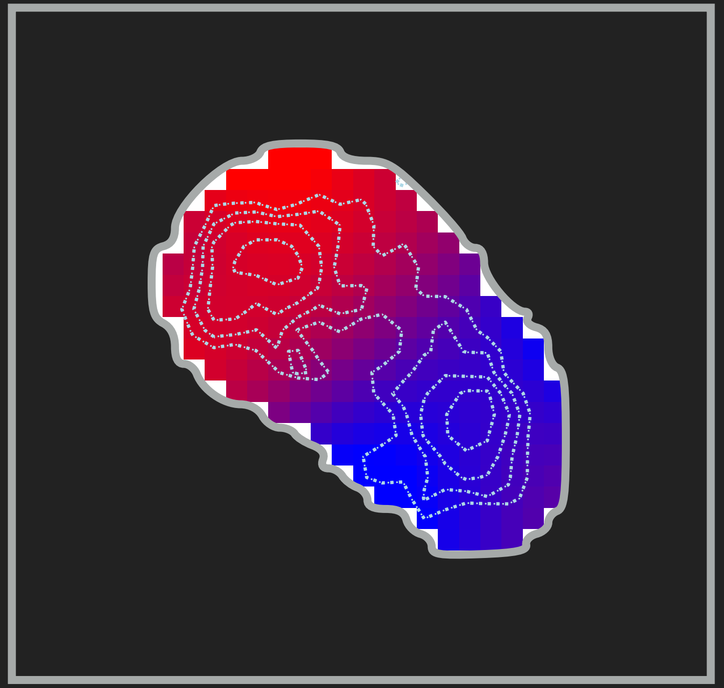
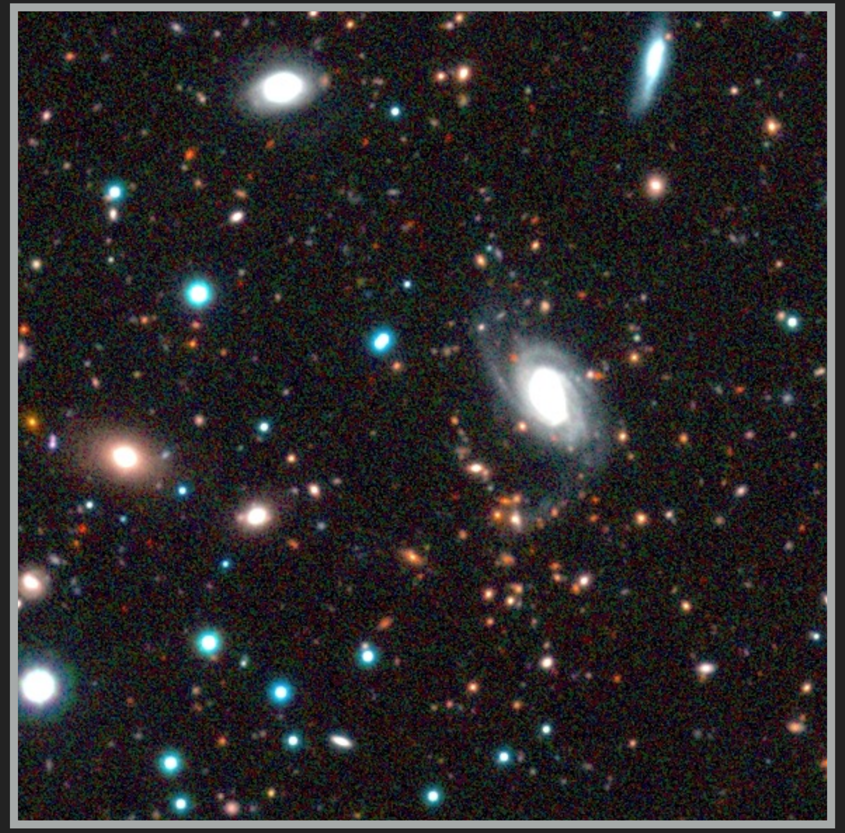
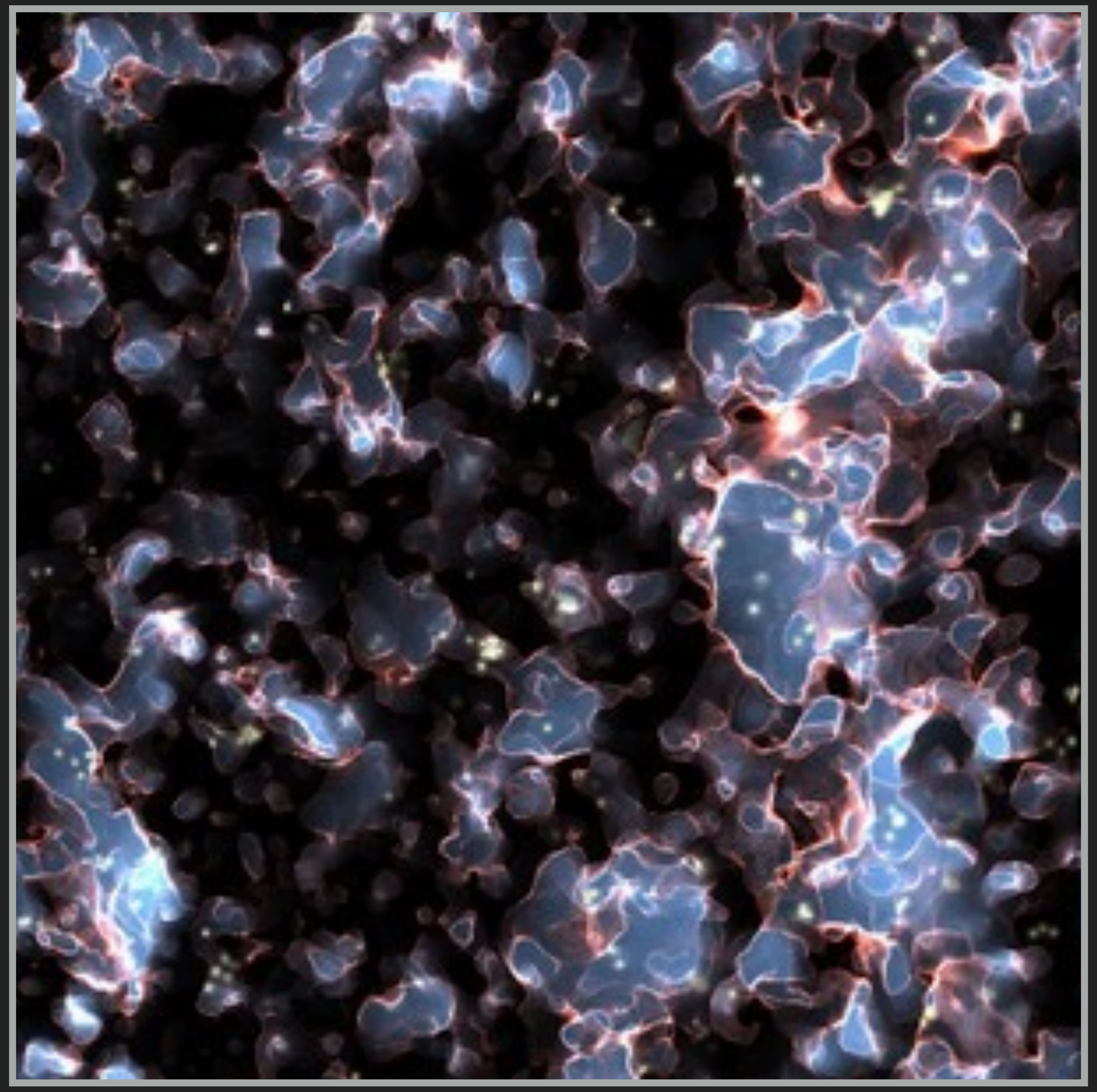






Dust in massive Lyman-break galaxies at z = 4-8

Rebecca Bowler

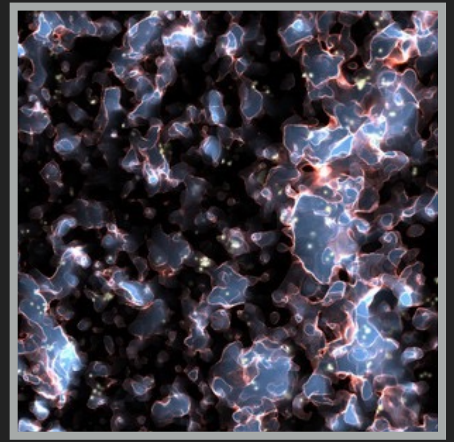
STFC Rutherford Fellow

Jodrell Bank Centre for Astrophysics

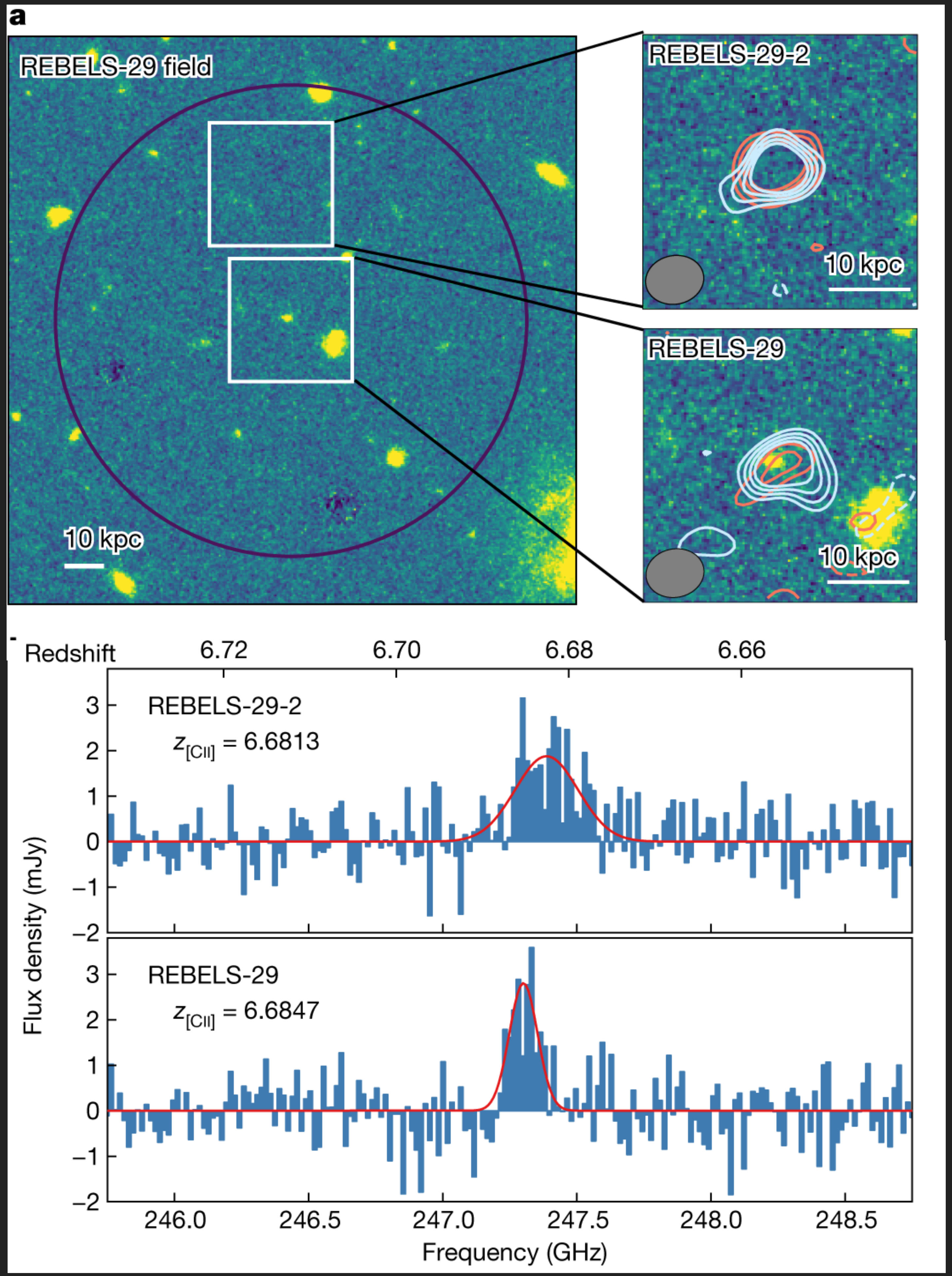
The University of Manchester

Summary

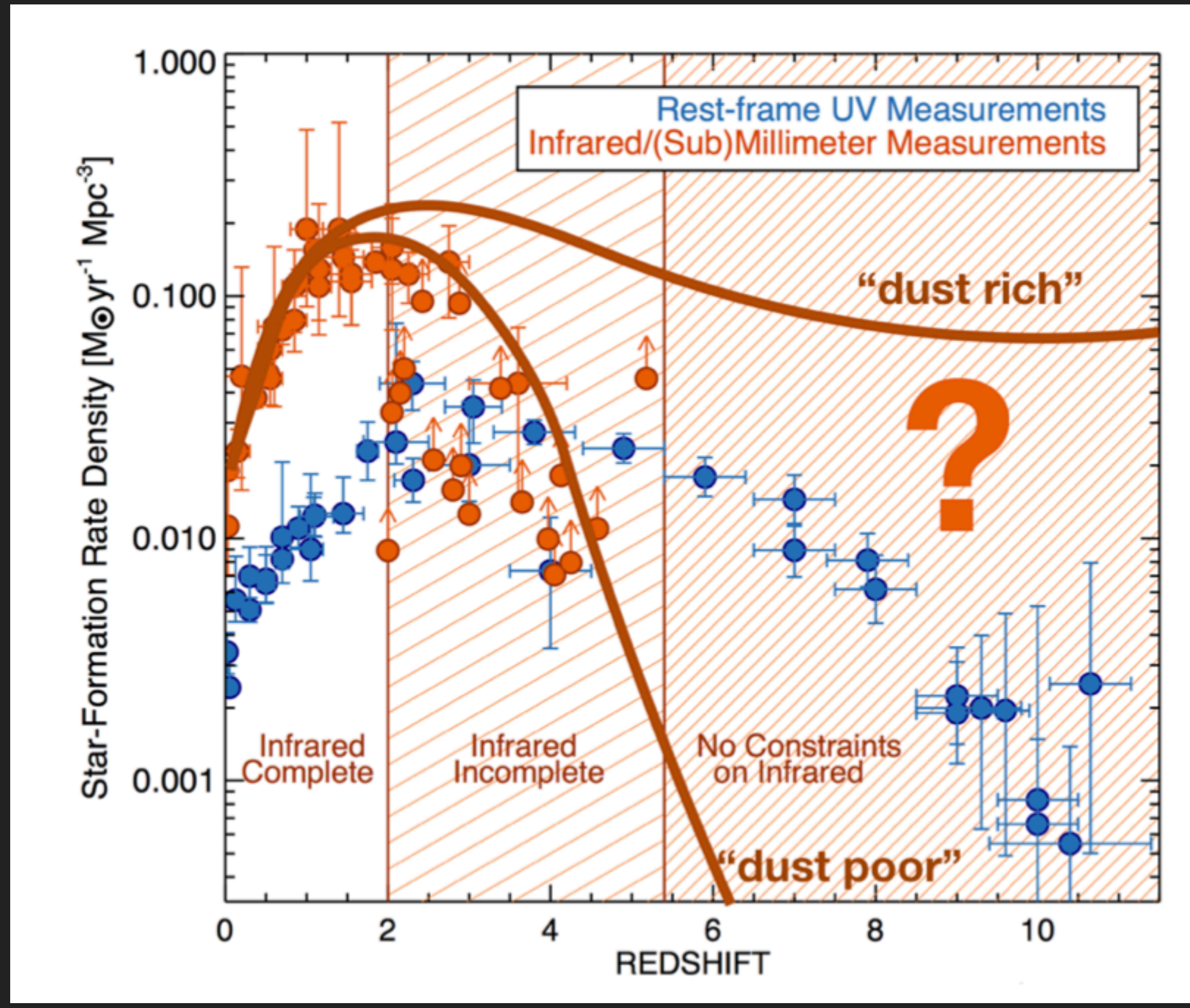
Dust in massive ($\log(M/M_\odot) \sim 9.5$) galaxies at $z = 4$-8 follow a Calzetti dust attenuation law, similar to local starburst galaxies



Importance of measuring dust at high-z

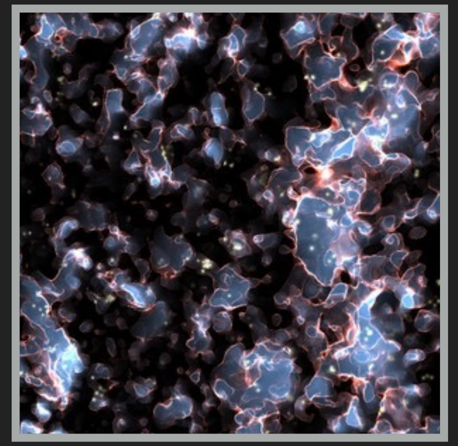


`HST-dark' sources found with [CII]; Fudamoto+21 (REBELS collaboration)



Cosmic star-formation rate density predictions from Casey+18

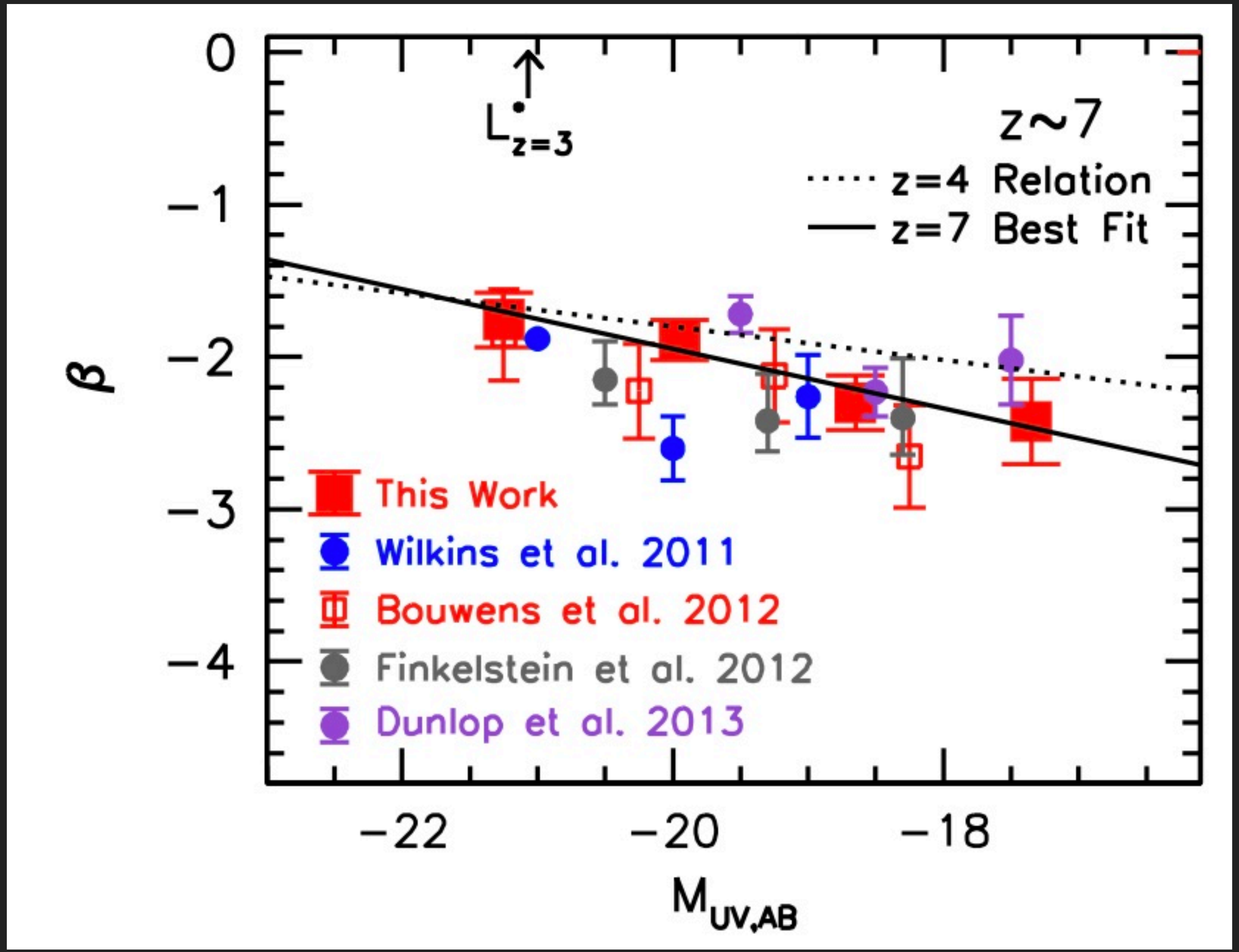
- Typically rest-UV selected samples, SFR derived from UV
- Missing star-formation and full objects e.g. 'HST-dark' sources
- Hence underestimate the cosmic SFR density
- Also dust is degenerate with age and Z in SED fitting



Observational probes of dust*

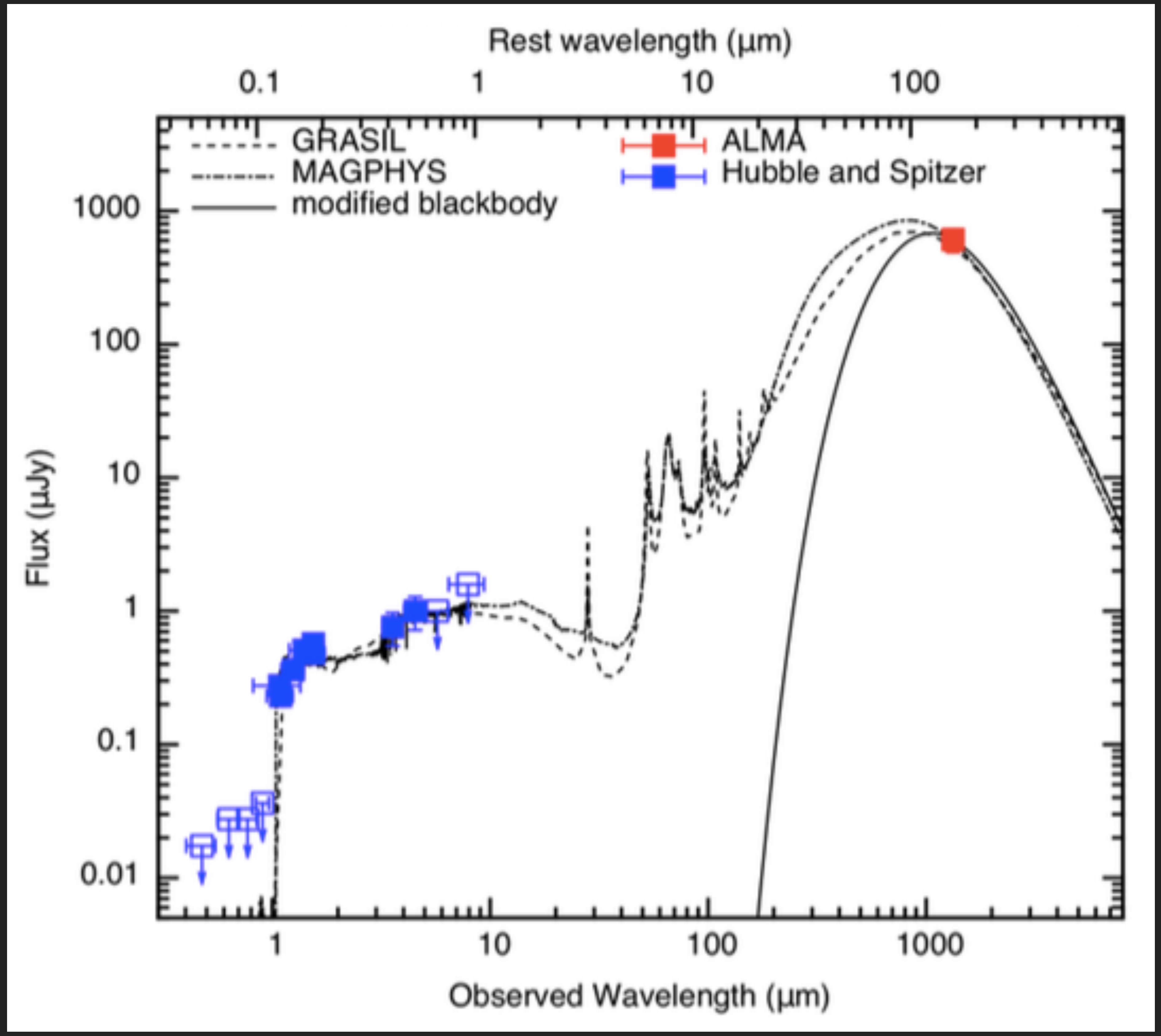
*pre JWST

Rest-UV



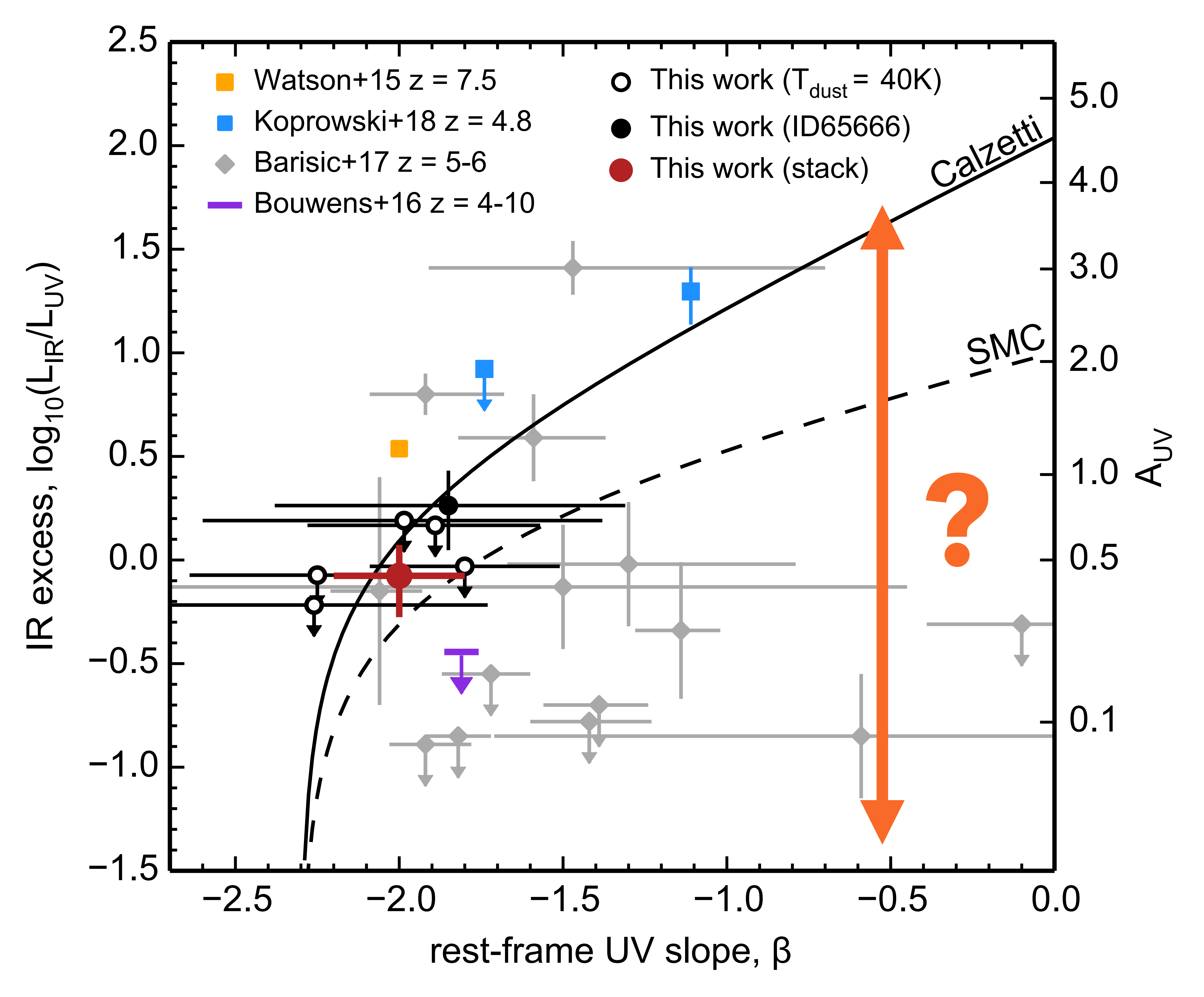
Colour-magnitude relation from Bouwens+14 indicating that brighter sources are potentially dustier (60% of effect from dust: Finlator+11)

Rest-FIR



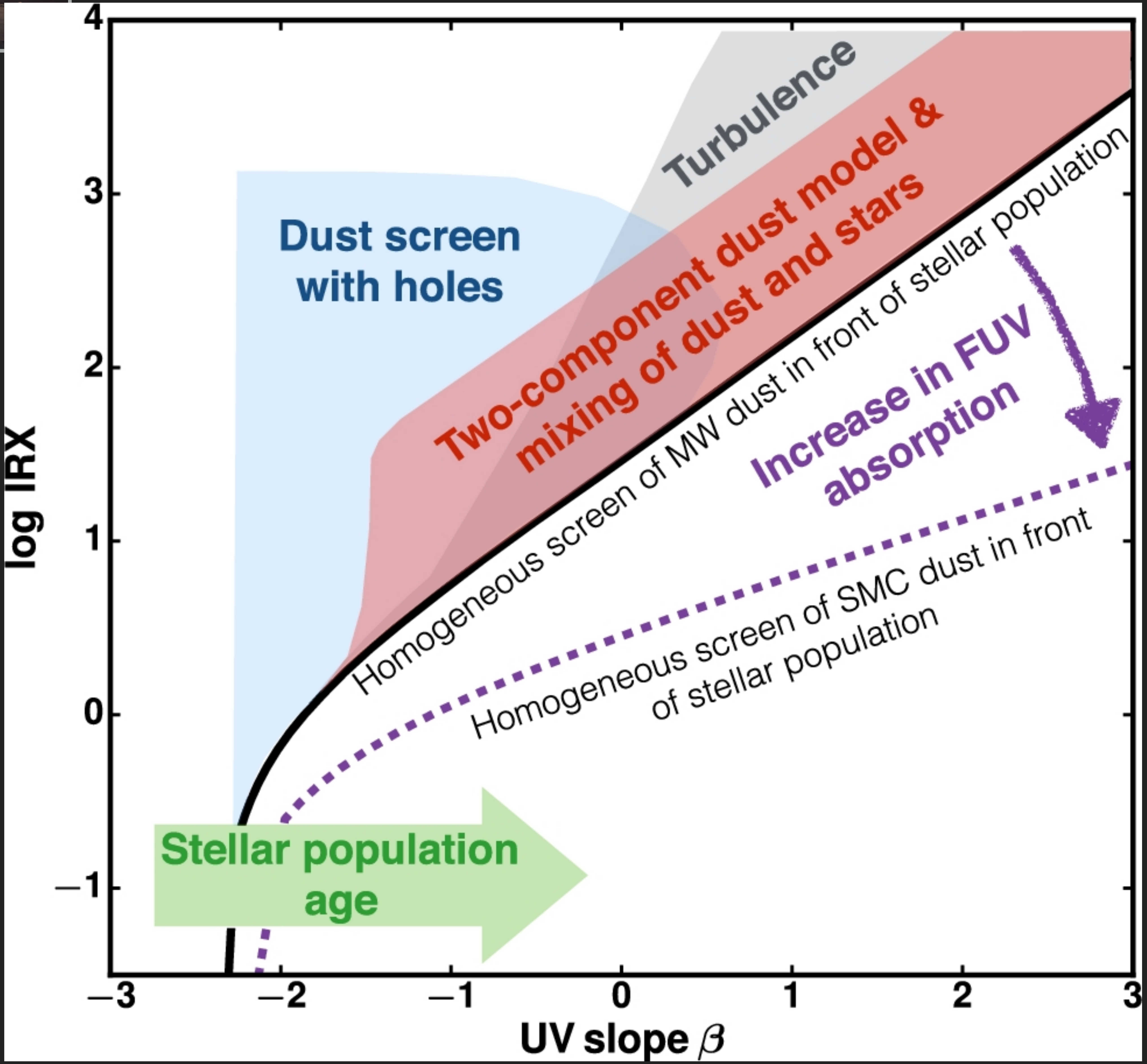
Direct detection of the emission from cold dust (150 micron) using mm observations (e.g. Watson+15). LIR from assuming an SED.

Probing dust at high-z with IRX scaling relations



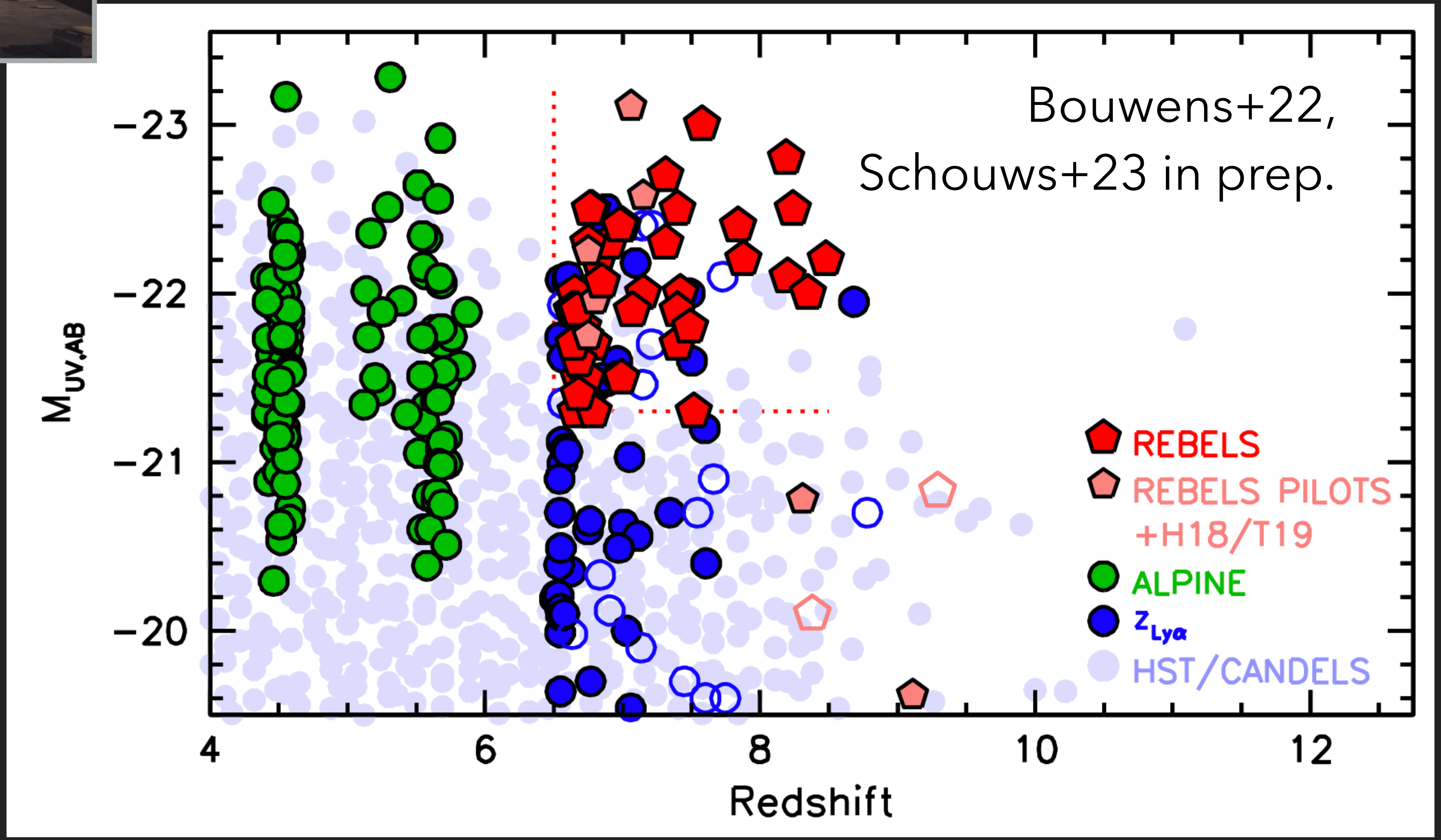
- From measured UV slope can correct for dust obscured SF.
- First samples at z ~ 5 showed a deficit compared to local starburst relation (Capak+15, Barisic+17)
- Other early detections showed an excess (e.g. A1689-zD1: Watson+15)
- Confusing picture at high redshift with small samples.

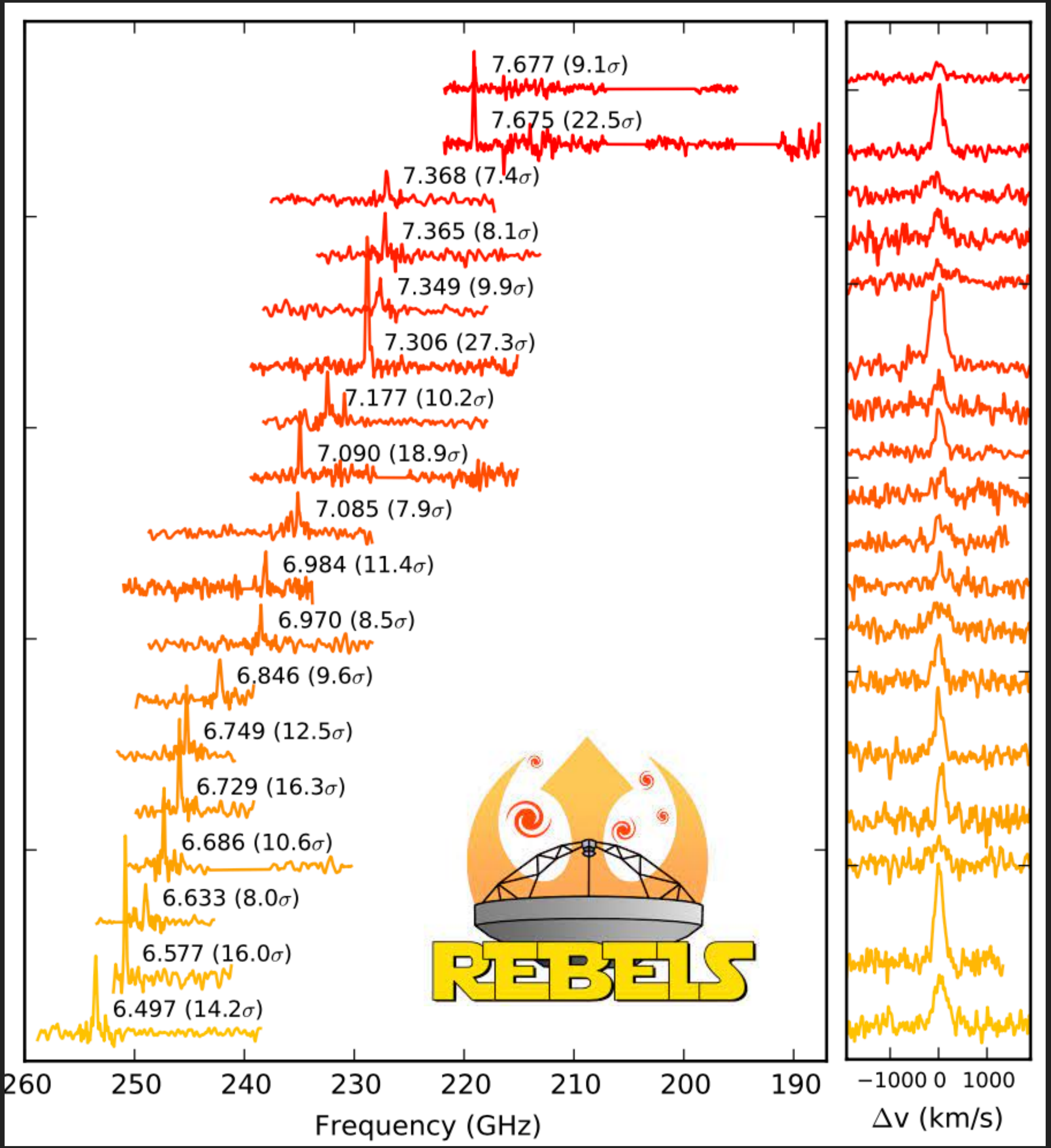
Probing dust at high-z with IRX scaling relations



- "Easy" to be above the relation (geometry) but hard to get below (age + steeper attenuation). Figure from: Popping+17, also e.g. Narayanan+18, Samir & Narayanan+20, Liang+21
- SMC *attenuation* curve is not as steep as the SMC *extinction* law once geometry is taken into account, do we expect to see SMC extinction relation? e.g. Cullen+17, talk by Aswin

ALMA as a redshift (and dust) machine



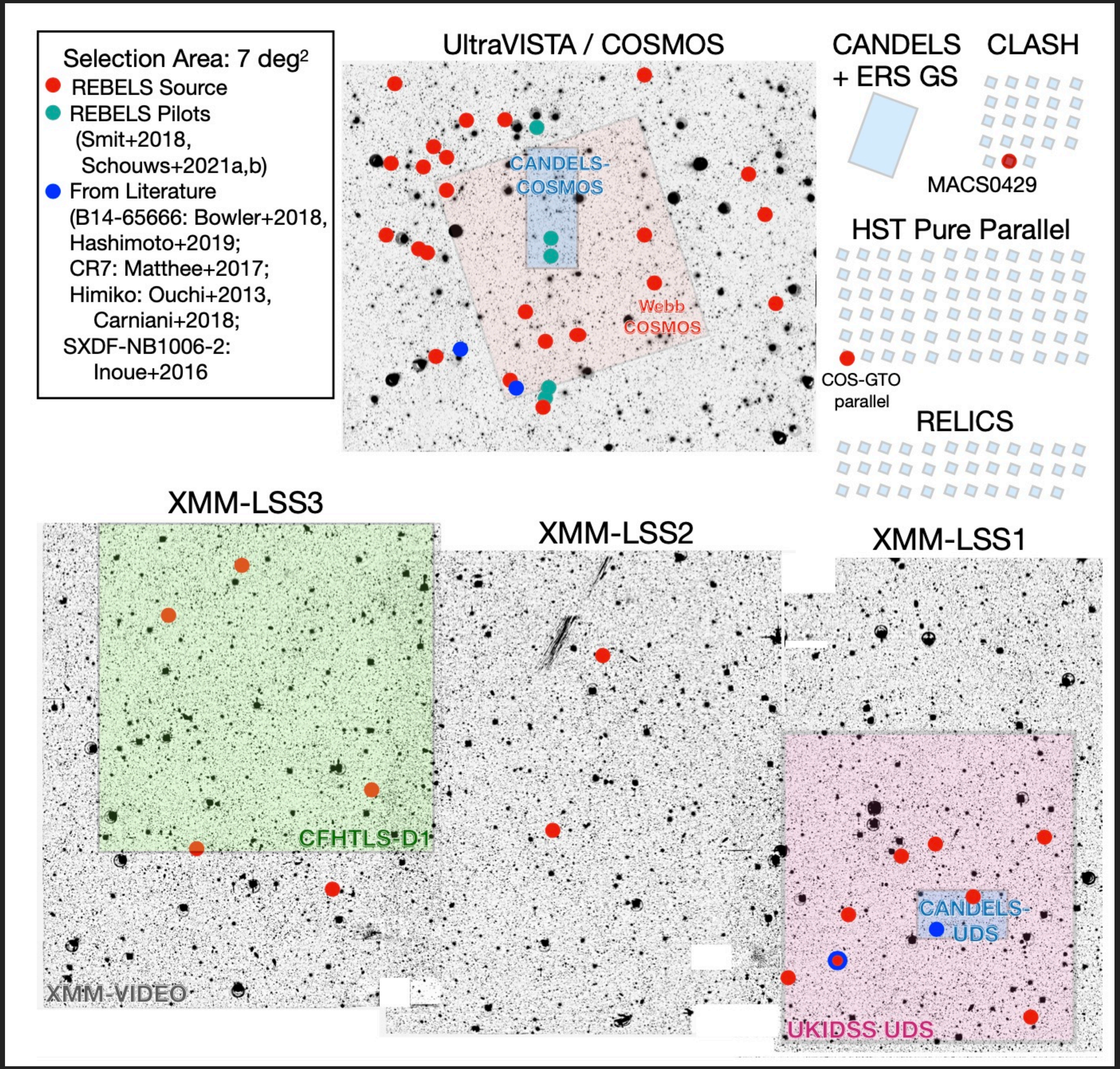


- Sensitivity and efficient line scans (+lack of Ly-α) makes ALMA powerful for spectroscopic confirmations.

- 25 new luminous objects [CII] detected (18 in dust) at z > 6.5 from 49 galaxies.

The power of ground-based data

REBELS sample selection (Bouwens+22)



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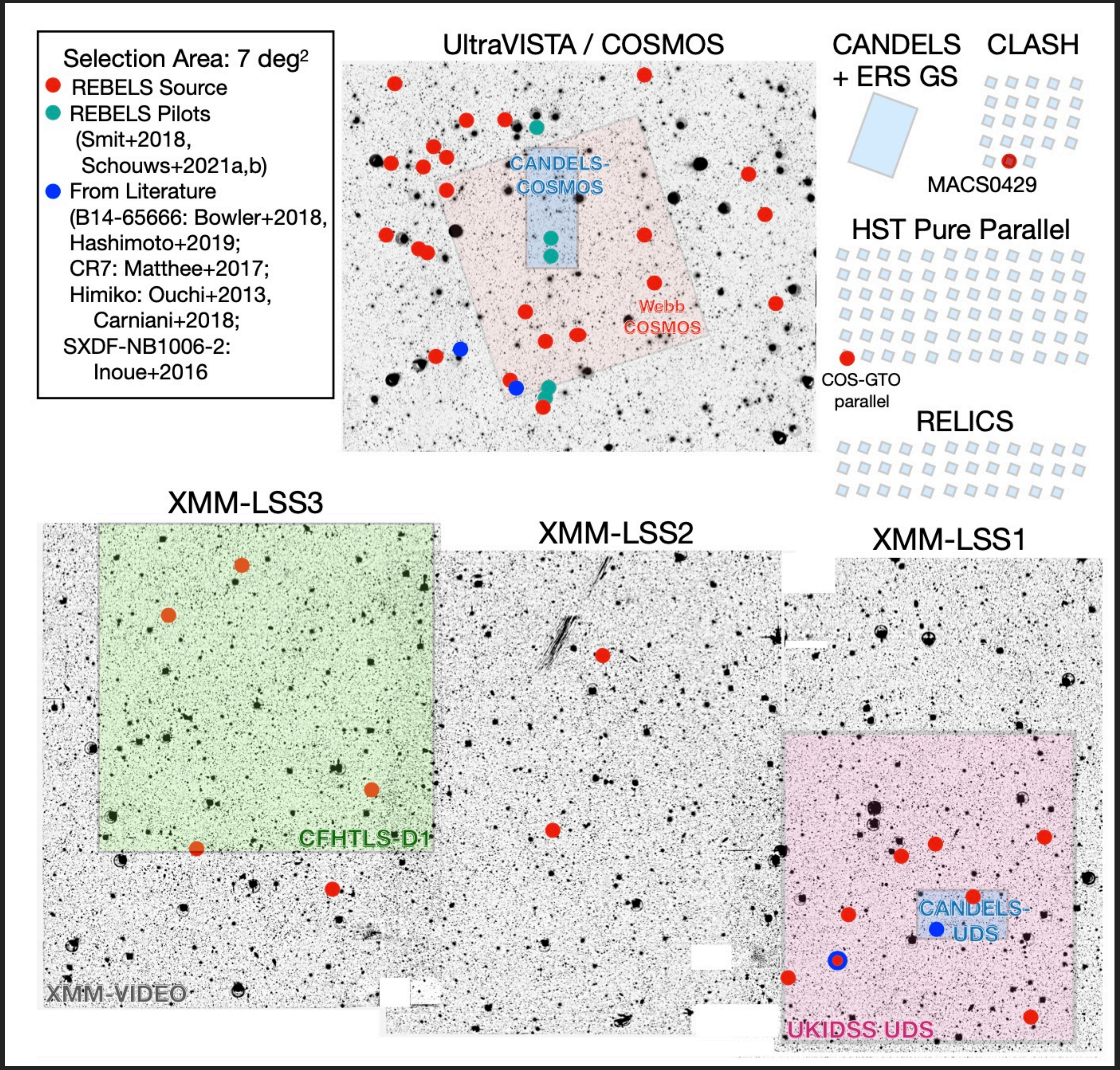
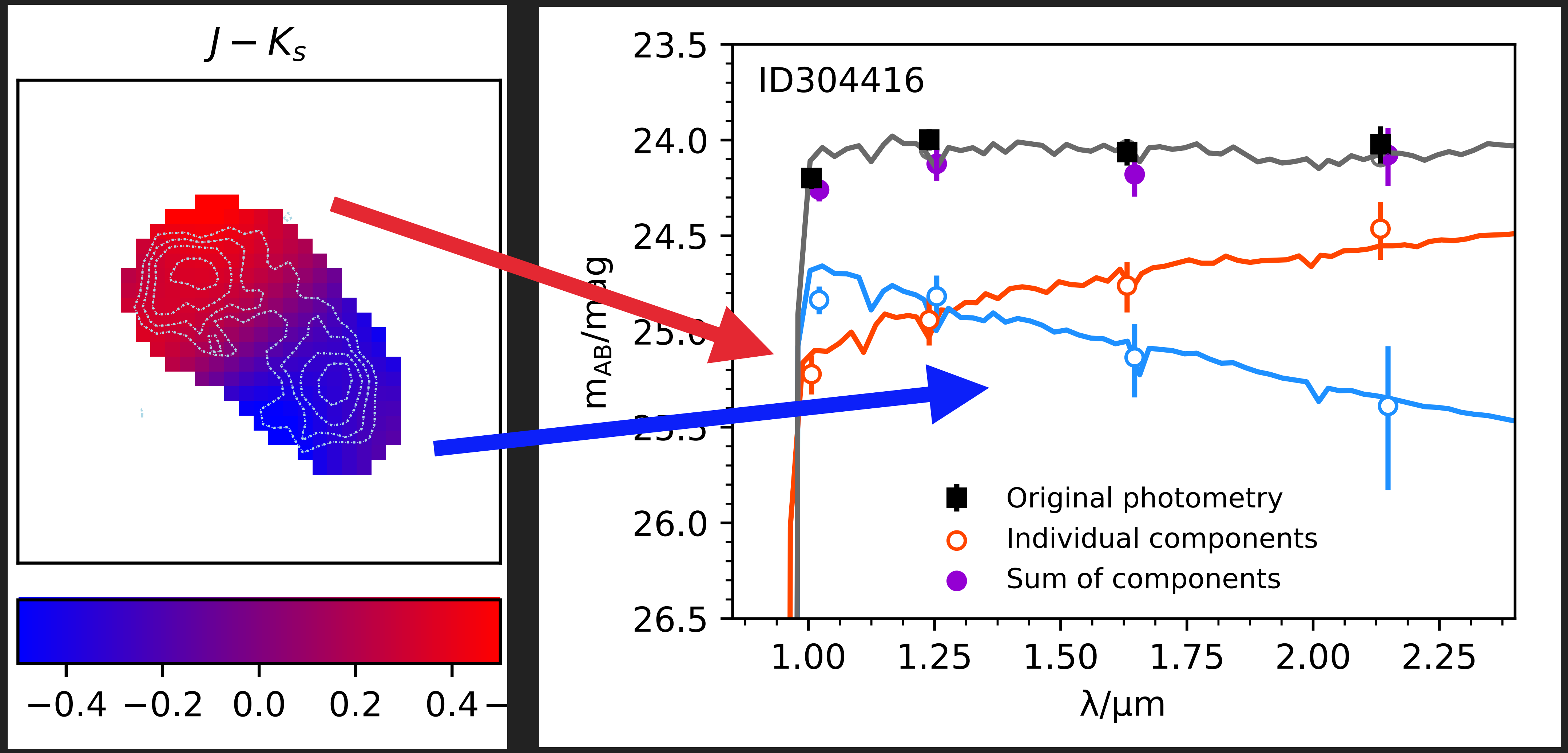
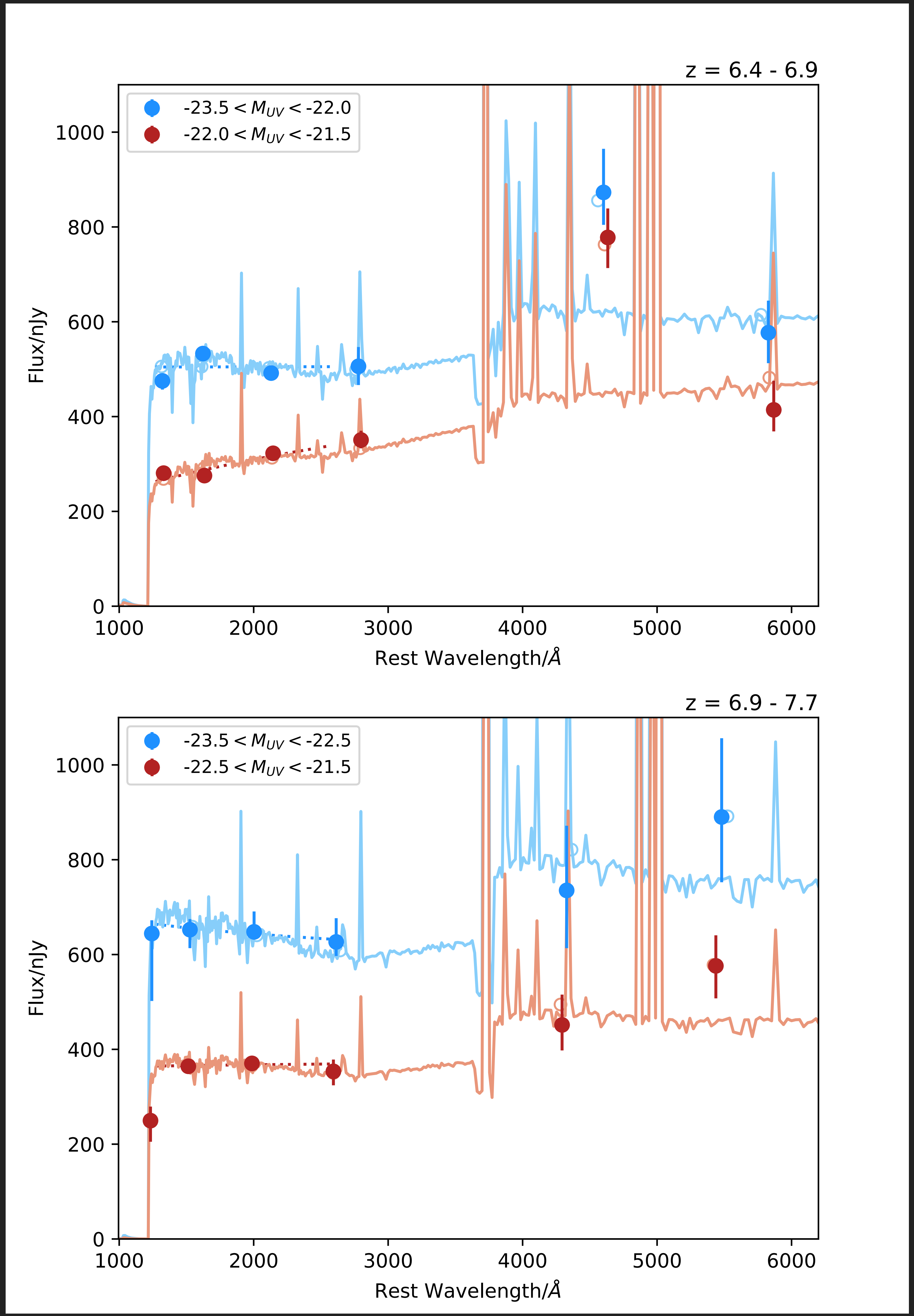




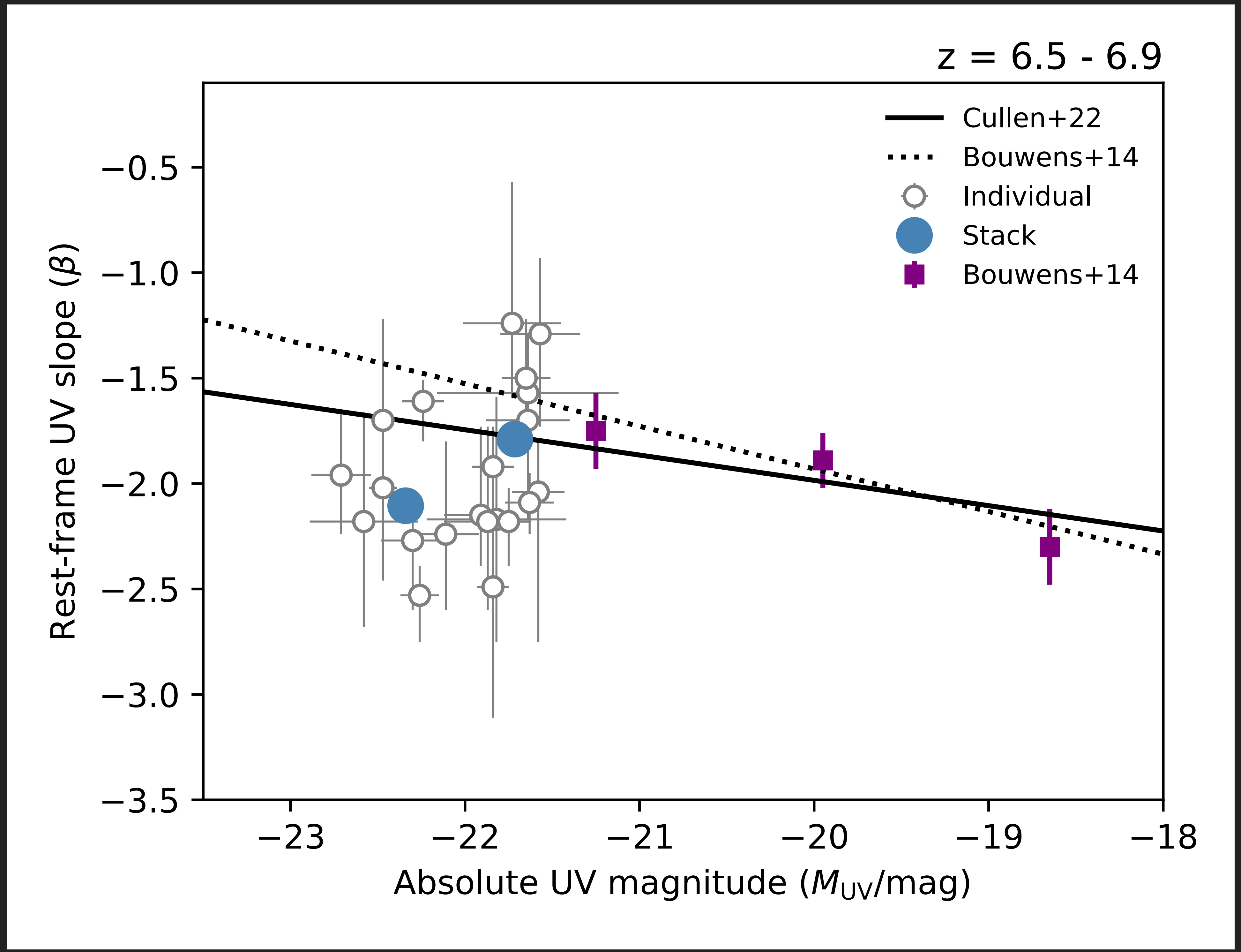
Colour gradients revealed by deconfusing VISTA data with HST (RB+22)

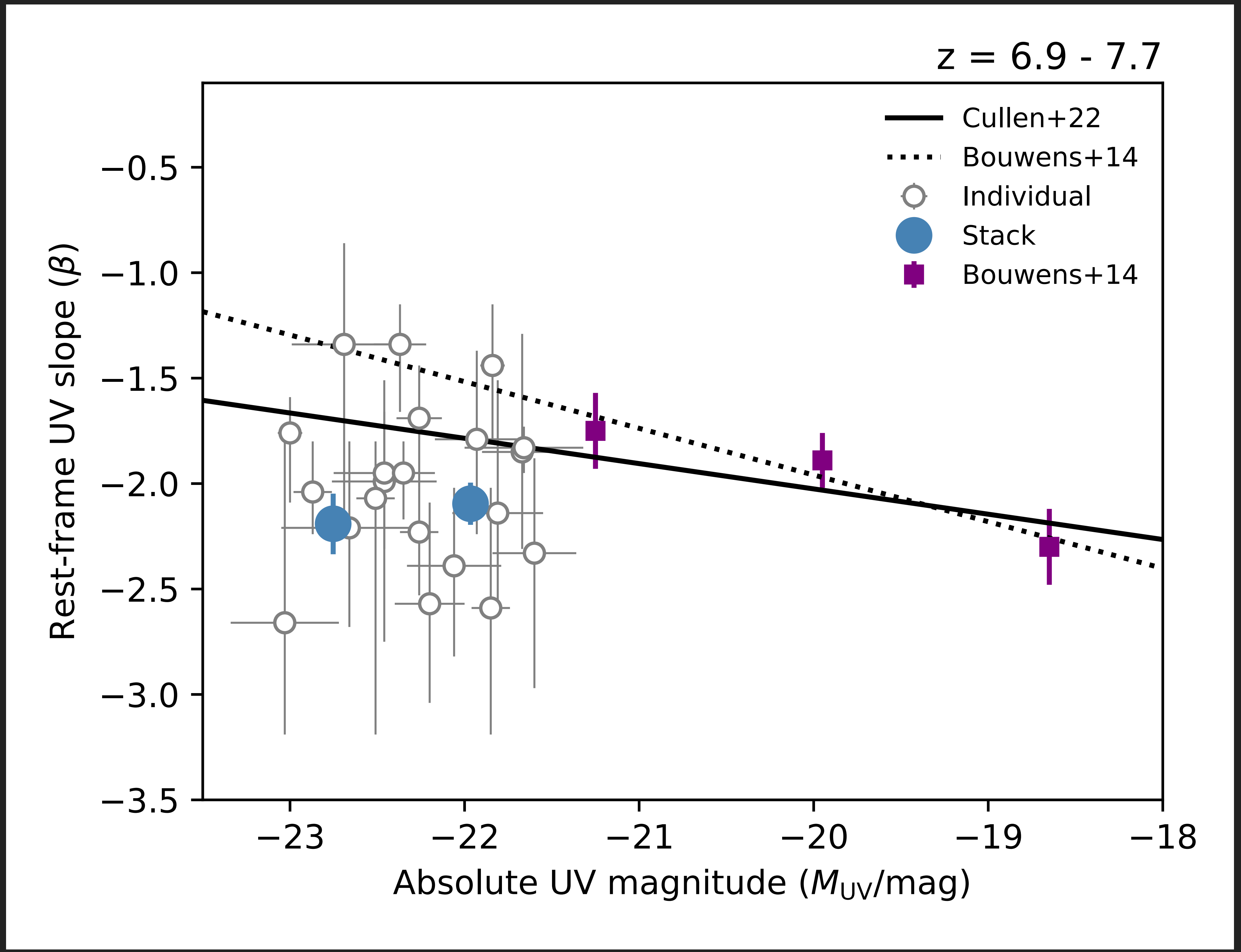
REBELS rest-UV and optical stacks



- Stacked the YJHKs[3.6][4.5] photometry to make average rest-frame UV + optical SED of bright REBELS LBGs.
- Stacked in bins of Muv and z.
- Physical parameters derived using Bagpipes.
- Stacked stellar mass: log(M) ~ 9.5

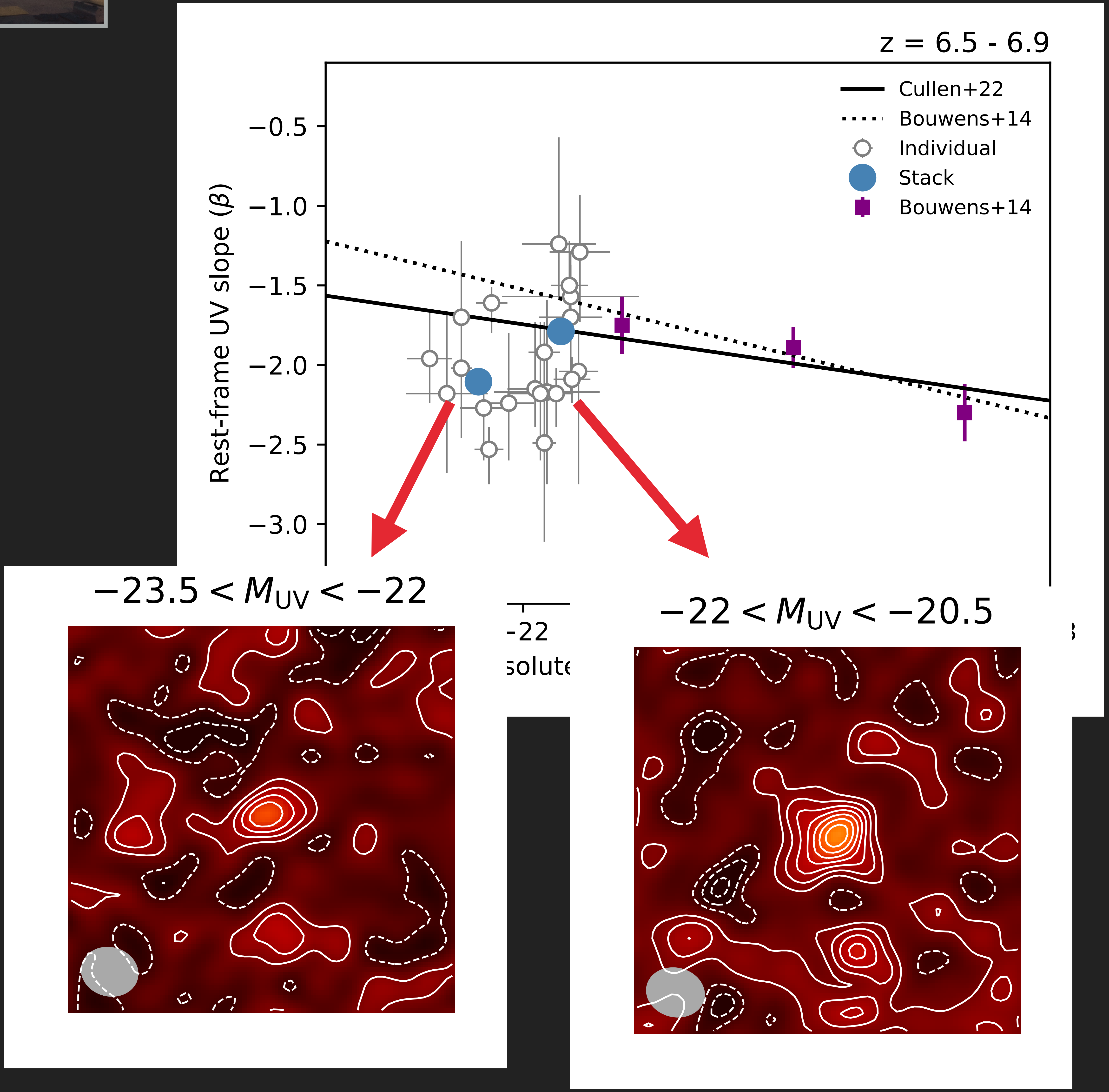
The brightest galaxies are unusually blue!

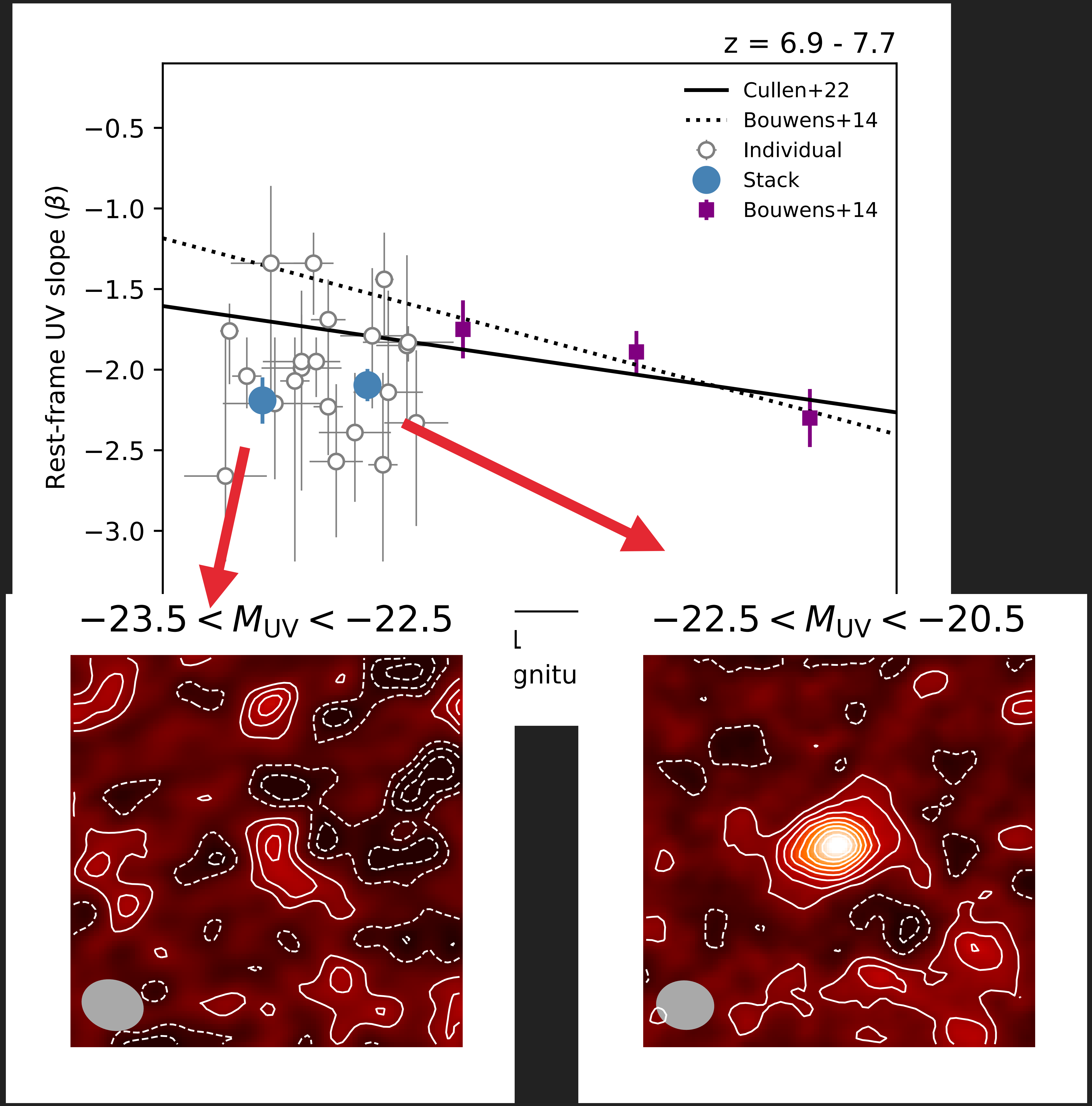




- The REBELS galaxies are offset below the colour-magnitude relation.
- Selection effect? Likely no, because the sources are high S/N in images.
- Bursty SFH/scatter in the stellar mass <-> Muv relation?

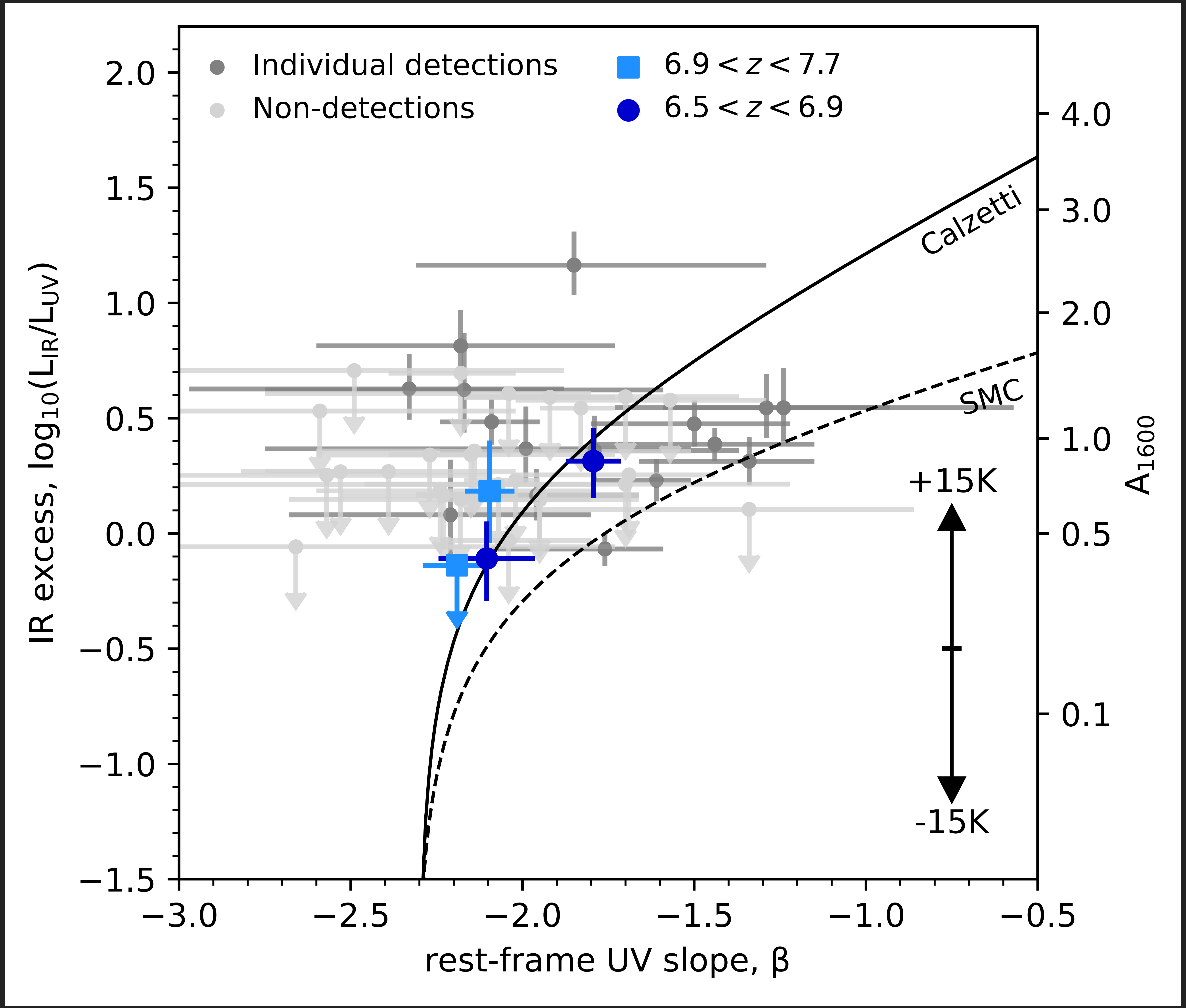
The brightest galaxies are unusually blue, but there is dust!





IRX-β relation from REBELS

- Dust detections in 18 (Inami+22)
- Stack and derived Lir assuming Td= 46K (Sommovigo+22)
- Small dynamic range probed, however results consistent with Calzetti-attenuation (with FIR SED assumptions!)
- See objects above with likely effect of geometry (REBELS-25, ULIRG: Hygate+23)



RB+23 in prep.

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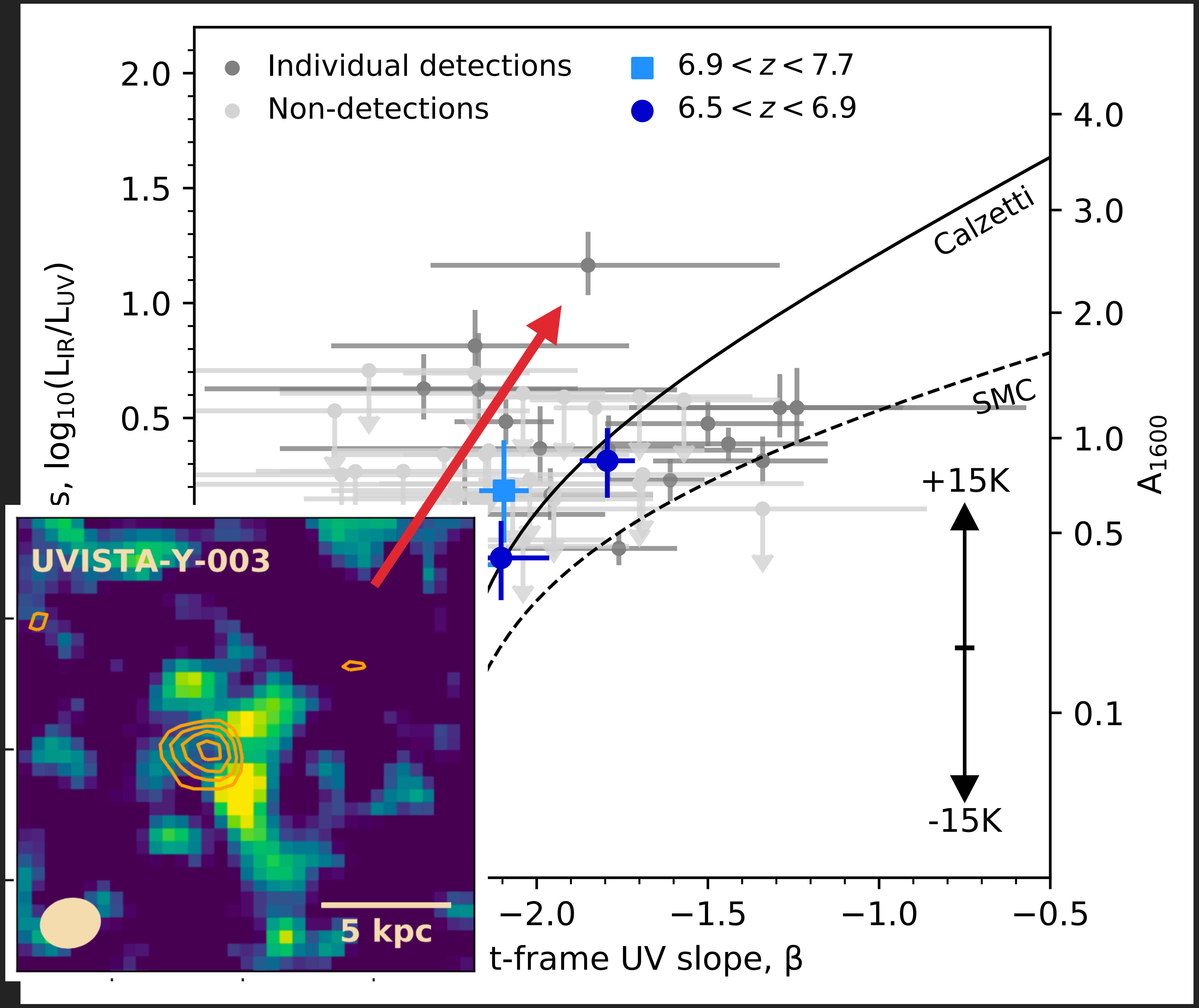
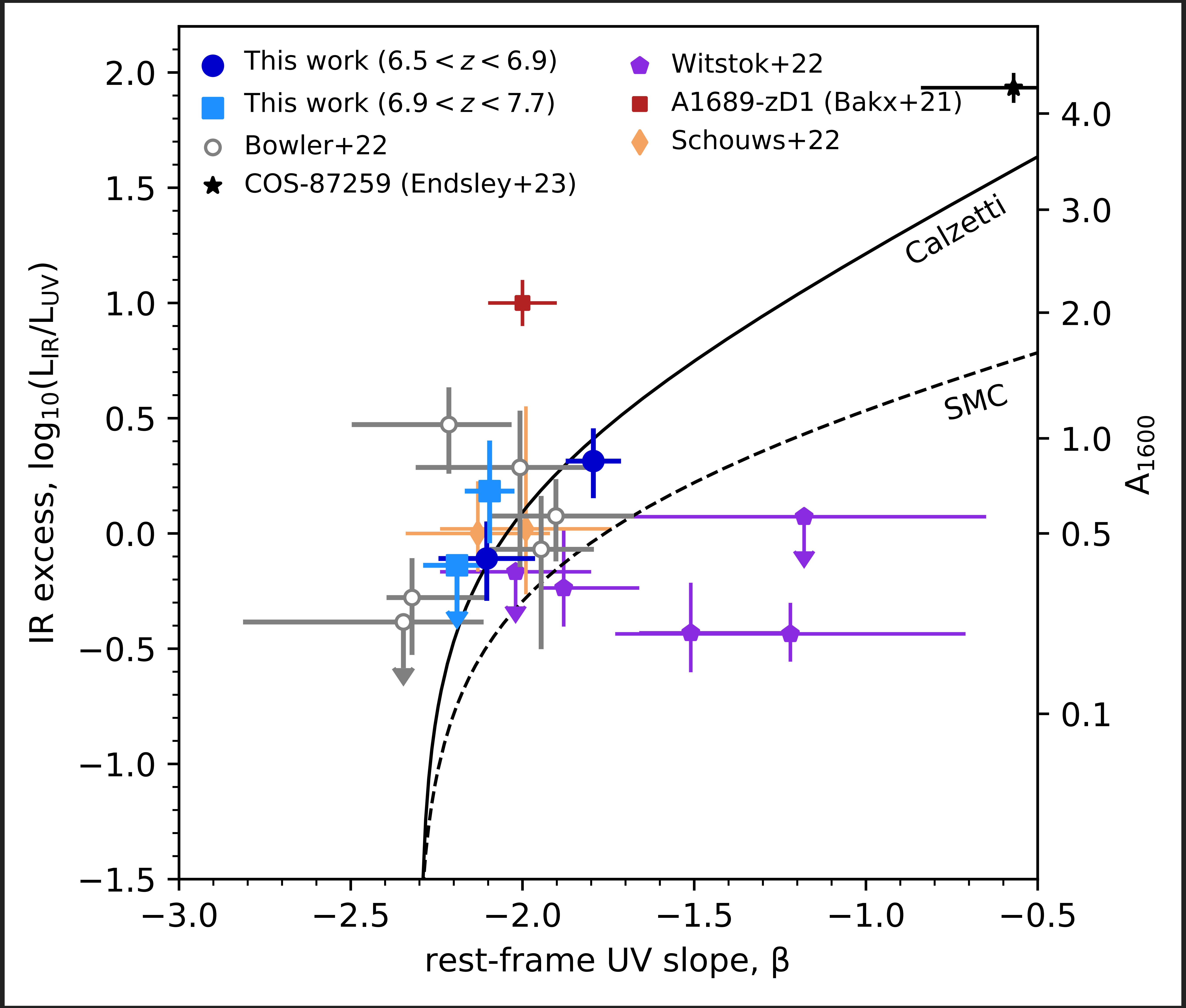


RB+23 in prep.

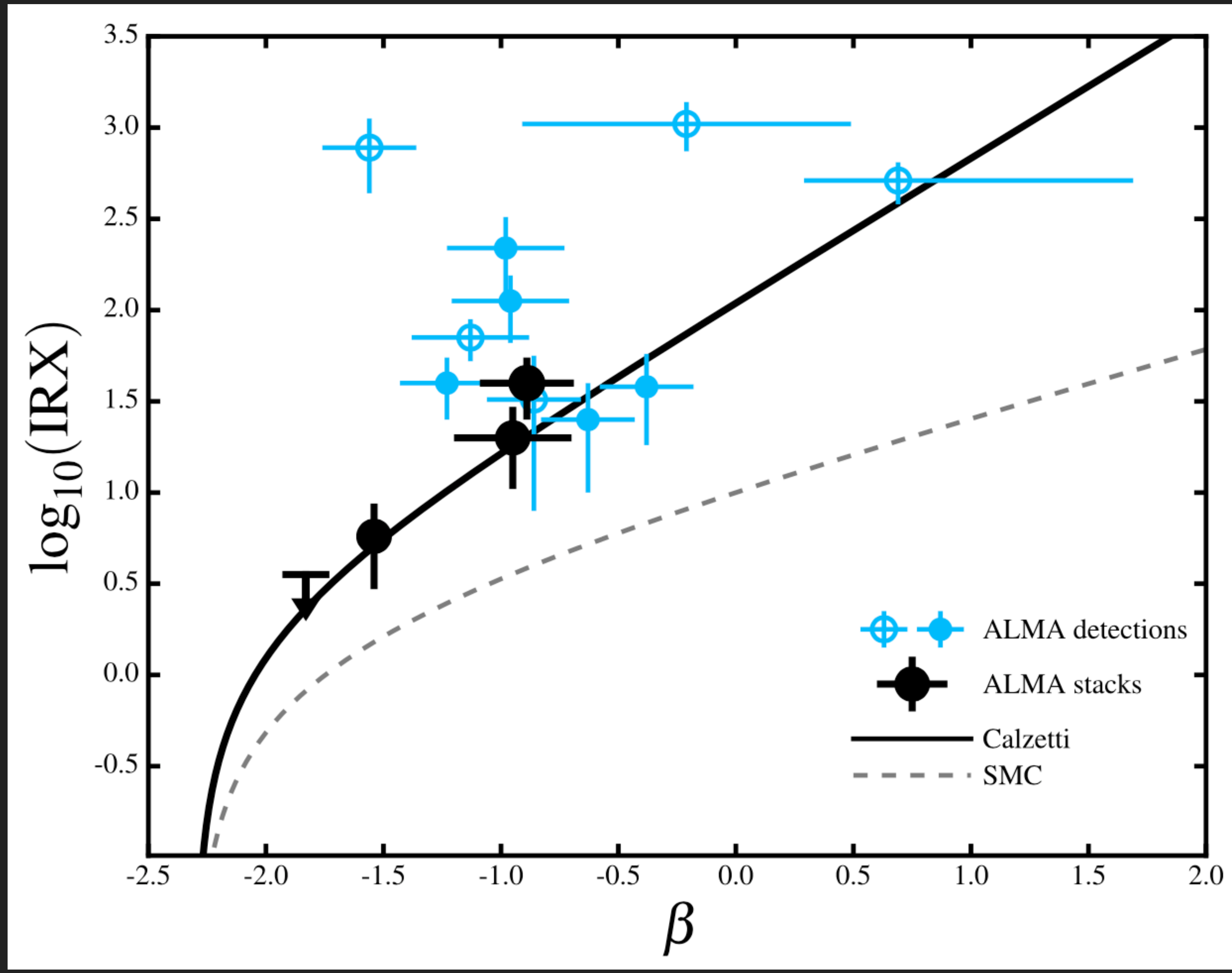
IRX-β relation from REBELS

- Compare to others that assume similar dust SED (Td ~ 40-50K)
- Scatter above and below, but results are remarkably in agreement with Calzetti at z = 7.
- Caveat: SMC and Calzetti curves converge for blue sources.



RB+23 in prep.

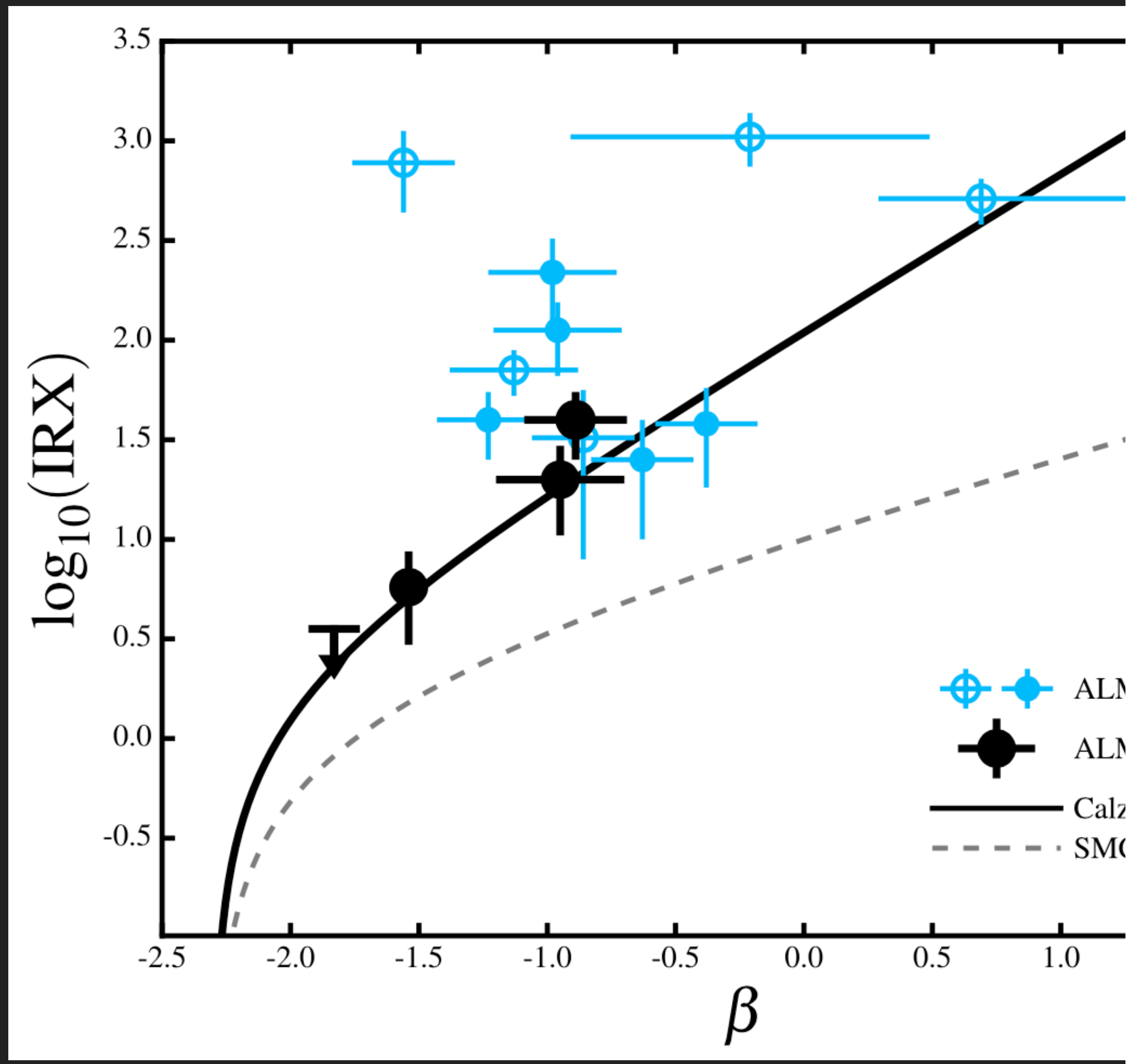
Puzzle - what is happening to IRX-β from z = 2-8?

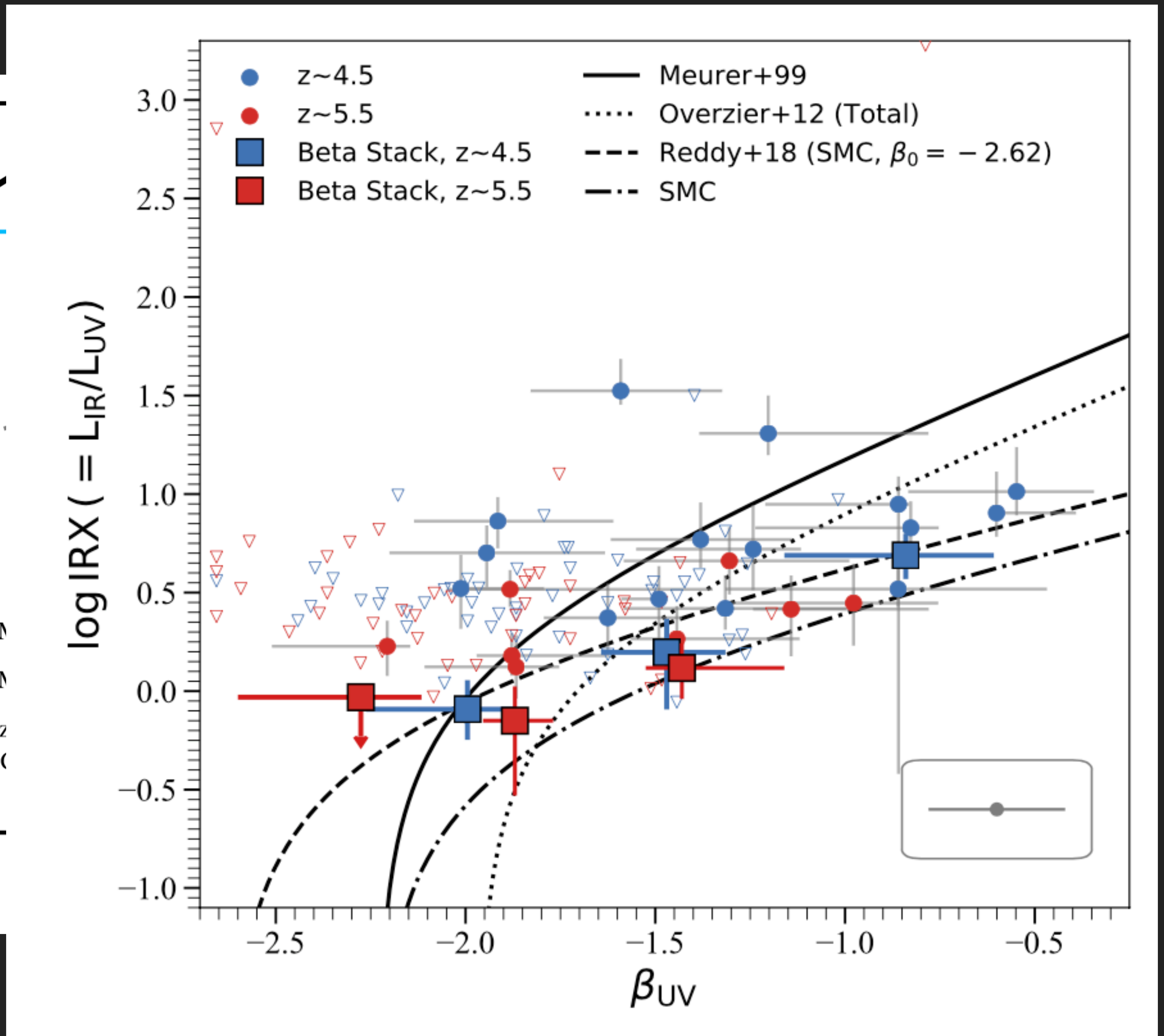


Z = 2-3 -> Calzetti

(e.g. McLure+18, Koprowski+18)

Puzzle - what is happening to IRX-β from z = 2-8?





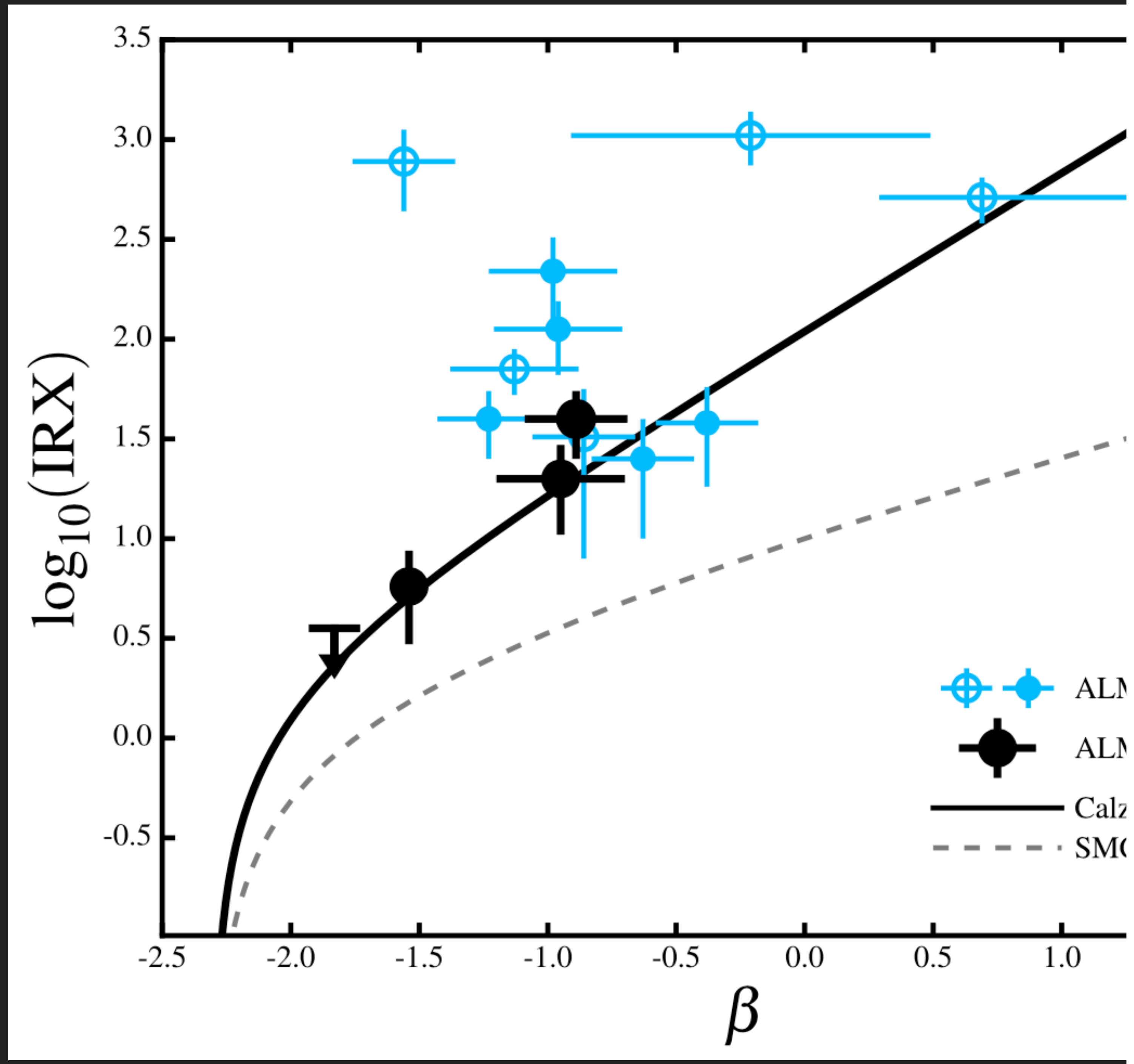
Z = 2-3 -> Calzetti

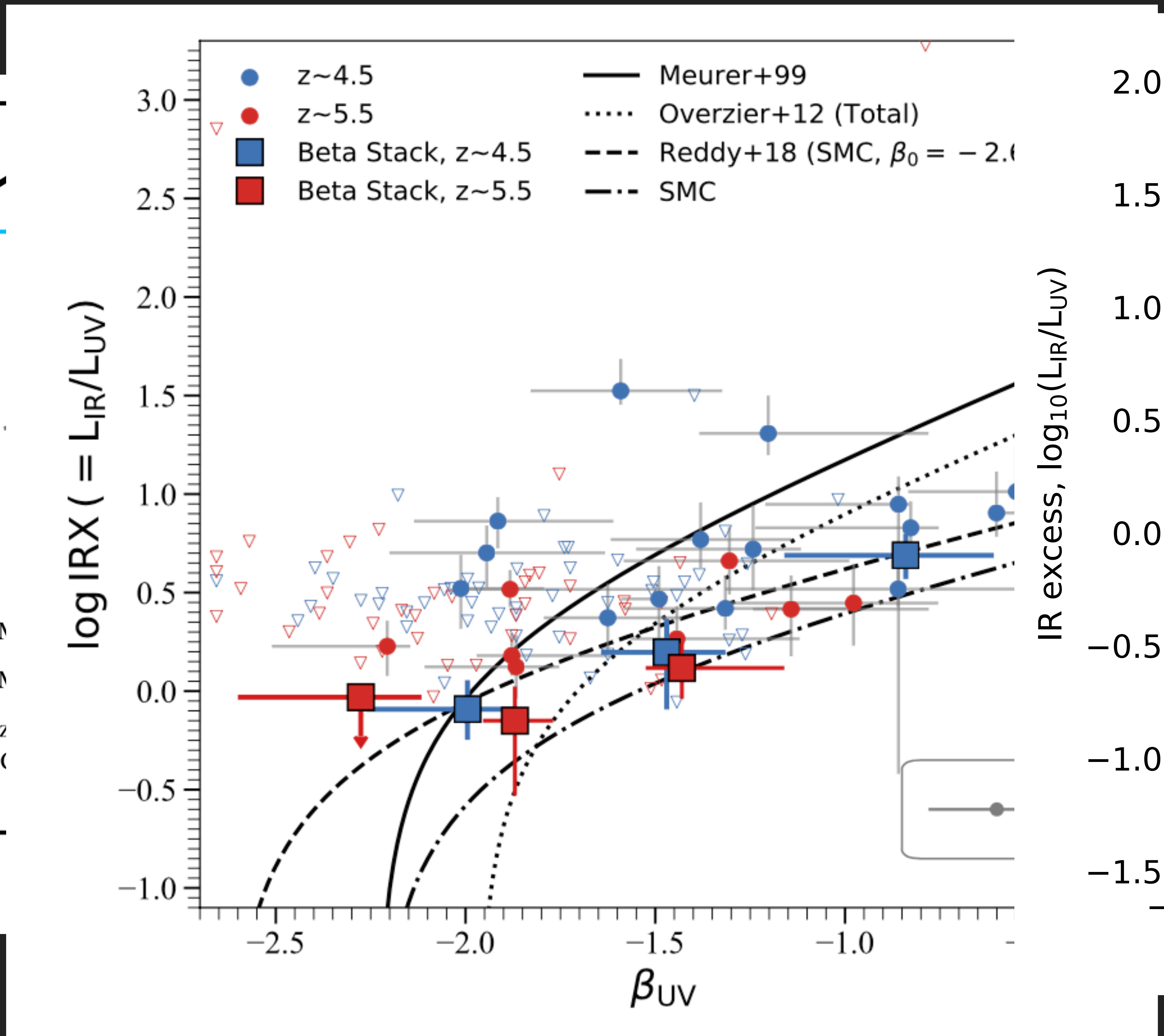
(e.g. McLure+18, Koprowski+18)

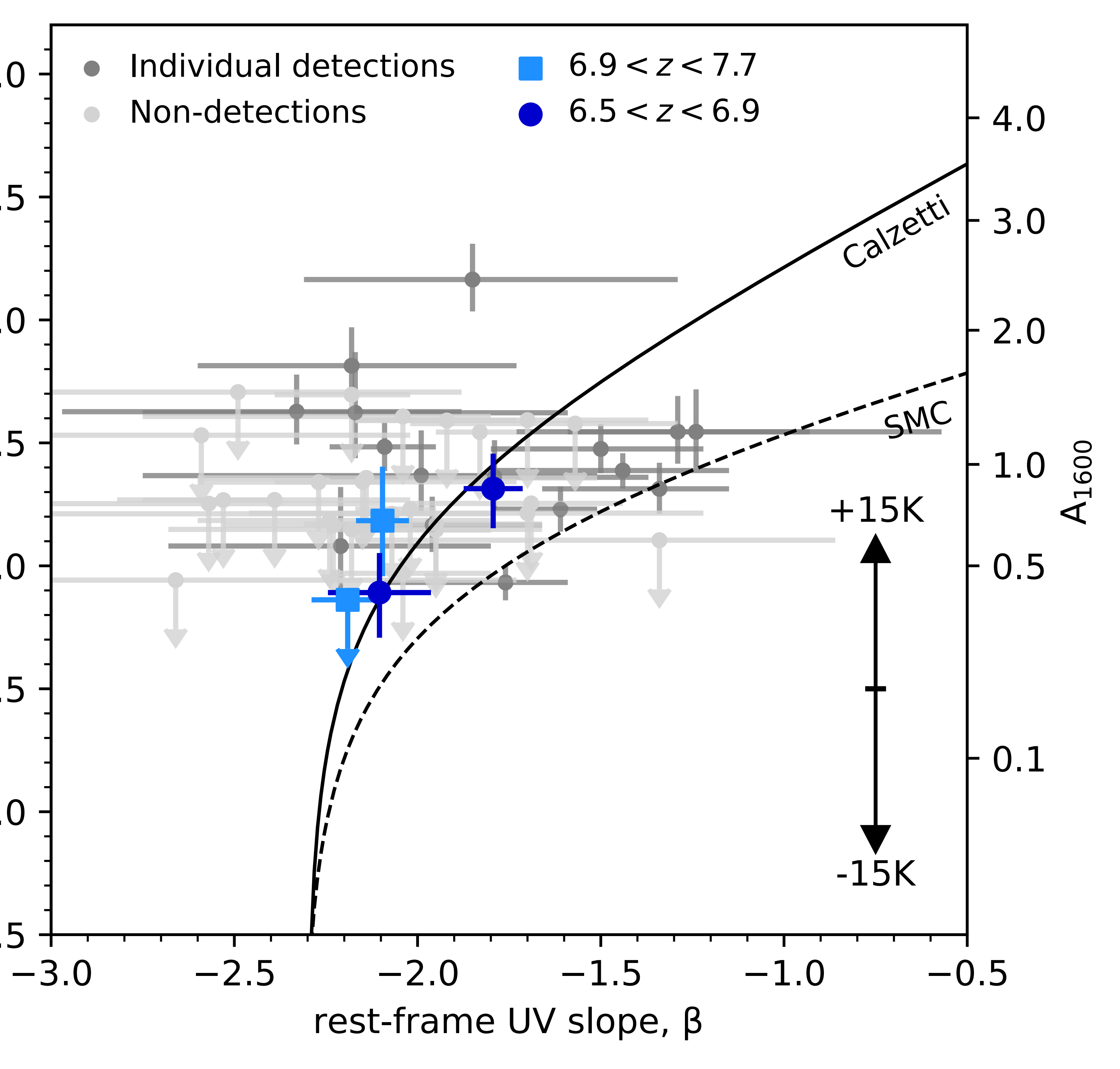
Z = 4-5 -> SMC?

(e.g. Fudamoto+20, Boquien+22)

Puzzle - what is happening to IRX-β from z = 2-8?







Z = 2-3 -> Calzetti

(e.g. McLure+18, Koprowski+18)

Z = 4-5 -> SMC?

(e.g. Fudamoto+20, Boquien+22)

Z = 7 -> Calzetti

(e.g. RB+22, 23, Schouws+22)

ALMA as a redshift (and dust) machine

Redshift range = 4.4-5.9
118 spectroscopically confirmed massive galaxies in COSMOS/GOODS-S with FWHM ~ 0.9-1.6″
(PI: Le Fevre)

20% dust detected at > 3.5 sigma [Fudamoto+21]

Redshift range = 6.5-9.5
49 (including Pilots) UV-bright Lyman-break galaxies in COSMOS/XMM/HST with FWHM ~ 1.2 x 1.5″
(PI: Bouwens)

37% dust detected at > 3.3 sigma [Inami+22]

ALMA as a redshift (and dust) machine

Redshift range = 4.4-5.9
118 spectroscopically confirmed massive galaxies in COSMOS/GOODS-S with FWHM ~ 0.9-1.6″
(PI: Le Fevre)

Redshift range = 6.5-9.5
49 (including Pilots) UV-bright Lyman-break galaxies in COSMOS/XMM/HST with FWHM ~ 1.2 x 1.5″
(PI: Bouwens)

ALPINE re-analysis

Both analysed with same FIR SED assumptions (Td = 46K)

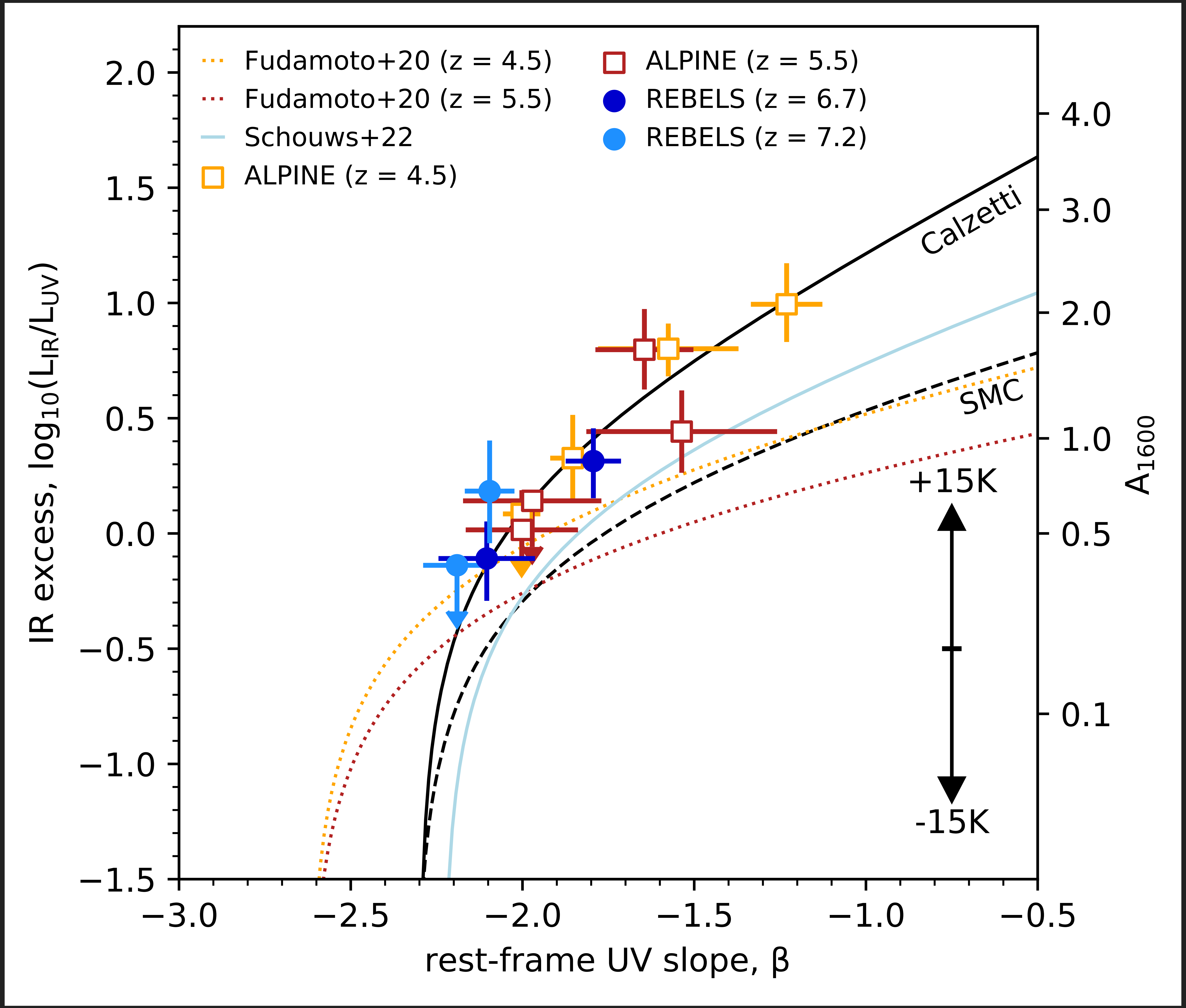
ALPINE photometry updated to COSMOS2020

Stacked in bins of UV magnitude *and* stellar mass

IRX-β relation from REBELS + ALPINE

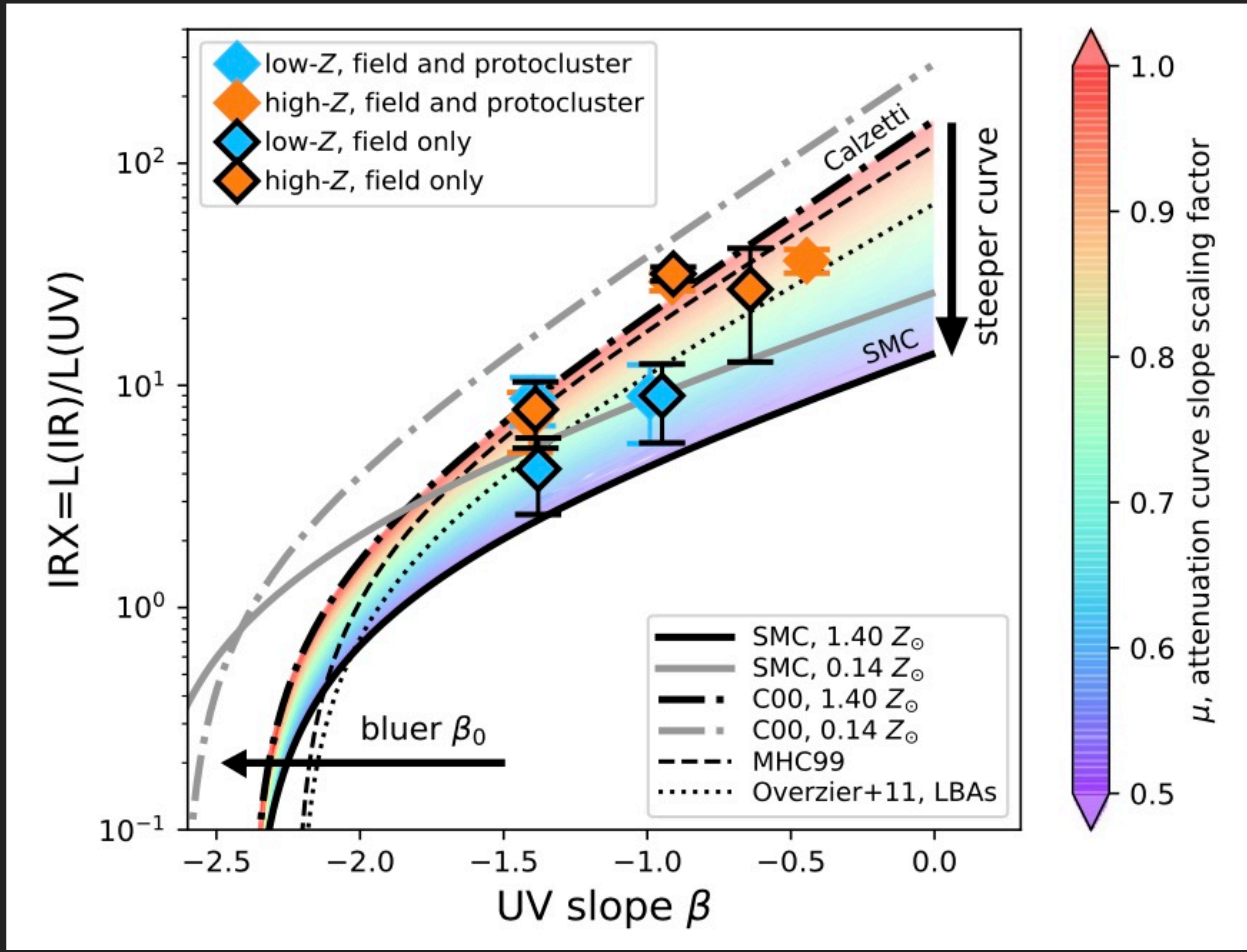
- Differences between analysis:
  - FIR flux determination
  - FIR SED assumption
  - Stacking bins
  - Photometry
  - Beta measurement

See also Boquien+22, Burgarella+22 for different analysis of ALPINE.

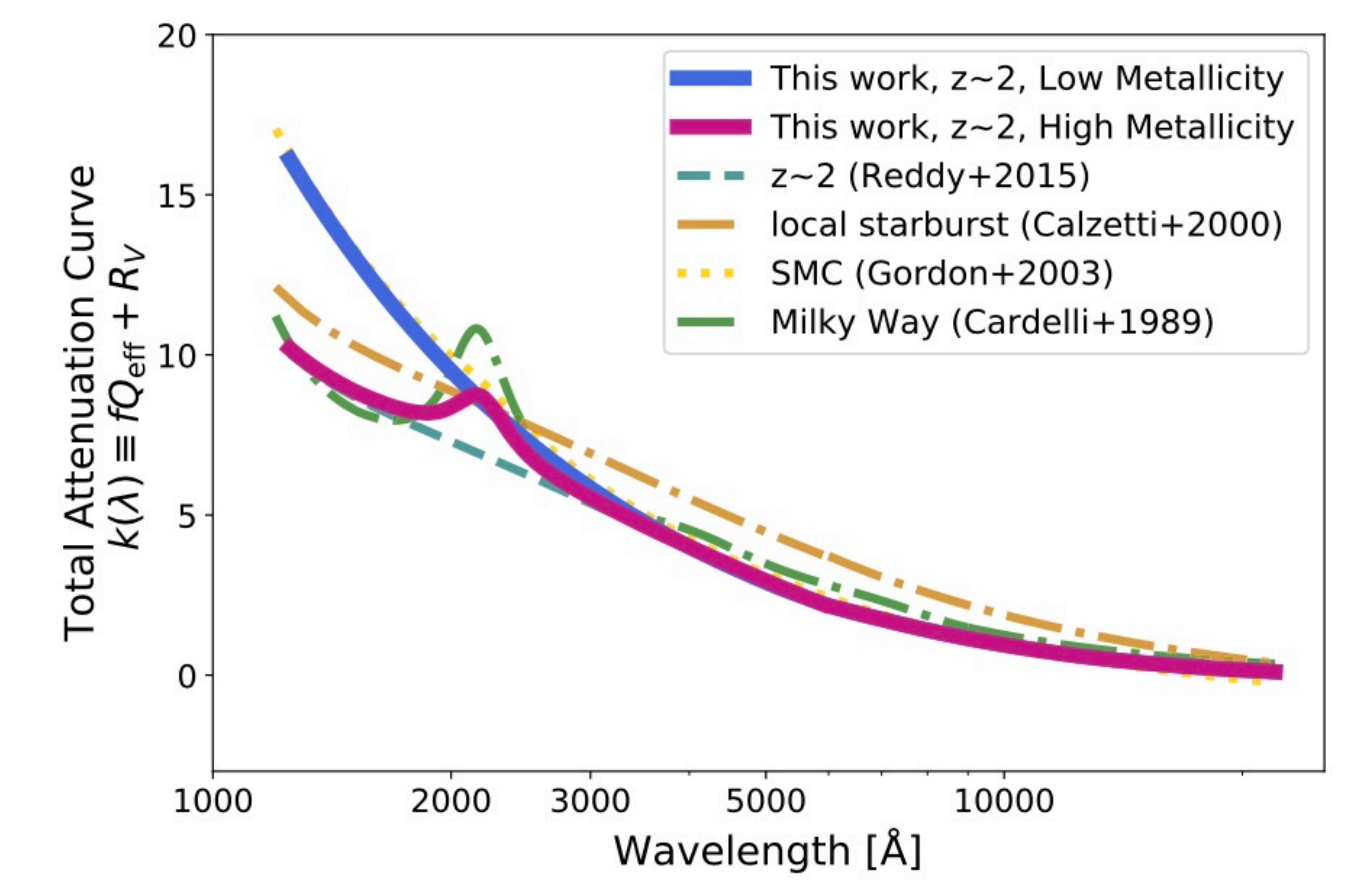


RB+23 in prep.

The importance of stellar mass and Z for dust attenuation



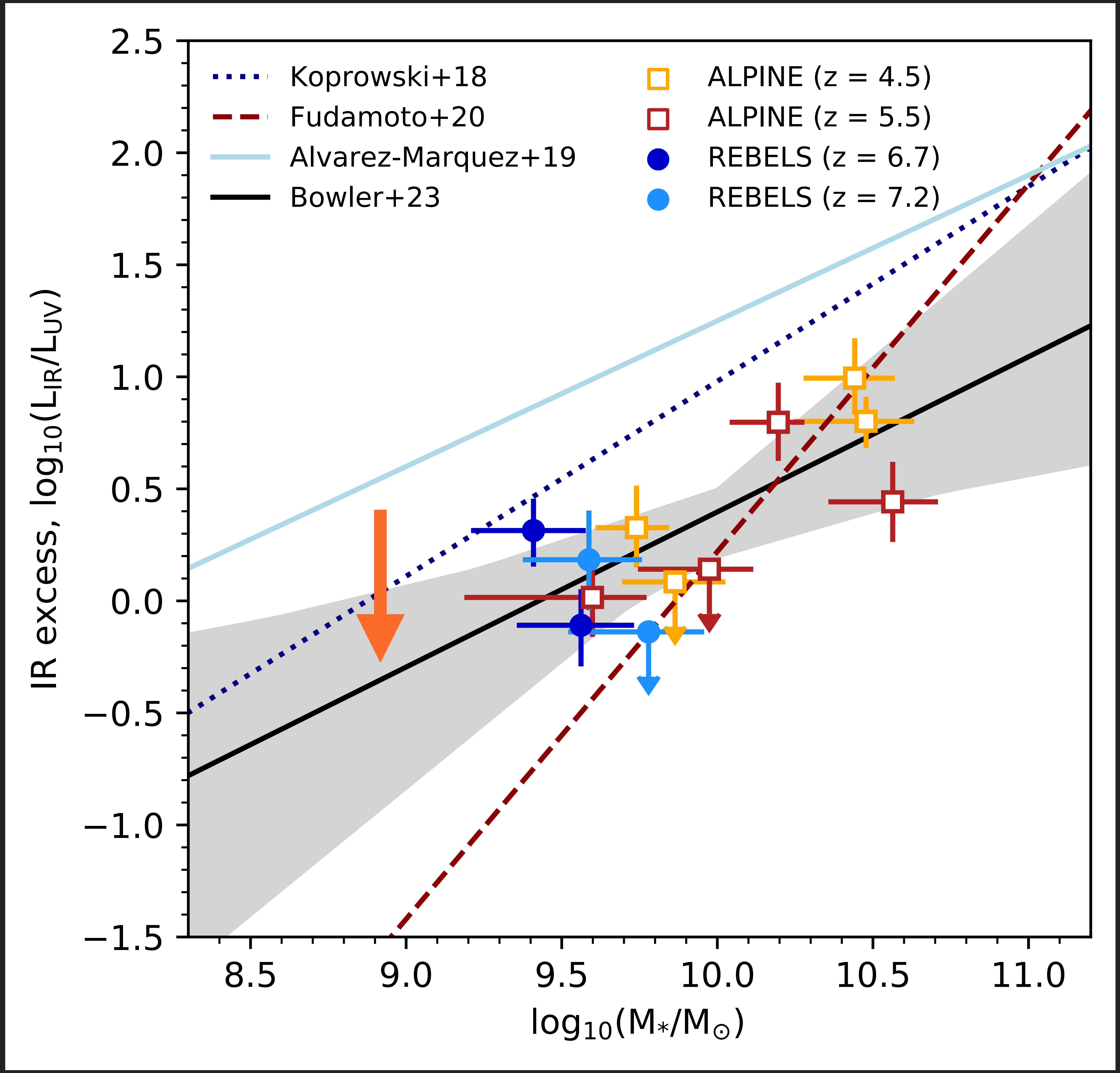
- At z = 2-3 Shivaei+20 show that the position on IRX-beta depends strongly on measured gas-phase metallicity



- Consistent with the REBELS and ALPINE sources having a shallower attenuation law than lower mass (hence lower Z) systems (e.g. ASPECS: Bouwens+20)
- Also see Camila's talk - different law for each galaxy! Also different dust T?

IRX-M* relation from REBELS

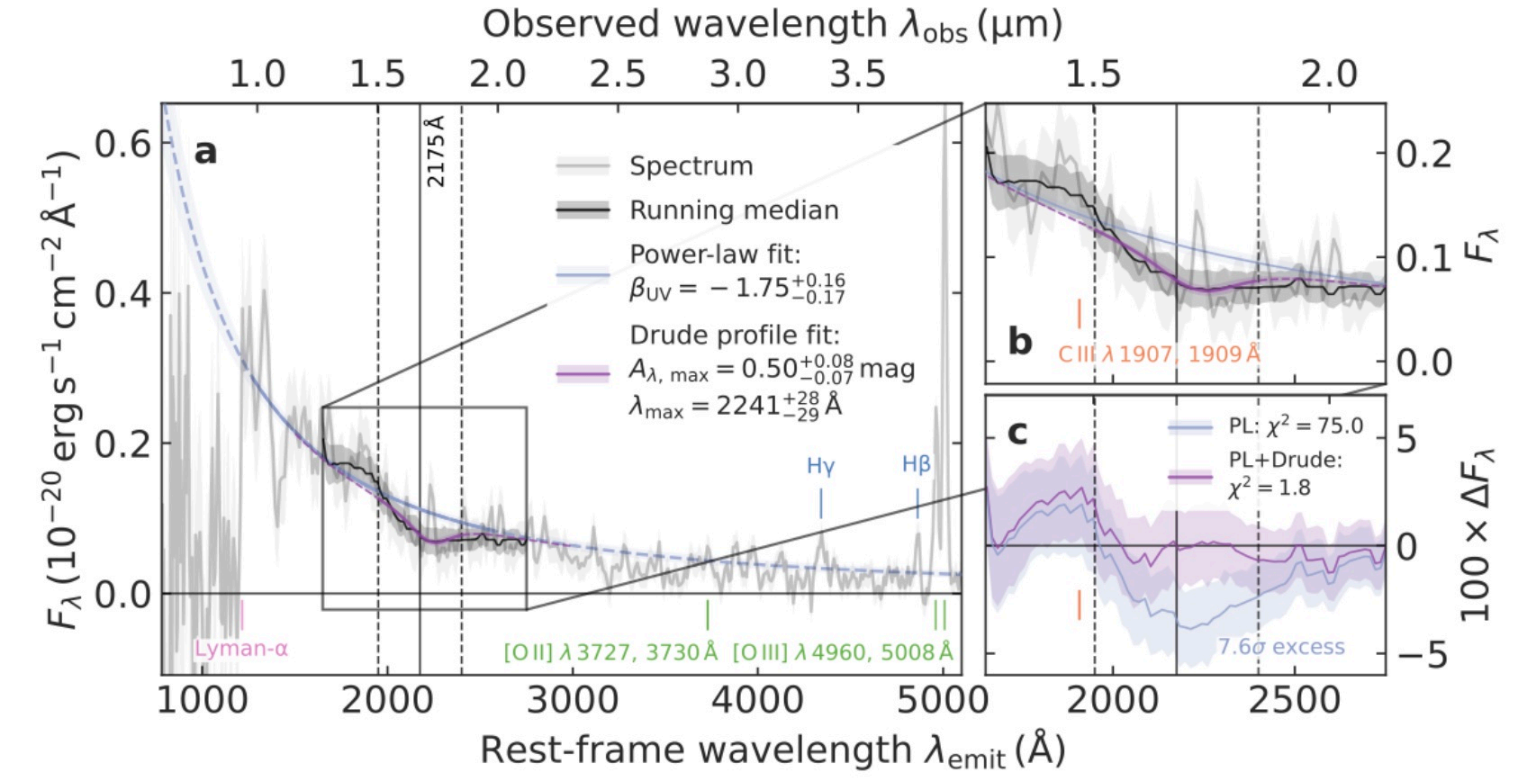
- Comparing to z = 2-3 results measured in a similar way, we see a deficit at z > 4.
- For a given stellar mass, less obscured SFR (consistent with other works e.g. Algera+22, Schouws+21).
- Slope of the relation is consistent (other works have found steepening e.g. Fudamoto+20).



RB+23 in prep.

Do we need to rethink dust in z = 7 galaxies?

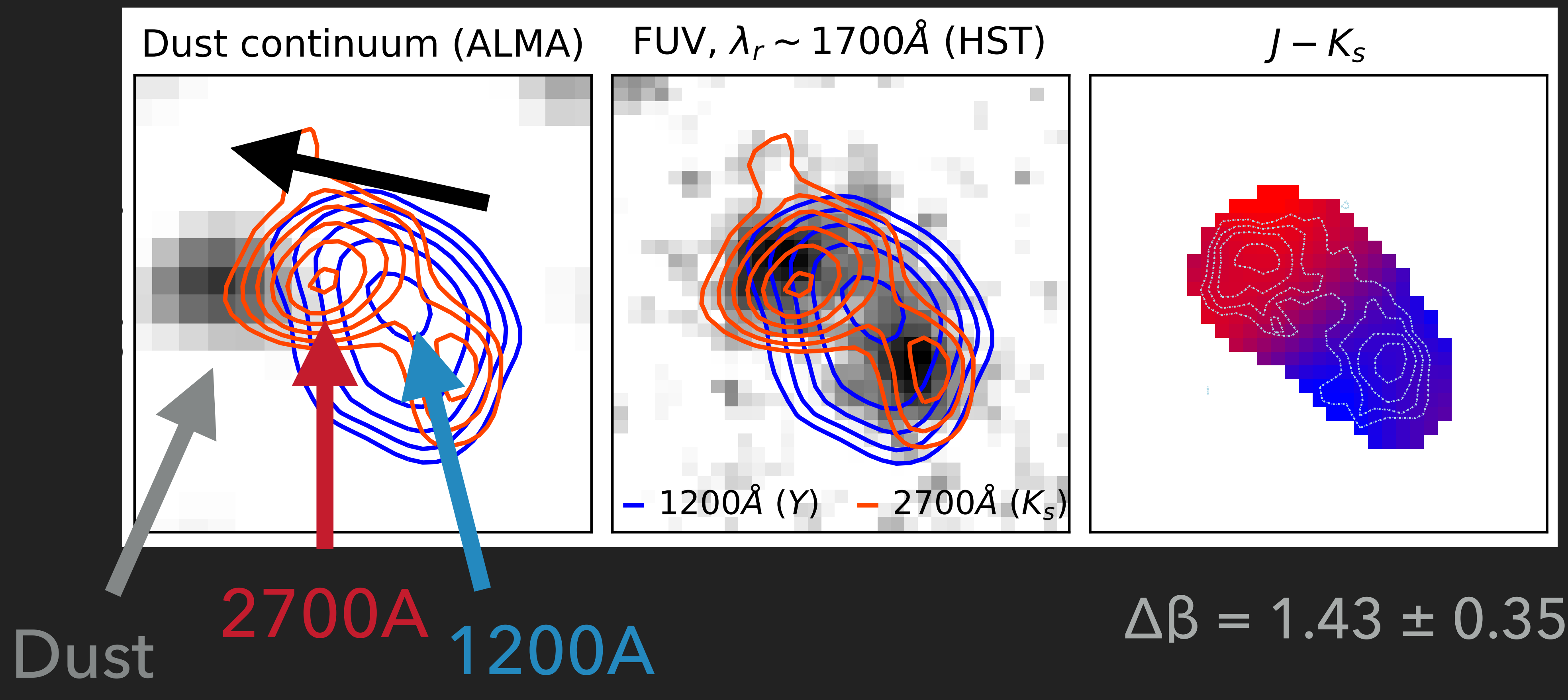
- Detection of 2174A dust bump associated with carbonaceous dust at z = 6.7 (Witstok+23) usually associated with evolved stars (100s of Myrs to form).



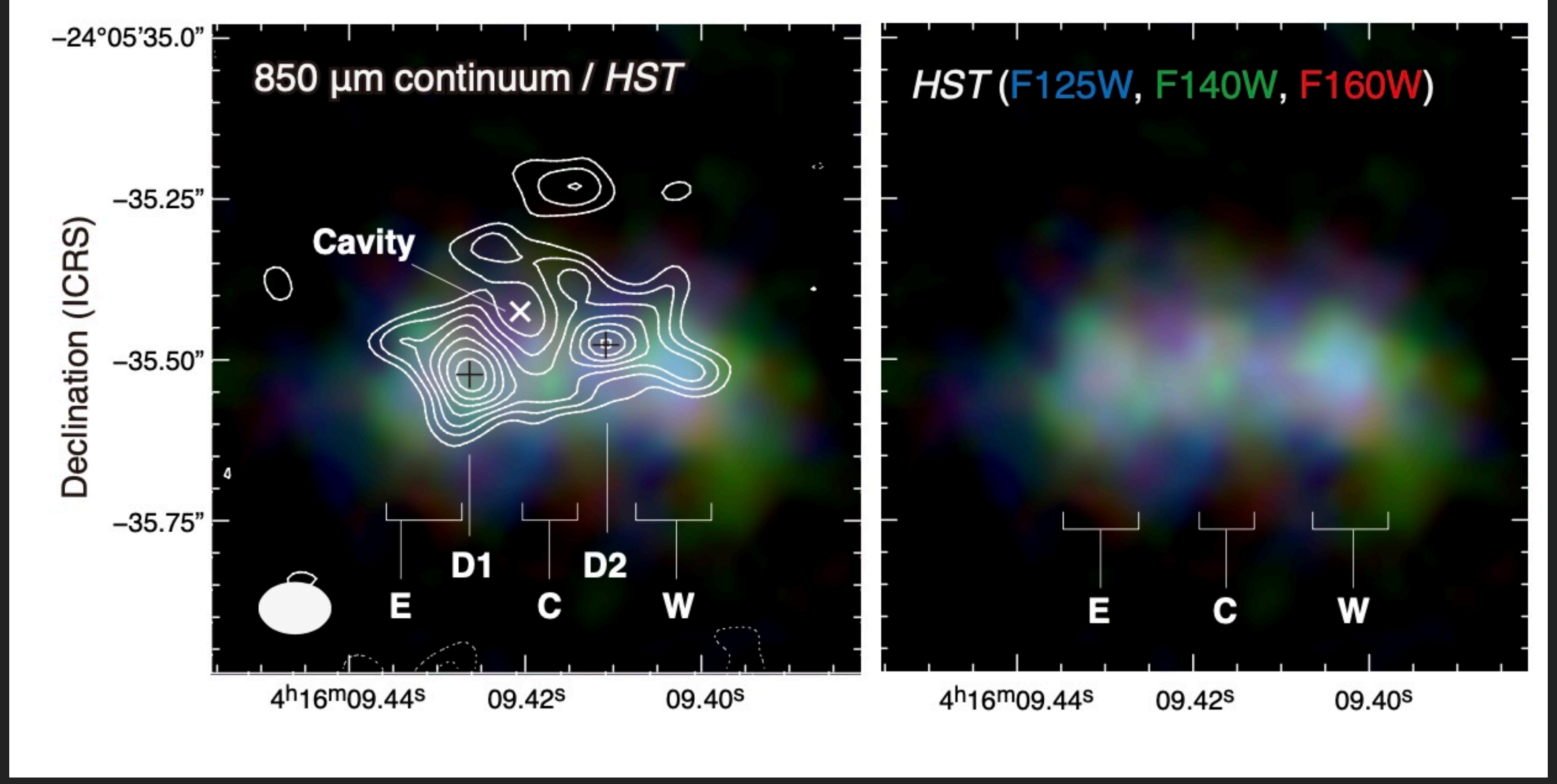
First results on the star-dust morphology

- At higher resolution, complex geometry. Rest-frame UV anti-correlated with location of rest-FIR, colour gradients (RB+22, Sugahara+23).
- Peak of the star-formation can be invisible in the rest-frame UV, dust obscured SF is important even at z = 7.

Z001 at z = 7.06 (RB+22)

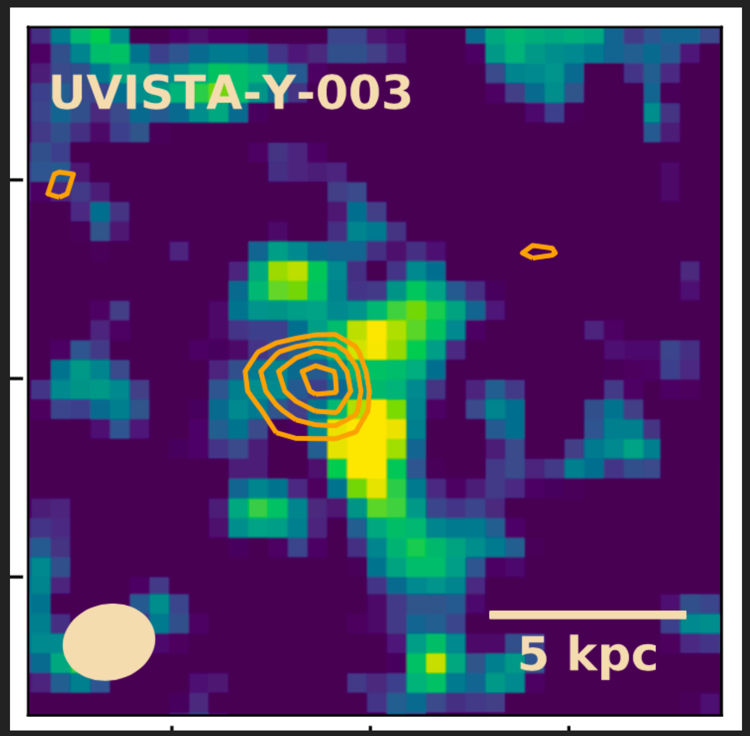


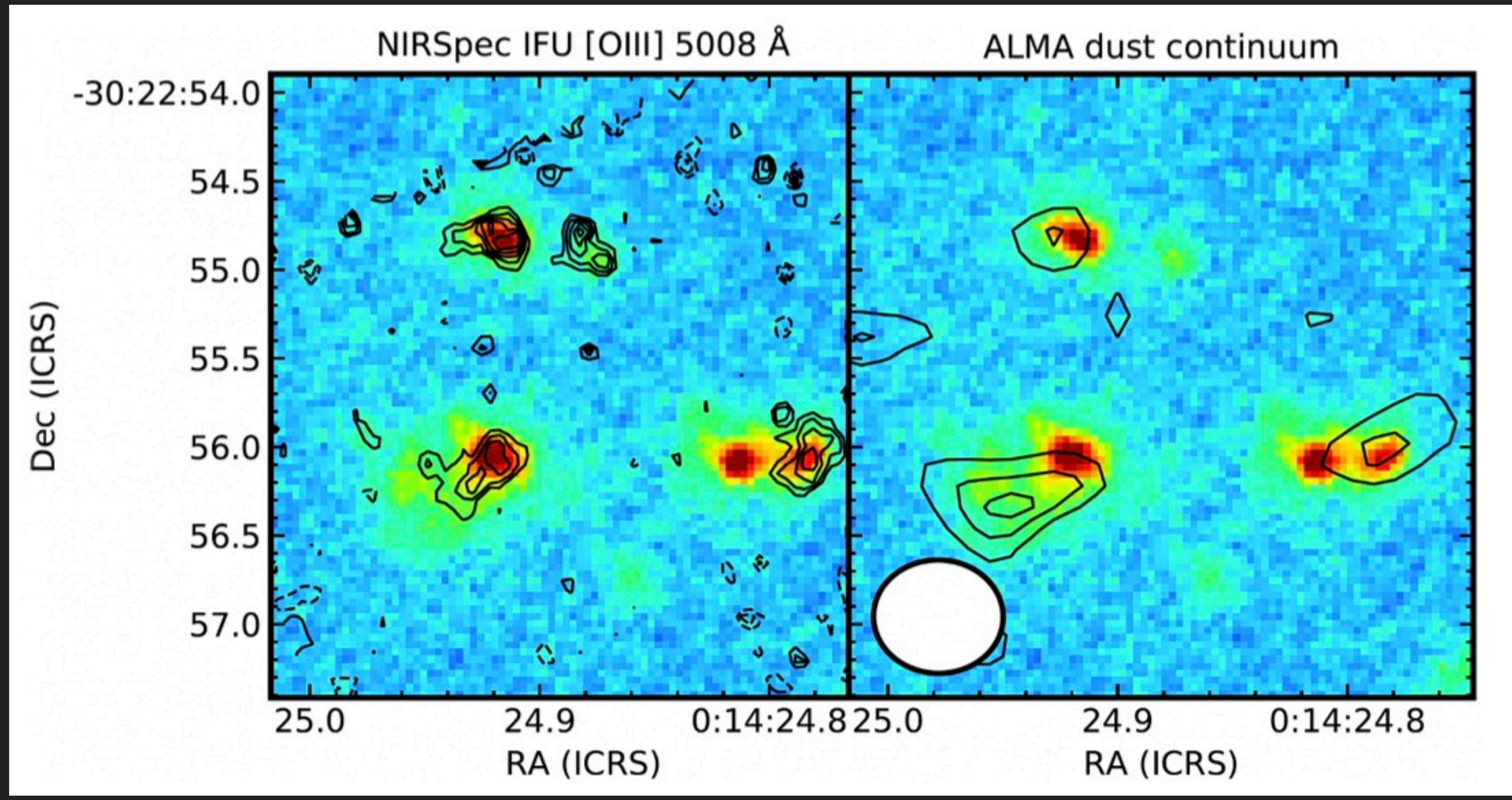
$\Delta\beta = 1.43 \pm 0.35$



MACS0416_Y1: z = 8.31 (Tamura+23)

REBELS-25 (ULIRG) Z = 7.30, Schouws+21, Hygate+22

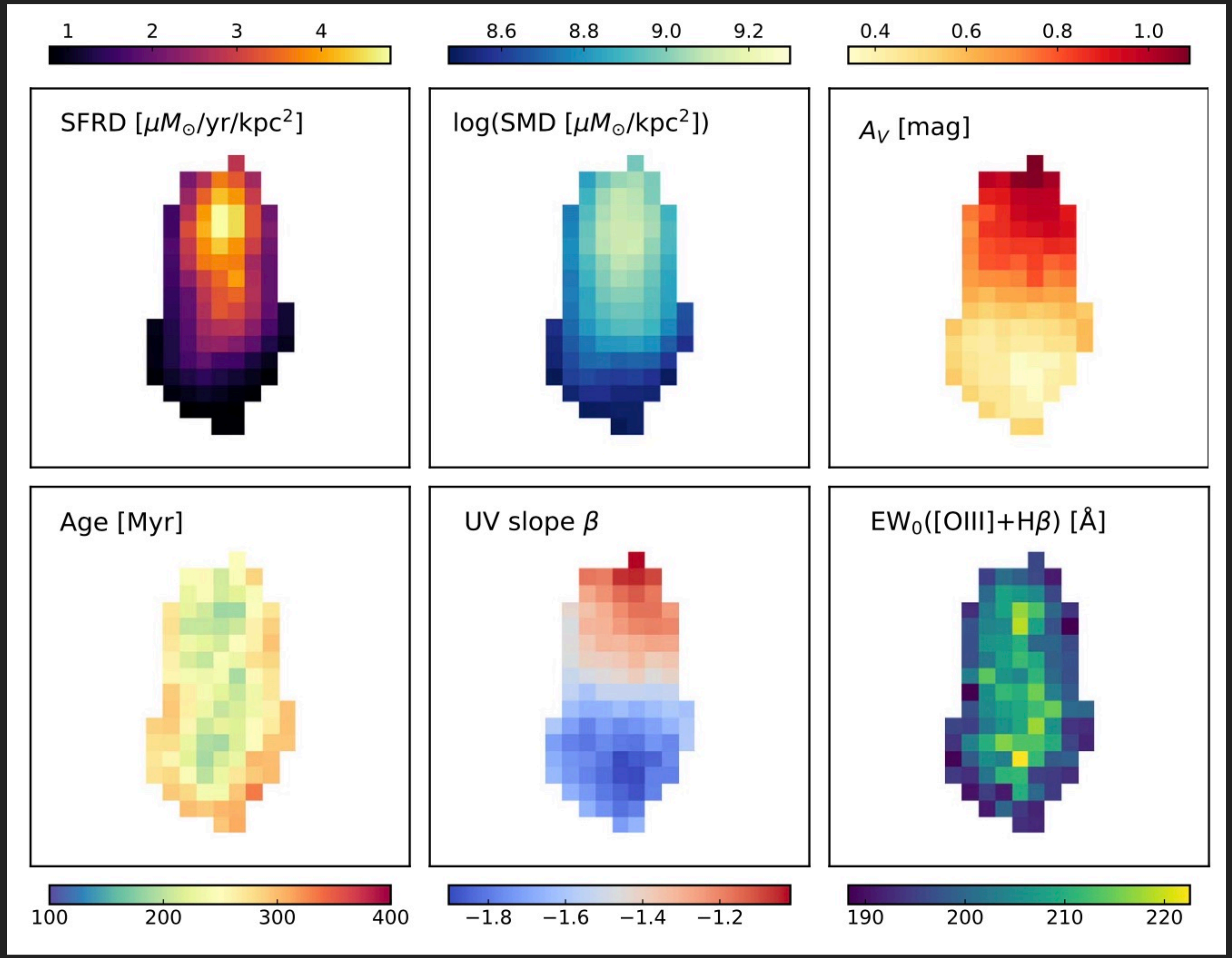




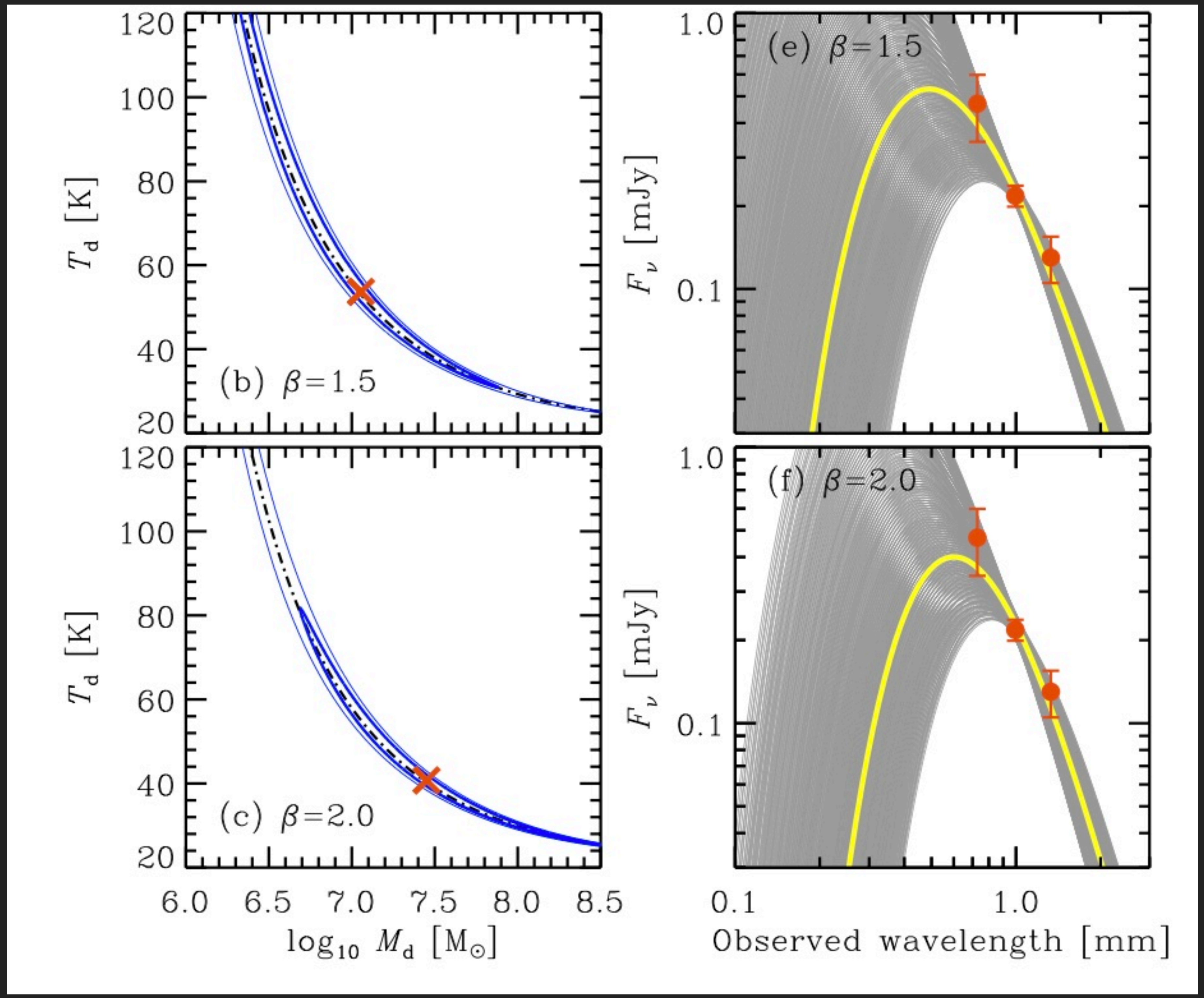
RIOJA over density at z = 7.88 (Hashimoto+23)

Summary and outlook

Dust in massive (log(M/M$_\odot$) ~ 9.5) galaxies at z = 4-8 follow a Calzetti dust attenuation law, similar to local starburst galaxies



- Early resolved measurements from photometry from JWST (Giménez-Arteaga+23).



- Multi-band observations to constrain the FIR SED (e.g. Sugahara+23, Witstok+22)