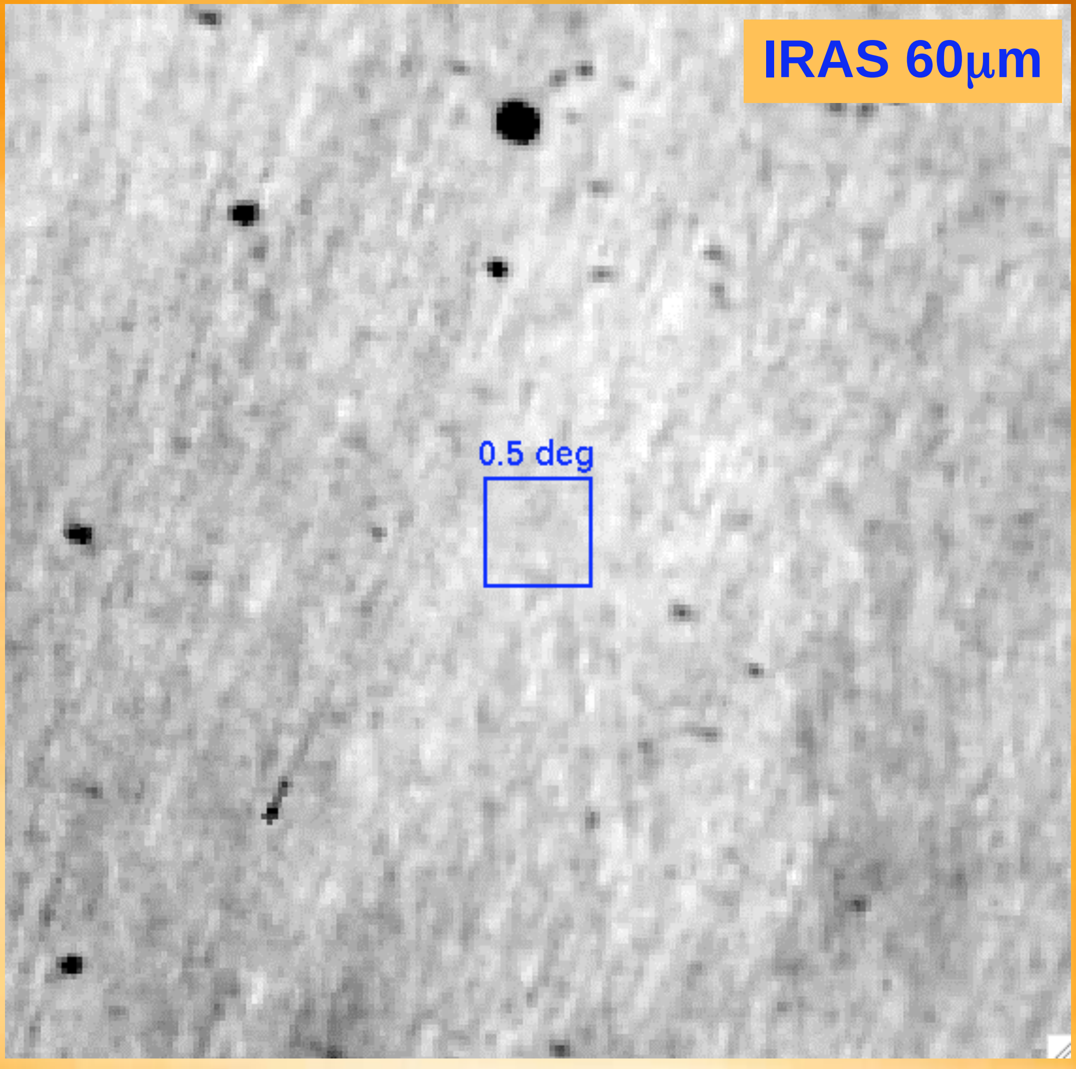
Galaxy Evolution at High Redshift: The Future Remains Obscure

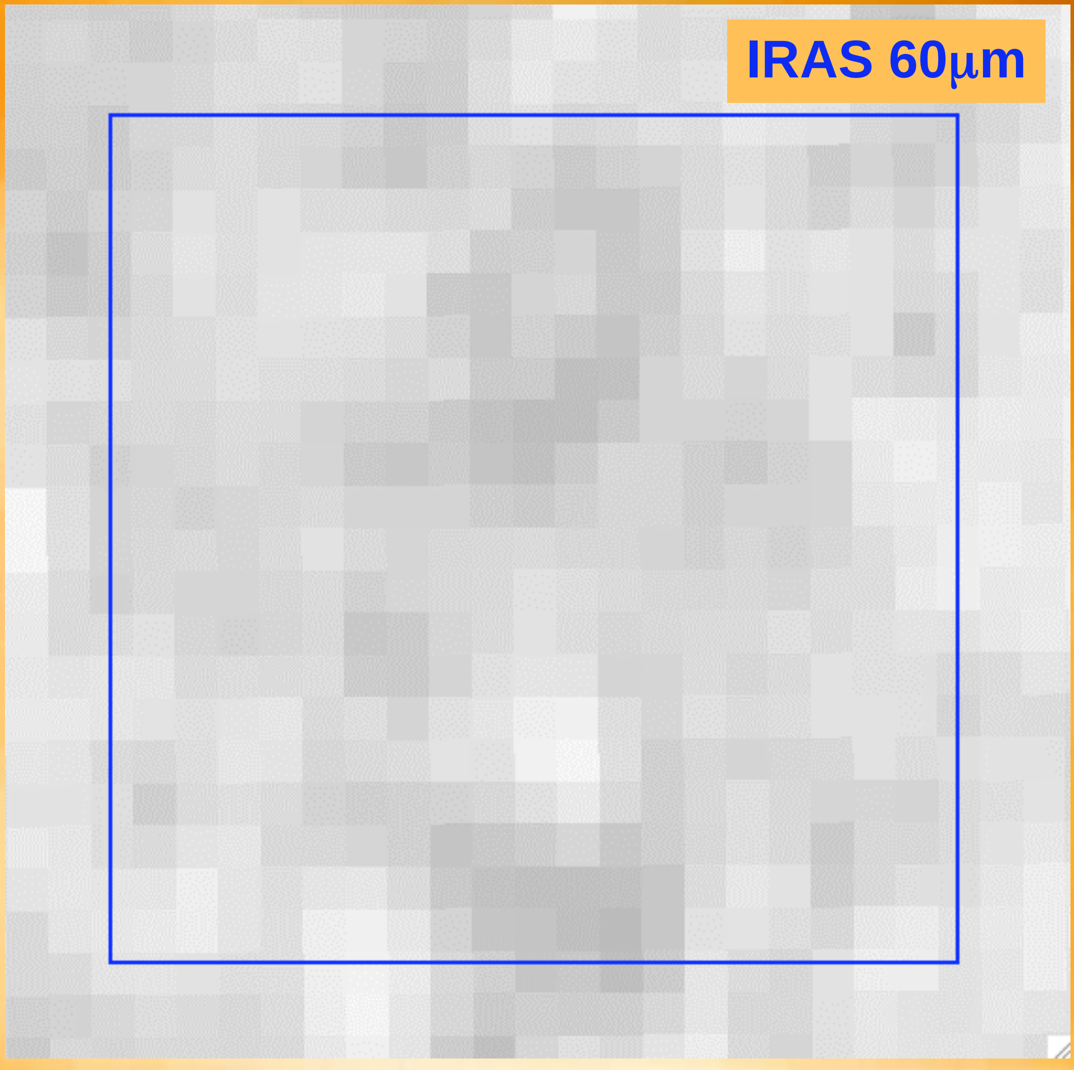
Mark Dickinson (NOAO)

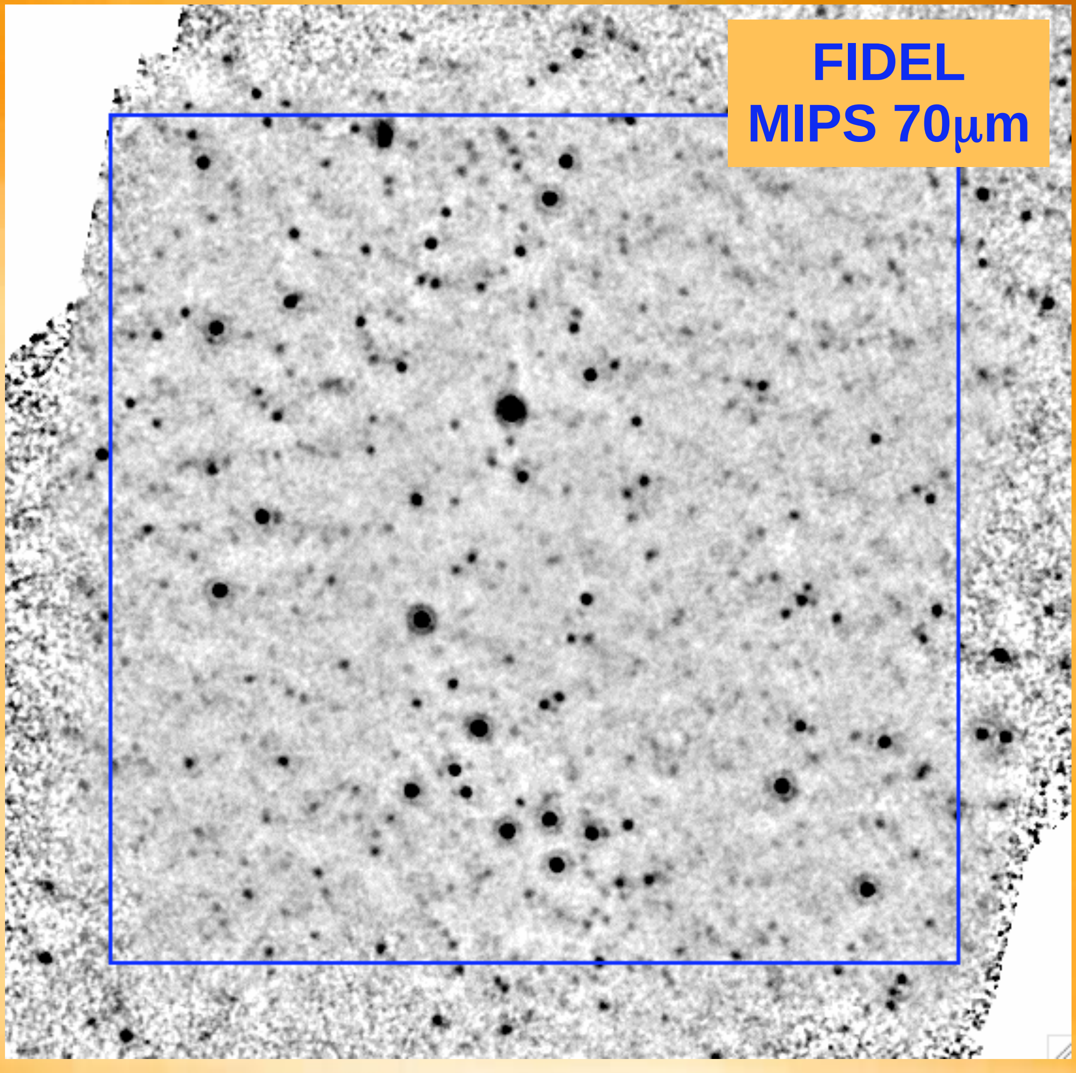
Galaxy Evolution at High Redshift: The ~~Future~~ Remains Obscure

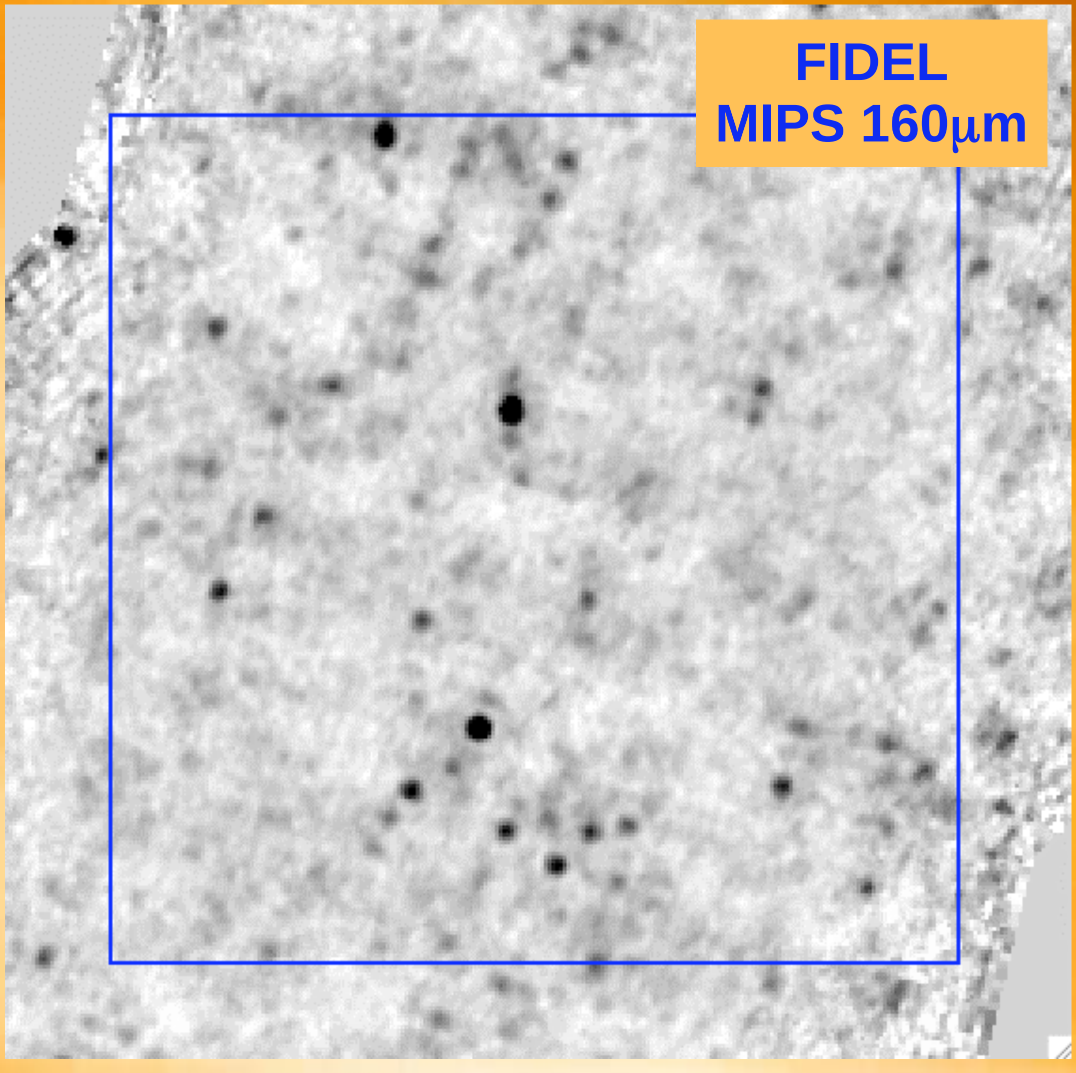
Past

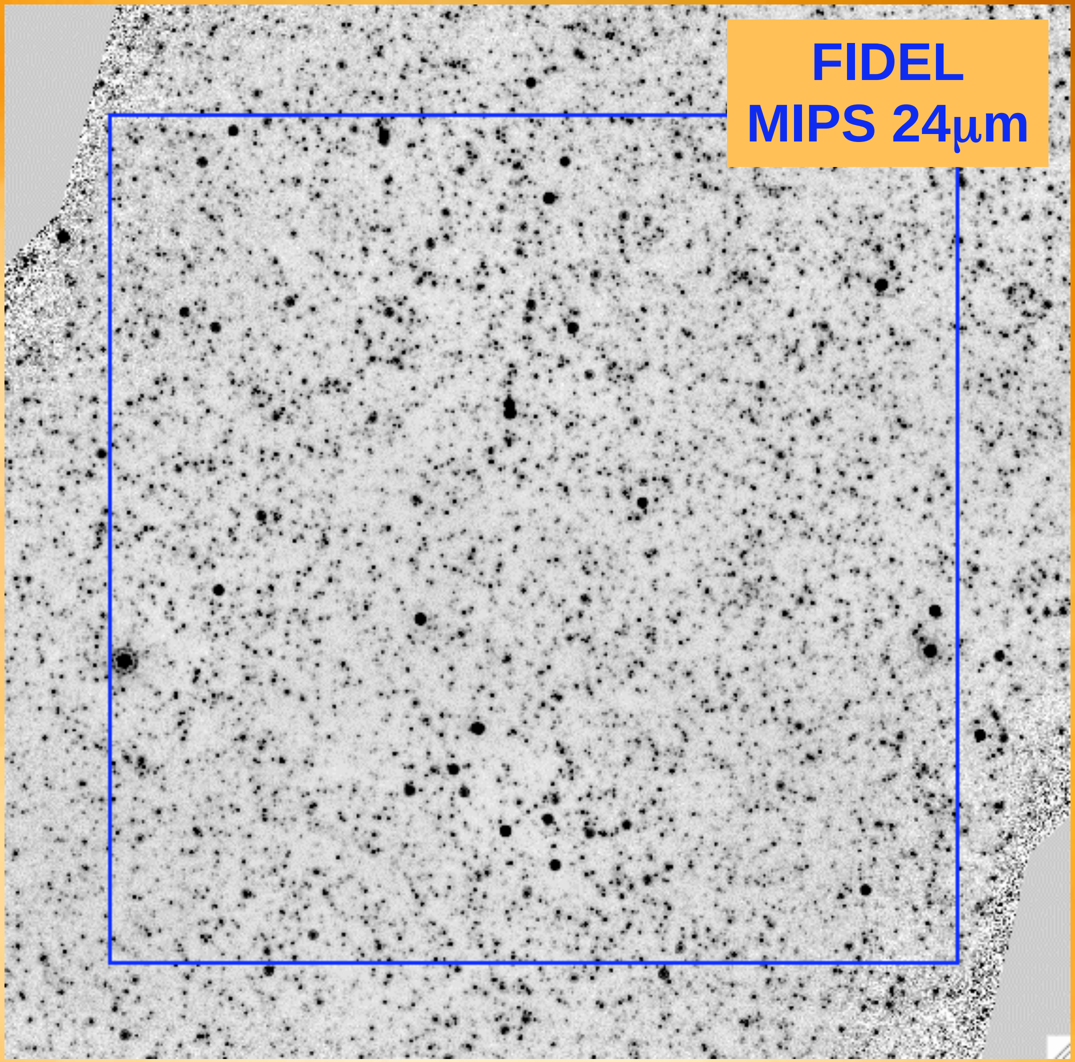
Mark Dickinson (NOAO)

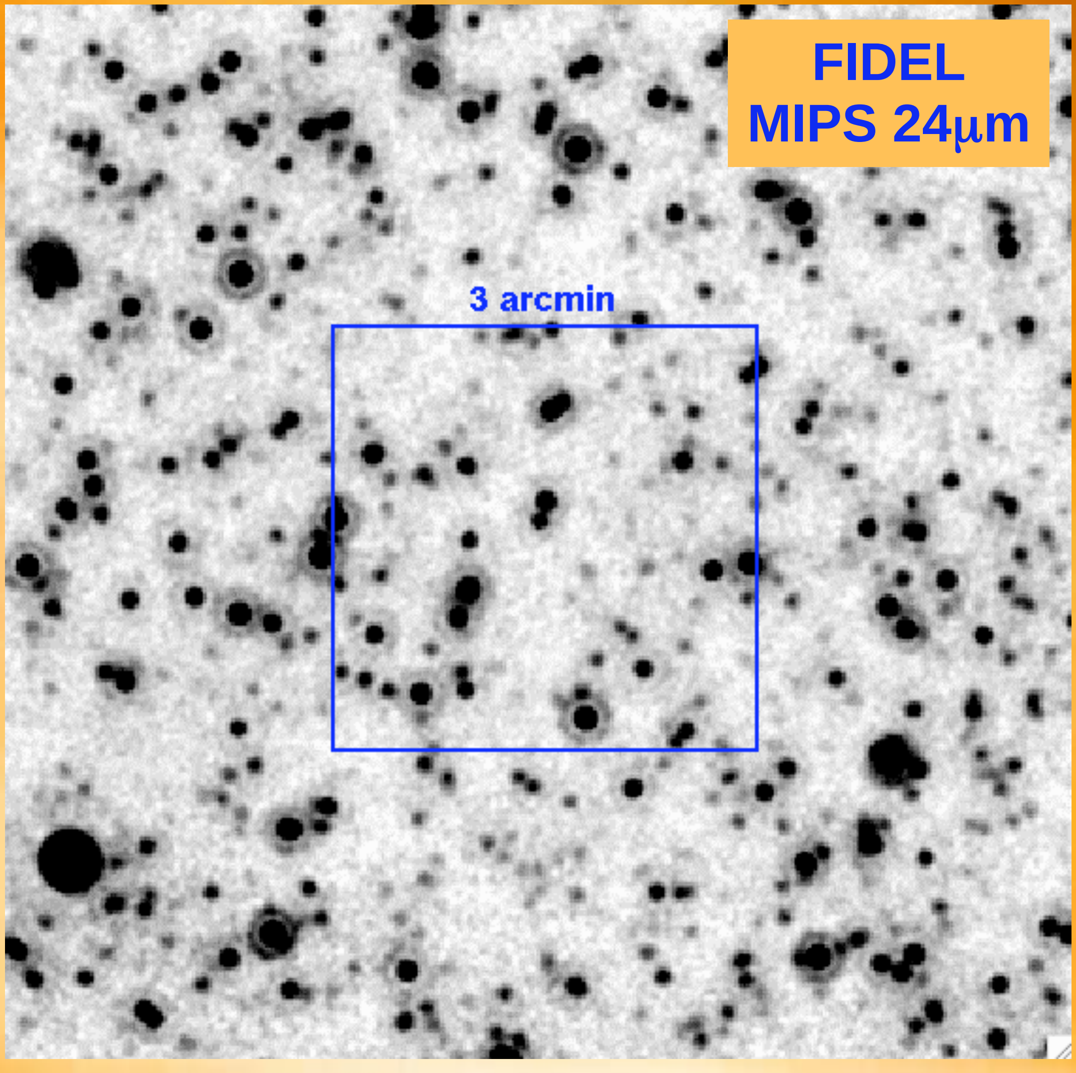

IRAS 60µm
0.5 deg


IRAS 60μm


FIDEL
MIPS 70μm

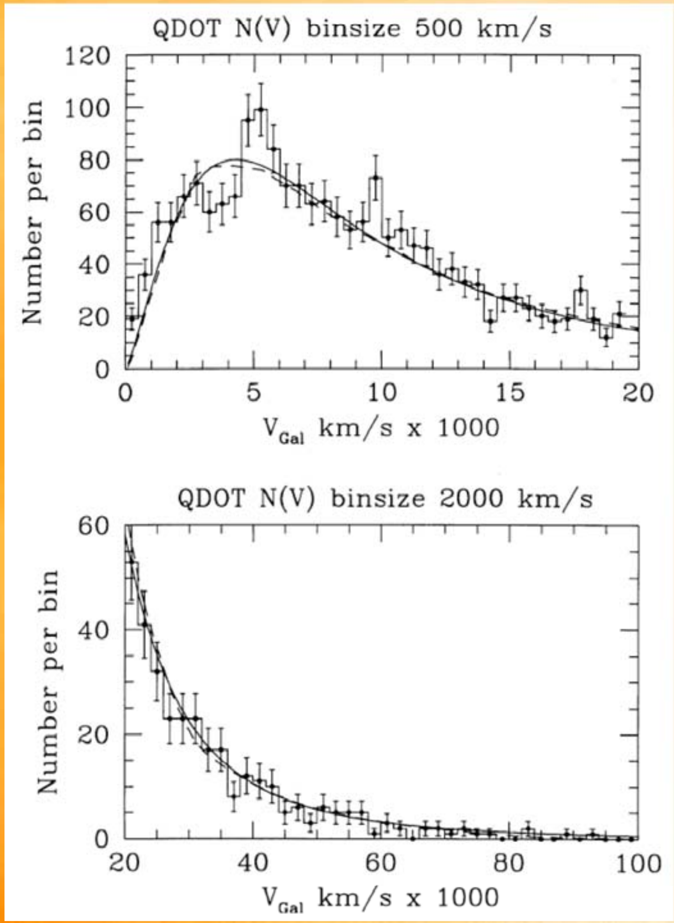

FIDEL
MIPS 160μm


FIDEL
MIPS 24μm

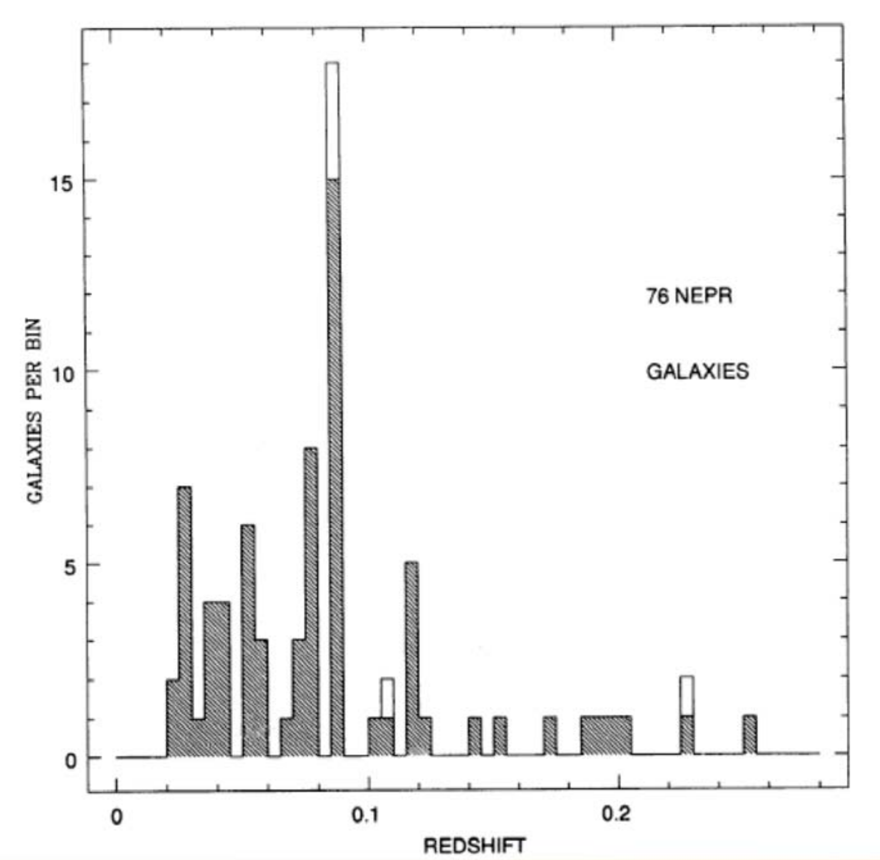

FIDEL
MIPS 24μm
3 arcmin

IRAS 60μm redshifts

Lawrence et al. 1999
f(60μm) > 0.6 Jy

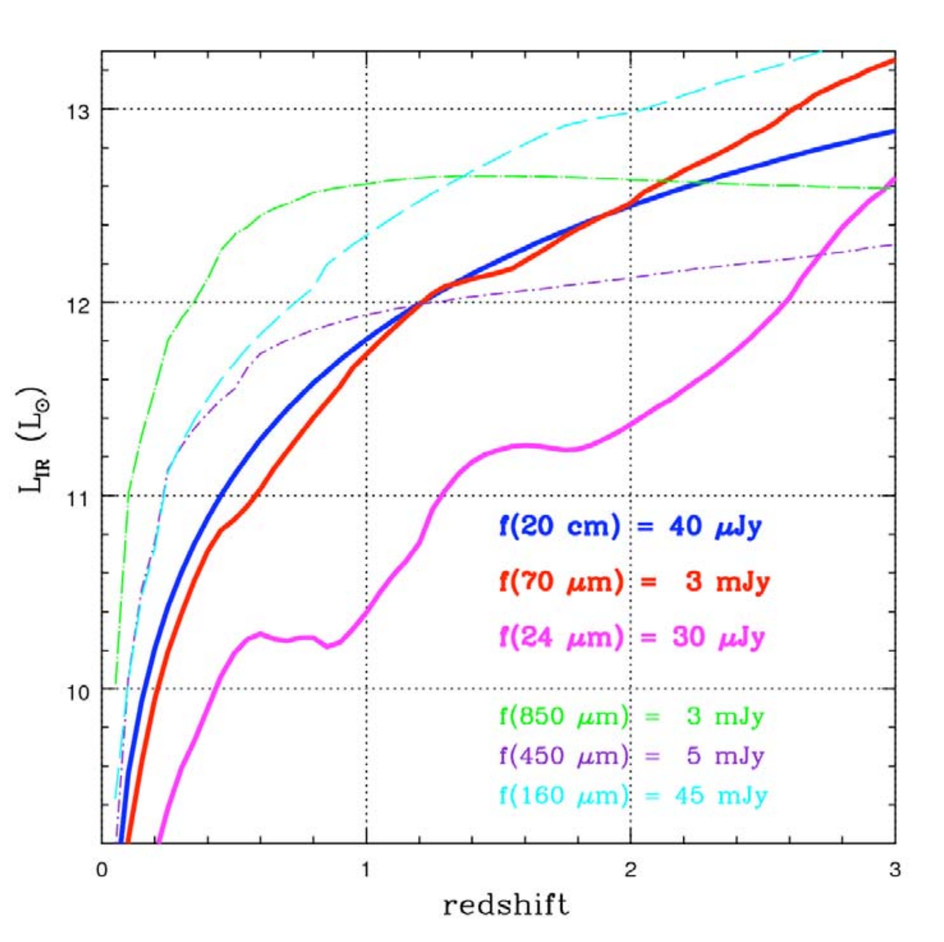


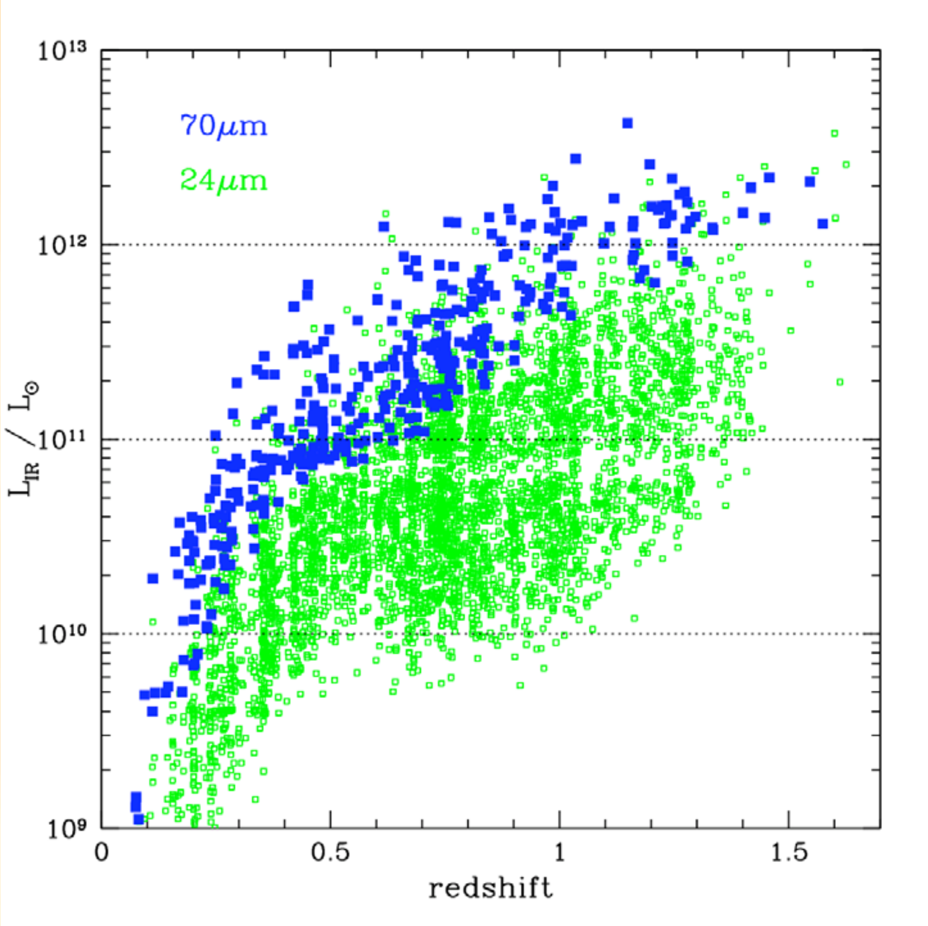
Ashby et al. 1996
f(60μm) > 0.05 Jy



FIDEL EGS redshifts

Redshifts from DEEP2: f(70μm) > 3 mJy, f(24μm) > 30 μJy

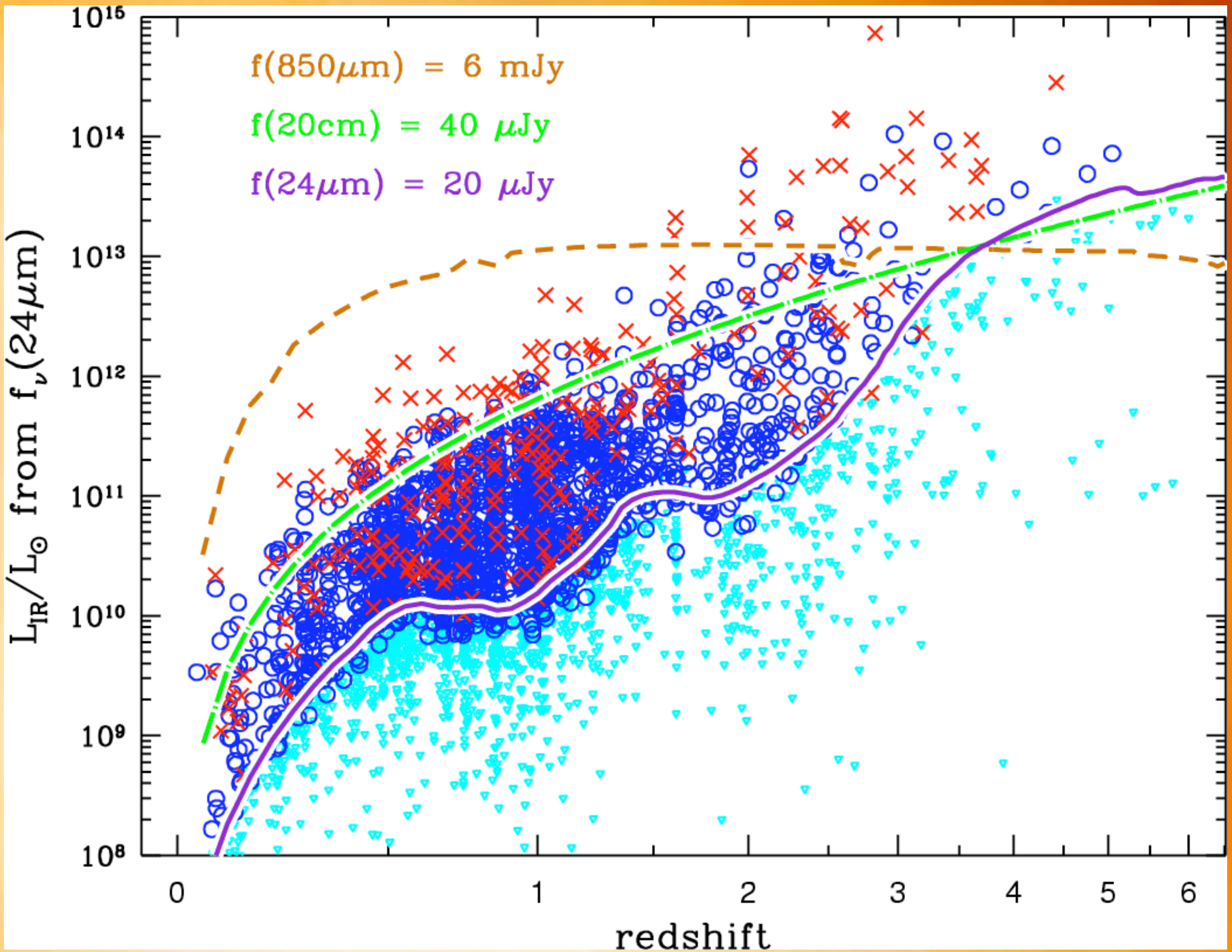




Ultradeep 24μm: "normal" dusty galaxies at z ~ 2 and beyond

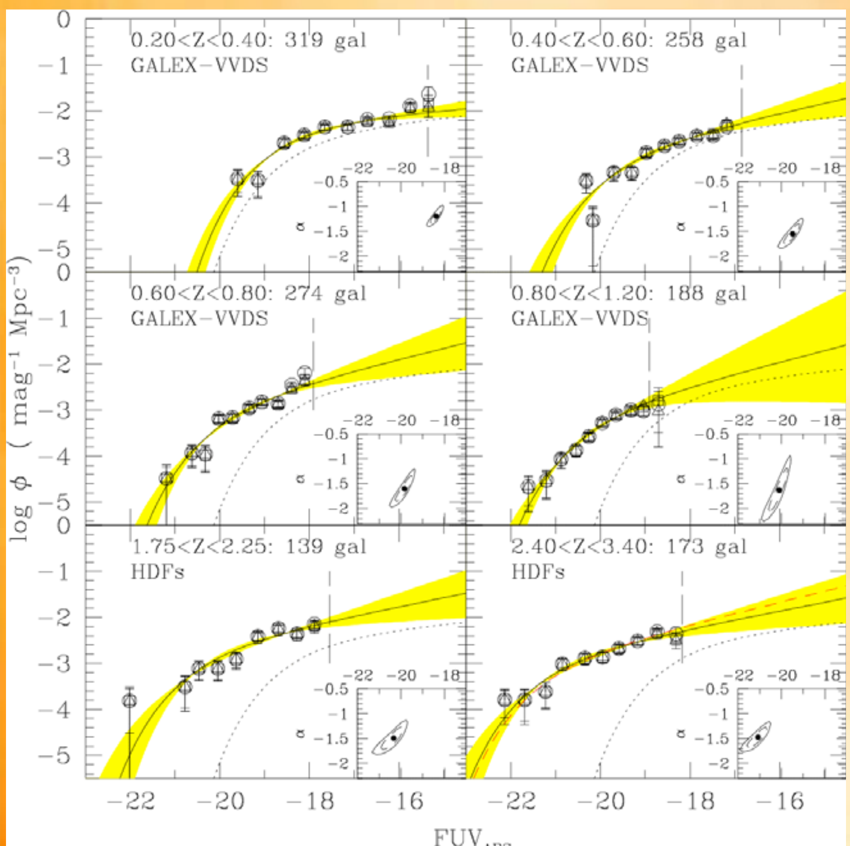
GOODS 24μm: detecting "normal" dusty galaxies at z~2

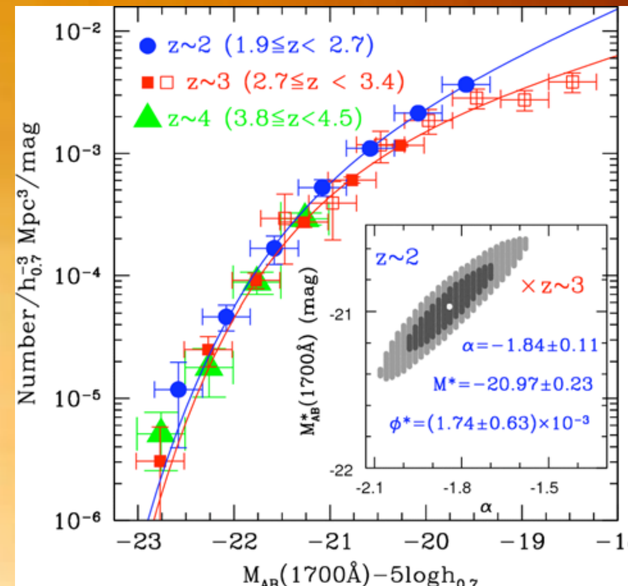
Ultradeep 24μm by far the most sensitive measure of dusty SFR at high redshift.



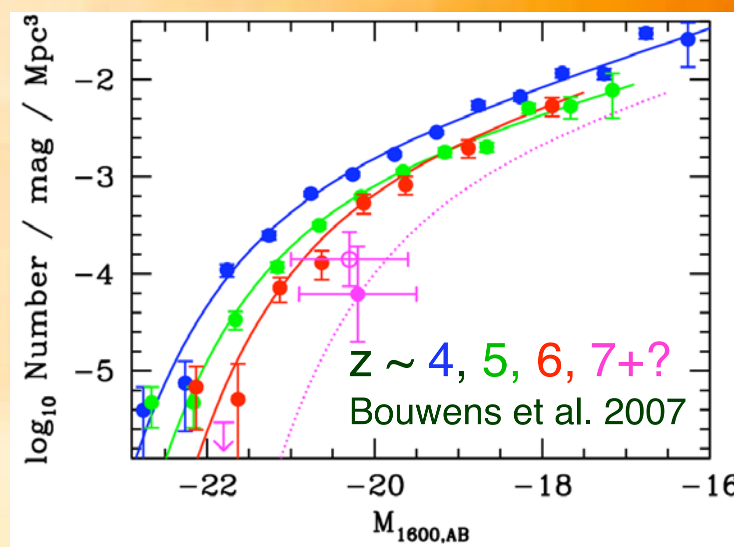
UV SF @ high z

GALEX, 0 < z < 1.2 : Arnouts et al. 2005





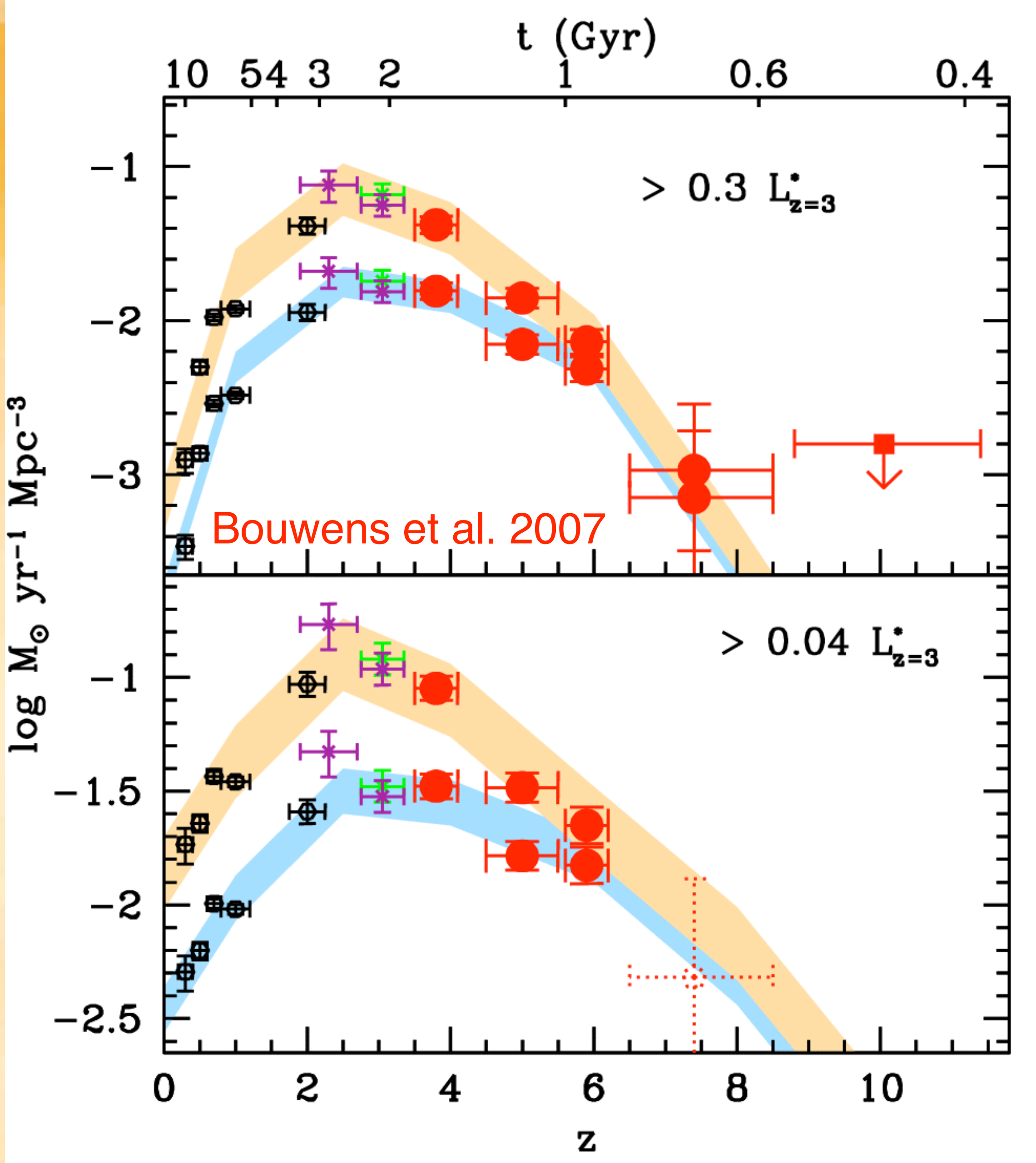
z ~ 2, 3, 4 (Reddy et al. 2007)



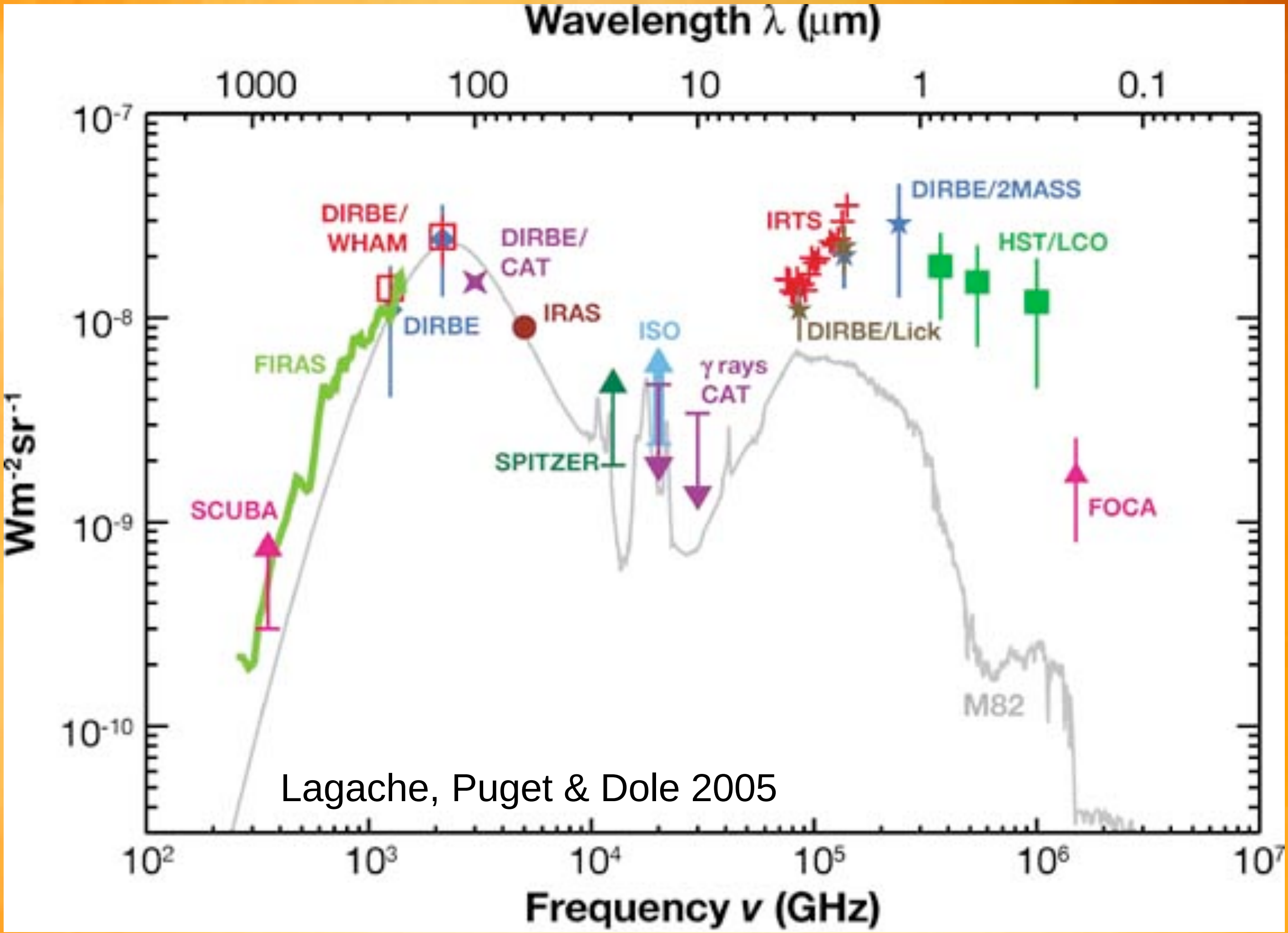
SFR(z) from the UV

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

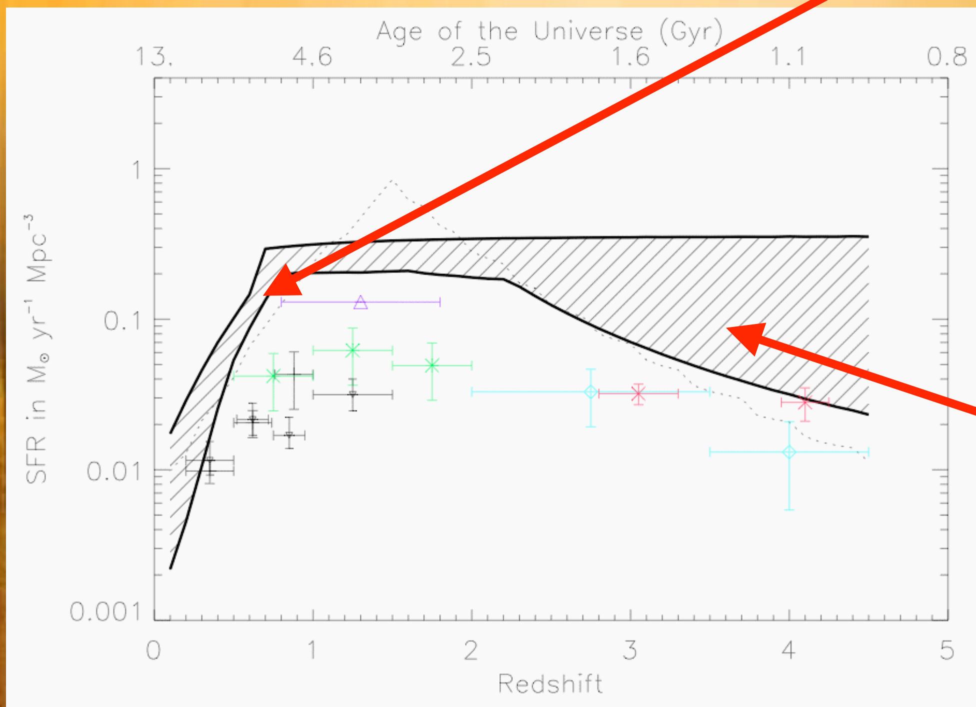
Increasing dust extinction flattens the trend for observed UV luminosity density.



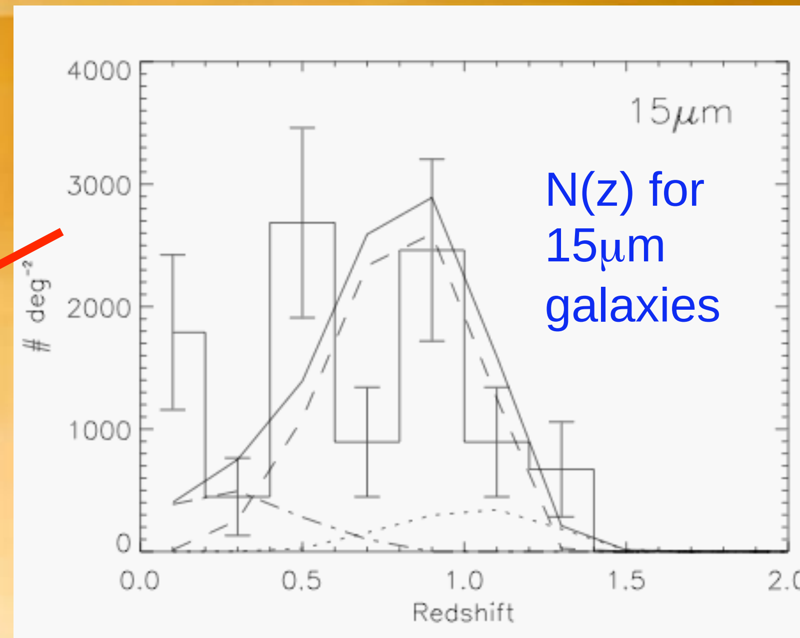
The dirty side of cosmic star formation

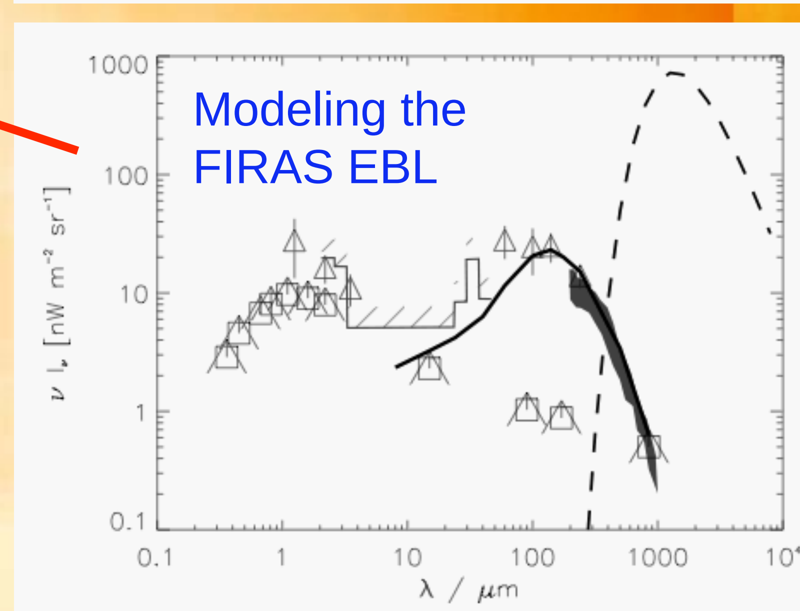


The dusty SFR(z)



Chary & Elbaz 2001



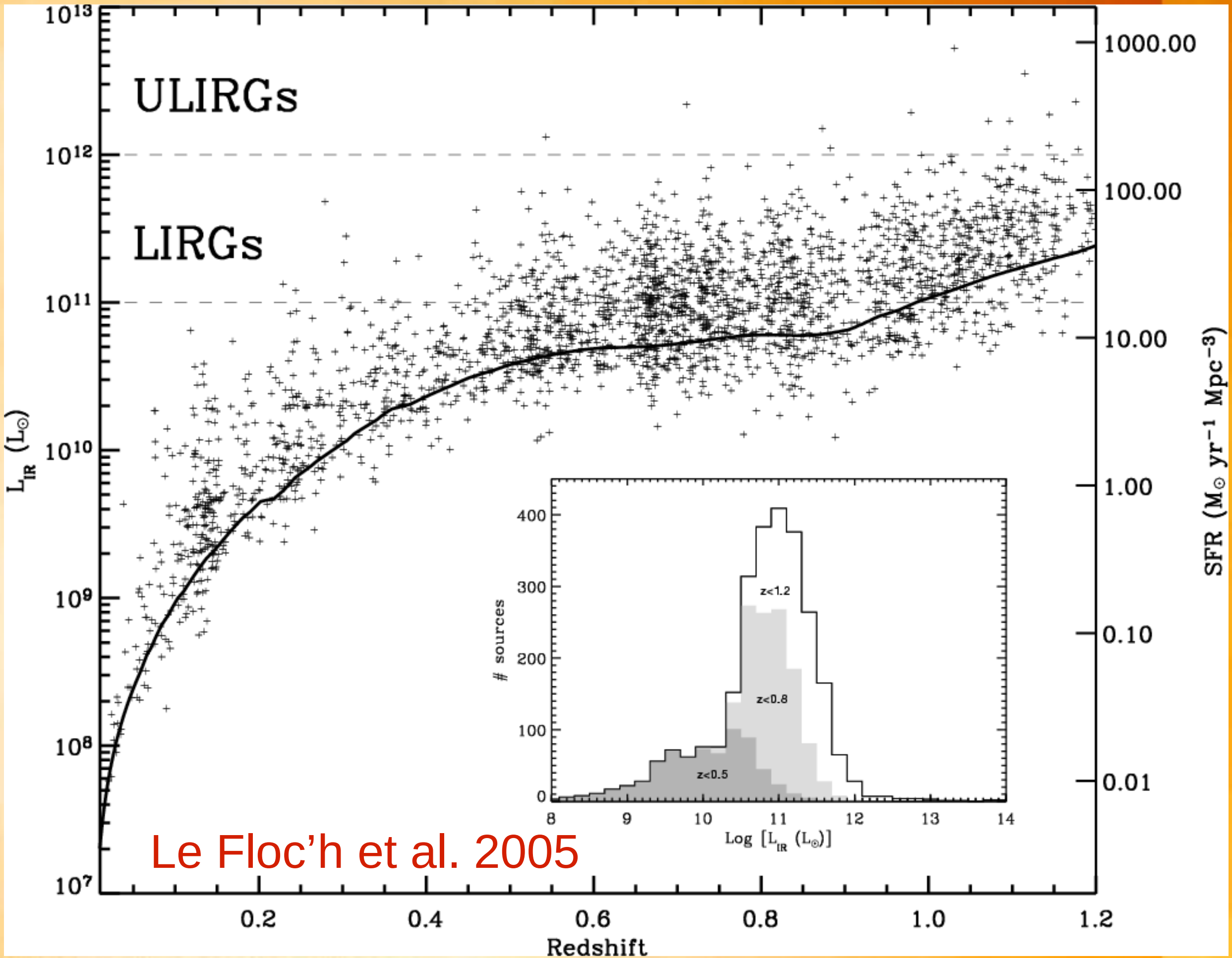


Spitzer: dusty SFR on an industrial scale

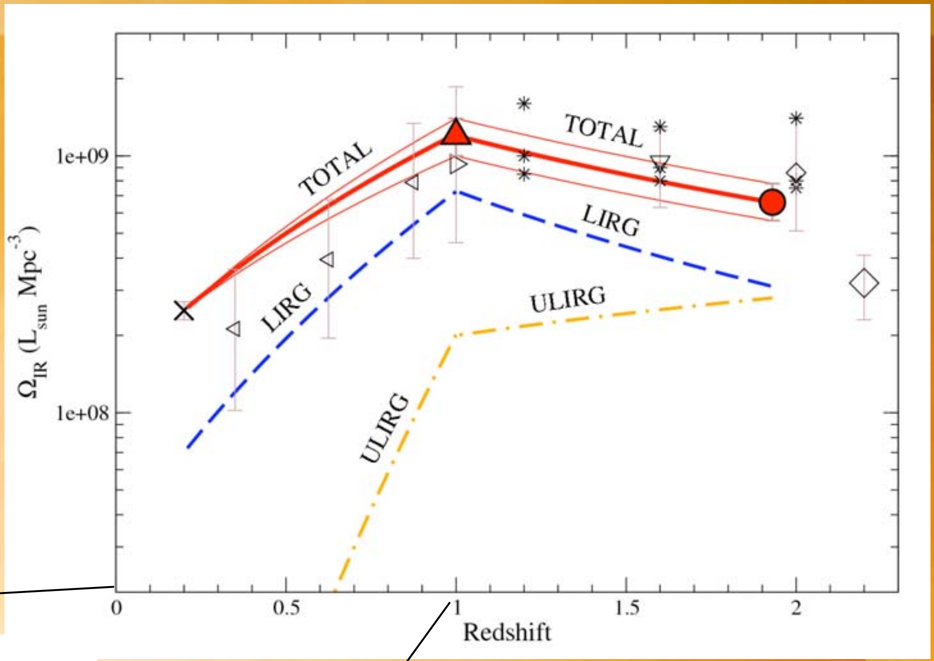
Spitzer 24μm surveys:

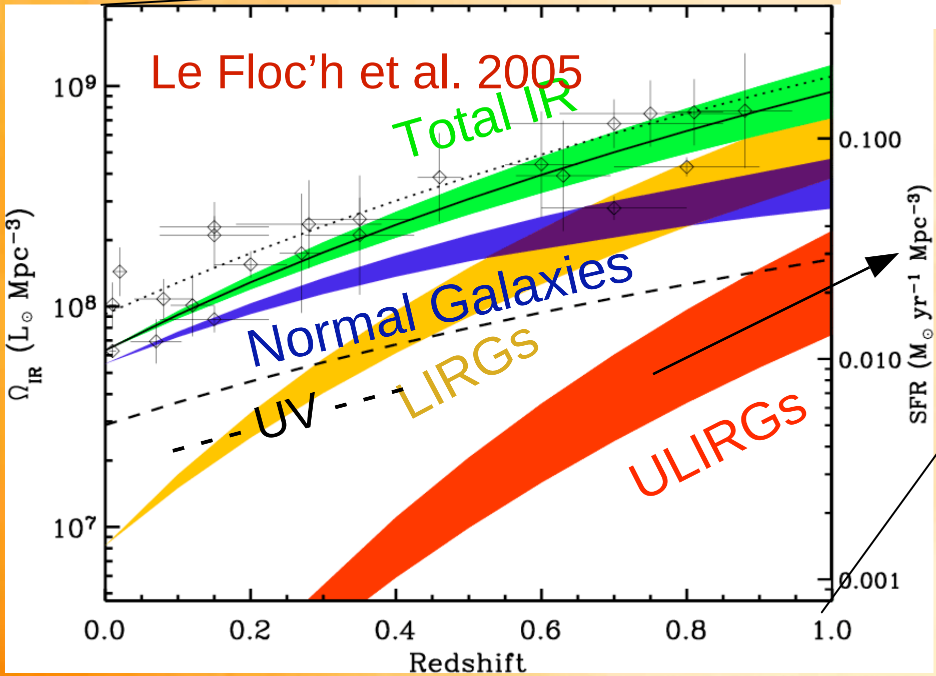
- Very efficient!
- Very sensitive!
- Excellent synergy with large redshift surveys
- Probably not too hard to interpret at z < 1

Rapid evolution in the IR LF at 0 < z < 1



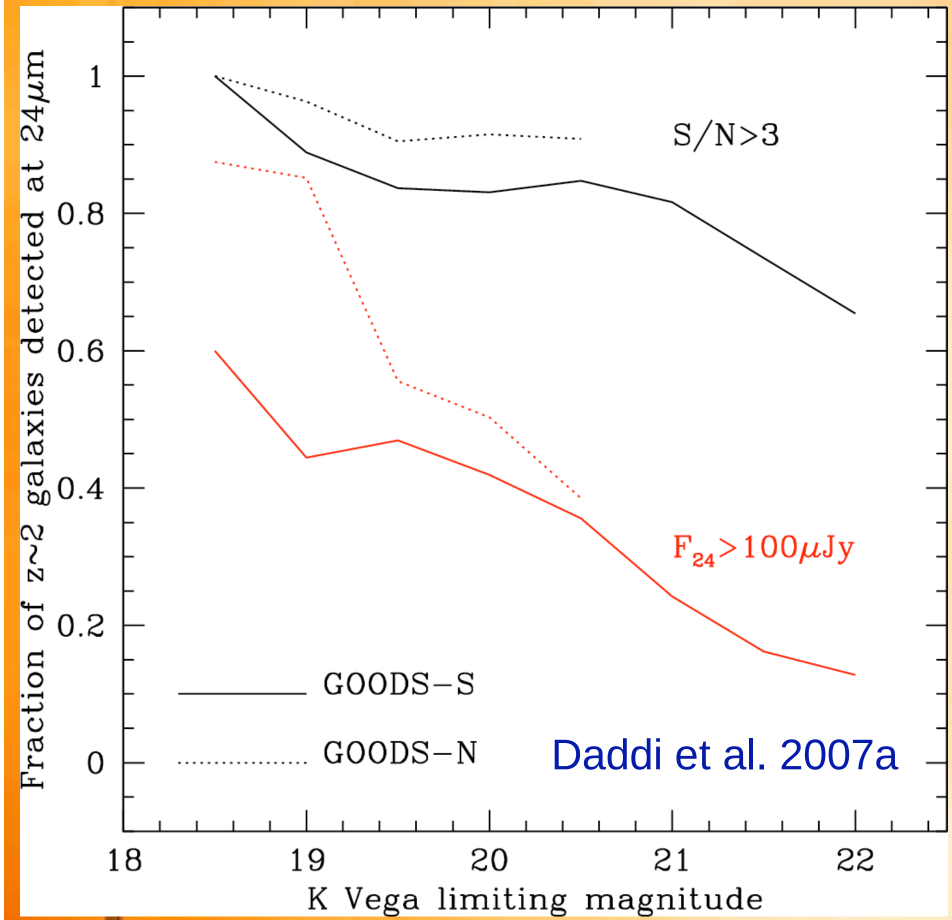
z > 0.7: The age of obscurity



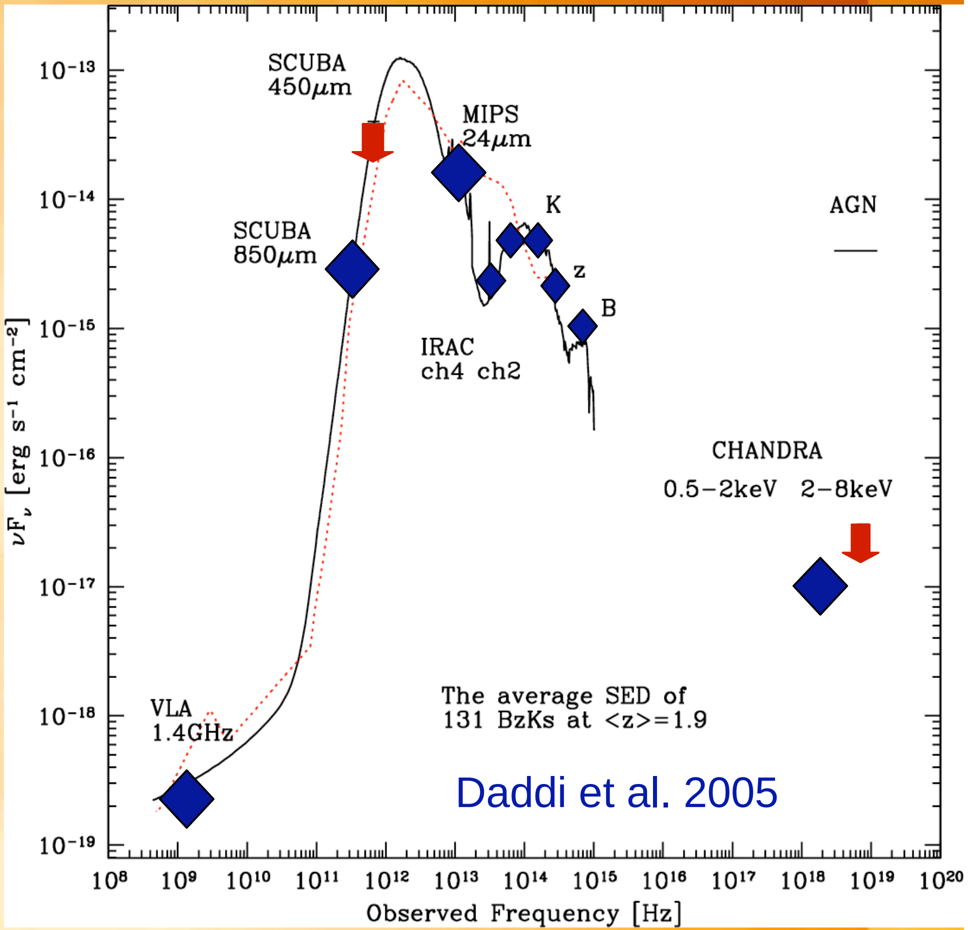


Rampant activity in massive z~2 galaxies

~80% of K-selected galaxies at z~2 are detected at 24μm!

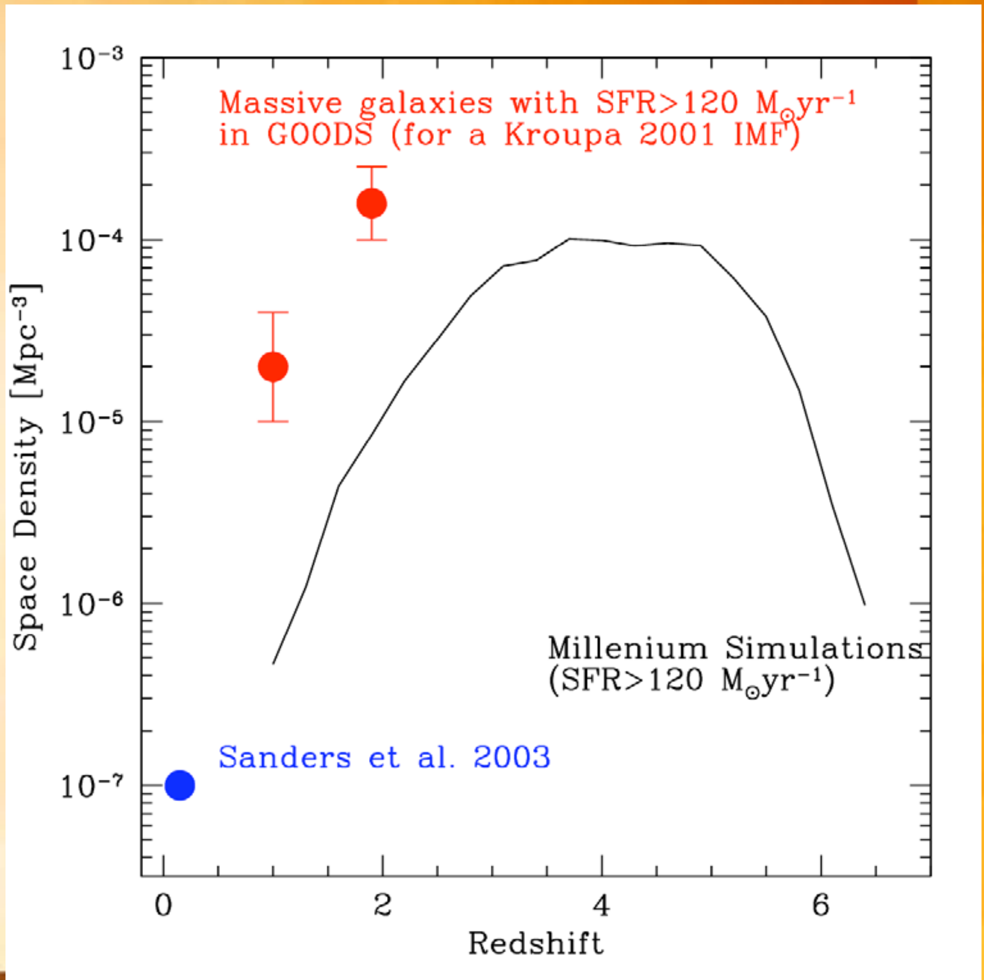


The typical K=20 z~2 galaxy is a ULIRG



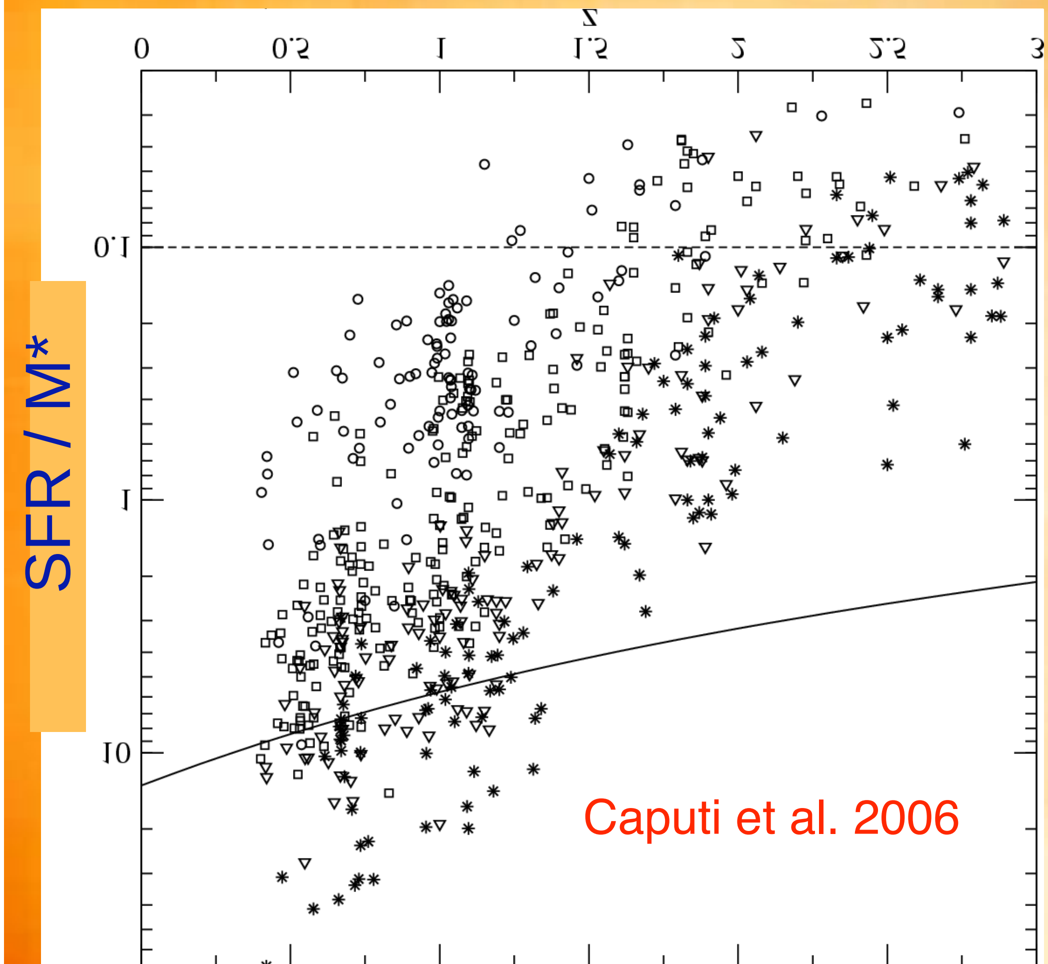
ULIRGs at high redshift:
expectations vs. observations

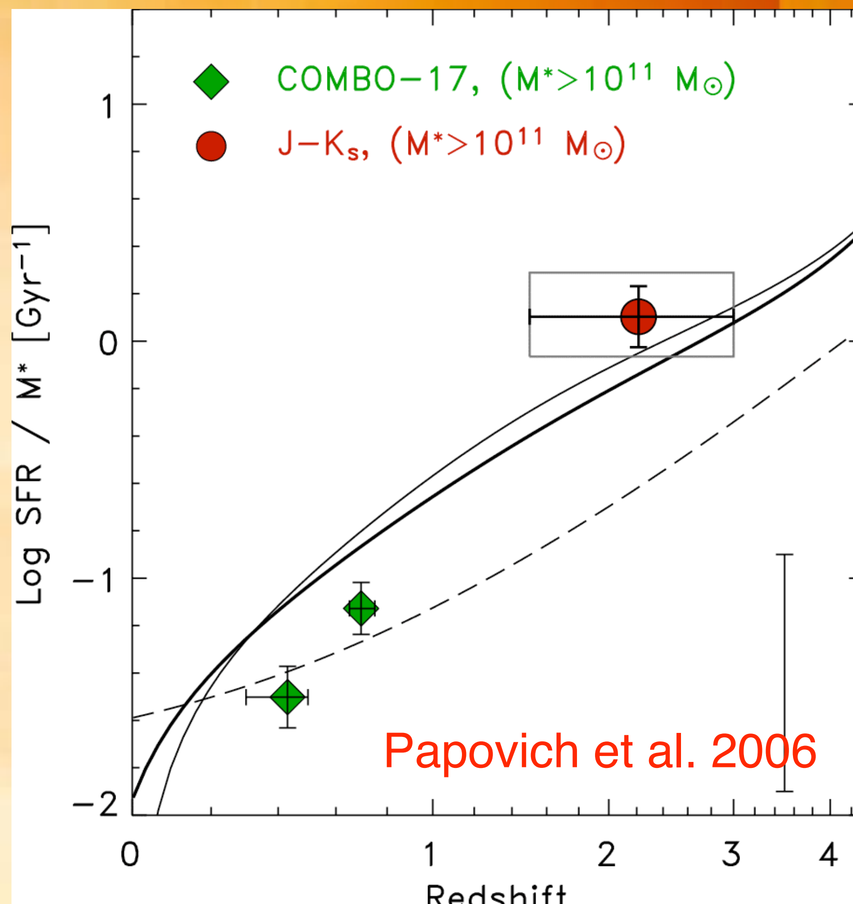
Abundance of high-redshift ULIRGS greatly exceeds predictions from most simulations
(e.g., Millennium: Springel et al. 2005; Kitzbichler & White 2007
Also: Oppenhemier & Davé 2006)



Rapid star formation in massive galaxies at z~2

Daddi et al. 2005, 2007, Papovich et al. 2006, Reddy et al. 2006, 2007, Caputi et al. 2006

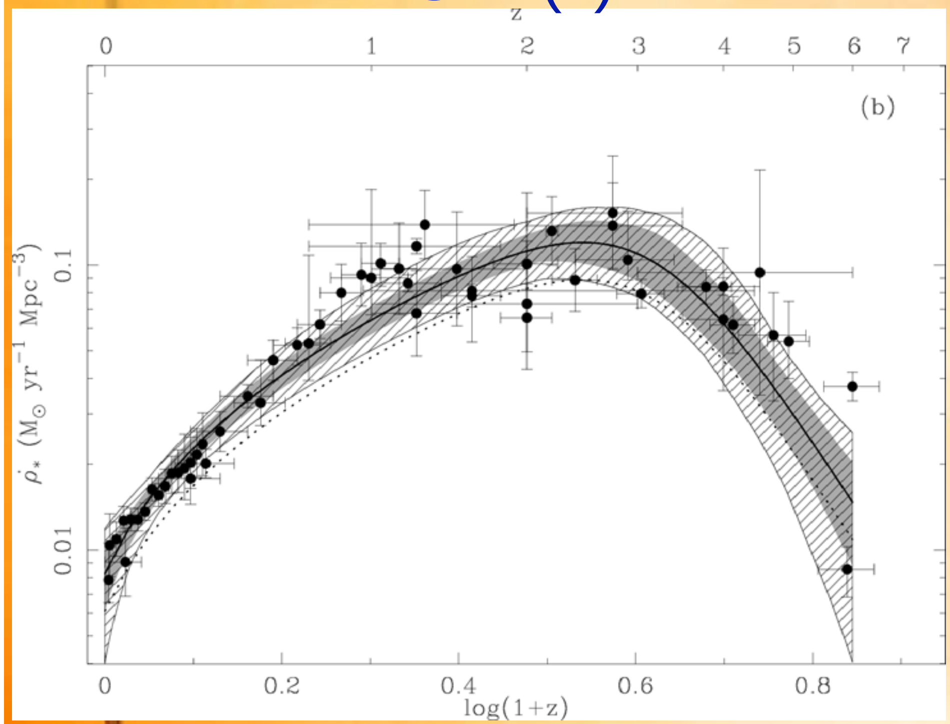




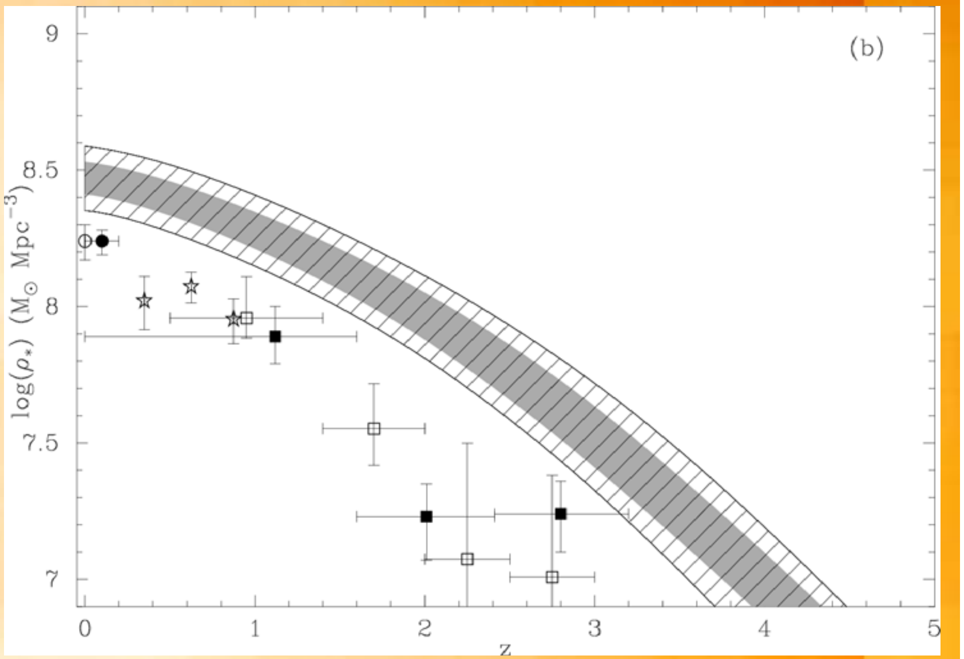
SFR(z) vs. Ω*(z): tension at all redshifts?

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

SFR(z)

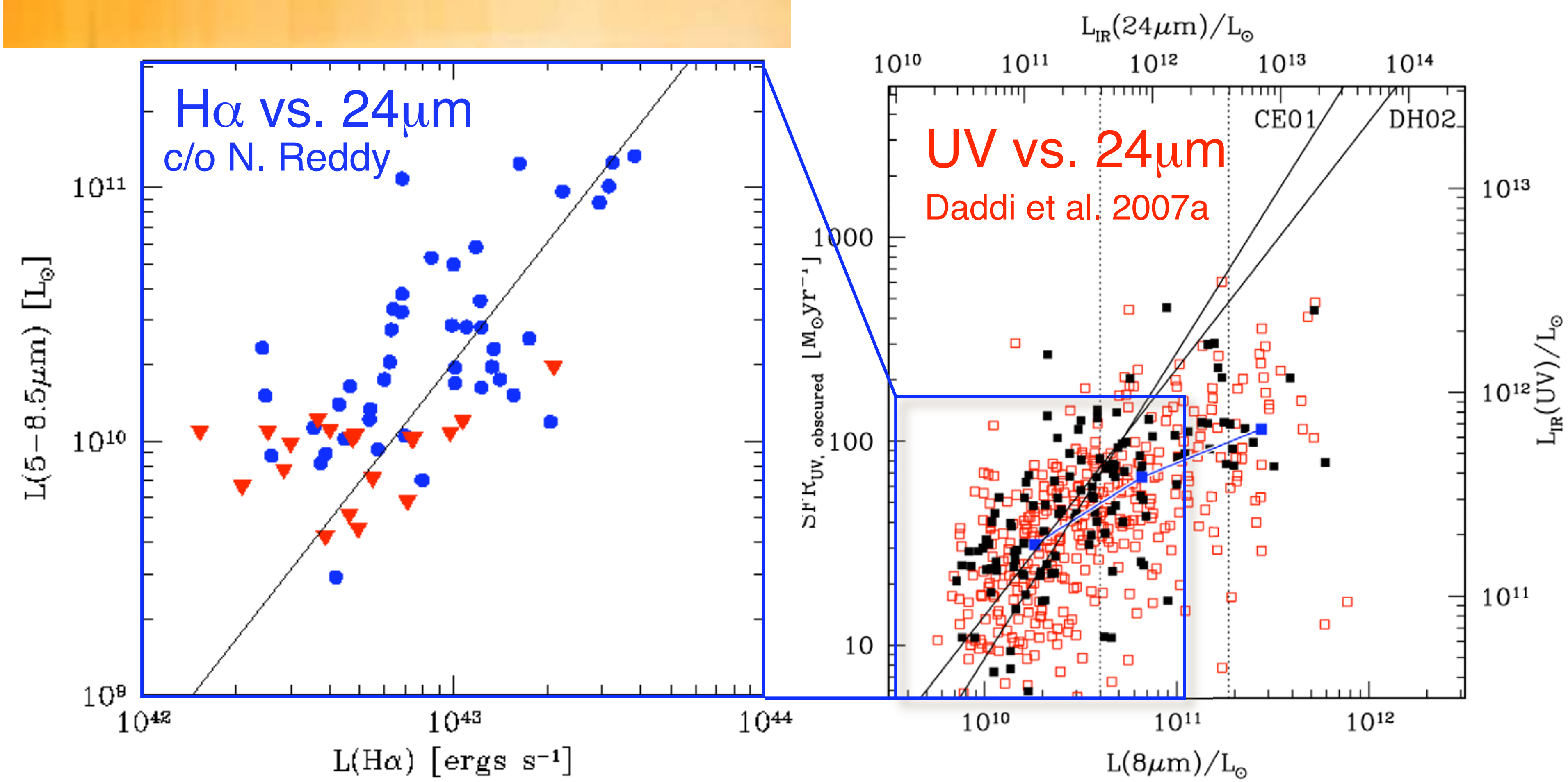


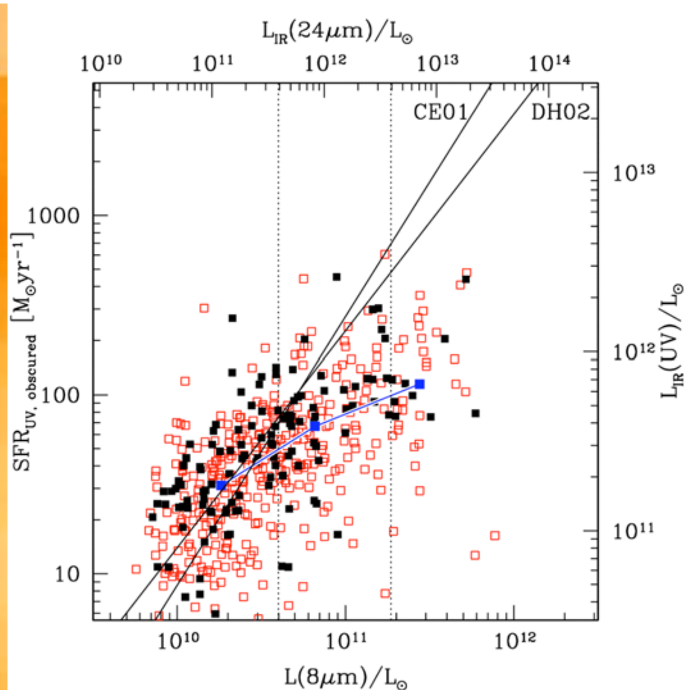
$\Omega_{stars}(z)$

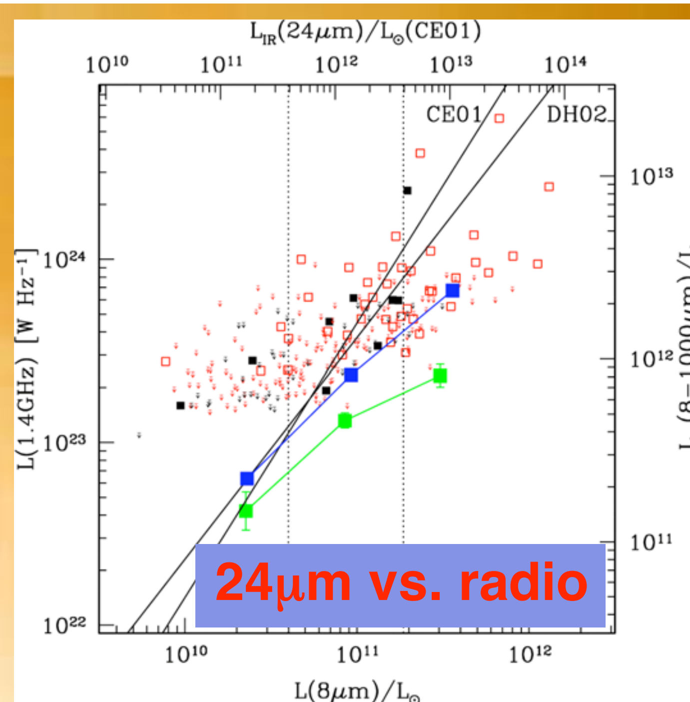


Hopkins & Beacom 2006; see also Chary & Elbaz 2001; Dickinson et al. 2003; Ferguson et al. 2003

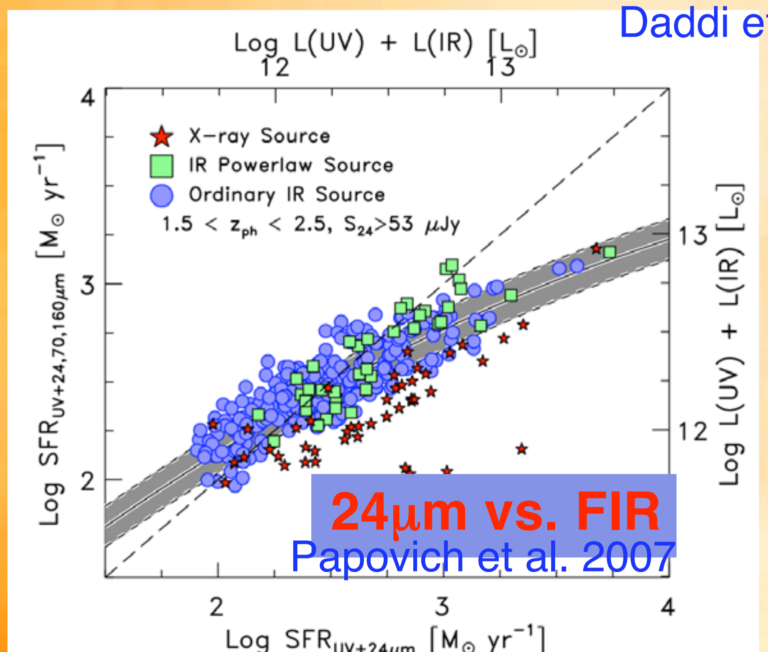
Testing SFR from 24μm @ z~2



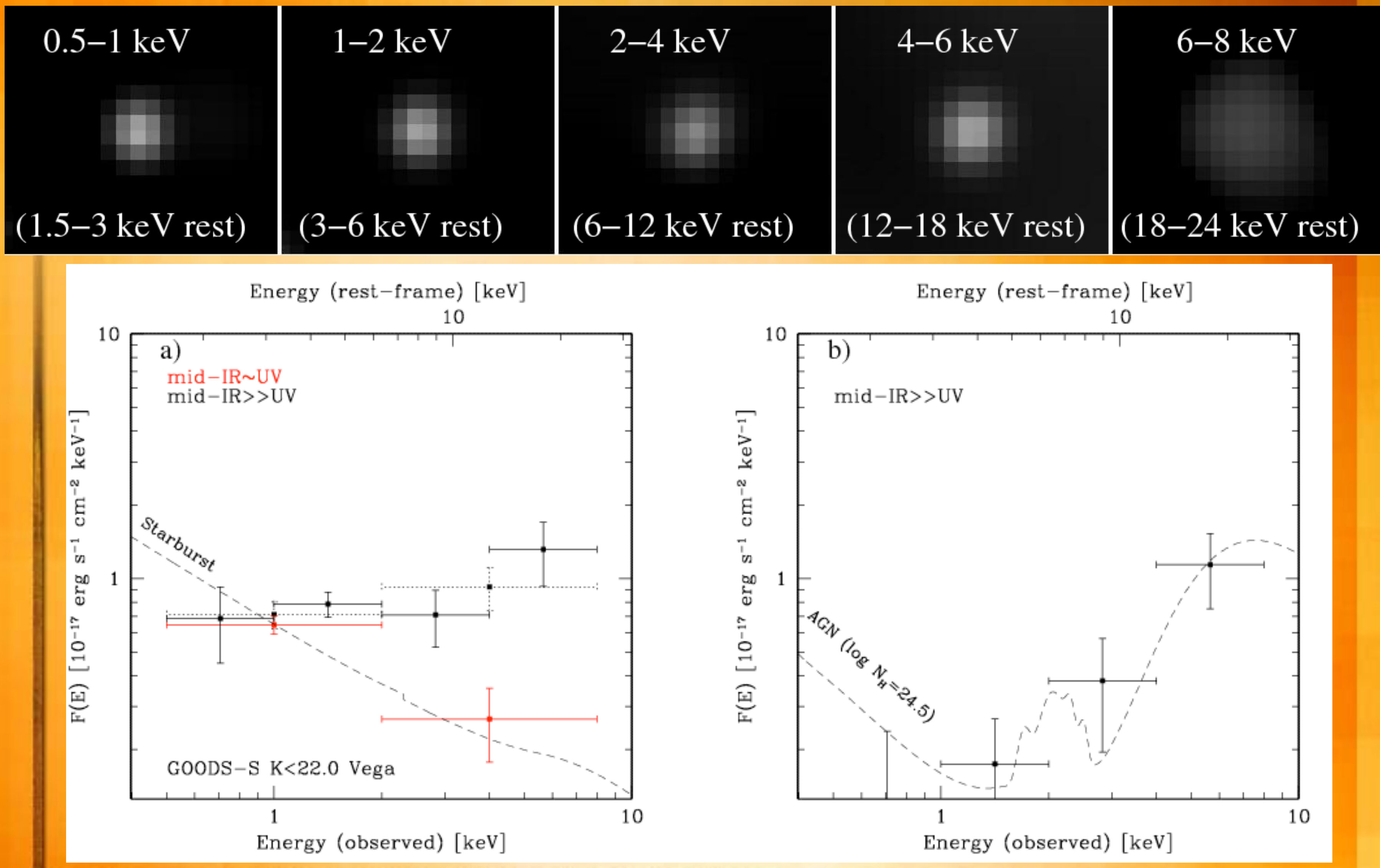




Daddi et al. 2007



X-ray evidence for hidden AGN



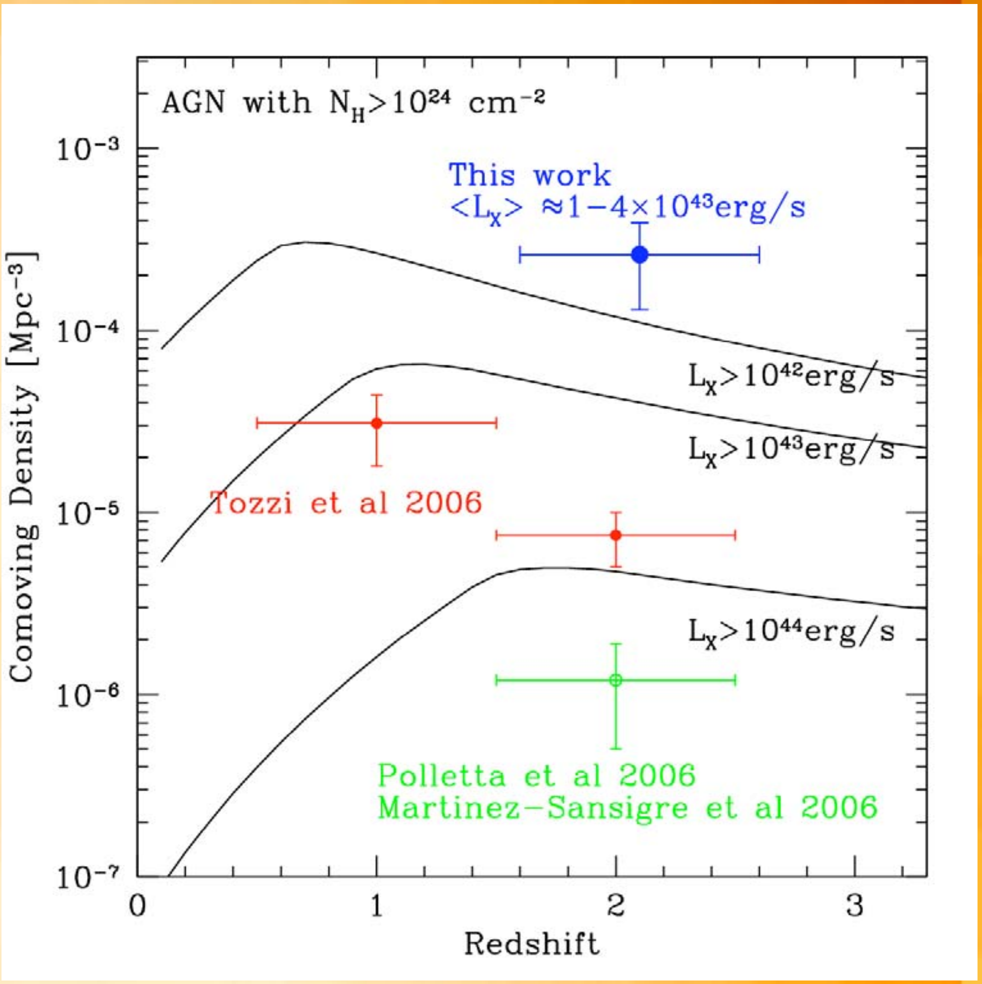
Abundant Compton-thick AGN at z~2

Daddi et al. 2007b

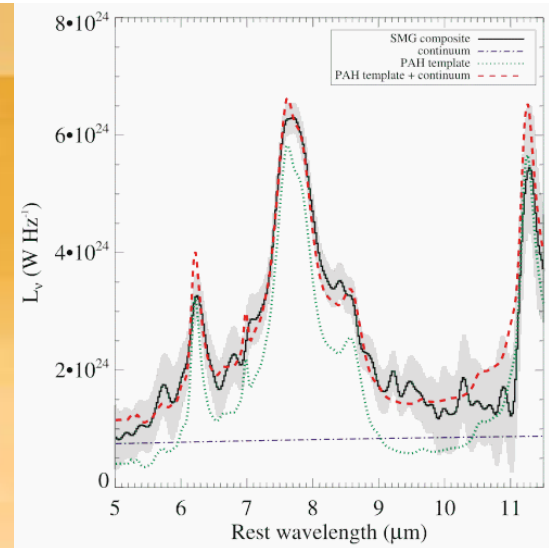
~50% of the most massive galaxies at z~2 host active, obscured AGN

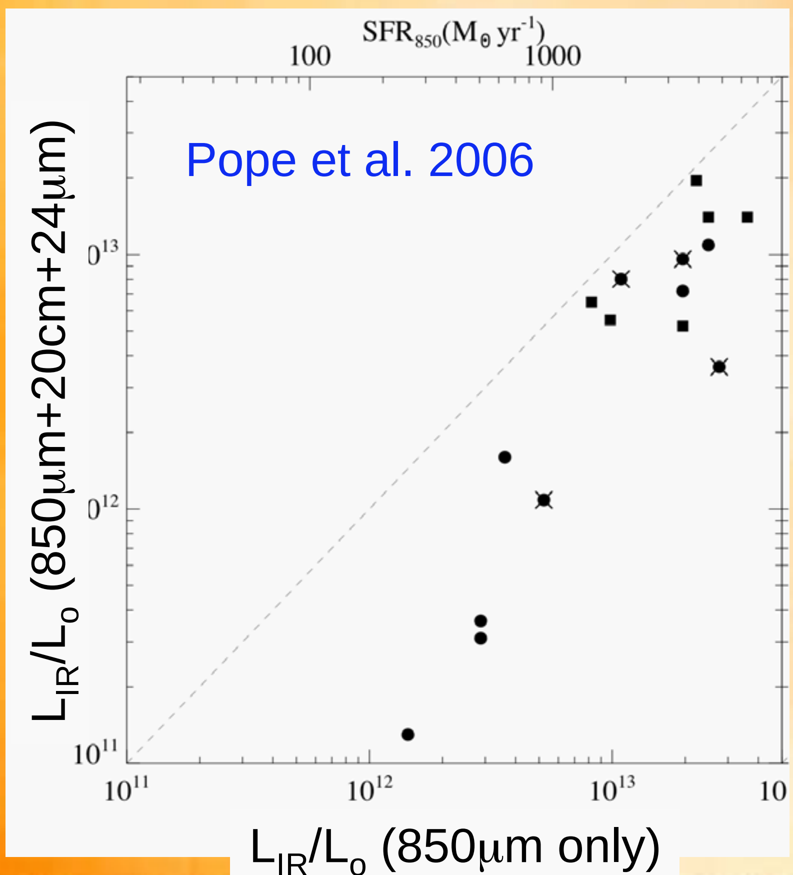
Implies high duty cycle for AGN activity (as for star formation)

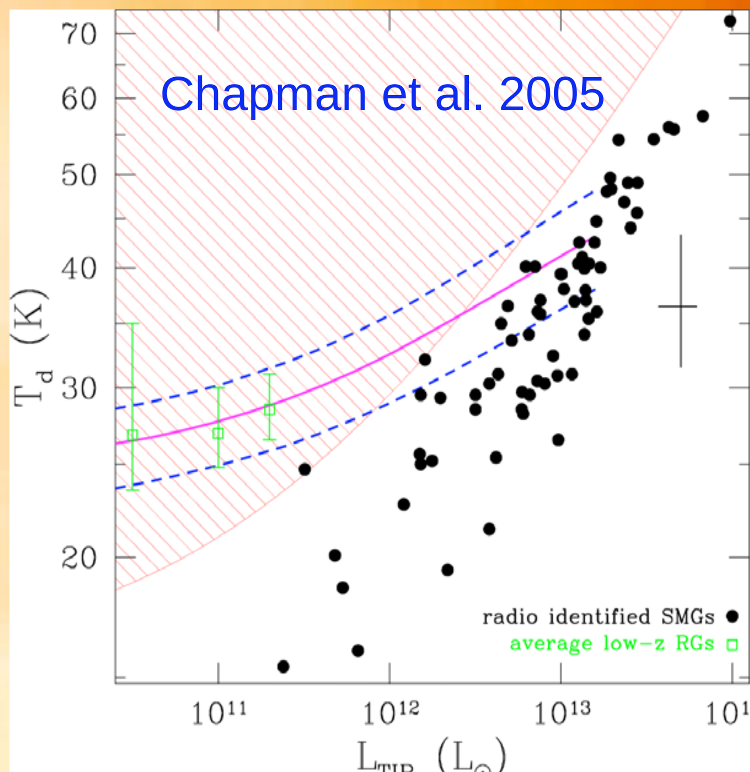
Intrinsic X-ray luminosities highly uncertain, but these may be more abundant than models predict, and could contribute to regulating SF and the establishment of the bulge-BH mass correlation.



Luminosities & temperatures for submm galaxies



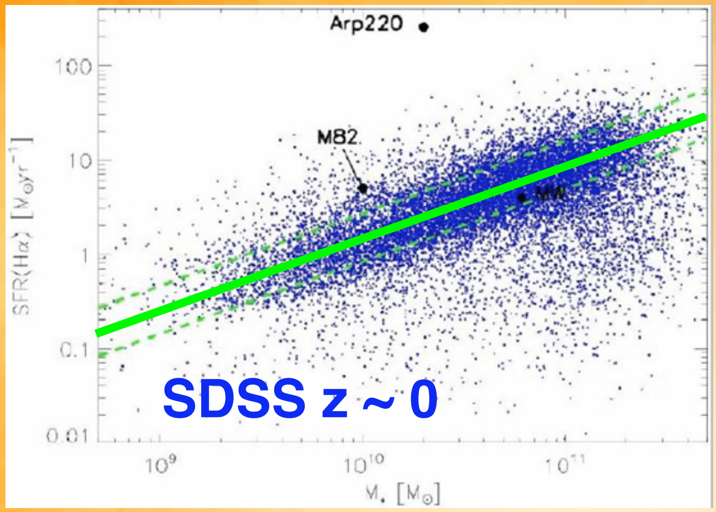


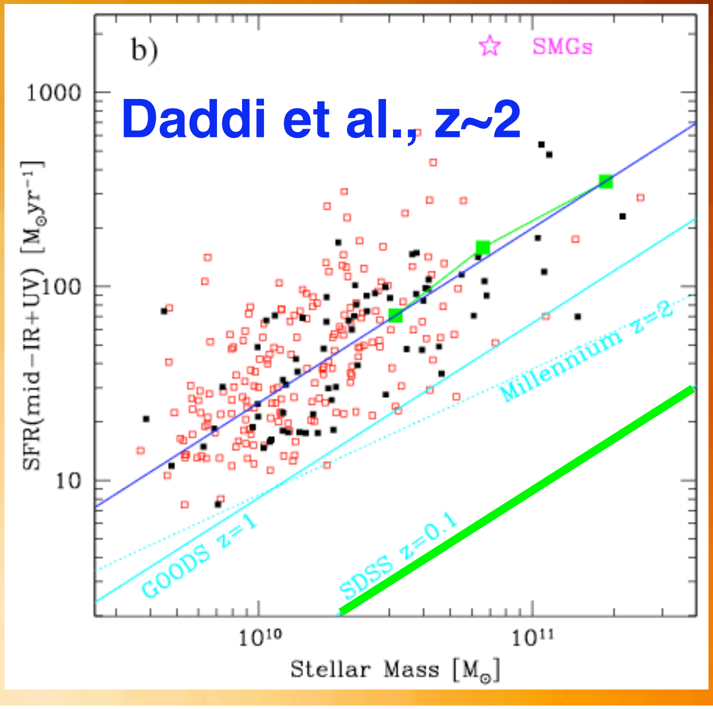


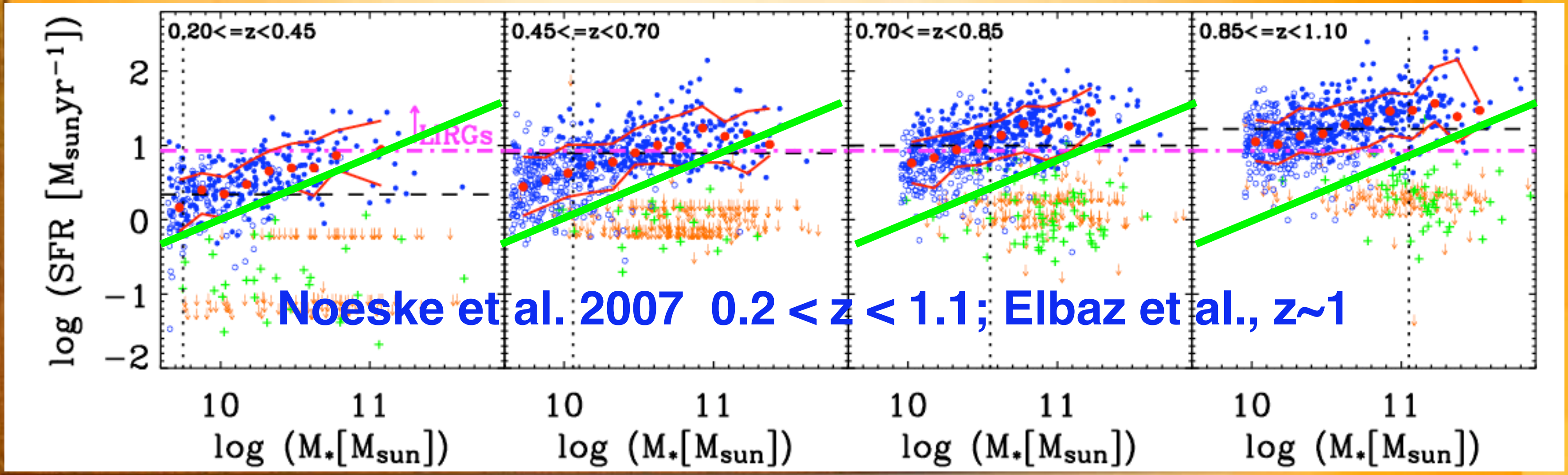
Modes of SFR

- ULIRGs @ z~0: clearly driven by interactions & mergers
- SMGs @ z~2: apparently similar?
  - Distorted morphologies
  - Very high SFR/M*
  - Short gas depletion timescales (L’(CO)/L_{IR})
- Typical z~2 ULIRG: longer timescales and large duty cycles?
  - Ubiquity
  - Tight M*-SFR correlation
  - Very large gas reservoirs

M*-SFR correlation



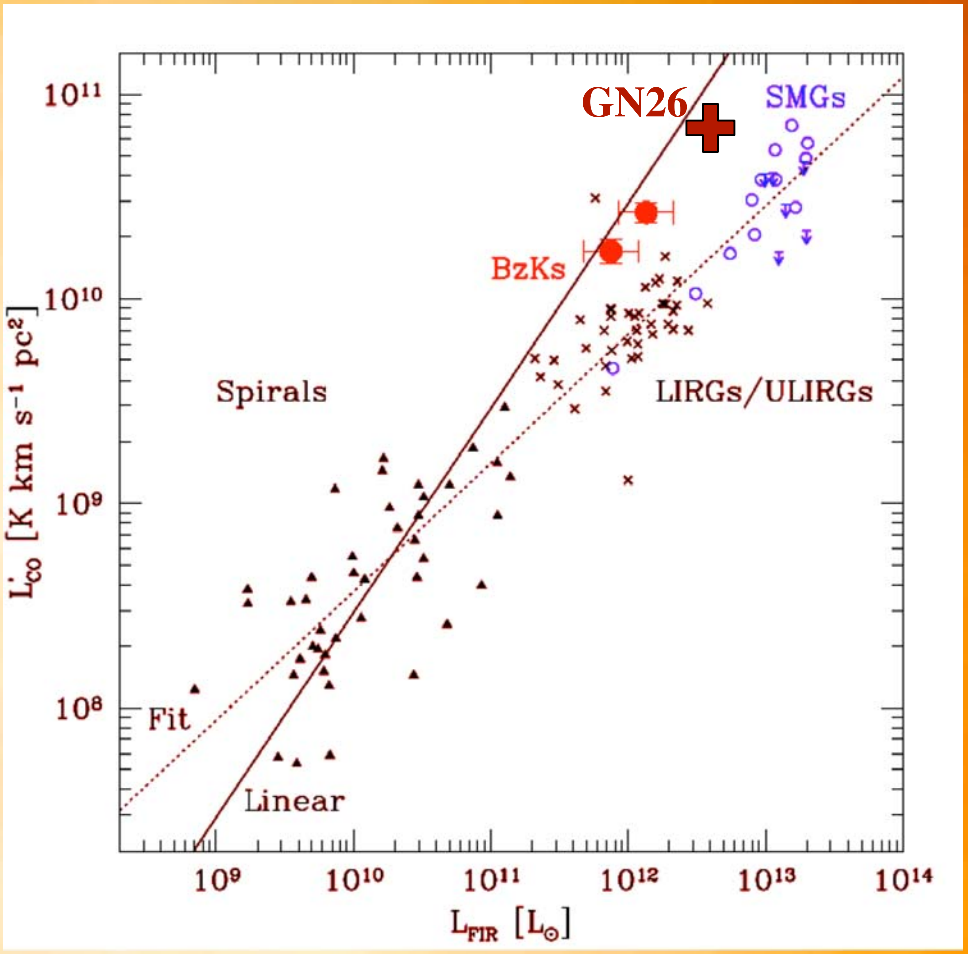




Molecular gas at z~1.5

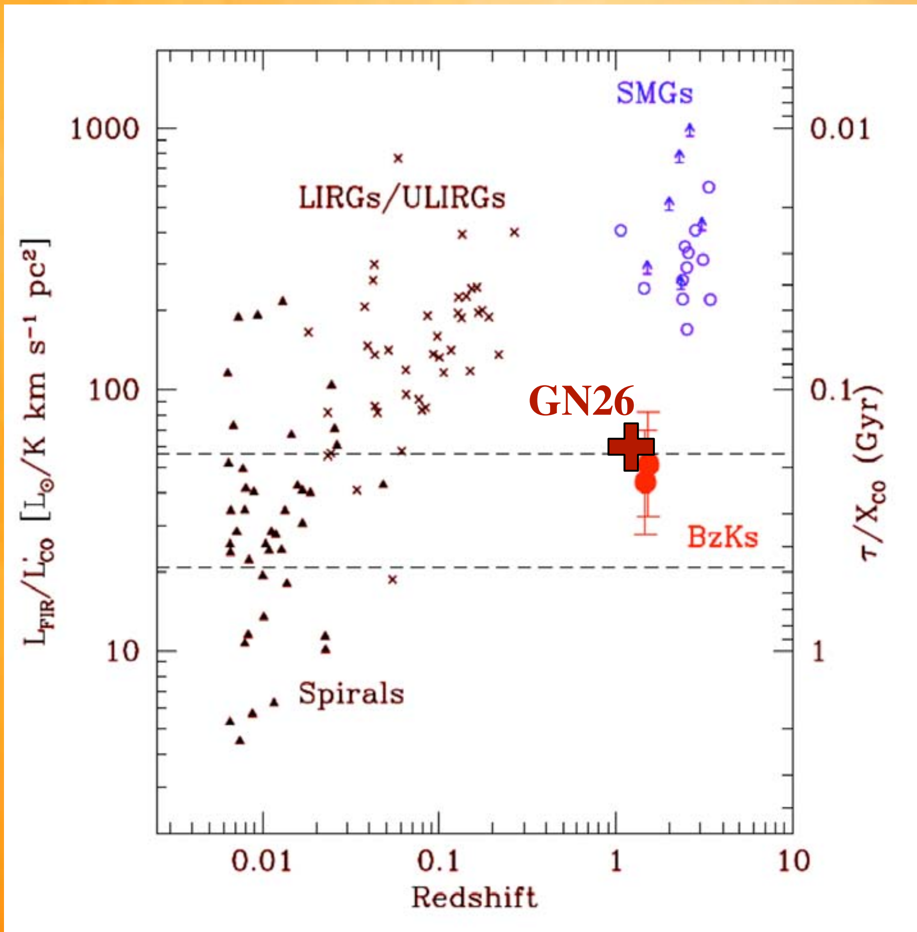
BzK-selected galaxies w/ PdBI: Daddi et al. 2008
70μm/submm galaxy w/ CARMA: Frayer et al. 2008

These objects have substantially larger $L'(CO)/L_{IR}$ than do local LIRGS & ULIRGs or typical SMGs



SF efficiencies and time scales

Do these galaxies resemble 'scaled-up' spirals in terms of their SF efficiency?



$M_{H2} \sim 2x10^{10}$ M_o if X_{CO} = 1 (as for local ULIRGs), or $\sim 10^{11}$ M_o if $X_{CO} \sim$ 4.6 as in the Milky Way

Implied SF timescales are much longer than for SMGs:

- 200-300 Myr (for X_{CO} =1),
- ~1+ Gyr ($X_{CO} \sim$ 4.6)

CO spatially extended for 1 galaxy on similar scale as UV light

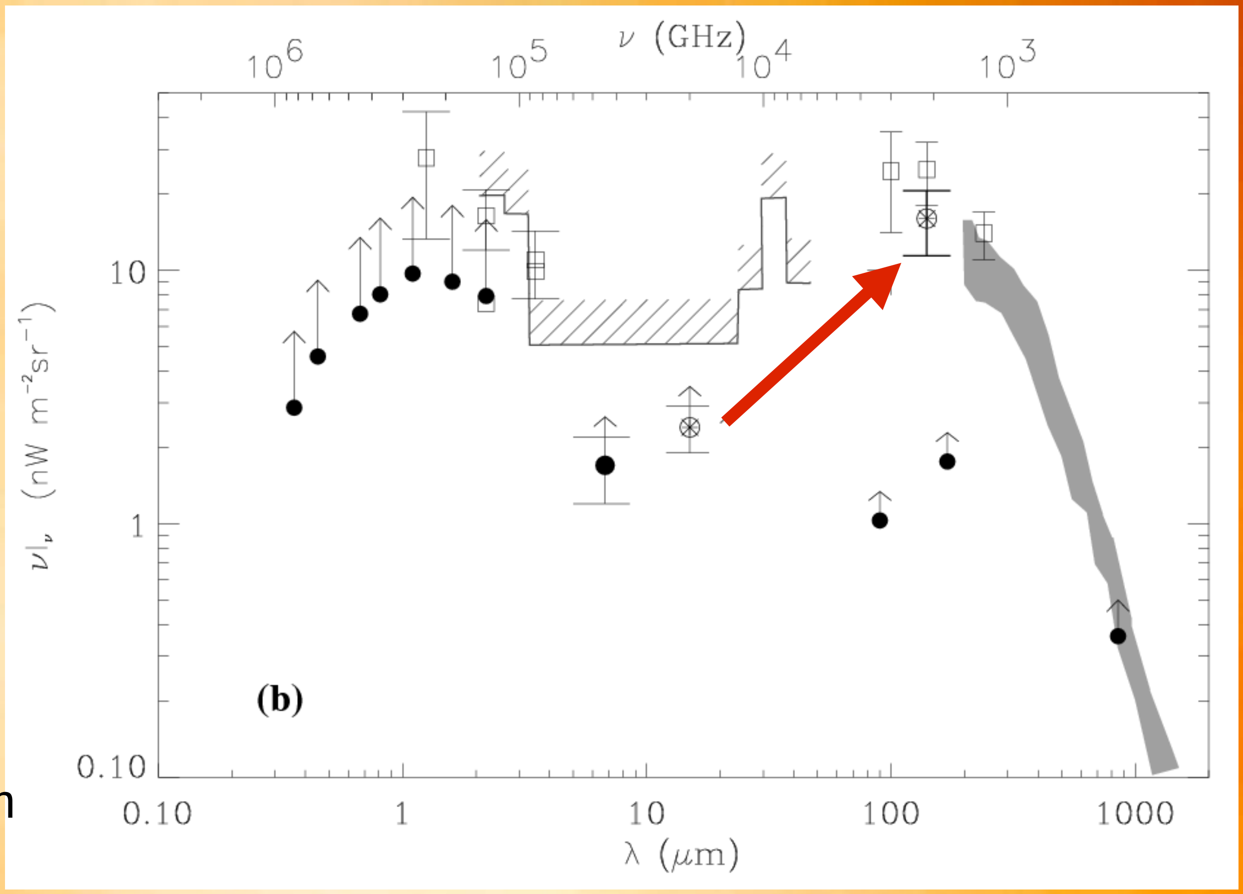
Low SF efficiency & large spatial extent may support X_{CO} more like local spirals than ULIRGs

Is there anything left to learn about the far-IR EBL?

Elbaz et al. 2002: Used a model to extrapolate from observed deep ISOCAM 15μm surveys to 140μm.

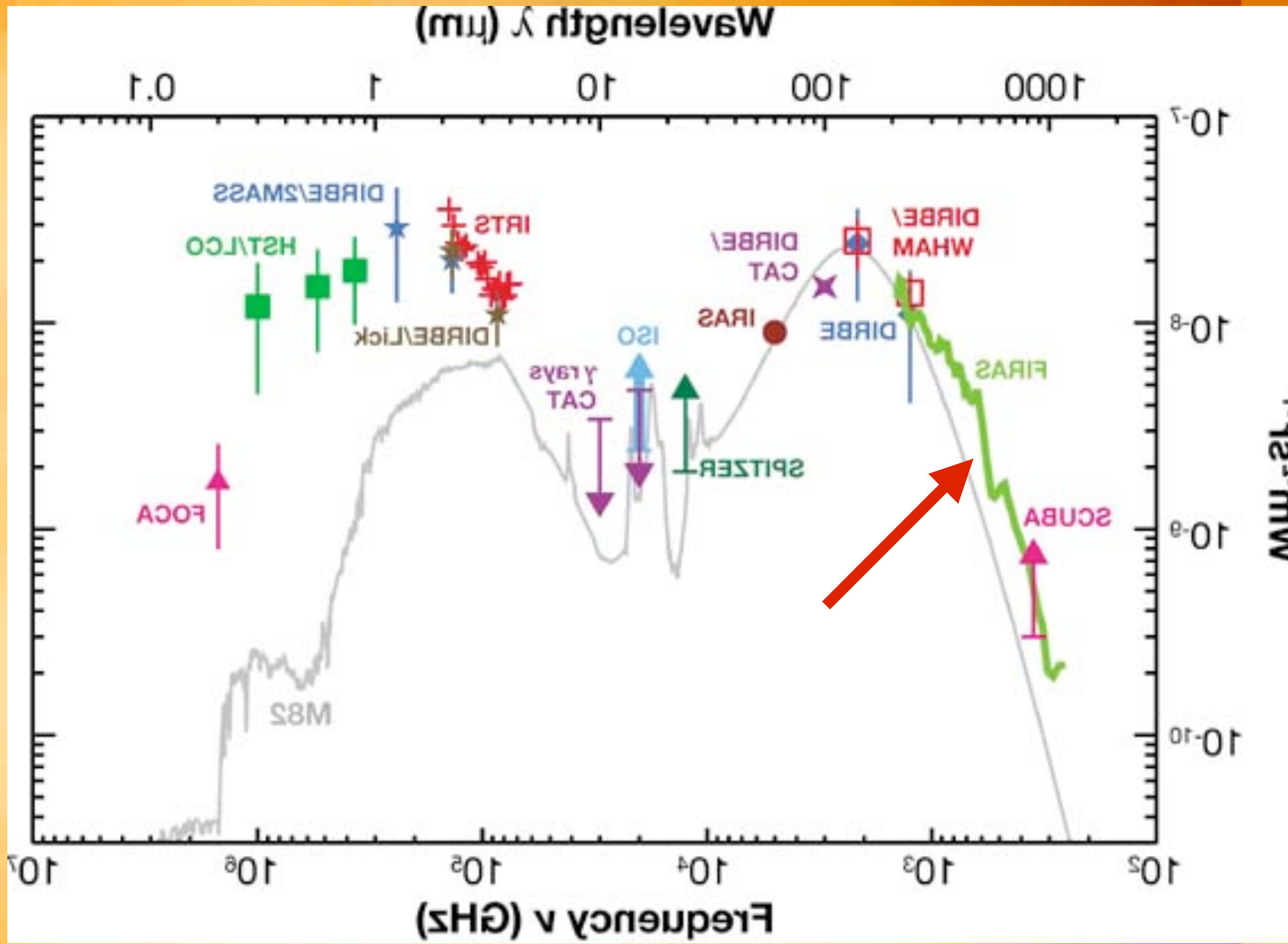
Implies ~65% of FIR background resolved & dominated by LIRGs @ z~1

Dole et al. 2006: MIPS 70μm and 160 μm stacking on 24μm positions: ~75% of EBL resolved



Resolving the peak isn't everything…

FIRAS EBL and submm source counts imply significant dusty SFR @ z >> 1



GOODS-Herschel
David Elbaz (CEA Saclay) + many others…

Dave Alexander, Durham University, UK
Bruno Altieri, ESAC, ESA
Herve Aussel, CEA / Saclay
Mark Brodwin, NOAO
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Denis Burgarella, OAMP, Marseille, France
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Catherine Cesarsky, ESO
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Vassilis Charmandaris, Dept. of Physics, Univ. of Crete
Ranga-Ram Chary, Spitzer Science Center, USA
Emanuele Daddi, SAp, CEA/Saclay, France
Mark Dickinson, NOAO, USA
Herve Dole, IAS, Orsay, France
Peter Eisenhardt, JPL/Caltech, USA
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Rene Gastaud, CEA / Saclay
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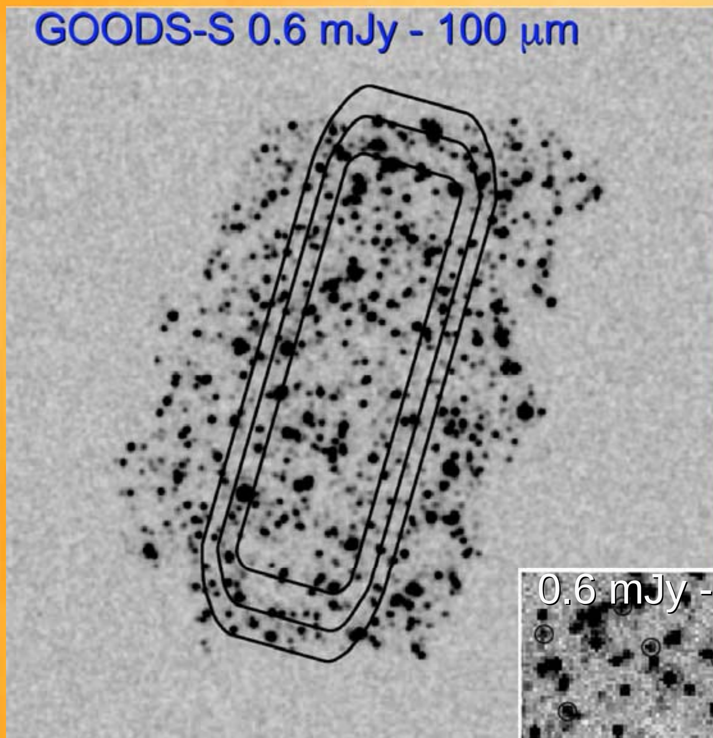
Casey Papovich, Texas, A&M University
Alexandra Pope, NOAA, USA
Paola Popesso, MPE, Garching, Germany
Naveen Reddy, NOAO, USA
Douglas Scott, University of British Columbia, Canada
Christian Surace, LAM, Marseille, France
Harry Teplitz, Spitzer Science Centre, USA
Ivan Valtchanov, ESAC, ESA
Min S. Yun, University of Massachussetts, USA
Grant Wilson, University of Massachussetts, USA

Collaborators (39):
France (10), USA, Germany, UK, Greece, Italy, Canada
ESO, ESA

362.6 hours (100μm & 160μm PACS, including 31 h SPIRE)

GOODS-Herschel



GOODS-N:

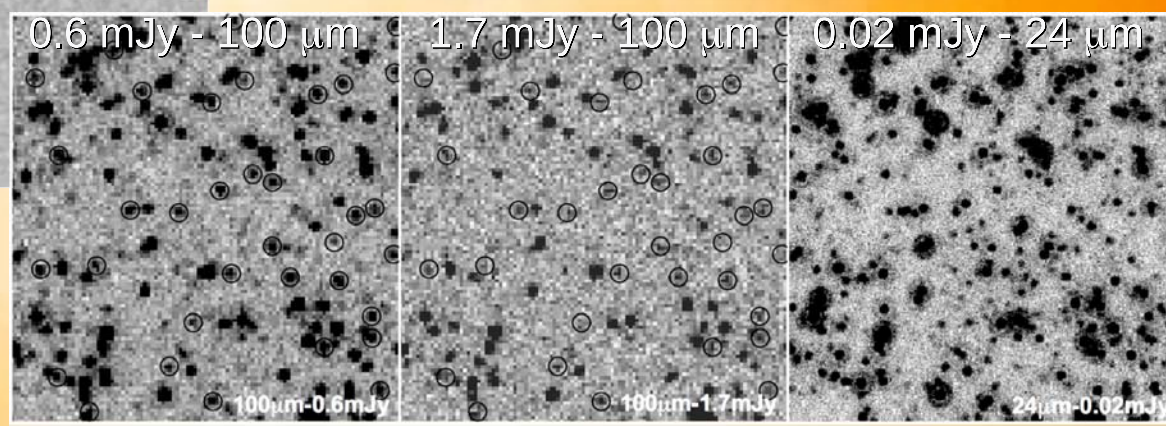
Matching GT GOODS-S program

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

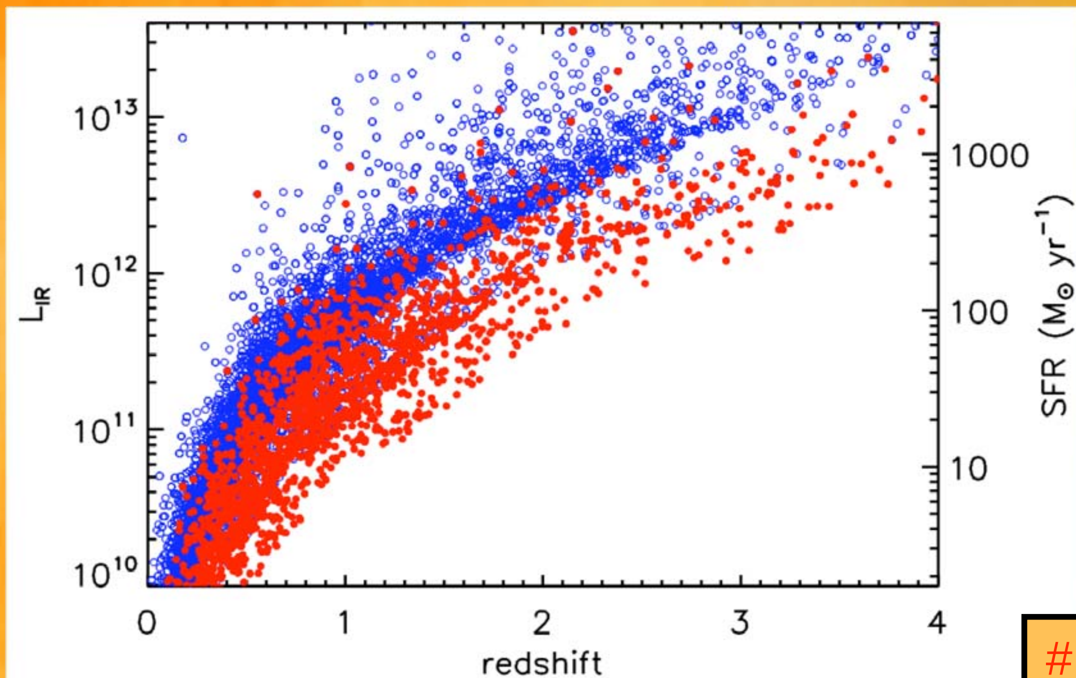
GOODS-S:

PACS ultradeep field, 207h

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



GOODS-Herschel (red) and GTO KP (blue)



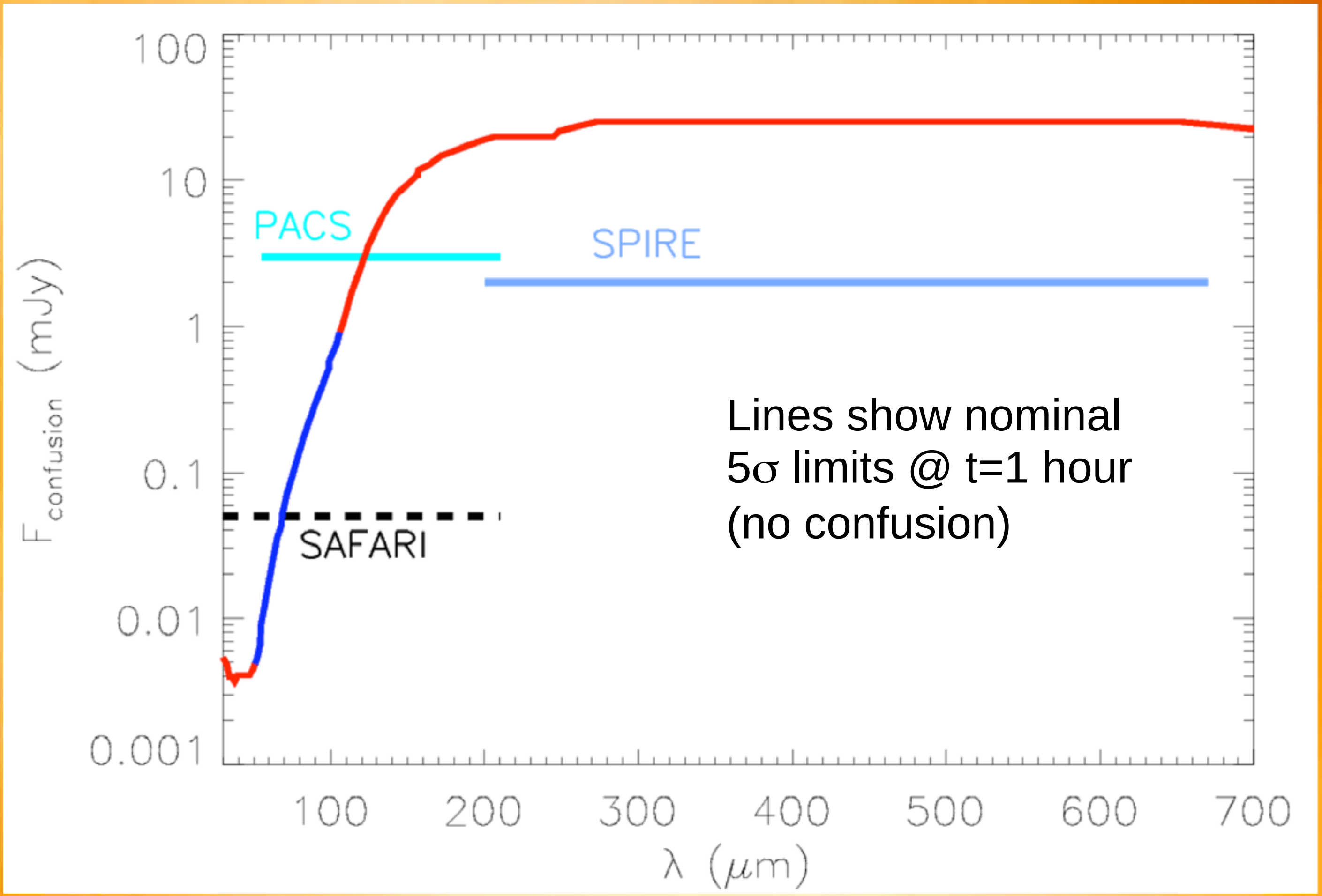
from mock Herschel catalogs

generated by Damien Le Borgne

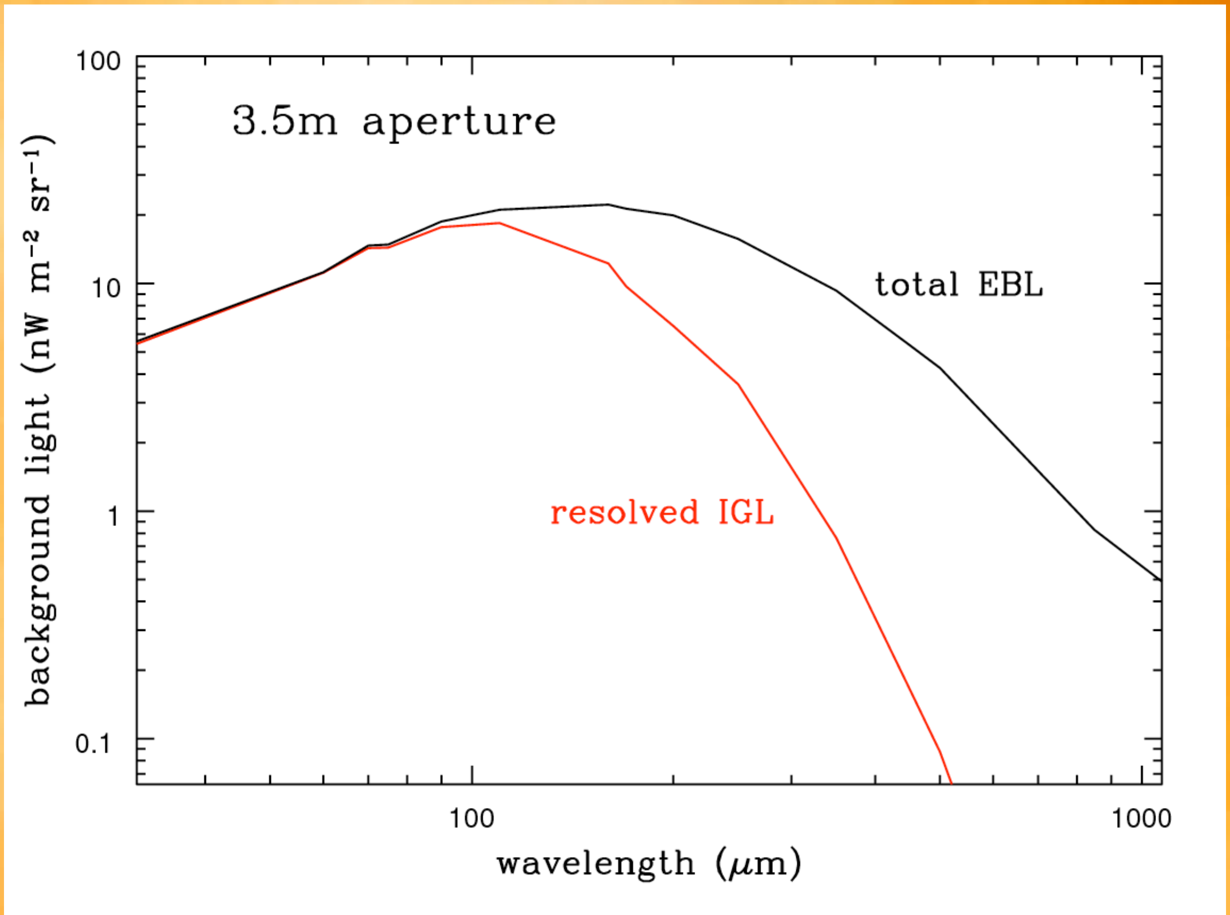
# gals	z_{min}	z_{max}	<Lir>	<SFR>
1148	0	1	10.63	7
551	1	2	11.59	66
149	2	3	12.31	354
52	3	4	12.70	861
10	4	5	13.19	2692
1910	**0**	**5**	**11.11**	**22**

Sensitivity limits for 3.5m FIR telescopes

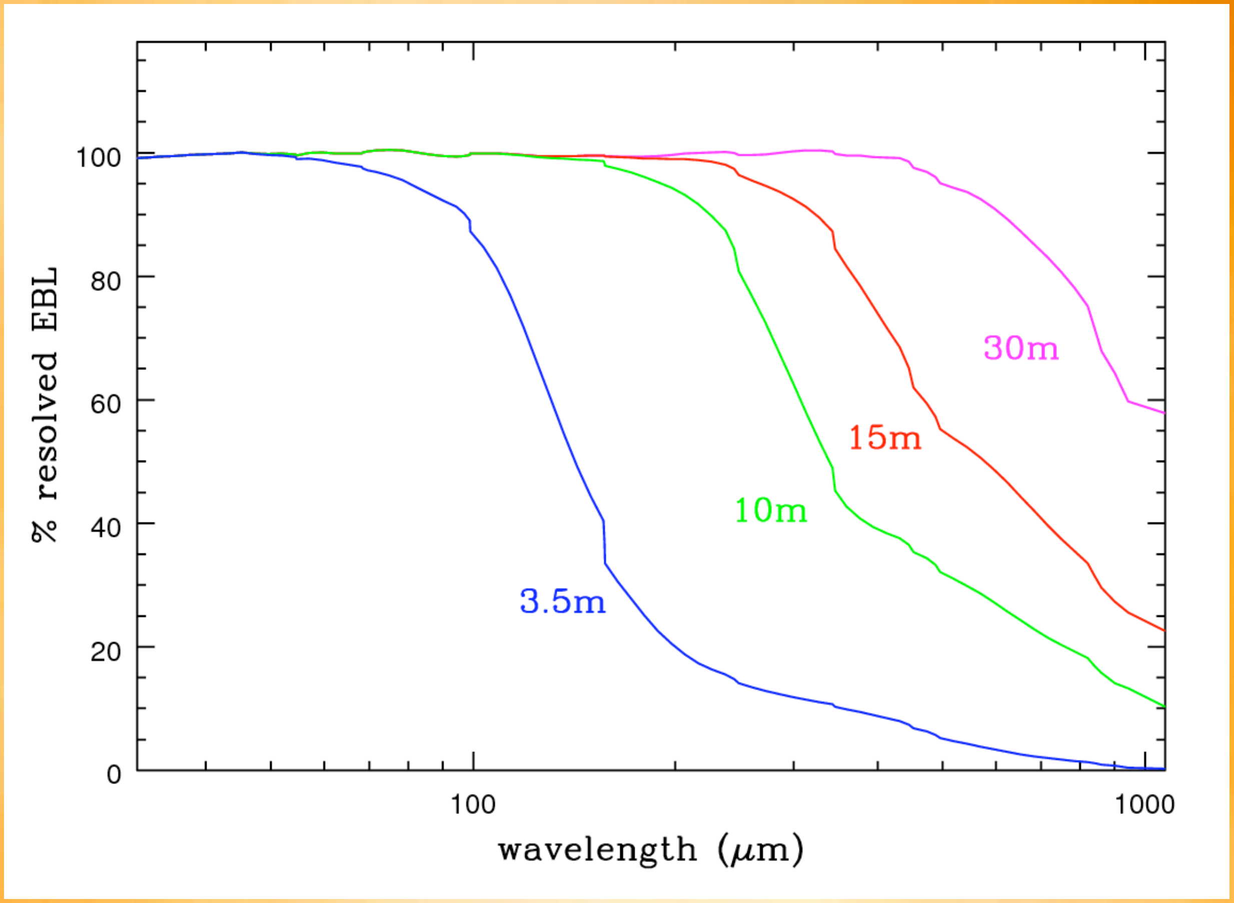
courtesy David Elbaz



Resolved EBL to the 3.5m confusion limit



Dreaming of bigger things…



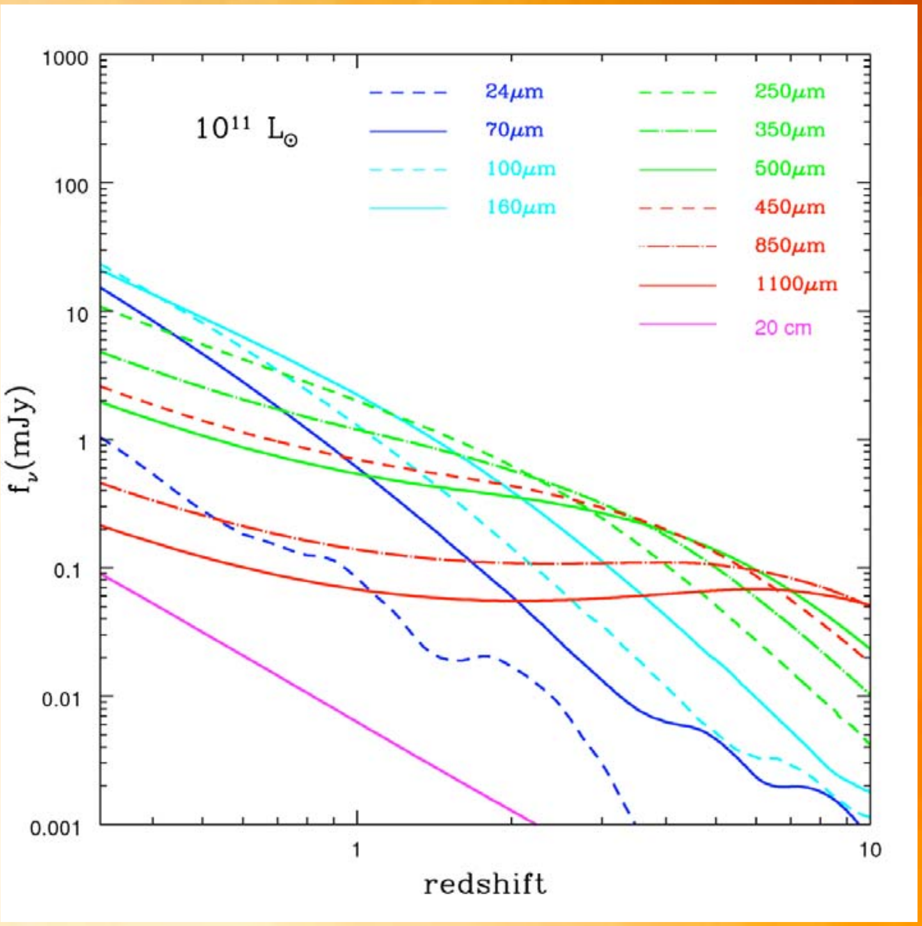
"Normal" at z > 2 is hard…

Detecting SFRs of ~10 M_o/yr at z ~ 2-6 requires:

• sub-mJy sensitivity at 200-400 μm, >10x below 3.5m confusion limit
- requires 10-15m aperture

• 0.1-0.5 mJy @ 450μm, well within reach of ALMA, but over tiny solid angles

• ~0.1 mJy @ 1 mm, "easy" for mapping with 50m LMT; "trivial" for ALMA over tiny fields



Summary

- The IR EBL appears to be dominated by LIRGs @ z~1
- ULIRGs appear may dominate SFR @ z~2
- Very little known directly about dusty SF @ z > 2
- Actual census of dusty SF at z > 1 still very uncertain:
  - Significant problems reconciling SFR(z) and Ω*(z)
  - Uncertain bolometric luminosities
  - AGN contribution to mid-IR
- Dust temperatures, masses, may vary enormously
- Modes of star formation, triggering, time scales may be very different than similar objects at other redshifts
- Obscured AGN may be ubiquitous in massive galaxies
  - perhaps critical to regulating galaxy growth?
  - duty cycles, fueling, etc. still unclear

Looking ahead

- Herschel & SPICA:
  - resolve most of the EBL at $\lambda < 120\ \mu m$
  - provide vital constraints on SFRs, AGN content, etc. at z~2
  - study ULIRGs to z~4 & beyond
- LMT & ALMA:
  - Resolve most of the EBL at $\lambda > 400\ \mu m$
  - Sensitive to highest-redshift dusty SFR
  - Long-wavelength constraints on dust temperatures, masses, etc
  - Subgalactic angular resolution with ALMA
  - Molecular redshifts, kinematics, etc.
  - 450-850 μm "easy" with ALMA, but over small fields
- TBD: Sensitive measurements at $100 < \lambda < 400\ \mu m$
  - Full SEDs for measuring dust luminosities, temperature distributions, masses
  - Studying SF and obscured AGN at $1 < z < 4$ at bolometric peak