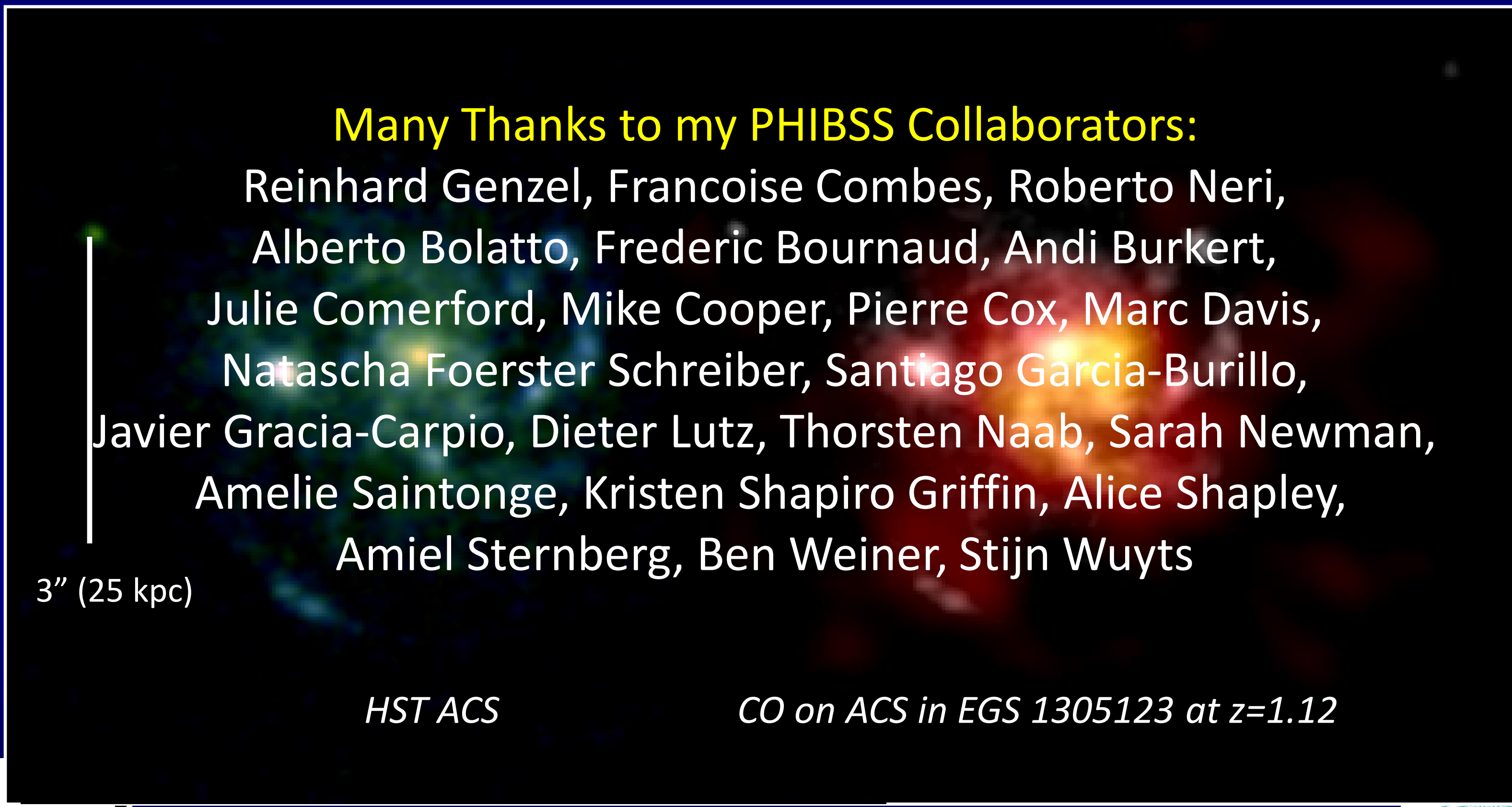
Gas Consumption in Extreme Environments: High Redshift

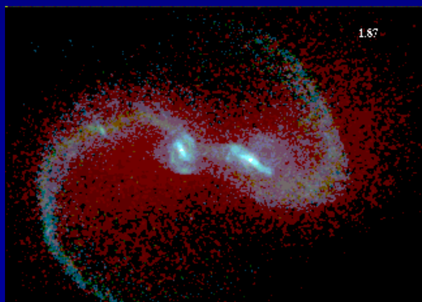
Linda Tacconi
Max-Planck-Institut für extraterrestrische Physik, Garching



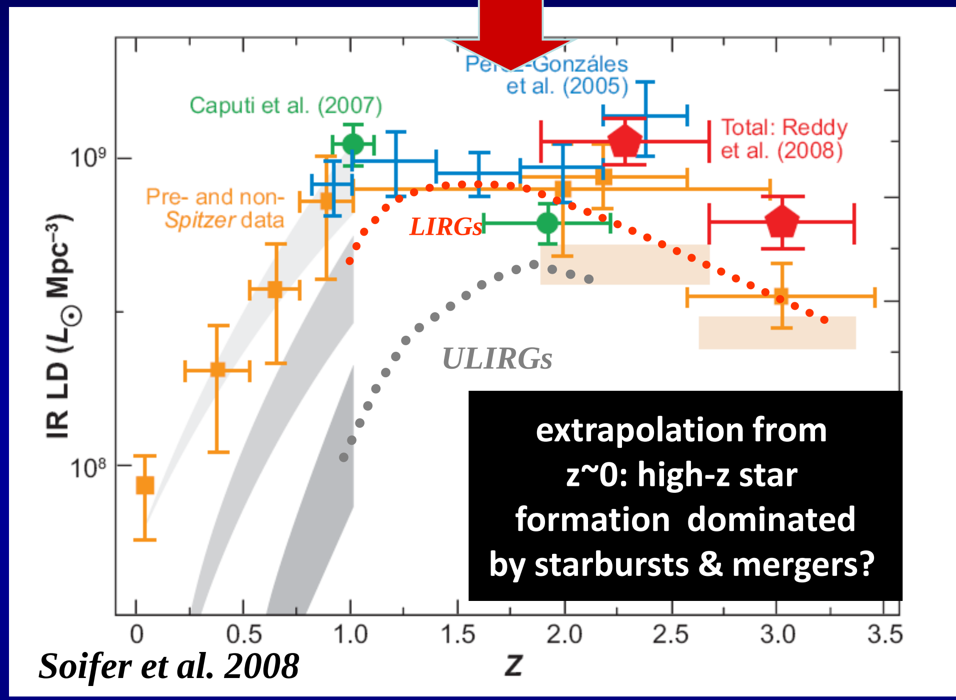
Many Thanks to my PHIBSS Collaborators:
Reinhard Genzel, Francoise Combes, Roberto Neri,
Alberto Bolatto, Frederic Bournaud, Andi Burkert,
Julie Comerford, Mike Cooper, Pierre Cox, Marc Davis,
Natascha Foerster Schreiber, Santiago Garcia-Burillo,
Javier Gracia-Carpio, Dieter Lutz, Thorsten Naab, Sarah Newman,
Amelie Saintonge, Kristen Shapiro Griffin, Alice Shapley,
Amiel Sternberg, Ben Weiner, Stijn Wuyts

Regulation of Star Formation in Molecular Gas: from Galactic to Sub-cloud Scales
Schloss Ringberg , June 27, 2013

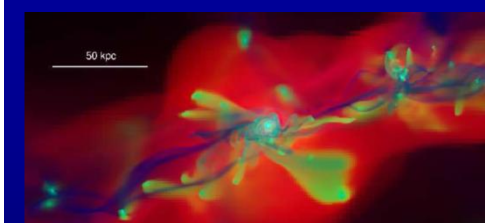
Extreme Environments: Star formation at the peak of the galaxy formation epoch



(major) mergers & starbursts

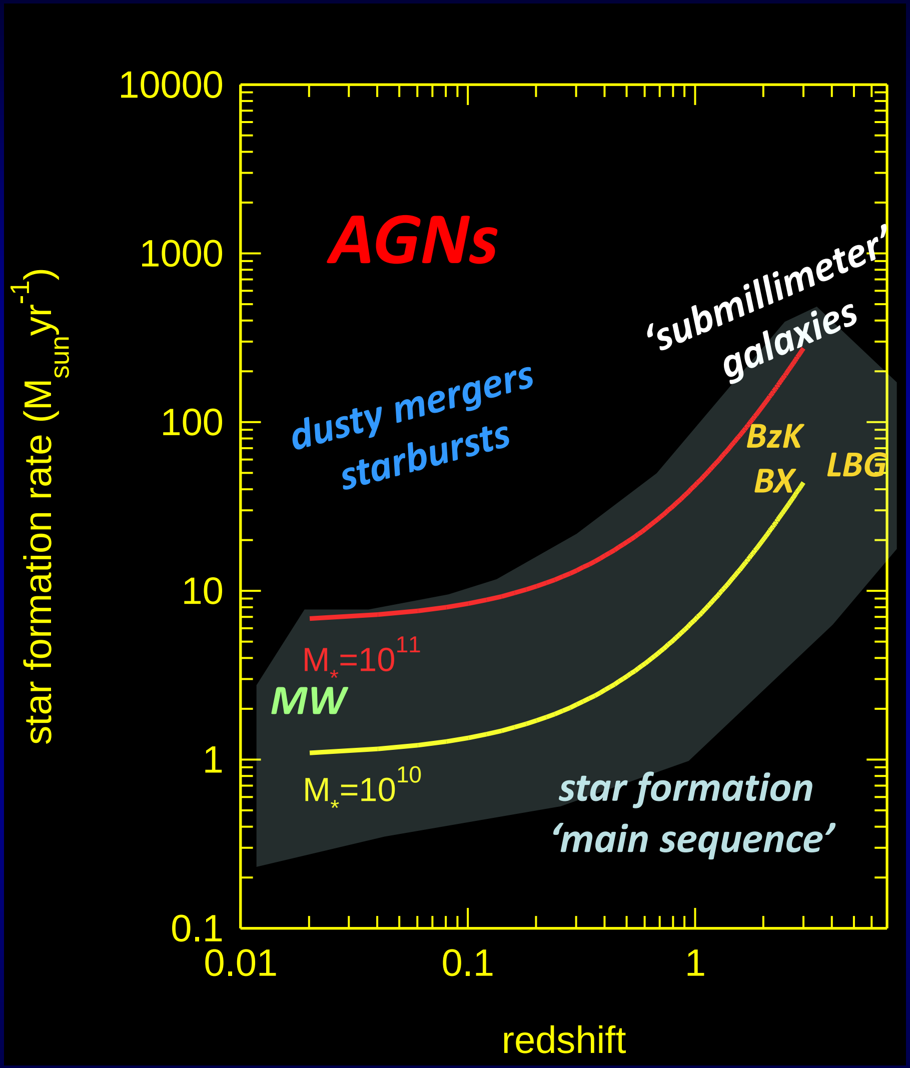


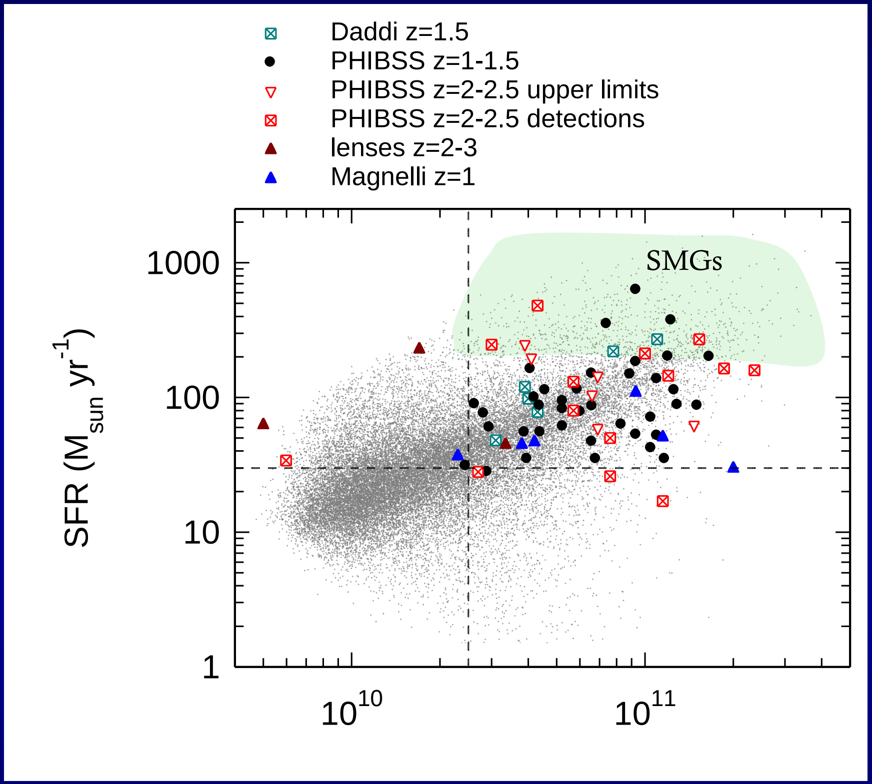
continuous accretion from halo & disk instabilities



Lilly+ 1996, Madau +1996, Steidel+1996, Hopkins & Beacom 2006, Soifer+2008, Rees & Ostriker 1977, Silk 1977, White & Rees 1978, Kauffmann+1993, Steinmetz & Navarro 2003, Hernquist, Springel, di Matteo, Hopkins+2003-2009, Robertson & Bullock 2008, Sanders & Mirabel 1996, Dekel & Birnboim 2003,2006, Keres +2005, 2009, Nagamine+2005, Davé 2007, Kitzbichler & White 2007, Naab+2007, Governato+2008, Ocvirk+2008, Dekel+2009, Agertz+2009, Guo+2009, Mayer+2010, Teyssier+2010, Bournaud 2010, Davé+ 2011……

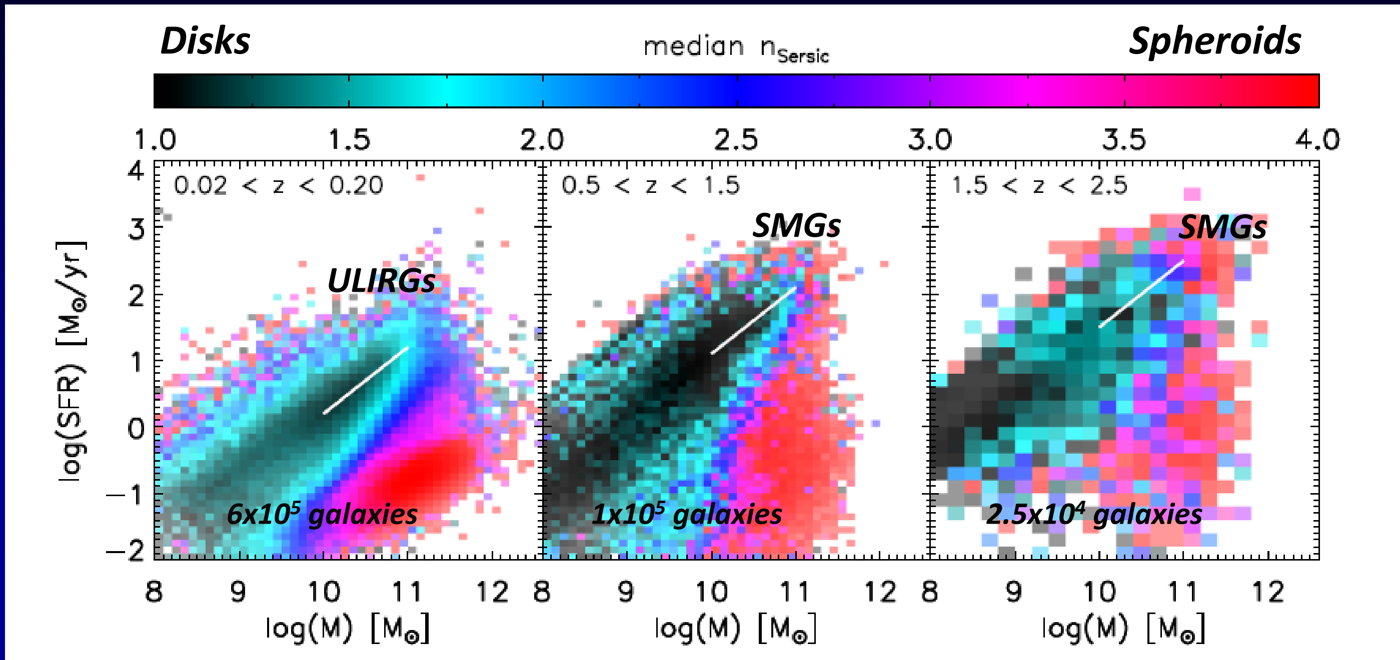
Star Formation Rates across Cosmic Time



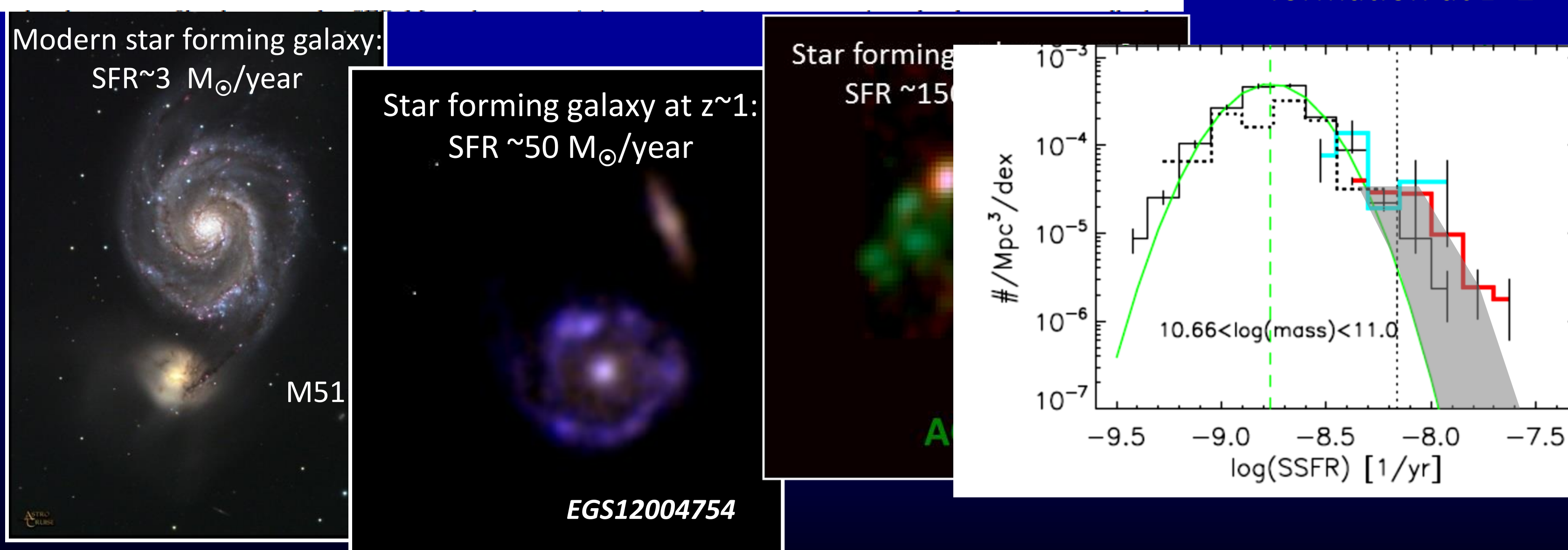


Schiminovich et al. 2007, Elbaz et al. 2007, Noeske et al. 2007, Daddi et al .2007, Perez-Gonzalez et al. 2008, Damen et al. 2009, da Cunha et al. 2010, Rodighiero et al. 2010,2011

Galaxies on 'Star Forming (Main) Sequence' Are Disks



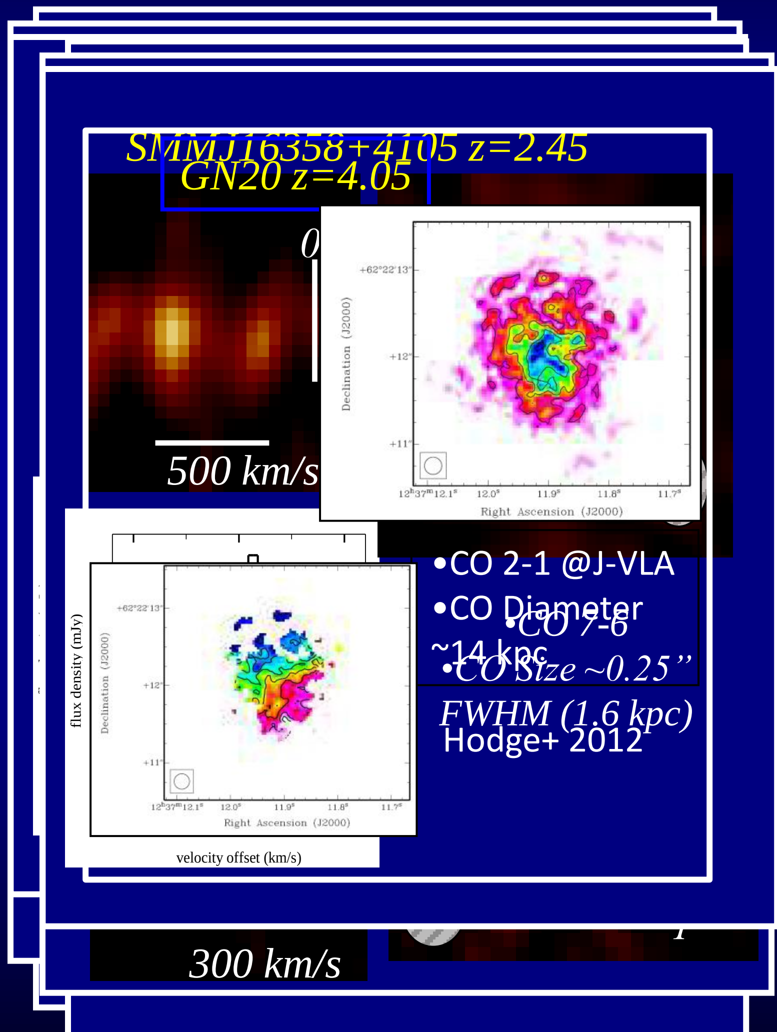
Wuyts +2011, Whitaker+2012



Rodighiero et al. 2011

Outlier galaxies above "main-sequence" account for ~10% of cosmic star formation at z~2

Above main sequence: many “submillimeter galaxies” show evidence for major merging

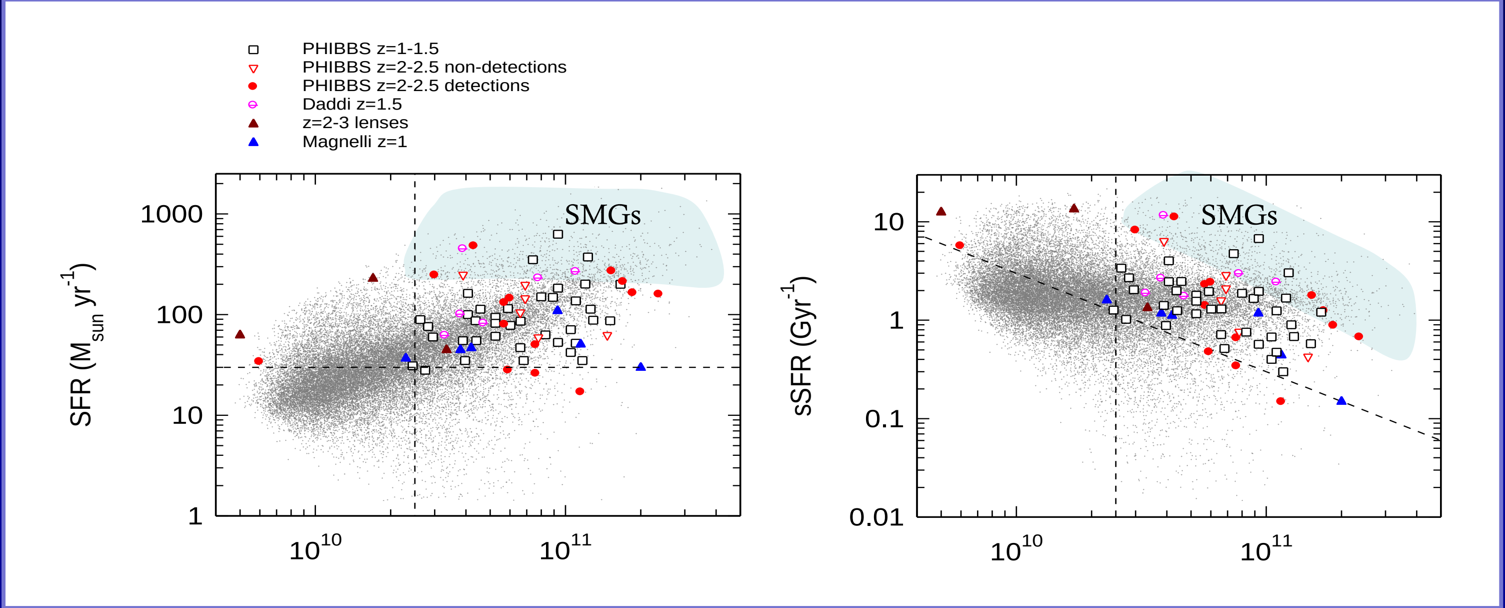


1998 – 2013:

- ~50 SMGs observed in CO
- Spatial information in ~1/3
- SFRs 500 – 1000 $M_{\odot}$/yr
- <v(FWHM)> ~500 km/s
- Double CO sources, high σ/v, broad lines in compact sources – evidence for major merging
- Few more extended disk structures, especially in low-J CO

Frayer+ 1998, 1999; Downes & Solomon 2003; Genzel+ 2003; Neri+ 2003; Greve+ 2005; Tacconi+ 2006, 2008; Daddi+ 2009; Schinnerer+ 2009; Bothwell+ 2010, 2013; Swinbank+ 2010,2011; Engel+ 2010; Ivison+ 2010,2011; Carilli+ 2011, Riechers+ 2011, Hodge+2012

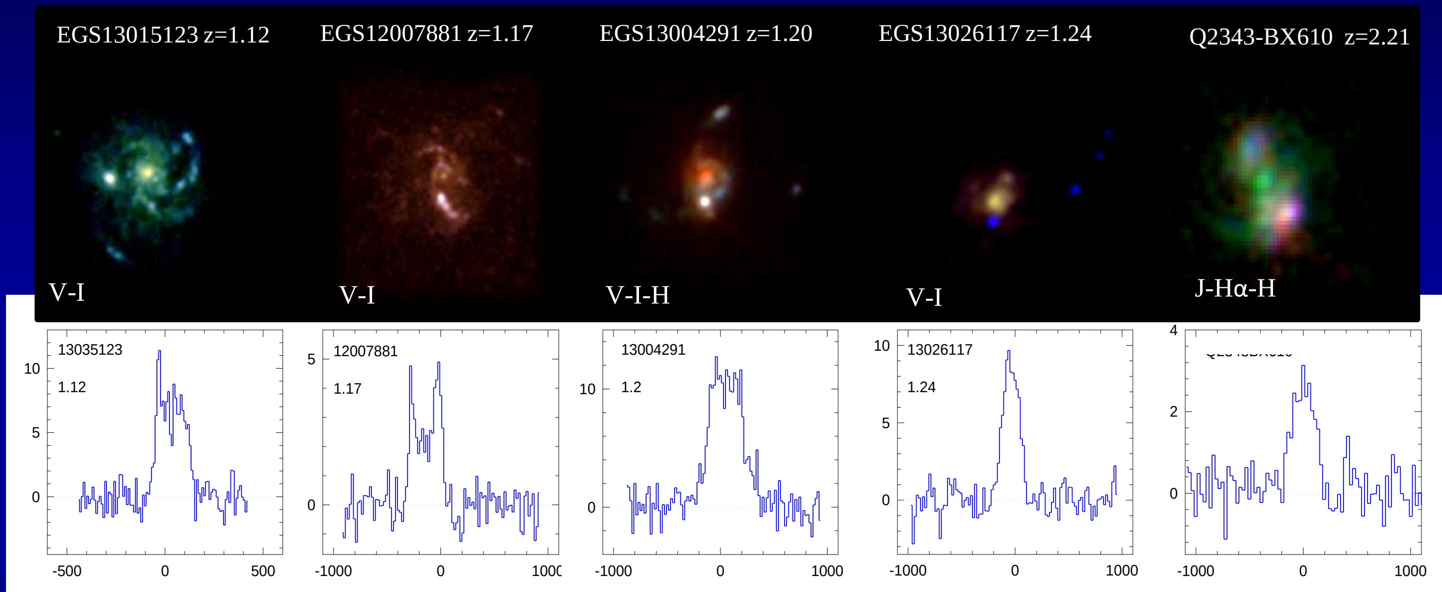
Molecular gas (through CO emission lines) can now be detected in moderate samples of z~1-2 main-sequence SFGs



Baker+ 2004; Bauermeister+ 2012, Combes+ 2012, 2013; Coppin+2007; Daddi+ 2008, 2010; Freundlich +2013; Geach+ 2011; Genzel+ 2010, 2012, 2013; Magnelli+ 2012, Swinbank+2011; Tacconi+ 2010, 2013

- CO 3-2 or 2-1 detected in ~75 z=1-2.5 main-sequence SFGs
- ~85% detection rate
- Mass and SFR Selected: $M_*=10^{10.7-11.2}$ $M_\odot$; SFR = 30-200 $M_\odot$/yr

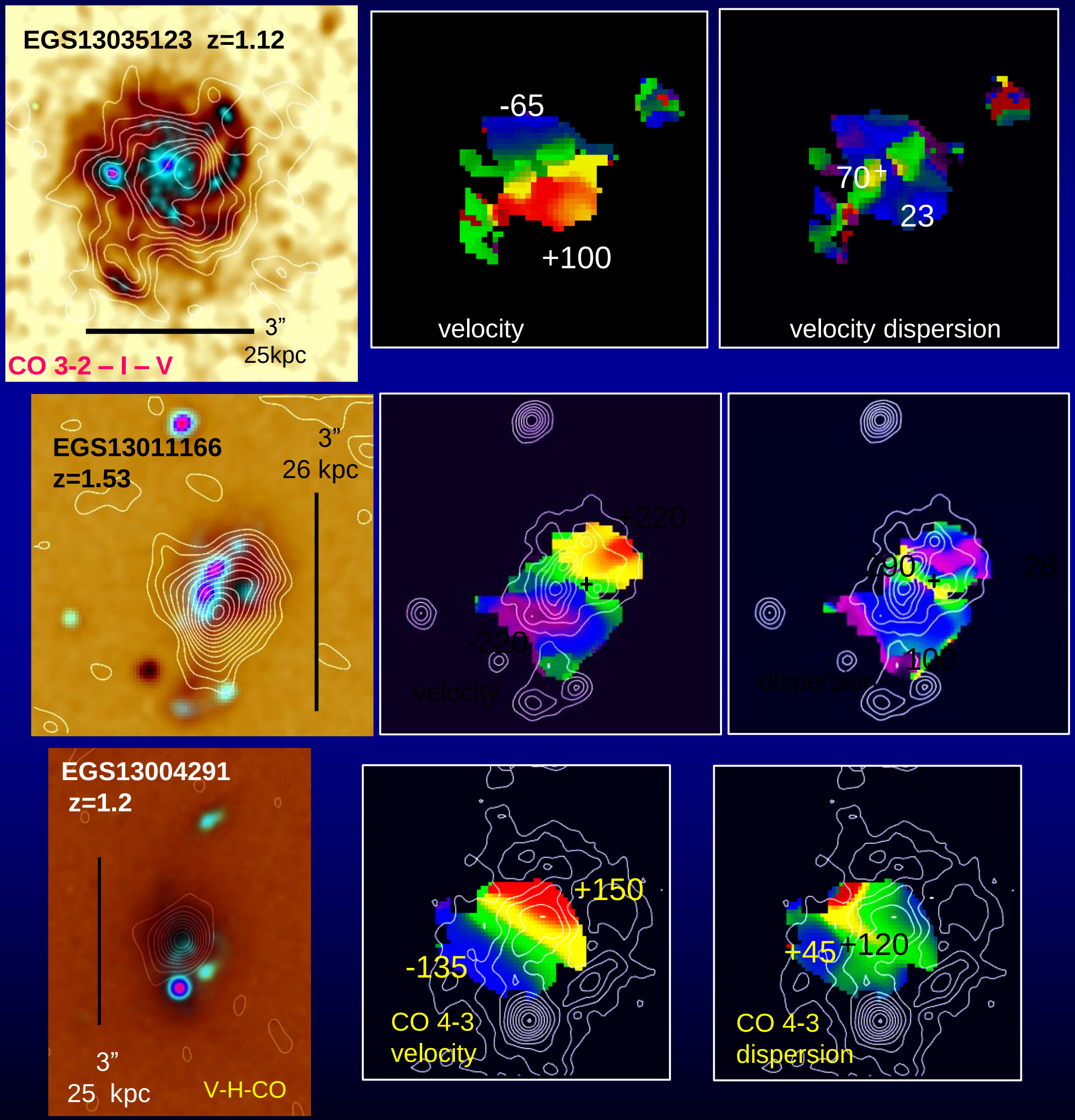
Molecular gas (through CO emission lines) can now be detected in moderate samples of z~1-2 main-sequence SFGs



Baker+ 2004; Bauermeister+ 2012, Combes+ 2012, 2013; Coppin+2007; Daddi+ 2008, 2010; Freundlich +2013; Geach+ 2011; Genzel+ 2010, 2012, 2013; Magnelli+ 2012, Swinbank+2011; Tacconi+ 2010, 2013

- CO 3-2 or 2-1 detected in ~75 z=1-2.5 main-sequence SFGs
- ~85% detection rate
- Mass and SFR Selected: $M_*=10^{10.7-11.2}$ $M_\odot$; SFR = 30-200 $M_\odot$/yr

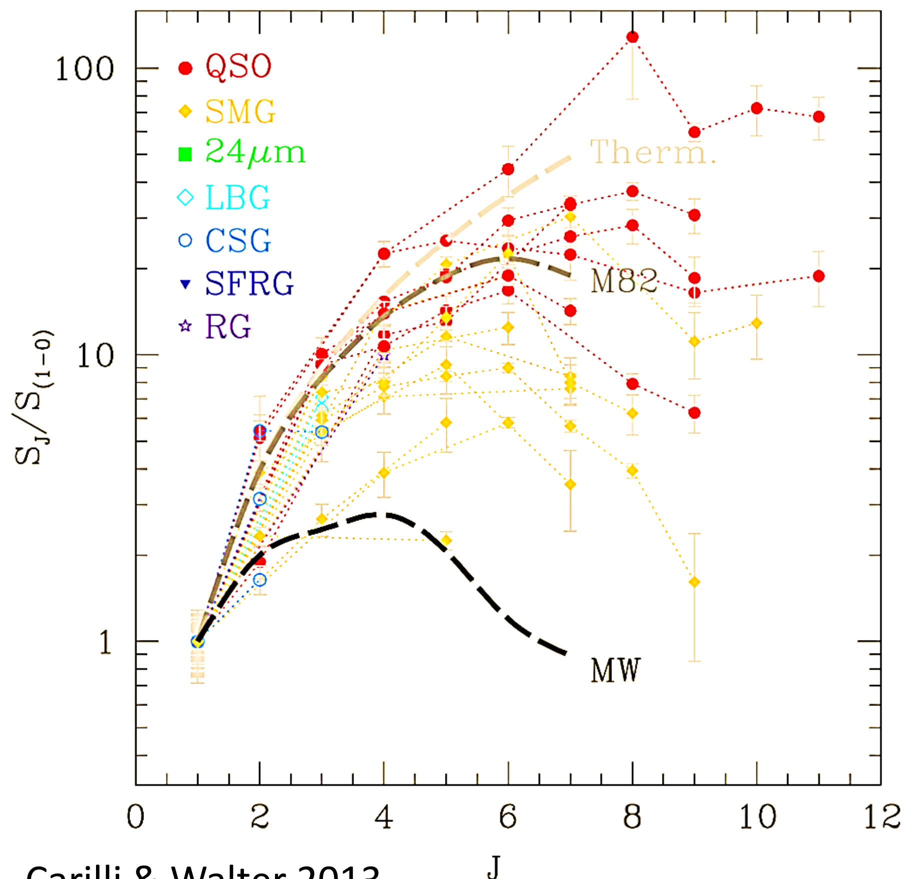
Sub-arcsecond Resolution Maps of the Cold Gas



- IRAM PdBI ~0.3"-0.7" resolution maps
- first rotation curves of massive end of main-sequence SFGs
- Typical <v/σ> ~6-8 from CO
- extended molecular disks

Combes et al. in prep,
Freundlich et al 2013,
Genzel et al. 2013,
Tacconi et al. 2010, 2013,

Molecular Gas Excitation at High Redshift



Carilli & Walter 2013

- Galaxy integrated excitation properties
- QSOs and SMGs excitation profiles similar to centers of SB galaxies and densest SF cores, but on kpc scales
- High-z "main sequence" SFGs more like MW excitation, but still very limited data sets and lines only up to 3-2

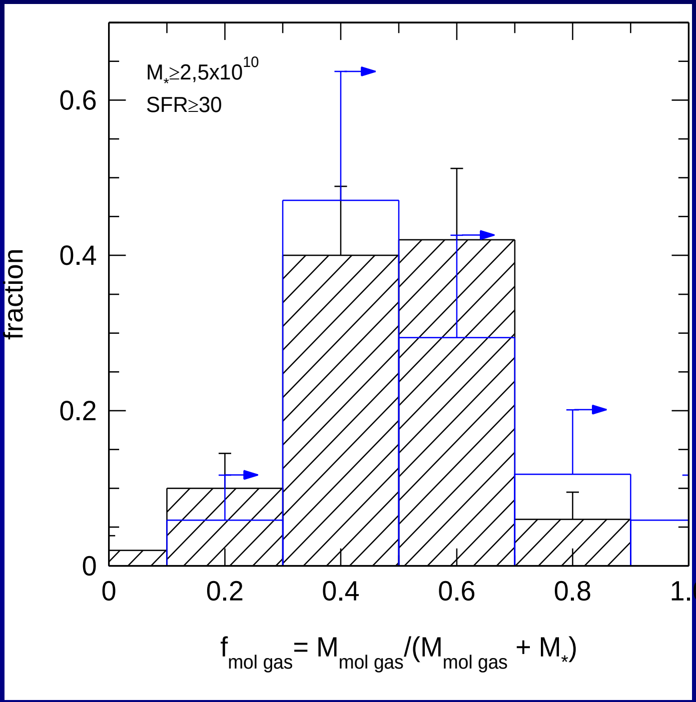
Also: Weiss+2007, 2011; Dannerbauer+2009, Aravena+2010, Bothwell+2013

Properties of star forming clouds for different galaxy populations

	Milky Way and nearby spirals	Main Sequence high-z SFGs: BzK/BX	Major Mergers: z~0 ULIRGs, brightest SMGs
M_{cloud}	$10^3 \ldots\ldots 10^{6.5}$	$10^{7.5} \ldots 10^{9.5}$	no clouds?
<Σ(gas)> $M_\odot pc^{-2}$	50…200 (N(H)~10^{22})	$10^{2.5} \ldots 10^3$	$10^{3.5 \ldots 4.5}$ (N(H)~10^{24})
P/k~19 Σ^2 (cm^{-3} K)	$10^{5.9}$ (<MW>~10^5)	$10^{7.3}$	$10^{9.3}$
σ (km/s)	~5	25-80	50-100

z=1-3 Massive SFGS Have High Molecular Gas Fractions

CO in ~70 "main sequence" SFGs



assuming:

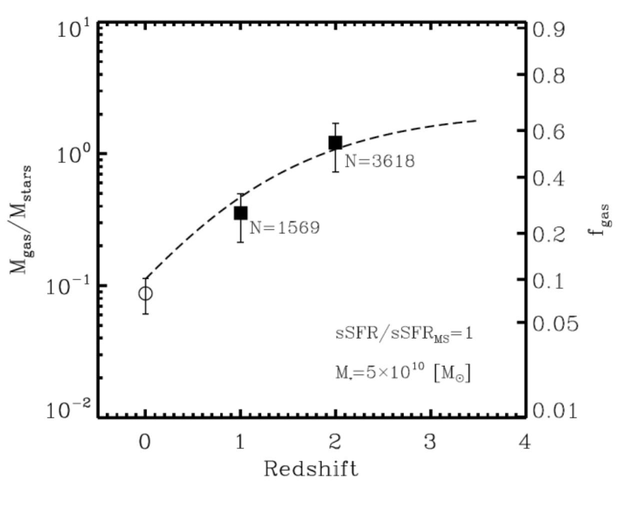
$$M_{mol\ gas} = \alpha_{CO}(n_{H2}^{1/2}/T, \Sigma_{gas}, Z) \times L_{CO\ 1\text{-}0}$$

$$\alpha_{CO} = 4.36\ M_\odot / (K\ km/s\ pc^2)\ \ (=\text{Milky Way})$$

$$L'_{CO\ 3\text{-}2} / L'_{CO\ 1\text{-}0} = 0.5$$

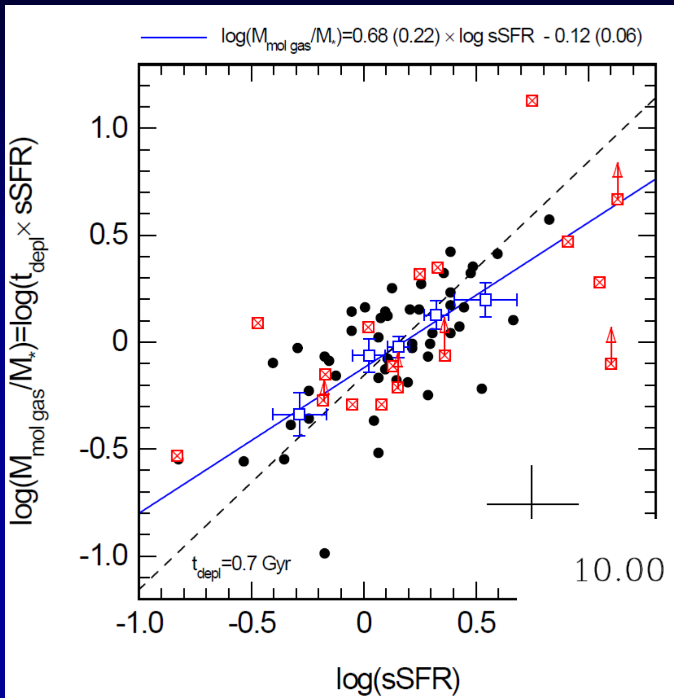
after correction for incomplete sampling of M_*-SFR plane:
$<f_{molgas}>$= 0.33 at z~1.2
0.47 at z~2.2

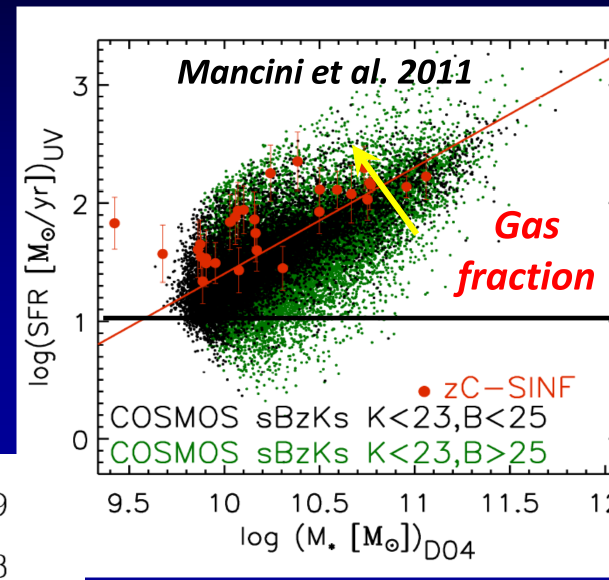
Dust masses from stacked ensembles with IR-mm SEDs

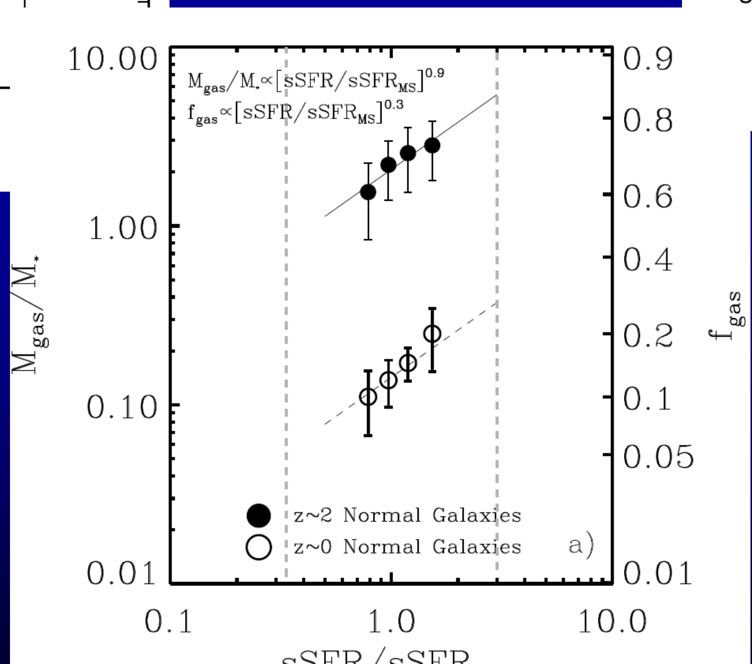


CO: Tacconi+2010,2013; Genzel+ 2010, 2012, 2013, Combes+ 2012, 2013, Freundlich+ 2013, Daddi+ 2008, 2010, Baker+ 2004, Coppin+ 2007, Geach+ 2011, Bauermeister+2012

Strong Correlation between Molecular Gas Fraction and sSFR





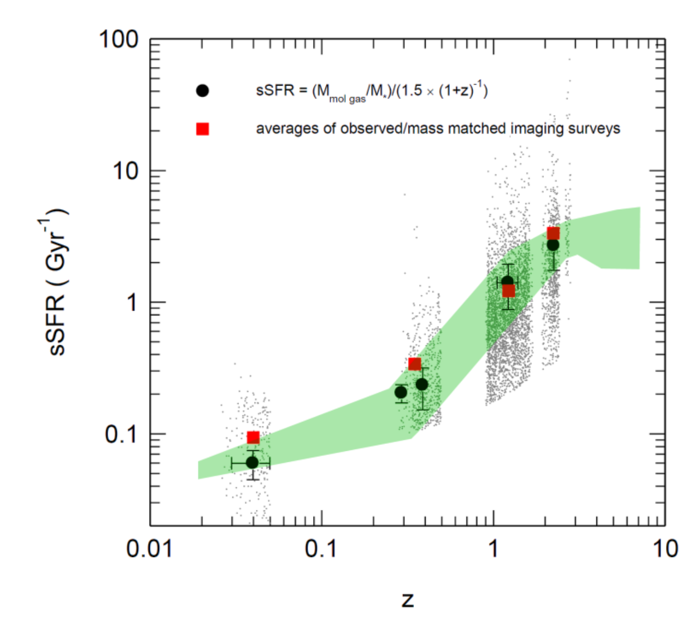


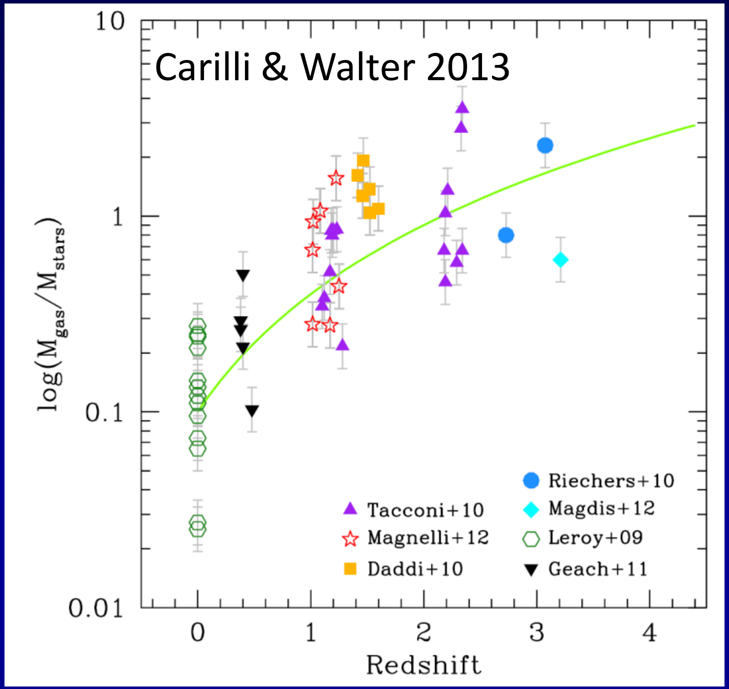
Dust continuum and CO gas mass estimates are in very good agreement

Magdis et al 2011, 2012; Tacconi et al. 2013

Evolution of Molecular Gas Fractions

PHIBSS – sSFR vs z



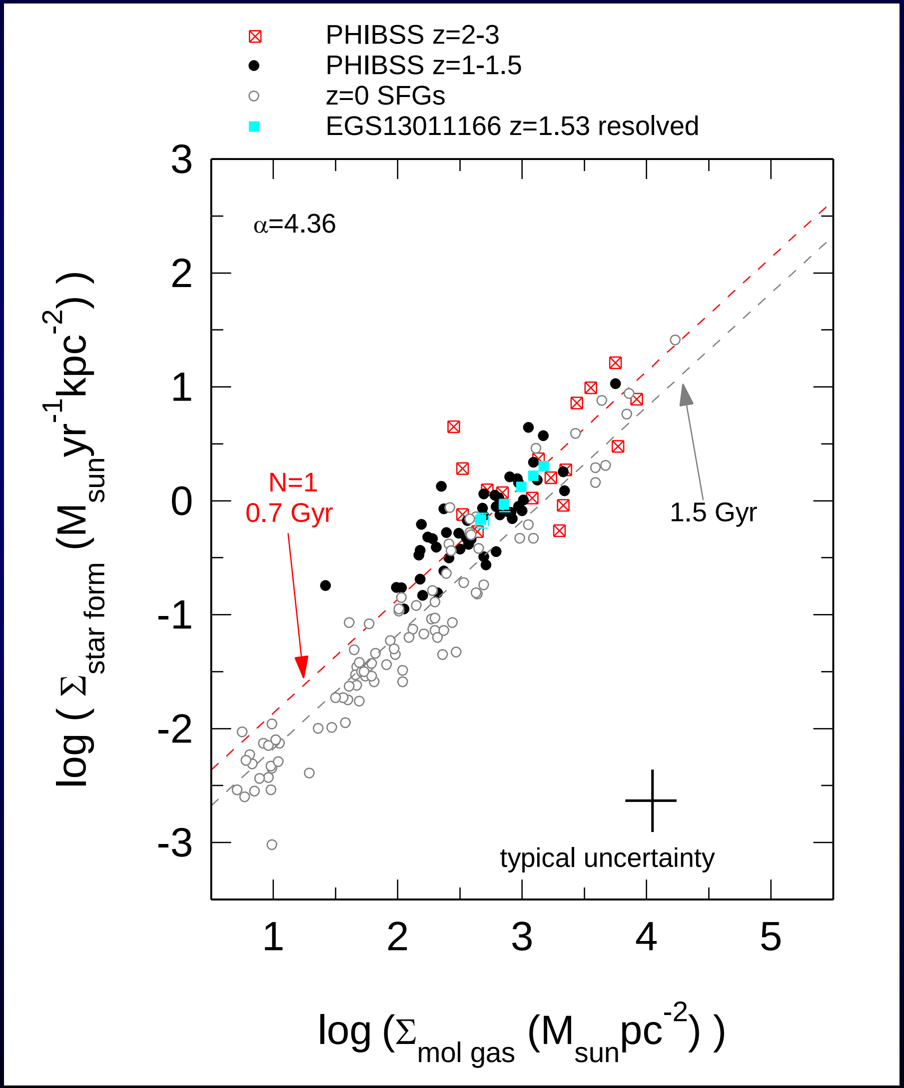


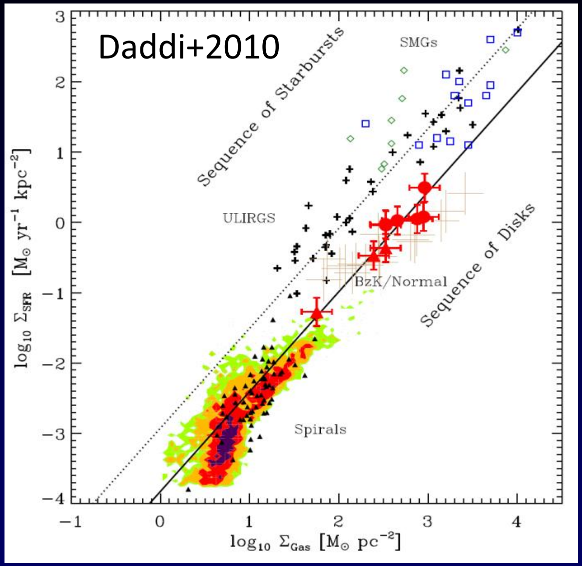
CO: Tacconi+2010,2013; Genzel+ 2010, 2013, Combes+ 2011, Daddi+2008, 2010, Baker+2004, Coppin+ 2007, Geach+ 2011, Bauermeister+2013, Saintonge+2011a,b

Dust continuum: Magdis+2012, Scoville 2012

Imaging survey compilations: Weinmann+2011, Sargent+2010, Gonzalez+2012

Galaxy Integrated SFR-Gas Relation from z=0-3





$$\tau_{depletion} = \frac{M_{gas}}{SFR} = \text{~.7 Gyrs at z~1-3}$$

$$= \text{1.5-2.5 Gyrs at z~0}$$

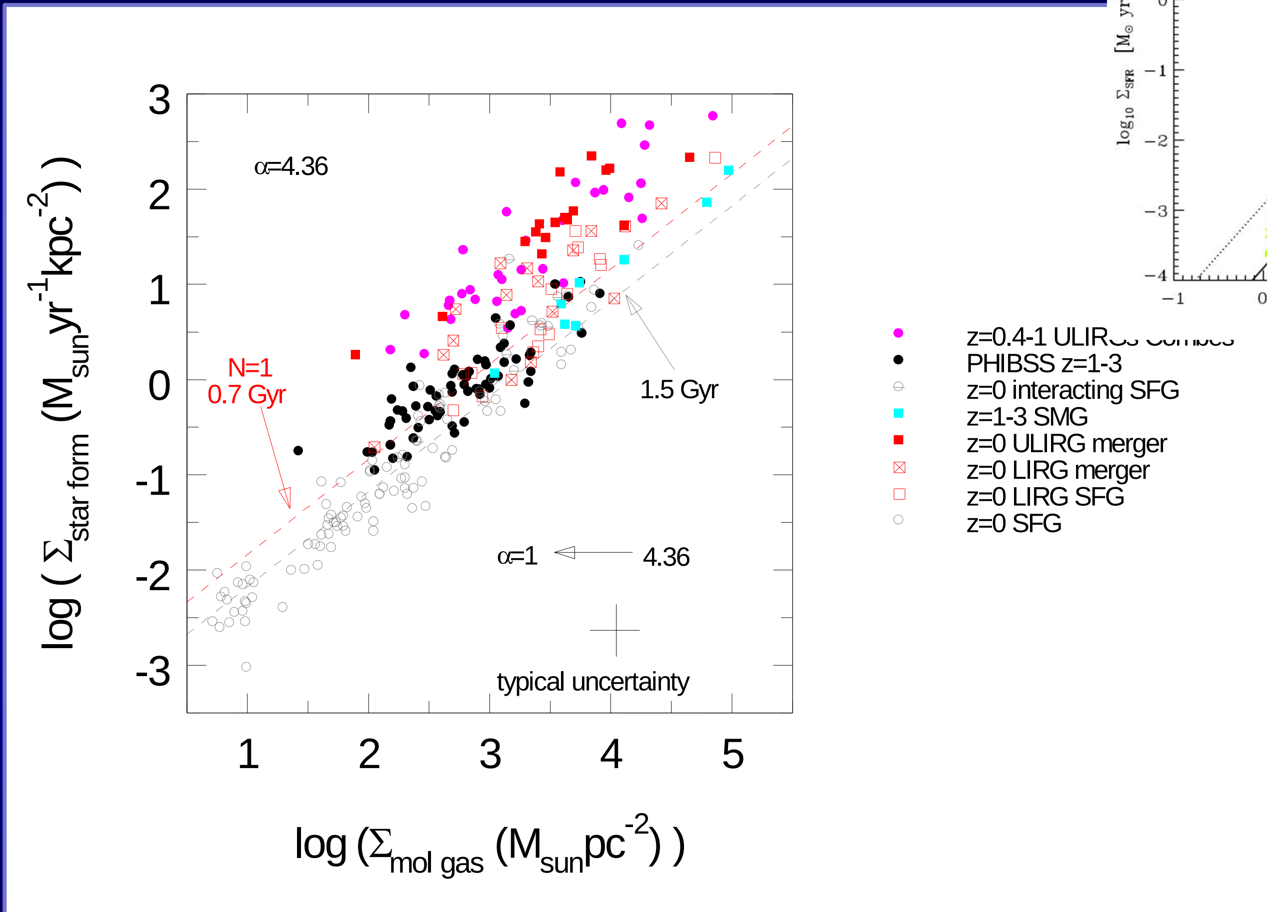
$$< T_{Hubble}$$

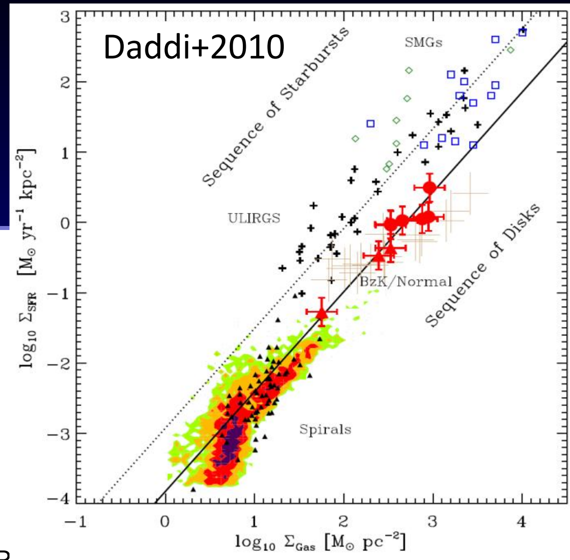
requires semi-continuous replenishment

N_{mol}=1.1±0.15
for 50 z=1-1.5 PHIBSS SFGs

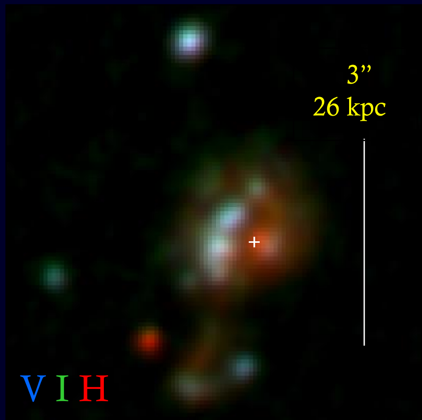
(Kennicutt 1998, Kennicutt+2007, Bigiel+2008, 2011, Daddi+2010, Genzel+2010, 2013, Kennicutt & Evans 2012, Tacconi+2013)

Galaxy Integrated SFR-Gas Relation from z=0-3

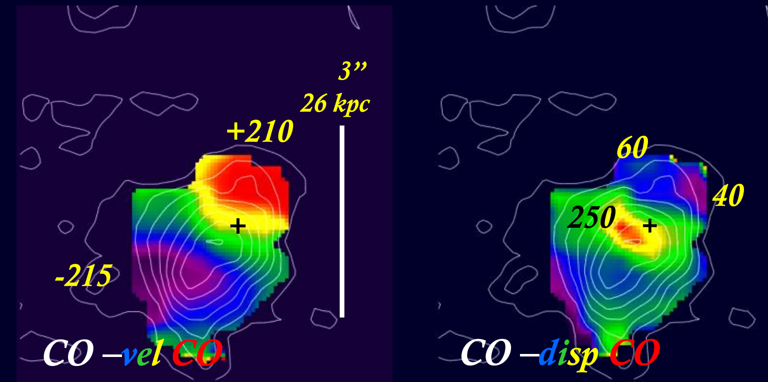


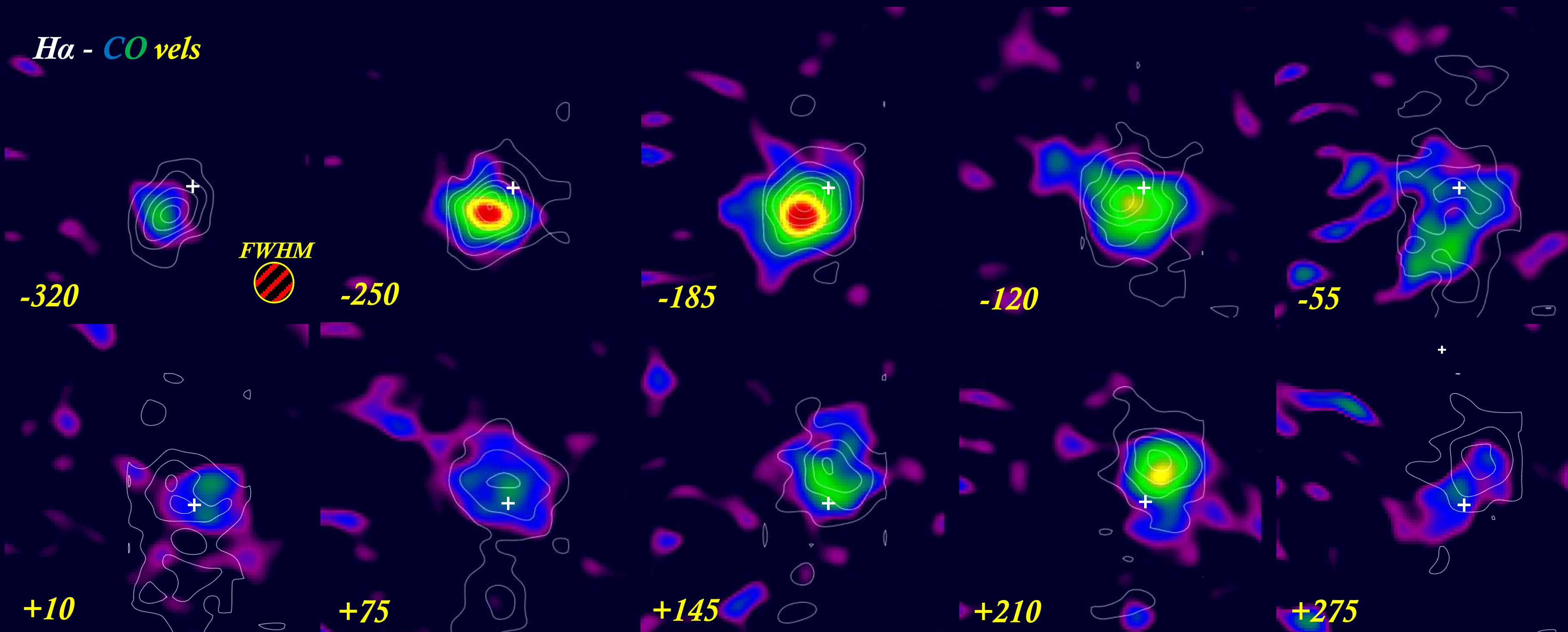


(Kennicutt 1998, Kennicutt+2007, Bigiel+2008, 2011, Daddi+2010, Genzel+2010, 2013, Kennicutt & Evans 2012, Tacconi+2013)

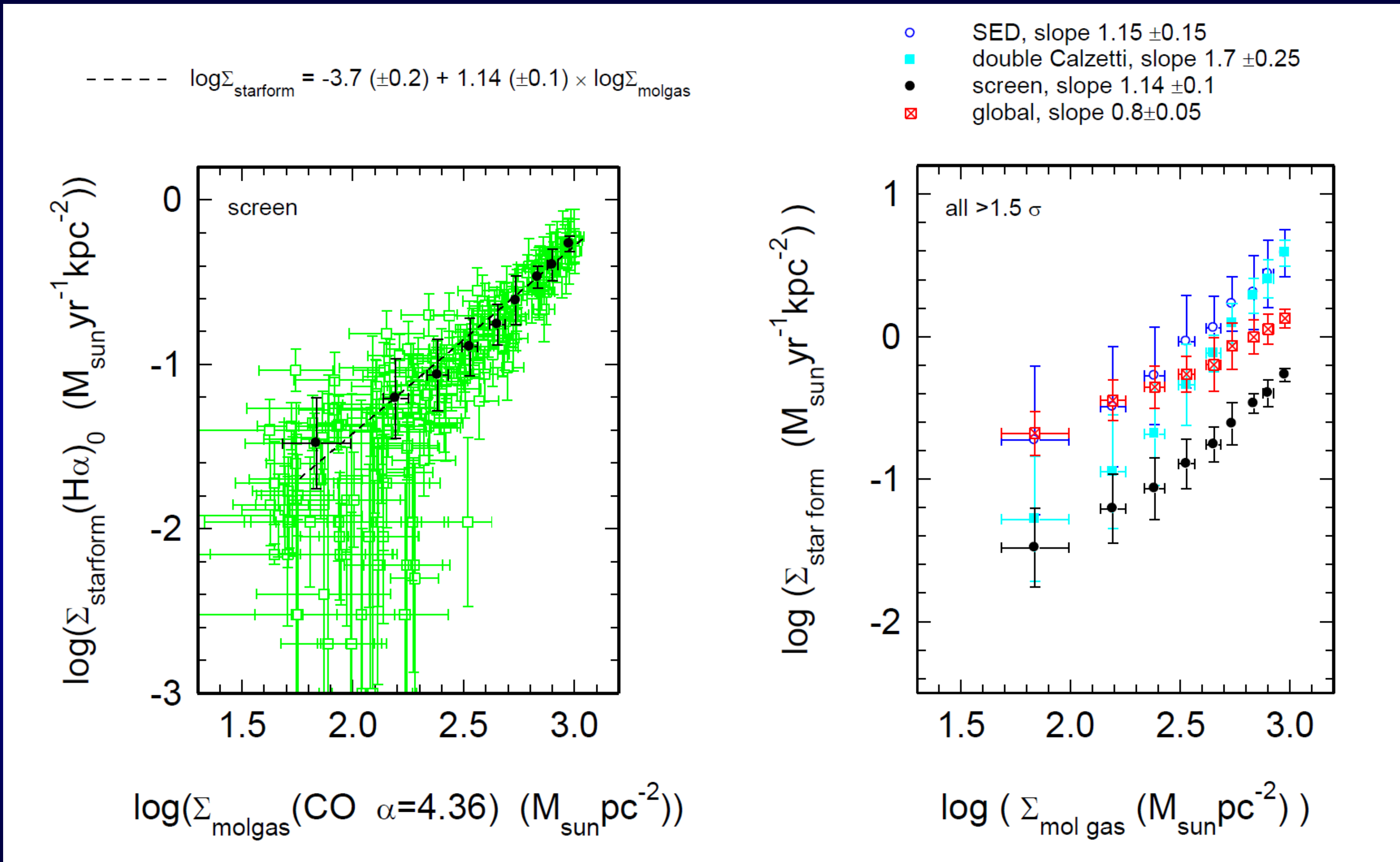


CO and Hα Kinematics in EGS13011166





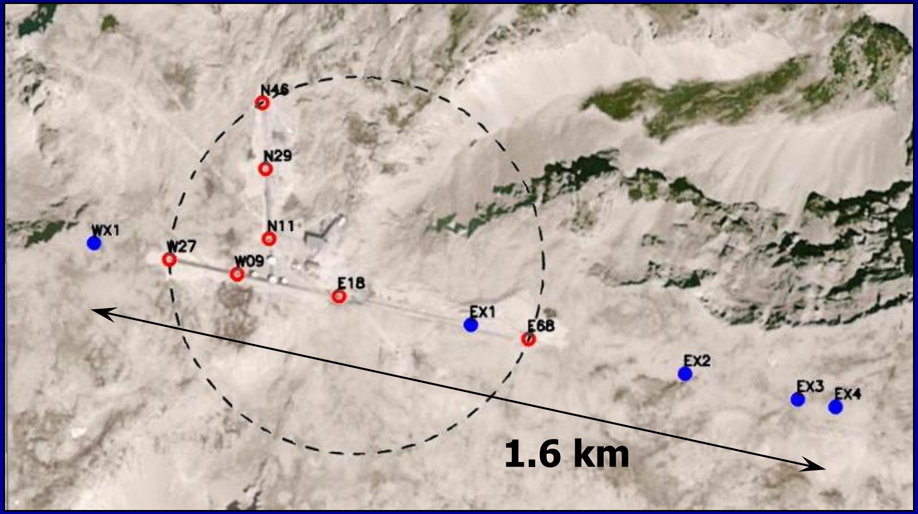
Spatially Resolved KS-relation



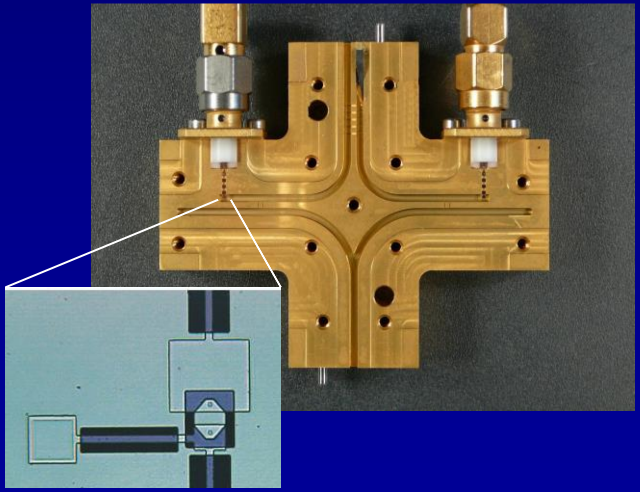
Genzel et al. 2013

What is NOEMA?

doubling the collecting area: 6 ⇒ 12 telescopes



improving resolution by factor ~2 to 0.2”



quadrupling bandwidth to 32 GHz

Summary

• Molecular gas estimates from CO now in well over 100 star forming galaxies at high-z, including SMGs, "main-sequence" SFGs, and strongly lensed sources. Spatially resolved dynamical information in ~25-30 sources.

• High-redshift main sequence SFGs follow molecular gas-star formation K-S relation with a roughly linear slope, indicating roughly constant t_{depl} ~700 Myr. Extreme "Above main sequence" galaxies seem to follow an independent near linear relation with shorter $t_{depl.}$

• Massive star forming galaxies from z=1-3 are gas-rich with observed $\langle f_{gas} \rangle$ ~ 0.35-0.50, ~6x larger than similarly selected main sequence galaxies at z=0.

• Gas fractions correlate strongly with the specific star formation rate, sSFR=SFR/M*, suggesting that at constant stellar mass, the vertical location of a galaxy on the M*-SFR plane largely driven by gas fraction.