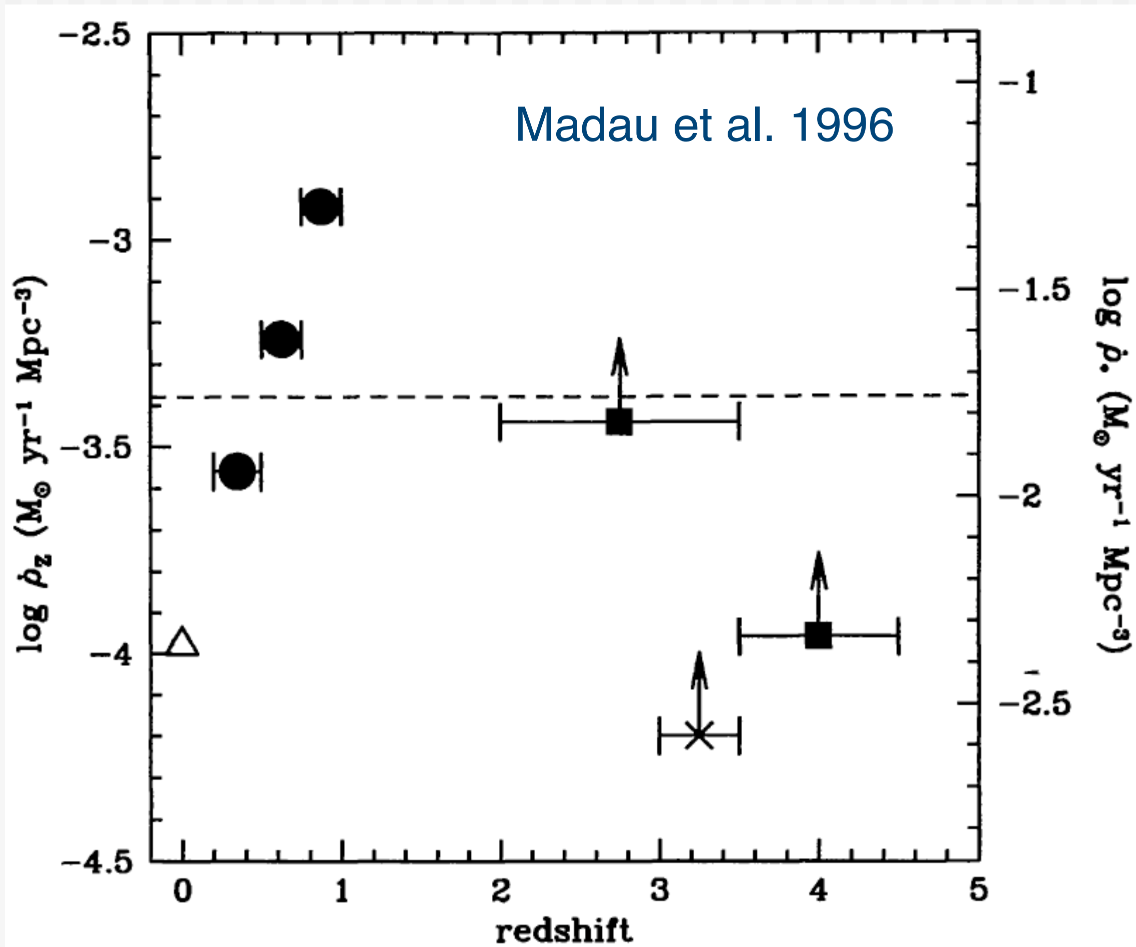
The History of Star Formation

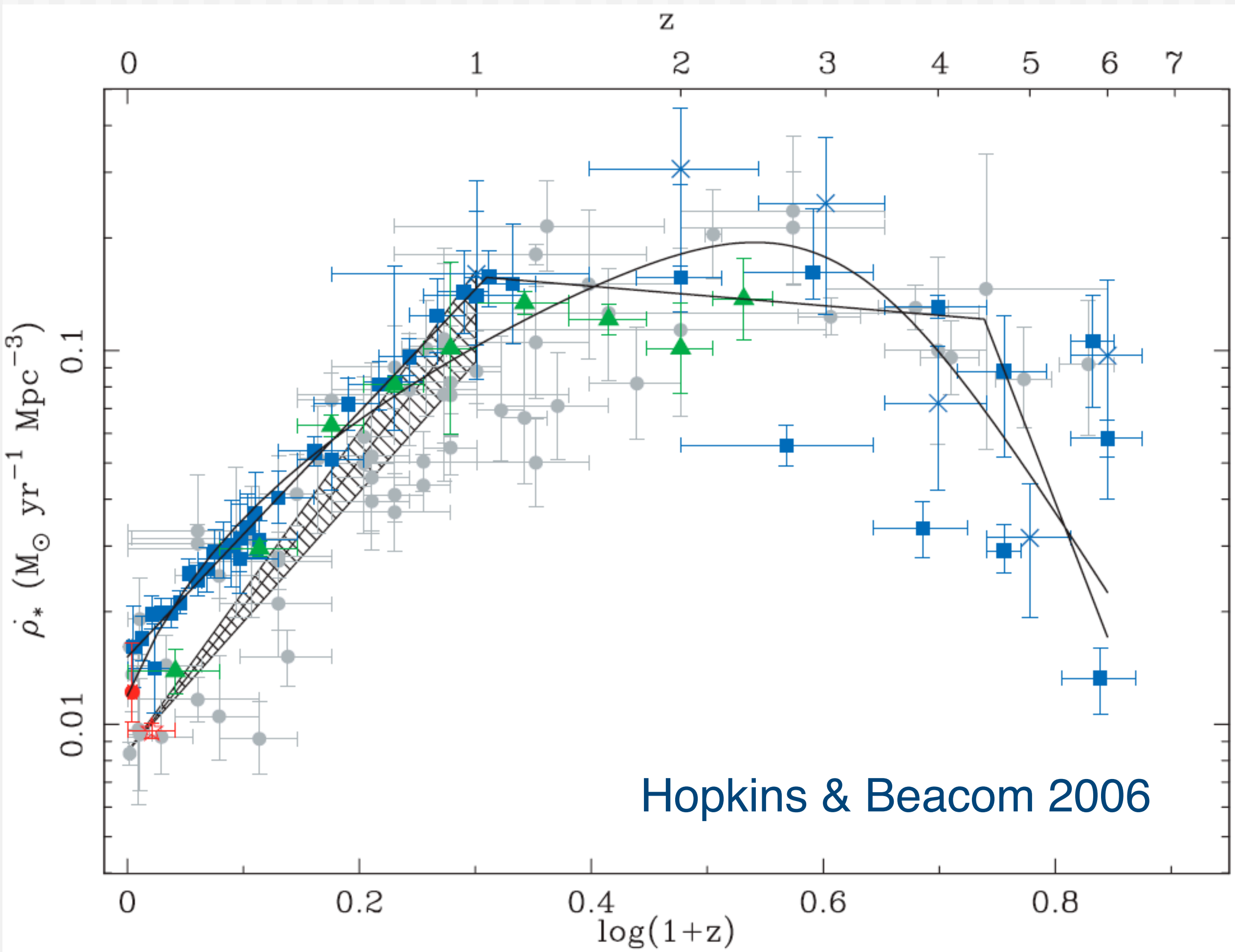
Mark Dickinson, NOAO

Star formation rate vs. redshift

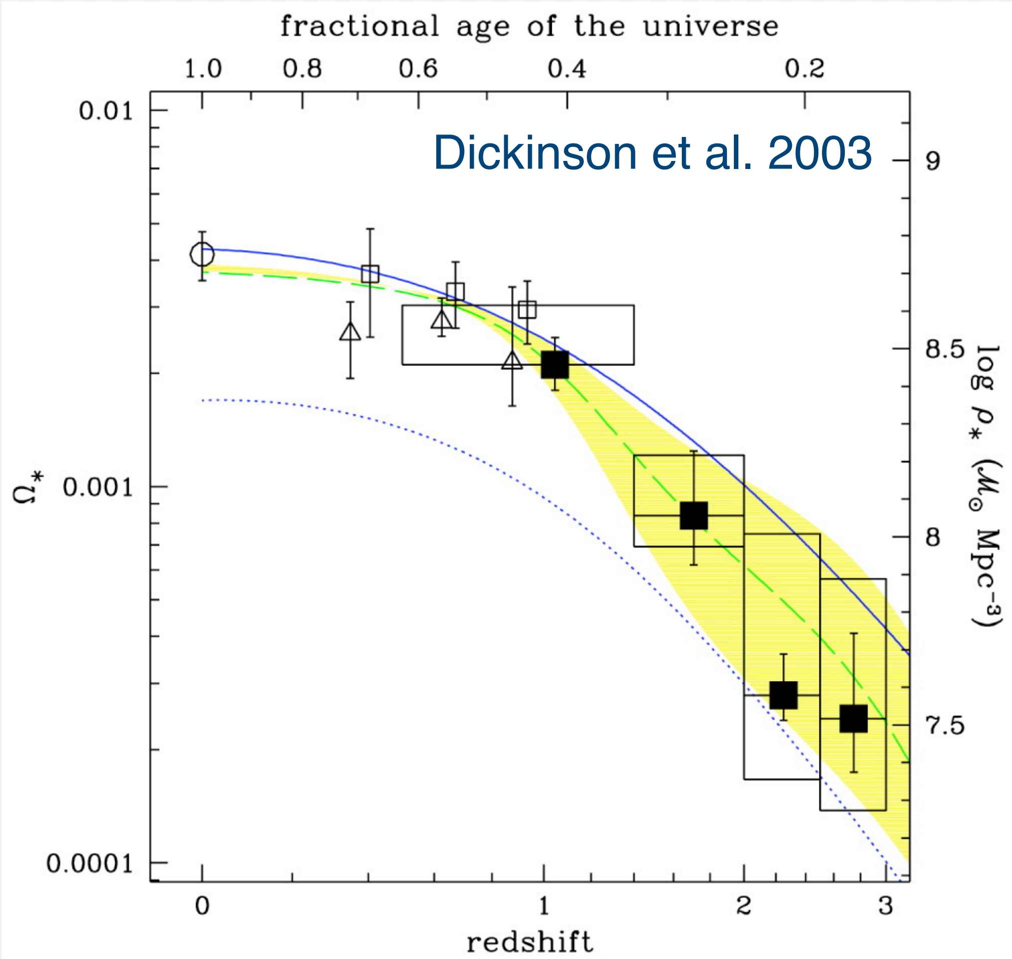


Hopkins & Beacom 2

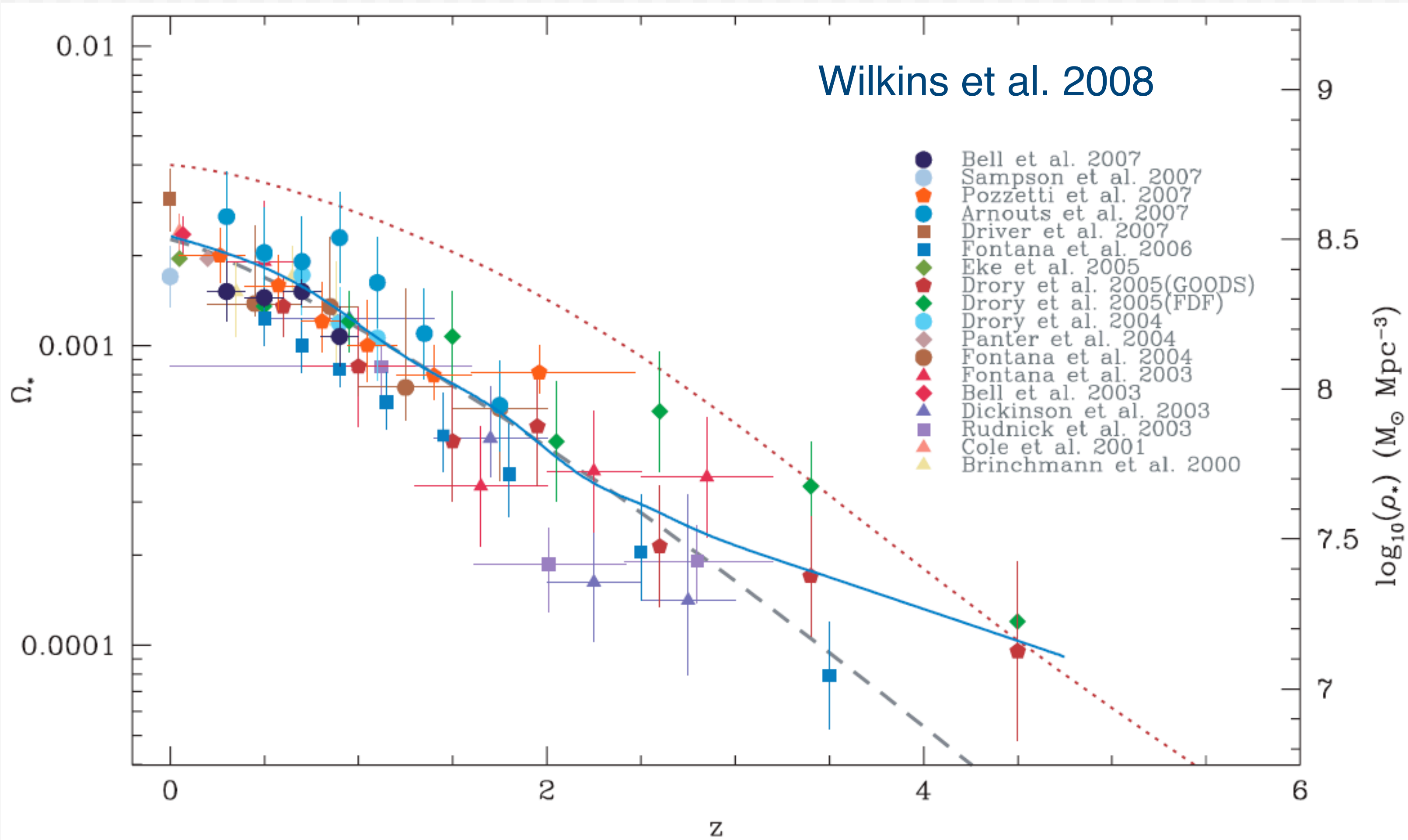
Star formation rate vs. redshift



Stellar mass density vs. redshift



Stellar mass density vs. redshift



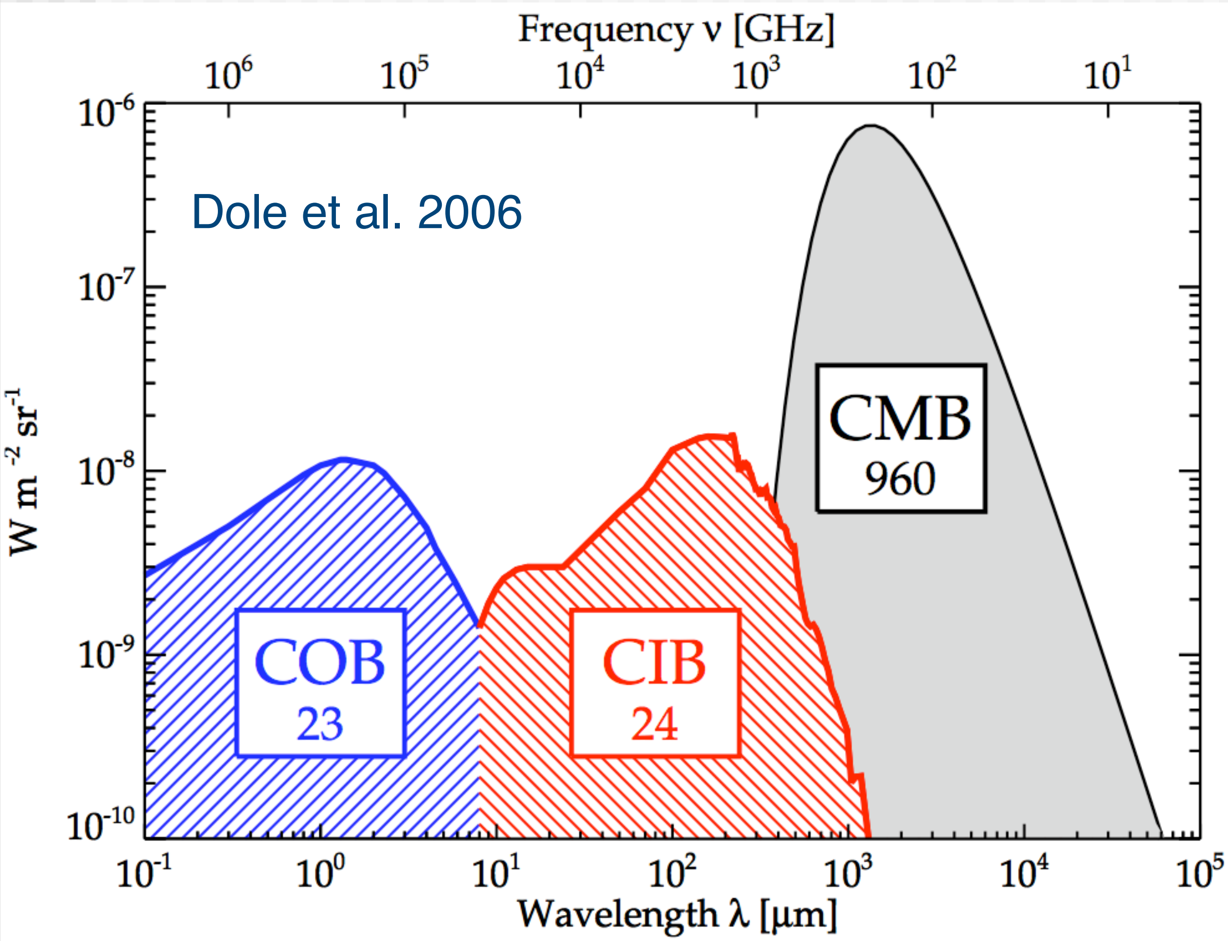
The global history of star formation

- Considers the universe as a mechanism transforming gas into stars, metals, energy, and back to gas
- Averages over all details of individual galaxies
  - But … measurements usually come from individual galaxies and depend on those details
- Depends crucially on modeling to interpret light as mass
- Spitzer's key contributions to the subject include:
  - Dust emission from star formation at cosmological distances
  - Rest-frame optical starlight at high redshift

Steps on the road toward SFR(z)

- Integrated backgrounds
- Number counts
- Redshift distributions
- Luminosity functions

Extragalactic background light



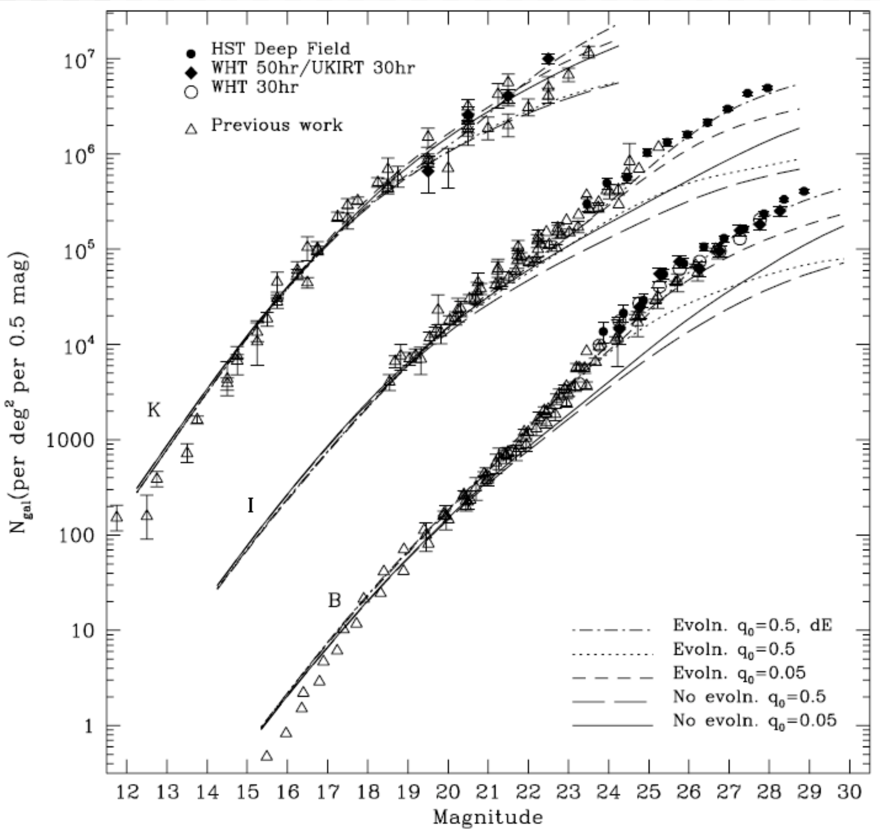
Integrated infrared and optical backgrounds have comparable energy density.

For z~0 galaxies, L(opt) ~ 3 x L(IR)
(Soifer & Neugebauer 1991)

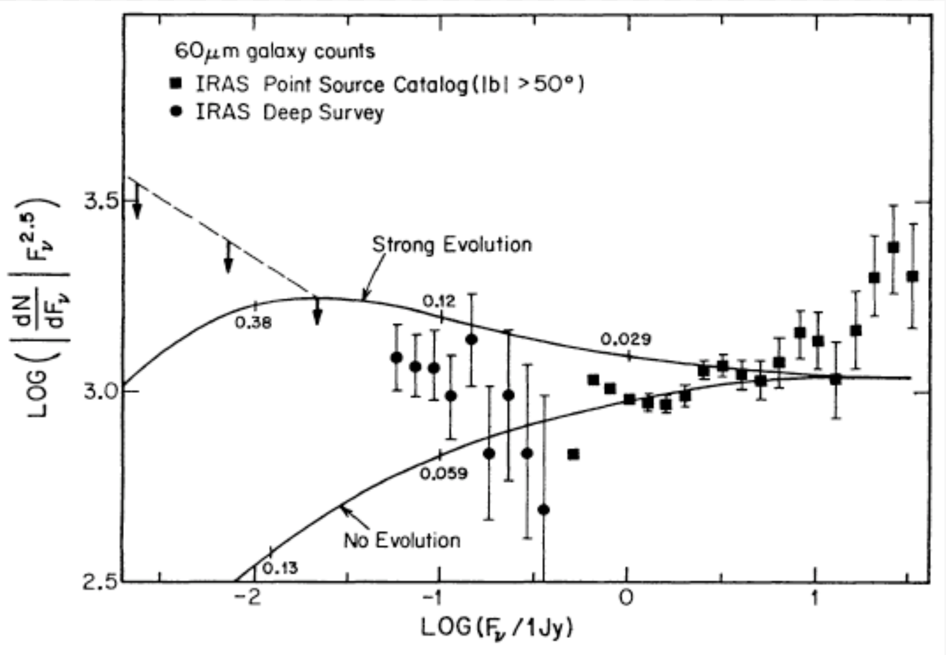
Implies much stronger infrared emission in the past.

Early evidence from source counts

Metcalf et al. 1996 (optical+NIR)

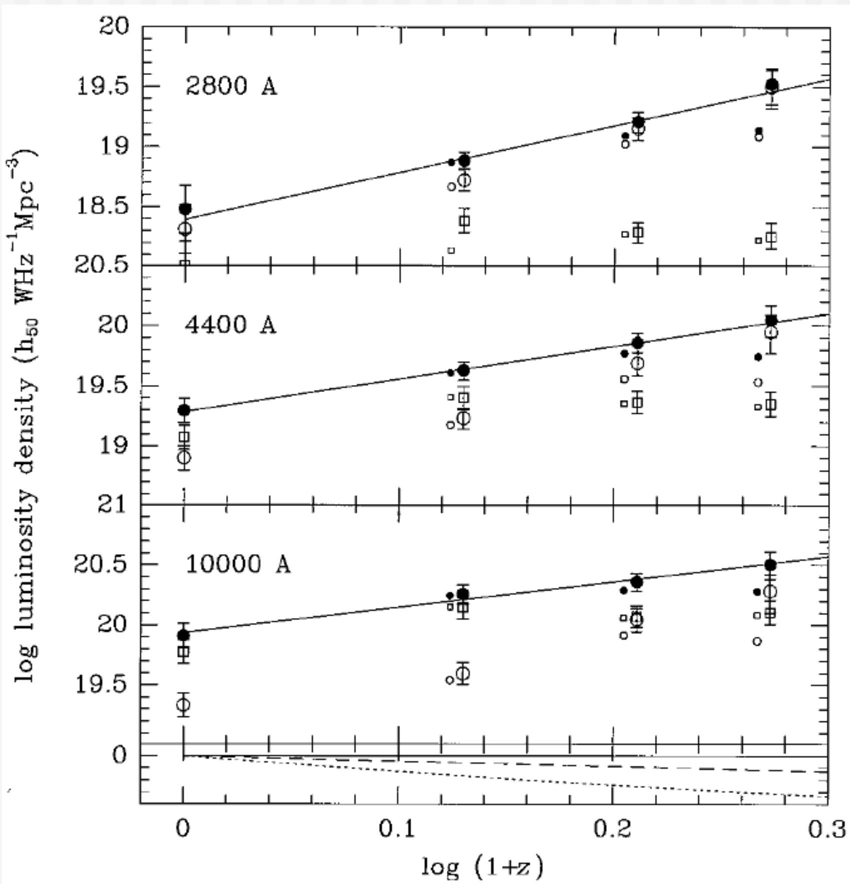


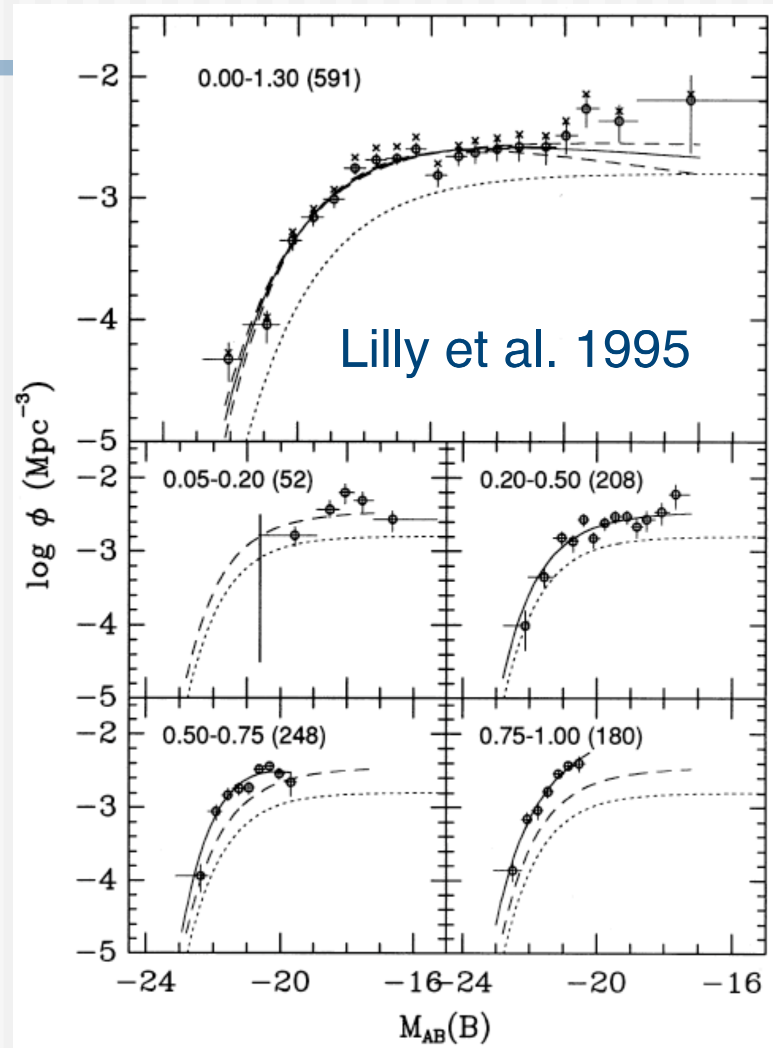
Hacking et al. 1987 (IRAS)



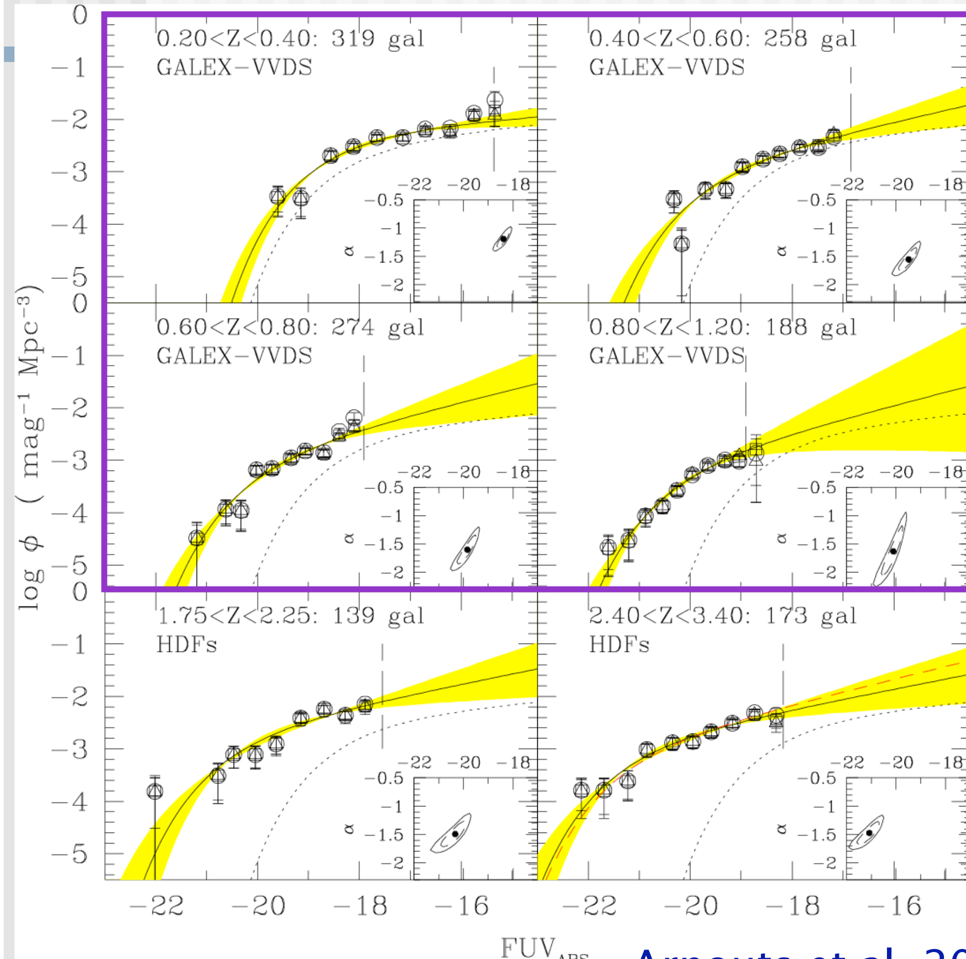
Luminosity functions and luminosity densities

Lilly et al. 1996

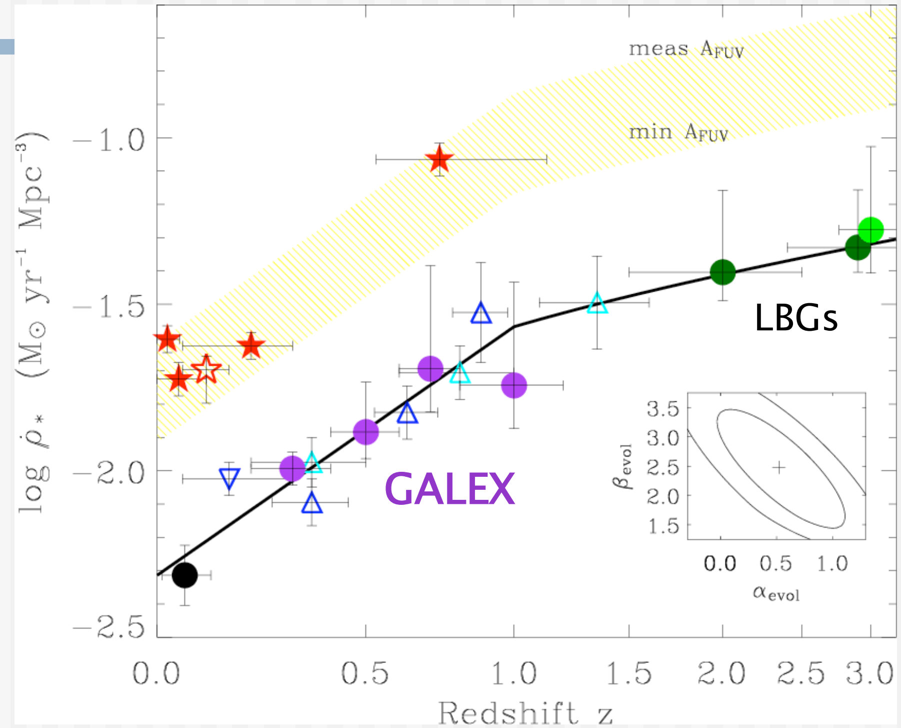




UV at z < 1.2 from GALEX



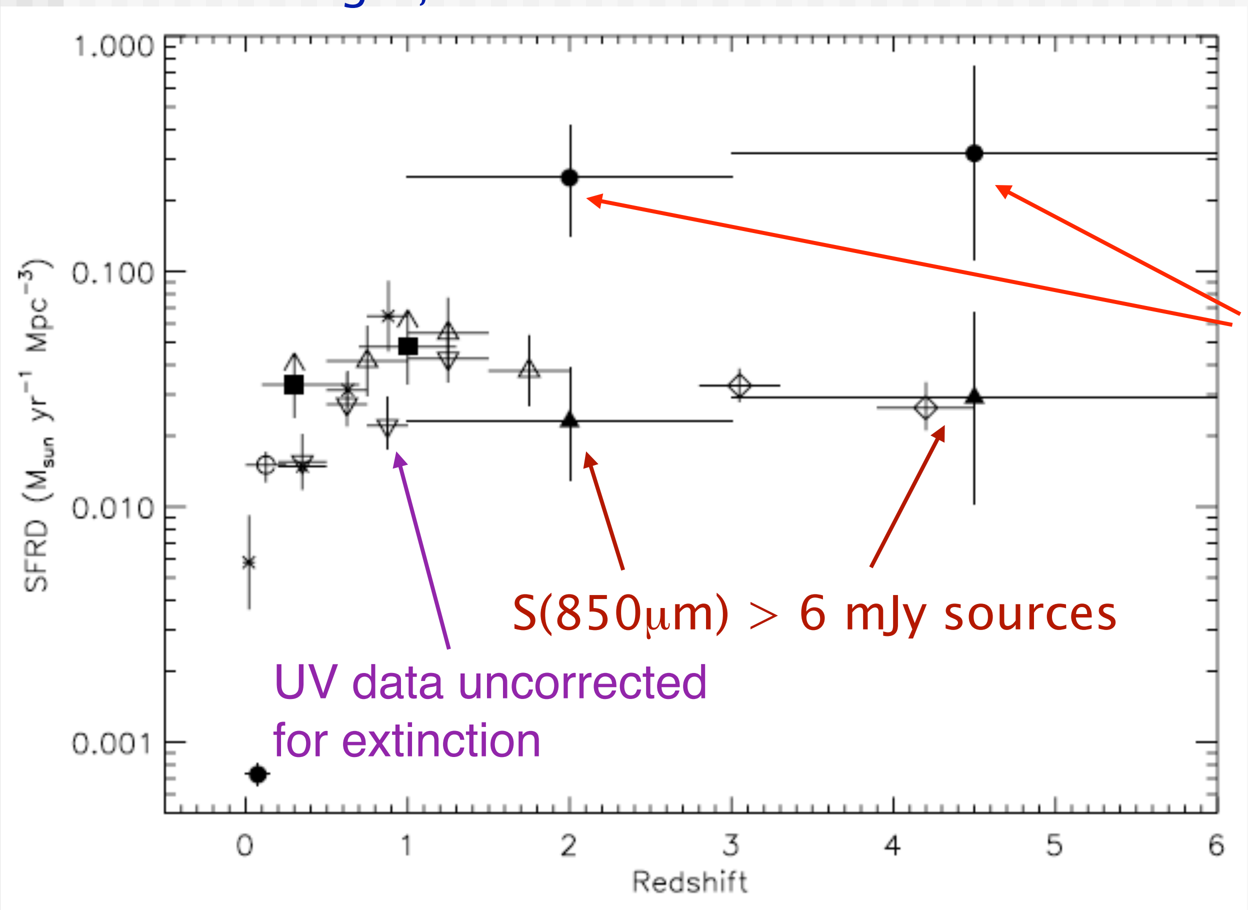
Arnouts et al. 2005

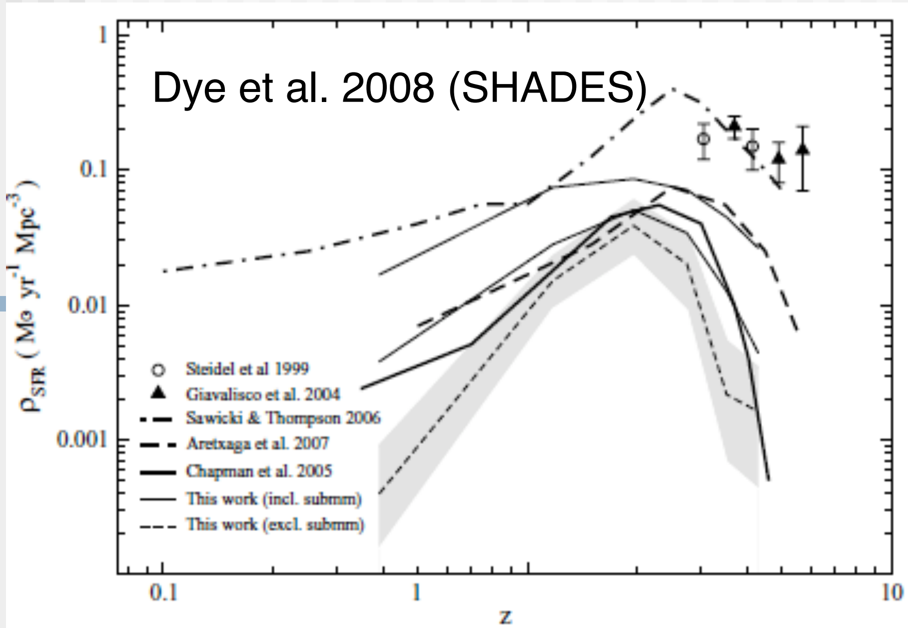


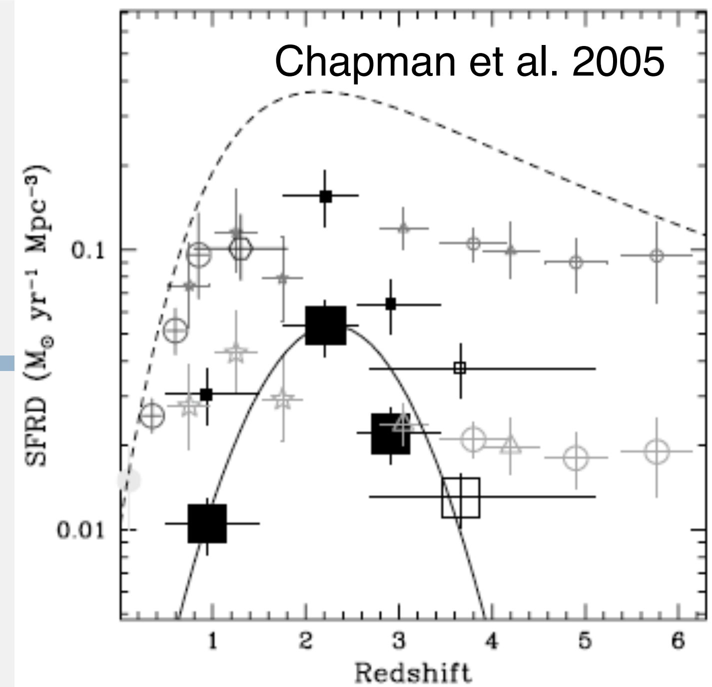
Schiminovich et al. 2005

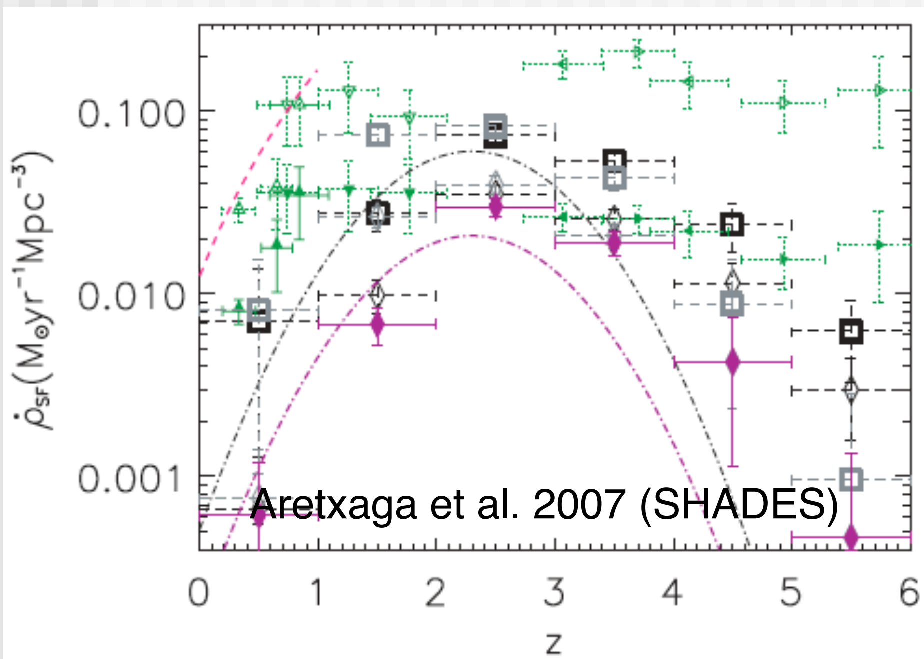
SFR(z) from submillimeter sources

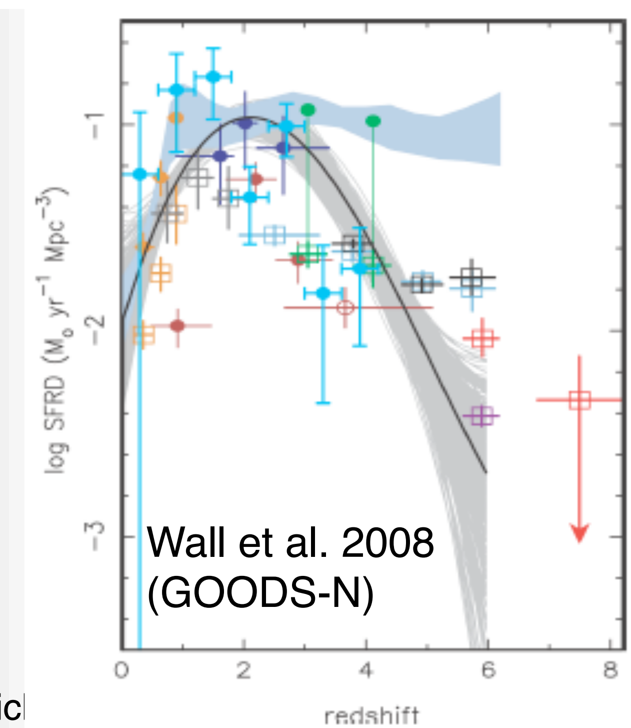
Barger, Cowie & Richards 2000




Dye et al. 2008 (SHADES)
ρSFR (M⊙ yr⁻¹ Mpc⁻³)
z
Steidel et al 1999
Giavalisco et al. 2004
Sawicki & Thompson 2006
Aretxaga et al. 2007
Chapman et al. 2005
This work (incl. submm)
This work (excl. submm)


Chapman et al. 2005
SFRD (M⊙ yr⁻¹ Mpc⁻³)
Redshift


Aretxaga et al. 2007 (SHADES)
ρ̇SF(M⊙yr⁻¹Mpc⁻³)
z


Wall et al. 2008
(GOODS-N)
log SFRD (M⊙ yr⁻¹ Mpc⁻³)
redshift

ISO and other pre-Spitzer data

ISOCAM 15μm sources resolved most of the CIRB.
Dominated by LIRGs at z~1 (e.g., Elbaz et al. 2002; Chary & Elbaz 2001)

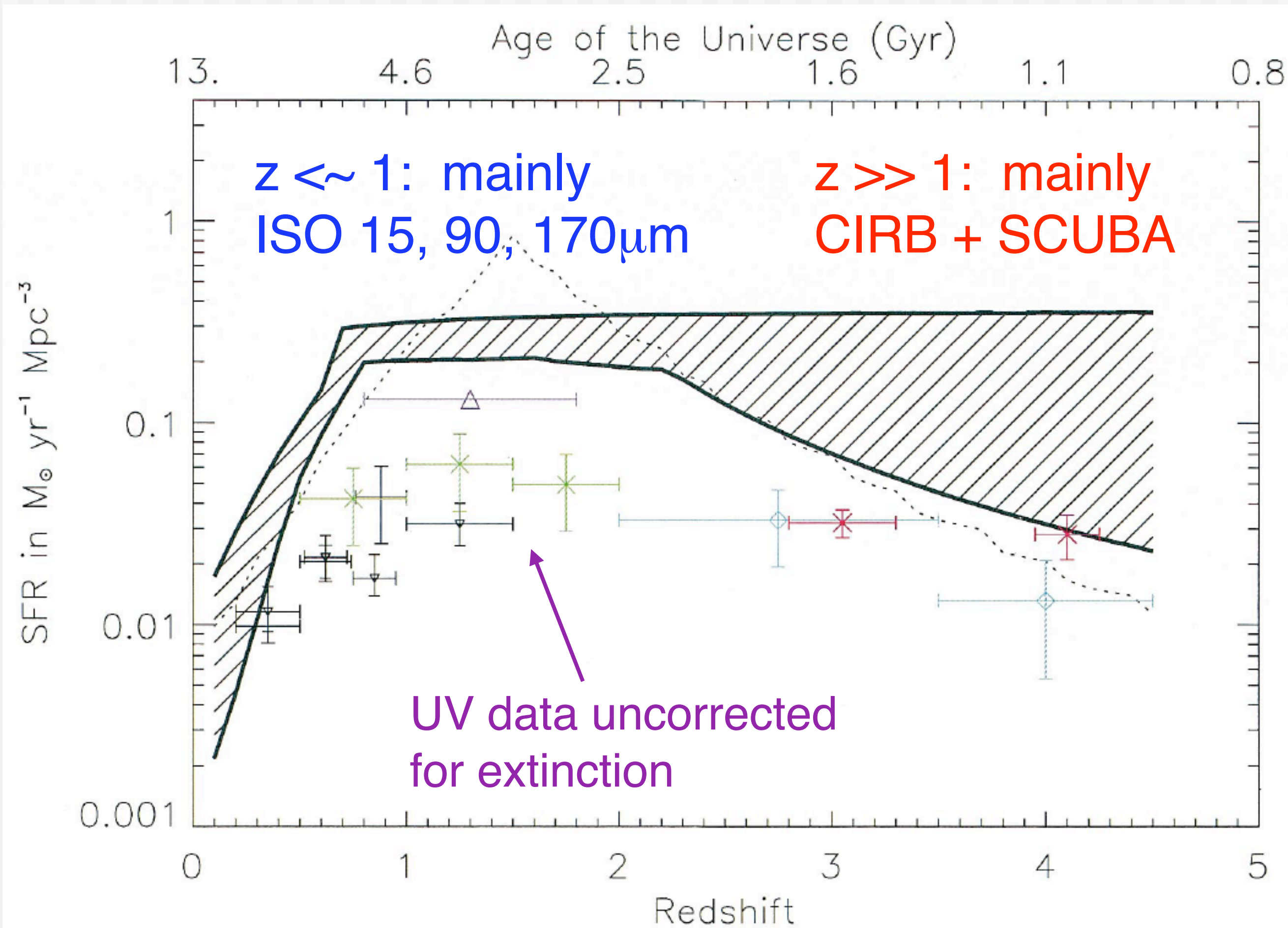
Chary & Elbaz 2001

Modeled:

- Number counts ISO 15, 90, 170μm, SCUBA 850μm
- N(z) for ISO 15μm
- Far-IR background

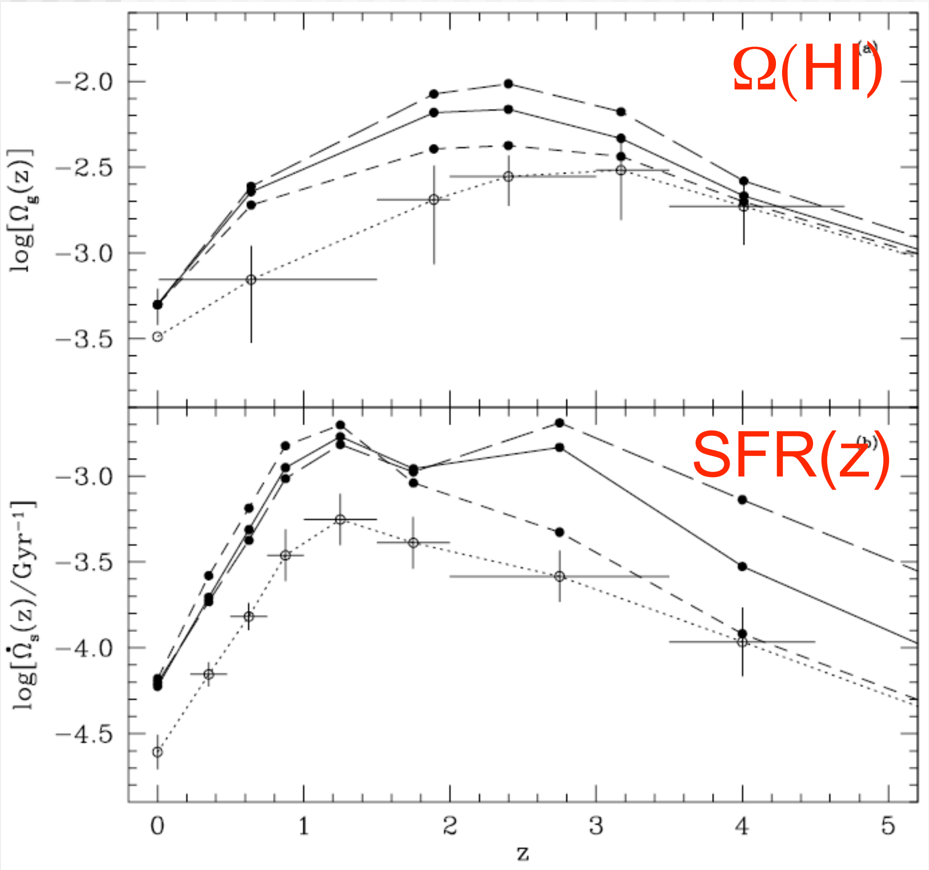
Features:

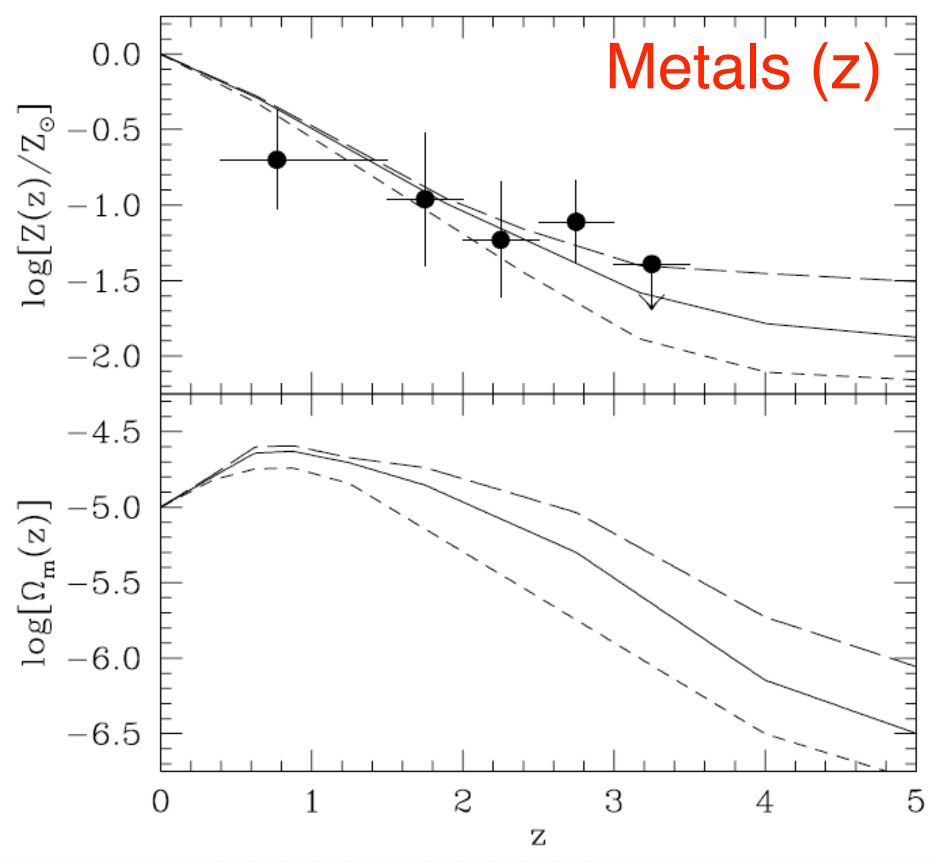
- LIRGs dominate SFR at z~1
- Fairly flat SFR(z) from 0.8 < z < 2
- CIRB sets upper limit for SFR(z) at z >> 2



Gas, stars, metals, and the cosmic infrared background

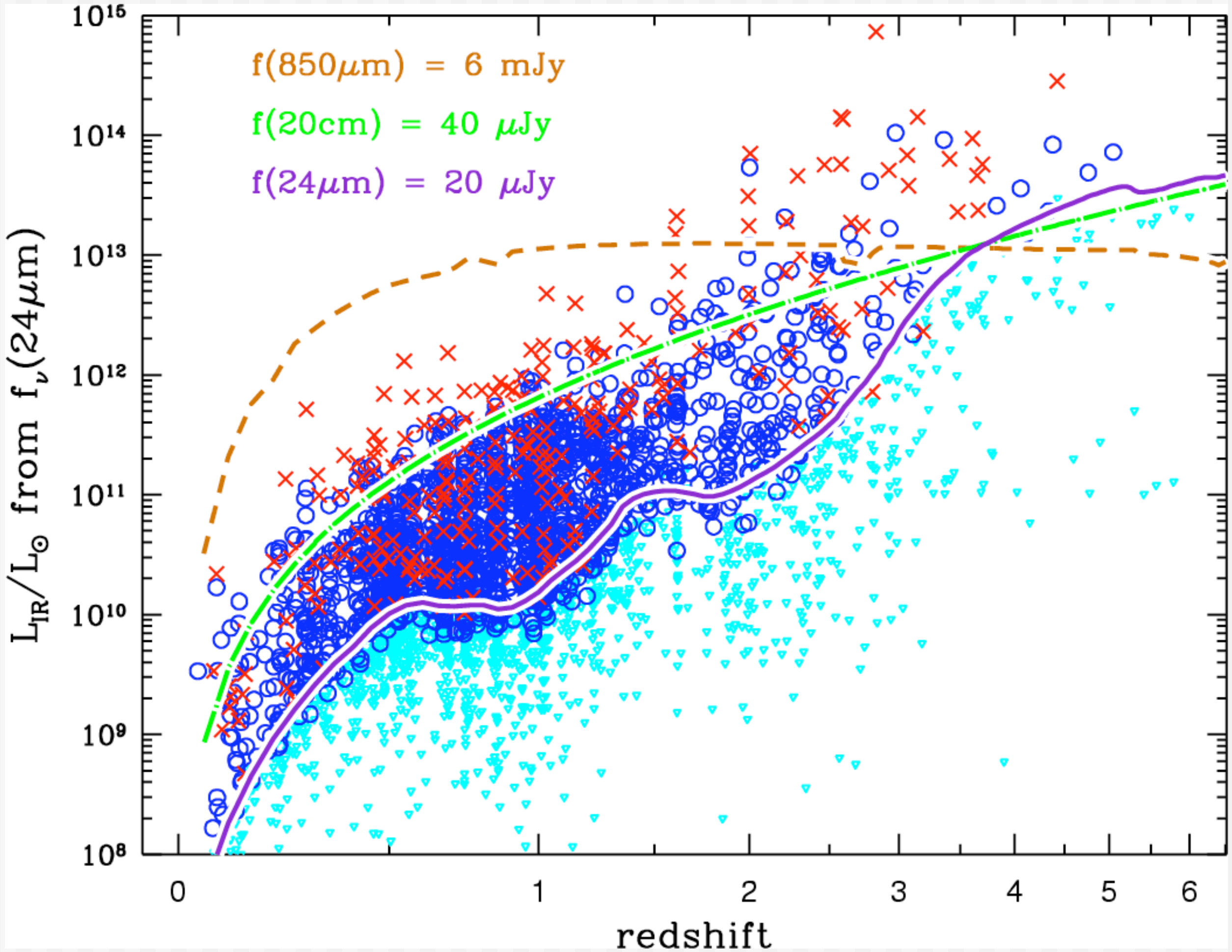
Pei, Fall & Hauser 1999; also Pei & Fall 1995; Fall, Charlot & Pei 1996



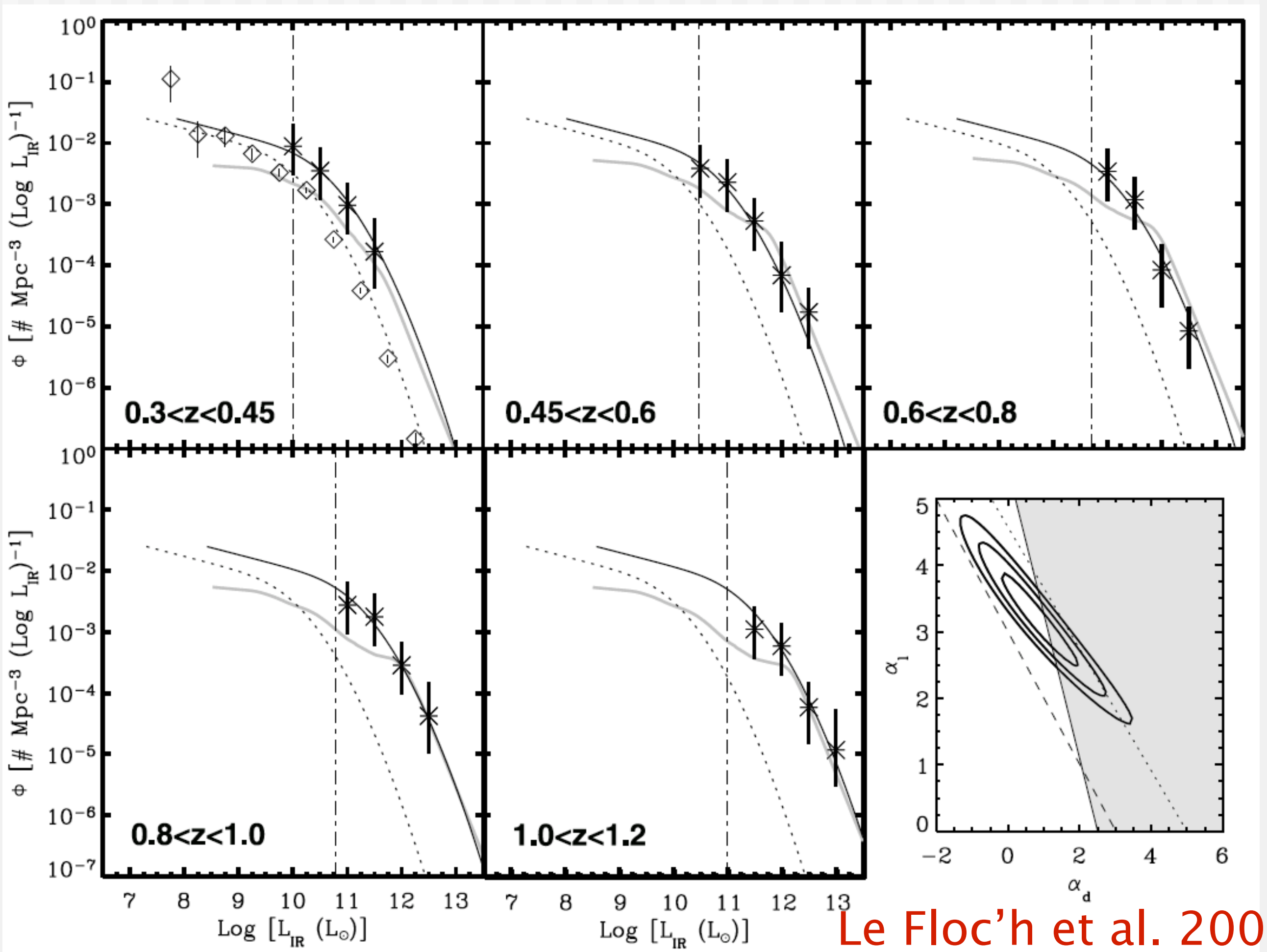


Dusty SF at high-z: the Spitzer era

- Unprecedented sensitivity and dynamic range at 24μm
- Many thousands of sources detected over large solid angles
- Large overlap with spectroscopic and photometric redshift surveys



Spitzer + redshifts = IR LF



Le Floc'h et al. 2005

z~1: The age of the LIRGS
(Luminous Infrared Galaxies)

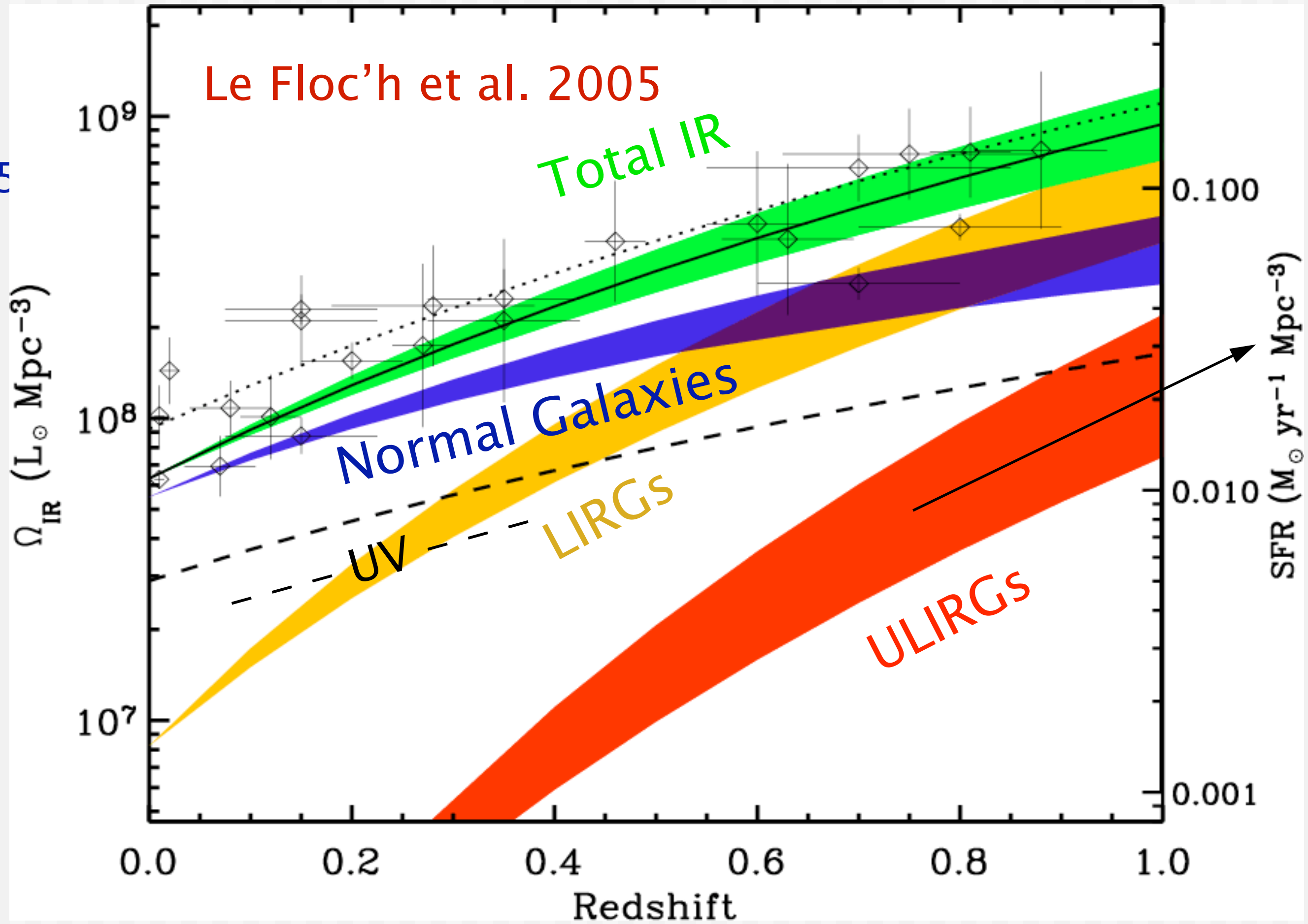
0 < z < 1:

$\rho_{UV}(z) \sim (1+z)^{2.5}$
(Schiminovich et al. 2005

$\rho_{IR}(z) \sim (1+z)^{3.9}$
(Le Floc'h et al. 2005)

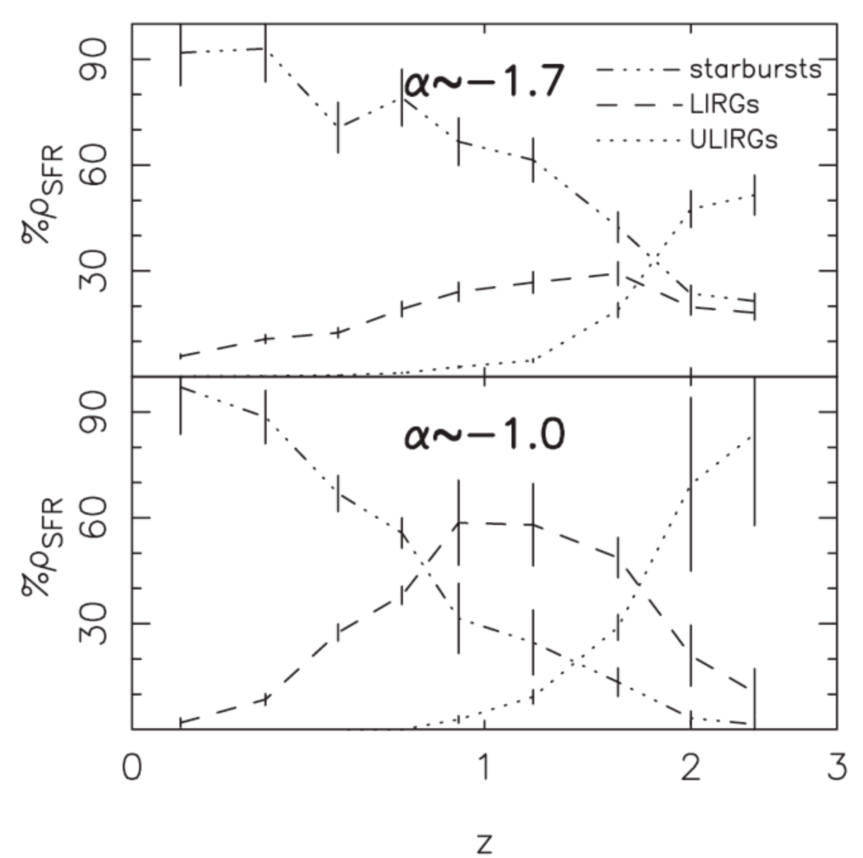
Infrared/UV emitted energy from star formation:

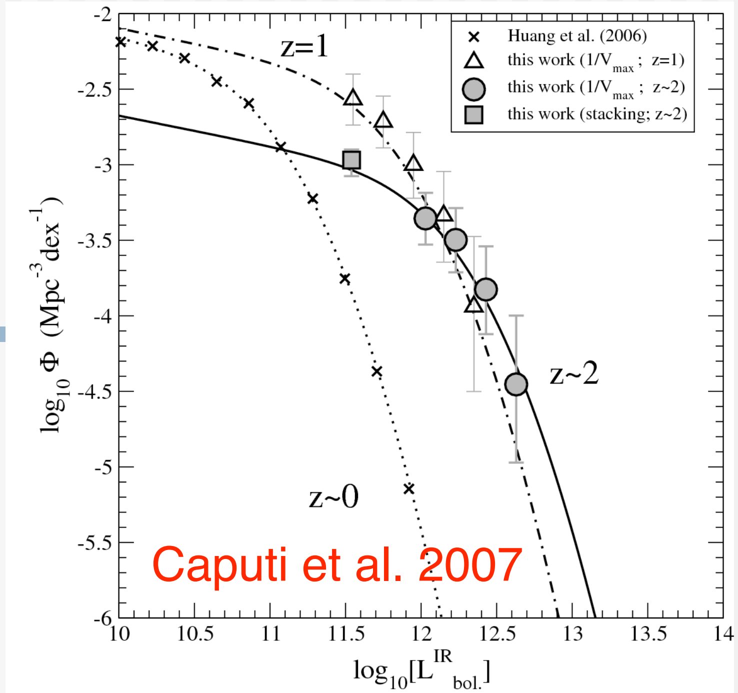
z=0 ~1.5 : 1
z=1 ~ 4 : 1

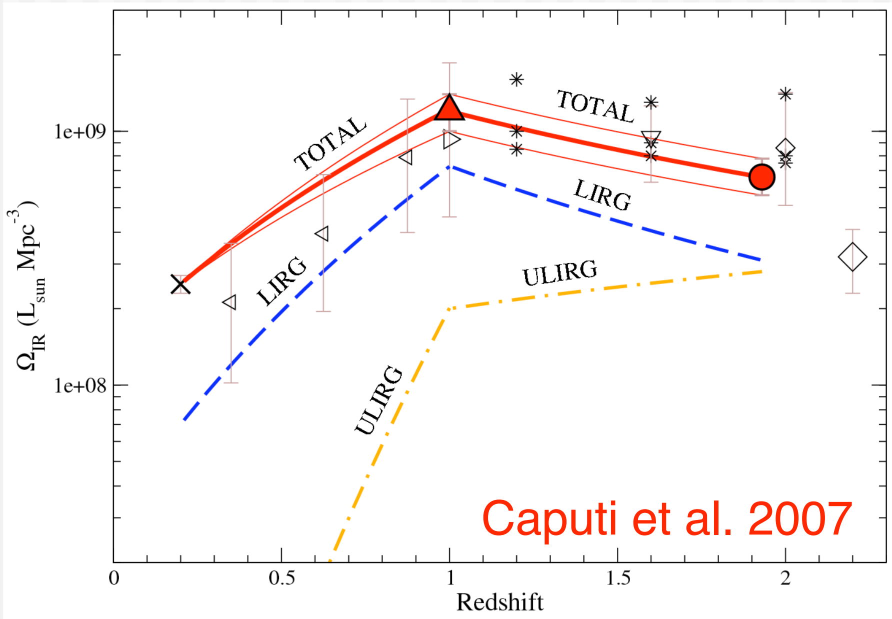


z~2: The ULIRGS take over?

Pérez-González et al. 2005



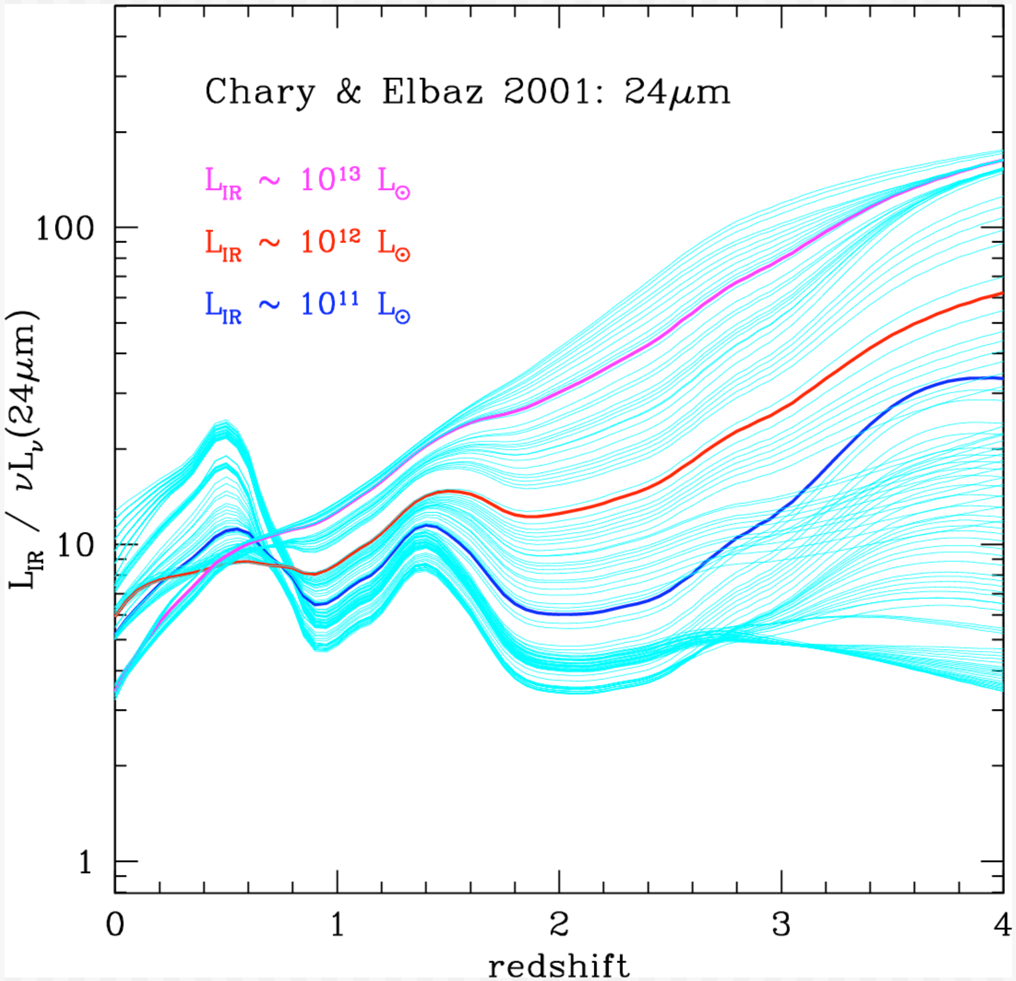




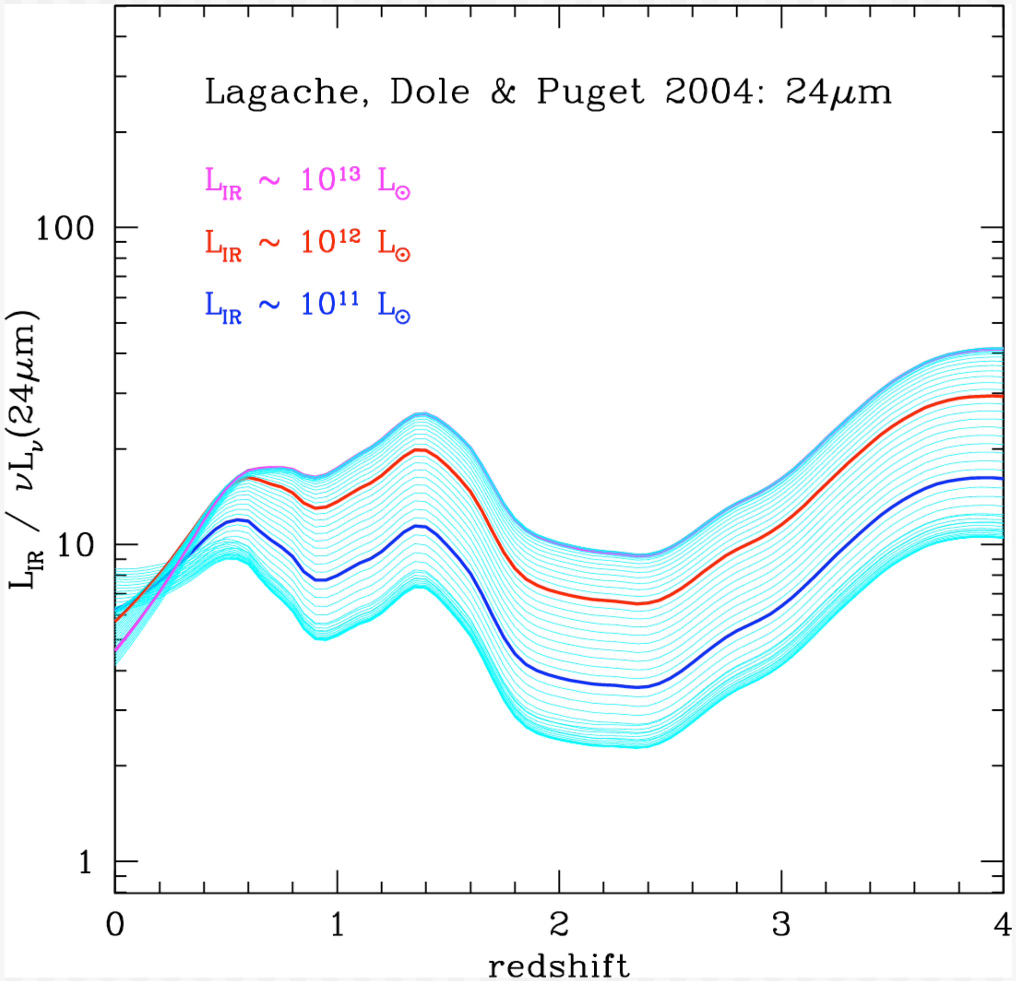
Important questions to ask:

- Are the 24μm bolometric corrections valid?
  - And are we measuring star formation? (i.e., effects of AGN)
- Are the MIPS data deep enough?
  - Faint end of the IR luminosity function?
- Have we sampled enough volume?
  - Cosmic variance?
- Are the (photometric) redshifts reliable?

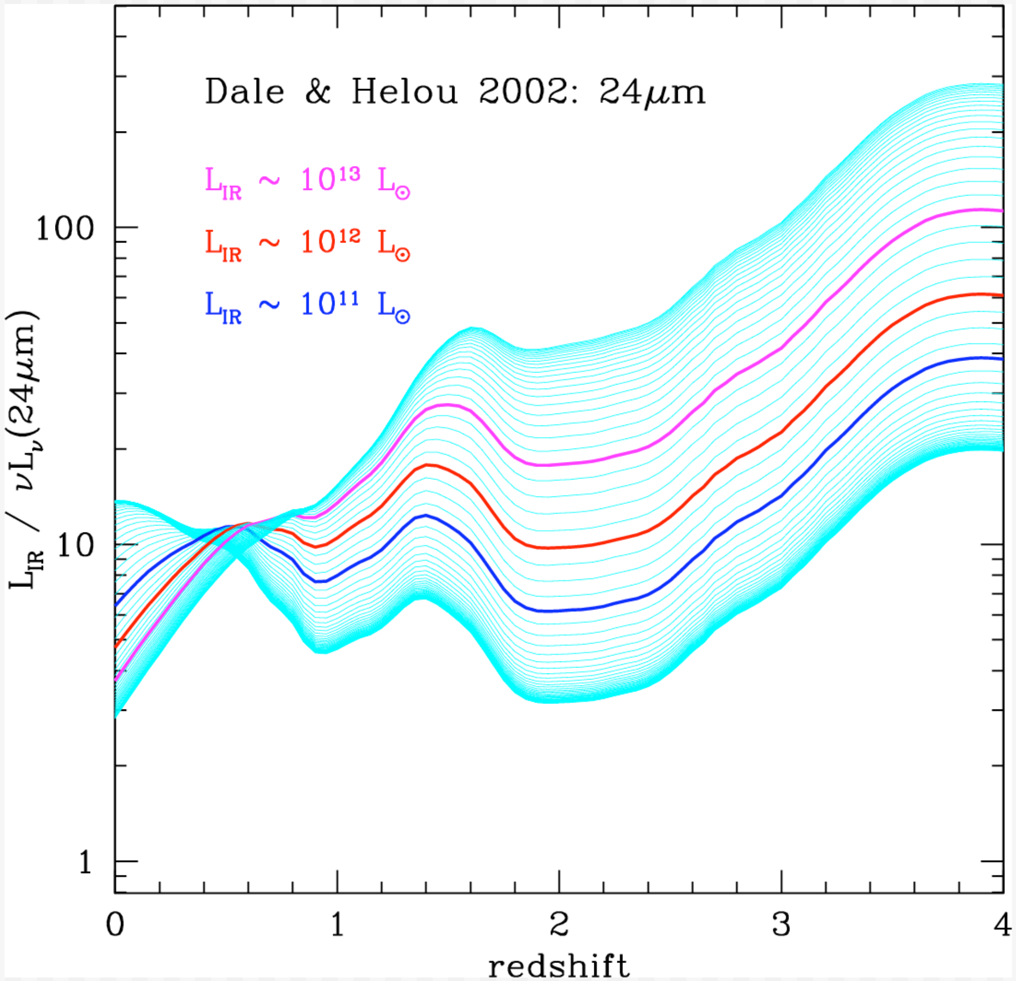
Bolometric corrections



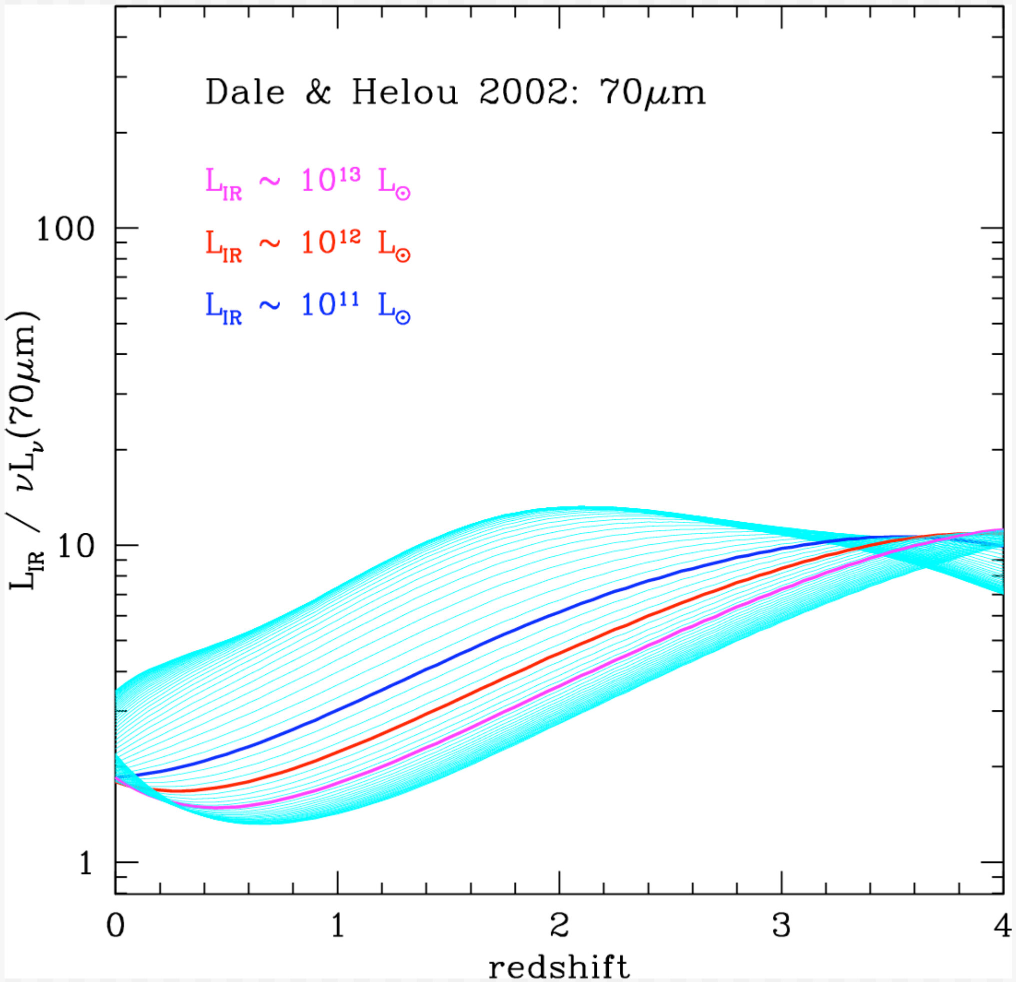
Bolometric corrections



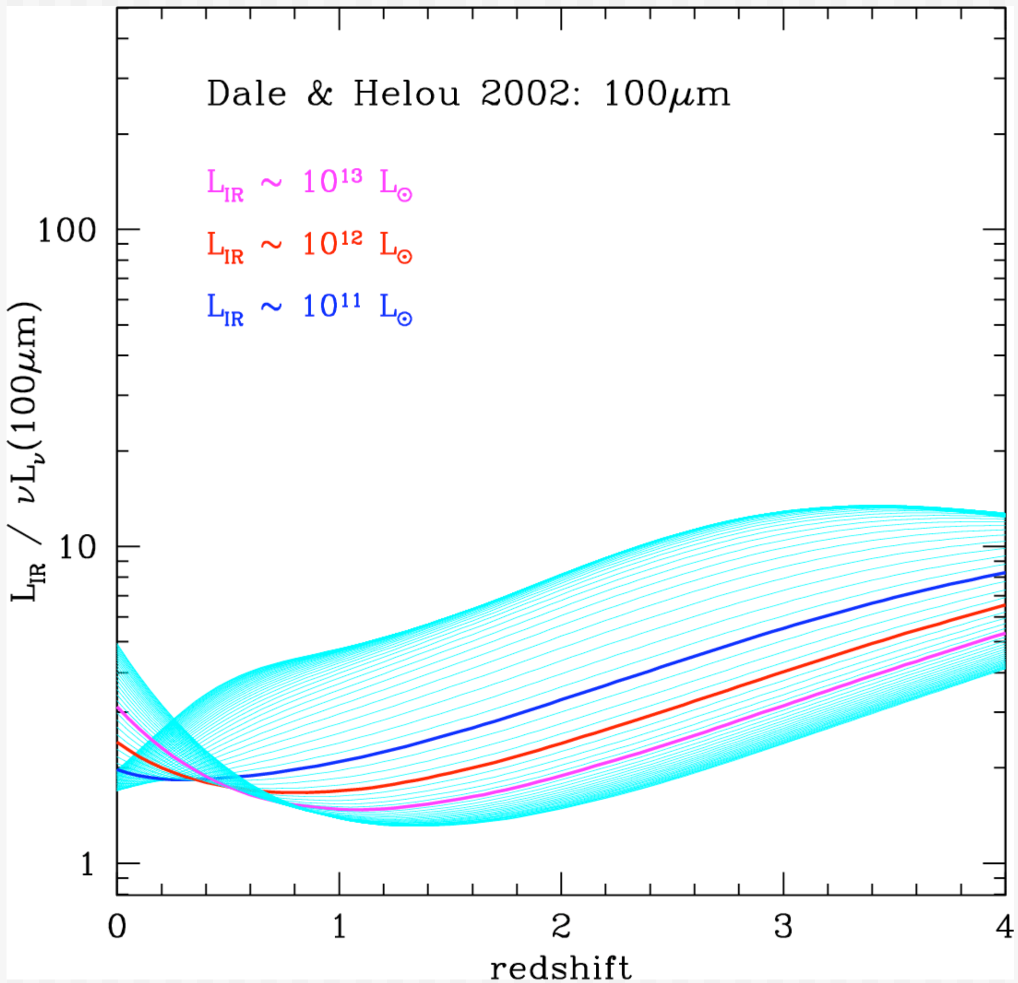
Bolometric corrections



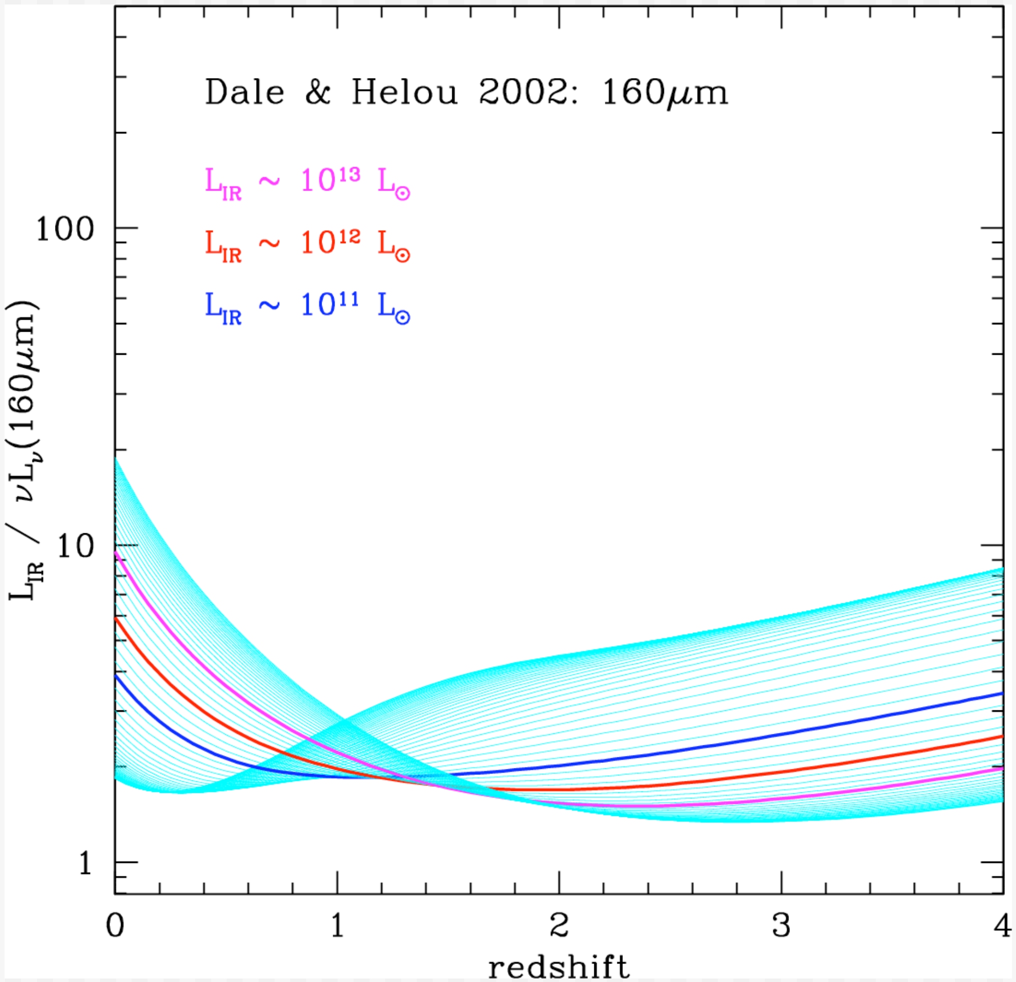
Bolometric corrections



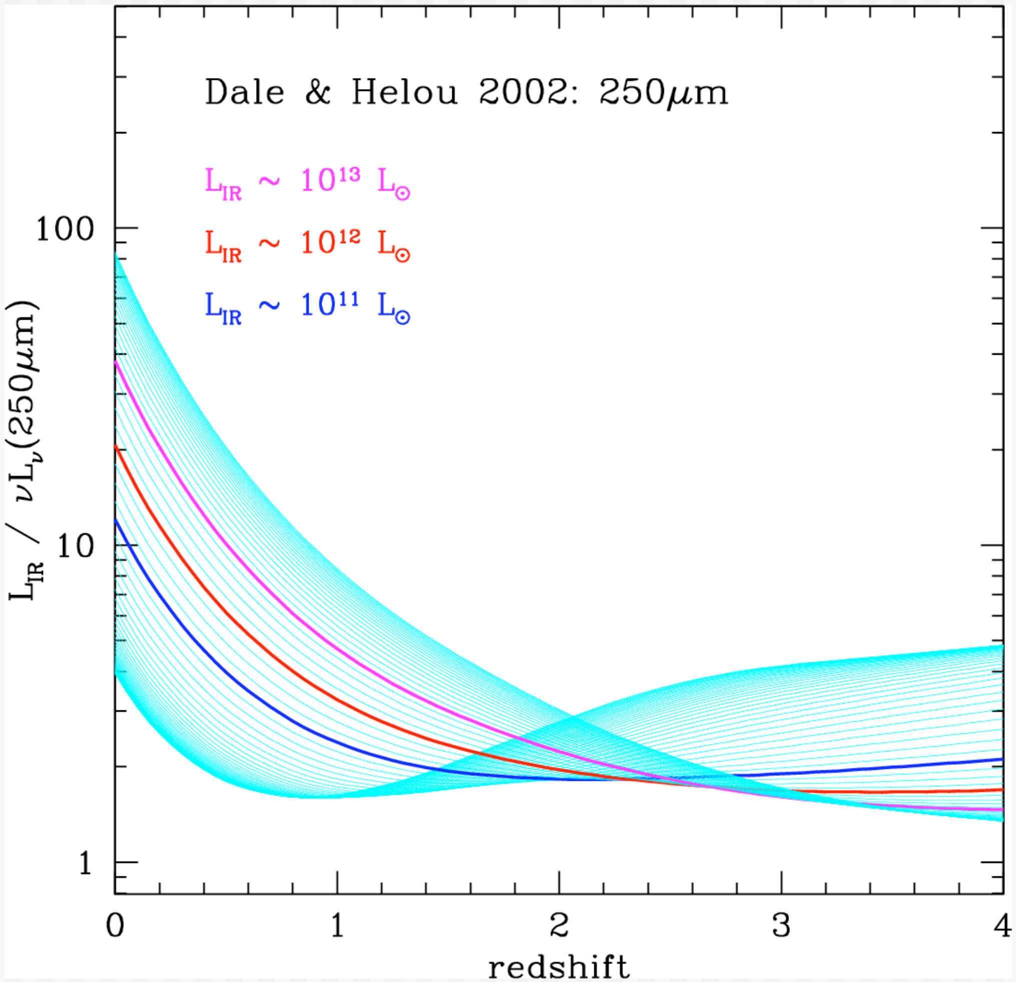
Bolometric corrections



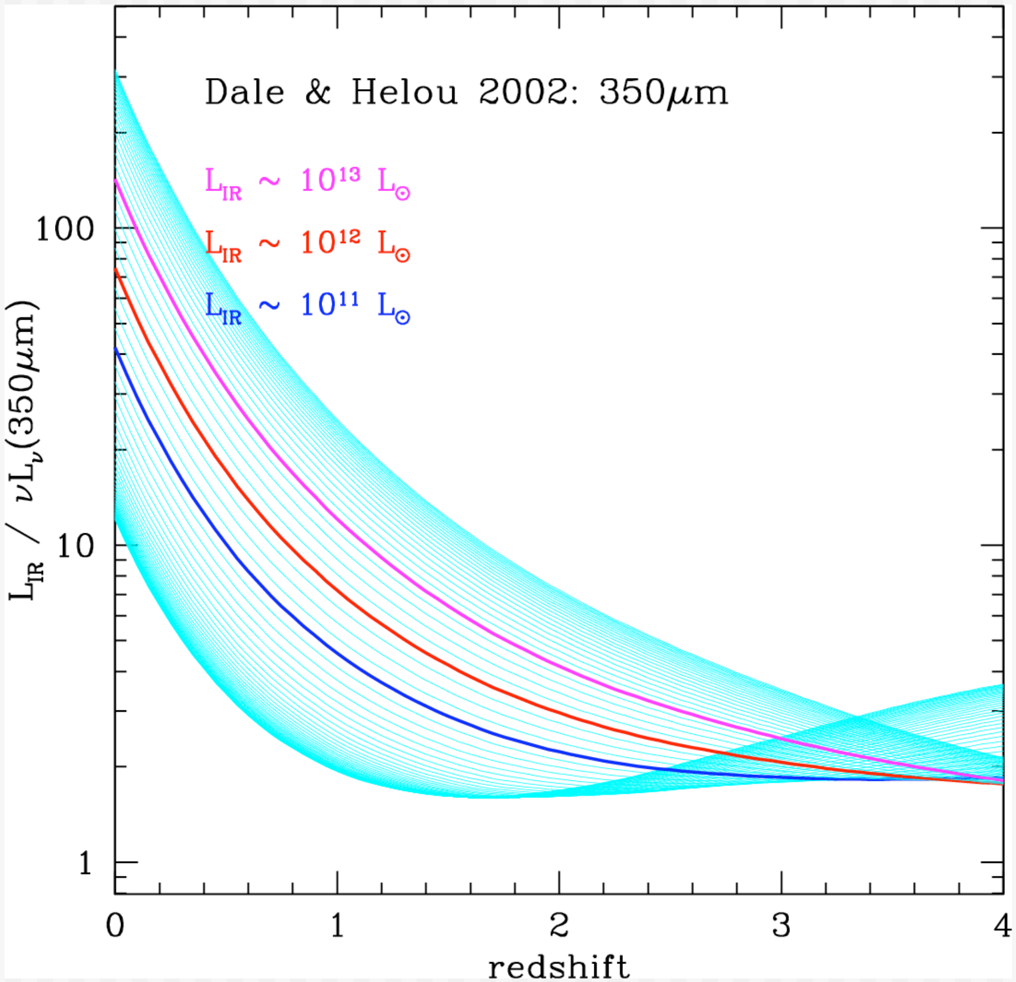
Bolometric corrections



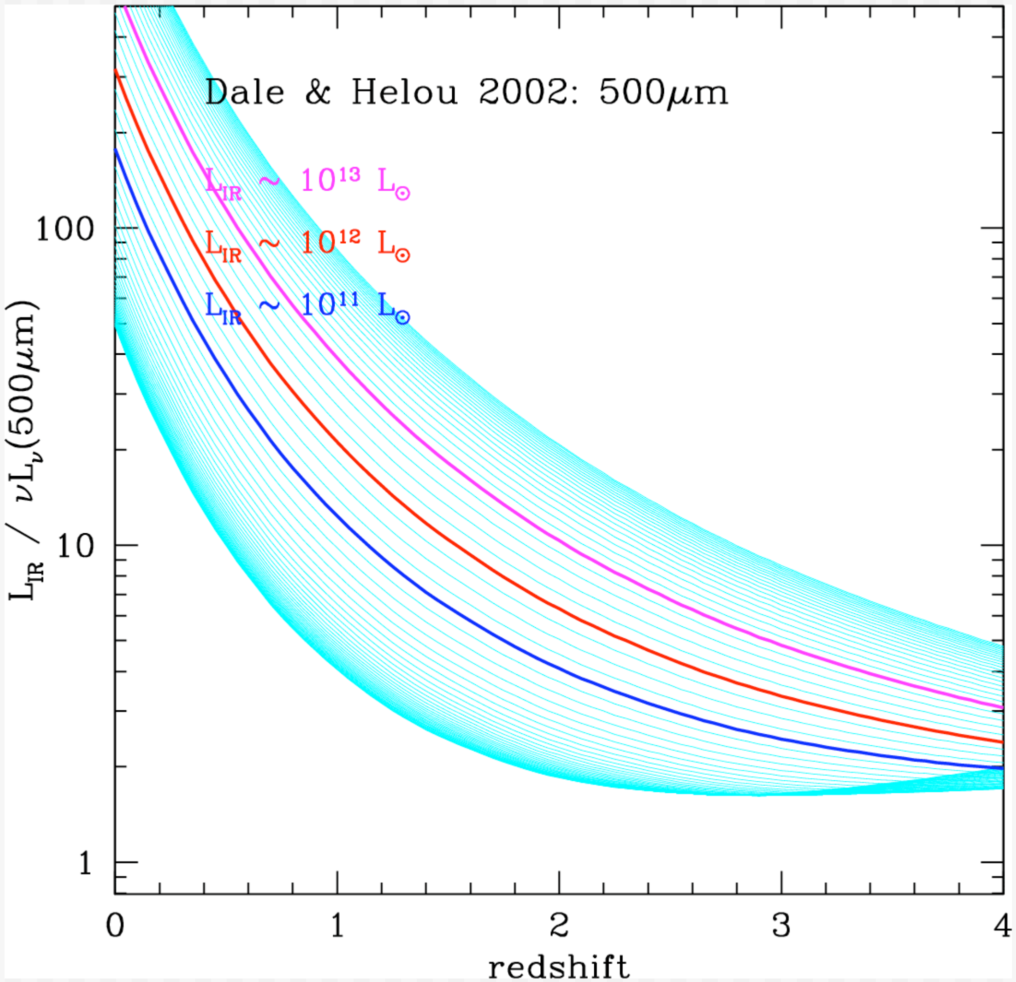
Bolometric corrections



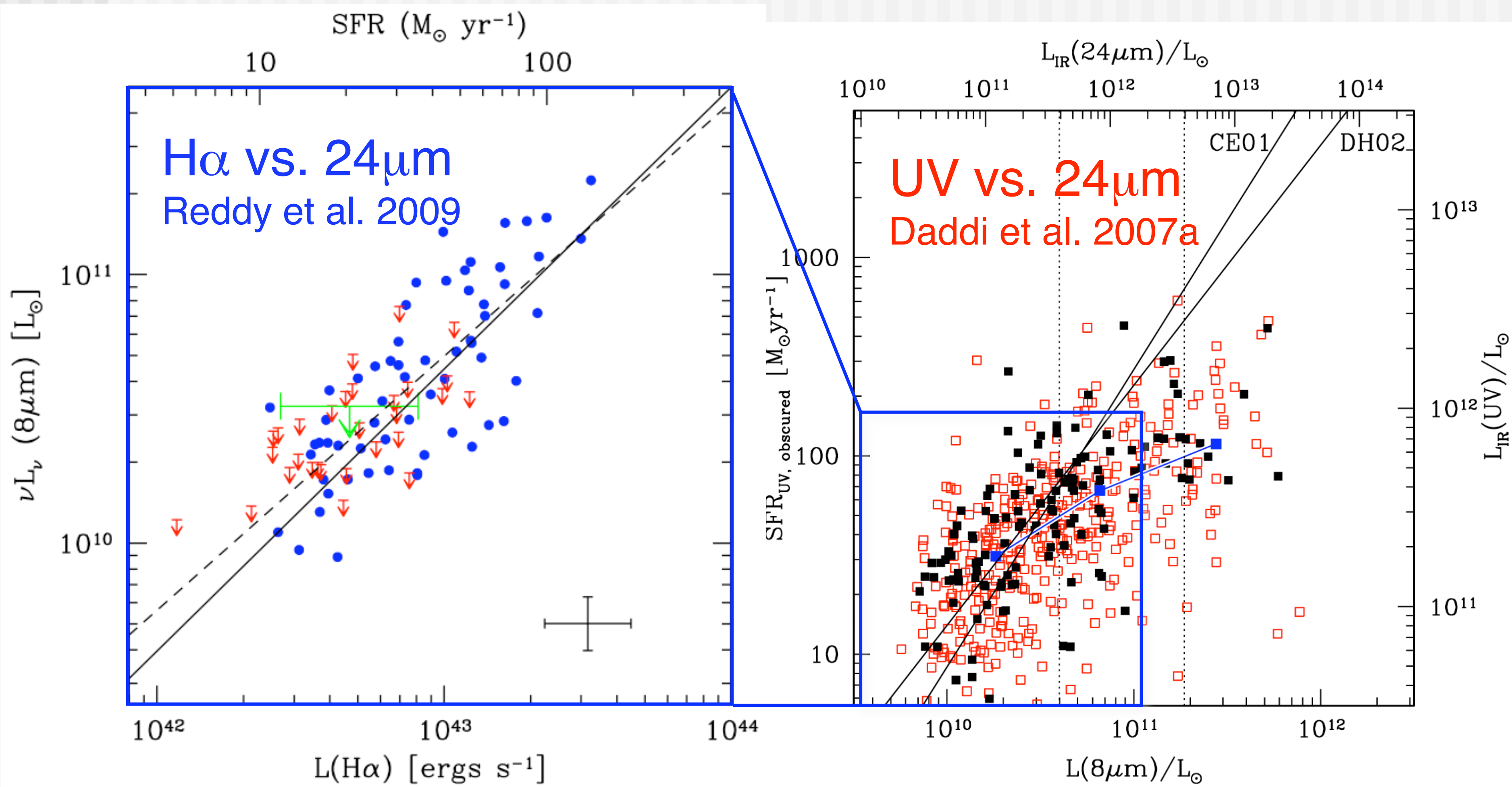
Bolometric corrections

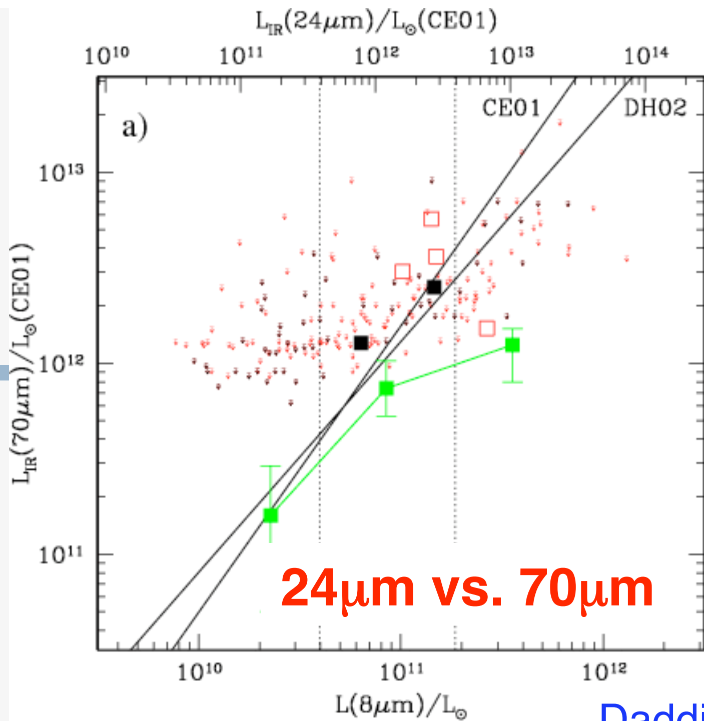


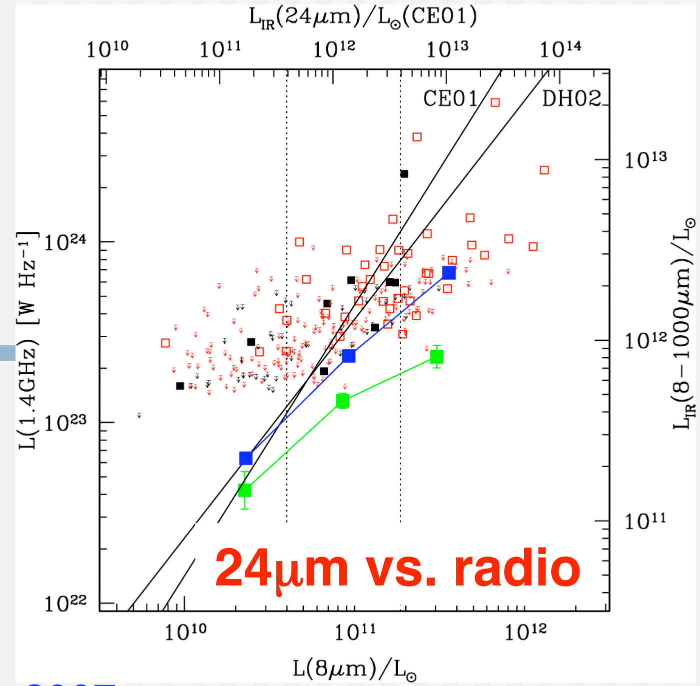
Bolometric corrections



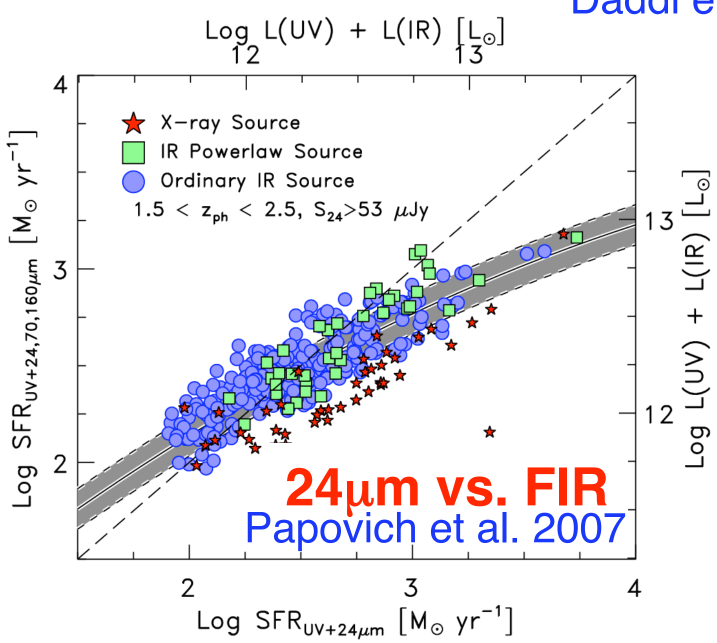
Testing SFR from 24μm @ z~2

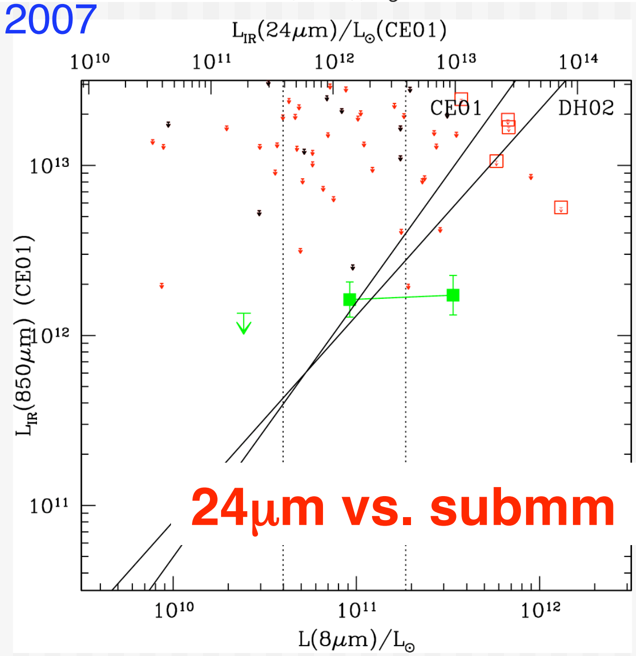






Daddi et al. 2007





Luminosity functions from MIPS 70μm data

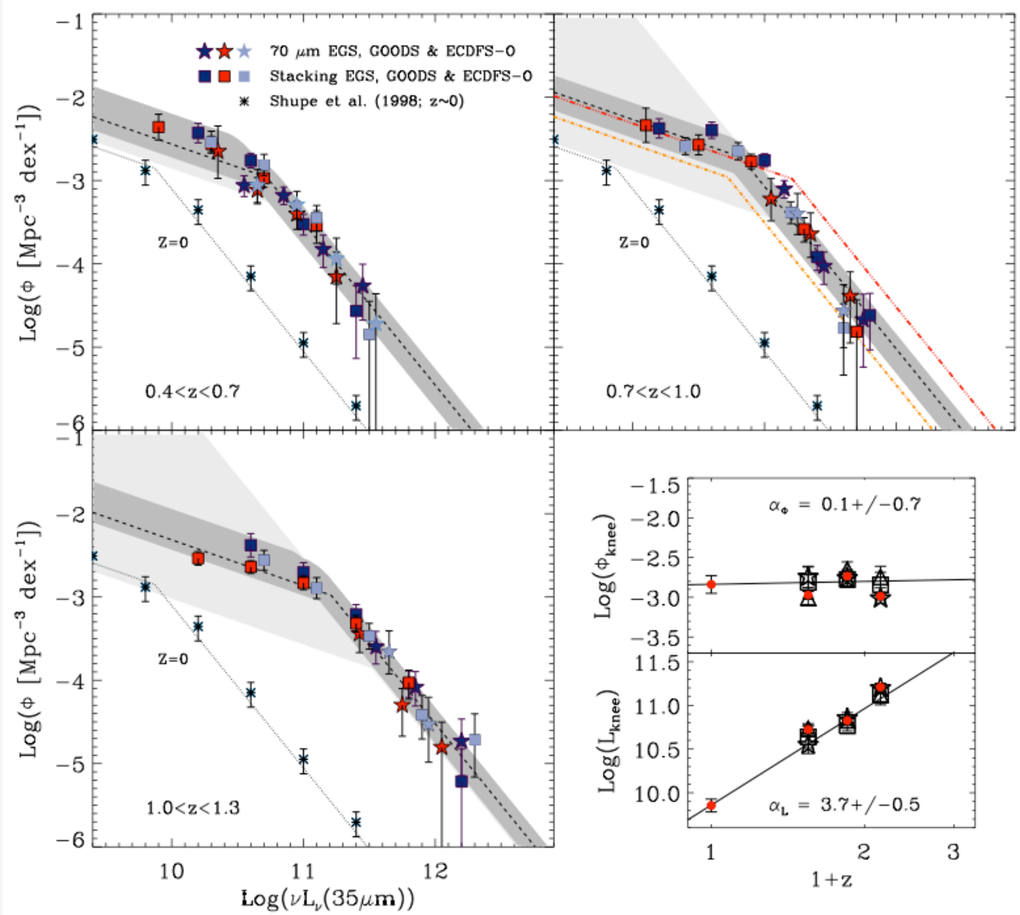
Huynh et al. 2007: GOODS-N, 140 galaxies, f(70μm) > 2 mJy
Magnelli et al. 2009a: FIDEL EGS+ECDFS+GOODS-N

- 680 galaxies, f(70μm) > 2.5 mJy
- ~9000 galaxies, f(24μm) > 30 μJy with 70μm stacking

Magnelli et al. 2009:

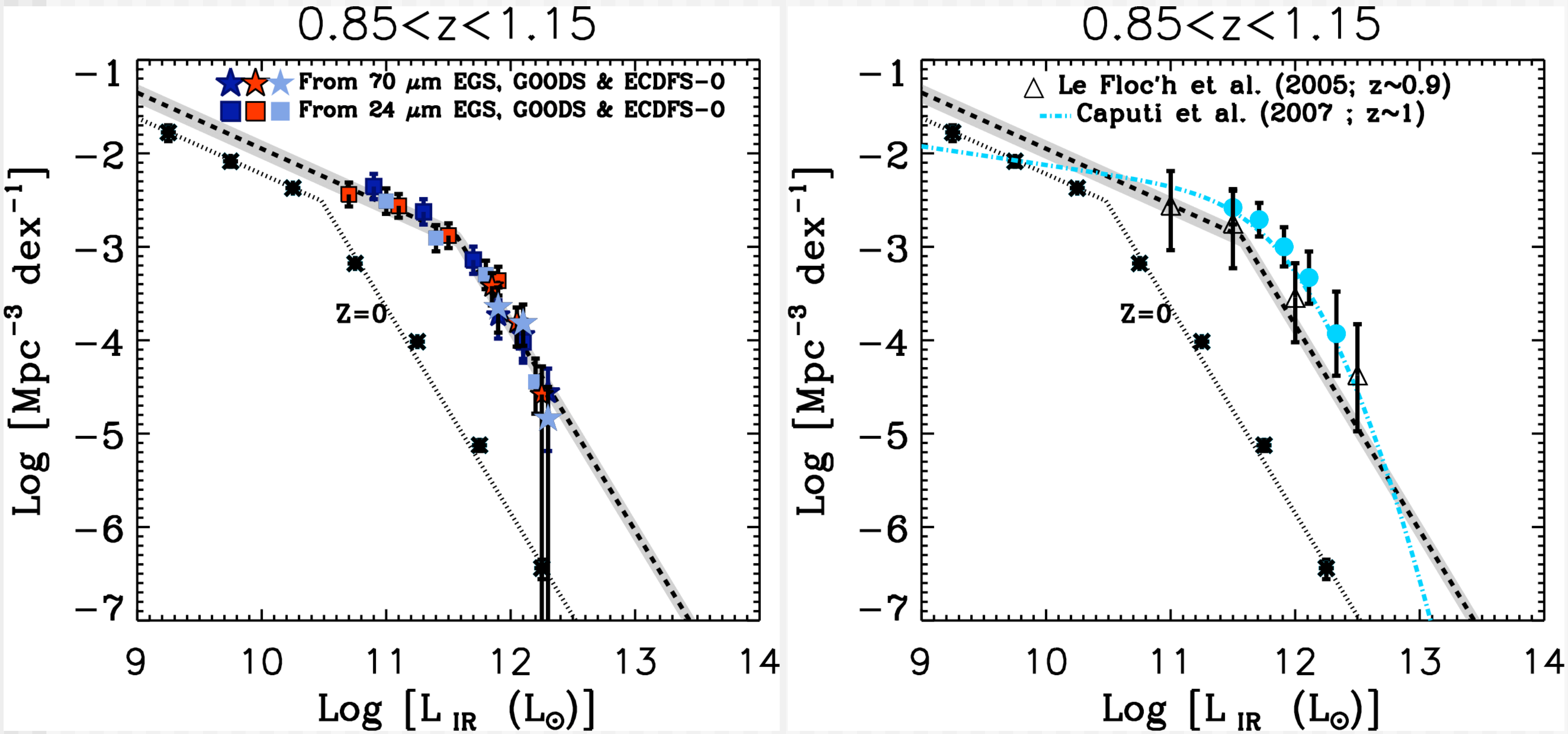
70μm stacking in bins of f(24μm):

- 0.4 < z < 1.3: mean trend agrees reasonably well with standard template SEDs
- 1.3 < z < 2.3: significant deviation from most templates, which predict stronger 70μm fluxes
- Model mean 24μm/70μm trend and use to derive rest-frame 35μm LF



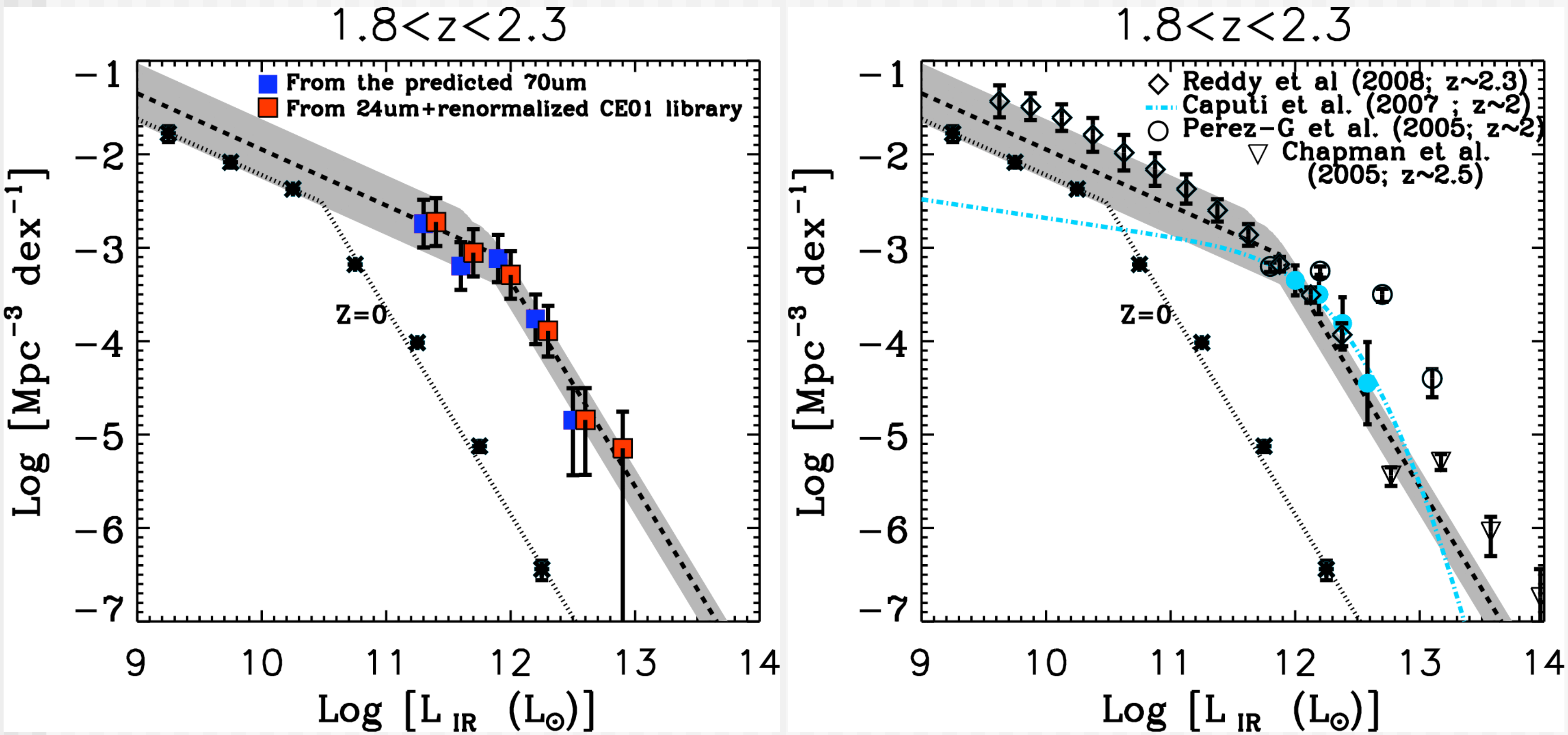
IR LF from 70μm & 24μm data

Magnelli et al. 2009a,b



IR LF from 70μm & 24μm data

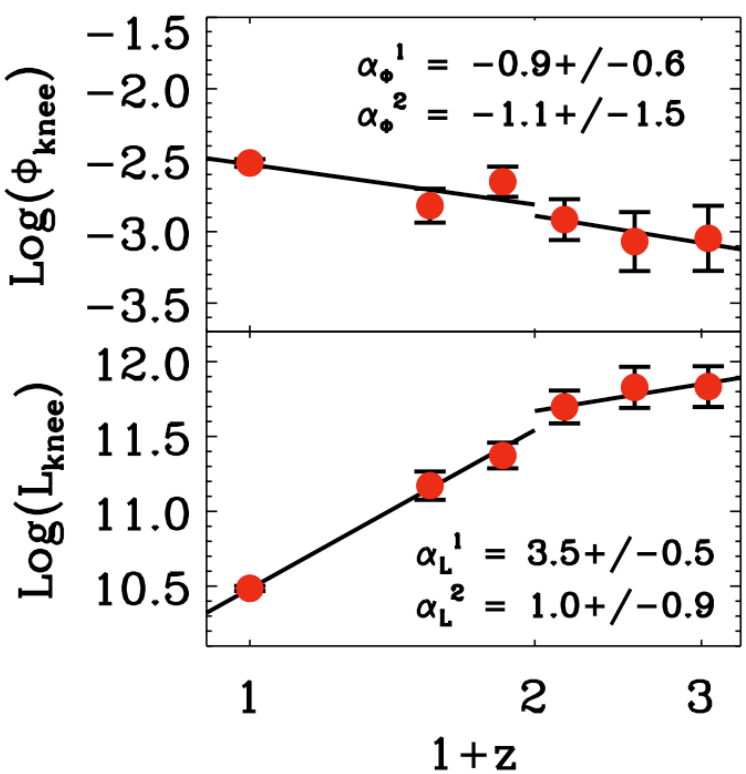
Magnelli et al. 2009a,b

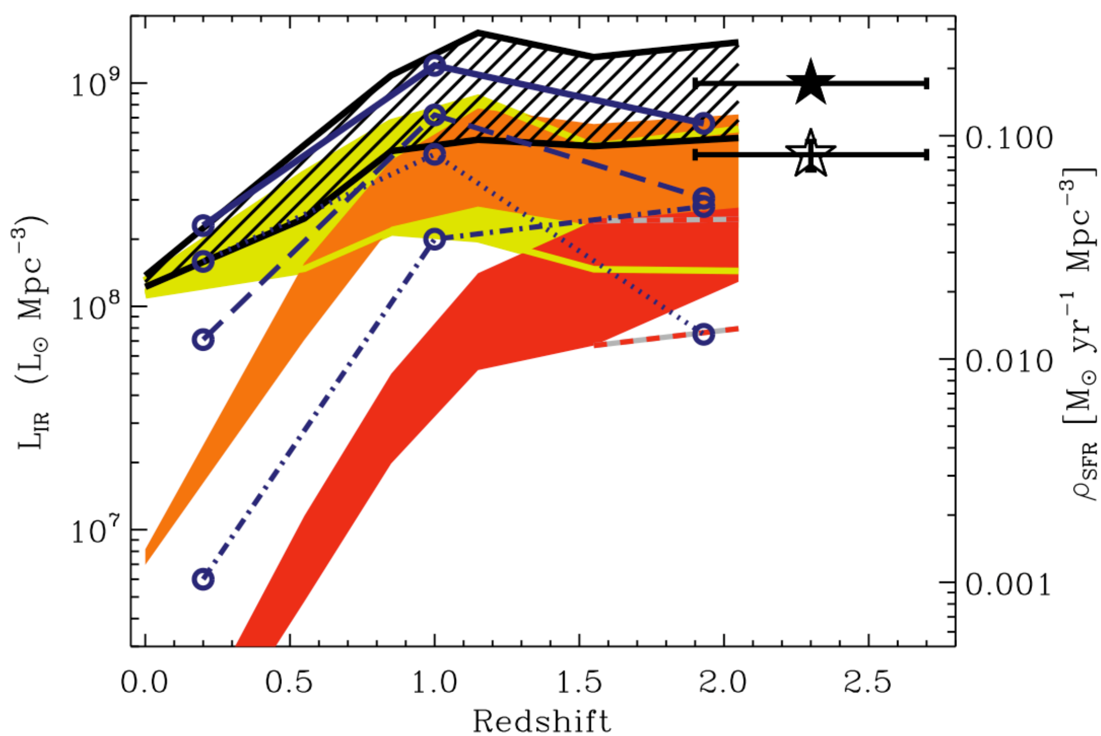


Revised integral SFR(z)

LIRGs (and perhaps "normal" galaxies as well) continue to rule at z~2

Magnelli et al. 2009b





Spitzer MIPS luminosity functions
Data summary

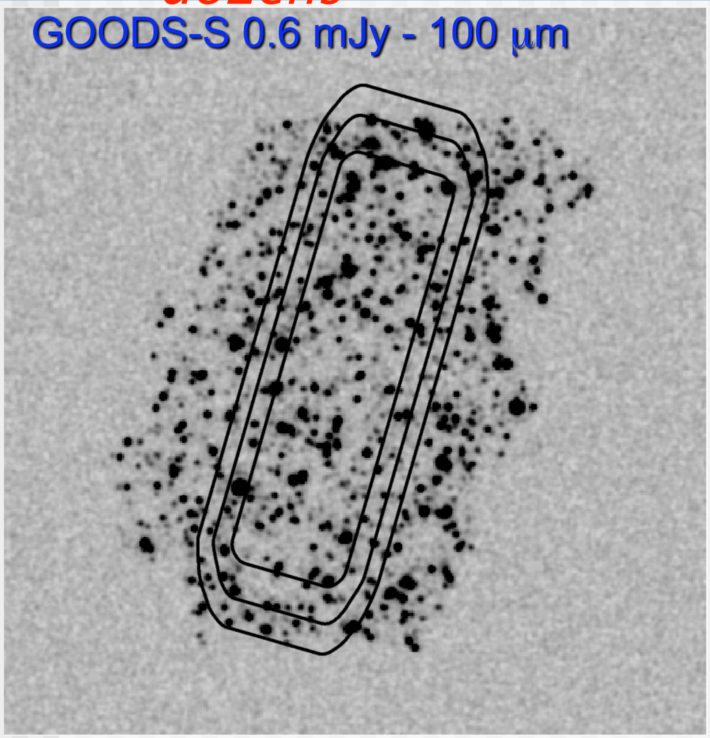
Reference	Field(s)	Area	Flux limits	# of sources
Le Floc'h+05 $0.3 < z < 1.2$	ECDFS	775 arcmin^2	f24 > 80 μJy	2600
Pérez-González +05 $0 < z < 3$	ECDFS, EHDFN	1180 arcmin^2 (z >> 1 mainly from GOODS, ~300 arcmin^2)	f24 > 80 μJy	8000
Caputi+07 $z \sim 1, 2$	GOODS-S+N	291 arcmin^2	f24 > 80 μJy	1371
Huynh+07 $0 < z < 1$	GOODS-N	185 arcmin^2	f70 > 2.0 mJy	143
Magnelli+09a $0.4 < z < 1.3$	GOODS-S+N, ECDFS, EGS	1350 arcmin^2	f24 > 30-70 μJy f70 > 2.5-3.5 mJy	9591 @ 24μm 680 @ 70μm
Magnelli+09b $1.3 < z < 2.3$	GOODS-S+N	285 arcmin^2	f24 > 30 μJy f70 > 2.5 mJy	2823 @ 24μm 149 @ 70μm

GOODS-Herschel:

The deepest view of the universe at 100-500 μm

PI: David Elbaz (CEA/Saclay) + international cast of dozens

GOODS-S 0.6 mJy - 100 μm



GOODS-N:

Matching GT GOODS-S program

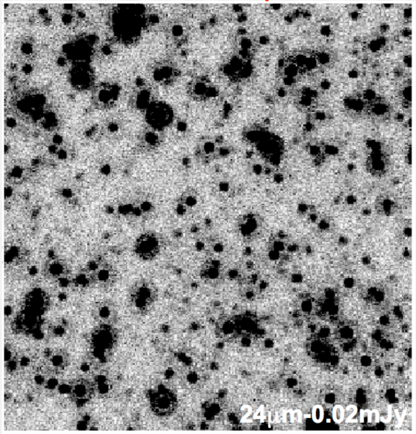
- PACS: 125h: 1.7 mJy @ 100μm
- SPIRE 31h: confusion limited @ 250-500 μm

GOODS-S:

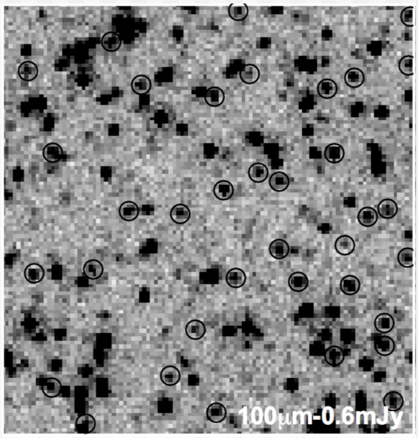
PACS ultradeep field, 207h

- 0.6 mJy @ 100μm over 30 $arcmin^2$
- 1.0 mJy @ 100μm over 83 $arcmin^2$

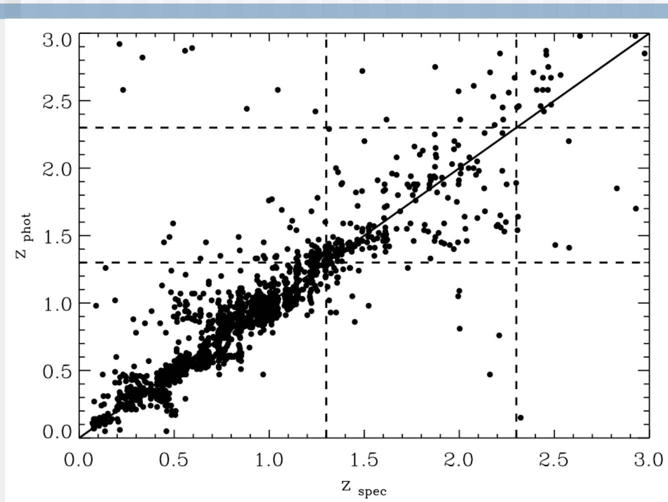
GOODS 24μm

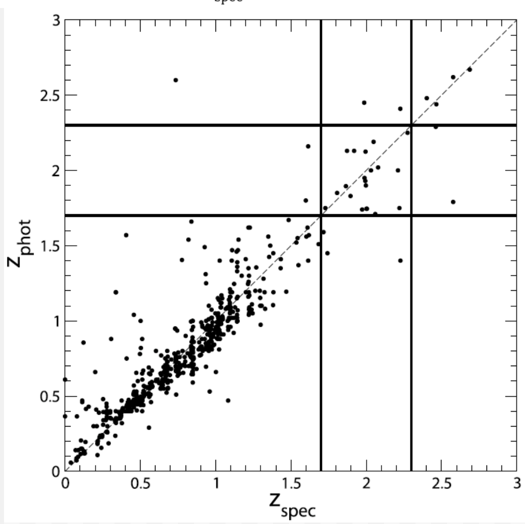


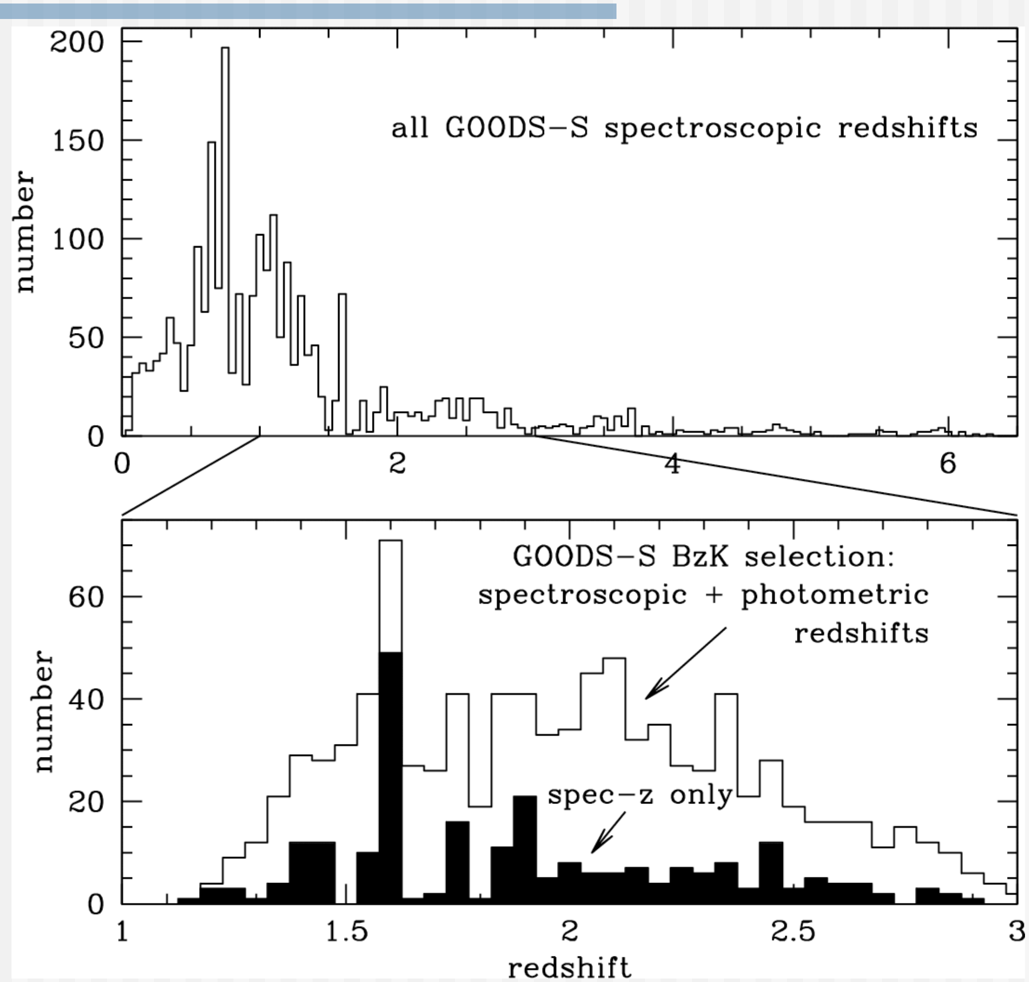
Simulated PACS 100μm



(Very) Heavy reliance on photometric redshifts and color selection, especially at z ~ 2

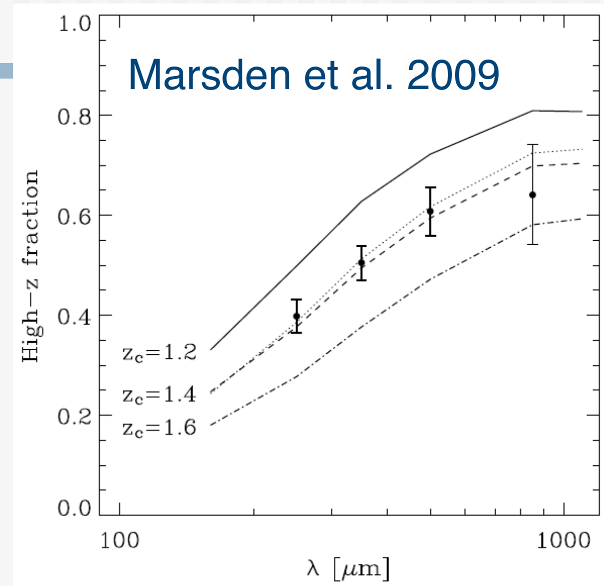


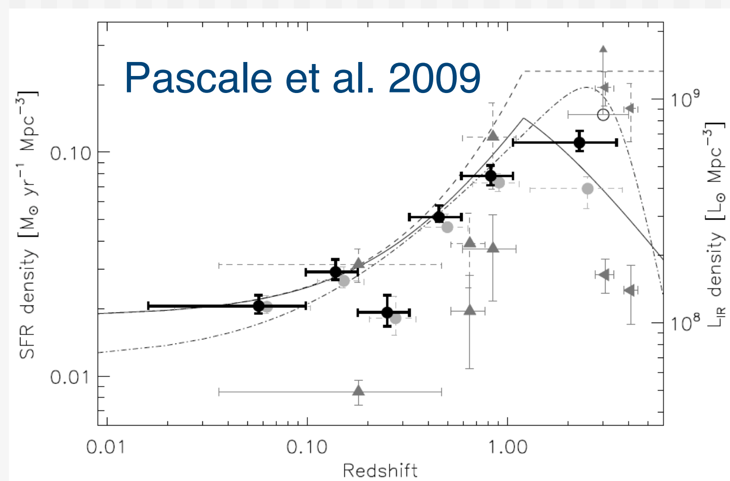




Far-IR + submm stacking analyses

- Dole et al. 2006: stacking MIPS 70μm and 160μm at 24μm source positions
  - Recovers ~70% of CIRB at 70μm and 160μm
  - Dominated by LIRGs at z ~ 1
    (as per Elbaz et al. 2002)
- BLAST 250-500μm stacking at 24μm source positions (Devlin et al. 2009, Marsden et al. 2009, Pascale et al. 2009)
  - Recovers 75-100% of CIRB at 250-500μm
  - 40 - 60% of 250-500μm CIRB from z > 1.2
- But…Chary & Pope (submitted) disagree, concluding that >70% of CIRB at λ < 500μm comes from z < 1.5

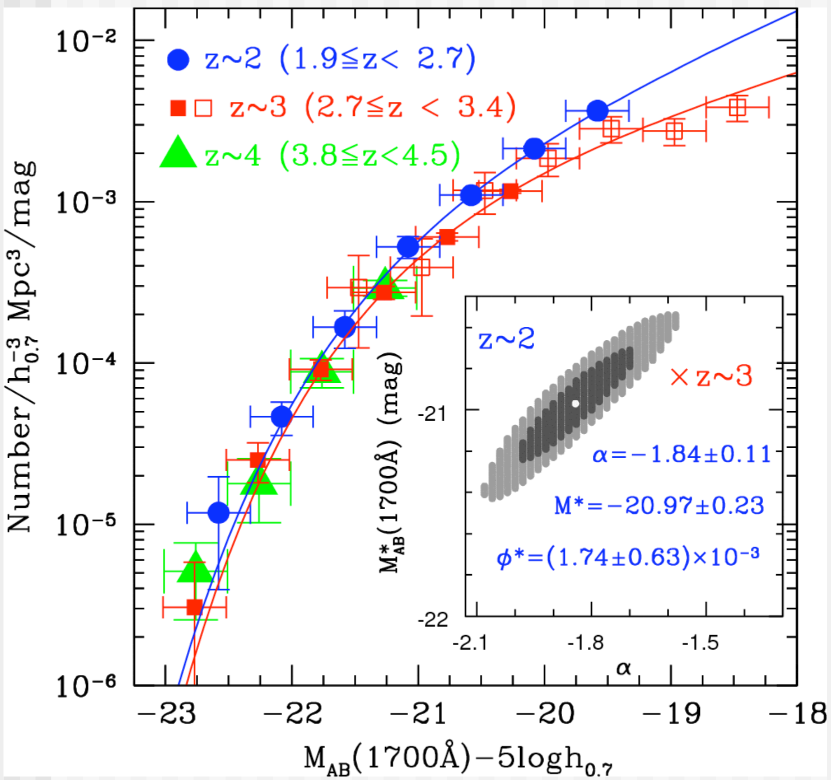




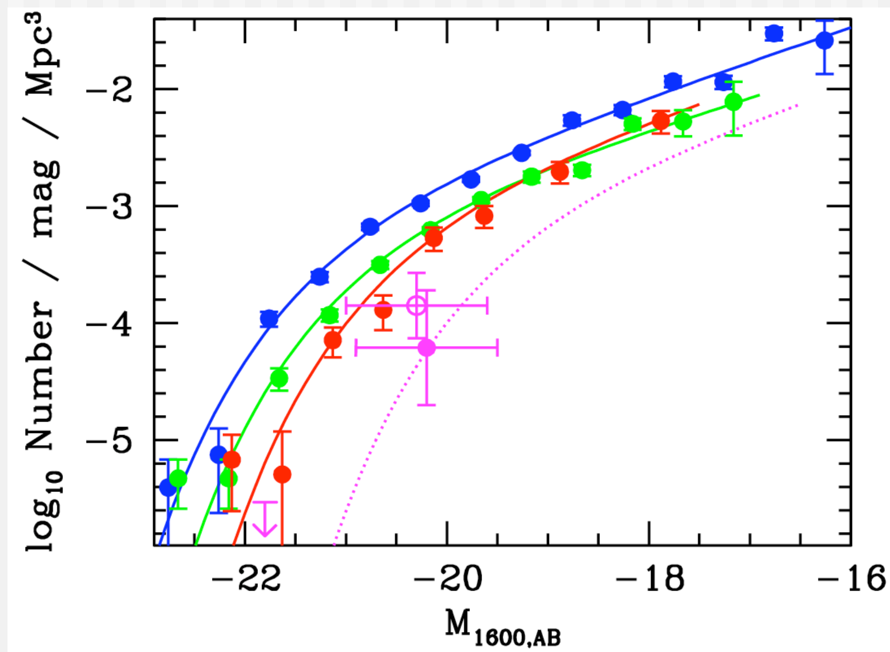
Rest-Frame UV Luminosity Functions, 2 < z < 6+

At z > 2, most of our current information on SF comes from the rest-frame UV.
Very steep UVLF faint end slope (α ~ -1.7); large contribution from sub-L* galaxies

z ~ 2, 3, 4 (Reddy et al. 2007)



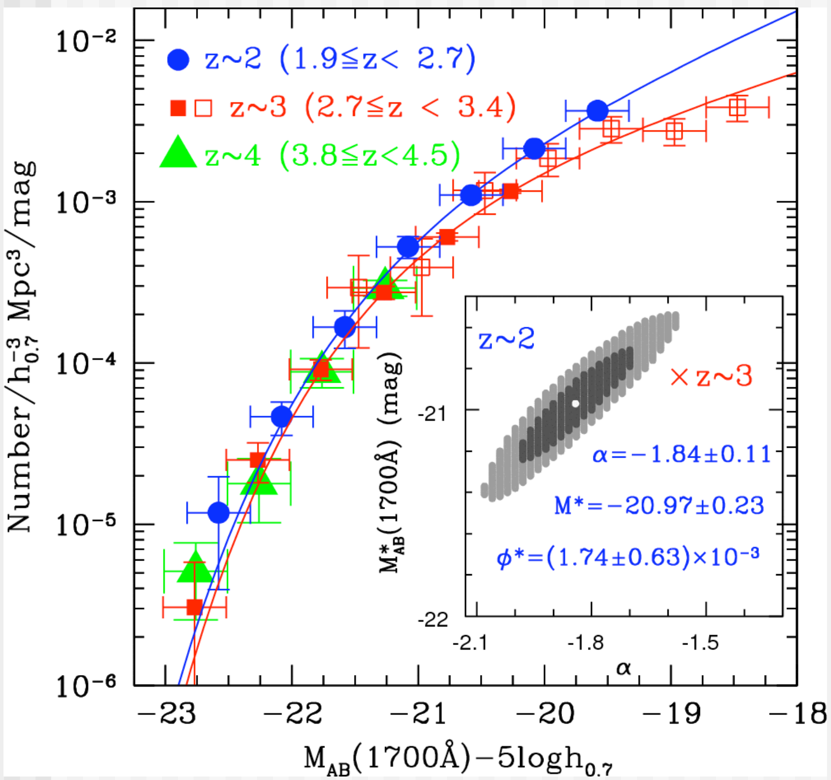
z ~ 4, 5, 6 (Bouwens et al. 2007)



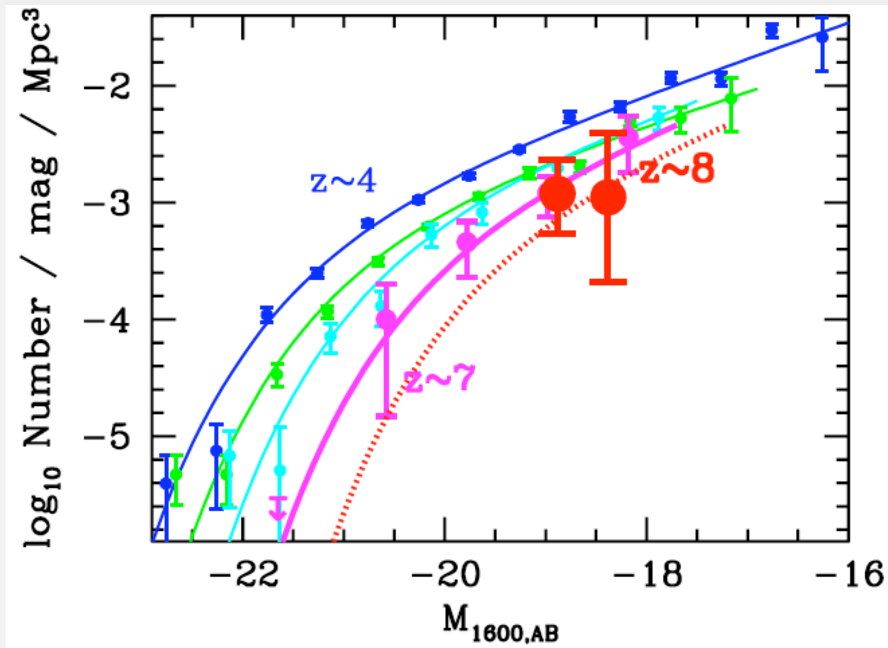
Rest-Frame UV Luminosity Functions, 2 < z < 6+

At z > 2, most of our current information on SF comes from the rest-frame UV.
Very steep UVLF faint end slope (α ~ -1.7); large contribution from sub-L* galaxies

z ~ 2, 3, 4 (Reddy et al. 2007)



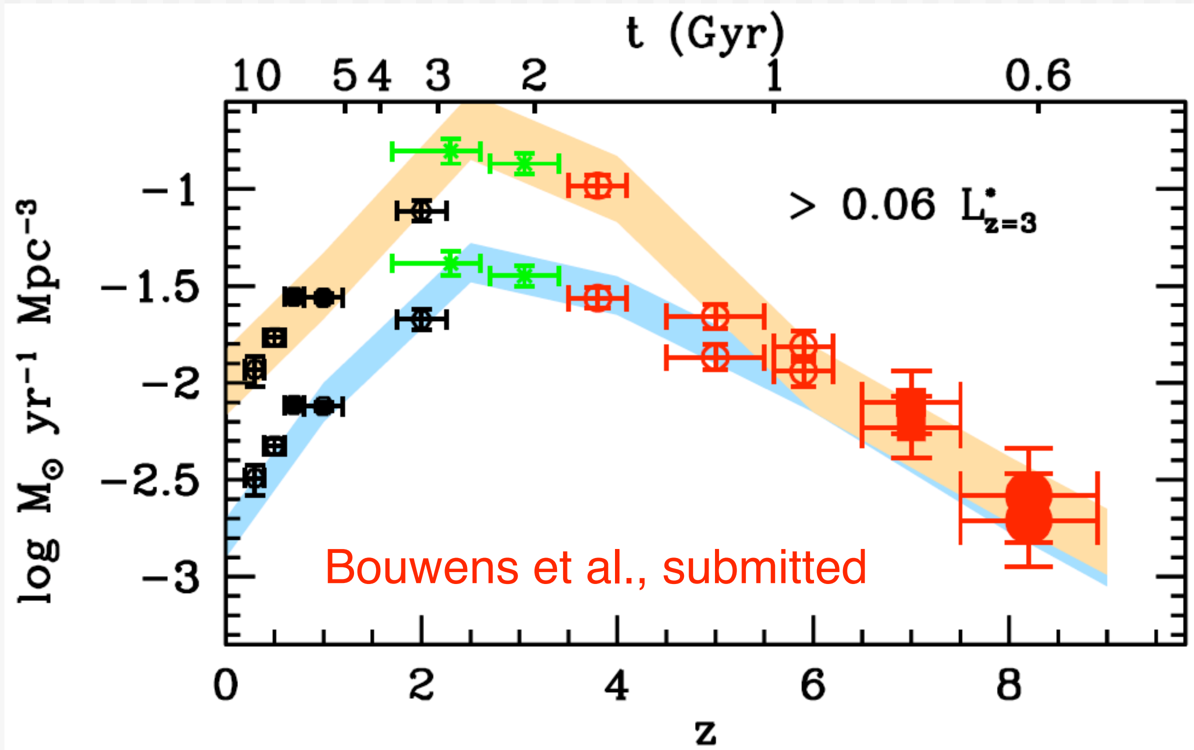
z ~ 4, 5, 6, 7, 8
(Oesch et al., Bouwens et al., submitted)



SFR(z)

Best current UV-based estimates indicate SFR(t) rising to z~3, then rolling over.

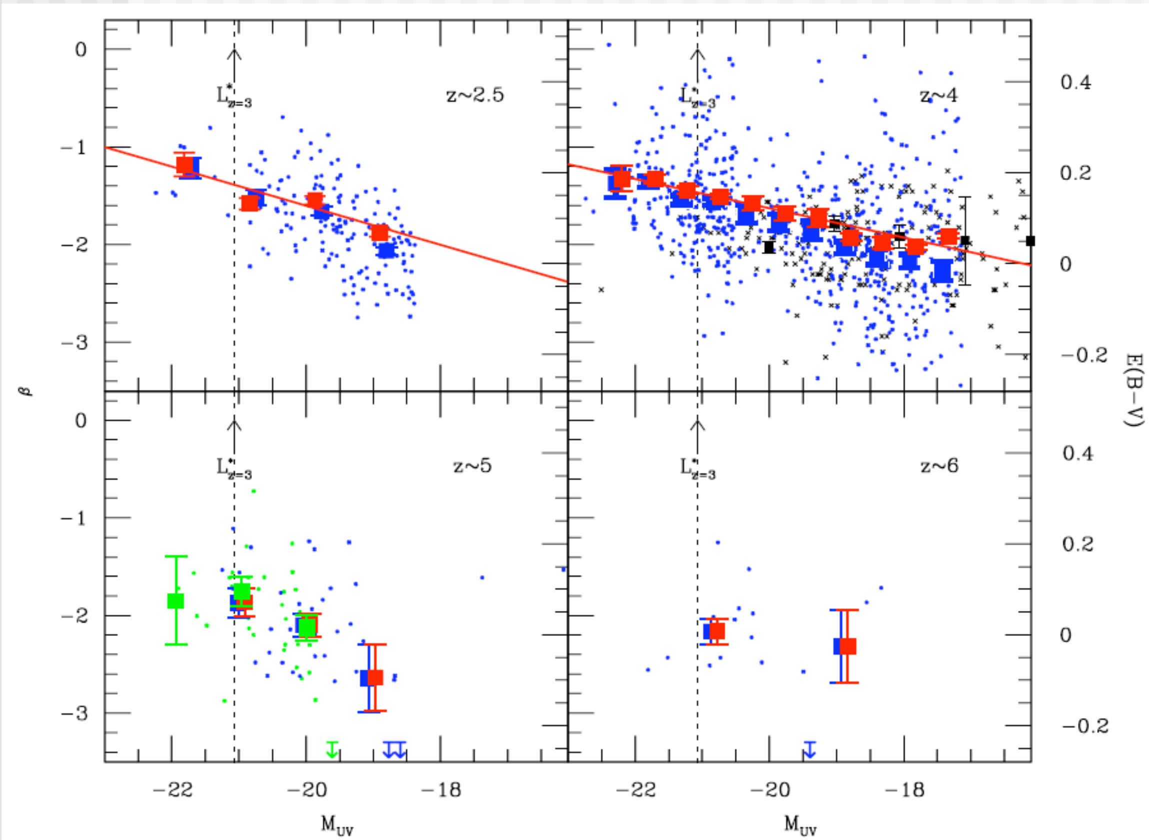
Increasing dust extinction at z < 4 implies larger corrections to the UV-based SFR(z)

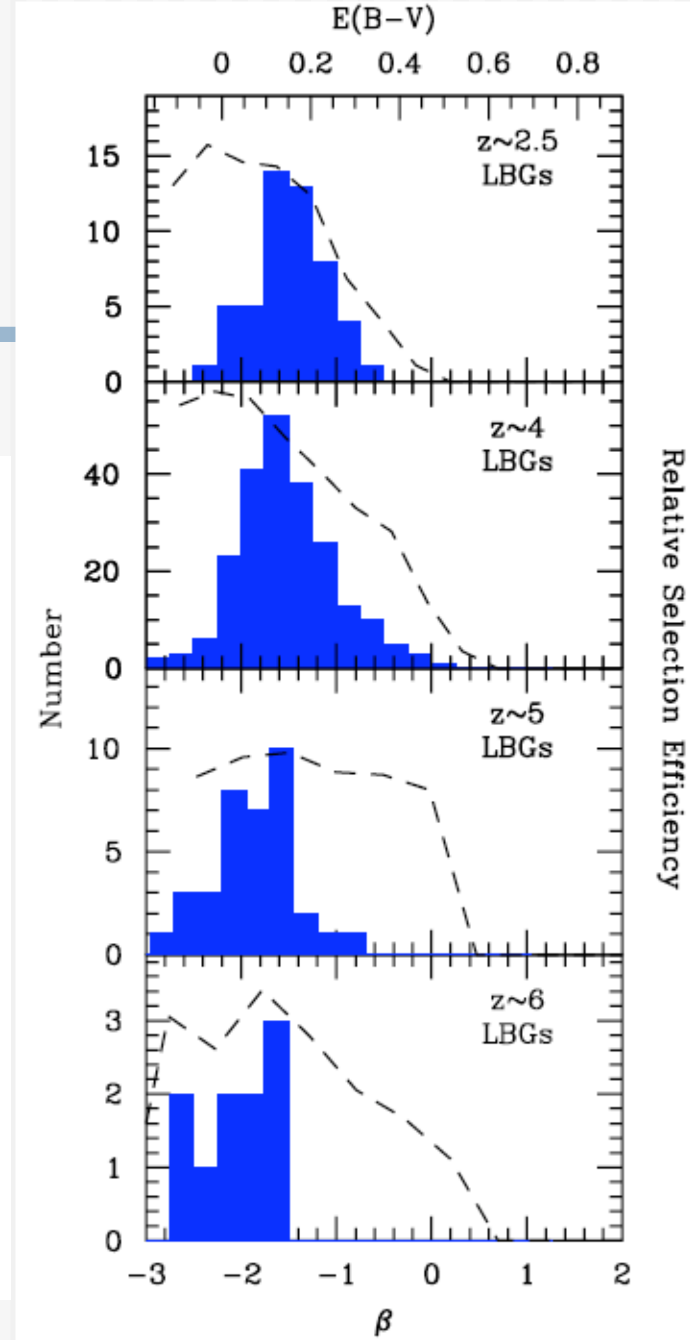


Evolution in UV reddening of LBGs at 2.5 < z < 6

Bouwens et al. 2009

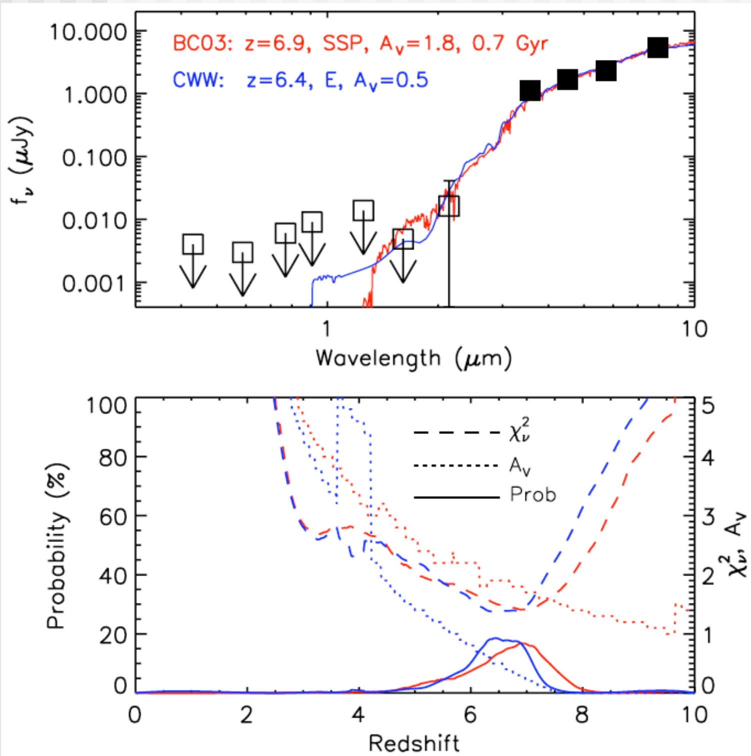
see also Lehnert & Bremmer 2003, Ouchi et al. 2004, Yan et al. 2005, Stanway et al. 2005

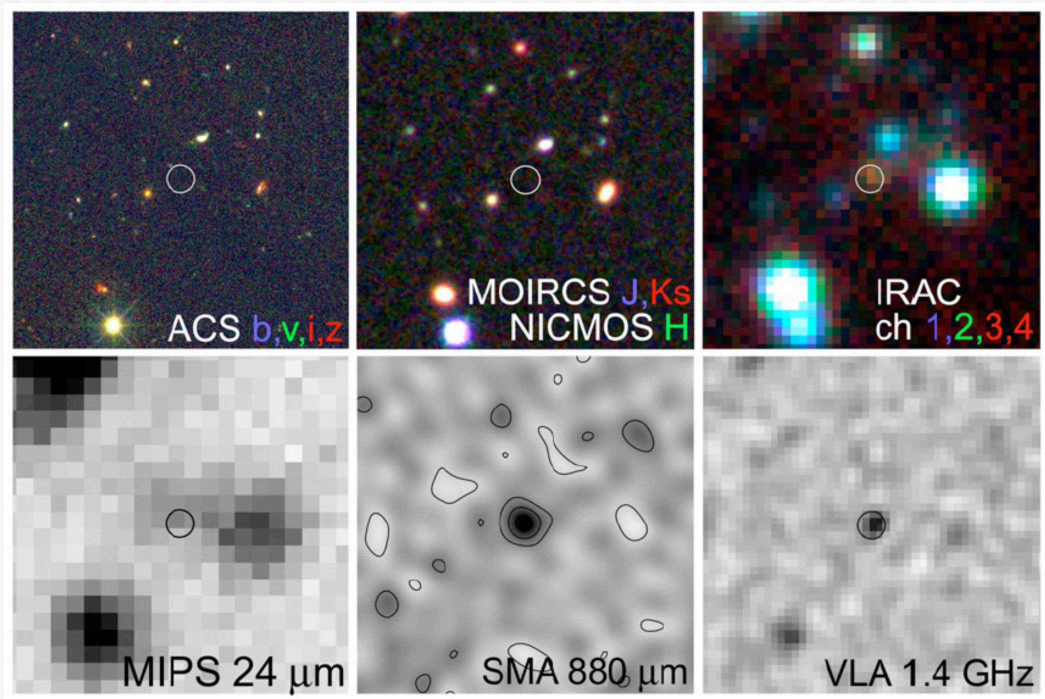




GN10: a submm galaxy undetected at λ < 3 μm

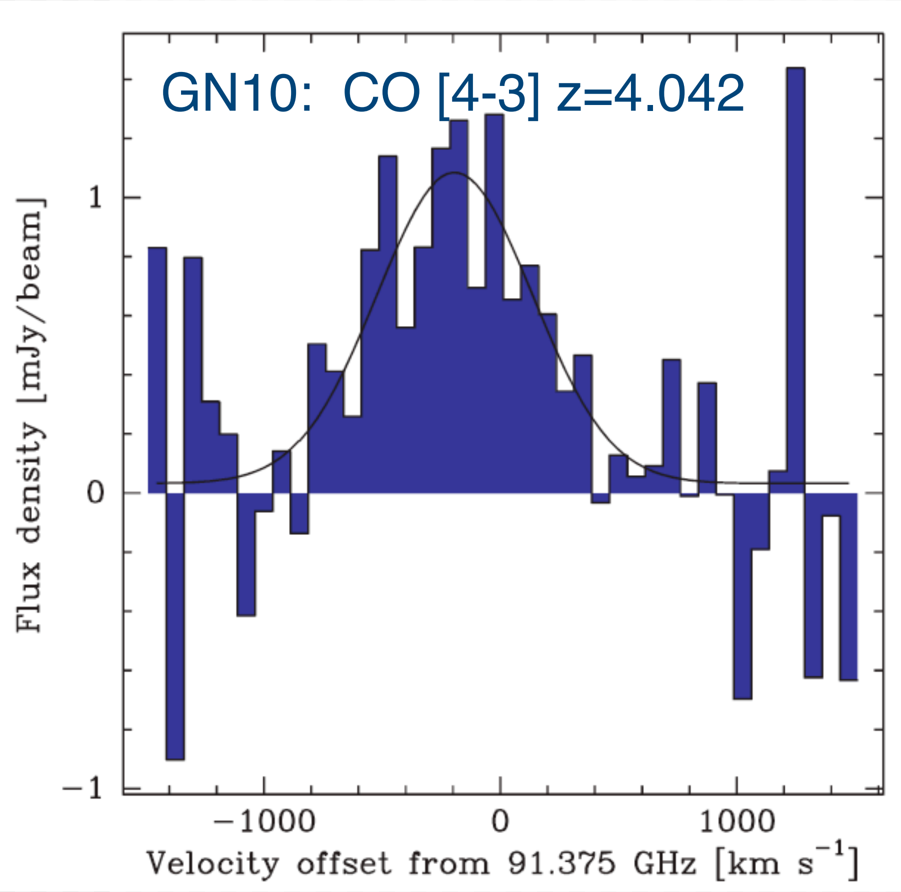
Wang, Cowie & Barger 2009

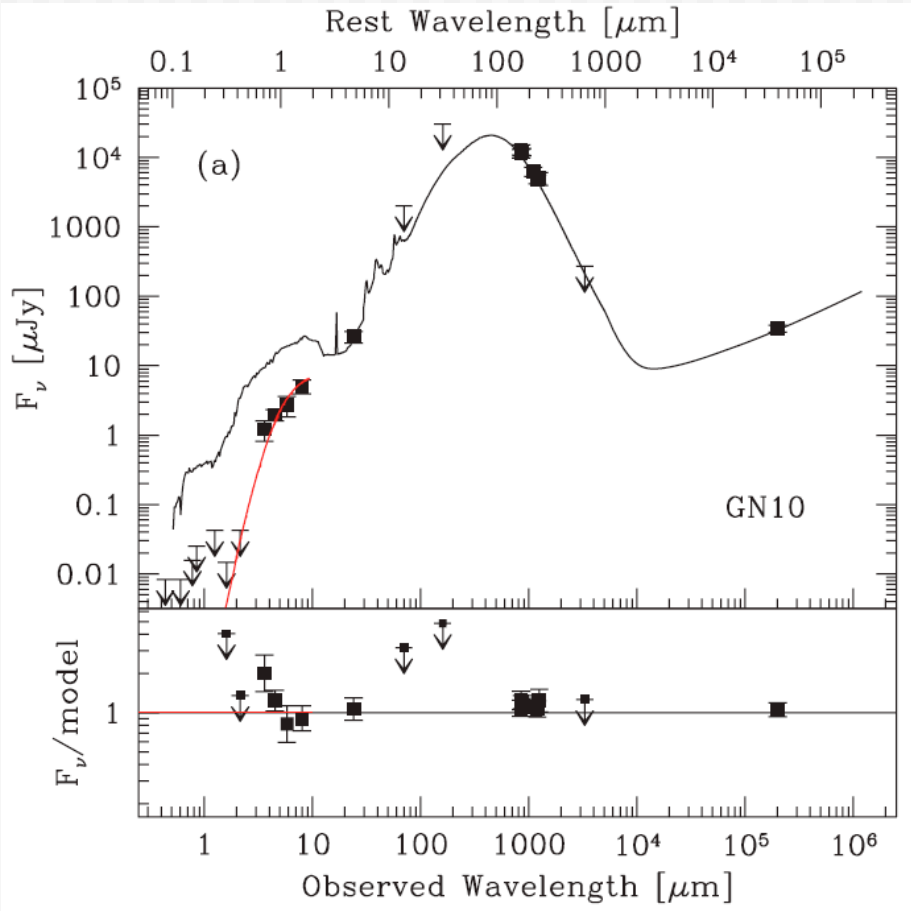




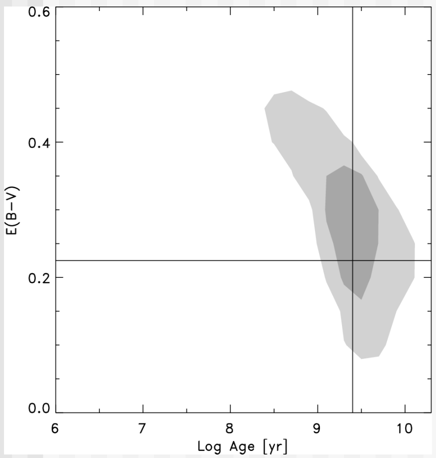
GN10: z=4.042 from CO

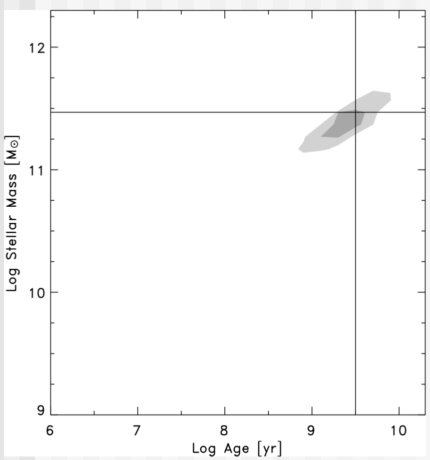
Daddi et al. 2009; part of GOODS-N “SMG protocluster” at z=4.05
L(IR) = 2 x 10^{13} $L_{o;}$ Growing number of SMG identifications at z > 4
(Daddi et al. 2008; 2009; Capak et al. 2008; Coppin et al. 2009)

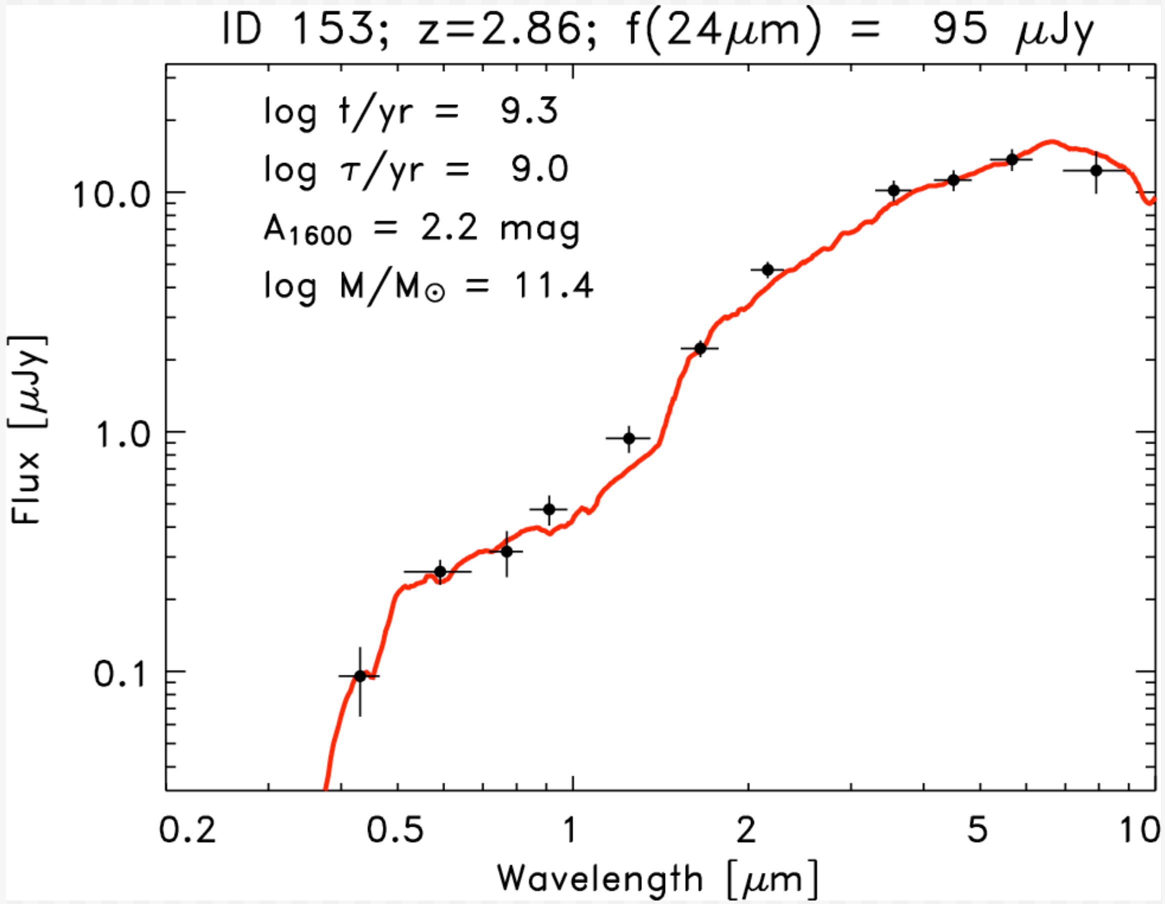




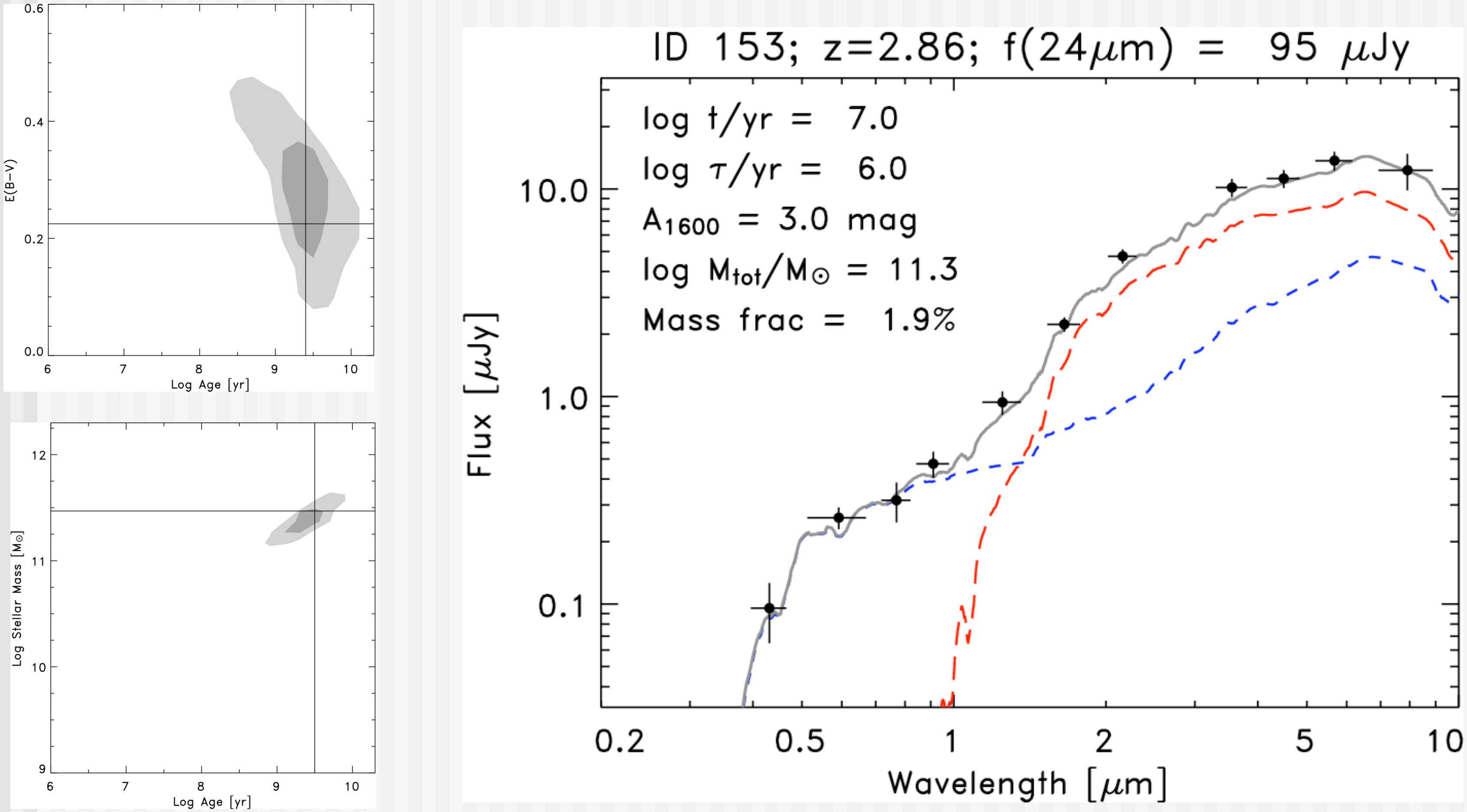
Mass from light



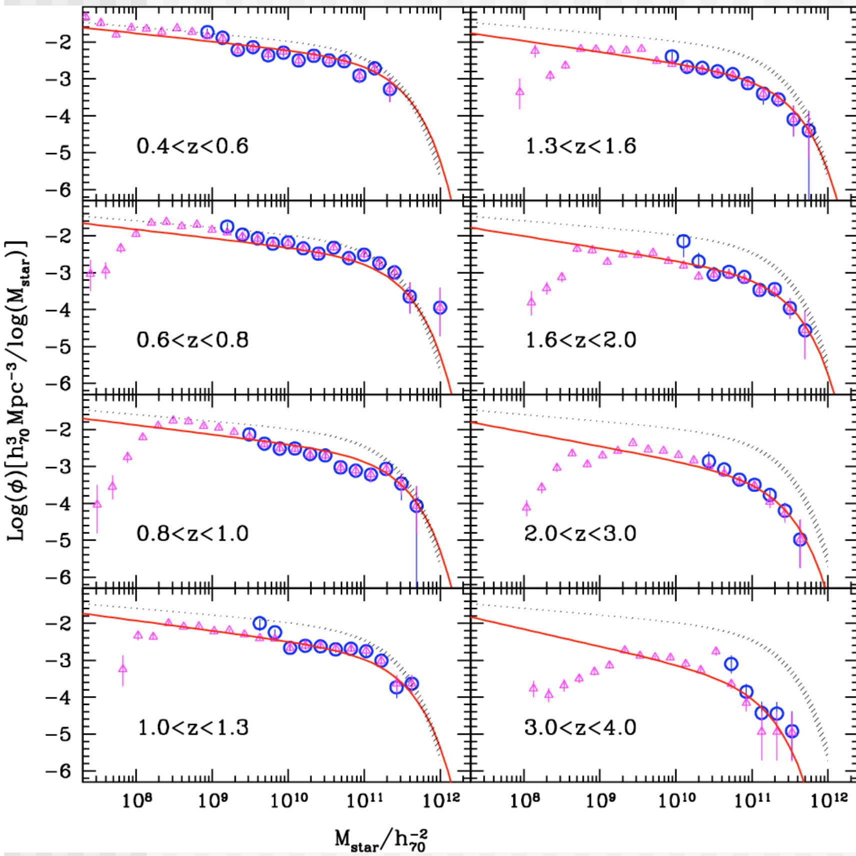


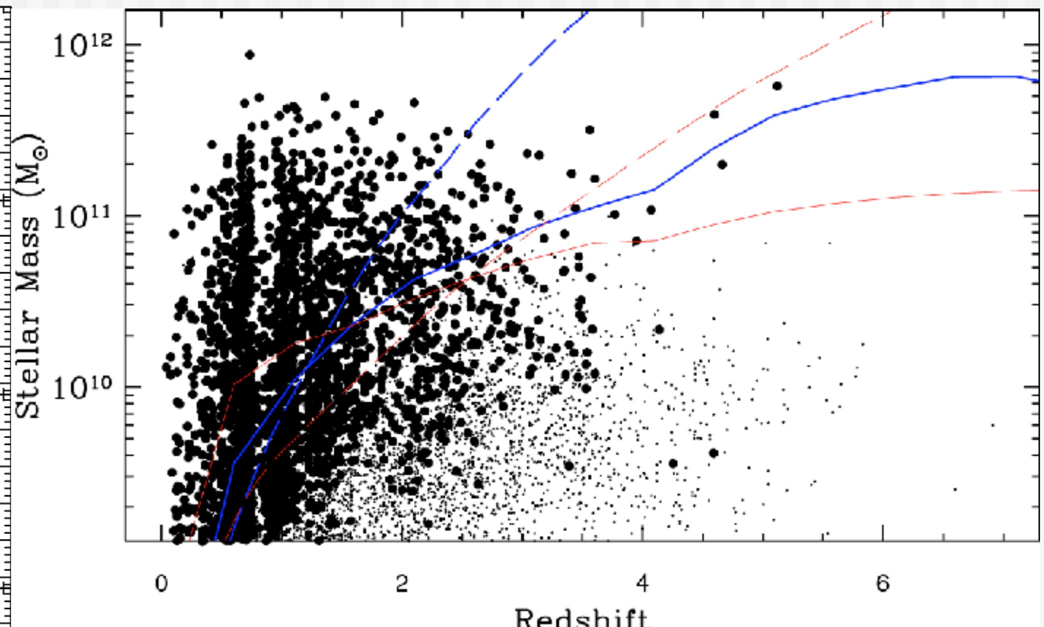


Mass from light



Stellar mass at high redshift





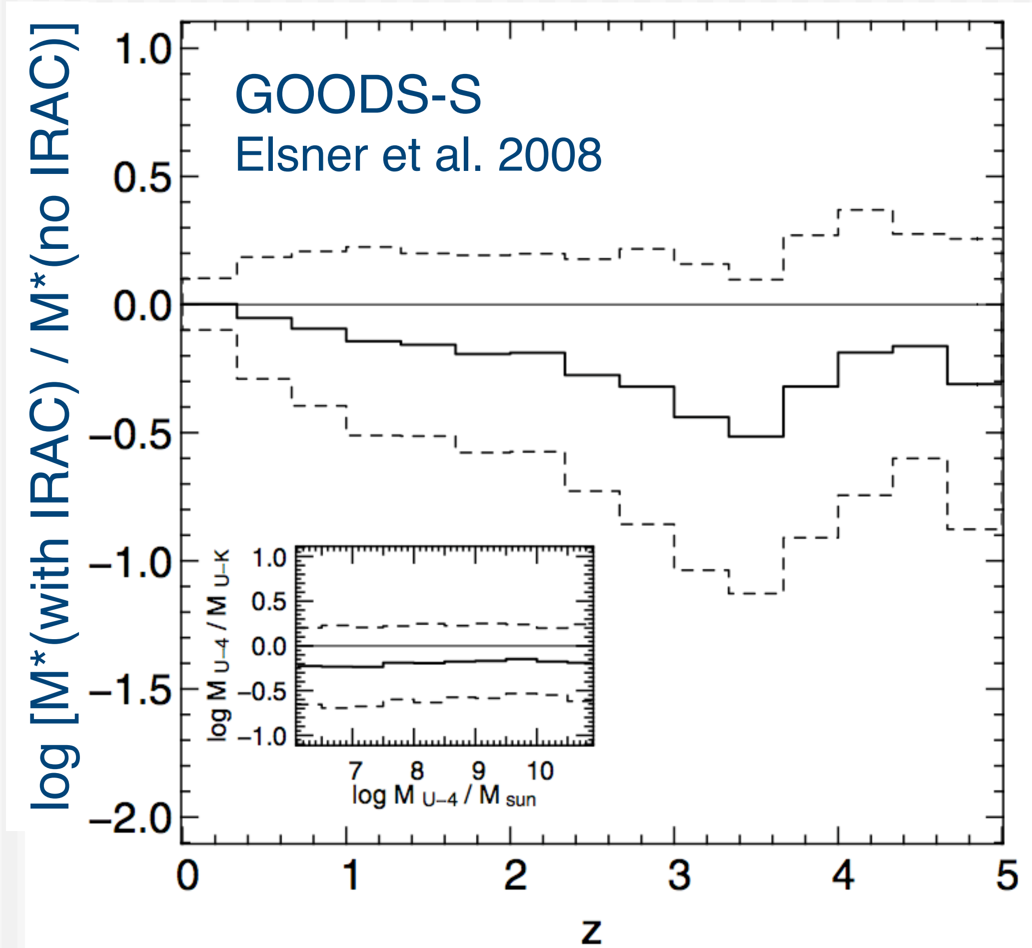
Fontana et al. 2006
GOODS with Spitzer, z < 4

The importance of IRAC

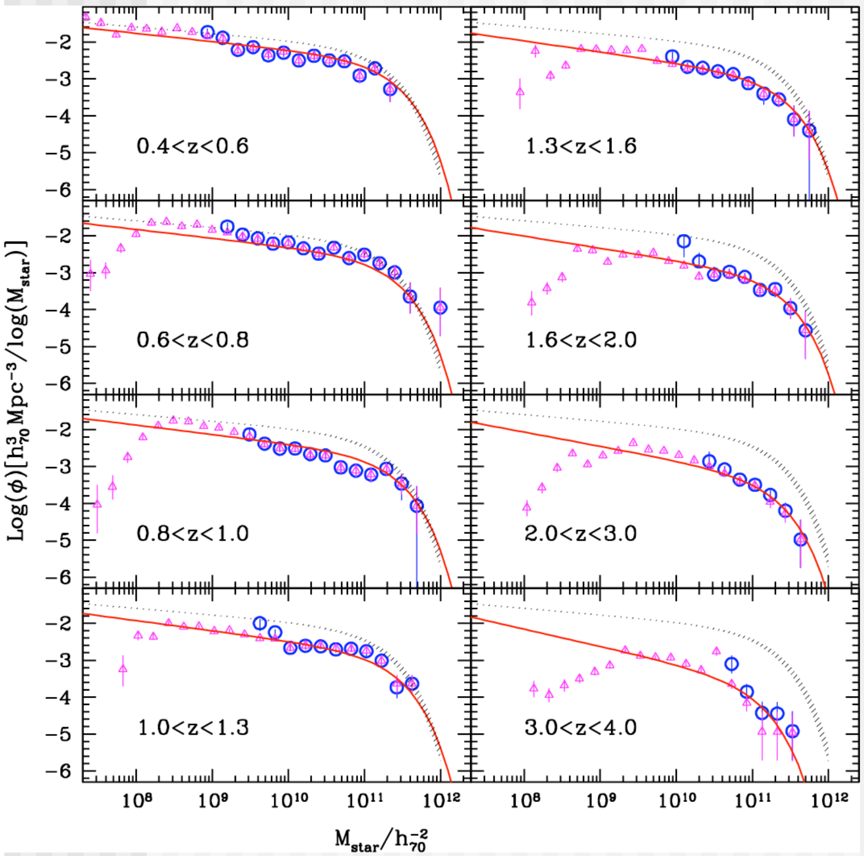
At z > 4, IRAC provides the only means to directly measure rest-frame optical light and reliably estimate stellar mass.

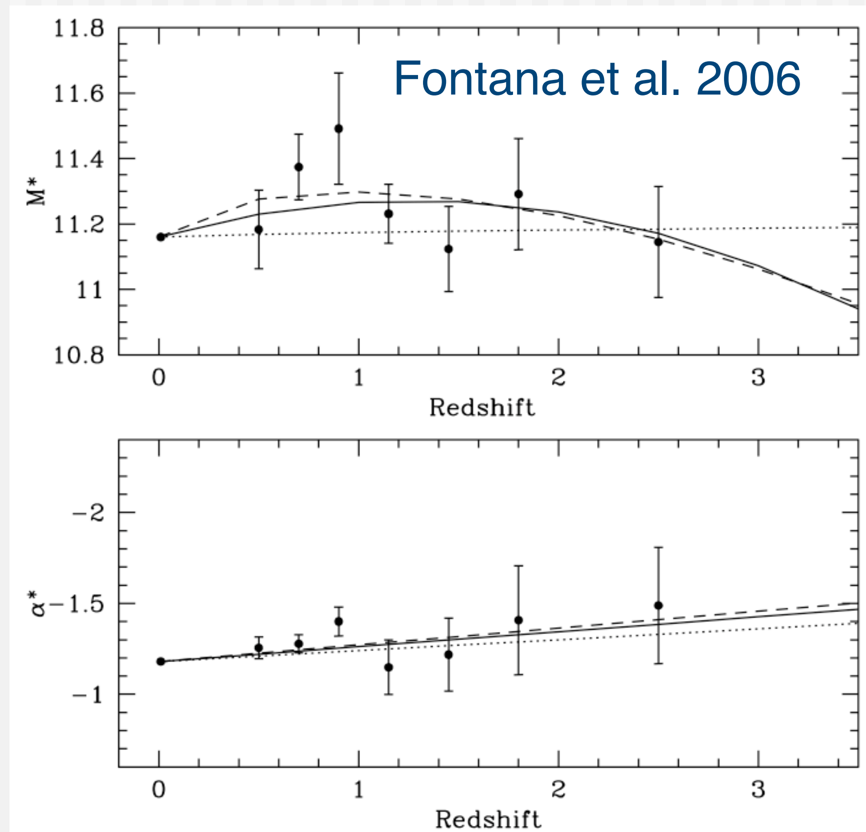
Stellar masses derived *including* IRAC data tend to be smaller than those *without* IRAC.
This effect increases at z > 2.

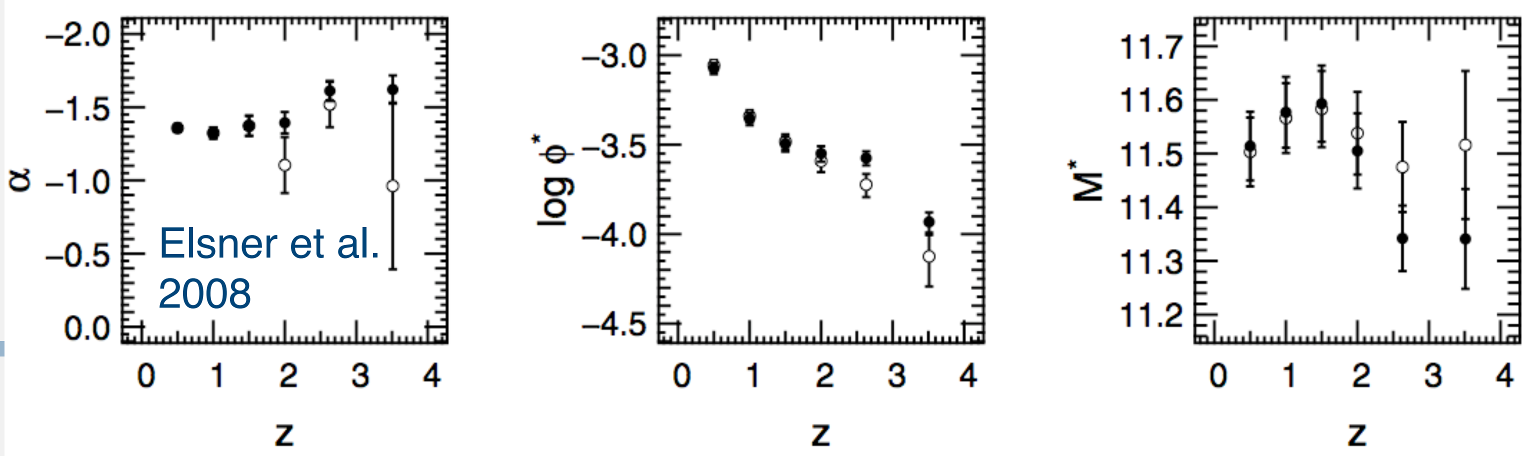
Stellar population models with increased TP-AGB red starlight (e.g. Maraston 2005) furter amplify this trend.

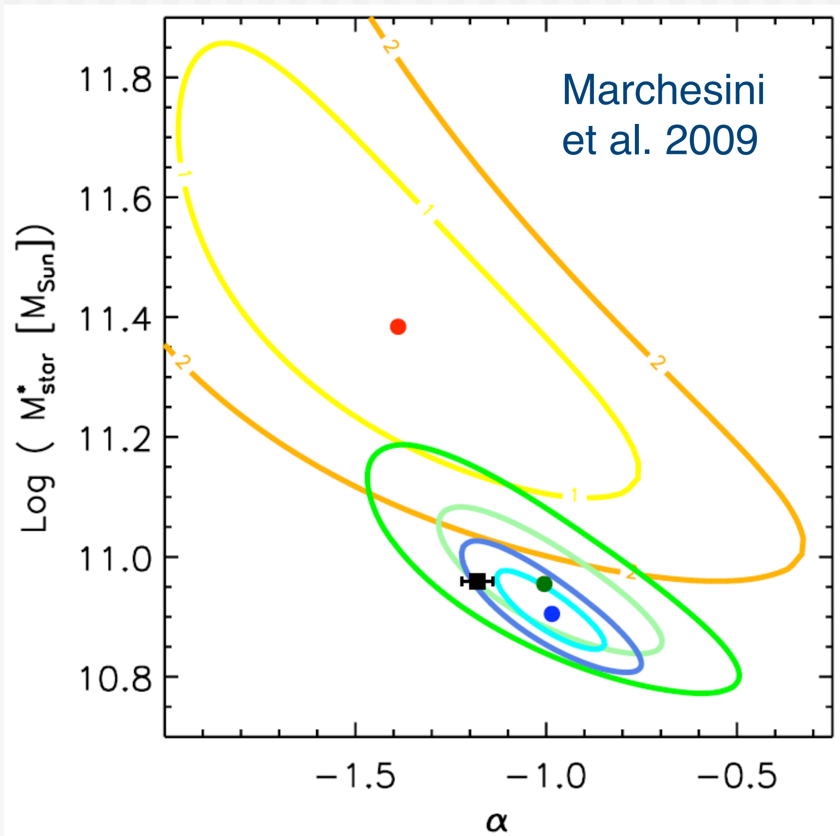


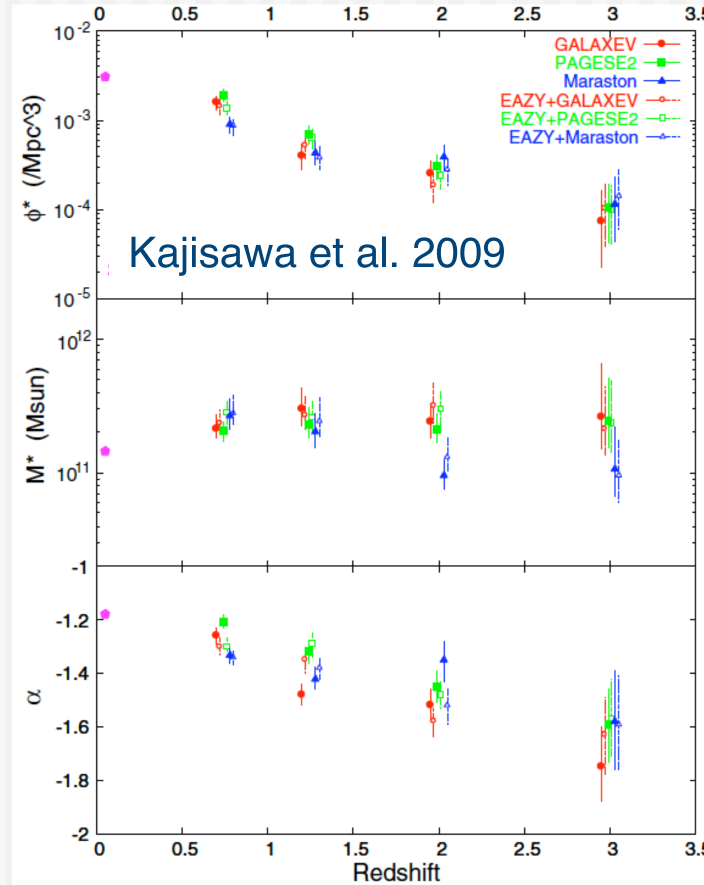
Evolution of the stellar mass function

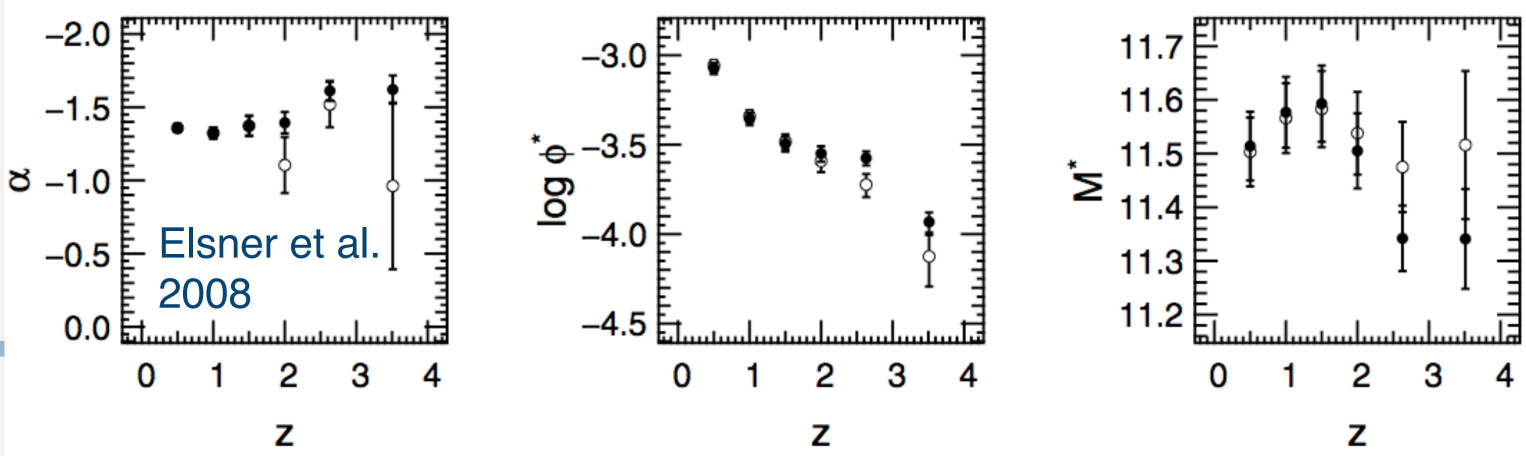


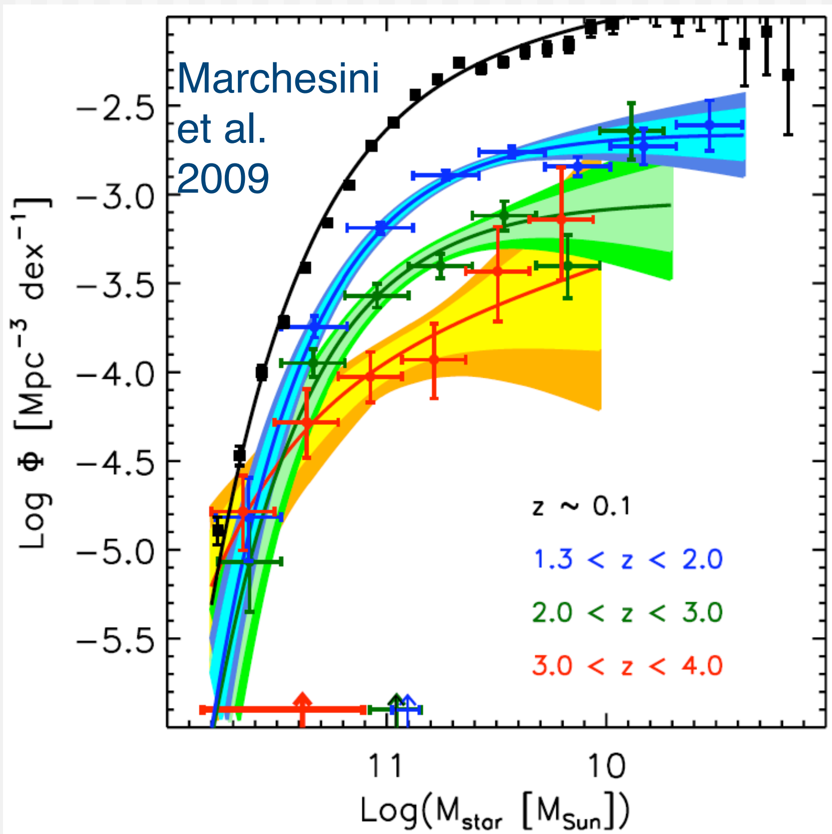


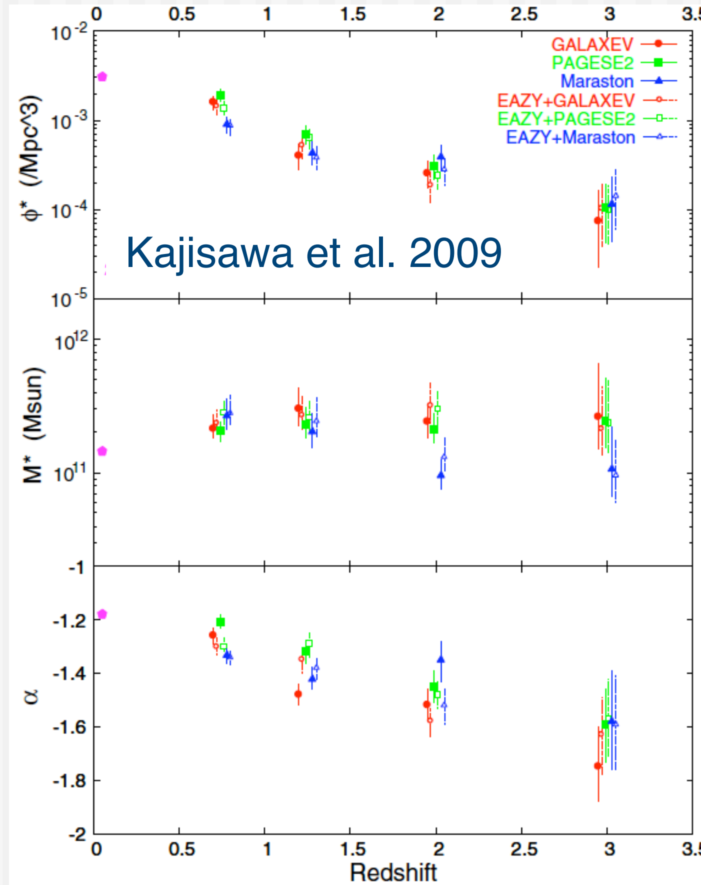

Elsner et al. 2008
α
log φ*
M*
z
z
z


Marchesini et al. 2009
Log (M*star [MSun])
α

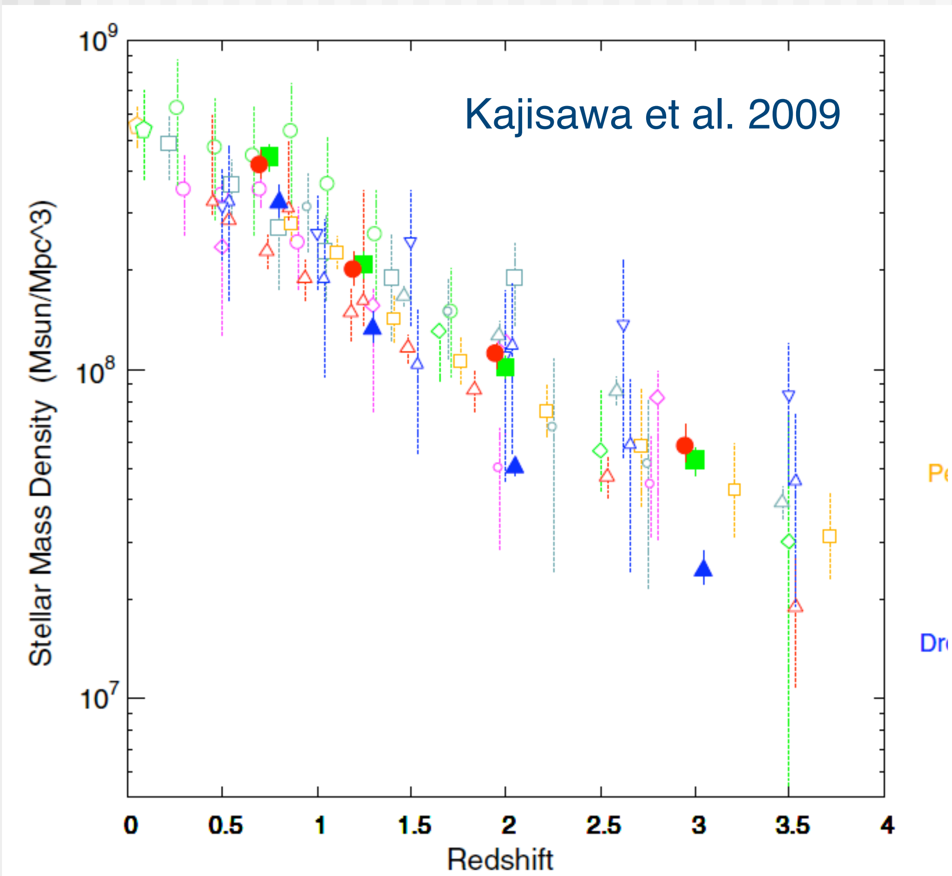

Kajisawa et al. 2009
GALAXEV
PAGESE2
Maraston
EAZY+GALAXEV
EAZY+PAGESE2
EAZY+Maraston
φ* (/Mpc^3)
M* (Msun)
α
Redshift

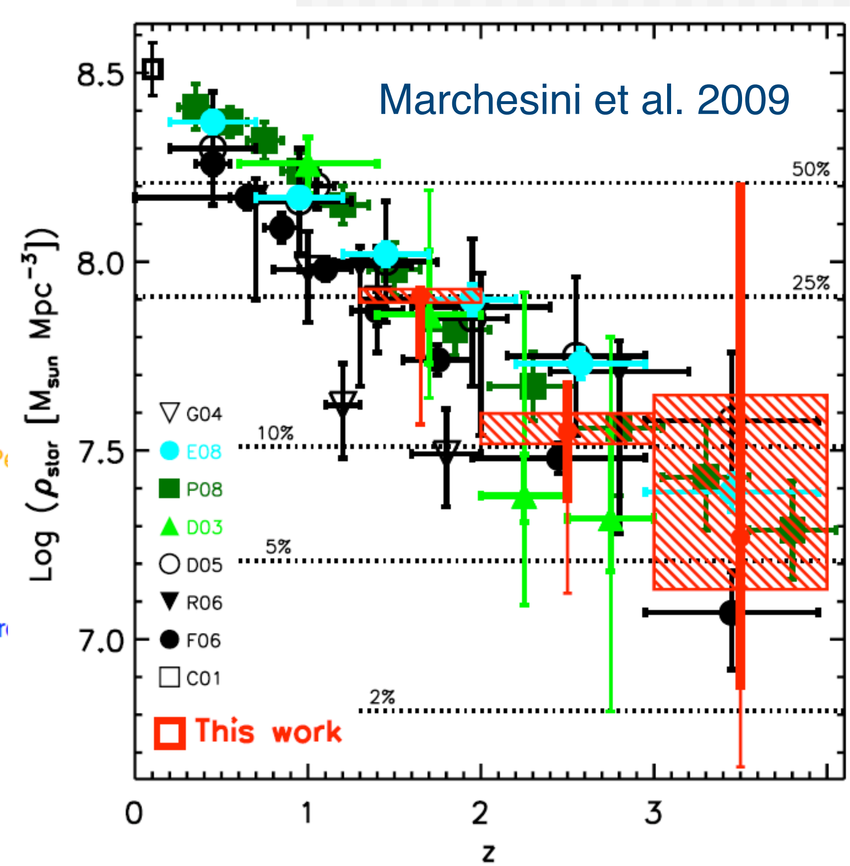

Elsner et al. 2008
α
log φ*
M*
z
−2.0
−1.5
−1.0
−0.5
0.0
−3.0
−3.5
−4.0
−4.5
11.7
11.6
11.5
11.4
11.3
11.2
0
1
2
3
4


Marchesini et al. 2009
Log Φ [Mpc−3 dex−1]
Log(Mstar [MSun])
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
11
10
z ~ 0.1
1.3 < z < 2.0
2.0 < z < 3.0
3.0 < z < 4.0


Kajisawa et al. 2009
GALAXEV
PAGESE2
Maraston
EAZY+GALAXEV
EAZY+PAGESE2
EAZY+Maraston
φ* (/Mpc^3)
M* (Msun)
α
Redshift
0
0.5
1
1.5
2
2.5
3
3.5
-1
-1.2
-1.4
-1.6
-1.8
-2

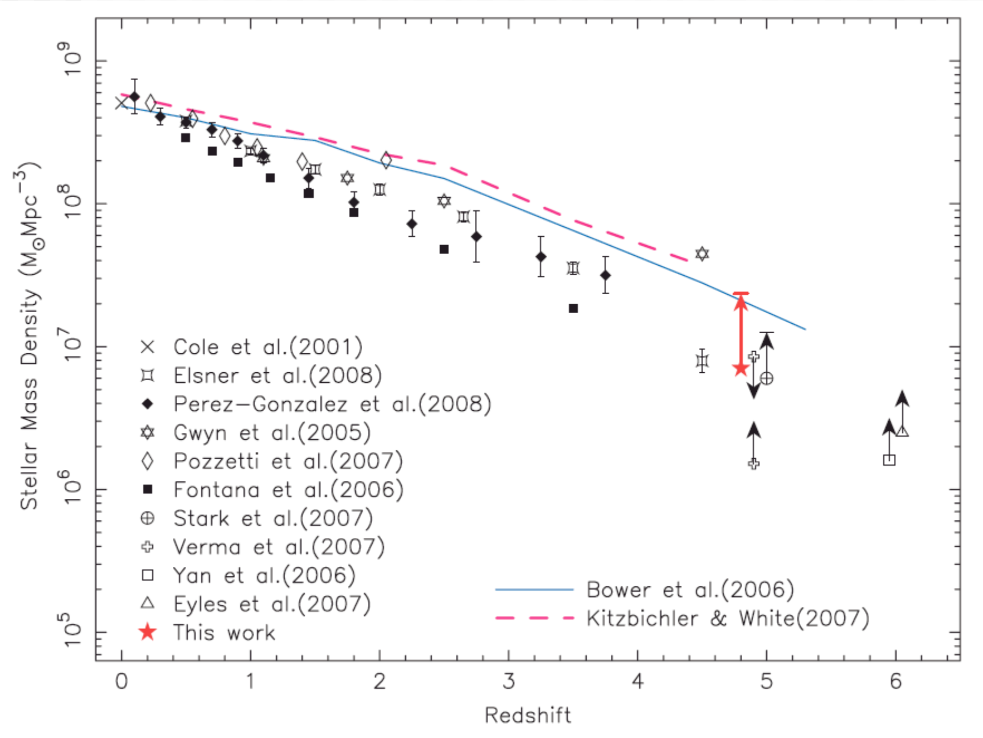
Stellar mass density vs. redshift



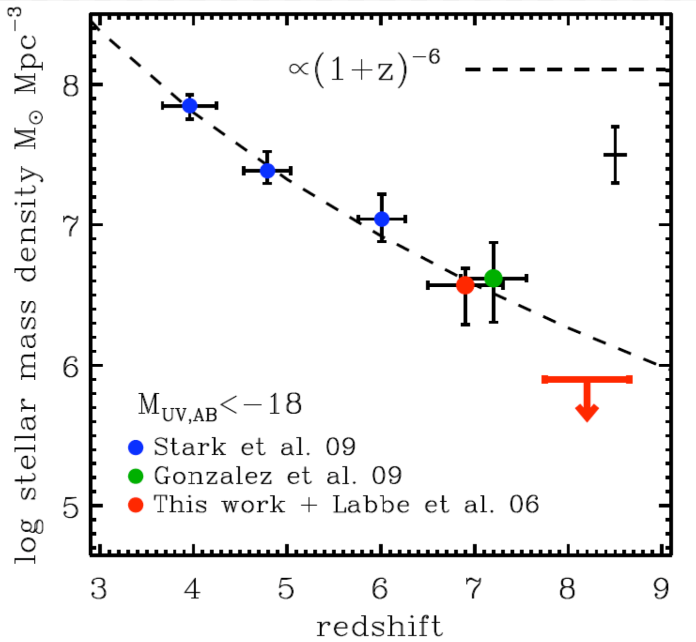


Stellar mass densities at z > 4

Yabe et al. 2009 (+ many others)



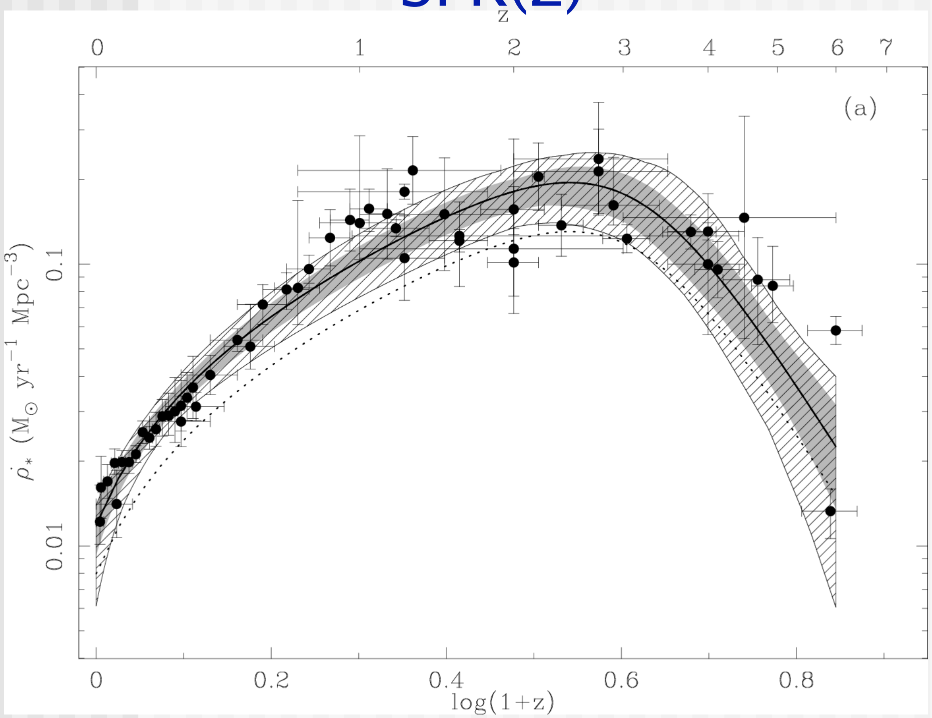
Labbé et al., Gonzalez et al. submitted
NICMOS+WFC3 LBGs z~7-8
Stark et al. 2009 (LBGs 4 < z < 6)



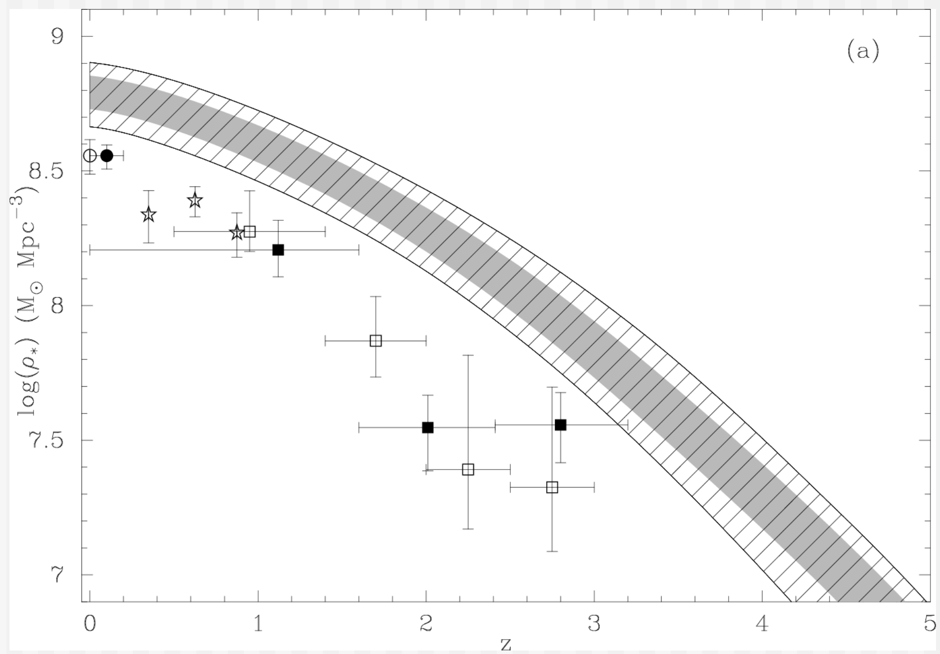
SFR(z) vs. Ω*(z): tension at all redshifts?

Derived SFR(z) *may* overproduce derived Ω*(z) at most redshifts

SFR(z)



$\Omega_{stars}(z)$

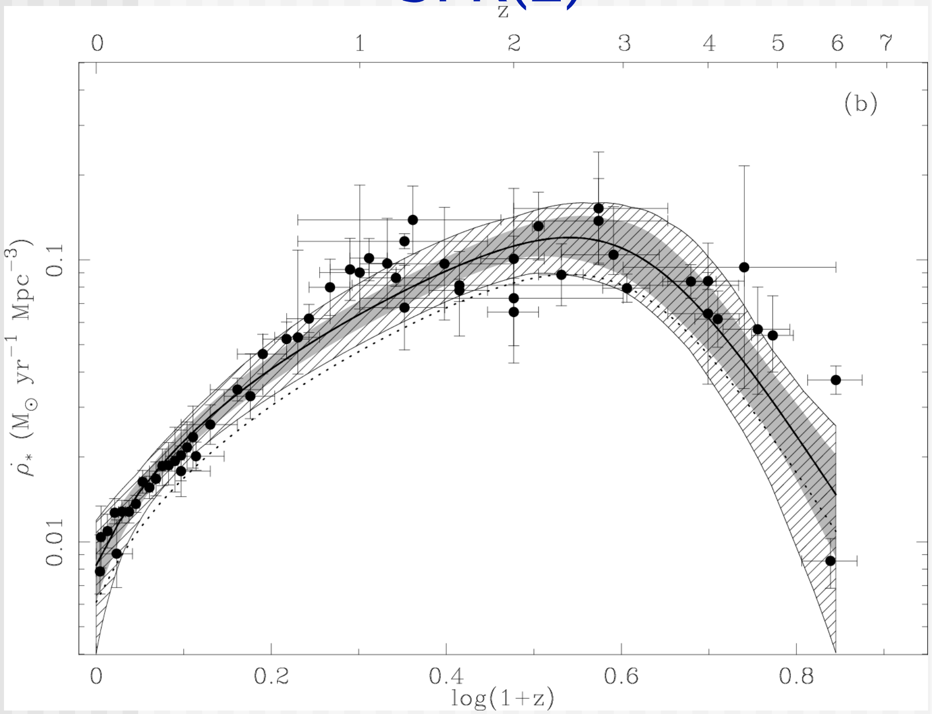


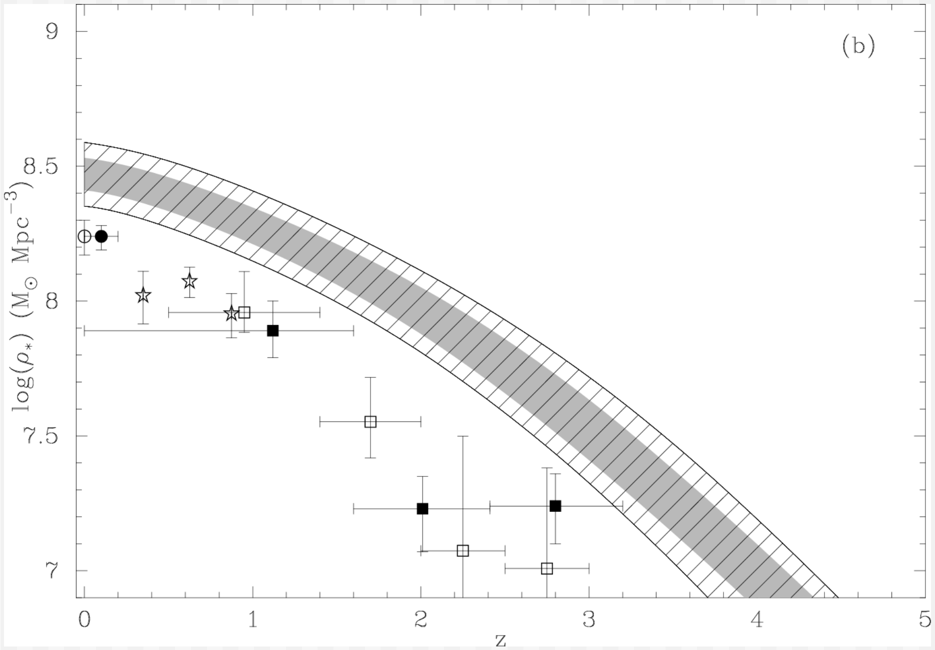
Hopkins & Beacom 2006; see also Chary & Elbaz 2001; Dickinson et al. 2003;; Borch et al. 2006; Pérez-González et al. 2008; Cowie & Barger 2008

SFR(z) vs. Ω*(z): tension at all redshifts?

Derived SFR(z) *may* overproduce derived Ω*(z) at most redshifts

SFR(z) $\Omega_{stars}(z)$





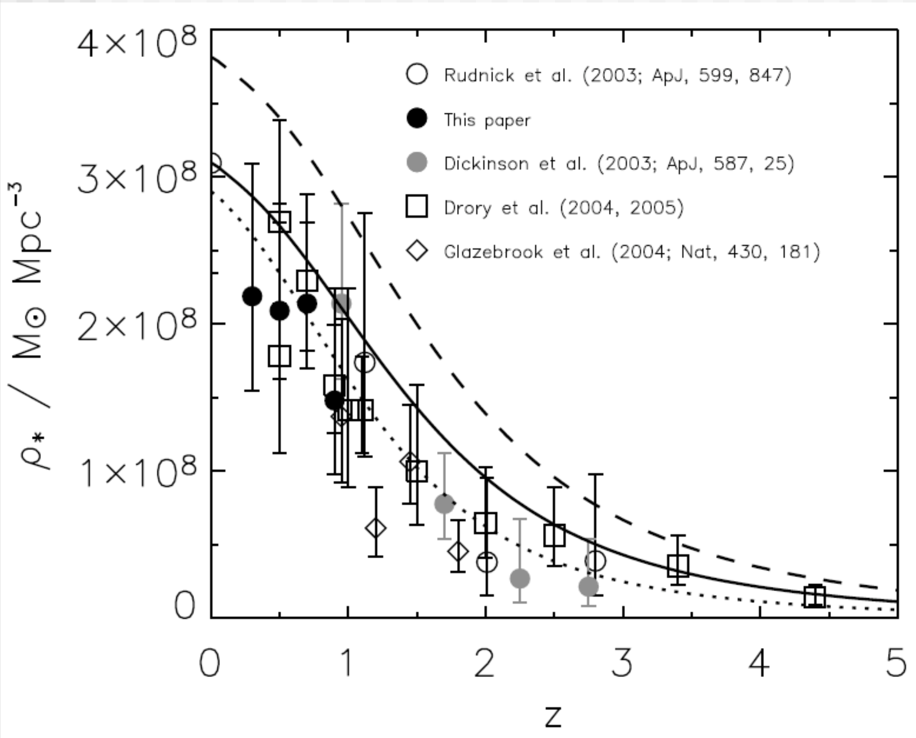
Hopkins & Beacom 2006; see also Chary & Elbaz 2001; Dickinson et al. 2003;; Borch et al. 2006; Pérez-González et al. 2008; Cowie & Barger 2008

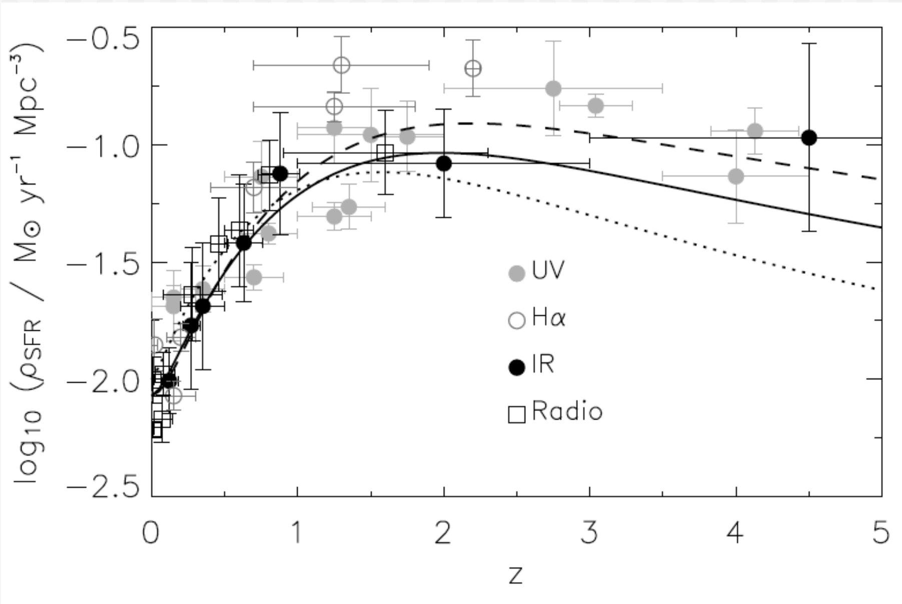
Is it really that bad?

Not everyone agrees.

Only mild discrepancies at z < 1

(Data on both SFR(z) and $\rho_*(z)$ at z < 1 are surprisingly poor!
But are getting better - e.g., Ilbert et al. 2009 stellar mass functions from COSMOS)



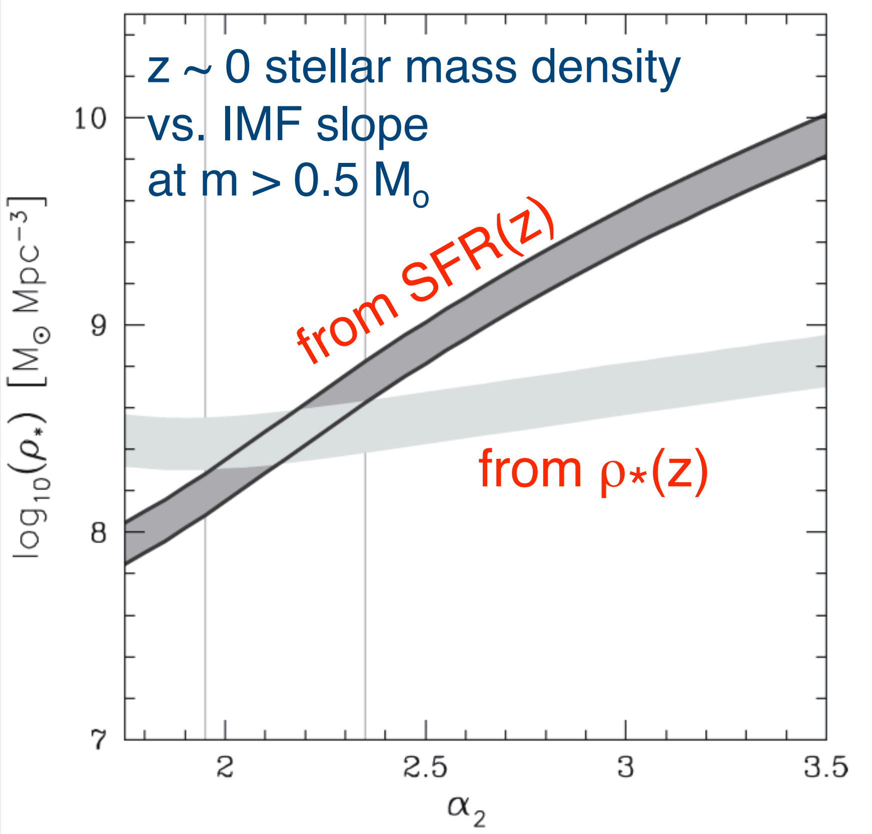


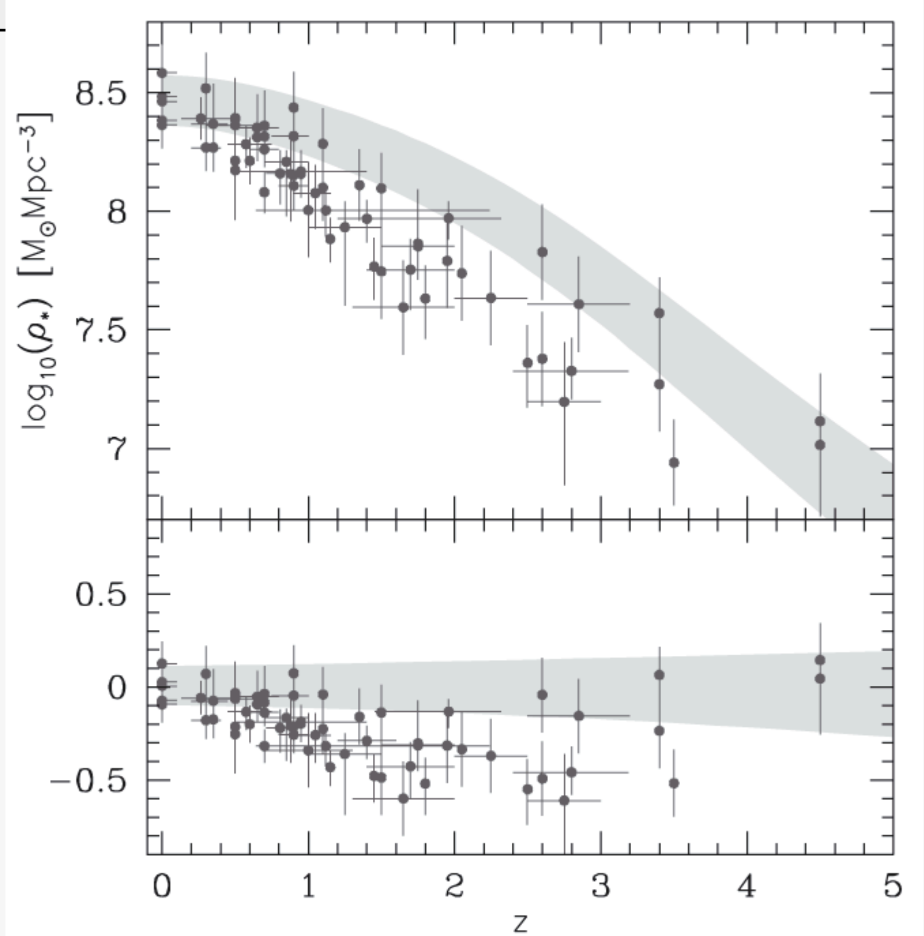
Borch et al. 2006

Fiddling with the IMF

This helps … but not enough?

- SFRs overestimated at z~2-3 ?
  - Larger AGN contribution to dusty mid-IR LF at z~2 ?
  - Chary & Pope '09: z~2-3 LBG extinction corrections too large? May overproduce CIRB.
- Stellar mass densities underestimated?
- More complex or evolving IMF?





Stellar mass densities and reionization

- Most studies have concluded that observed Lyman break galaxies at z >~ 6 produce insufficient UV to reionize the IGM unless Lyman continuum escape fraction and/or IGM clumping are *extremely* favorable.
- Star formation needed for reionization would *overproduce* the observed stellar mass density at z~3 (Ferguson et al. 2003) and 6 (Chary 2008).
- Ways out:
  - Hide the star formation, hide the stars:
    - Very steep LF(UV) at z > 6 ?
    - Very steep stellar mass function at z ~ 3-6 ?
  - Fiddle with the IMF:
    - Top heavy IMF during reionization: more UV, less surviving mass

Conclusions

- Spitzer MIPS made the high-z IR LF into an industry
  - SFRD(z~1) dominated by LIRGs
  - ULIRGS 1000x more common at z~2 than at z~0, but SFRD (z~2) still dominated by less luminous galaxies
  - Herschel will give more robust measurements, less subject to uncertainties from bolometric corrections & AGN
    - But sensitivity at $\lambda > 200\mu m$ will still be limited
  - Still much work TBD exploiting existing Spitzer data
    - Analyze more fields!
    - Get better (real) redshifts
  - Significant uncertainties may remain about the faint end of the IRLF at high redshift and its relevance for SFR(z)

Conclusions

- Still much to be learned about SFR(z) at $z \gg 2$.
  - UV-selected samples provide most of our knowledge
  - Extinction corrections may be uncertain even for these
  - Very luminous SMGs perhaps more common at $z > 4$ than had been thought until recently, but the overall contribution of dusty star formation at very high redshift uncertain
  - Luminosity functions are very steep, so a lot is going on near or beyond the limits of our data

Conclusions

- Spitzer IRAC vitally important for high-z stellar masses
  - Improves (& reduces) stellar mass estimates at high redshift
  - Offers the only game in town at $z > 4$
- Mass function appears mainly to have evolved in density - does this make sense??
- There are apparent discrepancies between SFR(z) and the integrated stellar mass density.
  - Overestimated SFRs or underestimated mass densities?
  - Non-Salpeter or evolving IMF?
- Still TBD:
  - We can do much more with existing data at $z < 1$
  - High redshift measurements substantially limited by near-IR data
  - Stellar population modeling issues are critical