Multiwavelength properties and kinematics of lensed galaxies

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- Details of galaxy formation in situ still awaits revelation & understanding
  - Link between mass and light - and triggering of luminous activity - inside galaxies
  - Establishing the relationship between galaxies and their environment
  - Lensed galaxies are ideal places to look - enhanced flux and angular scale

- There are capabilities for resolving distant galaxies
  - HST provides optical appearance, Chandra shows any (Compton-thin) active nucleus
  - IR IFUs offer spectra of substantial part of galaxies - IFU geometry not great for arcs
  - ALMA (JWST) will provide details of rotation/collapse/interaction in active regions directly

- ALMA will be a tremendously powerful **transformational** tool for all astrophysics
  - 50 12-m antennas, with baselines from 15 to 20000m
  - Resolution down to of order 10 milli-arcsec (10-20x better than current, in excess of JWST and ground-based AO)
  - Sensitivity of order 1mJy in 1s (30x better than existing)
    - ALMA makes a day to minute integration time transformation
  - Field of view is antenna primary beam, of order 10-30 arcsec, so ALMA is best for:
    - spectroscopic imaging of individual 1-5 arcsec scale galaxies (good for arcs)
    - Ultradeep surveys (possible in parallel with deep pointed observations)

- Lensing allows ALMA/IFUs/JWST to better see - and see into - galaxies' internal astrophysics. Multiwavelength coverage is essential to trace details

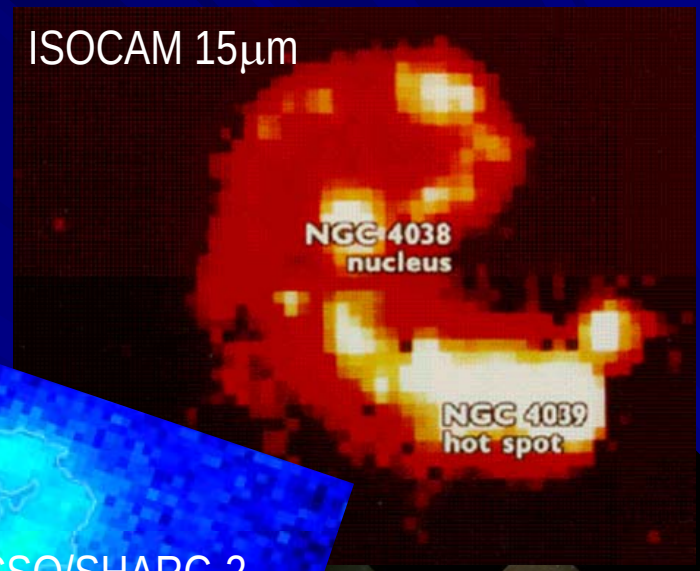
Most active regions of the Universe

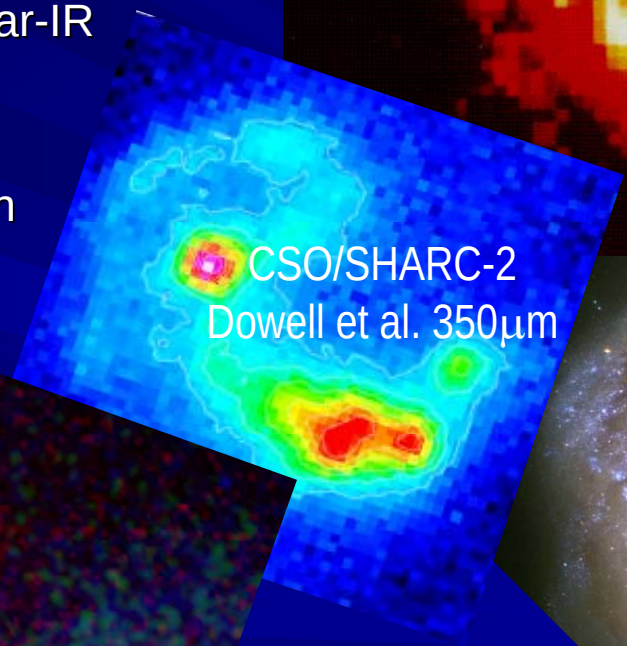
- Detail resolved so far only in Milky Way
- ~50% of all AGN and starlight absorbed by dust
  - More in molecular star-forming regions
  - Dust cooling is crucial for Pop-I star formation
  - Extremely strong effect on visible morphology: ‘activity-light’ ratio
- Dust present at z>6
- Combined with molecular gas rotational and atomic fine structure emission
- Physics and chemistry of dust is complex and ill constrained
  - But, SED accessible through atmospheric windows is well known

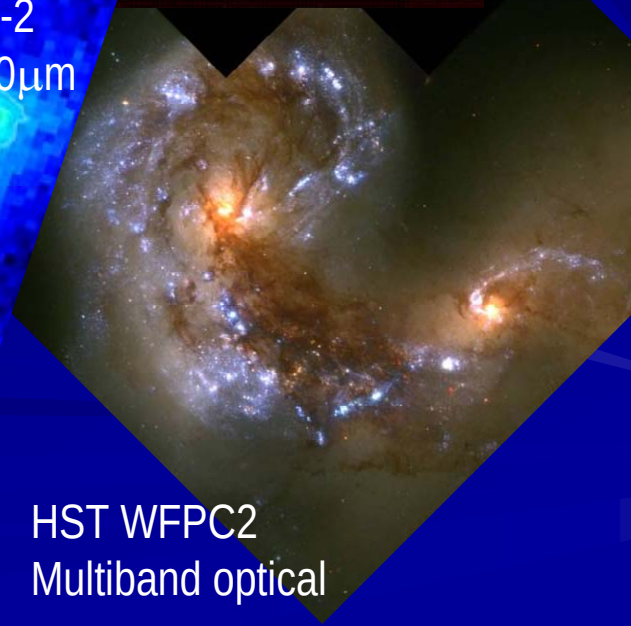
Orion through telephoto lens (~2 degree field)

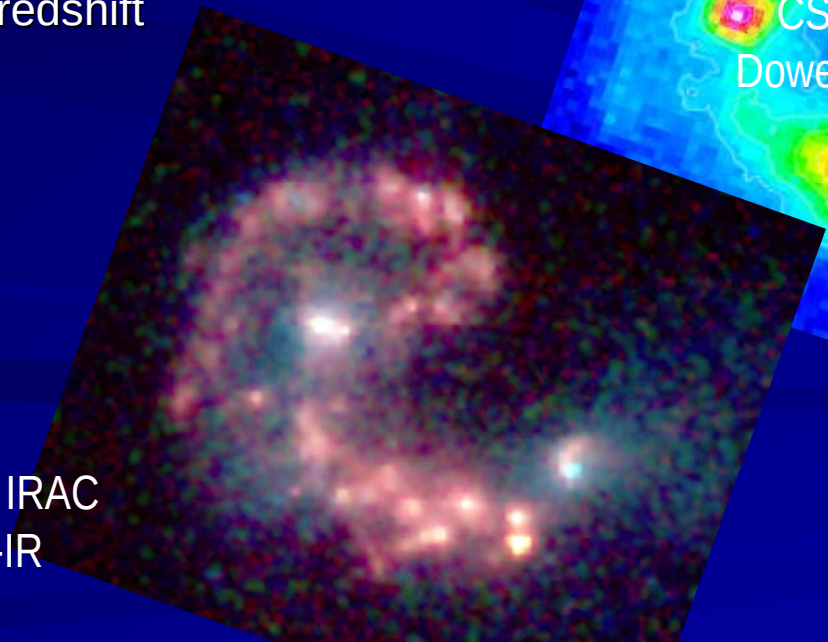
Resolved ‘example’: the Antennae

- 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



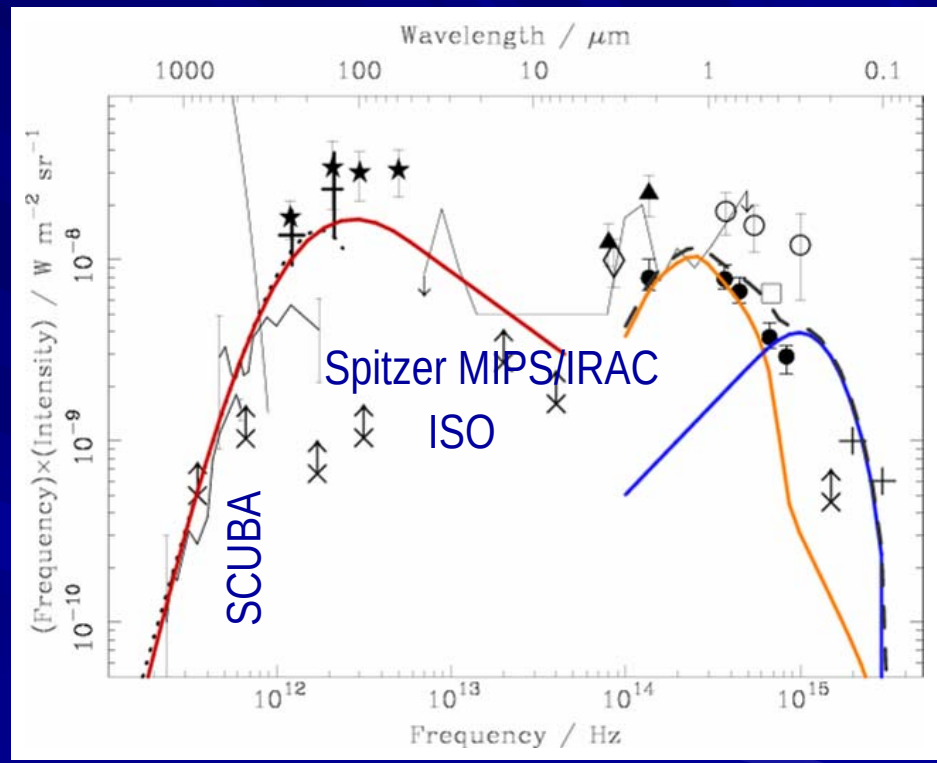






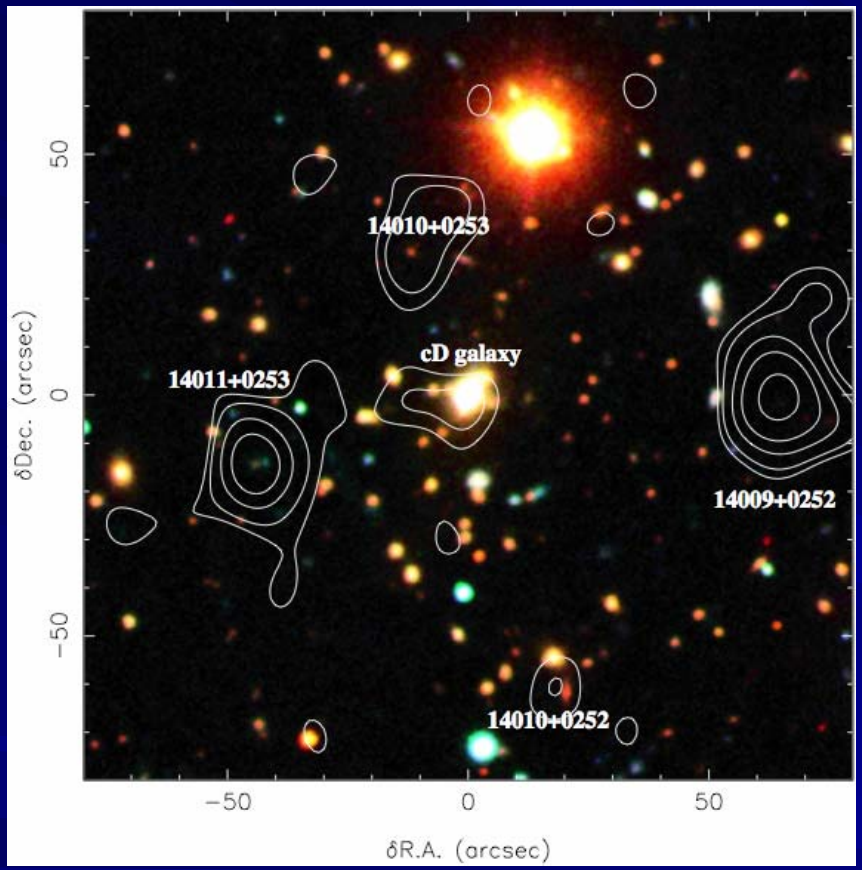
Obscured galaxies: background

- Many sources of data
- Total far-IR and optical background intensity comparable
- Most of the submm (0.85mm) background was detected by SCUBA imager
  - 14” resolution
- 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

Example of multiavelength cluster image

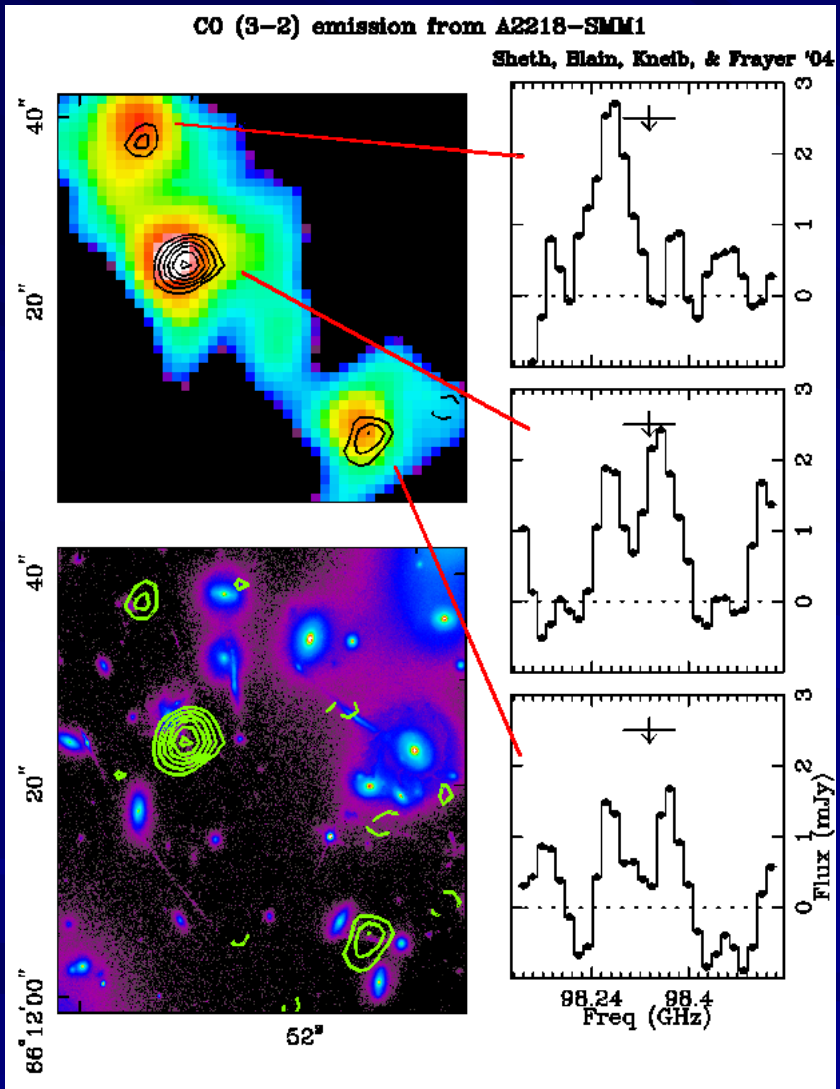


Ivison et al. (2000)

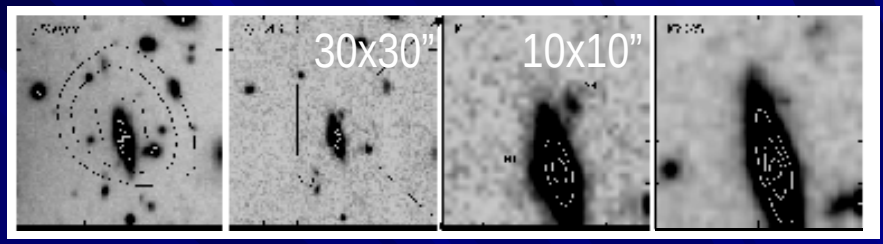
2.5’ square

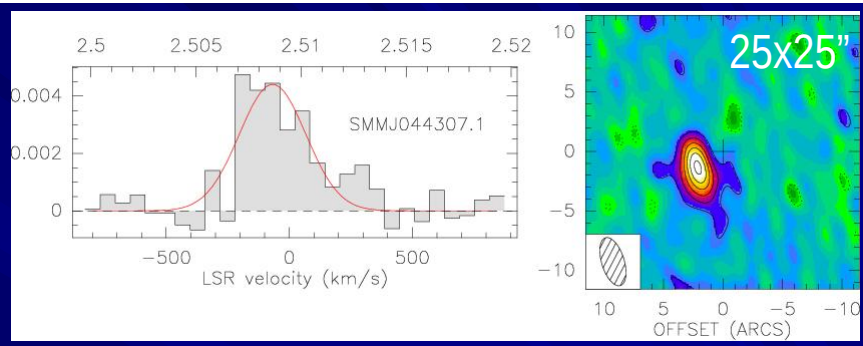
- Abell 1835
  - Hale 3-color optical
  - 850-micron SCUBA
- Contrast:
  - Image resolution
  - Visible populations
  - Orthogonal submm and optical views
- About 25 images like this
  - Both bright sources have redshifts (2.5 and 2.3; Ivison et al. 2000 & G P Smith priv comm)
- Combination of Spitzer, submm & optical views find many interesting objects
  - Multiwavelength examples are all ‘ultraluminous’

CO examples



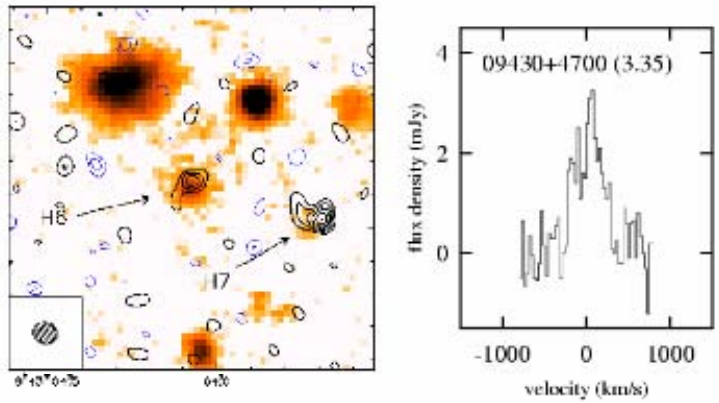
Upper: submm continuum; lower optical HST





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

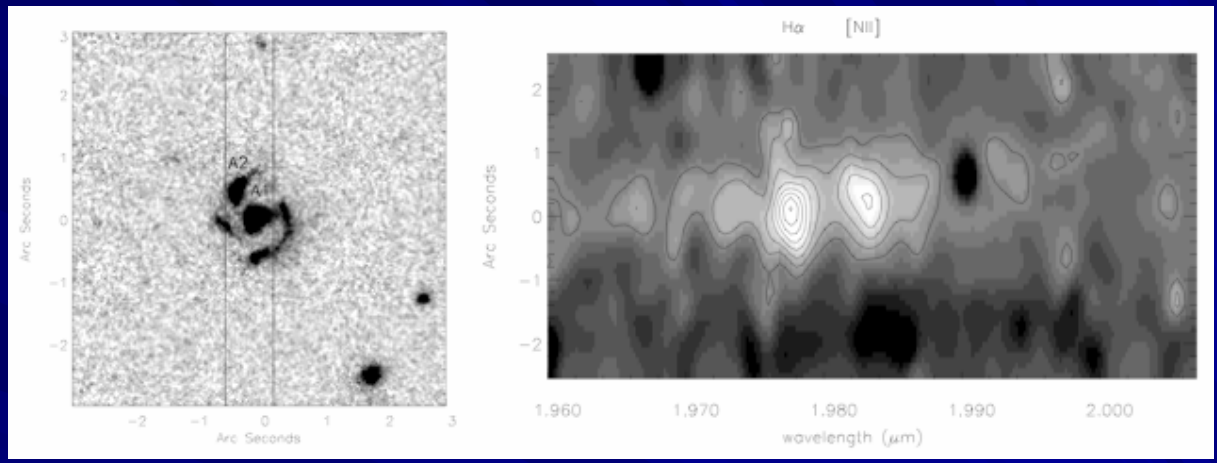


Abell 851

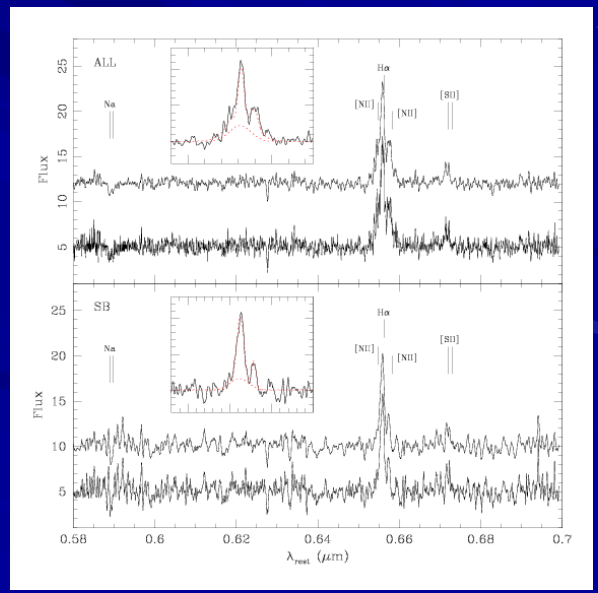
Genzel et al. (2004)

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

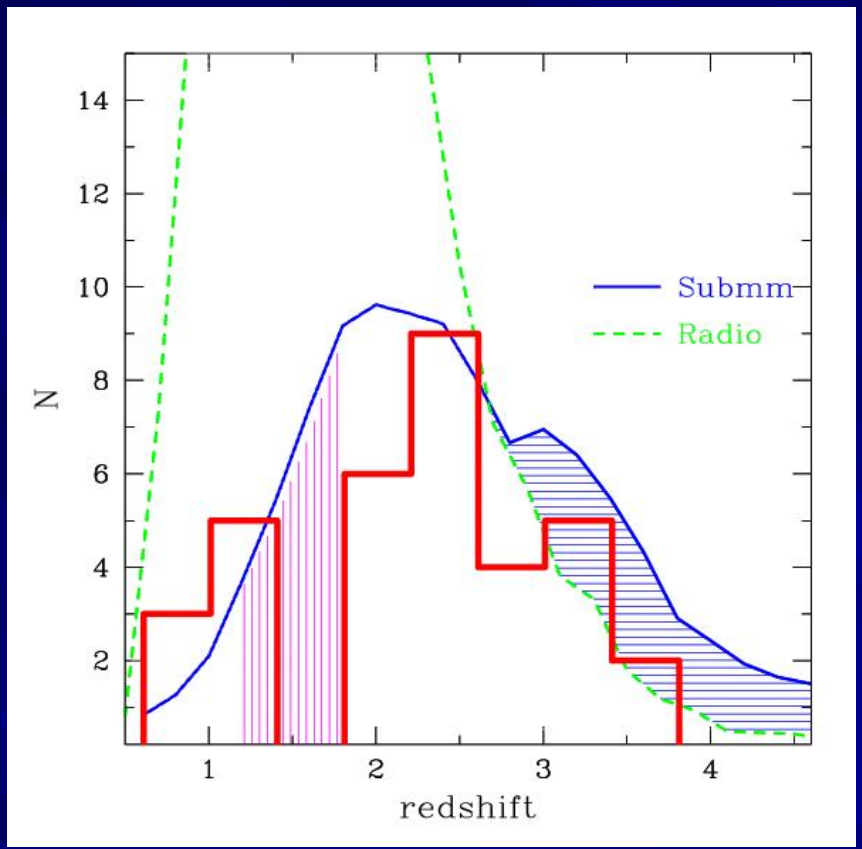
- 25 targeted
  - Optical redshifts allow near-IR spectroscopy in favorable sky windows
- Hα/[NII] ratios and Hα line widths provide hints at presence of AGN
- Composite spectrum of examples with narrow (<400km/s) Hα show underlying broad line; narrow component gives dynamical mass - few 10^{11} M_o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



Swinbank et al. 2004



Redshift distribution N(z) for radio-pinpointed SMGs

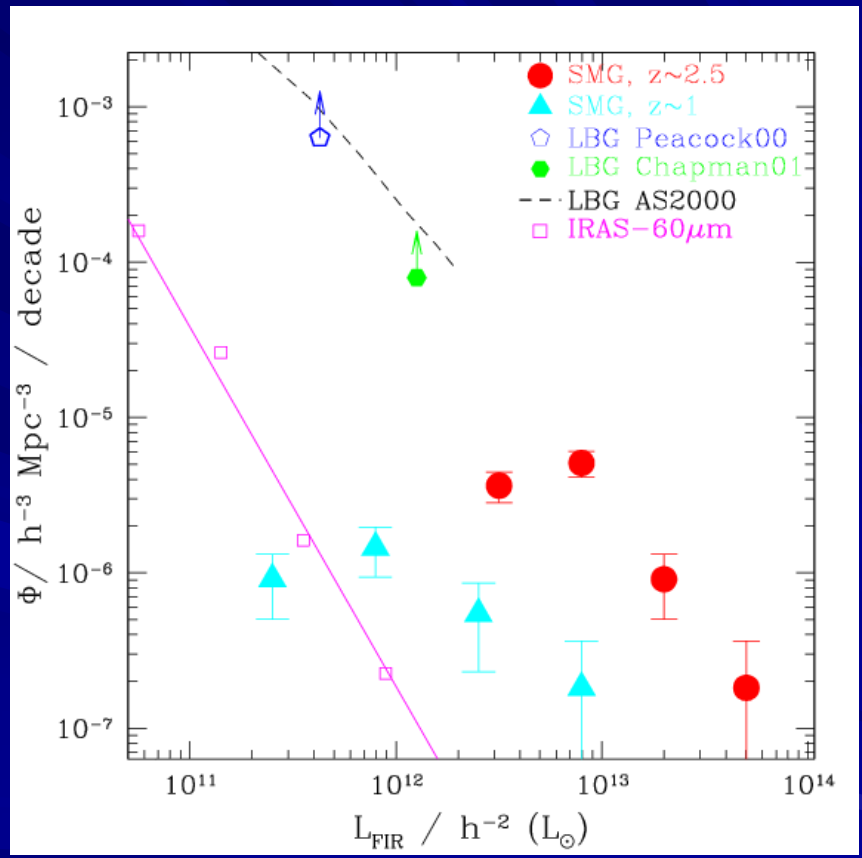


Chapman et al. (2003; 2005)

- Red histogram: Chapman et al ApJ 2005
  - 73 redshifts
  - Median z=2.4 and spread in redshift z~0.65 is good description
- Lines: expected submm & radio N(z)'s from Chapman's model
  - 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
- Difficulty of finding positions will vanish for ALMA

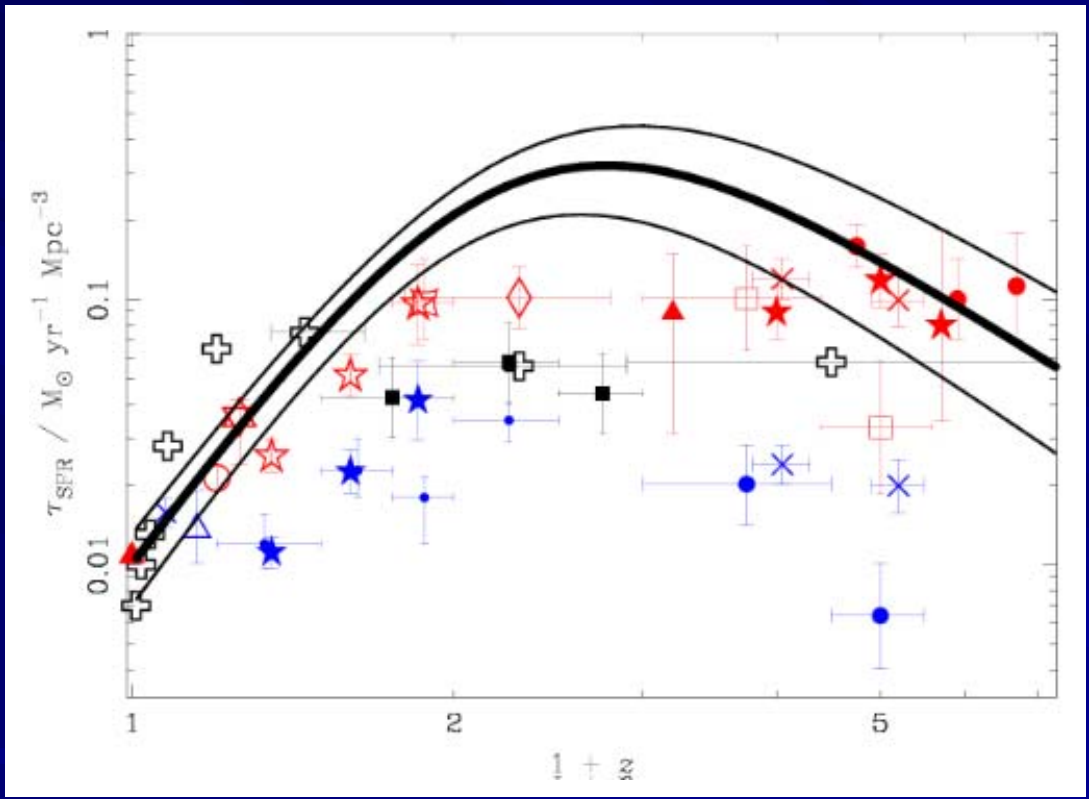
Luminosity function

- Based on known redshifts and fraction of population with redshifts (~50%) can see dramatic evolution from z=0 to 1 to 2.5
- Plausible connection to the luminosity function of optically-selected high-z galaxies
  - Lower limits as only a fraction of far-IR luminous objects are detected in UV surveys
- Interesting to obtain Spitzer LF results at z~1-2 for comparison
- Key goal is overall high-z LF



Chapman et al. (2005); astro-ph/0412573

Global luminosity evolution

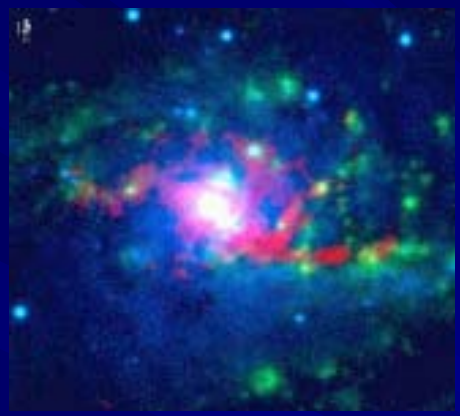


WMAP cosmology

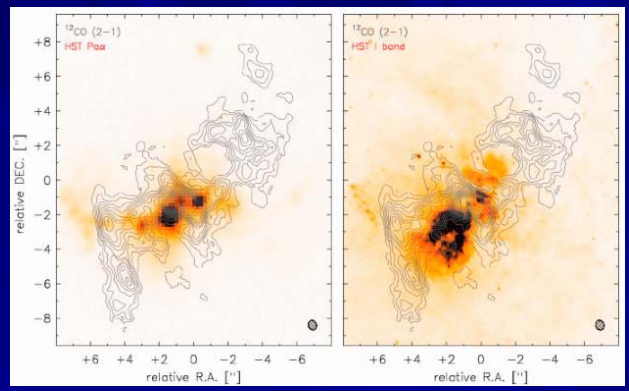
- Points
  - Blue: optical / UV
  - Red: IR and dust corrected
  - Black: SDSS fossil record
  - Uncertainty remains
- Lines:
  - results from combined submm/far-IR information
  - Note high-z decline certain
  - Less rapid than for QSOs?
- Caveats
  - AGN power (modest?)
  - High-z / high-L IMF change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

Local example of best results

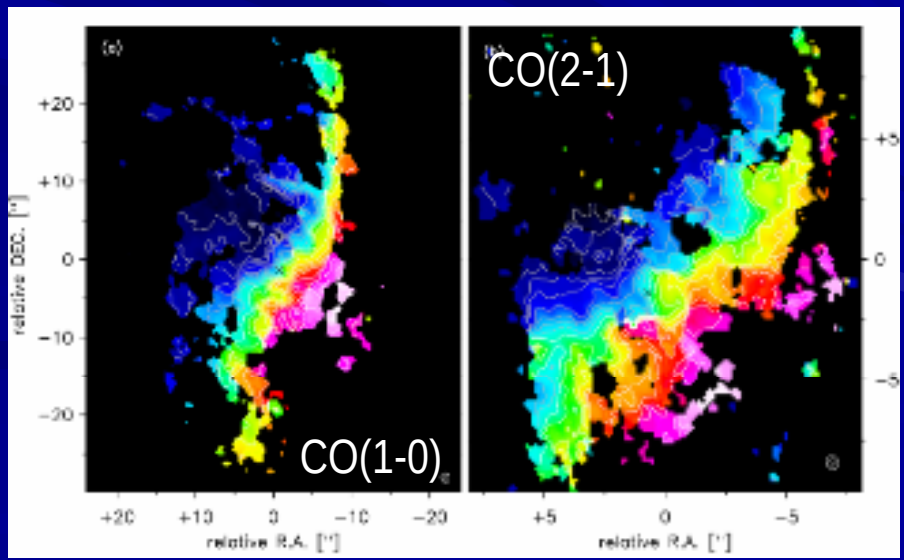
- IRAM PdB CO in NGC 6946 (Schinner et al. 2006)
- Spatial structure & gas dynamics
- ALMA can probe at z~3
  - Resolution
  - Primary beam
- Note synergy with eVLA
  - Ultimately SKA



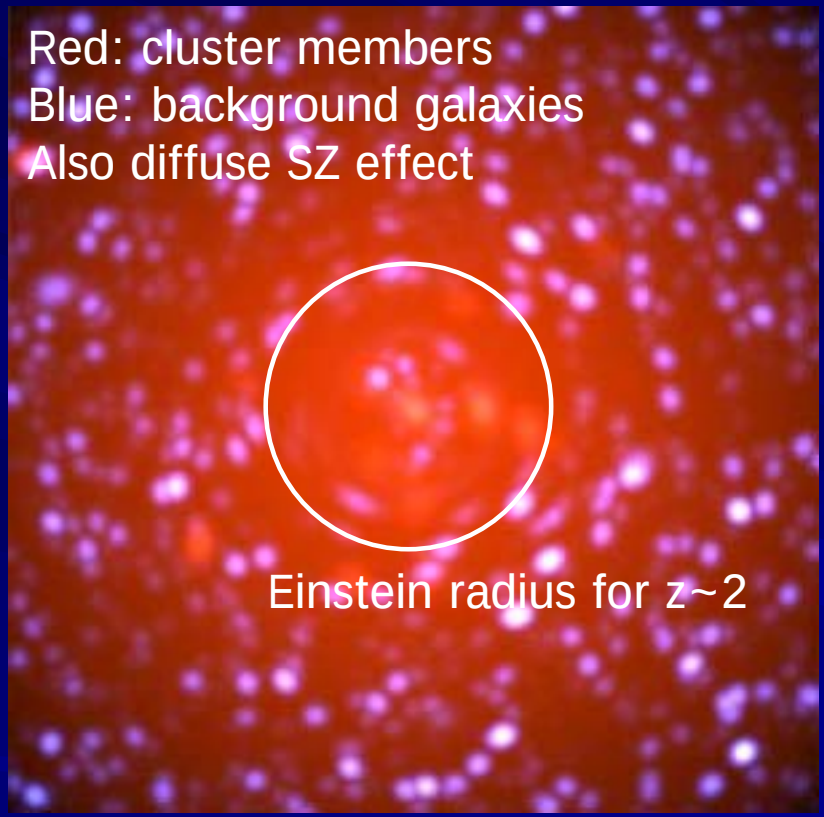
Red: CO; green: Hα; blue: continuum

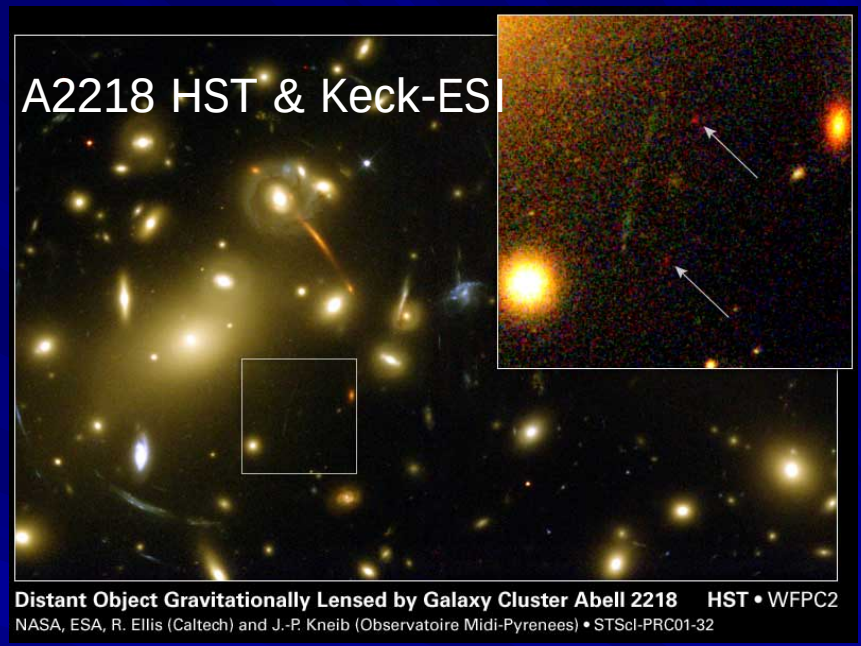


CO(2-1) contours
HST: Paα & I band



ALMA cosmology: imaging of clusters





Very faint z>5 object shows what can be seen along high-magnification critical lines in all clusters

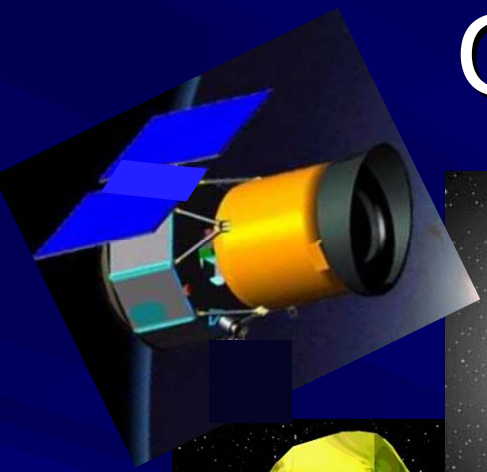
Simulation shows some of the swarm of faint sources expected in the cluster centre if the potential strongly peaked

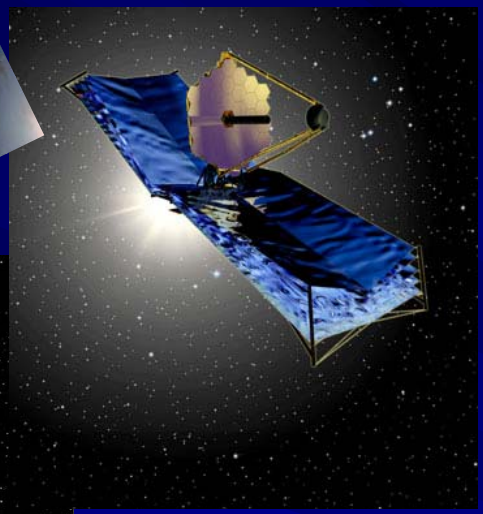
- Excellent probes of clusters' strong lensing when ALMA's angular resolution is available

Summary

- Detailed astrophysics of galaxies where most stars are forming is becoming observable. At present can only catch the brightest
  - IFU resolution of lensed galaxies is not usually favored by geometry, but can see ‘ordinary’ galaxies (Lemoine-Busserolle poster)
  - ALMA will provide spectral and spatial resolution to image regions of galaxies where stars are forming and blackholes are fueling most intensely at z~2, and beyond
- Galaxies’ spectra can be studied in detail from local Universe to far ***beyond*** reionization
- Resolved spectra will allow unprecedented accuracy for derived dynamical masses, and pinpointing active regions
- All studies can be assisted by exploiting gravitational telescopes
  - Planck surveyor point source catalog is new CLASS
  - Foreground lenses are relatively dark to ALMA

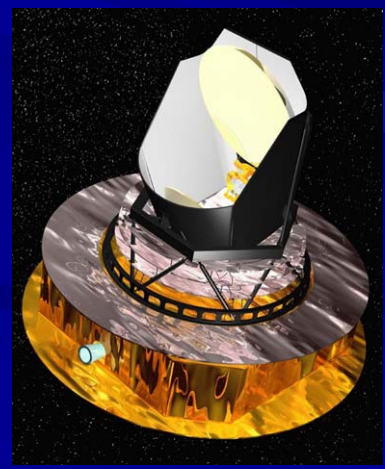
Other (near-) future tools





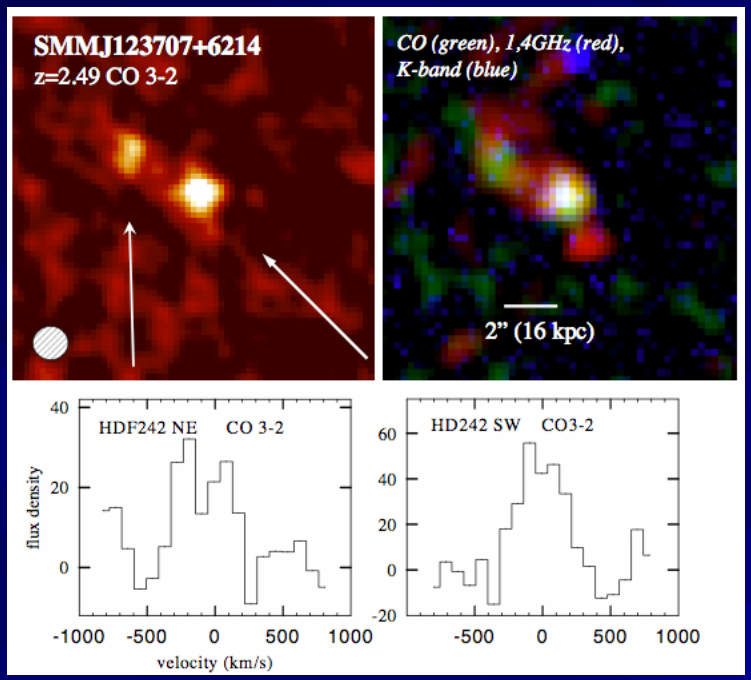
See also Spitzer & Akari

QuickTime™ and a Sorenson Video 3 decompressor are needed to see this picture.

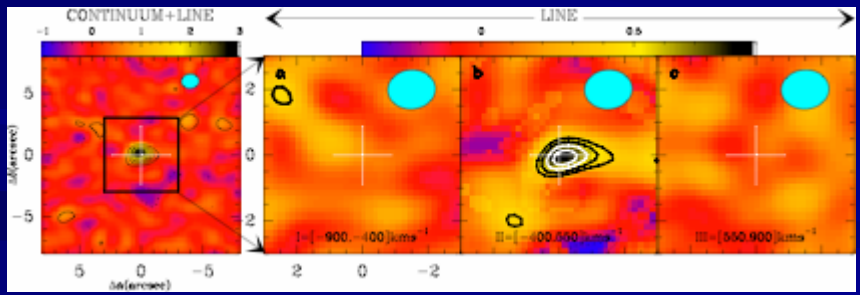


*-shown
CARMA*, APEX*, SOFIA*, SCUBA-II, LMT, Herschel*, Planck*, WISE*, ALMA*, CCAT*, SPICA, SAFIR (JWST-based?)* SPECS/SPIRIT

Best high-z cases now



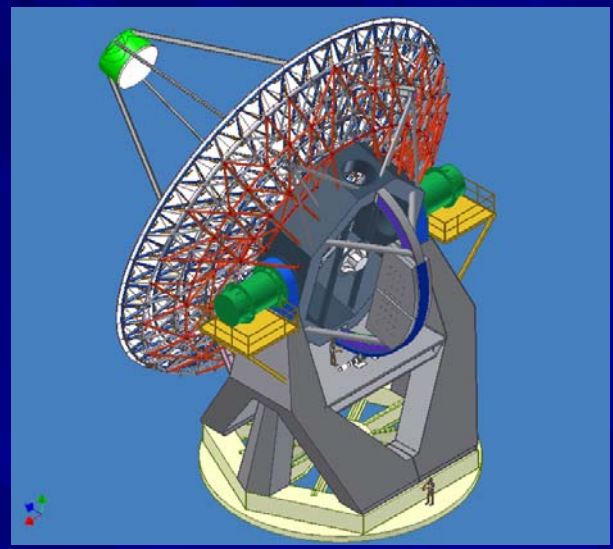
PdB: Genzel et al in prep



PdB HCO^+(5-4) Garica-Burillo et al (2006)

- Only marginal spatial resolution possible
- Narrow spectral bandwidth
- Situation will improve dramatically with ALMA,
  - a step up in imaging quality is under test at CARMA & IRAM

CCAT: future survey telescope



- Existing submm facilities are limited to ~2mJy sensitivities by confusion
  - CSO JCMT APEX
- ALMA will have great sensitivity with 9000m^2 area
  - But, its field of view is modest (like existing interferometers); at highest frequencies field is only a few arcsec
- Large format detectors are possible
  - Established capability of CSO's BOLOCAM and SHARC-2
  - SCUBA-2 soon to be deployed with 64x80 bolometers
  - Zmuidzinas et al's 'kinetic inductance devices' - microwave addressed detectors using mobile phone switching technology - could be >>1000^2 pixels
  - Detectors for a larger single-aperture ground based telescope, and moving towards a space-based large cold aperture
- Caltech--Cornell CCAT study & Colorado & CfA?
  - Best possible site, and atmospheric performance to 200 microns
  - Wide field of view (~30 arcmin) to accommodate new detector technology