Problems of Dust and Galaxy Evolution

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Major dust-related Issues

- Disappearing bright LBGs — quenched or dusty?
- Biases of SED-fit or UV-slope SFR & E(B-V) estimates
- Difficulties of "total IR" estimates
- Dust temperature evolution and its cause
- SMGs:
  - very high SFRs…real? Top-heavy IMF? inappropriate correction for dust?
  - dust crisis in SMGs
- Dust production at very early times

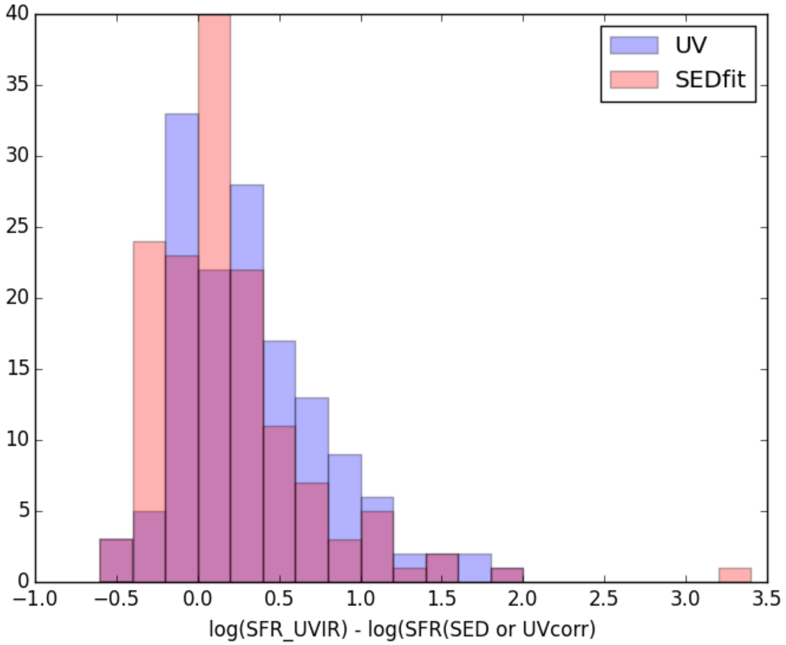
Sub-topics for today…

- SFR estimates from SED fitting vs. UV+IR ladder
- Effect of dust on high-z samples
- Importance of dust mass evolution
- Behavior UV slope

SFR estimates compared

- GOOD-S
  - PhotFlag = 0, AGN_Flag = 0
  - Herschel CLEAN_INDEX <= 1
  - 24-micron S/N > 10
  - IR SFR estimate >0.01 (Wuyts+11 formula)
    - Monochromatically from longest λ based on Wuyts+08 template
  - CANDELS-Team Median SFR estimates from SED fitting
  - 141 galaxies z<3

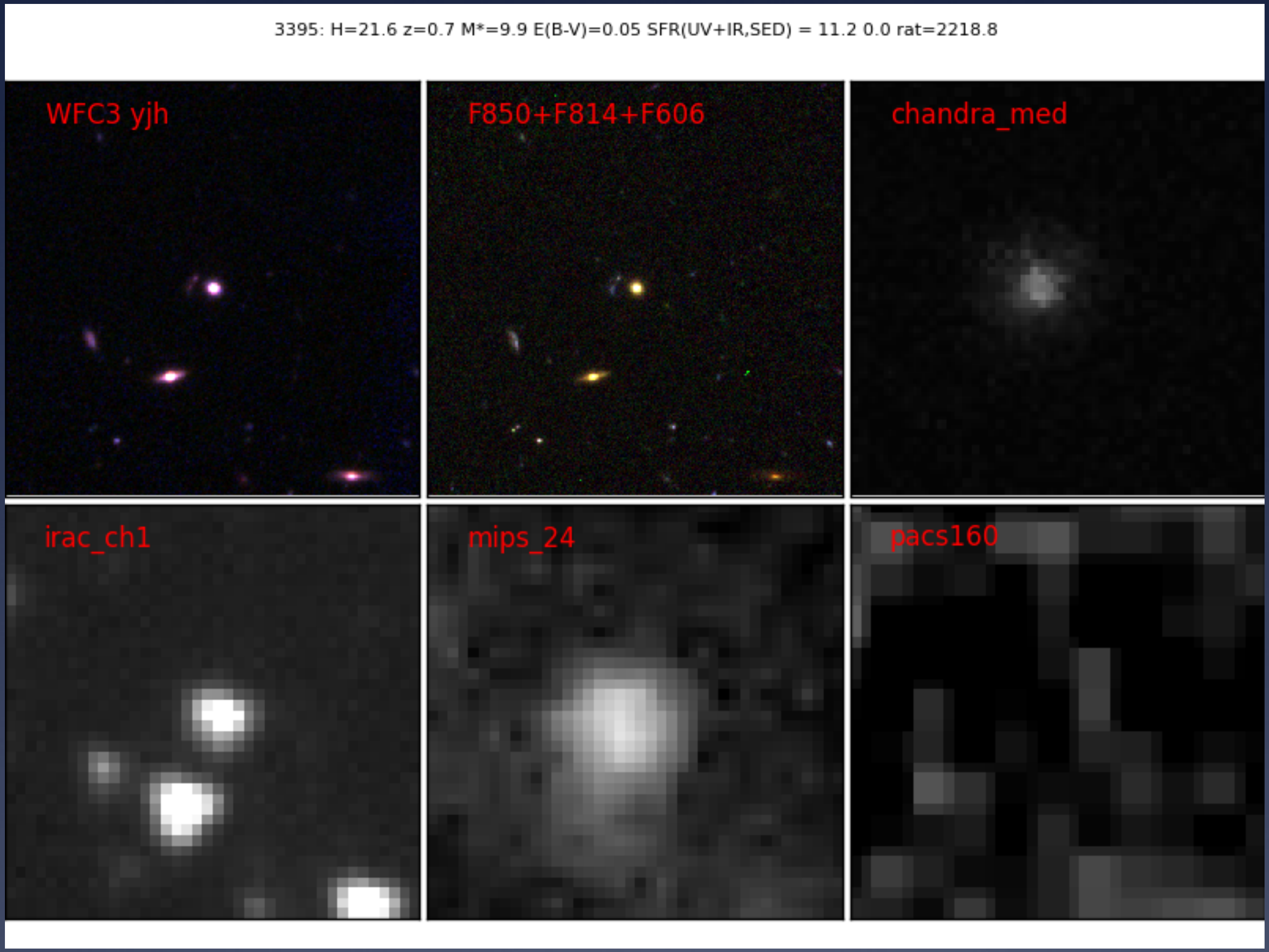
SFR Estimates compared



Offset in log(SFR):

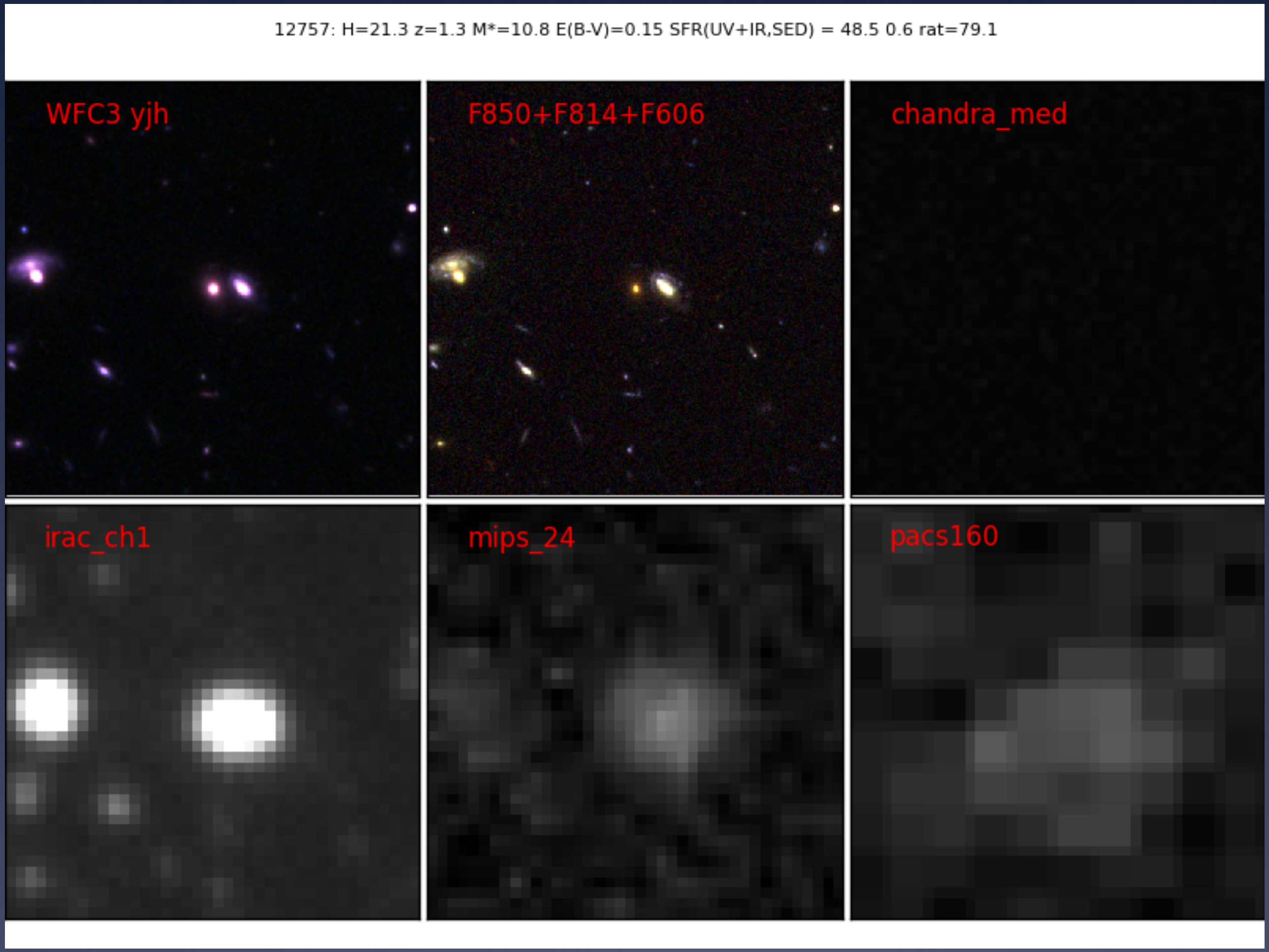
Sample	N	Median UVIR-SED	Median UVIR-UVCorr	σ UVIR-SED	σ UVIR-UVCorr
z<3	141	0.12	0.26	0.5	0.45
z<1	66	-0.12	-0.02	0.52	0.37

Outliers



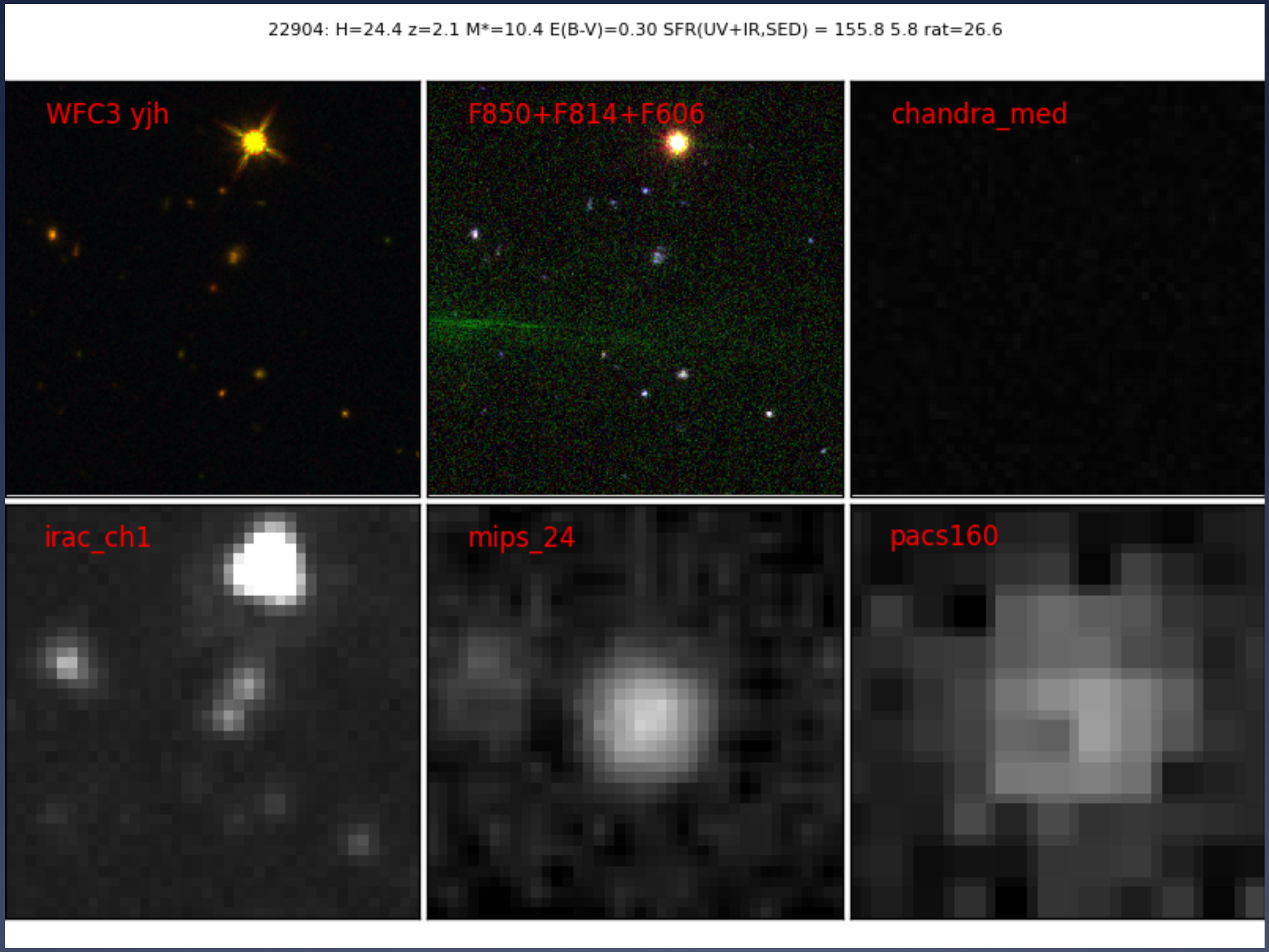
Blend with AGN?

Outliers



Blend with AGN? Blend?

Outliers

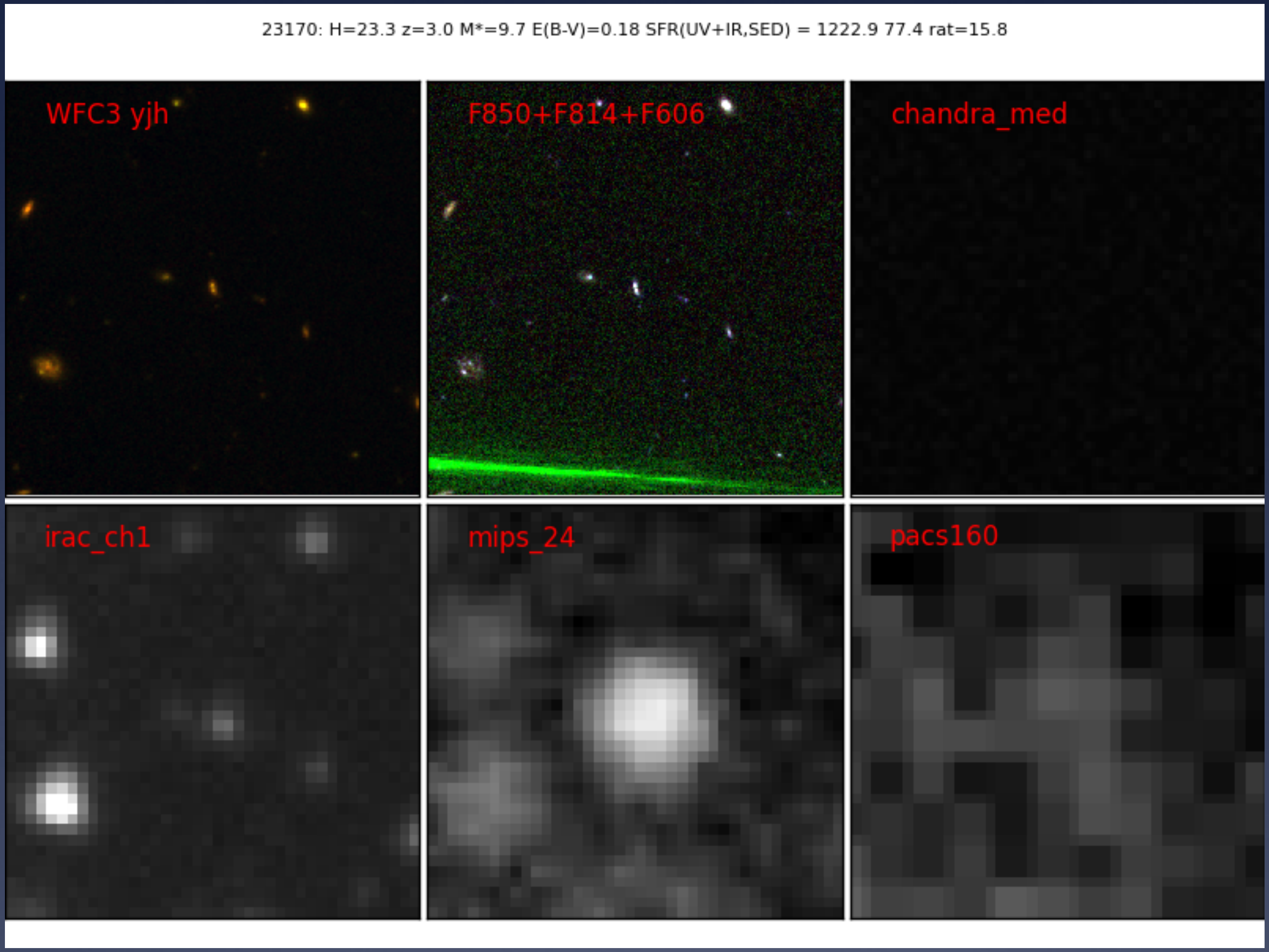


Blend with AGN? Blend? Blend?

Outliers

Blend?

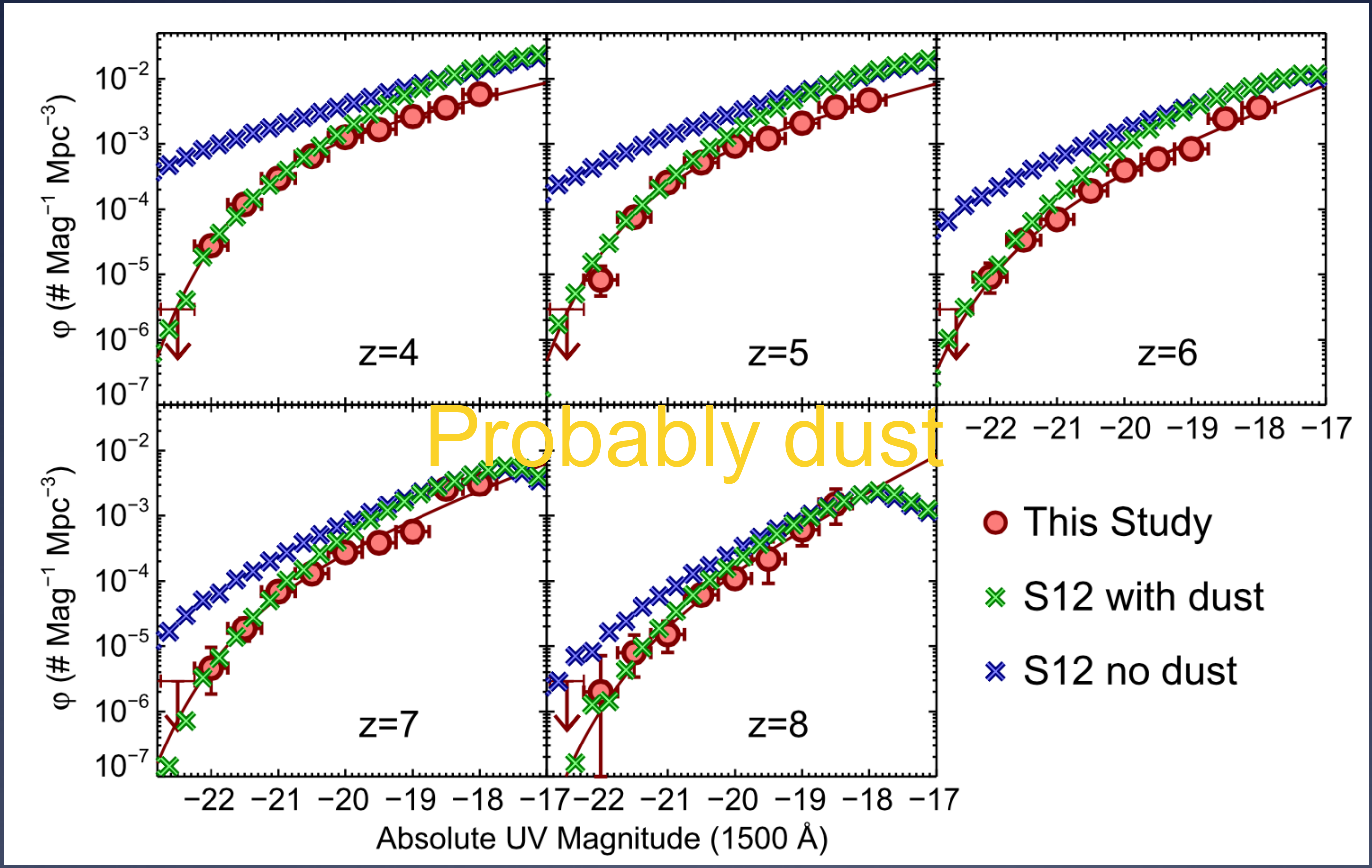
Outliers



Blend?

Enhanced PAH?

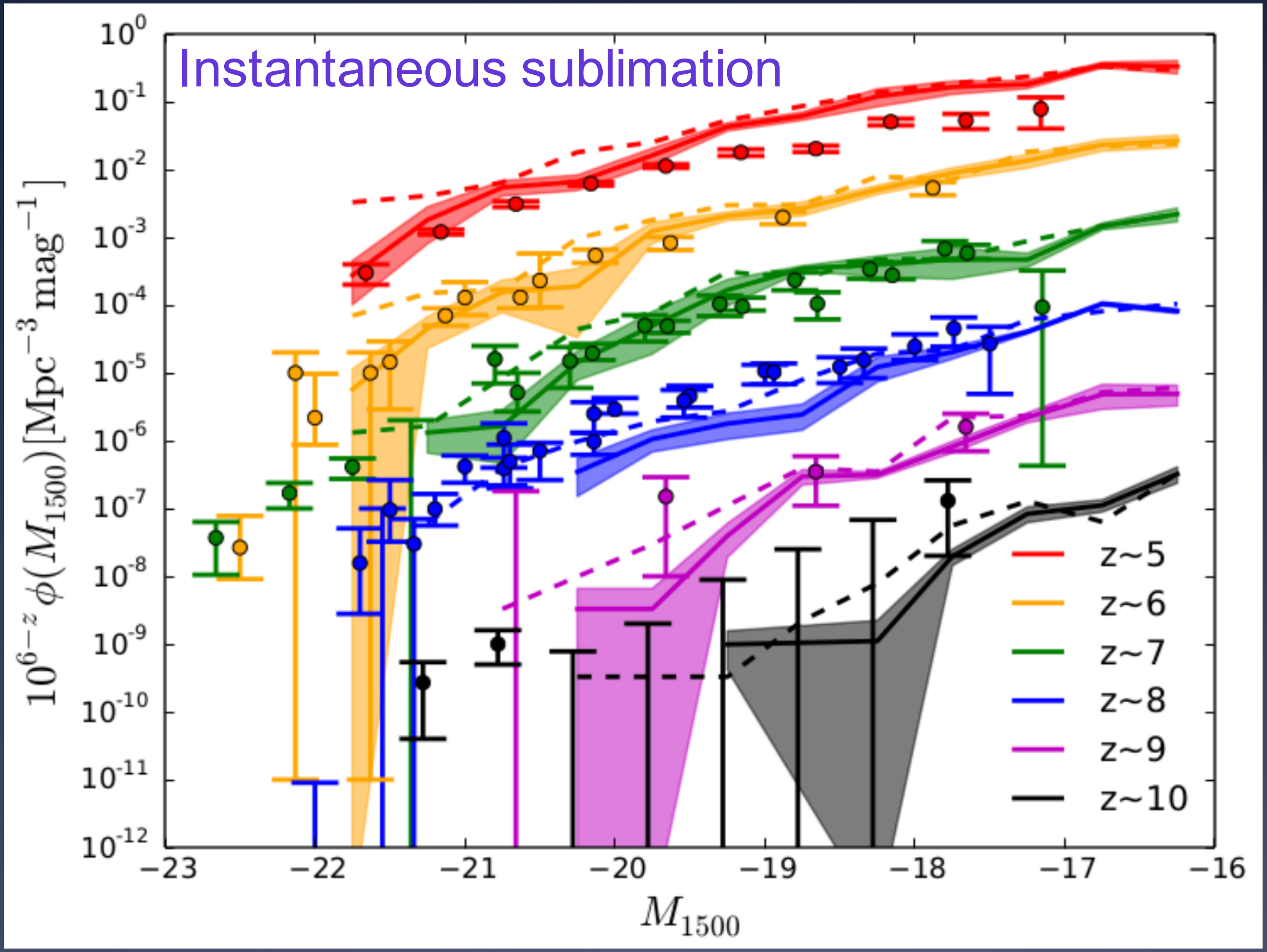
What shapes the bright end of the UV Luminosity function?



Finkelstein+15

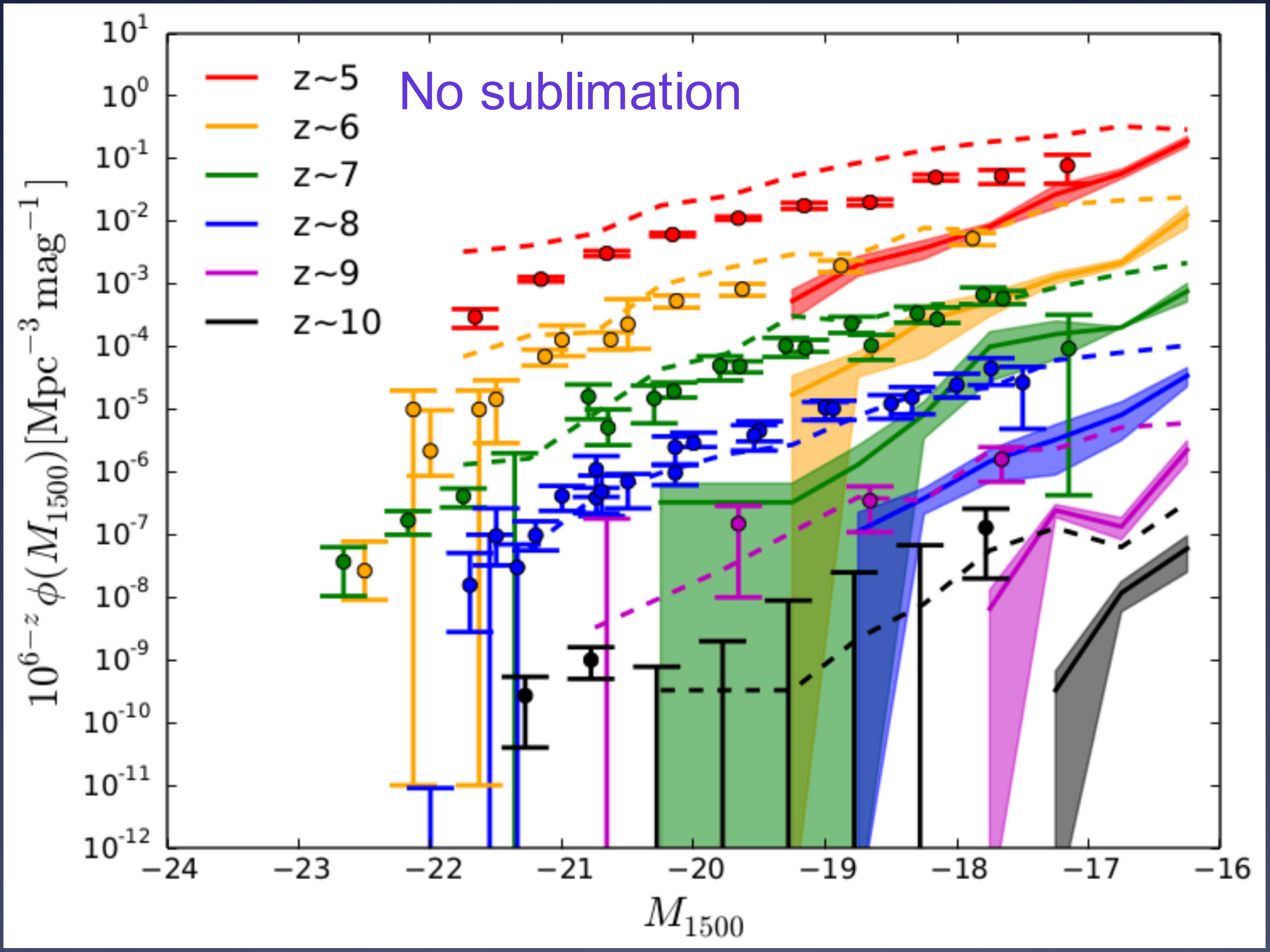
Somerville+12 models with and without dust attenuation.

UVLF & Dust: second opinion



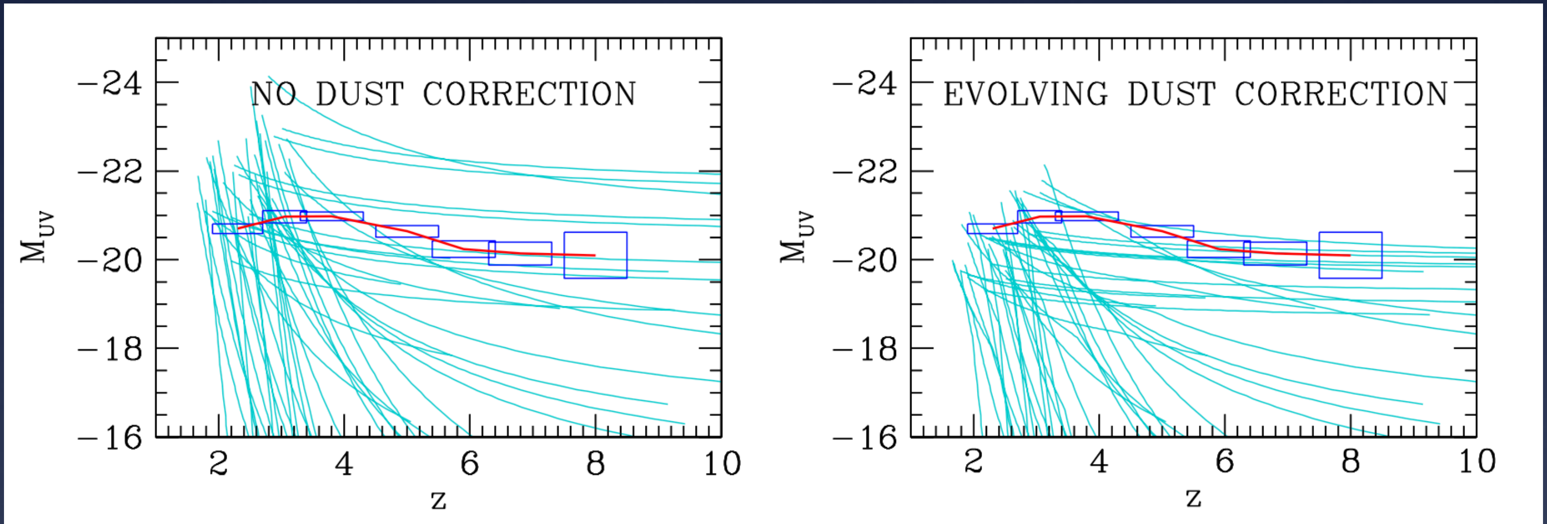
Khakhaleva-Li & Gnedin 16

UVLF & Dust: second opinion



Khakhaleva-Li & Gnedin 16

Bright LBGs at z~3 were not bright at z~4

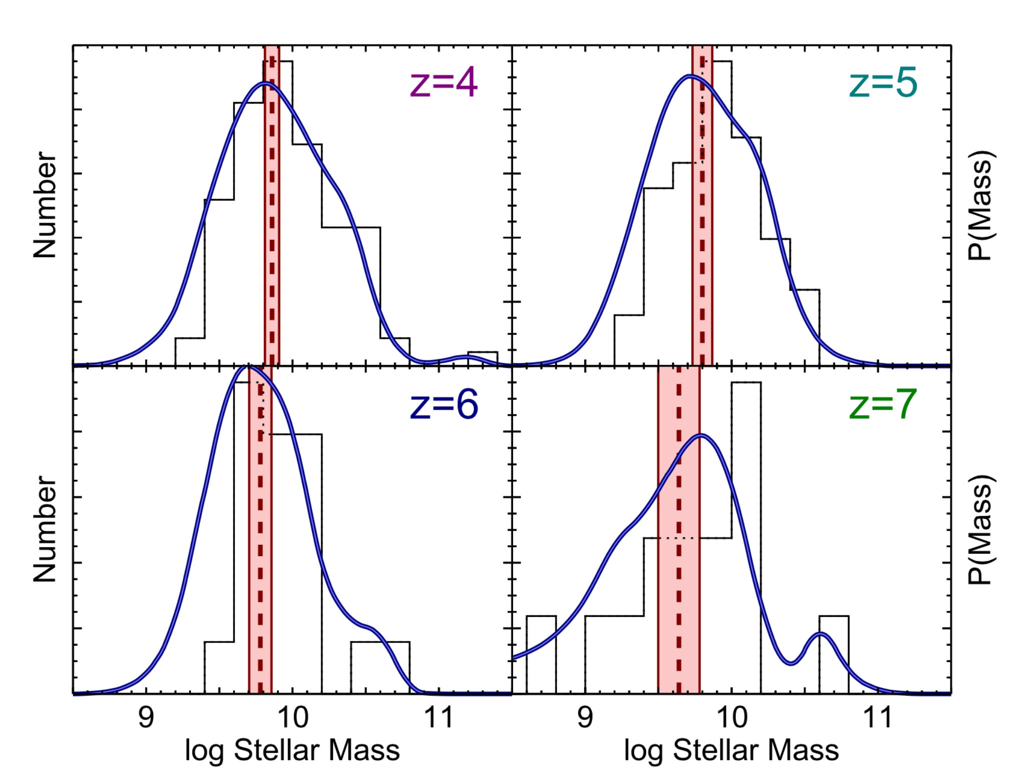


Ferguson+02, Reddy+12

- For any plausible star-forming history, L* Lyman-break galaxies at z~3 were *much fainter* at higher z.
- Where are the descendants of the L* galaxies at z>4 at z=3?
- Likely to be in the fainter part of the UV LF, or even missing from UV-selected samples (possibly included in other samples, though)

Table 1
Median Physical Properties of Galaxies with $M_{1500} < -21$

Redshift	Number	$\log(M_*/M_\odot)$	Age (Myr)	$E(B-V)$	SFR ($M_\odot$ yr^{-1})
$z = 4$	94	9.86 ± 0.04	44 ± 2	0.13 ± 0.01	56 ± 4
$z = 5$	46	9.80 ± 0.06	35 ± 2	0.12 ± 0.02	52 ± 10
$z = 6$	19	9.78 ± 0.07	40 ± 4	0.07 ± 0.02	40 ± 8
$z = 7$	14	9.64 ± 0.13	29 ± 8	0.09 ± 0.02	41 ± 9



At L=L*:

- Stellar masses,
- SFRs
- Ages

Don’t evolve much
From z=7 to z=4

Finkelstein+15

Abundance-matched by SFR

Abudance-match log(SFR)>1.5 at z_0 to same number density at z_1. Take SFR*dt*(1-$M_{lost/}M_{formed}$) + M_0 to predict M_1. Masses exceed observed masses at z_1.

z0	z1	M0	M1	SFR0	dt	Mass Ratio predicted/ observed
6	5	9.92	10.1	77	0.24	1.4
5	4	10.0	10.1	72	0.37	2.2
4	3	9.94	10.1	56	0.61	2.5

Problem does not exist if you abundance match in mass instead of SFR in CANDELS phot-z samples.
Simplest explanation:

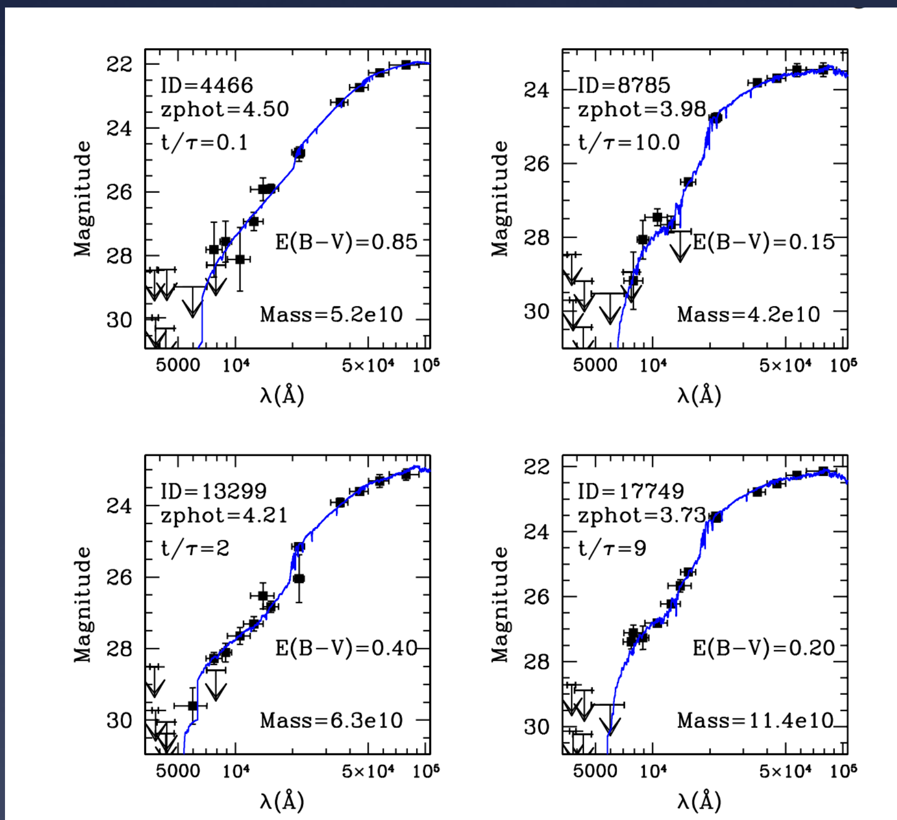
- high-SFR galaxies are quenching

Abundance-matched by SFR

Abudance-match log(SFR)>1.5 at z_0 to same number density at z_1. Take SFR*dt*(1-M_{lost}) + M_0 to predict M_1. Masses exceed observed masses at z_1.

z0	z1	M0	M1	SFR0	dt	Mass Ratio predicted/ observed
6	5	9.68	10.2	41	0.24	0.9
5	4	9.90	10.4	46	0.37	0.8
4	3	10.1	10.5	47	0.61	1.0

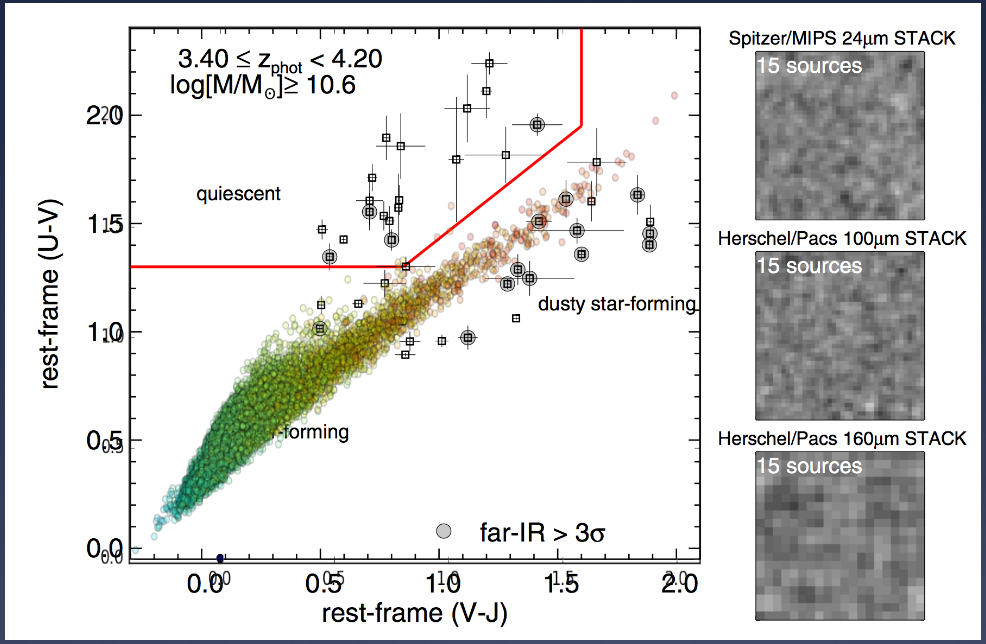
Somerville+12 simulation does not have this issue; massive galaxies not disappearing from SFR-selected samples at z>3 (perhaps because quenching in the models doesn't start until lower redshifts.)



Grazian+14
Examples of passive red galaxies at z~3-4 that would miss LBG detection.

of red galaxies at

UVJ selection



ZFOURGE: Straatman+14

Color: Somerville+11 SAM

ZFOURGE finds a substantial population of massive red galaxies at z~4, many of them passive

SED models with dust

Global dust geometry

Charlot&Fall

+Geometry

Chavallard

MAGPHYS

Semi Analytical Models

Hydro-dynamical output

Spherical shell, SF regions

SAM OUTPUT

Radiative Transfer

SUNRISE

GRASIL-3D

DIRTY

GRASIL

axially-symmetric

Fontanot+09

Dusty Radiative Transfer in realistic realistic simulated galaxies

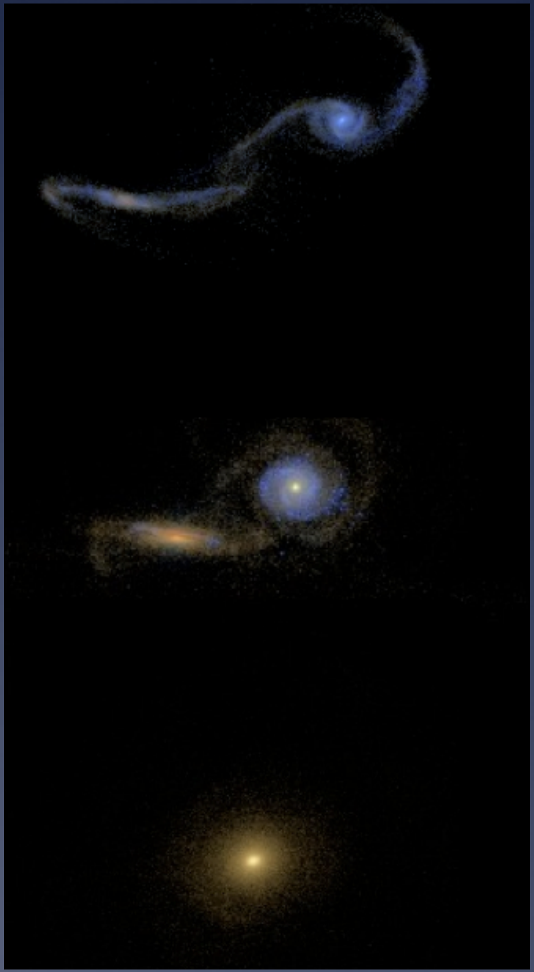
12000, 6500 SEDs at z=0,3

- Major & minor mergers & isolated disks.

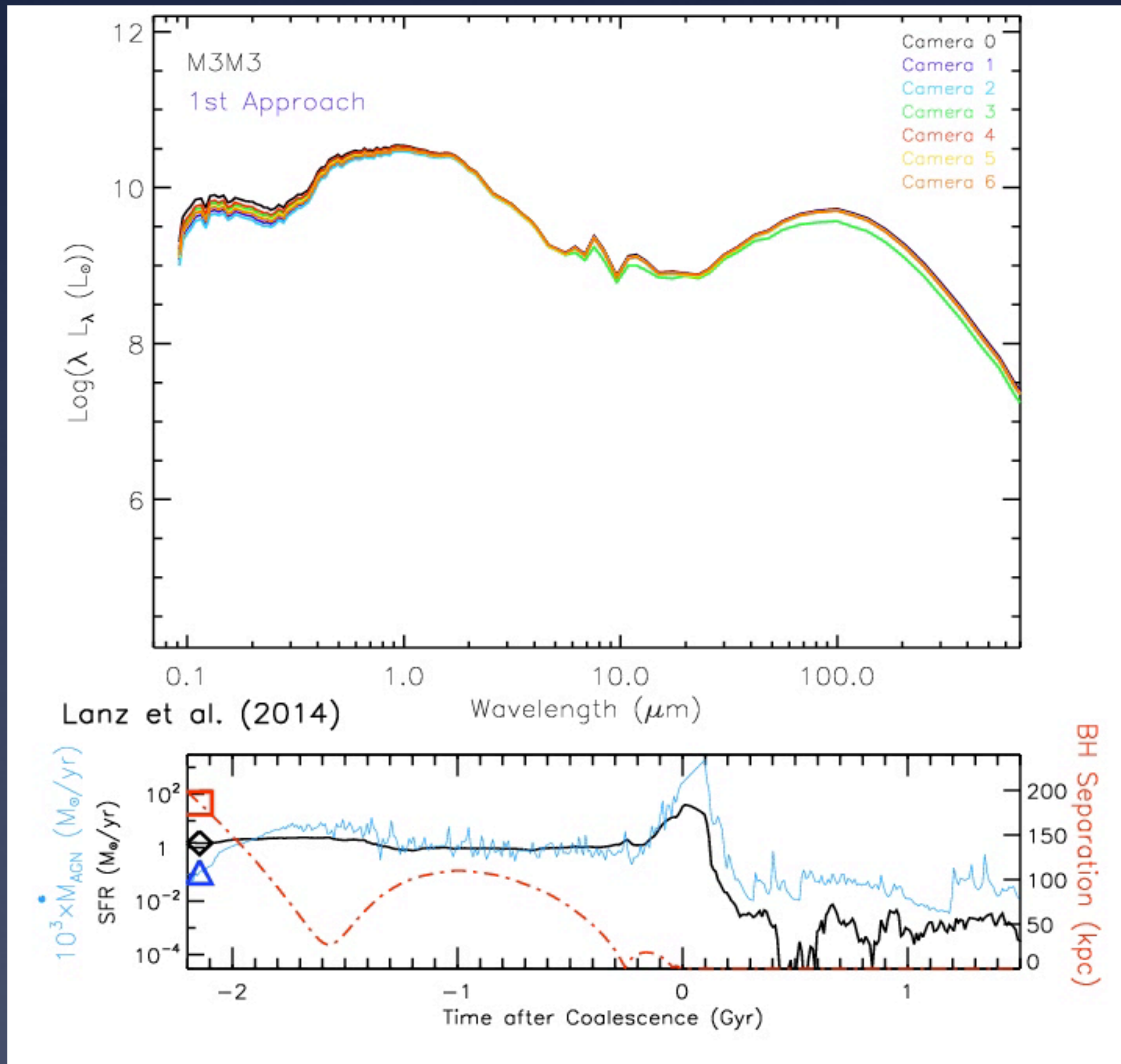
- Non-cosmological but with initial ISM & Star properties set up to match typical isolated massive disks at z=0 and z=3

- Gadget-2 N-body/SPH (Springel 05)
- Schmidt-Kennicutt SF recipe
- Two-phase ISM of Springel & Hernquist 03
- Radiative Heating & Cooling (Katz+96
- BH Growth & Feedback (Springel+05)

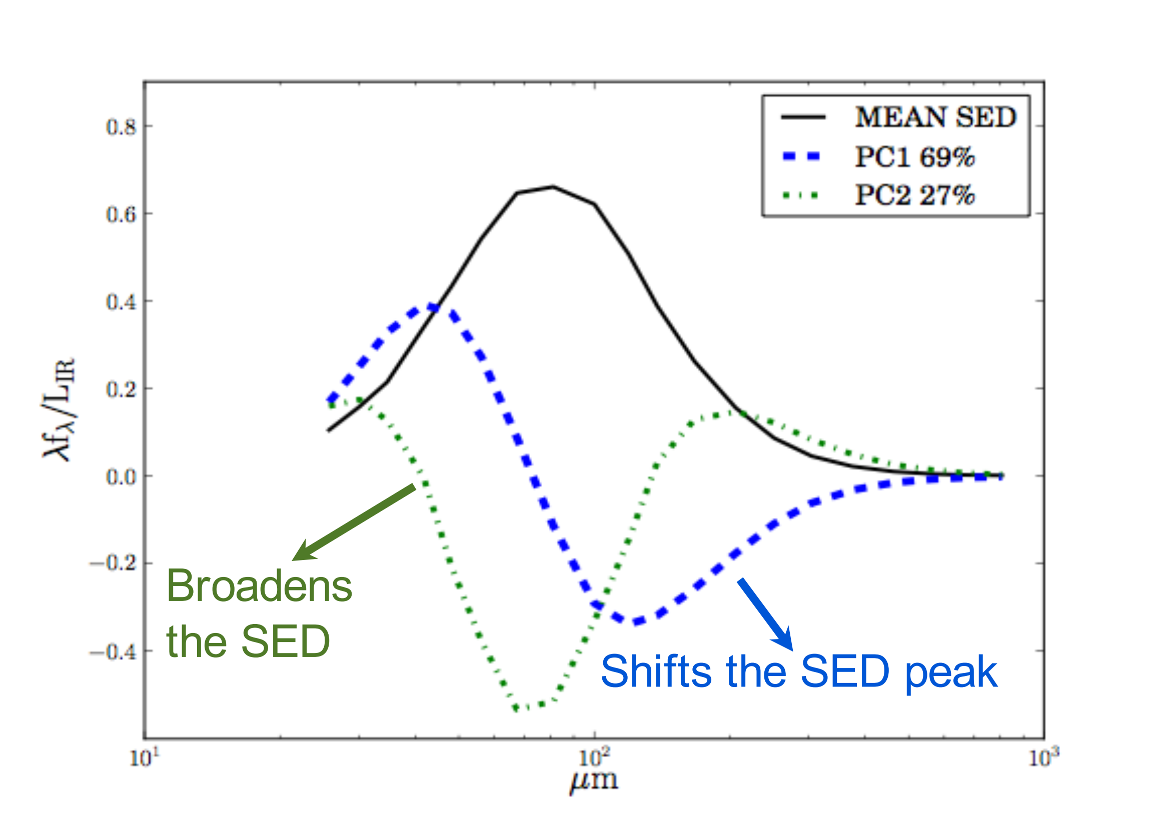
Hayward+11,12,13,14, Lanz+13
Safarzadeh+16a,b



SED evolution



Principal Component Analysis

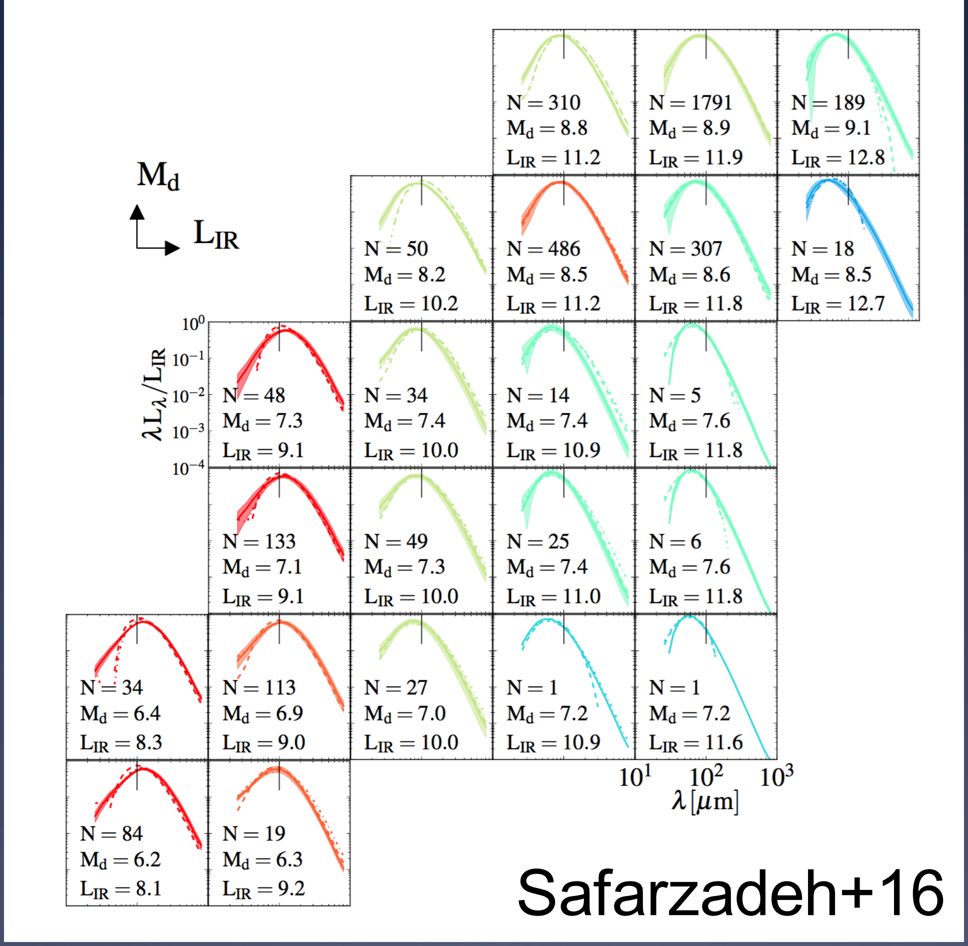


Safarzadeh+16

Two components explain 96% of the variance

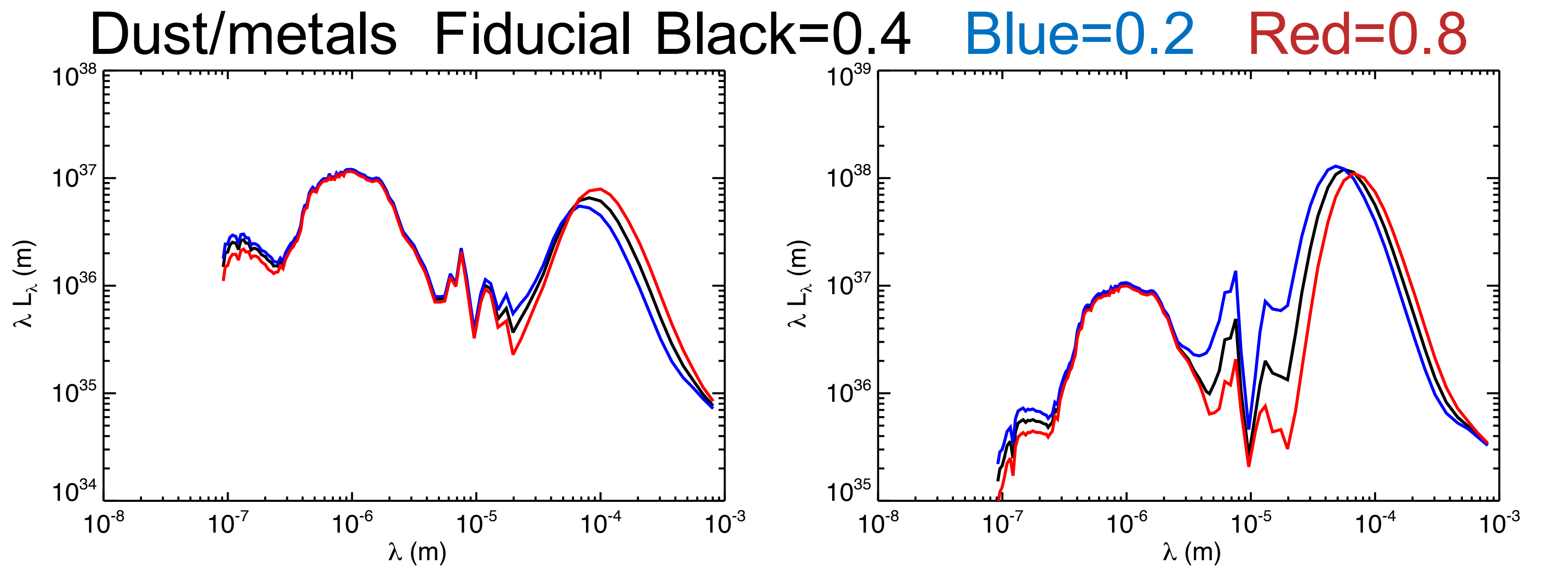
Best predictors of SED shape are L_{IR} and M_{dust}

Higher M_{Dust} => Lower T at fixed L_{IR}



Not a trivial result: Depends on geometry

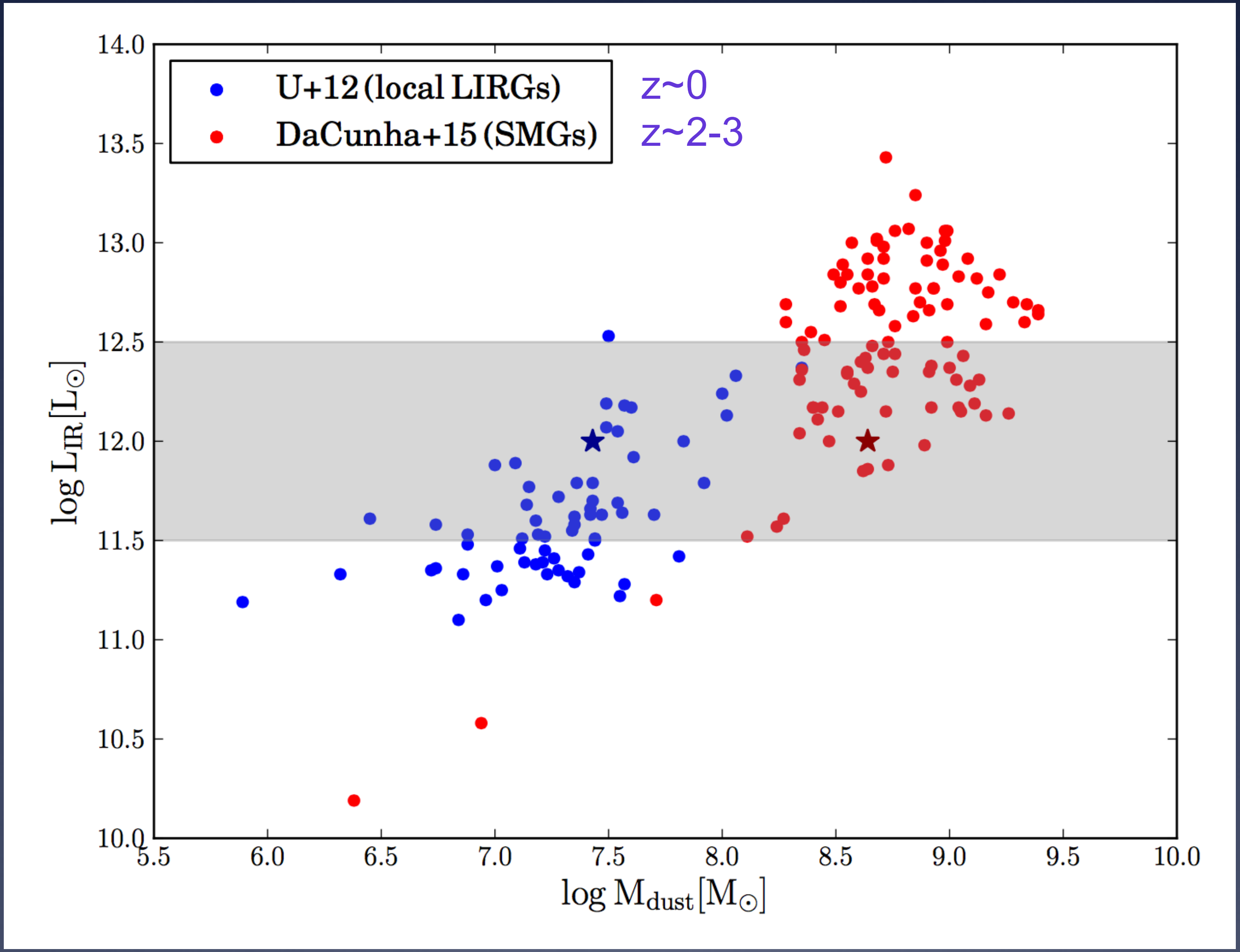
Effect increasing M_{Dust} holding geometry fixed



Adding dust with fixed geometry lowers the temperature.

Alternative to Rujokaparn+11 suggestion that size of SFR regions is responsible for lower T in high-z ULIRGs.

Trend is evident in observations



Safarzadeh+16

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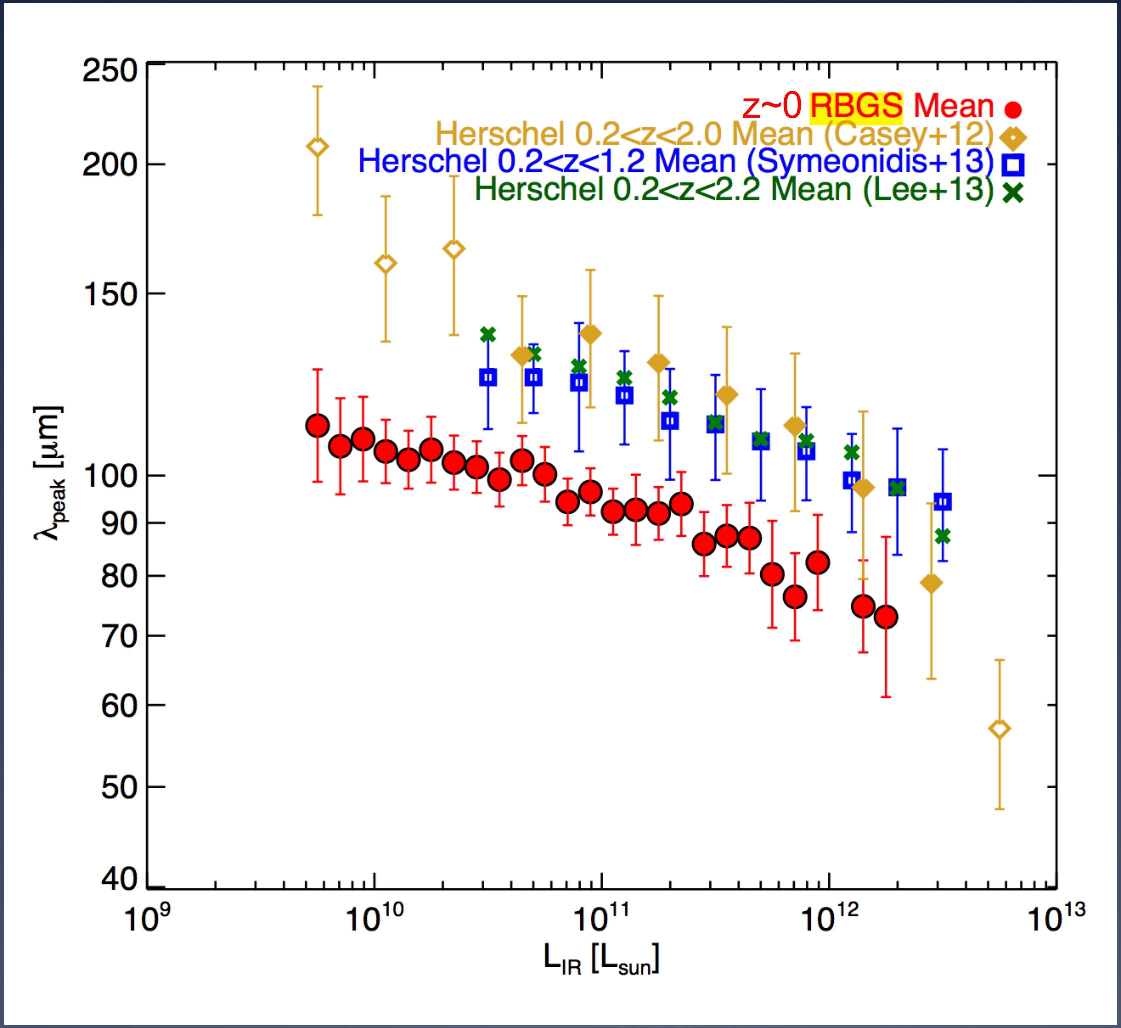
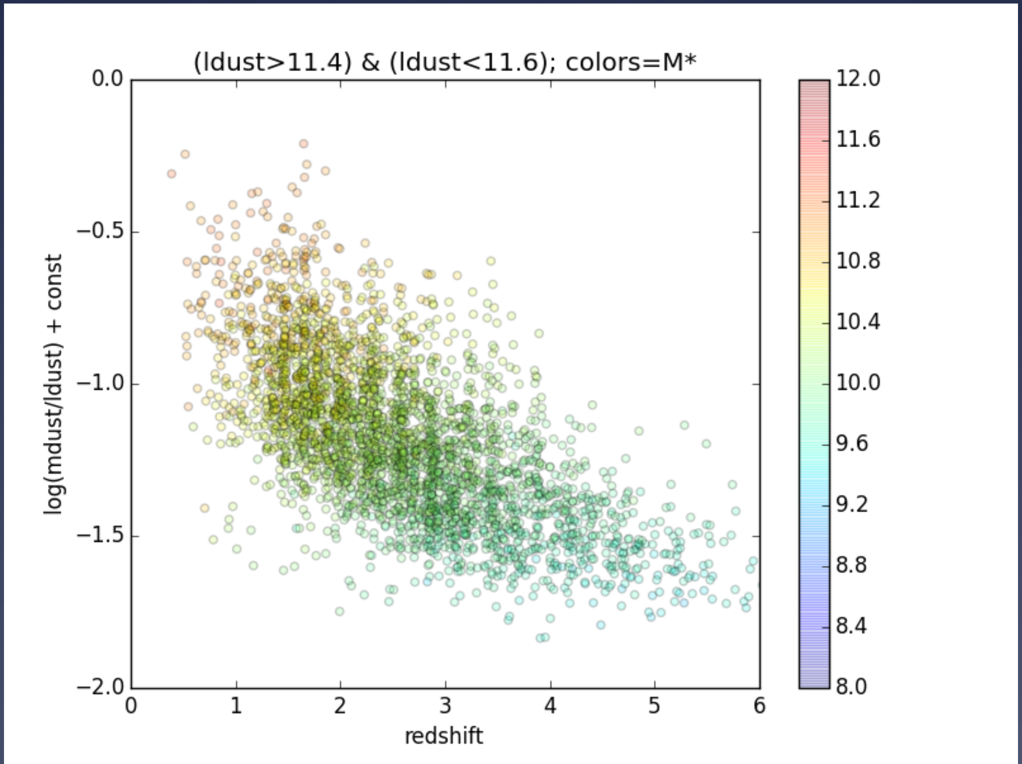


Safarzadeh+16

Galaxy-evolution models

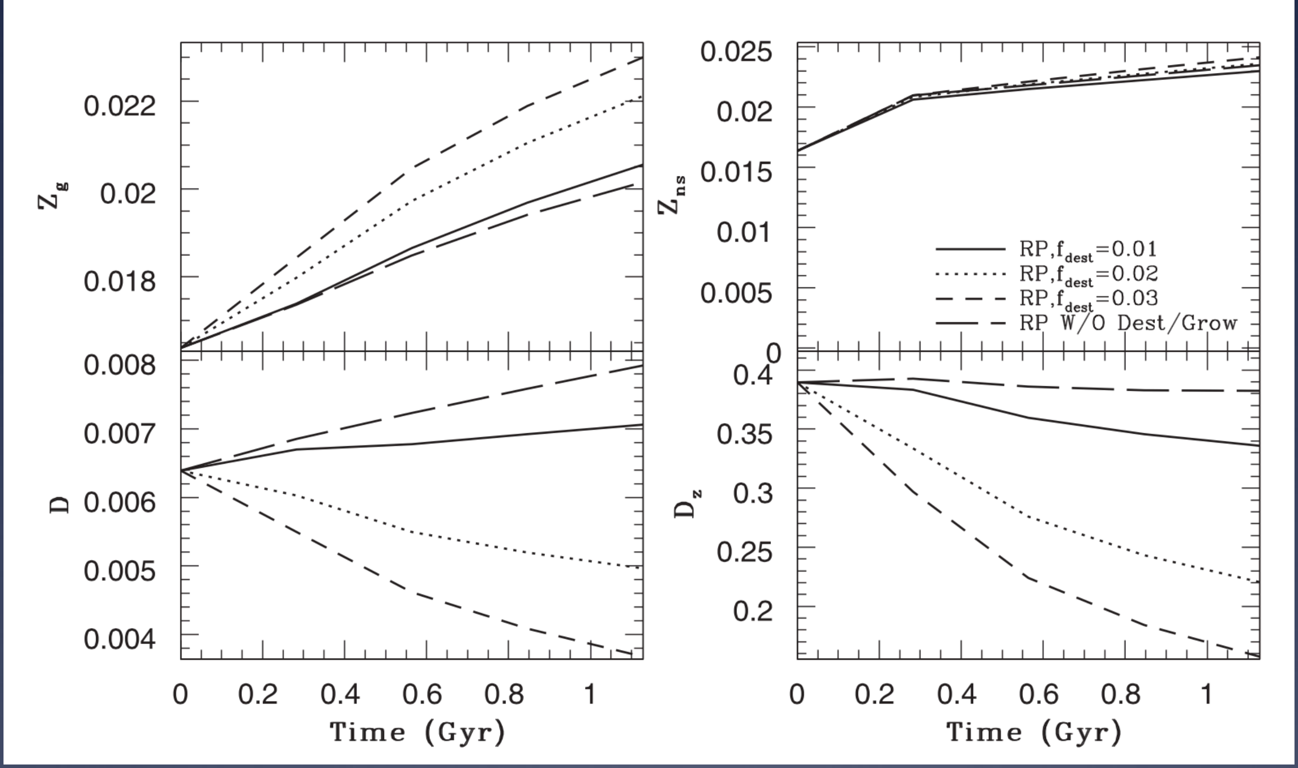
Competition between pristine gas accretion, dust creation & dust destruction



Somerville+12 – predicts lower M_{Dust} at fixed L_{IR} at high z

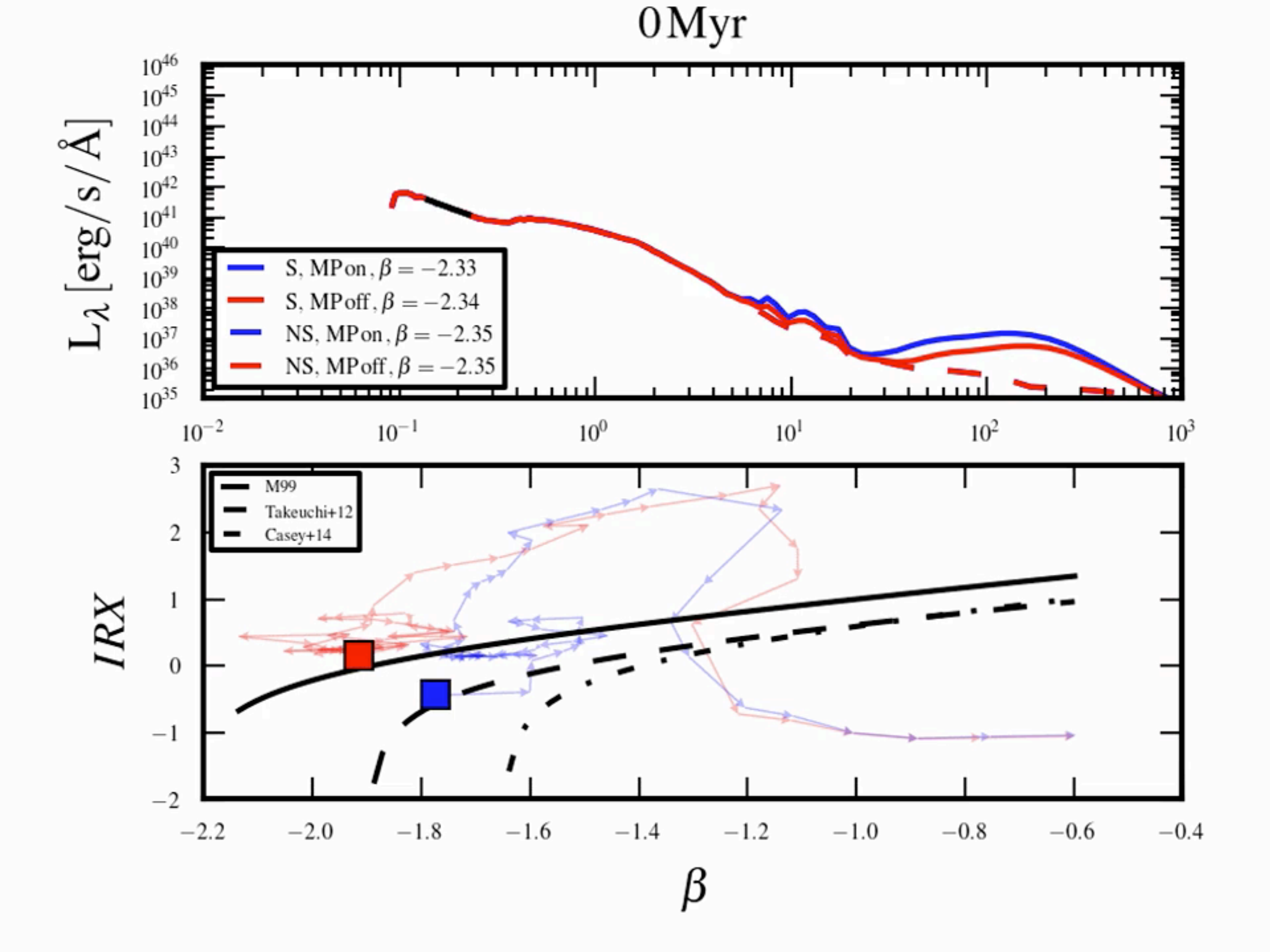
Galaxy-evolution models

Competition between pristine gas accretion, dust creation & dust destruction



Bekki+15 model with dust regulating feedback can produce strong decreas of Dust/metals with time

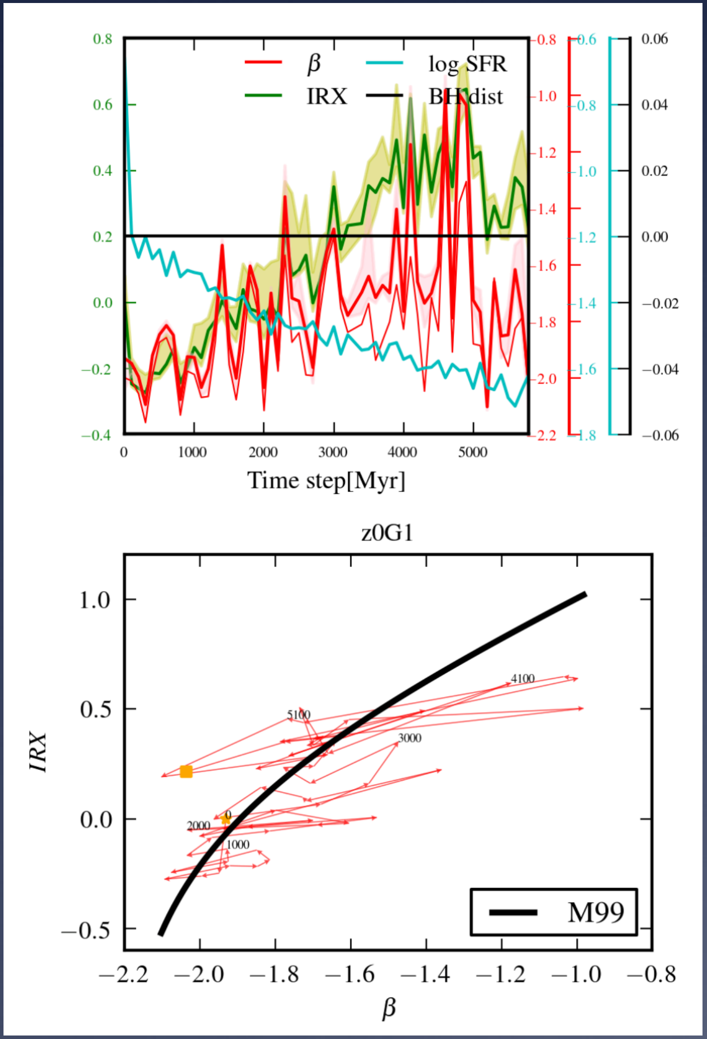
Behavior of UV slope



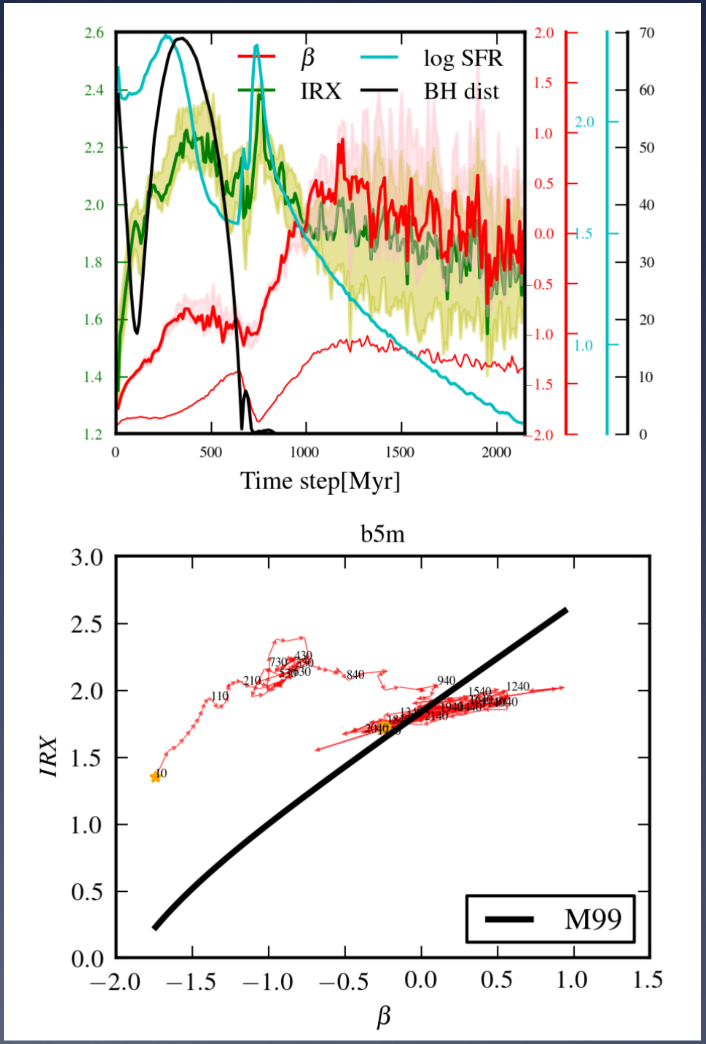
Safarzadeh+16 in prep

Behavior of UV slope

z=0 isolated disk

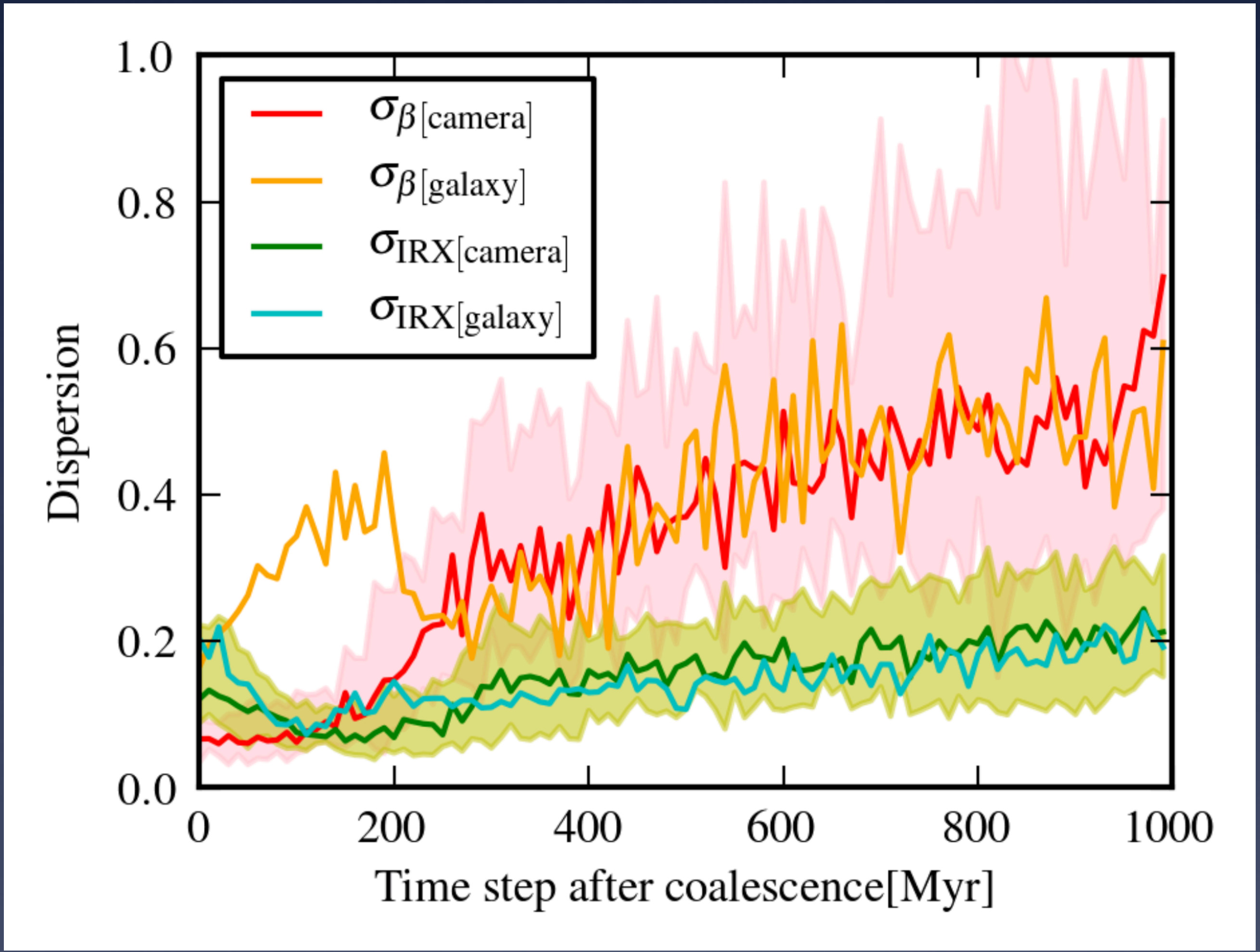


z=3 merger



Safarzadeh+16 in prep

Variation with viewing angle



Dispersion due to viewing angle is comparable to dispersion between galaxies for z~3 merger simulations

The optimists say…

Should we believe the results of ultraviolet–millimetre galaxy spectral energy distribution modelling?

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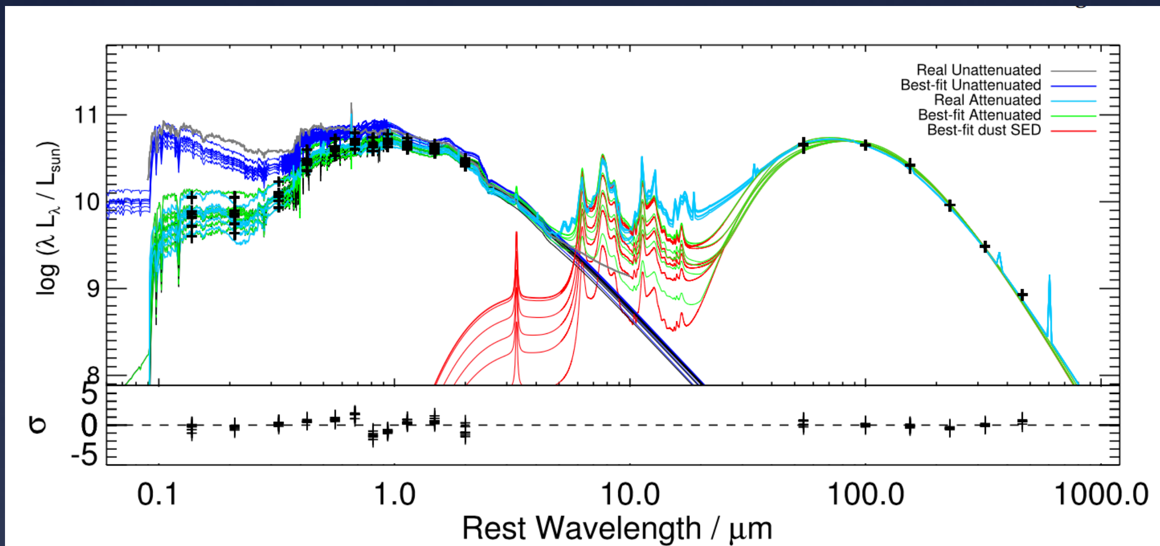
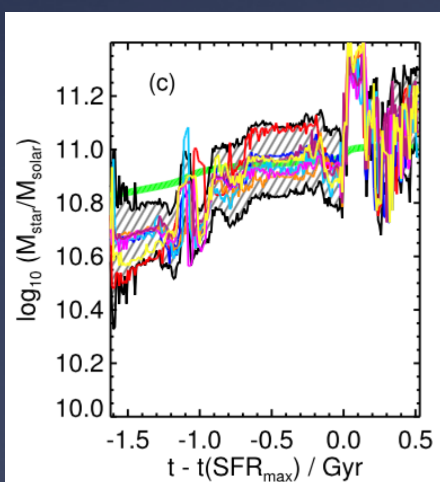
[3] *Centre for Astrophysics, Science and Technology Research Institute, University of Hertfordshire, Hatfield, Herts AL10 9AB, UK*

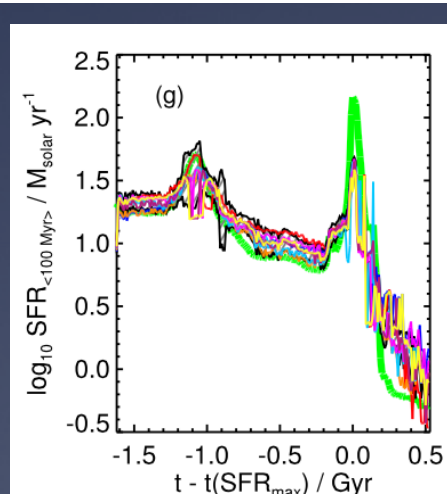
simulations can provide a means of testing SED modelling techniques. Here, we present a numerical experiment in which we apply the SED modelling code MAGPHYS to ultraviolet–millimetre synthetic photometry generated from hydrodynamical simulations of an isolated disc galaxy and a major galaxy merger by performing three-dimensional dust radiative transfer. We compare the properties inferred from the SED modelling with the true values and find that MAGPHYS recovers most physical parameters of the simulated galaxies well. In particular, it recovers consistent parameters irrespective of the viewing angle, with smoothly varying results for neighbouring time steps of the simulation, even though each viewing angle and time step is modelled independently. The notable exception to this rule occurs when we use a Small Magellanic Cloud-type intrinsic dust extinction curve in the radiative transfer calculations. In

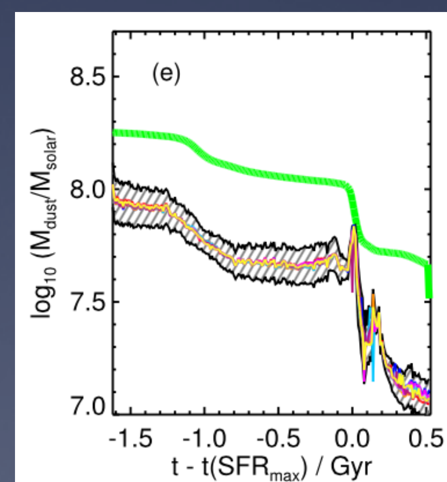
The optimists say...

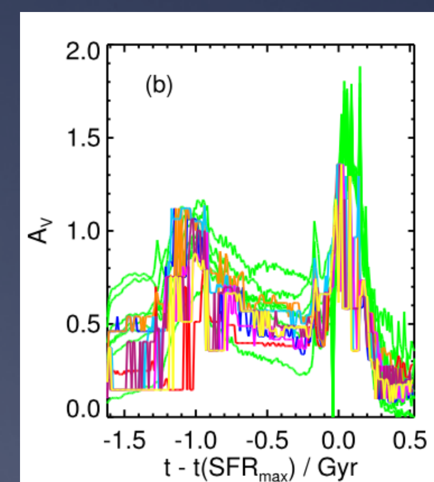


The optimists have excellent "data"



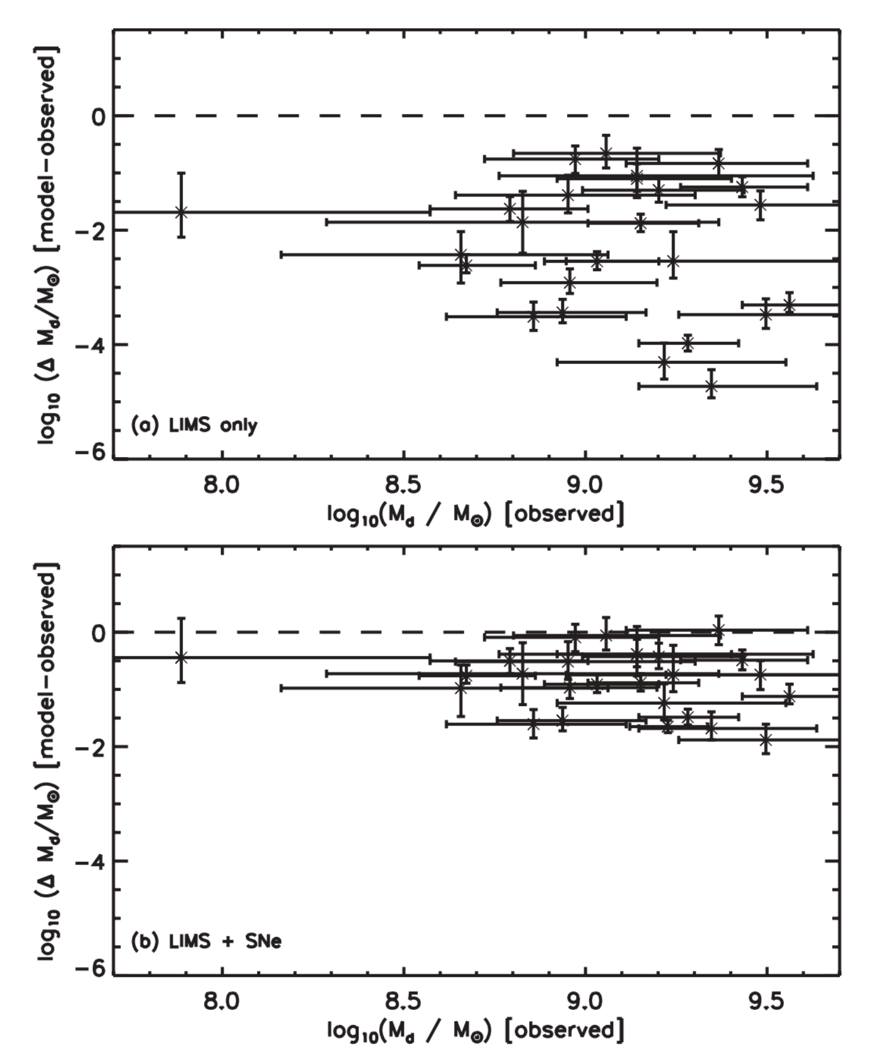






$M_{stellar}$ SFR A_V M_{dust}

If the optimists are right, and SMGs aren't mostly blends, there is a dust crisis



Rowlands+14:

Dust masses in SMGs exceed masses expected from chemical evolution by several orders of magnitude

Even ignoring destruction

The pessimists say

- None of the cosmological hydro+RT simulations yet match colors & color trends of high-z galaxies
  - Or IRX/beta relations
- There is no agreement on the effect of dust on high-z galaxy colors & luminosities
  - Critical for understanding high-mass evolution
- A lot of FIR & Sub-mm data is badly confused

Conclusions

- SED fitted SFRs aren't too bad, on average
  - Not obvious that IR is best in all cases, even for "clean" examples
- At z>3, highest SFR galaxies are not evolving along the MS
- Evolution of dust mass with redshift is an alternative explanation for why high-z ULIRGS are cooler than z=0 ULIRGS
- Viewing-angle variations in UV slope are likely comparable to intrinsic variations