Cluster strong lensing as a probe of the high redshift Universe

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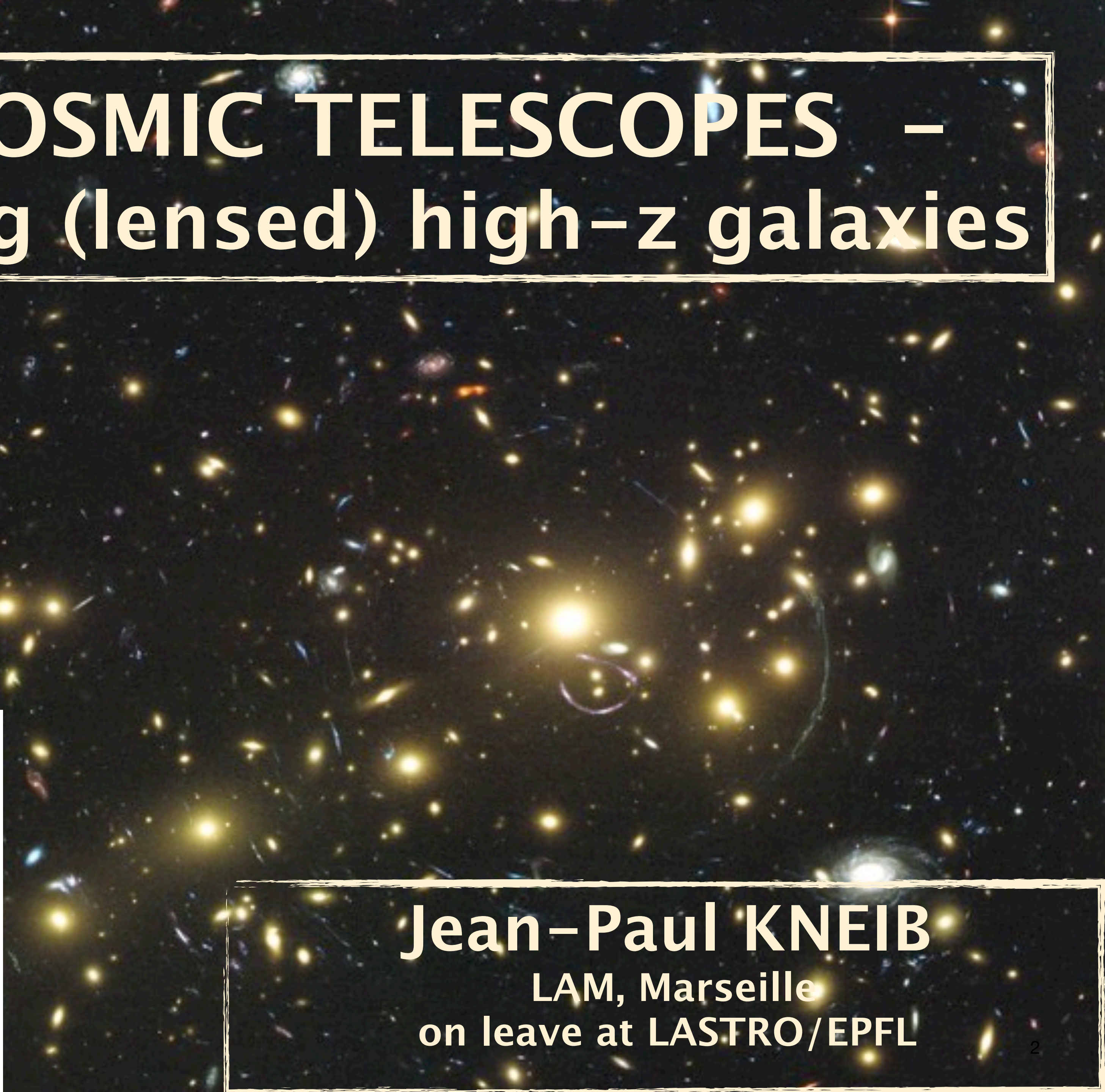
- COSMIC TELESCOPES -
Probing (lensed) high-z galaxies



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on leave at LASTRO/EPFL

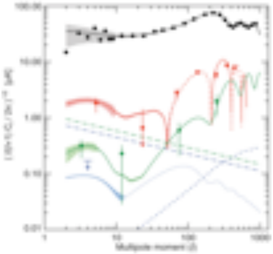
Outline

- Motivation: exploring the distant Universe (See Also First presentation by Roser Pello)
- The Benefit of Lensing in massive clusters
- Lensed Lyman-α Emitters & Dropouts
- Lensed FIR/Submm/mm sources
- Future Prospects

Key Questions for Galaxy formation and Evolution

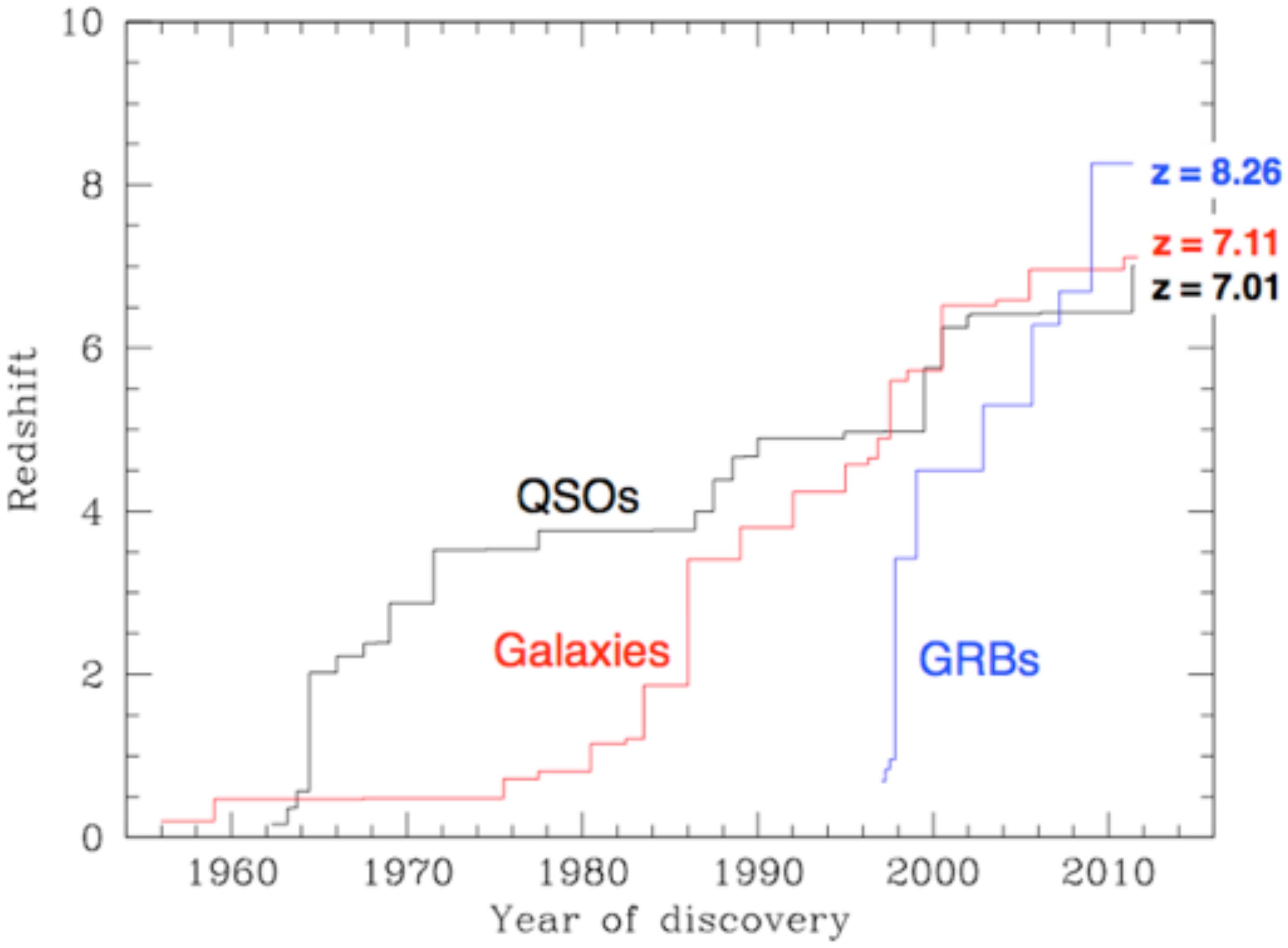
- What are the first sources?
  - Stars (Pop II vs. Pop III), BH/mini-QSOs
  - How did they form?
- What sources reionized the Universe (galaxies/QSOs)?
- How galaxies formed, assembled and evolved?
- When dust became important?
- What is the morphological/dynamical/star-formation evolution of galaxies?

Key Probes and Telescopes of the Distant Universe



- CMB (integral constraint) [WMAP, Planck]
- Redshifted 21 cm emission (absorption) [LOFAR, pre-SKA experiments]
- Lyman forest of high-z QSOs and GRBs [SDSS, PanSTARRs, Swift, ...]
- Luminosity function of (dusty) galaxies and quasars
    - Deep imaging/spectroscopy in optical/NIR (HST, 8-10m telescopes, ... JWST)
    - Deep mapping in FIR/Submm/mm probing the obscured galaxies, with follow-up spectroscopy (JCMT, APEX, SMA, Herschel, LMT, ALMA ...)

The most distant objects!



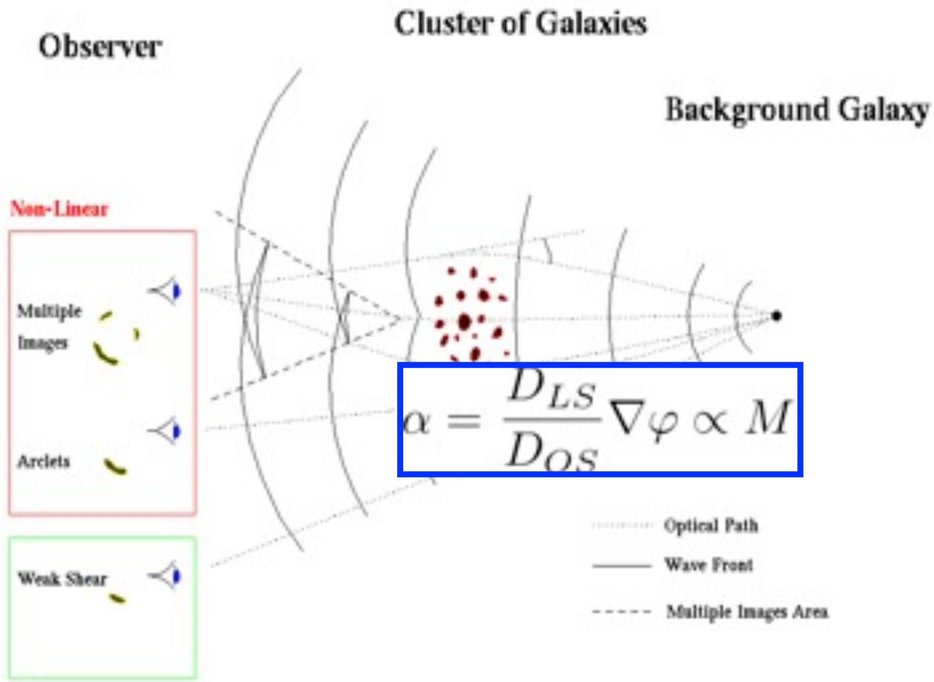
Steady redshift increase of the most distant objects!

Recent rate is: dz/dt=0.3 yr^{-1} for galaxies.

In 10 years we will hit z~12 !!! (JWST? sooner with ALMA? **or with lensing**)

Cluster Lenses as Telescopes

How Gravitational Lensing can help?

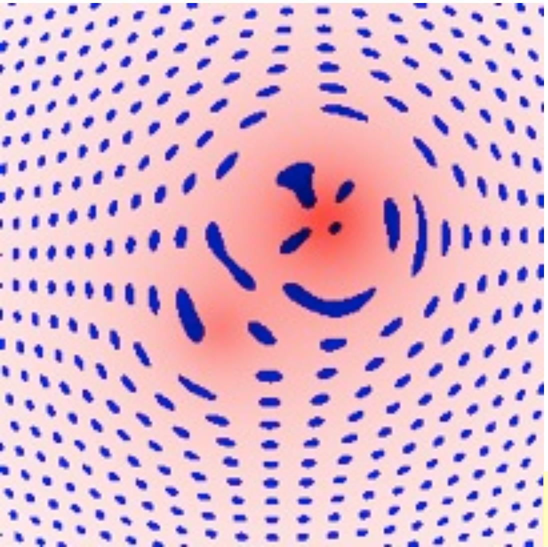


$$\alpha = \frac{D_{LS}}{D_{OS}} \nabla\varphi \propto M$$

- **Basics of lensing:**
  - Important mass density locally deform the Space-Time,
    - *A pure geometrical effect, no dependence with photon energy*
    - *Multiple-images with large magnification >10*

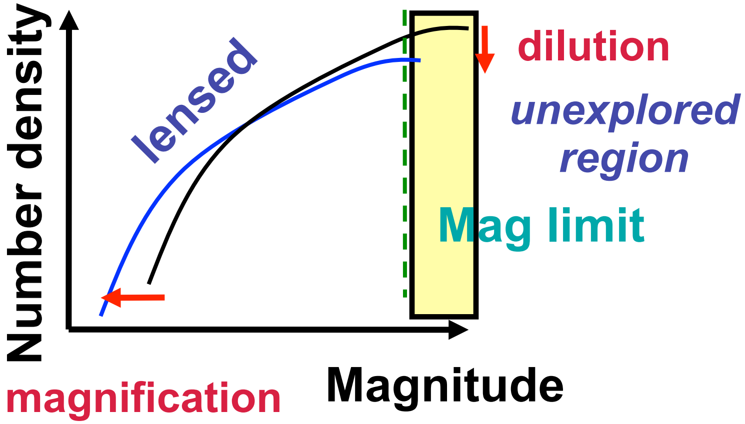
- **Lensing by a (massive) galaxy**
  - Deflection of ~1 arcsec
  - strongly lens only ~one background source
  - ~10 galaxy-lens per sq.degree

- **Lensing by a (massive) cluster**
  - Deflection of ~10-50 arcsec
    - *strongly lens many background sources*
  - ~1 cluster-lens per ~50 sq. degree

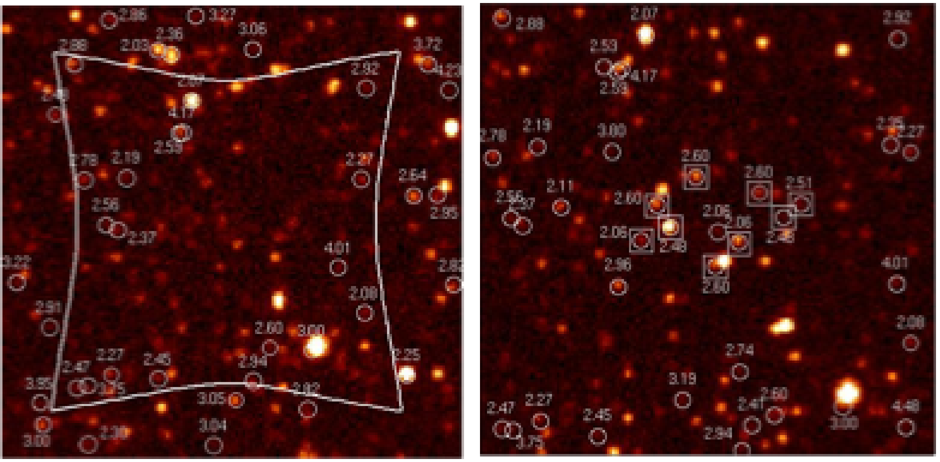


Ned Wright

Clusters as a Cosmic Telescope



7x7 arcmin^2 Herschel simulation



Unlensed field **Lensed field**

- Source plane, Image plane transformation

  $N_L(f)=N_0(f/A)/A$

  - Magnification of sources
  - Dilution of area

- Benefits of cluster-lens obs:
  1. **Magnification**, makes spectroscopic follow-up/ size measurement possible for most amplified sources
  2. Observe below the usual detection limit (faint luminosity)
  3. Multiple images confirmation of strongly lensed sources
  4. Avoid confusion (important in FIR/Submm)

Gravitational telescopes:

- **Advantages**:

  - boosts the total flux by increasing the observed size of background sources (constant surface brightness)

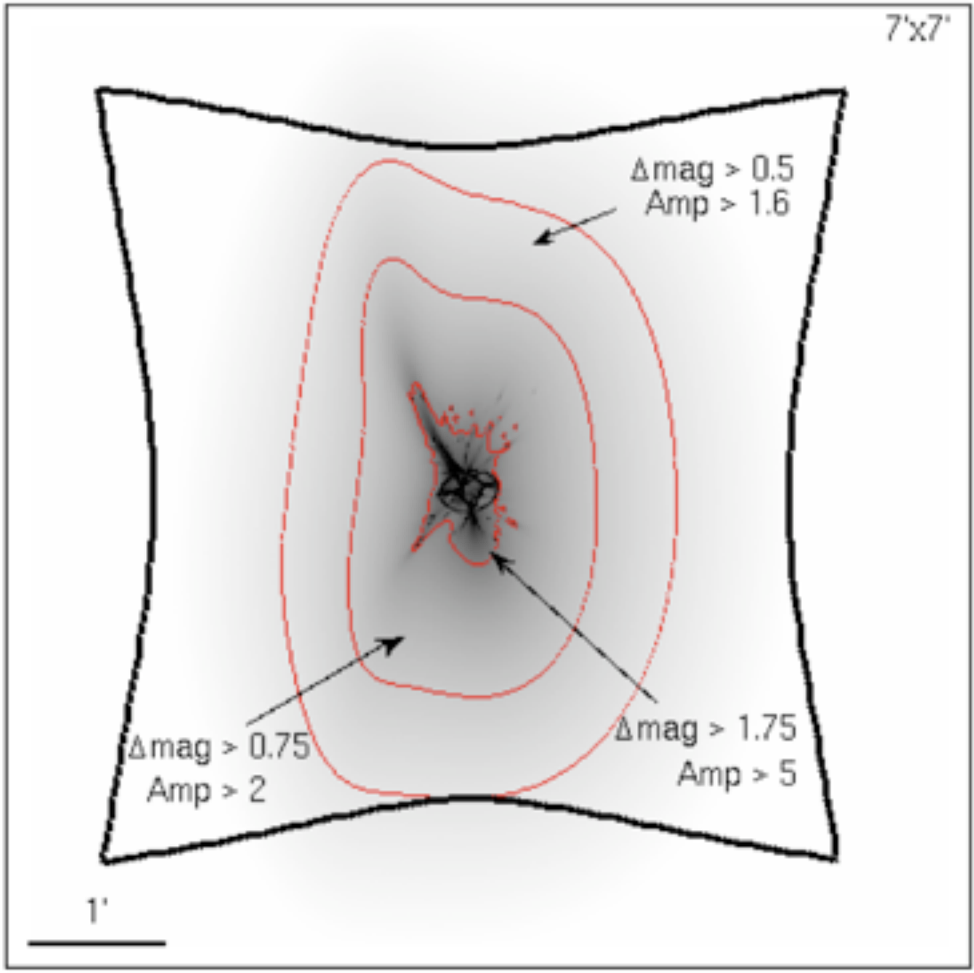
  - *efficient for unresolved sources*

  - multiple images configuration gives a hint on z

- **Drawbacks**:

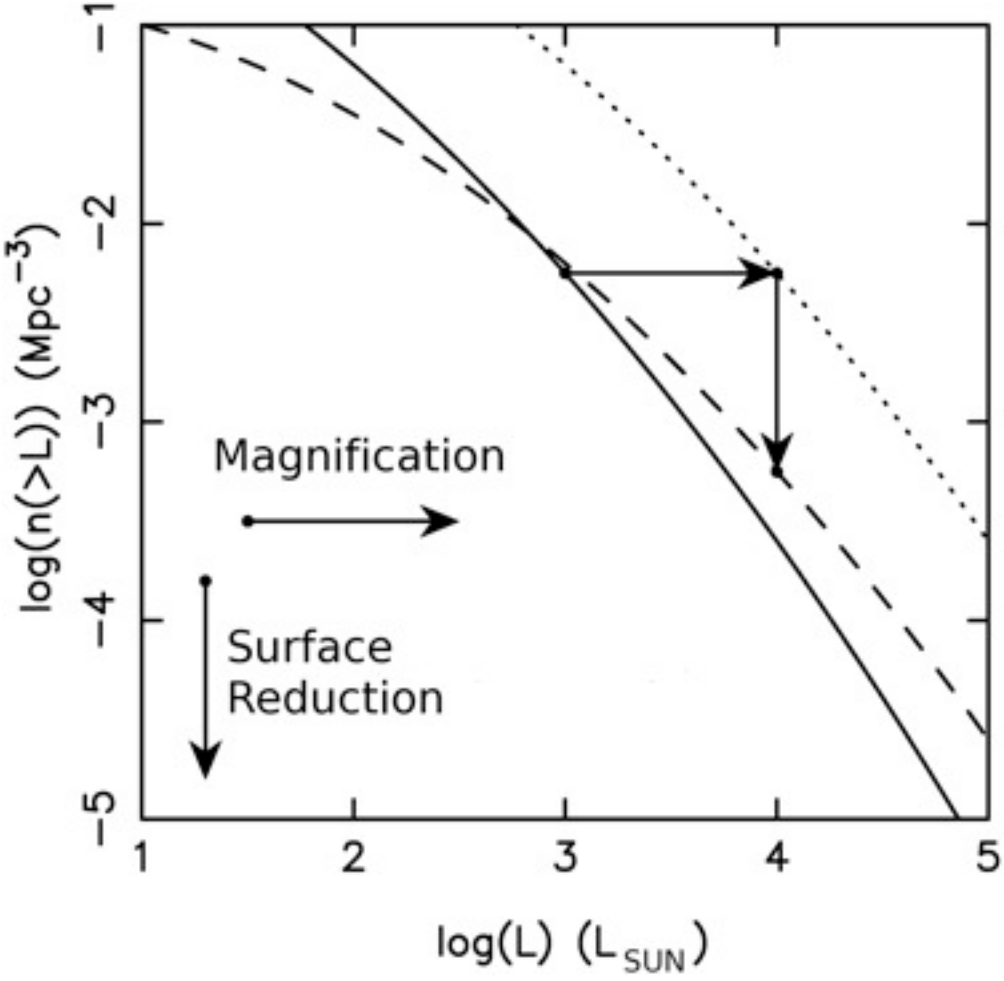
  - Effective area smaller in the source plane (compensate by observing more clusters)

  - Need to estimate the magnification to correct it (good lens model: HST data)

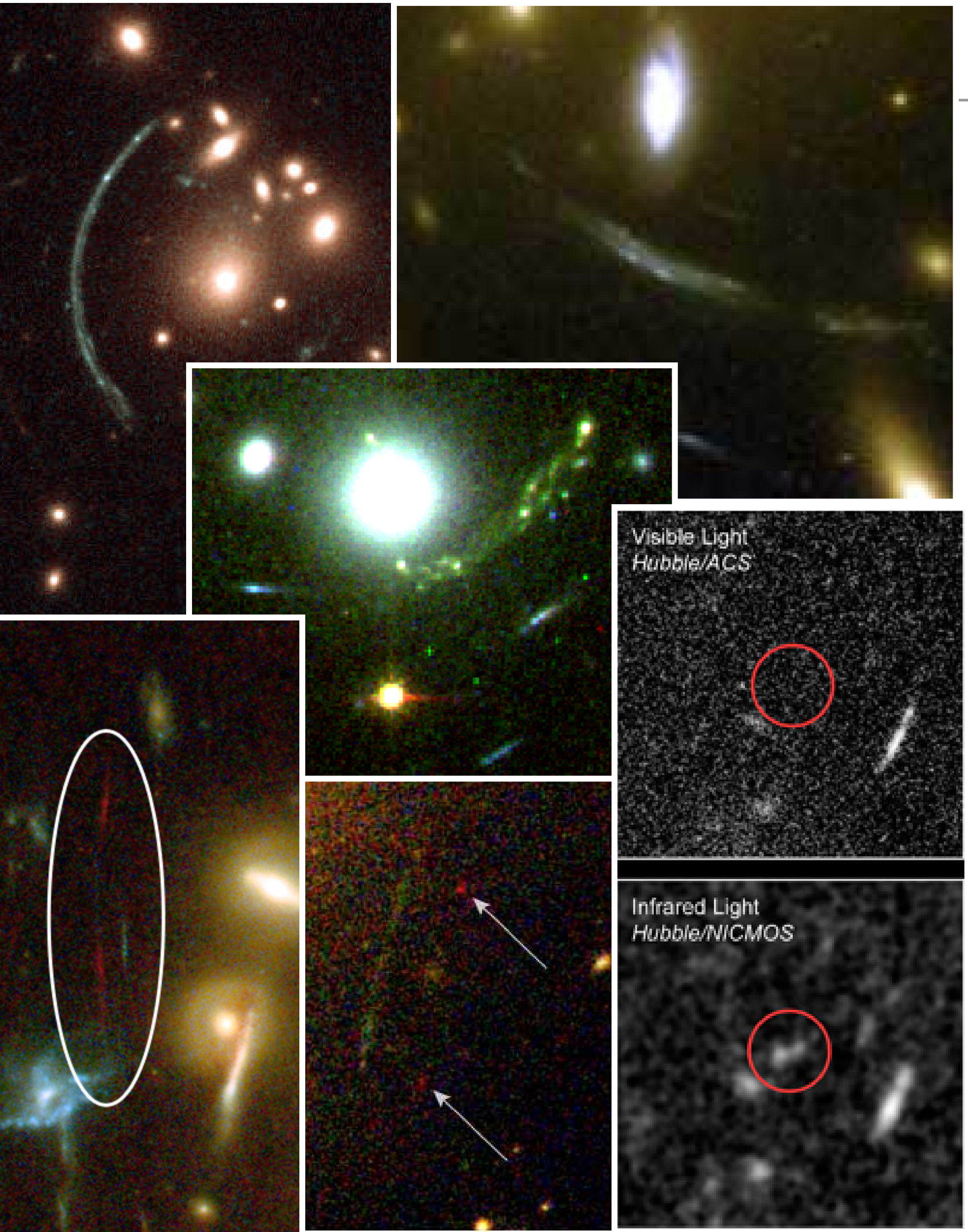


Magnification bias

- The observed LF is offseted, with more or less objects than a blank field depending on the luminosity range (**Broadhurst 95**)
- Current LF fits at z > 6 suggest a positive magnification bias for unresolved sources down to ~ 27_{AB} (**Maizy et al. 10**)
- Lensing cluster fields are complementary to blank fields to probe the LF



History of searching hi-z lensed galaxies



- 1987: Cl2244 one of the first gravitational arc, latter recognized as a z=2.2 galaxy
- Ebbels et al 1996: a z=2.5 LBG in a2218
- cB58 z=2.7 recognized as a strongly lensed source (Seitz et al 1998)
- Franx (1998): z=4.91 [ms1358]
- Ellis(2001): z=5.578 [a2218]
- Hu(2002): z=6.56 [a370]
- Kneib(2004): z~6.8 [a2218]
- Pello(2004): z=10.0? [a1835]
- Stark(2007): z~9.5? [survey]
- Bradley(2008): z~7.6 [a1689]
- Richard (2009): z=5.827 [a1703]
- Richard(2011): z=6.027 [a383]
- Bradley(2012): z~7 [a1703]
- Zheng(2012): z~9.6? [macs1149]
- Bradac(2012): z=6.74 [bullet]
- **z~11?**

Recipes to counts lensed galaxies

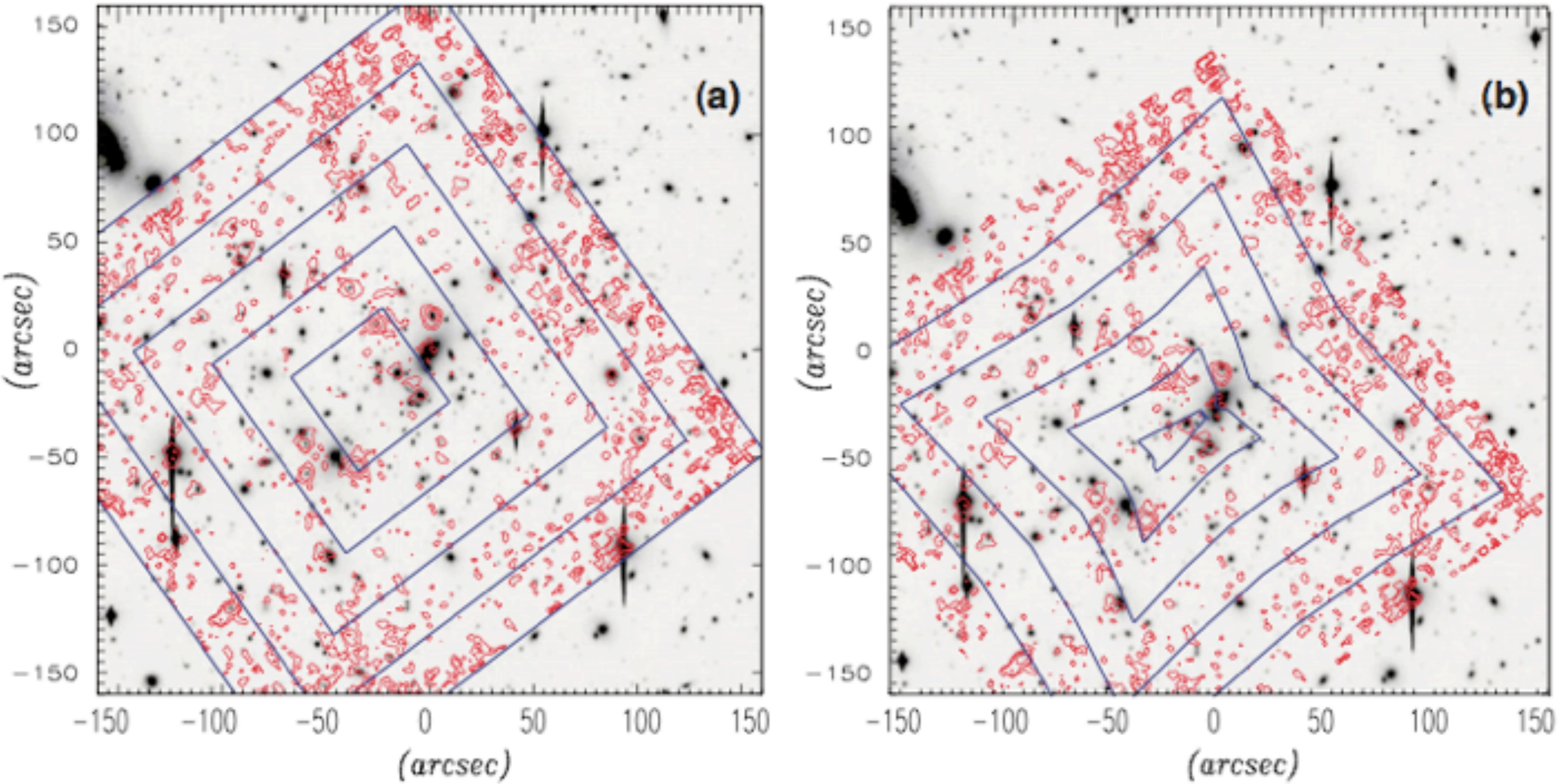
How to ‘inverse’ lensed counts

- Need accurate lens mass model
- For each lensed source, compute its magnification (require approximate knowledge of redshift - photo-z)
- Compute the detection flux limit as a function of area in the source plane
- Compute the number density of sources as a function of flux.
- Alternative: model galaxy population, lensed it, compare to observation

Example: Abell 2390

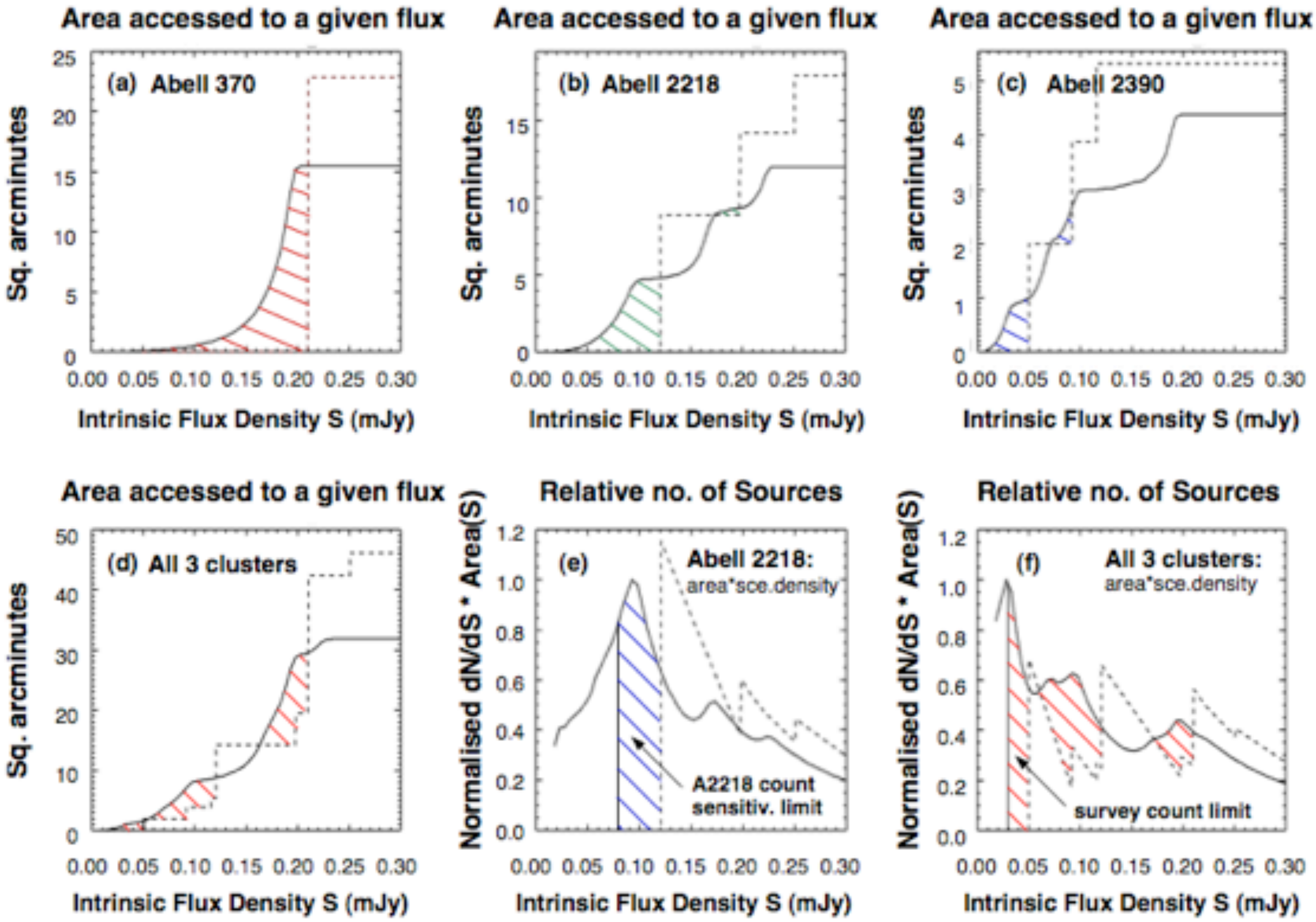
Metcalfe et al 2003

- How the image plane is shrinked into the source plane



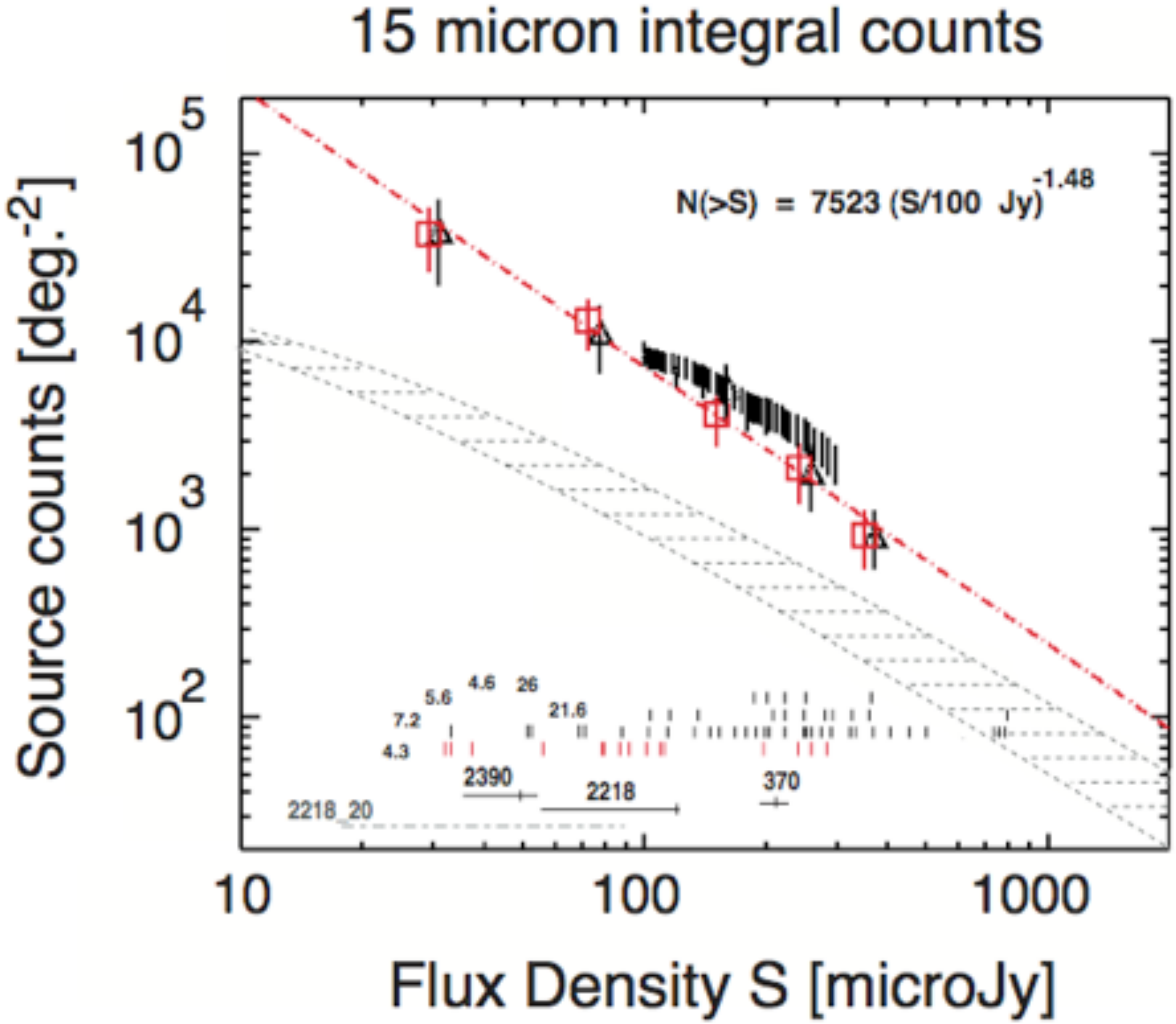
Flux limit as a function of Area

Metcalfe et al 2003



Corrected lensed counts

Metcalfe et al 2003

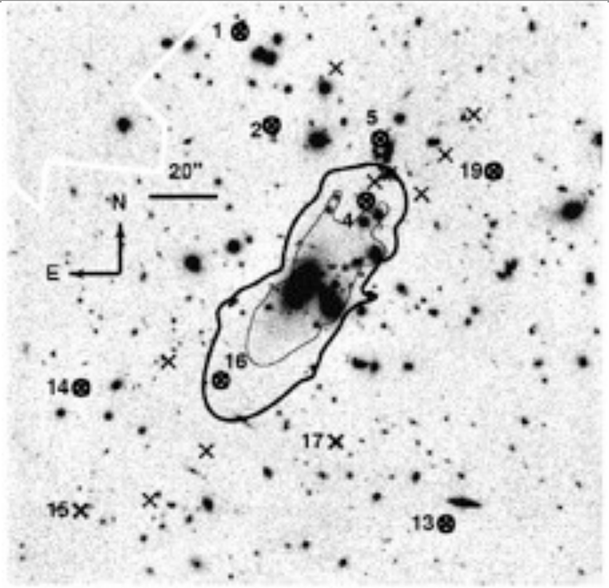


Lensed Lyman-break galaxies

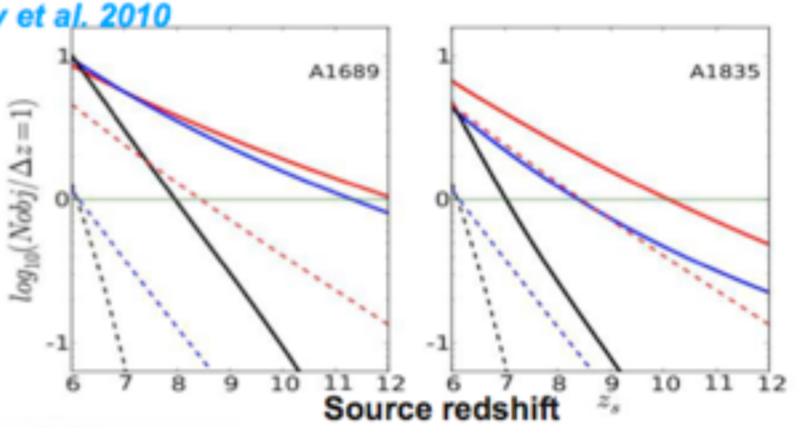
Hubble Legacy

Lensed dropouts: ground-based

- Very deep near-infrared imaging towards massive clusters. ISAAC, HAWK-I, MOIRCS
- Pilot program with ISAAC: 2 clusters H ~ 25.5 (**Richard et al. 06**) with spectroscopic follow-up, no strong candidate. One tentative z~10 which was then dismissed afterward.
- Dropouts are bright enough for spectroscopy, study contamination by low-z interlopers

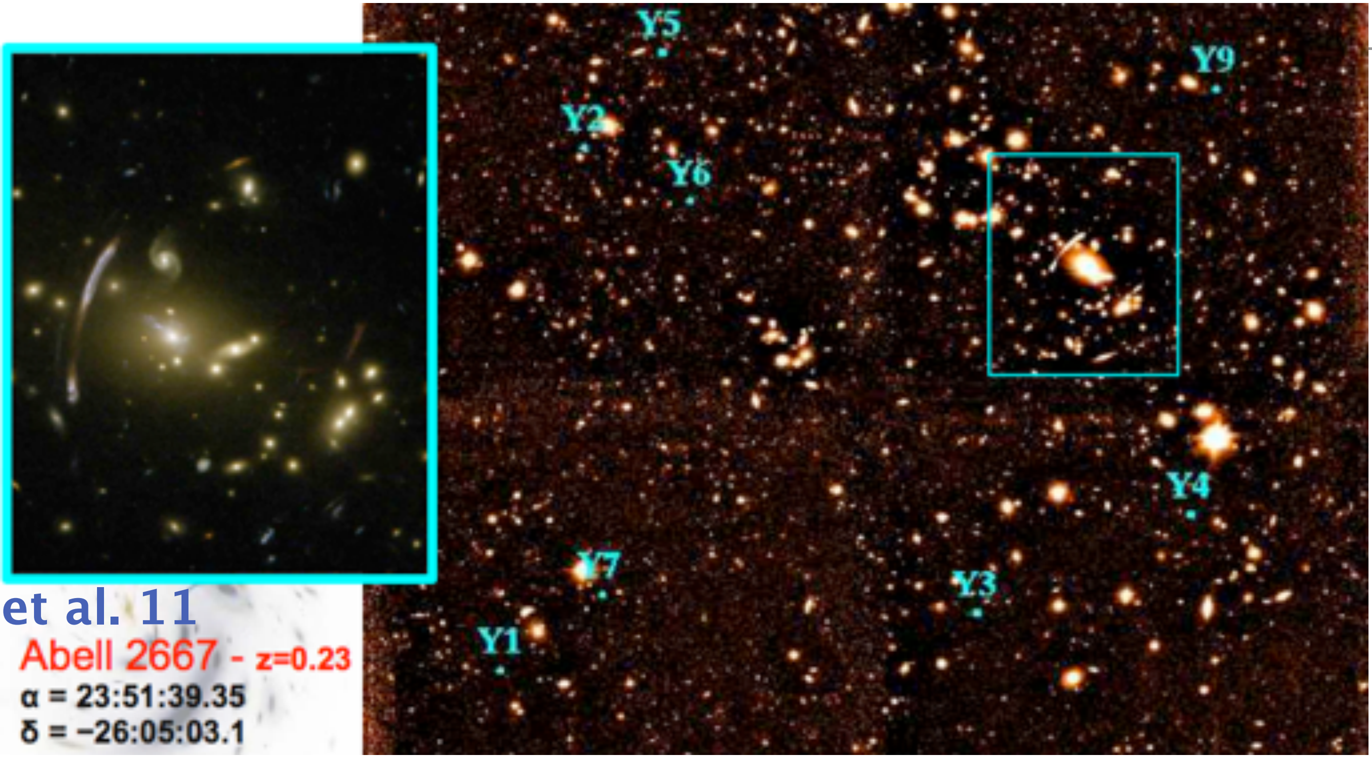


Maizy et al. 2010



Blank field (dashed), cluster (solid)

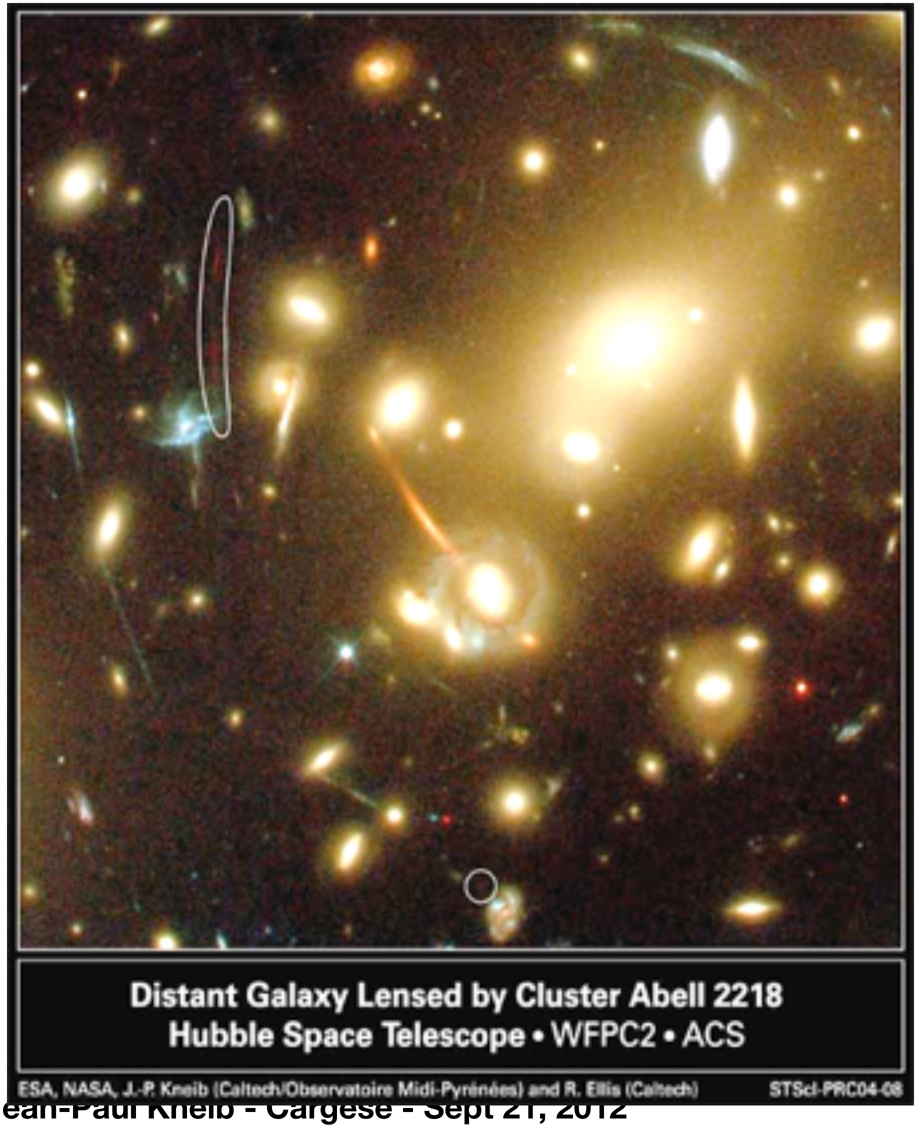
Lensed dropouts: ground-based



Laporte et al. 11

- Hawk-I survey YJHK, 1 cluster. Only limited magnification effect.
- Identify 10 “bright” dropouts. SED-fitting yields a best solution at z~7.5 to 9 in all cases, with a less significant solution at z~1.7-2.8. Several of these sources seem too bright, suggesting strong contamination by mid-z interlopers which must be also present in other current LBGs surveys.

Power of Hubble



Distant Galaxy Lensed by Cluster Abell 2218
Hubble Space Telescope • WFPC2 • ACS

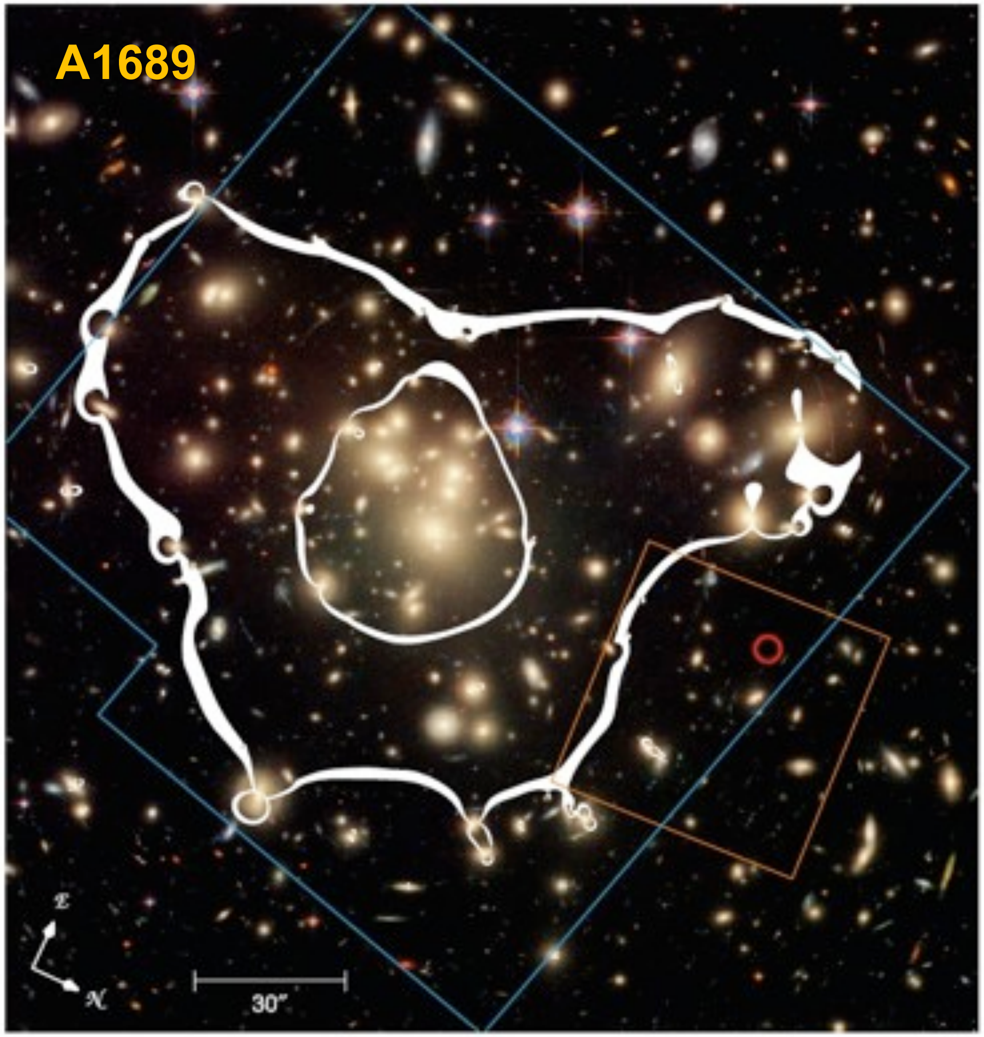
ESA, NASA, J.-P. Kneib (Caltech/Observatoire Midi-Pyrénées) and R. Ellis (Caltech) STScI-PRC04-08

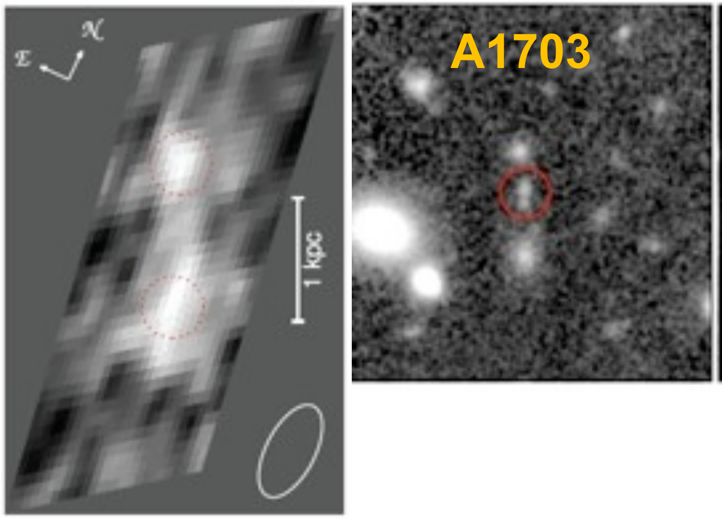
- First detection of a z ~ 6.8 dropout galaxies in Abell 2218
- Redshift confirmed by multiple image detection
- Source identified in Spitzer data, showing an already old population of stars, arguing for a possible formation redshift of z~10

Kneib et al 04

Egami et al 05

NICMOS lensed dropouts

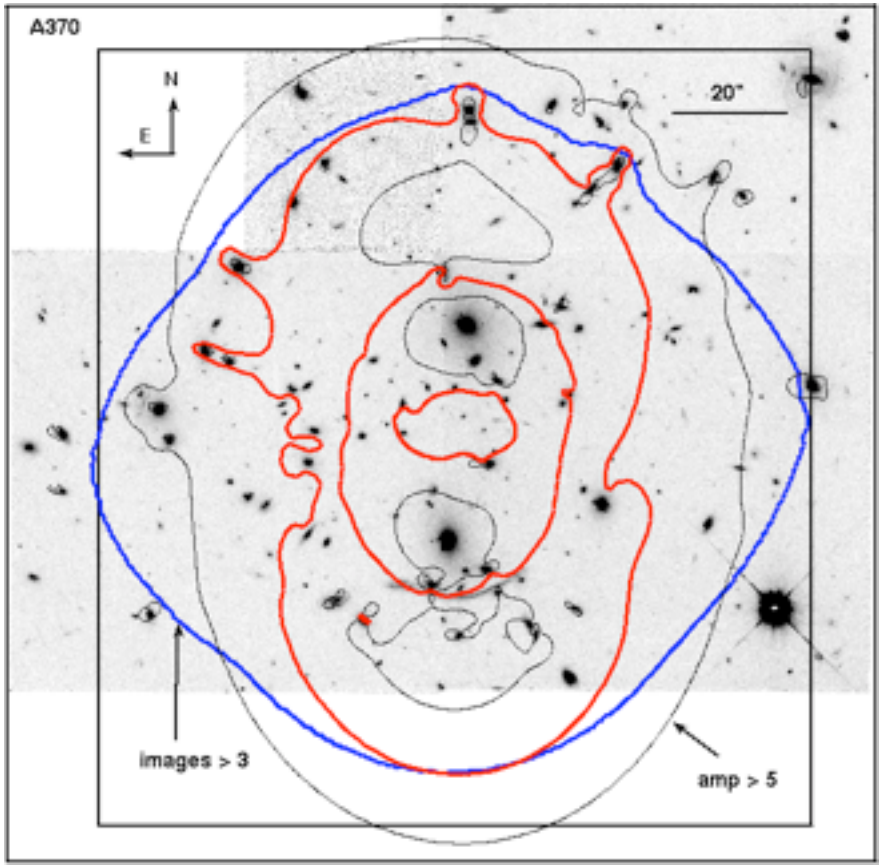




- **Bradley et al 08** z ~ 7.6
- **Richard et al 09,**

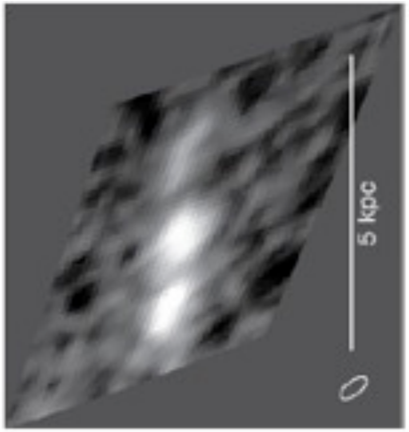
  Zheng et al 09 z = 5.9 – 7.0
- single images, μ ~ 5-10
- complex source morphology

WFC3+lensing



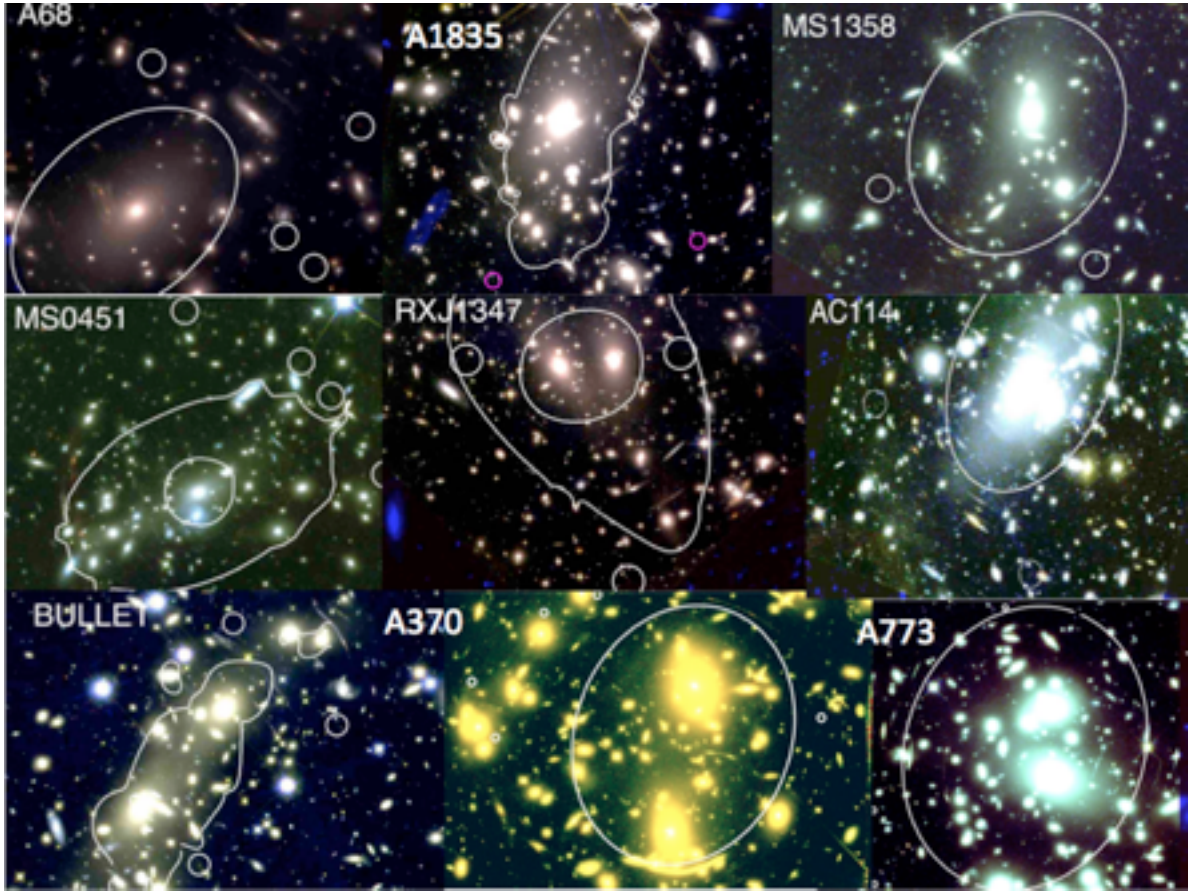
Red : critical line at z=7
Blue: multiple image region
Black: amplification larger than 5

- **Hall et al. 11**: 10 z-dropouts behind bullet cluster
- **Bradley et al. 11**: 8 z ~ 7 candidates behind A1703, maybe multiple images
- **Likely spurious object present in these 2 selections**



WFC3 is matching the region of high amplification

WFC3 search in 10 massive clusters
Probing low luminosity dropouts



PI: Kneib

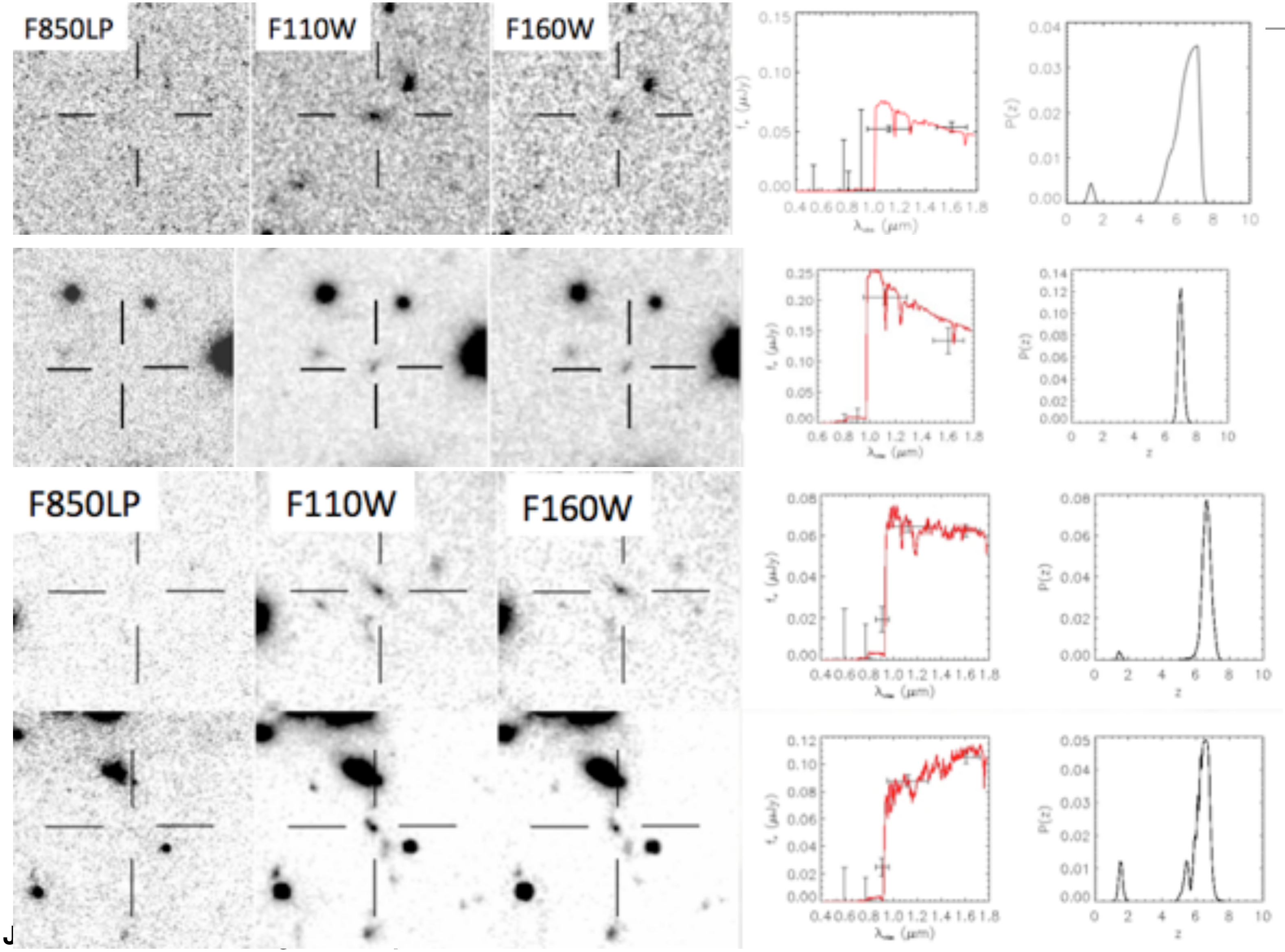
iz/J/H imaging of 10 massive clusters (43 orbits of HST)

Preliminary dropout candidates:

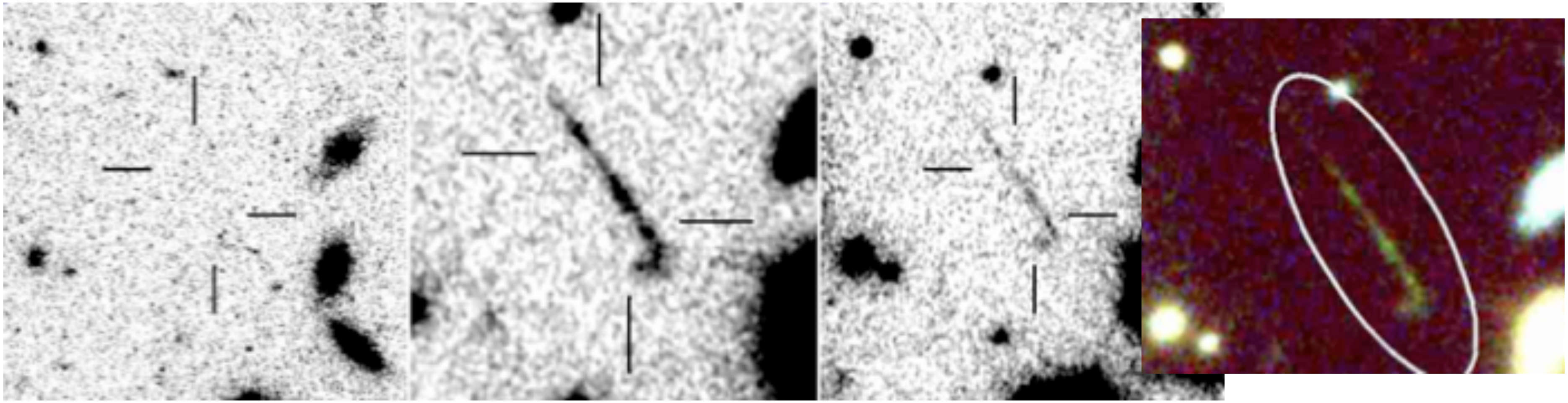
~50 i-dropout (z~6)
~20 z-dropout (z~7)
no J-dropout (z~8.5)

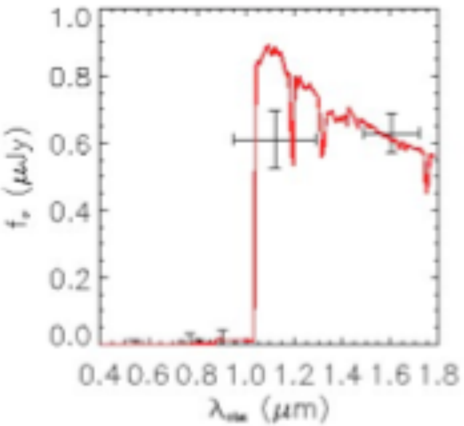
WFC3 search in 10 massive clusters
Hi-z candidates

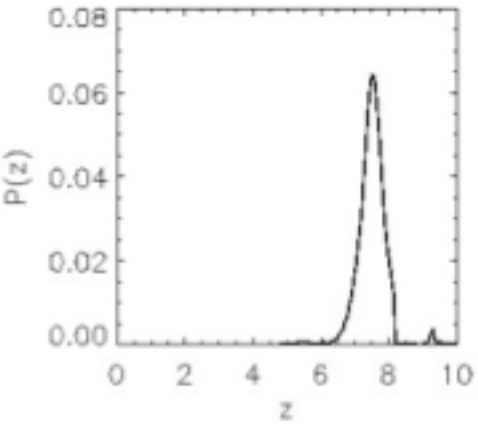
Paraficz et al 2012 in prep



WFC3 search in 10 massive clusters
Best candidate !







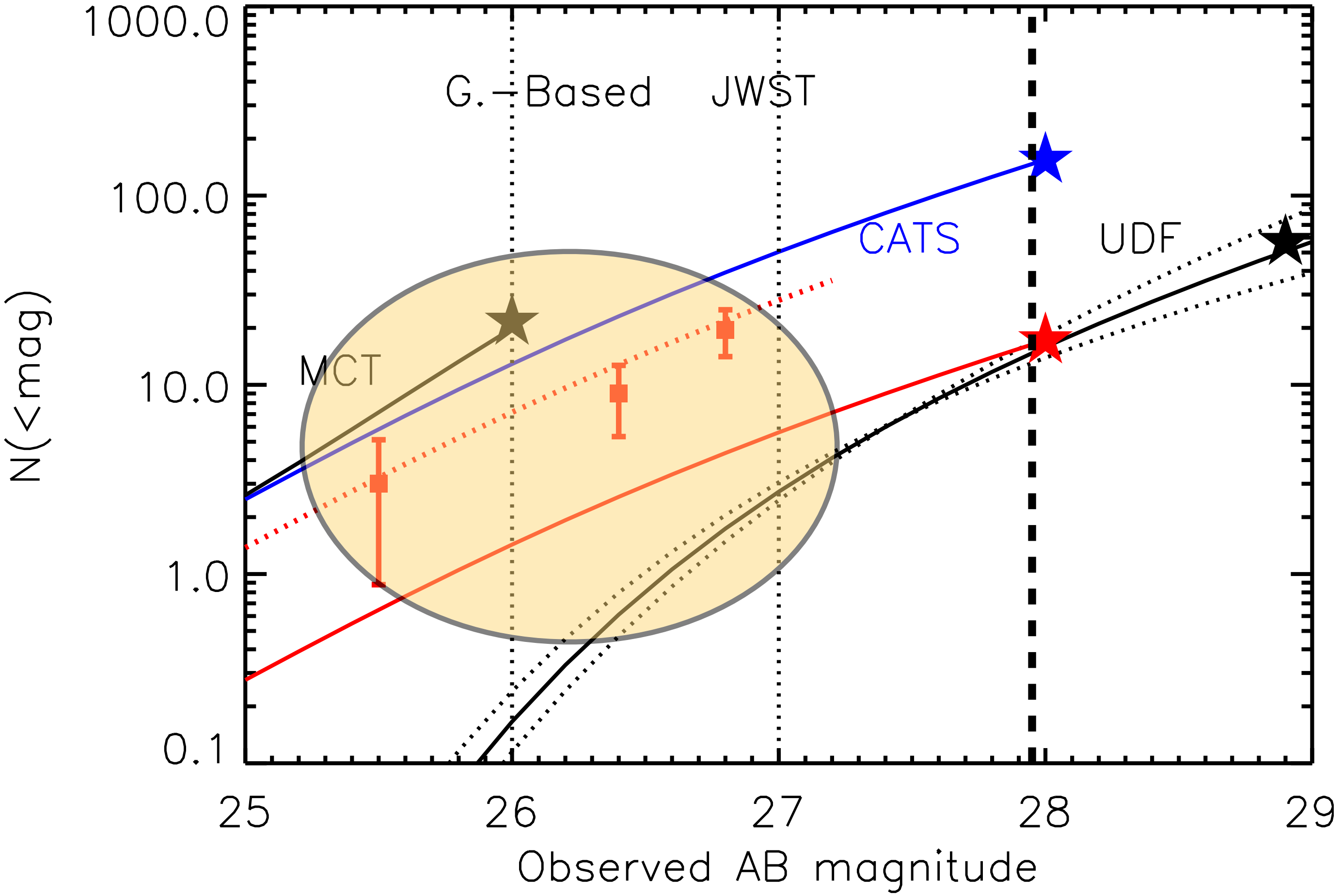
Observed=F110W=24.6 AB
Magnified by 2.1
Intrinsic=26.7 AB
X-shooter spectra
No lines !!!

Kneib et al 2012 in prep

WFC3 search in 10 massive clusters
Counting sources

Preliminary dropout counting is as expected assuming Bouwens LF.

Proper analysis in progress.



Paraficz et al 2012 in prep

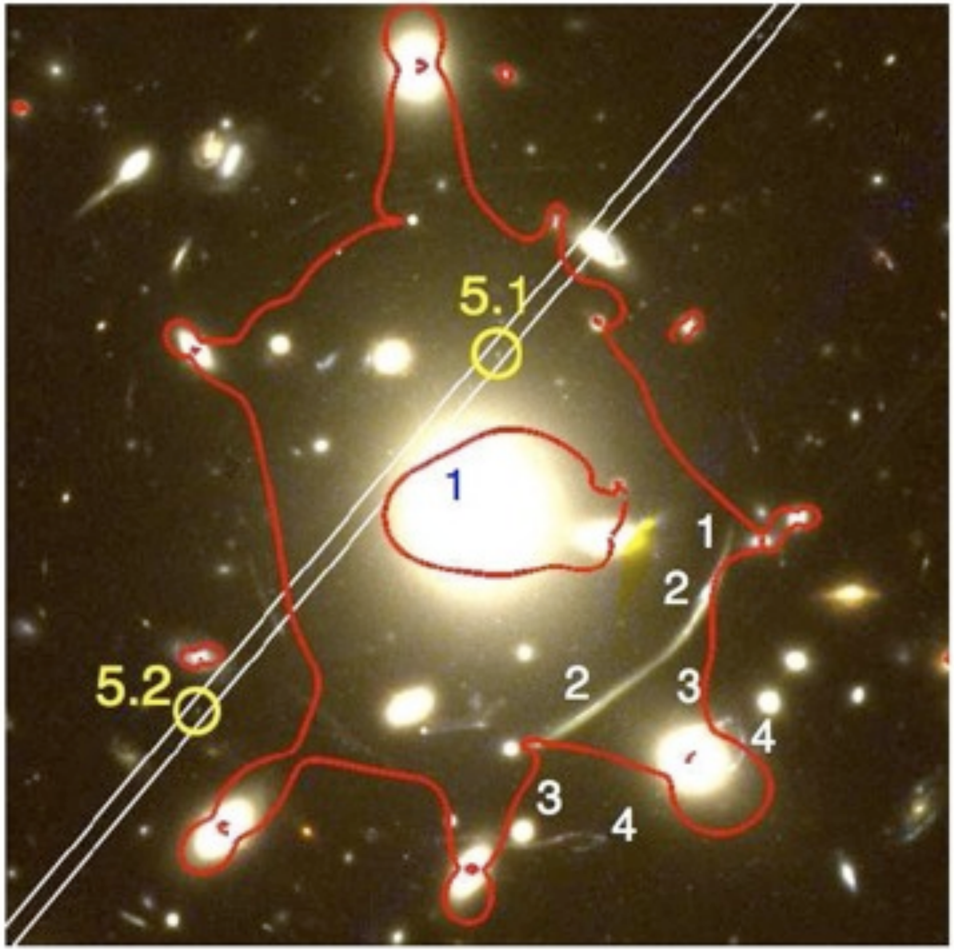
Hubble Multi-cycle treasury program

CLASH

- PI: M. Postman
- ~ 500 orbits with HST/ACS and HST/WFC3, 25 clusters
- 14 UV/optical/NIR filters for accurate photo-z
- First cluster observed: A383

1 confirmed z=6.027 source (**Richard et al. 11**),

accurate cluster mass model (**Zitrin et al. 11**)

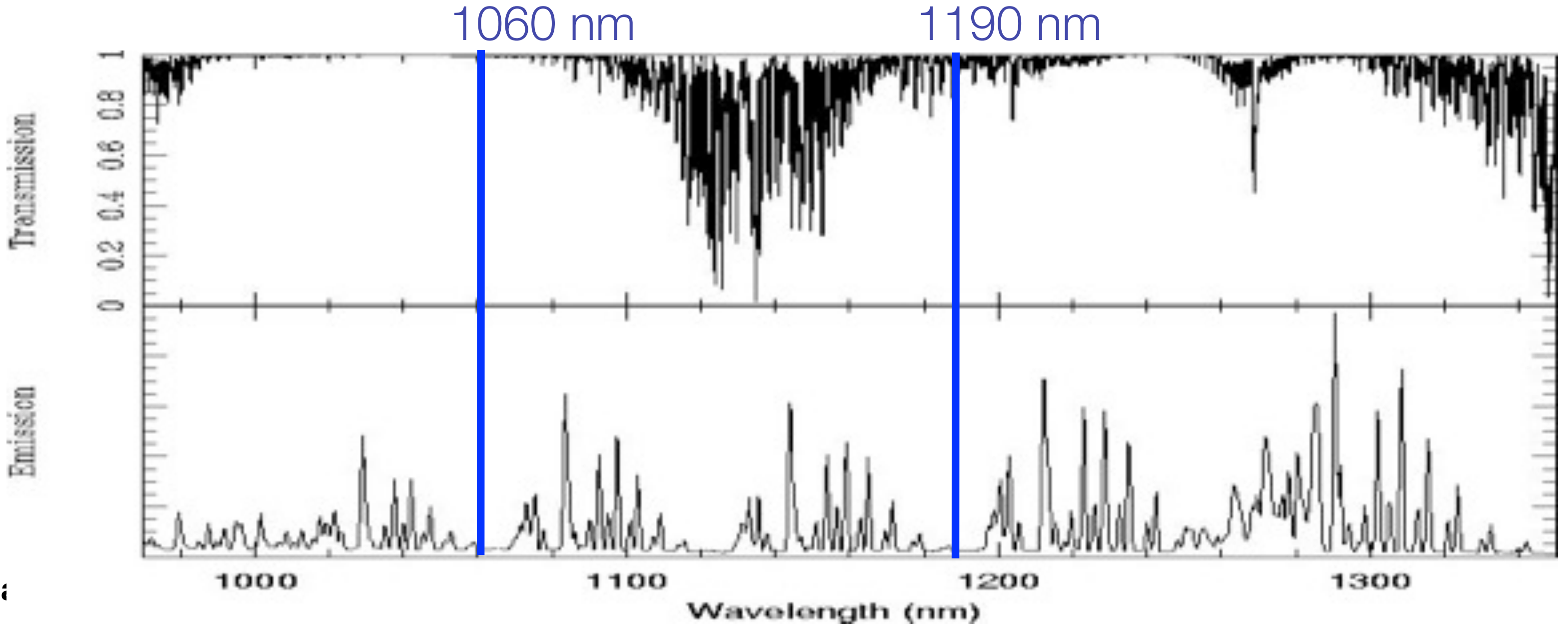


Expect ~0.5 or 1 z>6 dropout per cluster in the strong-lensing region

Narrow-Band Search Lyman-alpha Emitters

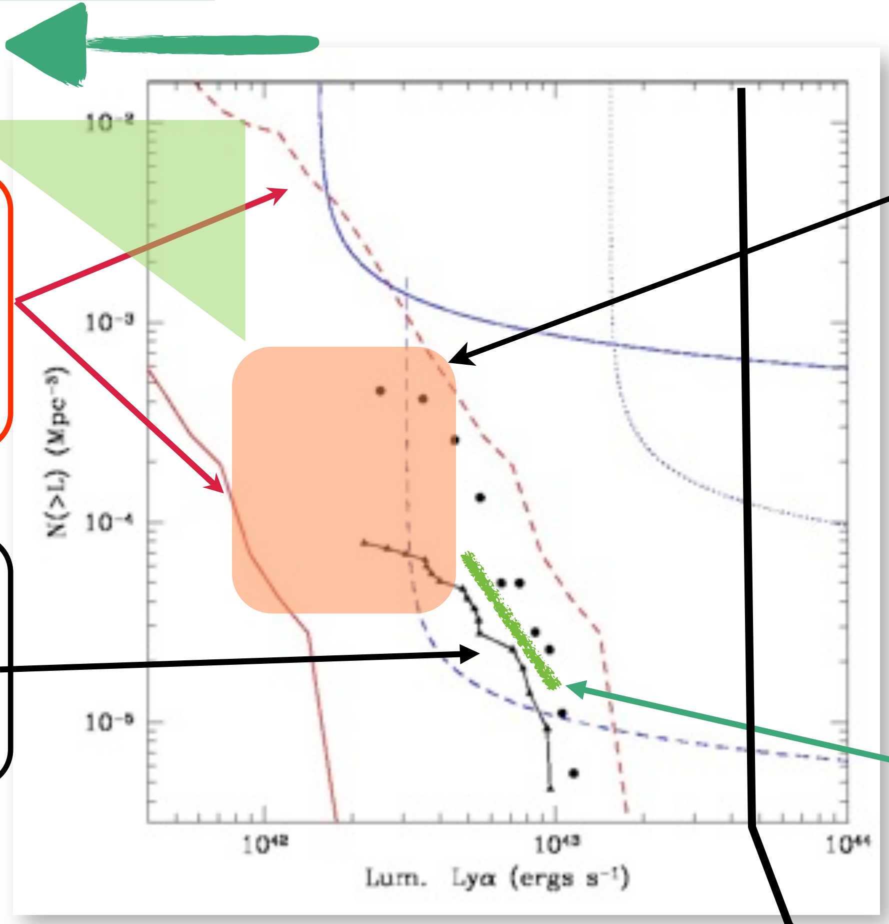
Narrow Band Survey: ZEN & others

- **ZEN1:** a single deep field within the HDF South (NB<25.5), NB119 is sensitive to z=8.8. Willis and Courbin (2005). And also Cuby et al 2007
- **ZEN2:** three fields containing massive lensing clusters (magnified background galaxies). Willis et al (2007).
- CFHT/WIRCam fields (0.1 deg2) located in CFHTLS D1 40h in NB:Low-OH1 (z=7.7): cf Hibon et al 2009
- **LP-ESO:** Hawk-I (z=7.7) Clement et al 2011
- UltraVista (z=8.8) on COSMOS field - just started in 2010



NB constraints (z>7, field+clusters)

Critical line mapping



Semi-analytic model of star forming galaxies at z=9 Le Delliou et al. (2006)

NB selected galaxies at z=6.6 Kashikawa et al. (2006)

Hawk-I

ZEN 1+2

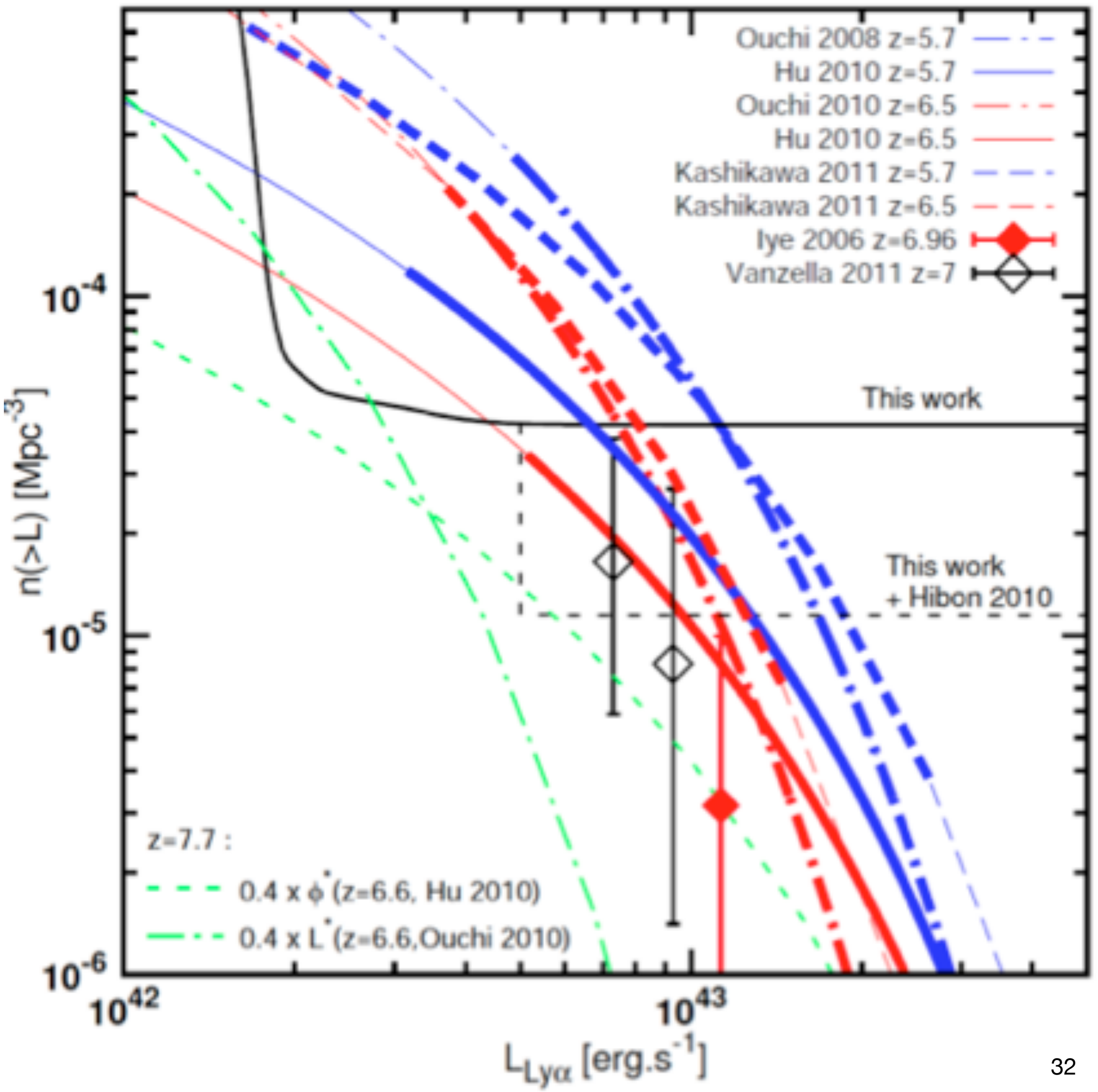
Cuby et al. (2007)

ZEN3: WIRCAM
Hibon et al 2009
7 candidates @ z~7.7

Sobral et al 2009, z~8.8

WIRCAM & HAWK-I NB Imaging LAE Sensitivities

- WIRCAM data (Hibon et al 2009) 0.1 sq.deg on D1 field (NO spectro confirmation!!!)
- Hawk-I LP (PI:Cuby)
  - *4 fields*: 2 clusters (A1689, Bullet Cluster), 2 blank fields (D4, Goods South)
- Probe down to a few 10^{42} erg/s in L(Ly-alpha)
- **Exclude no-evolution model - 60% natural HI fraction**



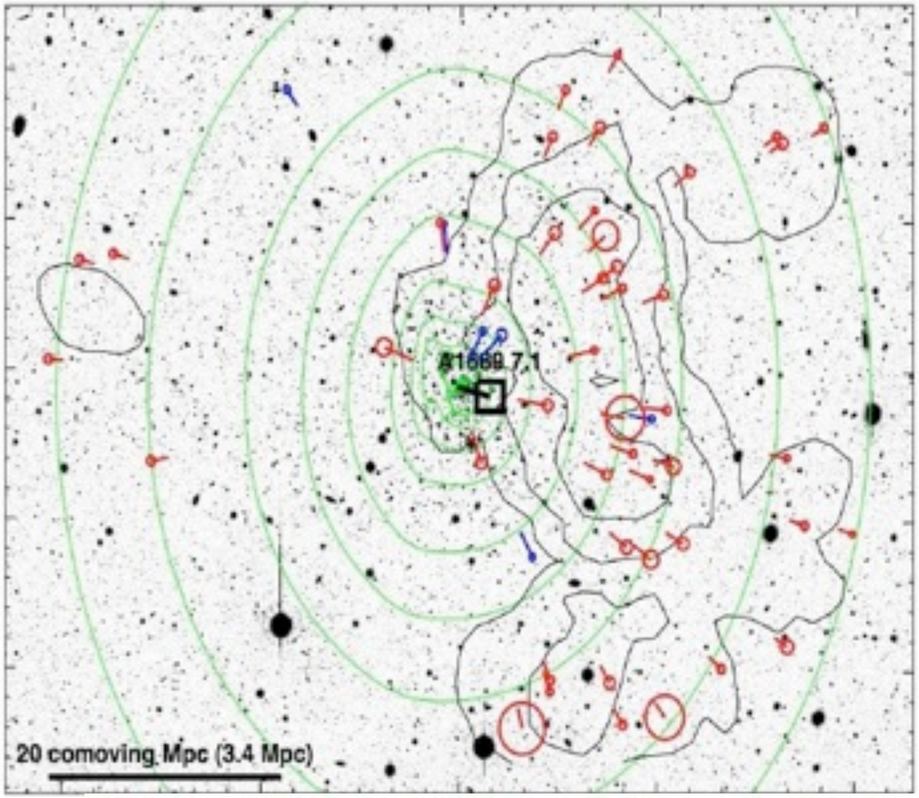
Clement et al 2011

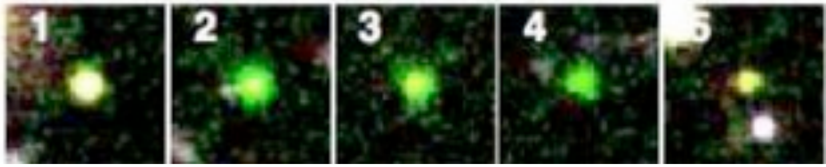
Lensed LAEs

- Narrow-band searches: wide field needed, limited gain of lensing magnification
- Searches behind lensing clusters:
  - ➢ **Hu et al. 02** z=6.56
  - ➢ **ZEN2** (**Willis et al. 07**):

    3 massive clusters, z ~ 9
  - ➢ **Matsuda et al. 09 / 11**
  - ➢z~5 LAEs over-density behind

    A1689 => importance of covering wide field imaging (or many clusters!) this also apply to LBG work.





Critical line mapping Lyman-alpha Emitters

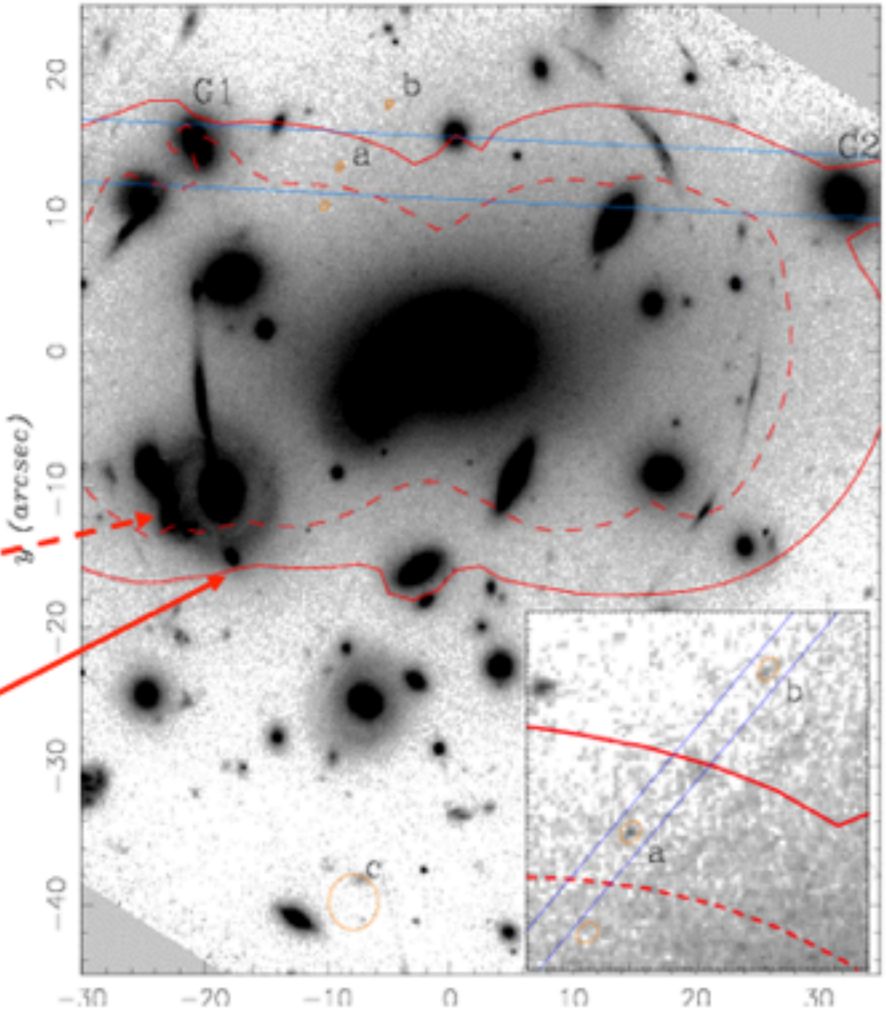
Critical line surveys

From lens modeling the location of the “critical lines” is known precisely for

z=1

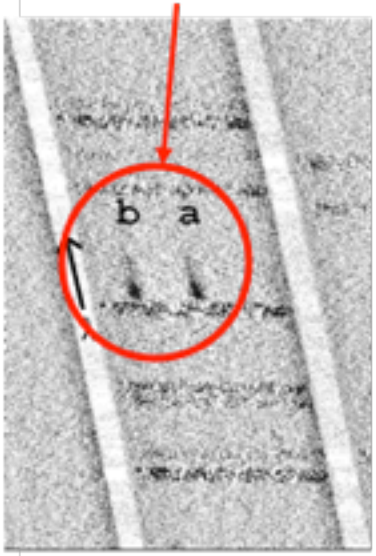
and for

z=5



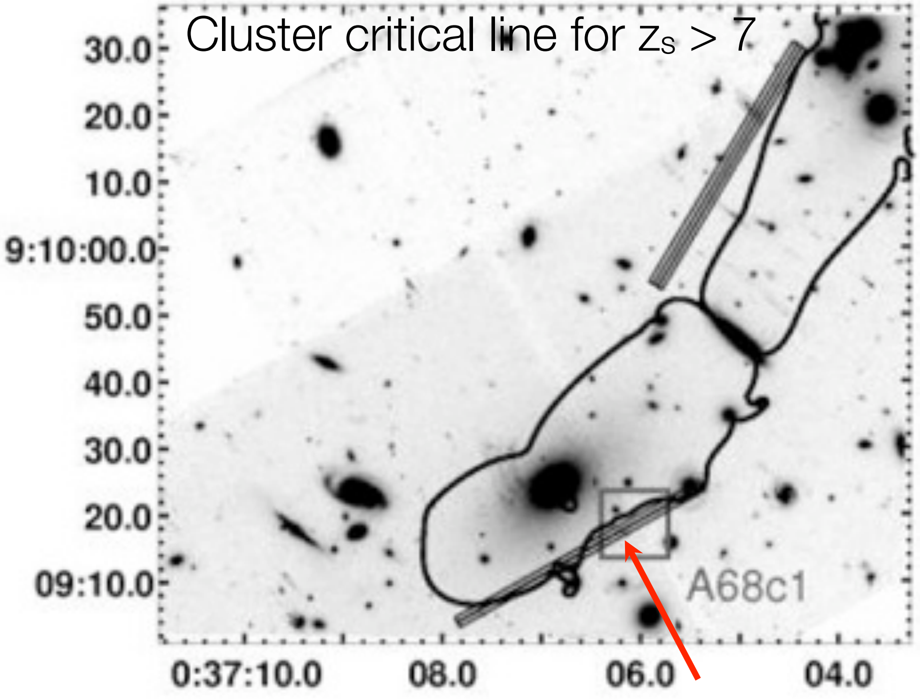
Ellis et al 2001

Blind Ly-a search with LRIS: hi-res follow-up with ESI

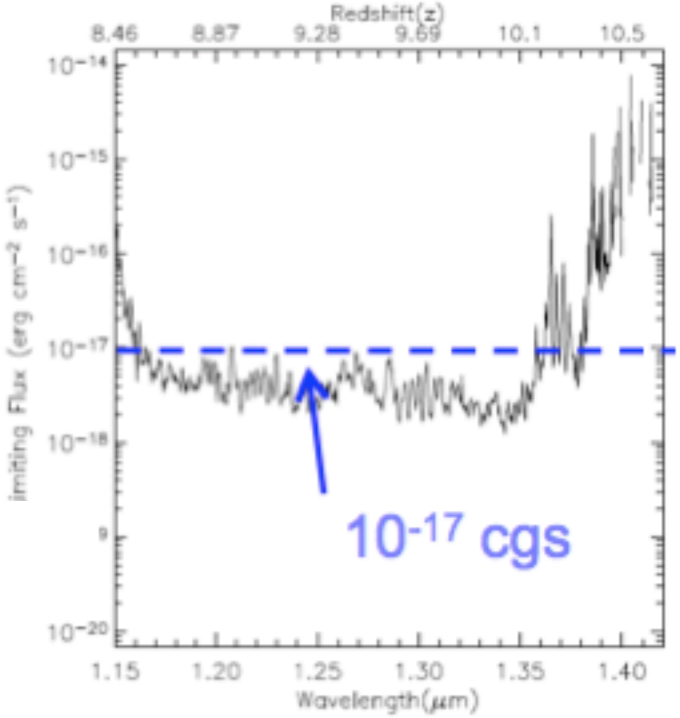


Utilizing strong magnification (´10-30) of clusters, probe much fainter than other methods in small areas (<0.1 arcmin2 cluster-1)

NIRSPEC critical line survey



NIRSPEC slit positions



Stark et al. 07

- 9 clusters with well-defined mass models & deep ACS
- Obs. Sensitivity ~ 3-9. 10^{-18} cgs; mag > x 15-20 throughout
- Sky area observed: 0.3 arcmin^2 V(comoving) 50 Mpc^3
- LAE candidates $8.6 < z < 10.2$; L ~ 2 – 10. 10^{41} cgs; SFR ~ 0.2-1 $M_\odot$ yr-1

SINFONI critical line survey

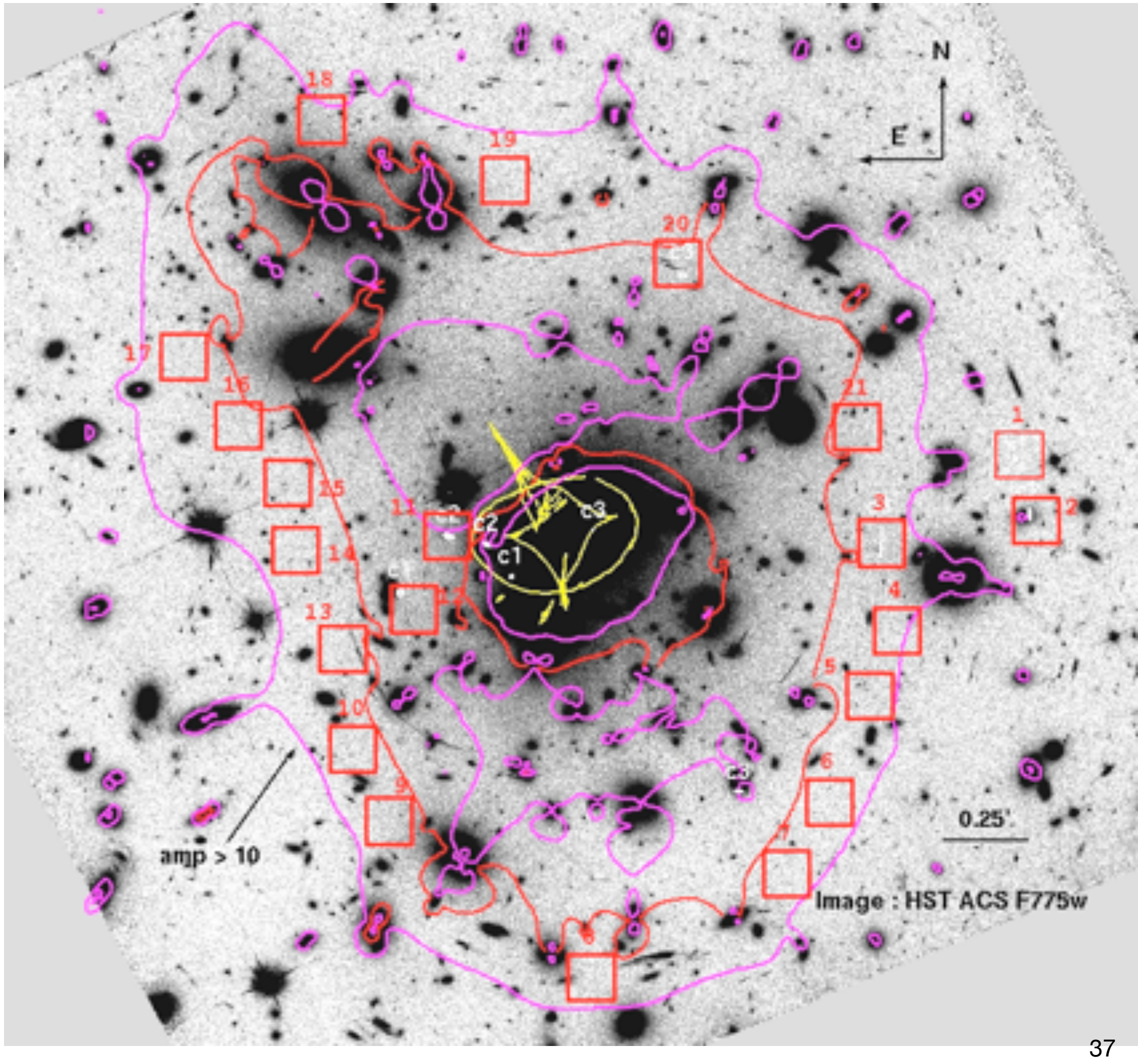
- 45min/pointing - R~1400
- 21 pointings (5”x6.5”)
- effective area

680 sq.“ in image plane

50 sq.“ in source plane

- probe ~ 10^{41} Ly-alpha luminosity
- down to ~3 times lower surface density than critical line survey

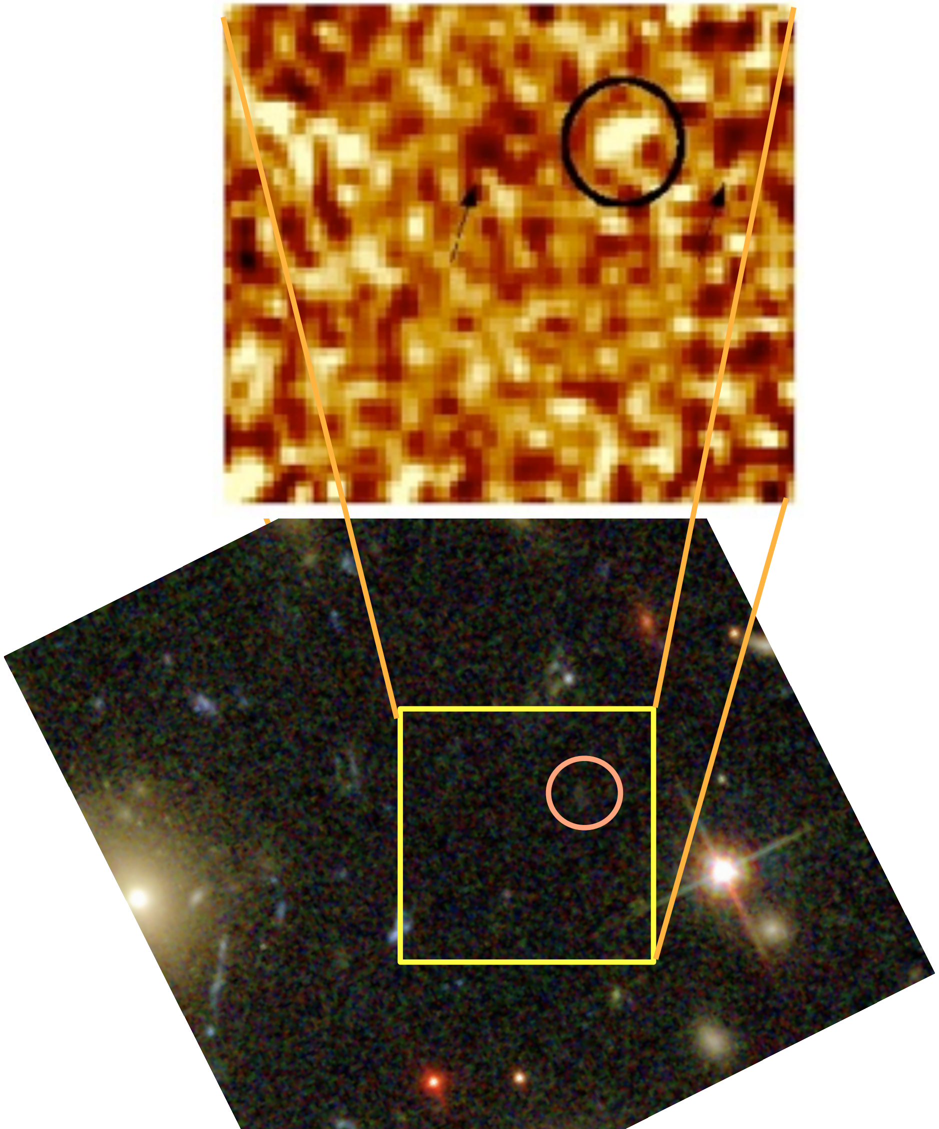
Clement et al. in prep.



SINFONI critical line mapping

Clement et al. in prep.

- Emission line detection (lambda=1.187micron) of a galaxy, possibly
  OII @ z=2.18 or
  Ha @ z=0.808
- I_{AB}~26
- Line flux ~3e-17 erg/s/cm^2



Constraints on the z~9 Luminosity Function

- SINFONI 20h (- - 60h)

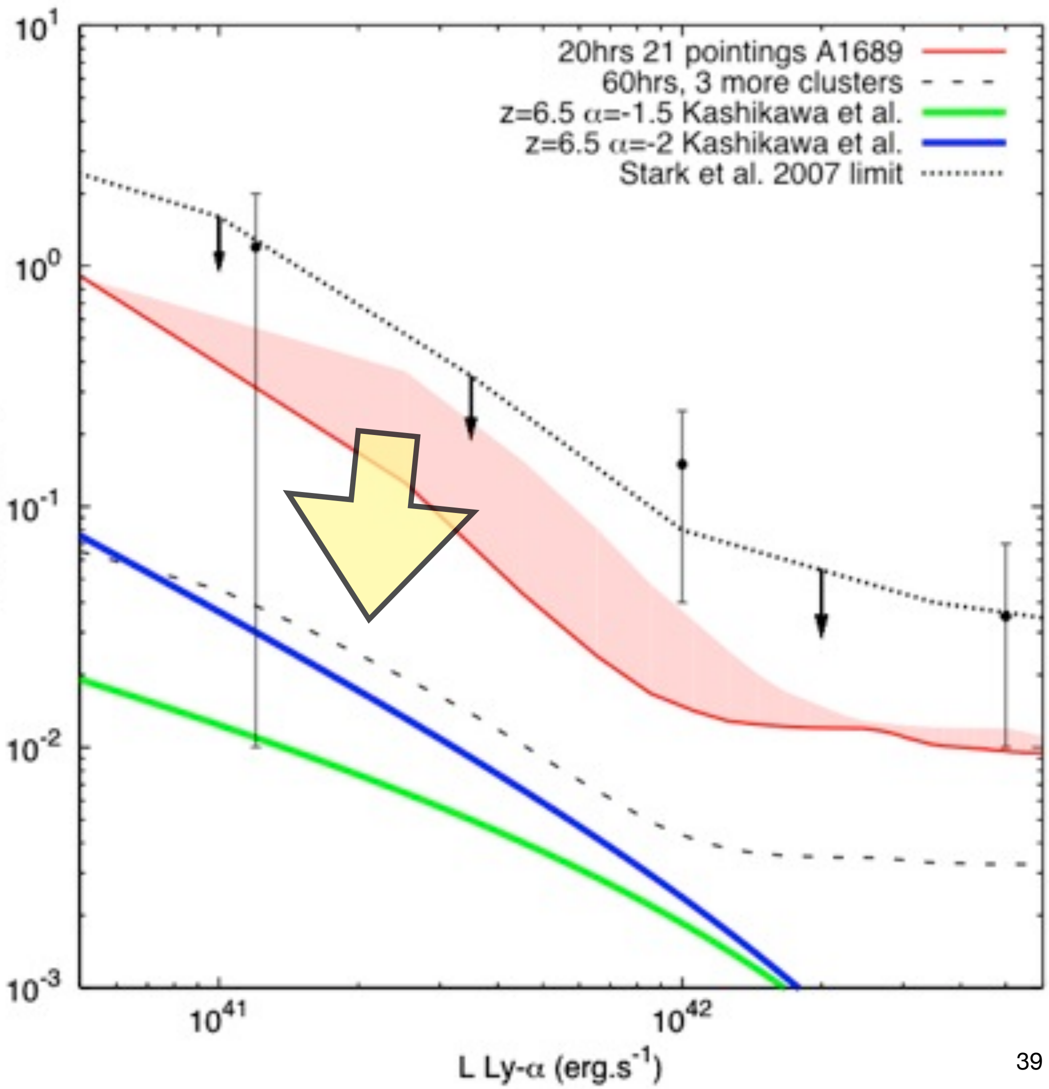
\- LF z=6.5 Kashikawa

(slope LF: -1.5 -2)

\- *Need more data for any useful constraints (more clusters = bigger volume)*

\- Just compatible with Stark et al 2007 if only ~2 of their candidates real => Need to increase the volume probed

Clement et al. in prep.

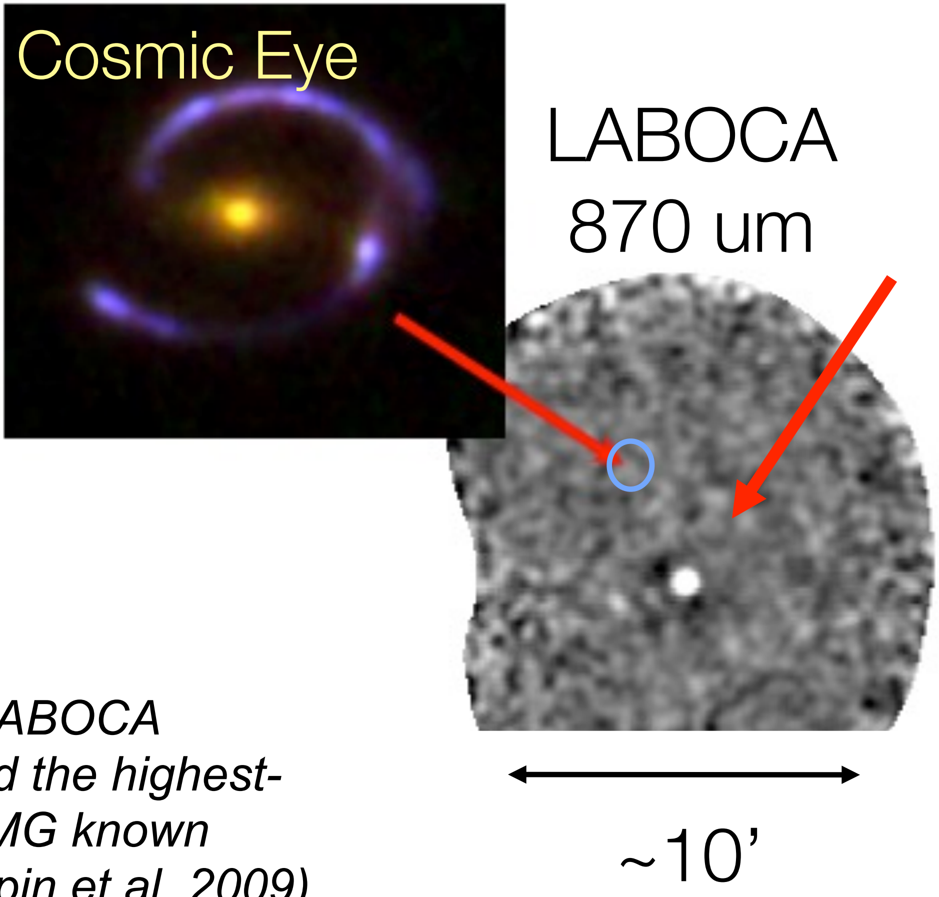


Distant Dusty Galaxies

Herschel Revolution

Discovery of the Brightest High-Redshift SMGs

State of the art in 2010

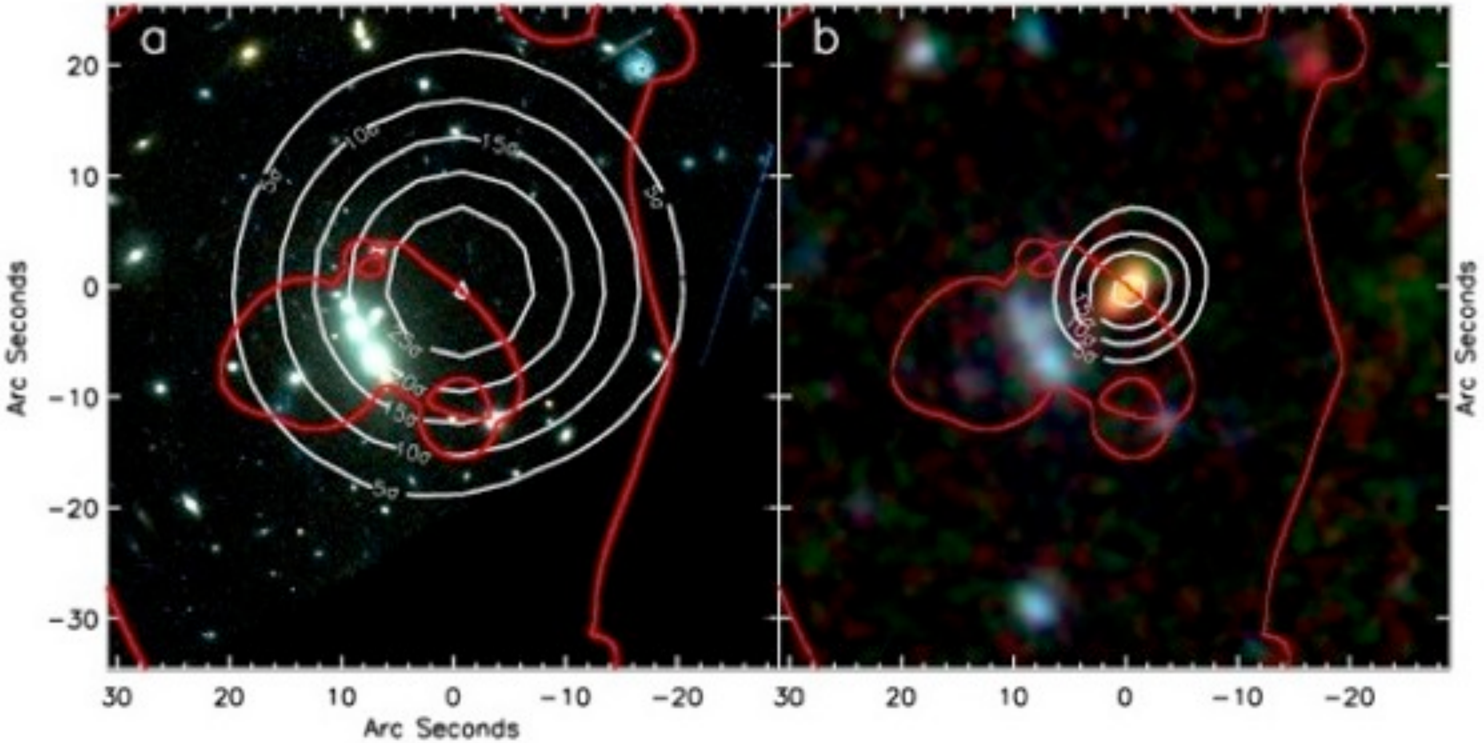


SMG at z=2.3
106 mJy@870um
530 mJy@350um
2.6 mJy@24um
mag = x32

c.f., 2nd brightest
SMG in the Bullet
Cluster at z=2.8
48 mJy@870um
100 mJy@350um
8.5 mJy@24um
mag= x50-75

APEX/LABOCA
also has found the highest-redshift SMG known
at z=4.76 (Coppin et al. 2009)

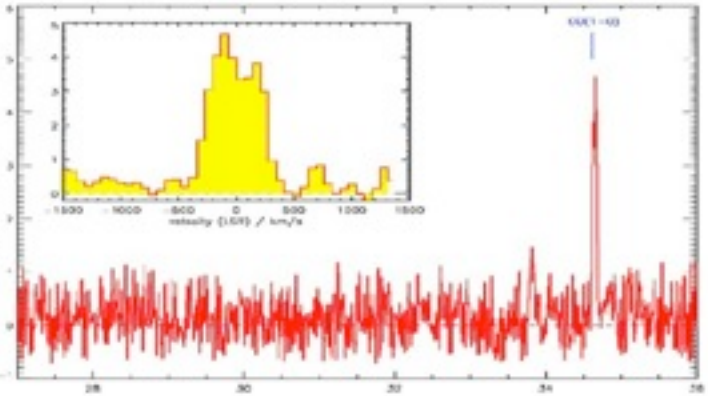
The Eyelash



HST V,I-band color image
870um contours (white)
106 mJy, FWHM=19”
z=2.3 critical lines (red)

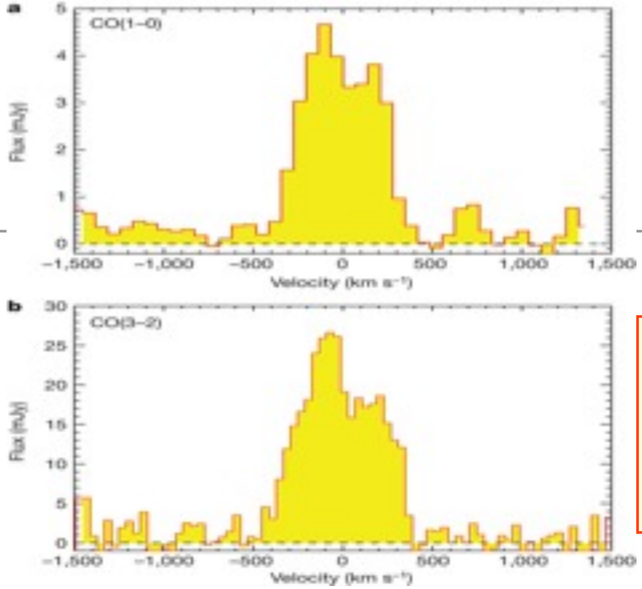
Spitzer IRAC true-color image
(3.6, 4.5, and 8.0 um)
350um contours (white)
530 mJy, FWHM=8”

Eyelash

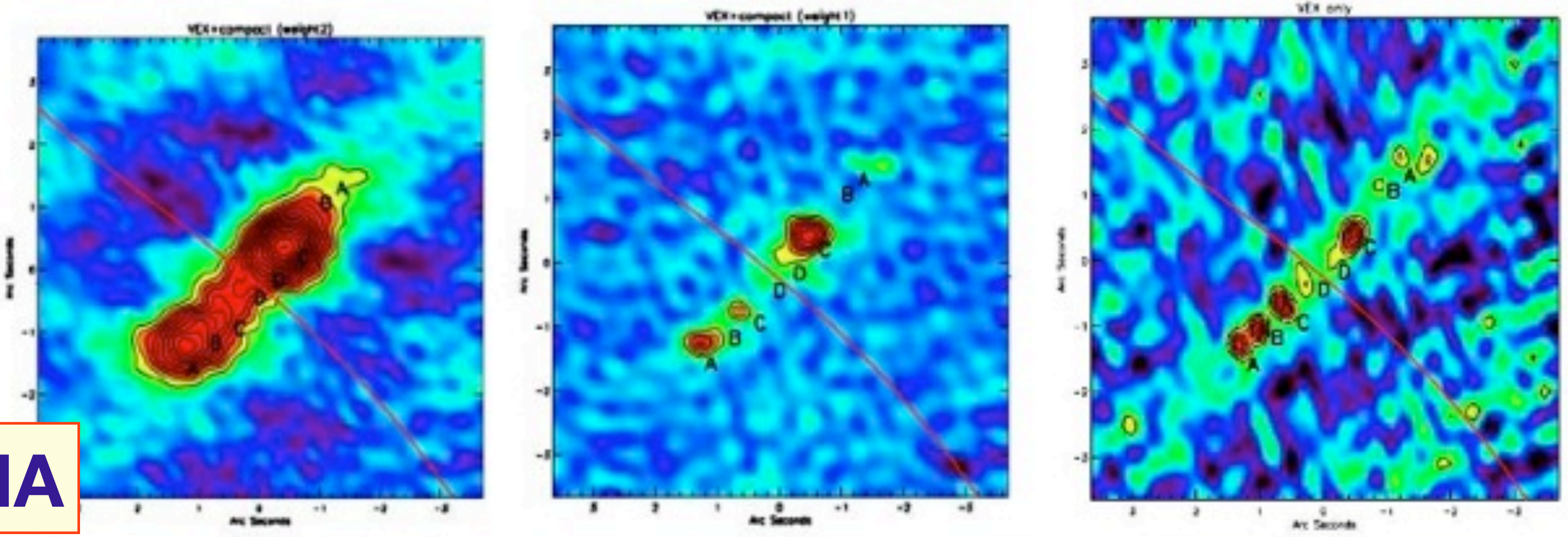


GBT Zspectrometer:

CO (1-0) detection@z=2.3



CO (3-2)
with PdBI
M_{gas} = 1.6 x 10^{10} $M_\odot$



SMA

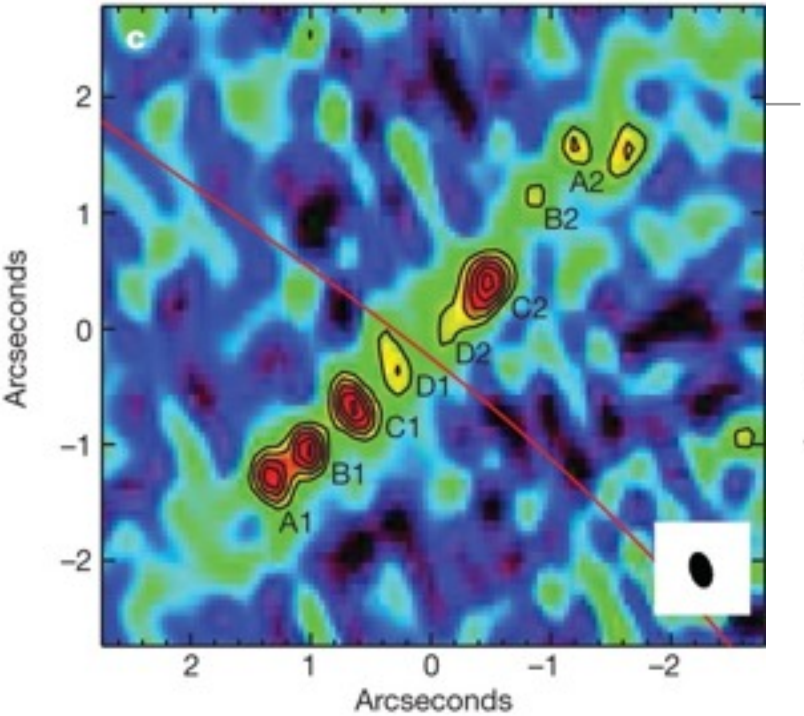
To resolve the sub-mm emission, we used the Smithsonian Sub-mm Array (SMA) at 3 configurations: compact (1.5"), Extended (0.7"), Very Extended (VEX; 0.2")

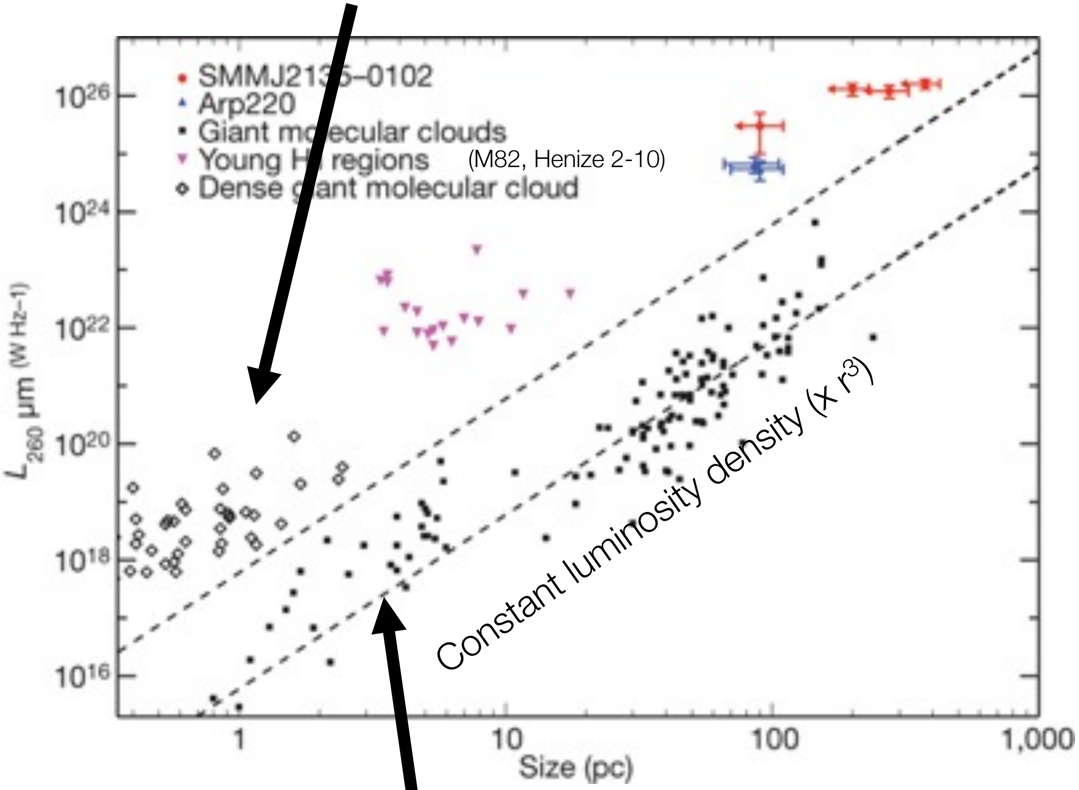
In all configurations, we detect the source and it continues to break up into smaller clumps

In highest configuration, beam is 0.2" (90-150pc after accounting for lensing).

Eyelash

Submm luminosity of dense cores in GMCs





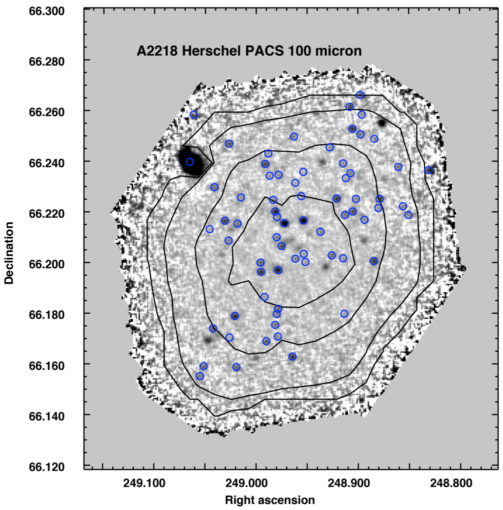
4 star-forming regions in
the source plane (A, B, C, D)
Intrinsic sizes ~ 100-400 pc

Submm luminosity of giant molecular clouds (GMCs)

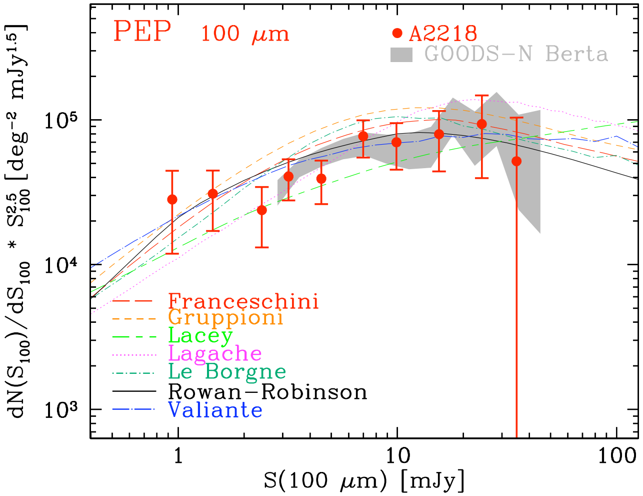
Star formation physics seems the same at z=2.3.
Star-forming regions just larger and therefore more luminous.

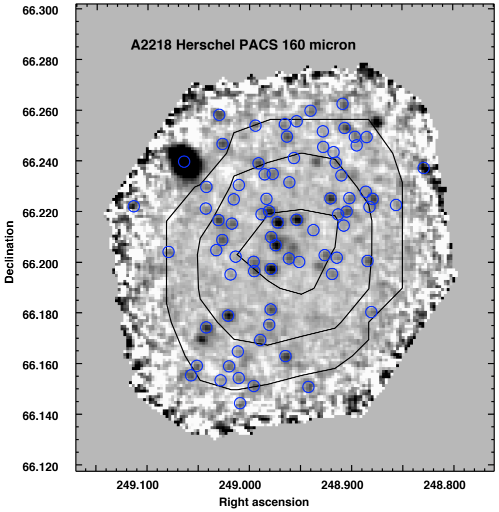
Deep Herschel Lensed Counts in the cluster A2218

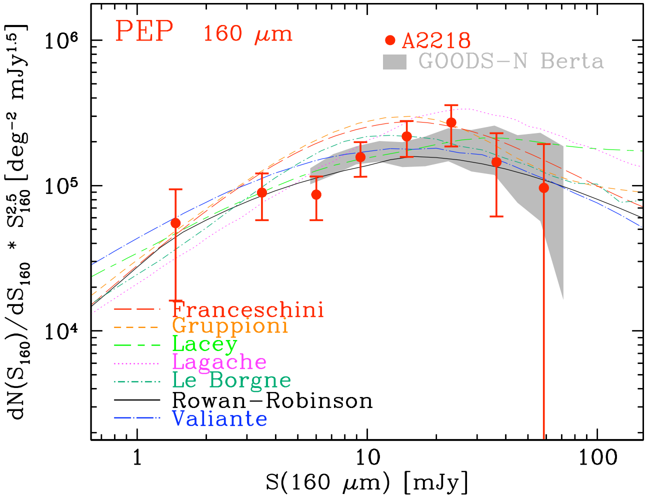
- ★Identification of sources
- ★foreground/ background/ redshift
- ★lens inversion
- ★unlensed counts - comparaison to blank field counts



Altieri et al 2010

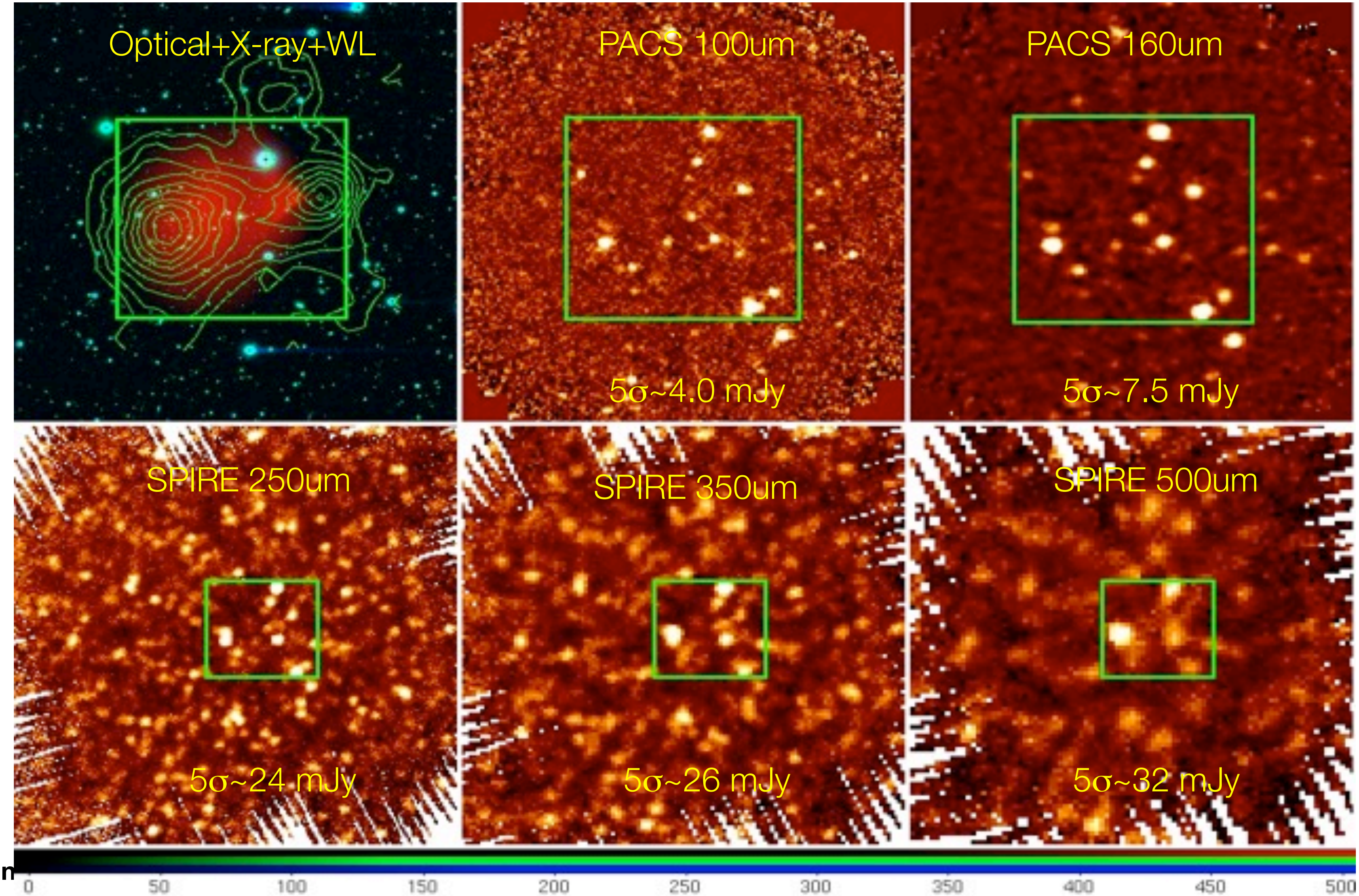




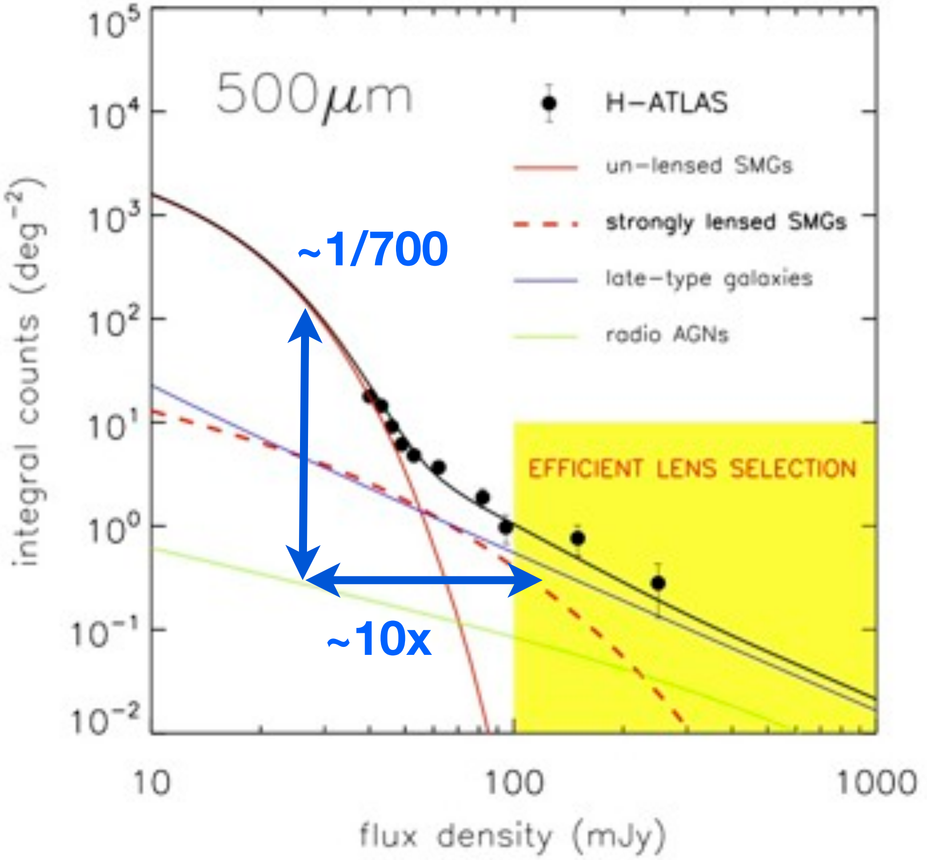


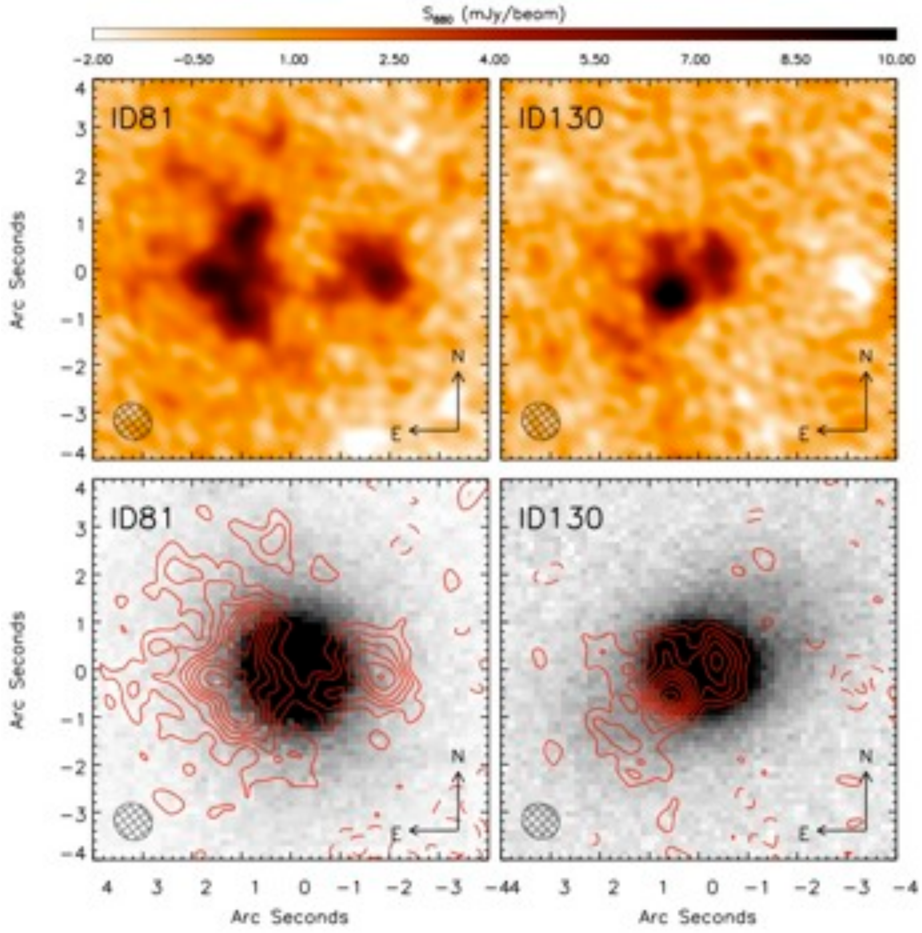
The Herschel Lensing Survey : The Bullet Cluster

Egami et al., Rex et al., Rawle et al., Perez-Gonzalez et al., Zemcov et al. (2010)



H-ATLAS - Galaxy scale - Lensed FIR source e.g., Negrello et al. (2010)





Also candidates from South Pole Telescope (SPT)

How do we find more of such bright lensed galaxies?

- The surface density of >100 mJy SPIRE-detected lensed galaxies ~ 0.5 deg^2 (from H-ATLAS)
  - With Herschel, it is difficult to conduct a survey larger than H-ATLAS, which images 550 deg^2 (600 hrs) and will find a few hundred >100 mJy lensed galaxies ...
- Alternatively, we can target known powerful gravitational lenses (= massive clusters of galaxies)
  - OT1 SPIRE Snapshot Survey of 279 X-ray-luminous clusters
  - Foreground galaxy clusters will also increase the probability of galaxy-galaxy lensing -> bright SPIRE sources outside cluster cores (HLS, LoCuSS surveys).

Why Cluster Lenses (HLS, Snapshot) vs. Galaxy Lenses (H-ATLAS) ?

- One single lens magnify a number of background galaxies.
- Lens modeling is easier and more robust.
- Effects of differential magnification is less severe (shallower magnification gradient).
- No bright foreground lens obstructing the view of lensed images.

On-Going/Proposed Surveys

- **Cluster lensing**
  - The Herschel Lensing Survey (OTKP; 44 clusters; Egami et al.)
  - SPIRE Snapshot Survey (OT1; 279 clusters; Egami et al.)
  - The Herschel Lensing Survey II (OT2; 10 clusters; Egami, Postman et al.)
  - SPIRE Snapshot Survey II (OT2; 353 clusters; Egami, Carlstrom, Finoguenov et al.)

Rate ~1/10 brighter than 100 mJy

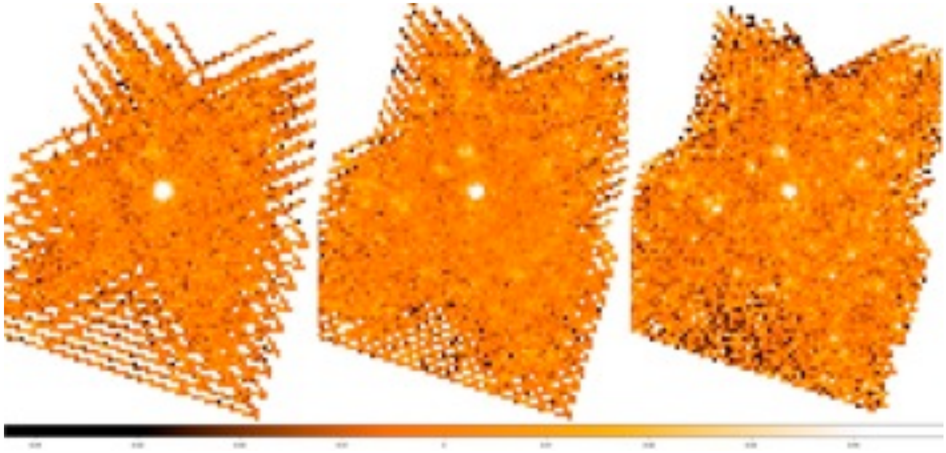
- **Galaxy lensing**
  - HerMES (GTKP; Bock & Oliver et al.)
  - H-ATLAS (OTKP; Eales et al.)
  - SPT (Carlstrom et al.)
  - **Planck**

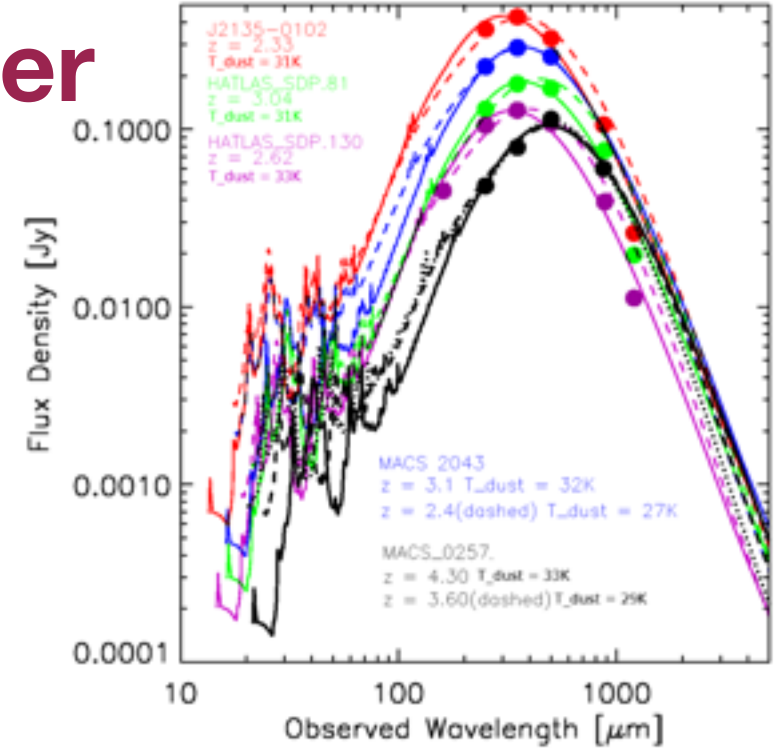
Observational Strategy for High-z Lensed SMG Surveys

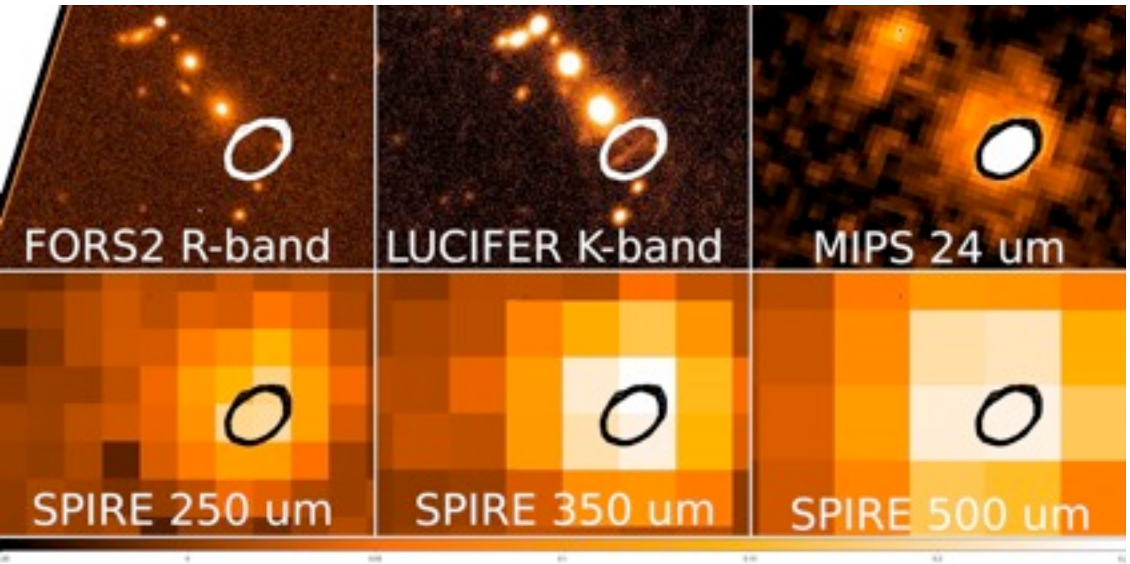
1. Identify bright (>100 mJy) sources (Herschel/SPIRE)
    - SPIRE SEDs give rough redshift estimates
2. Submm/mm photometry (LABOCA, Bolocam, SCUBA2)
3. CO redshift search (**IRAM30m/EMIR**, GBT/Zspectrometer, CARMA)
4. High-resolution imaging via submm/mm interferometers (**PdBI**, SMA, CARMA, ALMA)
5. HST imaging from archive or new observations (lens model)

Exciting but requires a lot of effort (and energy..) to plan, arrange, and execute observations with so many observing facilities...

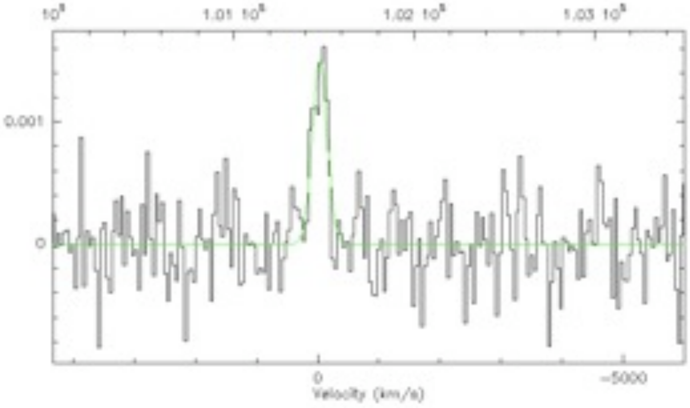
Bright 350micron peaker [MACSJ2043]





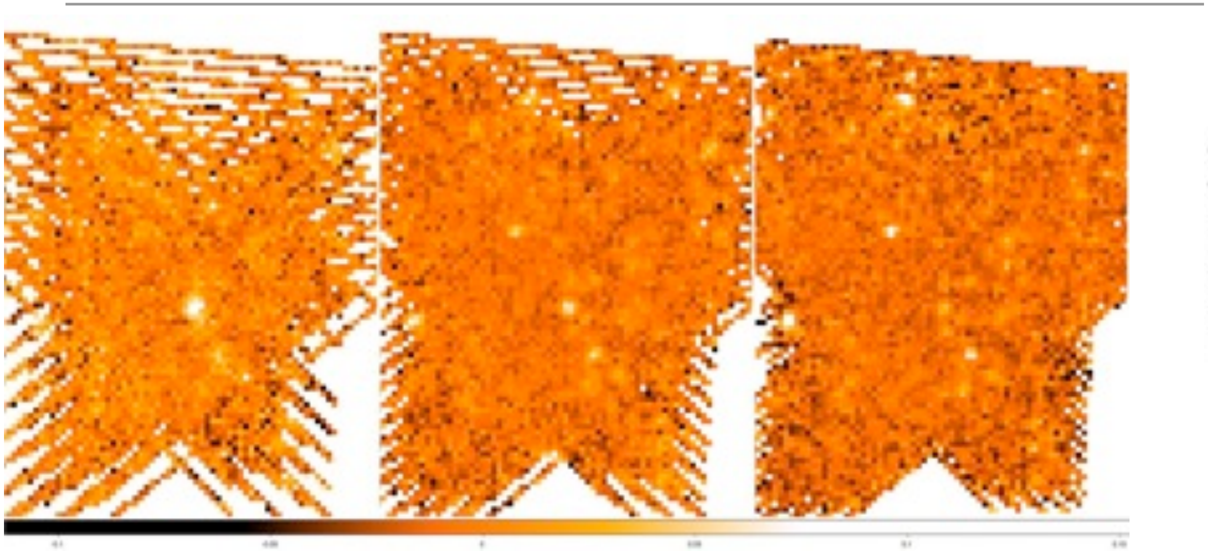


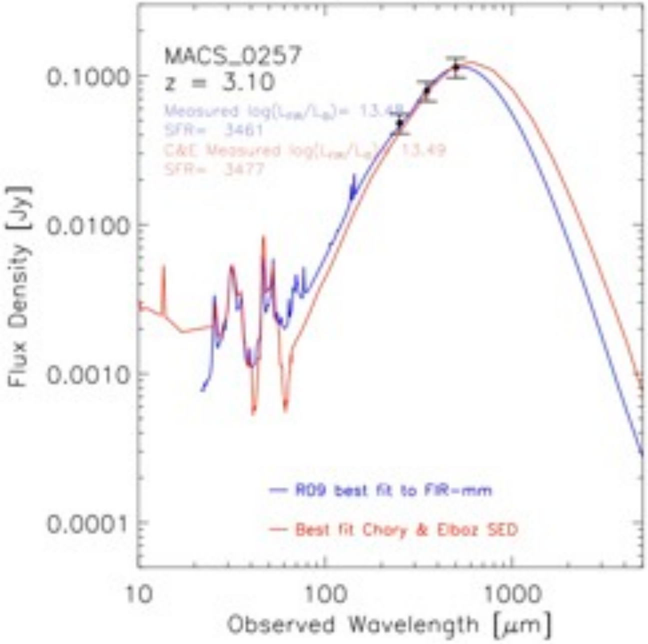
CO(3-2) at z=2.4

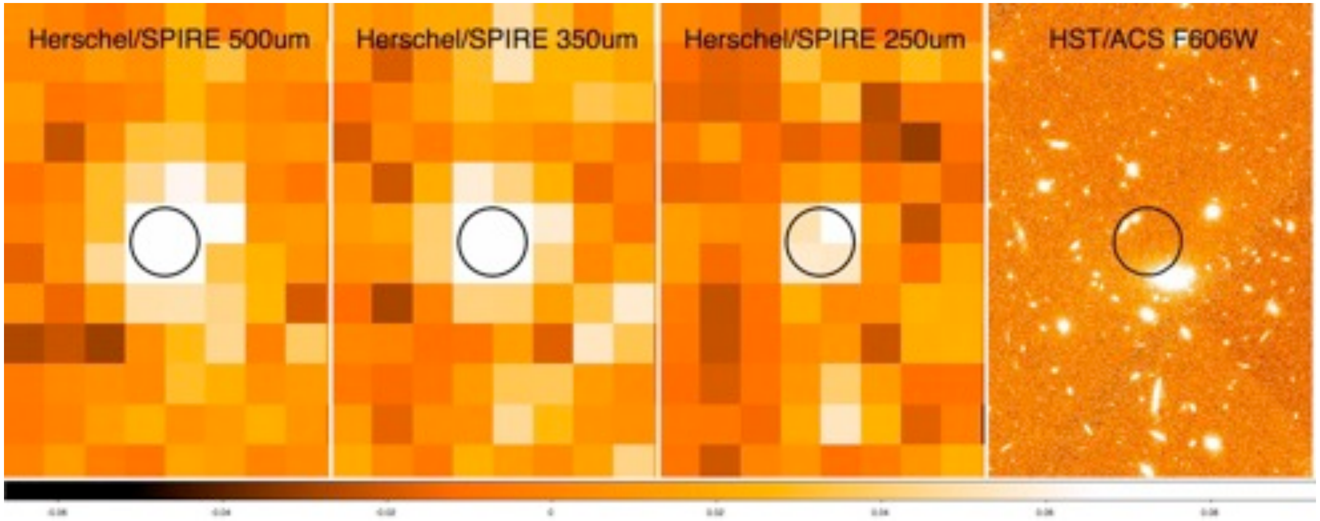


Data obtained by M. Dessauges

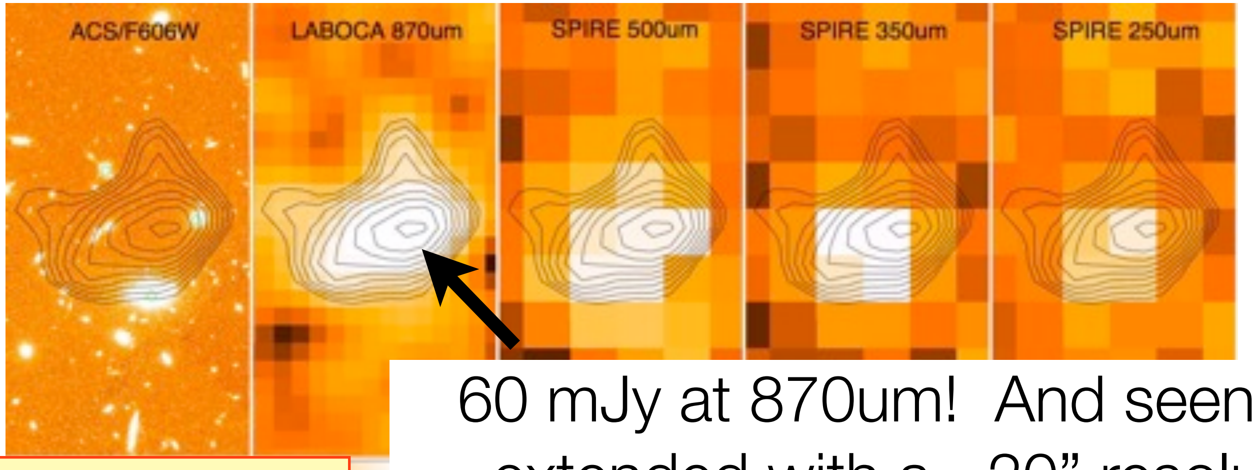
Probing z>4 with 500 micron Peakers/Risers [MACSJ0257-22]







[MACSJ0257-22]

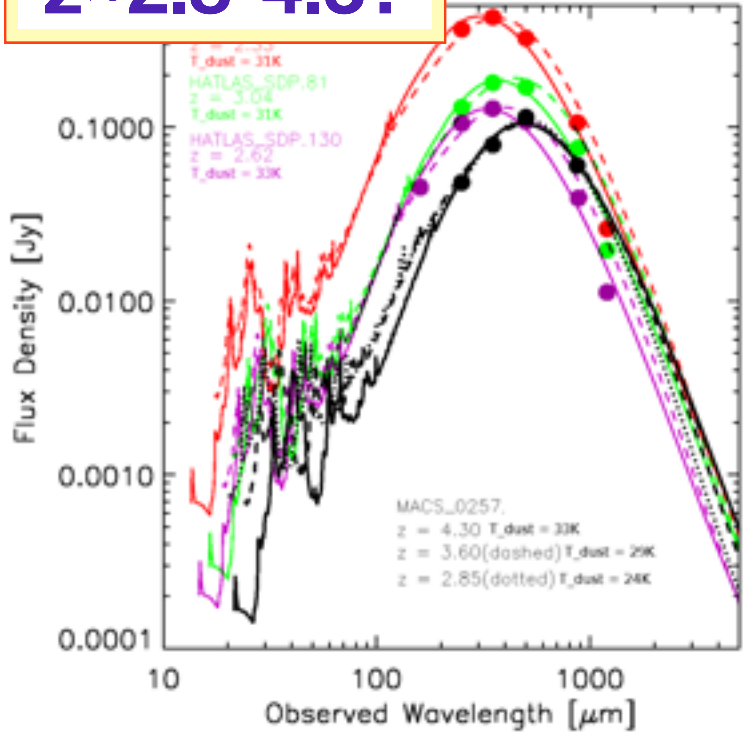


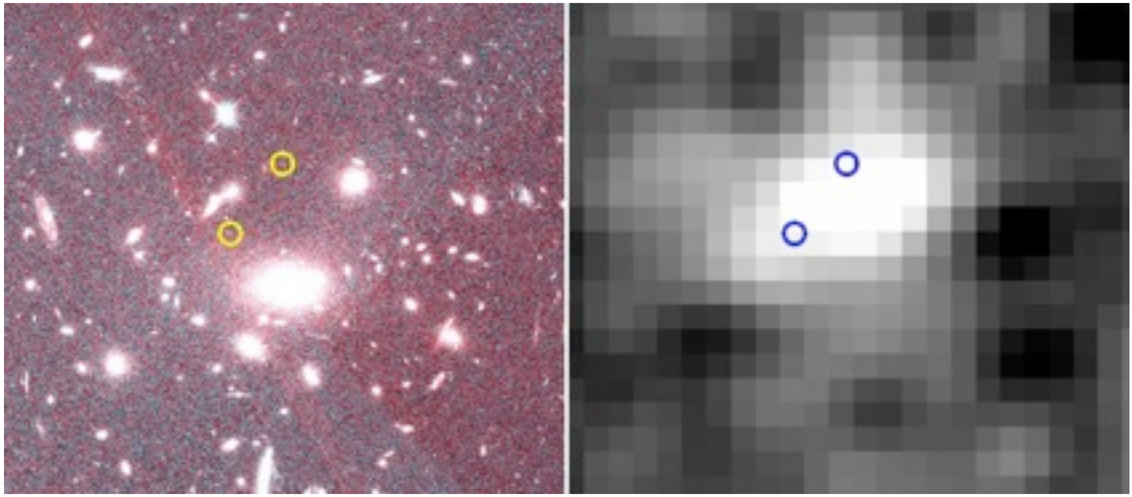
60 mJy at 870um! And seen to be extended with a ~20” resolution!

LABOCA data
from
D. Lutz
A. Weiss

HST/ACS data
from
H. Ebeling

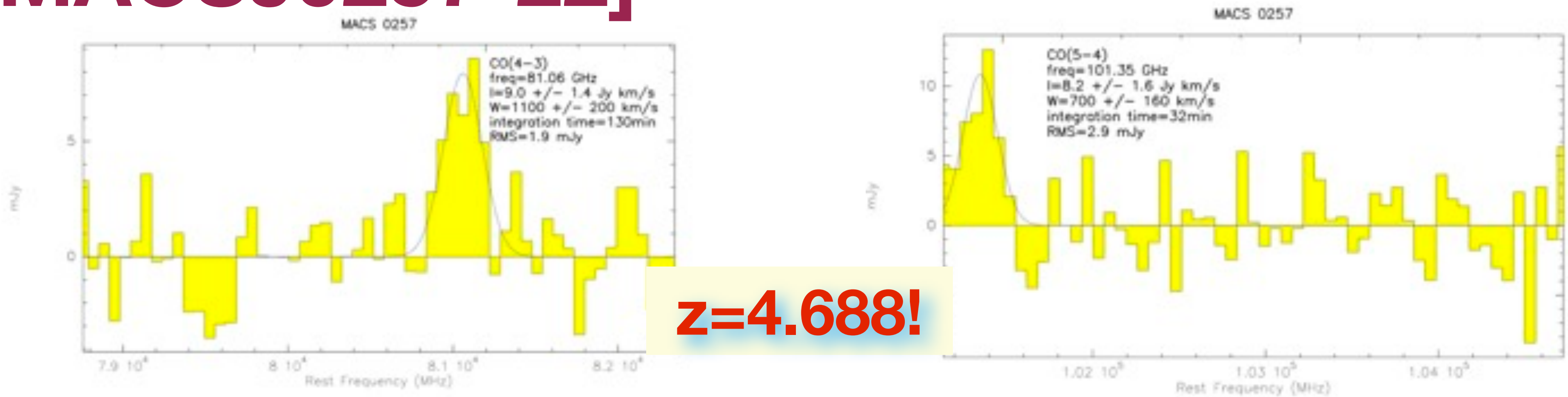
z~2.8-4.3?





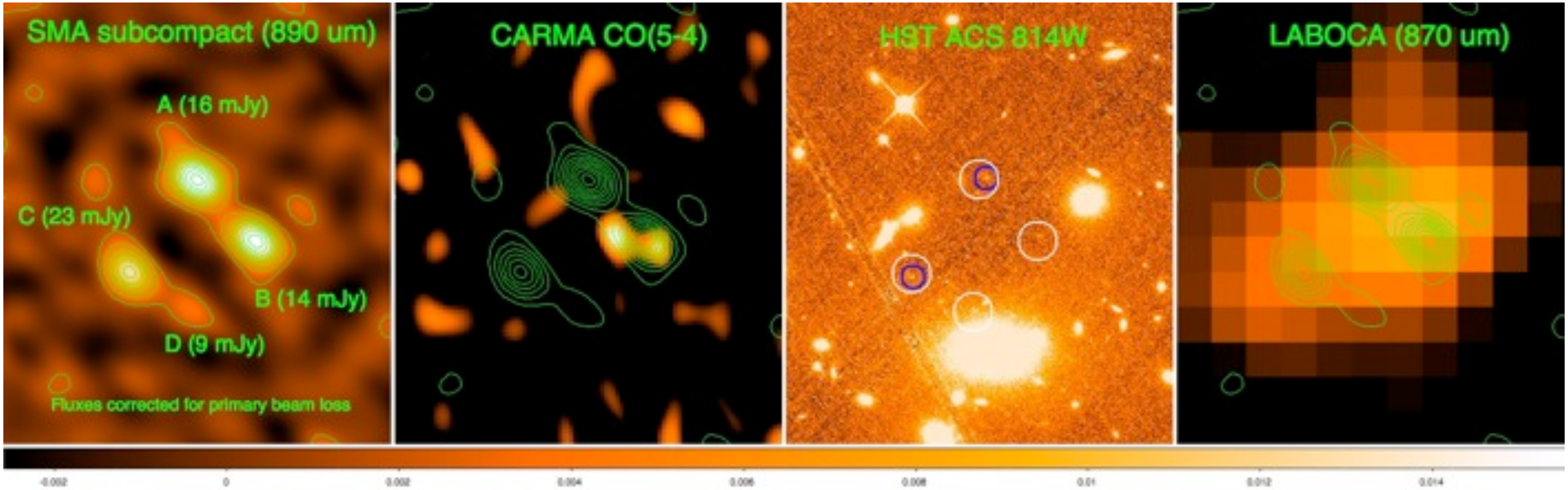
But where are the counterpart(s)?

[MACSJ0257-22]



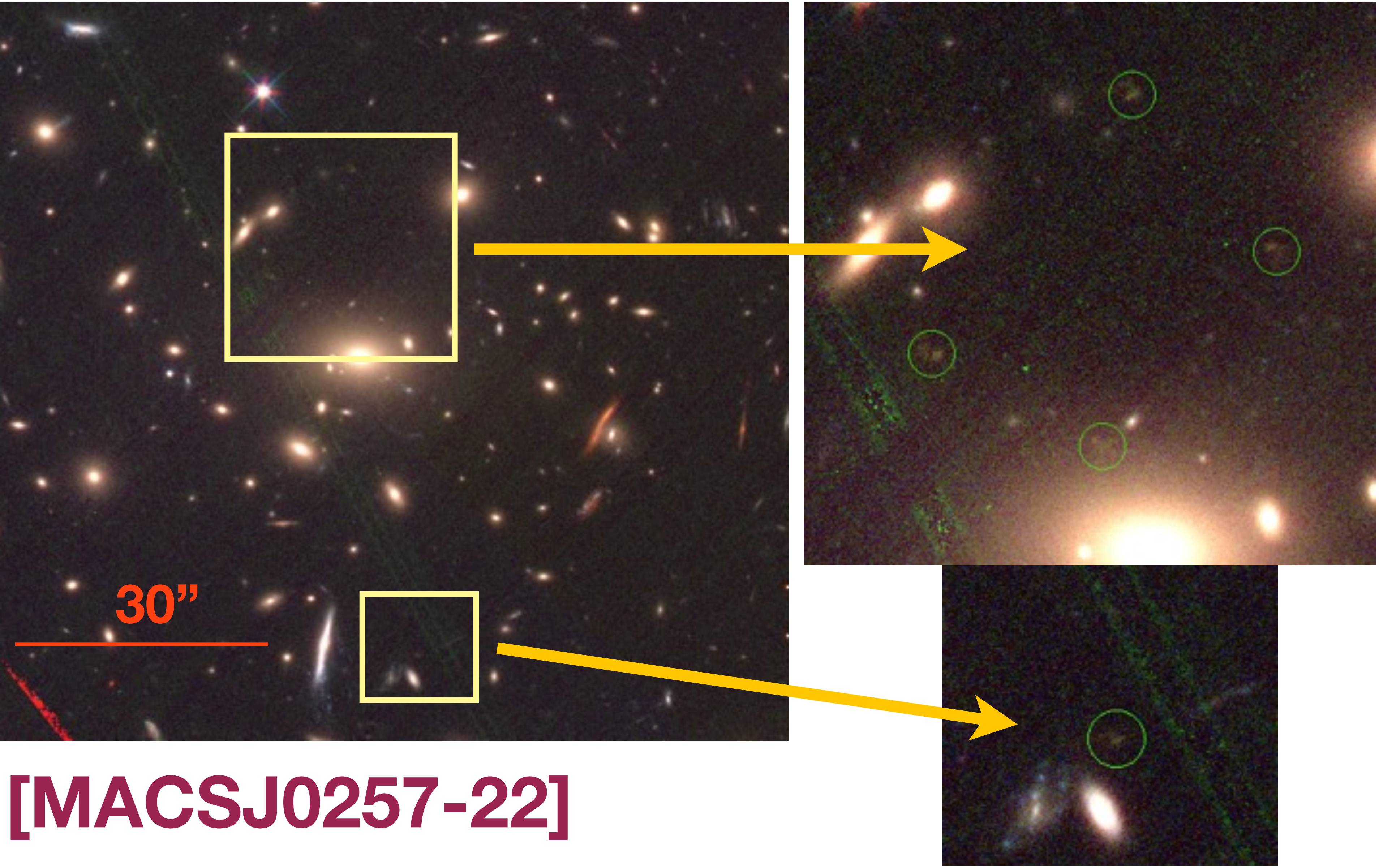
z=4.688!

IRAM30m/EMIR data obtained by F. Boone



SMA Extended & Very Extended currently being analyzed.

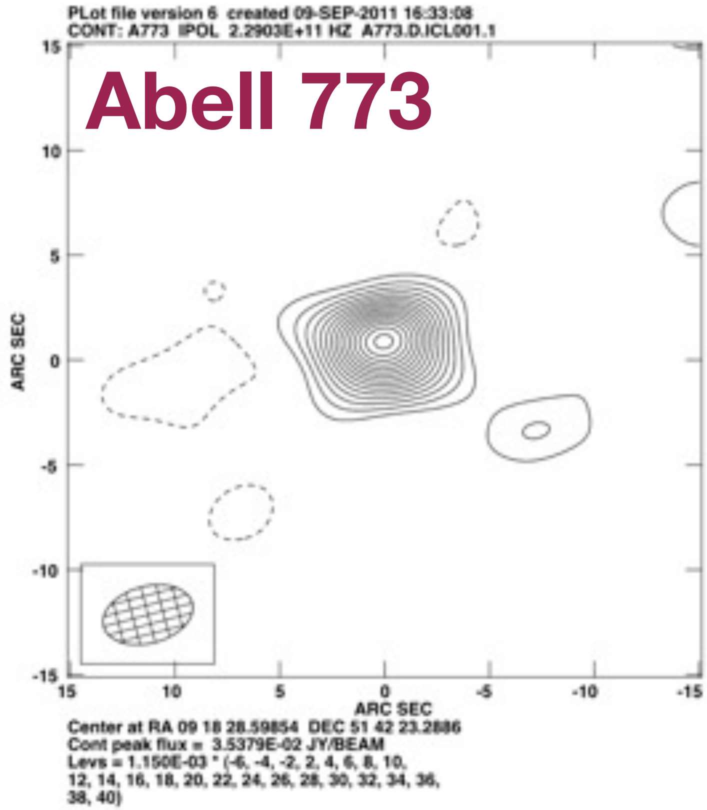
(SMA data: G. Fazio; CARMA data: D. Riechers)



[MACSJ0257-22]

HST/WFC3 F140W image finds the expected 5th image.
(data by H. Ebeling; lens modeling by J. Richard)

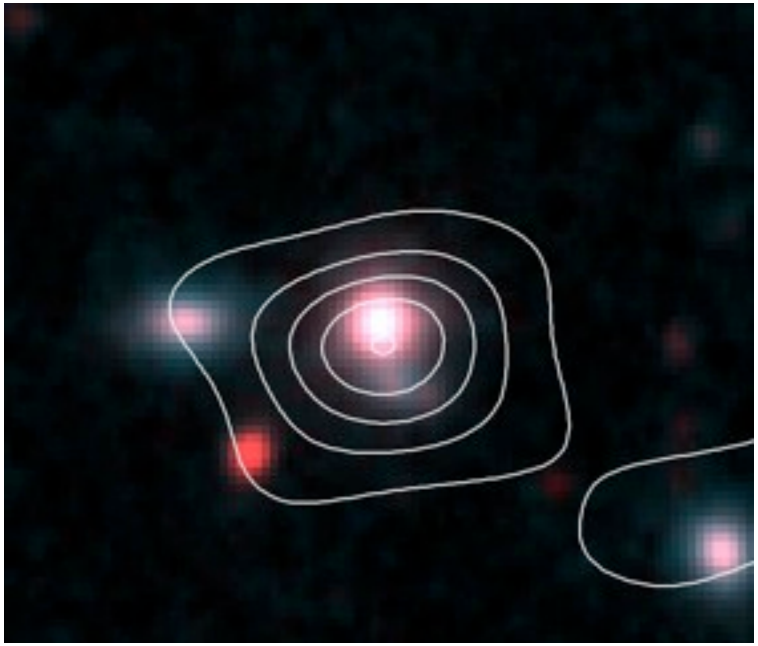
Exceptionally bright 500 micron peaker (~200 mJy)!



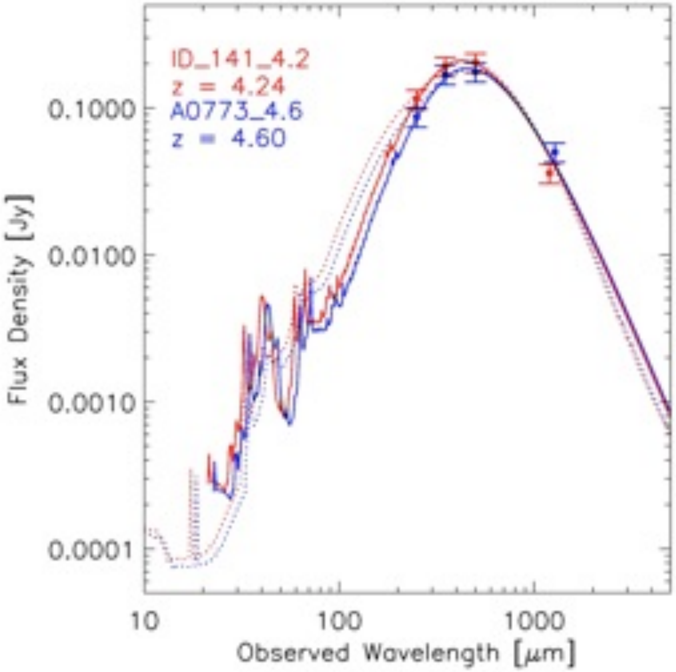
50 mJy at 1.3 mm!

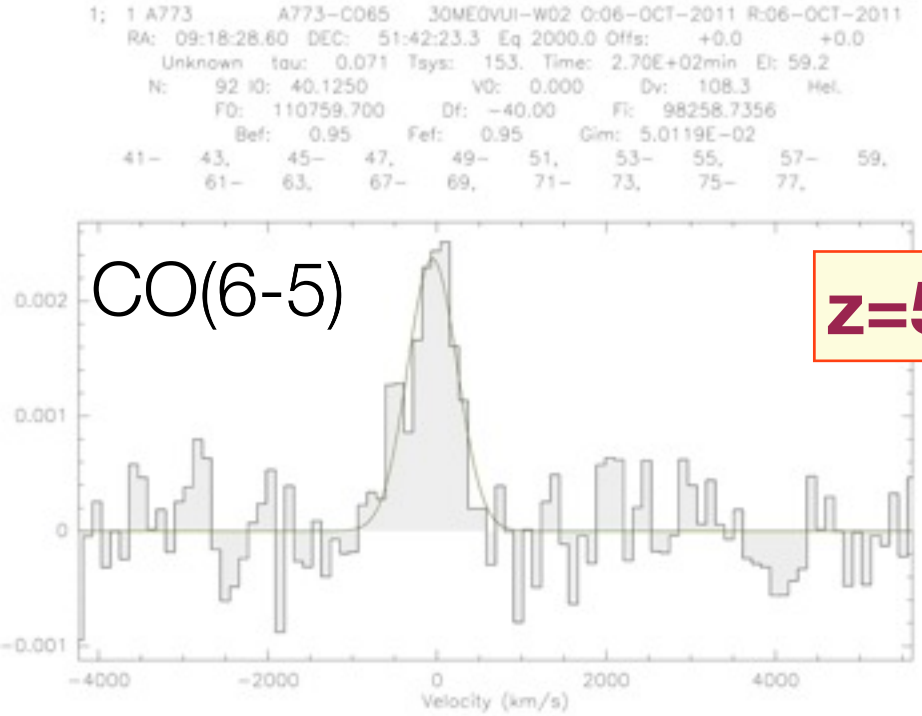
Square shape...

(SMA Compact - C. Casey)



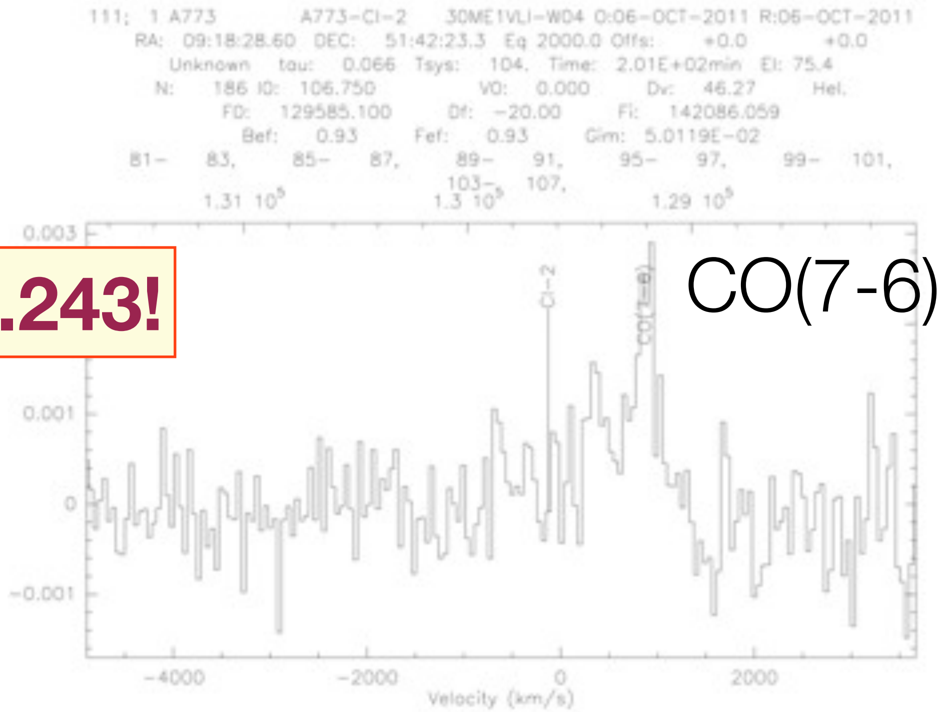
Suprime-Cam - G. Smith





```
1;  1 A773          A773-CO65     30ME0VUI-W02 O:06-OCT-2011 R:06-OCT-2011
   RA:  09:18:28.60  DEC:    51:42:23.3  Eq 2000.0 Offs:      +0.0         +0.0
       Unknown    tau:    0.071  Tsys:    153.  Time:  2.70E+02min  El: 59.2
      N:        92 I0:  40.1250                V0:   0.000       Dv:   108.3        Hel.
              F0:    110759.700        Df:   -40.00        Fi:   98258.7356
                 Bef:     0.95        Fef:     0.95       Gim:  5.0119E-02
    41-     43,       45-     47,       49-     51,       53-     55,       57-     59,
              61-     63,       67-     69,       71-     73,       75-     77,
```

z=5.243!



```
111;  1 A773          A773-CI-2     30ME1VLI-W04 O:06-OCT-2011 R:06-OCT-2011
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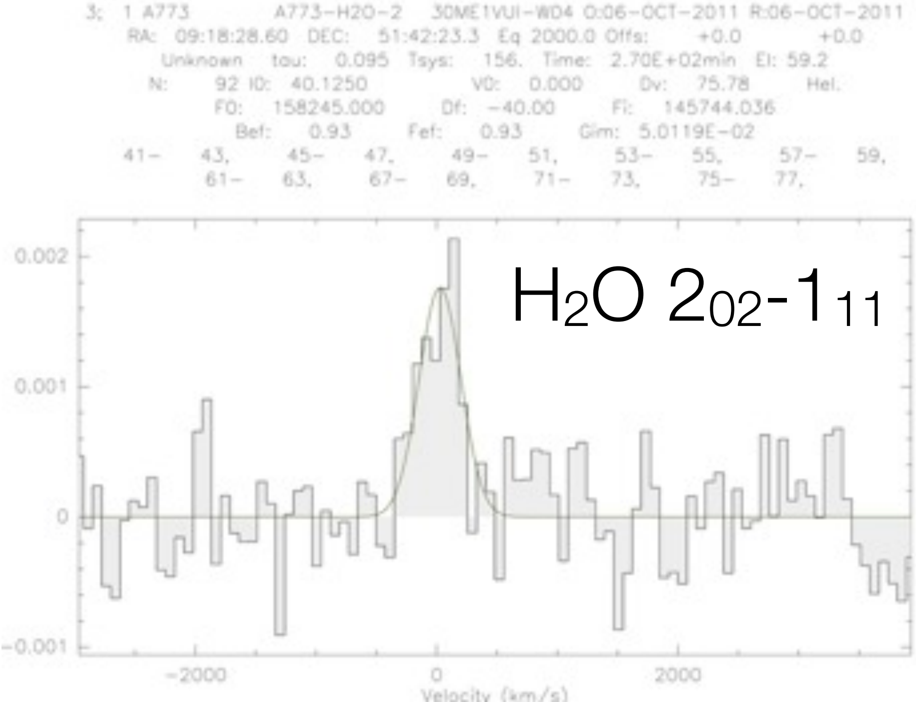
       Unknown    tau:    0.066  Tsys:    104.  Time:  2.01E+02min  El: 75.4
      N:       186 I0:  106.750                V0:   0.000       Dv:   46.27        Hel.
              F0:    129585.100        Df:   -20.00        Fi:   142086.059
                 Bef:     0.93        Fef:     0.93       Gim:  5.0119E-02
    81-     83,       85-     87,       89-     91,       95-     97,       99-     101,
                                        103-    107,
          1.31 10^5                  1.3 10^5                  1.29 10^5
```

Abell 773



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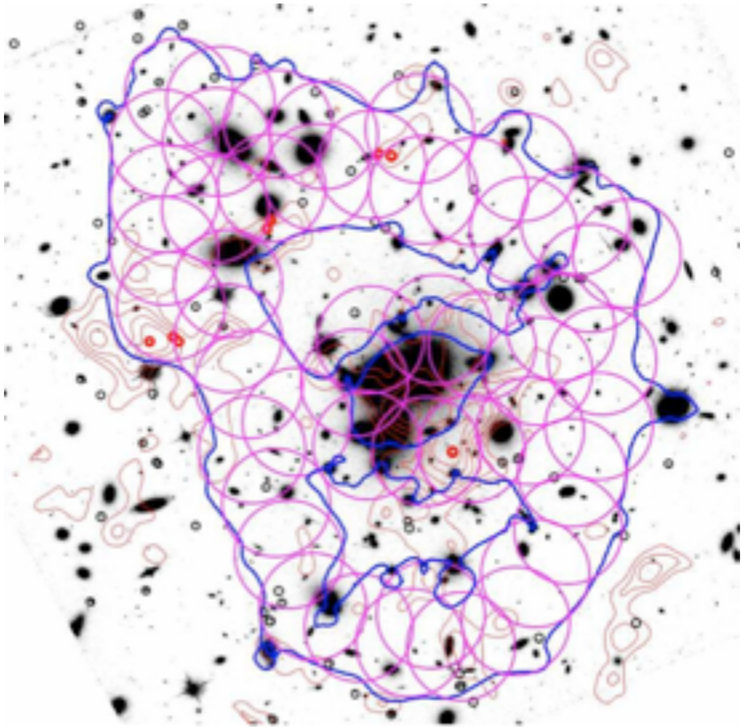
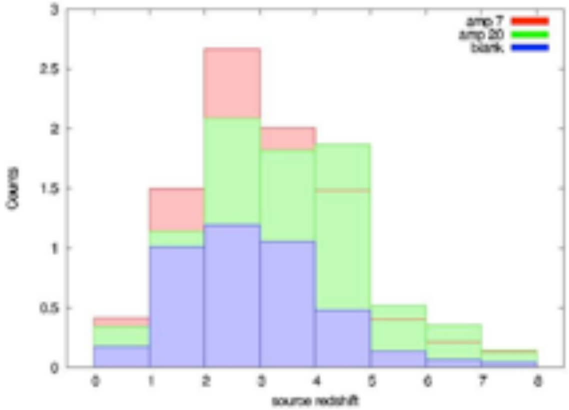
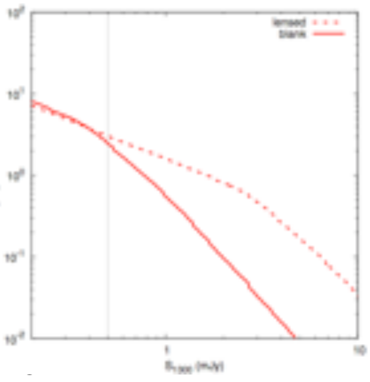
       Unknown    tau:    0.095  Tsys:    156.  Time:  2.70E+02min  El: 59.2
      N:        92 I0:  40.1250                V0:   0.000       Dv:   75.78        Hel.
              F0:    158245.000        Df:   -40.00        Fi:   145744.036
                 Bef:     0.93        Fef:     0.93       Gim:  5.0119E-02
    41-     43,       45-     47,       49-     51,       53-     55,       57-     59,
              61-     63,       67-     69,       71-     73,       75-     77,
```

Combes et al
2012
IRAM/30m/EMIR

Prospects: ALMA critical line mapping
Exploring the low-luminosity galaxies







- ❑ Building on a running large proposal at PdB/Widex at 1.3mm on 5 clusters
- ❑ Critical line mapping at 1.3mm (Band 6) of the Abell 1689 cluster – probe down to 0.05 mJy (taking into account magnification) + probe CO redshift of SCUBA detected galaxies
- ❑ Effective strategy to cover critical lines of many clusters in ~one hour per cluster once ALMA is completed => focus on the most magnified region => new science

Conclusions

- Great progress in hi-redshift investigations (WFC3, Hawk-I, FORS/X-Shooter, Herschel+follow-ups ... soon ALMA)
- A large sample (>100) of strong lensing clusters has been built and modeled, with enough accuracy to use them as Cosmic Telescopes. They have a wide multi-wavelength coverage, with HST, IRAC, Herschel
- Lensing + HST is efficient to find strongly z~7 lensed dropouts bright enough for spectroscopic follow-up
- Herschel cluster surveys of large number of clusters is finding numerous strongly lensed sources magnified more than 10x. Highest redshift is currently z=5.243. But *many* more to be found – some at even higher redshift !
- Blind search around critical offer the possibility to go down the luminosity function very effectively, new science?

THANKS !