HerMES: Herschel/SPIRE-Selected Massive Starburst Galaxies at very high Redshifts

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and

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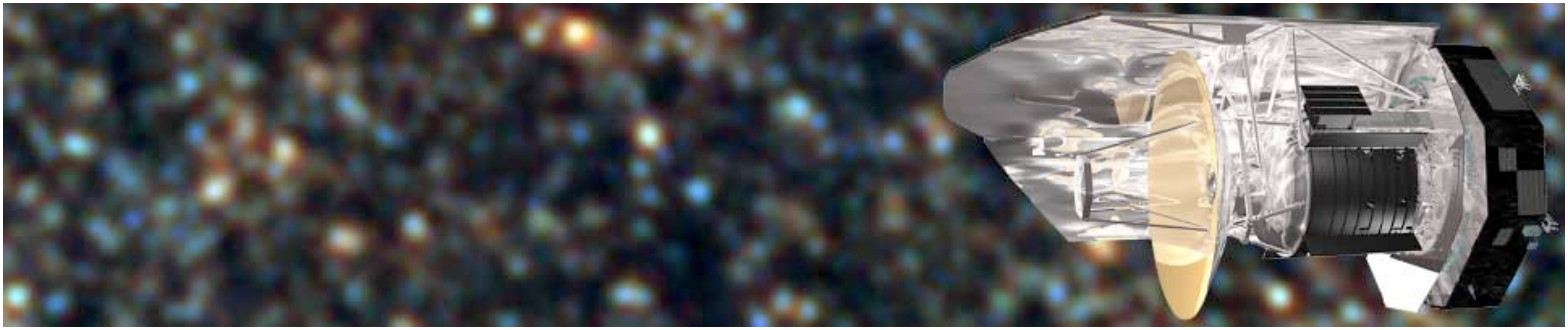
and the HerMES and SPIRE projects

The Universe Explored by Herschel, ESTEC, 16 October 2013

HERMES

hermes.sussex.ac.uk



Herschel Multi-Tiered Extragalactic Survey

HerMES Key Project

- HerMES is the Herschel Multi-tiered Extragalactic Survey, an astronomical project to study the evolution of galaxies in the distant Universe.
- Guaranteed Time project of the SPIRE team
- HerMES is coordinated by Seb Oliver (University of Sussex) and Jamie Bock (Caltech)
- The first paper (Riechers et al. 2013, Nature, 496, 329) on HFLS3, the highest redshift (z=6.34) massive starburst known, has been coordinated by Dominik Riechers (Cornell University)
- Paper describing the selection of SPIRE "red sources": Dowell, Conley et al. 2013
- See other HerMES contributions at this conference, some in collaboration with other Herschel surveys (PEP)

The Legacy of Herschel

- The formation of stars in our galaxy
- Astrochemistry in our galaxy and in nearby galaxies
- Galaxy evolution
- ....

More challenging ...

- The formation of the first galaxies?
- Can we look into the epoch of recombination?
- Do we find new type of galaxies and star formation conditions?
- Astrochemistry in the early Universe

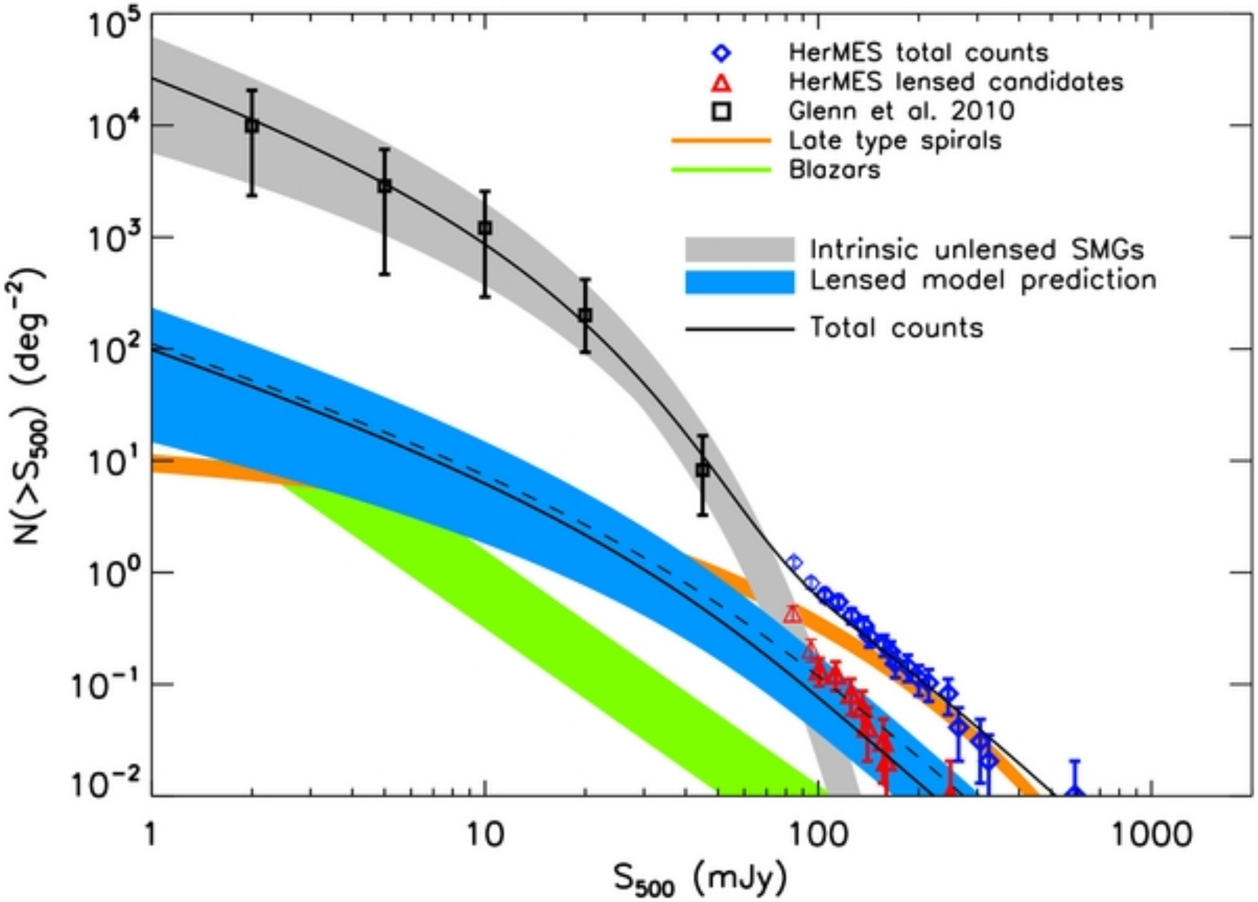
Herschel versus Hubble extragalactic surveys

- Hubble can go very deep in the optical and near-infrared with great angular resolution ... but in small fields and volumes that do not include rare, low density objects
- Herschel has mapped quickly large areas of the sky ... but limited to bright sources and with poor angular resolution
- Complementary views of the high redshift Universe with Herschel giving us examples of the most extreme star forming galaxies probably located in the most massive dark matter haloes

Lensed/unlensed high-z Herschel galaxies

Bright SPIRE sources are nearby spirals, or Blazars or high-z lensed galaxies

Negrello et al. 2010
Wardlow et al. 2013



HerMES and H-ATLAS SMA sample of bright lensed galaxies at z > 1.5

Bussmann et al. 2013

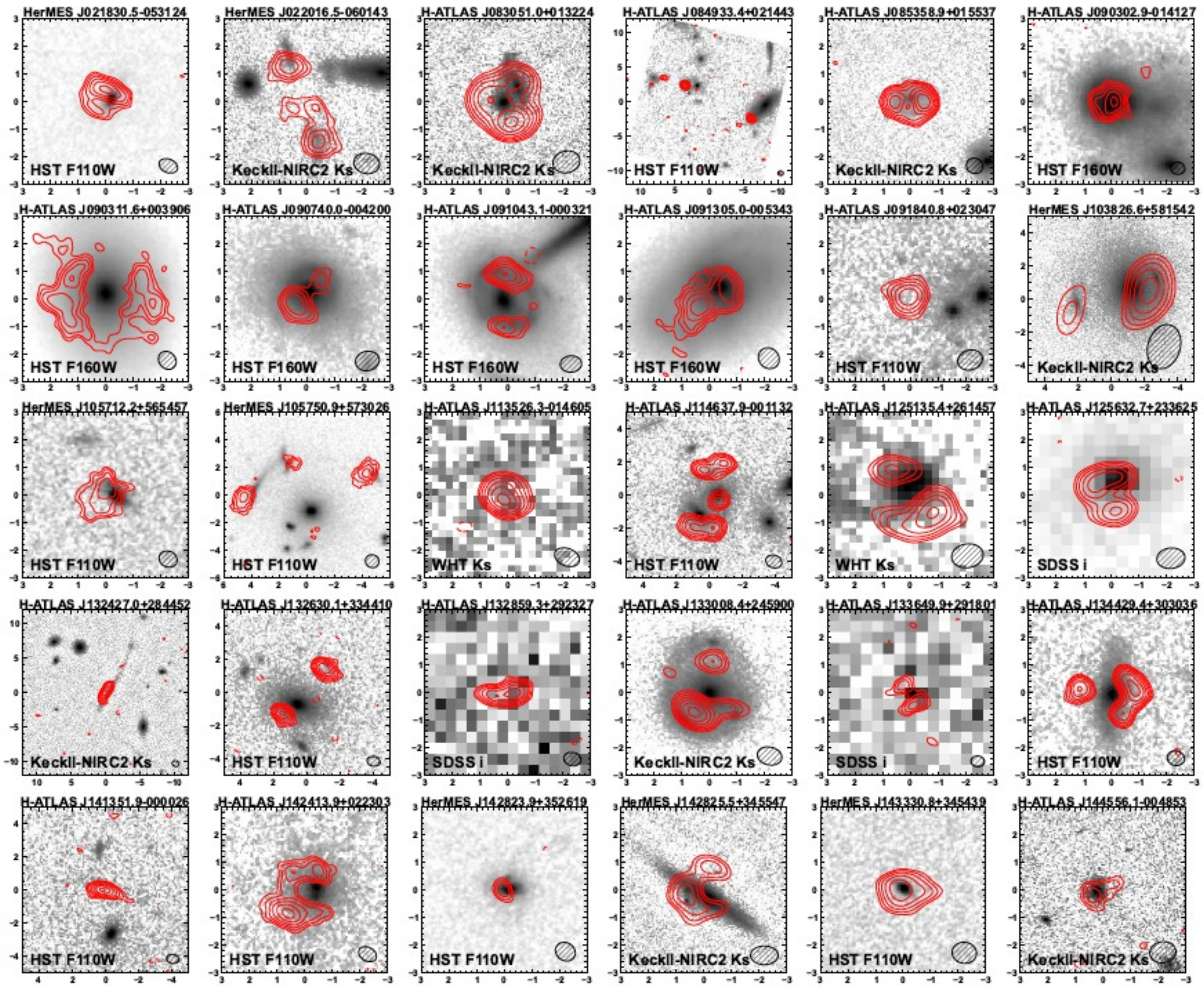


Figure 2. SMA 880μm images (red contours, starting at $\pm 3\sigma$ and increasing by factors of $\sqrt{2}$) of candidate lensed SMGs from H-ATLAS and HerMES, overlaid on best available optical or near-IR images (logarithmic scaling; telescope and filter indicated in lower left corner of each panel). North is up and east is left, with axes having units of arcseconds relative to the 880 μm centroid as given in Table 1. The elliptical FWHM of the SMA's synthesized beam is shown in the lower right corner of each panel. The image separations are $\approx 1-2''$, suggesting gravitational potential wells typical of isolated galaxies or small numbers of galaxies for the lenses (only two lensed sources are associated with galaxy clusters: J132427.0+284452 and J141351.9−000026).

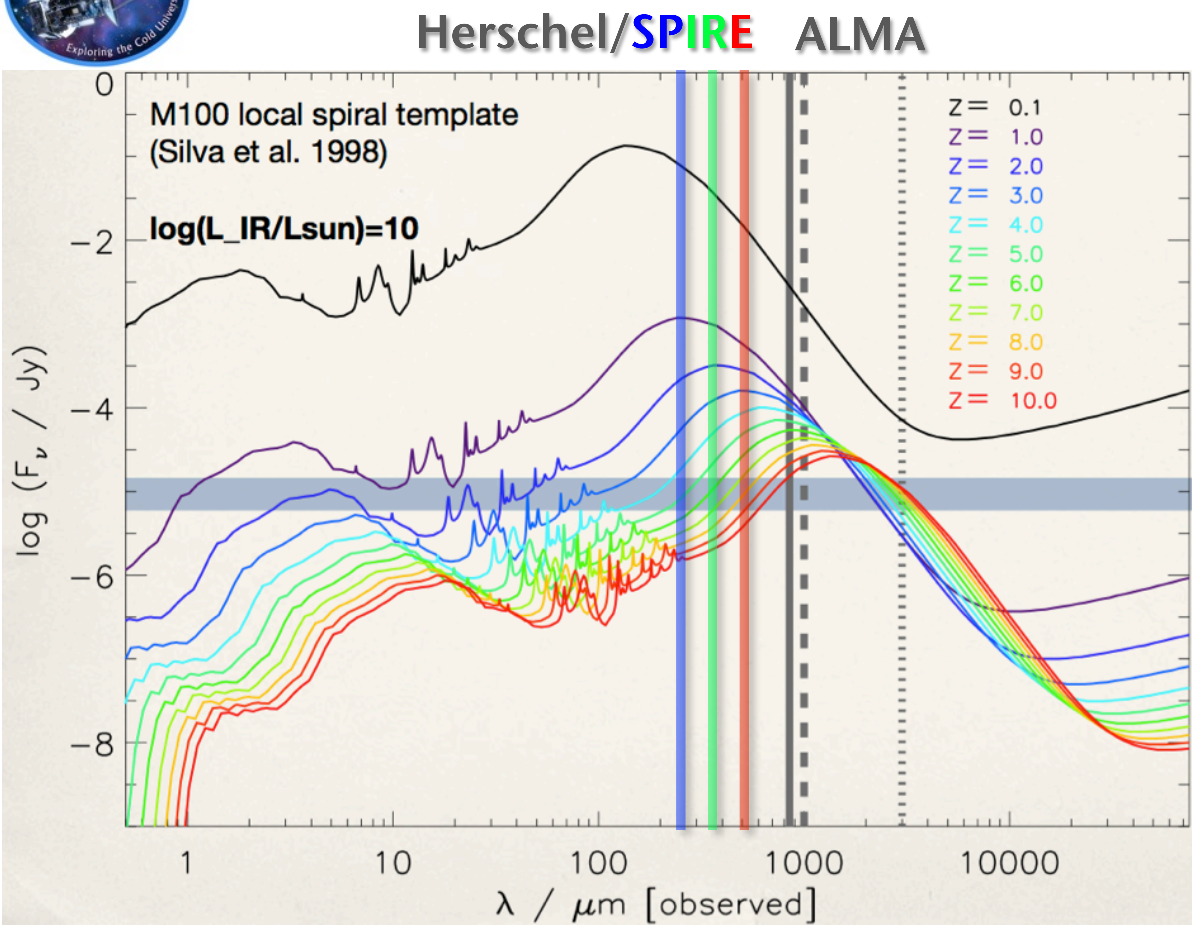
HerMES "red" sources first results

- First paper: Riechers et al. 2013, Nature, 496, 329

HFLS3: a dust-obscured massive maximum-starburst galaxy at a redshift of 6.34.

- Sample selection, source density, comparison with models, a few redshifts and main properties: Dowell, Conley et al. 2013

Detecting the Most Distant Massive Starburst Galaxies



- problem: z>4 dusty starburst galaxies very difficult to find (it took until 2009 to find the first z>4 SMG, detection was serendipitous)
- >850μm z selection *broad*
- idea: z>4 galaxy SEDs peak beyond 500μm

⇒ "red" in Herschel/SPIRE

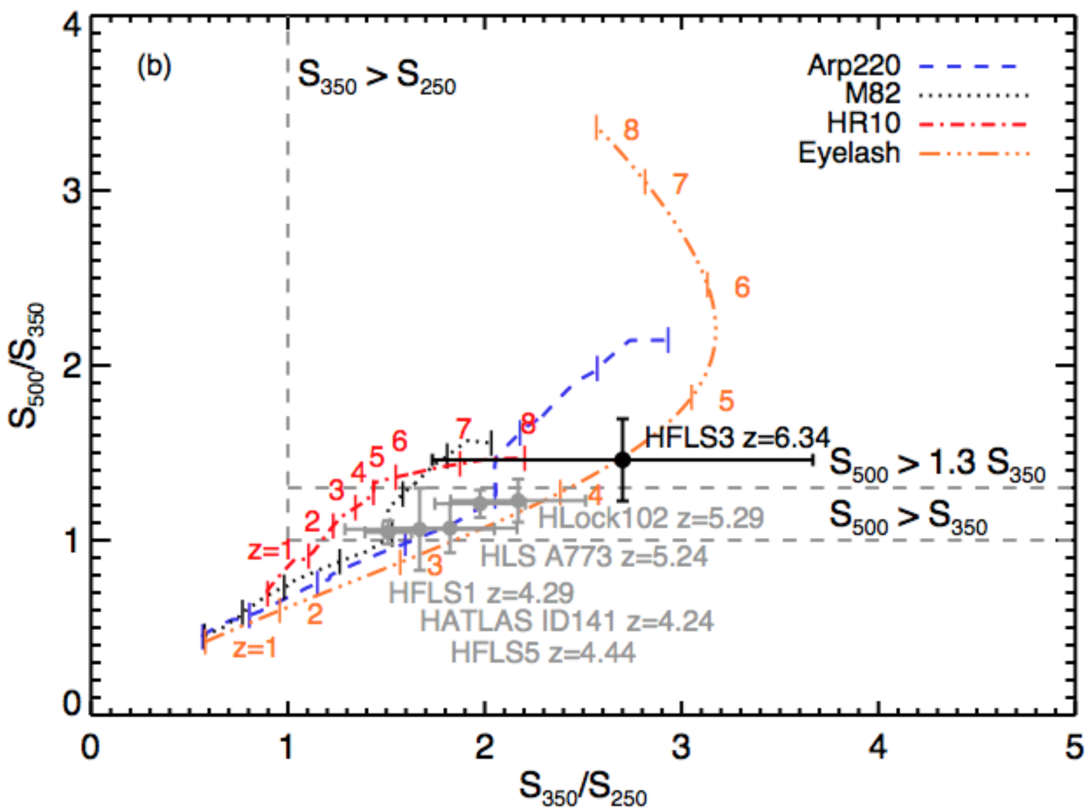
⇒ can develop efficient technique to ID very high-z dusty starbursts

Herschel finds the "tip of the iceberg"
⇒ CCAT needed to probe more normal galaxies & to best match ALMA

But: does it really work?

HFLS3: SPIRE selection of z > 4 submm Galaxies

SPIRE selection of z > 4 submm Galaxies is described in more detail in Dowell et al. 2013



SPIRE colour-colour selection
Flux ratios S500/S350 vs. S350/S250

Redshift tracks of a few FIR templates

HFLS3 and other high-z (z > 4) SPIRE-selected galaxies

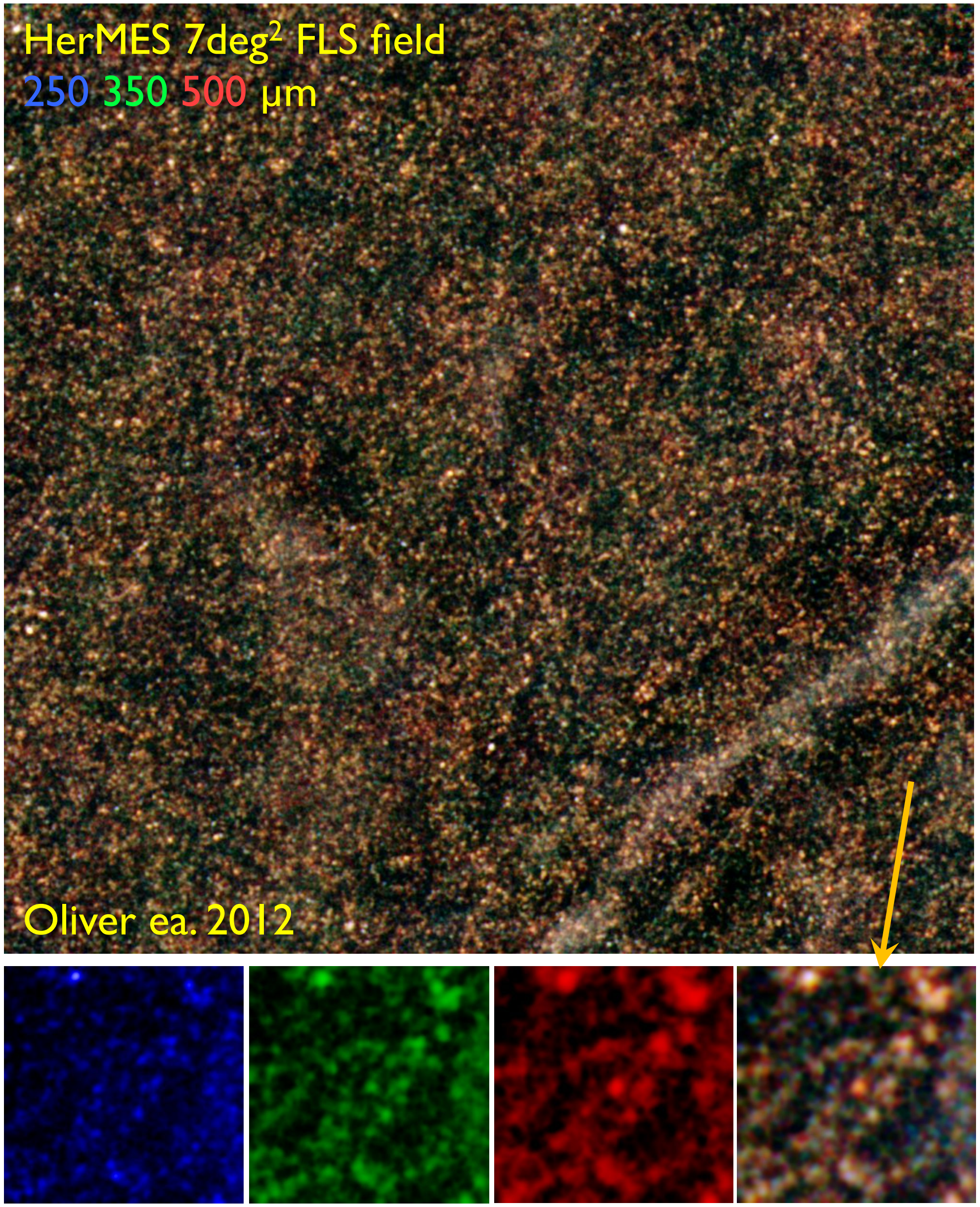
Cox et al. 2012
Combes et al. 2012
This study and Riechers et al. 2013b
Pérez-Fournon et al. 2013

BUT:

But the Herschel angular resolution in the SPIRE bands is 18", 25", 36" at 250, 350, 500 um

Very efficient selection of z > 4 Dusty Star Forming Galaxies

Herschel/SPIRE "Ultra-Red" sources



Bethermin et al. models of SPIRE galaxies:

Expect density of massive starbursts at z>6 with $S_{500\mu m}$>30mJy (~5x confusion limit; L_{FIR} ~ 10^{13} L_{sun}) to be **0.014 deg^{-2}**, so one per ~70 deg^2 (models account for lensing)

define "ultra-red" source selection:

$S_{250\mu m} < S_{350\mu m} < (S_{500\mu m}/1.3)$

⇒ Arp 220, M82,… at z>6

⇒ **Find 0.24 deg^{-2}** (initial ~30 deg^2) @$S_{500\mu m}$>30mJy

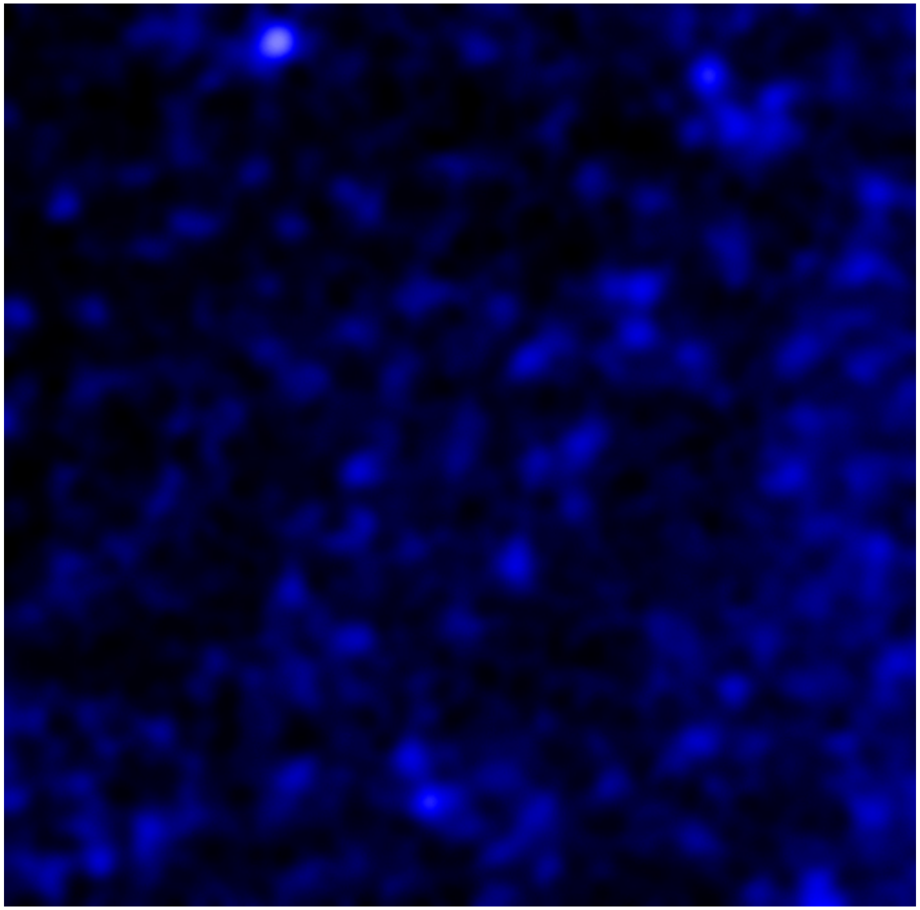
⇒ **Expect many high-z galaxies in the 1000 square degrees of all the Herschel surveys!**

"hottest" candidate"

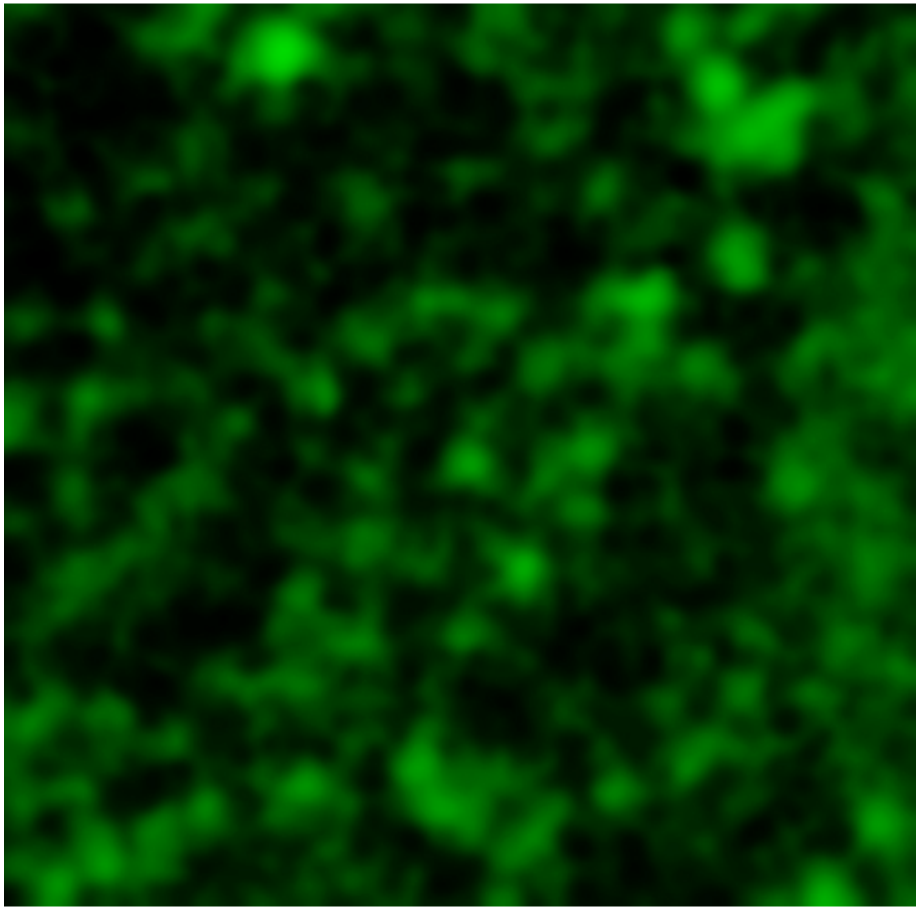
$S_{500\mu m}/S_{350\mu m}$=1.45 & $S_{500\mu m}$ = 47 mJy

⇒ let's try to get a redshift!

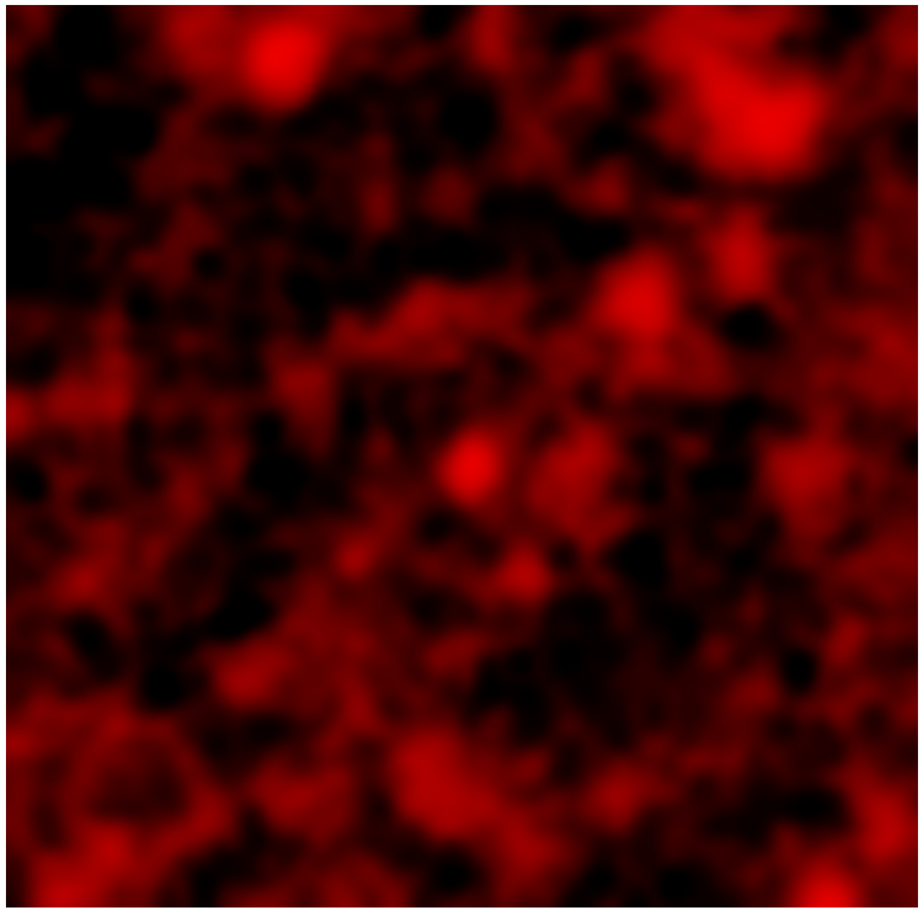
HFLS3 SPIRE 250



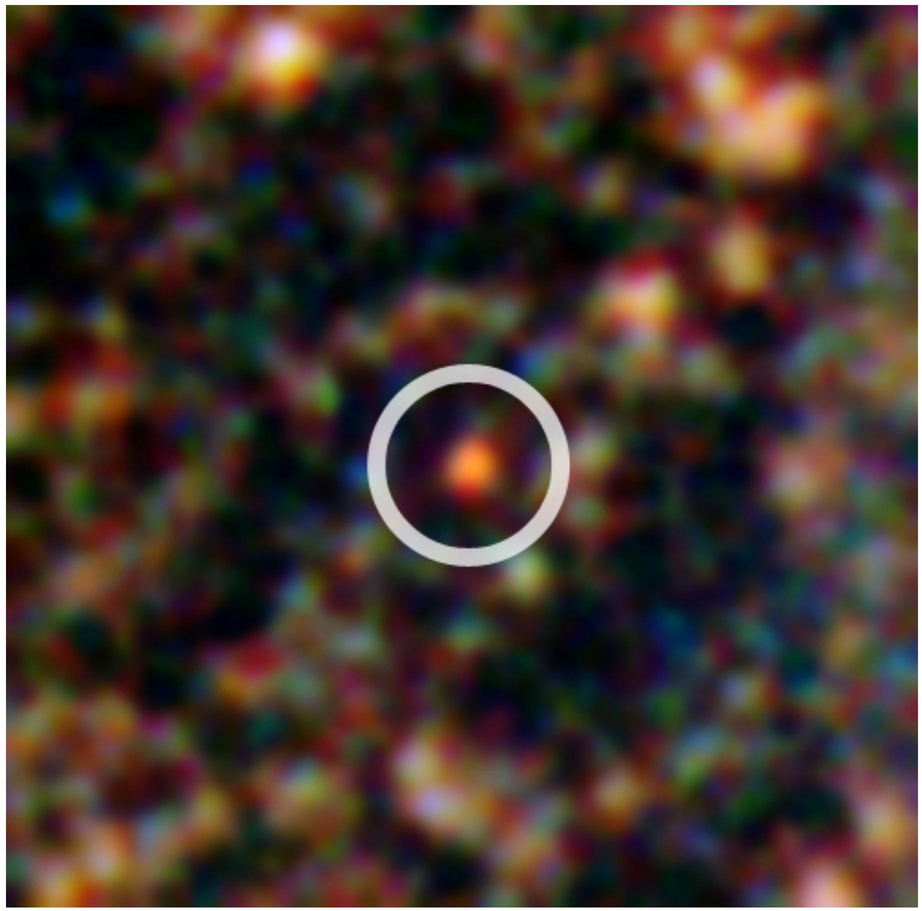
HFLS3 SPIRE 350



HFLS3 SPIRE 500

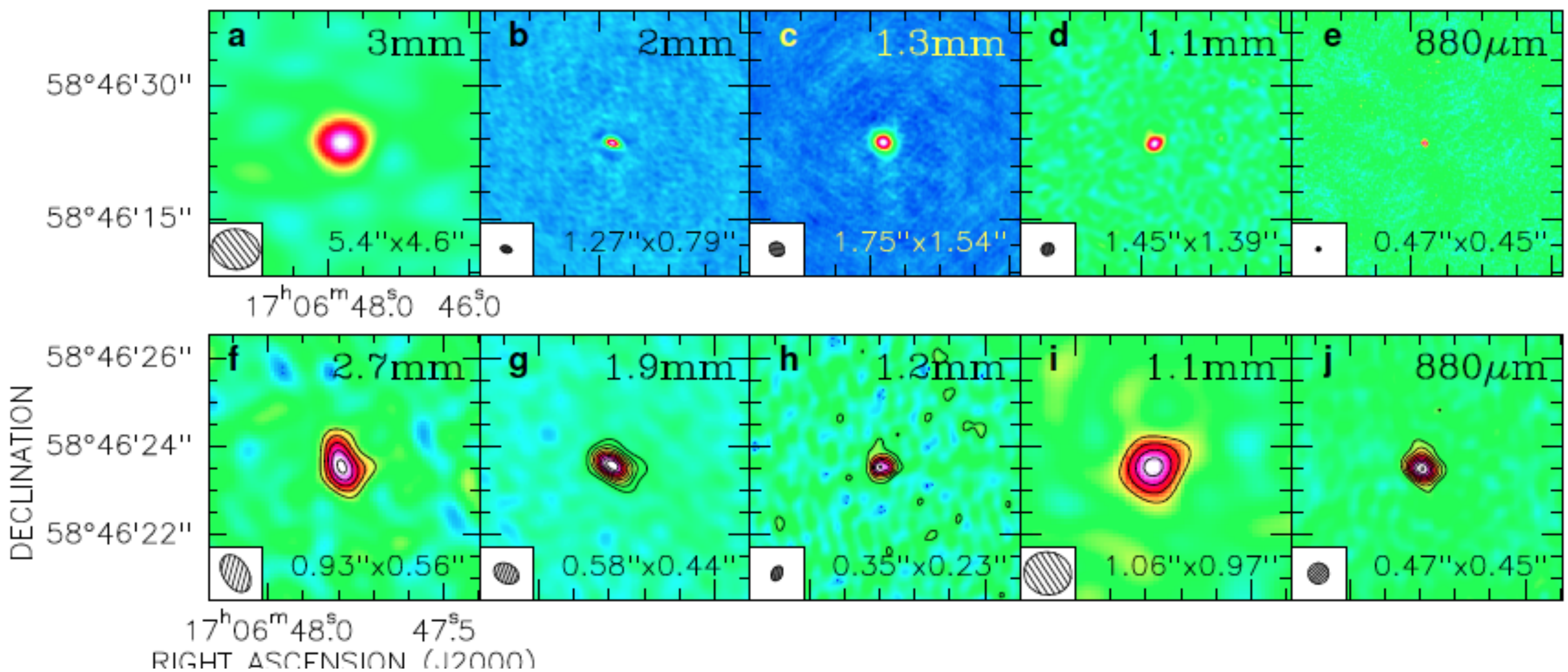


HFLS3 SPIRE colour map

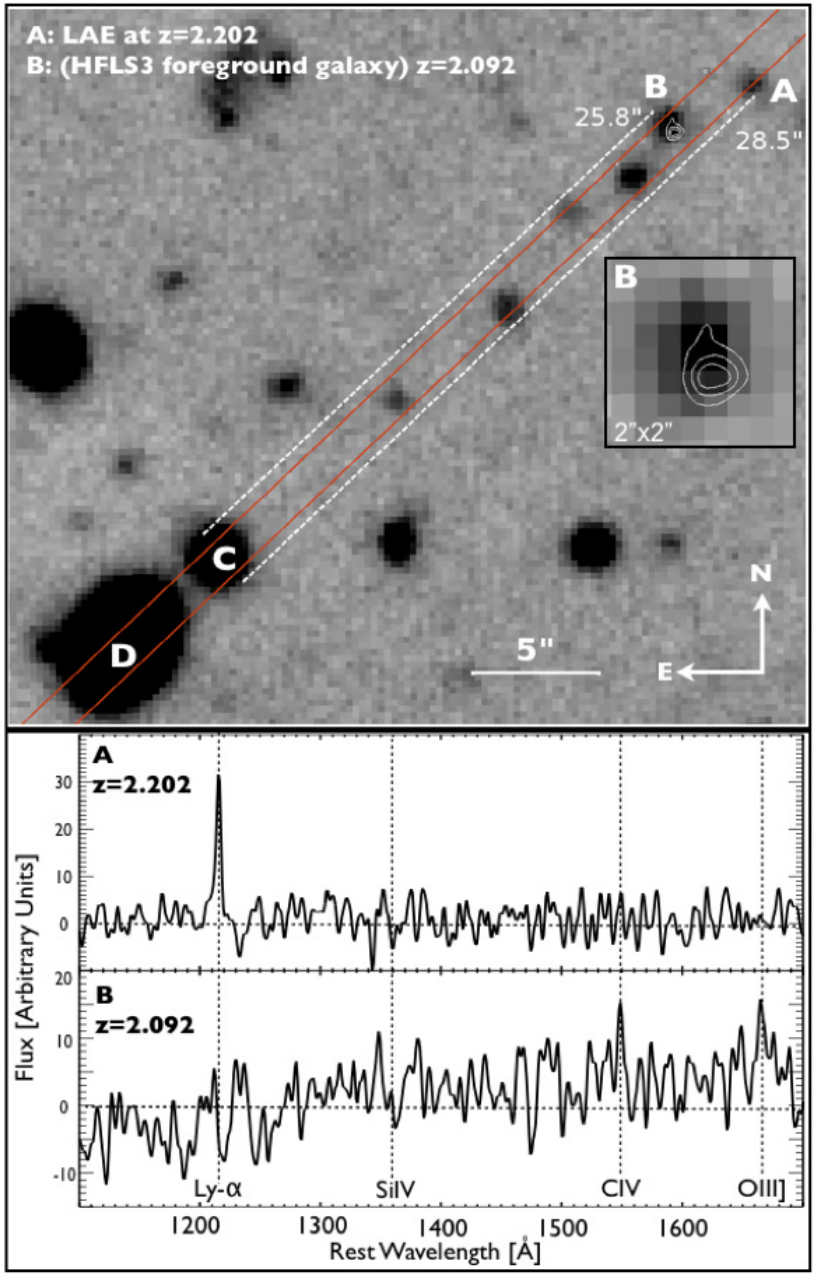


(sub)mm/radio interferometry

- Interferometric positions are needed for spectroscopic follow-up at other wavelengths
- We have observed HFLS3 with the SMA, PdBI, and CARMA in many bands at different angular resolutions



First Try: (Sub)Millimeter Position, **Optical Spectrum**



SMA/PdBI 1 mm continuum interferometry

⇒ Precise position; <<1”

Within <<1” of optically detected galaxy (WHT and GTC, PI Pérez-Fournon)

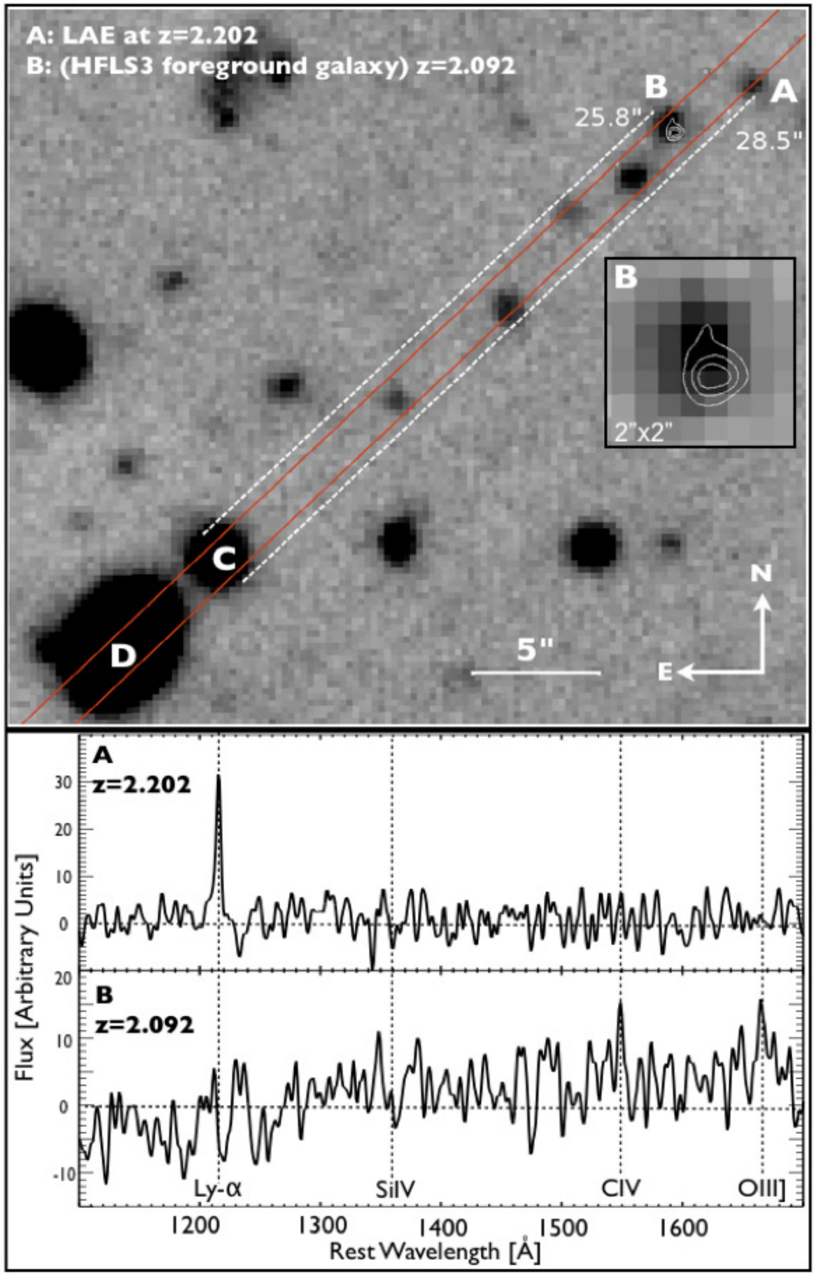
Keck/LRIS deep spectrum (PI Carrie Bridge)

⇒ faint low-mass emission line galaxy at z=2.1

⇒ Nearby z=2.2 Ly-α emitter, not associated

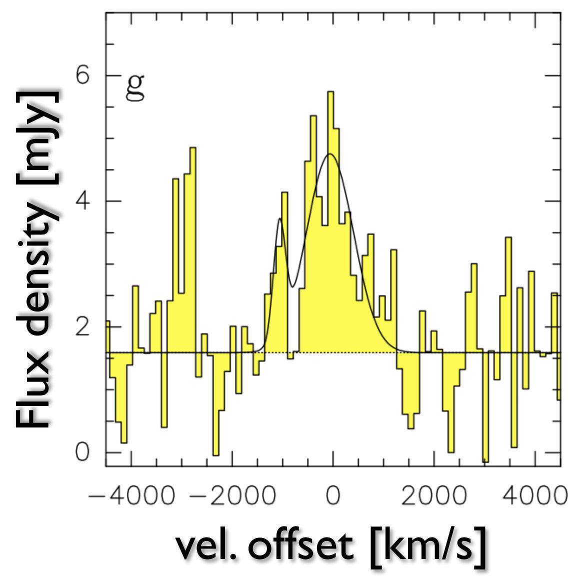
Background image from GTC/OSIRIS i-band (ITP, PI Pérez Fournon)

Second Try: (Sub)Millimeter Position, CO spectroscopy (CARMA)



CARMA CO spectroscopy

⇒ detect CO line, consistent with CO 3-2 at z~2.1
⇒ weird properties, but perhaps time to move on?



Third try: observations with all relevant facilities

See the details in the supplementary information of Riechers et al. 2013 Nature paper.

VIDEO of all the astronomical facilities used in this study:
http://bia.iac.es/videos.php?tag=HFLS3&id=1&vid=155

⇒ Herschel SPIRE, part of the HerMES survey, PIs Oliver and Bock
⇒ Herschel PACS, Open Time, PI Riechers
⇒ Combined-Array for Research in Millimeter-wave Astronomy (CARMA), PI Riechers
⇒ Caltech Submillimeter Observatory (CSO), Z-spec, PI Bradford
⇒ IRAM Plateau de Bure Interferometer, PIs Riechers and Pérez-Fournon
⇒ Jansky VLA (JVLA), PI Ivison
⇒ Submillimeter Array (SMA), PI Clements
⇒ IRAM 30m and Goddard-IRAM Superconducting 2-Millimeter Observer (GISMO), PI Pérez-Fournon
⇒ WHT (ACAM and LIRIS) and GTC (OSIRIS), PI Pérez Fournon
⇒ Keck Second Generation Near-Infrared Camera (NIRC2), PIs Fu and Riechers
⇒ Keck Low-Resolution Imaging Spectrometer (LRIS), PI Bridge
⇒ Wide-Field Infrared Survey Explorer (WISE), Preliminary Release Catalog
⇒ Spitzer Space Telescope InfraRed Array Camera (IRAC), PI Vieira

⇒ And also SCUBA2 and HST (Ivison et al. 2013, Cooray et al. 2013, Laporte et al. 2013)

Atomic and molecular lines

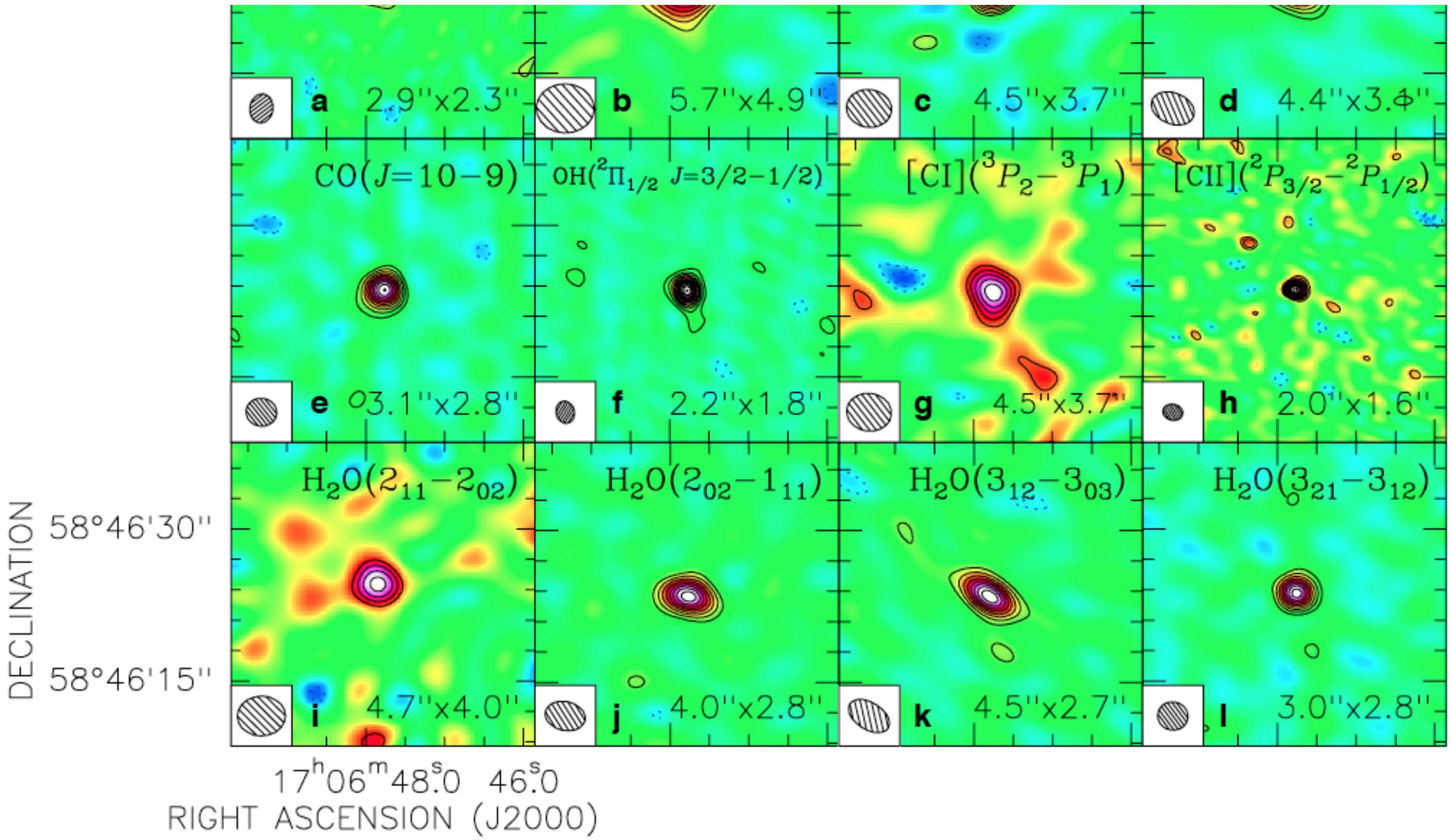


Figure S3: Atomic and molecular line emission towards HFLS3. CARMA, PdBI, and JVLA maps of

CSO Z-spec spectrum

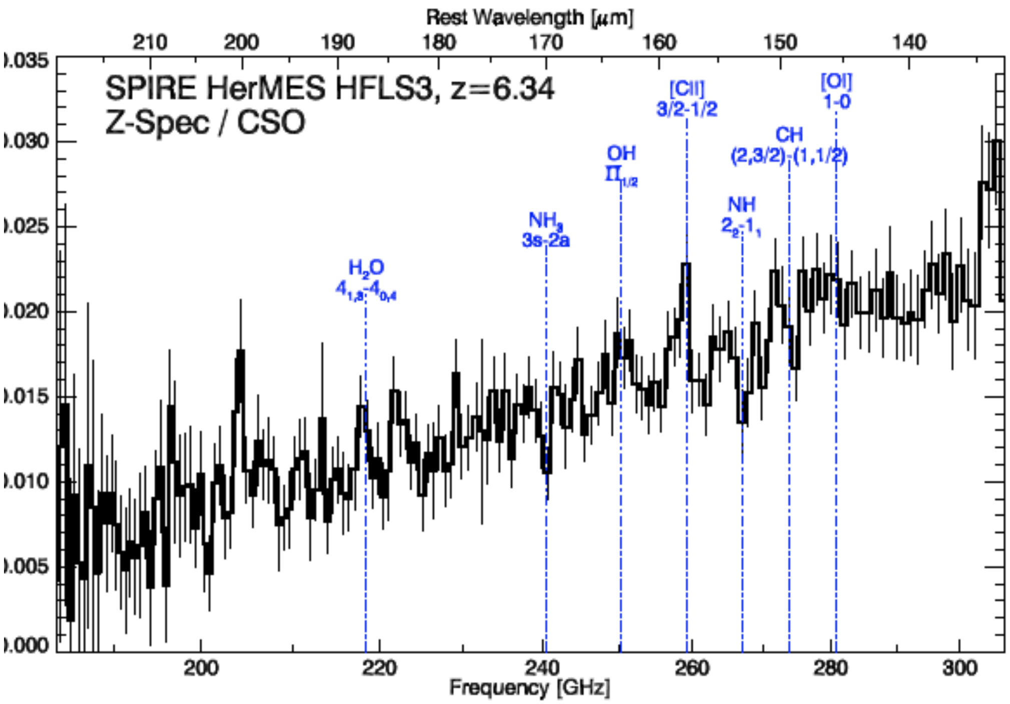
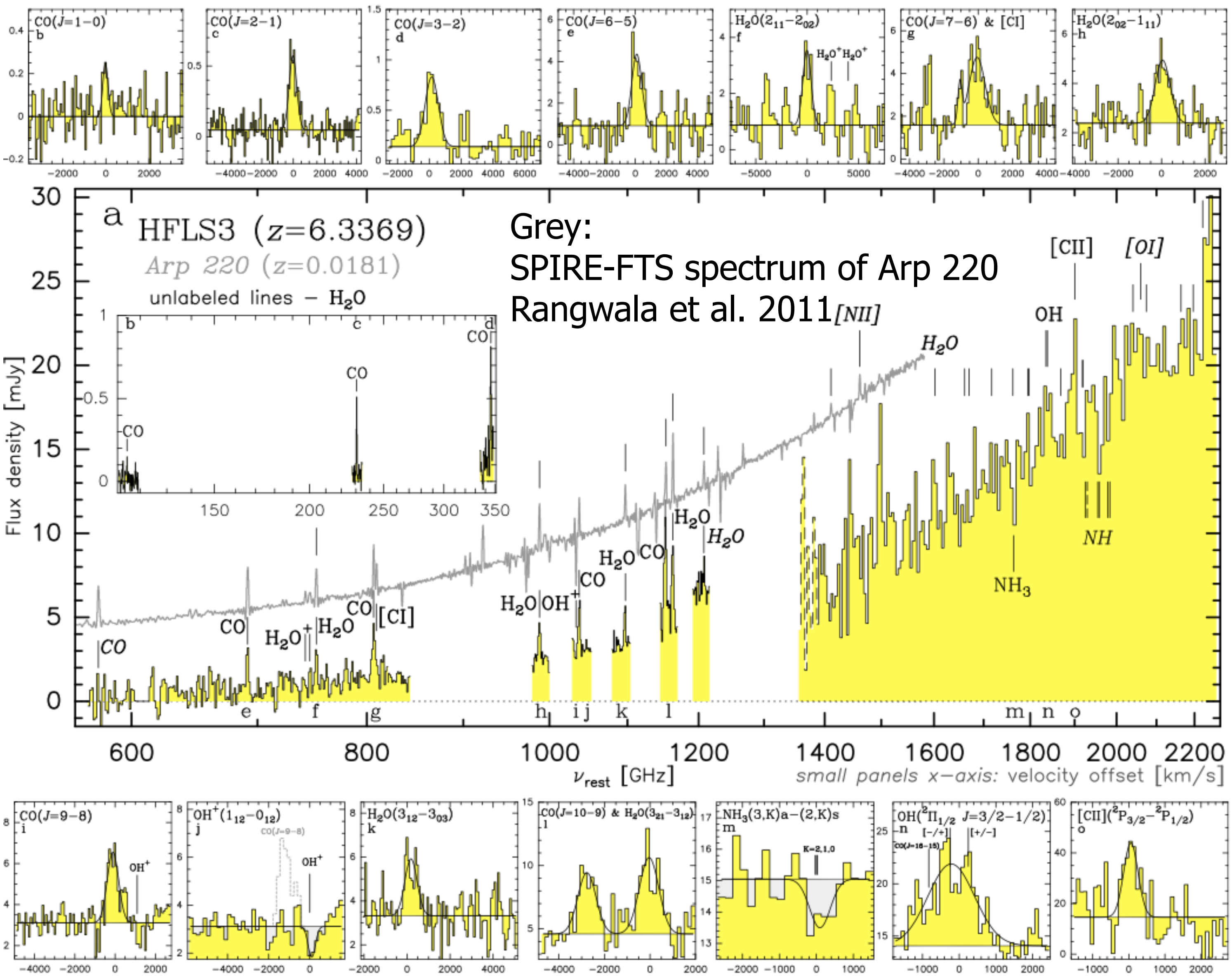


Figure S4: Tracers of the star-forming interstellar medium redshifted to the 1 mm window in HFLS3. CSO/Z-spec spectrum of HFLS3 with 1σ r.m.s. error bars and tentative line identifications overlayed. The [CII], OH $^2\Pi_{1/2}$ $3/2-1/2$, and NH_3 (3,K)a−(2,K)s features were independently confirmed (NH_3 was only tentatively confirmed) through interferometric observations with CARMA and the PdBI. The spectrum shows an interloper line close to the redshifted frequency of CO J=13−12 which is not seen in interferometric observations with the PdBI (and thus unlikely to be associated with HFLS3)

HFLS3: Sometimes, persistence is the key



Follow up with all we have:

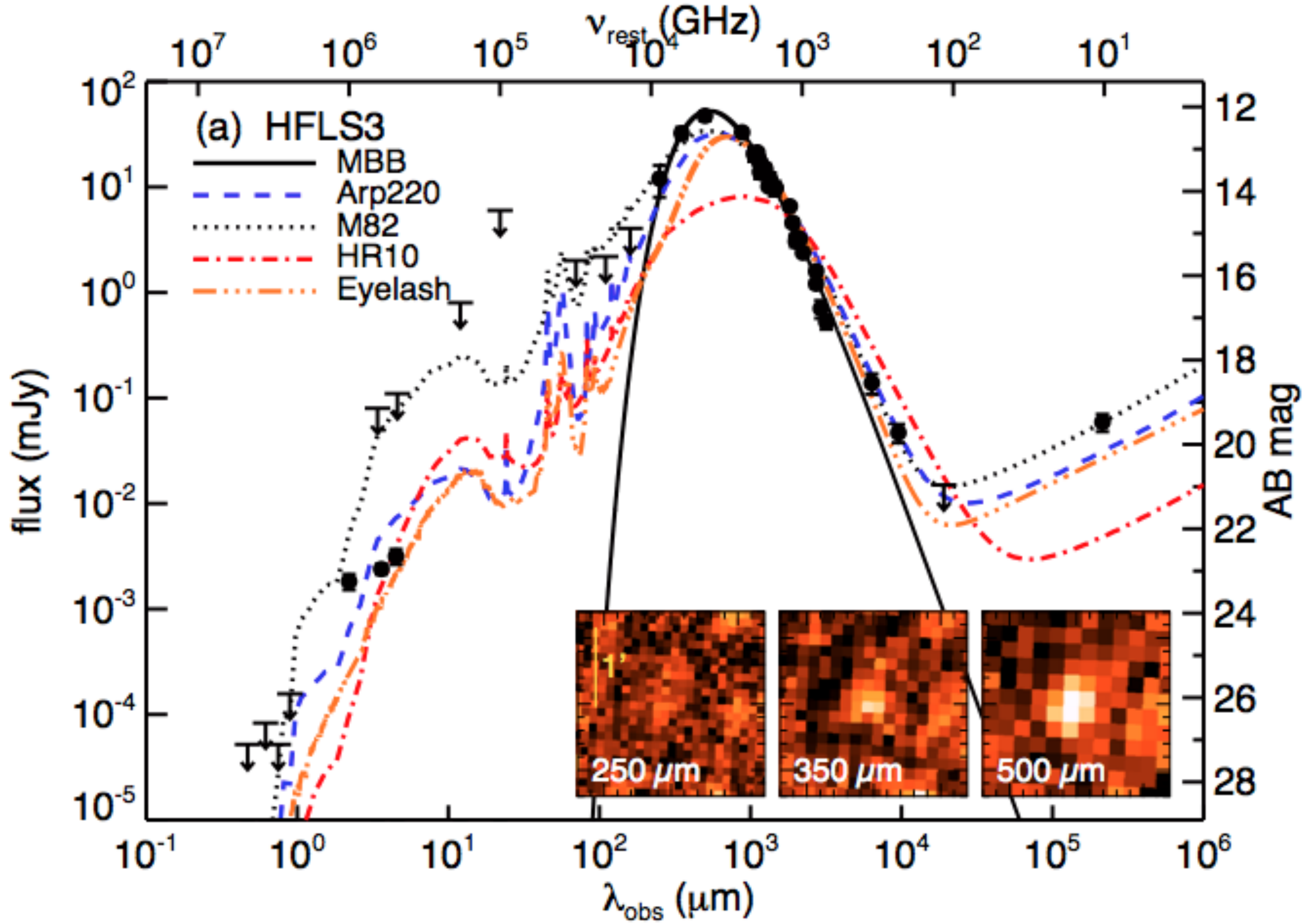
Line was CO 7-6 … at z=6.3369 !!

Detect
- 7 CO lines
- 7 H_2O lines
- H_2O^+
- NH_3 (absorption)
- OH
- OH^+ (absorption)
- [CI]
- [CII]
- Hints of others…

⇒ Highly enriched

Gray line is the SPIRE-FTS spectrum of the *nearby* starburst Arp 220 Rangwala et al. 2011

HFLS3 SED



ν_{rest} (GHz)
(a) HFLS3
MBB
Arp220
M82
HR10
Eyelash
flux (mJy)
AB mag
λ_{obs} (μm)
1'
250 μm
350 μm
500 μm

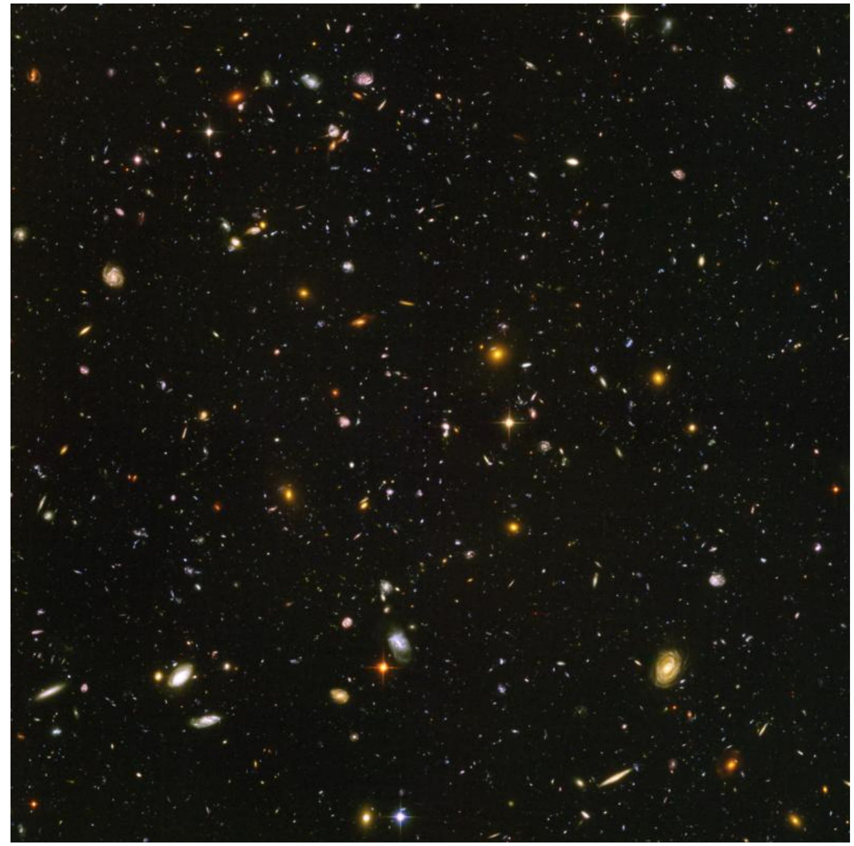
HFLS3: Warm, Dusty Starburst, not Luminous AGN

SFR of HFLS3 alone
~ 4.5x $\Sigma(SFR_{UV})$
of *all* z=5.5-6.5 galaxies in HUDF

Very gas-rich, highly metal-enriched

Warm, lower dust optical depth than Arp 220

	HFLS3	Arp 220*
redshift	6.3369	0.0181
M_{gas} (M_{sun})[a]	(1.04+/-0.09) x 10^{11}	5.2 x 10^{9}
M_{dust} (M_{sun})[b]	$1.31^{+0.32}_{-0.30}$ x 10^{9}	~1 x 10^{8}
M_{*} (M_{sun})[c]	~3.7 x 10^{10}	~3-5 x 10^{10}
M_{dyn} (M_{sun})[d]	2.7 x 10^{11}	3.45 x 10^{10}
f_{gas}[e]	40%	15%
L_{FIR} (L_{sun})[f]	$2.86^{+0.32}_{-0.31}$ x 10^{13}	1.8 x 10^{12}
SFR ($M_{sun}yr^{-1}$)[g]	2,900	~180
T_{dust} (K)[h]	$55.9^{+9.3}_{-12.0}$	66



Hubble Ultra Deep Field

HFLS3: observations at short wavelengths

Optical to mid-infrared images of HFLS3

GTC/OSIRIS griz, WHT LIRIS Ks and Spitzer 3.6 and 4.5 um

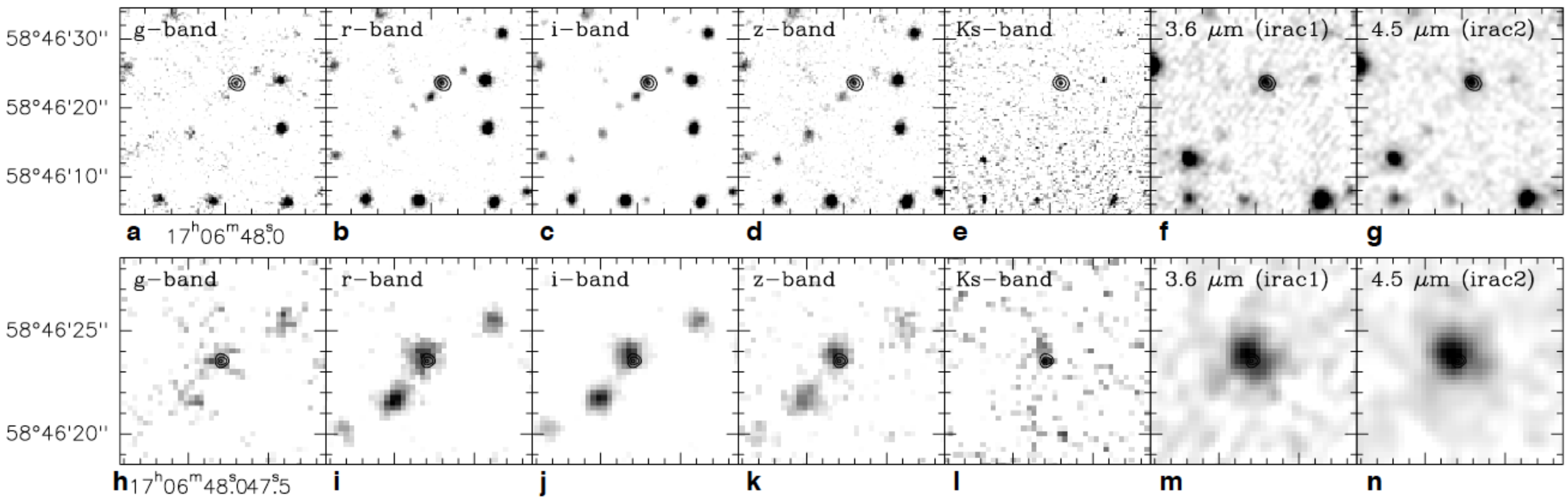
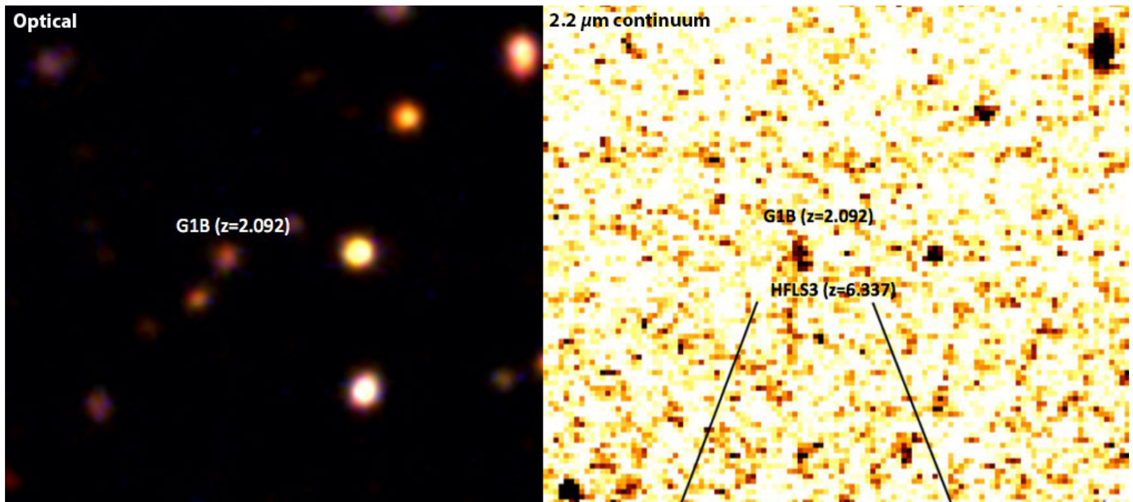


Figure S9: Optical to mid-infrared images of the region around HFLS3. **a–g**, 30”×30” size regions in the optical *g*, *r*, *i*, *z* (**a–d**), near-infrared K_s (**e**), and mid-infrared 3.6 and 4.5 μm bands (**f** and **g**). **h–n**, zoom-in on 10”×10” size regions in the same bands. Contours of the 1 mm continuum emission are overlayed on all panels. HFLS3 is not detected in the optical bands, but is detected in K_s band and longwards. The emission close to HFLS3 is dominated by the foreground galaxy G1B in all bands.

HFLS3: observations at short wavelengths

Optical (GTC) and near-IR observations (WHT LIRIS Ks and Keck NIRC2)



WHT LIRIS Ks

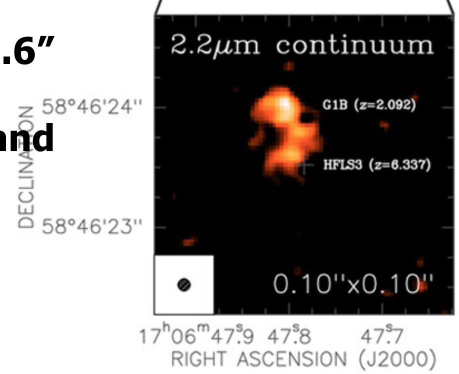
Seeing limited

0.6" FWHM

We see two different galaxies separated by 0.6"

G1B, z=2.092, detected in the optical (GTC) and near-IR

HFLS-3, z=6.34, detected only in the near-IR with both LIRIS and NIRC2



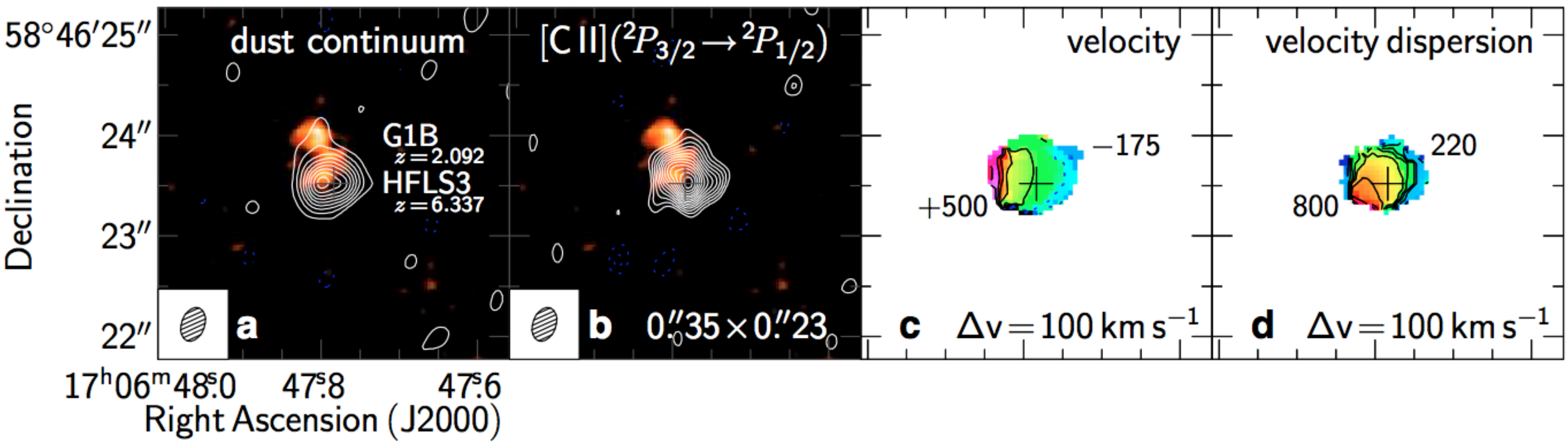
Keck NIRC2

Laser Guide Star AO imaging

Outside seeing 0.4"

AO FWHM 0.1"

HFLS3: Giant “Maximum” Starburst, not Strongly Lensed SMG



Compact (~3.5 kpc), high-dispersion gas and dust reservoir

⇒ No evidence for strong lensing morphology

⇒ Lensing models based on nearby z=2.1 galaxy: μ_L<1.2

⇒ Galaxy is intrinsically very massive and luminous

High SFR surface density: Σ_{SFR} ~600 $M_{sun} yr^{-1}$

⇒ “maximum” starburst over few kpc responsible for high energy release

Consistent with models of CO, H_2O, and OH excitation

⇒ Gas is warm and dense

⇒ Excitation consistent with starbursts, not AGN environments like Mrk 231

An extraordinary system, even compared to “typical” SMGs at lower redshift

HFLS3
measured and derived source properties

Table S4: Measured and derived source properties

Parameter	Value
L'_{CO}	$1.04\pm0.09\times10^{11}$ K $kms^{-1}pc^{2}$
L_{CO}	$5.08\pm0.45\times10^{6}$ L_{sun}
$L_{[CI]}$	$3.0\pm1.9\times10^{8}$ L_{sun}
$L_{[CII]}$	$1.55\pm0.32\times10^{10}$ L_{sun}
L_{FIR}	$2.86^{+0.32}_{-0.31}\times10^{13}$ L_{sun}
M_{gas} [a]	$1.0\times10^{11} M_{sun}$
M_{CI} [b]	4.5×10^{7} M_{sun}
M_{HI} [c]	2.0×10^{10} M_{sun}
M_{dust}	$1.31^{+0.32}_{-0.30}\times10^{9}$ M_{sun}
M_{*}	3.7×10^{10} M_{sun}
M_{dyn}	2.7×10^{11} M_{sun}
SFR [d]	2,900 $M_{sun}yr^{-1}$
Σ_{gas}	1.4×10^{4} M_{sun} pc^{-2}
Σ_{SFR}	600 $M_{sun}yr^{-1}kpc^{-2}$
f_{gas}	40%
gas-to-dust ratio	80
t_{dep}	36Myr
ε	0.06
$d_{[CII]}$	3.4 kpc×2.9 kpc
d_{FIR}	2.6 kpc×2.4 kpc
T_{dust}	$55.9^{+9.3}_{-12.0}$K
β	1.92 ± 0.12

How unique is HFLS3?

- Several hundred high-redshift (SPIRE-red) candidates in the HerMES, H-ATLAS and other surveys (HERS, HLS, etc)
- 38 red sources in 21 square degrees discussed in Dowell, Conley et al.
- A few objects with even more extreme properties than HFLS3
- The future: NOEMA, ALMA, HST, JWST, ELTs, etc.
- A good case for SPICA multi-band observations
- SPICA can provide a full view from the near-IR (optical rest frame) to the far-IR (mid-IR rest frame) of similar objects and their environments to much fainter luminosities

Summary and open questions

- Massive, star-forming galaxies found with Herschel/SPIRE up to $z = 6.34$ (HFLS3, Riechers et al. 2013)
- This type of galaxies is not predicted in current galaxy formation models
- What is the formation mechanism?
- What are the physical properties?
- What is the environment in which they form?
- What can we learn about these galaxies and their environments with future facilities?
- We need a new, powerful infrared telescope: **SPICA!**

Many thanks!