A Panchromatic Overview of Starburst Galaxy Evolution

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SMITH COLLEGE

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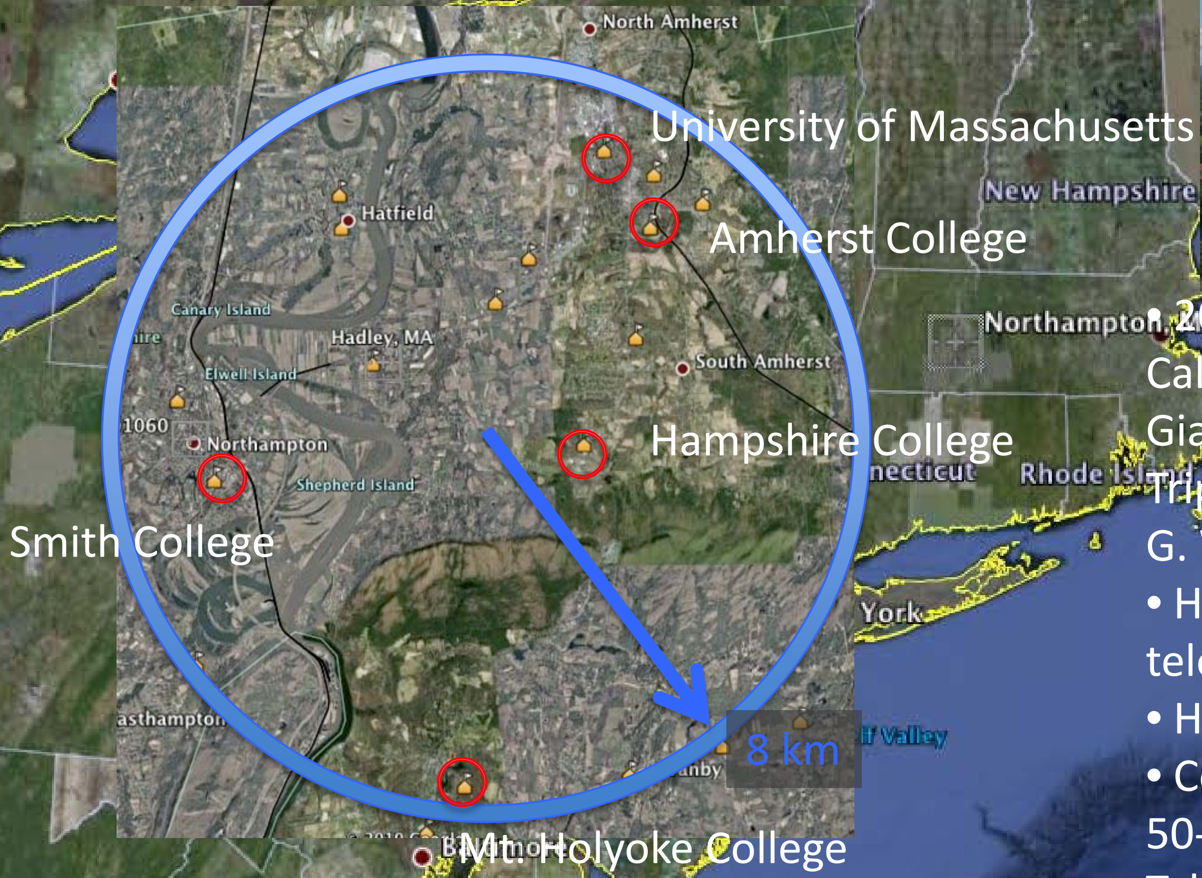
The “punch lines”

More than 10% of star formation in galaxies selected in UV, optical, and IR is in starbursts

- Lyman break galaxies at z~3 are starbursts with *wide range* of morphologies + masses but masses uncertain
- LBG analogs at z<1 (LCBGs) also show wide variety of morphologies, low mass, maximal SF, strong evolution
- ULIRGs at z<1 (usually dusty merger starbursts) are bluer and brighter in optical than “blue cloud” field galaxies, can evolve to middle of red sequence
- Submm galaxies at z>2 are strongly evolving, ULIRG-like, clustered, dusty starbursts, broad range of z

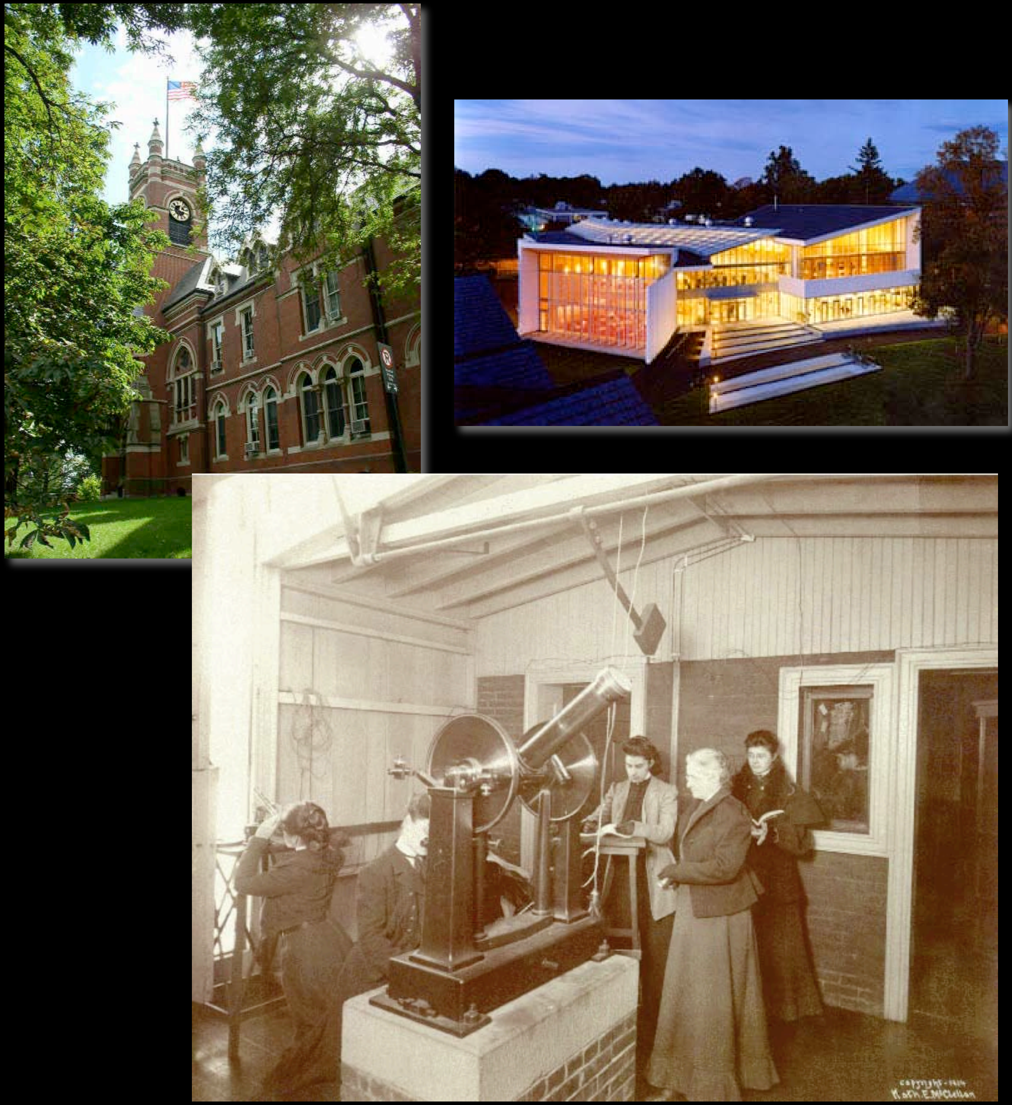
Smith College/Five College Astronomy Department



- 20 faculty, including D. Calzetti, S. Edwards, M. Giavalisco, N. Katz, H. Mo, T. Tripp, D. Wang, M. Weinberg, G. Wilson, M. Yun (A. Pope)
- Home of FCRAO 14-m telescope
- Home of 2MASS
- Co-leading (with Mexico) the 50-m Large Millimeter Telescope/Gran Telescopio Milimetrico (LMT/GTM)

Smith College

- Founded 1871
- 2500 students, all women, all undergrad (B.A.), liberal arts
- The 7 sisters: Barnard, Bryn Mawr, Mt. Holyoke, Radcliffe (Harvard), Smith, Vassar, Wellesley
- 7 liberal arts (e.g., medieval Western university): grammar, rhetoric, logic, geometry, arithmetic, music, astronomy
- Private, but supports 70% of students with financial aid; 25% are first-generation college students
- Alumnae: Julia Child ("Mastering the Art of French Cooking"), Gloria Steinem, Sylvia Plath, Madeleine L'Engle, Nancy Reagan, Barbara Bush, Julie Nixon...
- Astronomy Department: JL and Suzan Edwards (YSOs, SF, protoplanetary disks)



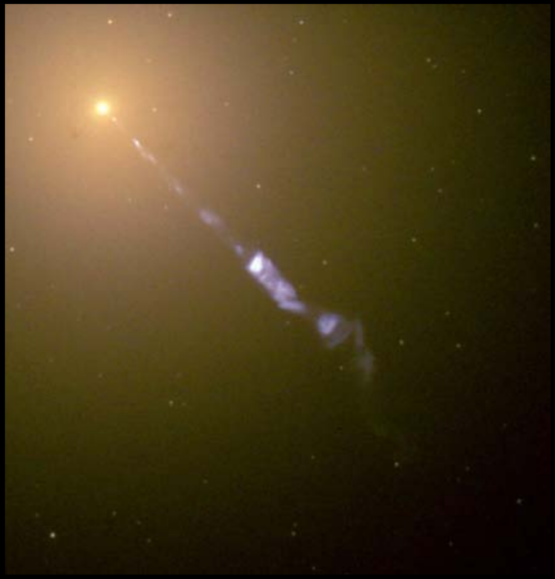
Motivating Questions

How and when do galaxies form and evolve?

What role do starburst galaxies play in those processes?

NGC 1300

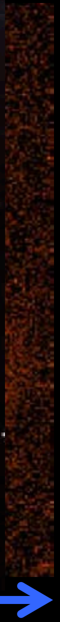
M87



What is a Starburst Galaxy?

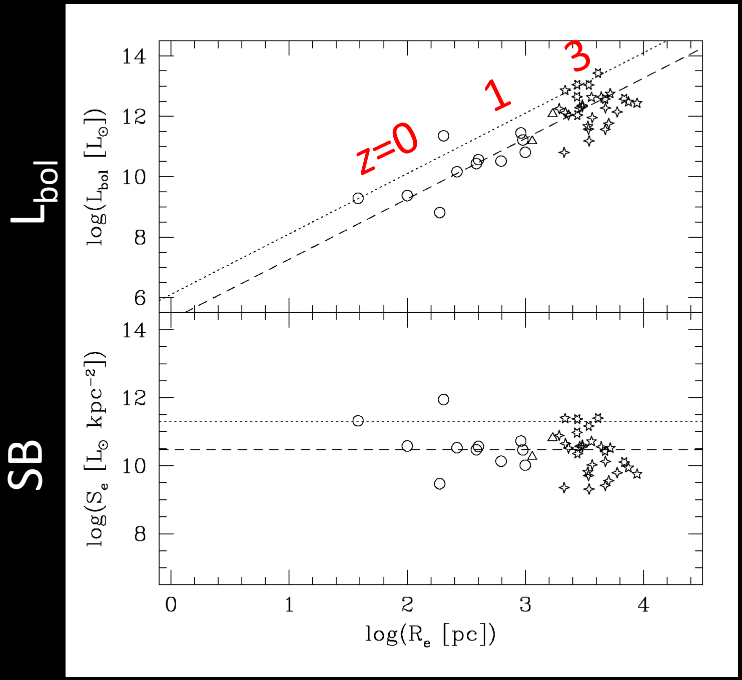
- M82, HII galaxies, ultraluminous inf galaxies (ULIRGs), break galaxies (LE

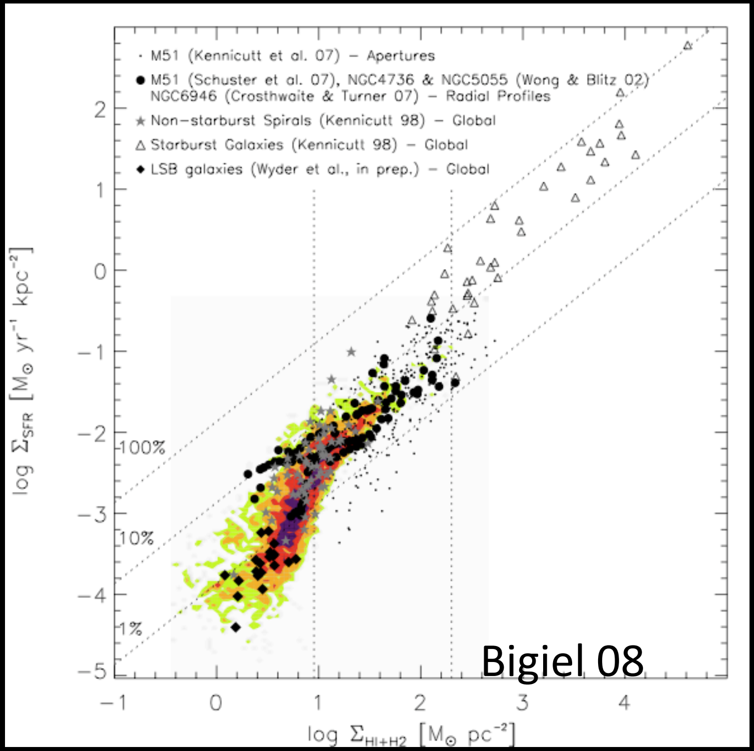
- Note huge range mass, luminosity, morphology, phys conditions, enviro



90 kpc ULIRG; Borne

Star formation in starbursts





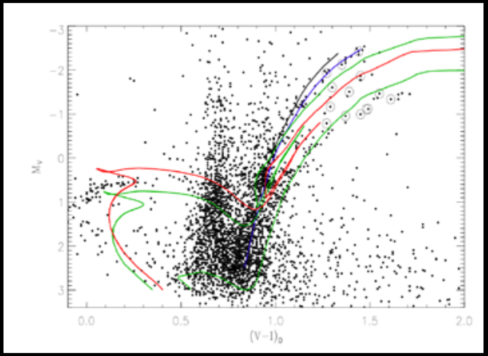
Bigiel 08

- SBs have extreme
  - specific star formation rate (SSFR) = SFR/M
  - star formation efficiency = SFR/M_{gas}
  - surface brightness
- SB's obey Schmidt-Kennicutt, but with different mode (low SF, high SFE) of SF than in non-SB galaxies? (BzK's: Daddi…)

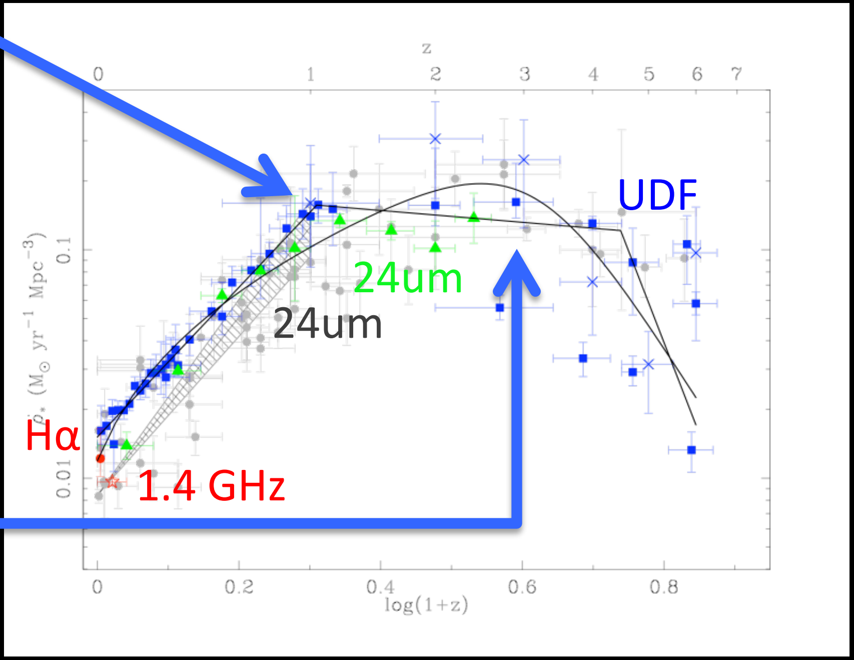
How important are starbursts in galaxy formation and evolution?

Some hints:

- optical z<1:
  - Multiple SF episodes in stellar pops
  - 10x rise in SF to z=1: 40% due to low-mass SBs (“downsizing”)
- optical z>1: LBG, sBzK: SFR~10-100 $M_\odot$/year; LF provides enough for >10% of current stars in galaxies (esp. if dust correction is large)



Smecker-Hane

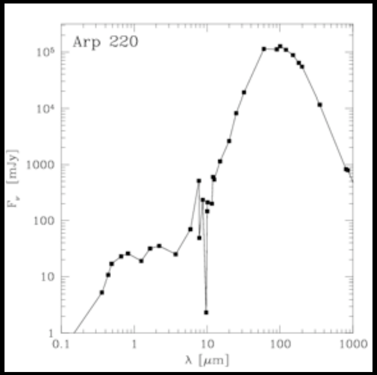


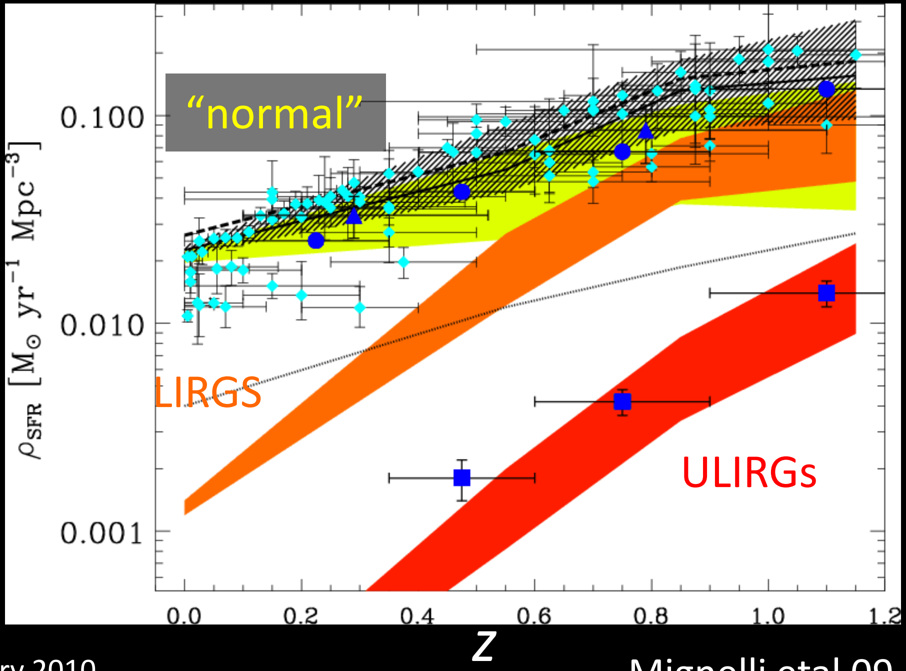
Hopkins & Beacom 2006

How important are starbursts in galaxy formation and evolution?

More evidence:

- infrared z<1: ULIRGs SFR~1000 $M_{\odot}$/year; rare today, but strongly evolving (100x more at z=1)
- infrared z>1: SMGs SFR>1000 $M_{\odot}$/year; similar to UV selection (LBGs) in total SFRD

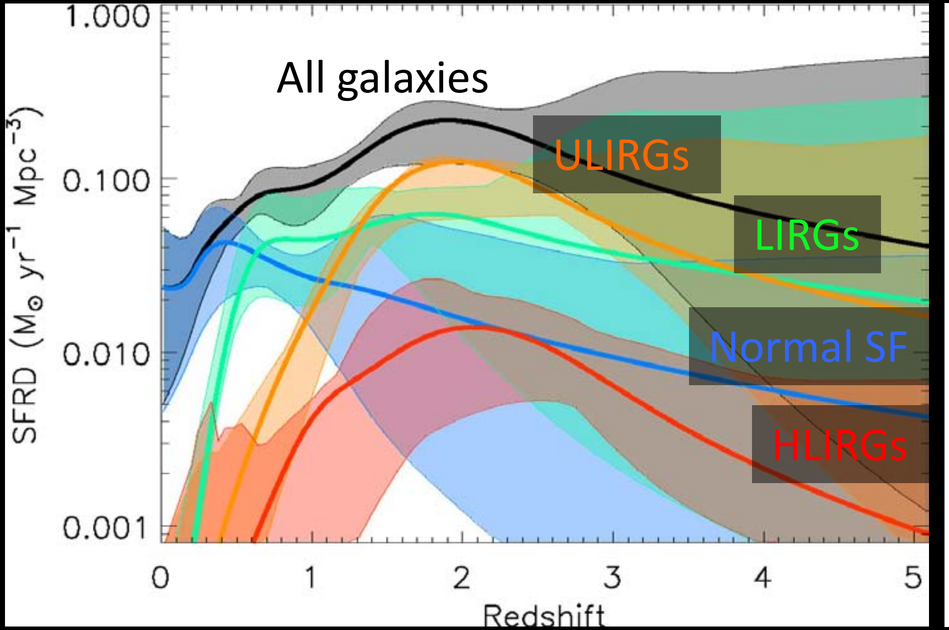


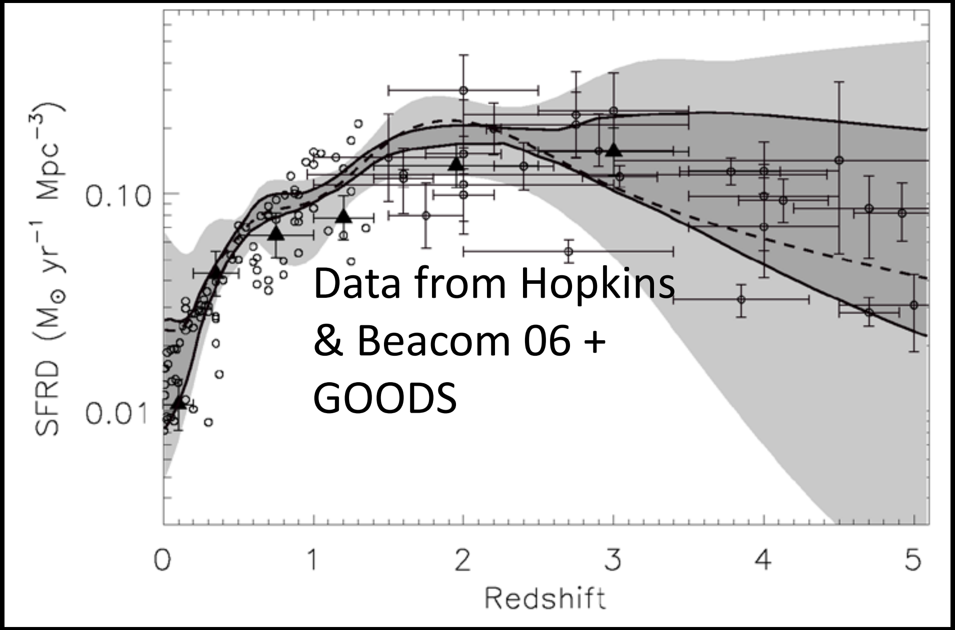


Mignelli etal 09

How important are starbursts in galaxy formation and evolution?

Infrared:





Data from Hopkins & Beacom 06 + GOODS

Le Borgne 09

At z>1, ULIRGs and LIRGs dominate normal star-forming galaxies

Four views of Starburst Galaxies

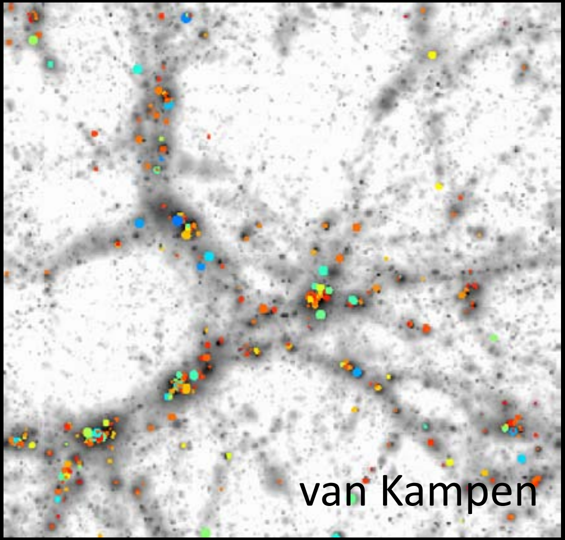
- Lyman break galaxies (LBGs) at z~3
- Luminous compact blue galaxies (LCBGs) at z<1
- Ultraluminous infrared galaxies (ULIRGs) at z<1
- Submillimeter galaxies (SMGs) at z>2

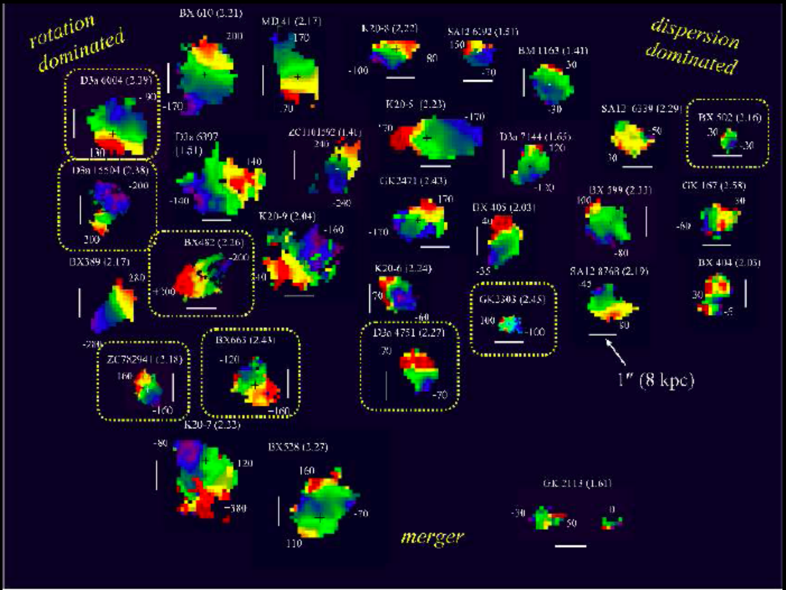
I. Dynamics of LBGs at z≈3

- What are masses of LBGs? Crucial info for interpreting role of LBGs, eventual fate, comparison to GF models.

- Can get stellar masses from stellar pop fitting, e.g. Erb, Shapley, w/ HST, Spitzer
- Can get dynamics for bright gal's z<2 (e.g. Förster-Schreiber, Genzel VLT/SINFONI IFU; Law 07; Erb 07)
- Can measure clustering to estimate total halo mass (Adelberger, Steidel)

But: total masses, detailed study of fainter LBGs at higher redshift still elusive.

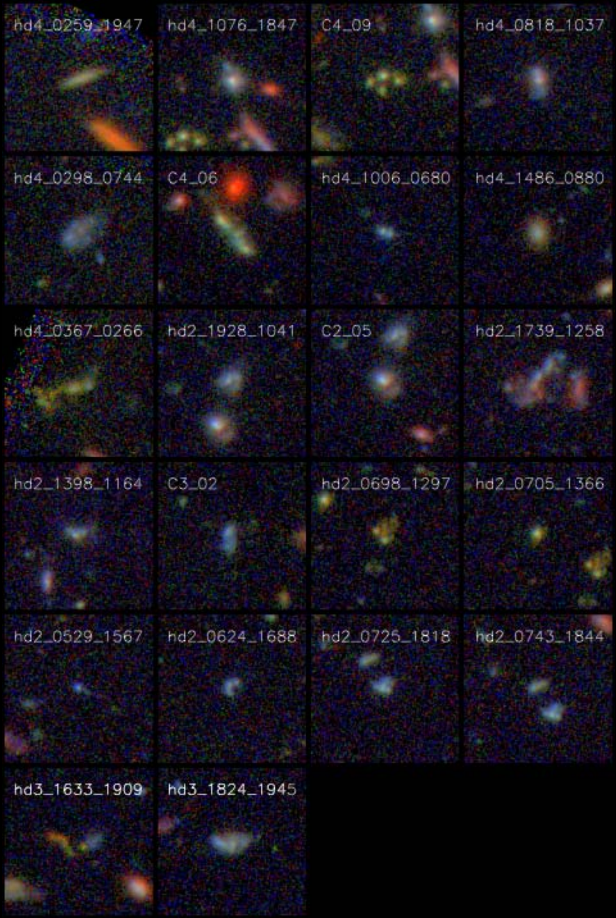

van Kampen



Förster Schreiber

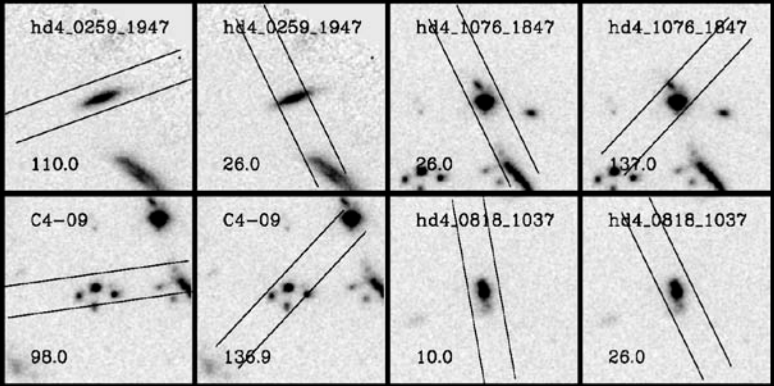
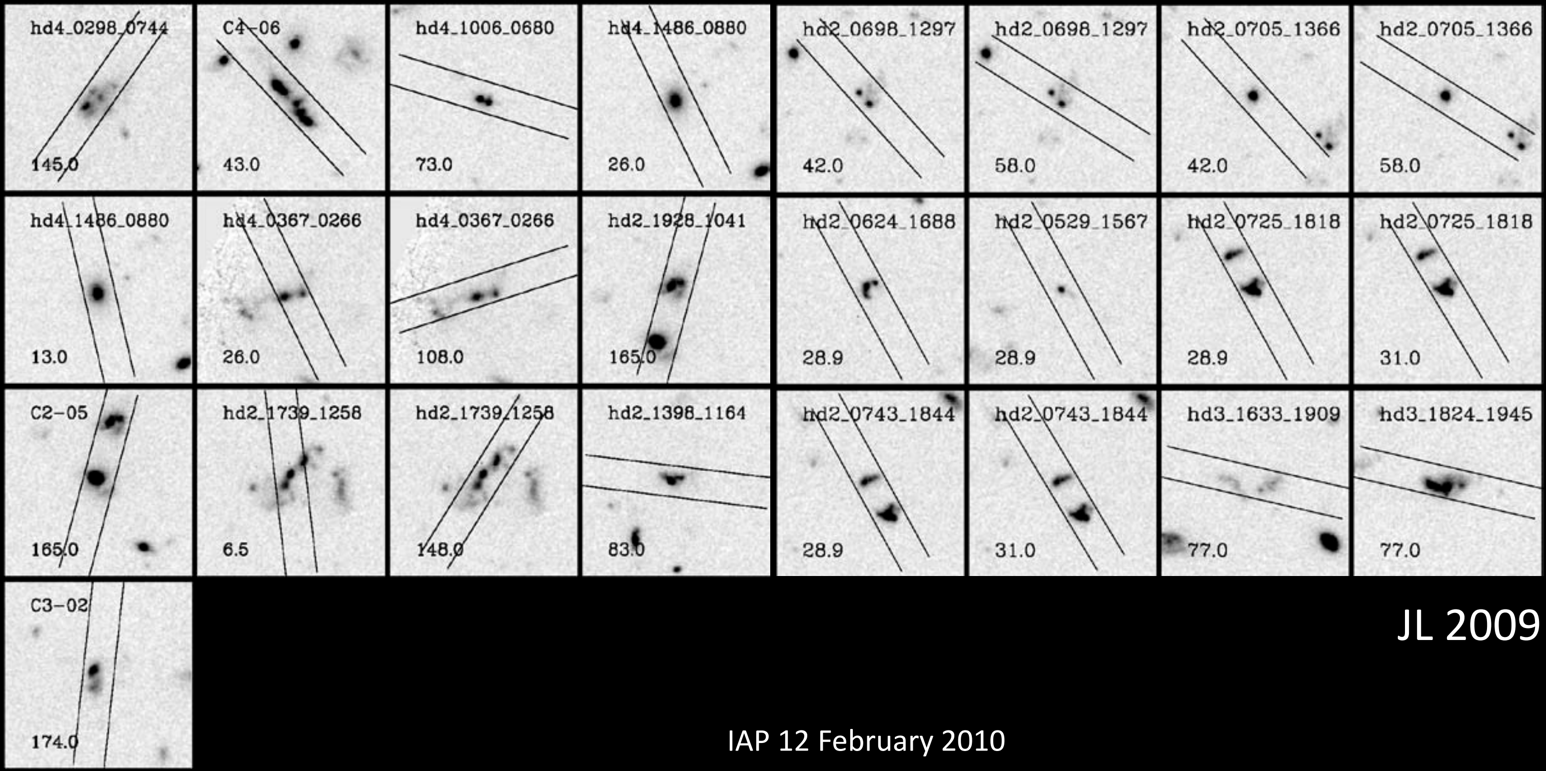
LBG kinematics

- Project: Try long, deep, spatially-resolved spectra with Keck + LRIS slitmasks of most promising LBGs
- Choose HDF targets with best chances of showing kinematics: clumpy, elongated, multiple.
- Sample: 14/22 targets used, median $I_{814}=25.3$, $2<z<4$
- Data: 10-50 ks, tilted slits, 300 km/s FWHM
- With Koo, Simard, van Kampen



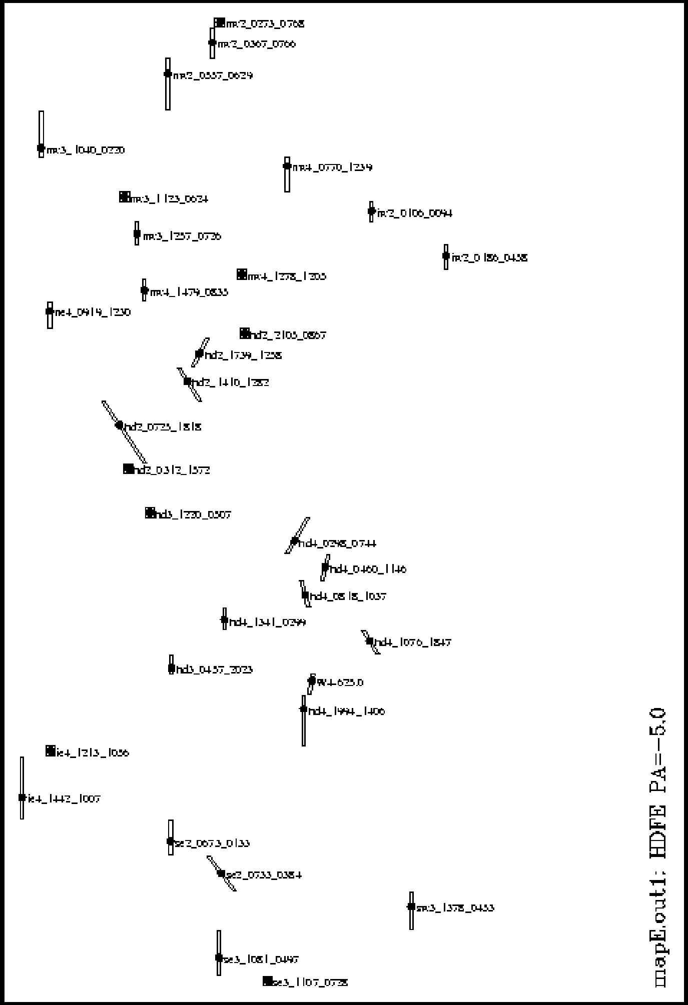
JL 2009

Keck/LRIS + tilted slits

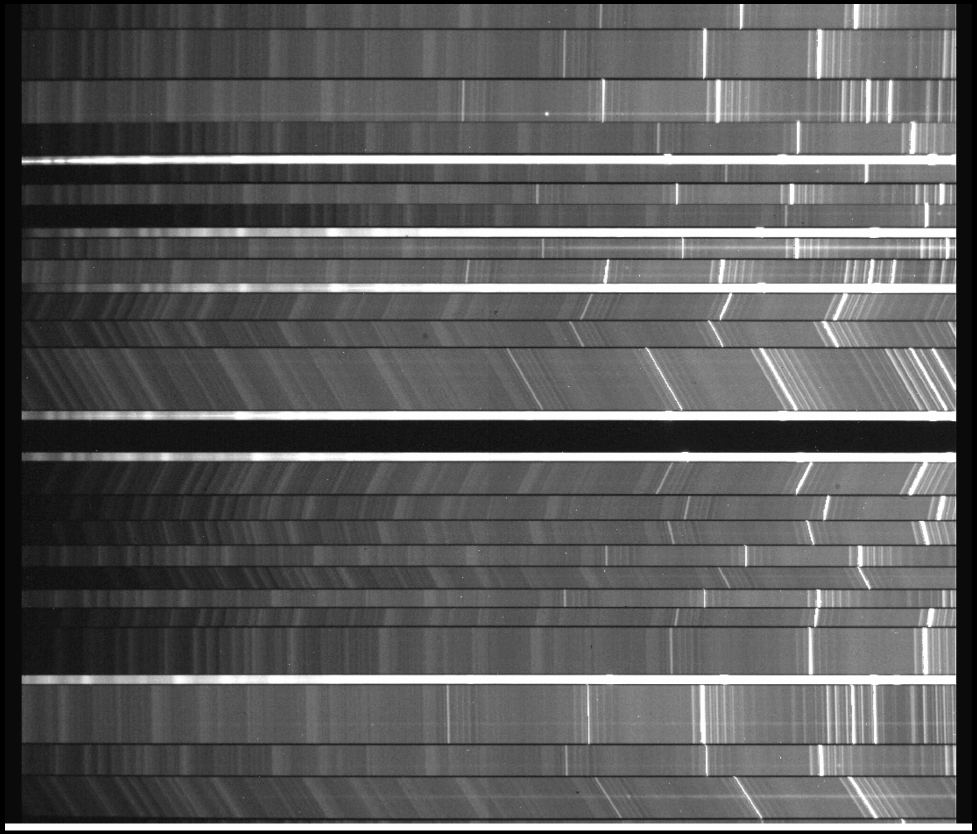



JL 2009

Keck/LRIS + tilted slits

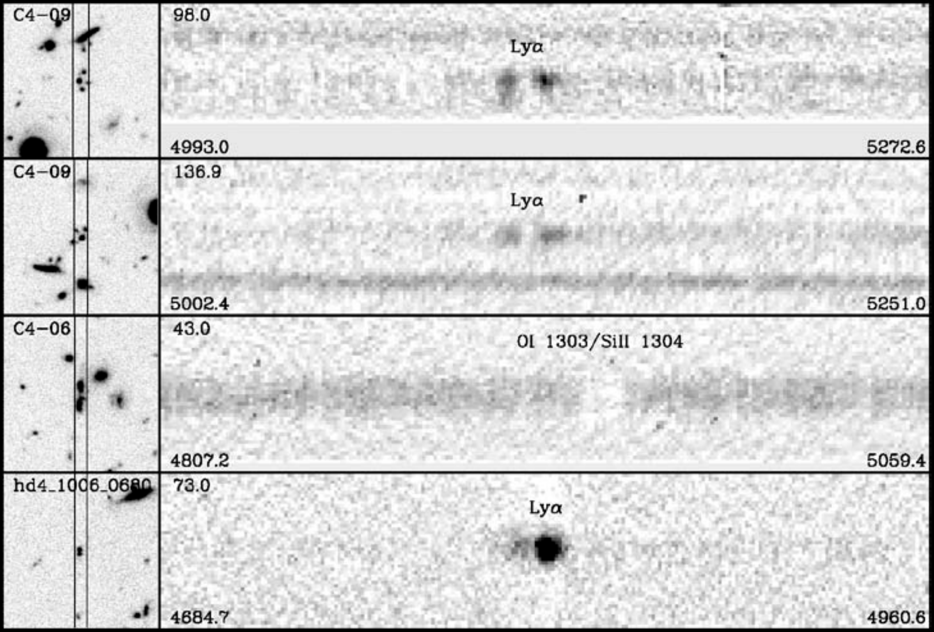


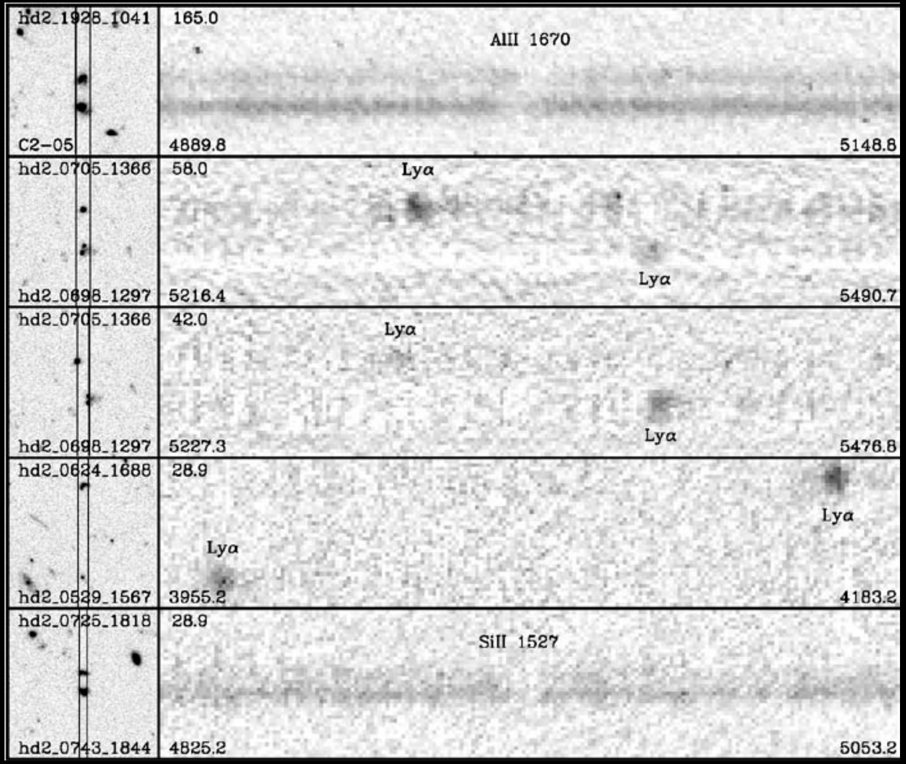
Slit mask (1/8)



Single 2400-sec frame

Extended kinematic features





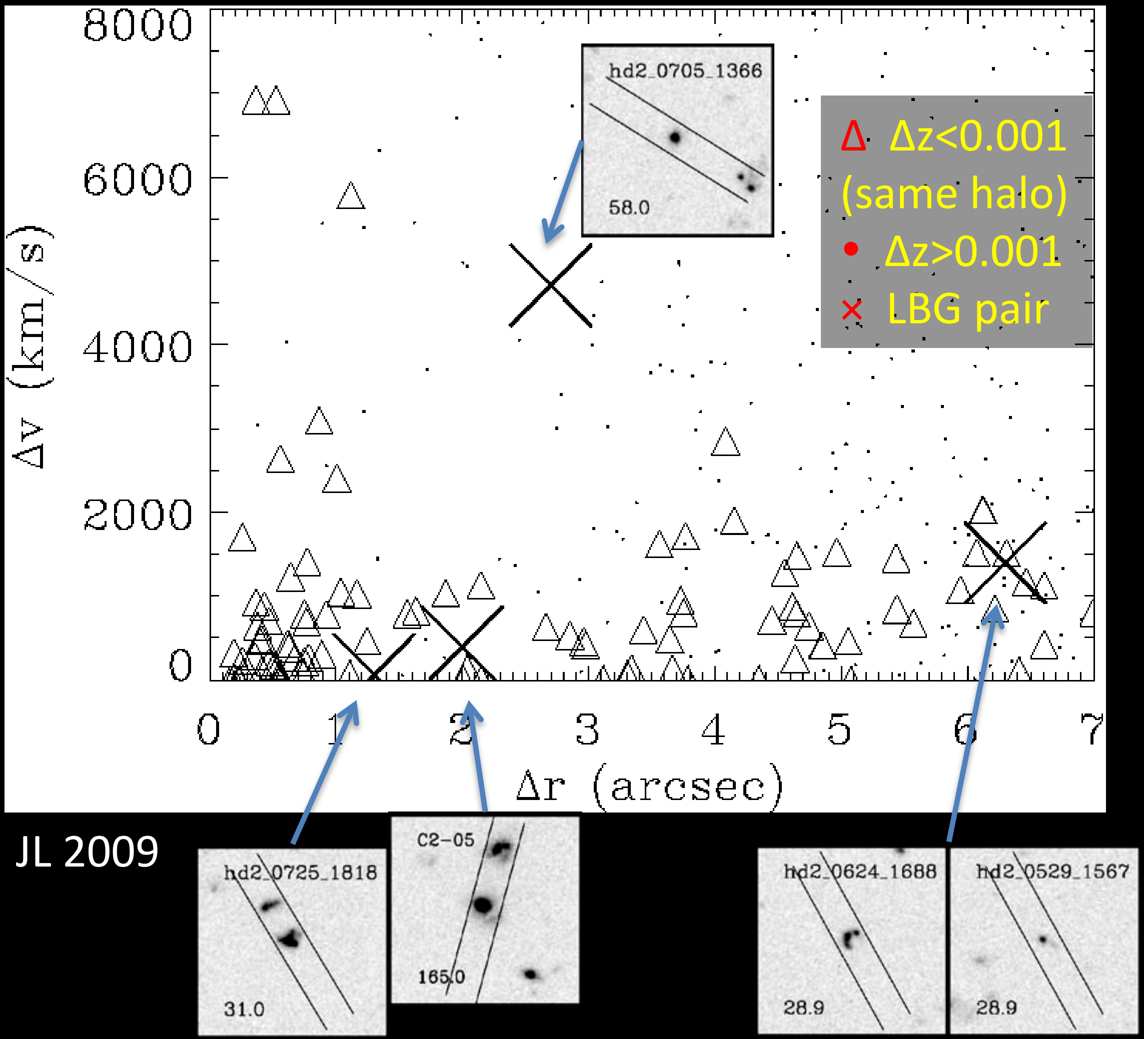
10” ~ 80 kpc

250 Å ~ 15,000 km/s

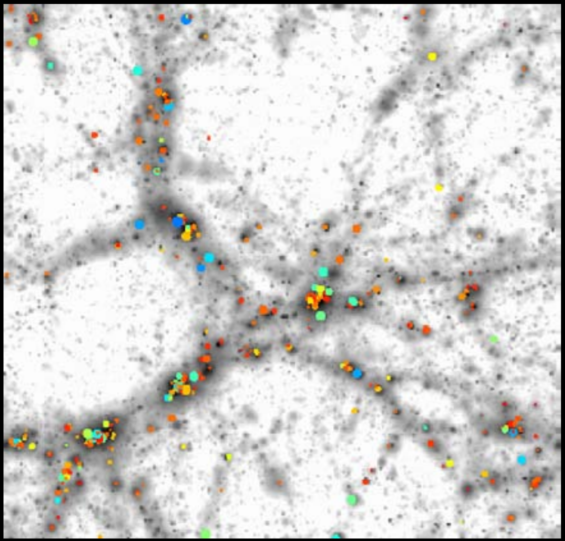
JL 2009

- Lya: double emission from close pairs/multiple knots
- Extended continuum: (Inter)stellar absorption lines
- No sign of rotating disks

Compare 4 close pairs to semi-analytic galaxy formation model

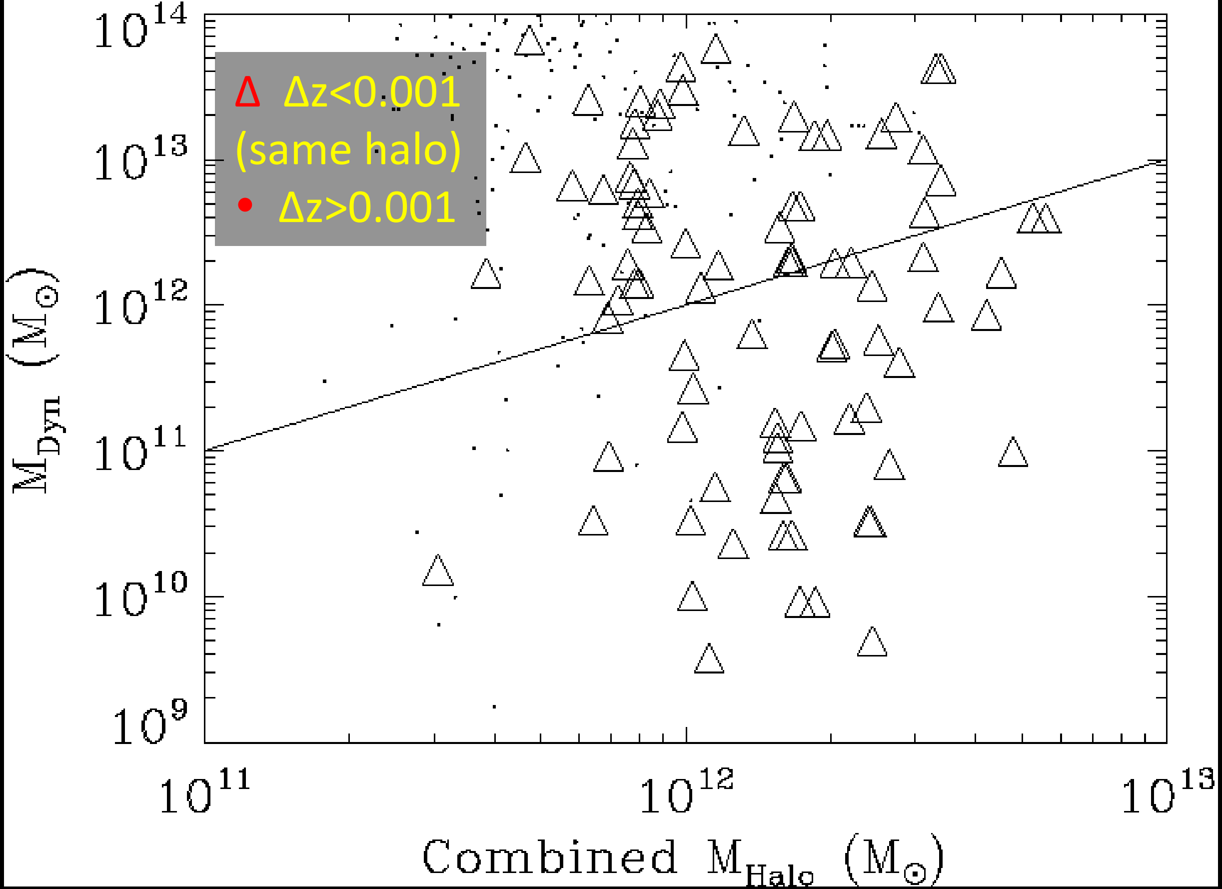


JL 2009



- “Observe” LBG pairs in SAM of van Kampen
- Find real Δr, Δv similar to model distribution

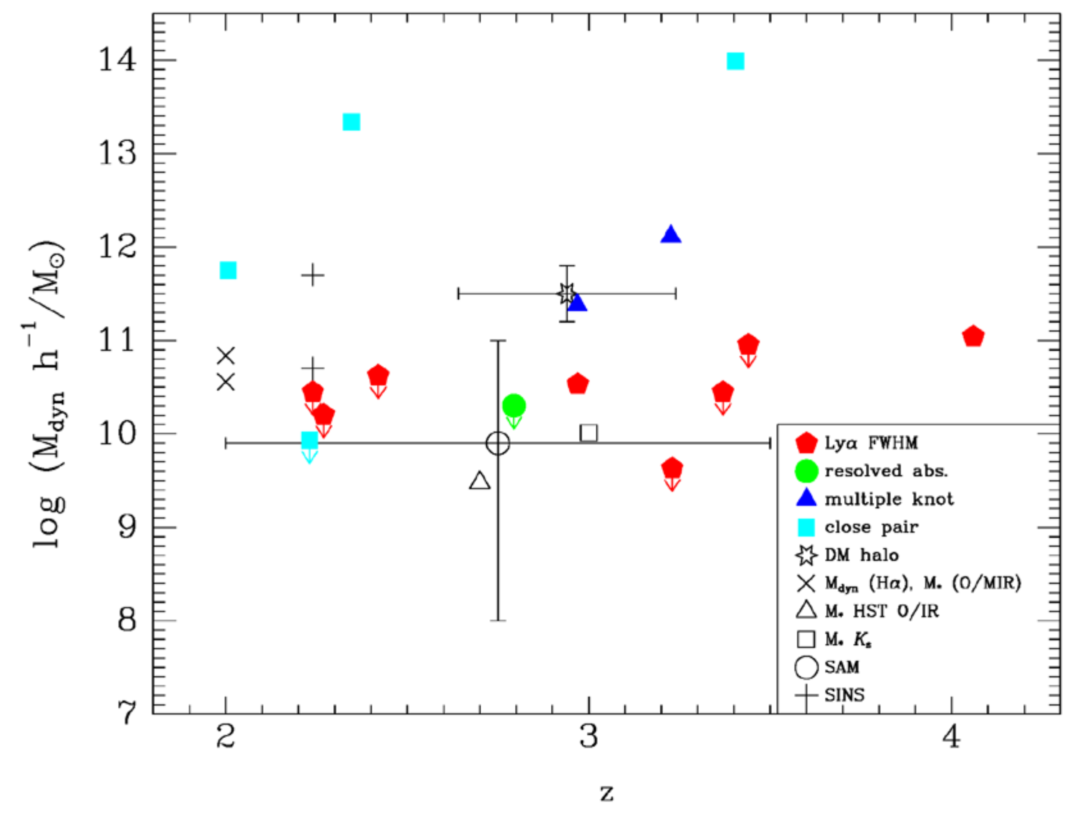
Do close pairs even yield halo mass?

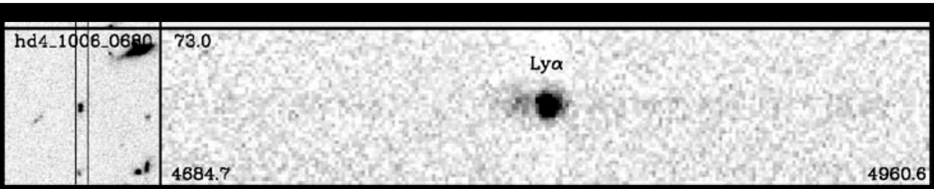


JL 2009

- Calculate $M_{dyn}=\Delta v^2 \Delta r/G$
- Surprise! no correlation between M_{dyn} and M_{halo} in model
- Proceed with caution in interpreting close pairs
- (cf Cooke '10: Lyα, interactions in pairs)

Estimated masses

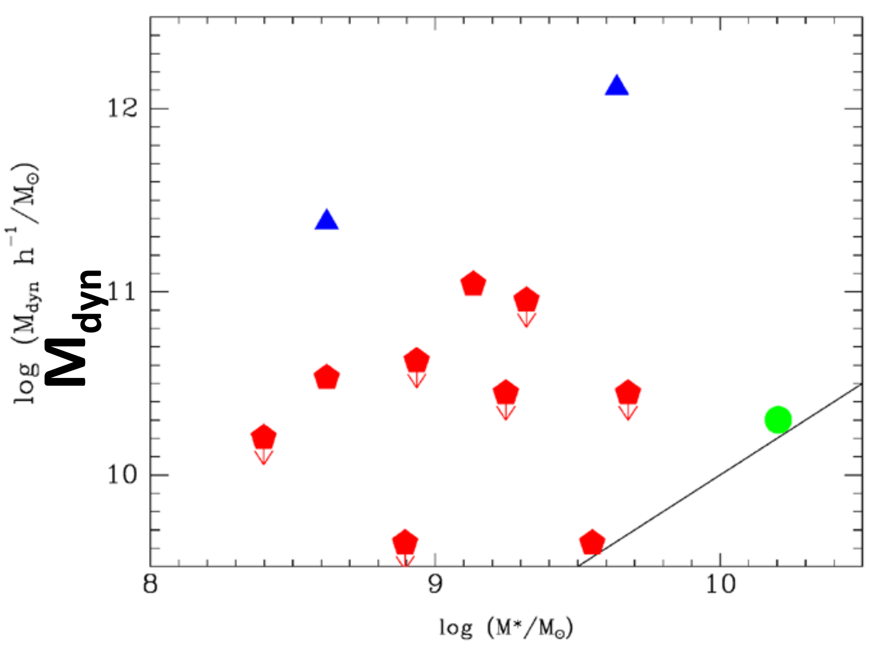


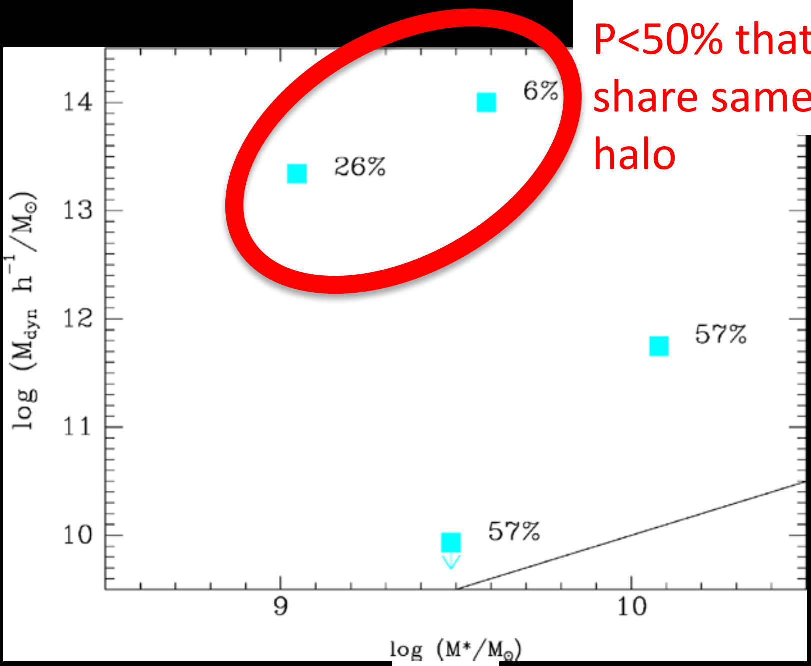


- Keep caveats in mind (Lya, close pairs, knots vs. halos)
- Include Lya emission line widths (or upper limit): resonant scattering should *broaden* line (Kunth, Atek…) so true mass is *lower*
- M_{dyn} ranges from $<10^9$ to 10^{14} $M_\odot$ (dwarf galaxy to cluster halo)

JL 2009

Compare dynamical mass estimates to stellar masses



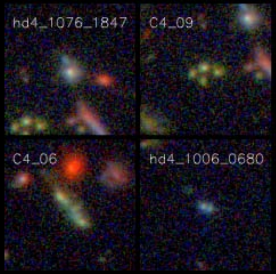


P<50% that pair share same halo

JL 2009

- Stellar masses M_* from Papovich 05
- M_{dyn} always > M_* (good!)
- No strong correlation

Conclusions I. LBG kinematics

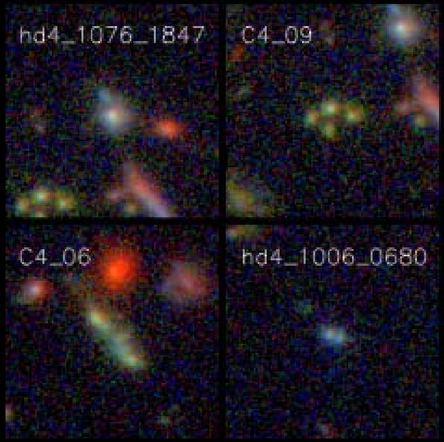


- Mixed! no clear pattern of clean dynamical signature; no disk signatures (vs. lower-z, brighter sources); LBG total masses still elusive
- 4 close pairs: <60 to 4700 km/s. Simple dynamical masses: 10^{10} to 10^{12} $M_\odot$ (best pairs)
- Model results: pairs not reliable for masses
- Clumpy/elongated: 10^{10} - $10^{12} M_\odot$
- Lya emission lines? tricky! But generally small widths, low masses ~$10^{10} M_\odot$
- No evidence that LBGs are uniform, high-mass (cf. Dekel, Ceverino; Katz; Keres)

II. Local analogs of Lyman break galaxies: luminous compact blue galaxies (LCBGs) at z<1 (TBD at IAP)

- What are best local analogs of LBGs -- easier to study, could help interpret high-z gals?
- Top candidates for local LBGs analog: HII galaxies and luminous blue compact galaxies = LCBGs (*not* BCG or BCD)

z~0: NGC 7673



Z~3: LBGS

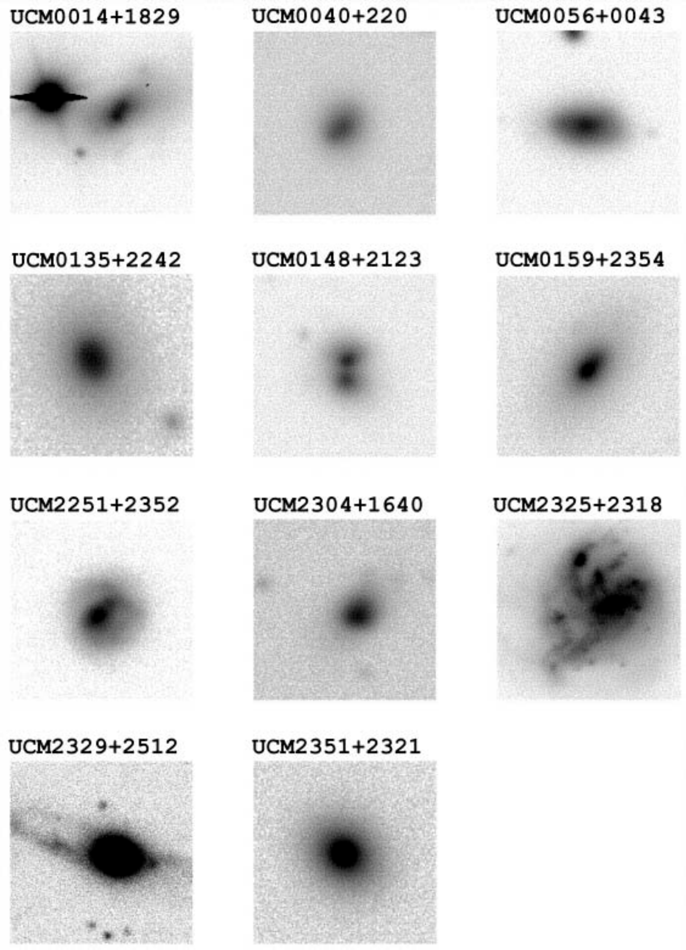
Properties of LCBGs

- L ~ L* but tiny, r_e ~ 2 kpc (L_{M31}, r_{N205})
- Extreme starbursts
  10-20 $M_\odot$/yr
- High surface brightness
  $\mu_B<21$ mag/arcsec^2
- Narrow emission lines
  30-120 km/s
- Low masses < $10^{10} M_\odot$
- $M_{burst}/M_{tot}>10\%$ (from SEDs)
- Strong evolution: 40% of SF↑ to z=1
- Similar to UVLGs (GALEX: Heckman, Overzier) and Small Green Peas (SDSS: Cardamone 09)

Cf. Pérez-Gallego 09; Melbourne 07; Noeske 07; Werk 04; Ferguson 04; Pisano 01; Lilly 98; Phillips 97; Guzmán 97

LCBG Examples

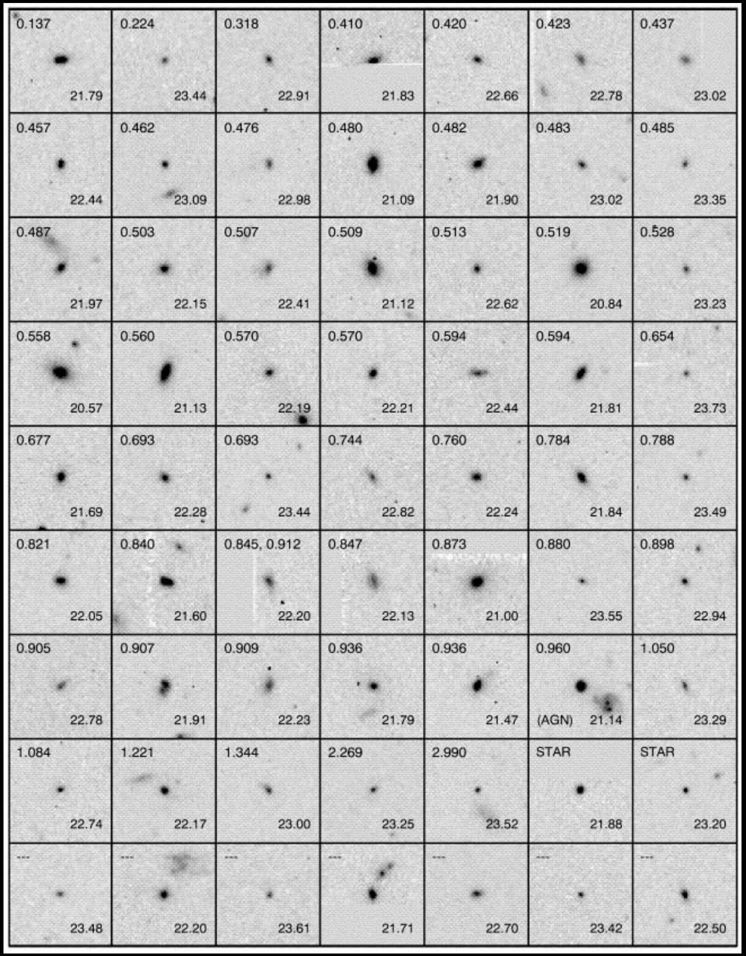
z<0.05



10 kpc

WIYN *R*-band (Pisano et al. 2001)

z~0.75



40 kpc

HDF-FF I_{814} (Phillips et al. 1997)

LCBGs at z<1

Project:

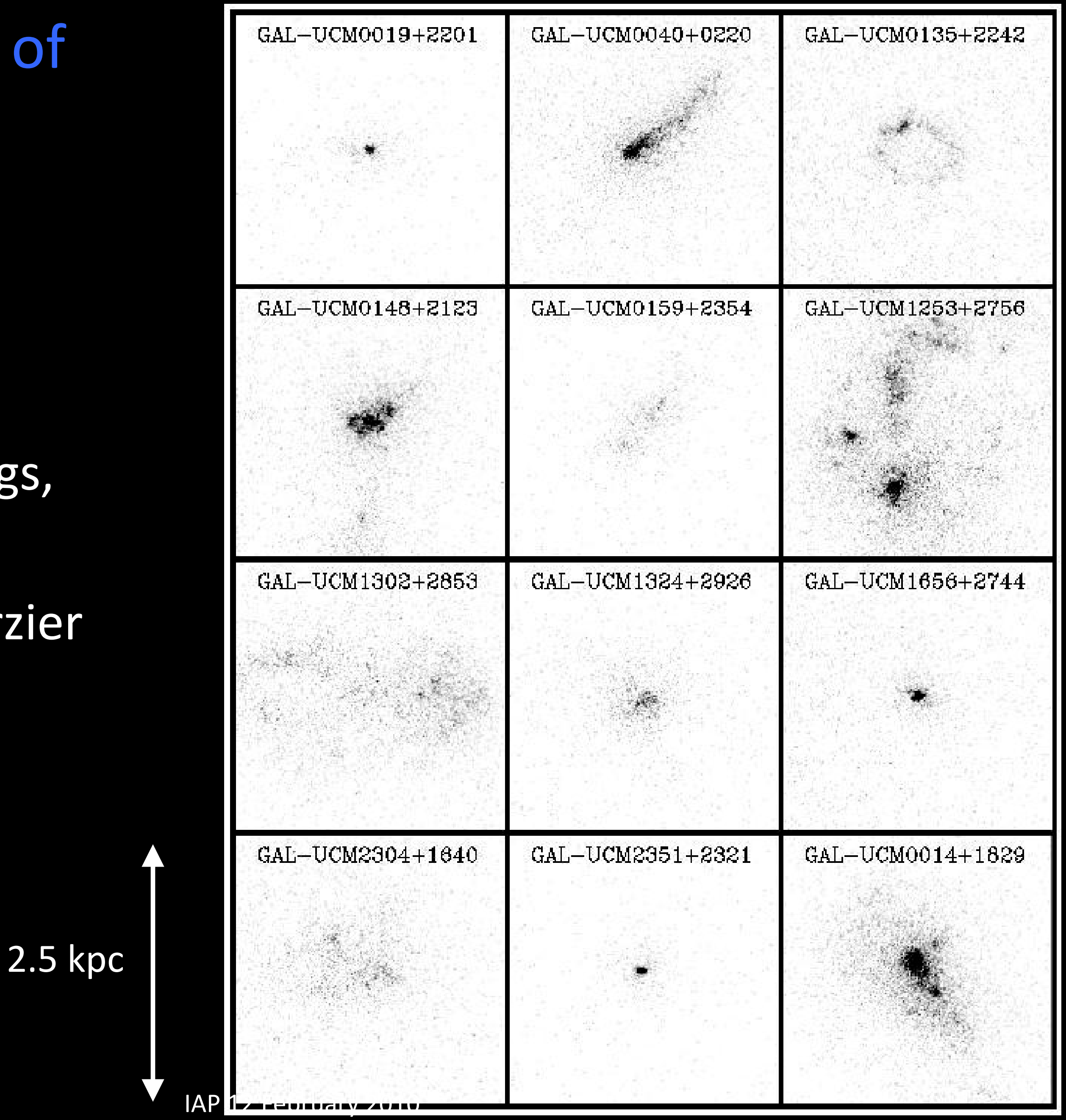
- compare LCBGs and LBGs in rest-UV and MIR with *HST* and *Spitzer*
- Search for additional SF hidden in dust

- Sample:
  - 12 HII gals at z=0 from UCM survey
  - 14 LCBGs at z<1 from LBDS
- Data:
  - *HST*/STIS FUV and NUV images = rest-UV
  - *Spitzer*/IRAC+MIPS photometry

With Bershady, Gallego, Guzman, Koo

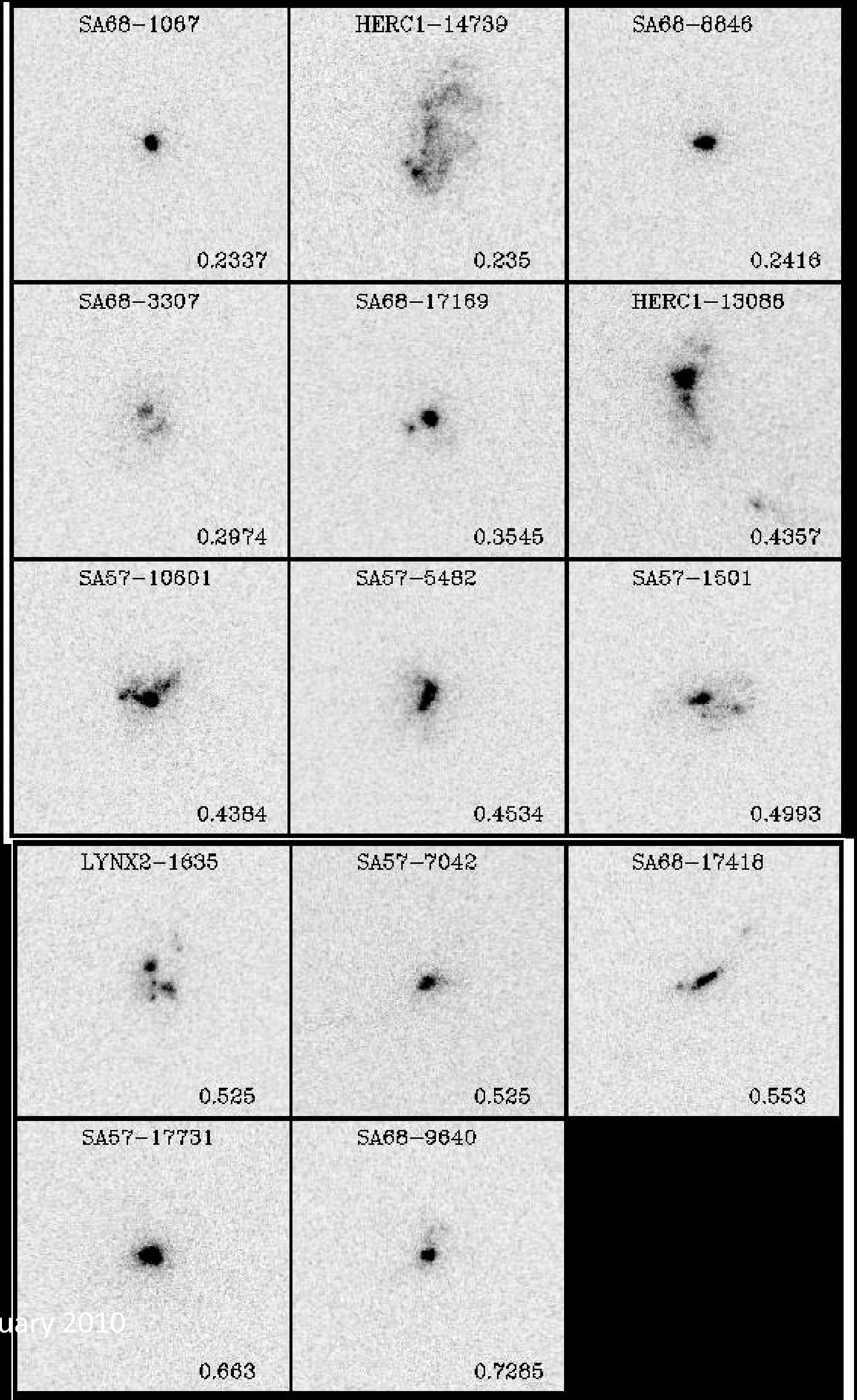
STIS FUV images of *z*~0 sample

- Morphologies: VERY diverse, disturbed, multiple knots, rings, etc.
- No definitive merger signature (vs. Overzier 08, 09, 10)



STIS NUV images of *z*<1 sample

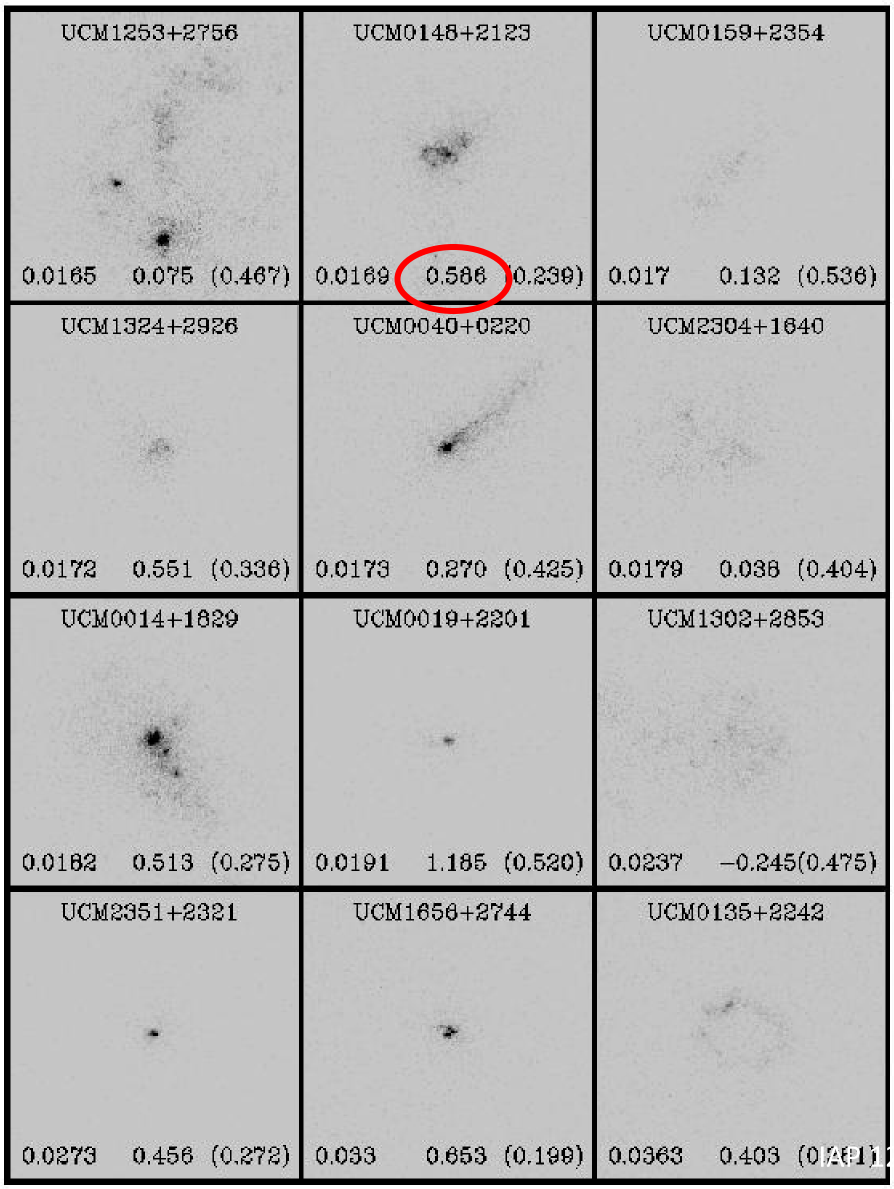
Morphologies: more disturbed, multiple knot systems

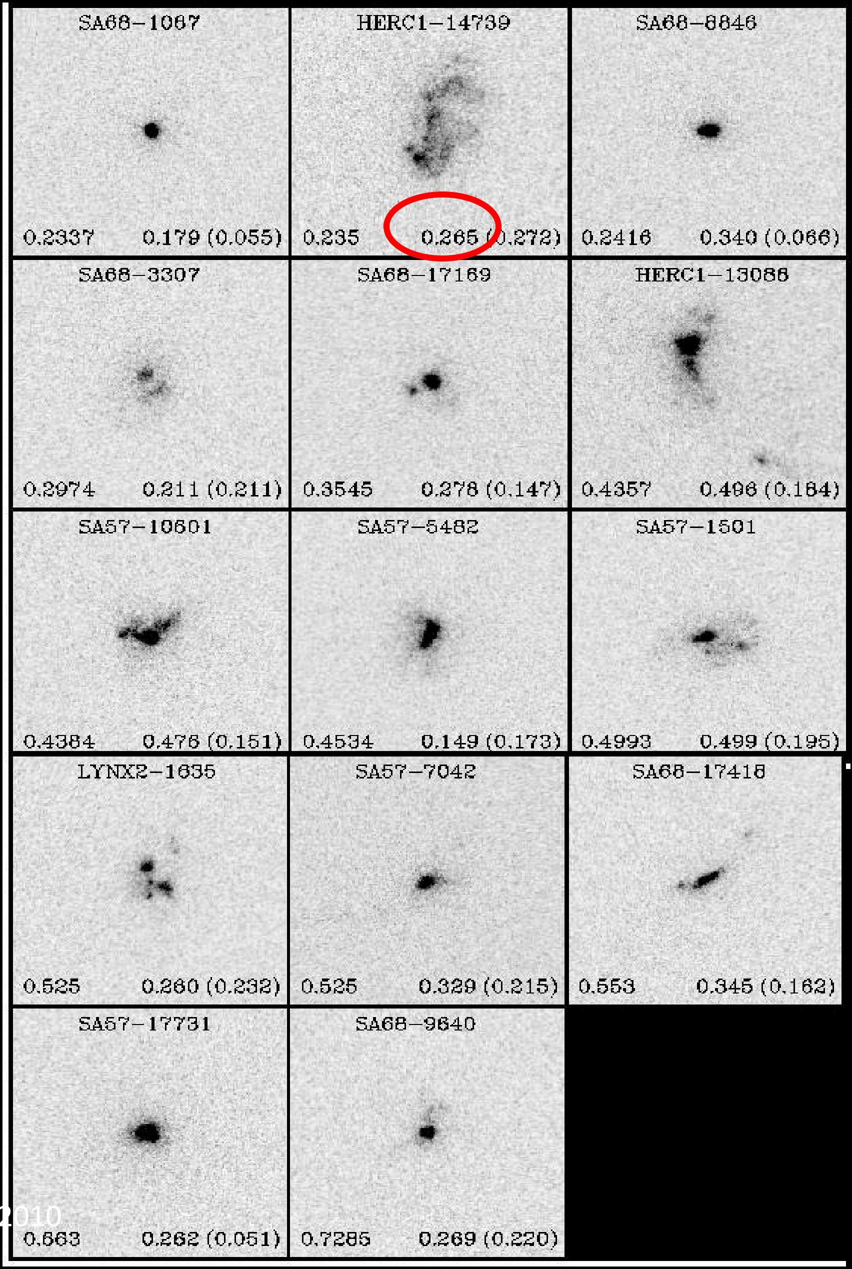


3.75" ~ 21 kpc

Rest-UV Asymmetries

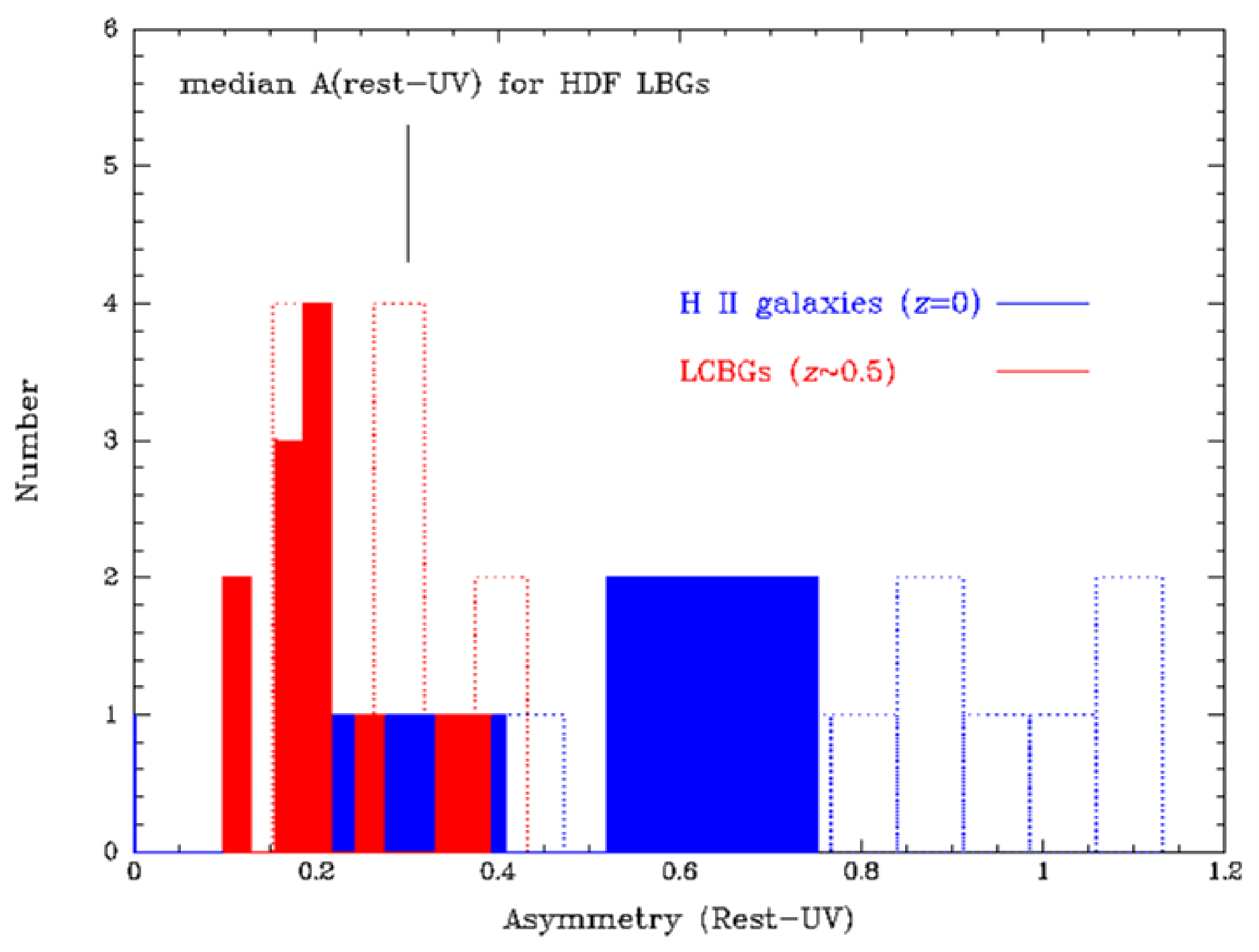
Measure image asymmetry A
following Conselice et al. (2000)



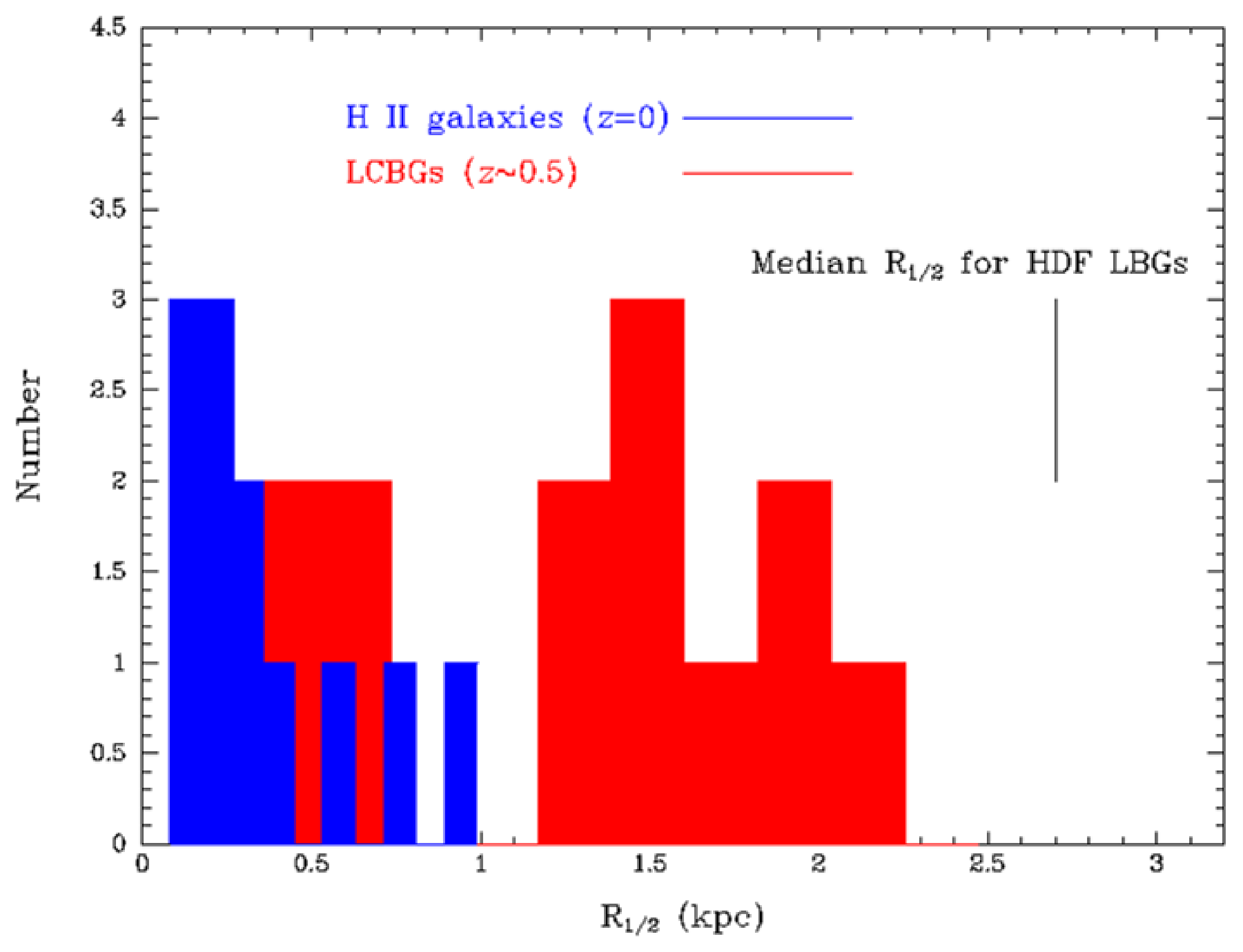


Rest-UV Asymmetries

Large range in A;
spans median
for LBGs

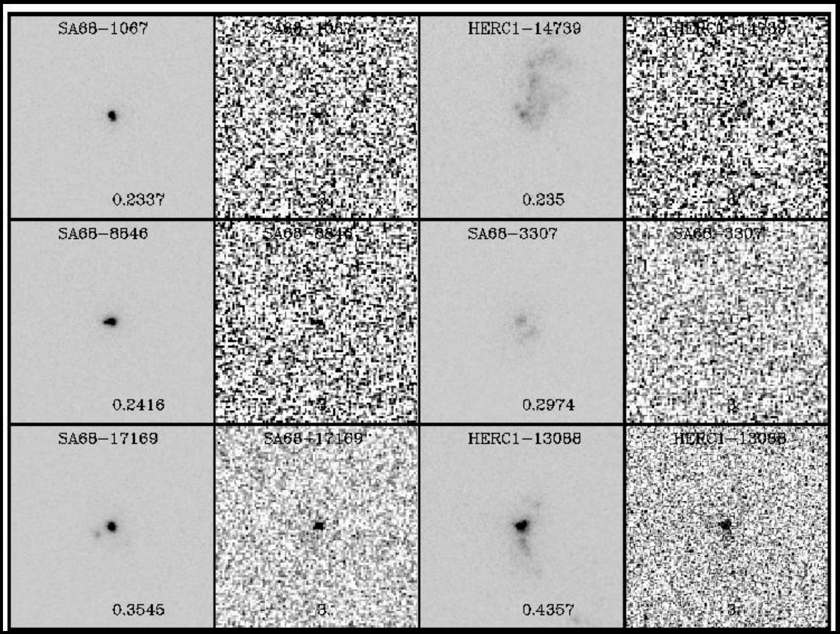


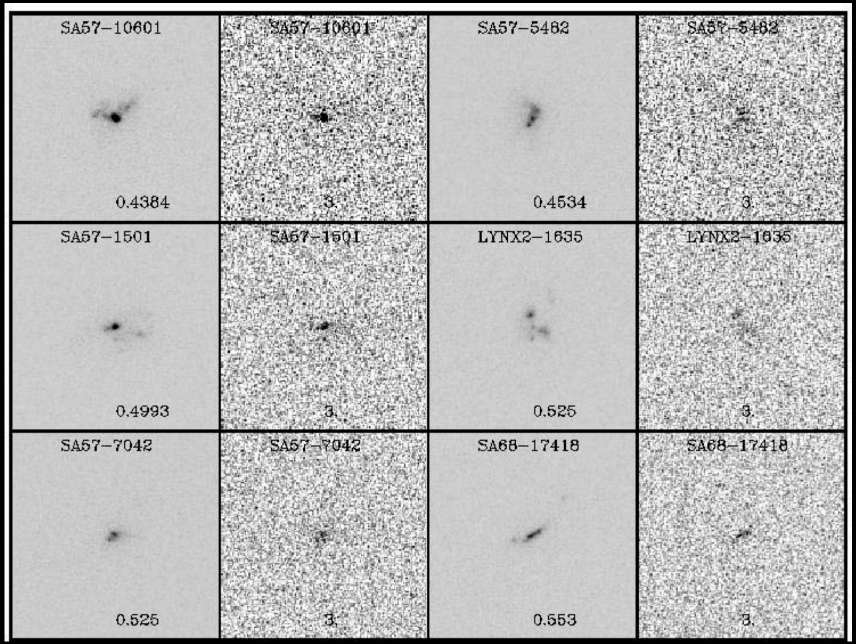
Sizes

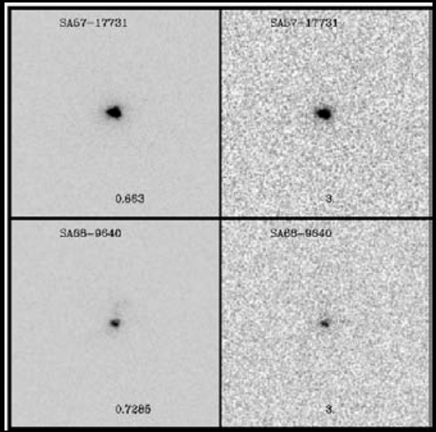


Local LCBGs and HII galaxies are even smaller than LBGs

How would LCBGs look at z=3?



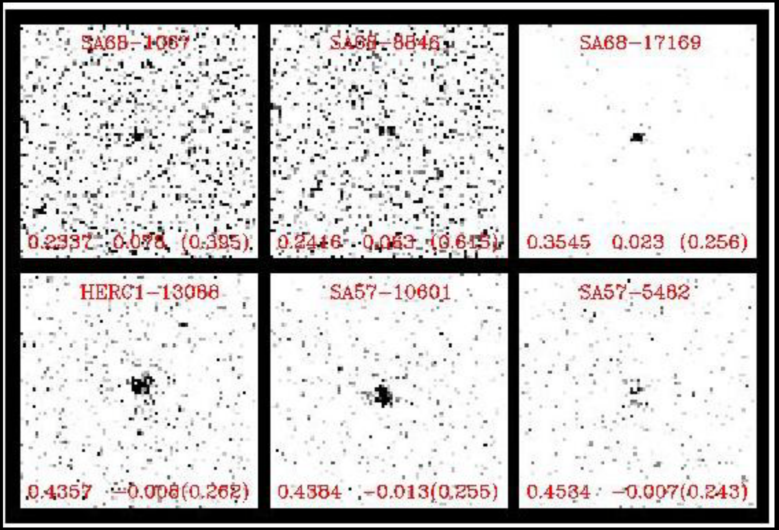


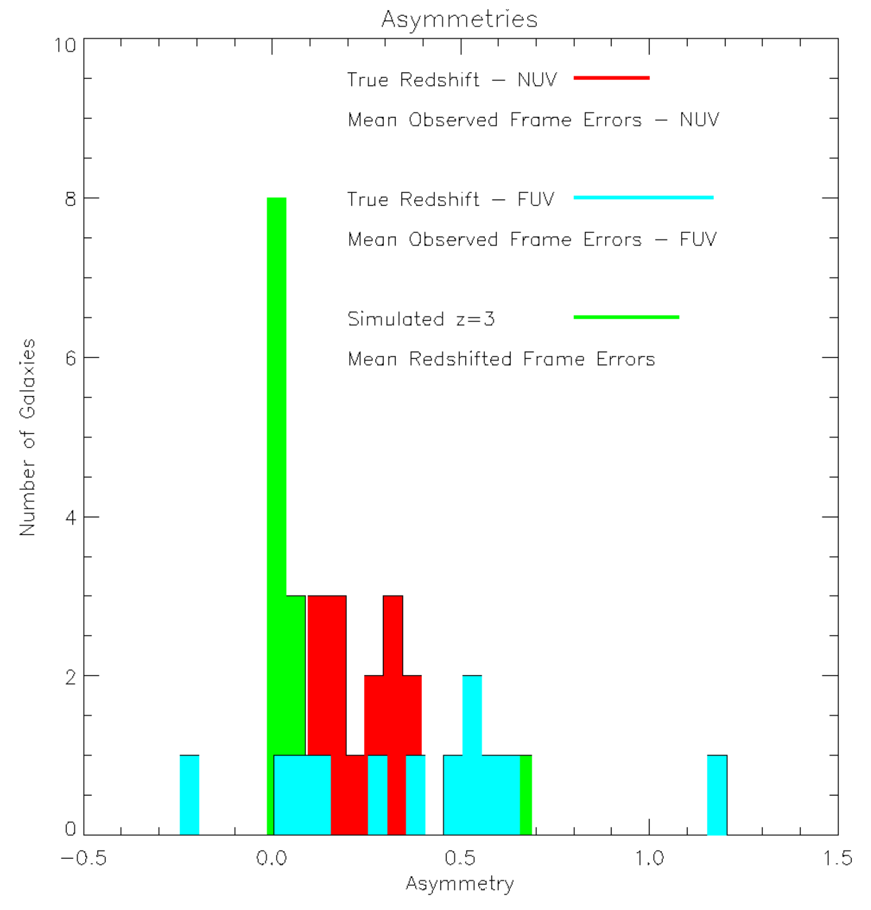


True *z*

Simulated *z*=3

Rest-UV Asymmetries of simulated z=3 view

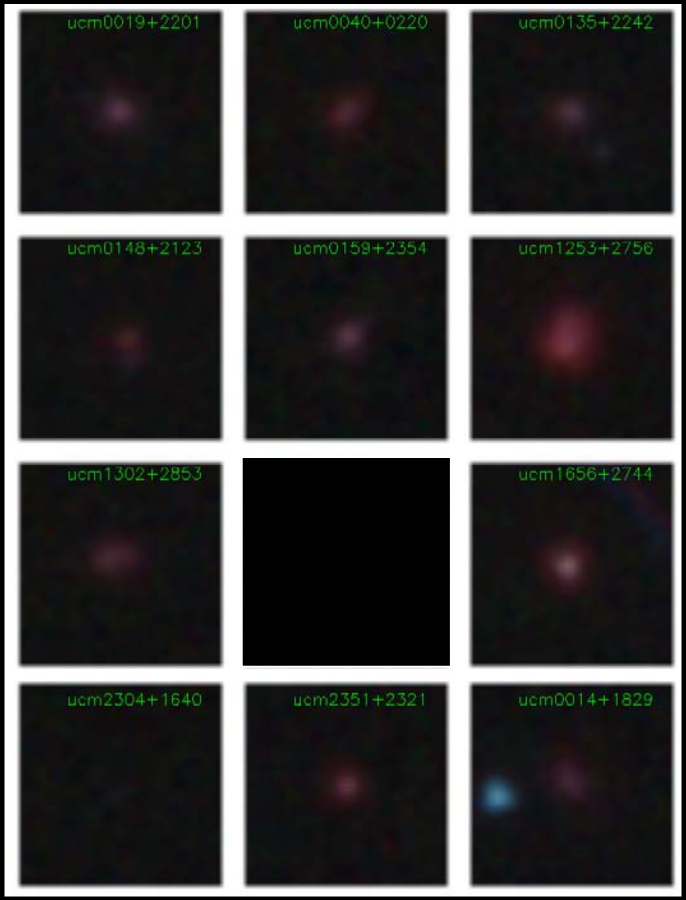




Asymmetries drop with redshift as faint outer regions fade

New: Spitzer/IRAC (+MIPS) photometry

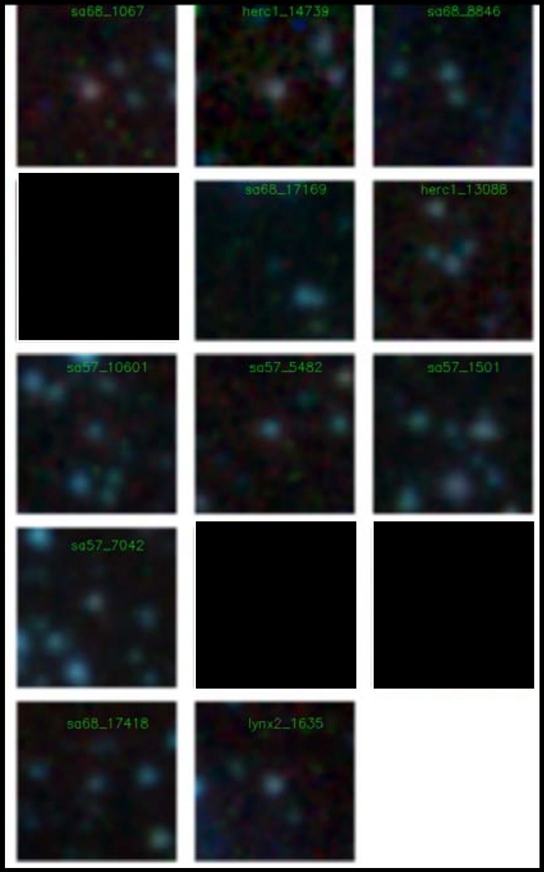
z~0 HII galaxies



30"~12 kpc

IRAC
ch 1,2,3

z<1 LCBGs



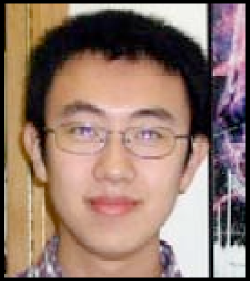
30" ~ 170 kpc

Conclusions II (à moitié cuits): LCBGs

- LCBGs are excellent local analogs of LBGs: sizes, colors, SF props, masses.
- rest-UV images show star formation in wide range of morphologies, from rings to compact nuclei. Almost all within 2 kpc radius, but not "nuclear" starbursts.
- SF apparently stochastic, not uniform process.
- No obvious merger signatures
- CAS analysis: comparable to LBGs.
- Spitzer: LCBGs mostly detected with IRAC; MIPS photom, SED fitting to come!

III. Ultraluminous Infrared Galaxies at z<1

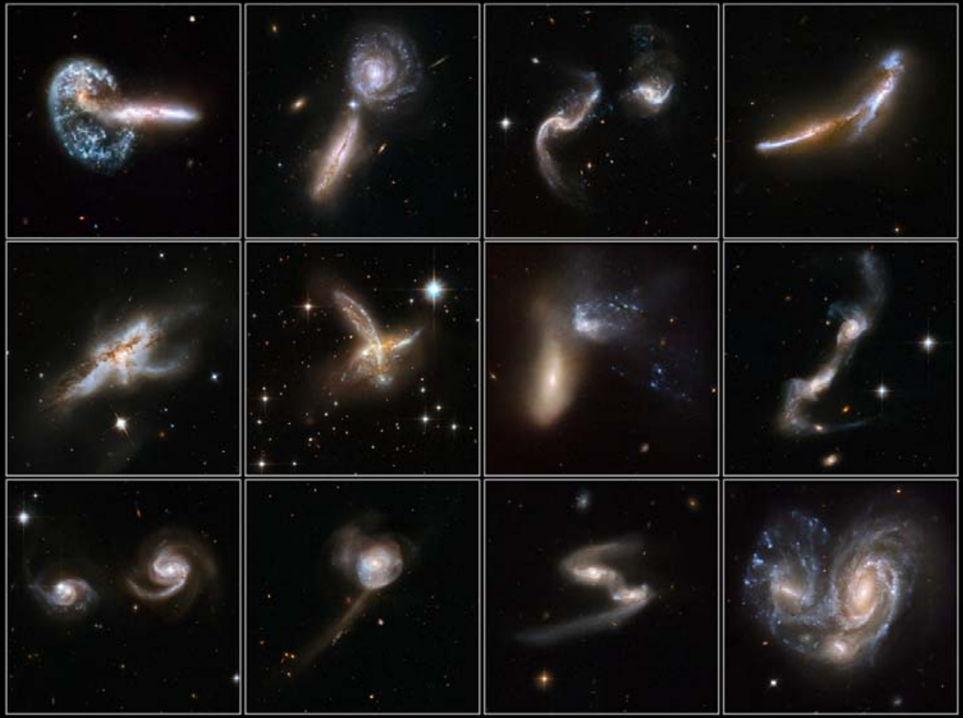
- What drives massive dusty starbursts? Always interactions? Role of AGN? Are progenitors always gas-rich disks? What are end products? Where do ULIRGs fall in color-magnitude diagram?



- Yuxi Chen (UMass) PhD thesis, w/ Min Yun

ULIRG background

- Huge bolometric luminosity, mostly in IR ($L_{IR} > 10^{12} L_{\odot}$)
- Dusty Starbursts/AGNs
- Galaxy mergers/interactions; final product – massive elliptical galaxies?
- QSO-ULIRG connection
- High-z SMGs may be the distant version of local ULIRGs



Evans

IIIa: Optical properties of ULIRGs at z<1

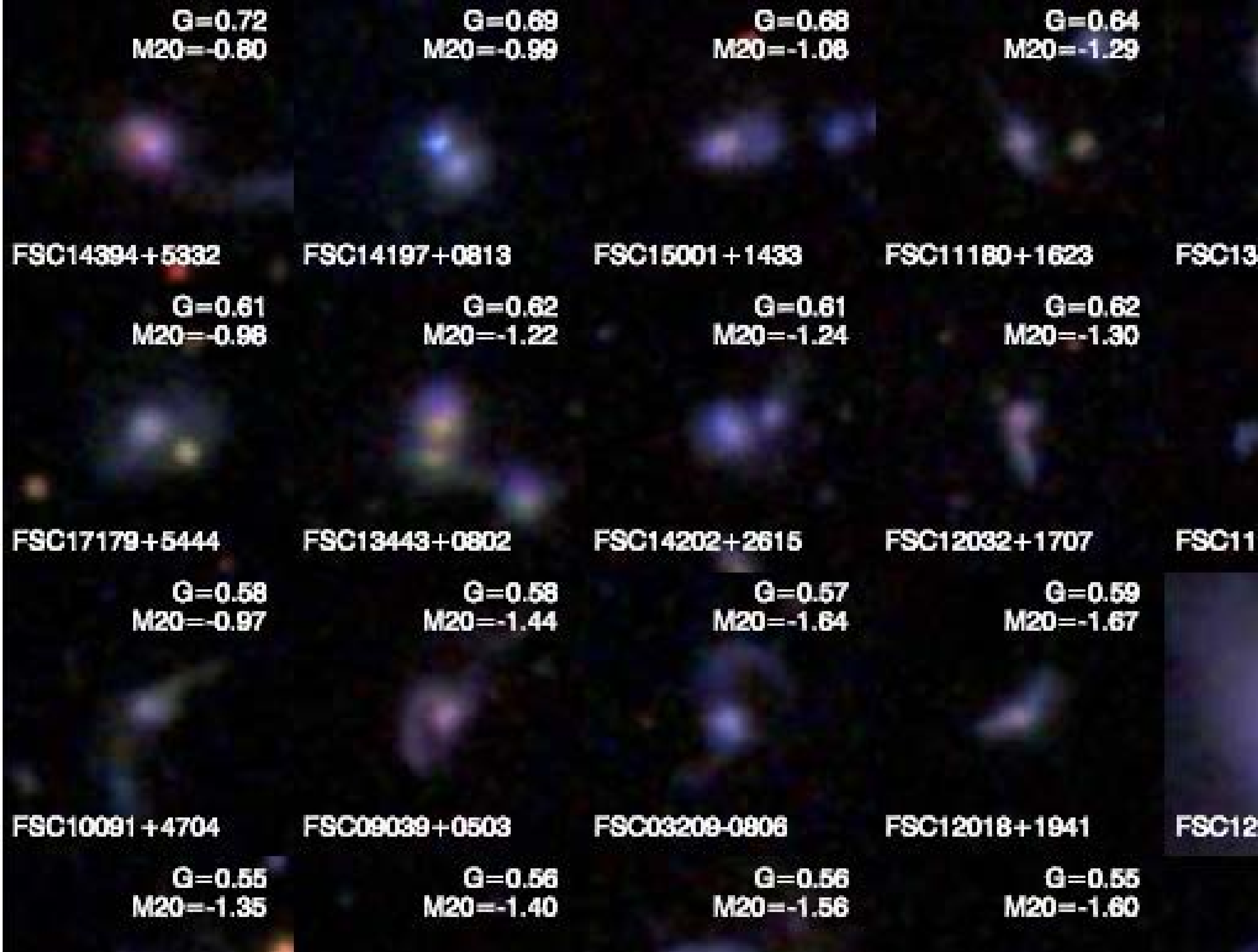
1. ULIRGs at *z*<0.3 in SDSS: morphology + color-magnitude relation
2. HST/STIS + NICMOS imaging (= rest *B*, rest *I*) of ULIRGs at *z*~1: connection between z=0 and z>2 SMGs?

Samples:

- z<0.3: IRAS 1 Jy sample, 54/118 in SDSS
- Z~1: 12 brightest bona fide FIR-selected ULIRGs (no extrap. from 10 um)

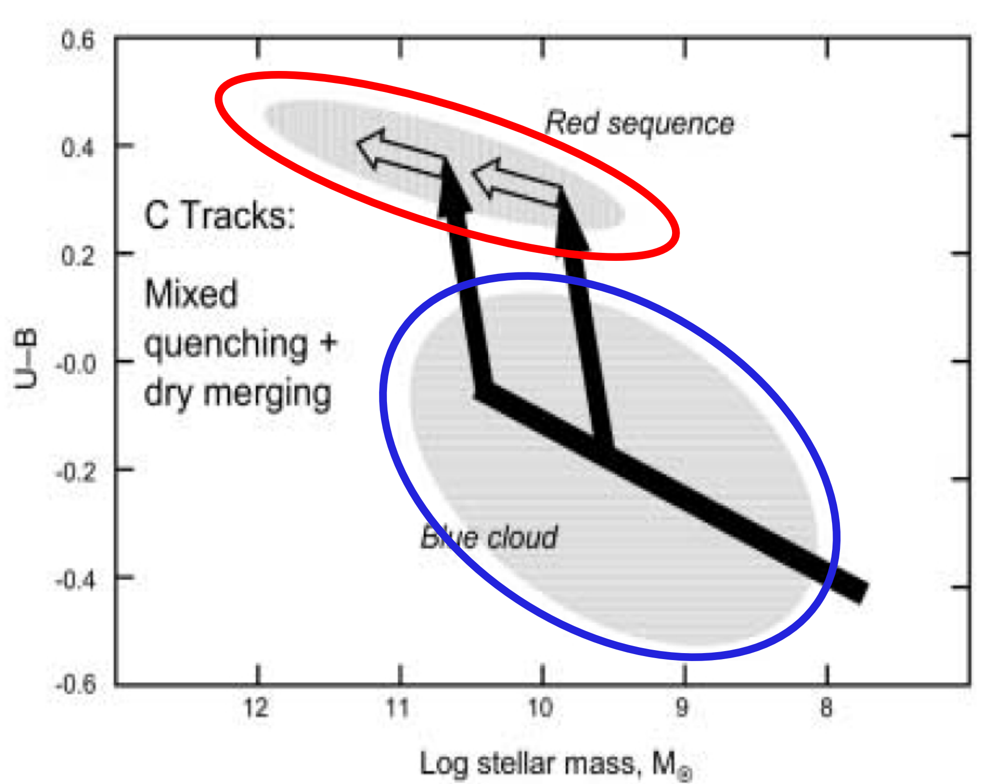
1 Jy ULIRGs in SDSS

- IRAS 1 Jy sample (Kim 1995; Kim & Sanders 1998) = most luminous ULIRG sample
- **54** (46%) of 118 ULIRGs in **IRAS 1Jy** covered in **SDSS DR5**
- $z = 0.02 - 0.3$, $\langle z \rangle = 0.151$
- $L_{IR} = 10^{12.0} - 10^{12.8} L_{\odot}$, $\langle L_{IR} \rangle = 10^{12.2} L_{\odot}$
- 14/54 classified as Seyferts (Veilleux et al.)
- good representative subset of 1 Jy sample
- SDSS provides robust, clean, well-calibrated baseline


G=0.72
M20=-0.80
FSC14394+5332
G=0.69
M20=-0.99
FSC14197+0813
G=0.68
M20=-1.08
FSC15001+1433
G=0.64
M20=-1.29
FSC11180+1623
FSC13
G=0.61
M20=-0.98
FSC17179+5444
G=0.62
M20=-1.22
FSC13443+0802
G=0.61
M20=-1.24
FSC14202+2615
G=0.62
M20=-1.30
FSC12032+1707
FSC11
G=0.58
M20=-0.97
FSC10091+4704
G=0.58
M20=-1.44
FSC09039+0503
G=0.57
M20=-1.64
FSC03209-0806
G=0.59
M20=-1.67
FSC12018+1941
FSC12
G=0.55
M20=-1.35
G=0.56
M20=-1.40
G=0.56
M20=-1.56
G=0.55
M20=-1.60

Color-magnitude relation in SDSS

- Building up the red sequence
  - Wet merger of disk galaxies
  - Dry merger of early-types
  - Quenching of star formation (AGN?)
- Where do ULIRGs fall in the Color magnitude diagram?
- Where do the ULIRGs harboring AGN fall?



Faber et al. 2007

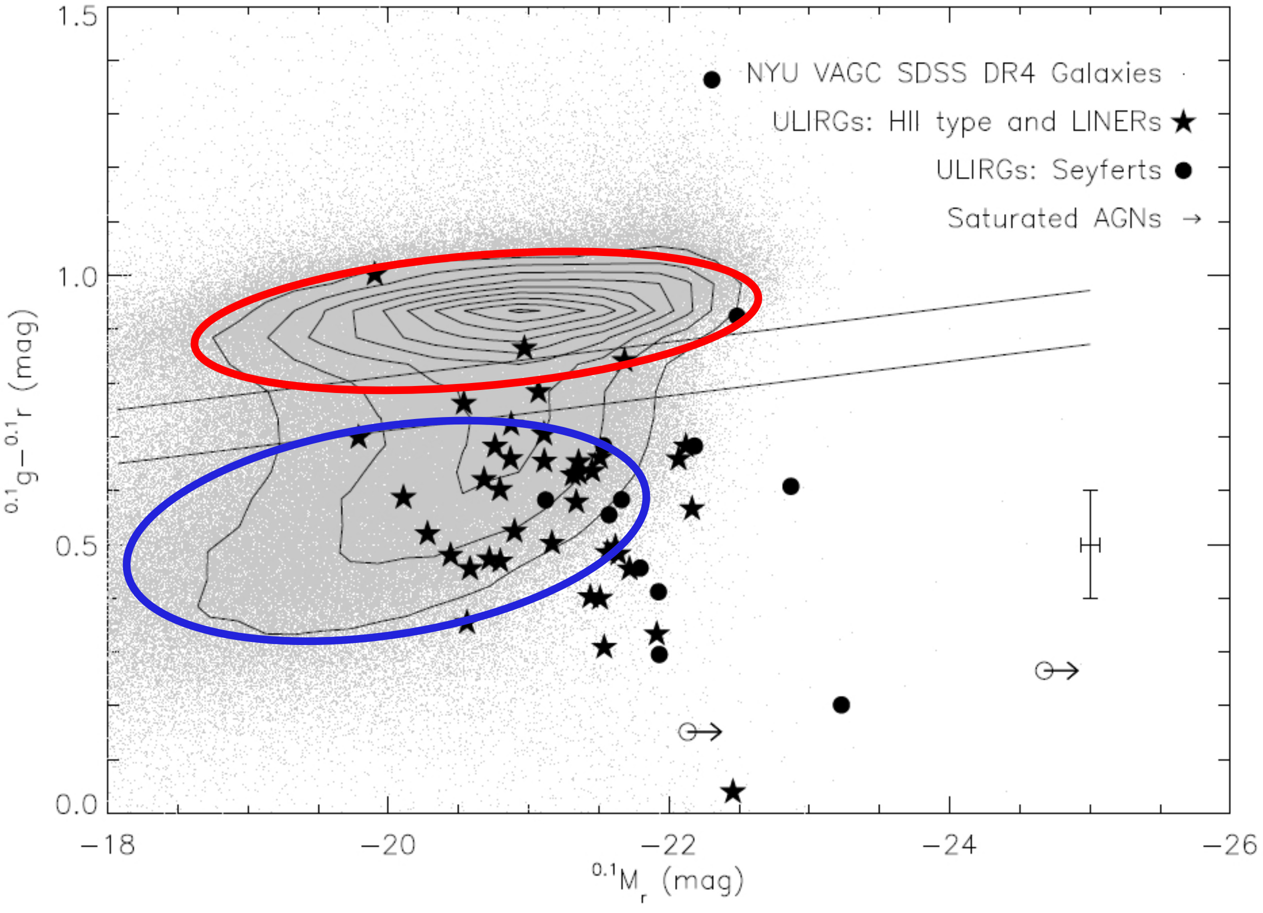
ULIRGs are optically bright and blue

ULIRGs are…

- **very luminous in the optical**: On average **1 mag** brighter than SDSS galaxies at same redshift (NYU VAGC DR4; Blanton et al. 2004)

- **very blue in the optical:** **$\langle {}^{0.1}(g-r) \rangle = 0.58$** for ULIRGs, compared to **$\langle {}^{0.1}(g-r) \rangle = 0.55$** for the blue cloud. **47** (**~87%**) have typical blue cloud colors

- **scarce in the green valley**: Only **3** (**6%**) lie in the green valley. **None** of the AGNs are in the green valley, they are among the most luminous, and most are blue.



Chen et al. 2010

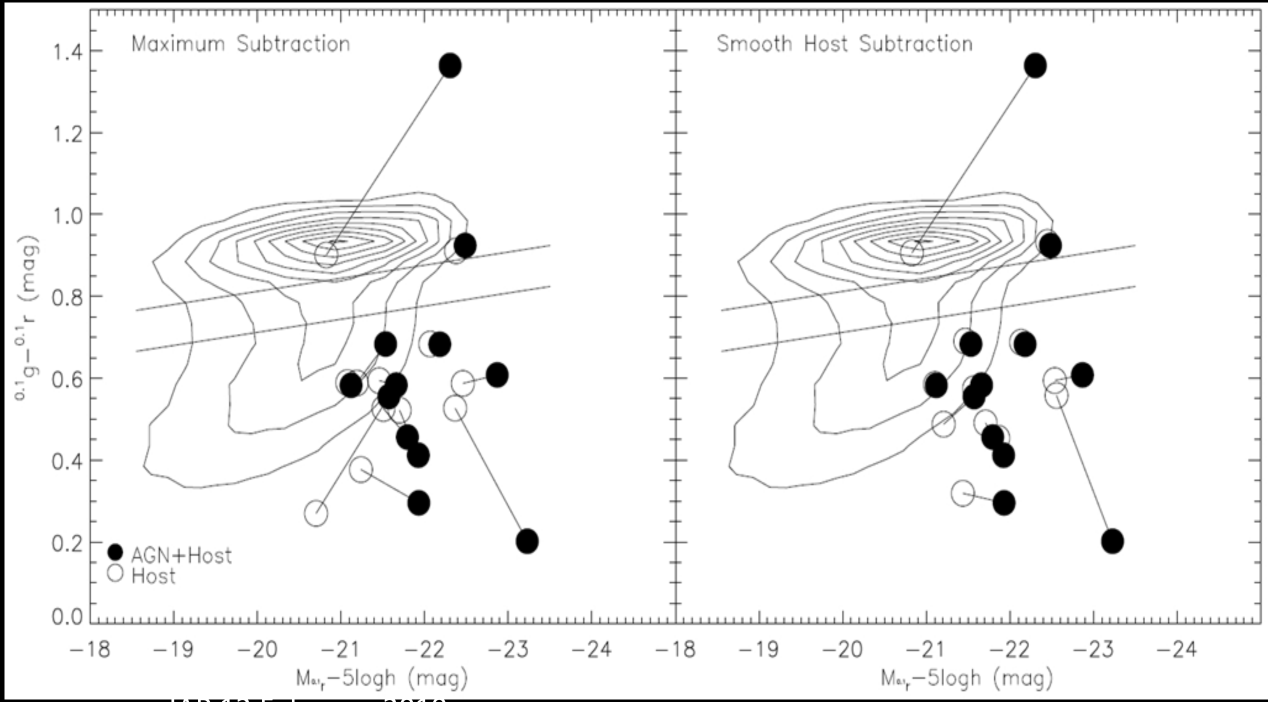
Color and Magnitude of AGN Host Galaxies

AGN ULIRGs are especially luminous and blue

- On average **0.8 mag** more luminous than non-AGN ULIRGs
- ~**83%** have typical blue cloud color
- **Are the blue color and high optical luminosity a result of AGN?**
- **Are the host galaxies "green"?**

Point source subtraction:

- Central point sources contribute only ~**25%** to total optical light
- Host galaxies dominate optical luminosity
- With or without central AGNs, AGN ULIRGs are not located in the green valley



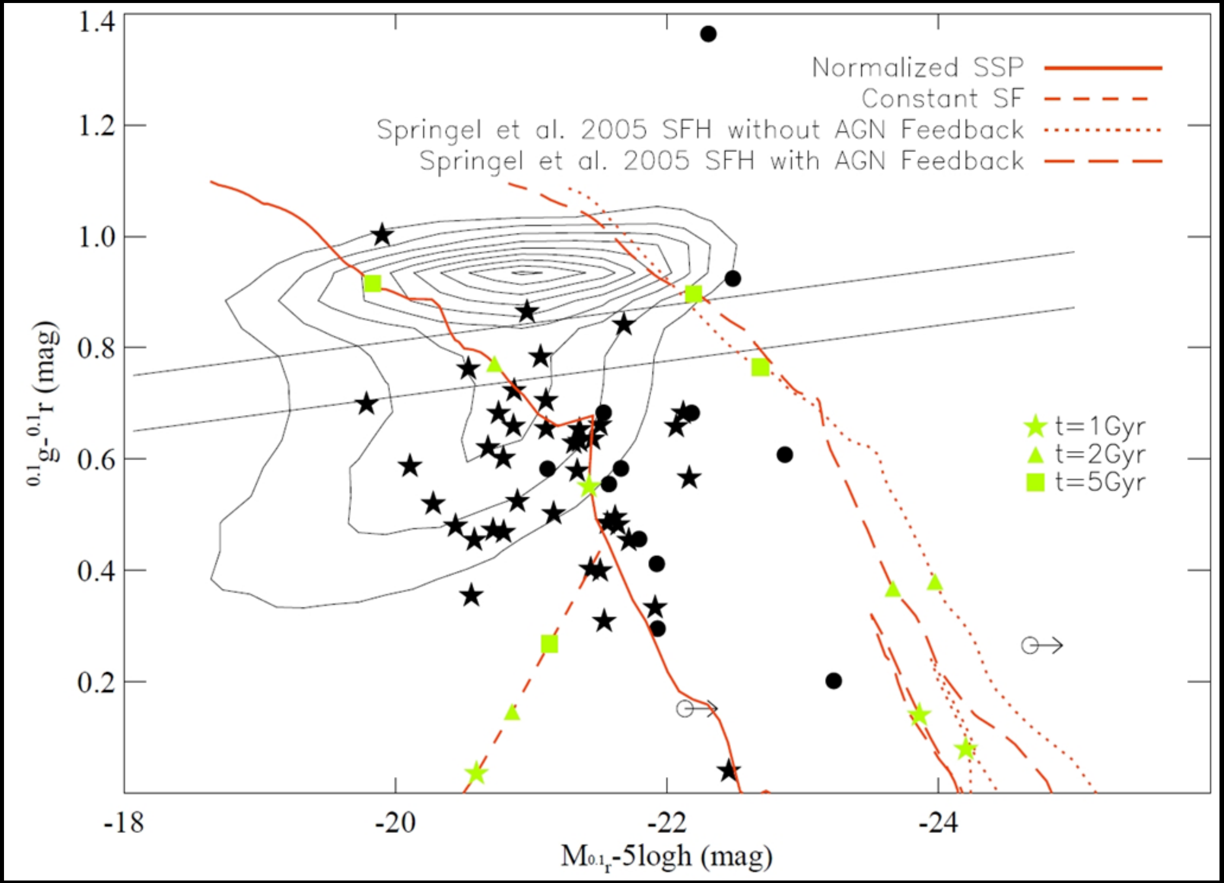
Chen et al. 2010

Implications of ULIRG optical color and magnitude

- Blue colors of ULIRGs are consistent with patchy dust extinction
- ULIRGs will be even more luminous and blue if corrected for extinction
- Scarcity of ULIRGs in the green valley and red sequence implies ongoing active star formation in optically visible regions; quenching of star formation has yet to happen

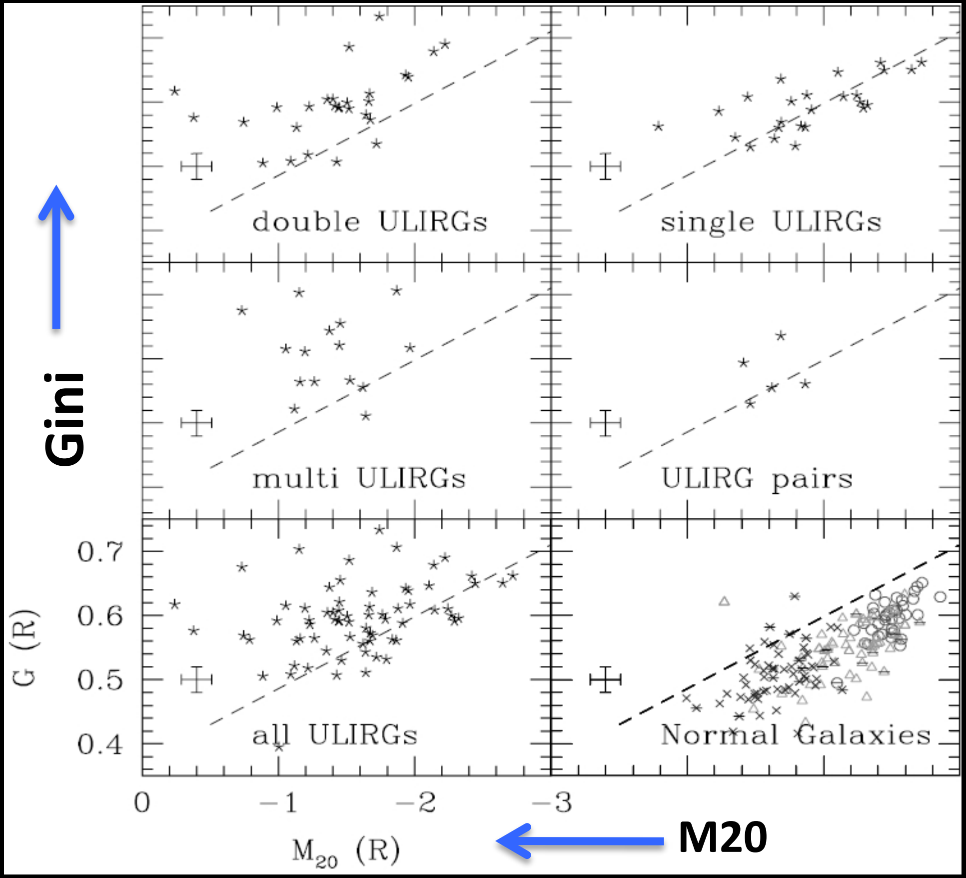
SED evolutionary tracks

- Models using BC03 (Bruzual & Charlot 2003), different SFHs
- ULIRG optical colors and magnitudes can be explained by simple models
- Optical component of most ULIRGs evolve to the faint end → need dry merger to feed the massive tip of the RS! (not including dusty SF)



Chen 10

Quantitative Morphology Analysis

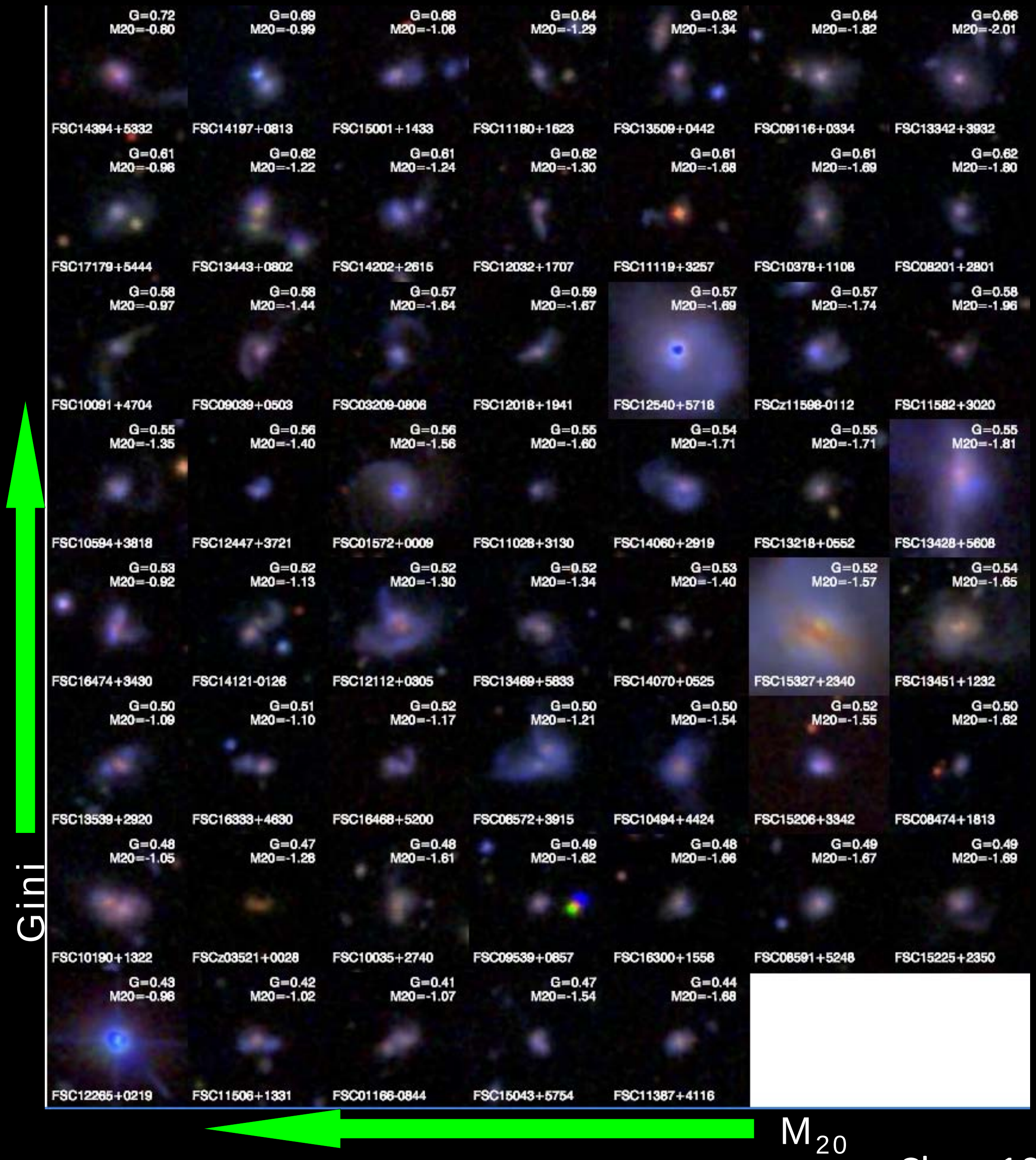


Lotz et al. 2004

- **Gini** (G): distribution of pixel intensities, concentration-like (Gini 1912; Abraham et al. 2003; Lotz et al. 2004)
- **M20**: normalized 2nd-order moment of the 20% brightest pixels, in logarithm scale (Lotz et al. 2004)
- Local ULIRGs (at high spatial resolution) are well separated from normal galaxies in the G-M20 plot (Lotz et al. 2004)

G, M20 of Low-z ULIRGs

More morphologically disturbed sources have higher ***Gini*** and ***M20***, qualitatively consistent with morphologies found for local galaxies (Lotz et al. 2004)



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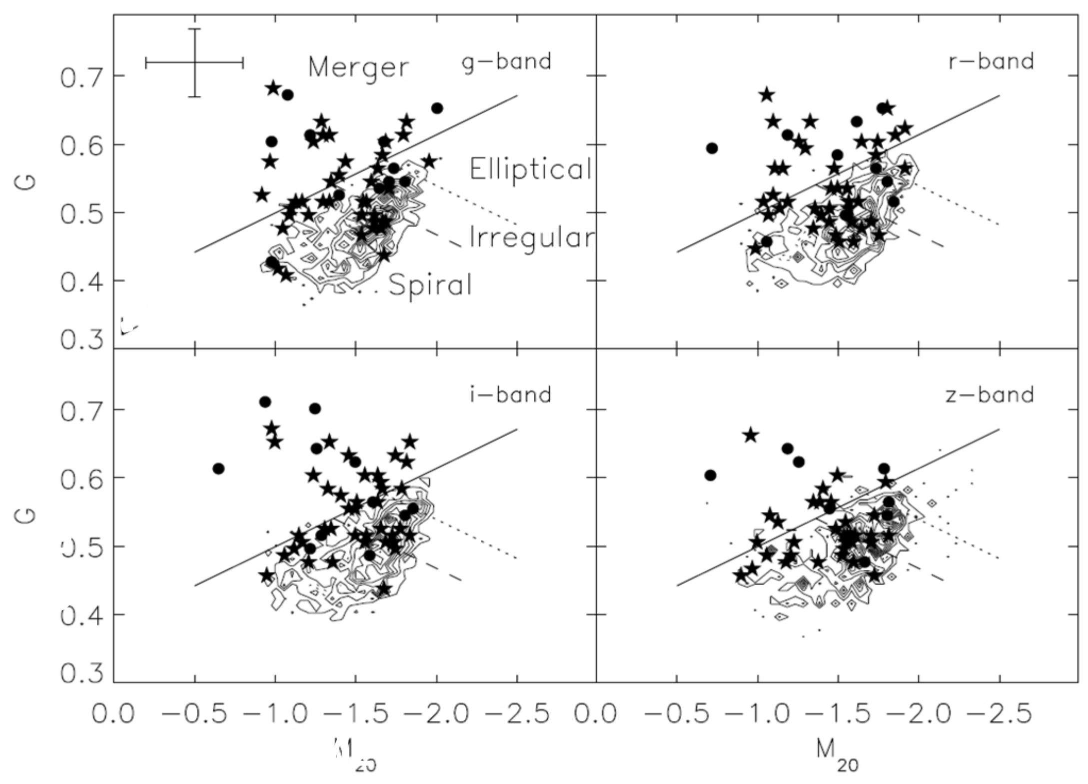
Gini and M20 of low-z ULIRGs

Heterogeneous distribution of G-M20:

	MERGER	**NORMAL**
ULIRGs	42%	48%
SDSS field galaxies	5%	95%



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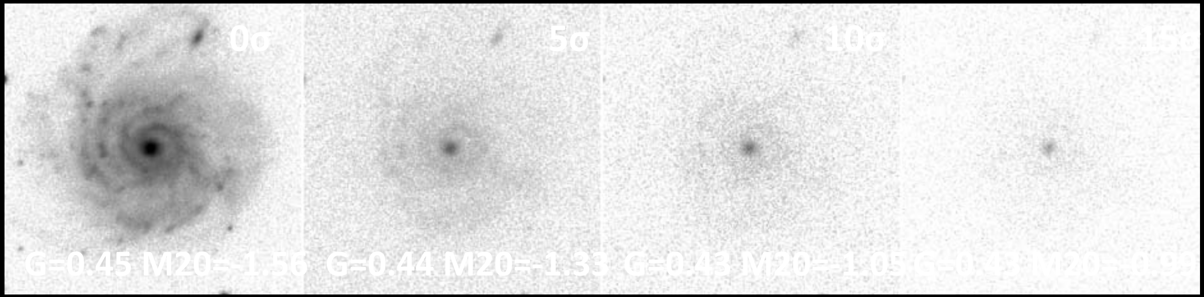
Why?

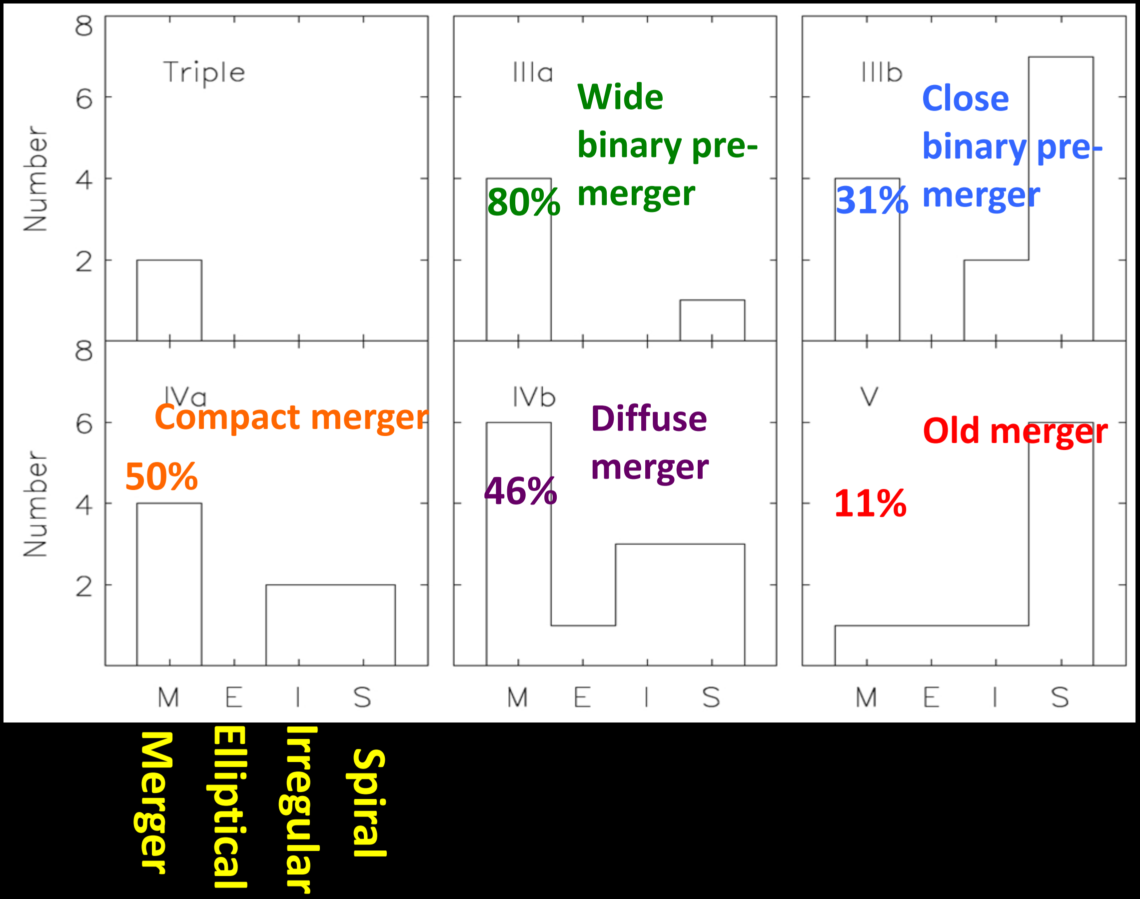
- Try simulations to measure G,M20 as f(S/N)
- Large uncertainties in G, M20
- G↓ and M20↑ as S/N↓



← S/N

Gini-M20 and merging stages

- SPH merger simulations by Lotz et al. (2008):
  - Merger-type G/M20 during first pass and maximum separation
  - Normal galaxy-type G/M20 toward later stages
- Test simulation results:
  - Compared to previous classifications of the same sources (Veilleux et al. 2002)
  - At early merging stages, more ULIRGs will be classified as G-M20 mergers; toward later stages, more ULIRGs will be classified as normal galaxies

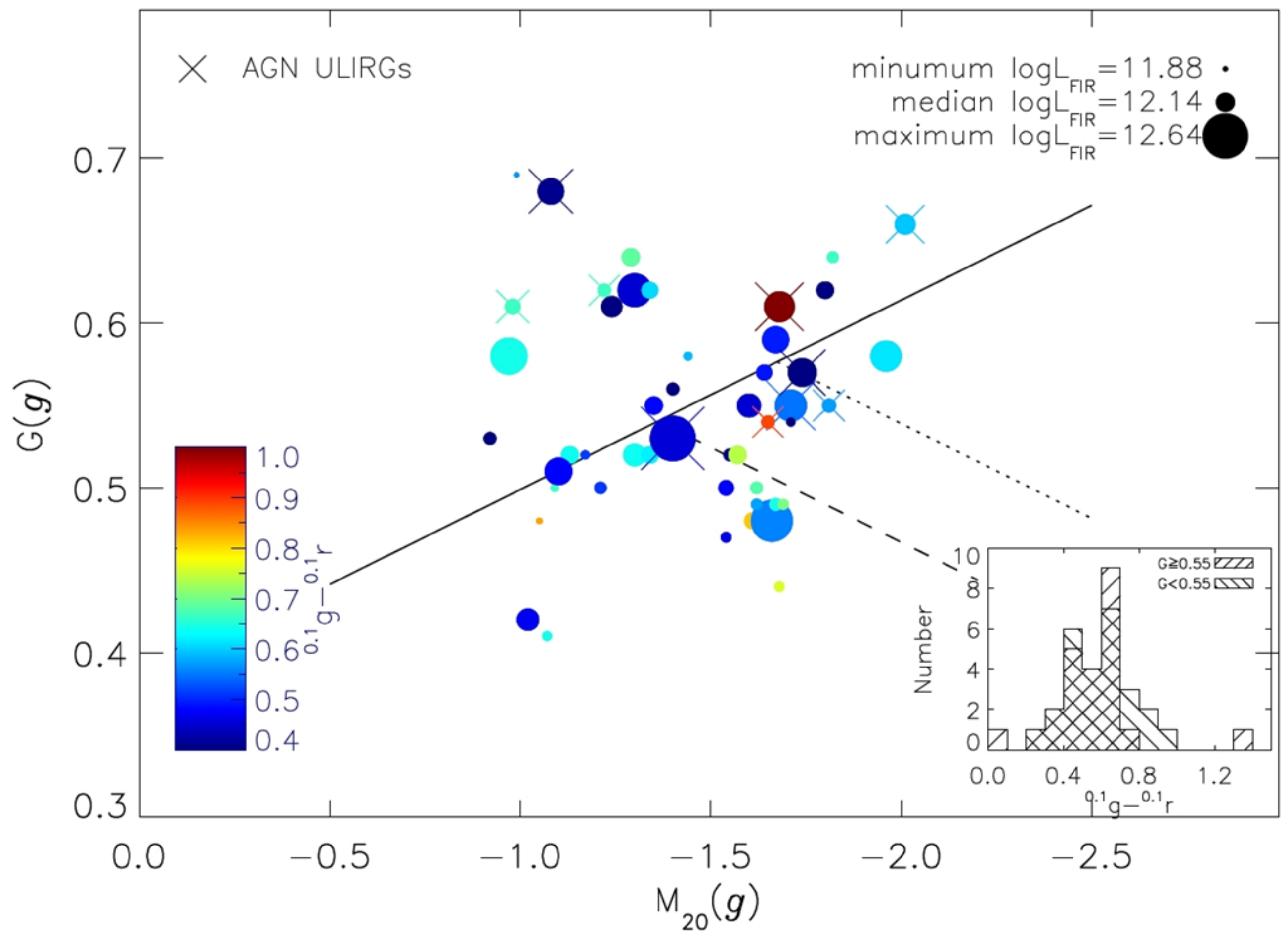


Heterogeneous distribution in G-M20 due to combination of:

- measurement uncertainties and
- different merging stages.

Color, L_{IR}, and morphology

- Point size shows L_{IR}
- No strong correlation between L_{IR}, color, G-M20
- Optically redder sources → slightly lower Gini → non-merger region
- Bluer optical colors seen in more disturbed systems, maybe not at their L_{IR} peak



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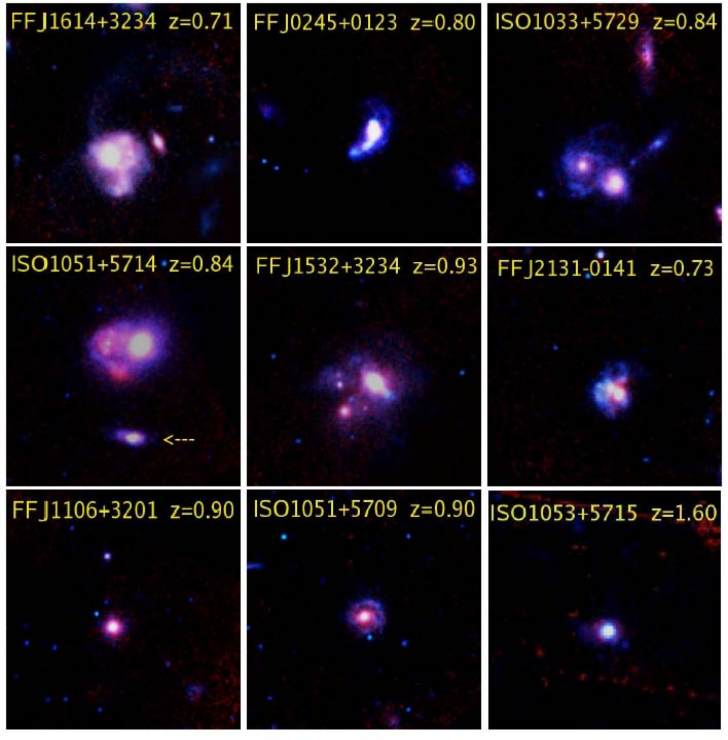
IIIb: ULIRGs at $z \approx 1$ (ongoing project)

Why z~1?

- Cosmic star formation peak
- Max distance to detect tidal tails etc with HST (pre-WFC3)
- Study in same way as low-z ULIRGs (original motivation for z~1 study)

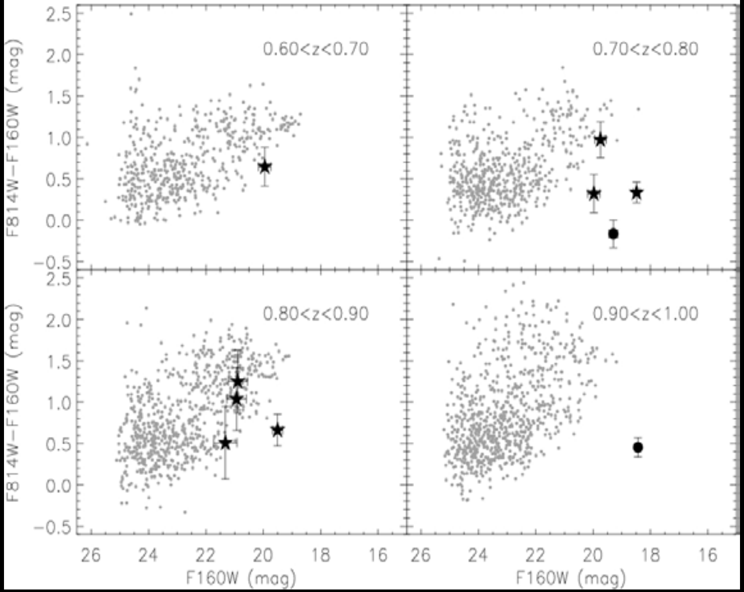
Sample

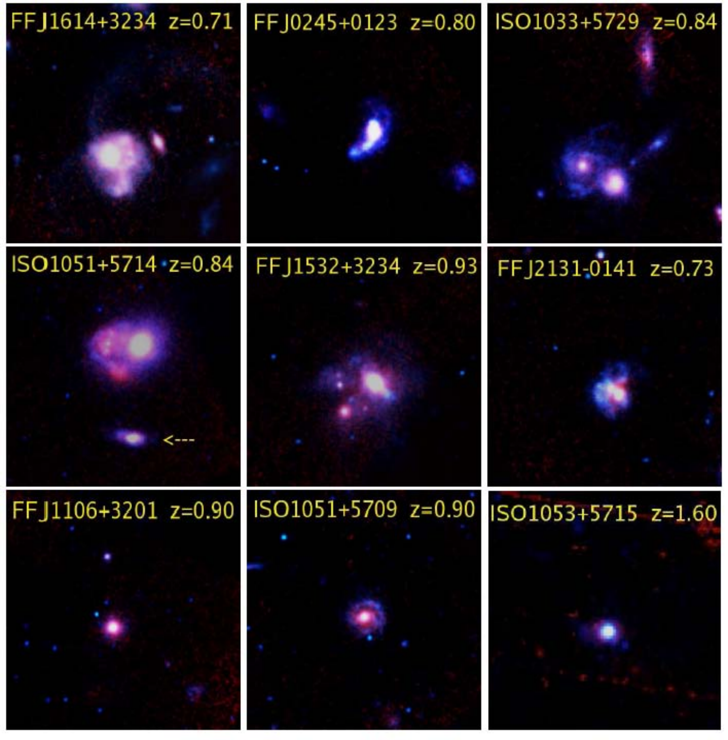
- 12 ULIRGs between z=0.69 and z=1.6, $L_{IR} > 10^{12}\ L_{\odot}$, selected by 60 or 130 μm flux
- Most luminous ULIRGs at z~1
- HST/ACS F814W and HST/NICMOS NIC2 F160W (rest-frame *B, I*)



ULIRGs at *z*≈*1*

- Variety of morphologies: tidal tails, mergers, some very compact
- Strong color gradients





z~1 ULIRGs are extremely luminous:

- *z*~1 ULIRGs: 3.2 mag brighter than field galaxies (COSMOS, Capak, priv. comm.)
 (vs. *z*~0.1 ULIRGs: only 1 mag brighter than field galaxies)
- Strong luminosity evolution between *z*=0 and *z*=1?
- 83% of *z*~1 ULIRGs have high G (>0.55) vs. <50% at *z*~0; earlier merger stage at high-*z*?

Conclusions III: ULIRGs z<1

- ULIRGs at *z*~0 are brighter and bluer than Blue Cloud of field galaxies; very few Green Valley
- AGN ULIRGs are esp. bright and blue
- BC03 models: can make Red Cloud w/ or w/o AGN feedback, but not bright tip
- Robust morphology elusive: G-M20 prone to large errors, merger stage; <50% of ULIRGs fall in merger region of G-M20
- At *z*=1: 1/3 tidal tails; high G, highly concentrated, 2 mag more luminous than at z=0

IV. Submillimeter Galaxies at z>2

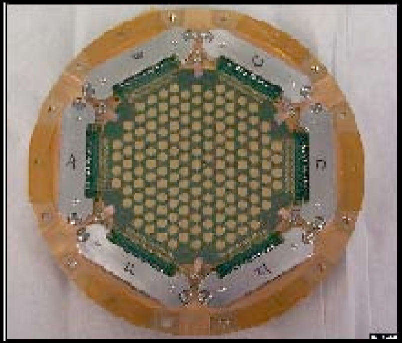
What is relation of SMGs to ultraluminous infrared galaxies (ULIRGs)? to massive ellipticals/bulges?

Submillimeter Galaxies

- $L_{FIR}>10^{12}\,L_{\odot}$ (= ULIRGs!)
- Dusty starburst galaxies, some AGN
- SFRs $10^3 - 10^4\,M_{\odot}$/yr (LBGs: 10-100 $M_{\odot}$/yr)
- N ~ 0.05 arcmin^{-2} (LBGs: 2 arcmin^{-2})
- Major contributor to CIB at $z>2$
- Faint/undetected in optical/NIR
- Progenitors of massive ellipticals today?
- Origin = ? (if not gas-rich spirals at $z>2$)

AzTEC

- Aztronomical Thermal Emission Camera
- 1-3 mm
- 144 Si_3N_4 micromesh “spider-web” bolometer pixels
- Beam Sizes (FWHM):
  - ASTE: 28 arcseconds
  - JCMT: 18 arcseconds
  - LMT: 5 arcseconds
- Mapping speed: 25x SCUBA/JCMT (LMT: 1000x SCUBA; ~SCUBA2)



AzTECs

UMass
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Min Yun
Stacey Alberts
Ryan Cybulski
David Welch
Seth Johnson
Christina Williams

UPenn
Kim Scott

UColorado
Jason Austermann

Illinois Wesleyan
Thushara Perera

INAOE
David Hughes
Itziar Aretxaga
Daniel Ferrusca
Miguel Velazquez
Milagros Zeballos
Alfredo Montana
Idalia Hernandez
David Omar Sanchez
Emally Aguilar

Sejong University
Young Woon Kang
Sungeun Kim
Soyoung Youn
Yonhwa Kim

Caltech
Jamie Bock

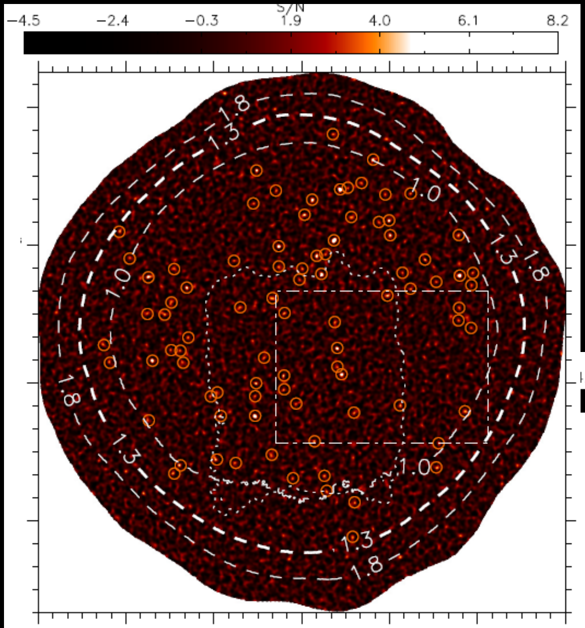
Smith College
James Lowenthal

Cardiff
Peter Ade
Phil Mauskopf
Douglas Haig
Simon Doyle
Piers Horner

SMG Surveys with AzTEC

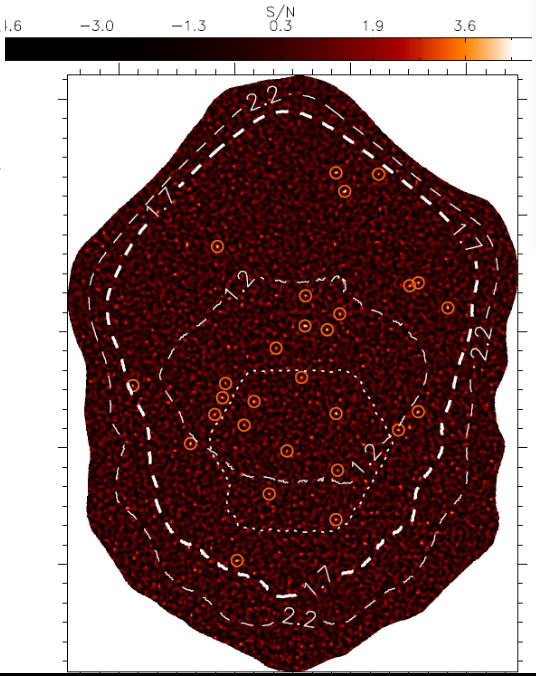
- Largest 1mm surveys yet
- 15-m JCMT (2005-2006):
  - GOODS-N
  - COSMOS
  - SHADES
- ASTE 10-m (2007-2009):
  - GOODS-S
  - COSMOS
  - SXDF
  - SEP
  - HZRG fields
  - High-z galaxy cluster fields
- (LMT/GTM 50-m in 2010?)

SMG Surveys with AzTEC

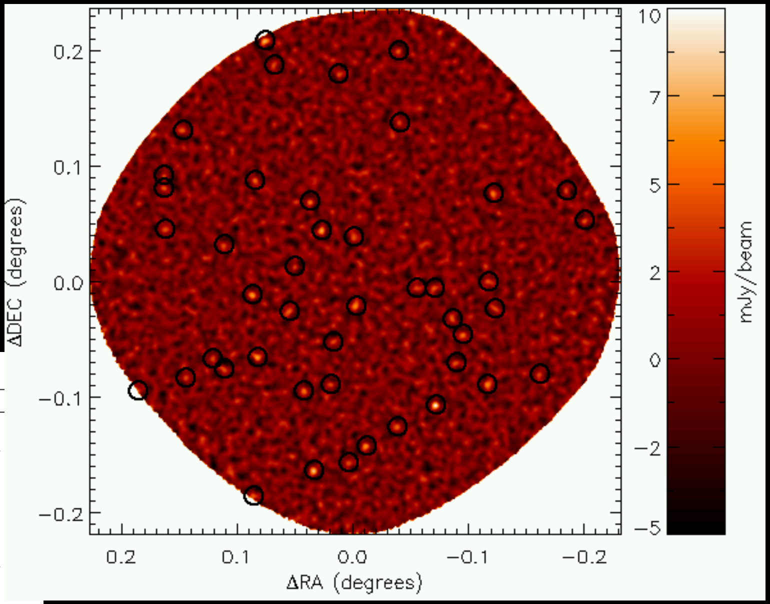


(Austermann et al. 2009)

AzTEC/SHADES – ½ deg^2



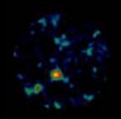
AzTEC/COSMOS('05)– 0.3 deg^2



(Scott et al. 2008)

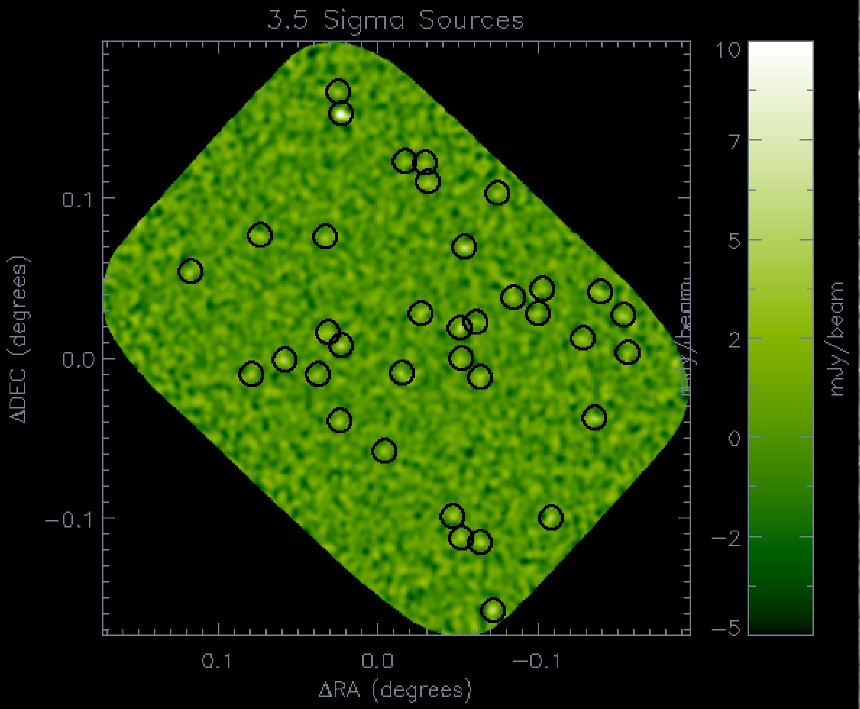
(G. Wilson)

SMG Surveys with AzTEC

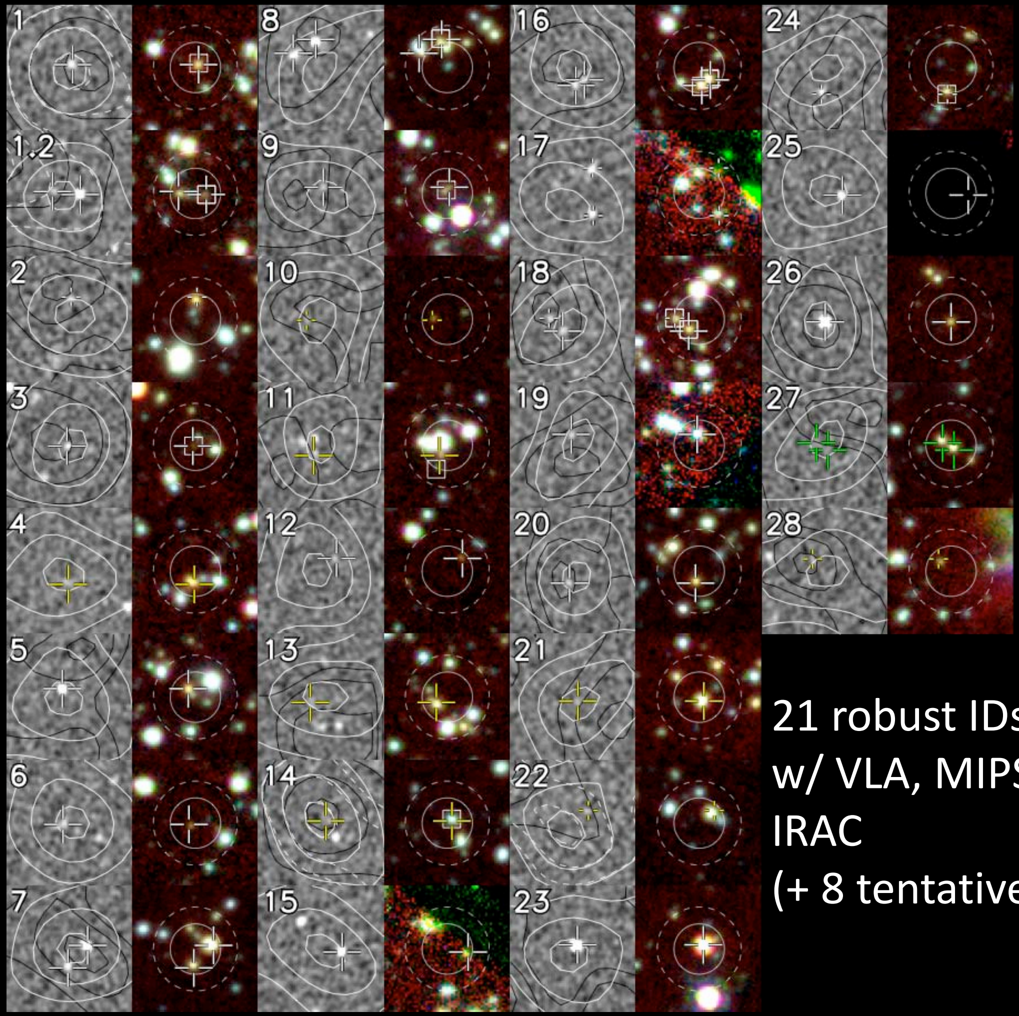


AzTEC/GOODS-N
245 arcmin^2

50 hours w/SCUBA:
5 sources (Hughes 98)



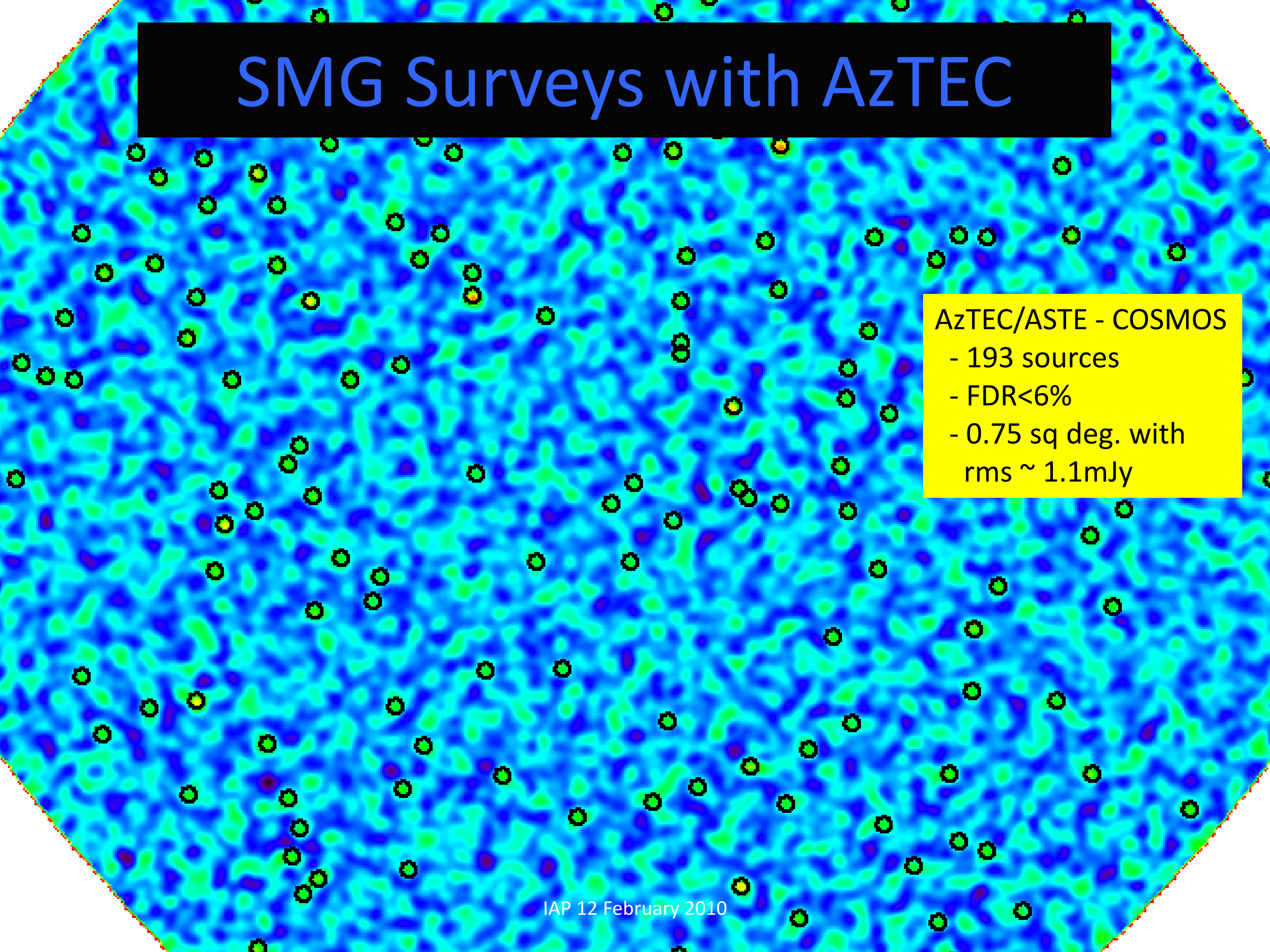
30 hours w/AzTEC: 29 sources (Perera 08)



21 robust IDs
w/ VLA, MIPS,
IRAC
(+ 8 tentative)

Chapin 09

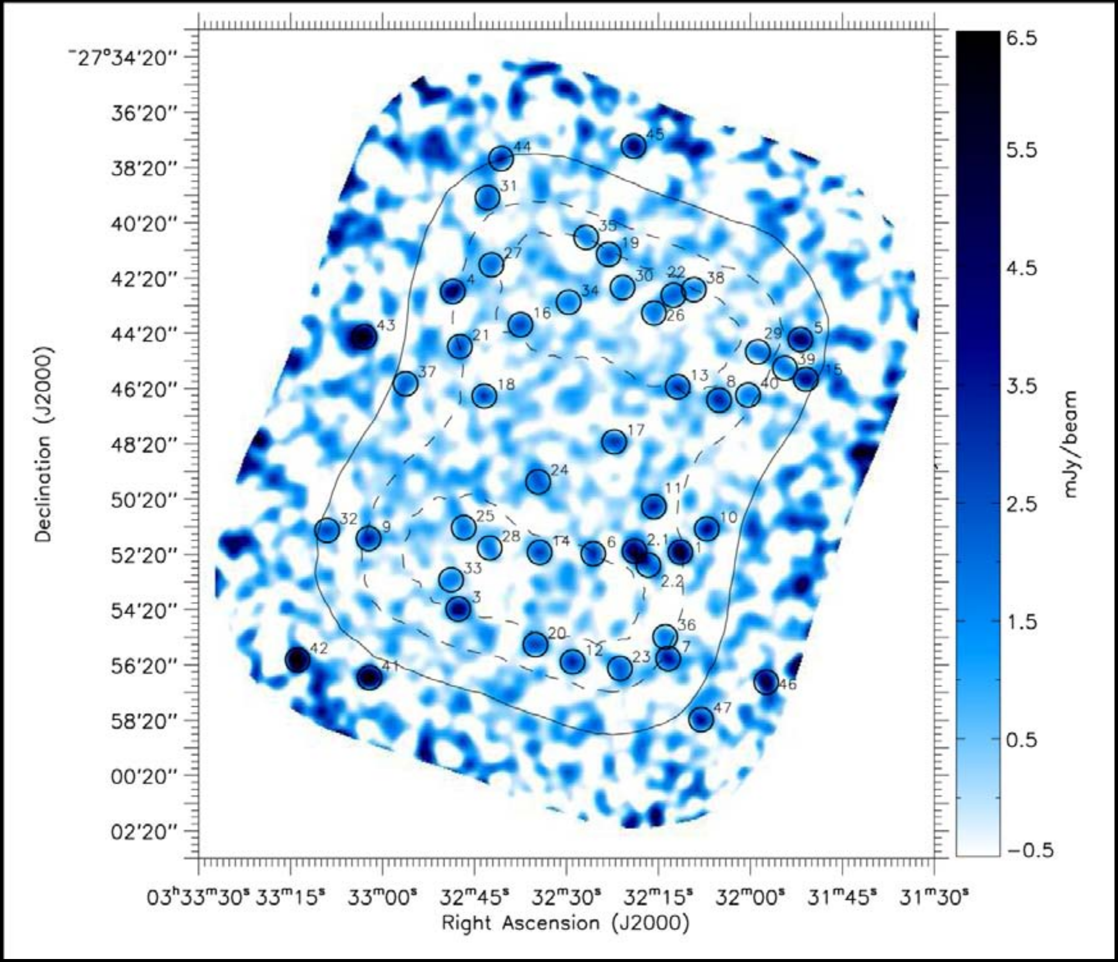
SMG Surveys with AzTEC



AzTEC/ASTE - COSMOS

- 193 sources
- FDR<6%
- 0.75 sq deg. with rms ~ 1.1mJy

SMG Surveys with AzTEC



GOODS-S
Scott et al. (submitted)

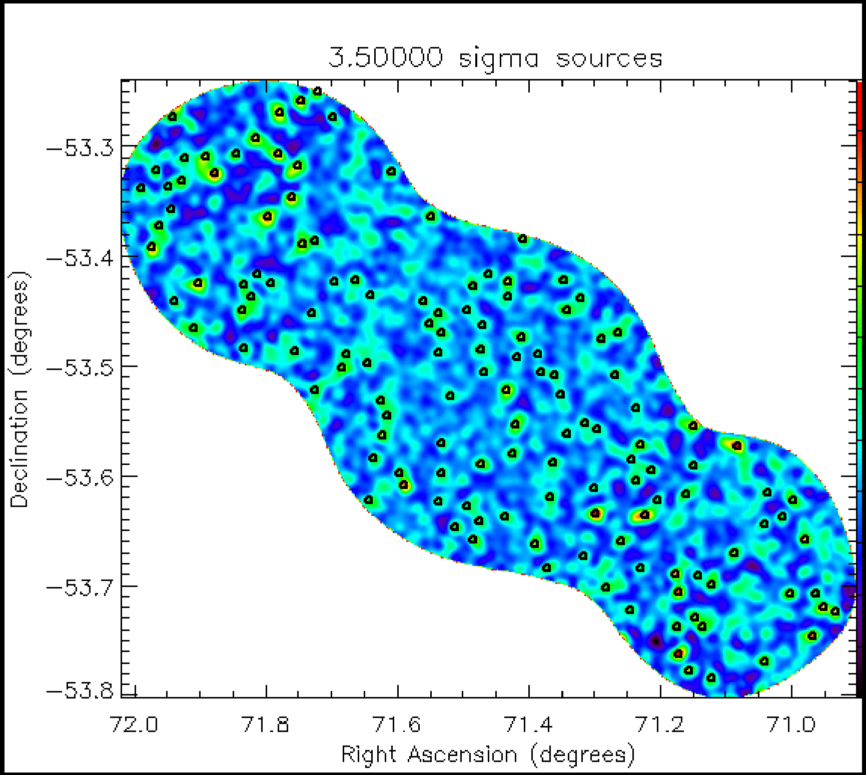
- 47 sources
- FDR<1
- 0.5mJy rms

(Scott et al. 2010)

(G. Wilson)

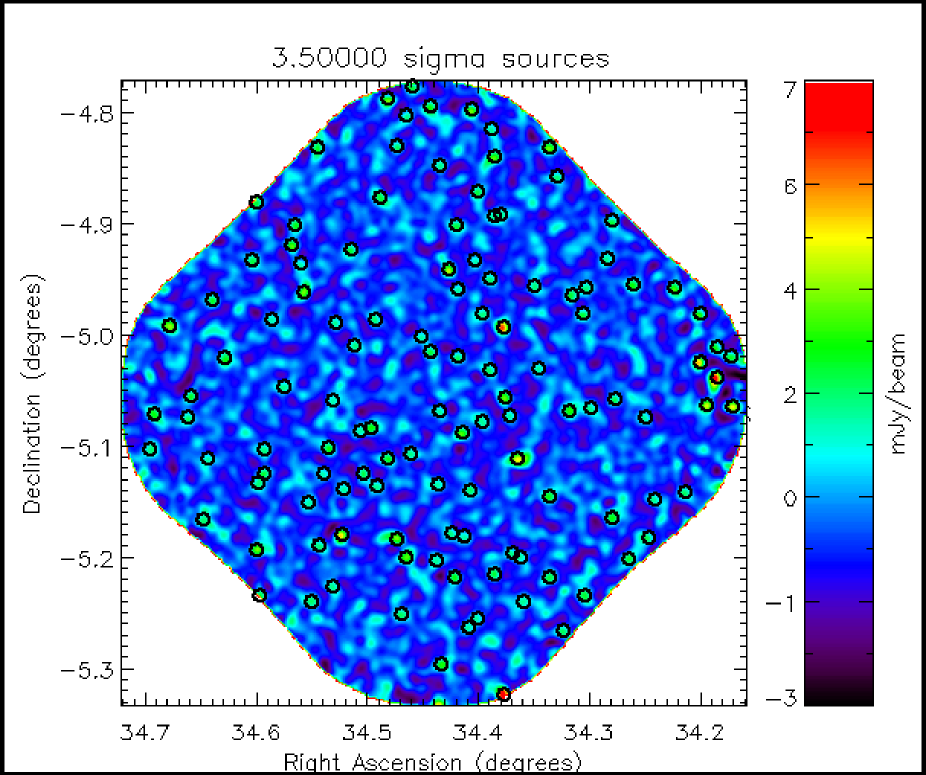
SMG Surveys with AzTEC

SEP



(Hatsukade et al. in prep.)

SXDF



(Kotaro et al. in prep.)

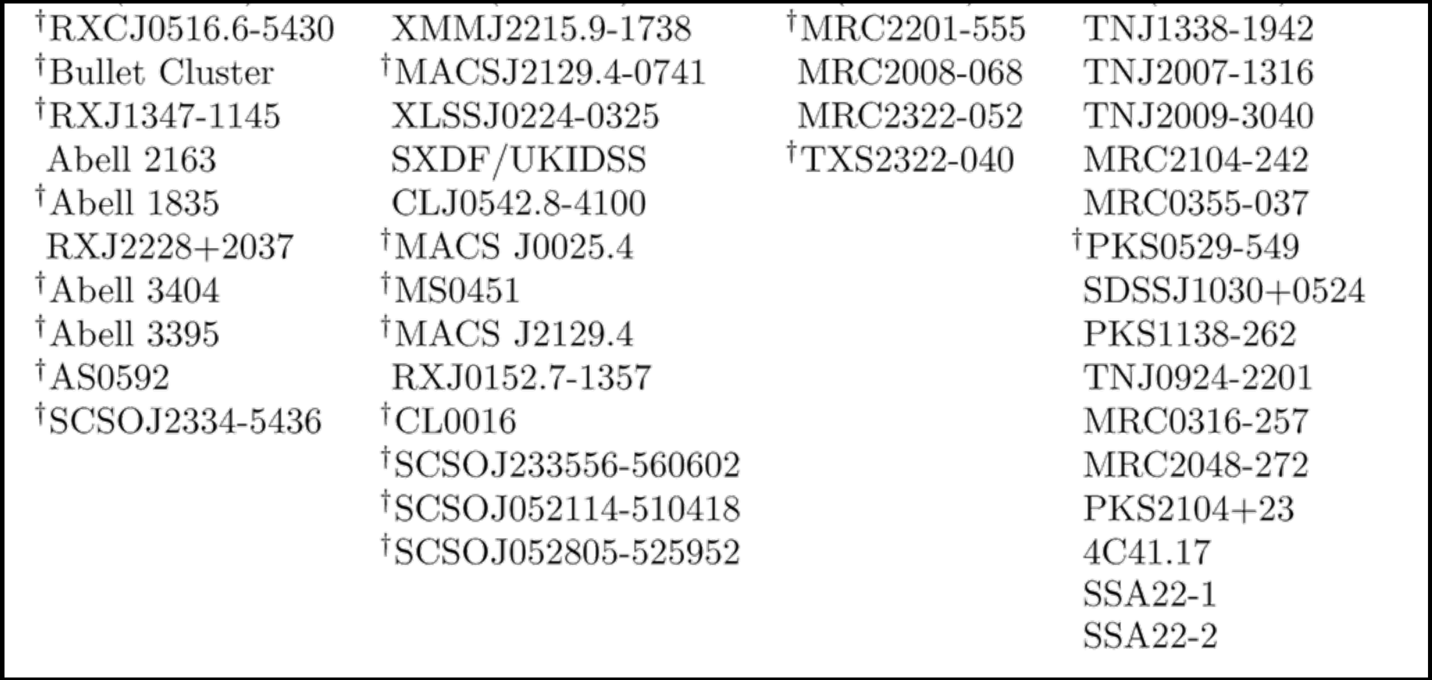
- both maps ~0.5 mJy rms
- total of ~250 new SMGs

(G. Wilson)

Plus: "ACES" Biased Field Targets

Clusters

HzRGs



†RXCJ0516.6-5430
†Bullet Cluster
†RXJ1347-1145
Abell 2163
†Abell 1835
RXJ2228+2037
†Abell 3404
†Abell 3395
†AS0592
†SCSOJ2334-5436

XMMJ2215.9-1738
†MACSJ2129.4-0741
XLSSJ0224-0325
SXDF/UKIDSS
CLJ0542.8-4100
†MACS J0025.4
†MS0451
†MACS J2129.4
RXJ0152.7-1357
†CL0016
†SCSOJ233556-560602
†SCSOJ052114-510418
†SCSOJ052805-525952

†MRC2201-555
MRC2008-068
MRC2322-052
†TXS2322-040

TNJ1338-1942
TNJ2007-1316
TNJ2009-3040
MRC2104-242
MRC0355-037
†PKS0529-549
SDSSJ1030+0524
PKS1138-262
TNJ0924-2201
MRC0316-257
MRC2048-272
PKS2104+23
4C41.17
SSA22-1
SSA22-2

SCUBA/SHADES
SXDF
Dunlop et al. 2006

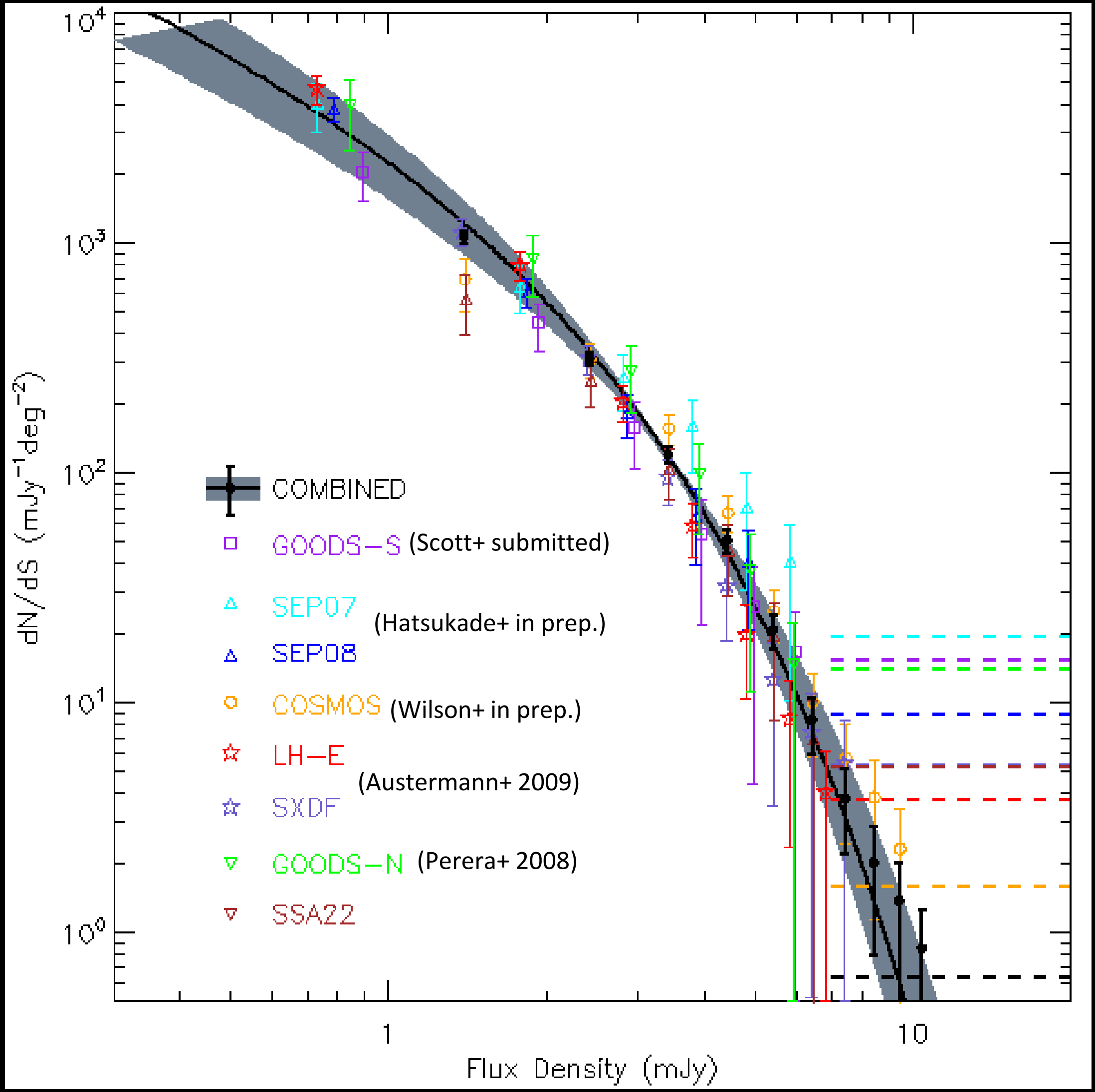
BO
-N2
e et al. 2004

Known Clusters

Submm survey

(G. Wilson)

“Blank-Field” SMG Number Counts

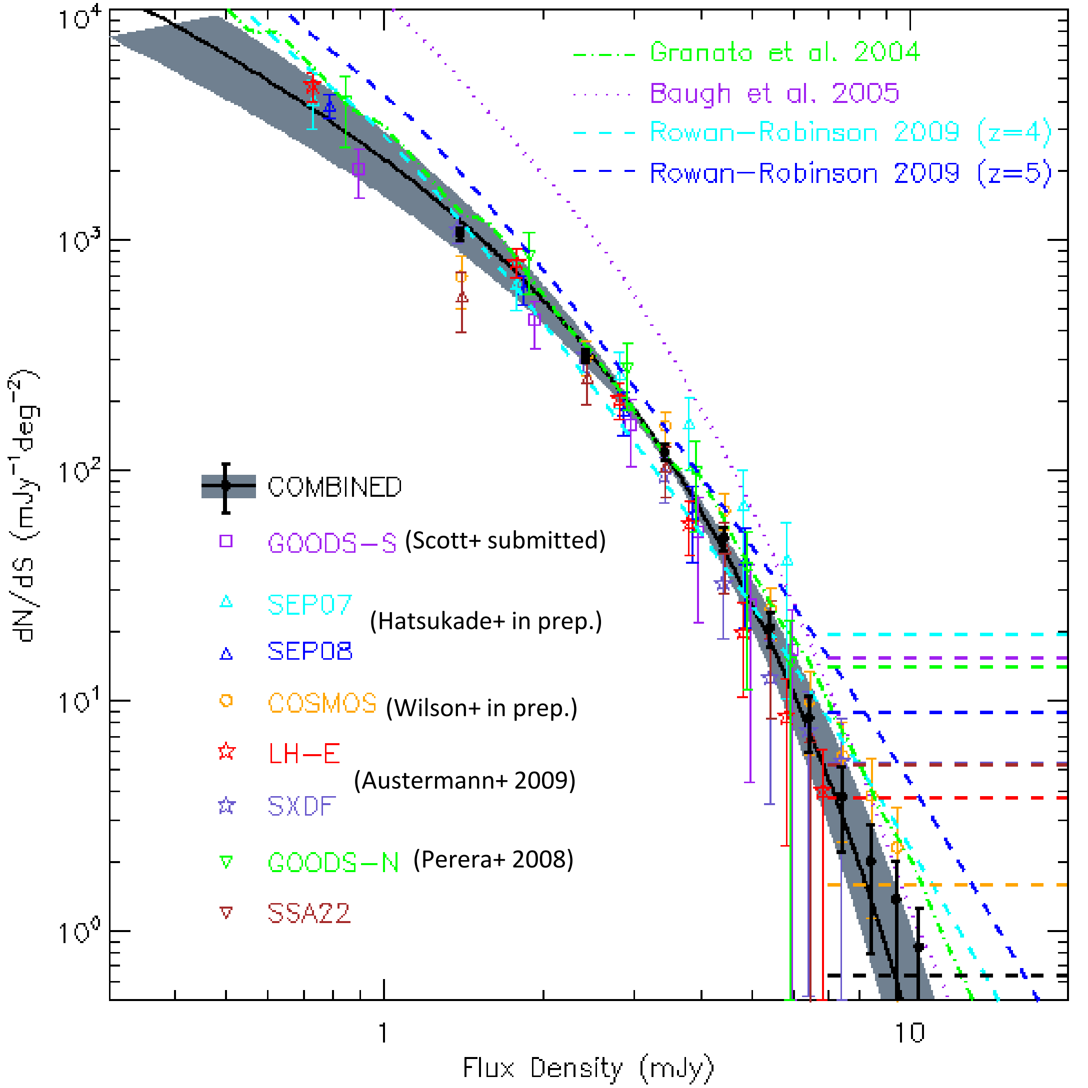


Scott et al. in prep

- 838 sources
- 1.74 sq deg.
- New constraints on counts at both bright and faint end

(G. Wilson)

“Blank-Field” SMG Number Counts

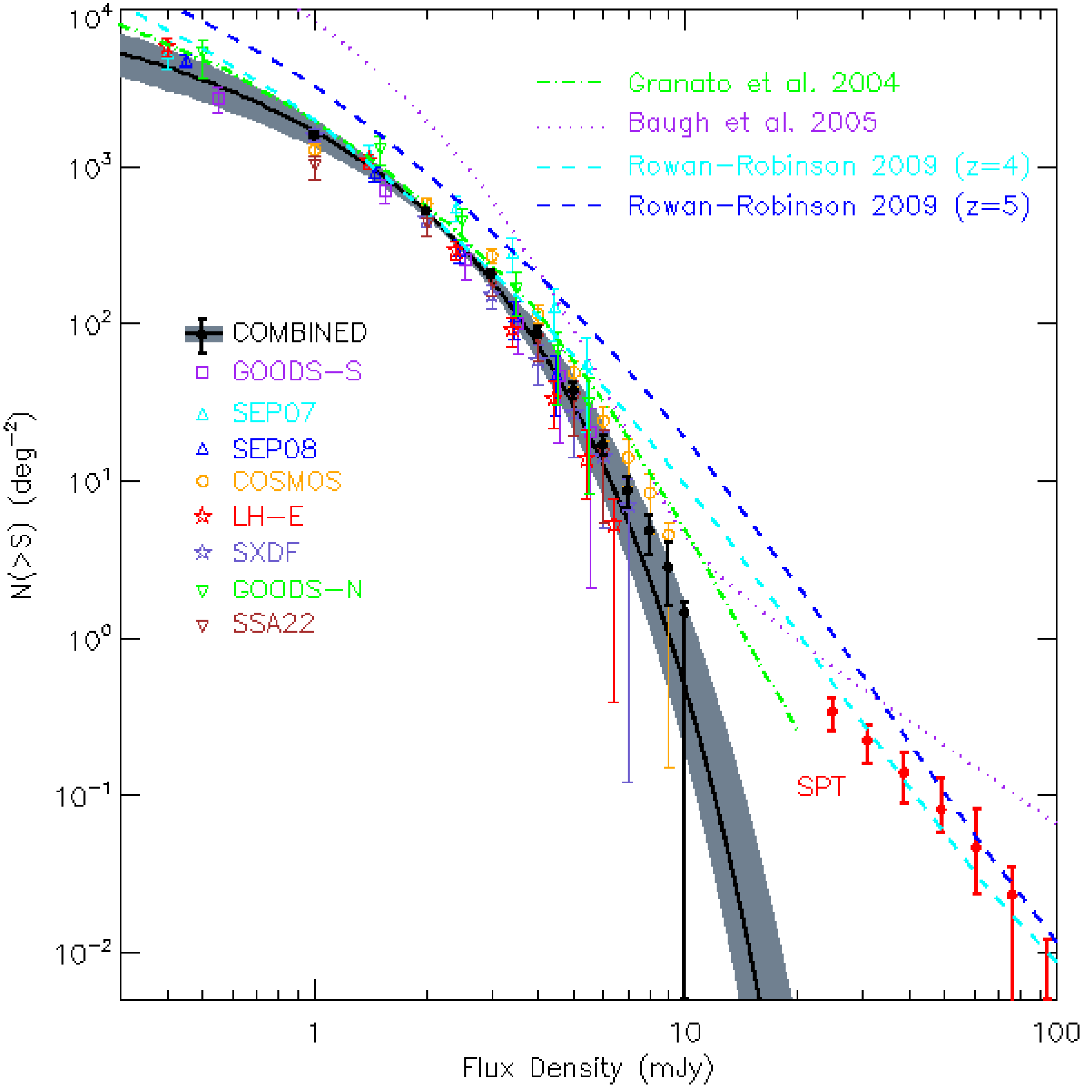


Scott et al. in prep

- 838 sources
- 1.74 sq deg.
- New constraints on counts at both bright and faint end
- Models stressed at both ends

(G. Wilson)

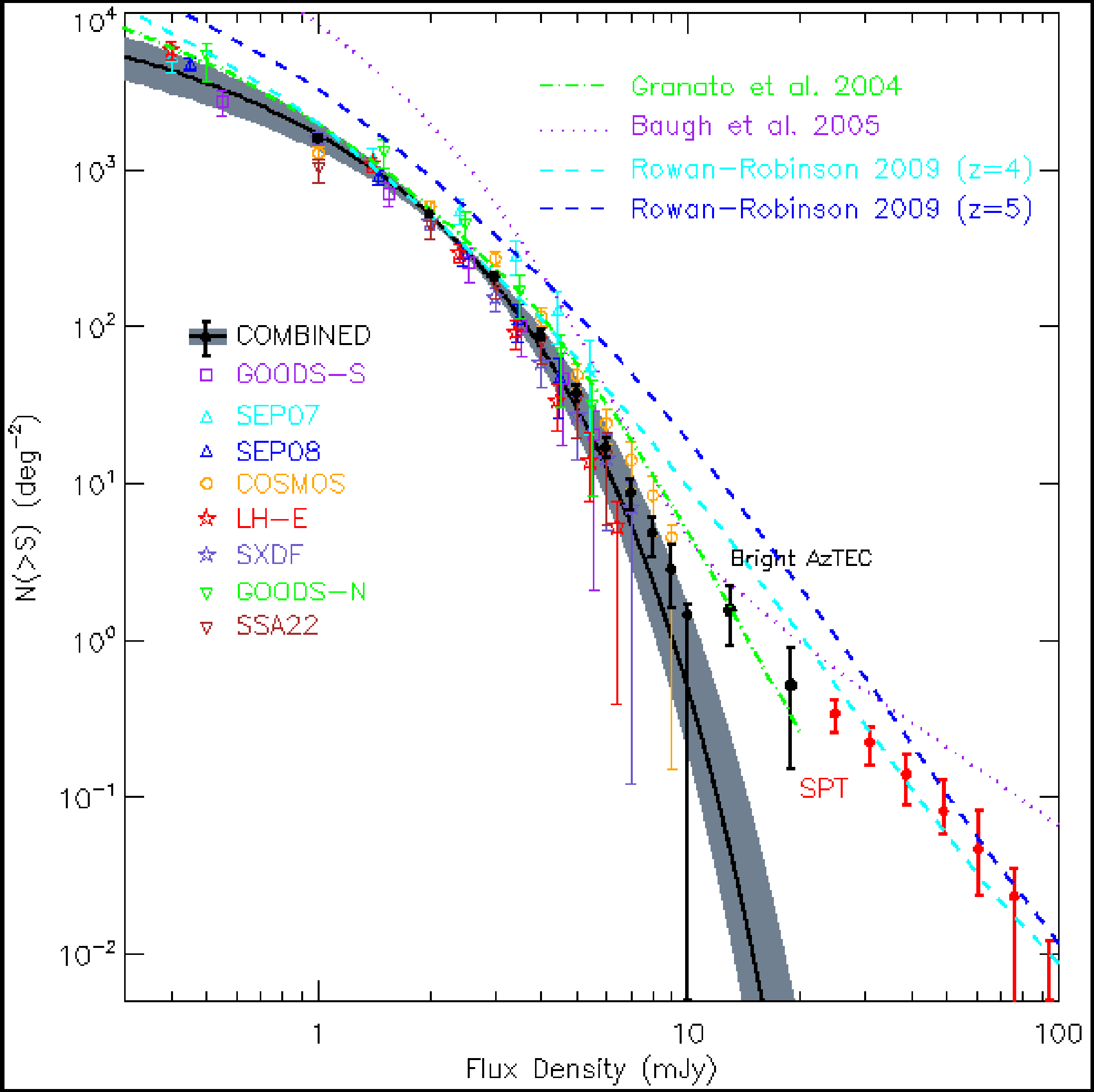
“Bright” SMG Number Counts



SPT from Vieira+ 2009 assuming $S_{1.1}/S_{1.4}=2$

(G. Wilson)

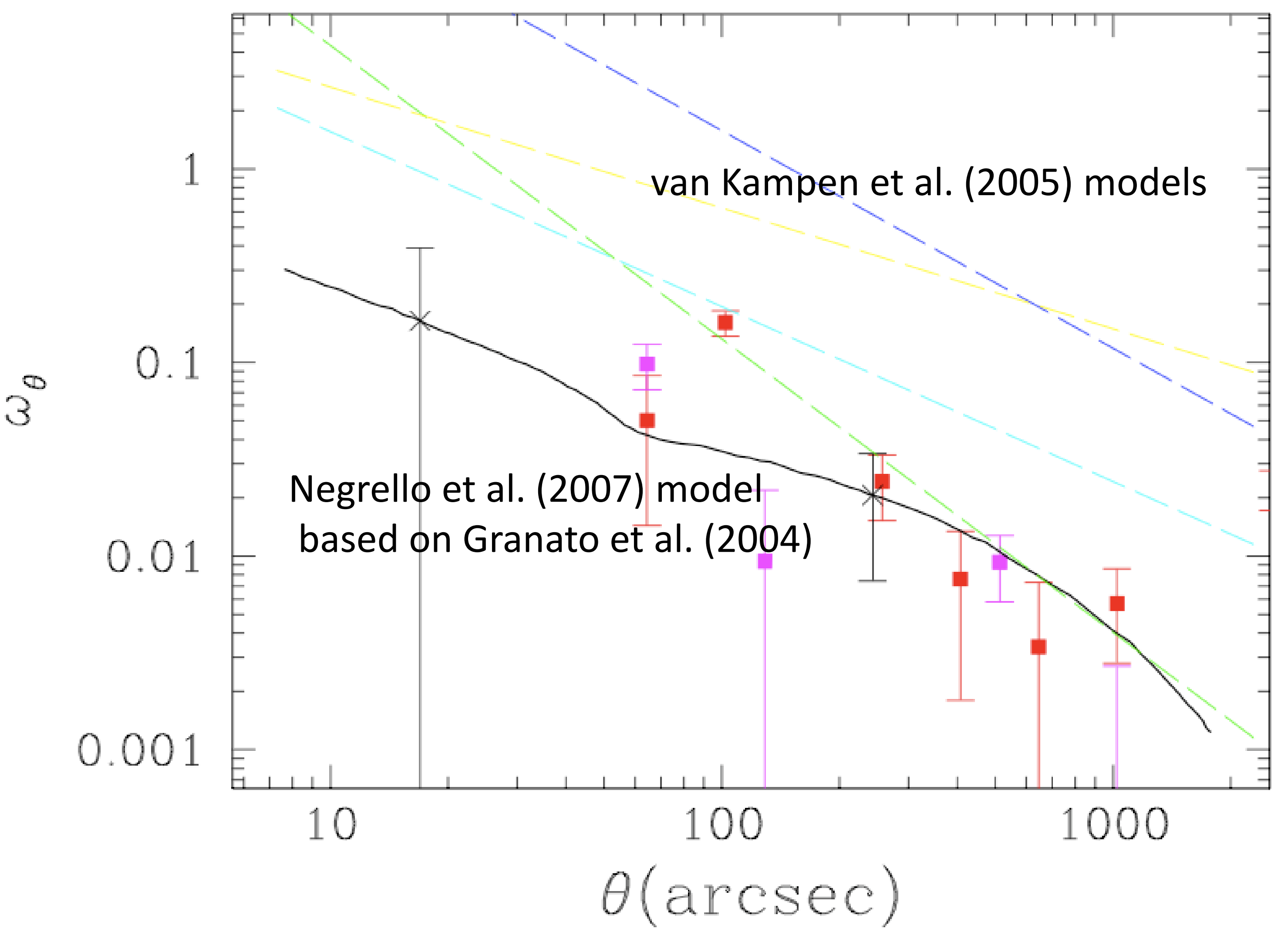
"Bright" SMG Number Counts



SPT from Vieira+ 2009 assuming $S_{1.1}/S_{1.4}$=2

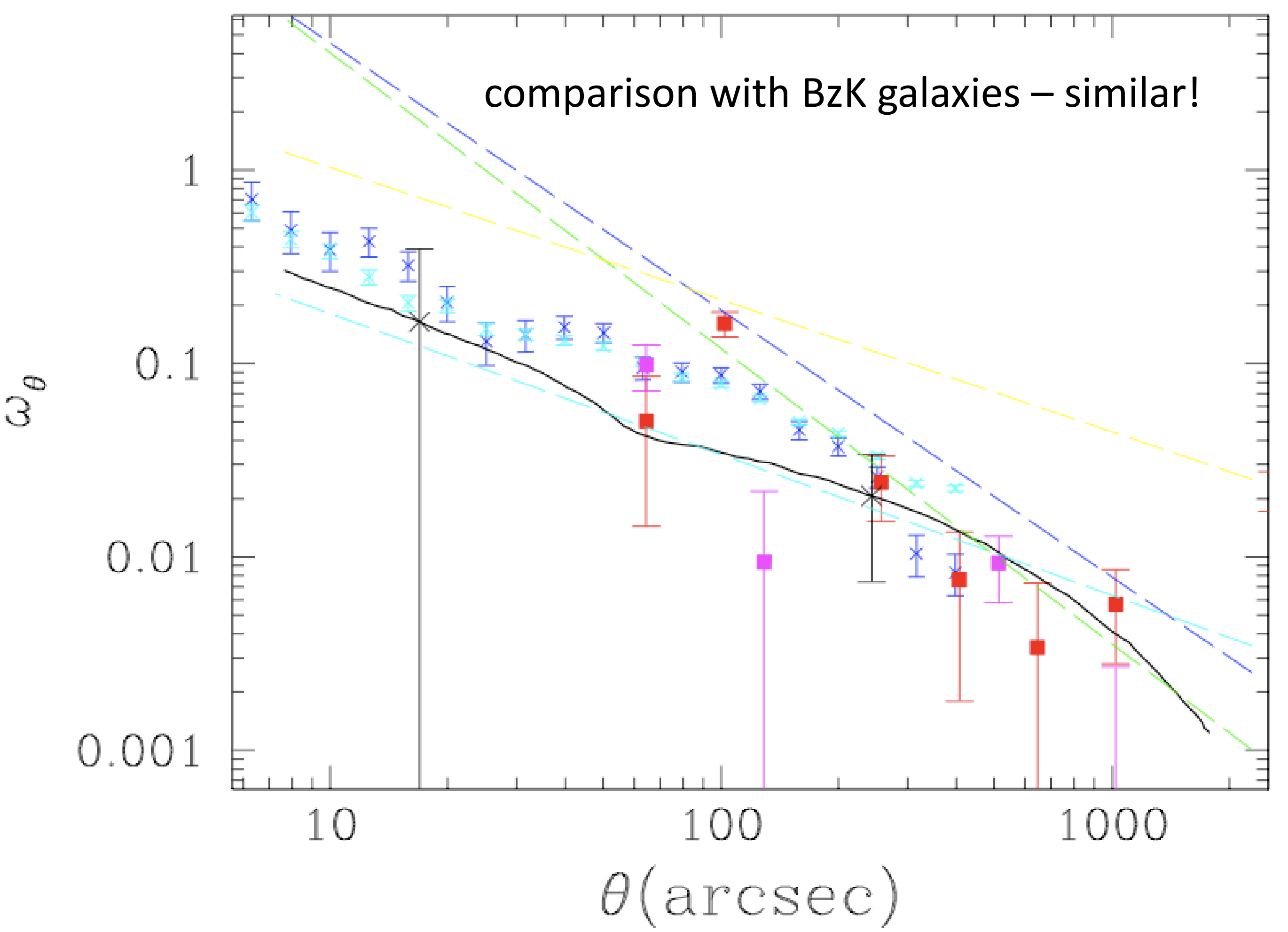
(G. Wilson)

Clustering of COSMOS AzTEC Sources



(Yun)

Clustering of COSMOS AzTEC Sources



(Yun)

Conclusions IV: AzTEC SMGs

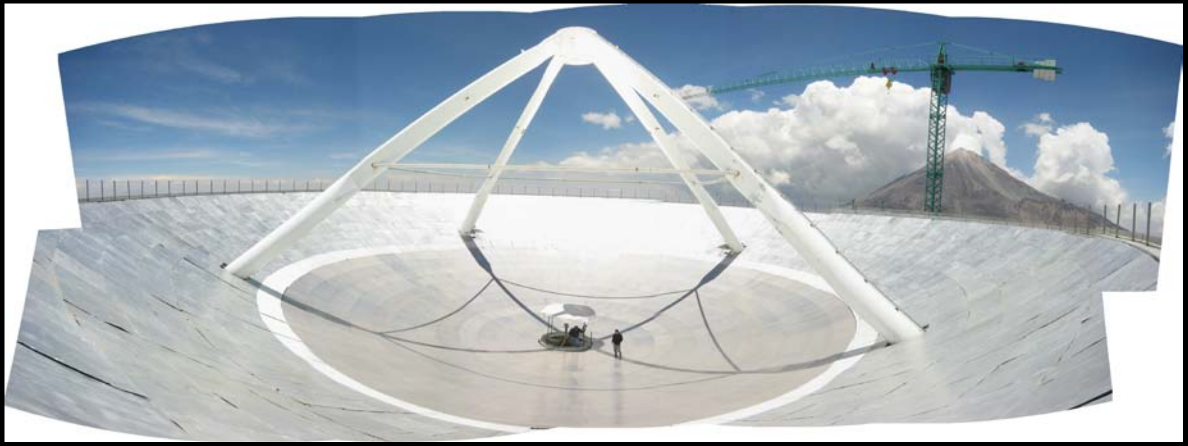
- “Blank field” SMG number counts ($0.5<S_{1.1mm}<10$mJy) now tightly constrained.
- Some evidence for a broader redshift distribution than $2 < z < 3$.
- COSMOS field: first estimate of the angular correlation function of SMGs.
- Remarkably similar to $\omega(\theta)$ of BzK galaxies.
- Sample of 300 objects still not sufficient to constrain true spatial distribution → need a sample 3-10 times larger at a higher resolution . . . .Where could we find such a sample?

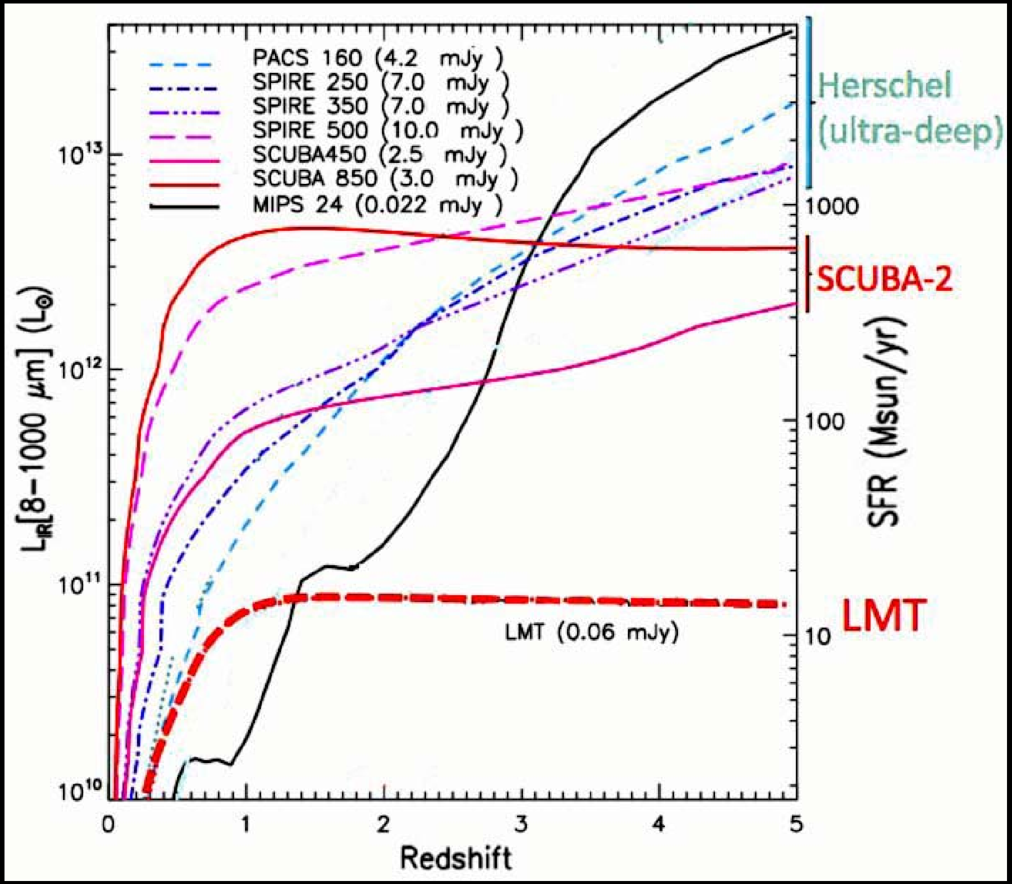
50-m Large Millimeter Telescope/Gran Telescopio Millimetrico

- UMass + Mexico
- Cierra la Negra (5000m)
- \$200M; largest science project ever for Mexico
- 65 µm (rms) active surface
- 6” FWHM beam at 1 mm
- Pointing to 1”
- AzTEC, Redshift, SEQUOIA, SPEED
- 1000’s of SMGs/night; pathfinder for ALMA

LMT/GTM First Light Campaign 2010

- Telescope has all major subsytems ready and inner 32-m diameter of reflector suface
- Next Steps:
  - Commission drive system
  - Holographic setting of inner segment
  - Integrate optical systems
  - First light with UMass receivers (AzTEC, Redshift)





(figure courtesy M. Dickinson/D. Elbaz)

(G. Wilson)

Instrument	Resolution	Mapping Speed [arcmin2/mJy2/hr]	Confusion Limit [mJy]
MAMBO/IRAM-30	11”	3	0.5
LABoCa/APEX	20”-30”	9	2
Bolocam/CSO	30”	10-13	2
AzTEC/JCMT	18”	20-30	1.5
AzTEC/ASTE	28”	20	2

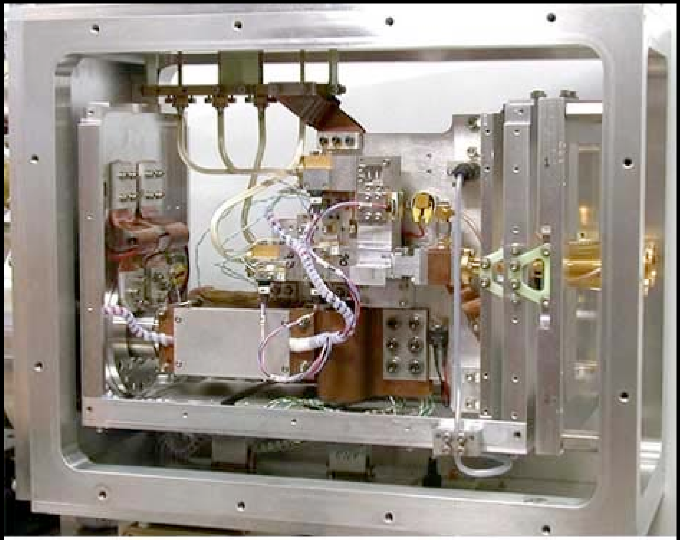
Perspective on 32m dish operation:

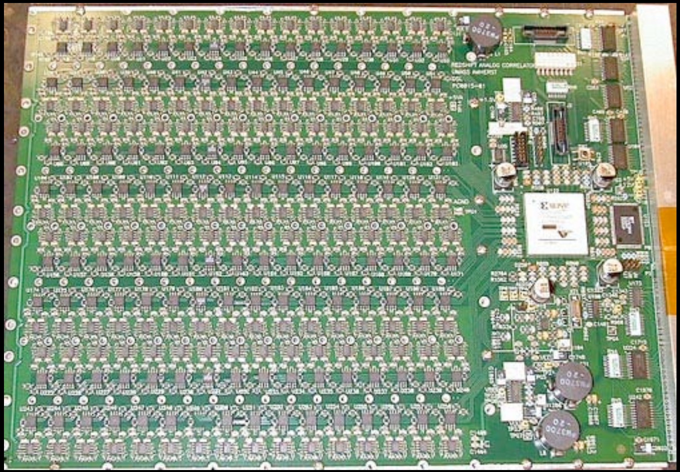
- repeating all deep SMG surveys to date takes 24 hours (8” resolution)
- imaging 2sq deg COSMOS field to 0.1mJy rms takes 1200 hrs (key project size)
- 100 sq. deg. at 10mJy rms (SPT-bright sources) takes 6 hours

(G. Wilson)

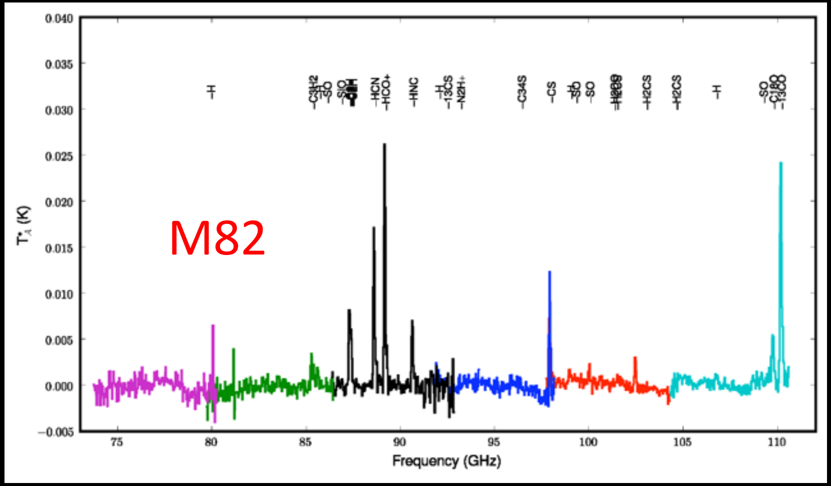
Redshift Search Receiver

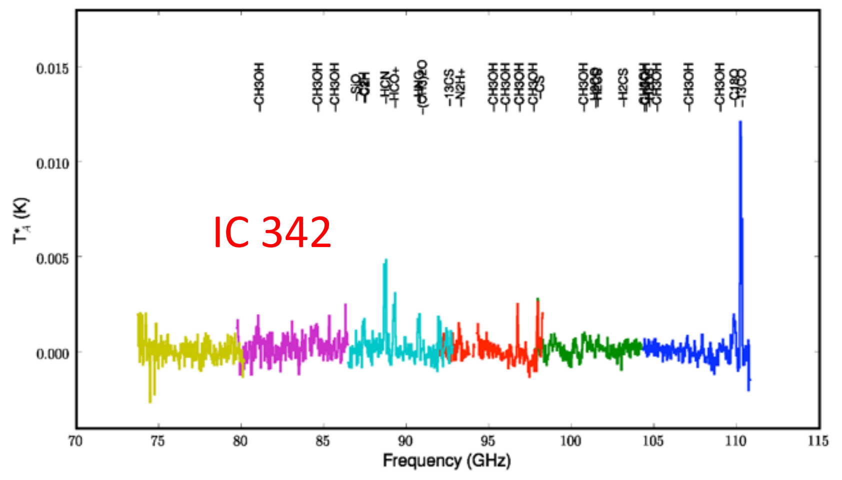
- 4 receivers cover 74-111 GHz (37 GHz bandwidth!) – like optical Δλ/λ
- MMIC amplifiers
- 4 pixels, 6 spectrometers each
- 31 MHz resolution (100 km/s)
- Stable baseline, sky sub
- Follow gas at high-*z*!
- Cf. CSO/Z-spec , IRAM/EMIR, GBT/zspectrometer, NRO 45-m…



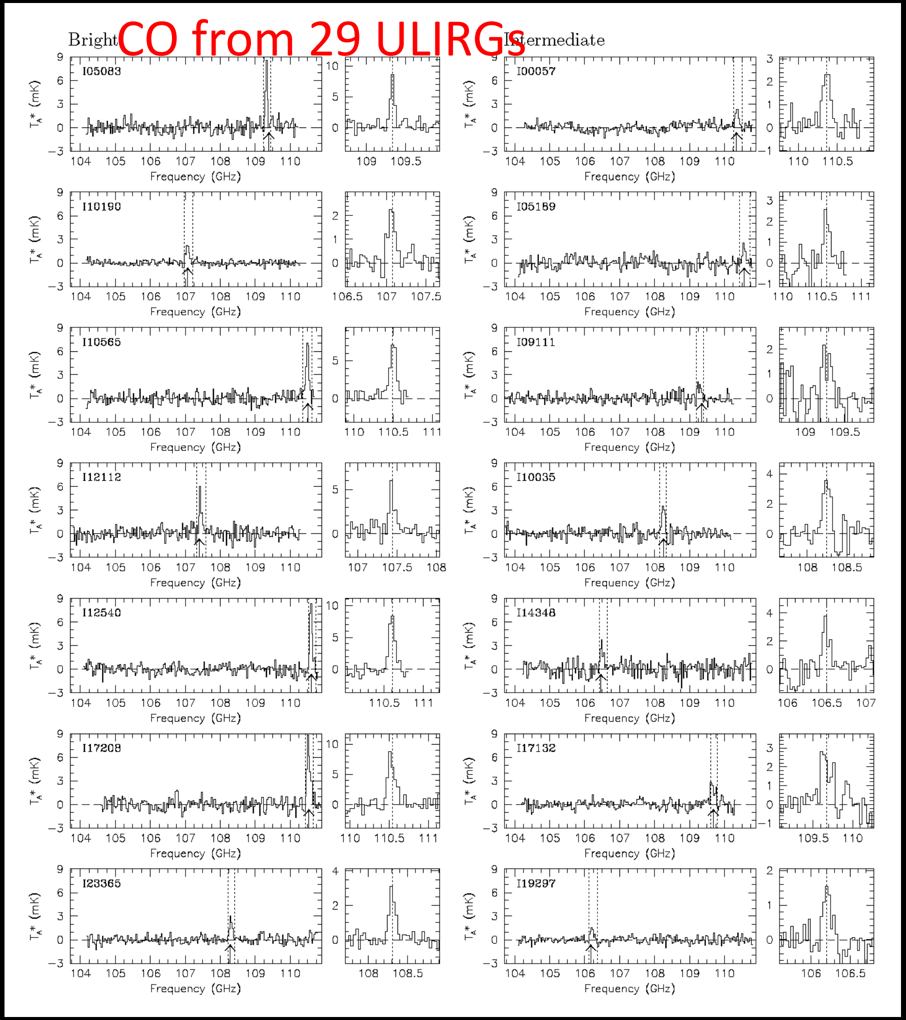


Redshift Search Receiver: early science with FCRAO 14m


M82


IC 342

Snell 08


CO from 29 ULIRGs

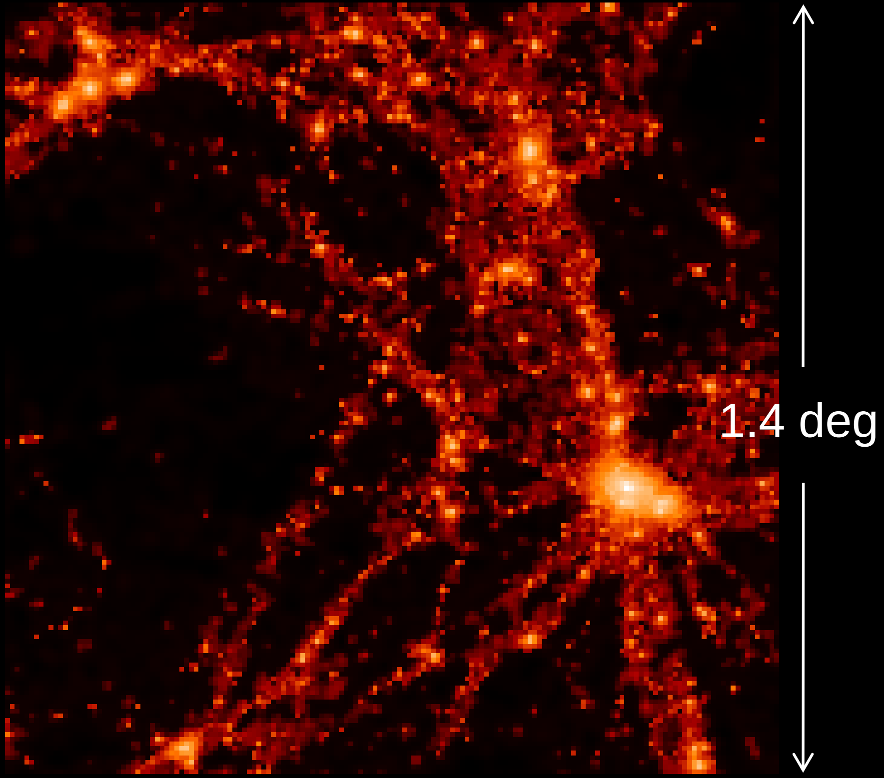
Chung 09

Planned Future LMT Continuum Inst.

TolTEC

- 1.1mm imager filling 4’ diameter field of view
- ~5000 detectors
- ~36,000 arcmin^2/mJy^2/hr mapping speed

Imaging the entire
2 sq. deg. COSMOS field
to 0.1mJy rms
(SFR~20-30 M_{sun}/yr)
will require only 20 hours.



(G. Wilson)

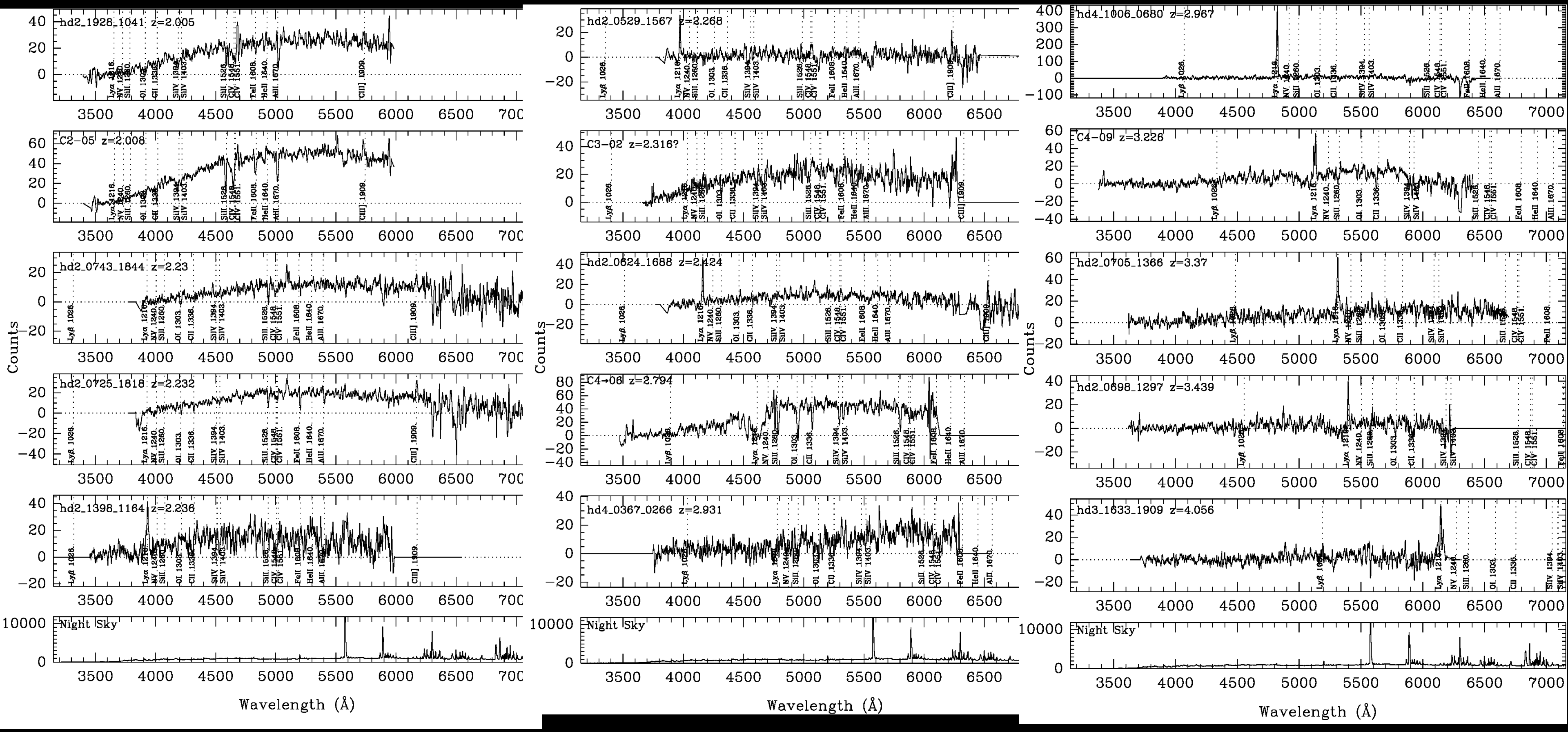
Final Summary

- Lyman break galaxies at z~3 are starbursts with *wide range* of morphologies, masses
- LBG analogs at z<1 (LCBGs) also show wide variety of morphologies, low mass, maximal SF, strong evolution
- ULIRGs at z<1 (usually dusty merger starbursts) are bluer and brighter in optical than “blue cloud” field galaxies, can evolve to middle of red sequence
- Submm galaxies at z>2 are strongly evolving, ULIRG-like, clustered, dusty starbursts, broad range of z
- Overall balance (optical vs. IR) still being debated. Panchromatic view required for full tally of SF in starbursts.

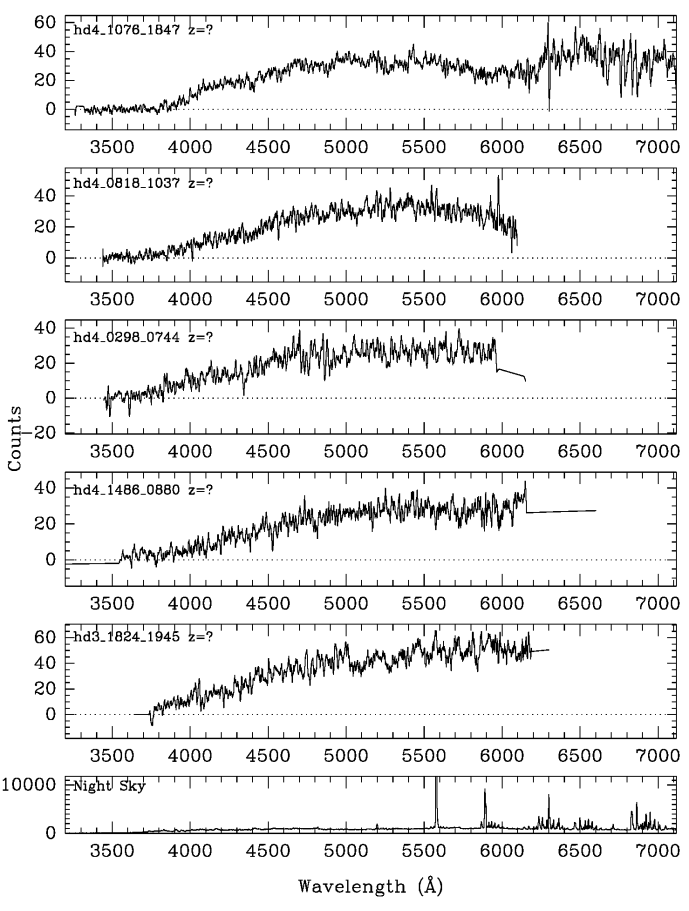
Merci!

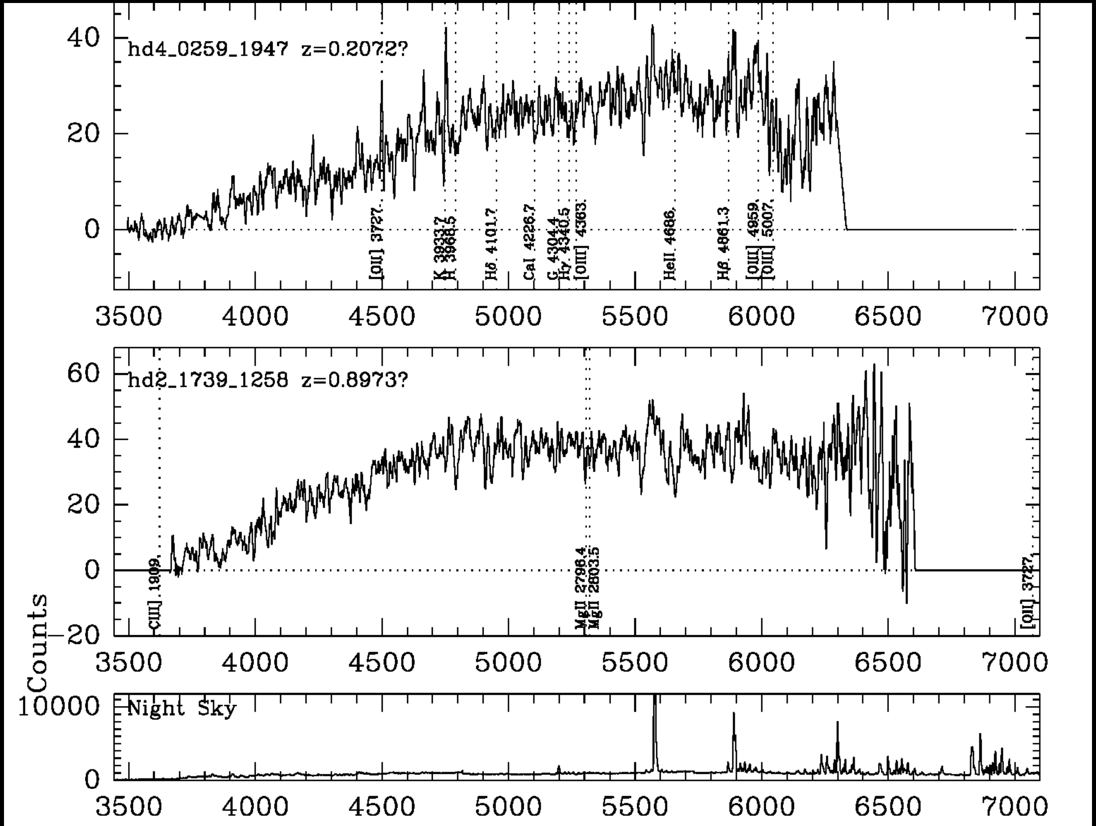
Miscellany

LBG 1D spectra 2 < z < 4



LBG 1D spectra: *z* uncertain



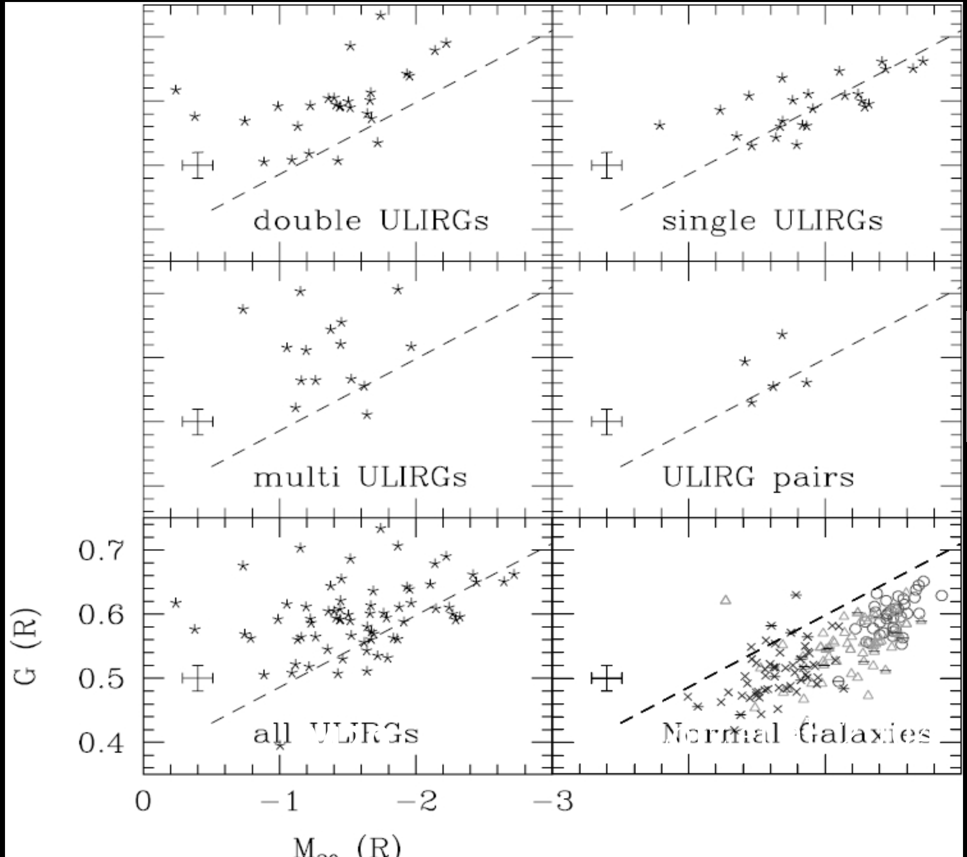


What would LCBGs and HII galaxies look like at z~3?

- Simulate z=3 HDF view:
  - Rebin STIS images
  - Add noise to match S/N at *z*=3
- Low redshift sample not visible at *z*=3 (but barely visible in ACS/GOODS/UDF)
- *z*~0.75 sample all visible at *z*=3; morphologies much simpler, more compact; low-SB structure lost.

Quantitative Morphology Analysis

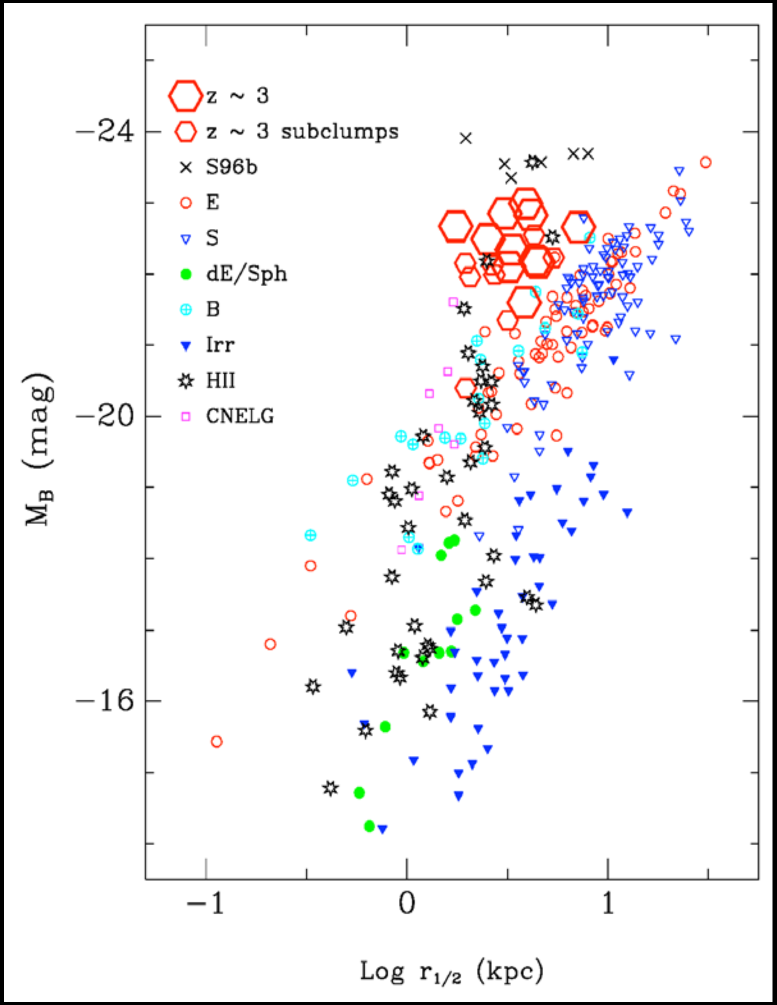
- **Gini** – the distribution of pixel intensities, concentration-like parameter (Gini 1912; Abraham et al. 2003; Lotz et al. 2004)
- **M20** – the normalized 2nd-order moment of the 20% brightest pixels, in logarithm scale (Lotz et al. 2004)
- Local ULIRGs with high spatial resolution are well separated from normal galaxies in the G-M20 plot (Lotz et al. 2004)

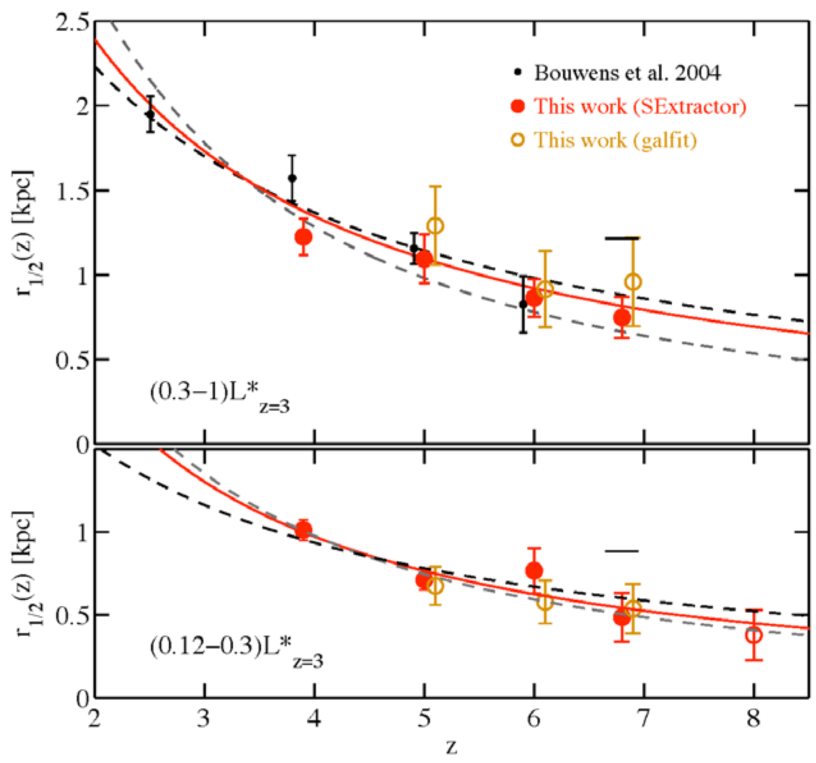


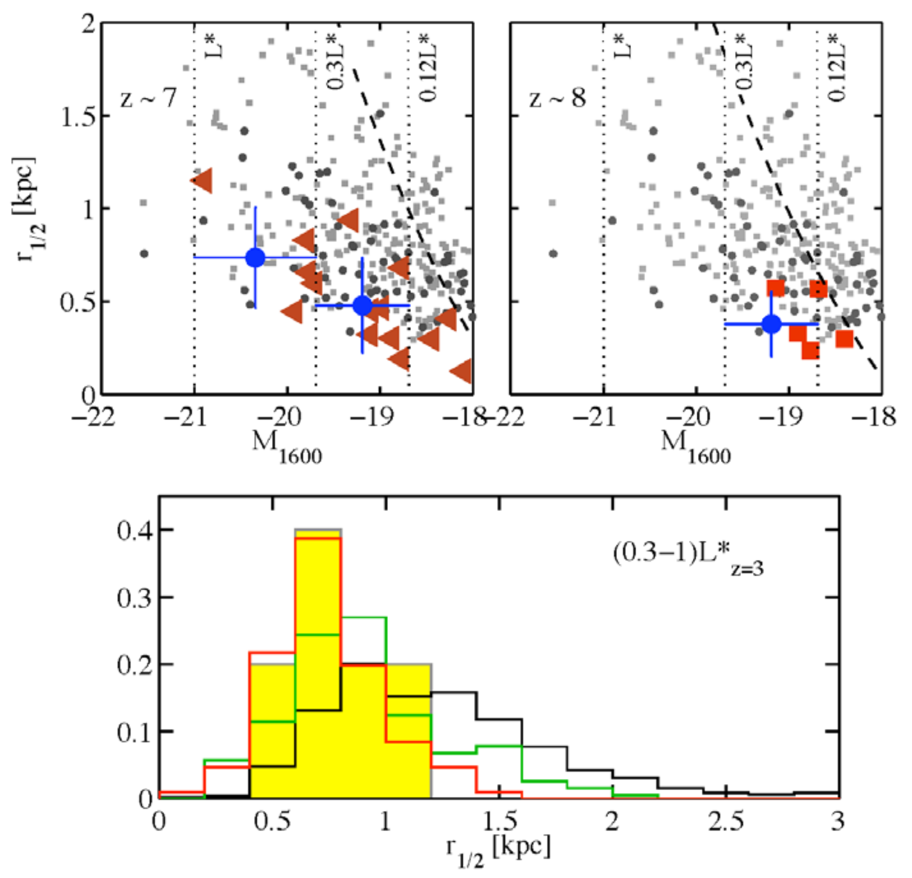
$$G = \frac{1}{|\bar{X}|n(n-1)} \sum_{i}^{n} (2i - n - 1)|X_i|$$

$$M_{\mathrm{tot}} = \sum_{i}^{n} M_i = \sum_{i}^{n} f_i\left[(x_i - x_c)^2 + (y_i - y_c)^2\right.$$

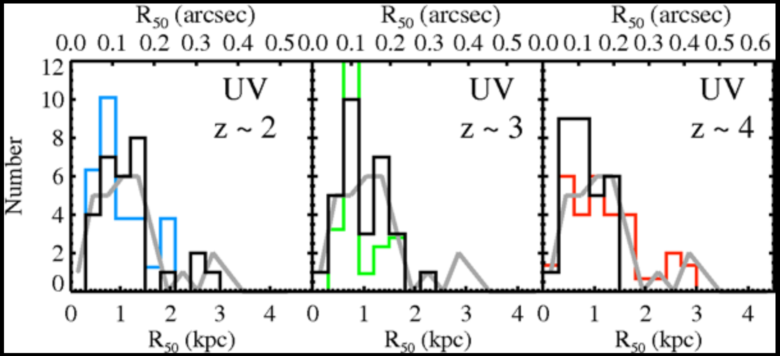
$$M_{20} \equiv \log 10\left(\frac{\sum_i M_i}{M_{\mathrm{tot}}}\right), \text{ while} \sum_i f_i < 0.2 f_{\mathrm{tot}}$$

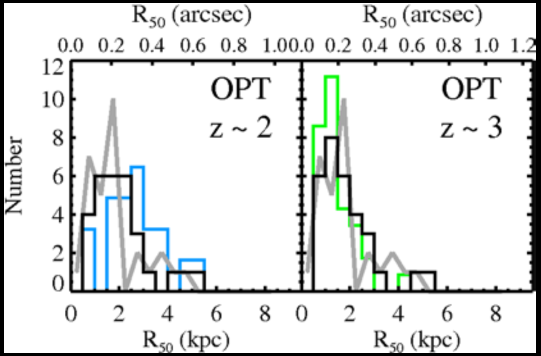

z ~ 3
z ~ 3 subclumps
S96b
E
S
dE/Sph
B
Irr
HII
CNELG
−24
−20
−16
M_B (mag)
−1
0
1
Log $r_{1/2}$ (kpc)


Bouwens et al. 2004
This work (SExtractor)
This work (galfit)
$r_{1/2}(z)$ [kpc]
2.5
2
1.5
1
0.5
0
$(0.3-1)L^*_{z=3}$
$(0.12-0.3)L^*_{z=3}$
2
3
4
5
6
7
8
z


z ~ 7
z ~ 8
L*
0.3L*
0.12L*
$r_{1/2}$ [kpc]
2
1.5
1
0.5
0
−22
−21
−20
−19
−18
M_{1600}
$(0.3-1)L^*_{z=3}$
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
2.5
3
$r_{1/2}$ [kpc]

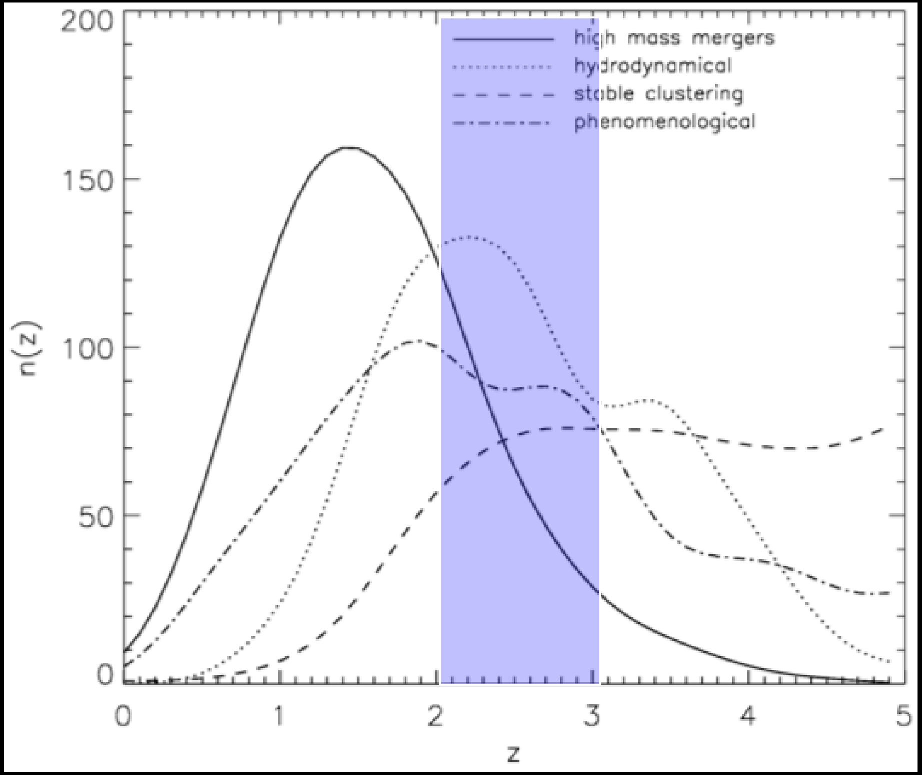
Oesch 10

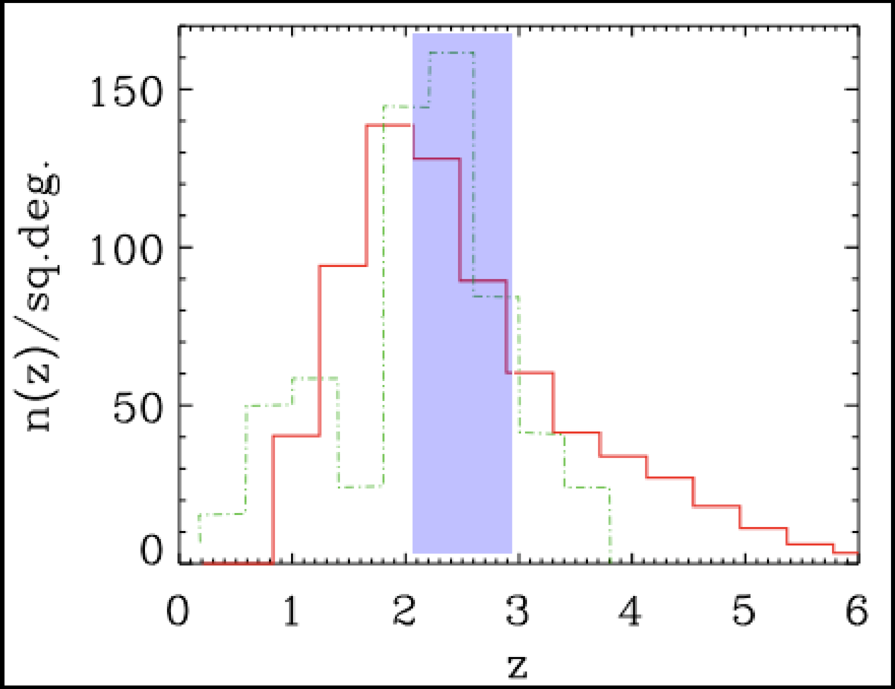

R_{50} (arcsec)
0.0 0.1 0.2 0.3 0.4 0.5
R_{50} (arcsec)
0.0 0.1 0.2 0.3 0.4 0.5
R_{50} (arcsec)
0.0 0.1 0.2 0.3 0.4 0.5 0.6
Number
0 2 4 6 8 10 12
UV
z ~ 2
UV
z ~ 3
UV
z ~ 4
0 1 2 3 4
R_{50} (kpc)
0 1 2 3 4
R_{50} (kpc)
0 1 2 3 4
R_{50} (kpc)


R_{50} (arcsec)
0.0 0.2 0.4 0.6 0.8 1.0
R_{50} (arcsec)
0.0 0.2 0.4 0.6 0.8 1.0 1.2
Number
0 2 4 6 8 10 12
OPT
z ~ 2
OPT
z ~ 3
0 2 4 6 8
R_{50} (kpc)
0 2 4 6 8
R_{50} (kpc)

Overzier 10

Model Redshift Distributions

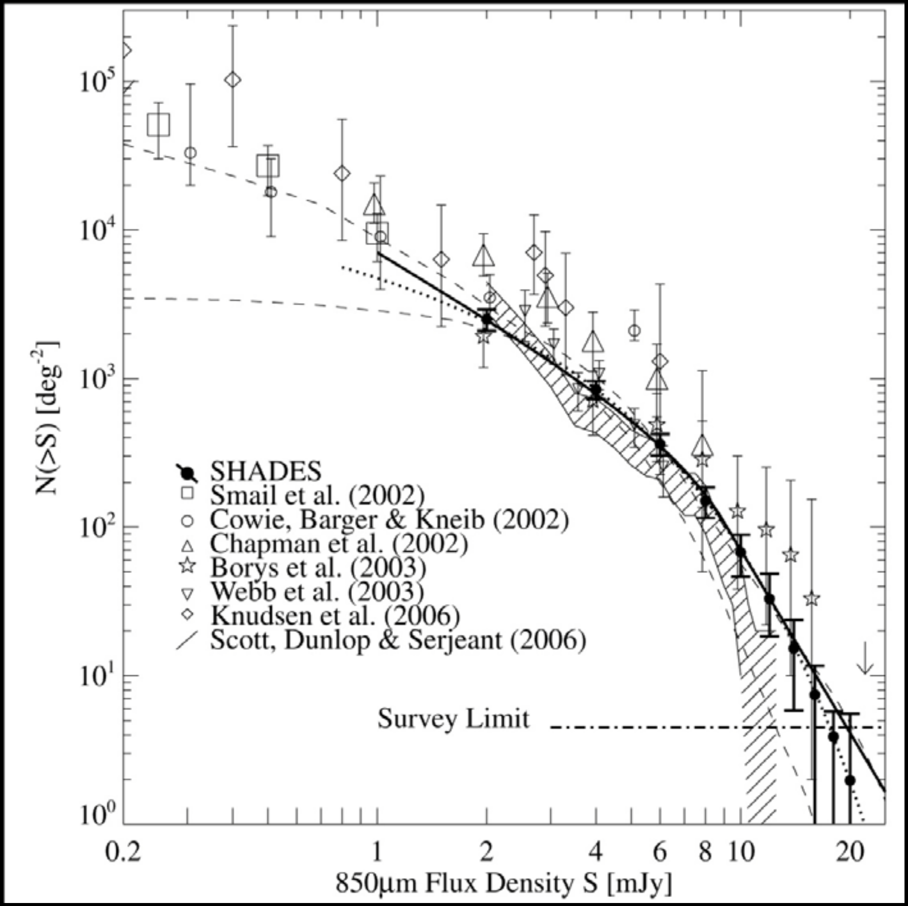




Blank Field SMGs

- Early work established
  - need for luminosity evolution,
  - constraints on background,
  - redshift distribution of radio-selected sources
  - use of clusters as lenses to probe faint population,
  - importance of radio-ID

  - target flux levels,
  - biases,
  - analysis techniques



(G. Wilson)