The Obscured Star Formation History of the Universe

revealed by the SCUBA-2 Cosmology Legacy Survey

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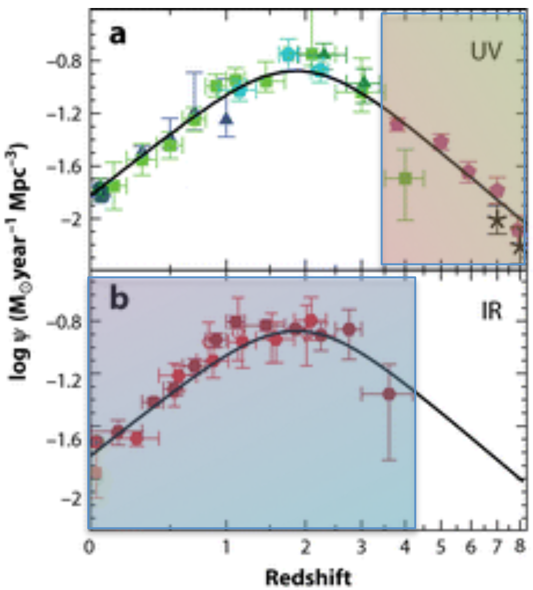
Why study obscured star formation at high redshifts?

INTRODUCTION

The Cosmic Star Formation History

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



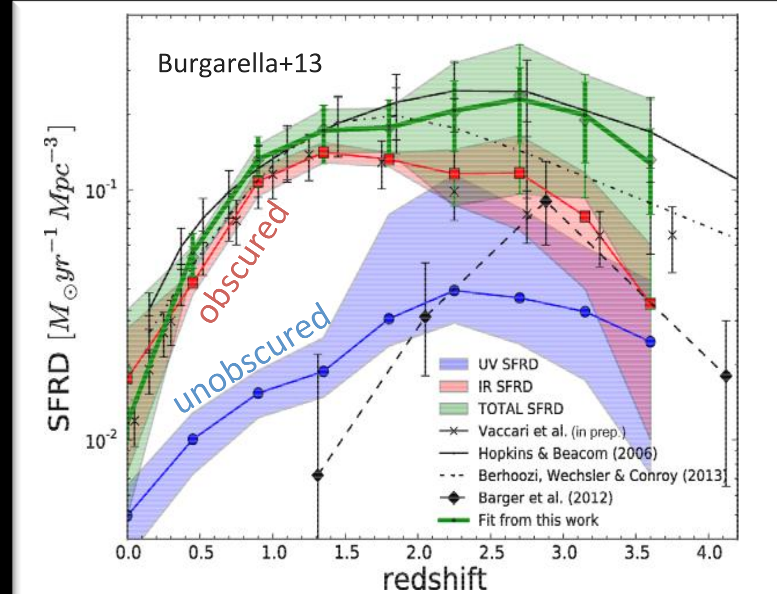
Madau P, Dickinson M. 2014.
Annu. Rev. Astron. Astrophys. 52:415–86

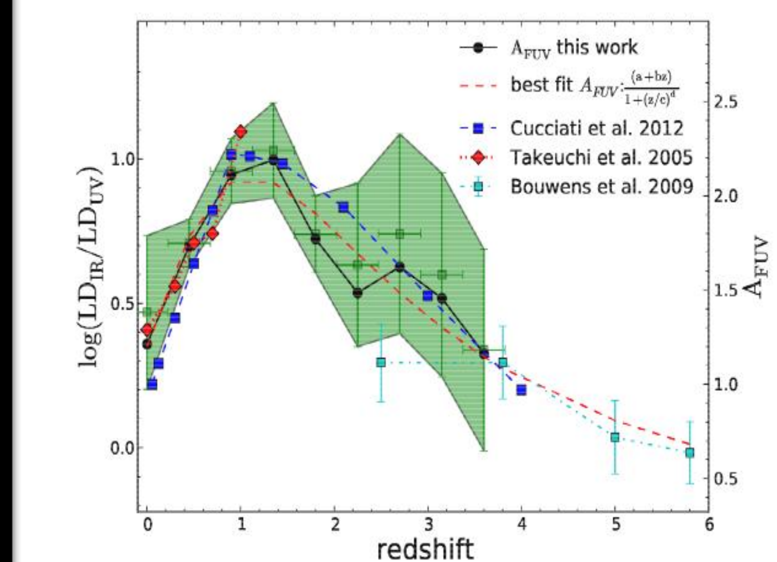
- Herschel probed the obscured SFR of the full star-forming population at z<3
- At z>3, FIR measurements are only possible for rare or unrepresentative systems
- Best estimates of SFRD at higher z come from rest-FUV LFs based on Lym (e.g. Bouwens et al., Bowle
- These UV-only methods re corrections whose calibrat at high redshift…

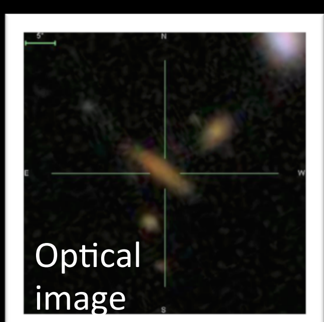
SFR density and obscuration at high-z

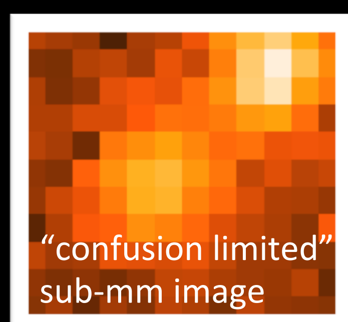
How well do we understand SFR measurements at high redshift?

- Dust is a severe obstacle to measuring total SFRs from the UV
- IR SFRs >> UV SFRs
- The obscuration is higher at the peak epoch of SF (z=2) than at z=0
- Beyond z=2-3, it is more uncertain…
- Herschel surveys limited by **confusion**
- ALMA etc limited by sampling





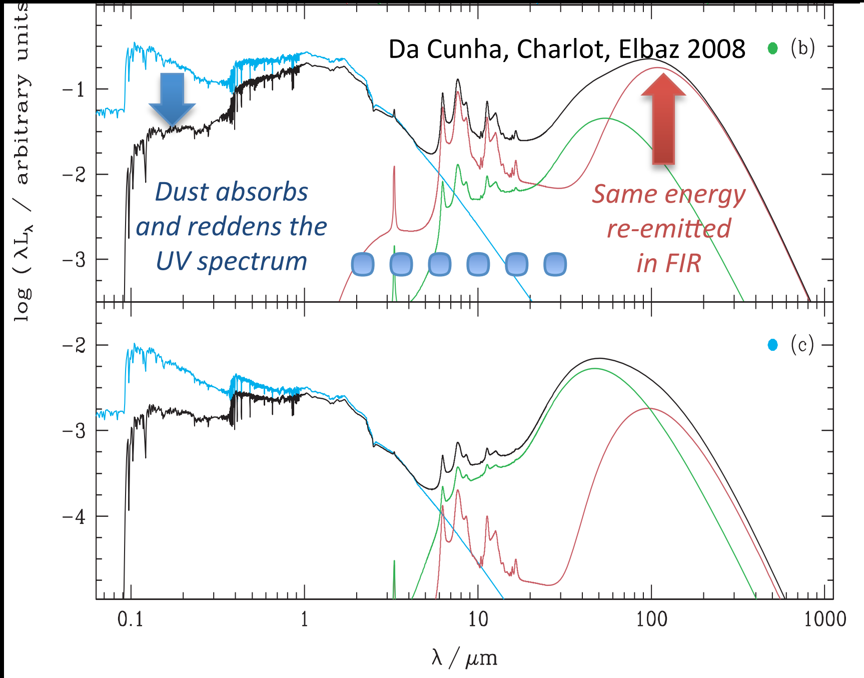


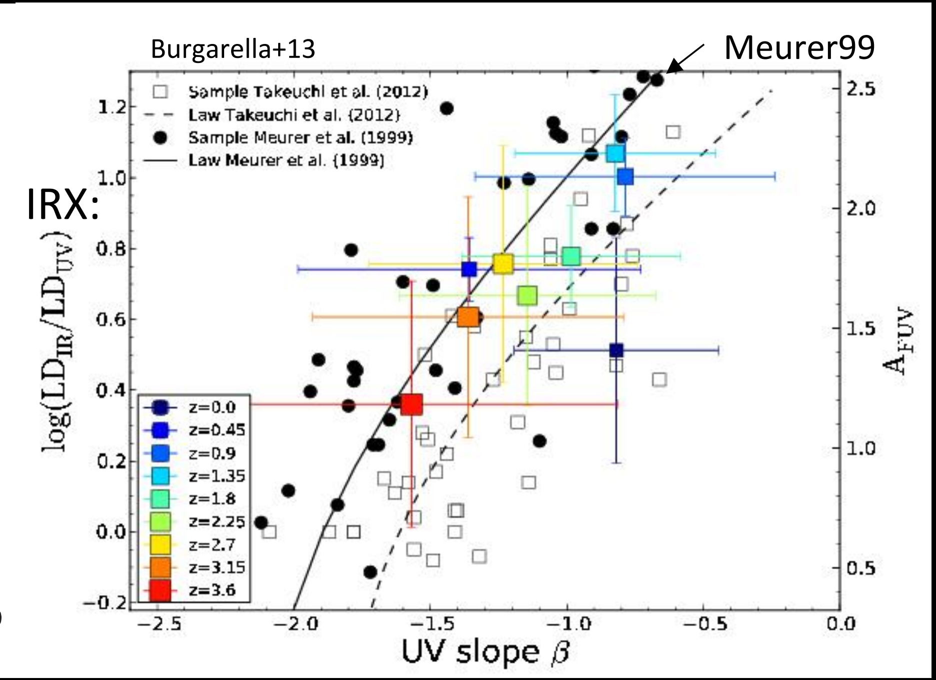


Predicting dust obscuration

How to estimate this in the absence of FIR detections?

- Need a calibration based on UV slope – *the "IRX-beta" relation*
- But this needs better validation at high redshifts





Where do we stand?

- Need better observations of rest-frame FIR emission from high-redshift star-forming galaxies
  - Current data begin to run out just when things are getting interesting

- It is very hard to measure FIR emission from representative samples of galaxies at high redshift
  - the confusion limit is a fundamental barrier to observations
  - due to high source density and diffraction-limited resolution

- SFRs at high redshifts can be inferred from the UV emission of individual star-forming galaxies, corrected for dust obscuration based on an assumed intrinsic spectrum and attenuation law
  - However, these assumptions are poorly tested at high redshift
  - Furthermore, UV-selected Lyman Break samples may not be a good tracer of the overall population of star forming galaxies at high redshifts

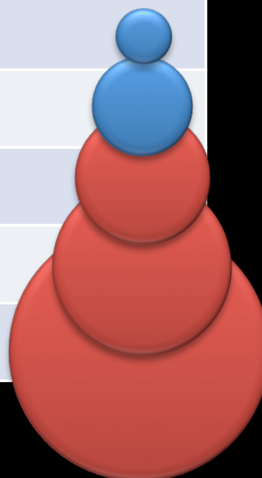
- *What we need is an unbiased measurement of total SFR in complete samples of star forming galaxies at high redshifts*

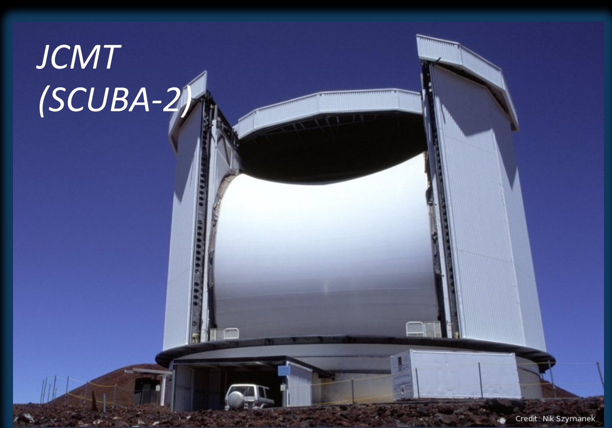
How to address these problems with the available data?

METHODS

Breaking through the confusion limit

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

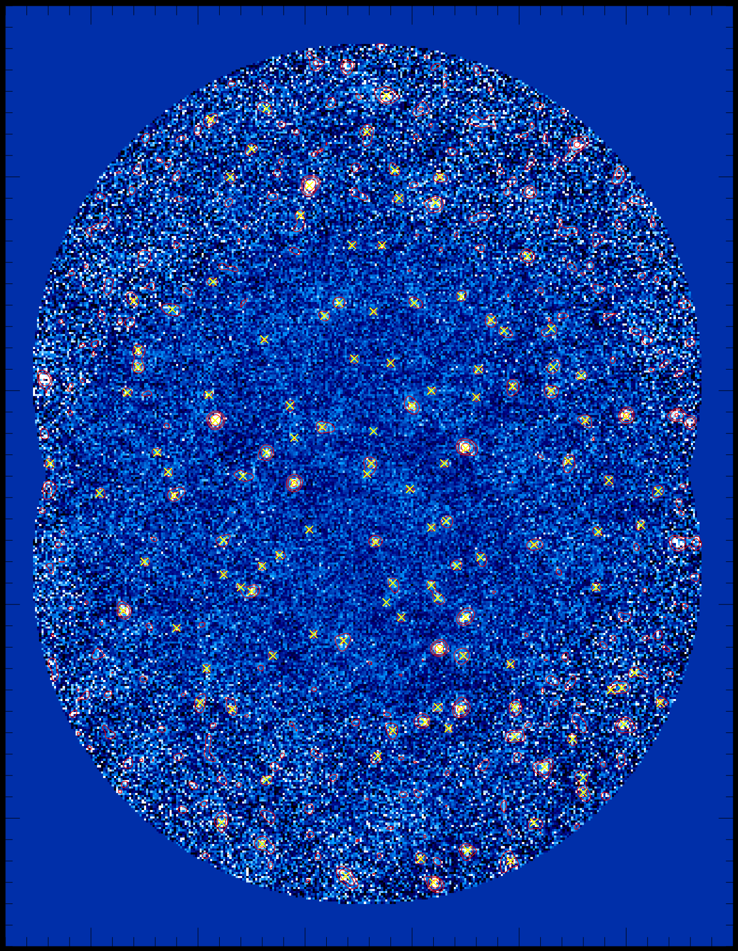




Breaking through the confusion limit

- COSMOS-CANDELS 450µm: ~3mJy rms unfiltered
- ~100 sources detected at SNR>4
- Prior information on thousands more galaxies in the field:
  - HST, Spitzer and ground-based surveys
  - CANDELS/3DHST near-infrared selected samples
  - Photometric+grism redshifts and SED measurements including stellar masses
- Using prior-based deconfusion…

Detected sources



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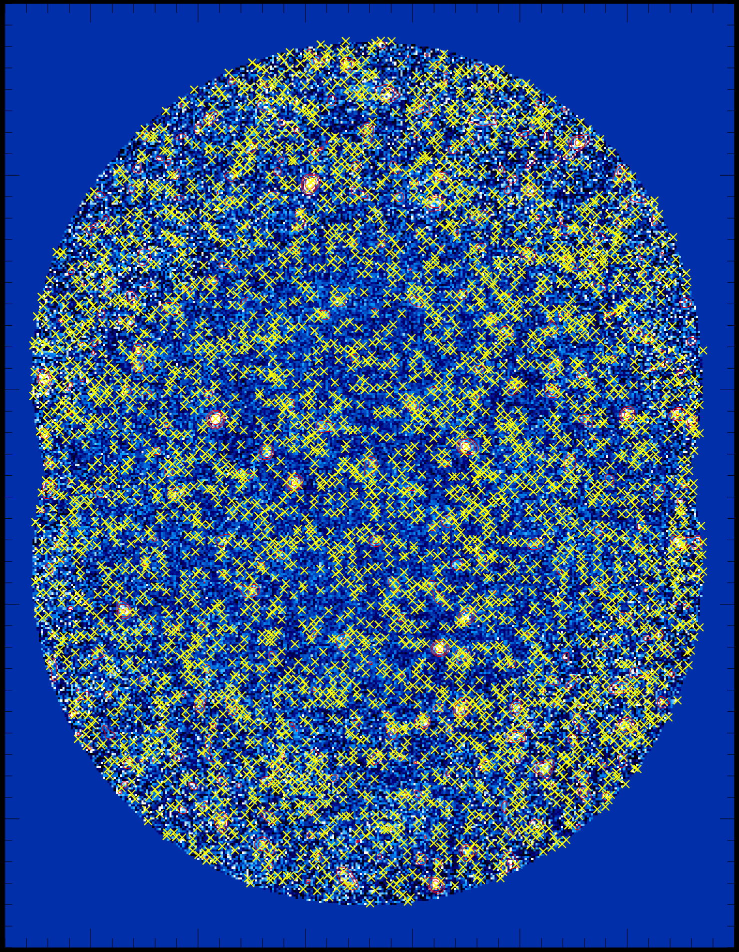
- Using prior-based deconfusion:
  - T-PHOT (Merlin+15,16)
  - measure fluxes of much denser sample
  - Obtain full covariance matrix
- Prior sample selection:
  - must be sufficient to describe the emission in the map but not over-fit
  - We select a stellar-mass limited sample with complete redshift and SED info from 3DHST

3D-HST near-IR selected galaxies



Measuring average FIR SEDs

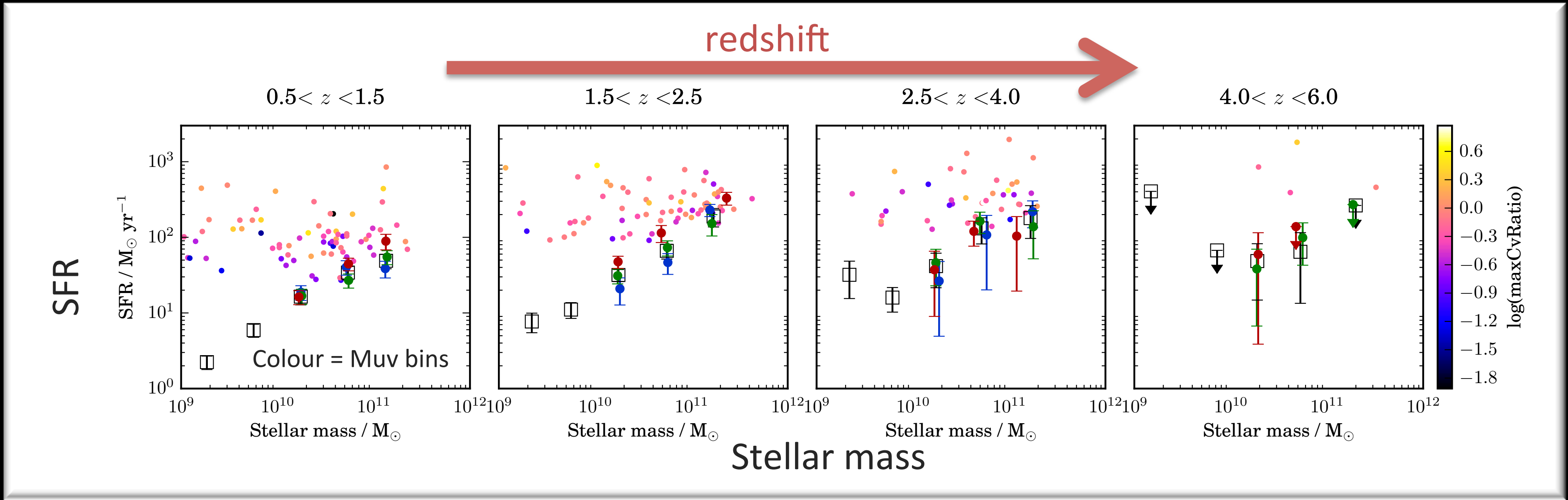
- TPHOT: fit the submm images with prior positions to obtain flux measurements for all galaxies in the sample
- Bright sources are individually detected with similar significance to traditional source extraction
- To study full sample, divide results into bins and stack the measurements in each, accounting for confusion/covariance between priors with measurement errors
- Bin priors by redshift, stellar mass, M_{UV} …
- Repeat in 100, 160, 250, 450, 850 μm maps (from Herschel and SCUBA2)
- Fit SEDs to measure average IR luminosity and thus obscured SFR

Results (I):

STAR FORMATION RATES AND OBSCURATION

SFR

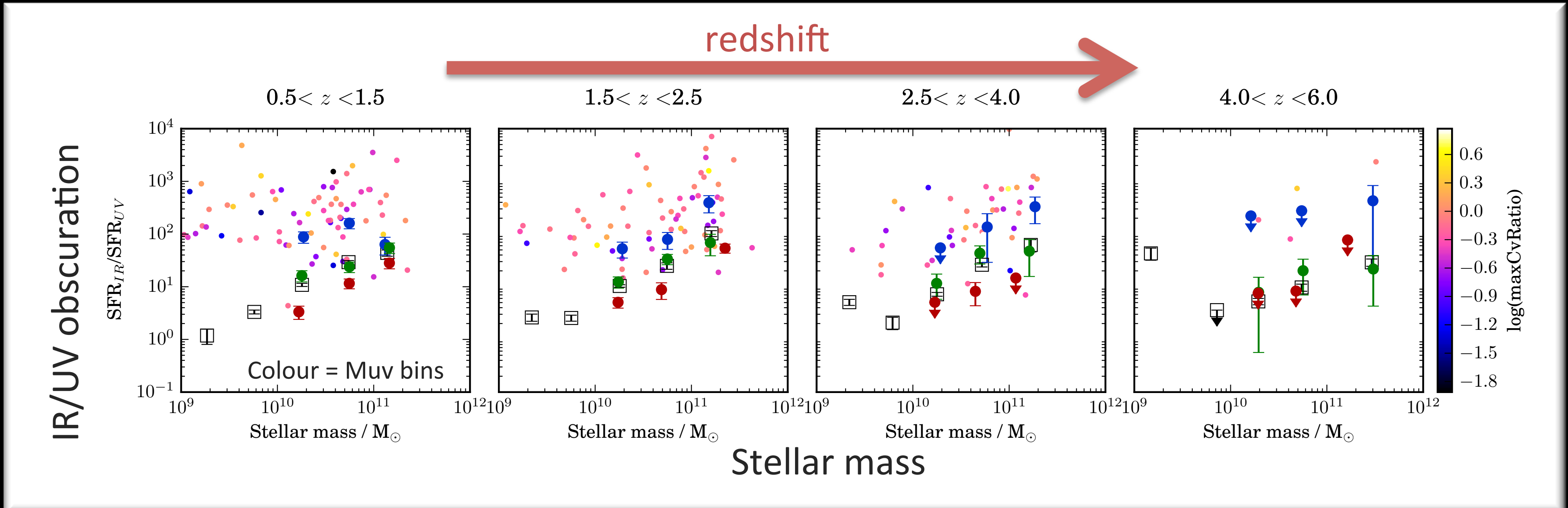
comparing FIR, UV, and mass-selected samples:



SFR_tot = SFR_IR + SFR_UV

SFR Obscuration

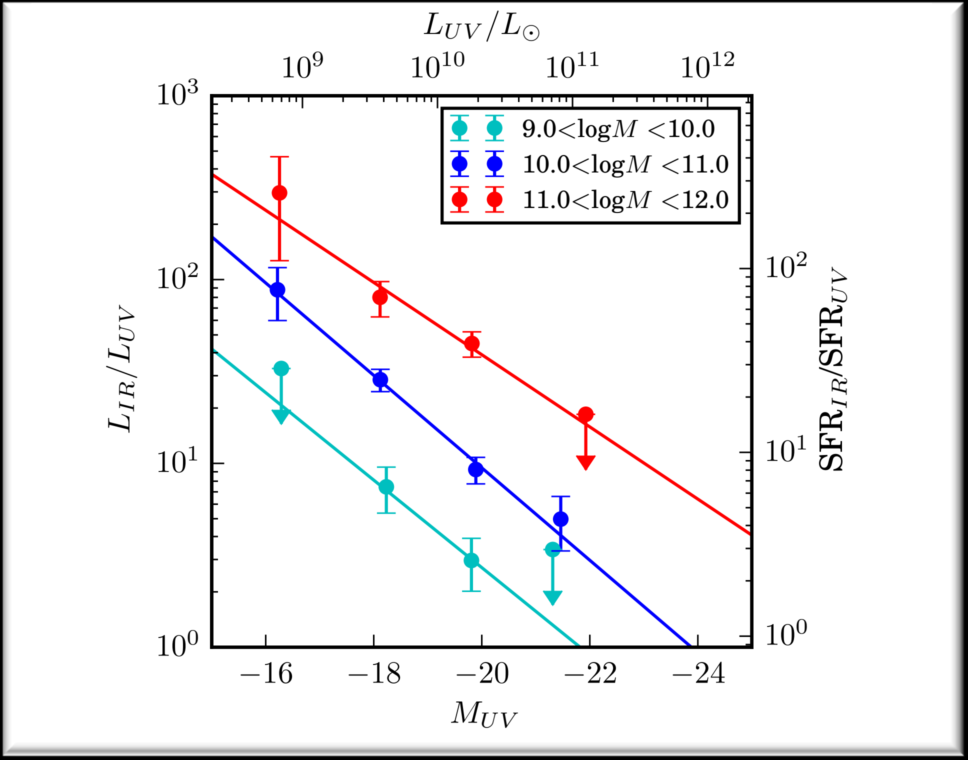
L_{IR}/L_{UV} strongly correlated with mass and M_{UV}



- More massive galaxies have higher SFR, and more of their star formation is obscured
- High FIR luminosities trace galaxies with the highest SFRs (wide range of obscuration)
- High UV luminosities trace the most unobscured star-forming galaxies

Obscuration as f(M,L_{UV})

$L_{IR}/L_{UV} \sim M_{star}^{0.7} L_{UV}^{-0.6}$ – independent of z



- The most obscured galaxies are the ones with the highest stellar mass and lowest UV luminosity, but obscuration doesn't depend on redshift

…See also previous Herschel work – Buat+12, Hilton+12, Heinis+14, etc

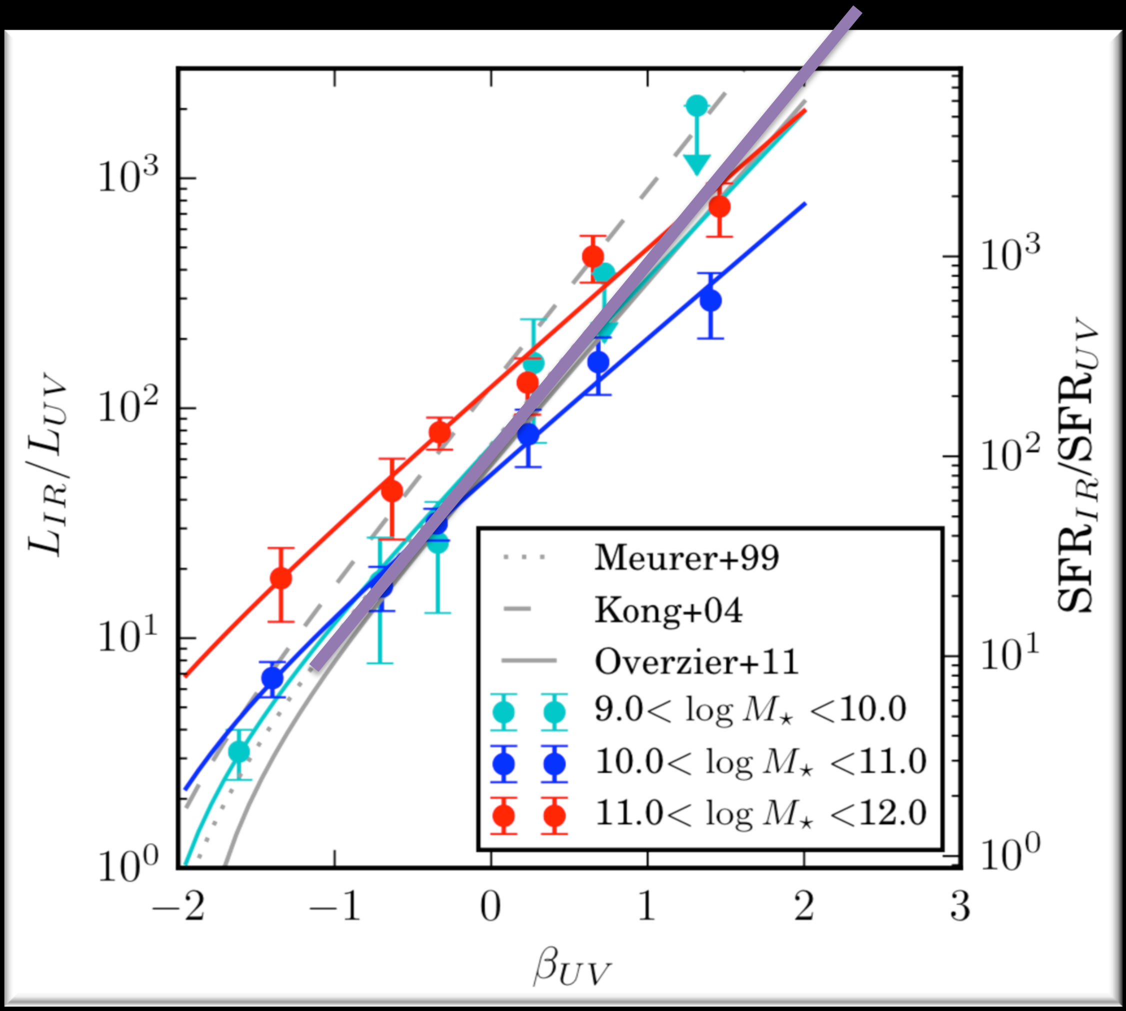
The IRX-beta relation

Obscuration (IRX=L_{IR}/L_{UV}) should be linked to UV slope β

- Excluding passive galaxies based on UVJ colours
- $M<10^{11}M_\odot$ galaxies close to Meurer law
- $M>10^{11}M_\odot$ galaxies have higher extinction for given UV slope

See also Coppin+15; Alvarez-Marquez+16; Bouwens+16 (studies of z~3 LBGs)

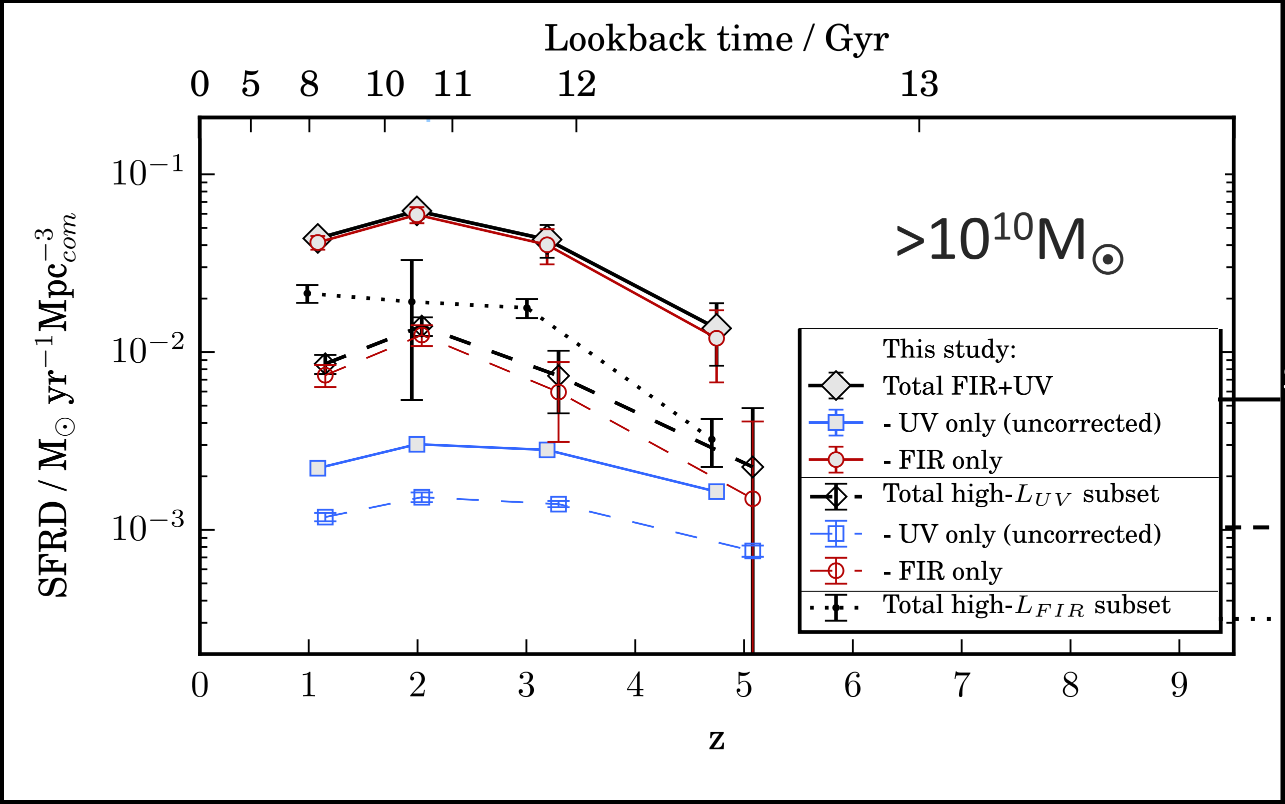
Meurer+99 law



Results (II):

COSMIC STAR FORMATION DENSITY AT Z<6

Cosmic SFR density in massive galaxies



Black=total
Blue=unobscured
Red=obscured

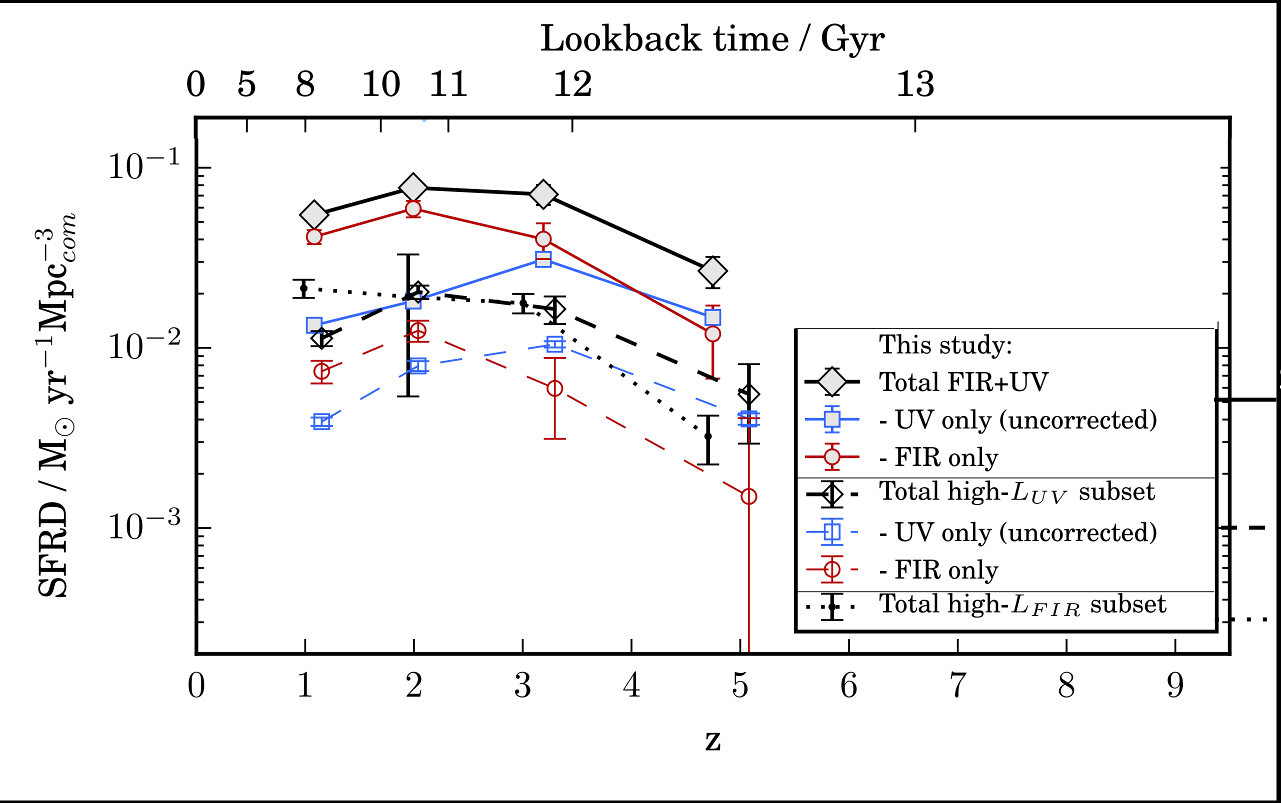
Solid lines = all galaxies

Dashed lines = $L_{UV}>L^*$

Dotted=450-det

- SFRD peak at z~2
- SFRD in massive galaxies is dominated by obscured SFR
- 1/5 of SFRD from $L_{UV}>L^*$ galaxies (also obscured)
- 1/3 of SFRD from 450μm-detected sources

Cosmic SFR density in *all* galaxies



Black=total
Blue=unobscured
Red=obscured

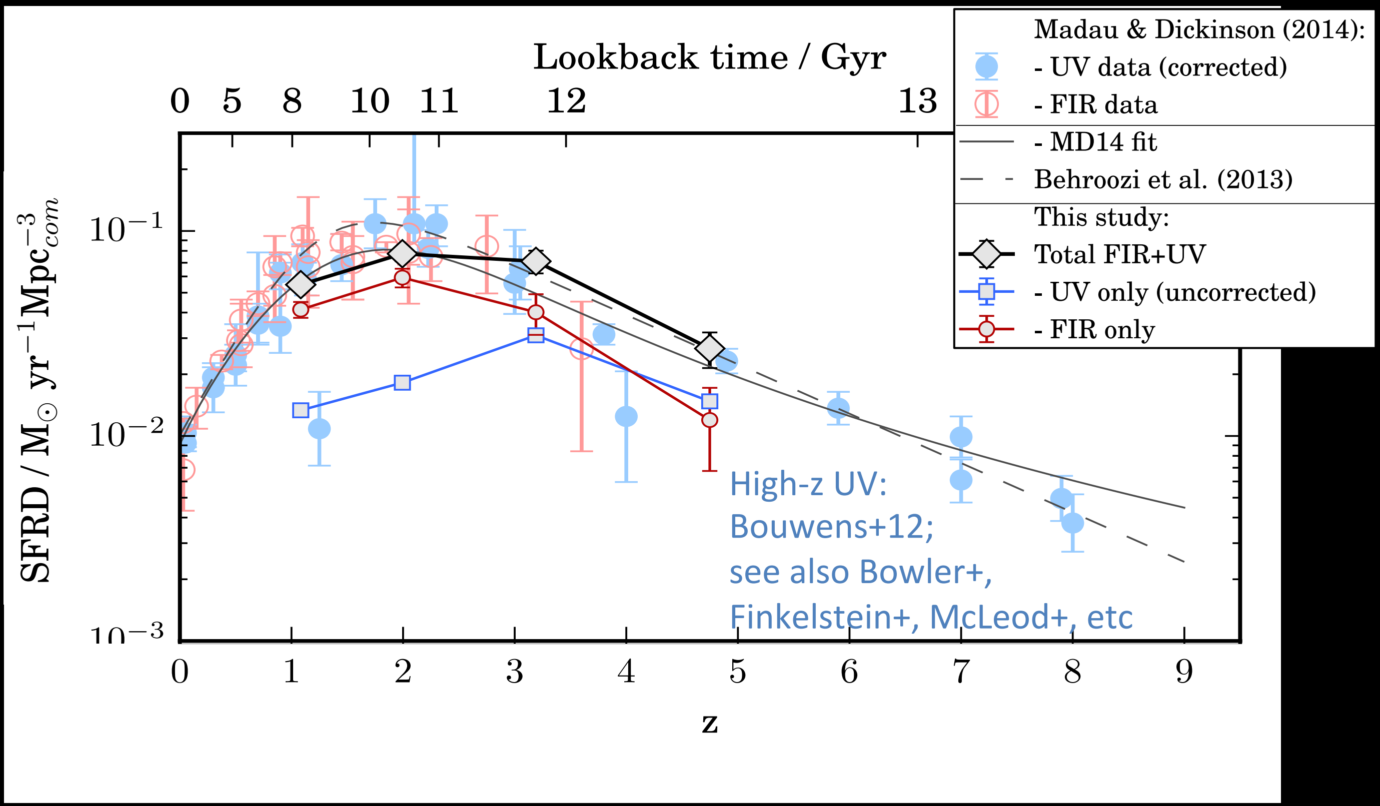
Solid lines = all galaxies

Dashed lines = L_{UV}>L*

Dotted=450-det

- Including UV emission from full LF integrated to -15 (Parsa+16)
- SFRD peak at z=2-2.5
- z<3: dominated by obscured SFRD (peaks at z=2)
- z>3: unobscured SFRD takes over (this peaks at z=3)

Cosmic SFR density in *all* galaxies



- SFRD at high-z broadly consistent with Behroozi+13, Madau & Dickinson14
- UV-corrected SFRD from the literature at z~5 is consistent with our IR+UV
- *The early universe (z>3) is increasingly dominated by unobscured SFRD*
- *But the peak epoch of SFRD (z=1-3) is dominated by obscured growth of high-mass galaxies – and in this regime, Meurer dust corrections are inadequate*

Take-home messages

- **Strong relationship between IR/UV, L_{UV} and M_*, independent of redshift:**
  $L_{IR}/L_{UV} \sim M_{star}^{0.7}\ M_{UV}^{0.6}$
- UV luminosity traces obscuration rather than SFR
- More massive galaxies have higher SFR and higher IR/UV

- **The SFRD is mostly obscured at z=1-3, and is dominated by the growth of high-mass star-forming galaxies**
  – These galaxies are heavily obscured and Meurer dust corrections are insufficient

- **At z>4, the SFRD is predominantly *unobscured* and is dominated by lower-mass galaxies**
  – Because they have lower stellar mass, Meurer dust corrections appear to be successful

If you want to know more? → `arXiv:1607.04283`

Thank you for listening……..   any questions?