The legacy of Herschel for studies of Galaxy evolution

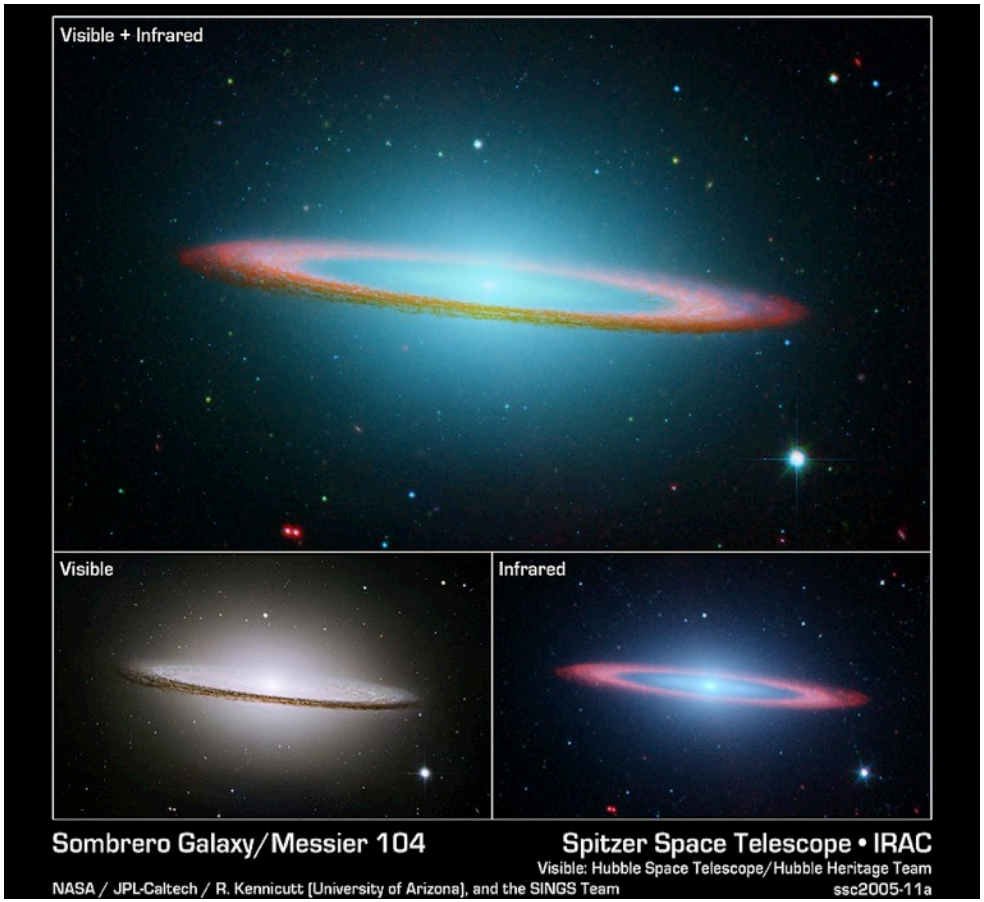
Loretta Dunne

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

THE UNIVERSITY OF EDINBURGH

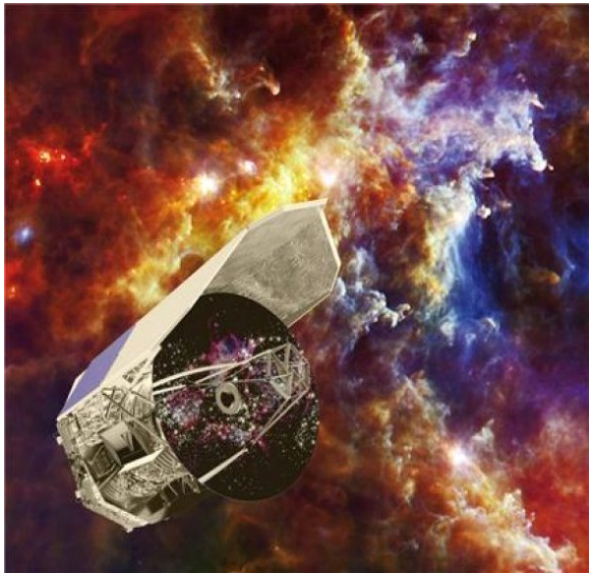
Seeing the Stolen Starlight

- Dust grains absorb UV/optical photons
- Heated to 20-80 K and re-radiates in the FIR and sub-mm.
- Use FIR (8-1000 micron) luminosity as a tracer of obscured star formation.
- Dust is also a good tracer of gas mass in galaxies.
- Simple to relate FIR emission to star formation rate and dust mass.



$$M_d = \frac{S_\lambda \, D^2}{\kappa(\lambda) \, B(\lambda, T_d)}$$

Herschel – the good, the bad…



- Covers the peak of the FIR SED across a range of redshift (70-500 microns).
- Incredible speed and fidelity of mapping.

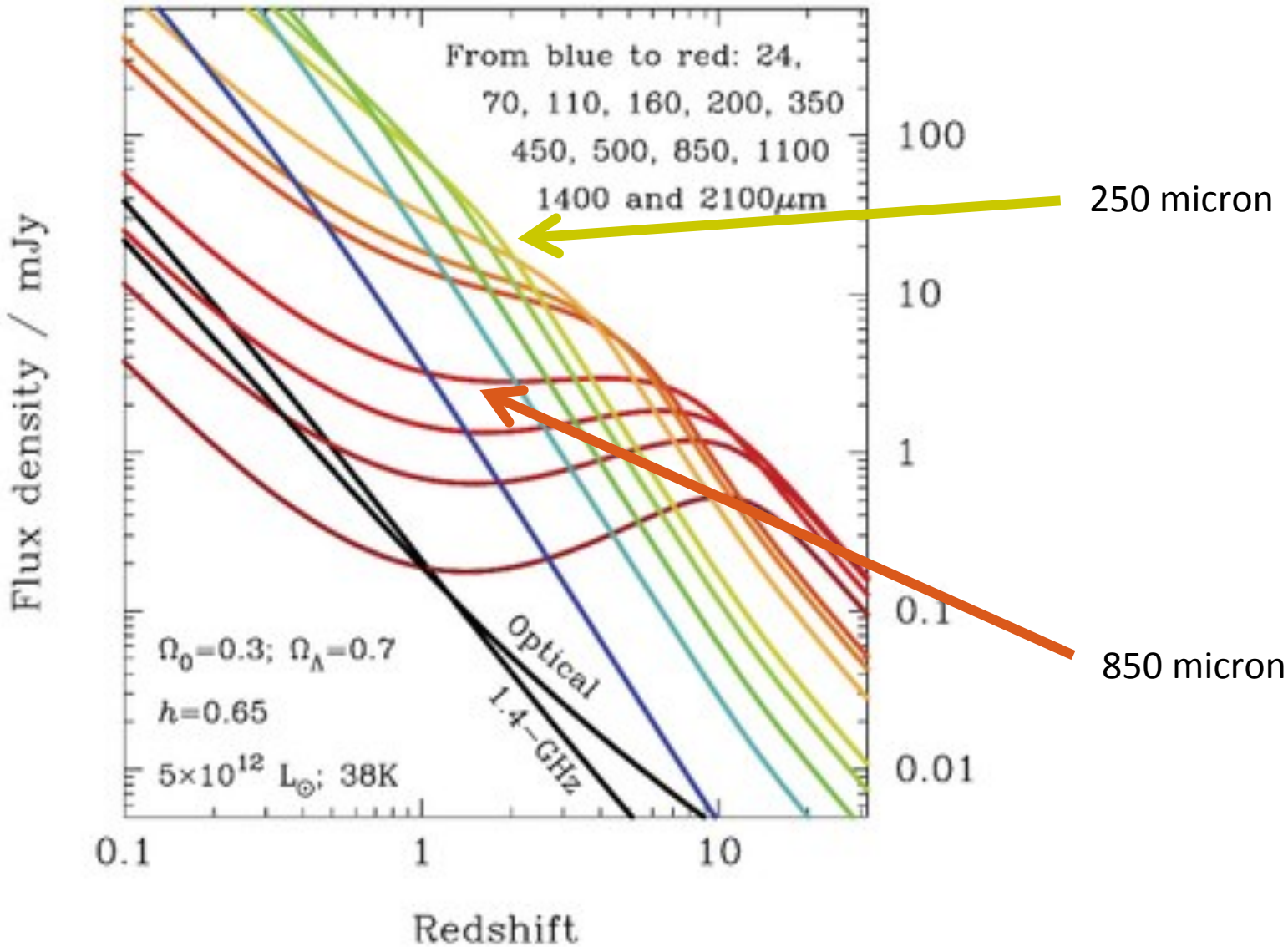
Pilbratt+10
Griffin+10
Poglitsch+10

Blind – statistical properties

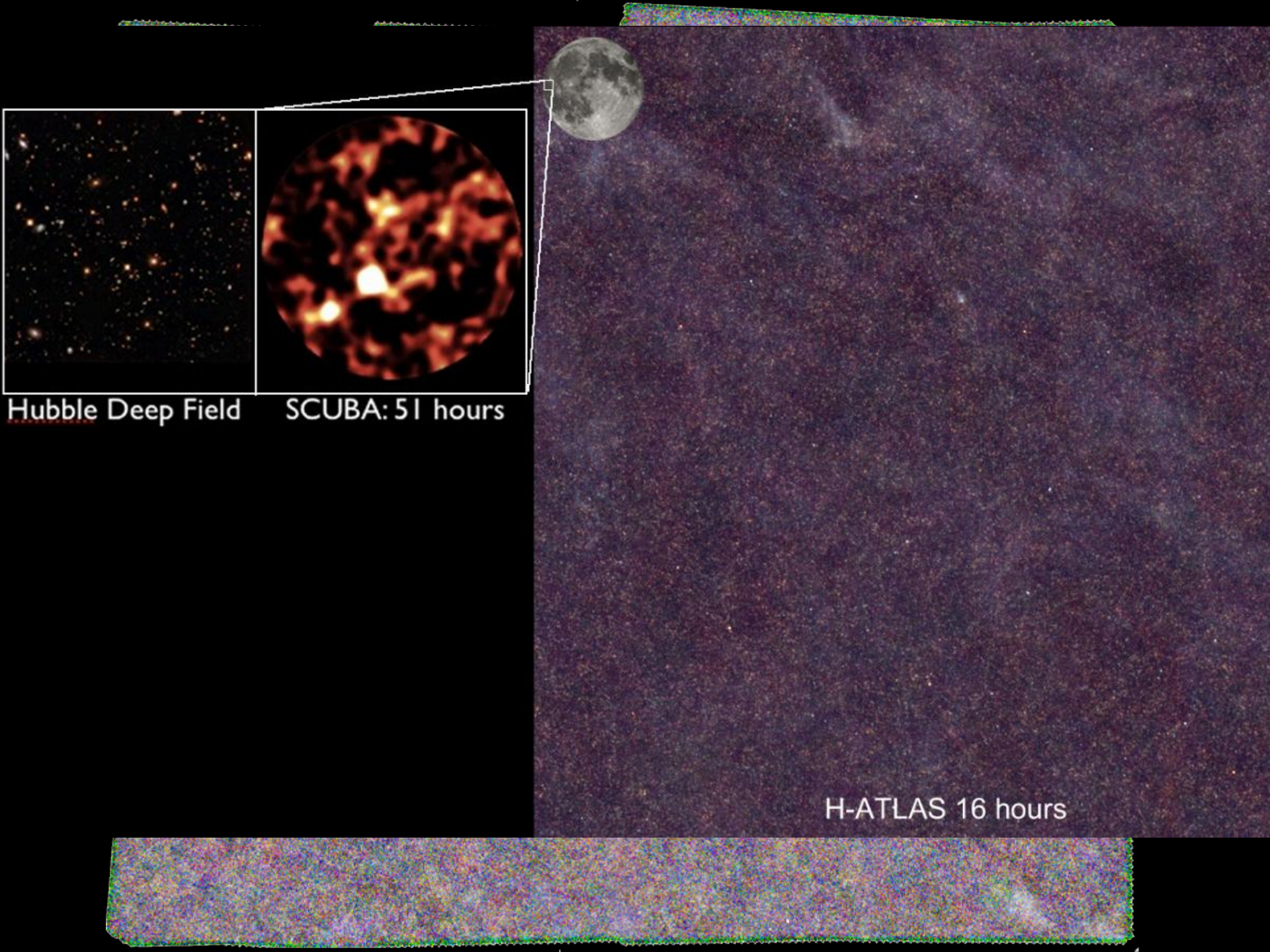
- Poor angular resolution (8-36”)
- Relative mismatch in sensitivity between PACS and SPIRE so small areas with deep 100/160 data

  Negative K-correction not as strong

Herschel-ATLAS (Eales+10)
Hermes (Oliver+12)
PEP (Berta+11)
HeVICS (Davies+10)
Herschel-GOODS (Elbaz+11)


From blue to red: 24,
70, 110, 160, 200, 350
450, 500, 850, 1100
1400 and 2100μm
Flux density / mJy
Redshift
0.1
1
10
100
0.01
Optical
1.4–GHz
Ω_0=0.3; Ω_Λ=0.7
h=0.65
5×10^{12} $L_\odot$; 38K
250 micron
850 micron

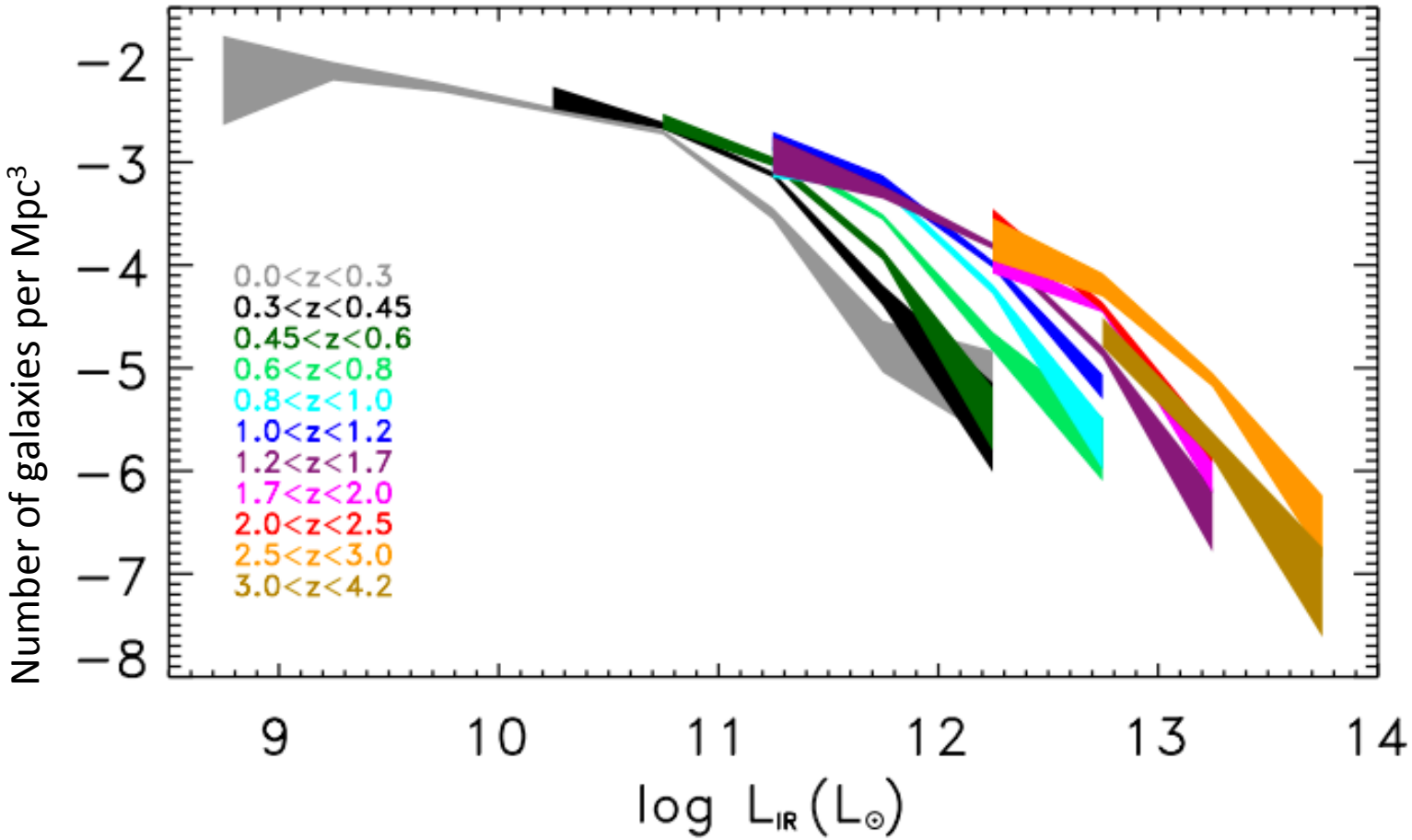
Blain 2002


Hubble Deep Field
SCUBA: 51 hours
H-ATLAS 16 hours

The cosmic evolution of ….

Evolution of obscured star formation

Evolution of the IR luminosity function from deep Herschel surveys



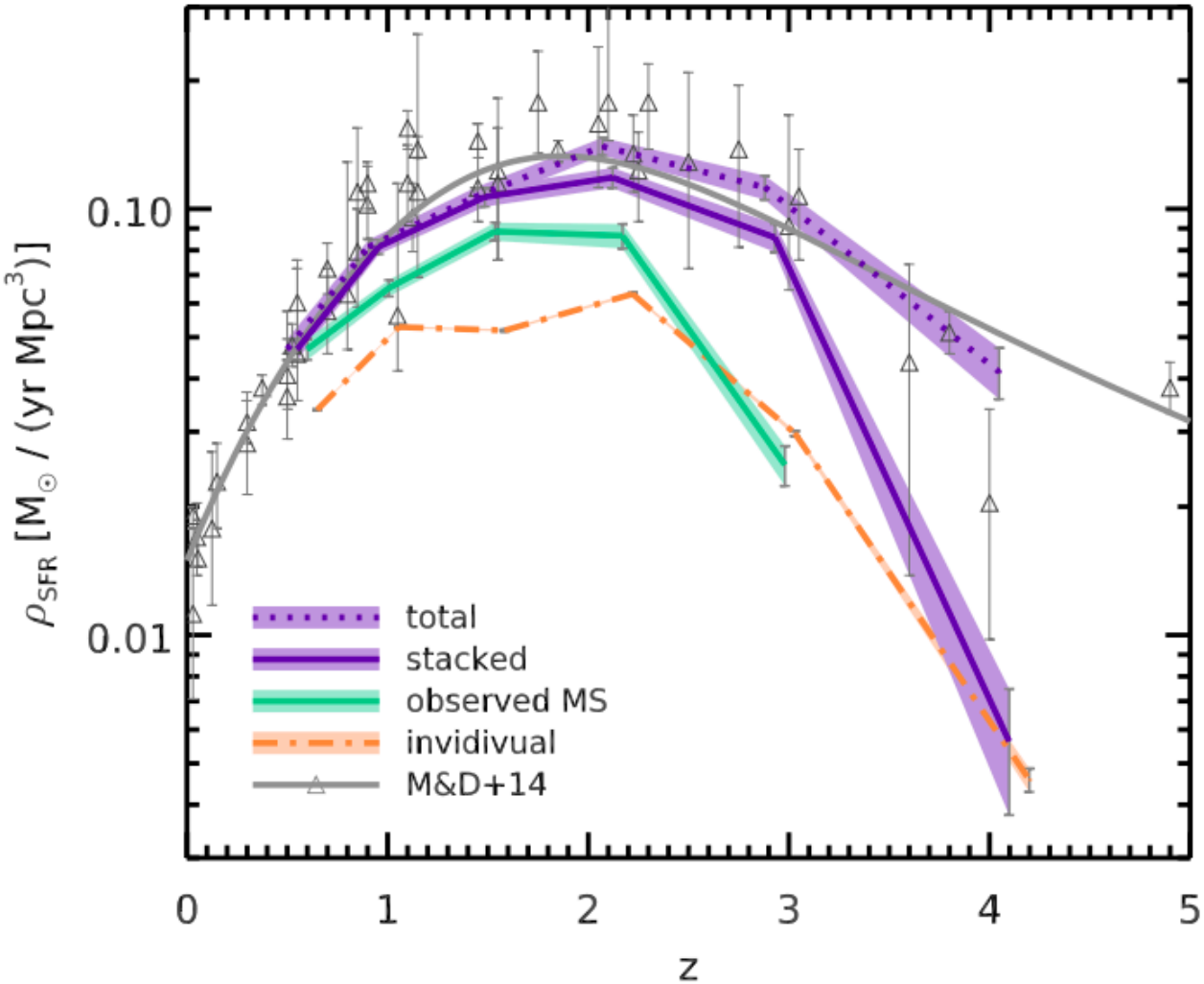
L_{IR} proportional to star formation rate

Gruppioni et al. 2013

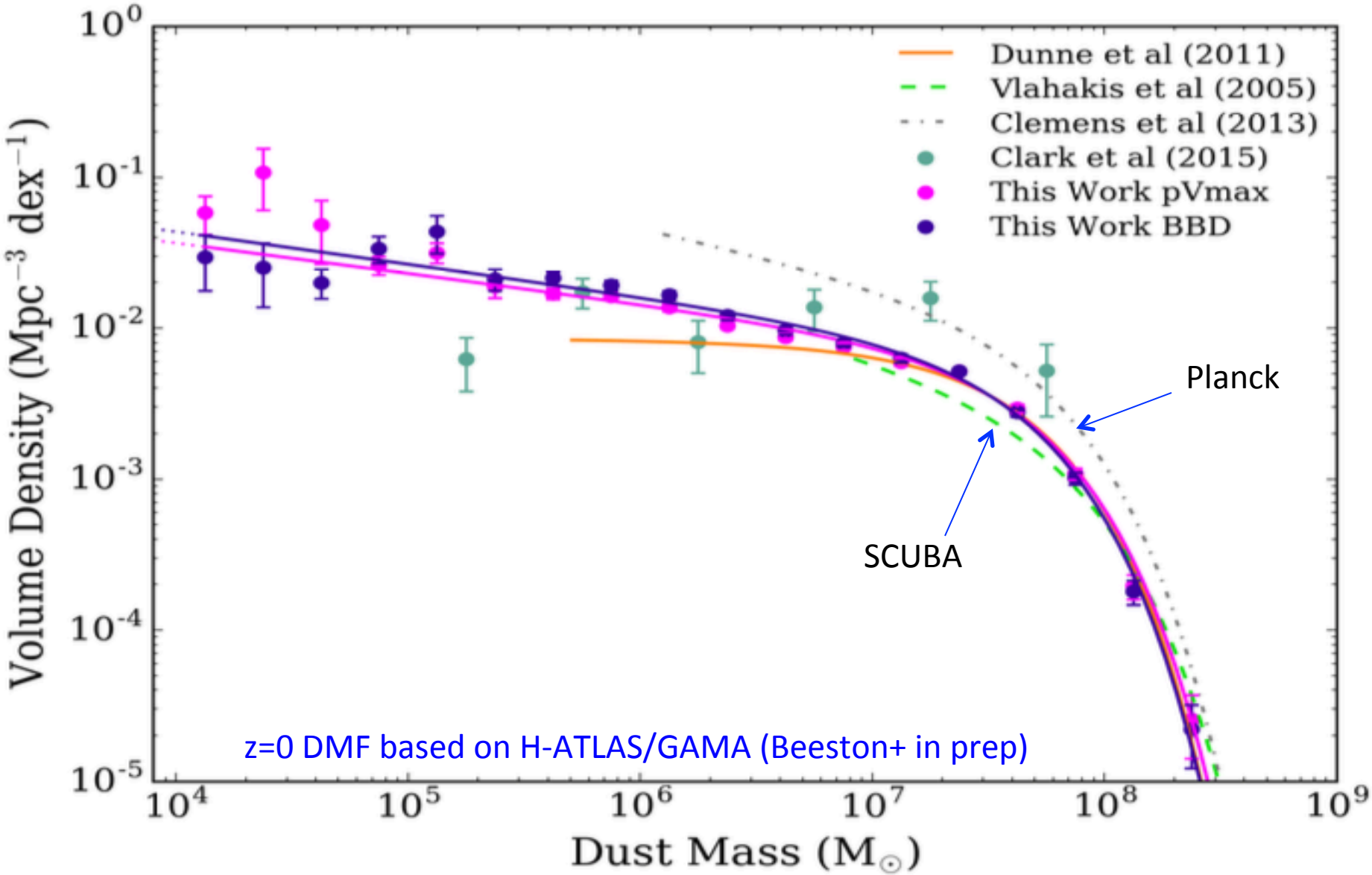
Cosmic SFRD

Stacking Herschel data
FIR individual detections
Schreiber+ 15

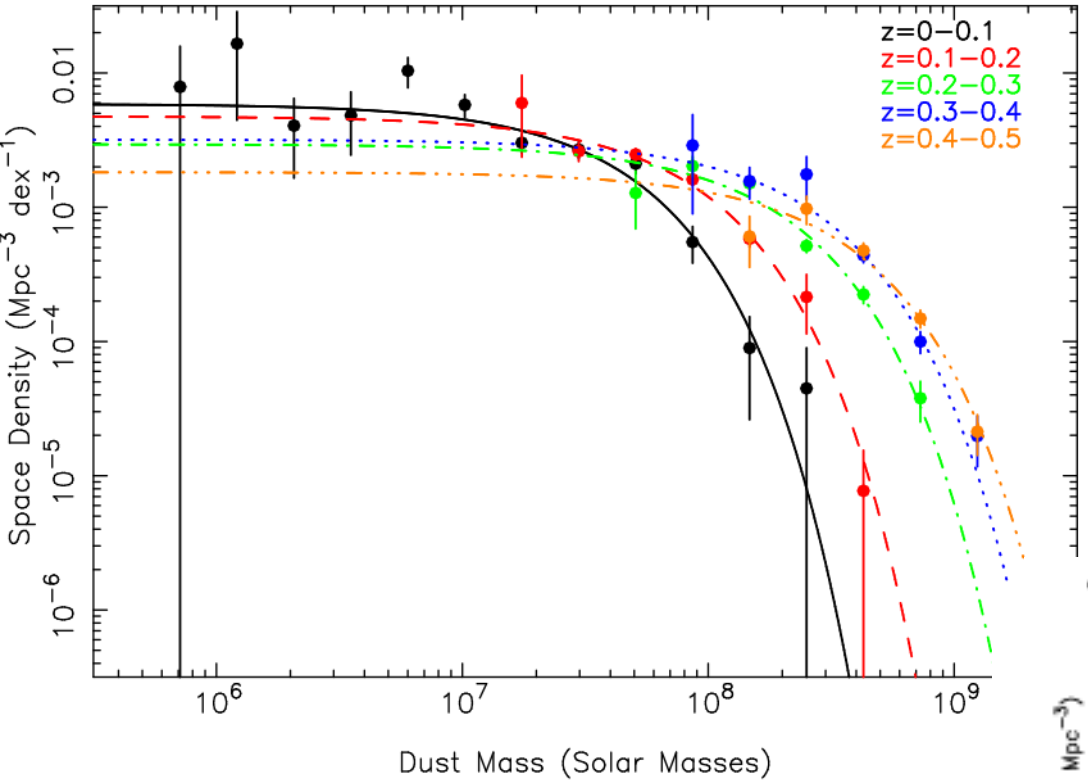
Herschel detections account for ~50% of all stars formed.



Evolution of dust and ISM



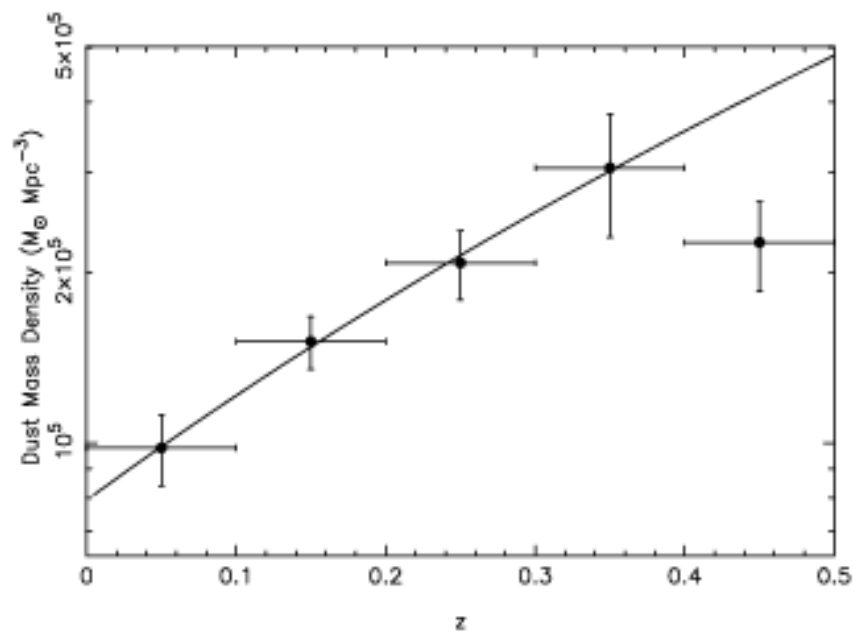
Evolution of dust and ISM



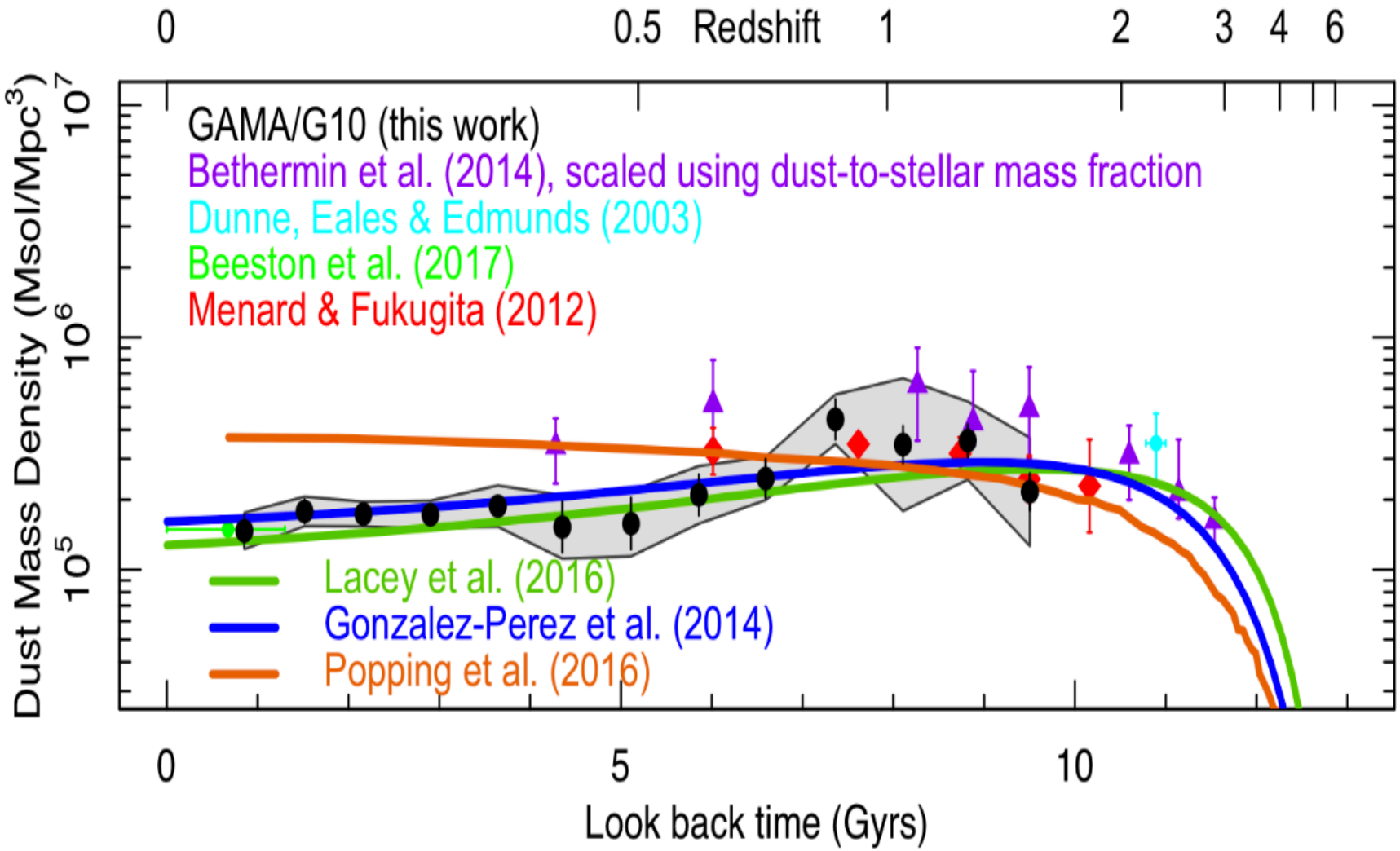
Strong evolution in dust mass function over past 4-5 billion years.

Galaxies more dust and gas rich at z=0.5

Dunne et al. 2011, Berta+ 13

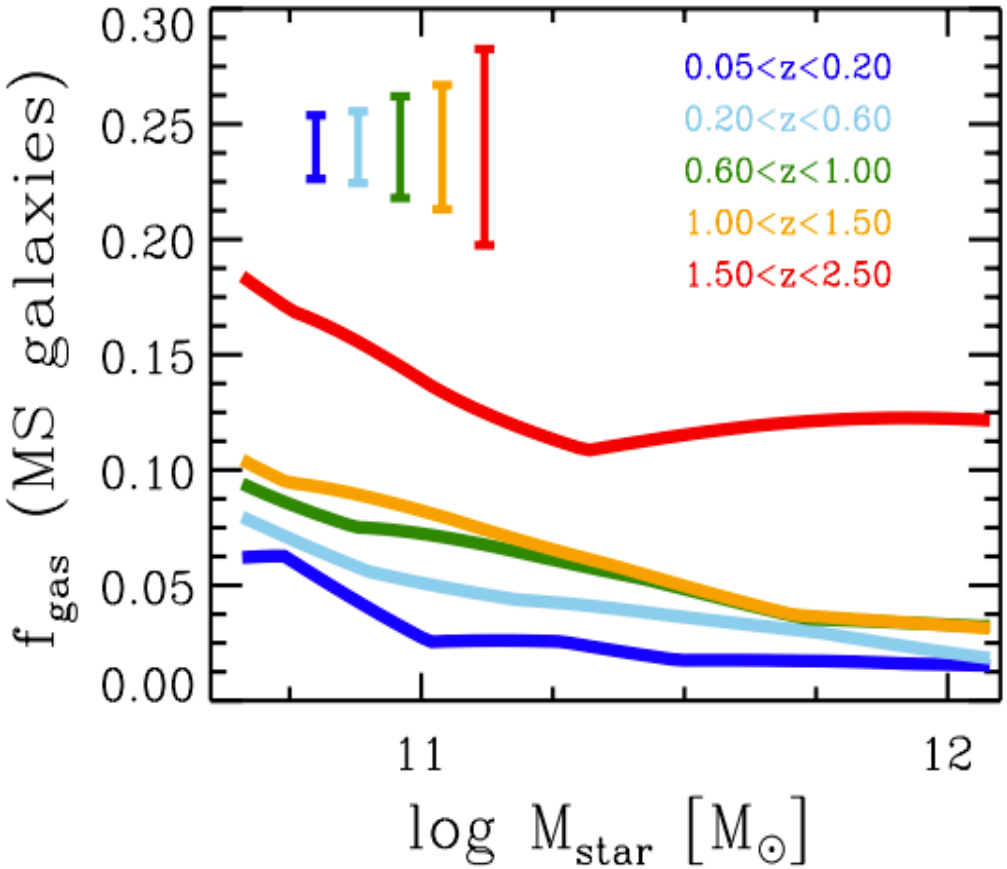


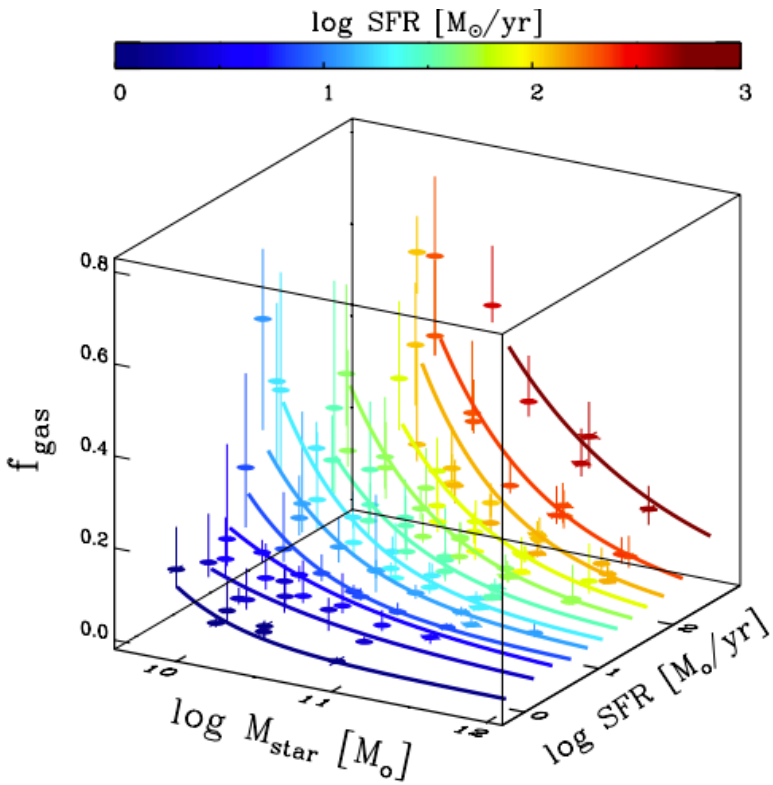
Driver+ submitted, using H-ATLAS, Hermes and MAGPHYS



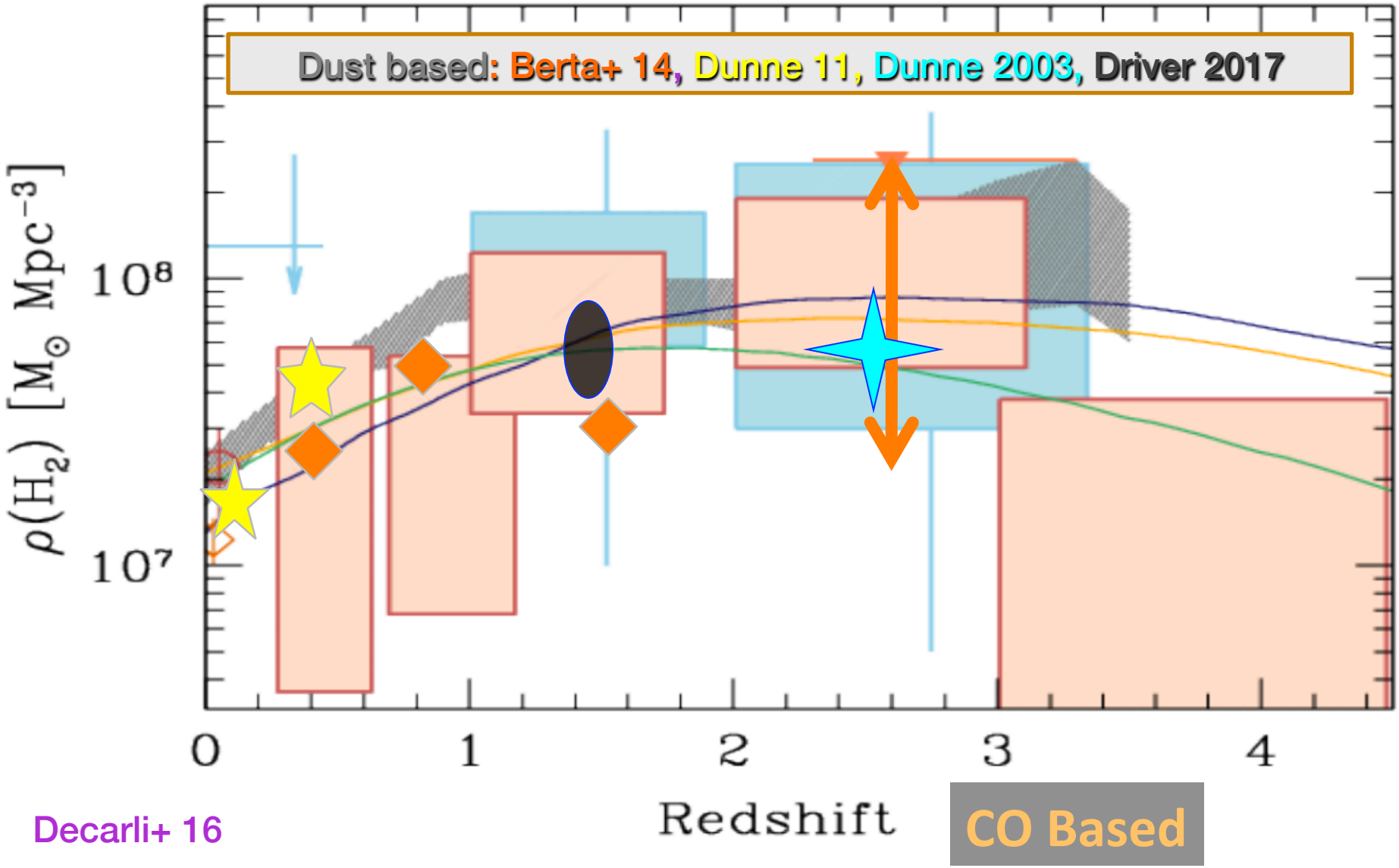
Dust as a tracer of gas

Using dust as a gas tracer, there appears to be a fundamental plane in fg-SFR-M*
Gas fraction increases with redshift (and decreases with stellar mass).





Santini+14 (see also deVis+2017, Rowlands+14, Genzel+15, Scoville+14,16,17)

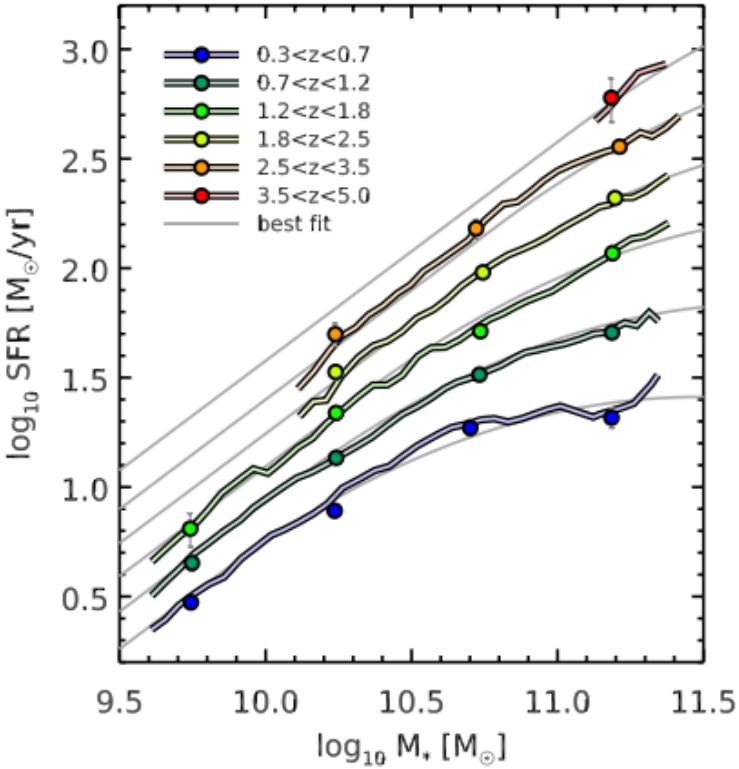

Dust based: Berta+ 14, Dunne 11, Dunne 2003, Driver 2017
$\rho(H_2)$ [$M_\odot$ Mpc^{-3}]
10^8
10^7
0
1
2
3
4
Redshift
CO Based
Obreschkow et al.(2009a,b)
Lagos et al.(2011)
Sargent et al.(2013)
Popping et al.(2014)
Keres et al.(2003)
Boselli et al.(2014)
Keating et al.(2016)
Walter et al.(2014)
ASPECS

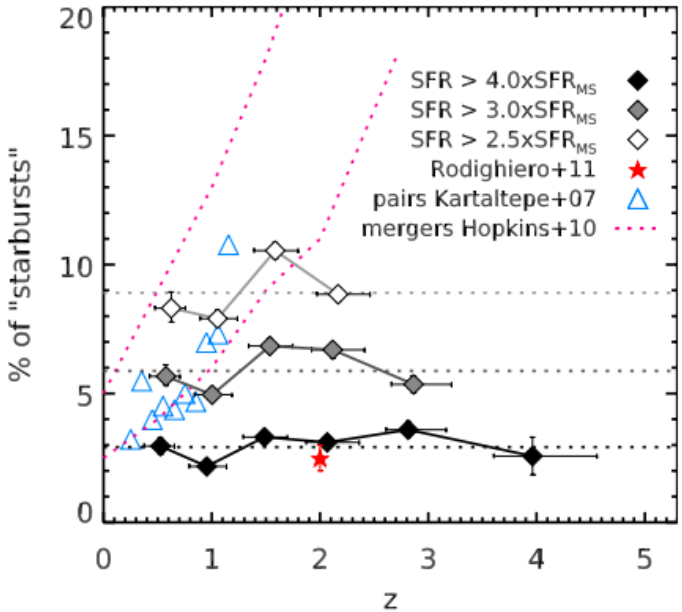
Decarli+ 16

Modes of star formation

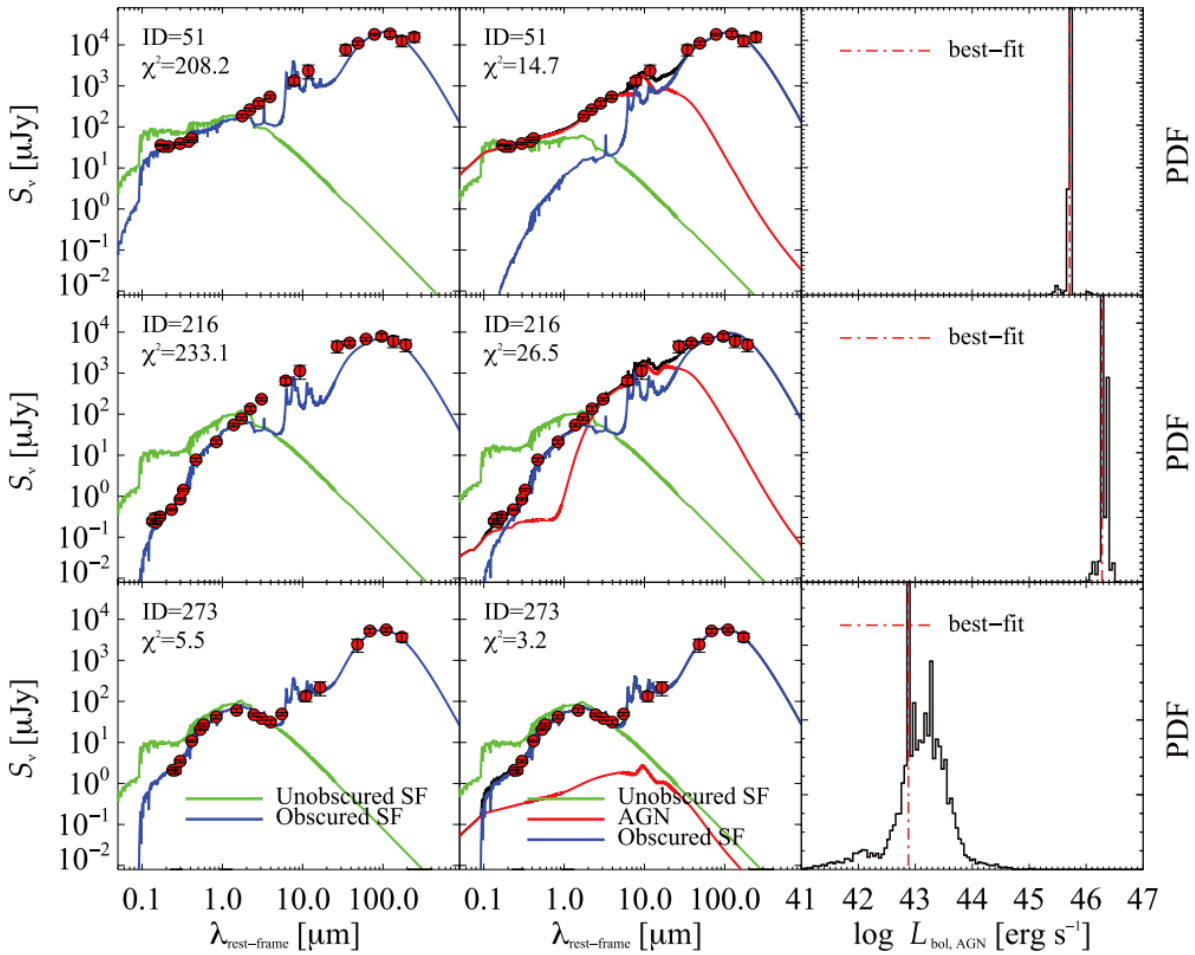
- Deepest Herschel surveys, and mass complete sample > 10.3 Msun
- sSFR continually rises with redshift
- 2/3 of stars formed in galaxies within 0.3 dex of these SFR/M* relations
- Fraction of starbursts does not evolve, even though merger rate predicted to.
- Starbursts are rare, and contribute ~15% to the SFR budget.

Schreiber+ 15, Bethermin+15, Sargent+12, Rodighiero+ 11, Elbaz+ 11





SF-AGN connection



FIR provides uncontaminated view of SF in AGN

<10% of moderate AGN hosted by starbursts

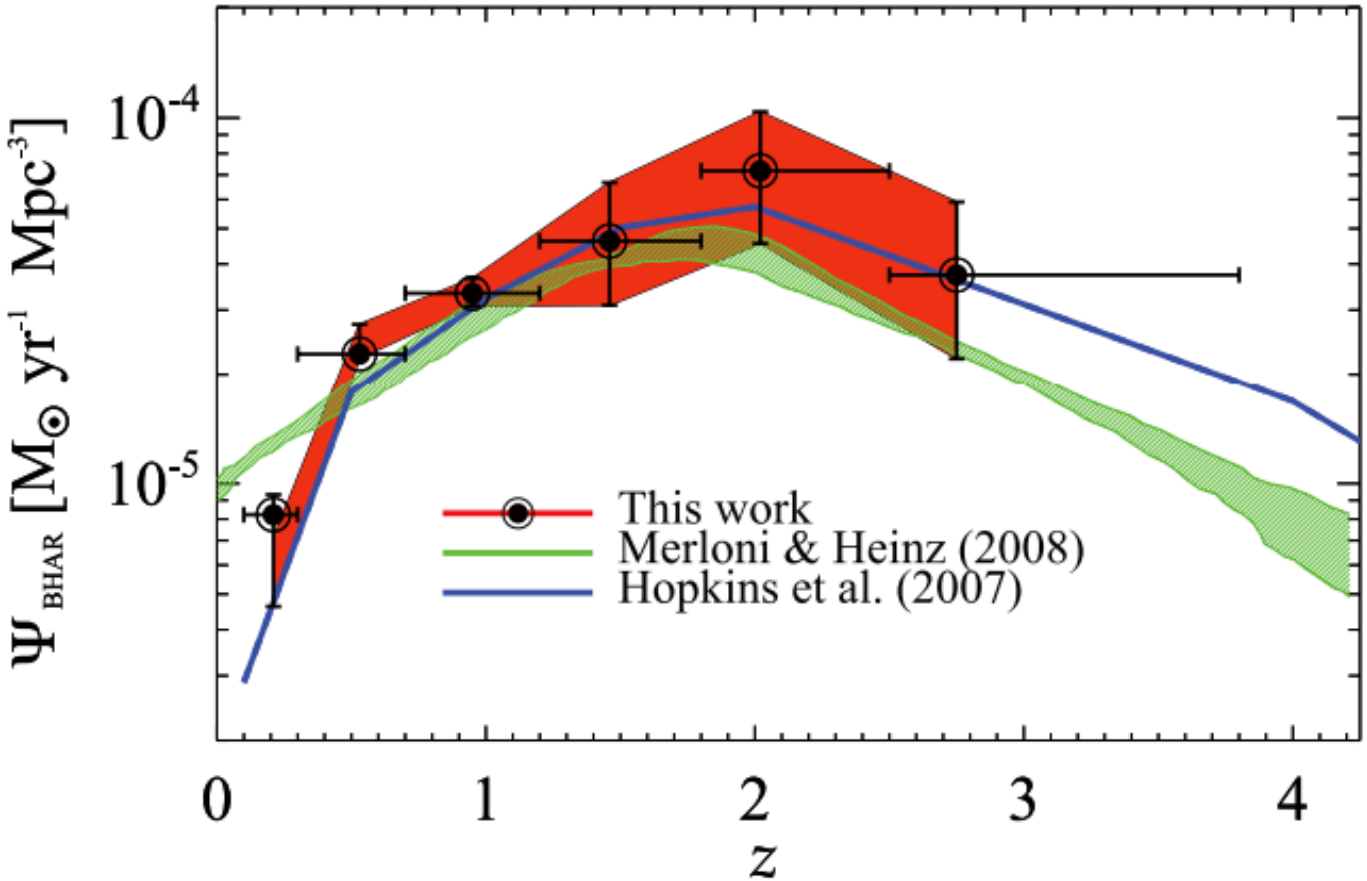
Fuelling of moderate AGN secular and not merger driven

Mullaney+ 12, Santini+ 12
Rosario+12

Now can use multi-wavelength fitting to determine probability of AGN

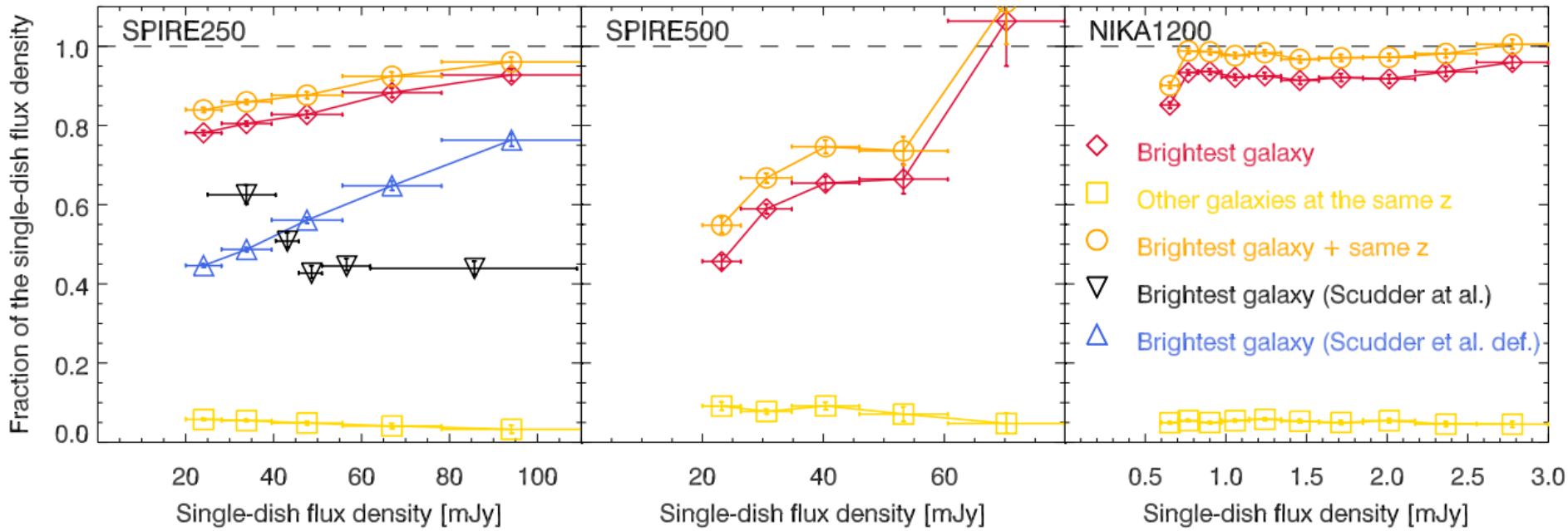
Delvecchio+14

Evolution of black hole accretion



Delvecchio+14

Effects of angular resolution



Herschel sources often found to be multiples at higher angular resolution

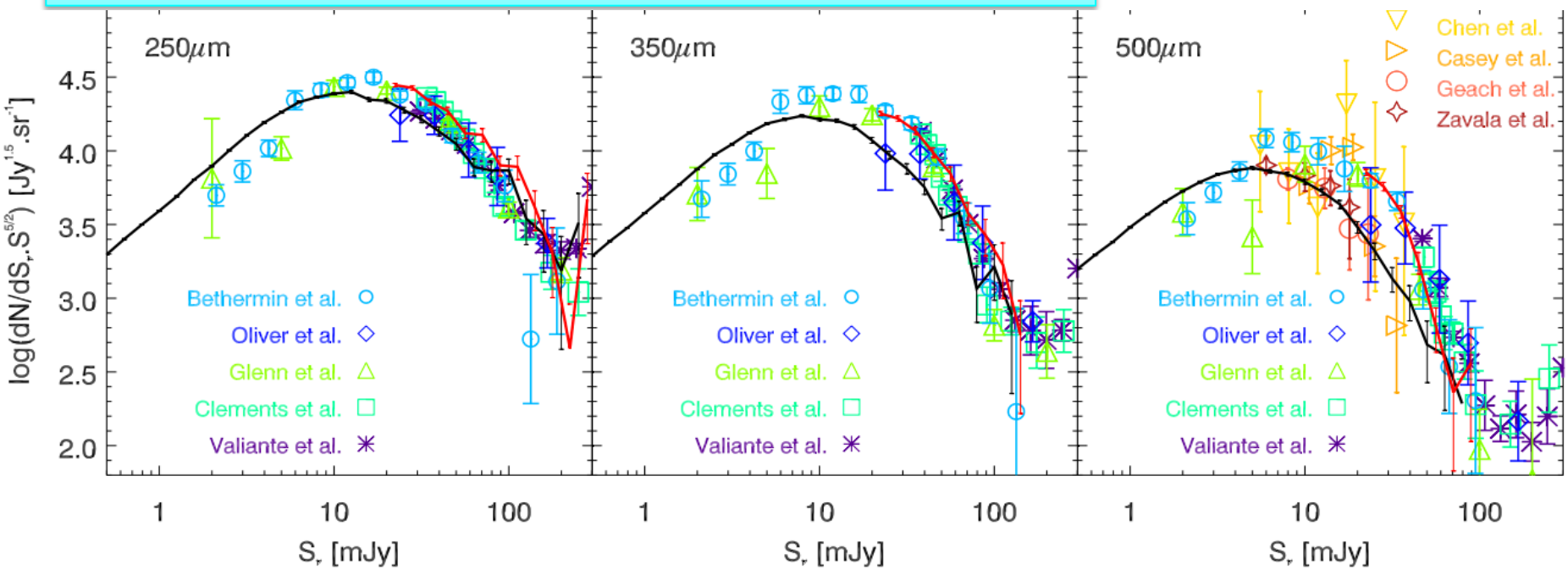
Stacking analyses need to take into account clustering (e.g. Bourne+11, Schreiber+ 15)

Clustering also affects P(D) analyses and must be accounted for at 350/500 micron

Number counts are overestimated by as much as x2 at 500 mic for S=5-50mJy.

Bethermin+ 17, Karim+ 13, Hodge+ 13

Effects of angular resolution



Herschel sources often found to be multiples at higher angular resolution

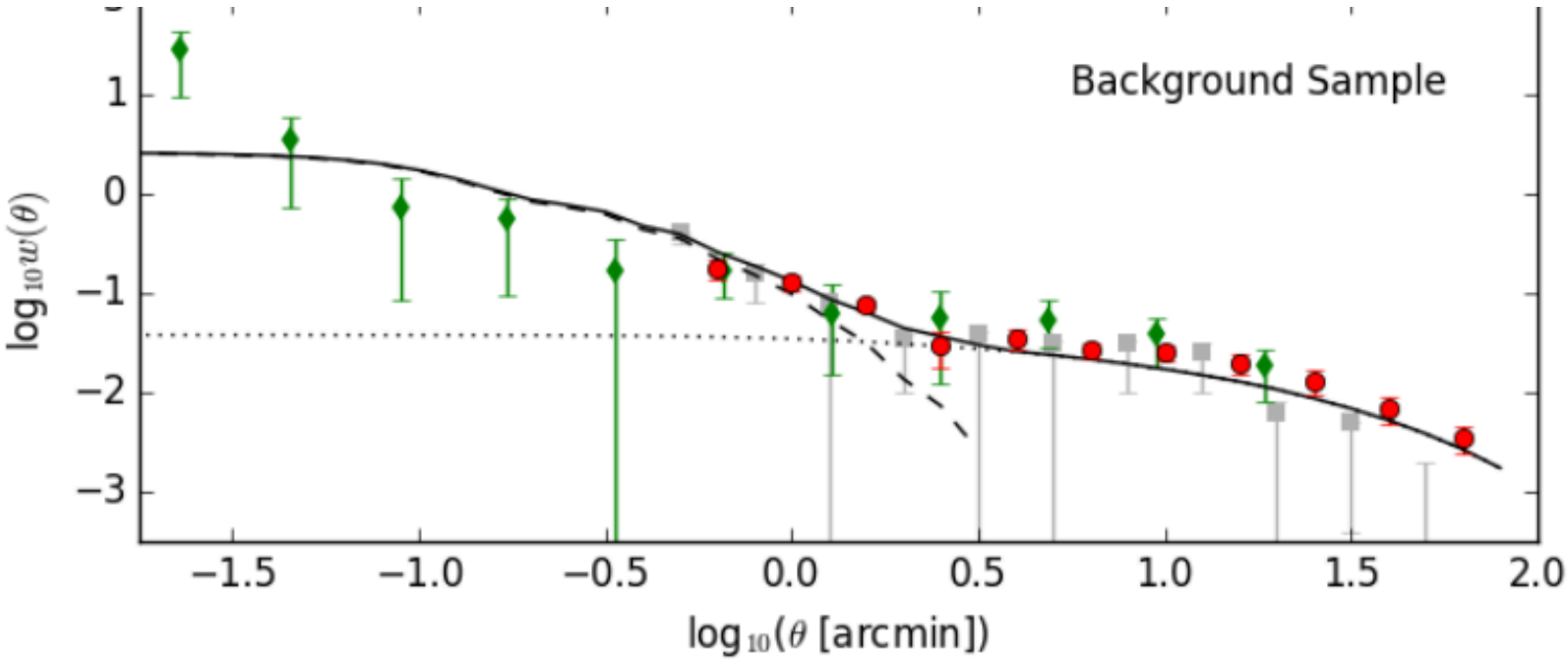
Stacking analyses need to take into account clustering (e.g. Bourne+11, Schreiber+ 15)

Clustering also affects P(D) analyses and must be accounted for at 350/500 micron

Number counts are overestimated by as much as x2 at 500 mic for S=5-50mJy.

Bethermin+ 17, Karim+ 13, Hodge+ 13

Clustering of Herschel galaxies



H-ATLAS angular correlation function for 1.2 < z < 4.

Similar to clustering of faint SMG at 2<z<3.

M_{min} = 12.23, M1=12.85, alpha=1.35

Gonzalez-Nuevo in prep, GN14, Chen+16, Cooray+10, Maddox+10

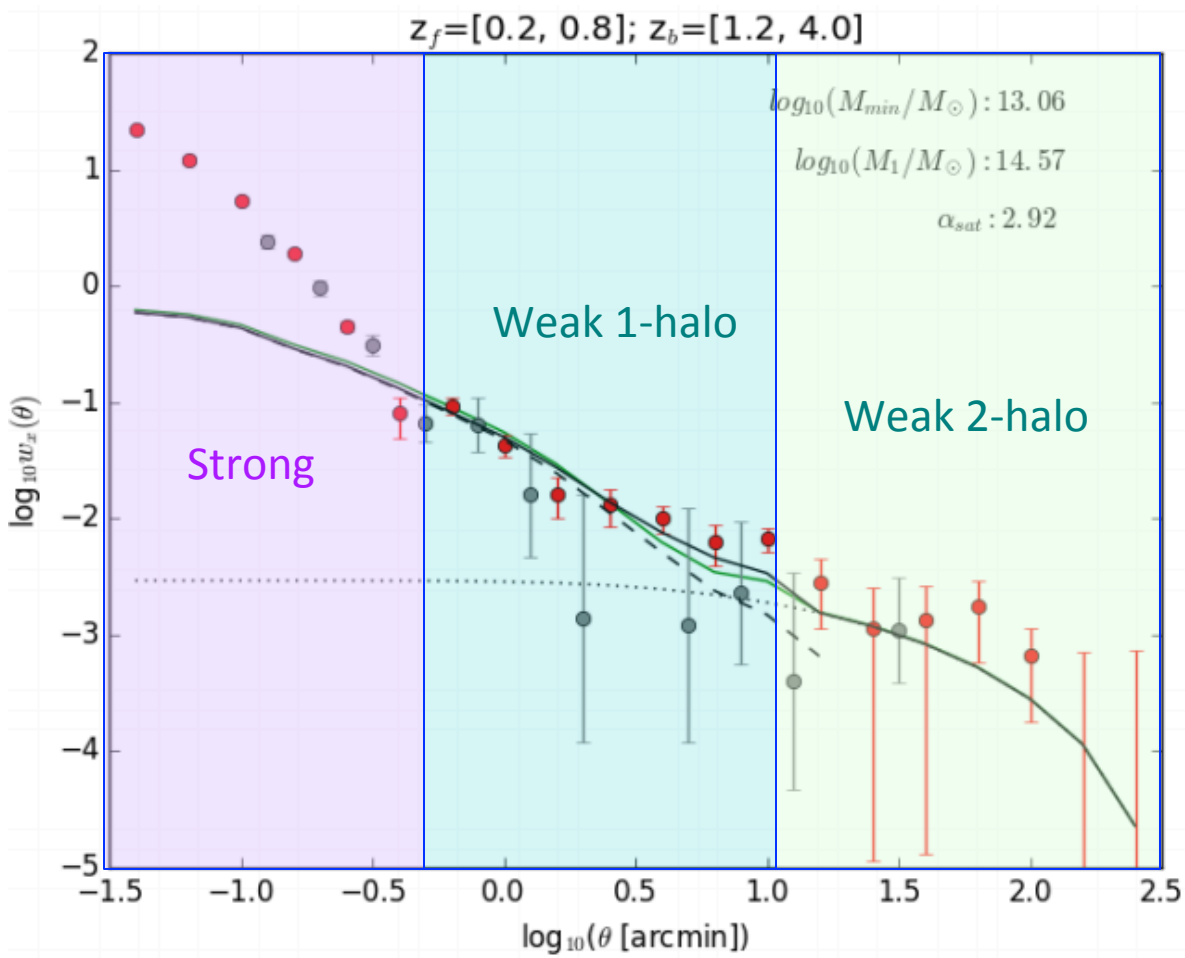
Effects of foreground structure on studies of high-z submm sources

Cross correlation between high-z Herschel sources and low-z GAMA sources.

Lensing is produced only by the most massive halos in the foreground sample

Such massive halos host massive galaxies, and these produce the strong lensing effect out to 30”

Has a direct impact on X-ID



Gonzalez-Nuevo in prep, GN14, Bourne+14

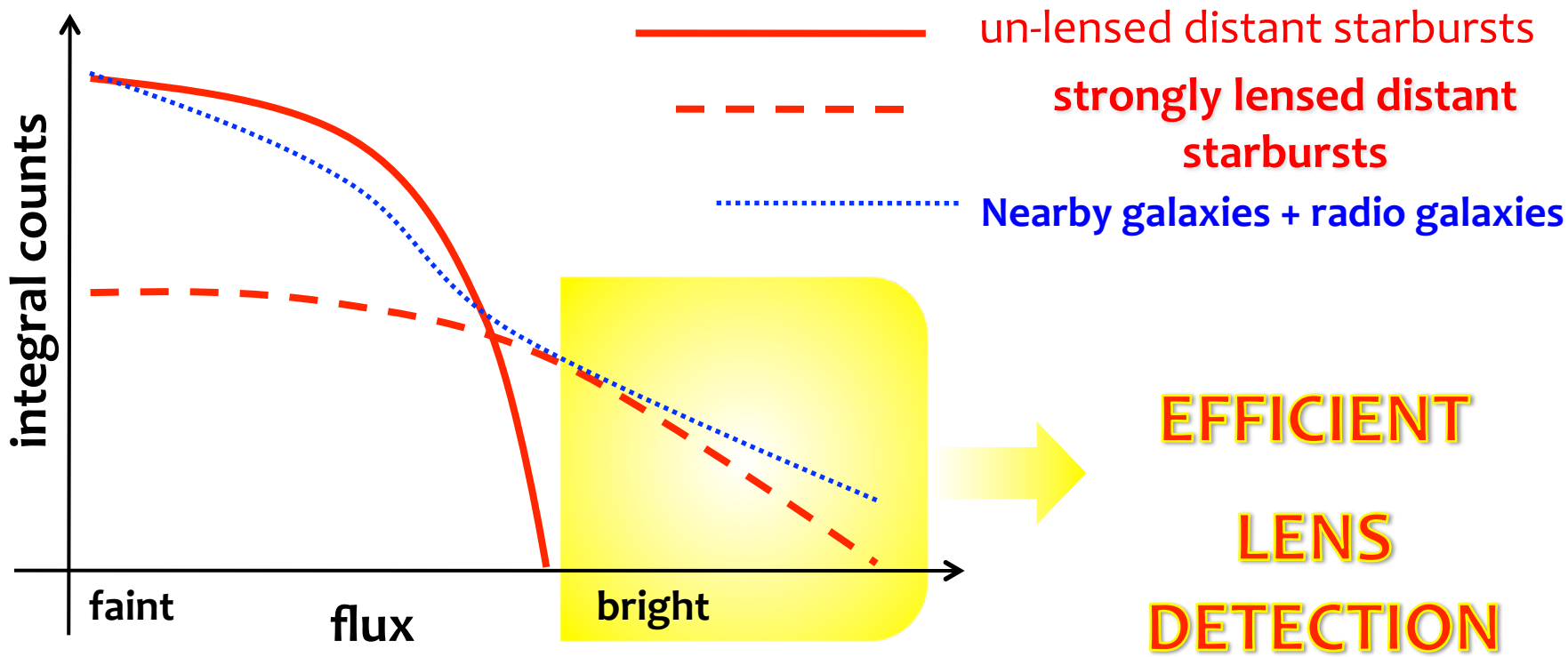
Zooming in on the highest redshift starbursts

Finding Gravitational Lenses with Herschel

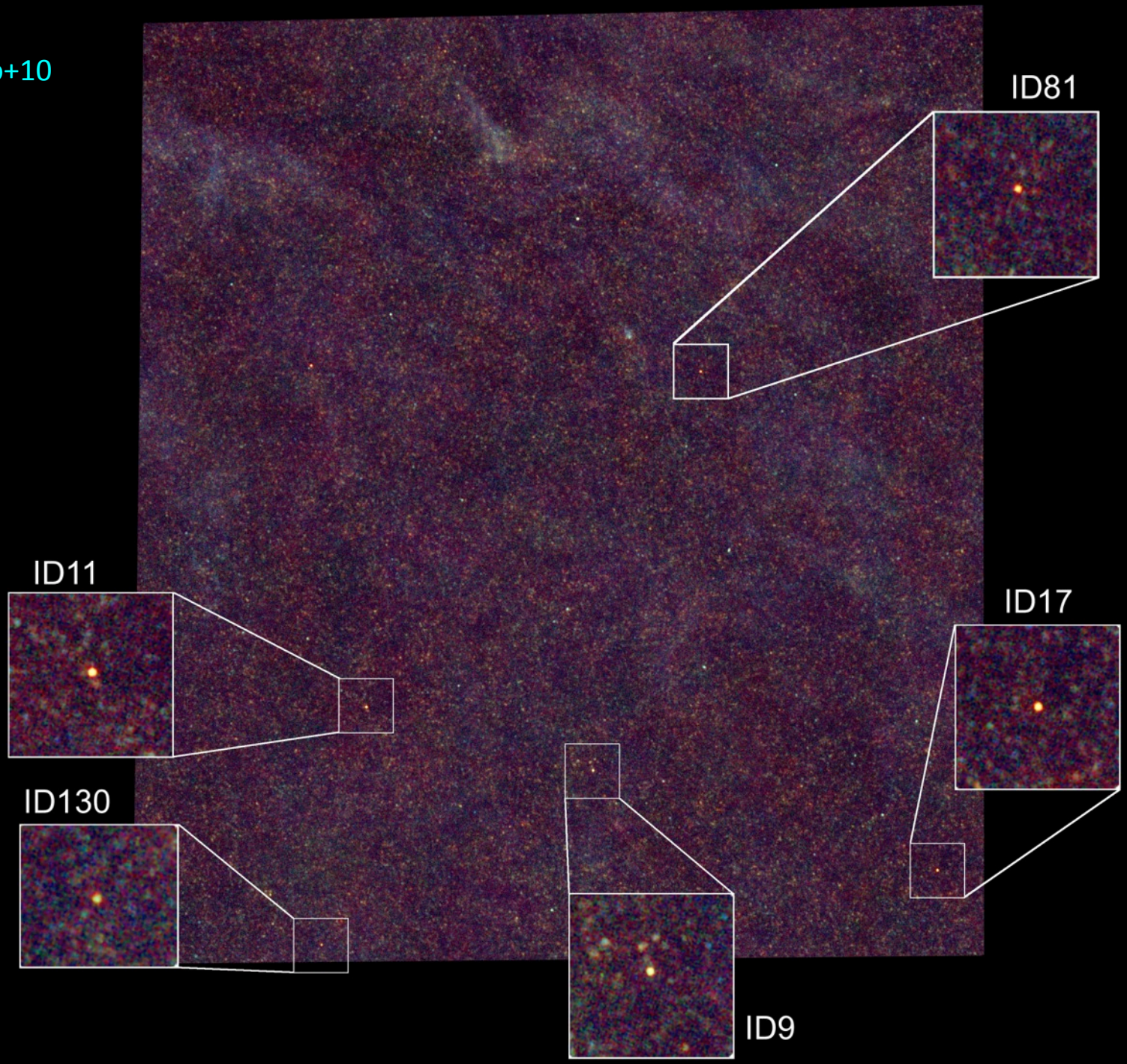
Sub-mm surveys are ideal for finding lenses

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

- **high redshift** → **high efficiency for lensing**
  Chapman et al. (2005)
- **steep counts** → **strong *magnification bias***
  Coppin et al. (2006

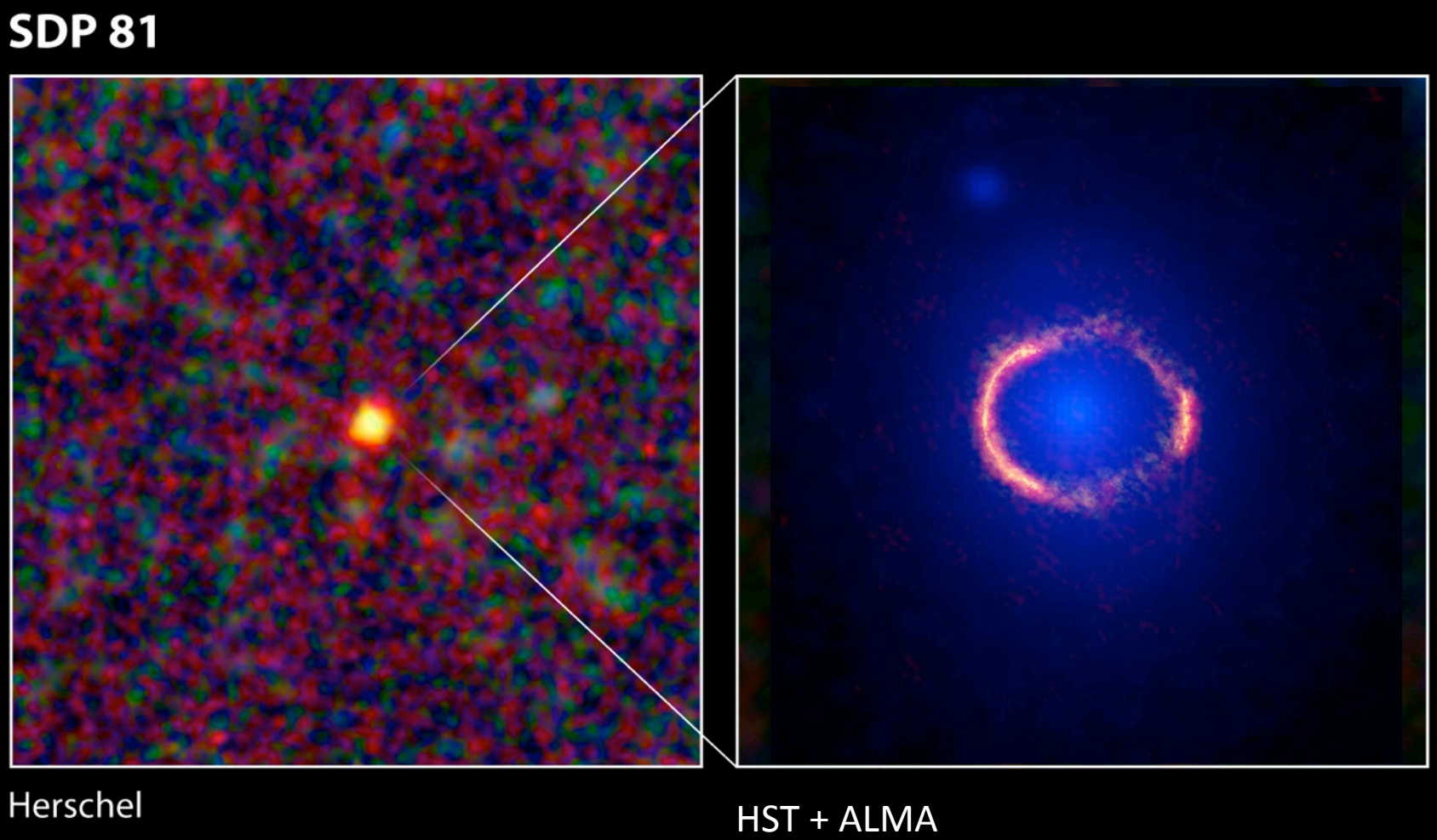


Negrello+10



Negrello+10, Vlahakis (ALMA) 15

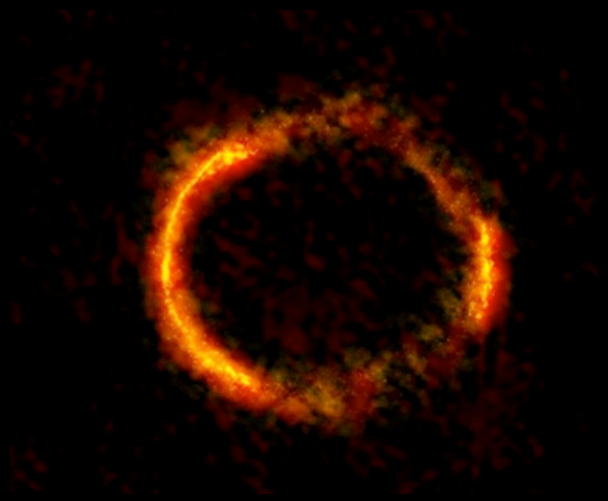
Gravitational Lensing



Foreground elliptical galaxy lens (optical) background distant starburst galaxy (FIR)

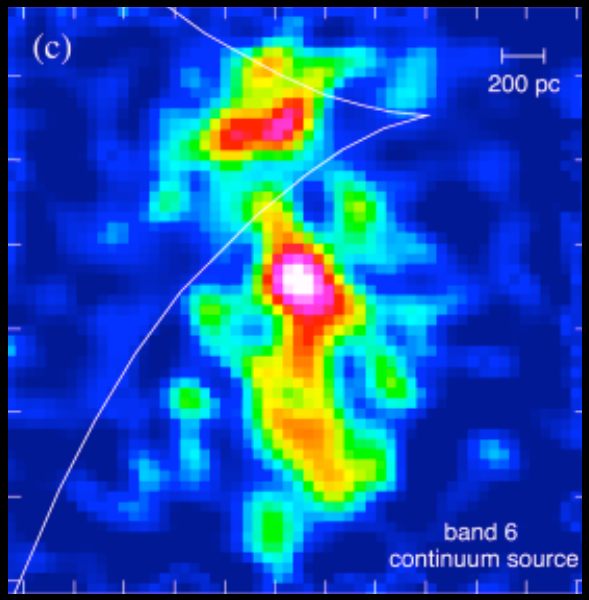
Collapsing turbulent disks

This is the same lensed galaxy with ALMA, now at ~200pc resolution at z~3



ALMA consortium+ 2015

Imaging of H-ATLAS ID81



Dye+ 2015, reconstruction of lensed source

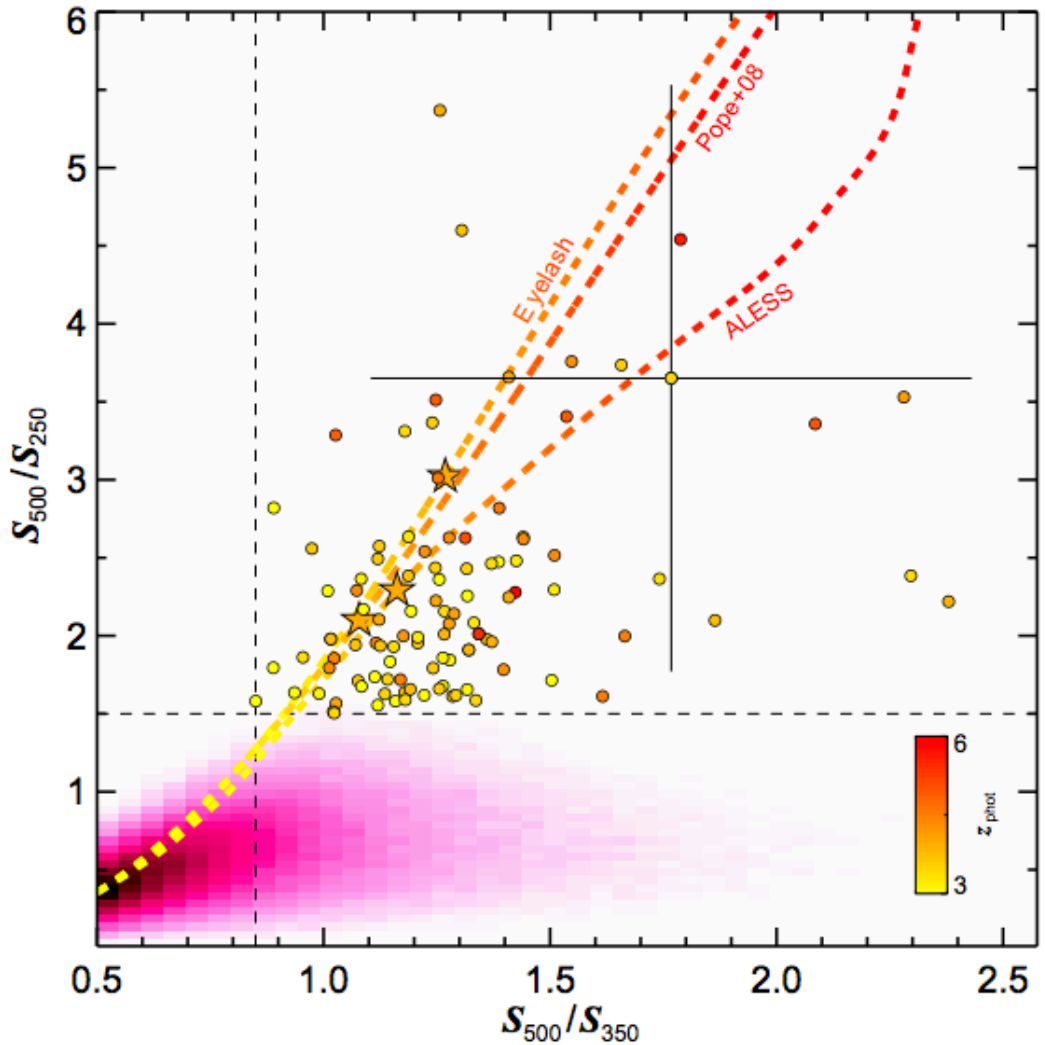
SFR ~ 500 Msun/yr, gas surface density ~ 5000 Msun pc^{-2}
Toomre Q ~ 0.3 -- unstable disk
SFE 60x greater than in local Universe
High pressure ISM (x10^4 MW), SF clouds at high-z more similar to those in Galactic centre

also Swinbank+15 Riechers+13,Ivison+13,Rawle+14, Huynh+13, Hezaveh+2013

The birth of the red sequence ?

Finding extreme starbursts at z > 4 can help pin down the origins of the red sequence which was already in place at z~2

Use colour selection with SPIRE to select 'ultra-red' objects (Dowell+14, Asboth +16, Ivison+16) from wide area Herschel surveys (Hermes, HELMS and H-ATLAS)

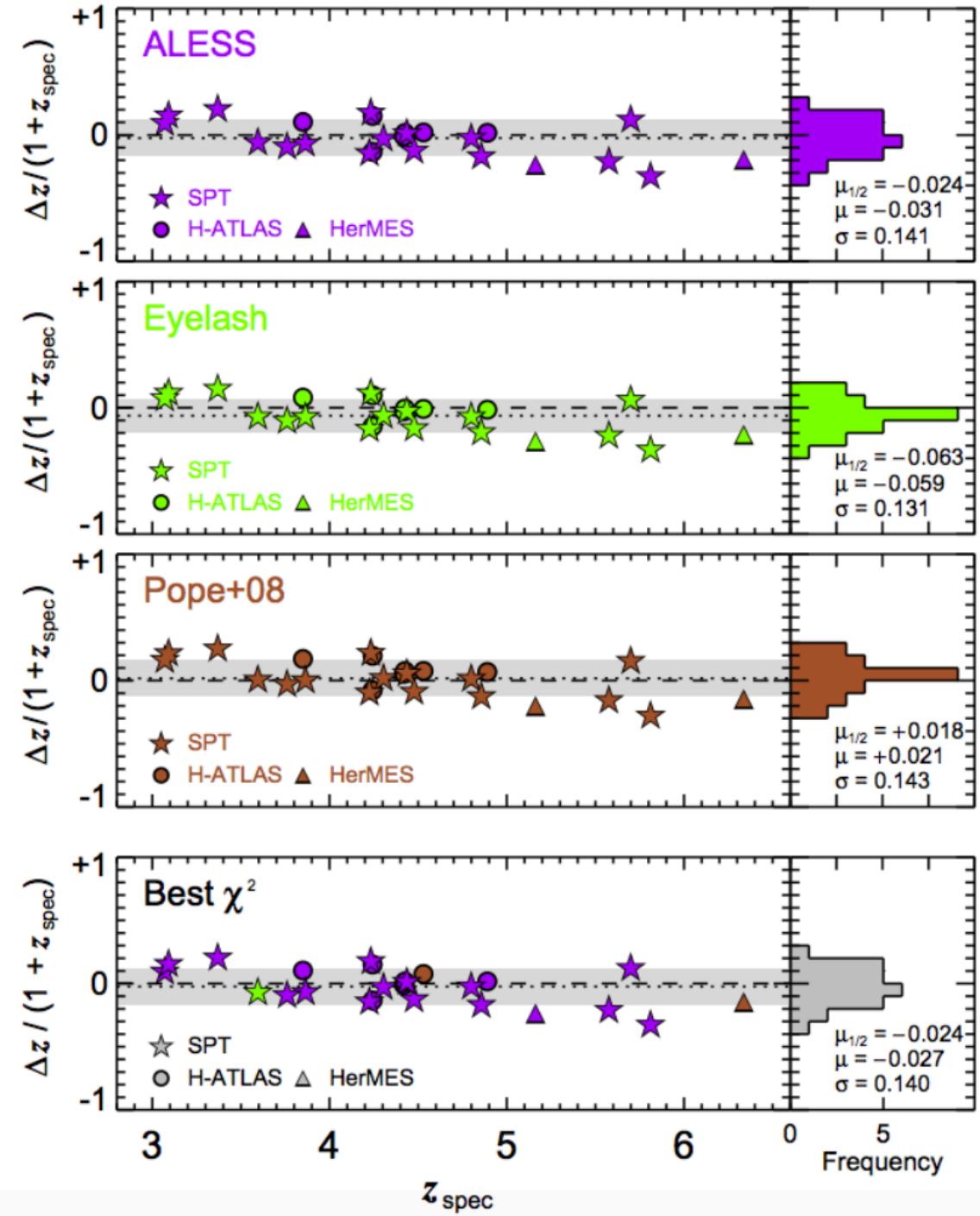


N(z) for ultra-red Herschel sources

Common SMG SED templates are good predictors for UR

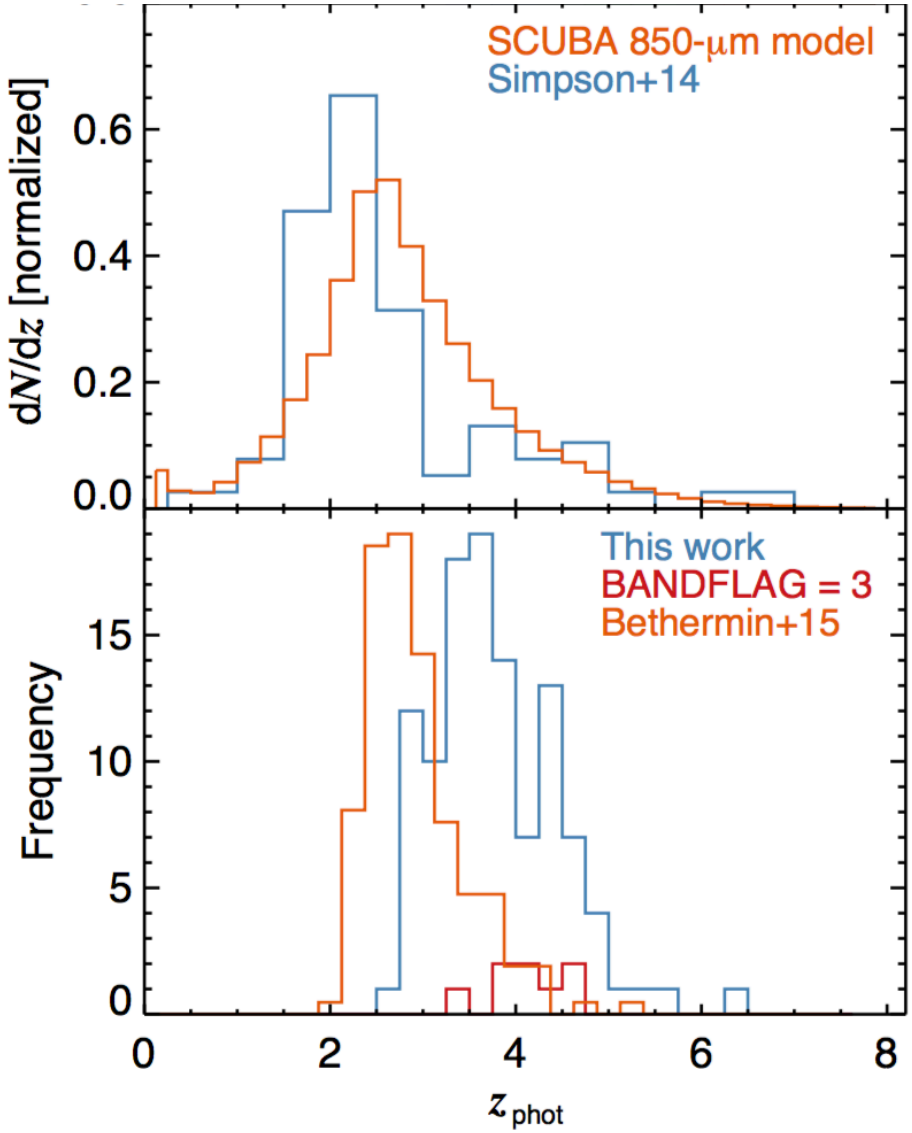
Trend with redshift possibly indicates Td evolution of ~7K from z=2-6

Original Herschel UR selection produces samples with 1/3 at z > 4



Ivison+ 16, Fudamoto+ 17, Zavala in prep.

Statistics of the UR Herschel sources



Extremely luminous, with $L>10^{13}$ L_{sun} at z>4

Space density ~ 6 x 10^{-7} Mpc^{-3} with 100 Myr duty cycle. VERY RARE.

10-30x too low to produce observed red sequence at z~3-4 (Straatman 2014)

N(z) significantly different to models

Fraction of lensed sources predicted to be high for S_{500} > 30 mJy **and** z>4.

Ivison+ 16

Nature of the UR Herschel sources

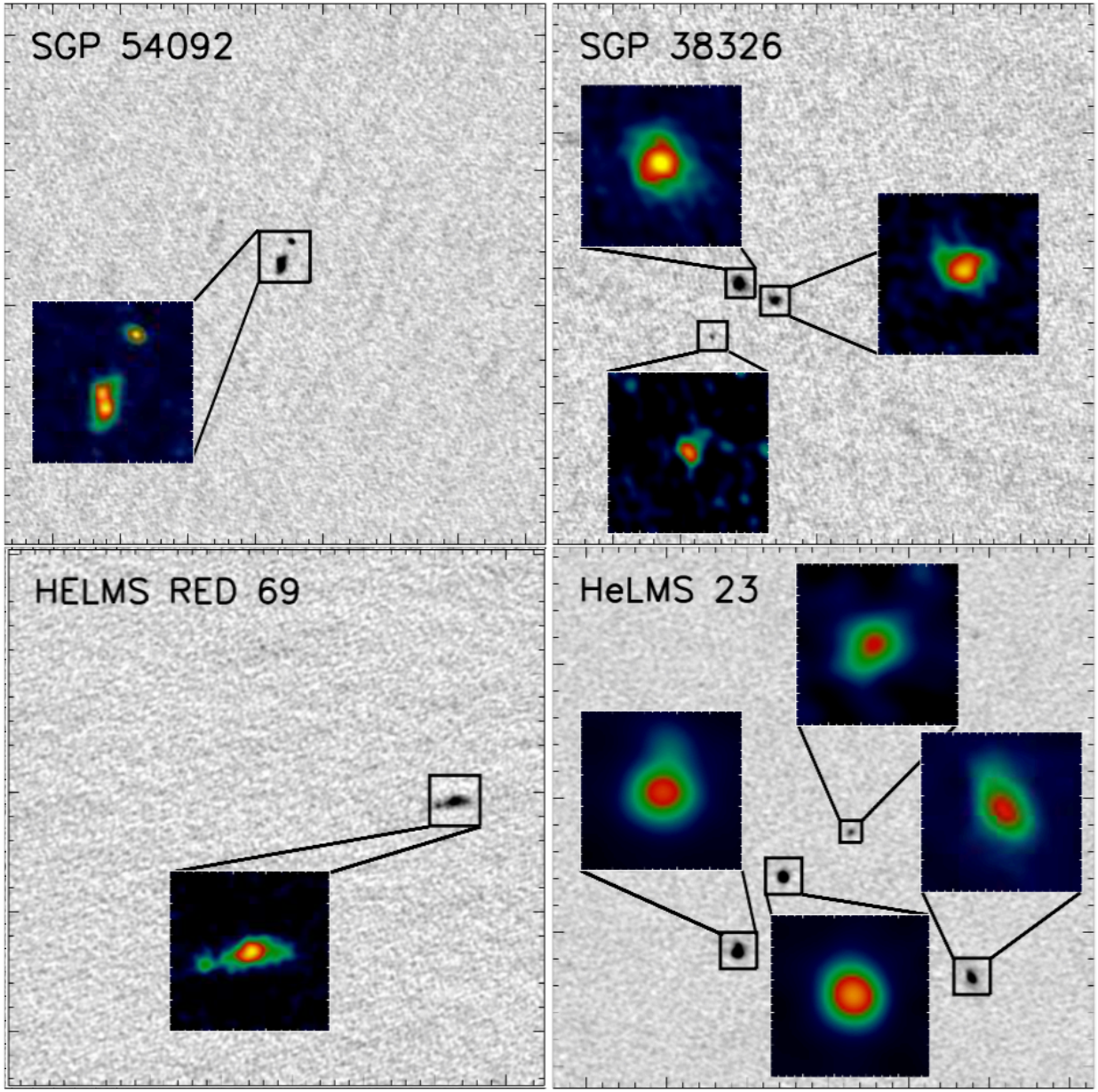
High res imaging with ALMA

~40% lensed

Mix of morphology – merger, Isolated disk.

Small size compared to lower z SMG (av. 1.5 kpc)

Many are Eddington limited starbursts and several with SFR > 1000 Msun/yr



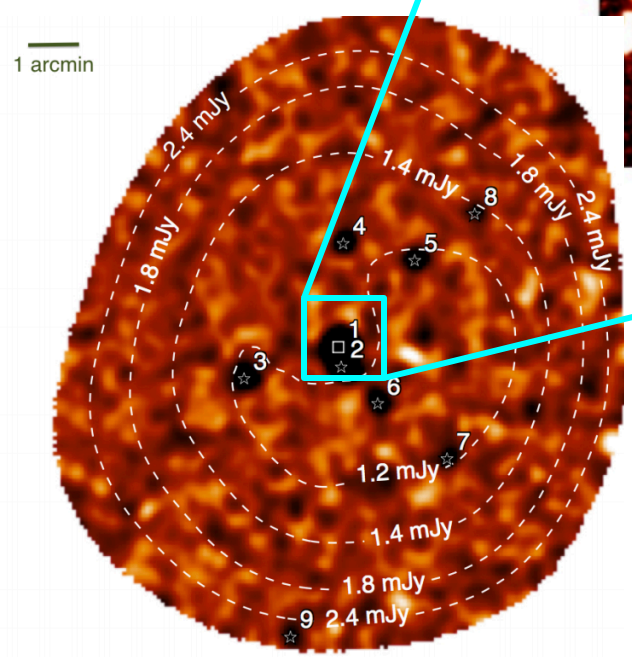
Oteo+ in prep, Oteo+ 16
Asboth+16, Ivison+16

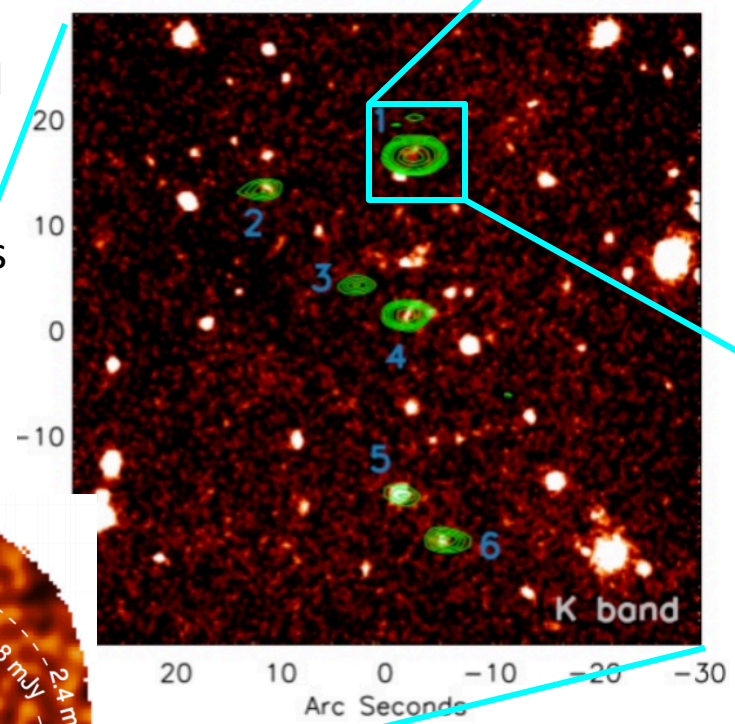
The most ‘happening’ place in the Universe:

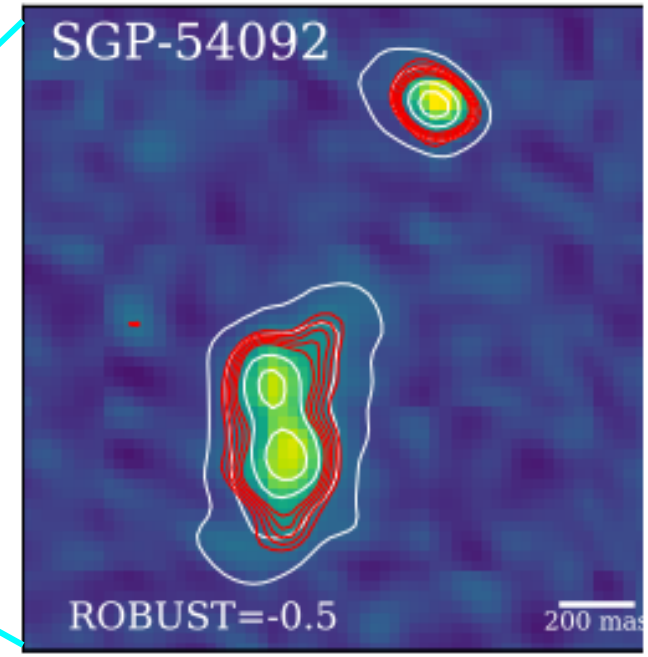
Proto-cluster at z=4 with total inferred SFR of >8500 Msun/yr.

Overdensity on several arcmin scales.

Dozens of synchronous starbursts and one flat spectrum radio AGN.







GRH = Great Red Hope
Oteo in prep

Summary

Herschel's key strengths were in producing huge statistical samples of FIR sources across a wide area and redshift range.

Herschel combined with multi-wavelength data has provided:

- Cosmic evolution of total SFRD.
- Cosmic evolution of dust/gas density
- Evolution of black hole accretion

Herschel also allows study of rare populations through very wide area surveys:

Strong lenses to study distant SF galaxies in exquisite detail

The most powerful starbursts in the Universe at $z > 4$

Beware the effects of angular resolution in Herschel studies