Institute for Astronomy

ASTRODEEP

Deeper into the Dust

Understanding relationships between SFR, stellar mass and obscuration at high redshift

with the

SCUBA-2 Cosmology Legacy Survey

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Outline

Introduction	The Cosmic Star Formation History Status of Galaxy Evolution Motivation for the work
Data	The Cosmology Legacy Survey Optical prior catalogue selection
Techniques	Problems with sub-mm maps De-confusion with T-PHOT Sample definition
Results	Some preliminary results Relating SFR and obscuration to mass and UV luminosity

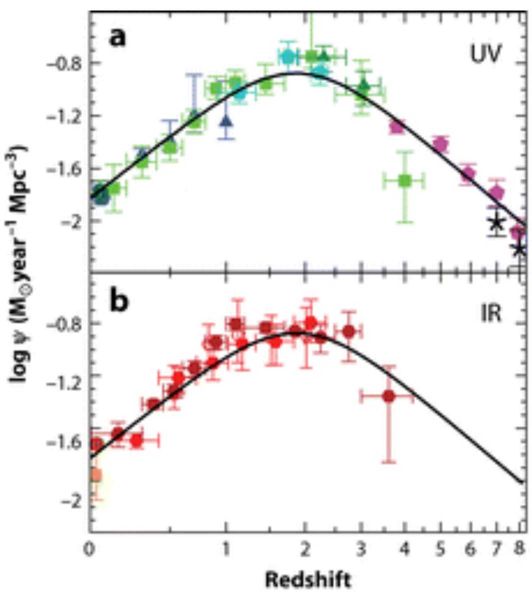
Understanding the evolution of galaxies

The Cosmic Star Formation History

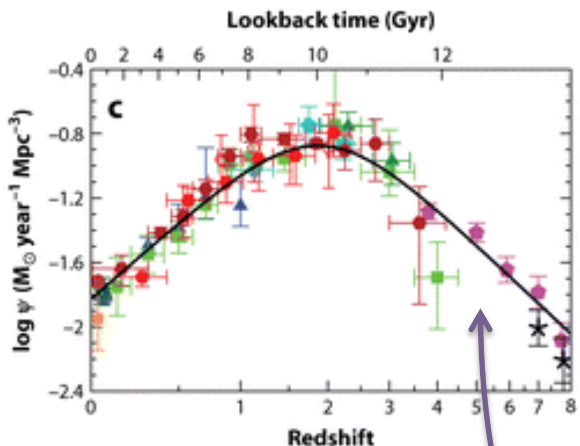
What do we know or understand?

- SFR density grows with lookback time from z=0 to z=2
- At z>3 UV observations indicate a fall, but we run out of IR samples
- IR samples become dominated by extremely obscured systems
- Best estimates of SFRD from rest-FUV LFs from Lyman Break samples

SFR density



Madau P, Dickinson M. 2014.
Annu. Rev. Astron. Astrophys. 52:415–86

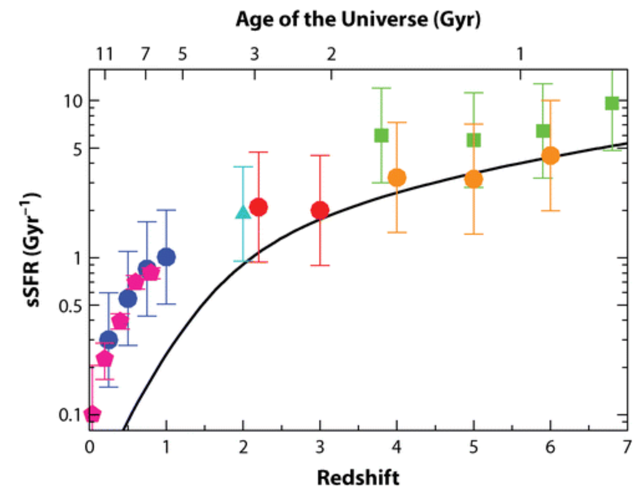


Bouwens et al. LBGs

The Cosmic Star Formation History

What else do we know?

- Average specific SFRs increase with z
- Stellar mass density traces accumulated star formation
- Mass density as a function of time should follow the integral of the CSFH up to that time



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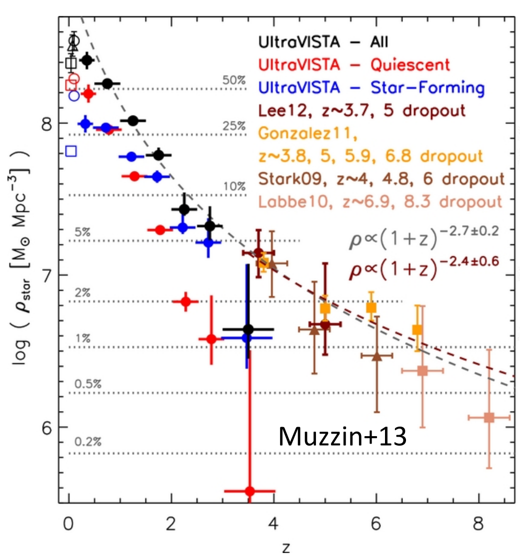
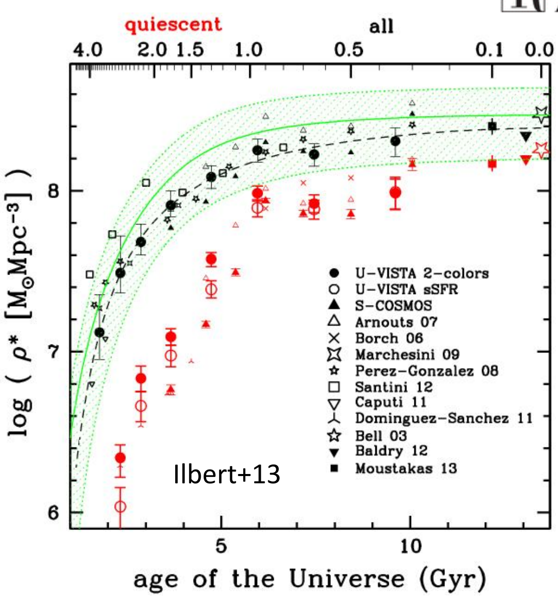
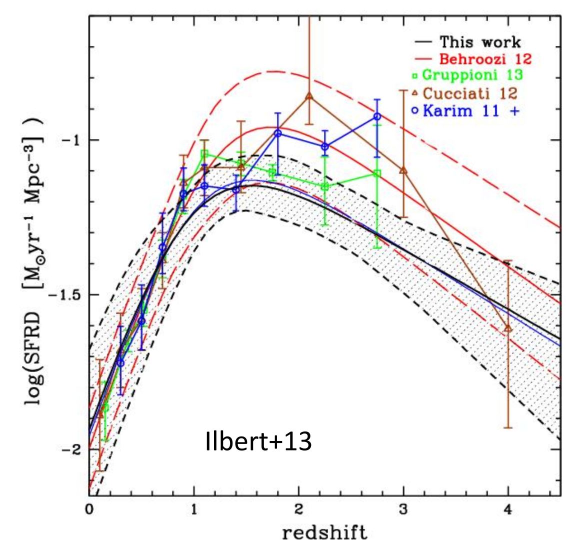
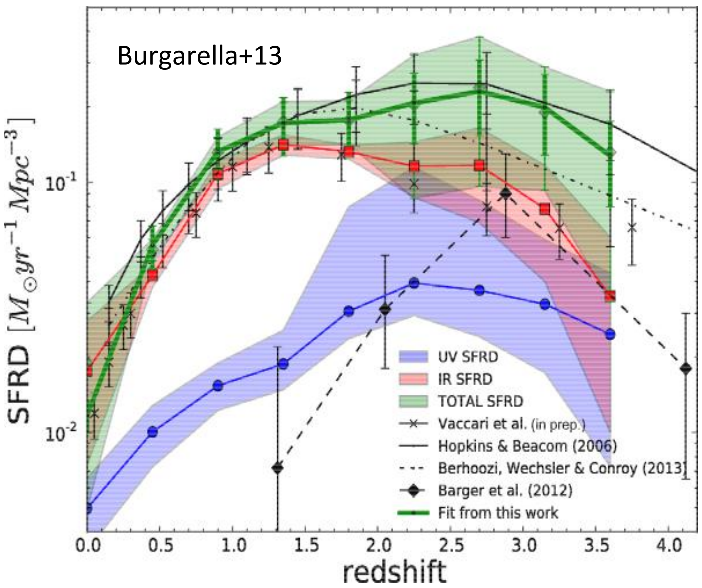
Stellar mass density

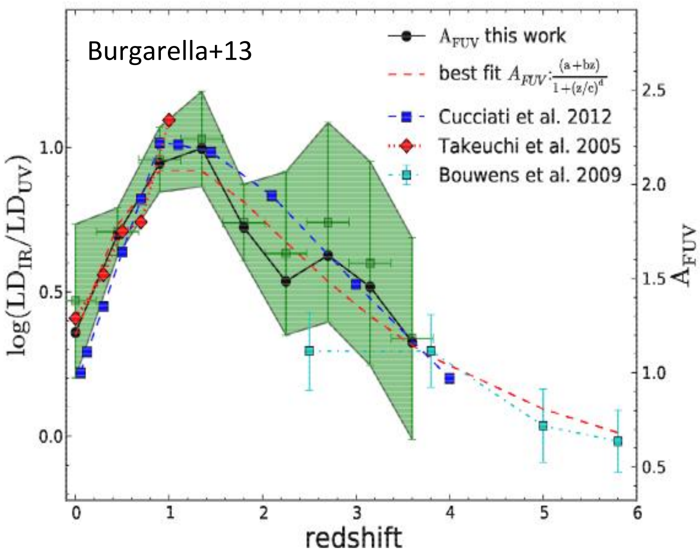






Dust obscuration

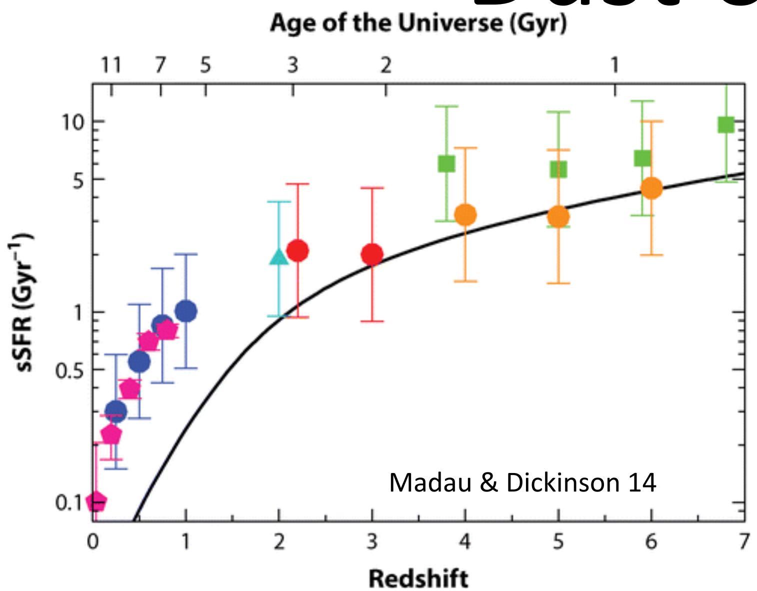




Why is this so difficult?

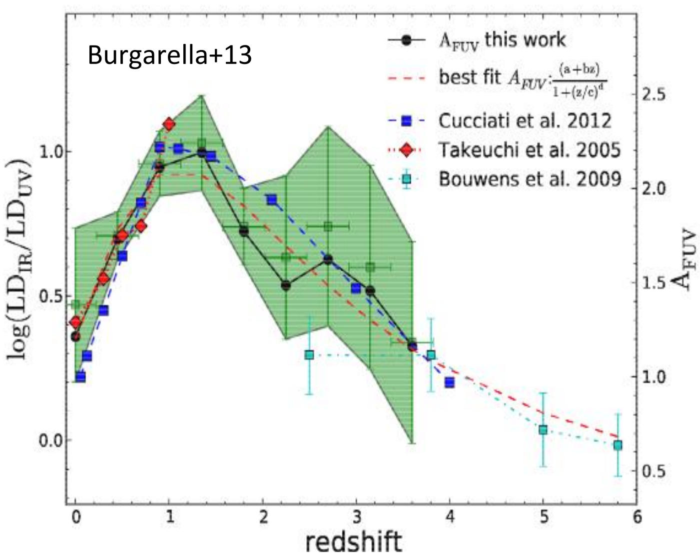
- Dust is a severe obstacle to measuring total SFRs
- Young stars are preferentially obscured within their birth-clouds
- IR SFRs > UV SFRs
- The obscuration is higher at the peak epoch of SF (z=1-2) than at z=0
- Beyond z=2, it is more uncertain

Dust obscuration

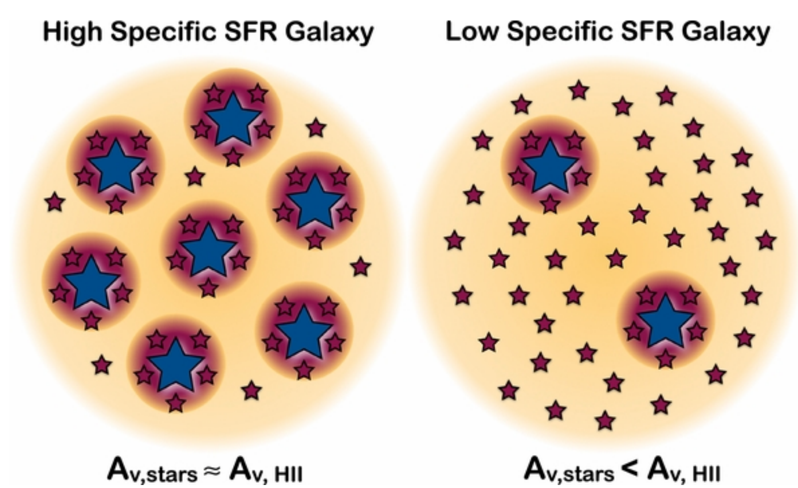


Why is obscuration higher at high-z?

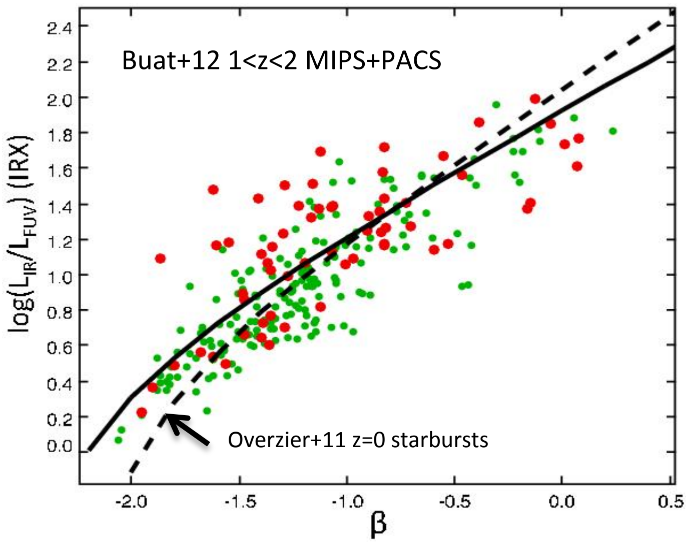
- SSFRs are generally much higher
- Stars are therefore forming in a different environment within the galaxy
- More of the stars are embedded within dense, dusty clouds



Price+14

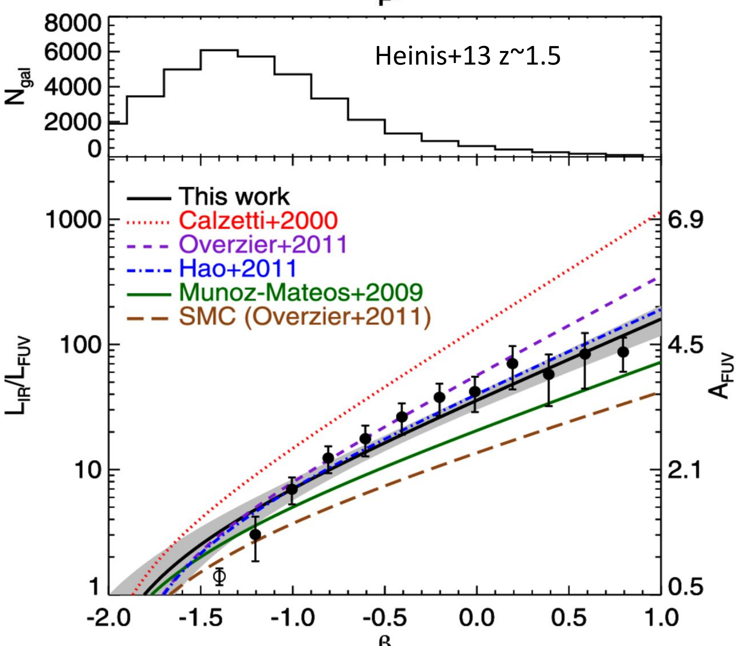


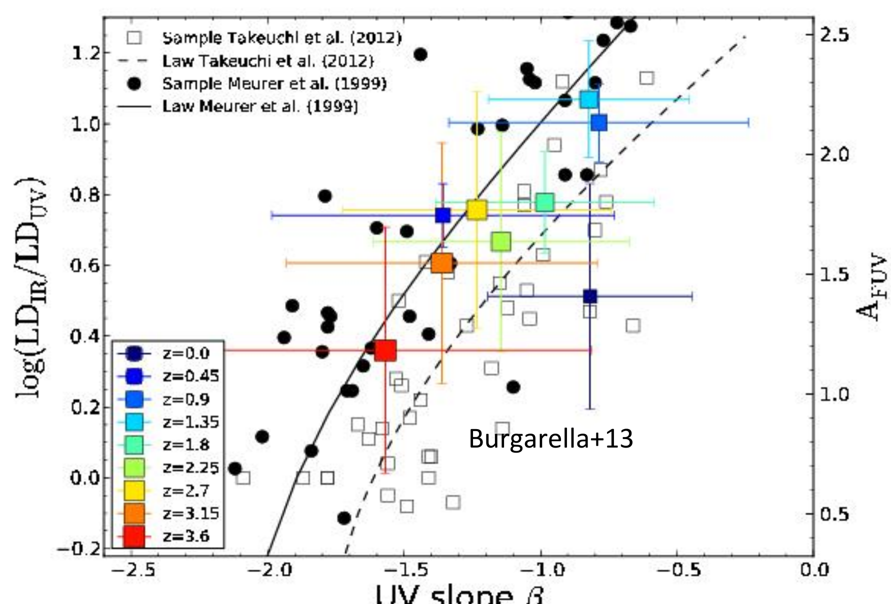
Dust obscuration



How to estimate this in the absence of FIR detections?

- Need a calibration based on UV slope
- But this needs better validation at high redshifts



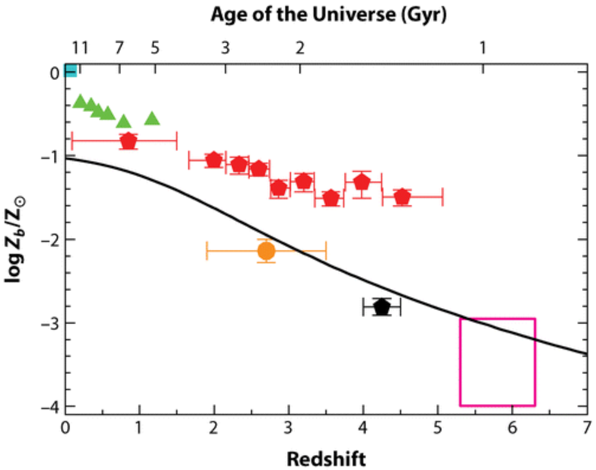


Dust at z>3

How dusty were (normal) SFGs at high redshift?

- High dust masses measured in SMGs and quasars at z>4... But these are atypical
- Lyman-break-selected and rest-UV selected samples may be FIR-bright at z<5

Mean metallicity in IGM absorption



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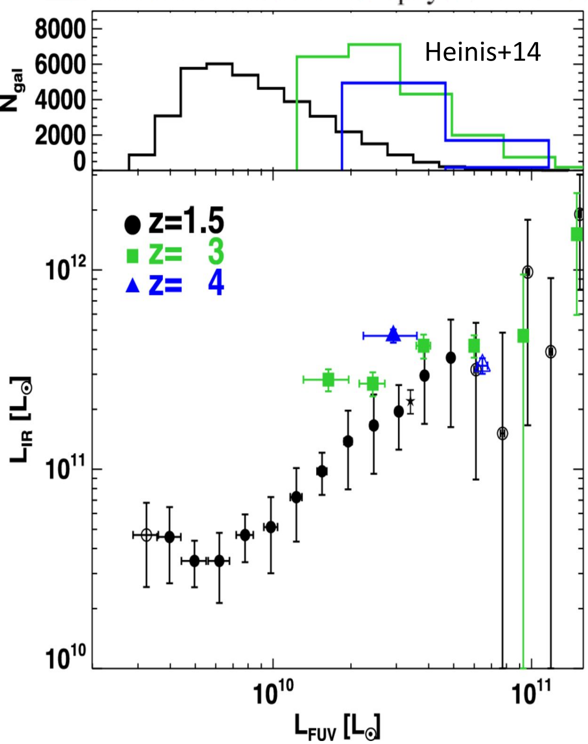
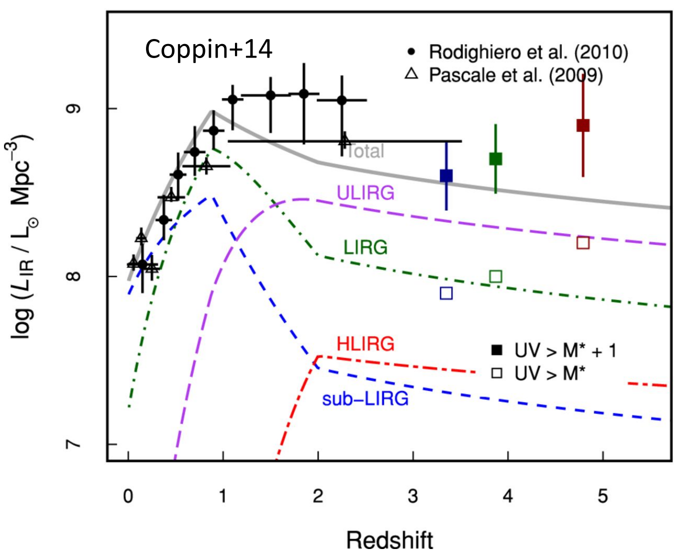
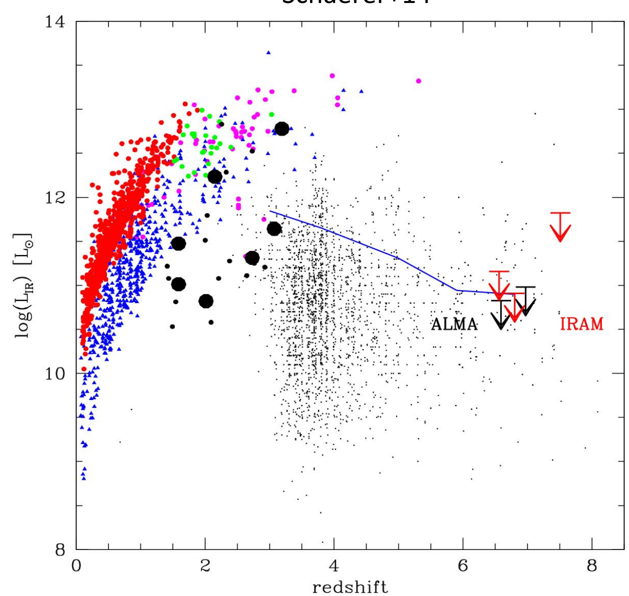


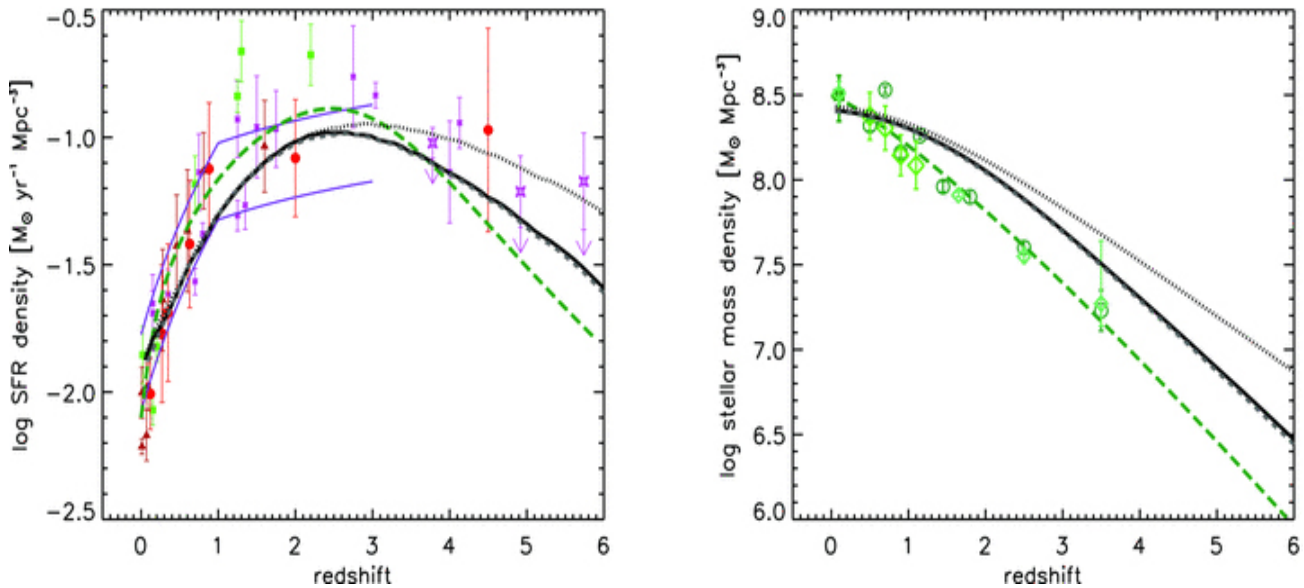


Schaerer+14



How much do we understand?

Somerville+12



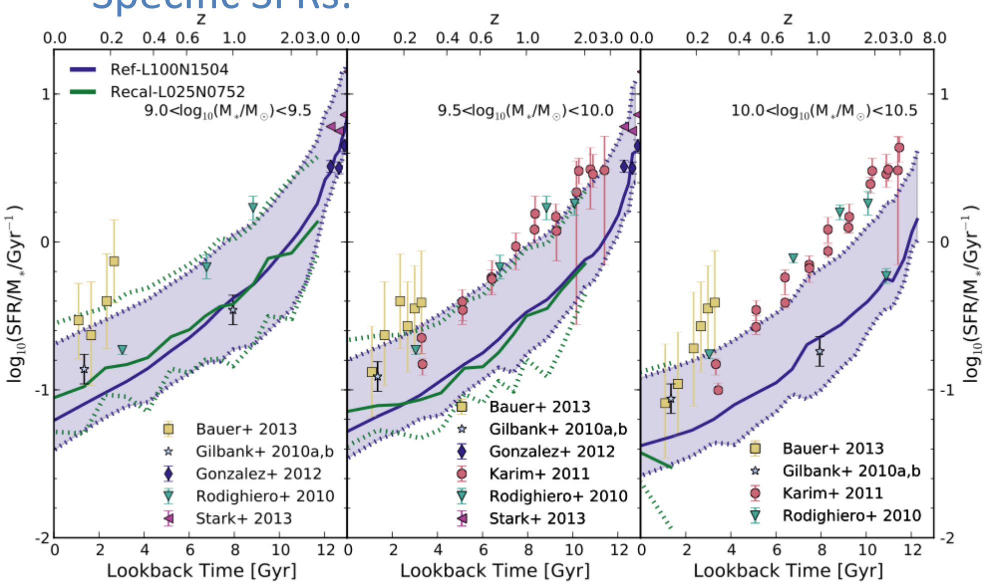
- Semi-analytic models can broadly reproduce observed CSFH and mass functions
- But the shape of evolving SFRs and mass buildup are problematic and require evolving dust/metals ratio or changes in geometry
- Also difficulty matching counts of bright SMGs
  - Baugh+05, Lacey+08, Guo+White09, Lo Faro+09, Somerville+12

How much do we understand?

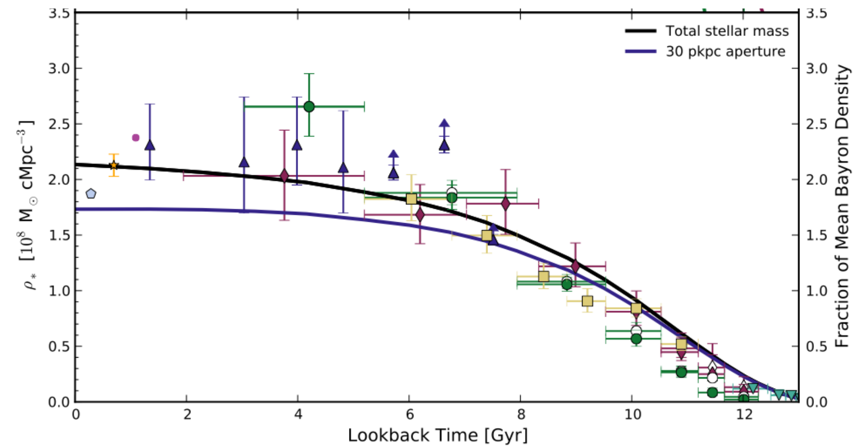
- Hydrodynamic simulations also struggle to match average (specific) SFRs while reproducing the observed mass functions

EAGLE – Furlong+14

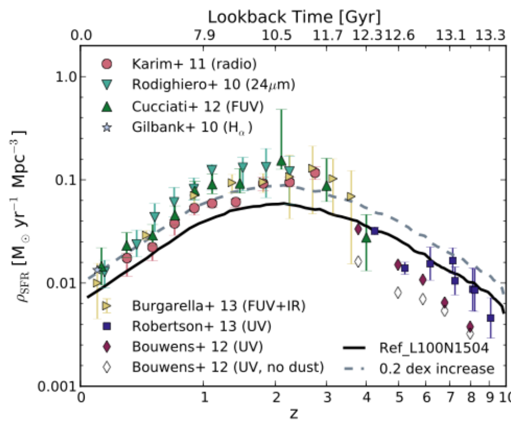
Specific SFRs:



Mass density evolution:



SFRD evolution:

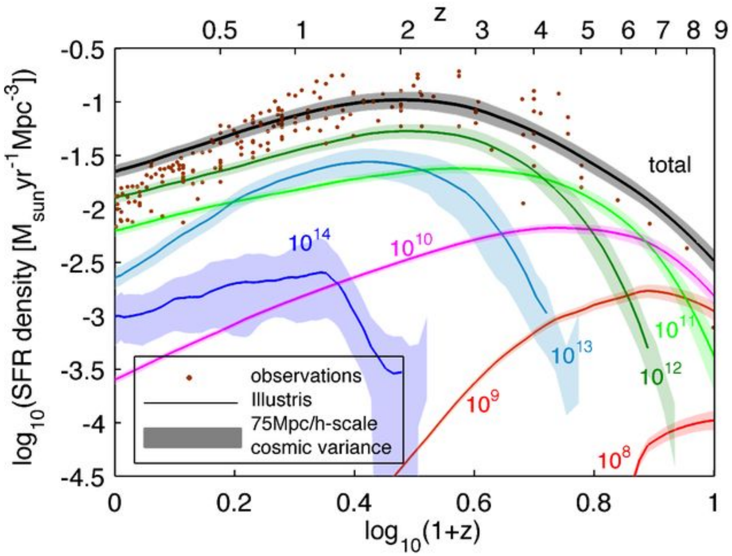


How much do we understand?

- Hydrodynamic simulations also struggle to match average (specific) SFRs while reproducing the observed mass functions

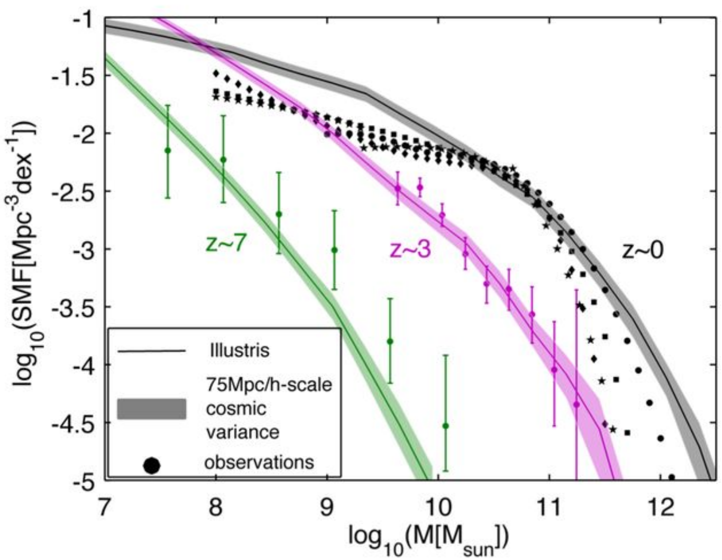
Illustris – Genel+14

SFRD evolution:



(c) Cosmic SFR density, 106.5 Mpc cosmic variance

Mass function evolution:



(d) Stellar mass functions, 106.5 Mpc cosmic variance

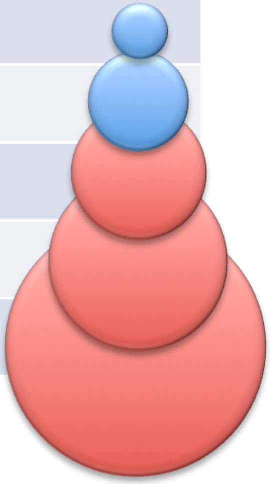
The cutting edge

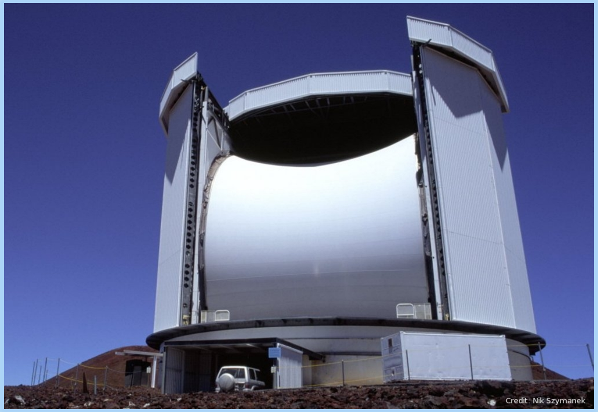
- Rest-frame FIR observations of star-forming galaxies begin to run out just when things are getting interesting
- Sub-mm surveys are dominated by extreme objects that are not likely to be representative
- Deeper stacking experiments can probe more typical populations but are still limited by sample selection as well as confusion issues – and they cannot resolve the full SFRD at high redshifts
- Rest-frame UV observations can trace unobscured SFR back to z<8, but corrections for dust rely on either full SED-fitting, or assumed correlation between UV slope and IR excess
- These corrections appear to be quite successful, but are not fully validated at z>~2

Addressing the gaps in our knowledge

What can we learn from SCUBA-2?

	wavelength / µm	PSF FWHM / arcsec
SCUBA-2	450	7.5
	850	14
Herschel-SPIRE	250	18
	350	24
	500	35





The SCUBA-2 Cosmology Legacy Survey

- Wide 850µm imaging over 35 sq.deg. to ~1mJy at 850µm in several deep survey fields such as COSMOS, GOODS, EGS, UDS, NEP, etc.
- Deep 450+850µm imaging over 1.3 sq.deg. to ~0.5mJy rms at 450µm over several fields in COSMOS, GOODS, UDS - overlapping with CANDELS
- Exploiting multi-wavelength coverage from Spitzer, Herschel, ground-based optical-NIR, and HST

- Deep COSMOS-CANDELS field: 120 sq.arcmin.
- Deepest multi-wavelength coverage from CANDELS, 3DHST, S-COSMOS, SEDS, etc.

Breaking through the confusion limit

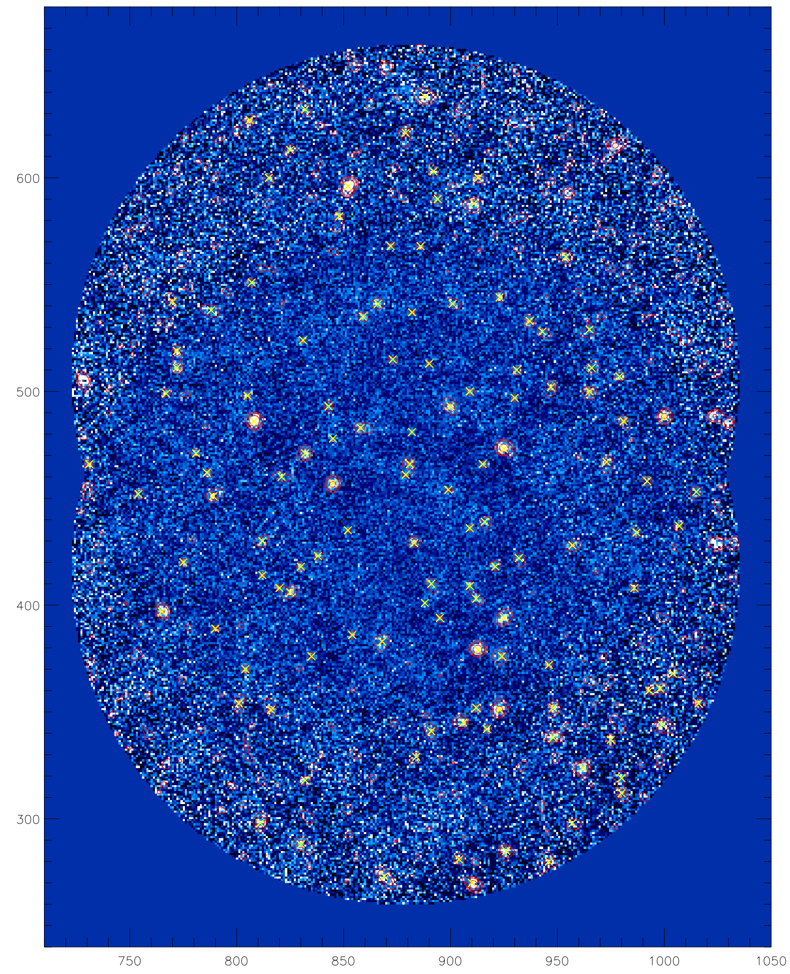
How can these datasets help us with our problems?

- Higher resolution imaging: to reduce confusion noise
- Deep imaging: to minimise instrumental noise
- Prior multi-wavelength information
- Apply deconfusion algorithms
  - Exploit high resolution priors
  - Probe denser source population
  - T-PHOT - E. Merlin et al. in prep.

De-confusing sub-mm maps with T-PHOT

- COSMOS-CANDELS 450µm: ~3mJy rms unfiltered
- ~100 sources detected at SNR>4
- Using prior-based deconfusion:
  - push the confusion noise down
  - measure fluxes of much denser sample
  - can assume all point sources
- Prior sample selection:
  - Source density must not be too high
  - TPHOT needs to be able to solve an equation

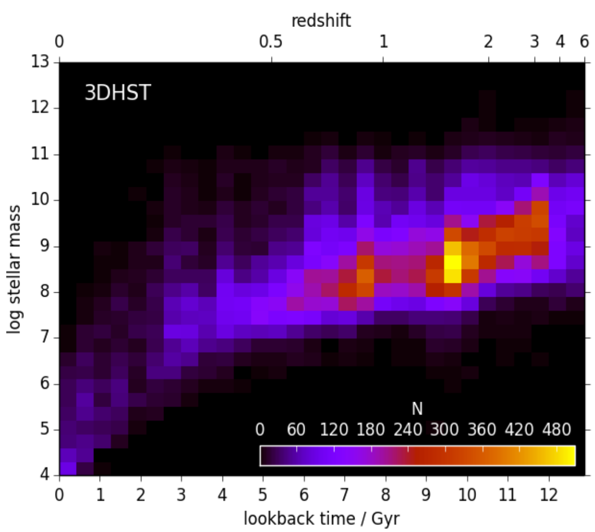
N free parameters < N independent data

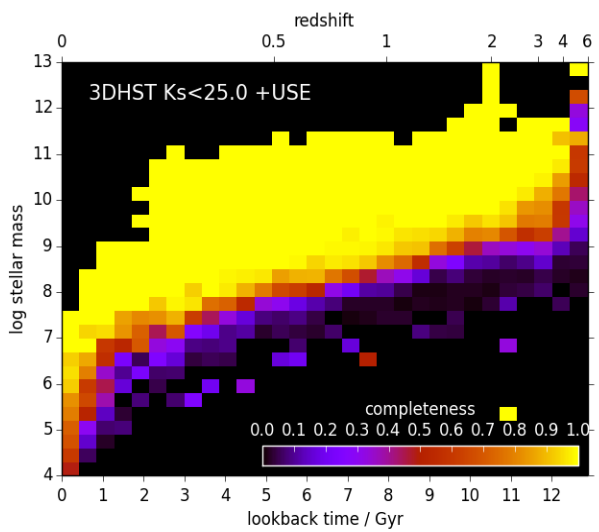


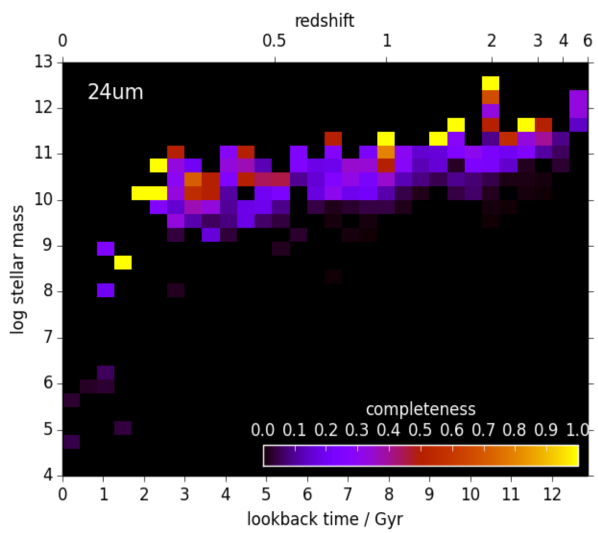
De-confusing sub-mm maps with T-PHOT

Selecting a sample: maximum completeness, minimum bias…

- 3DHST photometric sample – Skelton+14
- K < 25, USE photometry flag
- logM > 9
- 3DHST photo-z and SED fitting
- 4900 galaxies in total

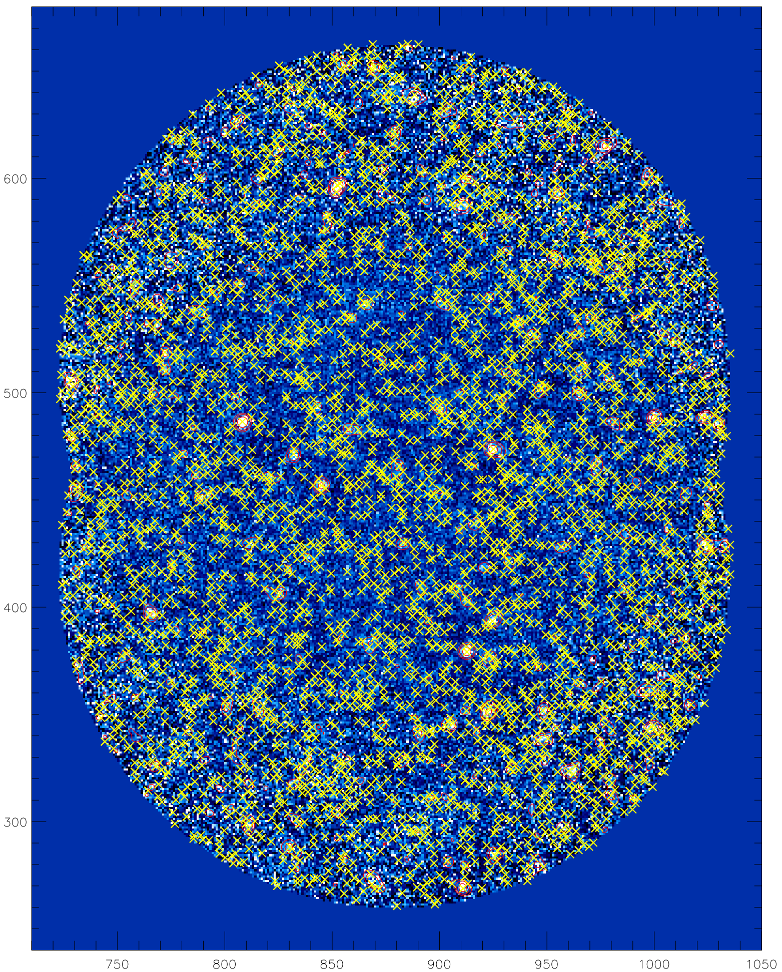






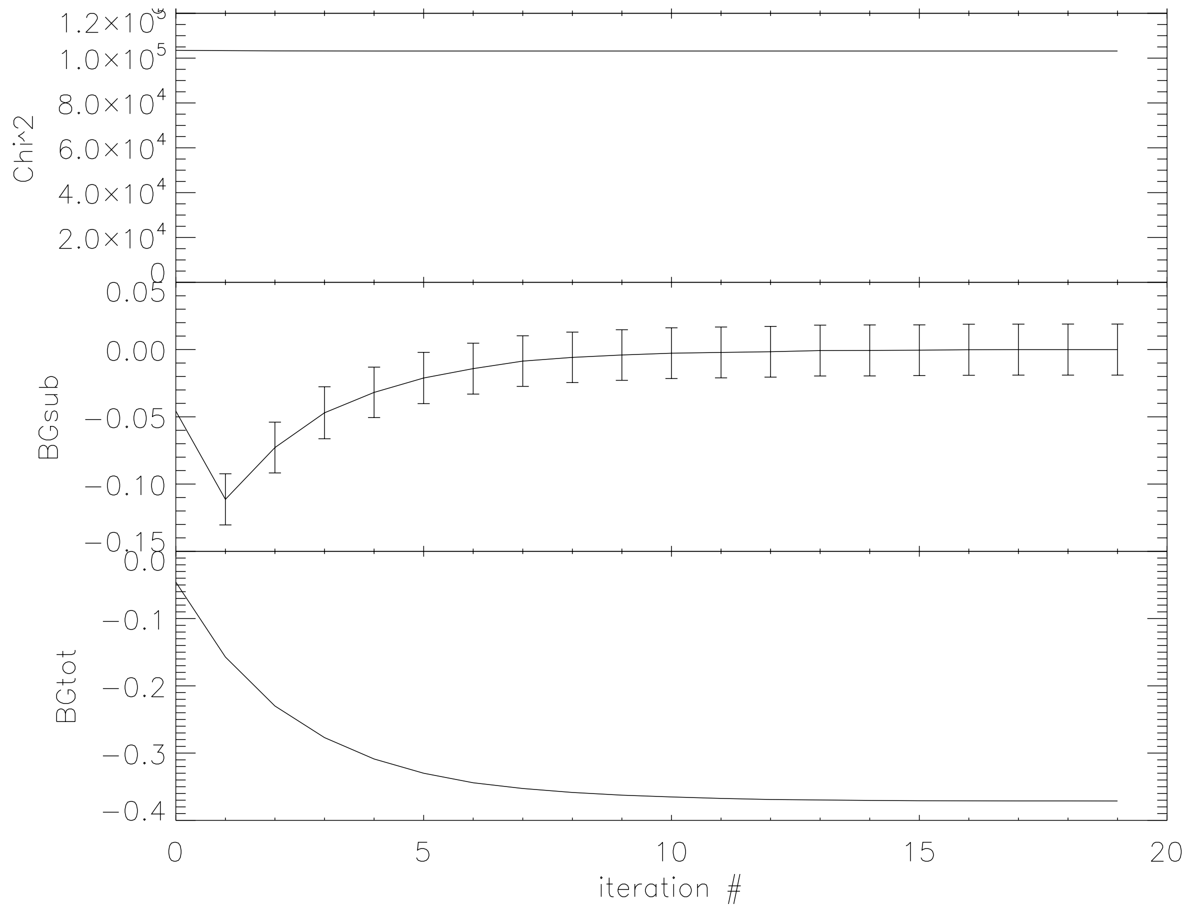
De-confusing sub-mm maps with T-PHOT

- T-PHOT models the map as the result of a set of blended point sources at the positions of the prior catalogue
- The fluxes are free to vary until a minimum chi-squared solution is obtained
- Objects with significant negative fluxes are clipped from the prior list
- Background is a fixed parameter

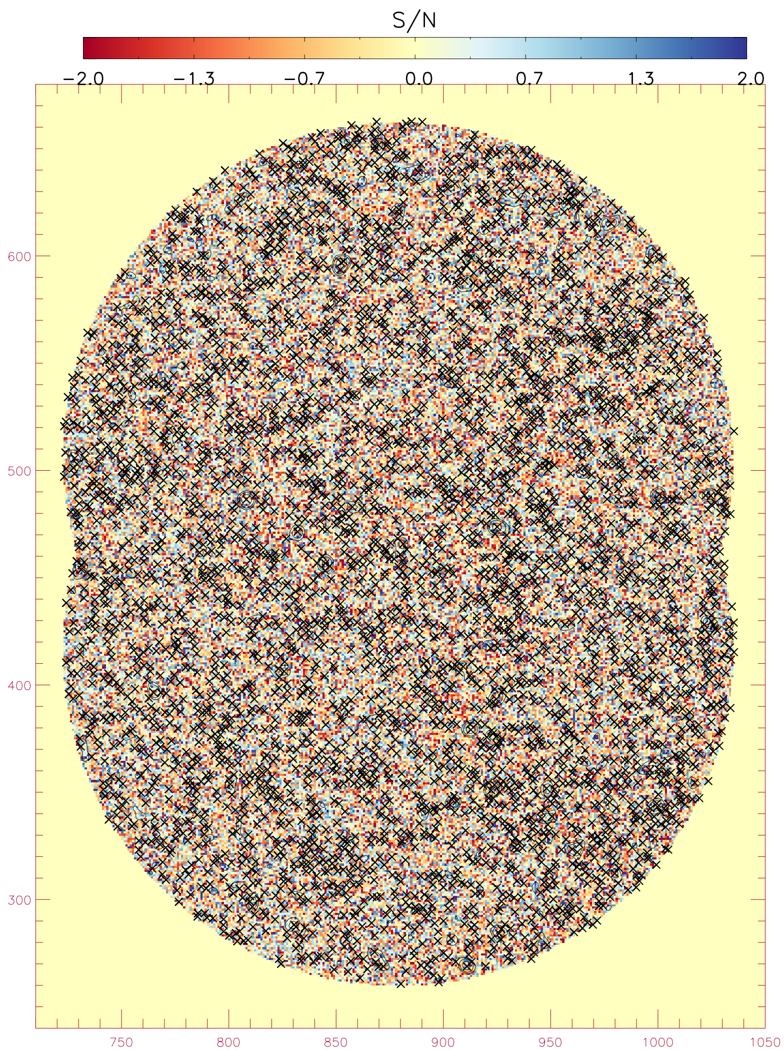


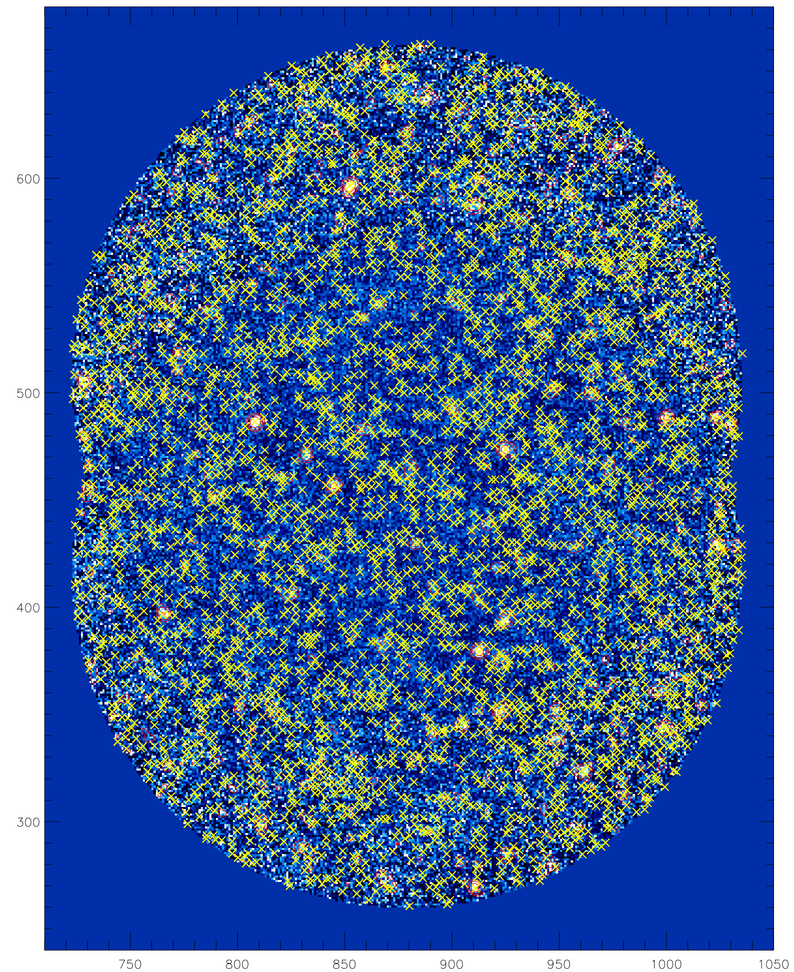
De-confusing sub-mm maps with T-PHOT

- Background in the map is the combined flux of all the unresolved sources – no empty sky due to steep source counts/negative k-correction
- But the map is not scaled by absolute flux, it has zero mean – so the background is negative
- Without adequate removal of this negative background, the best solution will be one where negative sources balance the positive ones
- The background we need to subtract is a function not only of the map, but depends on which of the contributing sources are included in the model



De-confusing sub-mm maps with T-PHOT

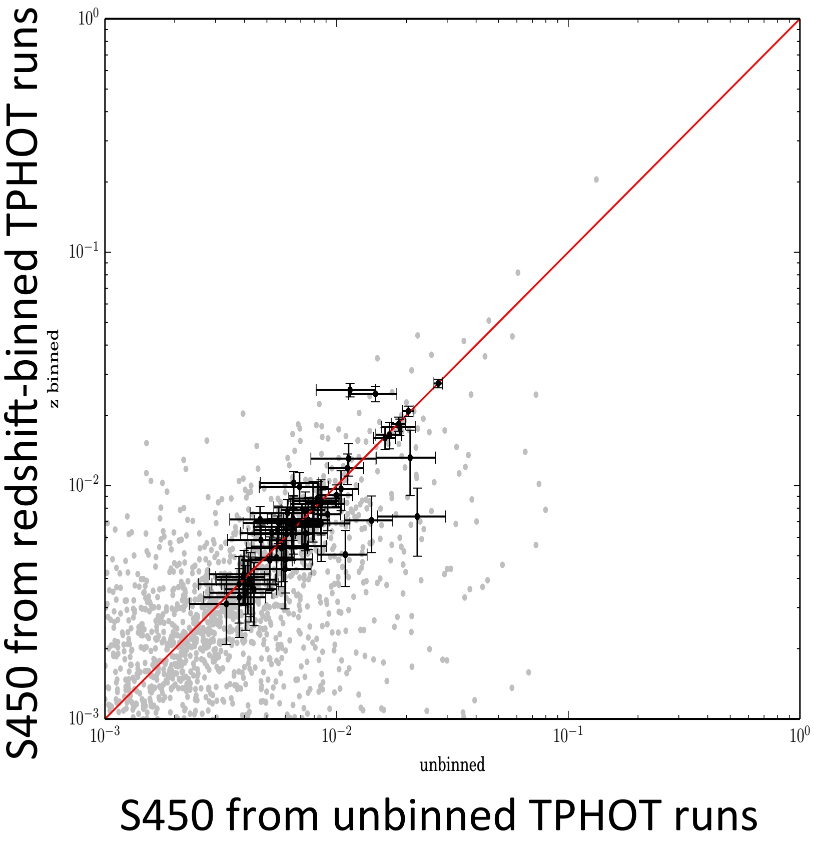




Optimising the prior catalogue

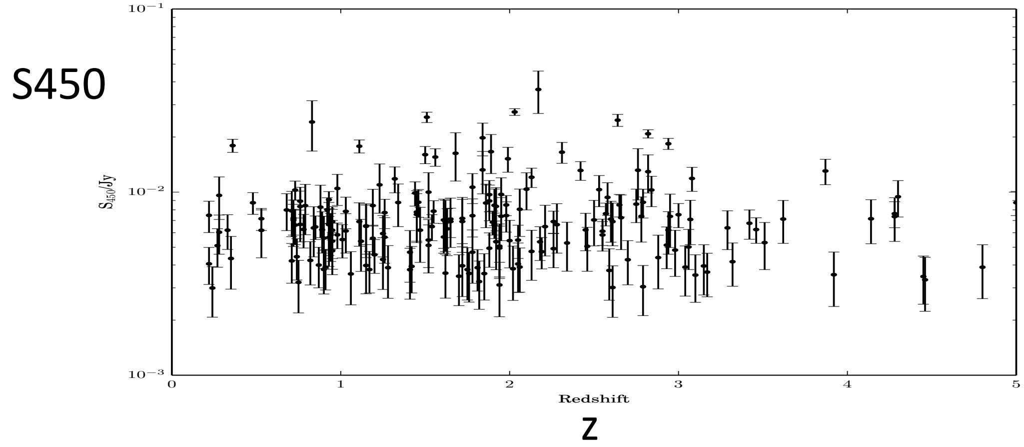
- Want to deconfuse as many sources as possible
- Anything we can't model becomes part of the background and is assumed to be uncorrelated
- Number of objects in the model is limited by the number of independent beams in the map:

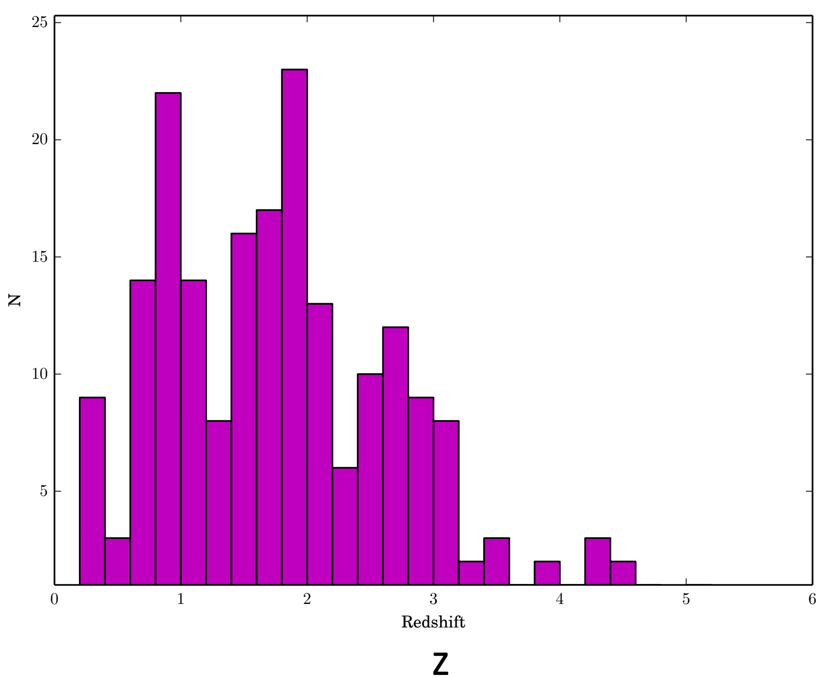
  $N_{dof} < N_{data}$
- Can we model more objects by splitting the prior list into uncorrelated slices and modeling each separately?
  - C.f. SIMSTACK, Viero et al. 2013
  - To obtain average fluxes in bins we are simply taking the cross-correlation between each bin and the map

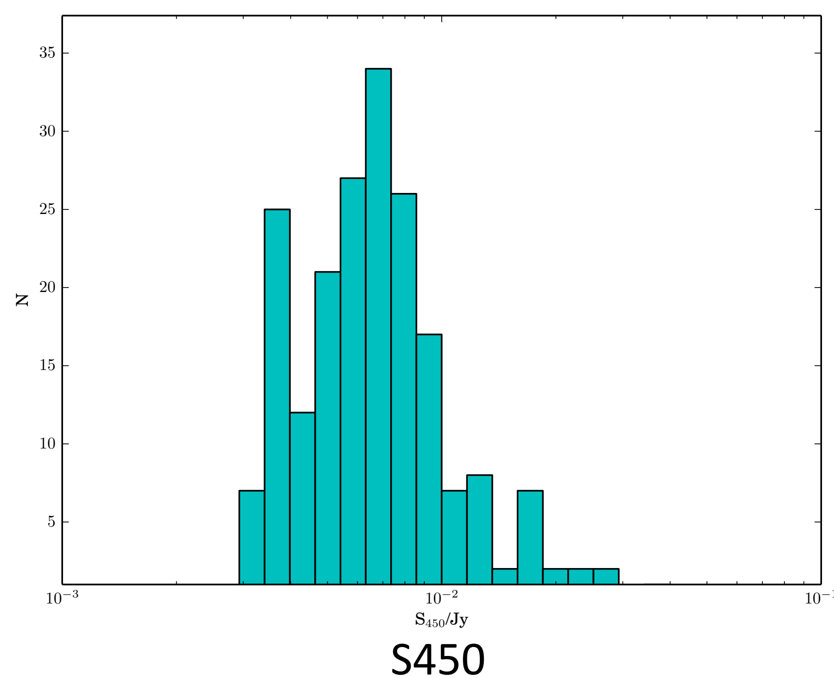


Preliminary results

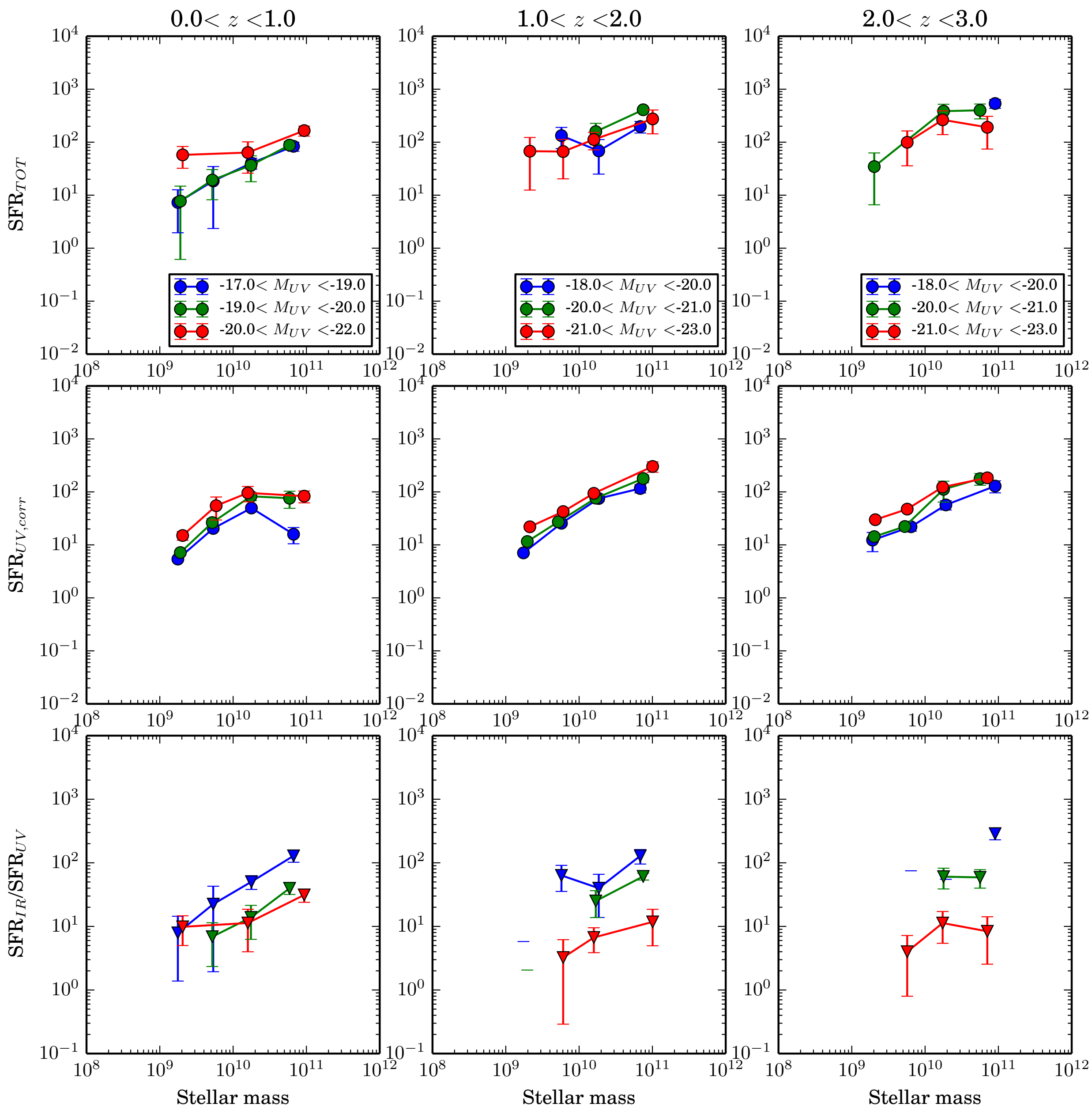
Preliminary Results





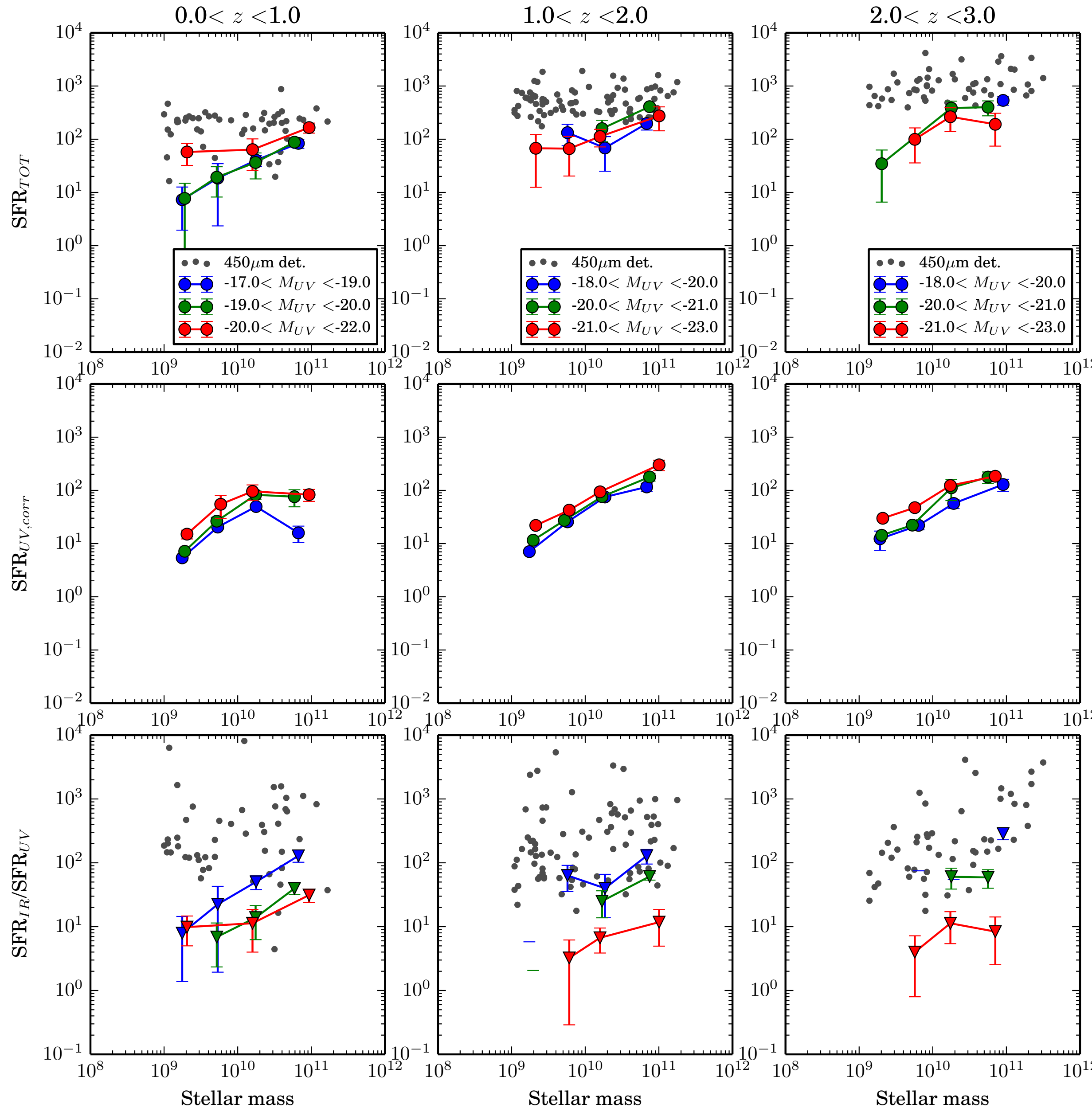


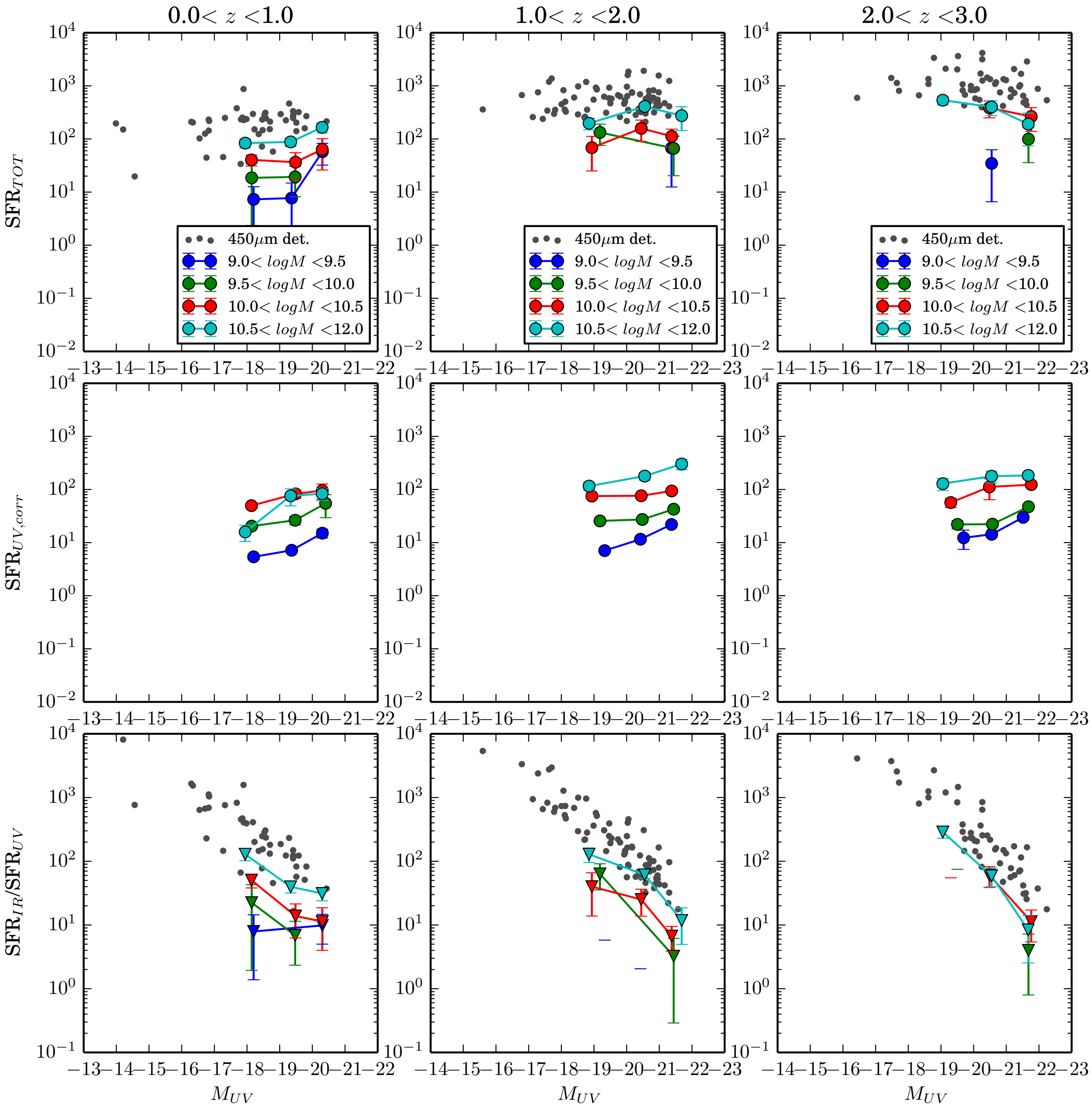
- S_450 -> SFR_IR assuming T=40K, β=1.5
- SFR sensitivity does not vary with redshift
- Total UV+IR SFRs correlated with stellar mass
- Independent of M_UV at z>1
- Corrected UV SFRs consistent except at high M / low z, where they appear to underestimate total SFR



- 450um detections are limited in absolute SFR, picking up only extreme starbursts at low masses but more normal SFGs at high masses

- UV-bright samples select SFGs in a way that is relatively unbiased with respect to total SFR (z>1), but is dominated by objects with lowest obscuration





- SFR vs M_UV relationship is mostly flat, with SFR only increasing with stellar mass
- SFR only correlated with M_UV at z<1 and M_UV >~M*
- At z>2 and high mass, total SFR falls with increasing UV luminosity
- UV luminosity is a tracer of IR/UV, not total SFR
- Stellar mass is a much better tracer of SFR

Future work

- Apply T-PHOT to lower-resolution sub-mm maps using prior information from 450µm, and combine additional fields
- Use these results to constrain SEDs and accurate SFRs
- Optimise prior catalogues to probe higher redshifts
- Explore relationship between obscuration and UV slope, to test calibrations of the SFRD from the UV at higher redshifts

Summary

- The obscured side of the cosmic star formation history remains uncertain due to a lack of direct measurements at high redshifts
- SCUBA-2 offers an opportunity to test predictions from the unobscured UV due to lower confusion noise than Herschel
- Additionally, prior-based deconfusion techniques such as T-PHOT allow us to push deeper into the confusion noise with samples selected from high-resolution data
- Initial results show that the measured UV luminosity does not correlate with total SFR at high redshifts, and so inferring SFRD from the UV luminosity function is probably subject to bias against obscured systems