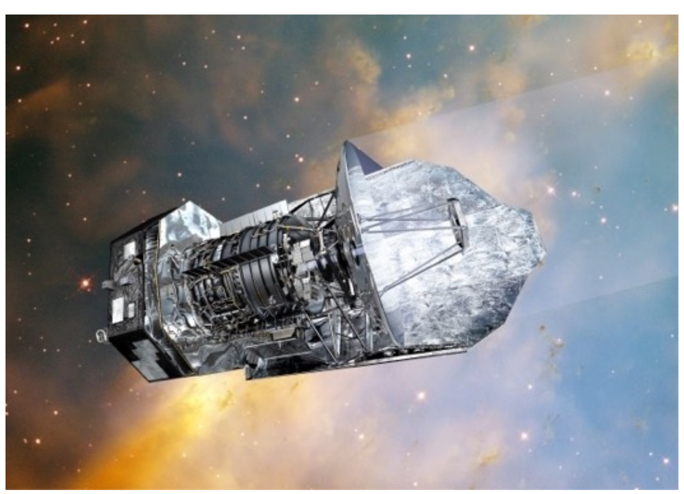
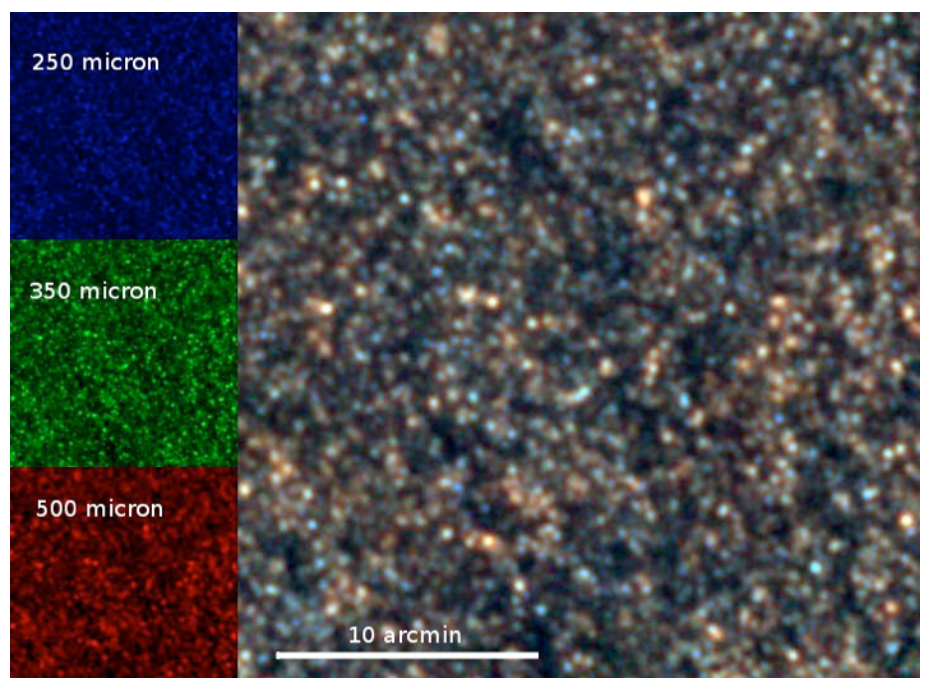
Durham University

Using Herschel and gravitational lensing to unveil extreme star-formation at z>2

Julie Wardlow
Centre for Extragalactic Astronomy, Durham University

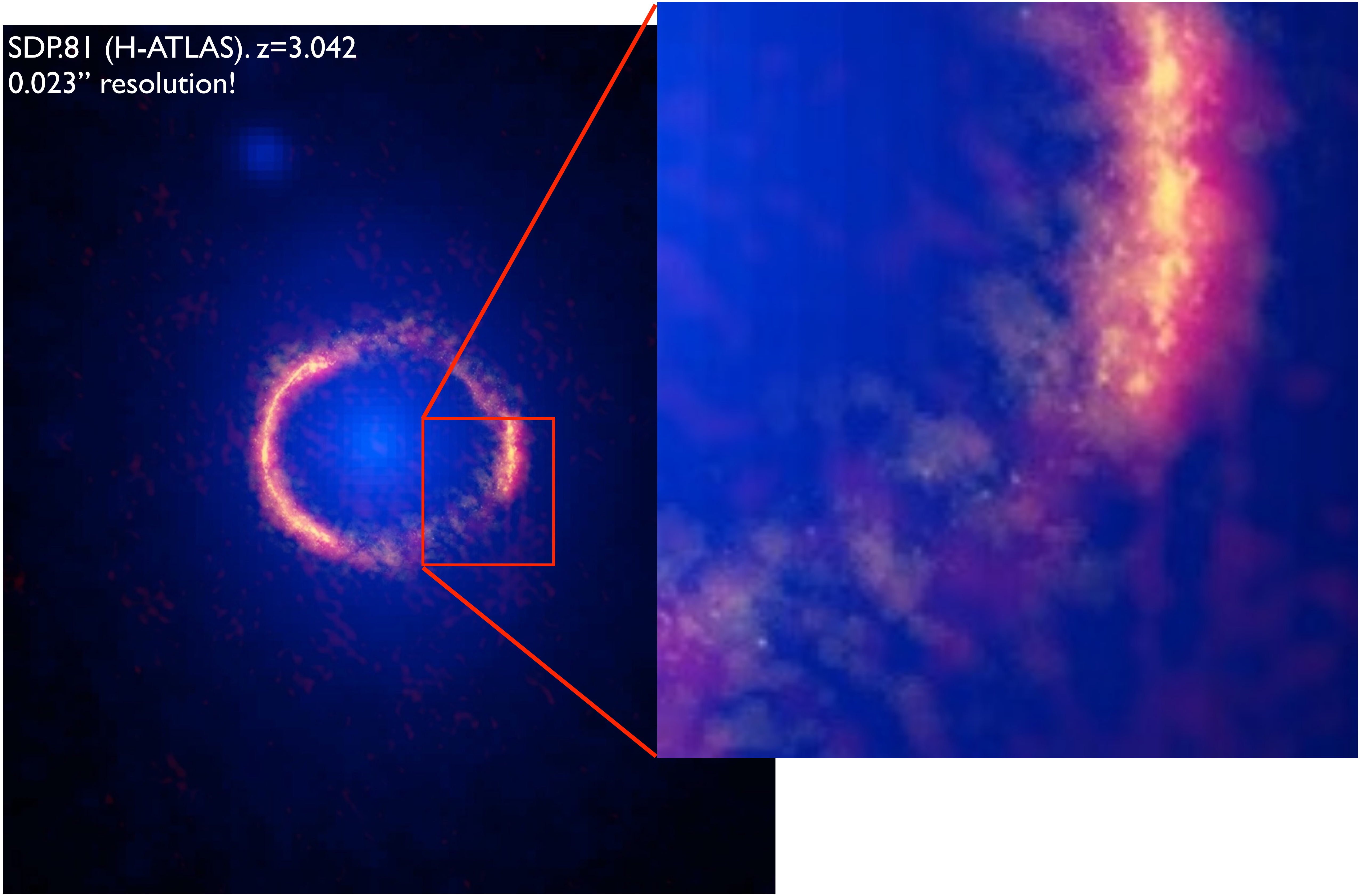




with Shane Bussmann, Jae Calanog, Alex Conley, Asantha Cooray, Francesco De Bernardis, Rui Marques Chaves, Paloma Martínez Navajas, Ismael Perez Fournon, Dominik Riechers & HerMES

What?

Example: SDP.81 discovered by Herschel, imaged by ALMA



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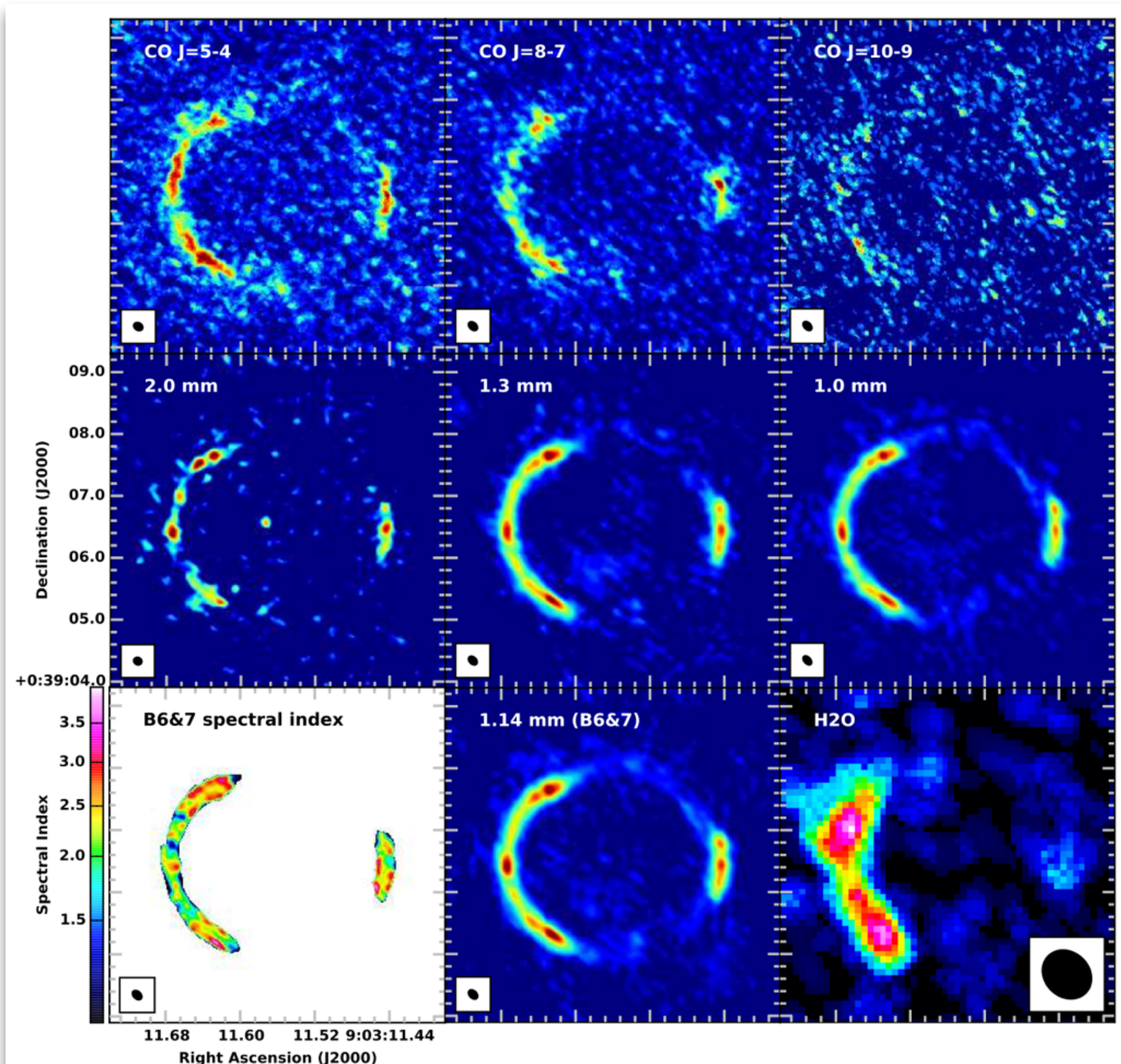
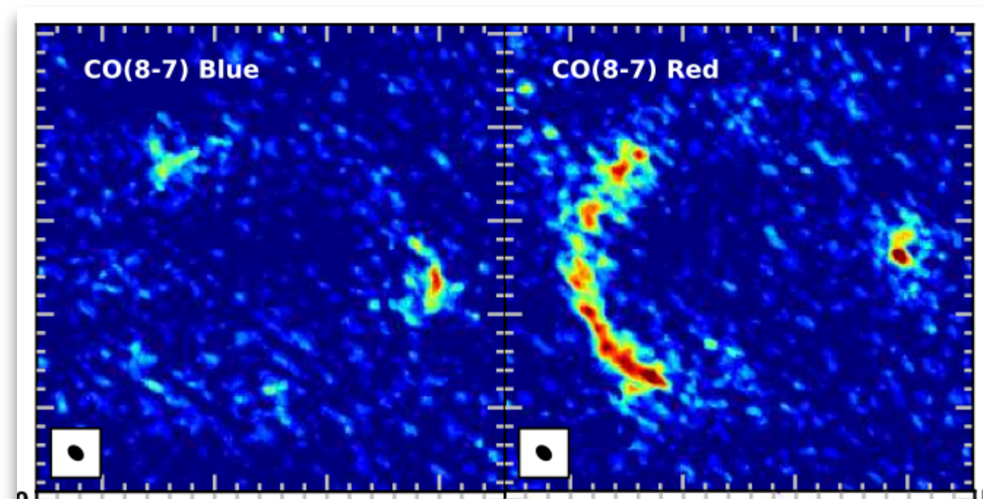


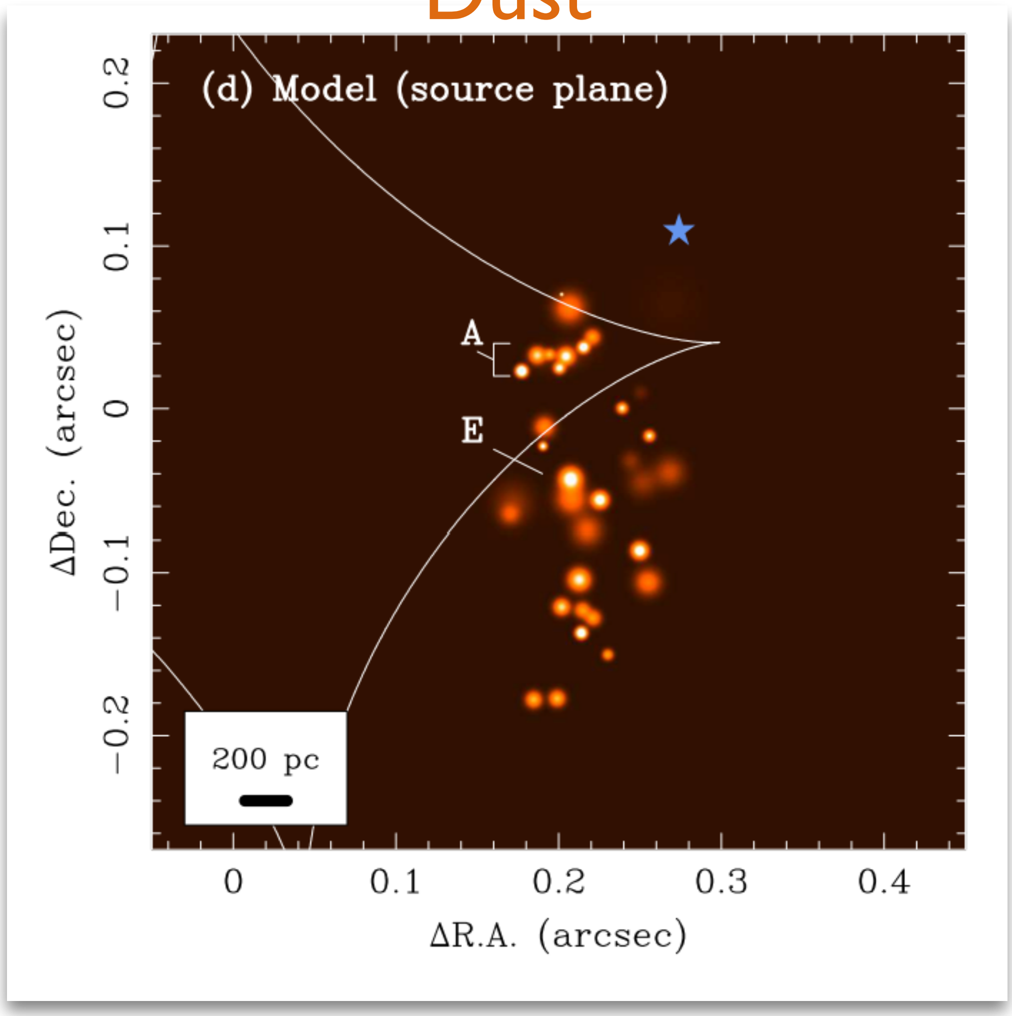


Since March:
Vlahakis et al. 2015
Swinbank et al. 2015
Rybak et al. 2015a,b
Hatsukade et al. 2015
Dye et al. 2015
Tamura, et al. 2015
Wong et al. 2015
Inoue et al. 2016
Hezaveh et al. 2016

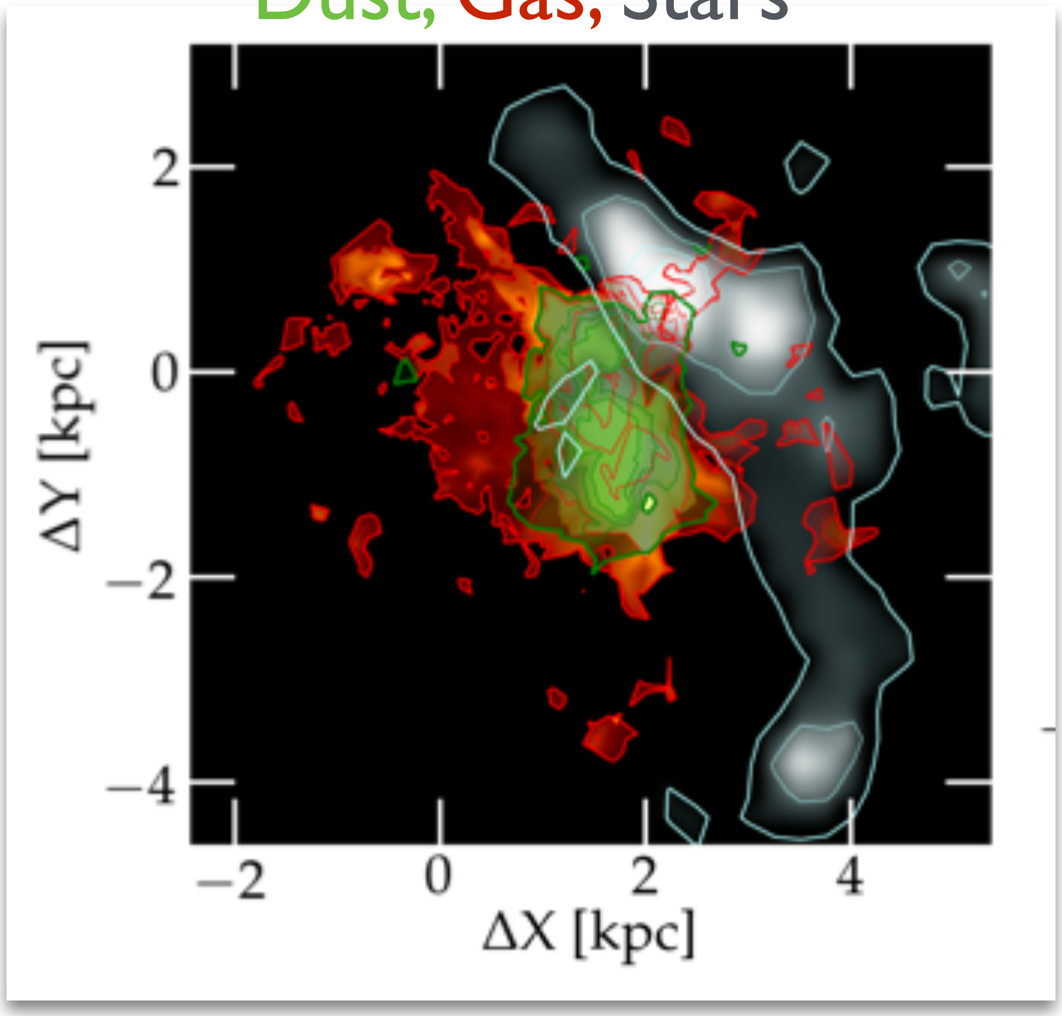
What?

Example: SDP.81 discovered by Herschel, imaged by ALMA

Dust



Dust, Gas, Stars



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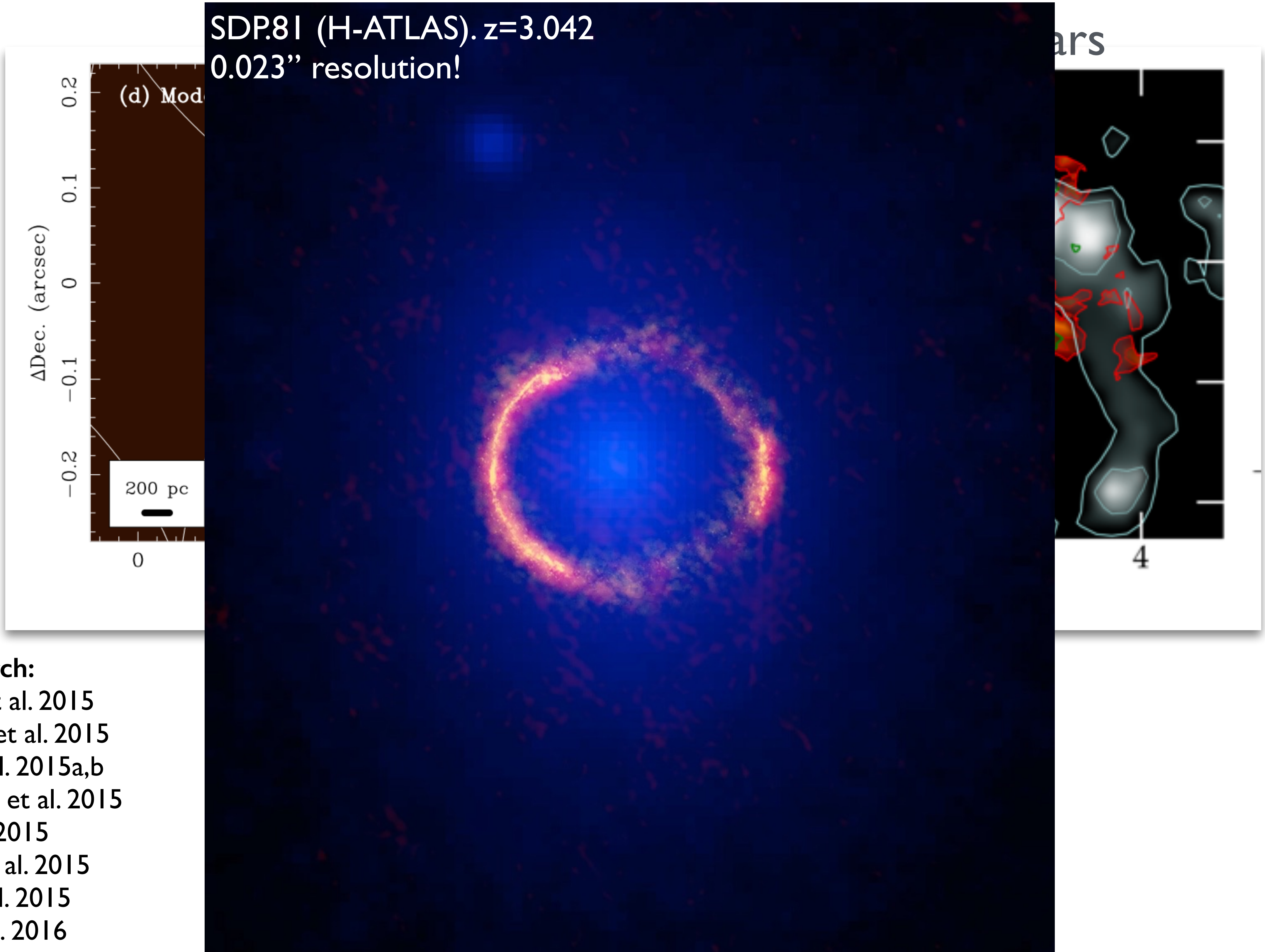

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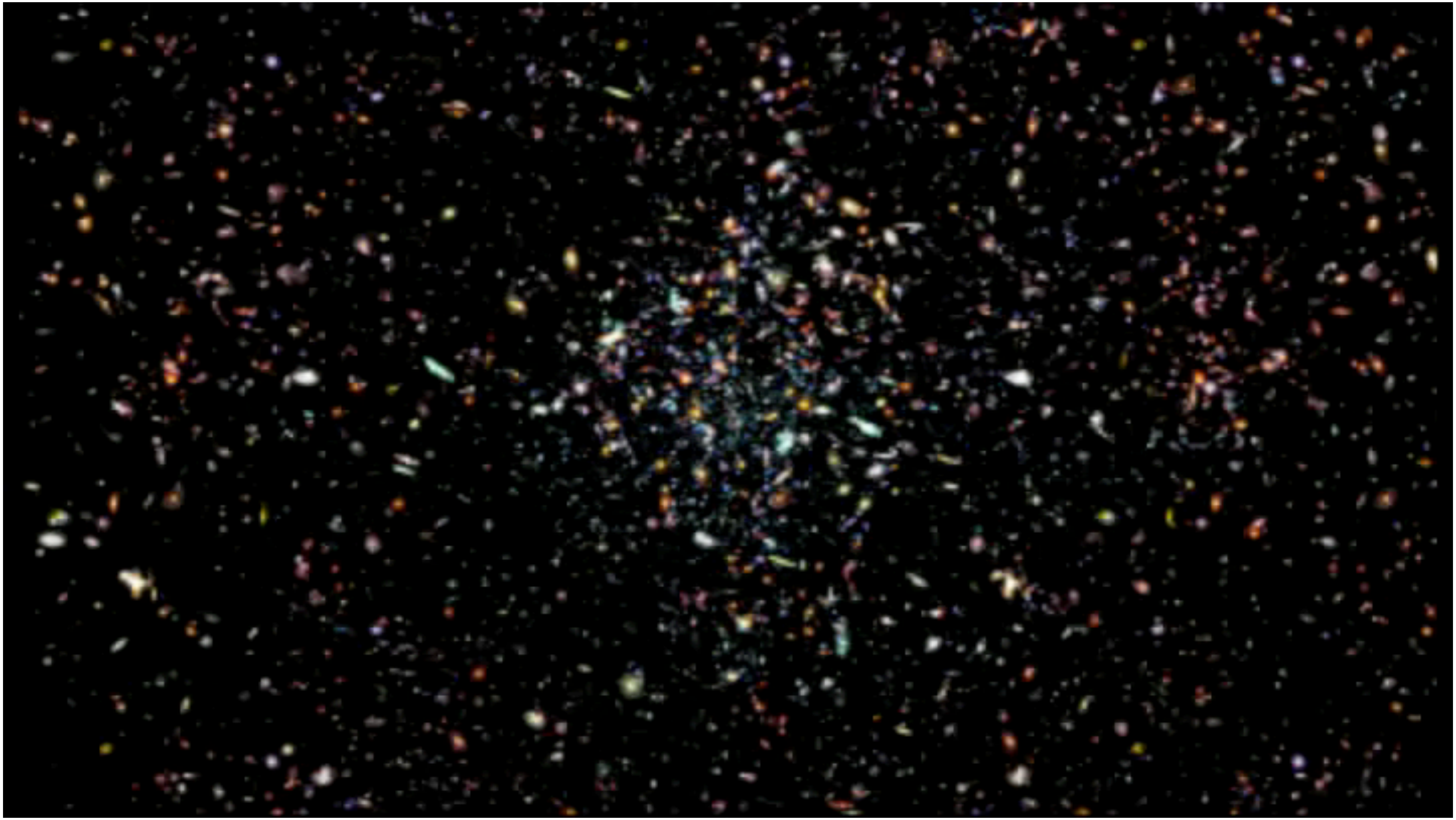
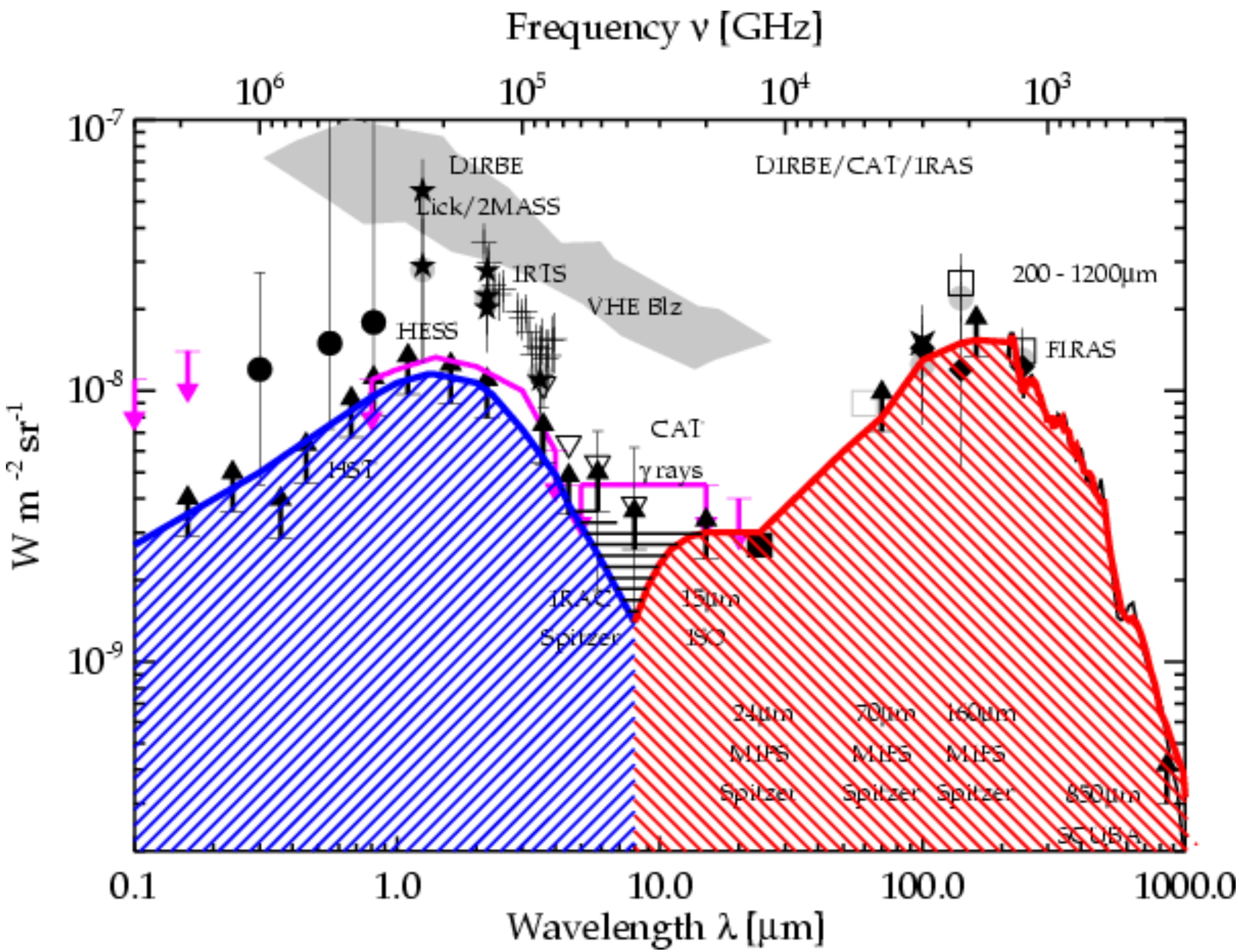
Why? HST UDF fly through: distant galaxies are very different to local galaxies



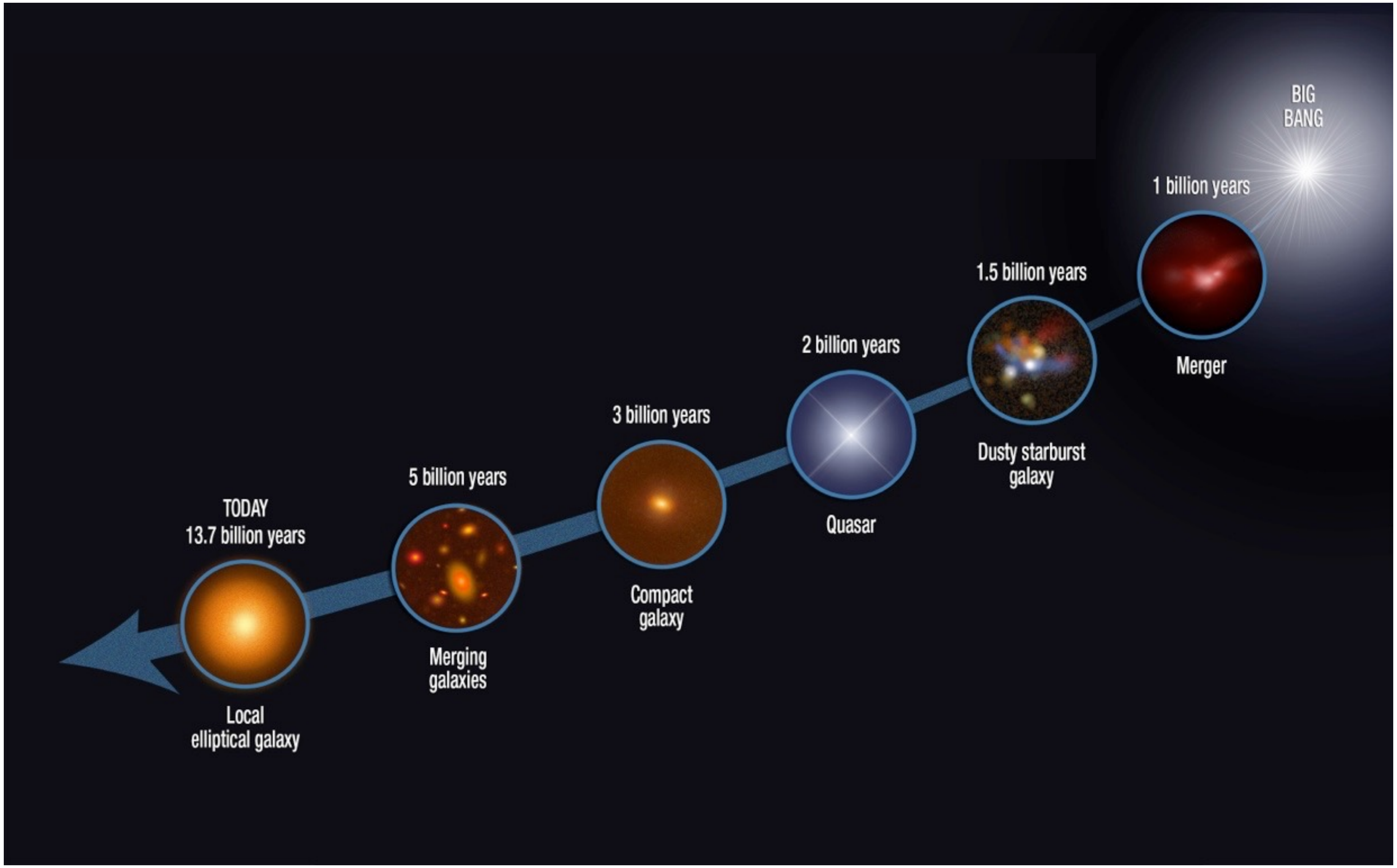
From Mark Swinbank

Why?
~50% of stellar & AGN emission is dust reprocessed



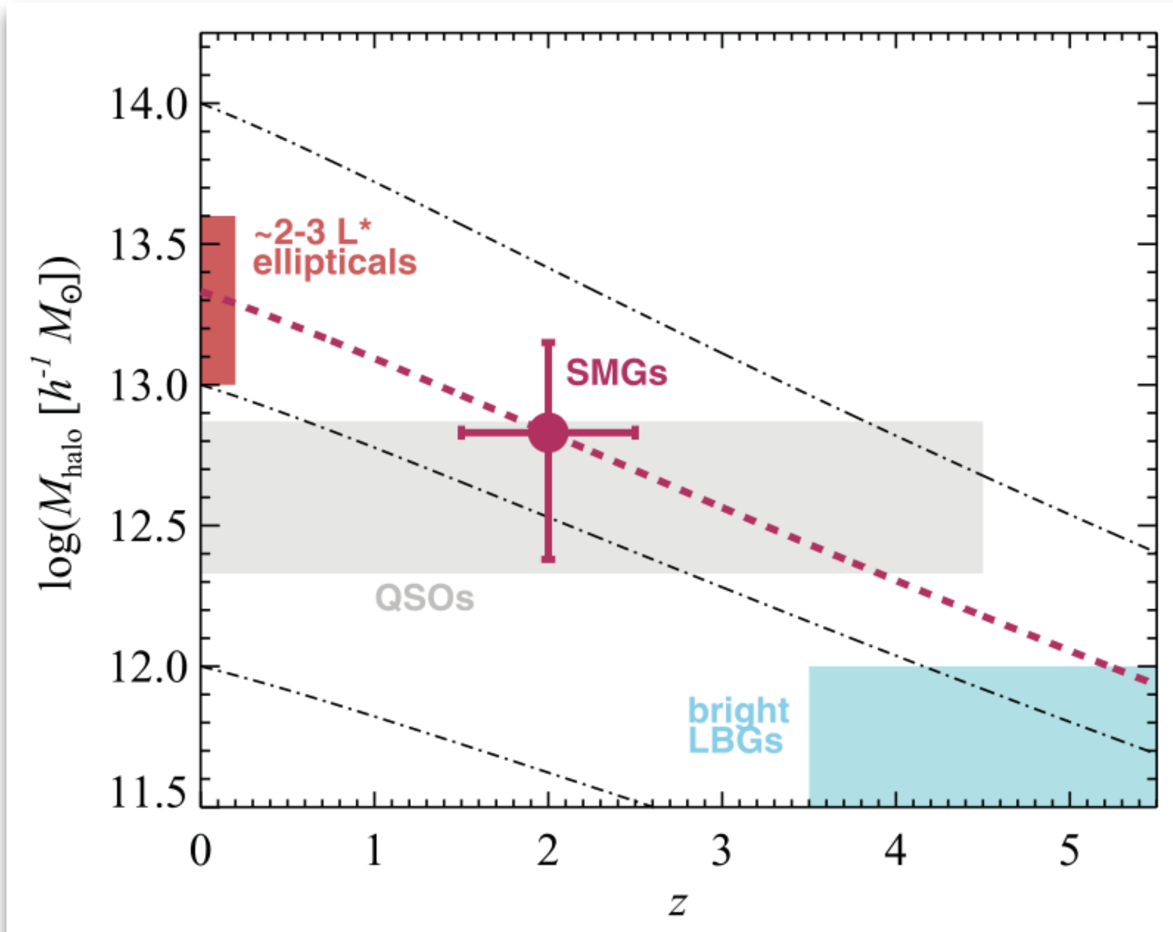
Dole et al. 2006

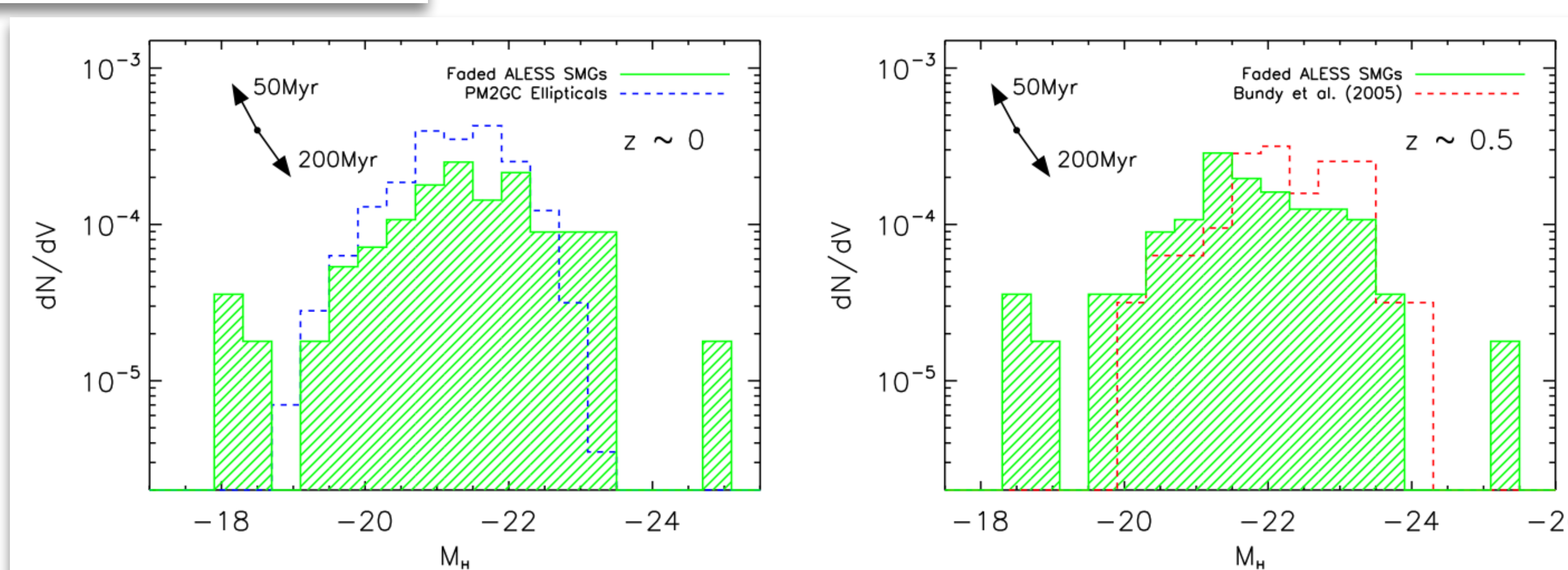
Massive ellipticals formed early in the Universe



Toft et al. 2014

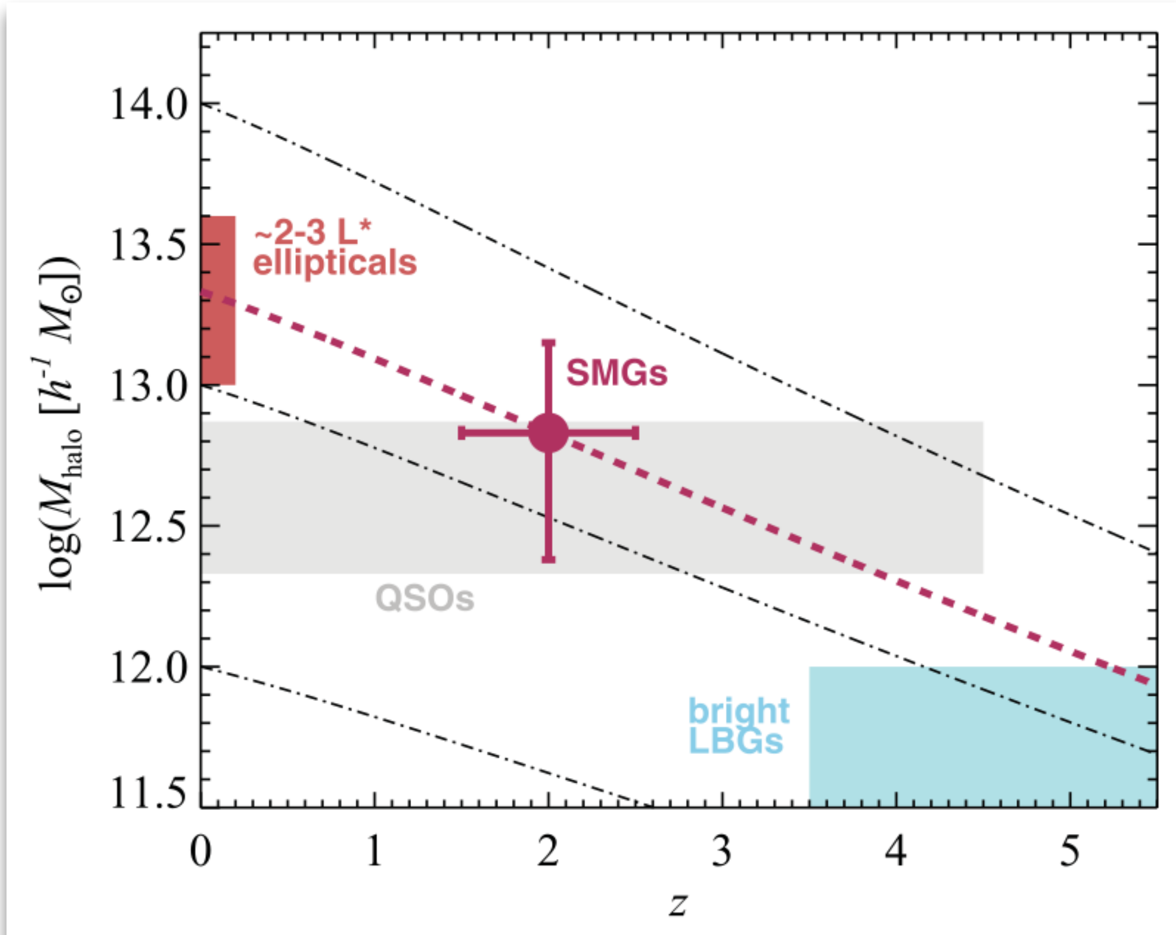
Why?
Massive ellipticals formed early; SMGs are massive & early

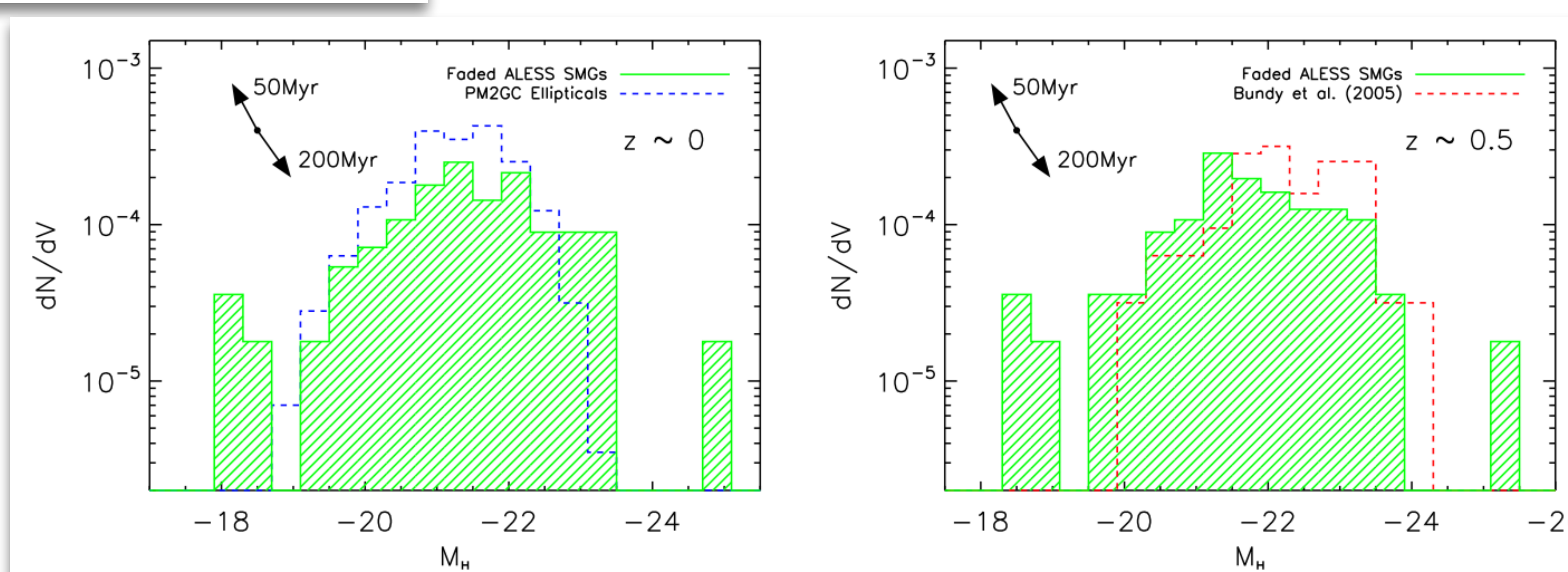




Hickox, JW et al. 2012
Simpson, JW et al. 2014

Why?
Dusty star formation: a crucial phase of galaxy evolution?

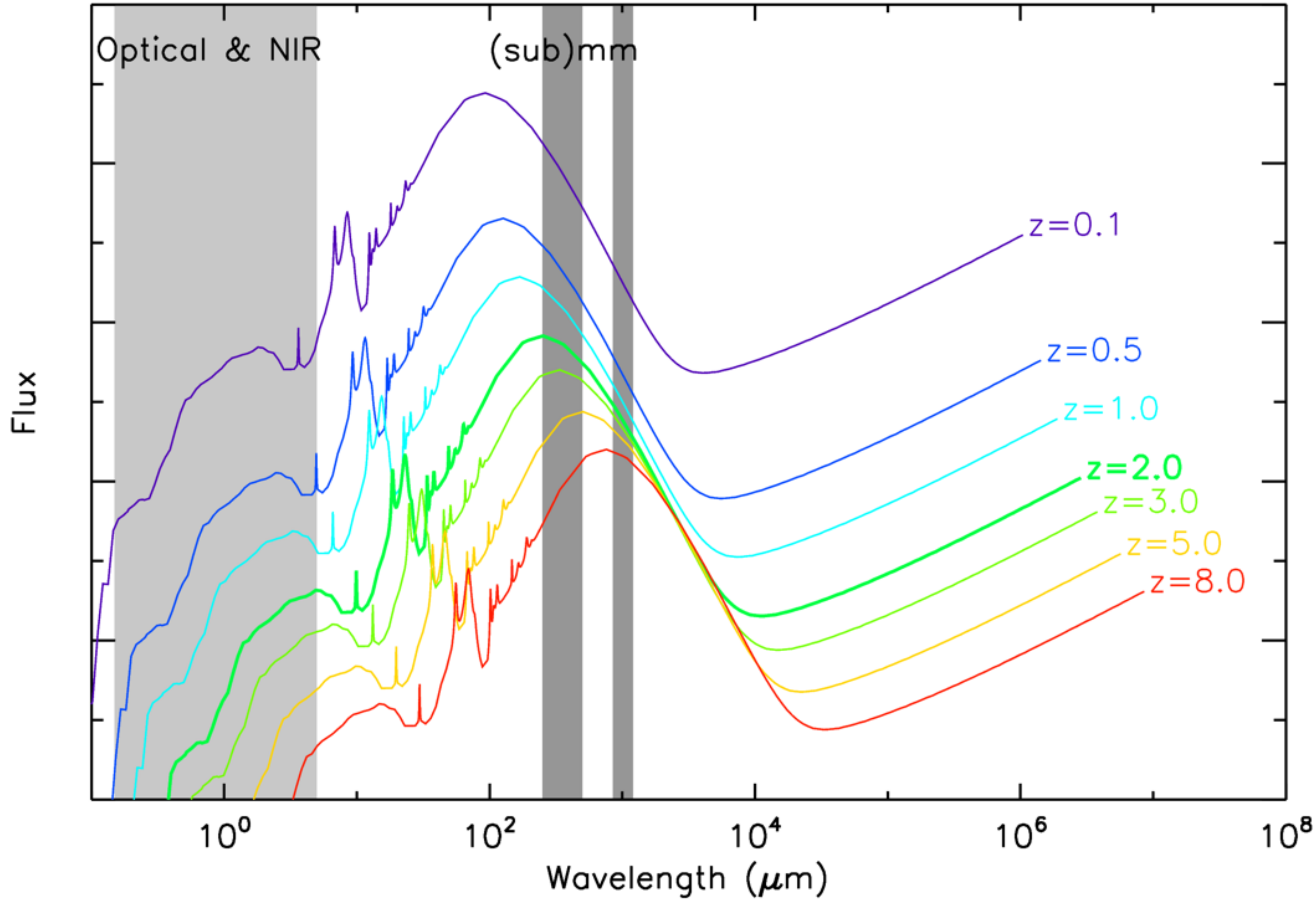




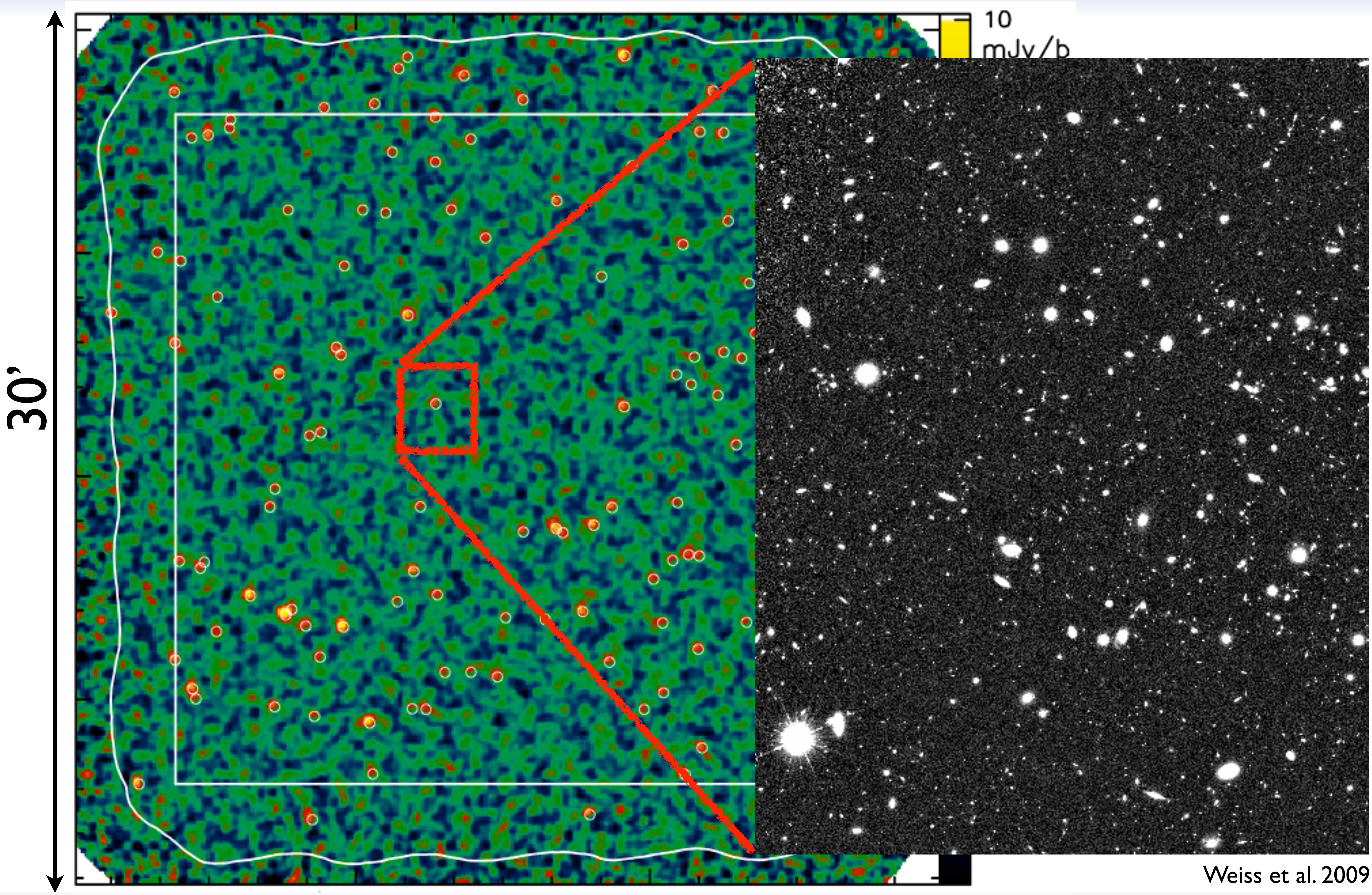
Hickox, JW et al. 2012
Simpson, JW et al. 2014

Negative K-correction: submm is visible to high-z

Arp 220 redshifted:



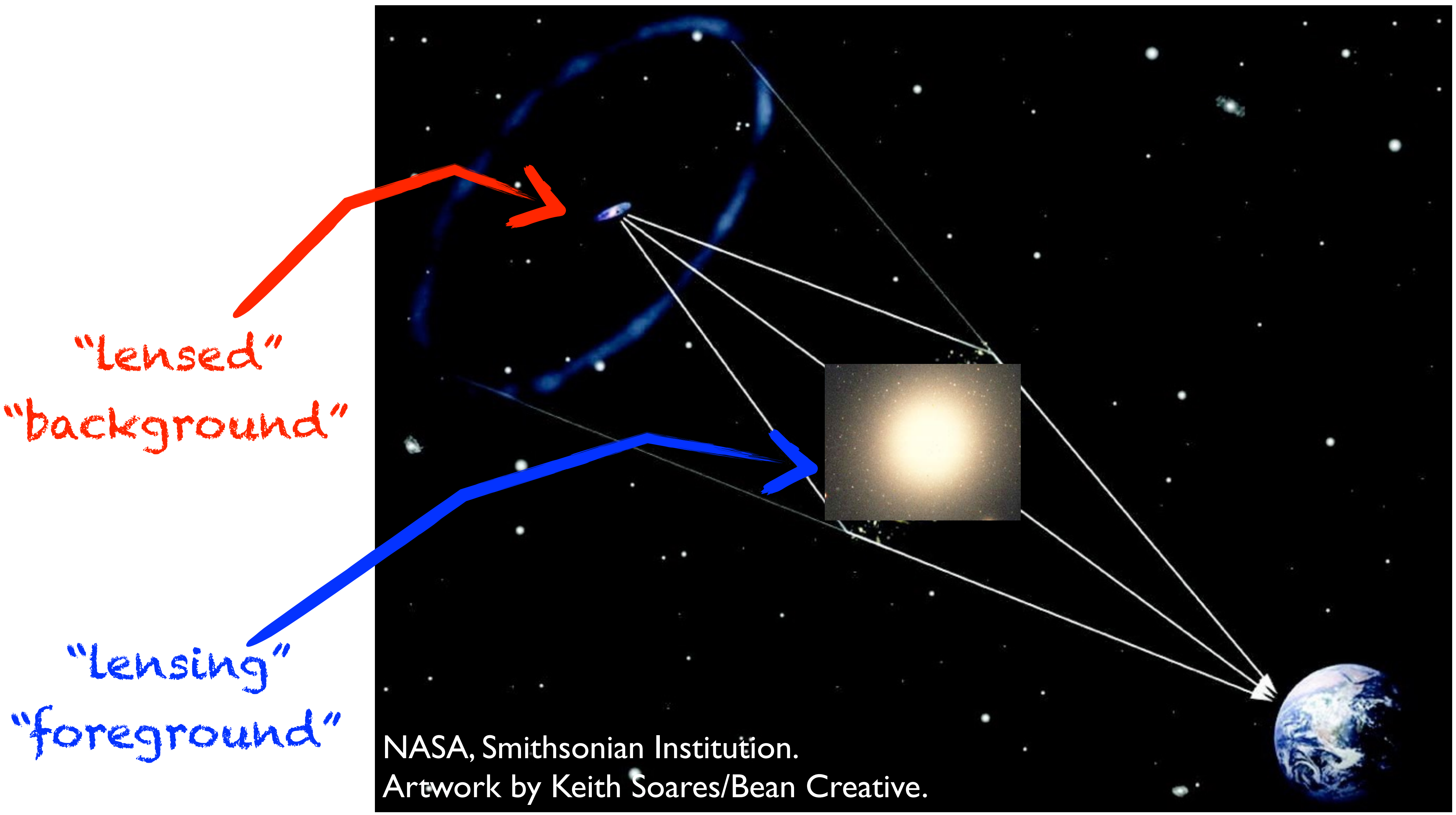
LESS: 300 hours on APEX (870μm)



Weiss et al. 2009

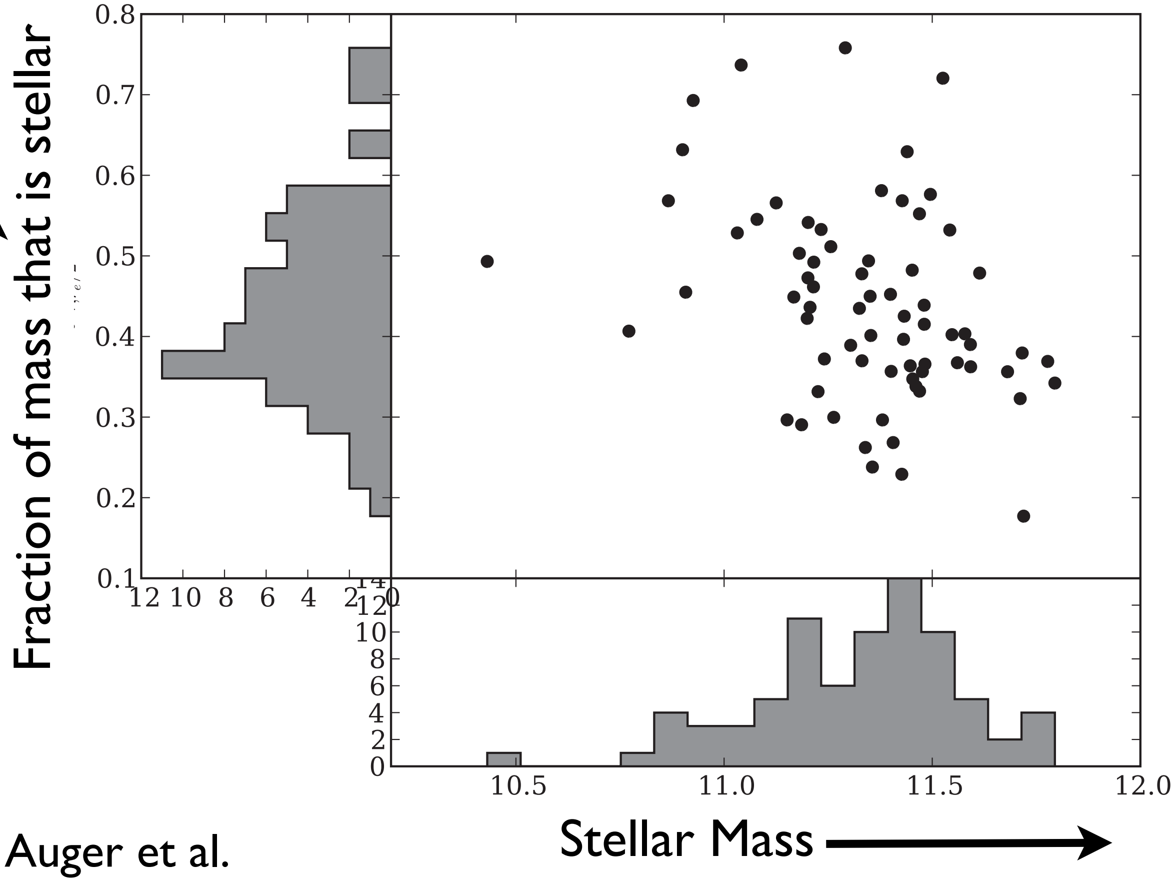
Gravitational Lensing

- Background galaxy: flux boost
- Background galaxy: spatial resolution boost
- Foreground galaxy: mass profile
- Cosmology: numbers and distribution of lensing



Lensing: the foreground mass

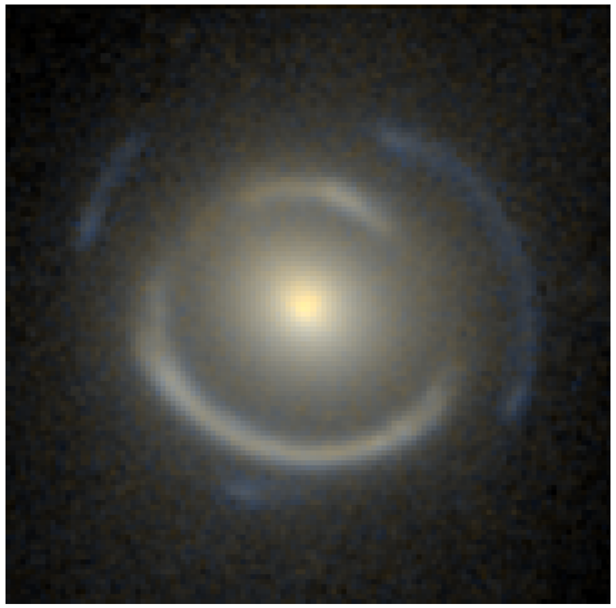
Stellar mass fraction within 0.5*R_{Ein}

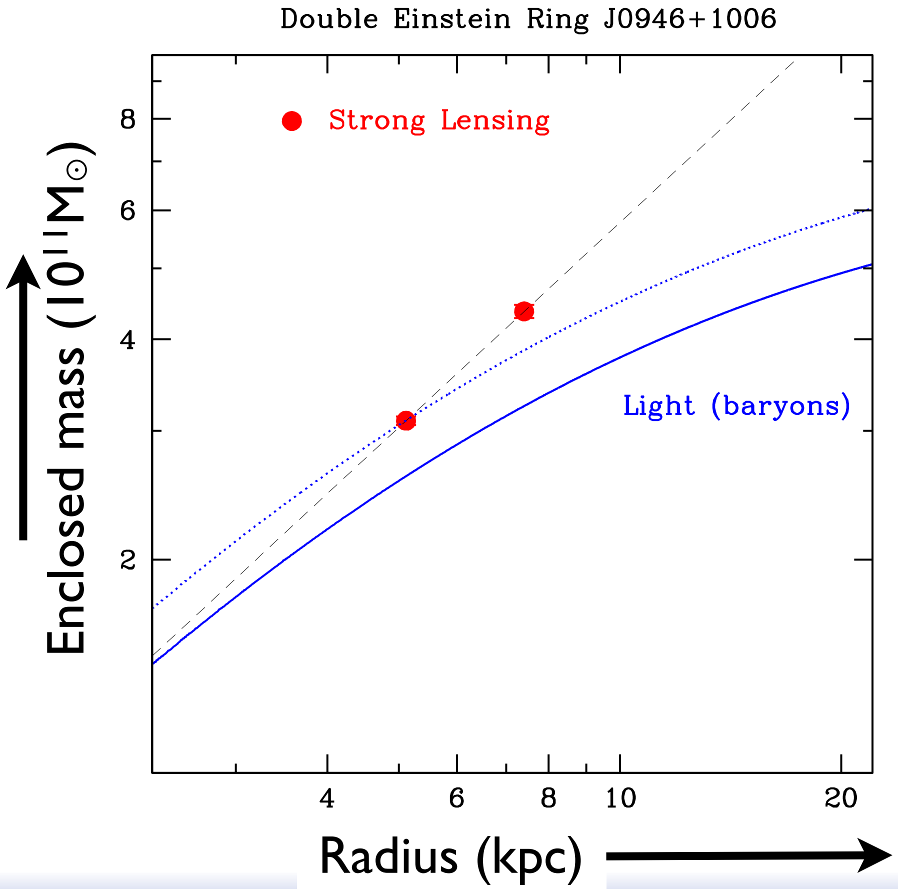


Auger et al. 2009

Total mass profile

(multiple lensed galaxies)

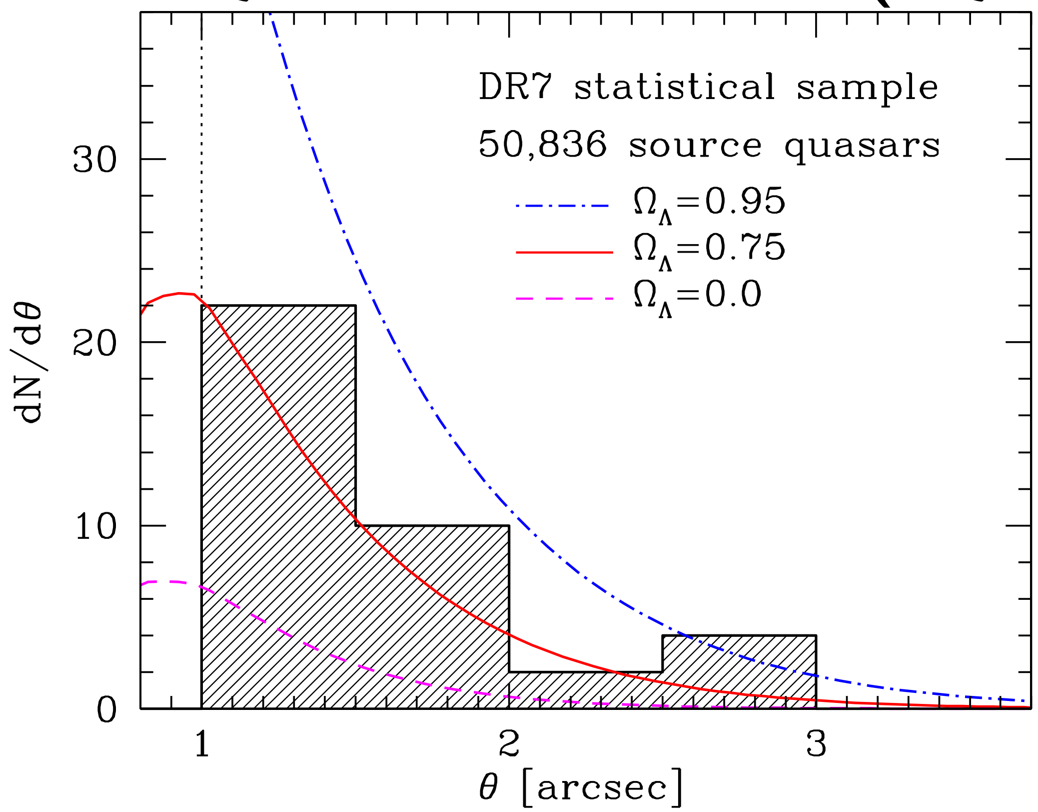


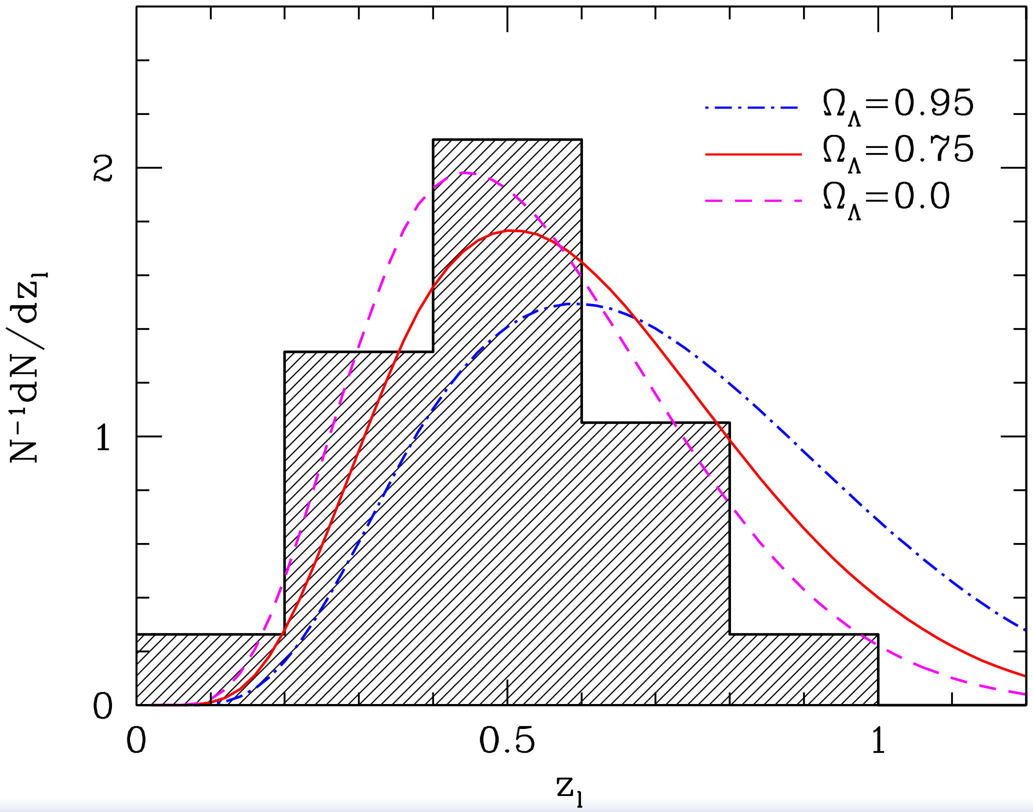


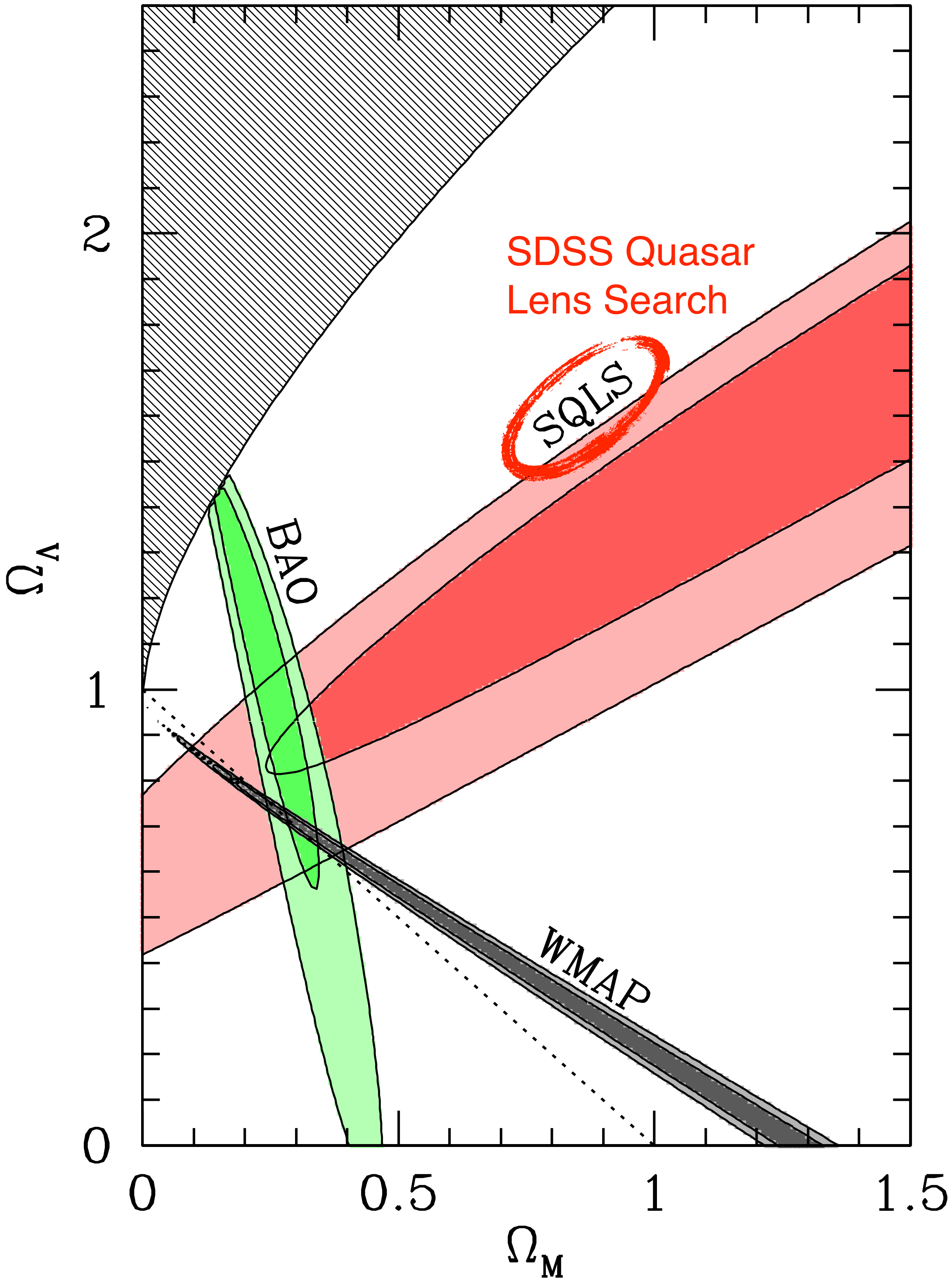
Treu 2010

Gravitational lensing: cosmology

SDSS Quasar Lens Search (SQLS)

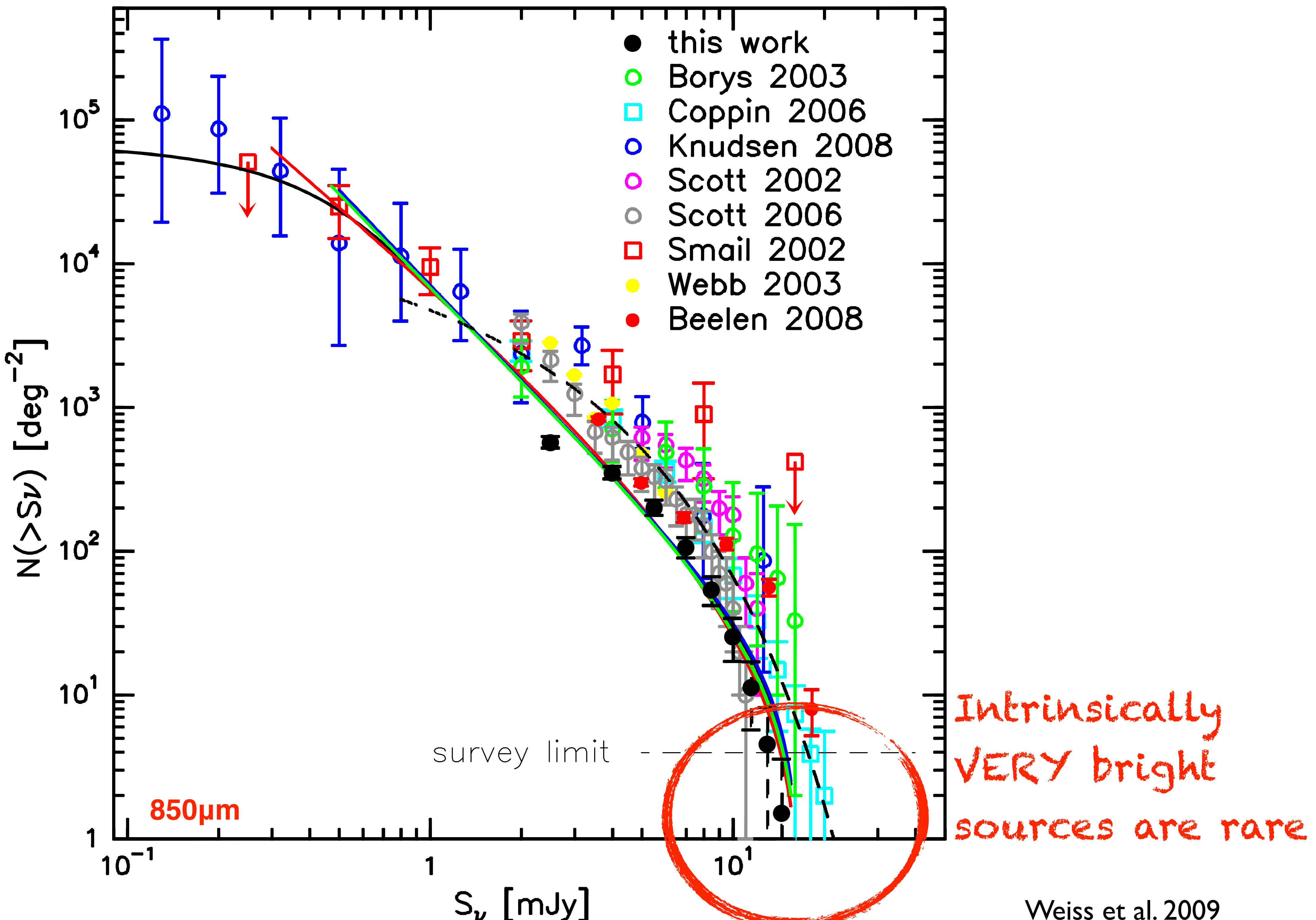






Oguri et al. 2012

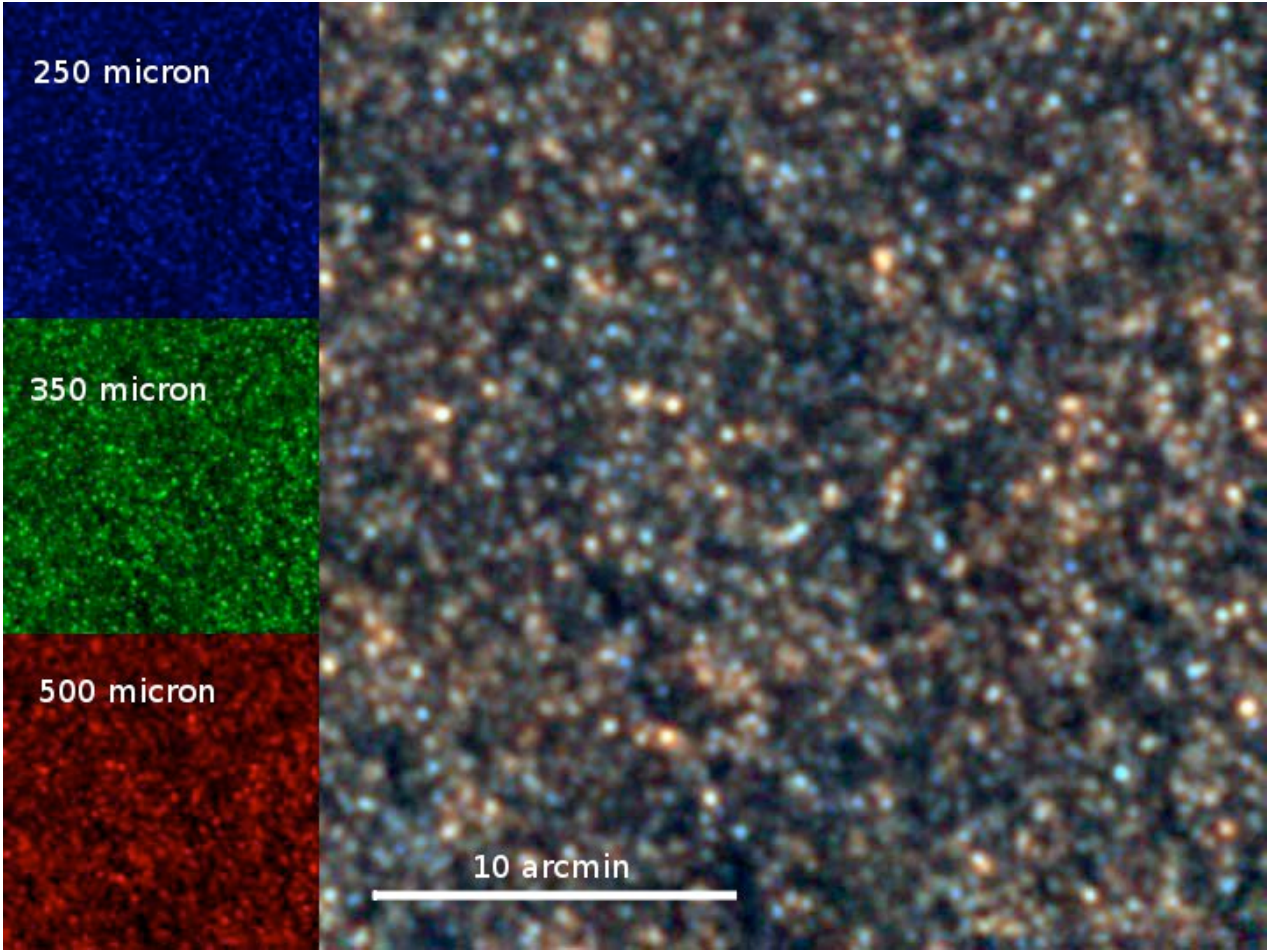
Far-IR number counts are steep at the bright end: very luminous DSFGs are very rare



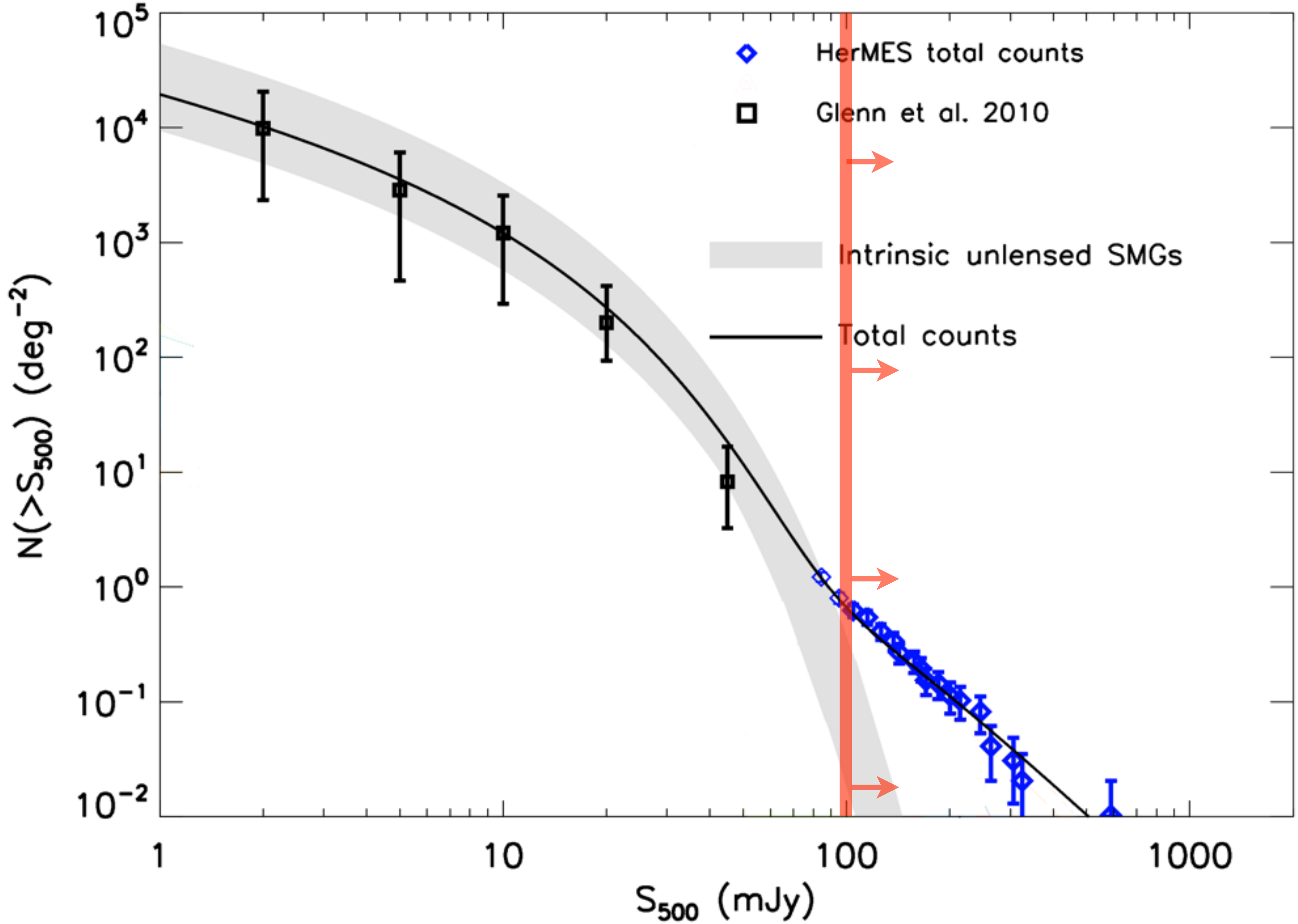
Weiss et al. 2009

See also Blain et al. 1996

HerMES: ~380 deg^2 extragalactic submm survey



HerMES lens candidates:
S_{500}>100mJy

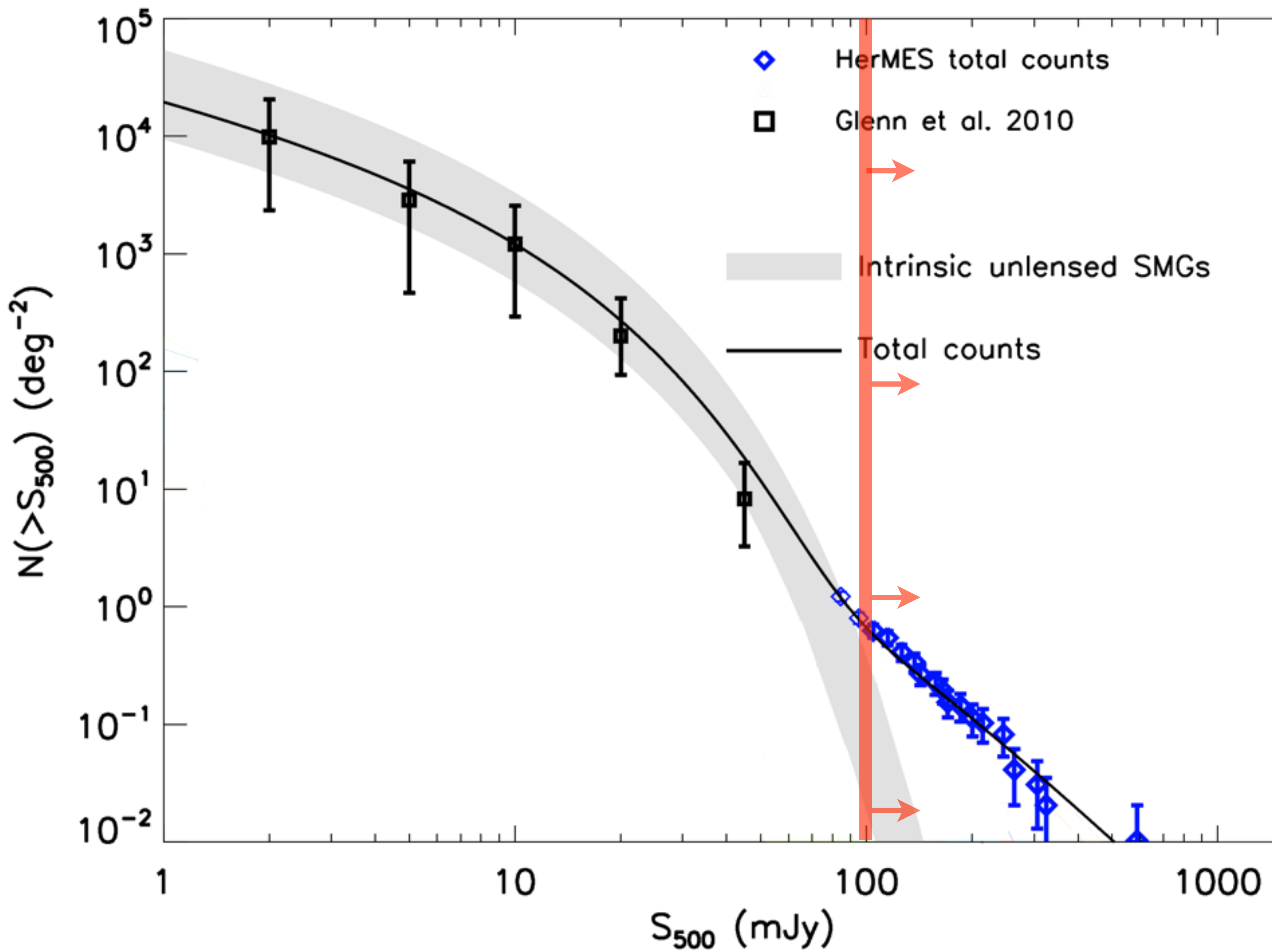


Candidates: ~0.15 deg^{-2}

Wardlow et al. 2013

HerMES lens candidates

S_{500}>100mJy & no blazars or local spirals



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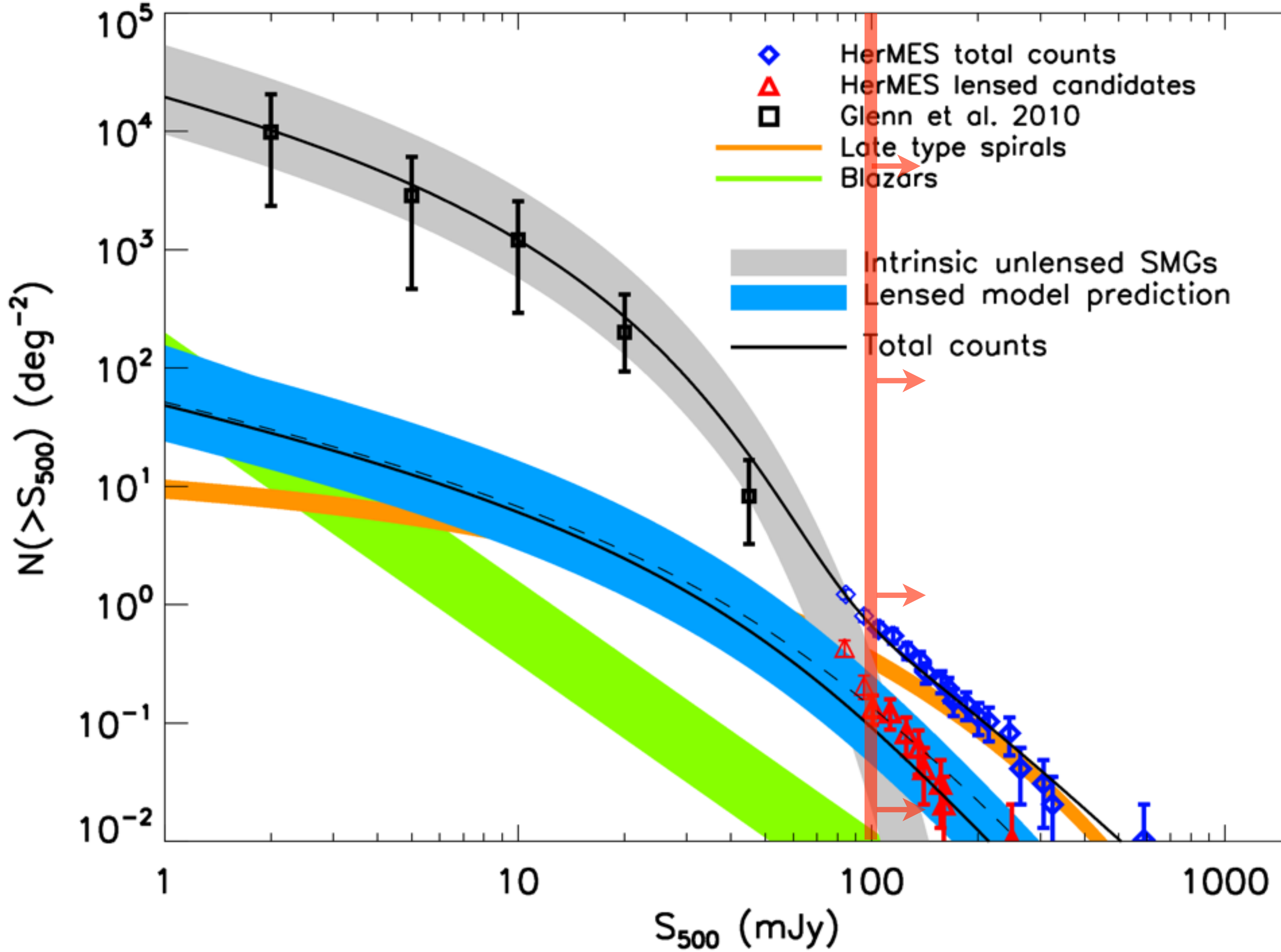

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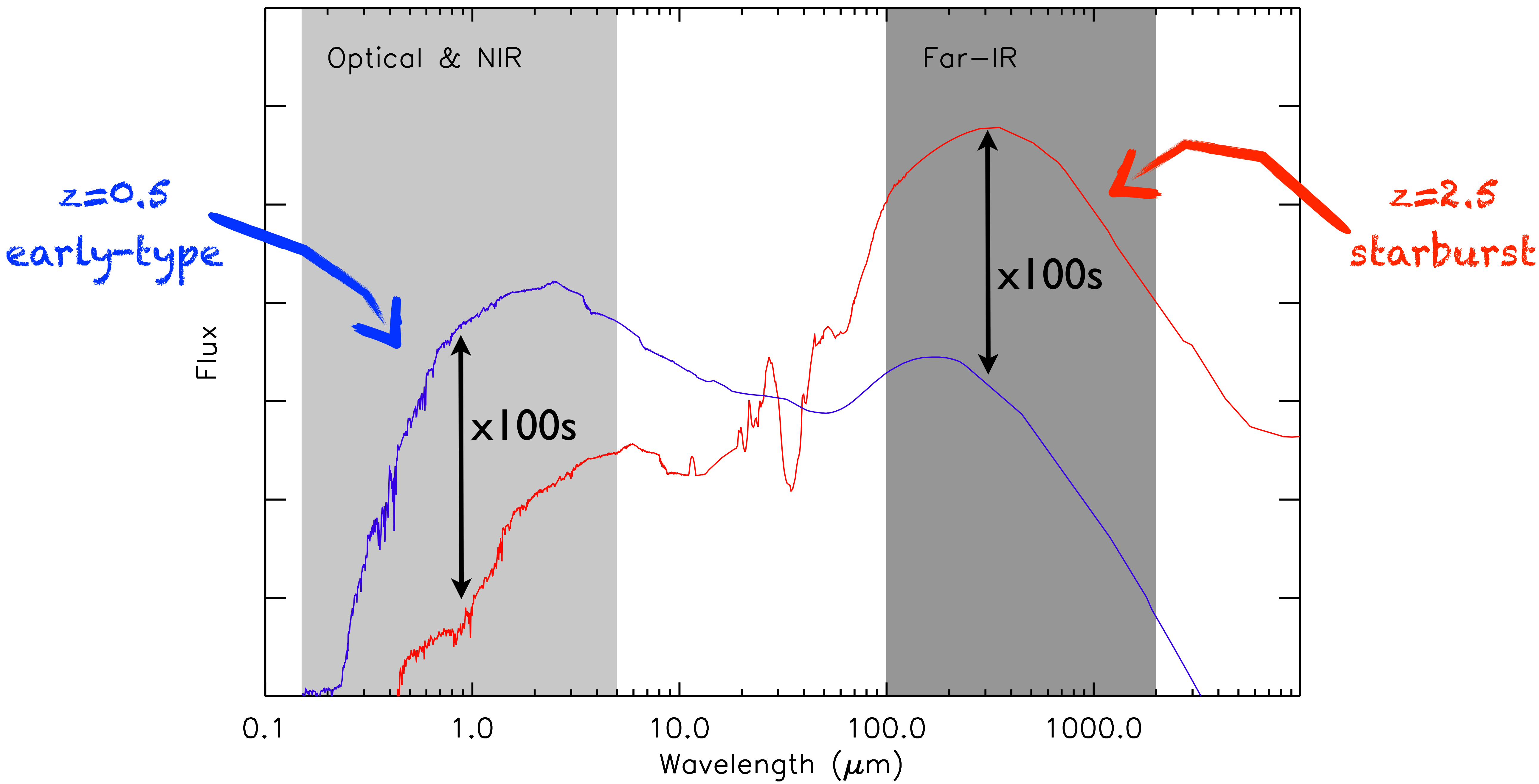
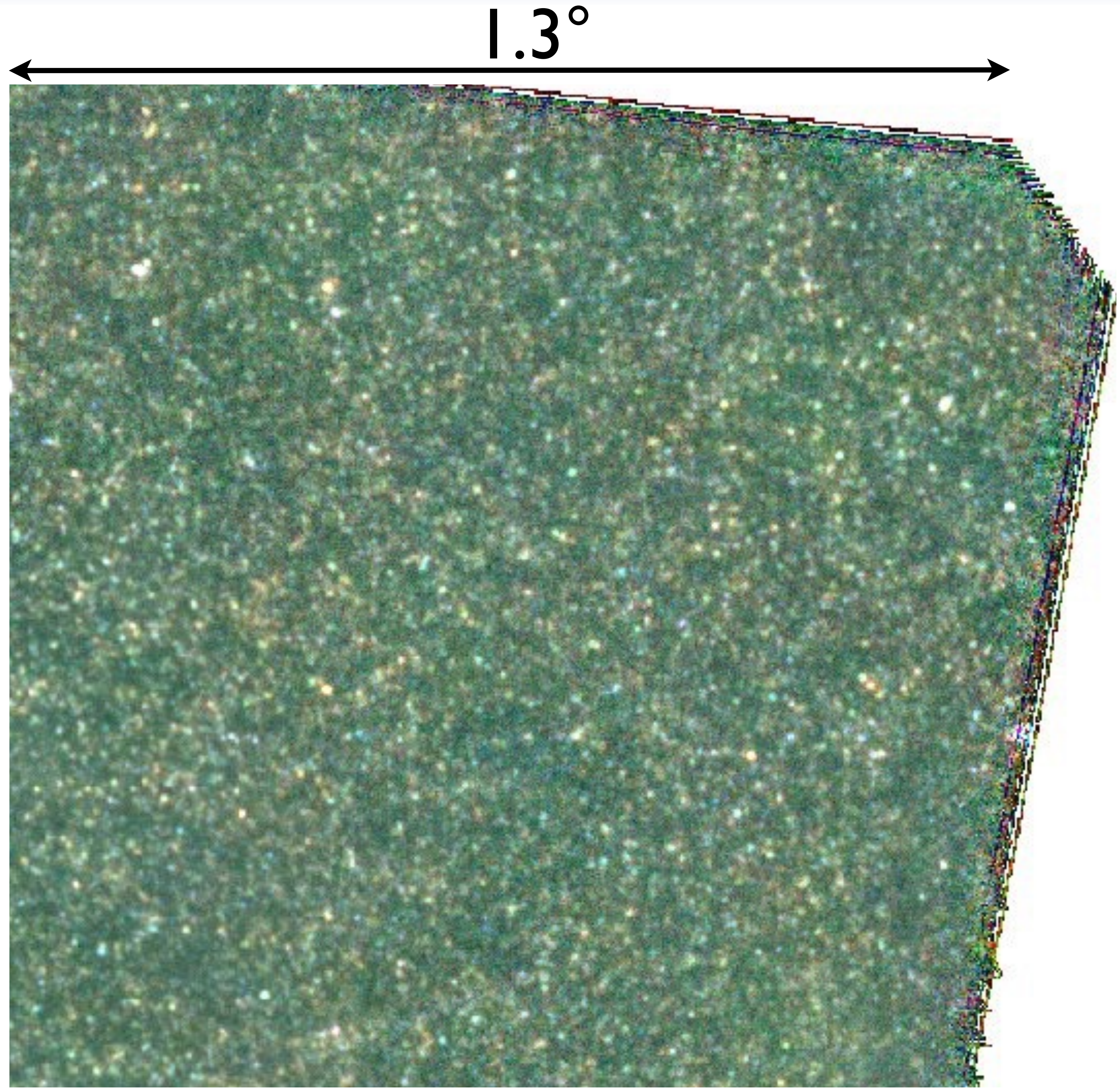
Wardlow et al. 2013

Lensed SMGs are easily distinguished from lenses



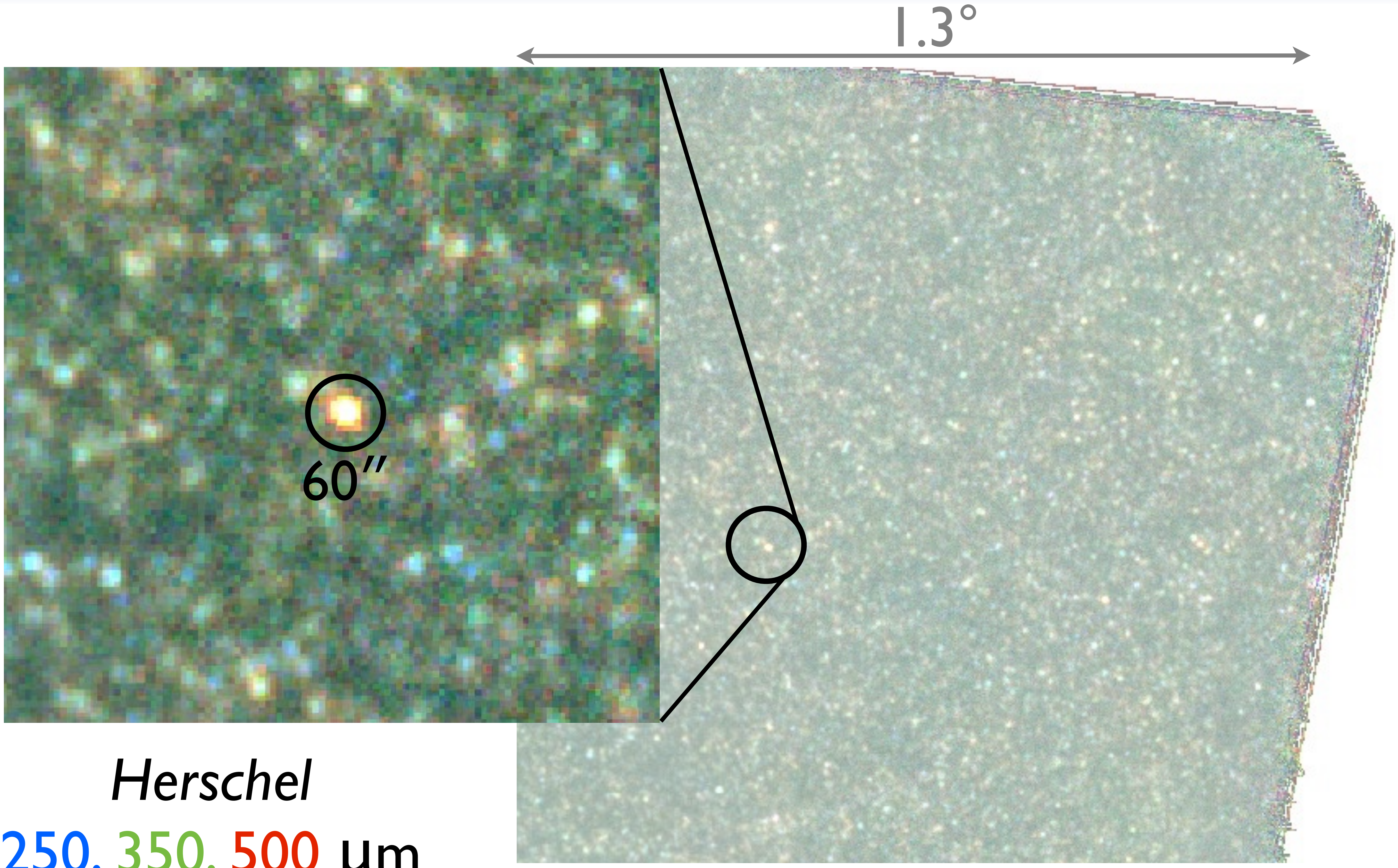
HerMES Boötes image



Herschel

250, 350, 500 μm

HerMES Boötes image



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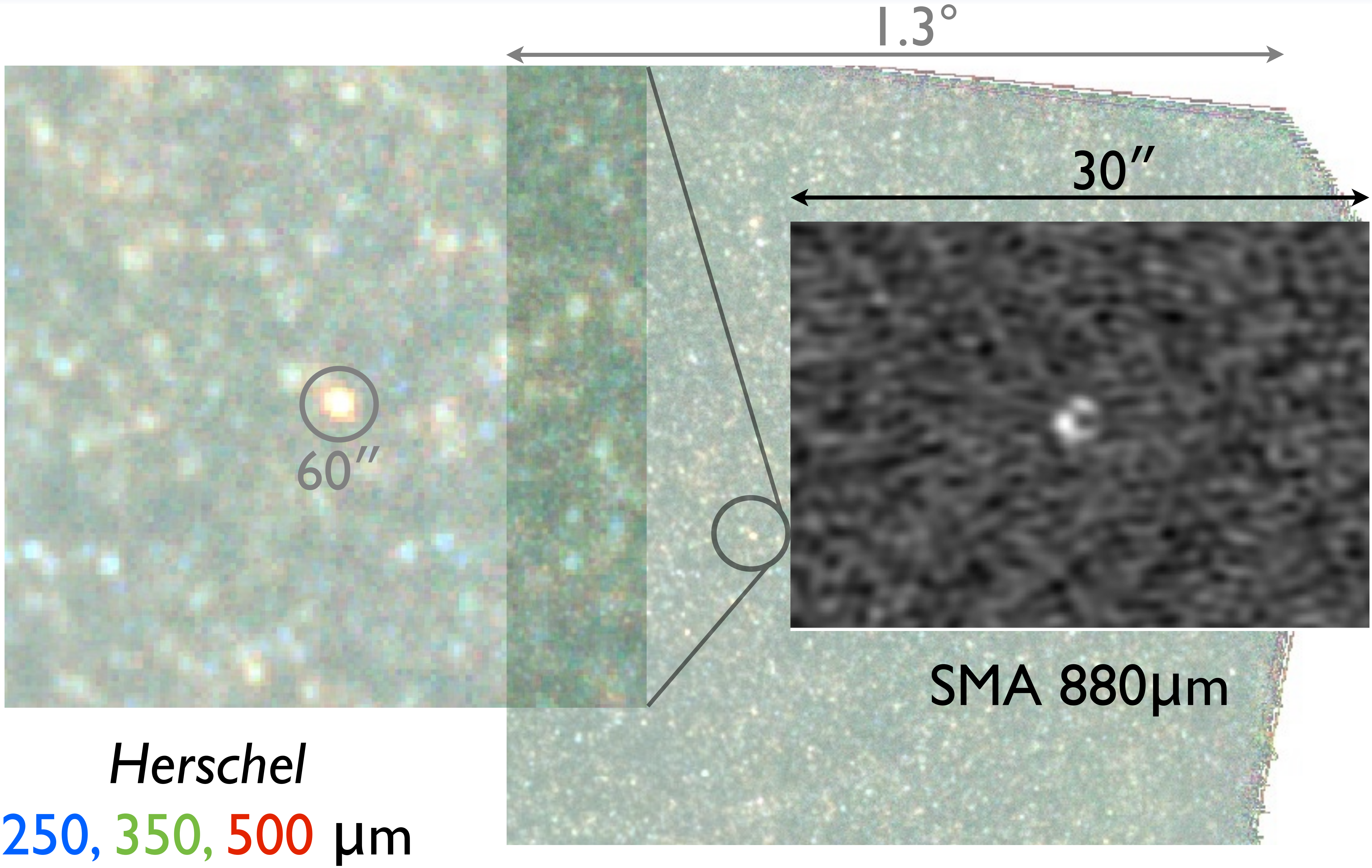
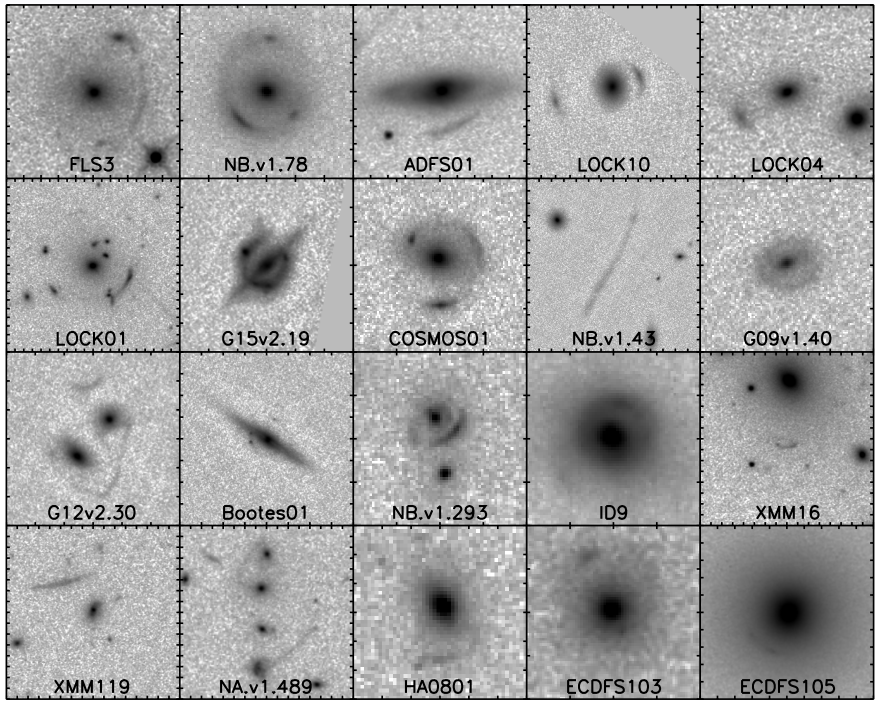
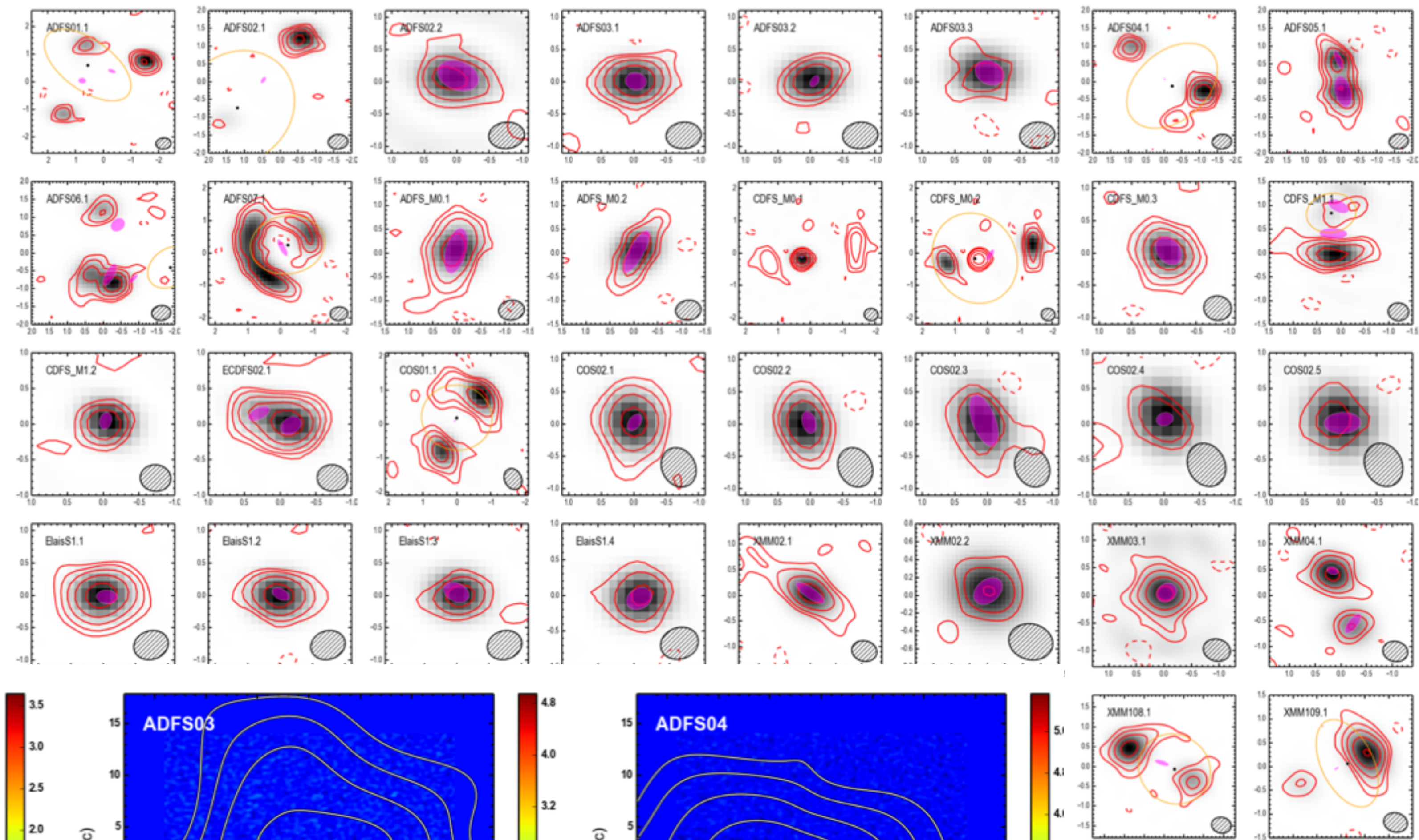


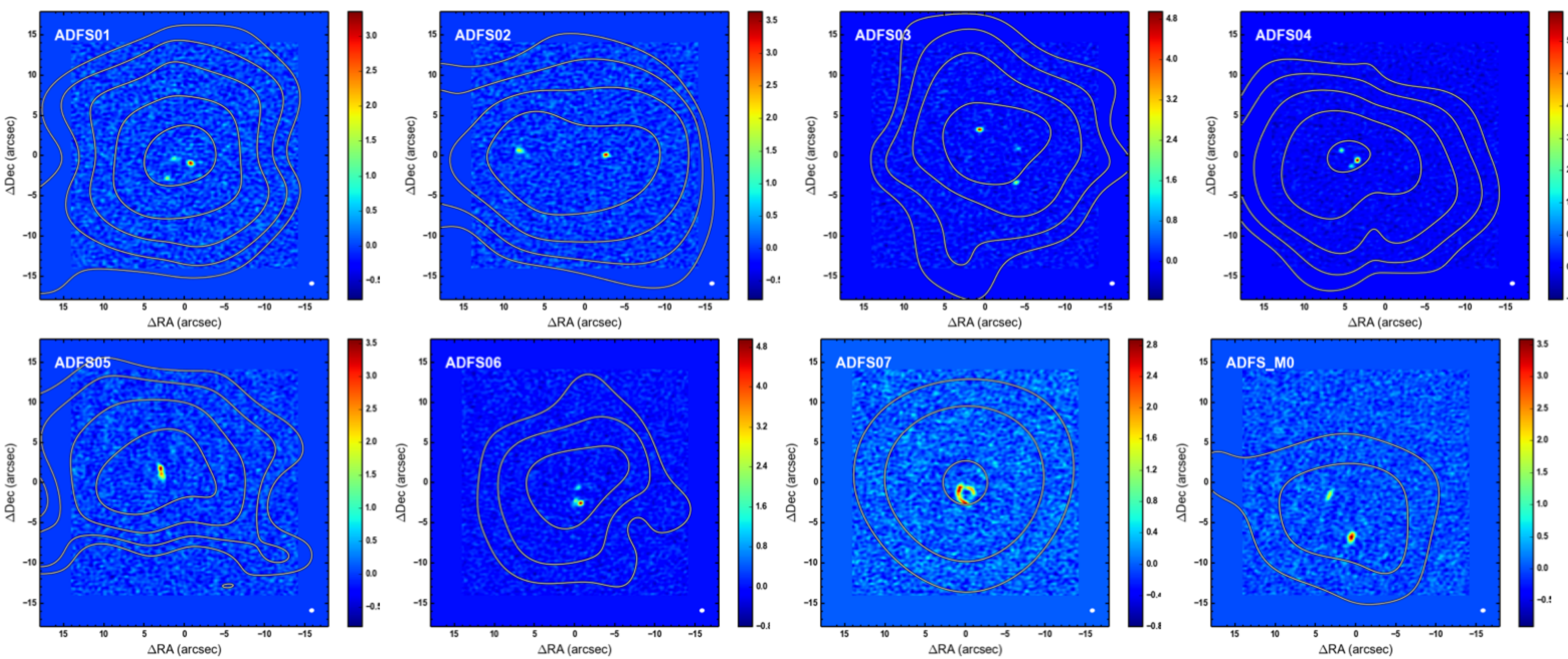
A sample of Herschel lens systems



Calanog, JW et al. 2014

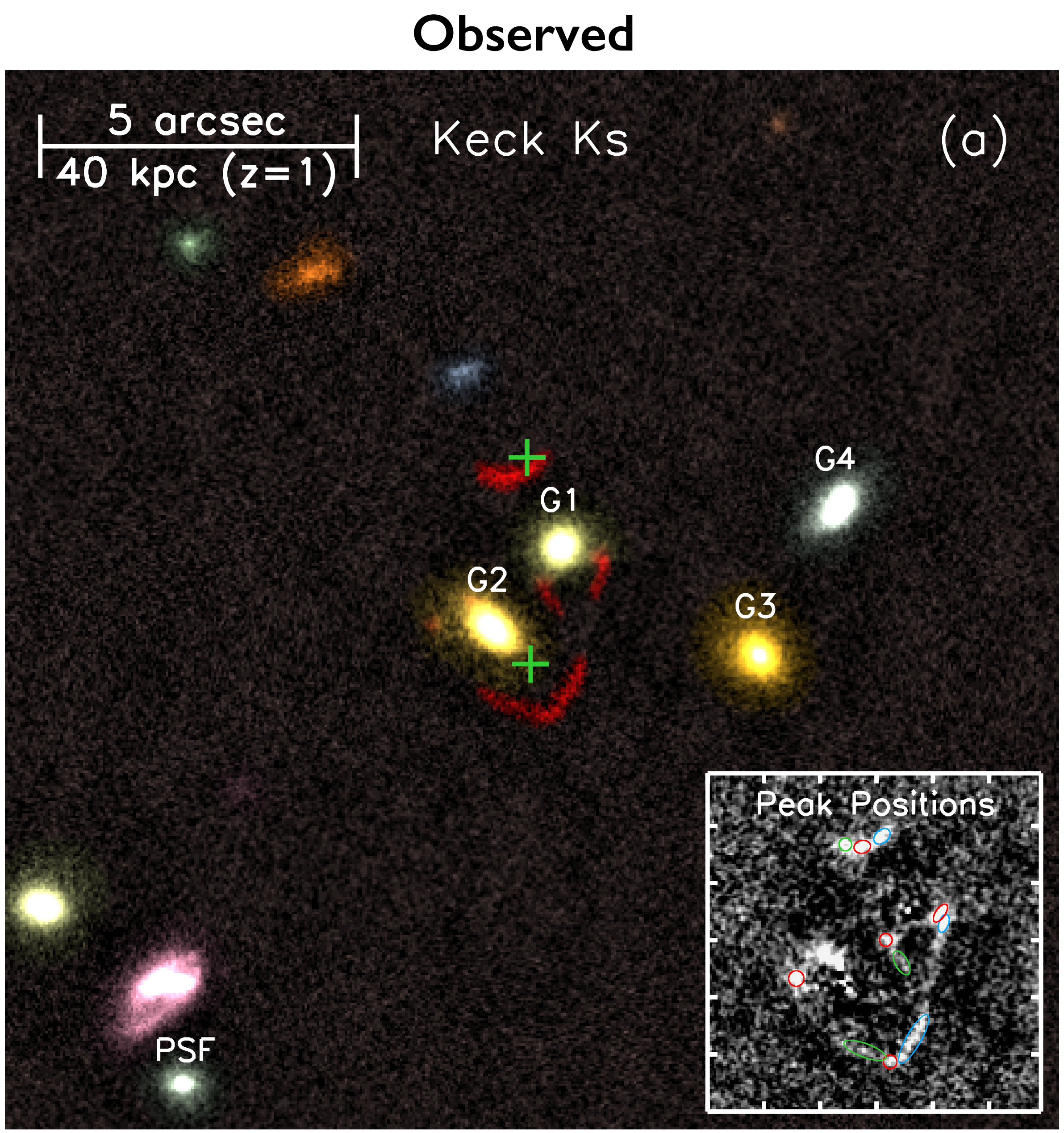


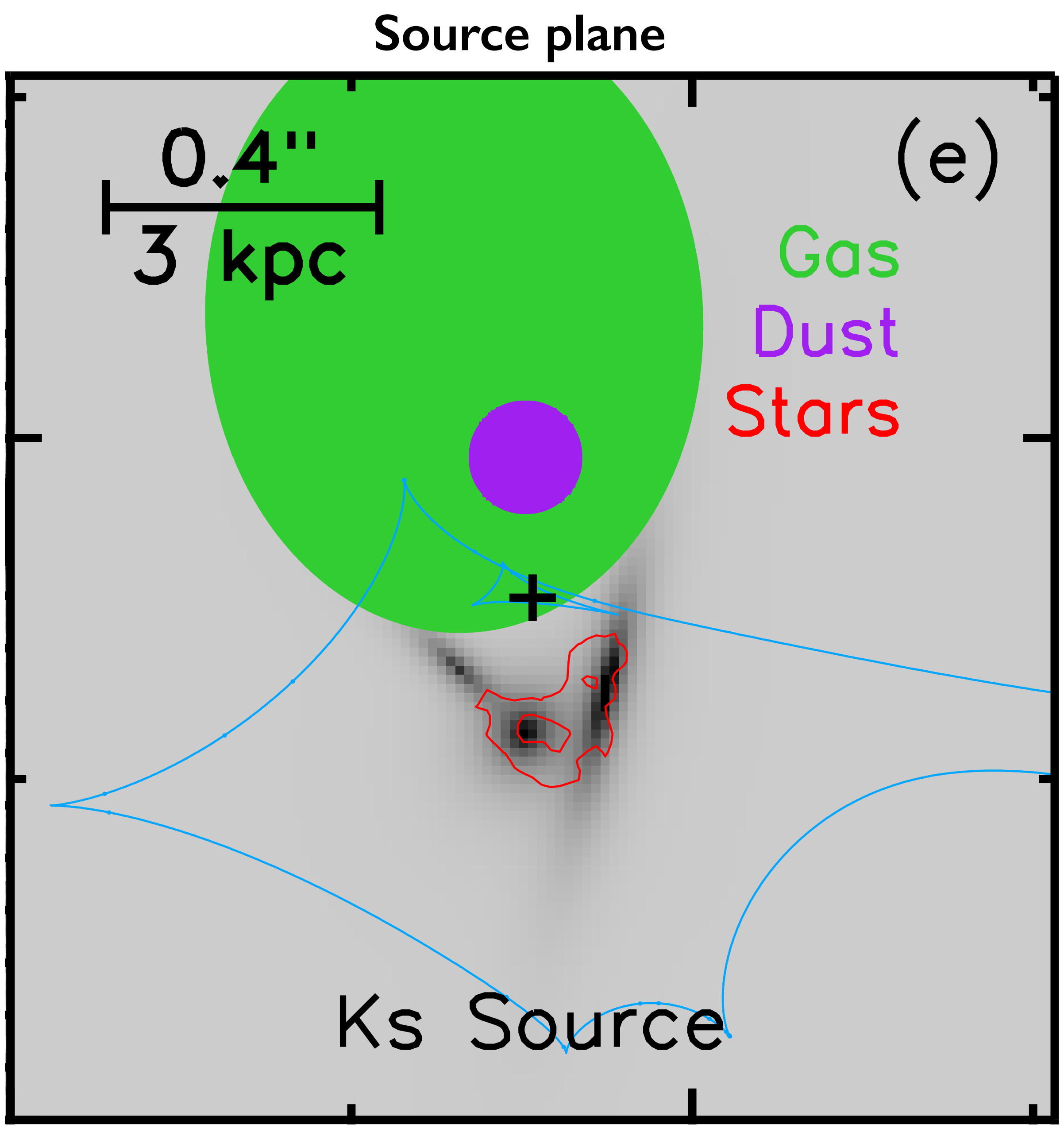
Bussmann, JW et al. 2014



Bussmann, JW et al. 2015

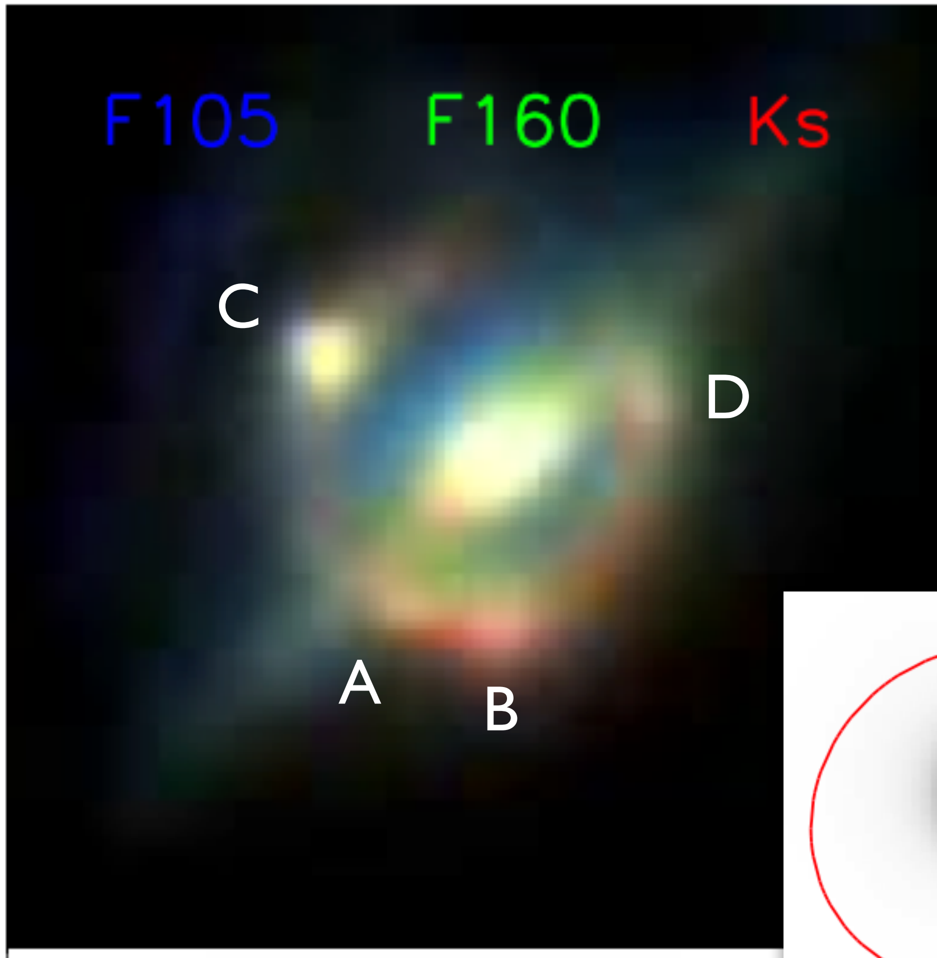
Lensed HATLAS12–00 @z=3.3: gas, stars & dust are offset

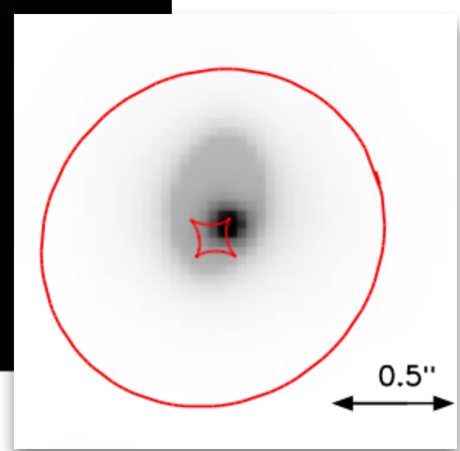


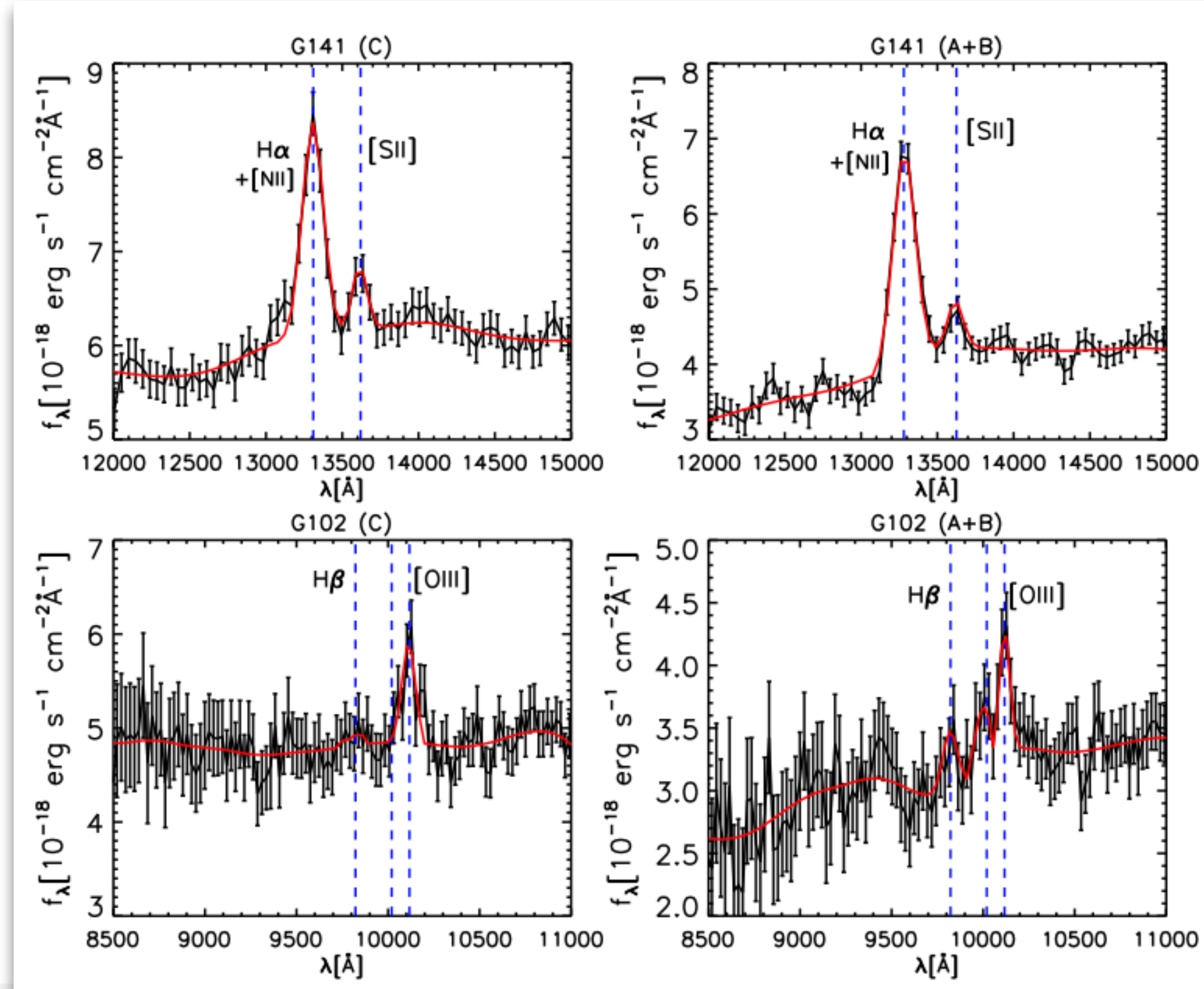


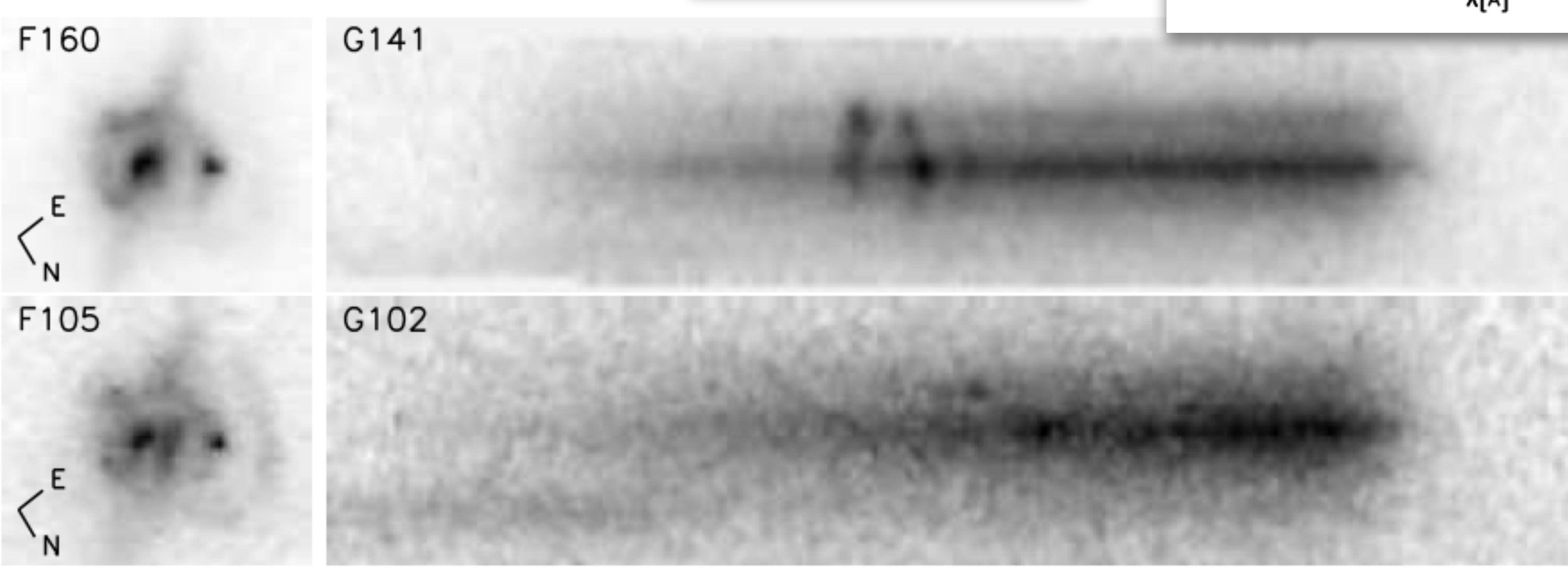
Fu, JW et al. 2012

HATLASJ1429 @z=1.03: HST Grism for optical line ratios



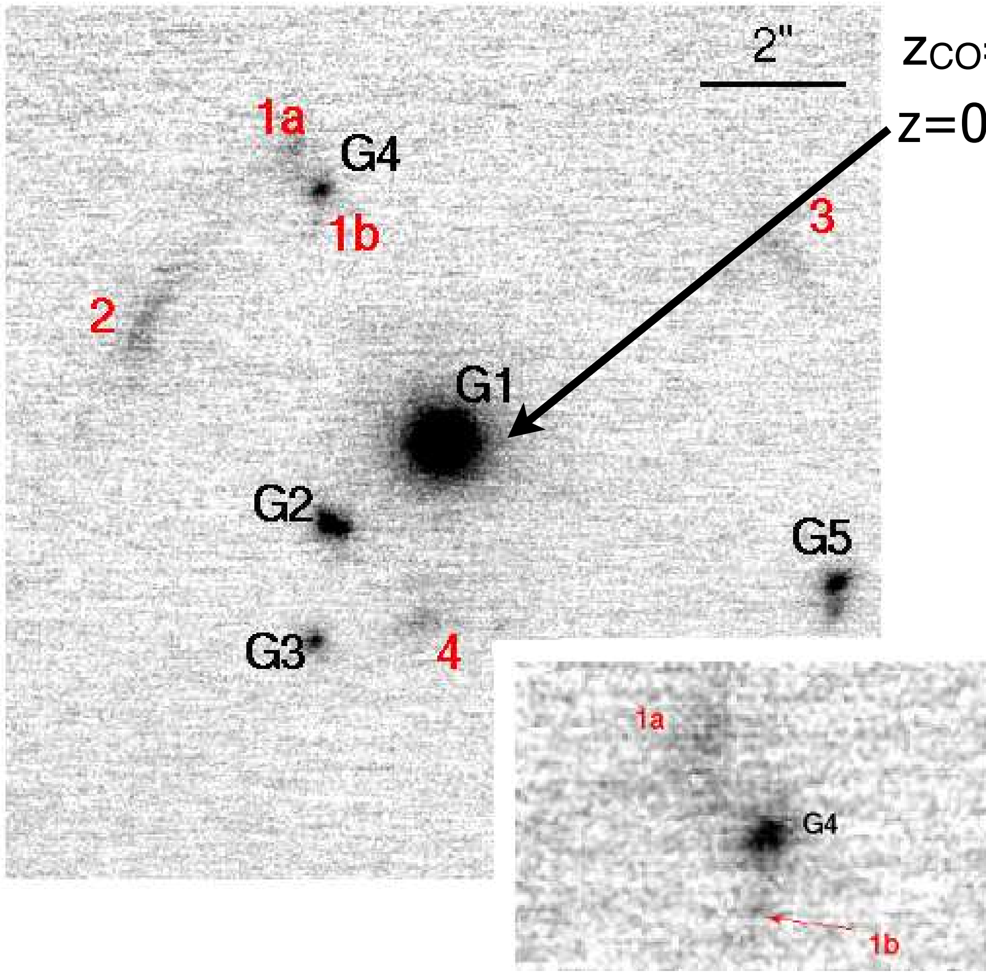






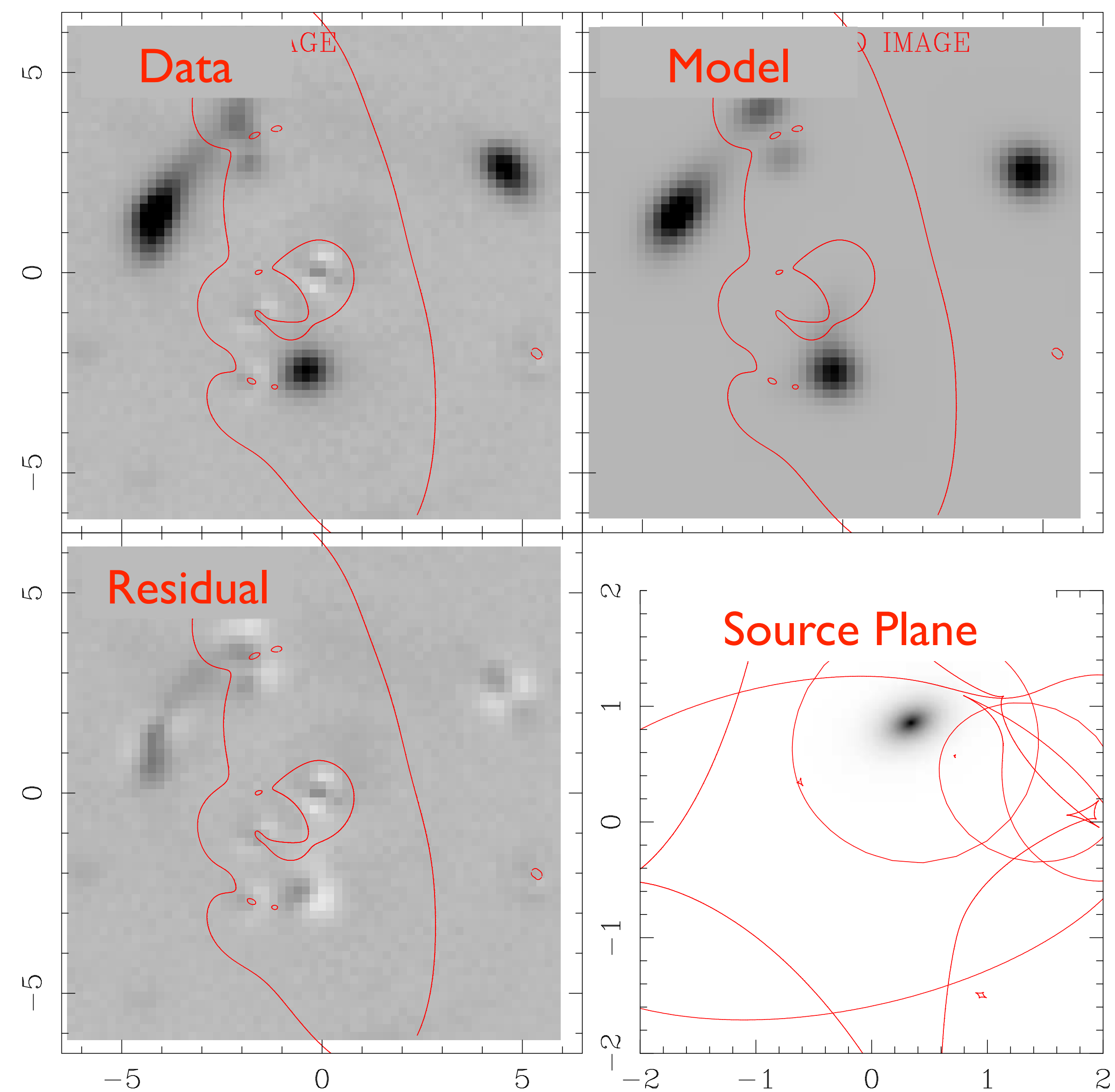
Timmons, JW et al. 2014
See also Messias et al. 2014

HLock01: a HerMES source lensed by a group



z_{CO}=2.957

z=0.60 ± 0.04



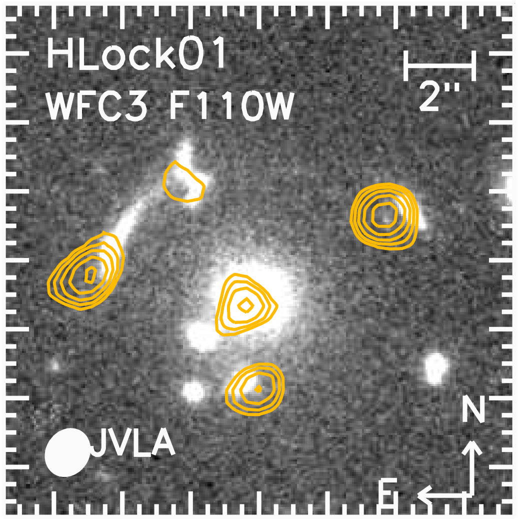
Half-light radius of the SMG:
$R_{eff,s}$ = 1.9 ± 0.1 kpc.

Magnification:

μ = 10.9 ± 0.7

Gavazzi et al. 2011

HLock01: a HerMES source lensed by a group



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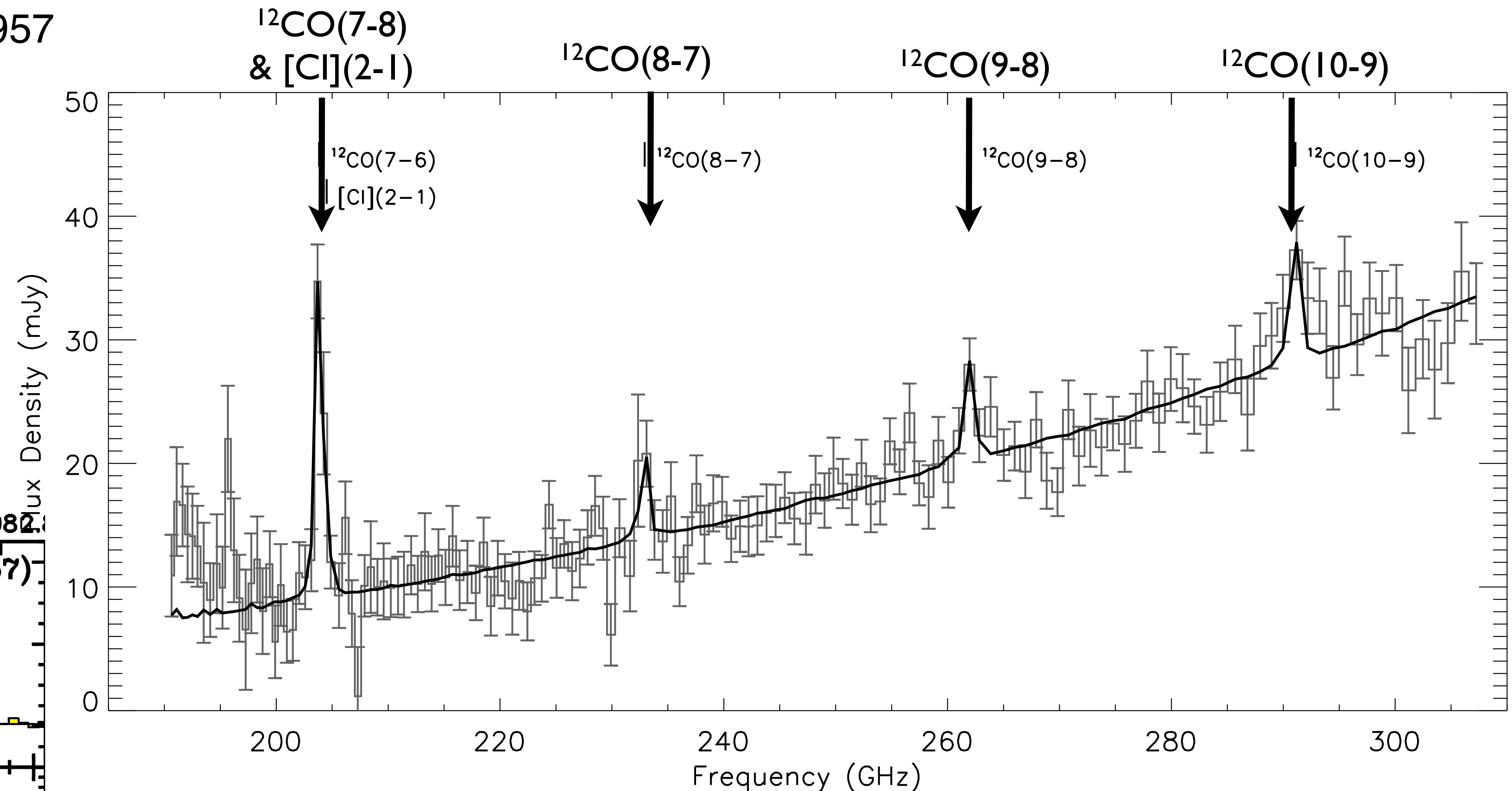
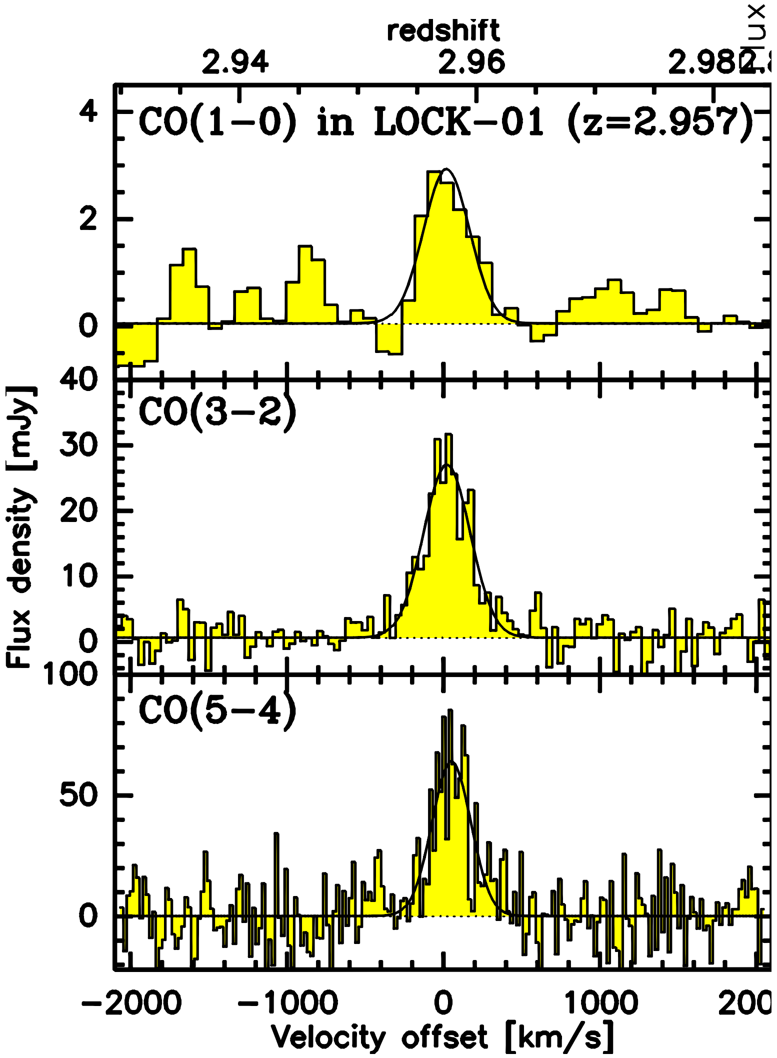




Scott et al 2011;
Riechers et al. 2011;
also Conley et al. 2011

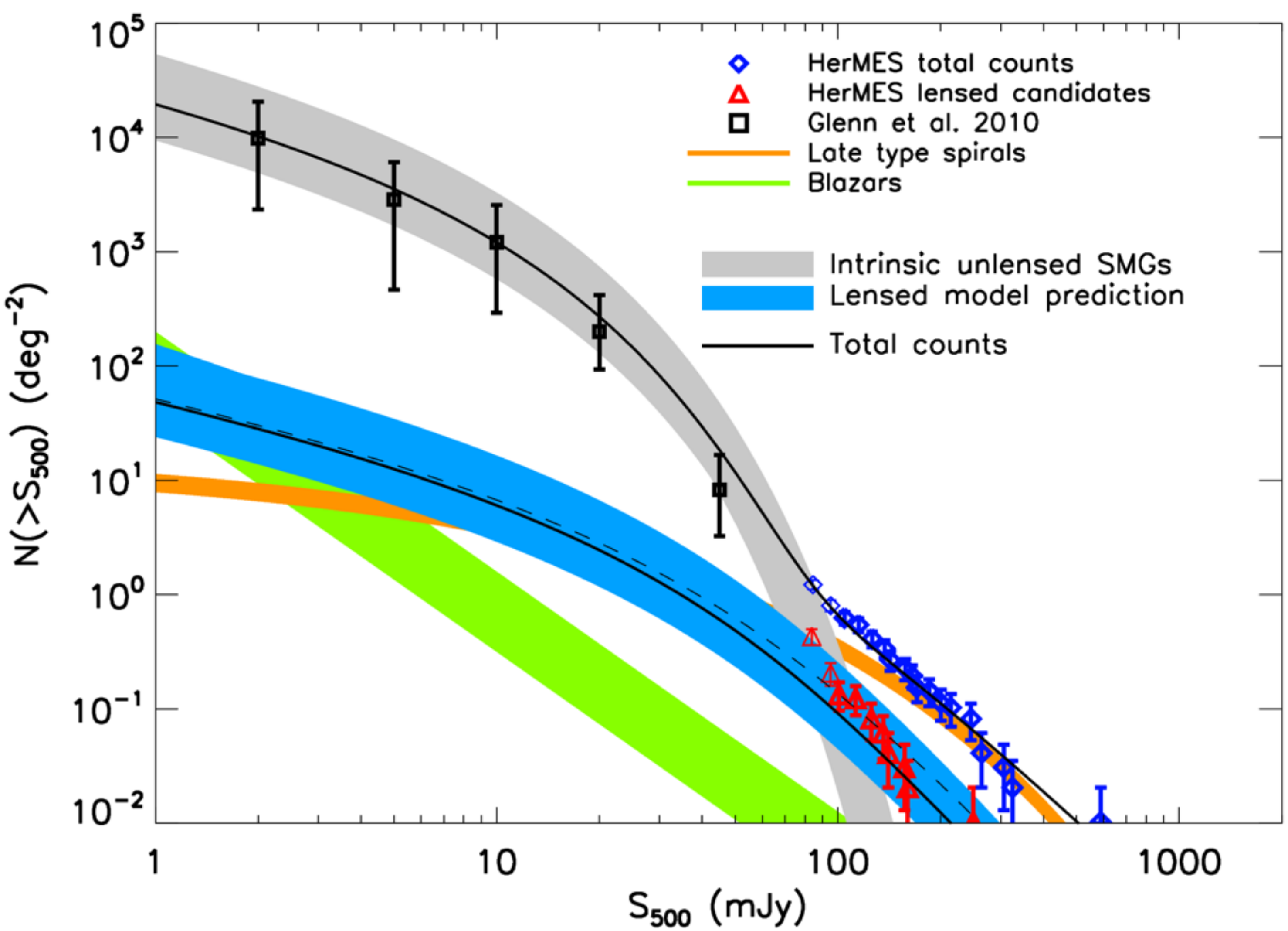
Model of lensed SMGs agrees with observed number

Components

- ΛCDM cosmology: $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, $H_0 = 71$km s^{-1} Mpc^{-1}
- NFW or SIS foreground mass profiles
- Sheth & Tormen distribution of foreground masses
- Béthermin et al. N(z) for SMGs

The model

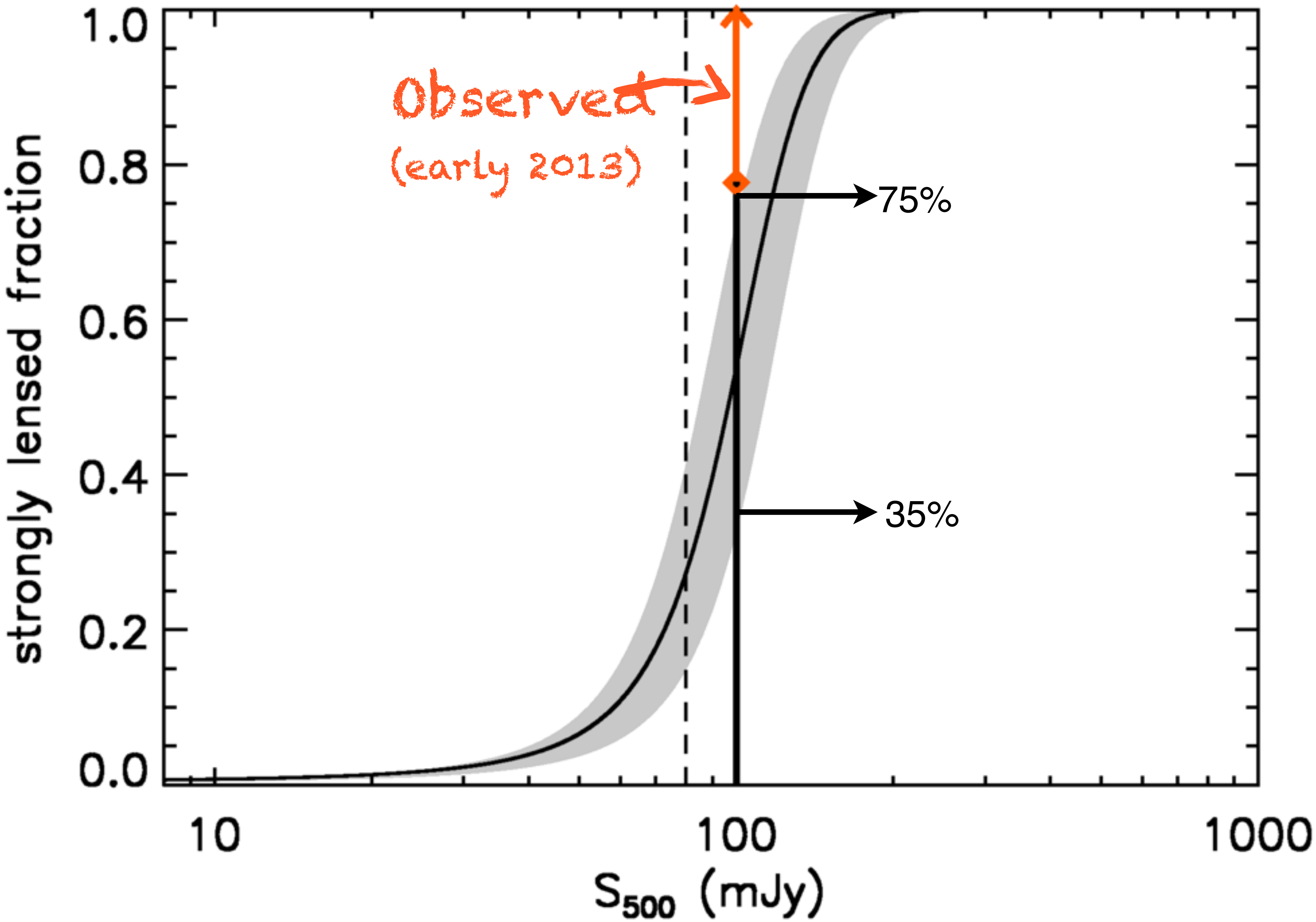
- Calculate the fraction of the sky that is strongly ($\mu>2$) lensed = f_μ
- Use f_μ to calculate lensing probability = $P(\mu)$
- Assume intrinsic counts have the shape of a Schechter function
- Integrate to apply $P(\mu)$ to the intrinsic counts
- Use MCMC to fit to the total observed HerMES number counts
- ***Number counts of lensed SMGs are predicted***



Wardlow et al. 2013

Other predictions: candidates have ~35–75% fidelity

Blazars & spirals removed



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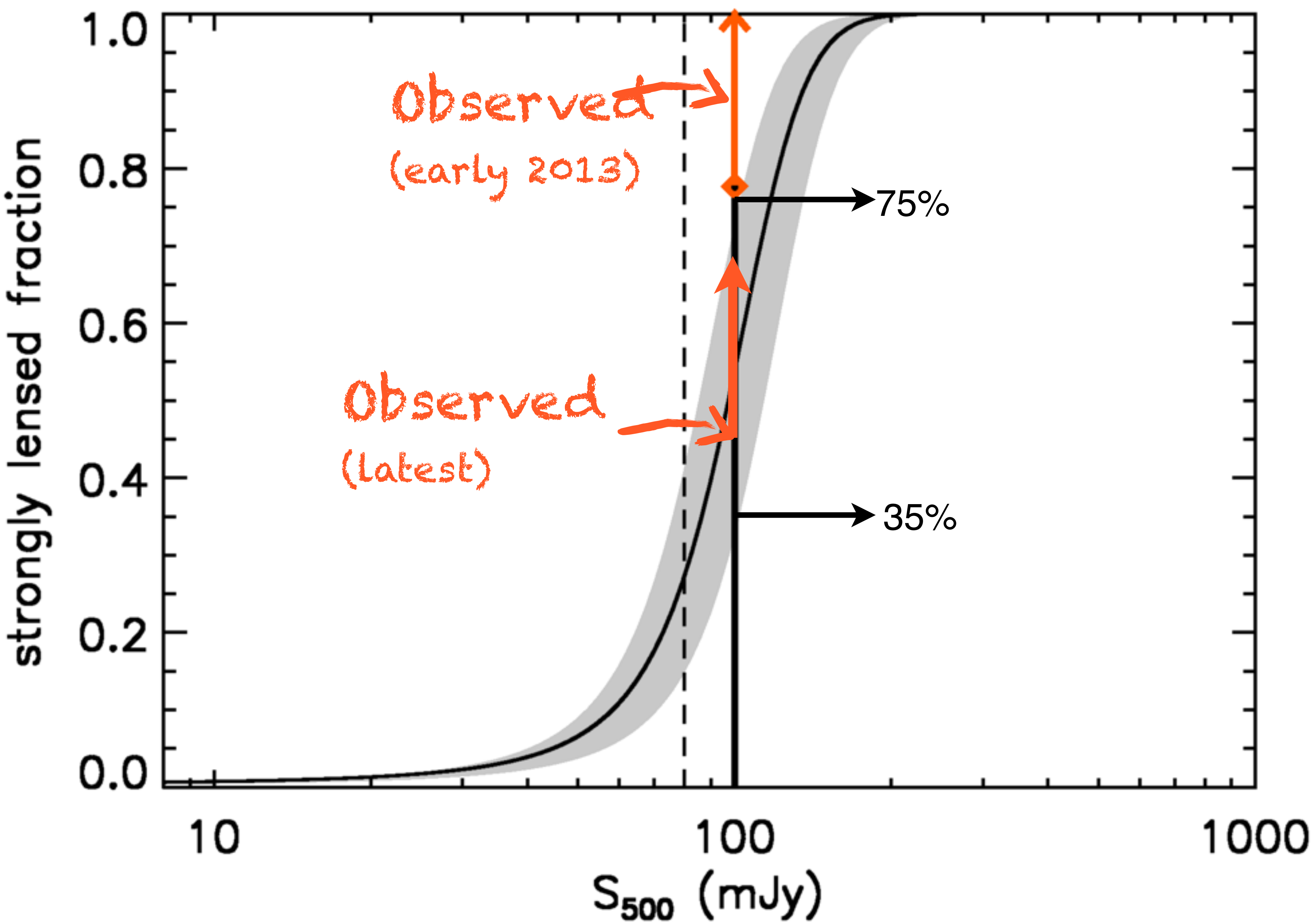
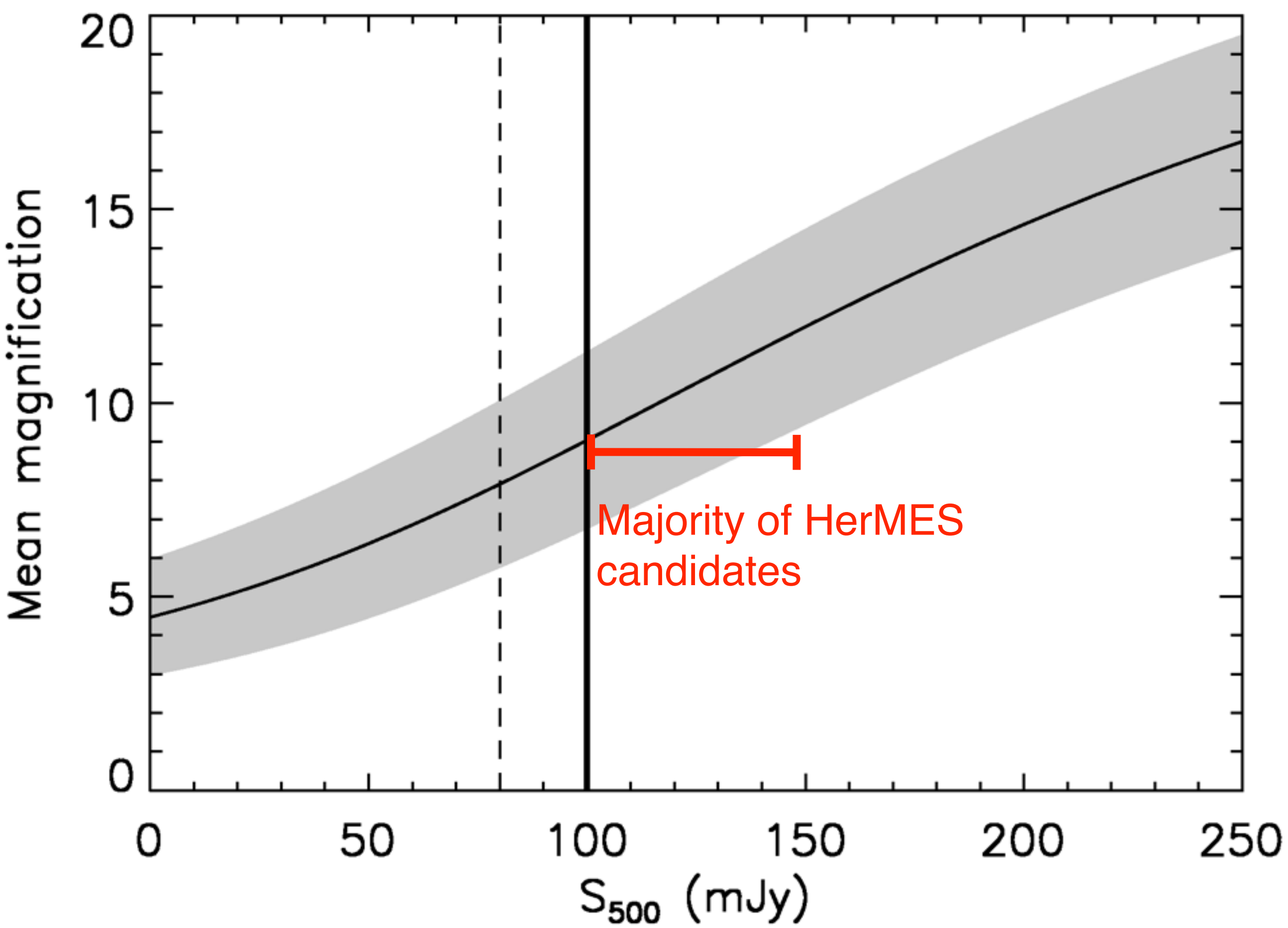


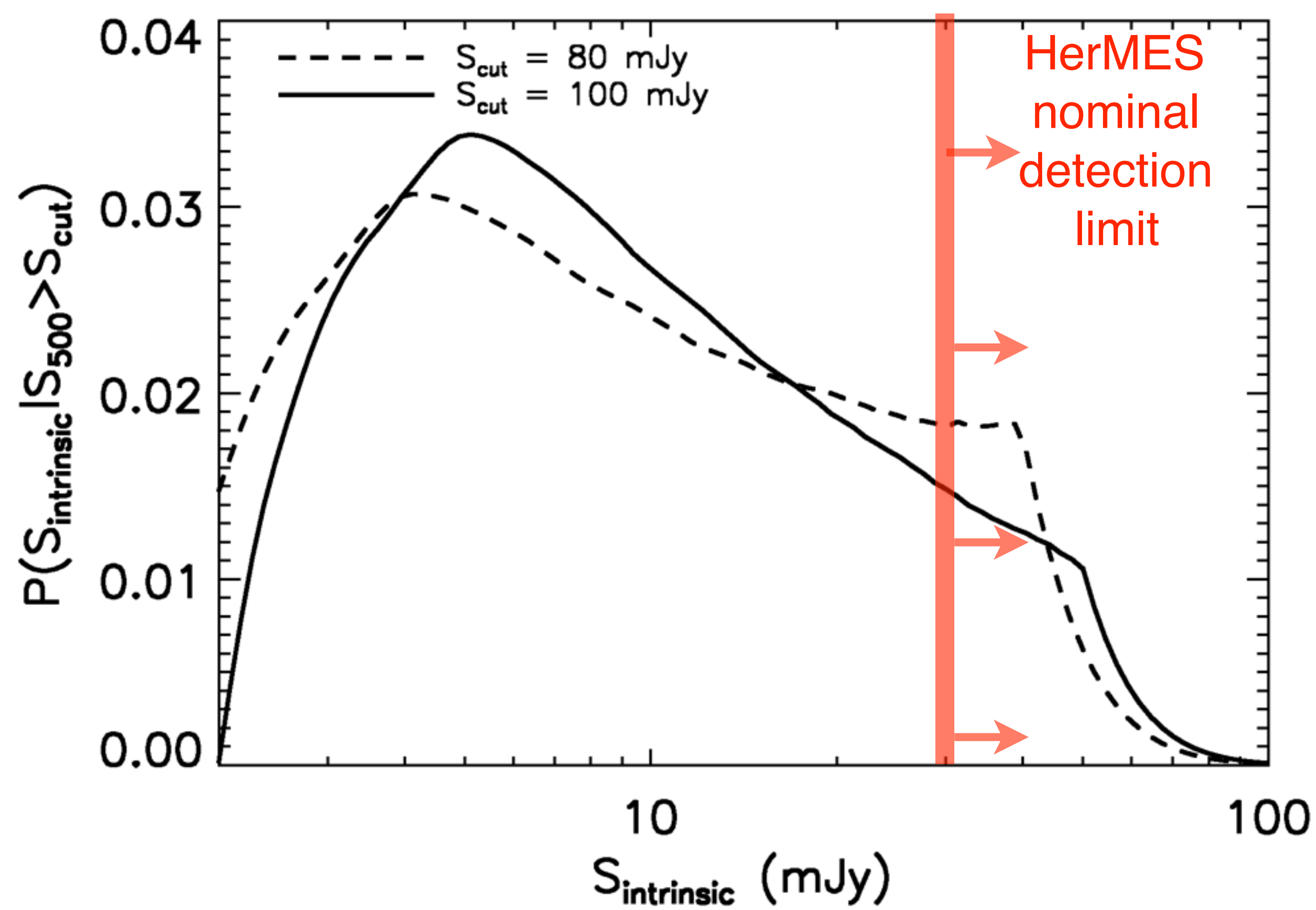
Wardlow et al. 2013

Other predictions: magnification factor

Mean magnification is μ~5–10

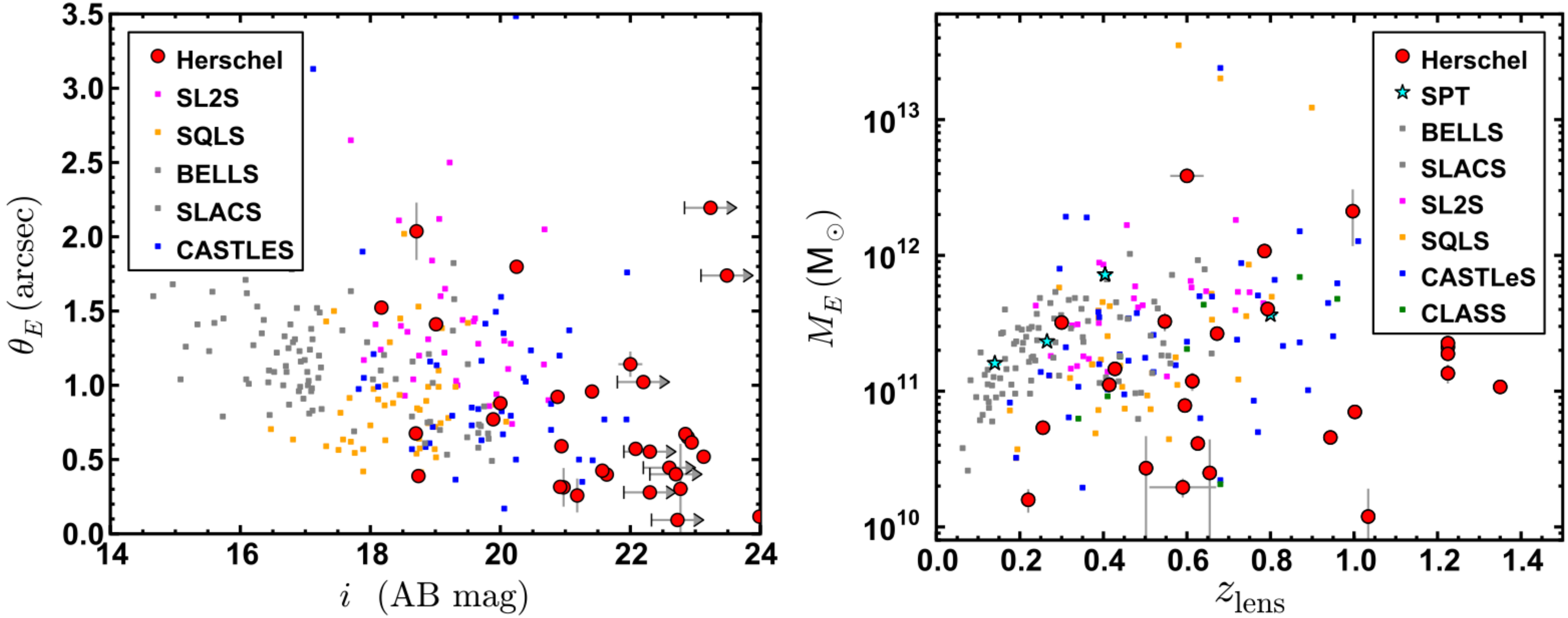


Sources are intrinsically faint



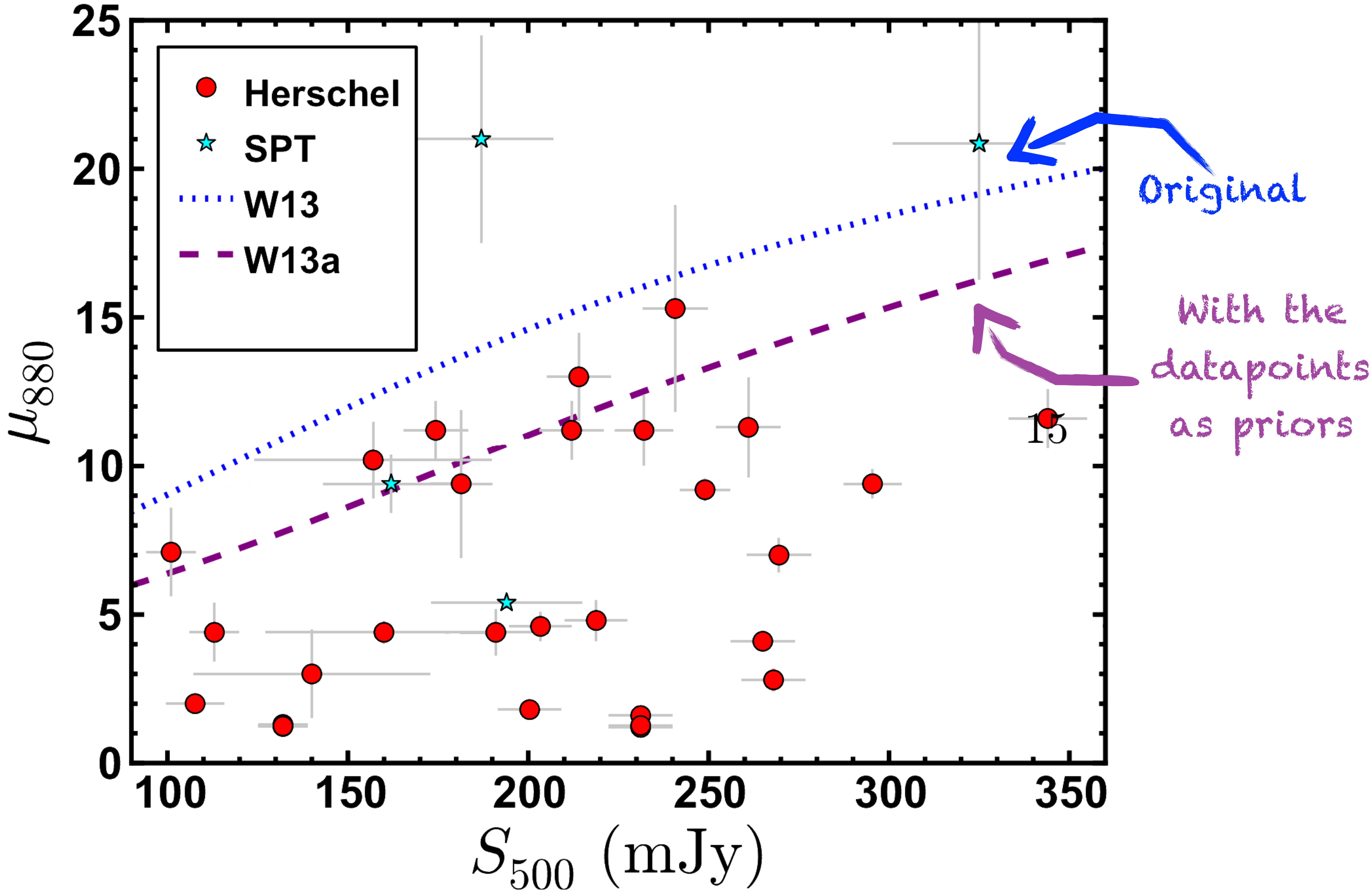
Wardlow et al. 2013

The lenses are fainter and higher *z* than other surveys



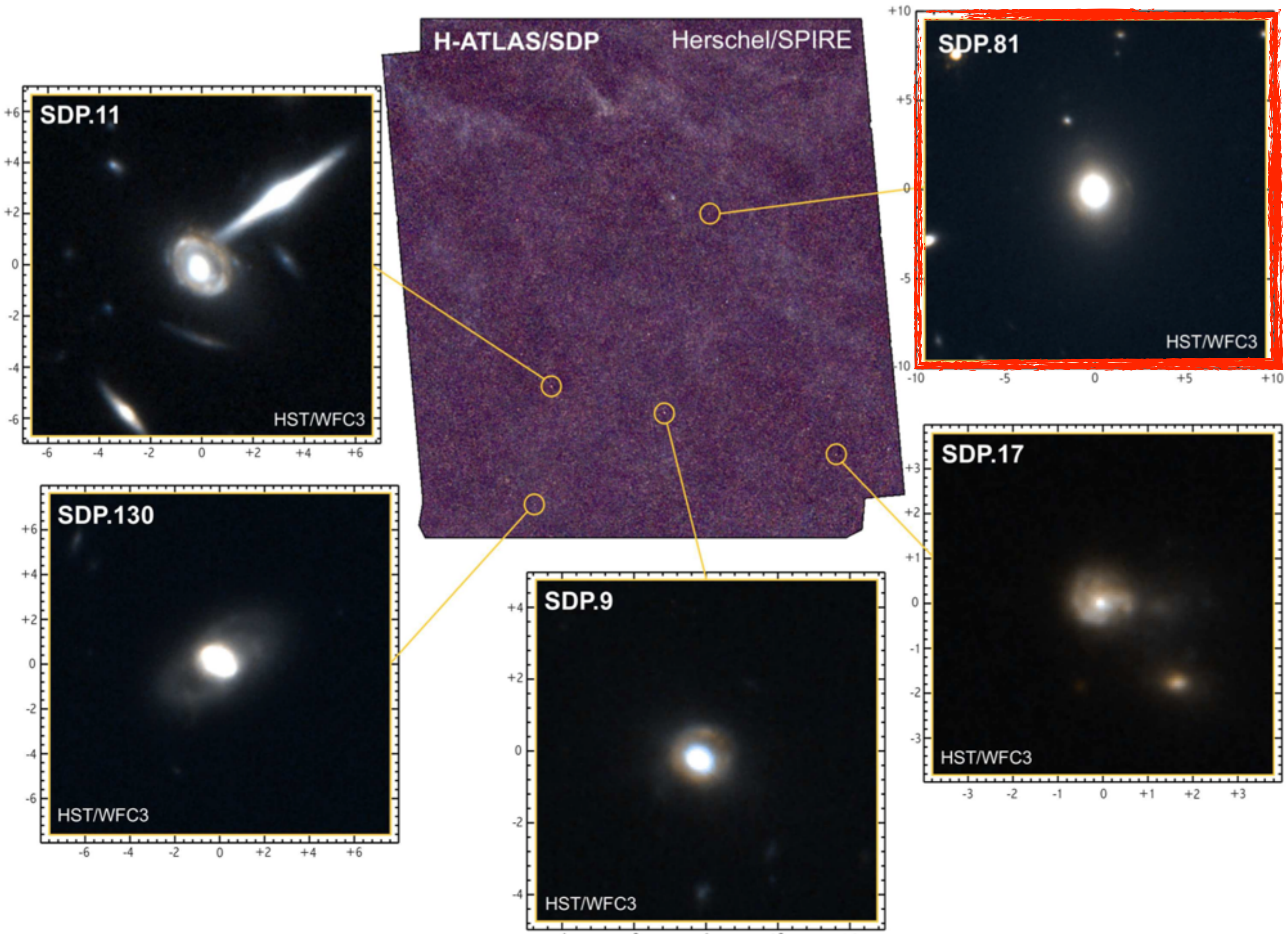
Bussmann, JW et al. 2013

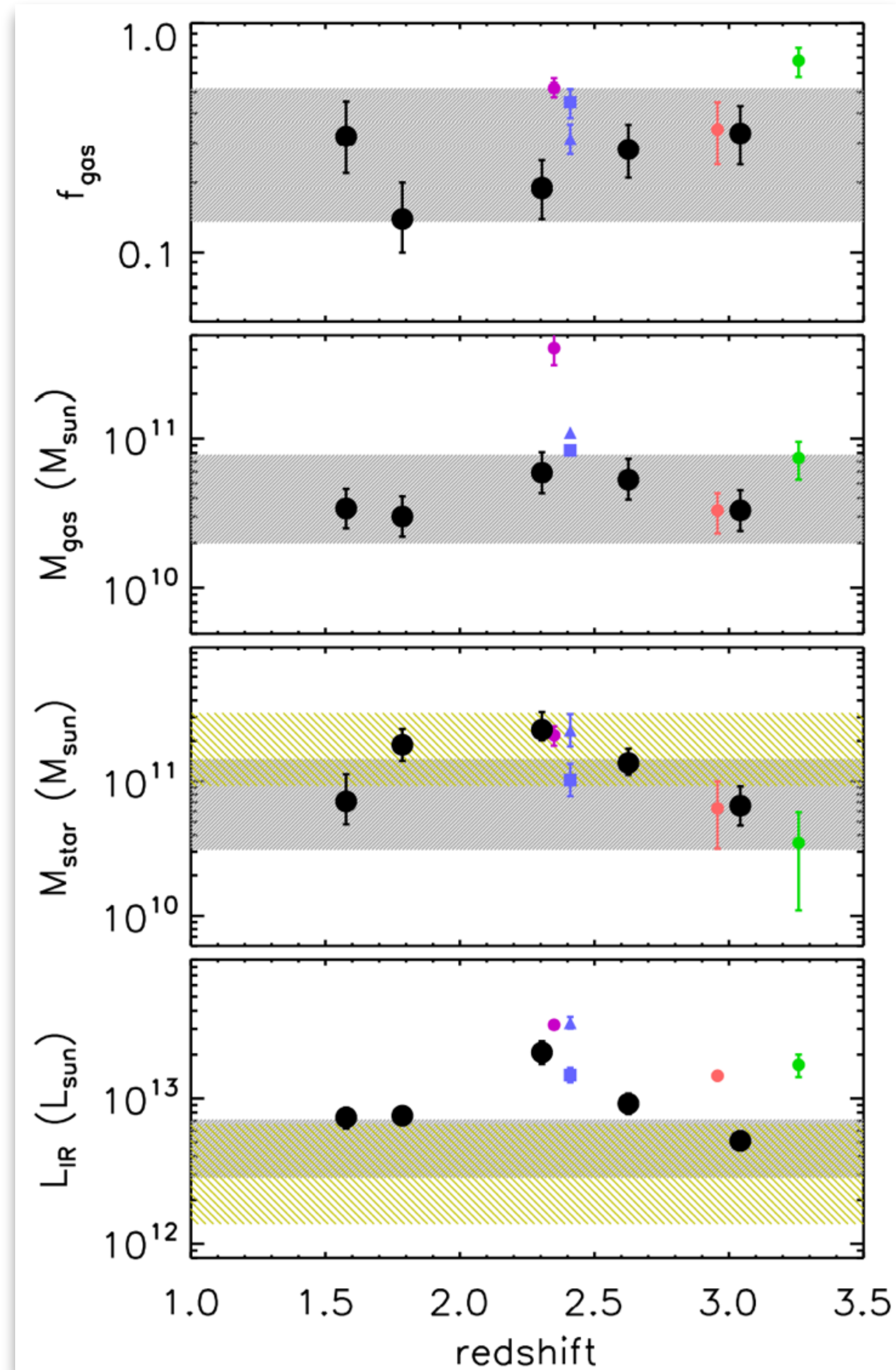
IR magnification factors are typically ~2–10



Adapted from Bussmann, JW et al. 2013

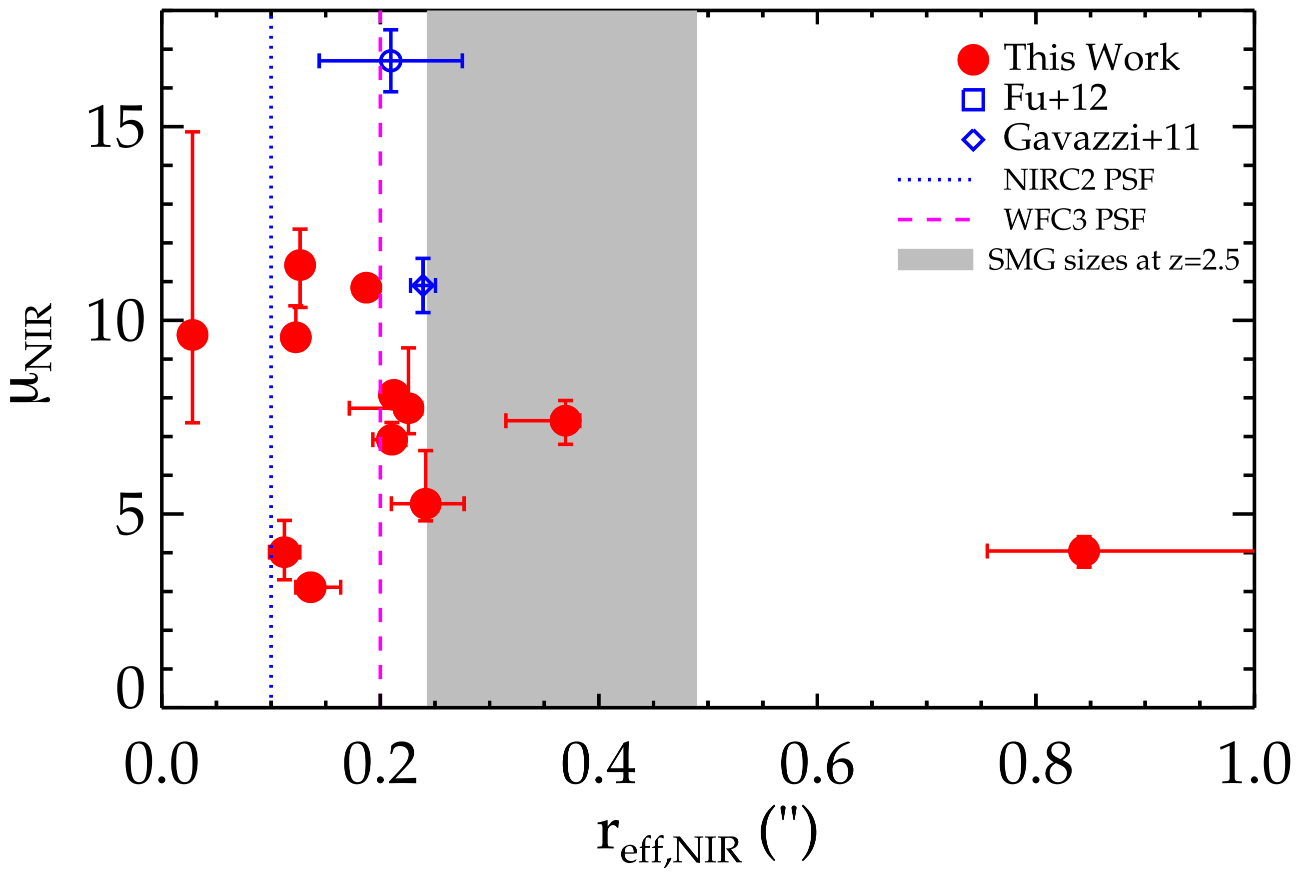
H-ATLAS:
The first 5 lenses are similar to unlensed SMGs

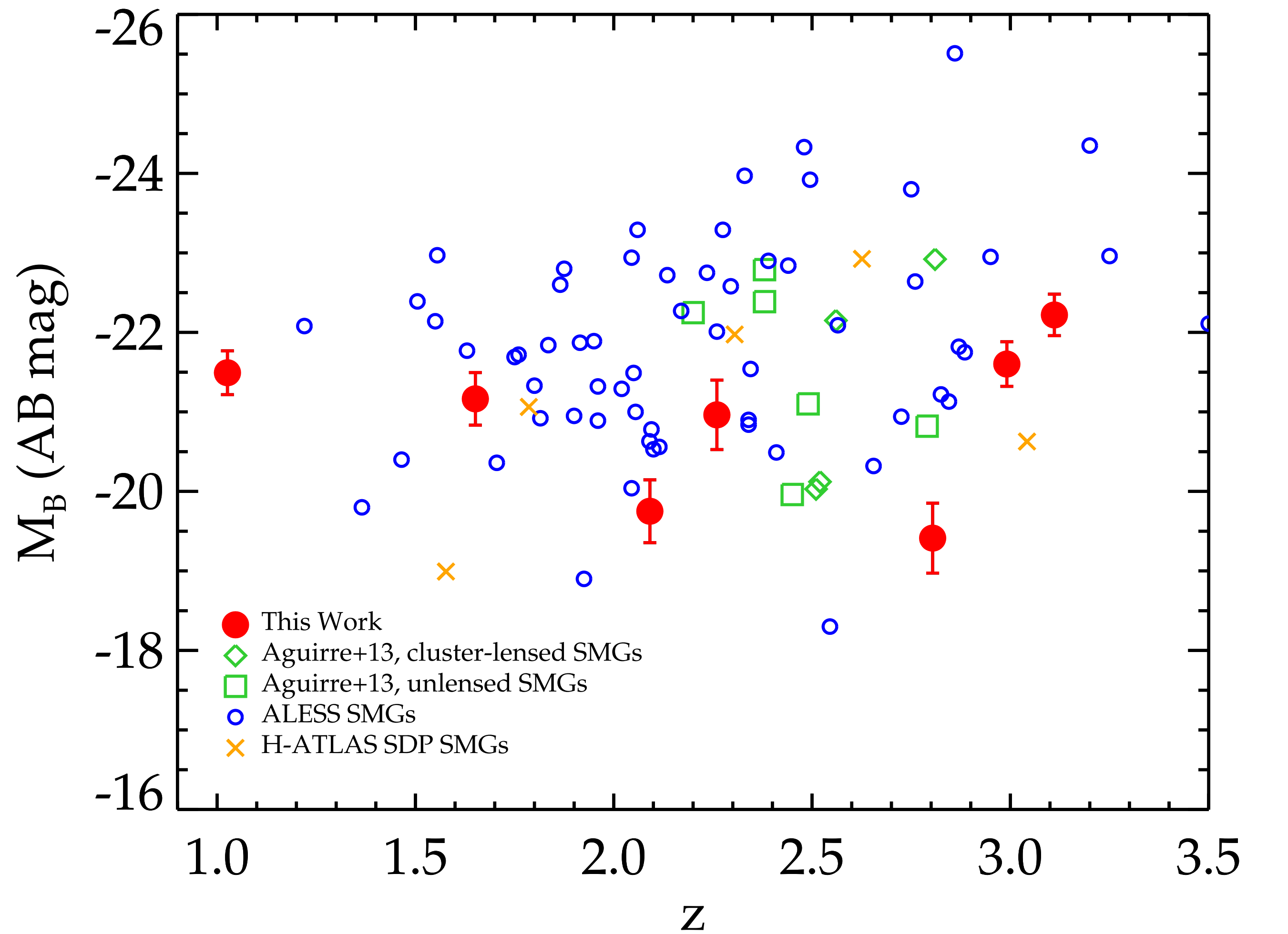




Negrello et al. 2010
Negrello, JW et al. 2014

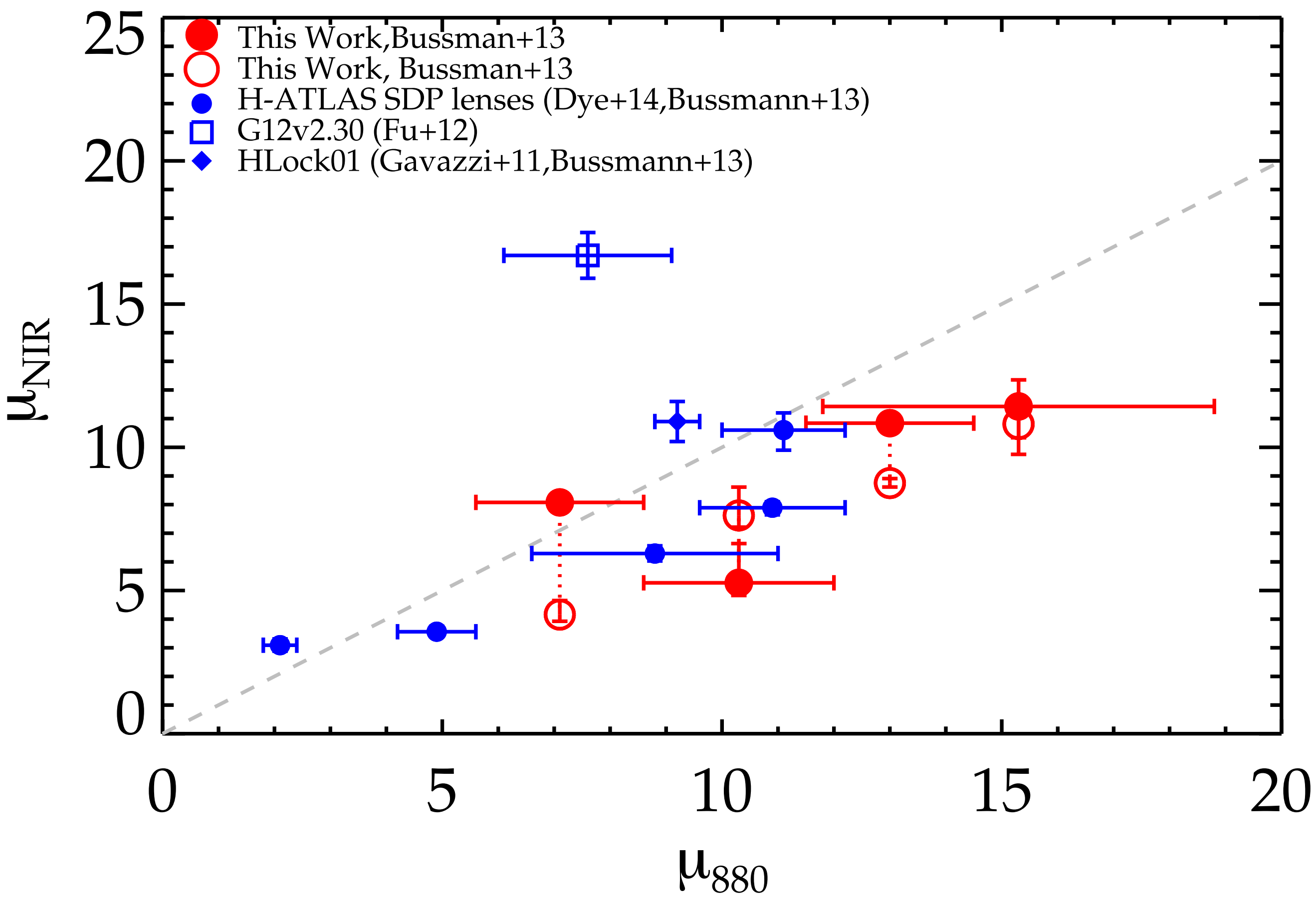
Lensing probes smaller & fainter optical systems than classical SMGs

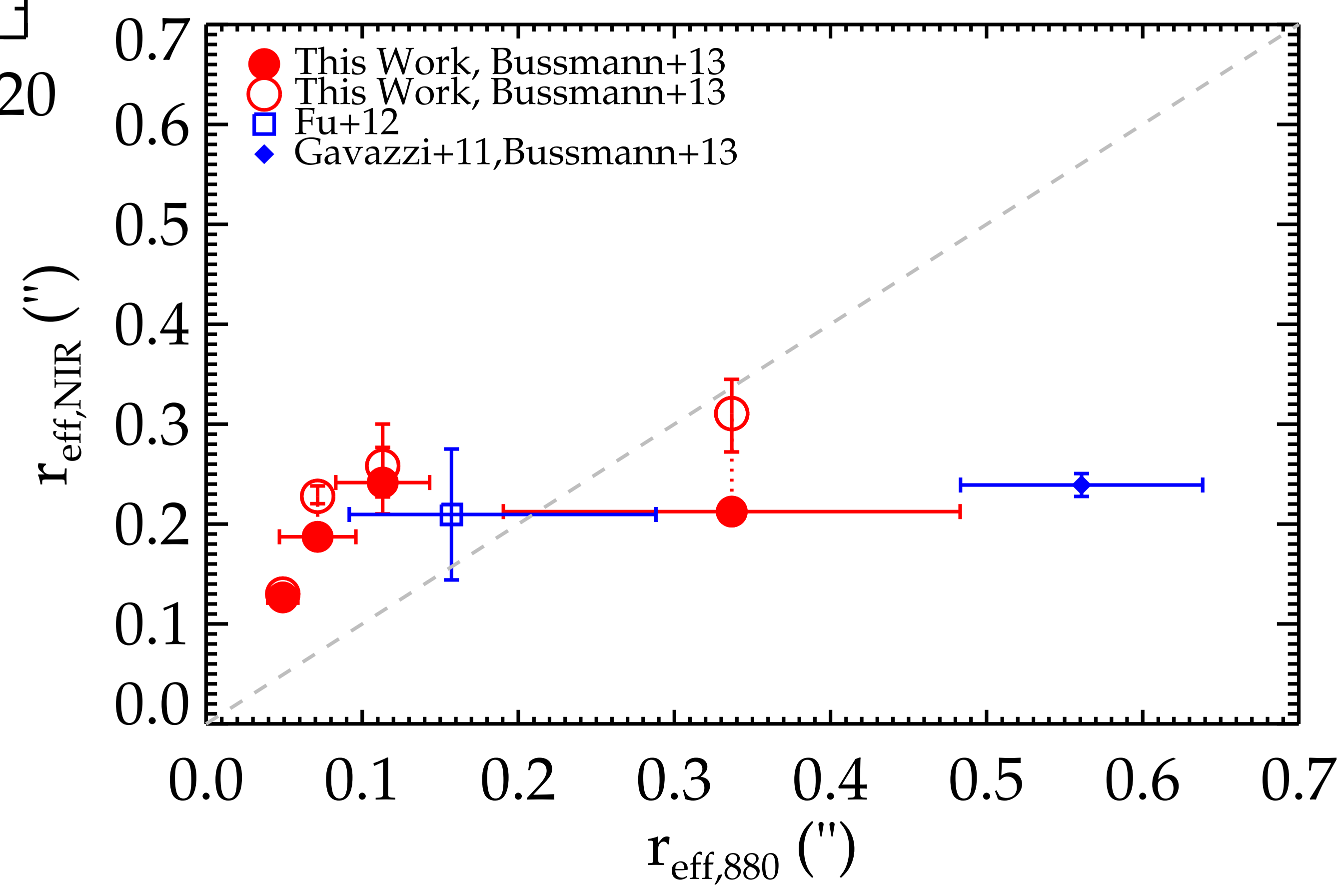




Calanog, JW et al. 2014

The submm emission is typically more magnified & smaller than the NIR

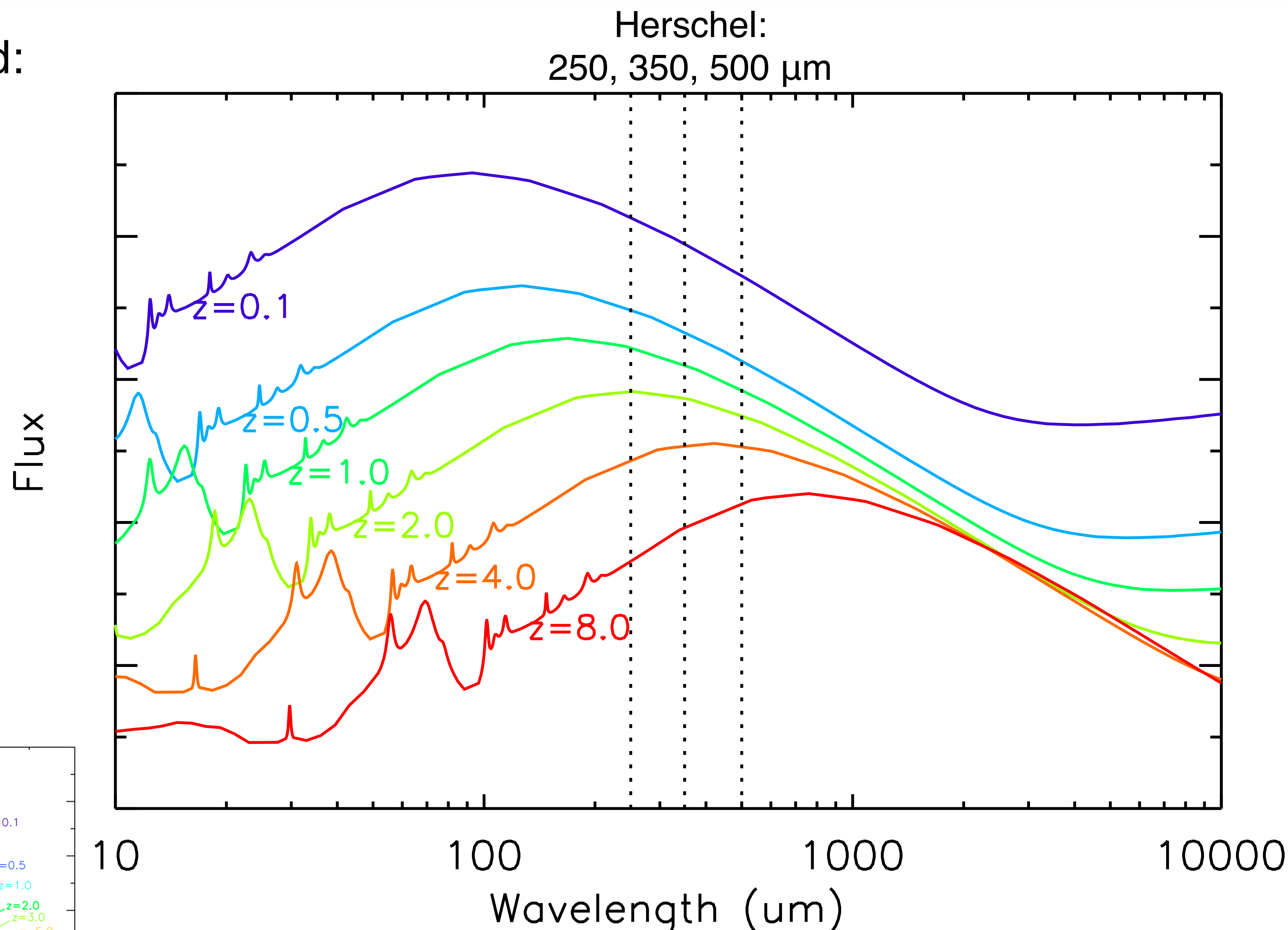


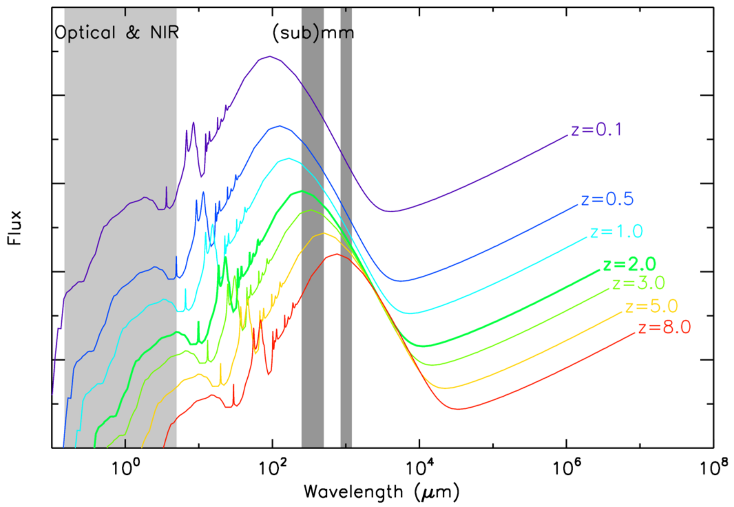


Calanog, JW et al. 2014

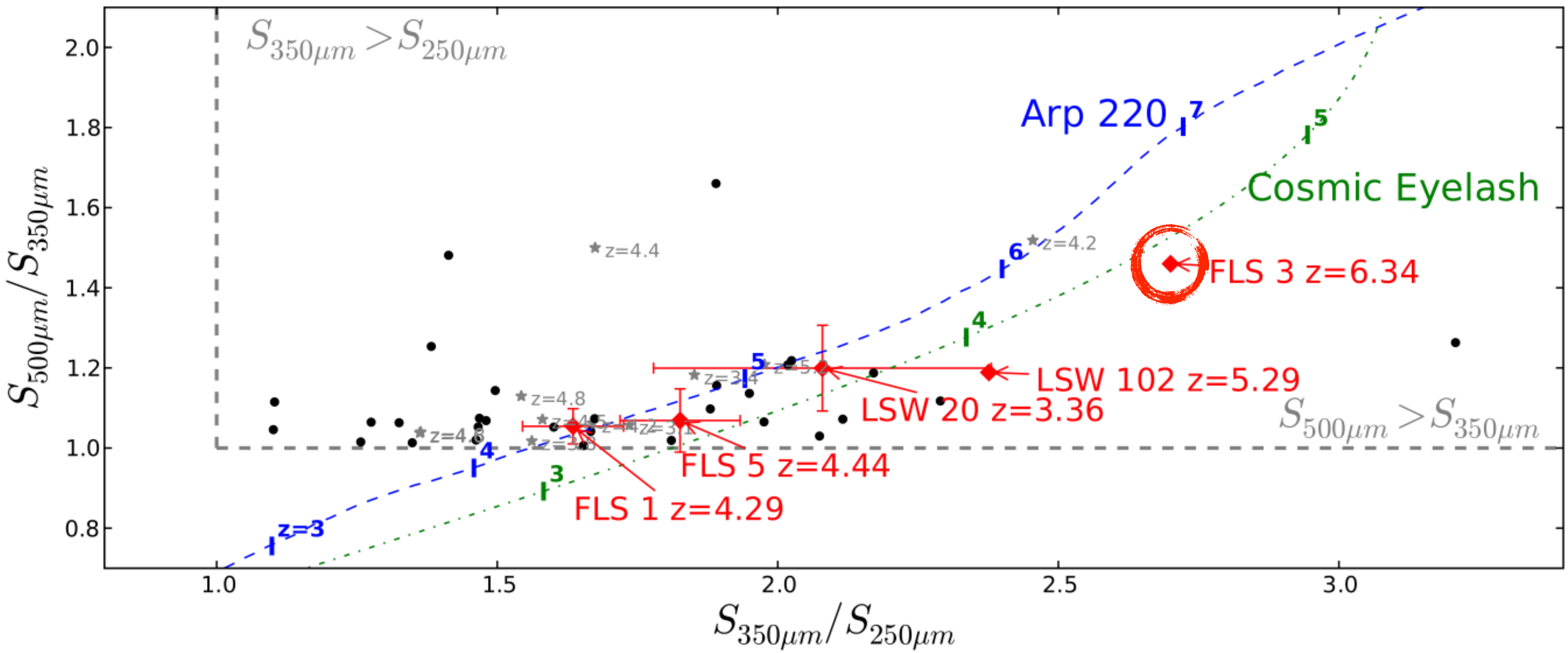
Submm colours are a proxy for redshift

Arp 220 redshifted:





‘Red’ SPIRE colours indicate z≳4



Dowell, JW et al. 2014

HFLS3: z=6.3 starburst

$L_{IR} \sim 3 \times 10^{13}\ L_\odot$

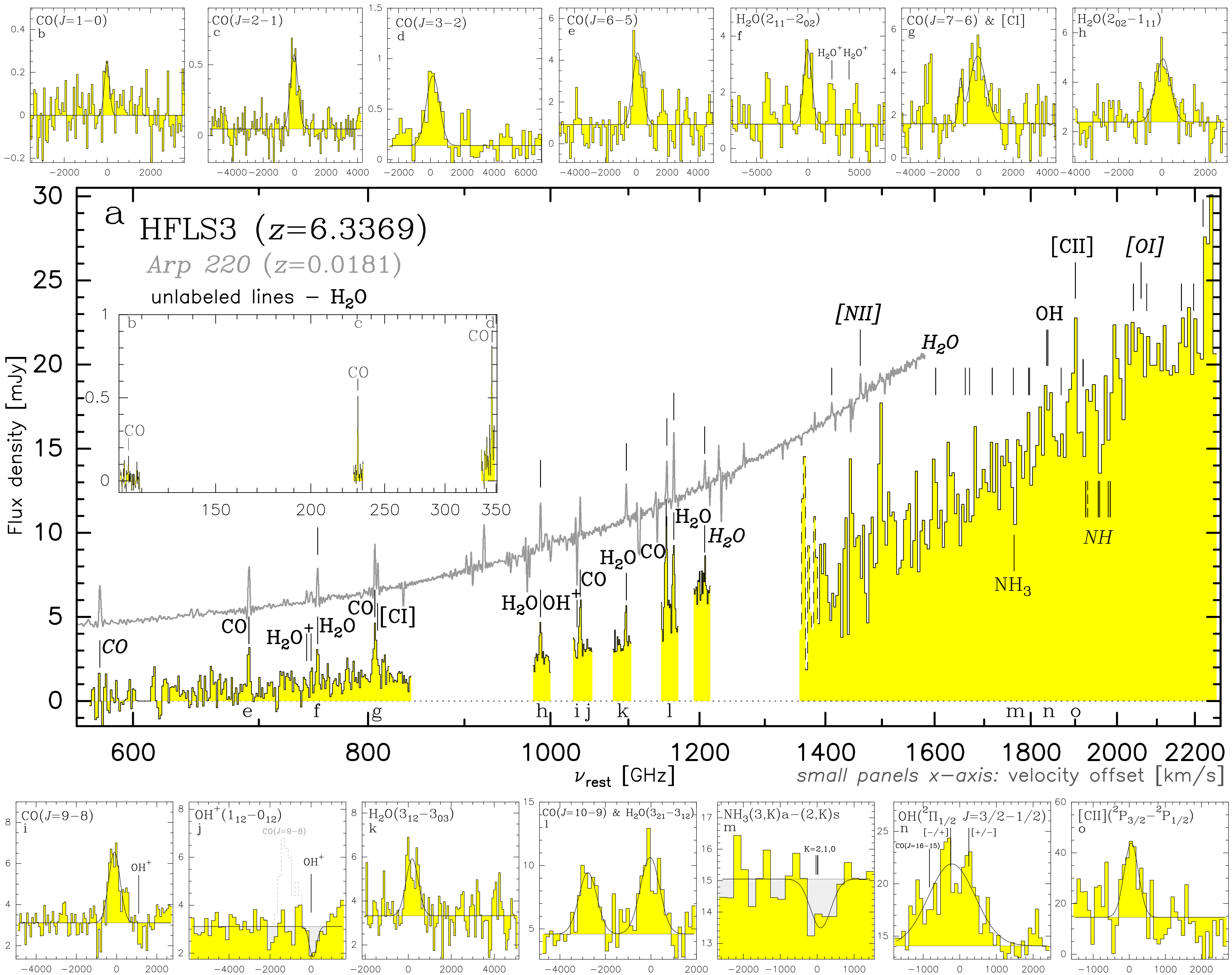
$SFR \sim 3000\ M_\odot yr^{-1}$

$M^* \sim 4 \times 10^{10}\ M_\odot$

$M_{gas} \sim 10^{11}\ M_\odot$

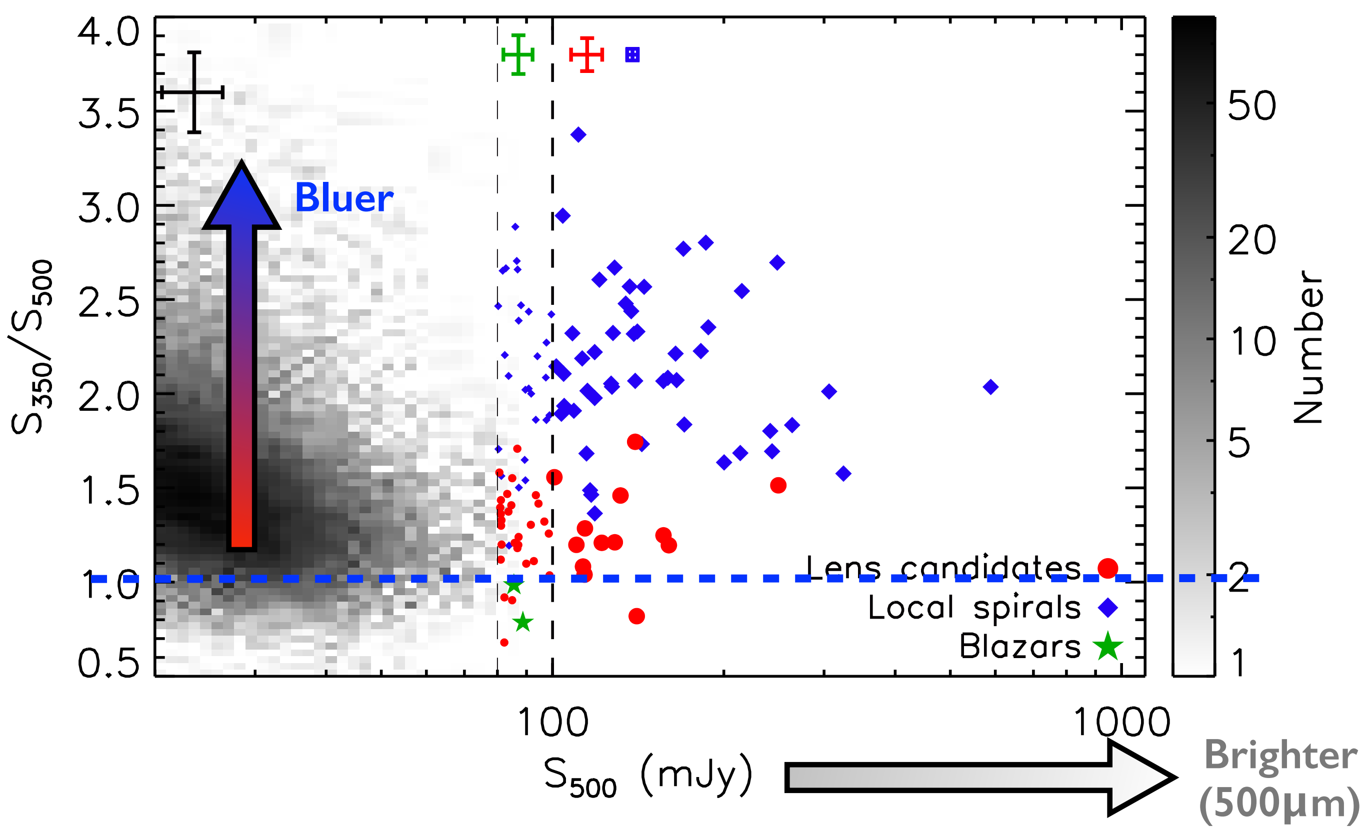
$M_{dust} \sim 10^{9}\ M_\odot$

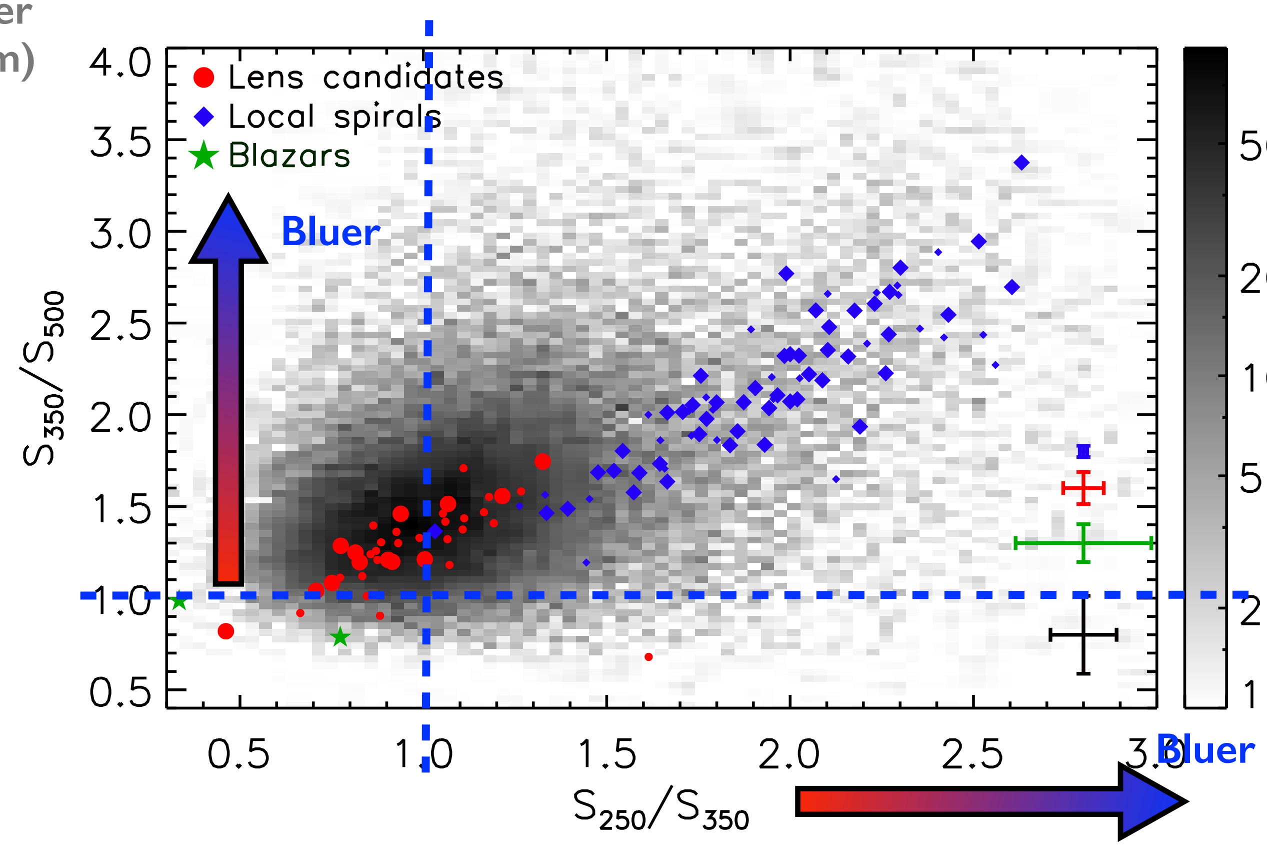
$M_{carbon} \sim 4.5 \times 10^{7}\ M_\odot$



Riechers, JW et al. 2013

Some lens candidates also have very red colours

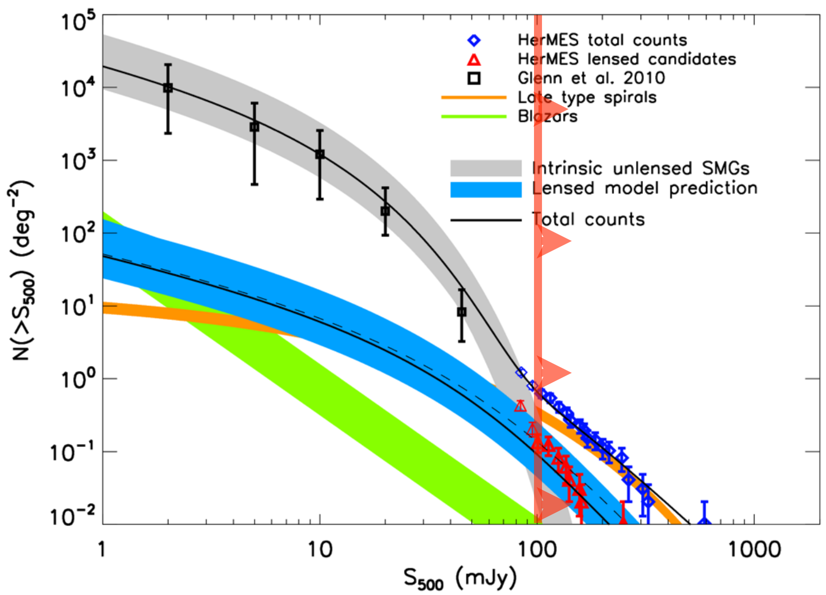




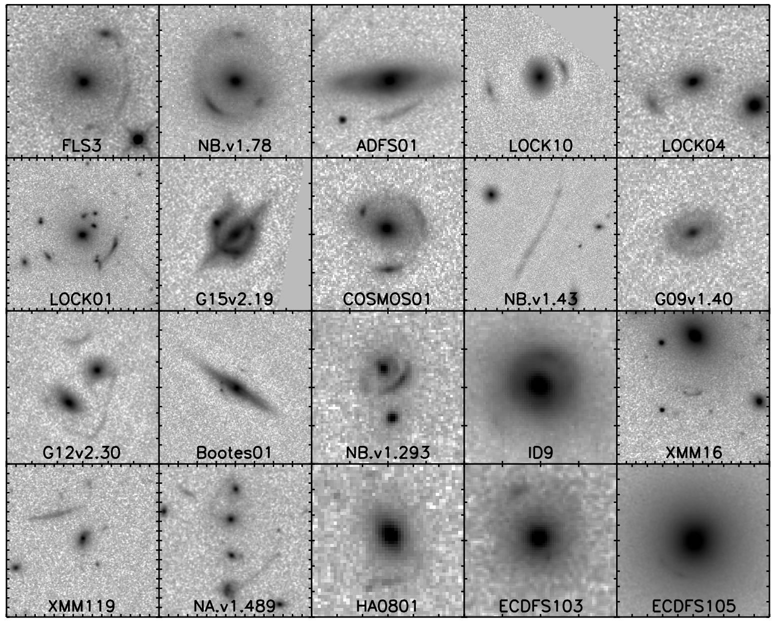
Wardlow et al. 2013

Summary

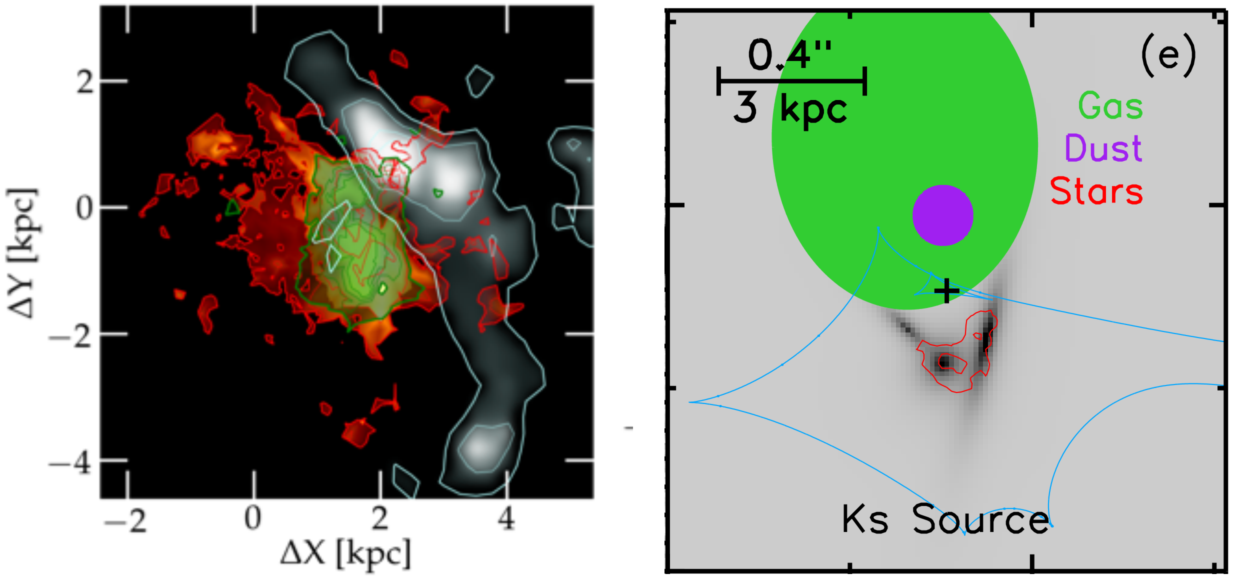
Wide-area, submm surveys can identify strongly lensed dusty star-forming galaxies by simply selecting the brightest sources….



… and they are very efficient at finding lensed galaxies.



Lensing is revealing the complicated structures & conditions in z>2 galaxies.



Typical magnifications are factors of ~5–10 and are often higher in the FIR than NIR.