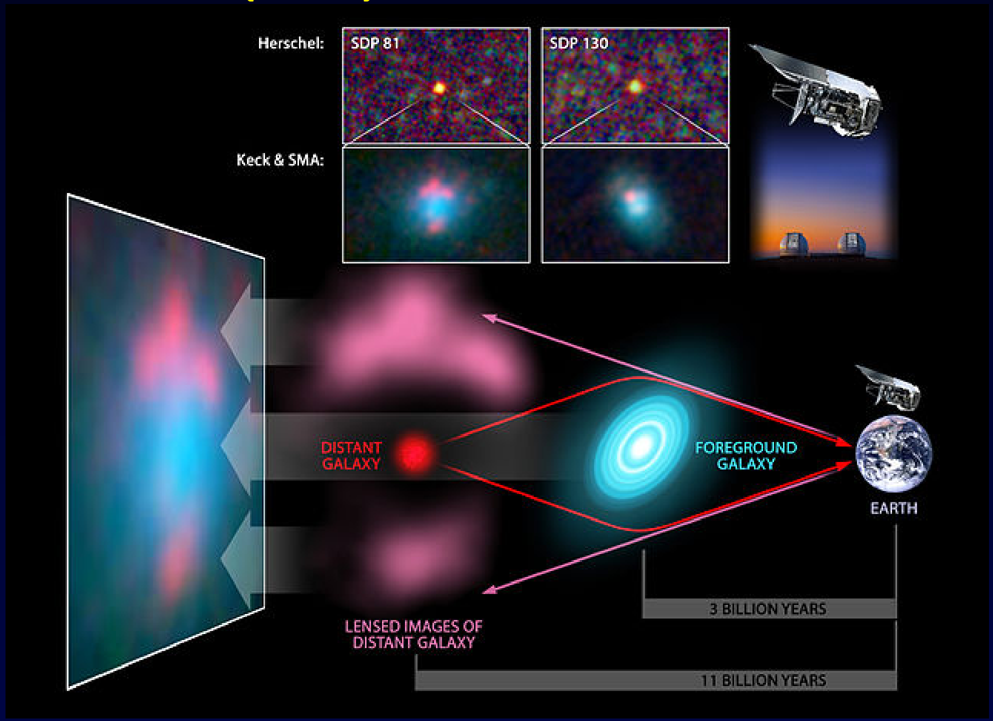
Studying lensed submillimeter galaxies at high redshift

Johan Richard (CRAL, Lyon Observatory)

starring

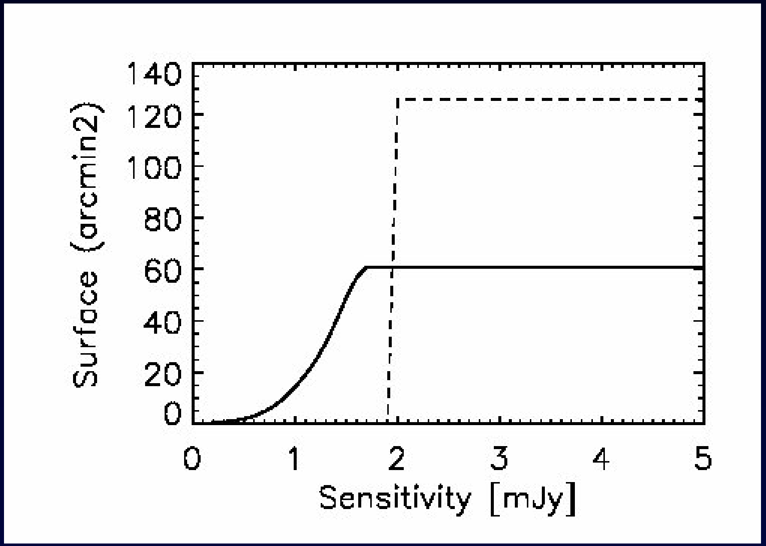
Kirsten Knudsen, Lukas Lindroos (Chalmers), Jean-Paul Kneib (EPFL), Eiichi Egami, Dan Stark (Arizona), Daniel Schaerer, Mirka Dessauges (Geneva), F.Boone (Toulouse), F.Combes (Paris), Roberto Neri (IRAM), Mark Swinbank, Ian Smail, Richard Bower, Rachael Livermore (Durham)

Lensing at (sub)-millimeter wavelengths



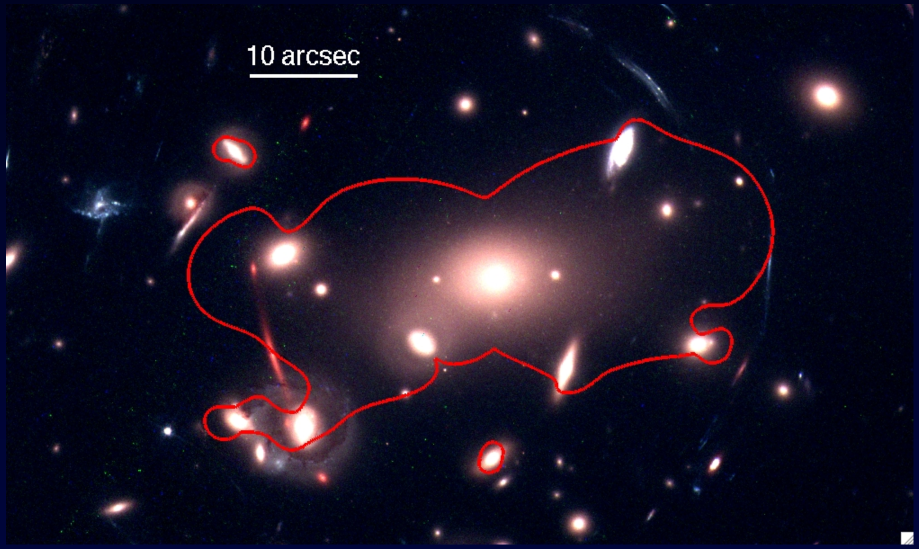
- Lensing allowed discoveries and studies of exceptionally bright (Speak > 100 mJy) IR/submm-luminous galaxies at high redshift.
- Past Herschel surveys: Galaxy-lensed: H-ATLAS ($z = 4.2$), HerMES ($z = 6.3$). Cluster-lensed: HLS, HLS-snapshot
- APEX/LABOCA, IRAM follow-up (continuum, CO lines)
- Ongoing surveys: JCMT/SCUBA2 Lensing Survey (S2LS), IRAM,ALMA

Massive clusters as gravitational telescopes



- Lensing effect is independent of wavelength: cluster mass models are used to correct for lensing in multiwavelength surveys
- Lensing pushes down the confusion limit of submm instruments (Herschel,SCUBA2,LABOCA)
- Image separation can be larger with cluster lensing
- Most cluster members do not emit at FIR wavelengths: Transparent lens!

Gravitational lensing and its effects

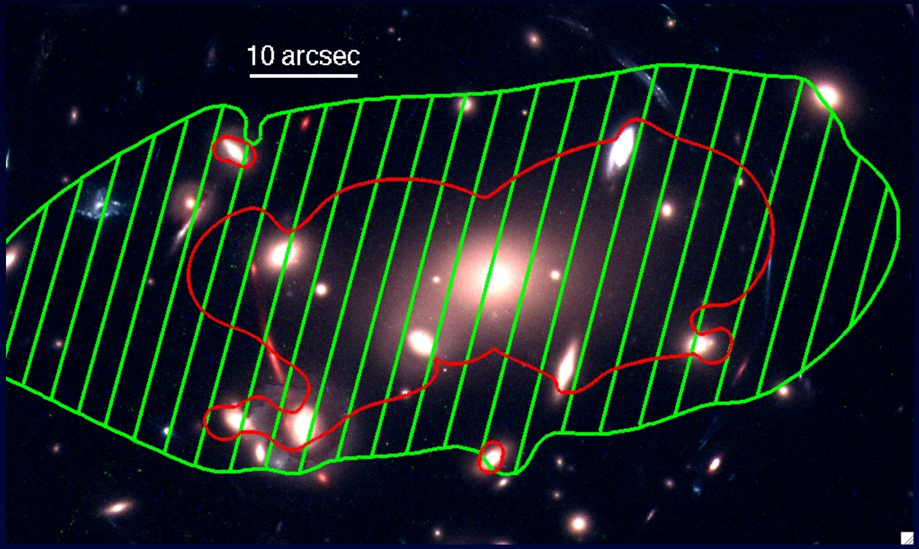


- Resolved sources: increases the angular size by the magnification factor (surface brightness conservation). Arcs and arclets. SNR $\propto \sqrt{\mu}$

- Unresolved sources: increases the magnitude by the magnification factor. Enables to detect lower luminosity objects (such as very high z sources). SNR $\propto \mu$

  - ⋆ Maximal magnification effect in the vicinity of the **critical lines**
  - ⋆ Using a cluster as a **gravitational telescope**: we need to understand the mass distribution to a good level of precision.

Gravitational lensing and its effects



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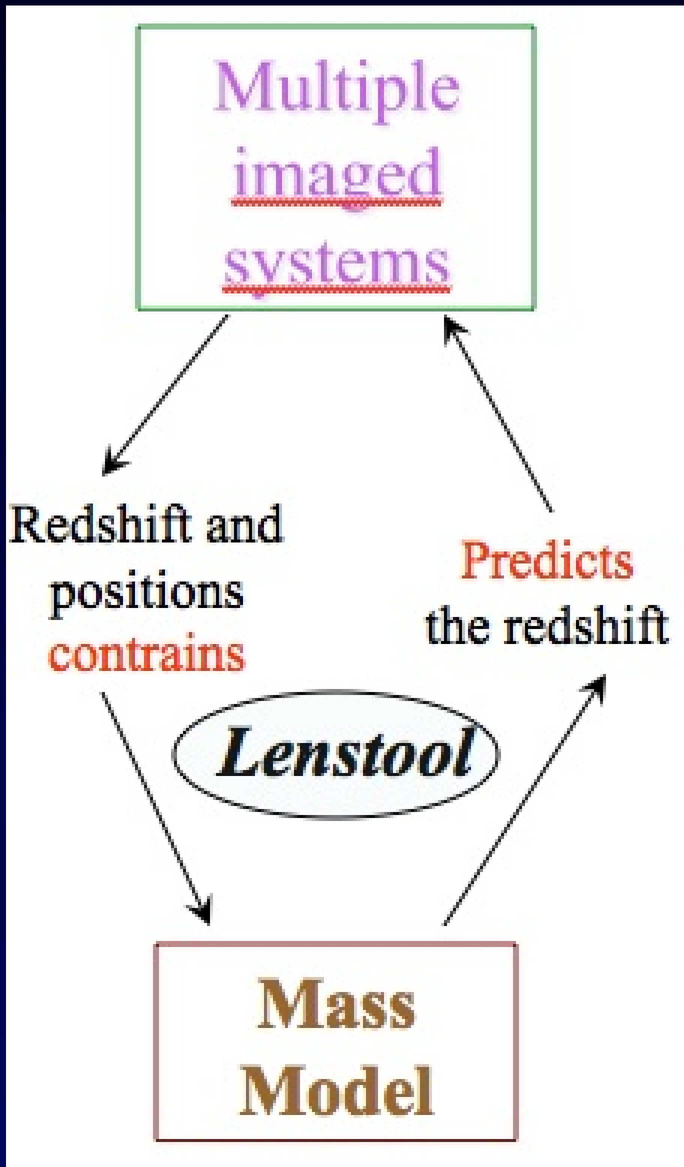
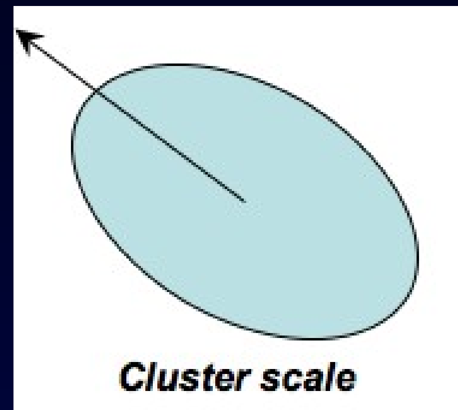
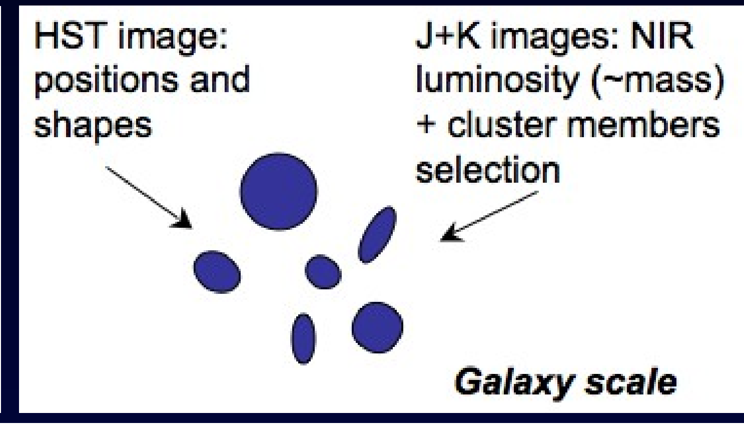
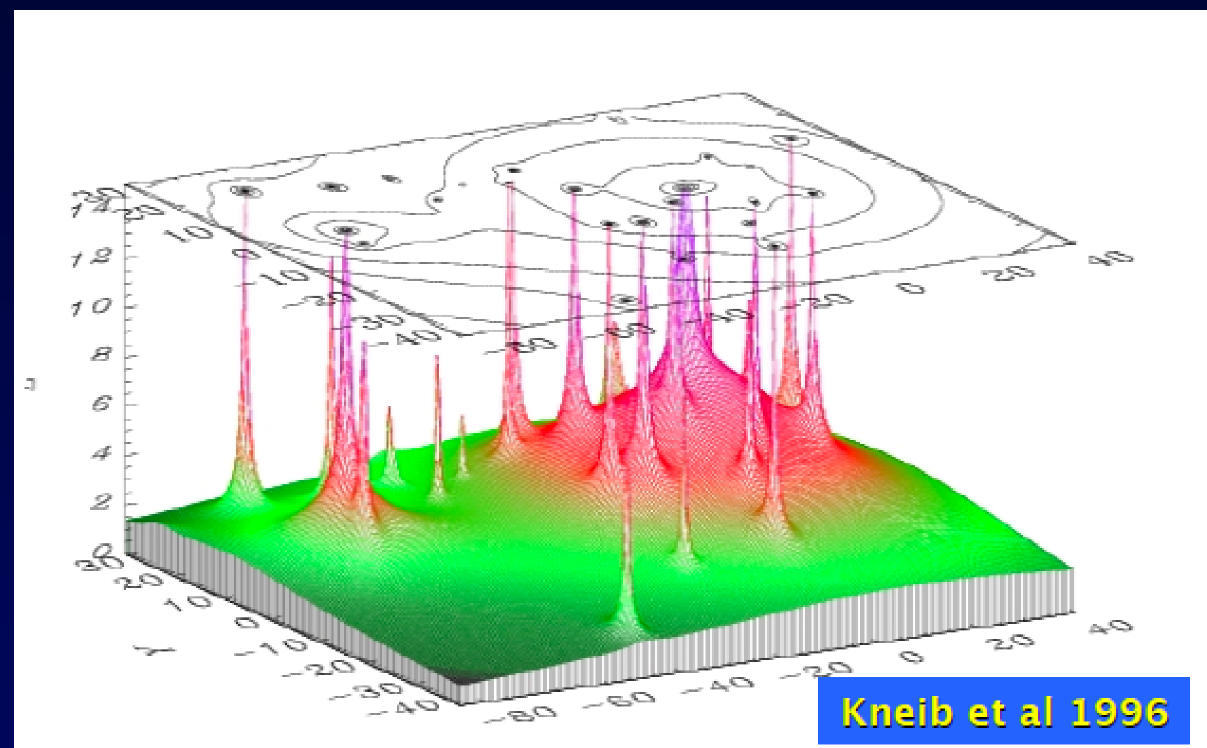
Parametric Modelling of lensing effects

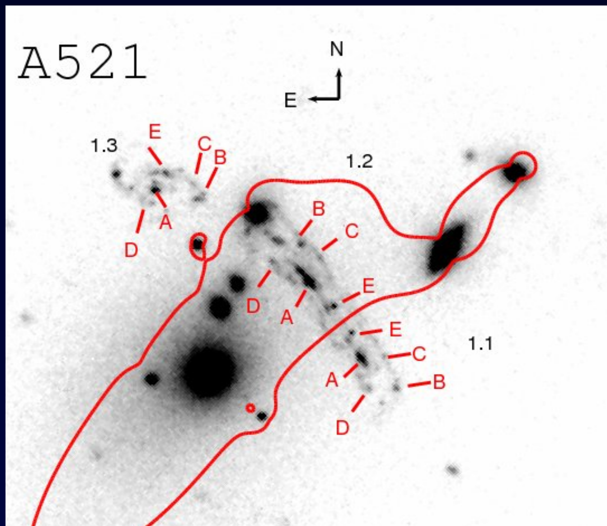


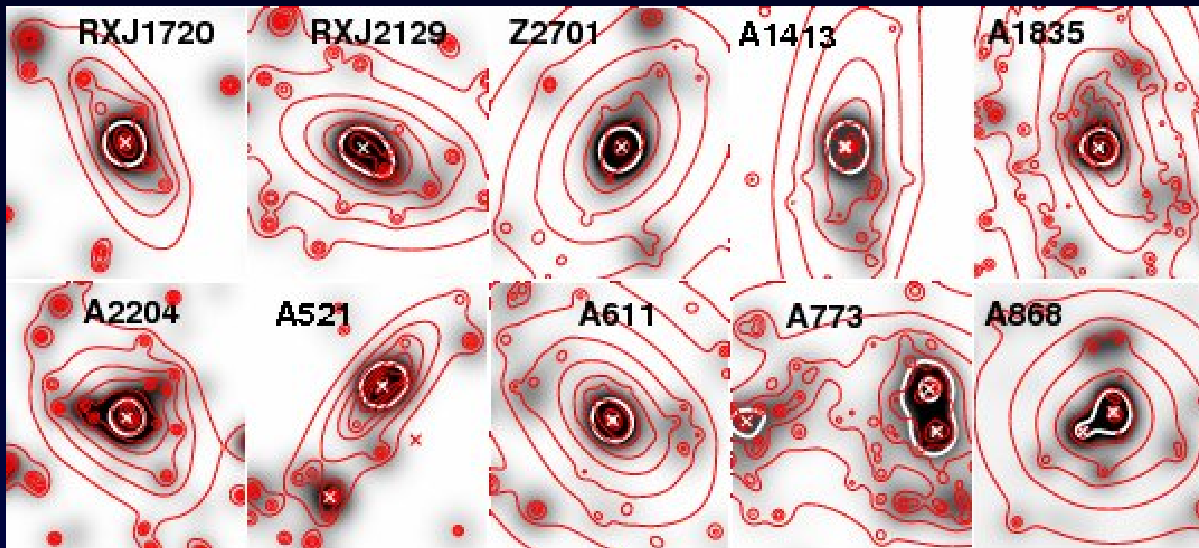






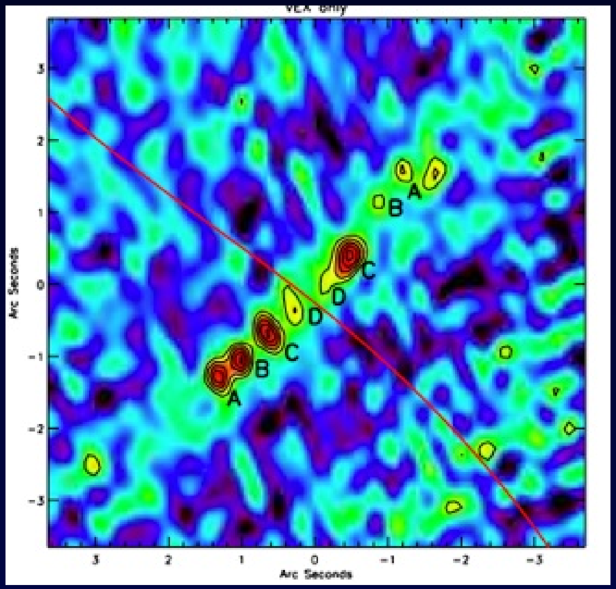
The Local Cluster Substructure Survey (LoCuSS), PI: G. Smith
The MAssive Cluster Survey (MACS), PI: H. Ebeling





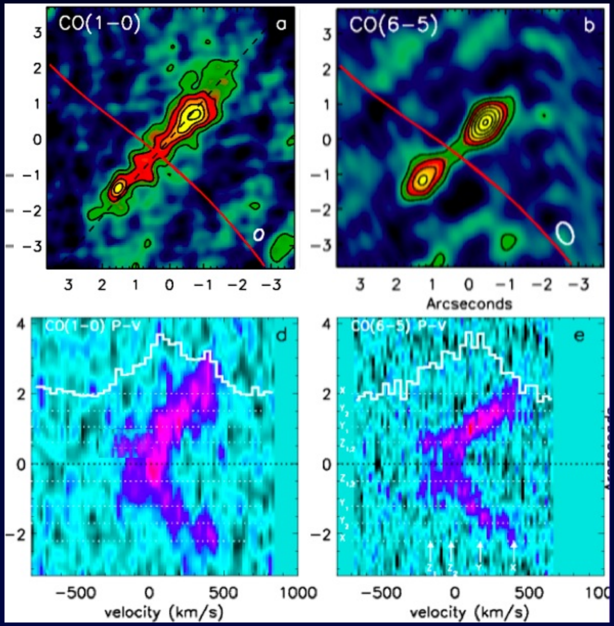
- ~ 200 X-ray selected clusters with HST imaging, ~ 100 have been well-modelled for strong-lensing *Richard et al. 2009, 2010a, 2010b, 2011, Limousin et al. 2007, 2008, 2009*
- Typical errors on magnification factors vary between 5% (in areas most constrained) and $\sim 30\%$. Typical value is $\sim 10\%$
- New Bayesian optimization allows us to assess better uncertainties

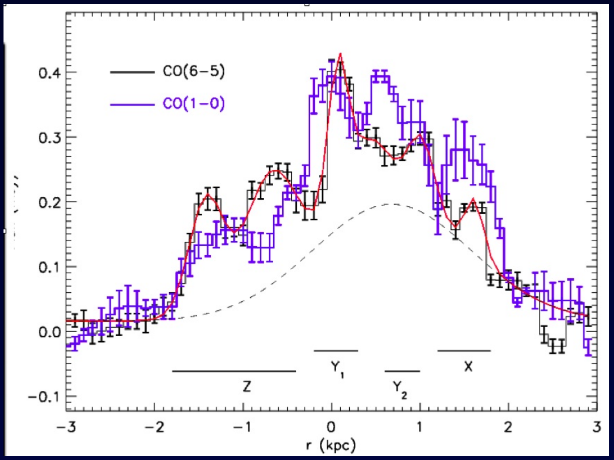
The "Eyelash" Swinbank et al. 2010, Nature



- Found with APEX/LABOCA when following-up the "cosmic eye"
- Not detected in HST optical bands, one of the brightest far-infrared / submm galaxy (800 mJy at 300μm)
- $z = 2.3$ confirmed with CO, now 11 CO transitions covered and some resolved (Danielson et al. 2010)

The "Eyelash" (2)



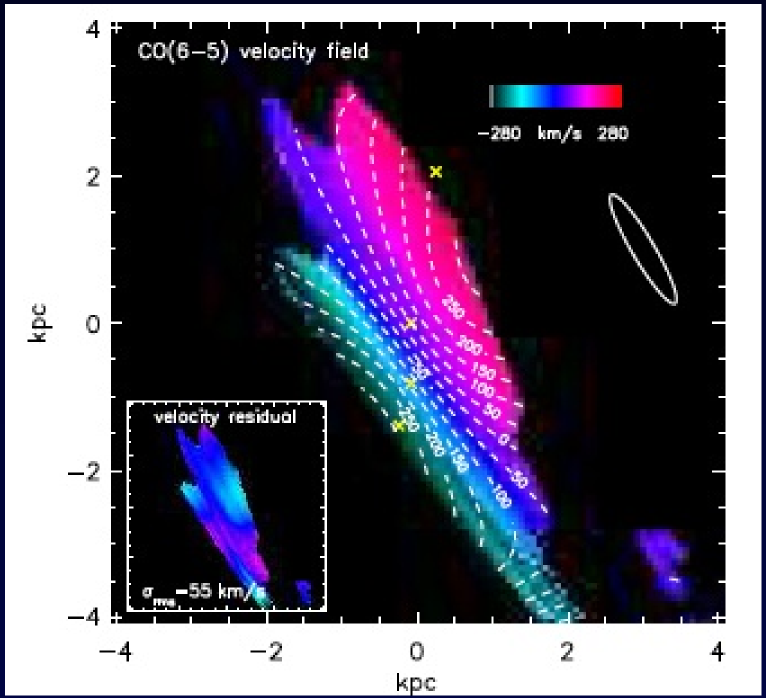


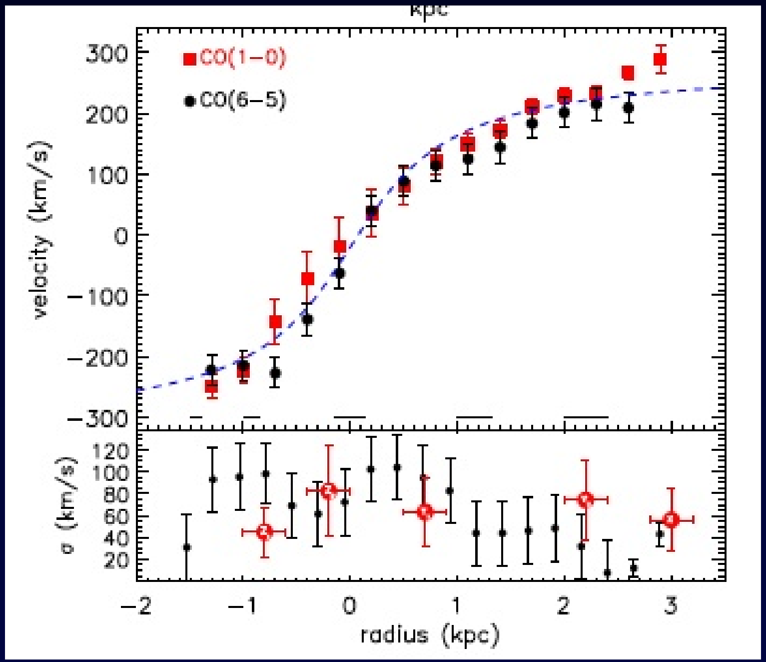
Eyelash

Play/Pause

- Detailed observations with PdBI (CO 6-5) and EVLA (CO 1-0) at 100 pc resolution
- 'Butterfly' shaped position-velocity diagram showing symmetry
- Observed CO structures coincide with continuum-detected clumps from SMA

The "Eyelash" (3)

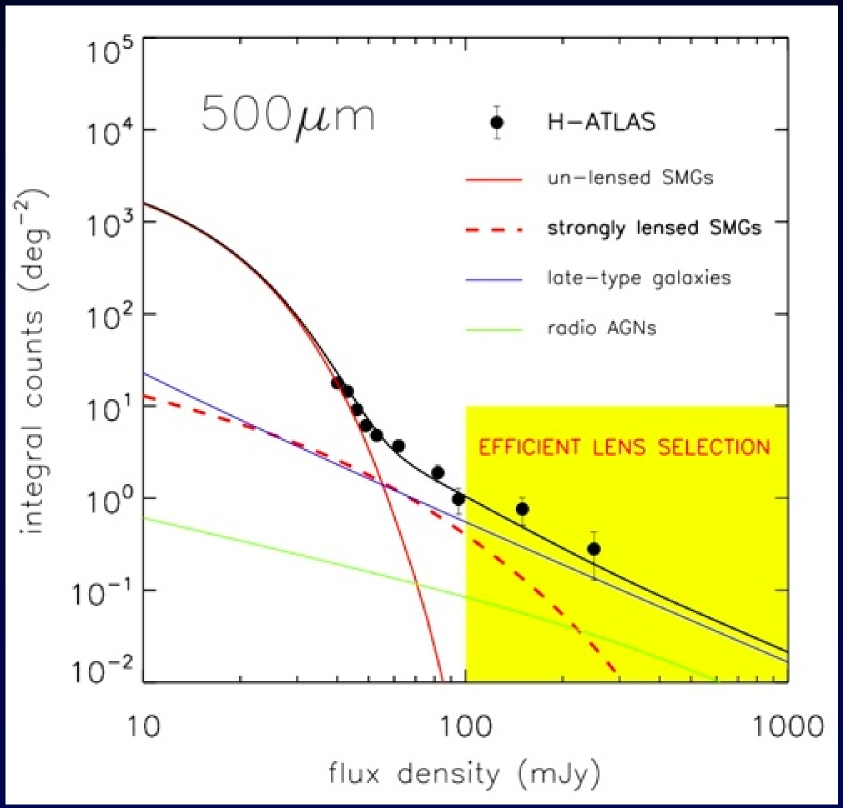


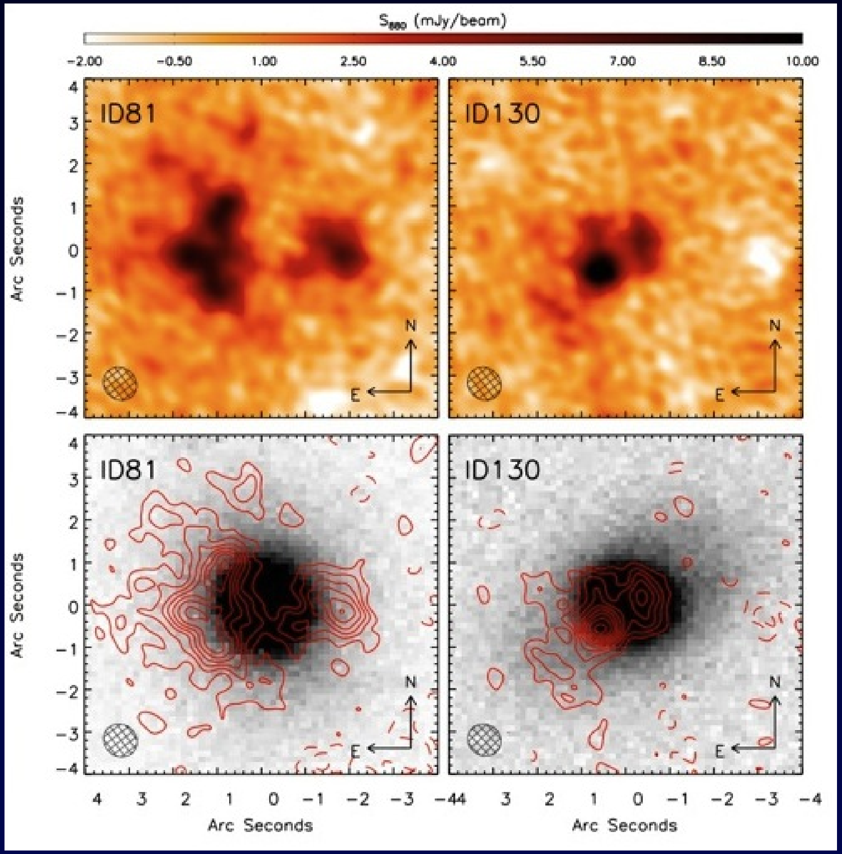


- Source reconstruction shows a clear velocity gradient for both CO lines
- The velocity curve is well fitted by a large rotating disk of $v_{rot} = 320 \pm 25$ km s^{-1}, $v/\sigma = 3.5 \pm 0.2$ (i corrected)
- M$_{dyn} = 6.0 \pm 0.5 \times 10^{10}$ M$_{\odot}$ within 2.5 kpc
- Large unstability: Q=0.50±0.15 lower than local ULIRGs where Q∼1

Herschel ATLAS lenses

Negrello et al. (2010)



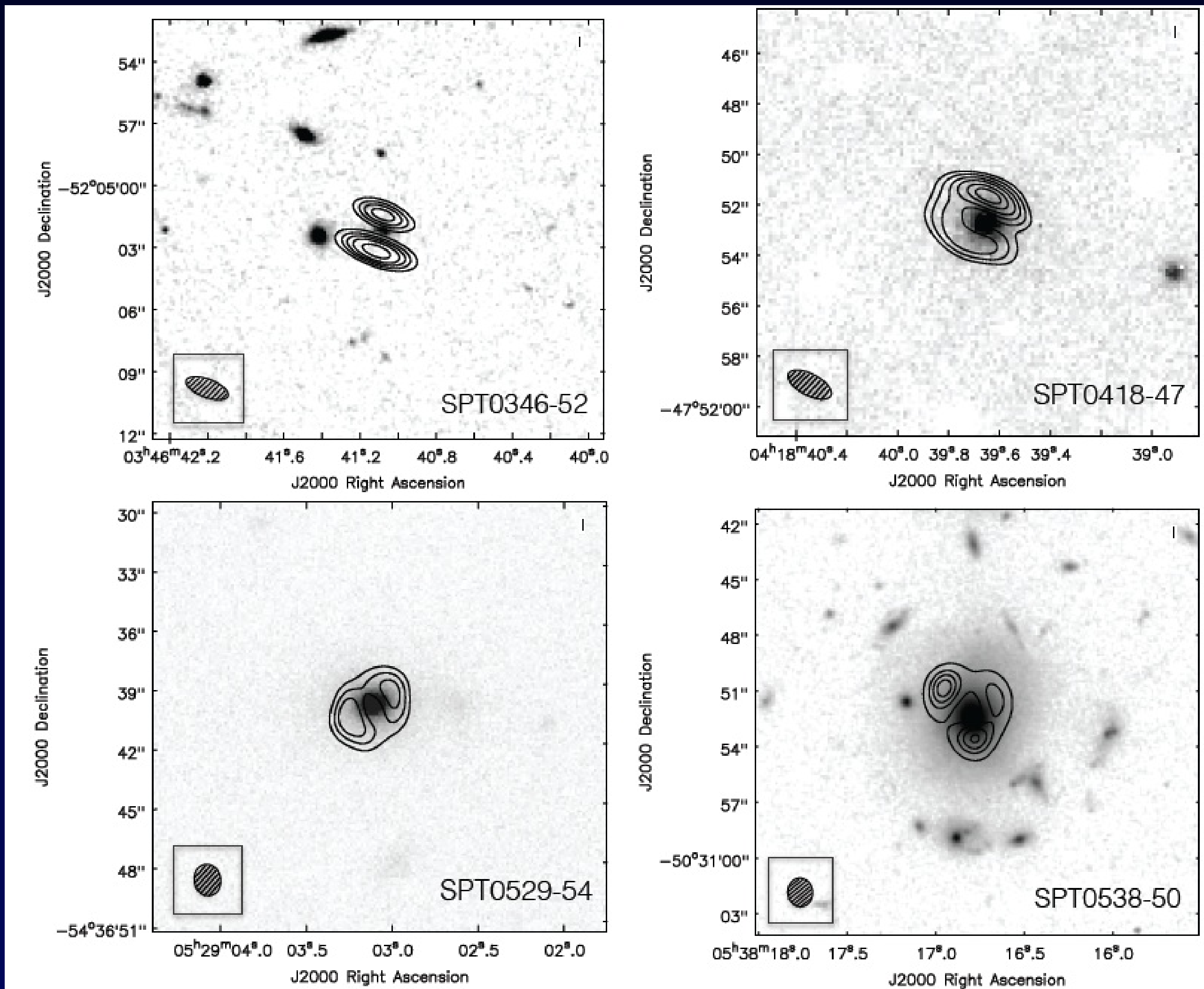


The surface density of > 100 mJy SPIRE-detected lensed galaxies ∼0.5 deg^2.

With Herschel, it is difficult to conduct a survey larger than H-ATLAS!

Alternatively, we can target known powerful gravitational lenses ($=$ massive clusters of galaxies)

SPT lenses: ALMA follow-up



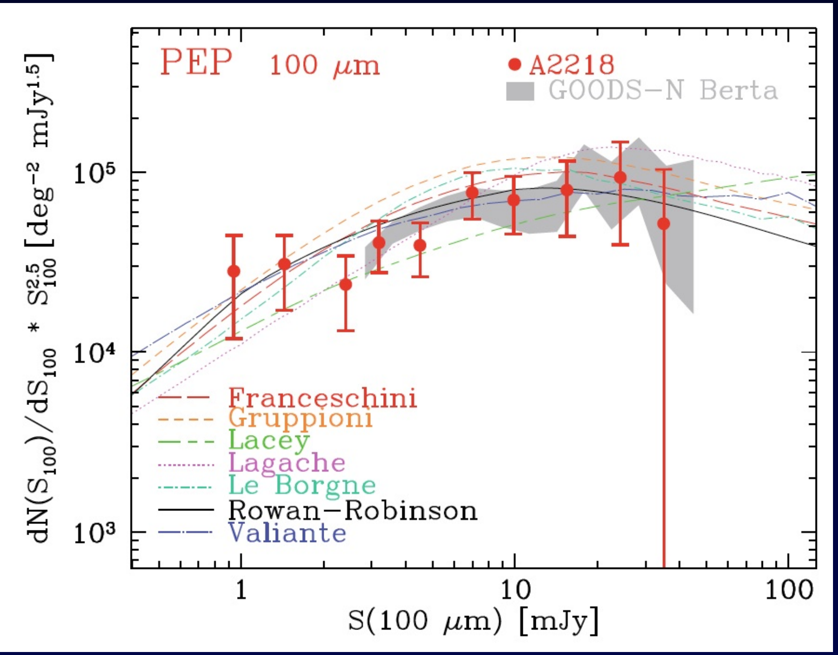
Hezaveh et al. (2013), Vieira et al. (2013), Weiss et al. (2013): ALMA follow-up of SPT mm sources.

- 860 μm imaging reveal galaxy-galaxy lensing of $z = 2.8 - 5.7$ sources
- CO follow-up with ALMA to measure source redshifts
- Image separation: a few arcsecs
- $5 < \mu < 20$

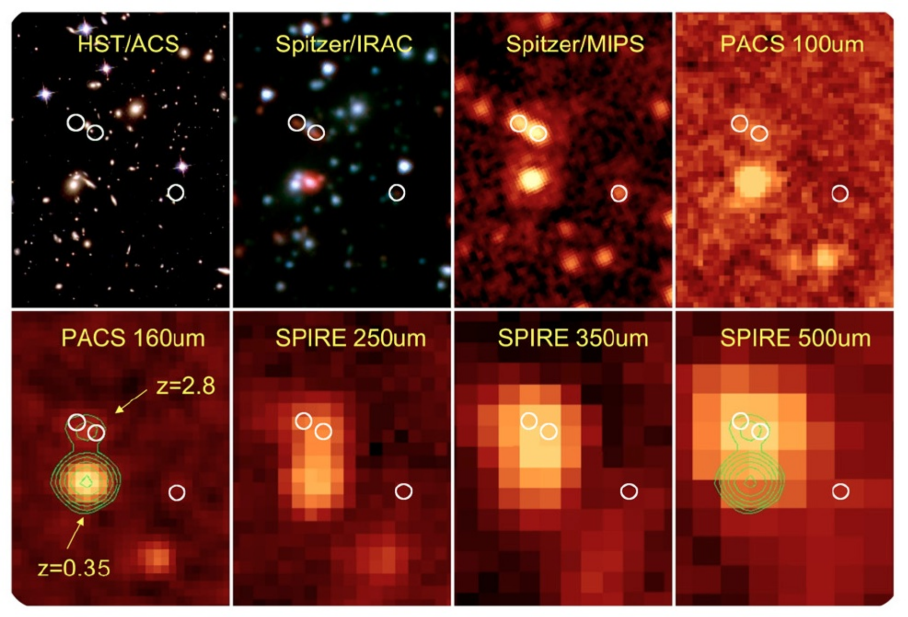
Herschel lensing: GTO and HLS

A&A 2010 special issue: Altieri et al., Egami et al., Rex et al, etc.

GTO cluster: Abell 2218

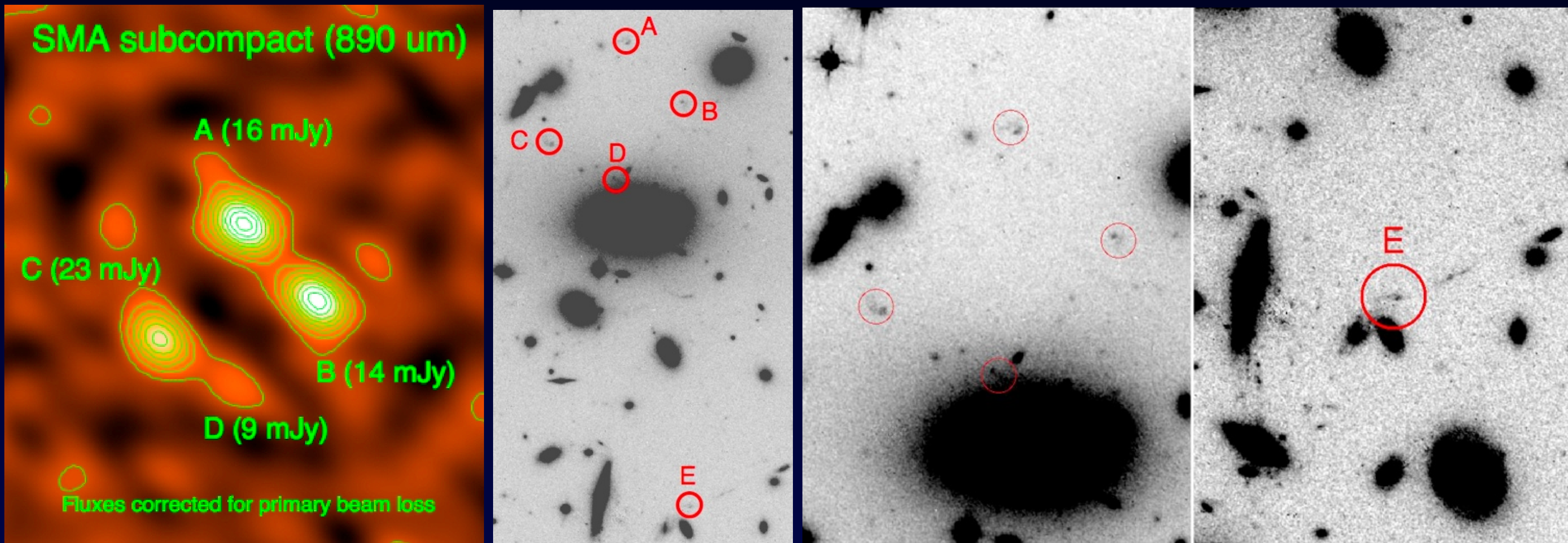


HLS cluster: Bullet



- FORS2 spectroscopic follow-up of Herschel sources (P86 and P87, 7 nights, PI:Richard), targetting 16 HLS clusters: produced > 300 redshifts already.
- Selection of 20 highly magnified sources (Rawle et al., in preparation). Ongoing follow-up with near-infrared spectroscopy, CO line measurements
- Luminosity functions / deep number counts of all 50 clusters in progress.

Herschel SNAPSHOT program (see D. Schaerer's talk)

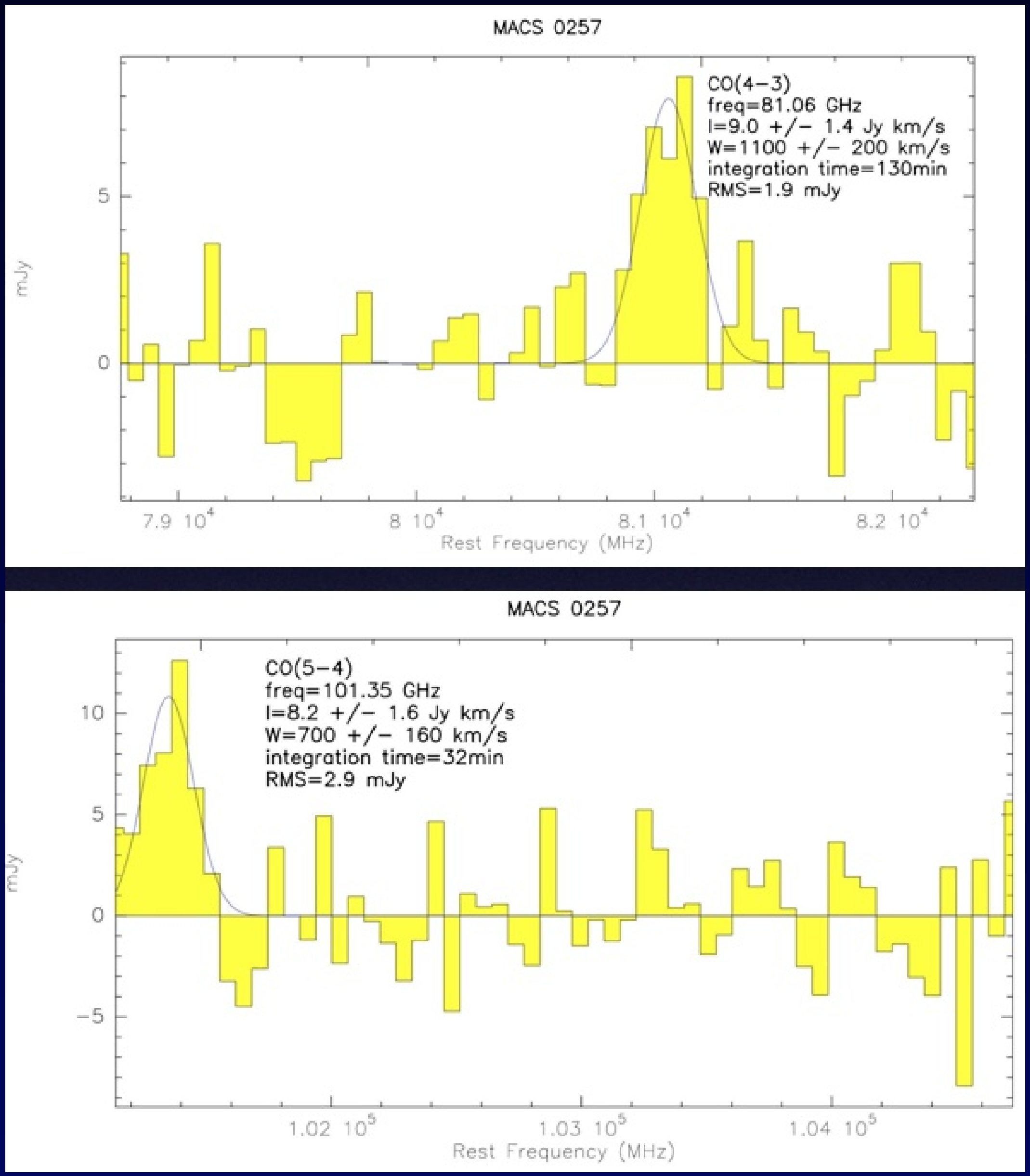


SMA extended and very extended configuration: continuum 890 μm

HST imaging + lensing model: configuration hyperbolic-umbilic

FORS spectroscopy: no Lyman-α emission but continuum break

Herschel SNAPSHOT program: IRAM/30m redshift

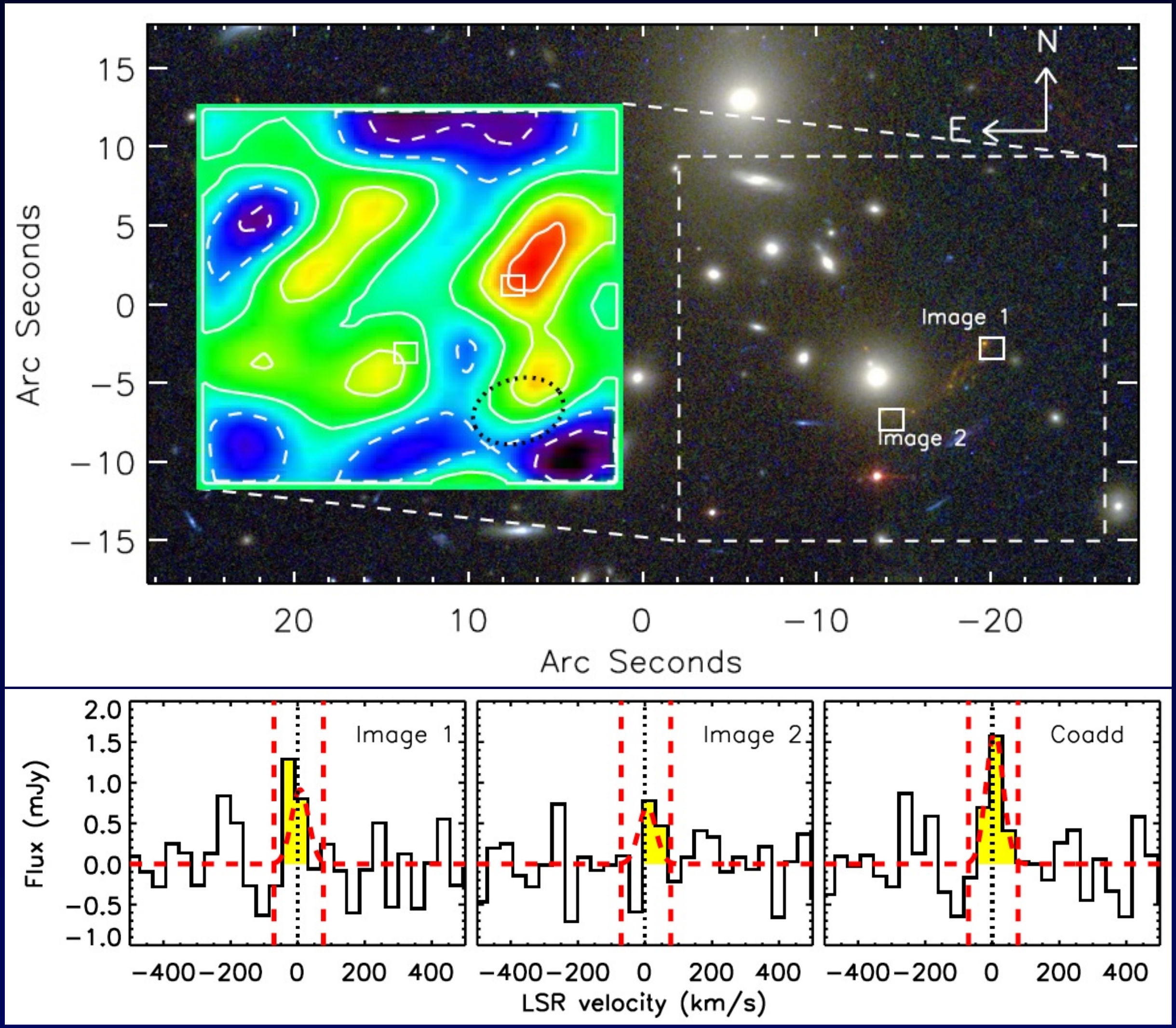


Egami et al. in preparation

- $z = 4.688$ from CO lines with EMIR
- Strongly magnified $\mu > 100$
- < 1 mJy source observed as 60 mJy 890 μm

MS1358: pushing at high redshift

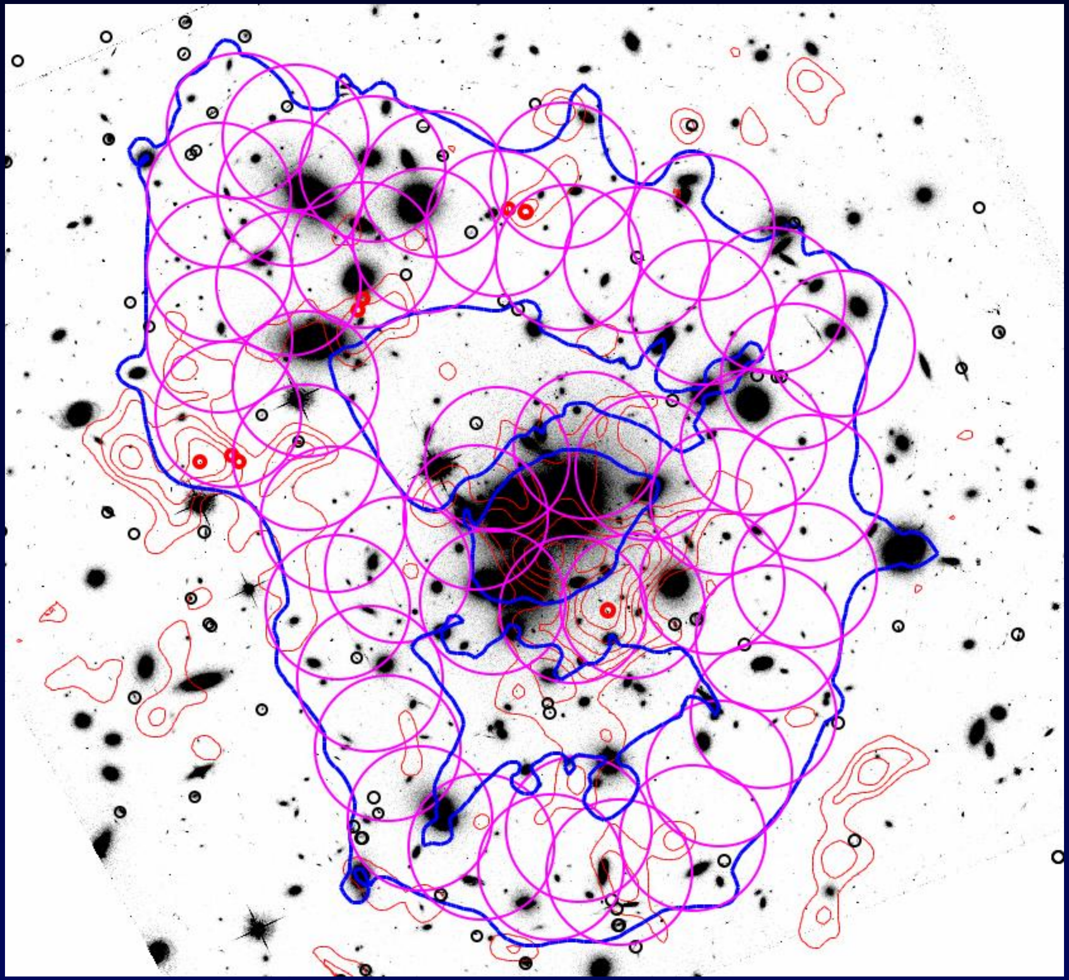
Livermore et al. (2012): CO(5-4) measurement of a z=4.9 galaxy



- L* lensed Lyman-Break Galaxy ($\mu = 22 \pm 5$)
- 4.3σ detection in 10 hrs with IRAM/WIDEX
- $M_{gas} \sim 10^9$ $M_\odot$ if $\alpha = 2$
- difficult until ALMA or NOEMA!

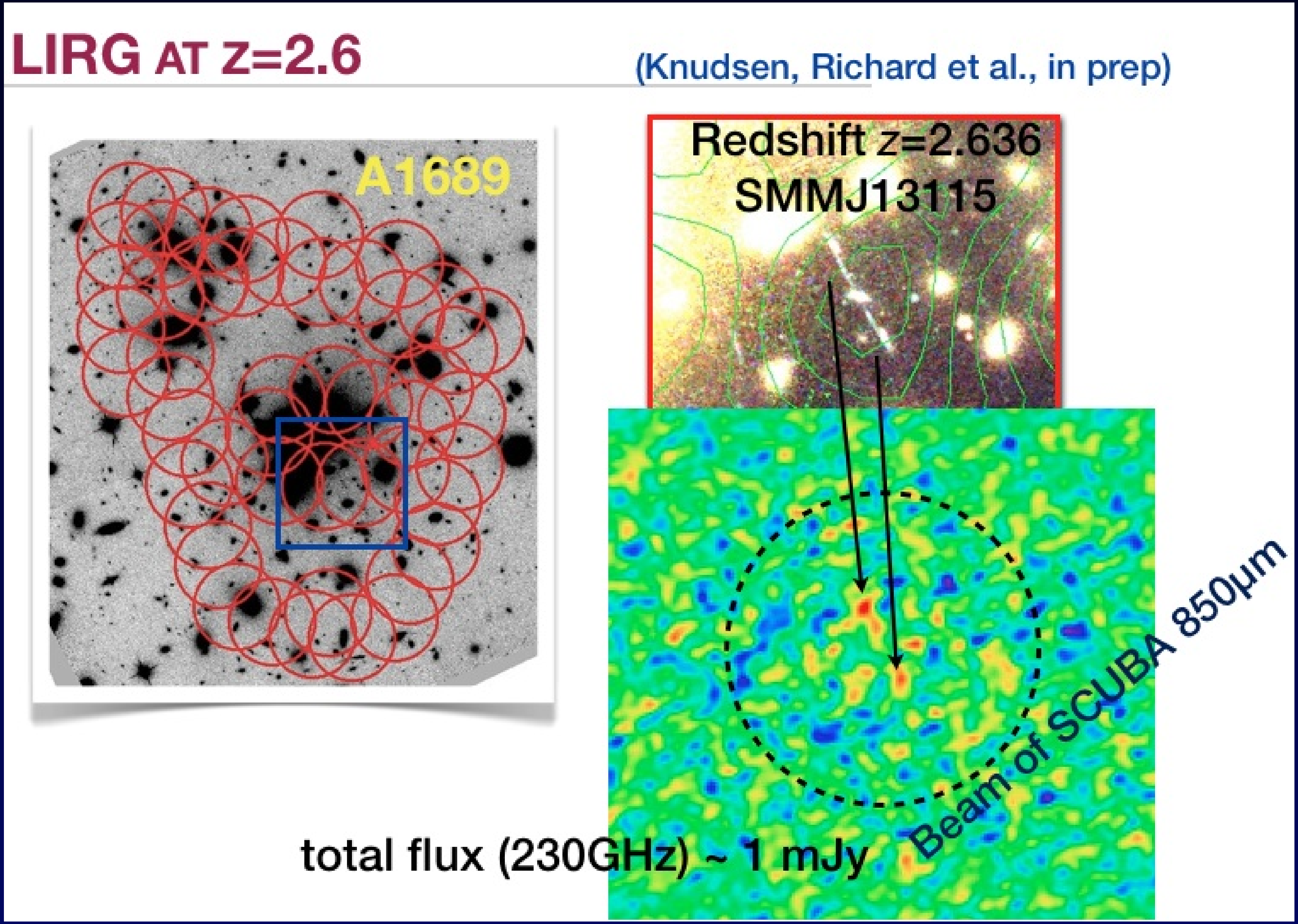
ALMA cycle 0 program

$\sim$50 pointings covering the high magnification region, total time 6.7 hours reaching 0.5 mJy per pointing in the continuum (4σ)



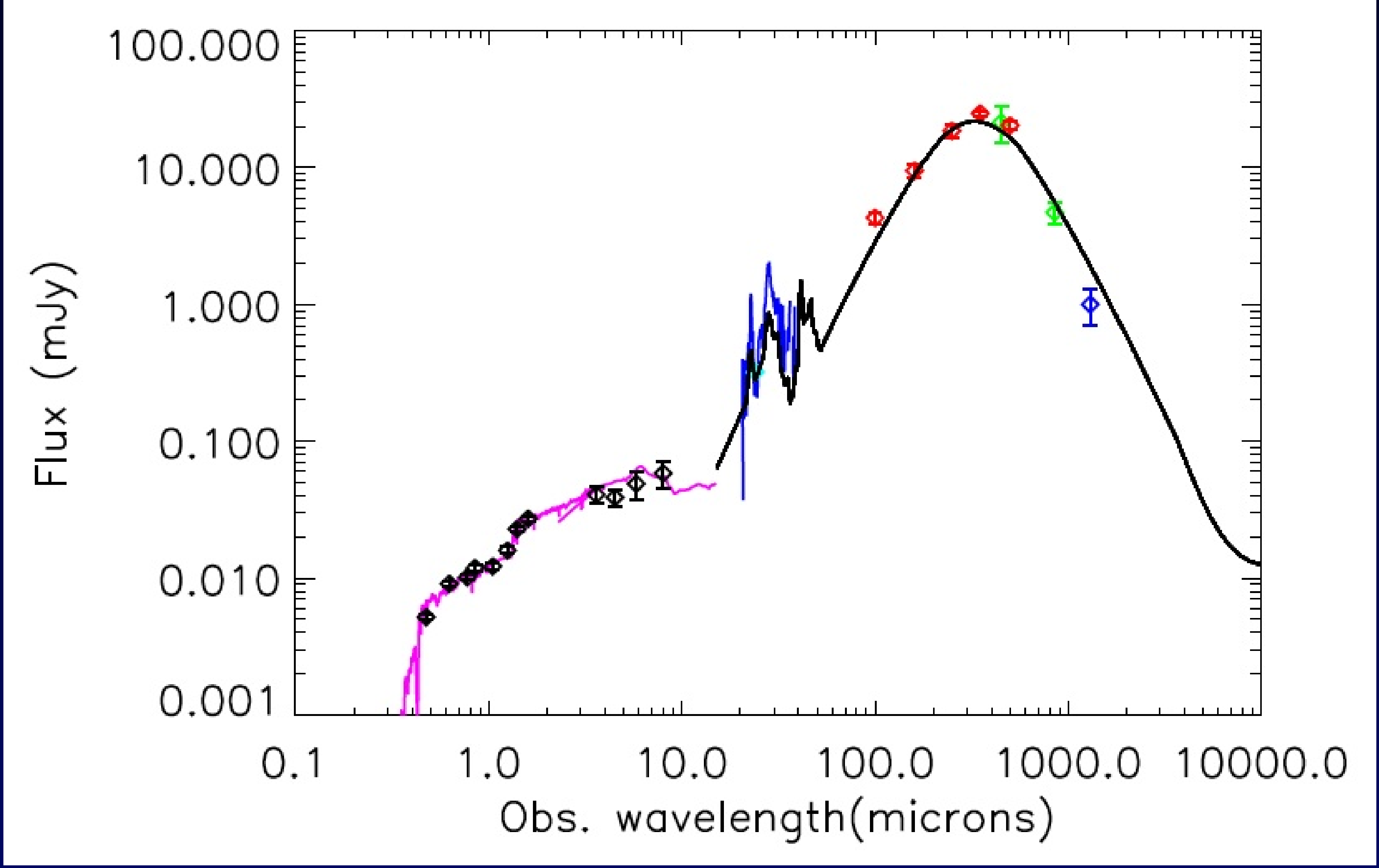
- Main goal: deep continuum image 1.3 mm, reaching $< 50\mu$Jy unlensed.
- CO search for known submm galaxies (Knudsen et al., SCUBA map)
- Stacked CO lines for 30 low-luminosity galaxies at known $1.5 < z < 3.0$

ALMA survey of A1689 (2)



ALMA (3)

Combined SED: HST + Spitzer + Herschel (PACS/SPIRE) + JCMT/SCUBA(2) + ALMA1.3mm

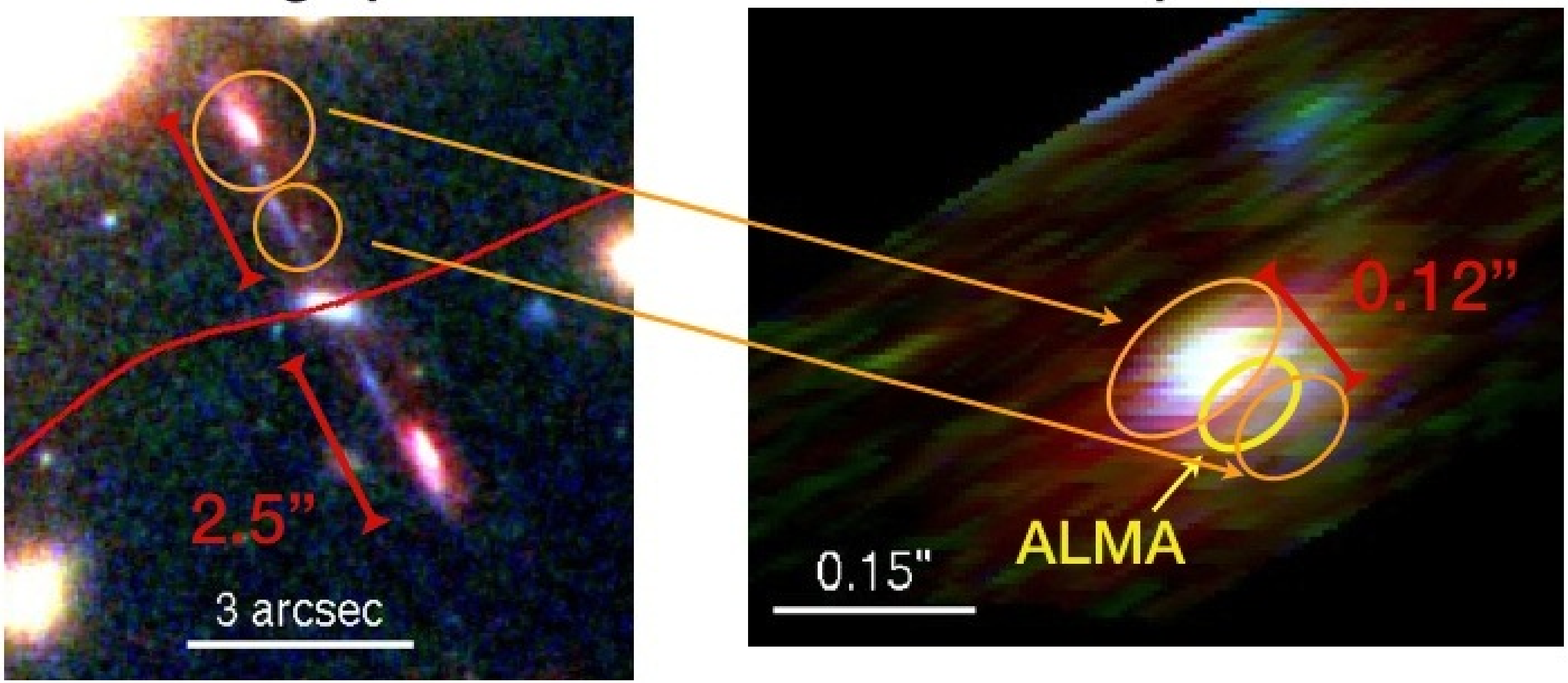


ALMA (4)

STARBURST IN A SMALL GALAXY

(Knudsen et al., Richard et al., in prep)

Image plane | Source plane



L_{FIR} ~ 1.0×10^{11} L_o
SFR ~ 20 M_o/yr
$M_{stellar}$ ~ 2×10^9 M_o

Reconstructed image:
Size of galaxy ~ 1-1.5 kpc
Starburst region ~ 200-300pc

ALMA (4)

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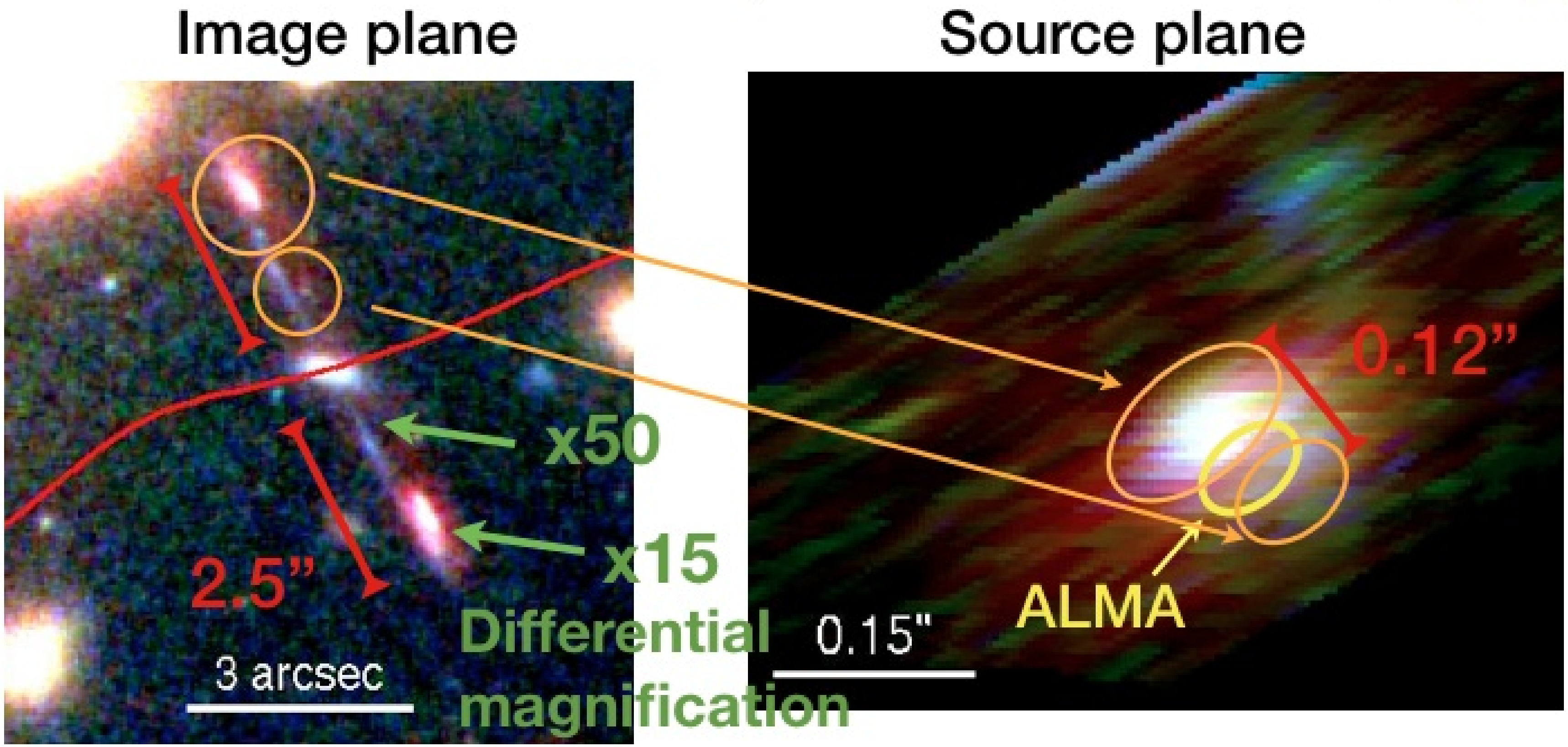

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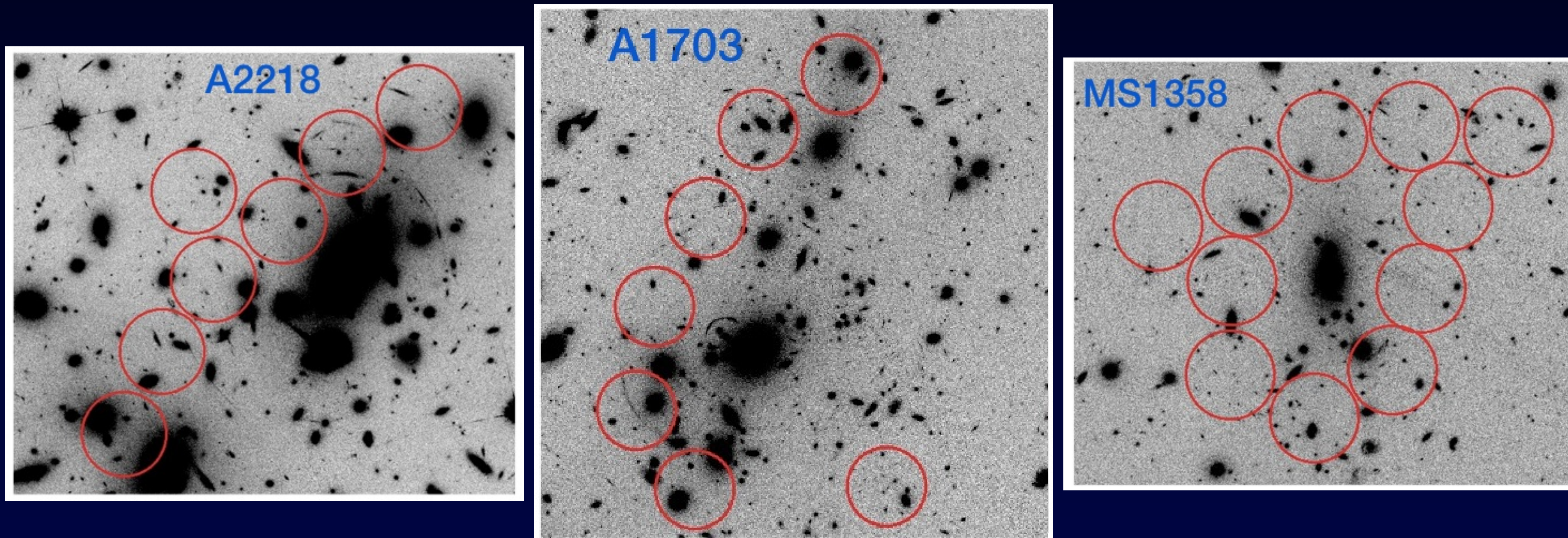
IRAM lensing survey



Similar strategy with IRAM/WIDEX 1.3 mm on Northern clusters (PI: Kneib)

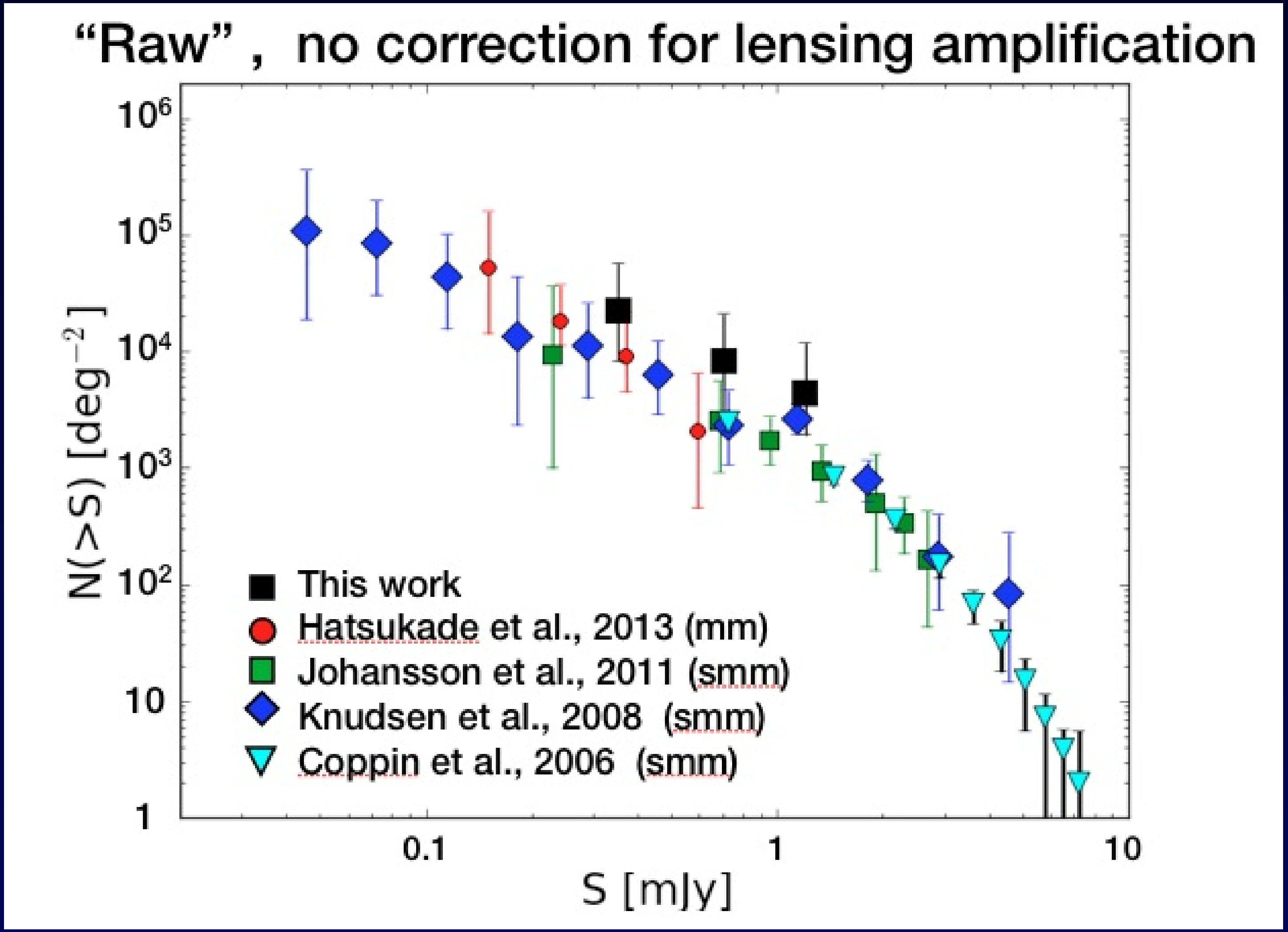
ALMA data: $\sim$5 hours rms $\sim$0.1 mJy/beam, LFIR $\sim 5 \times 10^{11}$ Lo (5σ)

IRAM data: $\sim$ 60 hours rms $\sim$ 0.2 mJy/beam, LFIR $\sim 1.1 \times 10^{12}$ Lo

Non-detection of Livermore et al. (2012) z=4.9 arc in MS1358: LFIR $<1.3\times10^{11}$ Lo, means a low star-formation efficiency SFR< 120 L$\odot$/M$_\odot$

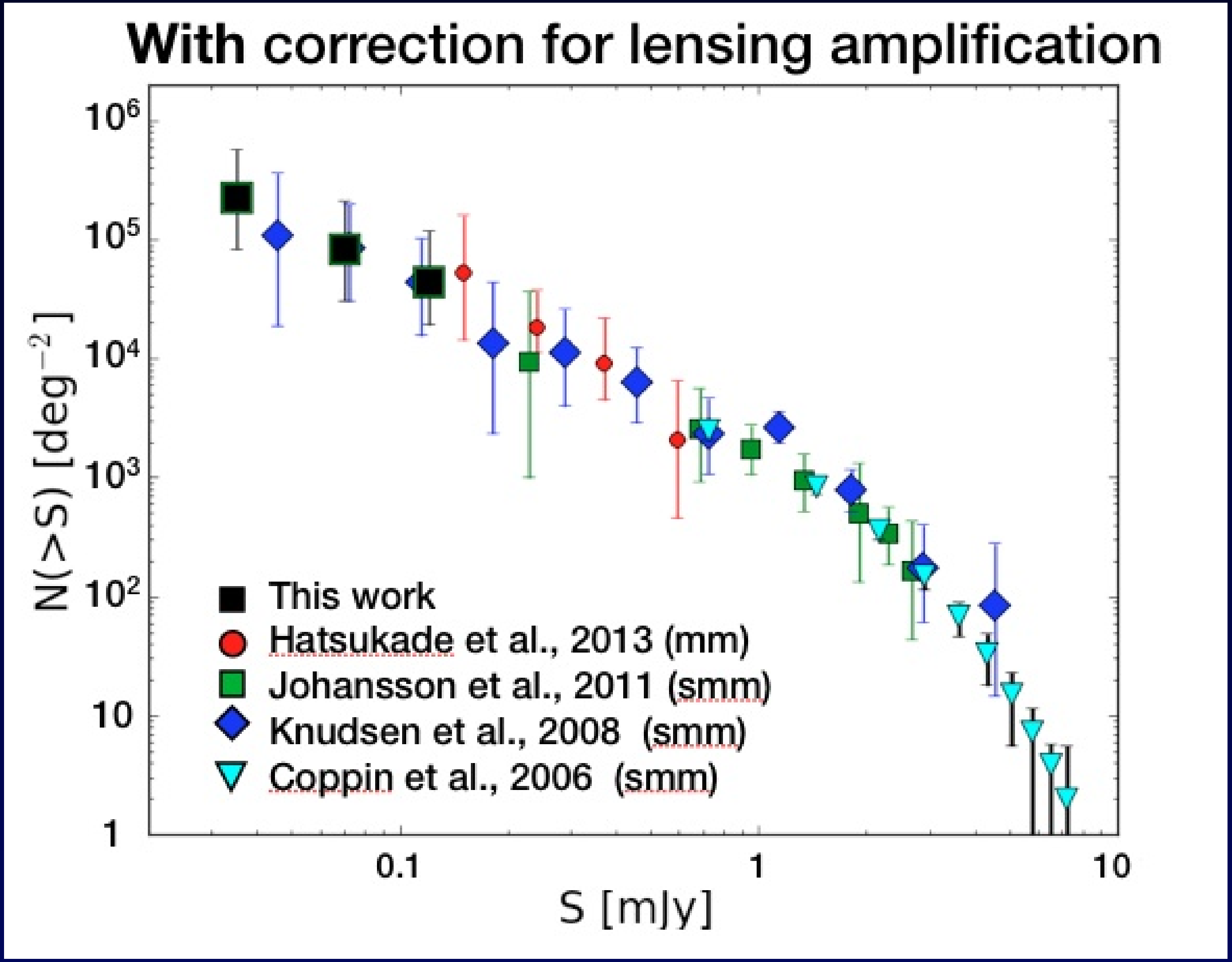
IRAM+ALMA number counts

Knudsen et al. in preparation



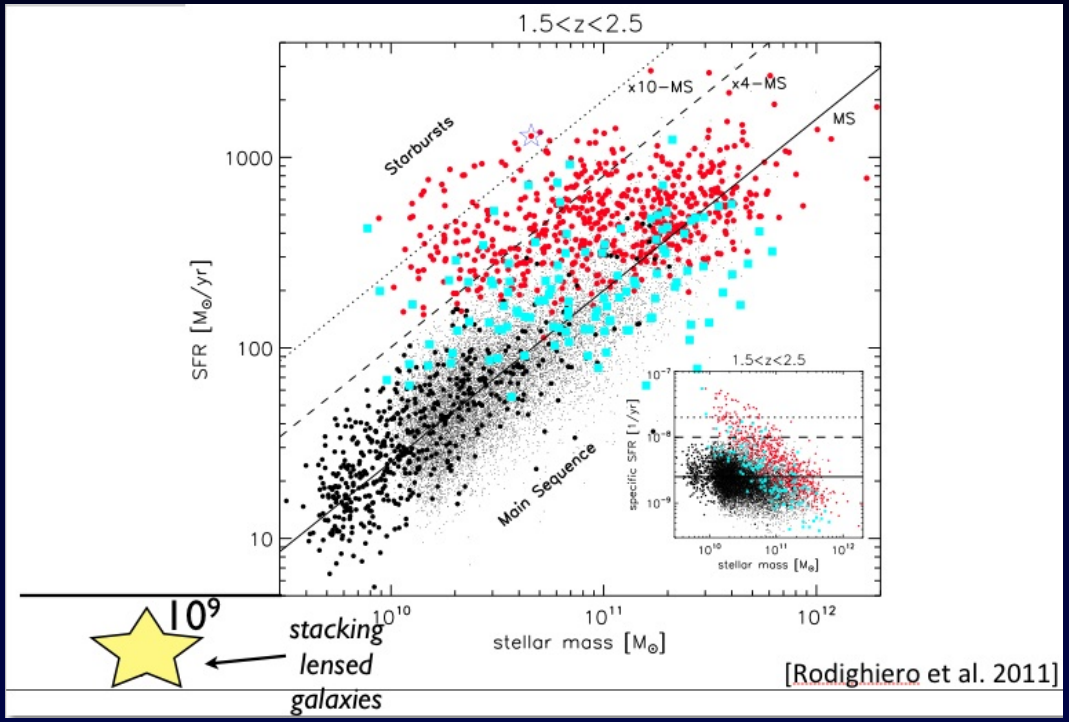
IRAM+ALMA number counts

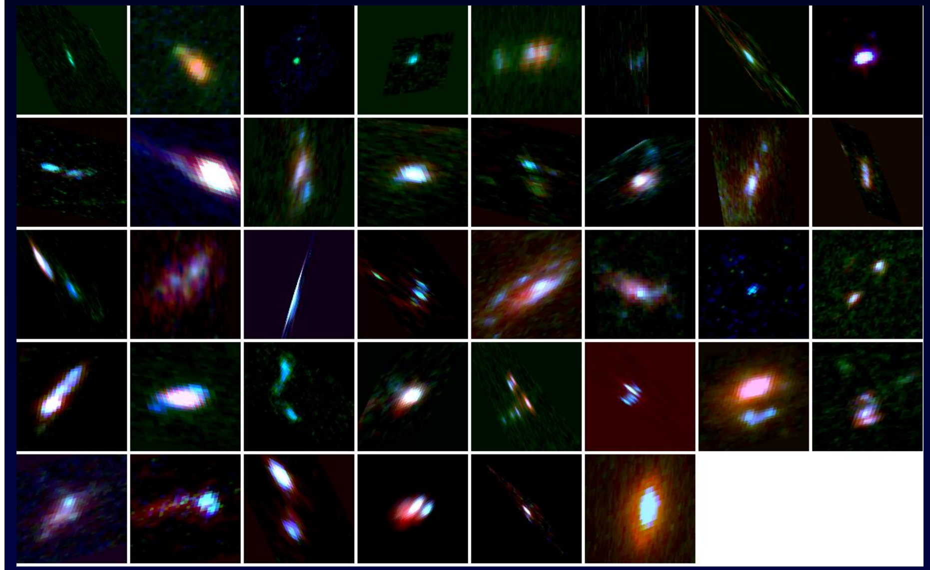
Knudsen et al. in preparation

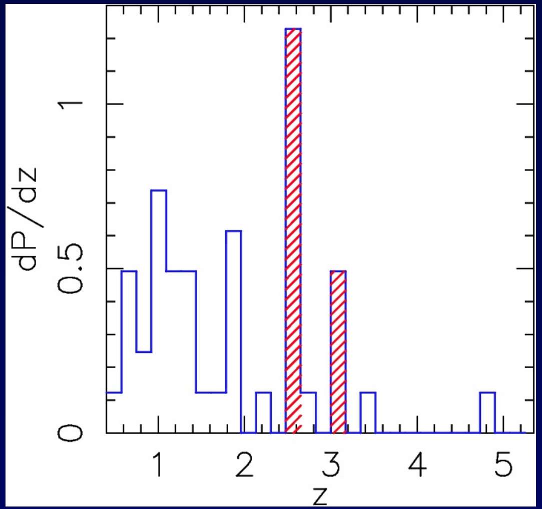


Now pushing much below the LIRG luminosity and SFR < 10 Mo/yr

Stacking of low-luminosity galaxies at high redshift







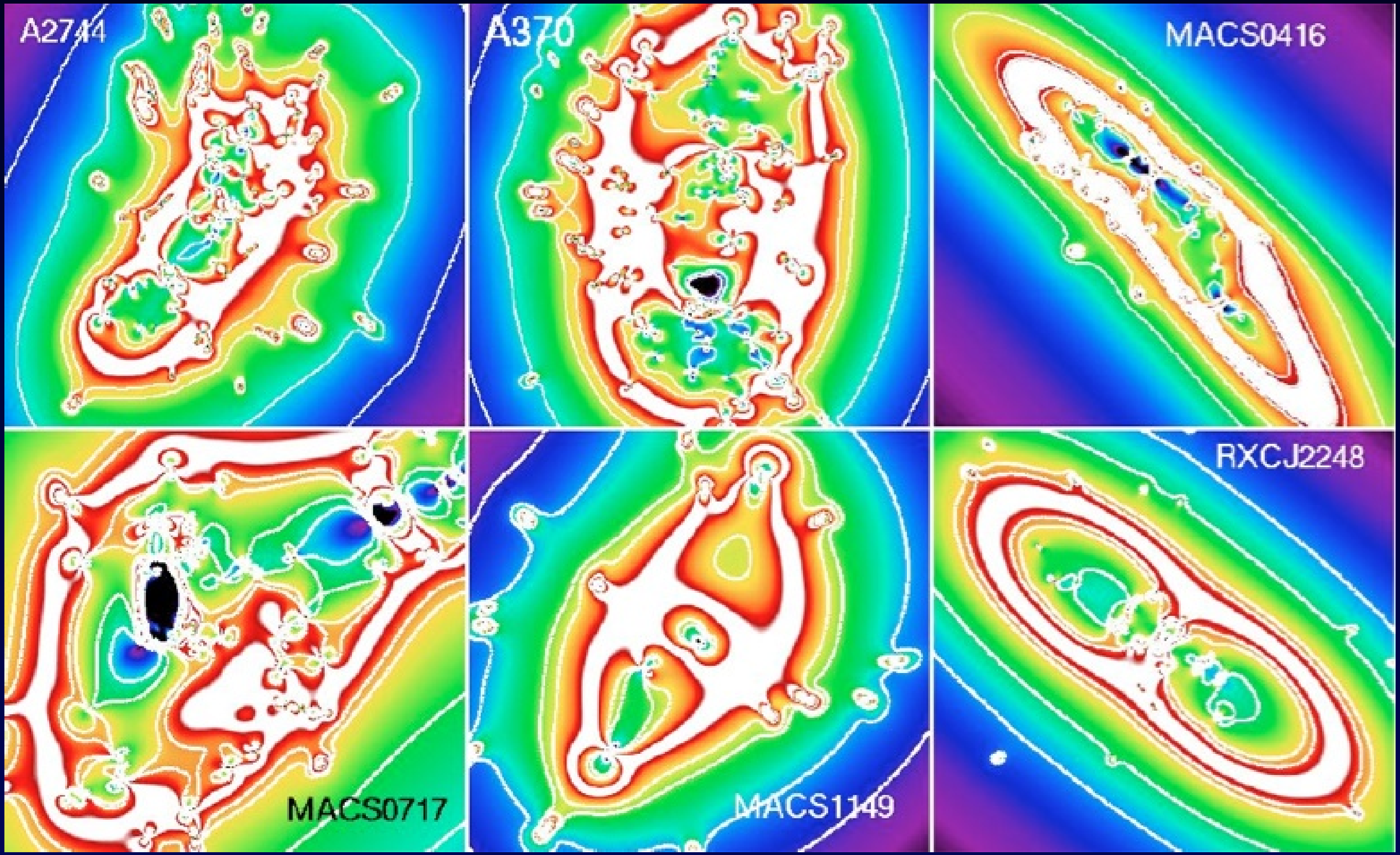
Interferometric (uv-)stacking of known star-forming galaxies at $z \sim 2.5$ and $z \sim 3$ (Lindroos et al., in preparation).

New exceptional dataset: Hubble Frontier Fields

www.stsci.edu/hst/campaigns/frontier-fields

- Deep HST imaging in 7 bands (optical-near infrared), 840 orbits in 4 (6) fields,$28.6 - 29.1$ AB
- Strongest lensing clusters based on available models
- Observable with Spitzer, JWST, ALMA, radio observatories
- Existing Herschel data, and linked with 1000 hrs of Spitzer/IRAC time

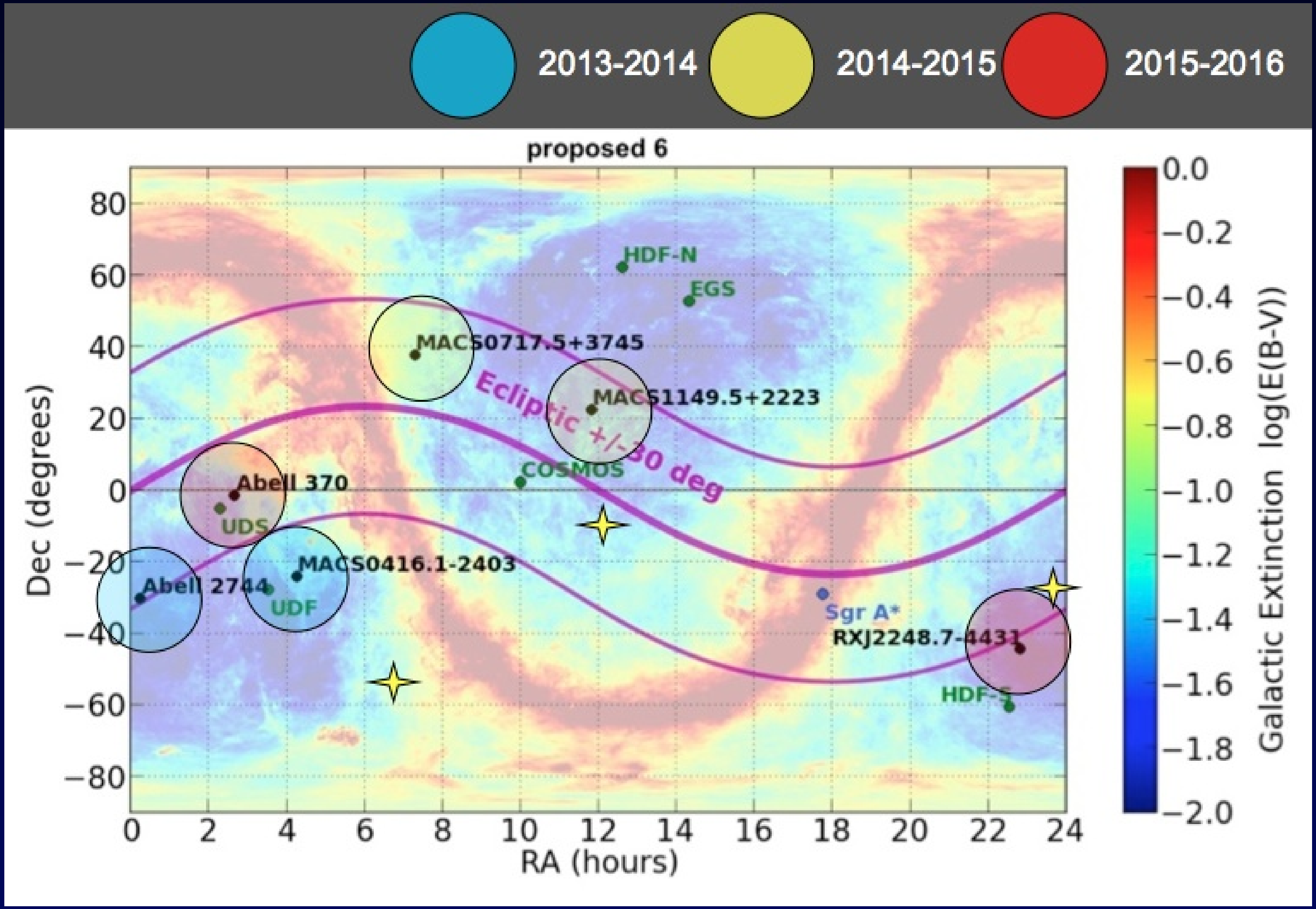
Hubble Frontier Fields: magnification maps



Results from 5 lensing teams (including CATS, Richard et al. to be submitted):

http://archive.stsci.edu/prepds/frontier/lensmodels/

Hubble Frontier Fields: sky coverage



Hubble Frontier Fields: follow-up with ALMA and PdB/NOEMA!

- Opportunity to do a deep follow-up at (sub)-mm wavelengths
- Reach 10^{10} LFIR in continuum for typical $1 < z < 3$ galaxies
- Follow-up bright $z \sim 7$ dropouts in [CII]

Conclusions

- The current sample of well-modelled strong lensing clusters offers a valuable set of gravitational telescopes to perform dedicated surveys
- Lensing clusters are very efficient to find IR-bright galaxies (> 100 mJy peak) at high redshift, easy to follow-up in continuum and CO lines.
- New, deep ALMA and IRAM surveys of the highest magnified regions around four galaxy cluster
- Detection of strongly lensed starbursts at $z > 2$, LFIR $\sim 1 - 10 \times 10^{11}$ $L_\odot$, SFR $\sim 10 - 100$ $M_\odot$/yr. Deep 1.3mm number counts, going to regime of normal galaxies.
- Because of the lensing amplification, good constraint on size, finding 200-300 pc sized SF region
- New Frontier Fields are ideal for magnification and ancillary data.

Thanks!