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Revealing the Obscured History of Galaxy Evolution

with the SCUBA-2 Cosmology Legacy Survey

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and the SCUBA-2 Cosmology Legacy Survey team

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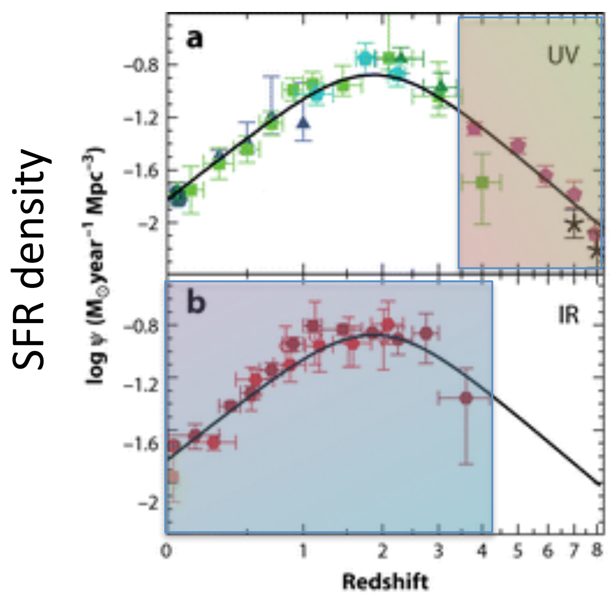
Motivation

The cosmic star formation history: Building up the galaxy population

- We need to constrain models for the formation and evolution of baryonic structures
- Important observational constraints come from the universal SFR density evolution, and the evolution of the typical specific star formation rates of individual galaxies
- Measuring SFR at high z: most widely available tracers are FUV and FIR



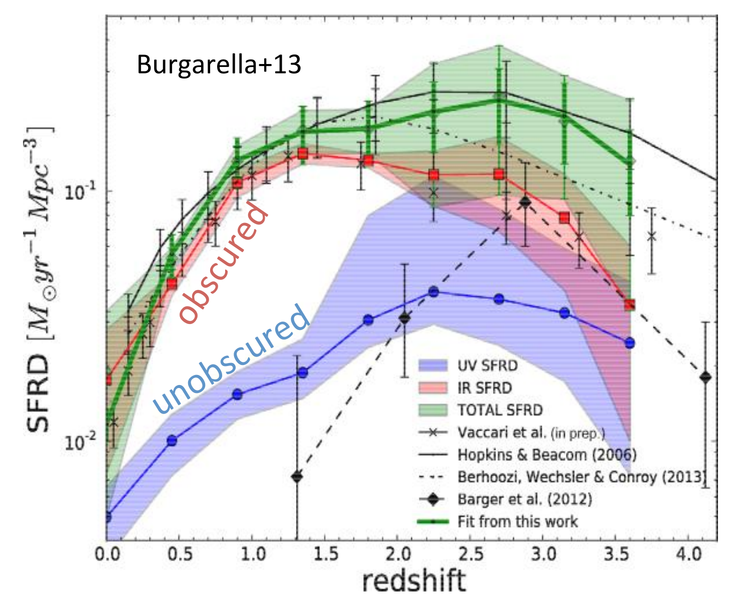
Madau P, Dickinson M. 2014.
Annu. Rev. Astron. Astrophys. 52:415–86

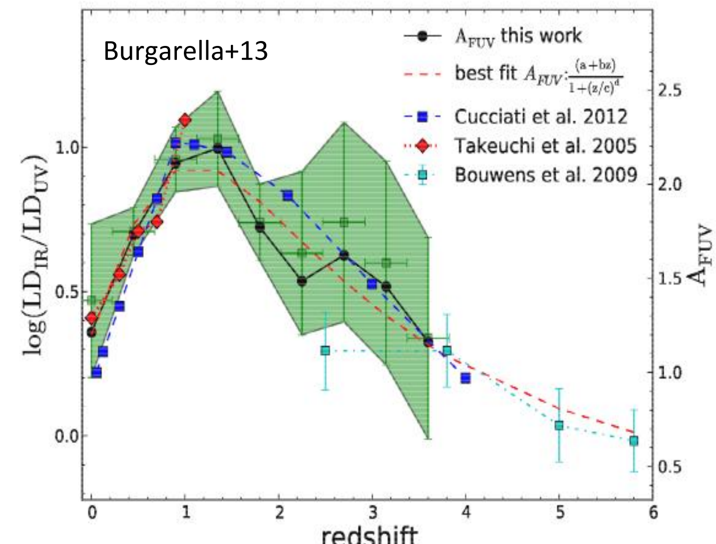
- Herschel probed the obscured SFR of the full star-forming population at $z<3$
- At $z>3$, FIR measurements are only possible for rare or unrepresentative systems
- Best estimates of SFRD at higher z come from rest-FUV LFs based on Lyman Break samples (e.g. Bouwens et al., Bowler et al., etc)
- These UV-only methods rely on dust corrections whose calibrations are uncertain at high redshift…

Dust obscuration at high redshift

How well do we understand SFR measurements at high redshift?

- Dust is a severe obstacle to measuring total SFRs from the UV
- Young stars are preferentially obscured within their birth-clouds (compared with the overall stellar population)
- IR SFRs >> UV SFRs
- The obscuration is higher at the peak epoch of SF (z=1-2) than at z=0
- Beyond z=2-3, it is more uncertain…



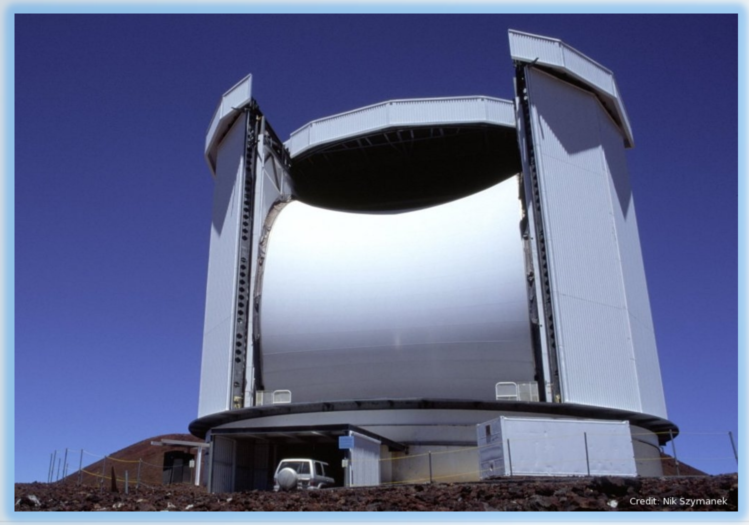


Breaking through the confusion limit

How can new datasets help us with our problems?

JCMT/SCUBA-2:

- Higher resolution imaging: reduce confusion noise
- Deep imaging: minimise instrumental noise
- High-res. multi-wavelength priors: apply deconfusion algorithms to probe dense source populations (T-PHOT; Merlin et al. 2015)



The SCUBA-2 Cosmology Legacy Survey:

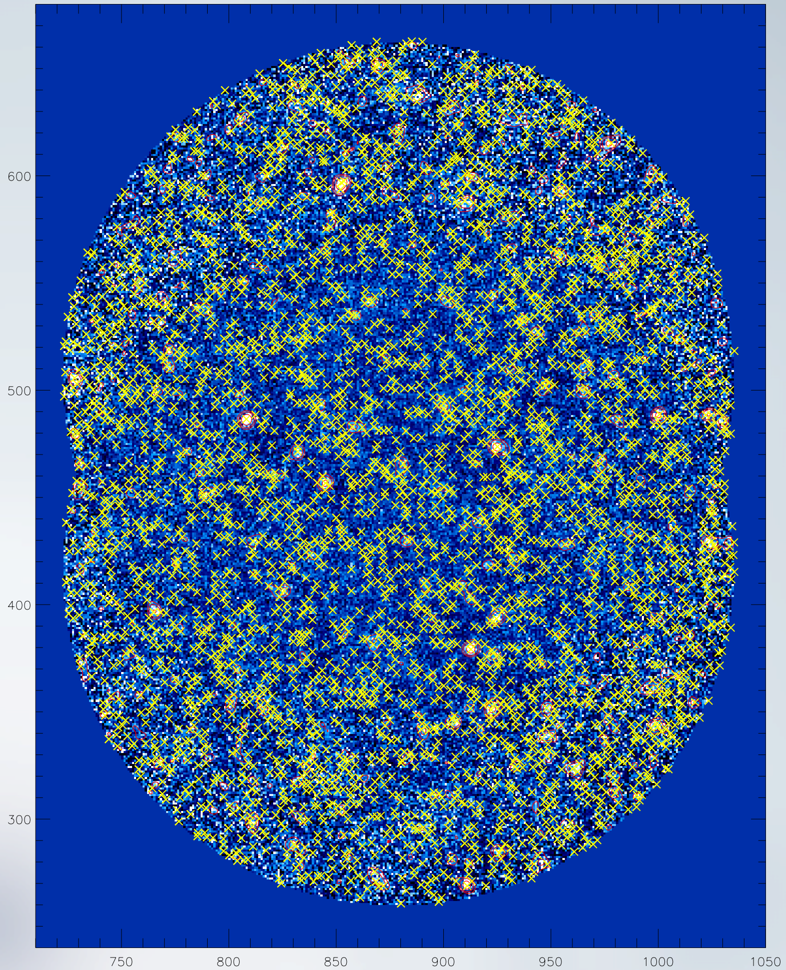
- 2 tiers:
  - Wide 850µm imaging over 35 sq.deg. to ~1mJy in several large survey fields
  - Deep 450+850µm imaging over 1.3 sq.deg. to ~0.5mJy rms (450µm) coinciding with CANDELS fields
- Exploiting multi-wavelength coverage from Spitzer, Herschel, ground-based optical-NIR, and HST

This work:

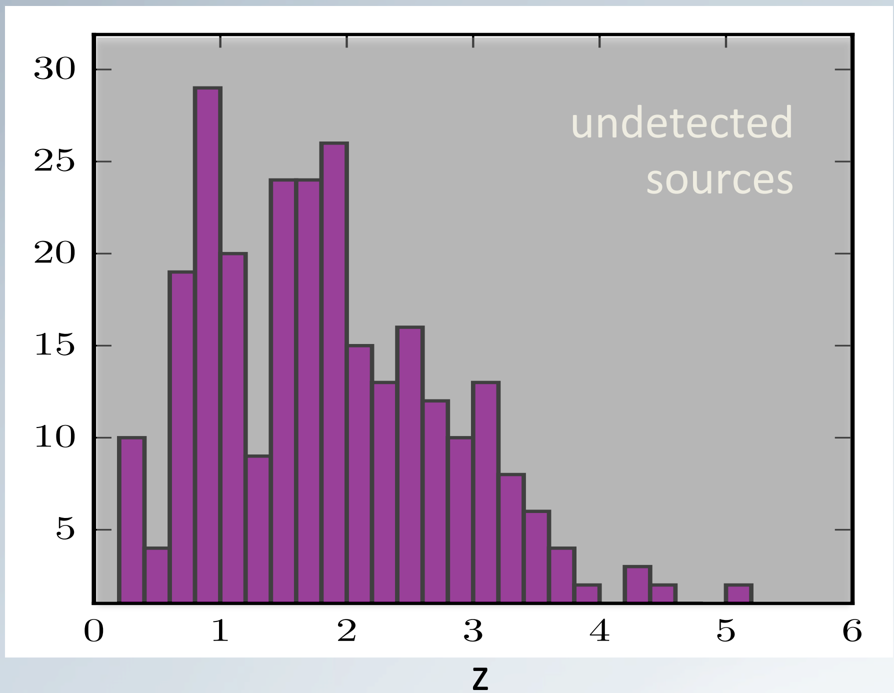
- Deep SCUBA-2 'Daisies' in UDS, COSMOS, AEGIS fields: ~250 arcmin^2
- Deepest multi-wavelength coverage from CANDELS, 3DHST, S-COSMOS, SEDS, etc.
- 3DHST photo-z and SED-fitting (Skelton+14; Momcheva+15)

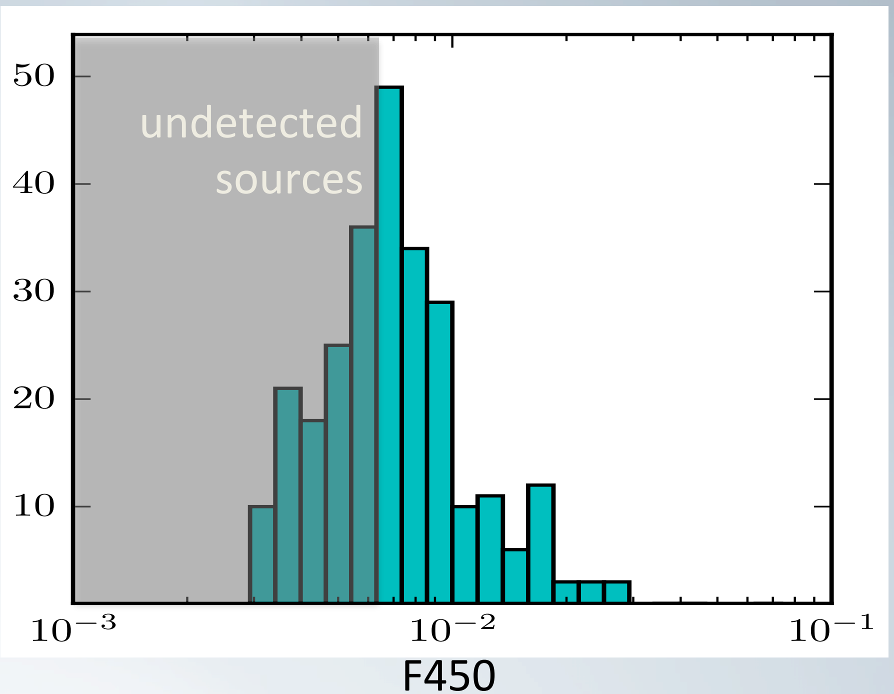
De-confusing sub-mm maps with T-PHOT

- T-PHOT: Merlin et al. (2015)
- Prior list: 3D-HST catalogue including grism/photo-z and SED-fitting results (Skelton+14; Momcheva+15):
  [K<24 or IRAC1<24]
  +USE flag
  +logM>9
- 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
- Since the map is filled with sources, the background is an arbitrary constant which is a free parameter in the fit



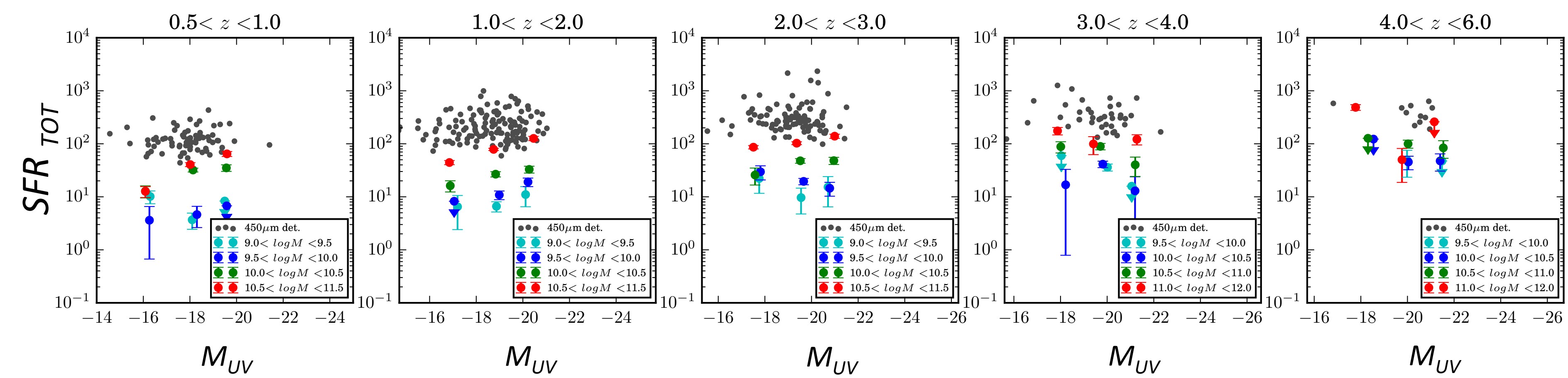
450μm detections





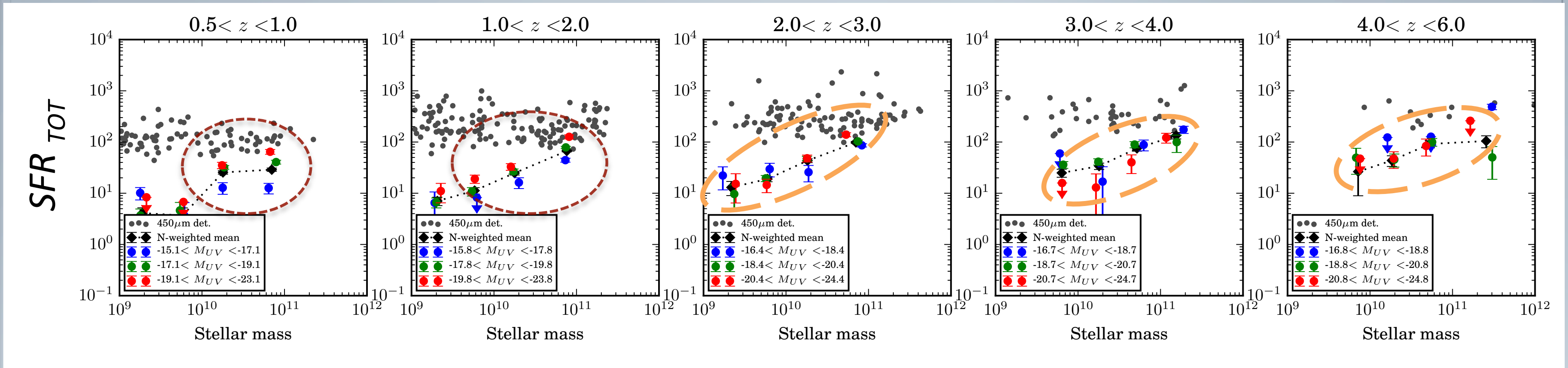
- … but the chief value of our method is in making deblended flux measurements for sources *below the confusion limit*
- We therefore divide the full prior catalogue into bins and measure *average* 450μm properties as a function of the prior properties
- Similar to stacking, but explicitly accounting for correlations between sources in the sample

UV luminosity vs Total SFR
$= SFR_{FIR} + SFR_{FUV}$



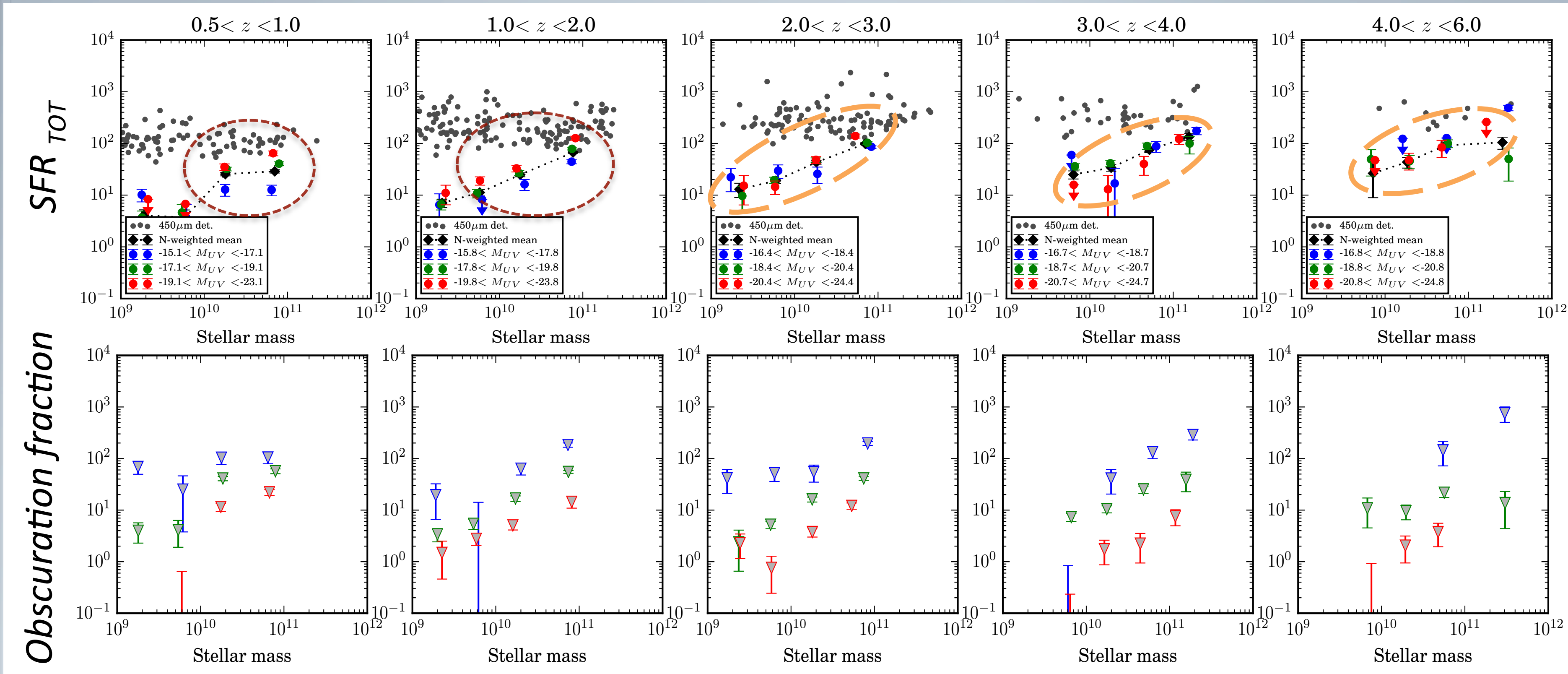
- 450μm detections:
  - limiting SFR ≈ $100 M_{\odot} yr^{-1}$, roughly constant with redshift
  - FIR-detected galaxies span wide range of M_{UV}
- Average IR+UV SFRs by mass, M_{UV}:
  - Raw UV luminosity (before dust correction) does not trace SFR at high-z.

Stellar Mass vs Total SFR



- Strong correlation between mass and SFR in each UV bin
- UV-luminous sample:
  - Massive galaxies at z<2: High UV luminosity → High SFR
  - Higher redshifts: SFR correlated with mass but consistent with average mass-selected galaxies
- Stellar mass is a better indicator of total SFR than raw UV luminosity

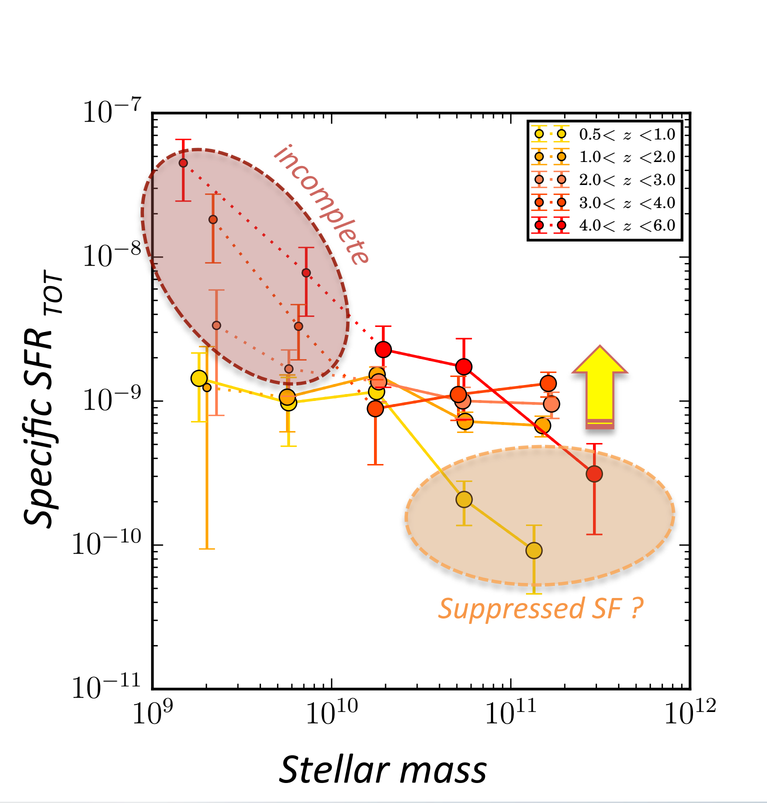
Stellar Mass vs Total SFR



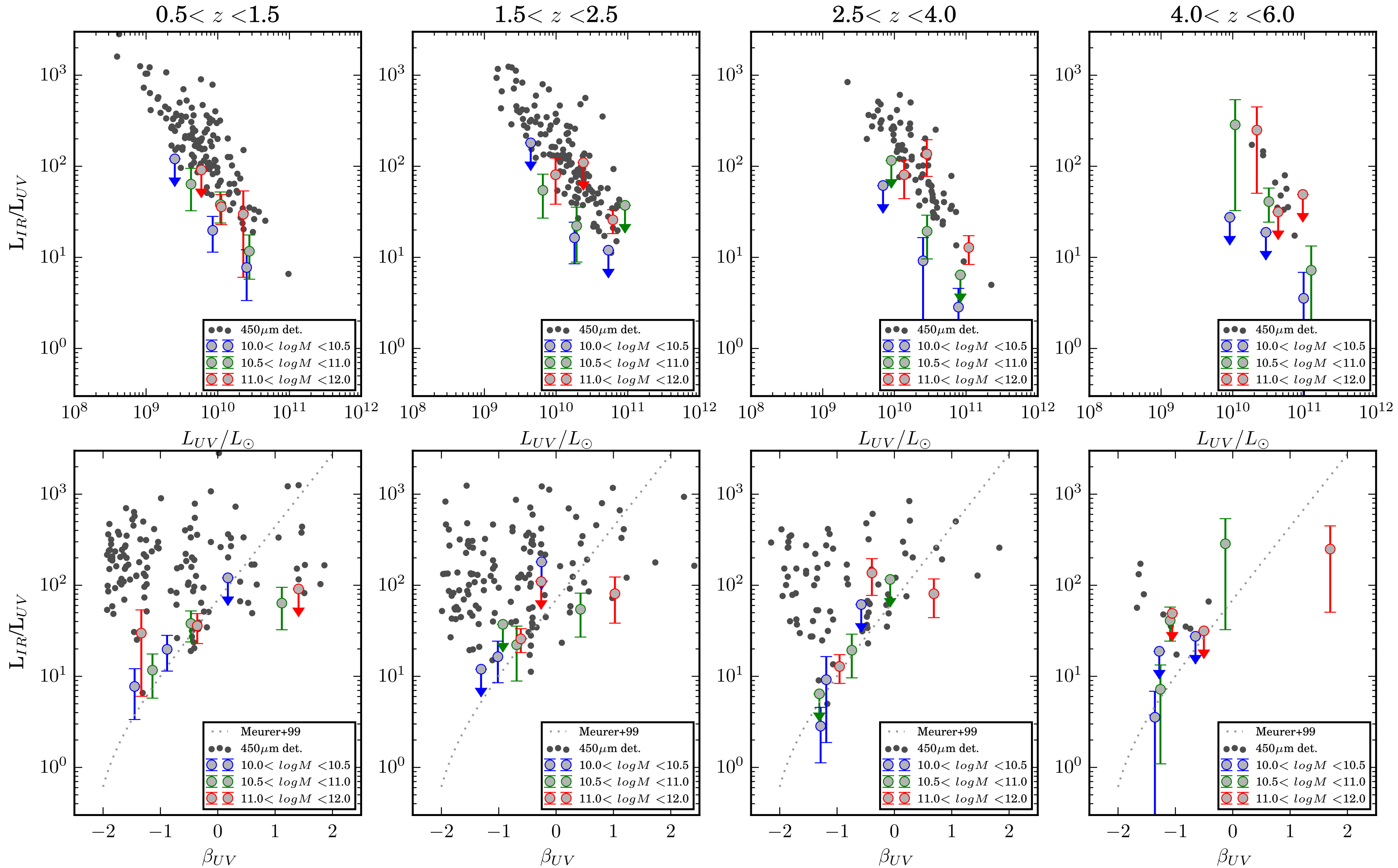
- Instead, M_{UV} is an excellent tracer of obscuration fraction
  - At all redshifts the UV-luminous galaxies (red points) are simply the least obscured
  - Also, more massive galaxies are always more obscured
- So how well can UV-selected samples trace the star-forming population?

The main sequence

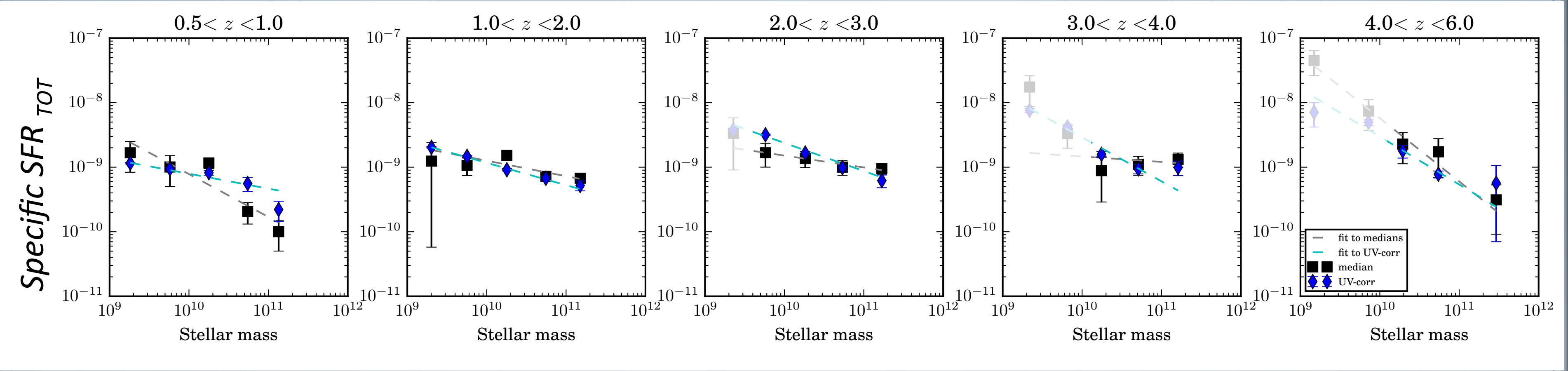
- Main sequence in specific SFR = SFR/stellar mass
  - This describes the typical star forming galaxy as a function of mass and redshift
  - Higher SSFR → shorter timescale to double mass
- We measure median total SSFR in bins of stellar mass and redshift
- Note that lowest mass bins are incomplete at z>1.5
- Results suggest a main sequence that is nearly flat where the sample is complete: SSFR ~ M^(-0.2±0.1)
- Exceptions to this are logM>10.5 at z<1 and logM>11 at z>4:
  - At the lowest and highest redshifts, high-mass galaxies have suppressed SSFR
- Normalization of the main sequence evolves slowly at z>1



IR/UV ratios: "IRX-β" relation



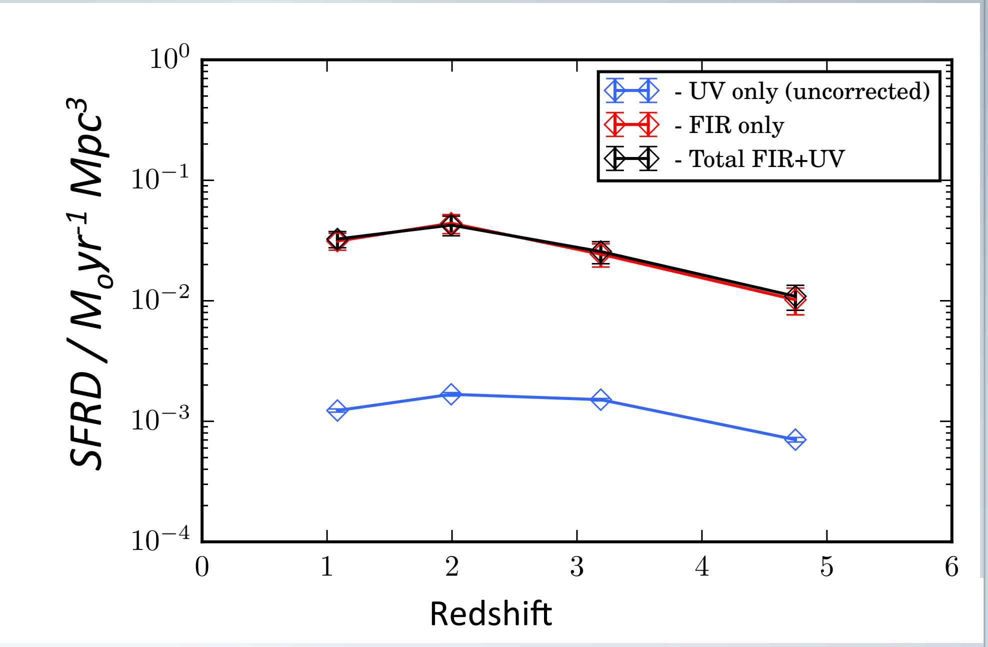
Implications for UV corrections



- UV-corrections based on Meurer relation agree with UV+FIR overall
- Only exceptions are bins likely to contain significant fraction of passive galaxies

Cosmic SFR density = $\Sigma SFR/V_{com}$

- **Integrated over $M>10^{10}M_\odot$**
- SFRD of massive galaxies dominated by obscured SFR
- Total SFRD of massive galaxies peaks at z≈2
- Begins to fall off beyond z≈3-4



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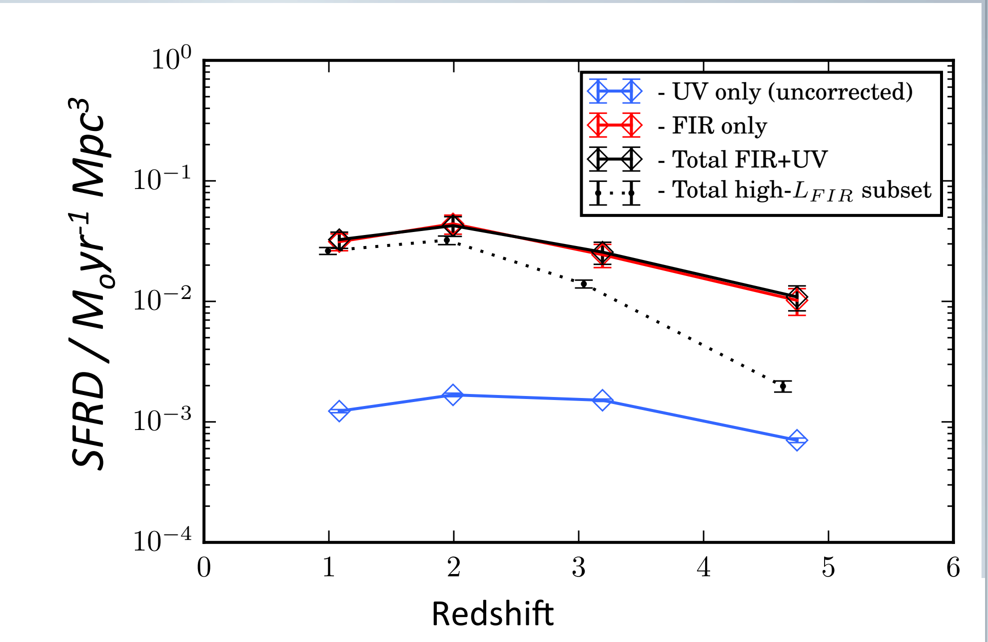
- FIR detections closely trace SFRD at z<3
- Constitute smaller fraction at z>3 as negative k-correction less effective



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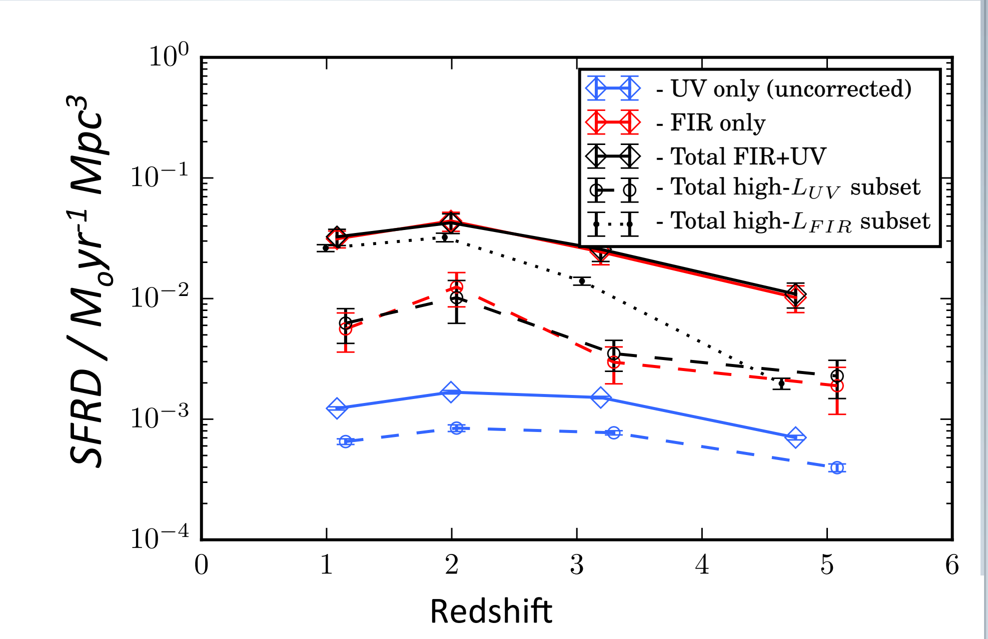
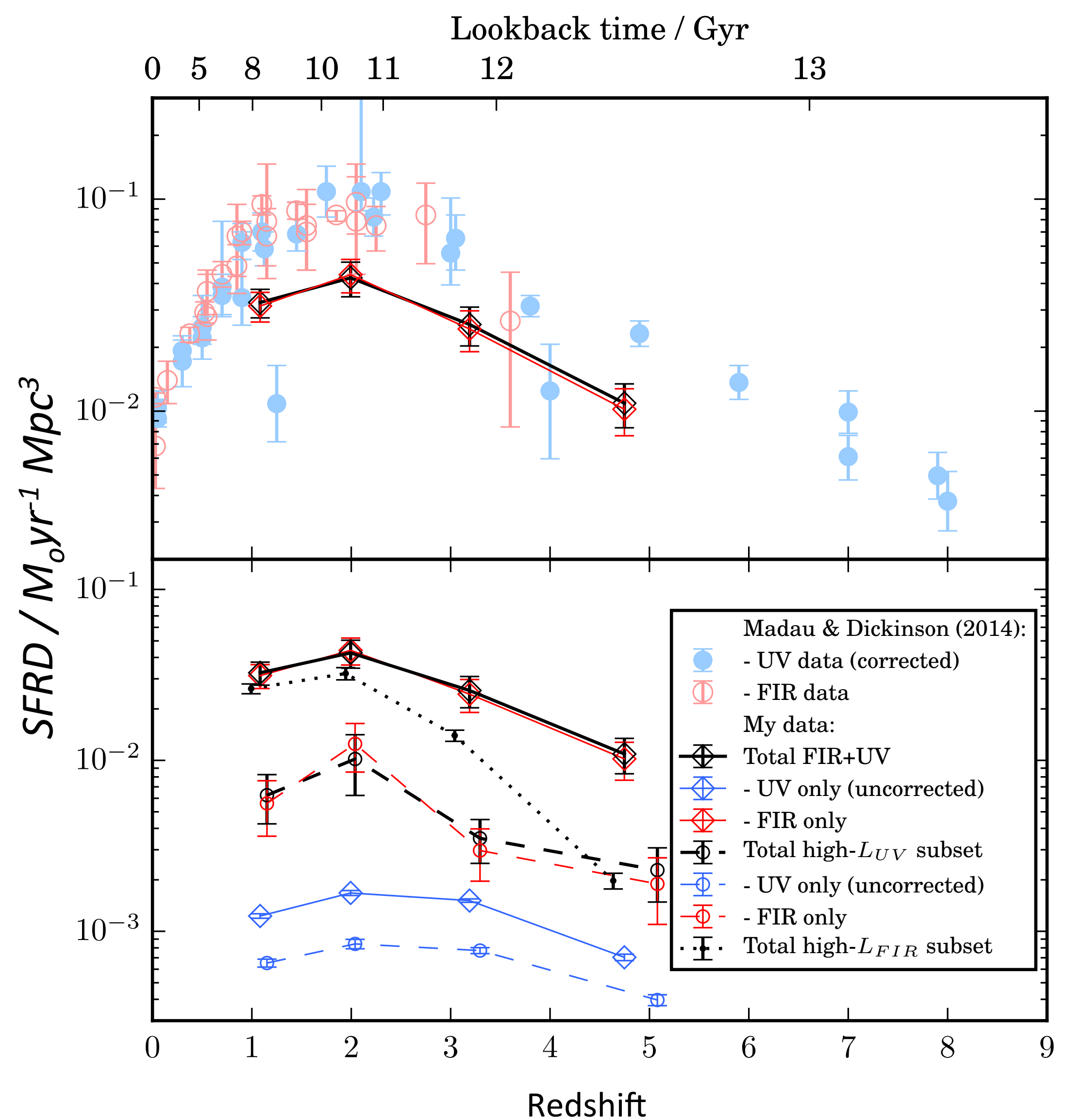


- UV-luminous (>L*) galaxies contribute a small fraction of the total SFRD of massive galaxies at all redshifts
- Total SFRD of these is still dominated by the obscured portion

Comparison with Literature 1

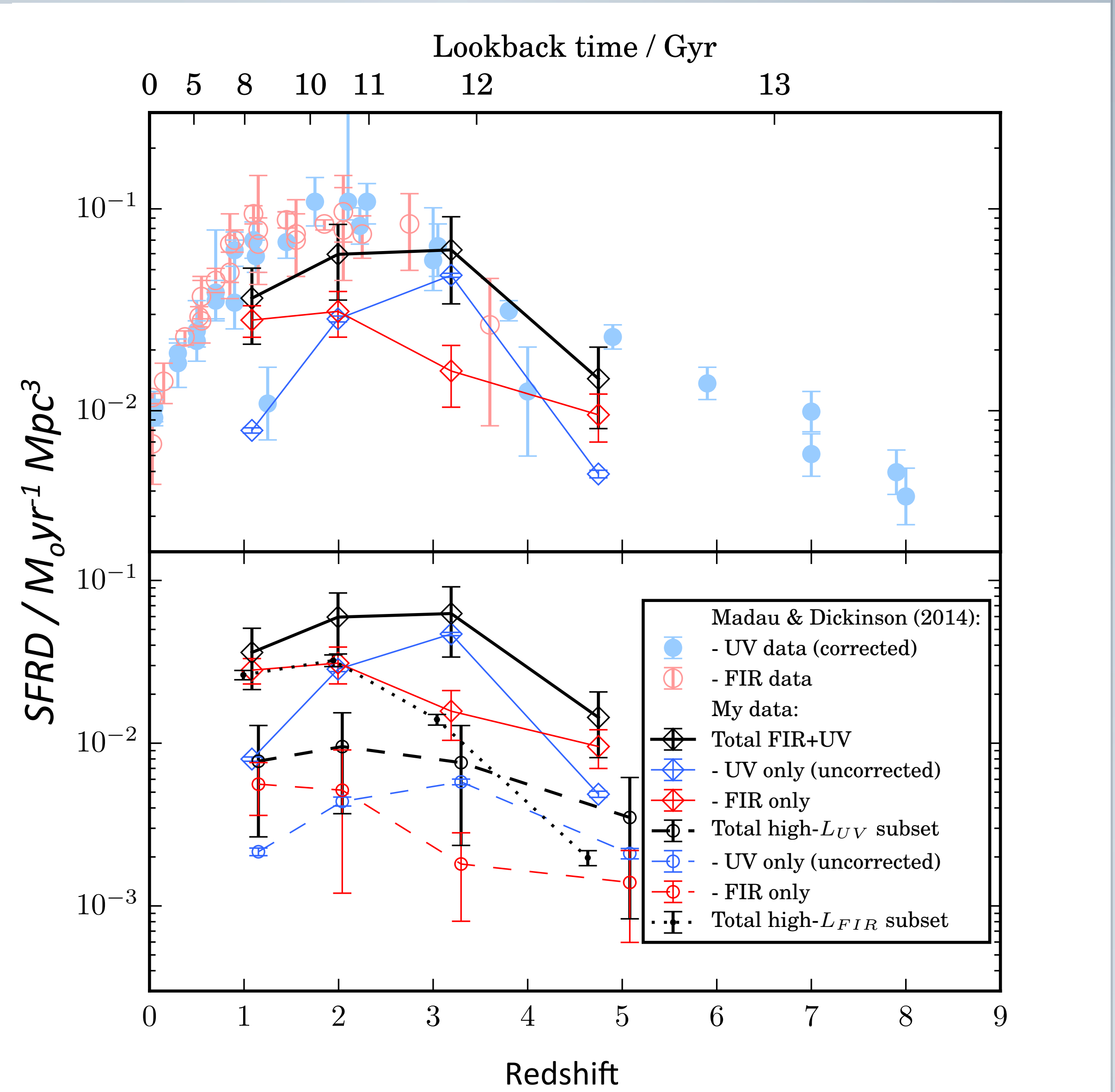
- **Total SFRD of *massive* galaxies (logM>10) traced by UV+FIR**

  compared with UV-based estimates of the total SFRD of all galaxies at z>3:
- The peak SFRD occurs around z=2 for both
- At all redshifts z>1, massive galaxies account for around 1/3 of the total SFRD



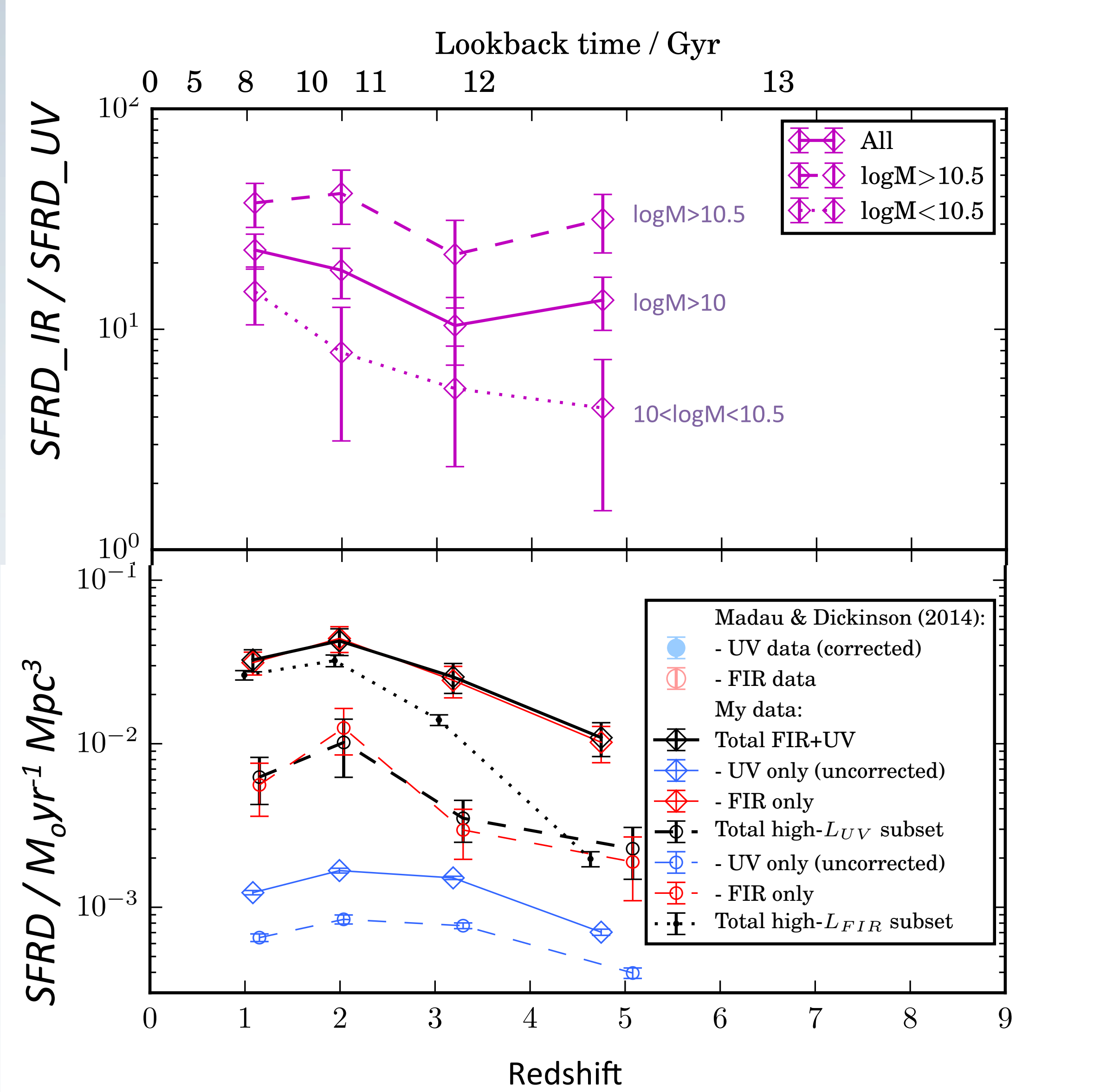
Comparison with Literature 2

- **Total SFRD of *all* galaxies** correcting for missing *unobscured* SFR of lower-mass galaxies… (using LFs from Parsa+15)
- This is assuming negligible *obscured* SFRD from galaxies with logM<10



Comparison with Literature 3

- **Within massive galaxies, the fraction of SFRD which is obscured…**
- …remains high at all redshifts
- …~30-40 for logM>10.5
- … falls for 10<logM<10.5



Summary

- SCUBA-2 offers an opportunity to probe deeper into the obscured cosmic star-formation history – thanks to lower confusion noise than Herschel
- Prior-based deconfusion techniques (e.g. T-PHOT) can push even deeper into the confusion noise with samples selected from high-resolution data

Results:

- Observed UV luminosity is poorly correlated with total SFR, but primarily traces obscuration ratio
- Total SFR is better correlated with stellar mass via the 'main sequence'
- The total SFR density of massive galaxies is dominated by obscured SFR and peaks at z=2
  - The contribution of SCUBA-2 detected galaxies is high at z<2 but falls at z>3
  - The contribution of the brightest UV-emitting galaxies is low at all redshifts, and even these are dominated by obscured star formation
  - UV-selected galaxies may not be a good tracer of the evolution of cosmic star formation, which is dominated by obscured galaxies at all redshifts
- With mass-complete samples at high-z we should be able to recover the full SFRD using UV+FIR, or UV+beta