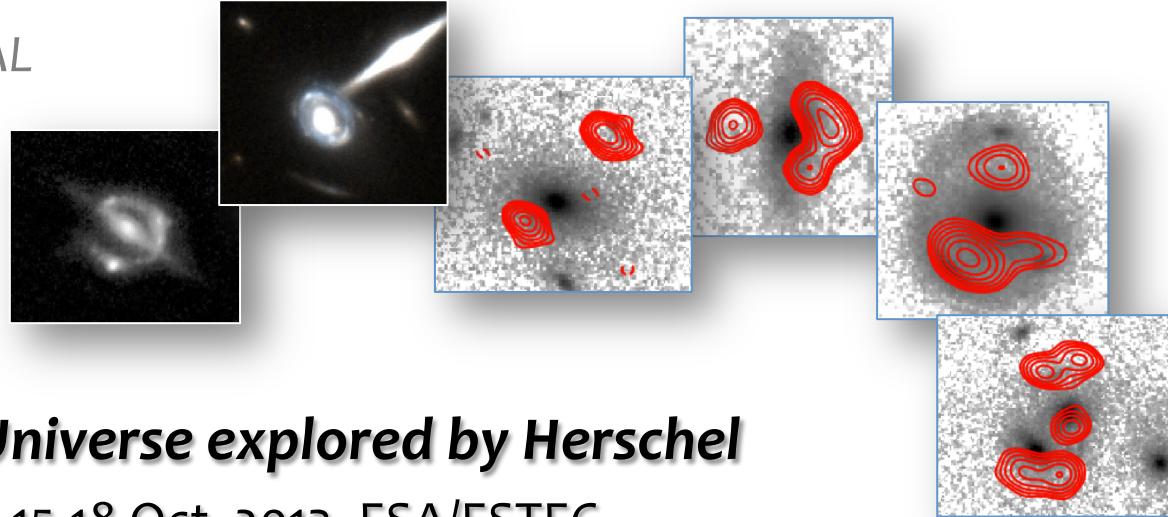




ASTROPHYSICAL
TERAHERTZ
LARGE
AREA
SURVEY



The Universe explored by Herschel

15-18 Oct. 2013, ESA/ESTEC

The *Herschel-ATLAS* sample of strongly lensed galaxies



Dr Mattia Negrello

INAF - Osservatorio Astronomico di Padova, Italy

on behalf of the H-ATLAS Team

Outline

- The H-ATLAS (Eales's talk)
- Finding lenses in H-ATLAS
- First results from H-ATLAS 16deg² SDP field
- Lensed galaxies from H-ATLAS GAMA+NGP fields
- Why should we bother about these lensed galaxies?
- Conclusions

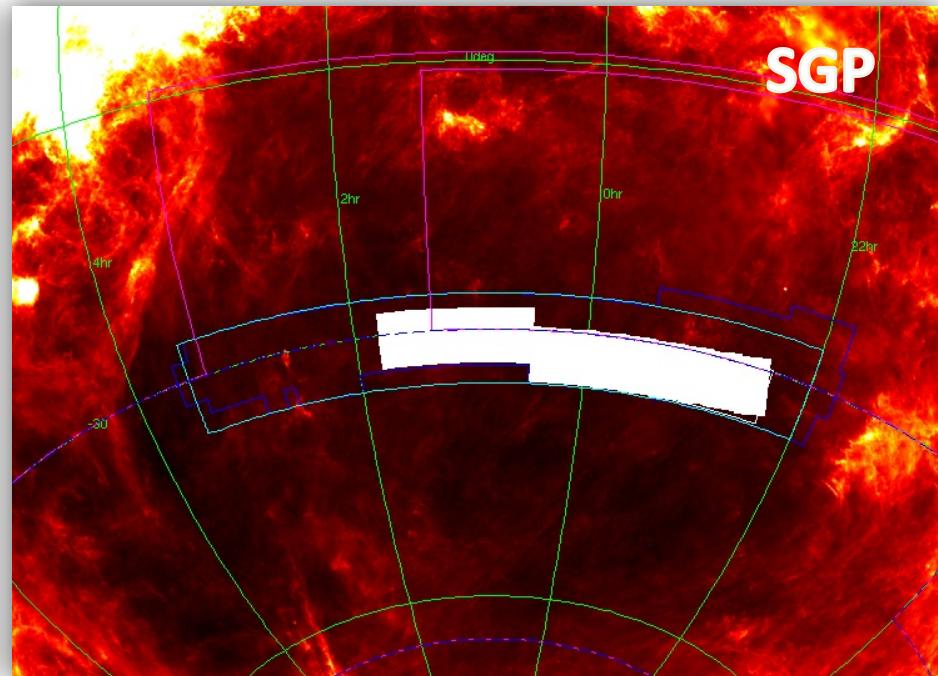
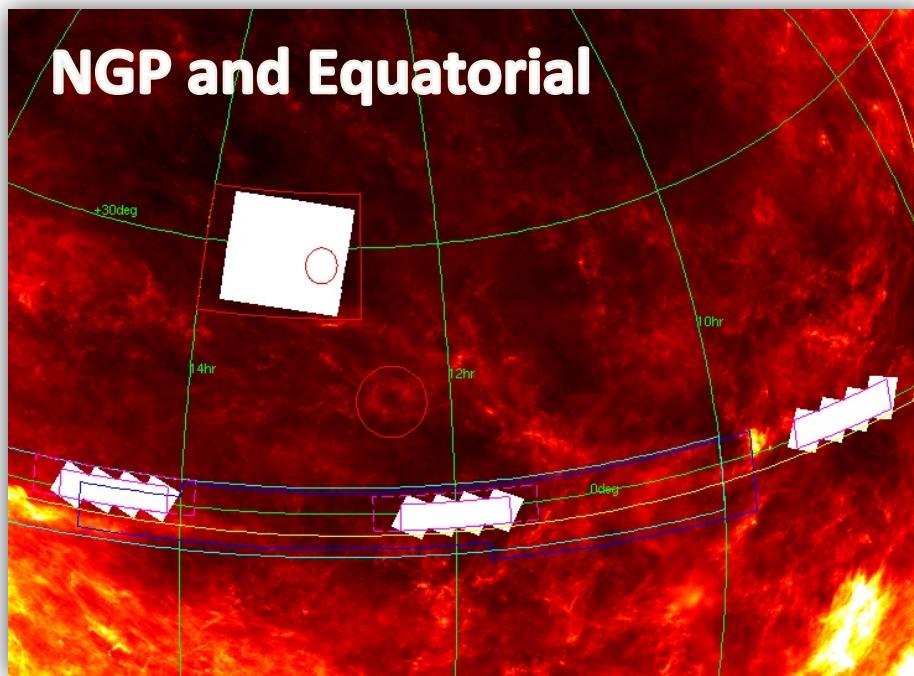
Herschel-ATLAS



Widest area extragalactic survey undertaken with Herschel
(PIs: Eales and Dunne)

Area = 570 deg²

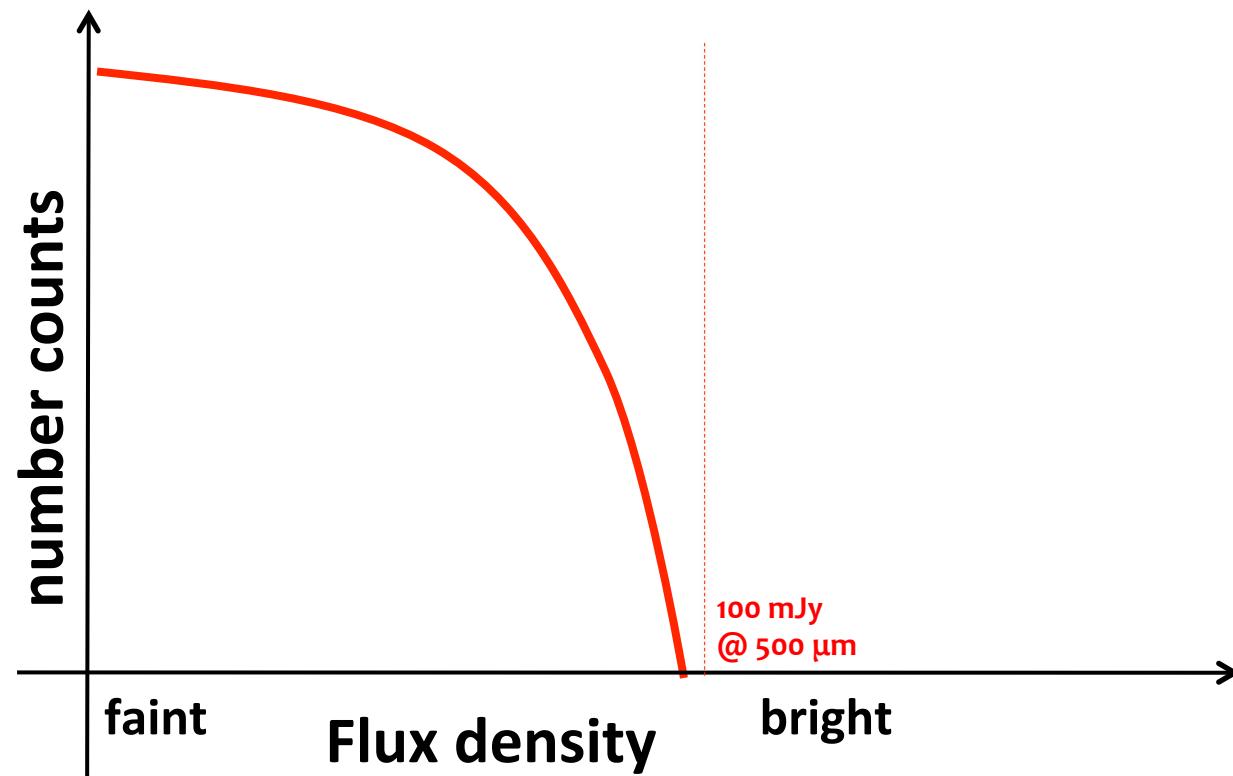
<http://www.h-atlas.org/>



PACS 100+160 μm (see poster #22 by Ibar) and SPIRE 250+350+500 μm

A lensing science case for H-ATLAS

Dusty star-forming galaxies (DSFGs) at $z>1$ have steep number counts
(e.g. Granato *et al.* 2001, 2004; Coppin *et al.* 2006; Negrello *et al.* 2007)

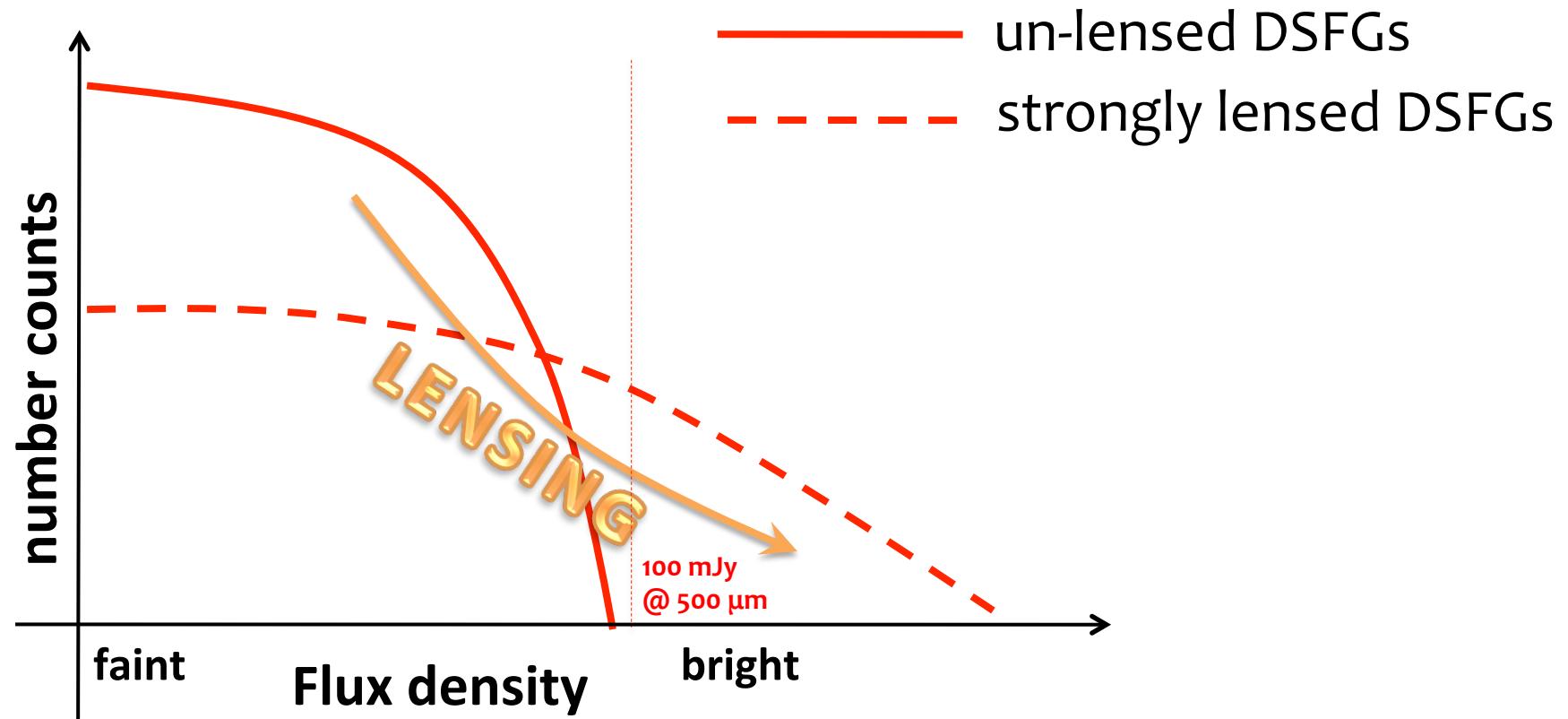


A lensing science case for H-ATLAS



Efficient selection of strongly lensed galaxies

(*Blain 1996; Perrotta et al. 2002, 2003; Negrello et 2007*)

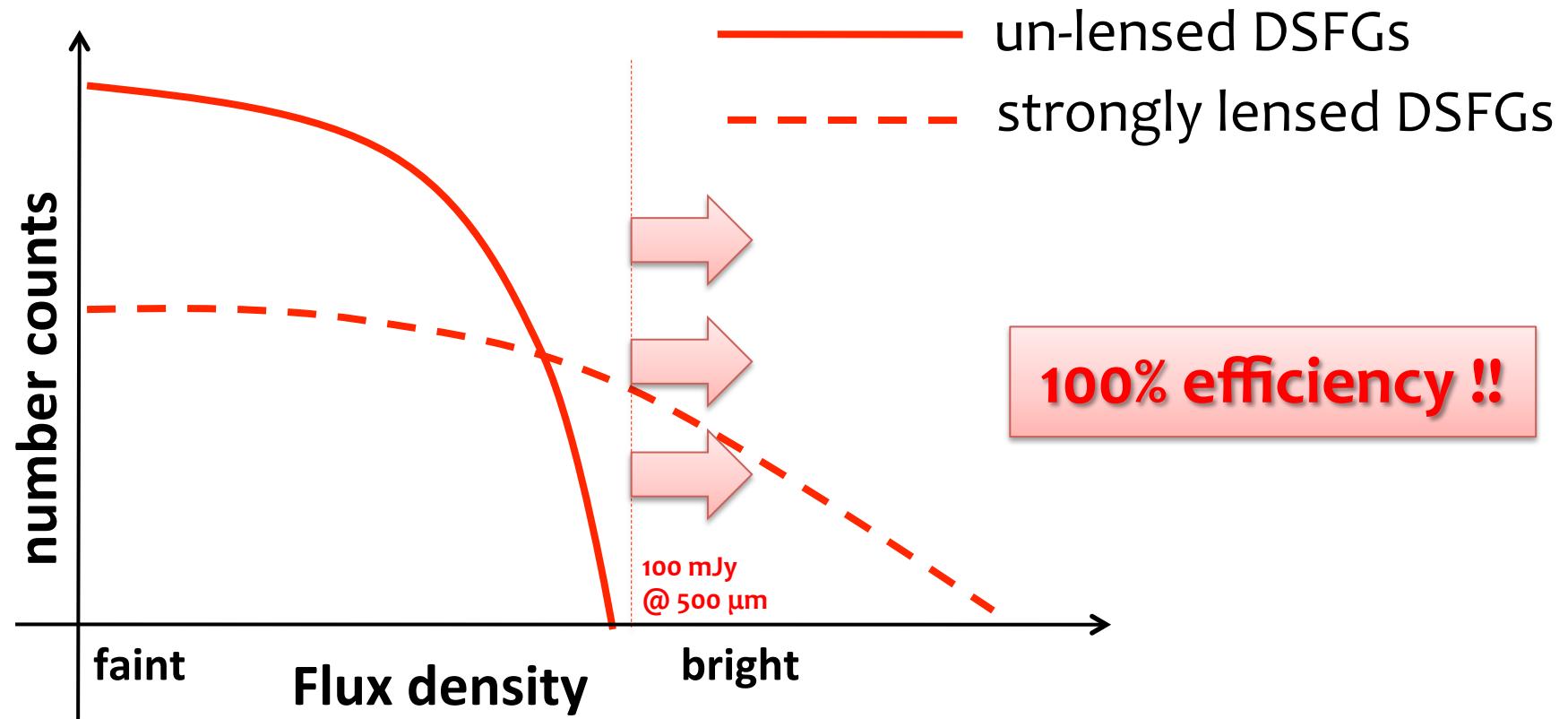


A lensing science case for H-ATLAS



Efficient selection of strongly lensed galaxies

(*Blain 1996; Perrotta et al. 2002, 2003; Negrello et 2007*)

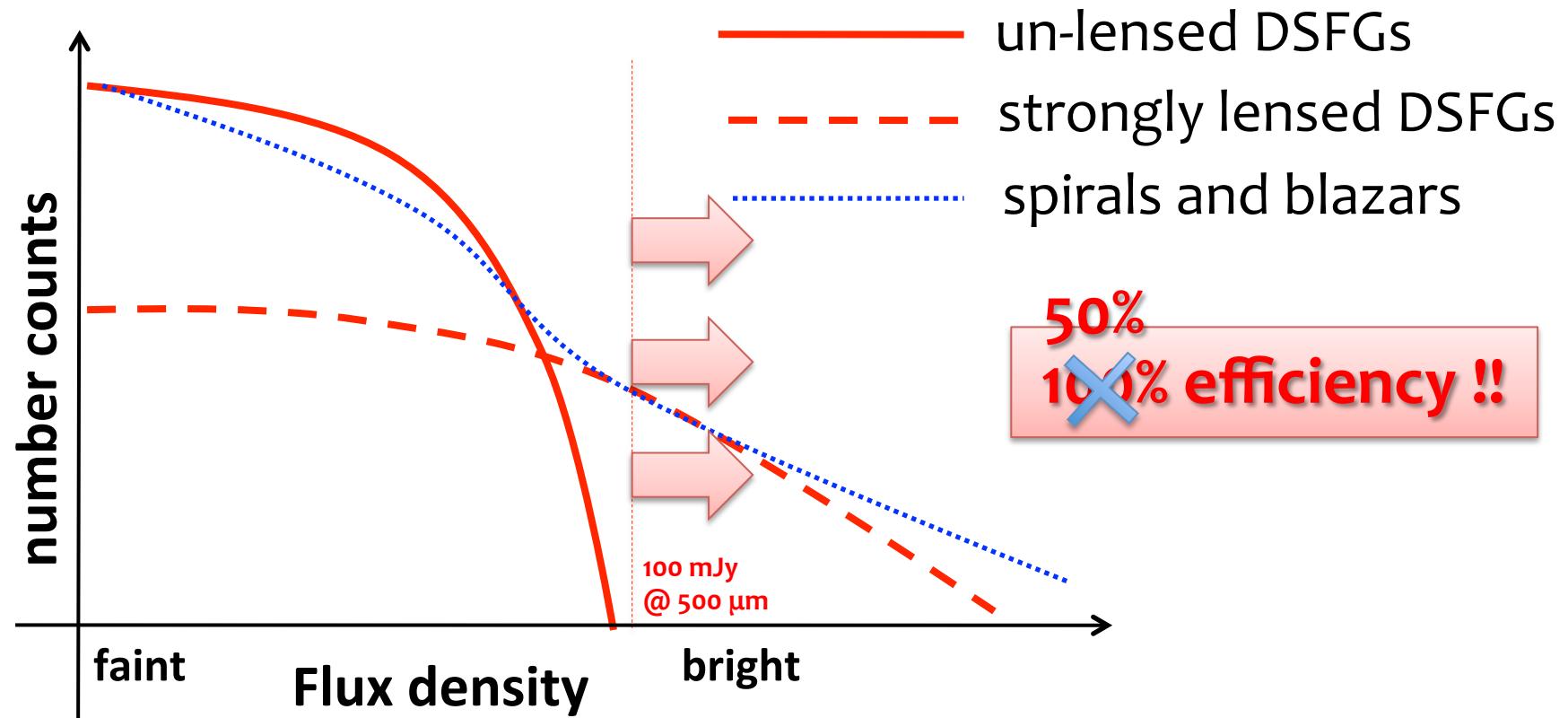


A lensing science case for H-ATLAS

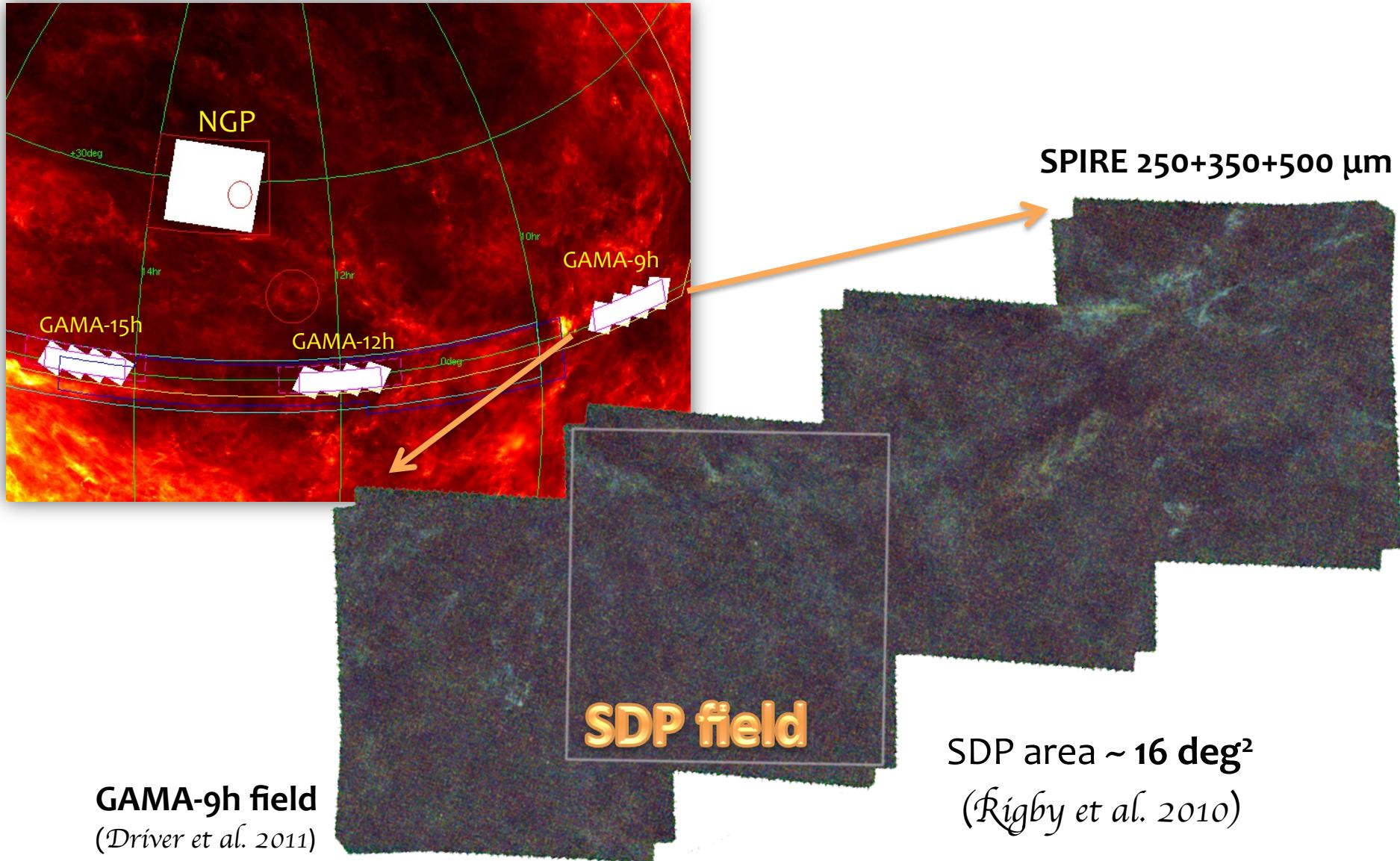


Efficient selection of strongly lensed galaxies

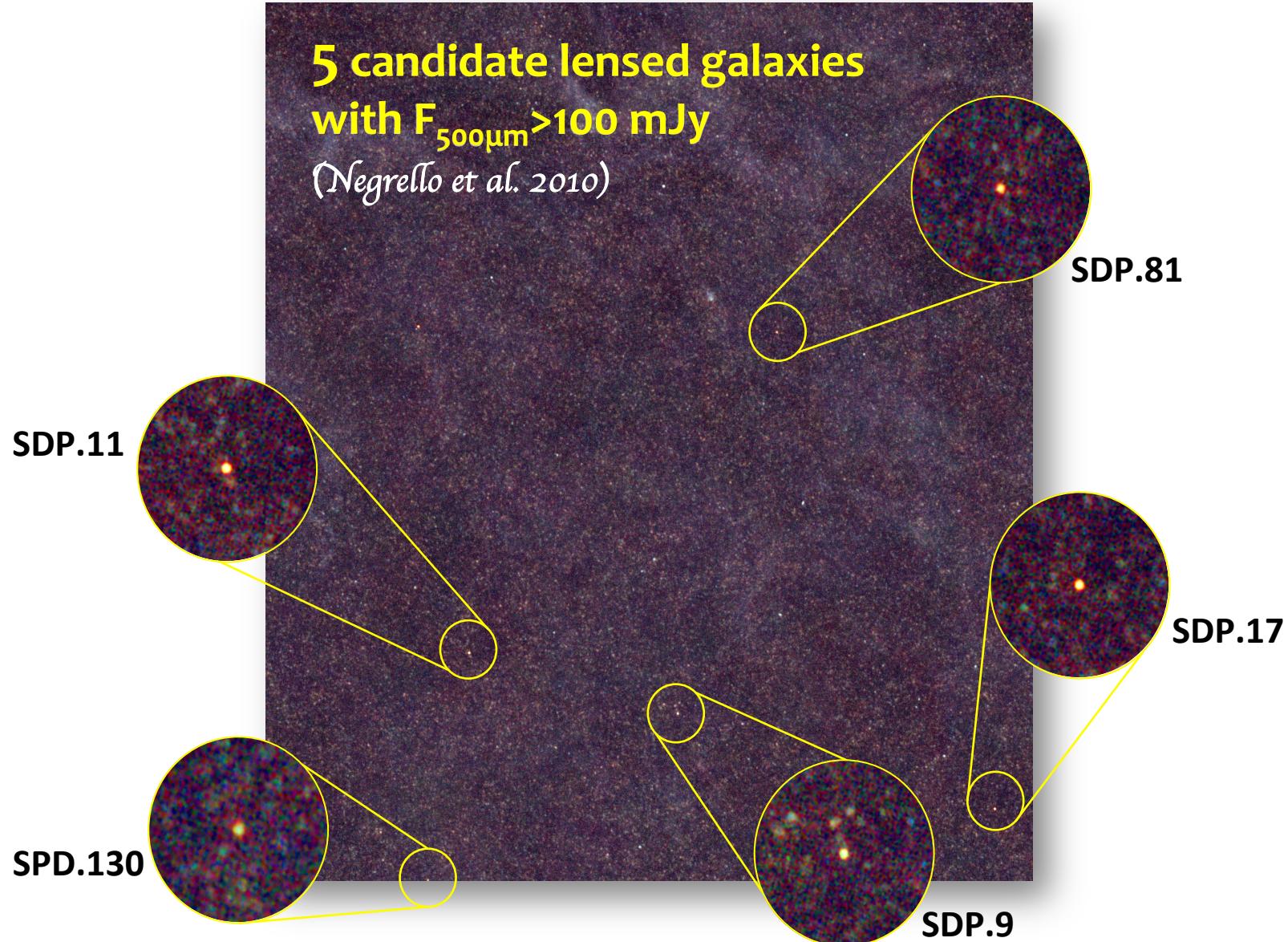
(*Blain 1996; Perrotta et al. 2002, 2003; Negrello et 2007*)



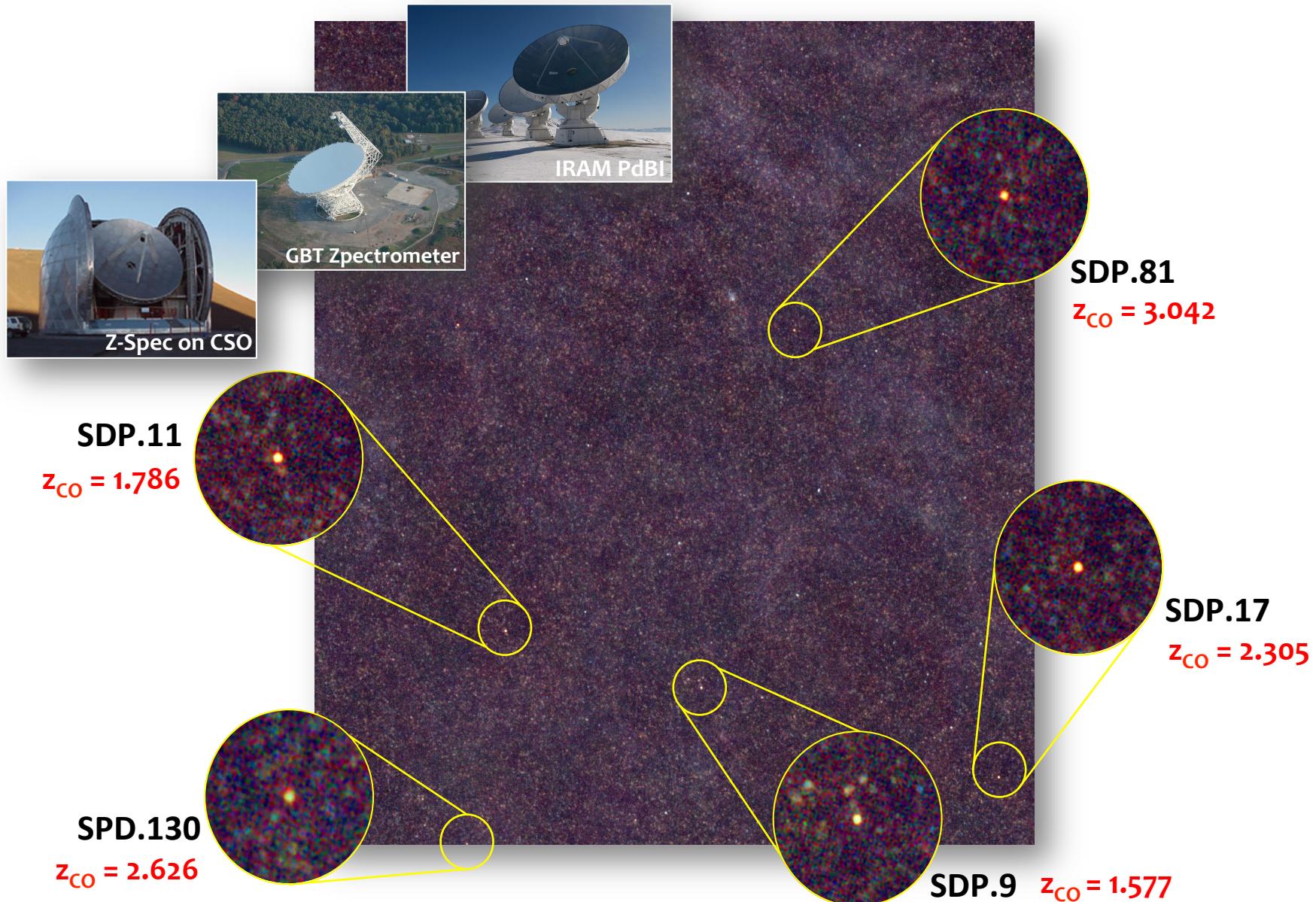
Herschel-ATLAS: SDP field



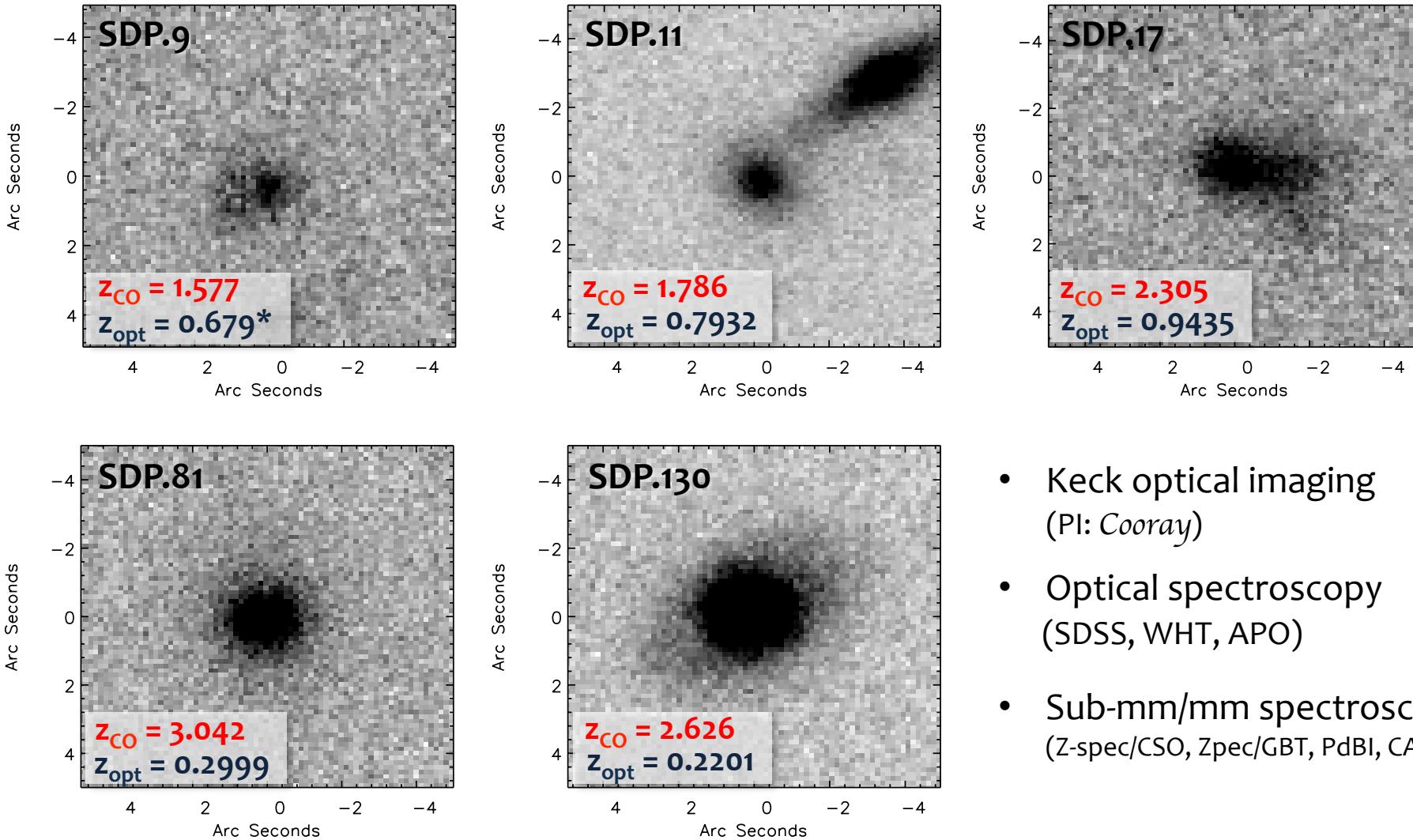
H-ATLAS: lenses in the SDP field



H-ATLAS: lenses in the SDP field

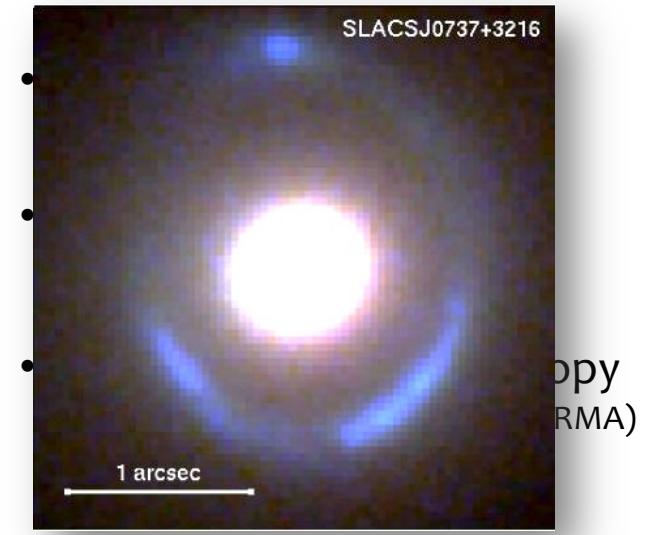
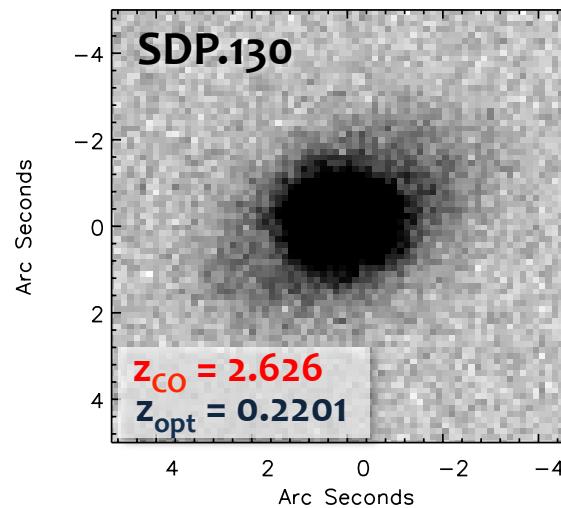
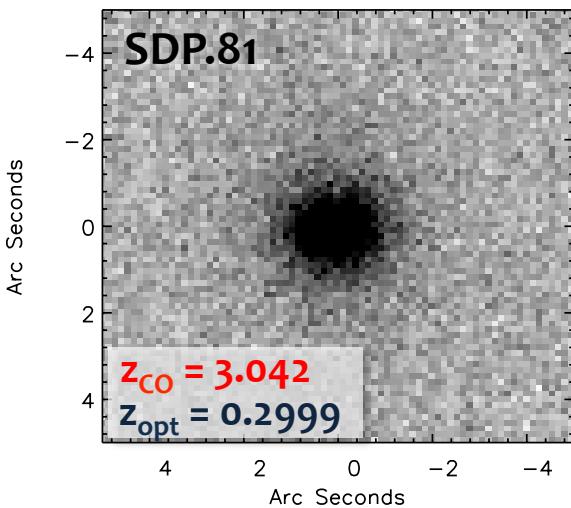
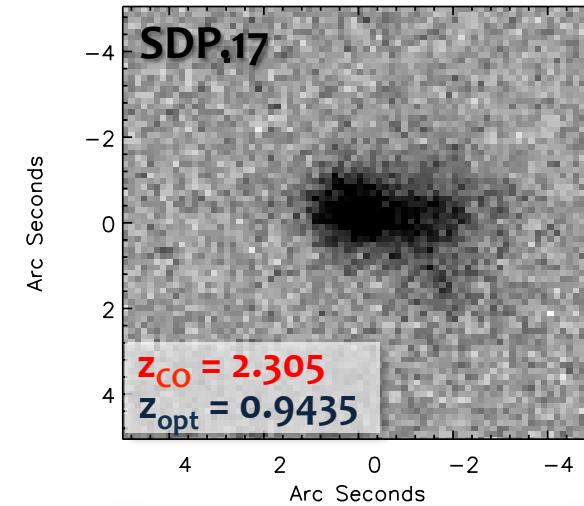
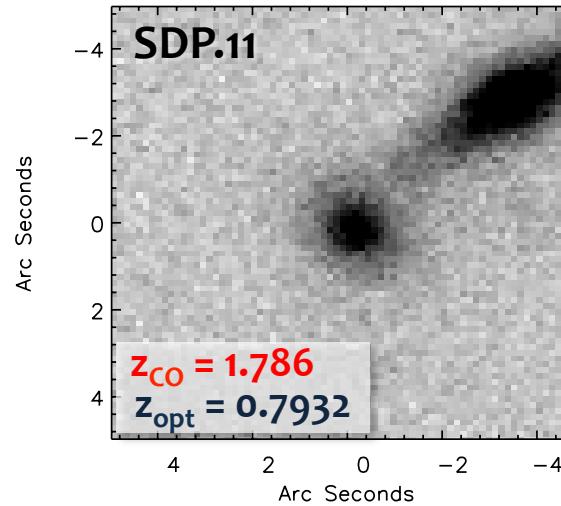
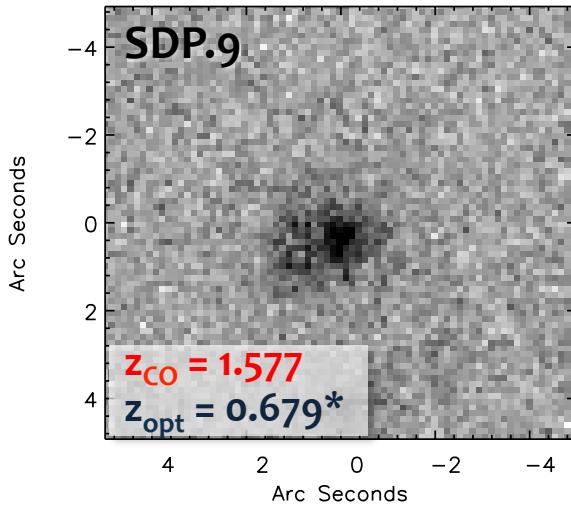


H-ATLAS: lenses in the SDP field

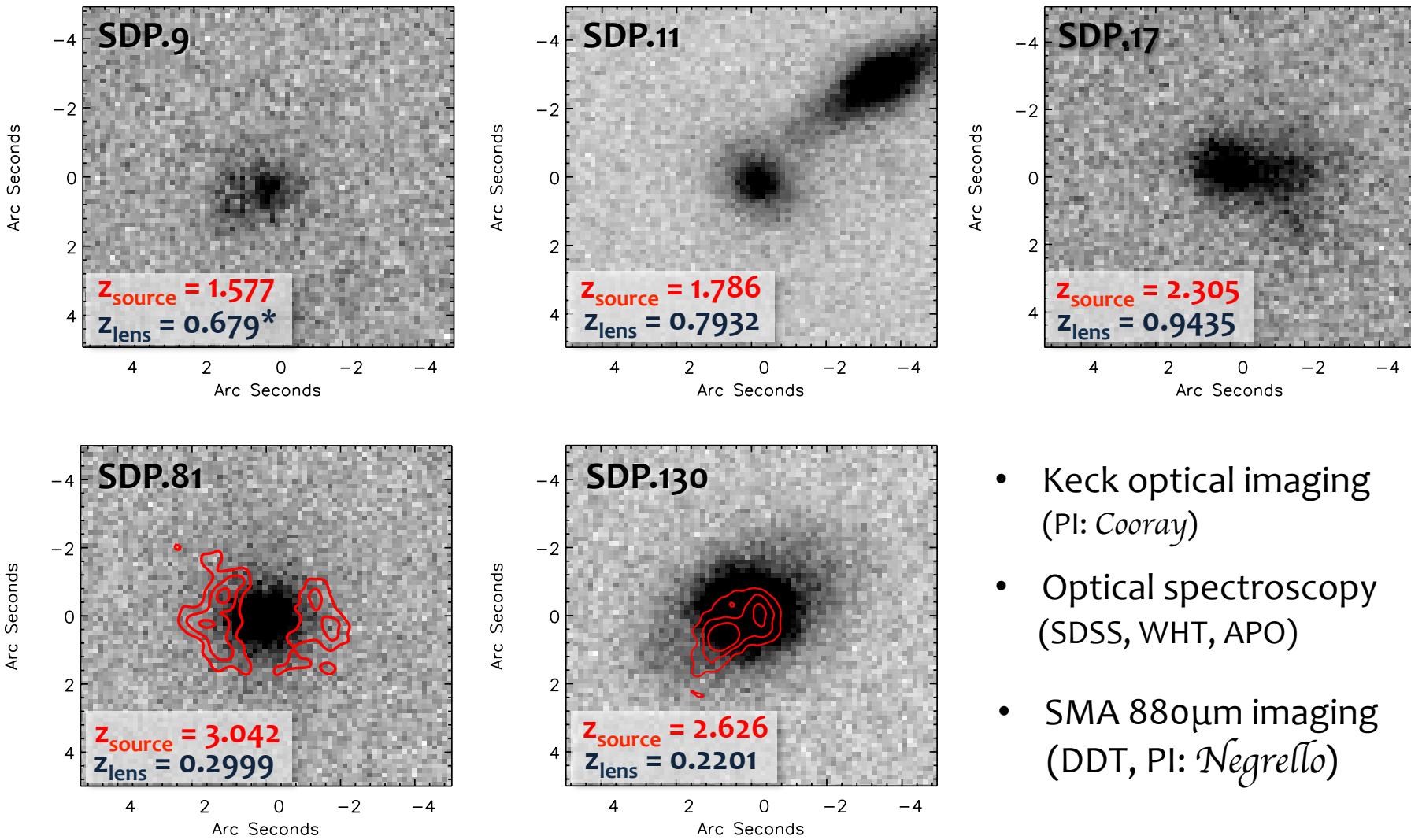


- Keck optical imaging
(PI: *Cooray*)
- Optical spectroscopy
(SDSS, WHT, APO)
- Sub-mm/mm spectroscopy
(Z-spec/CSO, Zspec/GBT, PdBI, CARMA)

H-ATLAS: lenses in the SDP field



H-ATLAS: lenses in the SDP field



- Keck optical imaging (PI: *Cooray*)
- Optical spectroscopy (SDSS, WHT, APO)
- SMA 880 μ m imaging (DDT, PI: *Negrello*)

Proof of concept paper

RESEARCH ARTICLES

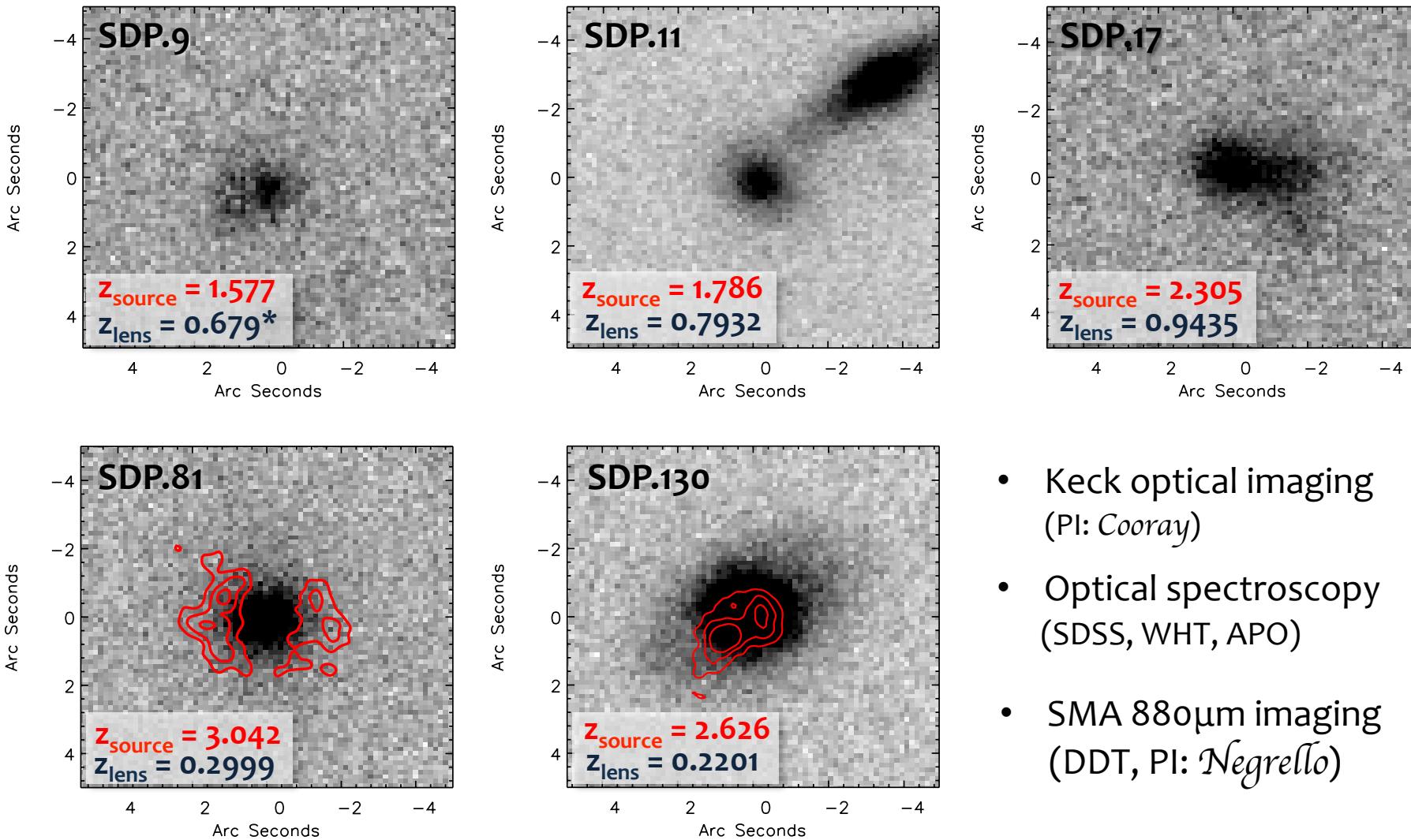
Science, 330, 800 5th of November 2010

The Detection of a Population of Submillimeter-Bright, Strongly Lensed Galaxies

Mattia Negrello,^{1*} R. Hopwood,¹ G. De Zotti,^{2,3} A. Cooray,⁴ A. Verma,⁵ J. Bock,^{6,7} D. T. Frayer,⁸ M. A. Gurwell,⁹ A. Omont,¹⁰ R. Neri,¹¹ H. Dannerbauer,¹² L. L. Leeuw,^{13,14} E. Barton,⁴ J. Cooke,^{4,7} S. Kim,⁴ E. da Cunha,¹⁵ G. Rodighiero,¹⁶ P. Cox,¹¹ D. G. Bonfield,¹⁷ M. J. Jarvis,¹⁷ S. Serjeant,¹ R. J. Ivison,^{18,19} S. Dye,²⁰ I. Arétxaga,²¹ D. H. Hughes,²¹ E. Ibar,¹⁸ F. Bertoldi,²² I. Valtchanov,²³ S. Eales,²⁴ S. P. Driver,²⁵ R. Auld,²⁰ S. Buttiglione,² A. Cava,^{26,27} C. A. Grady,^{28,29} D. L. Clements,³⁰ A. Dariush,²⁰ J. Fritz,³¹ D. Hill,²⁵ J. B. Hornbeck,³² L. Kelvin,²⁵ G. Lagache,^{33,34} M. Lopez-Caniego,³⁵ J. Gonzalez-Nuevo,³ S. Maddox,²⁴ E. Pascale,²⁰ M. Pohlen,²⁰ E. E. Rigby,²⁴ A. Robotham,²⁵ C. Simpson,³⁶ D. J. B. Smith,²⁴ P. Temi,³⁷ M. A. Thompson,¹⁷ B. E. Woodgate,³⁸ D. G. York,³⁹ J. E. Aguirre,⁴⁰ A. Beelen,⁴¹ A. Blain,⁷ A. J. Baker,⁴¹ M. Birkinshaw,⁴² R. Blundell,⁹ C. M. Bradford,^{6,7} D. Burgarella,⁴³ S. Cirasuolo,³ I. S. Dunlop,¹⁸ S. Fleuren,⁴⁴ J. Glenn,⁴⁵ A. I. Harris,⁴⁶ J. Kamei,⁴⁷ R. E. Lutz,⁴⁸ P. Maloney,⁴⁵ H. Matsuhara,⁴⁸ M. Rawlings,⁵⁰ S. Smail,⁵⁴ J. D. Vanden Berk,⁴⁹ and J. W. Ward,⁵¹

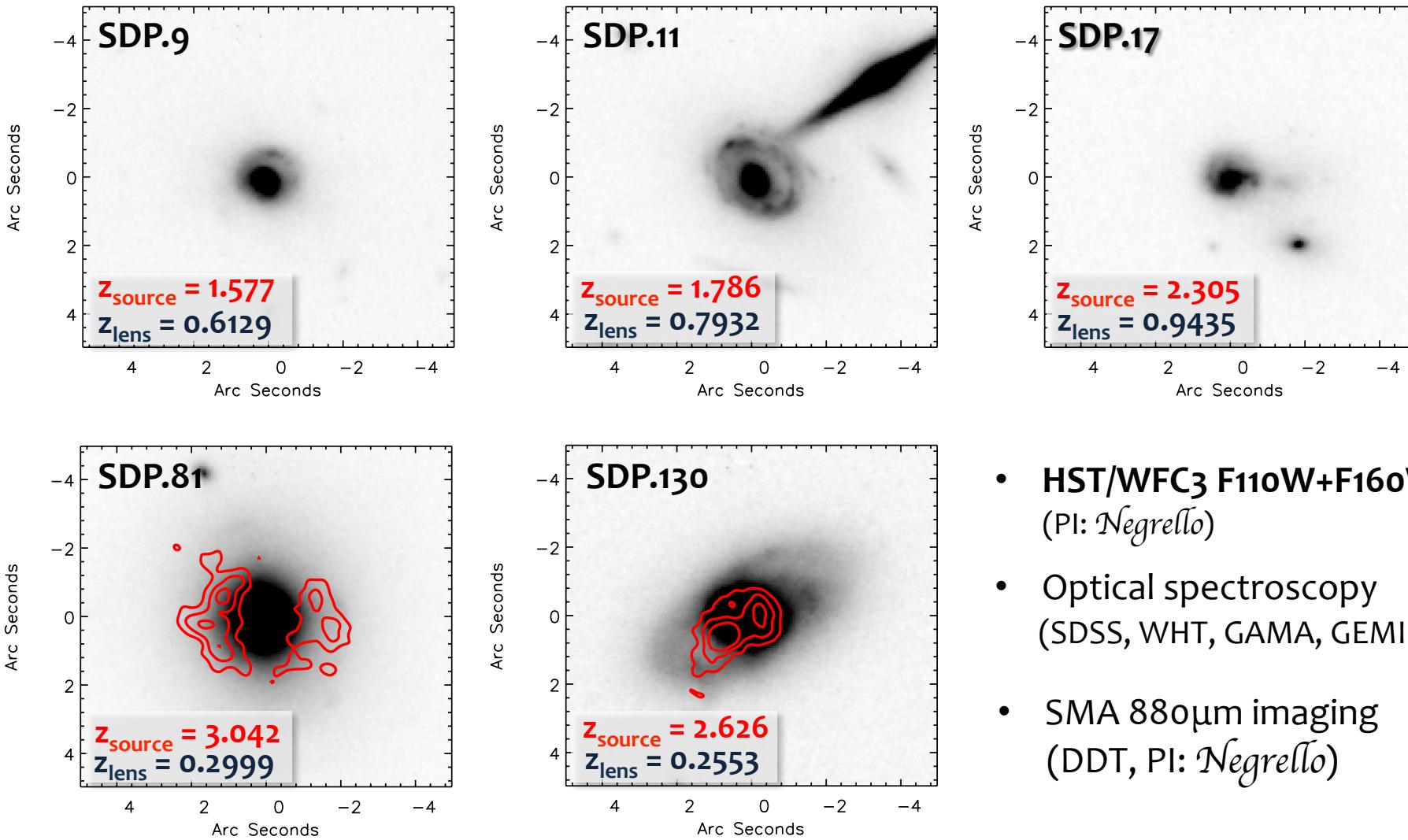


H-ATLAS: lenses in the SDP field



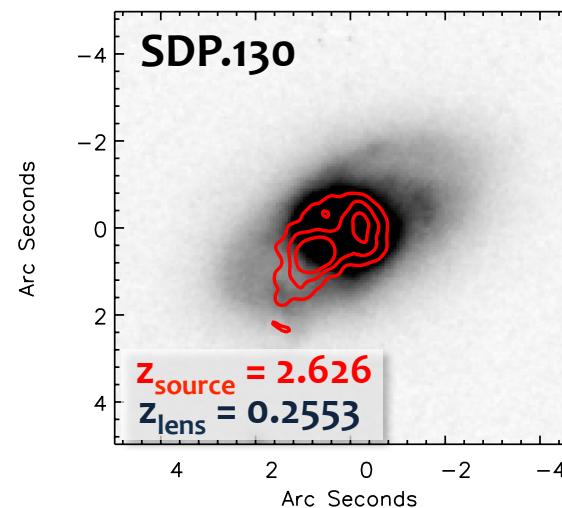
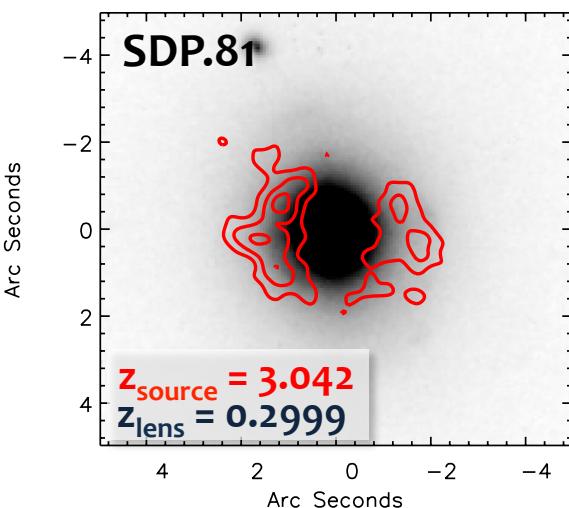
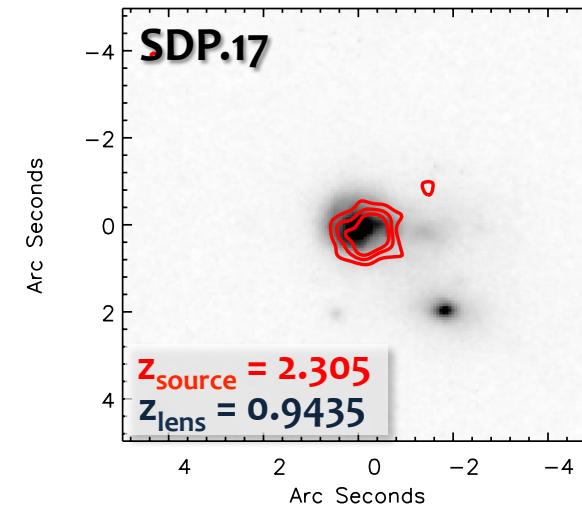
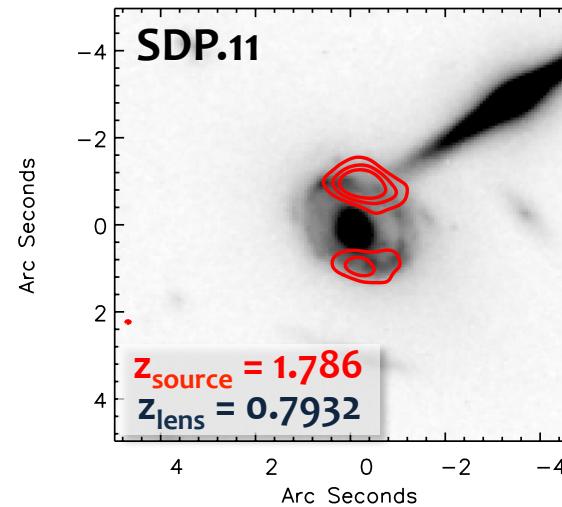
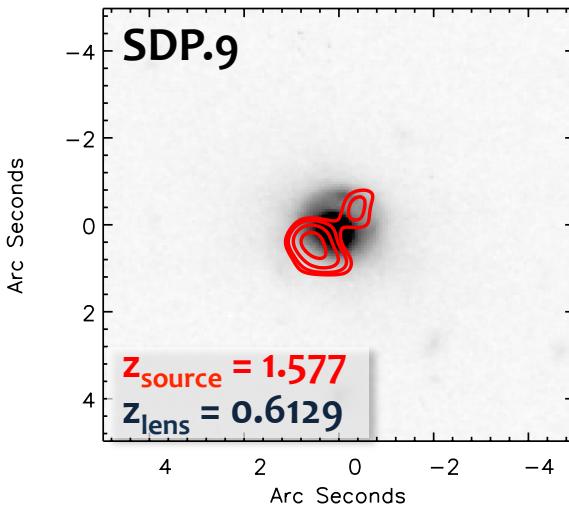
- Keck optical imaging (PI: *Cooray*)
- Optical spectroscopy (SDSS, WHT, APO)
- SMA 880 μ m imaging (DDT, PI: *Negrello*)

H-ATLAS: lenses in the SDP field



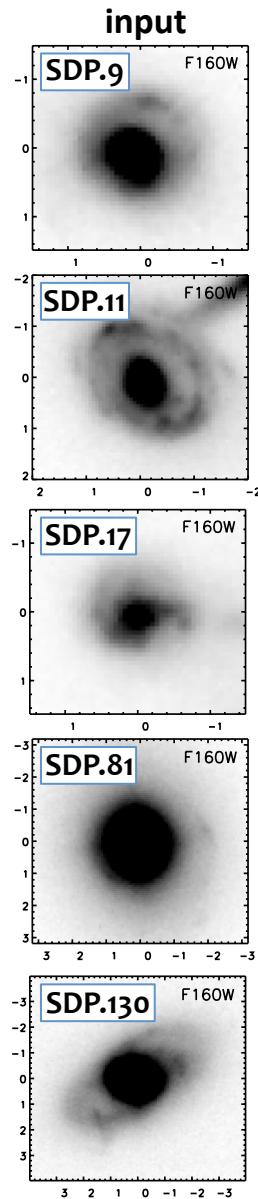
- **HST/WFC3 F110W+F160W**
(PI: *Negrello*)
- Optical spectroscopy
(SDSS, WHT, GAMA, GEMINI-S)
- SMA 880 μ m imaging
(DDT, PI: *Negrello*)

H-ATLAS: lenses in the SDP field

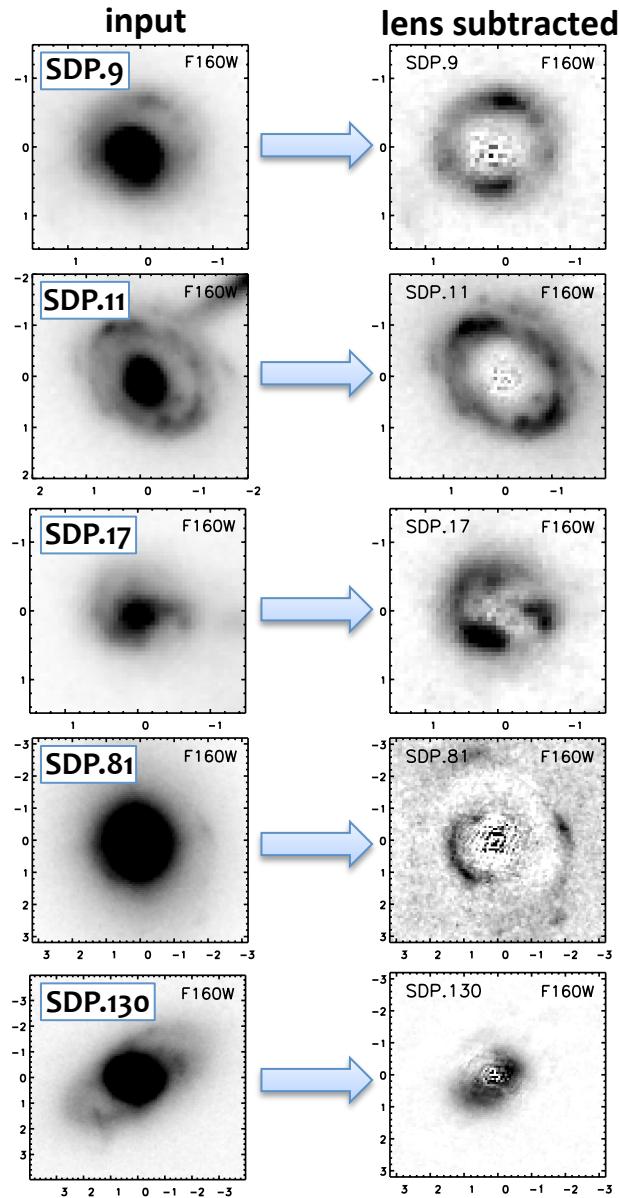


- **HST/WFC3 F110W+F160W**
(PI: *Negrello*)
- Optical spectroscopy
(SDSS, WHT, GAMA, GEMINI-S)
- **SMA 880μm imaging**
(PI: *Bussmann*)

H-ATLAS: lenses in the SDP field

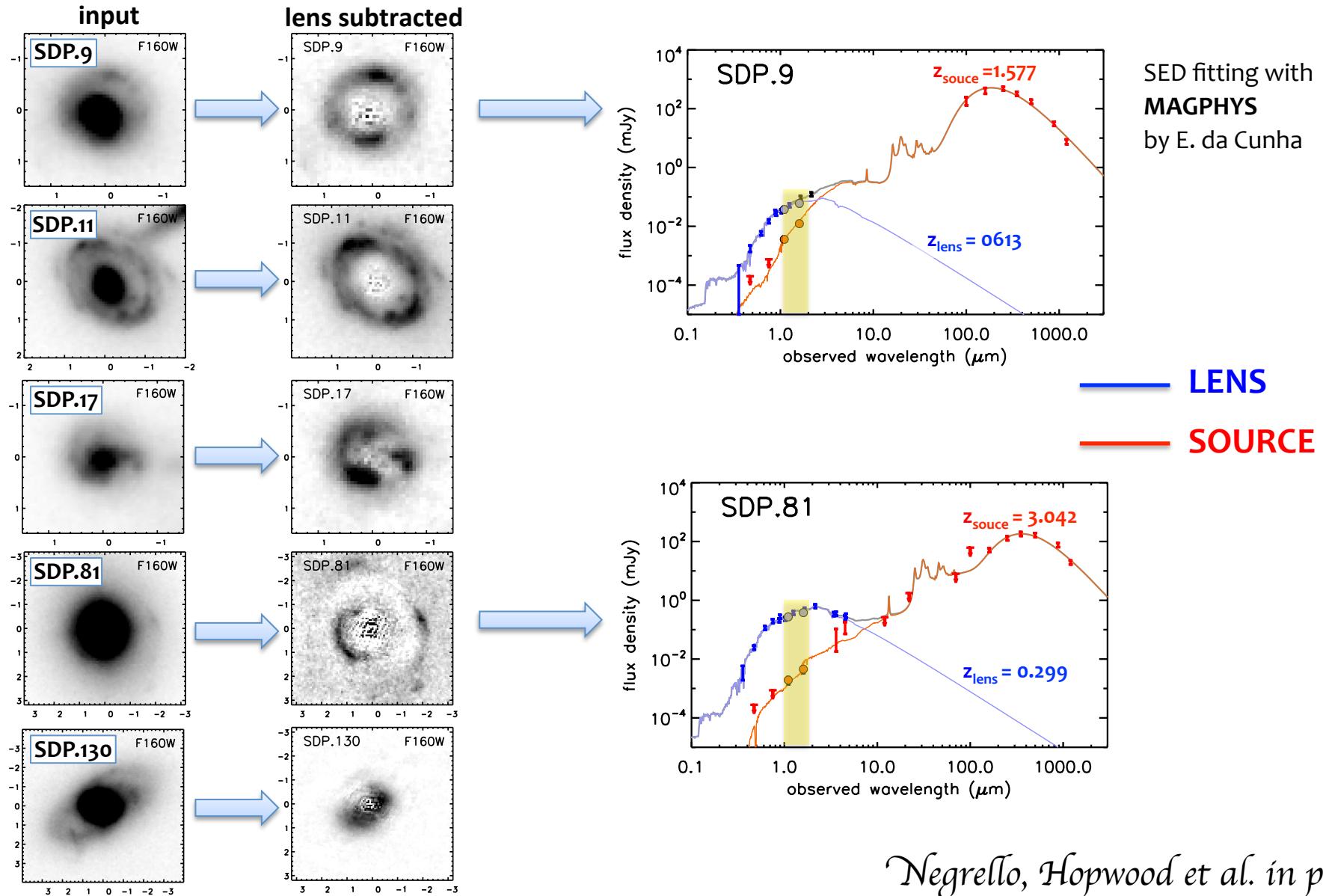


H-ATLAS: lenses in the SDP field

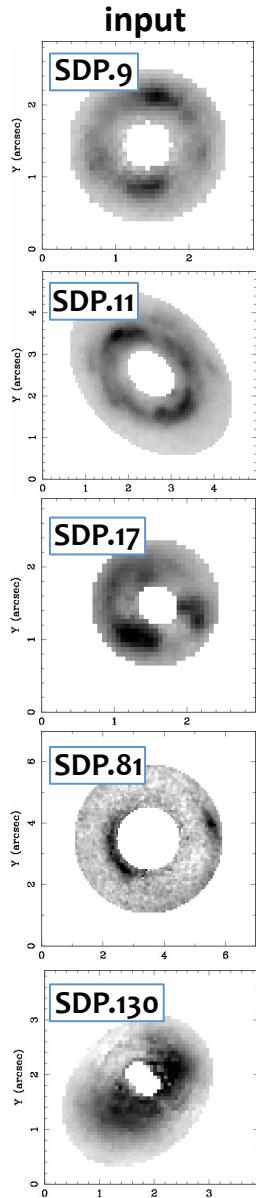


Negrello, Hopwood et al. in prep.

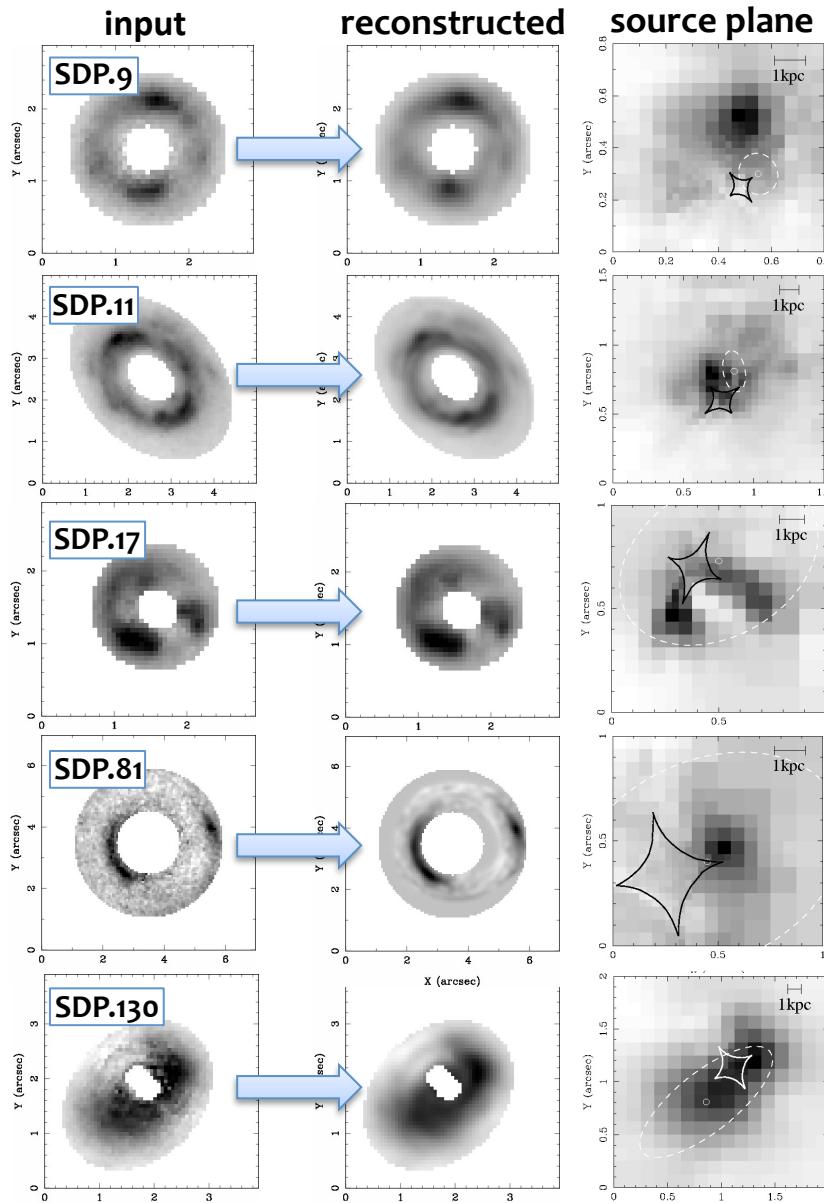
H-ATLAS: lenses in the SDP field



H-ATLAS: lenses in the SDP field

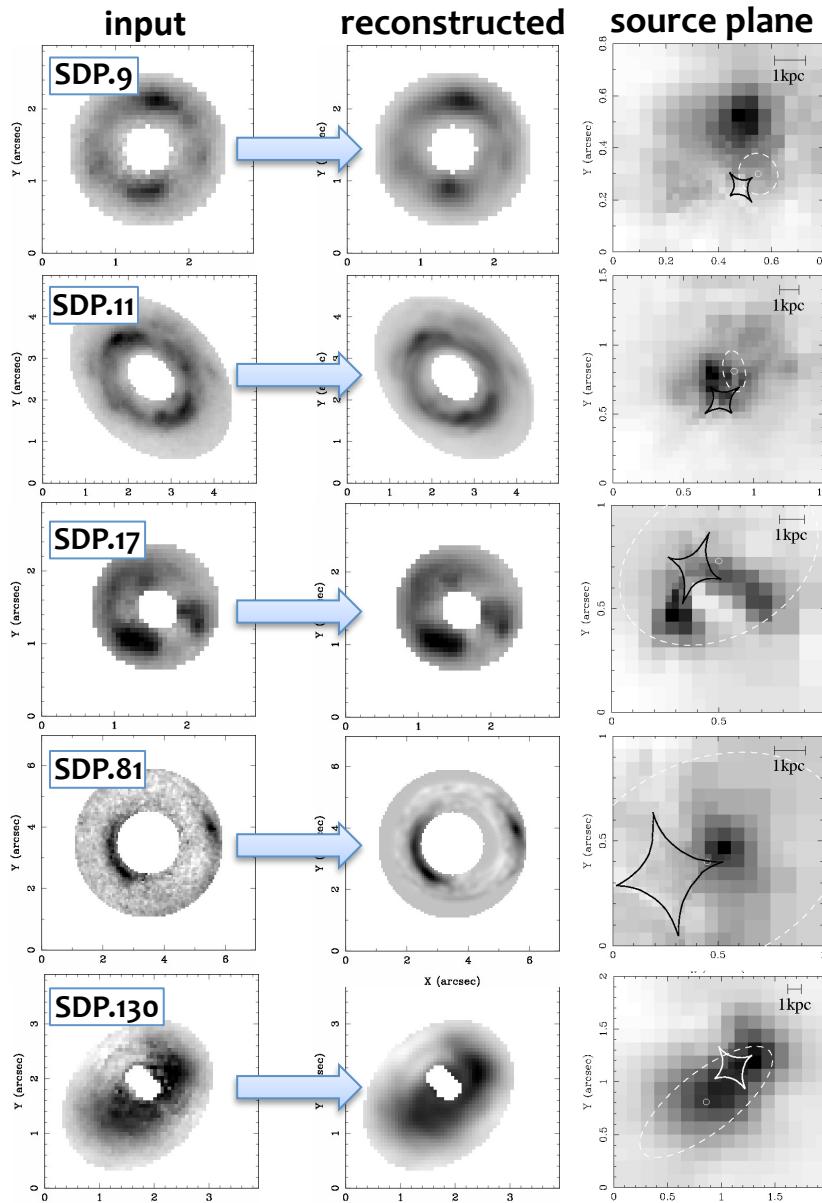


H-ATLAS: lenses in the SDP field



Dye, Negrello et al. in prep.

H-ATLAS: lenses in the SDP field



$$\mu = 6.3 \pm 0.3$$

$$\mu = 7.8 \pm 0.2$$

$$\mu = 3.6 \pm 0.2$$

$$\mu = 10.6 \pm 0.6$$

$$\mu = 3.1 \pm 0.2$$

$$L_{\text{IR}} = (5 - 20) \times 10^{12} L_{\odot}$$

$$\text{SFR} = 400 - 2000 M_{\odot}/\text{yr}$$

$$M_{\star} = (6 - 30) \times 10^{10} M_{\odot}$$

$$M_{\text{dust}} = (6 - 30) \times 10^8 M_{\odot}$$

From CO measurements:

$$M_{\text{gas}} = (2 - 5) \times 10^{10} M_{\odot}$$

Gas fraction

$$M_{\text{gas}} / (M_{\star} + M_{\text{gas}}) = 15 - 30 \%$$

SF efficiency

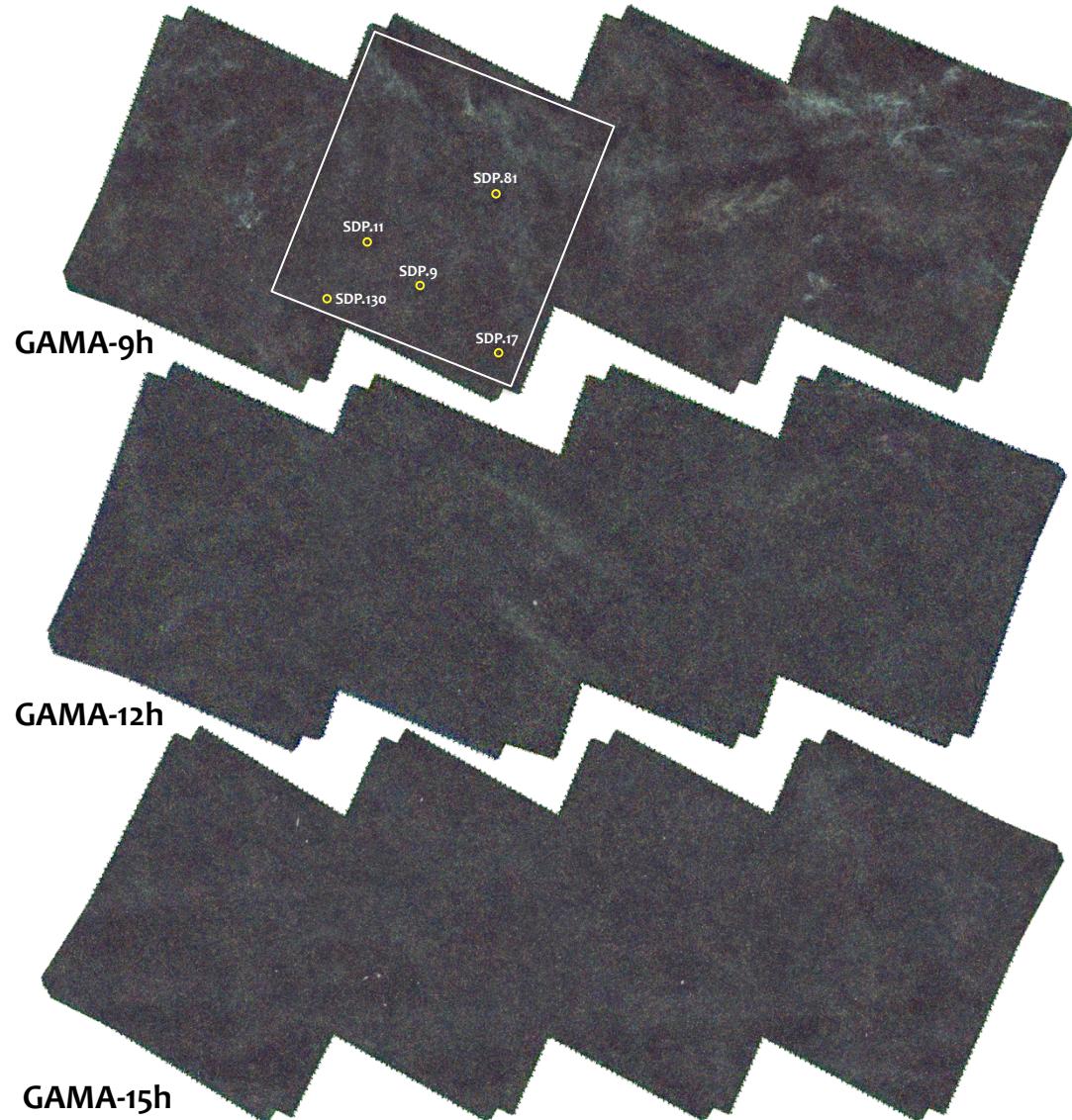
$$L_{\text{IR}} / M_{\text{gas}} = 150 - 350 L_{\odot} / M_{\odot}$$

gas consuption timescale

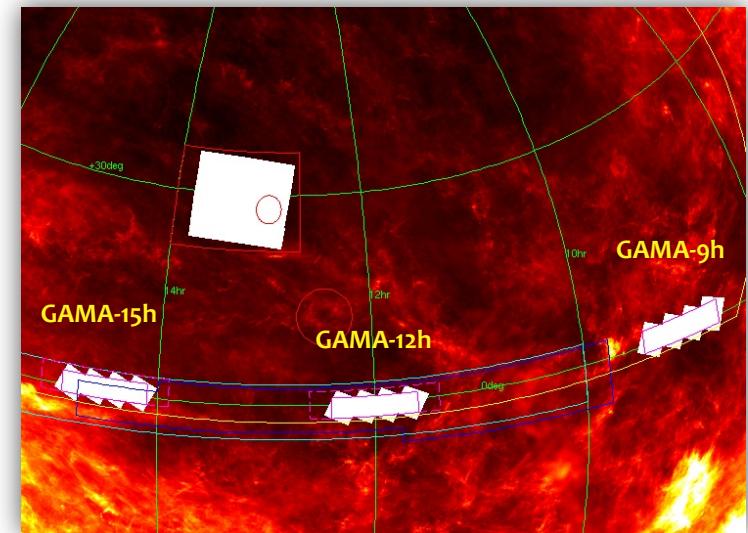
$$M_{\text{gas}} / \text{SFR} = 27 - 93 \text{ Myr}$$

Negrello, Dye et al. in prep.

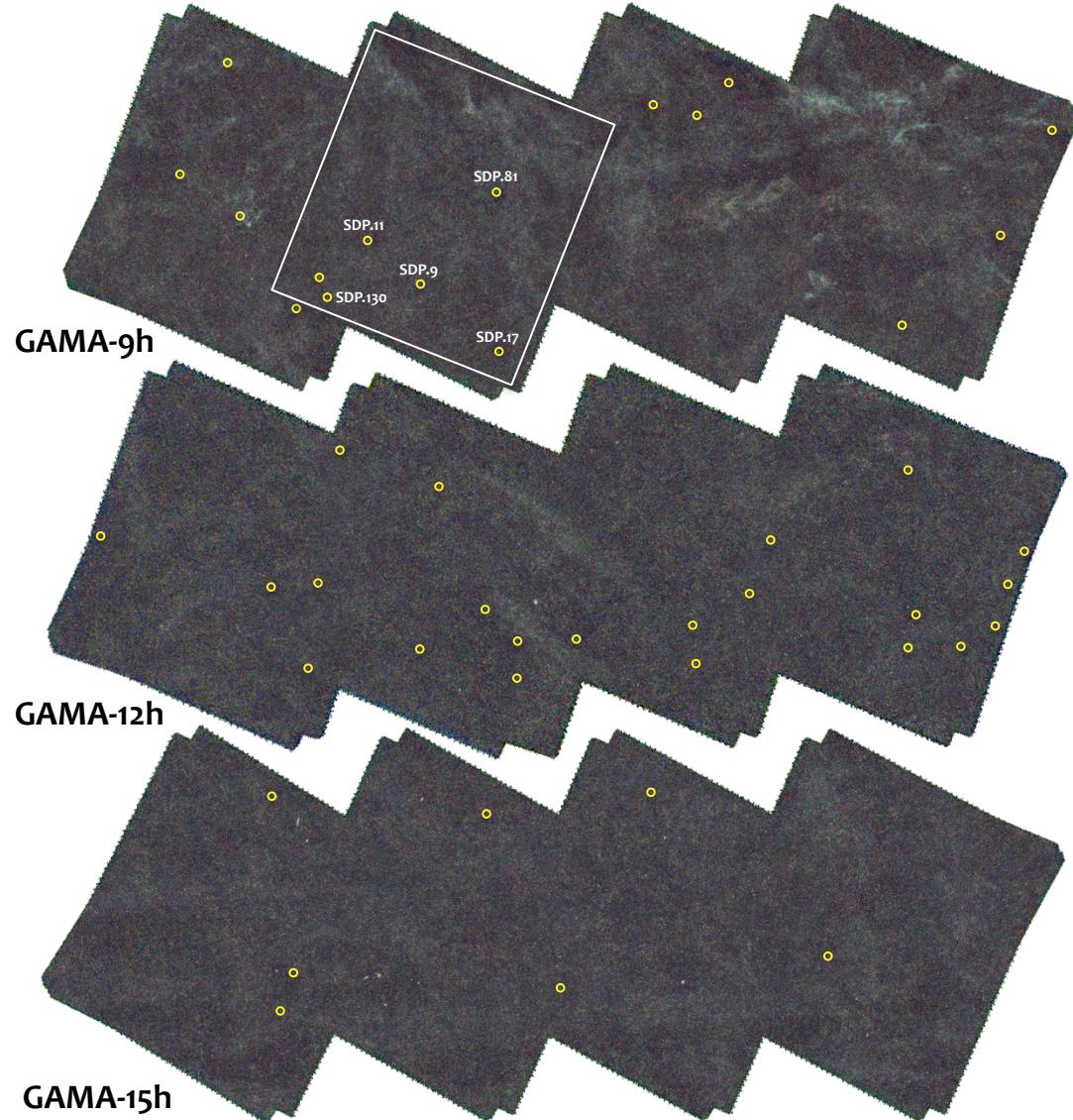
H-ATLAS phase-1 fields



GAMA equatorial fields
Area = 161 deg²



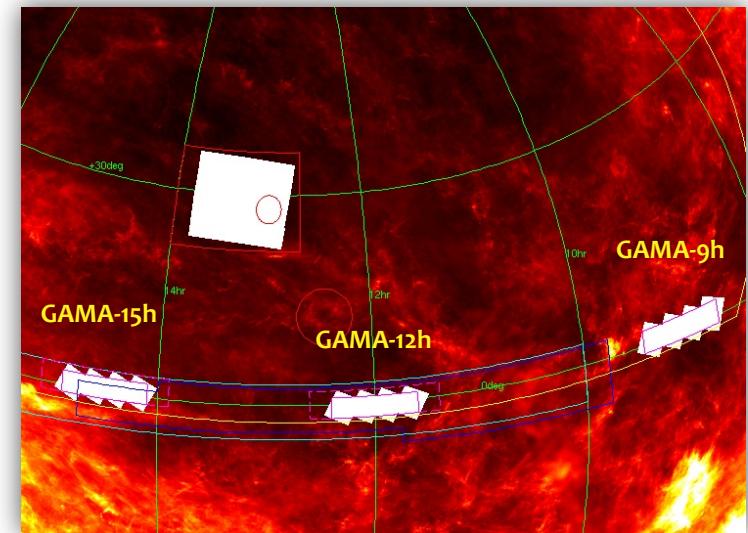
H-ATLAS phase-1 fields



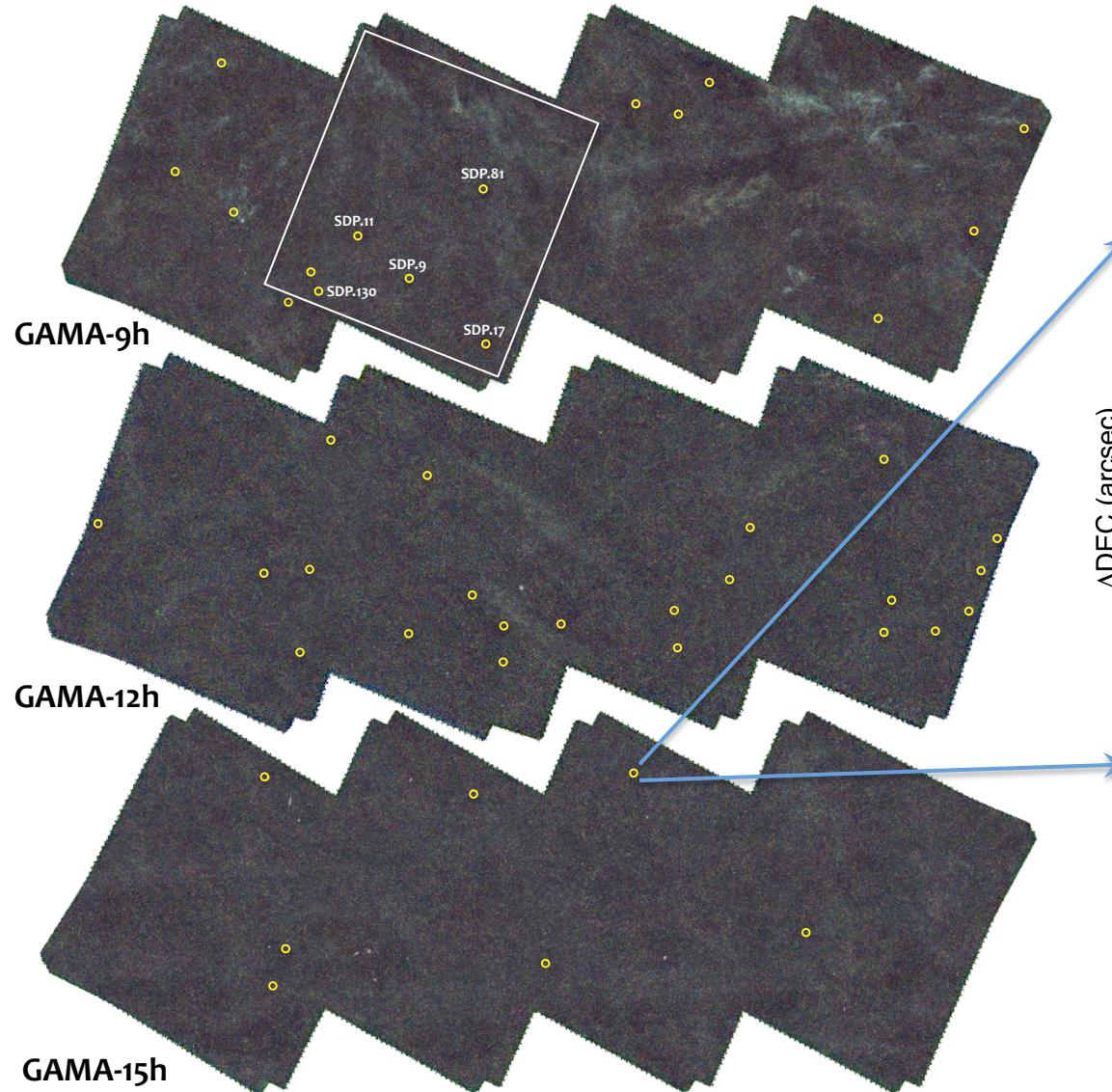
GAMA equatorial fields
Area = 161 deg²

**45 candidate lensed galaxies
with $F_{500\mu\text{m}} > 100\text{mJy}$**

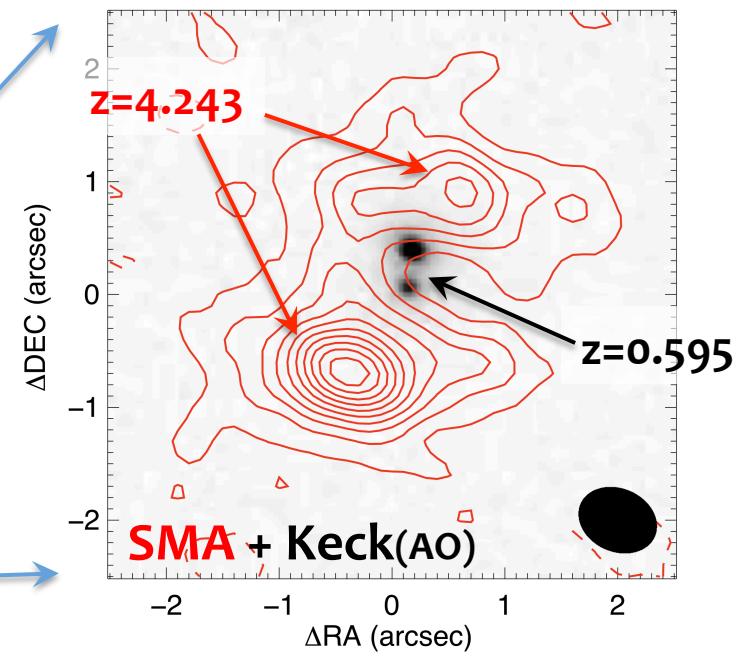
GAMA-9h: 16
GAMA-12h: 22
GAMA-15h: 7



H-ATLAS phase-1 fields



Cox et al. (2011)
Bussmann et al. (2012)
see also **poster #11** by *Dannerbauer*

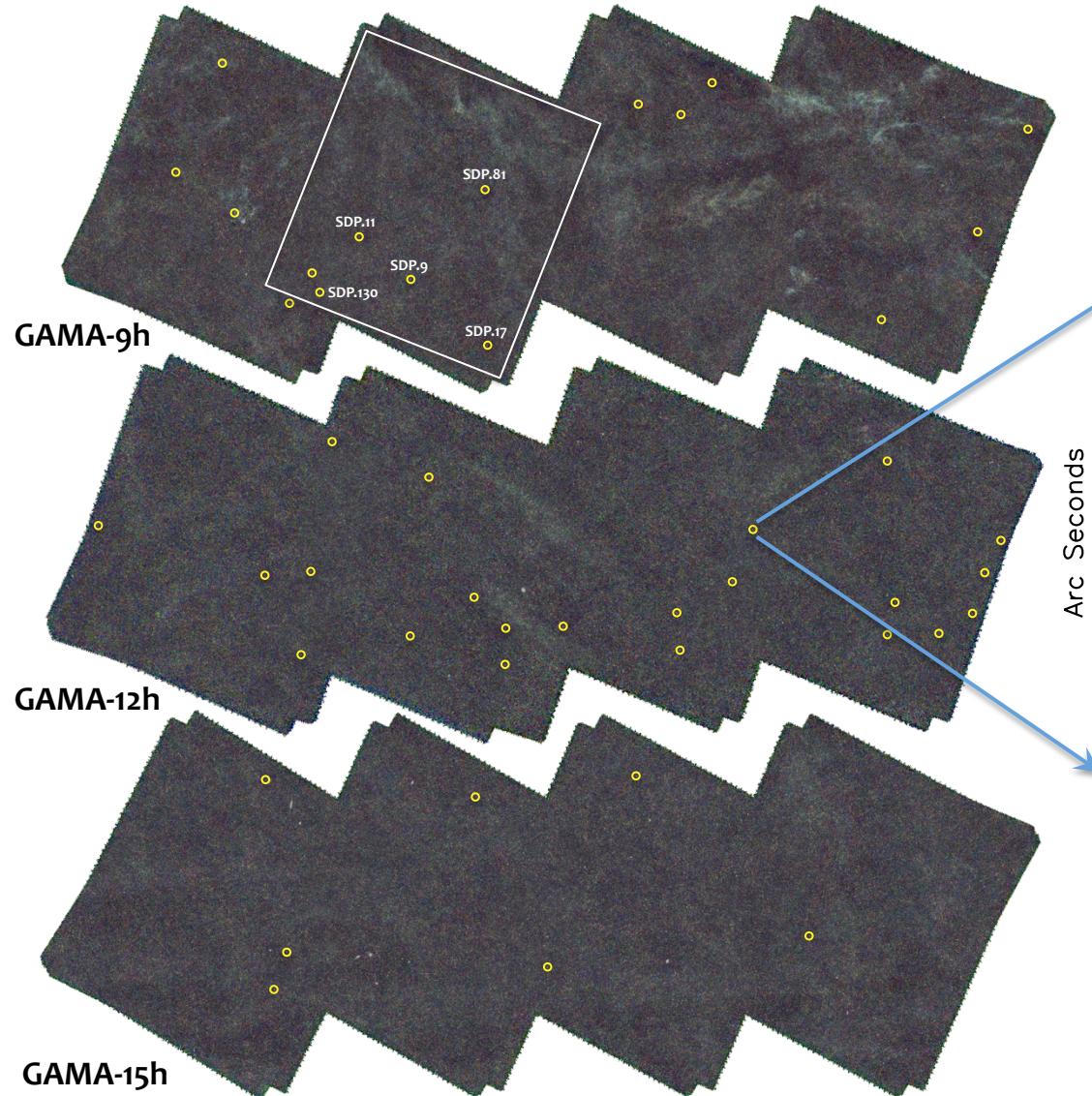


$$\mu = 4.1$$

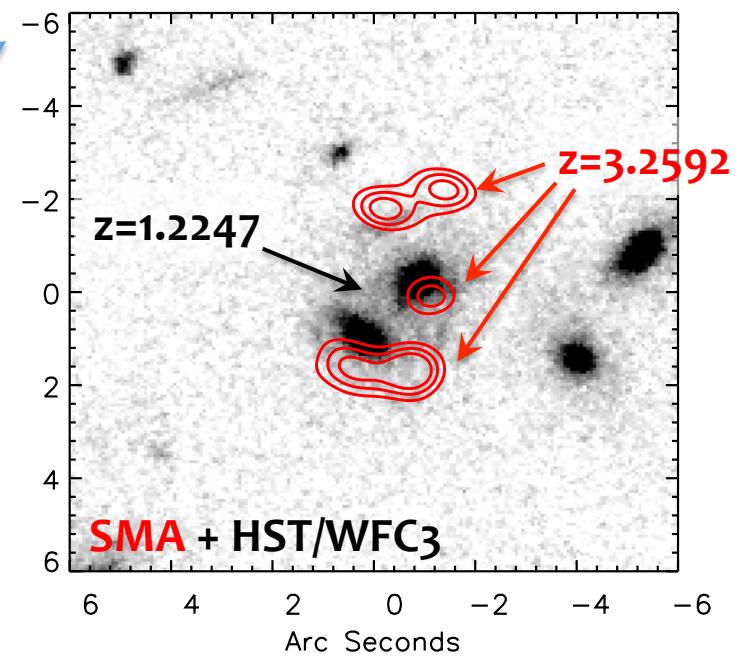
$$L_{\text{IR}} = 2 \times 10^{13} L_{\odot}$$

$$\text{SFR} = 3000 M_{\odot}/\text{yr}$$

H-ATLAS phase-1 fields



Fu et al. (2012)
Herranz et al. (2011)
Bussmann et al. (2013)

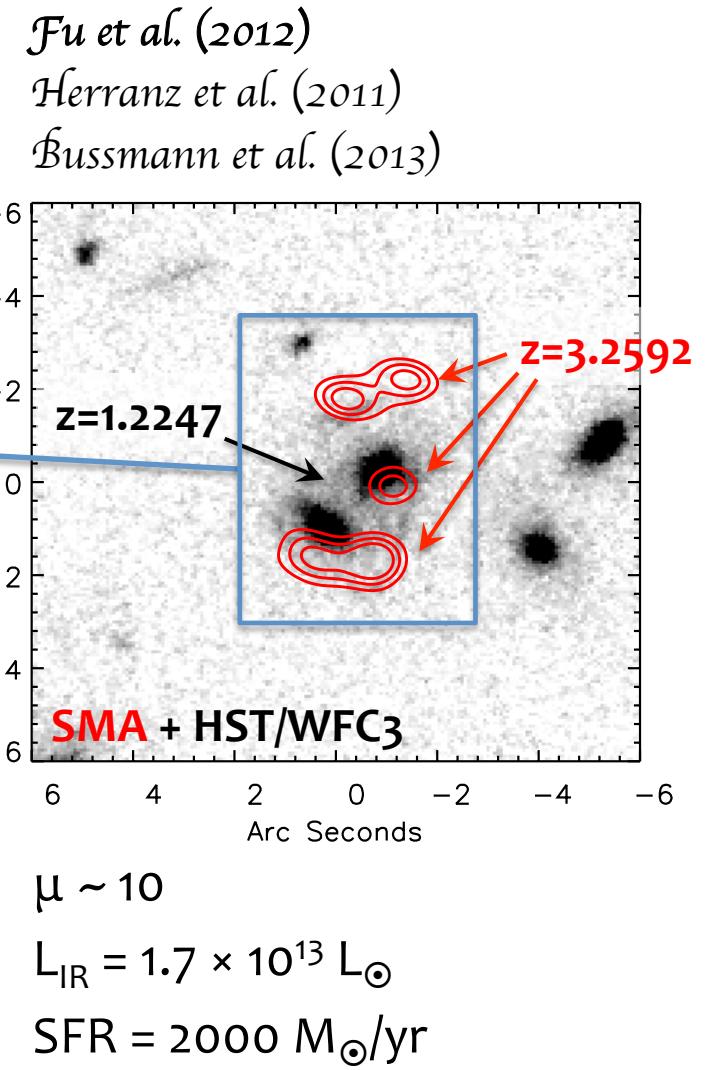
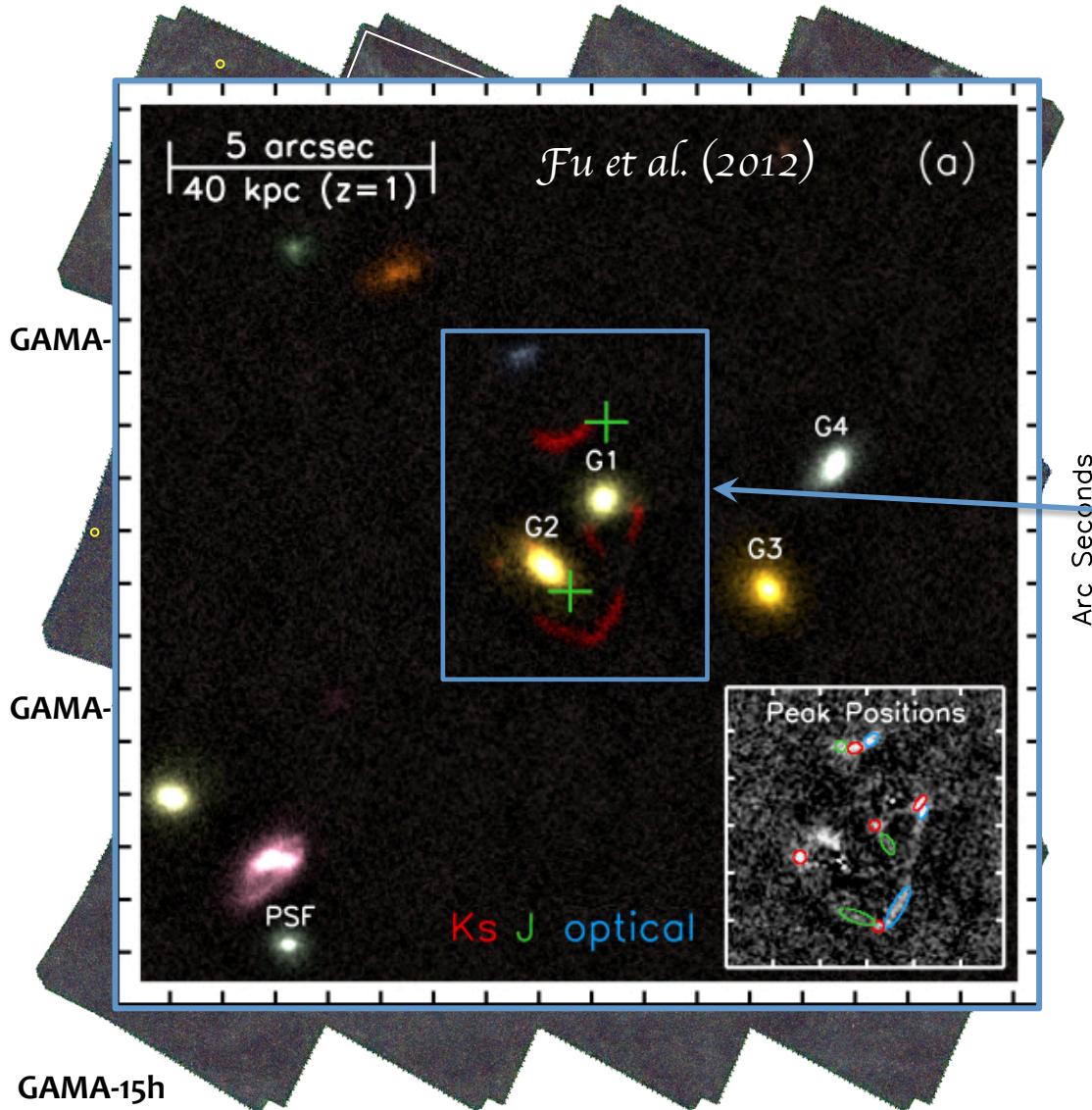


$$\mu \sim 10$$

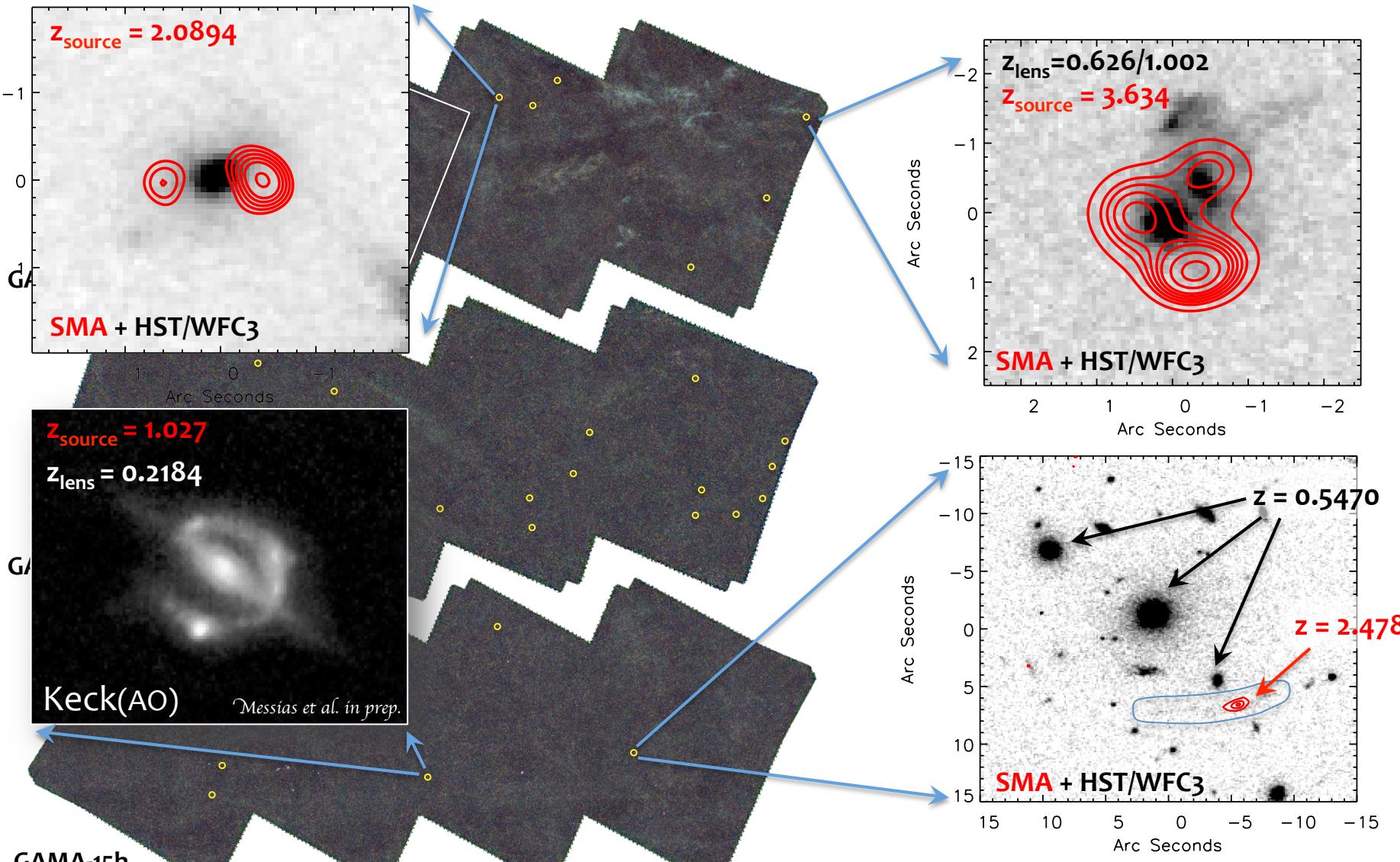
$$L_{\text{IR}} = 1.7 \times 10^{13} L_{\odot}$$

$$\text{SFR} = 2000 M_{\odot}/\text{yr}$$

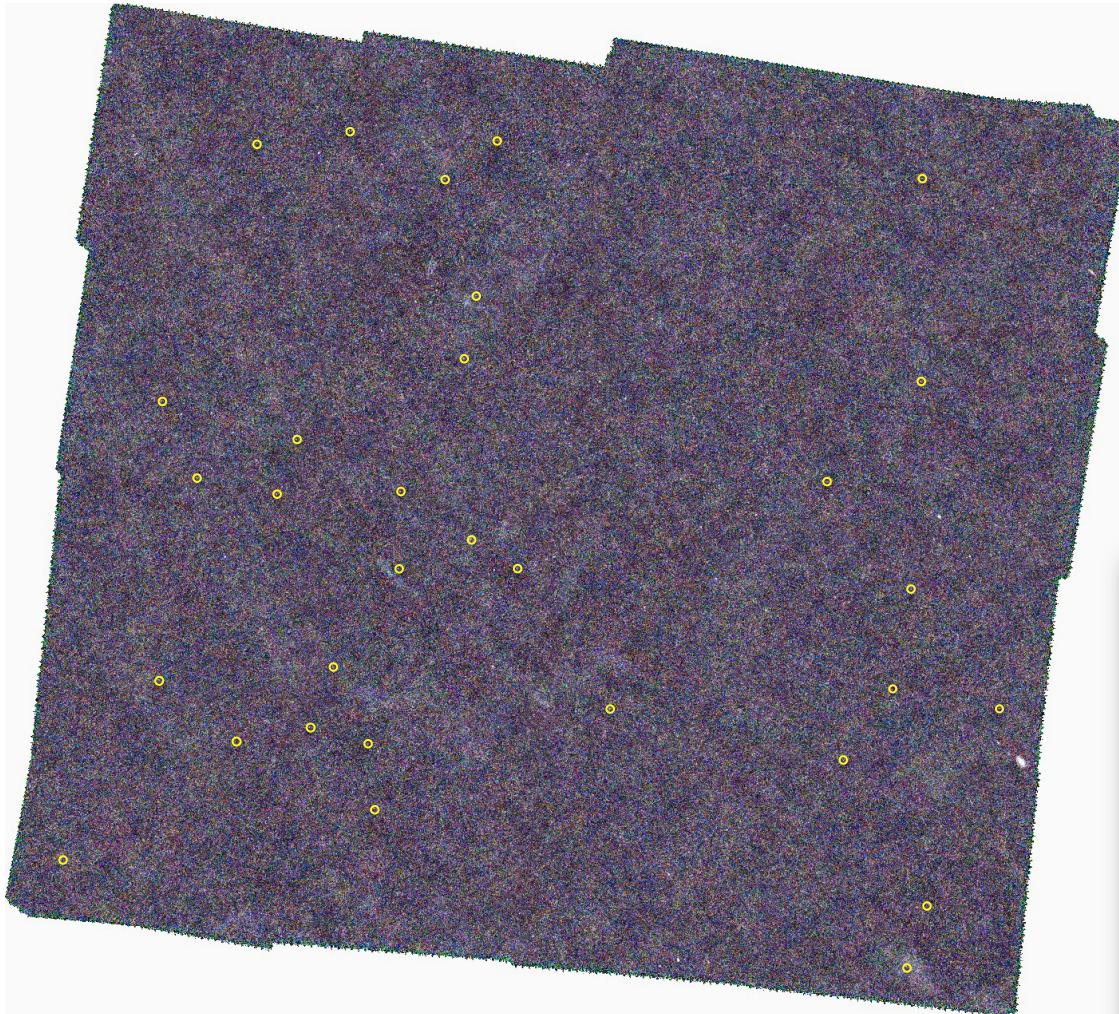
H-ATLAS phase-1 fields



H-ATLAS phase-1 fields

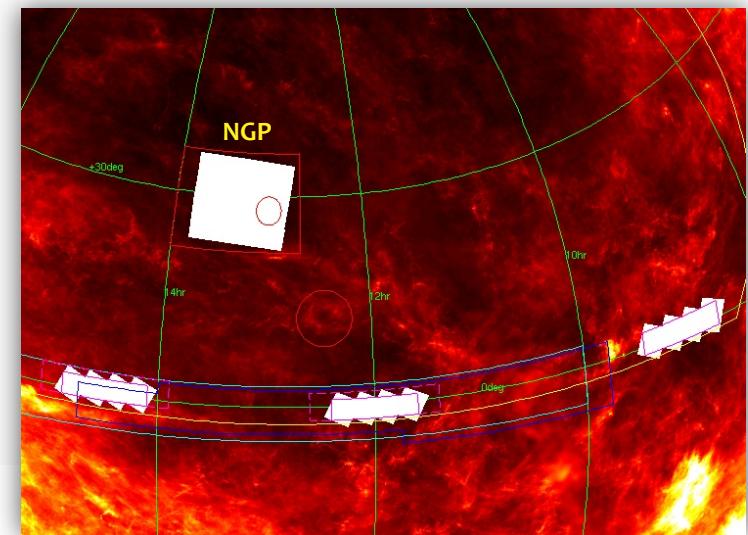


H-ATLAS NGP field

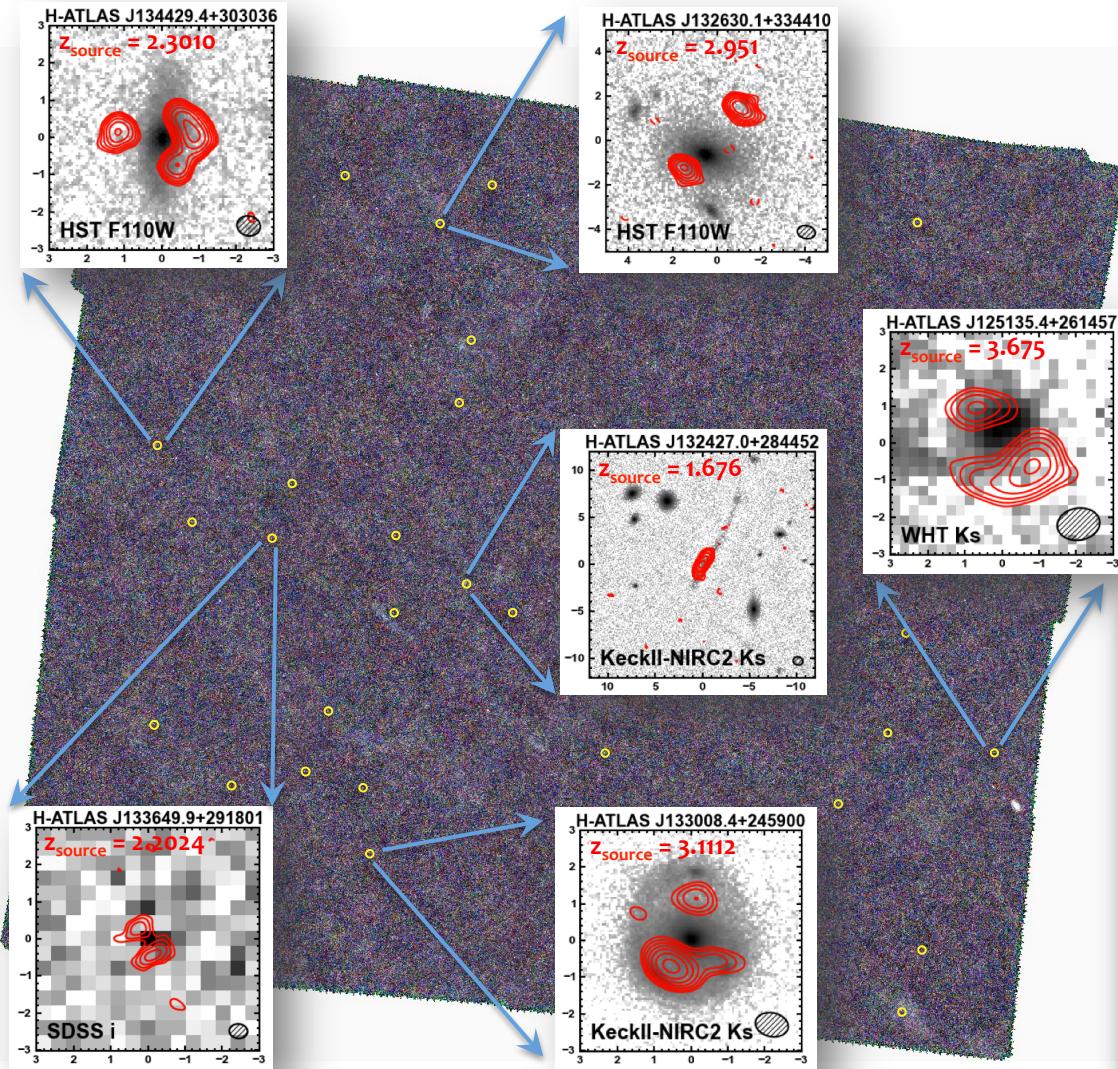


Area = 178 deg²

31 candidate lensed galaxies
with $F_{500\mu\text{m}} > 100\text{mJy}$

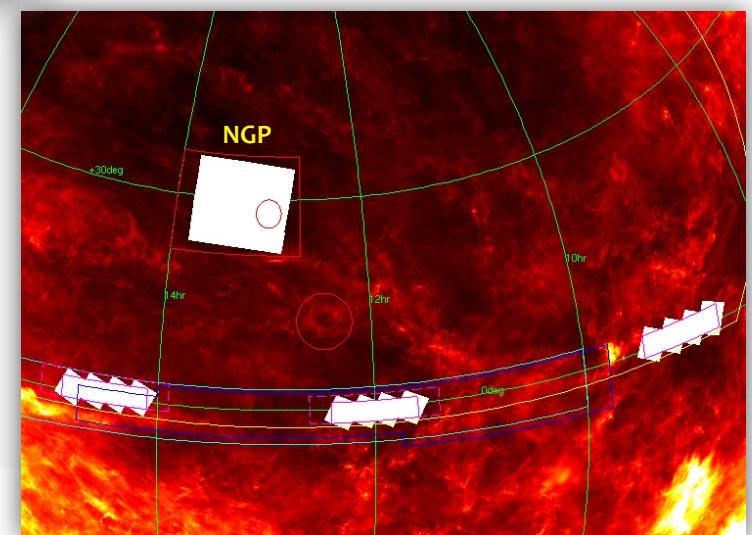


H-ATLAS NGP field



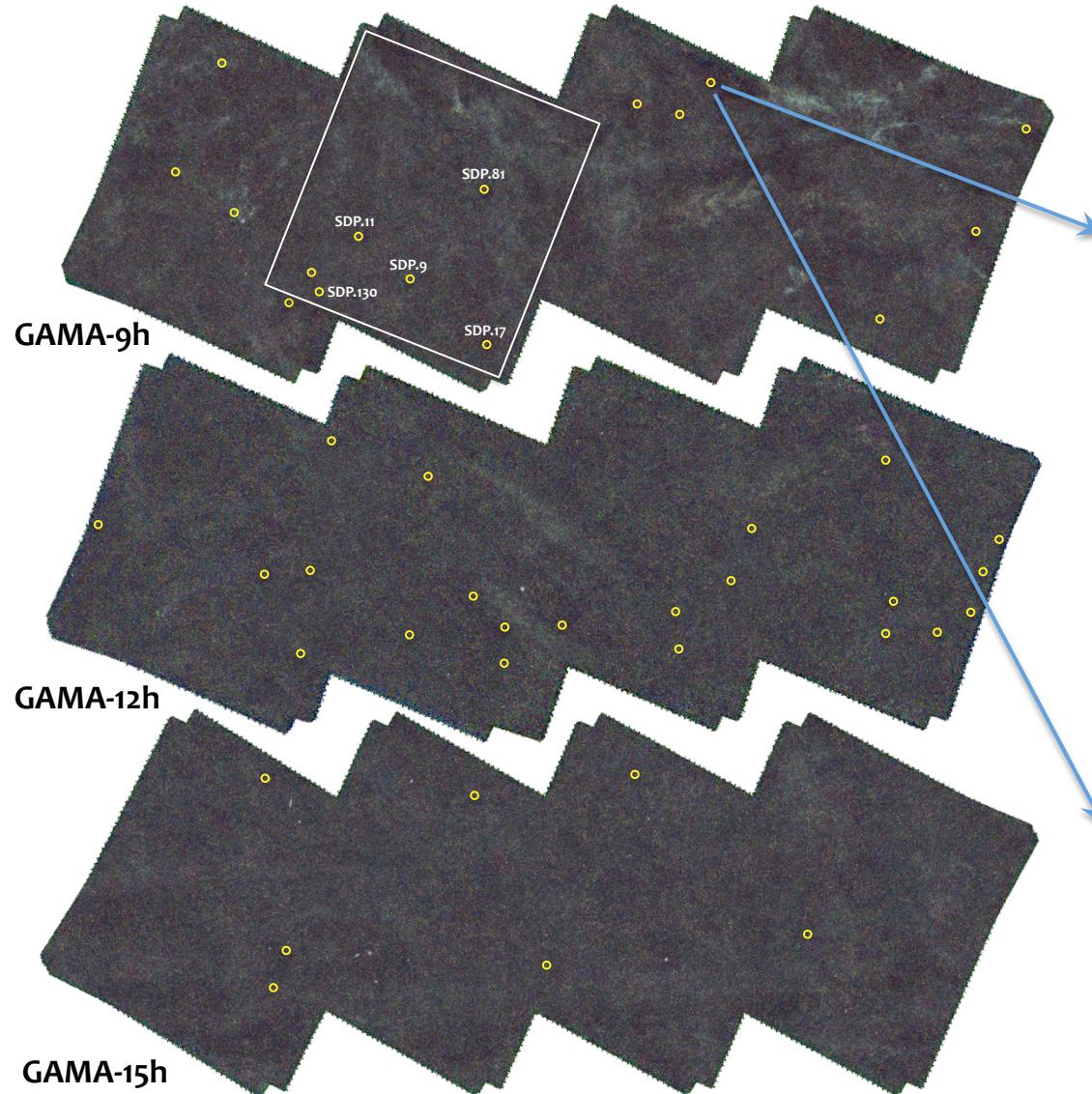
Area = 178 deg²

**31 candidate lensed galaxies
with $F_{500\mu\text{m}} > 100\text{mJy}$**



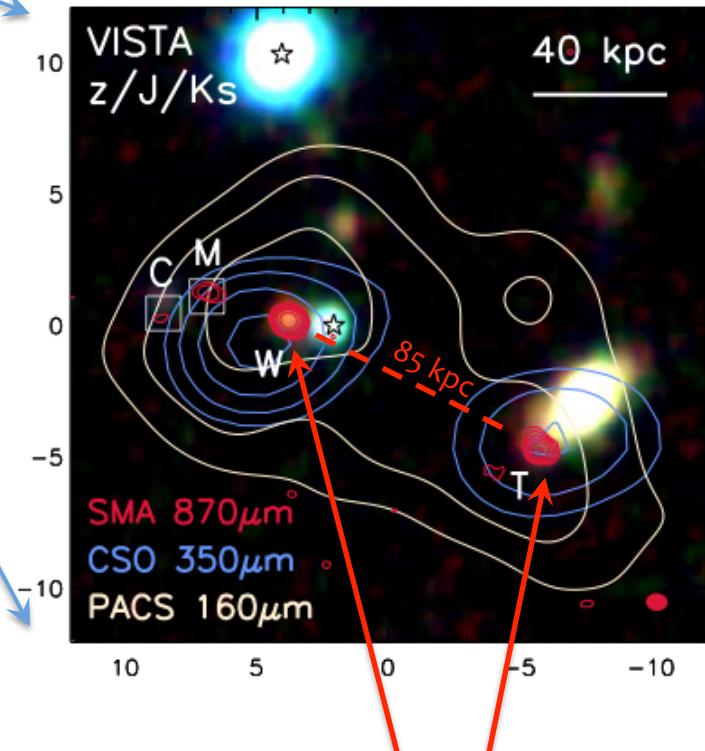
SMA data from Bussmann *et al.* (2013)

H-ATLAS phase-1 fields



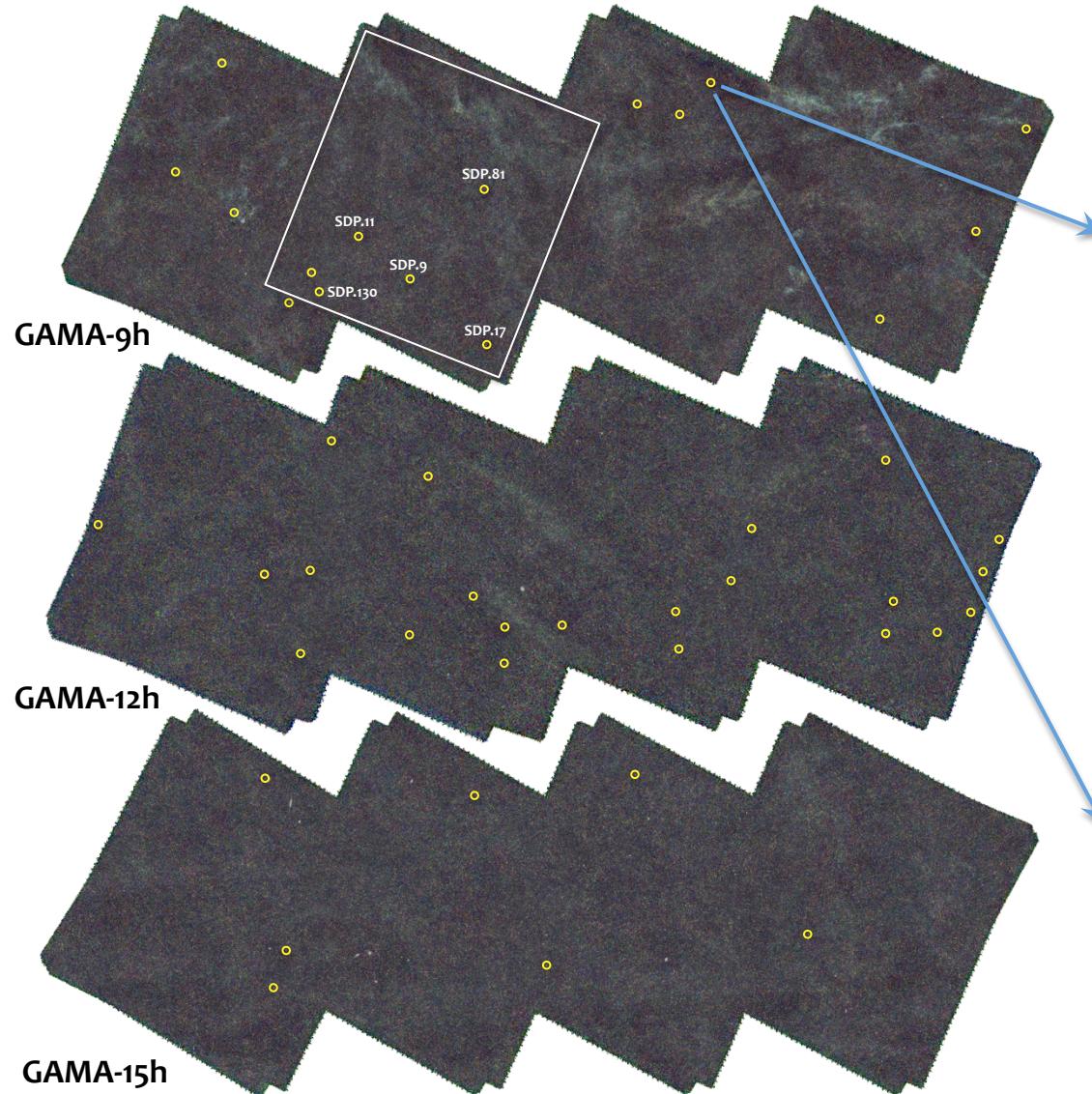
Not all of them are
strongly lensed !

Ivison et al. (2013)



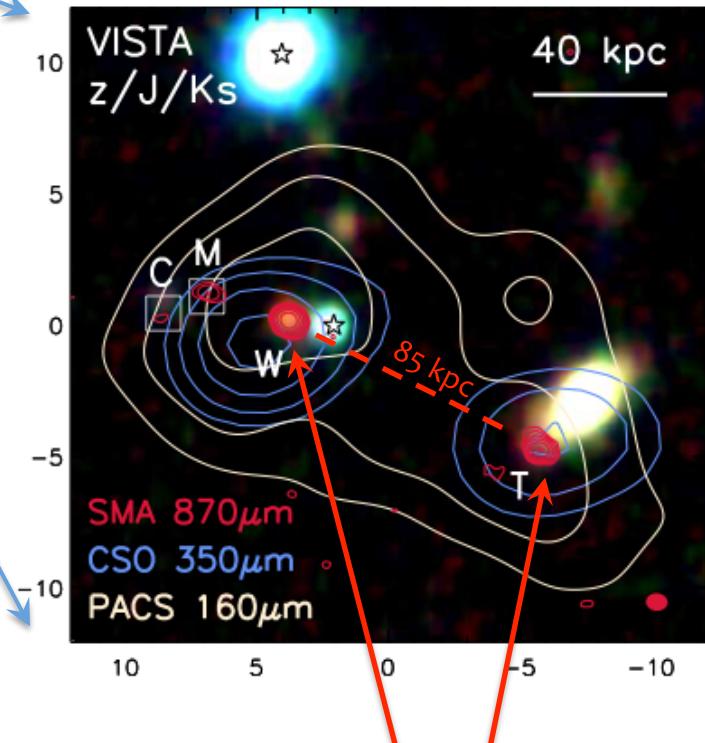
Binary system of $z=2.41$ HyLIRGs

H-ATLAS phase-1 fields



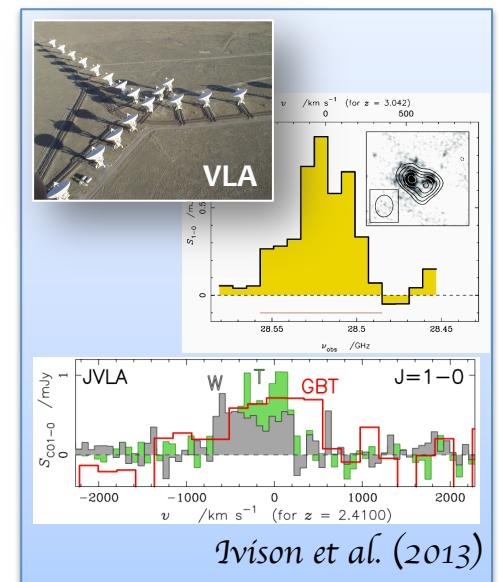
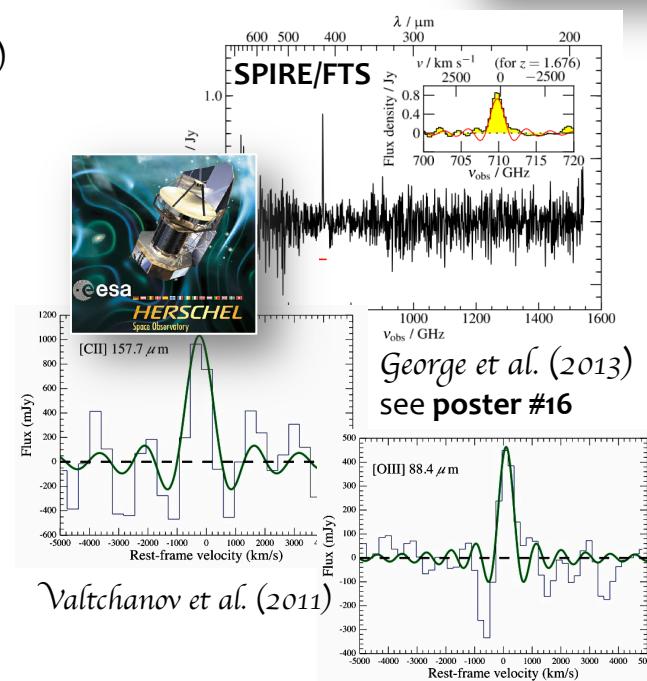
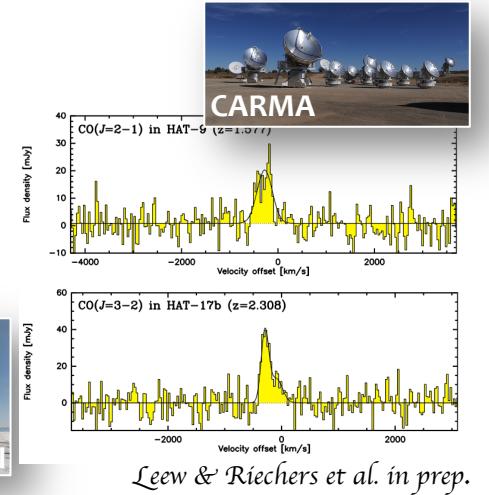
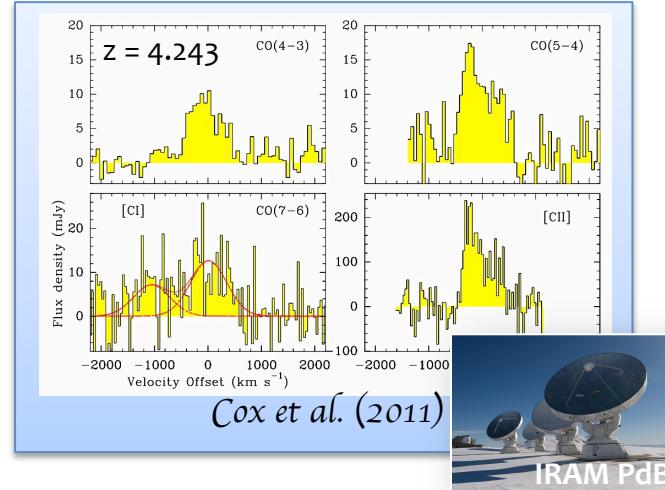
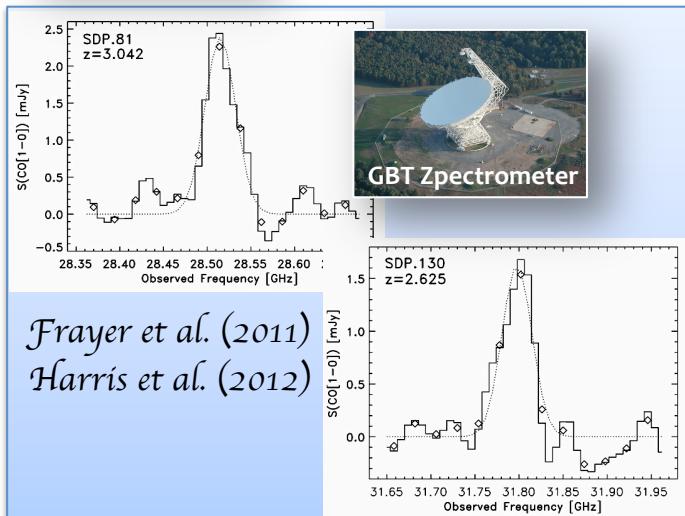
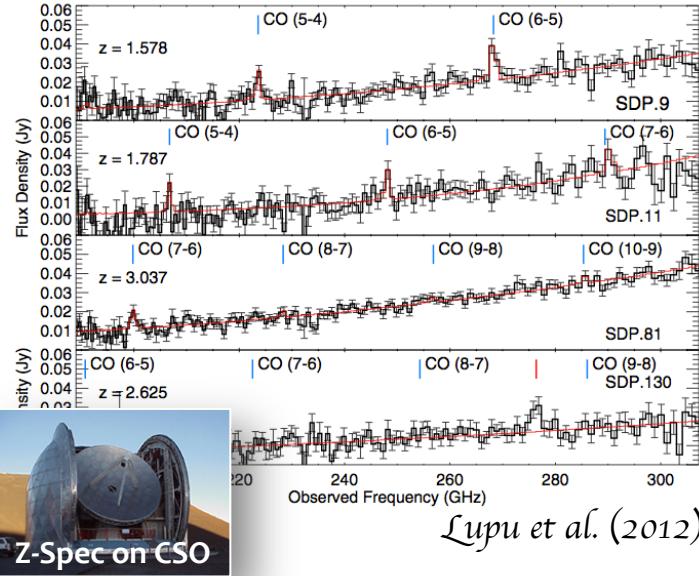
**Not all of them are
strongly lensed !**

Ivison et al. (2013)

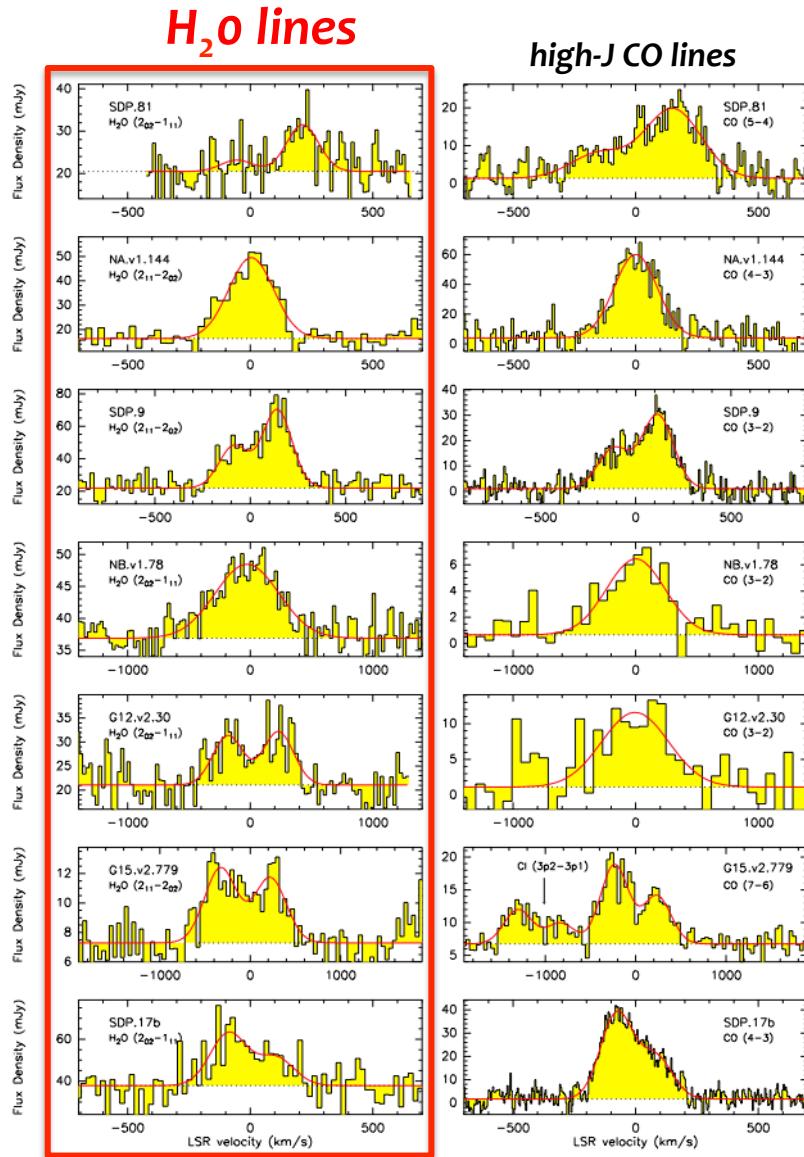


**A CLUSTER OF STARBURSTING
PROTO-ELLIPTICALS**

Properties of the gas at high-z



Properties of the gas at high-z



Water vapor emission lines

Omont *et al.* (2011, 2013)

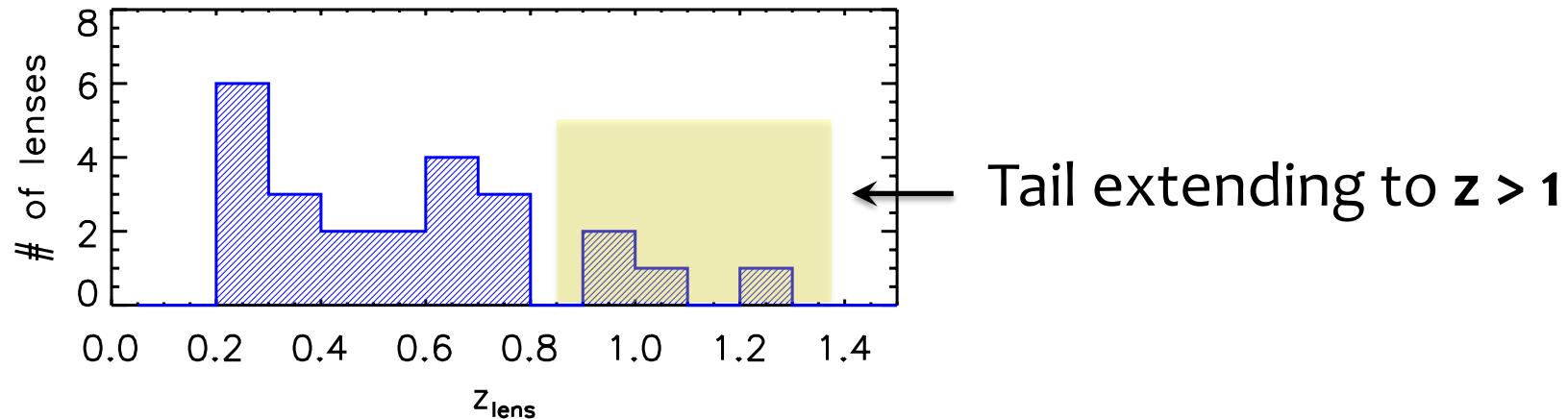
see poster #34

- Indicator of **warm** and **dense** gas
- Intensity comparable to high-*J* CO
- Profiles similar to high-*J* CO

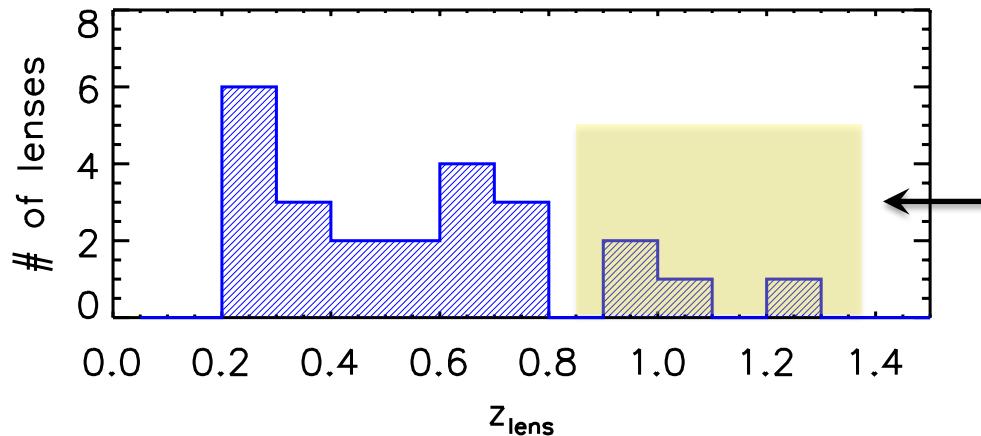


IRAM PdBI

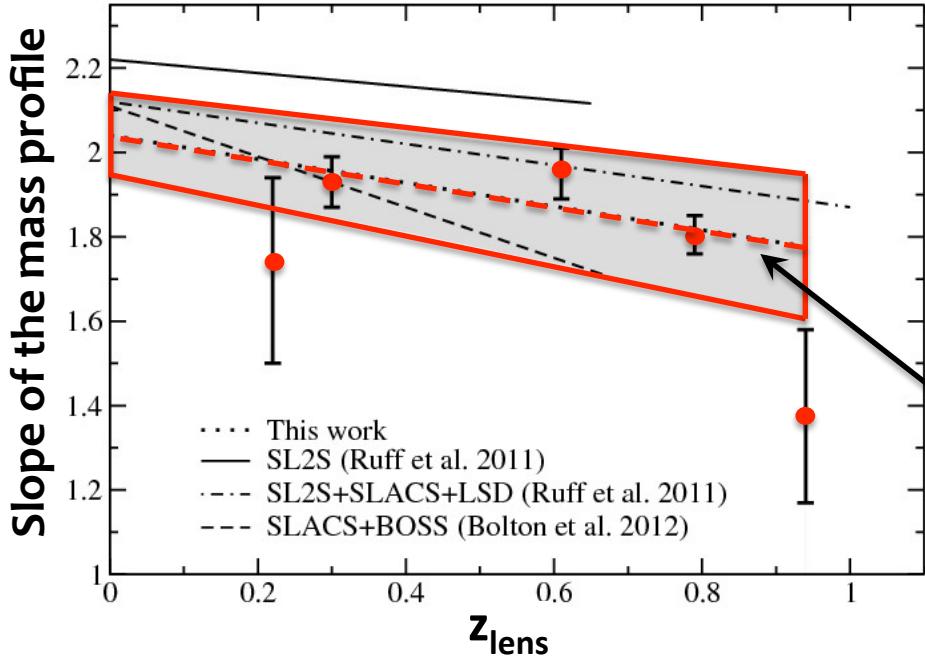
Mass profile of the lenses out to $z > 1$



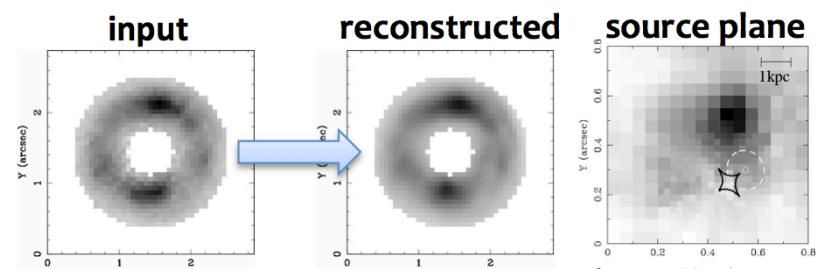
Mass profile of the lenses out to $z > 1$



Tail extending to $z > 1$



● H-ATLAS SDP lenses

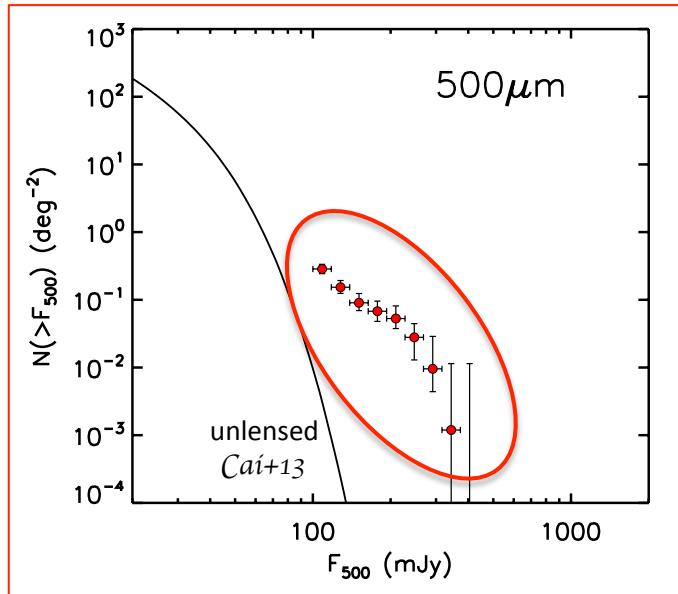


Constraint derived from the
first 5 H-ATLAS/SDP lenses

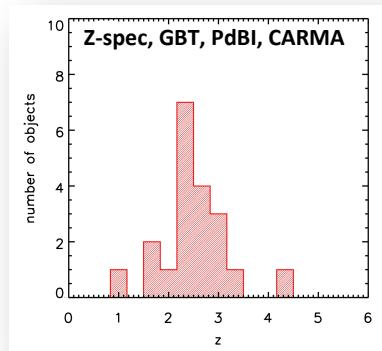
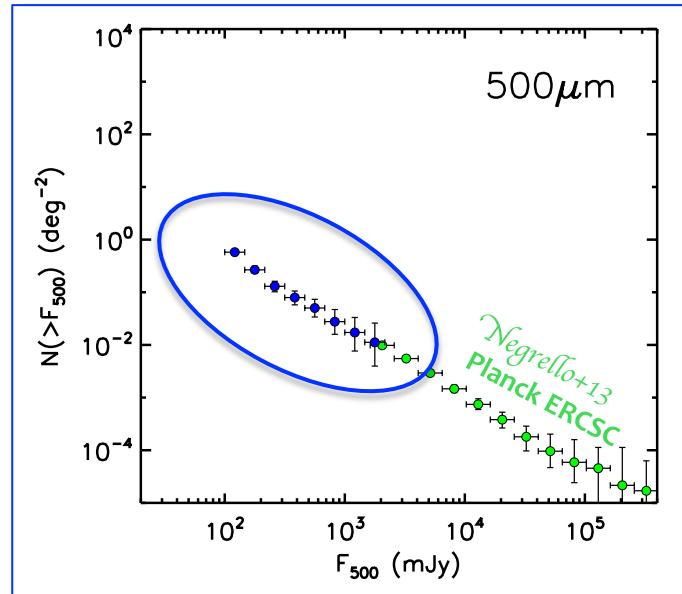
Dye et al. in prep.

Sub-mm bright number counts

LENSED GALAXIES AT $Z > 1$

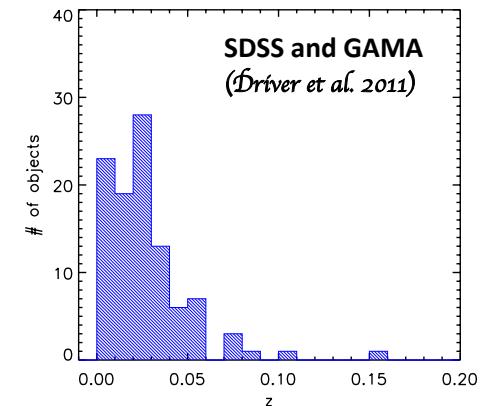


SPIRALS AT $Z < 0.2$



Harris et al. (2012), Lupu et al. (2012),
Cox et al. (2011), Leew et al. in prep.

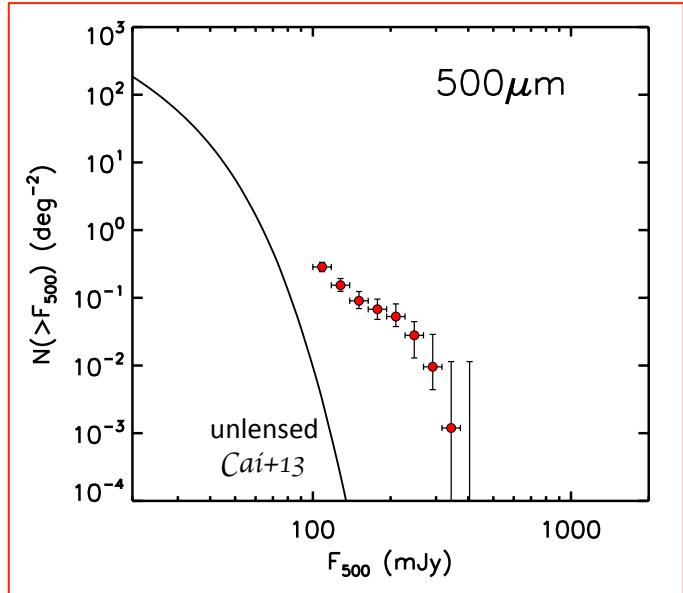
Integral number counts at
500 μ m for $F_{500} \geq 100$ mJy



Negrello et al. in prep.

Sub-mm bright number counts

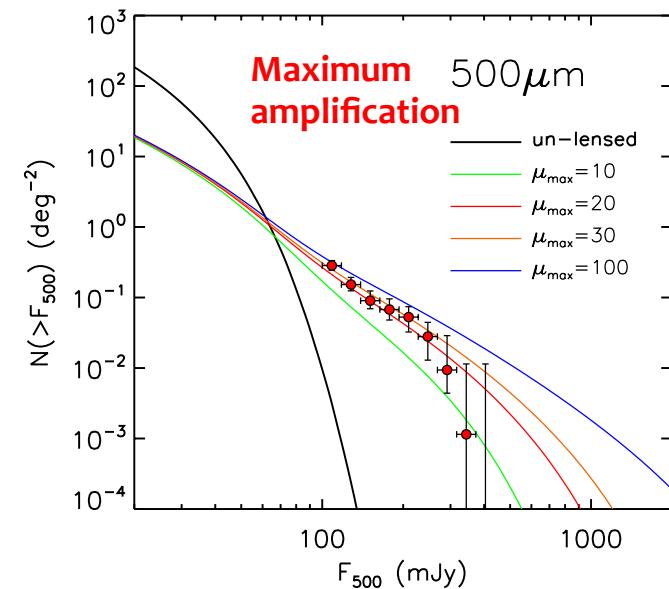
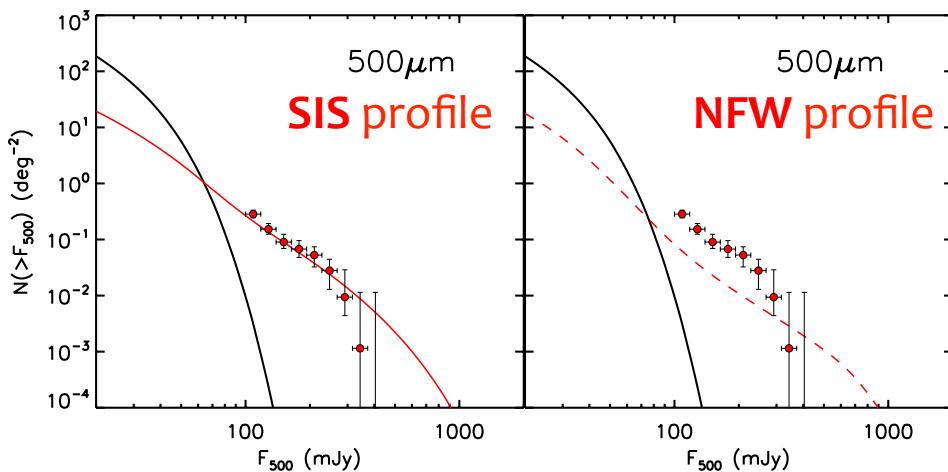
LENSED GALAXIES AT $Z > 1$



The counts of lensed galaxies depend on the

- shape of the unlensed counts
- mass profile of the lenses
- size of the background sources

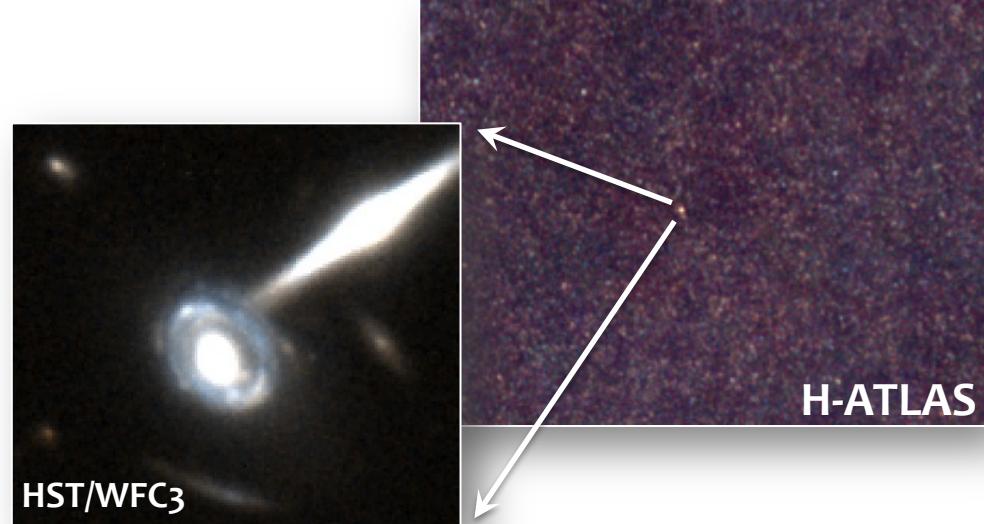
(see Lapi, Negrello *et al.* 2012)



Conclusions



ASTROPHYSICAL
TERAHERTZ
LARGE
AREA
SURVEY



The H-ATLAS lens sample is currently used to

- Study the **properties of the gas at high redshift**
- Measure the **mass profile of galaxies** out to $z > 1$
- identify the **most extreme HyLIRGs** in the Universe