Herschel Lensing Survey (HLS)

Beyond the Confusion: Enhancing our View of High-z Star Formation via Cluster Lensing

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Outline

Limits of Herschel blank fields at high redshift

The power of cluster lensing

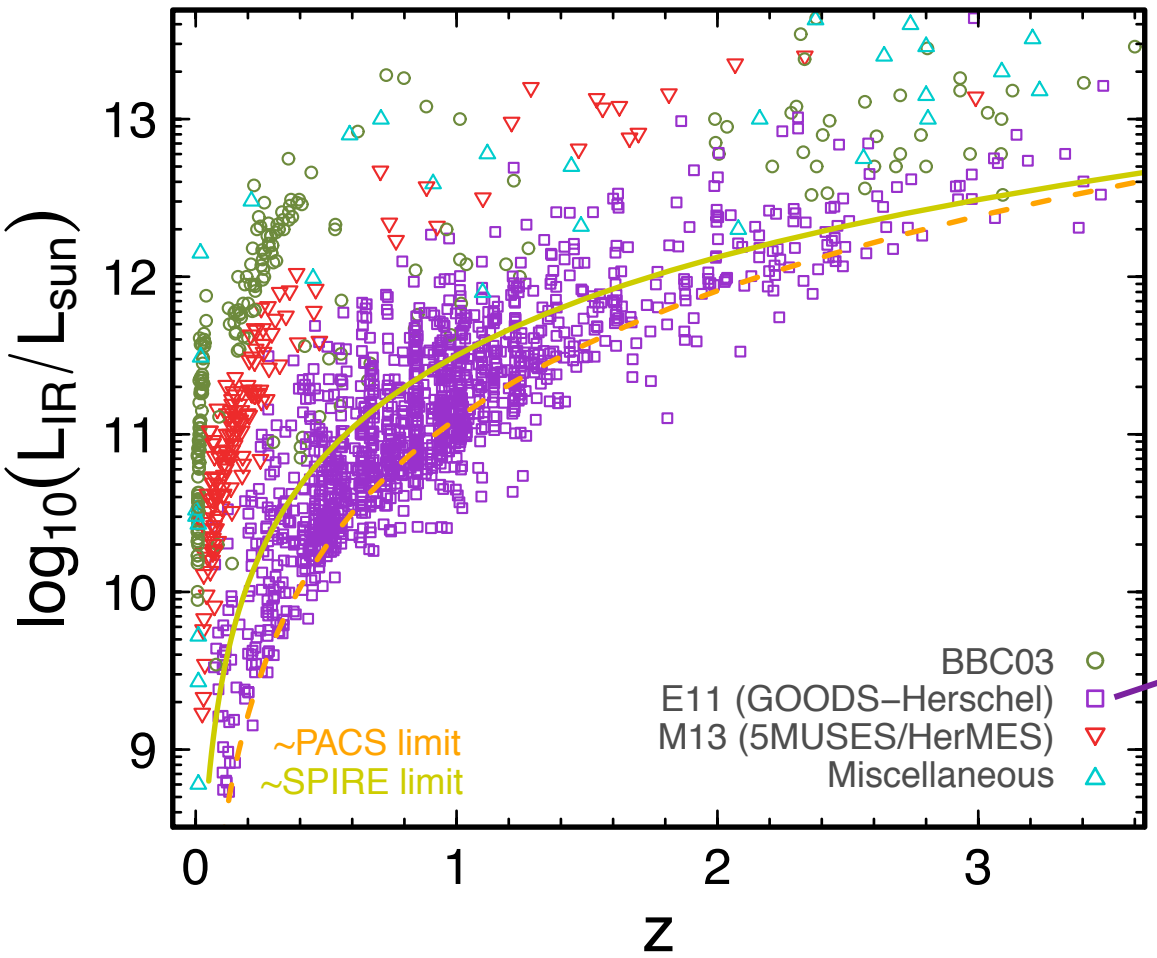
The Herschel Lensing Survey (HLS)

Overview of a few example lensed sources

- 75x magnified source @ z=2.8 behind the Bullet Cluster [Rex+10]
- A few interesting examples [Egami+prep, Walth+prep, Clement+prep]
- HLS0918: z=5.2 system behind A773 [Combes+12, Rawle+14, Boone+prep]

Summary: Lensing with Herschel (and beyond)

High Redshift from Herschel Blank Fields

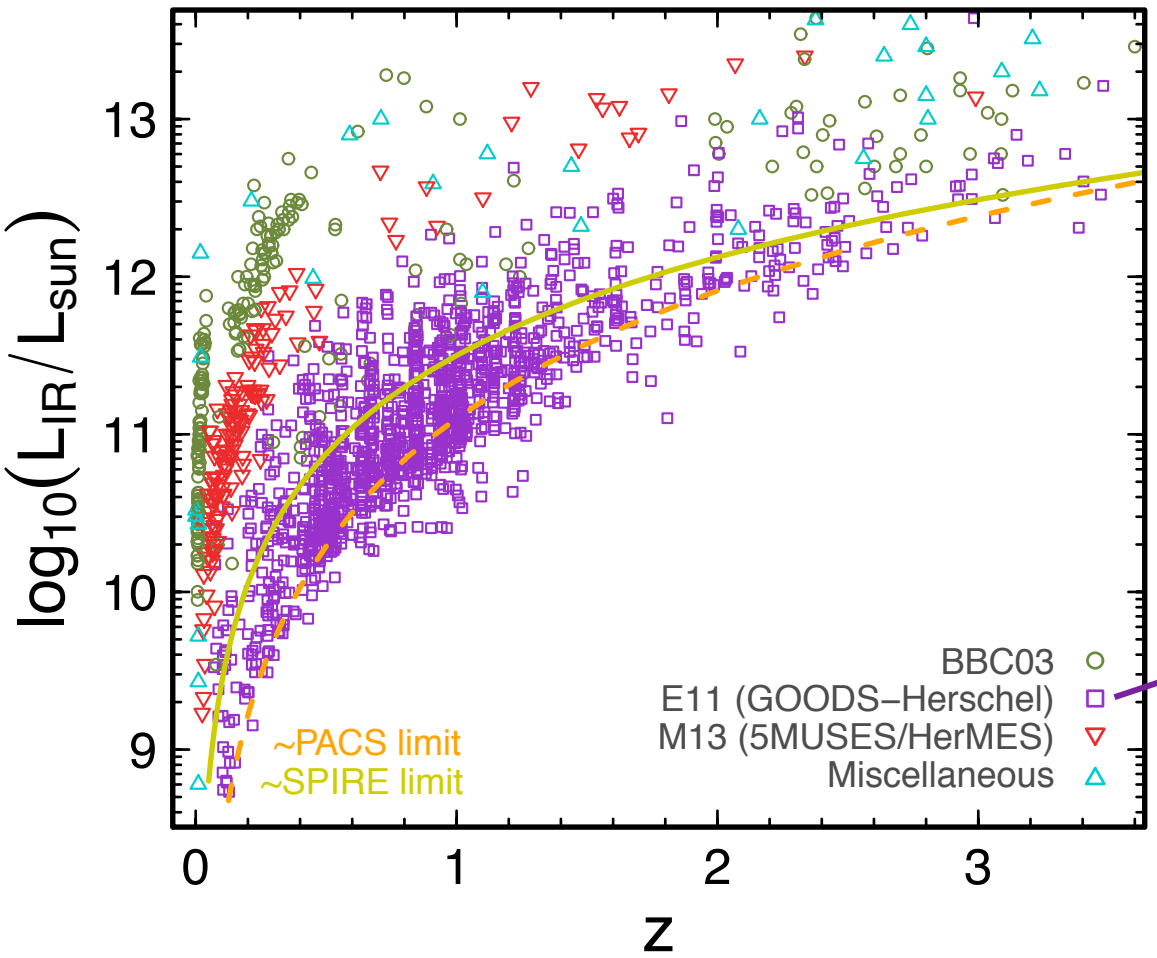


Elbaz+11

GOODS-Herschel

At z > 1.5, blank field surveys only probe the LIRG+ regime

High Redshift from Herschel Blank Fields



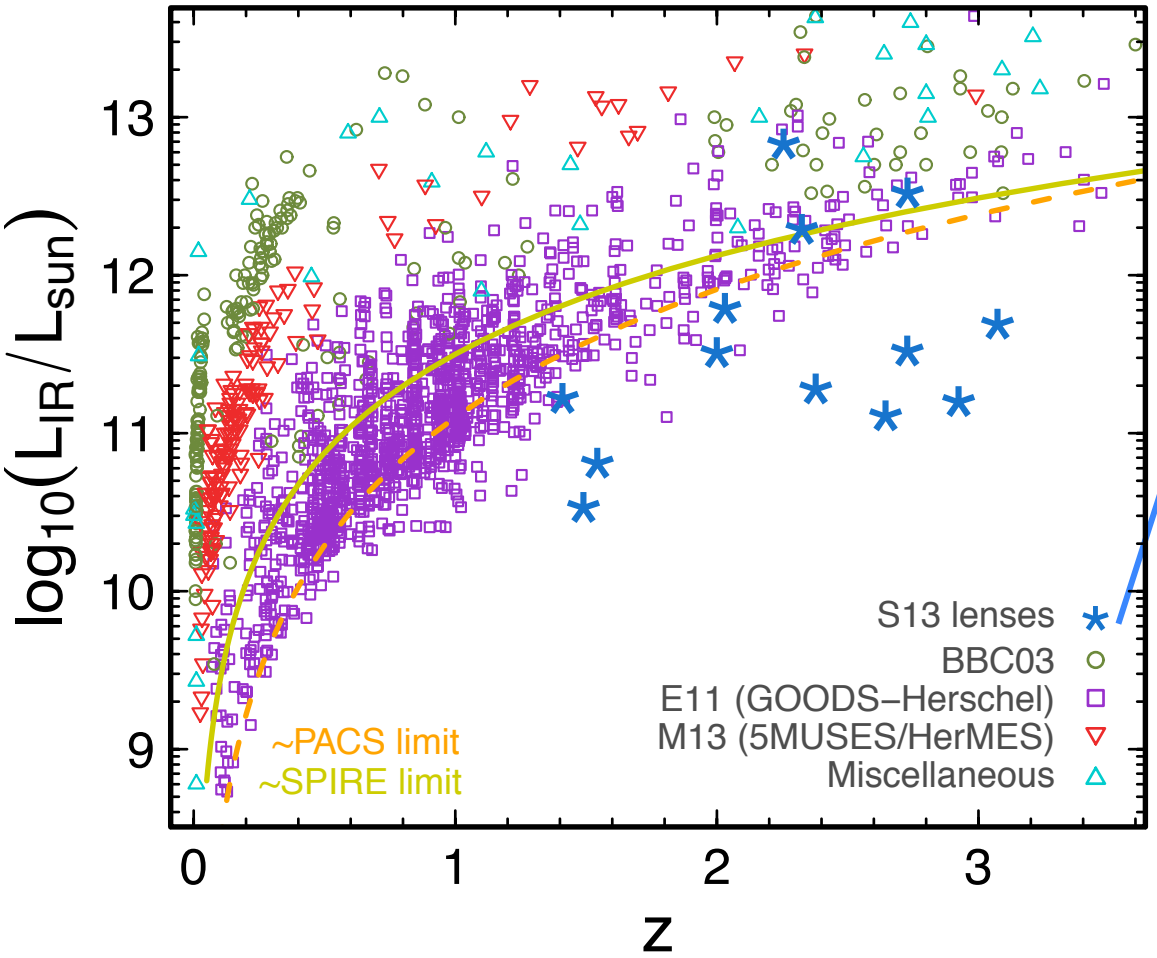
Elbaz+11

GOODS-Herschel

At z > 1.5, blank field surveys only probe the LIRG+ regime

You can probe deeper by exploiting gravitational lensing

High Redshift from Herschel Blank Fields

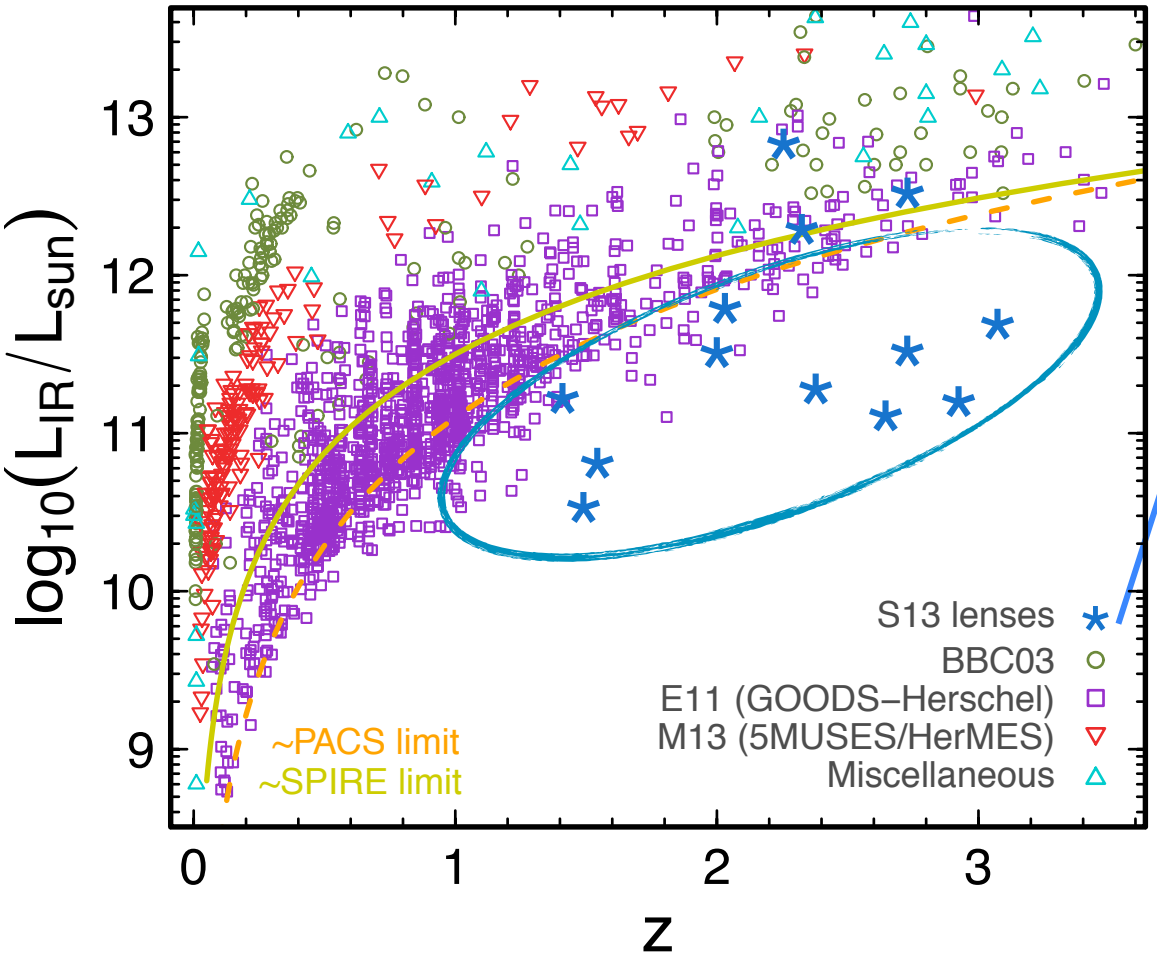


Saintonge+13

Well-constrained galaxy-lensed sources

Individual foreground galaxies can be lenses

High Redshift from Herschel Blank Fields



Saintonge+13

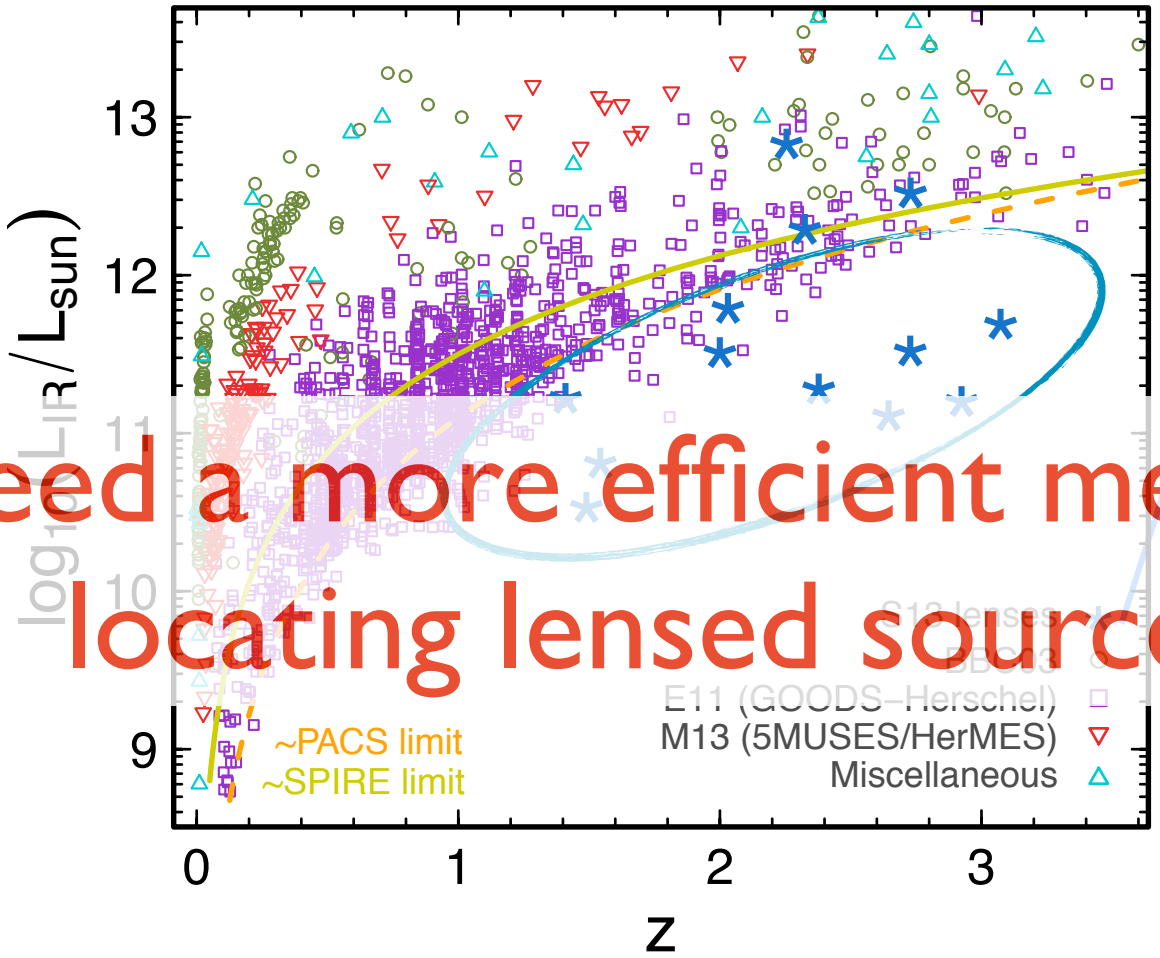
Well-constrained galaxy-lensed sources

Only ~10 are intrinsically fainter than Herschel limits

Individual foreground galaxies can be lenses... BUT

1) galaxy-galaxy lenses are only discovered serendipitously in large blank-field surveys
2) the lens and background source can be hard to disentangle

High Redshift from Herschel Blank Fields



Saintonge+13

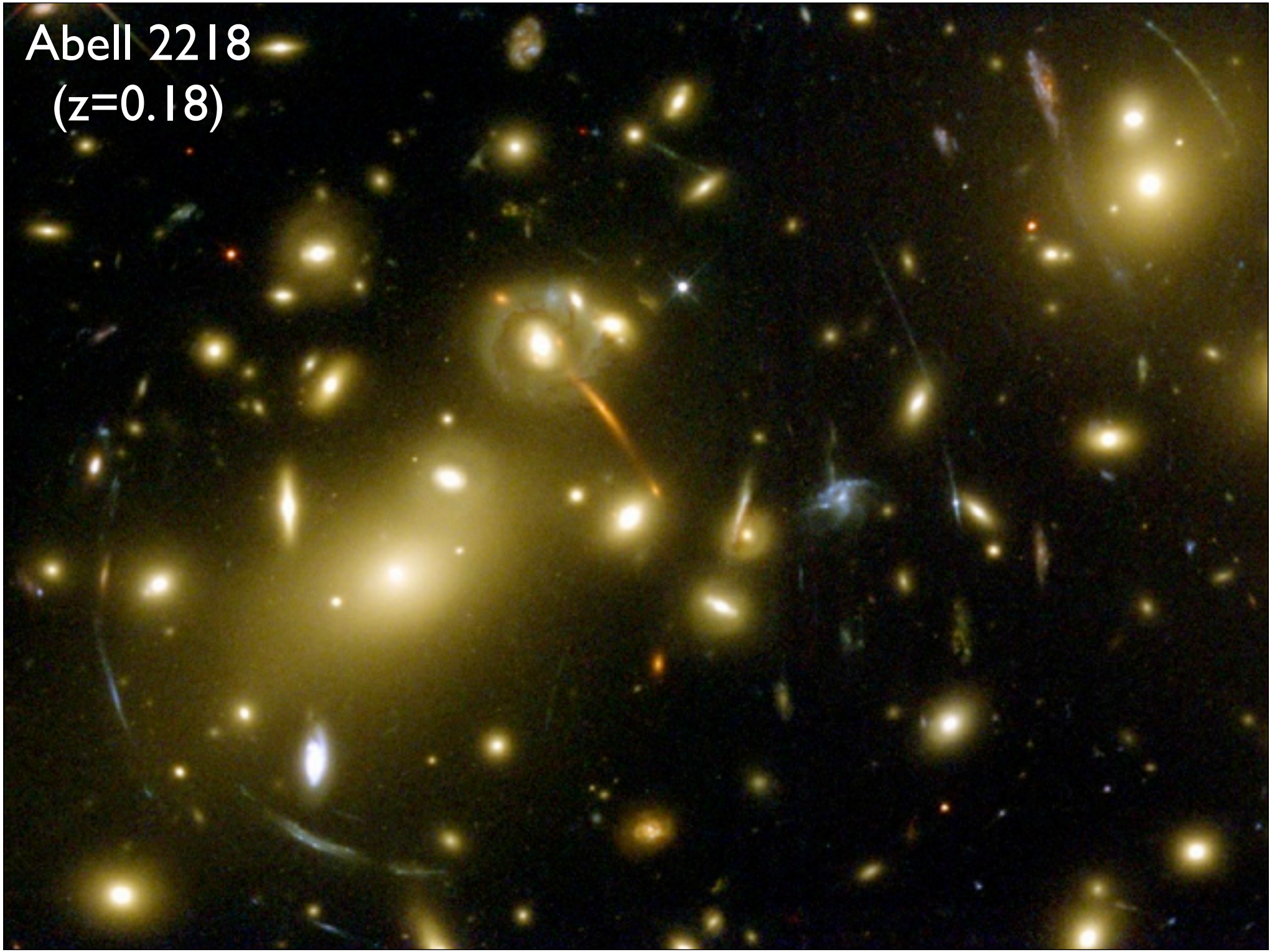
Well-constrained galaxy-lensed sources

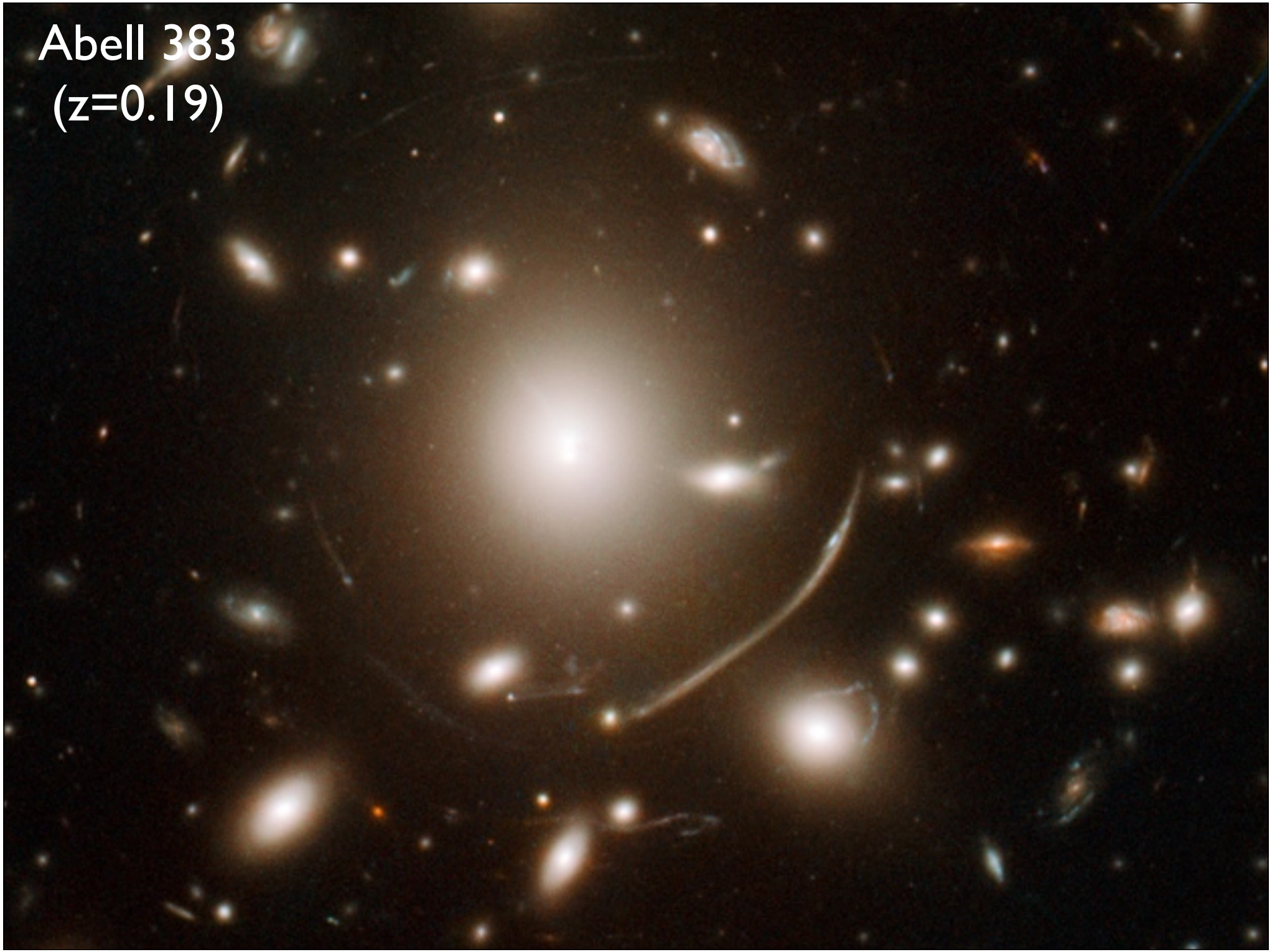
Only ~10 are intrinsically fainter than Herschel limits

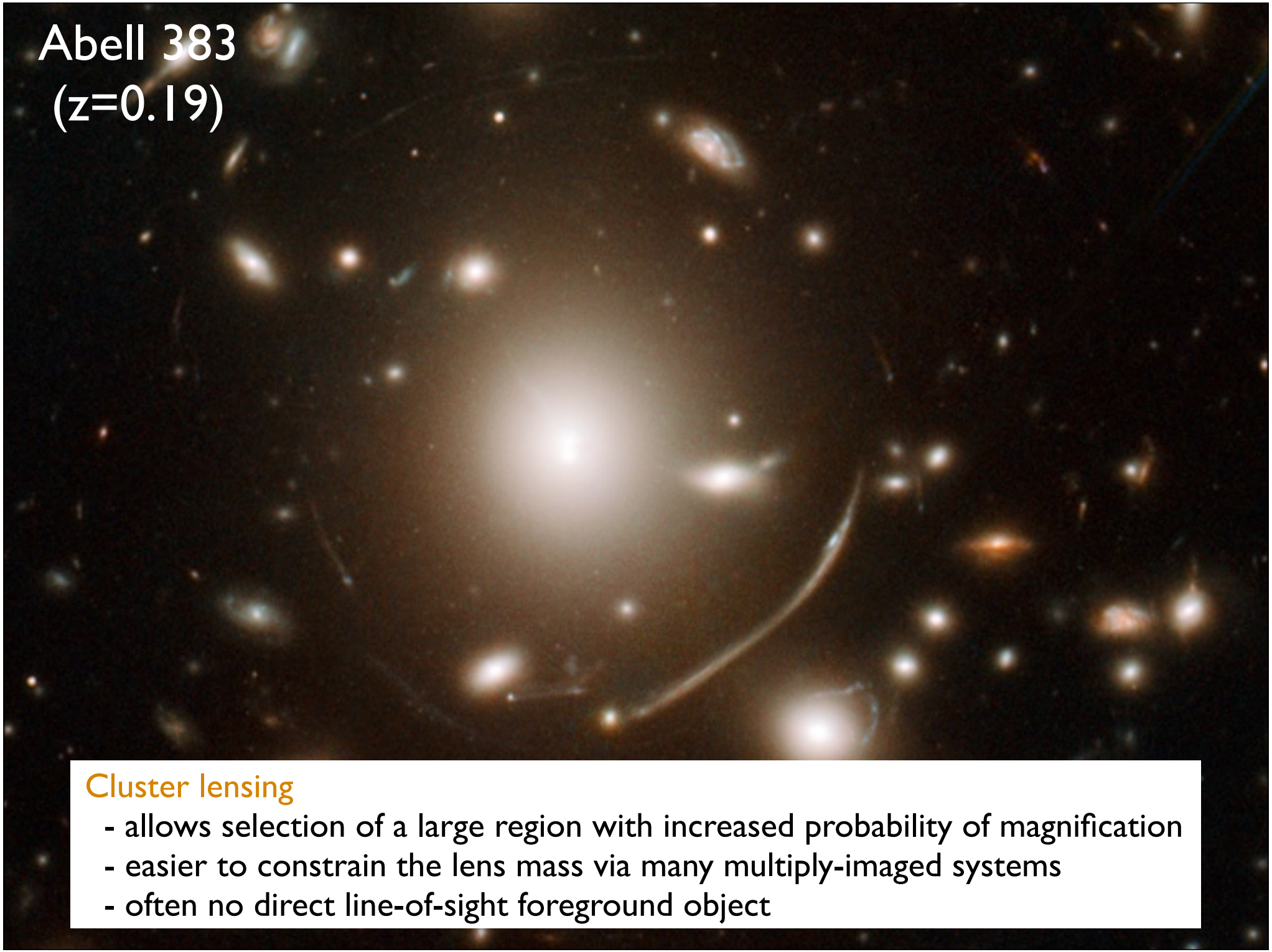
We need a more efficient method for locating lensed sources

Individual foreground galaxies can be lenses... BUT

1) galaxy-galaxy lenses are only discovered serendipitously in large blank-field surveys
2) the lens and background source can be hard to disentangle


Abell 2218
(z=0.18)


Abell 383
(z=0.19)



Cluster lensing

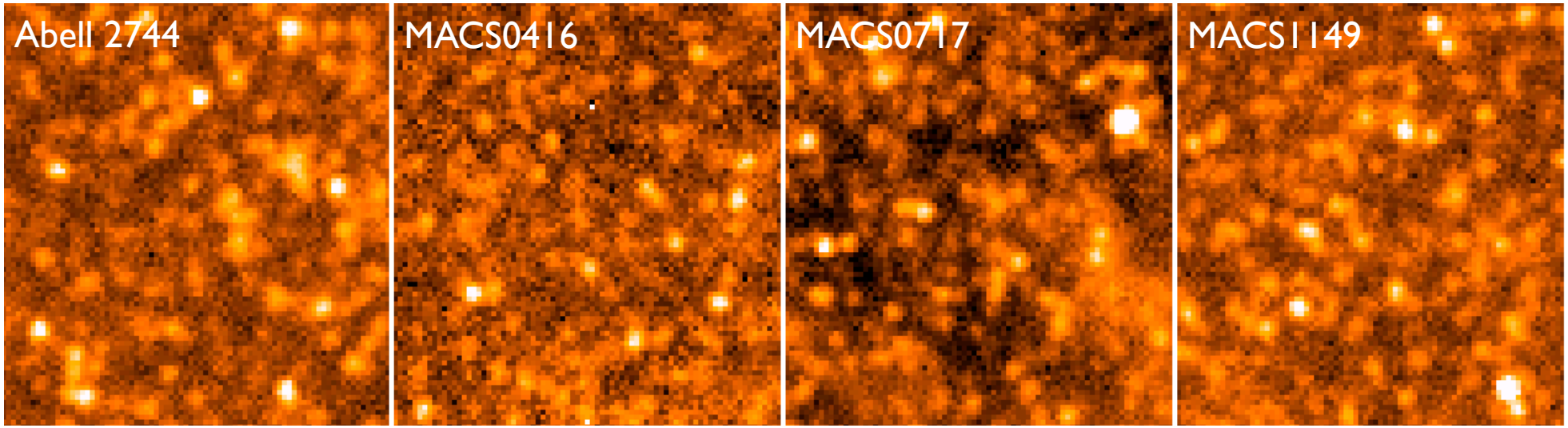
- allows selection of a large region with increased probability of magnification
- easier to constrain the lens mass via many multiply-imaged systems
- often no direct line-of-sight foreground object

The Herschel Lensing Survey (HLS)

PI: Eiichi Egami (Steward Observatory, Arizona)

- HLS-deep + GT clusters (~370 hours)

- 65 well-studied massive galaxy clusters (0.1<z<1.0)
- Deep 100-500μm PACS+SPIRE imaging (~2.4, 4.7, 9.4, 10.6, 12.0 mJy)... ~5 deg^2
- Full IRAC coverage and ~75% MIPS 24μm coverage
- Sample includes all 25 CLASH clusters (HST Treasury Survey with 16 UV-NIR bands)
- Sample includes all 4 HST Frontier Fields (ultra-deep HST DDT program)



- HLS-snapshot (~50 hours)

- 537 clusters (0.1<z<1.0) from the ROSAT, MACS, SPT and CODEX samples
- Near confusion 250-500μm SPIRE imaging (~14, 19, 20 mJy)... ~10 deg^2

The power of lensing in the far-infrared

Galaxies in the far-infrared (FIR)

- UV photons heat dust, and are re-emitted at longer λ: FIR probes dust properties
- In galaxies, dominant heat sources are young stellar populations and AGN - in the absence of AGN, FIR traces dusty star formation

- Peak of dust component in SPIRE bands at $z \sim 1-5$: FIR colour crudely traces redshift
- Negative K-correction implies there are abundant IR-bright systems at high redshift

- BUT confusion noise sets the fundamental sensitivity of current FIR surveys
- Blank-field surveys only observe U/HyLIRG population at high-z

Gravitational lensing

- Amplifies individual fluxes, while preserving surface density
- Reduces source density by spreading out other background galaxies
- Increases spatial extent (source-plane reconstruction possible with lensing model)

FIR surveys of massive clusters locate high-z lenses efficiently

The Herschel Lensing Survey (HLS)

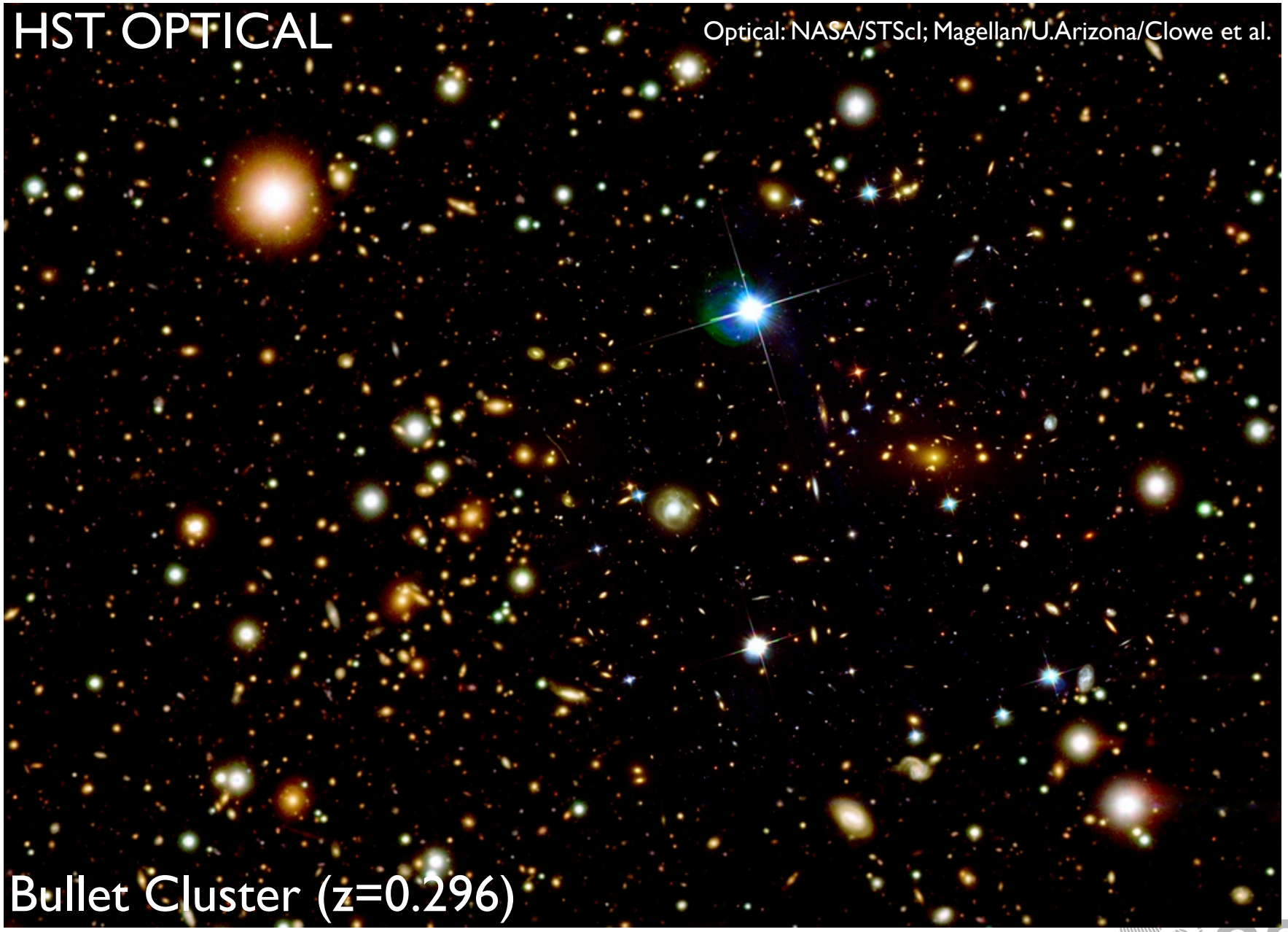
Selected High Redshift Publications:

- Egami+10, A&A, 518, 12 ..... A&A Special Edition Survey Paper
- Rex+10, A&A, 518, 13 ..... Bullet Cluster
- Combes+12, A&A, 538, 4 .....
- Rawle+14, 2014, ApJ, 783, 59 ..... A773 (IRAM-30m, PdBI, SMA follow-up)
- Boone+13, A&A, 559, 1 ..... AS1063 (LABOCA-detected, Herschel drop-out)
- Sklias+14, A&A, 561, 149 ..... SFHs of HLS sources
- Dessauges-Zavadsky+ (arXiv:1408.0816) CO gas content → Talk: Friday 9:50

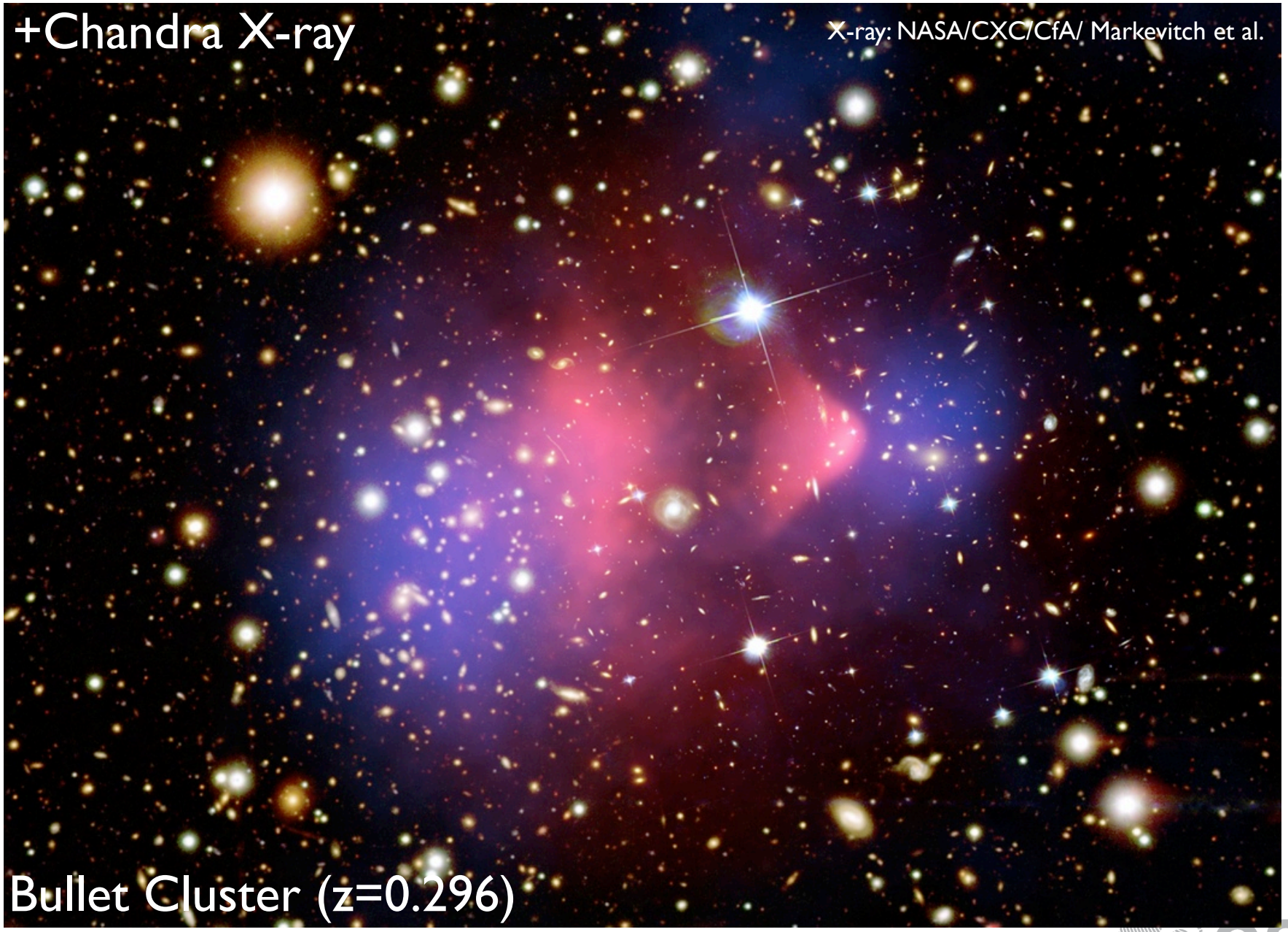
- Cluster sources: Rawle+10, Rawle+12a, Rawle+12b, Rawle+14b →
- SZ effect: Zemcov+10, Prokhorov+12, Sayers+13

Poster 4.06
The effect of a **cluster merger** induced shock on constituent galaxies

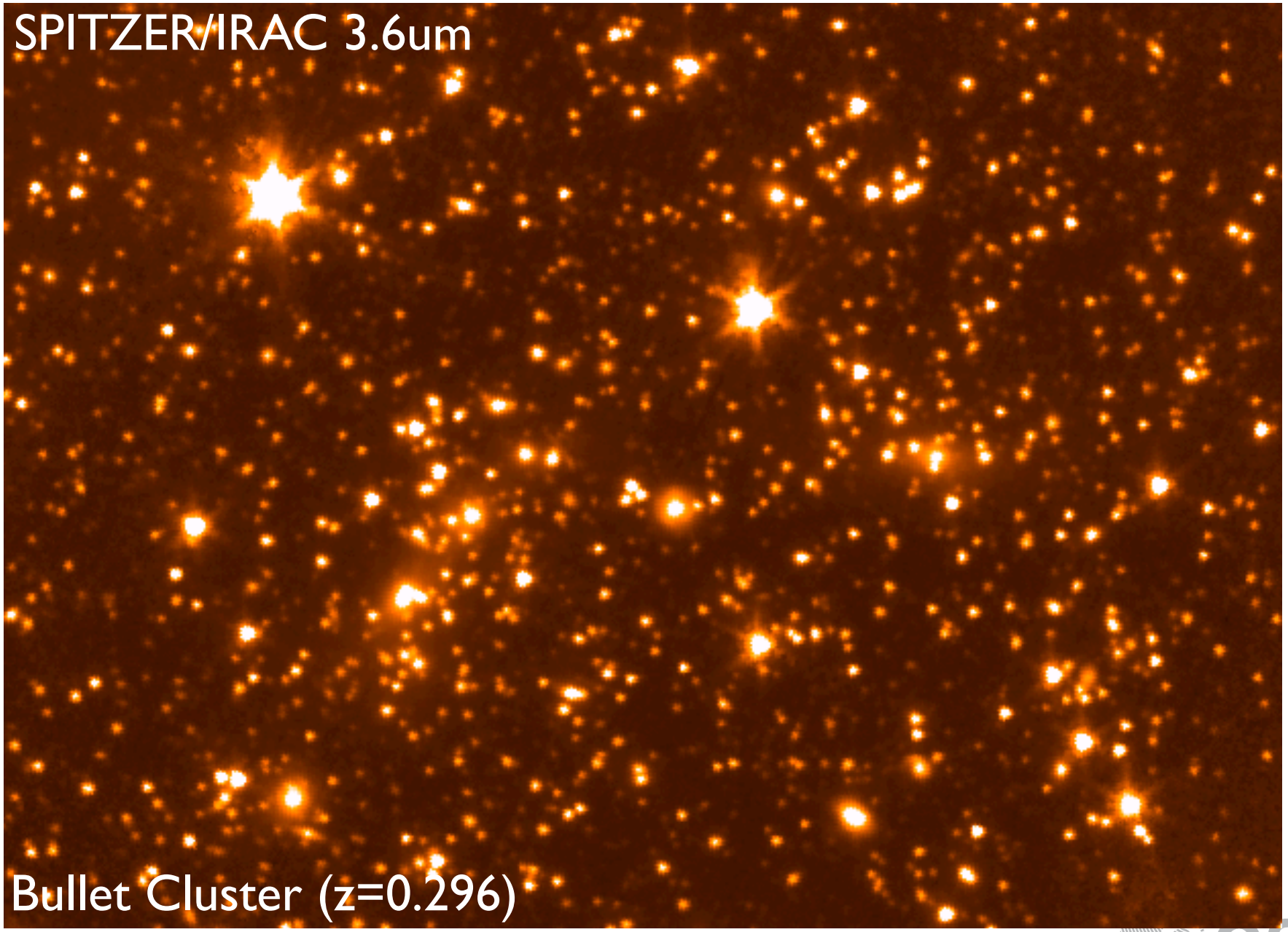
The power of Herschel



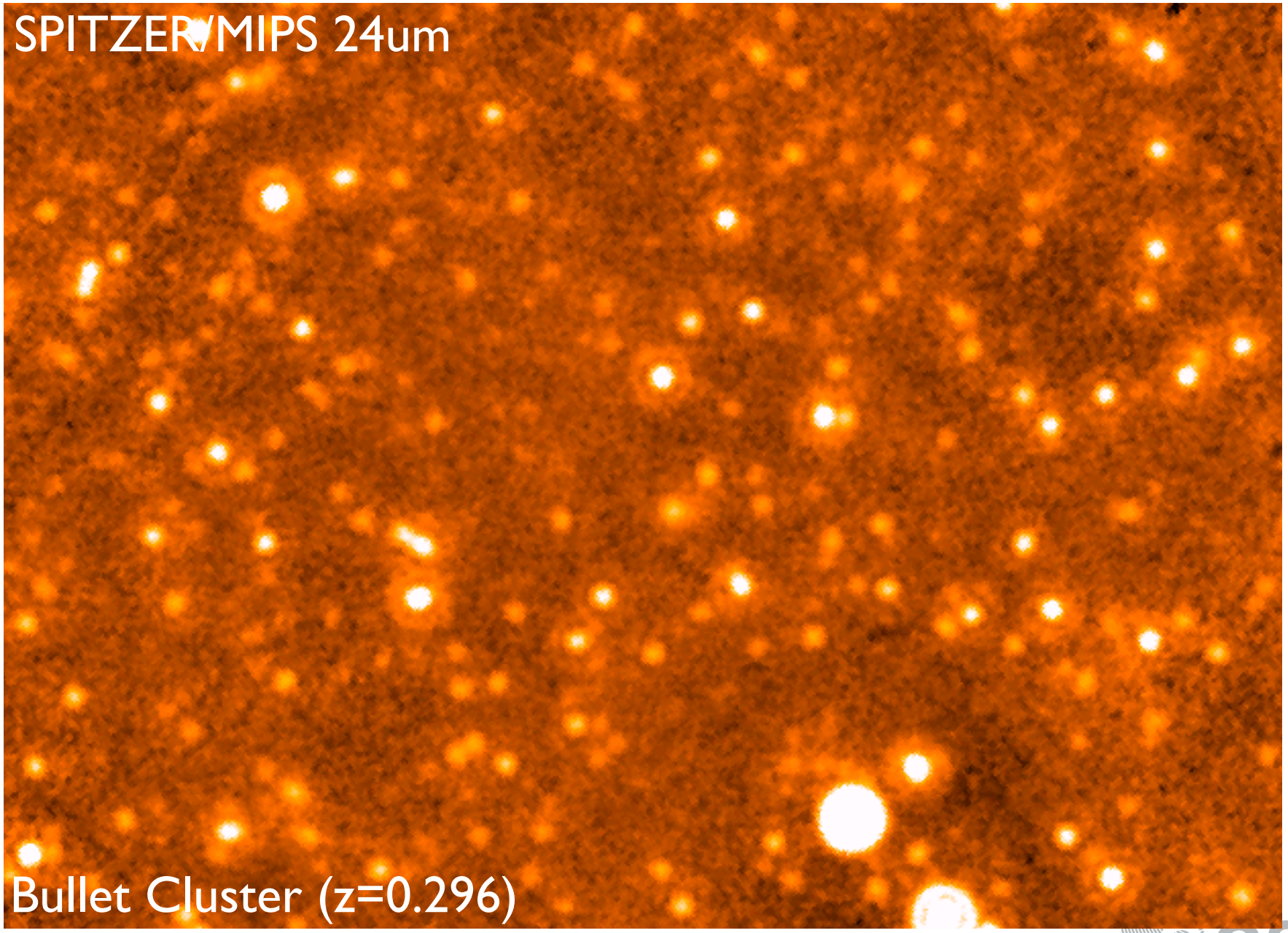
The power of Herschel



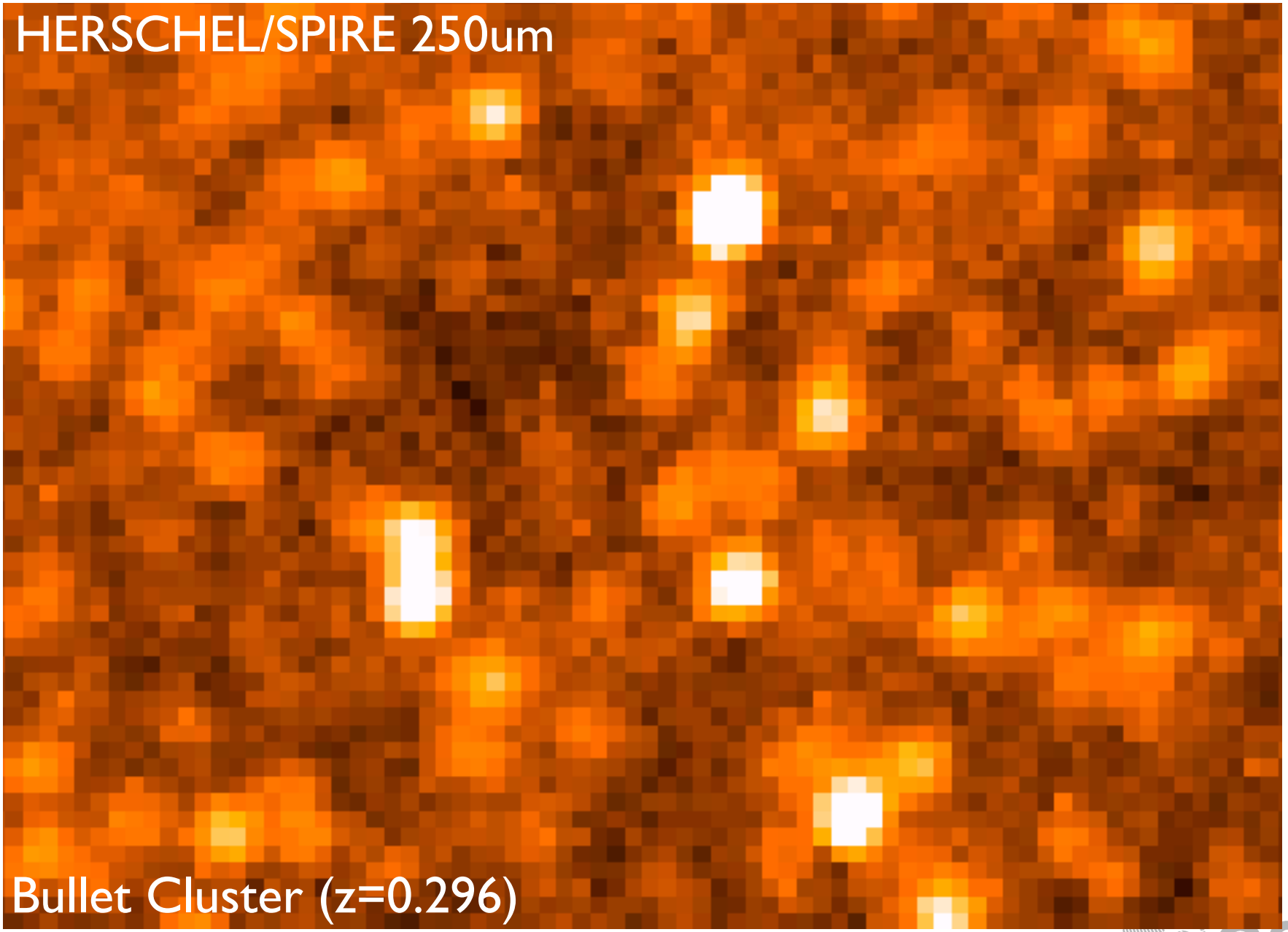
The power of Herschel



The power of Herschel



The power of Herschel



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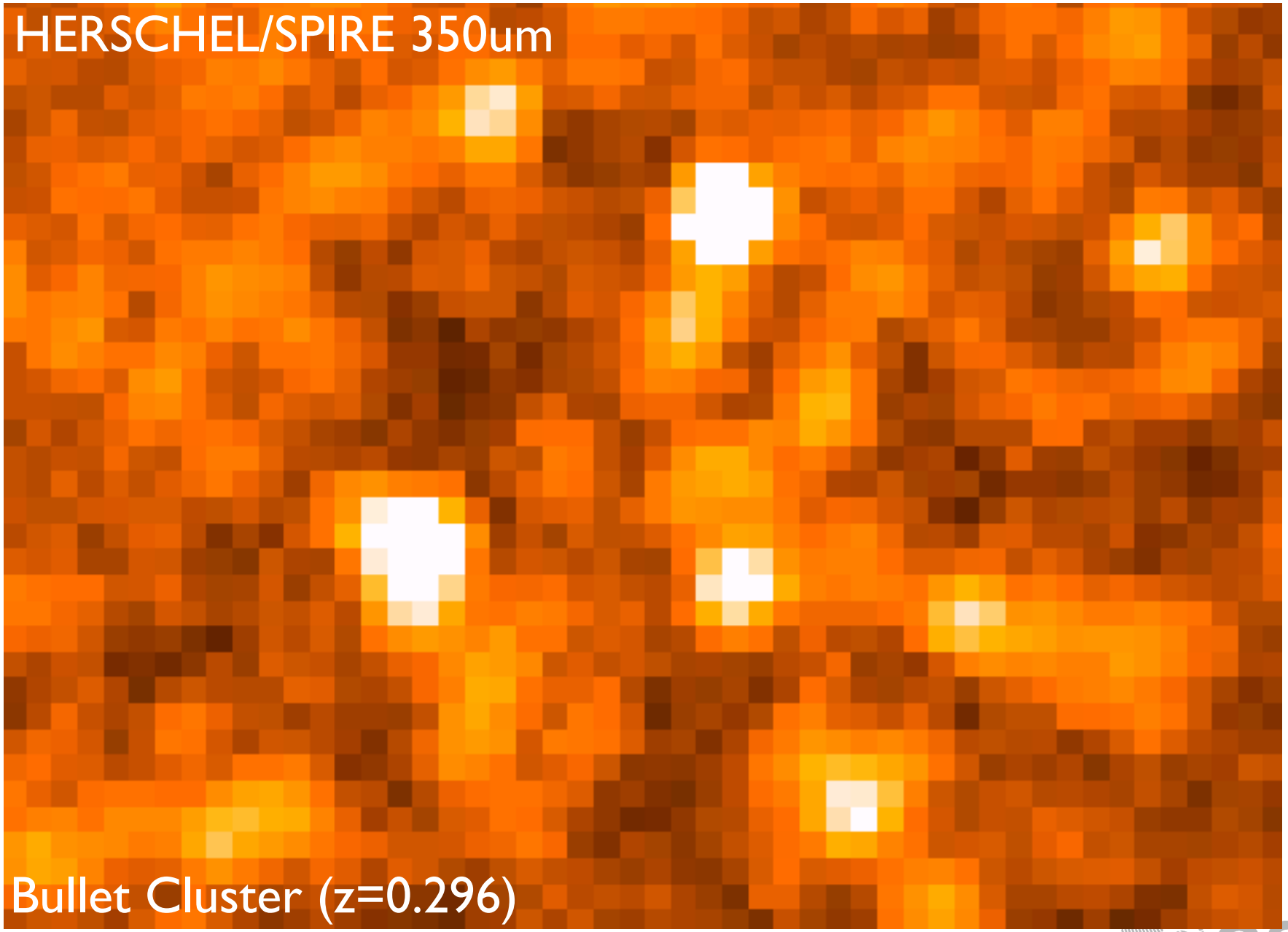
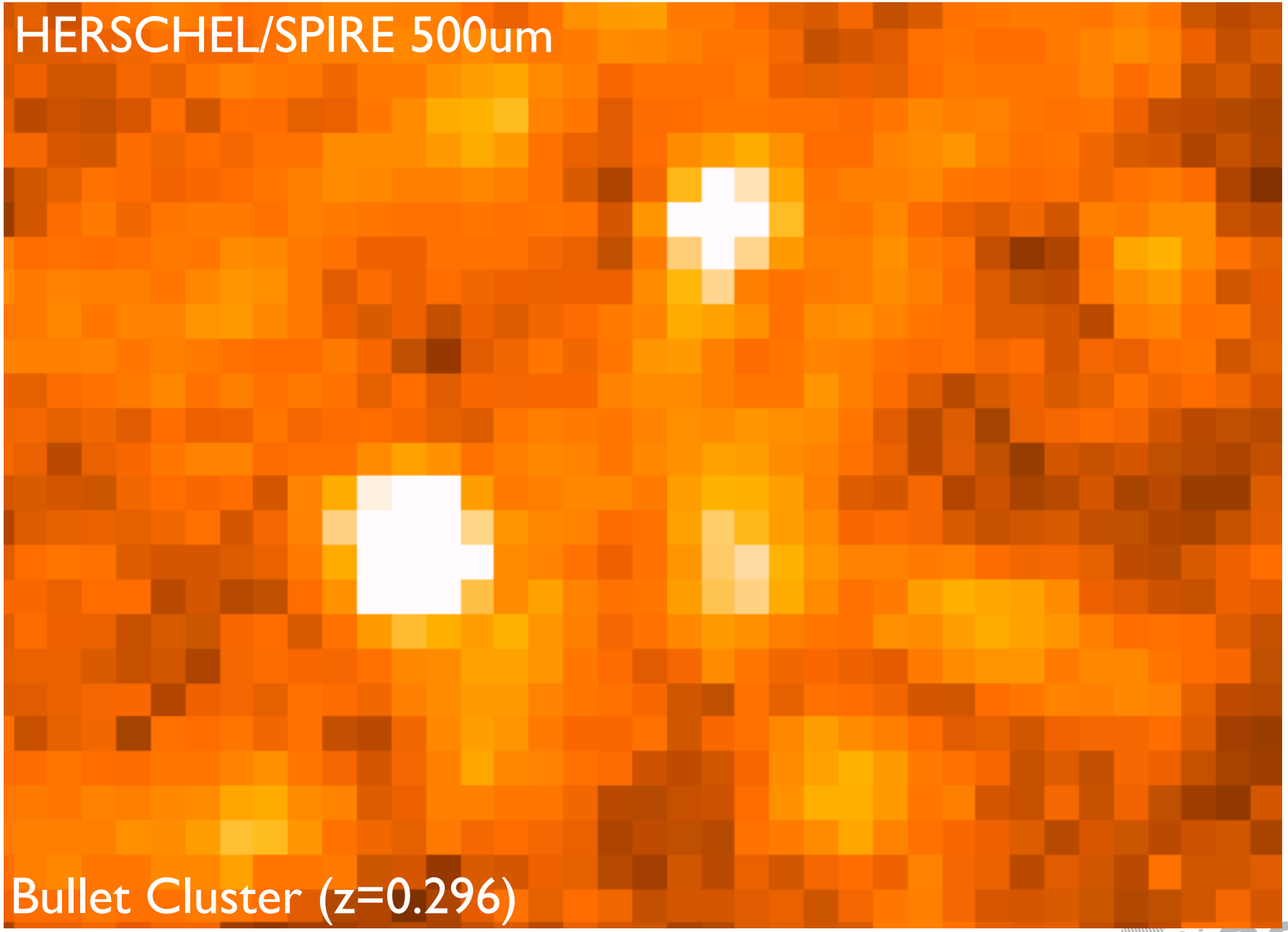
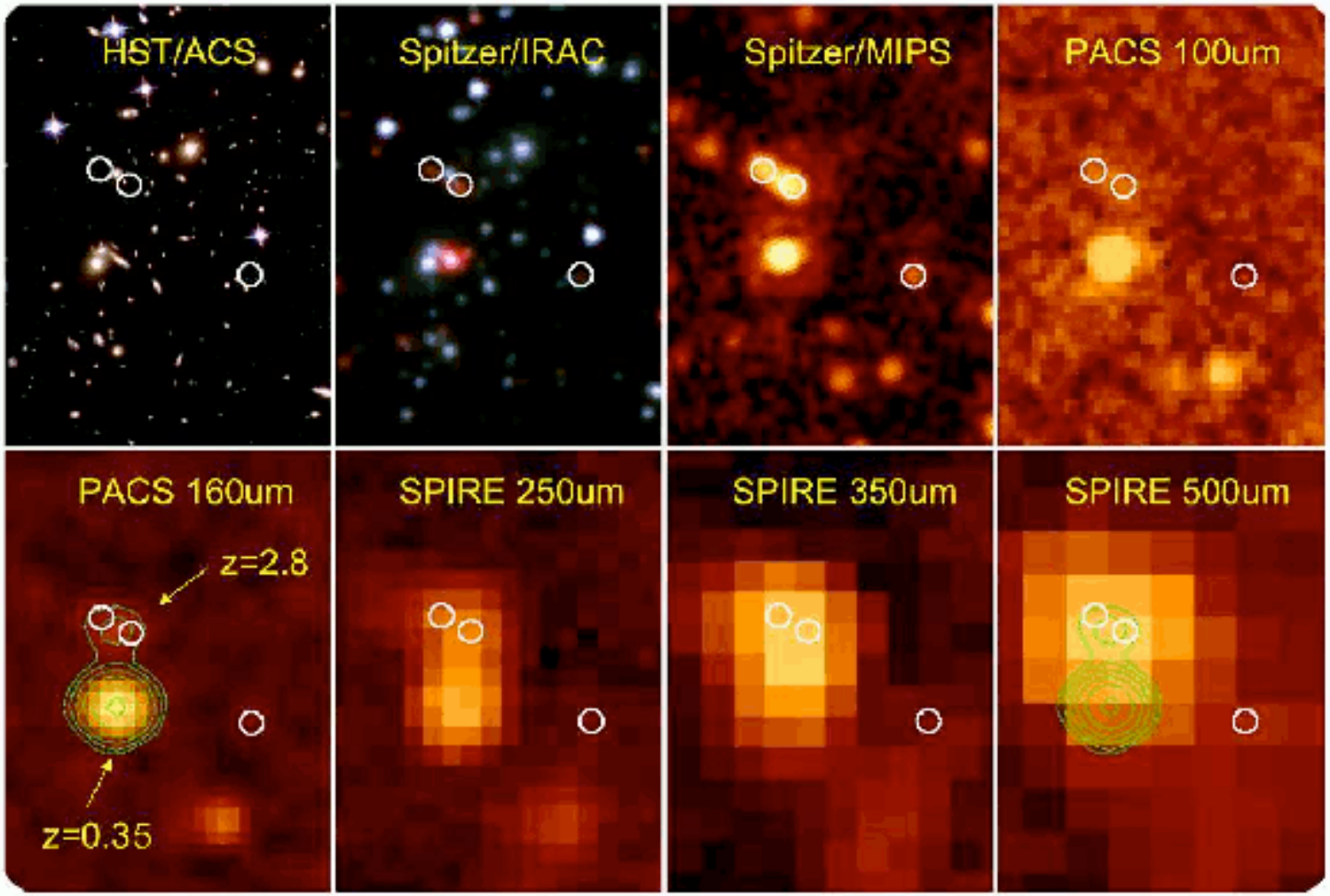


The power of Herschel



Faint (LIRG; 5×10^{11} $L_\odot$) lensed source at z=2.8



[Rex+10]

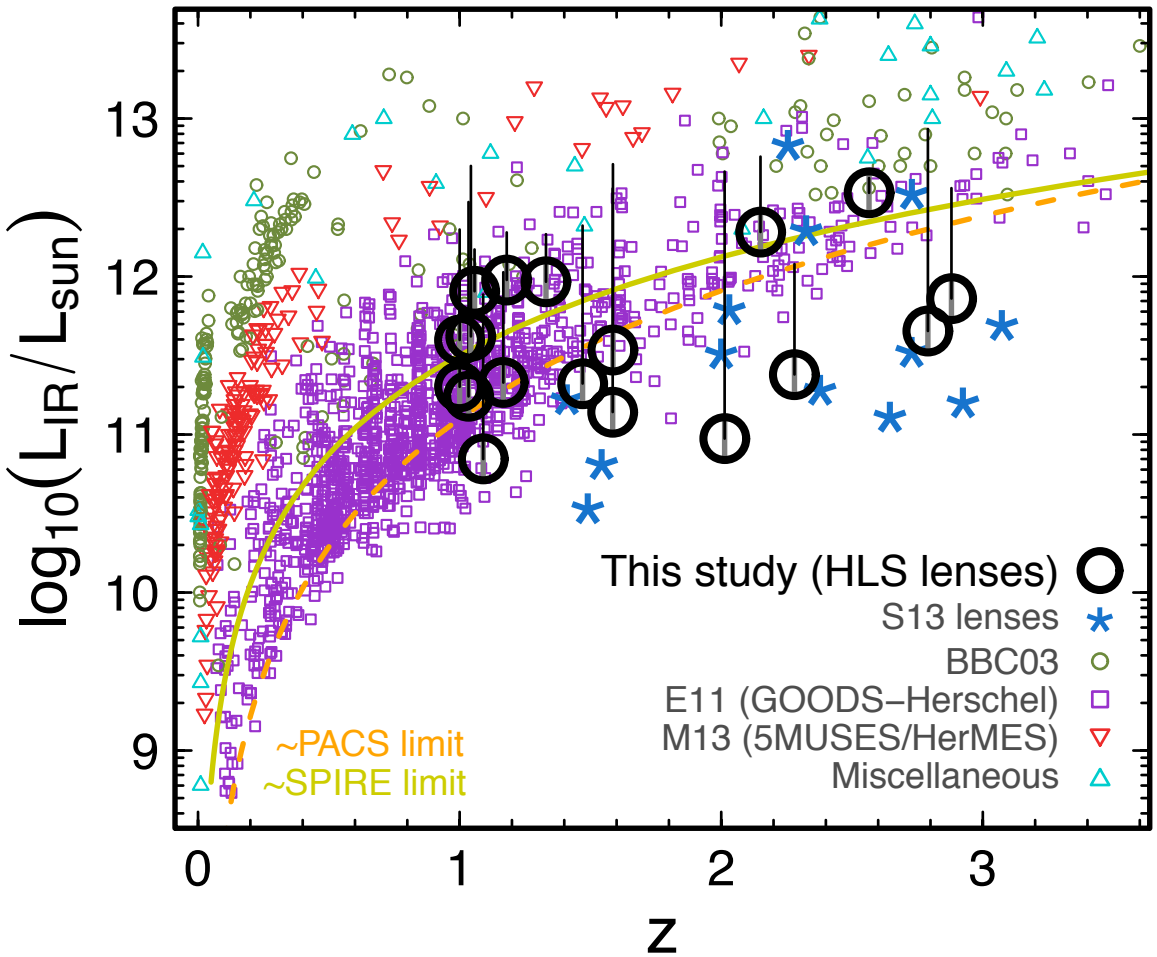
Magnification factor of ~75x

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

Corrected for lensing: 0.09, 0.3, 0.9, 1.3, 1.4 mJy

Such a source would be impossible to observe without lensing

The beginnings of the full HLS sample



[Rawle+in prep.]

From first 10 HLS deep clusters: ~8 well-constrained sources below Herschel limits

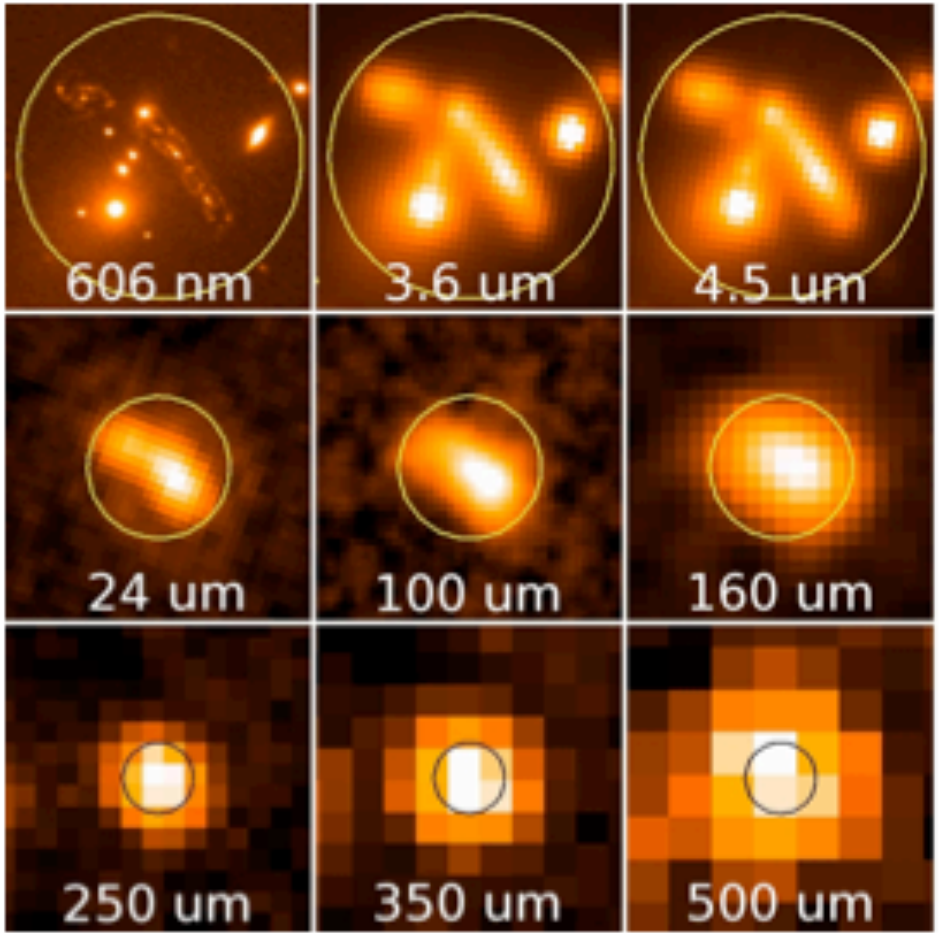
Full HLS-deep: ~50 similar sources

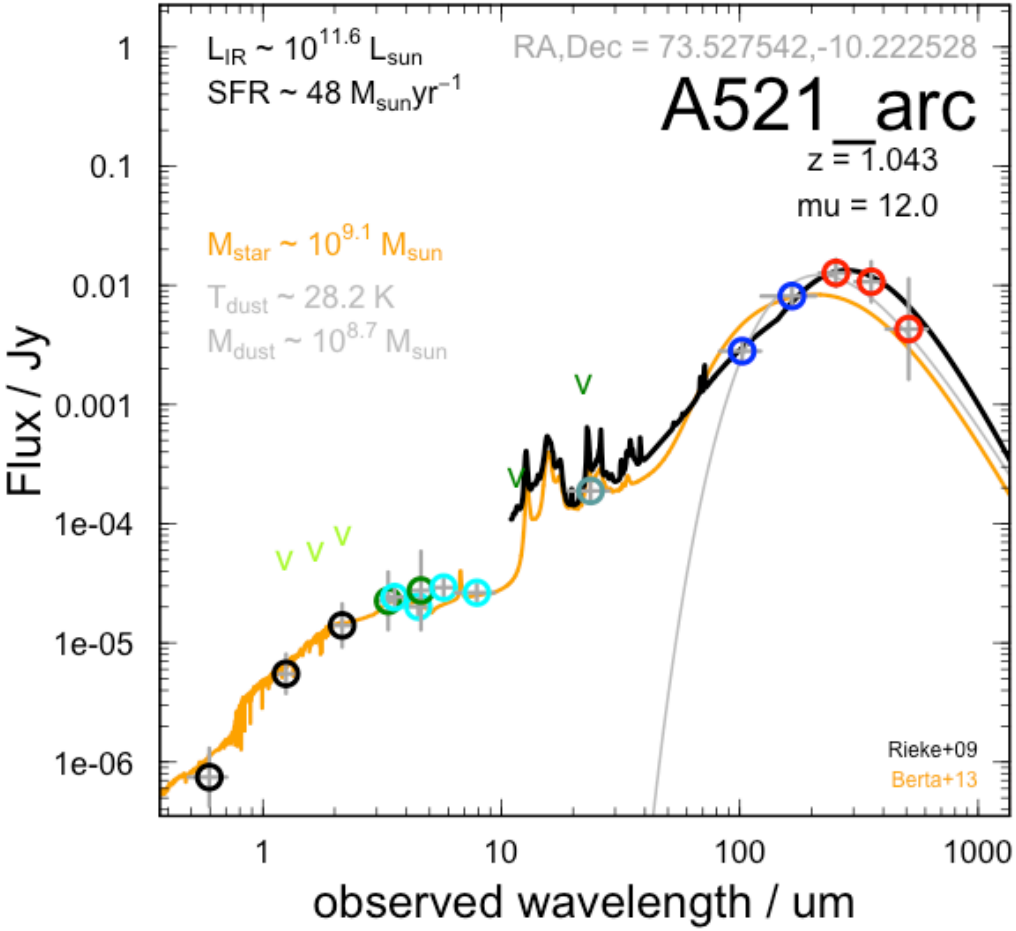
HLS (deep+snapshot): >150 (no PACS for snapshot)

Abell 521: giant arc @ z=1.04

cluster @ z=0.25

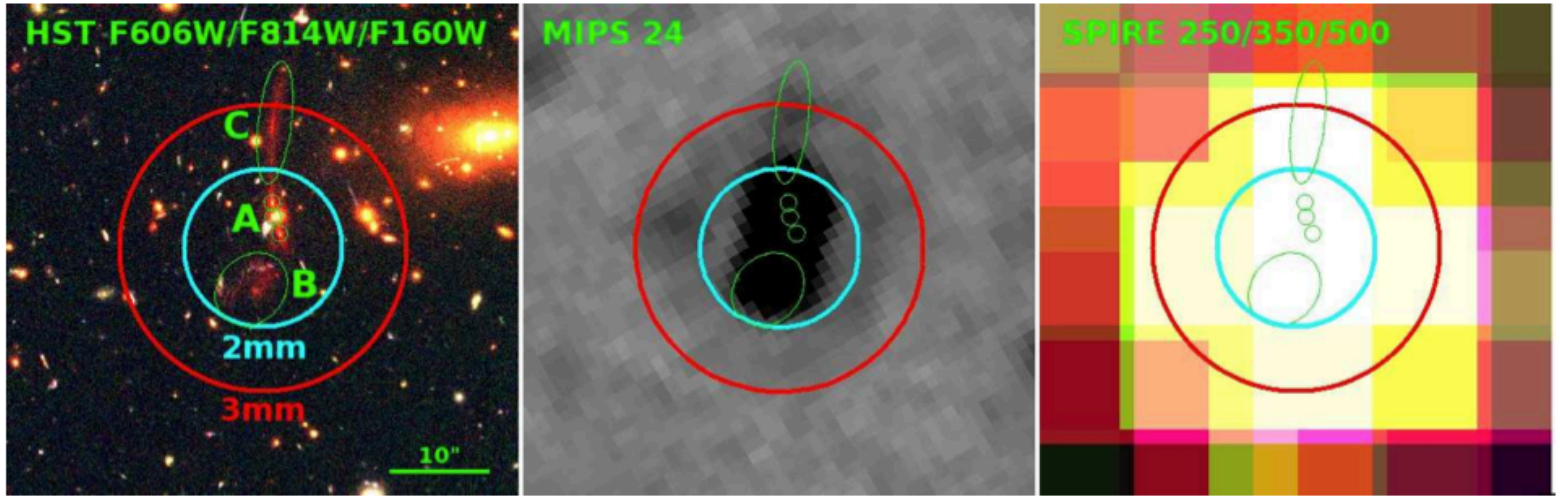
LIRG type @ 12x magnification





[Rawle+in prep.]

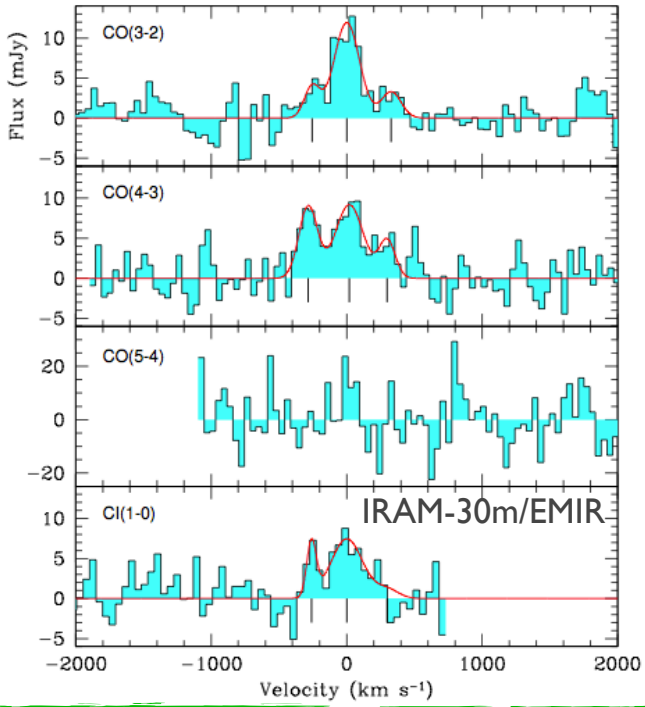
CLJ1226: 3 clustered SMGs?



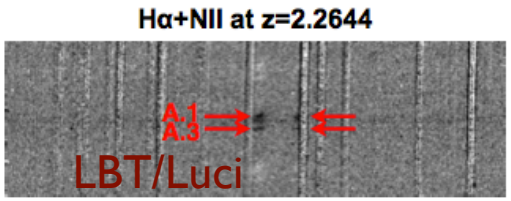
cluster @ z=0.89

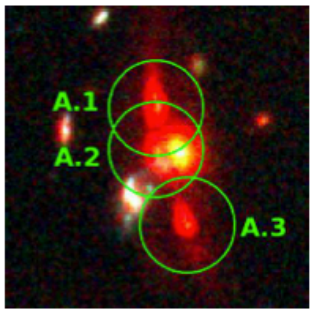
3 strongly-lensed systems (A,B,C)

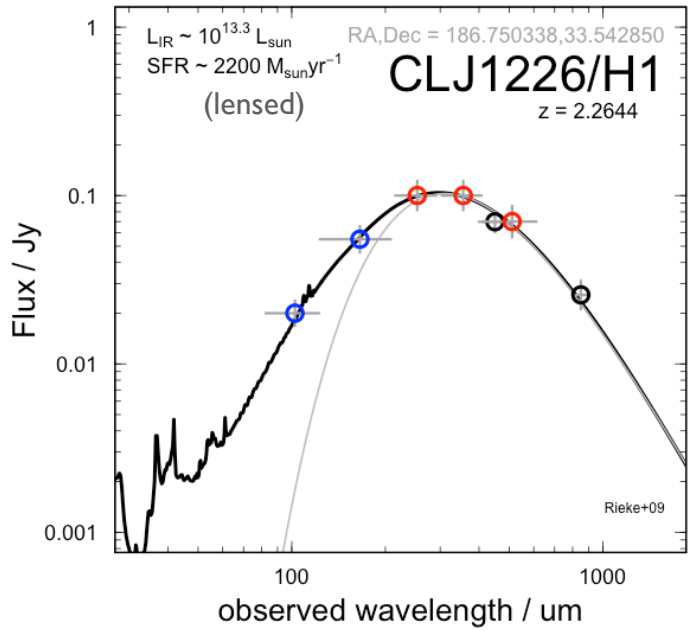
[Clement+in prep.]



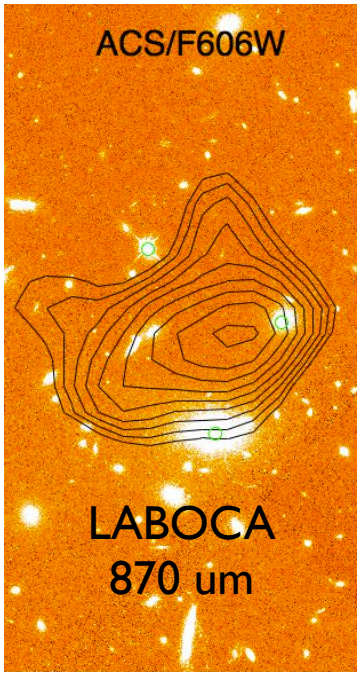
Triply-imaged system A @ z=2.2644

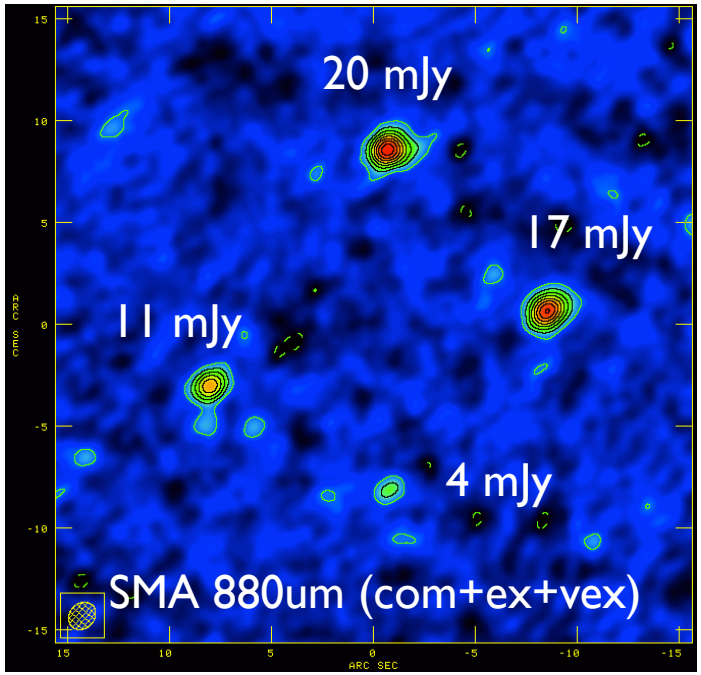


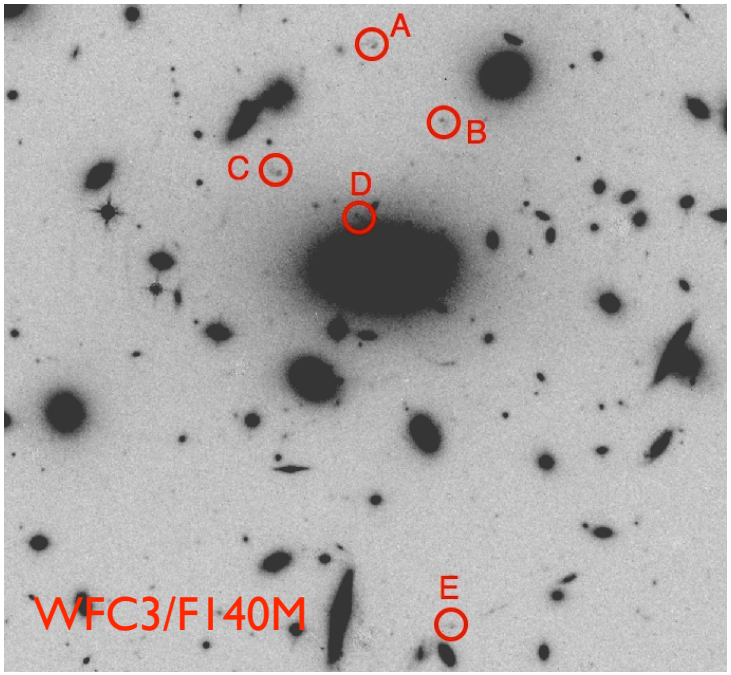




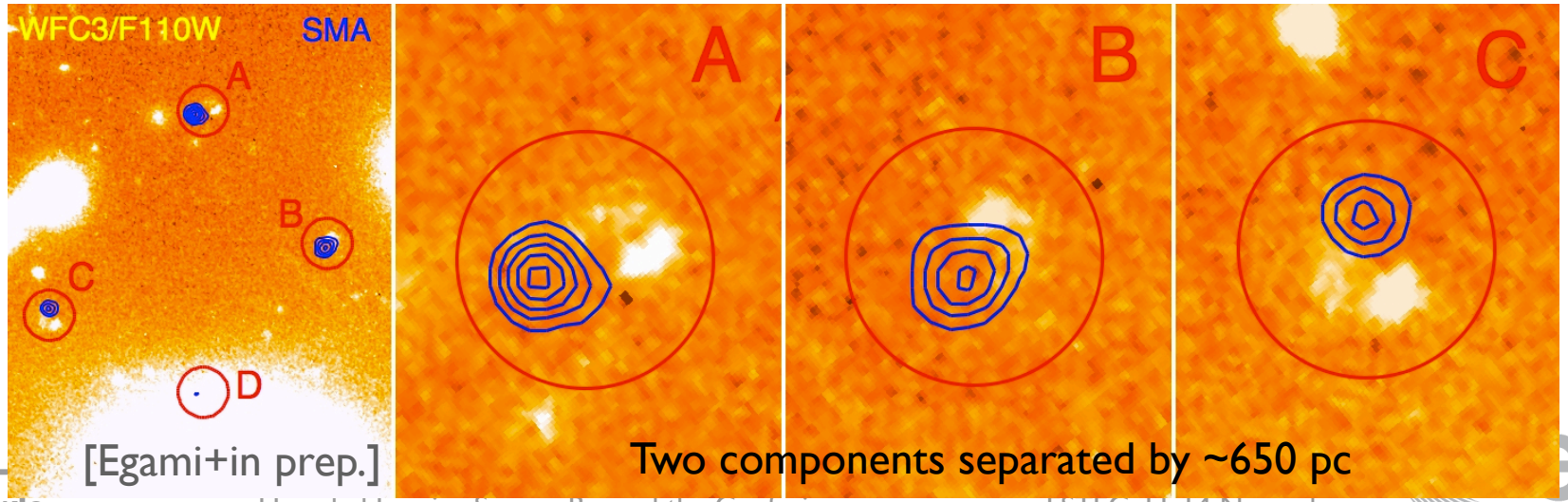
MACS0257: Quintuply-imaged SMG @ z=4.7







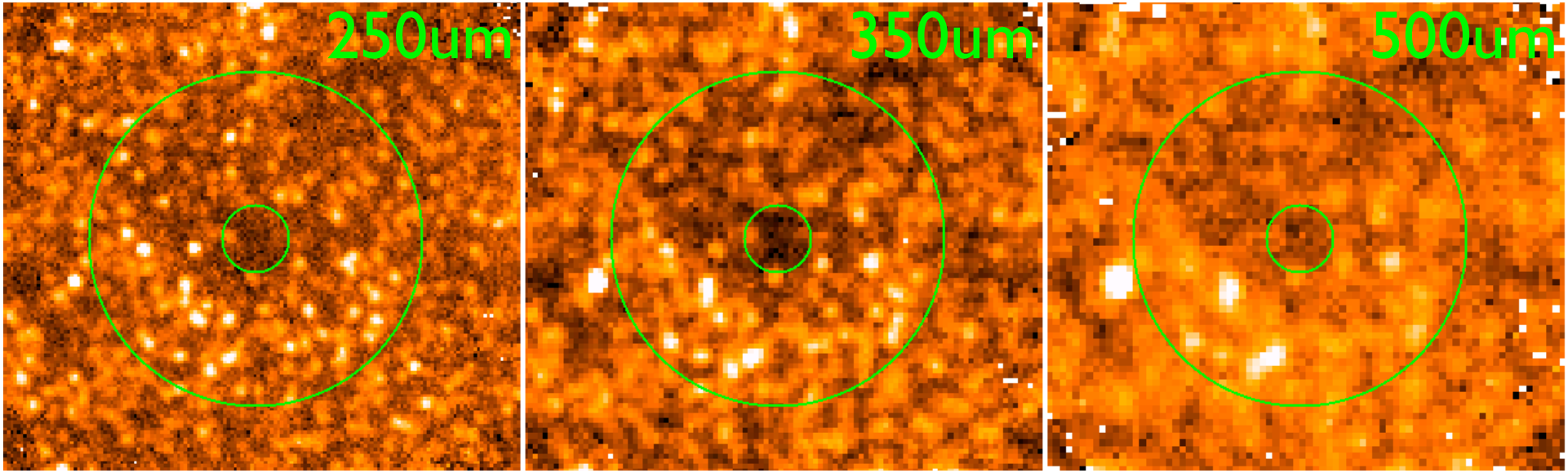
Magnification factor >130 for A+B+C+D➔ $L_{IR} < 5\times10^{11}\ L_\odot$



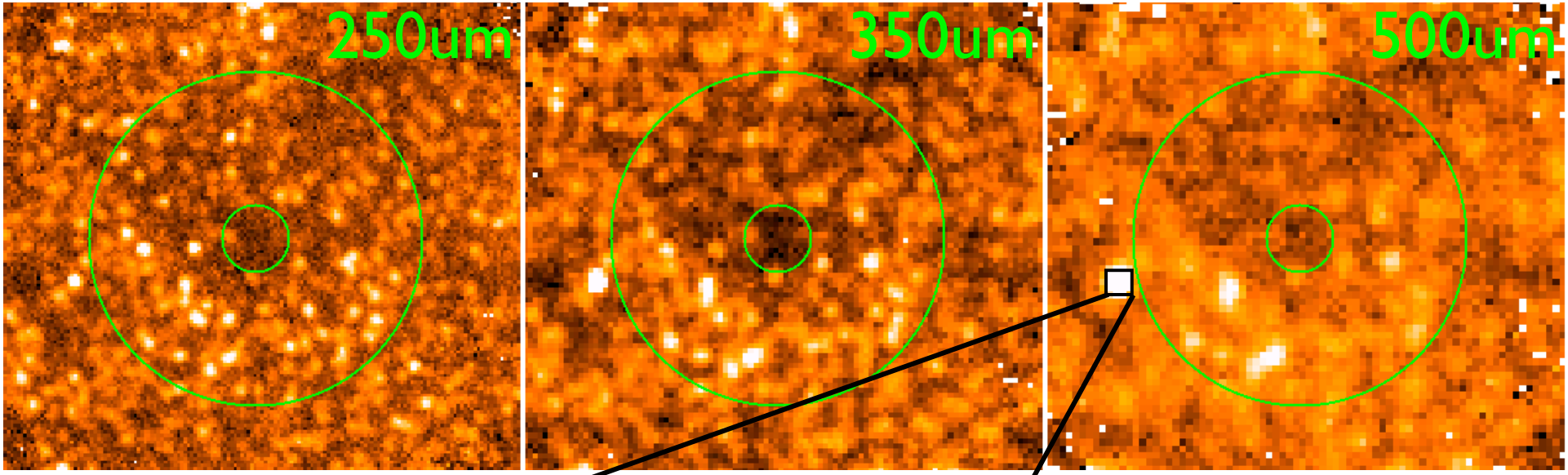
[Egami+in prep.]

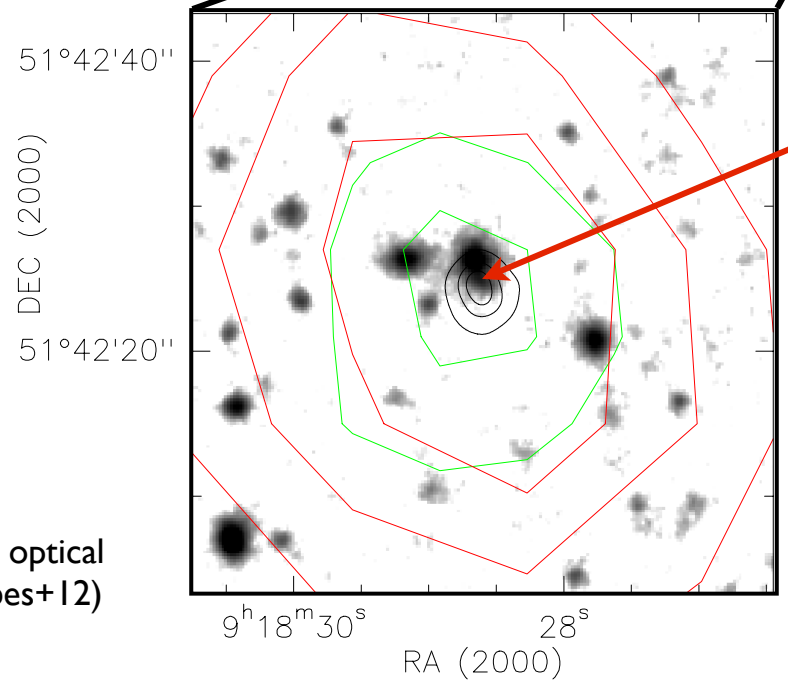
Two components separated by ~650 pc

A773 (z=0.217)



A773 (z=0.217)





Herschel source primarily magnified by a background source @ z=0.63

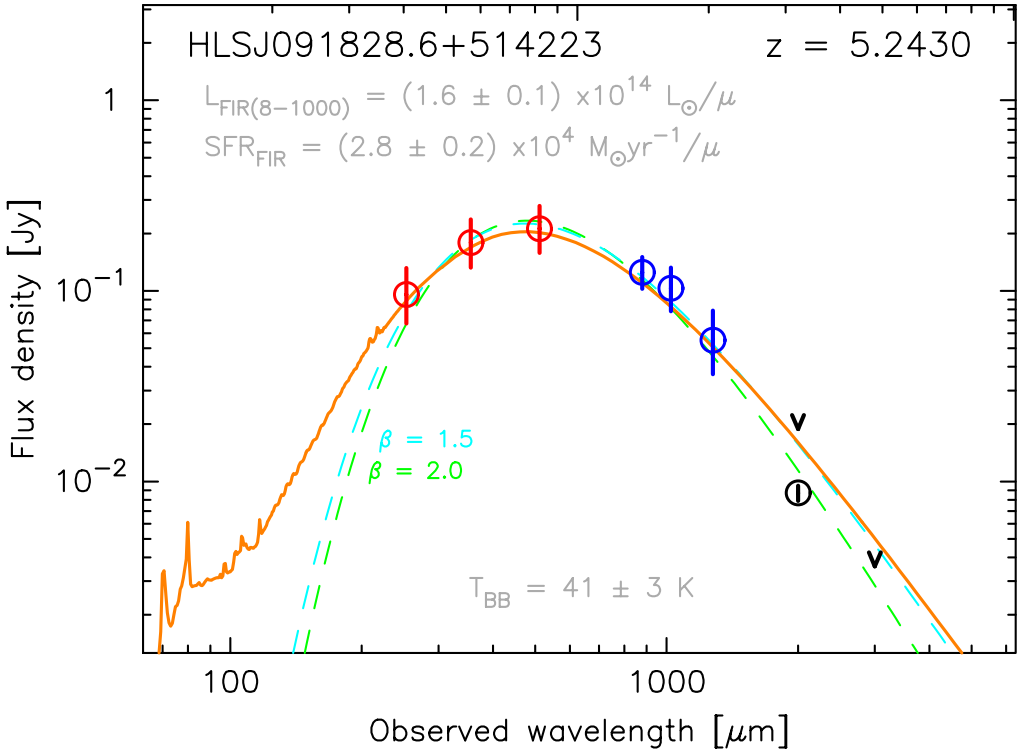
Black contour = 880μm (SMA)
2" FWHM PSF

Subaru optical (Combes+12)

HLS0918 @ z=5.2

Table 1: HLS0918 observed continuum fluxes

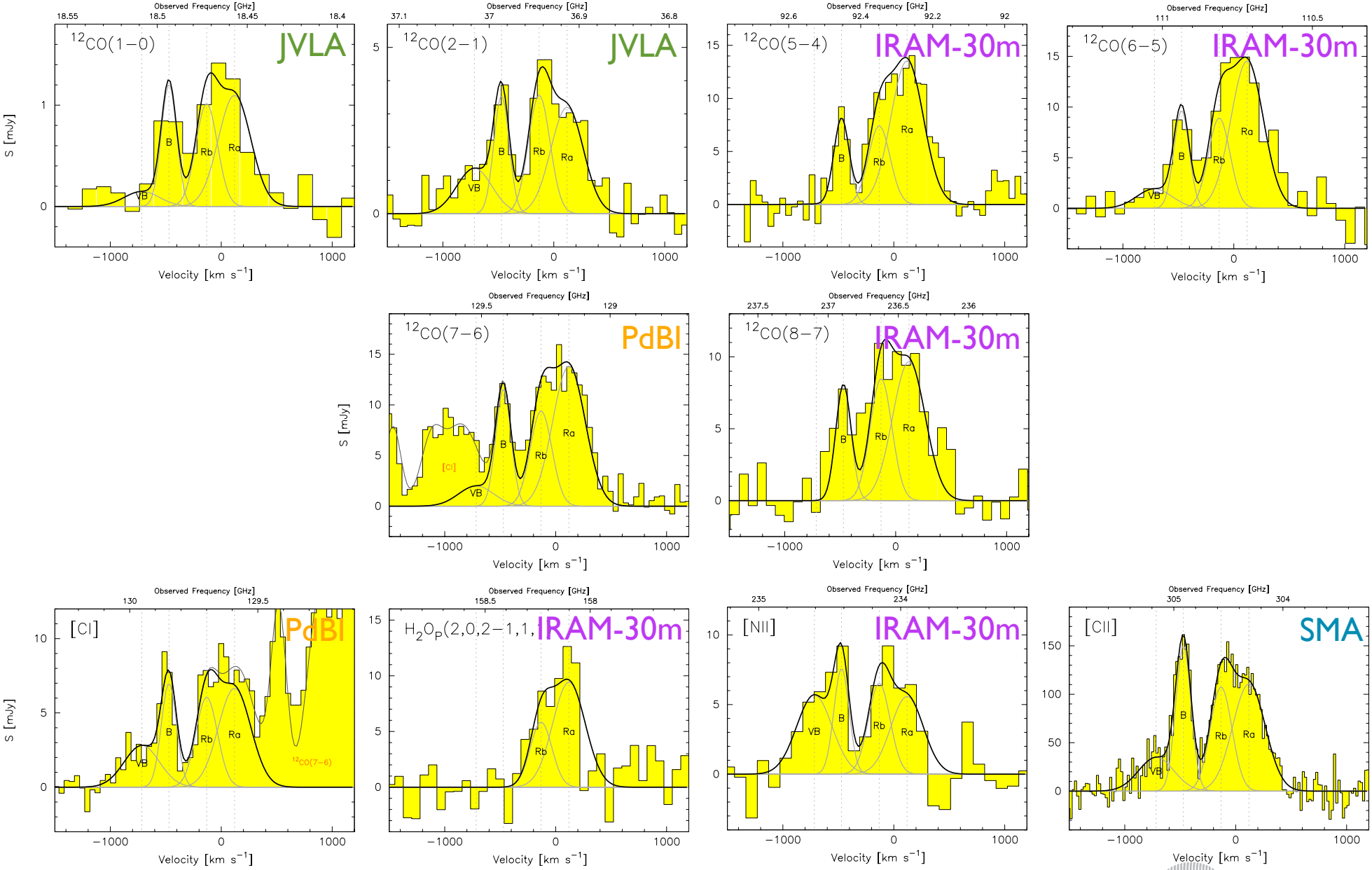
λ_{obs} mm		S_ν mJy
0.25	*Herschel*/SPIRE	96 ± 8
0.35	*Herschel*/SPIRE	179 ± 13
0.50	*Herschel*/SPIRE	212 ± 15
0.88	SMA	125 ± 8
1.0	SMA	103 ± 9
1.3	SMA	55 ± 7
2	IRAM-30m/EMIR	<21
2	IRAM-30m/GISMO	9 ± 1
3	IRAM-30m/EMIR	<2



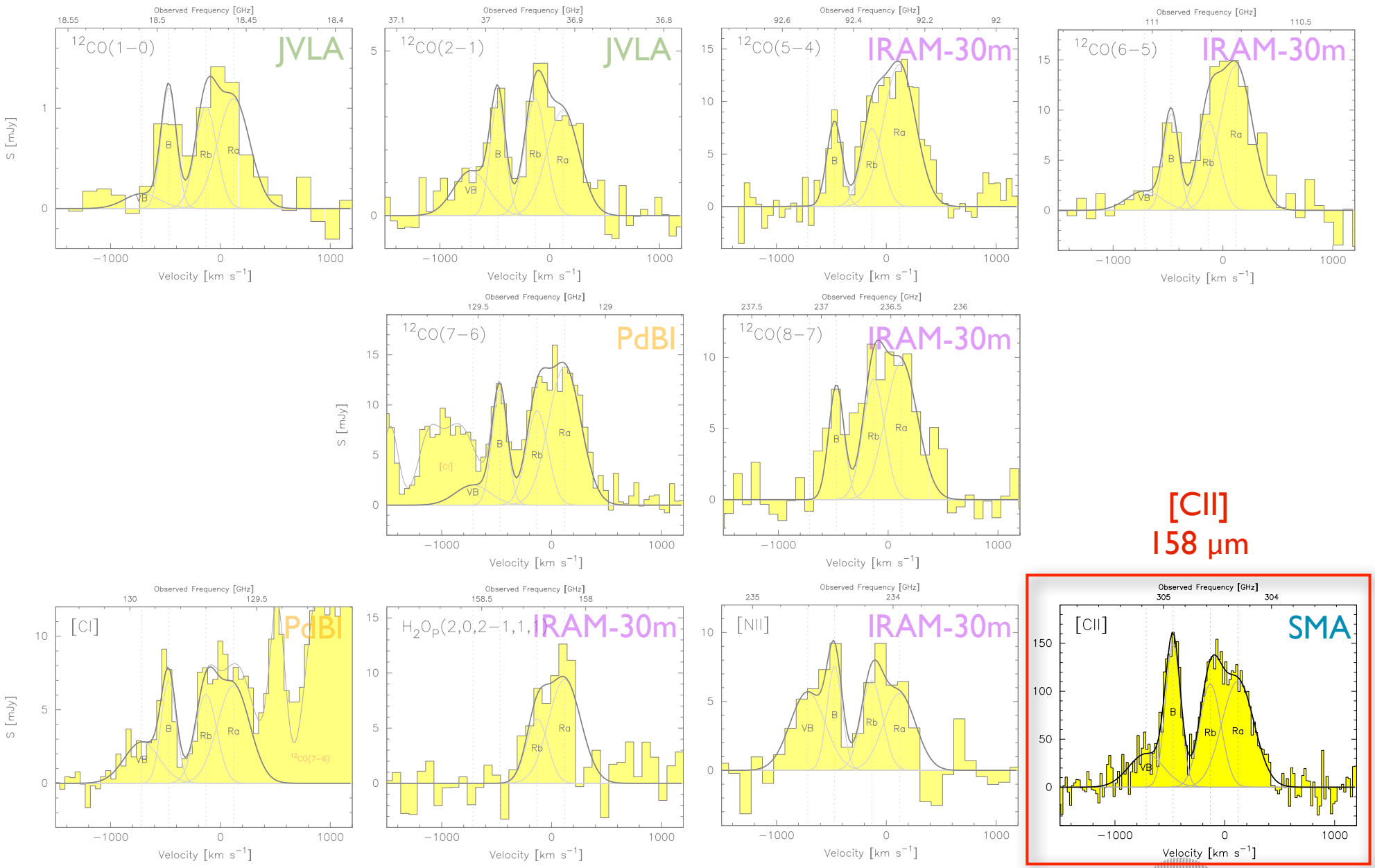
Parameter	unit	Total
Relative L_{1mm}		**1.00**
T_{dust}	K	**41 ± 3**
$L_{FIR(8-1000)}$	$\times 10^{12}$ $L_\odot$ μ^{-1}	**160 ± 10**
SFR	$\times 10^3$ $M_\odot$ yr^{-1} μ^{-1}	**28 ± 2**
$L_{FIR(42.5-122.5)}$	$\times 10^{12}$ $L_\odot$ μ^{-1}	**100 ± 6**

[Rawle+14]

Atomic and molecular emission

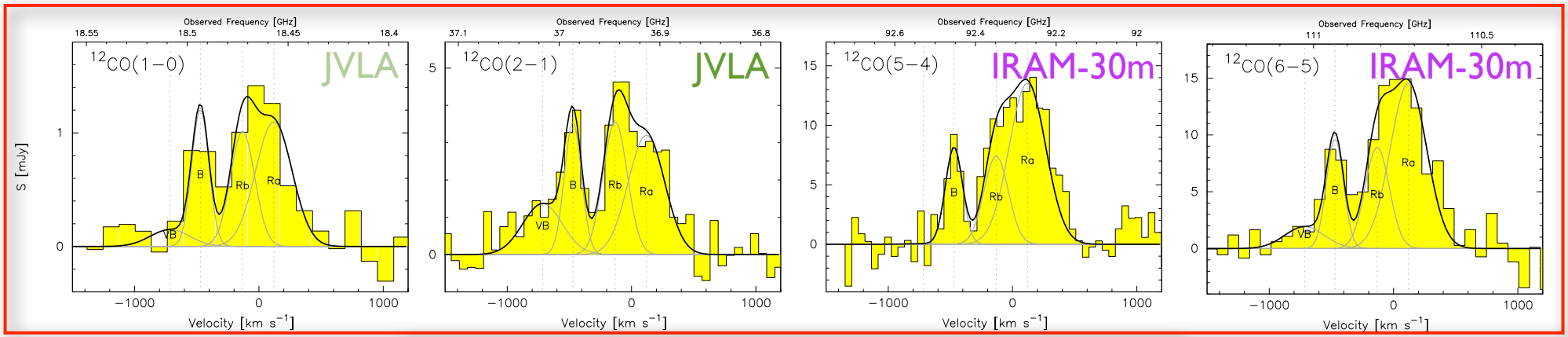


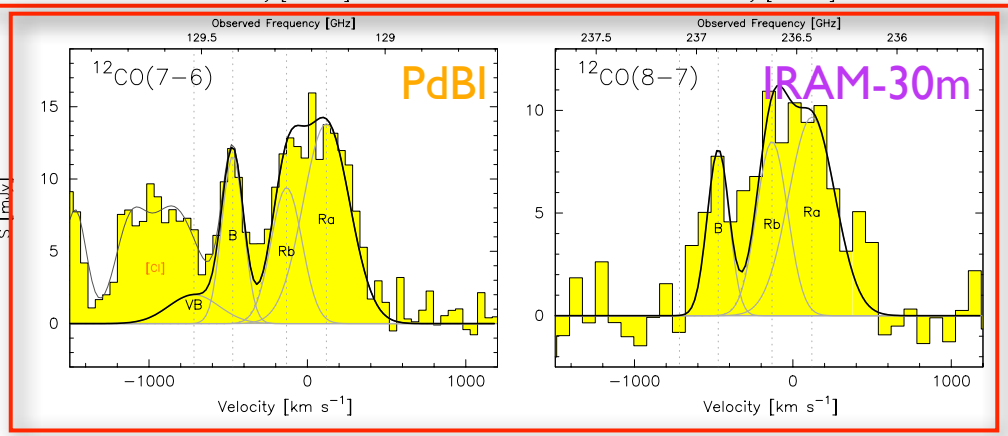
Atomic and molecular emission



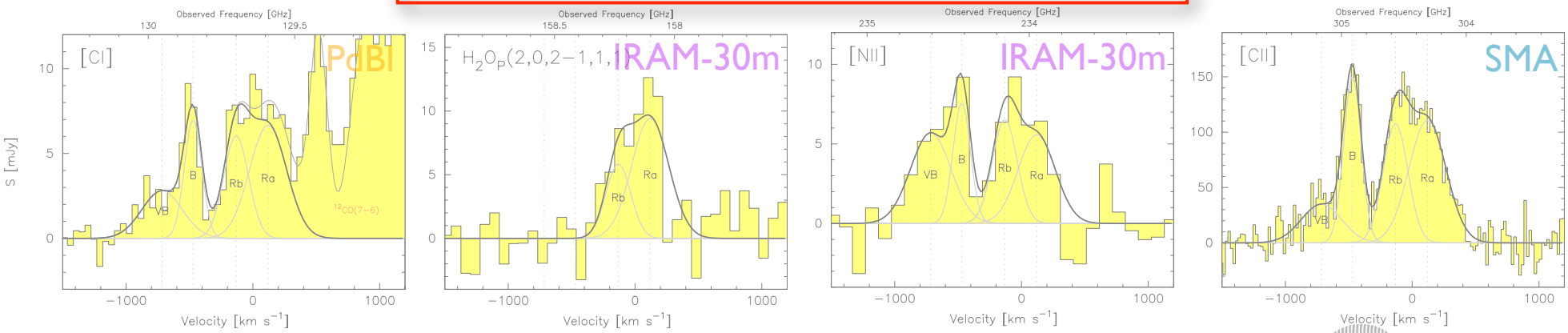
[CII]
158 μm

Atomic and molecular emission

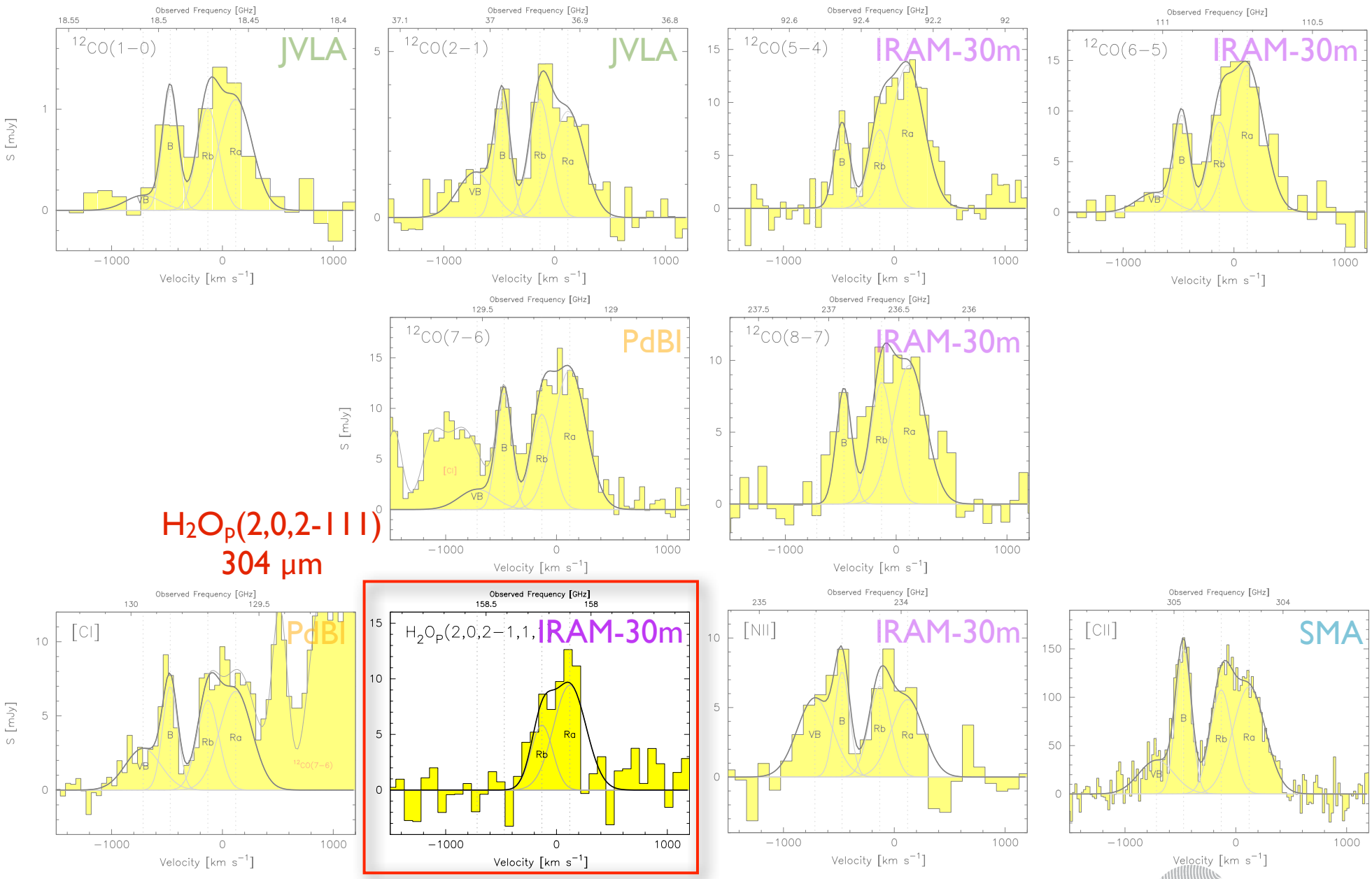




^{12}CO ladder



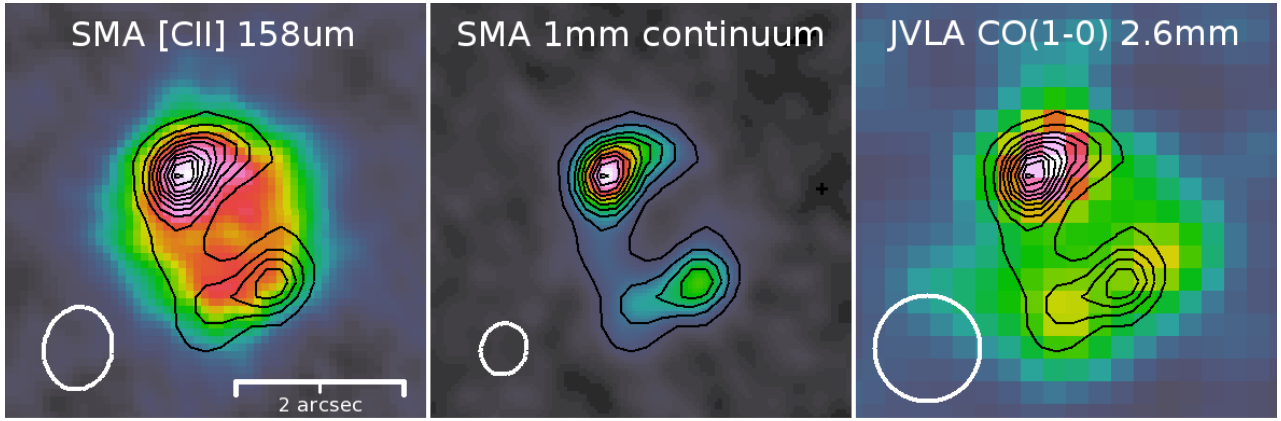
Atomic and molecular emission



$H_2O_p(2,0,2\text{-}111)$
304 μm

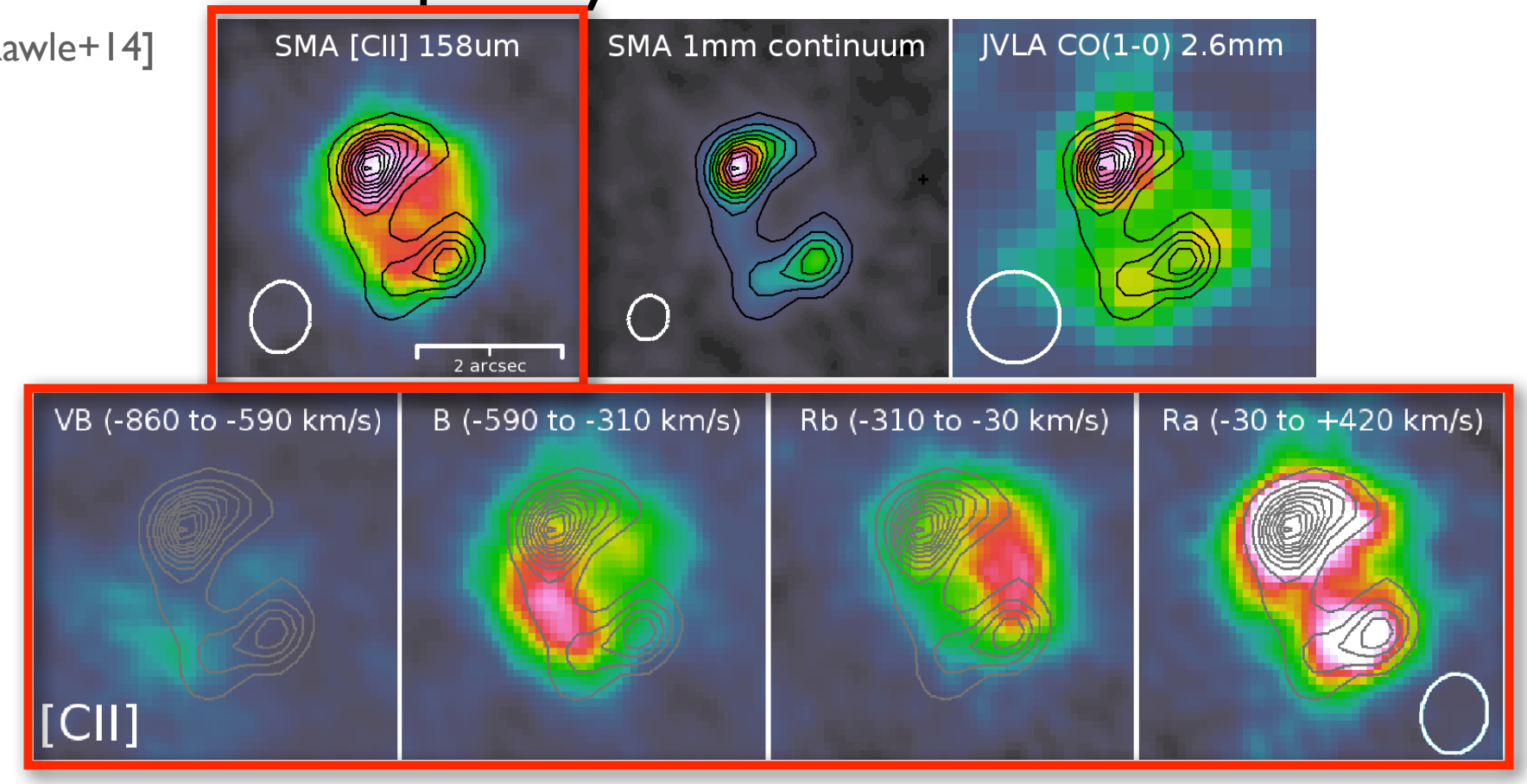
Spatially resolved emission

[Rawle+14]



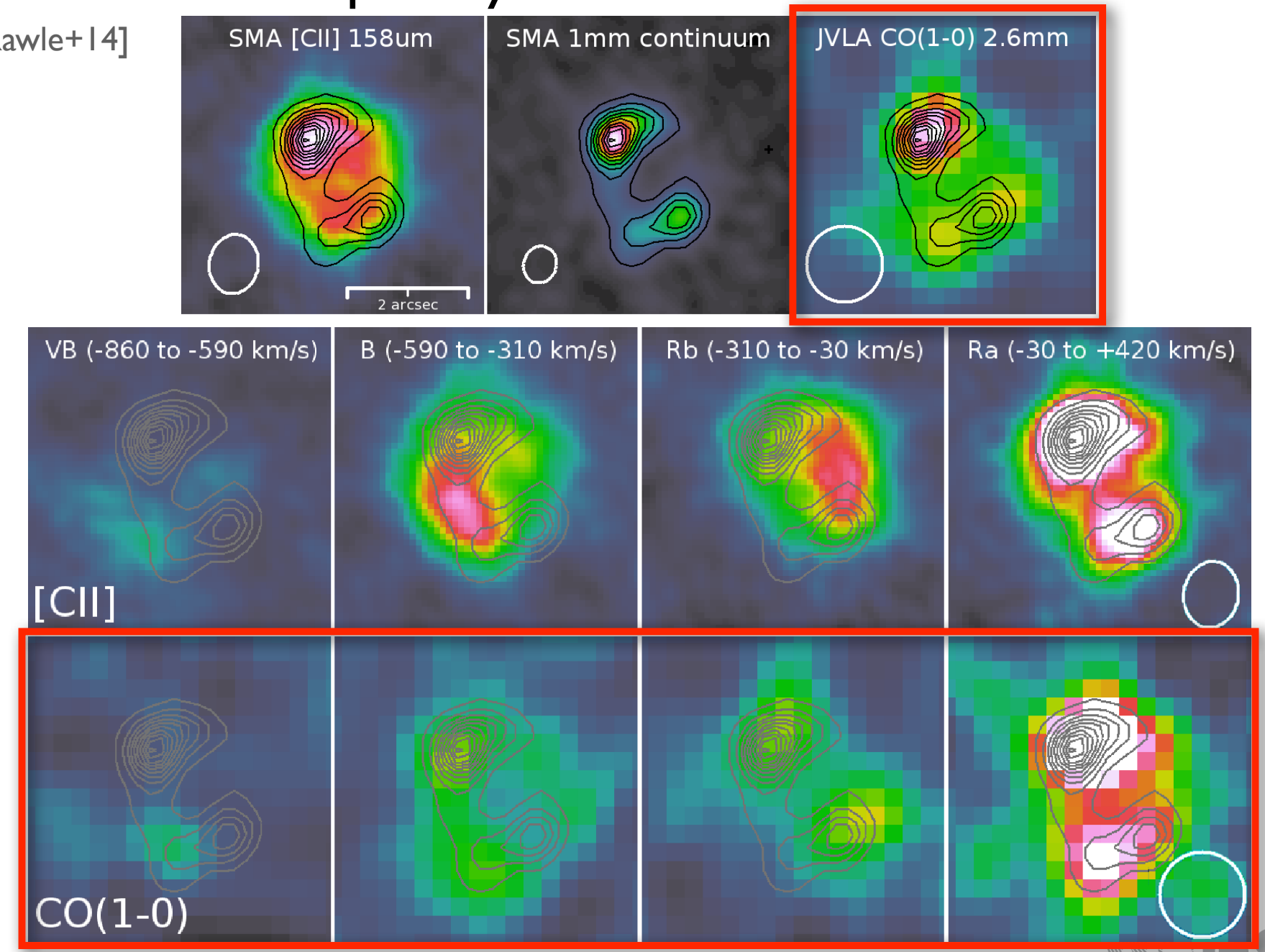
Spatially resolved emission

[Rawle+14]

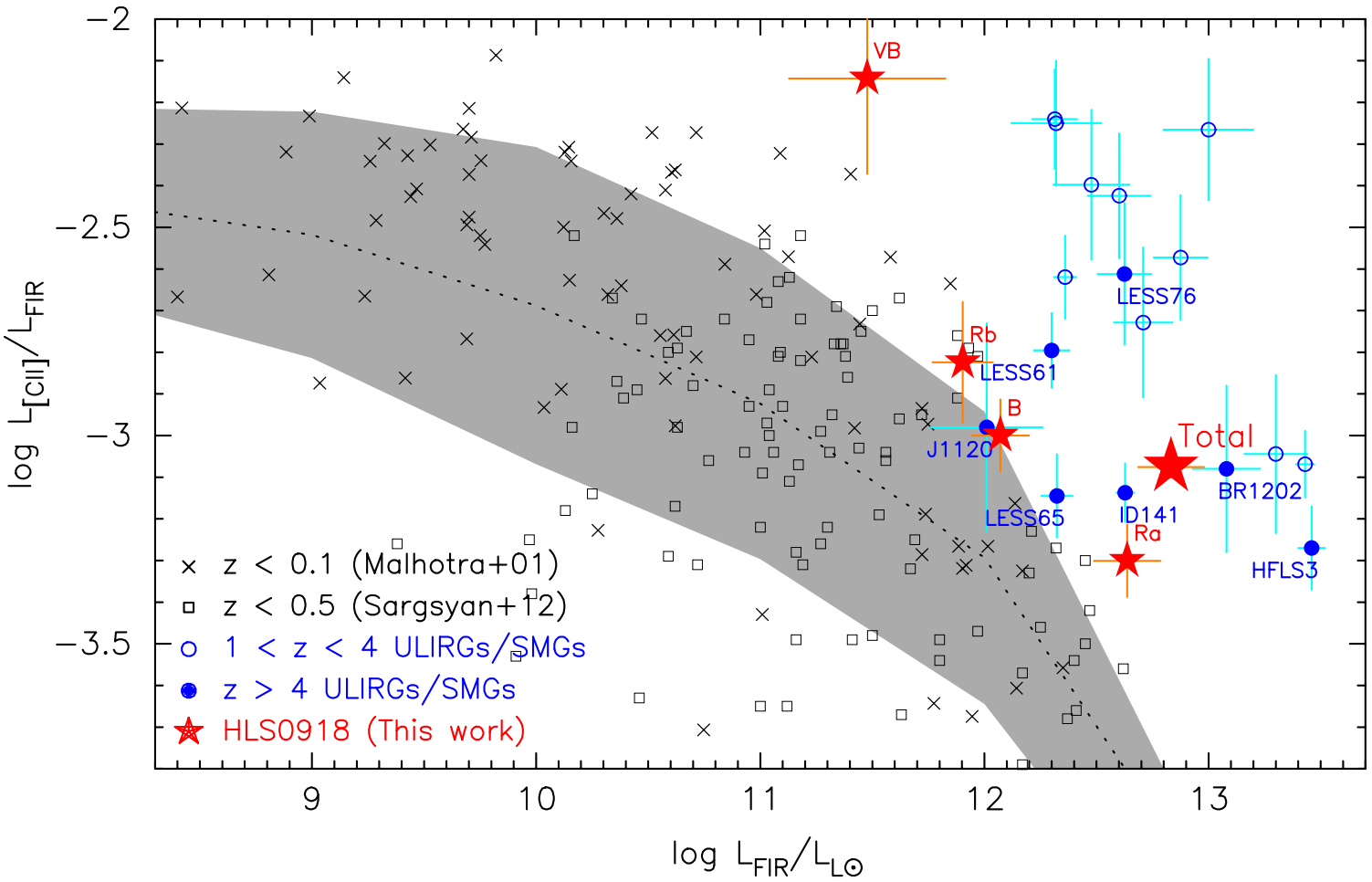


Spatially resolved emission

[Rawle+14]



$L_{[CII]}/L_{FIR}$



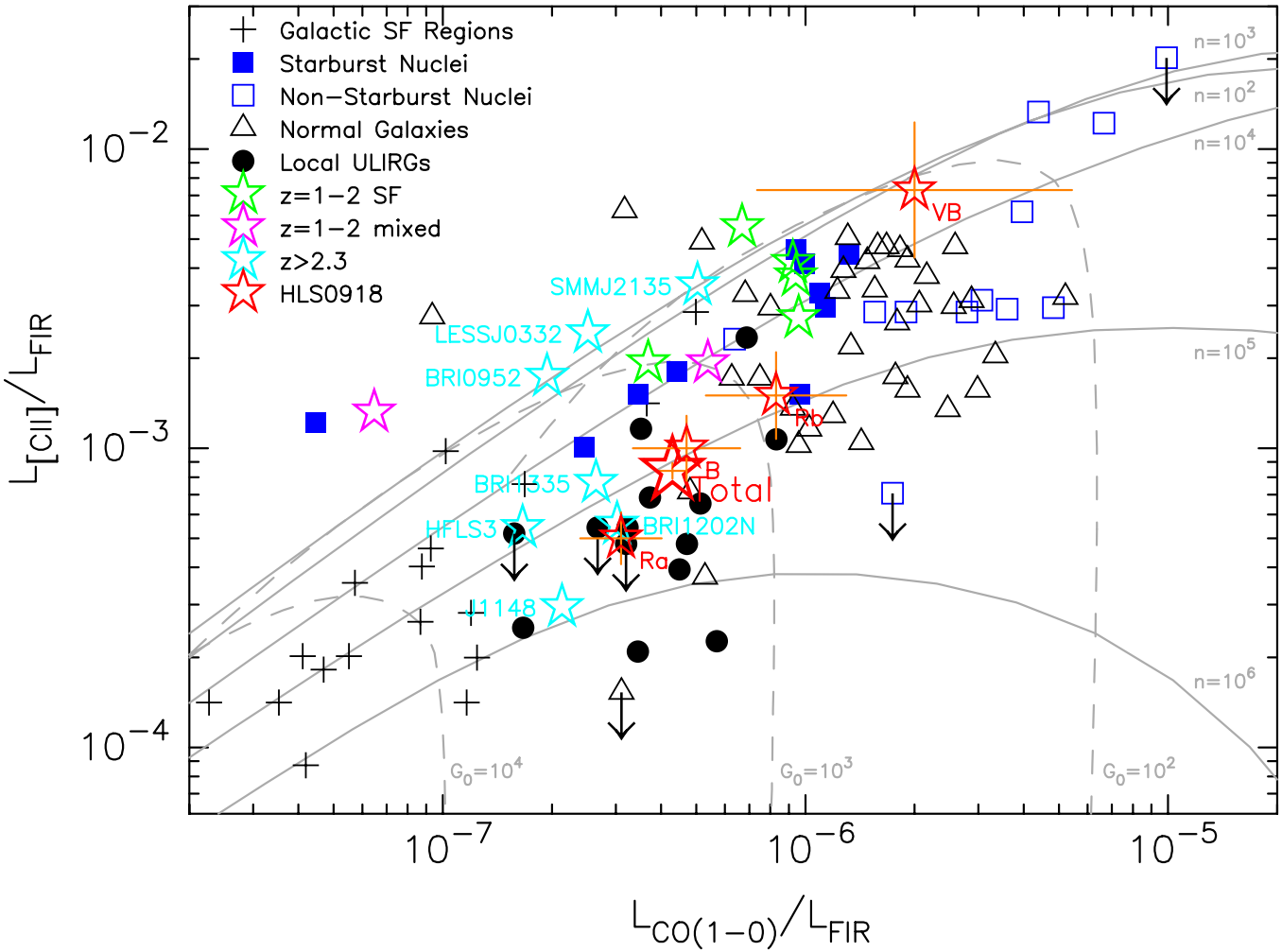
[Rawle+14]

Stacy+10, Cox+11, De Breuck+11, Valtchanov+11, Swinbank+12, Venemans+12, Wagg+12, Riechers+13

Malhotra+01, Sargsyan+12

- HLS0918 is located in the same region as other high-z sources
- low-z galaxies of the same L_{FIR} exhibit an order of magnitude lower $L_{[CII]}$
- attributed to extended [CII] reservoirs

Physical properties of the star-forming regions

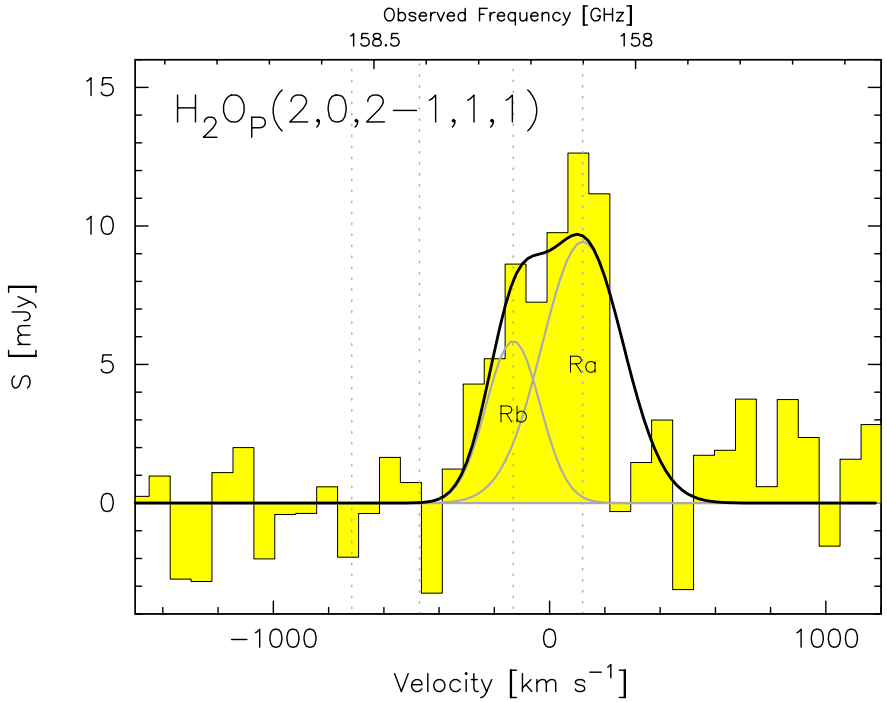


[Rawle+14]

adapted from De Breuck+11

- Grey lines represent (solar metallicity) PDR models with varying gas density (*n*) and FUV field strength (G_0) from Kaufman+99
- Ra, Rb and B similar to local ULIRGs (Ra resembles high-z quasar hosts)
- VB exhibits characteristics of normal local galaxies

H_2O emission



$H_2Op(2,0,2\text{-}1,1,1)$

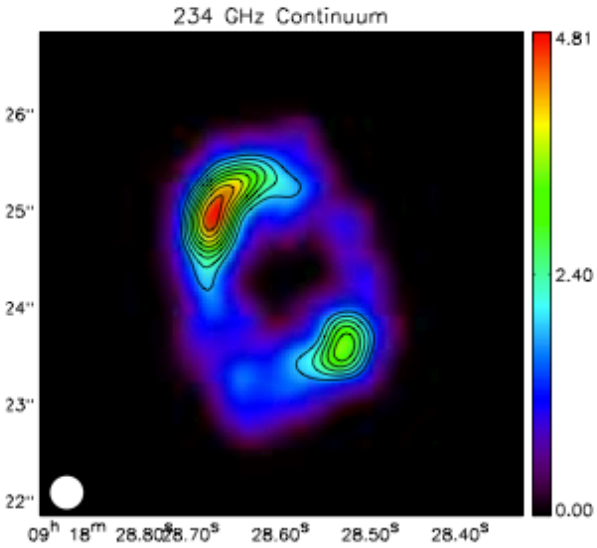
@ 304μm

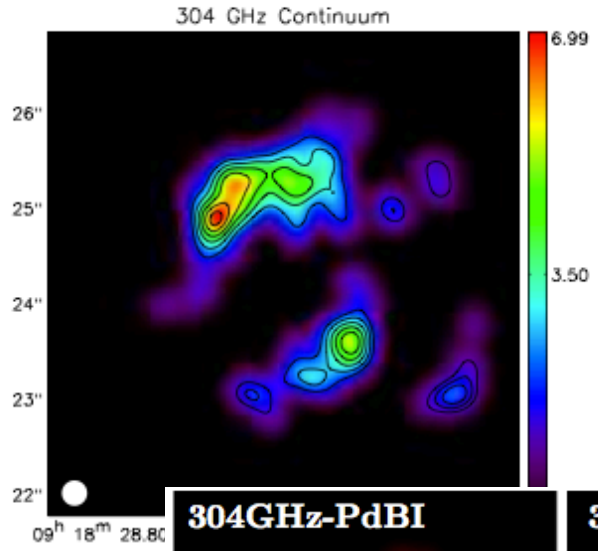
IRAM-30m
(Combes+12)

- Water emission is excited by strong FIR radiation field, from intense star formation
- Only detected from Ra and Rb
- Ra emission consistent with ULIRG trend $L_{H2O} = L_{FIR}^{\alpha}$ where $\alpha=1.1\pm0.1$ (Omont+13)
- Rb has very strong water emission for given L_{FIR} ($\alpha=2.5\pm0.7$)

- Ra ($L_{FIR,Ra} \approx 10^{13}\ L_{\odot}$) excites water emission in both components
- Ra and Rb have ΔV=250 km/s and a source plane separation of <1kpc
- Ra-Rb are two neighbouring components in the nucleus of a massive galaxy

HLS0918: high resolution PdBI maps



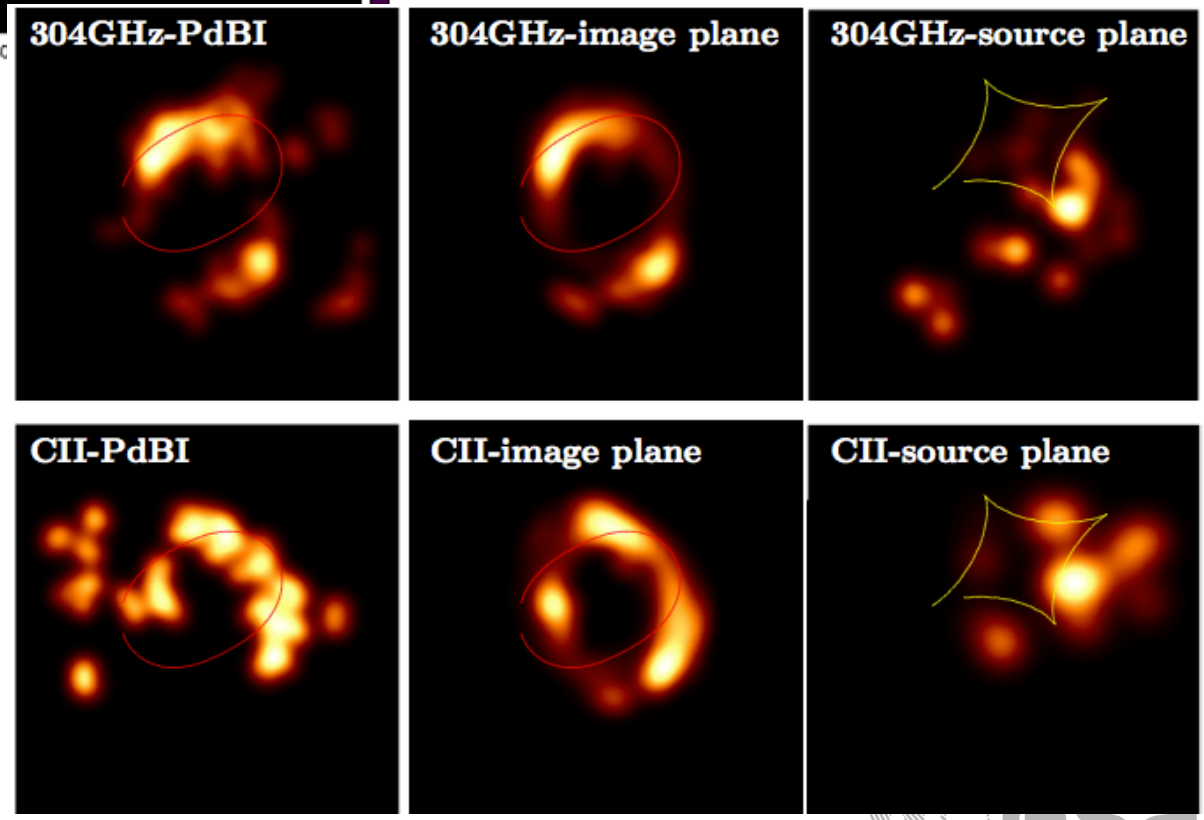


More to come
in Boone+prep

Non-Negative Least Squares method for PDBI image plane maps

Lens model (cluster + z=0.6 galaxy) derived using LENSTOOL

Source plane maps directly constrained from interferometer data using NNLS method



Summary

Gravitational cluster lensing

- Enormous gain in sensitivity for free
- Extraordinary spatial resolution at high redshift

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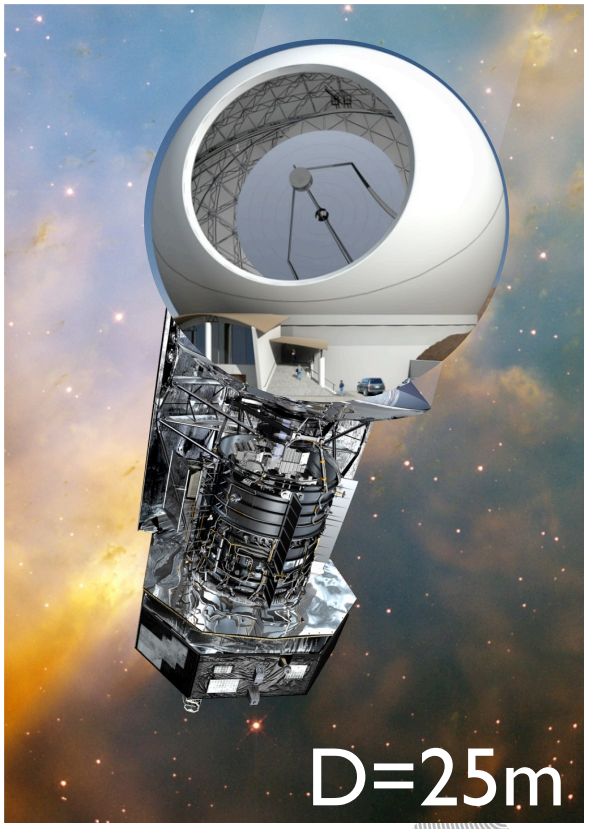
x7 magnification turns Herschel into CCAT in Space



Summary

Gravitational cluster lensing

- Enormous gain in sensitivity for free
- Extraordinary spatial resolution at high redshift

Investigating high-z lensed sources is efficient in clusters in FIR

HLS probes faint lensed galaxies (together with HST, e.g. CLASH, HFF)

↓

perfect for ALMA follow-up

Next frontier (ALMA / JWST):
aided by lensing magnification, resolve lensed galaxies into individual star-forming regions (HII regions, molecular clouds)