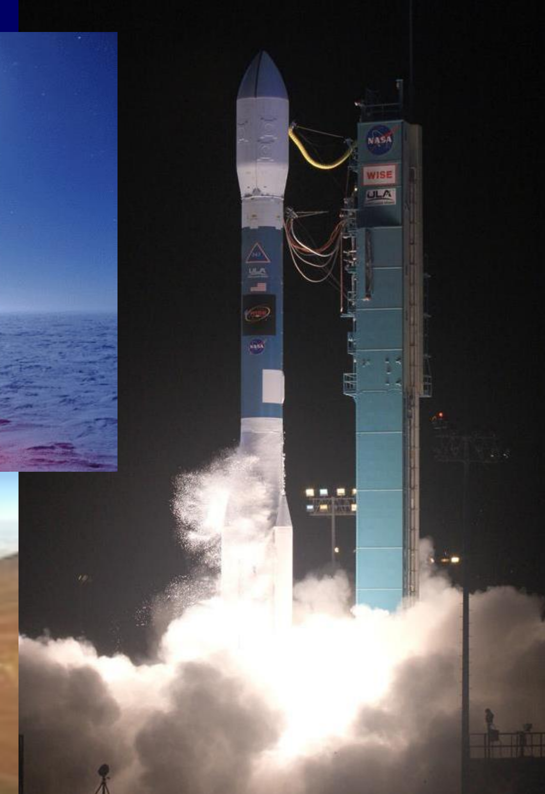


Redshift distribution of SMGs

Andrew Blain

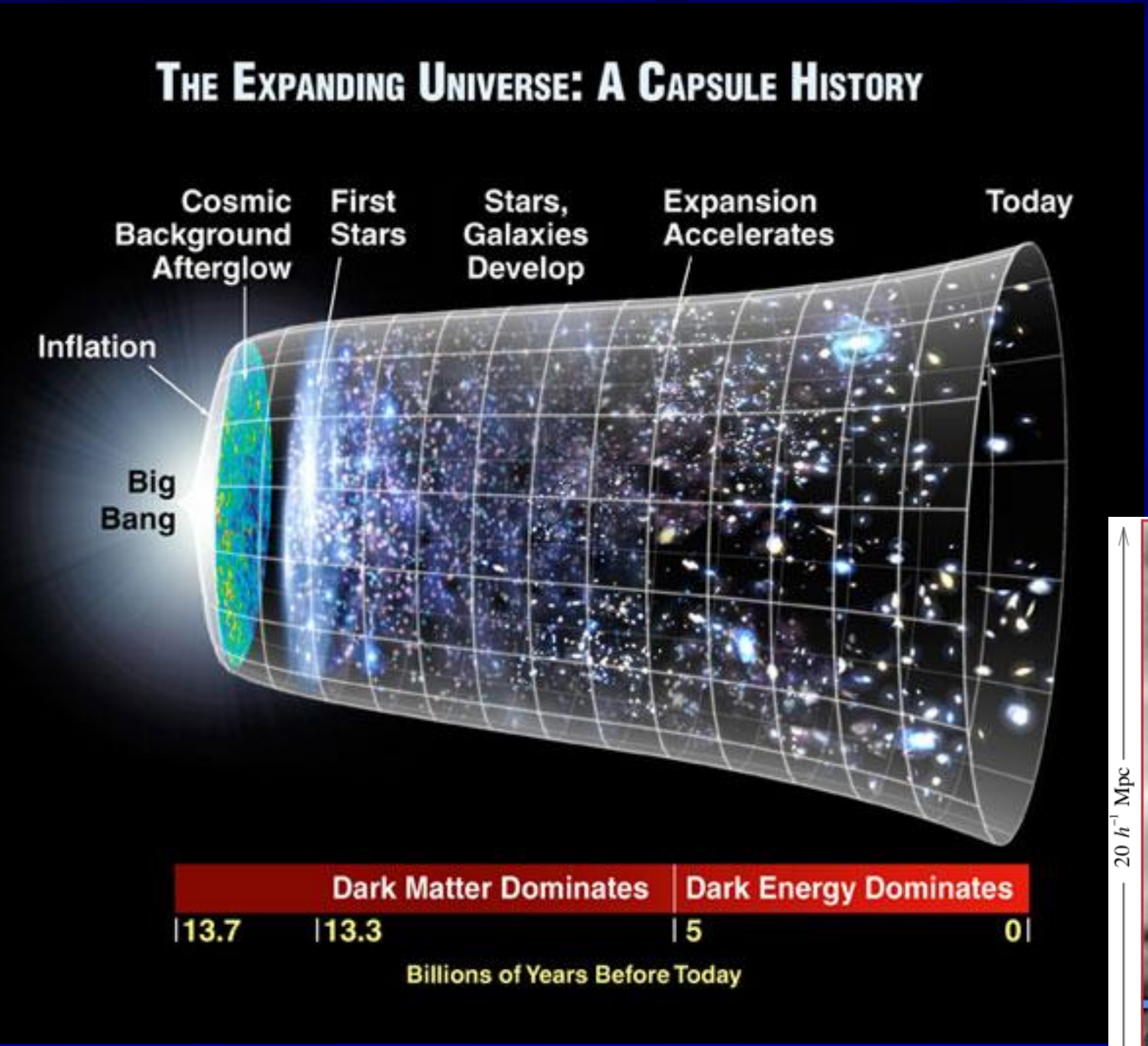
December 2013

Texas Symposium

Contents

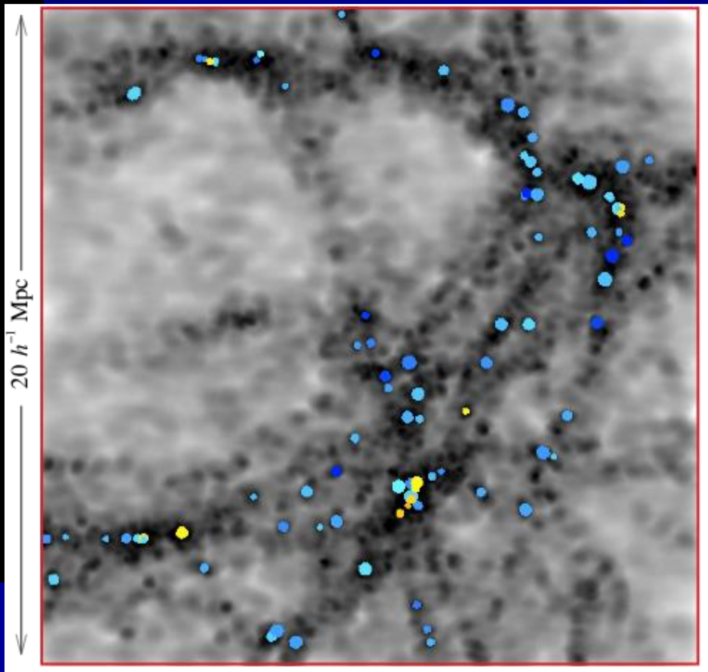
- "Ultraluminous" ULIRG galaxy properties.
  - "SMGs"? Submm/mm-wave selected
  - Caveats about our knowledge
  - Selection, or confirmation, mostly so far at long (far-IR to mm) wavelengths
- JCMT/SCUBA and OVRO (& VLA and Keck)
- ALMA (& Planck, Herschel, SPT and ACT)
- CCAT – future wide-field survey telescope
  - Context of ALMA/legacy of Herschel/SPICA

Cartoons of galaxy evolution



Hobby Eberly HetDex

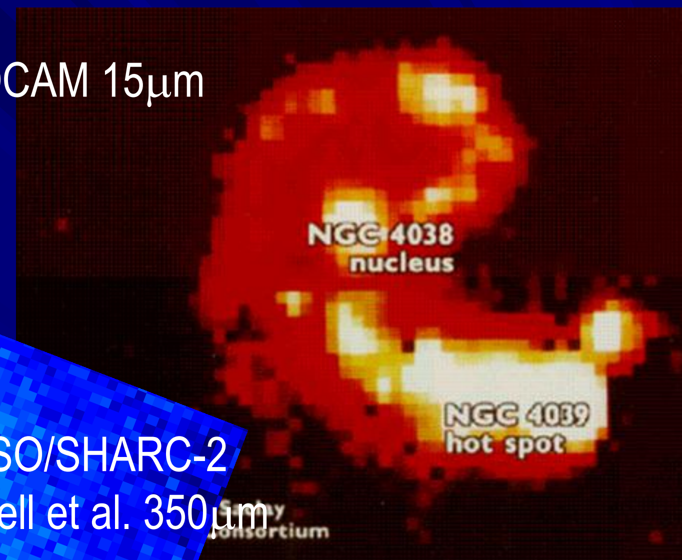
Benson et al. ~30 Mpc; z~2 cluster

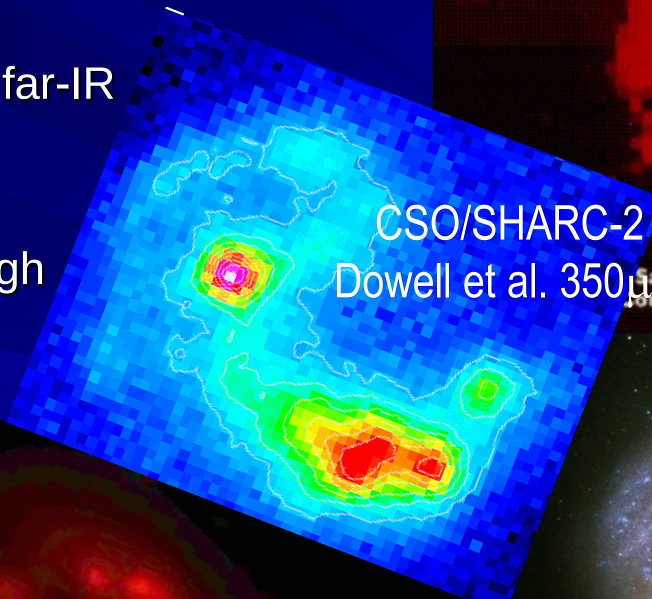


Resolved scaled-down ‘SMG’: Antennae

- 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

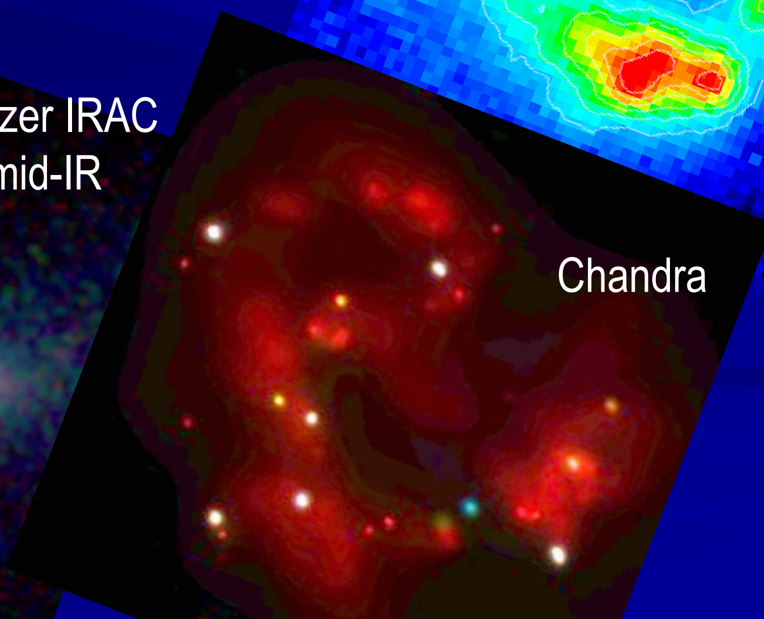
ISOCAM 15μm



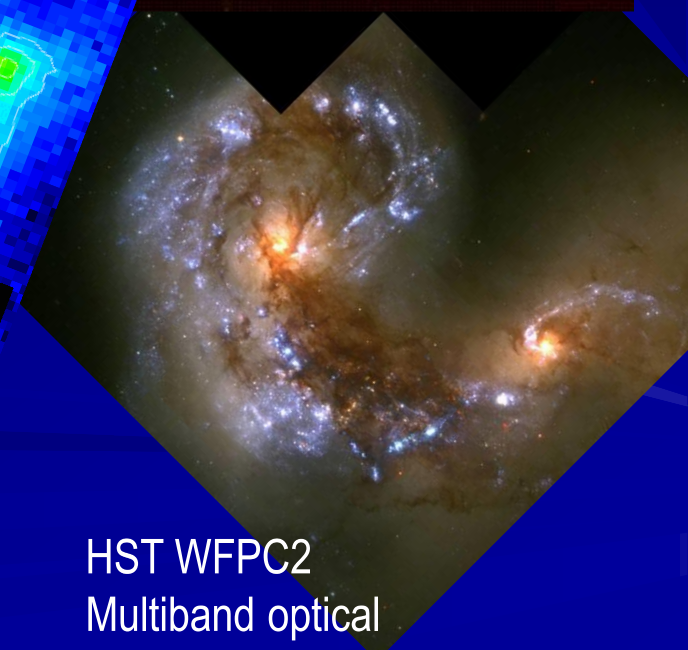


CSO/SHARC-2
Dowell et al. 350μm

Spitzer IRAC
mid-IR

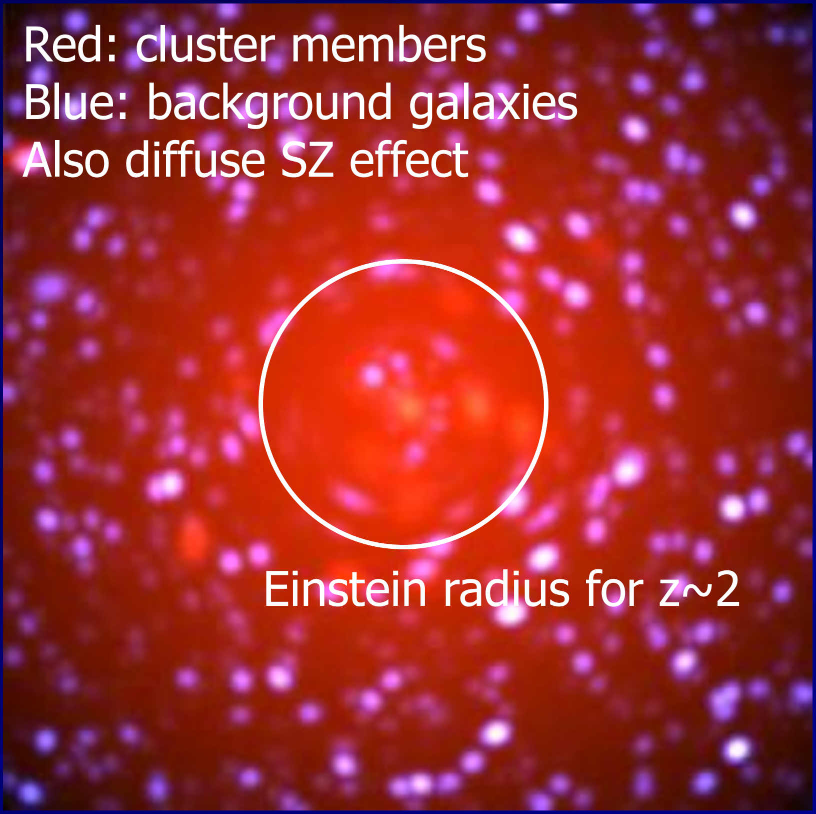


Chandra

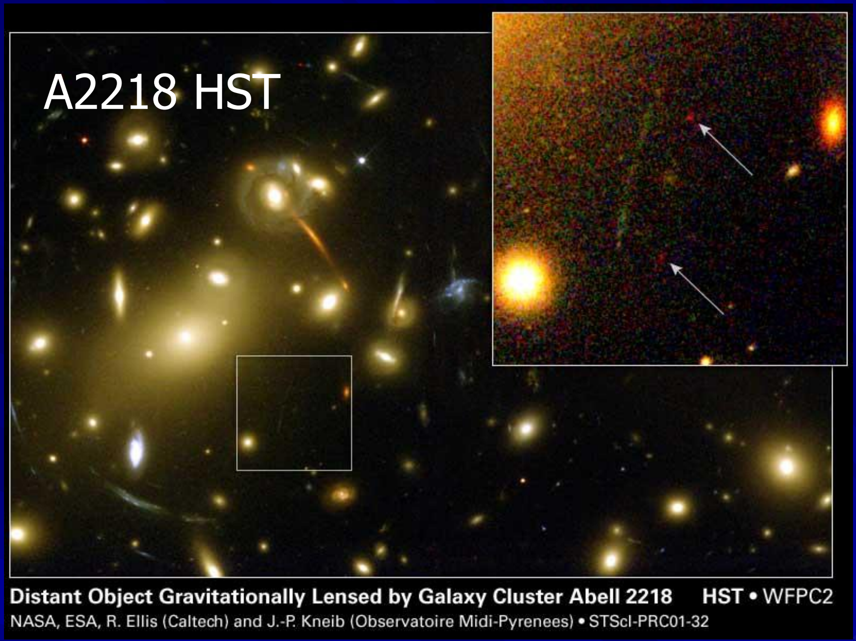


HST WFPC2
Multiband optical

Gravitational lensing in submm



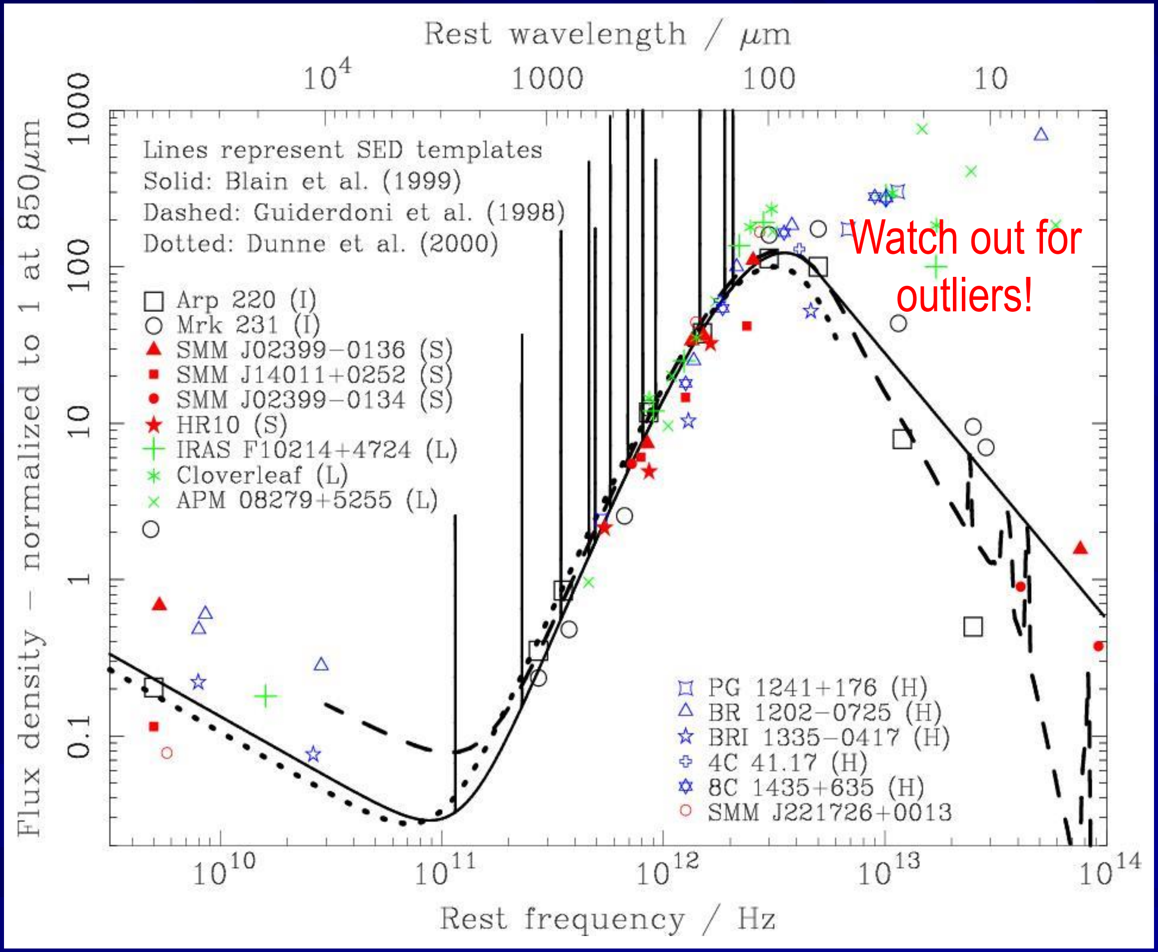
Cartoon simulation shows swarm of faint sources expected in the cluster centre if the potential strongly peaked. (For galaxies too.)



Very faint z=5.5 object shows what can be seen along high-magnification critical lines in all clusters; now CLASH, Frontiers

- Excellent probes of clusters' & galaxies' strong lensing with ALMA angular resolution

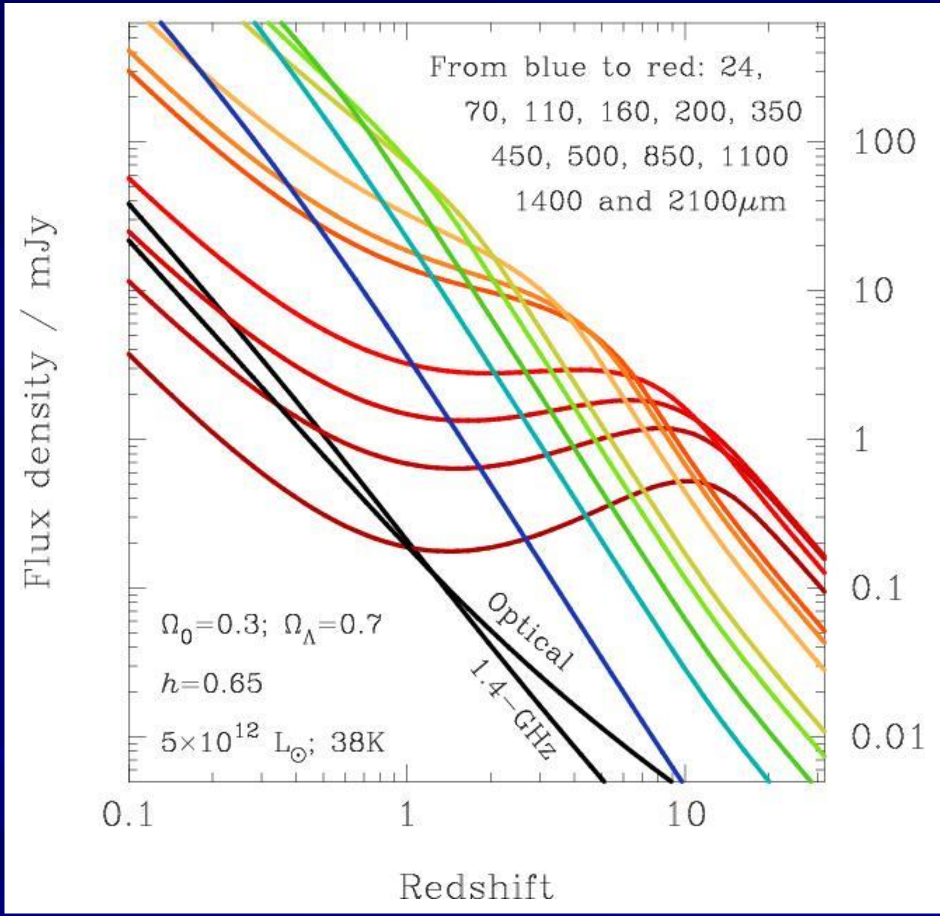
Far-IR/submm galaxies' SEDs



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
- Non-thermal radio
  - Radio-far-IR link
- Thermal dust dominates luminosity
- CO, HCN, HCO+, C fine structure lines carry redshift, dynamical, and physical information

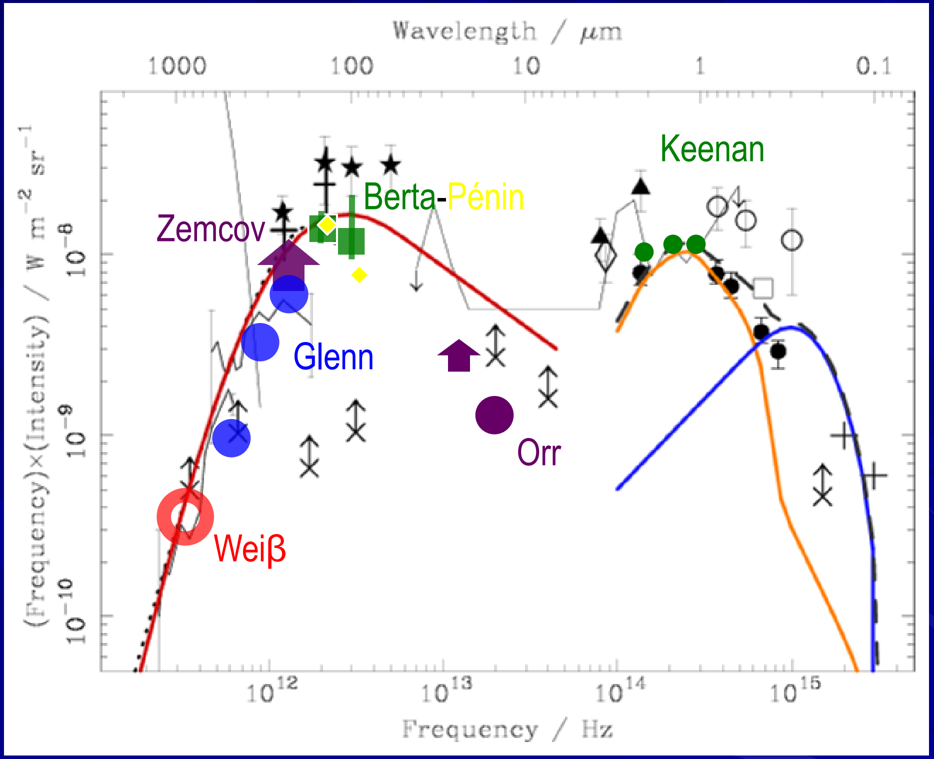
Unique (sub)mm access to high z



- 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 ~5×10^{12} L_o
  - Note matches current depth of submillimeter surveys
  - ALMA has no effective limit to depth

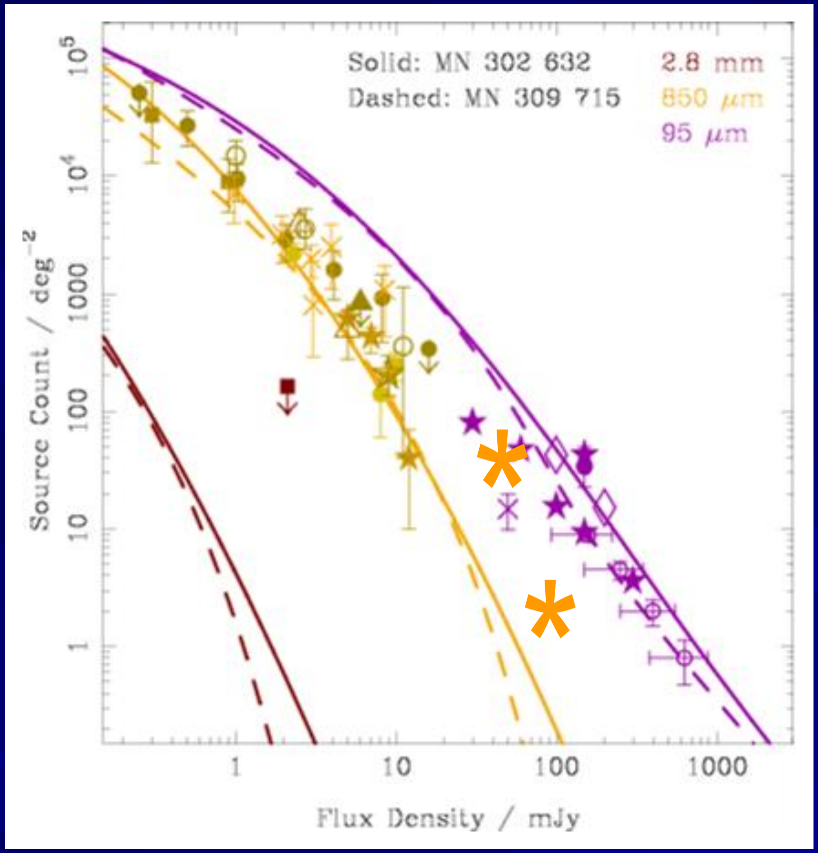
Extragalactic background light

- Many sources of data
- Total far-IR and optical background intensity comparable
- Most of the submm (0.85mm) background was already detected by SCUBA. Now see LESS (Weiβ)
- Spitzer detects ~20-30% in mid-IR
- Glenn (SPIRE), Berta-Penin (PACS), Zemcov (SPIRE clusters)
- Orr TeV
- Background data not very restrictive



Models: BJSLKI 99

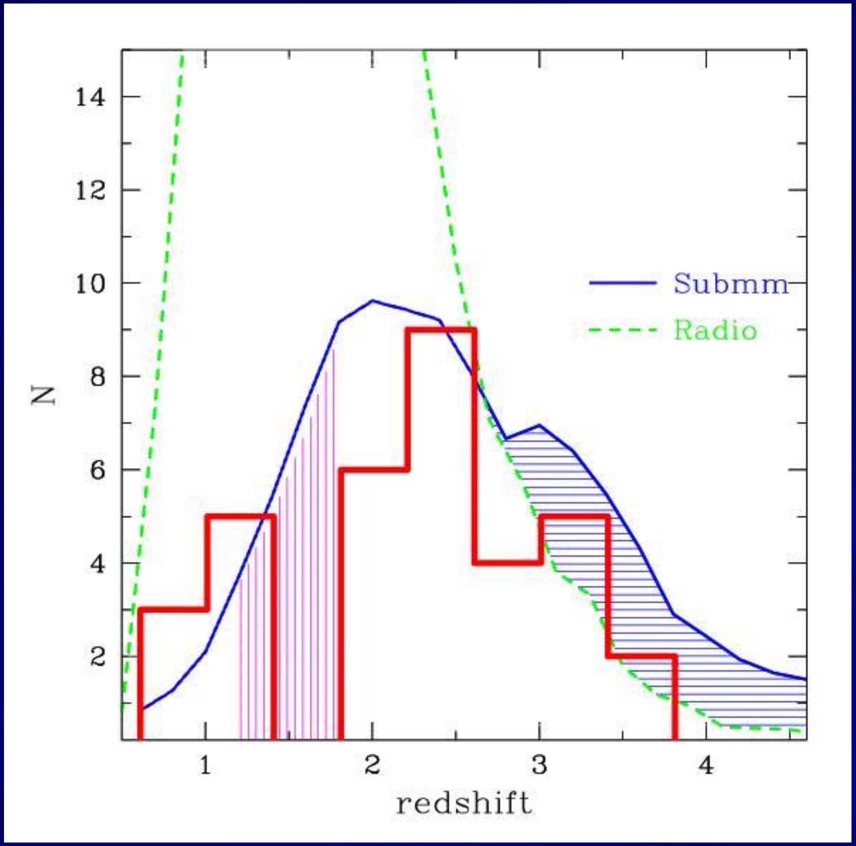
Population of dusty galaxies



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

- Unusually steep counts
- Most data is at 850 μm
  - Bright limit from Barnard et al
  - Very few are Galactic contaminating clouds
  - LESS at APEX
- First 2.8mm limit from BIMA
  - Bright SPT counts (Vieira)
- Bright 100 (&160) μm counts from ISO, dramatically improved by PACS (Magnelli)
- NOW data at 1.1mm (AZTEC), 1.3mm (ALMA Hatsukade) 1.4mm (SPT) and 450μm (SCUBAII Geach)
- AND **differential counts**

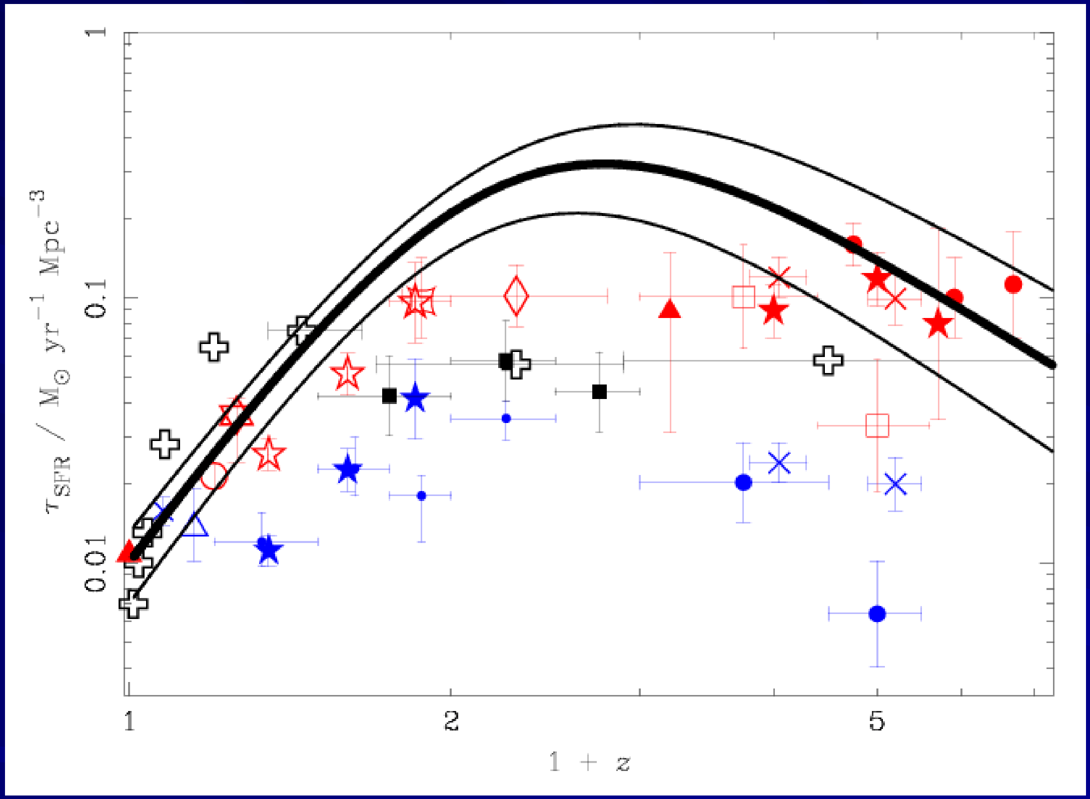
Redshift distribution: early SMG N(z)



Chapman et al. (2003; 2005)

- Red histogram: Chapman et al. (2005)
- Blue, green lines: expected submm & radio N(z)'s from Chapman 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
  - Well over 100 in total
- Redshifts most powerful constraints

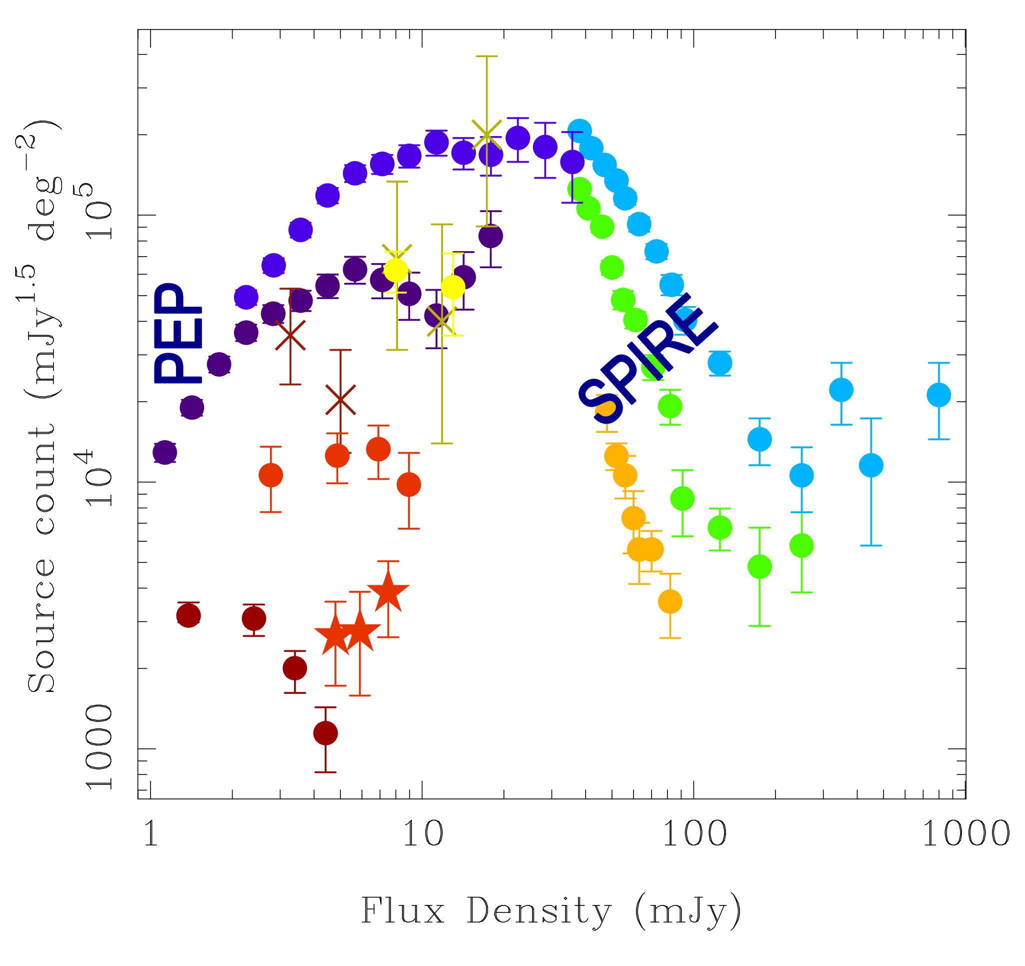
Global luminosity evolution



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

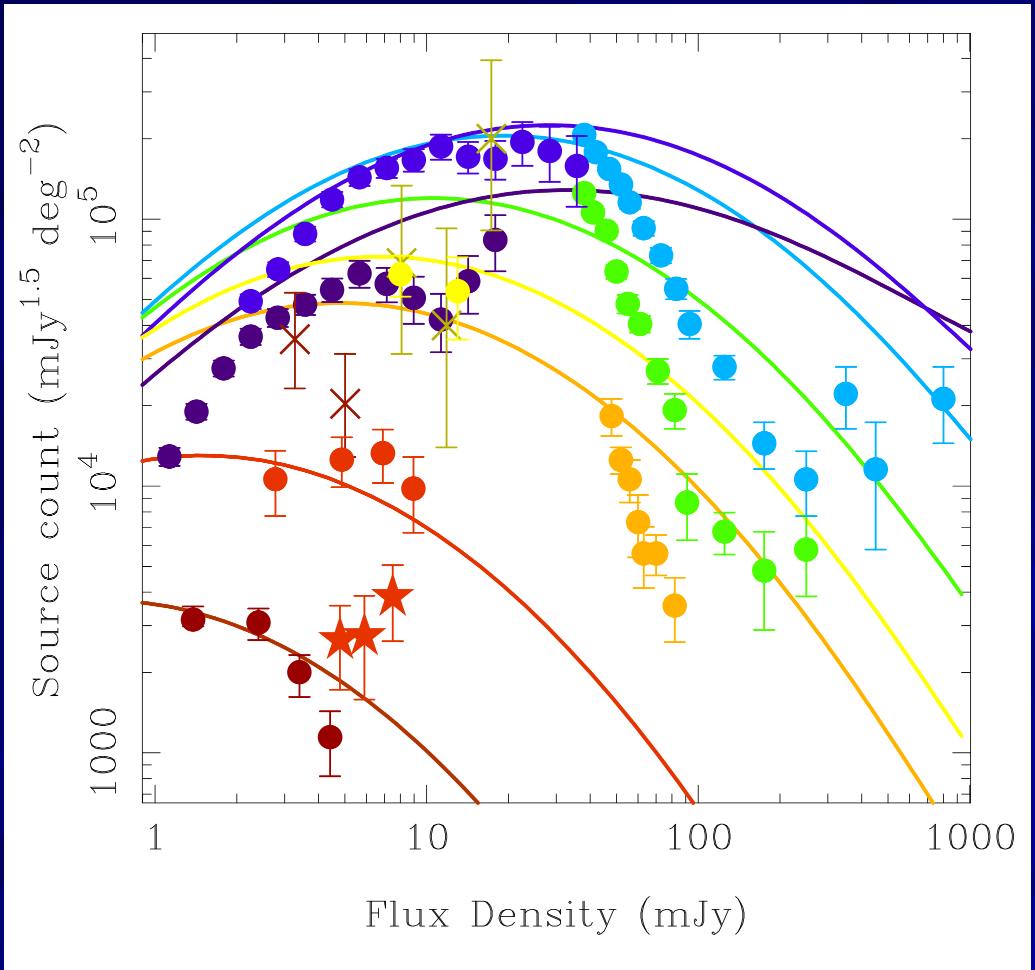
Current differential counts



Note submm/mm still rather sparse, c.f 10^5 HSO samples

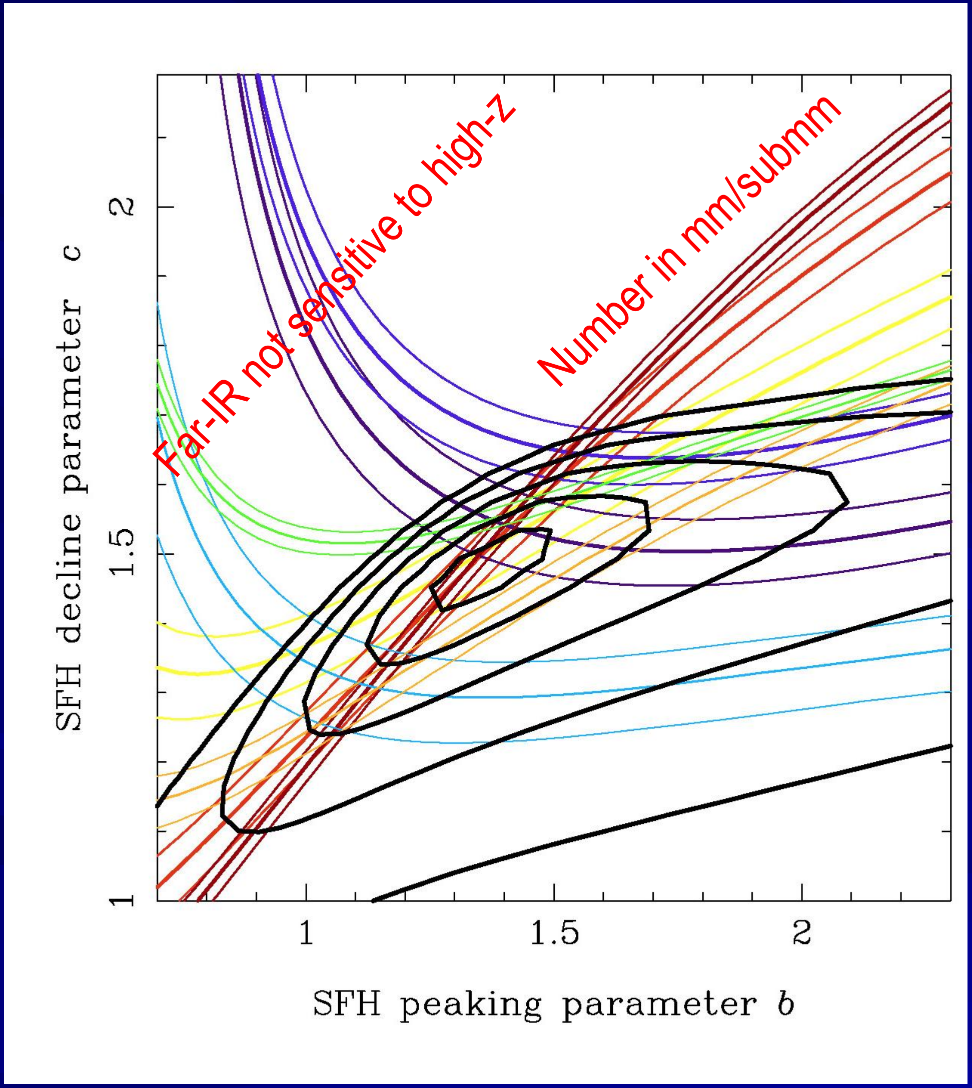
- This is the real information, for detailed matching
  - Previous counts just N(>S)
  - Up to ~3 constraints per count
- PACS (PEP-GOODS Magnelli)
- **SPIRE** (ATLAS Clements)
- SCUBAII 450 **Geach** & Chen
- SCUBA 850 Coppin & Chen
- ALMA 870 (LESS, **Karim**)
- AzTEC 1100 (Austermann)
- Also have 1.4mm and 2mm counts from SPT, and a stab at ALMA (Hatsukade)

And an ancient model of mine



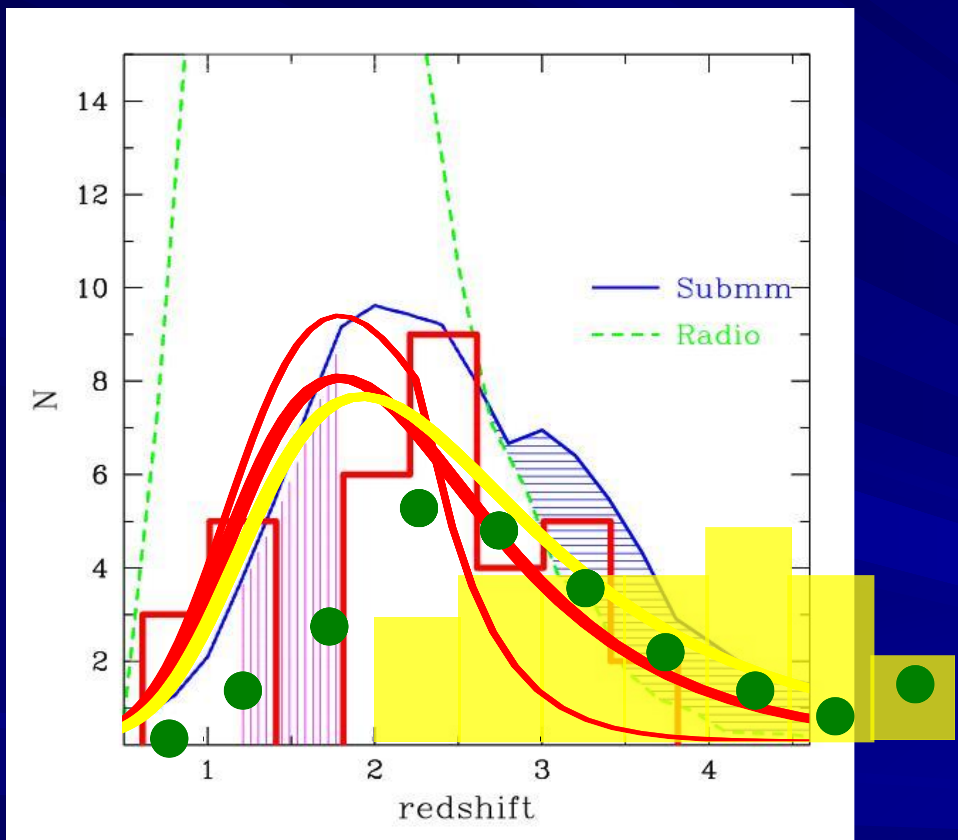
- 2002
  - Right cosmology
  - Matched to ~175/850 microns
  - IRAS LF
- Misses sharp upturn at SPIRE
  - Needs more hierarchical behaviour
  - Also at 1.1mm AzTEC?
  - Also needs Low-z cool things
- Too many objects with ~mJy fluxes in PACS
  - Not incompleteness
  - Needs tweak near z~1 with hotter SEDs in too
  - PACS faint downturn too slow

Luminosity density history



- Without redshift information
  - Was b,c~2.0,1.7
  - Now b,c~1.4,1.5
- Add redshifts gets more complex
- Not radically different

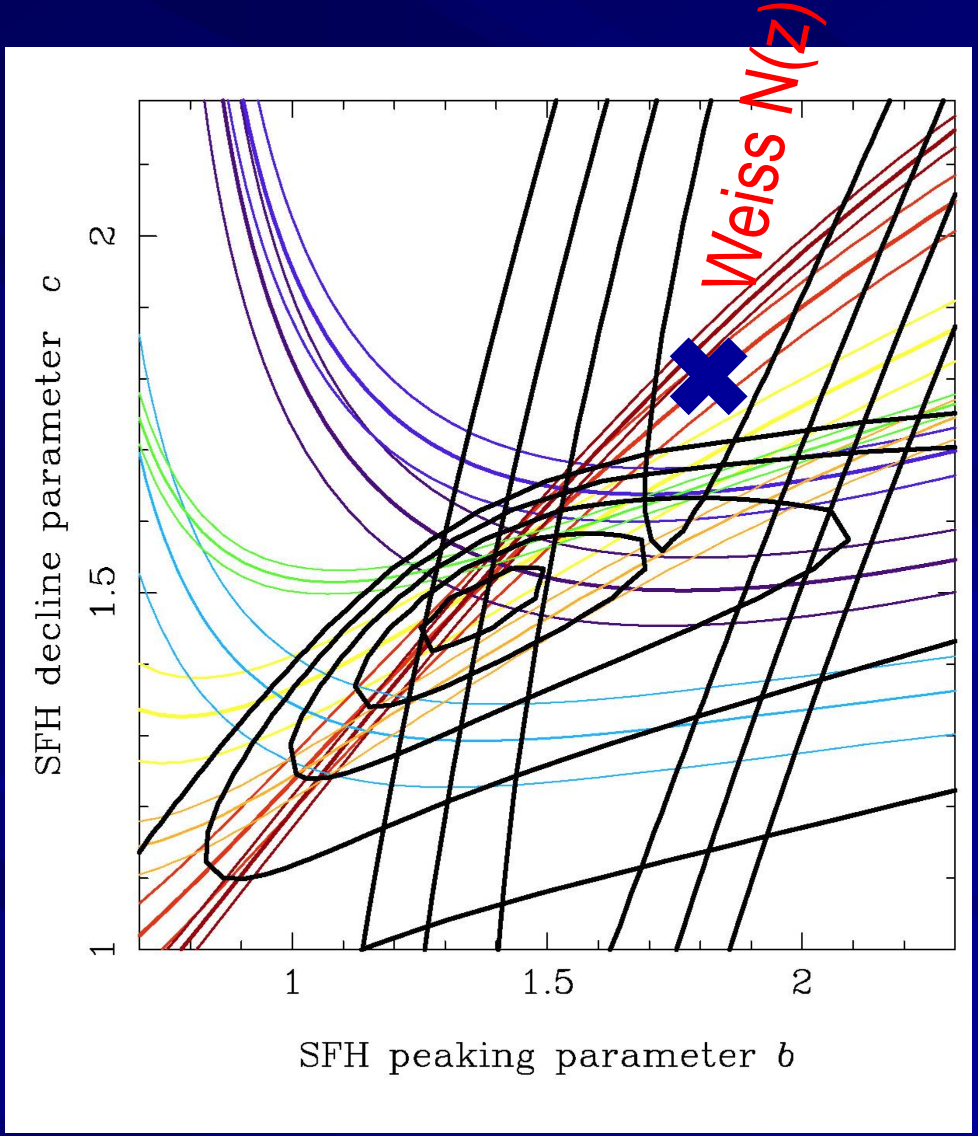
Redshift distribution N(z) for SMGs



Chapman et al. (2003; 2005); Weiβ et al. (2013)
Red lines: BSIKF 0.85mm 5mJy, w/wo radio cut
Yellow line: BSIKF 1.4mm 1mJy, green lenses

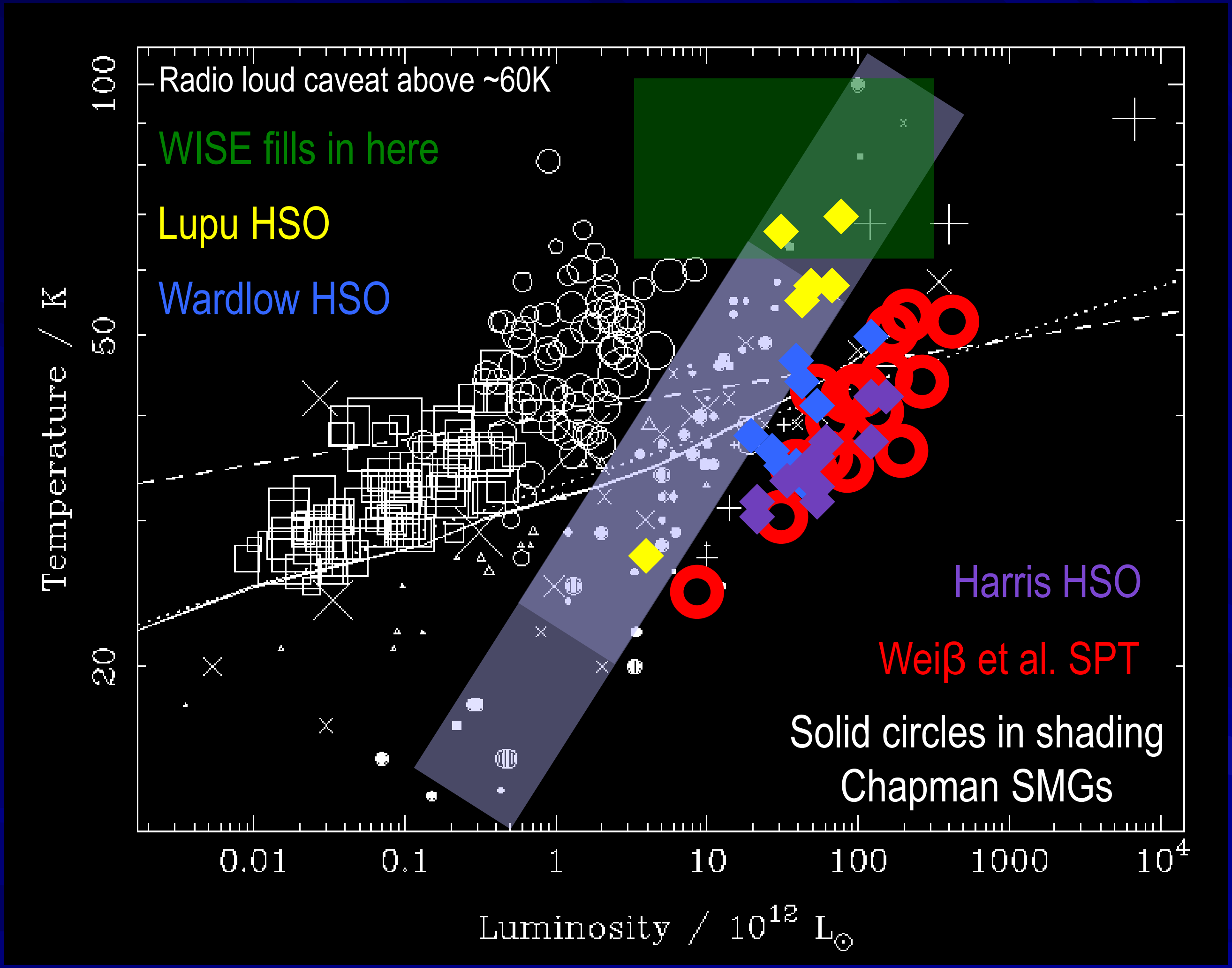
- Red histogram, blue & green
  - –Chapman et al. (2005)
- Red lines: previous model
  - –With and without radio cut
- Yellow histogram: SPT N(z)
  - –SPT selected, ALMA confirmed with CO-line redshift
  - –Censored modestly by lensing, in both redshift and size (distant, small objects preferred).
- Yellow line. Previous model
- Green dots. Censured by lensing. Effects clear?
- Significant tension
  - –COSMOS (Smolcic)
  - –Disk lens (Maller/Moeller)
  - –Multiple components (Hodge)
- Redshifts most powerful constraints

SPT/ALMA redshifts included



- Weiβ et al. (2013)
- Modest change b~1.7, c~1.7
  - Bet on X for simple high-z dust model?
- Not an excellent fit!
  - But very minimal model
- Caveats:
  - SED range
  - Cool/warm far-IR
  - Other populations
    - WISE, ALMA?

High-z ULIRGs with redshifts



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

Uncapped magnification μ distribution?

2-5: 3, 5-10: 4, 10-20: 5, 20-50: 9, 50-100: 7

Squares: low-z, Dunne et al.

Empty circles: moderate z, mainly Stanford et al.

Crosses: variety of known redshifts (vertical = lensed)

Lines: low-z trends

Scatter in T by at least ~40%

Argues for cap at mag' μ~50

Selection effects?!

SED Variation: Composite IR SEDs of SMGs

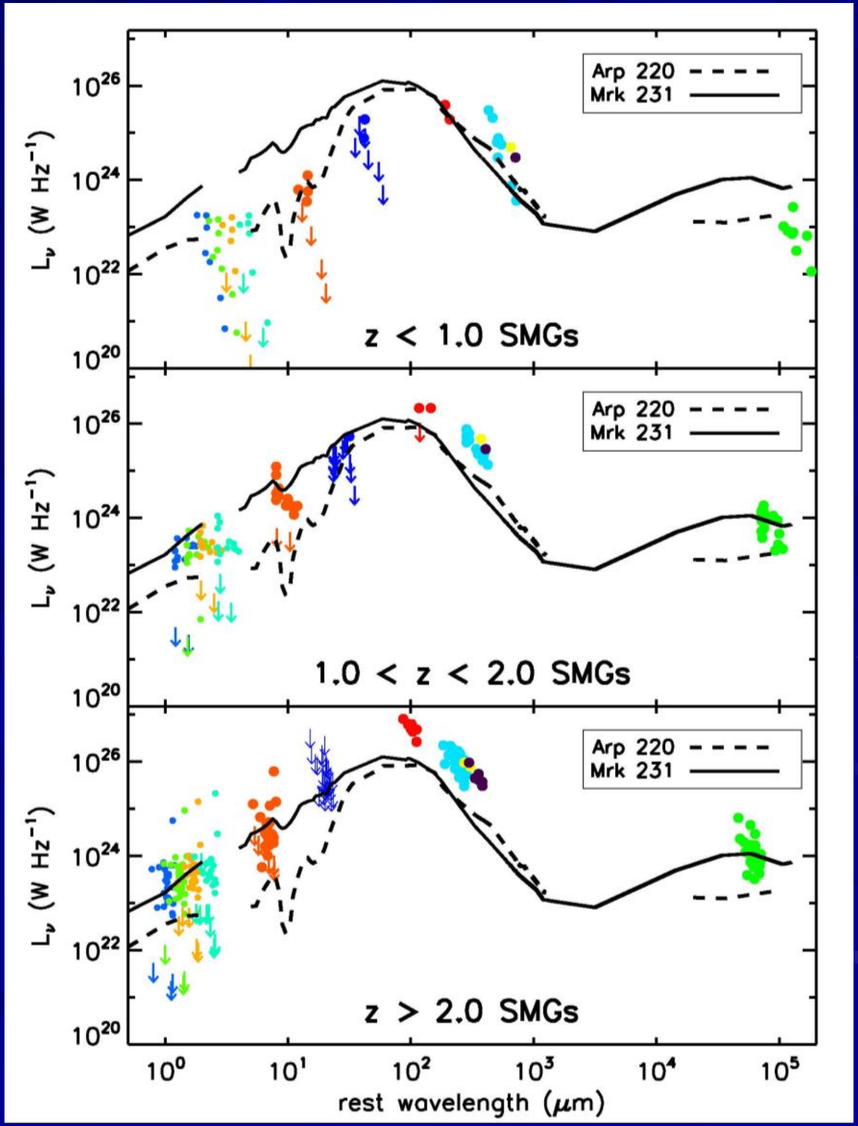
Use all mid-IR to radio data for Chapman SMG sample & compare "cold" and "warm" ULIRG templates.

Composite SEDs change with redshift (and luminosity?)

- 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

- Greater scatter in mid-IR and radio in *z* > 2 galaxies
    - More varied mid-IR properties?
    - Probably not a luminosity effect?



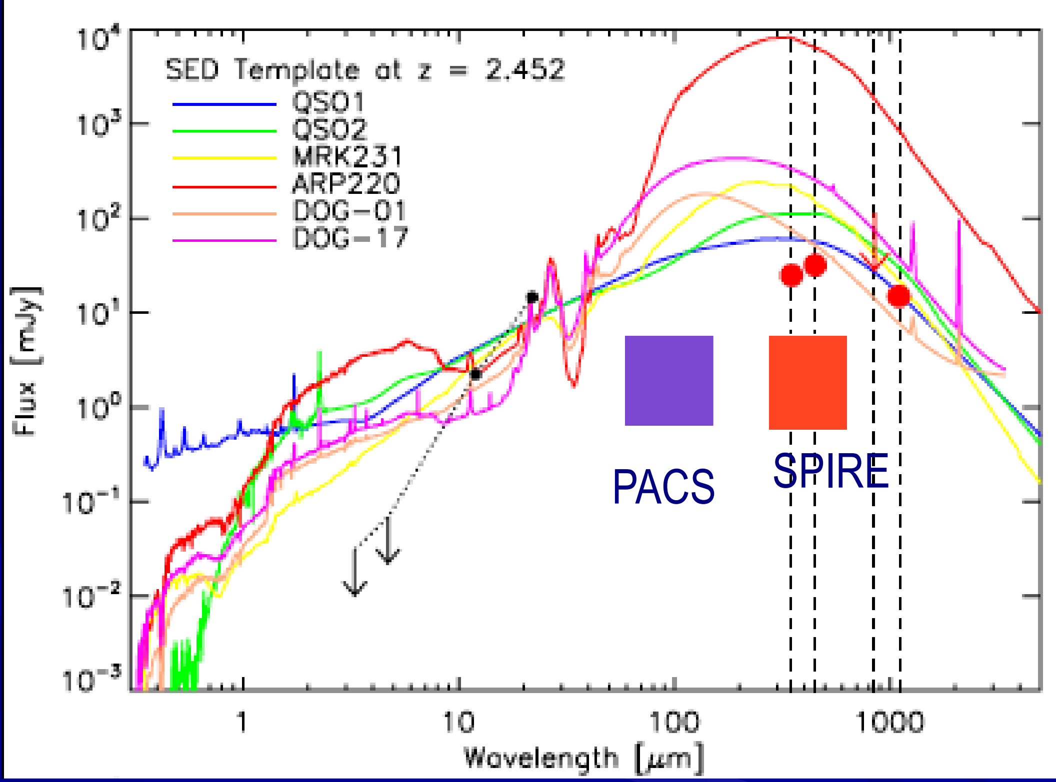
Hainline et al 2010

WISE spacecraft and instrument

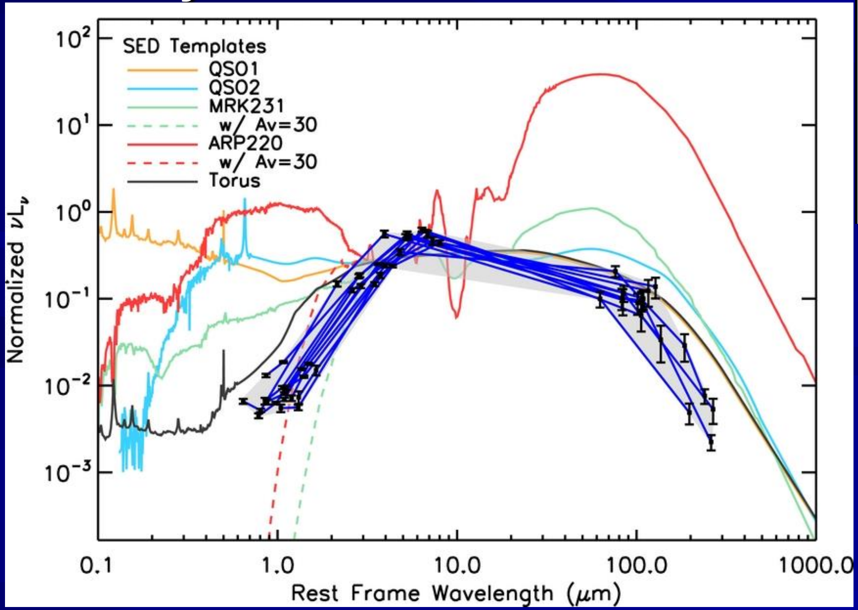
SDL, Logan, UT
Ball Aerospace, Boulder, CO
JPL, Pasadena, CA
UCLA, CA

WISE SEDs are odd

- WISE sources are sampling different regime of L,ρ
- Existing libraries of far-IR SEDs don’t stretch far enough
- WISE hot/blue far-IR objects

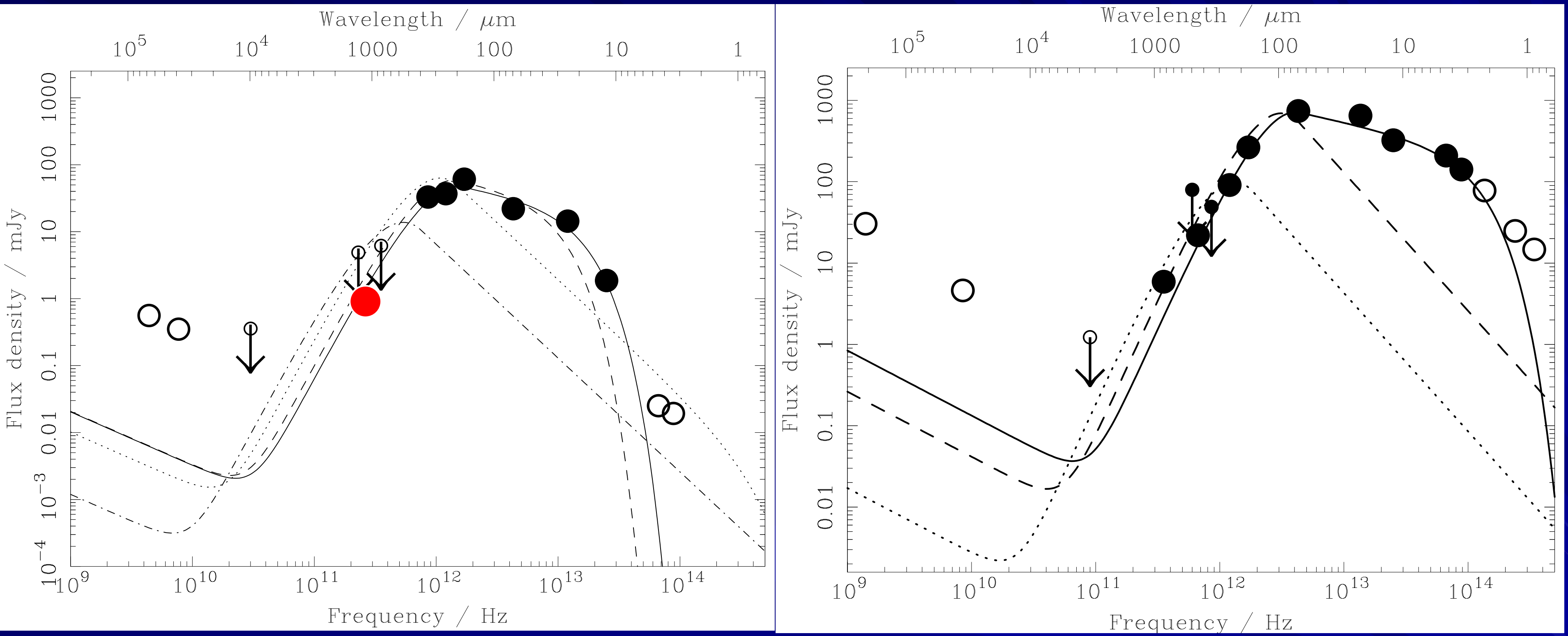


Compiled CSO results on 1814
Eisenhardt et al. (2012)



Wu et al. (2012)

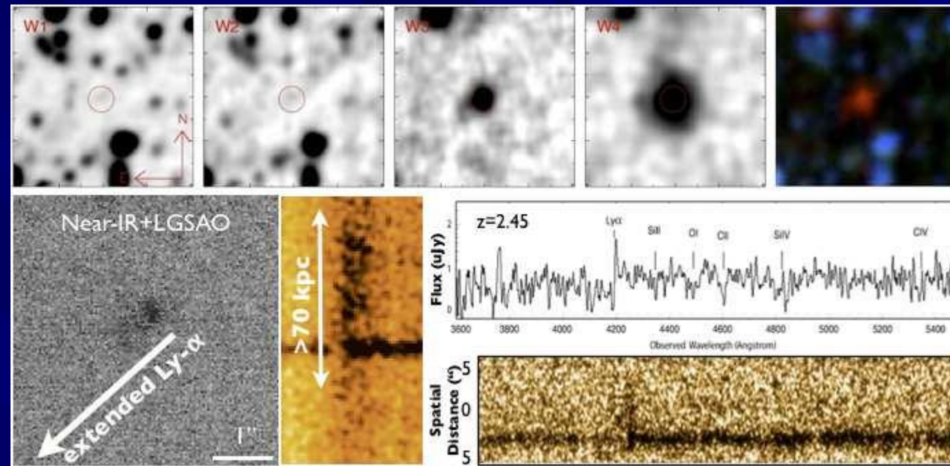
W1814 SED & low-z analogue?



- Left: W1814 (z=2.54, IRAM in red, Herschel & WISE)
- Right: PDS456 (z=0.184, SCUBA2, Herschel & WISE)
- Milky Way, 40-K ULIRG, & fitted SED
- Rather similar, although power from W1814 much more heavily obscured. Note radio model from low-z correlation

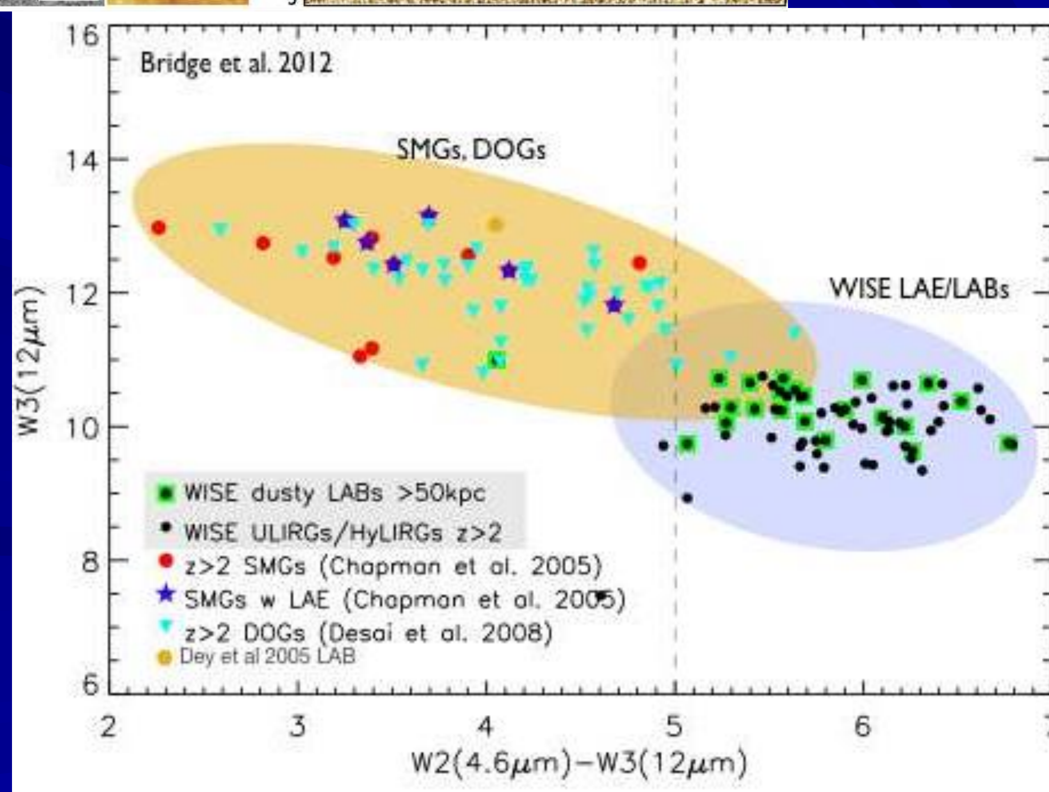
WISE Lyman-α blobs (WLABs)

- Follow-up spectra of hot dusty WISE ULIRGs at z~1-5
  - Bridge, Blain et al.
  - ApJ, 796, 91
- Unusually large number of large (~50kpc) LyA emitters
  - Including Eisenhardt’s first WISE `HyLIRG’
- WISE colours alone can select ~1000
  - Red, bright in WISE
  - No other selection finds dusty LABs
  - Feedback in action?

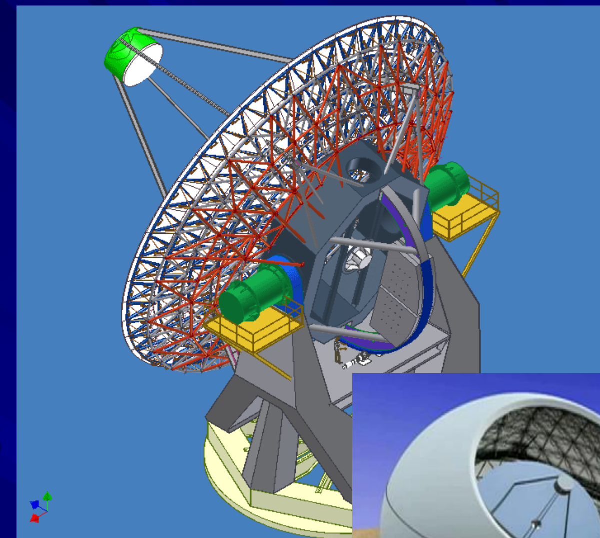


Top: WISE Bands, Bottom: NIR image & Spectra

Bridge et al.

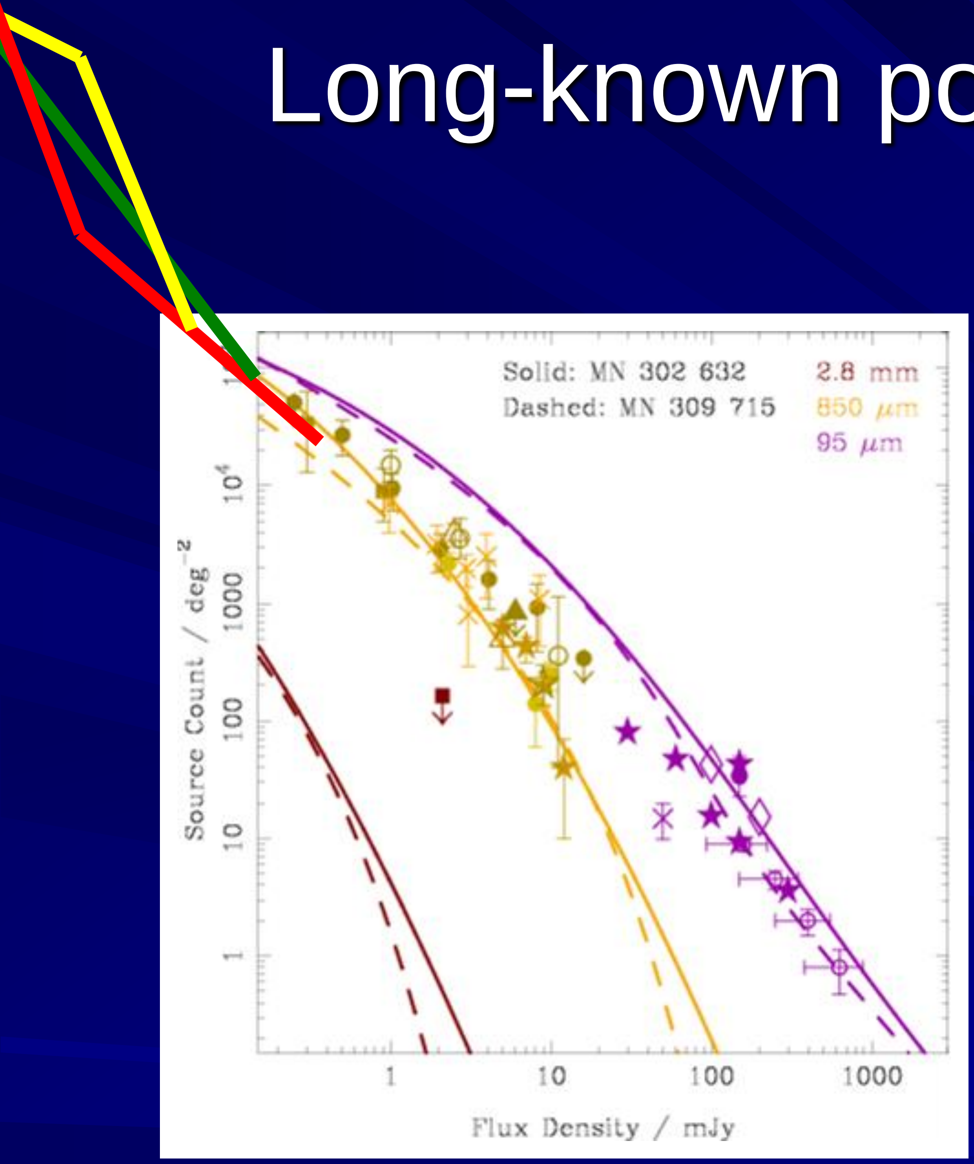


CCAT: future submm telescope



- Existing submm facilities are limited to [illegible] Jy sensitivities by confusion
  - CSO JCMT APEX
- ALMA has great sensitivity, limited FoV
- Large format detectors
  - SCUBA-2 deployed with 2x 4x64x40 TES bolometers
  - Zmuidzinas/others 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 initiated CCAT project. German involvement.
  - Best possible (non-polar) site: atmospheric windows to 200 microns
  - Wide field of view (~30 arcmin) to accommodate new detector technology.
  - 350 micron square-degree imaging, 350/450/750/850 micron colours
- Cerro Chajnantor Atacama Telescope: submm.org

Long-known populations revisited



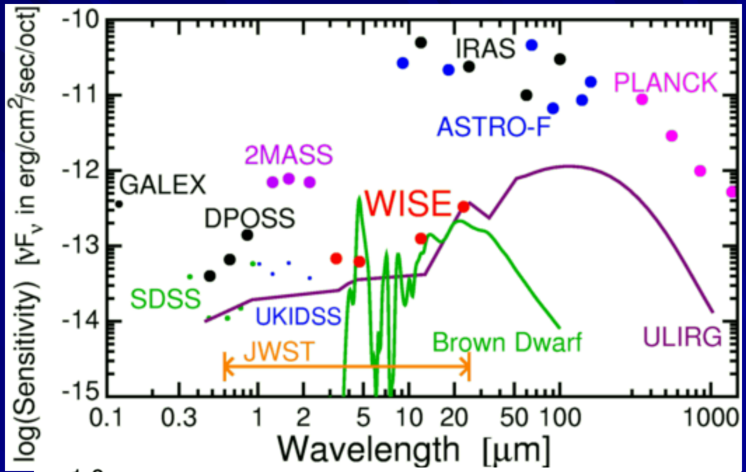
- Bright 95 (&175) μm counts from ISO dramatically improved at 70 & 160 μm by Spitzer-MIPS, Herschel-PACS
- Also data at IRAM's MAMBO/GISMO); CSO's BOLOCAM/SHARC-2; APEX's LABOCA; Herschel SPIRE; ALMA.
- Little more so far at <mJy level
  - IRAM & ALMA cycle-1 deep field
- Faint counts ill- constrained by background/N(z) measurements
  - Could be faint dwarf population (green)
  - Could be continuing very distant LIRGS (yellow)
  - Could be μJy 1st light fragments (red)

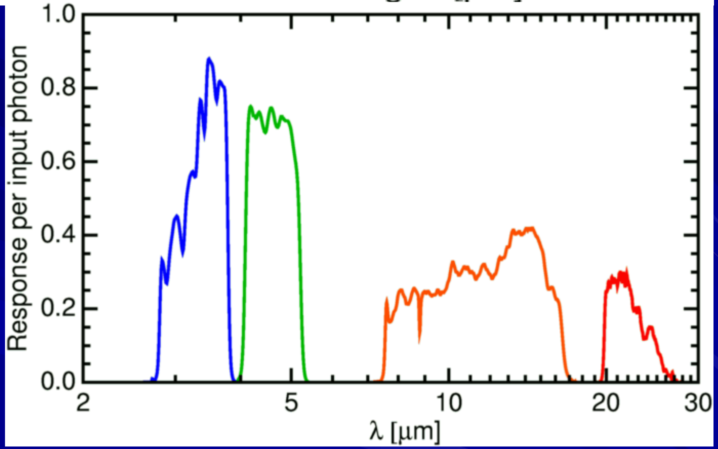
Issues

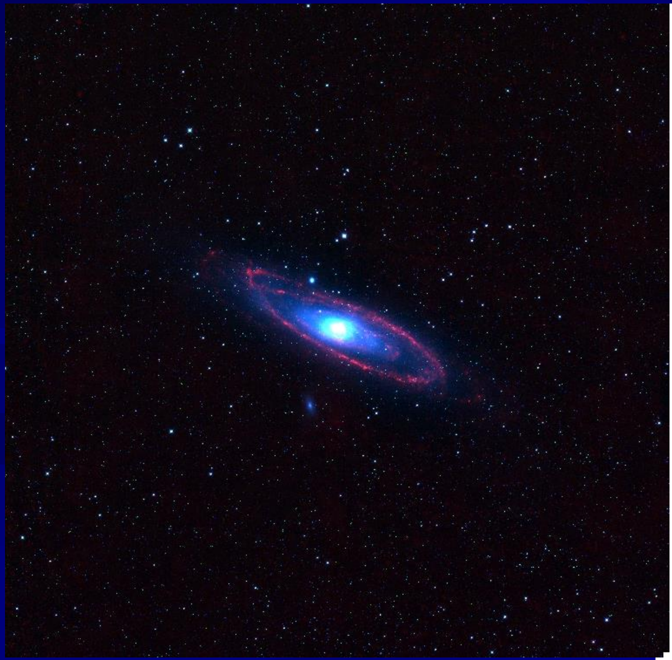
- Obscured objects trace peak of activity
- Can extend out much much further too
  - Upper limit to N(z) at z~6 interesting
  - Lack of z<2 lensed objects interesting
  - Confusion could be a factor
    - Multiple source structure could be a factor
  - SED range & evolution could be a factor
    - But no far-IR telescopes anymore!
- Full account of star-formation history?
  - ALMA (follow-up, deep), CCAT (multicolor, wide), SPICA (spectral)

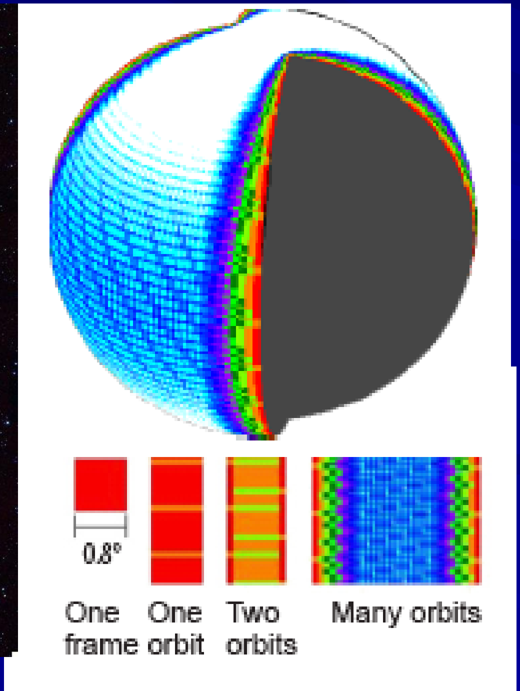
WISE: Dec 2009 to Jan 2011

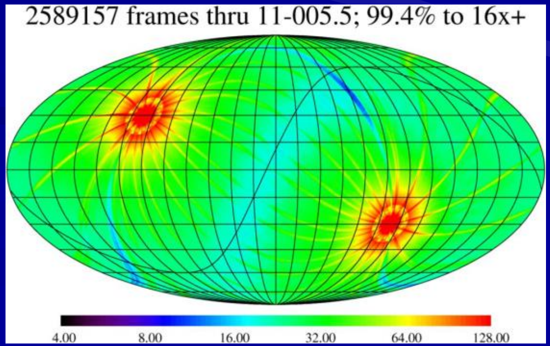
- Finished 1st sky pass on 17th July 2009
- 3.4, 4.6, 12, 23μm (W1-4)
- 6, 6, 6, 12” resolution
- 0.08, 0.08, 0.8, 4mJy





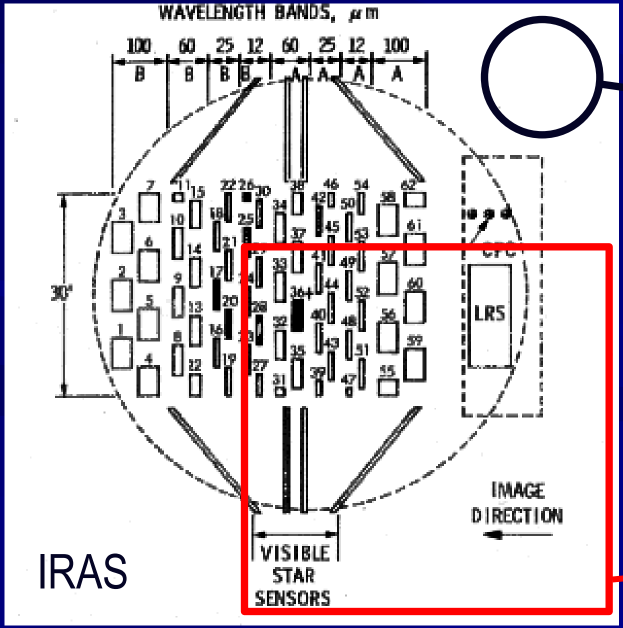




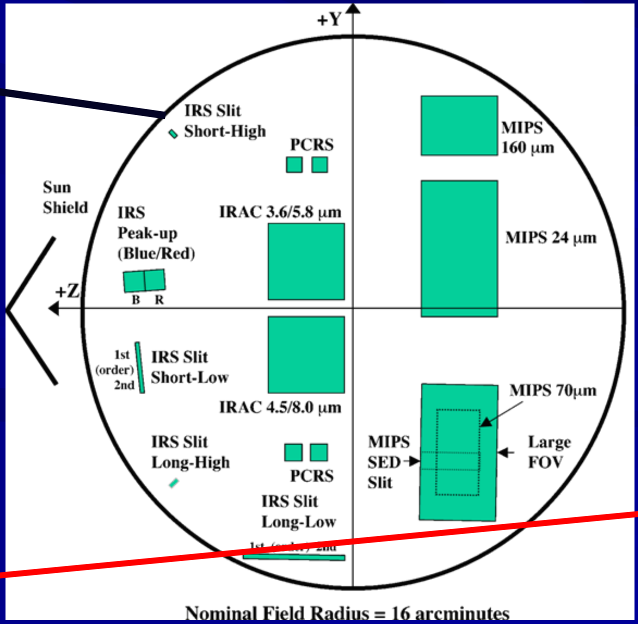


Technology

- Electronic infrared detectors
  - 1983 IRAS made first all-sky survey, 12-100 microns. 4 bands/62 detectors (spare in NSC)
  - 2003 Spitzer flew with 2 256x256 and 1 128x128 detector. Akari comparable
  - 2010 WISE flew with 4 1024x1024 detectors



IRAS

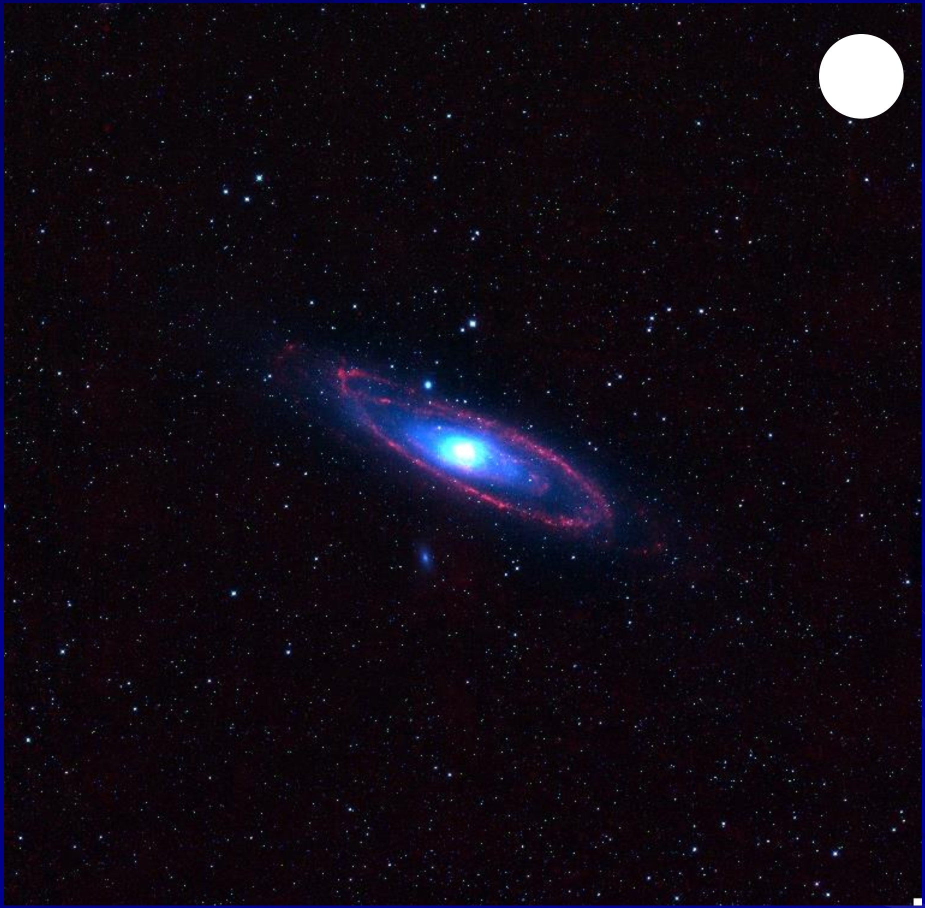


Spitzer

WISE detector package

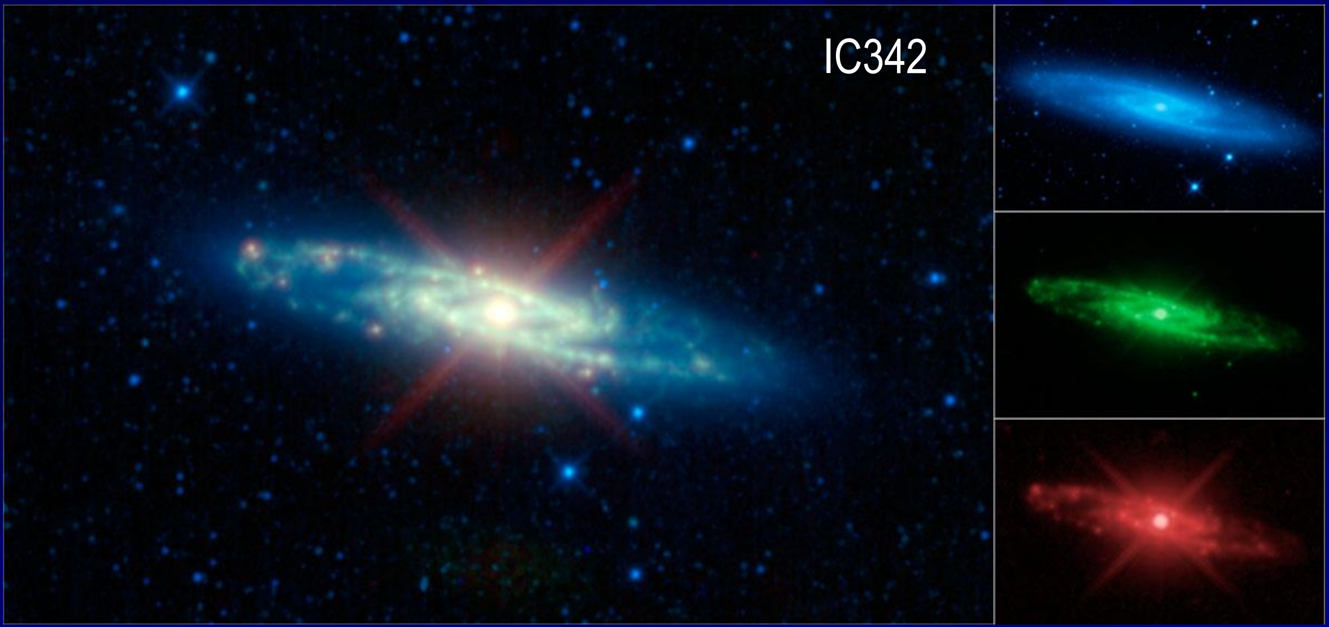
WISE sample images

Fornax 2.5 deg square



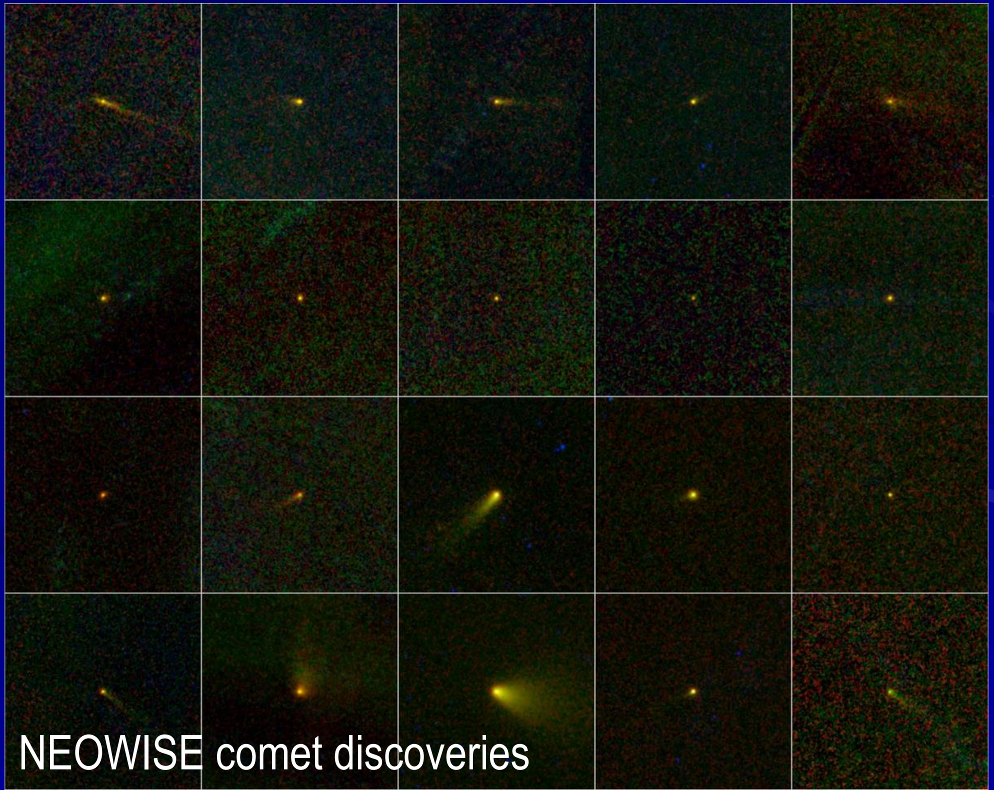
M31 5 deg square

Depth similar, scale different. Blue are stars/stellar populations

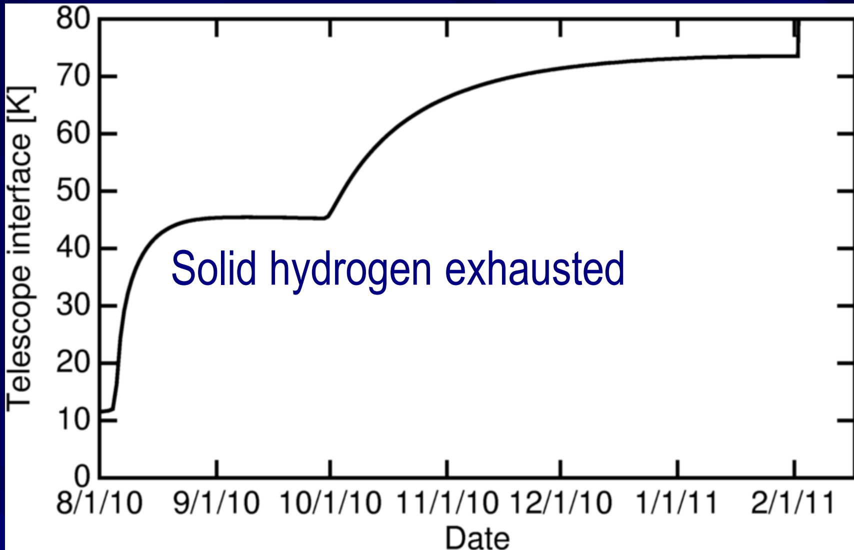

IC342


UltraCool Brown Dwarf

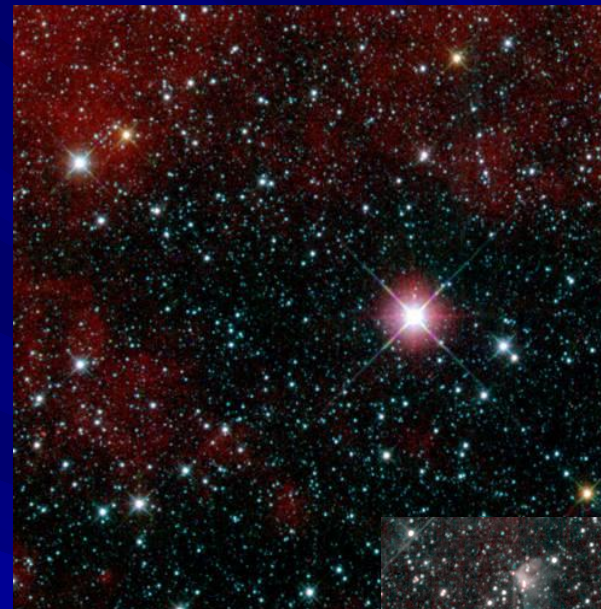

M81 & M82


NEOWISE comet discoveries

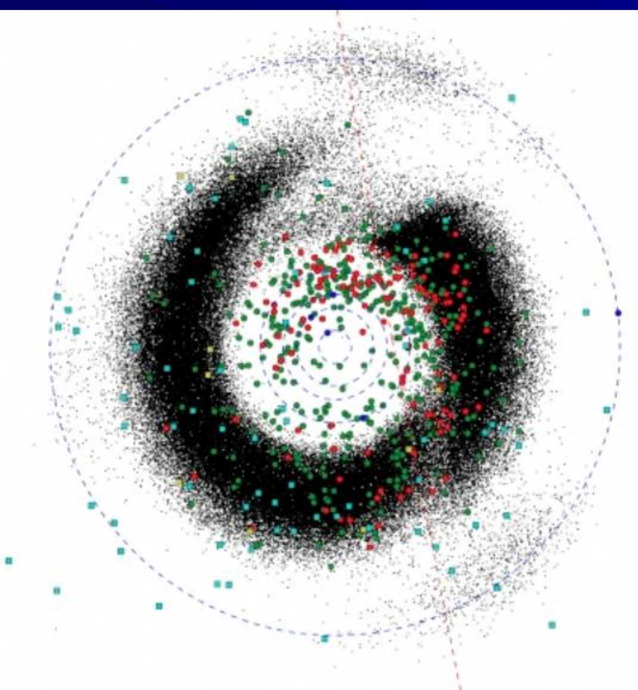
End of mission



Temperature profile for second sky coverage

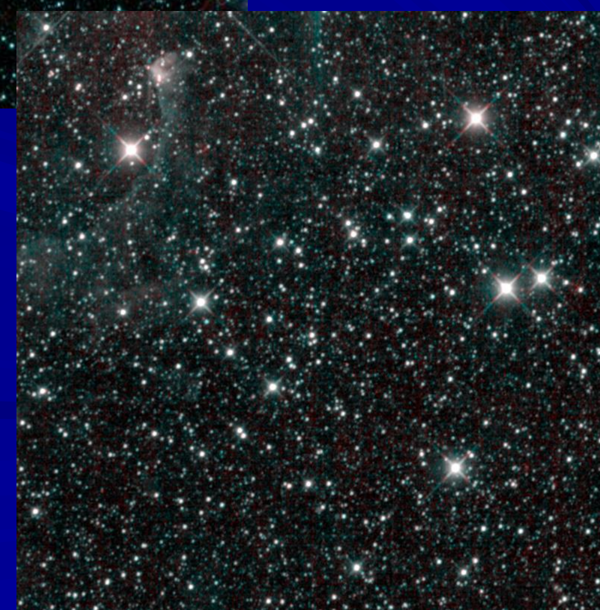


First light -
W1, W2, W3 & W4



Survey continued for 54 weeks for near-earth objects (NEOWISE)

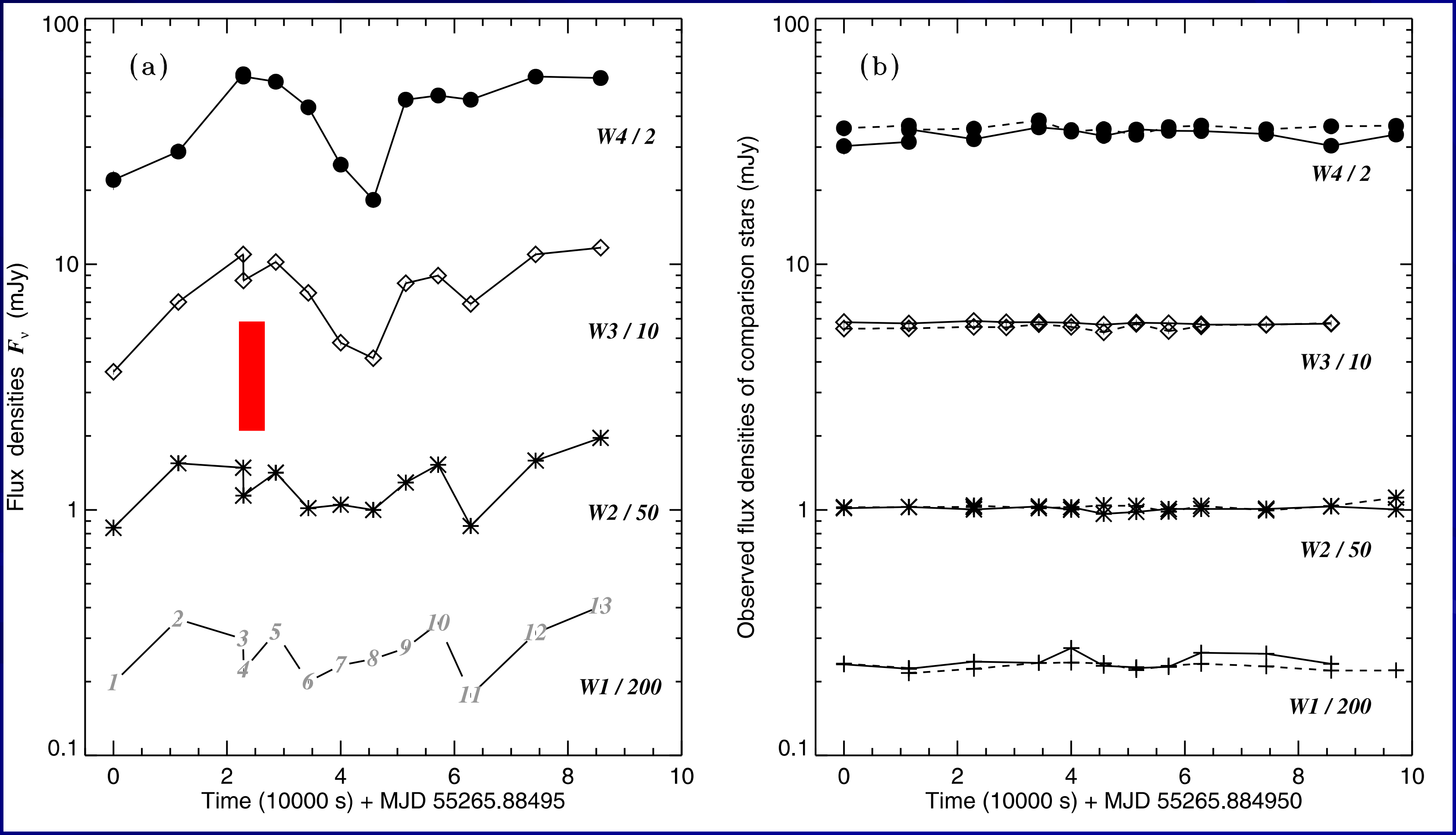
Responsible for accessibility of individual frames in archive



Last light – W1 & W2

Transients

- Gandhi et al.; 90 mins for 8 s, maybe x2
- XRB > 6M$_o$; X-ray activity just at right time

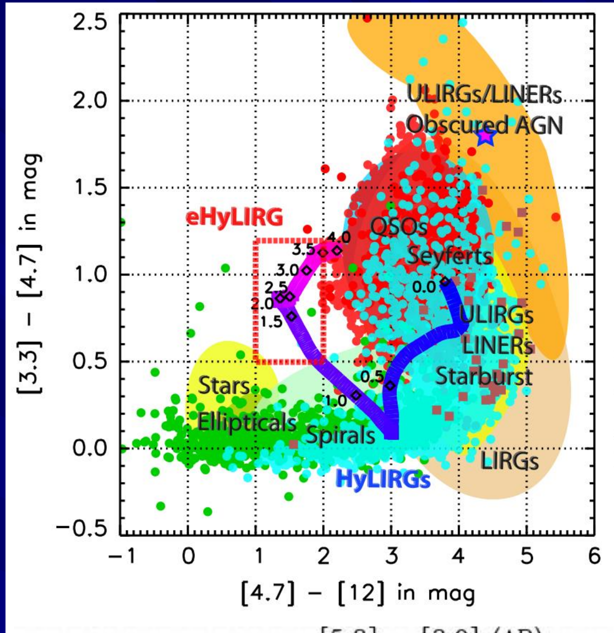


Existing knowledge of ultraluminous galaxies

- QSOs and quasars and radio galaxies
- IRAS found thousands, out to z=3.8
- ISO and (mainly) Spitzer found many more
  - DOGS from 24μm-R colour
  - BzK galaxies from optical-IR colours. Active and passive
- Ground-based submm telescopes have found ~1000, out to z>5.
- Follow up is a challenge
  - Requires all available capabilities
  - WISE can exploit rare, extreme examples

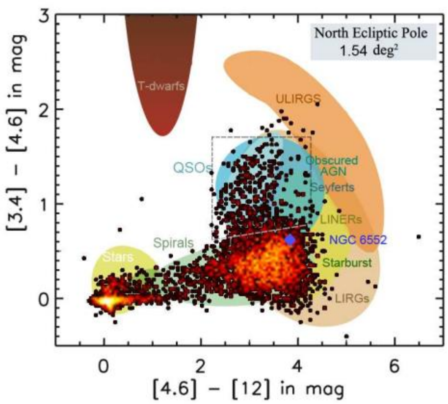
WISE colors

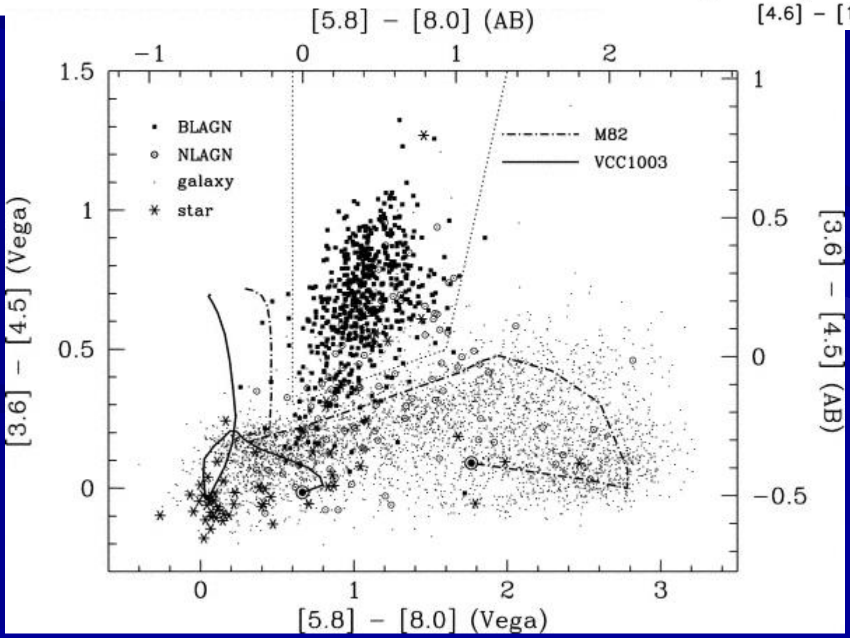
- 23μm W4 band is not as sensitive
- W1, W2, W3 provide best insight into galaxy and stellar populations
- Note that AGB stars scatter over the same region as ‘eHyLIRGs’, but they tend to be bluer in [3.3]-[4.7] and to have 2MASS/SDSS/DPOSS counterparts. Follow-up spectroscopy rate is <2% for stars.



SDSS comparison by Lin Yan

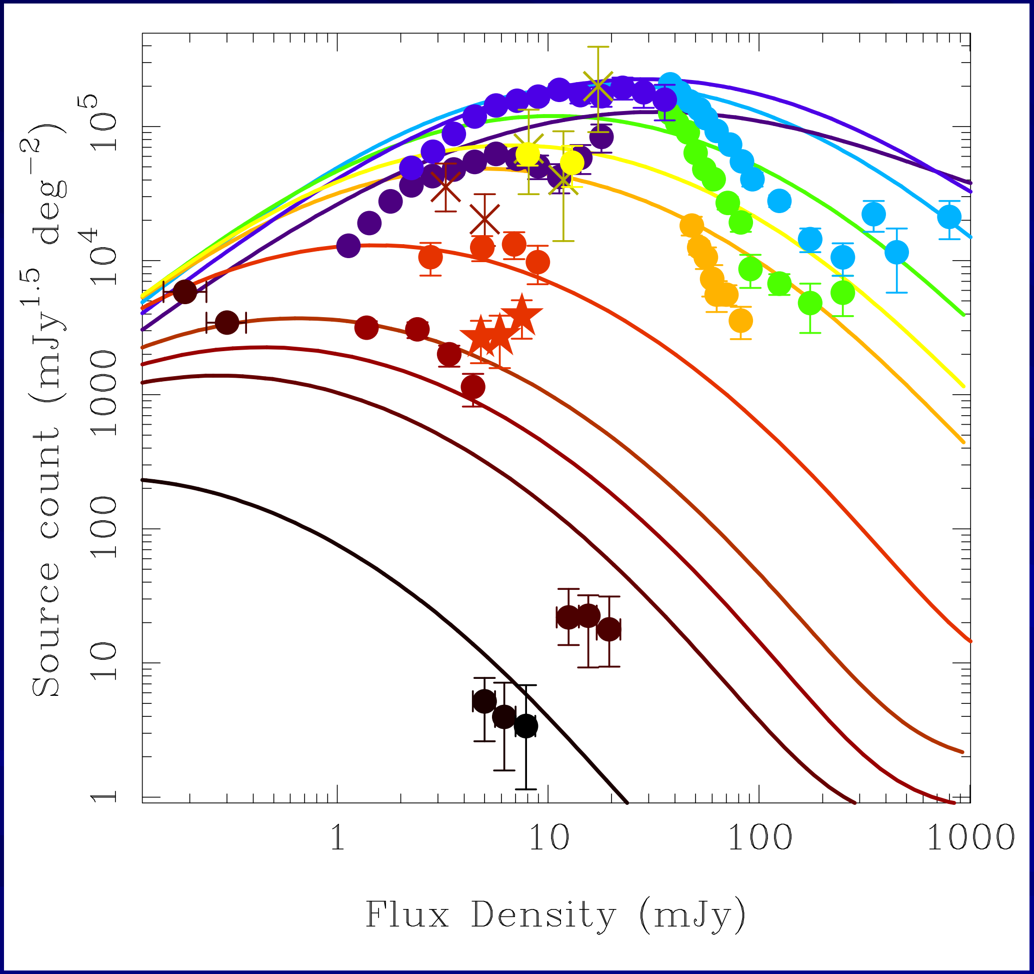
Jarrett et al. NEP





Stern & Eisenhardt

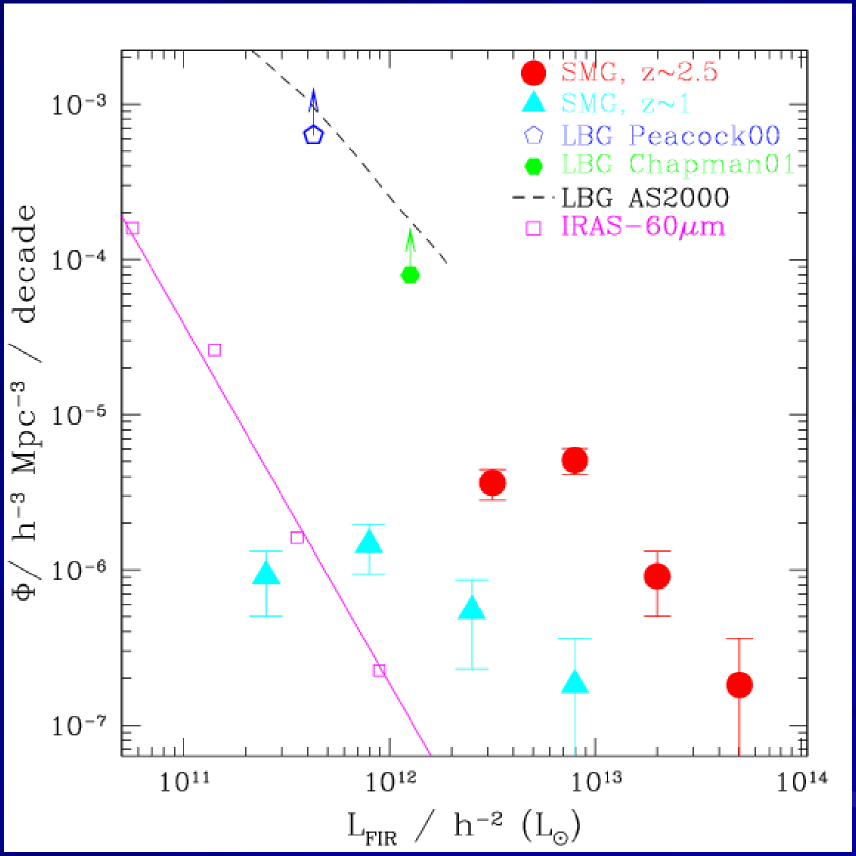
Included a wider range of data



- SPT included, subtracting non-thermal sources
- 1.3mm ALMA from Hatsukade, no errors as not really secure, but gives a hint
- Mm counts can be easily tweaked
- Maybe too few faint high-z 1.3mm objects
  - Interesting for using ALMA in larger samples
  - Deep ALMA counts should come from Cycle-1

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 see Spitzer LF results at z~1 for comparison
- Key goal is overall high-z LF

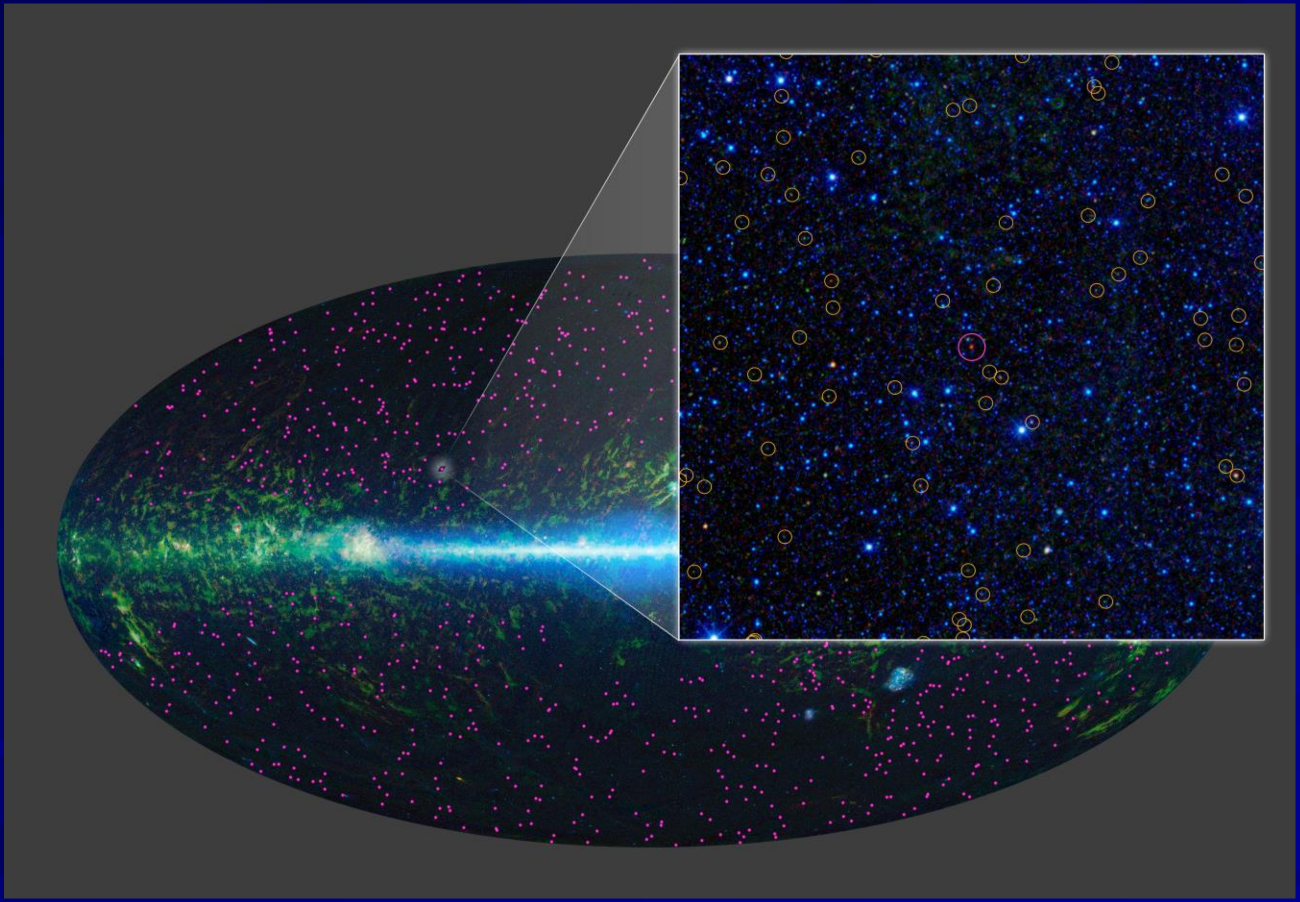


Chapman et al. (2005)

WISE selections

- W1/W2/W3 most sensitive bands
- W1/W2-W3 color – red is interesting ('dropouts' Eisenhardt)
- W1-W2-W3 color-color – isolate z~2 box
  - 'HyLIRG box' (Chao Wei)
- Adding W4 selection (Petty)
- R-W4 selection (DOGs – Yan)
- AGN color selection (~IRAC – Stern)
- These techniques work on extremes
- Also cross matching against other catalogs/surveys
  - NVSS, FIRST?, SDSS, 2XMM, GAMA, Herschel ATLAS, UKIDSS, SPT, galaxy cluster candidates…
  - These are a bit different, need full L3 depth

WISE-discovered ULIRGS



WISE Press conference Aug 2012

- Illustrates
  - W1-W2 drops
  - HotDOGs
  - 4 color shows:
  - R: W4/22
  - G: W3/12
  - B: W1/W2 (stars)
  - NB - Brown dwarfs

Key questions

- True luminosity function of galaxies
  - AGN/star formation
  - IMF evolution, metal production, Magorrian relation
- Nitty-gritty process of galaxy formation
  - Gastrophysics
  - Do bulges form in collapse or mergers?
  - Accretion from 'cold streams' (Birnboim/Dekel)
  - Dynamical state of short-lived bursts
  - Activity takes place within molecular material
- Big picture not complete without ability to assign bolometric luminosity galaxy by galaxy
- What drives the highest peaks of activity?
- Multiplicity of sources when observed with ALMA

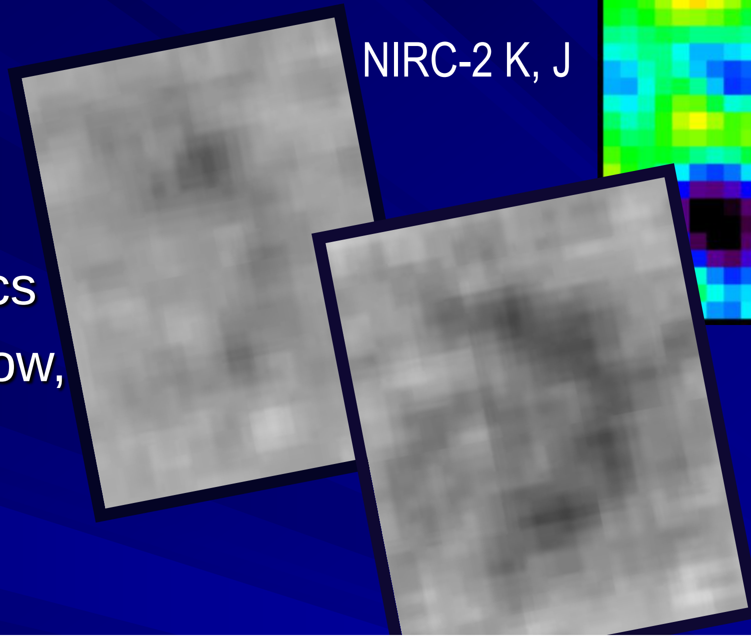
Resolved case

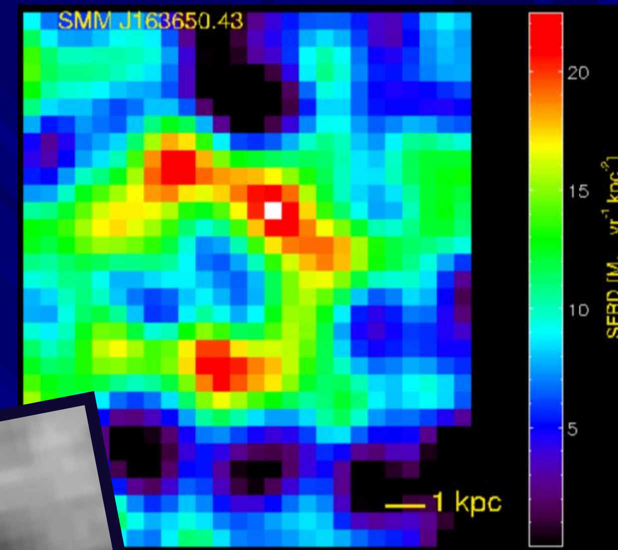
Karin Menendez-Delmestre

- Keck OSIRIS R~3400 (0.05” pixels)
- Laser AO resolution
  - 2D-resolved dynamics
  - Separate broad/narrow, compact/extended emission,
  - AGN, Hα, stars

0.25 arcsec square

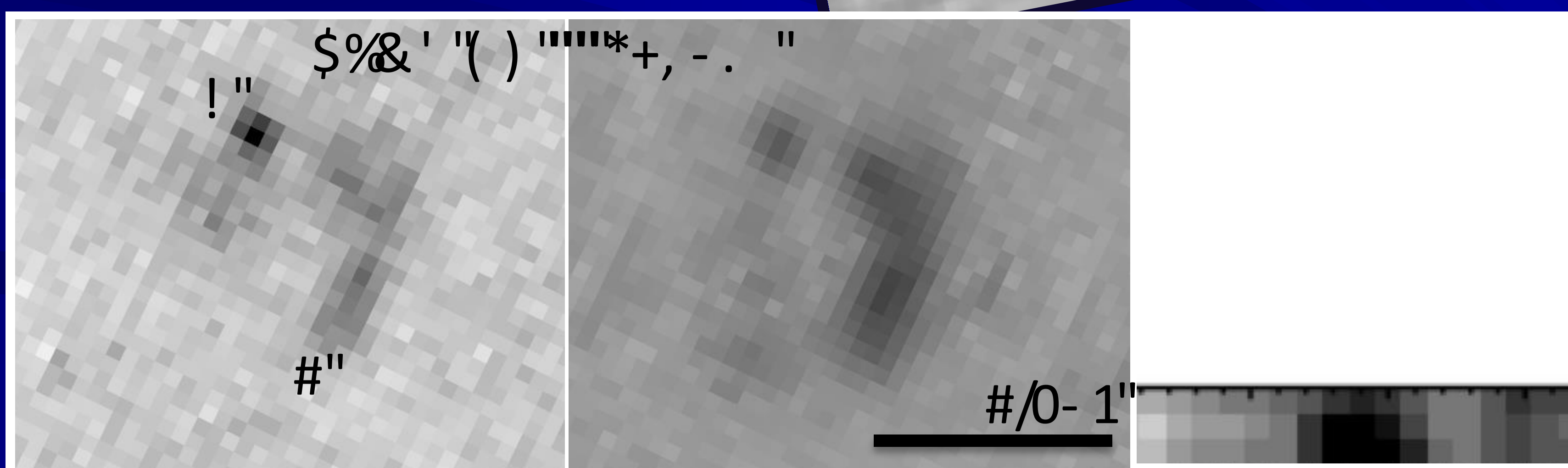
NIRC-2 K, J





SMM J163650, z=2.38

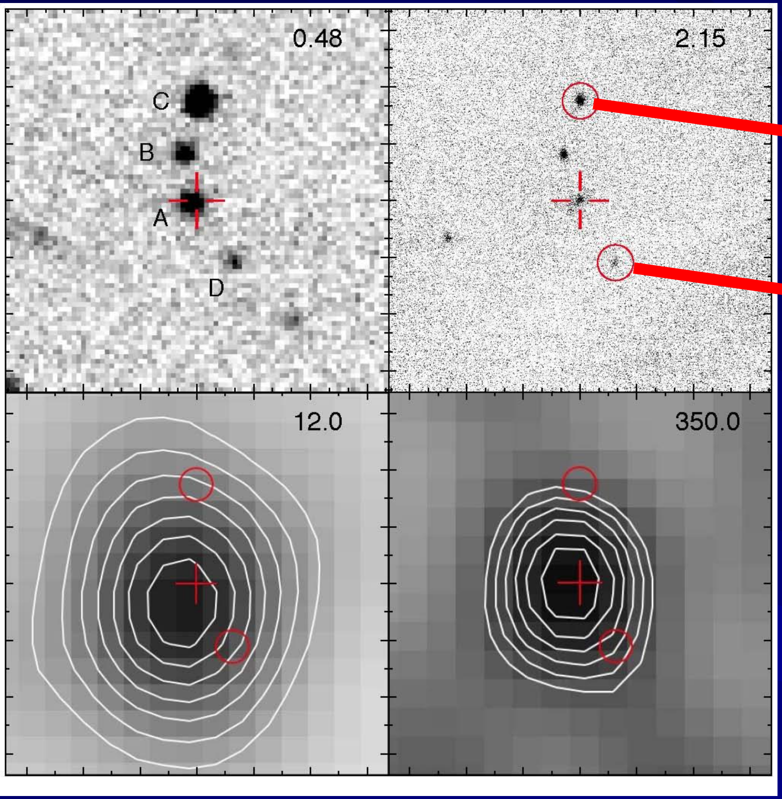
1: Broad (2000 km/s)
0: Narrow (500 km/s)



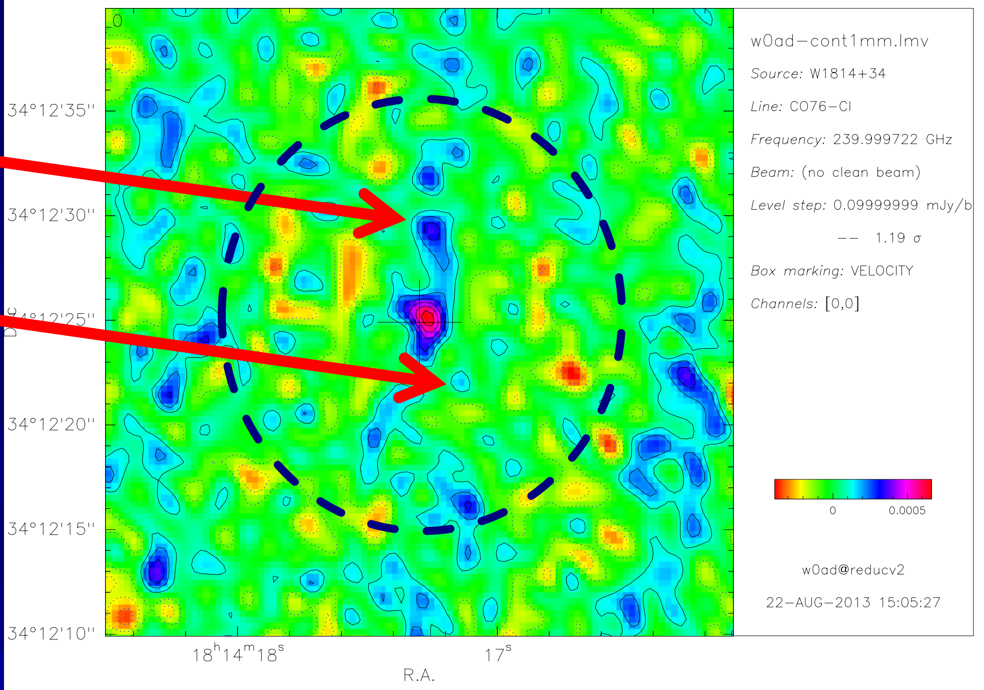
Targeted WISE follow-up

- Select interesting sample ~100's
  - 2-m's, 4-m's, MMT, Keck, SALT…
- Preselect even more interesting handfuls
  - eVLA, ATCA, CSO, IRAM, Herschel…
- This isn't complete or exhaustive
- Find lots of obscured AGN, some mainstream AGN, messy extended objects containing AGN. Lyman-α emitters
- Dust properties are unusual – hot F15307

IRAM image of W1814



Keck z=2.54, optical, near-IR AO
WISE 12, CSO SHARC-2 images

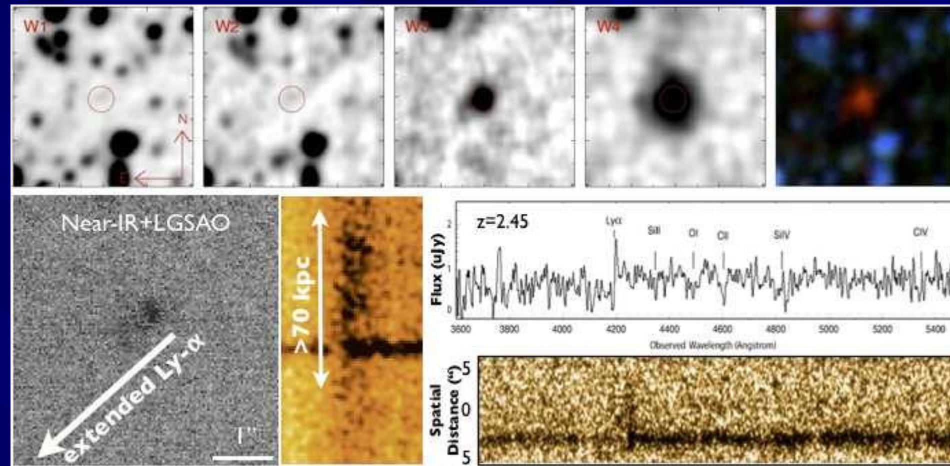


IRAM PdBI, ultrared A is dominant at 233GHz,
not broad-line AGN C. Mystery D positive flux

- WISE "HLIRG"
- Very clear SED
- Complex – an AGN & dustier object
- Too far North for ALMA

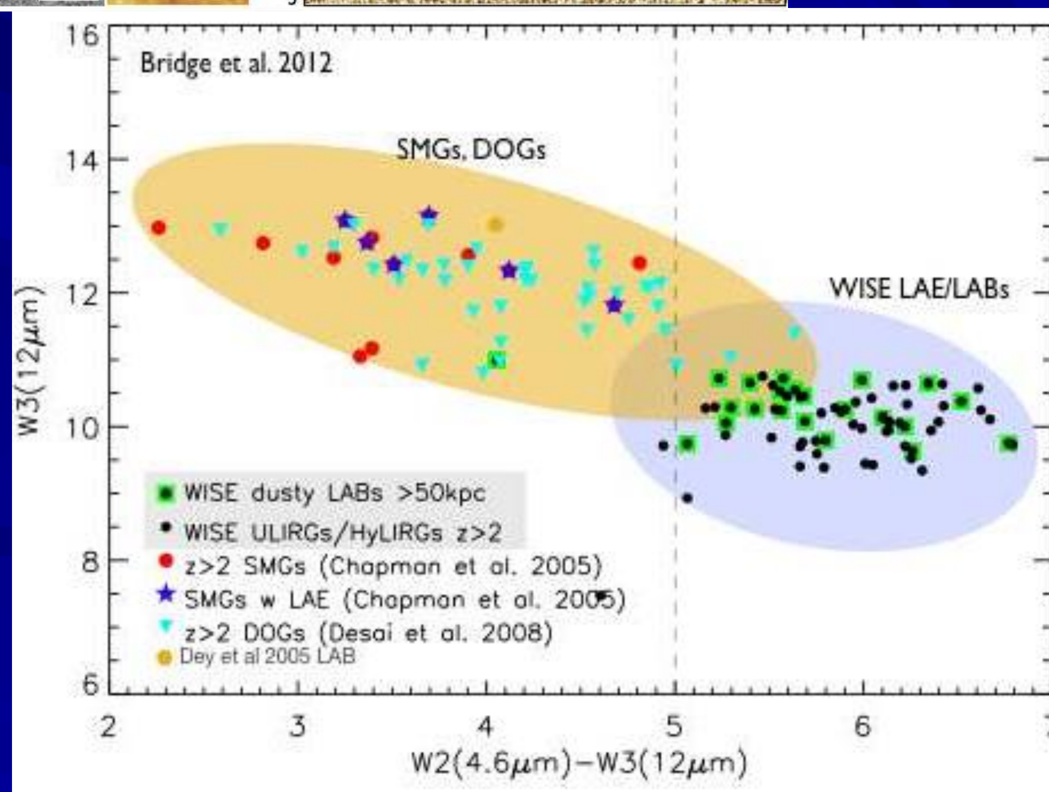
WISE Lyman-α blobs (WLABs)

- Follow-up spectra of hot dusty WISE ULIRGs at z~1-5
  - Bridge, Blain et al.
  - ApJ submitted
- Unusually large No. of large (~50kpc) LA emitters
  - Including Eisenhardt’s first WISE `HyLIRG’
- WISE colours alone can select ~1000
  - Red, bright in WISE
  - No other selection finds dusty LABs
  - Feedback in action?



Top: WISE Bands, Bottom: NIR image & Spectra

Bridge et al.



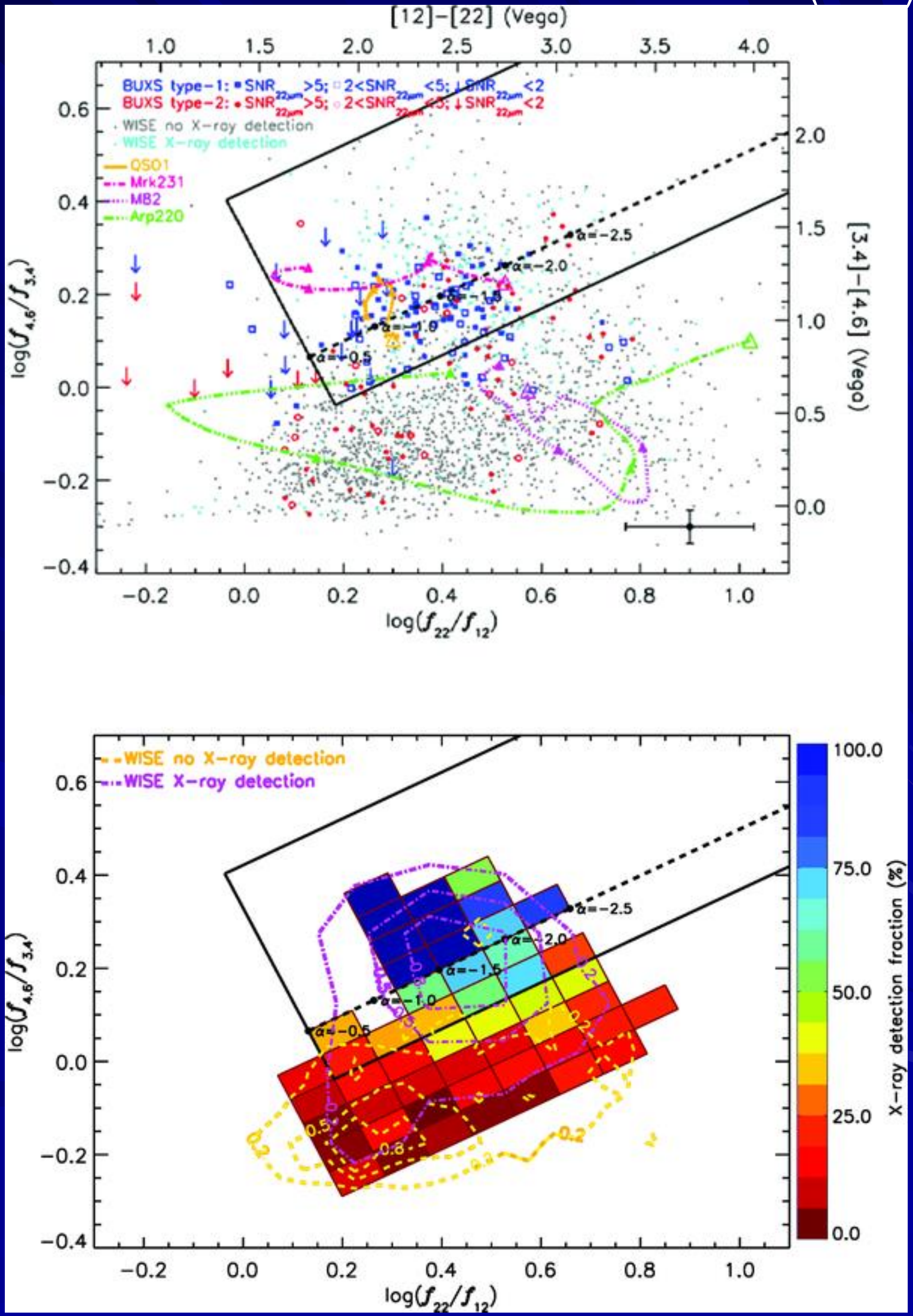
LABs: influencing environment

- Key ideas
  - Kennicutt-Schmidt law for star formation over 0<z<3; Halpha at z~2, CO at z~0 and z>1
  - Feedback recipes to keep red galaxies dead
  - `Cold flow' inflows, 1000km/s outflows in atomic and molecular gas >> v_{virial} or v_{rot}
- LABs could highlight some/all
  - 100kpc influence, energy to illuminate

WISE AGN Selection

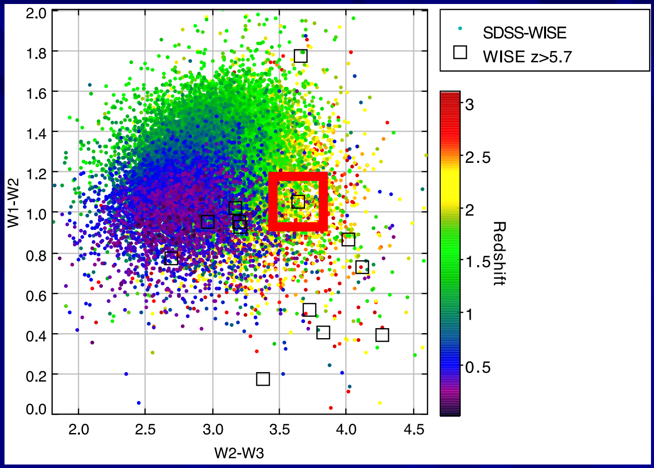
- Stern/Eisenhardt
  - COSMOS
- Mateos et al.
  - Trained using hard sample (2XMM)
- Assef et al.
  - Deeper Bootes sample
- Lots of spectra required
  - SDSS/2XMM

Mateos et al (2012)

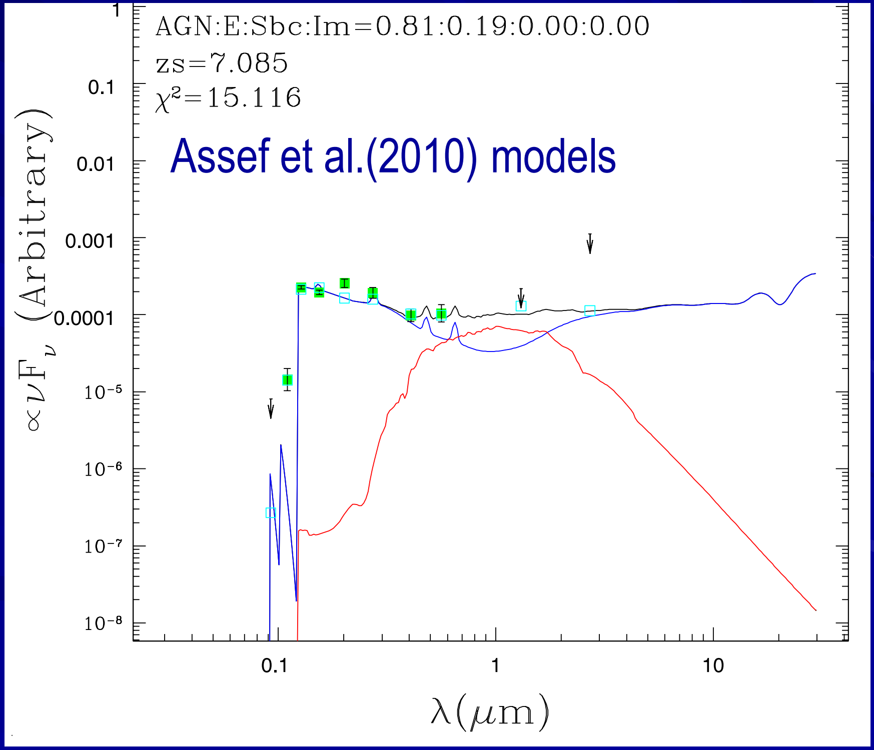


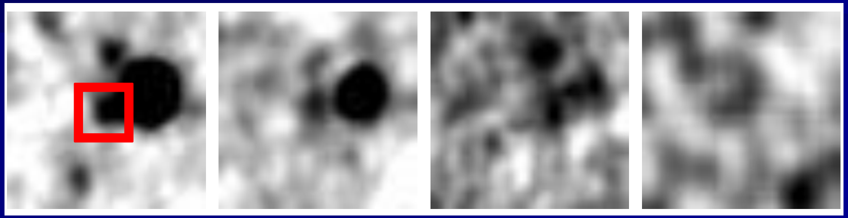
Highest z QSOs

- Individual targets.
  - SDSS, CHFTLS, **UKIDSS**, Spitzer
  - ~25 found over the sky
  - WISE detects ~ 60%
  - Spitzer can also do, but WISE makes it free, and adds in 12 microns.
  - VISTA-LSST-WISE?



ULAS1120 from Mortlock et al. (2011)



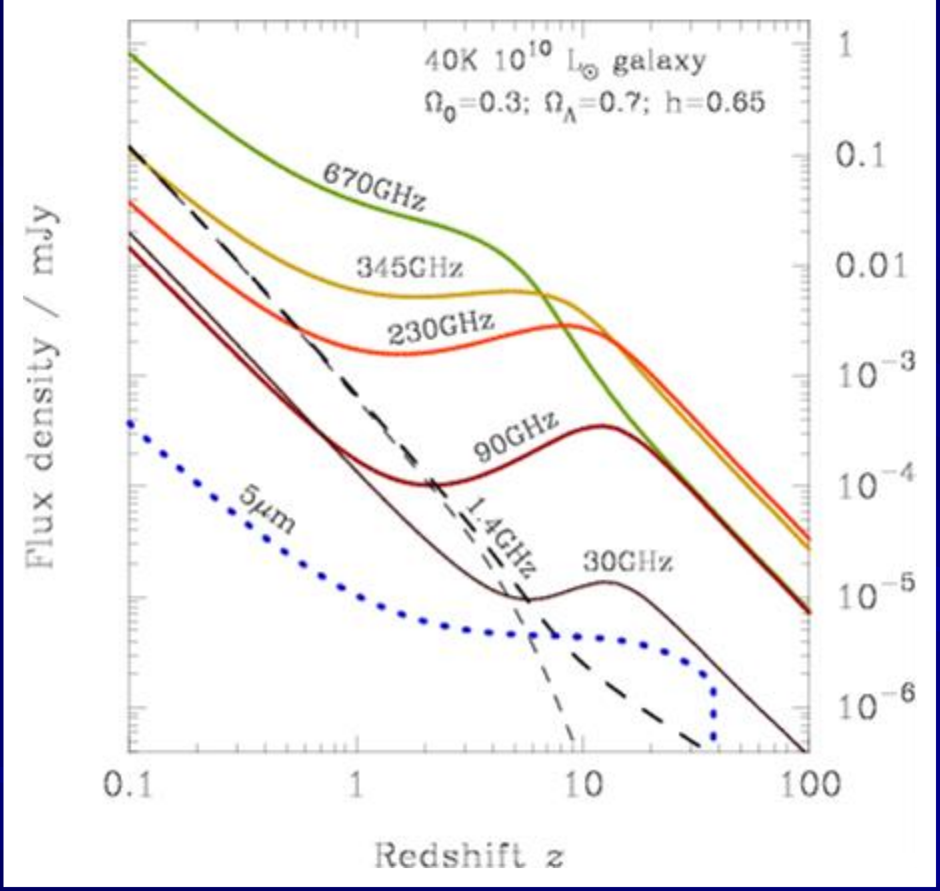


W1-W4; 1 arcmin

ALMA is a BIG step forward

- Resolved imaging spatial and spectrally
  - – HST and AO IFU rolled into one
- Probes most (all?) of active ISM gas
  - – Masses, non-virialised fraction, cf stars
  - – Timescale, likely immediate evolution
- Winds and outflows clear by comparison with 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

Mm/cm emission from ***high*** z

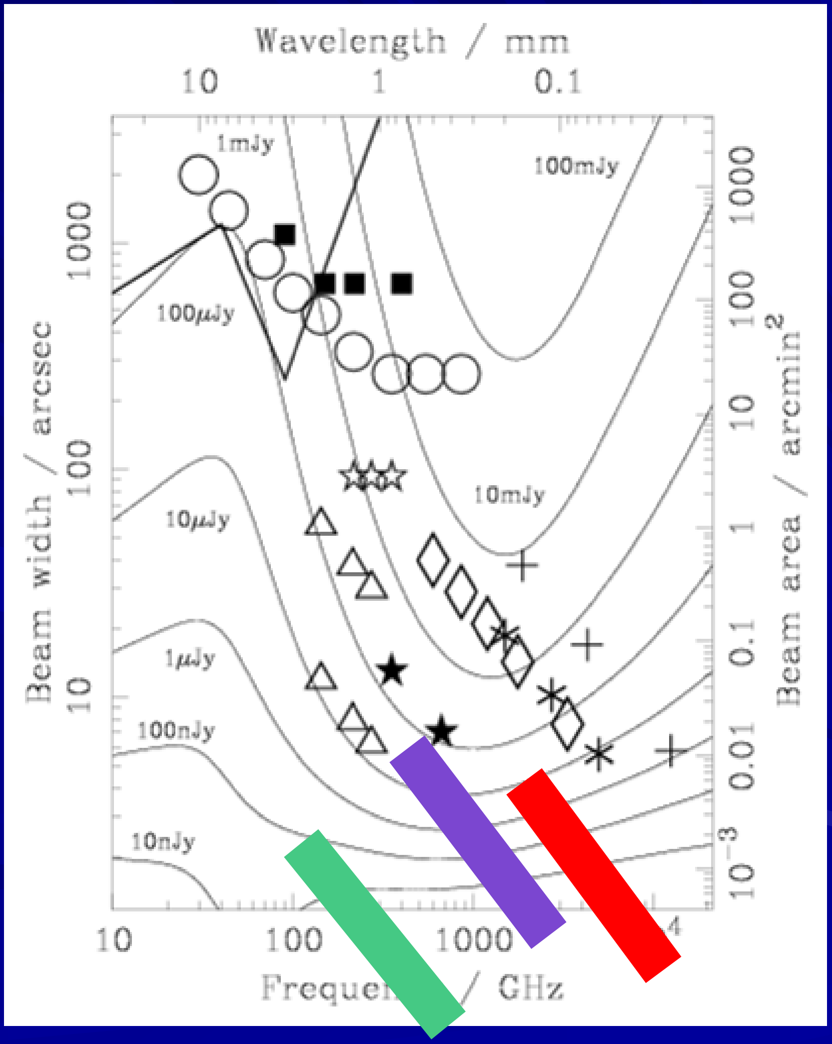


Blain et al. (2002)

- Issue only for ALMA
- K-correction ceases at highest z when CMB is included
  - CMB sets minimum T
  - CMB scattering suppresses radio synchrotron emission
  - free-free (not synchrotron) emission then dominates
- (sub)mm observations become less interesting at z>10 (even if dust is present!)
- At the highest redshifts:
  - need ultradeep cm-wave radio and near-/mid-IR imaging?
  - Not mm/submm continuum observations
  - Atomic and H_2 emission

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 10m in space 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”



WISE data releases

- References
  - wise.ssl.berkeley.edu/astronomers.html
  - Wright et al. AJ 140 1868
- 55% of sky released less than 6 months after end of data acquisition
  - Actually ahead of this May 2011
  - Last data Feb 1 2011 UT
- Final release 18 months after – March 14 2012
- NASA Planetary NEOWISE mission enables single frame data
- Now (yesterday) NASA ALLWISE project has produced `final' catalogue – Nov 13 2013. Announcement due.

Summary

- The most luminous galaxies are far-IR bright at $2<z<6$
  - Not currently well connected to the mainstream star-forming galaxies there
- Can be found in optical/near-IR/mid-IR/radio/X-ray; however,
  - Measuring true luminosity **requires** rest far-IR data
- Surveys with SPT, *Herschel* and *WISE* are yielding 'extremes'
- ALMA crucial for very deep imaging to reveal molecular astrophysics
  - Provides insight into universal (optical/radio/FIR) galaxy luminosity function object by object, for key examples, and within existing deep fields
  - Ultimately, space-borne spectroscopy will reach far-IR at redshifts where ALMA is blocked by atmosphere. 2030+ Interferometry.
- ALMA's efficiency will benefit from large area surveys – Planck, WISE, SCUBA-2, and CCAT: all lead by detector technology
  - But depth limited by confusion
  - CCAT alone can connect to L^* galaxies found in other wavebands over a fair sample of cosmic volume