Size Evolution at $z=0$-10

(Shibuya et al. 2015 in prep.)

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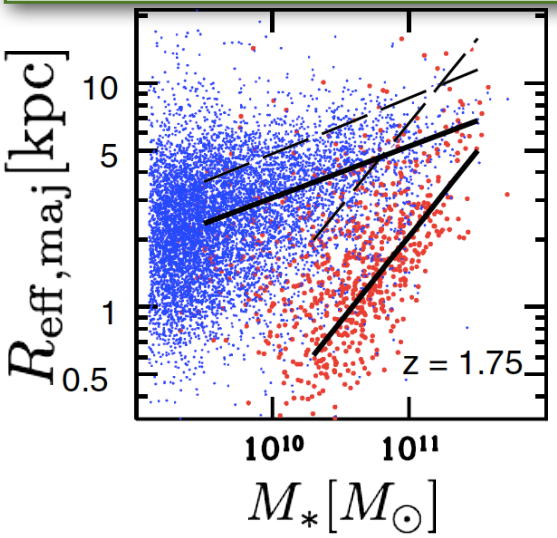
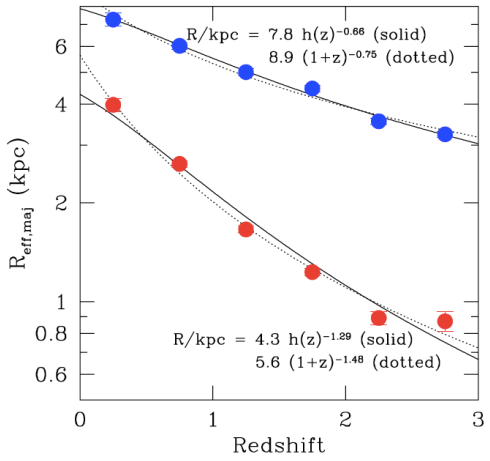
Studies on Size@$z \geqq 4$

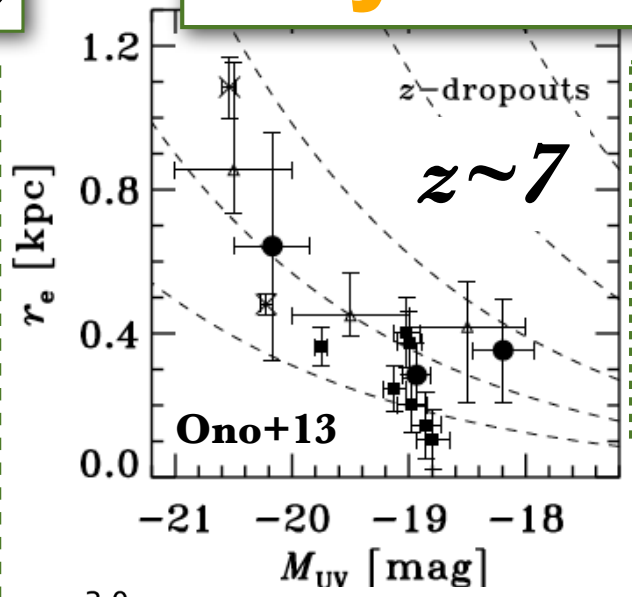
Intensive Studies for SFGs/QGs@$z=0\sim3$

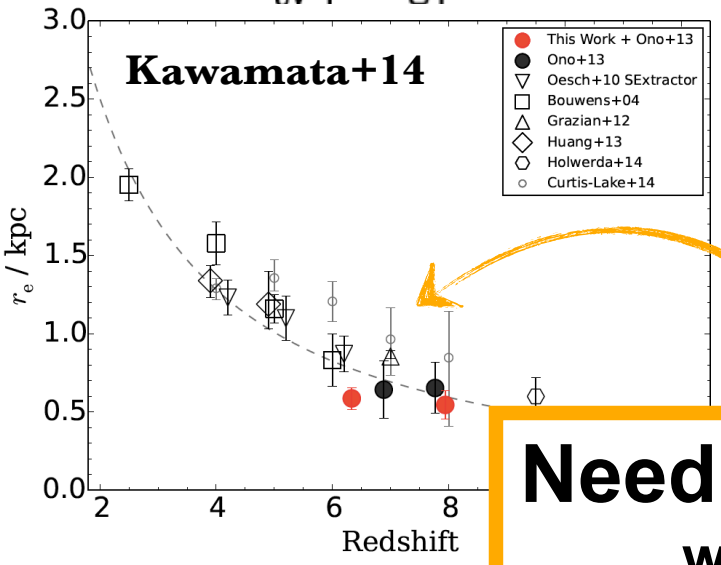




van der Wel+14

Beyond $z\sim4$?





- ✓ r_e-M (or L) relation evolve?
- ✓ $r_e \propto H(z)^{\beta=?}$ @$z \geqq 4$
- ✓ r_e-related quantities?

→ $\Sigma_{\rm SFR}$, $r_e/r_{\rm DM}$, $\sigma(r_e)$ …

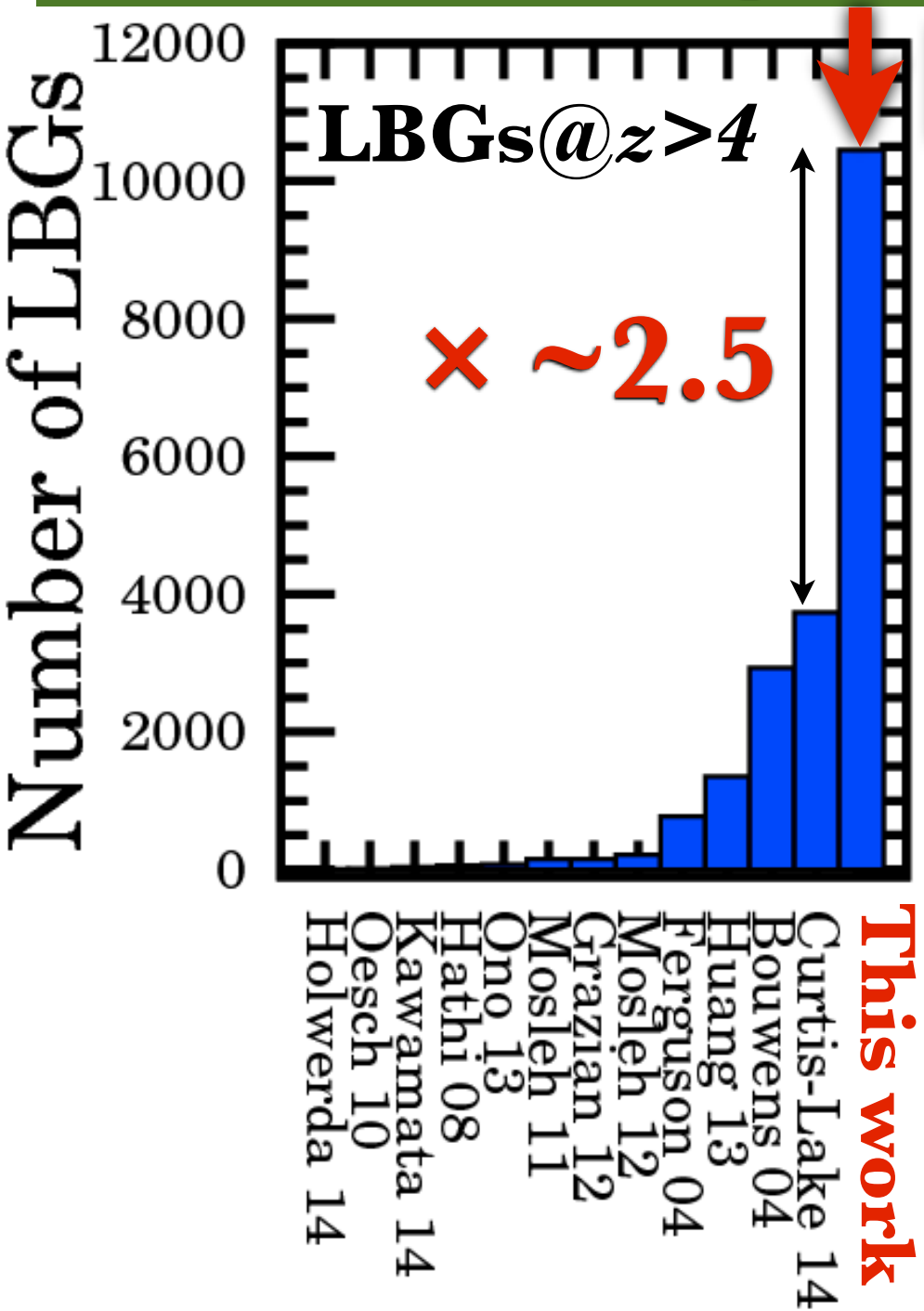
But, for $z \geqq 4$

- ✓ Small samples
- ✓ Data points in different tech.

Need to study r_e@$z=0$-10 w/ larger sample & self-consistent tech.

eg, many authors in this meeting.

Sample Galaxies



LBGs in deep *HST* Fields

- ✓5 CANDELS fields (AEGIS, COSMOS, UDS, GOODS-S/N)
- ✓HUDF 09/12
- ✓2 Parallel fields of HFF (Abell 2744, MACS 0416)

LBG selection of Bouwens+14

→ 10454 LBGs@z=*4-10*

~1000 even@$z \geqq 7$

incl. photo-z sample@z=*0-6* of 3D-*HST* (Skelton+14)

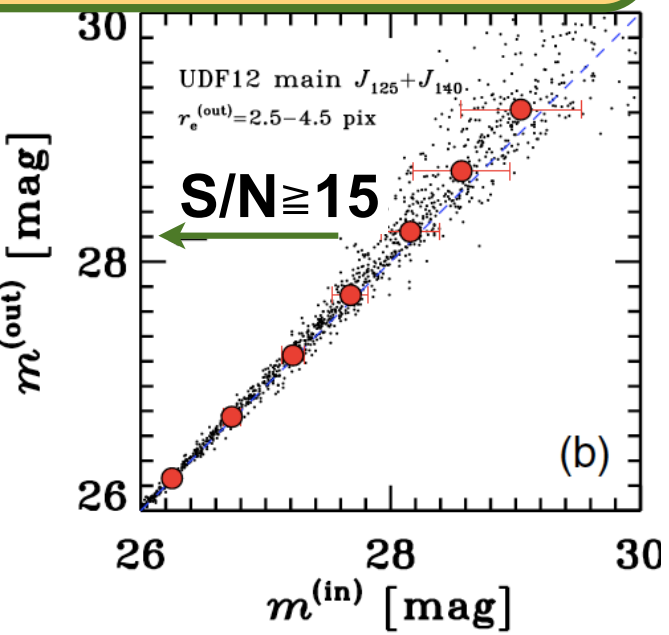
- ✓165517 SFGs
- ✓10631 QGs

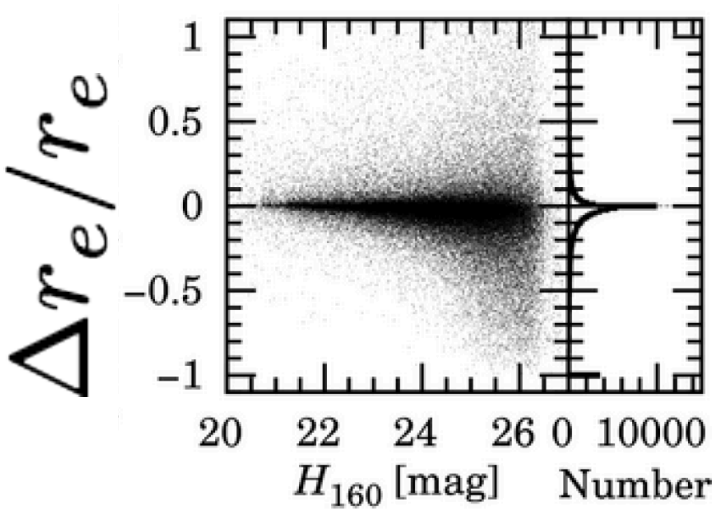
Size Measurements

Same as in eg, Mosleh+12, Ono+12

- ✓Single Sersic prof. w/ GALFIT
- ✓Circularlized r_e to well fit faint sources and fair comparison w/ high-z
- ✓V_{606}, I_{814}, J_{125}, H_{160} img
- ✓r_e@UV and/or Opt.
- ✓Free n (photo-z), n=1.5 (LBGs)
- ✓S/N≧15

MC simulation (Ono+13) for faint & small sources

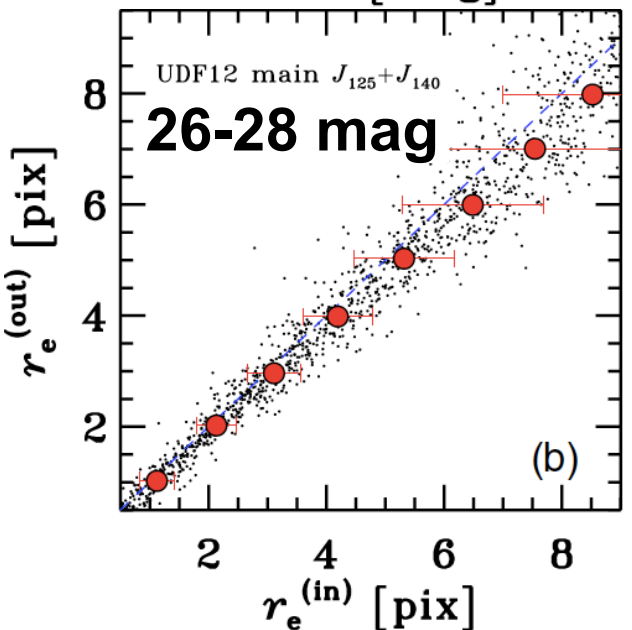




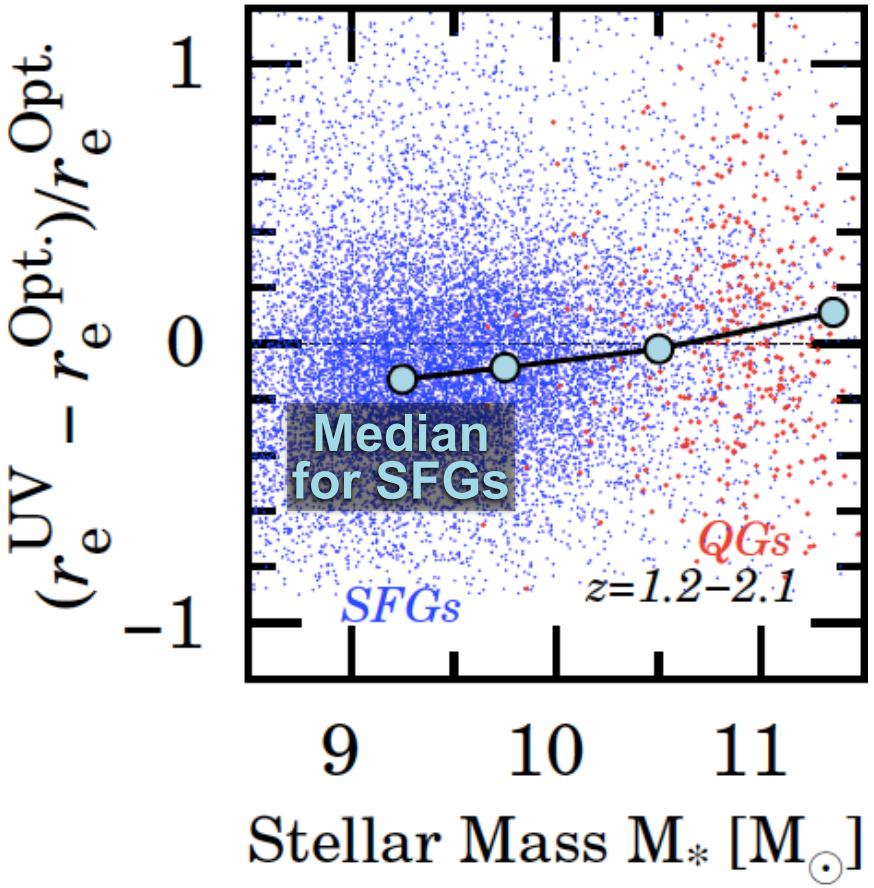
Comparison w/ GALAPAGOS

(van der Wel+14)

→ **Good agreement for obj w/ high S/N**



Effect of Morpho K-correction



✓Compare r_e^{UV} w/ $r_e^{Opt.}$ @z=1-2

✓Smaller r_e in redder bands in log $M_* \geqq 10.5$

✓Small difference in lower-M_*

✓Consistent w/ e.g., van der Wel+14, Kelvin+12, Vulcani+13, Haeussler's talk

Small effect on circularized r_e

→ We can connect $r_e^{Opt.}$@z<2 w/ r_e^{UV} for z=2-6 SFGs & z=4-10 LBGs

But, also discuss evolution excl. $r_e^{Opt.}$

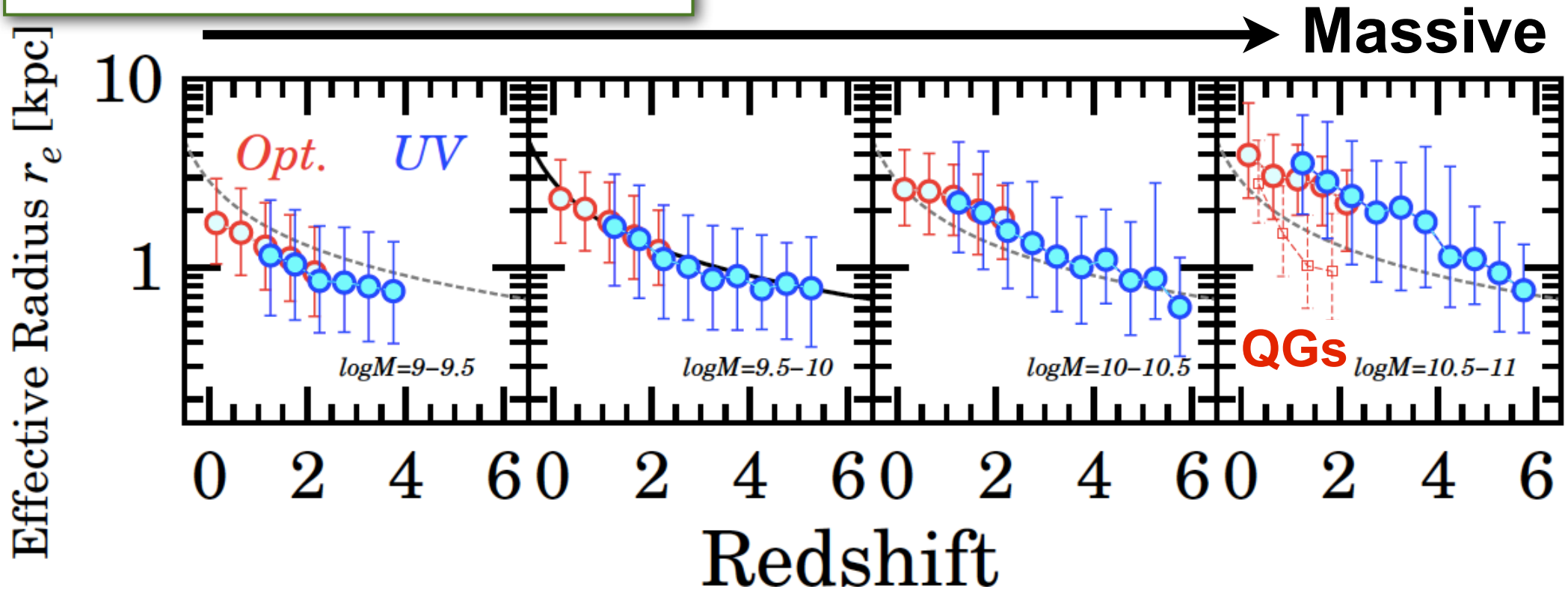
Photo-z sample

@z=0-6

in M_* bin

Properties of Photo-z Galaxies

1. Effective Radius r_e



✓**Smoothly connect r_e^{UV} w/ $r_e^{Opt.}$ @z=1-2 in all M$_*$-bins**

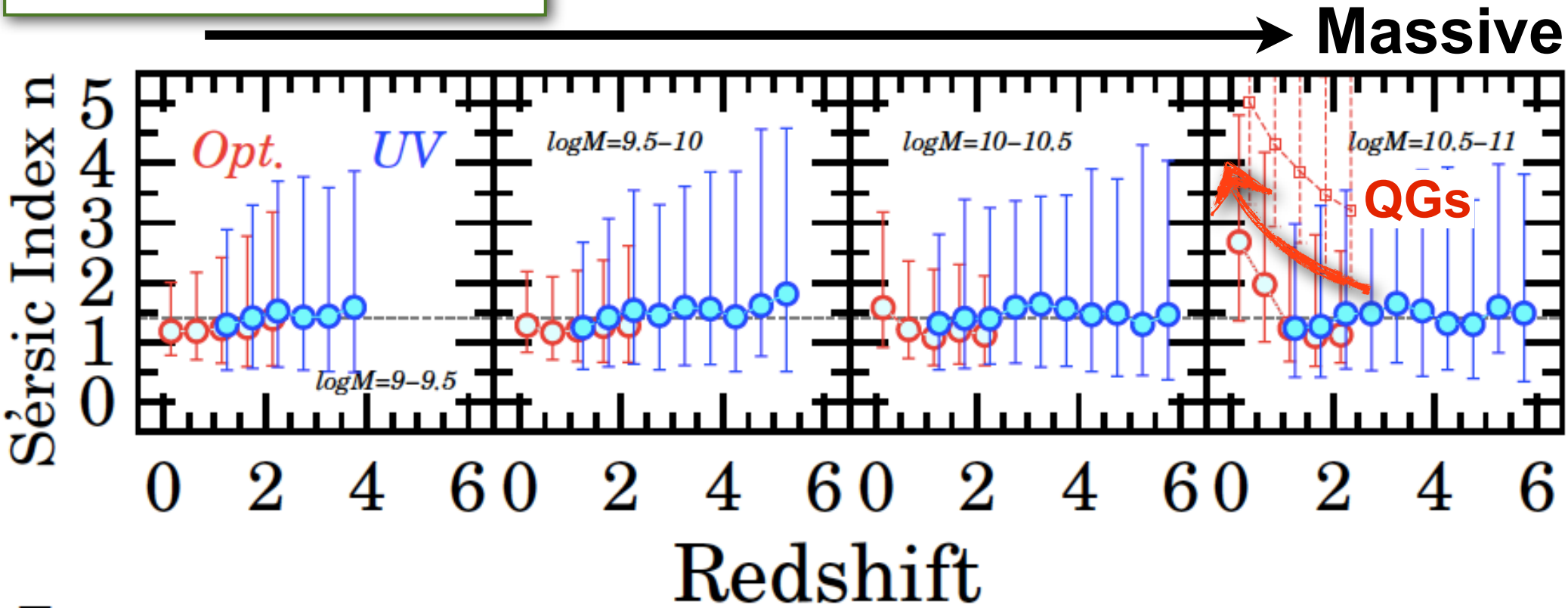
✓**Similar trends at $r_e^{Opt.}$@z=1-2 & r_e^{UV}@z=2-6**

$$r_e \propto h(z)^{\sim -0.65}$$

→ **consistent w/ eg, van der Wel results**

Properties of Photo-z Galaxies

2. Sersic Index n



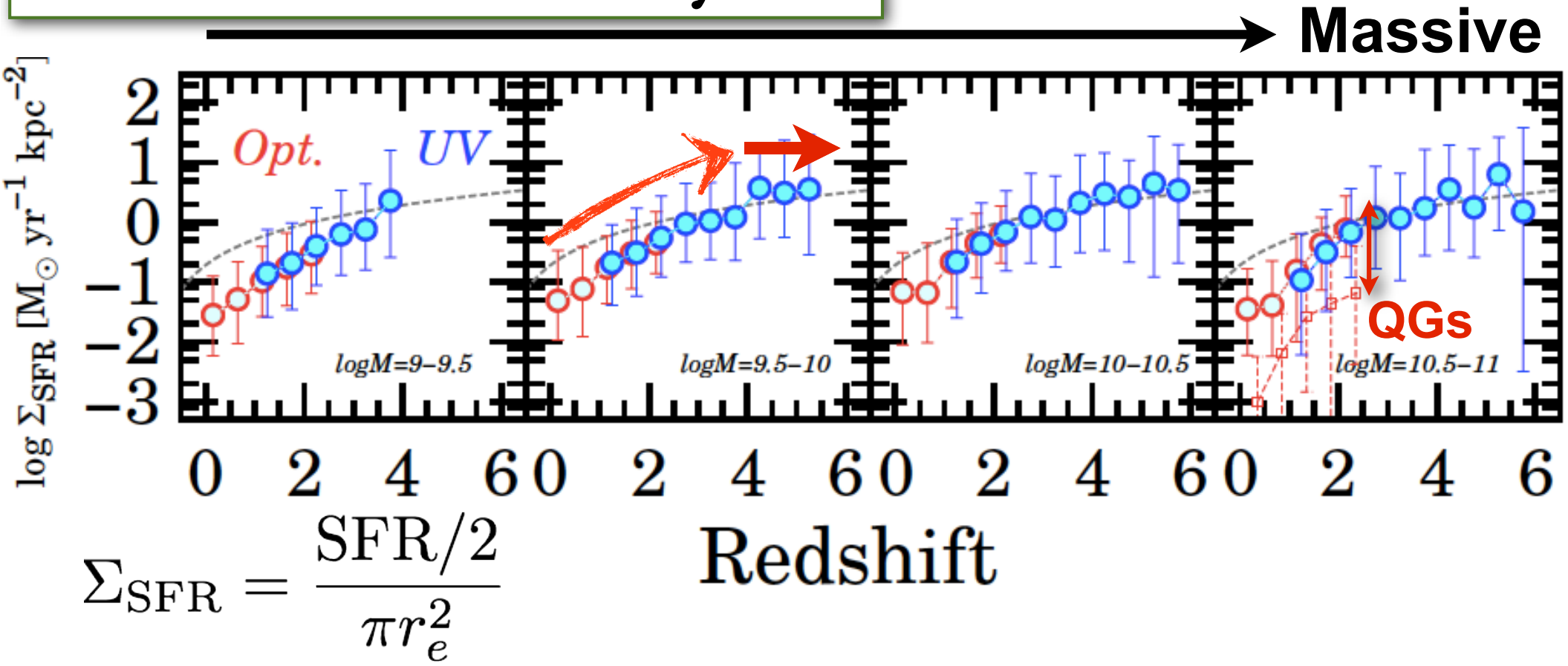
✓Constant n of n=1.5 for SFGs@z=0-6

✓Robustness of fixing n for LBGs@z>4

✓Increase@z<2 in massive bins (e.g., Buitrago+12, Huertas-Company+15, Vika+)

Properties of Photo-z Galaxies

3. SFR Surface Density Σ_{SFR}



$$\Sigma_{\rm SFR} = \frac{\rm SFR/2}{\pi r_e^2}$$

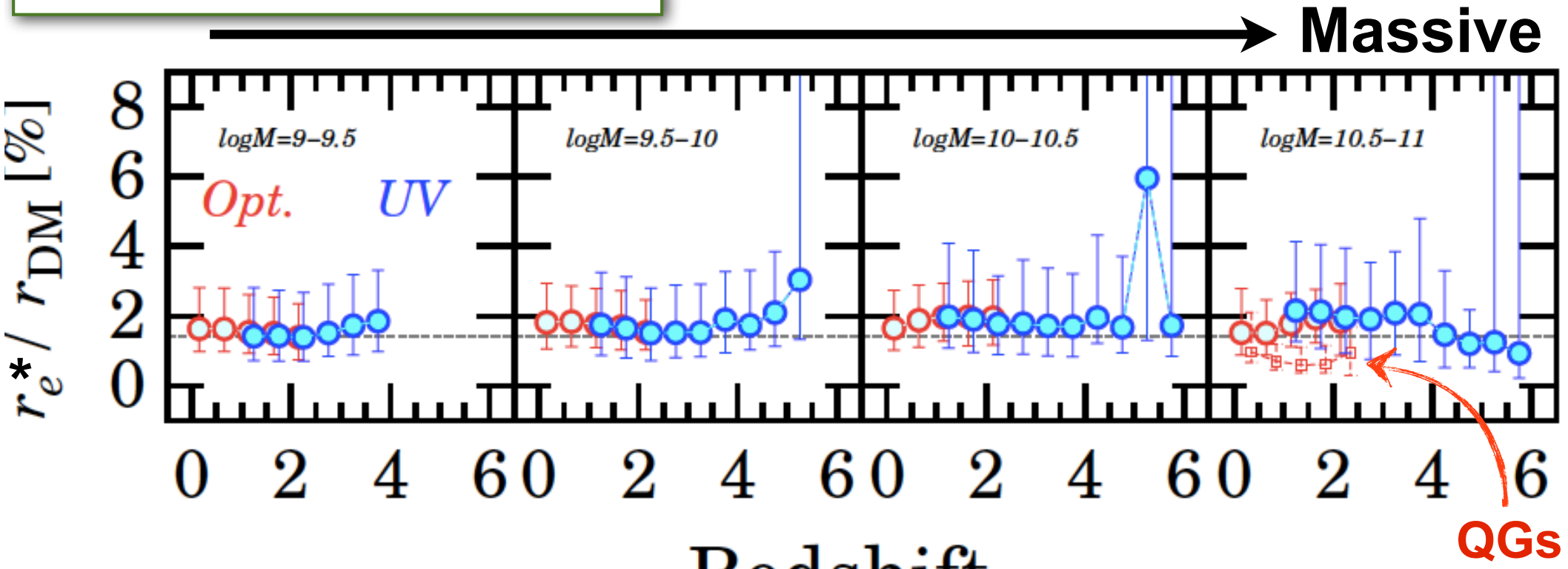
✓~1 order of mag larger Σ_{SFG} for SFGs than for QGs

✓Increase@z=0→4

✓But, plateau@z>4 ? → discuss later

Properties of Photo-z Galaxies

4. Size Ratio $r_e^*/r_{\rm DM}$



Virial radius
$r_{\rm DM,\ 200}$

$$r_{\rm DM} = \left(\frac{GM_{\rm DM}}{100H(z)^2} \right)^{1/3}$$

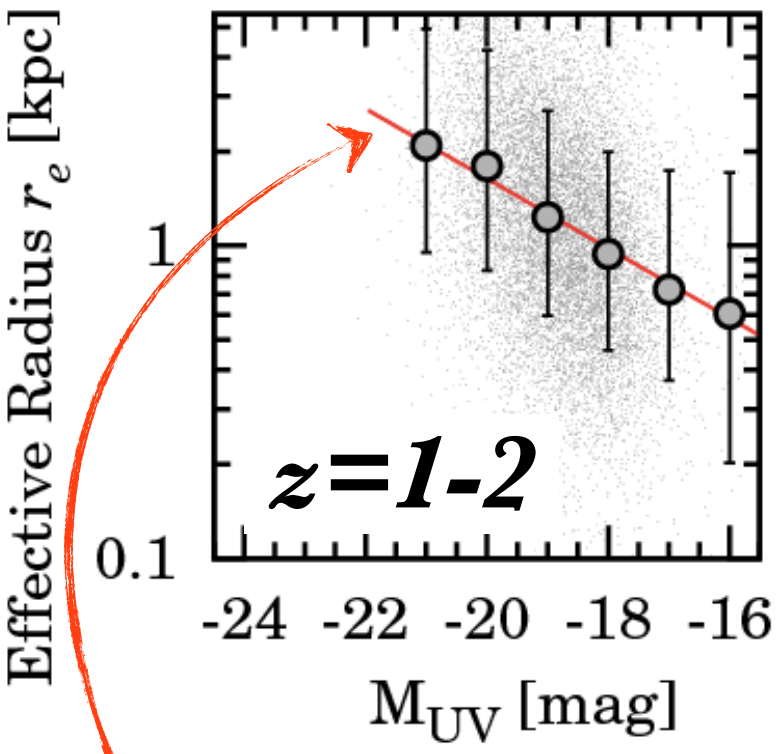
Behroozi+13, Abundance matching tech
$M_* \rightarrow M_{\rm DM}$

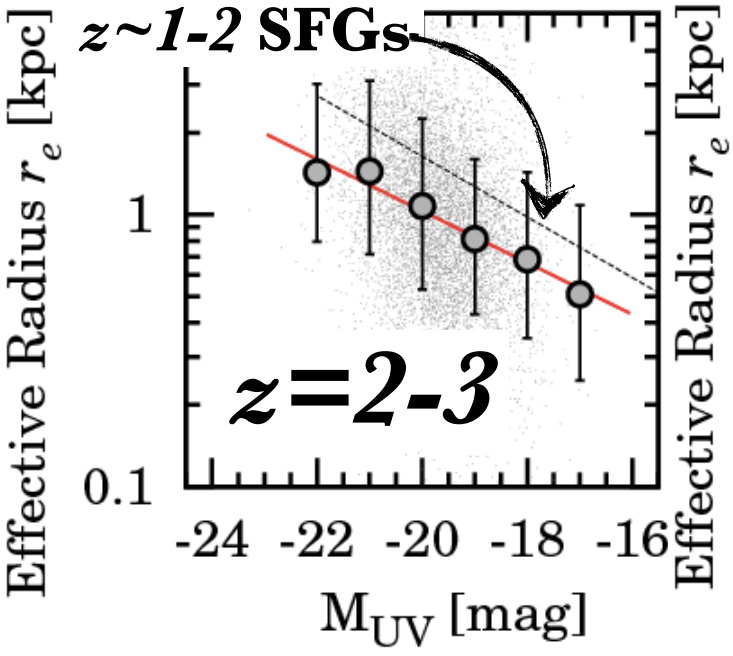
✓**No evolution** of $r_e/r_{\rm DM}$

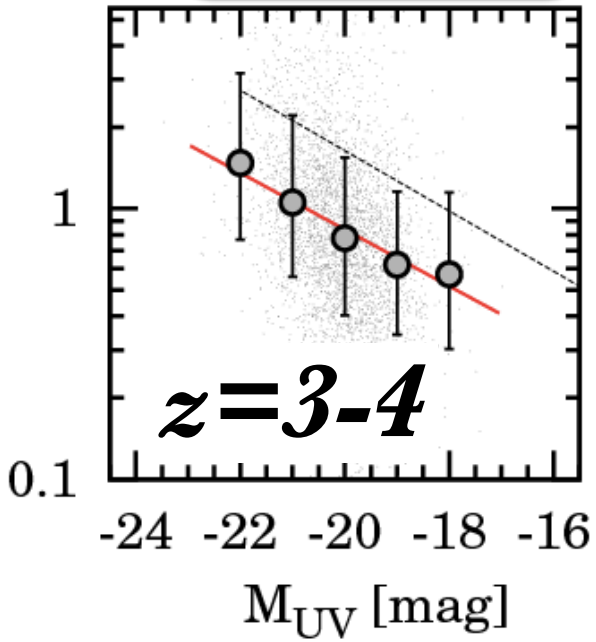
✓$r_e^*/r_{\rm DM}$ ~ 2-3 % for **SFGs**, ~1 % for **QGs**

Size Evolution incl. LBGs@z=0-10 in $L_{\rm UV}$ bin

Size-Luminosity Relation SFGs

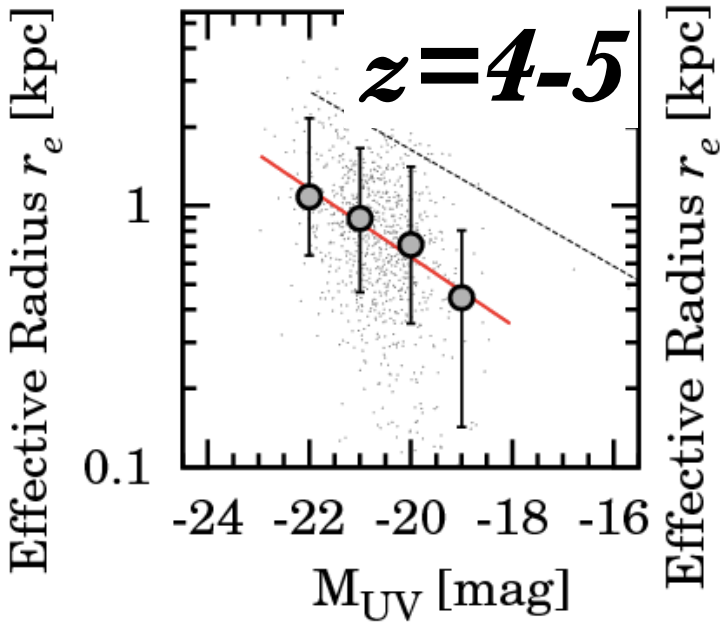


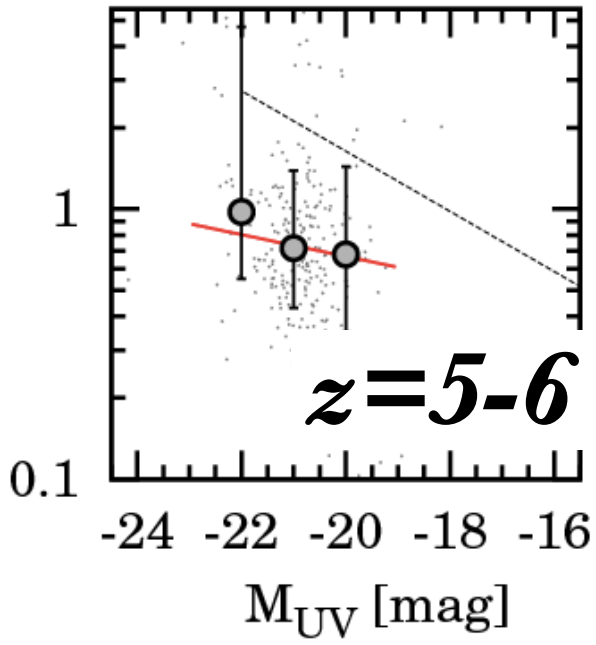




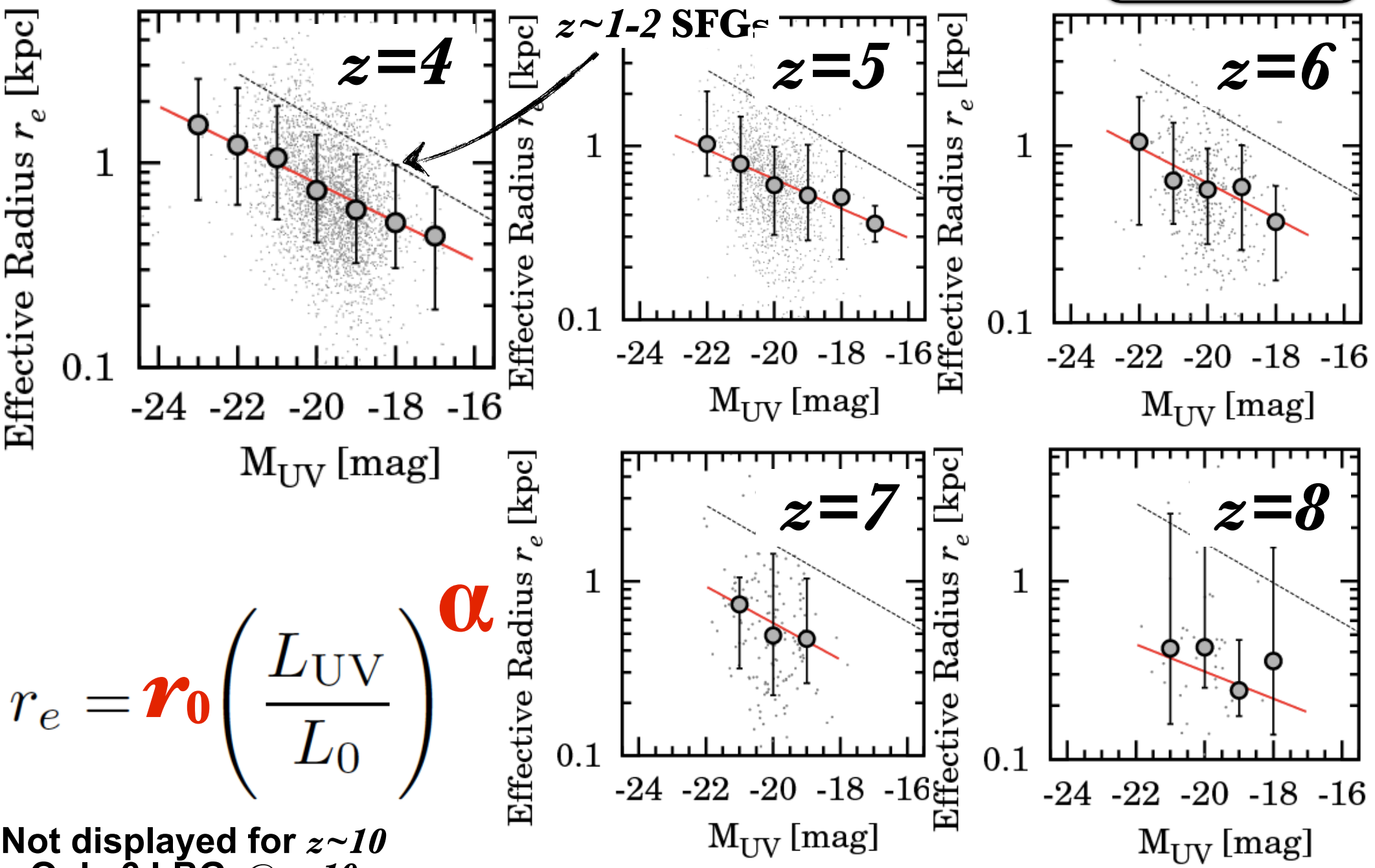
Best-fit power law
for median points

$$r_e = r_0 \left(\frac{L_{UV}}{L_0} \right)^{\alpha}$$





Size-Luminosity Relation LBGs

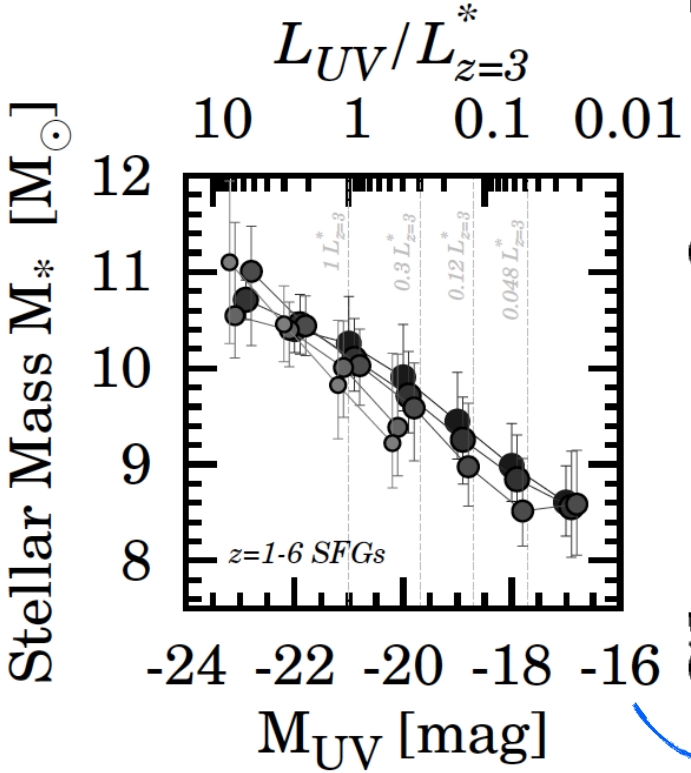


$$r_e = r_0 \left(\frac{L_{UV}}{L_0} \right)^{\alpha}$$

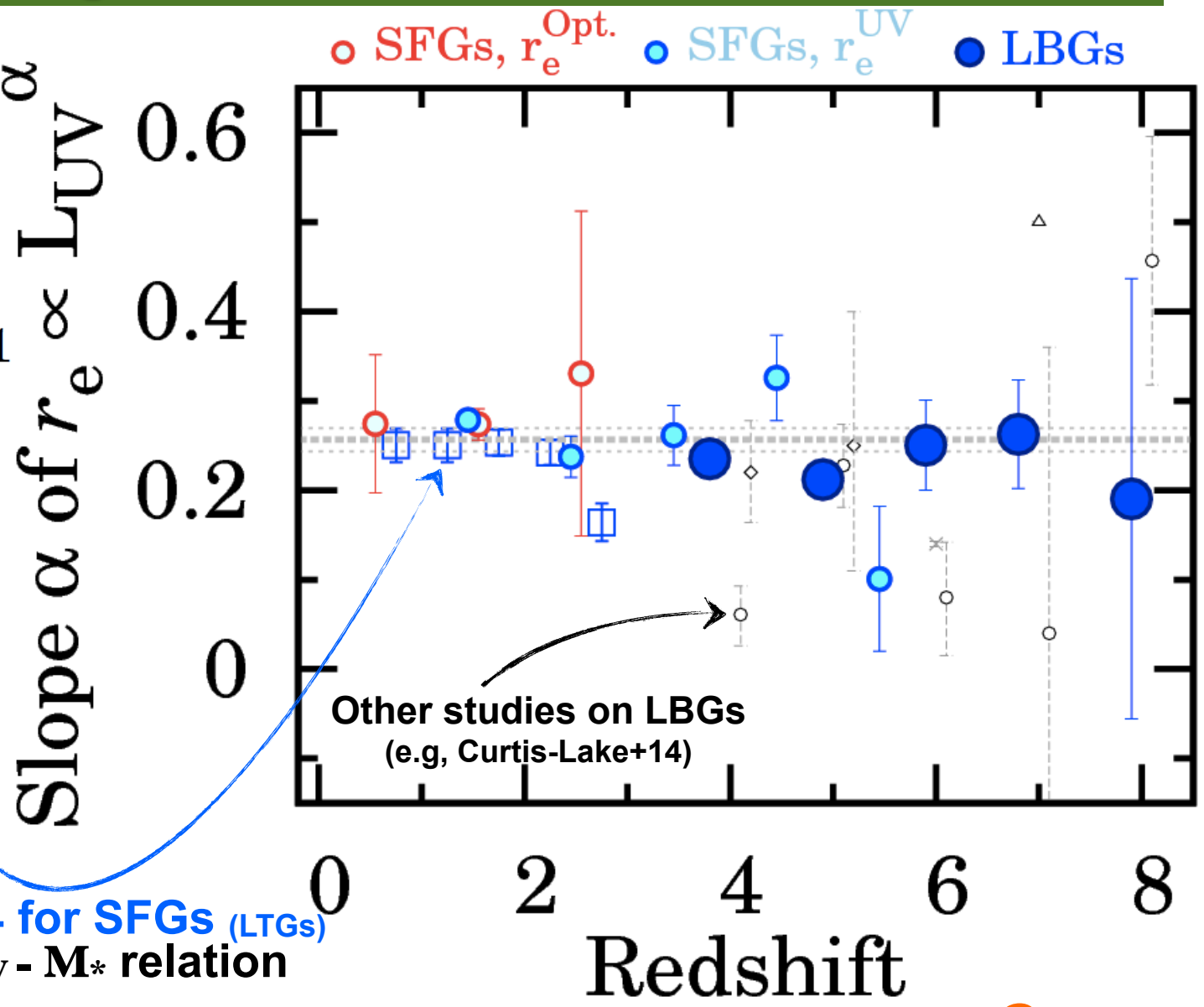
Not displayed for *z~10*
Only 6 LBGs@*z~10*

Slope Evolution

$$r_e = r_0 \left(\frac{L_{\rm UV}}{L_0} \right)^{\alpha}$$



van der Wel+14 for SFGs (LTGs)
assuming L_{UV} - M_* relation



✓**No strong evolution** of r_e - L_{UV} slope $z\sim 0$ - **8**

✓→**Strong constraint** on galaxy formation models

Size Evolution

$$r_e = r_0 \left(\frac{L_{\rm UV}}{L_0} \right)^{\alpha}$$

✓eg, Bouwens, Oesch, Mosleh

$\rightarrow (1+z)^{-1}$

$$r_{\rm DM} = \left(\frac{GM_{\rm DM}}{100H(z)^2} \right)^{1/3}$$

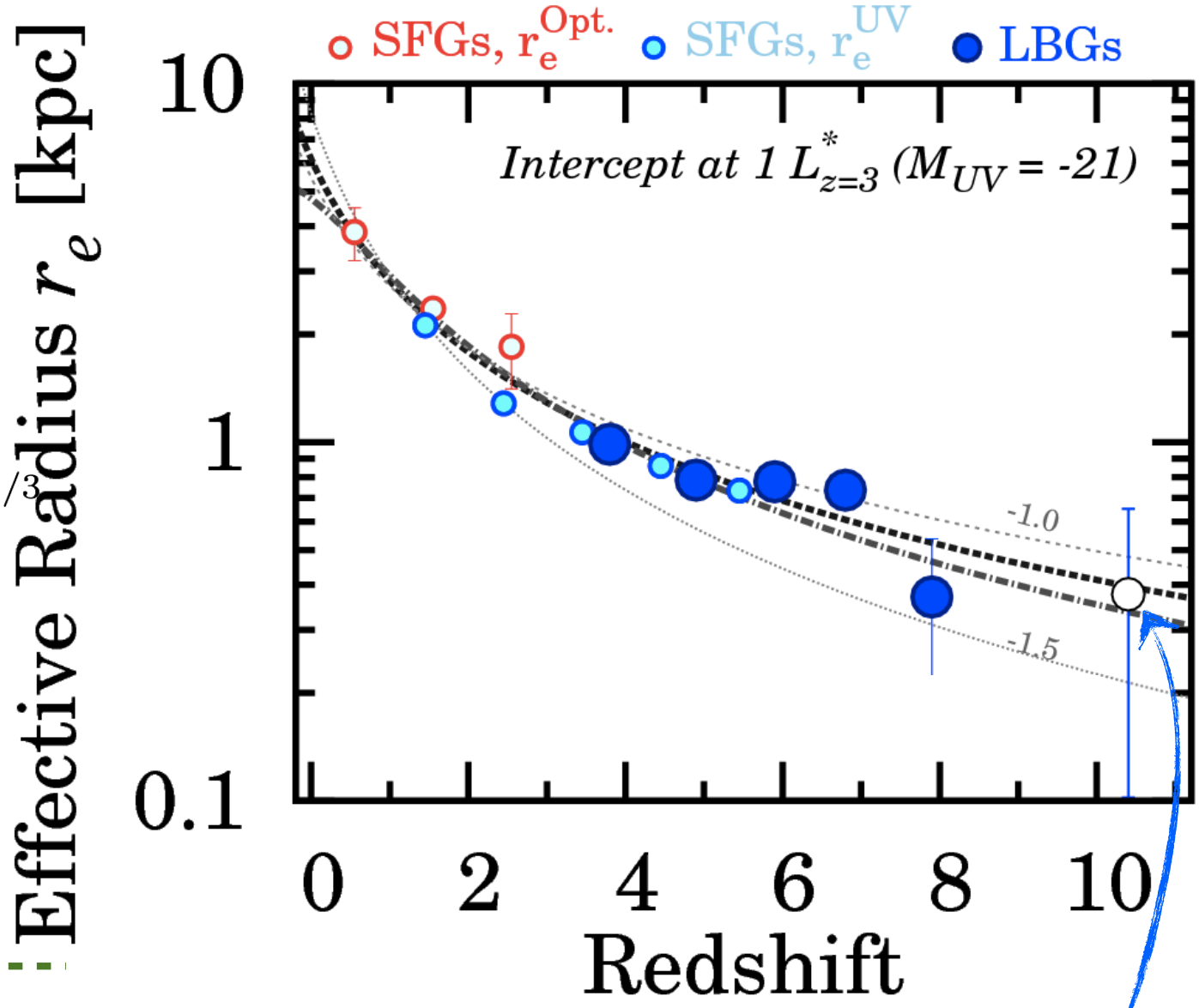
✓eg, Ferguson, Hathi

$\rightarrow (1+z)^{-1.5}$

$$= \frac{v_{\rm vir}}{10H(z)}$$

$$r_e \propto (1+z)^{-1.12} H(z)^{-0.86}$$

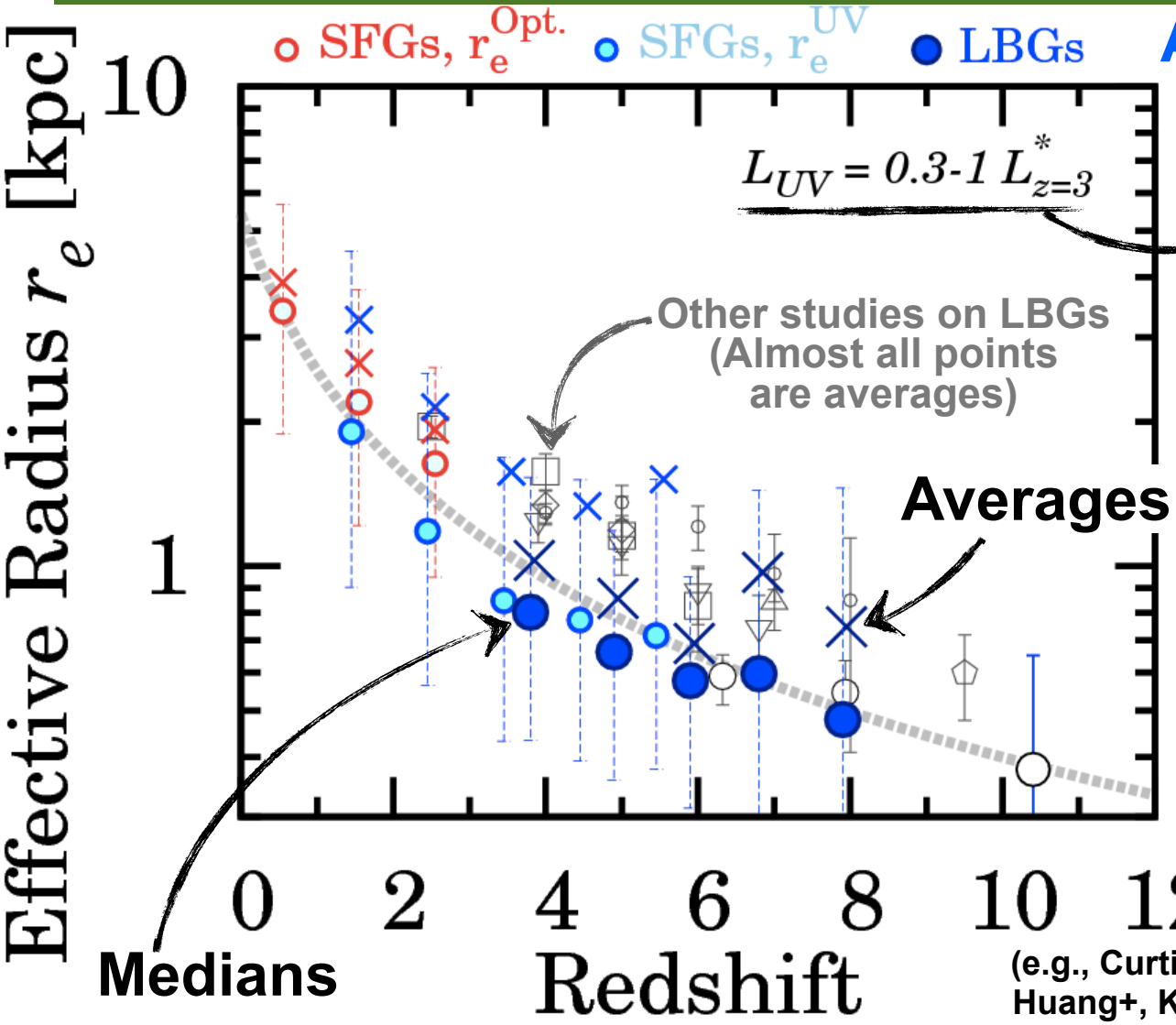
even excl. $r_e^{\rm Opt.}$



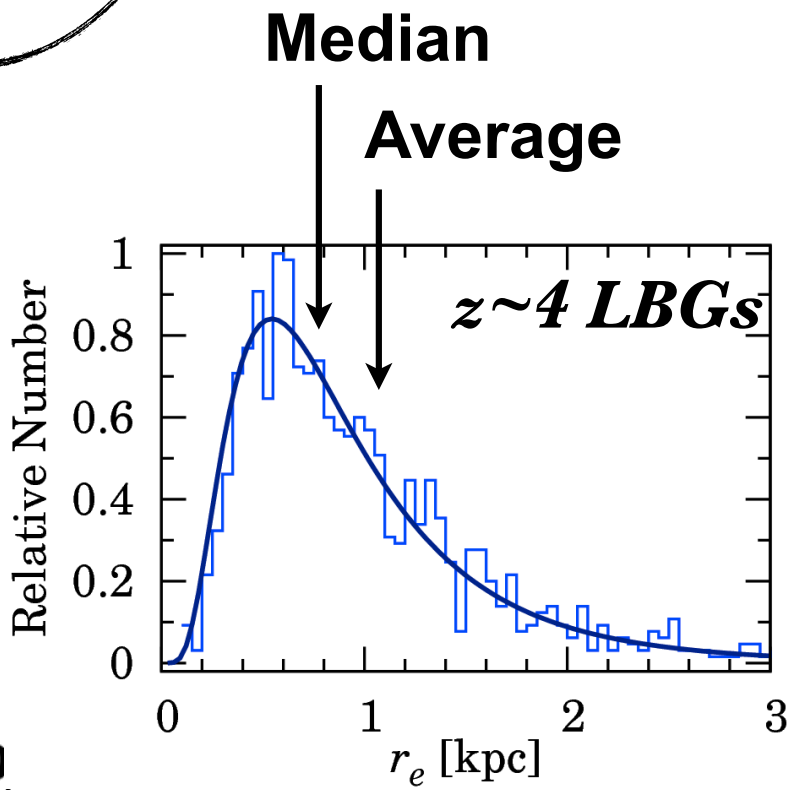
Favors evolution of constant $M_{\rm DM}$

Average@$z\sim10$ (not used for fit)

Comparison w/ Studies for $z \gtrsim 4$



All galaxies are bright in UV.



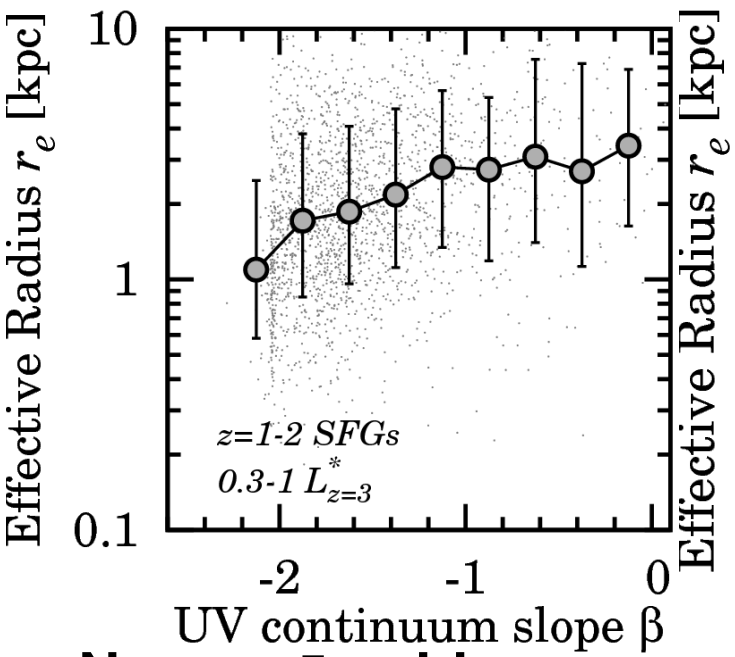
(e.g., Curtis-Lake+, Bouwens+, Oesch, Huang+, Kawamata+, Ono+, Grazian+)

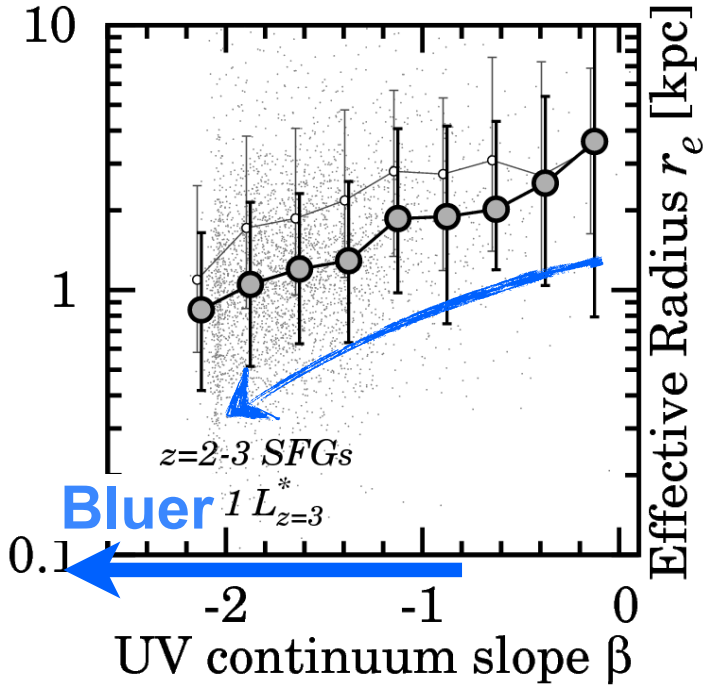
✓Averages are in good agreement w/ others

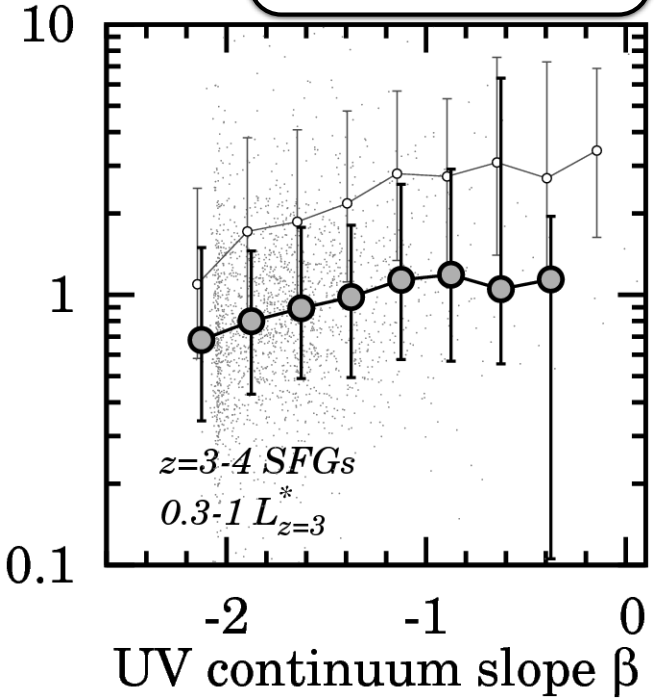
✓Medians trace well size evolution@high-z

Size - UV slope β

SFGs





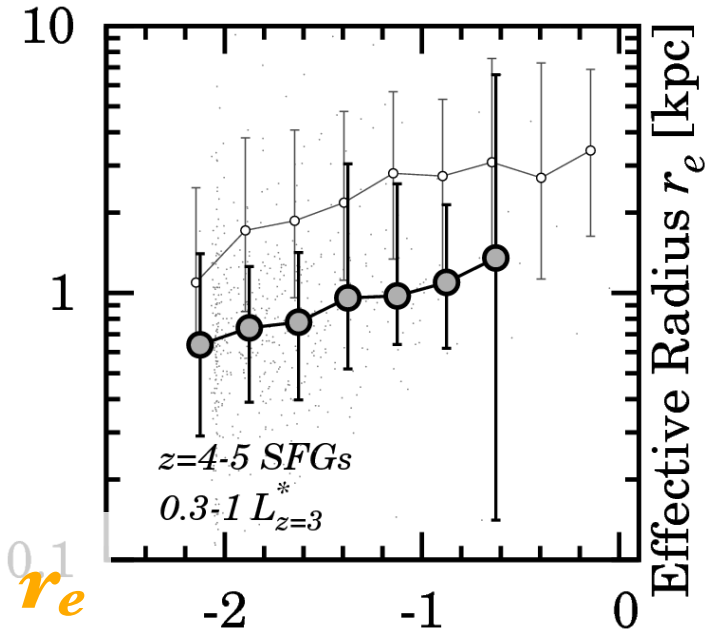


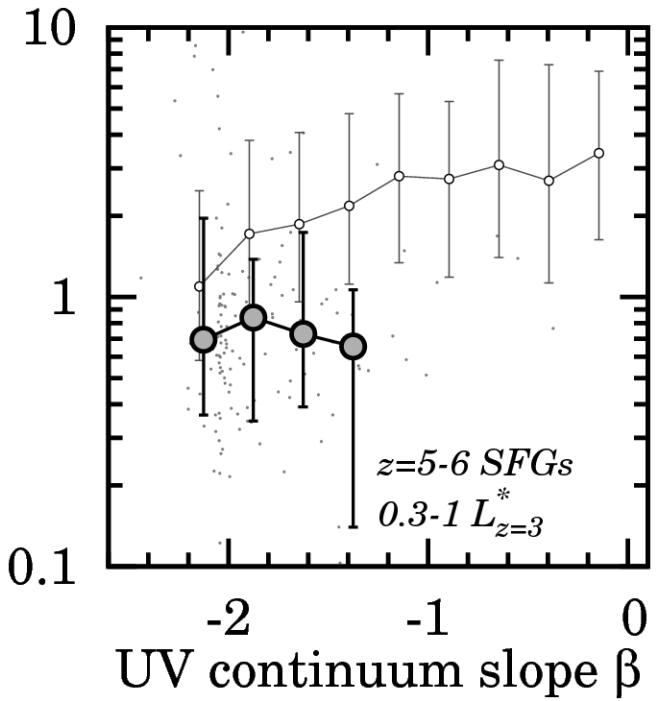
→**Narrow L_{UV} bin**

$$f_\lambda \propto \lambda^{\beta}$$

(in the rest-frame UV)

Small β → less dusty
low metal
Young



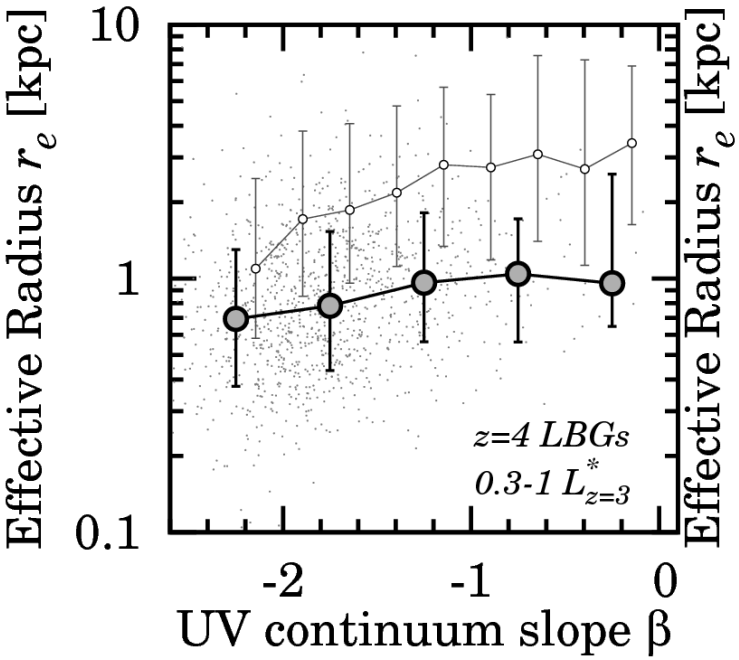


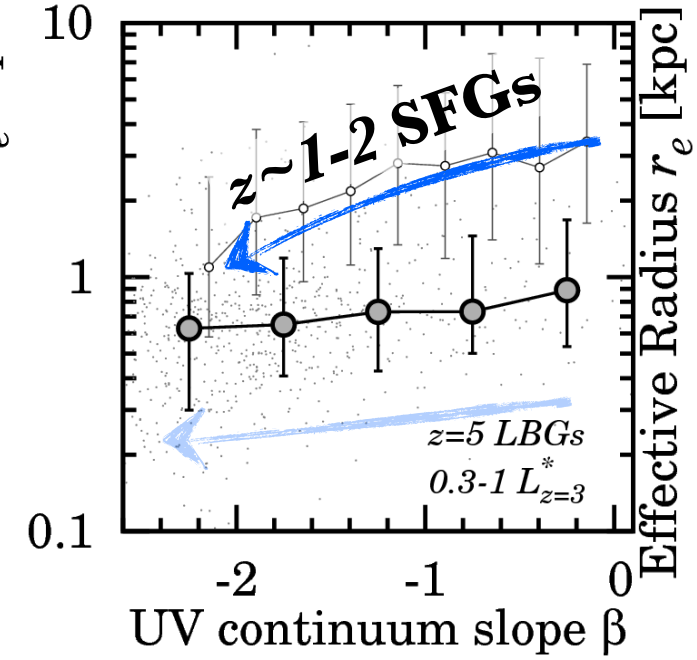
✓**Small β → small r_e**

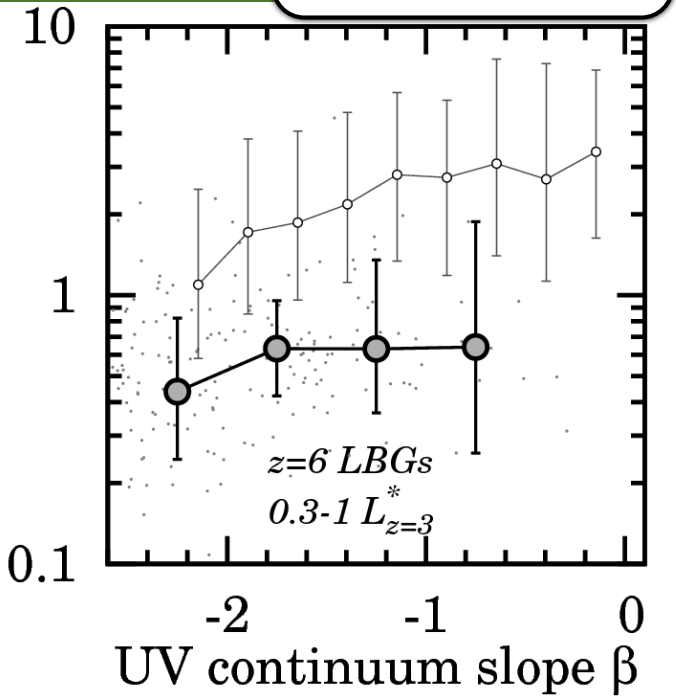
→ **Young galaxies are typically small**

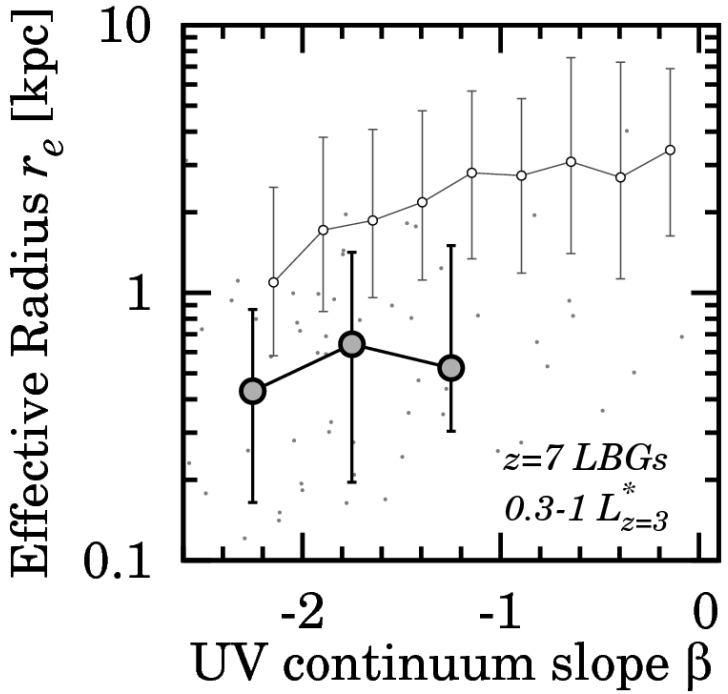
Size - UV slope β

LBGs





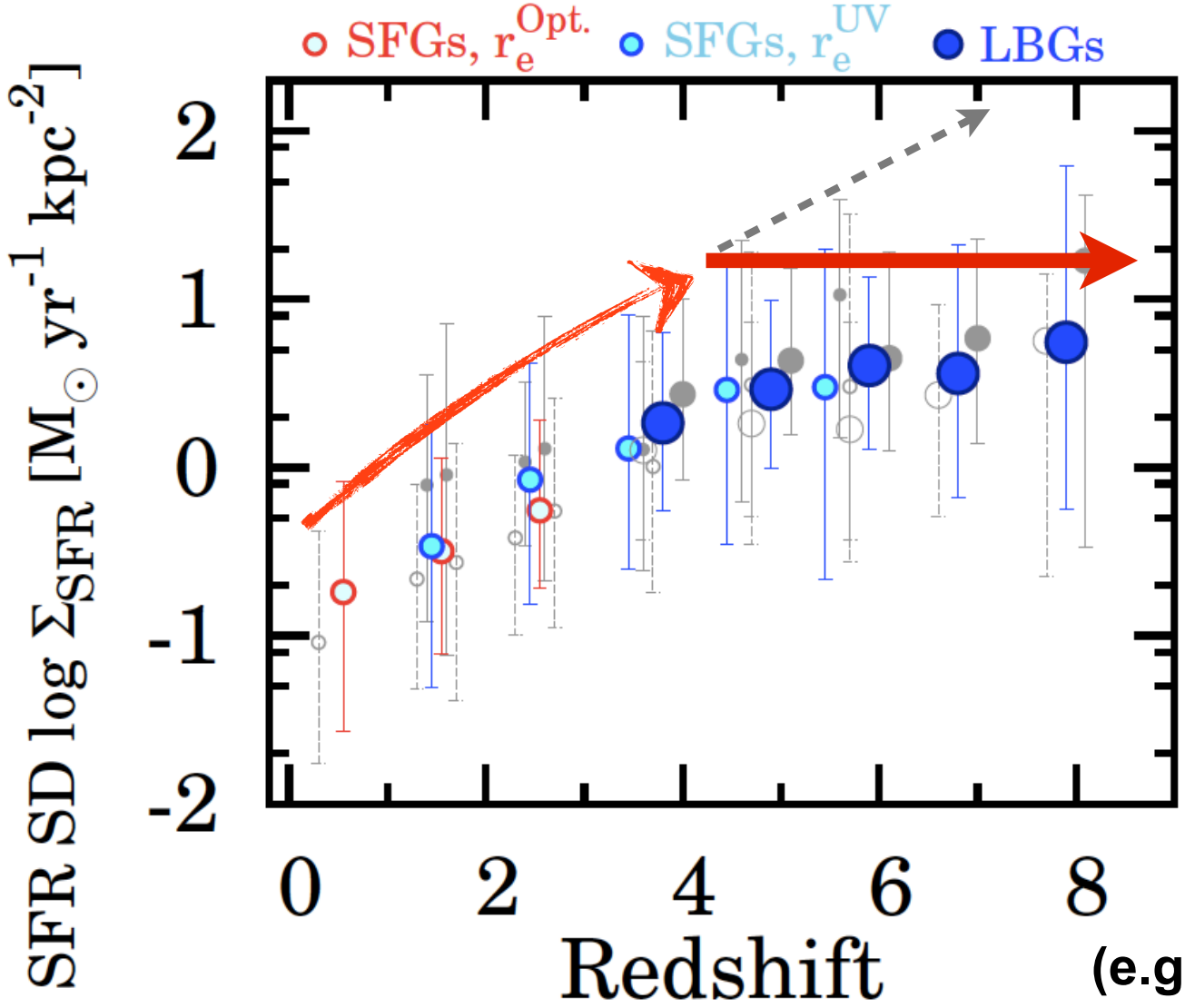




✓**Flatter β - r_e relation** (e.g., Kawamata+14)

✓→ **Photo-z sample includes heterogeneous population** (in age, dust...) **compared to Lyman Break selection**

SFR Surface Density Σ_{SFR}



- *1-10* $L^*_{z=3}$ **Bright in UV**
- *0.3-1* $L^*_{z=3}$ **Intermediate**
- *0.12-0.3* $L^*_{z=3}$ **Faint**

KS-law

$$\Sigma_{SFR} \propto \Sigma_{gas}{}^{n}$$

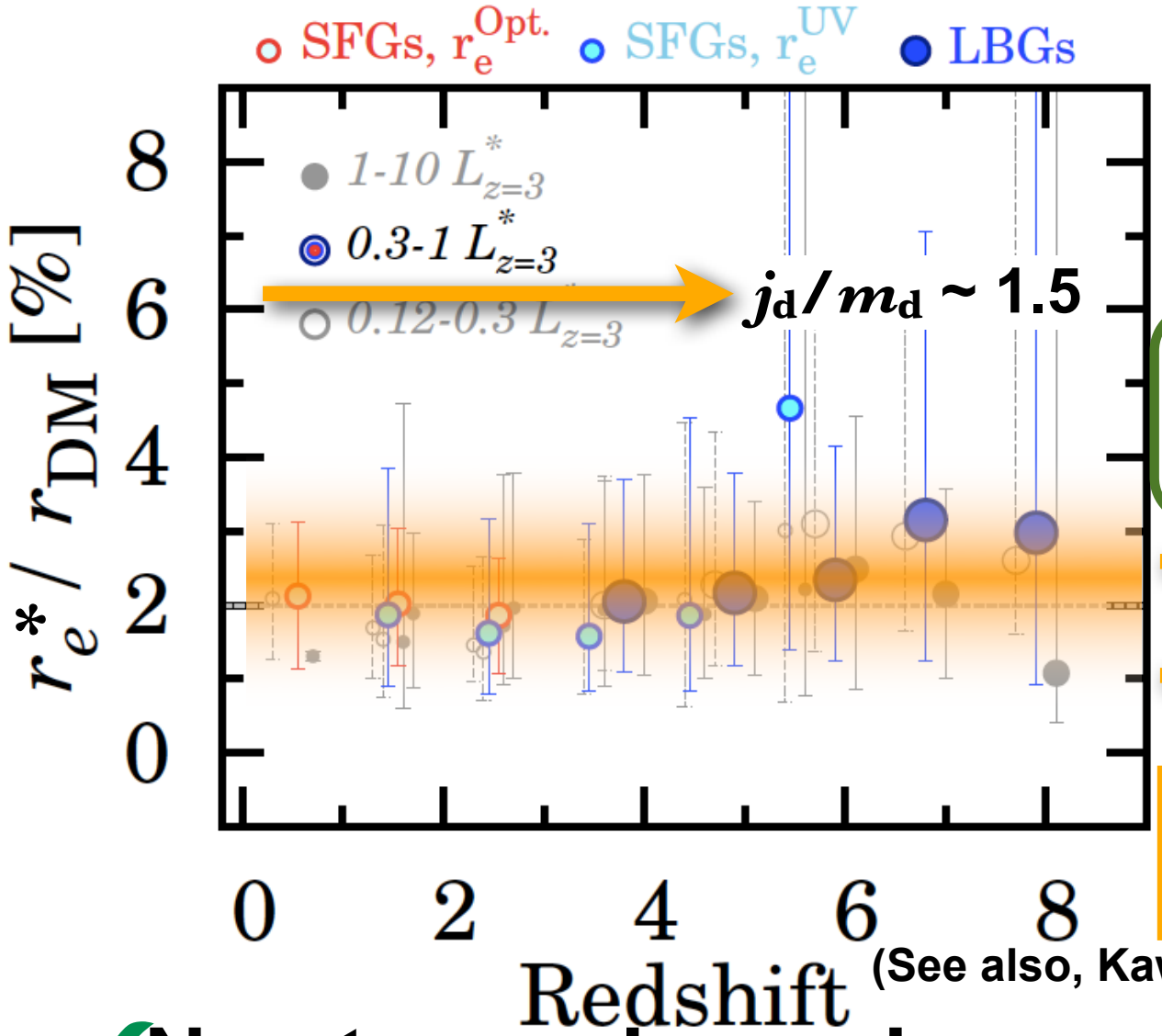
(e.g., Oesch+10, Ono+13 for *z*>4)

✓**No strong dependence on L_{UV} (~M_*)**

✓**Increase@*z*=0→4**

✓**Plateau@*z*>4** → **Inefficient SF in less dusty/metal high-*z* galaxies?**

Size Ratio r_e^*/r_{DM}



Size ratio r_e/r_{DM} is proportional to DM spin parameter λ, j_d/m_d e.g., Mo+98

$$\frac{r_e}{r_{vir}} = \frac{1.678}{\sqrt{2}} \left(\frac{j_d}{m_d}\lambda\right) f_c^{-1/2} f_R$$

well determined

→ $j_d/m_d \sim 1$

→ $j_d/m_d \sim 0.5$

Galaxy disk conserves almost all j/m

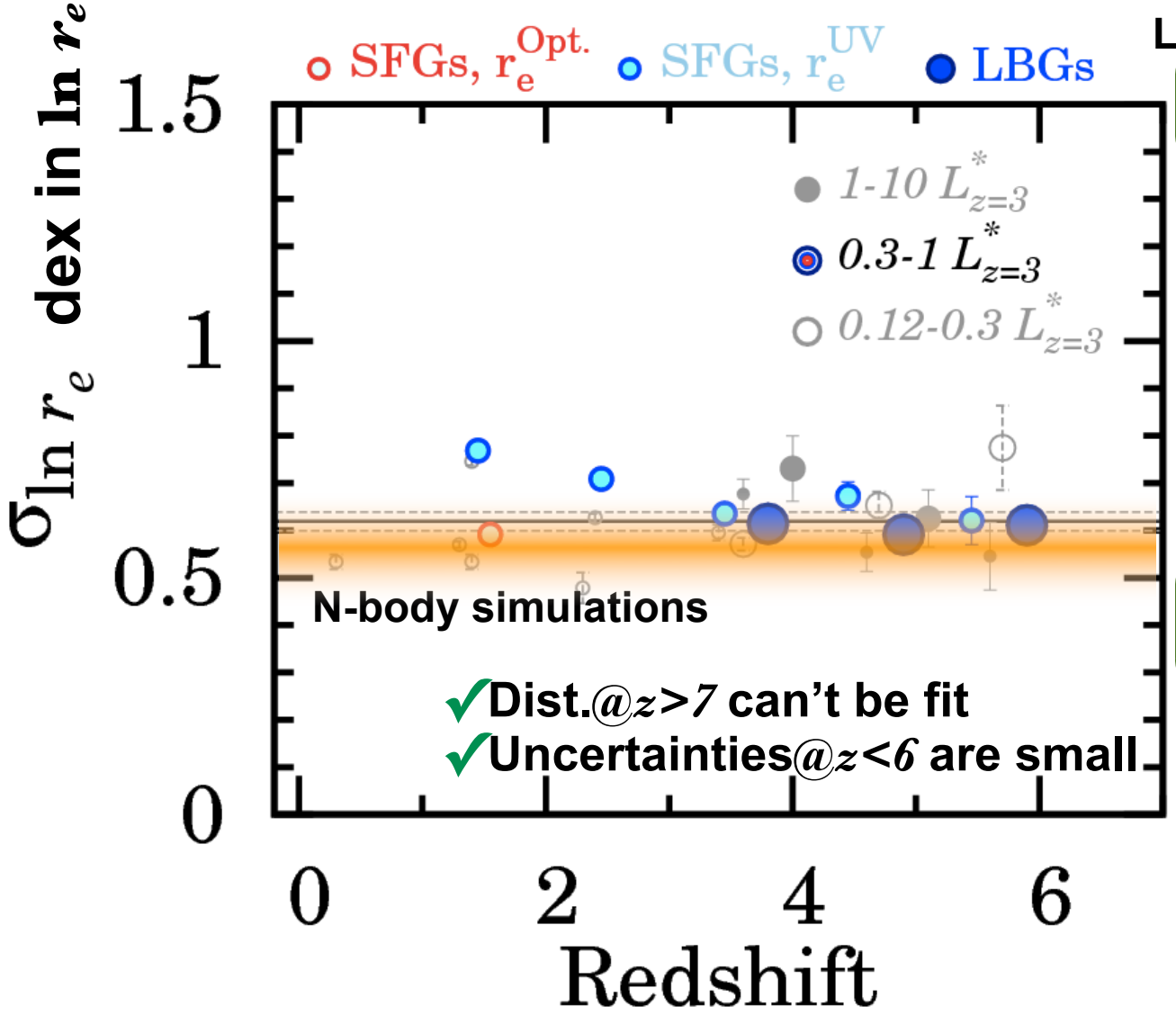
(See also, Kawamata+14)

✓**No strong dependence on L_{UV} (~M_*)**

✓**No significant evolution of r_e/r_{DM} @z=0-8**

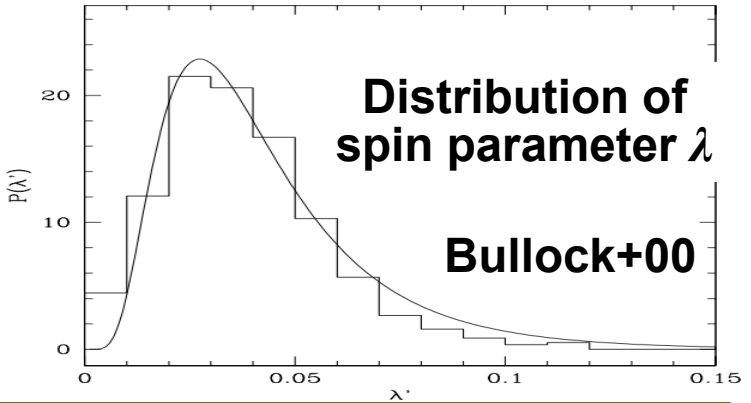
✓**r_e^*/r_{DM} ~ 2-3 % → $j_d/m_d \sim 1$** (eg, Nipoti+)

Width of Size Distribution



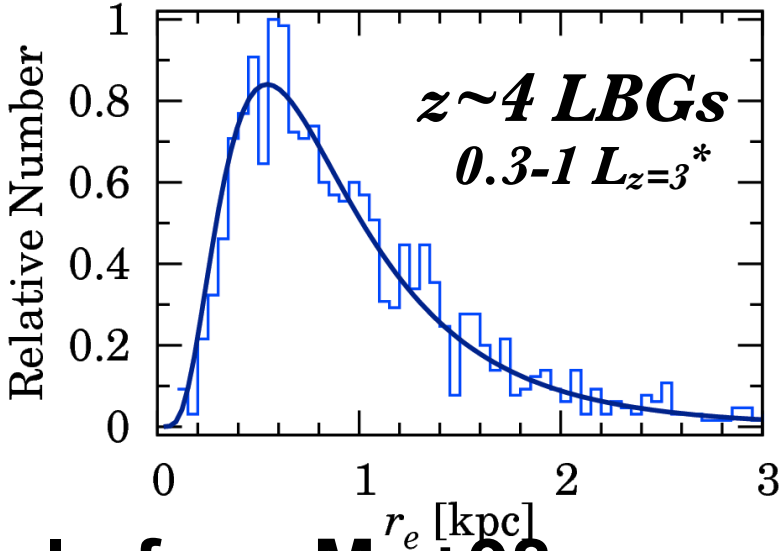
Log-normal distribution

$$p(\lambda) = \frac{1}{\lambda \sigma_{\ln \lambda} \sqrt{2\pi}} \exp\left[-\frac{\ln^2(\lambda/\overline{\lambda})}{2\sigma^2_{\ln \lambda}}\right]$$



if $r_e \propto r_{\rm DM}$

$$\rightarrow \frac{1}{r_e \sigma_{\ln r_e} \sqrt{2\pi}} \exp\left[-\frac{\ln^2(r_e/\overline{r_e})}{2\sigma^2_{\ln r_e}}\right]$$



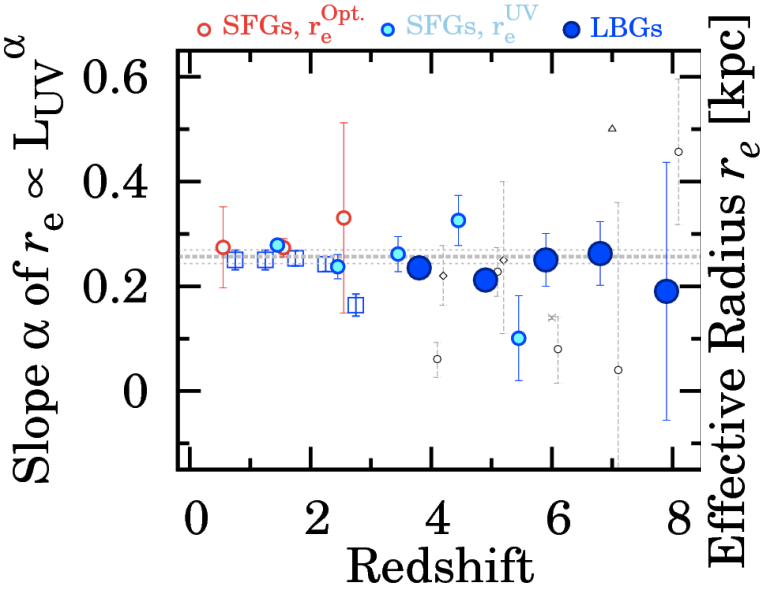
✓Simulations predicts $\sigma_{\ln\lambda}$~0.5~0.6

✓$\sigma_{\ln re}$=0.5-0.6@z=0-6

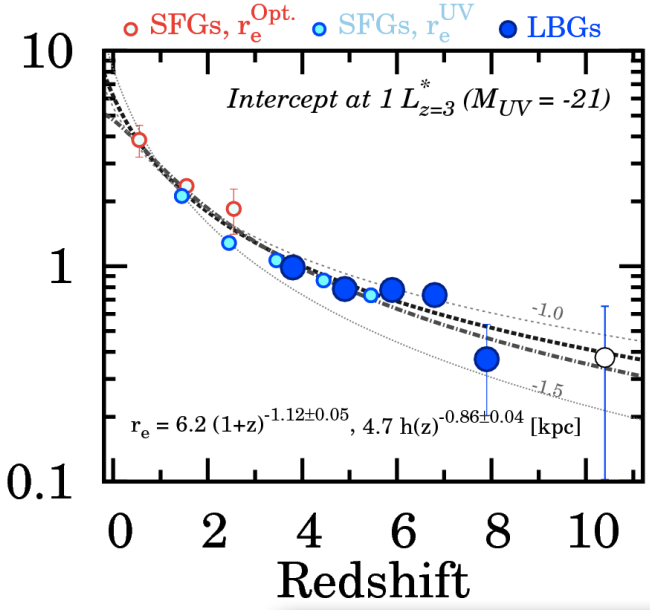
✓Consistent w/ disk formation model of eg, Mo+98

Summary

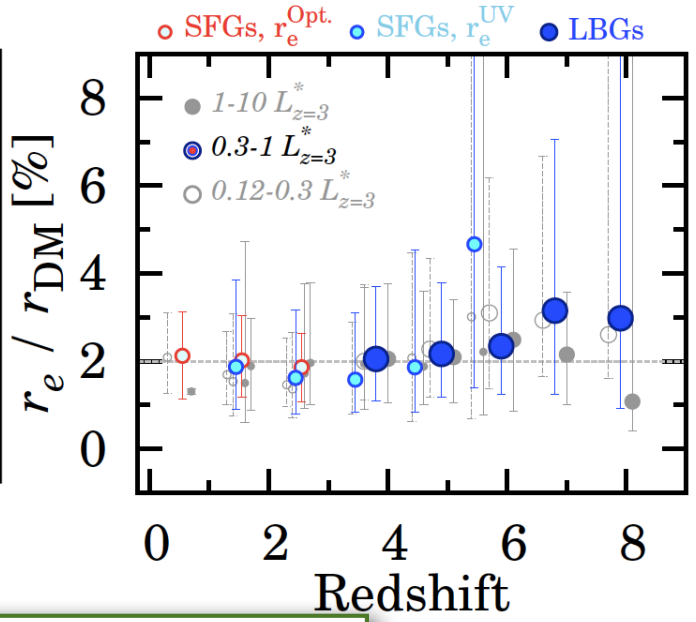
✓ **No evolution of L_{UV}-r_e slope**



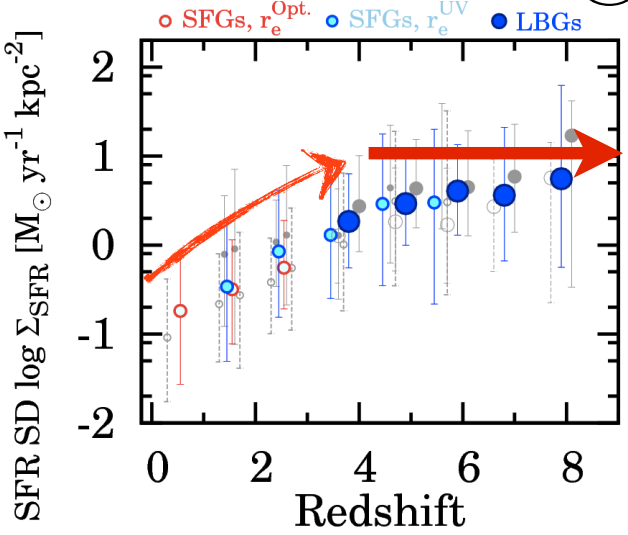
✓ $r_e \propto H(z)^{-0.86}$



✓ **Constant r_e/r_{DM}**



✓ **Plateau of Σ_{SFR}@z>4**



Open questions

✓ **When did L_{UV}-r_e relation emerge?**

✓ **First galaxies follow $H(z)^{\beta}$?**

✓ **r_e/r_{DM}, Σ_{SFR} are constant @z>8?**

→ **Larger sp.-resolved samples@z>8 w/ *JWST, WFIRST, WISH*, 30m ...**