January 27th, 2015

Sesto Workshop, Italy

The Evolution of Galaxy Stellar Mass Functions at z = 4 - 7 with CANDELS and S-CANDELS

Mimi Song

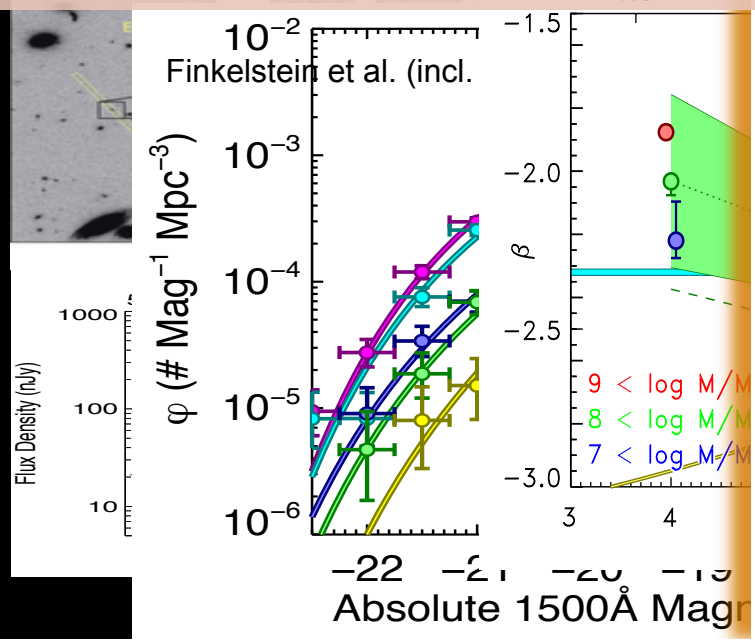
Department of Astronomy, University of Texas at Austin

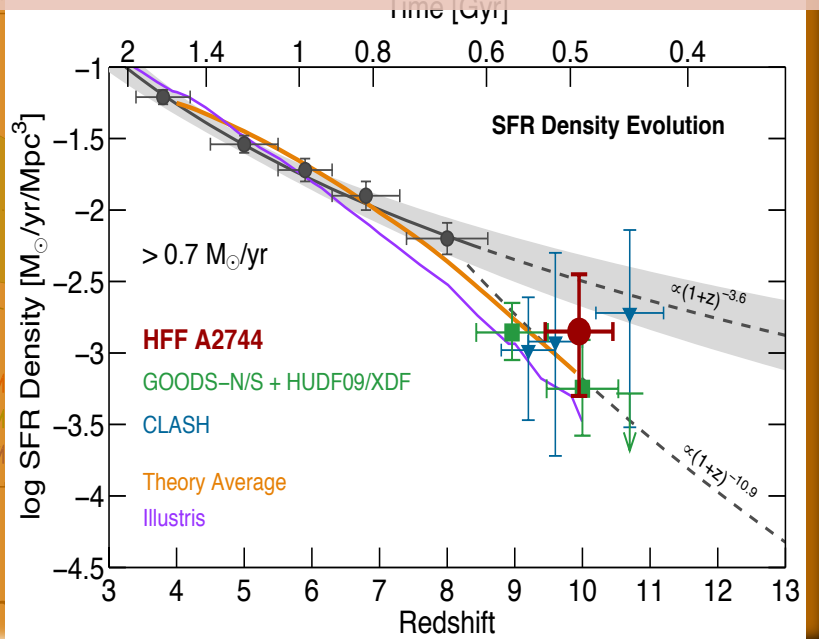
In collaboration with
Steven Finkelstein,
the CANDELS and S-CANDELS team

Image credit: Sigit Pamungkas (www.boston.com)

Galaxy Formation and Evolution at z>4

- Basic questions
  - How many galaxies are there?
  - How bright are they?
  - What (UV) colors do they have?
  - How massive are they? (Galaxy stellar mass function; MF)
  - How do they build up their mass? (Evolution of MF)



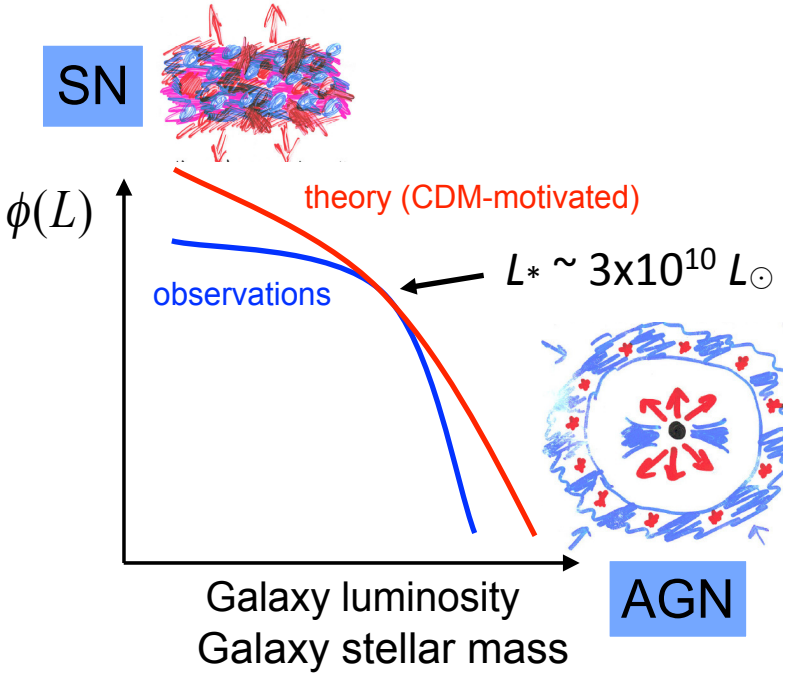


SFRD

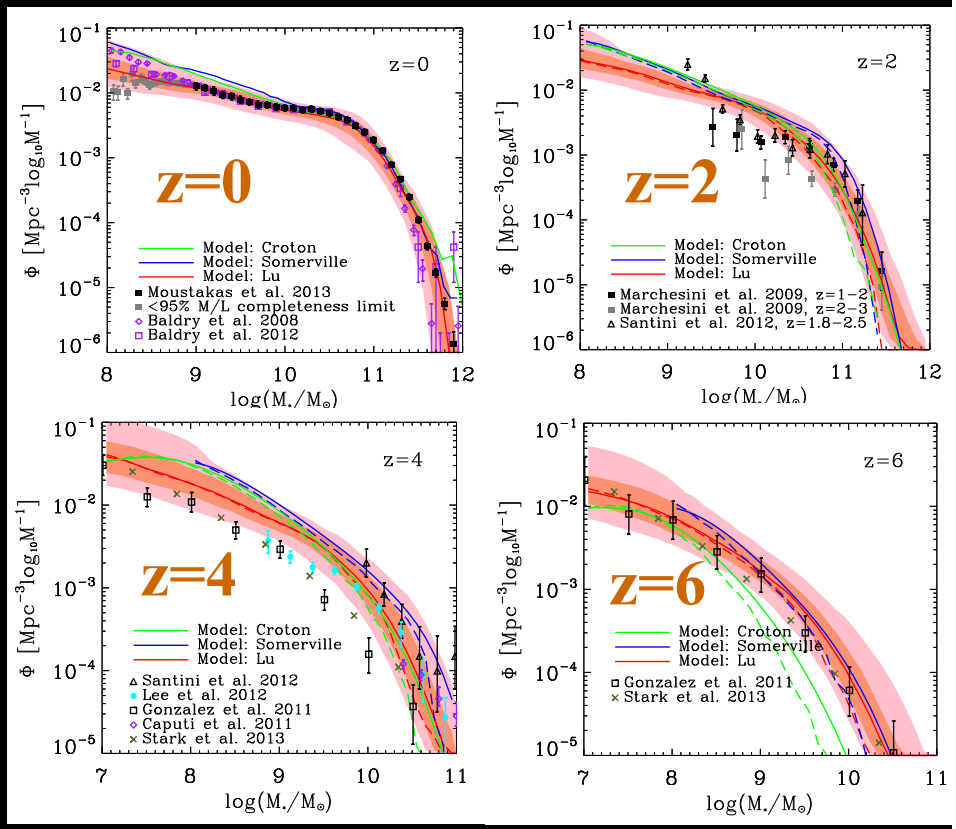
Motivation

High-z MF as a powerful way to constrain physics of galaxy formation

- SAMs Predictions
  (Croton, Lu, Somerville models)

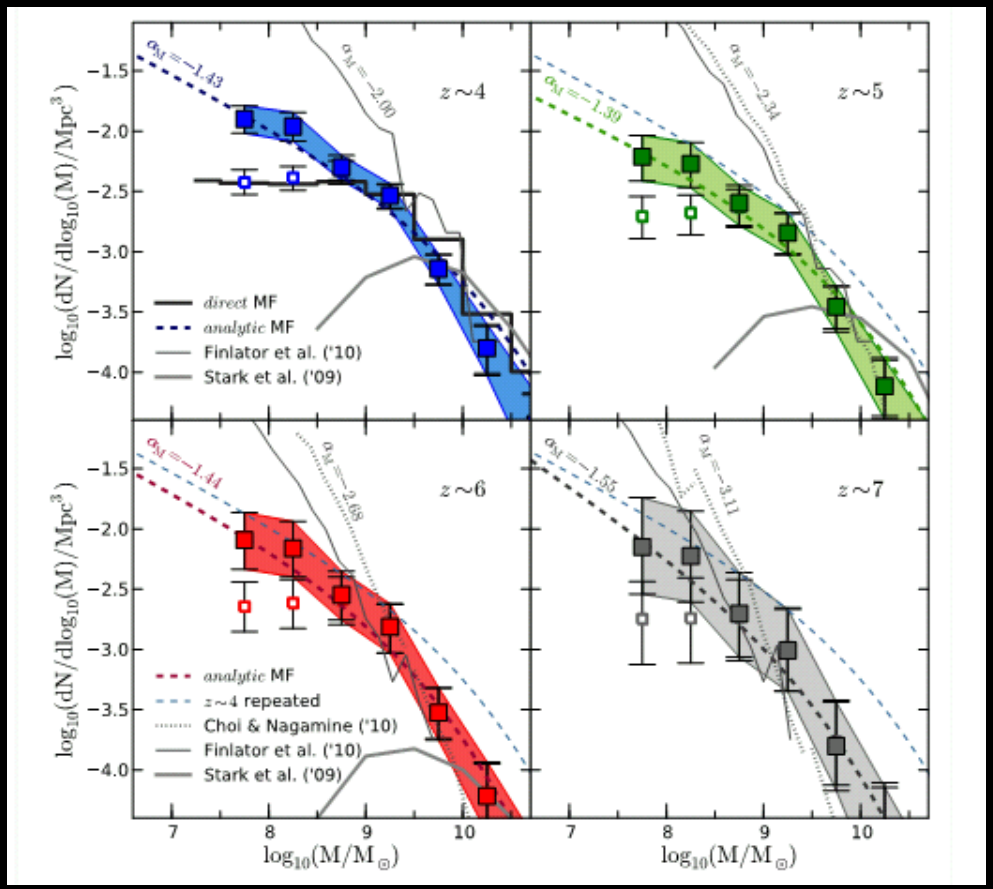


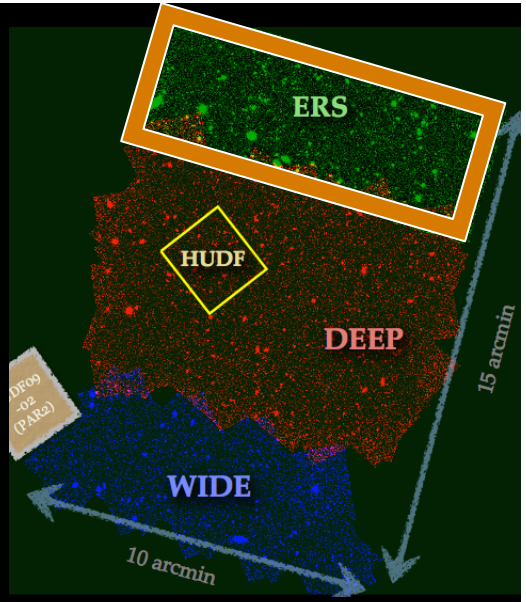
(Silk & Mamon 2012)



Previous Study on Galaxy Stellar Mass Functions at z=4-7

- Galaxy Stellar Mass Function (MF) at z=4,5,6,7 (Gonzalez et al. 2011)



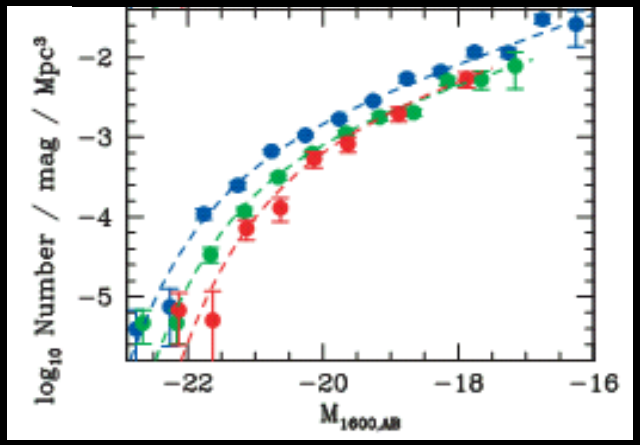


Sample & Data:

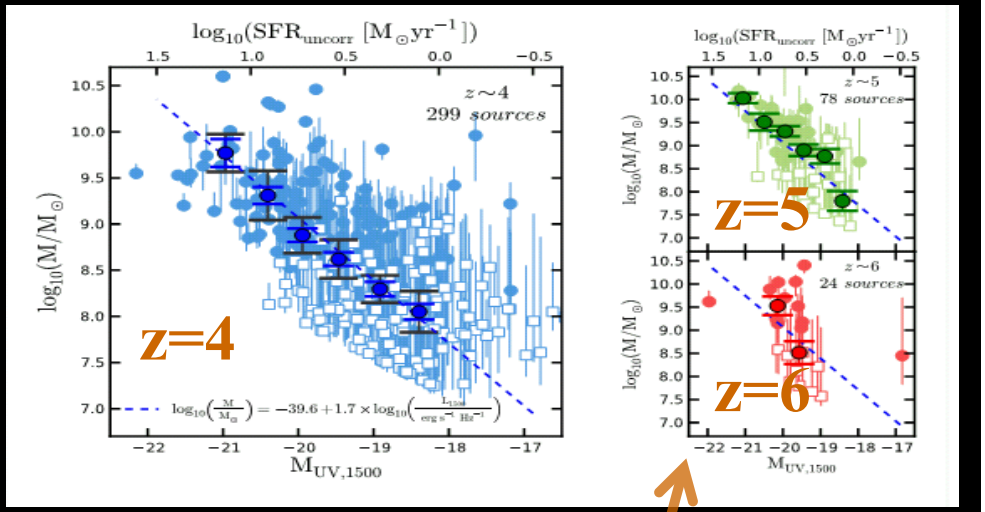
- WFC3 in ERS field (33 arcmin^2) + Spitzer GOODS-S (~23 hr/pt)
- LBG selection
- Sample size:
  - ~300 (z~4)
  - 78 (z~5)
  - 24 (z~6)

Methodology: LF x (M/L) = MF

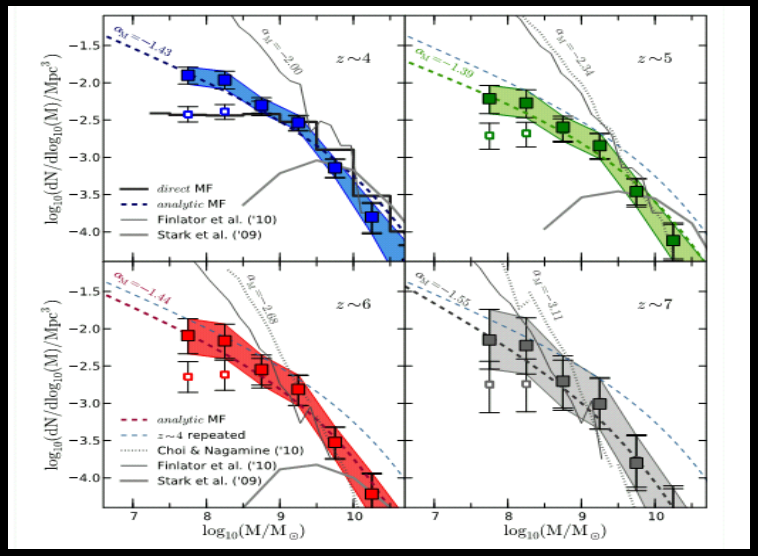
Public LF (Bouwens+07)



M – L distribution: $(M/L_{UV}) = f(L_{UV},z)$



MF



Assumption on the constant $(M/L_{UV})=f(L_{UV})$ at z=4-7

Now we can do a better job without this assumption !

New Datasets: Deep and Wide

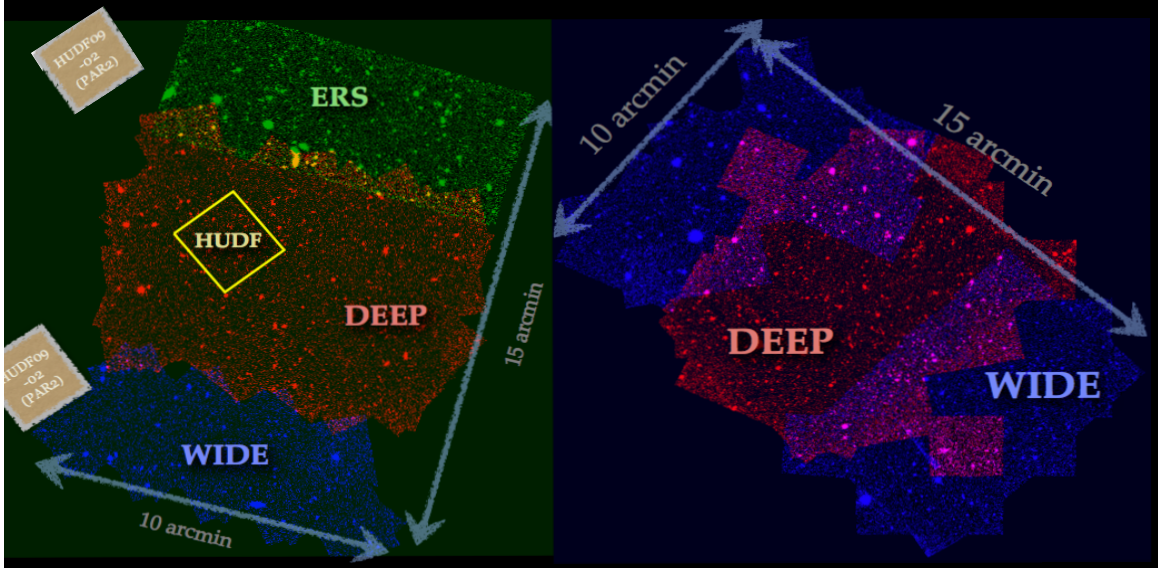
larger area coverage (~290 arcmin^2; GOODS-S & N + HUDF), sample size (>25 times), and redshift range (up to z=8)

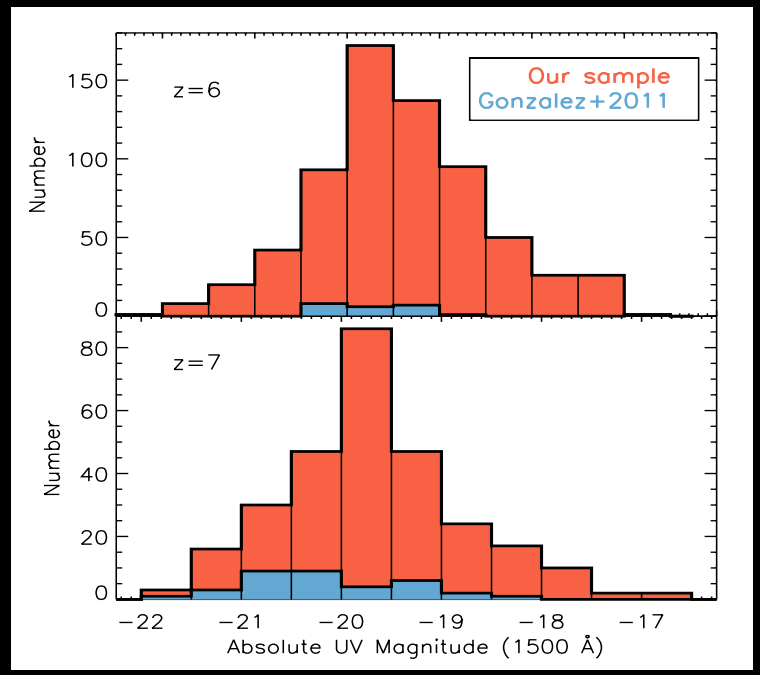
- Two major datasets:

1) HST/NIR data from CANDELS & HUDF

2) Spitzer/IRAC data from S-CANDELS (2x existing integration time) & RAC Ultra Deep Field 2010 Survey

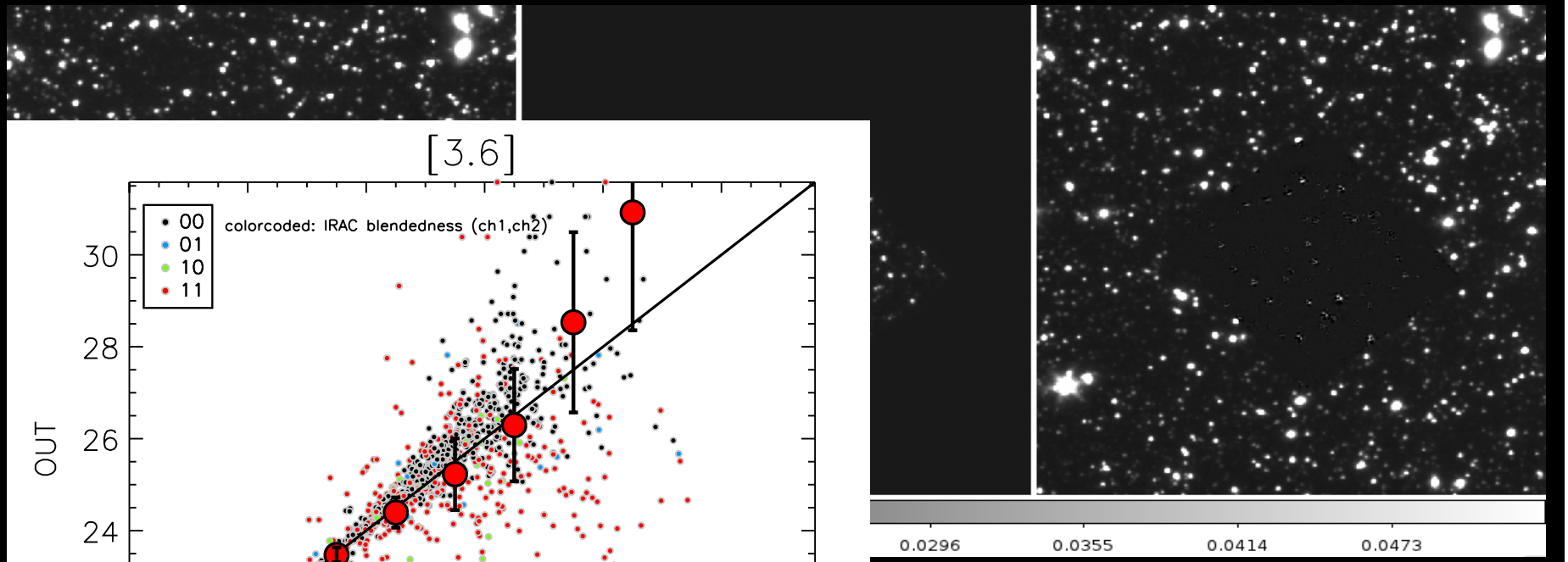
- Sample size: ~7000
  - z=4: ~4000
  - z=5: ~2000
  - z=6: ~700
  - z=7: ~300





PSF-matched IRAC photometry: TFIT/TPHOT (developed by E. Merlin)

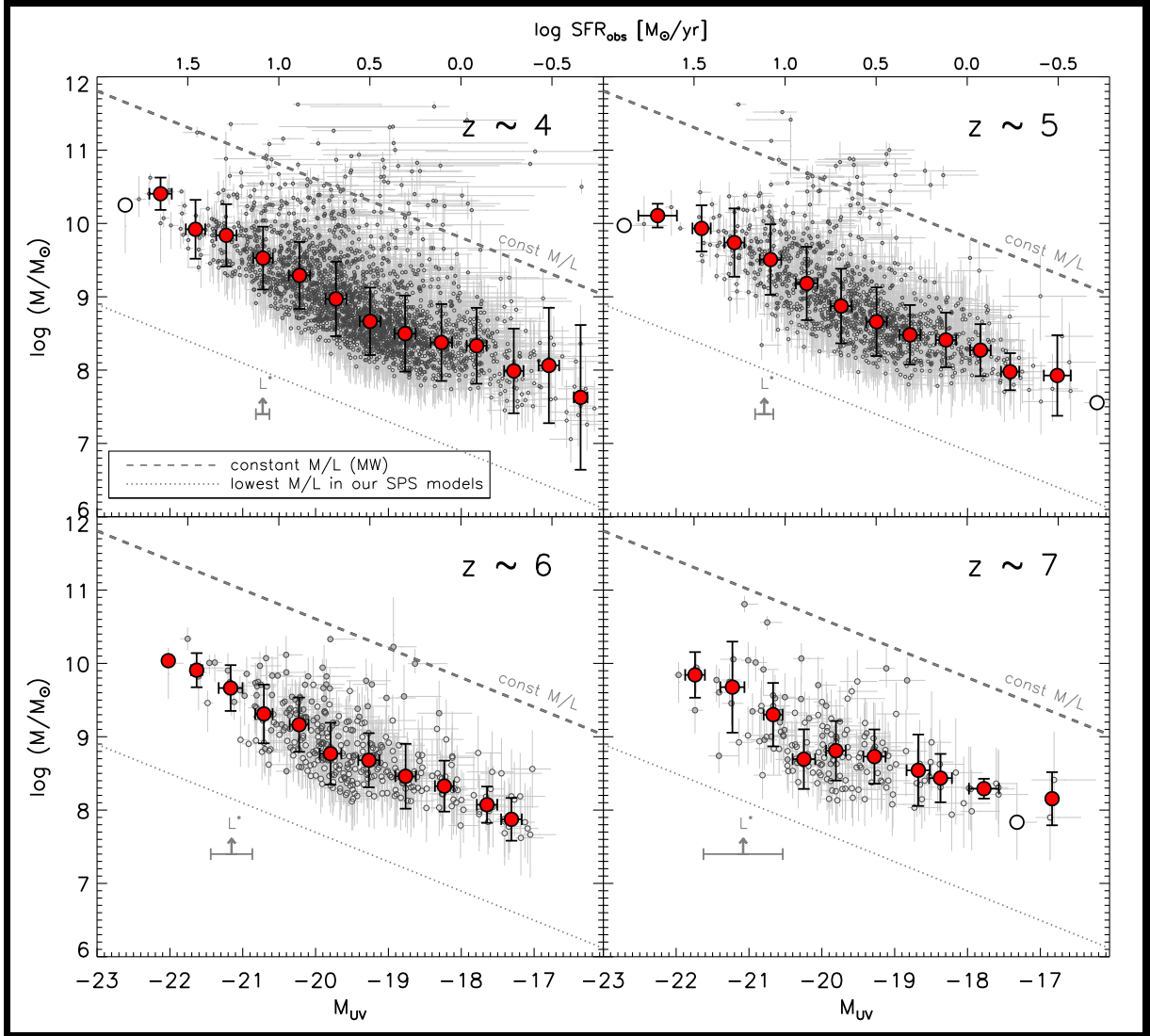
S-CANDELS 3.6μm - Model (H-band + kernel) = Residual



SED Fitting Prescriptions

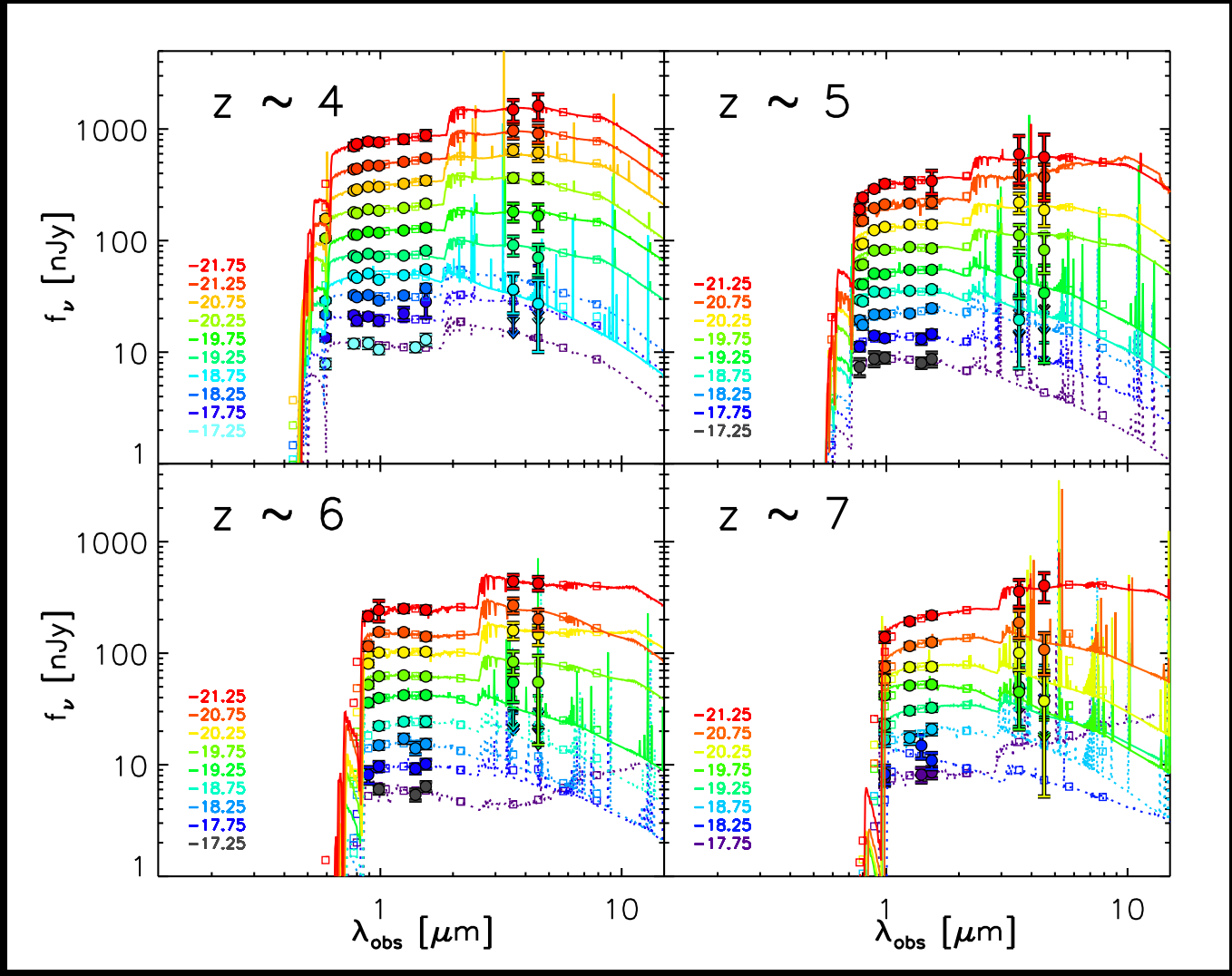
- HST: B,V, i, I814, z, Y, J, J140, H + IRAC: 3.6, 4.5 μm
- Bruzual & Charlot 2003 SPS models
- Rising/constant/declining SFHs
- Metallicity: [0.02,0.2,1] Zsun
- Nebular emission (Salmon et al. 2014)
- Dust: Calzetti, E(B-V)=0.0-0.8 with a 0.02 step
- Age: 10 Myr – age of the universe
- Madau IGM prescription

Stellar Mass - UV Luminosity Relation

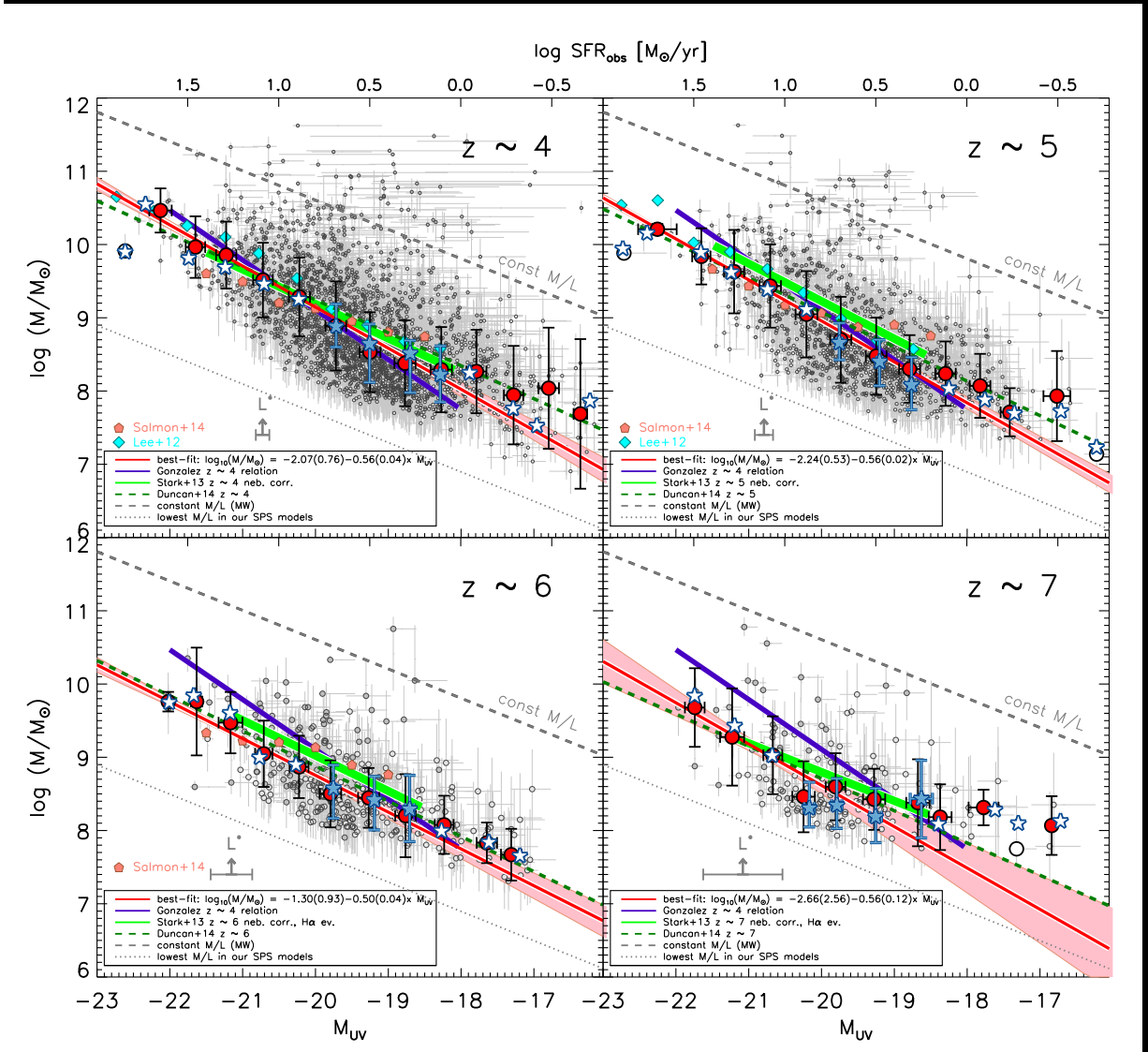


- Constant scatter of 0.4-0.5 dex
  (c.f., z=0-2 SF MS scatter: ~0.3 dex)
- Weak redshift evolution in the normalization towards lower M/L ratios

Median Stacked SEDs in Each UV Luminosity Bin



Stellar Mass - UV Luminosity Relation

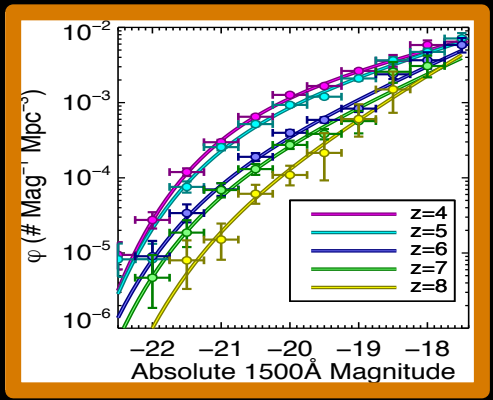


- Constant scatter of 0.4-0.5 dex (c.f., z=0-2 SF main-sequence scatter ~0.3 dex)
- Constant slope (~ -0.5) ~ marginally steeper than a constant M/L (=-0.4)
- Weak redshift evolution in the normalization

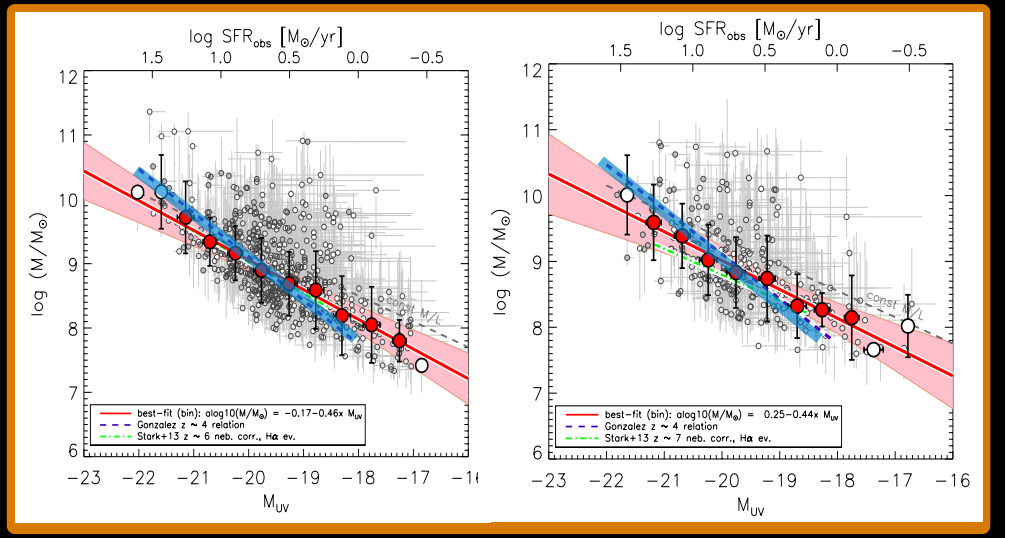
- **Red: this study**
- **Blue: z=4 relation (Gonzalez +11), without nebular emission**
- **Green: Stark+13, corrected for nebular emission inferred from z=4.**
- **Dark Green: Duncan+14**
- **Salmon Pentagons: Salmon +14**

New MF at z=4-7

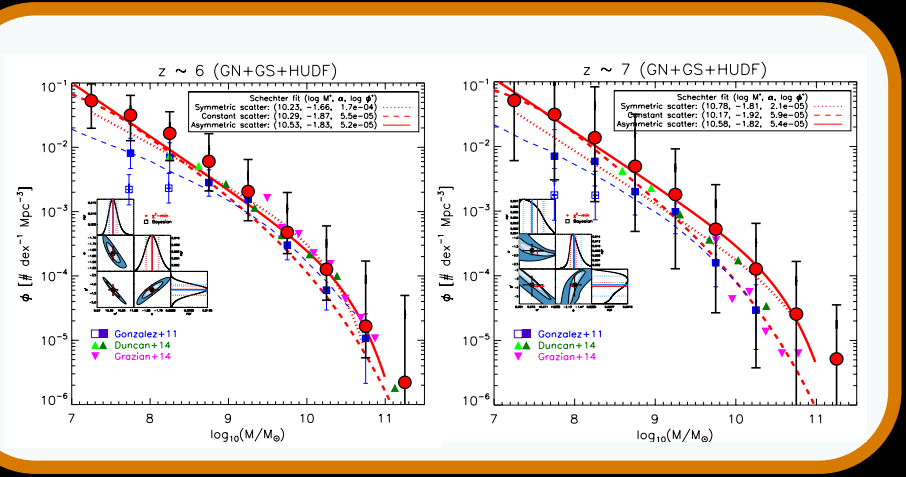
New LFs from CANDELS (Finkelstein+15, submitted)



New M – L distribution with S-CANDELS data



New mass function



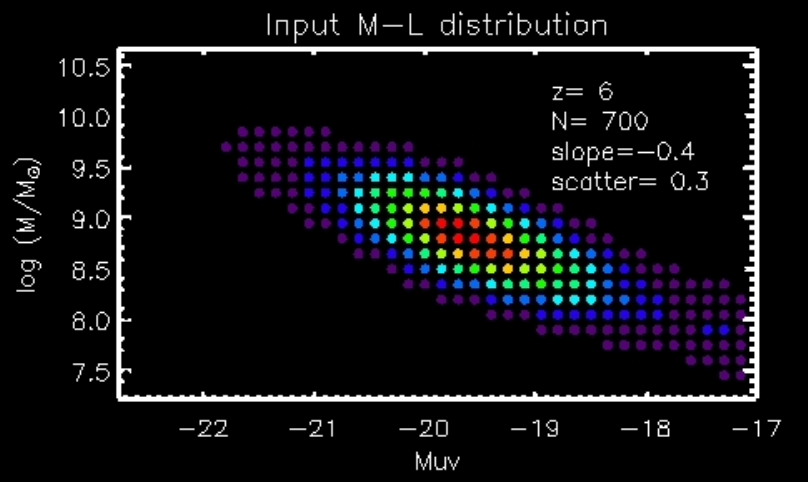
One more step toward the *intrinsic* MF

- can we recover the intrinsic slope, normalization, and scatter of M-L distribution?

Mock galaxy simulations

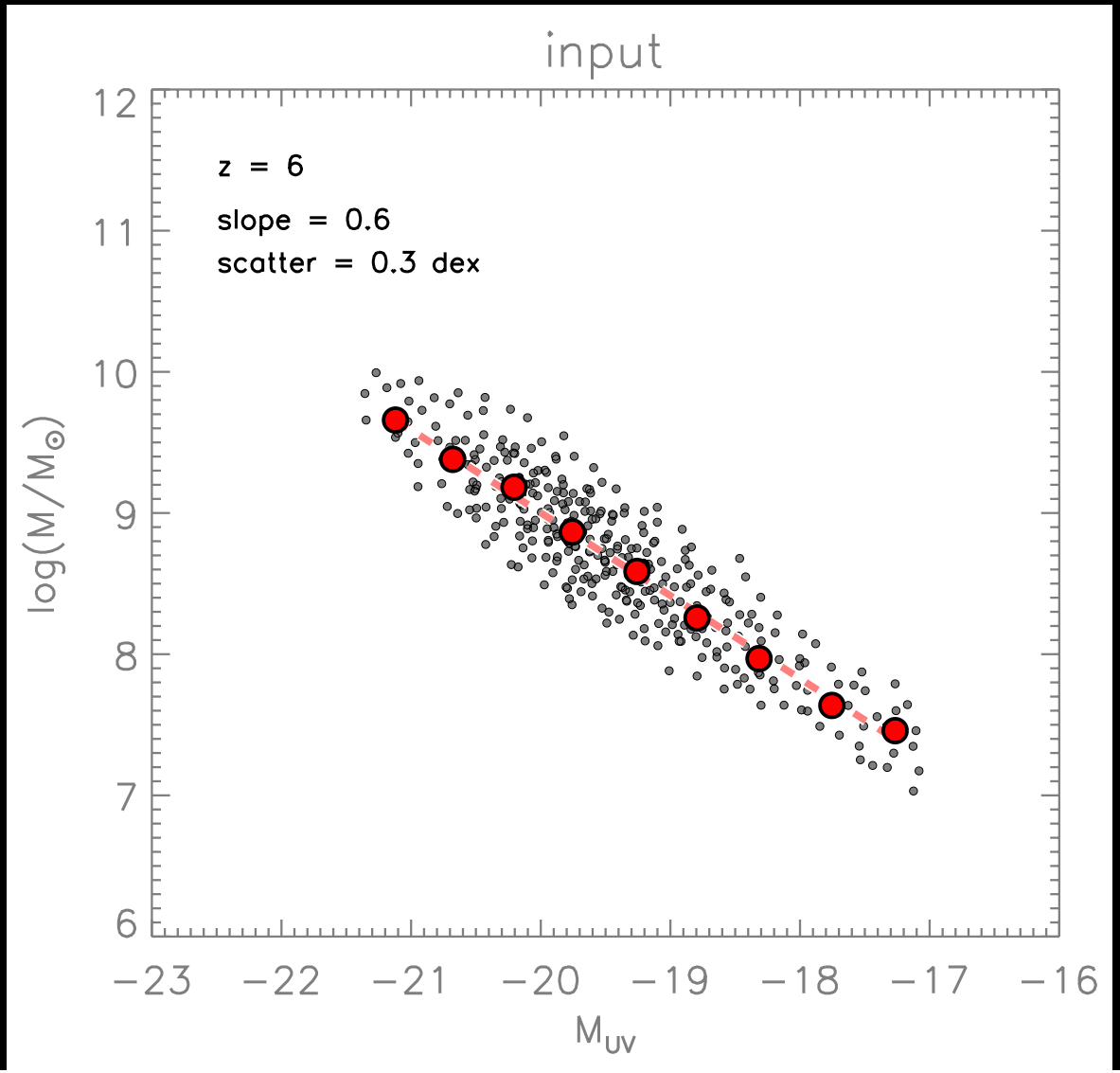
- Synthetic galaxy photometry from CANDELS-SAMS (Somerville; GOODS-S realization)
- Populate the M_*-M_{UV} plane with mock galaxies
  - w/ the same # and Muv dist. as the real sample
  - Log-normal distribution w/ various input slope - (0.2-0.8) and scatter
- Assign realistic errors & perturb photometry
- SED fitting
- Recover M-L distribution
- Stacking
- Derive the best-fit M-L relation

(20 realizations for each input slope and redshift)



The Nitty-Gritty in the Spirit of the Workshop

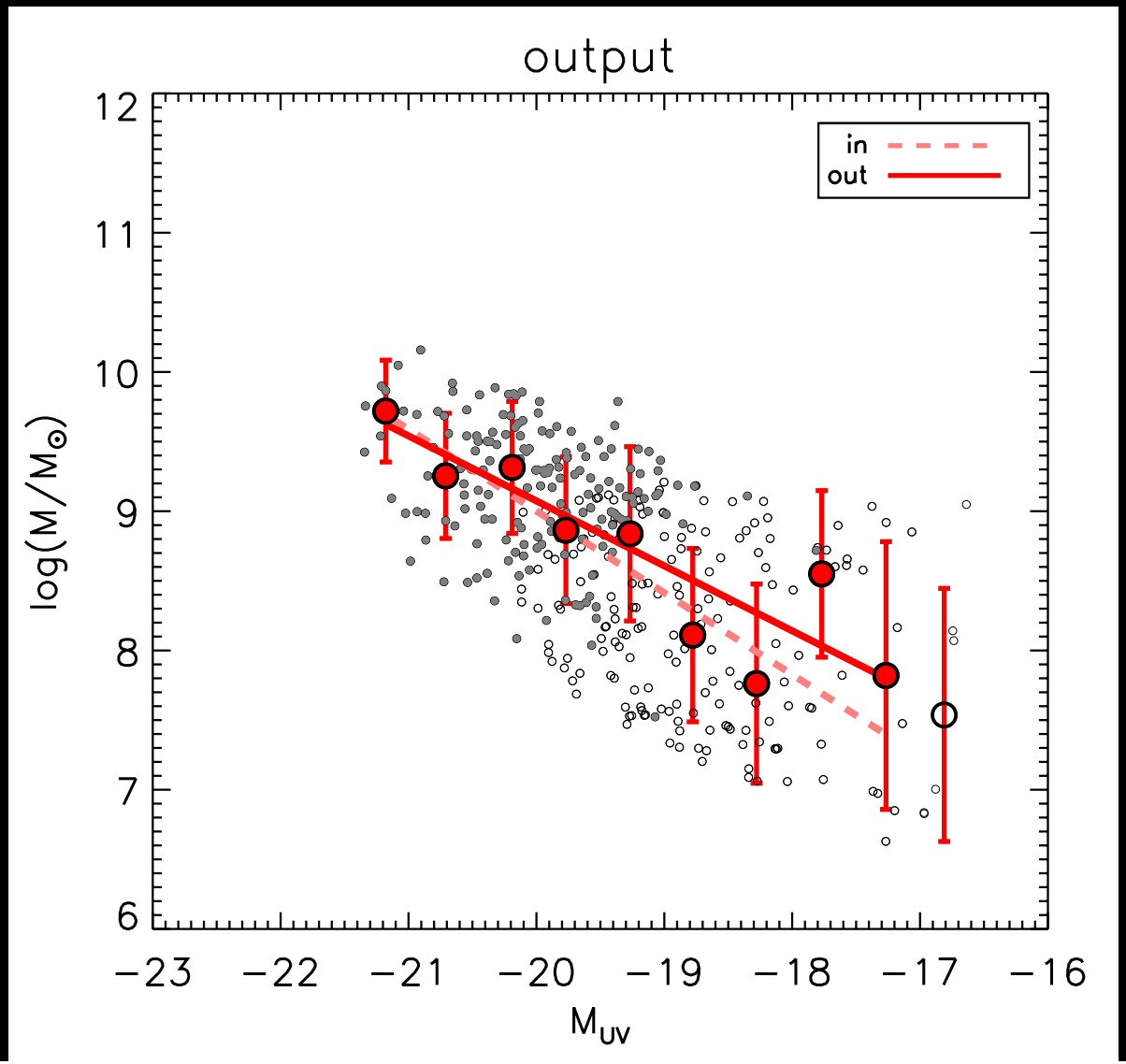
Mock Galaxy Simulation Example



Mock Galaxy Simulation Example

Recovered M-L Distribution w/ Best-fit Masses

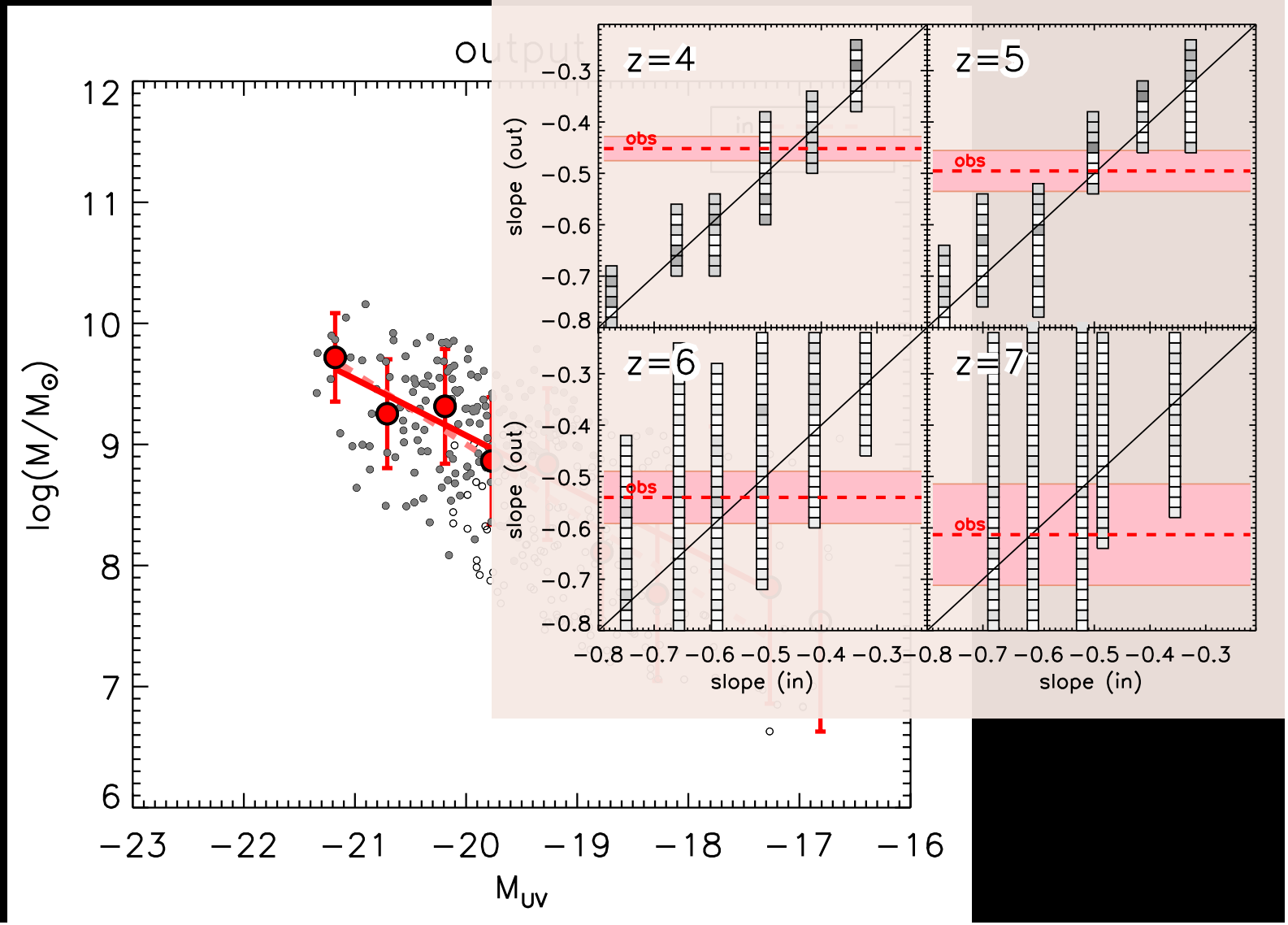
With current dataset, M/L relation hard to be recovered at z>6 with best-fit mass



Mock Galaxy Simulation Example

Recovered M-L Distribution w/ Best-fit Masses

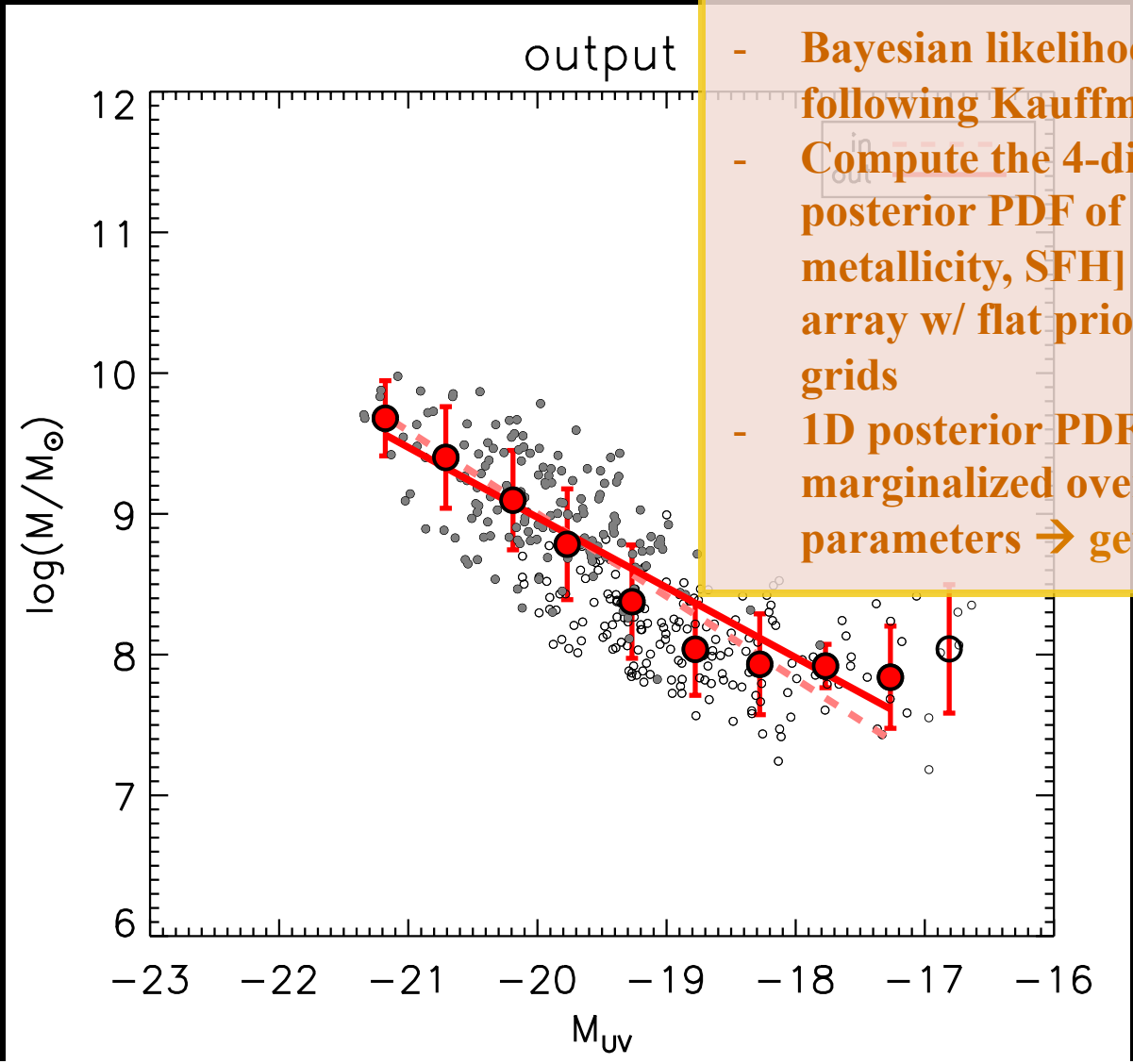
With current dataset, M/L relation hard to be recovered at z>6 with best-fit mass



Mock Galaxy Simulation Example

Recovered M-L Distribution w/ Marginalized Median Masses

Better in terms of scatter, but be cautious: bias in low S/N data

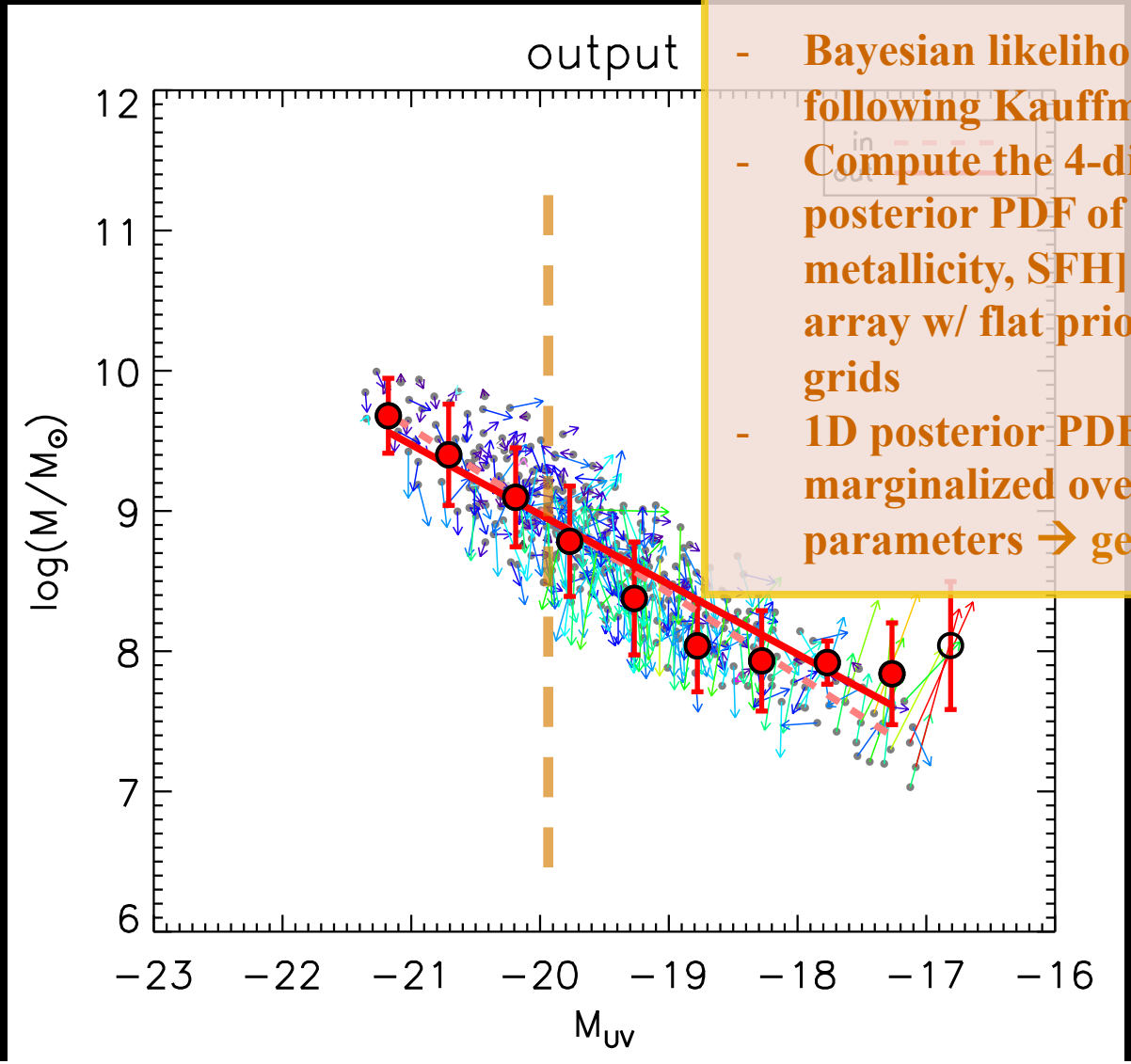


- **Bayesian likelihood analysis following Kauffmann et al. (2003)**
- **Compute the 4-dimensional posterior PDF of [age, dust, metallicity, SFH] using the χ^2 array w/ flat priors in parameter grids**
- **1D posterior PDF for stellar mass marginalized over all the other parameters → get median mass**

Mock Galaxy Simulation Example

Recovered M-L Distribution w/ Marginalized Median Masses

Better in terms of scatter, but be cautious: bias in low S/N data

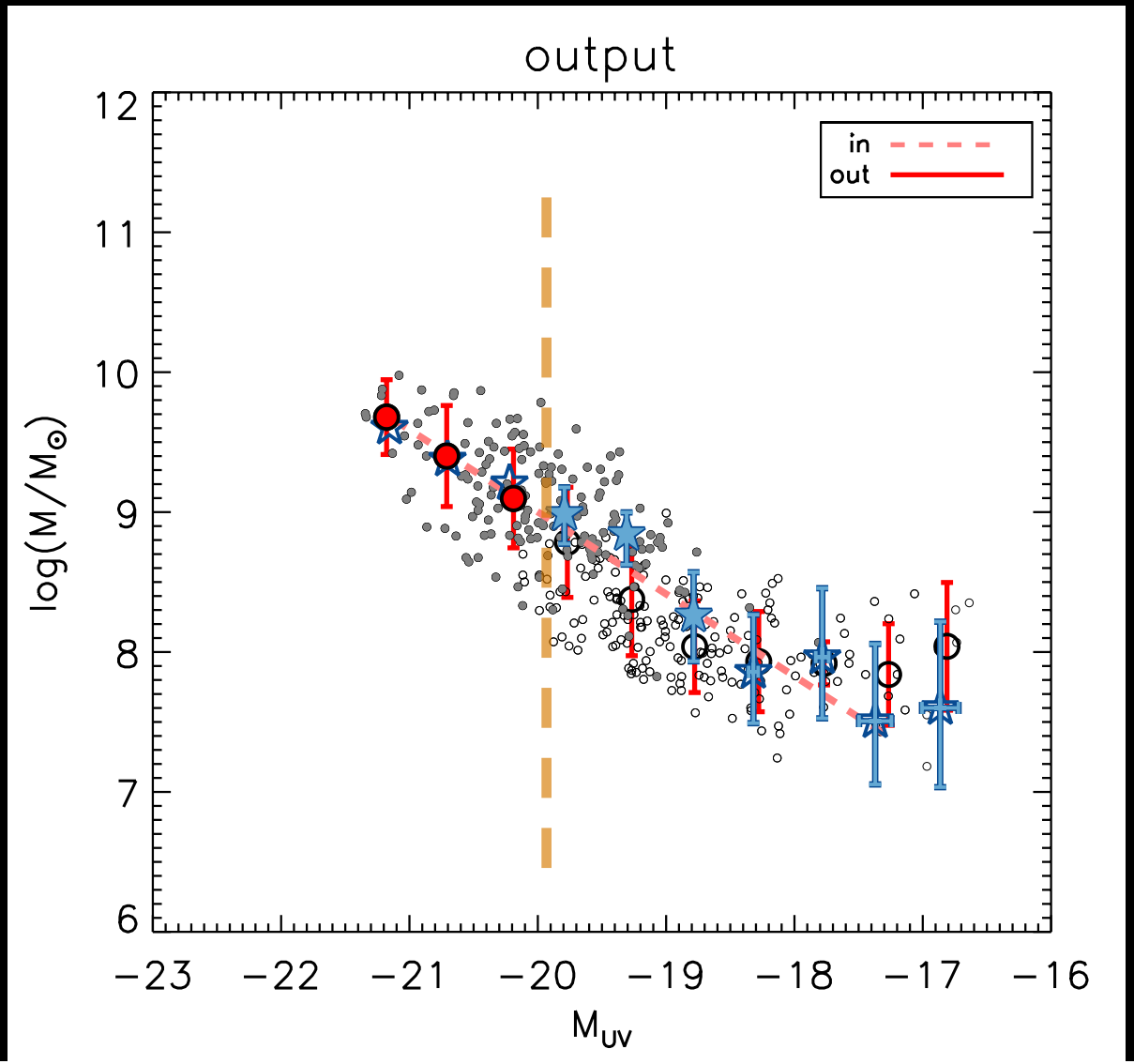


- **Bayesian likelihood analysis following Kauffmann et al. (2003)**
- **Compute the 4-dimensional posterior PDF of [age, dust, metallicity, SFH] using the χ^2 array w/ flat priors in parameter grids**
- **1D posterior PDF for stellar mass marginalized over all the other parameters → get median mass**

Mock Galaxy Simulation Example

Recovered M-L Distribution w/ Marginalized Median Masses

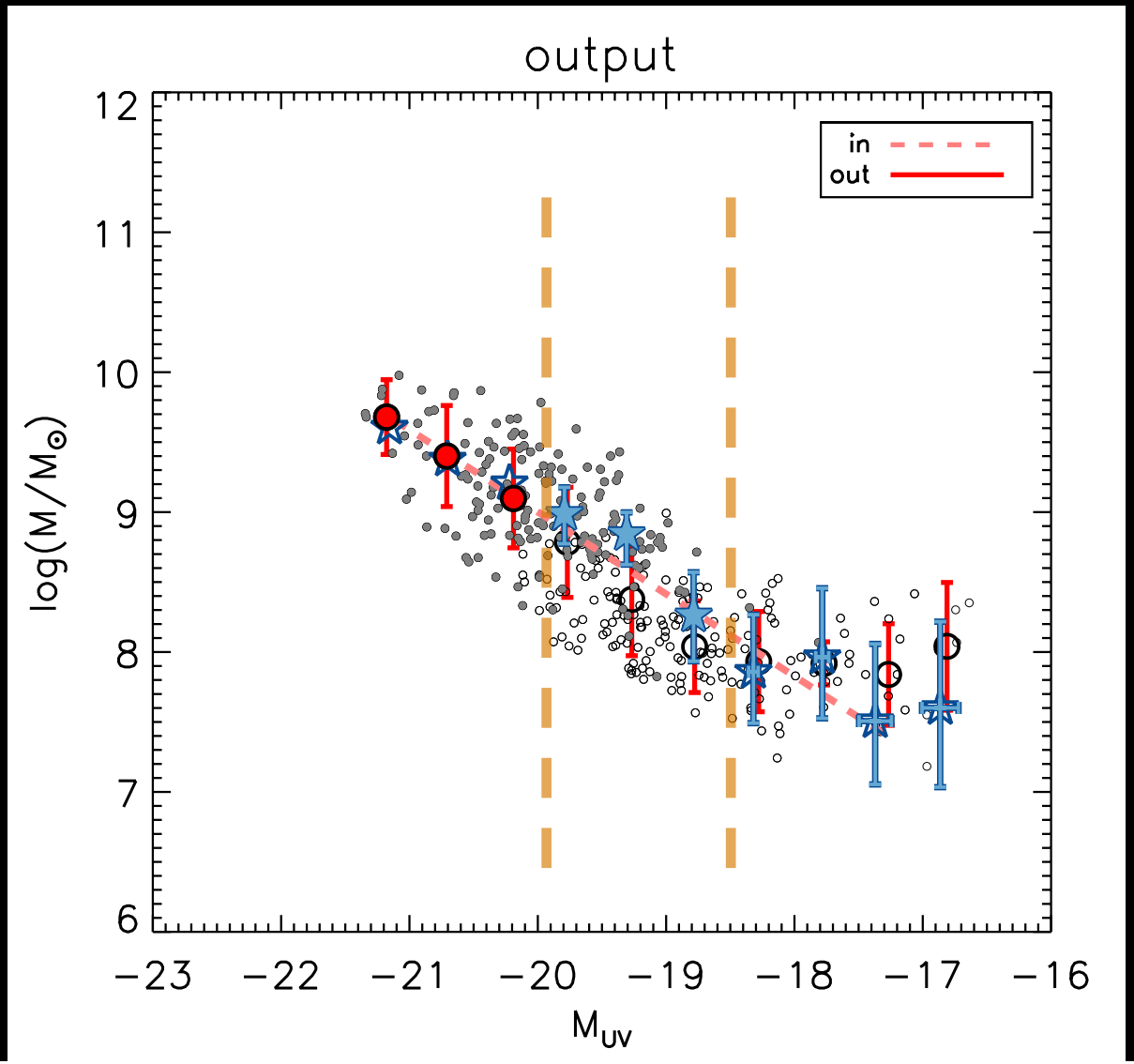
Stacking helps, but only to some extent



Mock Galaxy Simulation Example

Recovered M-L Distribution w/ Marginalized Median Masses

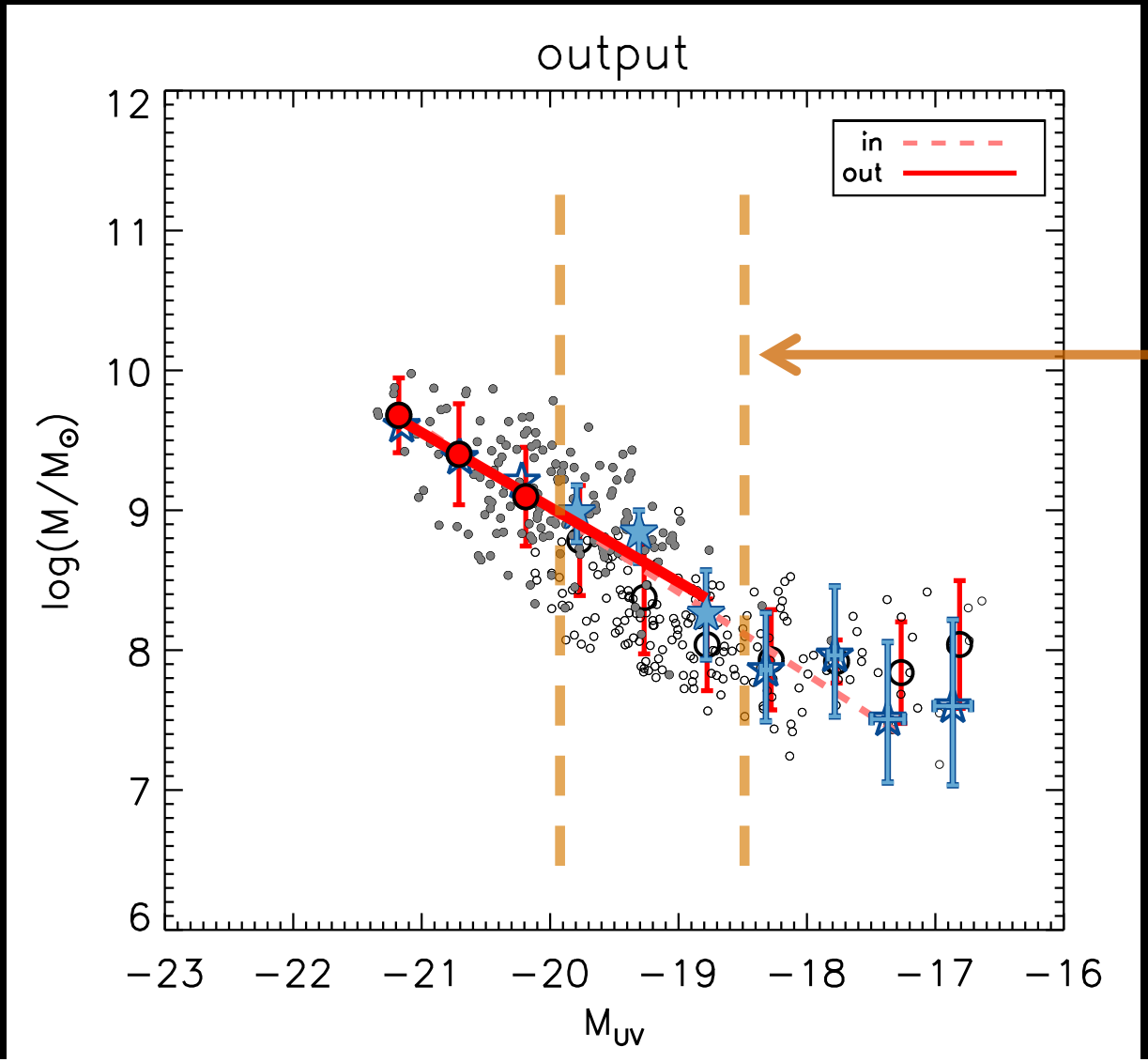
Stacking helps, but only to some extent



Mock Galaxy Simulation Example

Recovered M-L Distribution w/ Marginalized Median Masses

The intrinsic M-L distribution can be recovered better with prudence



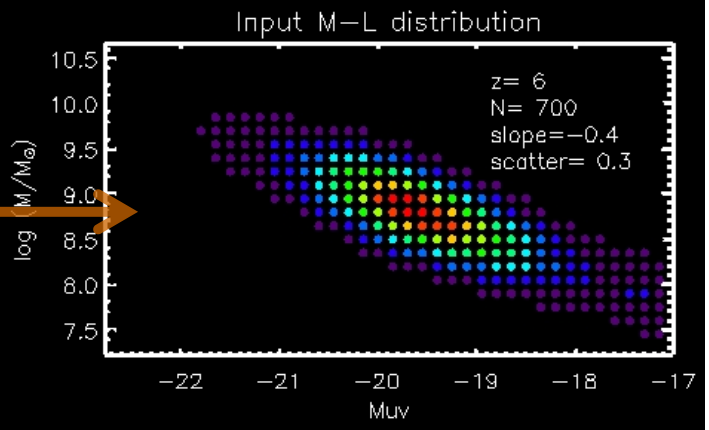
One more step toward the *intrinsic* MF

- can we recover the intrinsic slope, normalization, and scatter of M-L distribution?

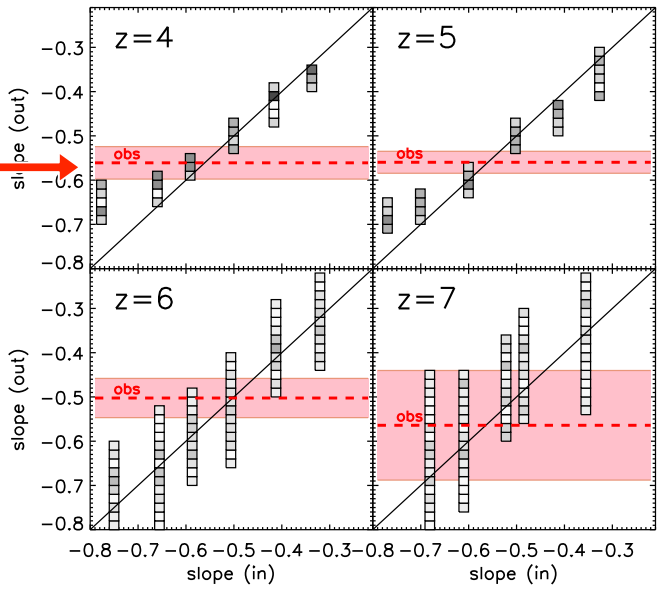
Mock galaxy simulations

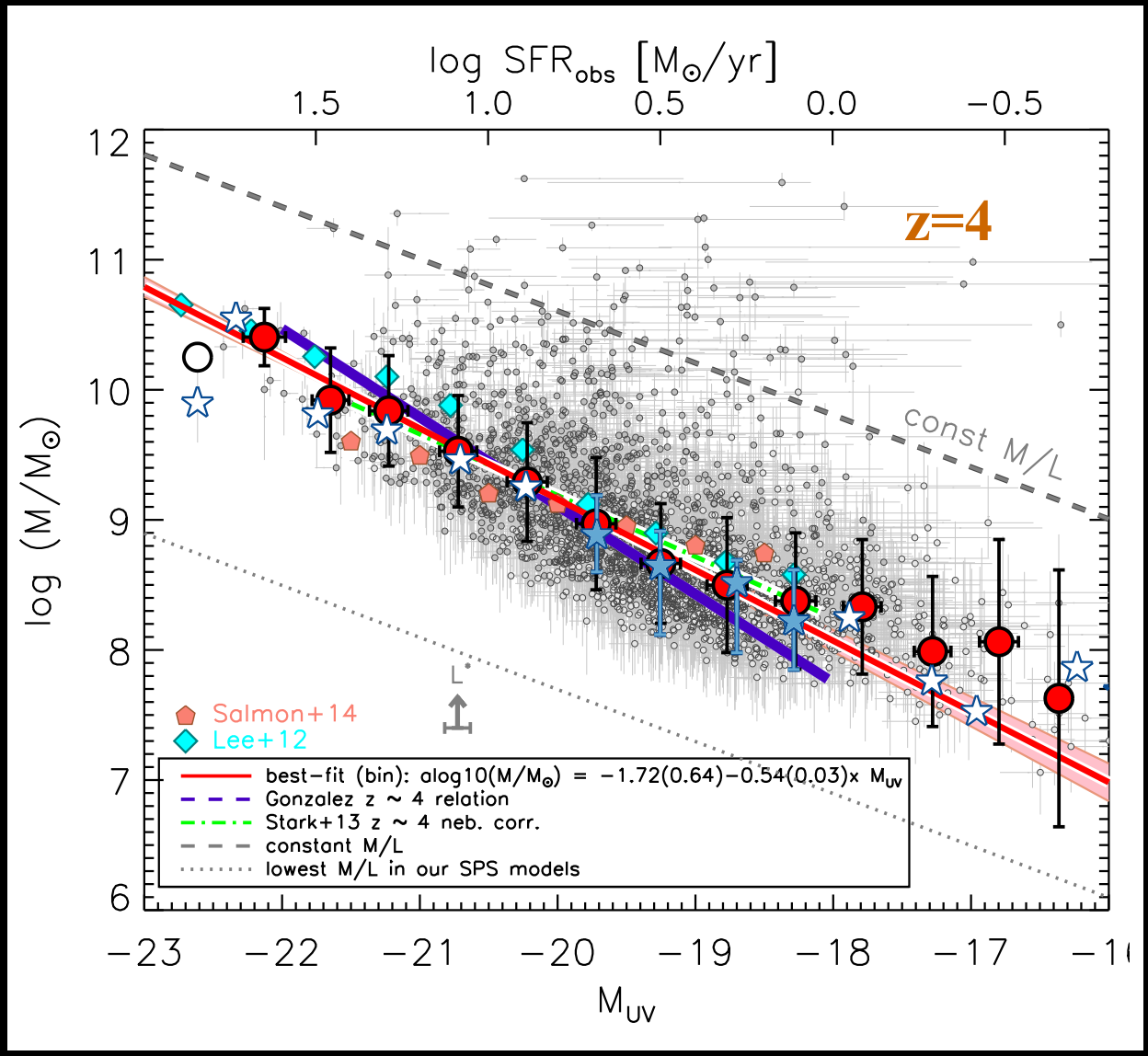
- Synthetic galaxy photometry from CANDELS-SAMS (Somerville; GOODS-S realization)
- Populate the M-L plane with mock galaxies
  - w/ the same # and Muv dist. as the real sample
  - w/ various input slope -(0.2-0.8) and scatter
- Assign realistic errors & perturb photometry
- Photo-z
- SED fitting
- Recover M-L distribution
- Stacking
- Derive the best-fit M-L relation

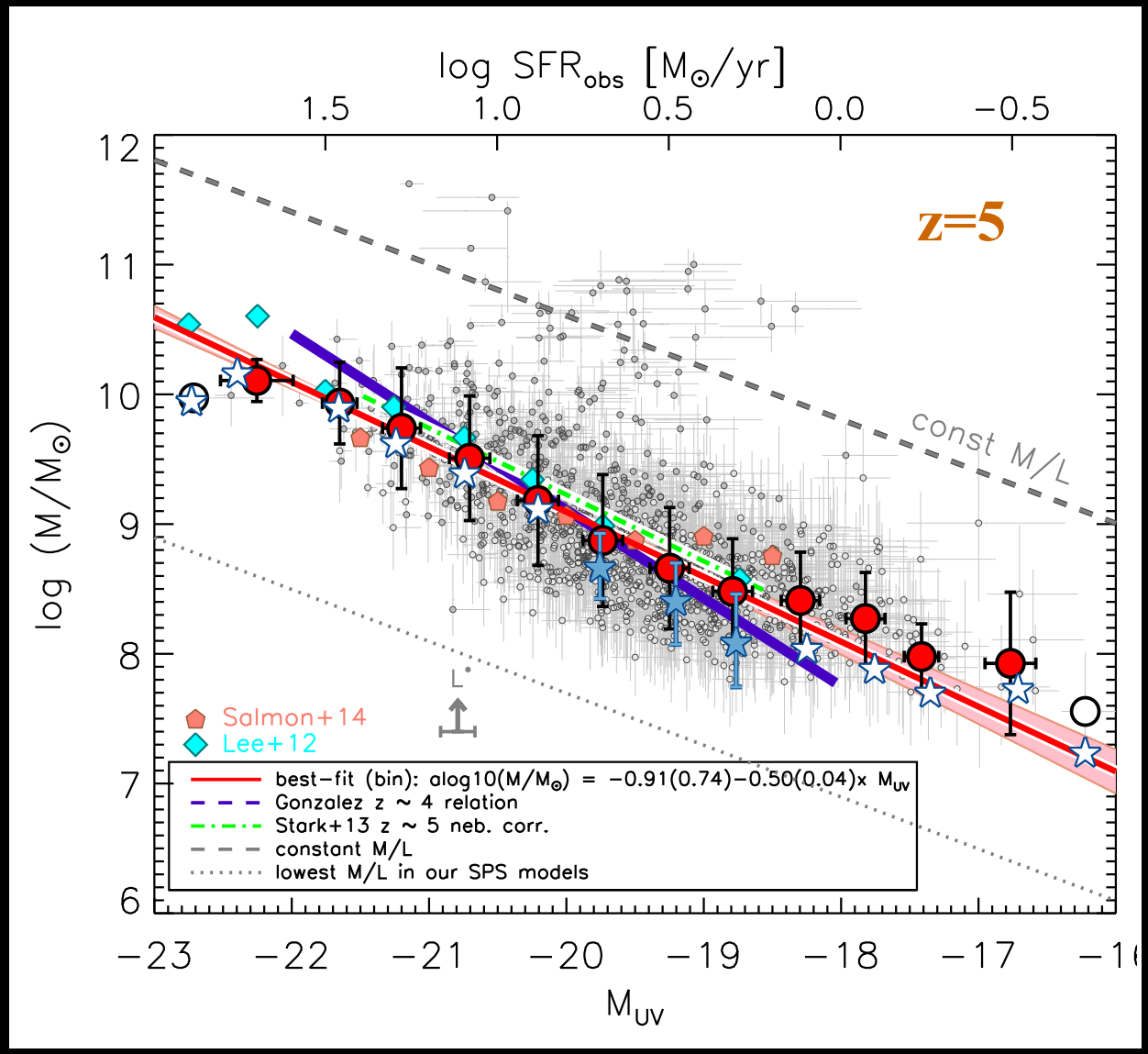
(20 realizations for each input slope and redshift)

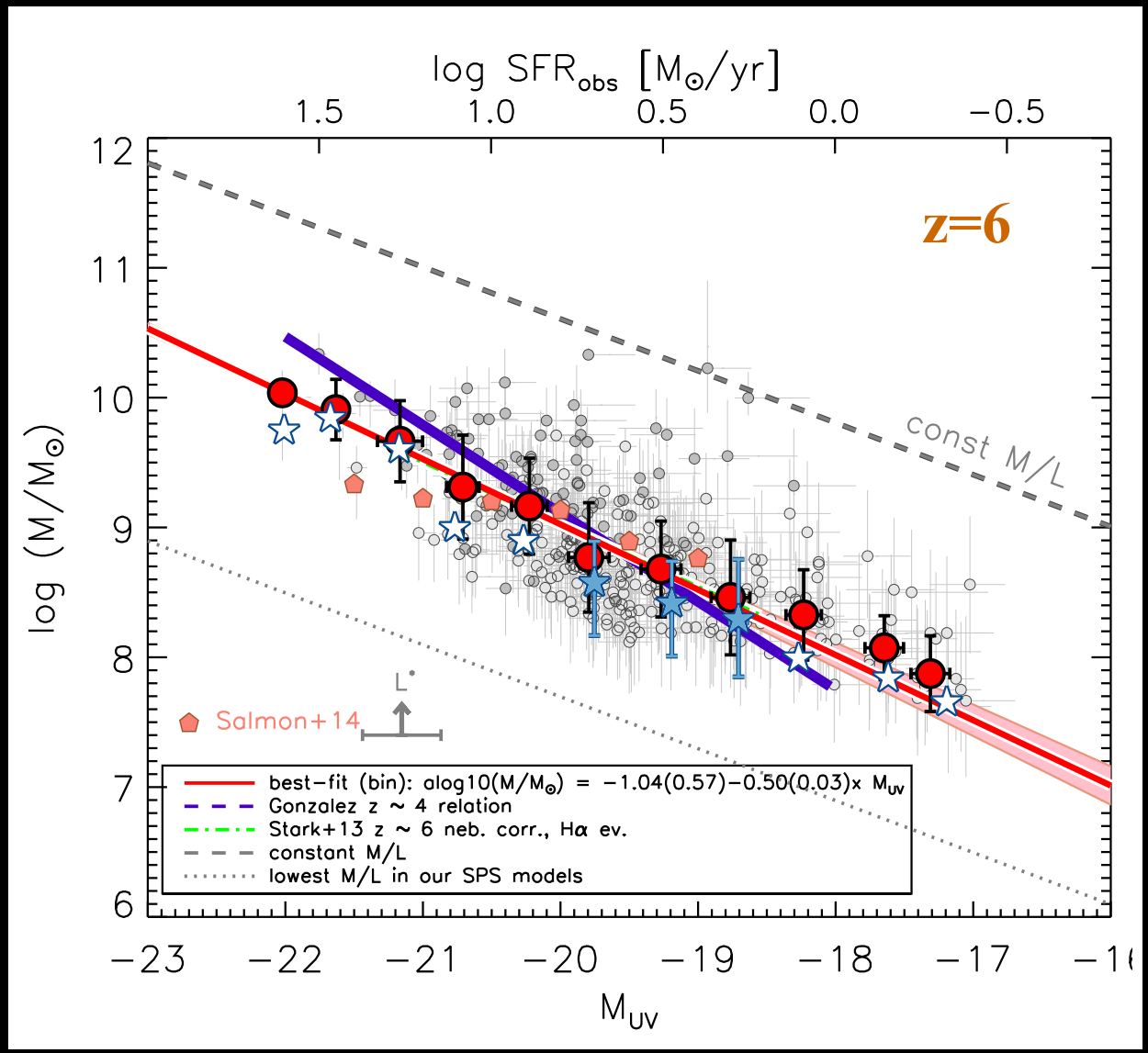


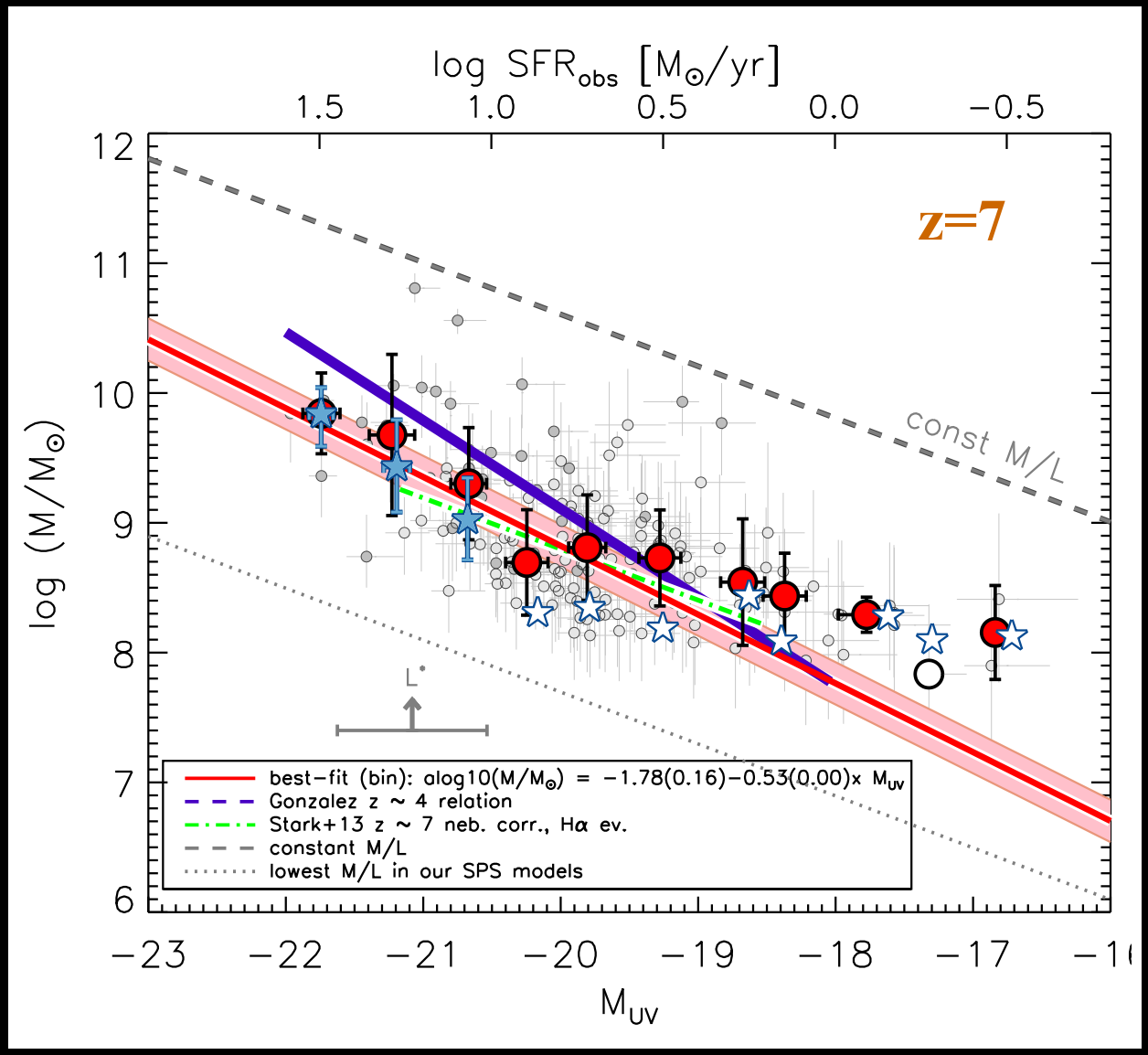
M-L slope
from our real sample

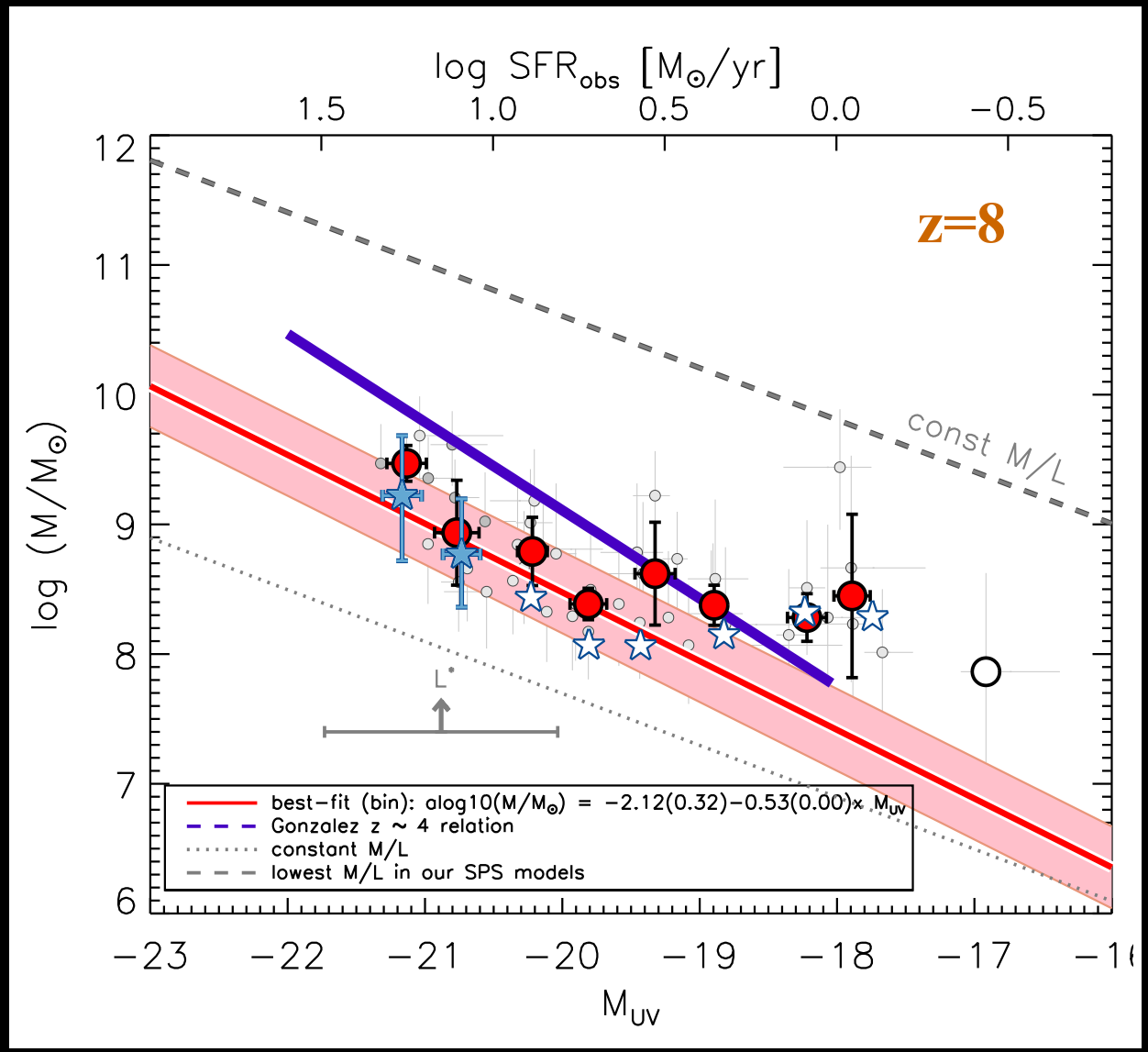



log SFR$_{obs}$ [M$_\odot$/yr]
1.5
1.0
0.5
0.0
−0.5
z=4
const M/L
log (M/M$_\odot$)
12
11
10
9
8
7
6
Salmon+14
Lee+12
best−fit (bin): alog10(M/M$_\odot$) = −1.72(0.64)−0.54(0.03)x M$_{UV}$
Gonzalez z ~ 4 relation
Stark+13 z ~ 4 neb. corr.
constant M/L
lowest M/L in our SPS models
−23
−22
−21
−20
−19
−18
−17
M$_{UV}$

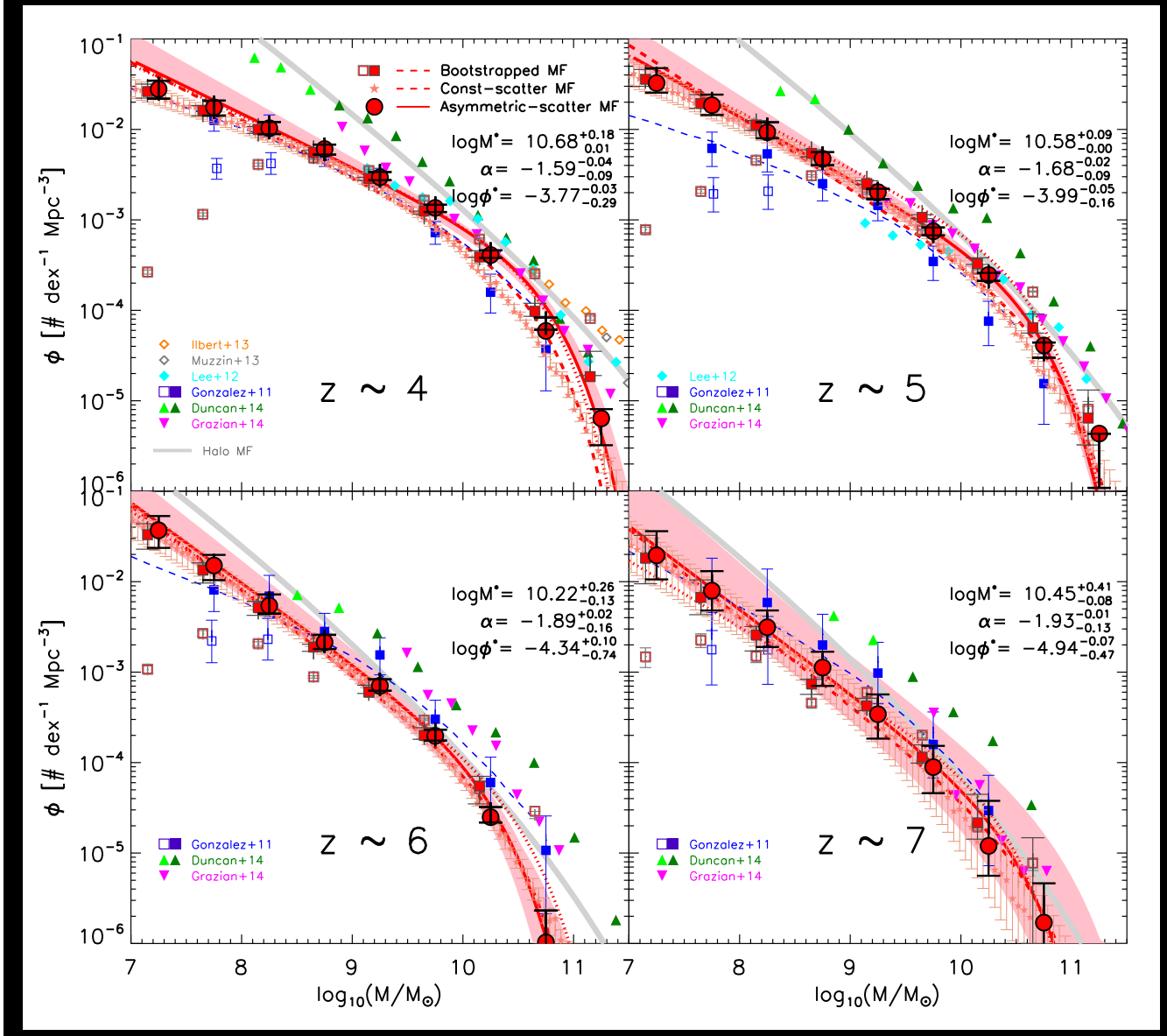

log SFR$_{obs}$ [M$_\odot$/yr]
1.5
1.0
0.5
0.0
−0.5
z=5
const M/L
log (M/M$_\odot$)
12
11
10
9
8
7
6
L*
Salmon+14
Lee+12
best−fit (bin): alog10(M/M$_\odot$) = −0.91(0.74)−0.50(0.04)x M$_{UV}$
Gonzalez z ~ 4 relation
Stark+13 z ~ 5 neb. corr.
constant M/L
lowest M/L in our SPS models
−23
−22
−21
−20
−19
−18
−17
M$_{UV}$


log SFR$_{obs}$ [M$_\odot$/yr]
1.5
1.0
0.5
0.0
−0.5
z=6
const M/L
log (M/M$_\odot$)
12
11
10
9
8
7
6
L*
Salmon+14
best−fit (bin): alog10(M/M$_\odot$) = −1.04(0.57)−0.50(0.03)× M$_{UV}$
Gonzalez z ~ 4 relation
Stark+13 z ~ 6 neb. corr., Hα ev.
constant M/L
lowest M/L in our SPS models
−23
−22
−21
−20
−19
−18
−17
M$_{UV}$


log SFR$_{obs}$ [M$_\odot$/yr]
1.5
1.0
0.5
0.0
−0.5
z=7
const M/L
log (M/M$_\odot$)
12
11
10
9
8
7
6
L*
best−fit (bin): alog10(M/M$_\odot$) = −1.78(0.16)−0.53(0.00)x M$_{UV}$
Gonzalez z ~ 4 relation
Stark+13 z ~ 7 neb. corr., Hα ev.
constant M/L
lowest M/L in our SPS models
−23
−22
−21
−20
−19
−18
−17
M$_{UV}$


log SFR$_{obs}$ [M$_\odot$/yr]
1.5
1.0
0.5
0.0
−0.5
z=8
const M/L
log (M/M$_\odot$)
12
11
10
9
8
7
6
L*
best−fit (bin): alog10(M/M$_\odot$) = −2.12(0.32)−0.53(0.00)× M$_{UV}$
Gonzalez z ~ 4 relation
constant M/L
lowest M/L in our SPS models
−23
−22
−21
−20
−19
−18
−17
M$_{UV}$

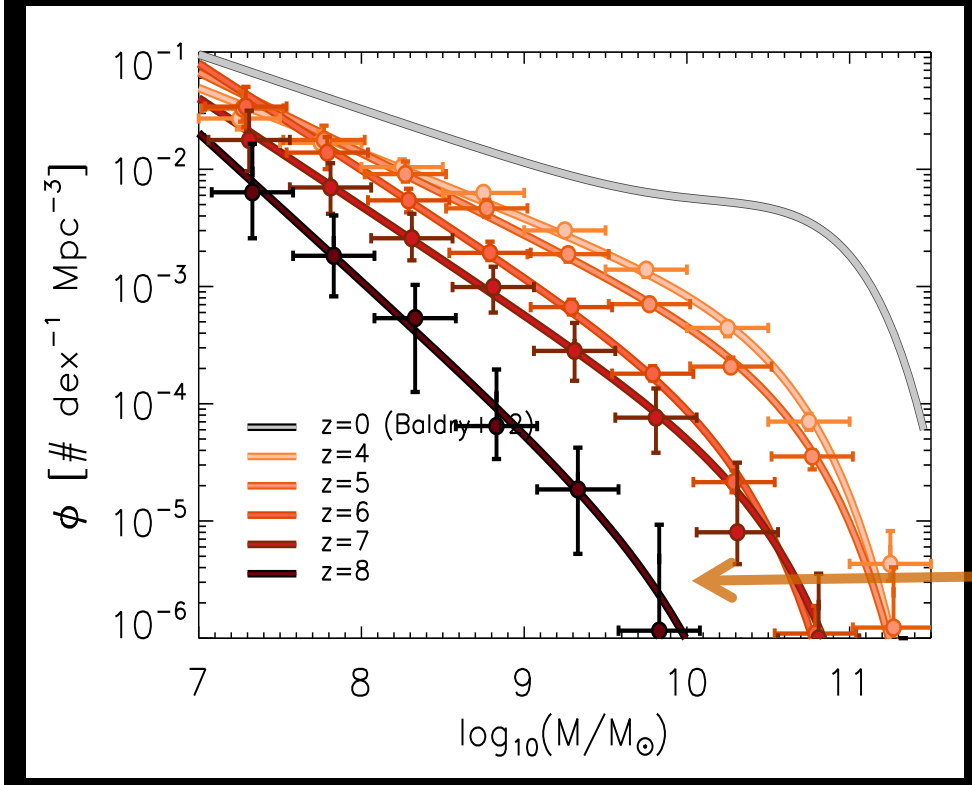
New MF at z=4-7



- MFs of SFGs

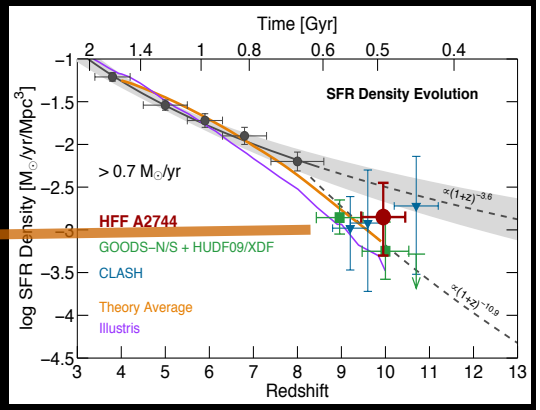
Song+15 (in prep)
Gonzalez+11
Grazian+14
Duncan+14

Galaxy Growth at z=4-7

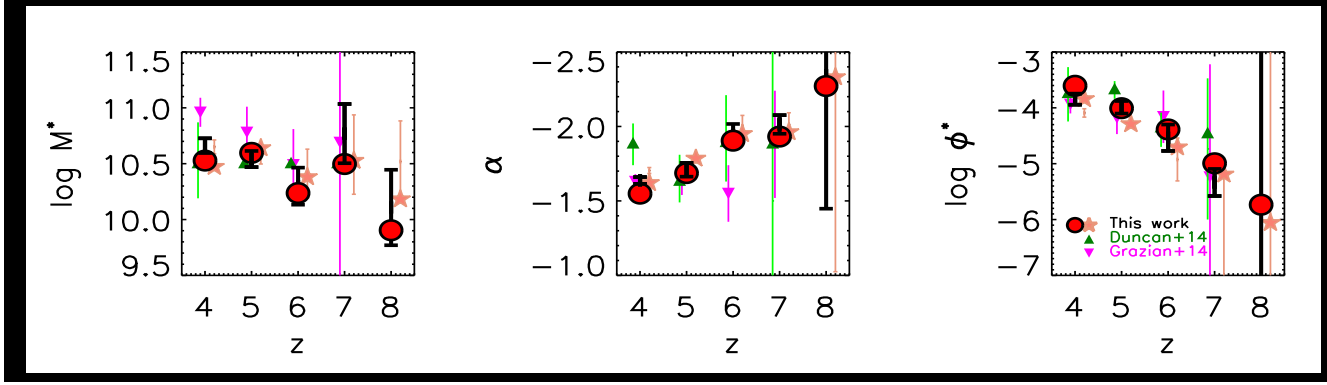


- Steep low-mass-end slope (α)
- Redshift evolution:
  - No evolution in M*
  - Steepening α

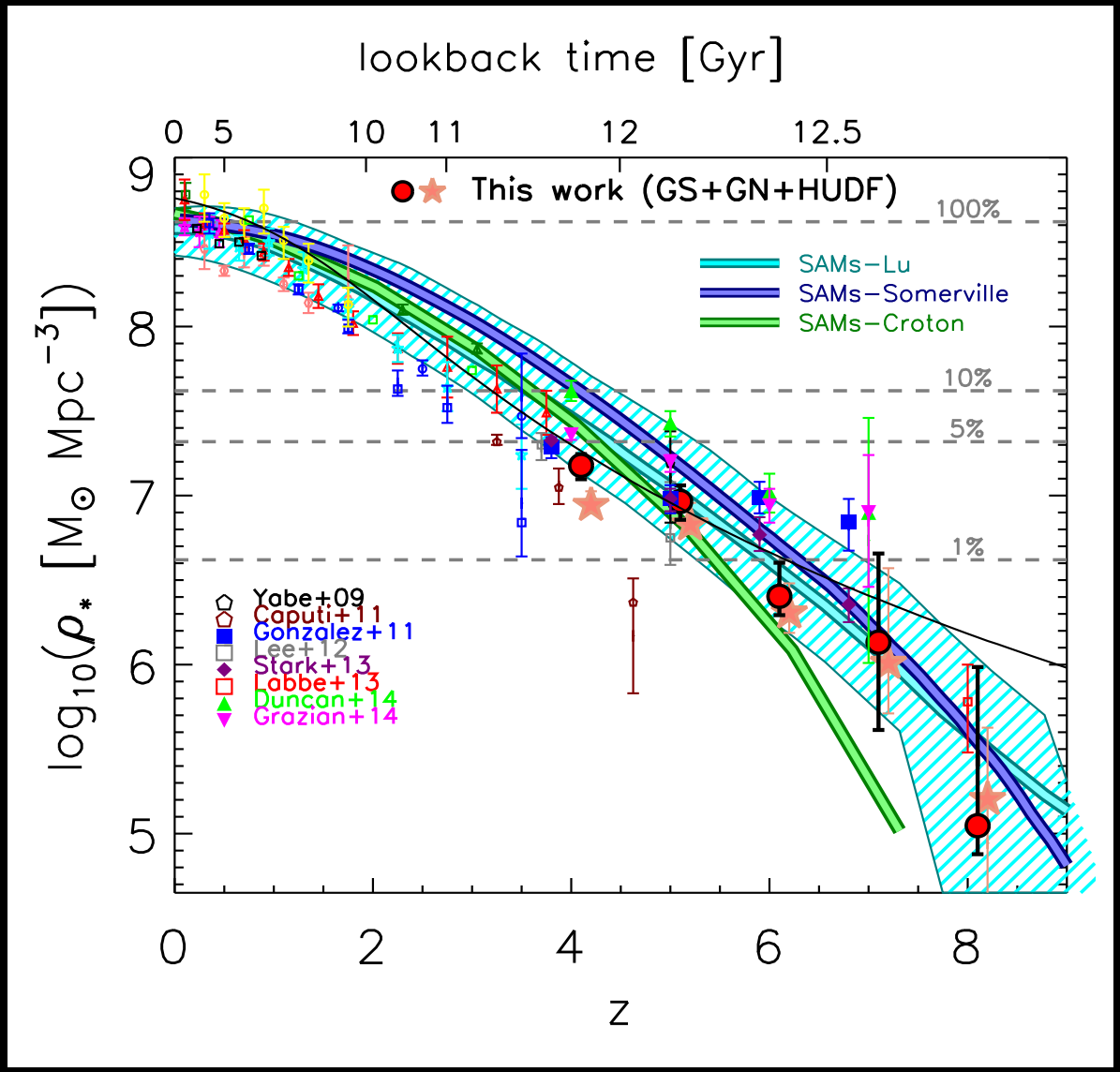
Imprint on MF of the sudden drop in SFRD at z>8 ?



(Oesch+2014)



Stellar mass growth since z~8



Summary

Galaxy Stellar Mass Function at z=4-7

- Combining HST and Spitzer/ IRAC data is extremely powerful to probe the stellar mass build-up out to z=7!
- New MFs at z=4-7 now with
  - a factor of magnitude increased sample
  - the deepest Spitzer/IRAC data yet-to-date with a deblending photometry
  - credibility test via mock galaxy simulations