Terzo workshop

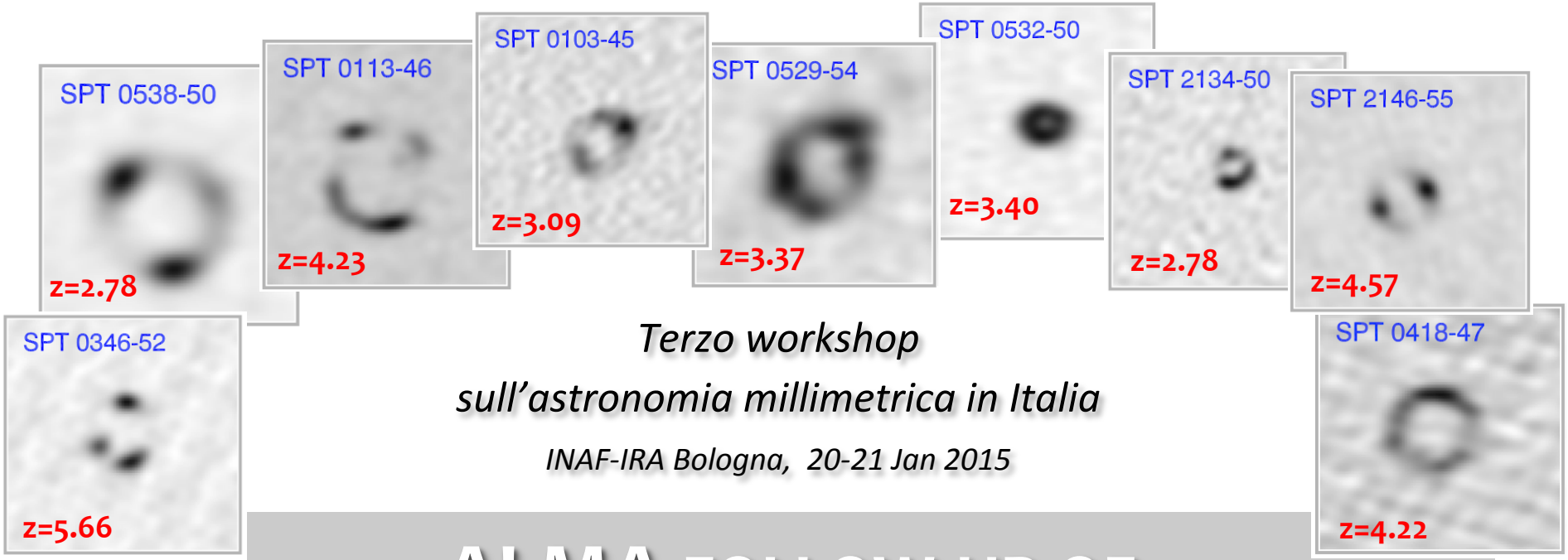
sull'astronomia millimetrica in Italia

INAF-IRA Bologna, 20-21 Jan 2015

ALMA FOLLOW-UP OF SUB-MM/MM-SELECTED LENSED GALAXIES

Presented by **Mattia Negrello**

INAF - Osservatorio Astronomico di Padova



Terzo workshop

sull'astronomia millimetrica in Italia

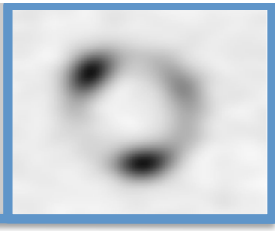
INAF-IRA Bologna, 20-21 Jan 2015

ALMA FOLLOW-UP OF SUB-MM/MM-SELECTED LENSED GALAXIES

Presented by **Mattia Negrello**

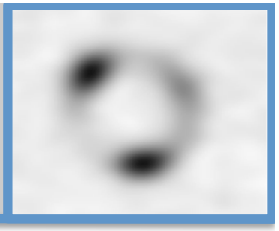
INAF - Osservatorio Astronomico di Padova

Outline



- Selection of *lensed galaxies* for ALMA follow-up
- Peculiarities of sub-mm/mm lensed galaxies
- ALMA contribution to strong lensing studies

ALMA gets into *Nature*



LETTER

doi:10.1038/nature12001

Dusty starburst galaxies in the early Universe as revealed by gravitational lensing

J. D. Vieira[1], D. P. Marrone[2], S. C. Chapman[3,4], C. De Breuck[5], Y. D. Hezaveh[6], A. Weiß[7], J. E. Aguirre[8], K. A. Aird[9], M. Aravena[5], M. L. N. Ashby[10], M. Bayliss[11], B. A. Benson[12,13], A. D. Biggs[5], L. E. Bleem[12,14], J. J. Bock[1,15], M. Bothwell[2], C. M. Bradford[15], M. Brodwin[16], J. E. Carlstrom[12,13,14,17,18], C. L. Chang[12,13,18], T. M. Crawford[12,17], A. T. Crites[12,17], T. de Haan[6], M. A. Dobbs[6], E. B. Fomalont[19], C. D. Fassnacht[20], E. M. George[21], M. D. Gladders[12,17], A. H. Gonzalez[22], T. R. Greve[23], B. Gullberg[5], N. W. Halverson[24], F. W. High[12,17], G. P. Holder[6], W. L. Holzapfel[21], S. Hoover[12,13], J. D. Hrubes[9], T. R. Hunter[19], R. Keisler[12,14], A. T. Lee[21,25], E. M. Leitch[12,17], M. Lueker[1], D. Luong-Van[9], M. Malkan[26], V. McIntyre[27], J. J. McMahon[12,13,28], J. Mehl[12,17], K. M. Menten[7], S. S. Meyer[12,13,14,17], L. M. Mocanu[12,17], E. J. Murphy[29], T. Natoli[12,14], S. Padin[1,12,17], T. Plagge[12,17], C. L. Reichardt[21], A. Rest[30], J. Ruel[11], J. E. Ruhl[31], K. Sharon[12,17,32], K. K. Schaffer[12,33], L. Shaw[6,34], E. Shirokoff[1], J. S. Spilker[2], B. Stalder[10], Z. Staniszewski[1,31], A. A. Stark[10], K. Story[12,14], K. Vanderlinde[6], N. Welikala[35] & R. Williamson[12,17]

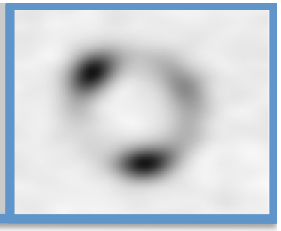
In the past decade, our understanding of galaxy evolution has been revolutionized by the discovery that luminous, dusty starburst galaxies were 1,000 times more abundant in the early Universe than at present[1,2]. It has, however, been difficult to measure the complete redshift distribution of these objects, especially at the highest redshifts ($z > 4$). Here we report a redshift survey at a wavelength of three millimetres, targeting carbon monoxide line emission from the star-forming molecular gas in the direction of extraordinarily bright millimetre-wave-selected sources. High-resolution imaging demonstrates that these sources are strongly gravitationally lensed by foreground galaxies. We detect spectral lines in 23 out of 26 sources and multiple lines in 12 of those 23 sources, from which we obtain robust, unambiguous redshifts. At least 10 of the sources are found to lie at $z > 4$, indicating that the fraction of dusty starburst galaxies at high redshifts is greater than previously thought. Models of lens geometries in the sample indicate that the background objects are ultra-luminous infrared galaxies, powered by extreme bursts of star formation.

We constructed a catalogue of high-redshift ($z > 1$) galaxy candidates from the first 1,300 square degrees of the South Pole Telescope (SPT)[3] survey by selecting sources with dust-like spectral indexes in the 1.4 and 2.0 mm SPT bands[4]. A remarkable aspect of selecting sources based on their flux at millimetre wavelengths is the so-called negative *k*-correction[5], whereby cosmological dimming is compensated by the steeply rising dust spectrum as the source redshift increases. As a result, a millimetre-wave-selected sample should draw from the redshift distribution of dusty starburst galaxies with little bias over the entire redshift range in which they are expected to exist. To isolate counterparts in the IRAS Faint Source Catalog[6] (typically $z < 0.03$) were removed, and those with counterparts in the 843 MHz Sydney University Molonglo Sky Survey[7] were removed to exclude sources with strong synchrotron emission (for example, flat-spectrum radio quasars) that may have passed the spectral index cut. A sample of 47 sources with 1.4-mm flux density >20 mJy and accurate positions were selected for high-resolution imaging with the Atacama Large Millimeter/submillimeter Array (ALMA). Our ALMA spectroscopic observations targeted a sample of 26 sources, all but two of which are in the imaging sample (see Supplementary Information). These objects are among the brightest dusty-spectrum sources in the $z > 0.1$ extragalactic sky at millimetre wavelengths.

Gravitationally lensed sources are expected to predominate in samples of the very brightest dusty galaxies because of the rarity of unlensed dusty starburst galaxies at these flux levels[8–10]. Massive elliptical galaxies, acting as lenses, will have Einstein radii as large as 2″ and may magnify background galaxies by factors of 10 or more. To confirm the lensing hypothesis and determine magnifications, we imaged 47 SPT sources with ALMA at 870 μm in two array configurations, which provide angular resolutions of 1.5″ and 0.5″ (full-width at half-maximum). A sample of these objects with infrared imaging, spectroscopic redshifts and resolved structure is shown in Fig. 1. Integration times of only one minute per source are adequate to show that most sources are resolved into arcs or Einstein rings—hallmarks of gravitational lensing. For all sources for which we have infrared and submillimetre imaging, as well as spectroscopic redshifts, the emission detected by ALMA coincides with massive foreground galaxies or galaxy groups/clusters but is spatially distinct and at drastically different

ALMA: Atacama **L**arge (sub-)**M**illimeter **A**rray

ALMA gets into *Nature*



LETTER

doi:10.1038/nature12001

Dusty starburst galaxies in the early Universe as revealed by gravitational lensing

J. D. Vieira[1], D. P. Marrone[2], S. C. Chapman[3,4], C. De Breuck[5], Y. D. Hezaveh[6], A. Weiß[7], J. E. Aguirre[8], K. A. Aird[9], M. Aravena[5], M. L. N. Ashby[10], M. Bayliss[11], B. A. Benson[12,13], A. D. Biggs[5], L. E. Bleem[12,14], J. J. Bock[1,15], M. Bothwell[2], C. M. Bradford[15], M. Brodwin[16], J. E. Carlstrom[12,13,14,17,18], C. L. Chang[12,13,18], T. M. Crawford[12,17], A. T. Crites[12,17], T. de Haan[6], M. A. Dobbs[6], E. B. Fomalont[19], C. D. Fassnacht[20], E. M. George[21], M. D. Gladders[12,17], A. H. Gonzalez[22], T. R. Greve[23], B. Gullberg[5], N. W. Halverson[24], F. W. High[12,17], G. P. Holder[6], W. L. Holzapfel[21], S. Hoover[12,13], J. D. Hrubes[9], T. R. Hunter[19], R. Keisler[12,14], A. T. Lee[21,25], E. M. Leitch[12,17], M. Lueker[1], D. Luong-Van[9], M. Malkan[26], V. McIntyre[27], J. J. McMahon[12,13,28], J. Mehl[12,17], K. M. Menten[7], S. S. Meyer[12,13,14,17], L. M. Mocanu[12,17], E. J. Murphy[29], T. Natoli[12,14], S. Padin[1,12,17], T. Plagge[12,17], C. L. Reichardt[21], A. Rest[30], J. Ruel[11], J. E. Ruhl[31], K. Sharon[12,17,32], K. K. Schaffer[12,33], L. Shaw[6,34], E. Shirokoff[1], J. S. Spilker[2], B. Stalder[10], Z. Staniszewski[1,31], A. A. Stark[10], K. Story[12,14], K. Vanderlinde[6], N. Welikala[35] & R. Williamson[12,17]

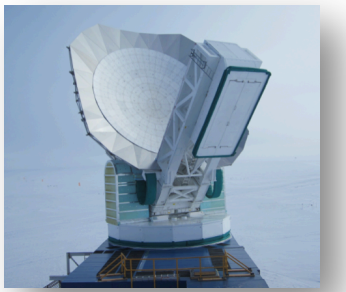
In the past decade, our understanding of galaxy evolution has been revolutionized by the discovery that luminous, dusty starburst galaxies were 1,000 times more abundant in the early Universe than at present[1,2]. It has, however, been difficult to measure the complete redshift distribution of these objects, especially at the highest redshifts ($z > 4$). Here we report a redshift survey at a wavelength of three millimetres, targeting carbon monoxide line emission from the star-forming molecular gas in the direction of extraordinarily bright millimetre-wave-selected sources. High-resolution imaging demonstrates that these sources are strongly gravitationally lensed by foreground galaxies. We detect spectral lines in 23 out of 26 sources and multiple lines in 12 of those 23 sources, from which we obtain robust, unambiguous redshifts. At least 10 of the sources are found to lie at $z > 4$, indicating that the fraction of dusty starburst galaxies at high redshifts is greater than previously thought. Models of lens geometries in the sample indicate that the background objects are ultra-luminous infrared galaxies, powered by extreme bursts of star formation.

We constructed a catalogue of high-redshift ($z > 1$) galaxy candidates from the first 1,300 square degrees of the South Pole Telescope (SPT)[3] survey by selecting sources with dust-like spectral indexes in the 1.4 and 2.0 mm SPT bands[4]. A remarkable aspect of selecting sources based on their flux at millimetre wavelengths is the so-called negative k-correction[5], whereby cosmological dimming is compensated by the steeply rising dust spectrum as the source redshift increases. As a result, a millimetre-wave-selected sample should draw from the redshift distribution of dusty starburst galaxies with little bias over the entire redshift range in which they are expected to exist. To isolate counterparts in the IRAS Faint Source Catalog[6] (typically $z < 0.03$) were removed, and those with counterparts in the 843 MHz Sydney University Molonglo Sky Survey[7] were removed to exclude sources with strong synchrotron emission (for example, flat-spectrum radio quasars) that may have passed the spectral index cut. A sample of 47 sources with 1.4-mm flux density >20 mJy and accurate positions were selected for high-resolution imaging with the Atacama Large Millimeter/submillimeter Array (ALMA). Our ALMA spectroscopic observations targeted a sample of 26 sources, all but two of which are in the imaging sample (see Supplementary Information). These objects are among the brightest dusty-spectrum sources in the $z > 0.1$ extragalactic sky at millimetre wavelengths.

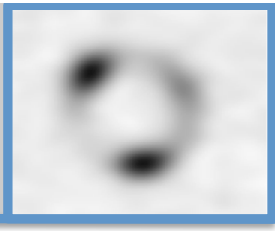
Gravitationally lensed sources are expected to predominate in samples of the very brightest dusty galaxies because of the rarity of unlensed dusty starburst galaxies at these flux levels[8–10]. Massive elliptical galaxies, acting as lenses, will have Einstein radii as large as 2″ and may magnify background galaxies by factors of 10 or more. To confirm the lensing hypothesis and determine magnifications, we imaged 47 SPT sources with ALMA at 870 μm in two array configurations, which provide angular resolutions of 1.5″ and 0.5″ (full-width at half-maximum). A sample of these objects with infrared imaging, spectroscopic redshifts and resolved structure is shown in Fig. 1. Integration times of only one minute per source are adequate to show that most sources are resolved into arcs or Einstein rings—hallmarks of gravitational lensing. For all sources for which we have infrared and submillimetre imaging, as well as spectroscopic redshifts, the emission detected by ALMA coincides with massive foreground galaxies or galaxy groups/clusters but is spatially distinct and at drastically different

SPT: South Pole Telescope

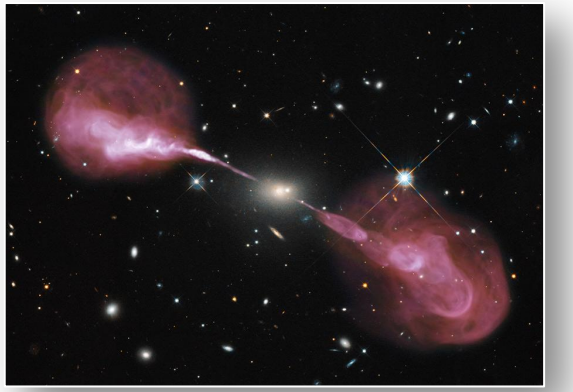
- Funded by U.S. NFS
- 10m telescope
- 1 deg^2 FoV
- **~1 arcmin** beam
- 3 bands: **1.4mm**, **2mm**, **3mm**
- Rms: ~ few mJy/beam
- Survey of **2500 deg^2**



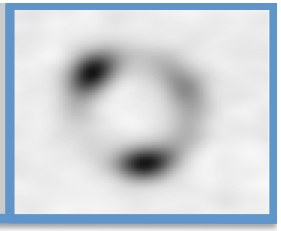
SPT-detected sources



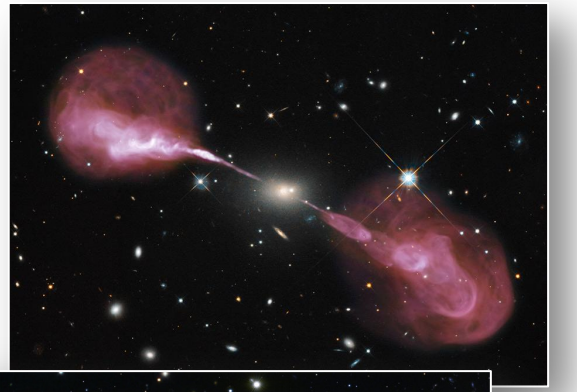
- **AGN-powered radio sources**



SPT-detected sources

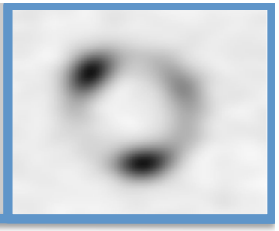


- **AGN-powered radio sources**

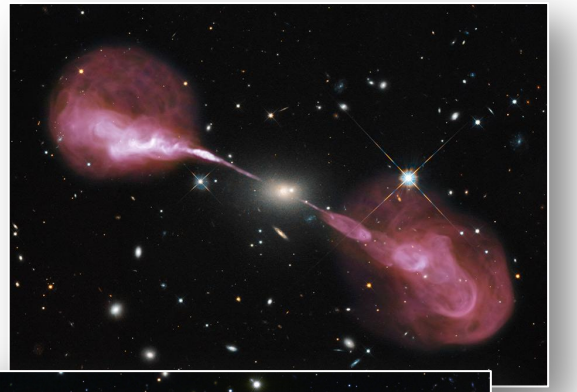


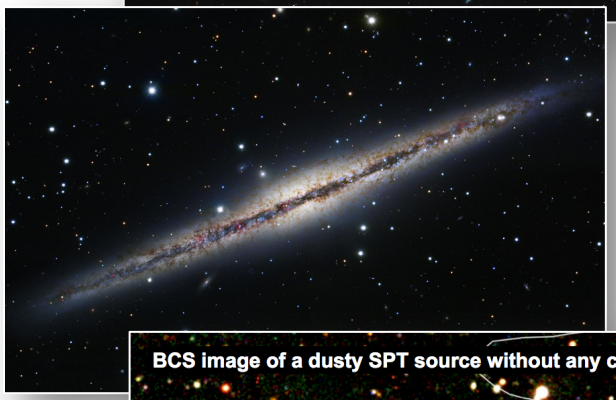
- **z ~< 0.1 late-type galaxies**

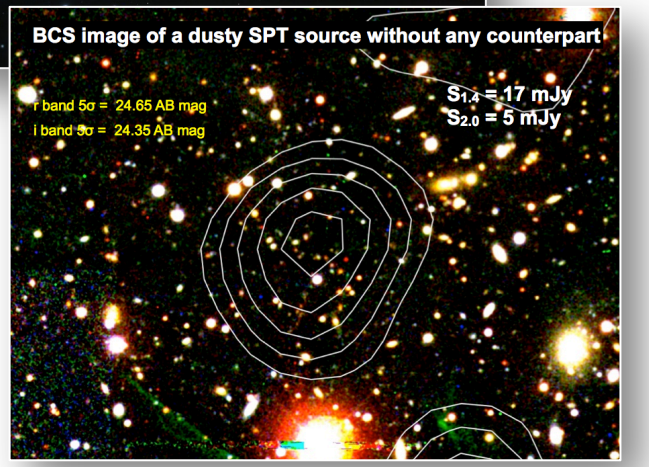
SPT-detected sources



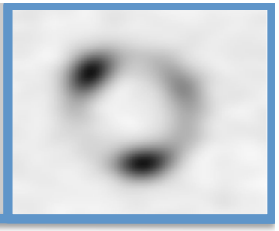
- AGN-powered radio sources
- z ~< 0.1 late-type galaxies
- dusty LENSED galaxies at z>1



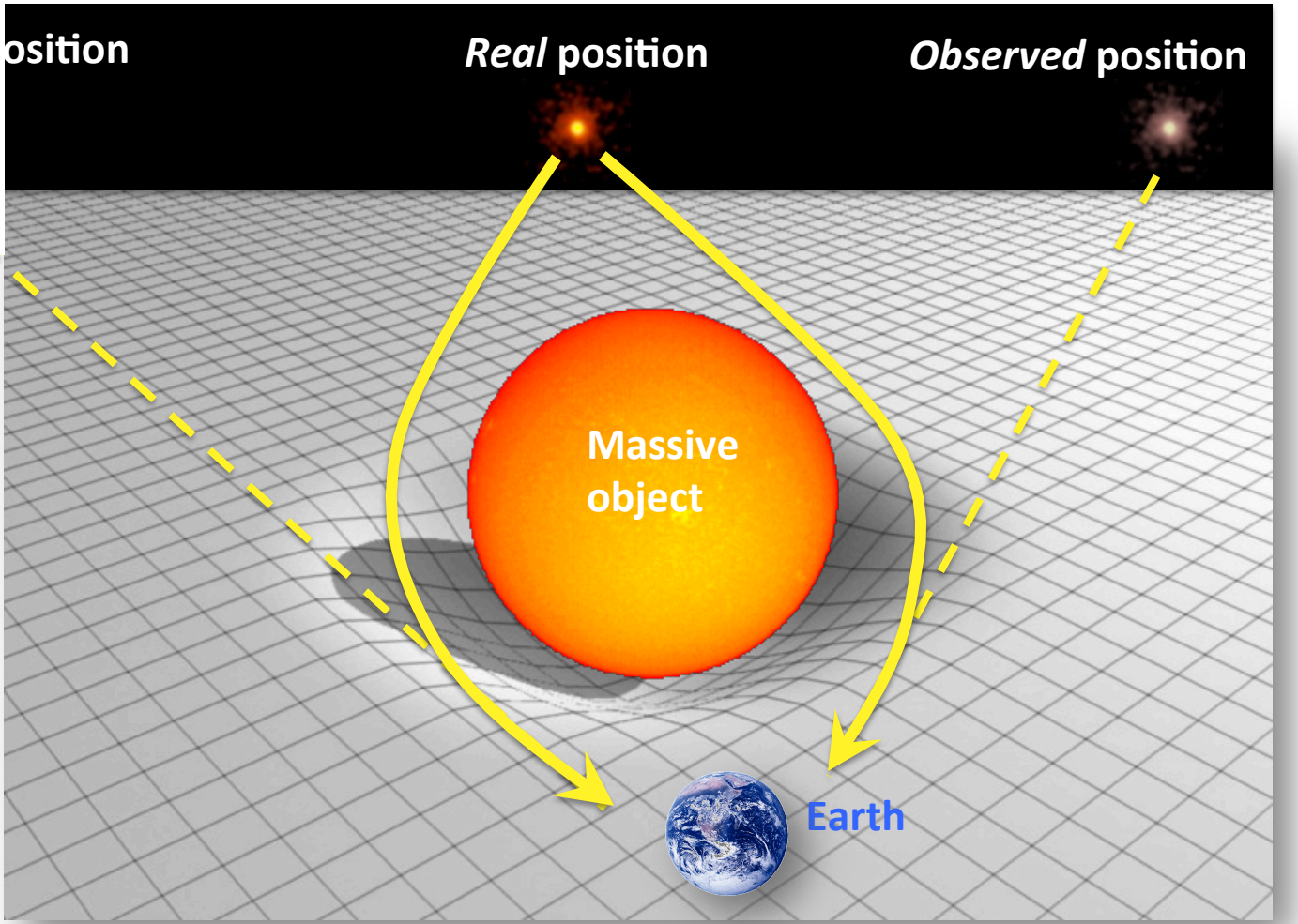




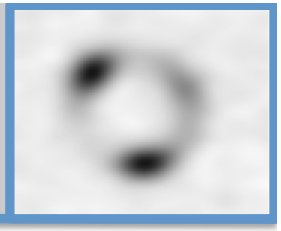
Strong gravitational lensing



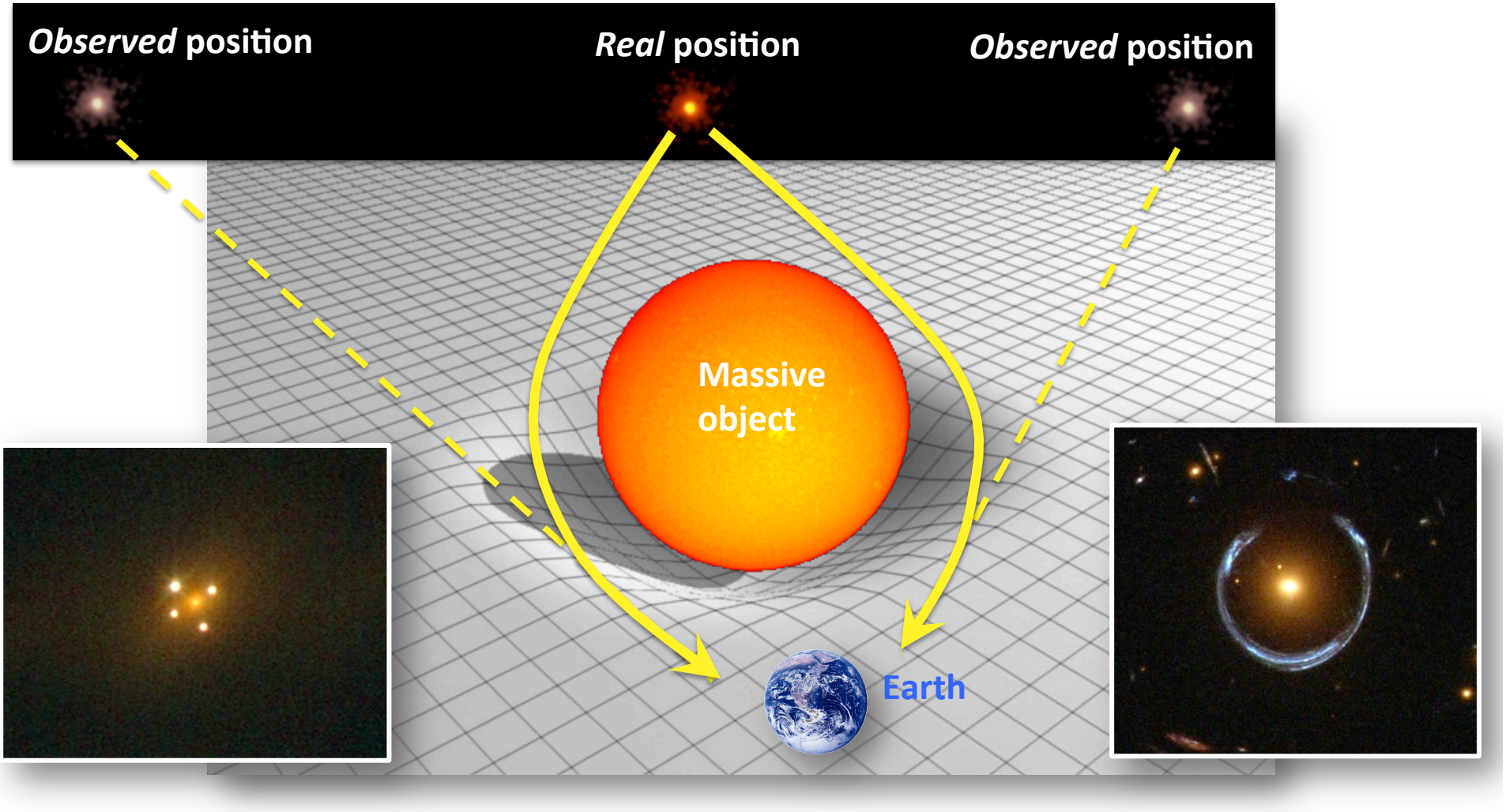
Almost **perfect alignment** Earth-Lens-Source



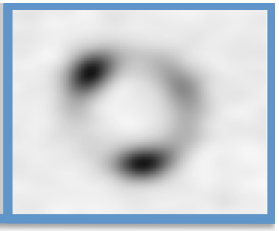
Strong gravitational lensing



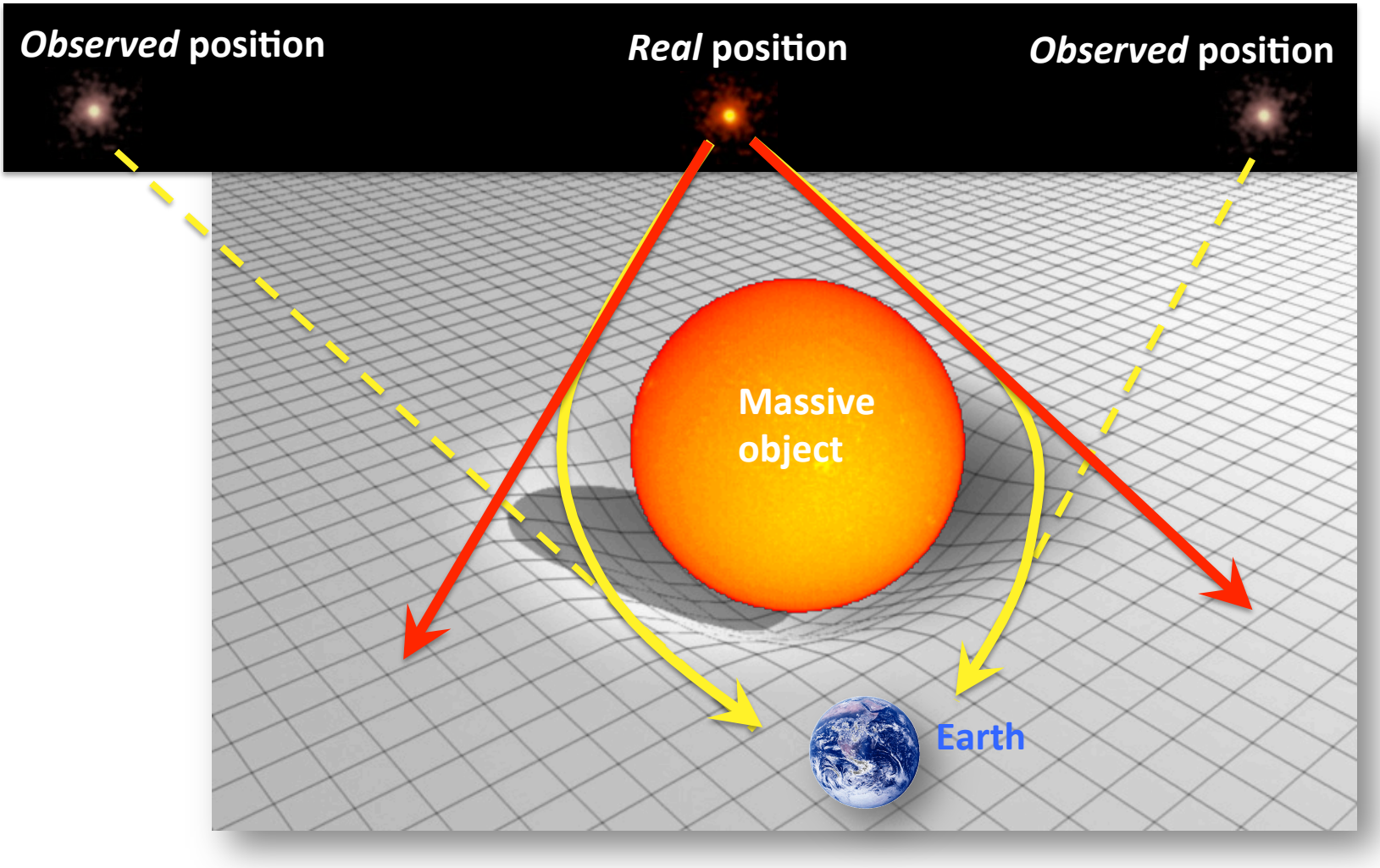
Formation of **multiple images**



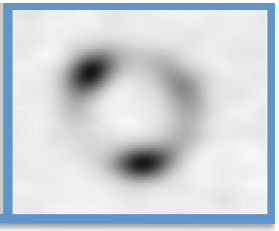
Strong gravitational lensing

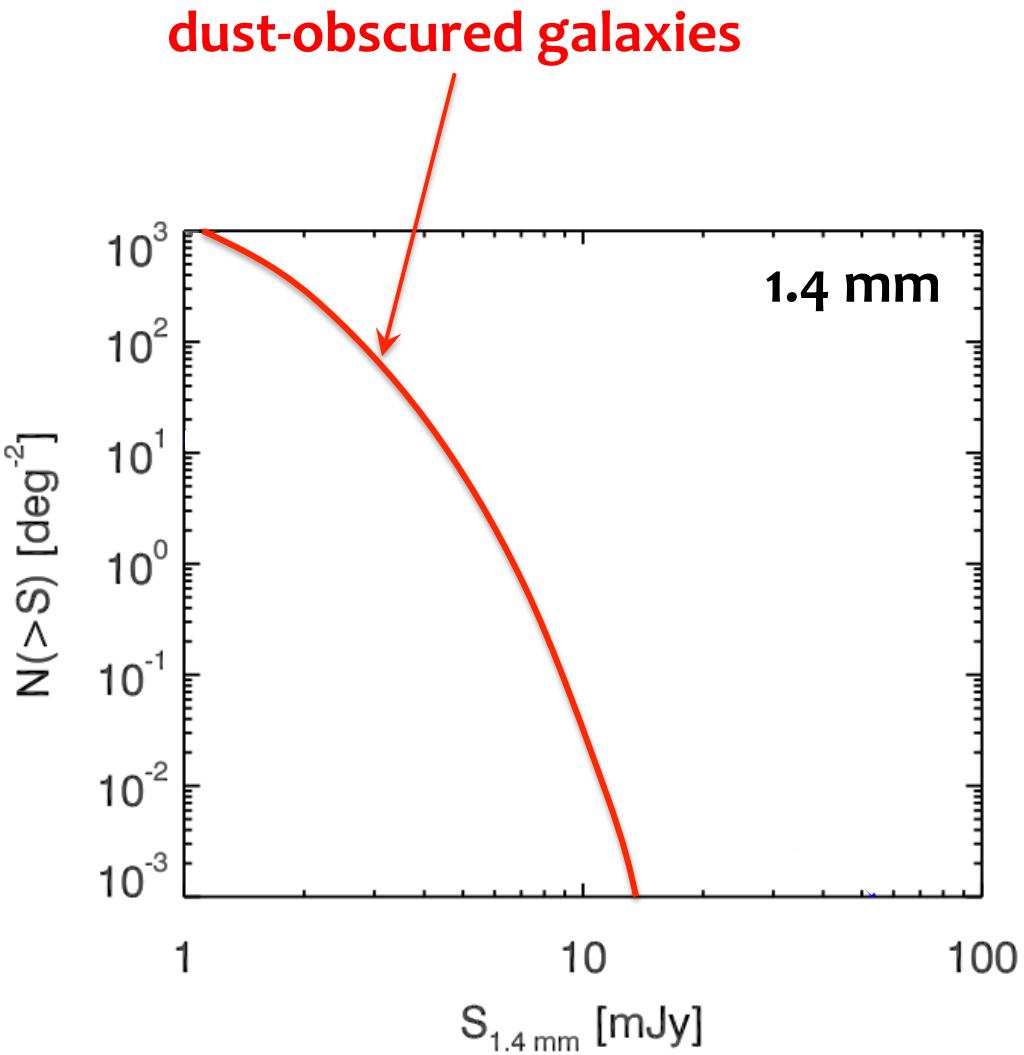


Formation of **multiple images**

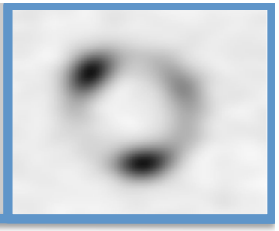


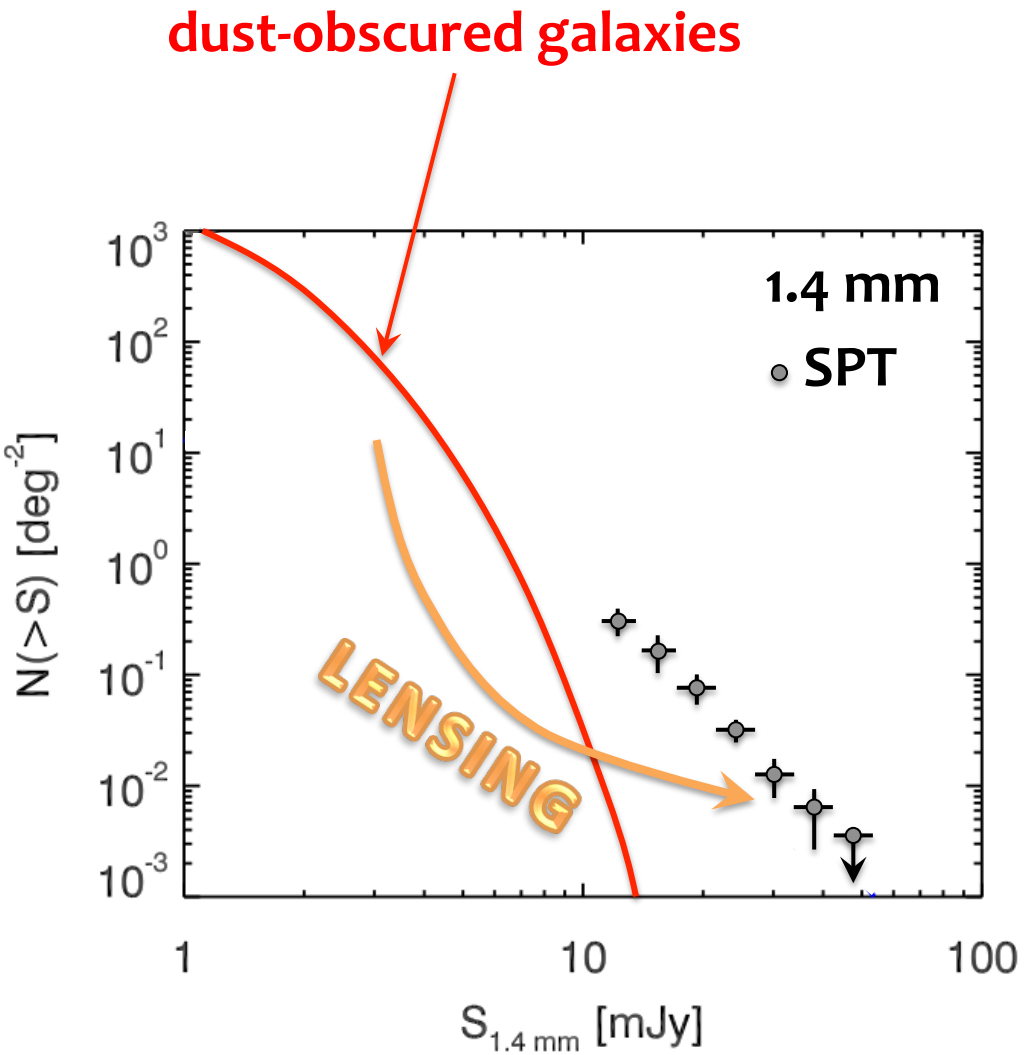
Number counts of dusty galaxies



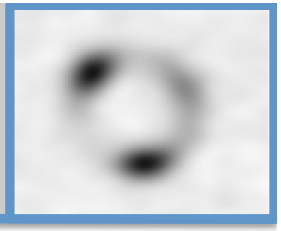


Number counts of dusty galaxies

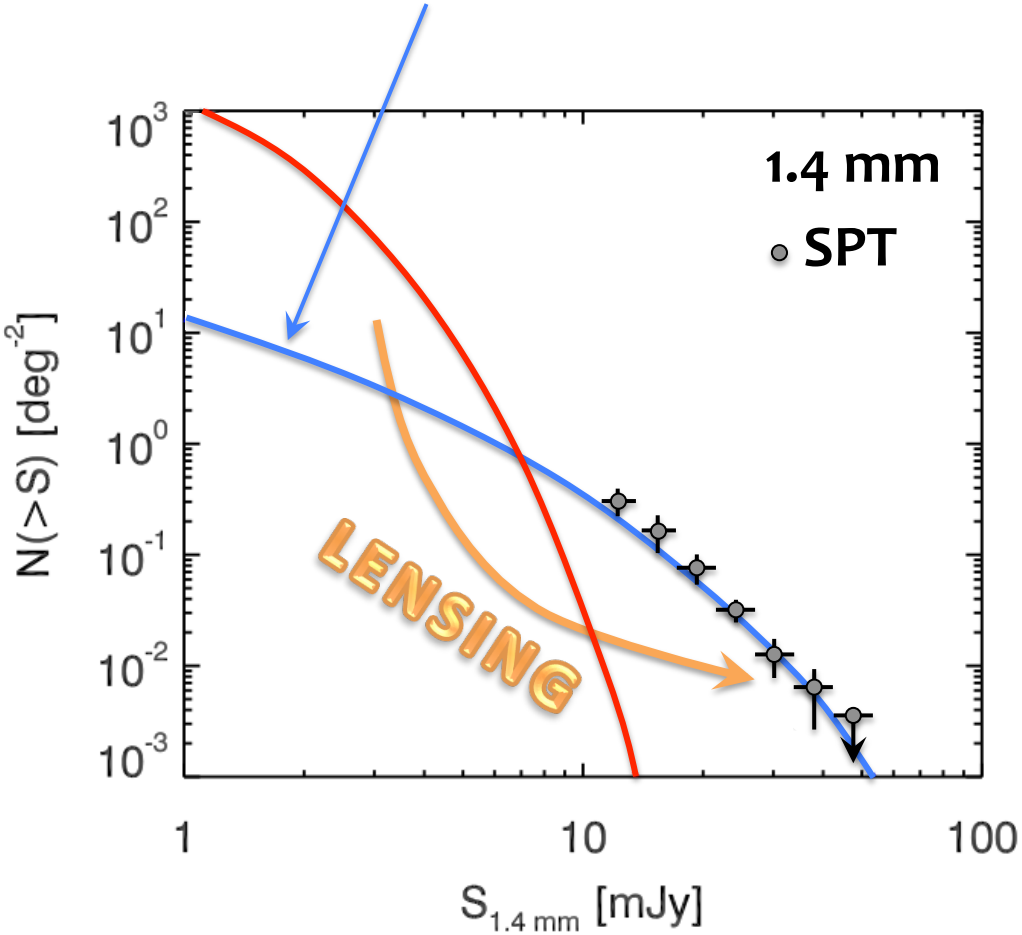


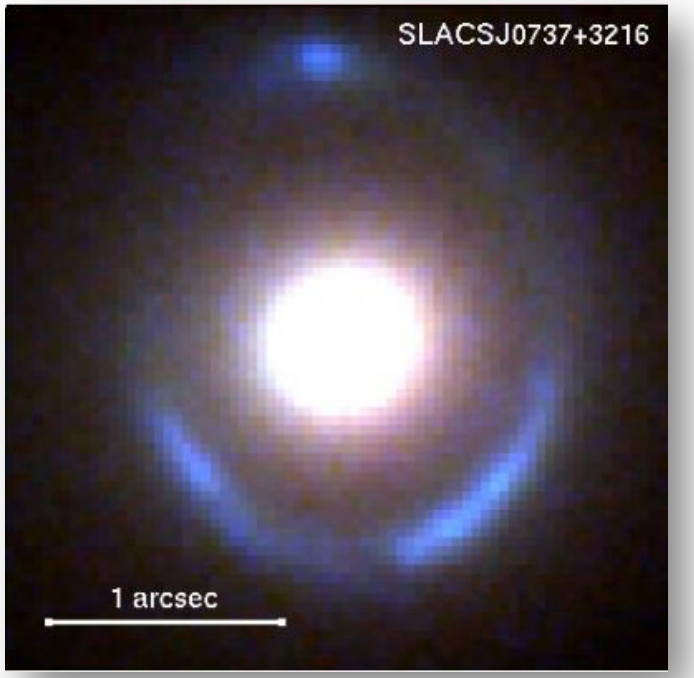


Number counts of dusty galaxies

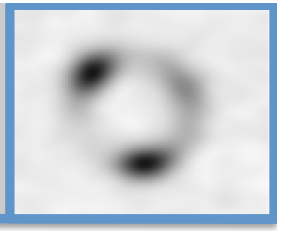


Lensed dusty galaxies predicted by *Negrello et al. 2007*

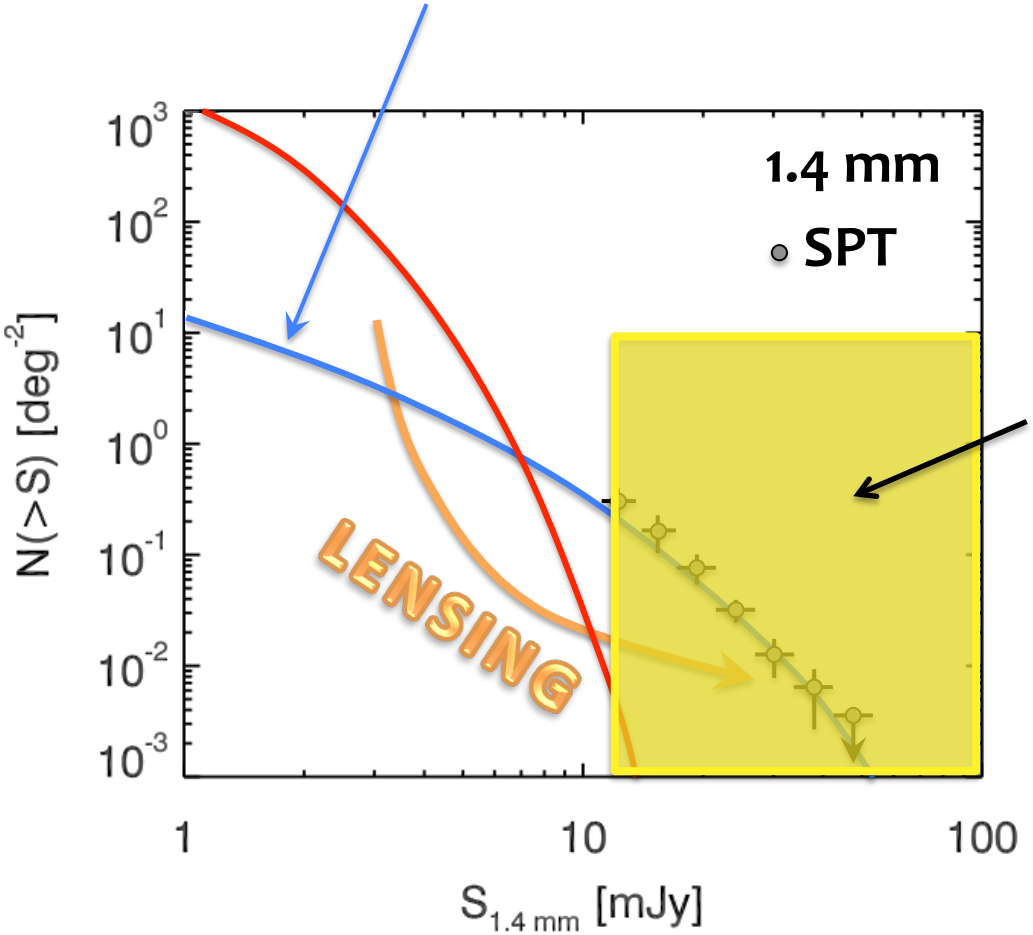




Number counts of dusty galaxies

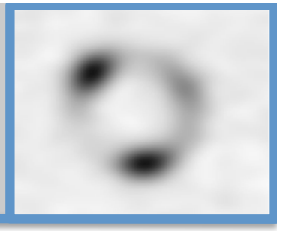


Lensed dusty galaxies predicted by *Negrello et al. 2007*

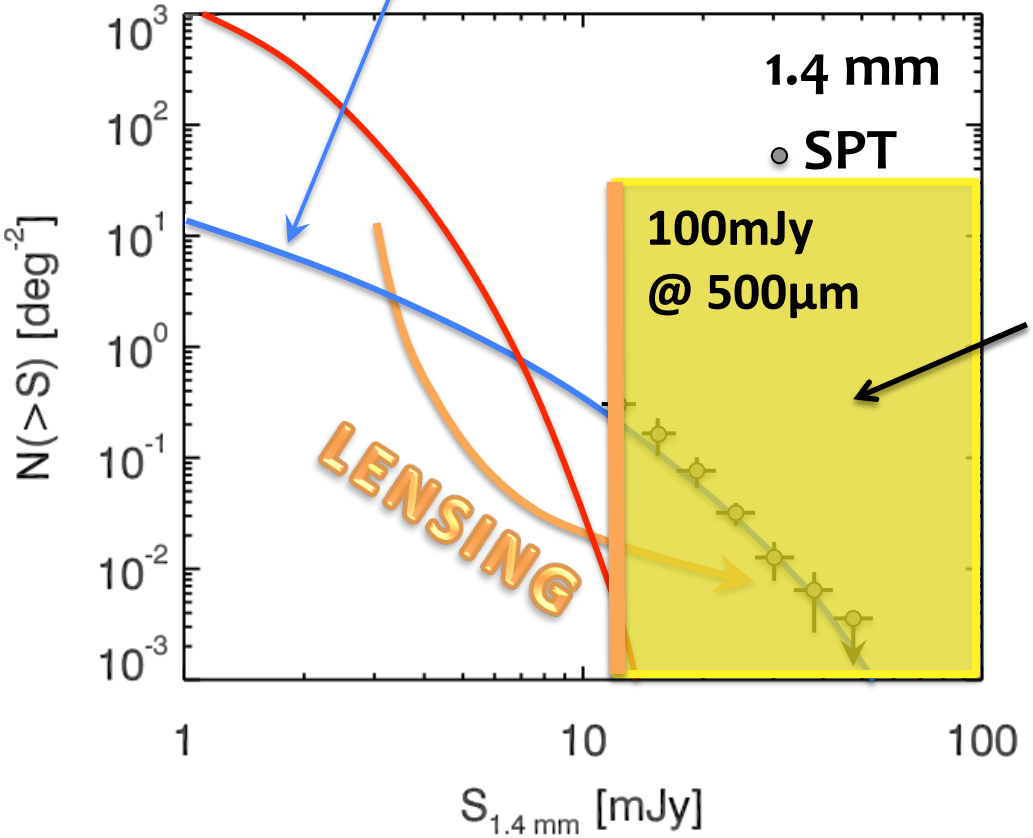


Efficient selection of lensed galaxies

Number counts of dusty galaxies



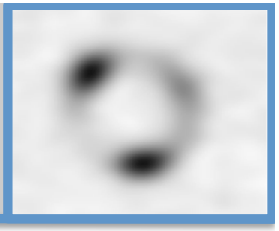
Lensed dusty galaxies predicted by *Negrello et al. 2007*



Efficient selection of lensed galaxies @ $F_{500\mu m}$>100mJy

Negrello et al. (2007)

H-ATLAS: first lensed galaxies



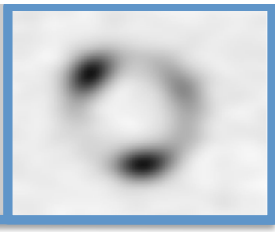
ASTROPHYSICAL
TERAHERTZ
LARGE
AREA
SURVEY

http://www.h-atlas.org/

Area = 550 deg²

- **100 μm**
- **160 μm**
- **250 μm**
- **350 μm**
- **500 μm**

H-ATLAS: first lensed galaxies

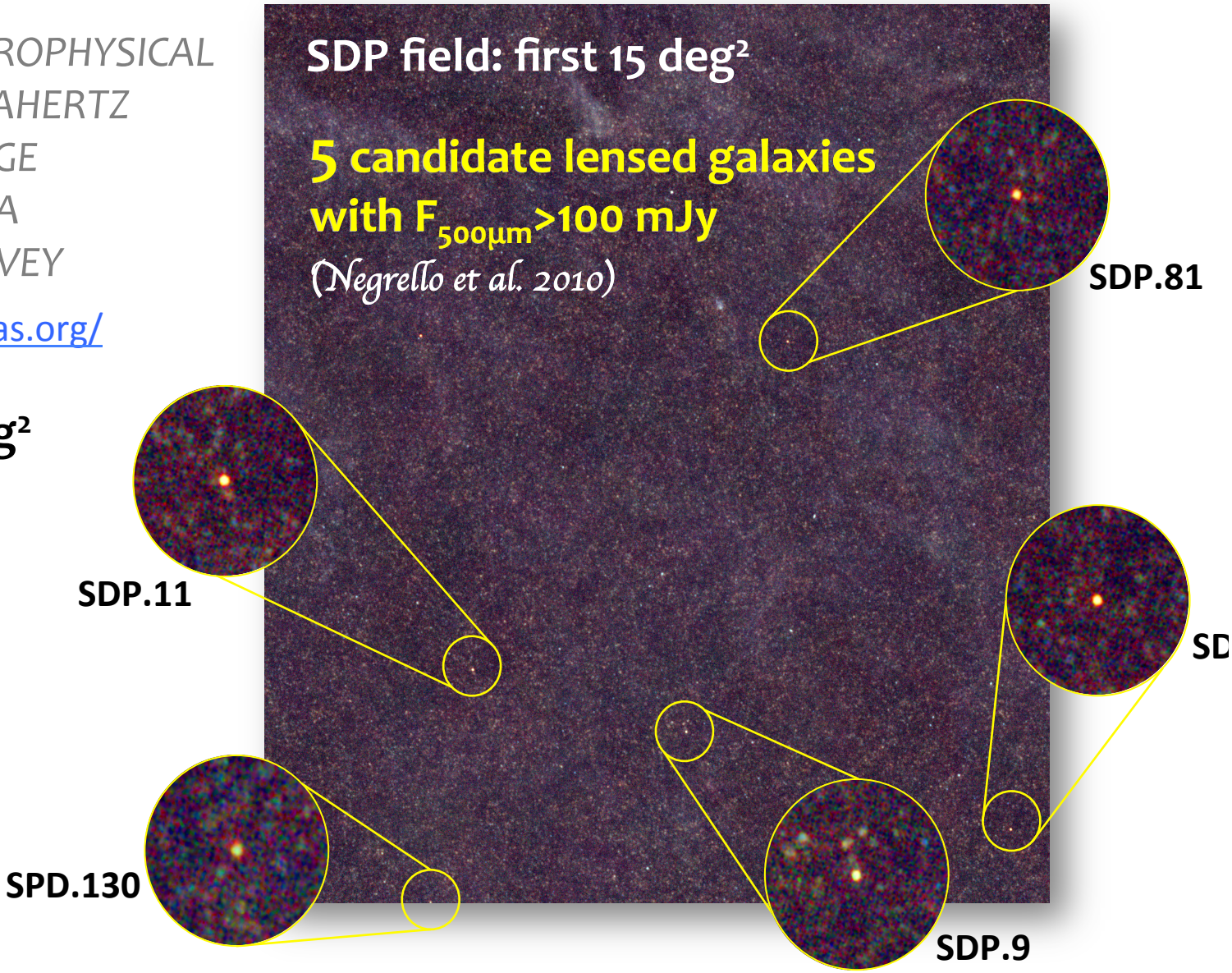


ASTROPHYSICAL
TERAHERTZ
LARGE
AREA
SURVEY

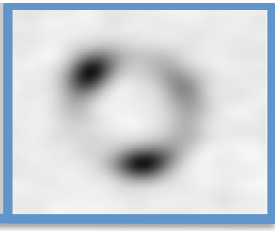
http://www.h-atlas.org/

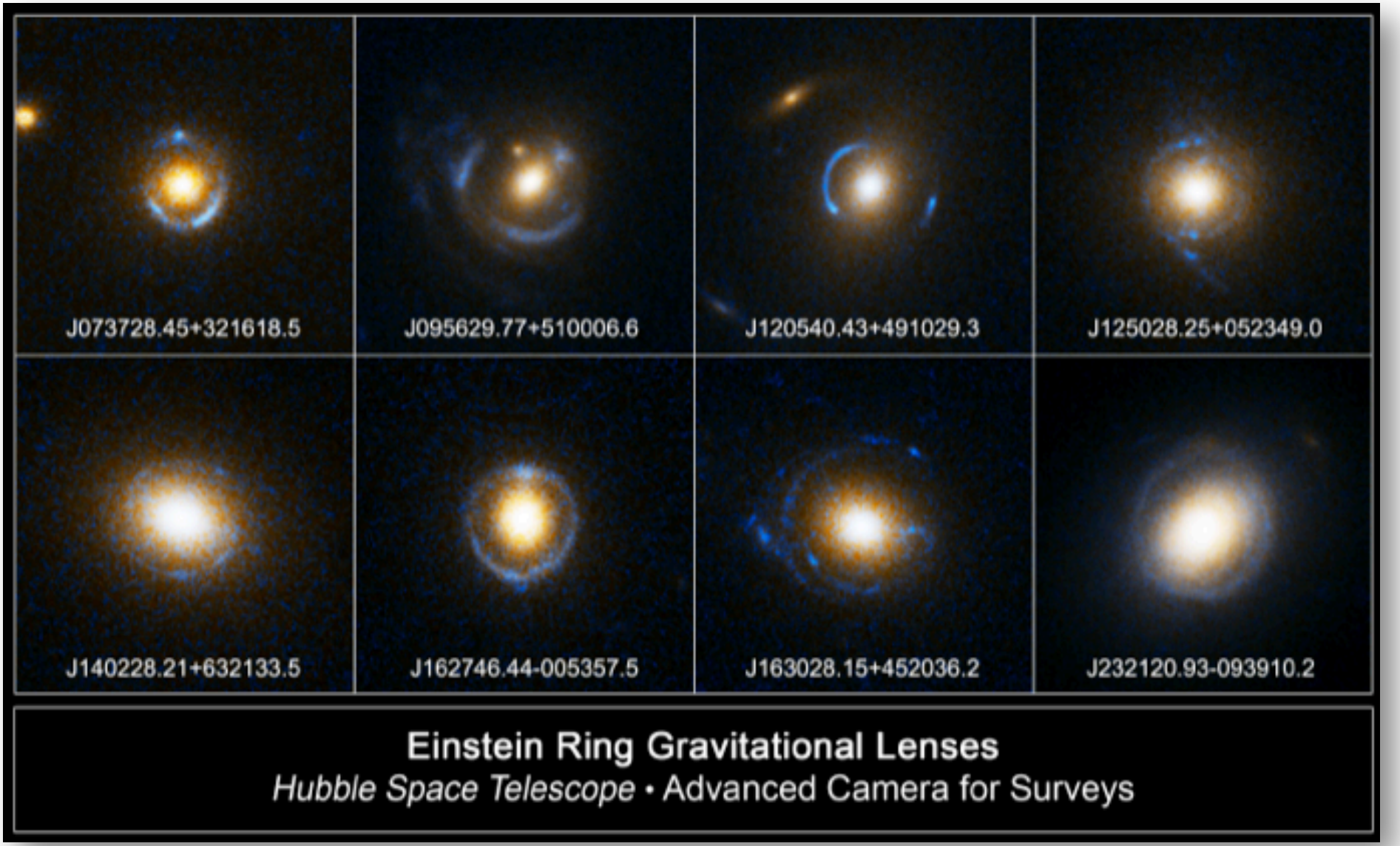
Area = 550 deg²

- **100 μm**
- **160 μm**
- **250 μm**
- **350 μm**
- **500 μm**

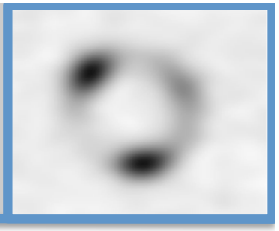


H-ATLAS: first lensed galaxies

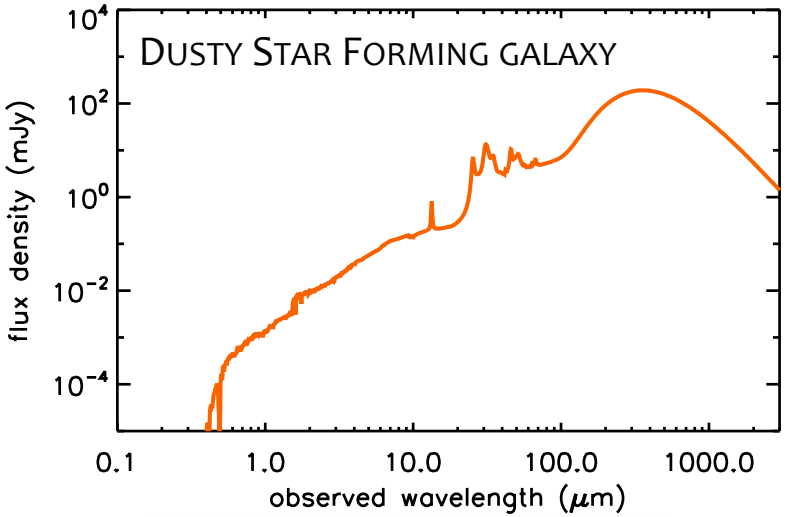


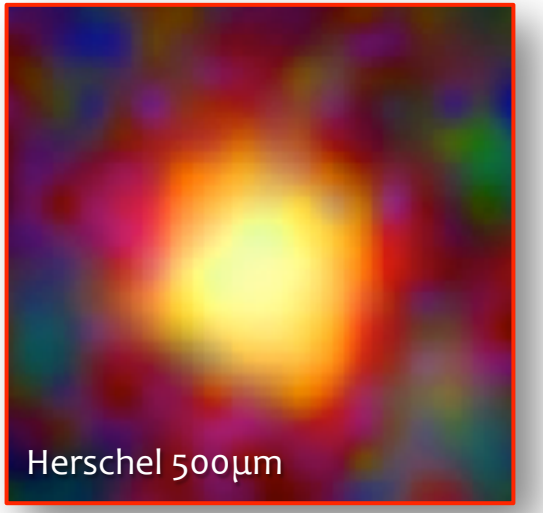


Sub-mm/mm lensed galaxies

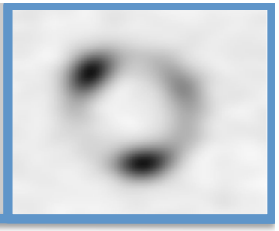


LENSED SOURCE

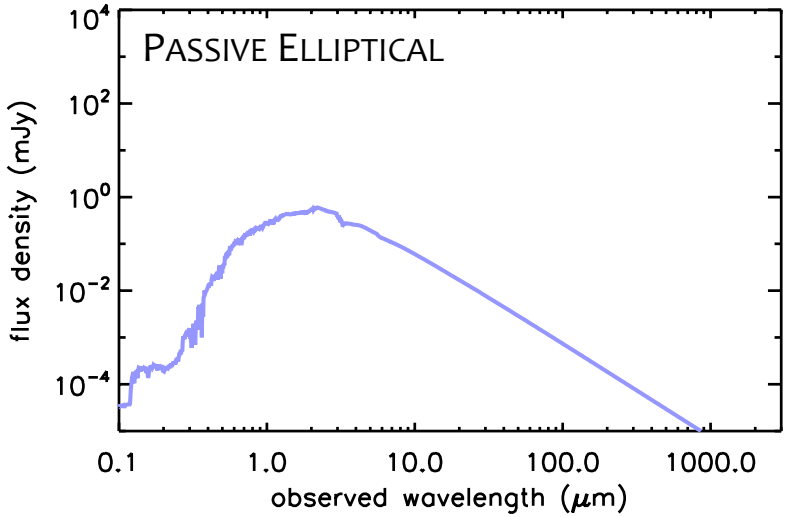


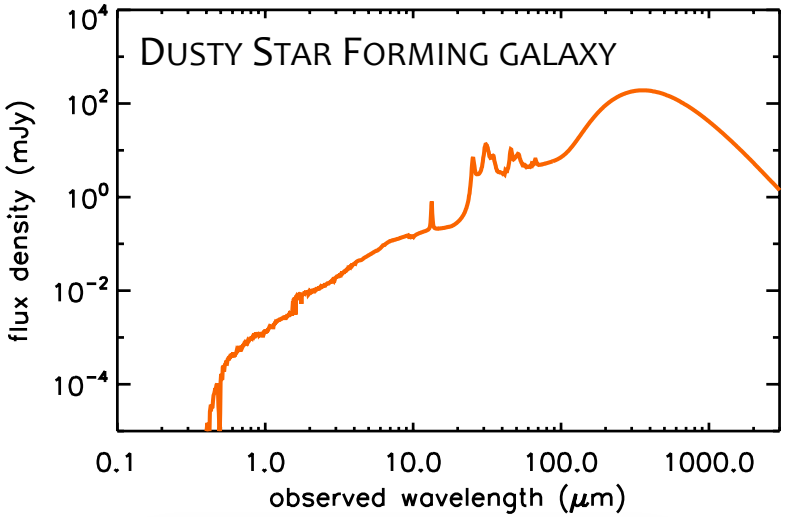


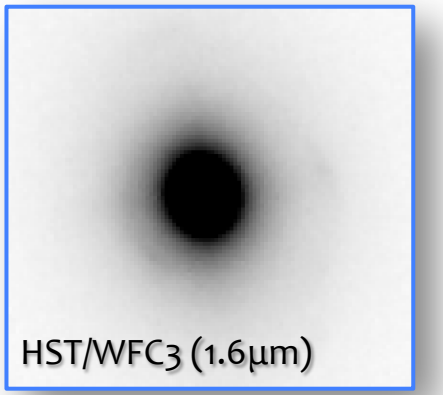
Sub-mm/mm lensed galaxies

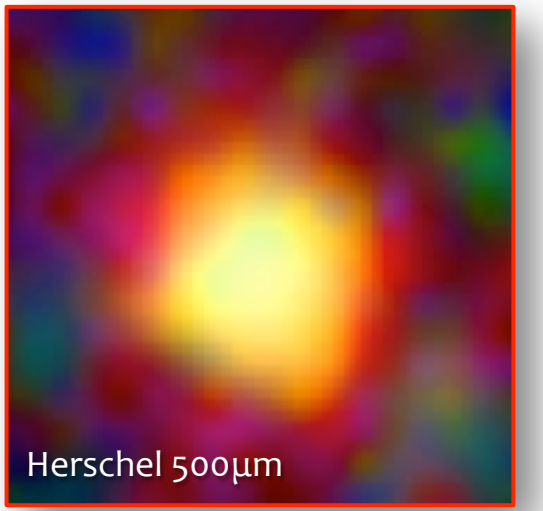


LENS **+** **LENSED SOURCE**

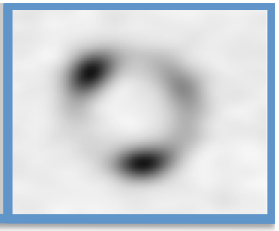






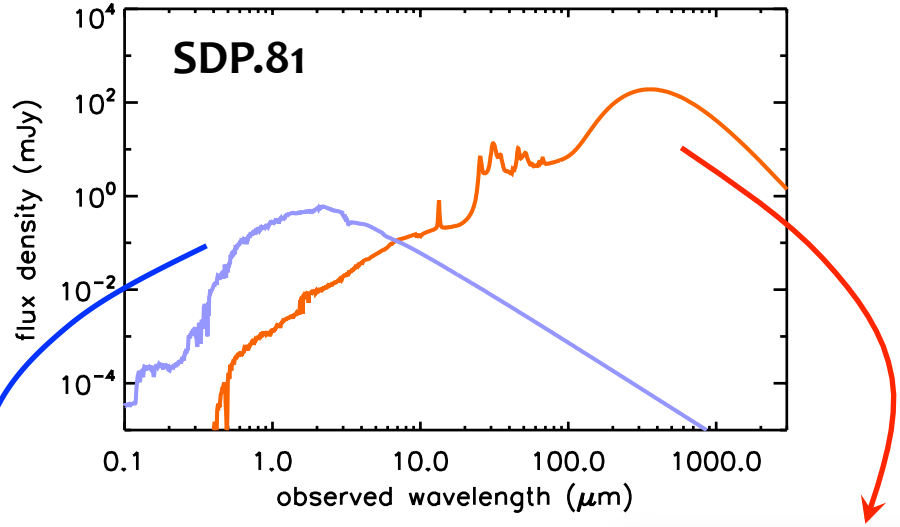


Sub-mm/mm lensed galaxies

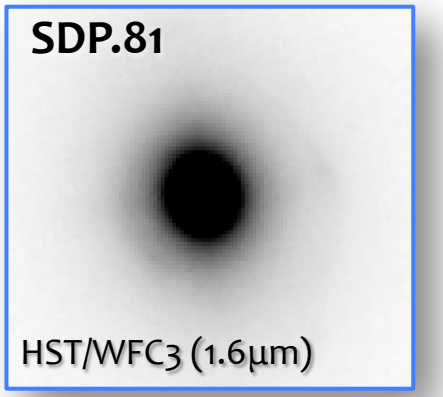


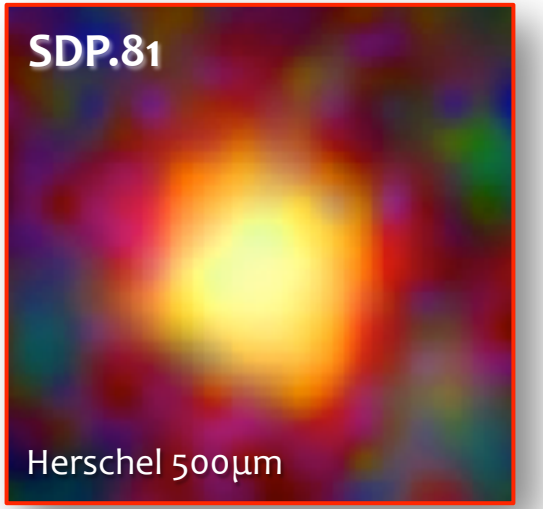
LENS + LENSED SOURCE

Hubble Space Telescope

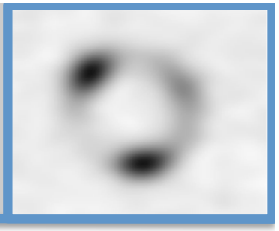


Herschel Space Observatory



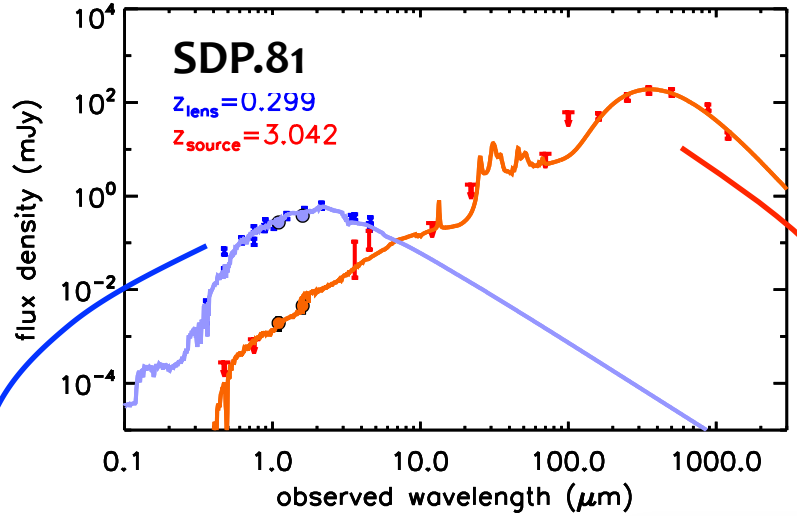


Sub-mm/mm lensed galaxies

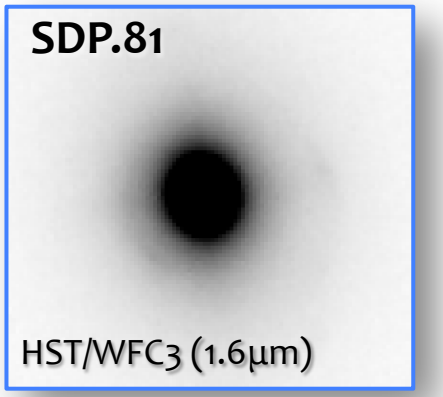


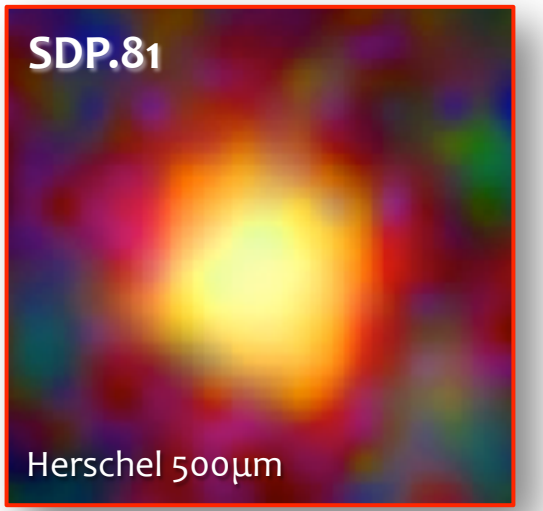
LENS + LENSED SOURCE

Hubble Space Telescope

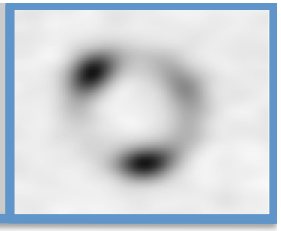


Herschel Space Observatory



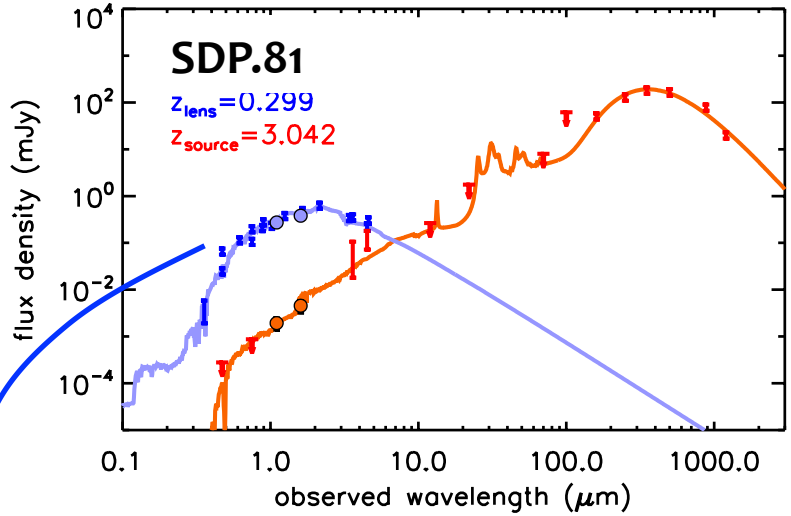


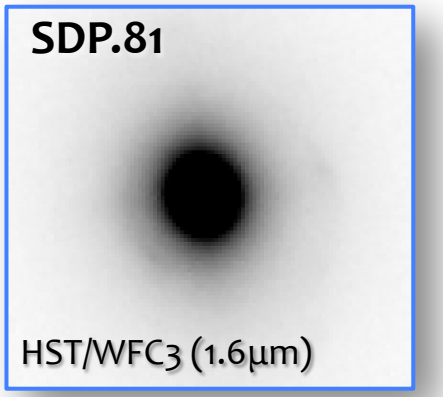
Sub-mm/mm lensed galaxies



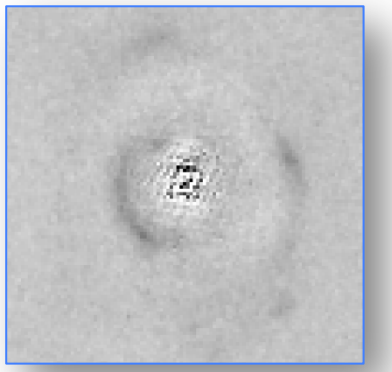
LENS + LENSED SOURCE

Hubble Space Telescope



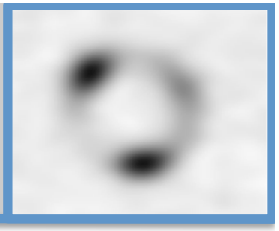


lens subtraction



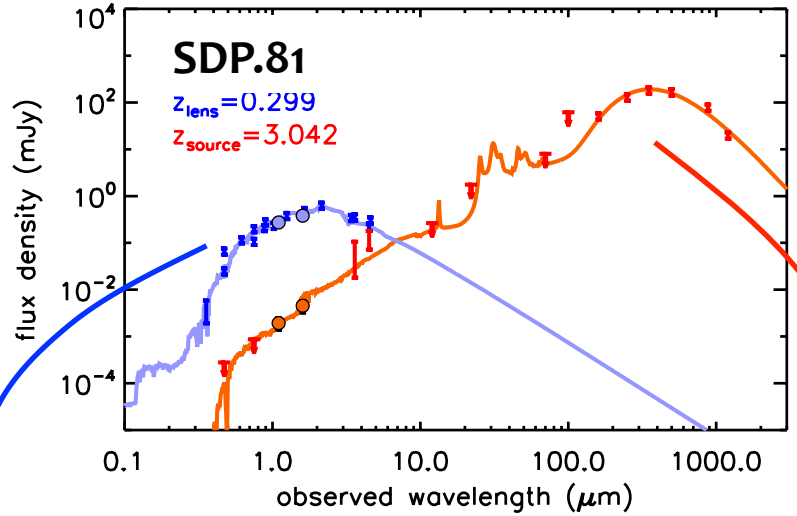
Negrello et al. (2014)

Sub-mm/mm lensed galaxies

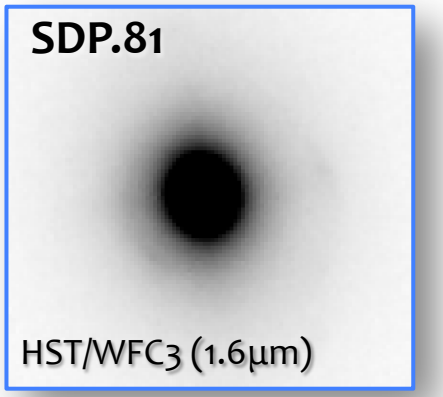


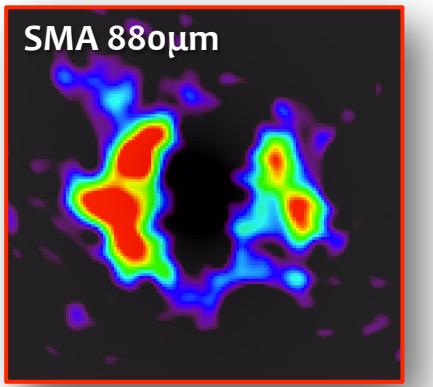
LENS + LENSED SOURCE

Hubble Space Telescope



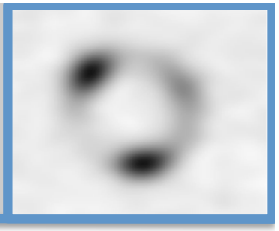
Sub-Millimeter Array





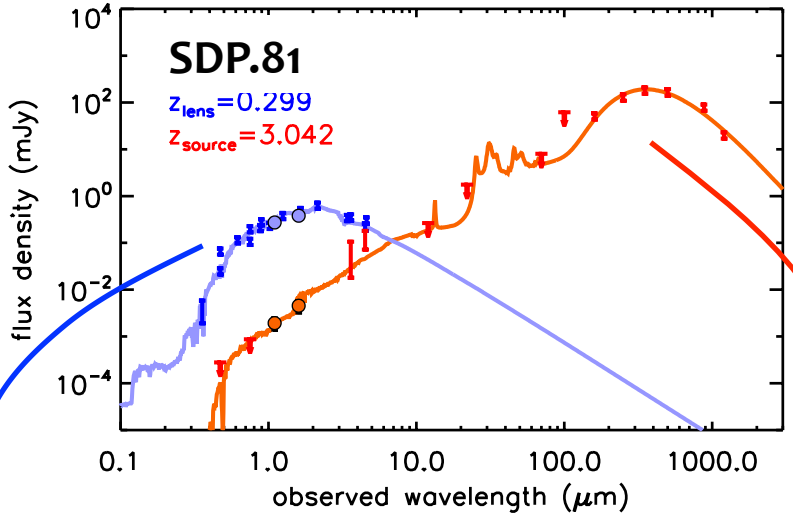
Negrello et al. (2010, Science)

Sub-mm/mm lensed galaxies

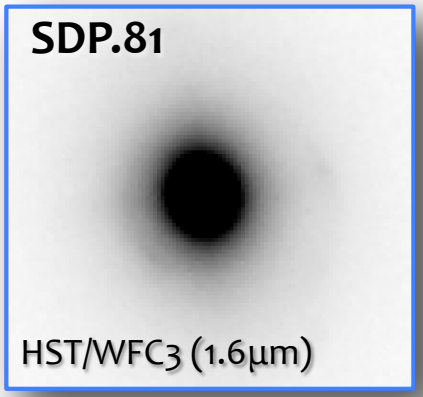


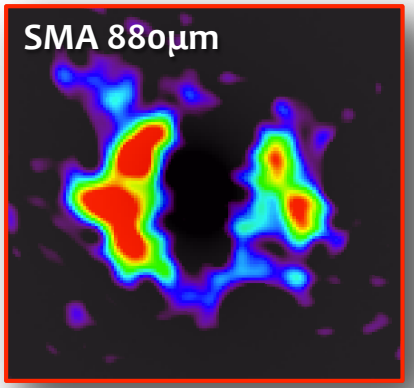
LENS + LENSED SOURCE

Hubble Space Telescope



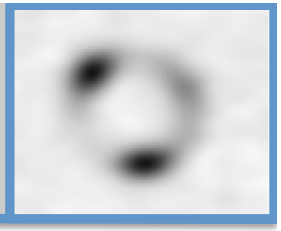
Sub-Millimeter Array





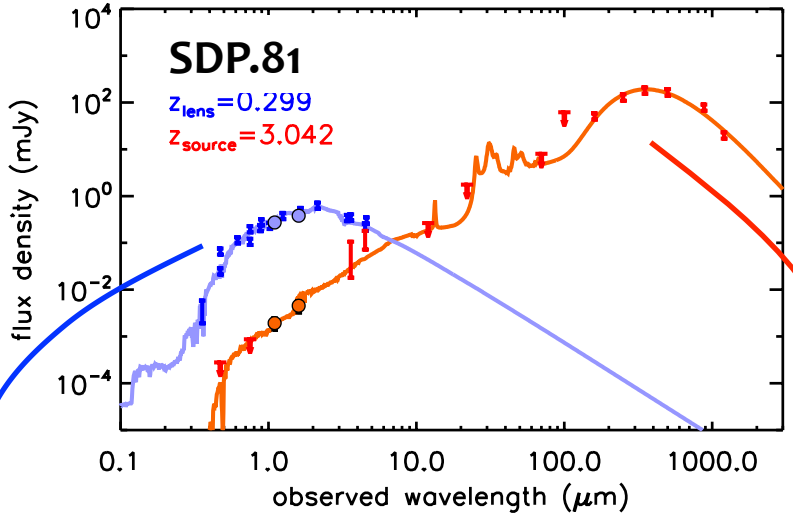
Negrello et al. (2010, Science)

Sub-mm/mm lensed galaxies

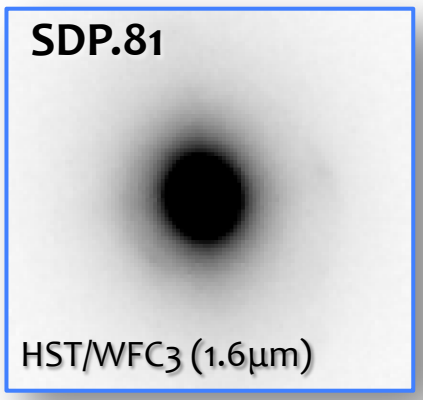


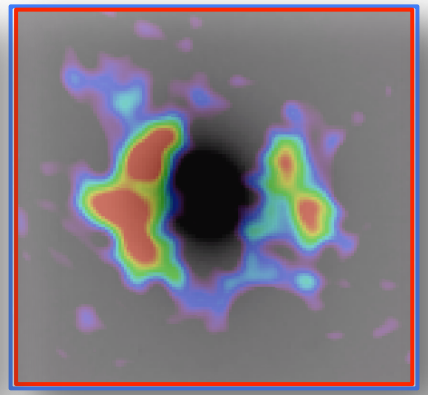
LENS + LENSED SOURCE

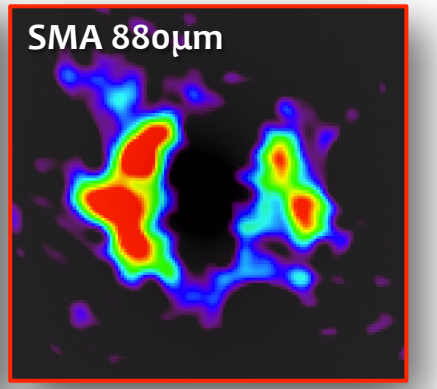
Hubble Space Telescope



Sub-Millimeter Array

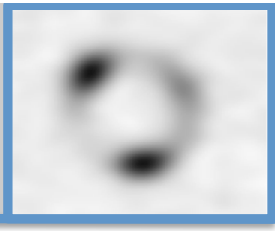






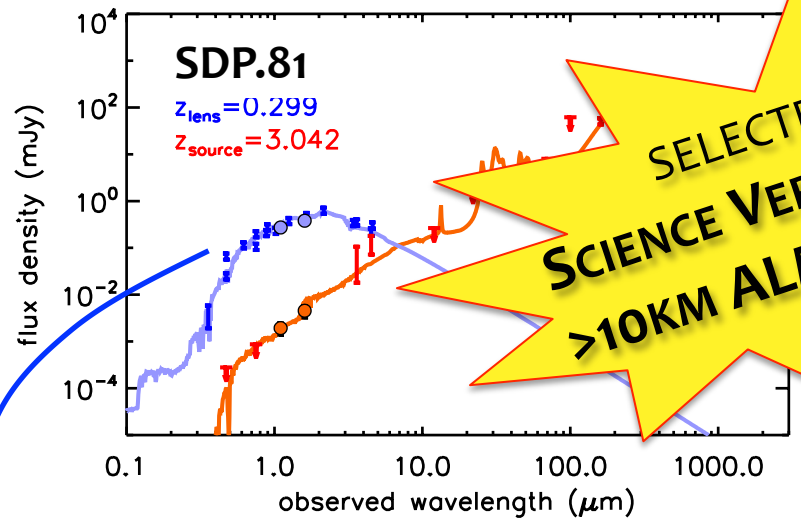
Negrello et al. (2010, Science)

Sub-mm/mm lensed galaxies



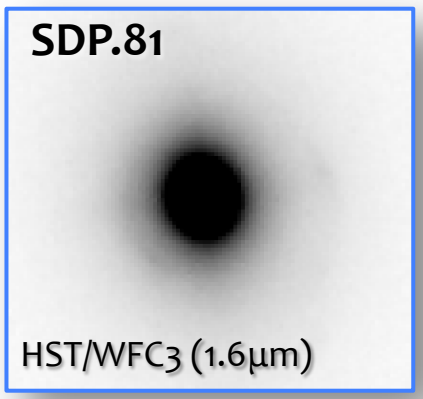
LENS + LENSED SOURCE

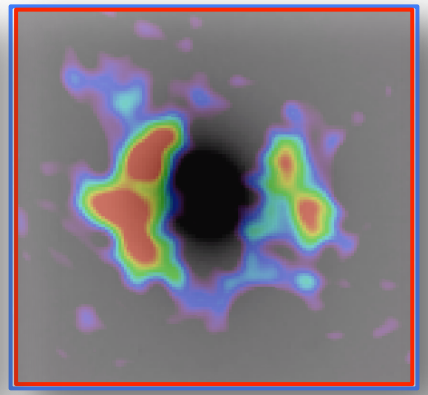
Hubble Space Telescope

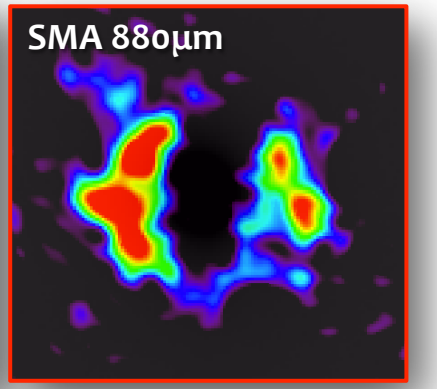


SELECTED FOR **SCIENCE VERIFICATION** OF **>10KM ALMA BASELINES**

Sub-Millimeter Array

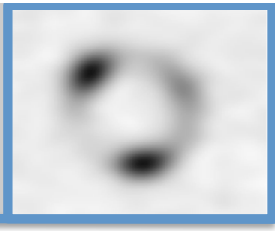


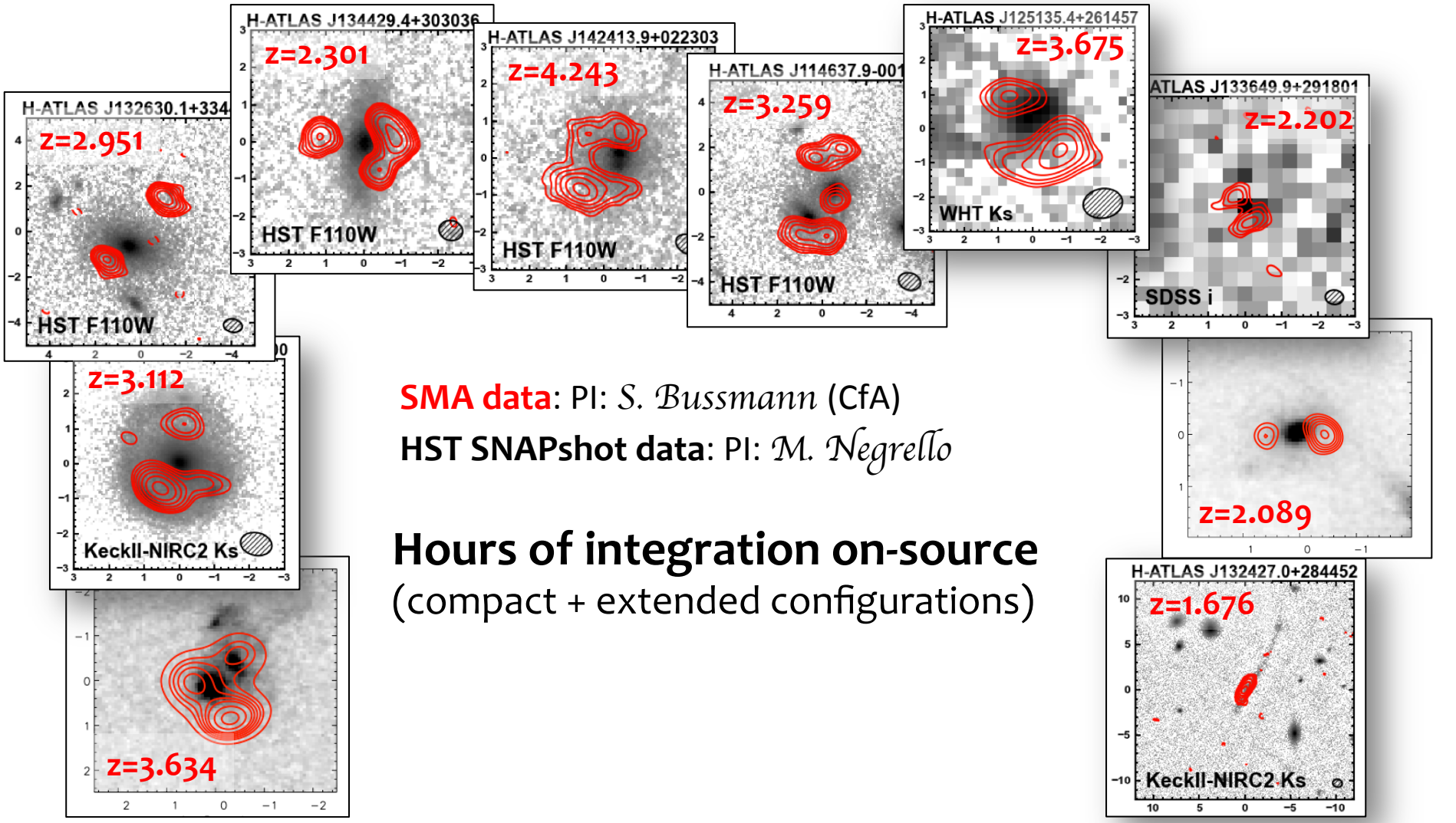




Negrello et al. (2010, Science)

SMA follow-up





SMA data: PI: *S. Bussmann* (CfA)

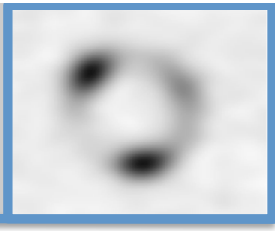
HST SNAPshot data: PI: *M. Negrello*

Hours of integration on-source

(compact + extended configurations)

Bussmann et al. (2013)

ALMA follow-up of SPT sources



SPT: 2 ALMA proposals accepted in cycle-0:

- ID: 2011.0.00958.S; PI: *Dan Marrone* (Univ. of Arizona, USA)

  "Imaging the brightest starbursts in the Universe"

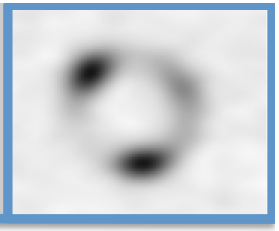
  Targets: **47 lens candidates** with **$F_{1.4mm}$>20mJy**

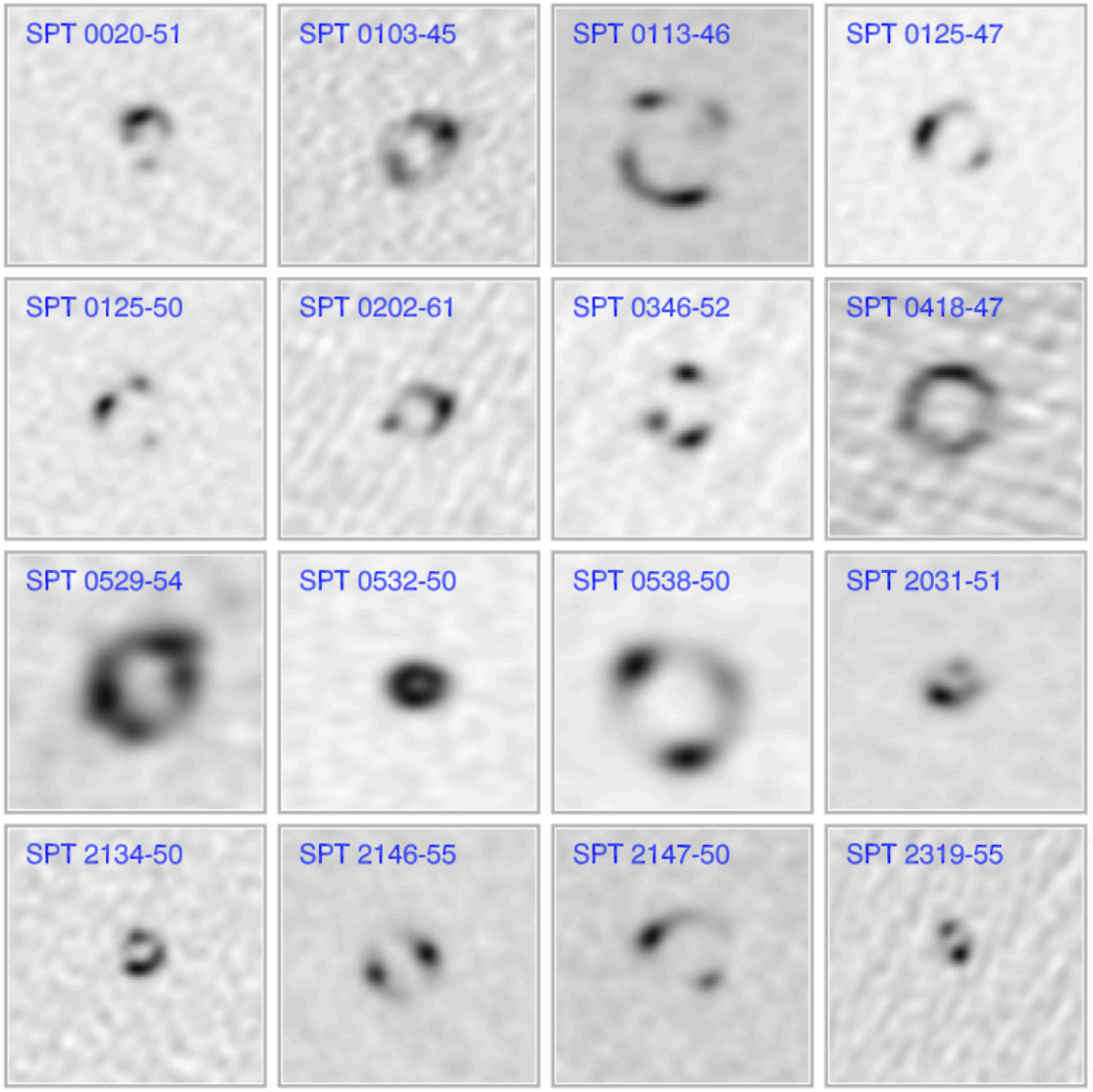
- ID: 2011.0.00957.S; PI: *Axel Weiss* (MPI, Germany)

  "The ALMA-SPT Redshift Survey"

  Targets: **26 lens candidates** with **$F_{1.4mm}$>20mJy**

ALMA follow-up of SPT sources



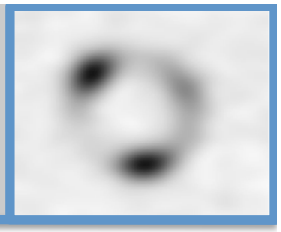


Imaging (Nov. 2011):

- band-7: 275-370GHz (~**870μm**)
- **~0.5"** resolution
- **few minutes** on-source (!!)

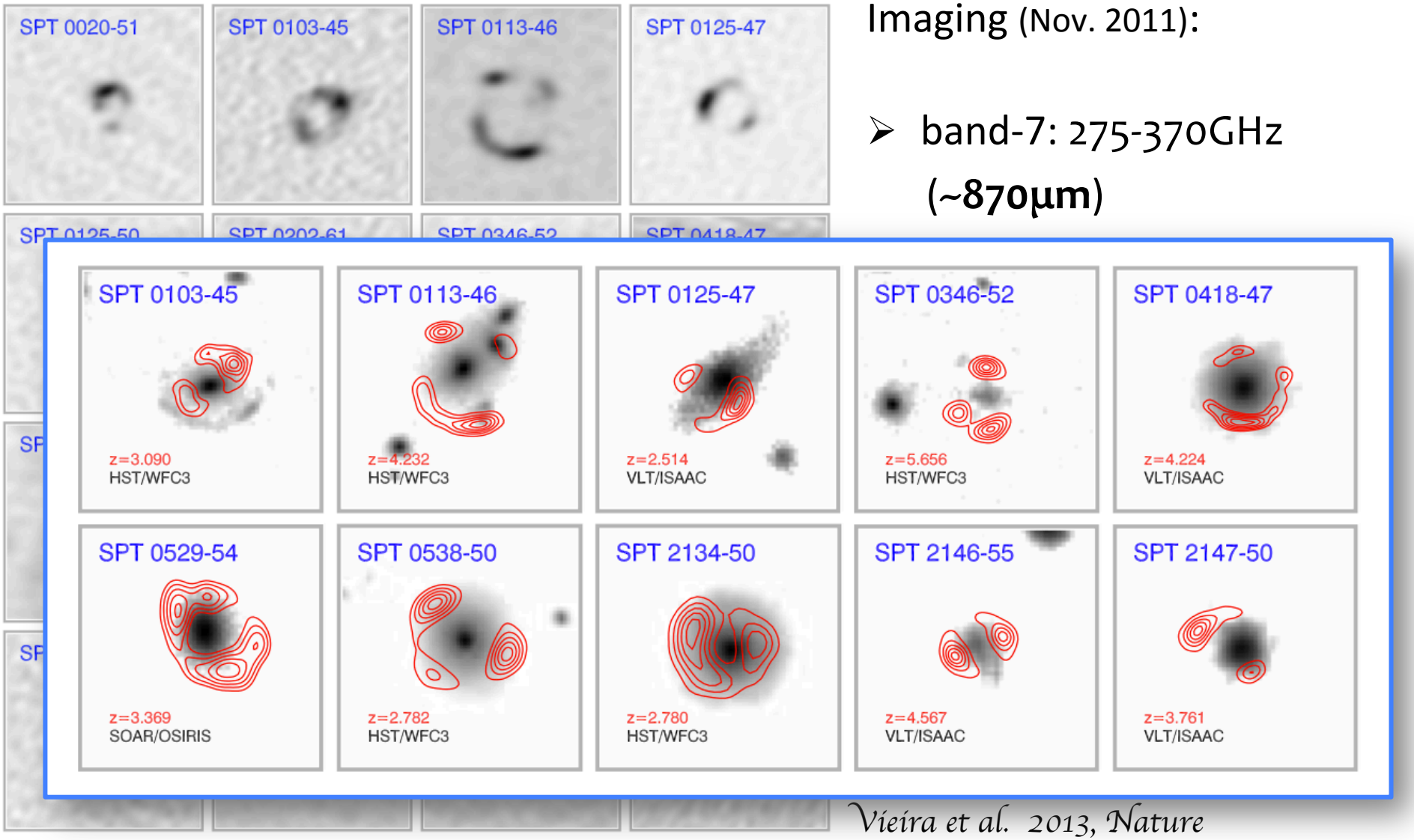
Vieira et al. 2013, Nature

ALMA follow-up of SPT sources



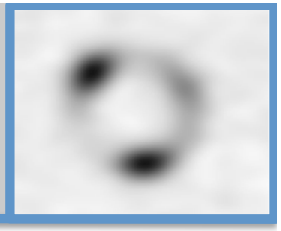
Imaging (Nov. 2011):

- band-7: 275-370GHz (~870μm)



Vieira et al. 2013, Nature

Spot the difference …

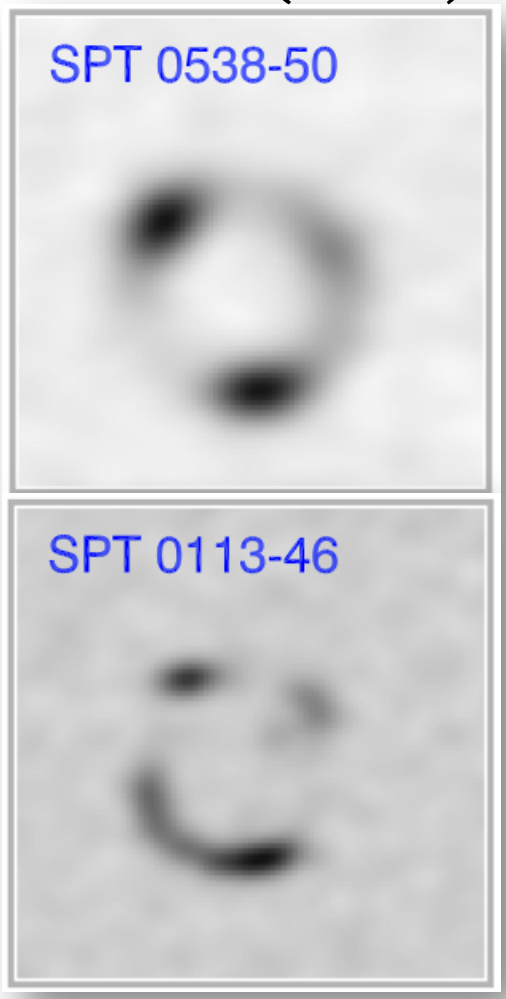


Optical (HST)

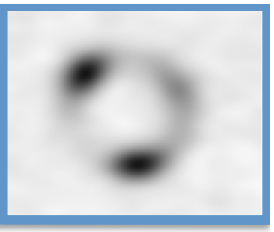
The lens is invisible in the sub-mm!

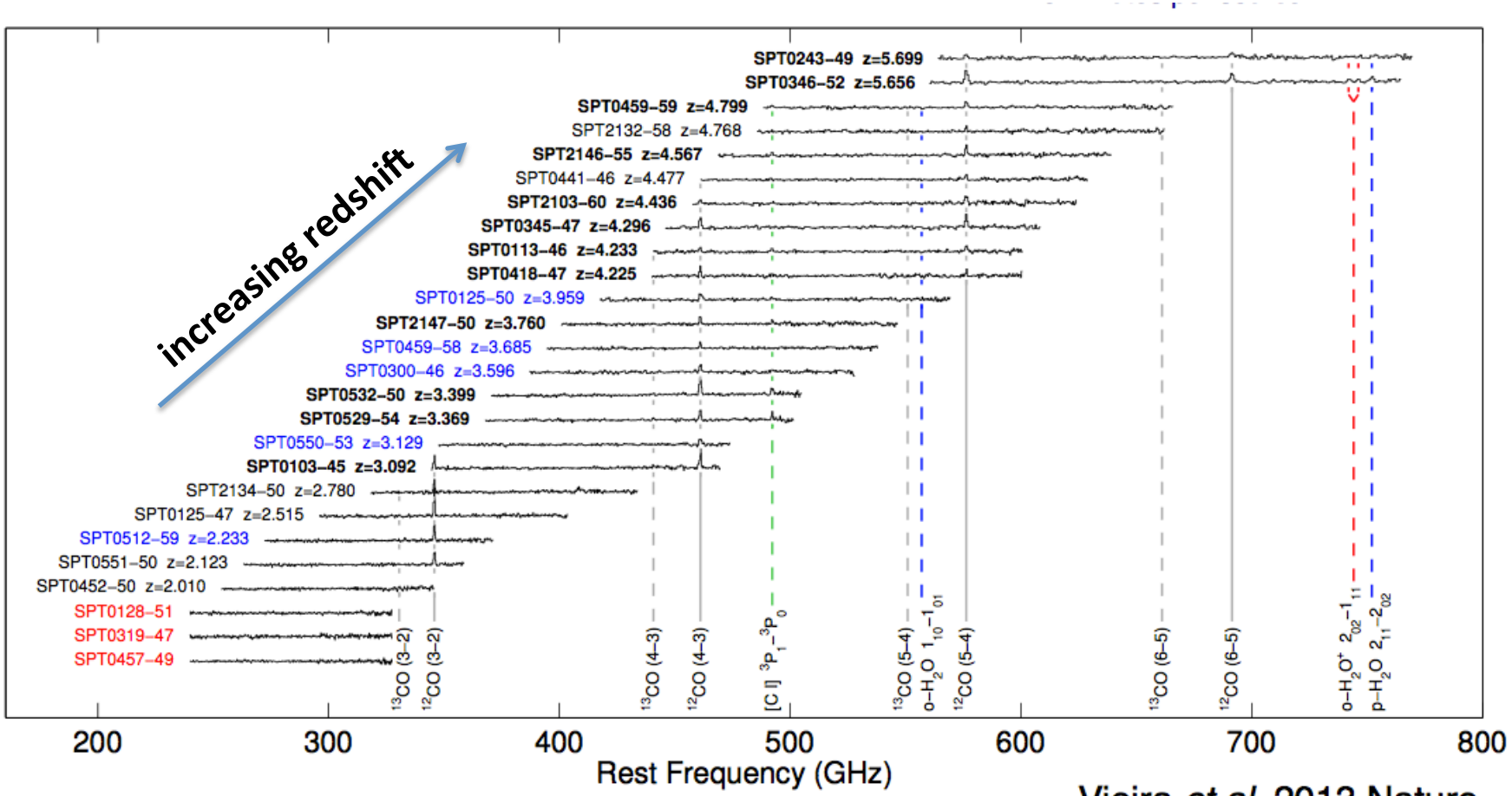
It is easier to model the lensed galaxy

Sub-mm (ALMA)



ALMA follow-up of SPT sources





Vieira *et al.* 2013 Nature

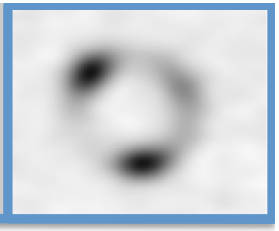
Bold = unambiguous redshift from ALMA

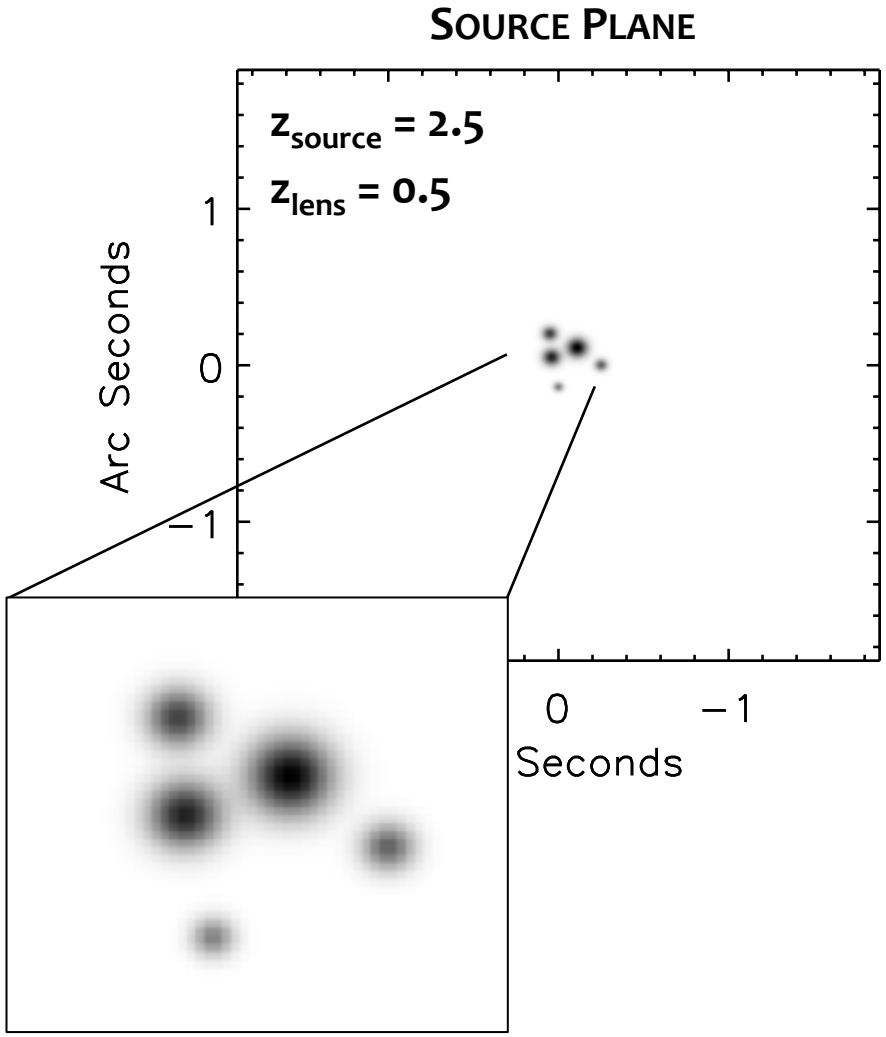
black = single lines with ALMA, confirmed with C+ or CO(1-0) with APEX or ATCA

blue = single line detected with redshift, most likely redshift from photo-z

red = no line detected

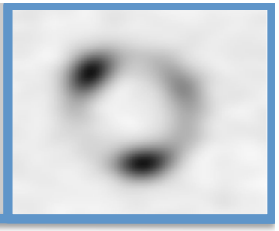
What to expect in the future?

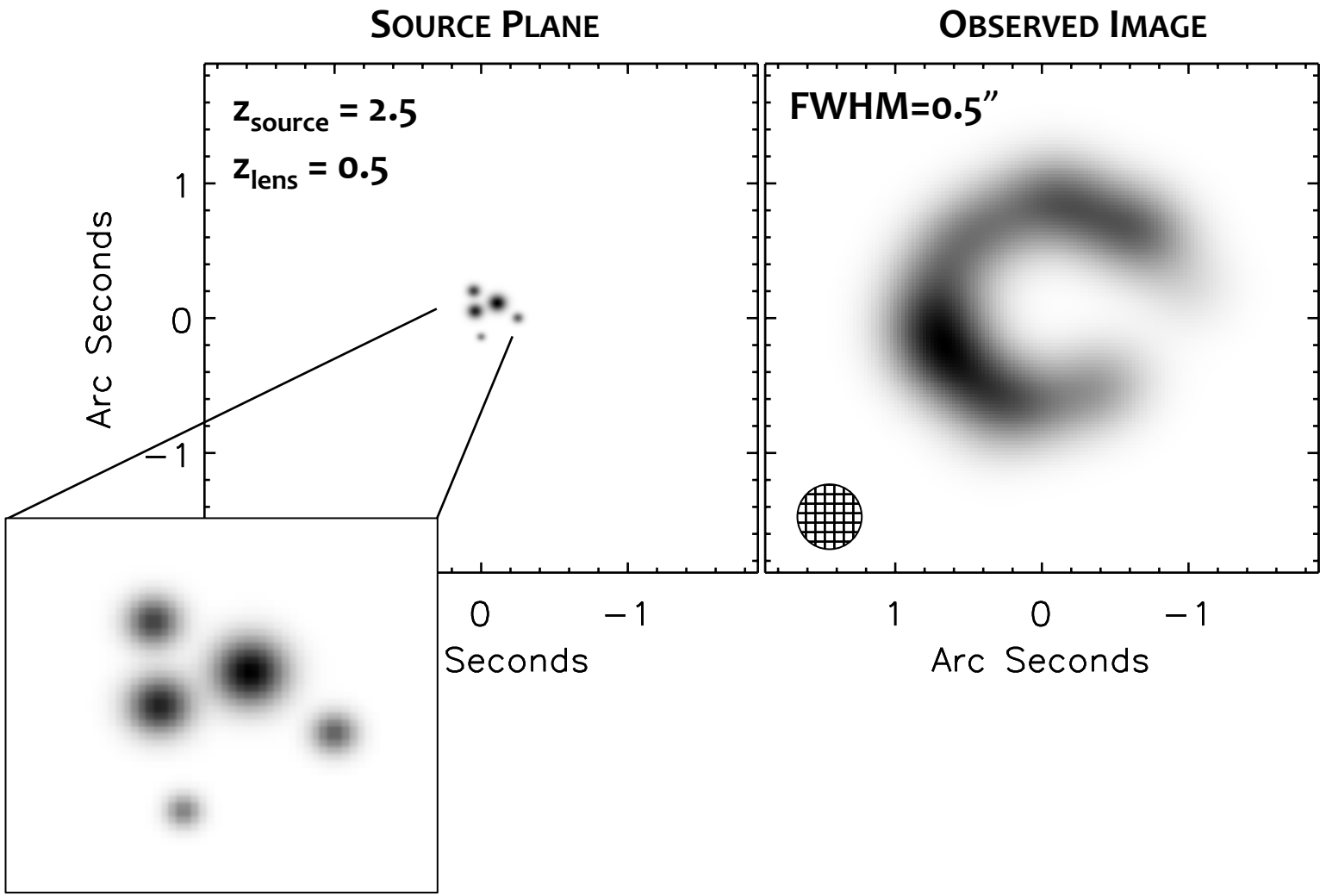




5 clumps of ≈ 300-800 pc

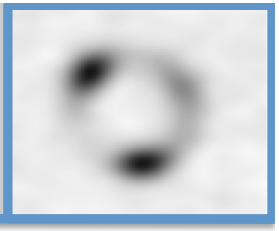
What to expect in the future?

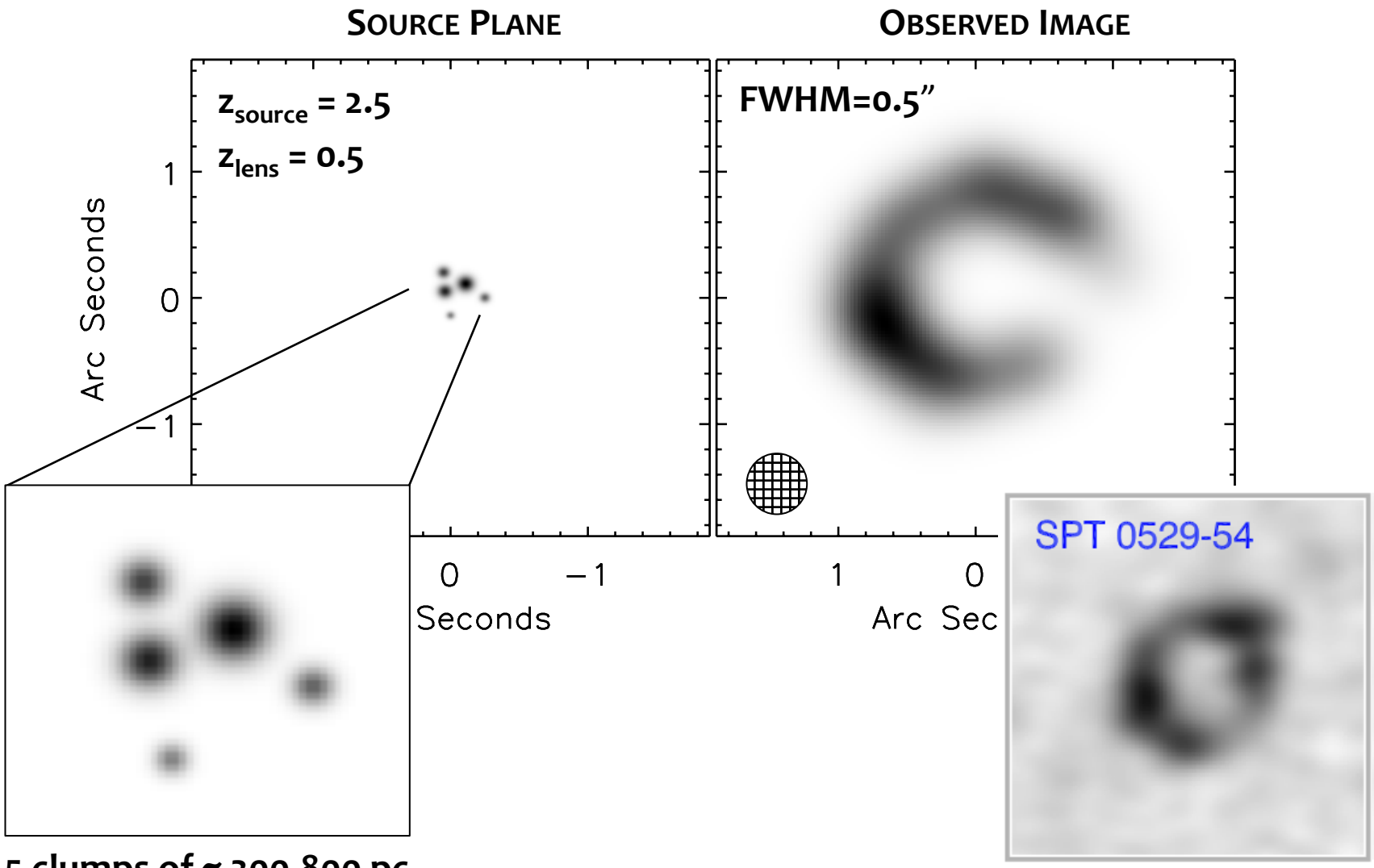




5 clumps of ≈ 300-800 pc

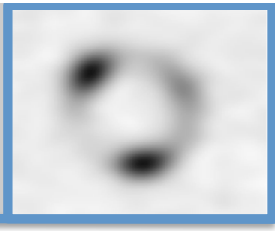
What to expect in the future?

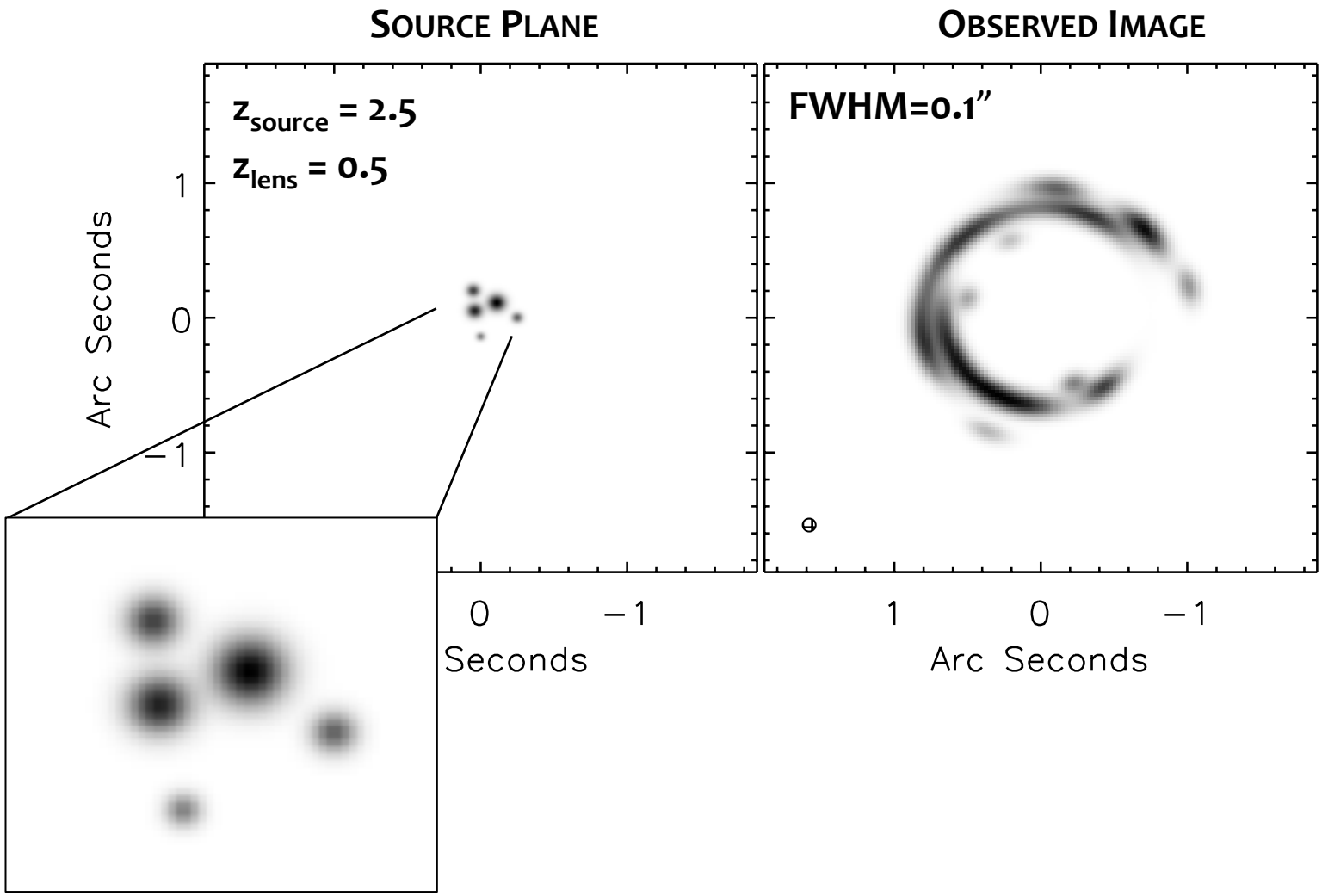




5 clumps of ≈ 300-800 pc

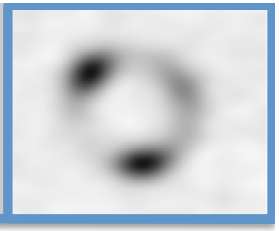
What to expect in the future?

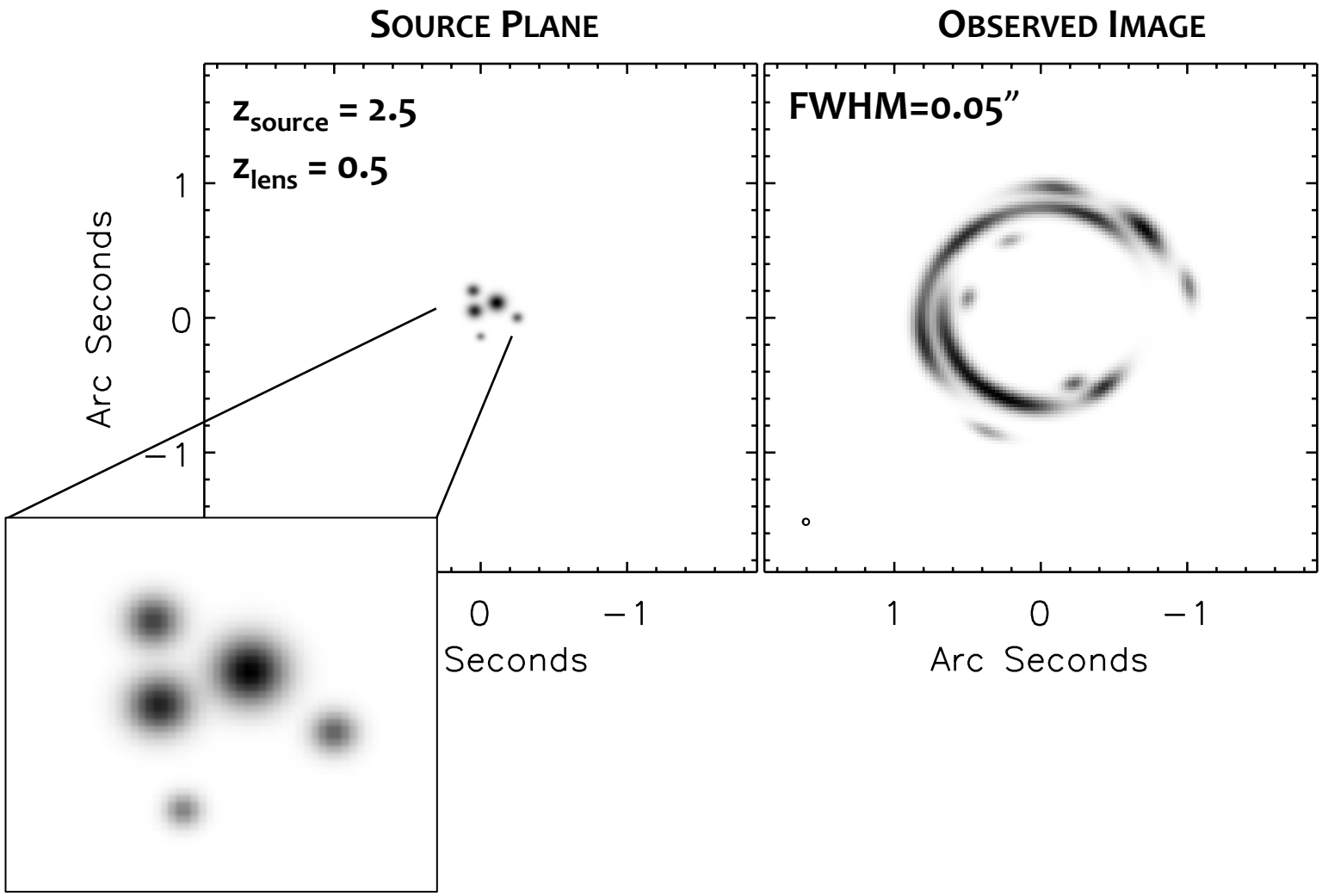




5 clumps of ≈ 300-800 pc

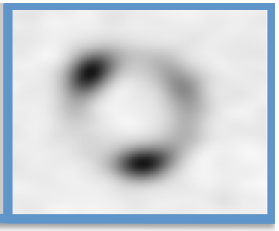
What to expect in the future?





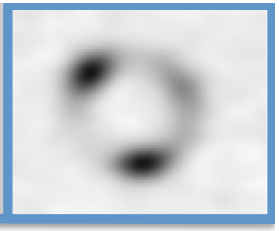
5 clumps of ≈ 300-800 pc

ALMA data: useful for what?



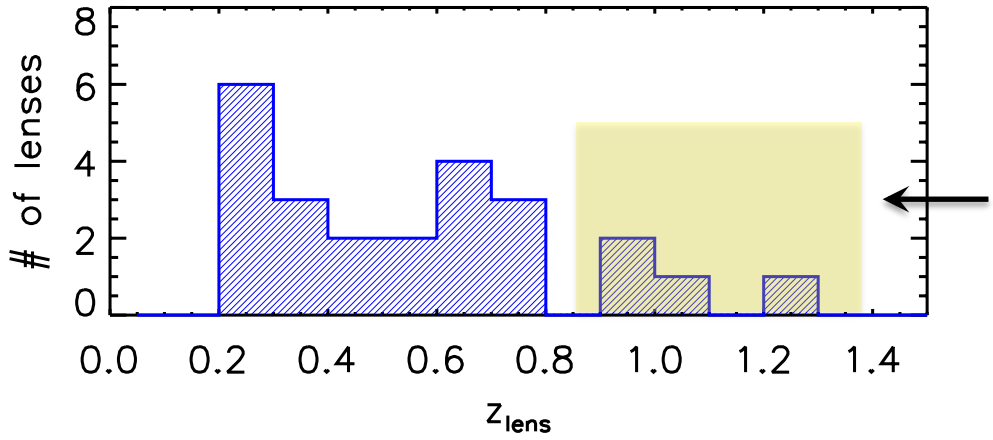
- Studying **faint/high-z galaxies**
  (e.g. *Swinbank et al. 2010, Nature*)

ALMA data: useful for what?



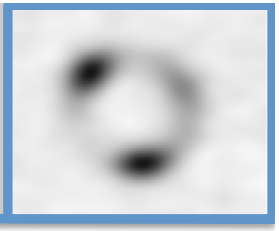
- Studying **faint/high-z galaxies**
  (e.g. *Swinbank et al. 2010, Nature*)

- Measuring the **mass profile** of the lenses
  (e.g. *Dye, Negrello et al. 2014*)



Tail extending to **z > 1**

ALMA data: useful for what?



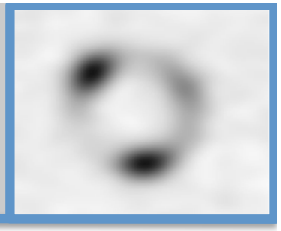
- Studying **faint/high-z galaxies**
  (e.g. *Swinbank et al. 2010, Nature*)

- Measuring the **mass profile** of the lenses
  (e.g. *Dye, Negrello et al. 2014*)

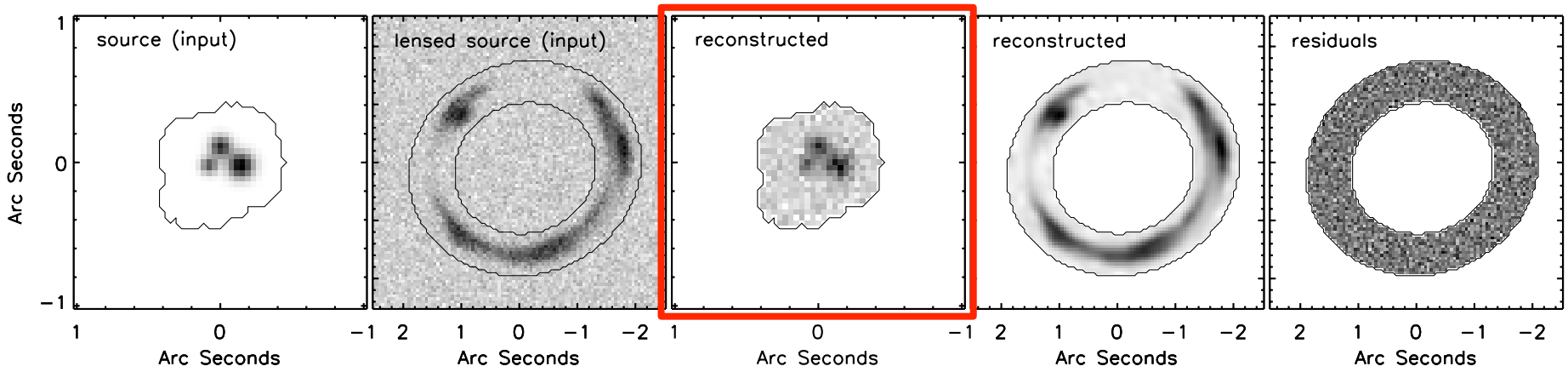
- Quantifing dark matter substructures in the lens
  (e.g. *Vegetti et al. 2012, Nature*)

- Constraining **cosmological parameters**
  (e.g. *Grillo et al. 2008*)

Source reconstruction



REGULARIZED SEMILINEAR INVERSION METHOD *(Warren & Dye 2033; Suyu et al. 2006)*

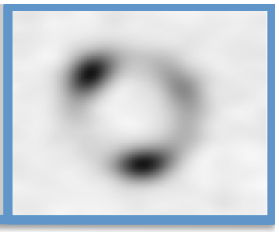


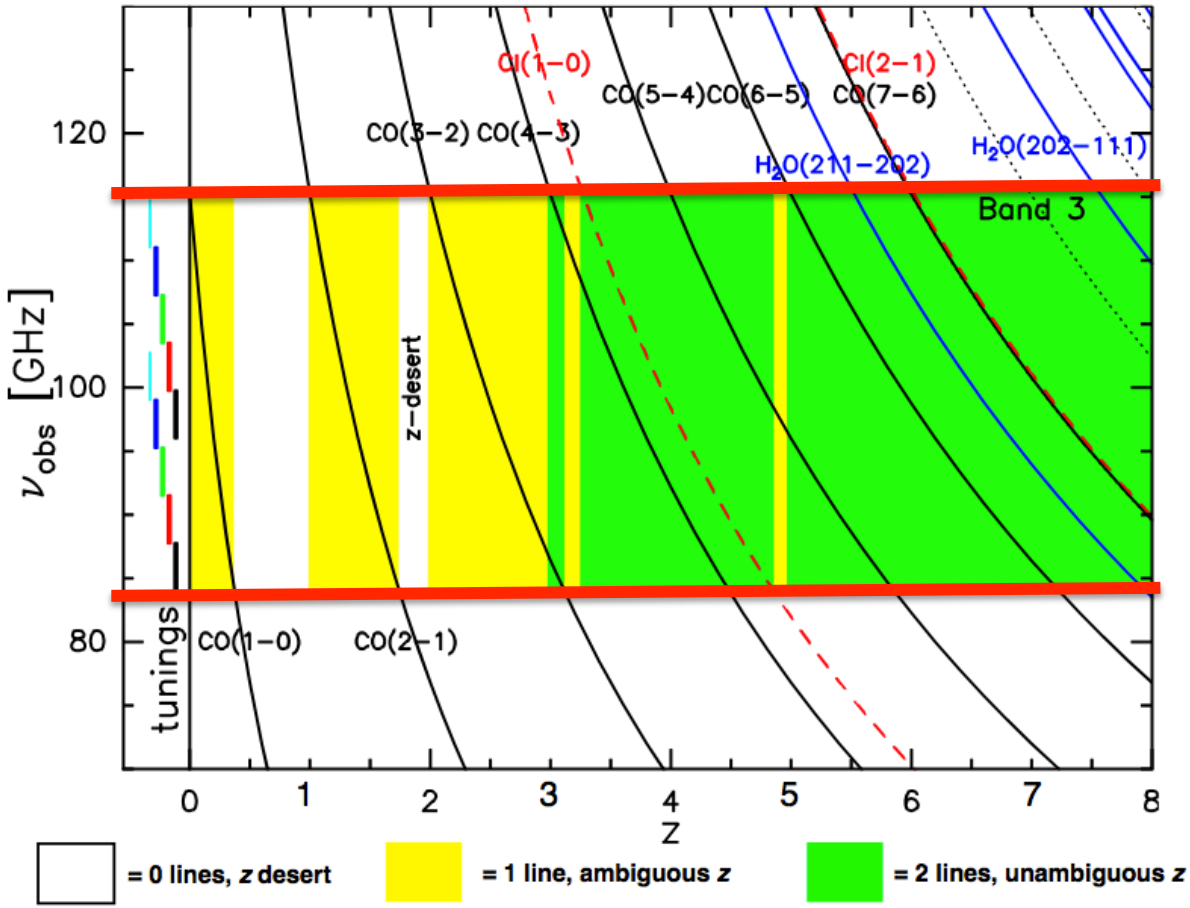
Pixelized source ⇒ no assumptions on

- Source light profile
- Number of clumps

Andrea Enia, *Tesi magistrale 2015*, UniPD

ALMA follow-up of SPT sources



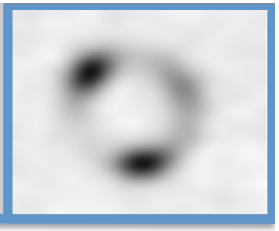


Weiss et al. 2013, ApJ, 767, 88

Spectroscopy
(Nov. 2011-Jan 2012):

- Band-3: 84-116GHz
  (**~3.5-2.6mm**)
- **compact** configuration
  (14-17 antennas)
- **~6”** resolution
- **10 minutes** on-source

ALMA follow-up

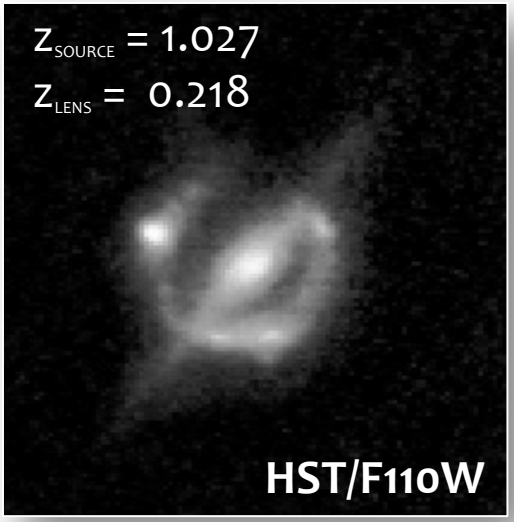


ALMA cycle-0: project 2011.0.00476.S (P.I. Orellana)

- Band 3 (84-116GHz)
- Band 6 (211-275GHz)

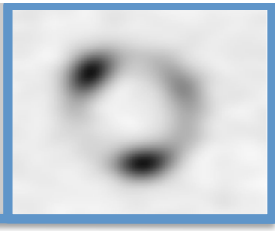
30 min on-source in each band

H-ATLAS lensed galaxy (230mJy @ 500μm)



Messias et al. 2014, A&A, 568, 92

ALMA follow-up

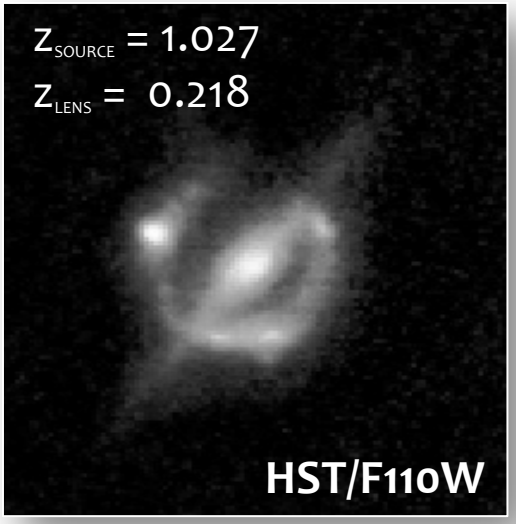


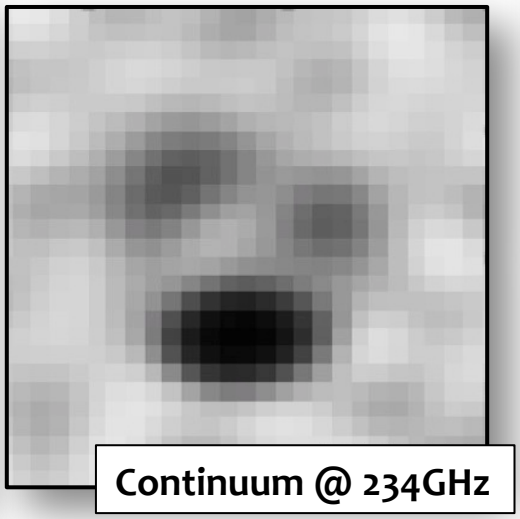
ALMA cycle-0: project 2011.0.00476.S (P.I. Orellana)

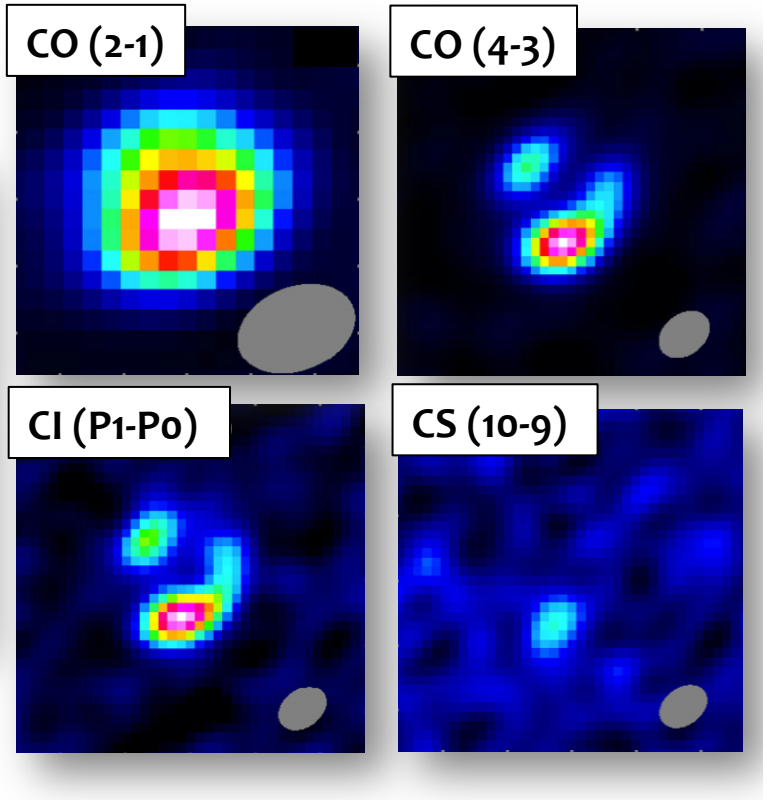
- Band 3 (84-116GHz)
- Band 6 (211-275GHz)

30 min on-source in each band

H-ATLAS lensed galaxy (230mJy @ 500μm)

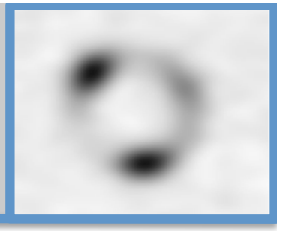






Messias et al. 2014, A&A, 568, 92

ALMA follow-up

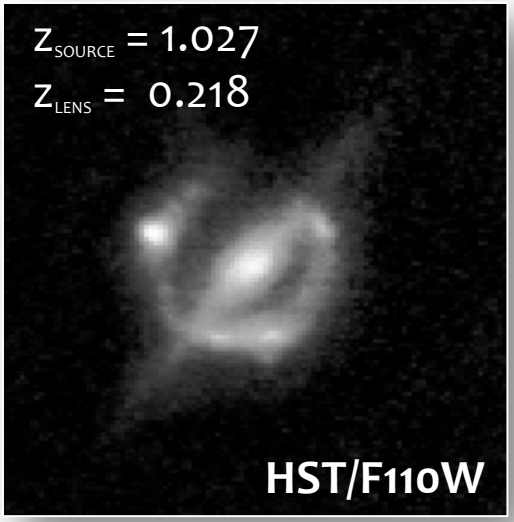


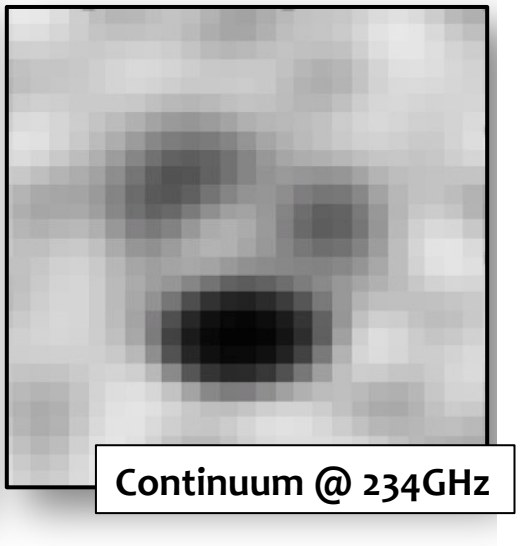
ALMA cycle-0: project 2011.0.00476.S (P.I. Orellana)

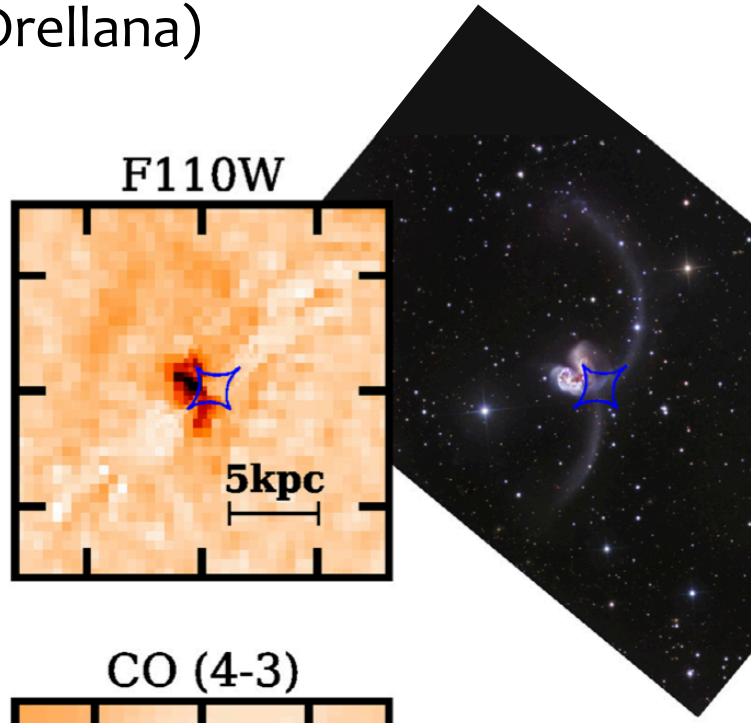
- Band 3 (107GHz)
- Band 6 (234GHz)

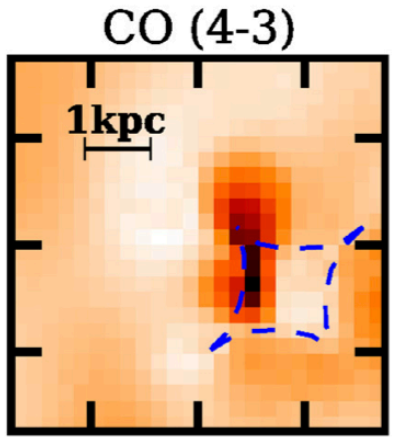
30 min on-source in each band

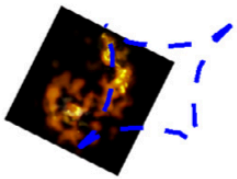
H-ATLAS lensed galaxy





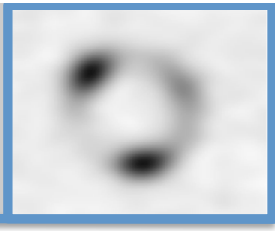






Messias et al. 2014, A&A, 568, 92

H-ATLAS vs SPT lensed sources



H-ATLAS in **red**

SPT in **blue**