Future extragalactic surveys

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Caltech
10th January 2008

AAS Austin

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Contents

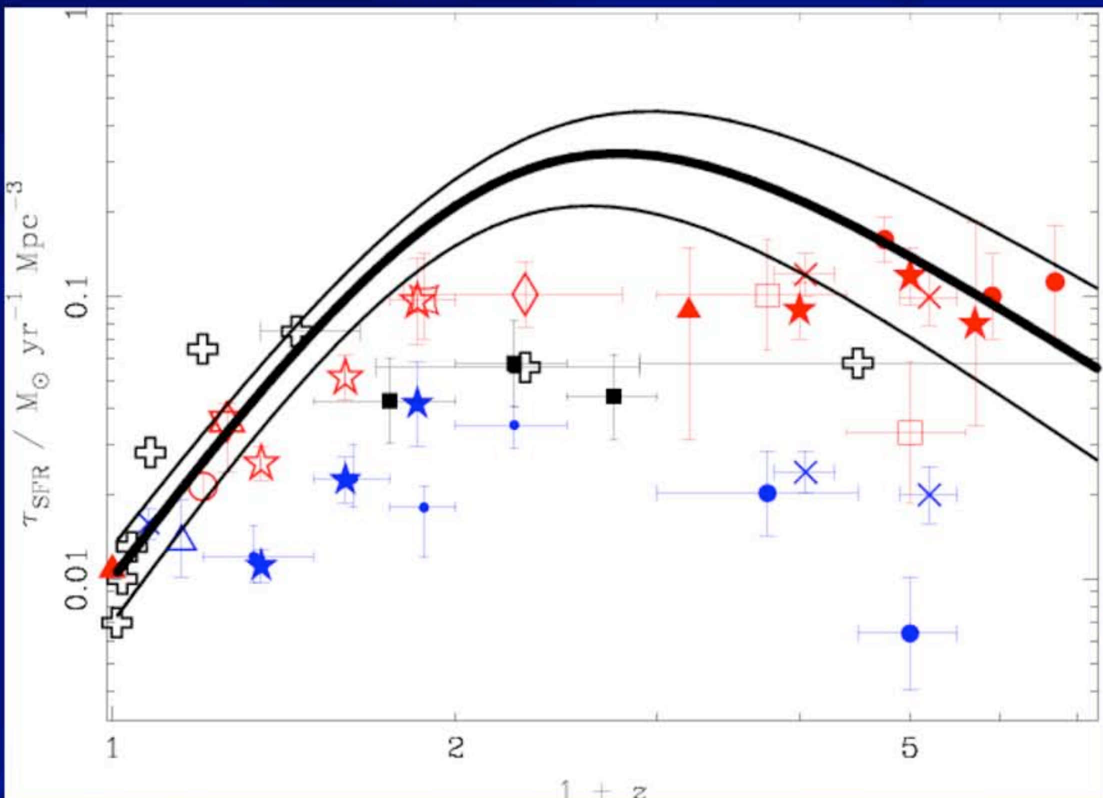
- Dust reprocesses about 50% of the energy released over the Universe's history
  - Less now than at most intense epoch z~2
  - Both star formation and AGN activity are responsible
  - Accompanied by molecular (and fine-structure atomic) gas emission

- Existing surveys find dust emission, but are challenging to follow up in detail at other wavelengths - HST - Spitzer - Chandra - VLA - 8-10-m spectroscopy

- ALMA will be a tremendously powerful & **transformational**
  - Unique capability to reach micro-Jy (sub-0.1-L* galaxy) sensitivity
  - Resolution down to of order 10 m-arcsec (~100 pc)
  - Sensitivity of order 1mJy in 1s
  - ALMA makes a day to minute integration time transformation

- BUT… Field of view is the antenna primary beam ~10-30 arcsec
  - Surveying is slow compared with sensitivity
  - Efficient imaging and imaging spectroscopy only of known targets
  - SCUBA2/Herschel/Planck make a start, but depth/area not to both L*/representative

Global luminosity evolution

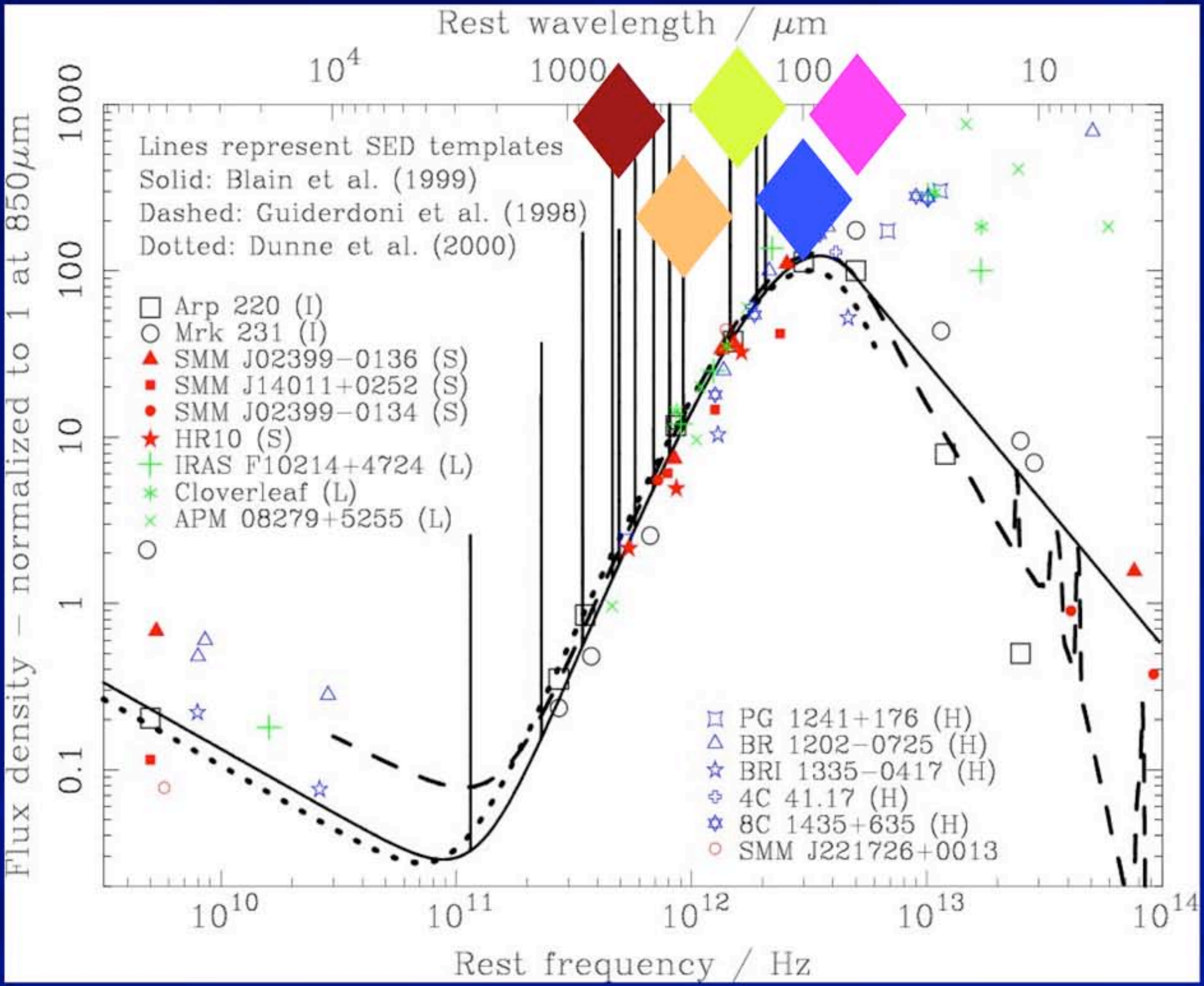


WMAP cosmology

- Points
  - Blue: optical / UV
  - Red: IR and dust corrected
  - Black: SDSS fossil record
  - Uncertainty remains
- Lines:
  - results from combined submm/far-IR information
  - Note high-z decline certain
  - Less rapid than for QSOs
- Caveats
  - AGN power (modest?)
  - High-z / high-L IMF change
- Submm-selected sample probes most intense epoch of galaxy evolution directly
  - Trace to L* at z~2 (0.1mJy)
  - Cover Gpc^3

What drives z~2 peak?
What happens beyond reionization?

Observed far-IR/submm SEDs



Normalized where sizeable sample of `submm galaxies' are selected. Redshifts z~2-3 from Chapman et al.

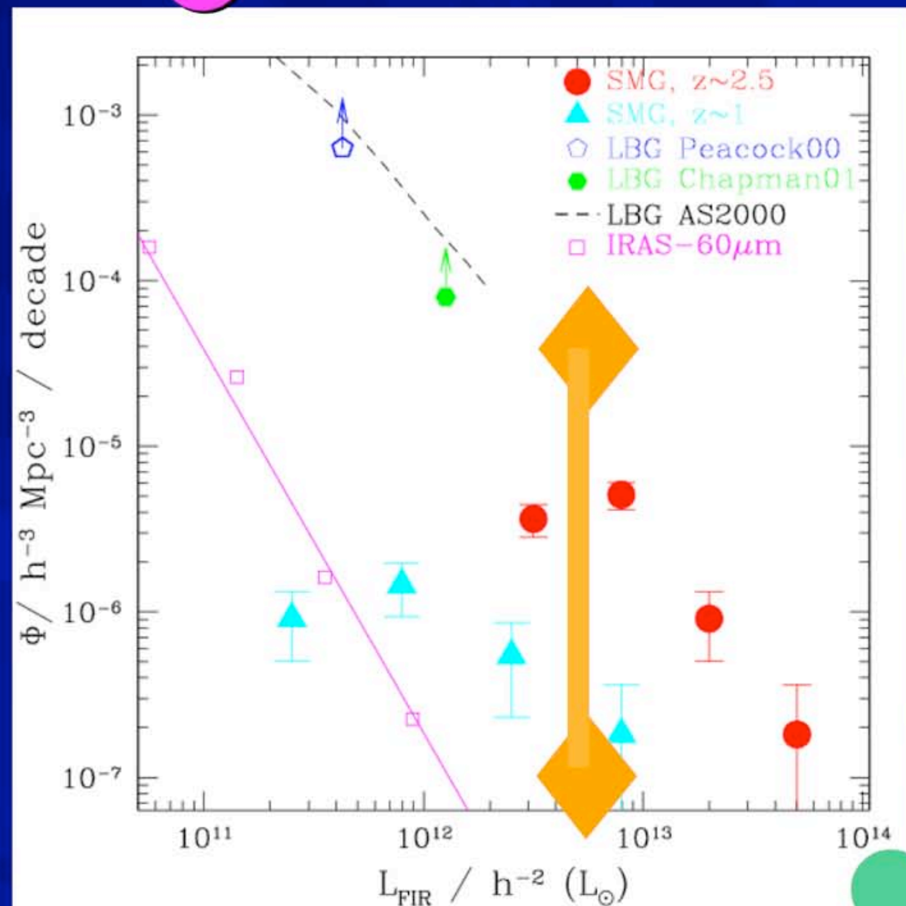
- Mix of different sources traces out **some** of the range of SEDs properties
  - Milky Way & APM08279 are extremes
- Blue/violet determines SED peak, thus luminosity
- ALMA can do this, but only source by source

Continuum detections & SEDs

- Sifting catalogs needs some color / optical / radio information
  - Prioritize for follow-up, reveal pre-ionization sources, spot low-z galaxies
- ALMA:
  - ~10% of ALMA continuum detections have a CO line in an 8-GHz band
  - Measure continuum slope in band - same information as a color?
    - Surprisingly tough
    - Even without line pollution & bandpass calibration uncertainties (ZSPEC)
    - Spectral index measurement to ±0.2 requires S/N ~ 1000 in continuum with 8-GHz-wide band. Even 50GHz band requires S/N ~ 100 for ±0.25 in spectral index
- Need to measure colors between ALMA or CCAT bands
  - Need to cover turn over in SED near 3-400 microns
  - *T* to ±5% requires S/N ~ 100 in each band (even at 350/670GHz)
  - CCAT's site & size favor speedy acquisition of quality colors, during mainstream survey

FIR & optical luminosity function

- Dramatic evolution from redshift 0 to 2.5
  - Optical surveys tie in
  - Current submm data not linked directly to them
- Key goal is to understand the overall LF from z~0.5 to 5
- Going deeper than ◆ needs
  - Less spatial confusion
  - Higher frequency(ies)
  - CCAT at 350/450 microns
- L* galaxies ● ~0.01 Mpc^{-3}
  - For 1<z<3 1 deg^2 covers ● 2.3x10^7 Mpc^3



Chapman et al. (2005)

Large scale structure

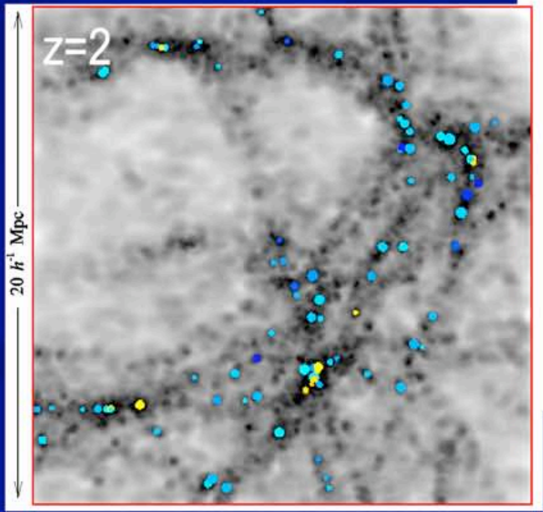
- N-body simulations track mass well (greyscale)
- Red labelled galaxies (ellipticals) form earlier, and are most clustered
- Relating submm galaxies is more difficult, and not so far done convincingly

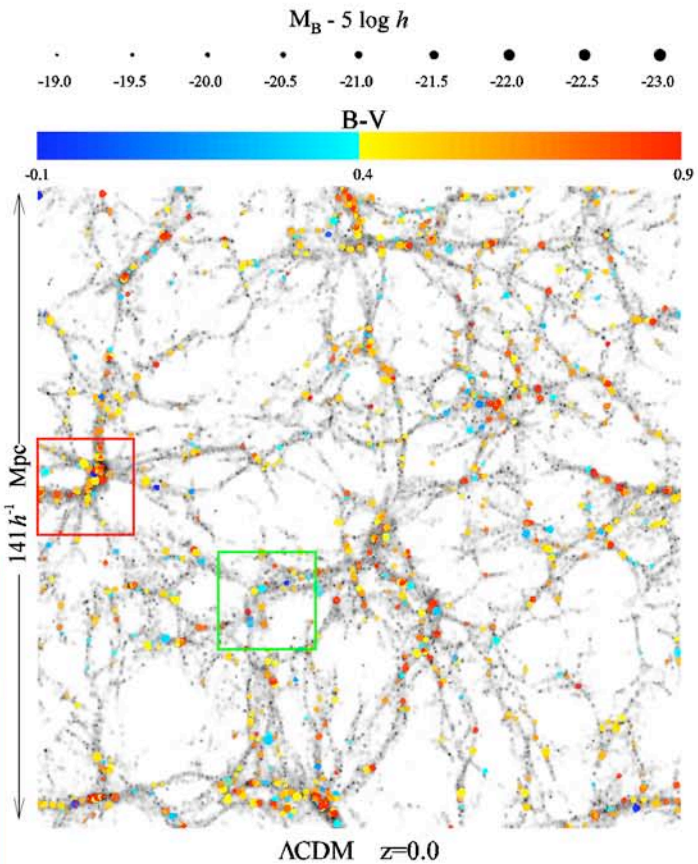
Prediction difficulties:

Strong feedback

Rare well-studied examples

Uncertain astrophysics

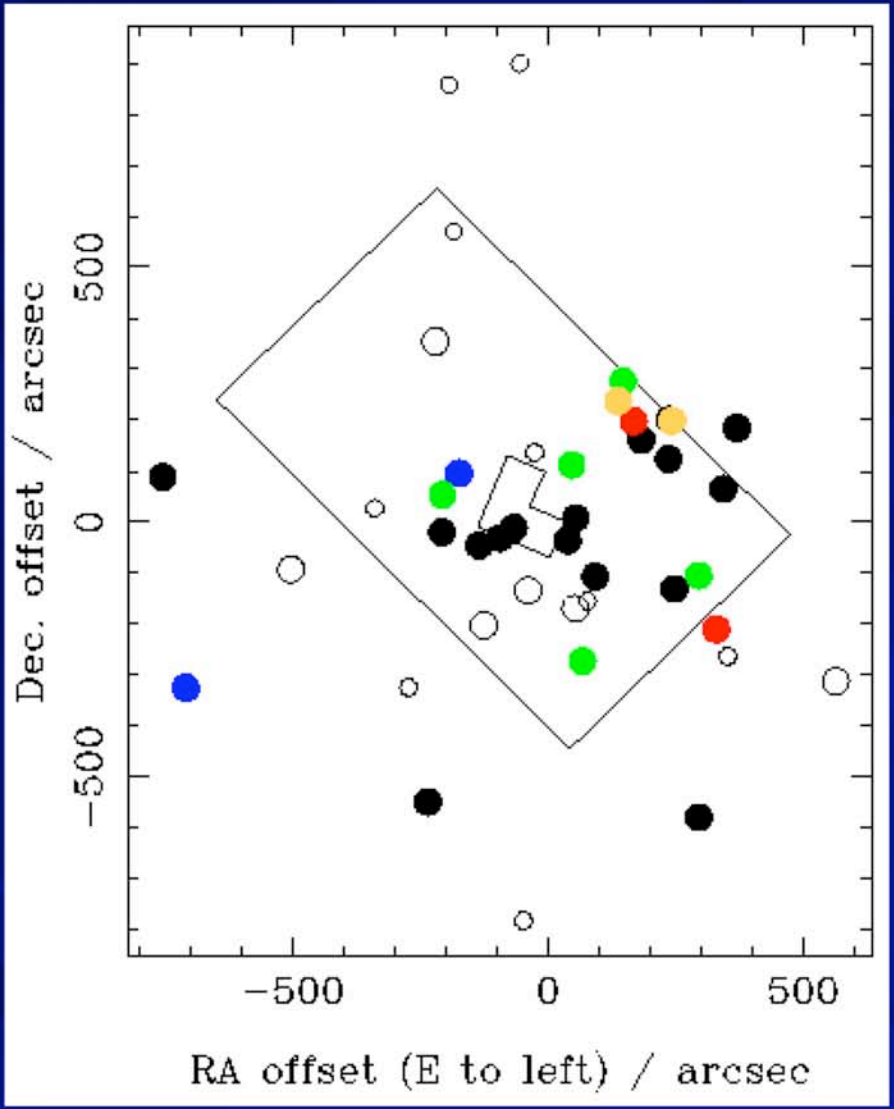




Benson, Frenk, Baugh, Cole & Lacey (2001)

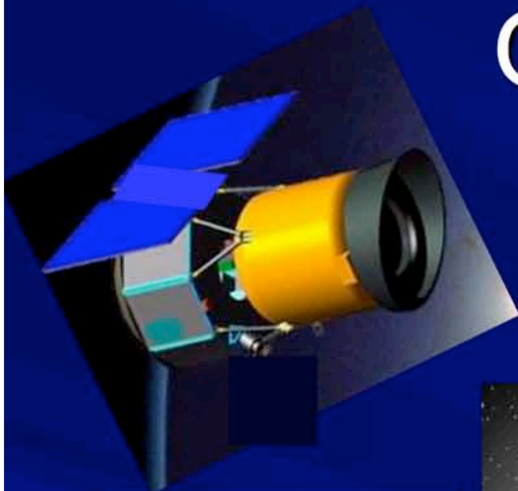
1 Mpc ~ 100 arcsec at high z
100 Mpc ~ 3 deg

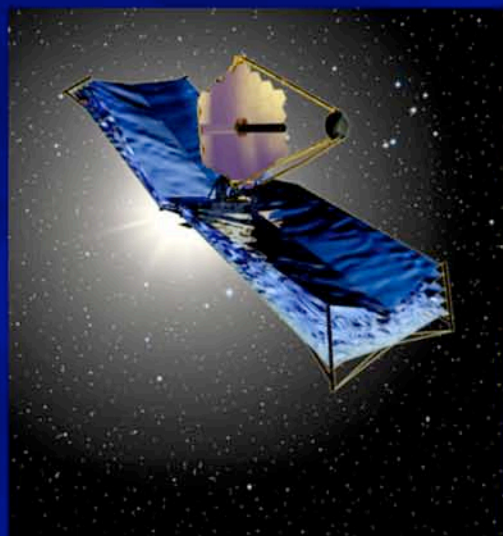
SMGs trace 3D large-scale structure (LSS) peaks?



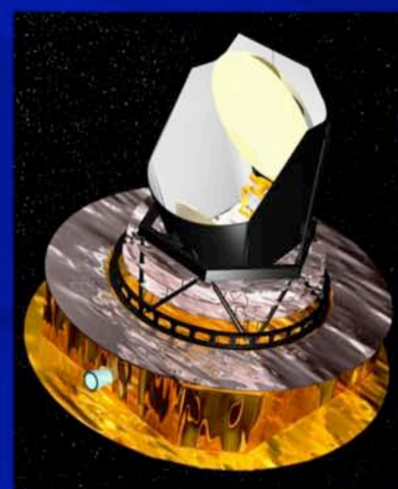
- Largest number of SMGs are in and around the HDF field
  - HDF & GOODS frames show where morphology information is available
- Circles: all known radio-submm galaxies
  - Small empty: no z attempt
  - Large empty: no z found
  - Black filled: z found
  - Colored filled: ‘associations’ - all z’s within 1200 km/s
- Green points (z=1.99) match optical galaxy z spike (Steidel et al)
- Only the spectroscopic redshifts from LRIS reveal structure
- Many more ‘clusters’ or associations expected than expected from our knowledge of SMG N(z)
- Narrow-band searches under way

Other new & (near-) future tools





See also Spitzer & Akari

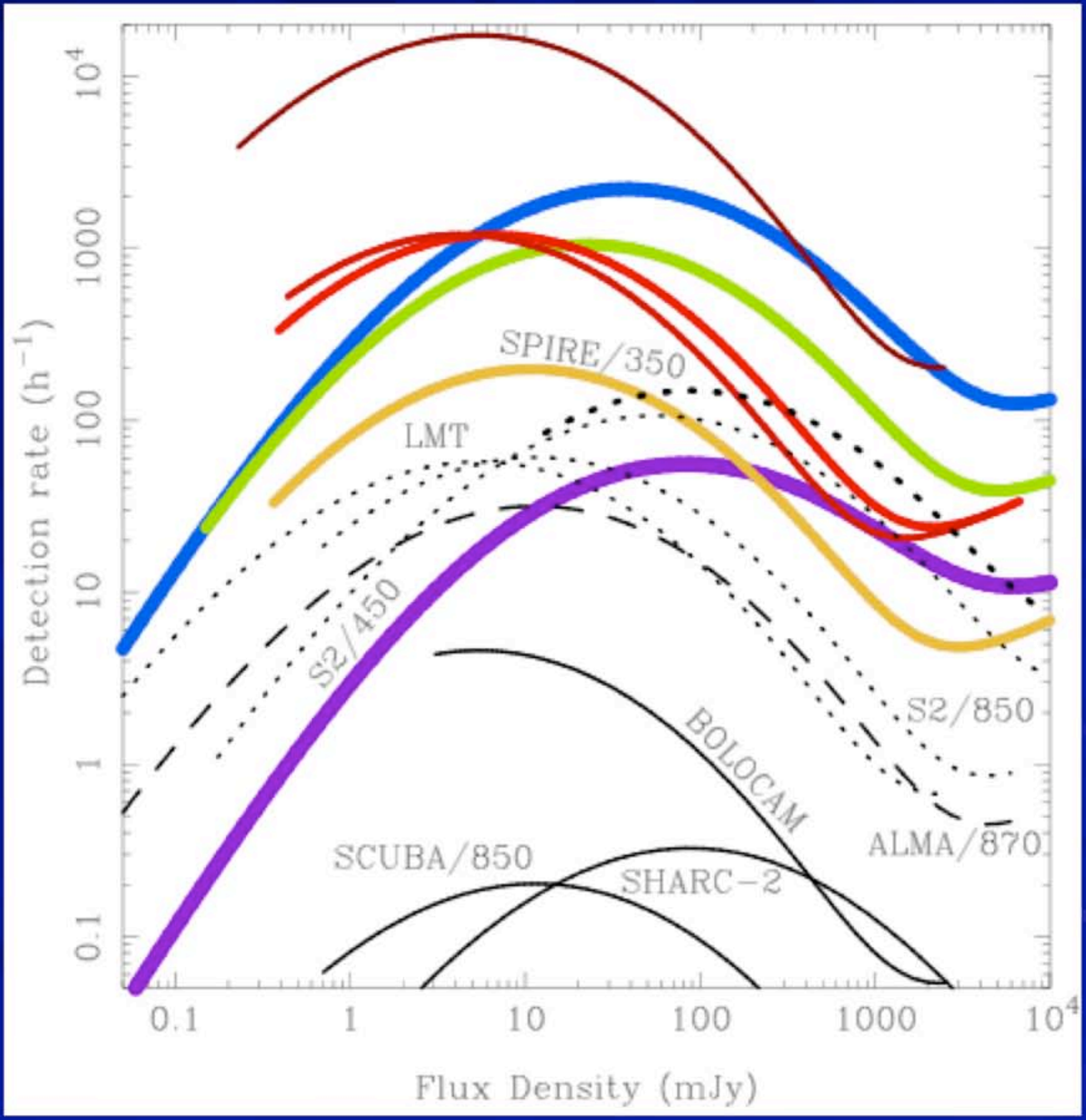


*-shown

CARMA*, APEX, SOFIA*, SCUBA-II, LMT*, Herschel*, Planck*, WISE*, ALMA*, SPICA, SAFIR, SPECS/SPIRIT/FIRI

CCAT: Speed vs other instruments

- ALMA, SCUBA-2, 50-m LMT, Herschel
- Assume CCAT cameras
  - 1100, 870, 740, 620, 450, 350, 200 microns
  - SWCAM 32000 pixels
  - LWCAM 16000 pixels
- Fastest depth ~few mJy at 1100 microns (current SMGs)
  - FOV 25 $arcmin^2$
  - 1mJy 5σ in 30s
  - 1/2-sky survey in 2.5 yr
  - 10^8 galaxies
- Confusion limited (350micron)
  - 0.05mJy 1σ in 600s (10^{11} L_o)
  - 2 deg^2 in 40hr
  - 10^6 galaxies over few yr
- Huge galaxy surveys
- CMB foreground maps



Making surveys and diagnoses

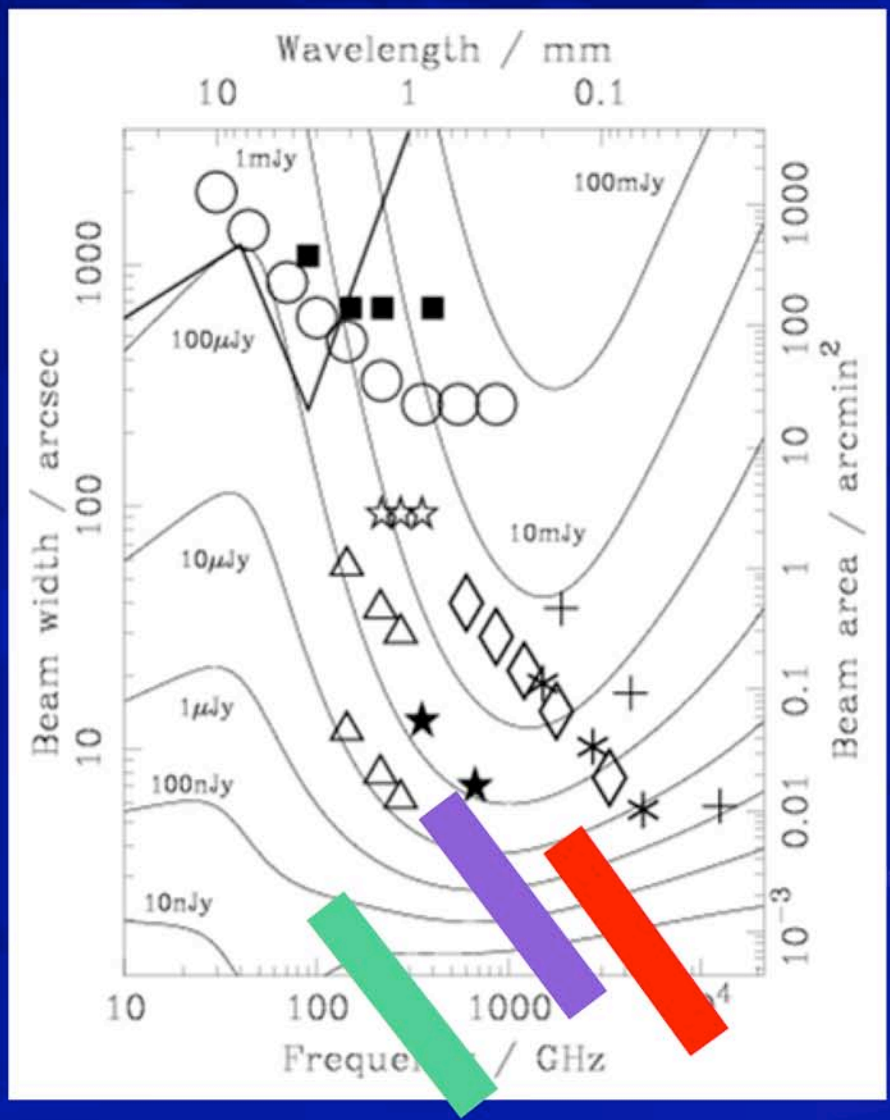
- Wide-field surveys, beyond current 10's deg^2
  - Find rarest, most extreme objects
  - Mid-IR all-sky mission WISE, submm CCAT
  - Links between environment, and luminosity function (LF) at all relevant wavelengths
  - Herschel/Planck find very top end of LF
- Resolved imaging of individual sources, and extremely deep surveys still require ALMA
  - Internal dynamics
  - Find ultrafaint galactic building blocks after first generation of stars generate metals (ices?) and before re-ionization

Summary

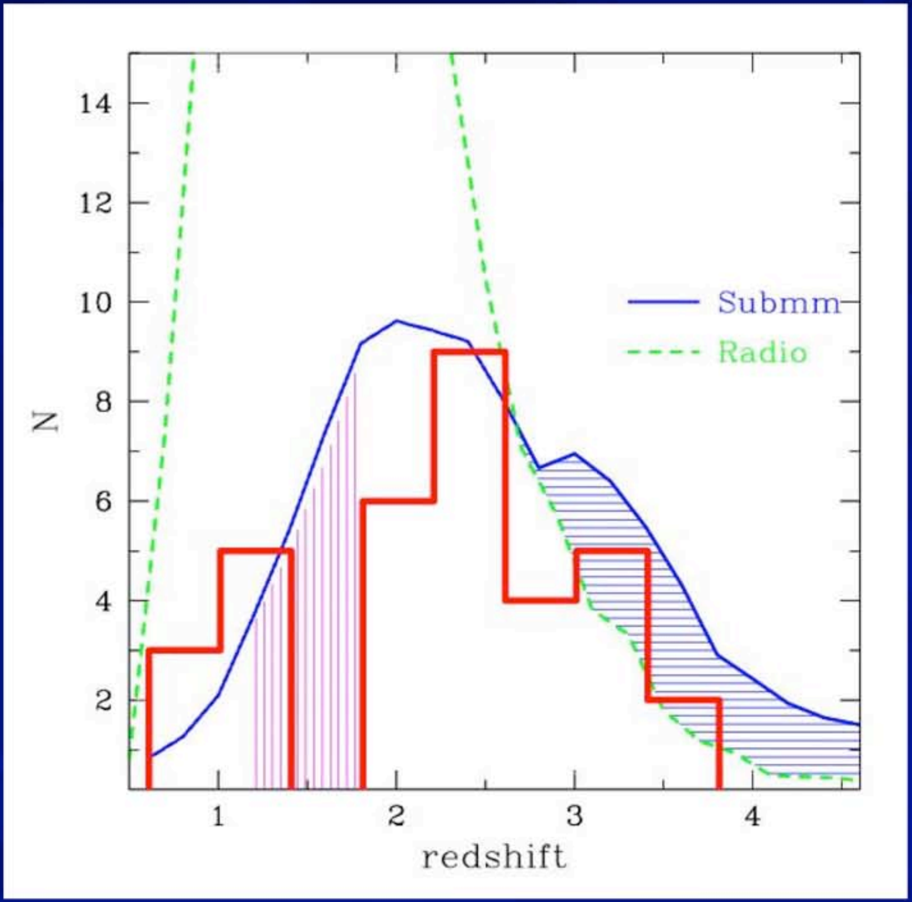
- Useful colors **require** submm measurements
- Context requires multicolor 10-deg^2 fields
- Completeness requires sub-mJy submm sensitivity
- ALMA crucial for very deep (spectral) imaging to understand astrophysics of dust-enshrouded galaxies
  - Revealing large-scale structure, measuring colors and compiling large samples is not its strength, because of speed
  - A single CO line and one continuum color is enough to give a good guess to redshift & luminosity

Overcoming confusion

- Current missions in black
  - Spitzer is +
- Green bar is just a 500m baseline ALMA
- Purple bar is ground-based 25-m CCAT
- Red bar is 10-m SAFIR
  - Confusion from galaxies not met for many minutes or hours
  - At shortest wavelengths very deep observations are possible
- Factor 2 increase in resolution over existing facilities is very powerful
  - Submm confusion dives at 5”



Redshift distribution N(z) for radio-pinpointed SMGs

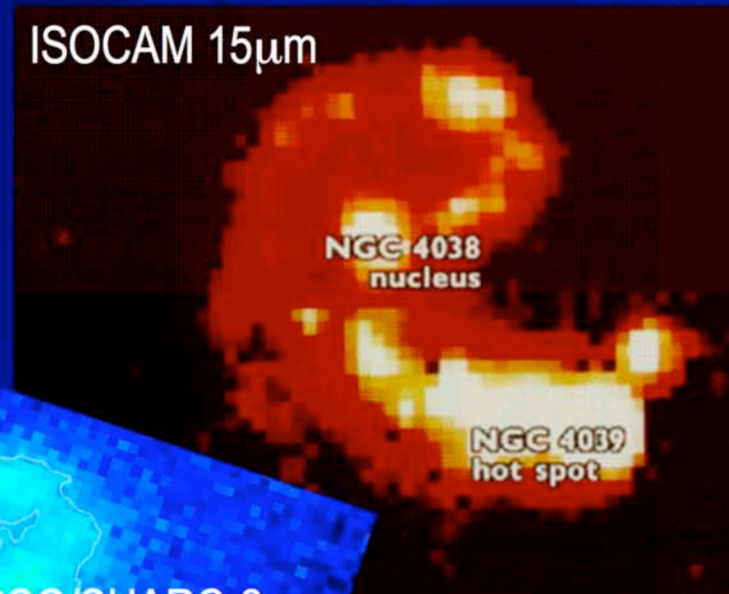


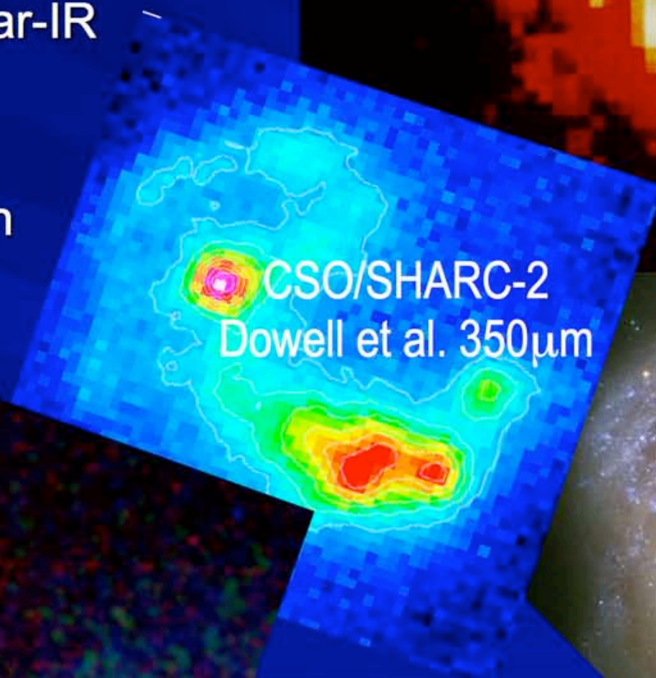
Chapman et al. (2003; 2005)

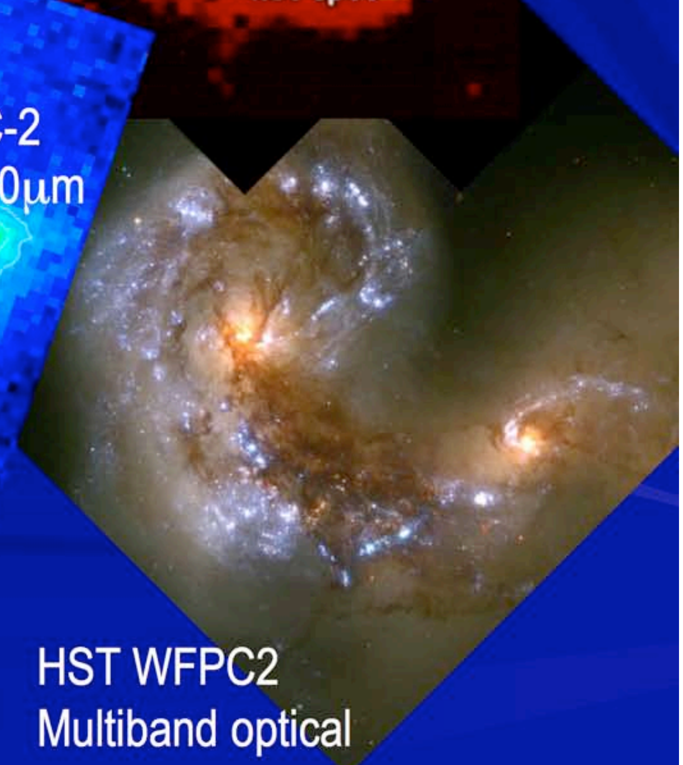
- Red histogram: Chapman et al
- Lines: expected submm & radio N(z)'s from Chapman's model
  - Consistent with early submm-derived Madau plots but result is now **MUCH** more robust
  - Magenta shade at z~1.5 is 'spectroscopic desert': rest-UV & rest-optical lines both hard to observe
  - Blue shading at highest z is incompleteness due to radio non-detection. Likely modest, but uncertain
- Now 73 redshifts (ApJ 2005)
  - Median z=2.4 and spread in redshift z~0.65 is good description

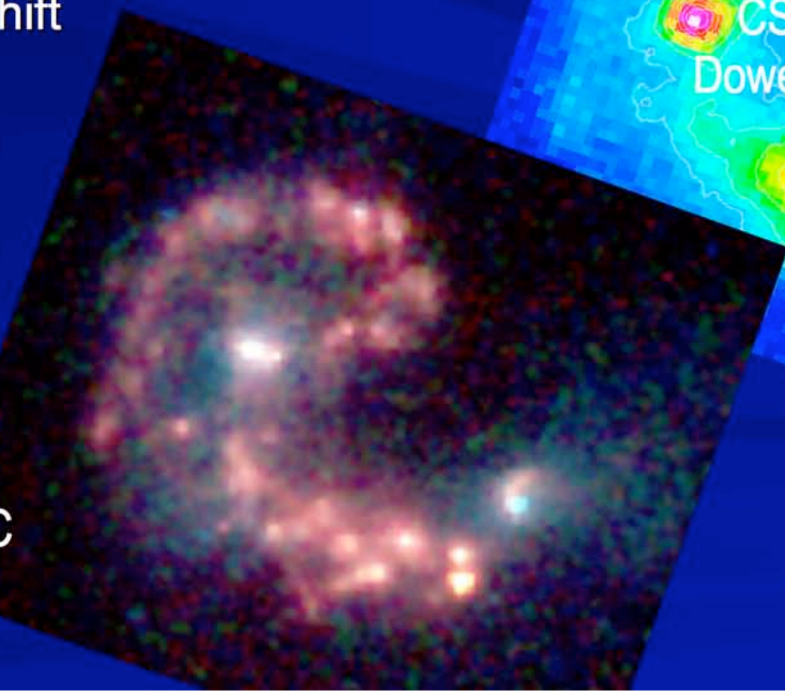
Resolved 'example': the Antennae

- Excellent example of distinct opt/UV and IR luminosity; BUT modest luminosity
- Interaction long known, but great IRAS luminosity unexpected
  - ~90% energy escapes at far-IR wavelengths
- Resolved images important
  - Relevant scales ~1" at high redshift





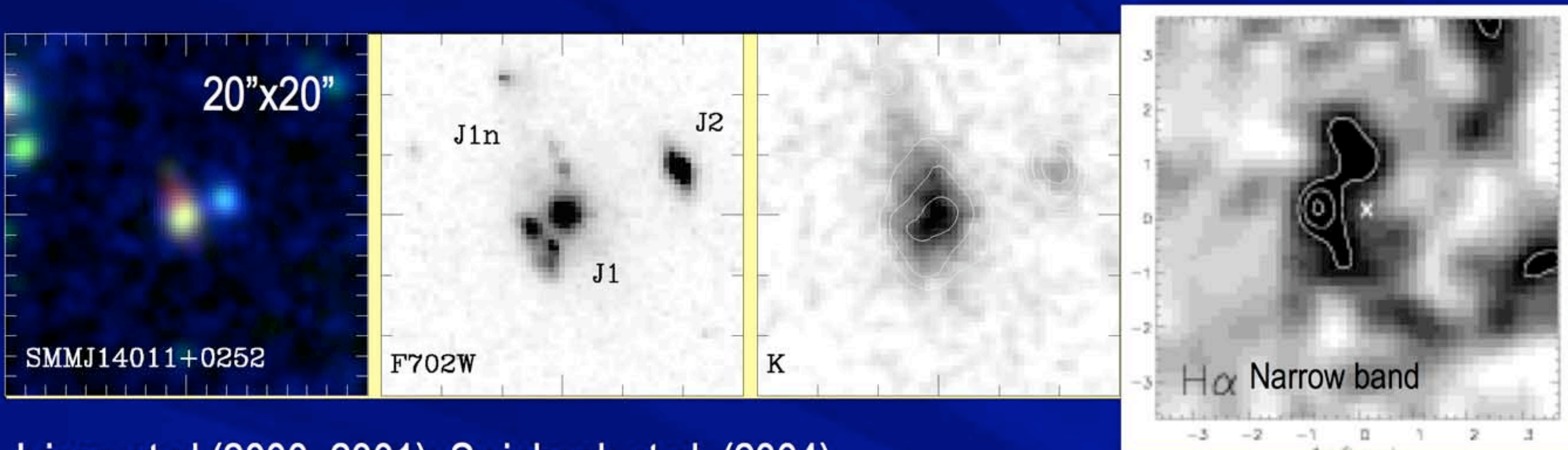




Spitzer IRAC
mid-IR

HST WFPC2
Multiband optical

Example IDed submm galaxy

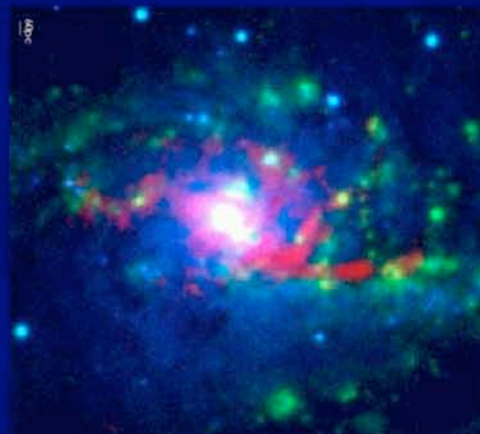


Ivison et al (2000, 2001); Swinbank et al. (2004)

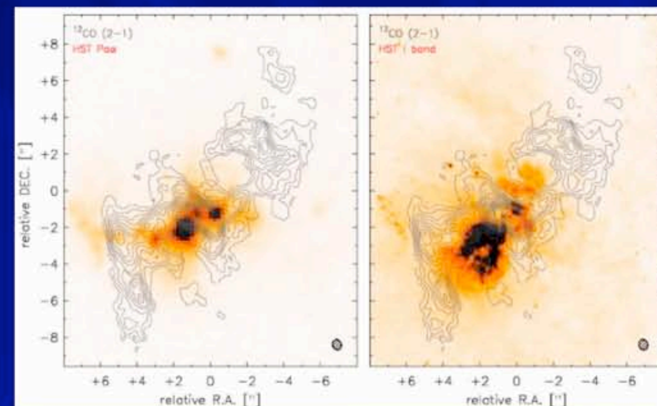
- Relatively bright, complex example
- May not see most important region in the optical - Spitzer IRAC can highlight interesting locations
- J2 is a Lyman-break galaxy (Adelberger & Steidel 2000)
- J1 is a cluster member post-starburst galaxy (Tecza et al. 2004)
  - Hα/continuum ratio imply this does not add significant magnification
  - J1n is an Extremely Red Object (ERO; Ivison 2001)
  - Remains red in deeper Keck-NIRC data
  - Powerful Hα emission
- Both J1n & J2 are at z = 2.55 – radio and mm appear to be from J1n

Local example of best results

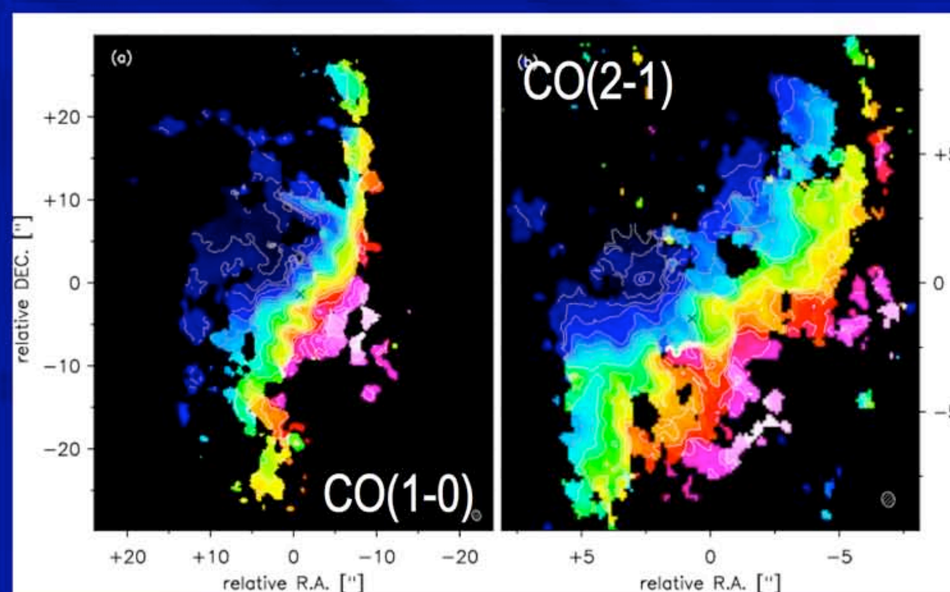
- IRAM PdB CO in NGC 6946 (Schinner et al. 2006)
- Spatial structure & gas dynamics
- ALMA can probe at z~3
  - Resolution
  - Primary beam
- Note synergy with eVLA/eMERLIN
  - Ultimately SKA



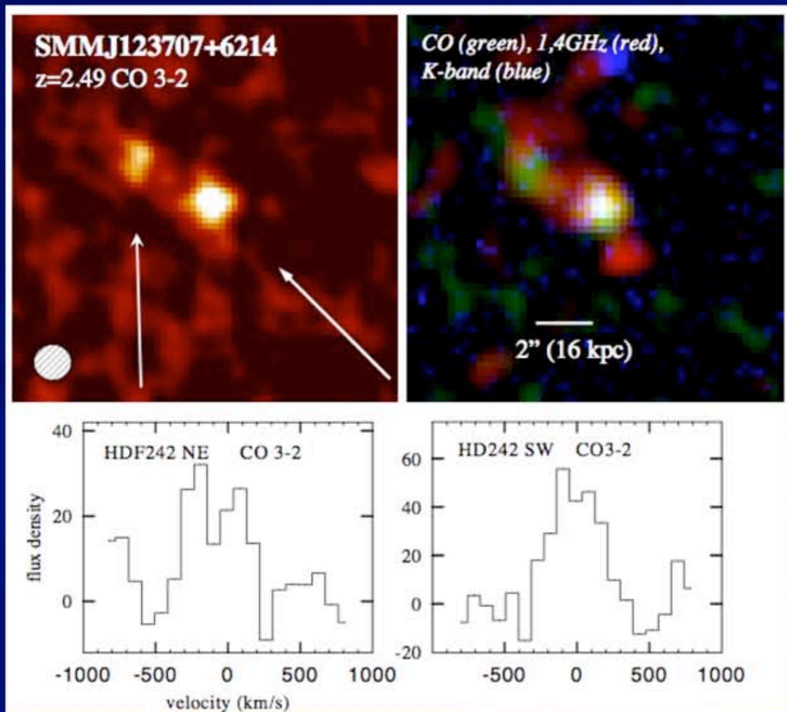
Red: CO; green: Hα; blue: continuum



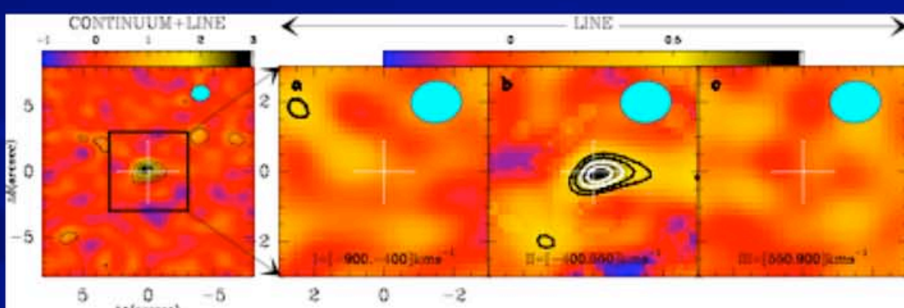
CO(2-1) contours
HST: Paα & I band



Best achievable now - distant



Genzel et al PdB



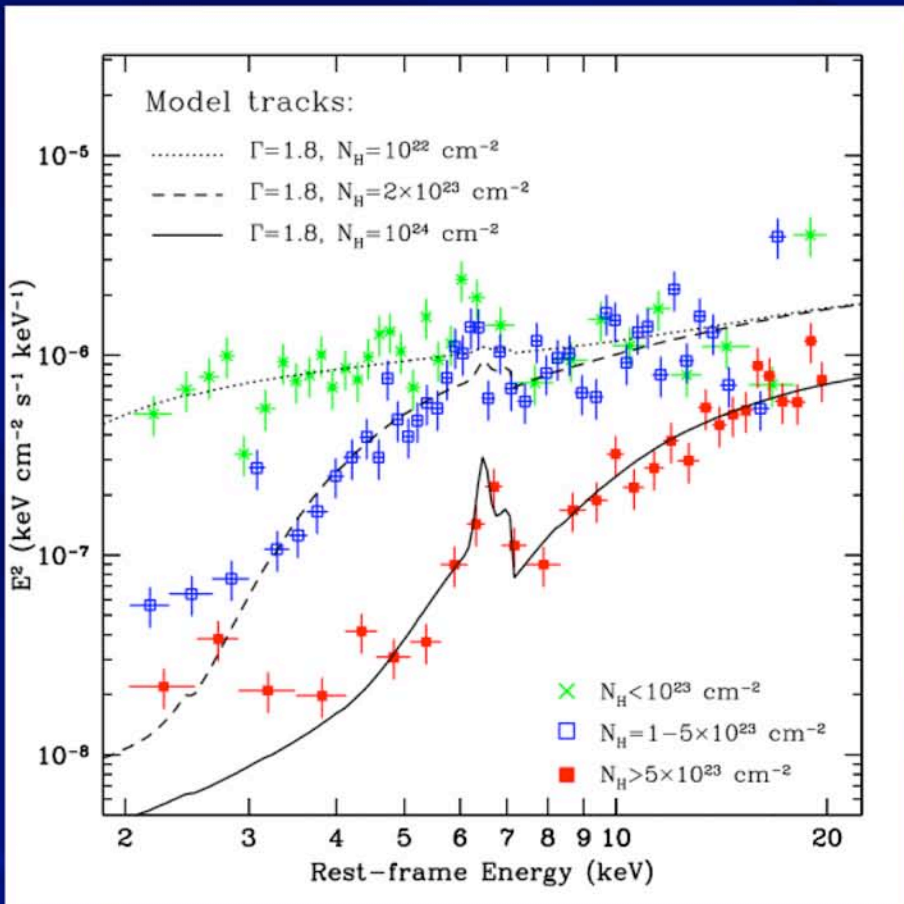
8'x8' field PdB HCO+(5-4) Garica-Burillo et al (2006)

- Only marginal spatial resolution possible
- Spectral bandwidth narrow
- Situation will improve dramatically with ALMA, a step in imaging quality tested at CARMA & IRAM

Astrophysics of examples

- First, redshifts necessary
  - In principle from CO, but in practice optical
- Then, CO/near-IR/X-ray targeting and stacking is possible
  - Also stellar mass from Spitzer IRAC colors
  - Also morphology, mergers, multiple/multicolour components
- X-ray probes of Compton-thin AGN
- CO / Hα images start to probe dynamics
- When investigated in detail, all get messy

X-ray reveals AGN in 2-Ms HDF

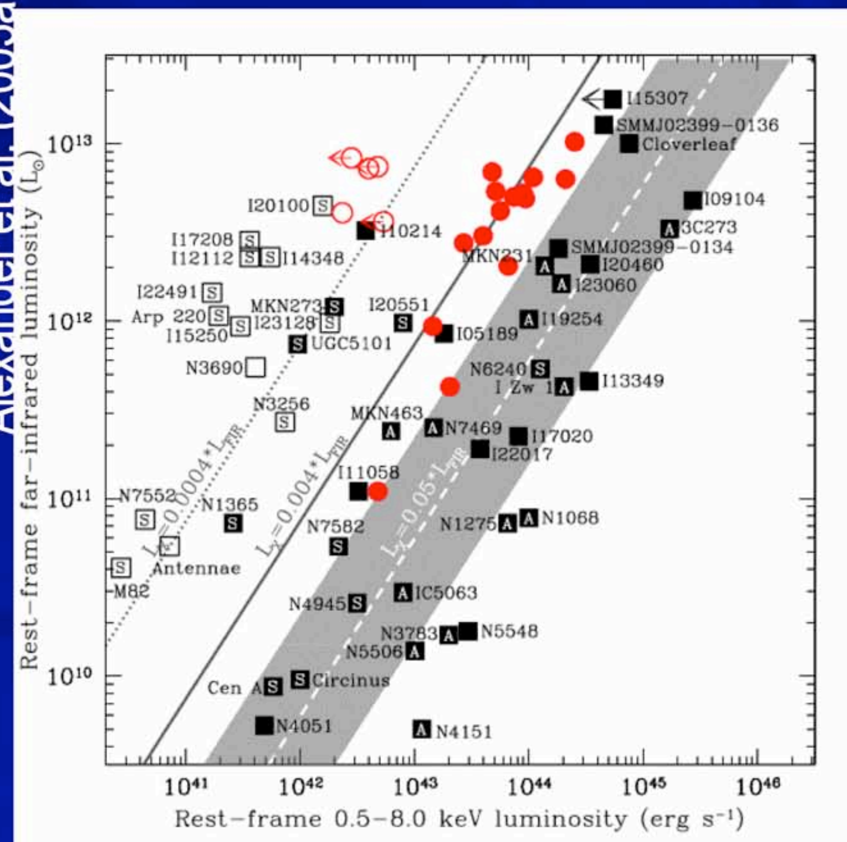


19 galaxies in GOODS-N field
Redshifts allow stacking in soft & hard classes

Excellent fit to X-ray SED models -
Fe emission & H absorption

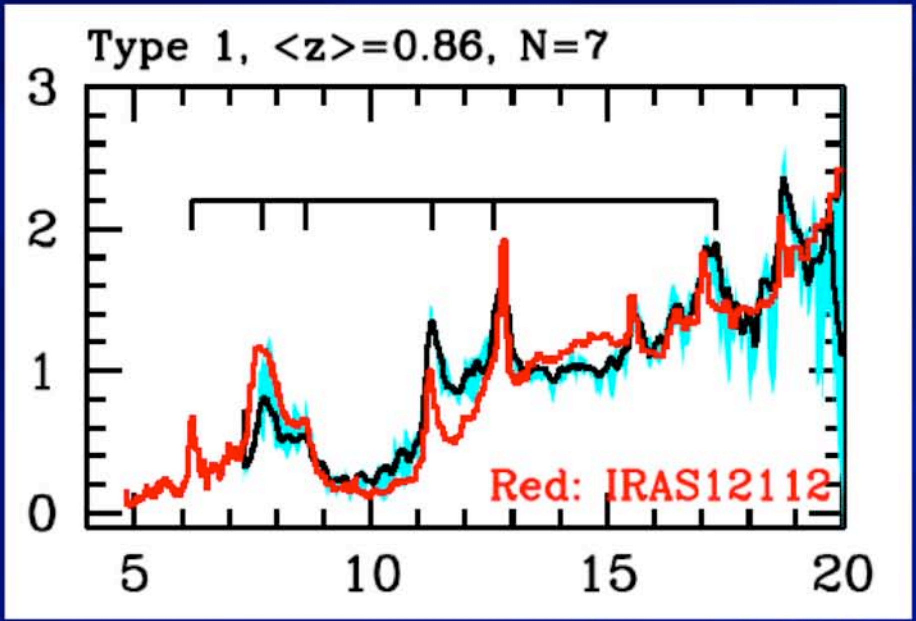
- 2-Ms exposure reaches 1% of typical QSO X-ray flux at z~2.5
- X-ray flux of SMGs implies significant AGN power

Alexander et al. (2005a,b)



The mid-IR window

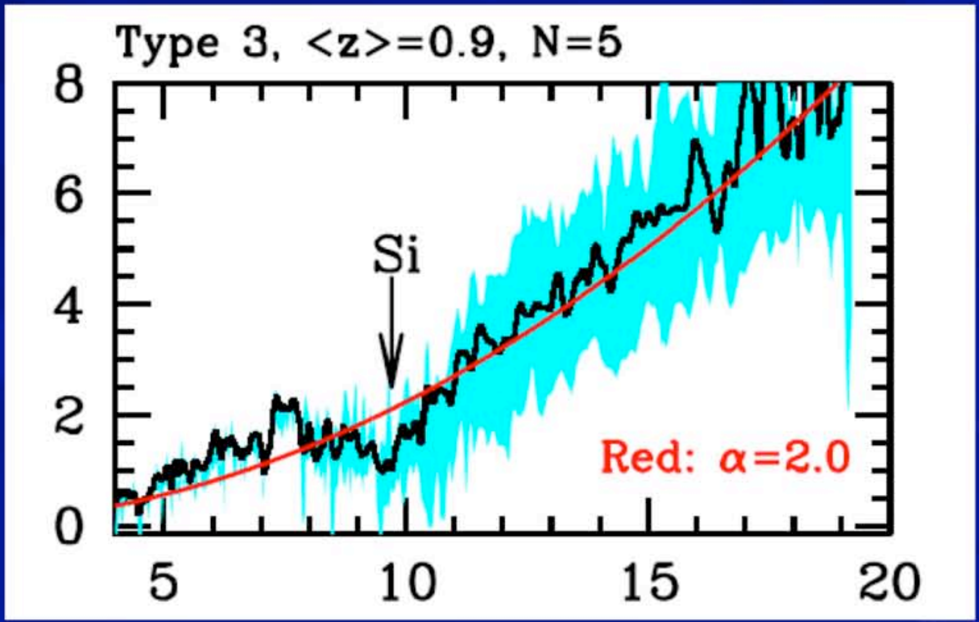
- Emission from Polycyclic Aromatic Hydrocarbons (PAHs) implies SF activity (?)



Yan et al. 2007

Weak/Absent PAHs imply AGN

- Continuum dilution
- PAH destruction (Voit 1992)



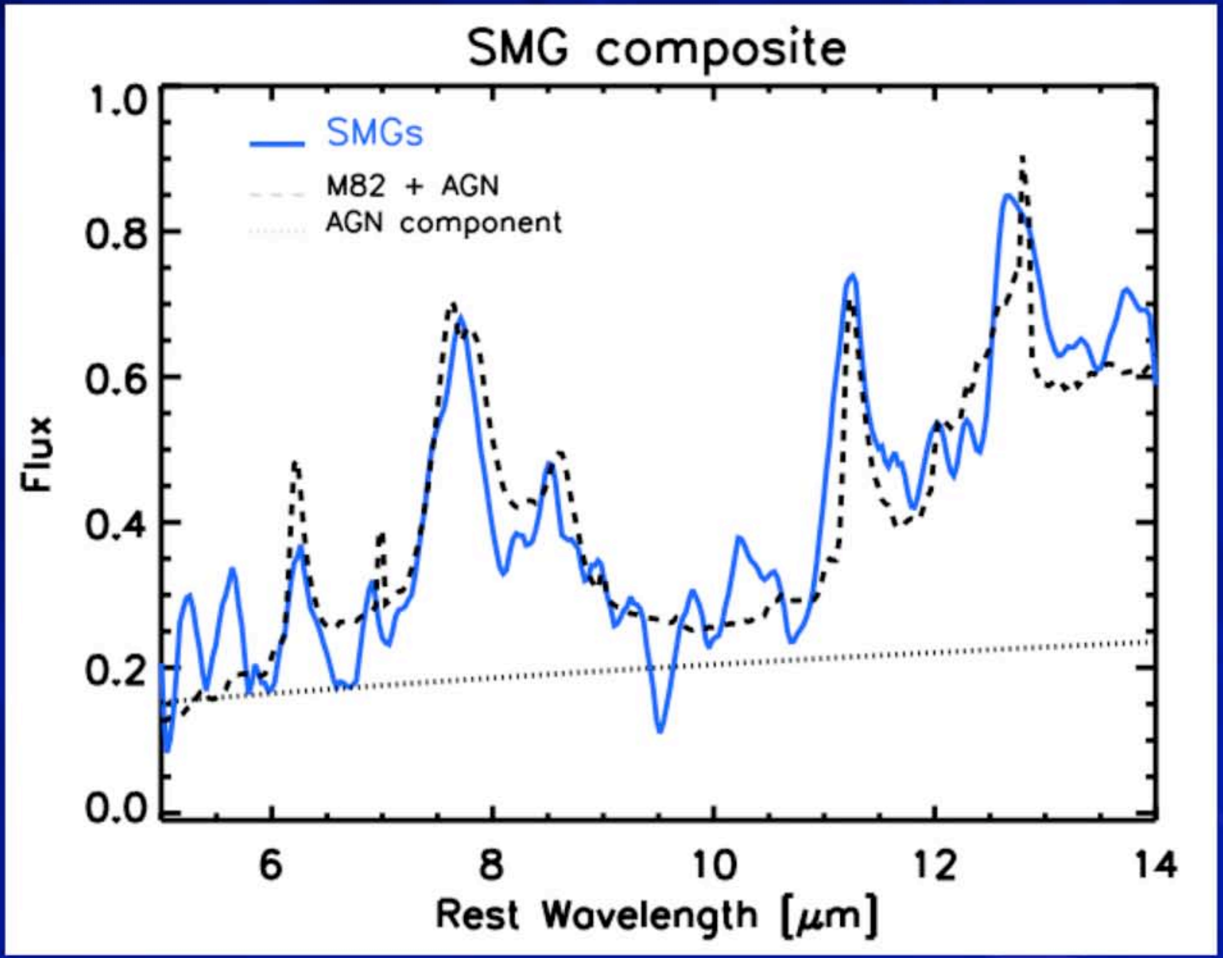
Mid-IR spectroscopy (ending with Spitzer in ~May 08) offers unique chance to separate the mechanisms

AGN Contribution

M82 + faint power-law continuum

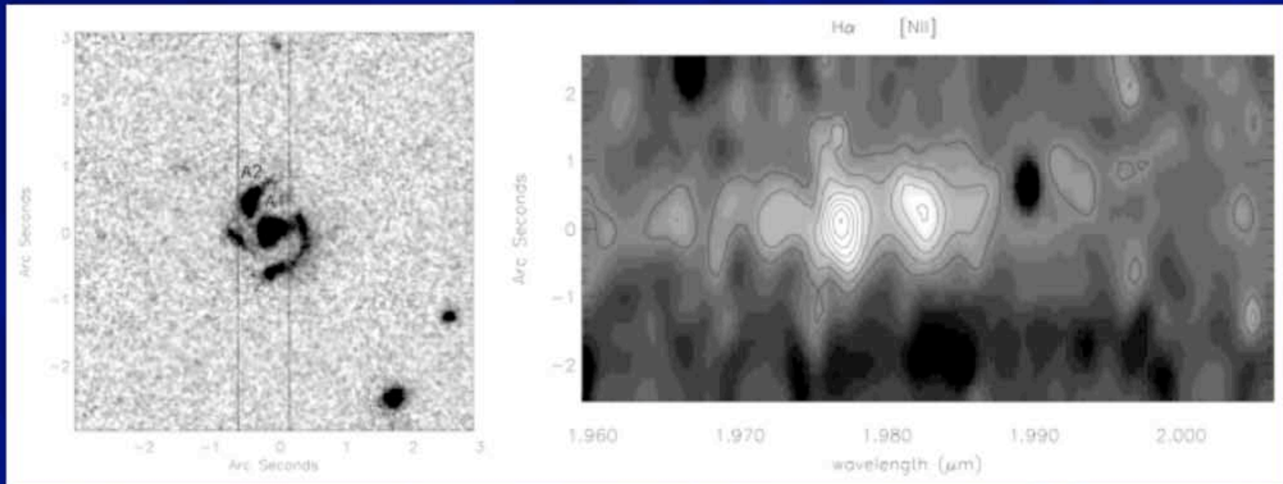
(from weak AGN?)

~ 10% AGN contribution, as in X-ray



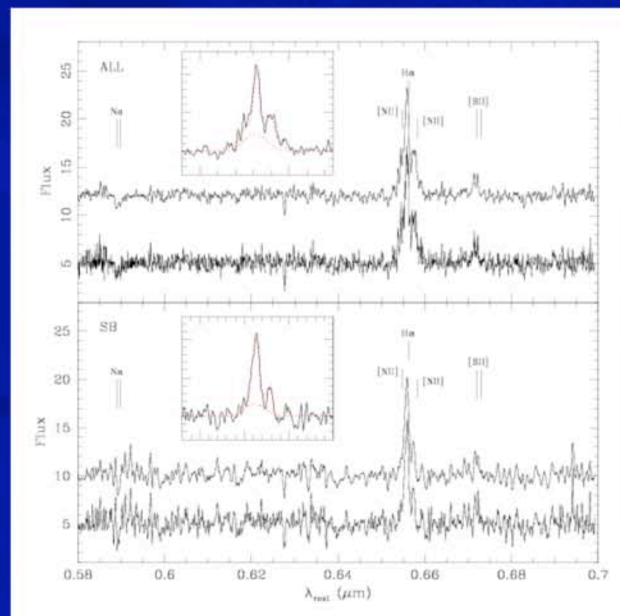
Menendez-Delmestre et al. (07, 08)

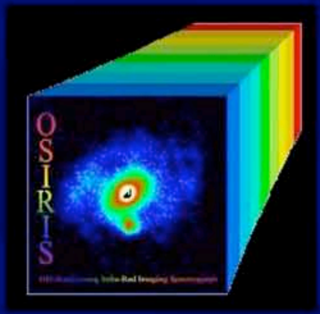
Near-IR spectroscopy (NIRSPEC, VLT and narrow-band at IRTF & UKIRT)



- ~25 targeted
  - Optical redshifts allow near-IR spectroscopy in favorable sky windows
- Hα/[NII] ratios and Hα line widths provide hints at presence of AGN
- Composite spectrum of examples with narrow (<400km/s) Hα show underlying broad line; narrow component gives dynamical mass - few 10^{11} M_o
- Adding [OII]/[OIII] ratios could bring in metallicity, but very time consuming!
- Aim to target brightest examples with OSIRIS to measure detailed dynamics

Swinbank et al. 2004

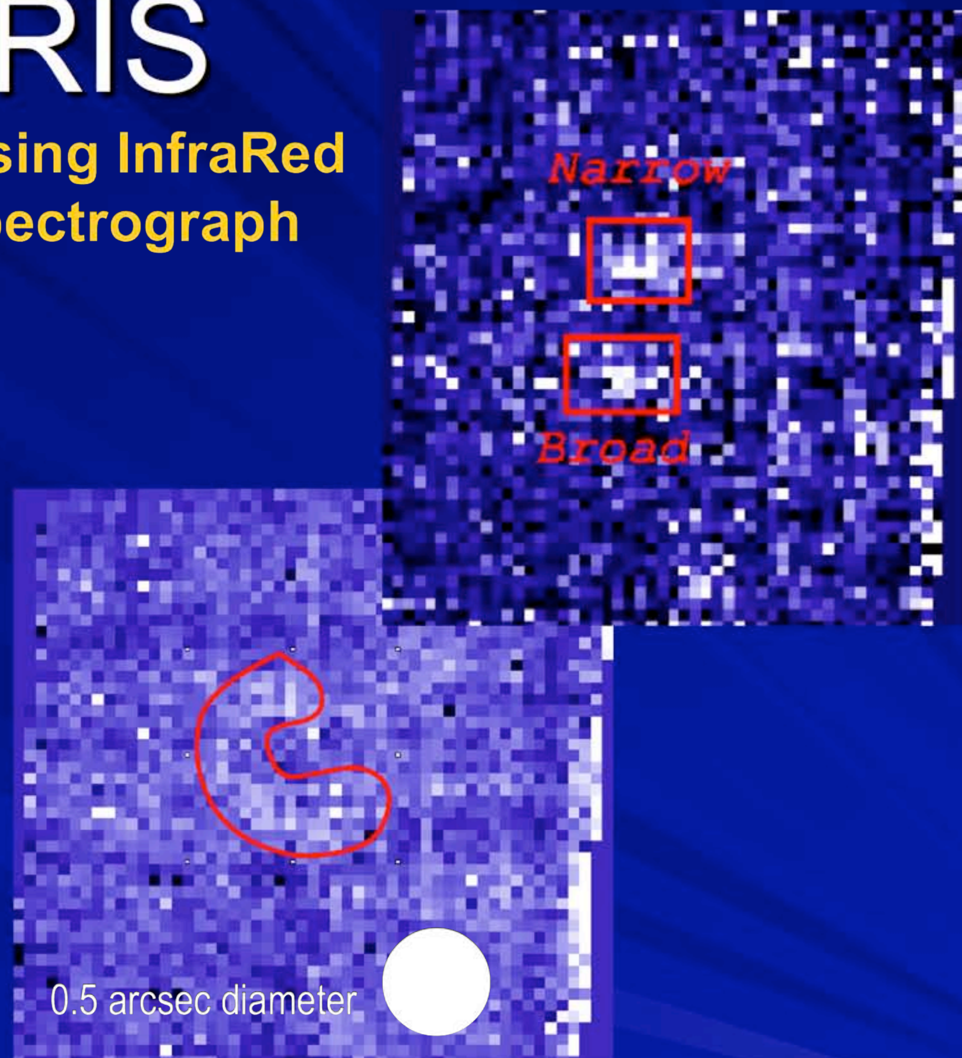




OSIRIS

OH-Suppressing InfraRed Imaging Spectrograph

SMM J163650, *z*=2.38



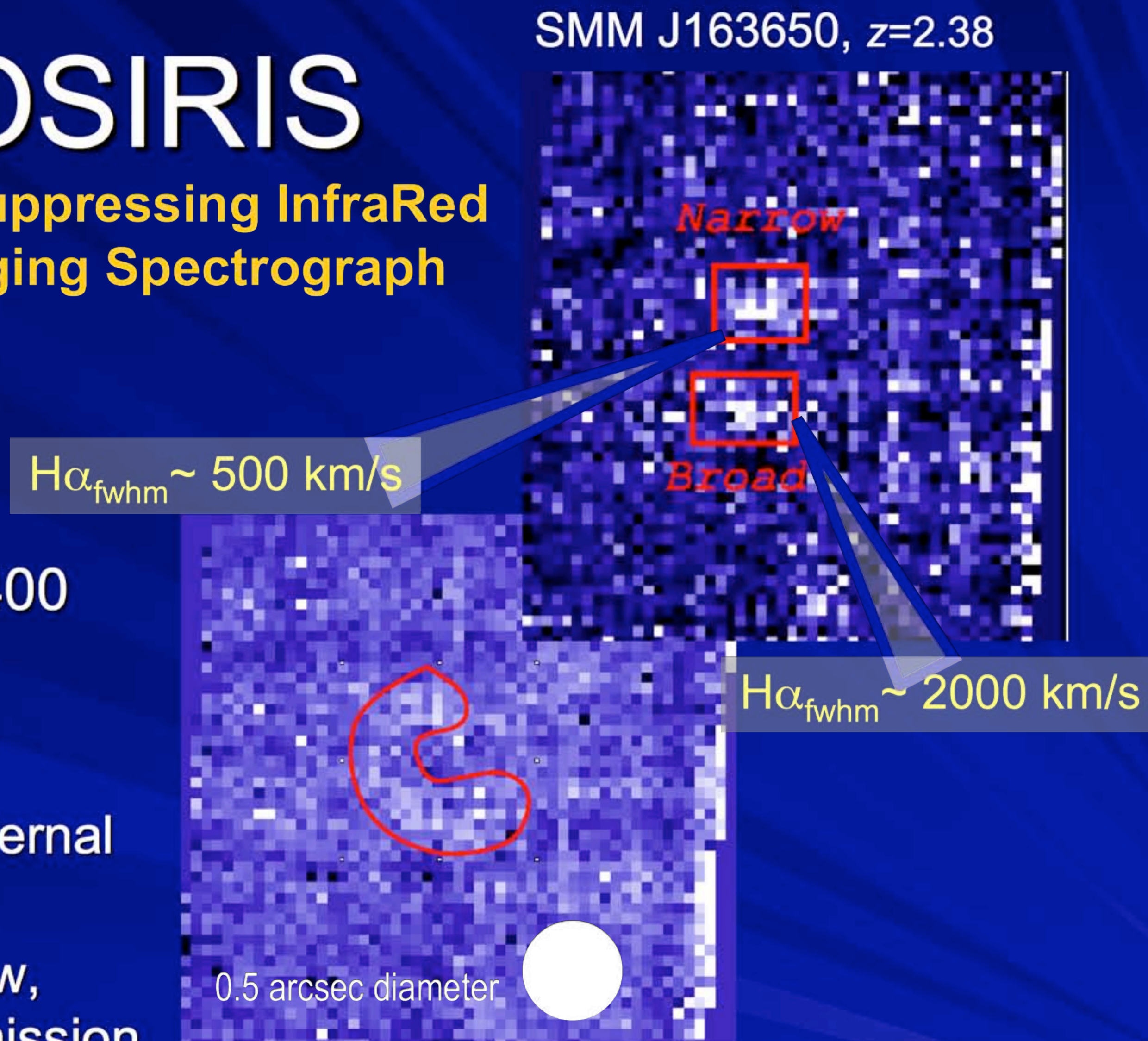
- FOV = 2.4 x 3.2”, R~3400

  (0.05” pixel scale)
- AO spatial resolution
  - Probe 2D-resolved internal dynamics
  - Separate broad/narrow, compact/extended emission

First OSIRIS results on select sample of SMGs shows compact AGN spatially distinct from stellar emission.

OSIRIS

OH-Suppressing InfraRed Imaging Spectrograph



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SED Variation: Composite IR SEDs of SMGs

Use all mid-IR to radio data for Chapman sample & compare to "cold" and "warm" ULIRG templates.

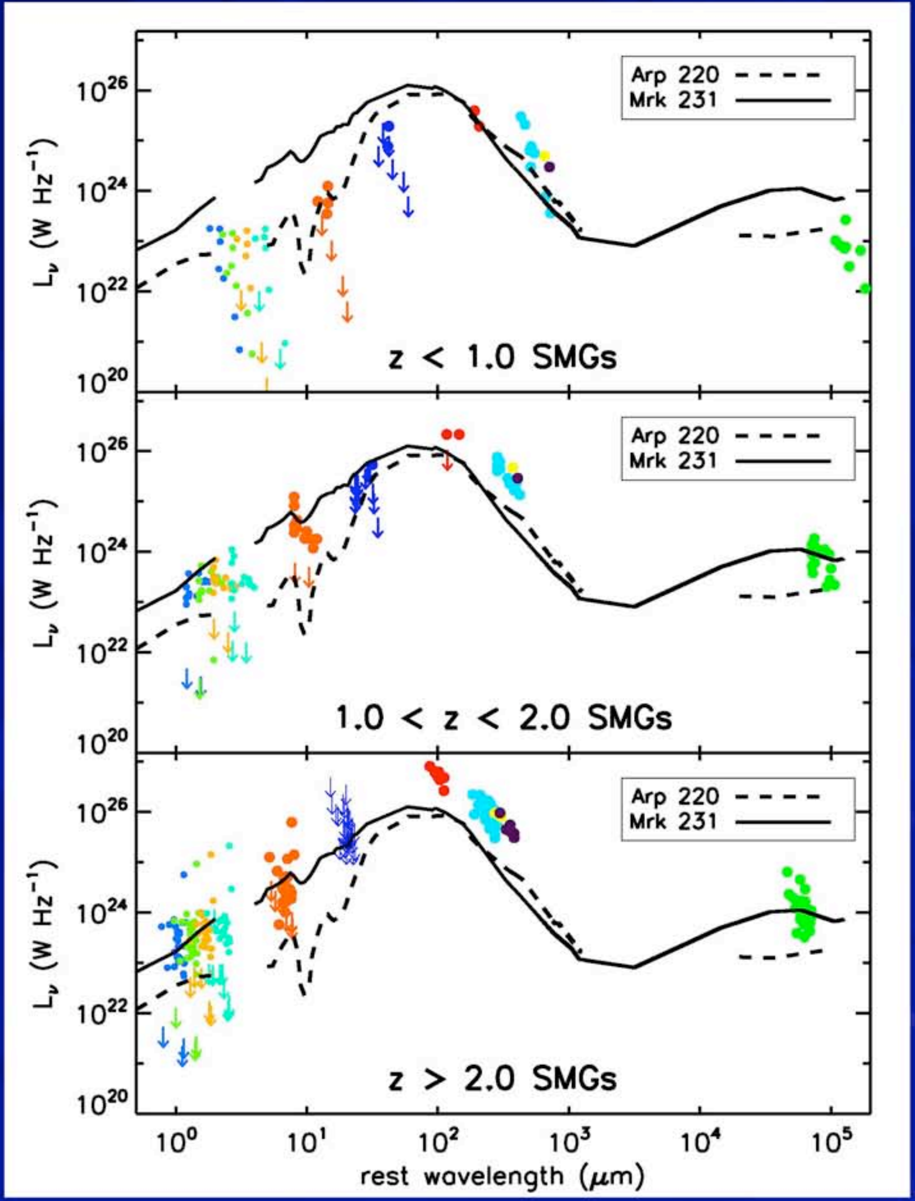
Strong redshift / luminosity dependence of composite SEDs:

• Low-z SMGs: less luminous than Arp 220, cold (like low-z disks?)

• z > 1 SMGs: brighter in mid, far-IR than Arp 220; SEDs peak longer

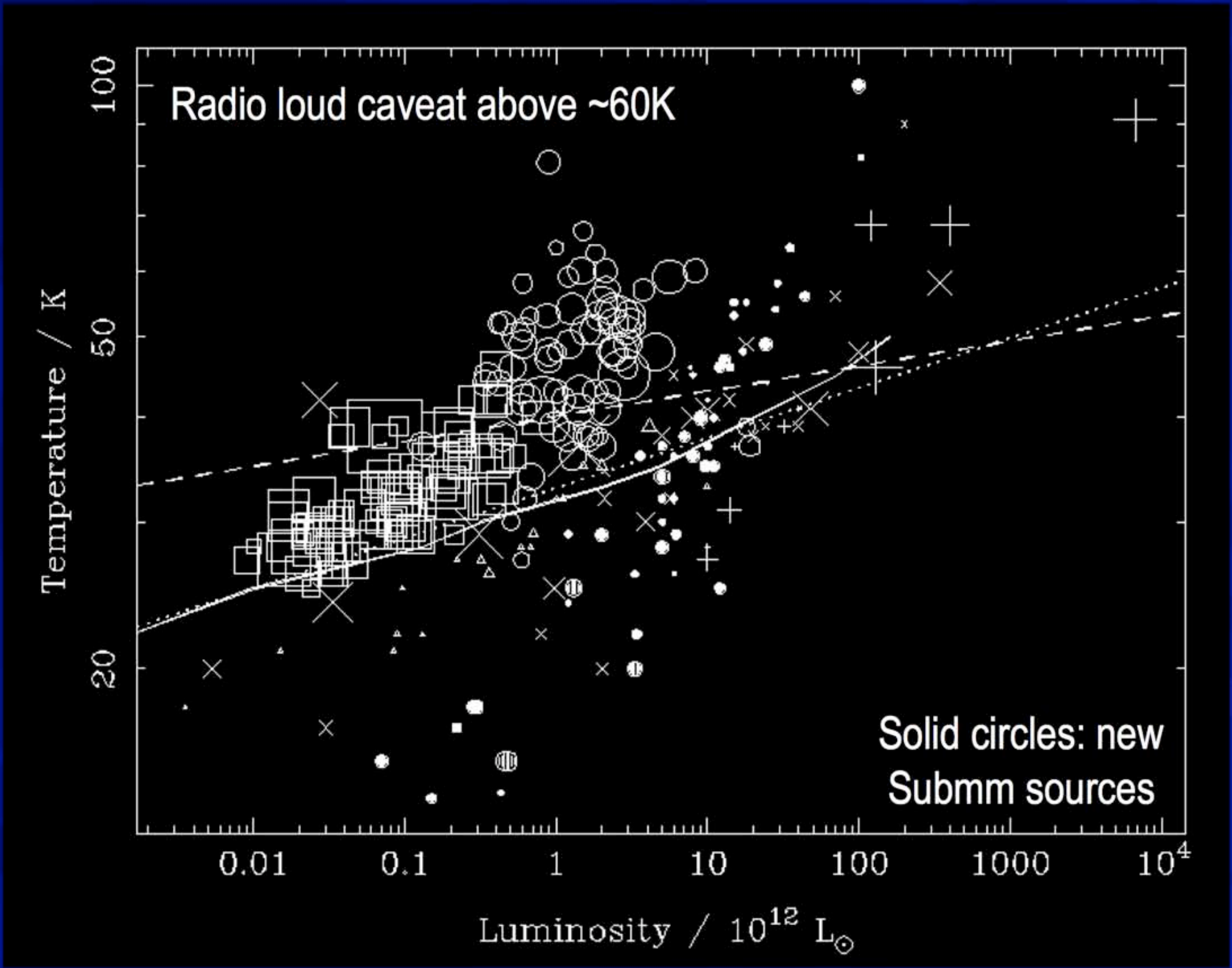
• Large scatter in mid-IR and radio points in z > 2 galaxies

- •Variation in mid-IR properties?
- • Luminosity dependence?



Hainline et al 2008

SMGs with z's: FIR-radio assumed



Blain, Barnard & Chapman 2003 & Chapman et al. 2003

Squares: low-z, Dunne et al.

Empty circles: moderate z, mainly Stanford et al.

Crosses: variety of known redshifts (vertical = lensed)

Solid circles: Chapman SMGs

Lines: low-z trends

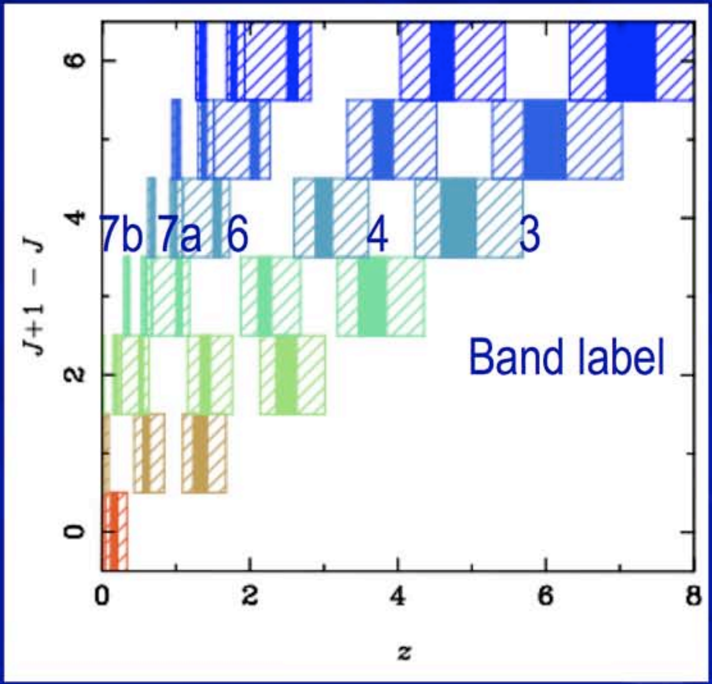
Scatter in T by at least ~40%

Next big step from ALMA

- Resolved imaging spatial and spectrally
- Probes most (all?) of active ISM gas
  - Masses, non-virialised fraction, cf stars
  - Timescale, likely immediate evolution
- Winds and outflows clear by comparison in optical/IR
- Hours of integration match object-by-object AO spectroscopy in near-IR
- ALMA is always a spectrometer - providing 8GHz of bandwidth to detect lines and continuum together
  - Developments in instrumentation funded soon

Detecting lines

- If continuum detected, a CO line can be detected in same data if z<2
  - Also [CI]-809GHz valuable, as double-line with CO(7-6)
  - Also [CII]-158μm potentially valuable beyond reionization
- However
  - only ~10% of sources give line detection
  - Several tunings required to confirm
- This is avoided if bandwidth could increase to match atmospheric windows, moving to 25-to-35 GHz
  - Band-3 86-110GHz, 24GHz-wide
  - Band-4 125-160GHz, 35GHz-wide
  - Band-6 211-275GHz, 64GHz-wide (in 2)
  - 'Band-7a' 275-300GHz, 25GHz-wide
  - 'Band-7b' 335-355GHz, 20GHz-wide



- Redesign mixers, expand correlator, dichroic feeds within cartridge?
- Lab mixers can now cover ~15GHz
  - Promising, relatively inexpensive ALMA development in bands 3, 4, 6?

Information from other lines

- Receivers/correlators for ~35GHz can cover complete range
  - Band 3, 4 & 6 always contain 1 line if z>4, 0.8, 2.2
  - Still favorable with 20-25 GHz
- Detect continuum in bands 4 & 6, then get 2 CO lines for z>2, and so an unambiguous redshift. For z>1 majority of redshifts are found
  - Continuum colour yields dust temperature and hence accurate luminosity, once redshift is known
- Immediate recognition of 806/809GHz line pair from wide z range
  - 86-110GHz 6.3<z<8.4 End of re-ionization
  - 125-160GHz 4.0<z<5.4
  - 211-275GHz 1.9<z<2.8 Prime ULIRG range
  - 275-300GHz 1.7<z<1.9
  - 335-355GHz 1.3<z<1.4
- [CII] line from high-z (211-275GHz; 5.9<z<8.0)

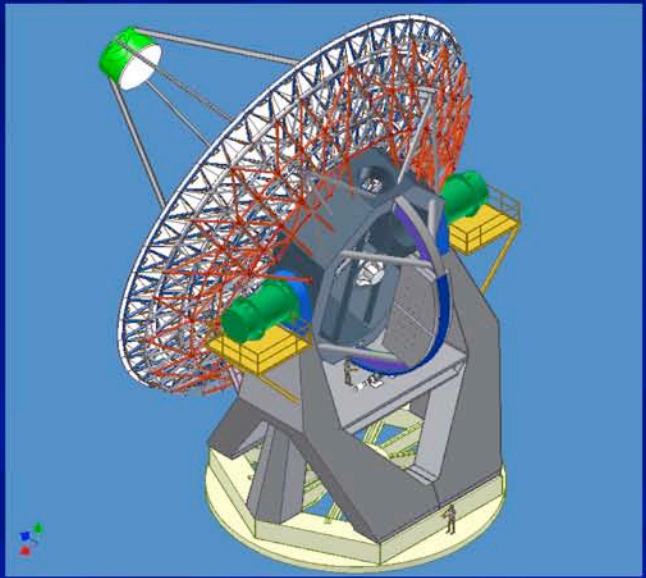
Line-to-continuum ratio

- Continuum in bands ~3 is modified Rayleigh-Jeans slope
  - Flux S α dust temperature T_d, L_{FIR} α $T_d^{\sim 5}$
  - SED bluer than blackbody
- CO line envelope redder than blackbody
- ΣL_{line} scales as $(L_{FIR})^{0.7}$
  - Strength of moderate-J line scales with $T_d^{\,0.7(\sim 5)-1}$
- Hence line EW
  - Falls as CO-line J increases
  - Rises as dust temperature $T_d^{\sim 2}$
  - Like all EWs α $(1+z)^{-1}$ or [for CO(J - J-1)] as $J_{assumed}^{-1}$

Line-to-continuum ratio

- Measured line EW depends on
  - $EW_{true}\ T_d^{\sim 2}\ J_{assumed}^{-1}$
- $EW_{true}\ J_{assumed}^{-1}$ about halves as $J \rightarrow J+1$
  - Different J thus differ by ~1.4 in T, or ~5 in L
  - Can again use T-L prior information
- Continuum colour gives complementary link to
  - $T_d\ J_{assumed}^{-1}$
- In principle, single CO line plus continuum colour thus gives $J_{assumed}$ (or z) and T_d, and hence L_{FIR}

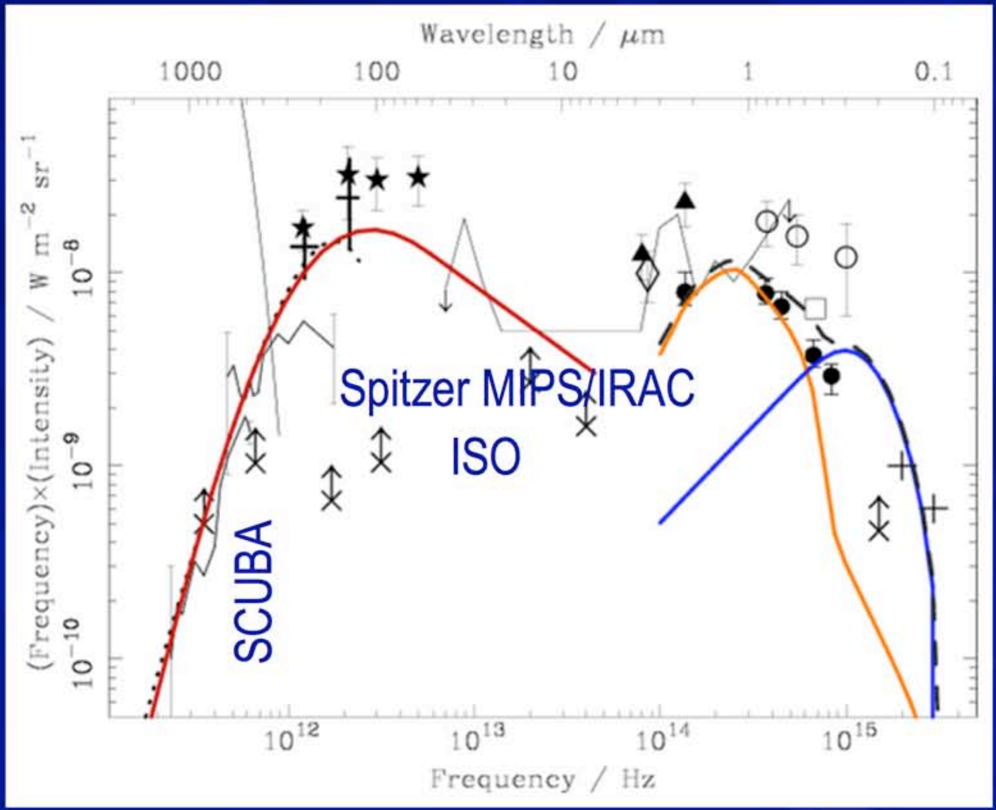
CCAT: future submm telescope



- Existing submm facilities are limited to ~2mJy sensitivities by confusion
  - CSO JCMT APEX
- ALMA has great sensitivity
- Large format detectors are possible
  - SCUBA-2 soon to be deployed with 4x64x40 bolometers
  - Zmuidzinas et al's 'kinetic inductance devices' - microwave addressed detectors using mobile phone switch technology - could be >>1000^2 pixels
  - Detectors for a larger single-aperture ground-based telescope, and moving towards a large space-based cold aperture telescope
- Caltech--Cornell CCAT study
  - Best possible site, and atmospheric performance to 200 microns
  - Wide field of view (~30 arcmin) to accommodate new detector technology

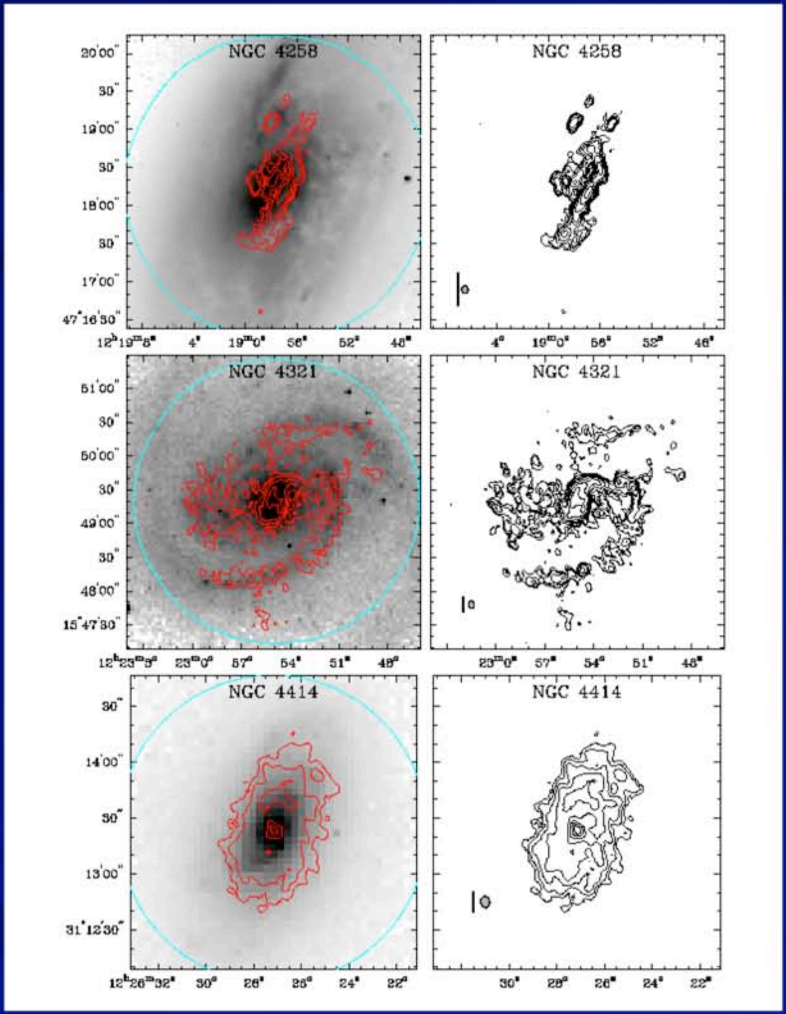
Obscured galaxies: background

- Many sources of data
- Total far-IR and optical background intensity comparable
- Most of the submm (0.8mm) background was detected by SCUBA
- ISO and more precise (but similar) Spitzer limits detect ~20-30% in mid-IR
- Note: backgrounds yield weaker constraints on evolution than counts



Models: BJSLKI 99

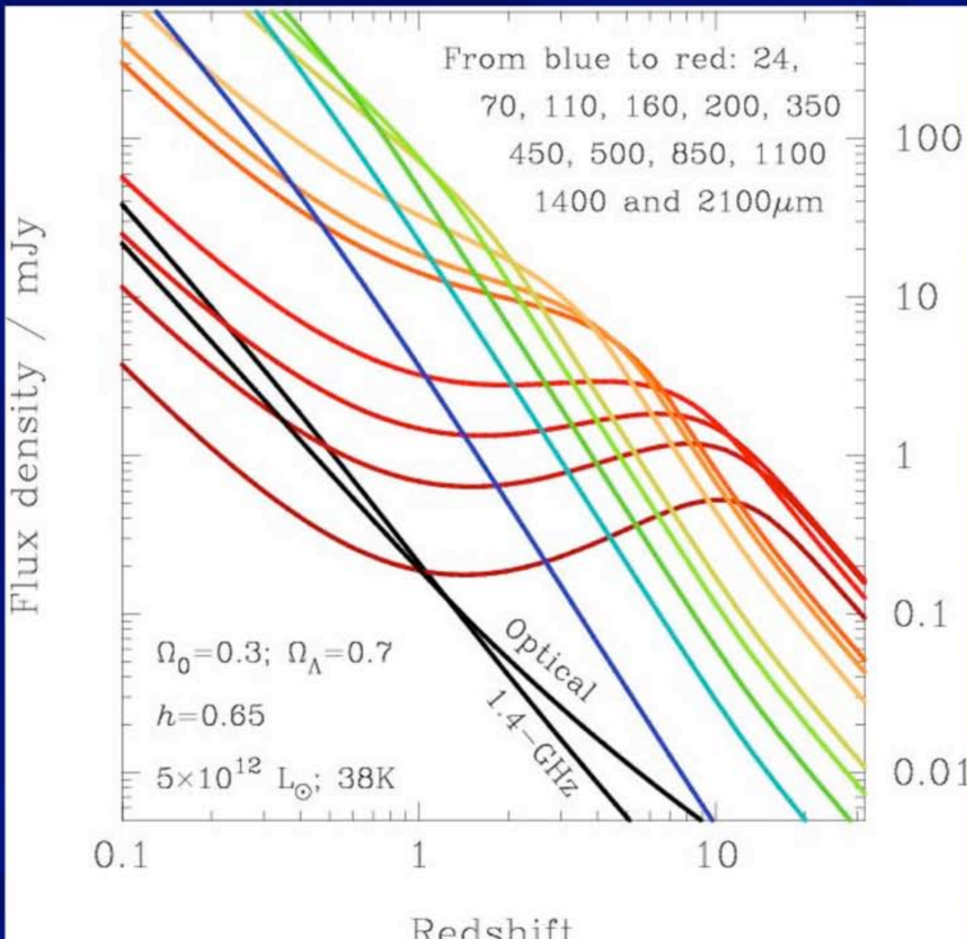
Current detailed CO images



Regan et al. astro-ph/0107211

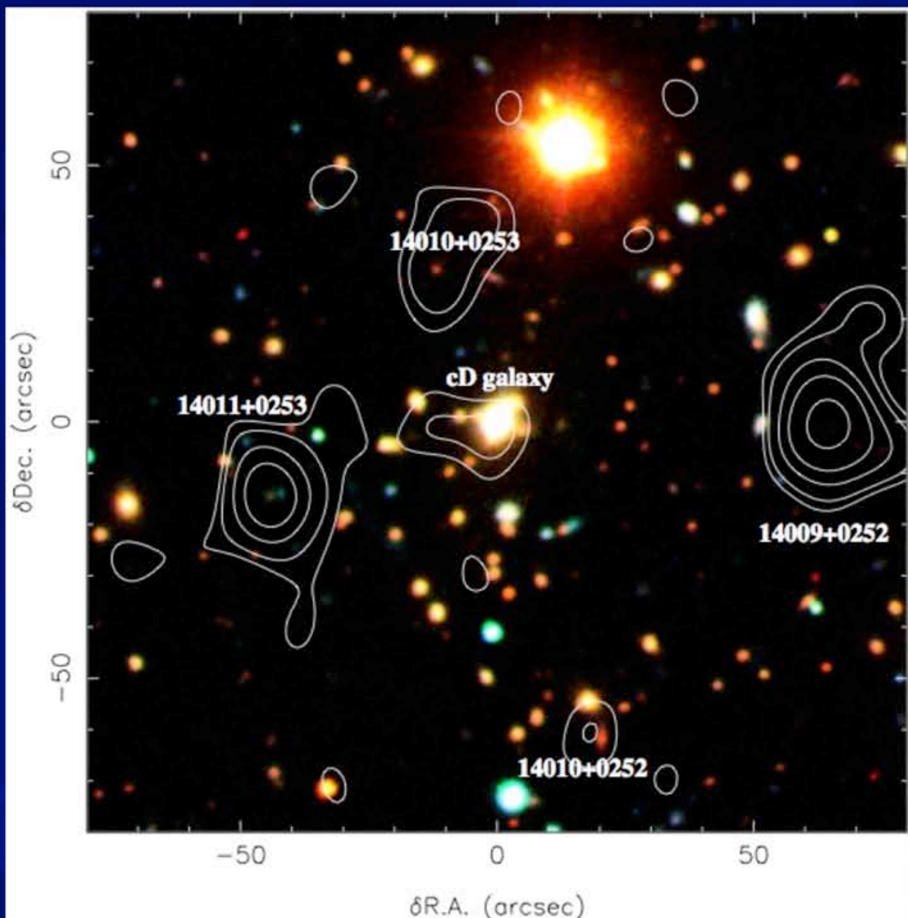
- Examples from BIMA SONG survey at z~0
- Irregular morphology in CO – gas traces active star formation
- Velocity field faithfully recorded to <10 km/s
  - Detailed velocity measurements are possible to z>2 with ALMA
- Images of this quality from high z with ALMA in ~24 h

Unique mm/submm access to highest z



- Redshift the steep submm SED
- Counteracts inverse square law dimming
- Detect high-z galaxies as easily as those at z~0.5
  - Low-z galaxies do not dominate submm images
  - Unique high-z access in mm and submm
- Ultimate limit at z~10 is set by CMB heating
- 2mJy at 1mm ~$5x10^{12}$ L_o
  - Note matches current depth of submillimeter surveys
  - ALMA has no effective limit to depth

Example of current single-antenna submm image

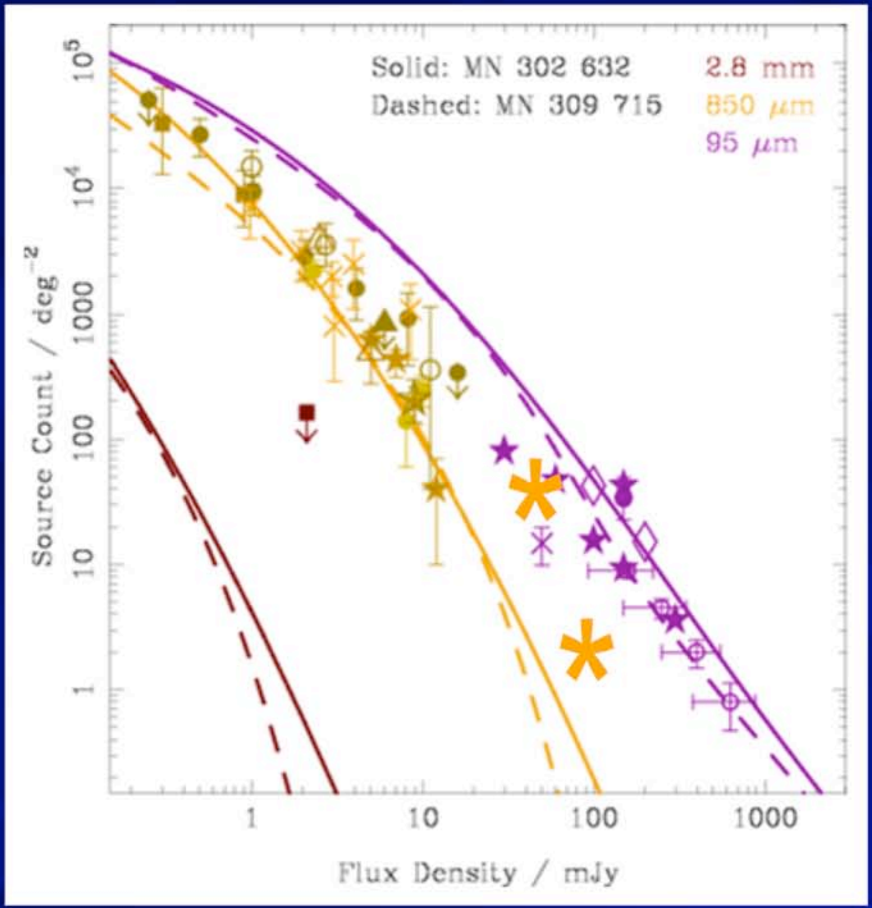


Ivison et al. (2000)

2.5’ square

- Abell 1835
  - Hale 3-color optical
  - 850-micron SCUBA
- Contrast:
  - Image resolution
  - Visible populations
  - Orthogonal submm and optical views
- One of 7 images from Smail et al. SCUBA lens survey (97-02)
  - About 25 other SCUBA cluster images
  - Both bright sources have redshifts (2.5 and 2.3; Ivison et al. 2000 & G P Smith priv comm)

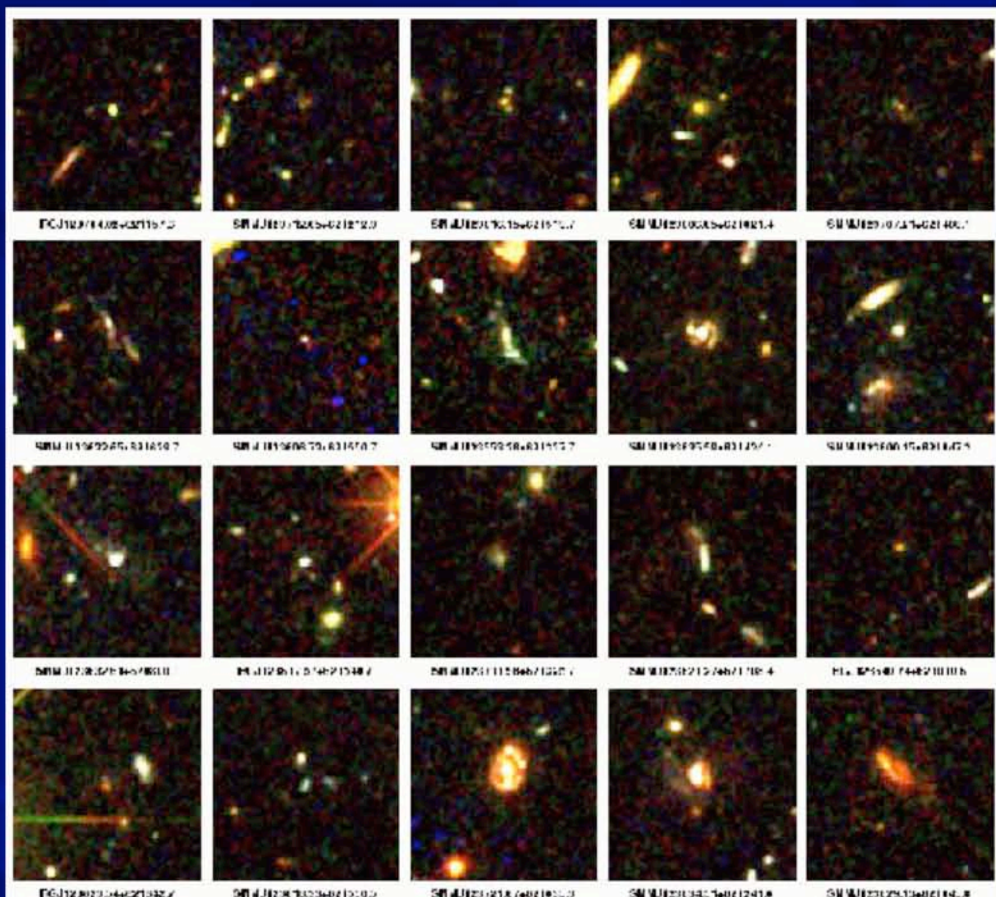
Population of dusty galaxies



Orange stars – Barnard et al (2004) 850-μm upper limits

- Most data is at 850 μm
  - New bright limit from Barnard et al (0405156)
  - Very few are Galactic contaminating clouds
- First 2.8mm limit from BIMA
- Bright 95 (&175) μm counts from ISO being dramatically improved at 70 & 160 μm by Spitzer (started August 04 ApJS)
- Also recent data at 1.2mm (IRAM's MAMBO); 1.1mm (CSO's BOLOCAM) and 350/450μm (SCUBA & SHARC-2)

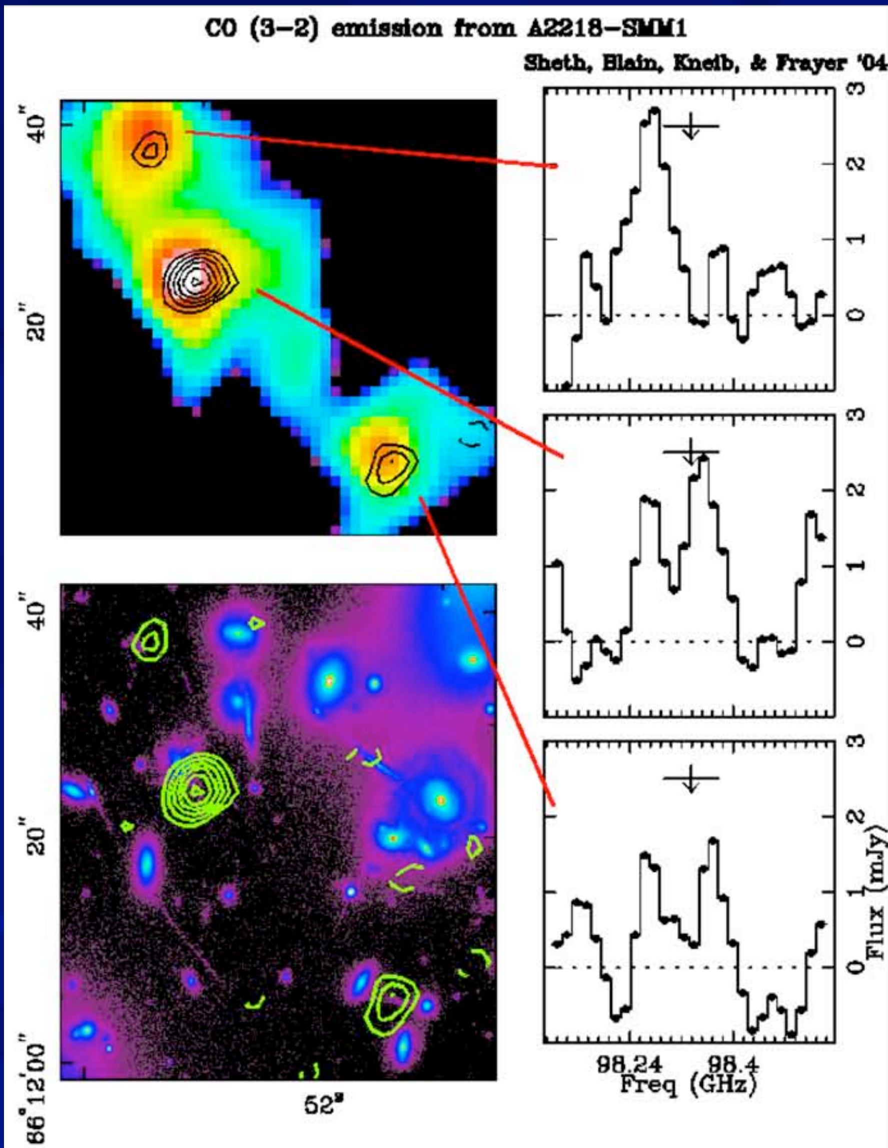
Morphologies for examples of SMGs



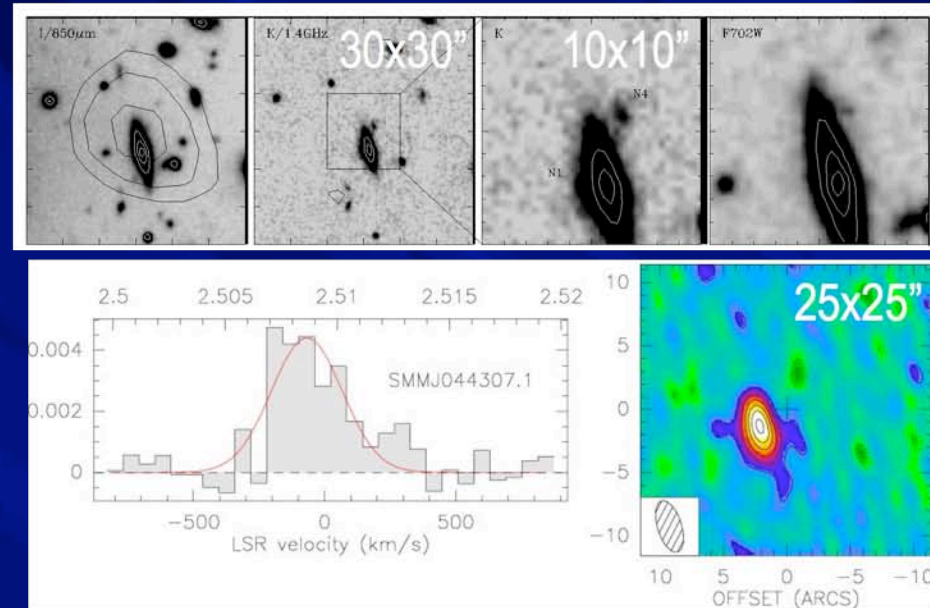
Smail et al. (2004) ApJ, 616, 71
Borys et al (in prep)

- GOODS images of SMGs with redshifts 3.4-1.9
  - Only radio detected examples included, so positions accurate
- Wide range of sizes, but typically larger than optically-selected galaxies at same redshift
- Range of colors, typically interacting and complex
- All detected by Spitzer-IRAC
  - Often as double sources

CO examples

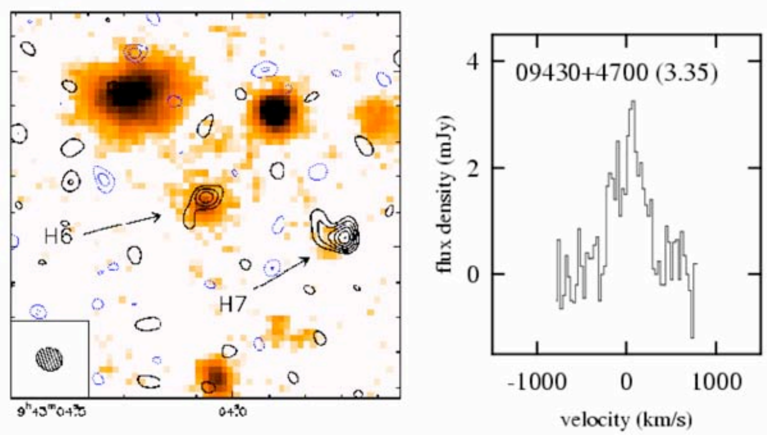


Upper: submm continuum; lower optical HST



Tacconi et al (2006), Neri et al. (2003), Greve et al. (2005)

K band image (8" square), with IRAM CO contours of an ultraluminous galaxy at z=3.35



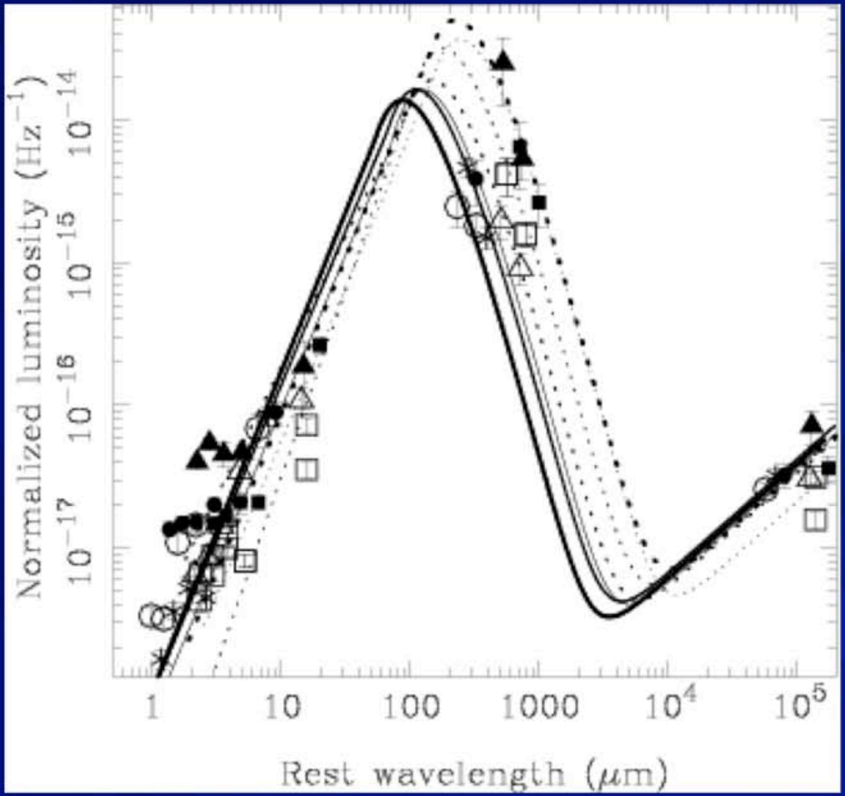
Abell 851

Genzel et al. (2004)

Submm observations of galaxies mature into the ALMA era (2012)

- ALMA has the resolution to match HST/JWST and resolve internal structure of high-z galaxies
- 3-D spectral information of even the most obscured regions
  - Reveals astrophysics at work
  - Provides direct redshifts
  - ALMA astrophysical probes are self contained
- New populations of objects, and pre-reionization galaxies
  - H_2 lines / first metals – dust and fine-structure lines

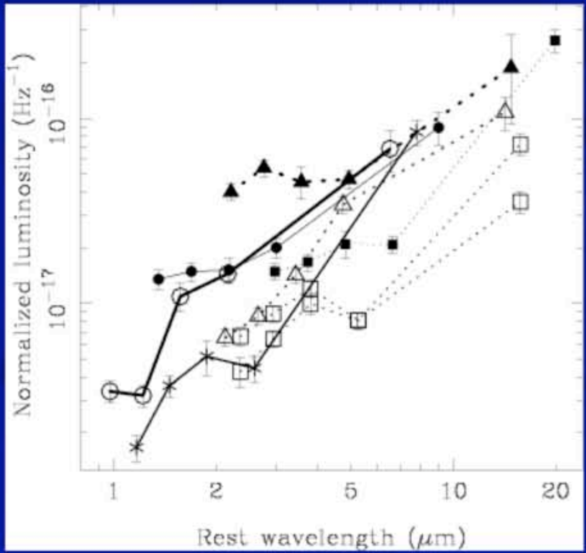
SEDs: full & zoom of IRAC-24 region



Normalised to 60 & 100 quantity from the far-IR:radio relation

Radio-far-IR relation seems OK

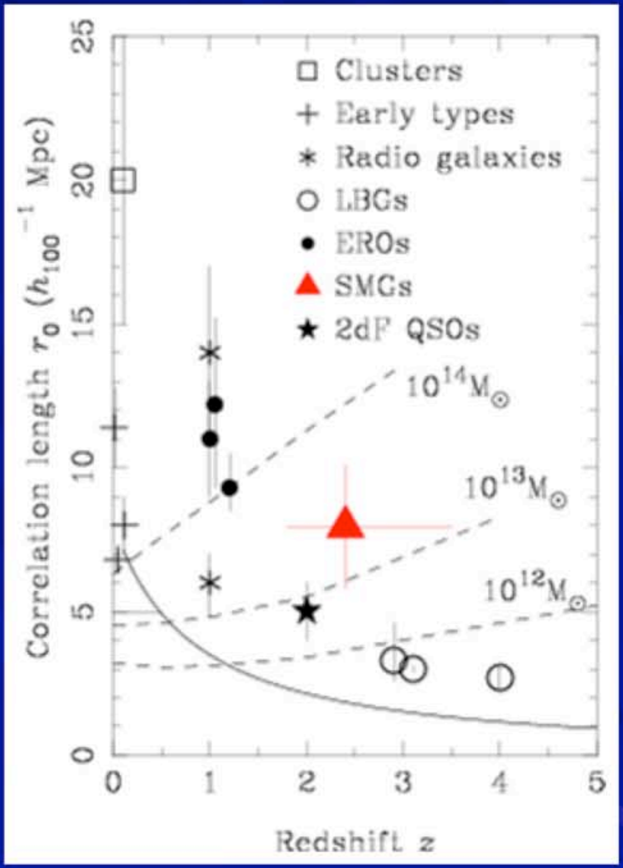
- SED peak wave-length ranges over factor 3
- No nice stellar SED peak in IRAC, no neat spectral breaks/features...
- All SMG photometric redshifts need care



IRAC & MIPS-24 zoomed plot

Comparison with other populations

- Other more numerous high-z populations have less powerful clustering
- Are SMG redshift associations linked to overdensities of more numerous galaxy classes at the same redshift?
  - At z~2.5 spectroscopy essential to test
  - Links with 'BX' optically selected galaxies at z~2 in HDF
  - Narrow-band imaging with LRIS in March to search for associated optical galaxies
- Do they reside in such massive halos?
  - Not every 10' field can contain such an object
  - What is the nature of the biasing process?
  - Near-IR spectra hint at central 4-kpc dynamical masses of few $10^{11}M_o$
  - Stellar population fitting implies few $10^{10}M_o$, but uncertainties from complex morphology
  - OSIRIS resolved spectra will be exciting



After Overzier et al. (2003)

ALMA & CCAT and cosmology

- Complementary facilities
  - CCAT surveys increase efficiency of ALMA
- Fast survey of sky for large scale structure
  - Identify several hundred gravitational lenses
- Nature of that structure found using ALMA
  - Redshift survey out to z~3-5
  - Not unique compared with WFMOS for example
- ALMA sees components of galaxies missing in optical/UV
- ALMA can see back prior to reionization
- ALMA can measure rotation curves in CO, which is a very cool, relaxed tracer
  - Opens new possibilities, see weak lensing