

# RESOLVED CO AND RADIO (1.4GHz) IN HIGH-Z SUBMILLIMETRE GALAXIES (SMGs)

(+ ADVERTISING C.CASEY'S POSTER  
"Z=2 HOT-DUST ULIRGS")

Scott C. Chapman (Cambridge, Institute of Astronomy)  
Caitlin Casey (PhD student, IoA)  
Matt Bothwell (PhD student, IoA)  
Linda Tacconi (MPE)  
+ SMG/SFRG CO collaboration

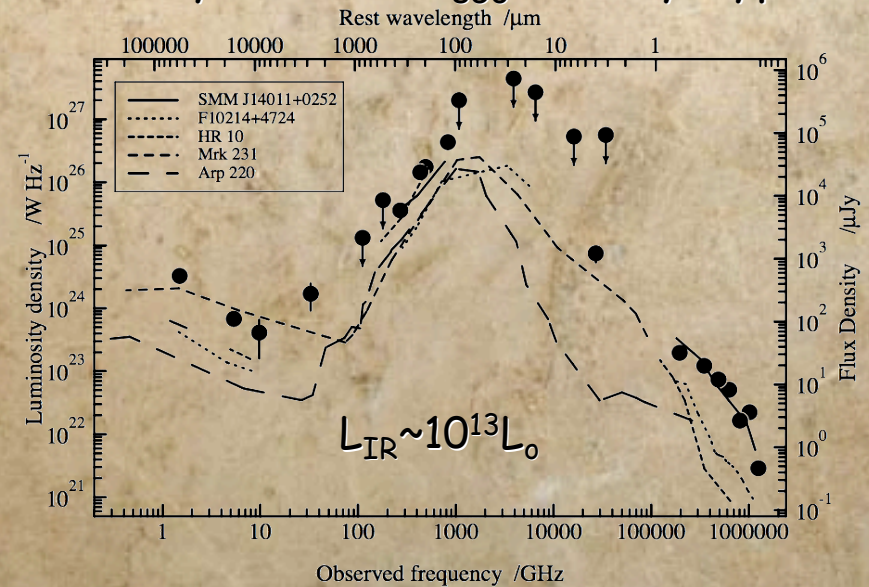


# HIGH-Z FIR-LUMINOUS GALAXIES

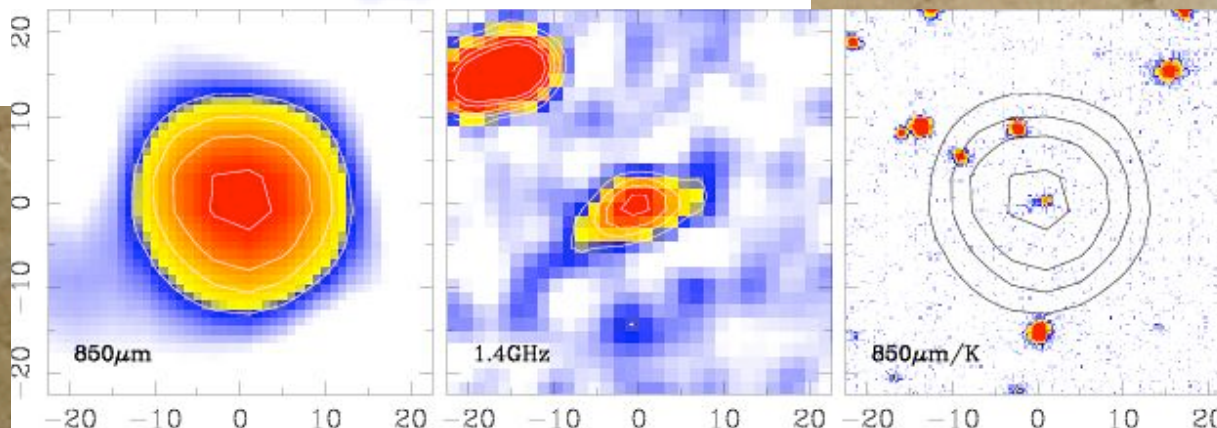
A370  $z=0.37$



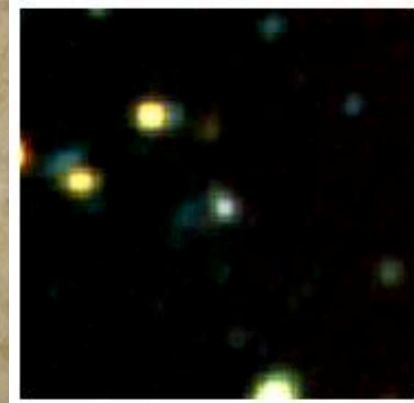
• SMMJ02399-0136 L1/L2  $z=2.80$   
 25.4mJy  $A=2.4\times$ :  $S_{850}\sim 10\text{mJy}$  Type2 AGN



Smail, Ivison & Blain 1997



Ivison et al. 1998





# OBSCURED STAR FORMATION AT HIGH-Z

## WHAT DO WE KNOW, WHAT DO WE NOT KNOW?

1. Are current sub/mm surveys representative?
2. Is the current  $N(z)$  of SMGs representative?
3. Do we have a complete FIR census at  $z > 1$ ?
4. How much SF is dust-obscured at  $z > 1$ ?

What are sub/mm galaxies (SMGs?)

5. Are SMGs SF-powered? Outflows?
6. Are SMGs clustered?
7. Are SMGs massive? Metal-rich?
8. Are SMGs predicted by theoretical models?



# OBSCURED STAR FORMATION AT HIGH-Z

## WHAT DO WE KNOW, WHAT DO WE NOT KNOW?

1. Are current sub/mm surveys representative? Maybe
2. Is the current  $N(z)$  of SMGs representative? Maybe
3. Do we have a complete FIR census at  $z > 1$ ? No
4. How much SF is dust-obscured at  $z > 1$ ? A lot

What are sub/mm galaxies (SMGs?)

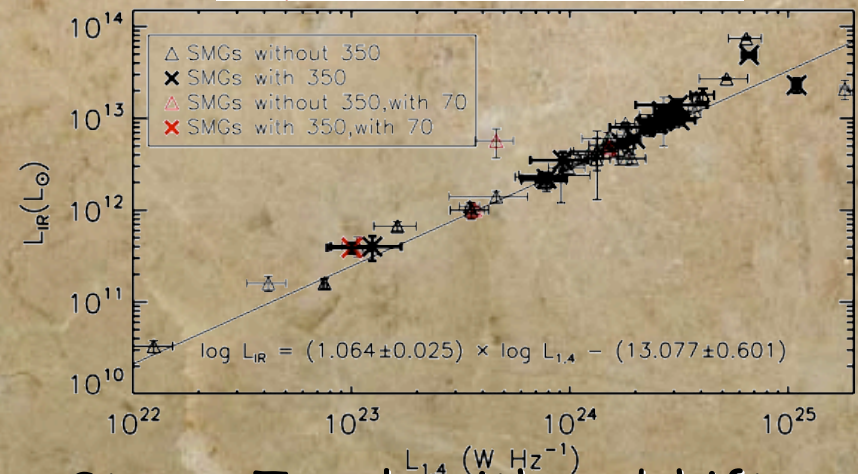
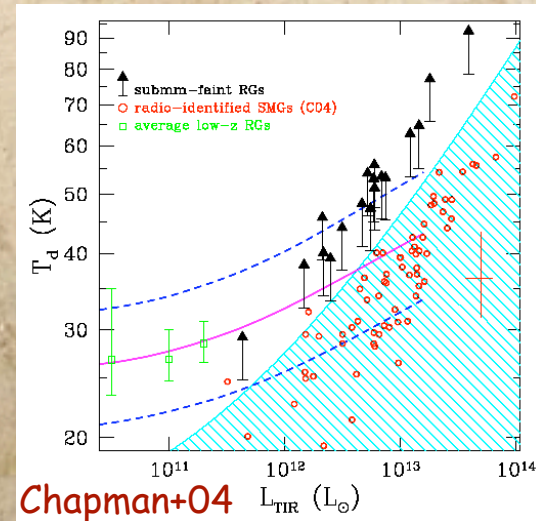
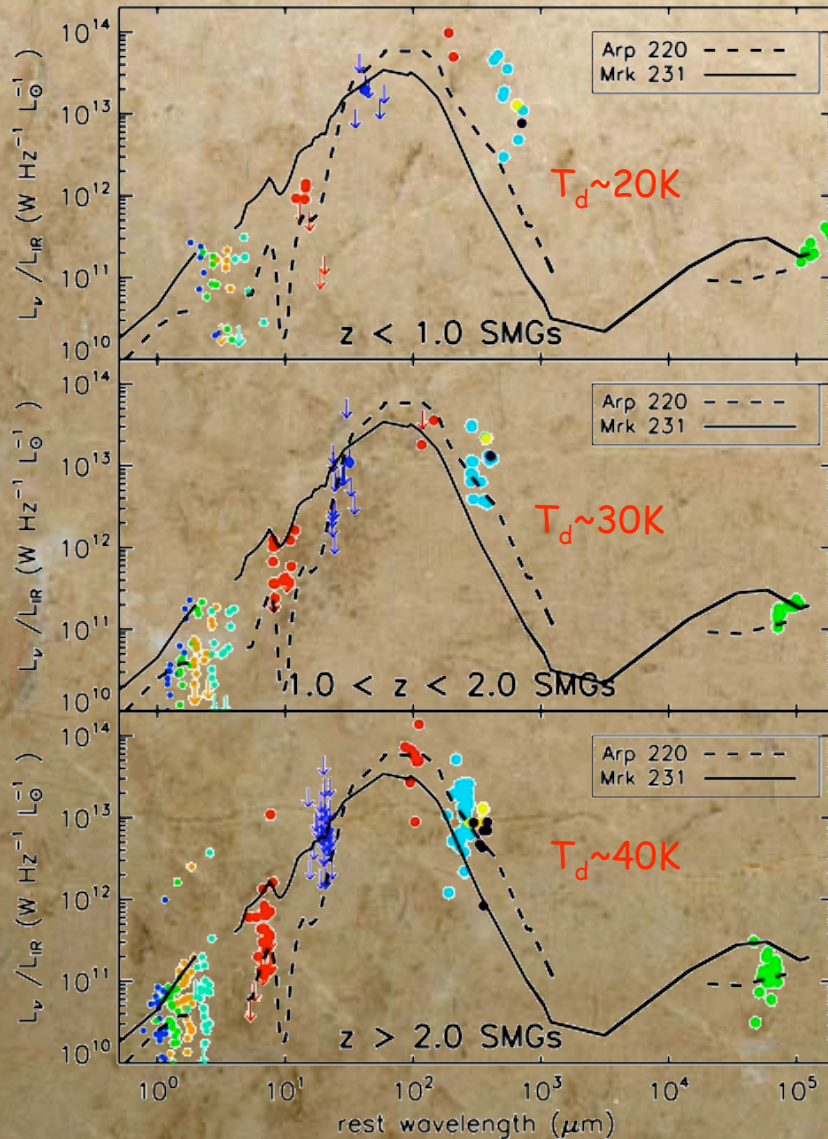
5. Are SMGs SF-powered? Probably
6. Are SMGs clustered? Maybe
7. Are SMGs massive? Maybe
8. Are SMGs predicted by theoretical models? Maybe

How are we going to make progress?



# DO WE HAVE A COMPLETE FIR CENSUS AT $z > 1$ ?

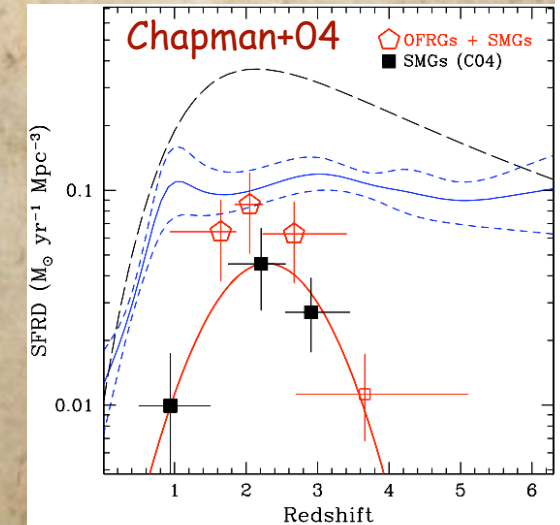
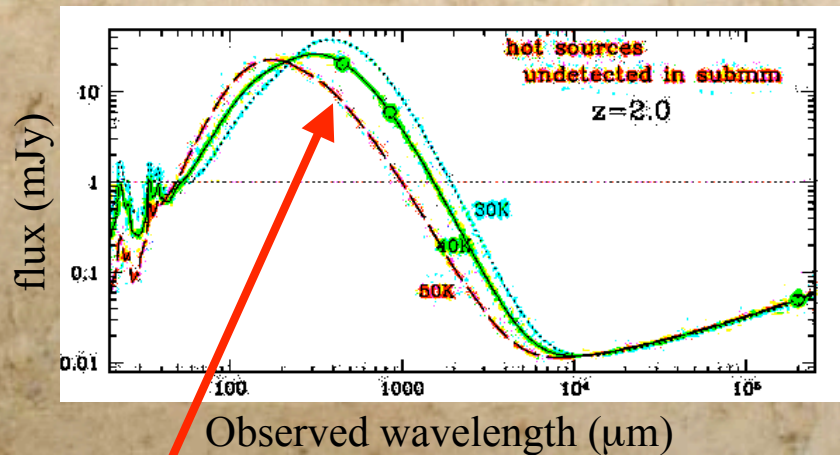
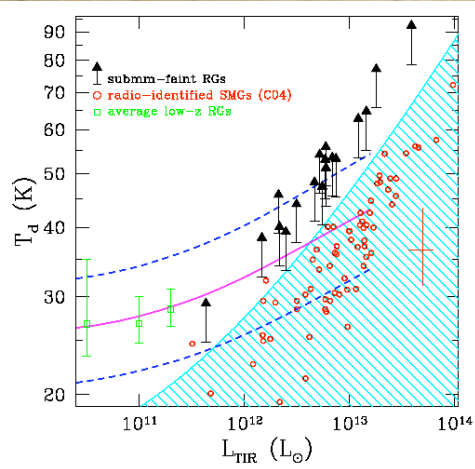
Hainline et al. 2009



- Strong  $T_d$  seln with redshift
- Significant scatter in SED shape
- FIR-radio shows little  $z$ -evolvn



# SUBMM-FAINT RADIO GALAXIES + SFRGs HYPOTHESIZED AS HIGHER $T_{\text{DUST}}$ SMGs



## *SFRGs as Hotter Dust cousins to SMGs*

Motivation: Blain1999, Eales+2000 Blain+04, Chapman+04, Hainline+2009

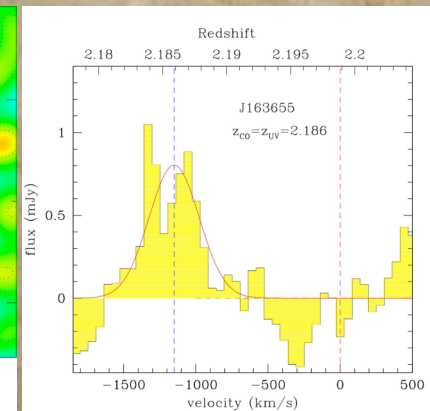
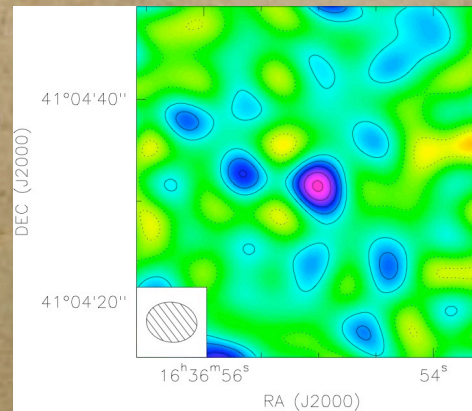
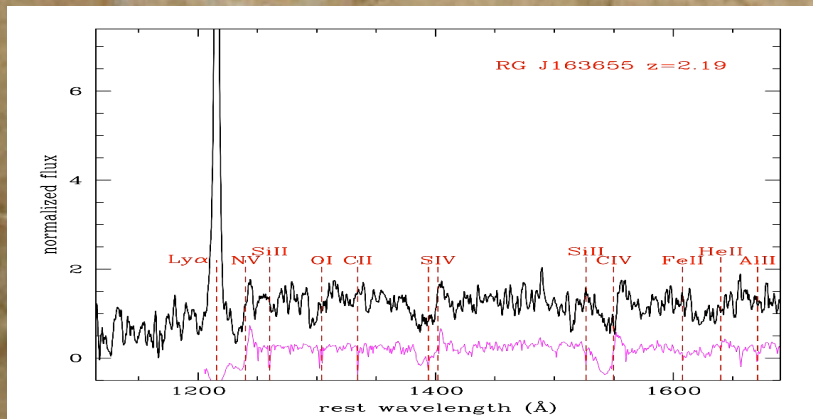
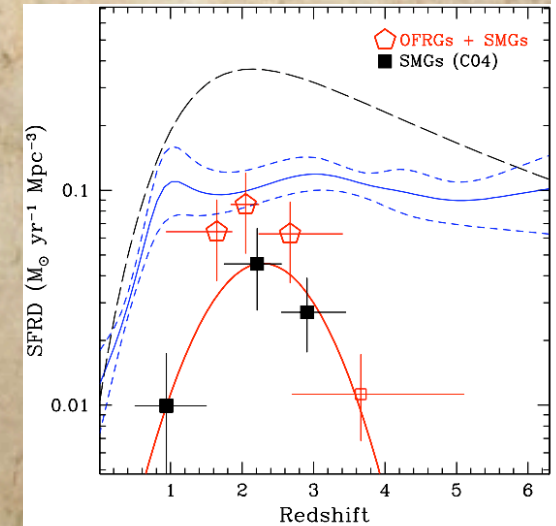
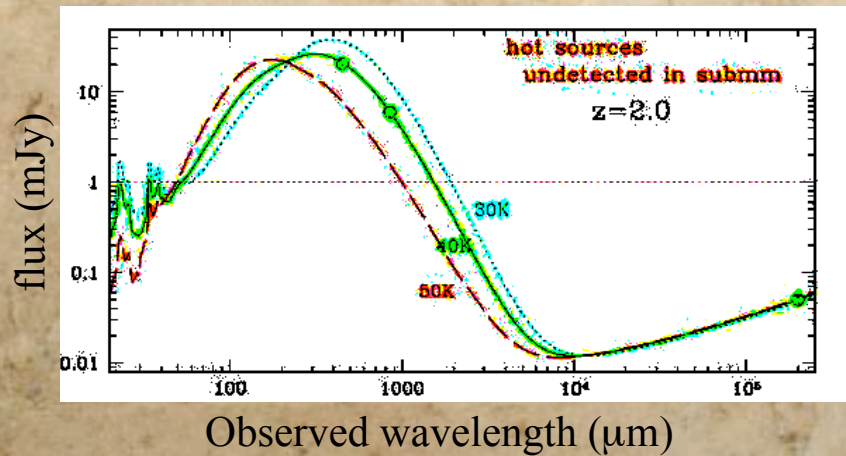
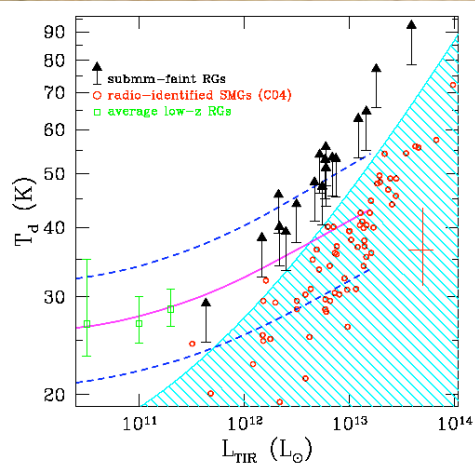
We miss the hotter ULIRGs in Submm ...

can we find them from submm-undetected radio?

Chapman et al. 2004 : UV spectra of 36 SFRGs showing mostly starburst features



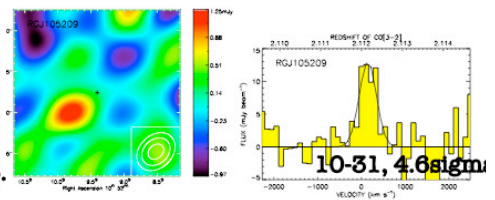
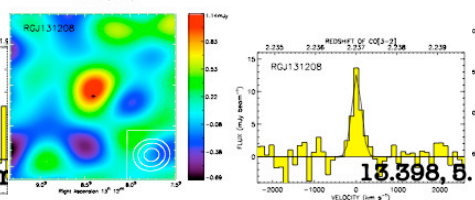
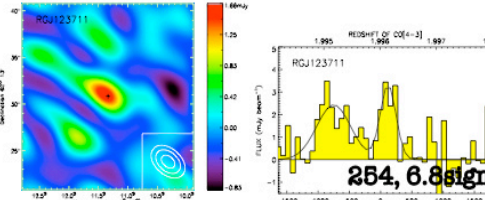
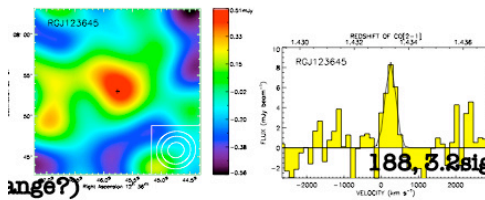
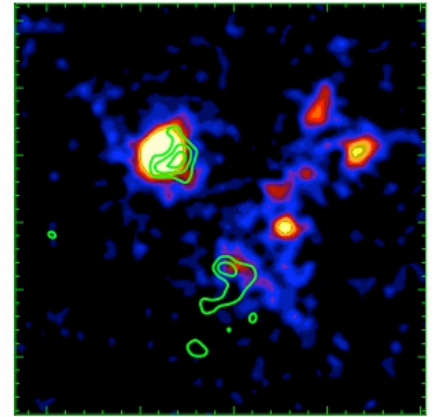
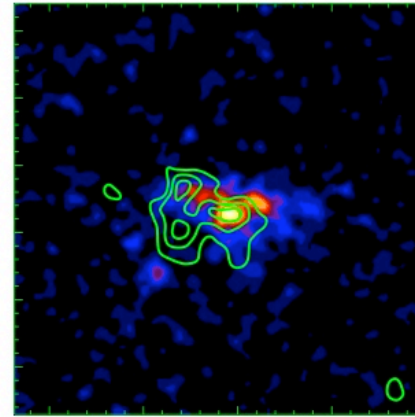
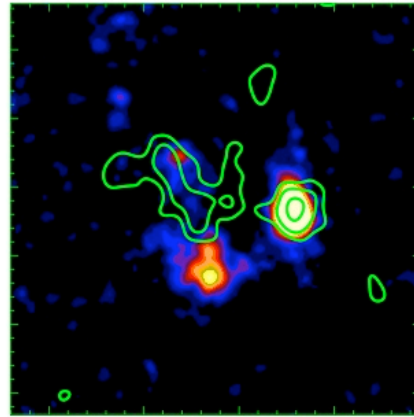
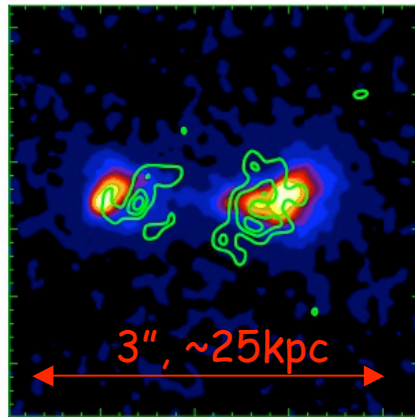
# SFRGs HYPOTHESIZED AS HIGHER $T_{\text{DUST}}$ SMGs



Chapman et al. 2004 : UV spectra of 36 SFRGs showing mostly starburst features  
 Chapman et al. 2008 : pilot CO gas study of 2 detected SFRGs

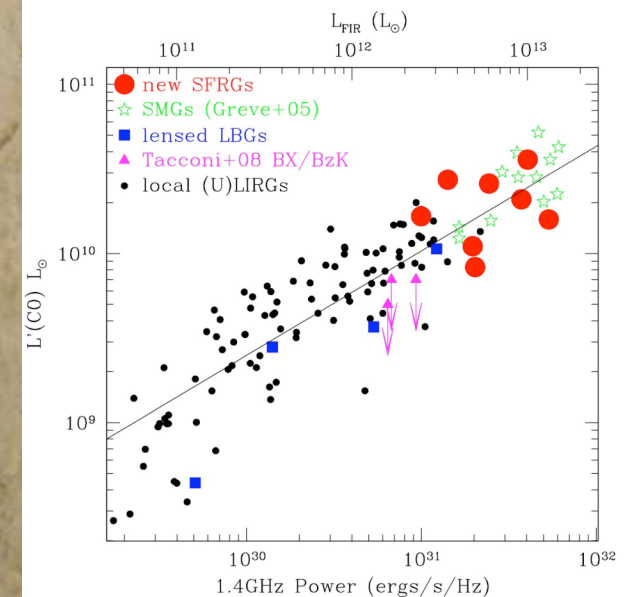


# SFRGs “CONFIRMED” AS HIGHER $T_{\text{DUST}}$ SMGS



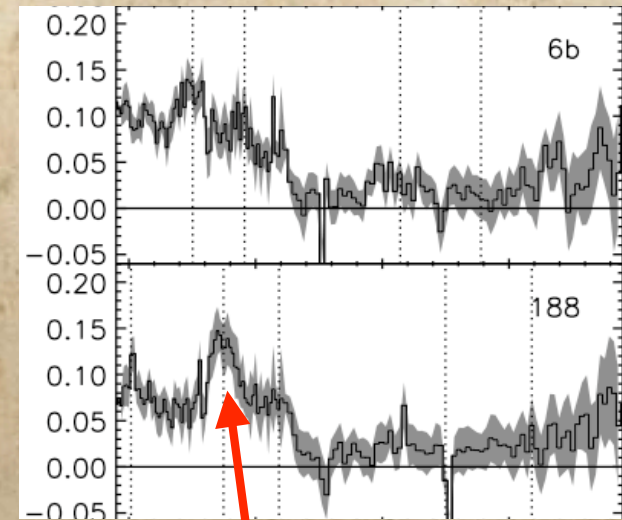
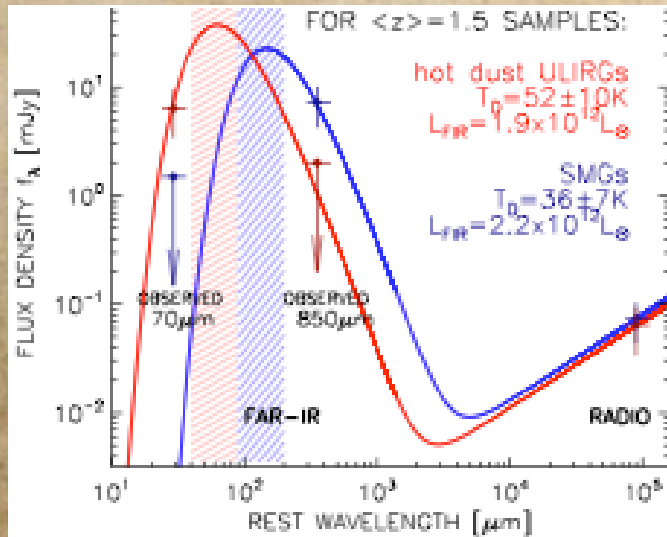
Casey et al. 2009a,b :

- 8/11 show CO detections;
- similar SF efficiency to SMGs
- Sample of 25 with resolved MERLIN radio





# SFRGs “CONFIRMED” AS HIGHER $T_{\text{DUST}}$ SMGS



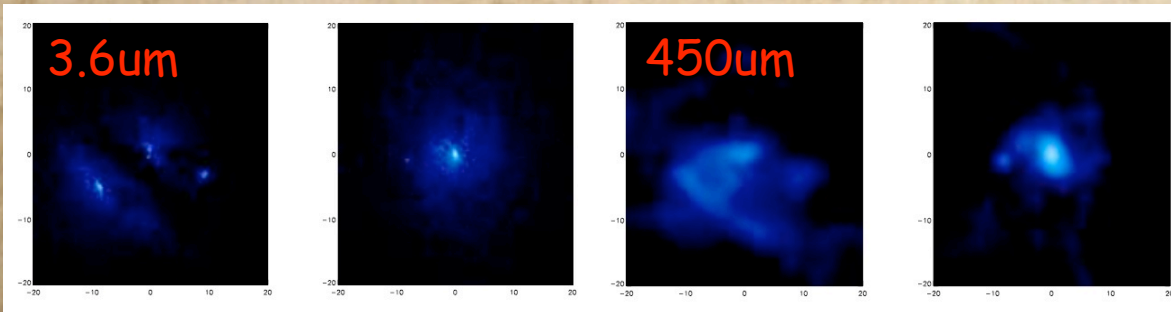
Casey et al. 2009c,d,e :

- 70um detected subset: hot  $T_d$ 's
- Spitzer IRS spectra for 17: many with strong PAHs
- Catalog of ~100 spectroscopically ID'd SFRGs  
... clustering, selection function, stellar masses,  
24um properties, luminosity function, comparison to theory

A sample to study with Herschel



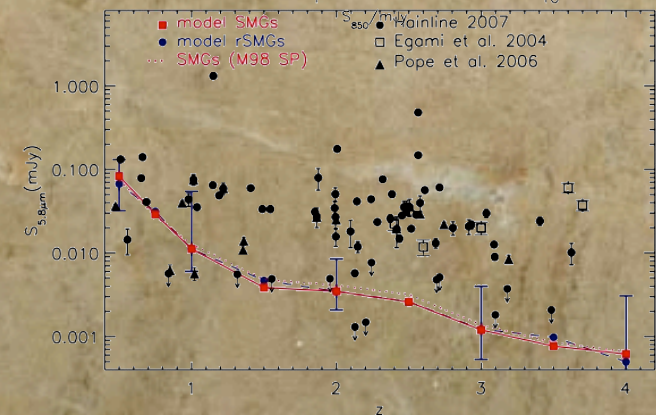
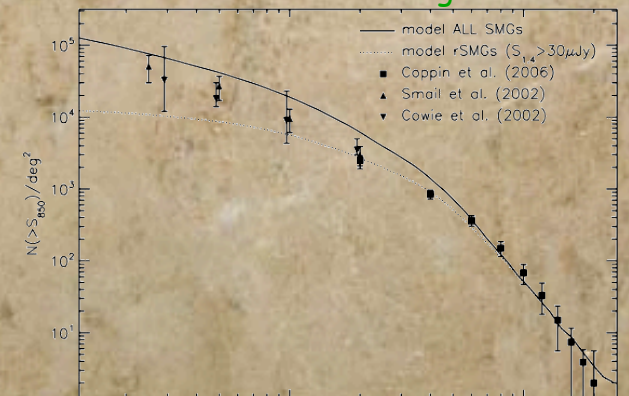
# THEORY



Chakrabarti+2007, Narayanan+2008,2009 (Harvard group)

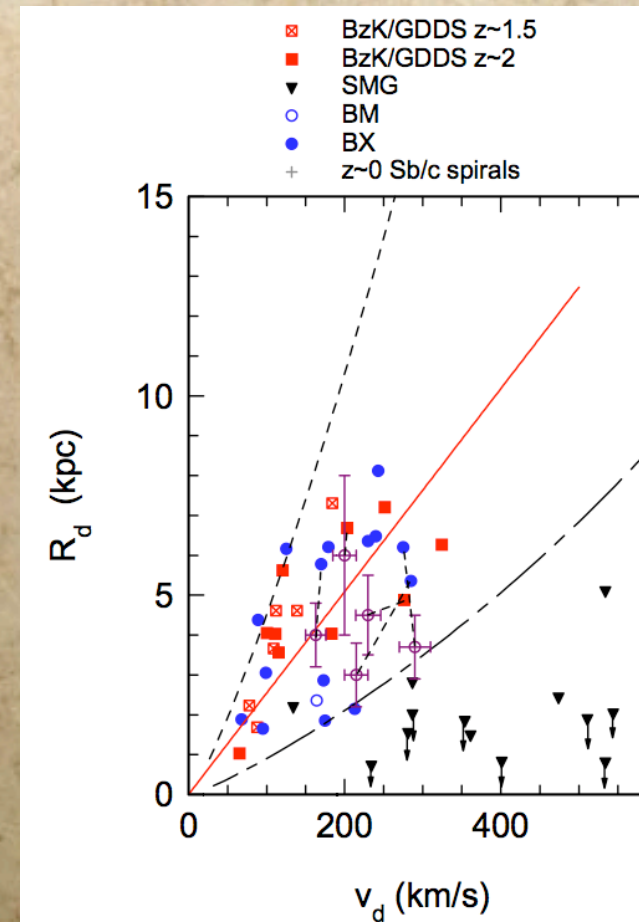
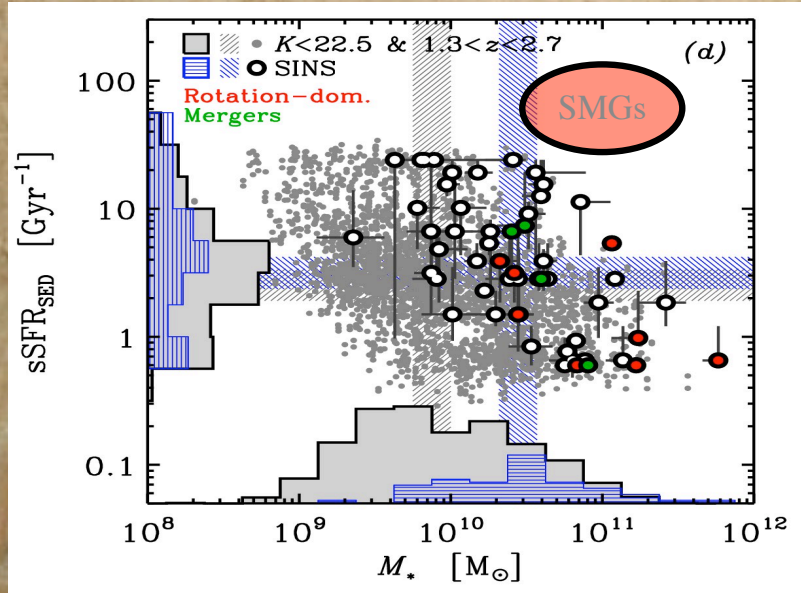
- Telling us they can model SMGs using numerical and semi-analytic models
  - Numerics limited by inability to match statistical measures of the population
  - Semi-analytics lack detailed physics
- SAMs require variation in IMF (top-heavy)
  - fails on stellar luminosities in NIR/MIR
- Hydro models (R. Dave et al. 2009) suggest most SMGs are not Major mergers
- Dekel+2009: cold flow major/minor mergers

Swinbank et al. 2008/Baugh et al. 2005





# STAR FORMATION IN SMGS VERSUS UV/OPTICAL-GALAXIES

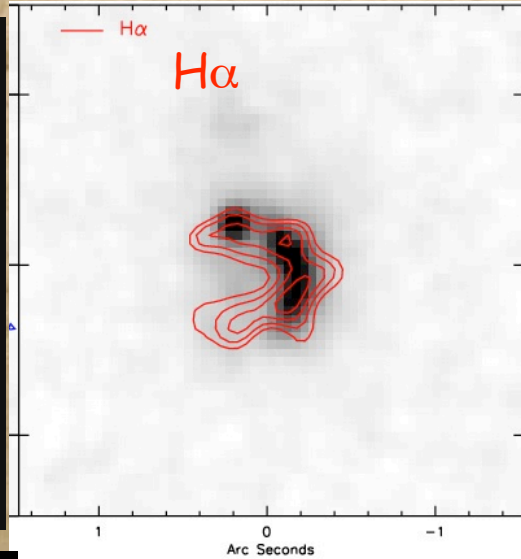
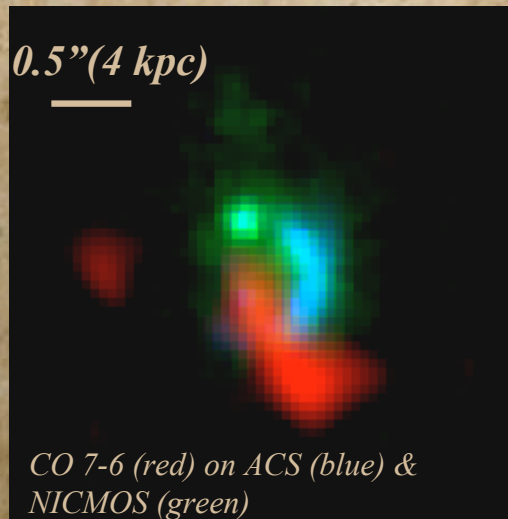


- SMGs seem to be (very?) different from UV/optical selected galaxies
- Merger dominated SMGs versus secular buildup of less luminous galaxies? (Forster-Schreiber et al. 2009, Daddi et al. 2009, Bouche et al. 2007)



# EXTENDED STAR FORMATION

Swinbank et al. 2005/Tacconi et al. 2008



Extended narrow (nebular) emission lines (H $\alpha$ , OIII)

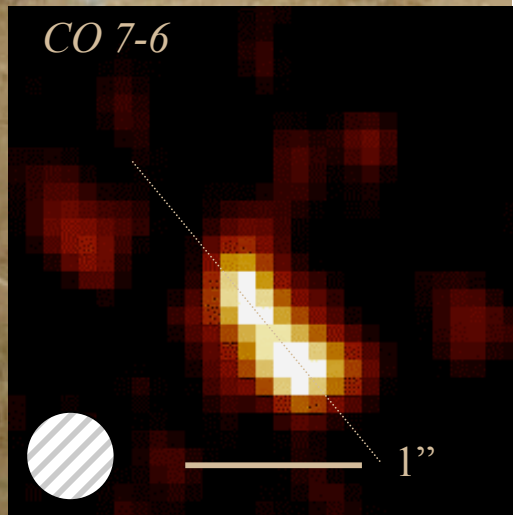
Swinbank et al. 2005, 2006

Delmestre-Menendez et al. 2009

Extended CO(7-6)

0.6" FWHM  $\sim$  5kpc

Tacconi et al. 2008



## • 6 PIECES OF EVIDENCE

suggest SMGs have SF over several kpc

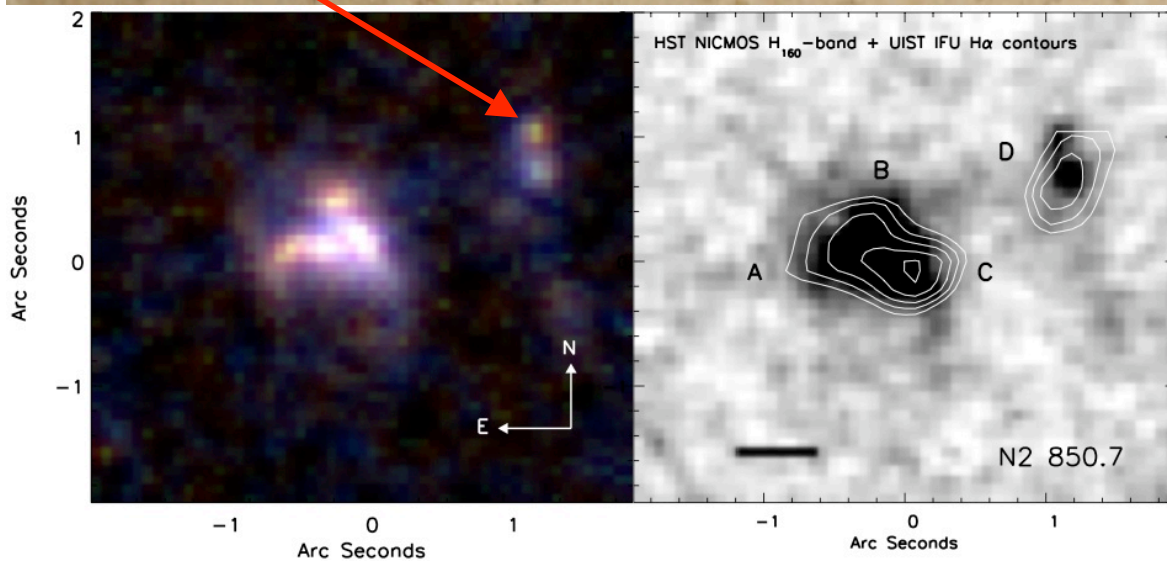
• SFR surface densities typically like local StarBursts?



# H $\alpha$ IFU FOR SMGs

(Swinbank, Chapman, et al. 2006)

L(850 $\mu$ m, via 1.4GHz)



CLEARLY H $\alpha$  OFTEN NOT  
ADEQUATE SFR PROBE  
FOR SMGS ...

DOES H $\alpha$  PROBES THE  
BOLOMETRIC ENERGY?

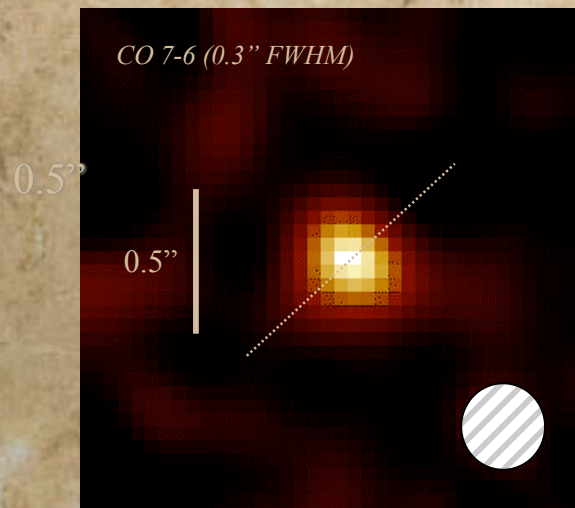
>> 100X EXTINCTION  
FACTOR:  $L_{\text{IR}}/L_{\text{UV}}$   
SFR  $\sim 1000 M_{\text{SUN}}/\text{YR}$

NEED MOLECULAR GAS:  
ROTATIONAL CO TRANSITIONS  
...



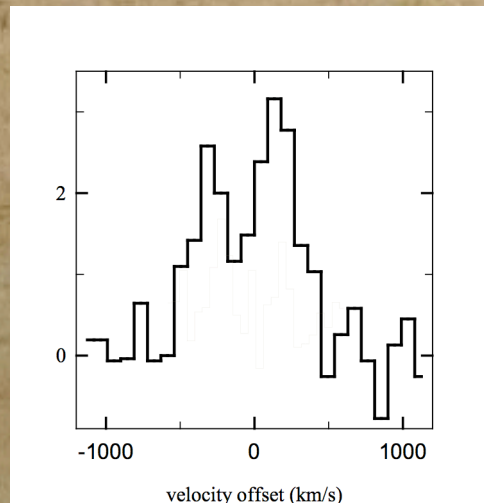
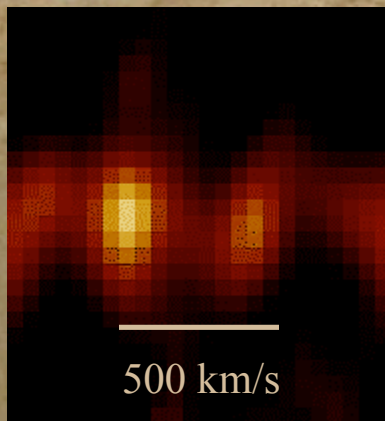
# TACCONI ET AL. 2006, 2008

## HIRES CO OF 8 SMGS



- BUT 3 WITH GOOD SIZE CONSTRAINTS ( $<0.5''$  BEAM)
- 2 ARE COMPACT/UNRESOLVED AT  $\sim 2$  KPC FWHM.

**AND ALL 3 IN CO(7-6)**



### Summary

N2.4: 0.6'' FWHM (major axis)

H76: 0.3''  $\sim$ unresolved

N2.2: 0.25'' FWHM

Other 5 SMGs  $< \sim 1''$  8kpc

*IRAM Plateau de Bure  
resolution = 0.3'' FWHM*

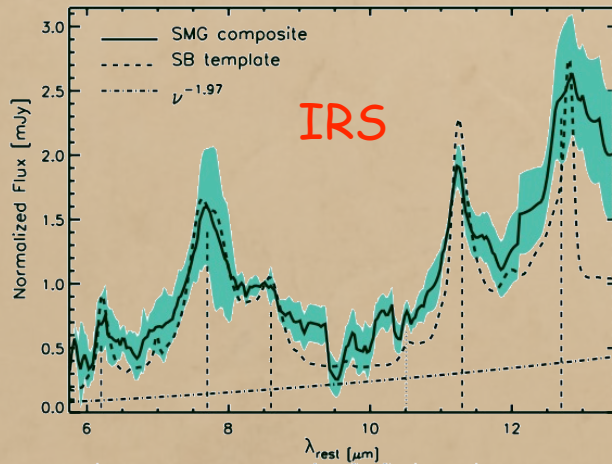
*CO Size  $\sim 0.25''$  FWHM (1.6 kpc)  
Tacconi et al. 2008*



# EXTENDED STAR FORMATION - 2 (INDIRECT) PIECES OF EVIDENCE

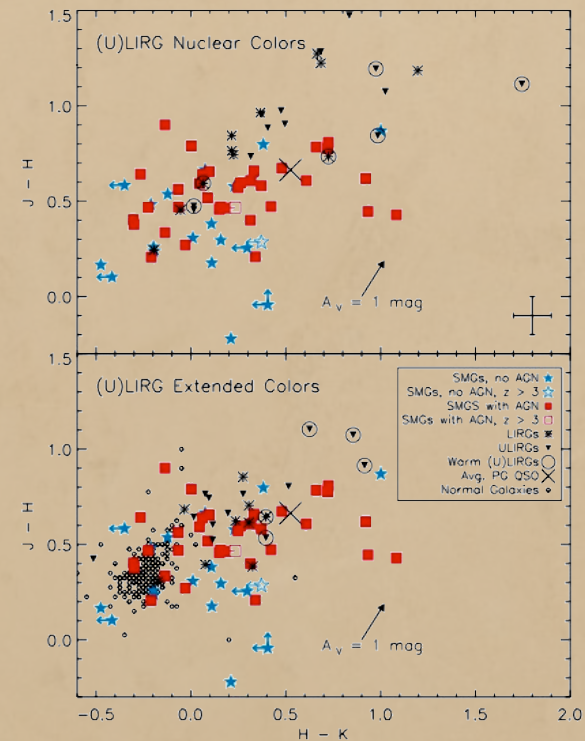
Hainline et al. 2009

Delmestre-Menendez et al. 2009



- IRS spectroscopy shows low 7.7/6.2 $\mu\text{m}$  PAH (also weak Silicate absorption feature)
  - $\Rightarrow$  lower extinction towards midIR line/ctm regions in SMGs, compared to local nuclear starbursts or ULIRGs
- SFR surface densities typically like local StarBursts

IRAC

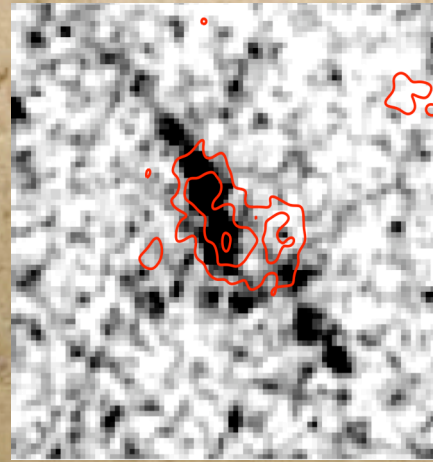
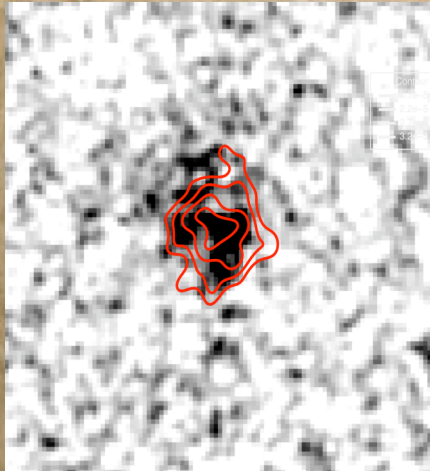


- Rest near-IR colours are more similar to **extended regions** of local ULIRGs than **nuclear cores**.
- Suggests less obscured SF, and therefore more extended.

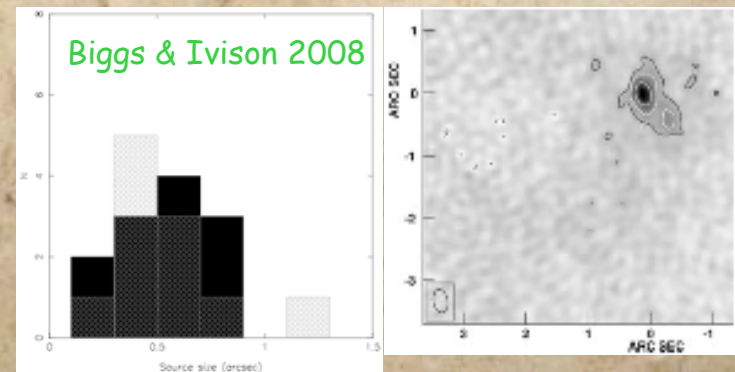


# EXTENDED STAR FORMATION

Chapman+2004

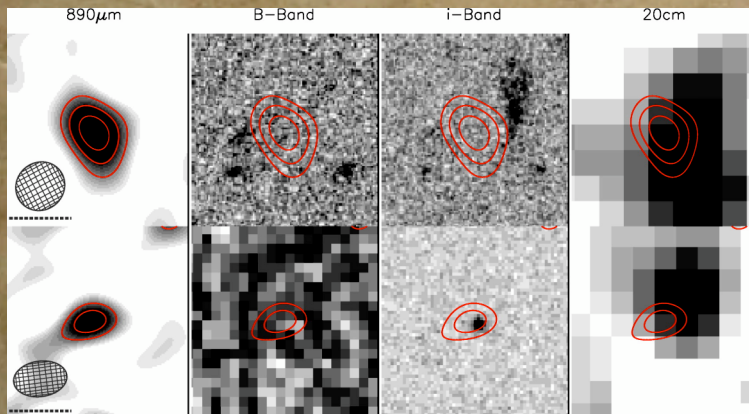


0.3'' MERLIN Radio



QUESTION: Is radio-farIR reliable?

Submm



Tacconi et al. 2006, Younger et al. 2008

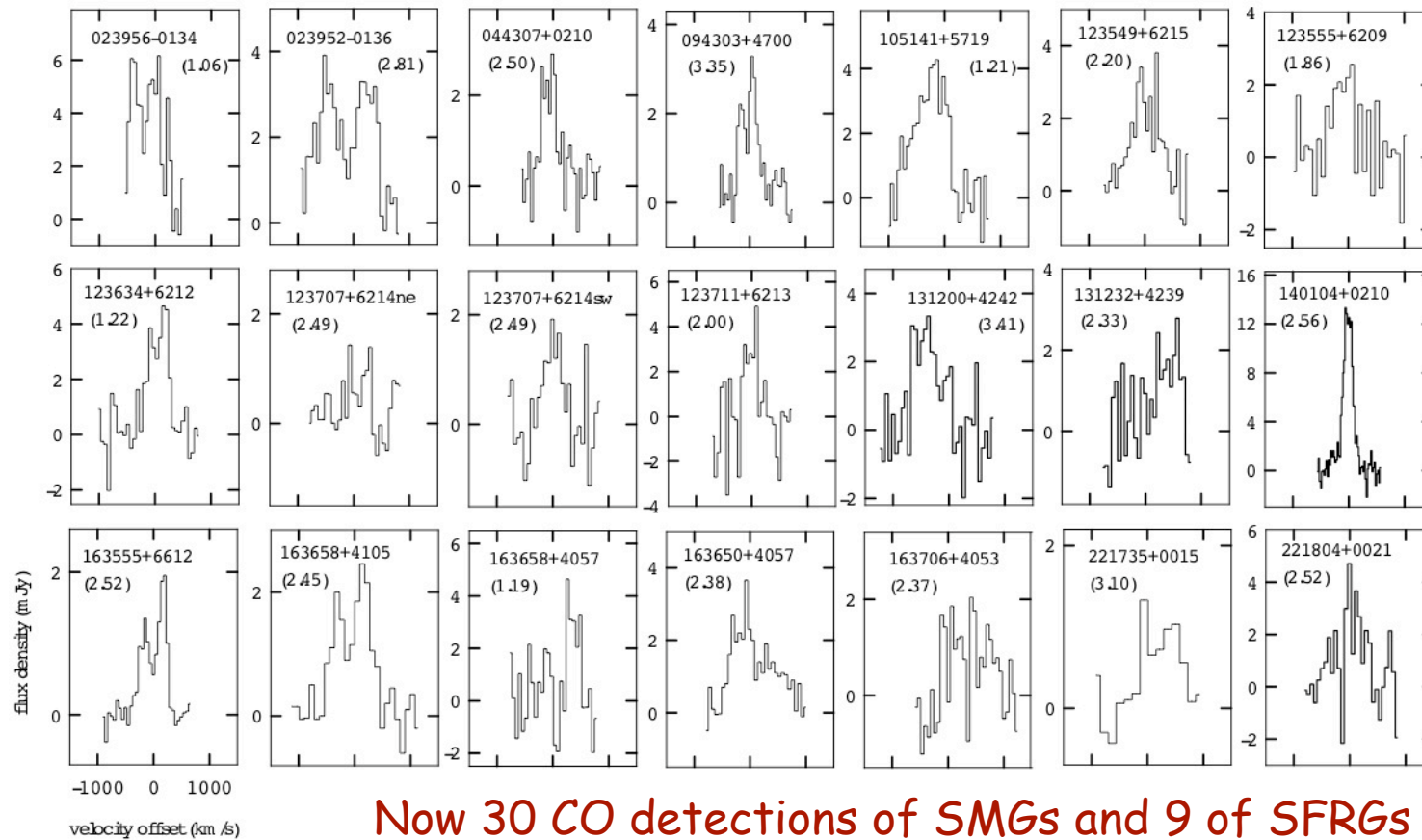
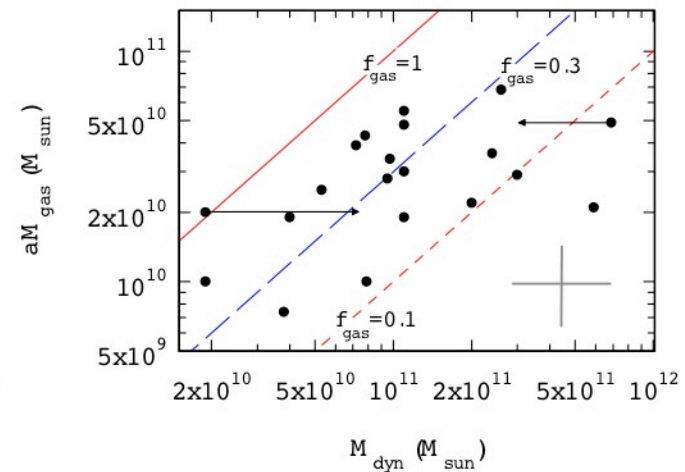
- radio and submm/mm continuum is extended  $\langle R_{1/2} \rangle \sim 0.5''$  4kpc

QUESTION: Is 850μm biased to parts of ULIRG with cold-dust? (recall SFRGs)





6x15m IRAM PdB Interferometer  
 Neri+03, Greve+05, Tacconi+06,08,  
 Chapman+08, Smail+10, Casey+10

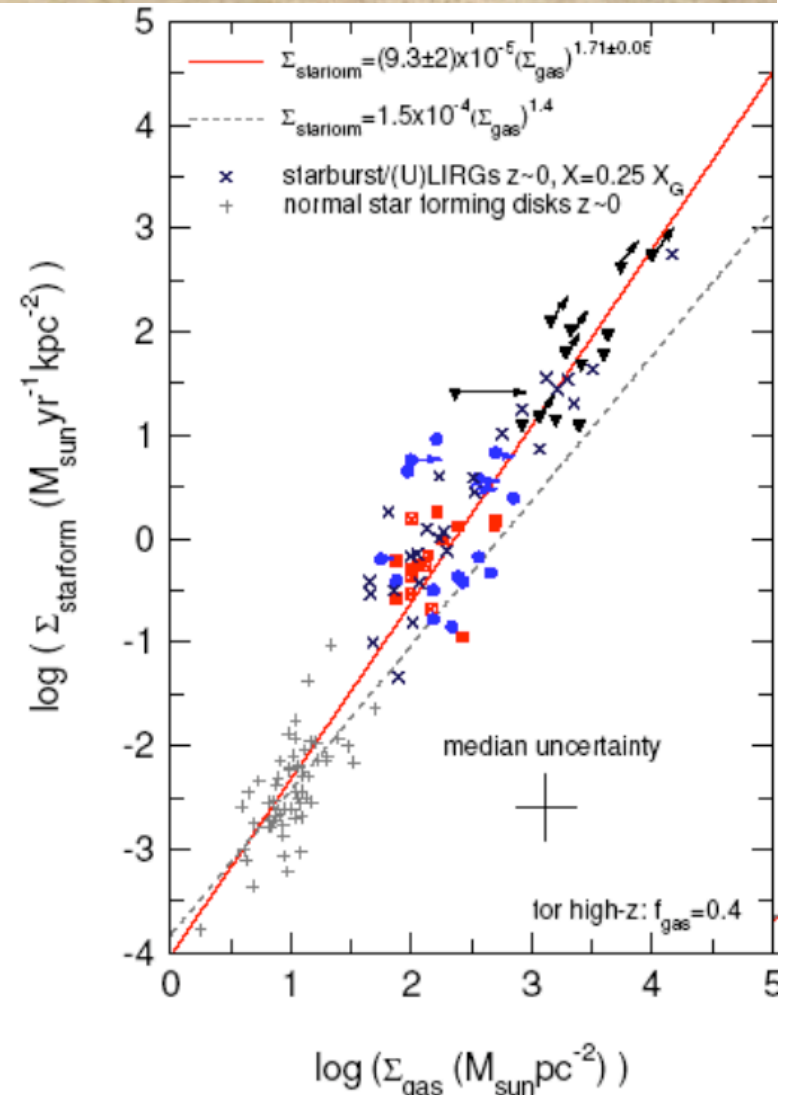




# KS-LAW: (E.G. BOUCHE+2007)

- SIMPLE PARAMETERIZATION FOR HIGH-Z GALAXIES LANDS THEM ALL ON A KS-RELATION.

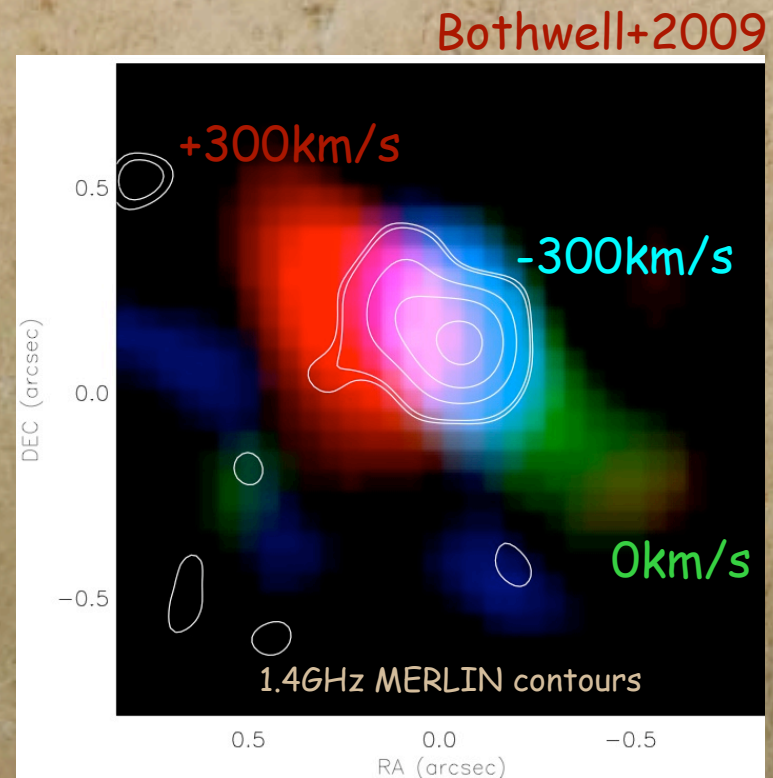
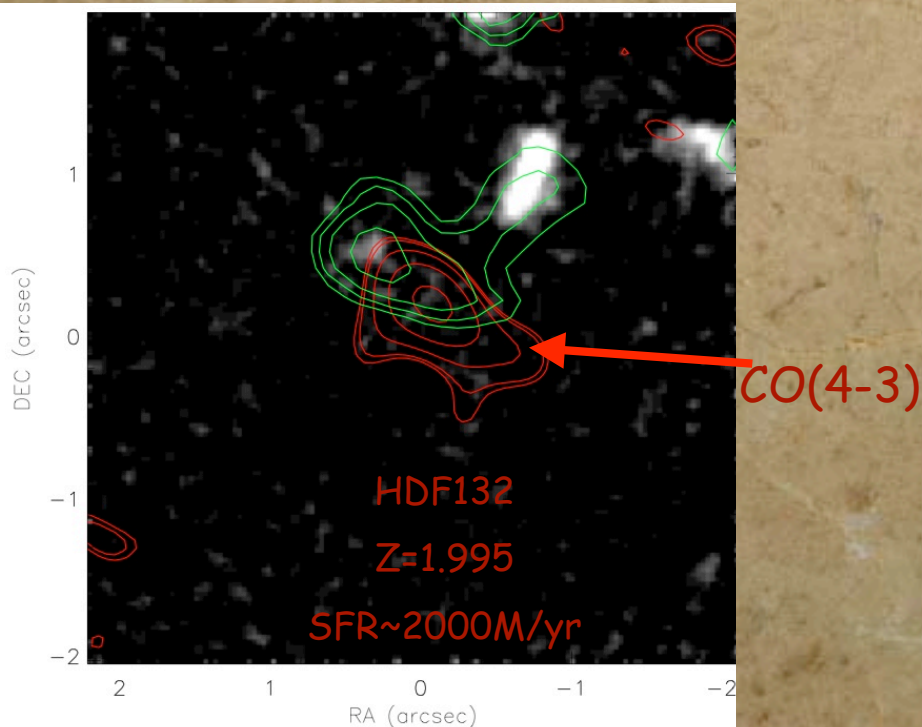
- SMGS HAVE MEASURED  $F_{\text{GAS}} \sim 0.4$
- ARE SFRs ACCURATE?
- ARE SMG SIZES CORRECT?  
BARELY/UNRESOLVED CO(7-6)
  - COMPACT!



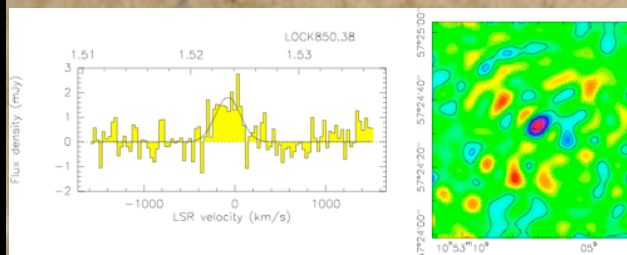
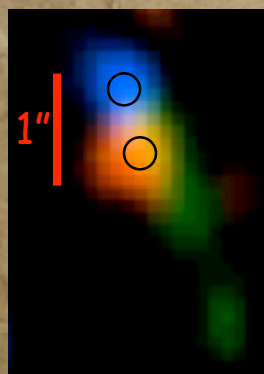
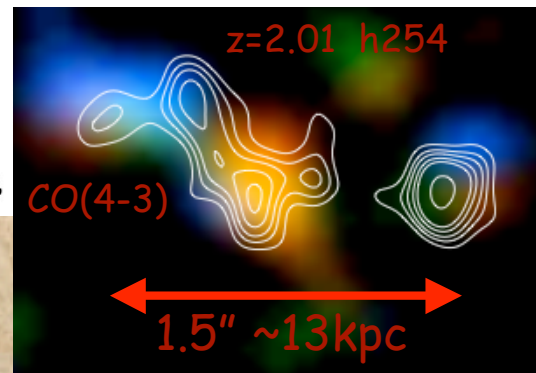
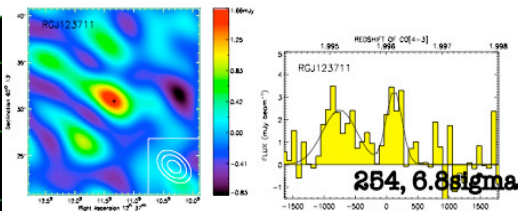
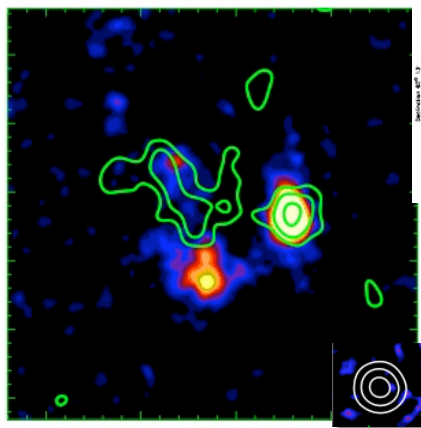


## CONTEXT FOR KS-LAW : HIGH-Z ULIRGS

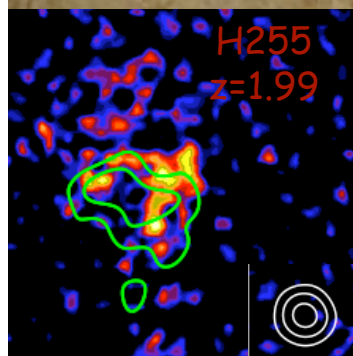
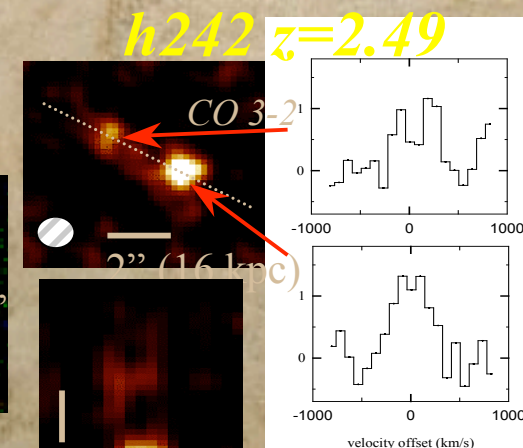
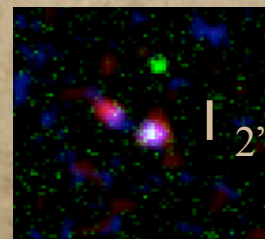
- NEW pilot study to detect CO in 10 SMGs with resolved MERLIN radio morphologies (8 detected)
- Followup 4 with low CO transitions and 0.4" resolution
- size(CO) not equal to size(FIR-radio) !
  - What size should we use ???
  - Do they "lie" on the KS-law
  - SFR ? Efficiency?



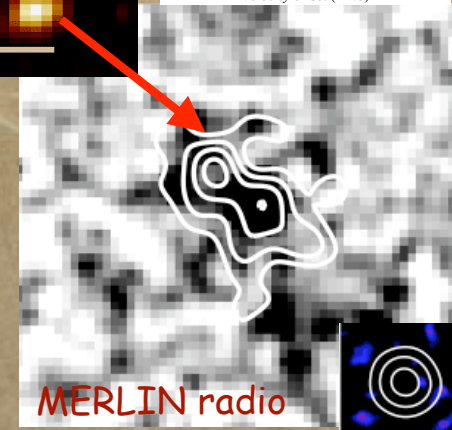
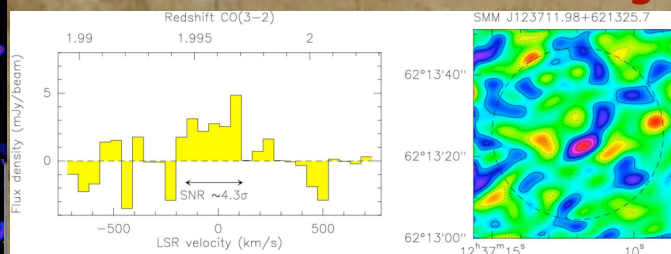




Lock850.38  $z=1.53$



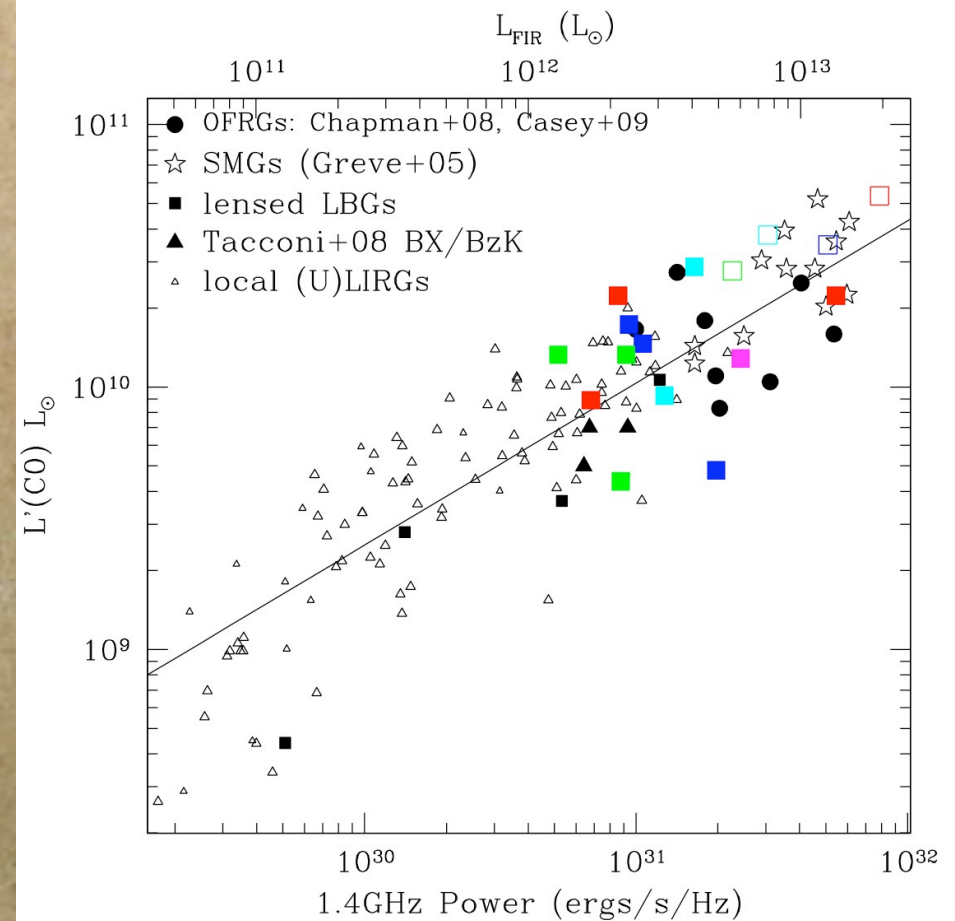
CO resolved out at A-config!





# INTERNAL SF EFFICIENCIES?

- NEW HIRES CO SOURCES ALL RESOLVED/EXTENDED IN (3-2) OR (4-3)
- SUBCOMPONENTS SHOW A LARGE RANGE IN  $L'_{\text{CO}}/L_{1.4\text{GHz}}$
- ARE WE SEEING MAJOR MERGERS OF DIFFERENT 'TYPES' OF ULIRGs?
- DO WE REALLY WANT TO INVERT KS-LAW TO INFER GAS PROPERTIES AT HIGH-Z?





# CONCLUSIONS

- MORE REPRESENTATIVE SAMPLE OF SMGS, WITH LOWER CO TRANSITIONS HAVE LARGER RANGE OF SIZES
  - (UP TO 8KPC FWHM - 4X LARGER THAN TYPICALLY INFERRED BY BOUCHE+2007)
  - THIS CAN WRECK HAVOC ON THE KS-LAW
    - DEPENDS ON INTERPRETATION
    - ACCURATE SFR INDICATOR?
- SMGS ARE MAJOR MERGERS?
- HAVE A LOOK AT CAITLIN'S POSTER AND SEE IF YOU THINK "SFRGS" ARE VIABLE HOTTER DUST ULIRGS