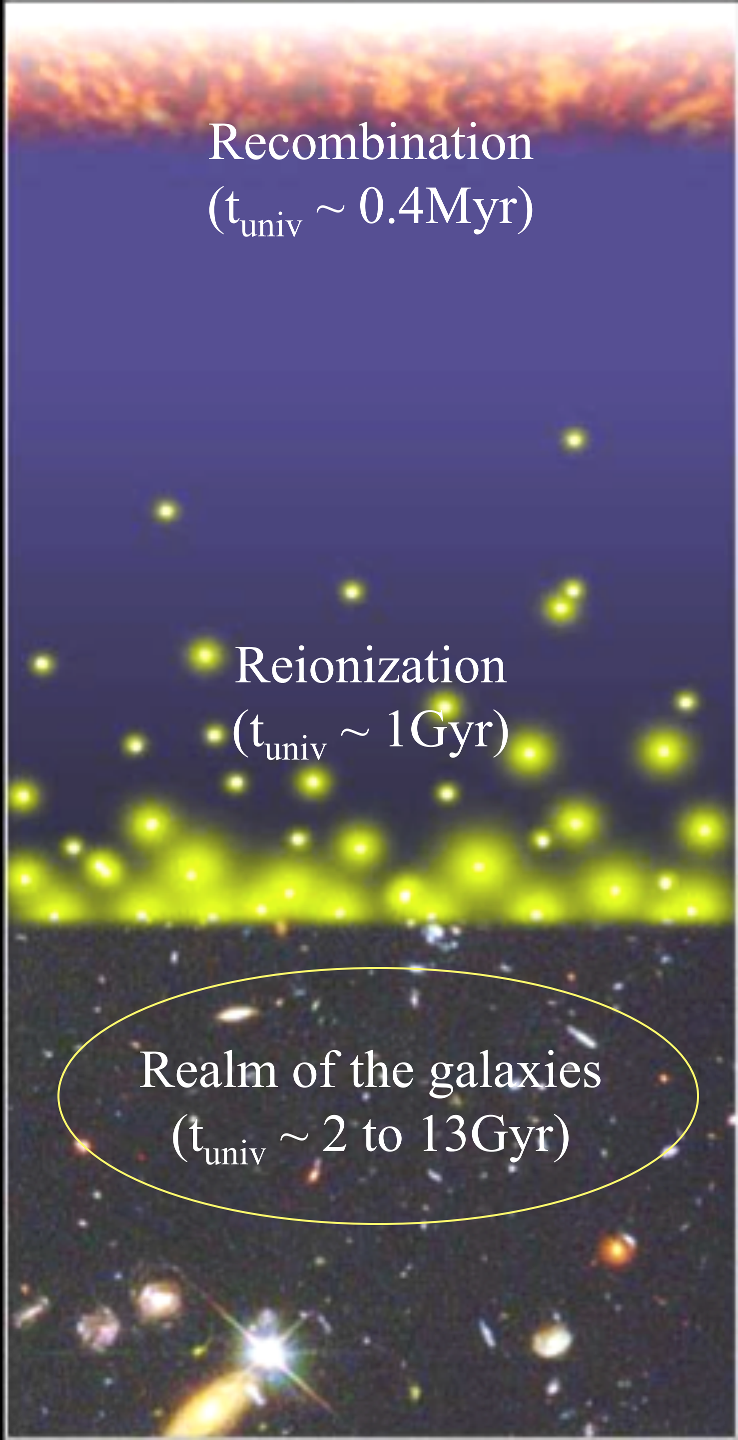
Santa Fe, March 2011

- Power of radio astronomy: dust, cool gas, and star formation

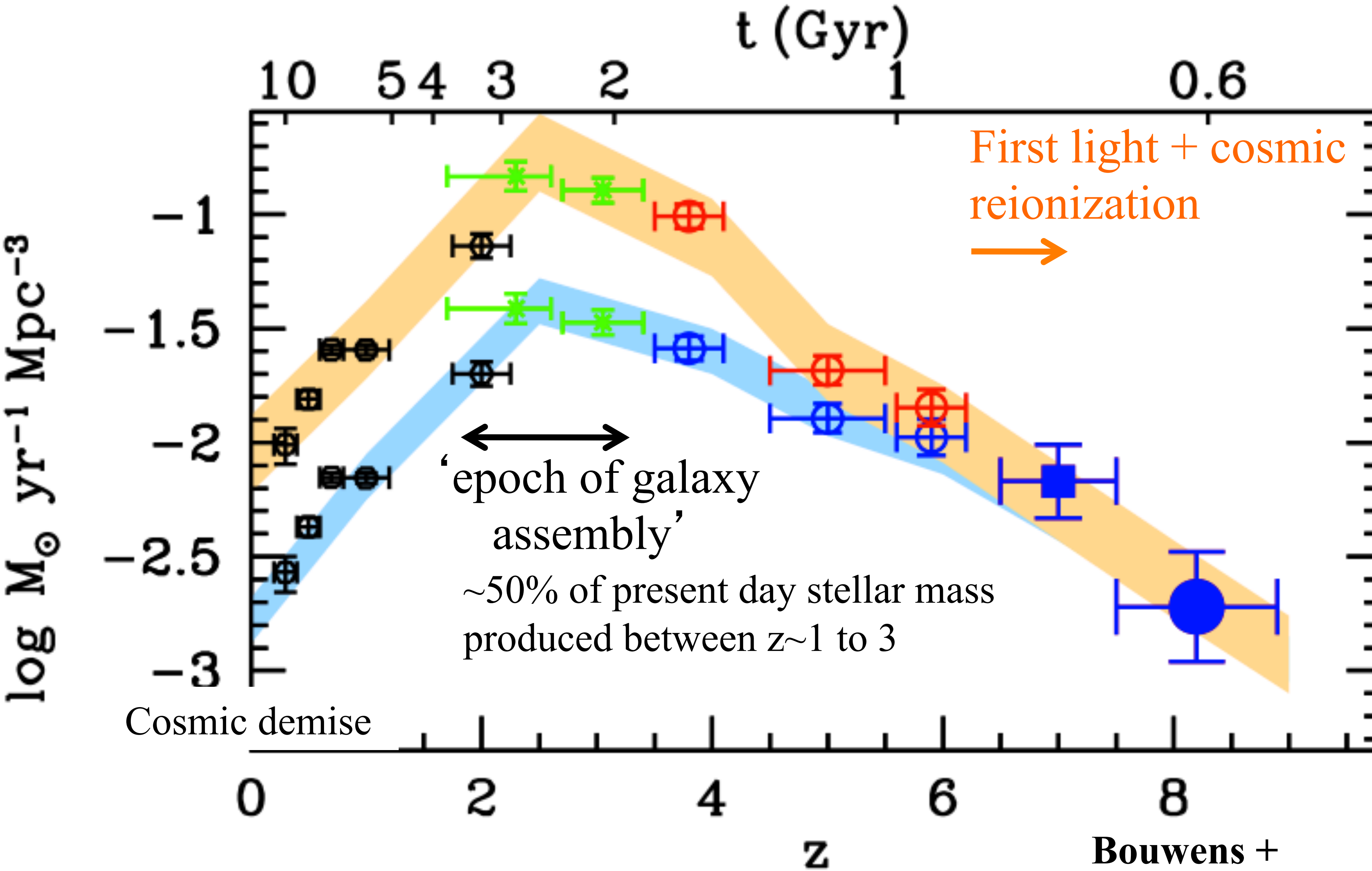
- Epoch of galaxy assembly (z~1 to 3)
  - Massive galaxy formation: dust obscured, hyper-starbursts
  - Early disk galaxy formation: gas dominated galaxies

- Bright (immediate!) future: The Atacama Large Millimeter Array and Expanded Very Large Array, with recent examples

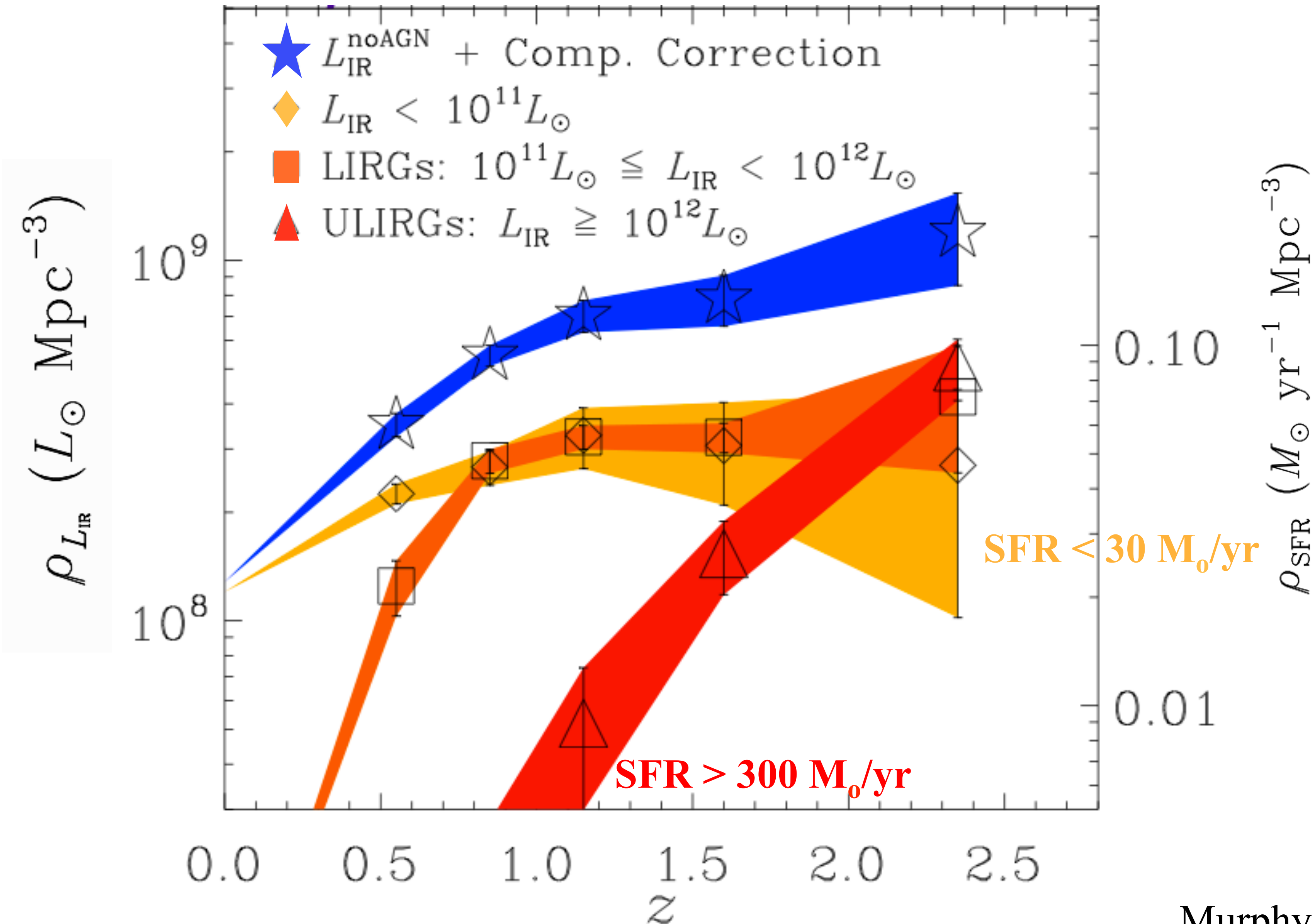


Star formation history of the Universe

(mostly optical/near-IR view)

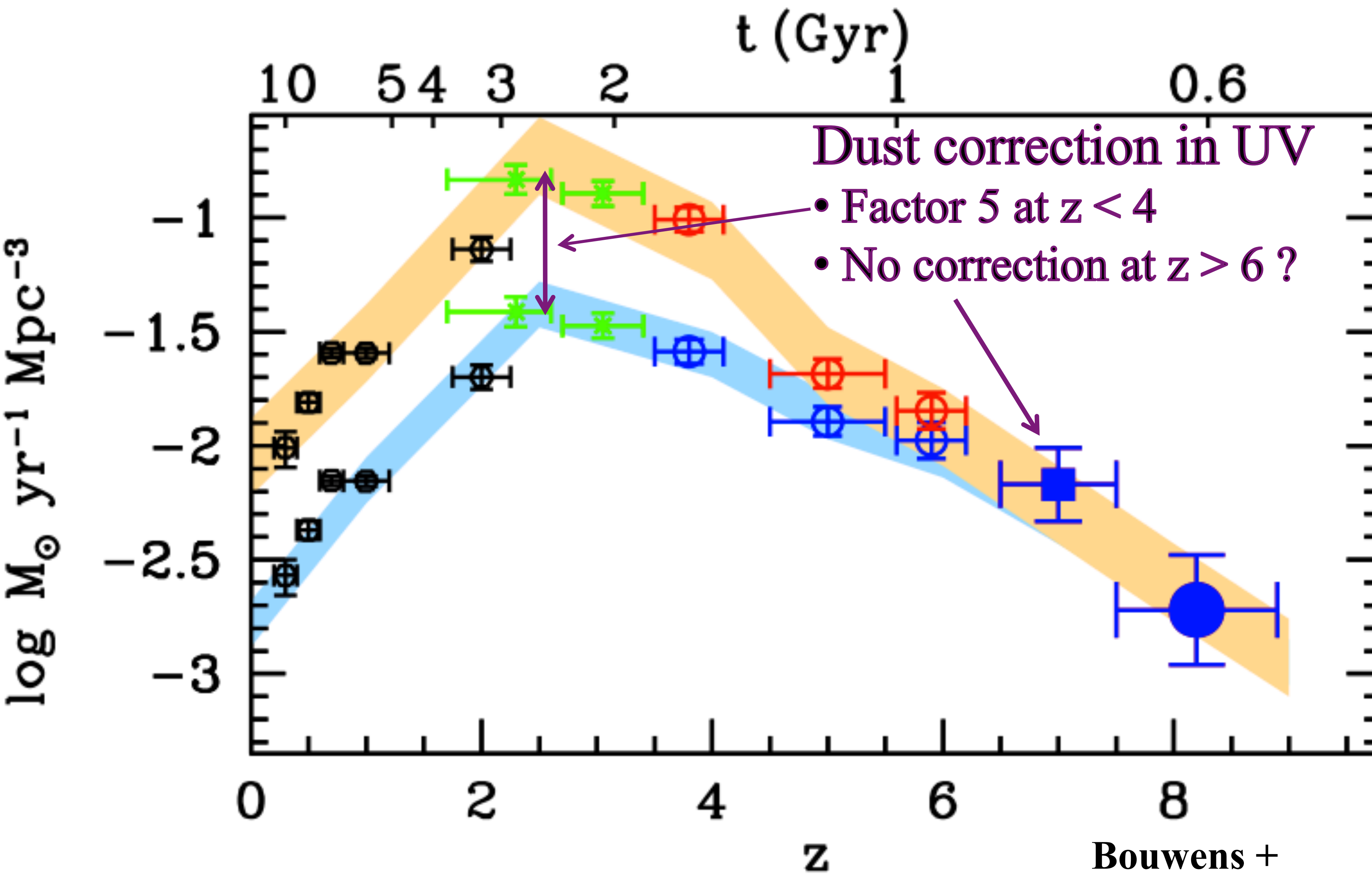


Star formation history as a function of L_{FIR} (~ SFR)



Murphy ea

Optical Limitation 1: Dust

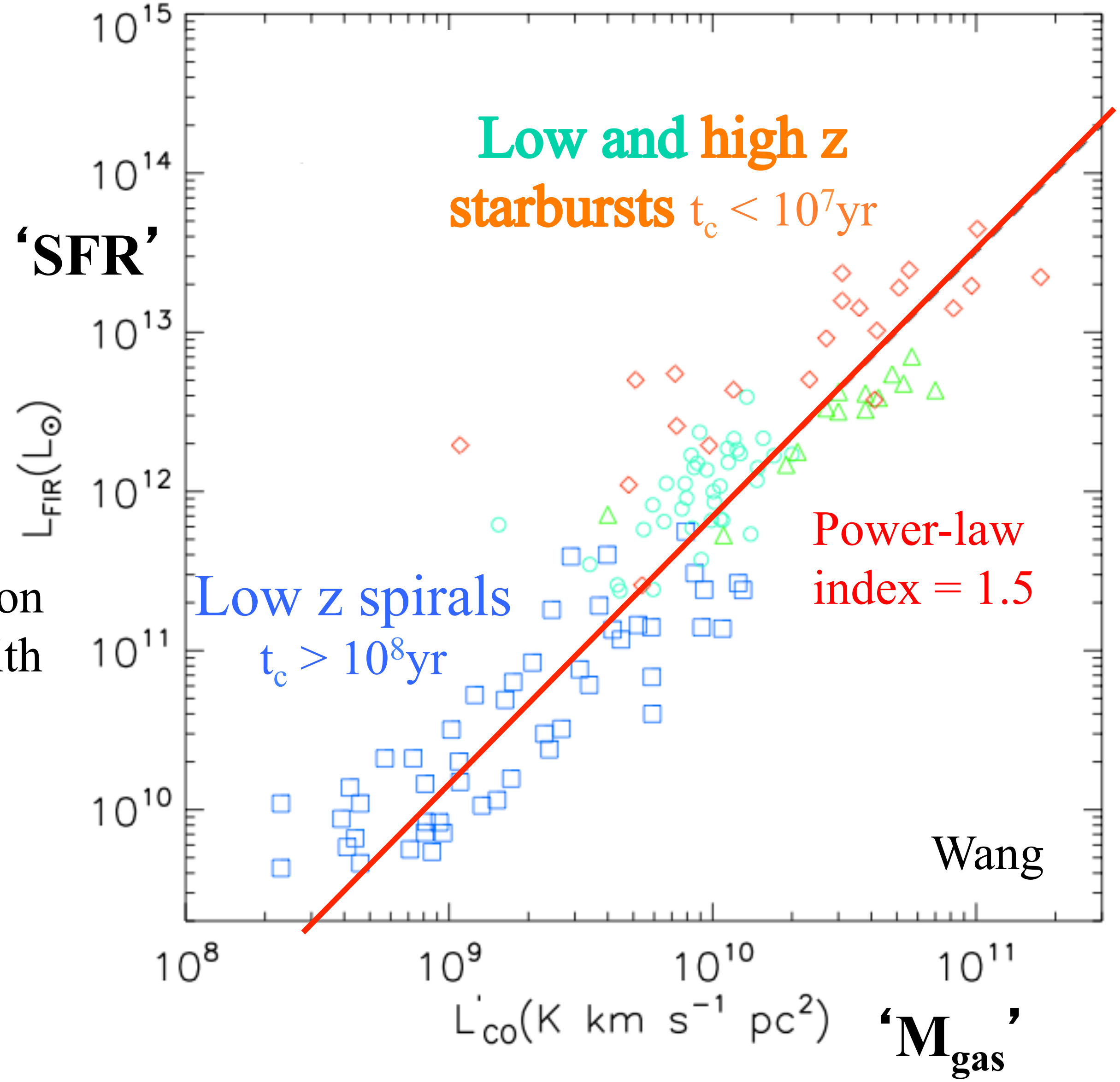


Bouwens +

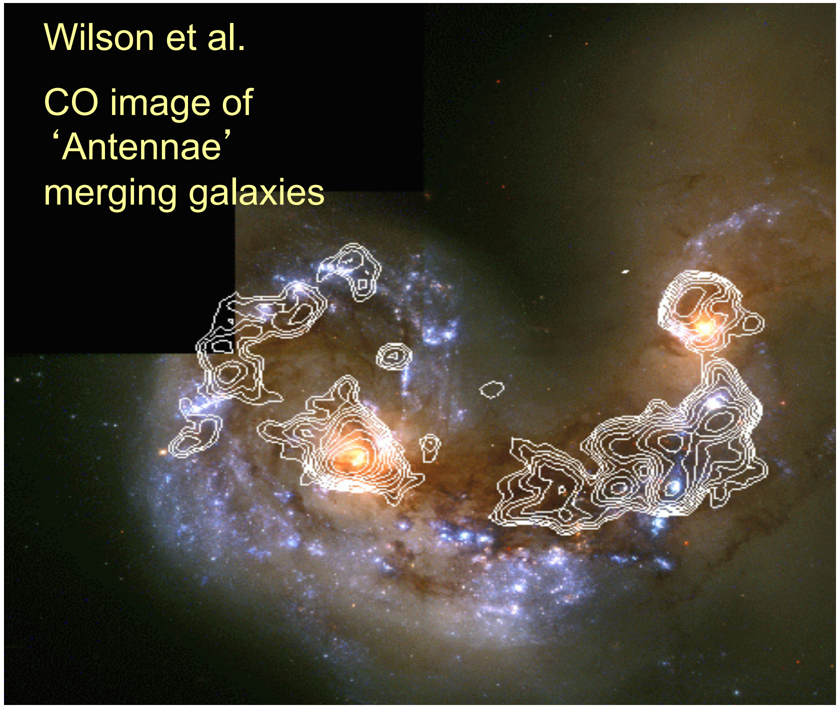
Optical Limitation 2: Cold gas = fuel for star formation
('The missing half of galaxy formation')

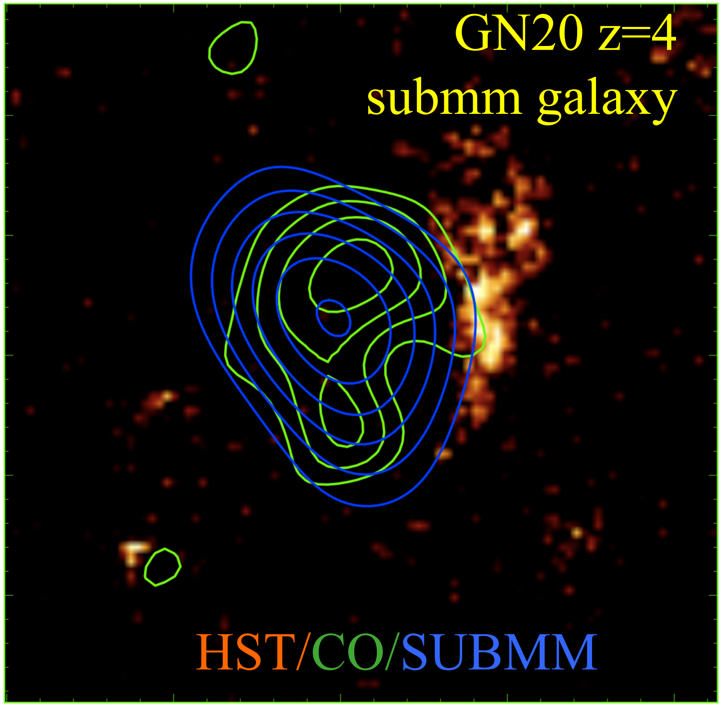
Integrated Kennicutt-Schmidt star formation law: relate SFR and gas content of galaxies

Non-linear => gas consumption time (Mgas/SFR) decreases with SFR



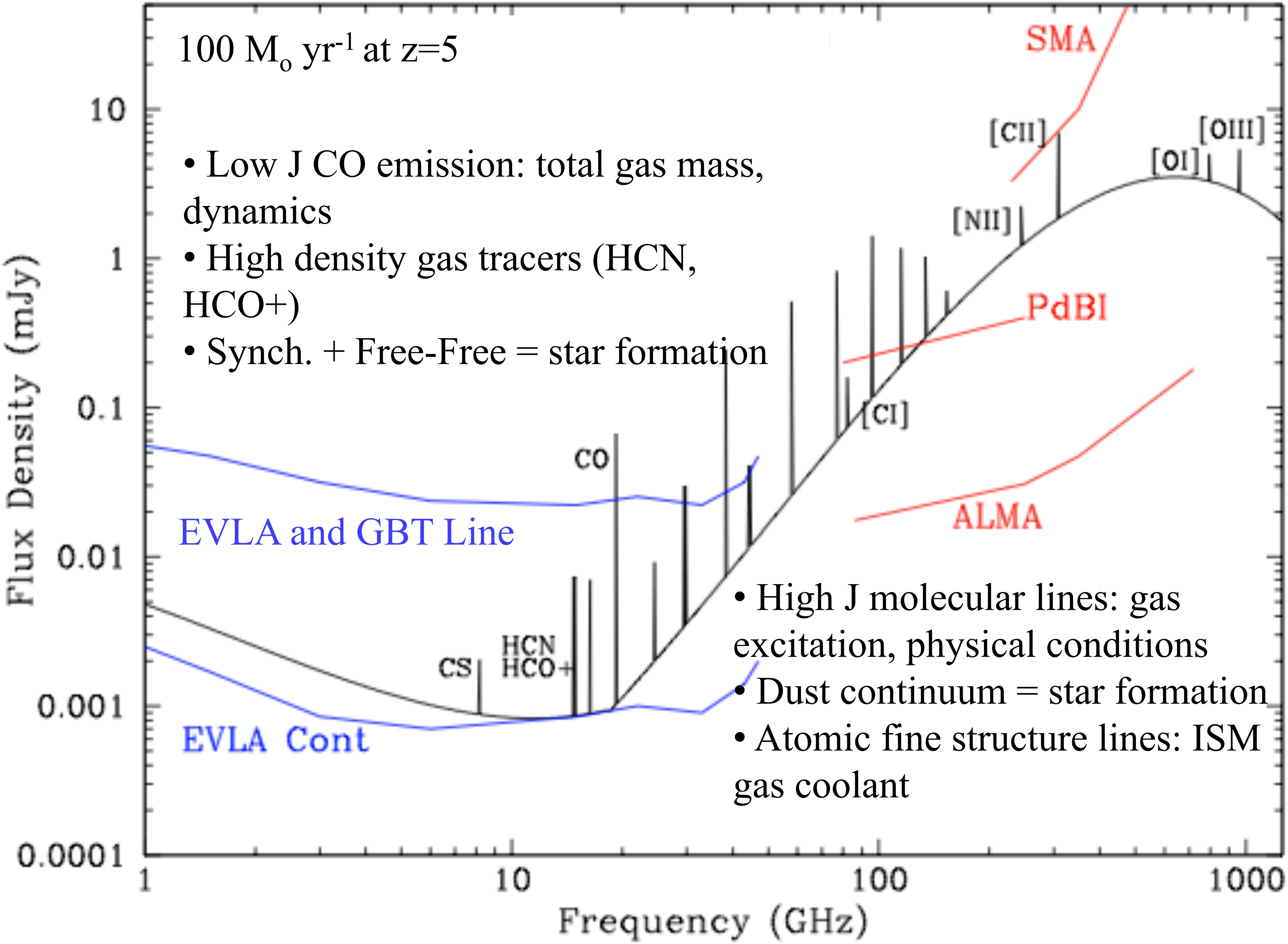
Millimeter through centimeter astronomy: unveiling the cold, obscured universe





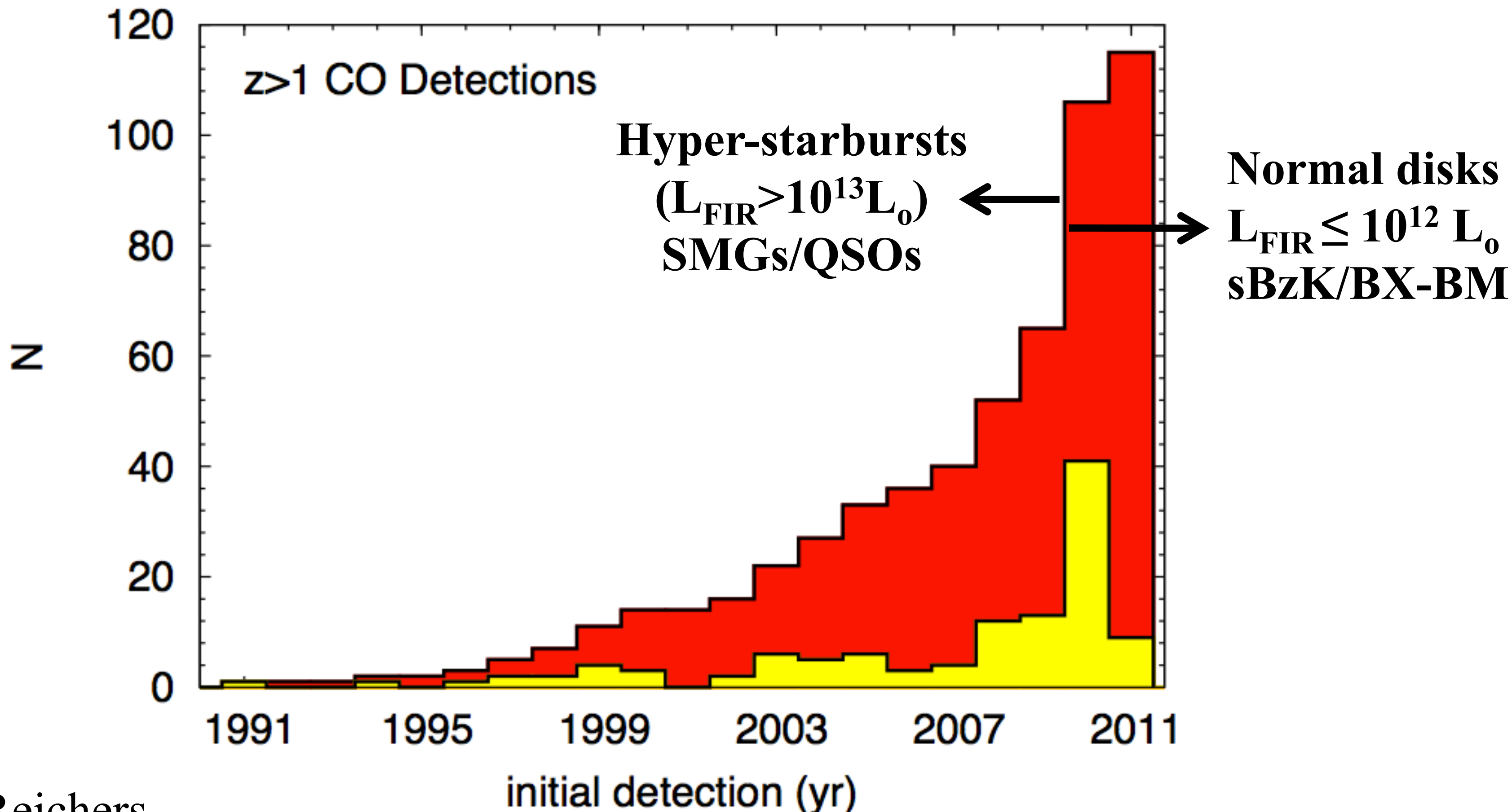
- cm/mm reveal the dust-obscured, earliest, most active phases of star formation in galaxies
- cm/mm reveal the cool gas that fuels star formation

cm → submm astronomical probes of galaxy formation



Today's focus: molecular gas

- 115 CO detections at z > 1 published to date
- ~50% in the last 2 years
  - ➢ PdBI improvements; EVLA, GBT Zpectrometer
  - ➢ Discovery of gas rich 'normal' SF galaxies z ~ 2

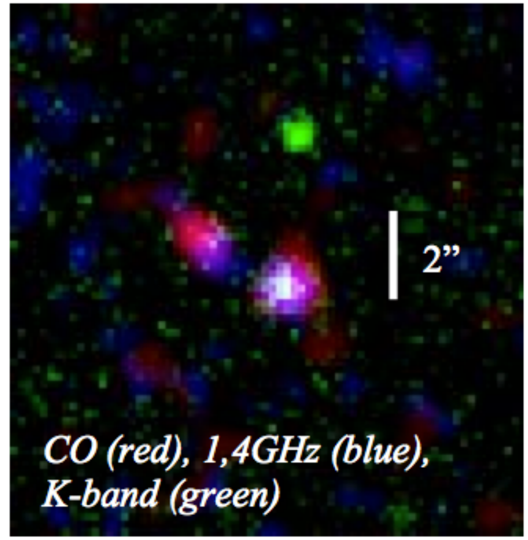


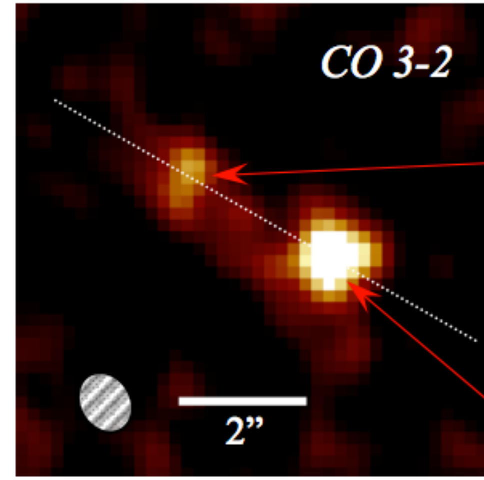
Reichers

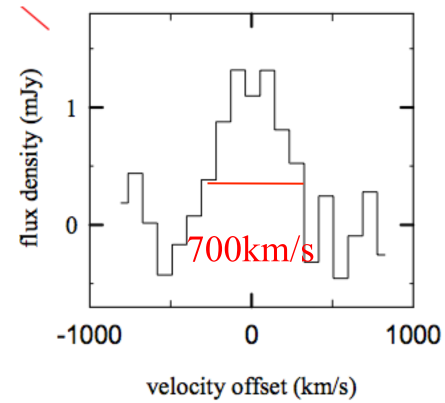
Hyper-starbursts at high redshift: Submm galaxies, and (~ 1/3) Quasar hosts

- $S_{250} > 3\text{mJy} \Rightarrow L_{FIR} > 10^{13} L_o \Rightarrow SFR > 10^3\ M_o/\text{yr}$
- $\langle FWHM\rangle_{SMG} = 800$km/s
- $M(H_2) \sim 10^{10-11}\ (\alpha/0.8)\ M_o$
- $M(\text{dust}) \geq 10^8\ M_o$
- Gas consumption times ~ 10^7 yrs
- CO compact (< few kpc) and chaotic in velocity
- Rare: 1 SMG per 20 arcmin^{-2}

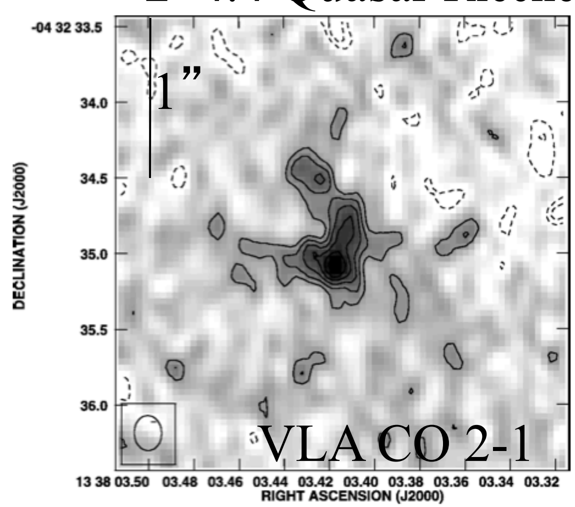
z~ 2 SMG (Tacconi ea)
PdBI CO3-2

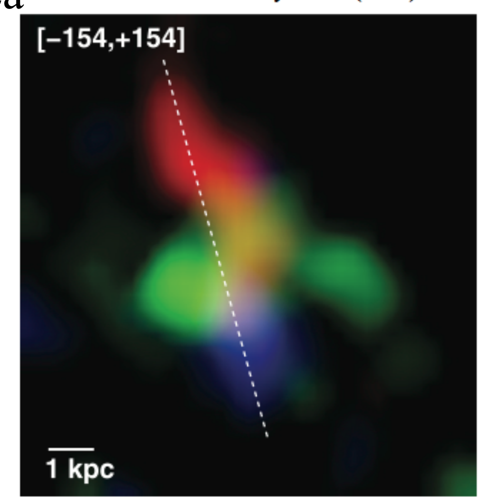




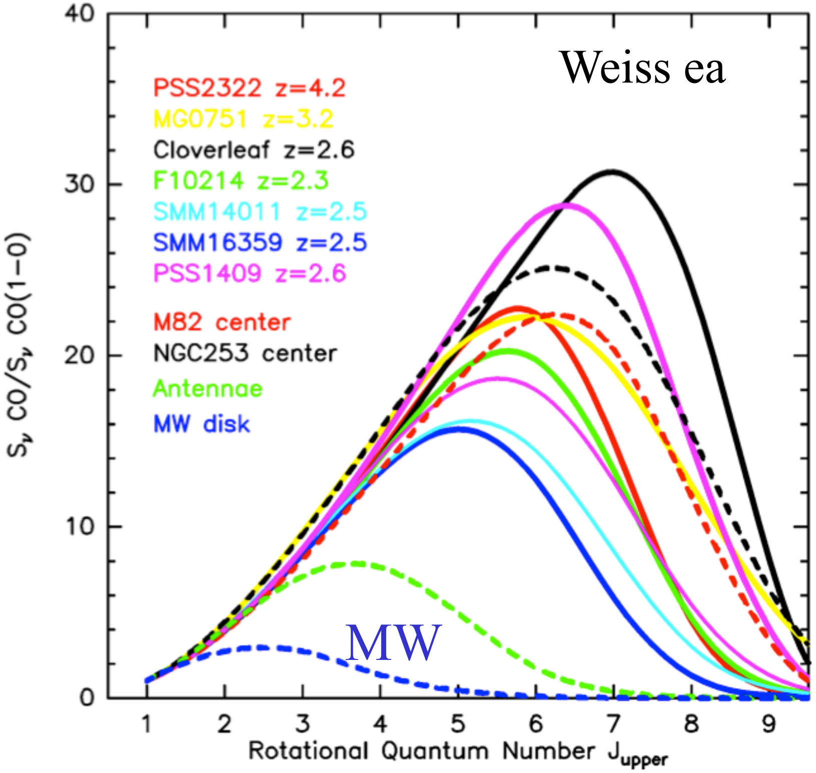


z=4.4 Quasar Riechers ea

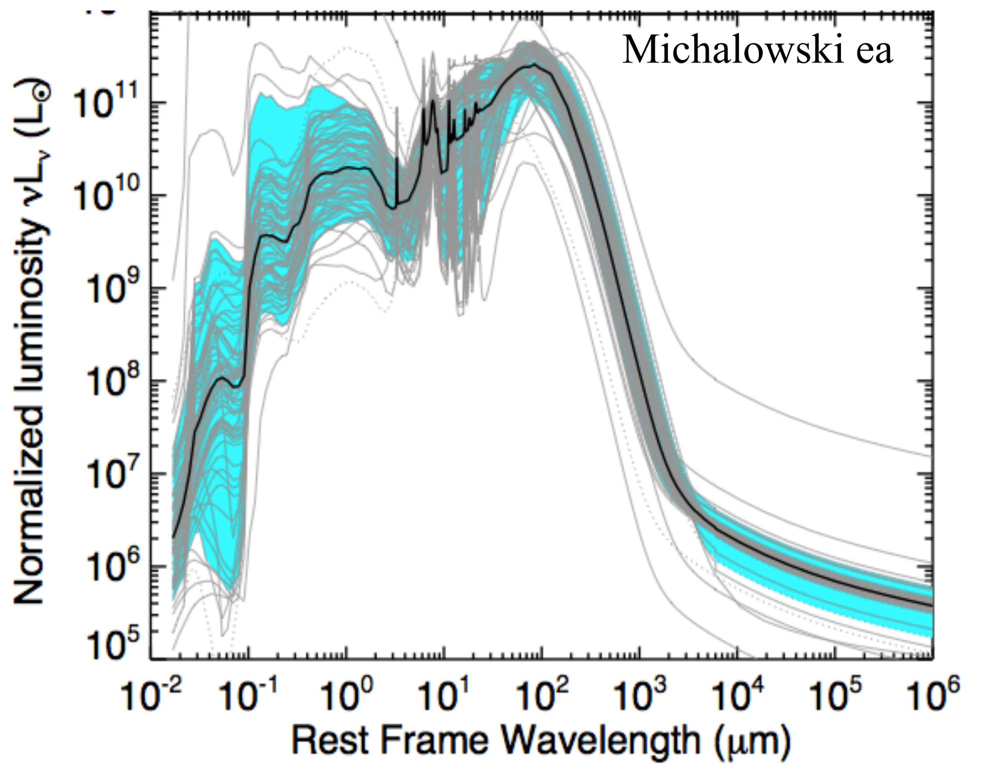




Line



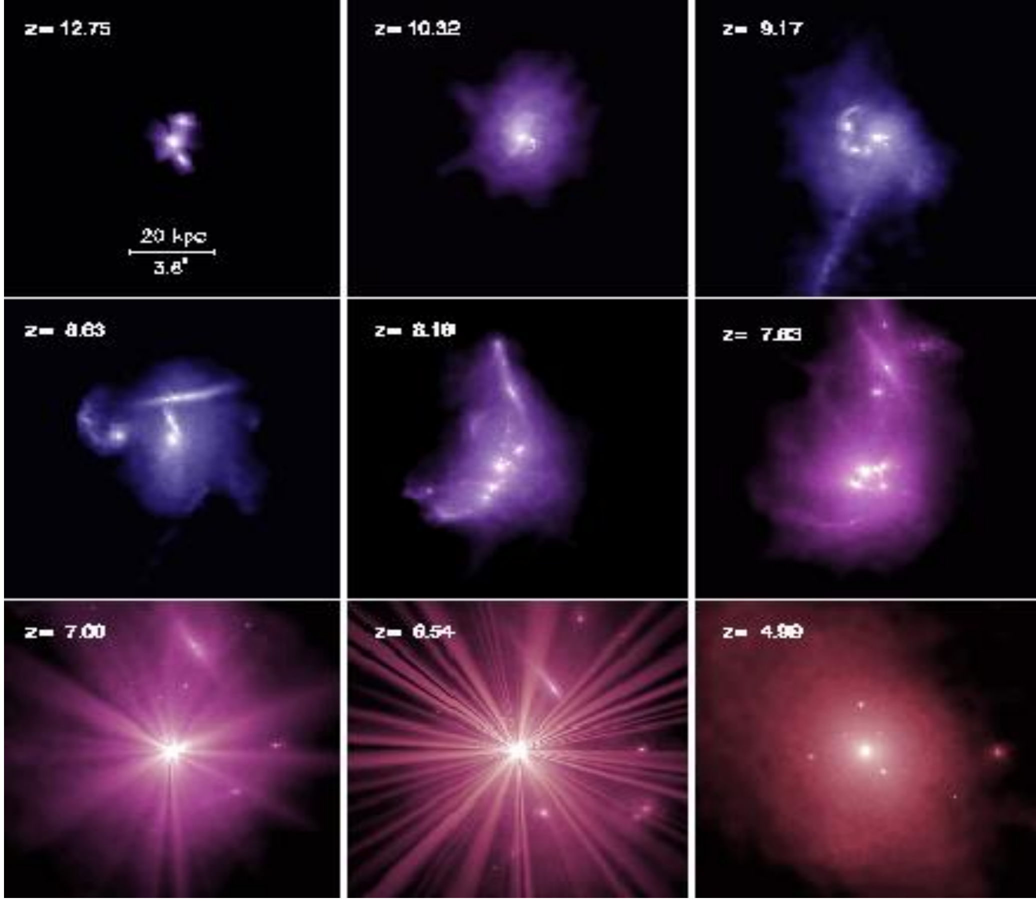
Continuum



- SLED: LVG model => T_k > 50K, $n_{H2} = 2x10^4$ cm^{-3}
  - ➢ Galactic Molecular Clouds (50pc): n_{H2}~ 10^2 to 10^3 cm^{-3}
  - ➢ GMC star forming cores (~1pc): n_{H2}~ 10^4 cm^{-3}
- SED: Warm dust ~ 30 to 50 K, follows Radio-FIR correlation => SFR > 10^3 M_o/yr

SMGs and Quasar hosts: Building large elliptical galaxies (and SMBH) in major gas rich mergers

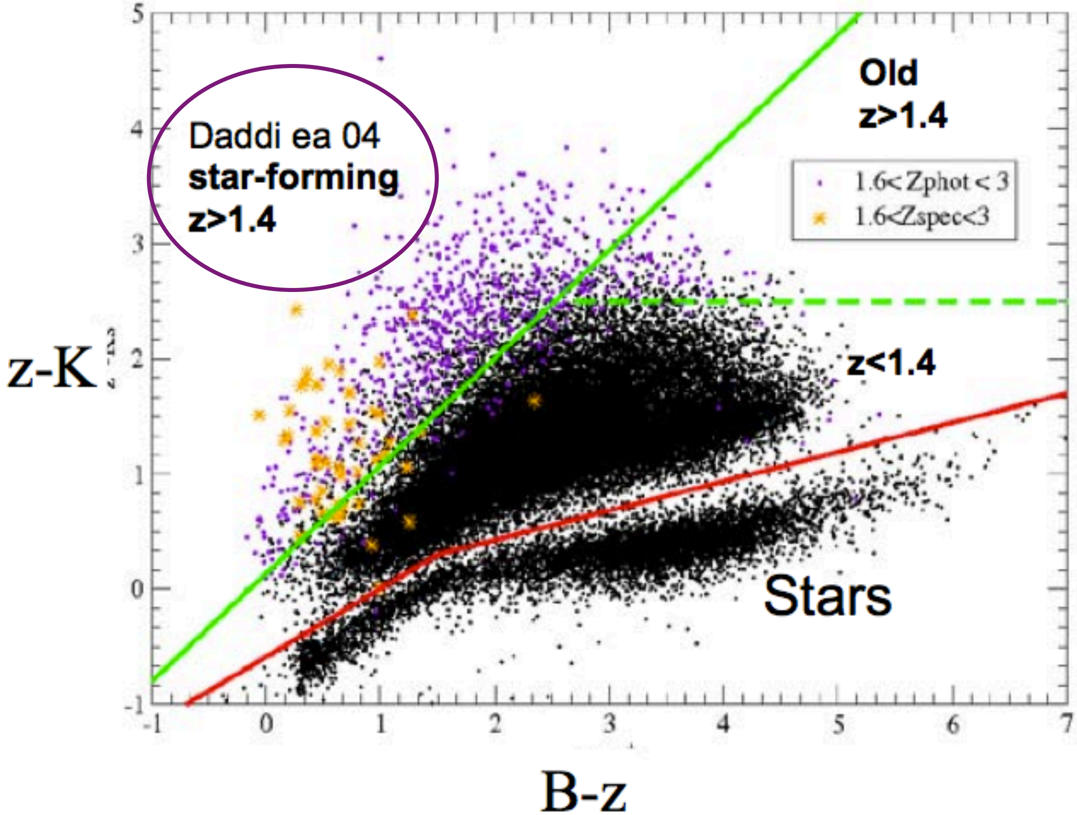
- Stellar mass $\geq 10^{11}$ M_o forms in a few gas rich mergers starting, driving SFR $>10^3$ M_o/yr
- SMBH of $\sim 10^9$ M_o forms via Eddington-limited accretion + mergers
- Evolves into giant elliptical galaxy in massive cluster ($\sim 10^{14\text{-}15}$ M_o) by z=0

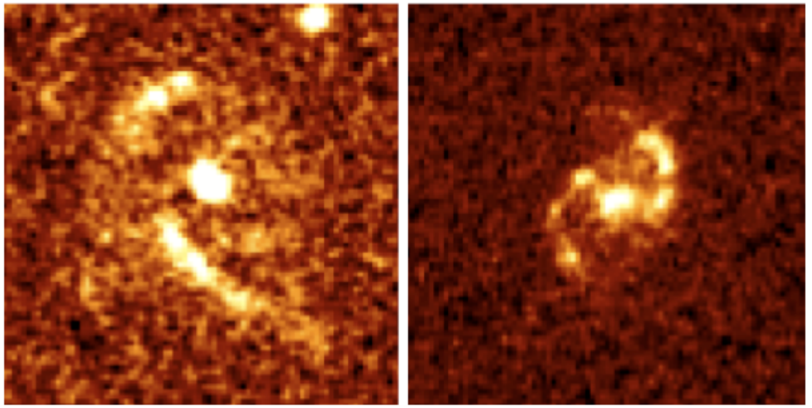


Li, Hernquist+

- Rapid enrichment of metals, dust in ISM (seen at z > 6)
- Rare, high mass objects
- Goal: push to normal galaxies at high redshift

Formation of disk galaxies during epoch of galaxy assembly sBzK/BX-BM at z ~ 1 to 3





- HST + Hα imaging => 'messy disk' ~ 10kpc, punctuated by massive star forming regions (Genzel, Tacconi, Daddi)

- color-color diagrams identify thousands of z~ 2 star forming galaxies
- SFR ~ 10 to 100 M_o/yr, $M_* \geq 10^{10}$ M_o
- Common ~ few x10^{-4} Mpc^{-3} (5 $arcmin^{-2}$) ~ 100x SMG

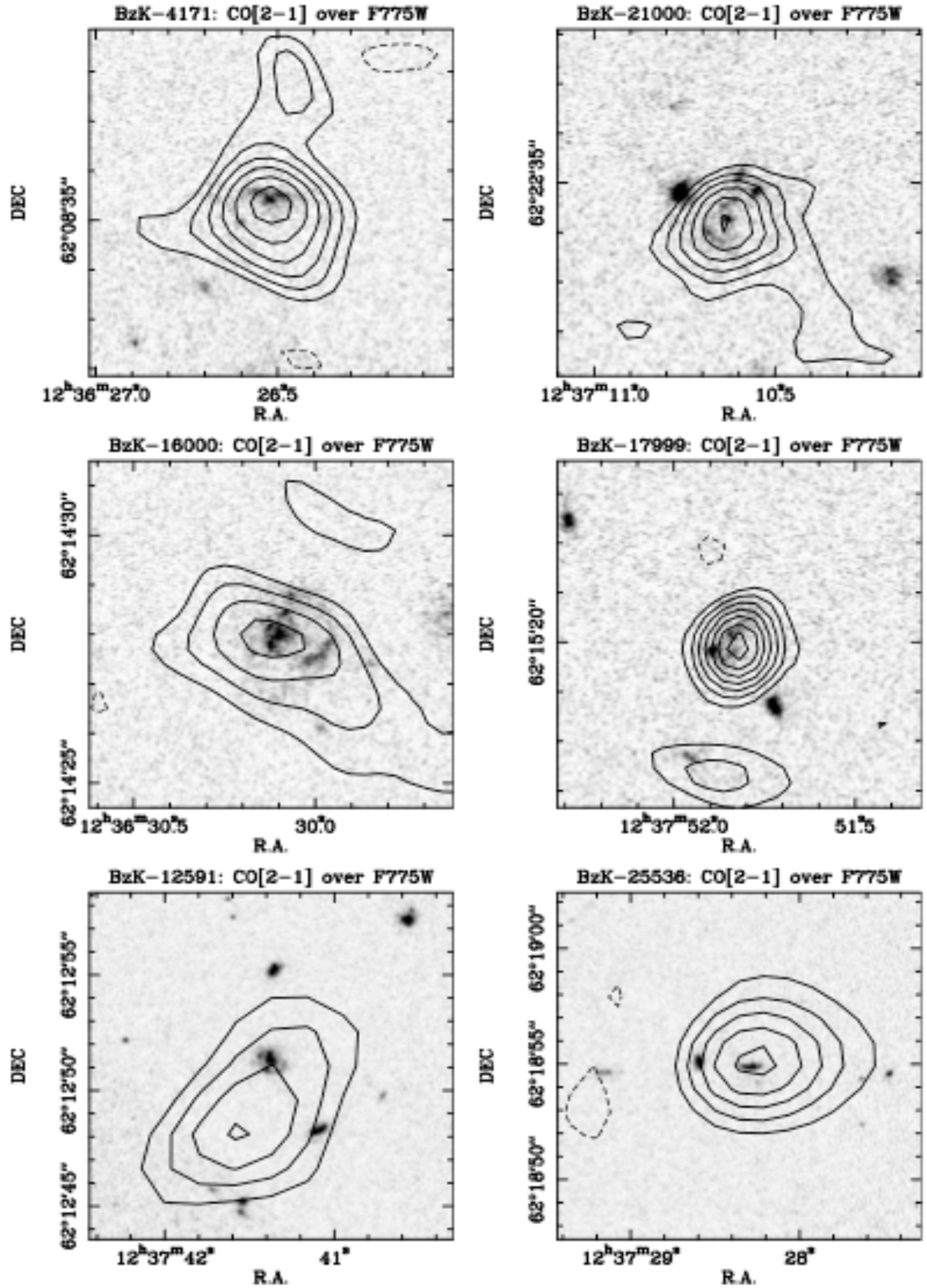
CO observations with Bure: Massive gas reservoirs without extreme starbursts (Daddi ea 2010)

- 6 of 6 z~2 sBzK detected in CO
- Gas mass ~ 10^{10-11} M_o ~ gas masses in SMG/Quasar hosts

but

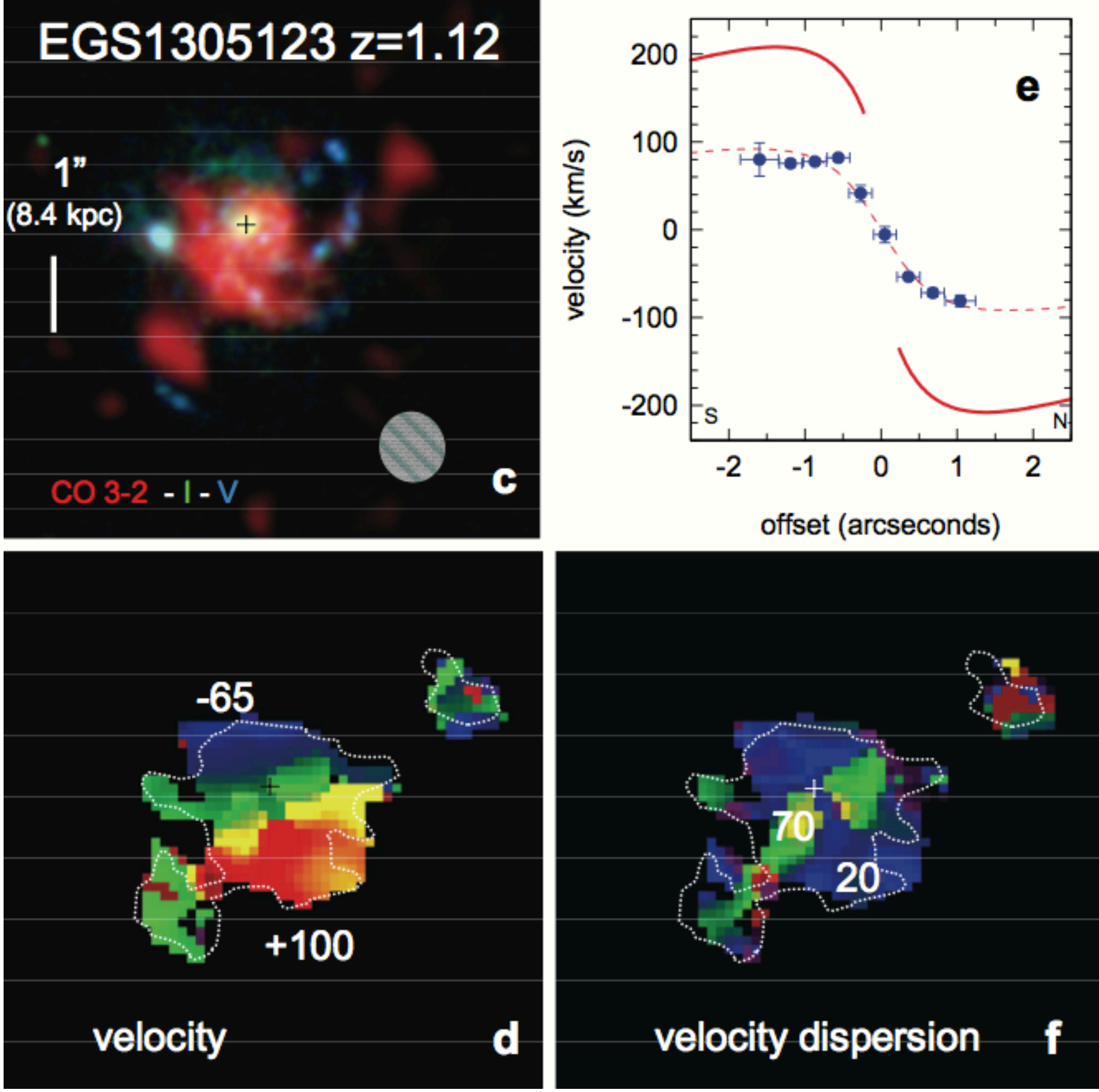
- SFR < 10% less (S_{250} < 1mJy)

(see also UV-selected BX/BM galaxies in Tacconi ea)

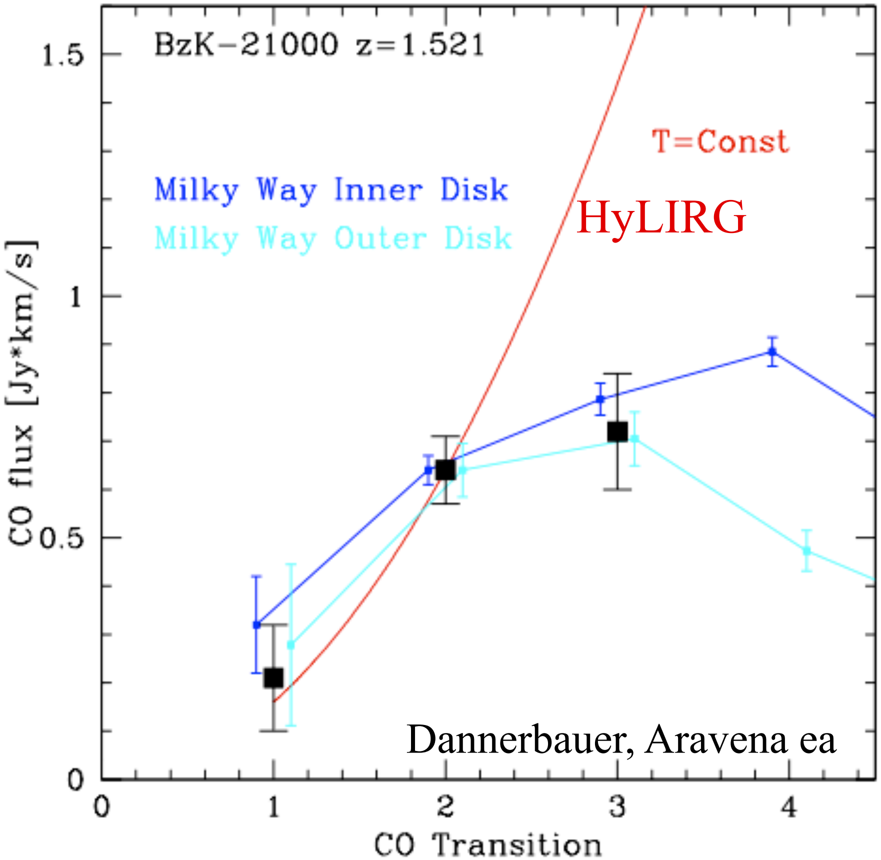


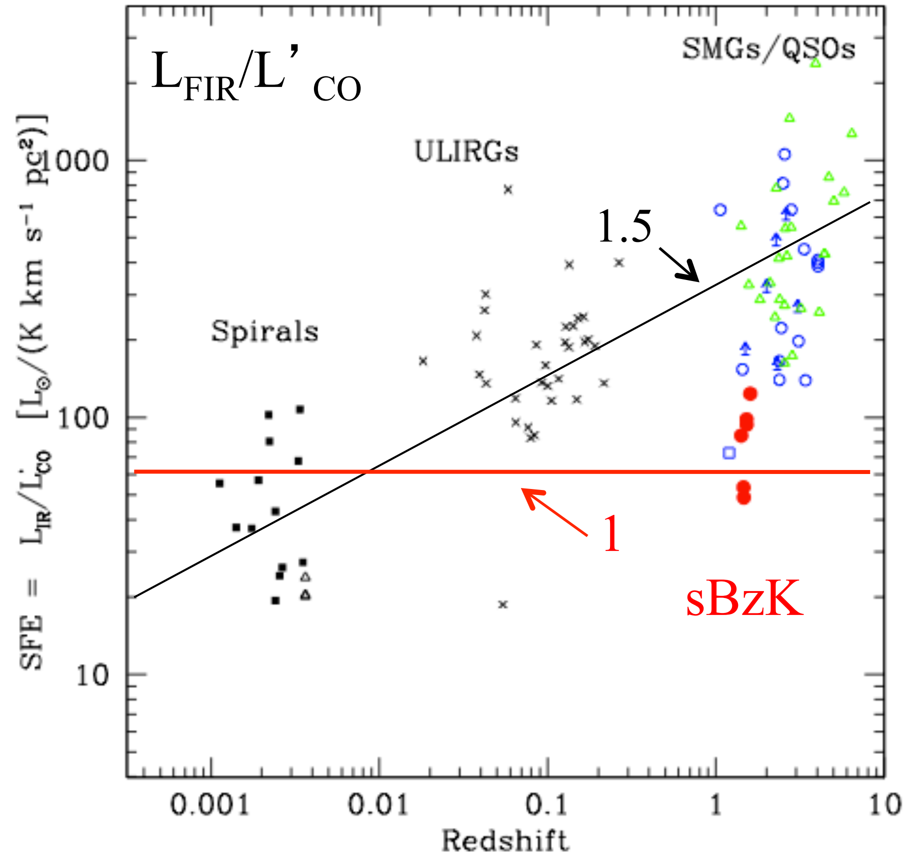
BX/BM: PdBI imaging (Tacconi ea)

- CO galaxy size ~10 kpc
- Clear rotation: v_{rot} ~ 200 km/s
- SF clump physics
  - ➢ Giant clumps > 1 kpc
  - ➢ $M_{gas} > 10^9 M_o$
  - ➢ Turbulent: $\sigma_v \sim 20$ km/s



Closer to Milky Way-type gas conditions





- Lower CO excitation: low J observations are key!
- FIR/L' CO: Gas consumption timescales ~ few x10^8 yrs

=> Secular galaxy formation during epoch of galaxy assembly

Baryon fraction is dominated by gas, not stars

$M(H_2) \geq M_*$

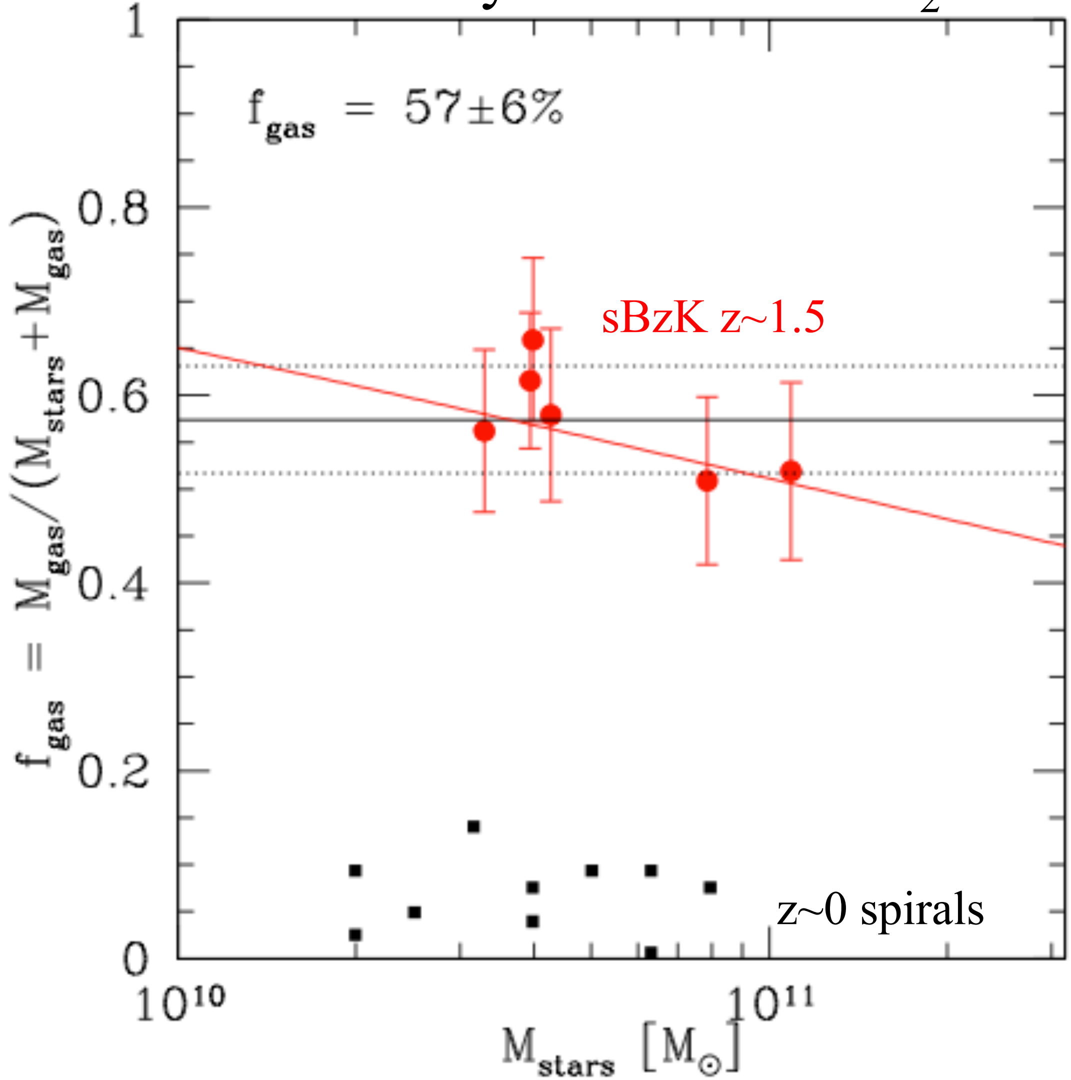
Caveat: using $\alpha = 4$ ~ MW value

- Dynamical modeling include DM (Bournaud)
- MW excitation
- MW FIR/L' CO
- MW disk sizes

(see Daddi ea, Tacconi ea)

Needs confirmation!

Baryon fraction in H_2



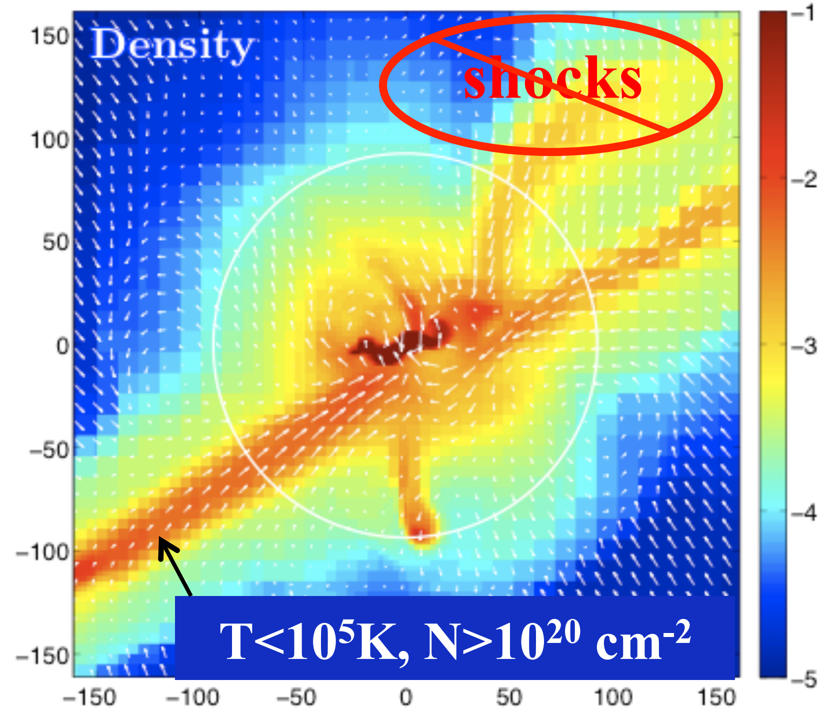
Emerging paradigm in galaxy formation: cold mode accretion (Keres, Dekel…)

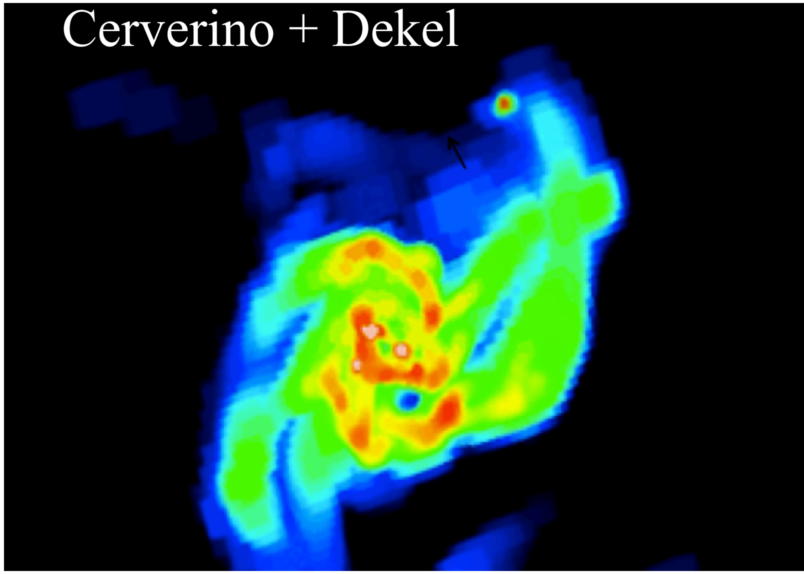
- Galaxies smoothly accrete cool gas from filamentary IGM onto disk at ~ 100 M_o/yr (high density allows cooling w/o avoid shock heating)

- Form turbulent, rotating disks with kpc-scale star forming regions, which migrate inward over ~ 1 Gyr to form bulge

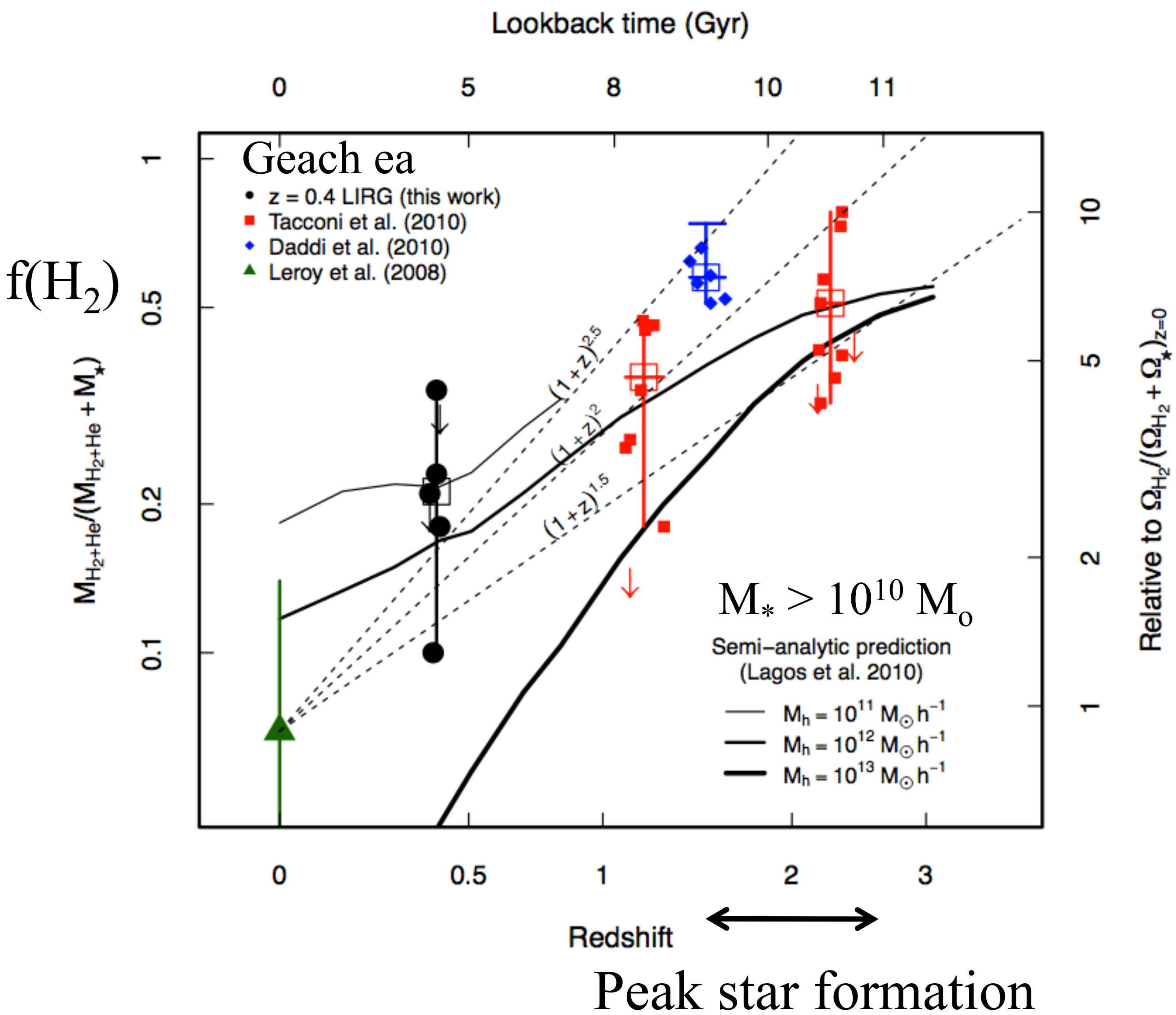
- Fuels steady star formation for ~ 1 Gyr; Feedback keeps SFR < accretion rate

'Dominant mode of star formation in Universe'





Fundamental change in galaxy properties during peak epoch of galaxy formation: Epoch of galaxy assembly = epoch of gas dominated galaxies



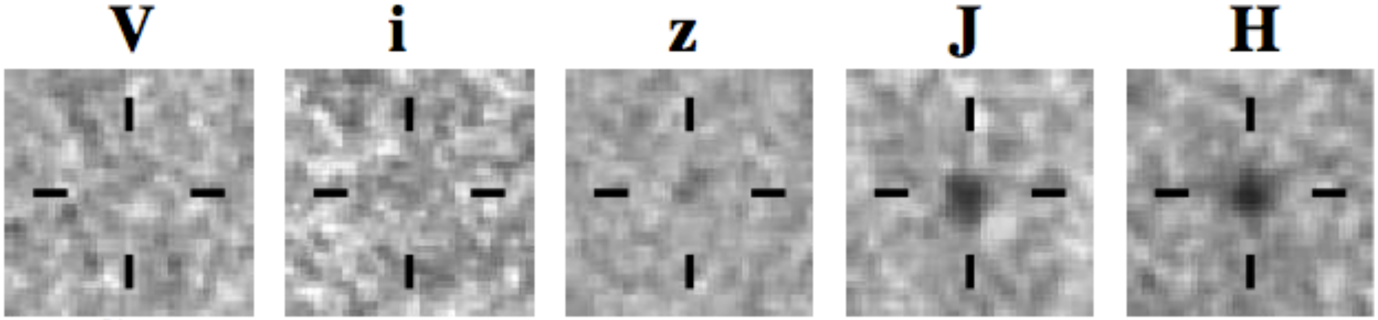
Atacama Large Milllimeter Array

- High sensitivity array = 54x12m
- Wide field imaging array = 12x7m
- Frequencies = 80 GHz to 900 GHz
- Resolution = 20mas at 800 GHz
- Sensitivity = 13uJy in 1hr at 230GHz

ALMA+EVLA represent an order of magnitude, or more, improvement in observational capabilities from 1 GHz to 1 THz!

Expanded Very Large Array

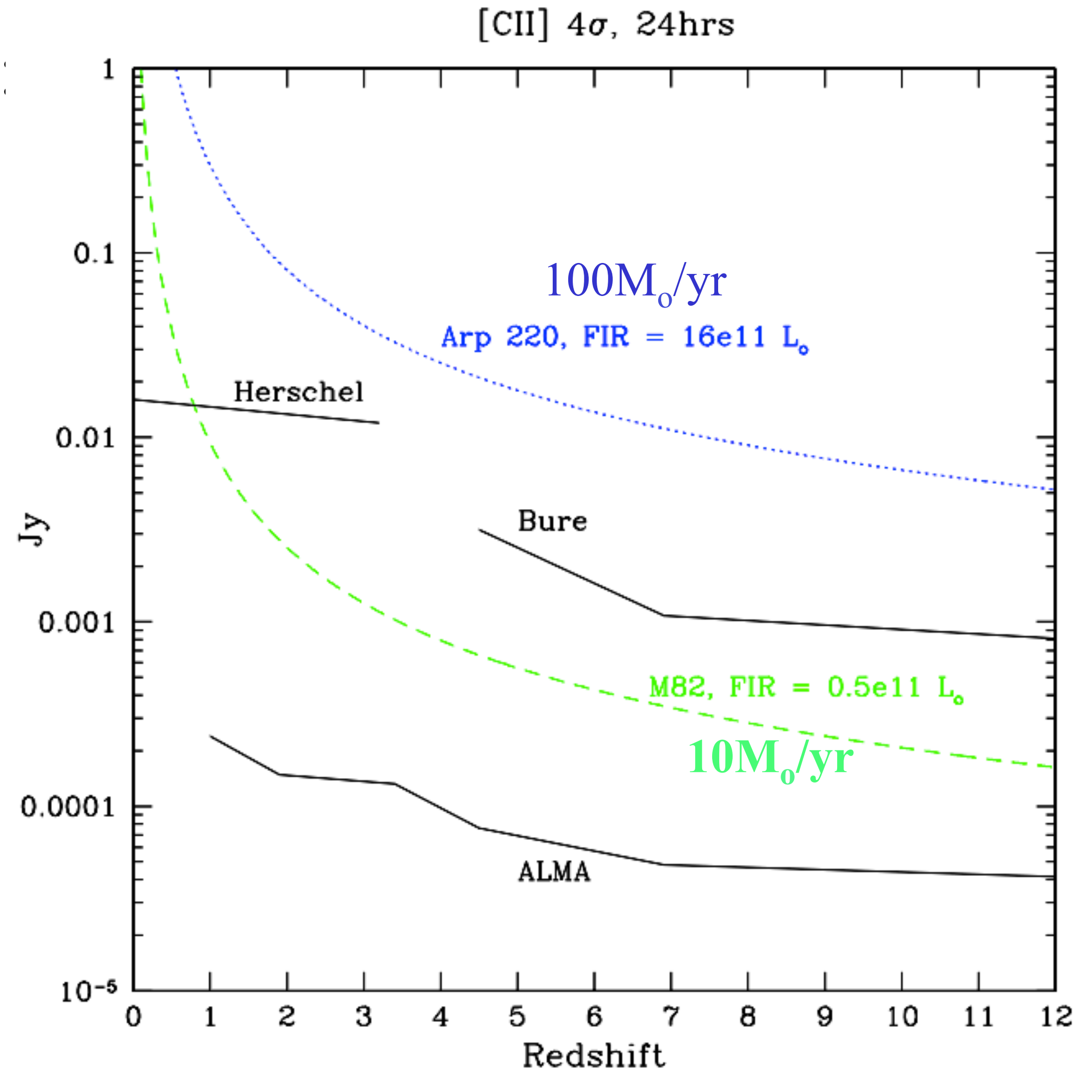
- 80x Bandwidth (8 GHz, full stokes), with 4000 channels
- Full frequency coverage (1 to 50 GHz)
- 10x continuum sensitivity (<1uJy)
- Spatial resolution ~ 40mas at 43 GHz

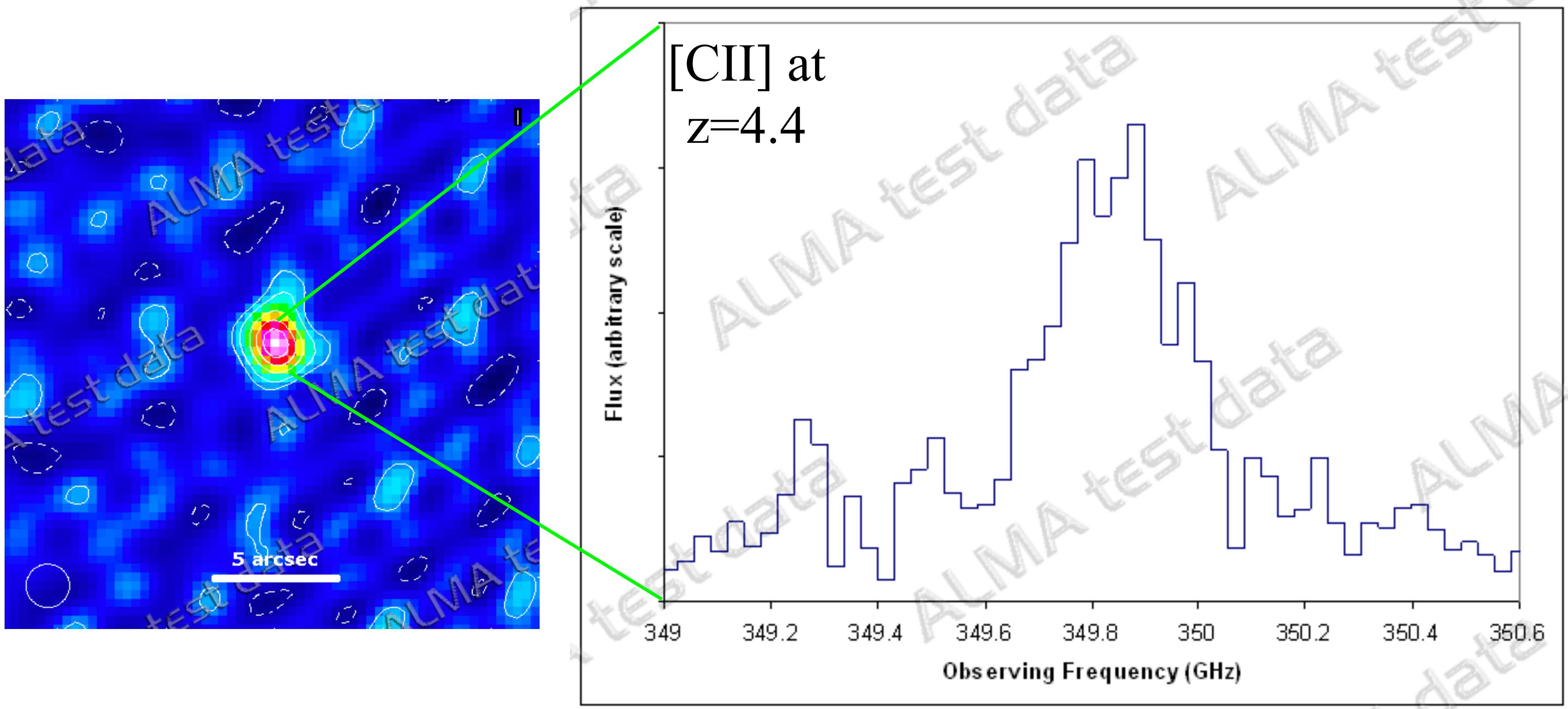


z-dropouts from UDF (Bouwens ea)
$z>7$ or $t_{univ} < 0.7$Gyr

ALMA and first galaxies: [CII] into reionization

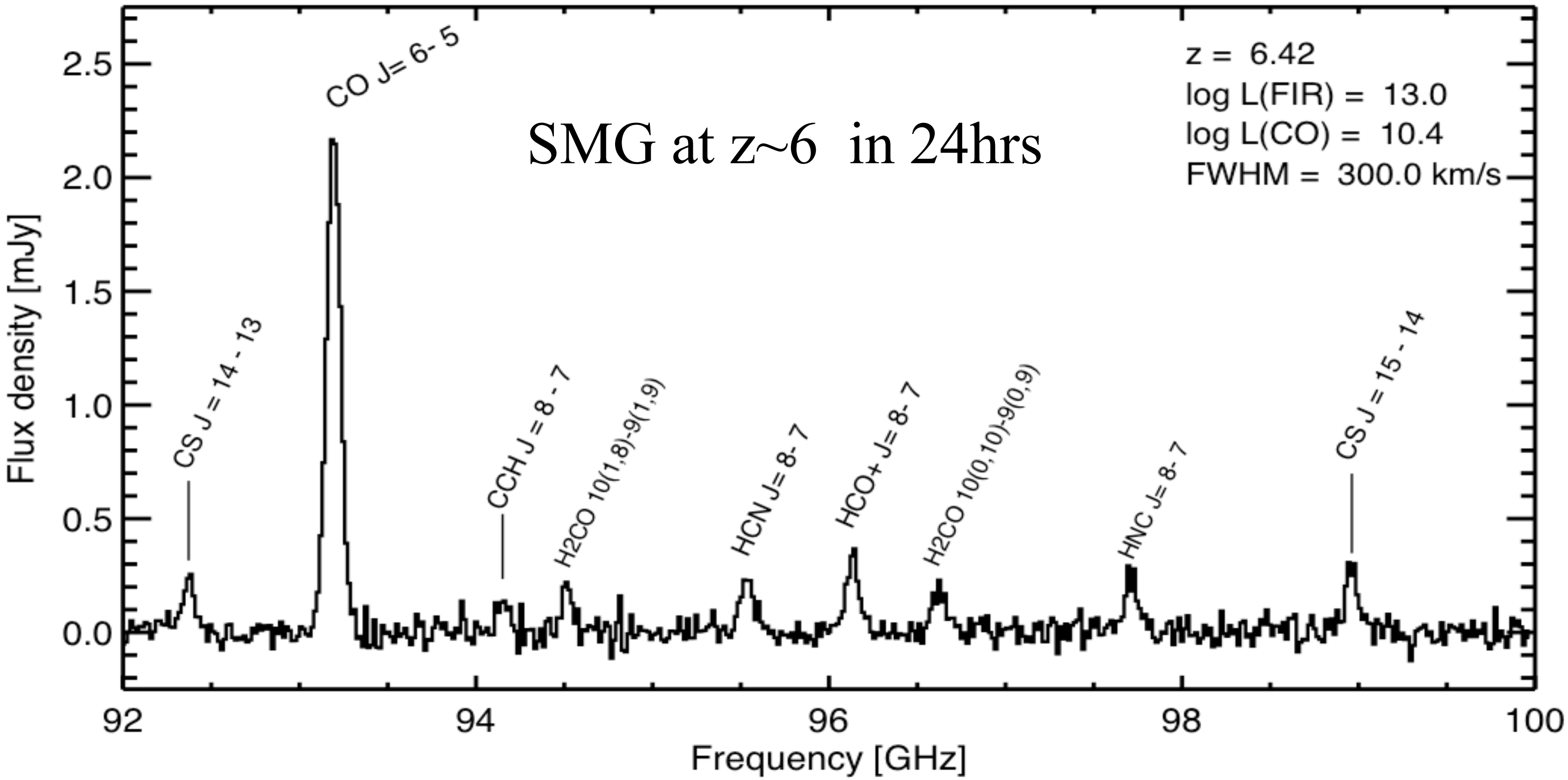
- $z > 7$ galaxies ~ 100 to date
  - 0.3 arcmin^{-2}
  - SFR ~ few M_o/yr
  - Difficult to get z_{spec}
- ALMA can detect [CII] in a few hours = redshift machine! [dz = 0.27]





- As a test of ALMA's ability to observe broad spectral lines, we observed the quasar BRI 0952-0115, which is at a red-shift of z = 4.43. The object is again unresolved on short baselines, but the 158 micron line from ionized carbon is clearly detected in the spectrum, which is impressive given that this observation took only one hour in total.

8GHz spectroscopy



- ALMA: Detect multiple lines, molecules per 8GHz band = real spectroscopy/astrochemistry

- EVLA: 30% FBW, ie.19 to 27 GHz (CO1-0 at z=3.2 to 5.0) => large cosmic volume searches for molecular gas (1 beam = 10^4 $cMpc^3$) w/o need for optical redshifts

EVLA/ALMA Deep fields: the 'missing half' of galaxy formation

- Volume (EVLA, z=2 to 2.8) = 1.4e5 $cMpc^3$
- 1000 galaxies z=0.2 to 6.7 in CO with $M(H_2) > 10^{10}\ M_o$
- 100 in [CII] z ~ 6.5
- 5000 in dust continuum

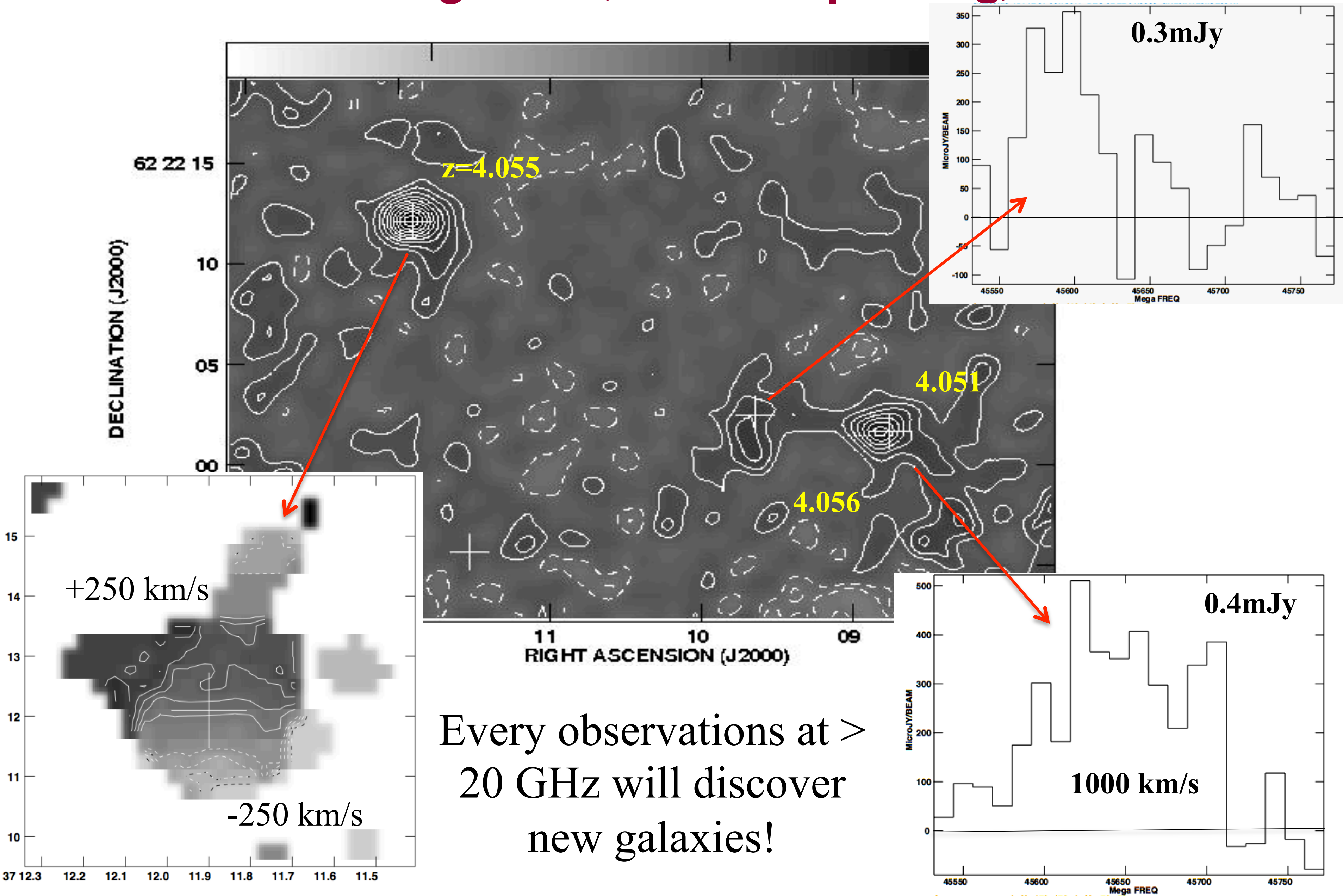
Table 1: EVLA (30-38GHz), ALMA (90-98GHz), 1000hrs, $50 arcmin^2$

	Tansition	z_{range}	Number of Galaxies
ALMA	CO 1-0	0.17 to 0.27	40
ALMA	CO 2-1	1.3 to 1.6	389
EVLA	HCN 1-0	1.3 to 2.0	7
EVLA	HCO^+ 1-0	1.3 to 2.0	7
EVLA	CO 1-0	2.0 to 2.8	130
ALMA	CO 3-2	2.5 to 2.8	122
ALMA	CO 4-3	3.7 to 4.1	66
ALMA	CO 5-4	4.9 to 5.4	24
EVLA	CO 2-1	5.0 to 6.7	13
ALMA	CO 6-5	6.0 to 6.7	7
ALMA(250GHz)	[CII] 158μm	6.36 to 6.6	110
ALMA(250GHz)	Continuum	$z < 10$	5000

New horizon for deep fields!

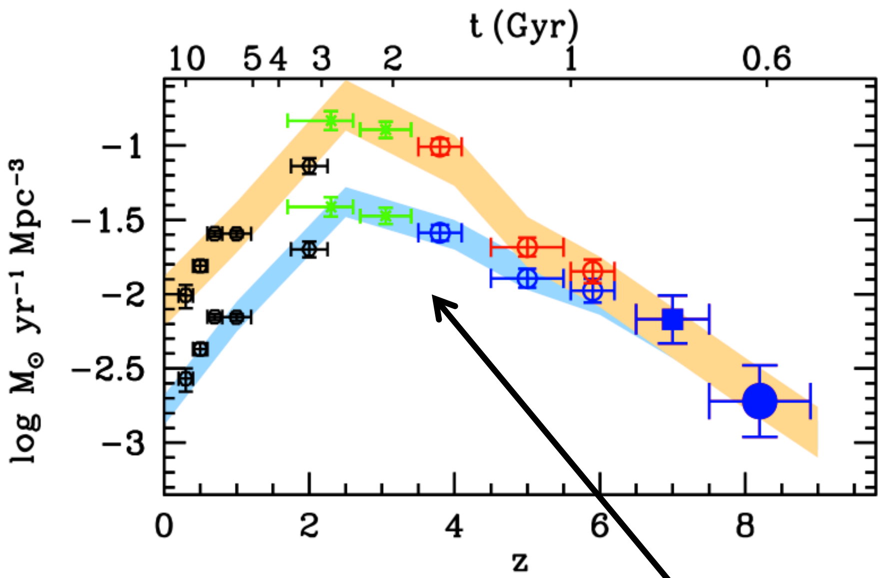
Millennium Simulations
Obreschkow & Rawlings

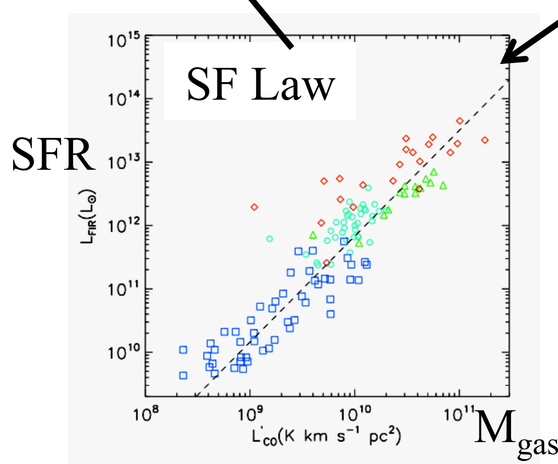
GN20 molecule-rich proto-cluster at z=4
CO 2-1 in 3 submm galaxies, all in one pointing, 256 MHz band

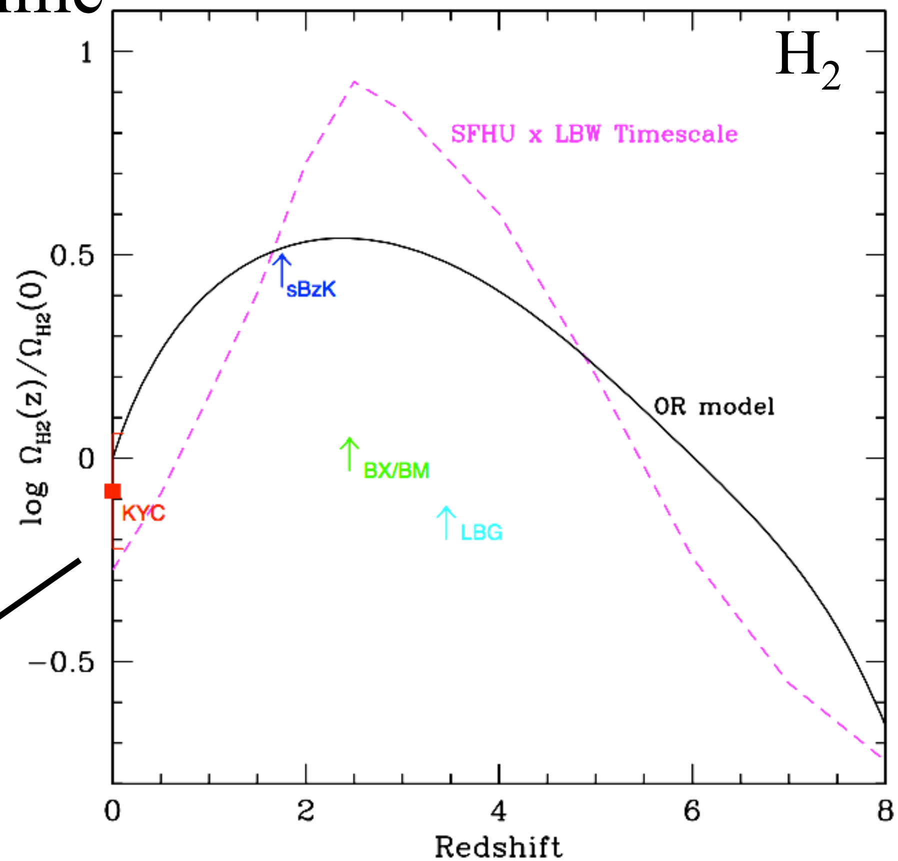


Every observations at > 20 GHz will discover new galaxies!

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







Millennium Simulations
Obreschkow & Rawlings
See also Bauermeister et al.

DGHU is primary goal for studies of galaxy formation this decade!

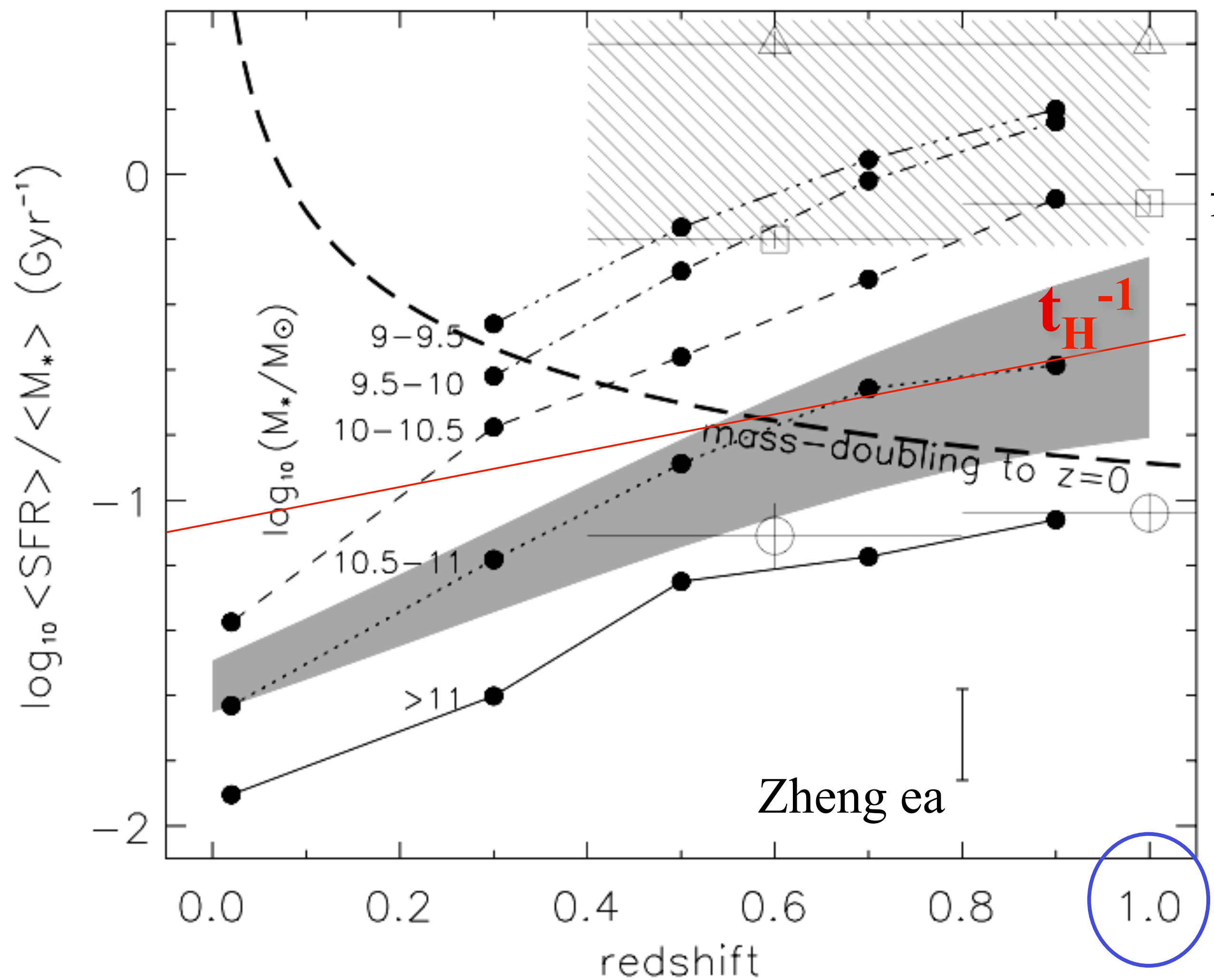
Major questions

- L'_{CO} to H_2 mass conversion factor: calibrate dynamically? Bivariate? [low order CO imaging]
- Universality of star formation laws? [Dust/CO imaging]
- Gas supply: CMA or mergers (or a bit of both?) [CO imaging?]
- Dust formation within 1Gyr of the Big Bang? [submm continuum $z > 7$ candidates]
- [CII] as a redshift machine? [ALMA!]
- Dense gas fraction: SF efficiency (HCN, HCO+)
- Driving SFR $> 10^3$ M_o/yr (maximal starburst, AGN)? [SED, Free-Free]


END

Star formation as function of stellar mass

specific SFR = SFR/M_* ~ e-folding time^{-1}

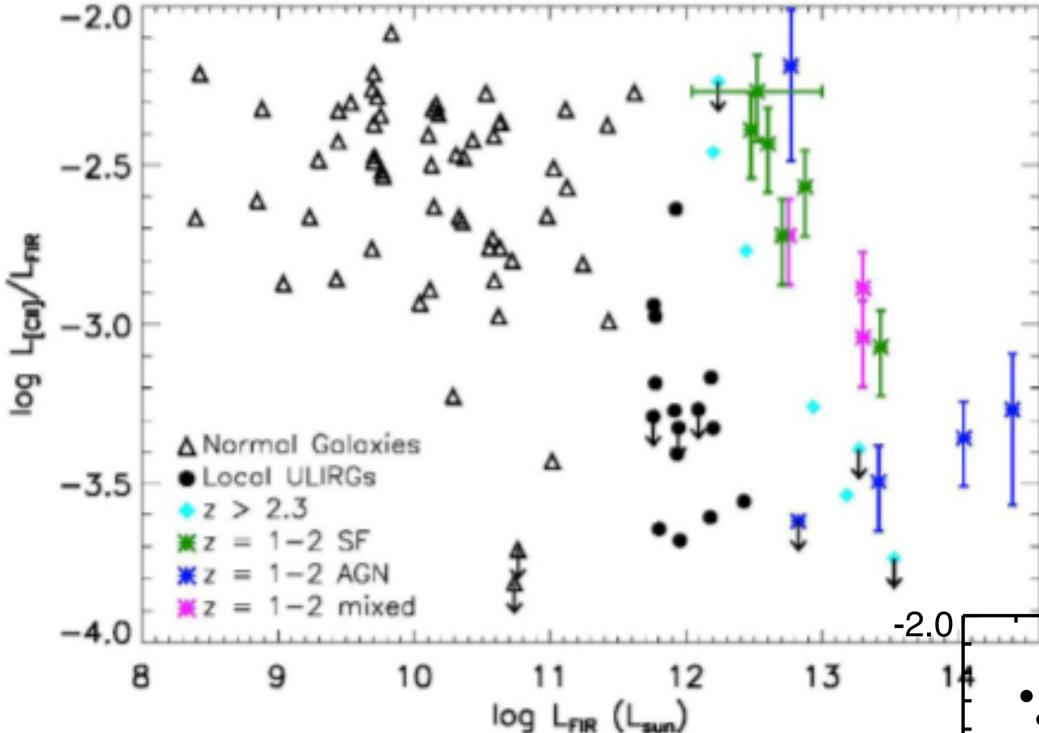


'active star formation'

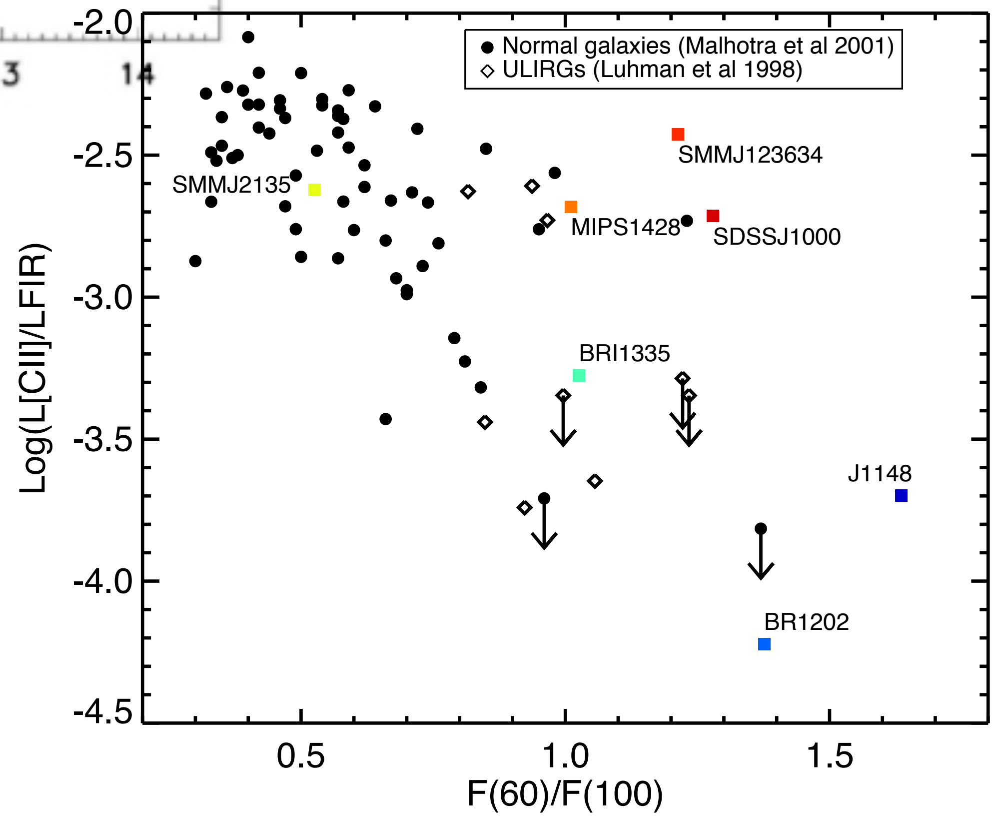
'red and dead'

'Downsizing' : Massive galaxies form most of stars quickly, at high z

(see also: stellar pop. synthesis at low z; evolved galaxies at z ~1 to 2)



log L[CII]/LFIR
log LFIR (Lsun)
Normal Galaxies
Local ULIRGs
z > 2.3
z = 1−2 SF
z = 1−2 AGN
z = 1−2 mixed



Normal galaxies (Malhotra et al 2001)
ULIRGs (Luhman et al 1998)
SMMJ123634
SMMJ2135
MIPS1428
SDSSJ1000
BRI1335
J1148
BR1202
Log(L[CII]/LFIR)
F(60)/F(100)

CCAT: wide field ‘finder’ surveys

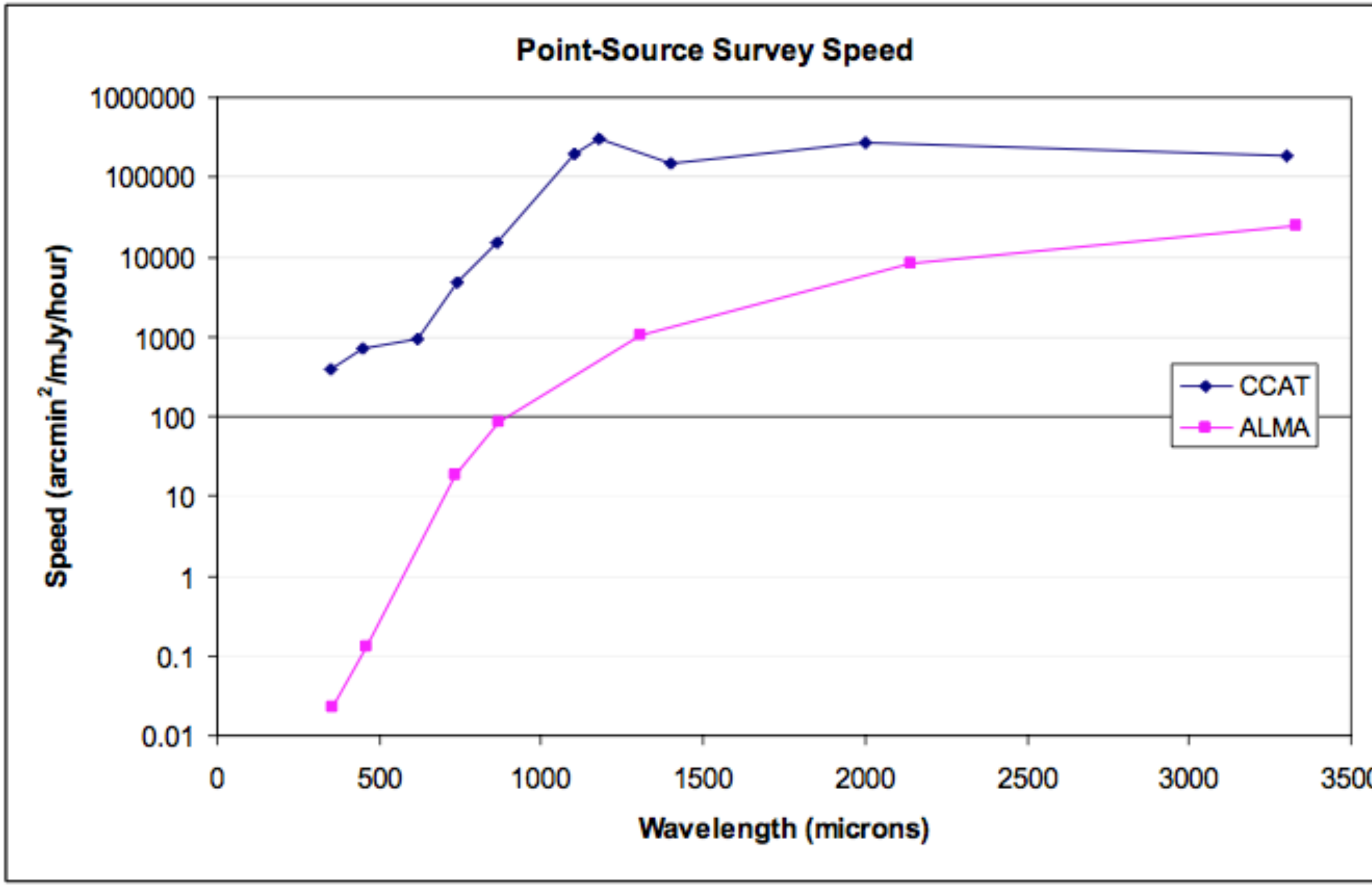
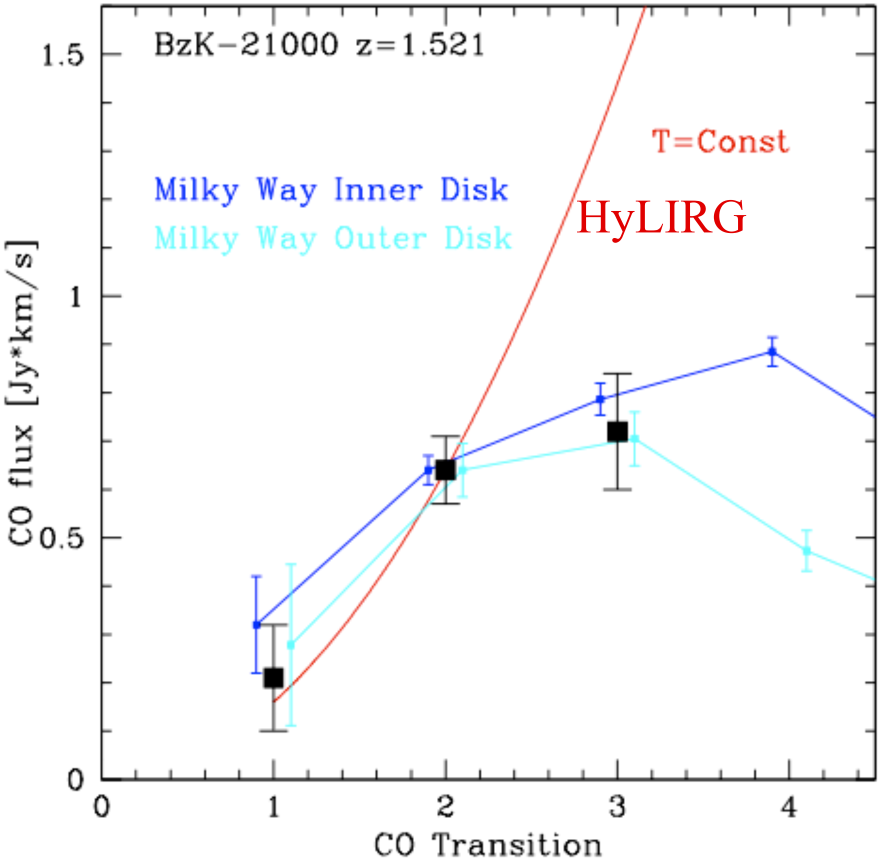
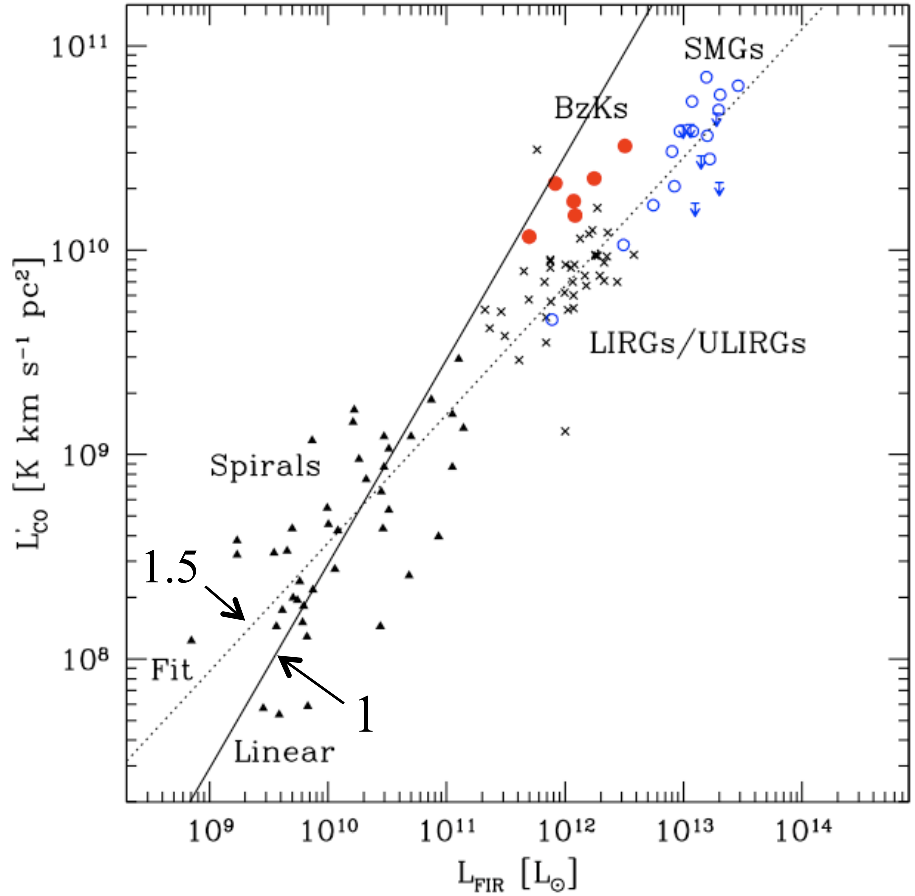


Figure 1: Point-source survey speed (rate at which sky can be mapped for point sources in units of arcmin^2/mJy/hour for a one-sigma detection) for CCAT and ALMA vs. wavelength). CCAT assumes a 150×150 focal plane array sampling two pixels/beam.

Closer to Milky Way-type gas conditions

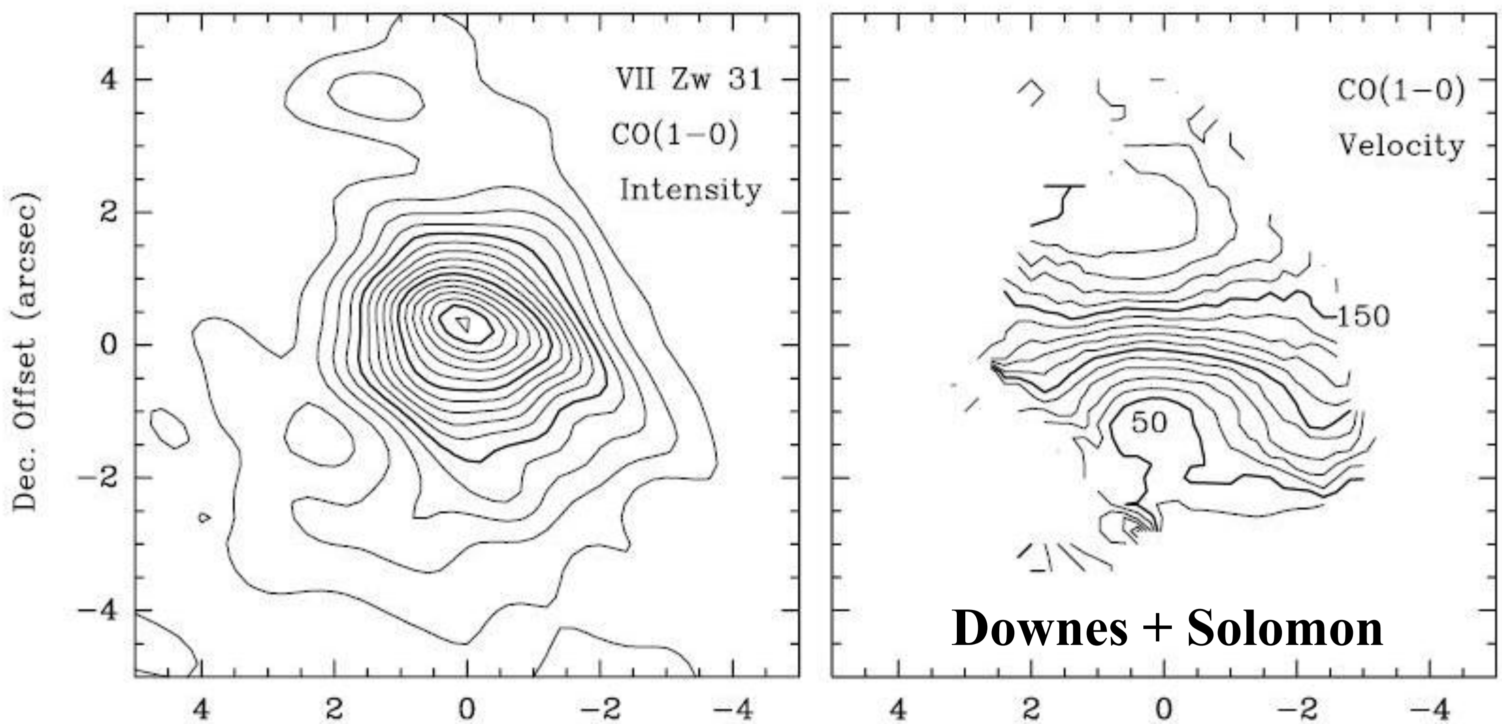




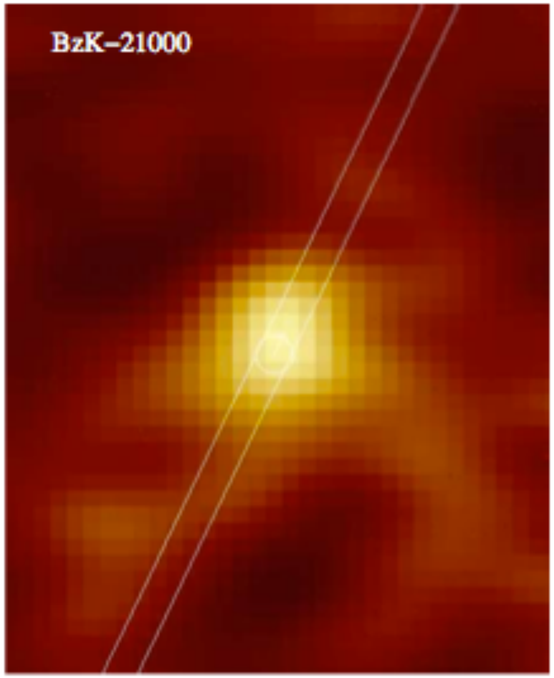
- Lower CO excitation: low J observations are key!
- FIR/L' CO: Gas consumption timescales >= few $x10^8$ yrs

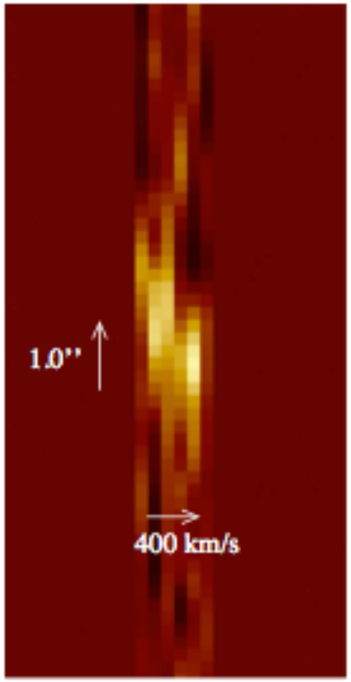
Molecular gas mass: X factor

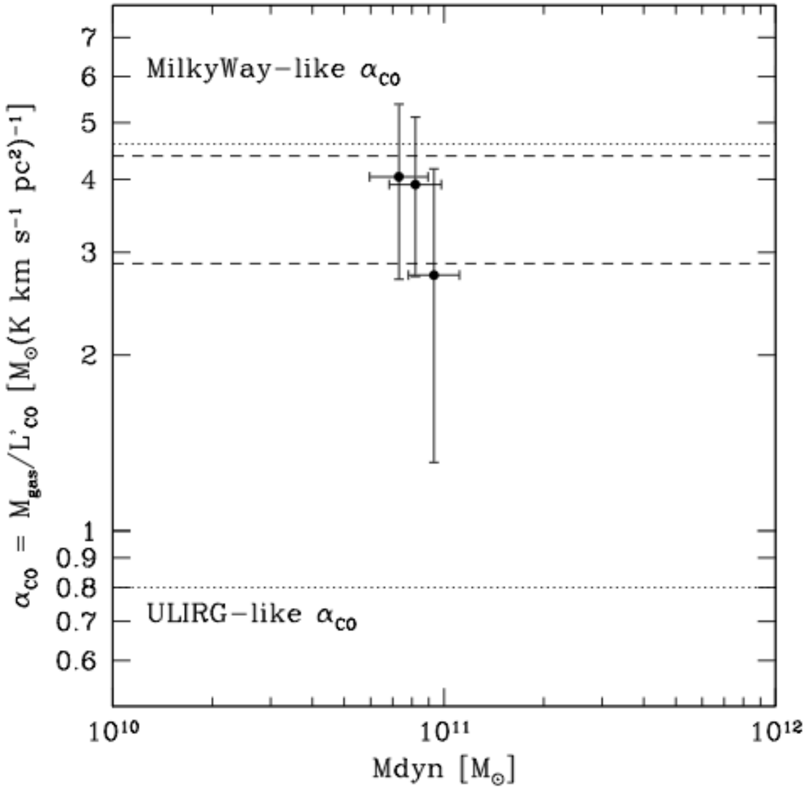
- $M(H_2) = X\ L'(CO(1\text{-}0))$
- Milky way: $X = 4.6\ M_\odot/(K\ km/s\ pc^2)$ (virialized GMCs)
- ULIRGs: $X = 0.8\ M_\odot/(K\ km/s\ pc^2)$ (CO rotation curves)
- Optically thin limit: $X \sim 0.2$

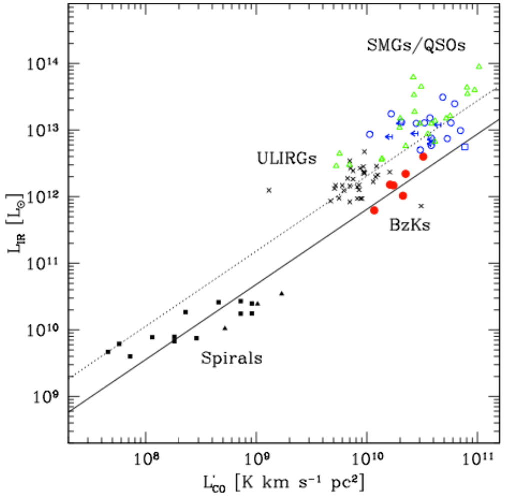


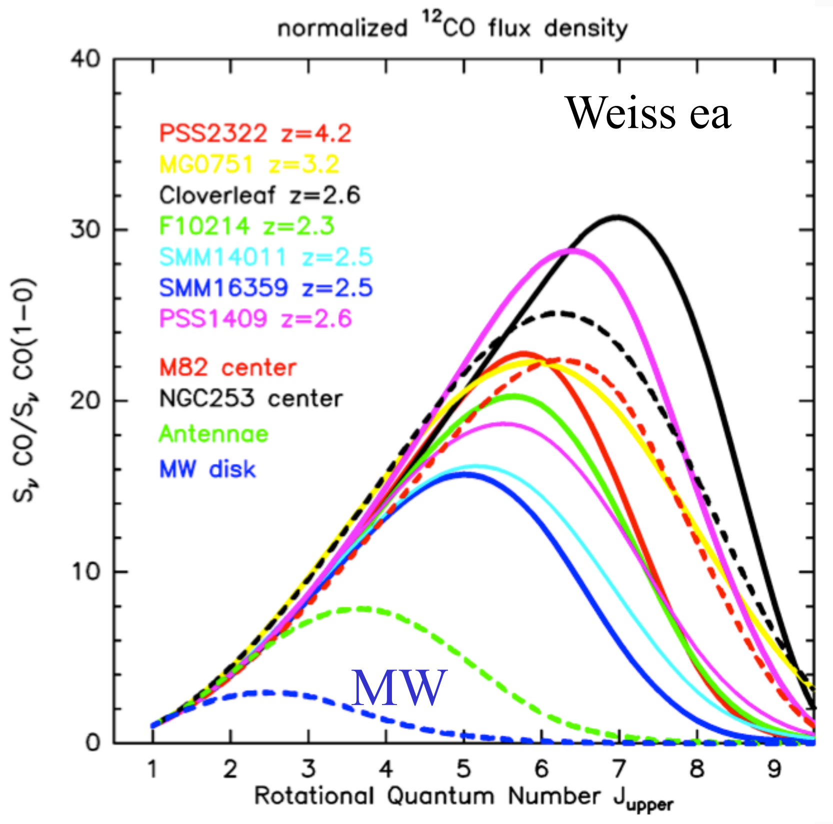
X factor sBzK = MW: dynamics + modeling

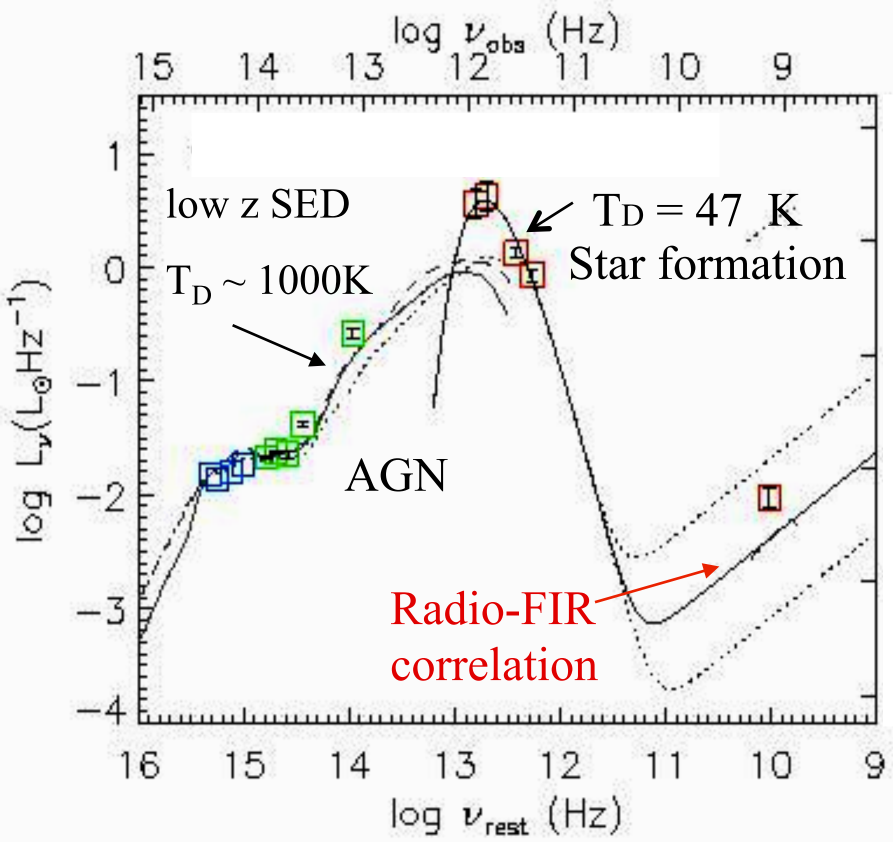








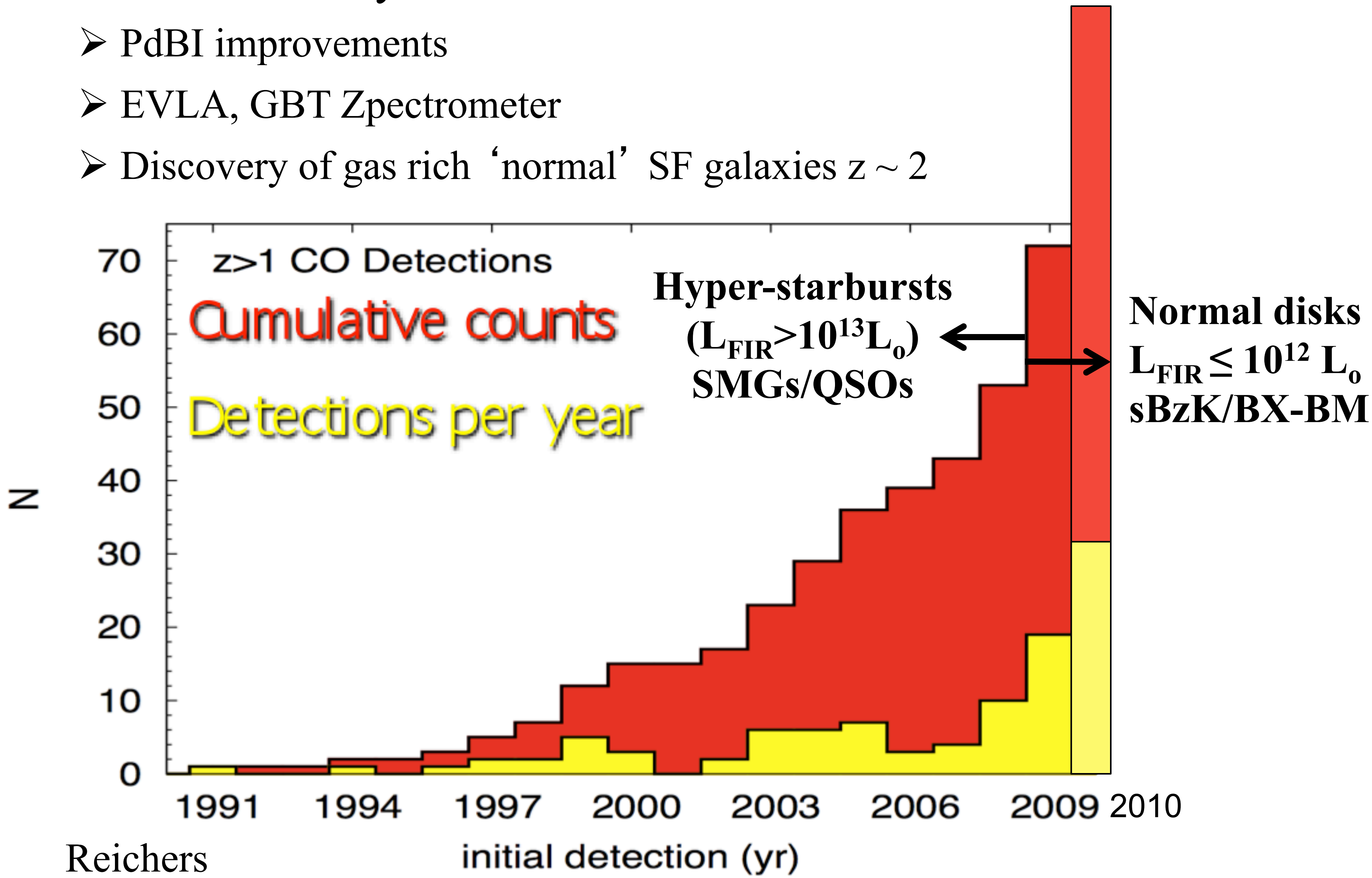




- SLED: LVG model => T_k > 50K, $n_{H2} = 2x10^4$ cm^{-3}
  - ➢ Galactic Molecular Clouds (50pc): n_{H2}~ 10^2 to 10^3 cm^{-3}
  - ➢ GMC star forming cores (~1pc): n_{H2}~ 10^4 cm^{-3}
- SED: Warm dust ~ 30 to 50 K, follows Radio-FIR correlation => SFR > 10^3 M_o/yr

Today's focus: molecular gas

- 103 CO detections at z > 1 published to date
- 50% in the last 2 years
  - PdBI improvements
  - EVLA, GBT Zpectrometer
  - Discovery of gas rich 'normal' SF galaxies z ~ 2



Reichers