Early Low-Mass Galaxies and Star-Cluster Candidates at z~6-9

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Shotaro Kikuchihara (U. Tokyo)

Masami Ouchi, Yoshiaki Ono, Ken Mawatari,
Jacopo Chevallard, Yuichi Harikane, Takashi Kojima,
Masamune Oguri, Gustavo Bruzual, Stephane Charlot

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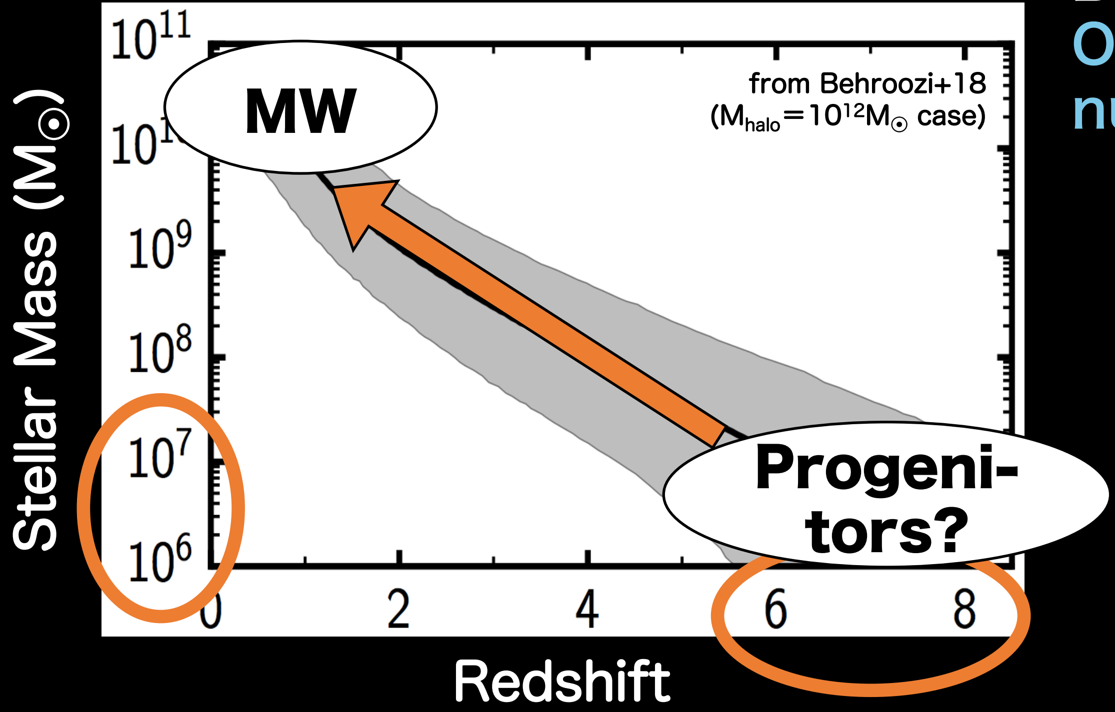
Early Low-Mass Galaxies

Why Early Low-Mass Galaxies?

- Dominant components in early Universe
- Progenitors to MW?

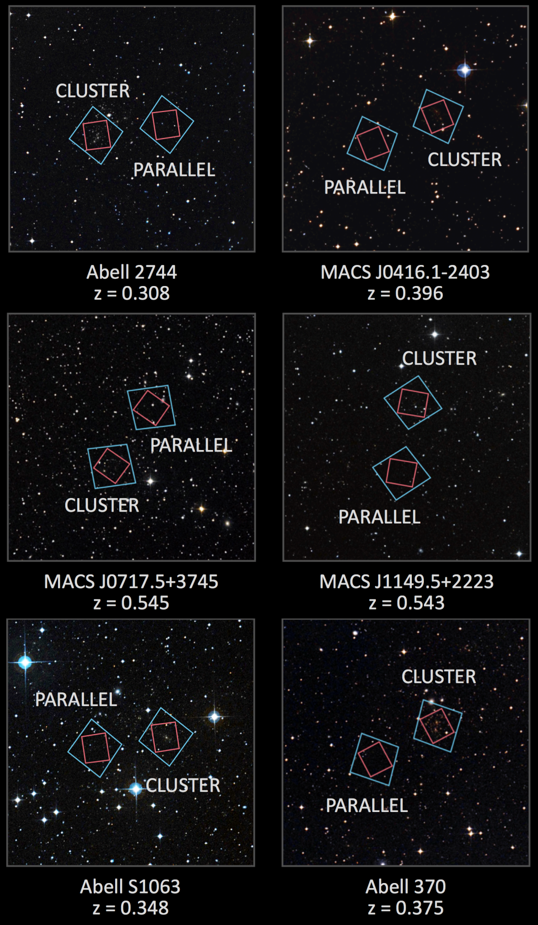


BUT;

Only a few constraints on number counts at $M_{\star}<10^{7}M_{\odot}$

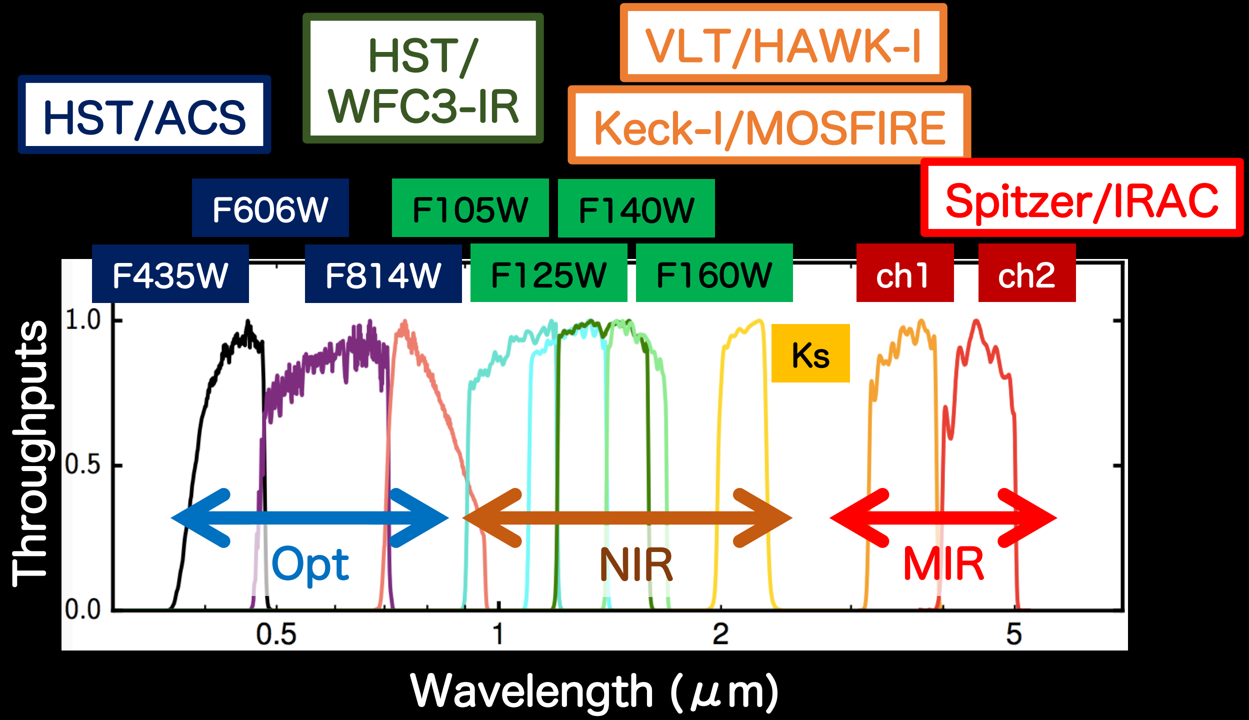
Deep HST-Spitzer
+
Lensing Magnification

Data ― Hubble Frontier Fields (HFF)



http://cosmos.phy.tufts.edu/~danilo/HFF/Home.html

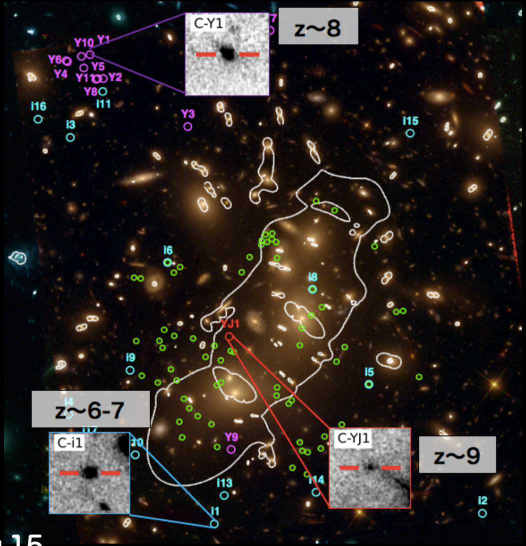
6 galaxy-cluster fields + 6 parallel fields



5σ～29-30 25-26 24-25

Samples

- 357 Lyman break galaxies (LBGs) at $z\sim6$-9
  - ✓ Original from Kawamata+18 & Ishigaki+18 (color selection)

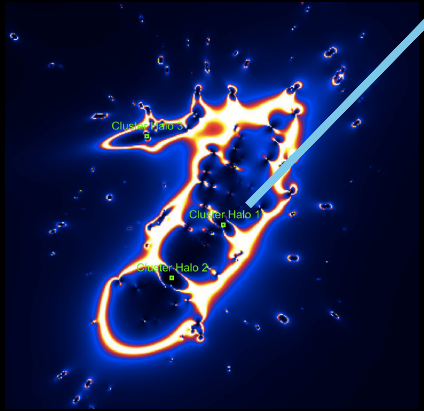


Ishigaki+15

Lens Models

Oguri10

- GLAFIC models from Kawamata+18 & Ishigaki+18



Kawamata+16

Lens Models

e.g., NFW halo:

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

Predict ↓ ↑ χ^2

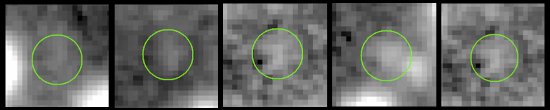
(α, δ) of multiple images

Intrinsic SED

Estimate Stellar Mass ($M_\star$)

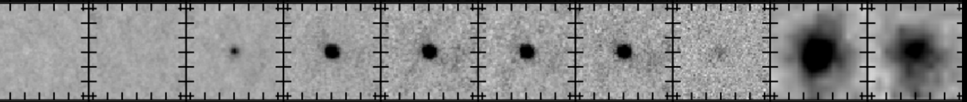
- LBGs too faint to directly estimate $M_\star$ ($M_{UV} \sim -19$)

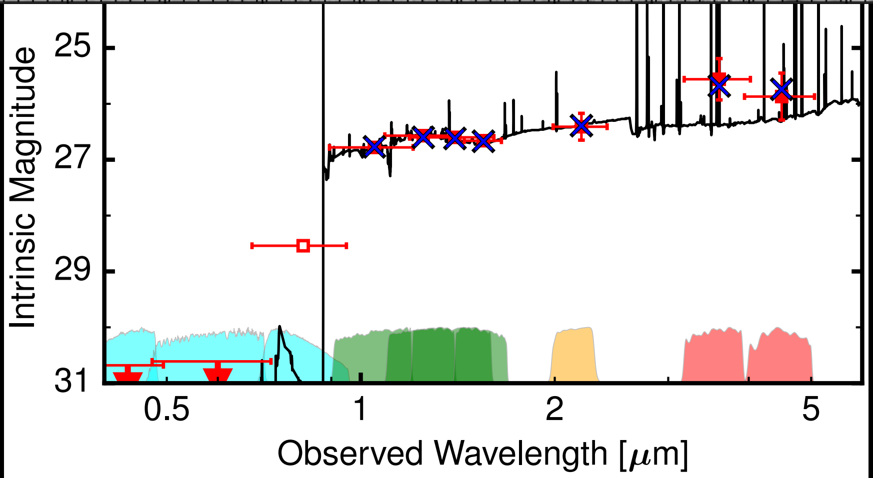
@ch1



…

Stack





Chevallard&Charlot16

Fit SED

BEAGLE model

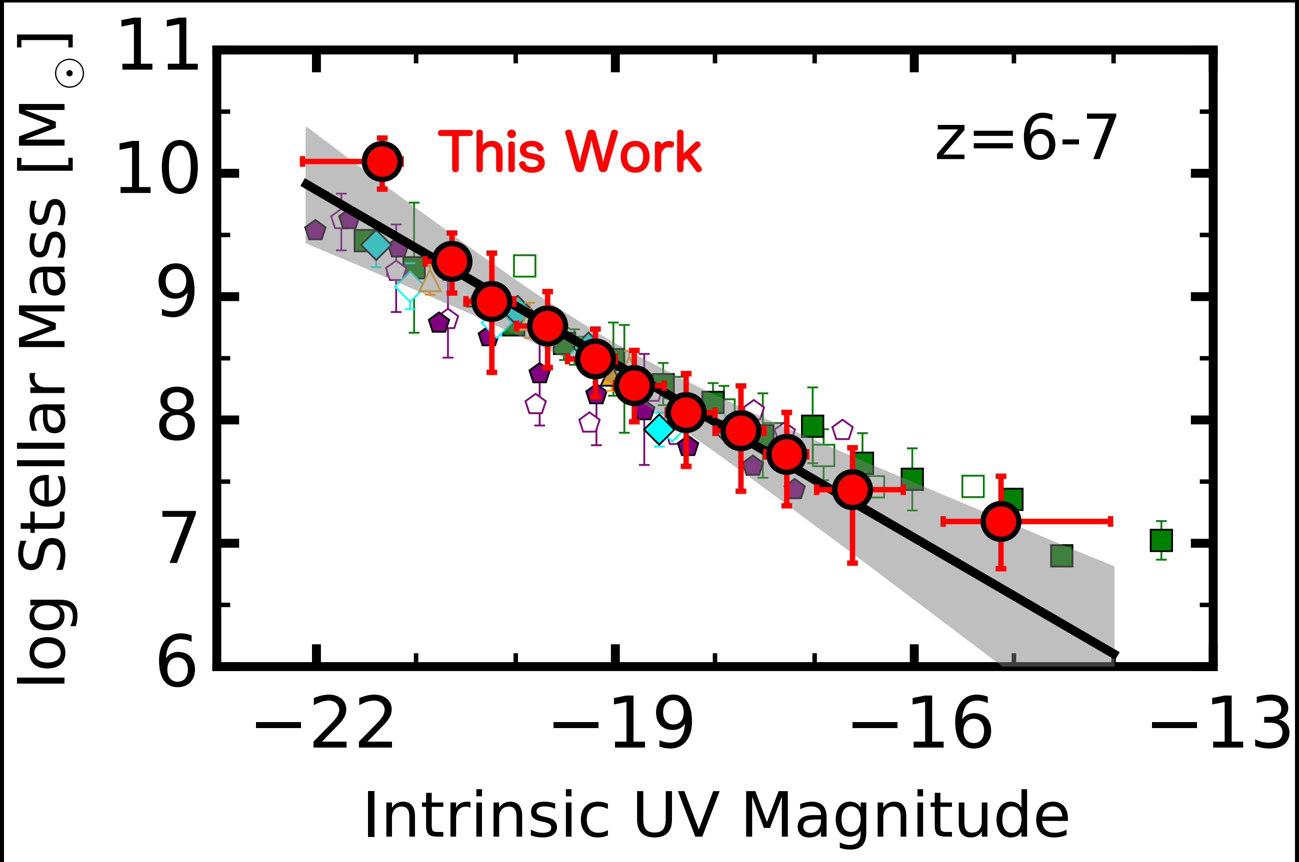
Templates

Stellar : BC03
Nebular : CLOUDY
Dust : Calzetti+94
IGM : Inoue+14

Parameters z, Age, U_{ion}, $M_\star$, Z, τ_V

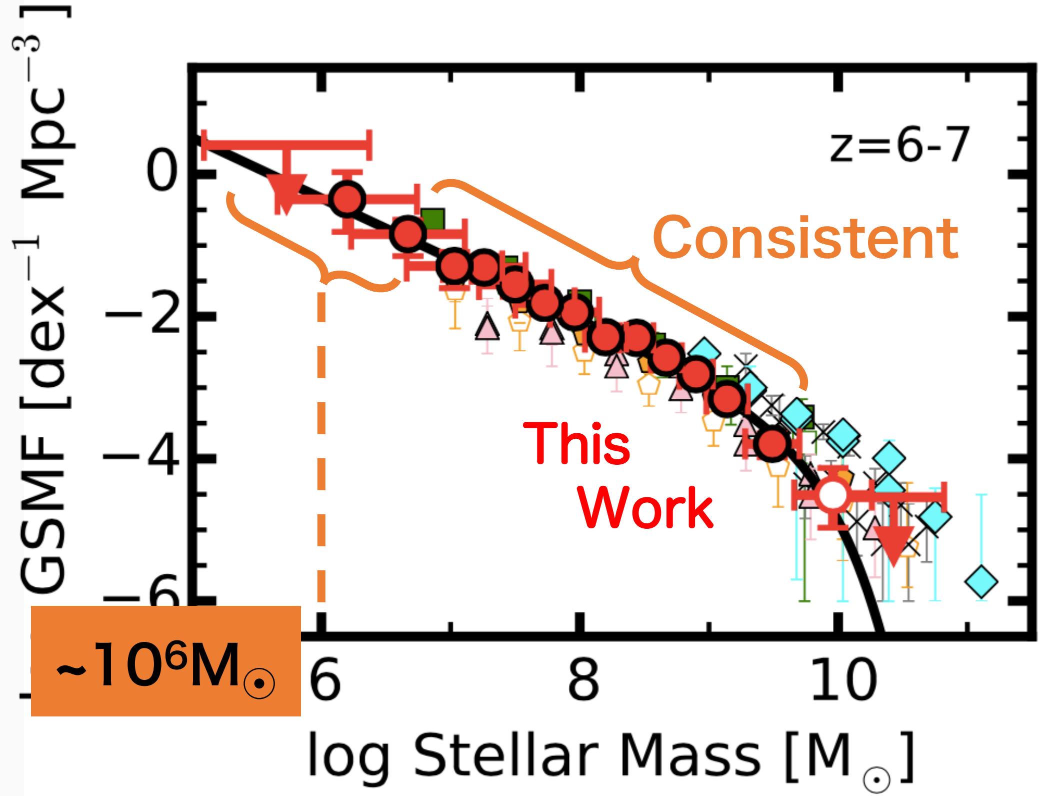
→ ($M_\star$, M_{UV}) for each M_{UV} bin

$M_\star$—M_{UV} Relations



Galaxy Stellar Mass Functions

- $M_\star$-M_{UV} relations x Ishigaki+18 luminosity functions



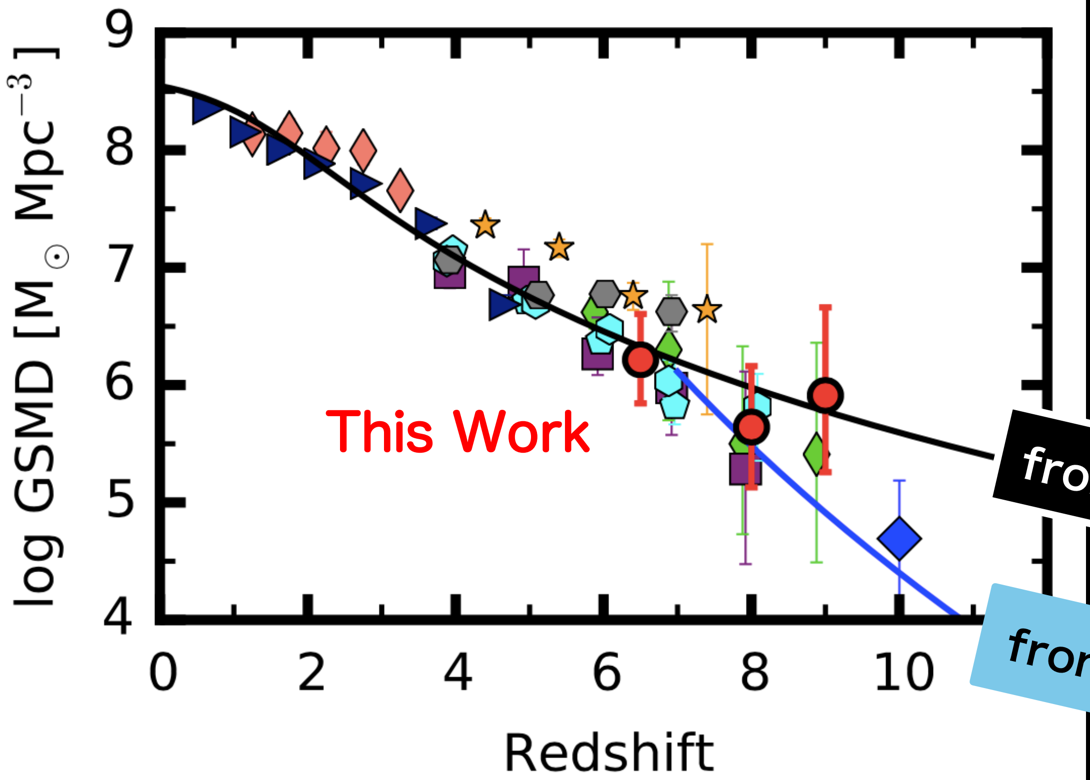
→ Low-mass end is >1dex fainter than ever

- Fit to Schechter function

$$\Psi(M_\star) = \ln(10)\Psi^* \left(\frac{M_\star}{M^*}\right)^{\alpha+1} \exp\left(-\frac{M_\star}{M^*}\right)$$

Galaxy Stellar Mass Density Evolutions

- Integrate stellar mass functions (Schechter)



✓ χ^2 smaller by ~2.8 for slow one

➡ Support slow evolution

✓ Star-formation efficiency was higher at z>8 +DMH evolution？

from Slow SFRDs

$$\mathrm{SFRD} \propto (1+z)^{-3.9}$$

Madau+18, +14, McLeod+16, Ellis+13

from Steep SFRDs

$$\mathrm{SFRD} \propto (1+z)^{-10.9}$$

Oesch+18, +14, Harikane+18

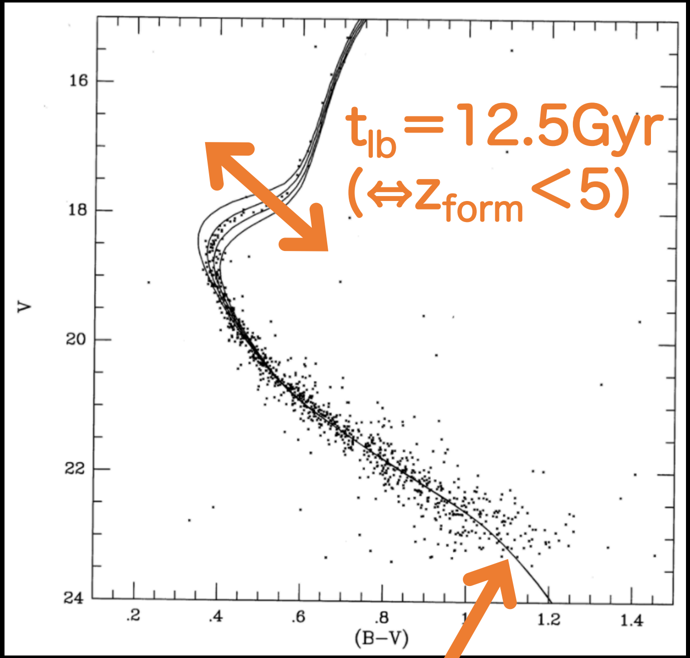
②
Early Globular Cluster (GC) Candidates

Why Early GCs?

- GCs = dense stellar systems
  - ✓Formation？ ✓Stellar population？
  - ✓Formed w/ single burst at $z>5$

©http://www.ing.iac.es/PR/science/m92_high.html

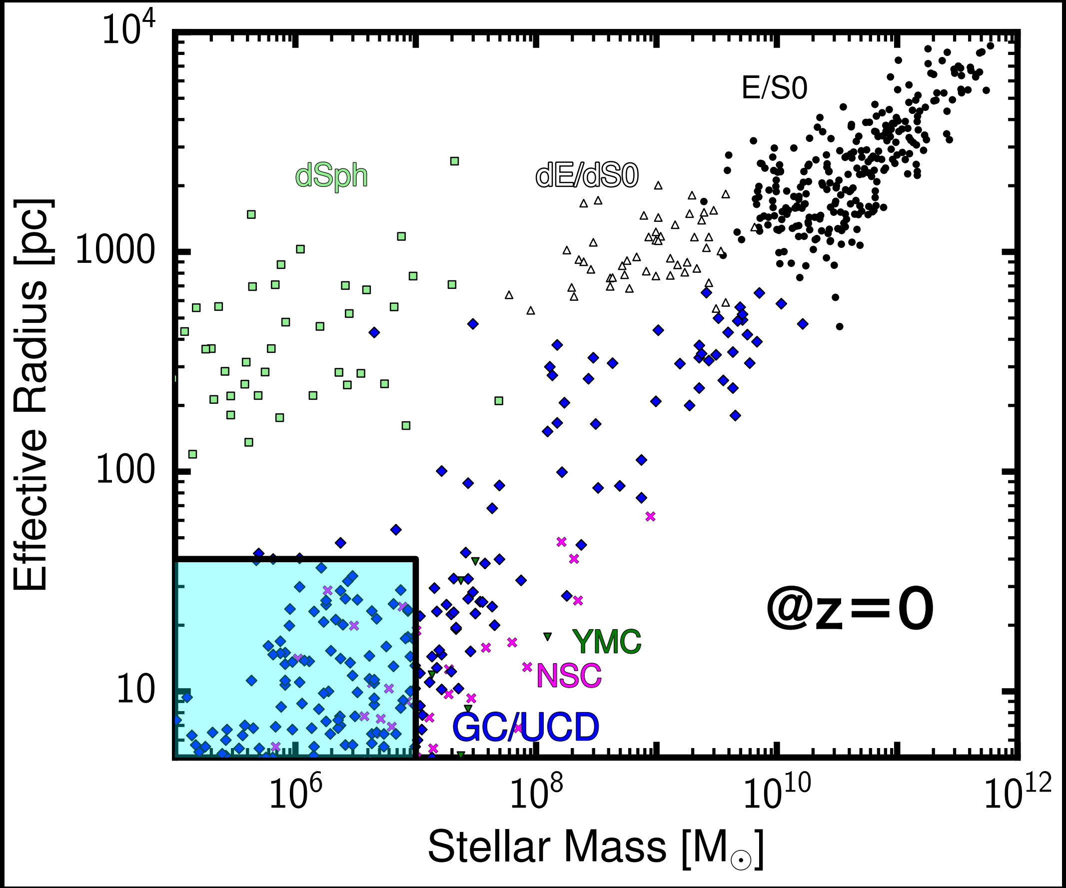
HR diagram of M92:



Model prediction from single star burst at t_{lb}

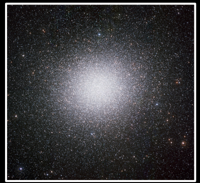
➡ Need to *directly* observe formation epoch

R_e—$M_\star$ Relations of Local GCs



- < 40pc
- $< 10^7 M_\odot$

✓ ωCen



©ESO

✓ Pal5

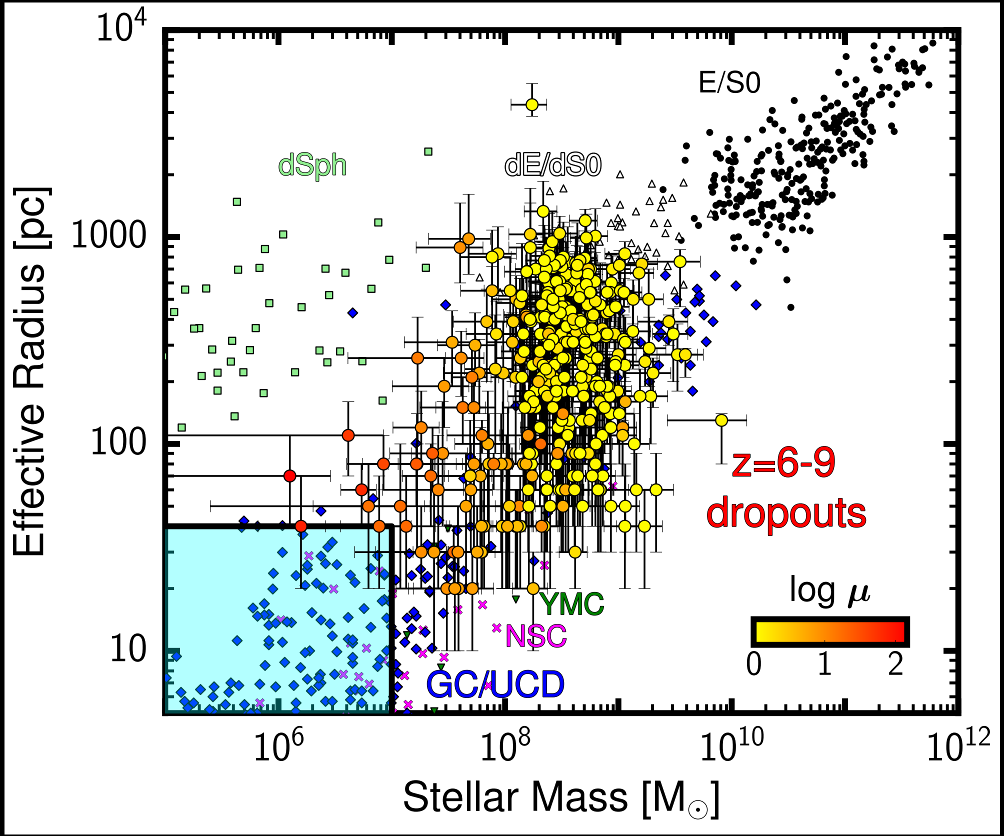
✓ Pal14

©SDSS

Early GC candidates
≡ z>6 LBGs w/
$R_e < 40$pc & $M_\star < 10^7 M_\odot$

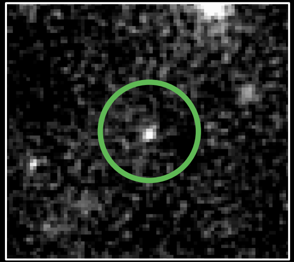
R_e—$M_\star$ Relations of High-z Galaxies

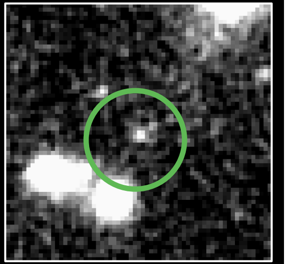
- R_e ← Sersic profile fitting (Kawamata+18)
- $M_\star$ ← M_{UV} x $M_\star$—M_{UV} relation



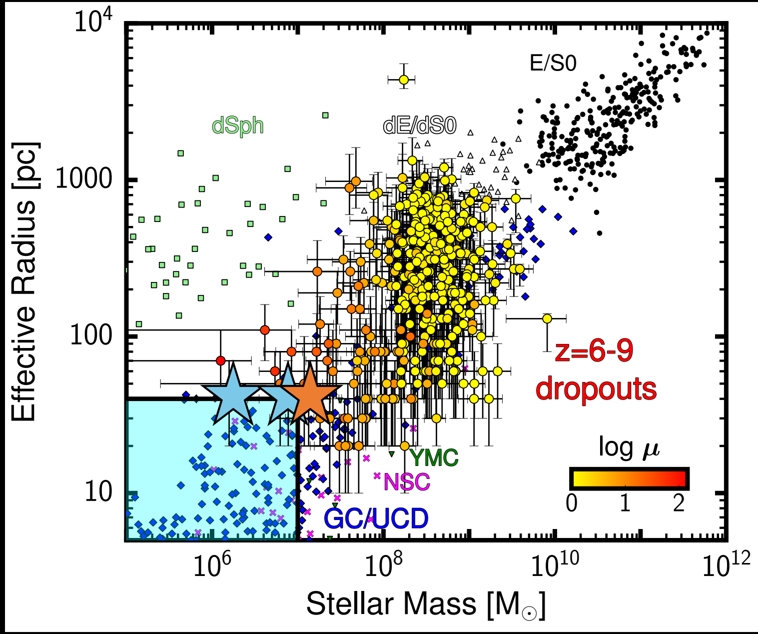
R_e—$M_\star$ Relations of High-z Galaxies

HFF5C-4260-1364
HFF5C-4039-1566

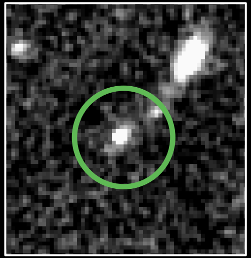




- ✓ In Abell S1063 (first to analyze)
- ✓ First to identify as early GC candidates



HFF2C-1156-3446



- ✓ M0416I-6115434445 in Bouwens+17
- ✓ GC1 in Vanzella+17a (Lya detected w/ MUSE)
- ✓ R_e & $M_\star$ consistent

Summary

deep HST

- Identify 357 LBGs at z~6-9 w/ full data sets of HFF
- Galaxy stellar mass functions extend to $M_\star$~$10^6 M_\odot$
  - ✓ >1dex lower mass than ever
- Galaxy stellar mass densities at z>8 support slow evolution of SFRD
- Find early GC candidates w/ R_e<40pc & $M_\star$<$10^7 M_\odot$
  - ✓ Progenitors to local GCs?

deep Spitzer

Magnification by lensing