Herschel Observations of Massive Galaxy Clusters:

Gravitationally Lensed Galaxies, IR/ Submm-Bright Cluster Members, and Sunyaev-Zel'dovich Effect

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This talk will cover,

1-page summaries

- **The Herschel Lensing Survey (HLS)**
  - PI: E. Egami (Univ. of Arizona, 292.3 hrs, 5 papers)
  - Deep PACS/SPIRE imaging of ~40 massive cluster cores
  - Studies lensed galaxies, cluster members, SZ effect
  - Discussion of related GT/OT programs
- **LoCuSS: A Legacy Survey of Galaxy Clusters at z=0.2**
  - PI: G. Smith (Univ. of Birmingham, 145 hrs, 3 papers)
  - Wide (25'x25') & shallow PACS/SPIRE imaging of ~30 clusters
- **Constraining the Cold Gas and Dust in Cluster Cooling Flows**
  - PI: A. Edge (Durham Univ., 140.5 hrs, 2 papers)
  - PACS/SPIRE photometry & PACS spectroscopy of ~13 brightest cluster galaxies (BCGs) in cooling-flow clusters
- ~~The Herschel Virgo Survey (PI: J. Davies – Cardiff Univ.)~~

Outline

10 related papers posted on astro-ph today (May 24, 2010)

1. **Gravitationally lensed galaxies**
   - HLS: The Bullet Cluster (Rex et al.; Perez-Gonzalez et al.; also see Gonzalez et al.)
   - GT: Exceptionally bright lensed galaxy at z=2.3 (Ivison et al.)
   - H-ATLAS: Search for bright lensed galaxies (Negrello et al.)
   - GT: Deep number counts (Altieri et al.)
2. **IR/submm-bright cluster members**
   - HLS: The Bullet Cluster (Rawle et al.; also see Chung et al.)
   - LoCuSS: A1689 (Haines et al.), A1835 (Pereira et al.), and other LoCuSS clusters (Smith et al.)
   - Cooling-flow cluster BCGs (Edge et al. x2)
3. **Sunyaev-Zel'dovich effect**
   - HLS: The Bullet Cluster (Zemcov et al.)

c.f. The Herschel Lensing Survey (HLS): overview (Egami et al.)

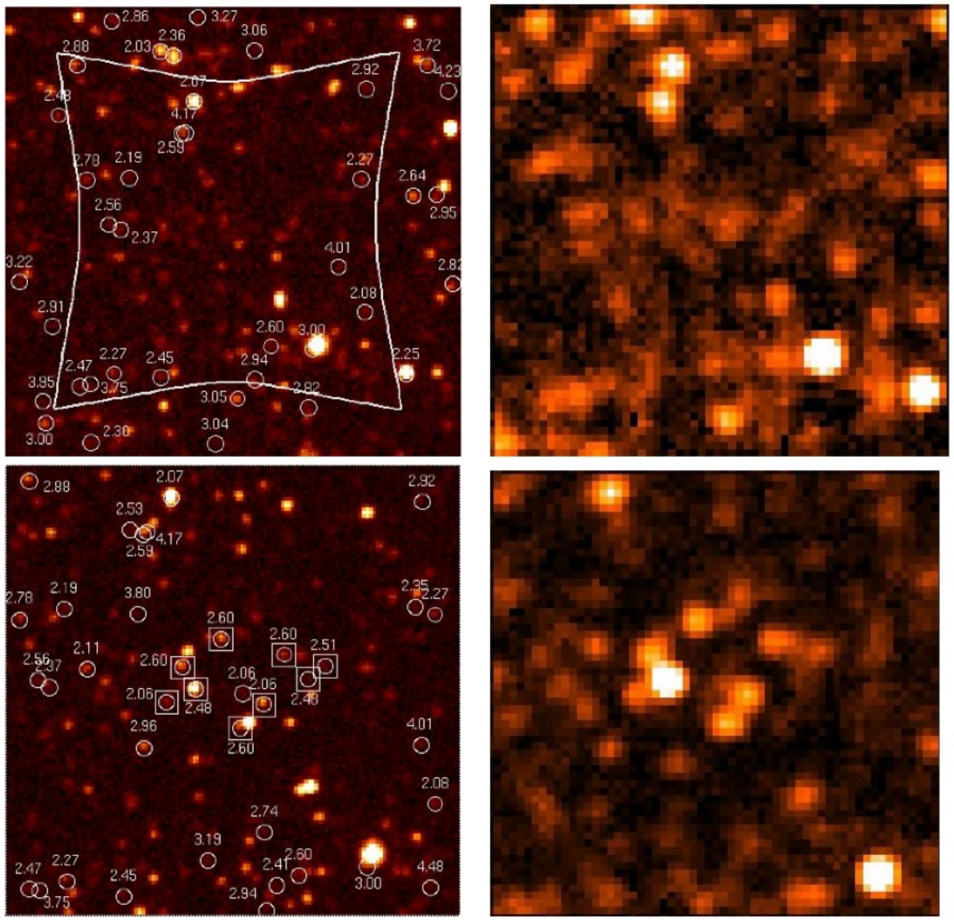
Scientific Goals

1. **Background lensed galaxies:** To detect and study IR/Submm sources that are below the nominal confusion limit of Herschel using the gravitational lensing power of massive galaxy clusters.
2. **Cluster-members:** To study IR/submm properties of galaxies in dense environment.
3. **Sunyaev-Zel'dovich effect:** To investigate the SZ effect increment (SPIRE can detect increment at 350/500 um).

Penetrating through the Confusion with Cluster Cosmic Telescopes

Without Lensing

With Lensing



Lensing is more Important for SPIRE images, which get confusion-limited quickly.

PACS 100 um

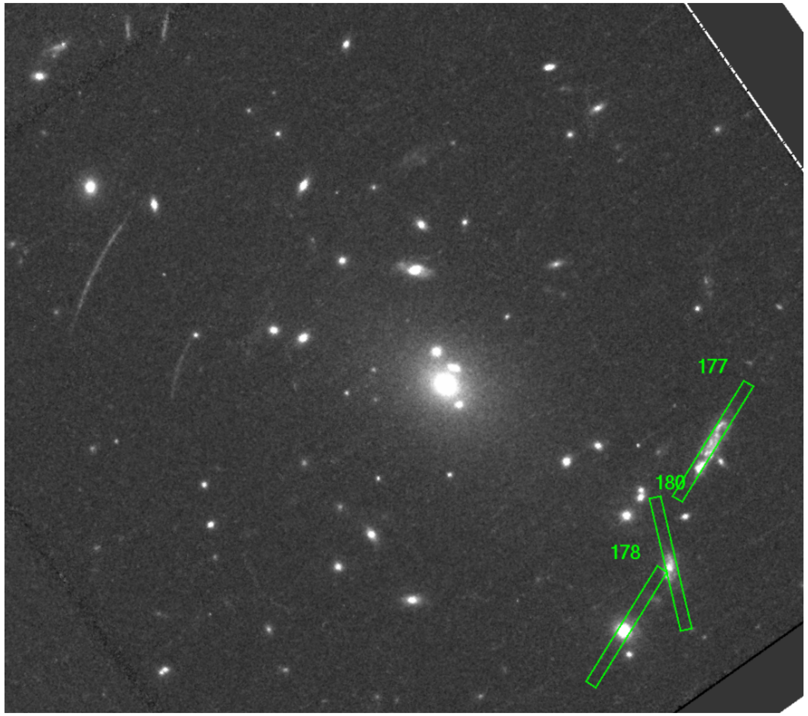
SPIRE 250 um

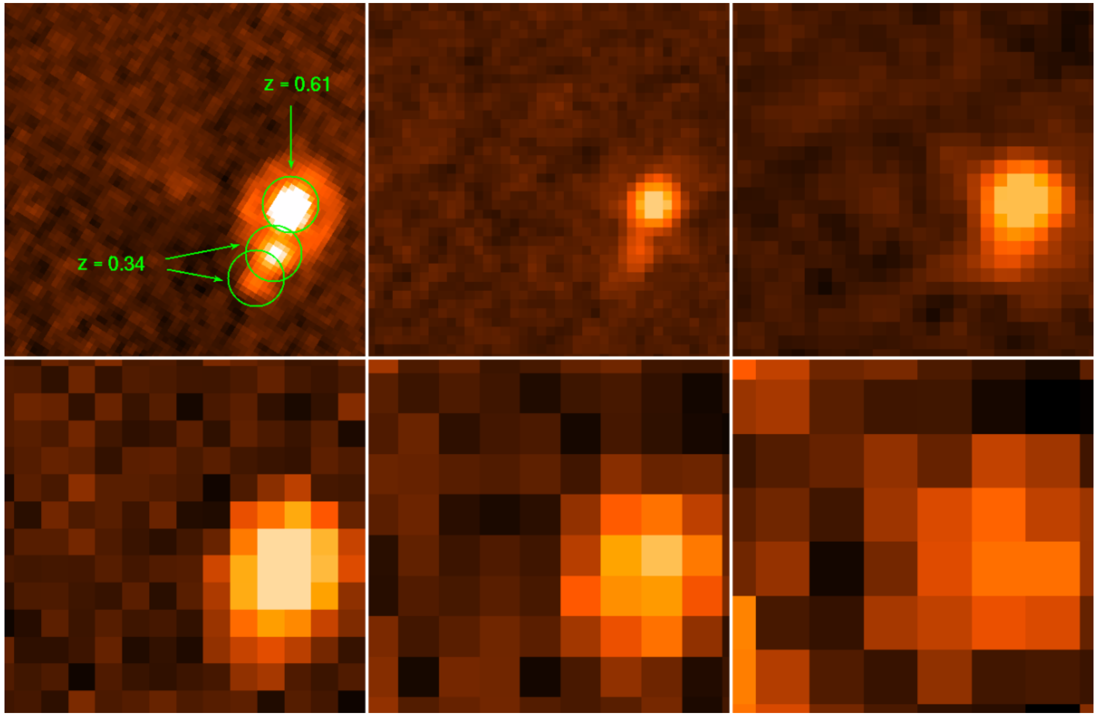
7’x7’

In IR/Submm, massive galaxy clusters act as transparent lenses (well, almost…)

AS 1063 (z= 0.34)

MIPS 24um PACS 100um PACS 160um





HST optical

SPIRE 250um SPIRE 350um SPIRE 500 um

Walth et al. In preparation

The Bullet Cluster: X-ray-luminous merging cluster at z=0.3

Special thanks to,

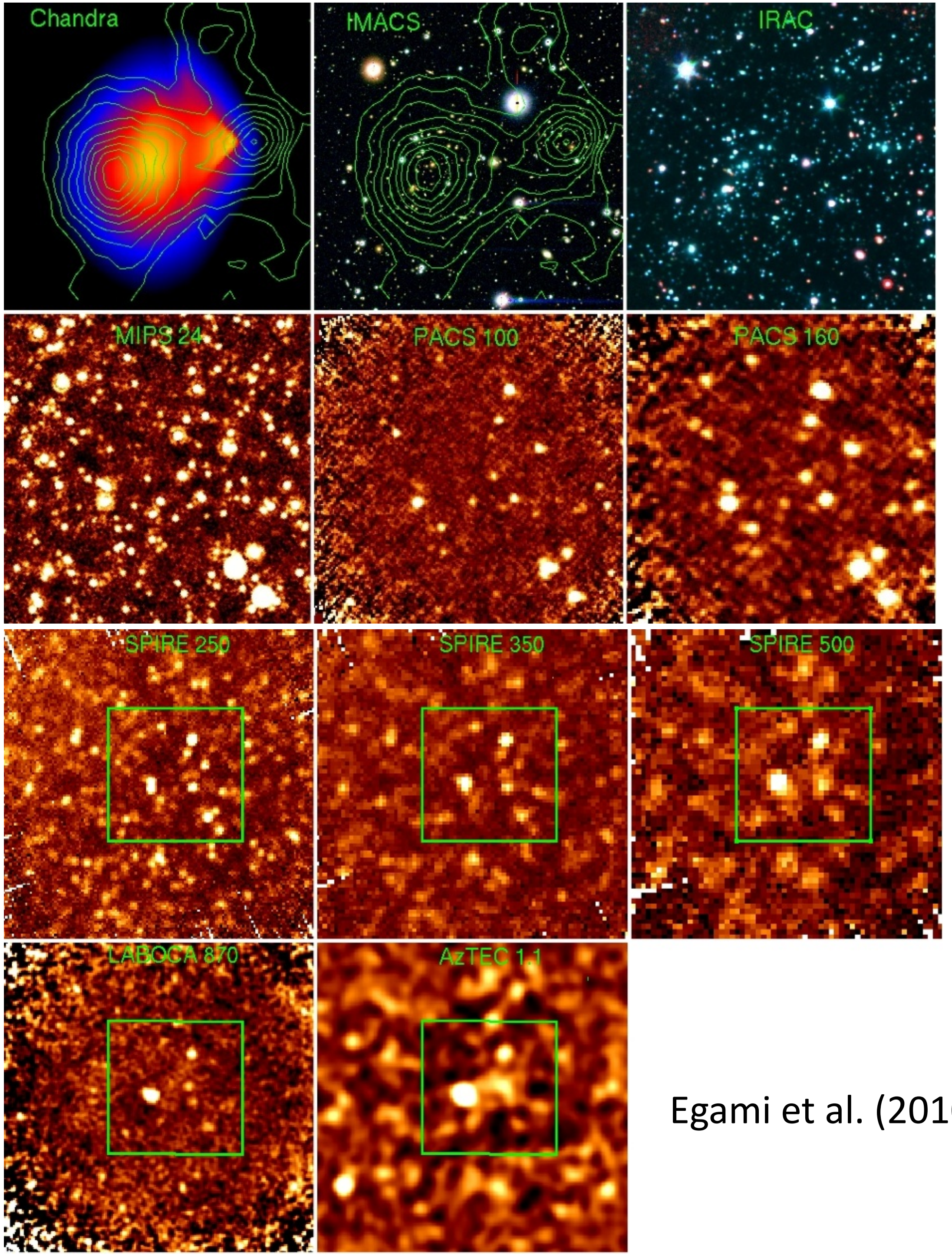
Doug Clowe
(Magellan/IMACS images)

Jean-Gabriel Cuby
(VLT/HAWKI images)

Anthony Gonzalez, Sun Mi Chung
(Magellan/IMACS redshifts)

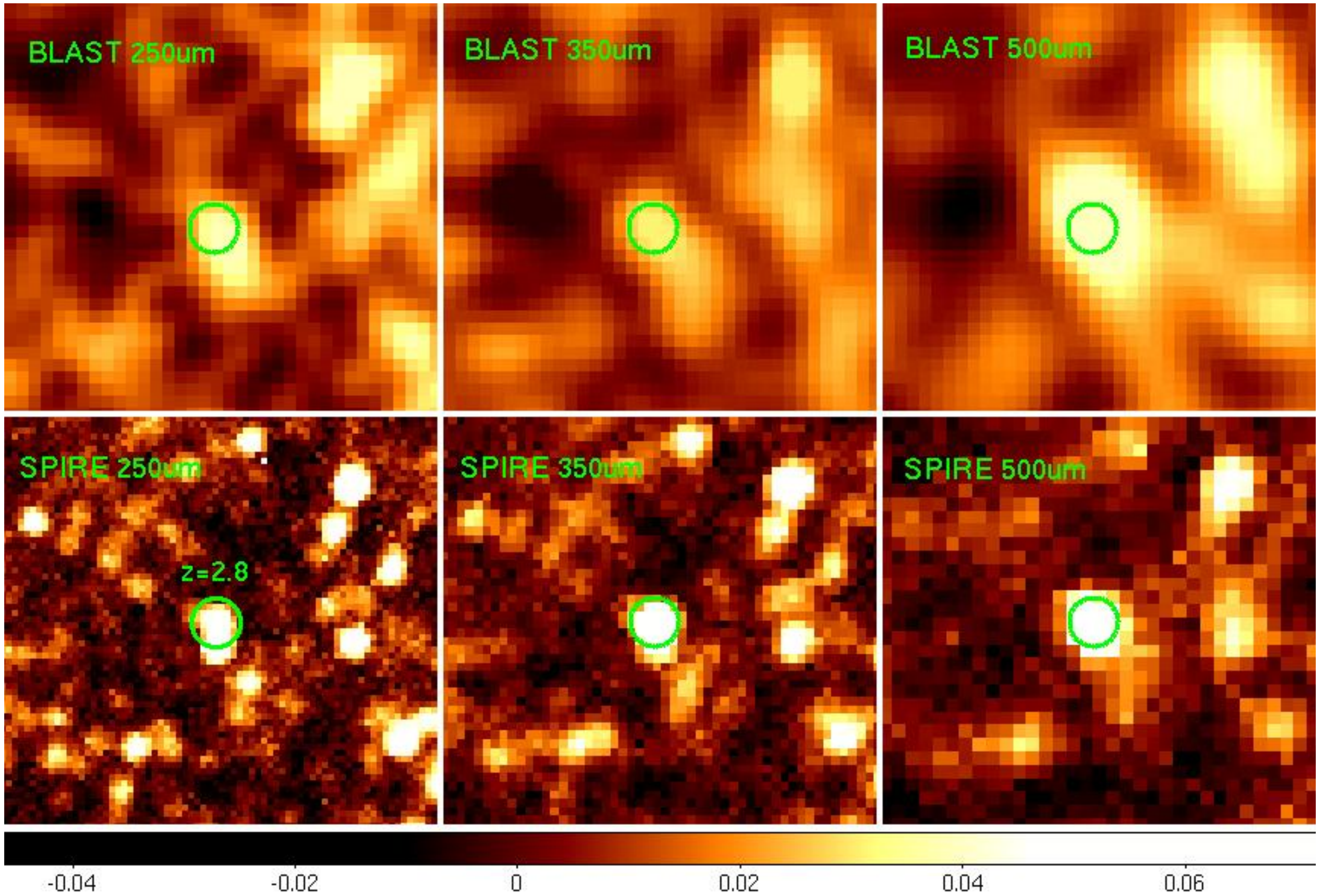
Cathy Horellou, Daniel Johansson and LABOCA team

David Hughes, Itziar Aretxaga and AzTEC team



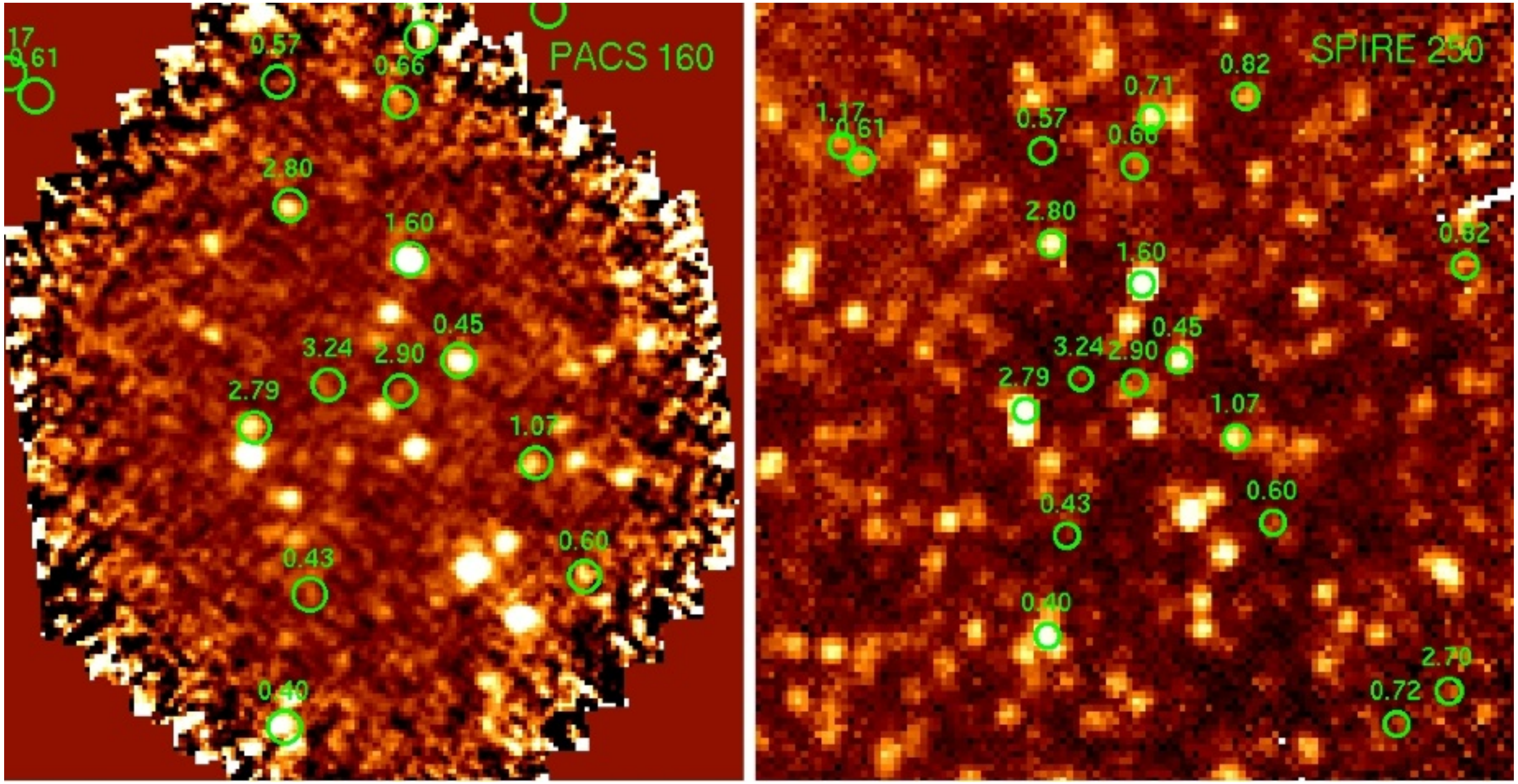
Egami et al. (2010)

BLAST vs. SPIRE



1. Lensed Galaxies in the Bullet Cluster

(z>0.4)

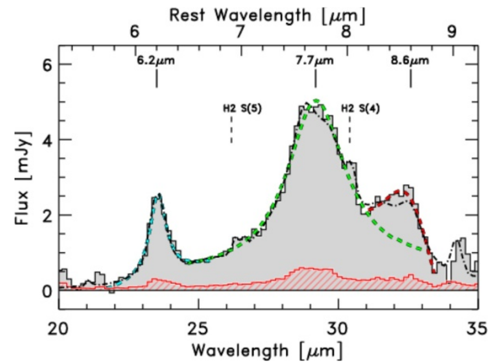


For the SDP papers, we limited the analysis to well-isolated,

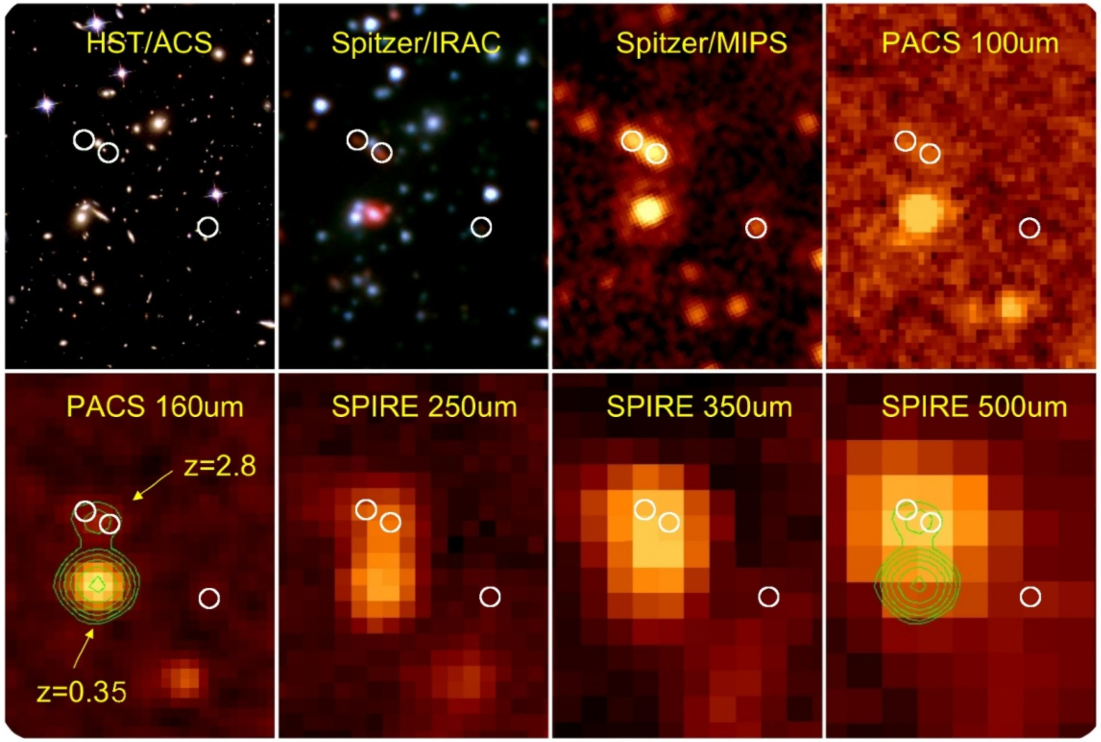
- 15 sources with spectroscopic redshifts
- 4 sources with good photometric redshifts

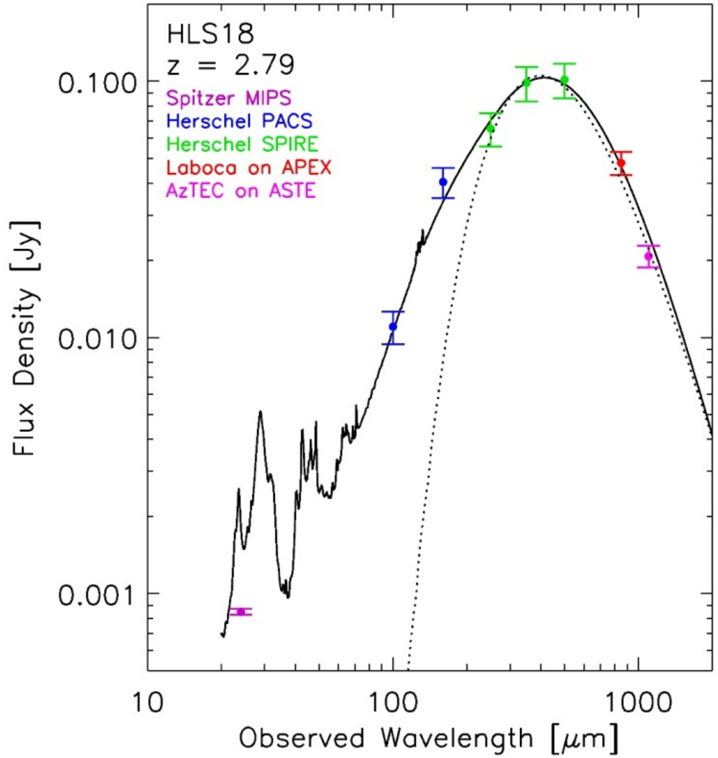
Full Far-IR/Submm SED of a LIRG ($<5\times10^{11}\ L_\odot$) at z=2.8!

Gonzalez et al. (2010)



Rex et al. (2010)





Also, see Rex et al. (2009) for BLAST

Magnification factor ~x50-100

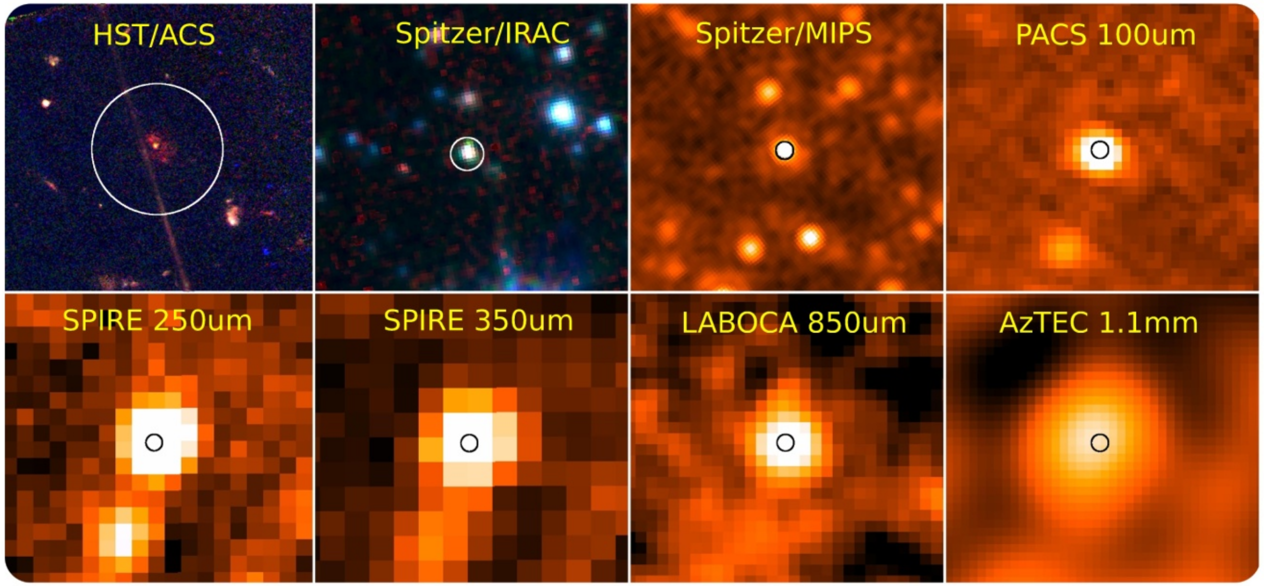
Observed flux densities : 7.0, 24.5, 65.3, 98.6, 101.4 mJy

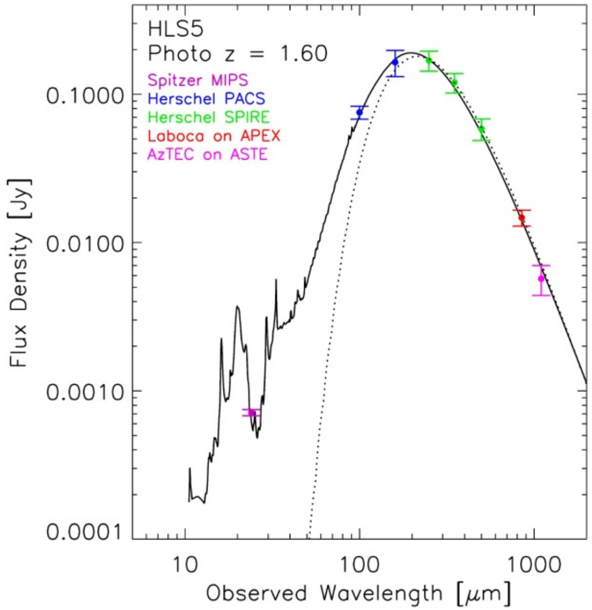
Corrected for lensing (x75): 0.09, 0.3, 0.9, 1.3, 1.4 mJy

Impossible to detect without lensing!!

HyLIRG ($1.6x10^{13}$ $L_\odot$) at z=1.6

(But not significantly lensed…more like a typical SMG)





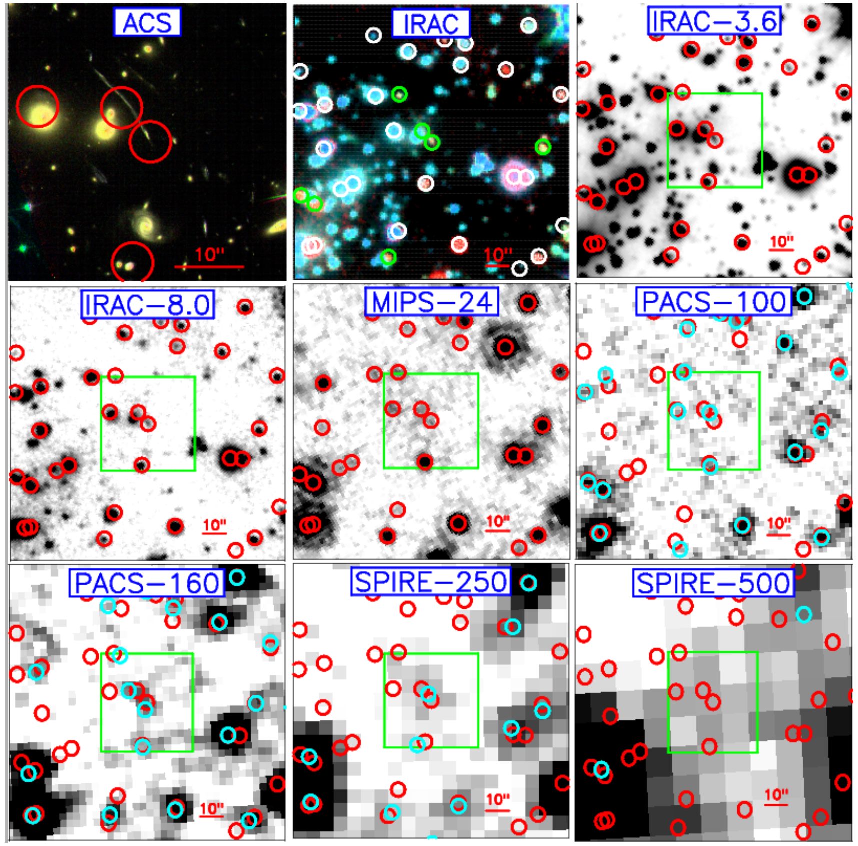
Magnification factor ~x1.2

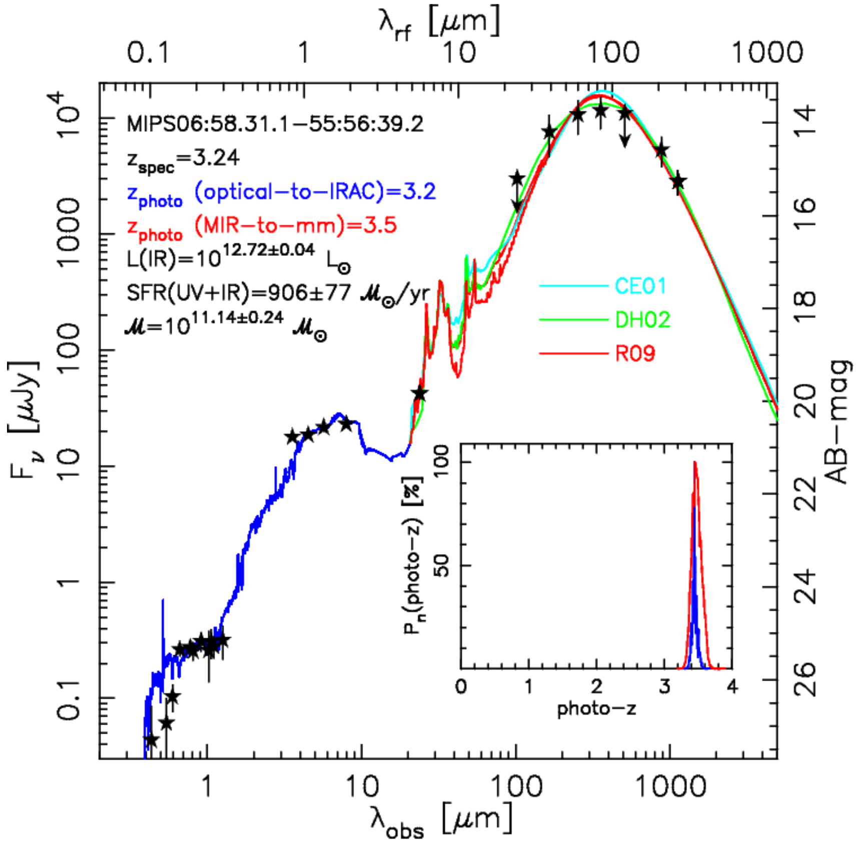
Observed flux densities : 75.4, 164.4, 168.9, 120.0, 58.4 mJy

Star-forming galaxy SED

Full SED of the z=3.24 Lensed Galaxy

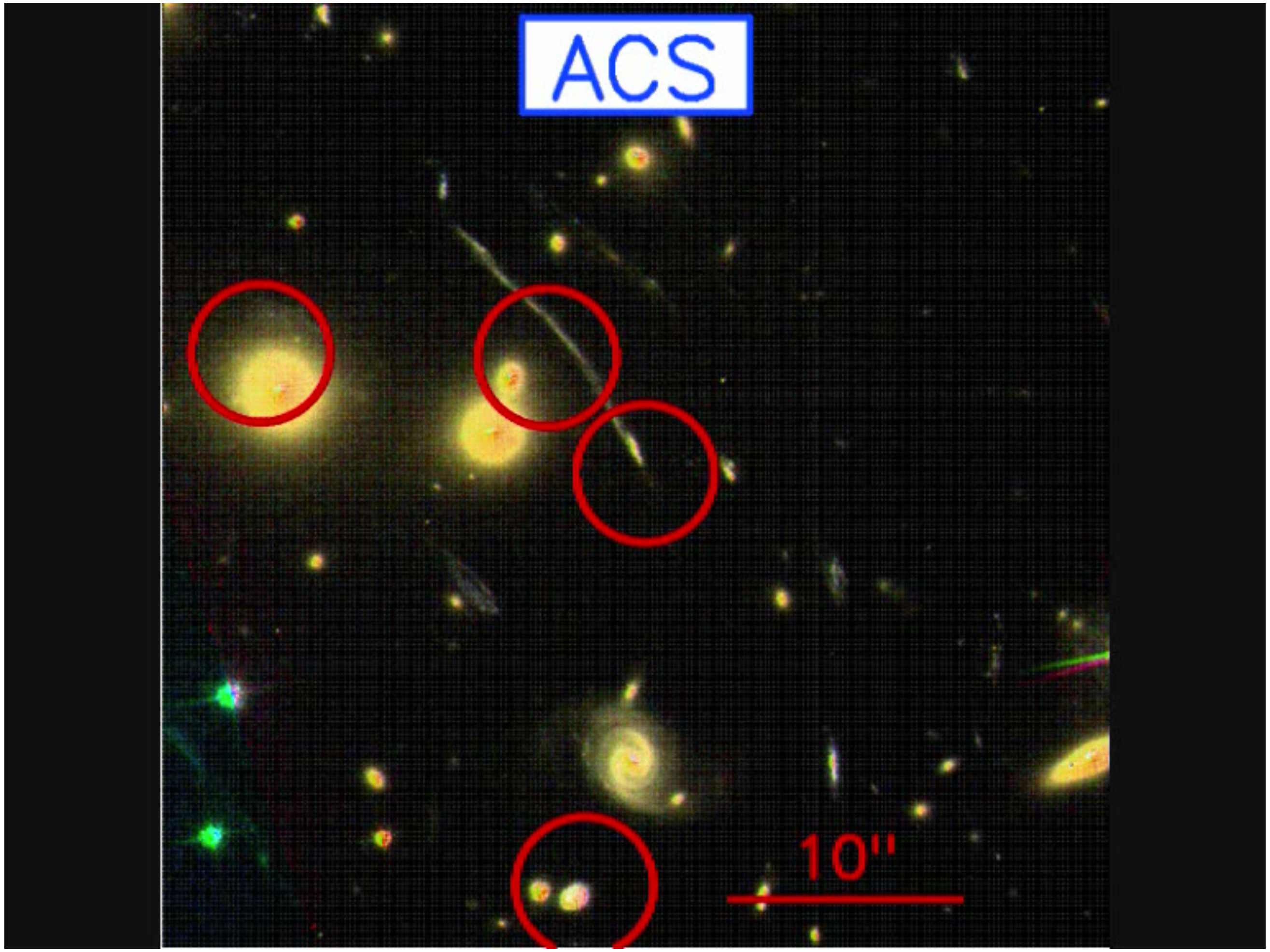
Perez-Gonzalez et al. (2010)





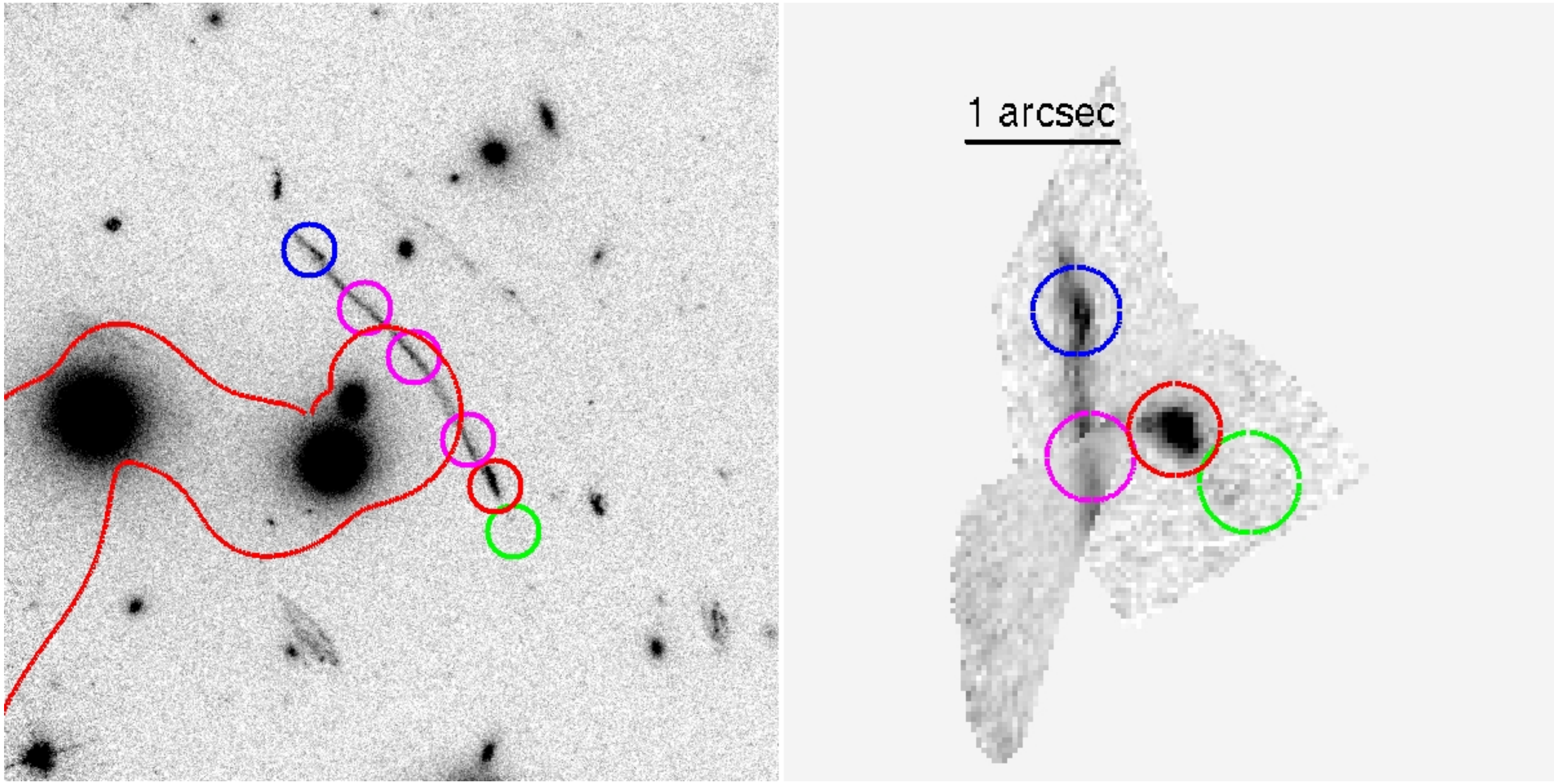
Multi-Wavelength Source Matching, Photometry & Far-IR/Submm Phot-z's

Perez-Gonzalez et al. (2010)



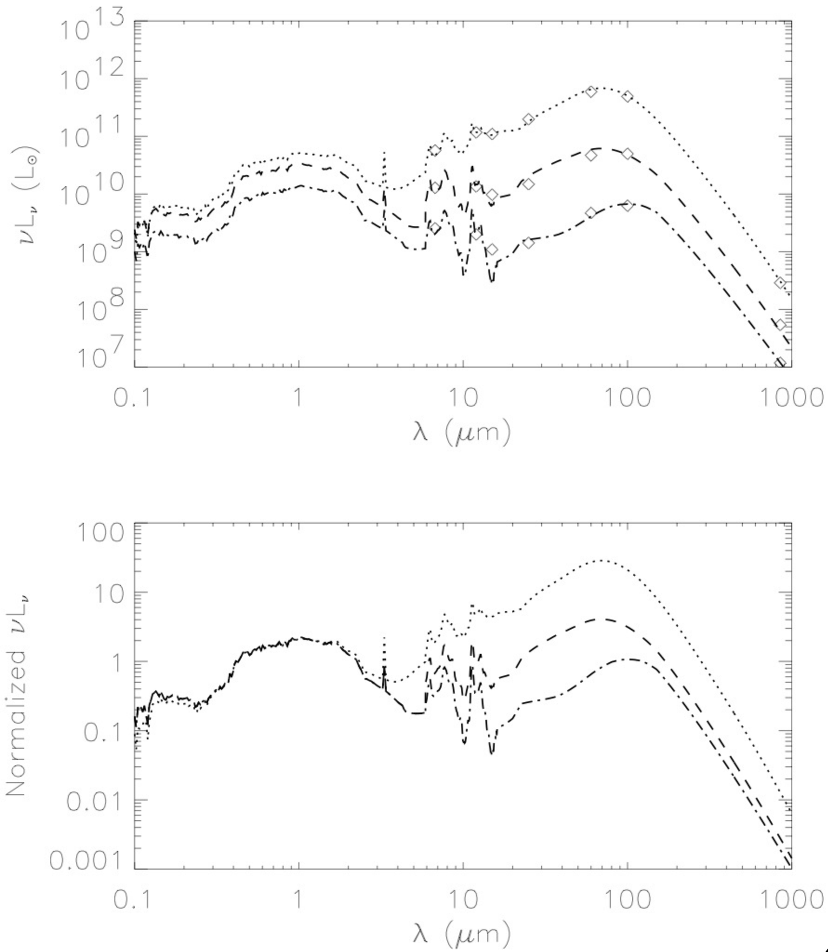
Z=3.24 giant lensed arc

HST Image Reconstruction in the Source Plane at z=3.24

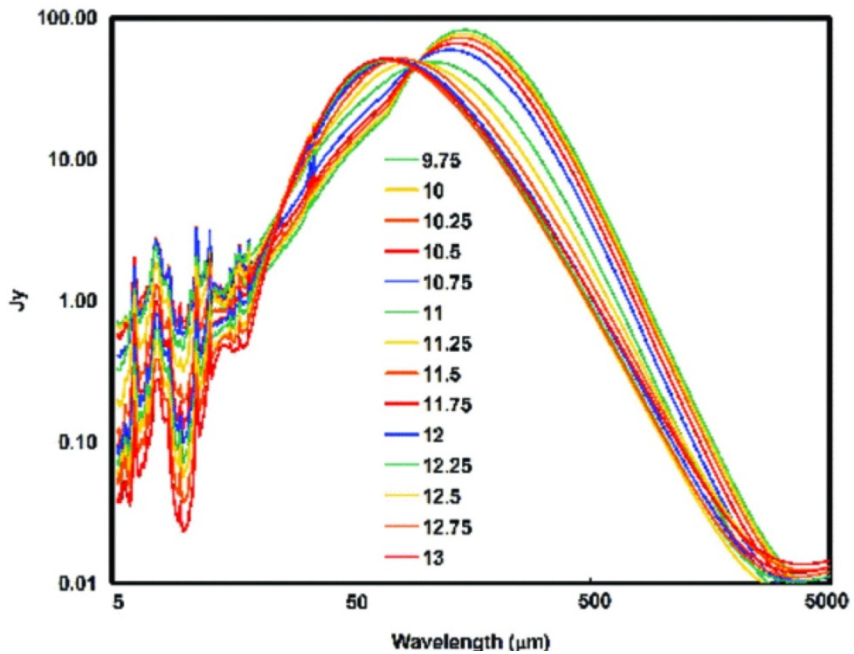


By Johan Richard

Far-IR/Submm SED Properties



Chary & Elbaz (2001)

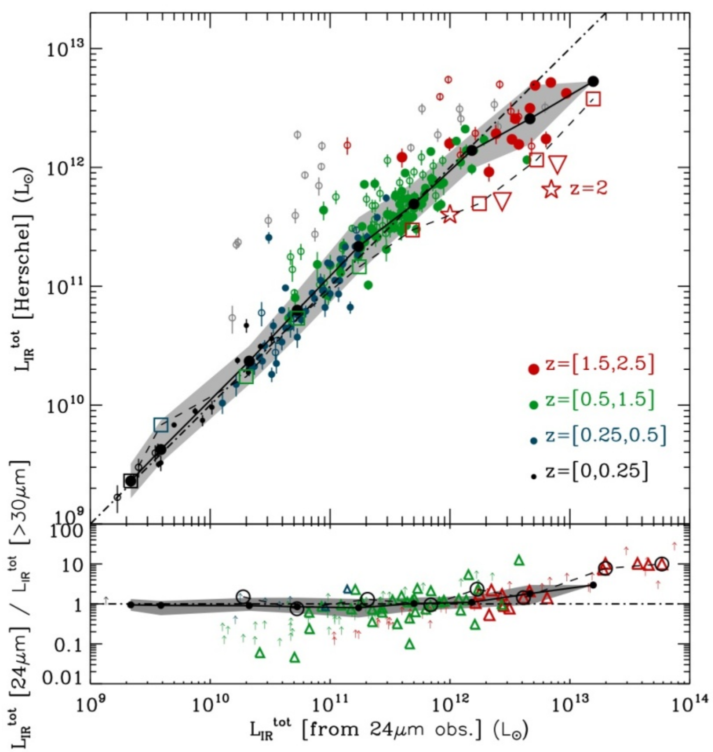


Rieke et al. (2009)

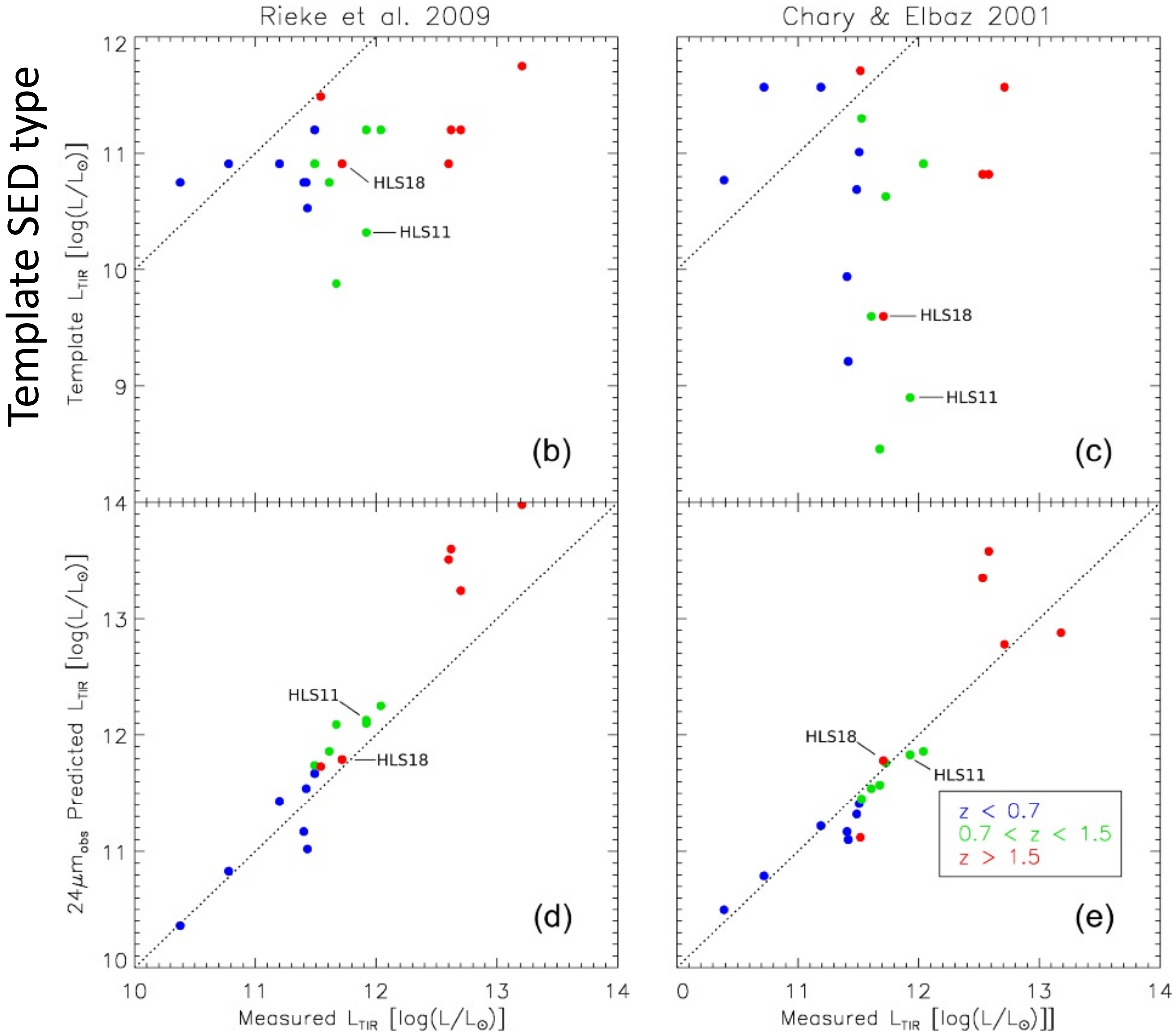
$L_{TIR}\uparrow \longrightarrow T_{dust}\uparrow \longrightarrow L_{FIR}/L_{MIR}\uparrow$

Q: Do the local galaxy SED templates work at high redshift?

Properties of High-z Galaxy SEDs



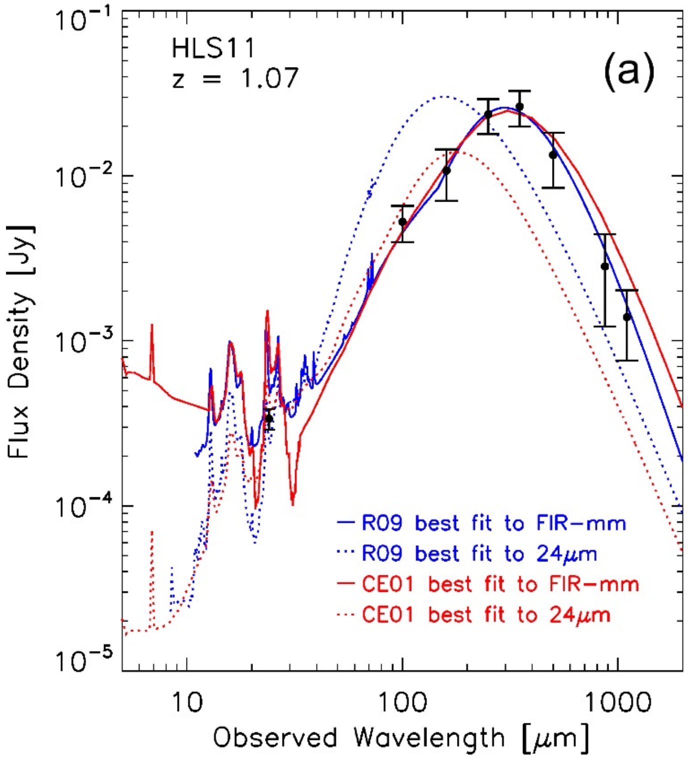
Elbaz et al. (2010)



Rex et al. (2010)

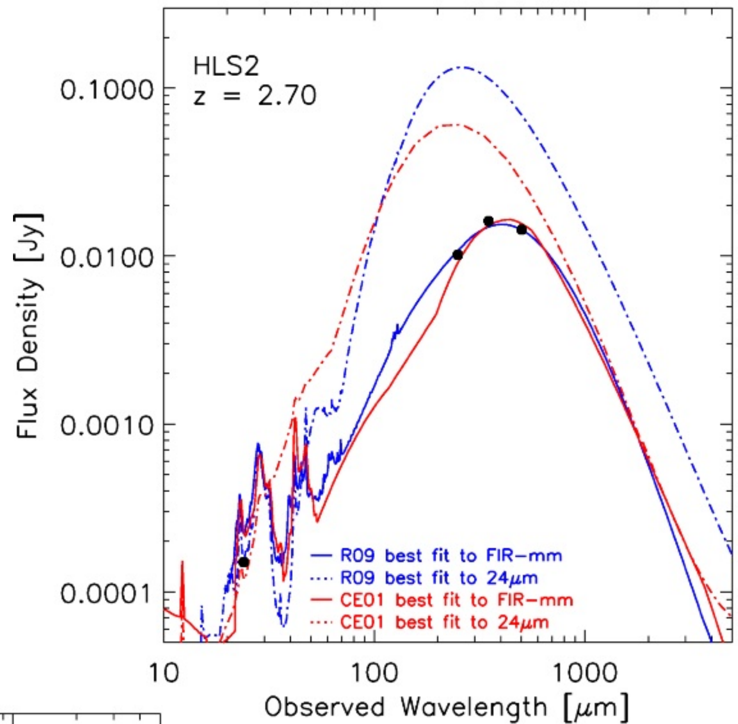
IR/Submm SEDs of high-redshift galaxies appear colder than their local counterparts with similar IR luminosities.

BUT, L_{TIR}(24um) vs. L_{TIR} (measured) still good at z < 1.5 (why?).

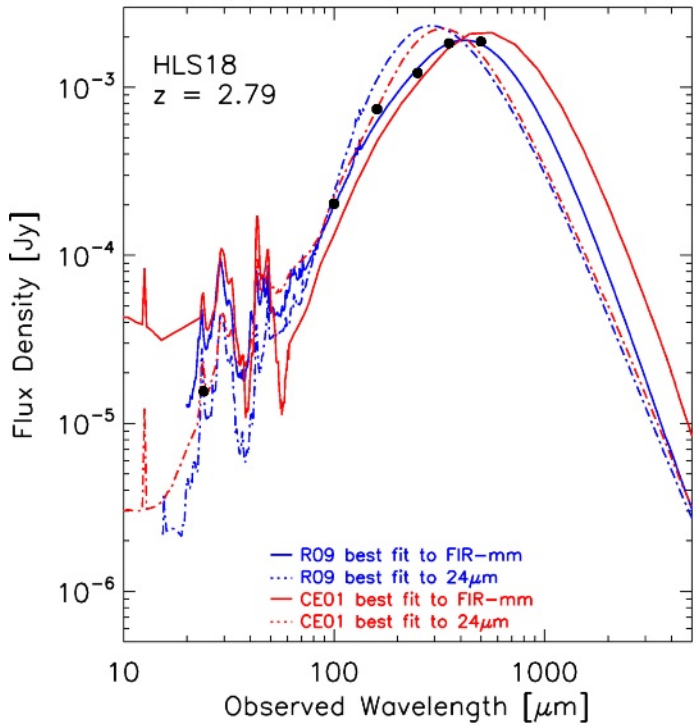


← LTIR (24um) and LTIR (measured) are close but the observed SEDs are much cooler (i.e., LTIR(template) is low)

At z>1.5 → LTIR(measured) could be much smaller than LTIR(24um)



BUT, even at z>1.5, LTIR (24um) can be close to LTIR(measured) even though 24um-estimted SED doesn't match the observed one.

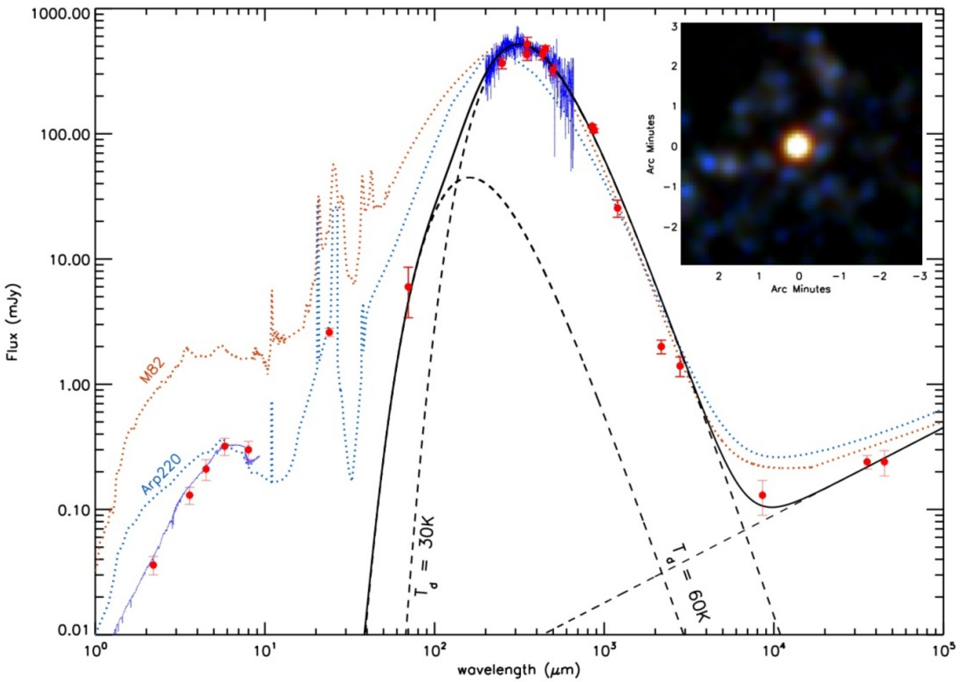


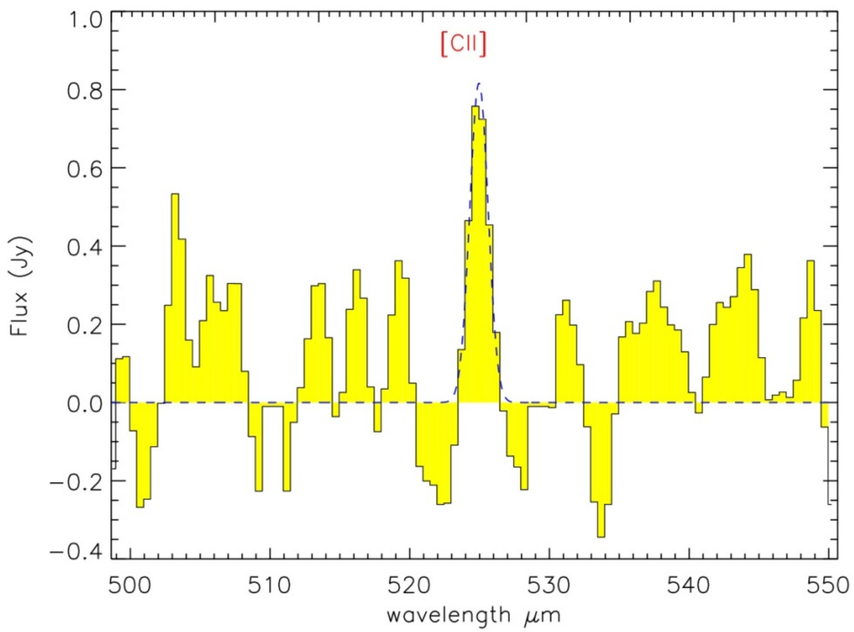
Suggest that there's still a lot to learn about the properties of Far-IR/Submm galaxy SEDs.

SMM J2135: Exceptionally bright lensed galaxy at z=2.3

ULIRG (2.3 x10^{12} $L_{\odot}$) magnified by x32.5

Ivison et al. (2010)
Discovered by Swinbank et al. (2010)





SPIRE FTS spectrum

430 mJy at 350 um
325 mJy at 500 um
115 mJY at 850 um

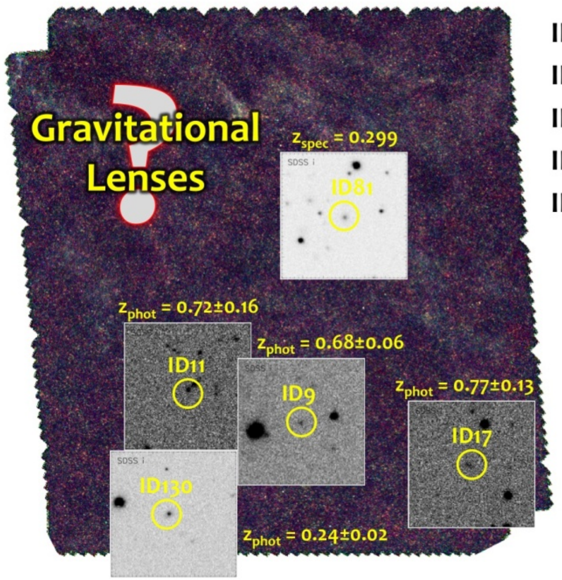
e.g., Bullet z=2.8 galaxy
99 mJy at 350 um
101 mJy at 500 um
49 mJy at 870 um

[CII] line property similar to those of lower-Luminosity star-forming galaxies in the local Universe → consistant with our SED fitting

Herschel-ATLAS: Search for bright lensed galaxies (mostly galaxy/galaxy lensing)

Negrello et al. (2010)

500 μm BRIGHTEST GALAXIES IN H-ATLAS SDP



ID9 : $S_{500\mu m}$ = 175 ± 28 mJy
ID11 : $S_{500\mu m}$ = 238 ± 37 mJy
ID17 : $S_{500\mu m}$ = 220 ± 34 mJy
ID81 : $S_{500\mu m}$ = 166 ± 27 mJy
ID130 : $S_{500\mu m}$ = 108 ± 18 mJy

optical counterparts
$z_{phot/spec}$ < 1.0

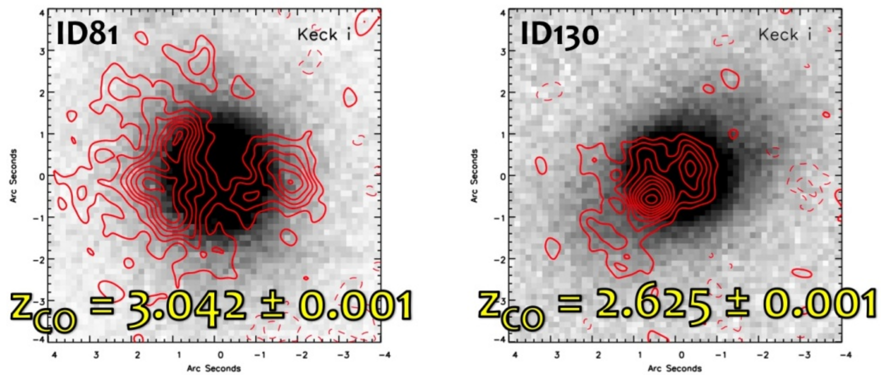
. . .

what about the sub-mm SED?

14.4 deg^2 so far
~7000 500 um sources
11 brighter than 100 mJy

GRAVITATIONAL LENS CANDIDATES ID81 – ID130

CSO/Z-spec + GBT/Zpectrometer + PdBI → z_{CO}



! STRONG GRAVITATIONAL LENS EVENTS !

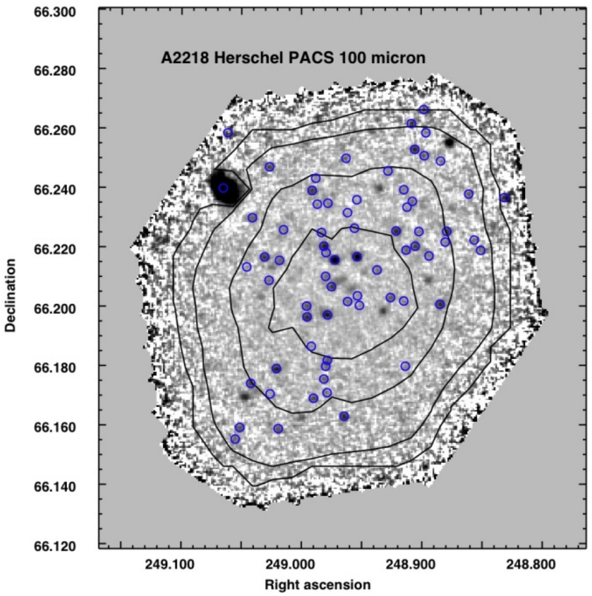
Red contours: SMA 870um maps

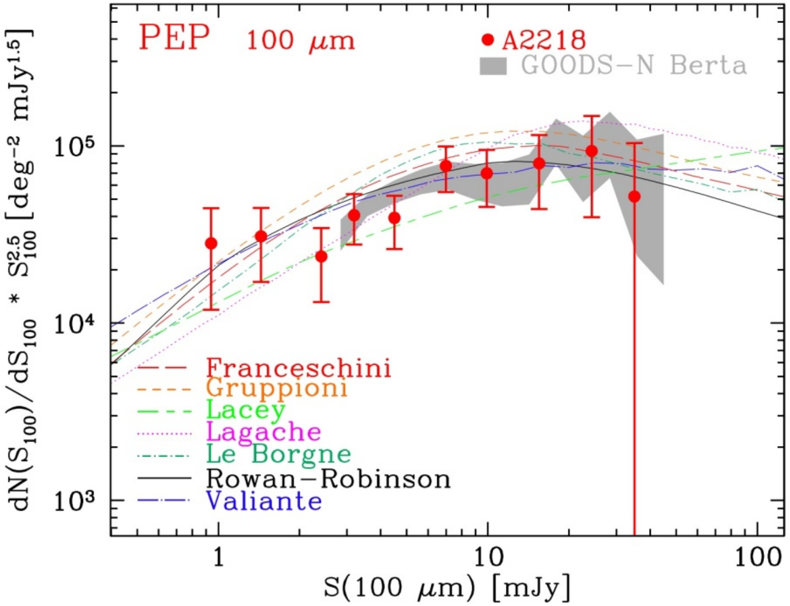
These sources are bright enough that redshift can be measured directly with CO using wide-band mm spectrometers!!

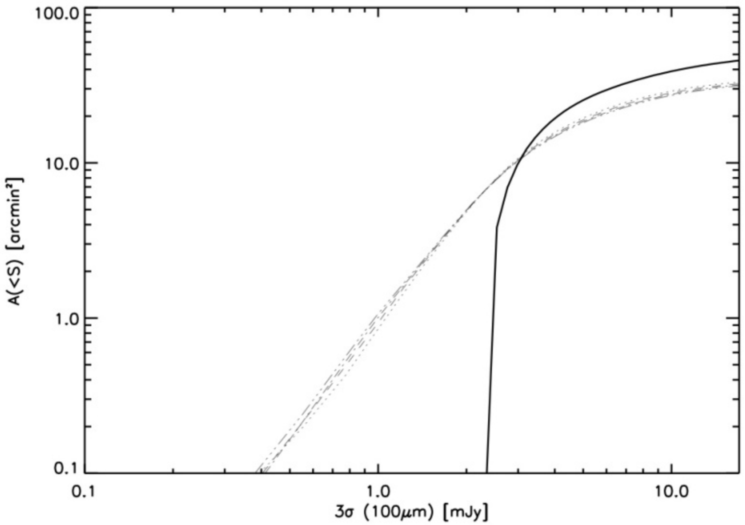
PACS Deep Number Counts

Altieri et al. (2010)

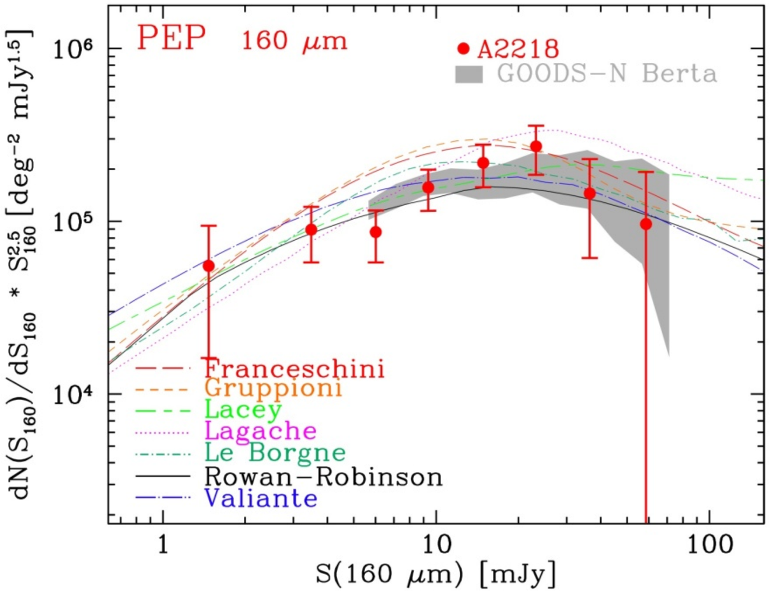
PACS 100um Map (A2218)







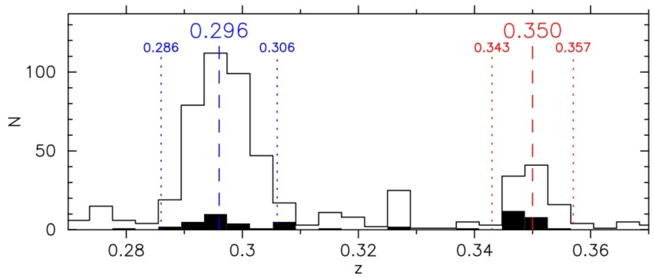
Survey depth with and without lensing

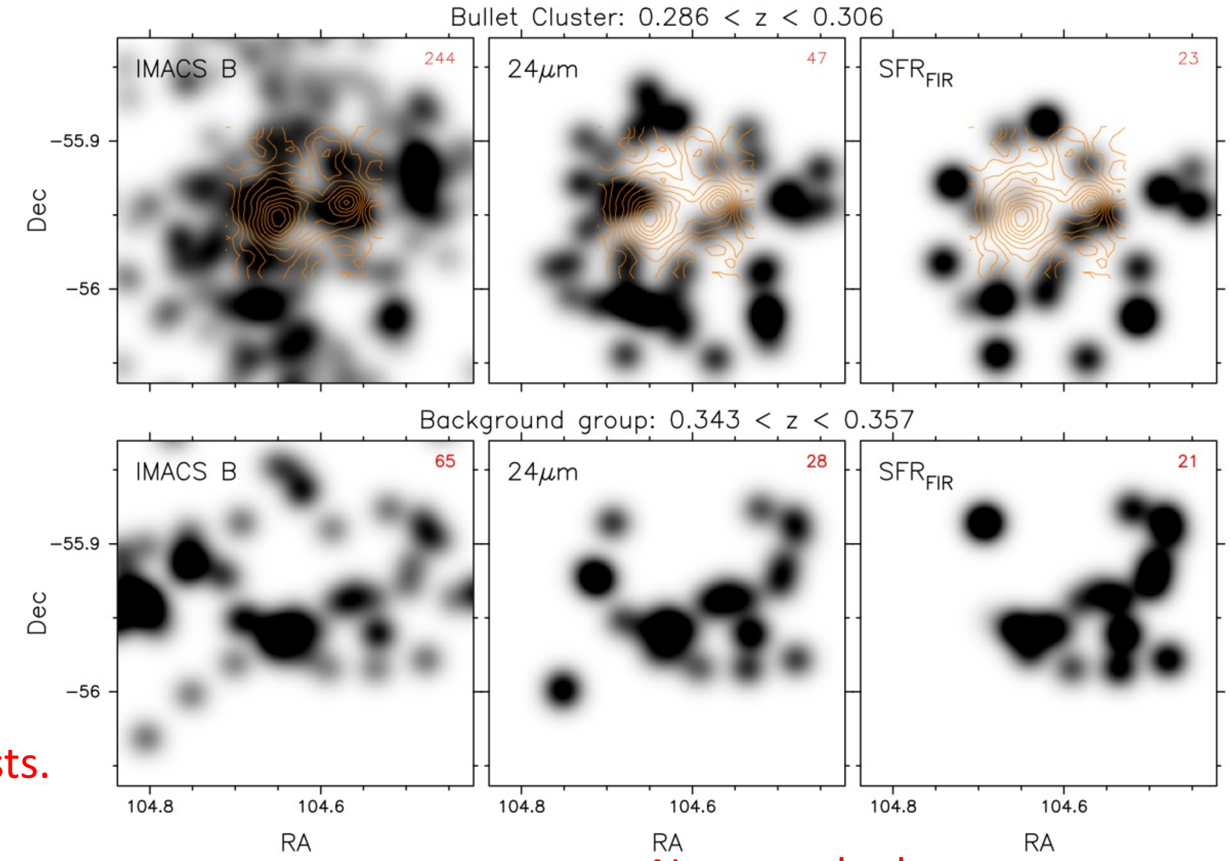


2. IR/Submm Properties of Galxaies in Dense Cluster Environment

Rawle et al. 2010

Comparing the Bullet Cluster (z=0.3) and the z=0.35 background system





144 $M_\odot$ yr^{-1} 207 $M_\odot$ yr^{-1}

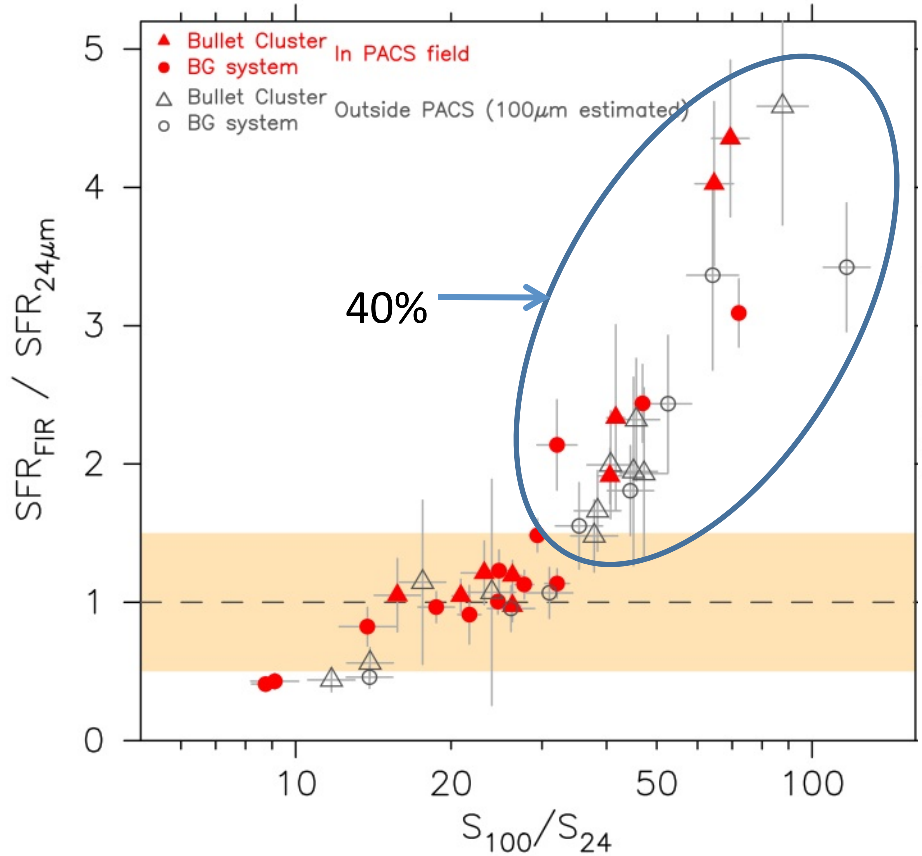
IR-derived total SFRs

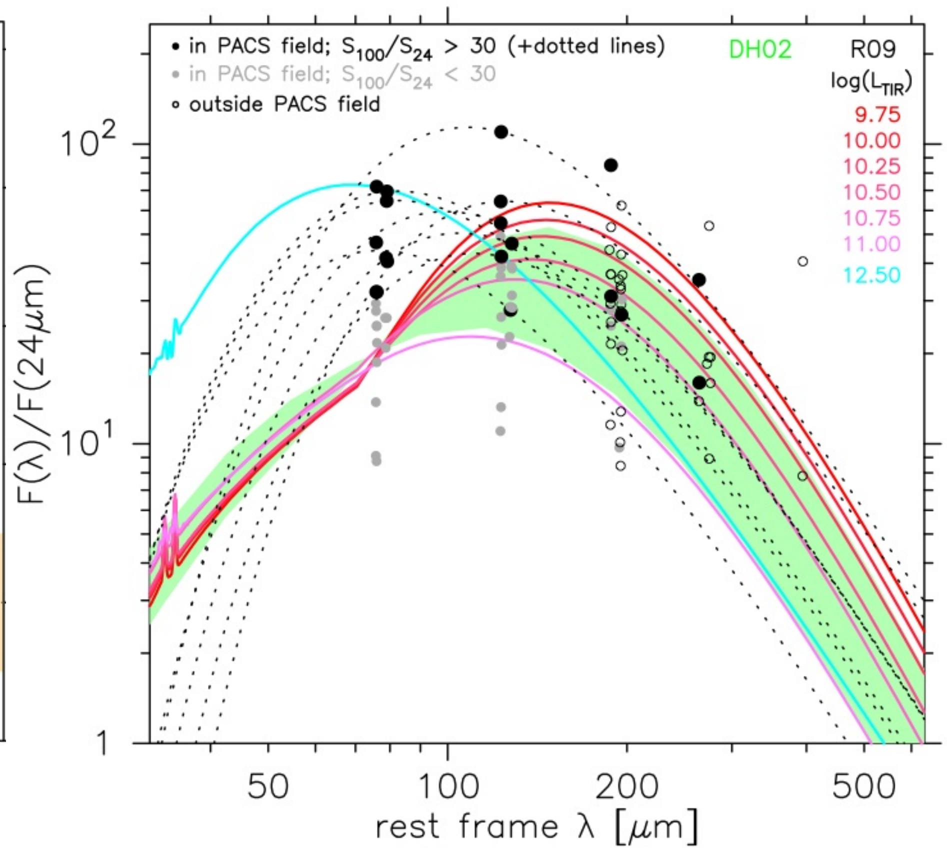
Cluster-cluster mergers may not be important for triggering IR-luminous starbursts.

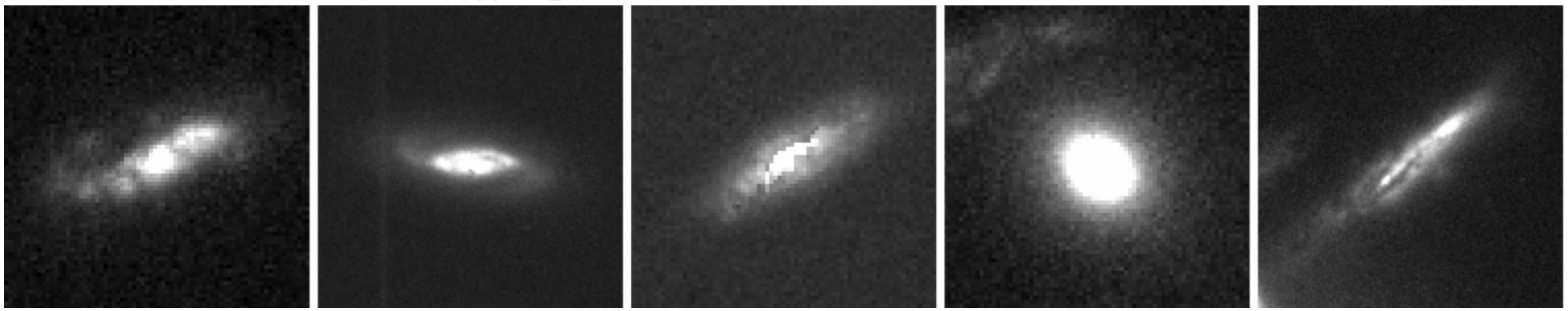
←Not exactly the same→

Discovery of 100 um-Excess Galaxies

Does the dense cluster environment modify the far-IR/Submm SED properties?



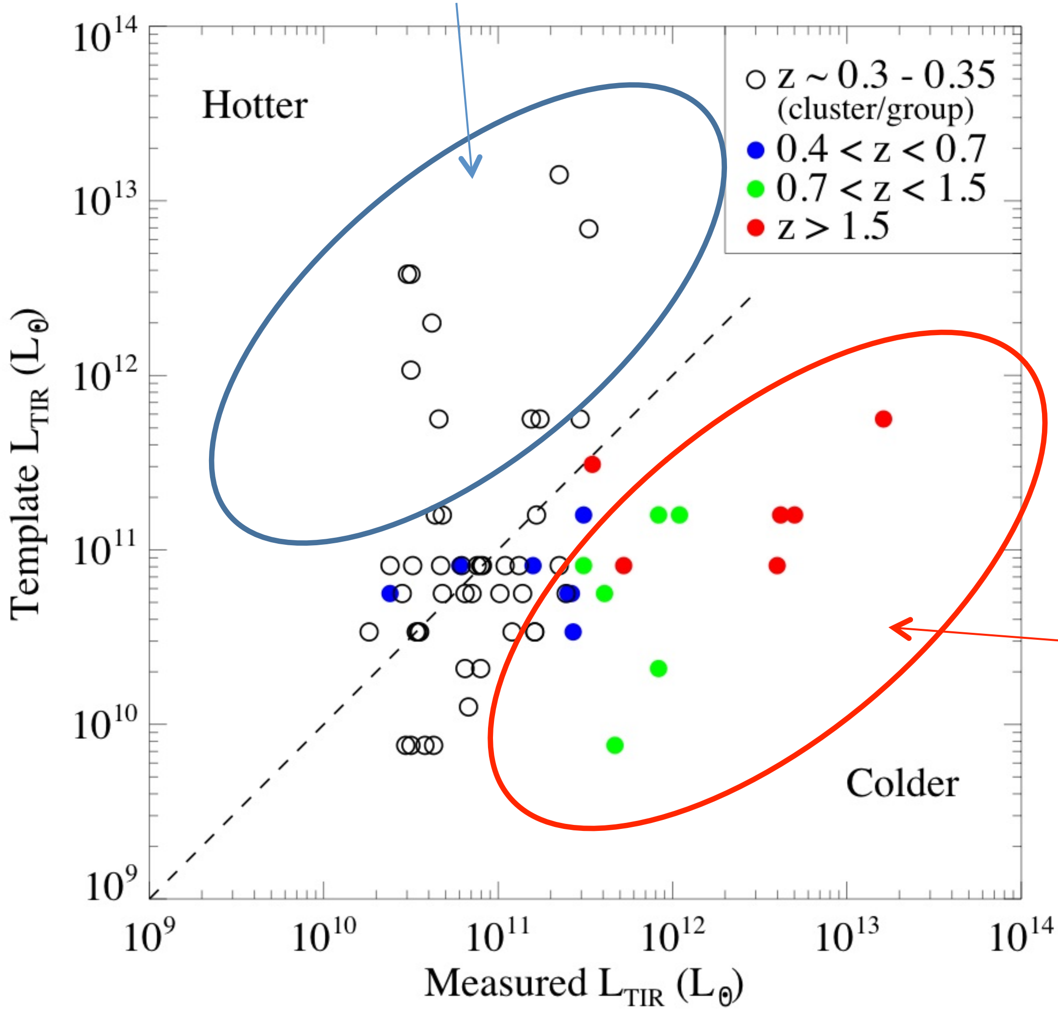




Diverse morphology

IR/Submm SED Properties: Summary

Surprise!!

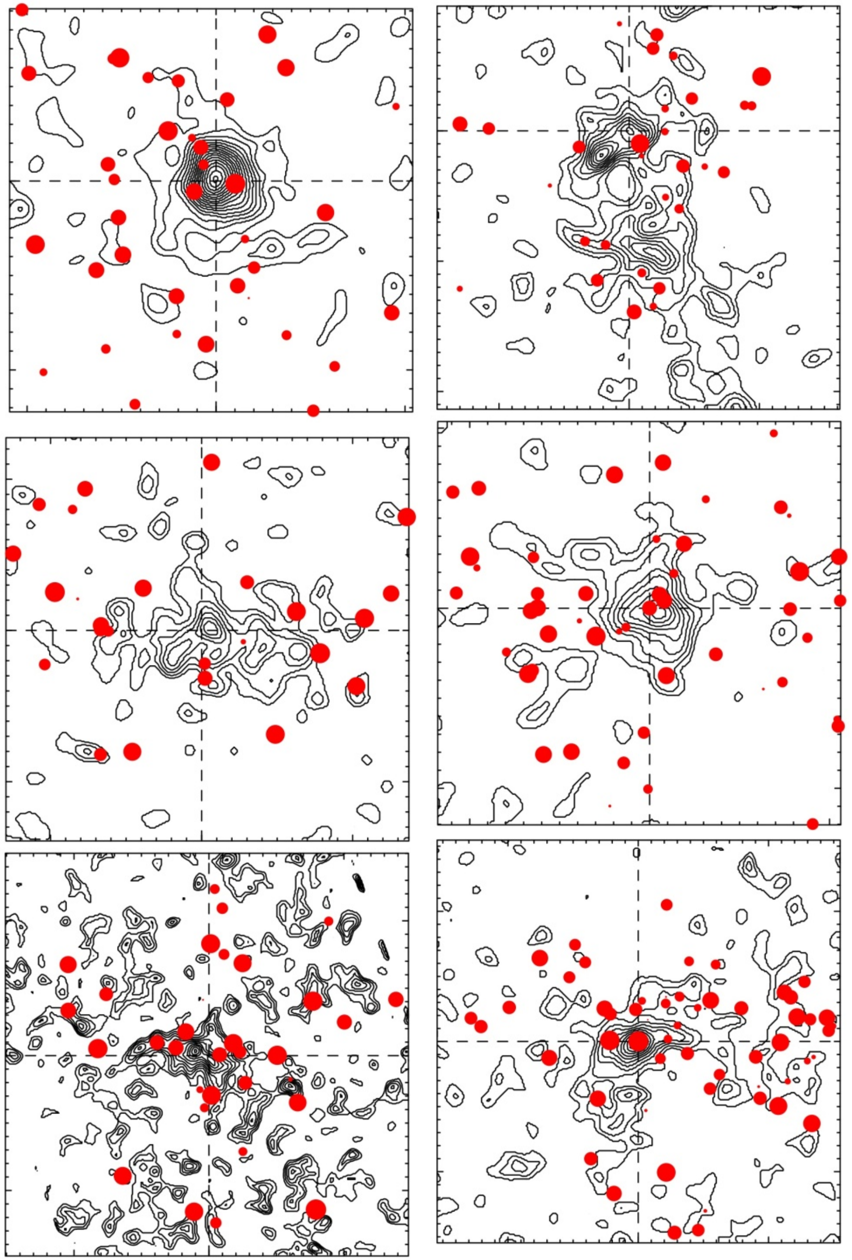


Consistent with Spitzer results.

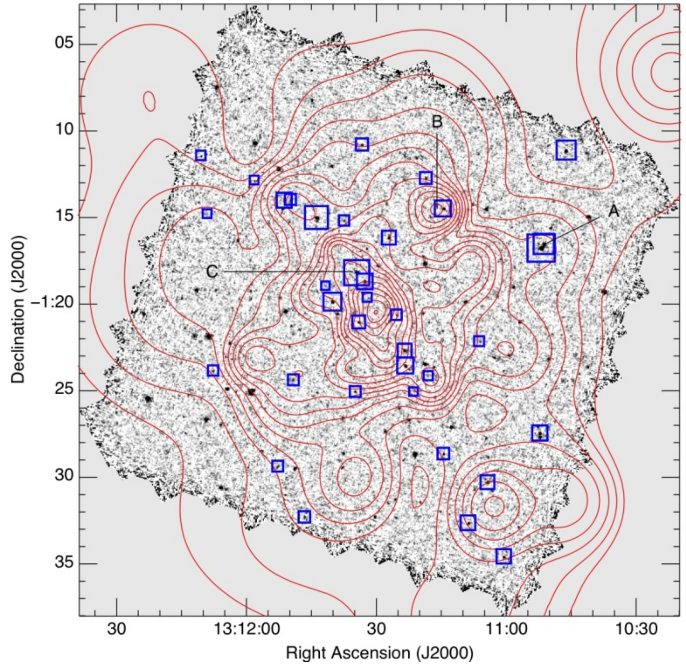
Papovich et al. (2007)
Rigby et al. (2008)
and etc…

LoCuSS

Smith et al. (2010)
WL mass map vs. Herschel sources

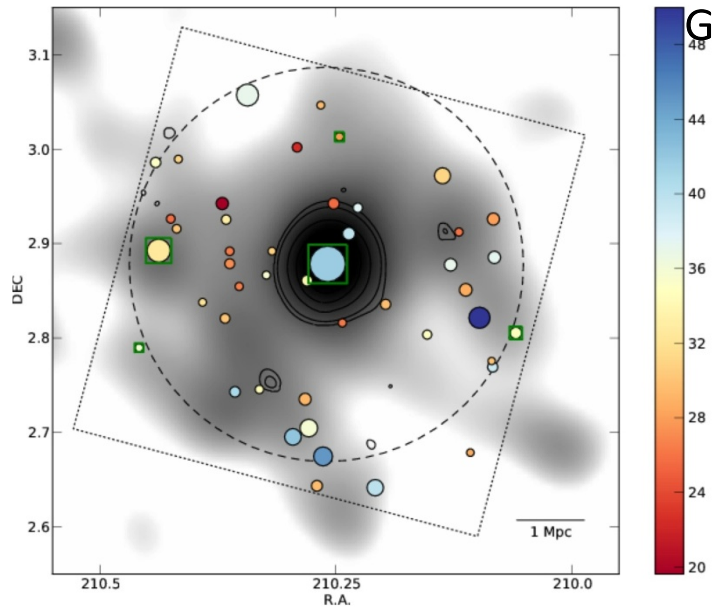


Spec-z highly complete
(MMT/Hectospec, PI: Egami)



Haines et al. (2010)
A1689

Star formation in filaments of infalling Galaxies?

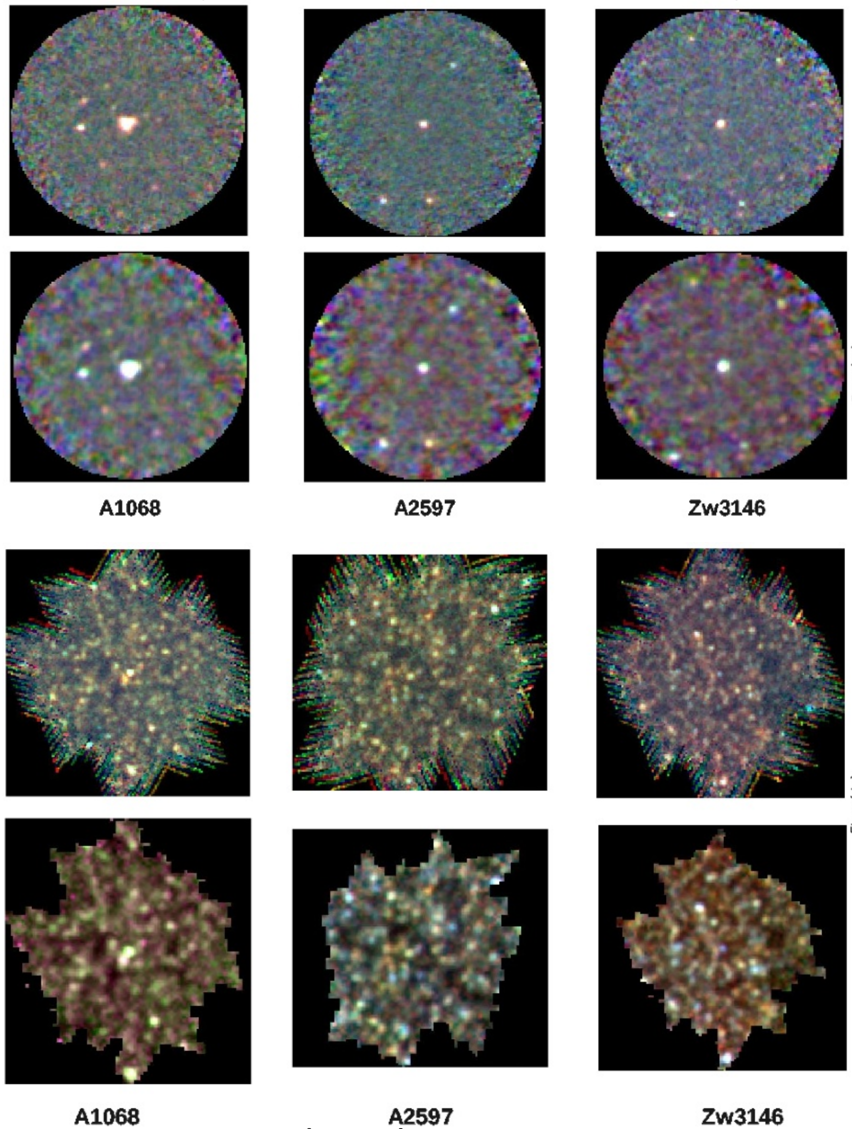


Pereira et al. (2010)
A1835

Cooling-Flow Cluster BCGs

PACS (70/100/160um three-color)

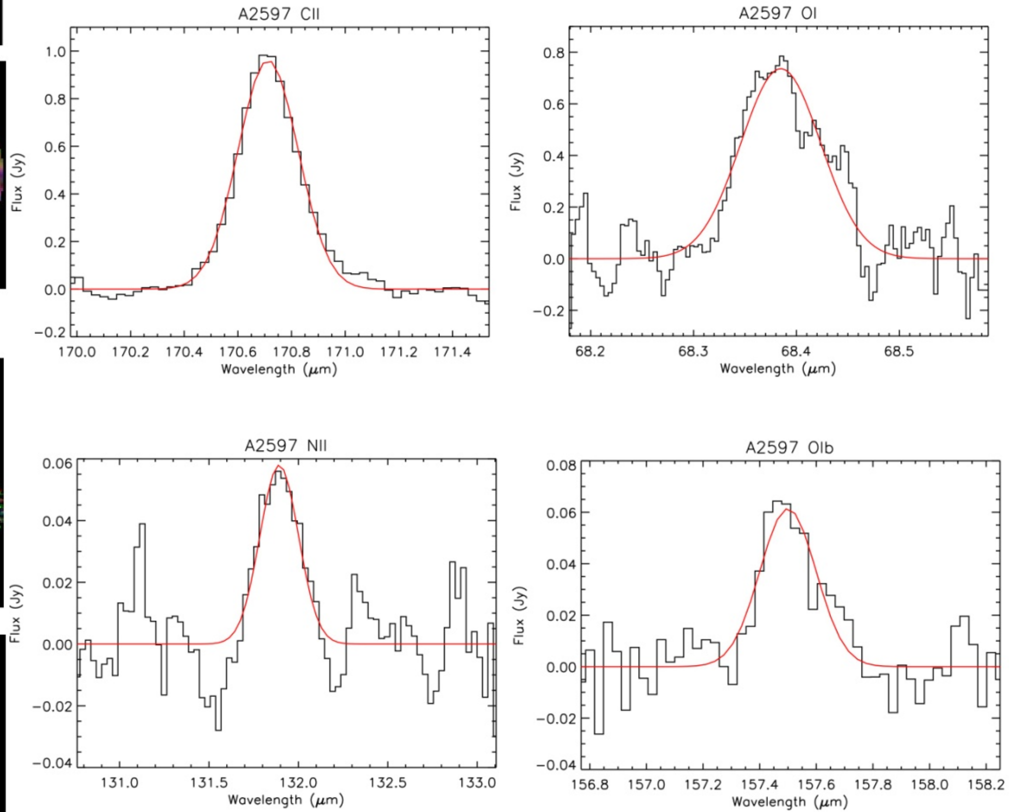
Edge et al. (2010a, b)



SPIRE (250/350/500um three-color)

[C II] 158 um

[O I] 63 um



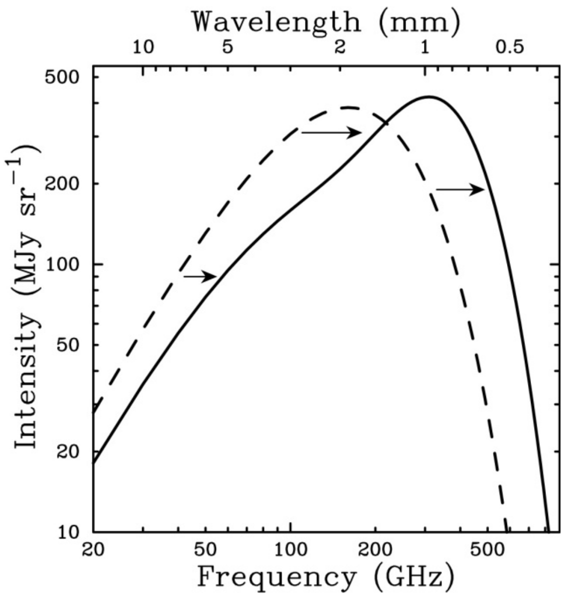
[N III] 122 um

[O Ib] 145 um

3. First Detection of the Sunyaev-Zel'dovich Effect Increment at < 650 um

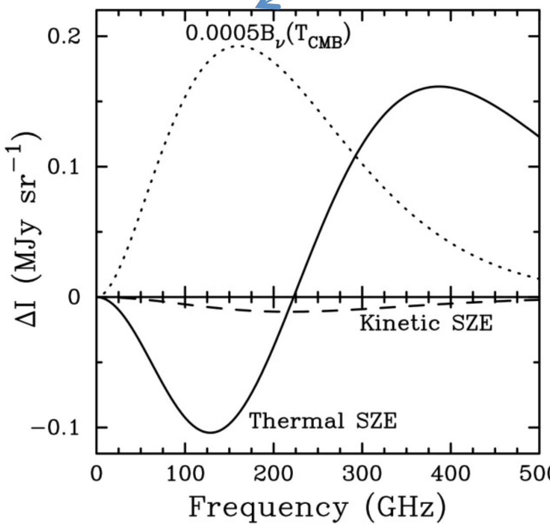
Zemcov et al. (2010)

First, some introduction….



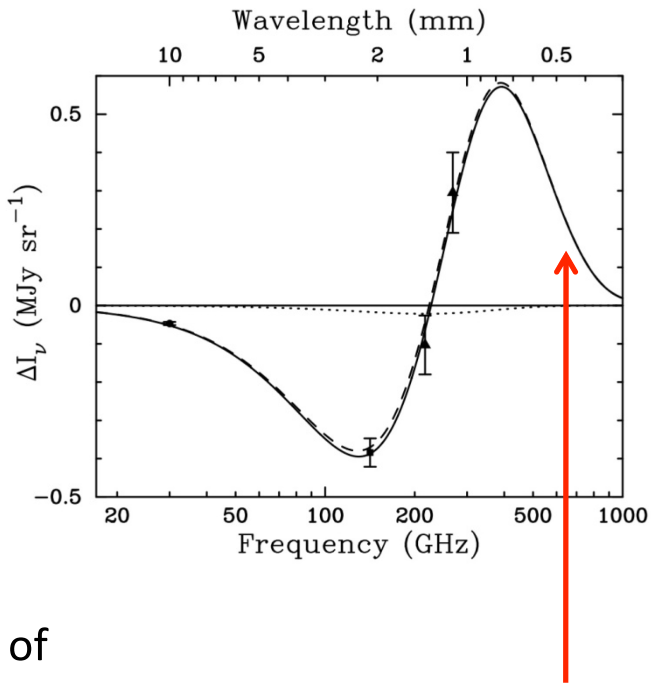
CMB photons gain energy when scattered by high energy electrons in ICM. (The effect exaggerated in the figure above.)

0.05%



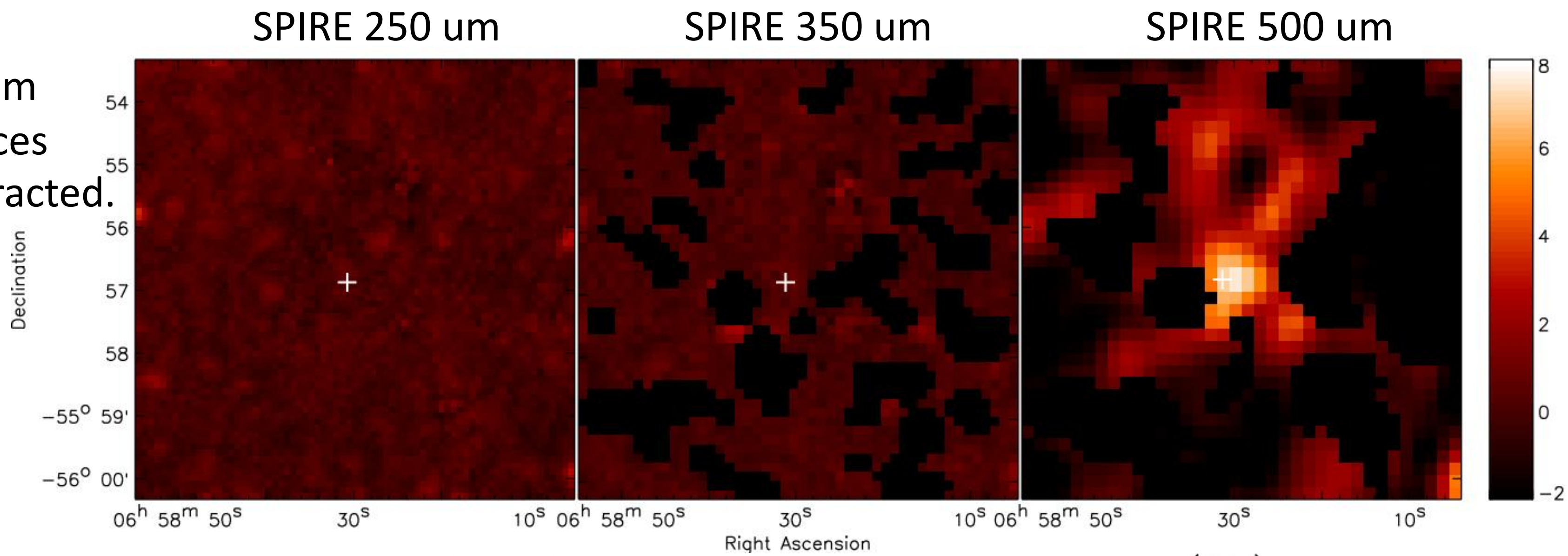
Resultant spectral distortion of the CMB due to the SZ effect.

(from Carlstrom et al. 2002)

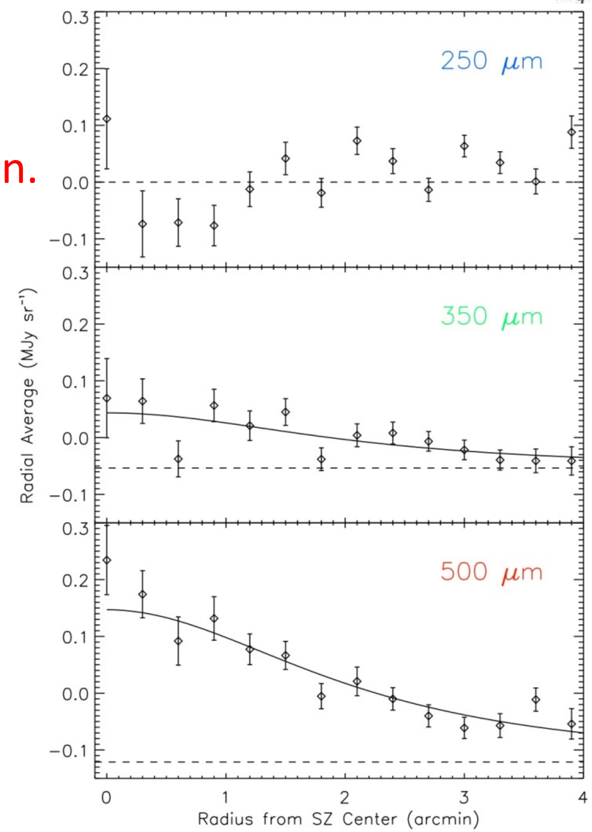


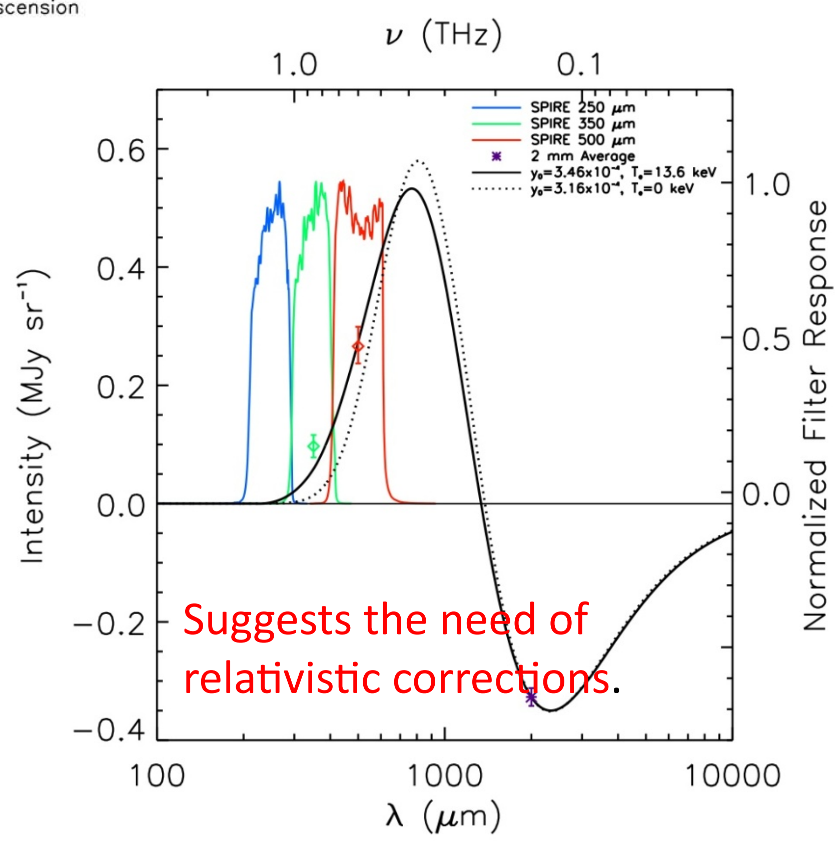
SPIRE will see this part of the SZ signal.

250um sources subtracted.



But no cluster diffuse emission.





Suggests the need of relativistic corrections.

Summary

- In addition to various large field-survey programs (PEP, HerMES, and Herschel-ATLAS), Herschel is conducting a number of observations targeting massive galaxy clusters.
- Gravitationally lensed background galaxies as well as IR/submm-bright cluster members can be studied (and SZ effect in some cases).
- First impression is that galaxy IR/Submm SEDs are quite diverse $\longrightarrow$ We have a lot to study with Herschel!

Survey Strategy & Design

- Target: ~40 massive galaxy clusters (GT surveys observe 10 clusters -> OT+GT~50)
- Selected X-ray-luminous clusters with good ancillary data and cluster mass models.
- Close collaboration with two other cluster OTKPs (LoCuSS – PI: G. Smith; BCGs – PI: A. Edge)
- PACS: 100/160um; FOV 8'x8'; 5/10 mJy (5σ)
- SPIRE: 250/350/500 um; FOV 17'x17'; confusion limit ~30 mJy (5σ)
- Total observing time: 292.3 hrs