

# Cold Gas in Star Forming Galaxies over Cosmic Time

Linda Tacconi

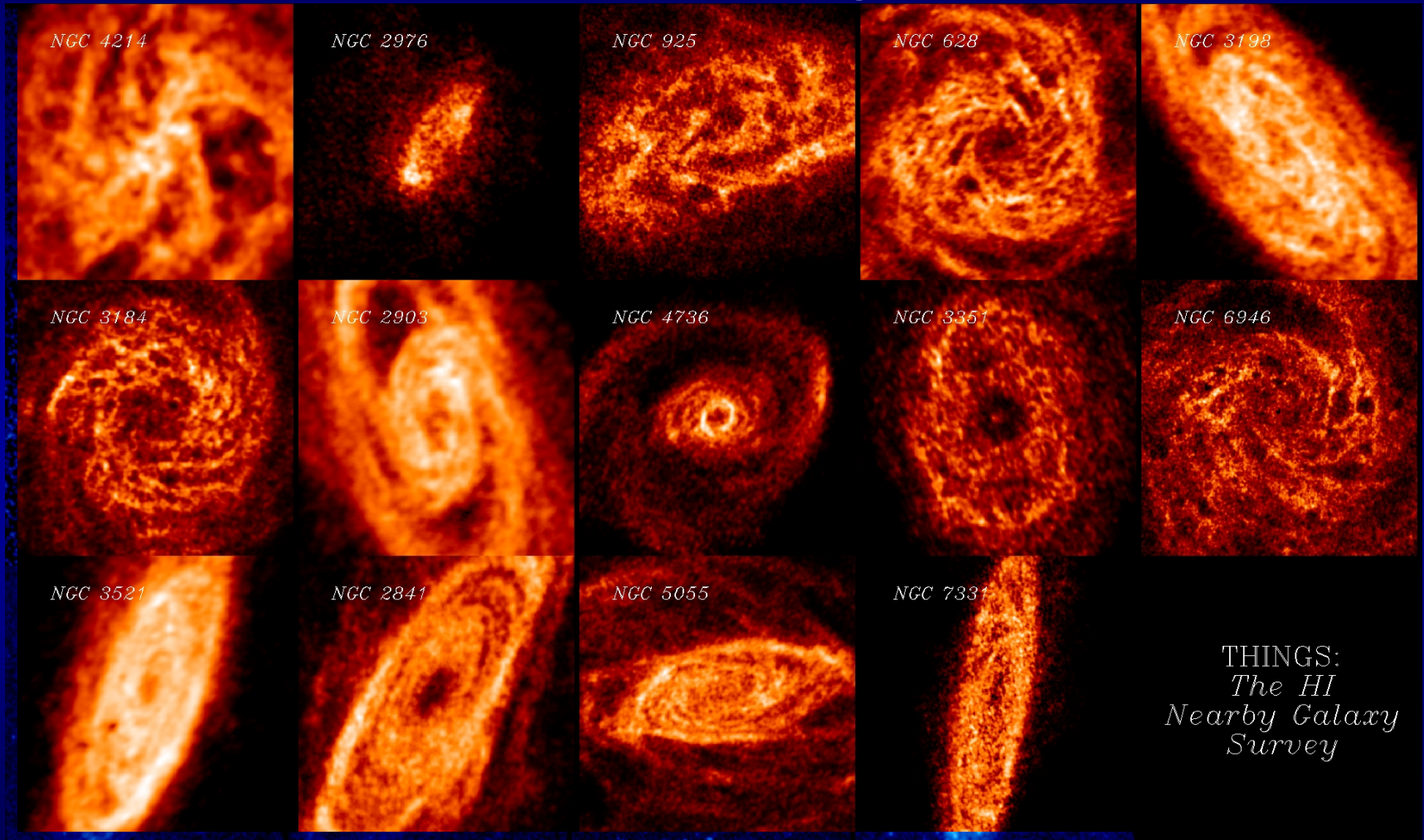
Max-Planck-Institut für  
extraterrestrische Physik, Garching

- Atomic and molecular gas in the local universe – scaling relations and distributions
- Molecular gas in star-forming galaxies from  $z \sim 1-2.5$
- Evolution of cold gas fractions from  $z \sim 0-2$
- Developments on the K-S relation at low and high  $z$

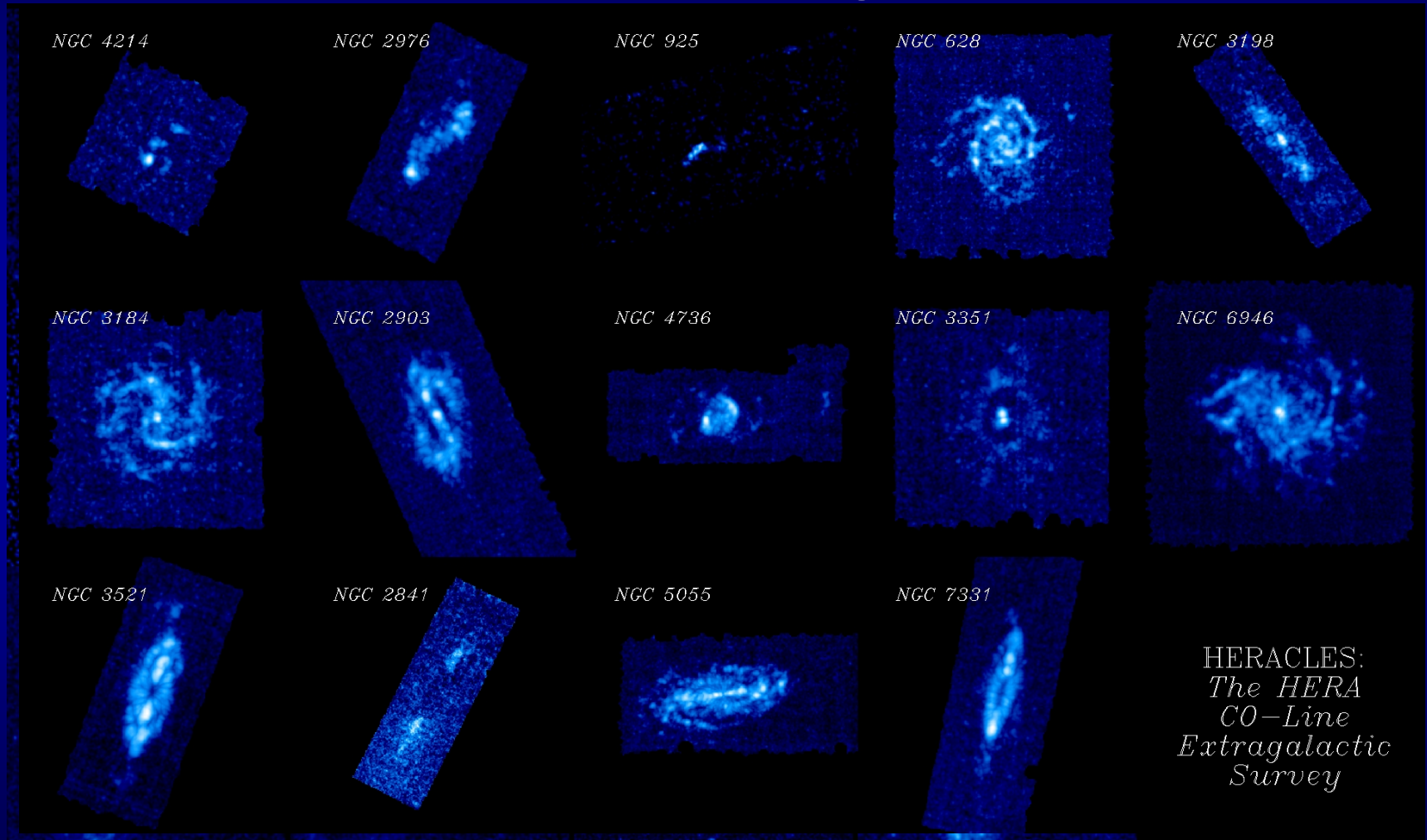
**Galaxy Formation 2011**

Durham University, Wednesday, 4 July 2011

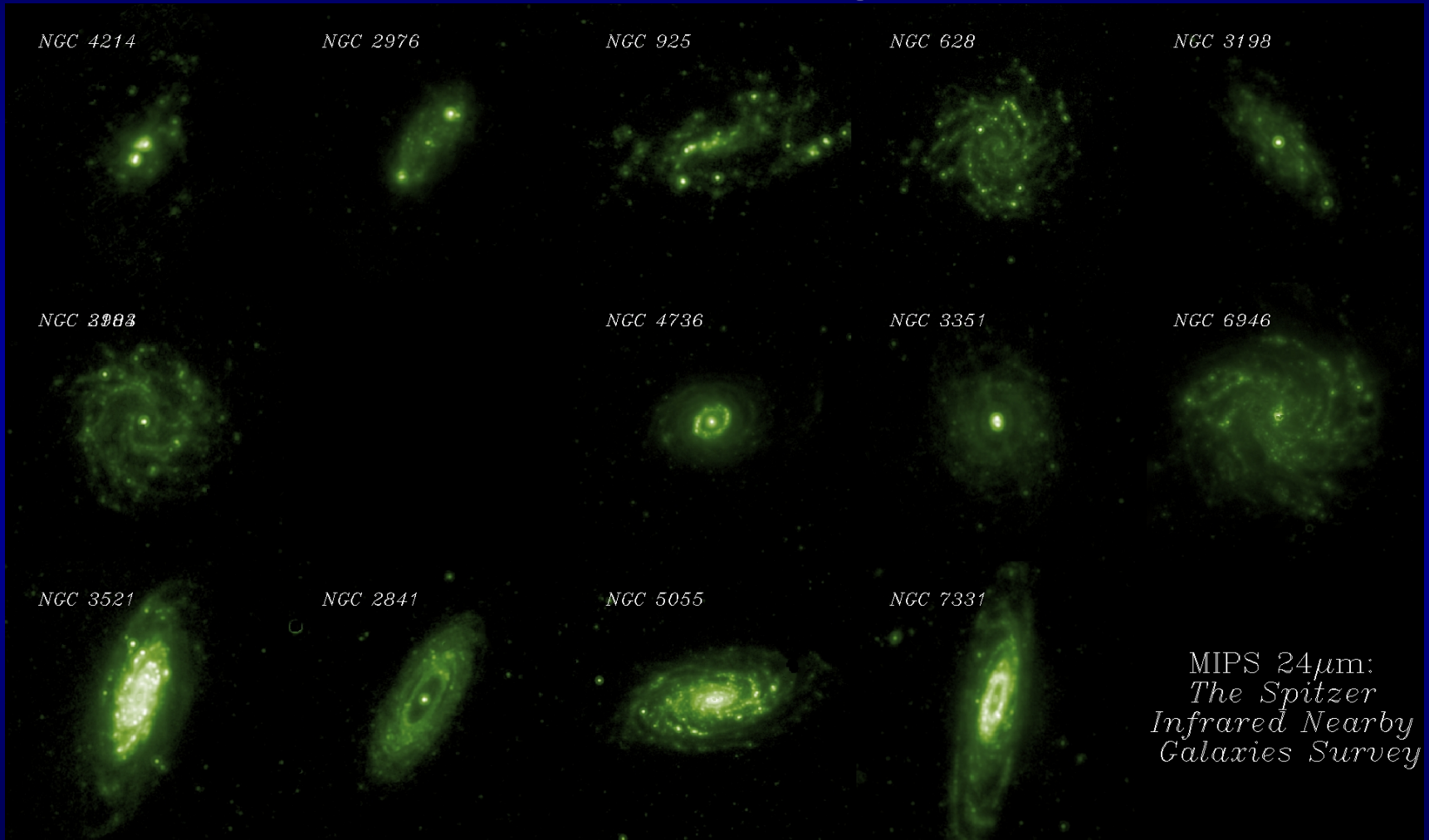
Lessons from  $z=0$ : SINGS (Kennicutt +)/GALEX (Gil de Paz+)/THINGS (Walter+)/HERACLES (Leroy+)  
Surveys of nearby galaxies



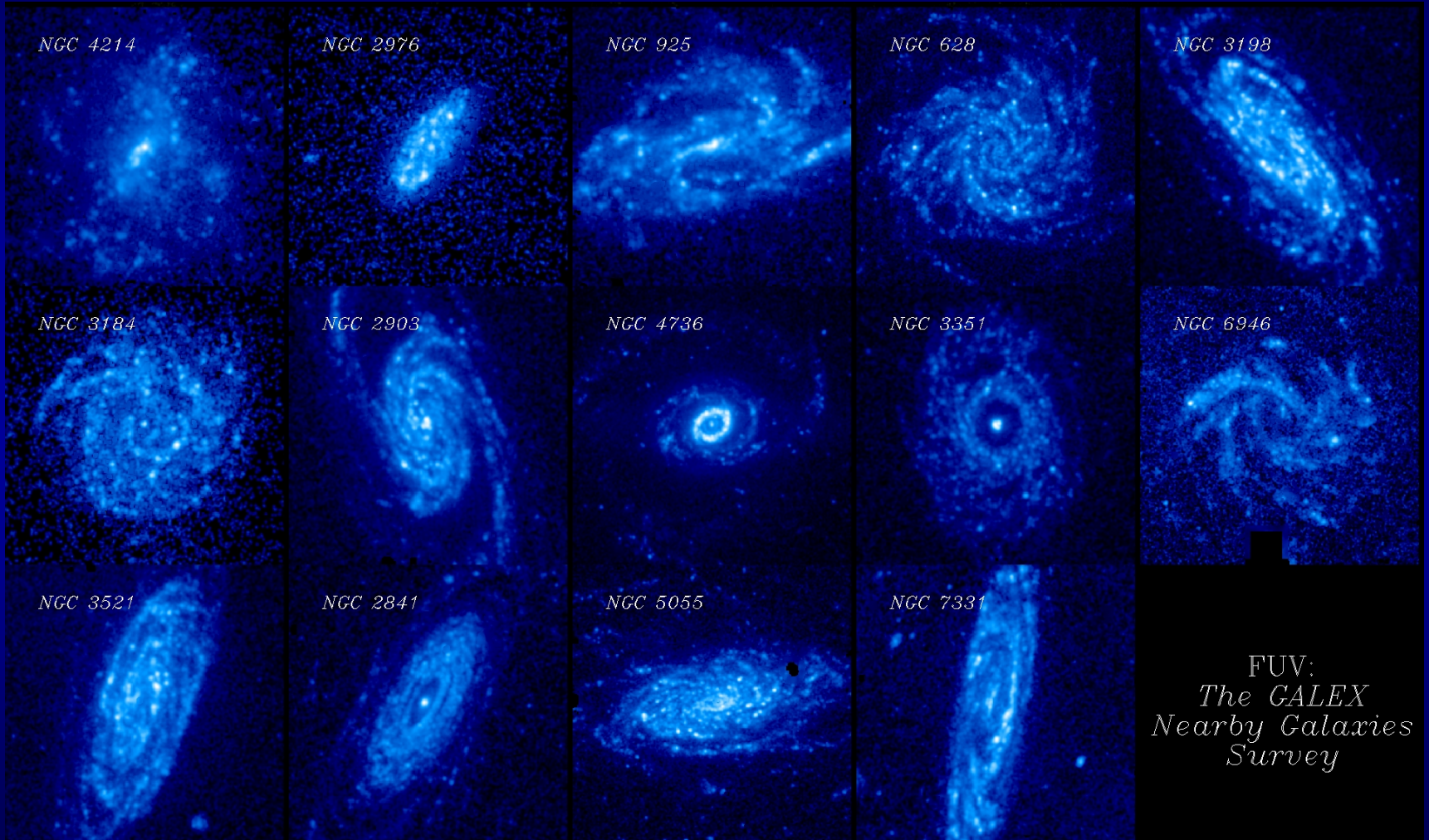
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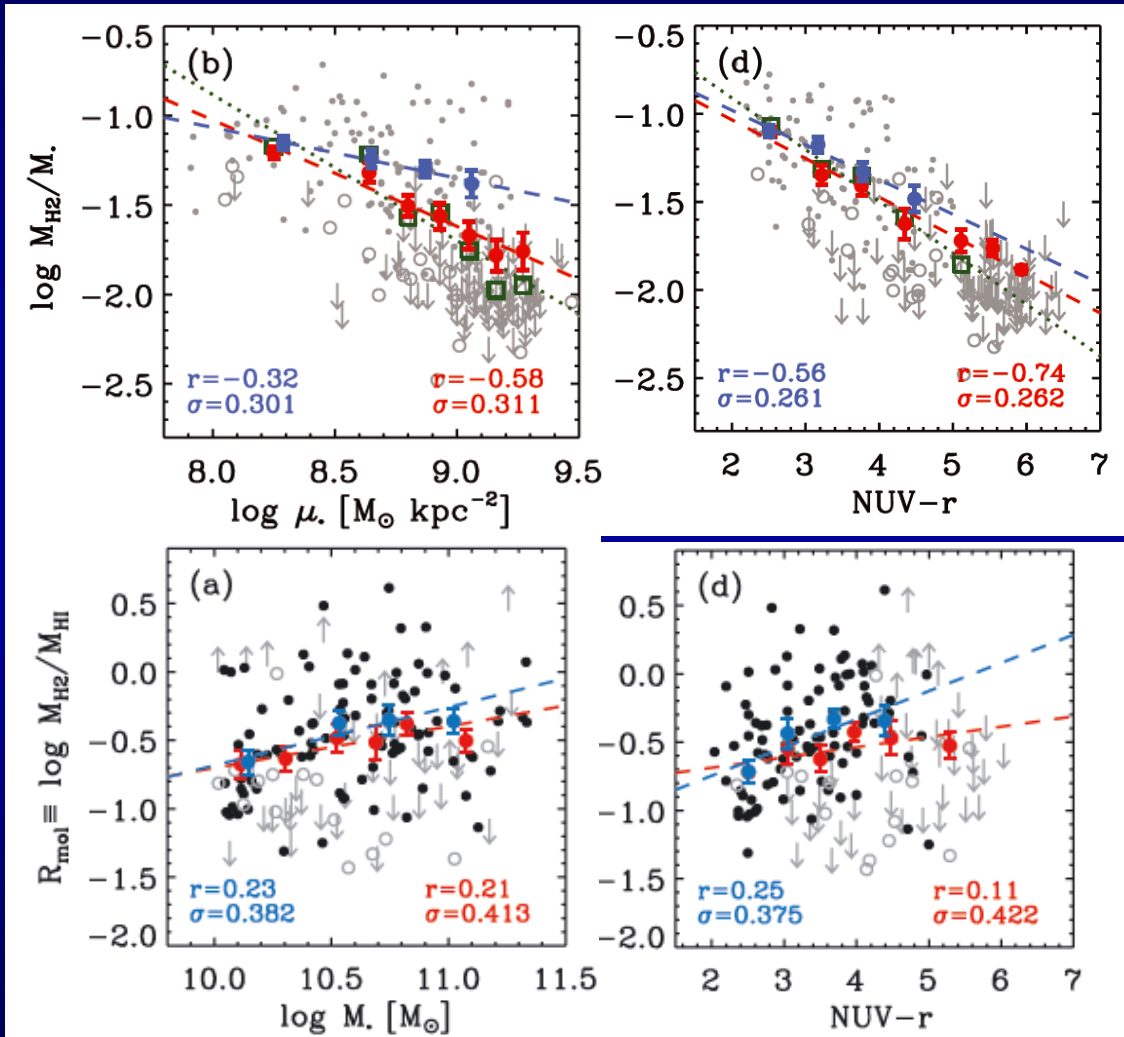
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# Lessons from $z=0$ unbiased surveys: GASS/COLD-GASS (Saintonge, Catinella, Kauffmann talks)



- Stellar mass selection  $> 10^{10} M_\odot$
- $0.025 < z < 0.05$  from SDSS/GALEX

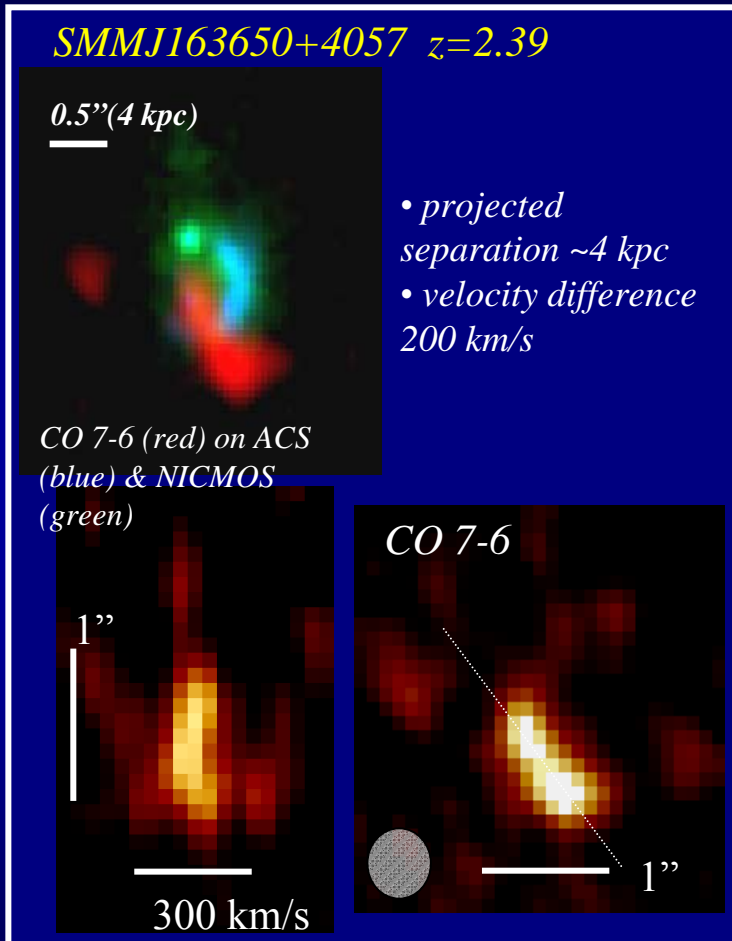
•  $M(\text{HI})/M^*$  decreases with increasing stellar mass, stellar mass surface density and NUV-r color

•  $M(\text{H}_2)/M^*$  correlated strongly only with galaxy color

• Sharp thresholds in structural parameters, above which fraction of galaxies with detectable HI or  $\text{H}_2$  decreases strongly.

• Weak variation in  $\text{H}_2/\text{HI}$  with galaxy properties

# Brightest high- $z$ star forming galaxies: “submillimeter galaxies”



- **>40 SMGs observed in CO**
- **Spatially resolved maps in  $\sim 12$**
- **Double CO sources, high  $\sigma/v$ , broad lines in compact sources – evidence for major merging**

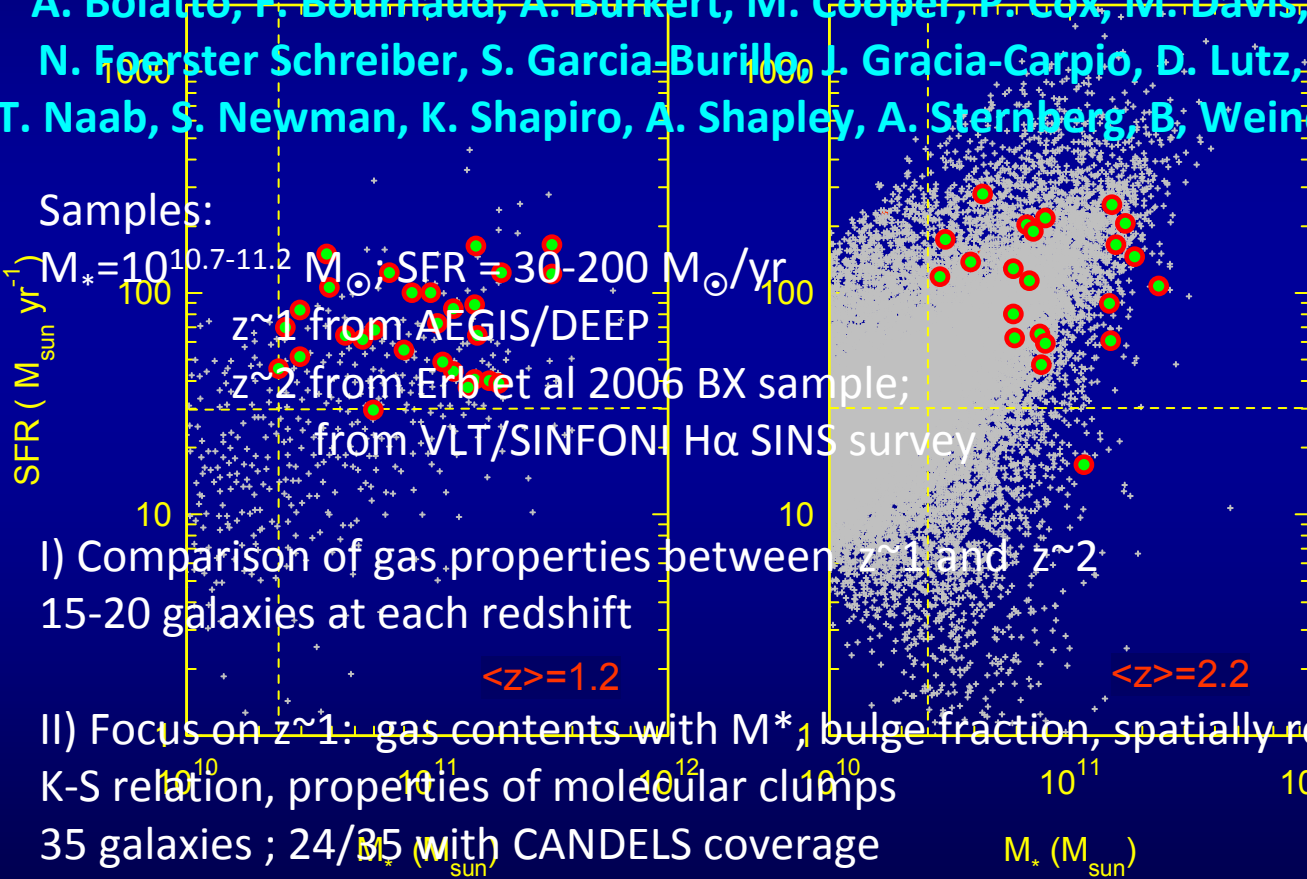
Frayer+ 1998, 1999; Downes & Solomon 2003;  
Genzel+ 2003; Neri+ 2003; Greve+ 2005;  
Tacconi+ 2006, 2008; Daddi+ 2009;  
Schinnerer+ 2009; Bothwell+ 2010, 2011;  
Swinbank+ 2010, 2011; Engel+ 2010;  
Ivison+ 2010, 2011; Riechers+ 2011

# Surveying CO (3-2) Line Emission in Massive $z \sim 1.2$ and $z \sim 2.2$ Star Forming Galaxies

R. Genzel, F. Combes, R. Neri, LT



A. Bolatto, F. Bournaud, A. Burkert, M. Cooper, P. Cox, M. Davis, N. Förster Schreiber, S. Garcia-Burillo, J. Gracia-Carpio, D. Lutz, T. Naab, S. Newman, K. Shapiro, A. Shapley, A. Sternberg, B. Weiner



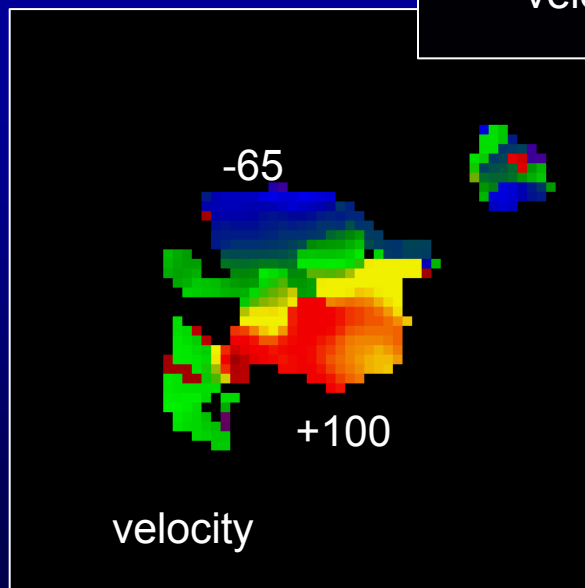
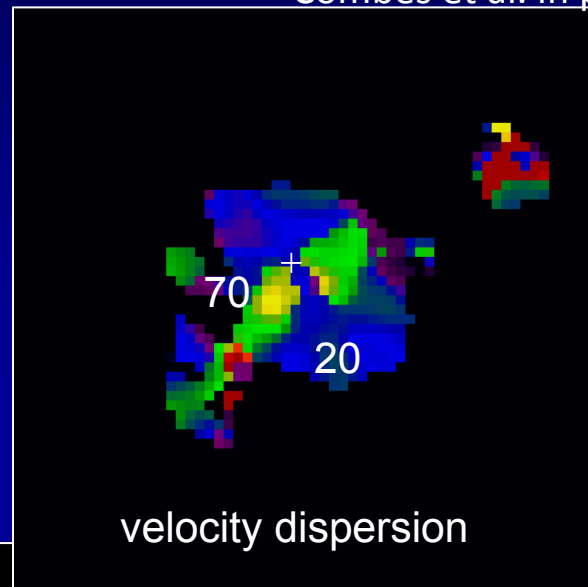
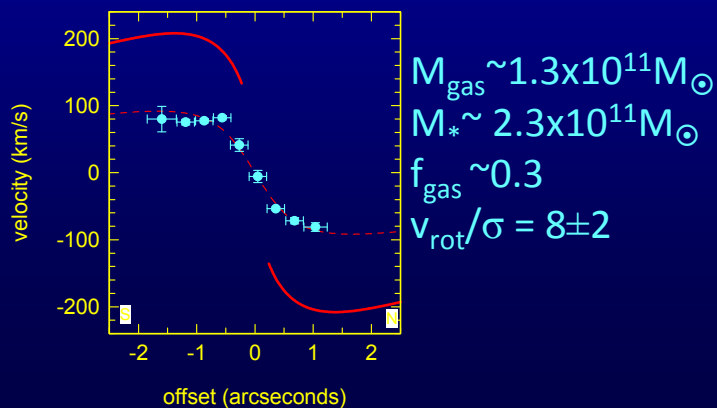
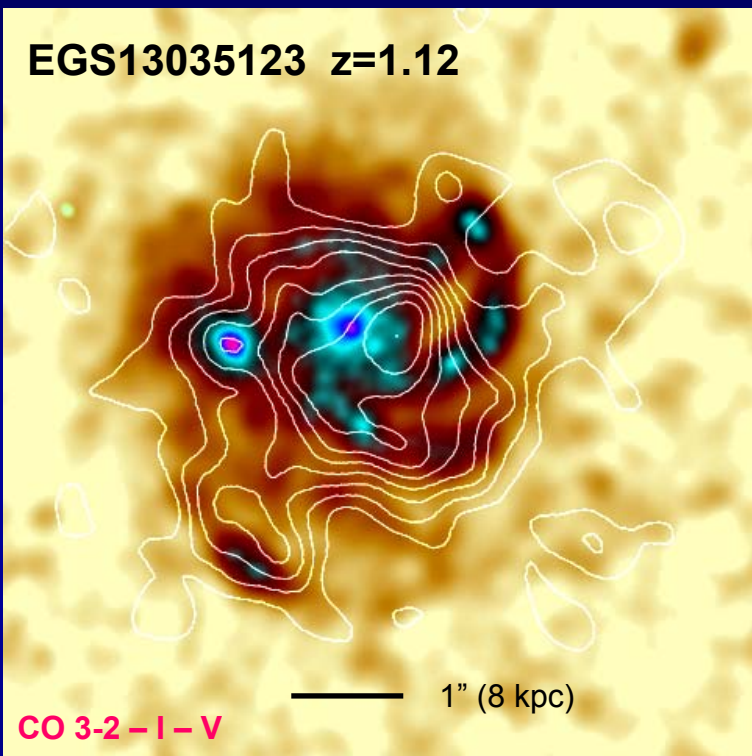
Status mid-2011:  
 21/21 detected at  $z \sim 1$ ;  
 12/18 detected at  $z \sim 2$   
 6 sub-arcsec resolution  
 spatially resolved maps  
 ~50 CO detections in MS  
 SFGs at  $z > 1$

Tacconi + 2010, in prep  
 Genzel + 2010, 2011,  
 Daddi + 2009,  
 Daddi + 2008, 2010,  
 Aravena + 2010,  
 Saintonge + in prep



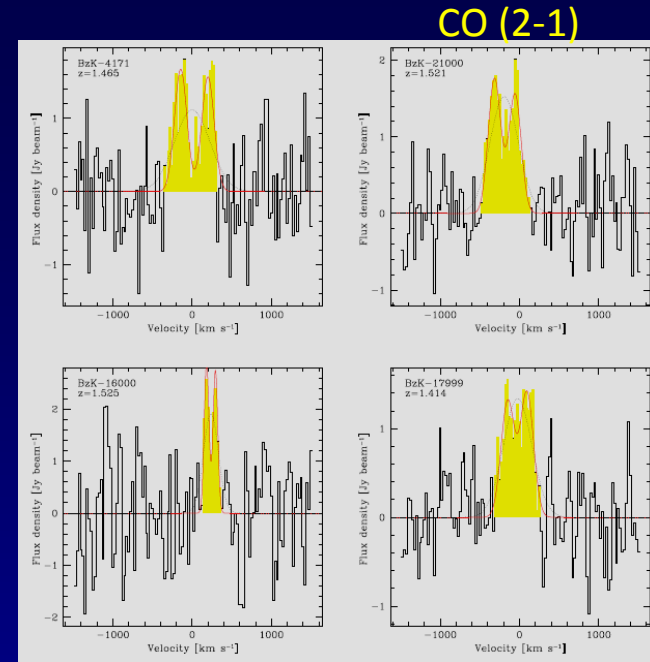
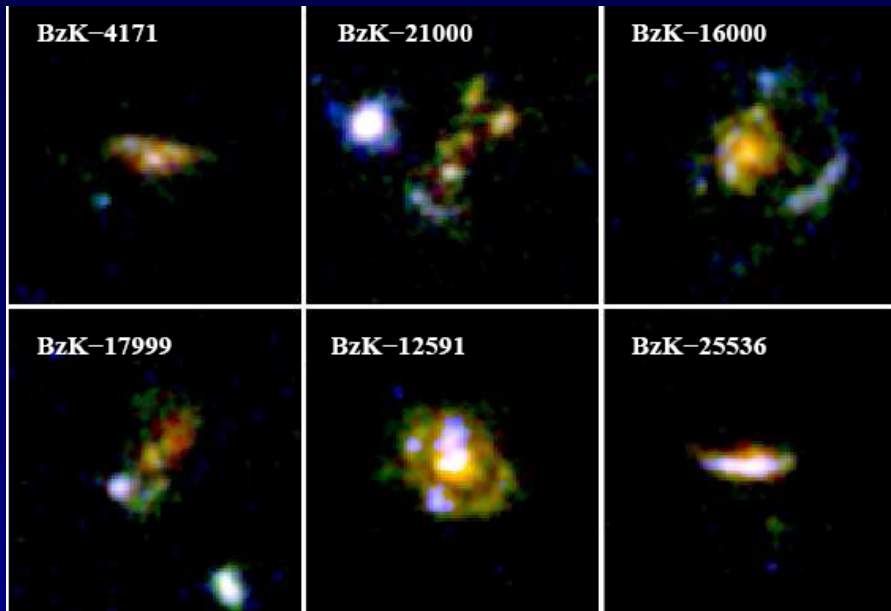
# Molecular Gas in SFGs at $z \sim 1$

Tacconi et al. 2010;  
Combes et al. in prep



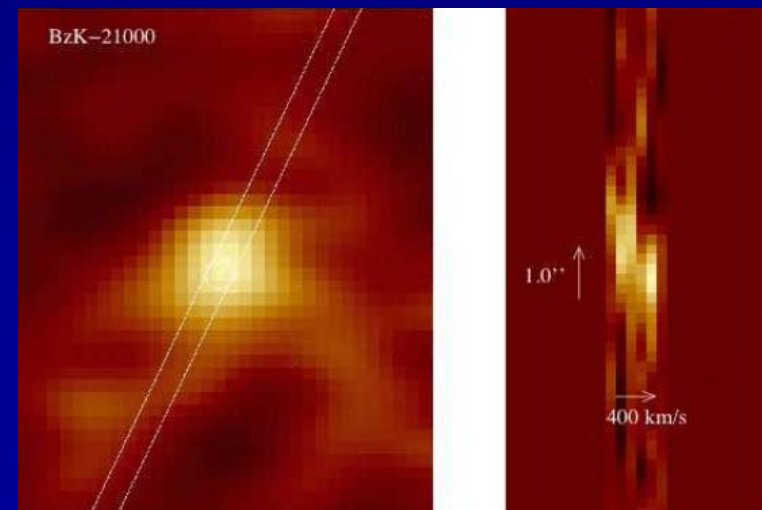
# CO in z=1.5 BzK Galaxies in GOODS-N

ACS – RGB Imaging



- 6 massive BzK galaxies
- Clumpy, unstable disks
- Spatially resolved emission in 4
- CO sizes (FWHM) 6-11 kpc
- $M_{\text{gas}} = 0.4-1.2 \times 10^{10} M_{\odot}$

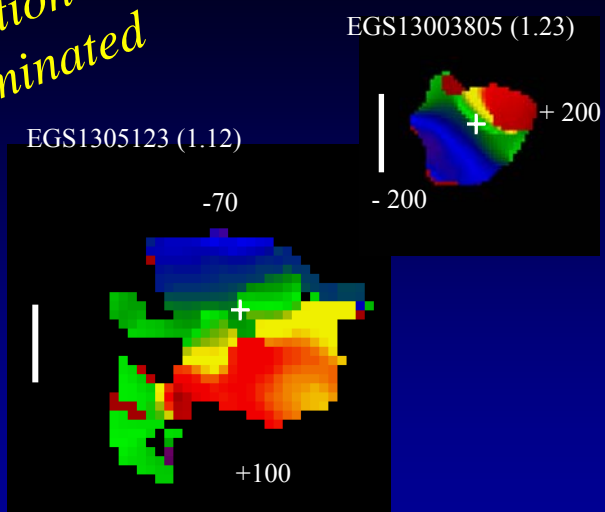
Daddi et al. 2008, 2010a, b  
Dannerbauer et al. 2009



*rotation-dominated*

*dispersion dominated*

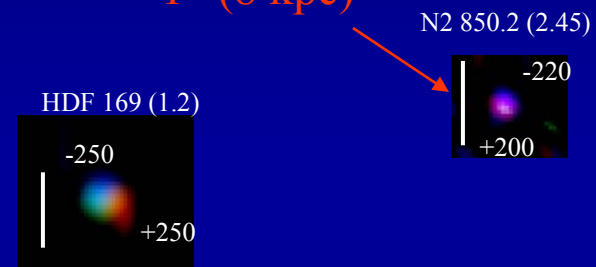
# Cold Gas Dynamics



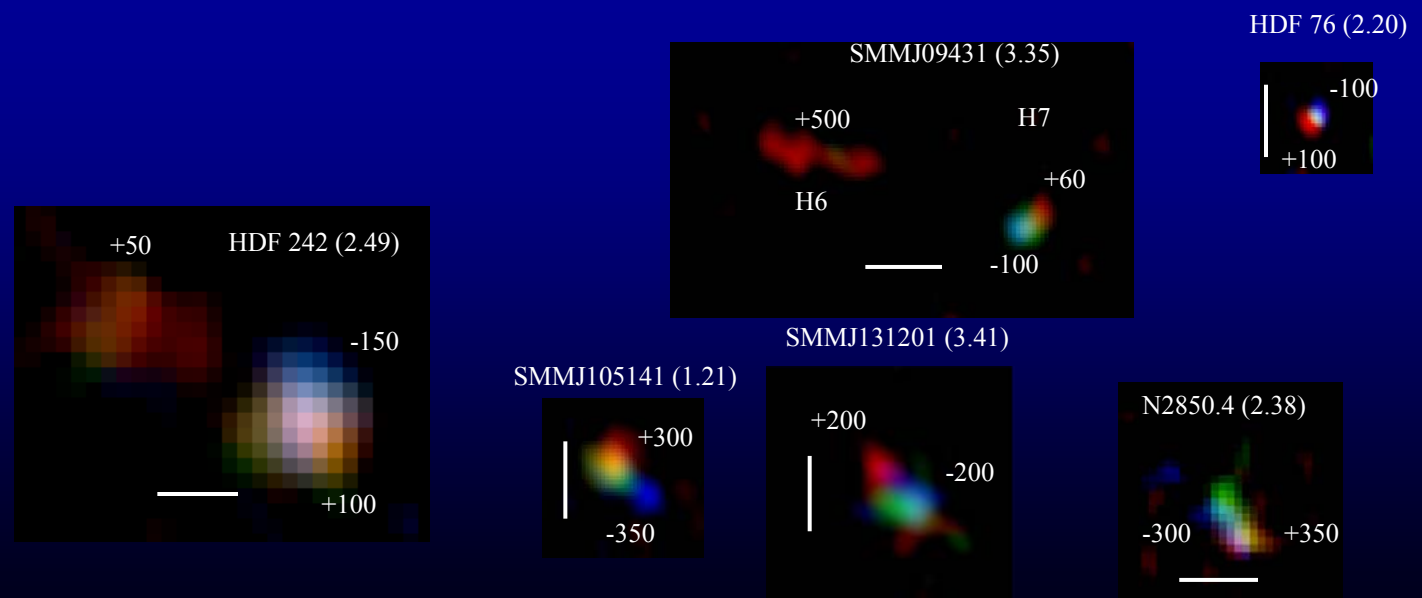
CO emission from  $z \sim 1.2$  AEGIS  $z \sim 1.5-2.5$  BX/BzK galaxies (Tacconi et al. 2010, Daddi et al. 2008, 2010, Combes et al in prep)

CO emission from submillimeter galaxies (Tacconi et al. 2006, 2008, Bothwell et al. 2010, Engel et al. 2010, Ivison et al. 2011)

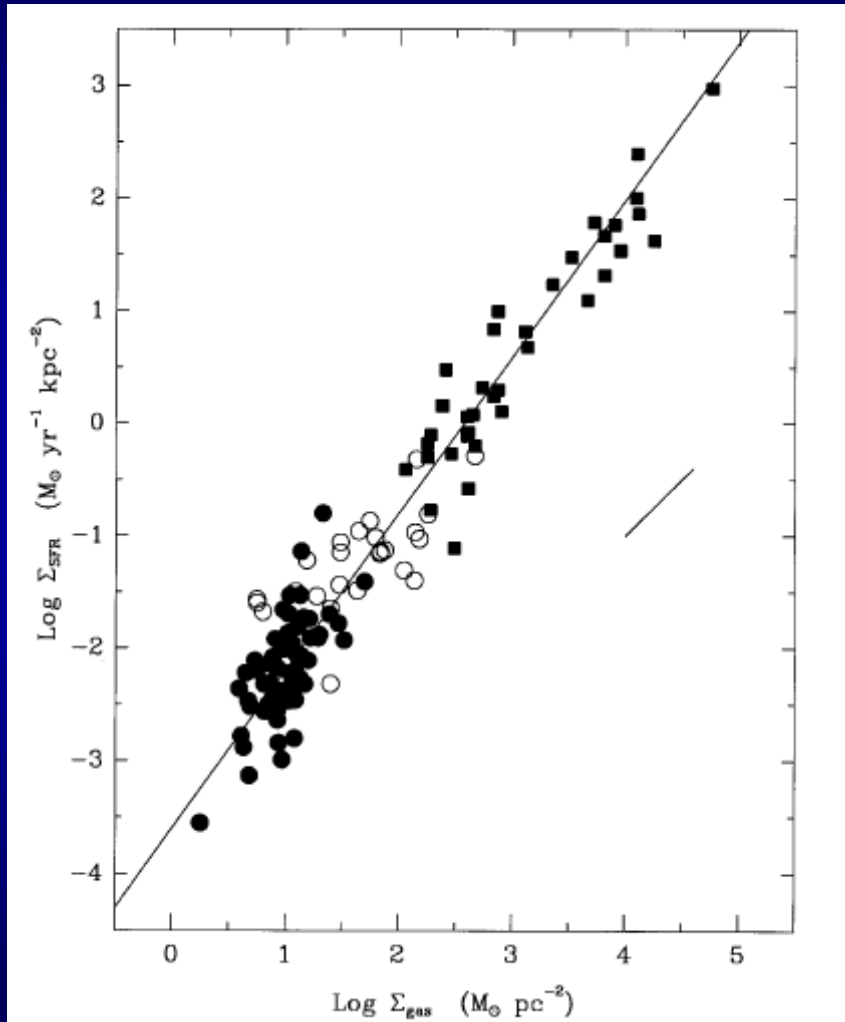
$1''$  (8 kpc)



*merger*



# Recent developments in gas–star formation relation (K-S relation)



Rob Kennicutt's  
talk

Kennicutt (1998)

# Low efficiency star formation in $z \sim 0$ disk galaxies

distance 130pc

Pipe nebula  
 $\sim 8 \times 10^3 M_{\odot}$ ,  $D=20\text{pc}$   
21 YSOs

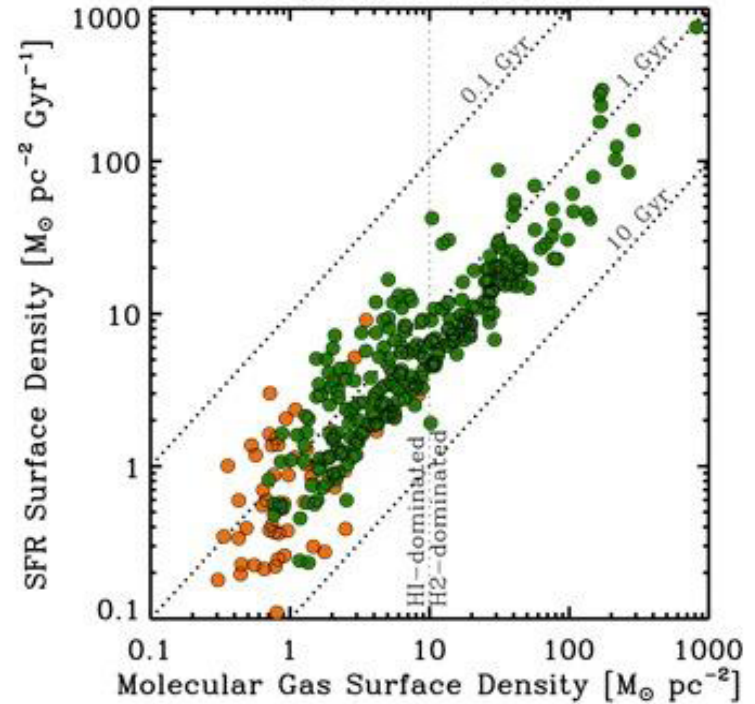
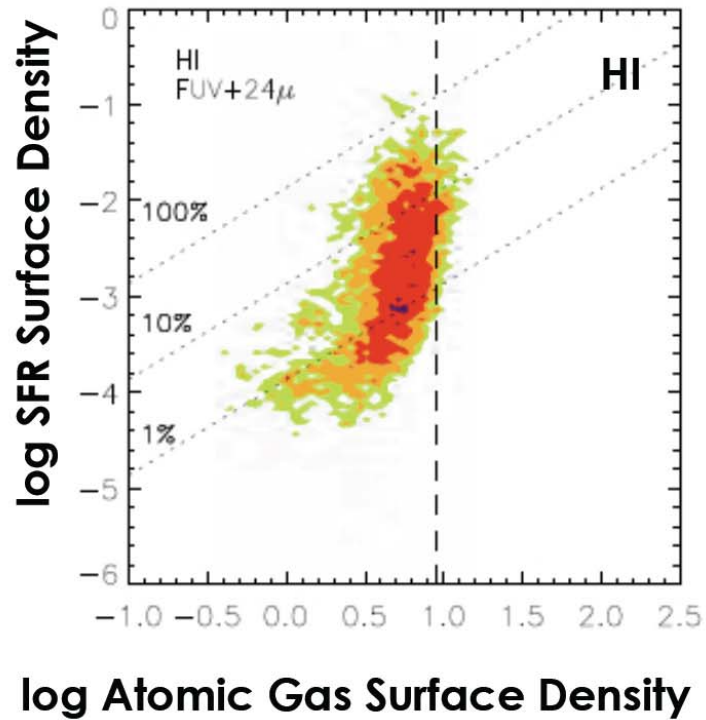
$\rho$  Oph  
 $\sim 1.4 \times 10^4 M_{\odot}$ ,  $D=20\text{pc}$   
316 YSOs

active star formation only occurs  
in dense ( $>10^4 \text{ cm}^{-3}$ ), highly obscured ( $A_V > 7$ )  
regions

Lada, Alves, Lombardi 2006-2009

Rosetta cluster GMC: PACS & SPIRE

# Spatially resolved gas–star formation relation



- ~kpc scale resolution
- HI alone shows little correlation with SFR
- Strong correlation for molecular gas in regions where  $H_2 > HI$

Bigiel et al 2008, 2011, Leroy et al. 2009, Schruba et al. 2011

# Summary

- Well defined gas scaling relations now exist for local Universe galaxies, both globally and within galaxies.
- Statistics on molecular gas census of massive high- $z$  SFGs rapidly accumulating. Now  $\sim 100$  CO detections in various SFG populations.
- Star forming galaxies from  $z=1-3$  are gas-rich with  $\langle f_{\text{gas}} \rangle \sim 0.45-0.55$ ; starting to observe decreasing trend with  $z$  from  $z=2$  to  $z=0$ .
- The molecular gas–star formation relation does not depend much on redshift. Low- and high-redshift star-forming galaxy populations follow similar molecular gas–star formation relations with slope 1.1 to 1.2, over three orders of magnitude in gas mass or surface density.