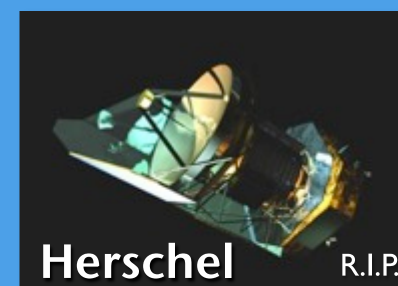
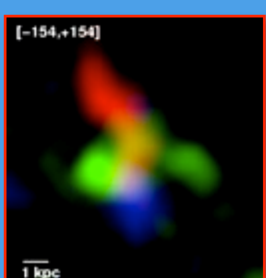
The Interstellar Medium in High Redshift Galaxies

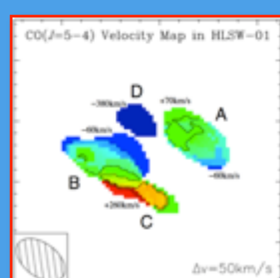
Dominik A. Riechers
Cornell University

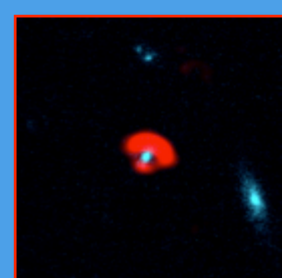


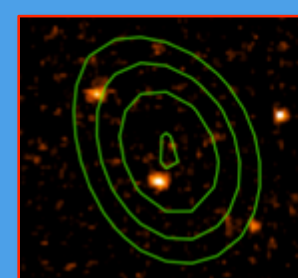
Phases of the ISM – MPIA Summer Conference

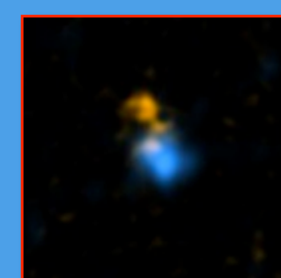
Aug 1, 2013



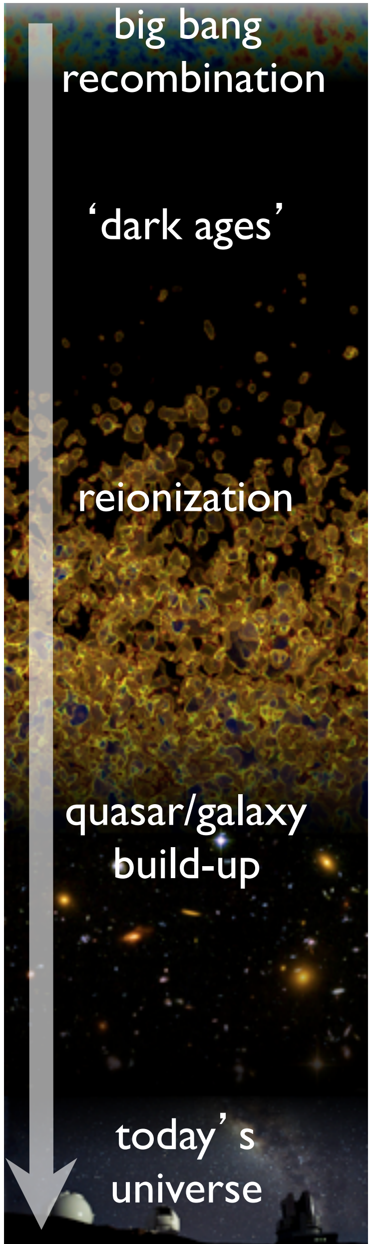








history of the universe	



z~1000
0.0003 Gyr

z~15-1000
0.0003-0.3 Gyr

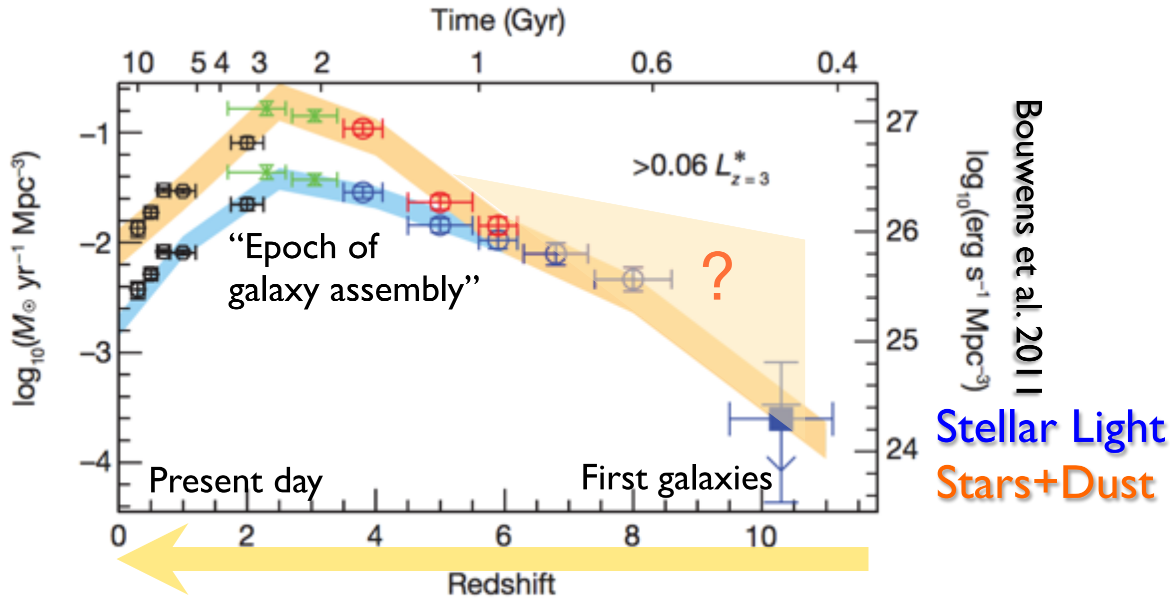
z~8-15
0.3-1 Gyr

z<~8
>1 Gyr

z~0
13.8 Gyr

cosmic star formation

Volume density of star formation in galaxies as f(cosmic time)



Star Formation in Galaxies at High Redshift is Exciting:

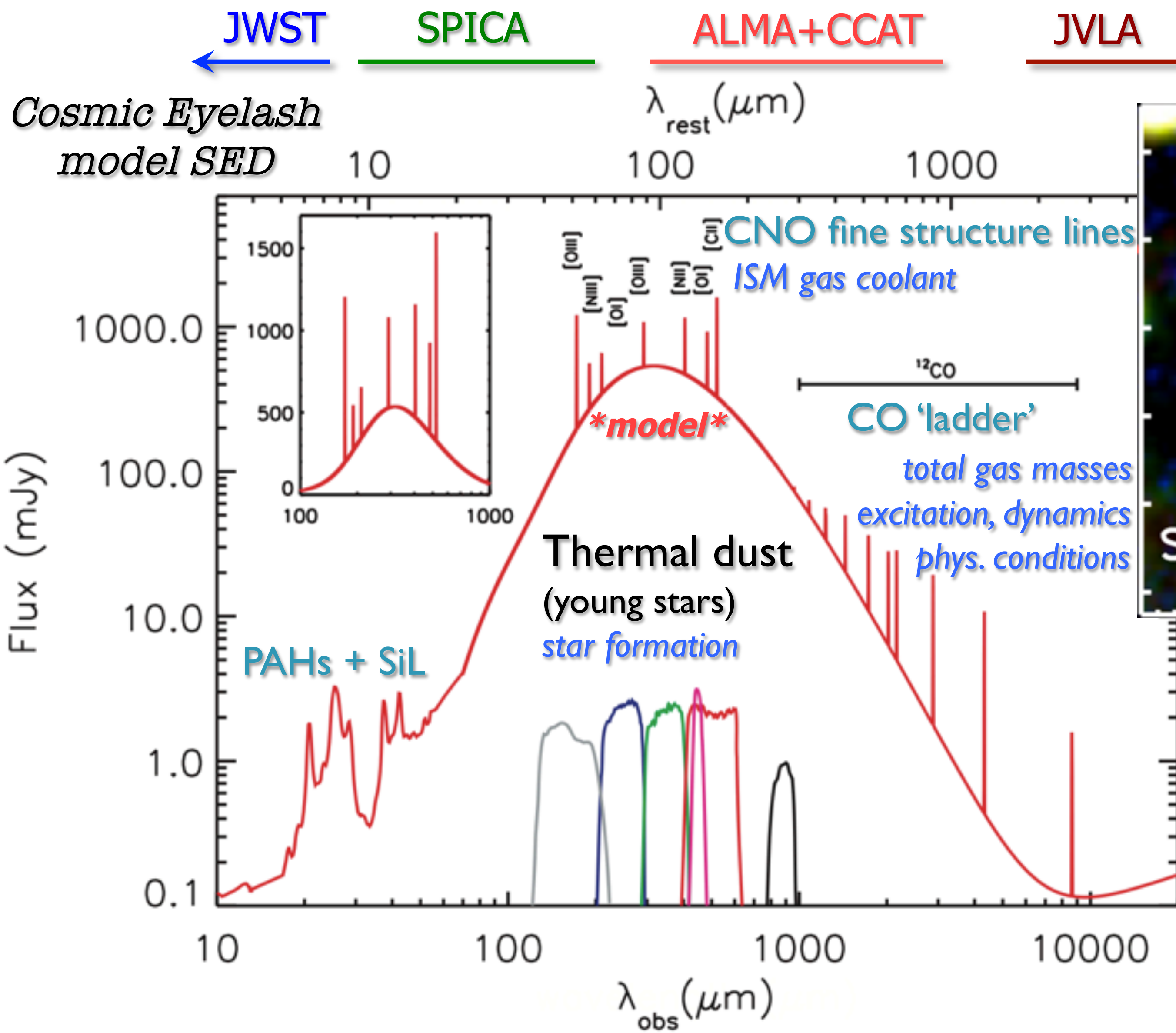
- A few billion years ago, galaxies in the universe formed ~30x more stars than today (making up the stars we see now) …why?

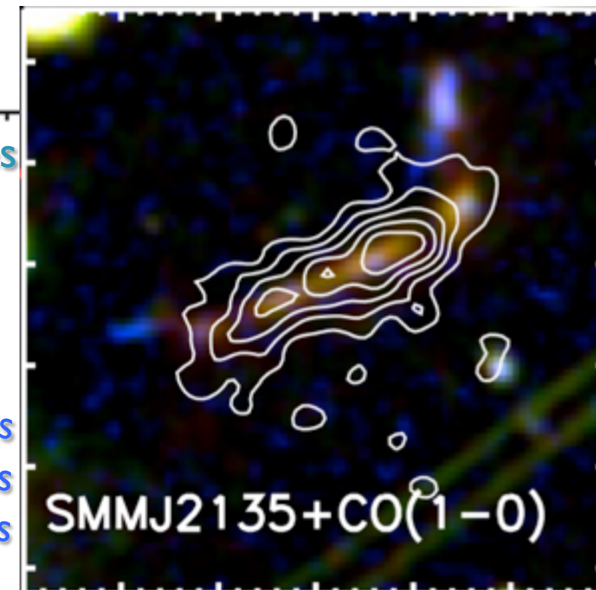
- The most intensely starbursts at high z form 10-30x more stars than the most extreme examples today …why?

sites of star formation enshrouded by *dust*, absorbing a fraction of the stellar light (which is re-radiated in the rest-frame far-infrared)

Clues to Cosmic Star Formation: Gas Cooling Through Emission Lines

cm/mm: rich in line + continuum diagnostics





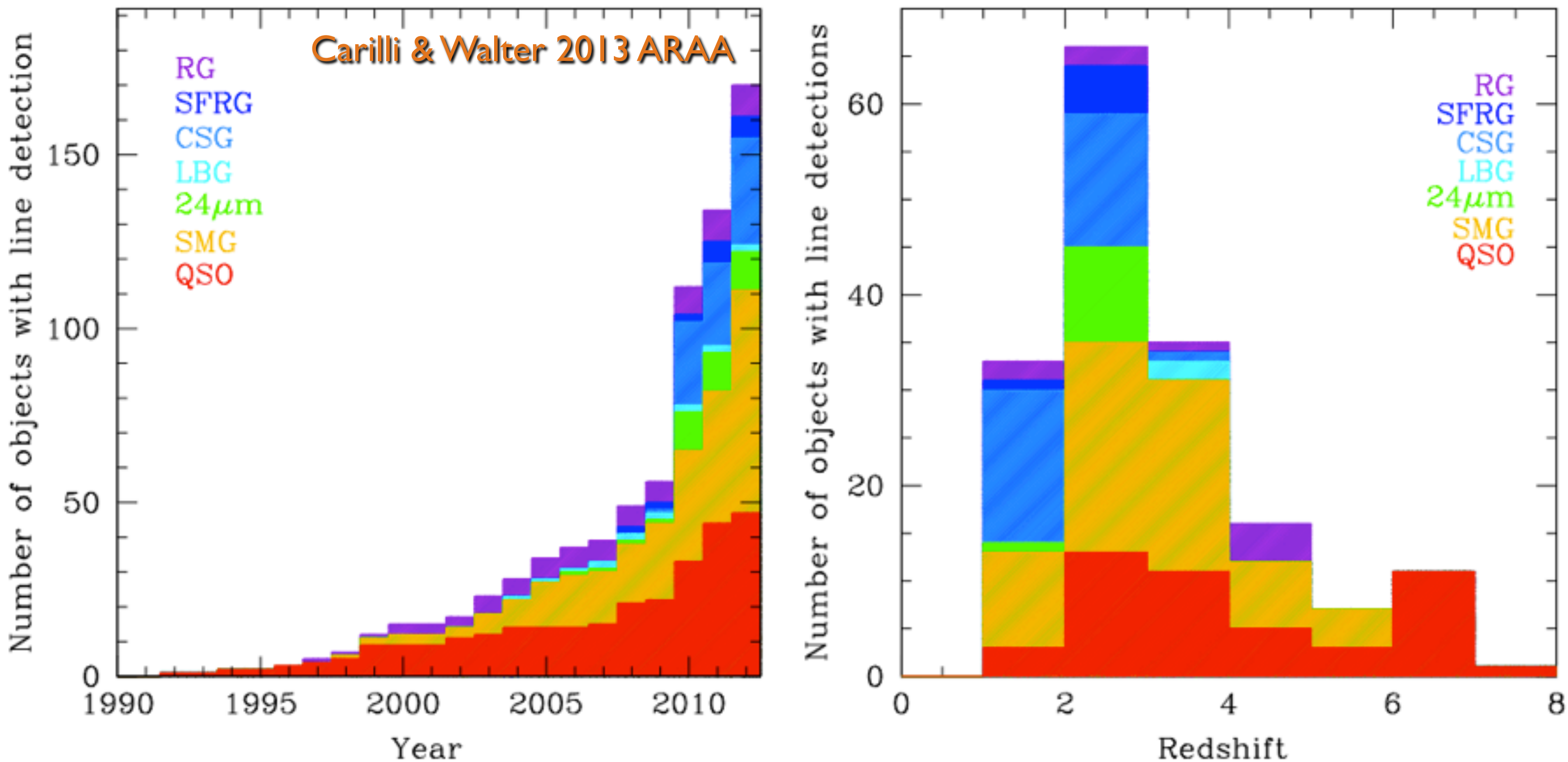
Smail et al. 2011

Swinbank et al. 2011

Synchrotron + Free-Free

(AGN+SNR) *star formation*

Detections of the Molecular/Atomic ISM at High Redshift

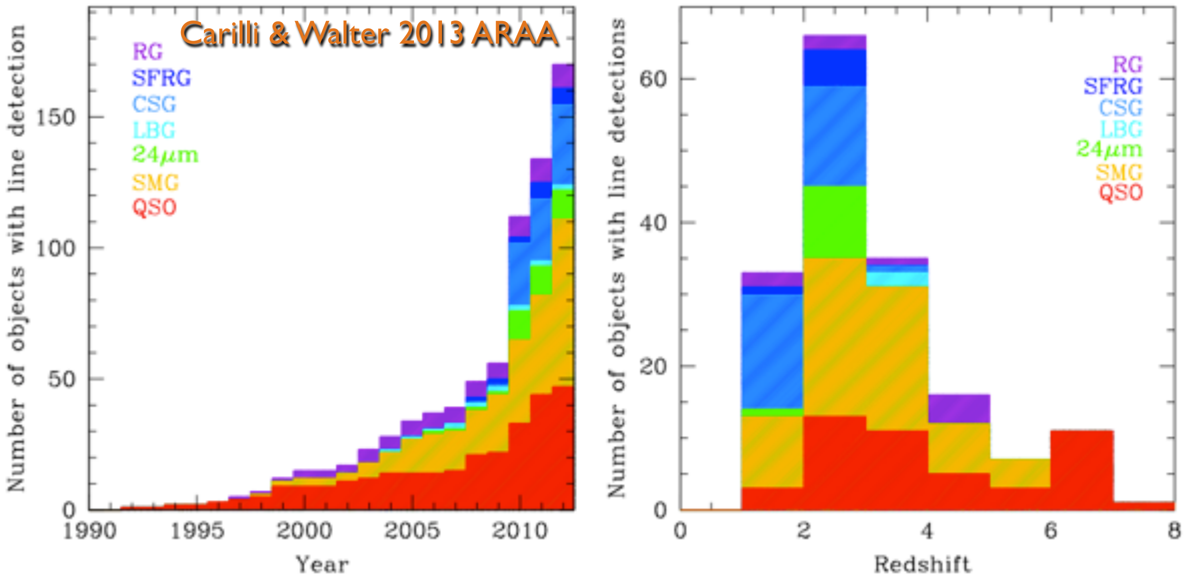


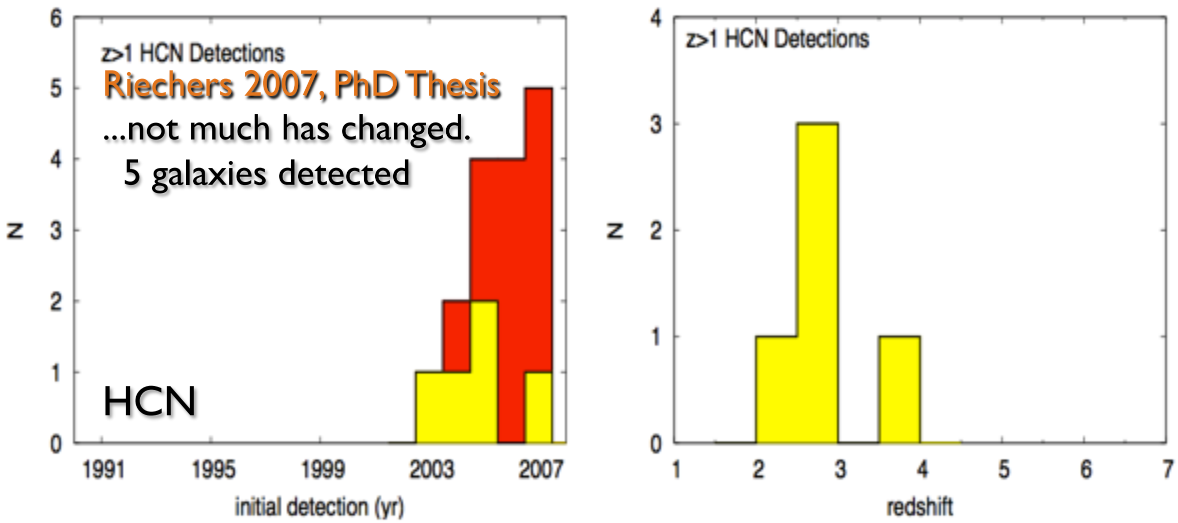
Dramatic (~10x) increase in number of detections in the past decade

- Many different populations selected in UV/optical, mid-IR, FIR/submm, radio
- Star-forming galaxies & AGN host galaxies
- Most detections are in CO, some are initially detected in [CII]

⇒ This fraction may dramatically change with ALMA…[CII] accessible at most z>1

The Dense ISM at High Redshift





APM 08279+5255 (z=3.911)
Riechers et al. 2010, 2013

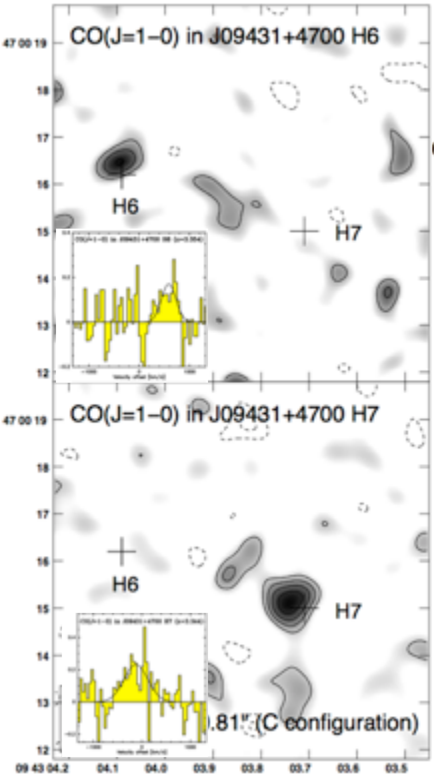
HCN, HCO^+ et al.: better tracers of dense, actively star-forming component.

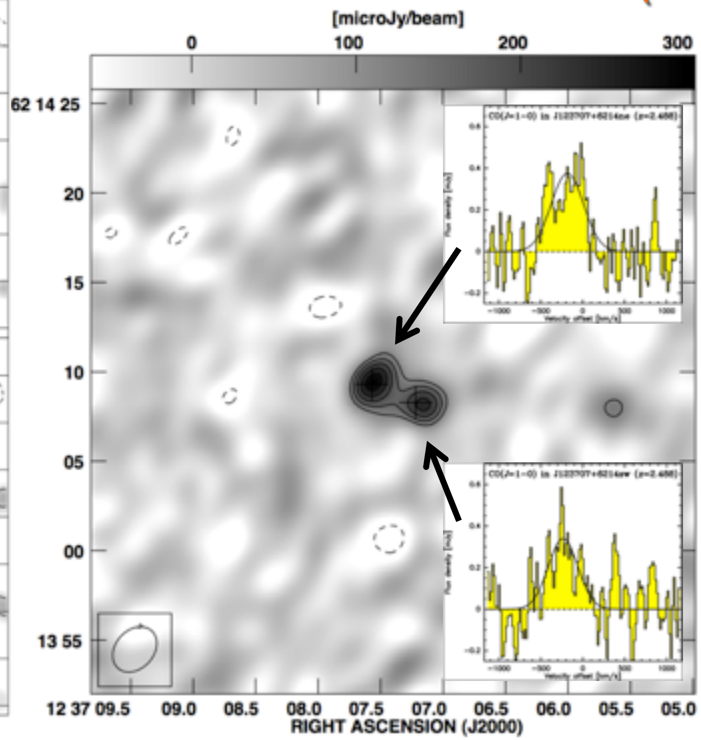
<u>BUT:</u> 10-30x fainter than CO…need ALMA to obtain significant samples

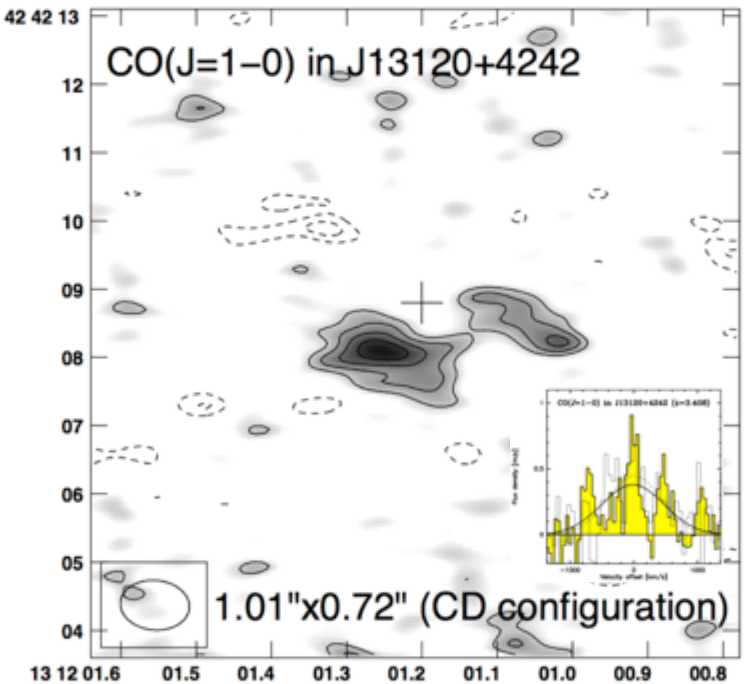
Possible alternative: H_2O, but excitation complex and likely not dominated by collisions

Increase in Star Formation History at High z: Prevalence of Major Mergers?

Riechers et al. (2011d, 2011f); see also: Ivison et al. (2011)







Early stage ⟶ **Intermediate stage** ⟶ **Late stage**

Early stage: ~30kpc & 750km/s separation

Intermediate stage: ~20kpc & <100km/s separation

Late stage: 7-15kpc nucleus & tidal structure; single broad, multi-peaked line; abundant low-excitation gas

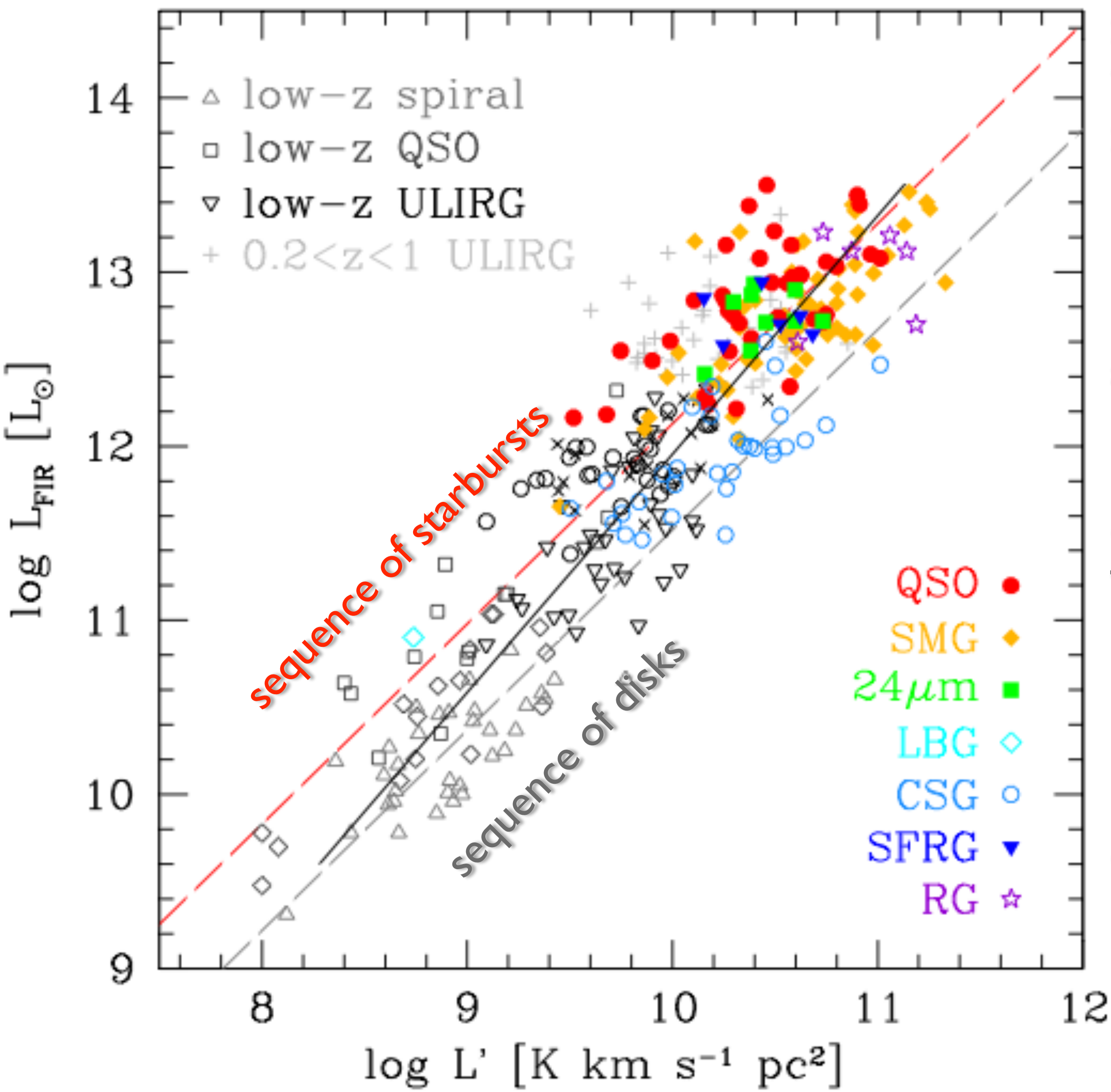
M_{gas} = 1-20 x 10^{10} M_{sun} & SFR >500 $M_{sun} yr^{-1}$

Submillimeter Galaxies: Gas-Rich Starbursts along the "Merger Sequence" at z>2

⇒ Nearby major mergers show increased SF efficiency relative to disks
SMGs are "scaled up" versions of nearby IR-luminous galaxies/mergers

So could explain increased SF History as f(z) in principle…but SMGs are too rare

Kennicutt-Schmidt Relation: The ISM drives Star Formation



Simplest Version of "Star Formation Law": Spatially Integrated Observables

L'_{CO} vs. L_{FIR}

as a surrogate for

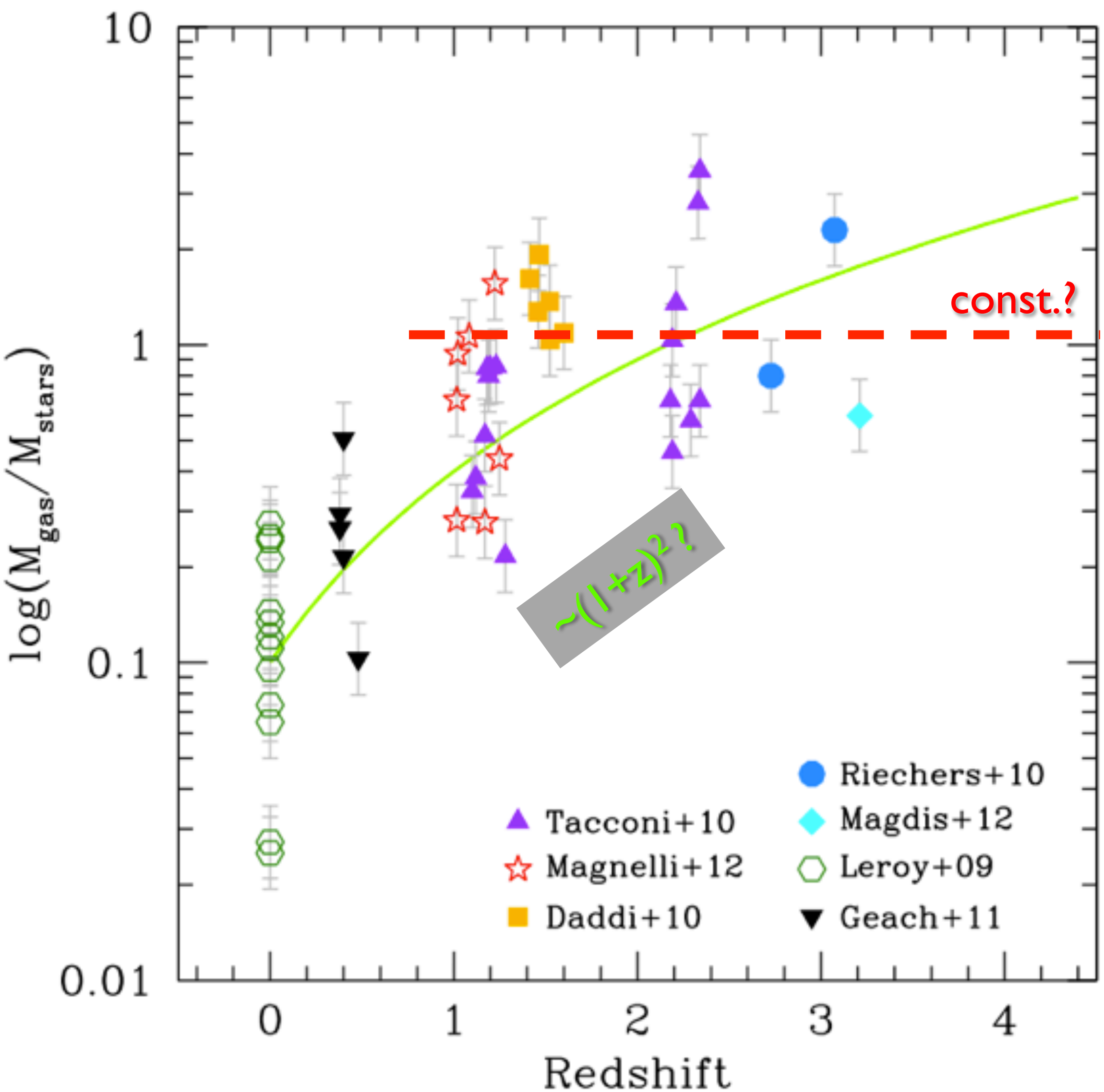
M_{gas} vs. SFR

One super-linear relation or
Two sequences (*quiescent/starburst*)
Bimodal or running *conversion factor*

…many subtleties, but:
High-z galaxies higher on *both* axes
Quiescent *and* Starburst Galaxies

Carilli & Walter 2013 ARAA; after Daddi et al. 2010, Genzel et al. 2010

Gas Fractions: The ISM drives Star Formation



Even "main sequence" galaxies (defined as typical SFR/$M_*(z)$)

show 10-30x higher gas fractions at z=1-3 compared to present day

⇒ Increased SF history driven by high gas fractions of galaxies (not by extreme merger rates)

⇒ $L_{FIR} = 10^{12}\ L_{sun}$ is the new "normal"

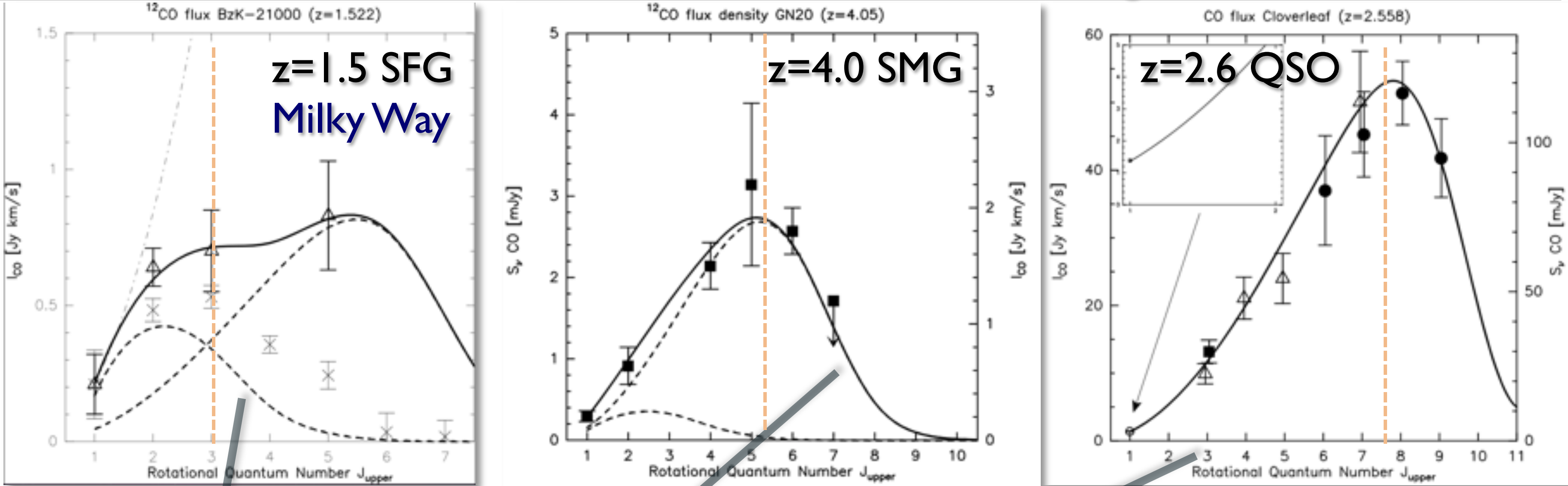
⇒ $L_{FIR} = 10^{13}\ L_{sun}$ are high starbursts (SMGs)

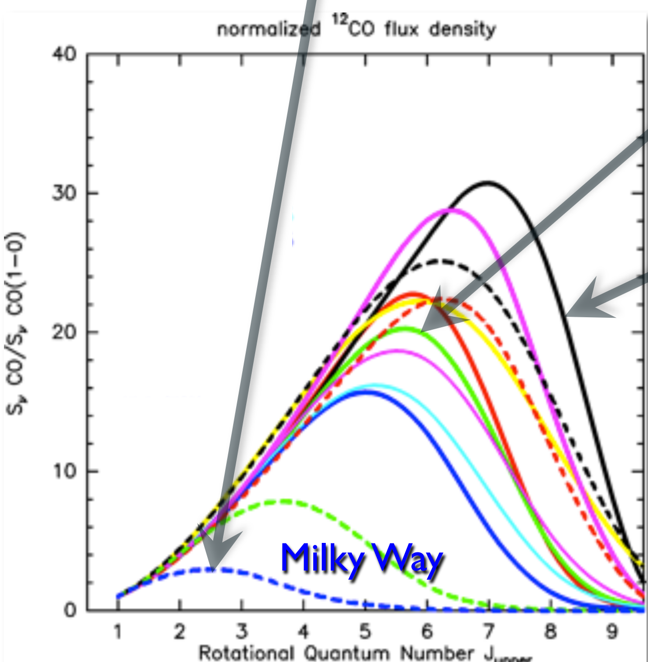
⇒ Star formation is elevated, but underlying physics are the same

⇒ Gas depletion makes z=0 "special"

Carilli & Walter 2013 ARAA; after Magdis et al. 2012

Further Evidence: Molecular Gas Excitation at High Redshift





CO Excitation Line Ladders:

(1) low, "Milky-Way-like" CO excitation

T_{kin} ~ 10-20K , n_{gas} ~ 300 cm^{-3} (GMCs)

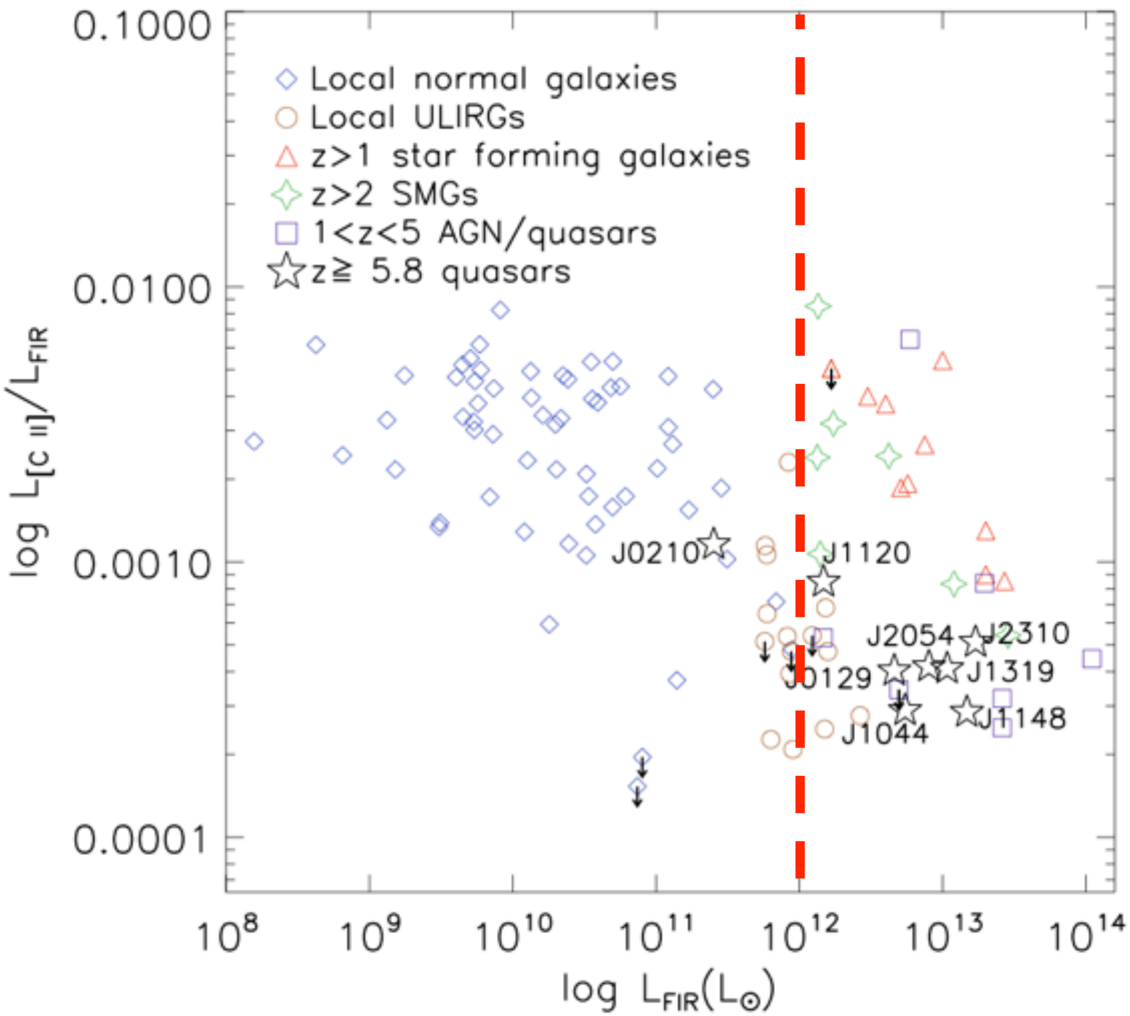
(2) high, "ULIRG-like" CO excitation

T_{kin} ~ 40-60K , n_{gas} ~ 3x10^{4} cm^{-3}

- SFGs: strong MW-like, some ULIRG-like
- SMGs: some MW-like, strong ULIRG-like
- QSOs: ULIRG-like & higher

Riechers ea. 2006b, 2009b, 2011a, Weiss ea. 2007
Dannerbauer ea. 2009, 2011, Carilli ea. 2010

Supporting Evidence: [CII]/FIR at high L_{FIR} in z>1 Galaxies



[CII]/FIR suppressed in nearby ultra-luminous IR galaxies (i.e., $L_{FIR} = 10^{12}\ L_{sun}$)

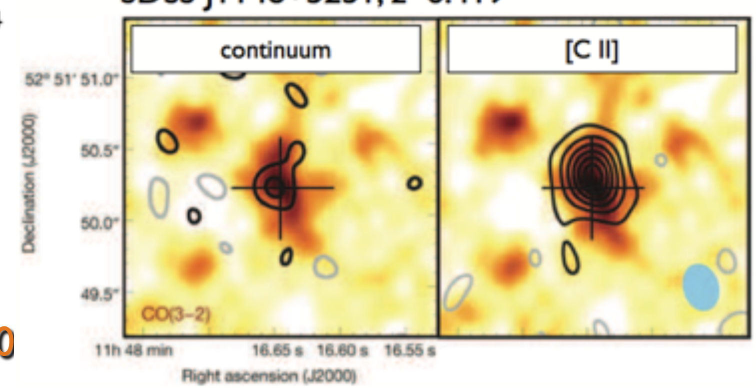
- at high T_{dust}
- at high Σ_{IR} or Σ_{SFR}
- at strong IR radiation fields

But many z>1 star-forming galaxies w/ $L_{FIR} = 10^{12}\ L_{sun}$ do *not* show deficit

- "normal" ISM conditions

Some do show strong deficit, but these are the compact starbursts (i.e., ULIRG analogs) or strong AGN

SDSS J1148+5251, z=6.419



Walter, DR et al. 2009, Nature; Wang et al. 2013; Stacey et al. 2010

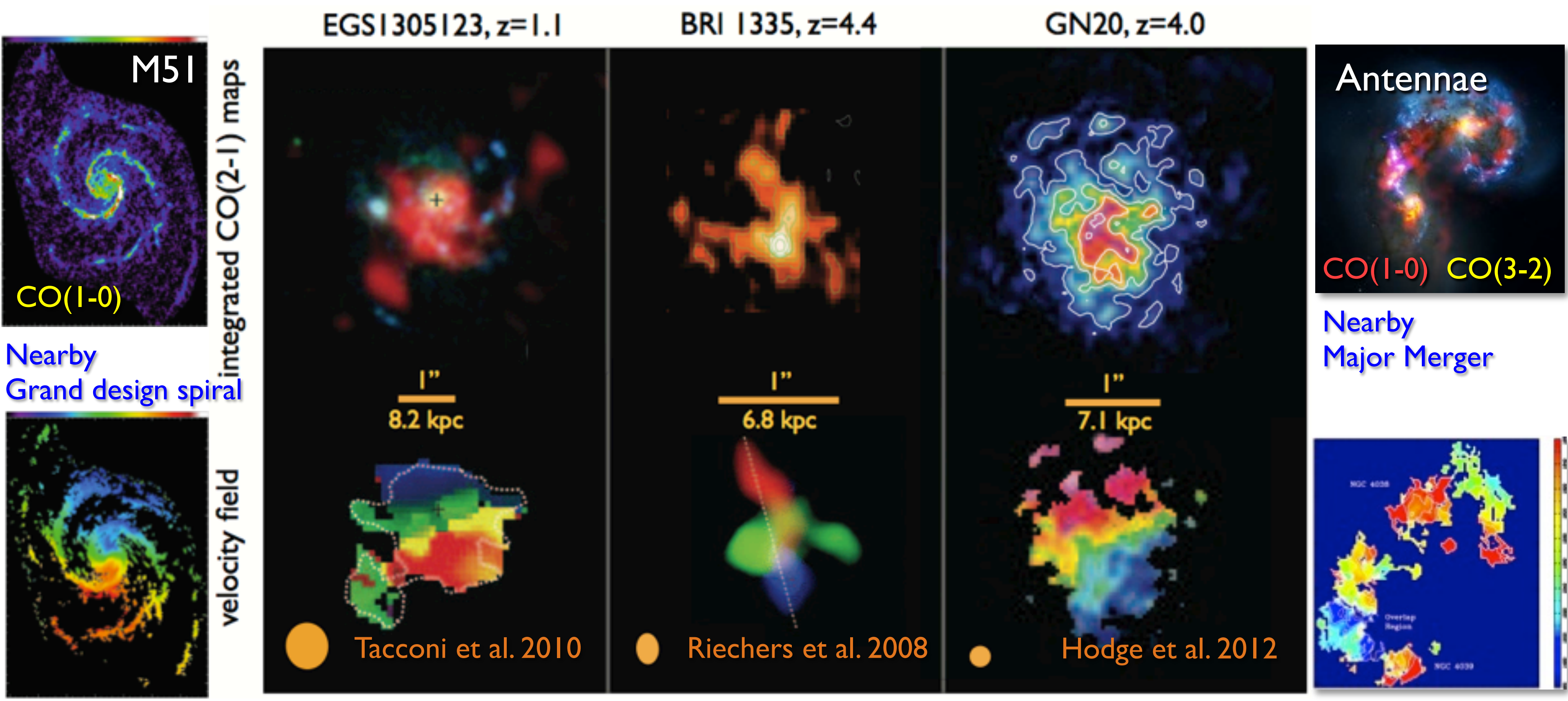
Drivers of Star Formation at High Redshift: Gas Dynamics

High-Resolution Molecular Line Spectroscopy w/ interferometers yields velocity fields

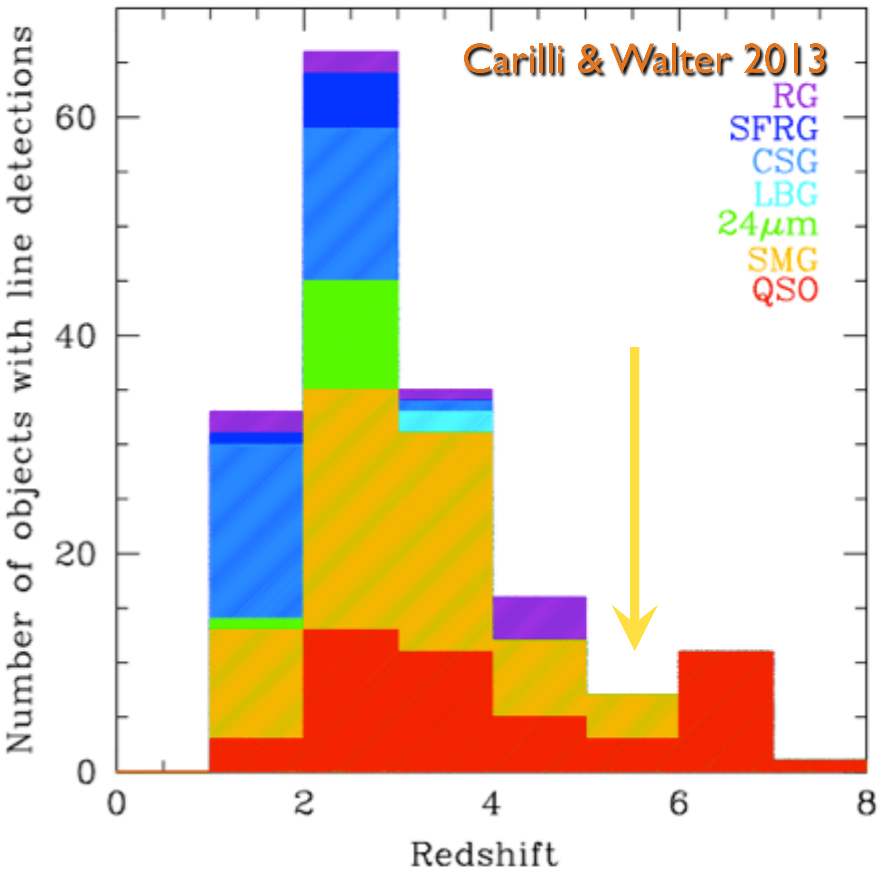
⇒ 3-dimensional structure of the galaxy

⇒ Gas dynamics: dynamical drivers of star formation (and black hole activity)

⇒ *Disk galaxies* vs. *major mergers*, *secular evolution* vs. *bursts* of star formation



Challenges and Future Perspectives: ALMA



Atacama Large (sub)Millimeter Array (ALMA)

66 antennas (7-12m) *4mm – 300μm*

Can detect massive starburst galaxies at z>5 today…why do we need ALMA?

⇒ Detailed morphologies, gas dynamics, gas excitation, chemical composition

⇒ Build statistically significant samples

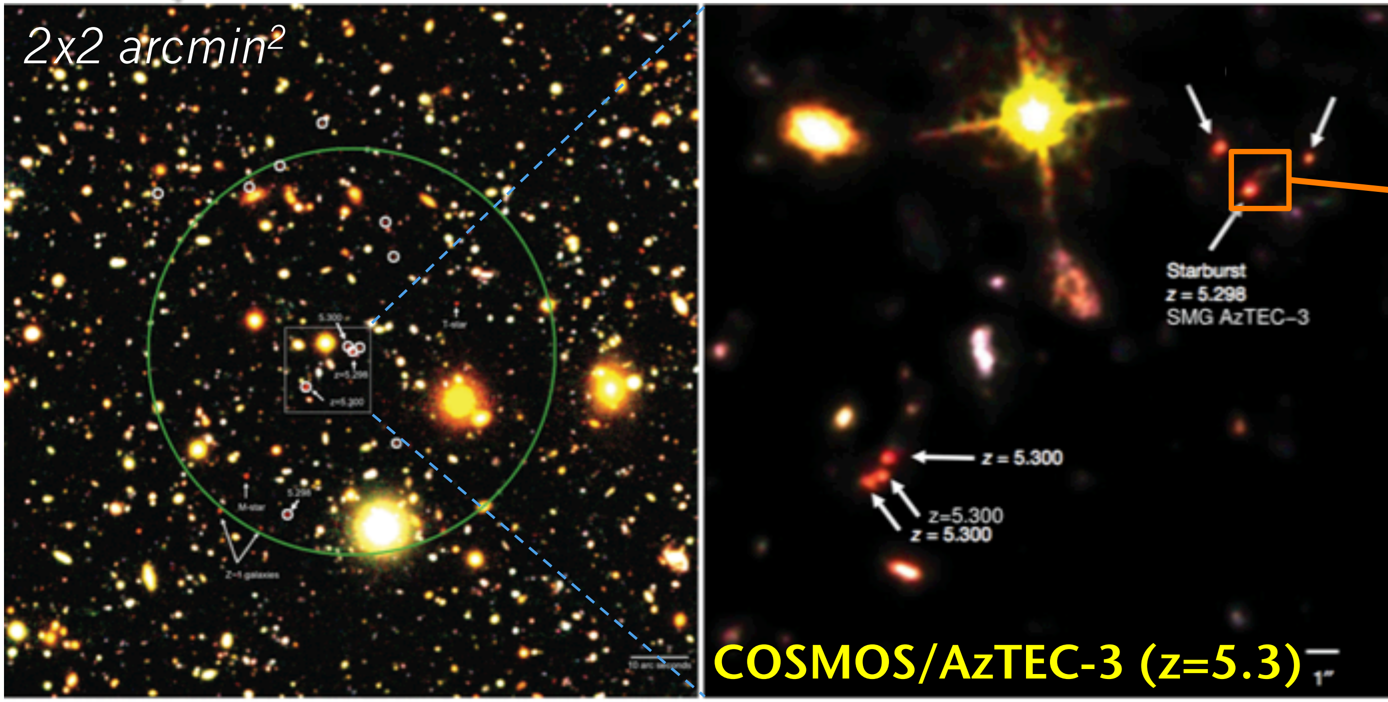
⇒ Study environments

⇒ Probe the faint end of the high-z galaxy luminosity function, e.g., in [CII]

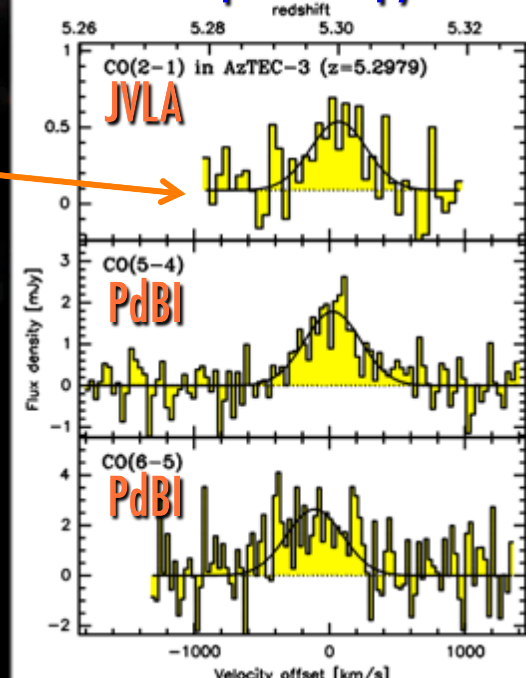
…let ALMA speak for itself

Environments of z>5 SMGs: Forming in the Most Distant Galaxy Protoclusters?

Galaxy Evolution vs. Environment



CO spectroscopy



(no radio detection)

- Most Distant *Massive Starburst Galaxy (SMG)* known (2010-2013):
  M_{H2} = 5.3 x 10^{10} M_{sun} SFR >1800 M_{sun}/yr

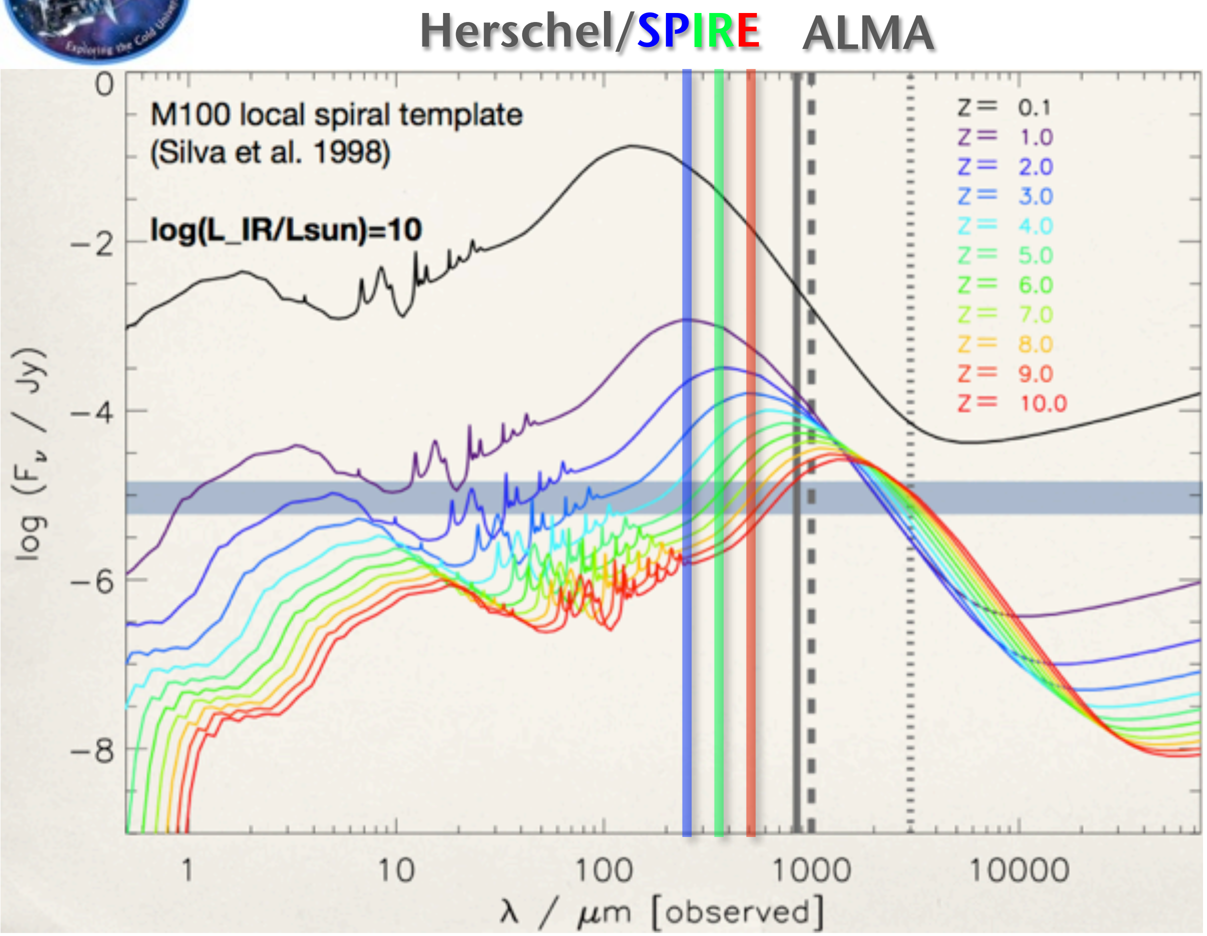
- Most Distant Galaxy *Proto-Cluster*:
  11 Lyman-break galaxy companions within r~2 Mpc, structure extends to >14 Mpc

+


+


Riechers, Capak et al. 2010, ApJ
Capak, Riechers et al. 2011, Nature

Detecting the Most Distant Massive Starburst Galaxies



- problem: z>4 dusty starburst galaxies very difficult to find (it took until 2009 to find the first z>4 SMG, detection was serendipitous)
- idea: z>4 galaxy SEDs peak beyond 500μm

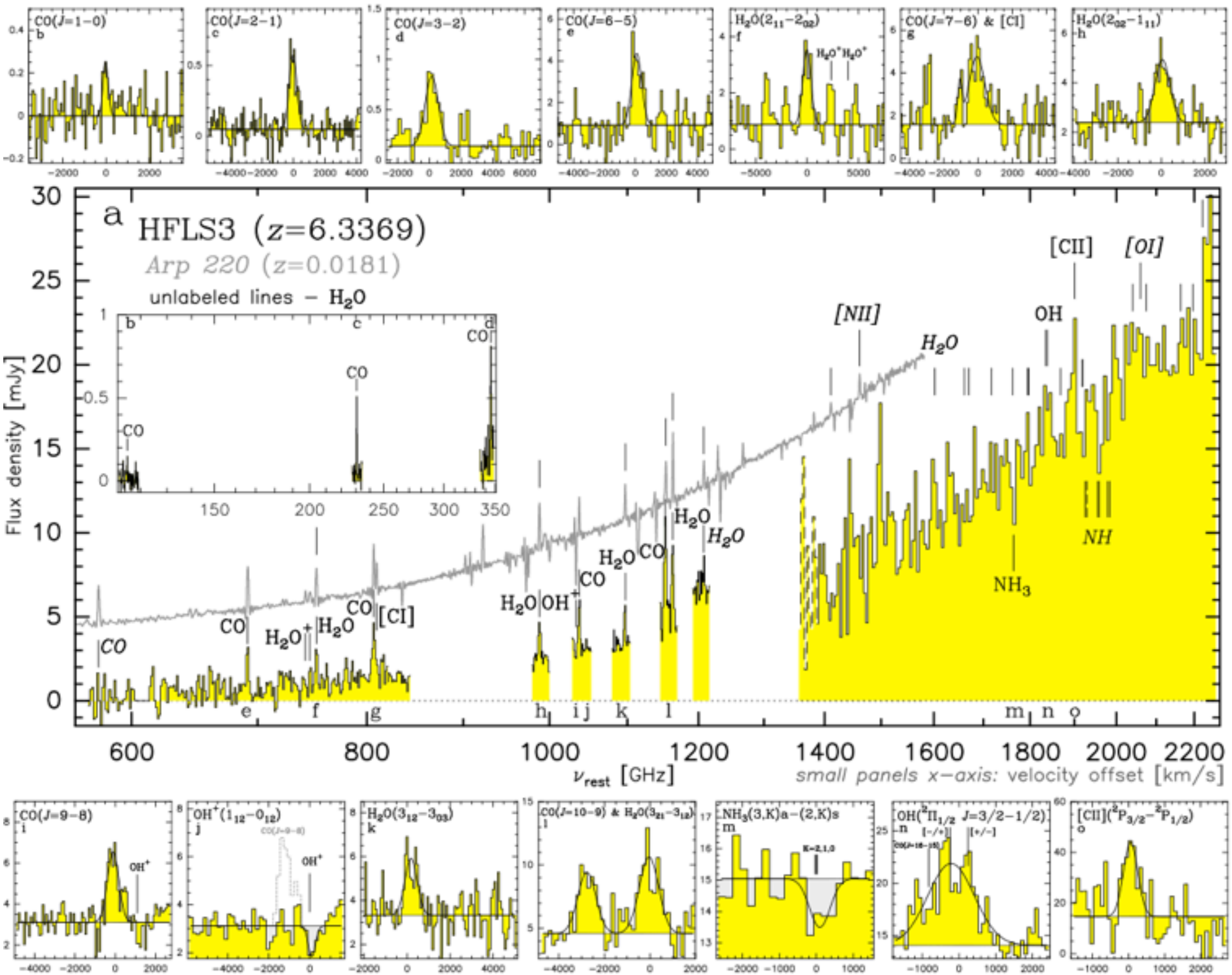
⇒ "red" in Herschel/SPIRE

⇒ can develop efficient technique to ID very high-z dusty starbursts

Herschel finds the "tip of the iceberg"
⇒ CCAT needed to probe more normal galaxies & to best match ALMA

But: *does it really work?*

HFLS3: The Most Distant Massive Starburst Galaxy



Follow up with all we have:

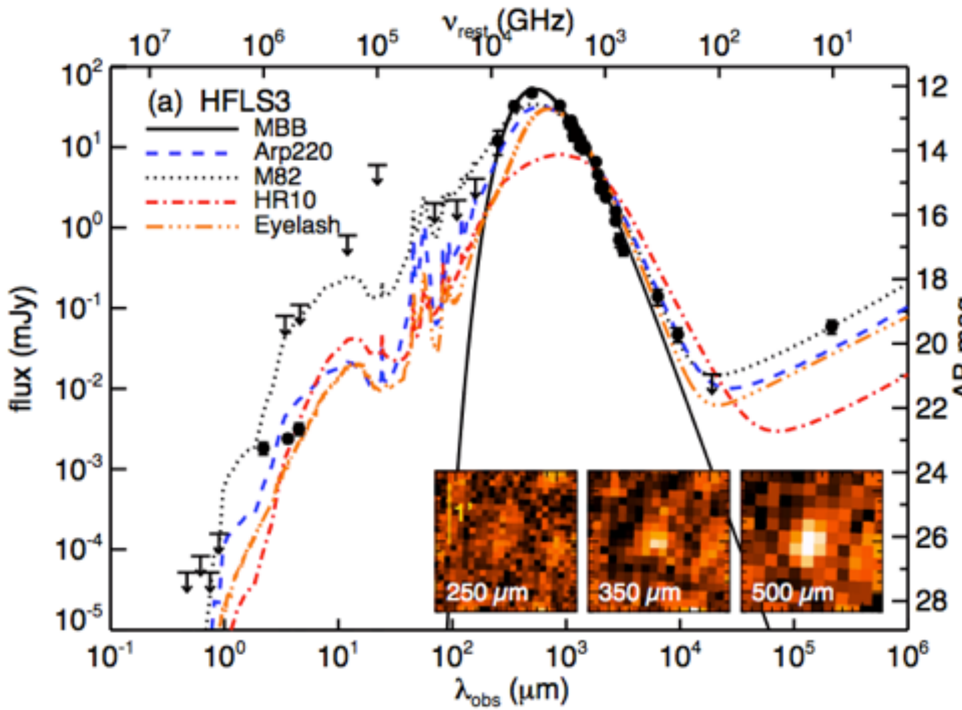
Galaxy confirmed … at z=6.3369 !!

Detect
7 CO lines
7 H_2O lines
H_2O^+
NH_3 (absorption)
OH
OH^+ (absorption)
[CI]
[CII]
Hints of others…
⇒ Highly enriched

Gray line is best existing spectrum of *nearby* starburst

Observed 880 million years after the Big Bang (current age: 13.8 billion yrs) Riechers et al. 2013b, Nature

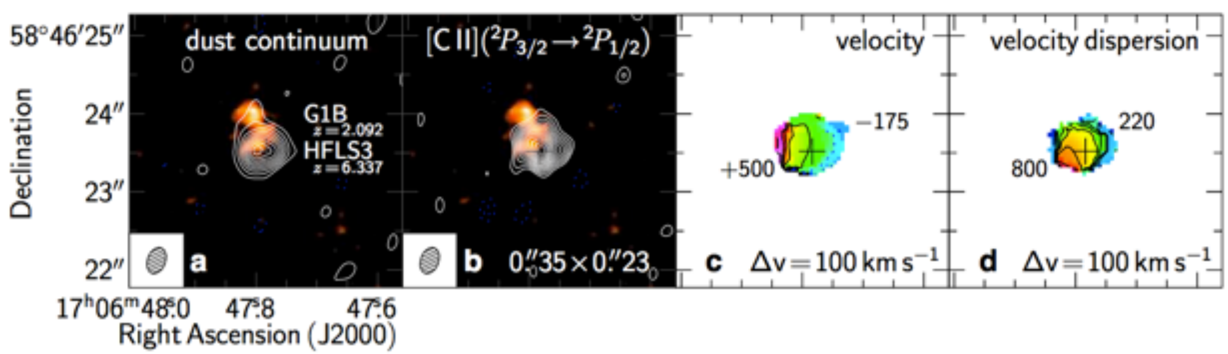
HFLS3: Warm, Dusty Starburst, not Luminous AGN



	HFLS 3	Arp 220*	Milky Way*
z	6.3369	0.0181	
M_{gas} (M_{sun})†	$(1.04 \pm 0.09) \times 10^{11}$	5.2×10^9	2.5×10^9
M_{dust} (M_{sun})‡	$1.31^{+0.32}_{-0.30} \times 109$	$\sim 1 \times 10^8$	$\sim 6 \times 10^7$
M_* (M_{sun})§	$\sim 3.7 \times 10^{10}$	$\sim (3\text{–}5) \times 10^{10}$	$\sim 6.4 \times 10^{10}$
M_{dyn} (M_{sun}) ‖	2.7×10^{11}	3.45×10^{10}	2×10^{11} (<20 kpc)
f_{gas} (%)¶	40	15	1.2
L_{FIR} (L_{sun})#	$2.86^{+0.32}_{-0.31} \times 10^{13}$	1.8×10^{12}	1.1×10^{10}
SFR (M_{sun} yr^{-1})☆	2,900	~180	1.3
T_{dust} (K)**	$55.9^{+9.3}_{-12.0}$	66	~19

Almost as many stars as the Milky Way
Similar total mass, already at z=6.34
40x more gas
2000x more star formation
…and ~20x more star formation than extreme nearby starburst

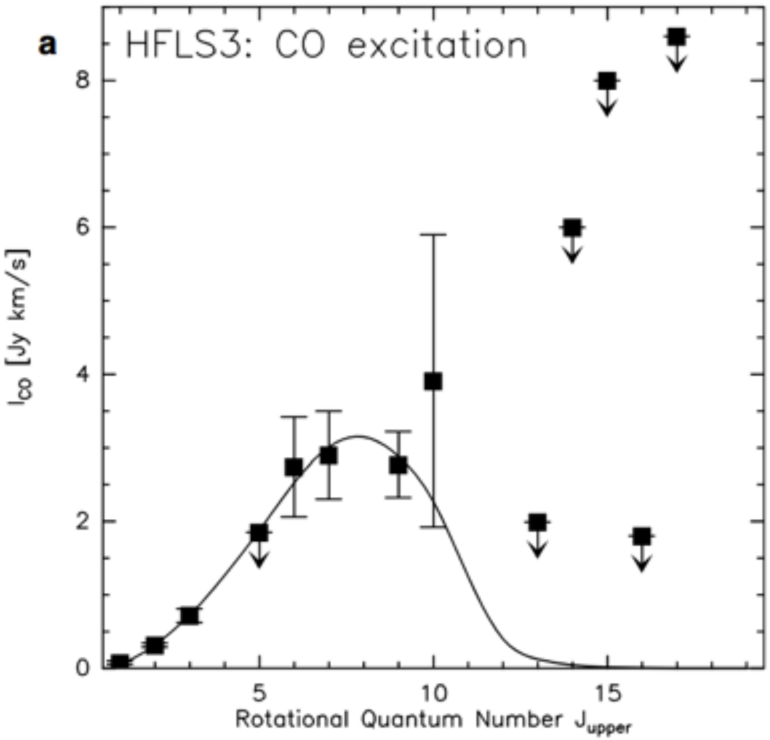
…consistent with a so-called "maximum starburst" galaxy



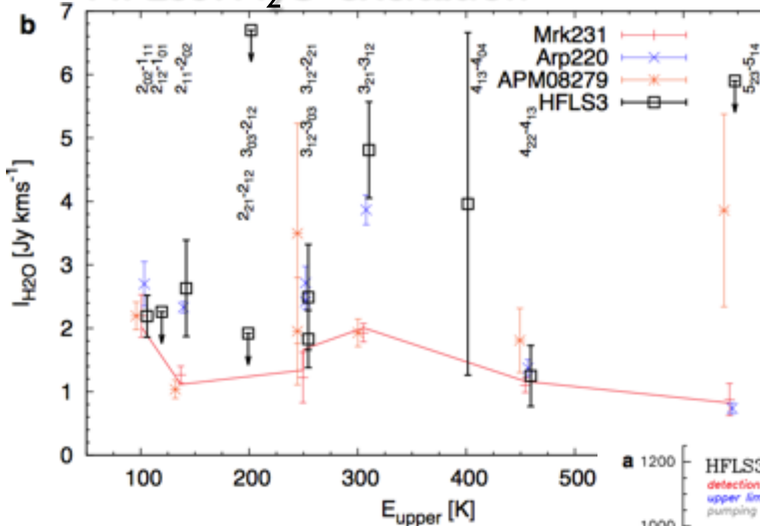
Also: a compact (~3.5kpc), high velocity dispersion gas reservoir
⇒ High star formation rate likely driven by a major merger
⇒ An extraordinary starburst, even compared to others at high z

Riechers et al. 2013b

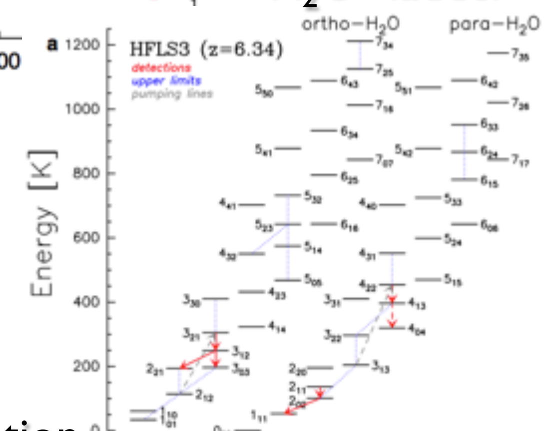
HFLS3: Molecular Gas Excitation



HFLS3: H_2O excitation



H_2O "ladder"



CO: Dense, warm, highly excited interstellar medium

Extreme integrated properties, but physical conditions for star formation similar to nearby starbursts/major mergers (just more gas-rich and larger)

H_2O: Lines too bright to be excited by collisions, must be excited by radiation field

Radiation field appears also similar as in nearby starbursts

Riechers et al. 2013b

HFLS3: Rare Monster or New Window to Galaxy Evolution?

Deepest Herschel/SPIRE surveys (i.e., $rms_{detector} < rms_{confusion}$):
~100 deg^2 out of ~1000 deg^2 surveyed (HerMES, HeLMS, HeRS, H-ATLAS)

Model-predicted space density:
one per ~70 deg^2 down to $S_{500\mu m}$= 30mJy (Herschel's limit)

⇒ Rare, unlikely to have many massive enough halos at z>6

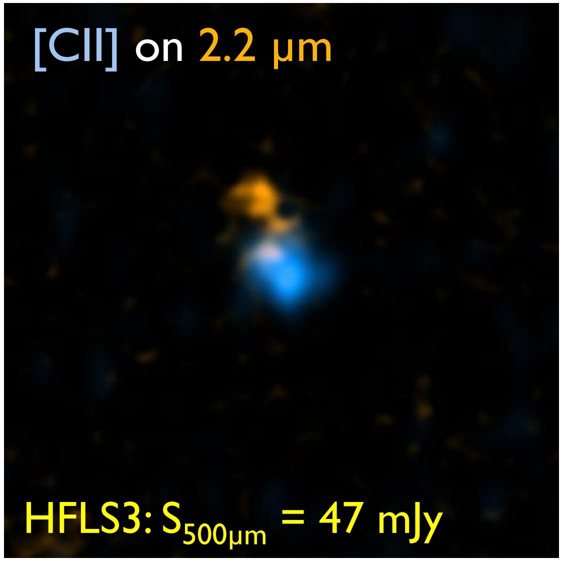
⇒ If we confirm more of the candidates, it will impact models of early structure formation

But: we may not confirm more…need to push below Herschel's confusion limit

(1) Find (extremely rare) strongly lensed versions
low probability, also challenging to interpret environments

(2) A bigger "survey" telescope operating at 200-500μm…

⇒ CCAT



Summary

- ISM studies at high redshift
  - revealed large samples of diverse populations in the past 20 years
  - are almost exclusively based on CO and [CII], need ALMA for more
- high-redshift star-forming galaxies
  - form up to 10-30x more stars than their local counterparts
  - these higher SFRs are driven by high gas fractions
  - like locally the most extreme starbursts are dusty, major mergers, but also "scaled up" by an order of magnitude or more in gas content/SFR
- massive starburst galaxies at very high redshift
  - are massive, metal-enriched galaxies, likely growing in the most massive dark matter halos at early cosmic times
  - we are starting to find a population of very luminous z>5-6 SMGs, brighter than the bulk of the z=2-3 population, in clustered environs

Radio/(sub)mm interferometry critical to unveil their properties

⇒ JVLA+ALMA will be a powerful duo to disentangle this population

Herschel offers key insight but is limited by source confusion => CCAT