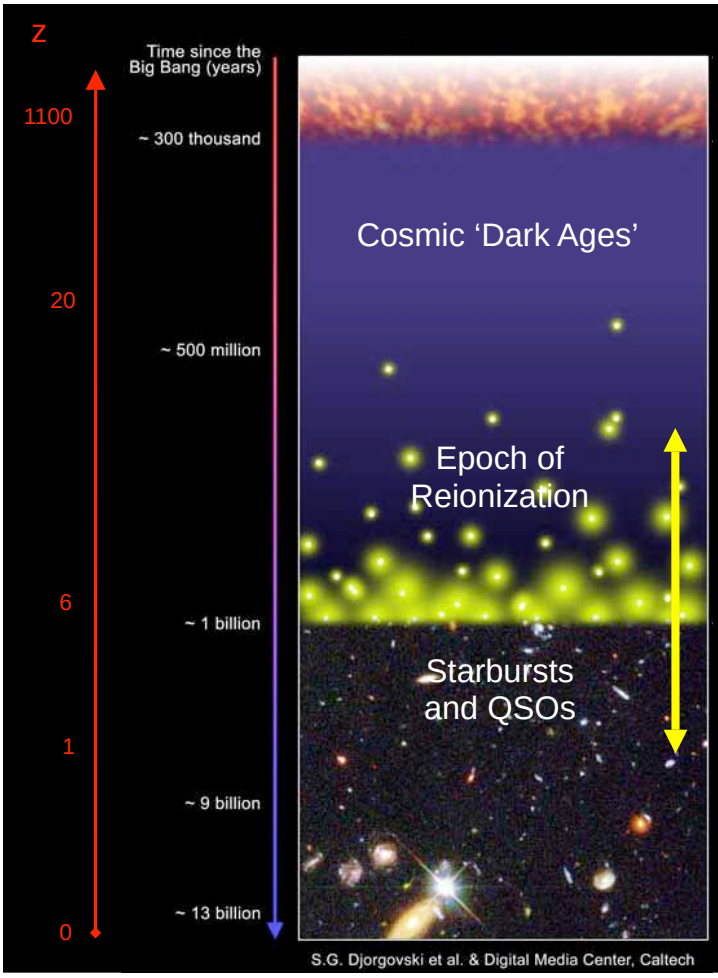
Starburst galaxies

Observational Cosmology 20.5.2009

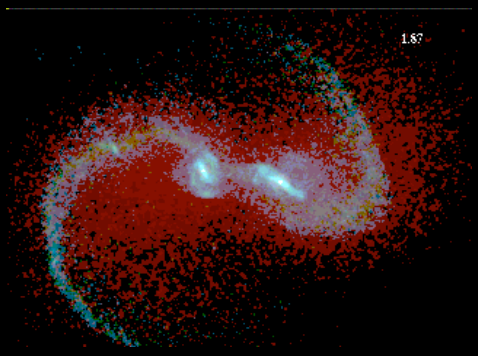


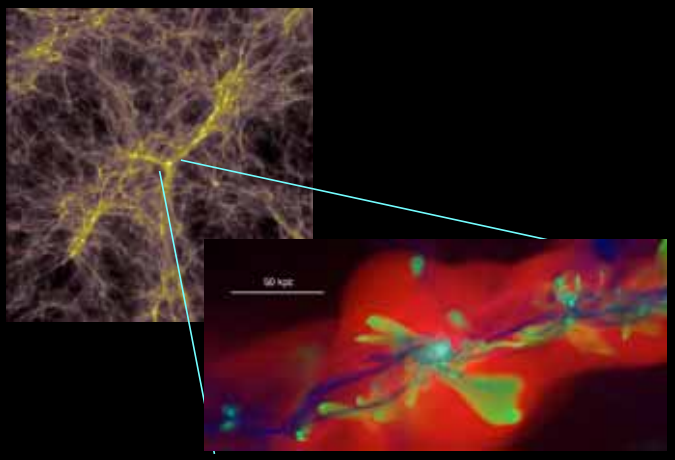
Major themes and questions regarding the formation and evolution of galaxies:

- First stars and AGN
- Mergers vs. cold streams driving galaxy formation
- Spatially resolved distributions of SF, gas, stellar populations, metallicities
- Rotation curves & connection to halo; angular momentum distribution
- Co-evolution of massive black holes and host galaxies
- Roles of mergers vs. secular evolution / environment
- Bulge vs disk formation
- Roles of stellar and AGN feedback

What drives galaxy and star formation at high-z ?

How do galaxies get their gas ? What are gas fractions in galaxies as a function of mass, redshift, environment…? Effect on star formation efficiency?





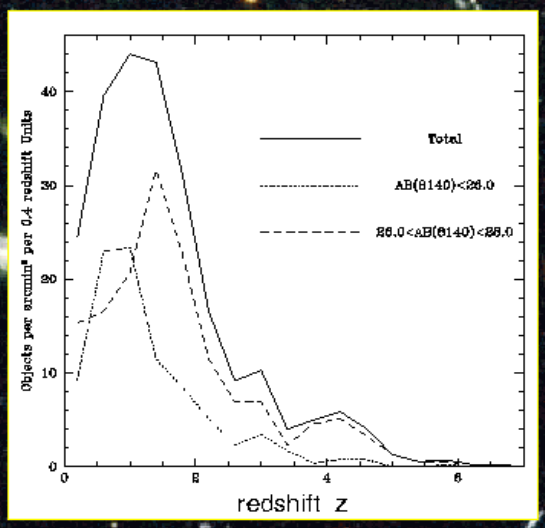
Major mergers

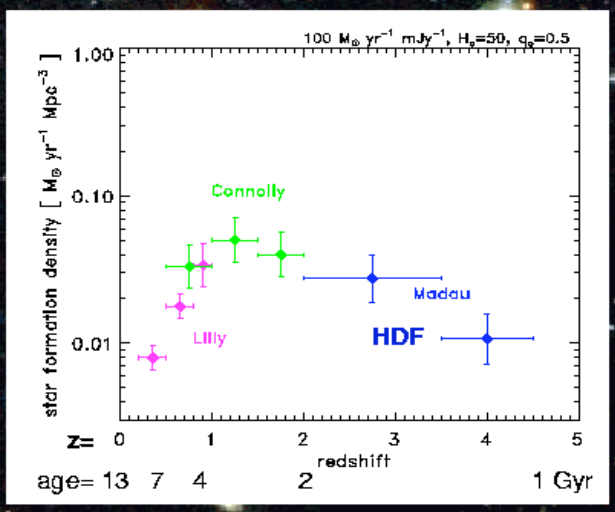
Kauffmann et al. 1993, Steinmetz & Navarro 2003, Hernquist, Springel, di Matteo, Hopkins et al. 2003-2006, Robertson & Bullock 2008

Minor mergers and steady accretion:

Dekel & Birnboim 2003,2006, Keres et al. 2005, Nagamine et al. 2005, Davé 2007, Kitzbichler & White 2007, Naab et al. 2007, Governato et al. 2008, Ocvirk et al. 2008, Dekel et al. 2009, Agertz et al. 2009

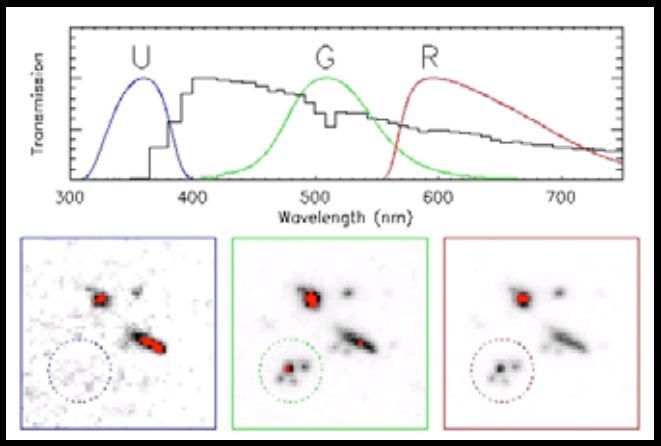
1996: Star formation history from the Hubble Deep Field

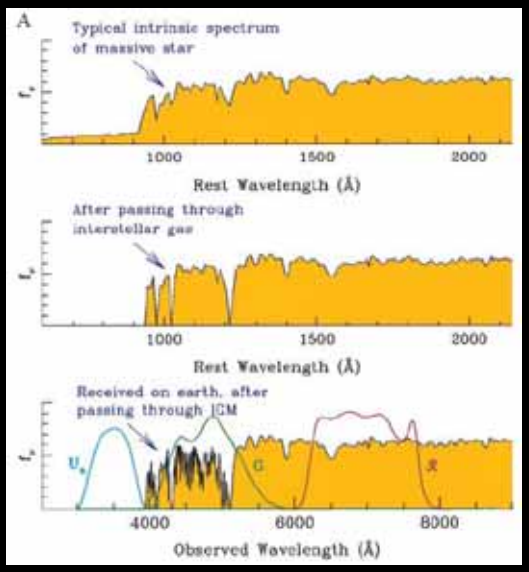


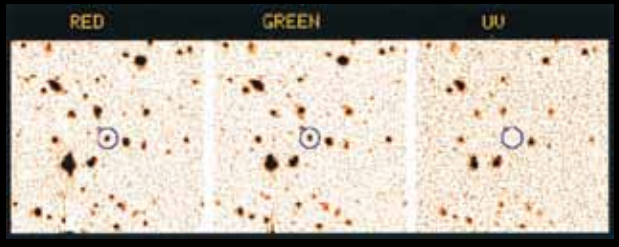


Problems: extinction, massive bulges, extragal. IR background

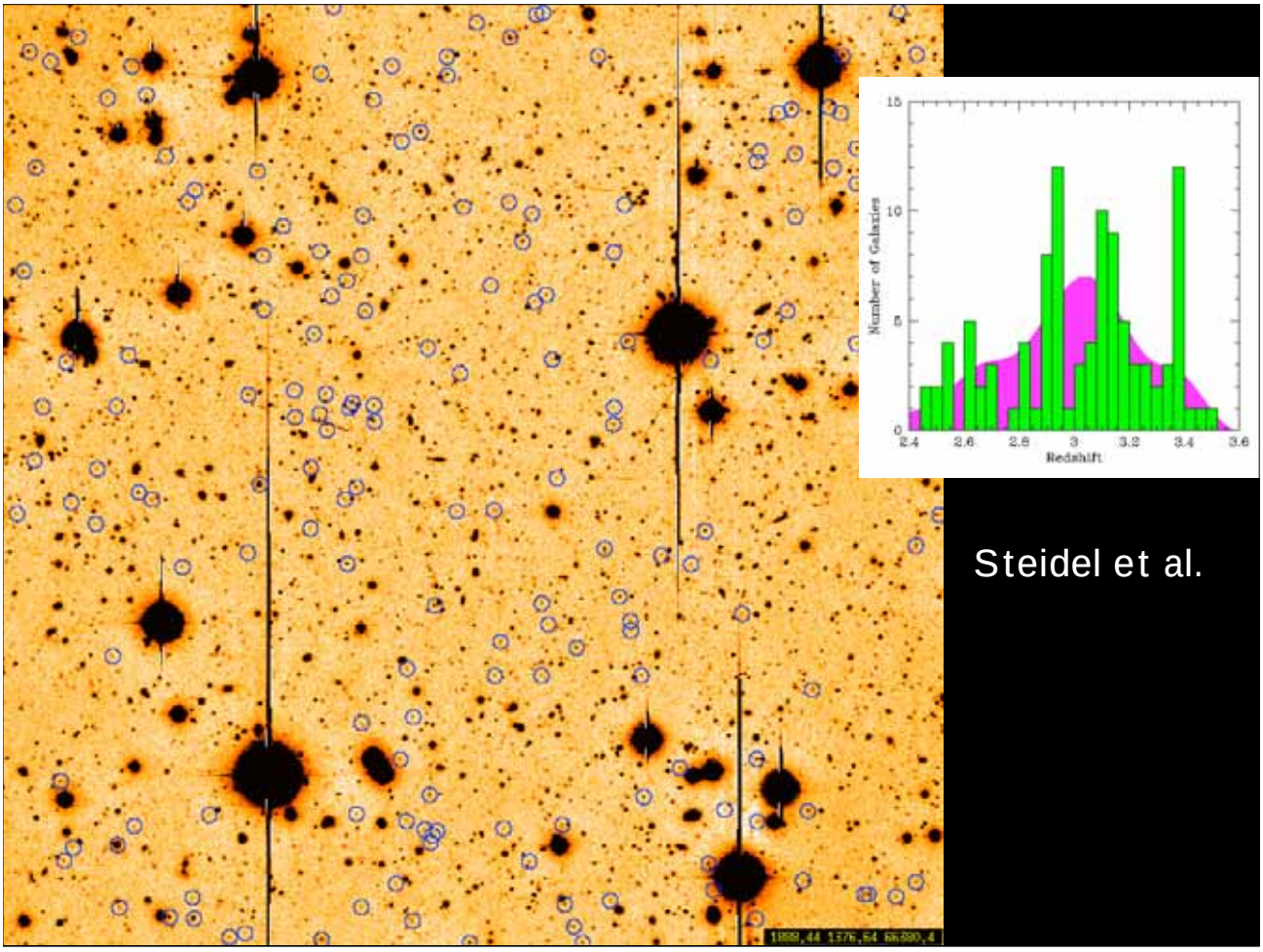
Lyman Break Galaxies



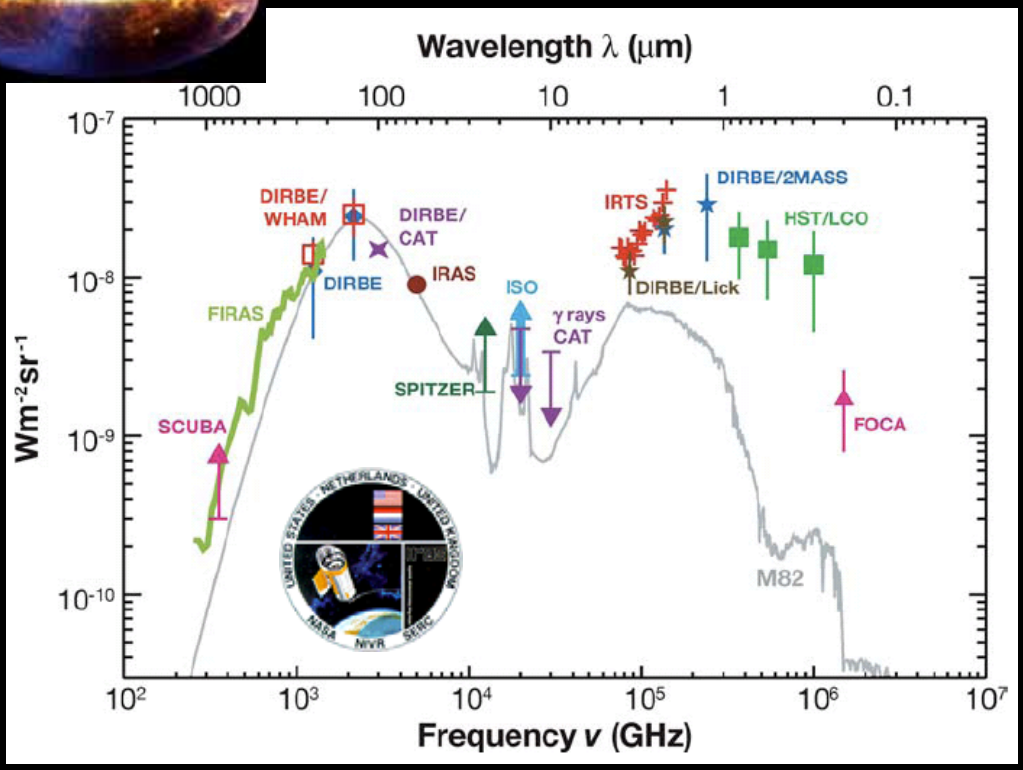




u-dropouts at z>2.5

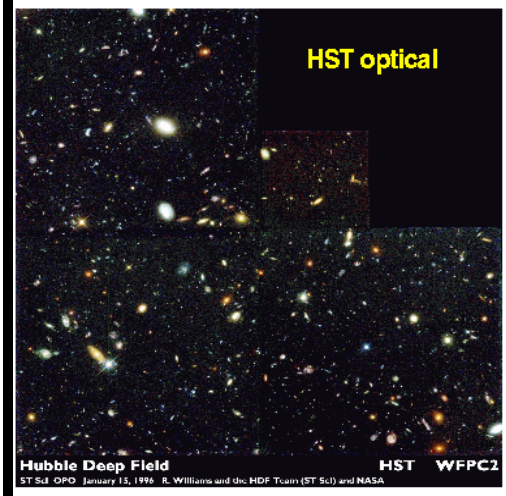


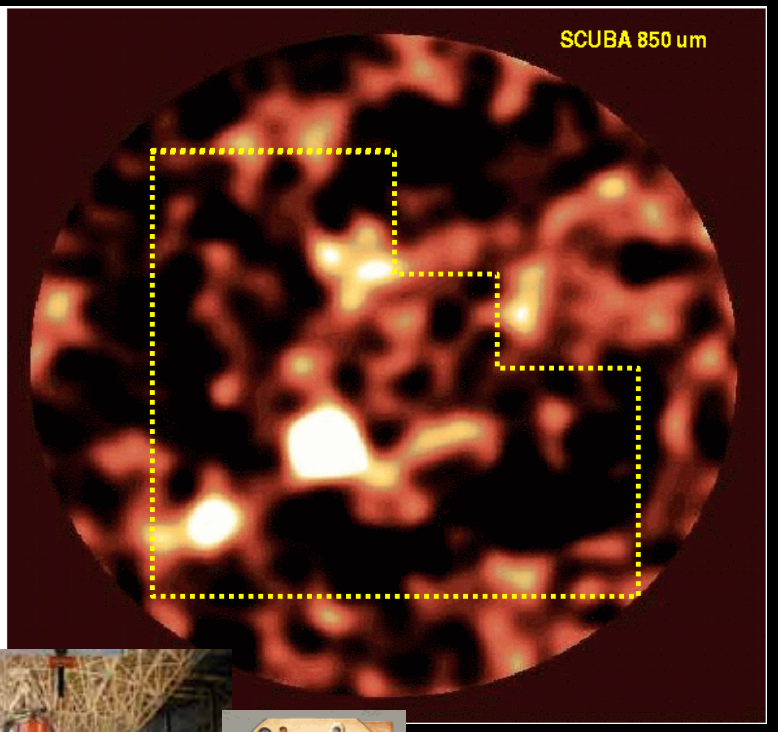
The „Diffuse“ Extragalactic Background

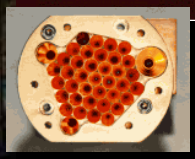


The submillimeter extragalactic Background

The Hubble Deep Field



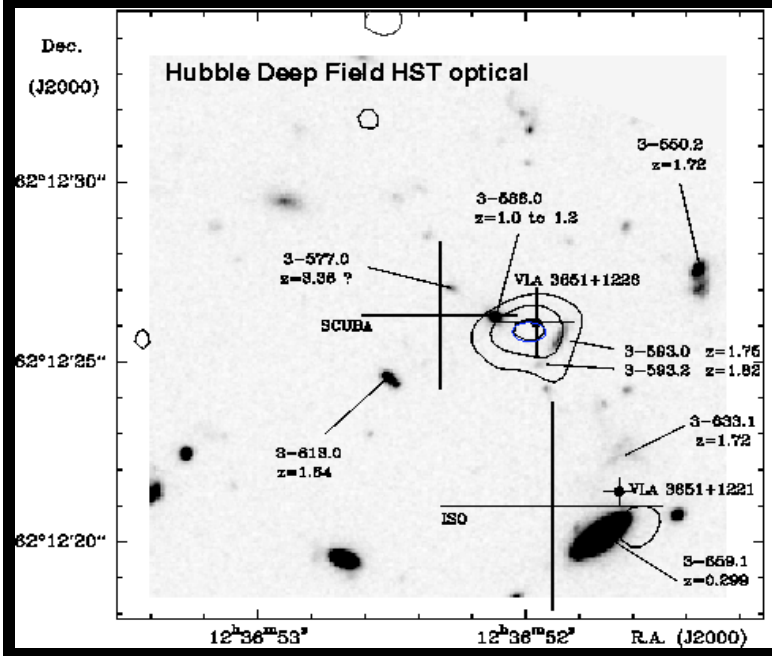


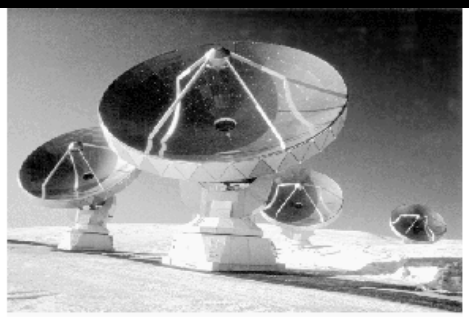


Hughes et al. 1998

SCUBA first resolved the submm background

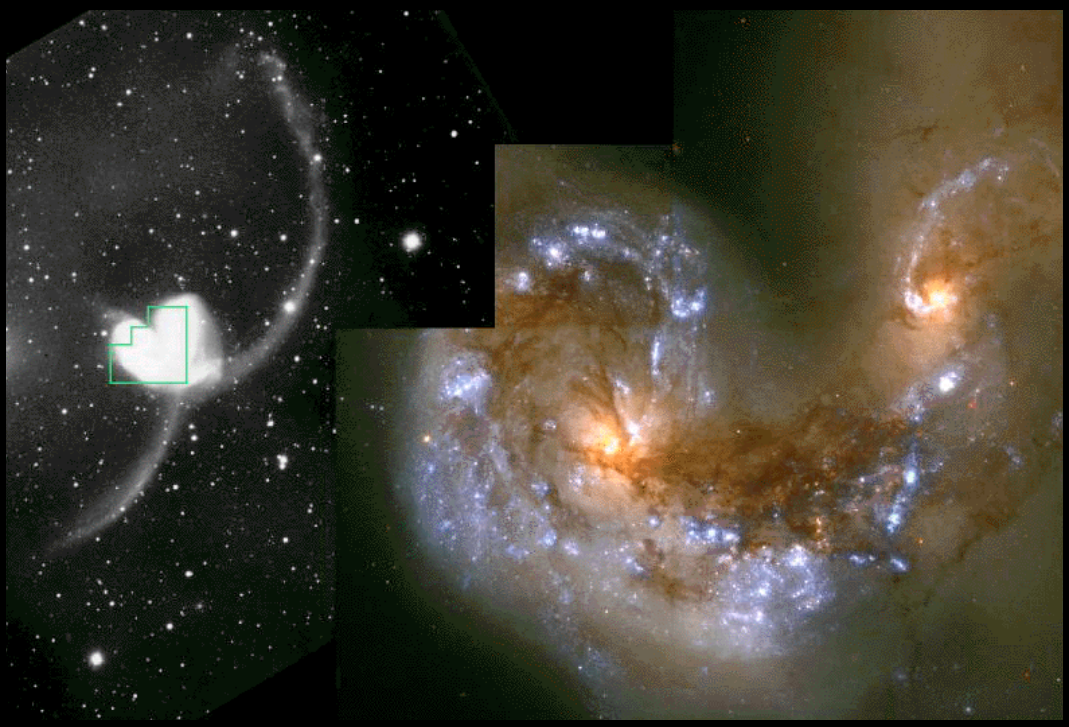
... first resolved, but not identified:





IRAM Plateau de Bure Interferometer
1.25mm

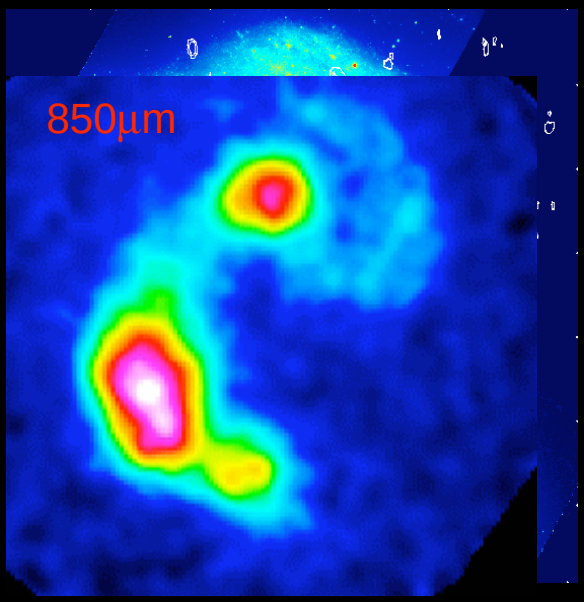
(sub)mm-background sources typically have no optical or near-infrared counterpart !



Arp 244 (Antenna)

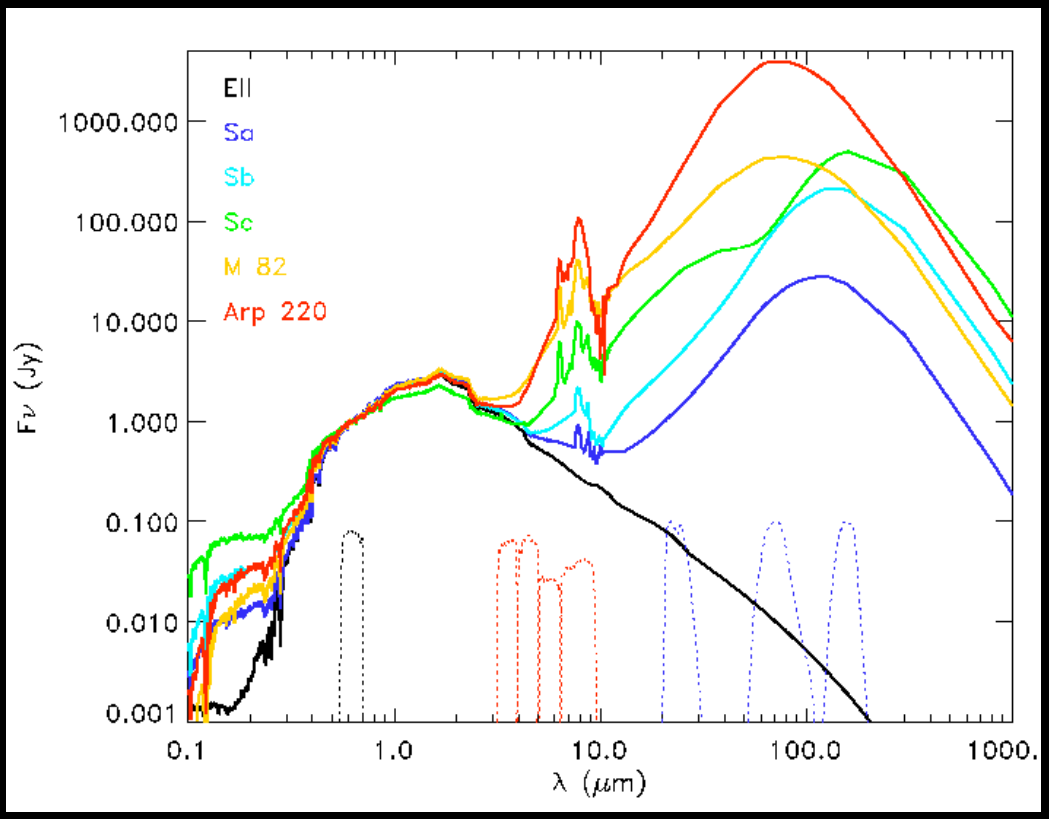
The archetypical interacting galaxy

CO + optical



The starburst is hidden behind dense dust clouds

Variety of Galaxy SEDs



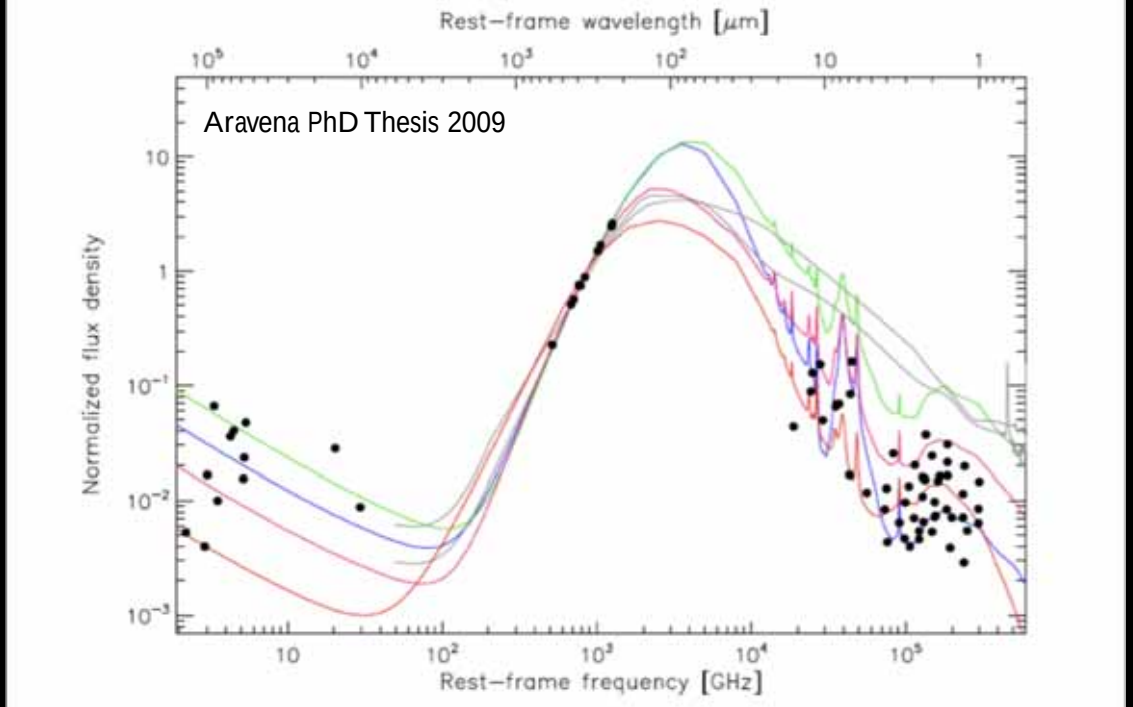
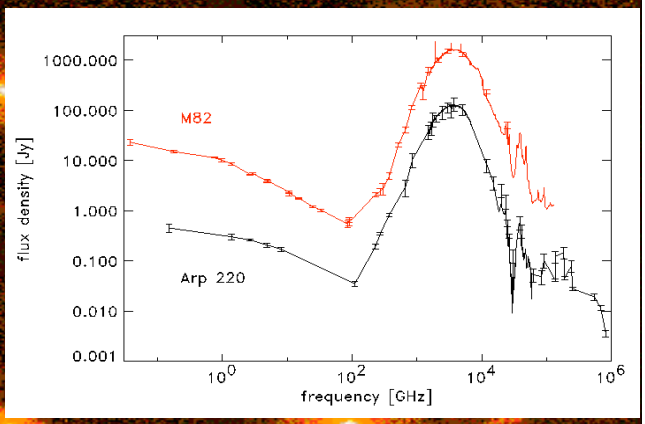
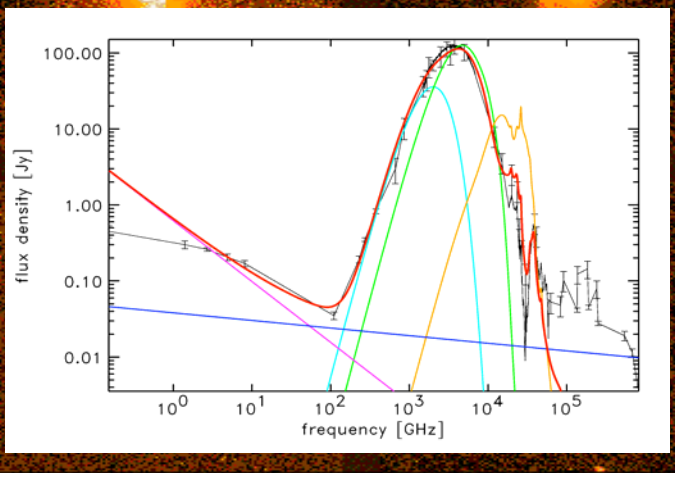


Figure 1.4: *Various observed restframe spectral energy distributions (SEDs) of starburst galaxies and QSOs from the radio to the optical wavebands normalized to unity at 350 μm. Solid curves represent model SEDs for three luminous low-redshift starburst galaxies Arp220 (blue), M82 (green) and NGC6090 (magenta), and for an extremely red object (ERO) at z = 1.44, HR10 (red), from Silva et al. (1998). The grey curves show the model SEDs for a QSO type-1 and type-2 from Polletta et al. (2007). Filled circles show the multi-frequency SED for SMGs detected in the Hubble Deep Field North (HDF-N), from Pope et al. (2006).*

Starburst Galaxies



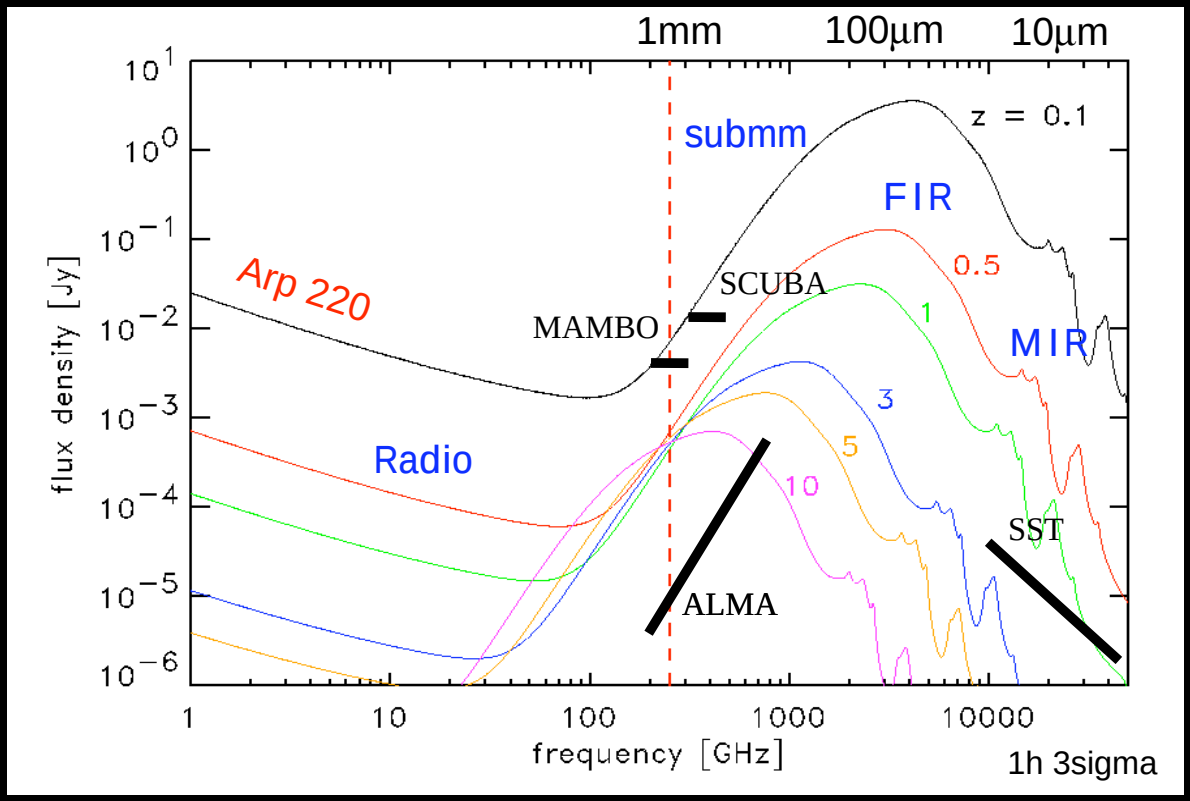


Archetypical local starbursts: Arp220 and M82

Can be decomposed into Different temperature Components.

Redshifted SED of a starburst galaxy

the negative K-correction makes the brightness at mm-wavelenths independent of distance (at z>0.5)

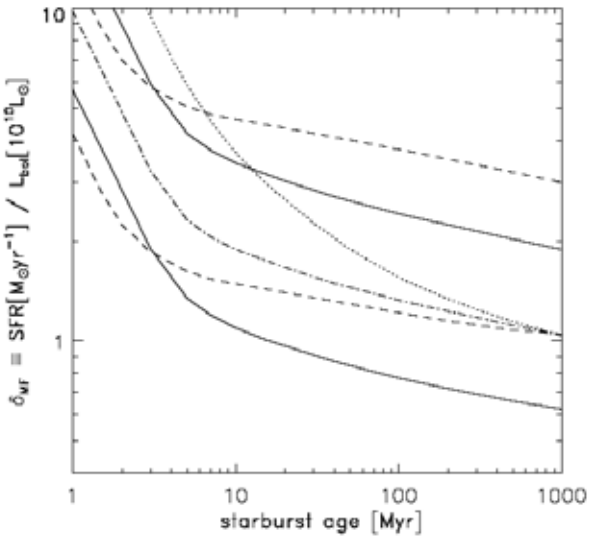


Estimating the star formation rate

$$L_{\rm FIR} \sim 3.6 \times 10^{12}\ (S_{250}/{\rm mJy})\ \ L_\odot\ .$$

$$\dot{M}_{\rm SF} = \delta_{\rm MF}\ (L_{\rm FIR}/10^{10}\ L_\odot)\ \ M_\odot\ {\rm yr}^{-1}\ ,$$

$$\dot{M}_{\rm SF}\ \approx\ 360\ \delta_{\rm MF}\ \delta_{\rm SB}\ (S_{250}/{\rm mJy})\ M_\odot\ {\rm yr}^{-1}\ .$$



Solid: Salpeter IMF m_l=0.1/1.6Msun.
Dashed: Telescop & Gatley instead of Schaerer.
Dash-dotted: flat IMF below 1 Msun
Dotted: log-normal IMF dlogN/dlogm=-log m

Estimating dust mass:

$$M_{\rm d} = \frac{S_{250}\, D_{\rm L}^2}{(1+z)\,\kappa_{\rm d}(\nu_{\rm r})\,B(\nu_{\rm r}, T_{\rm d})}\ ,$$

$$M_{\rm d} \approx 1.1 \times 10^8\, F(T_{\rm d}) \left(\frac{7.5\ {\rm cm^2\ g^{-1}}}{\kappa_{\rm d}(230\ \mu{\rm m})}\right) \left(\frac{S_{250}}{\rm mJy}\right) M_\odot$$

$$F(T_{\rm d})\ =\ (\exp[h\nu/kT_{\rm d}] - 1)/(\exp[h\nu/k \cdot 50\ {\rm K}] - 1)$$

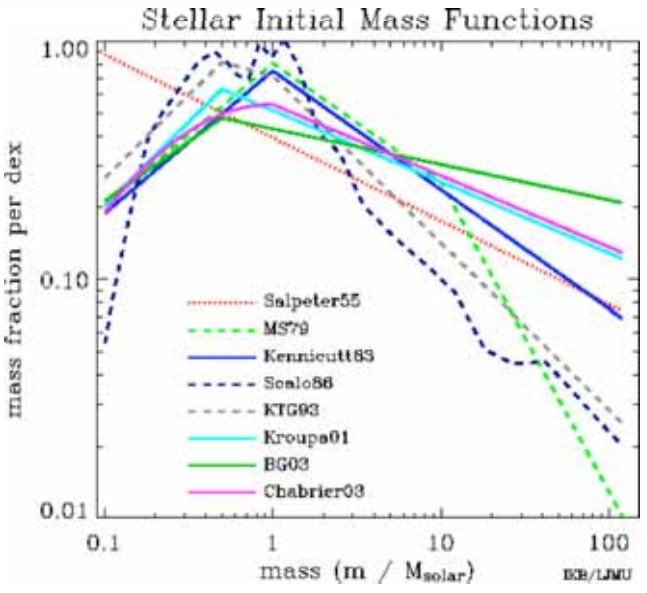
The IMF is often stated in terms of a series of power laws, where $N(M)dM$, the number of stars with masses in the range M to $M + dM$ within a specified volume of space, is proportional to $M^{-\alpha}$, where α is a dimensionless exponent. The IMF can be inferred from the present day stellar luminosity function by using the stellar mass-luminosity relation together with a model of how the star formation rate varies with time.

The IMF of stars more massive than our sun was first quantified by Edwin Salpeter in 1955. His work favoured an exponent of $\alpha = 2.35$. This form of the IMF is called the **Salpeter function** or a Salpeter IMF. It shows that the number of stars in each mass range decreases rapidly with increasing mass.

Later authors extended the work below one solar mass. Glenn E. Miller and John M. Scalo suggested that the IMF "flattened" (approached $\alpha = 0$) below one solar mass. Pavel Kroupa kept $\alpha = 2.3$ above half a solar mass, but introduced $\alpha = 1.3$ between 0.08-0.5 solar masses and $\alpha = 0.3$ below 0.08 solar masses.

There are large uncertainties concerning the substellar region.

WIKIPEDIA
Die freie Enzyklopädie



The Initial Mass Function for stars in the Solar neighborhood was determined by Salpeter in 1955. He obtained:

$$\xi(M) = \xi_0 M^{-2.35}$$ **Salpeter IMF**

ξ_0: constant which sets the local stellar density

Using the definition of the IMF, the number of stars that form with masses between M and M + ΔM is: $\xi(M)\Delta M$

To determine the total number of stars formed with masses between M_1 and M_2, integrate the IMF between these limits:

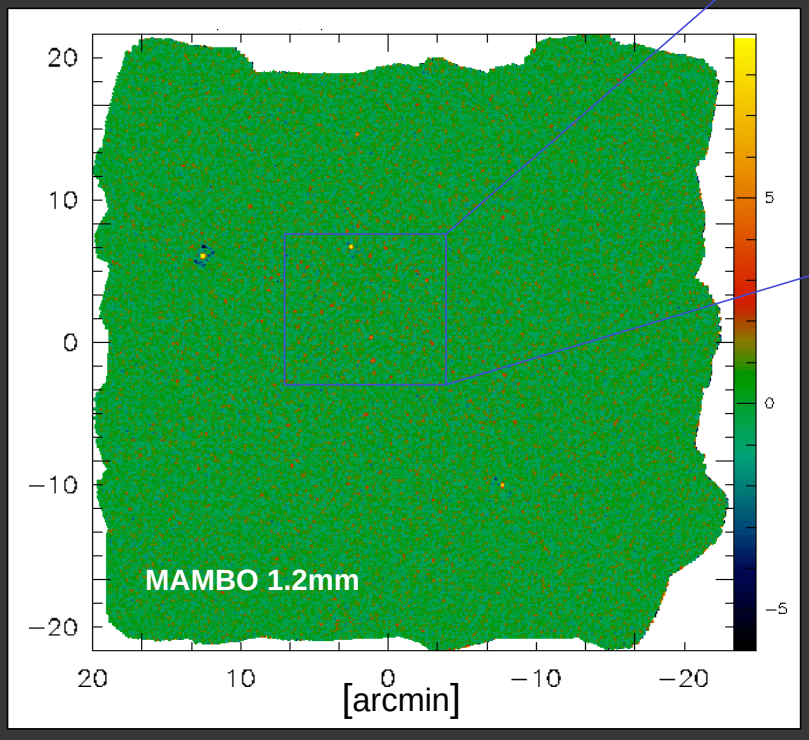
$$N = \int_{M_1}^{M_2} \xi(M)dM = \xi_0 \int_{M_1}^{M_2} M^{-2.35} dM$$

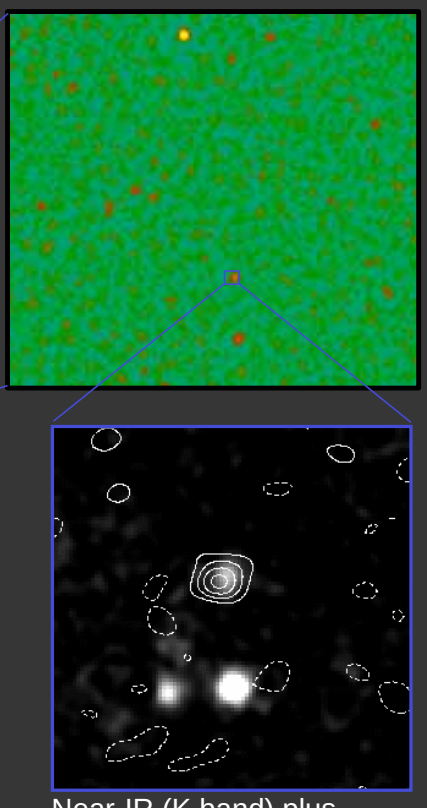
$$= \xi_0 \left[\frac{M^{-1.35}}{-1.35} \right]_{M_1}^{M_2} = \frac{\xi_0}{1.35} \left[M_1^{-1.35} - M_2^{-1.35} \right]$$

lheawww.gsfc.nasa.gov/~ddavis/courses/phys315/week2/week2.pdf

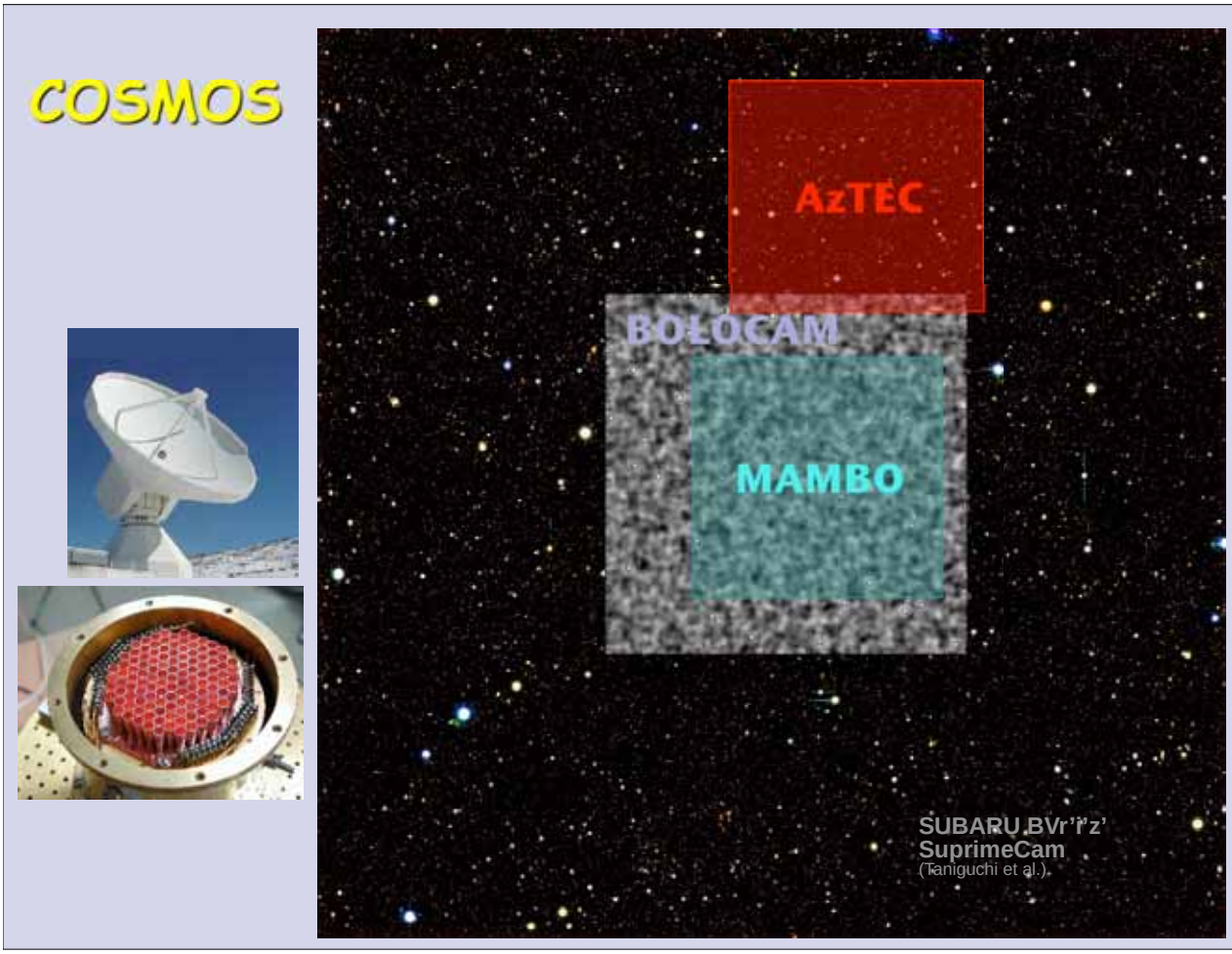
mm "Blank Field Surveys"

vigorous starbursts (HLIRGs) and QSOs





Near-IR (K band) plus radio 1.4 GHz contours

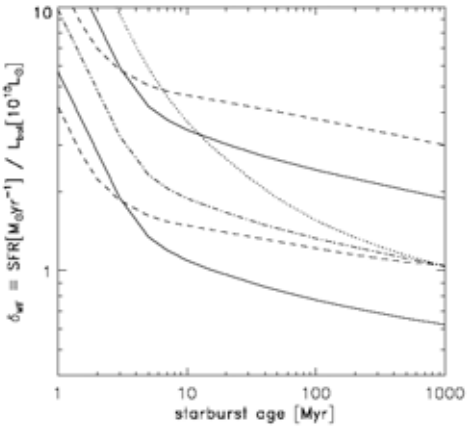


Exercise 1

Given an observation in the RJ-tail of an unresolved grey-body optically thin dusty source such as a star forming region, explain how we can relate the observed flux density to the dust mass or the object luminosity.

Exercise 2

For a starburst with constant star formation since some time 0, outline how the observed total infrared-luminosity, LIR, or equivalently the total bolometric luminosity, can be related to the star formation rate. Consider this as a function of the shape of the intitial mass function and the starburst age. How does the luminosity evolve in time? How does this differ between a continuous starburst and a short (delta-function) starburst? Explain Fig.3 (see right) from Omont et al. 2001, A&A 394, 391.



Additional information you may or may not need: (stellar masses in M_{sun})

lifetime of a star as function of mass: $t/Myr = 2.7+171M^{-1.13}$
cf. Maeder & Meynet AA 210, 155 (1989), Table 2

Lyman-continuum flux: $S_{lyc} = 4.8e45\ M^{2.17}$ for $40\text{-}120M_{sun}$
$= 3.9e42\ M^{4.11}$ for $20\text{-}40\ M_{sun}$

Mass-Luminosity relation: try your own fit from:
M / log L = 20/4.625,30/5.082,40/5.361,60/5.717,80/5.947,100/6.120
(search values for lower M, see works of Maeder & Meynet, e.g.)

Use Initial Mass Functions shown in lecture notes.

Additional optional task: follow Lyman-continuum flux or SN-rate as a function of time.

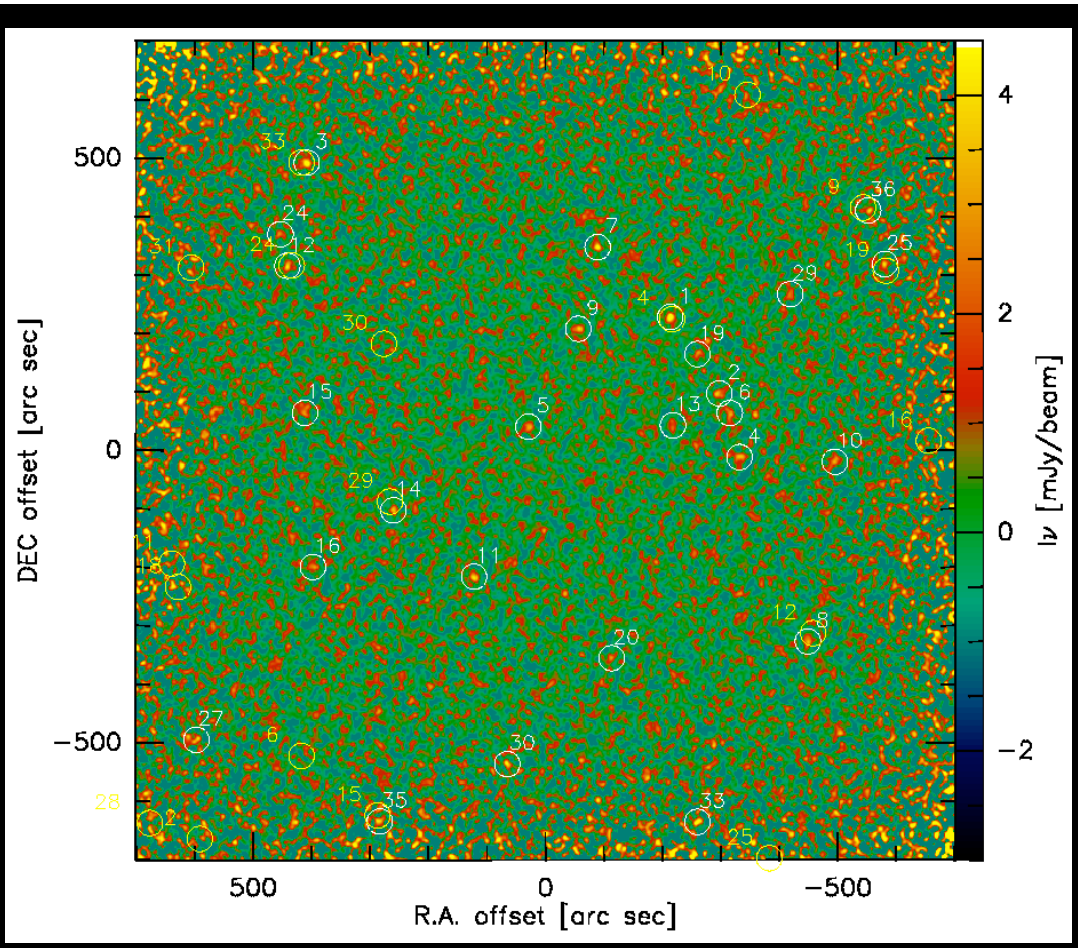
COSMOS

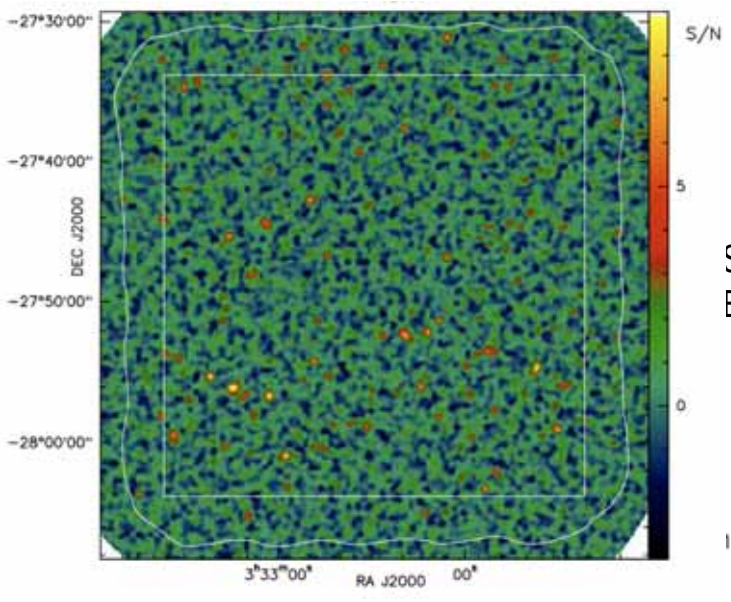
rms ~ 1 mJy

15 sources
S/N > 4

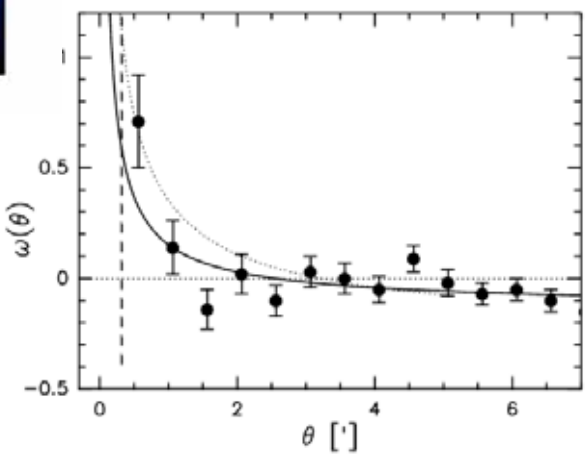
12 sources
S/N = 3.5-4
and radio

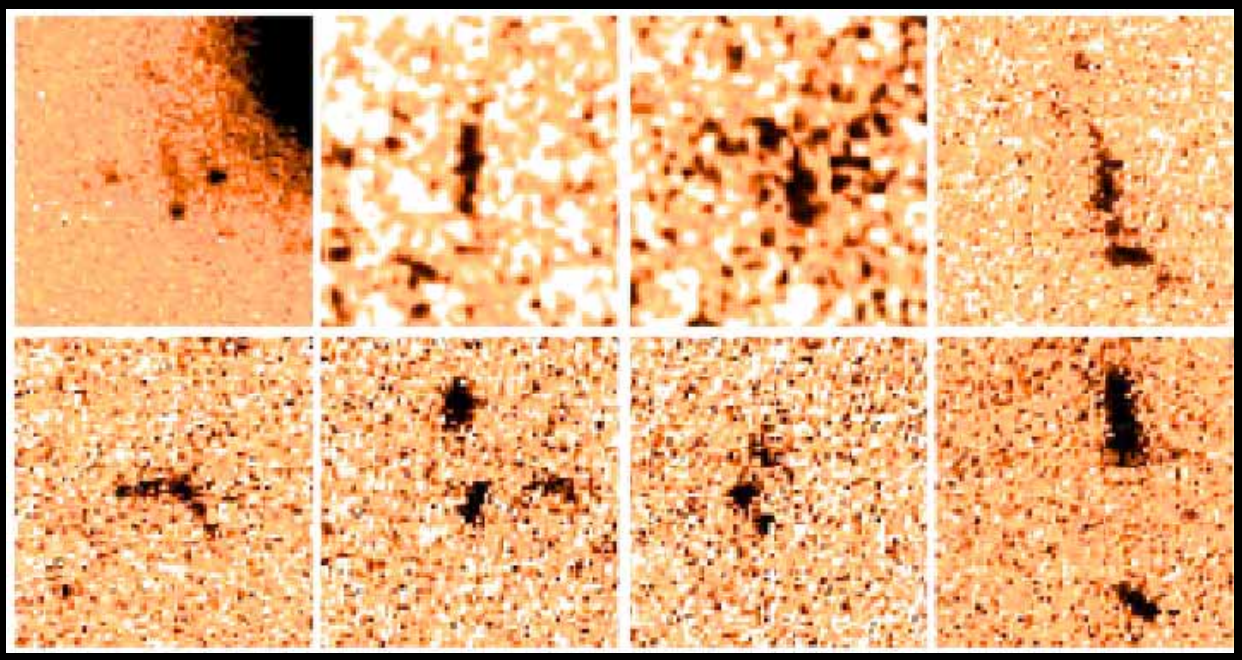
paper in ApJS





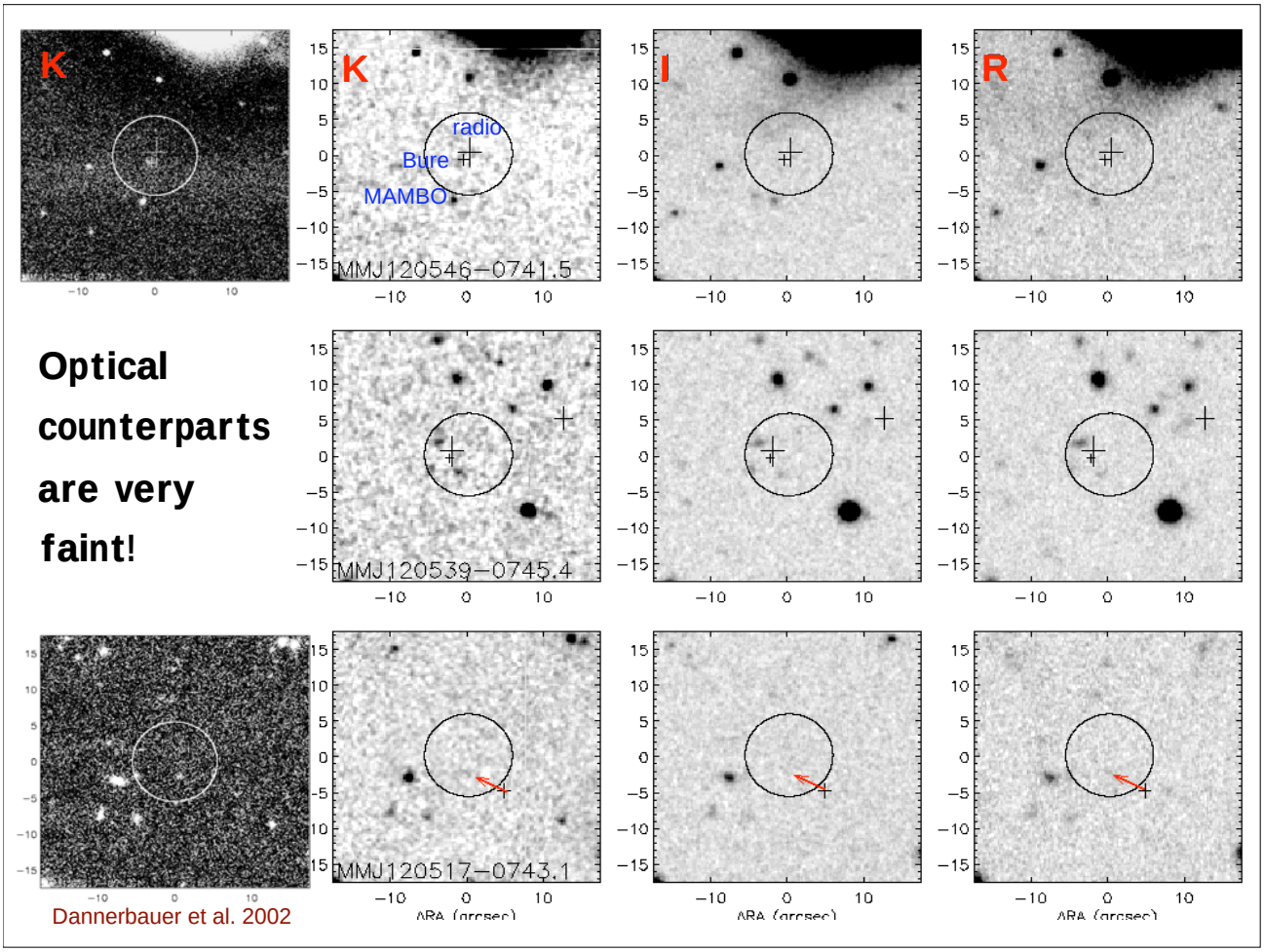
SMG 2-point correlation function
ECDFS (Weiß et al. 2009)





HST images of submm galaxies (Chapman et al.)

apparently these are interacting, irregular systems



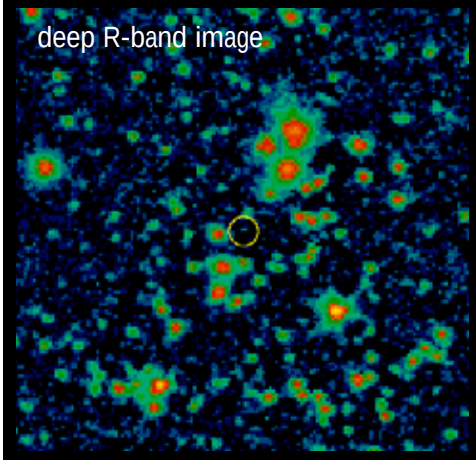
Optical counterparts are very faint!

Dannerbauer et al. 2002

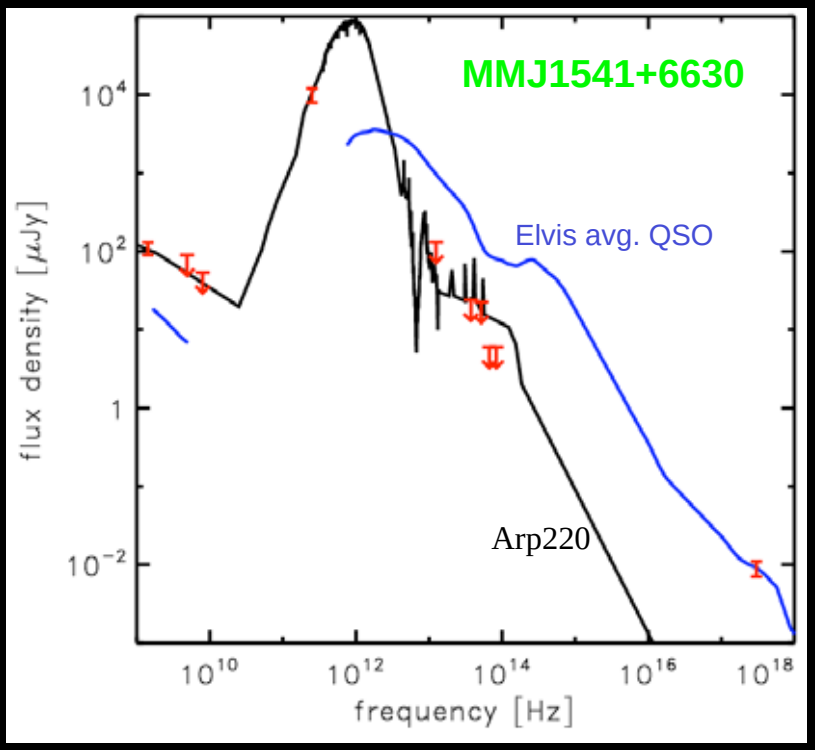
radio: S(1.4GHz)=80μJy
no optical-MIR counterpart
→ Starburst galaxy at z = 3 ± 0.5

$L_{FIR} = 4 \cdot 10^{13} L_{sun}$

SF rate: 5000 M_{sun} yr^{-1}
Dust: $10^9 M_{sun}$



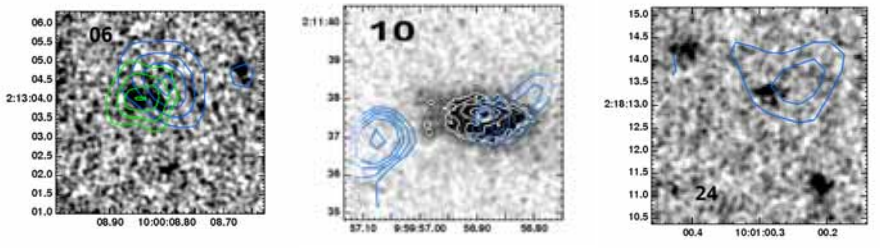
But some SMGs are too faint to detect in the IR



Peculiar optical identifications: blank or lensed

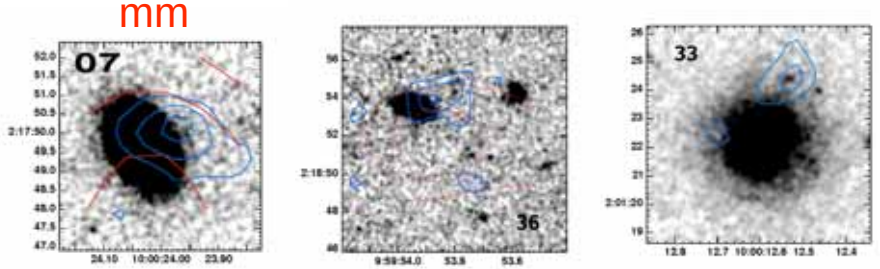
K radio

bright-blank
I_{AB}=27mag



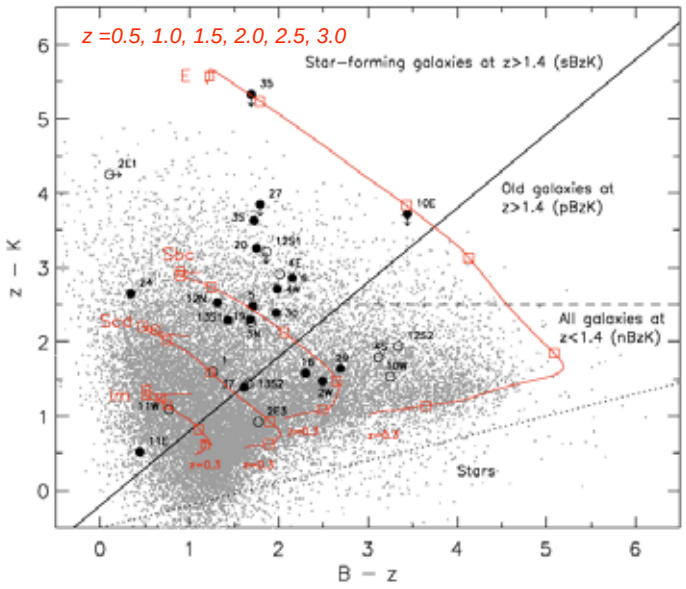
mm

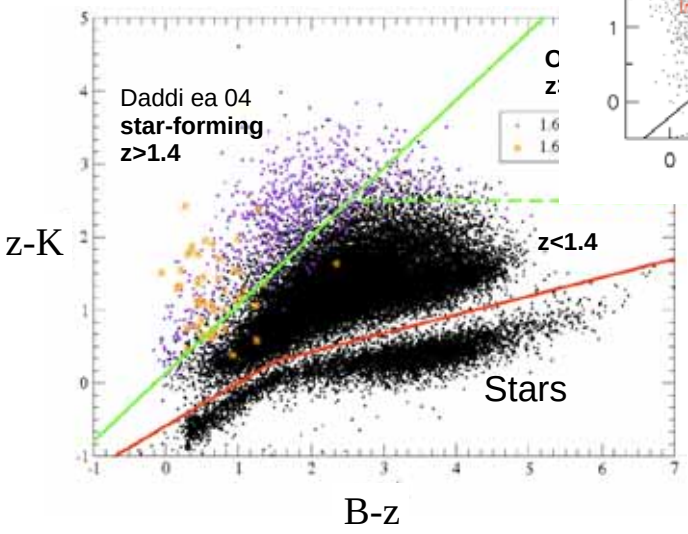
Lensed?



BzK Color Selection

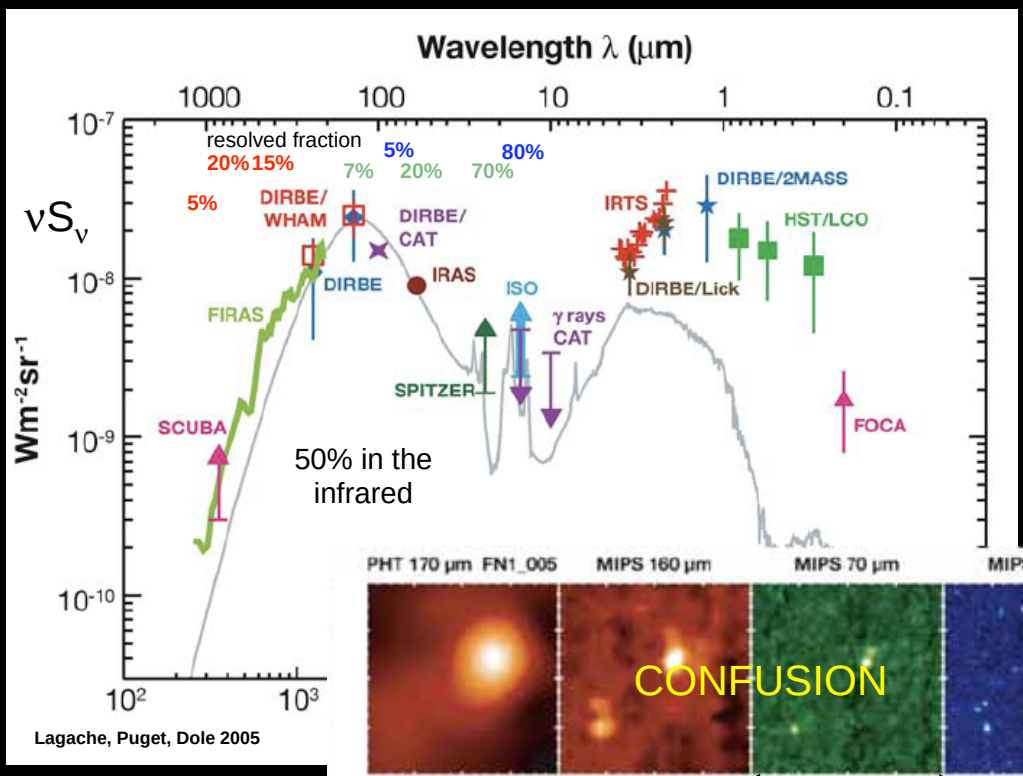
easy identification of high-redshift star-forming galaxies using 3 bands. (Daddi et al. 2004)

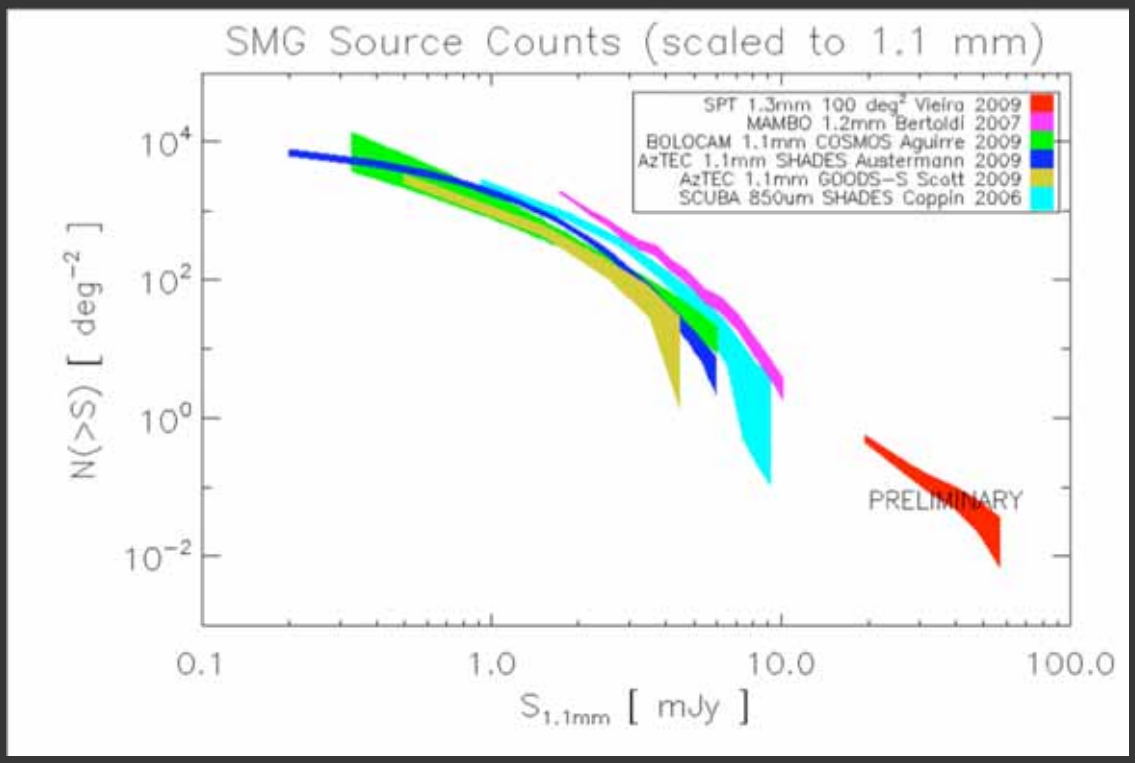




Almost all MAMBO SMGs are optically star-forming high-z galaxies.

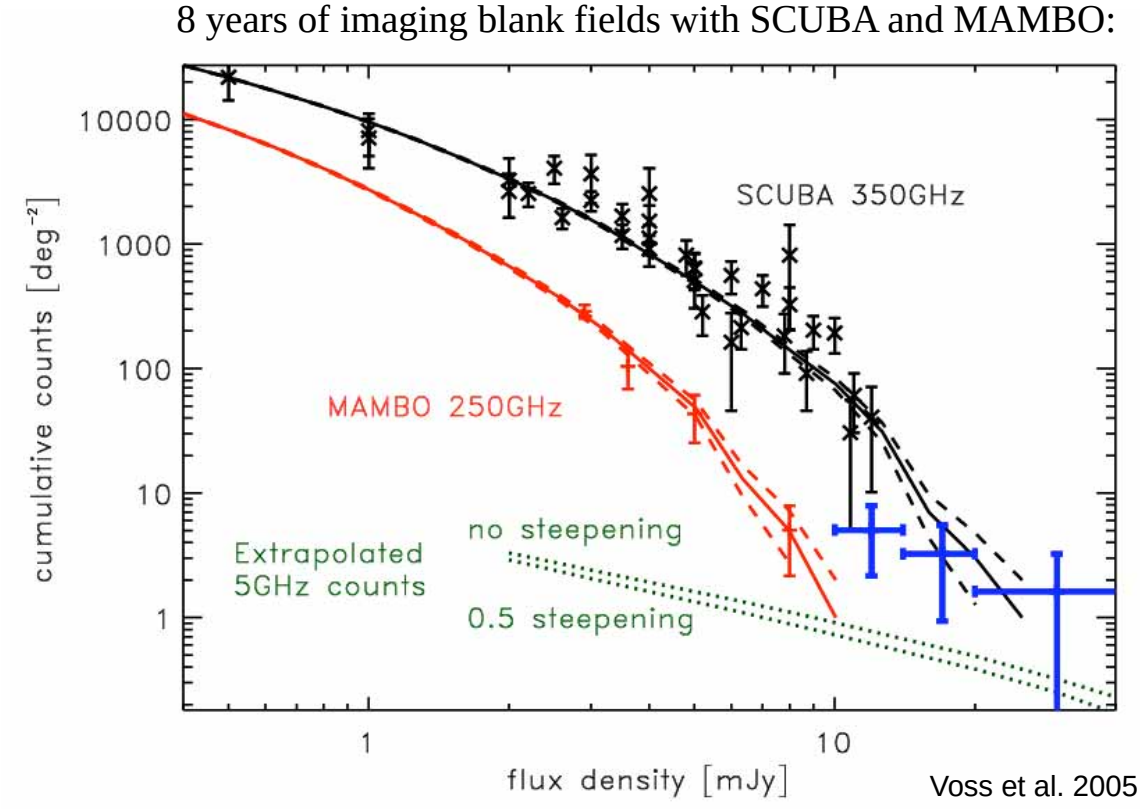
Brightness of the Extragalactic Background





Cumulative Number counts [per sqd]

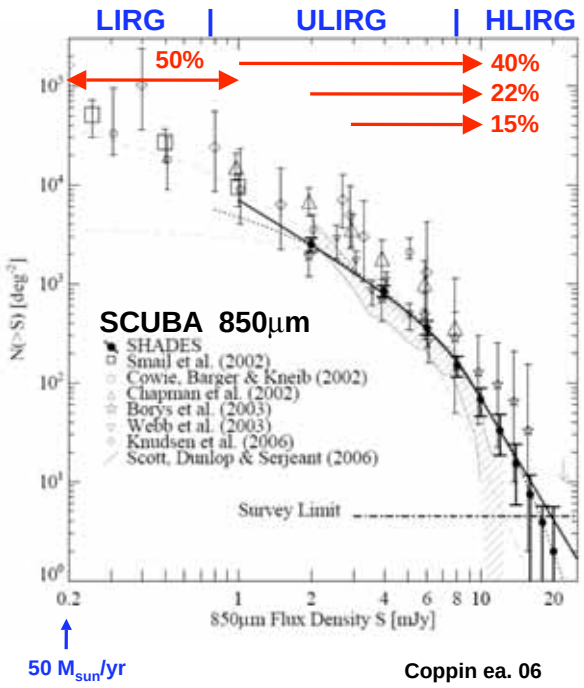
8 years of imaging blank fields with SCUBA and MAMBO:



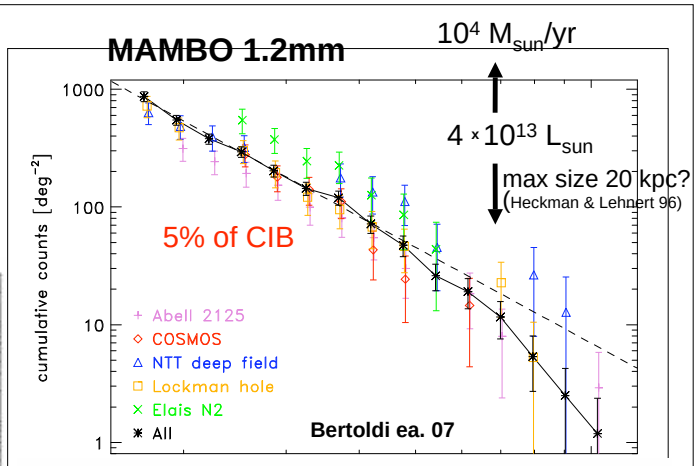
Voss et al. 2005

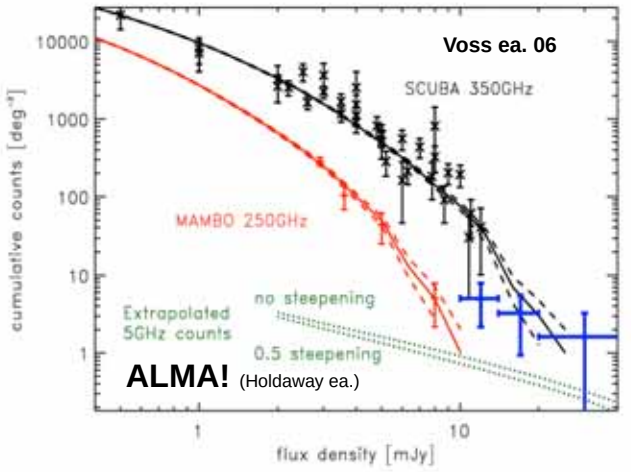
SMG Number Counts

only a small fraction of the CIB has been resolved

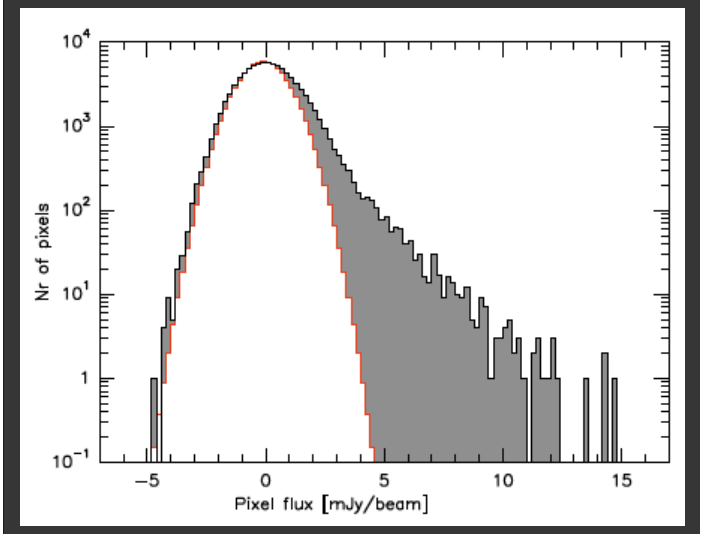


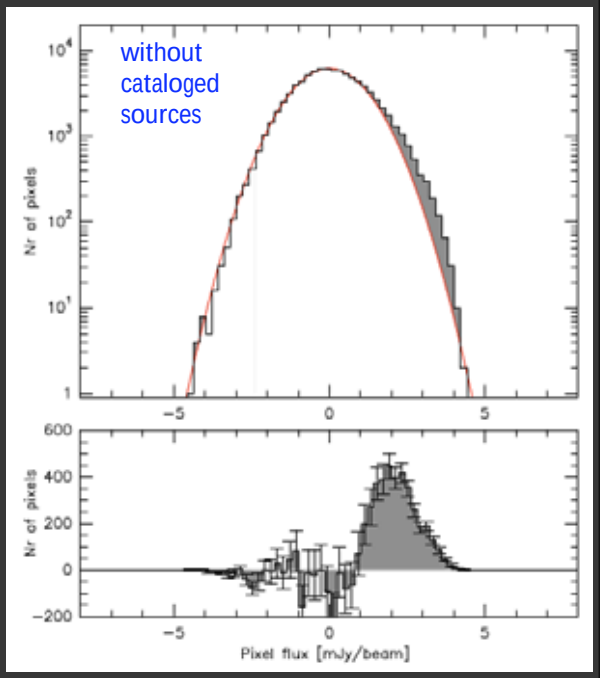
Coppin ea. 06





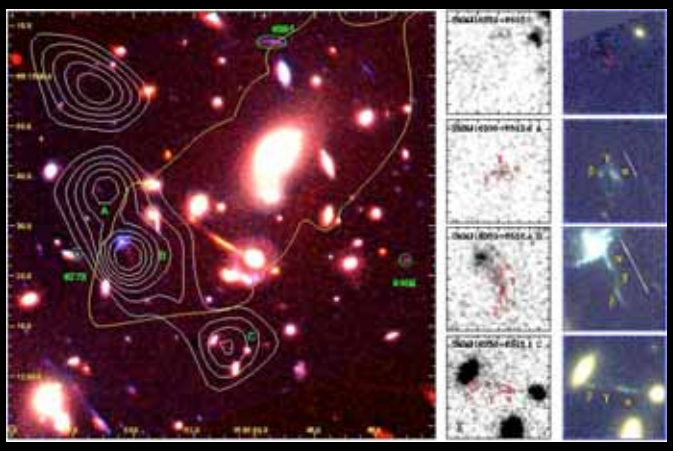
Pixel flux histograms show source and confusion noise



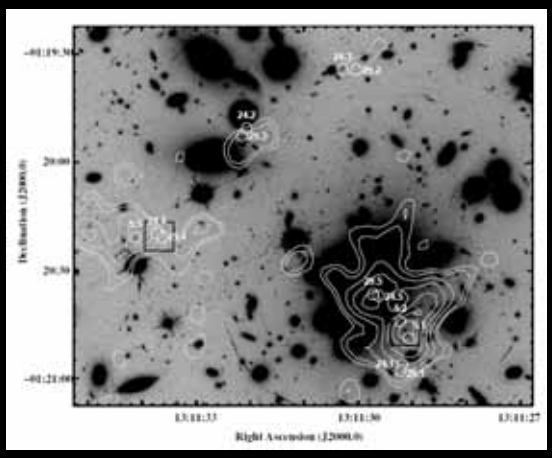


Strong lensing reveals fainter SMGs

Currently 5 strong SMGs with S_{350GHz}<1mJy

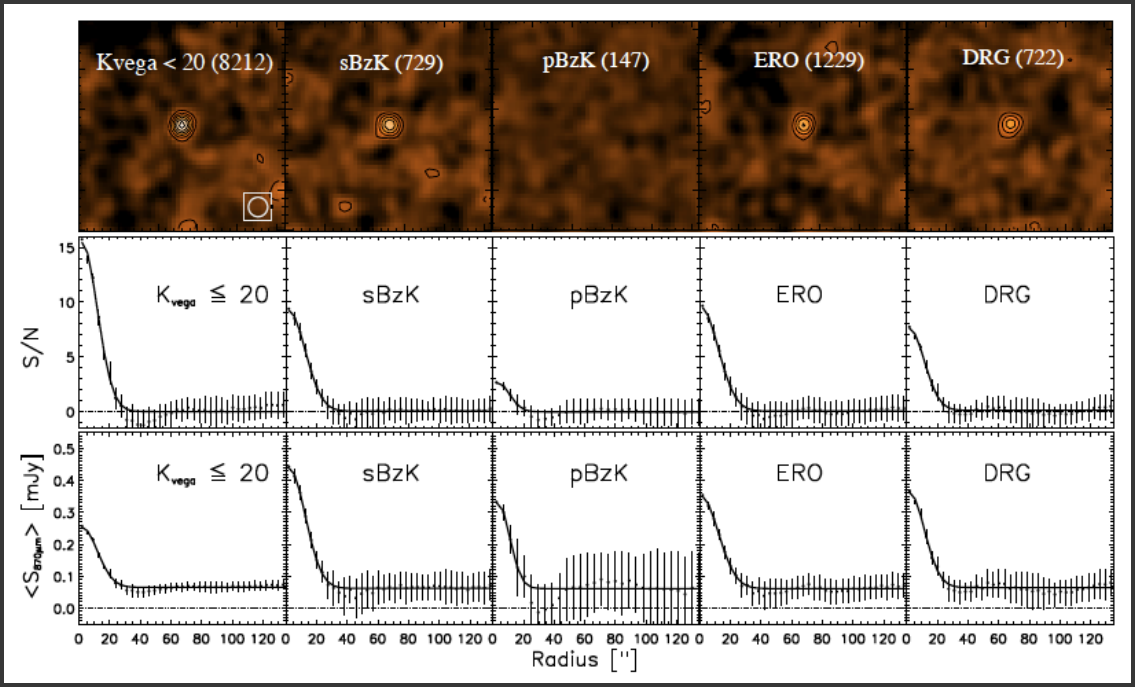


Abell 2218: Kneib ea 04

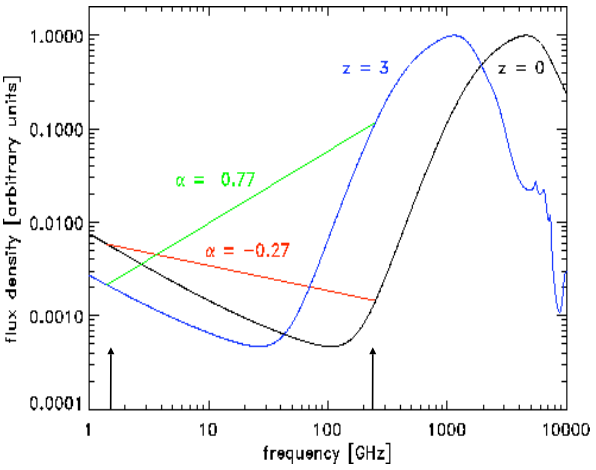


Knudsen ea 07

Stacking individually undetected sources
yields average flux of a selected object class.
(e.g. Greve et al. 2009, astro-ph)

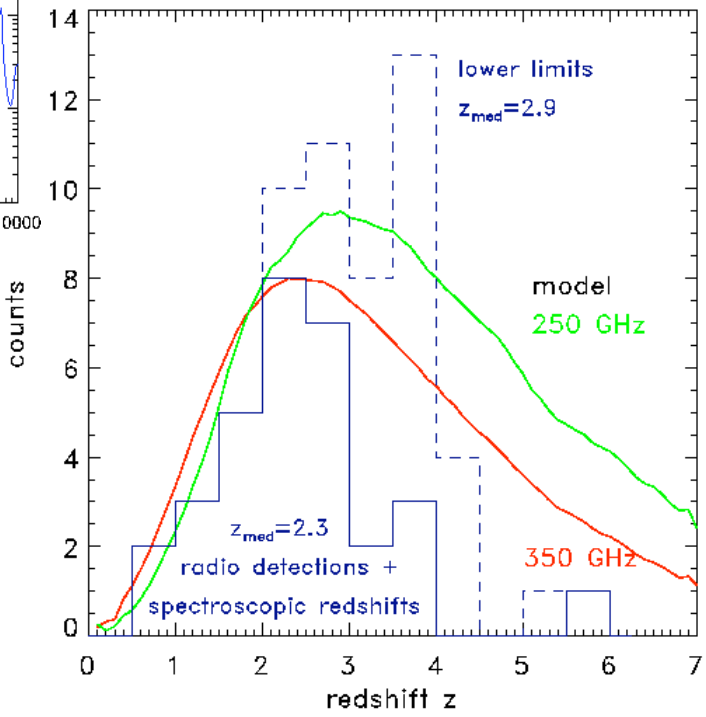


BzK galaxy (Daddi 2004), EROs: extremely red object; DRG: distant red galaxy (Franx et al. 2003)

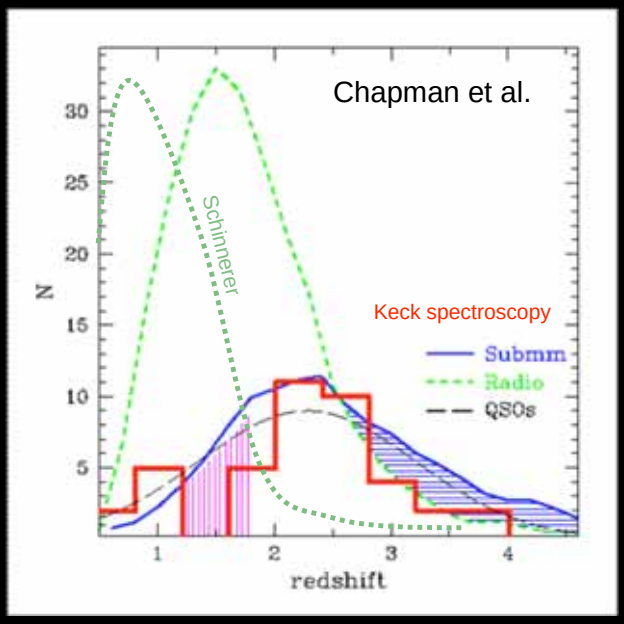


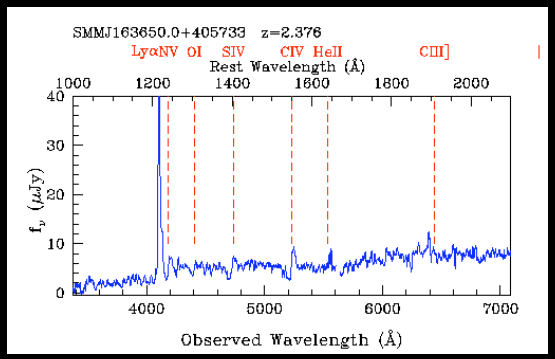
Redshift Distribution

estimated from the mm/radio flux ratio, which steepens with increasing z.



SMG Redshift Distribution

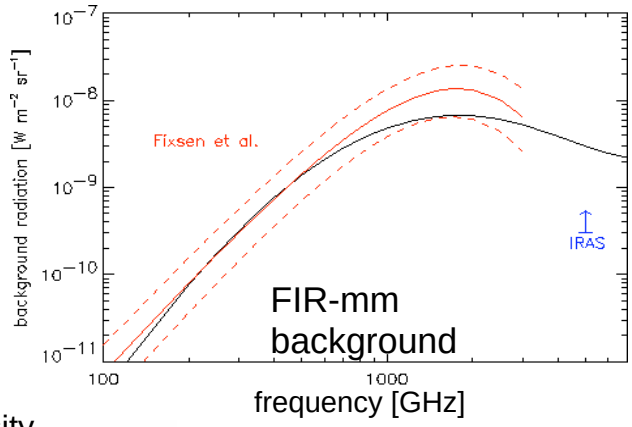


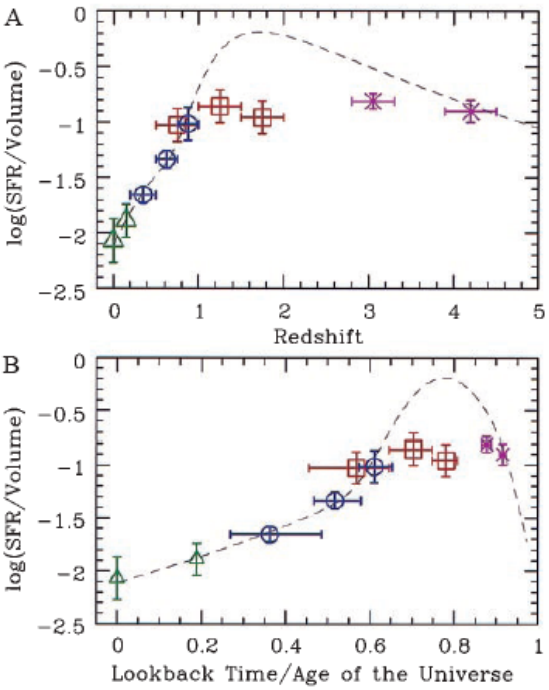


- SMGs are at high z.
- radio-submm photo-z agree on average with spectroscopic z
- radio selection introduces bias against z>3.

It has been very difficult to follow up SMGs without radio counterparts: potentially high-z or cold dust.

Fitting the COBE FIR-mm background

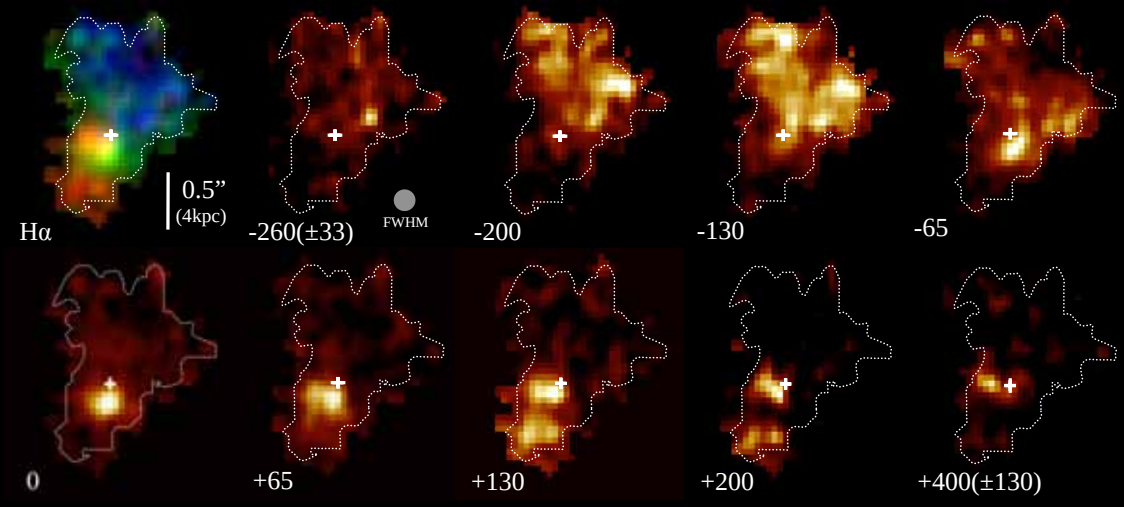




Correcting the star formation history of the Universe: 80% stars in t<40%

Integral Field Spectroscopy with SINFONI/VLT:

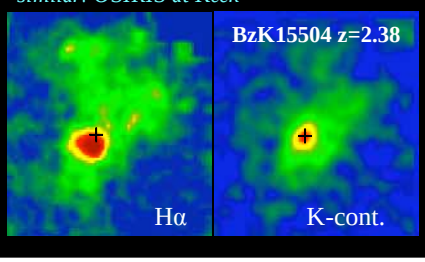
BzK 15504 z=2.38: A Thick, Clumpy & Globally Unstable Disk

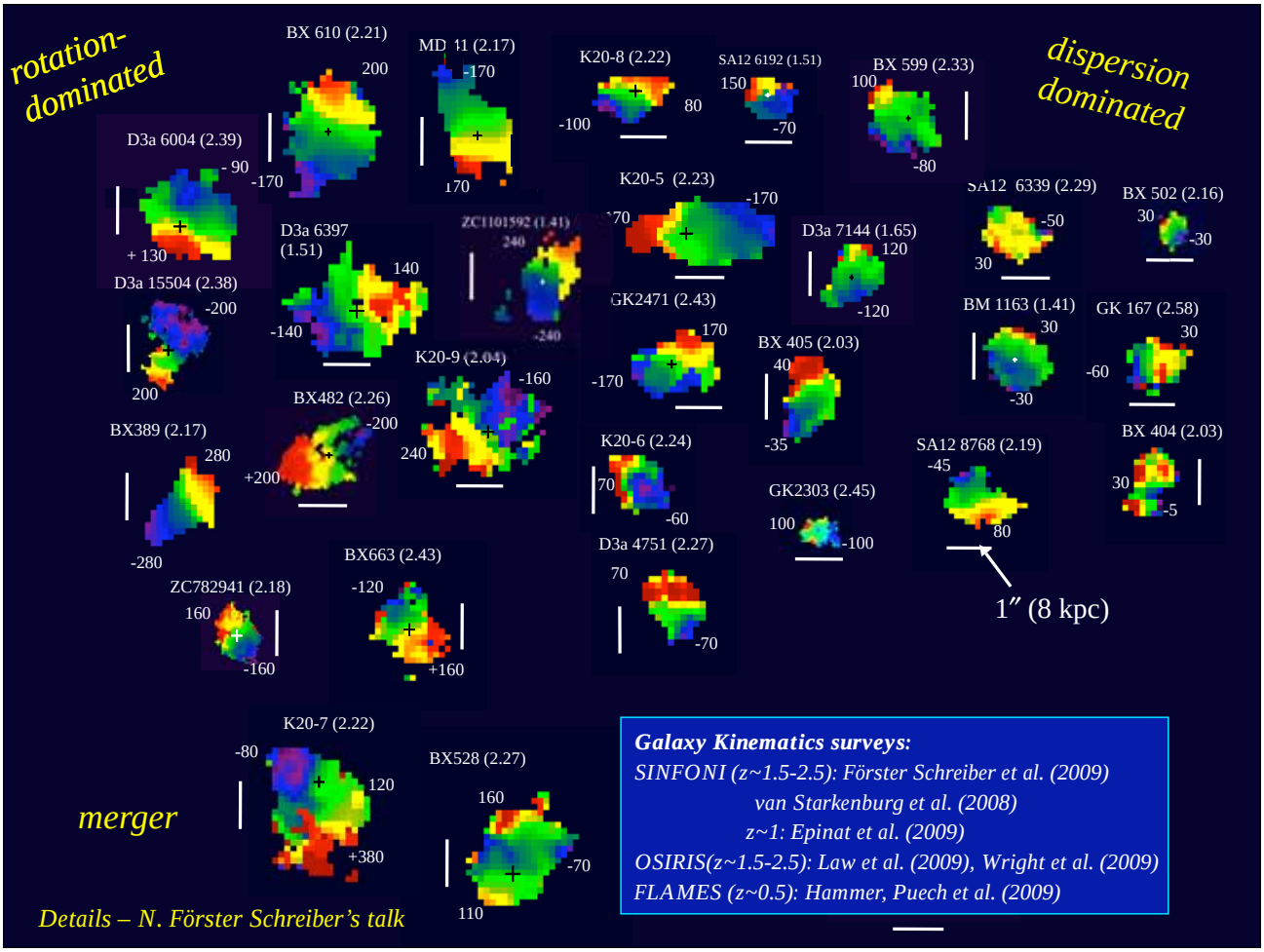


M_{dyn}(<10 kpc) ~10^{11} $M_\odot$
v_c=230 km/s, σ = 50 km/s,
R_d=4 kpc, Q=0.8
SFR = 150 $M_\odot yr^{-1}$, f_{gas}~0.3

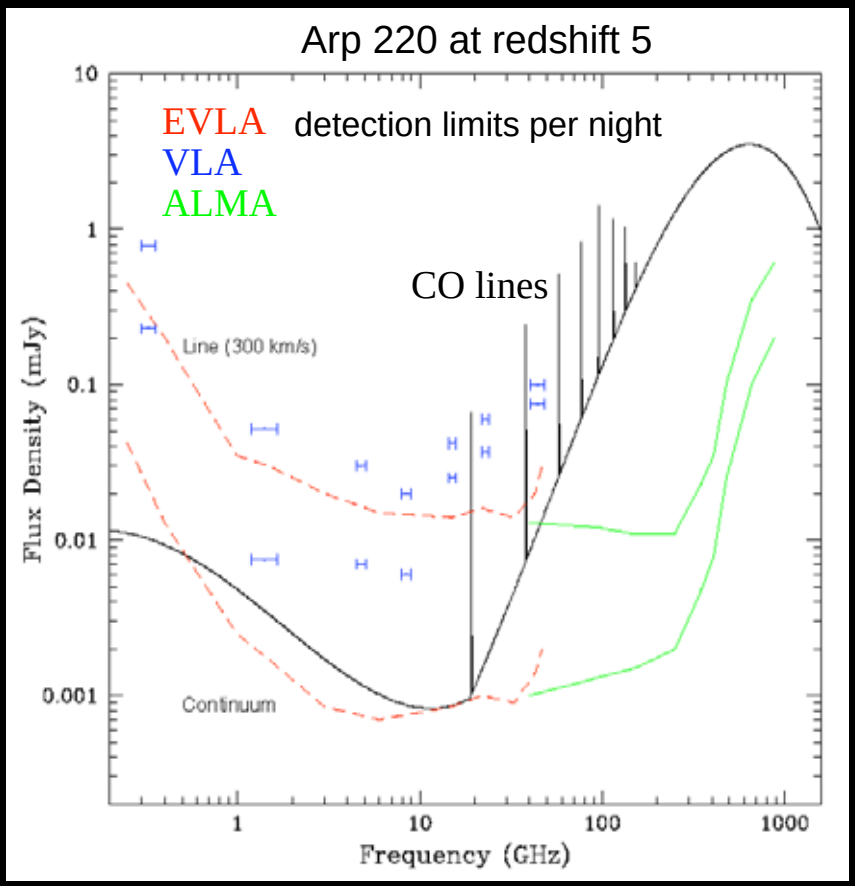
Genzel et al. 2006

SINFONI +AO (VLT):
0.2" (1.6 kpc) resolution
similar: OSIRIS at Keck



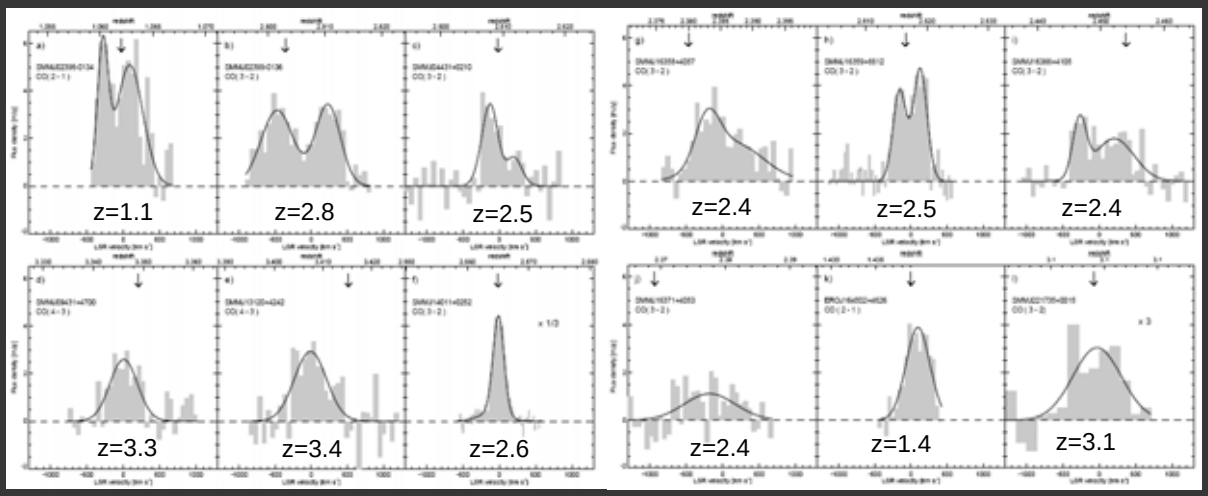


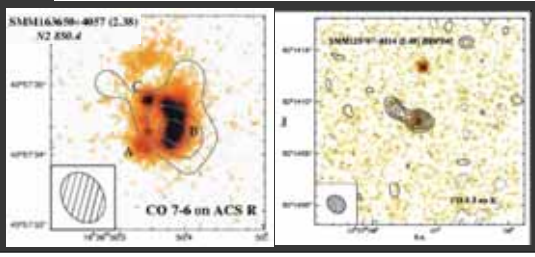
Next step: molecular lines as diagnostics of the dynamics and mass



CO Observations of submm Galaxies

Neri ea. 03, Greve ea. 05, Tacconi ea. 06



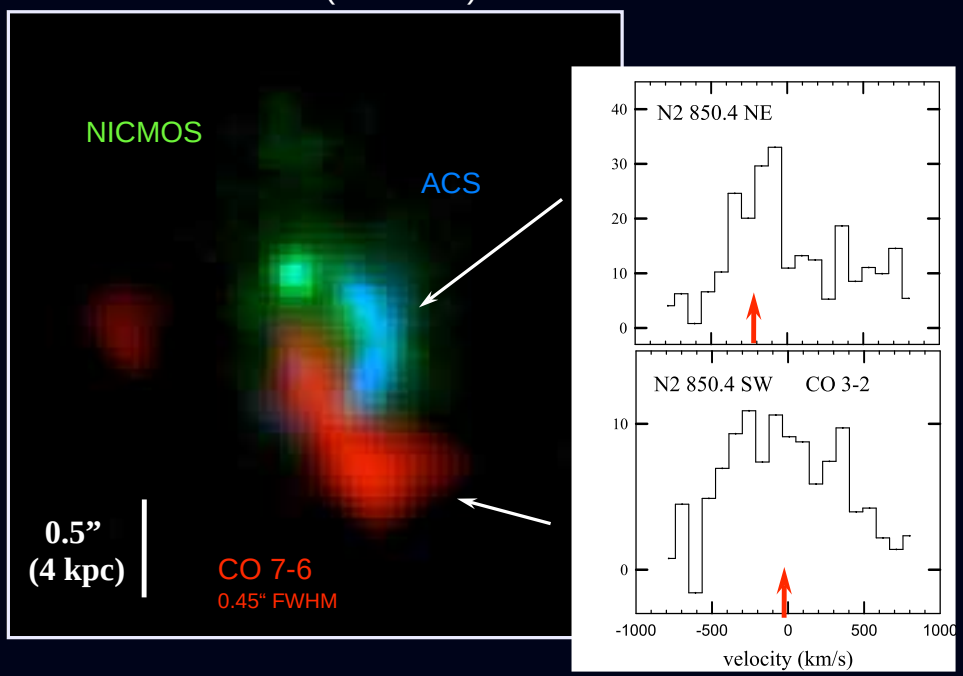


Dynamic and luminous mass:

$M \sim r\,\Delta v^2 \rightarrow 10^{11}\ M_{sun}$

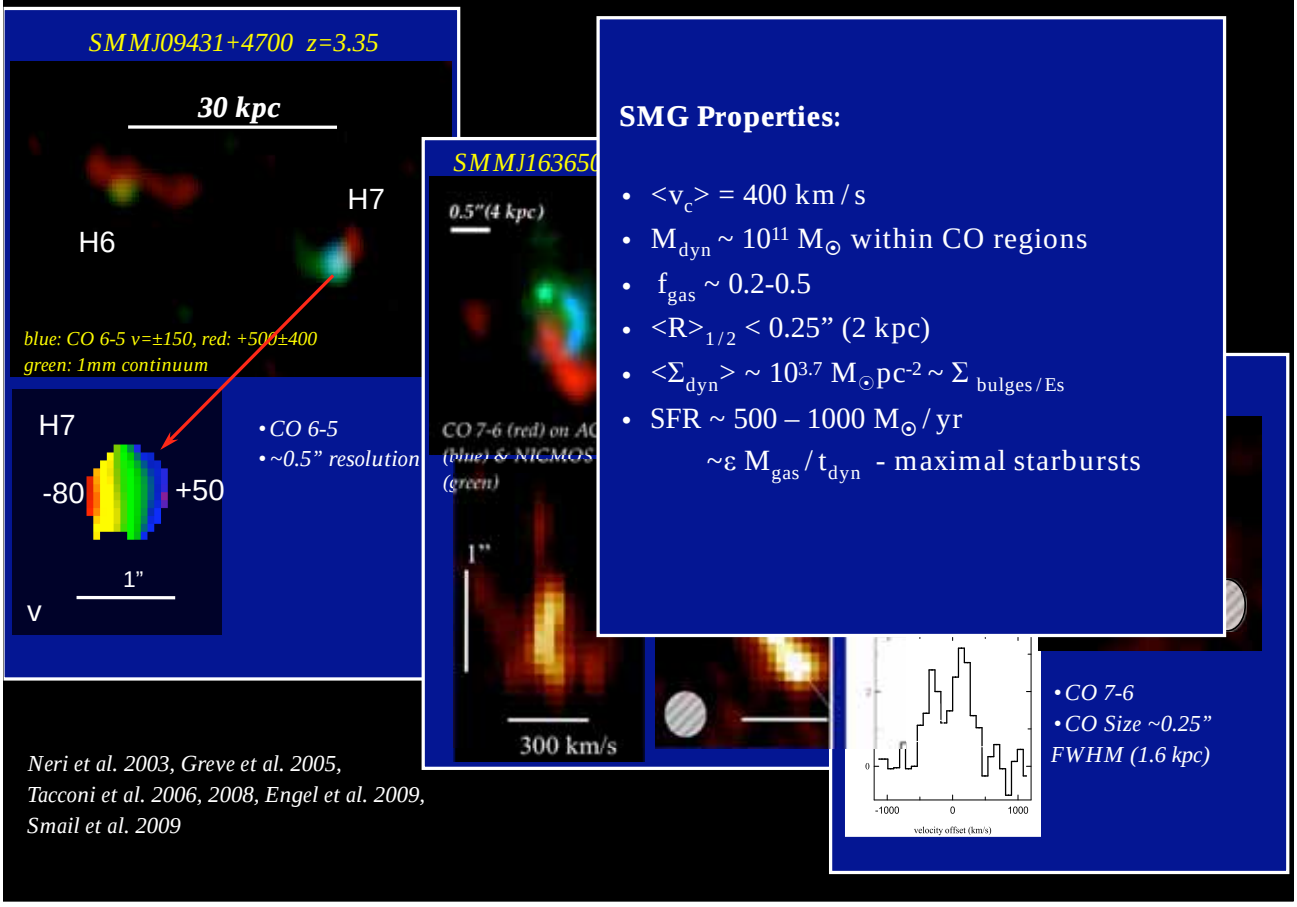
Most recently: ~0.5"mm-Interferometry

SMMJ 163650+4057 (N2 850.4) z=2.39



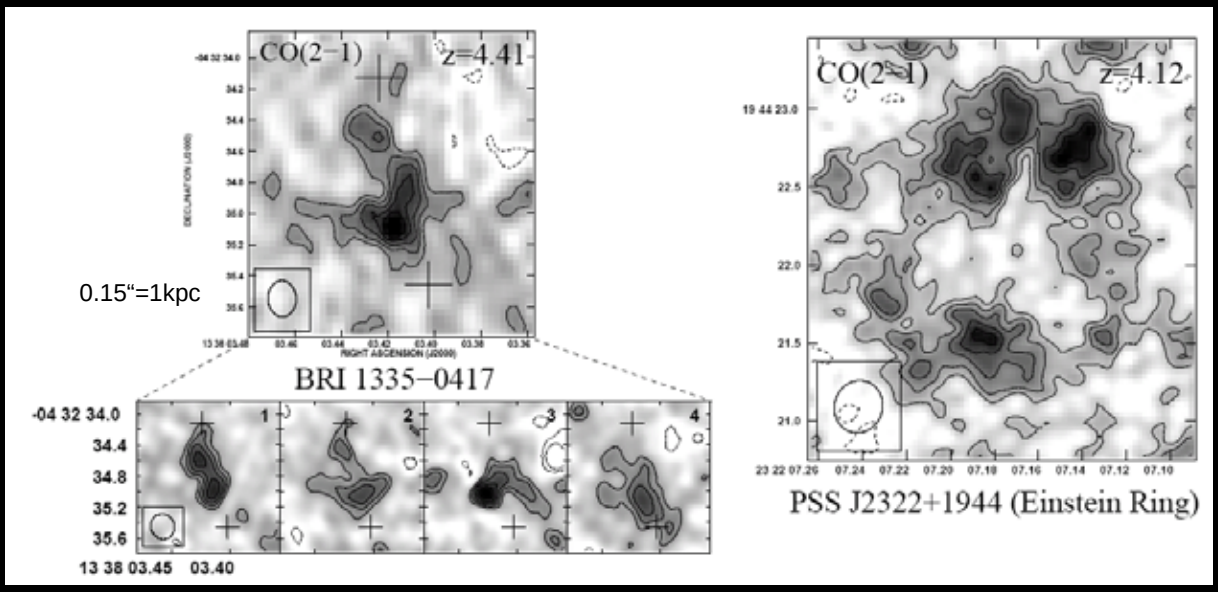
Smail et al. 2005, 2007, Swinbank et al. 2005, Tacconi et al. 2006

Sub-millimeter Galaxies Are Dissipative Gas Rich Mergers



Neri et al. 2003, Greve et al. 2005, Tacconi et al. 2006, 2008, Engel et al. 2009, Smail et al. 2009

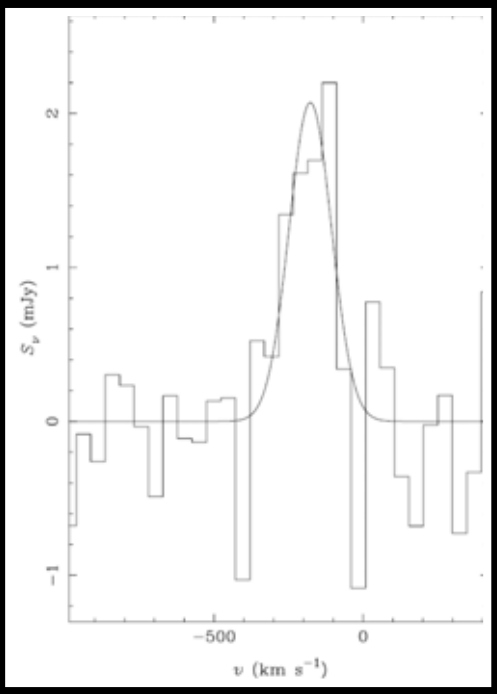
Ultimate goal: image molecular and atomic emission at sub-kpc scale, e.g.:



„Merger caught in the act"

Riechers, Walter, Carilli ea.

Resolving Molecular Gas in a Moderate Mass z~3 Lyman-Break Galaxy

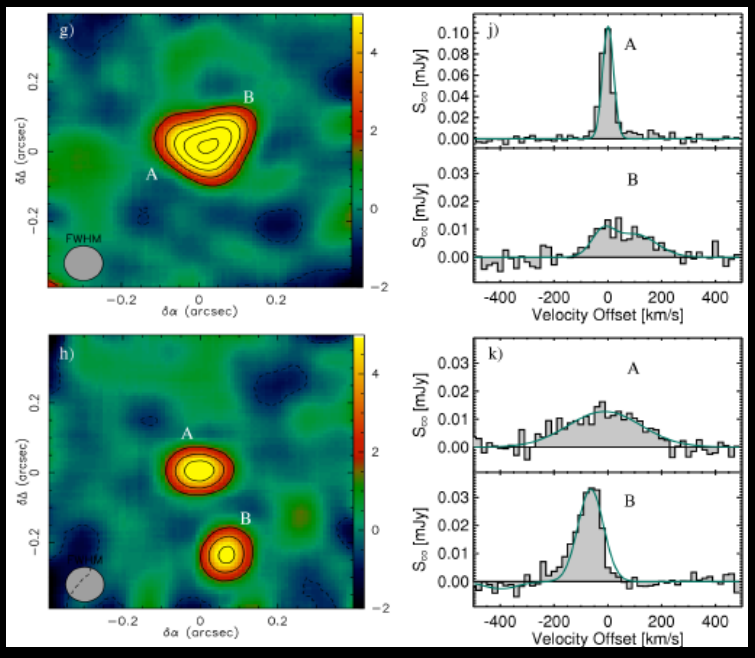


CO 3-2 in MS1512-cB58

- Gravitationally lensed Ly-Break galaxy @z=2.7
- M_{H2}~2.3x10^9 $M_\odot$
- 30 hours PdBI

Baker et al 2004

Resolving Molecular Gas in a Moderate Mass z~3 Lyman-Break Galaxy with ALMA

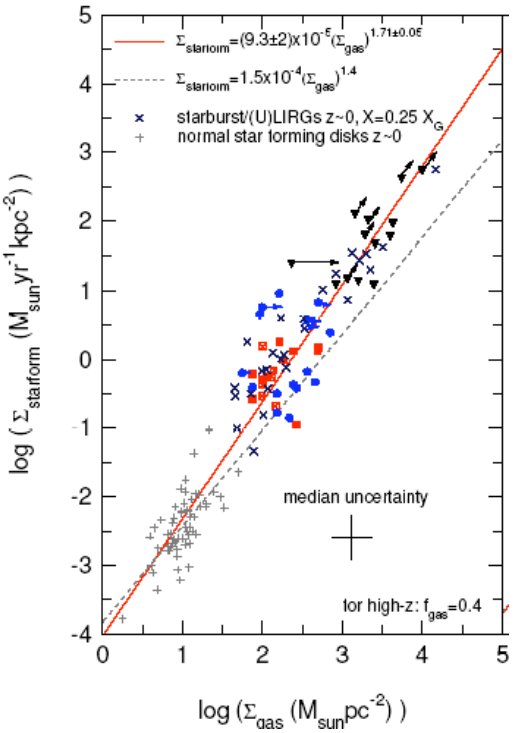


- Simulating CO 4-3 in z~3 Lyman-Break Galaxy
- 0.1" resolution => 700pc
- 2x10^9 M_{sun} of H_2
- 12 hours integration with ALMA

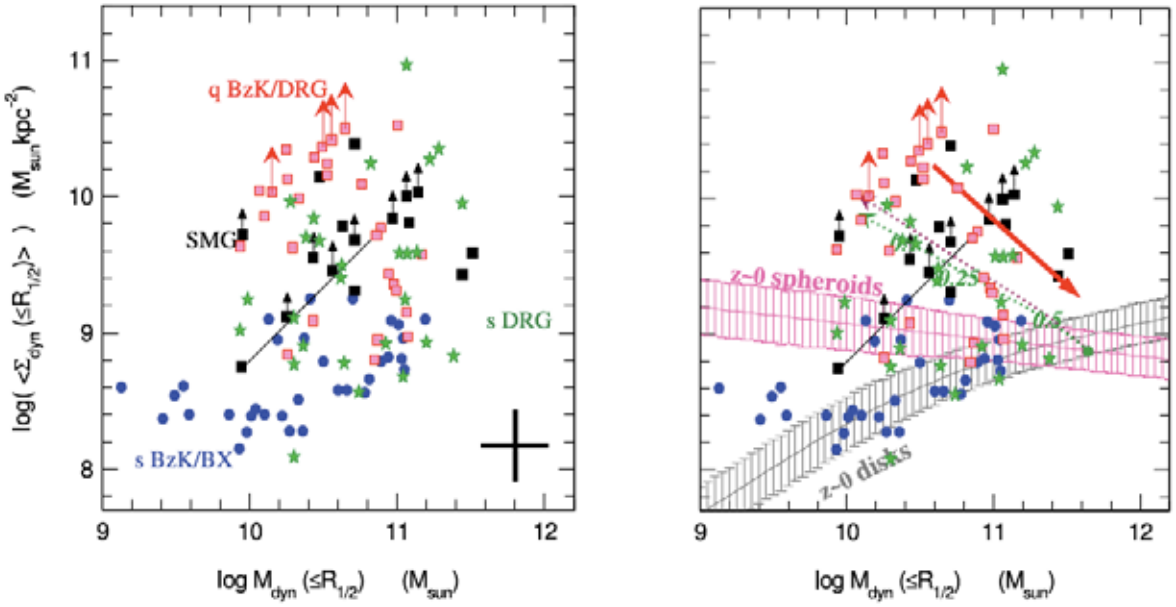
Greve & Sommer-Larsen 2006

Star formation rate vs. gas surface density

Kennicutt-Schmidt law



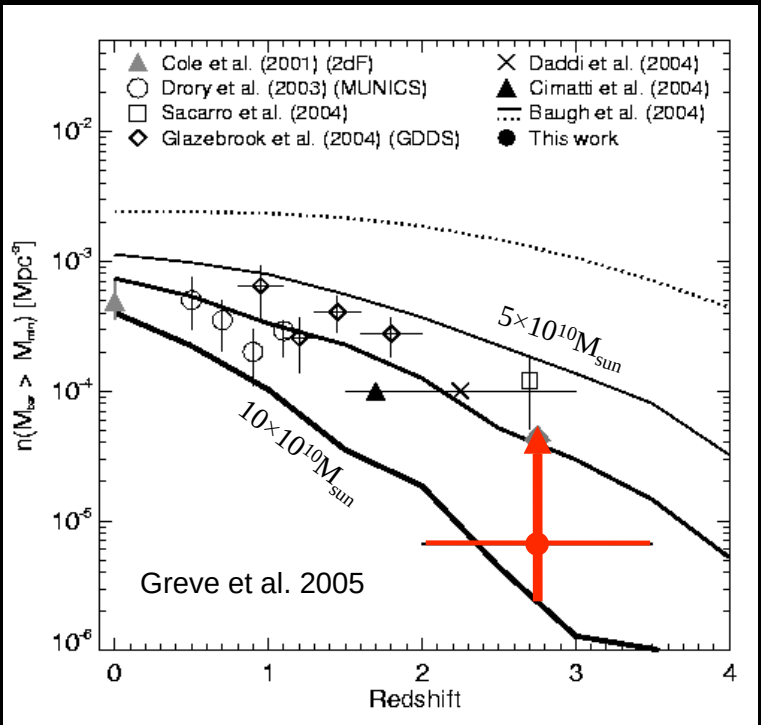
TACCONI ET AL.



The observations presented above add new information on the formation and evolution of massive spheroids. If the properties of the small SMG sample we have studied so far are typical for the SMG population as a whole, we have found the smoking gun for an (or possibly the most) important creation process of spheroids at high redshift: a major and highly dissipative, "wet" merger of very gas-rich galaxies, leading to rapid and efficient star formation and compact merger remnant formation. This conclusion is not surprising. A merger origin

Testing Mass Assembly

Comparison with semi-analytic models of galaxy formation.

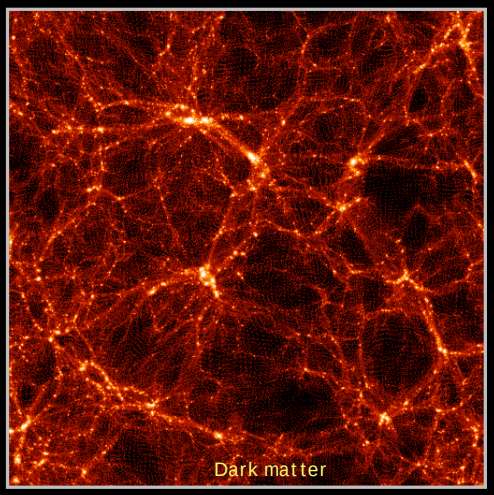


Submm Galaxies (SMG) with
S_{850}>5mJy : $1.6\cdot10^{-5}$ Mpc^{-3}

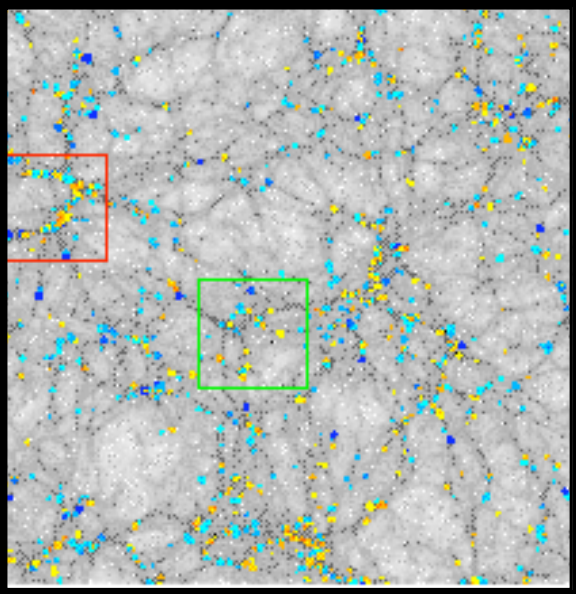
Gas exhaustion time 60-100 Myr
time(z=1.6-3.6) = 2 Gyr
→ completeness correction 20-30

Consistent within CDM framework if 10% of baryons within dark matter halos are rapidly assembled into galaxies.

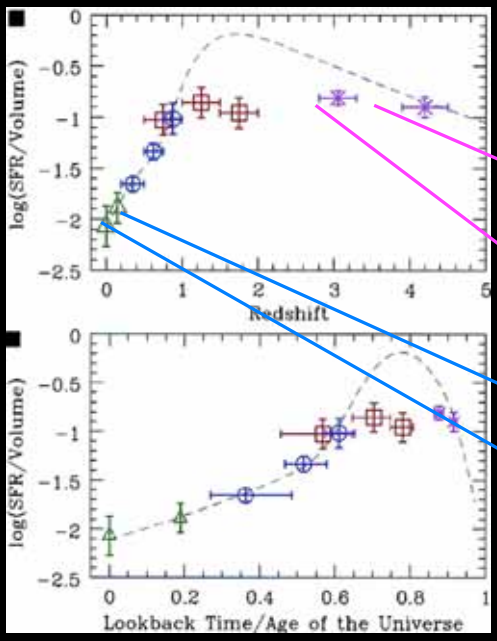
Star formation and LSS

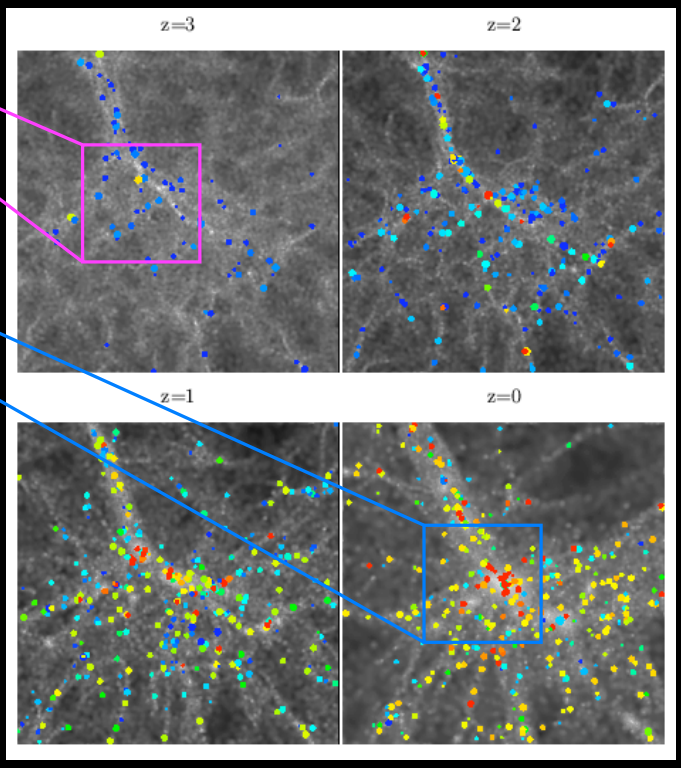


z=1

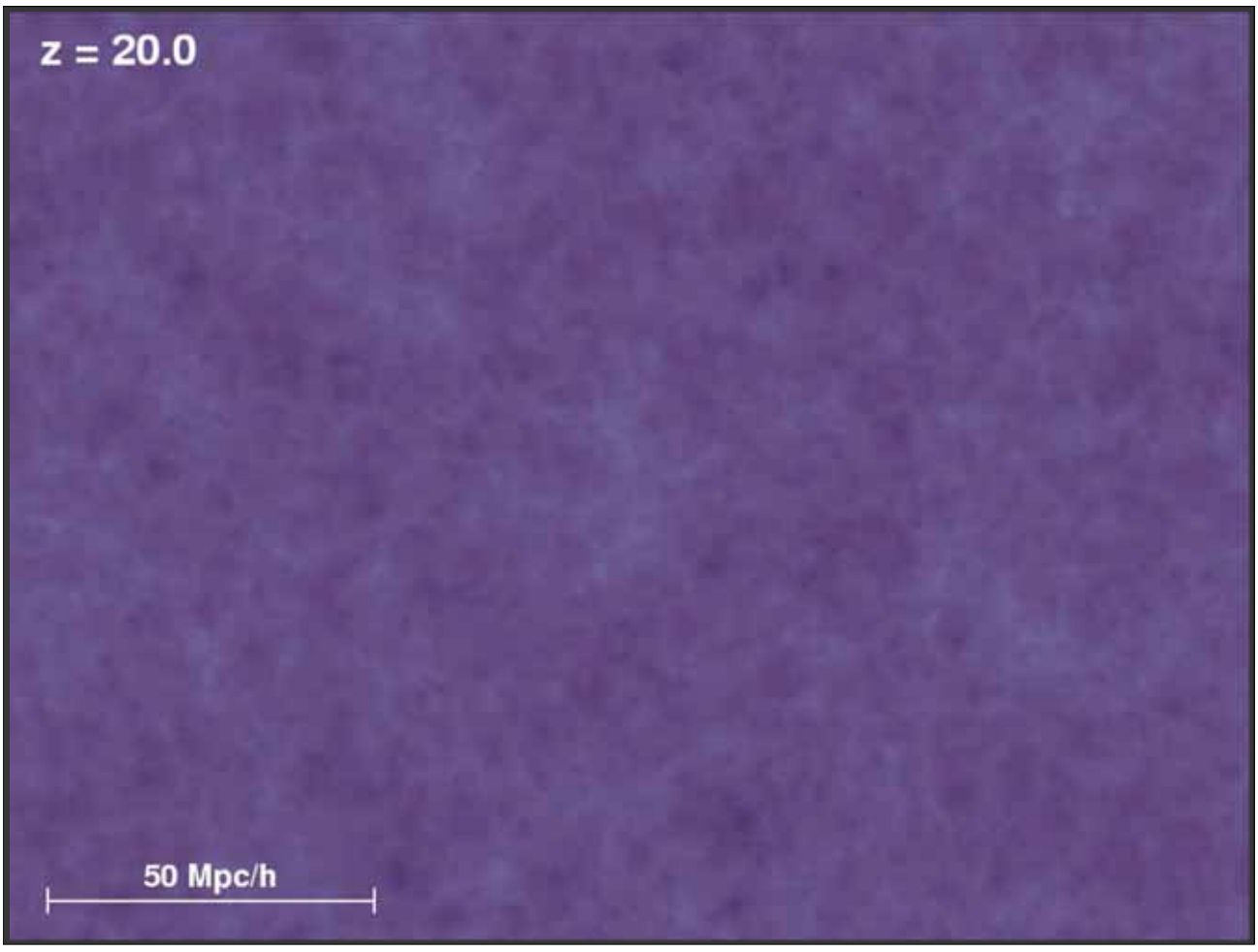


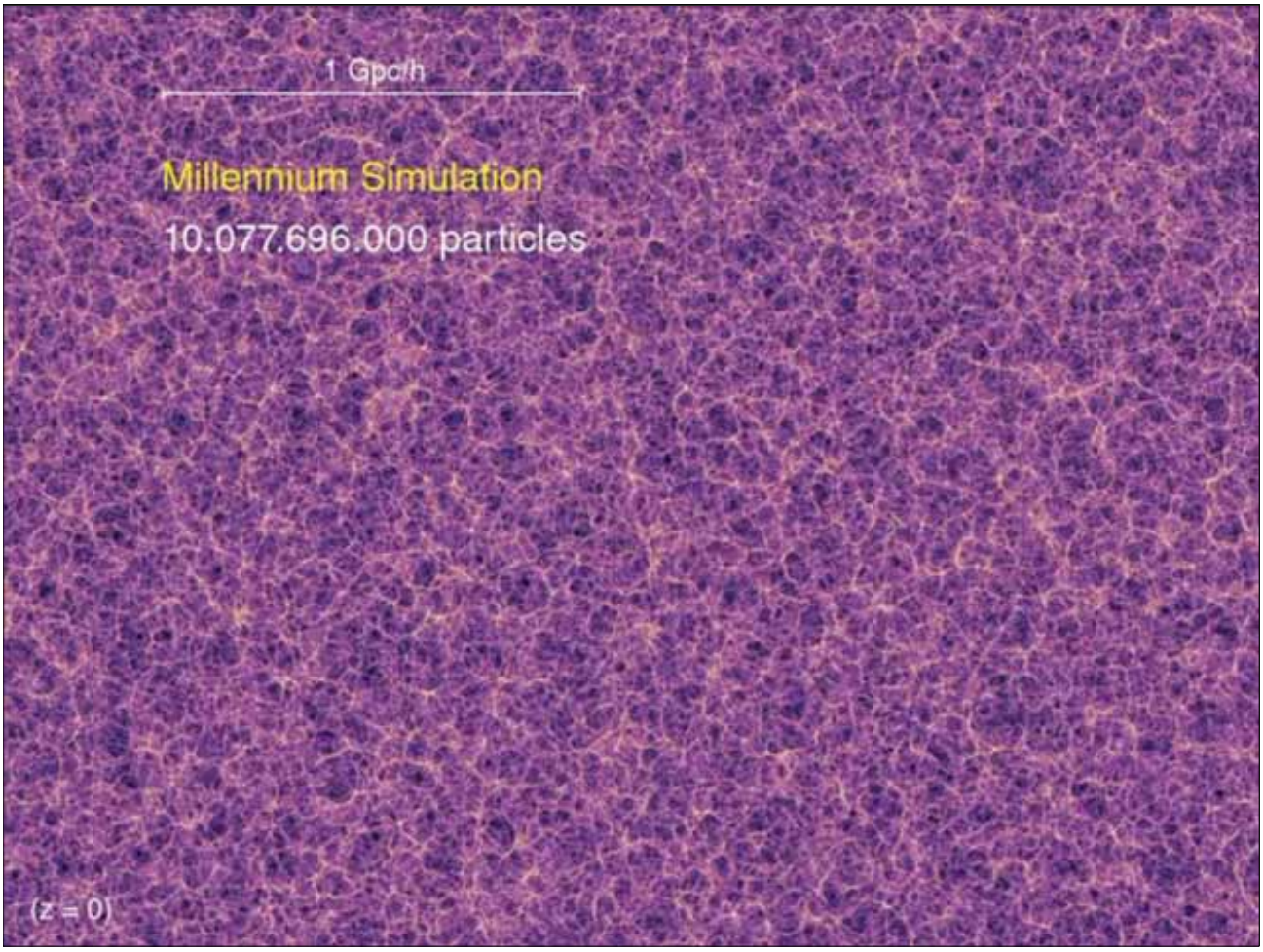
Star formation and LSS

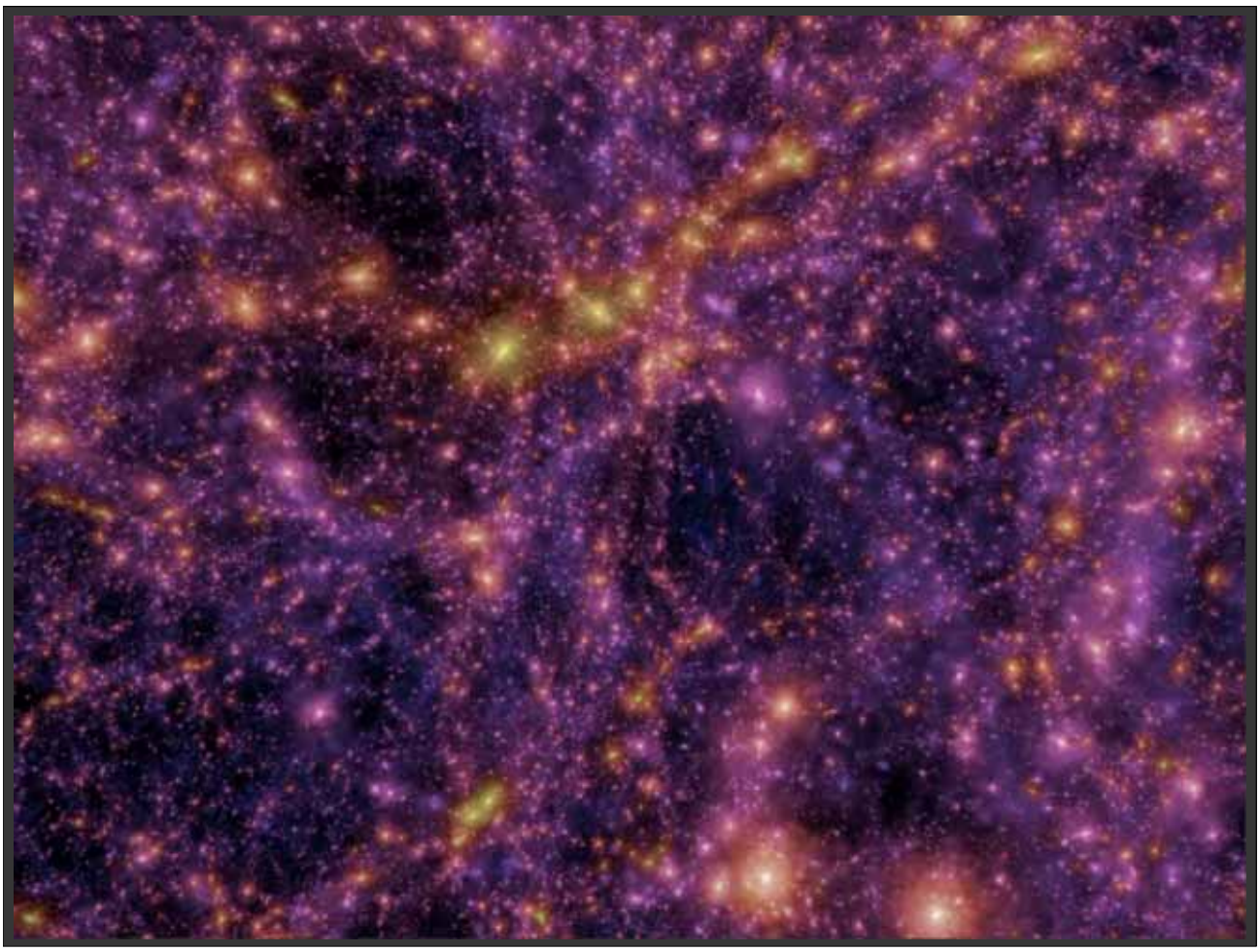




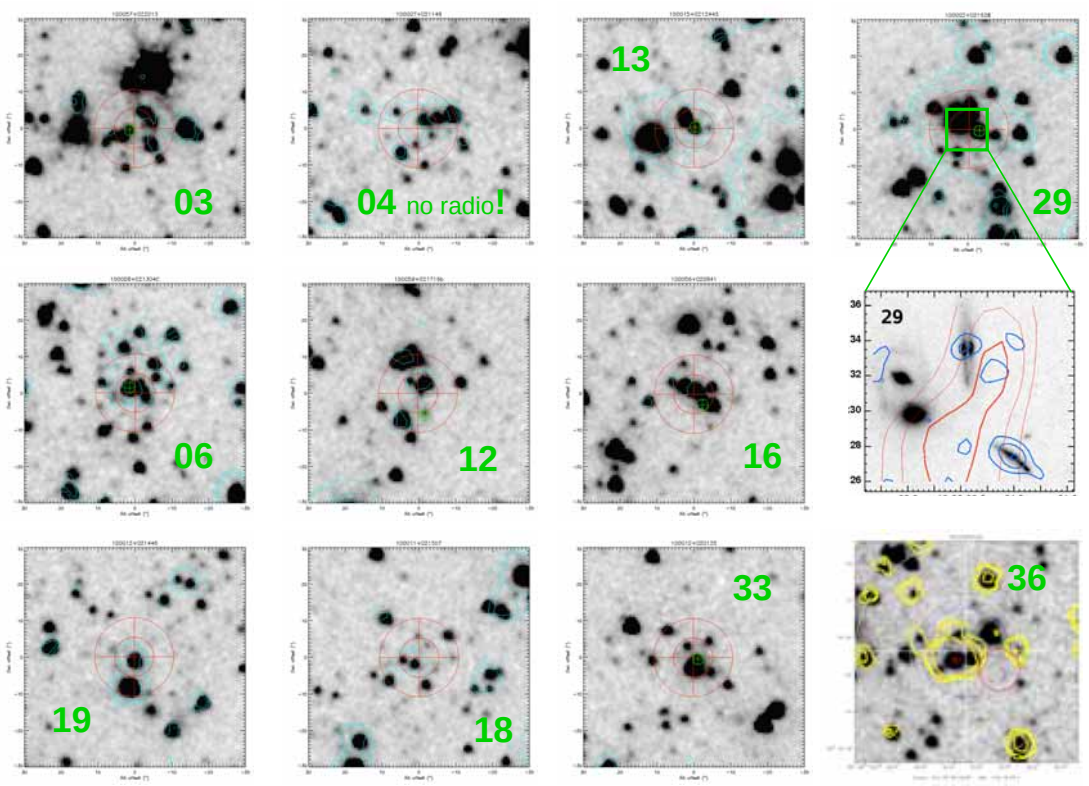
red ➠ blue:




1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)



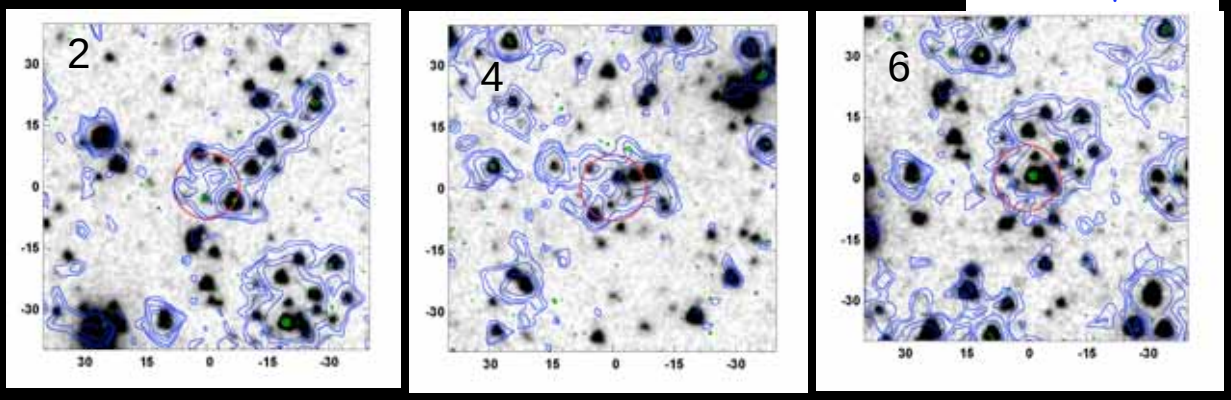
Spitzer shows groups of red galaxies around MAMBO sources

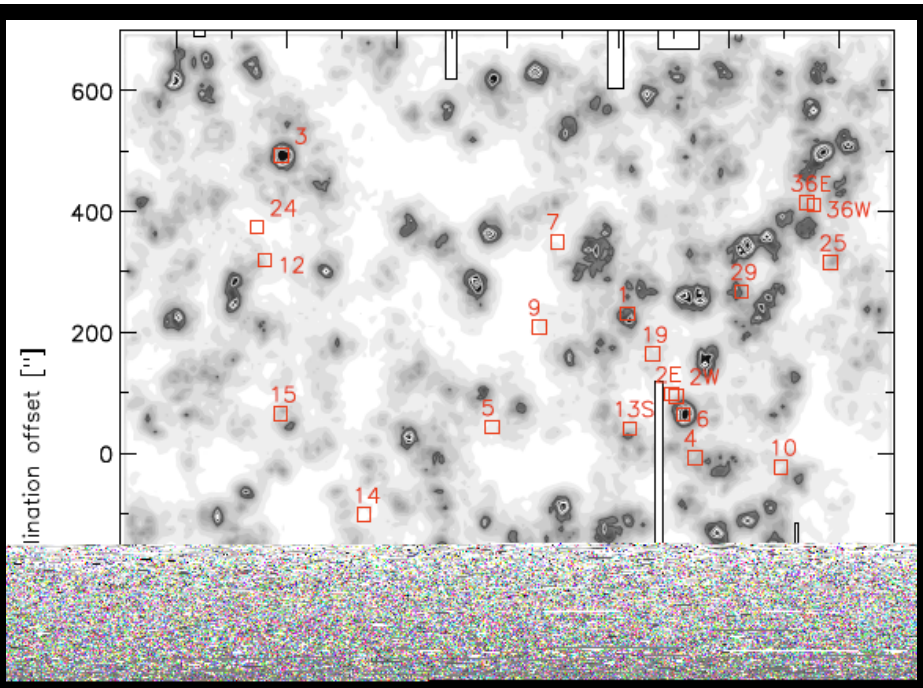


Spitzer IRAC MIPS radio MAMBO

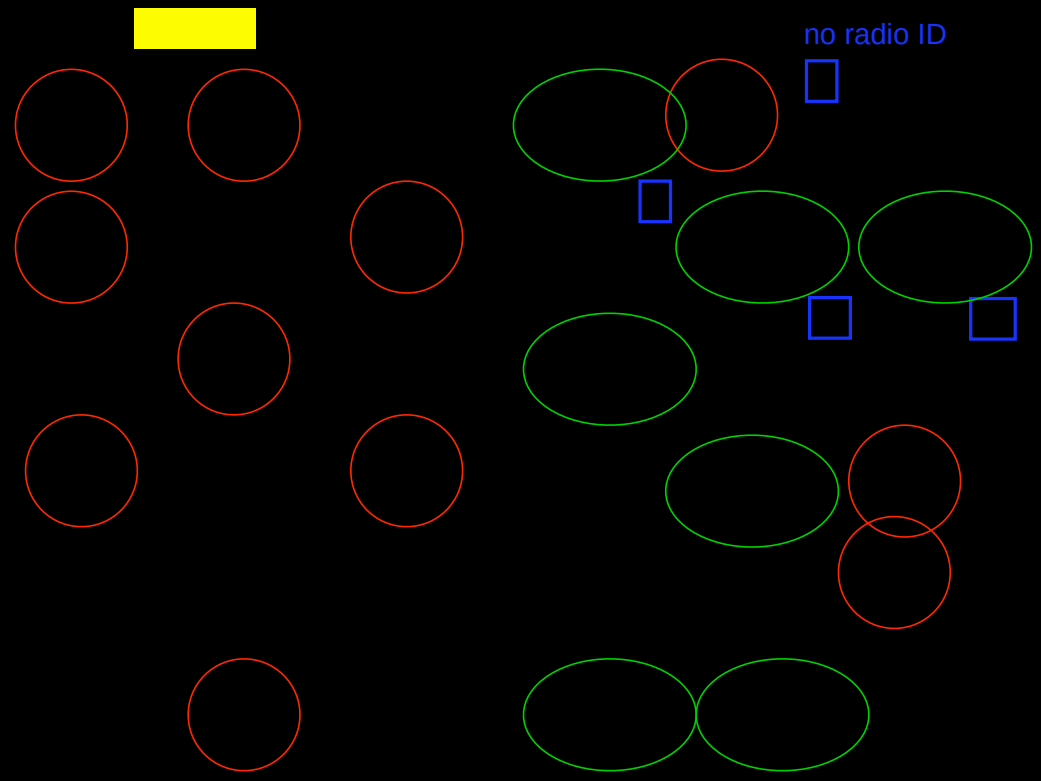
started looking at this in more detail (Manuel Aravena´s PhD)

MAMBO 1.2mm
VLA 1.4GHz
IRAC 3.6 μm
MIPS 24 μm





Radial distribution of red galaxies r-[3.6]>2 around COSBOs

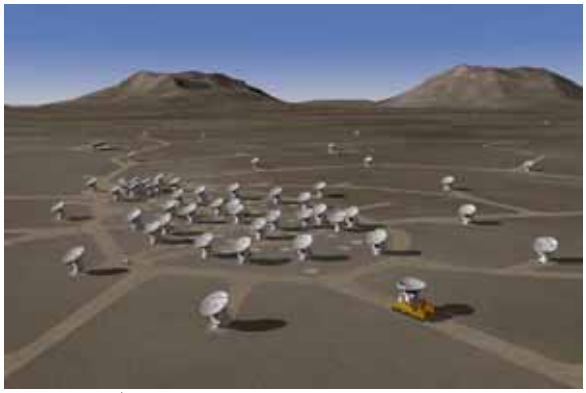


Open Questions:

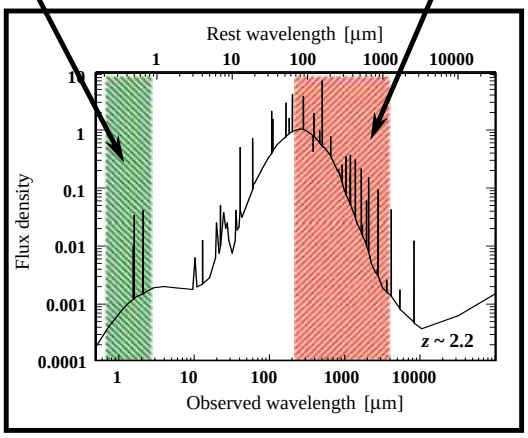
- Mapping the Cosmic Web over time
  - Tracing the evolution of bias of starbursts, spheroids, disks, AGN across the dark matter density field.
- Effect of environment on the physics of galaxy evolution
  - LSS is well modeled by CDM; need to sample the full range of environments to understand the relationship of structure to star formation, black hole formation, AGN-ignition, etc.
- Dominant evolutionary modes?
  - Bulges vs disks
  - Starbursts vs Quiescent
  - Star-formation (nucleosynthesis) vs AGN (accretion) activity
- Mass buildup at high-redshift

  How do we relate high-SFR (submm) sources to formation of massive objects, which are a challenge for CDM models;

  Need large volumes for rare high-mass halos. ($10^{15.5}$ M_0 halos)



ELTs:
Stars, Black Holes, Warm ISM



ALMA:
Cold Gas & Dust:
Building Blocks for Stars & Black Holes,

What ALMA Will Do for Galaxy Evolution:

- Determine robust rotation curves and study velocity fields for distant galaxies as a function of redshift and mass
- Establish a clean dynamical estimate of galaxy merger fractions as a function of redshift and mass
- Measure gas fractions as a function of redshift, mass, environment and galaxy morphology; explore the dependence of star formation rates on galaxy properties
- Resolve clumps, measure dynamical masses, velocity dispersions and gas fractions at ~few hundred pc (~0.03" - 0.05") resolution; together with ELTs, resolve nature and internal evolution of clumpy high-z galaxies
- Measure outflow rates of cold gas and test feedback models
- Together with ELTs, establish MBH/Mgal as a function of z, L for obscured and unobscured AGN population