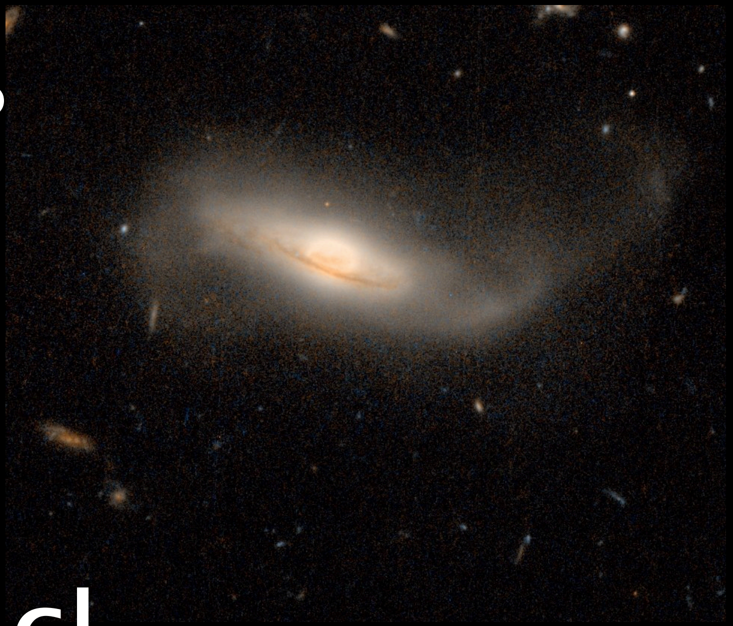
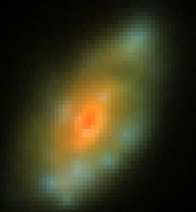
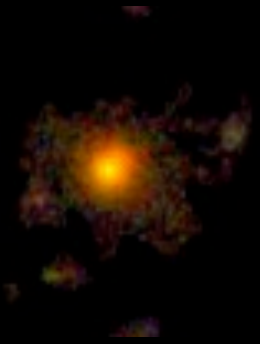


# Tracking the Assembly of Galaxies with Morphology

Jennifer Lotz - STScI

with Mike Peth, Alireza Mortazavi,
Greg Snyder, CANDELS team

# Summary

Galaxy “morphology” can trace underlying physics of galaxy evolution,
but need to capture rare/subtle features

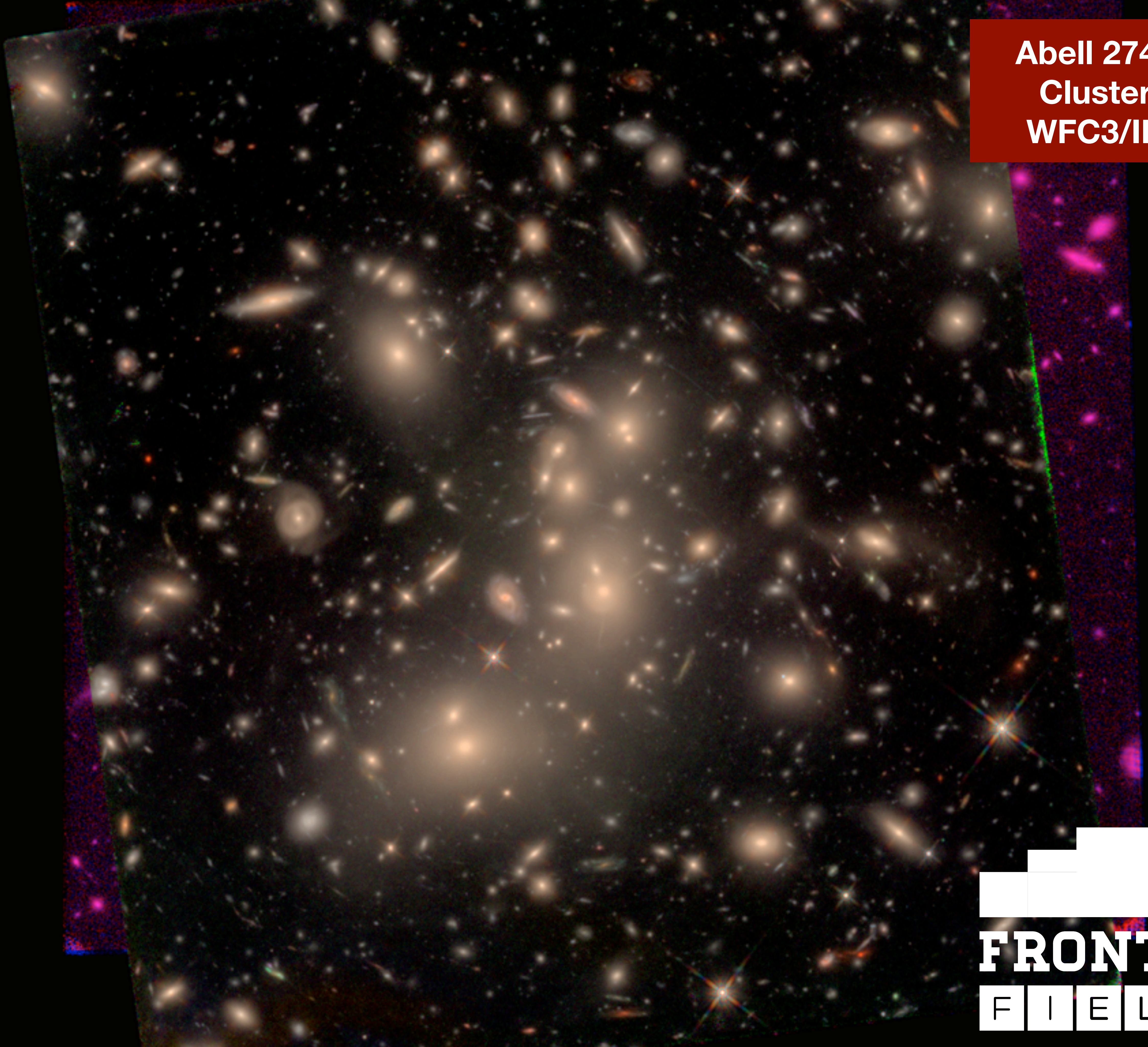
Hubble Sequence does not apply so well at high redshift
⇒ need to move beyond “disk”, “spheroid”, “other” to make progress

PCA of G-$M_{20}$-CA-MID at $z>1$, Mstar > 10.5

- *finds structural progenitors of today’s large E/S0*;
- rare, star-forming and massive at $z>2$;
  increase rapidly after $z<1.5$, before decline of compact quenched galaxies
- consistent with multiple formation pathways,
  including (re)growth of disks around compact galaxies

**Abell 2744 Cluster**

FRONTIER FIELDS



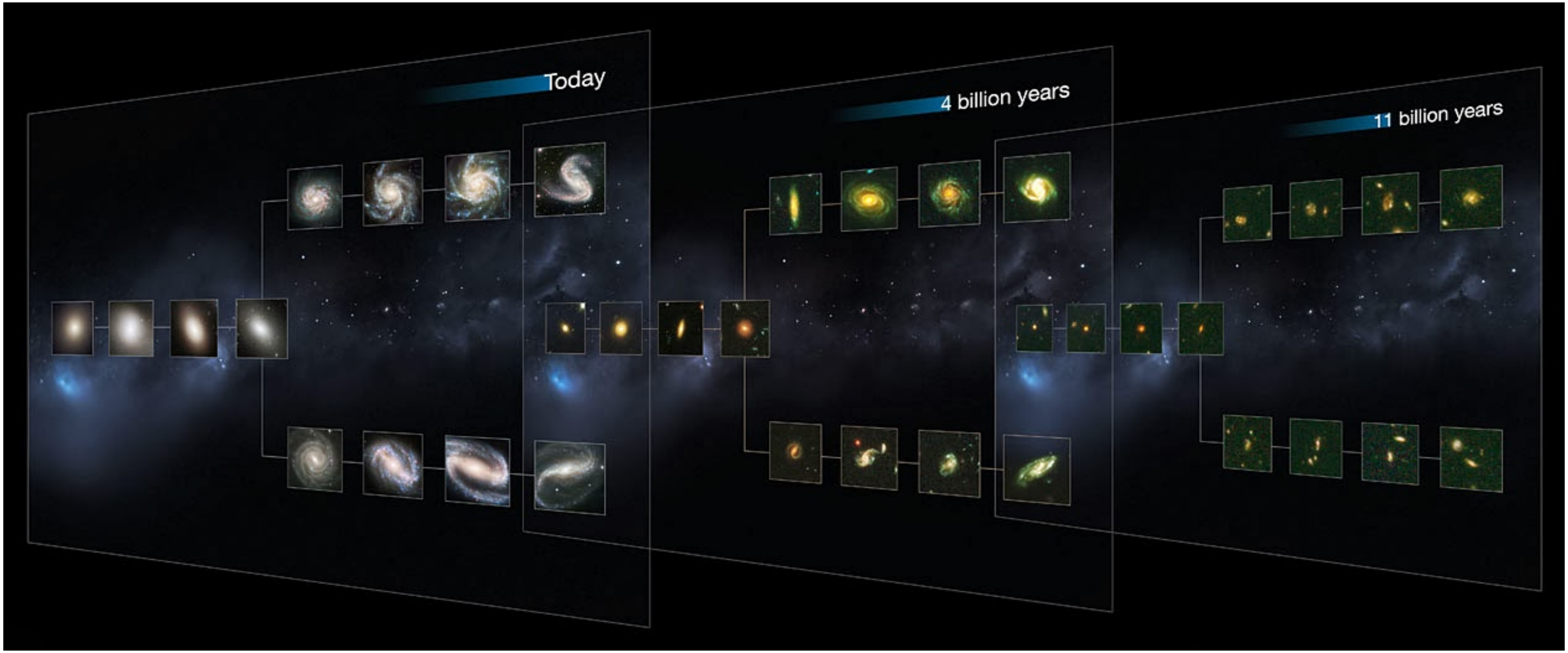
**Abell 2744**
**Cluster**
**WFC3/IR**

FRONTIER
FIELDS

**Abell 2744**
**Cluster**
**ACS/optical**

FRONTIER
FIELDS

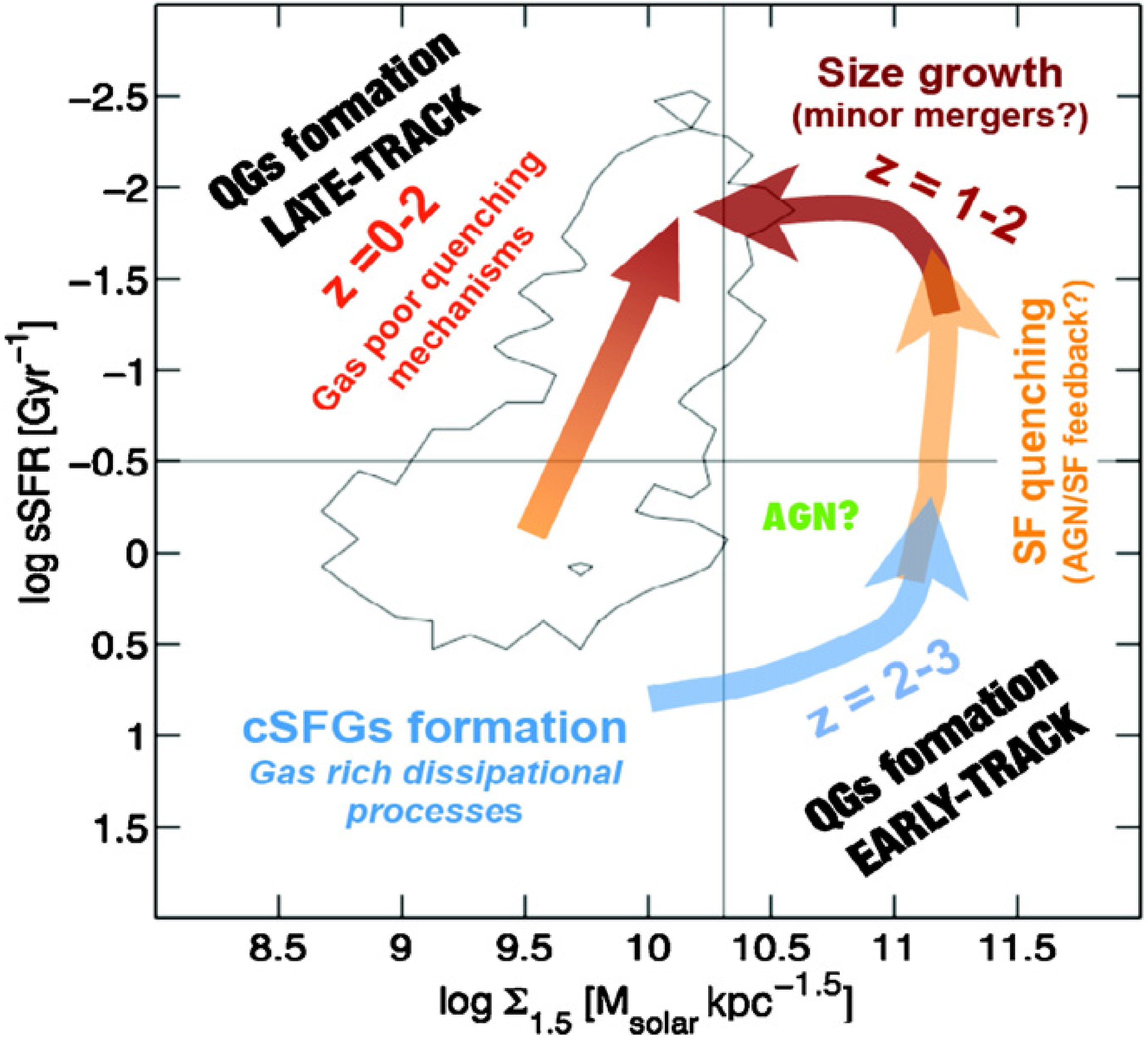
# evolution of Hubble Sequence with redshift



Tracking “the evolution of the Hubble Sequence” is key science goal for JWST

but... Roger Davies: “The Hubble Sequence is wrong” (at z=0)
Bob Abraham: “The Hubble Sequence disappears” (at high z)

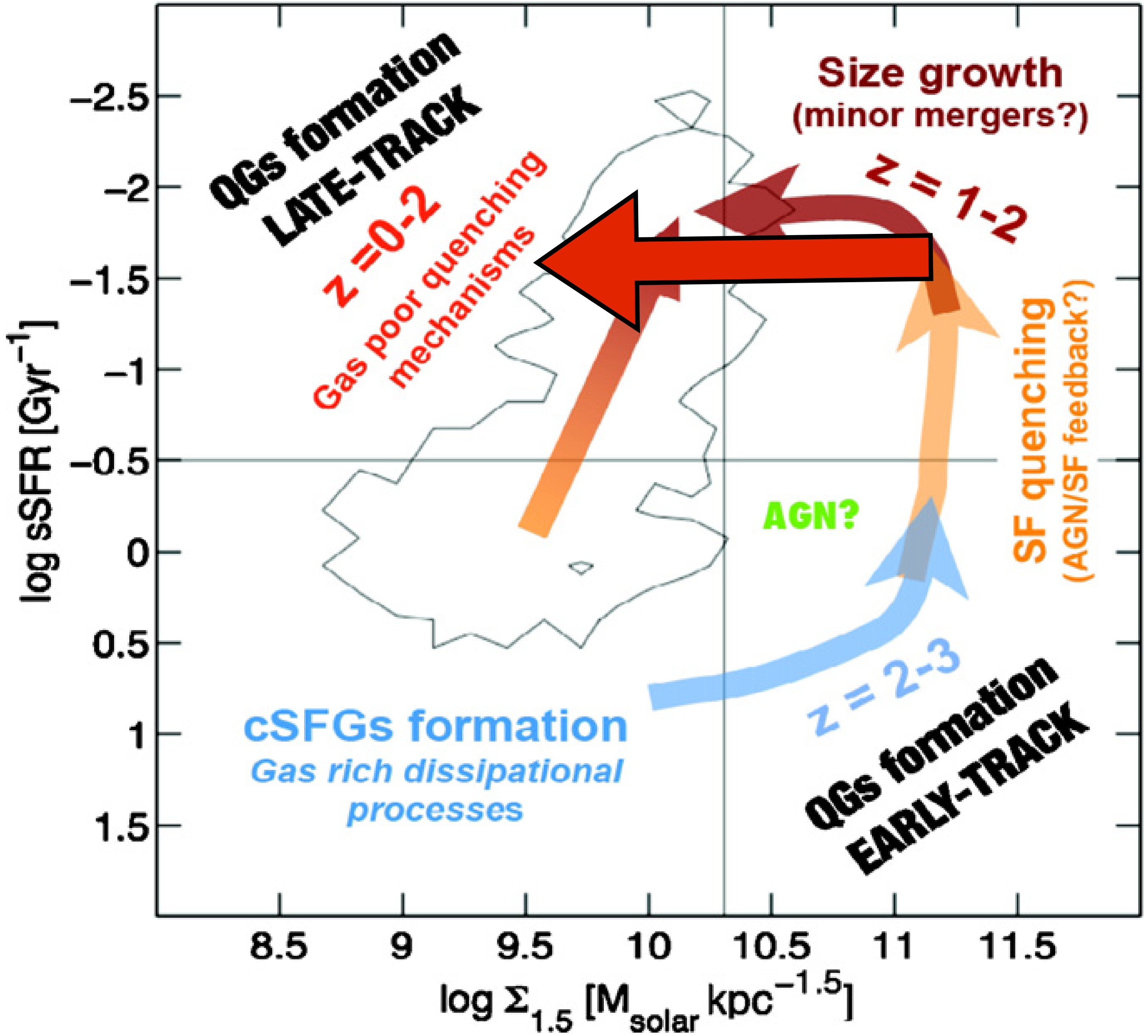
# evolutionary paths of high-z galaxies

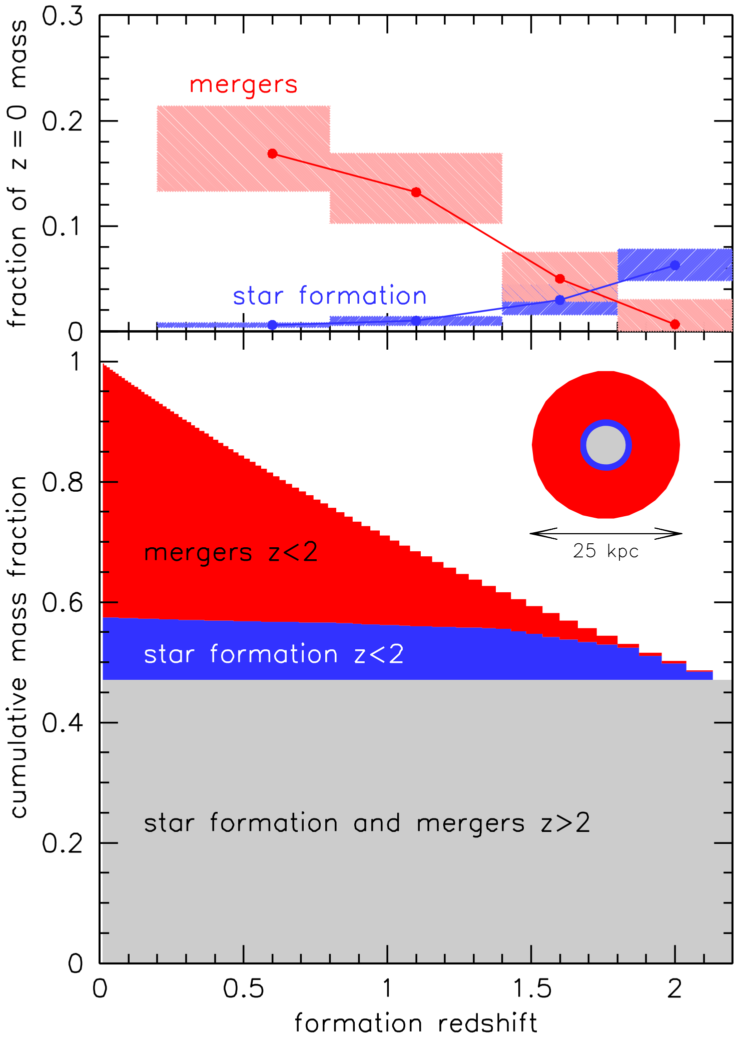


Barro et al. 2014

tracking major mergers,
minor mergers,
VDI/clumps
requires measuring more
than Hubble types
and Sersic fits

# evolutionary paths of high-z galaxies

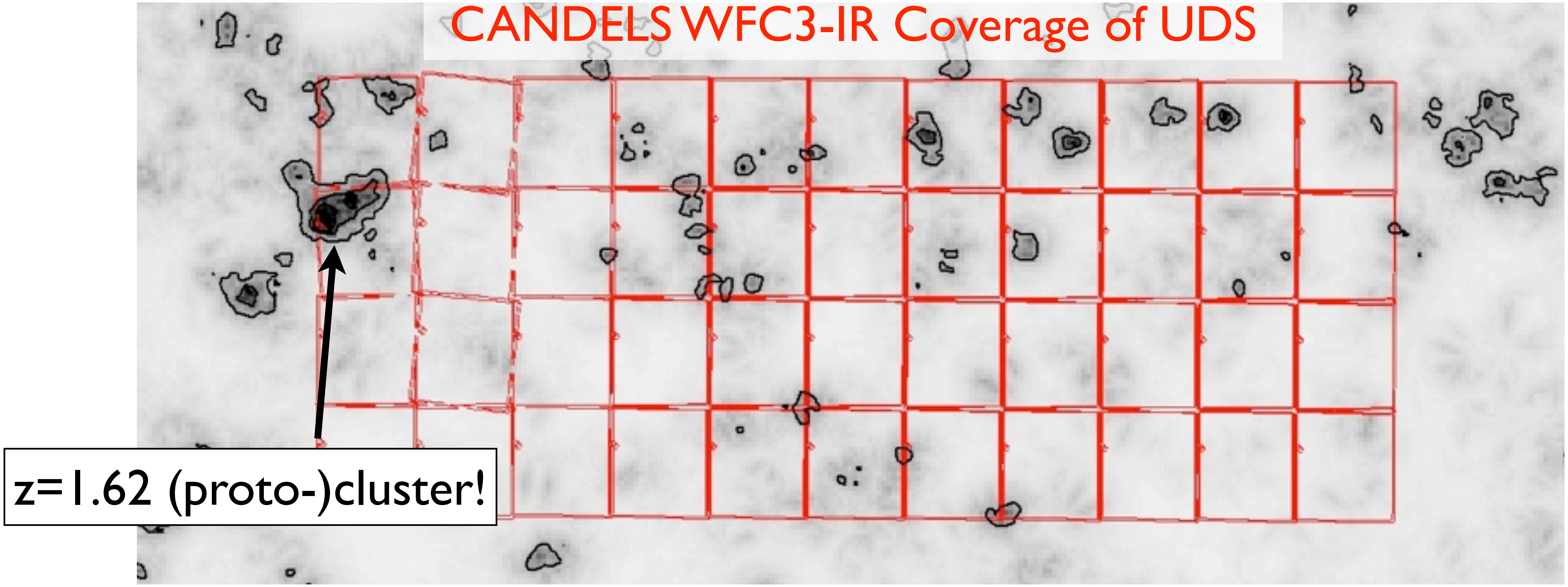




van Dokkum et al.

direct evidence for z~1-2 dry minor mergers?

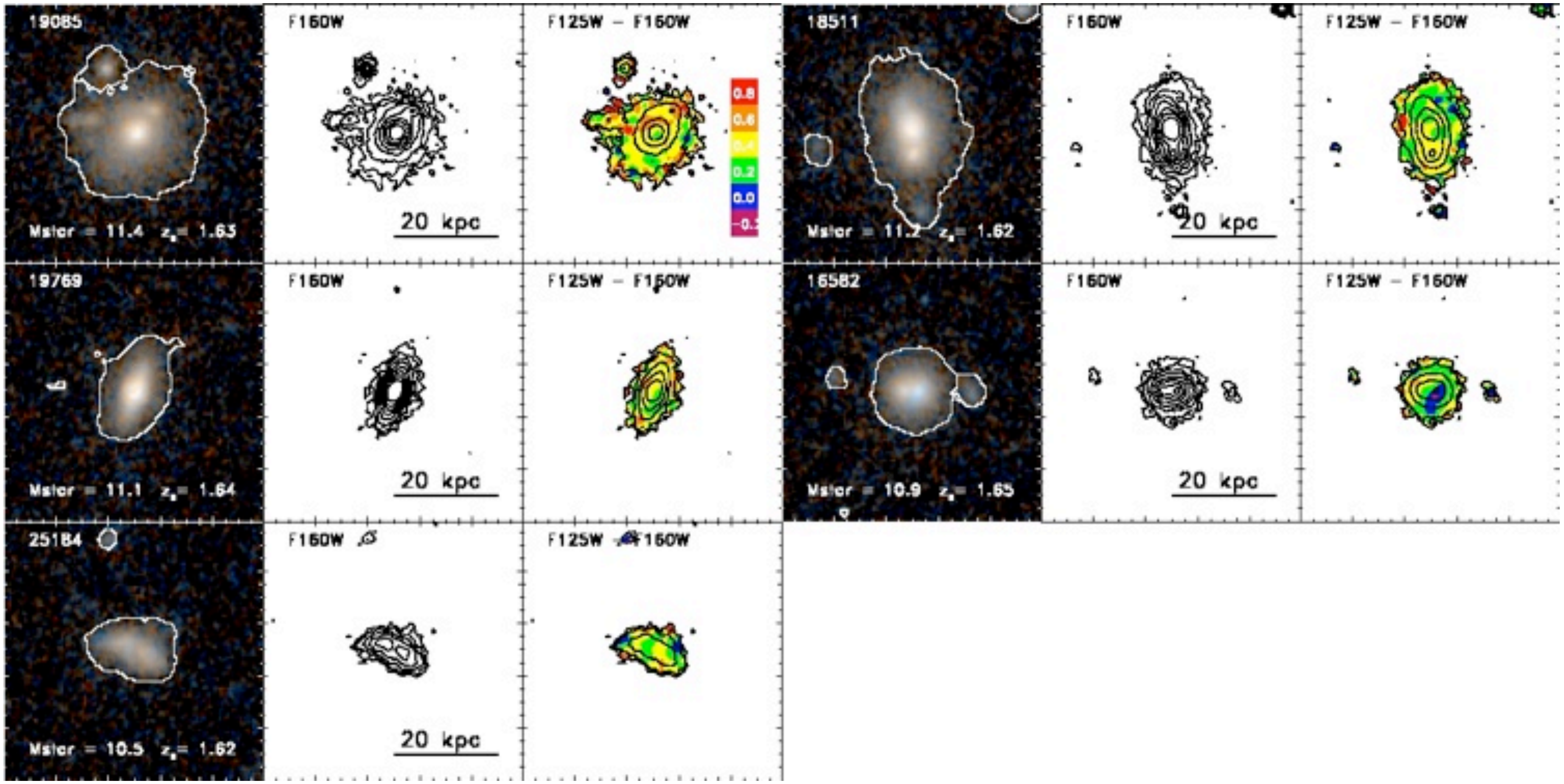
# UDS proto-cluster at z=1.62



20 sigma over-density of IRAC z>1.4 galaxies;
>15 spectroscopic members, clear red sequence
$\sigma \sim 360$ km/s; $M_{200} \sim 9\times10^{13}$ Msun (if virialized)

Papovich et al. 2007, 2010; Tanaka et al 2010

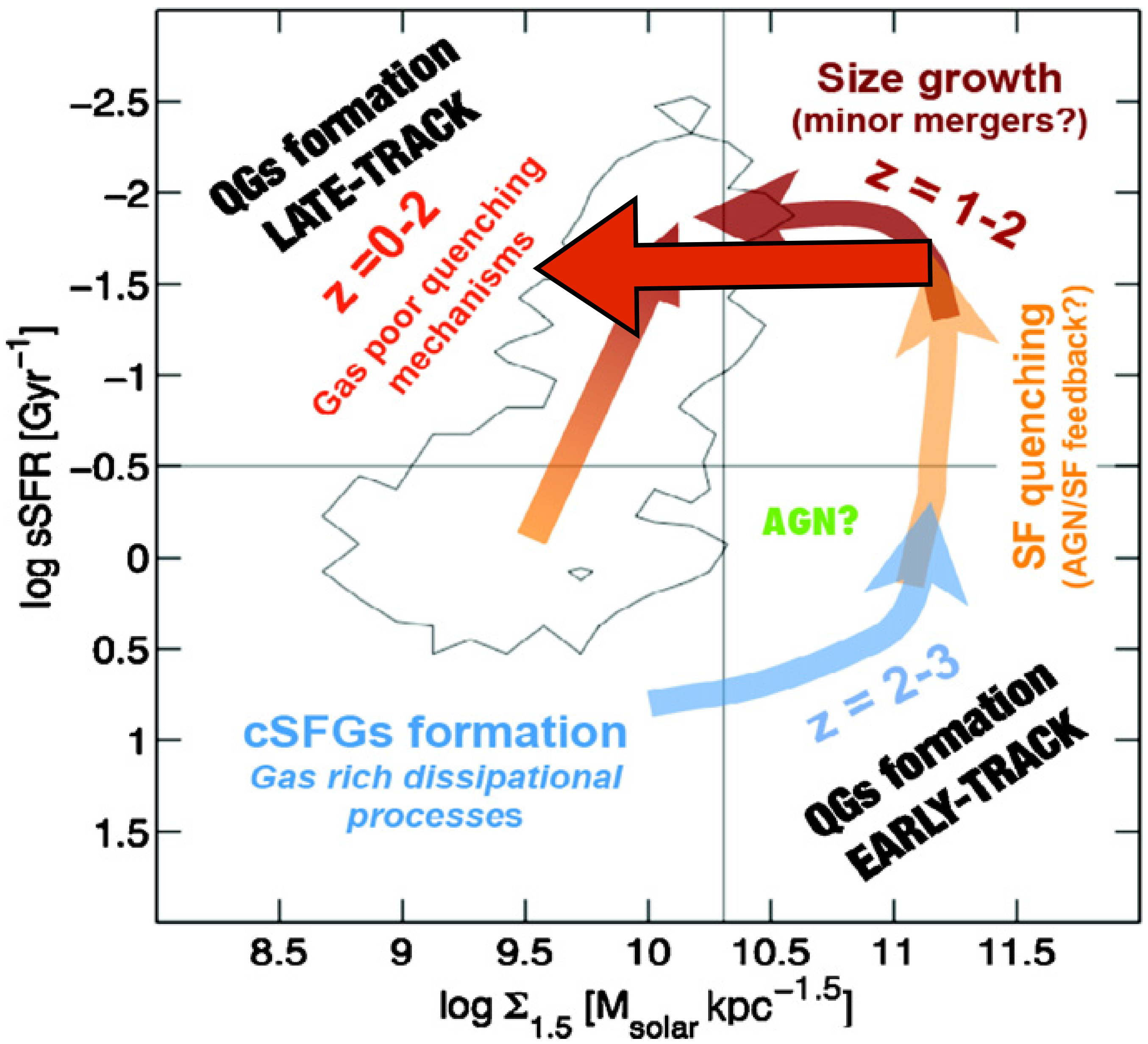
# Massive Elliptical Galaxy Assembly via Mergers

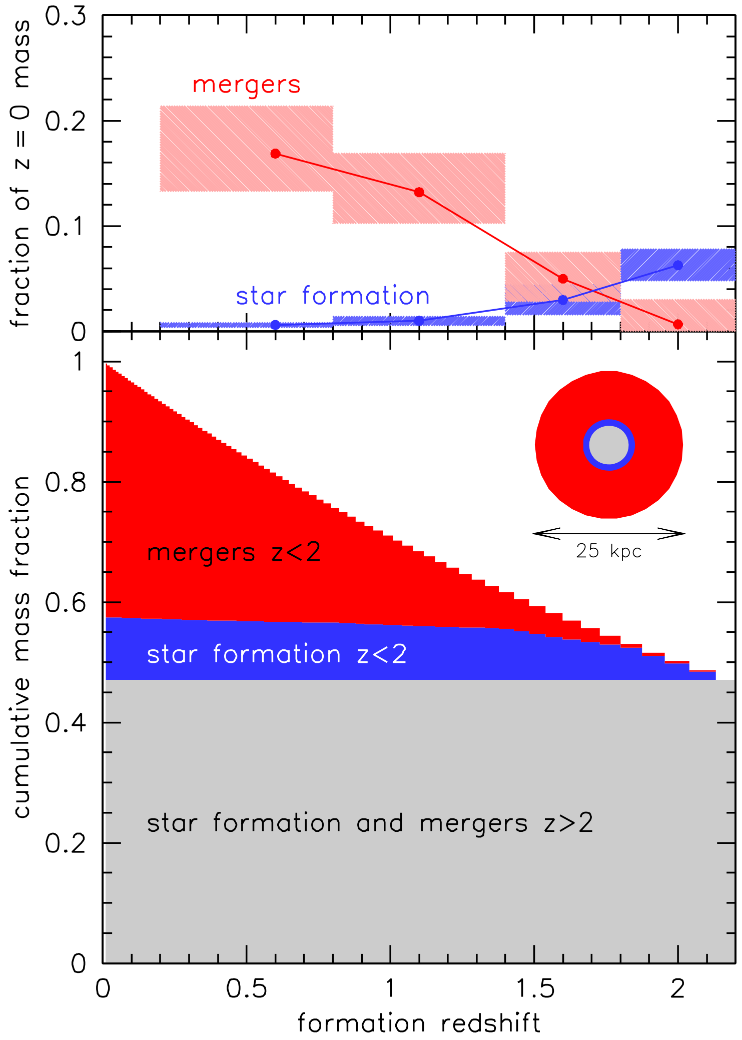


$f_{pair}$ (cluster) ~ 40-80%  v. $f_{pair}$(field) ~ 5%
(> $3 \times 10^{10}$ $M_{sun}$ ; 1:1 - 1:10; Rproj < 20 kpc comoving)
⇒ proto-cluster galaxy merger rate >> z~1.6 UDS field galaxy merger rate

Lotz et al. 2013 (also Rudnick et al. 2012, Papovich et al. 2012)

# evolutionary paths of high-z galaxies

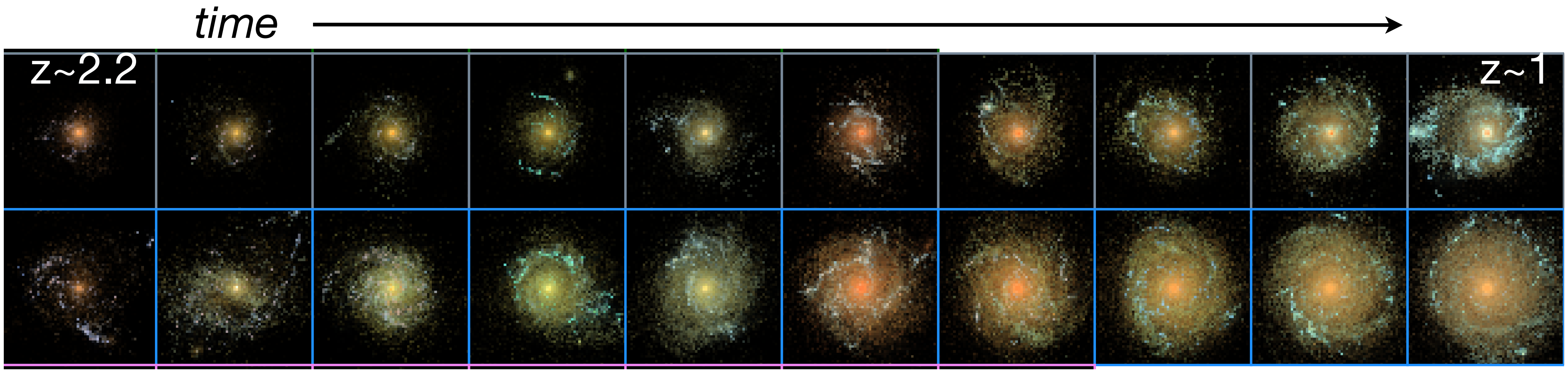




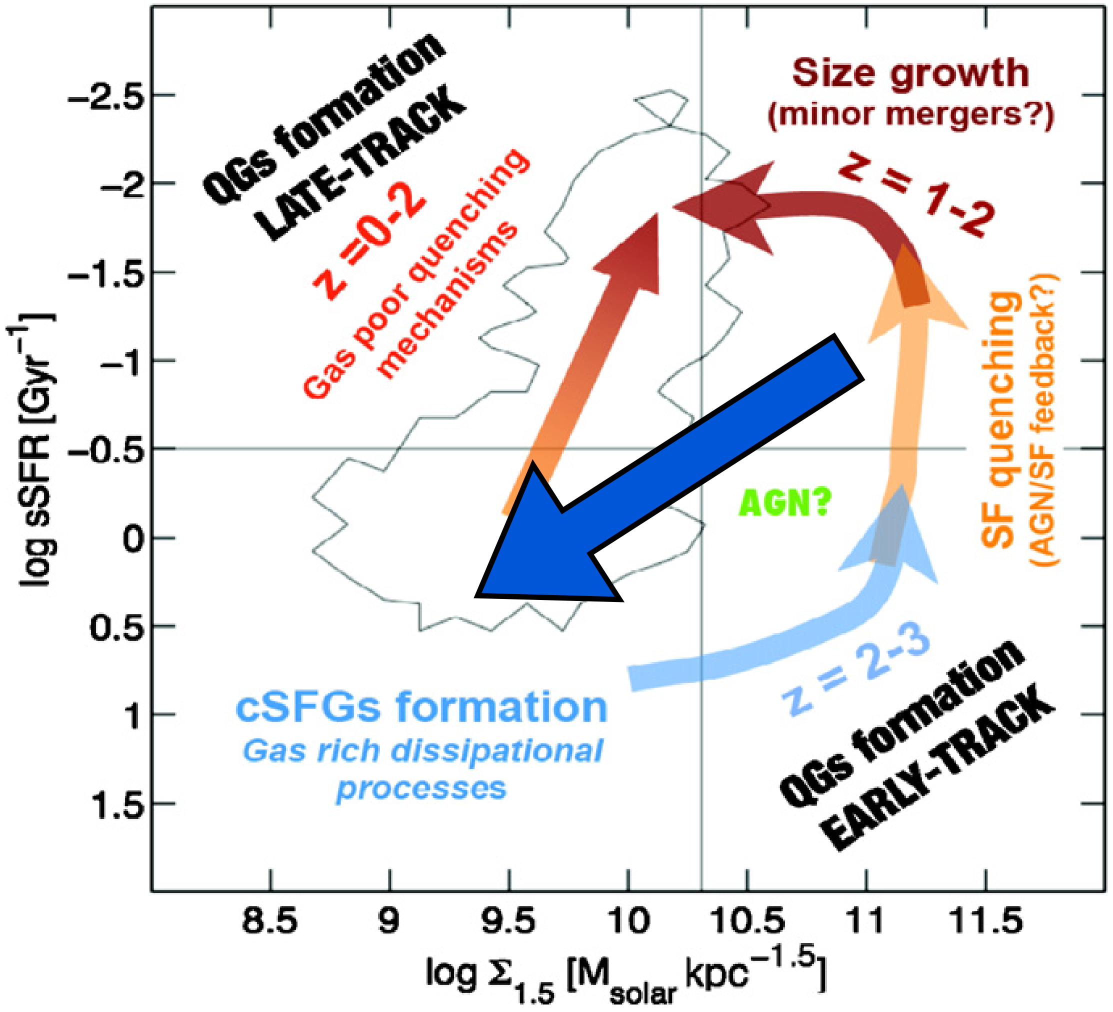
van Dokkum et al.

✓direct evidence for z~1-2 dry minor mergers

# evolutionary paths of high-z galaxies



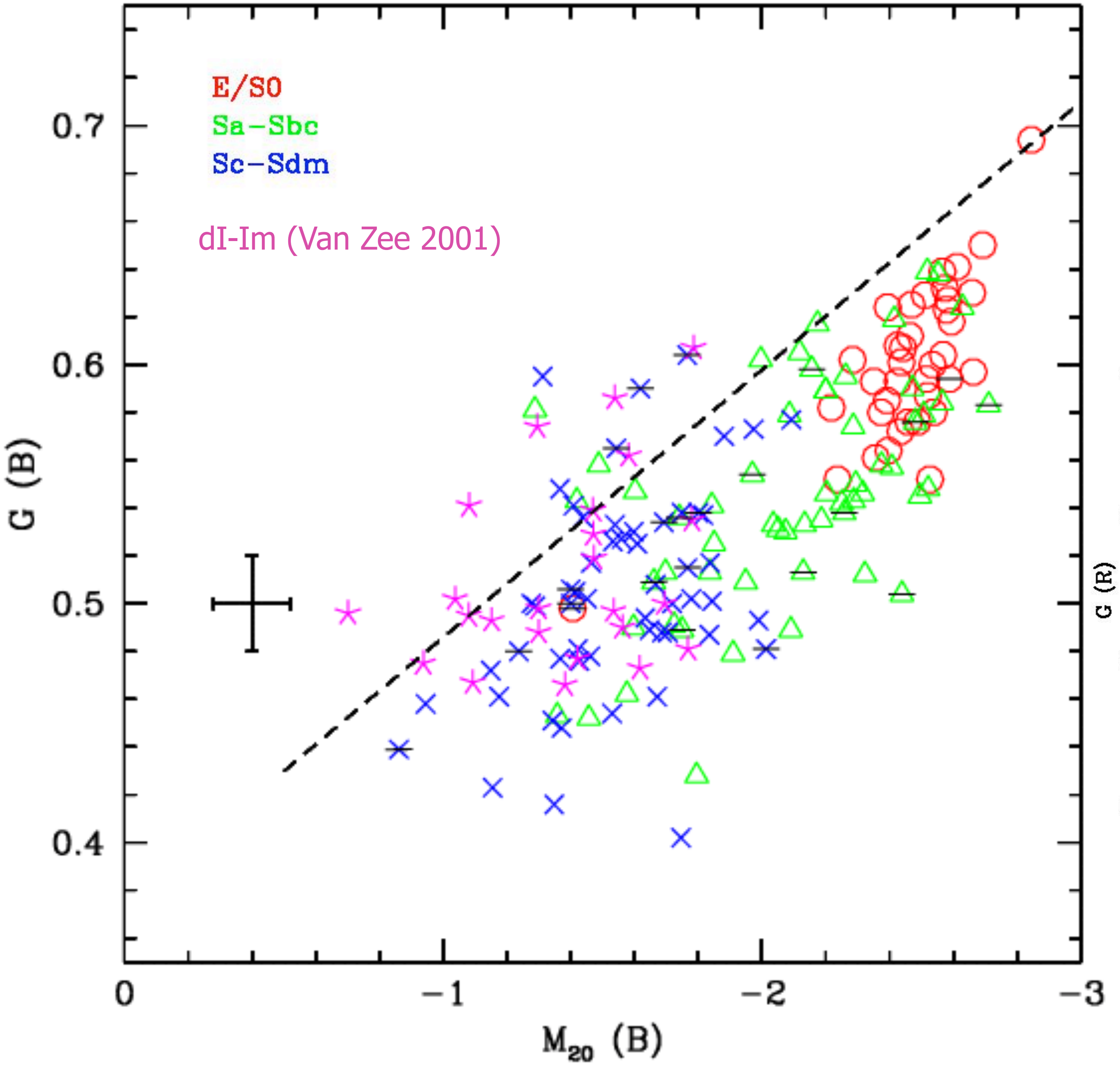
Snyder et al. 2014



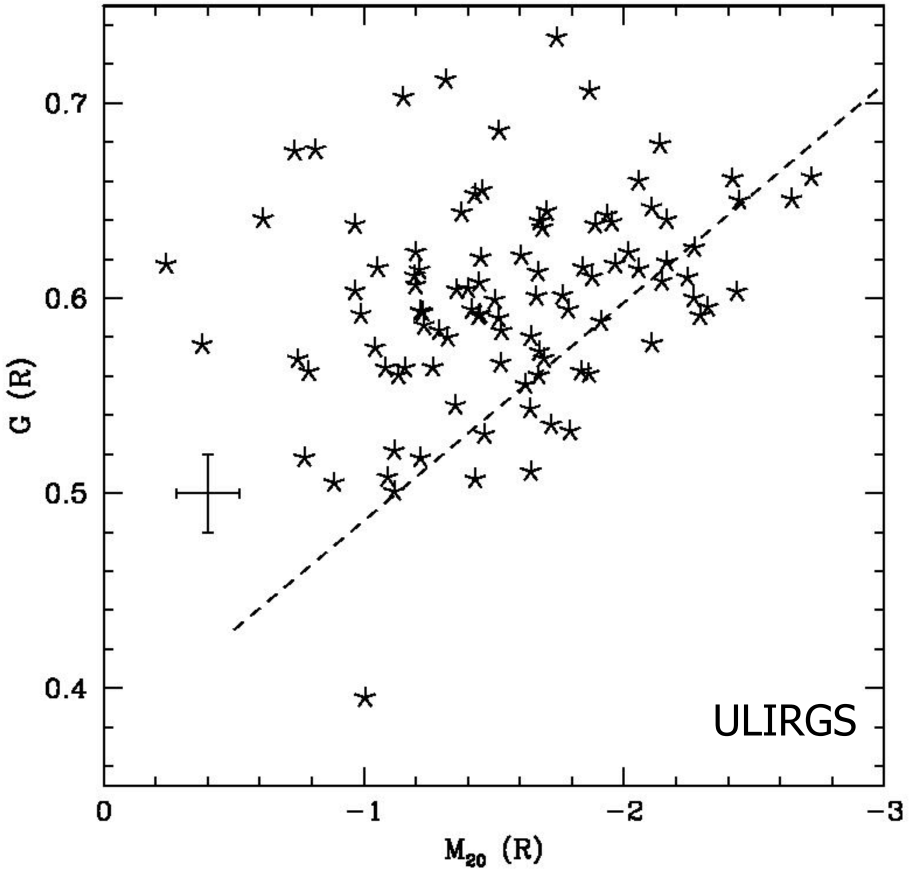
structural evolution not monotonic?
simulated compact galaxies can
develop star-forming disks

triggered by accretion and/or
gas-rich minor mergers?

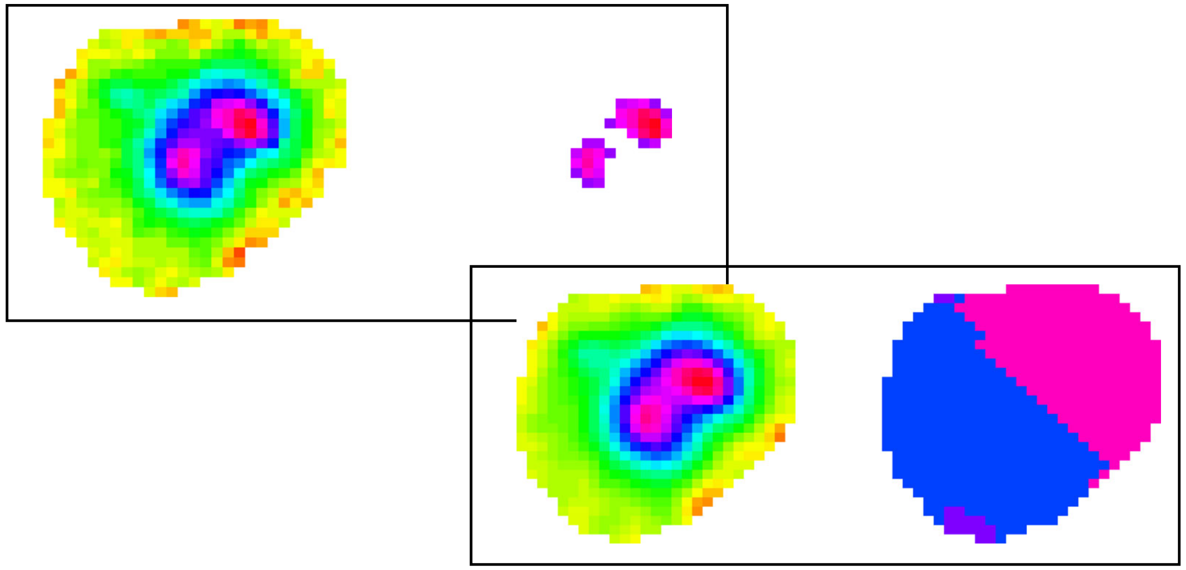
# gini-m20 z=0



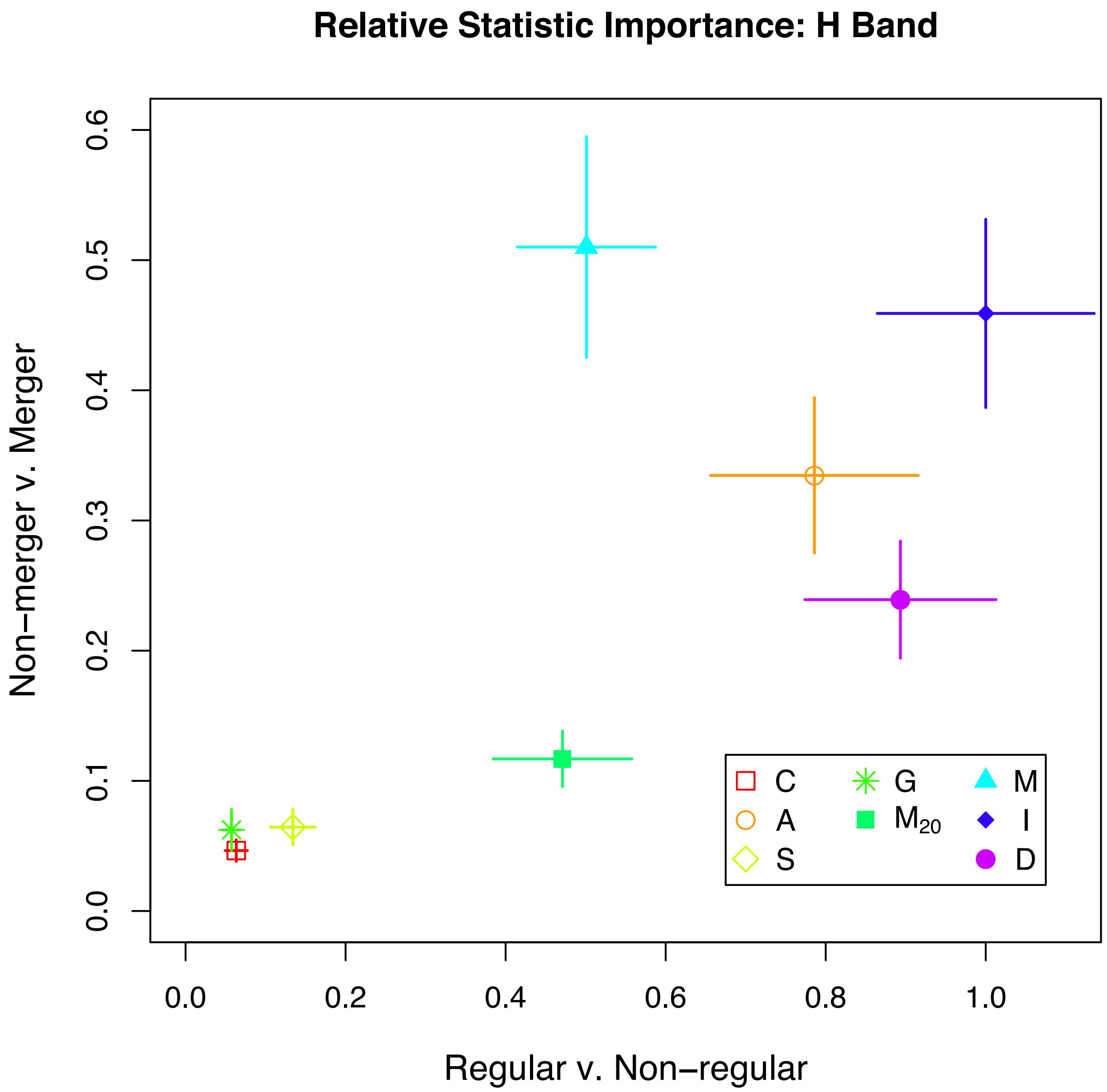
gini-m20 captures B/D ratio
as well as major+minor mergers



# New (better) way to find z~2 Mergers



Freeman et al. 2013



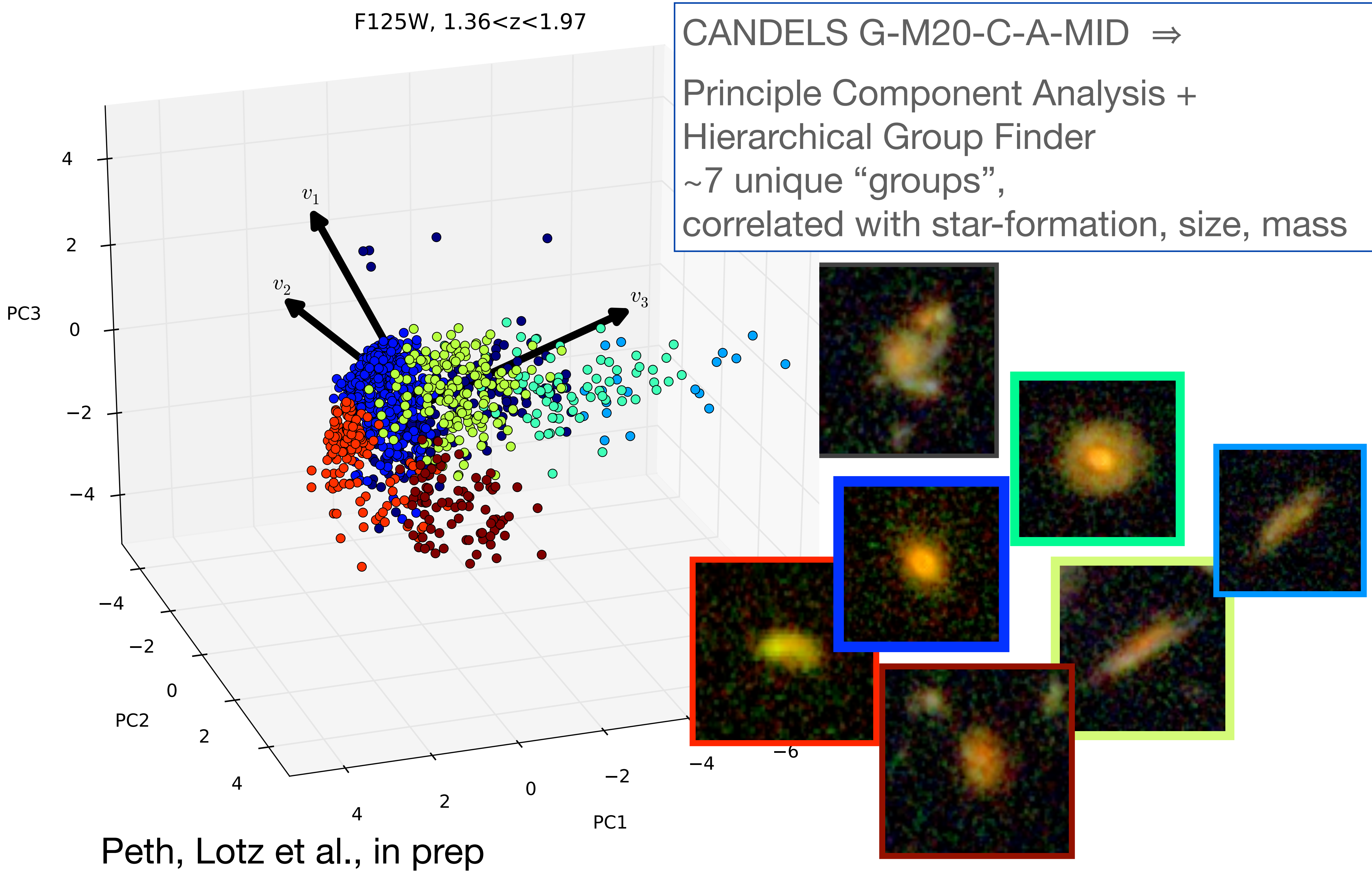
new statistics M-I-D examine
the ratios of
area (M), intensity (I) and the distance (D)
between 1st and 2nd brightest clumps

beats G-$M_{20}$, CAS at finding CANDELS visually classified mergers
for WFC3/H < 24 galaxies

# Beyond the Hubble Sequence

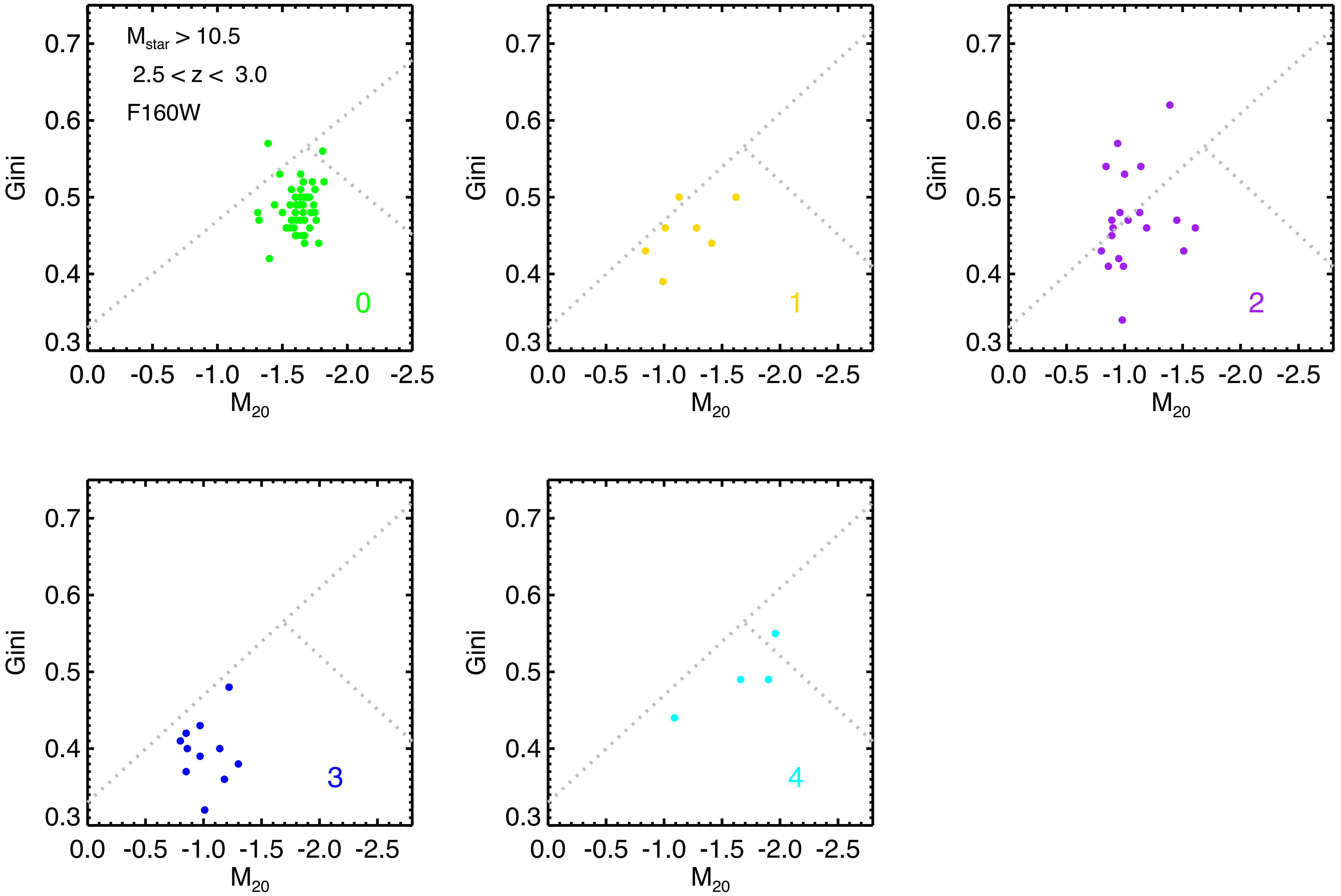
CANDELS G-M20-C-A-MID ⇒

Principle Component Analysis +
Hierarchical Group Finder
~7 unique “groups”,
correlated with star-formation, size, mass



Peth, Lotz et al., in prep

# gini-m20 2.5 < z < 3.0 Mstar > 10.5



Lotz, Peth et al., 2014

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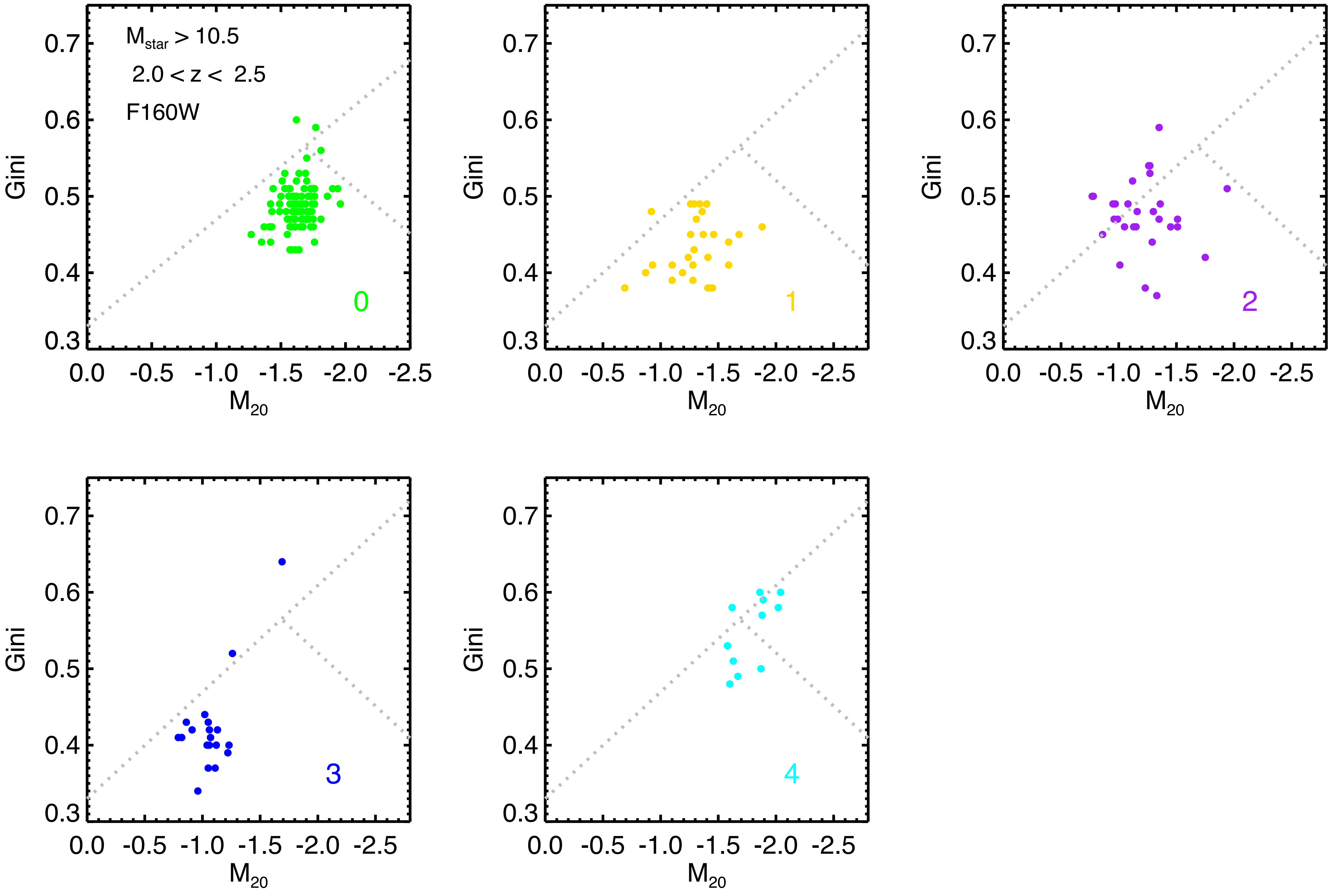

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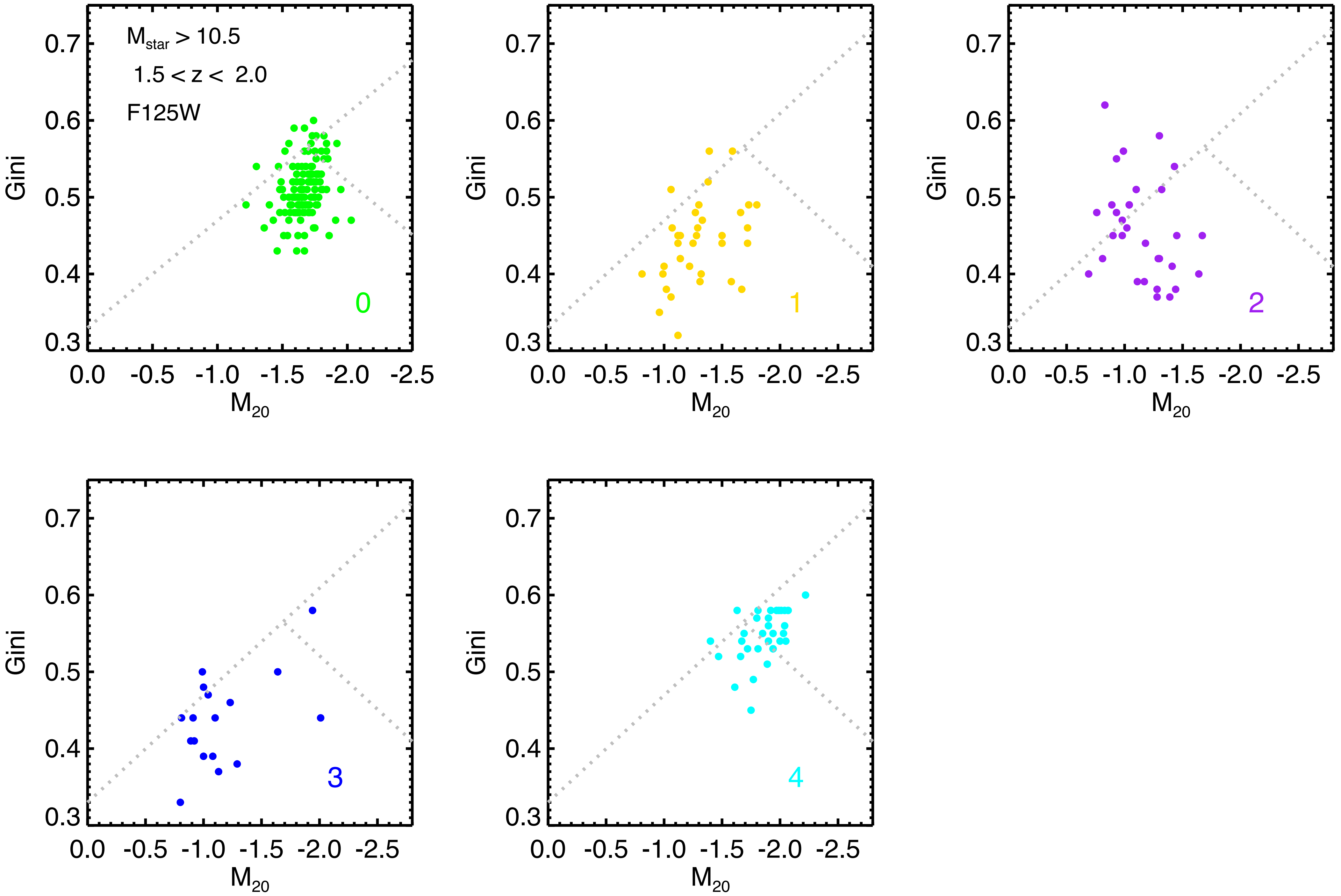
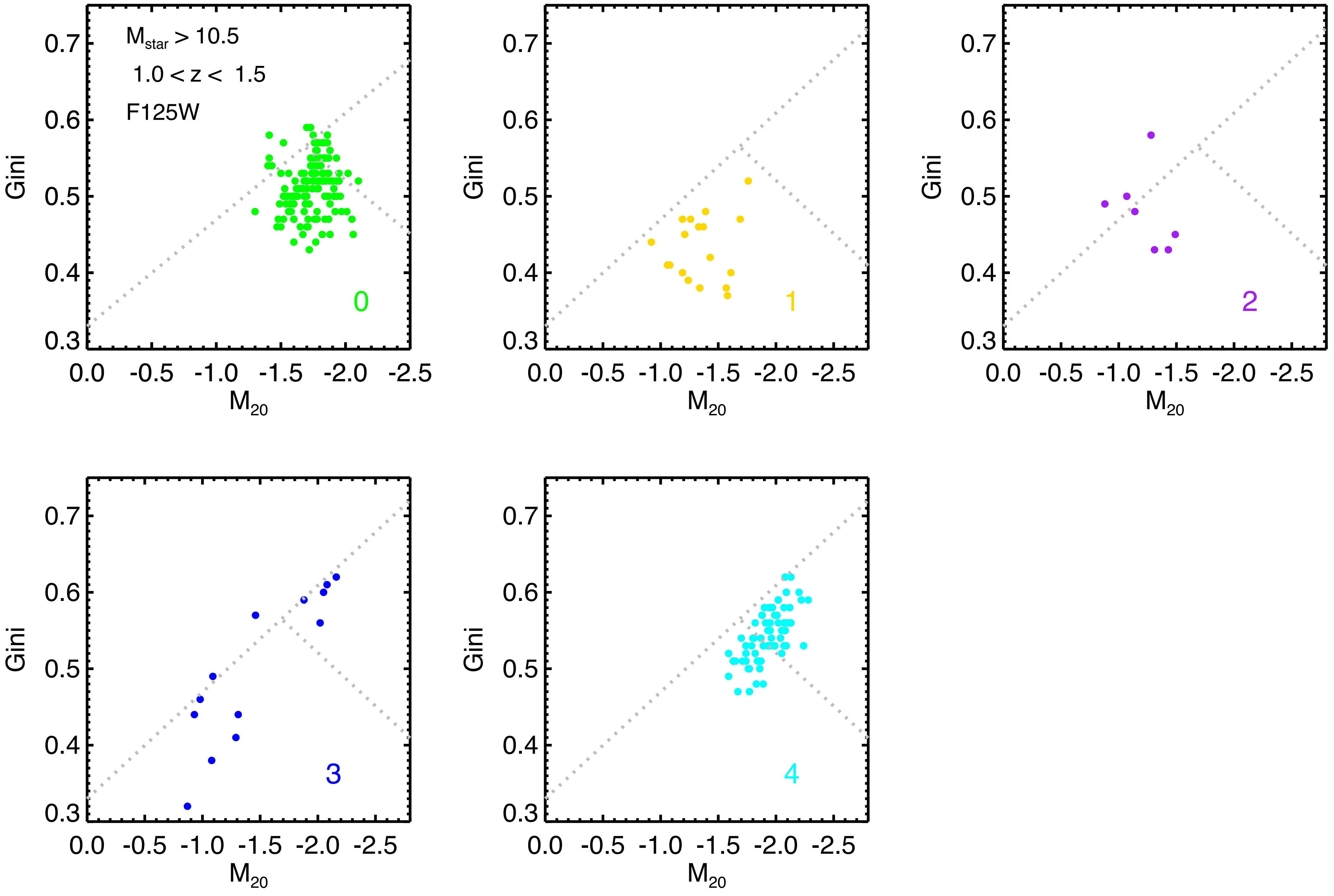
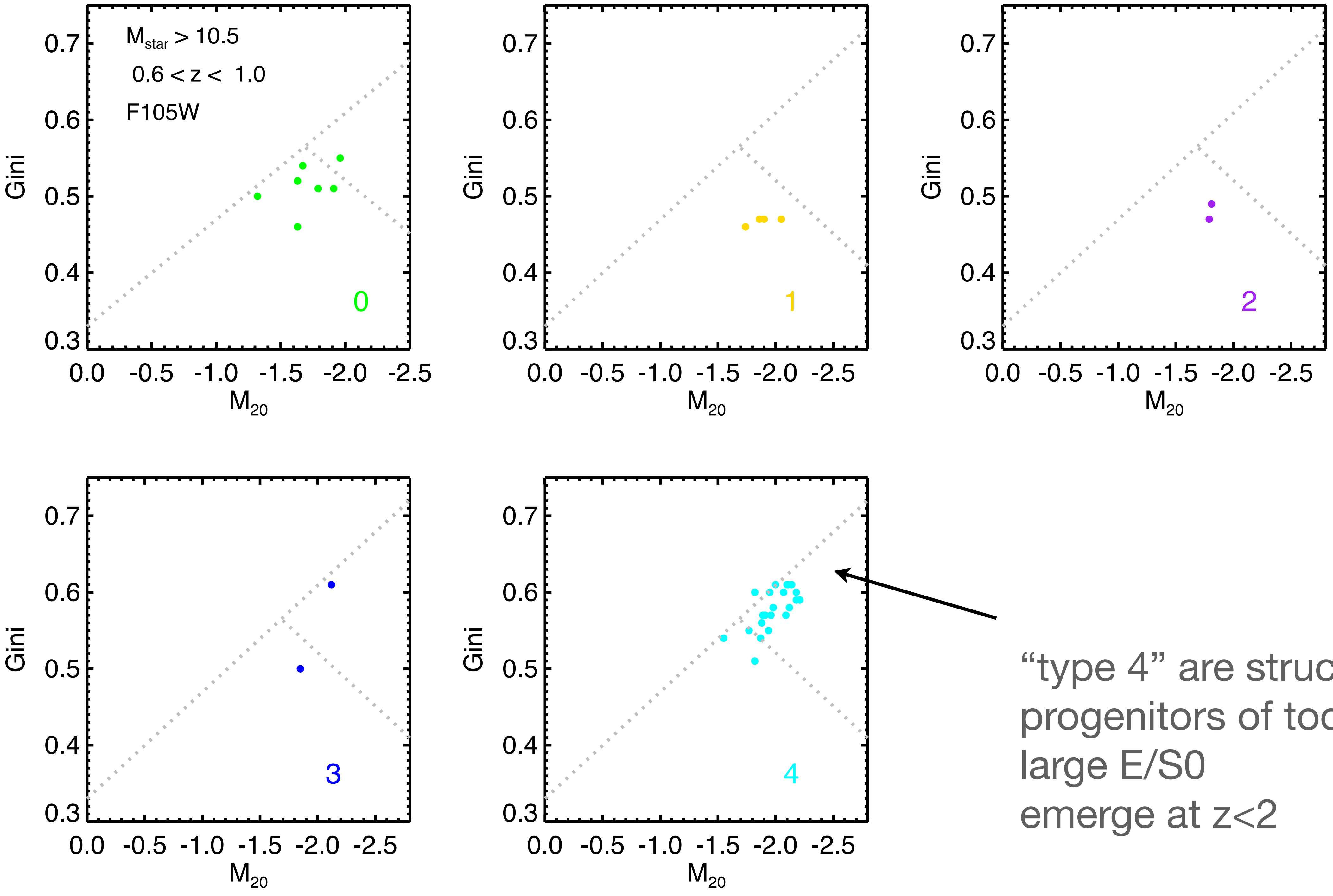


# gini-m20 $1.0 < z < 1.5$ Mstar > 10.5

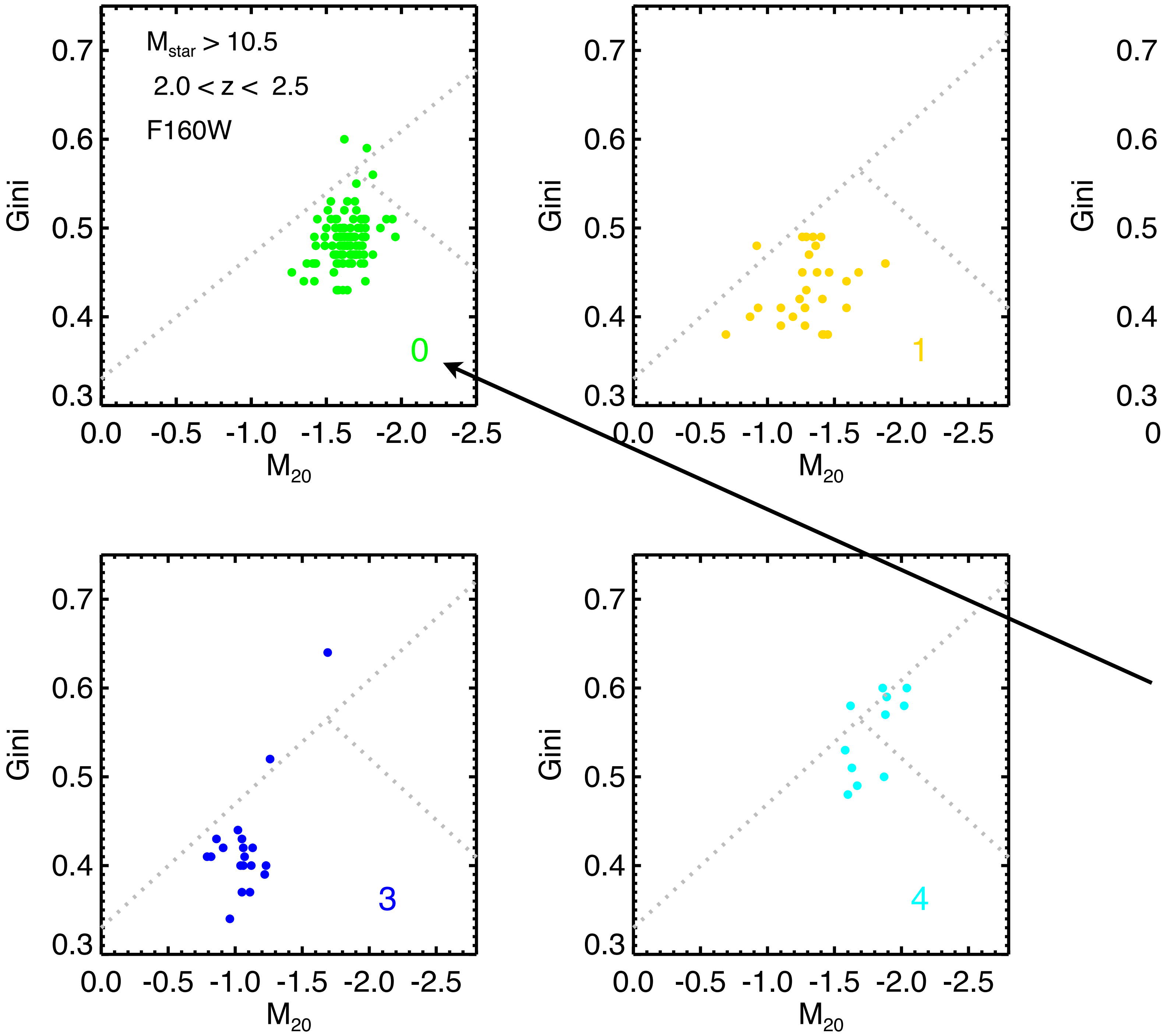


# gini-m20 0.6 < z < 1.0 Mstar > 10.5



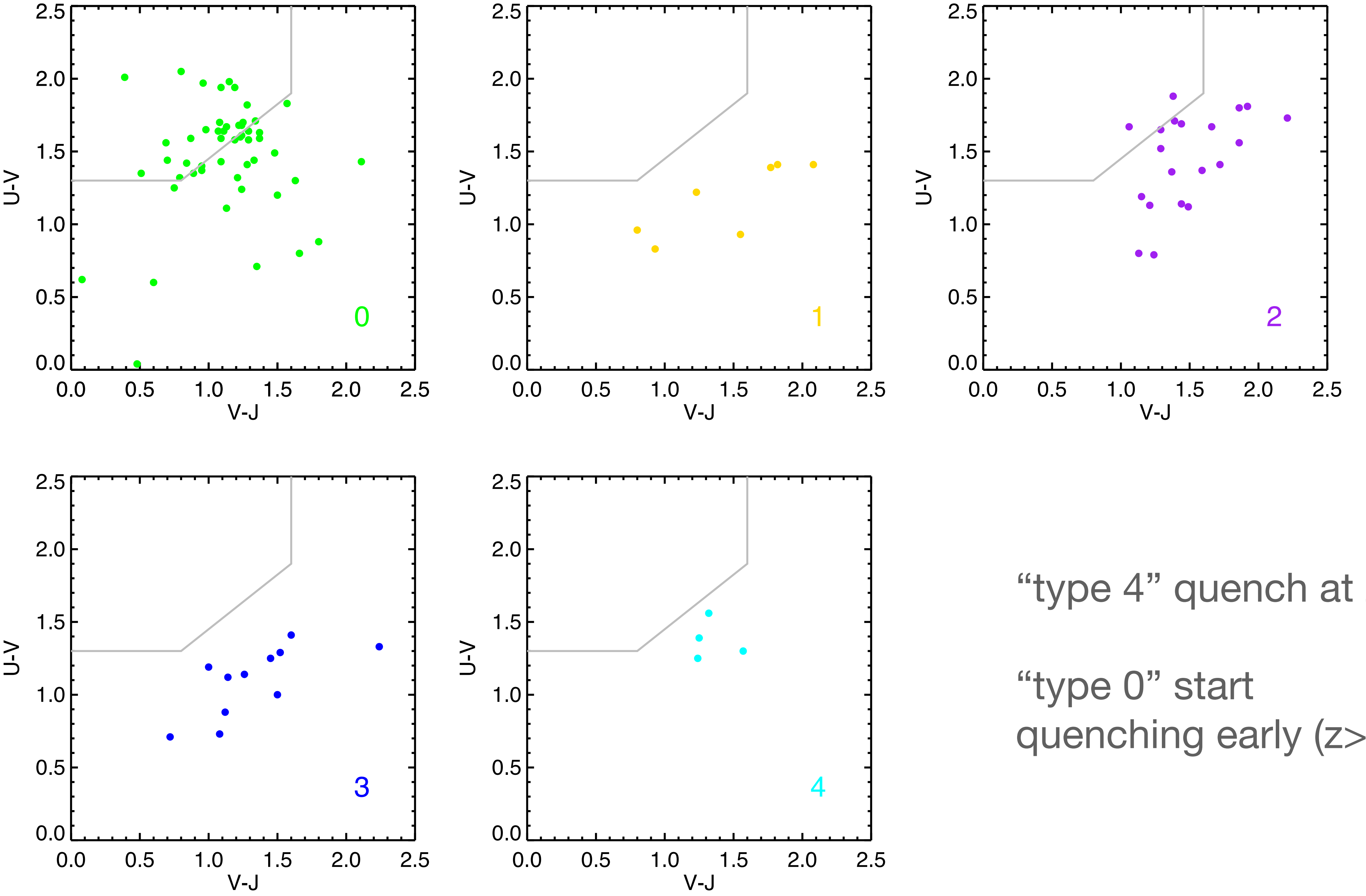
"type 4" are structural progenitors of today's large E/S0 emerge at z<2

# gini-m20 2.0 < z < 2.5 Mstar > 10.5



“type 0” are small + smooth galaxies (mix of unresolved disks and compact gals); dominant at z~1-3

# UVJ $2.5 < z < 3.0$ Mstar > 10.5

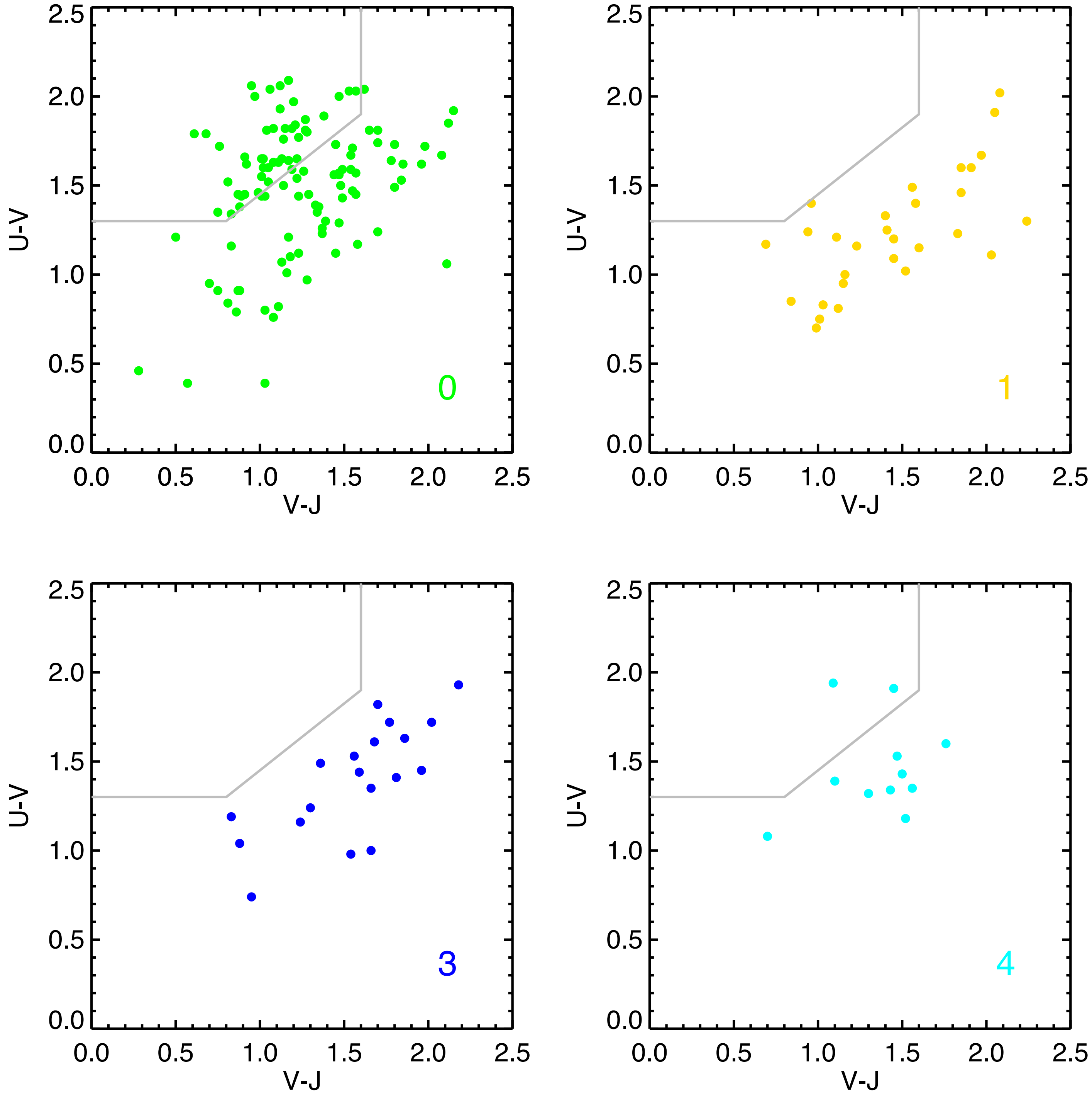


"type 4" quench at z<2

"type 0" start
quenching early (z>3)

from Lotz, Peth et al in prep, CANDELS team photometry

# UVJ 2.0 < z < 2.5 Mstar > 10.5



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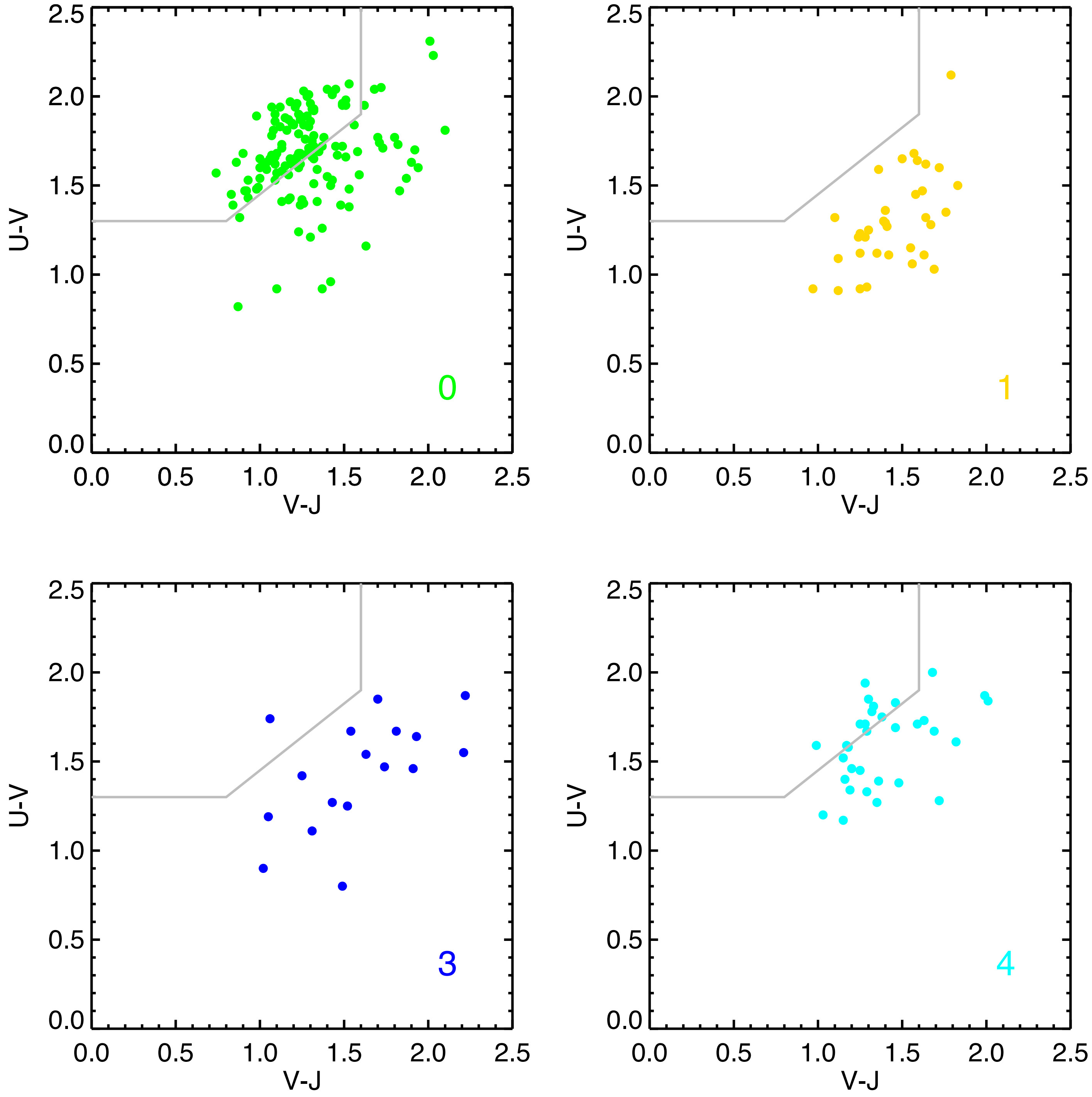

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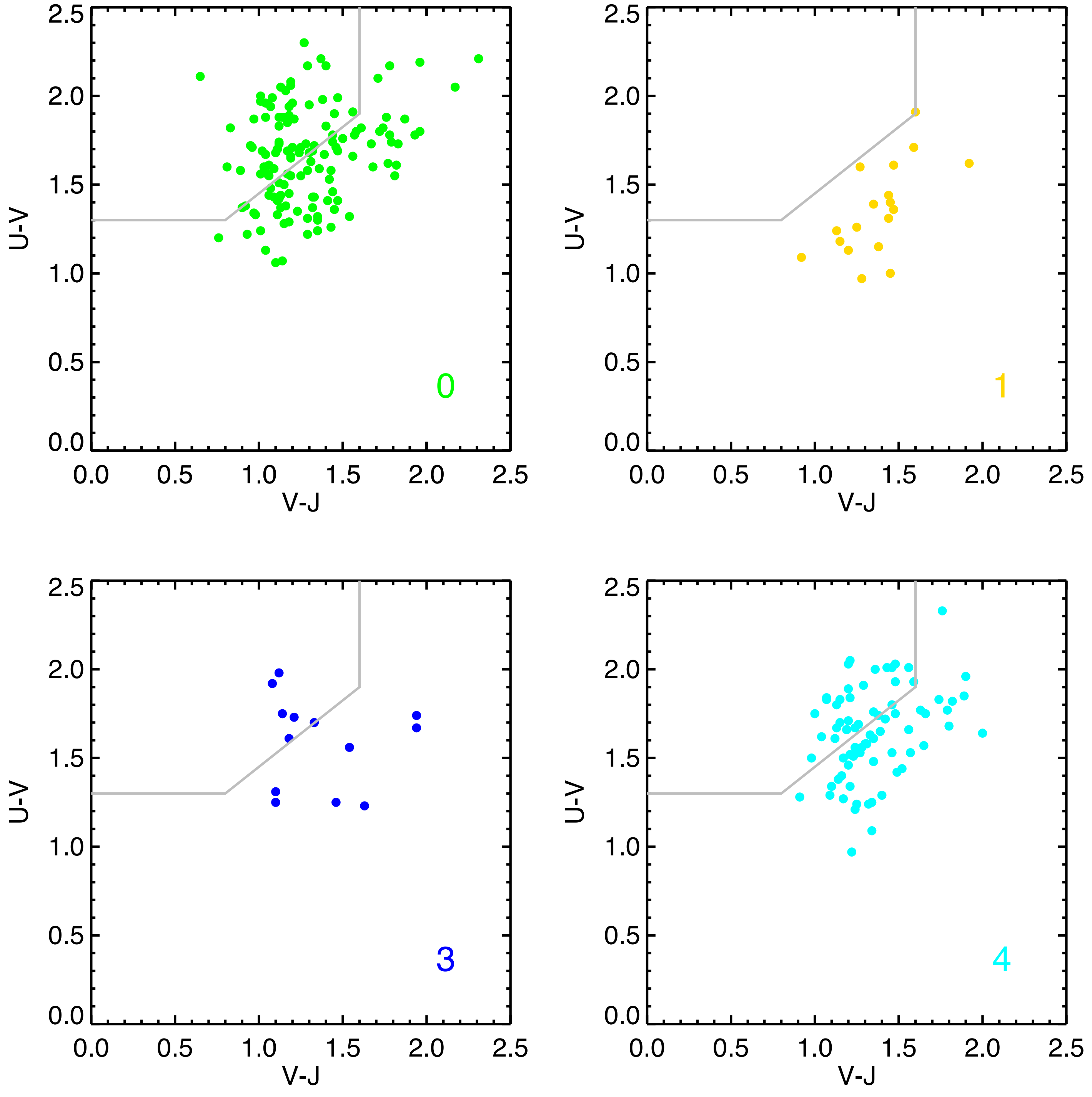
# UVJ $1.0 < z < 1.5$ Mstar $> 10.5$



“type 4” quench at z<2

“type 0” start
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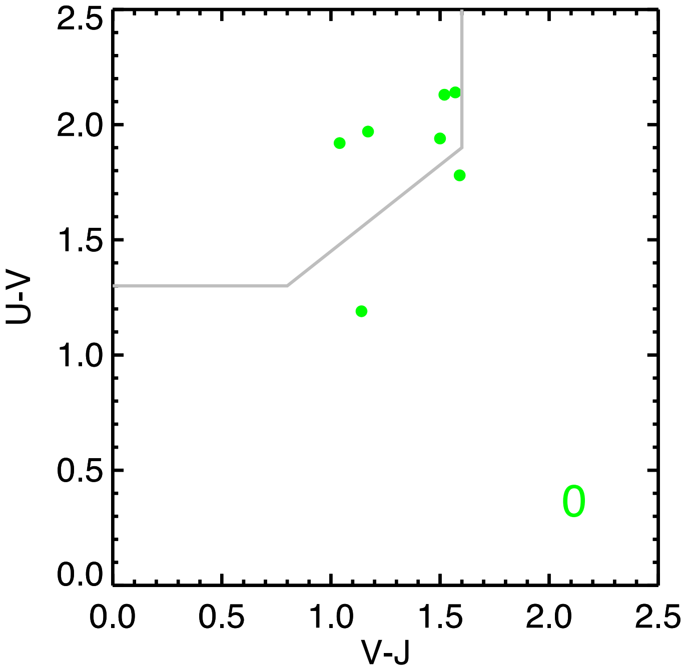
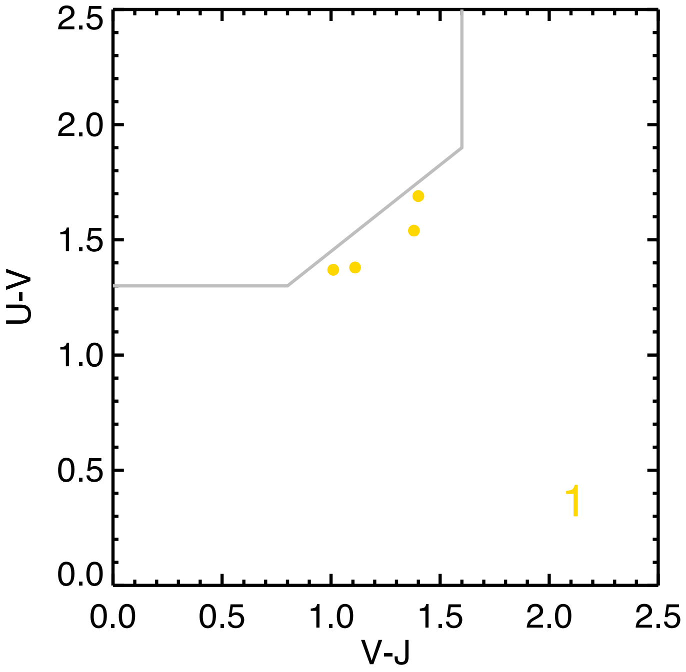
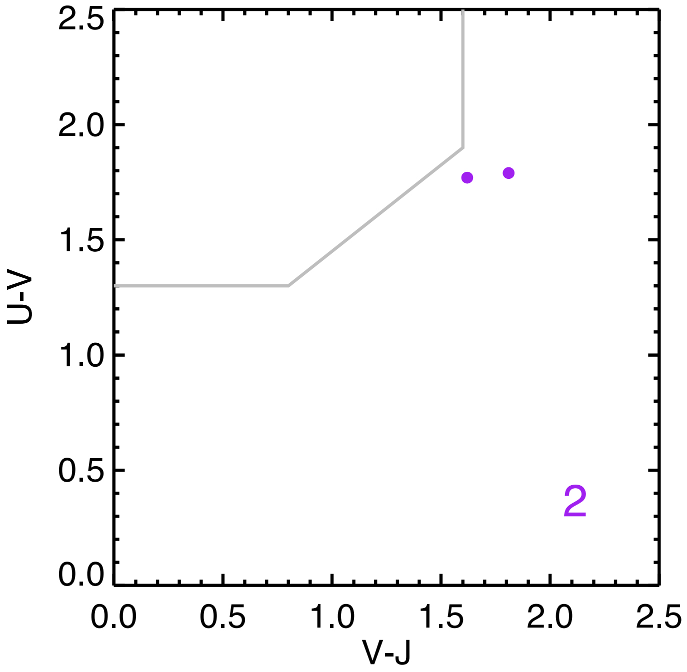
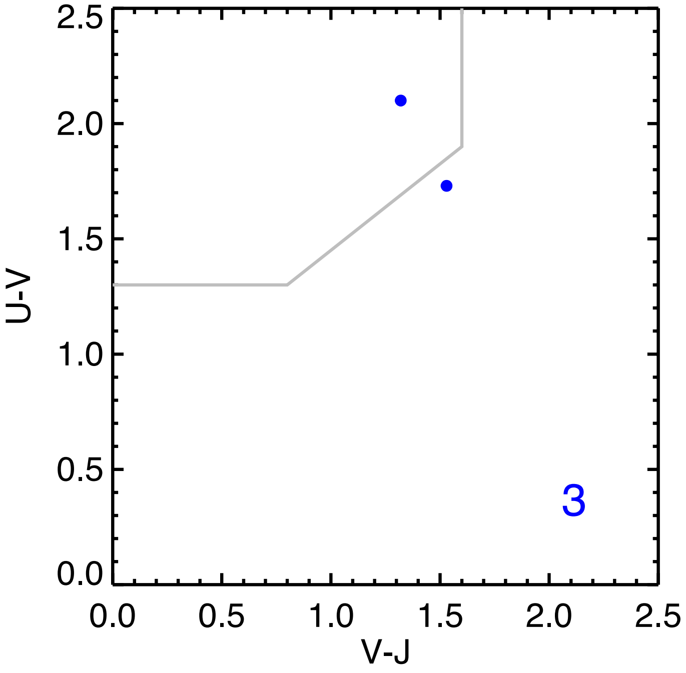
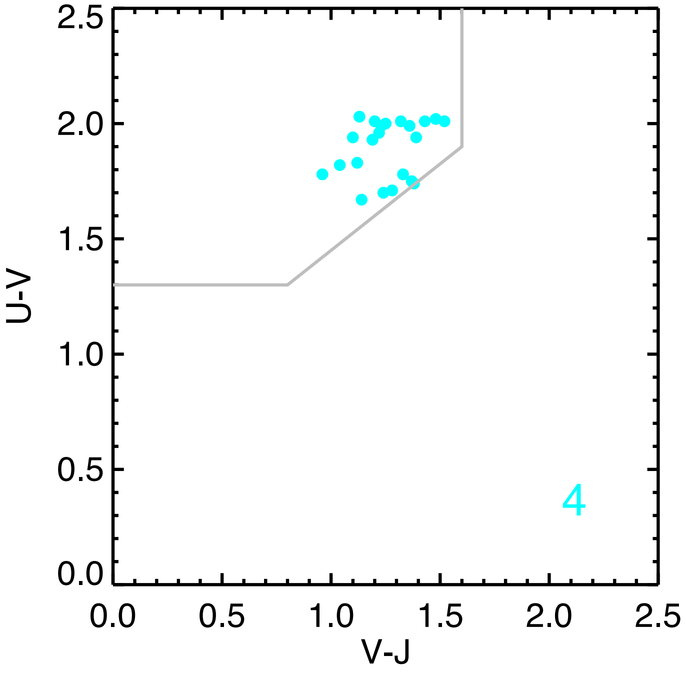
# UVJ 0.6 < z < 1.0 Mstar > 10.5











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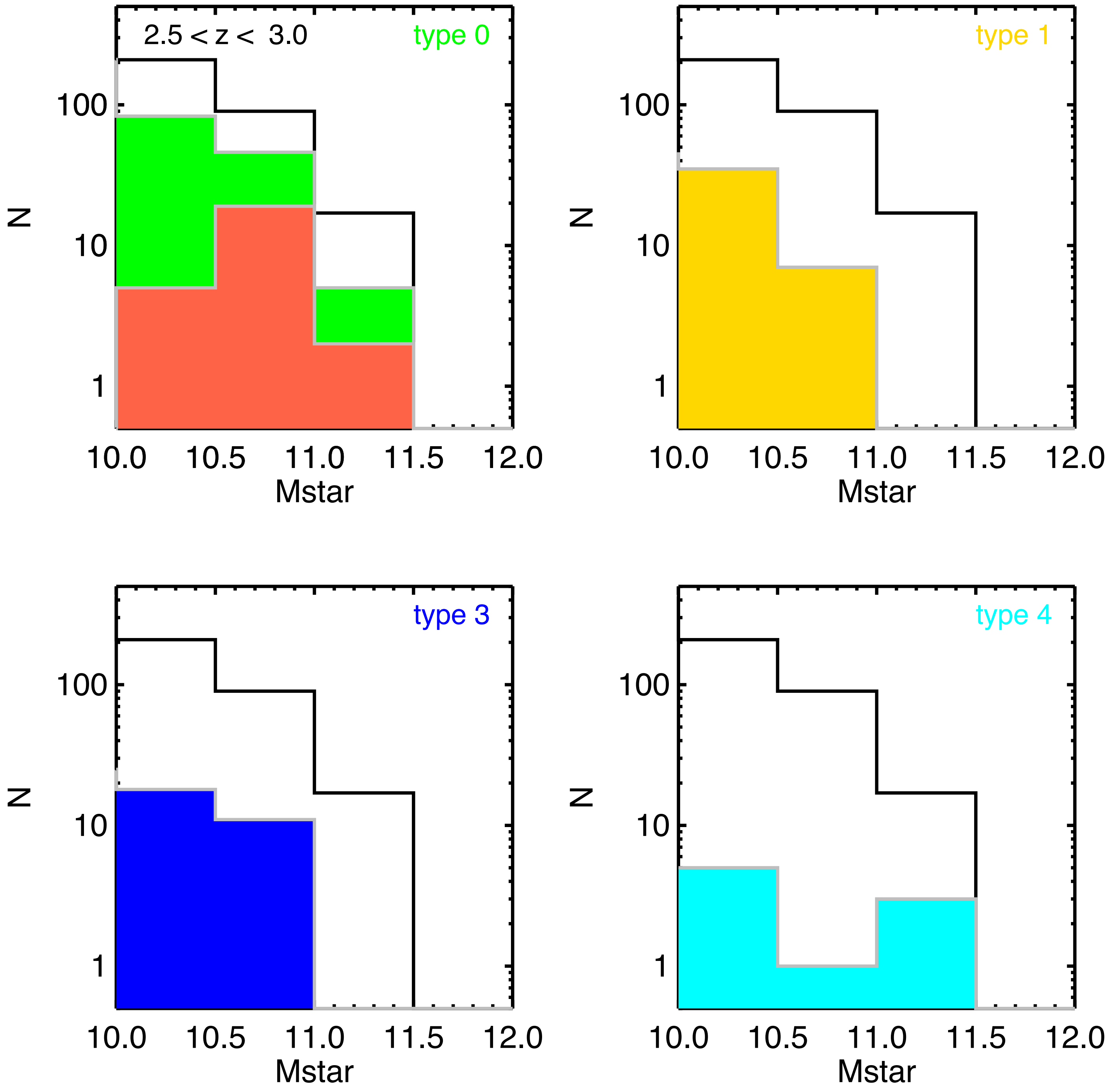
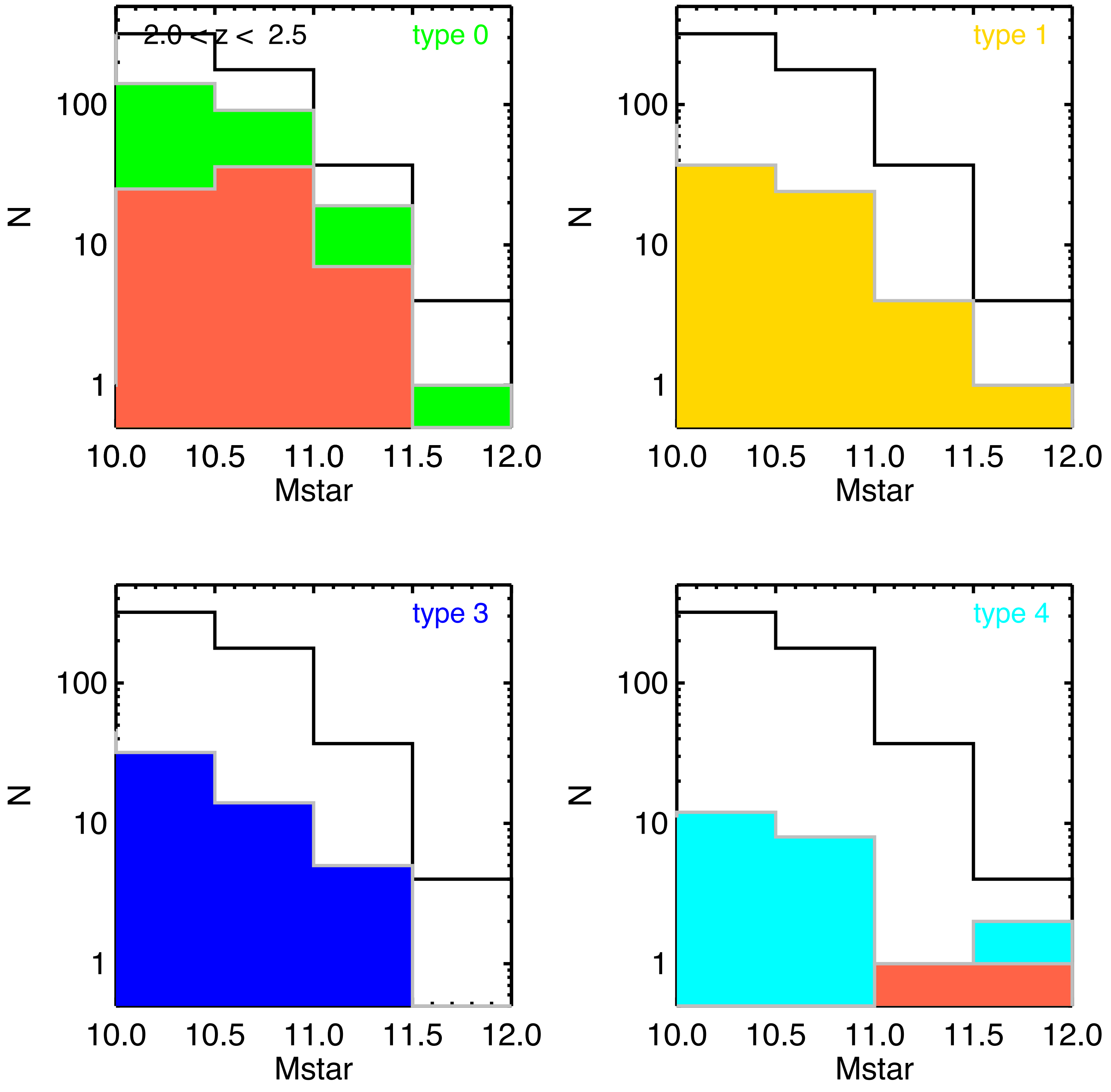
# stellar masses $2.5 < z < 3.0$



“type 4” dominate massive galaxies at $z<1.5$

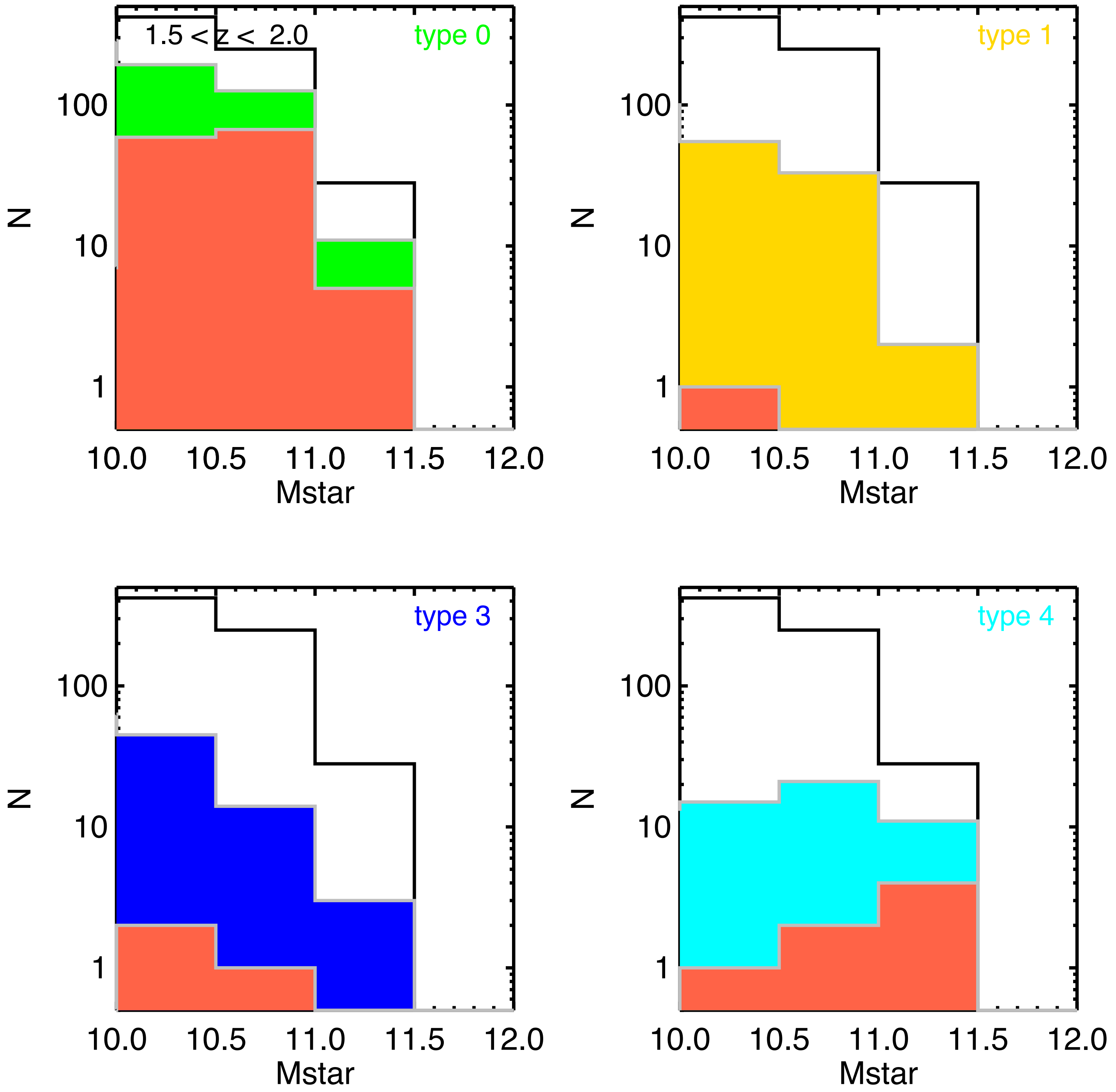
from Lotz, Peth et al in prep, CANDELS team photometry

# stellar masses 2.0 < z < 2.5



“type 4” dominate massive galaxies at z<1.5

# stellar masses 1.5 < z < 2.0



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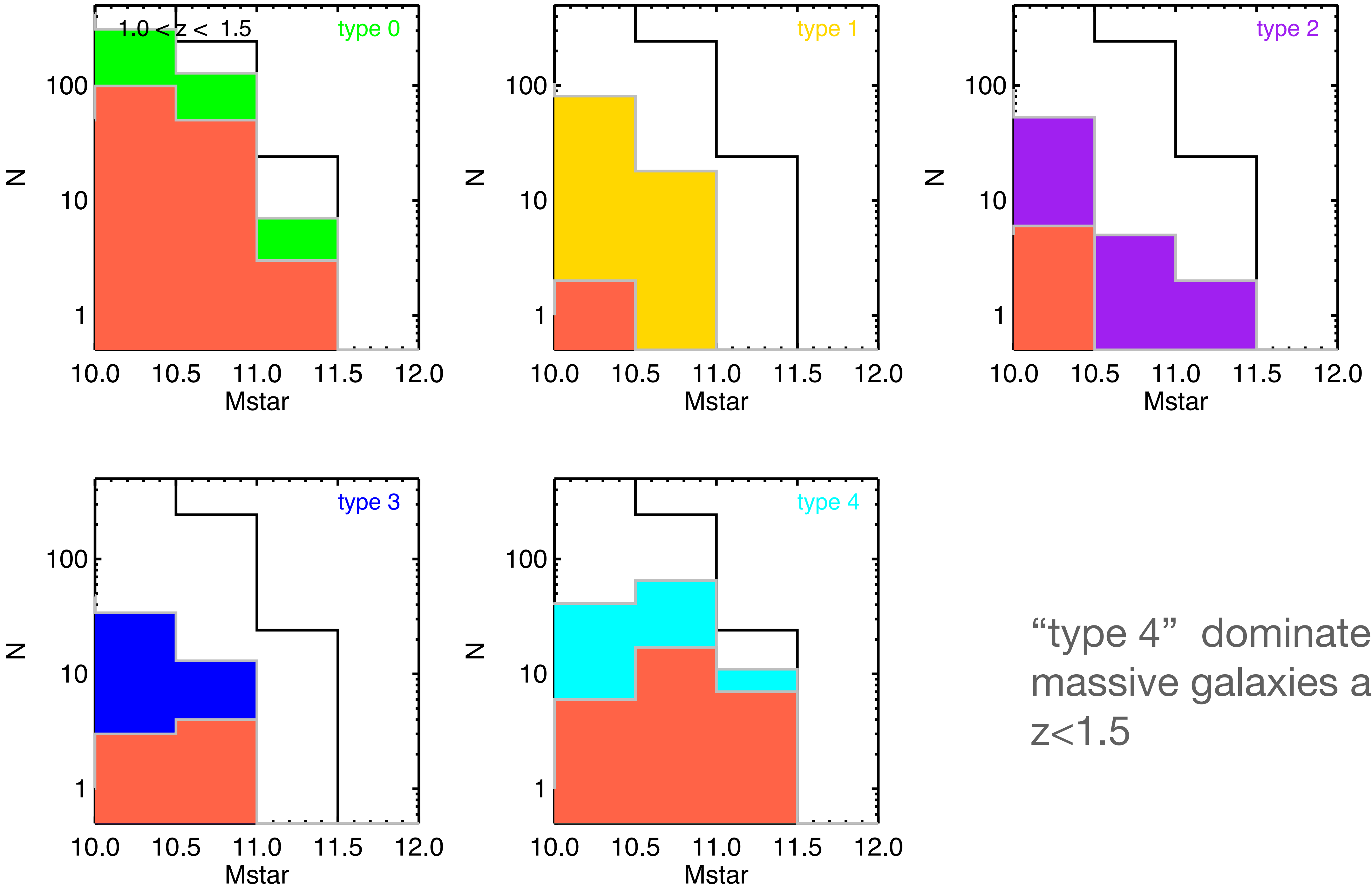

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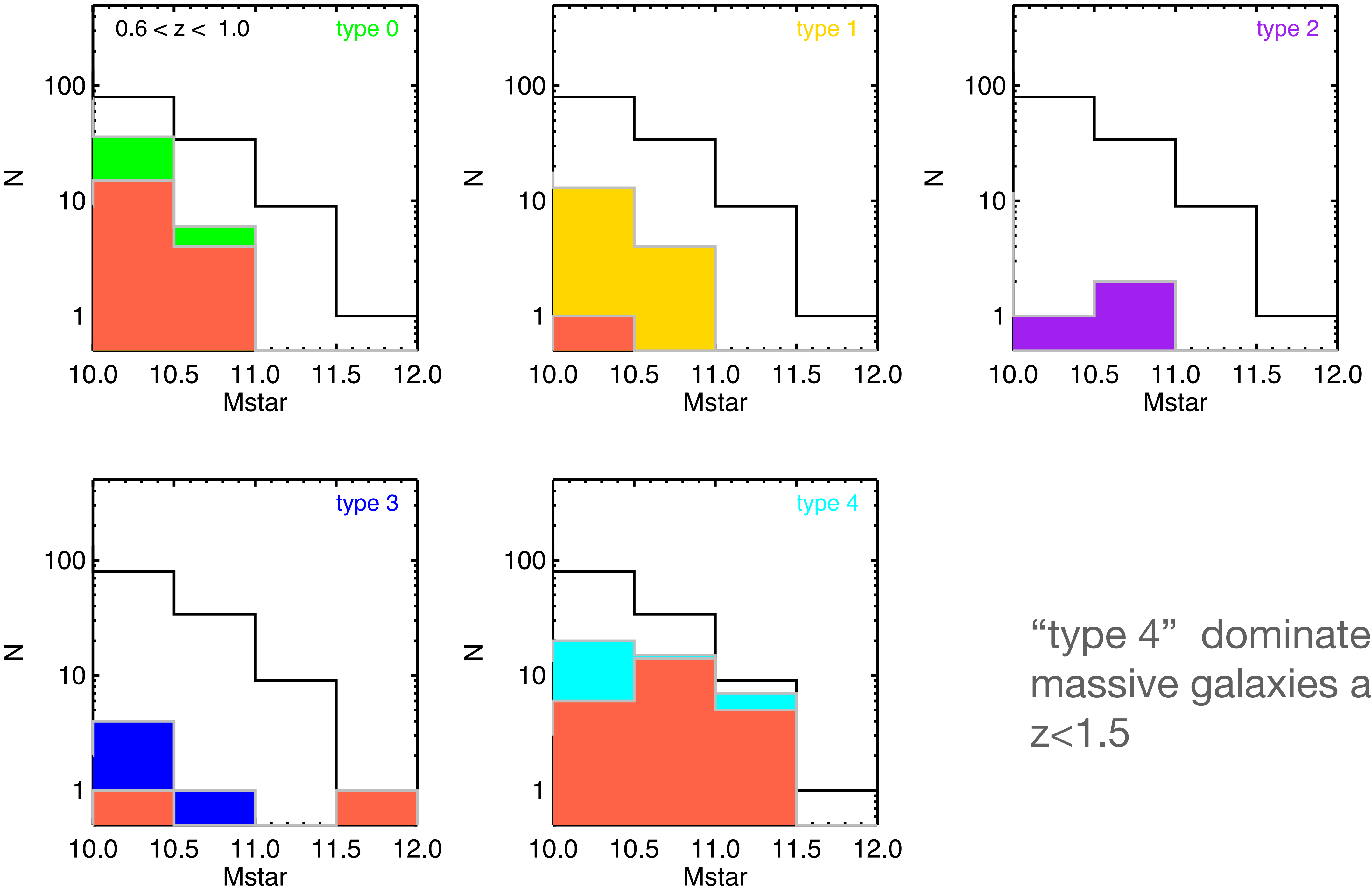
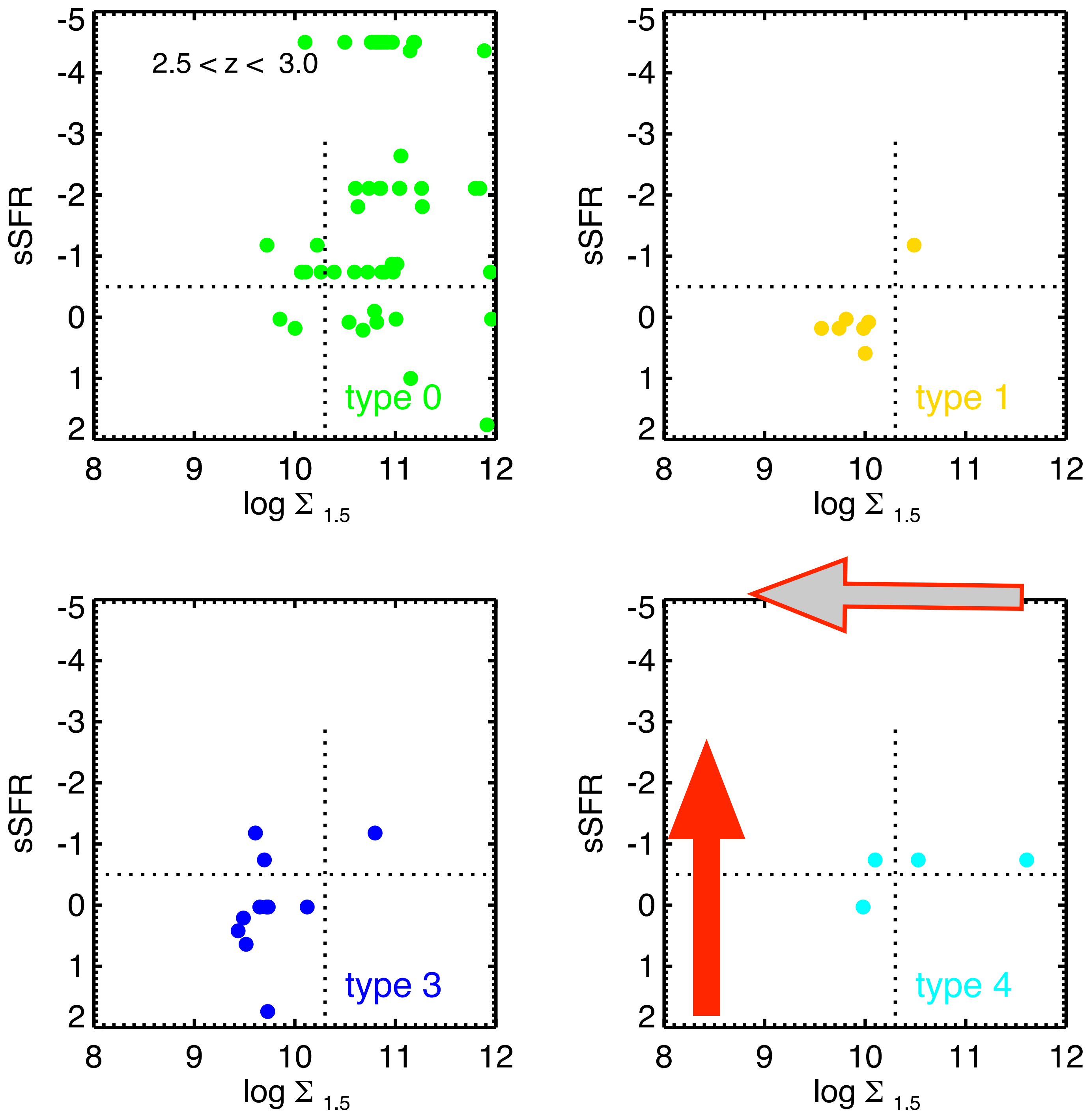
Lotz, Peth et al., 2014

# stellar masses 0.6 < z < 1.0



“type 4” dominate massive galaxies at z<1.5

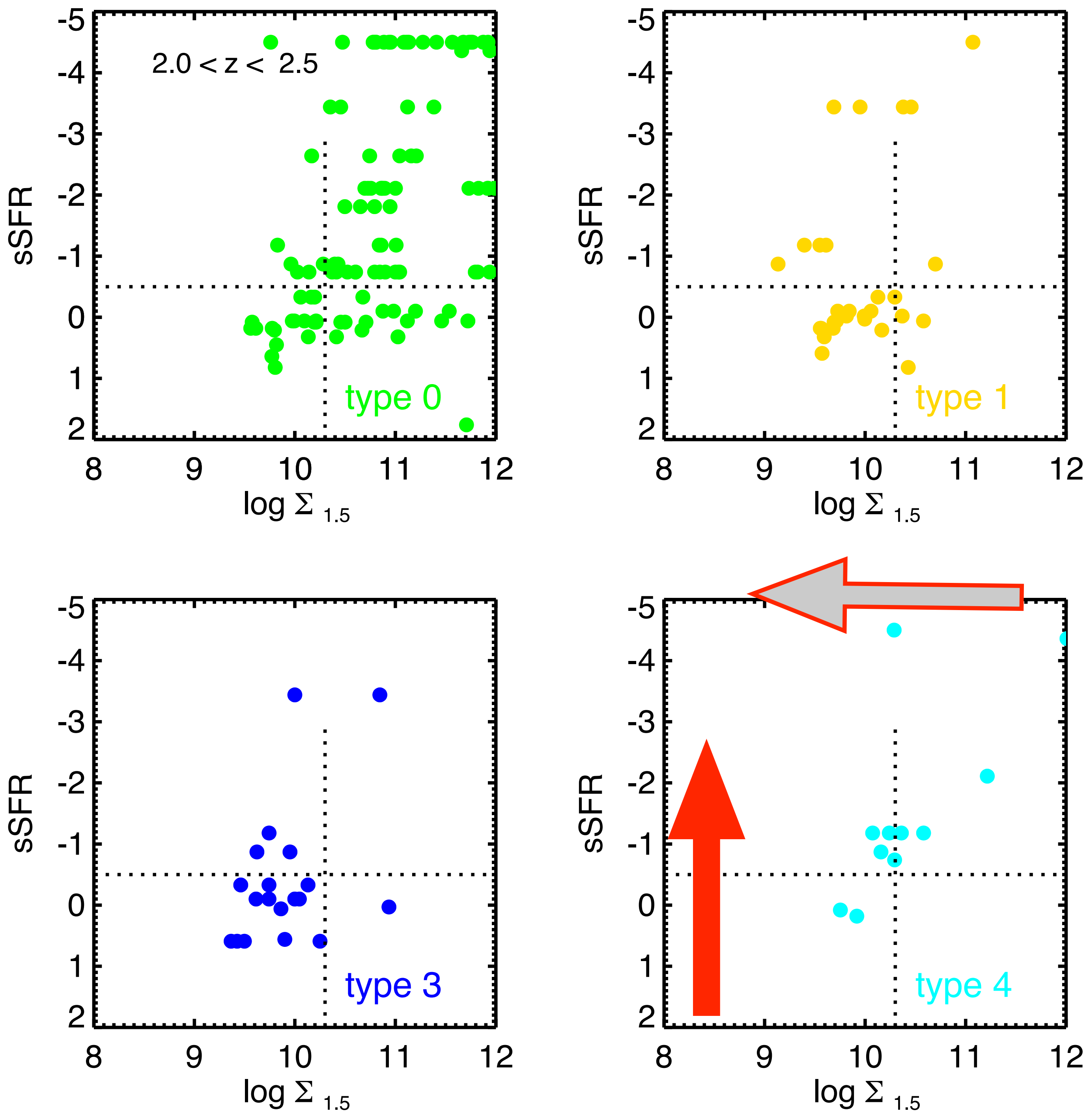
# sSFR v. $\Sigma_{1.5}$ $2.5 < z < 3.0$ Mstar > 10.5



“type 4” formation consistent with both quenching of disks (type 1, 2, 3) and mergers of compacts (type 0)

reff from Van der Wel et al 2014; sSFR from Lotz et al in prep (FAST -SED fitting)

# sSFR v. $\Sigma_{1.5}$ $2.0 < z < 2.5$



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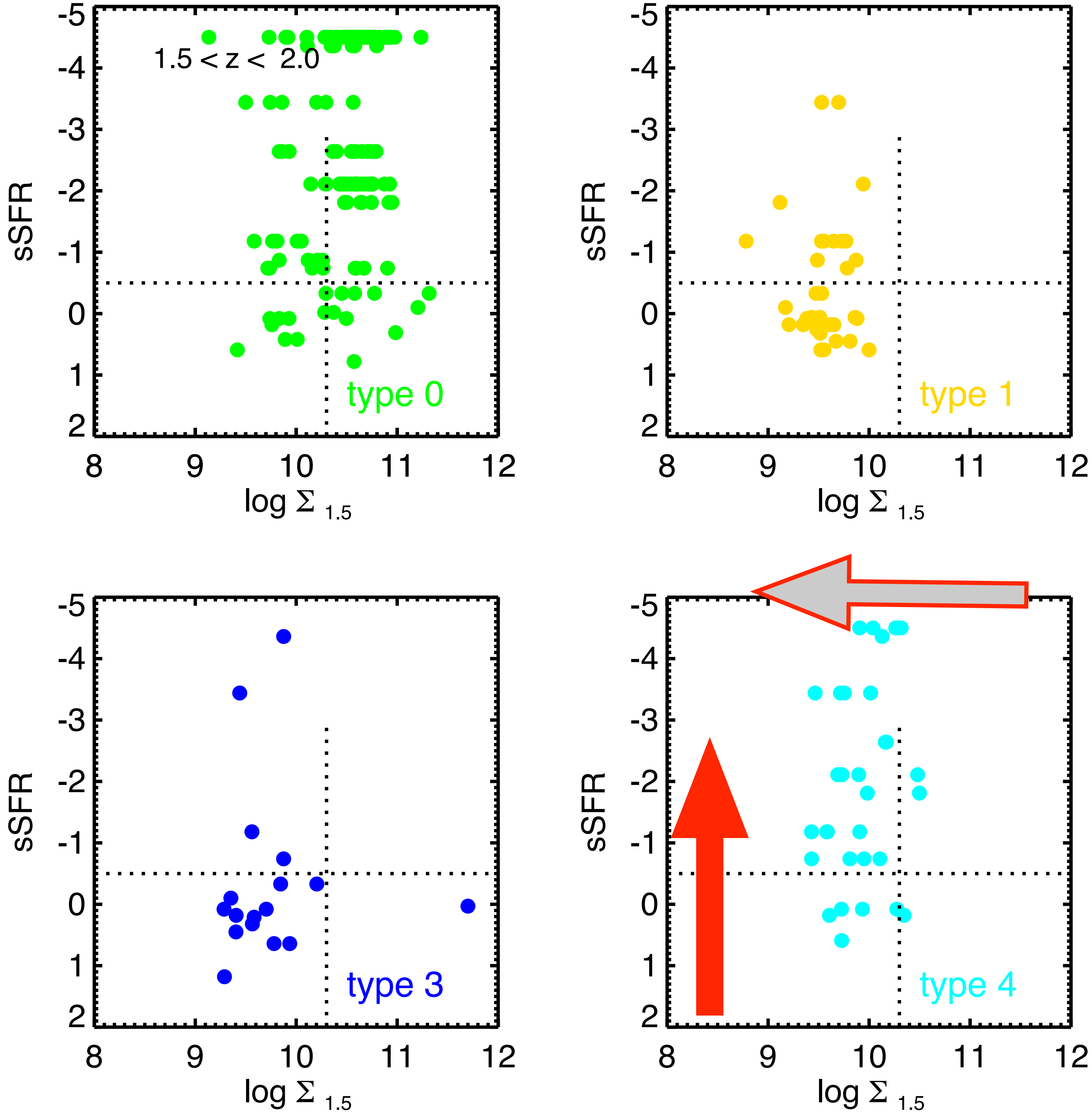

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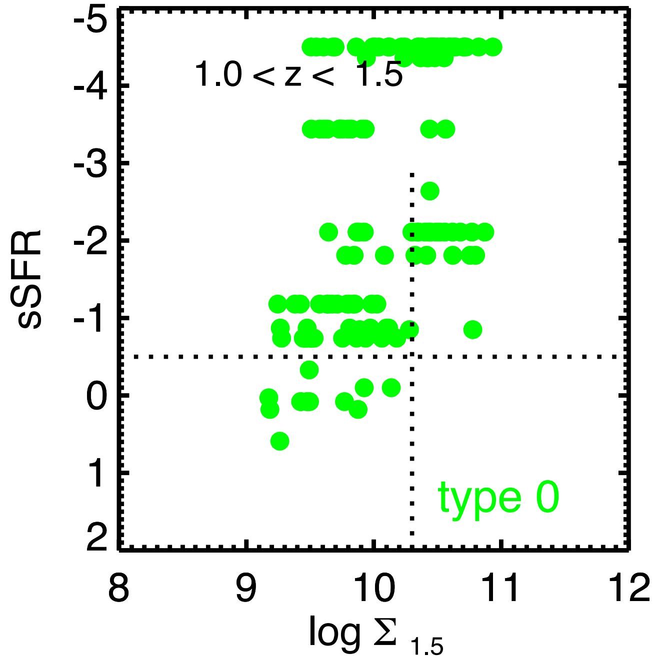

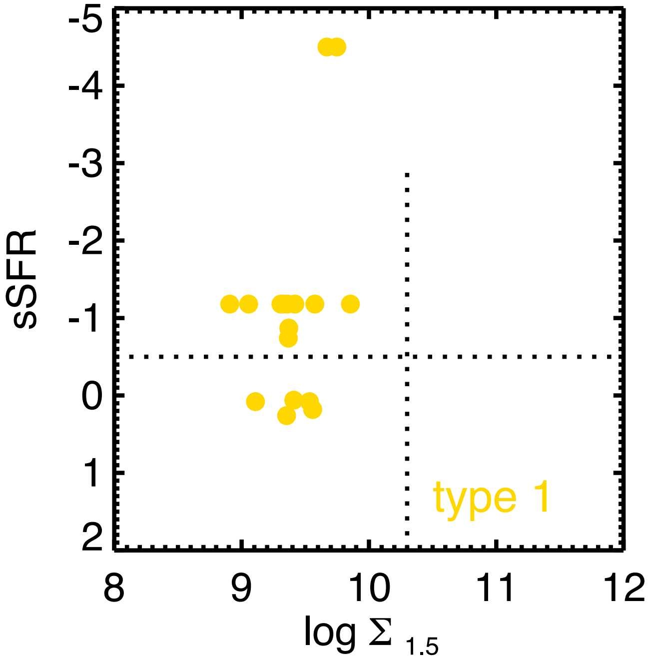

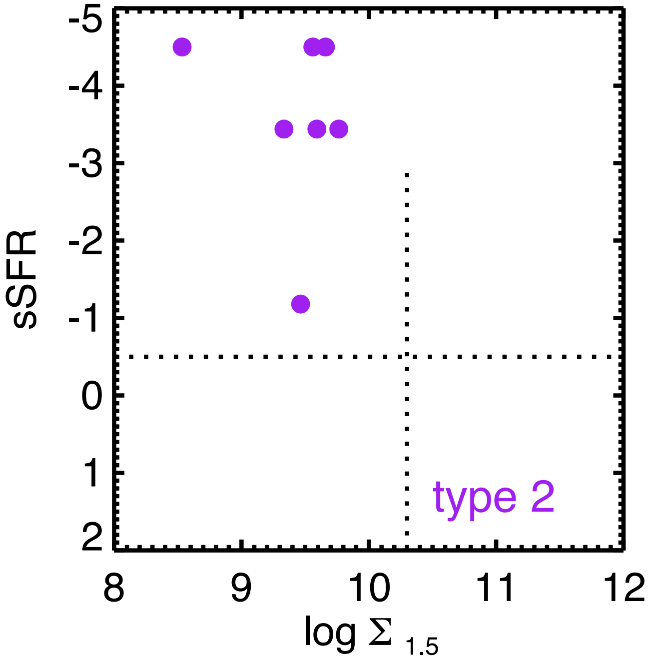

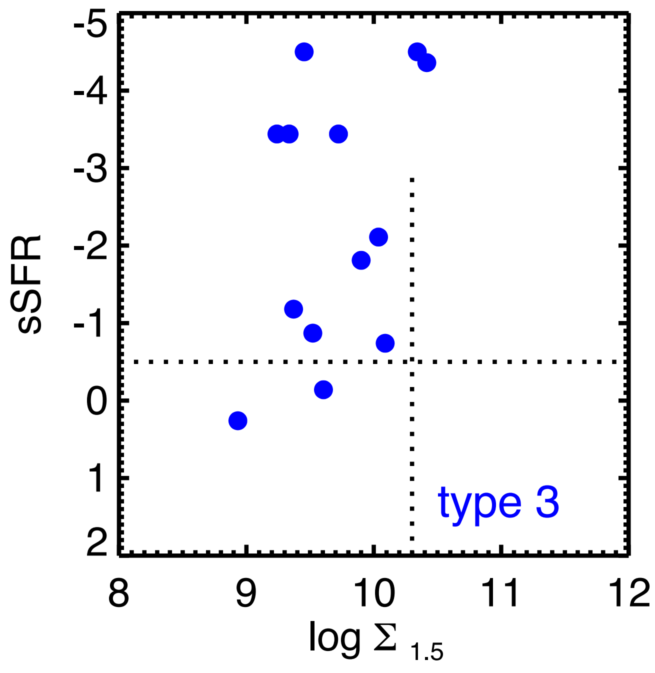

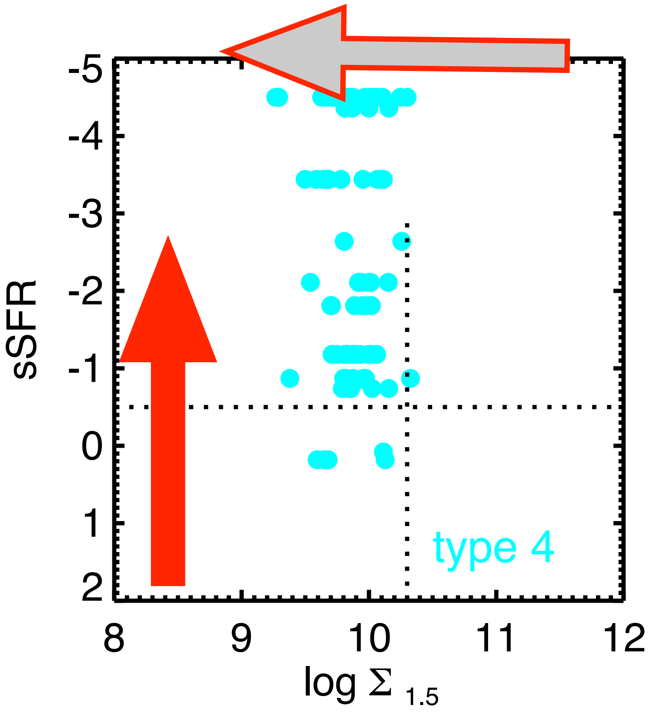

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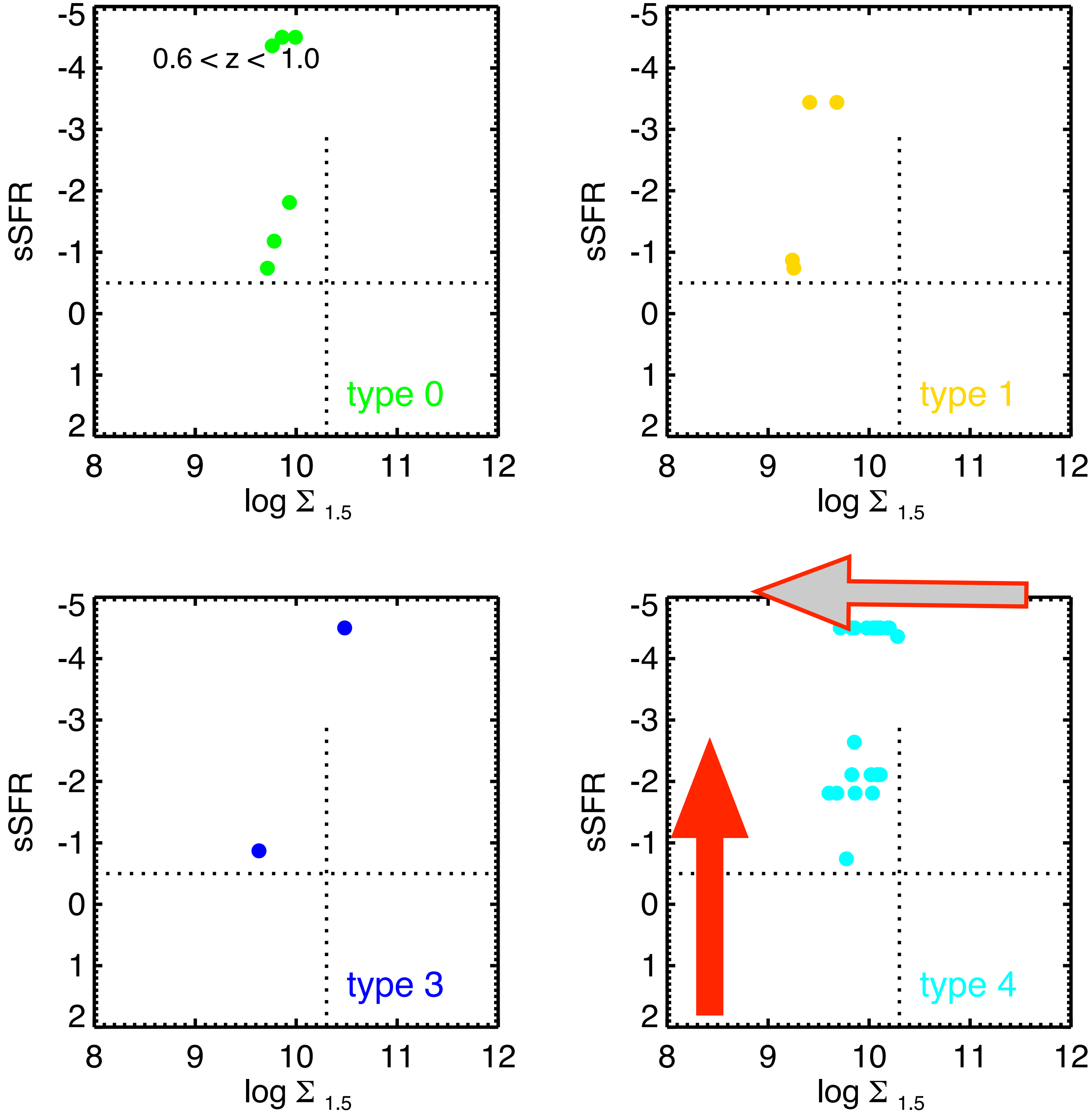
# sSFR v. $\Sigma_{1.5}$ $0.6 < z < 1.0$



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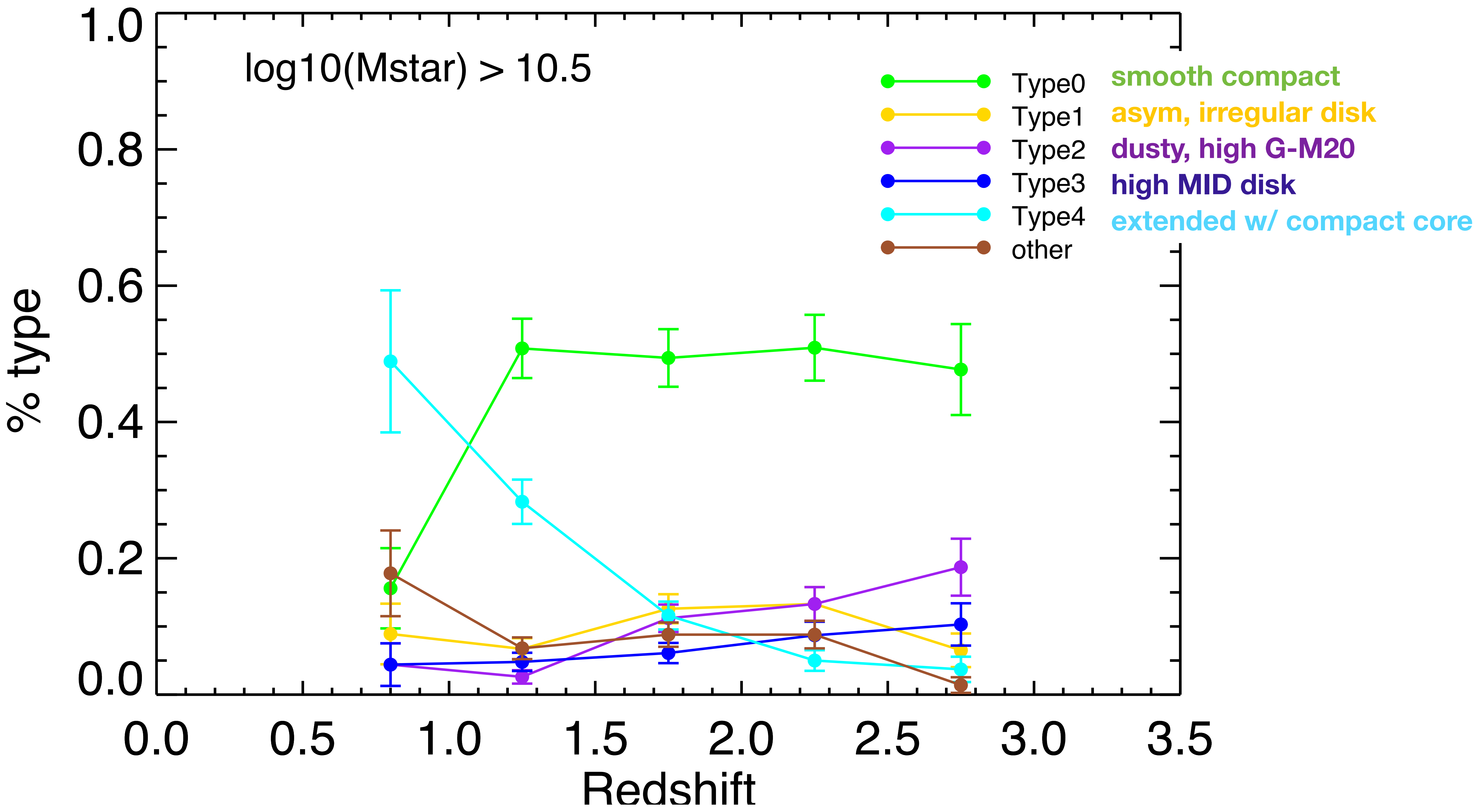
# Evolution of massive galaxies 0.6 < z < 3.0



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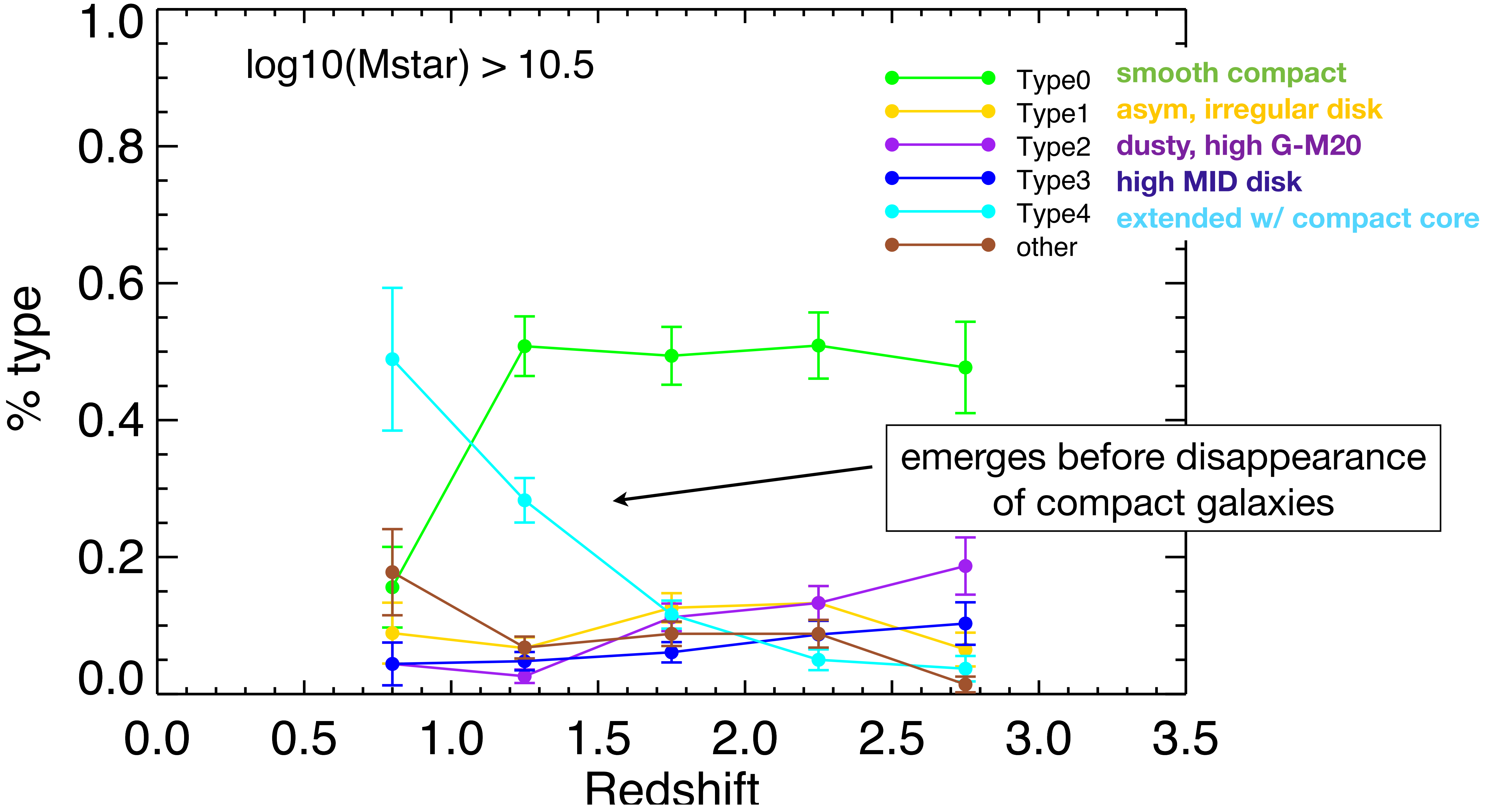
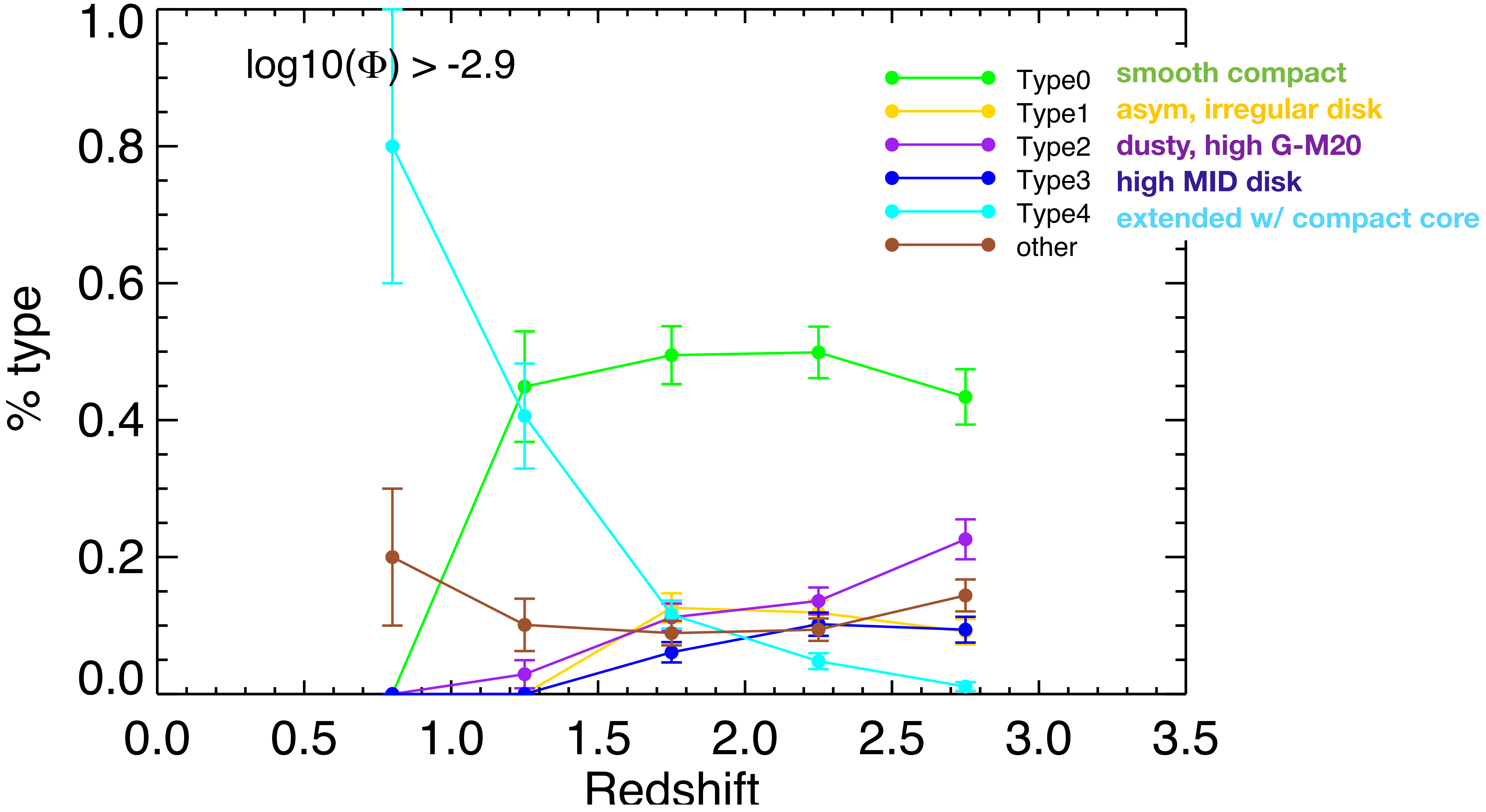


smooth compact
asym, irregular disk
dusty, high G-M20
high MID disk
extended w/ compact core

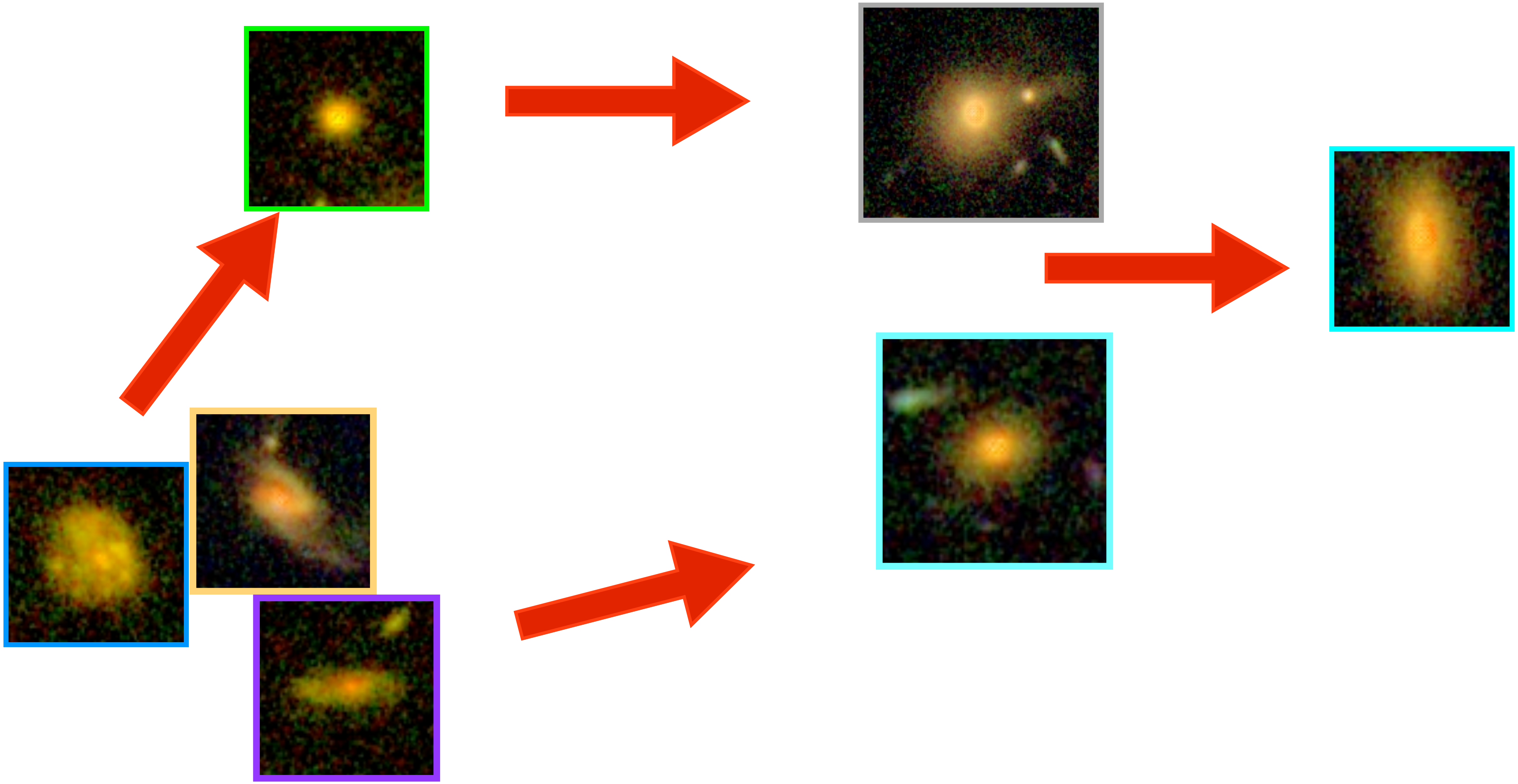
emerges before disappearance of compact galaxies

# Evolution of massive galaxies 0.6 < z < 3.0



**smooth compact**
**asym, irregular disk**
**dusty, high G-M20**
**high MID disk**
**extended w/ compact core**

# evolutionary paths of high-z galaxies



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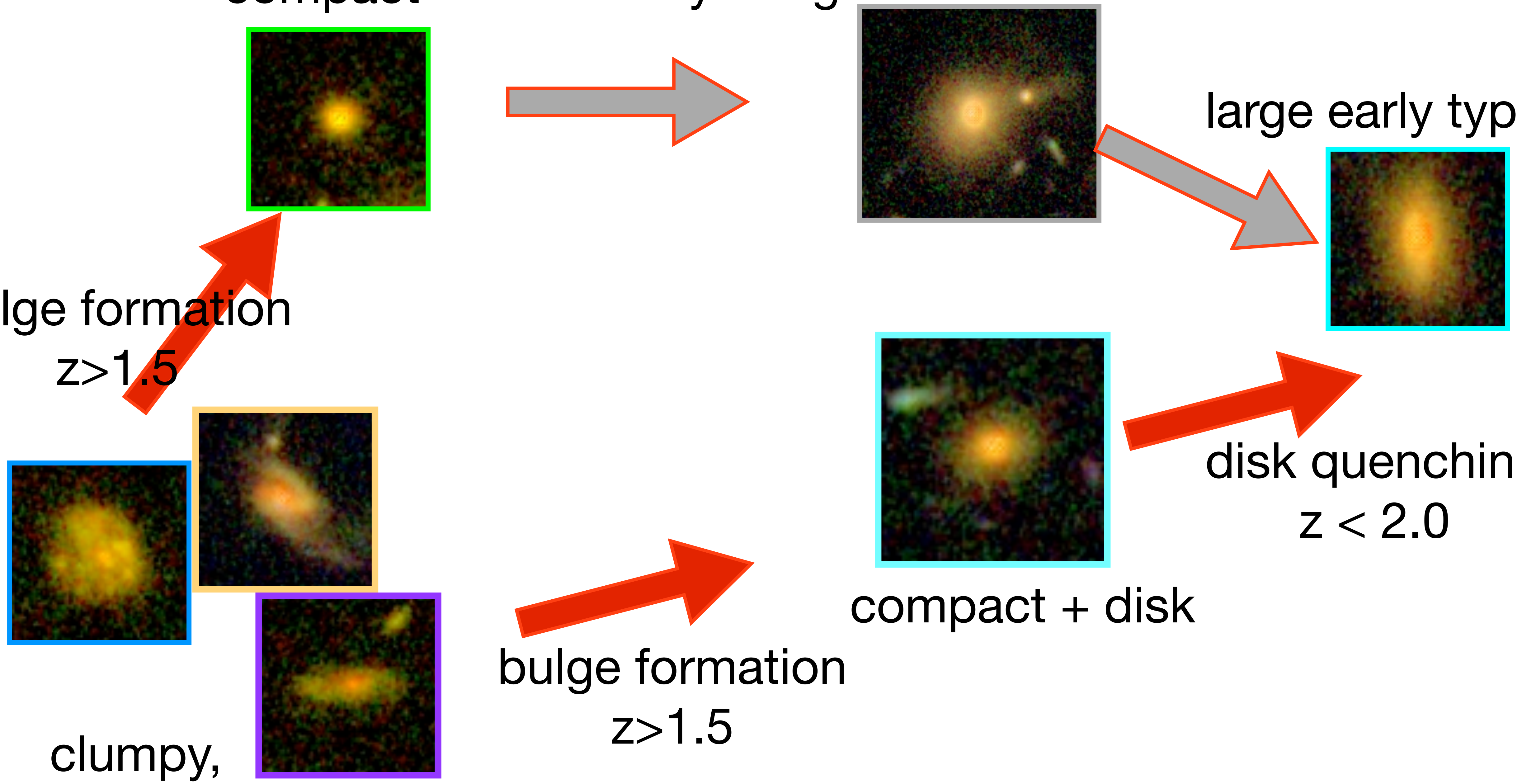


compact

z<1.5 dry mergers

large early type

bulge formation
z>1.5

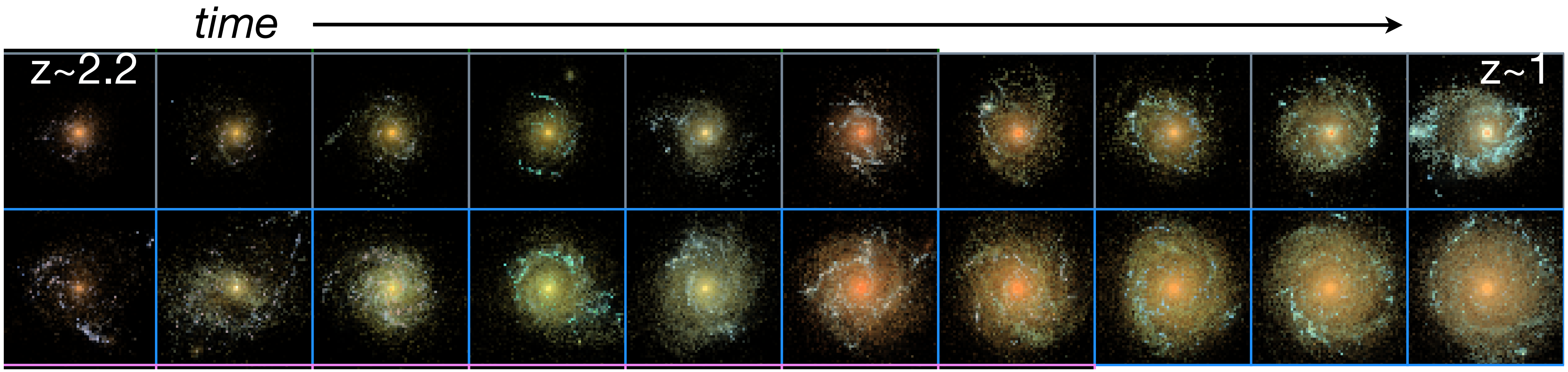
disk quenching
z < 2.0

compact + disk

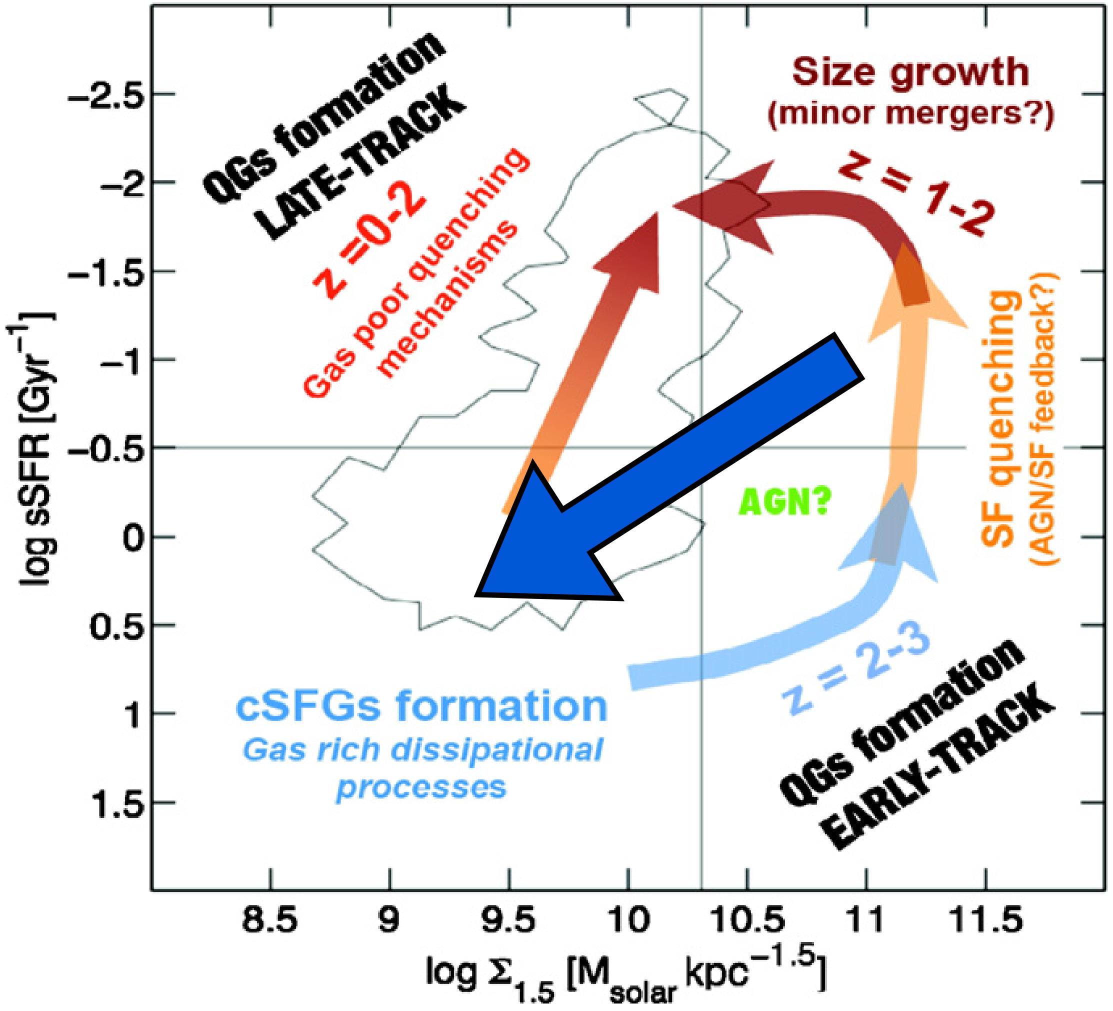
bulge formation
z>1.5

clumpy,
asym, dusty disks

# evolutionary paths of high-z galaxies



Snyder et al. 2014



structural evolution not monotonic? simulated compact galaxies can develop star-forming disks

triggered by accretion and/or gas-rich minor mergers?

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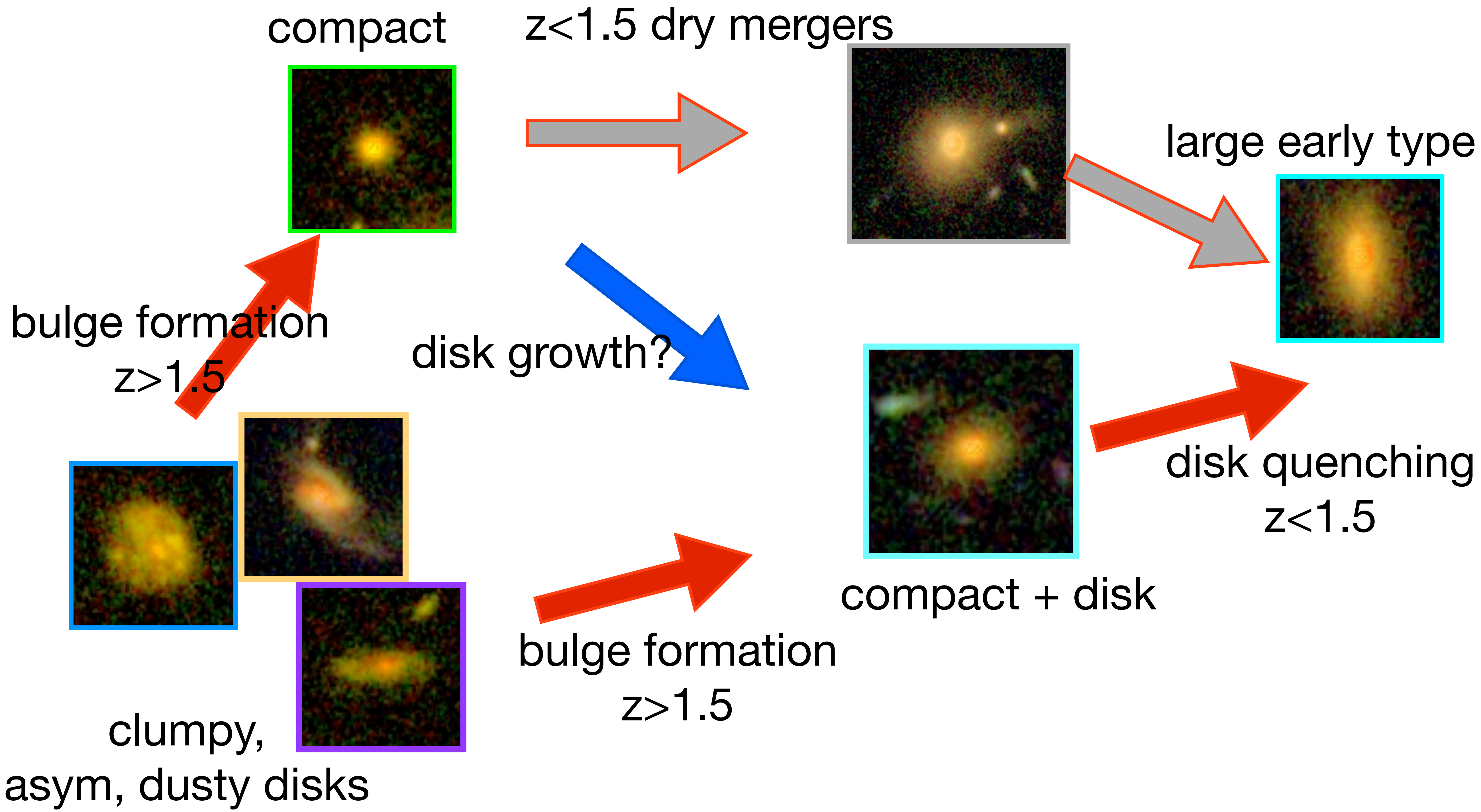


compact

z<1.5 dry mergers

large early type

bulge formation
z>1.5

disk growth?

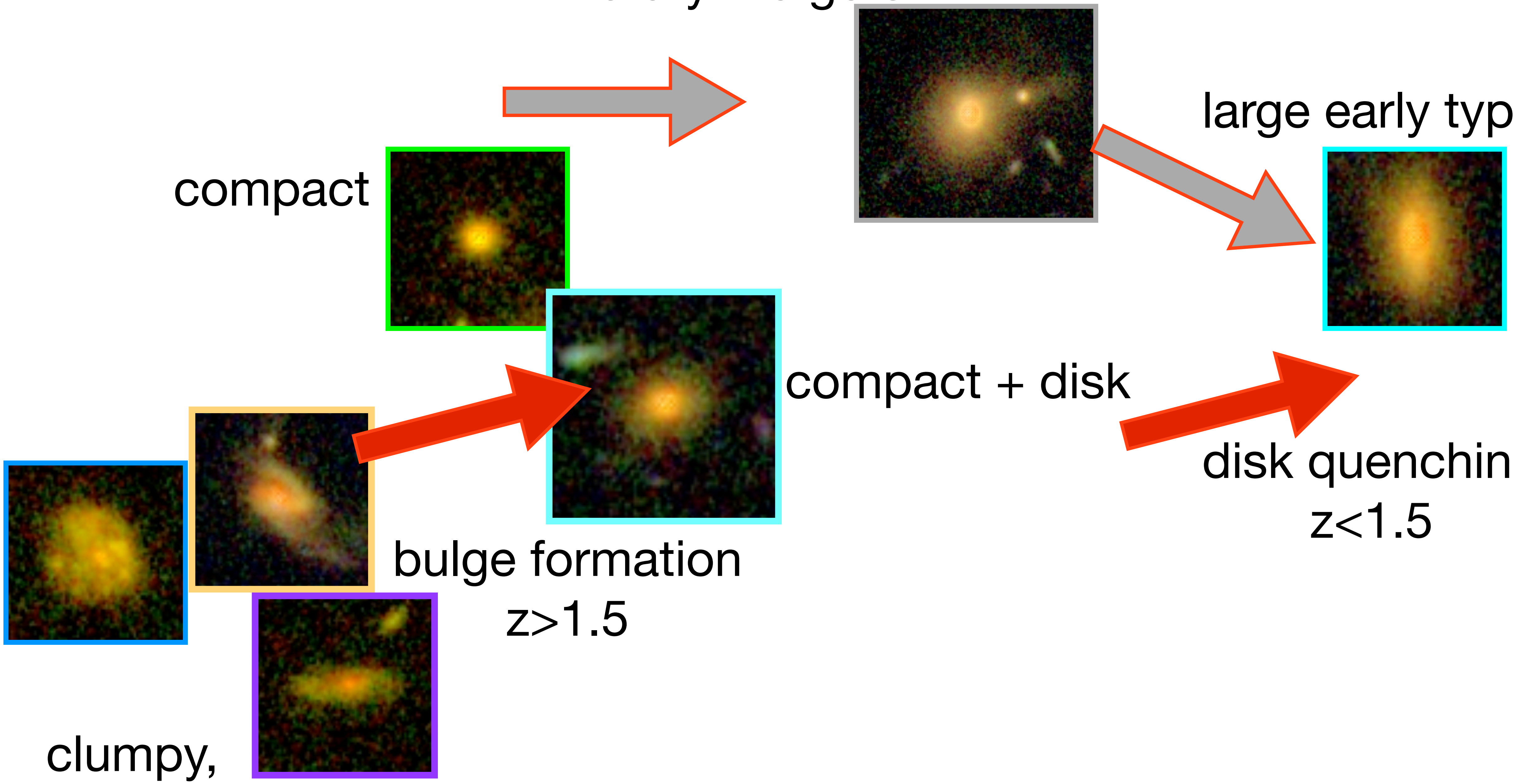
disk quenching
z<1.5

compact + disk

bulge formation
z>1.5

clumpy,
asym, dusty disks

# evolutionary paths of high-z galaxies



z<1.5 dry mergers

large early type

compact

compact + disk

disk quenching
z<1.5

bulge formation
z>1.5

clumpy,
asym, dusty disks

# Summary

Galaxy “morphology” can trace underlying physics of galaxy evolution, but need to capture rare/subtle features

Hubble Sequence does not apply so well at high redshift
⇒ need to move beyond “disk”, “spheroid”, “other” to make progress

PCA of G-$M_{20}$-CA-MID at $z>1$, Mstar > 10.5

- *finds structural progenitors of today’s large E/S0*;
- rare, star-forming and massive at $z>2$;
  increase rapidly after $z<1.5$, before decline of compact quenched galaxies
- consistent with multiple formation pathways,
  including (re)growth of disks around compact galaxies