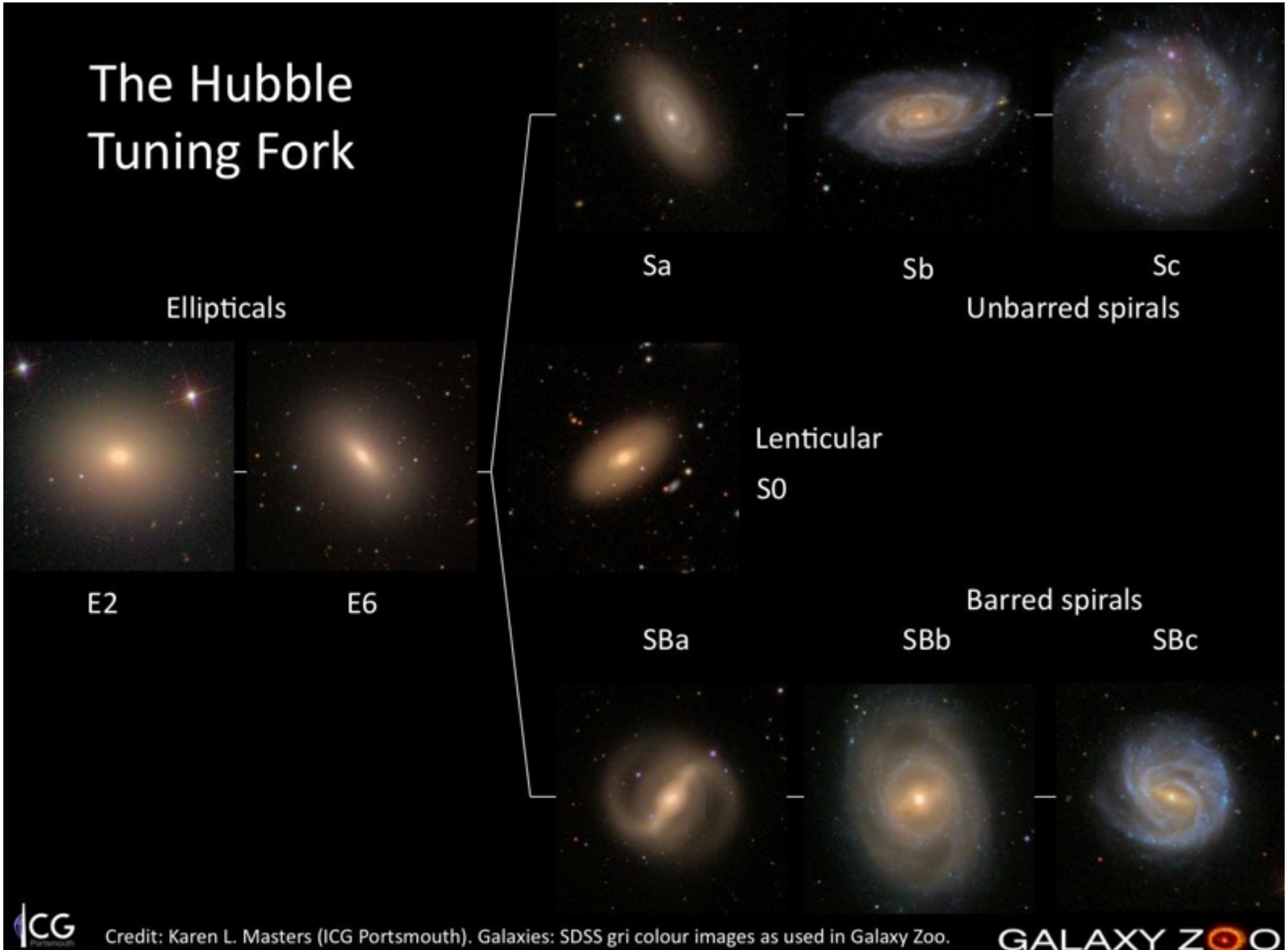
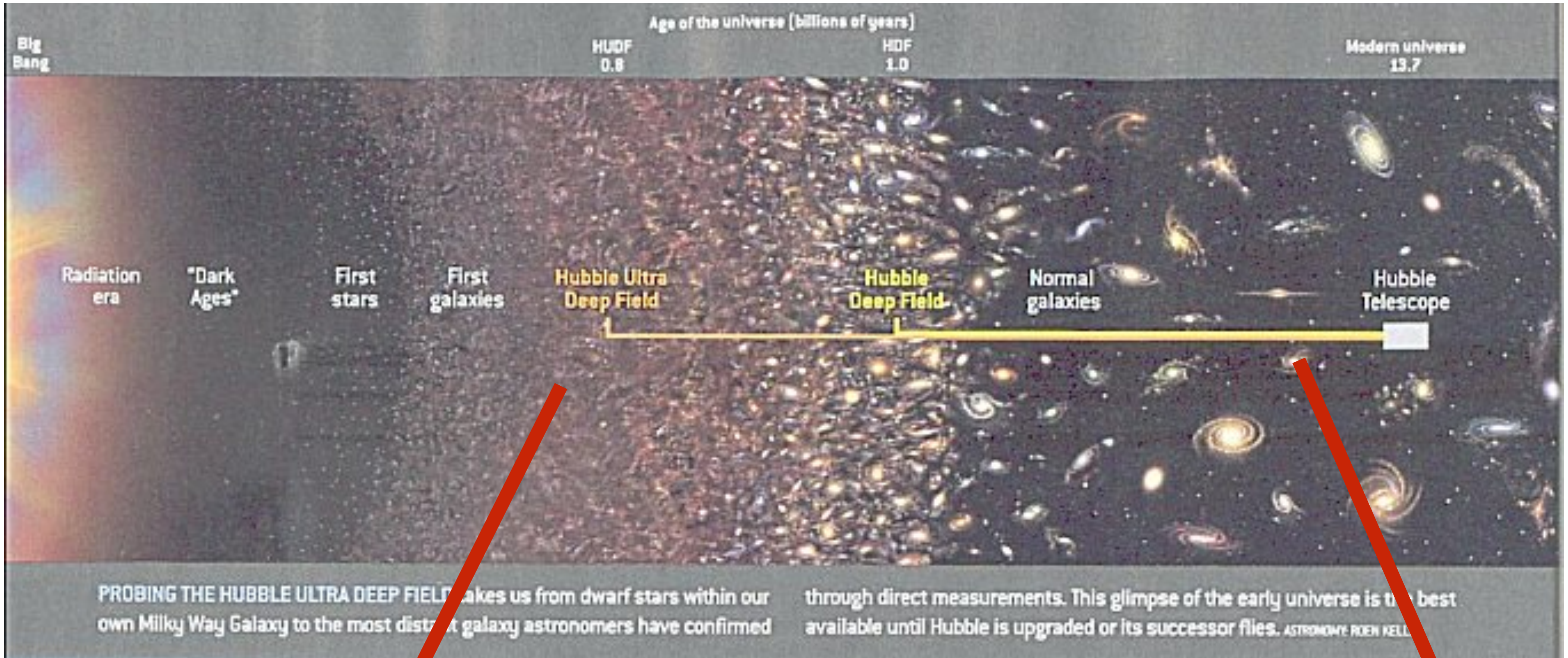
Quenching and bulge growth in massive galaxies

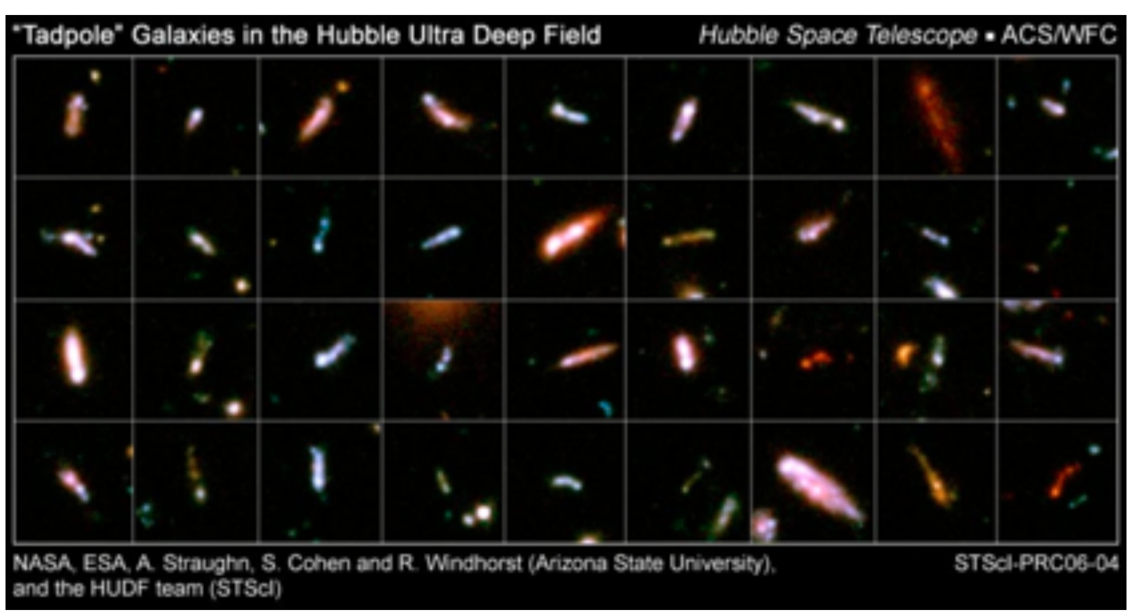
M. Huertas-Company

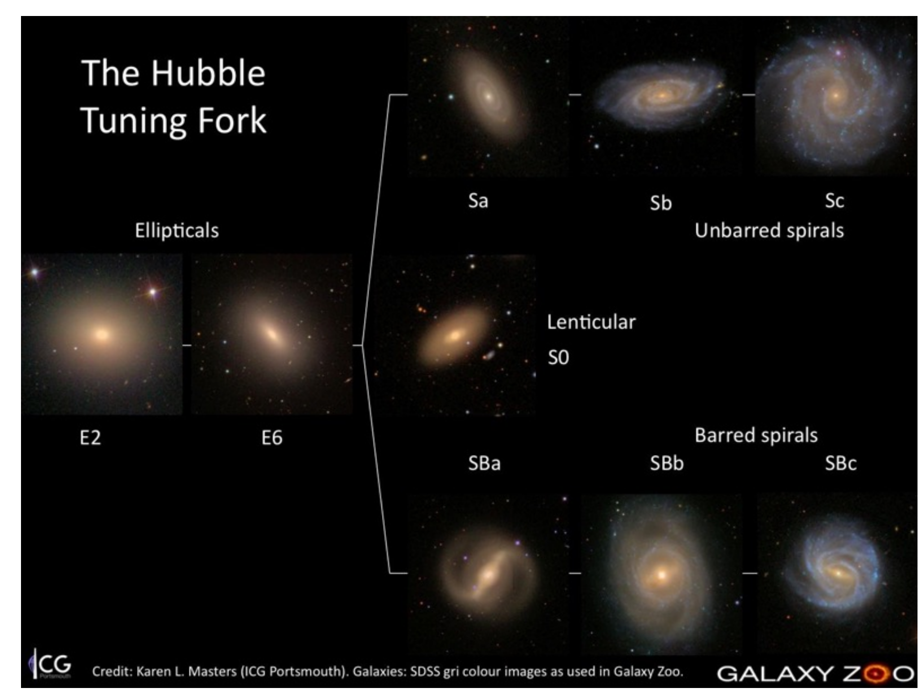
Webinar - Inter-institutional Laboratory for e-Astronomy
September 29 2016



Credit: K. Masters


Age of the universe (billions of years)
Big Bang
HUDF 0.8
HDF 1.0
Modern universe 13.7
Radiation era
"Dark Ages"
First stars
First galaxies
Hubble Ultra Deep Field
Hubble Deep Field
Normal galaxies
Hubble Telescope
PROBING THE HUBBLE ULTRA DEEP FIEL akes us from dwarf stars within our own Milky Way Galaxy to the most dist t galaxy astronomers have confirmed
through direct measurements. This glimpse of the early universe is t best available until Hubble is upgraded or its successor flies.

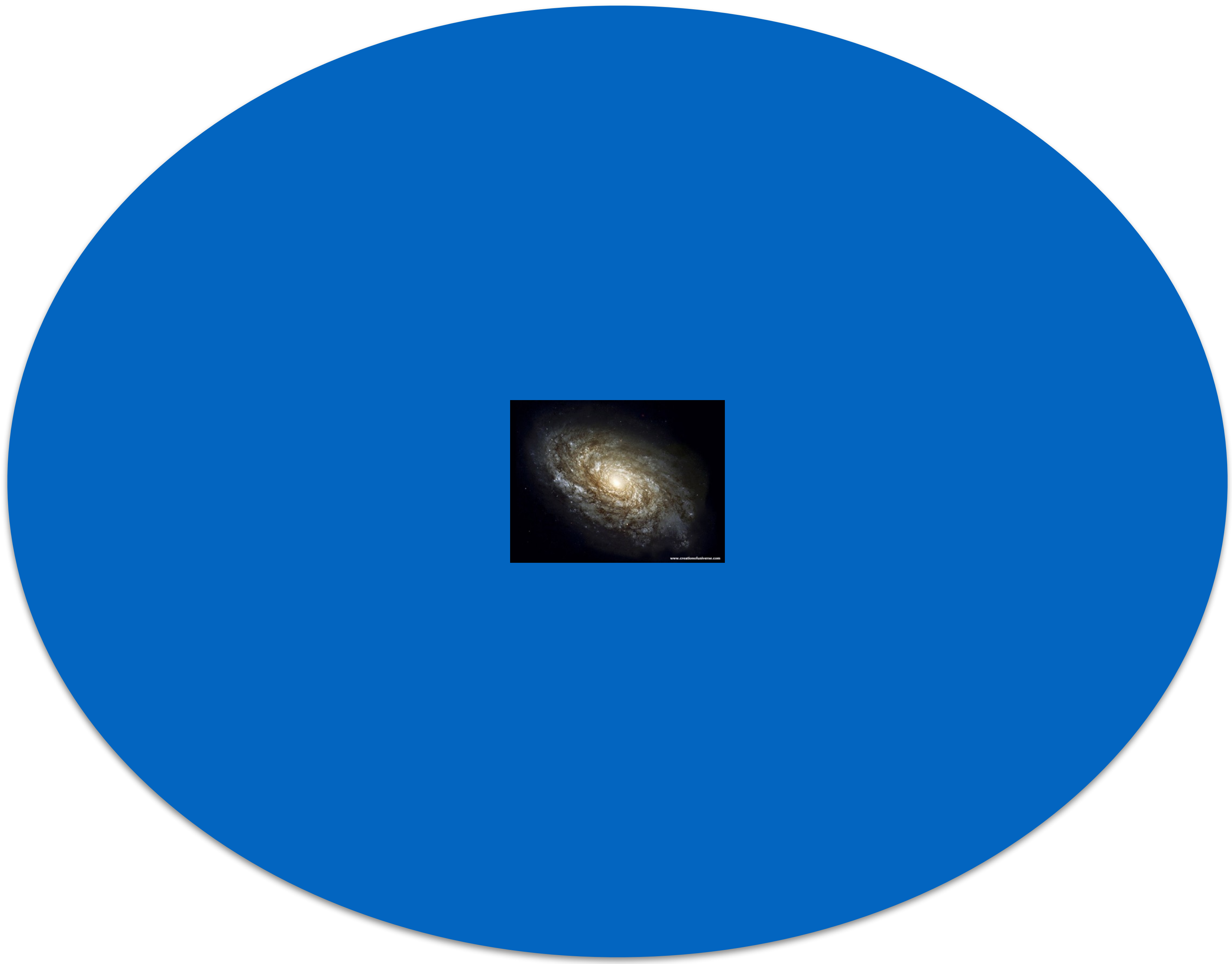

"Tadpole" Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope • ACS/WFC
NASA, ESA, A. Straughn, S. Cohen and R. Windhorst (Arizona State University), and the HUDF team (STScI)
STScI-PRC06-04


The Hubble Tuning Fork
Ellipticals
E2
E6
Sa
Sb
Sc
Unbarred spirals
Lenticular
S0
Barred spirals
SBa
SBb
SBc
ICG
Credit: Karen L. Masters (ICG Portsmouth). Galaxies: SDSS gri colour images as used in Galaxy Zoo.
GALAXY ZOO

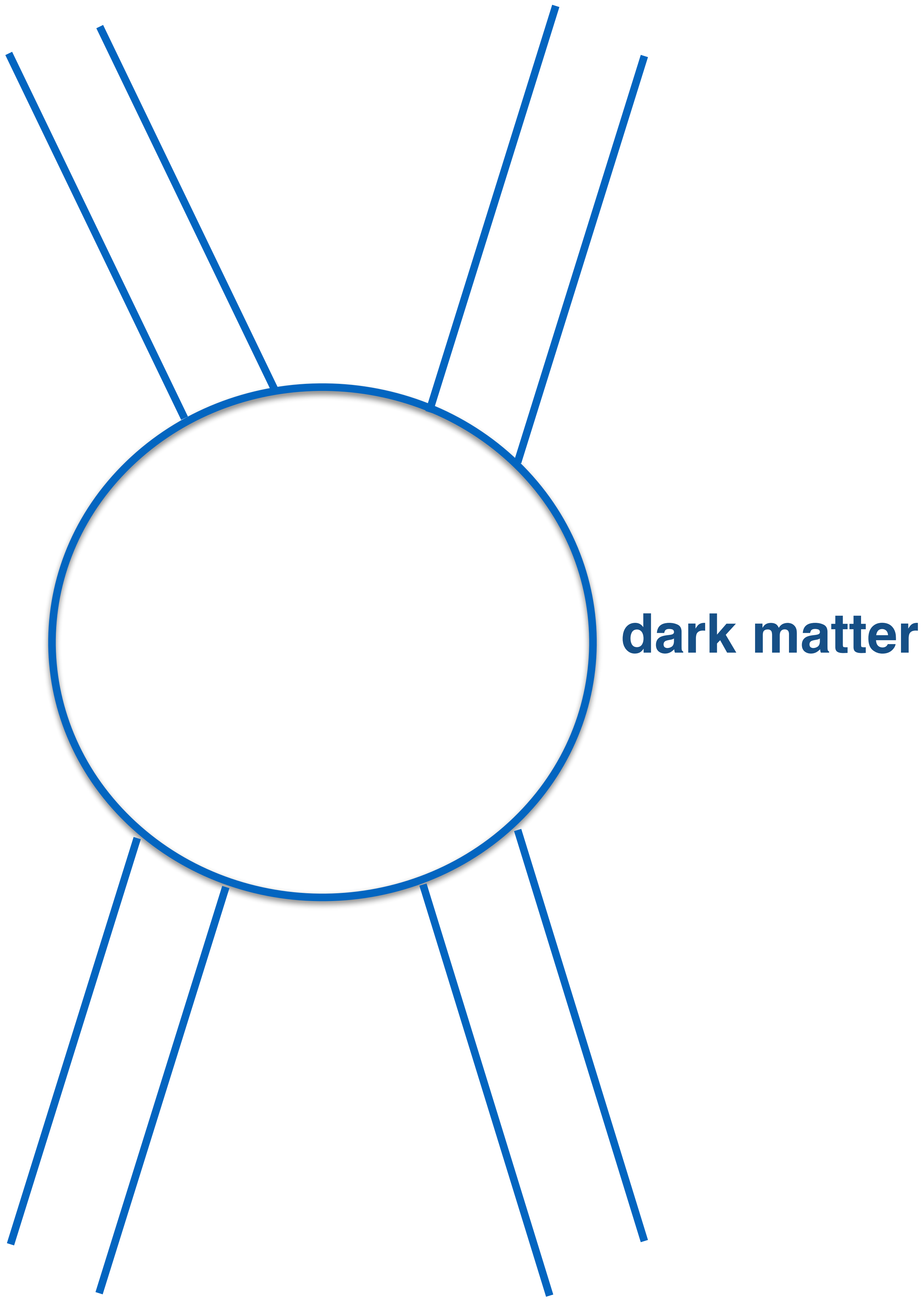
GALAXY

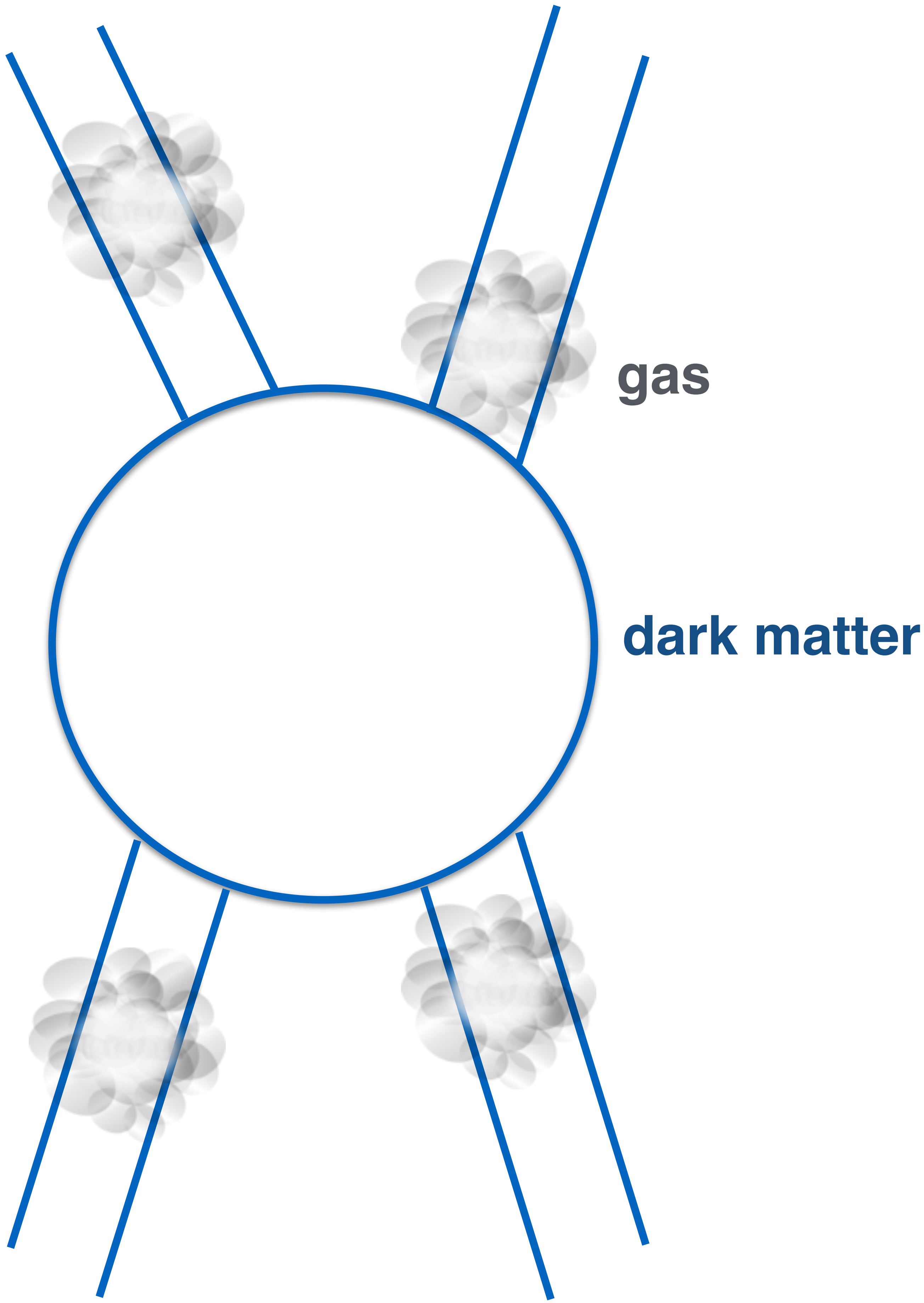
"A gravitationally bounded system made of stars, gas and dust"

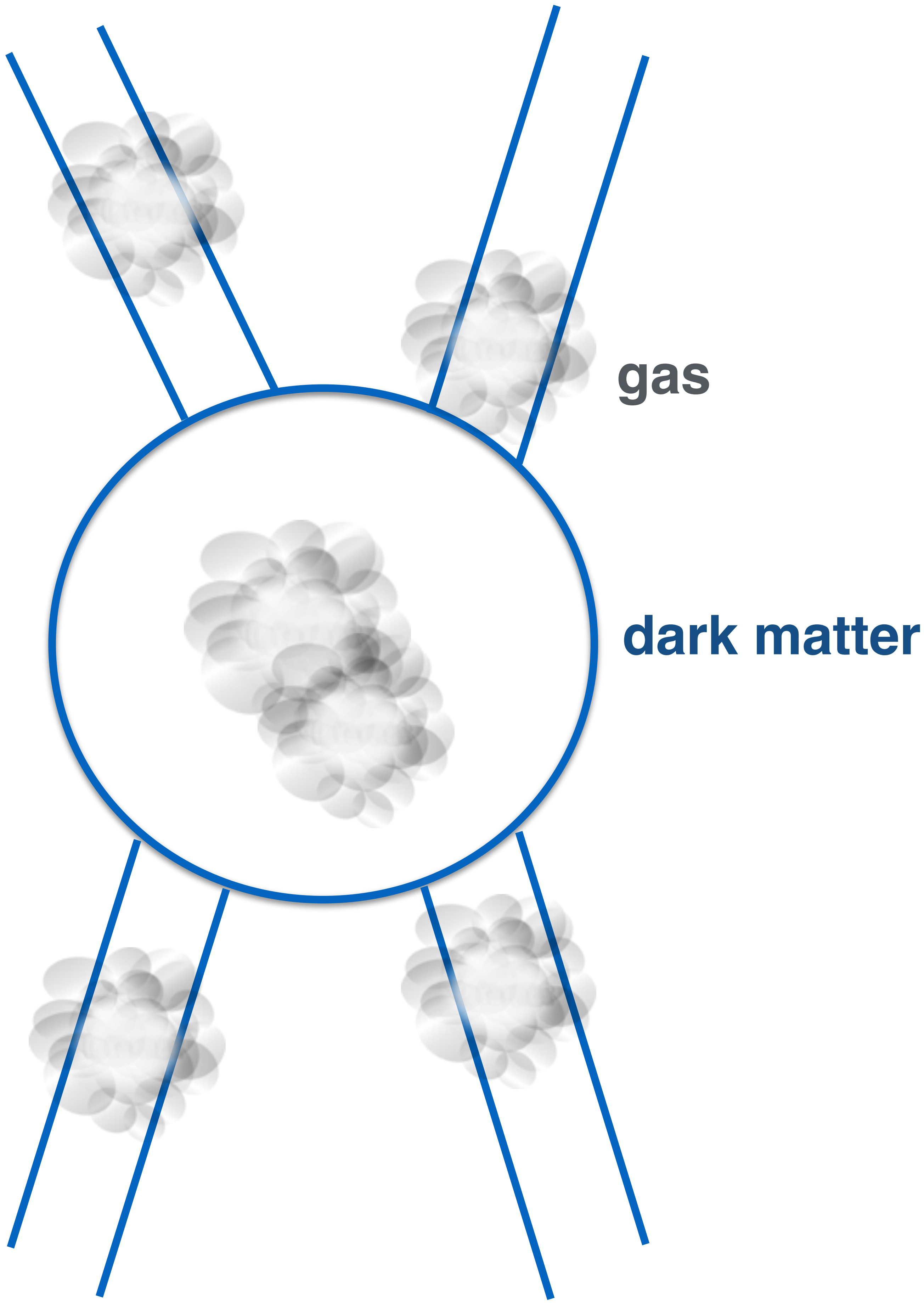
GALAXY

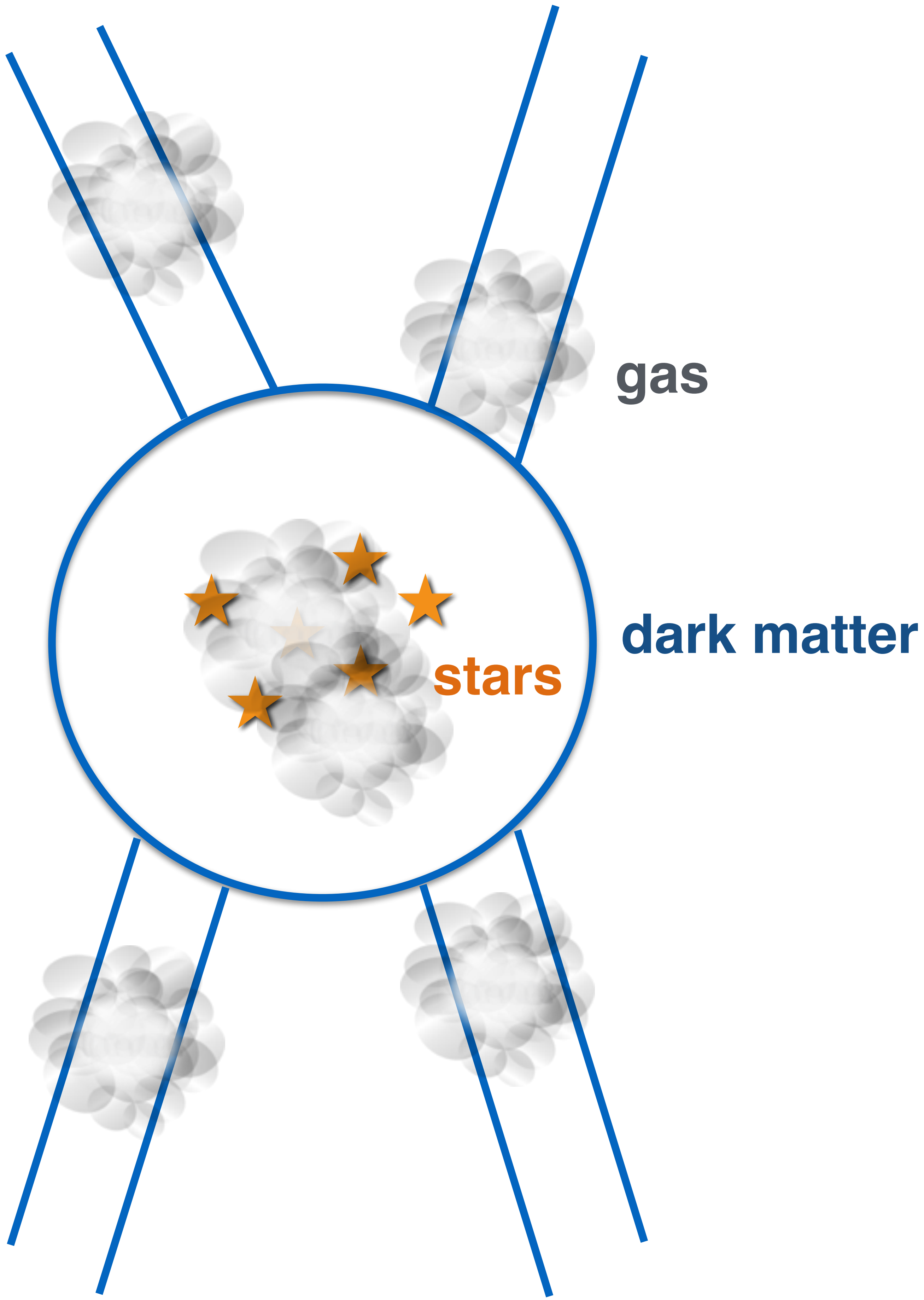


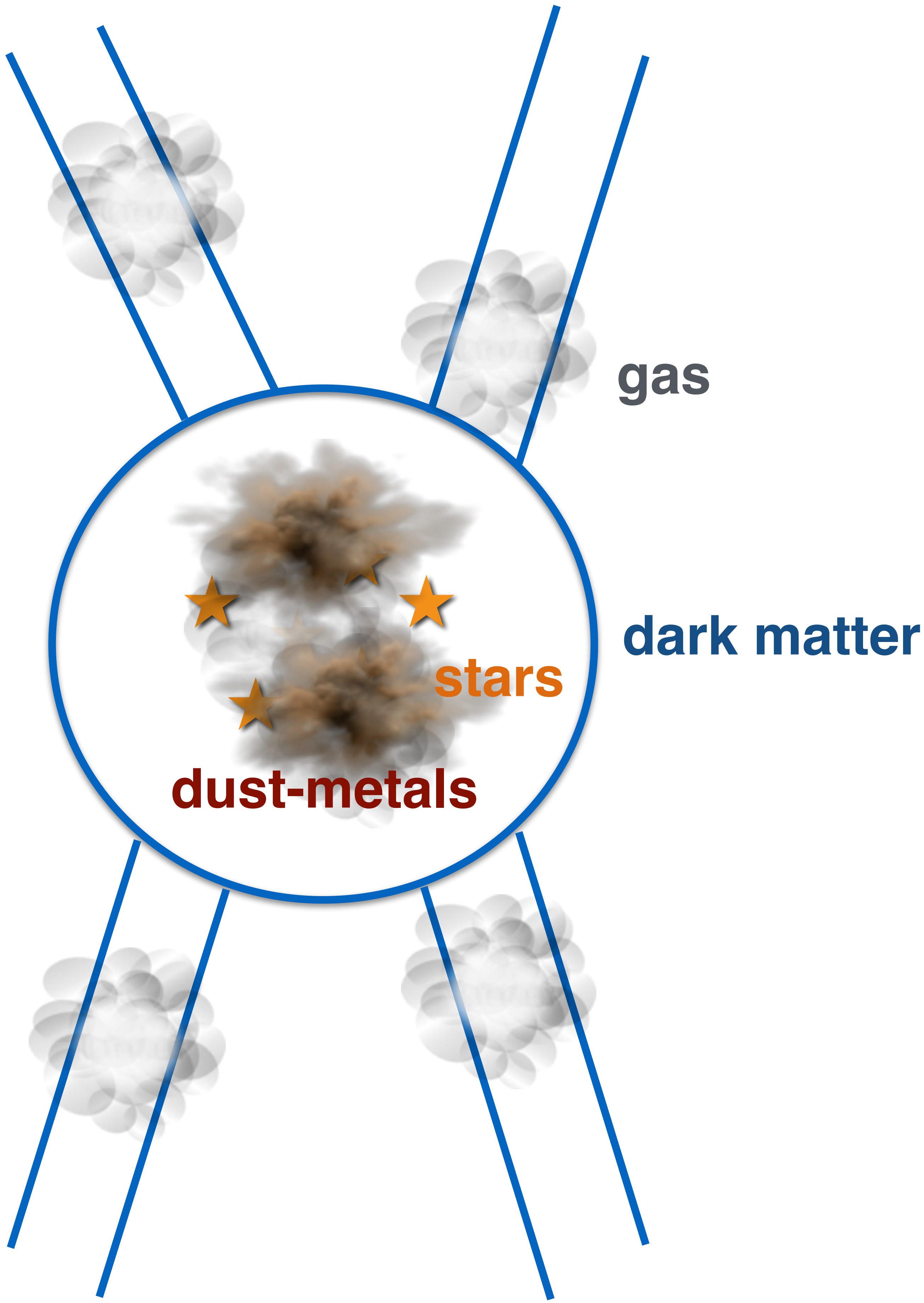
"A dark matter potential well with a small fraction of baryonic matter in the central regions"

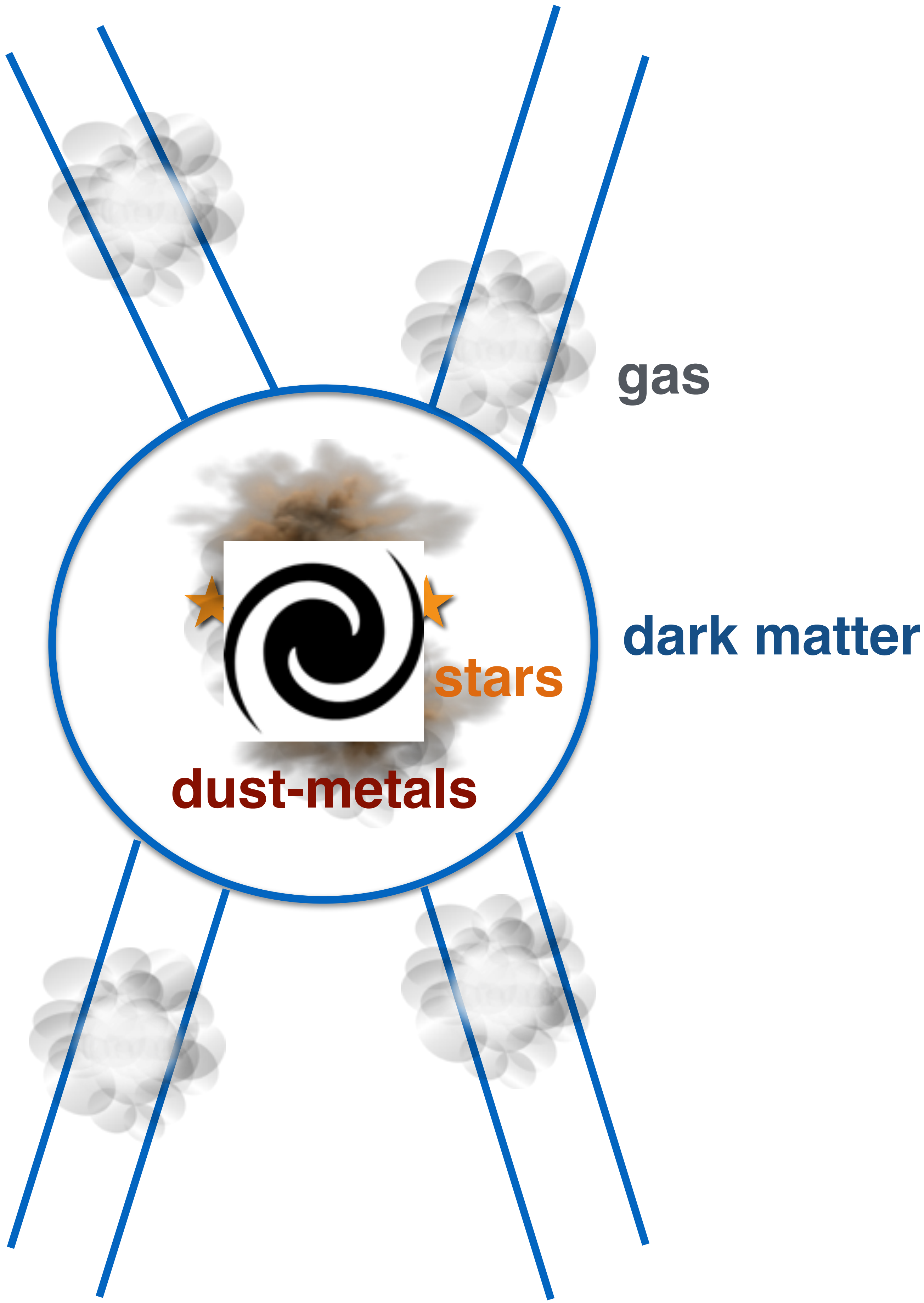

dark matter


gas
dark matter

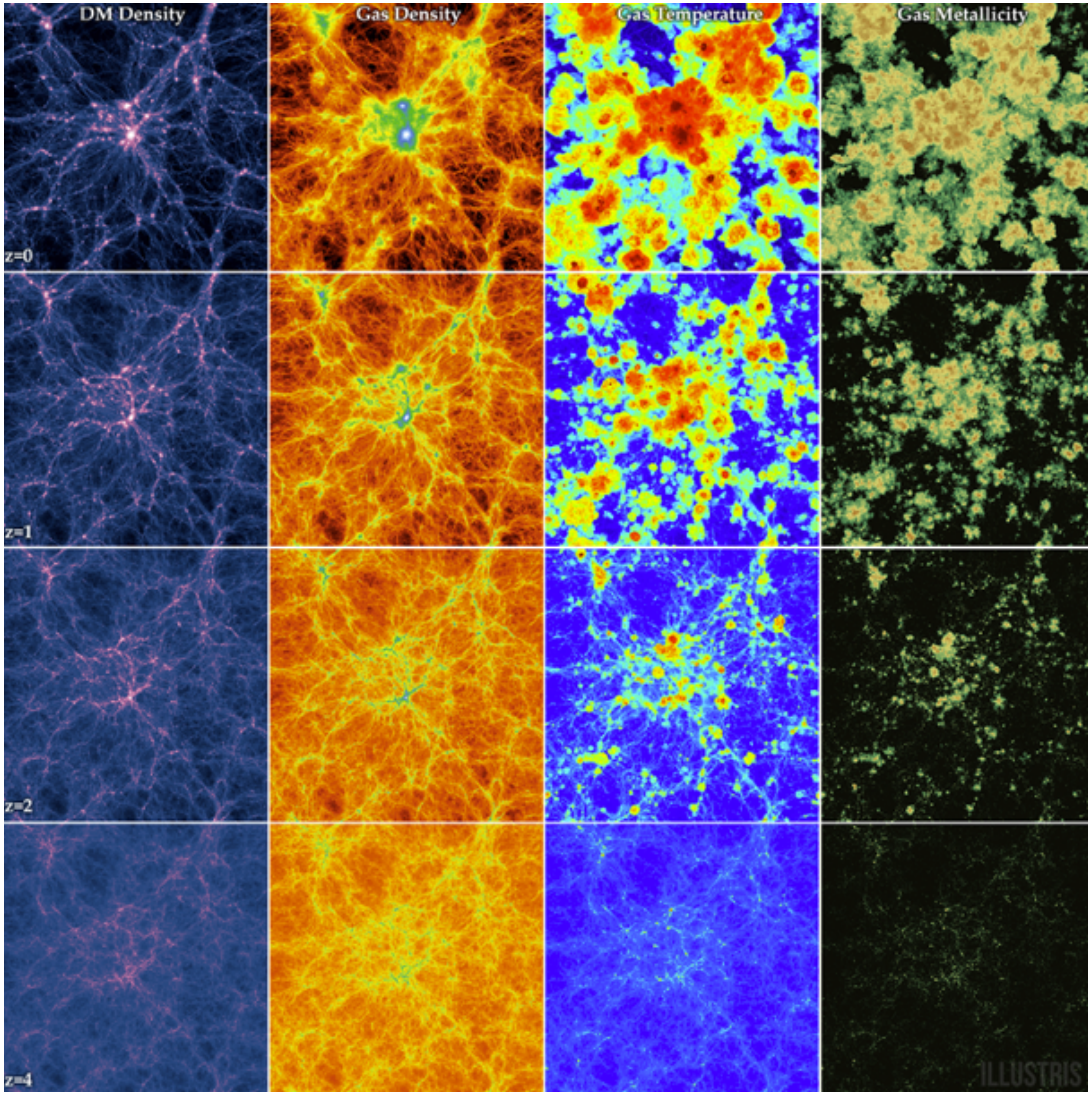

gas
dark matter


gas
dark matter
stars

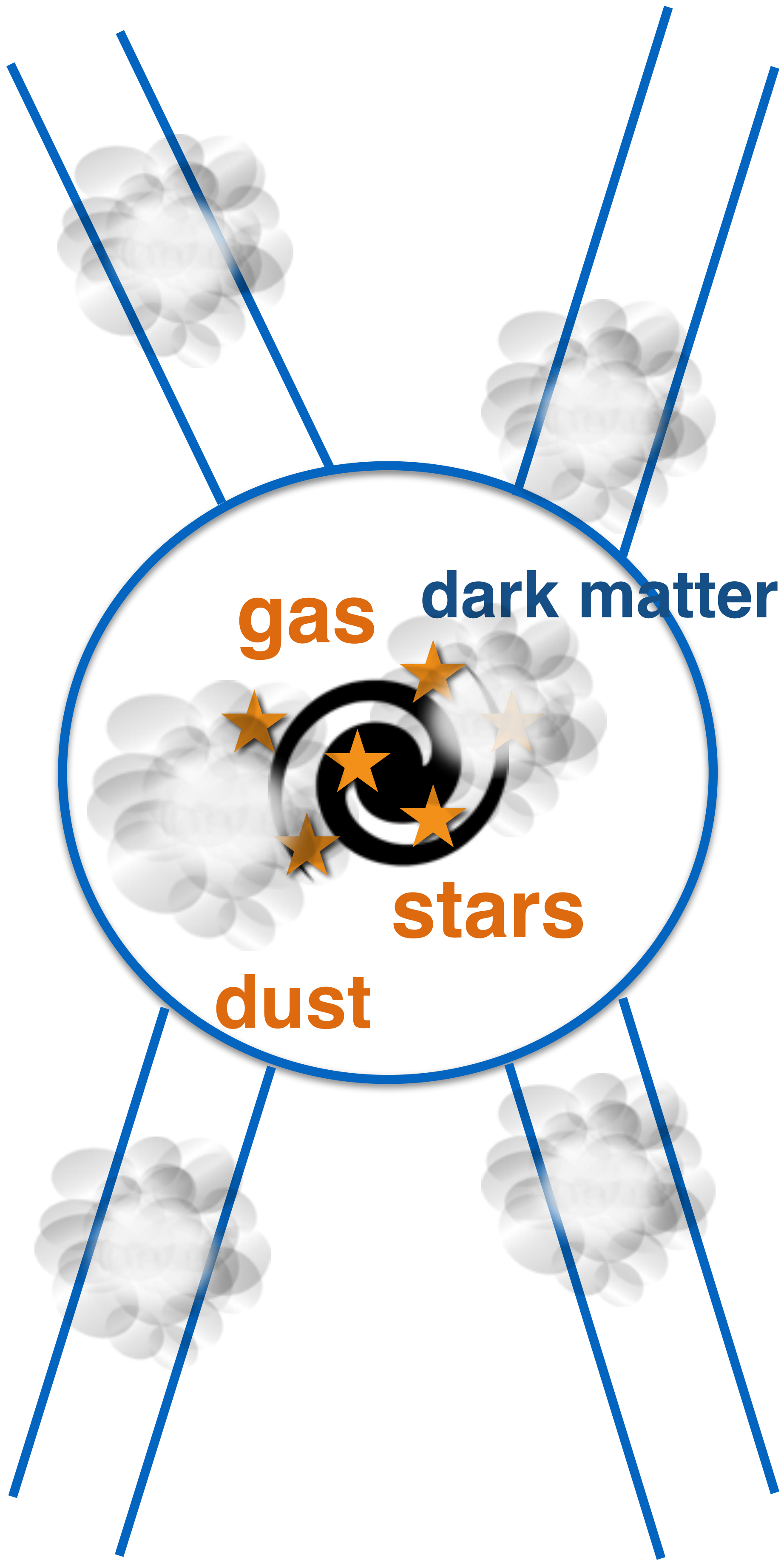

gas
dark matter
stars
dust-metals

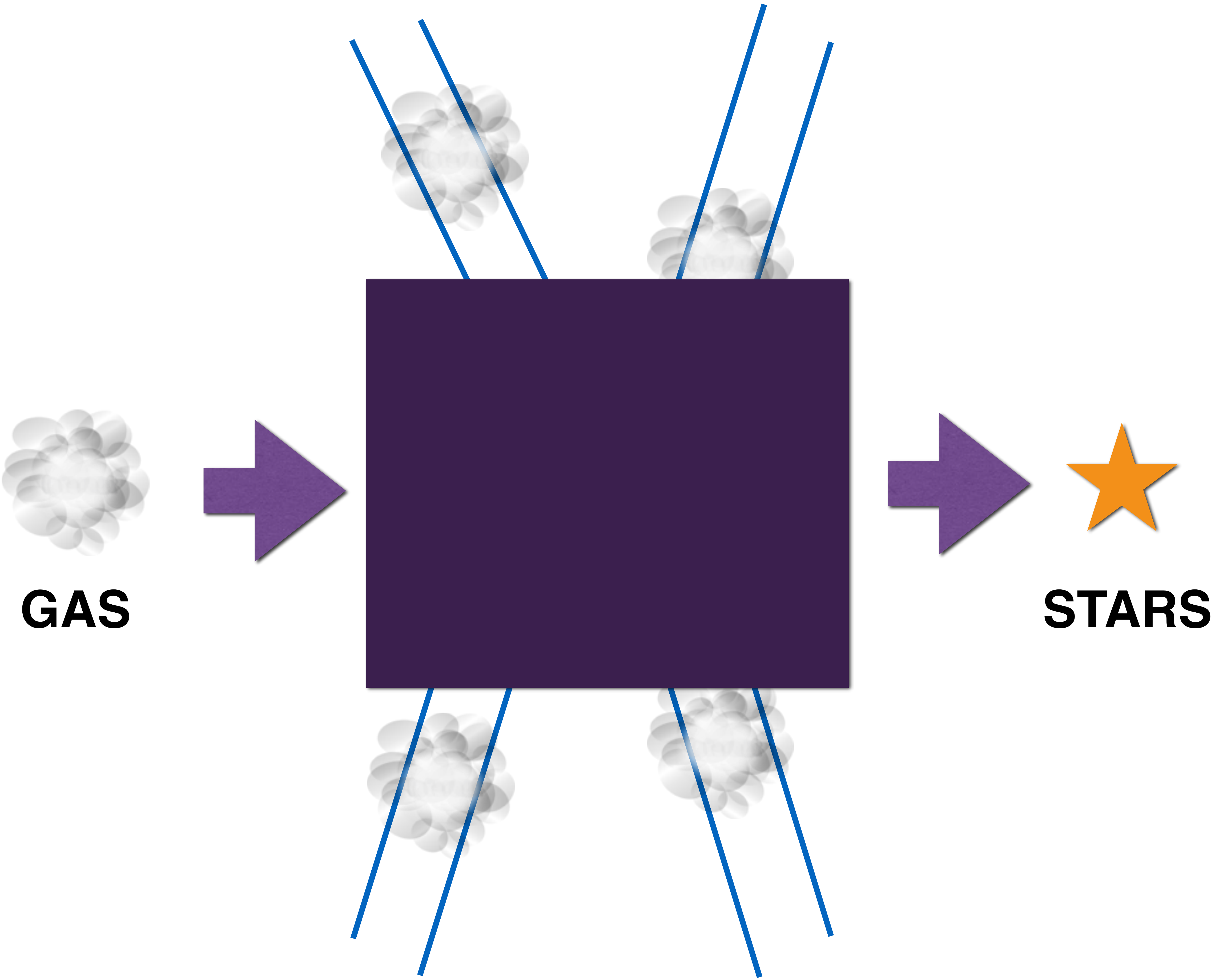

gas
dark matter
stars
dust-metals

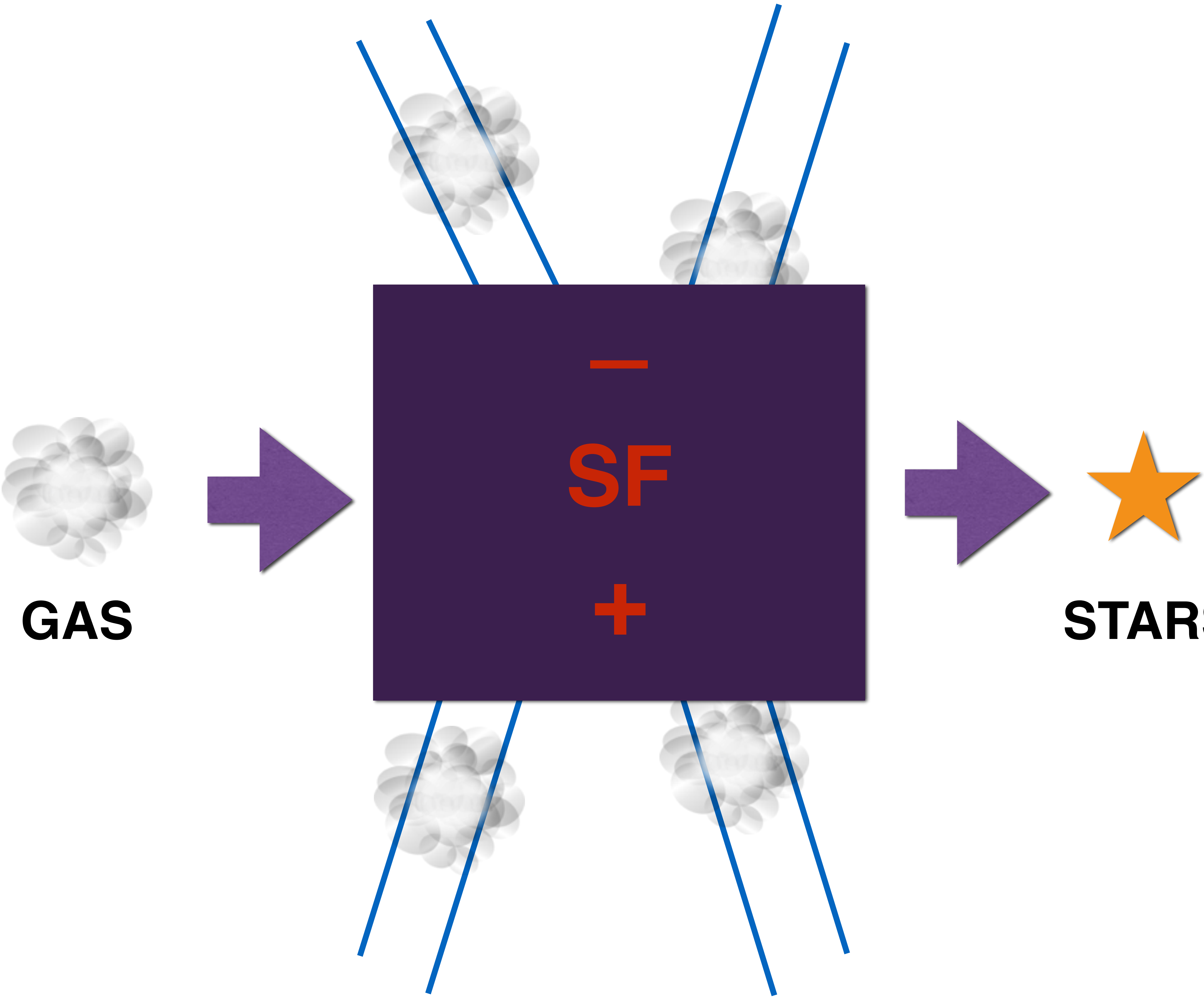
DARK MATTER —> GAS —> STARS —> METALS



Illustris Simulation (illustris-project.org)

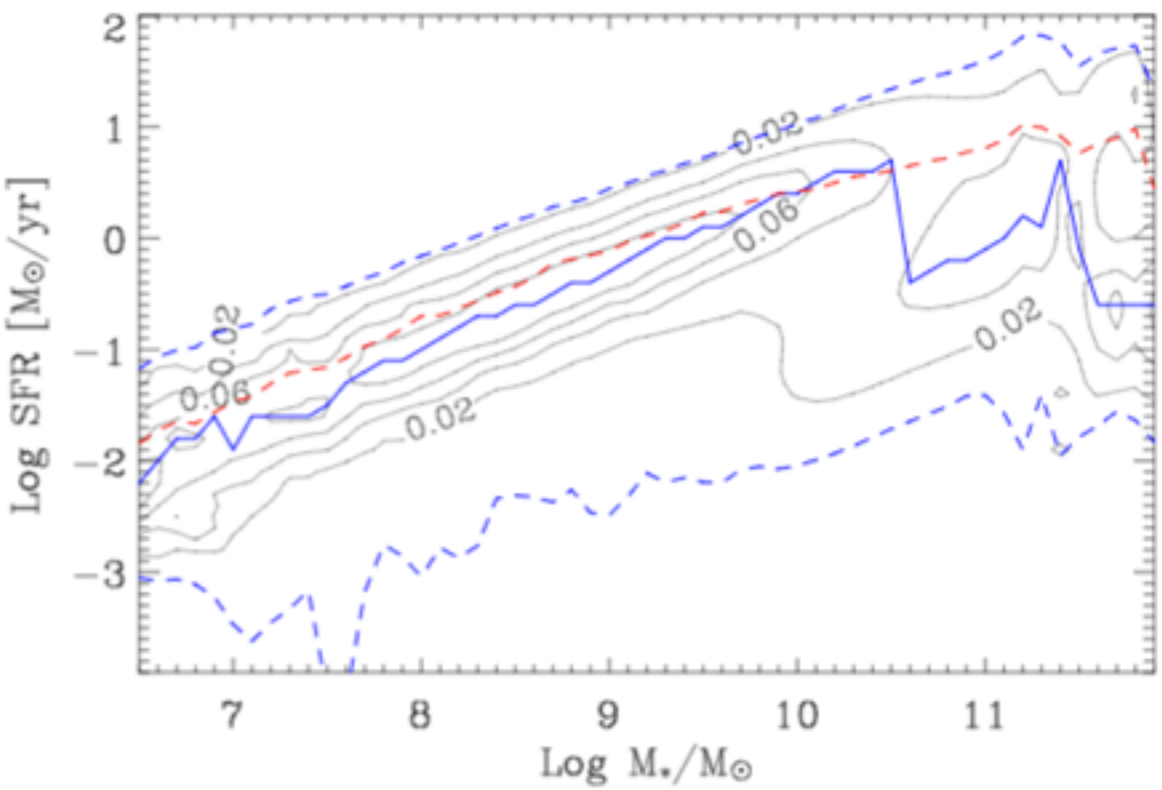

gas
dark matter
stars
dust


GAS
STARS

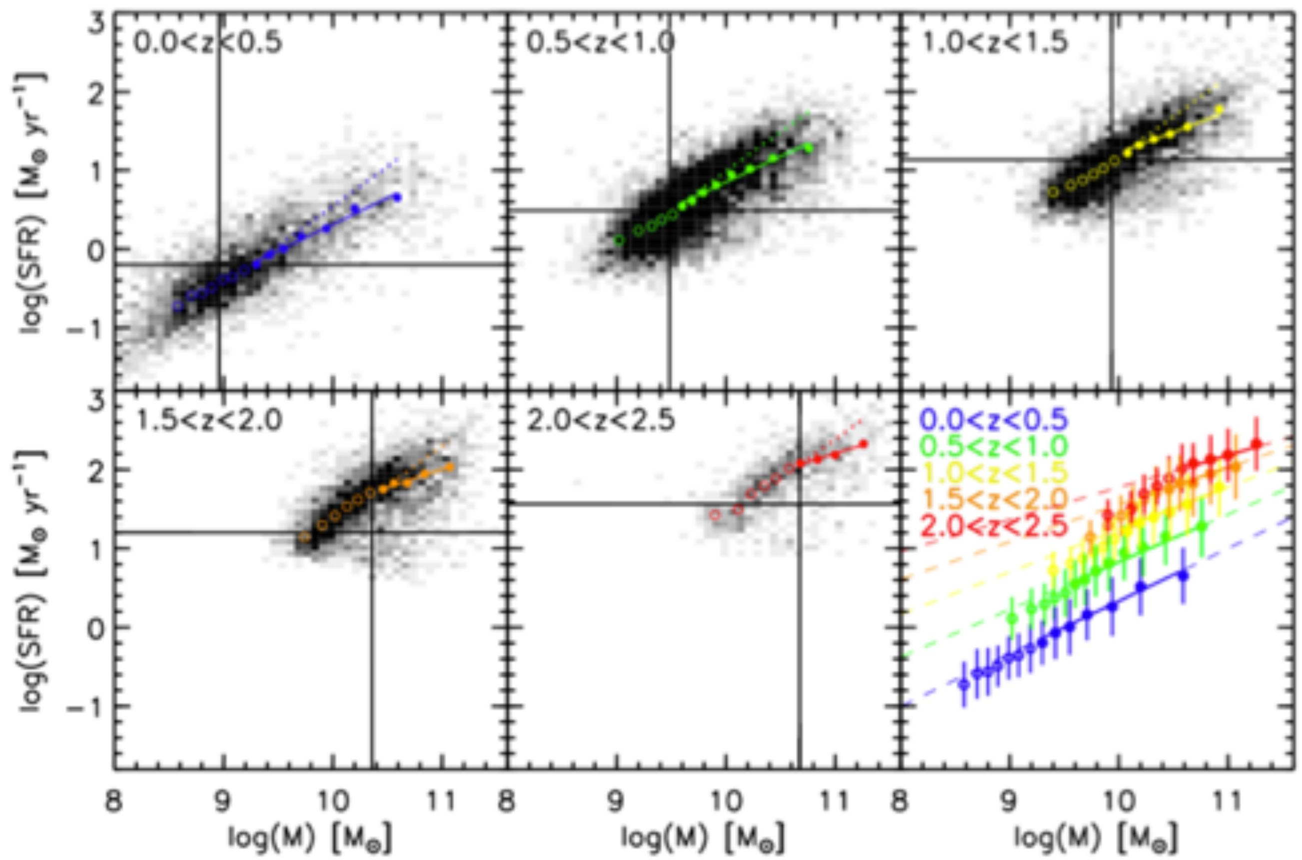

−
SF
+
GAS
STARS

Star-formation is not "chaotic": Main sequence of star-formation

Whitaker+13

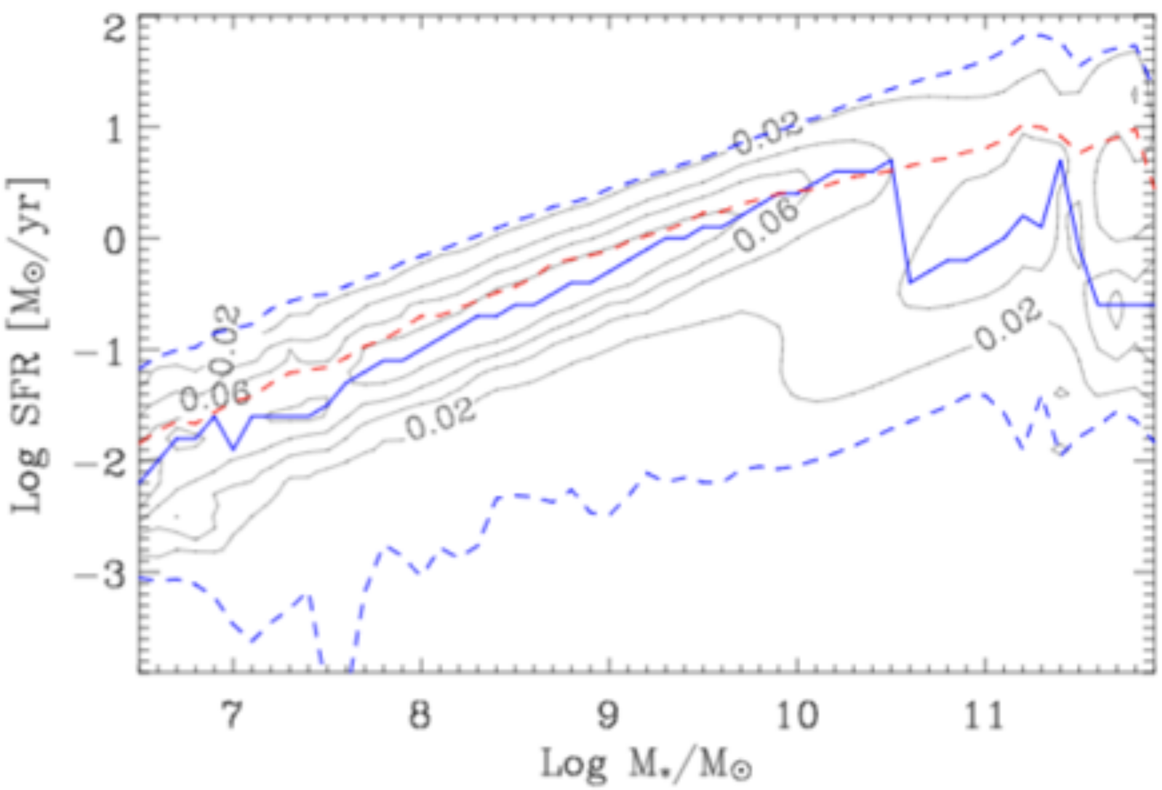


Brinchmann+04

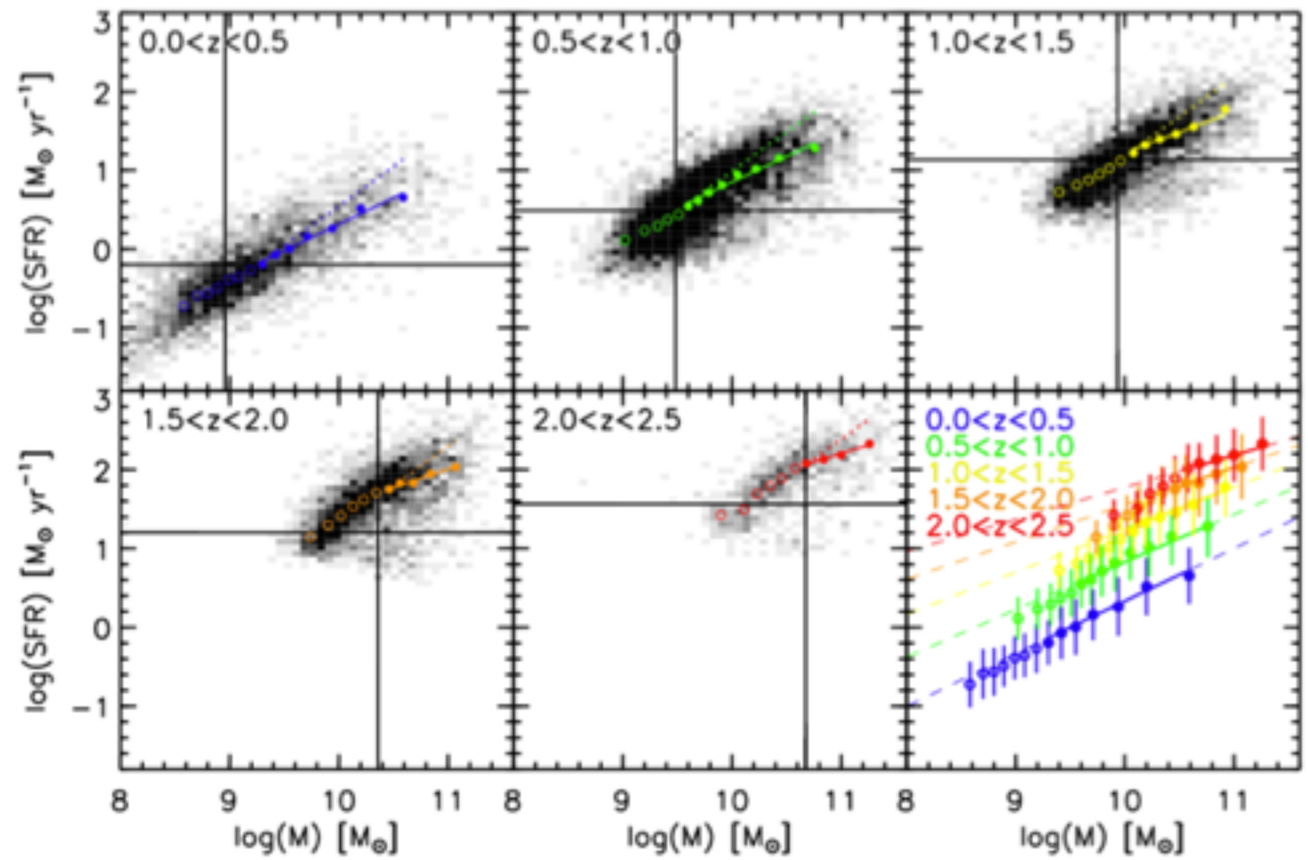


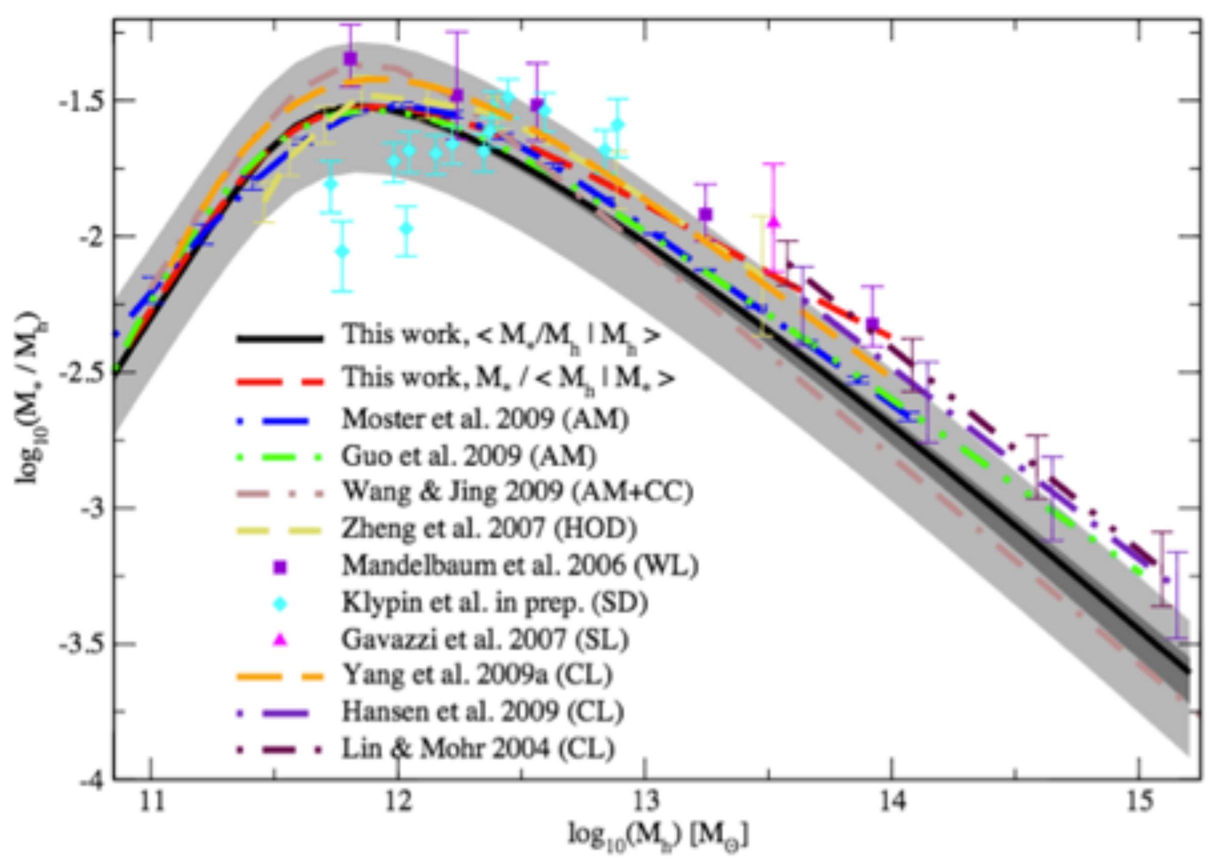
Star-formation is not "chaotic": Main sequence of star-formation

Whitaker+13



Brinchmann+04

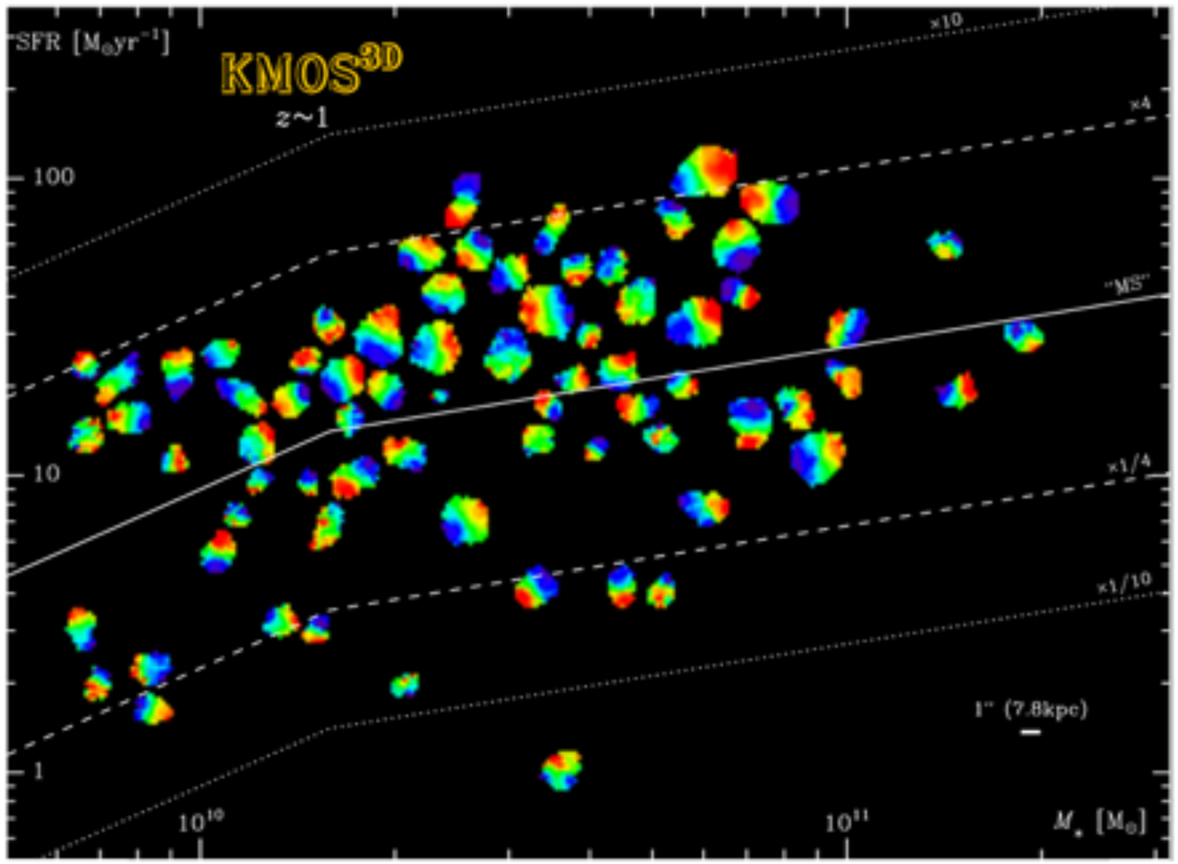


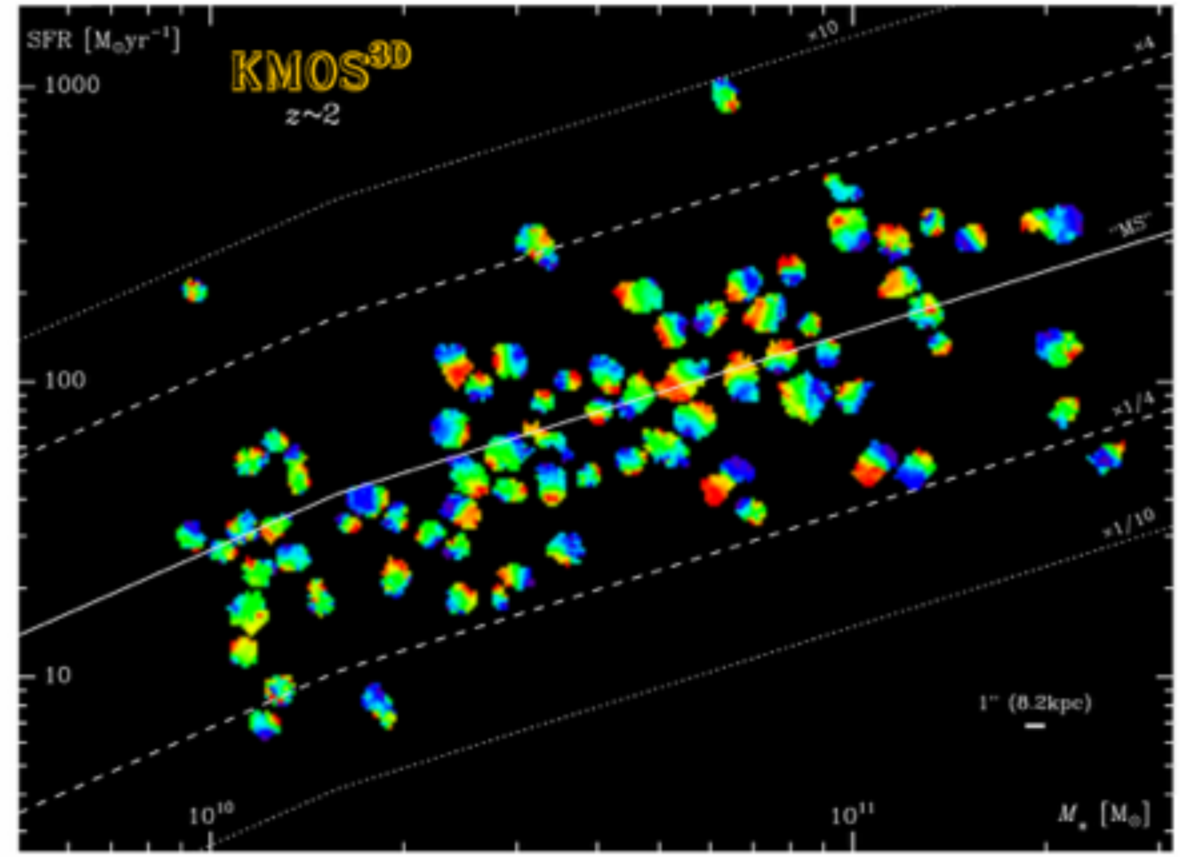


Most efficient star-formation in Milky-Way like galaxies

Behroozi+13

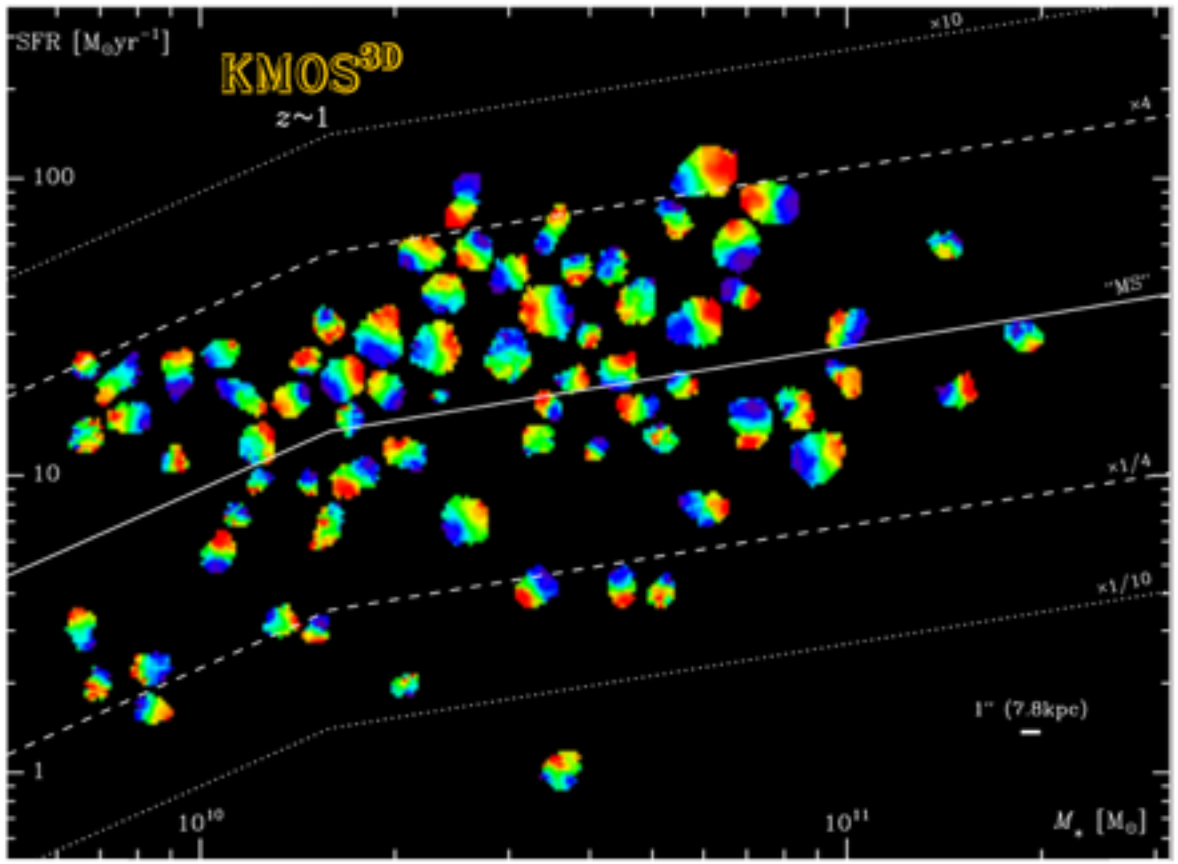
Rotating but very gas rich and turbulent

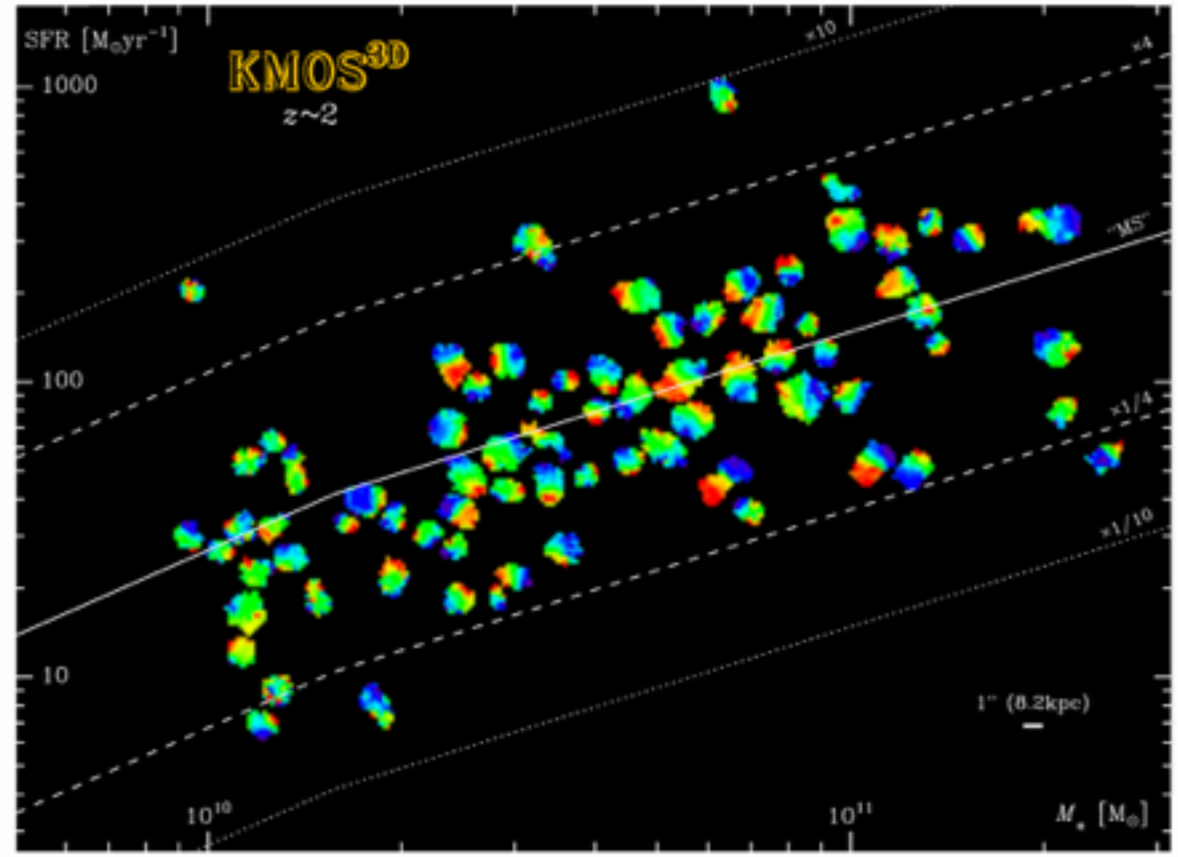




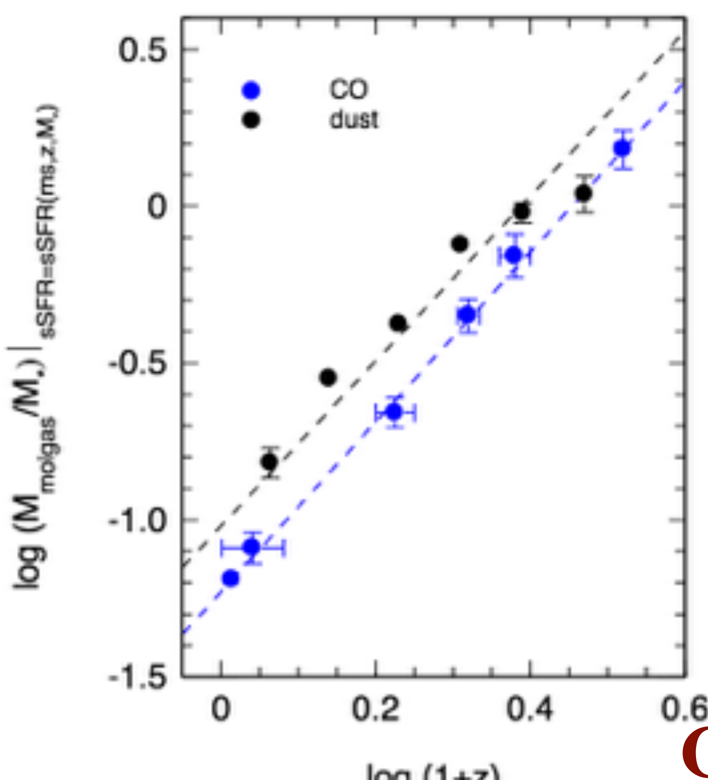
Wisnioski+15

Rotating but very gas rich and turbulent

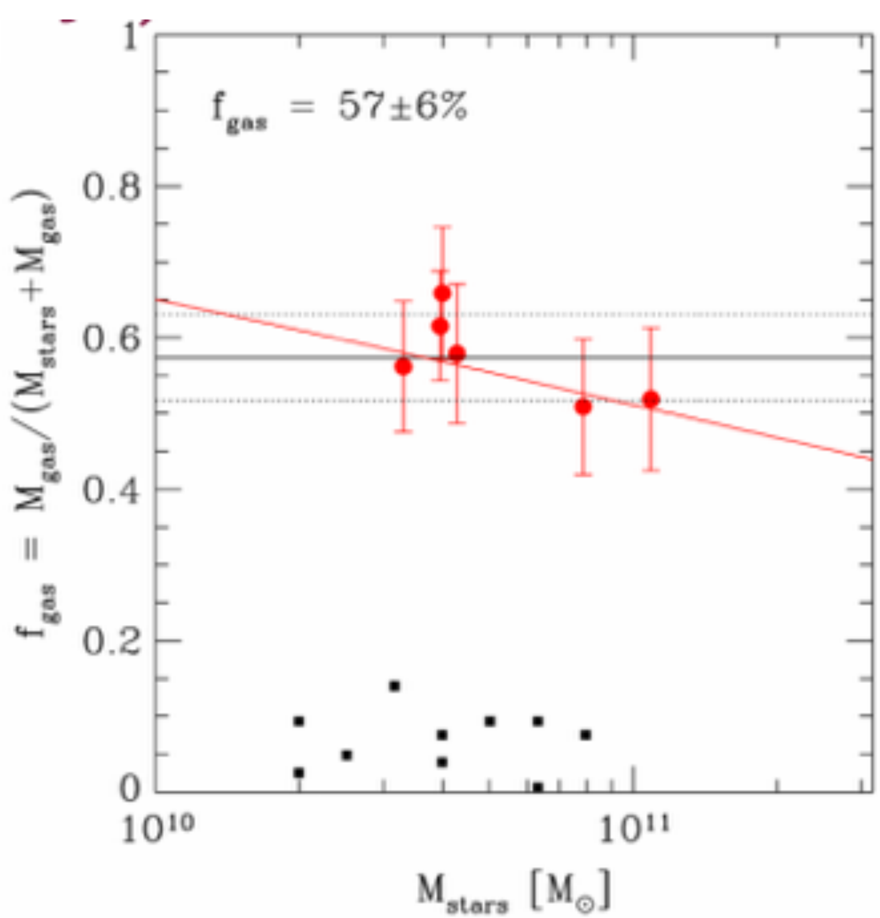




Wisnioski+15



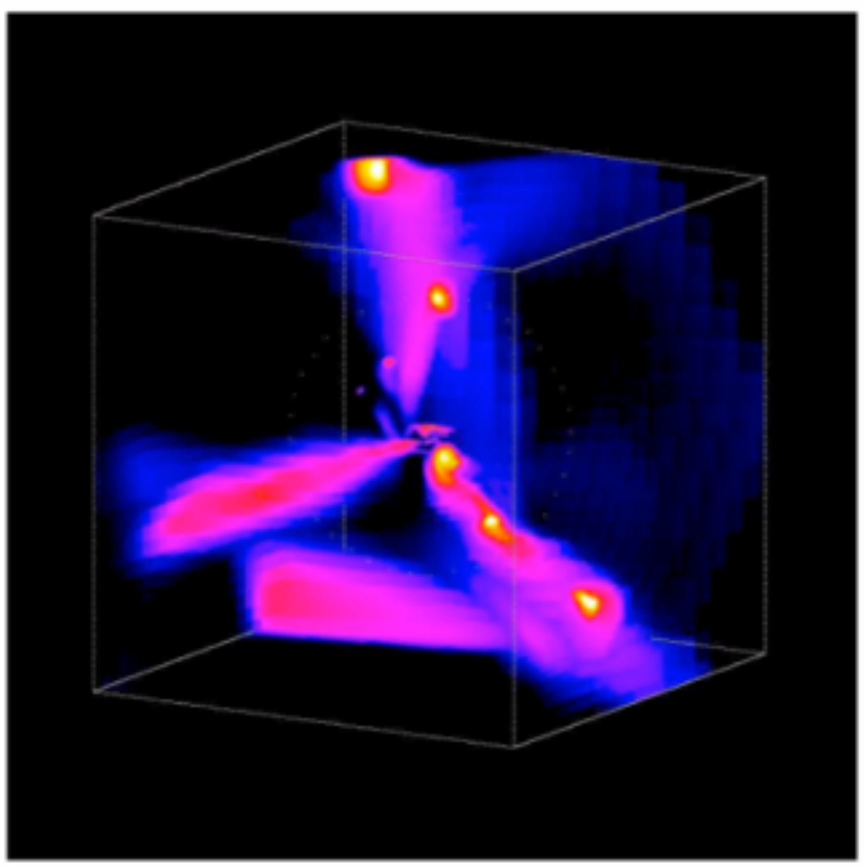
Genzel+15



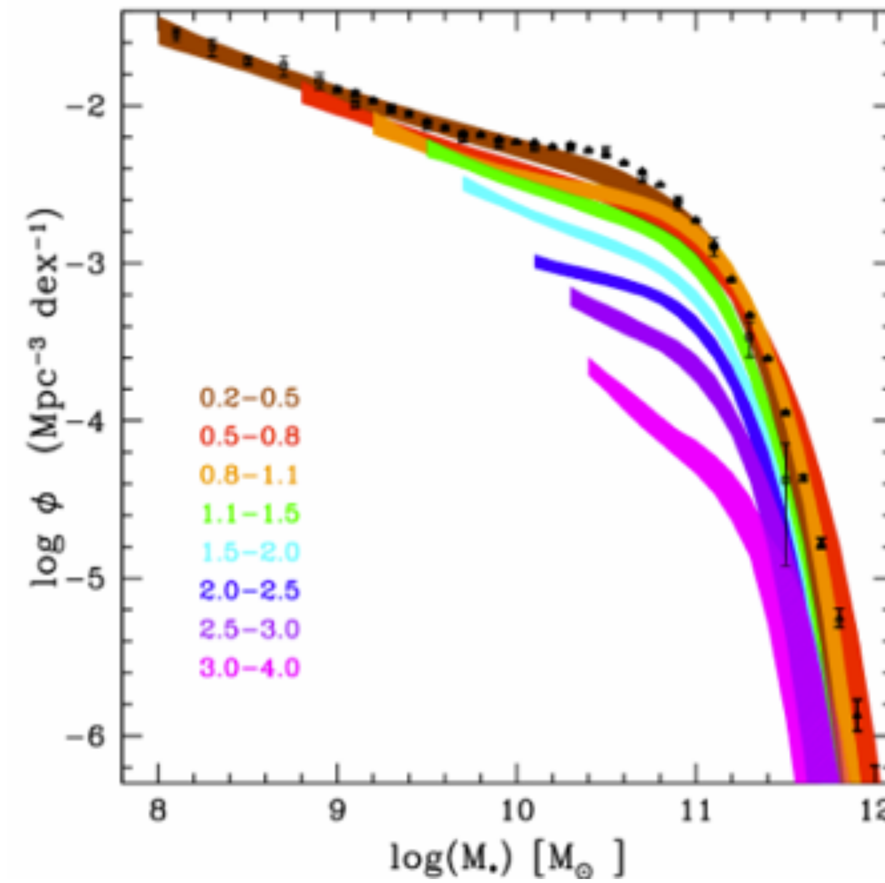
Daddi+07

Sustained star-formation

continuous
gas feeding into galaxies
(flows, mergers)

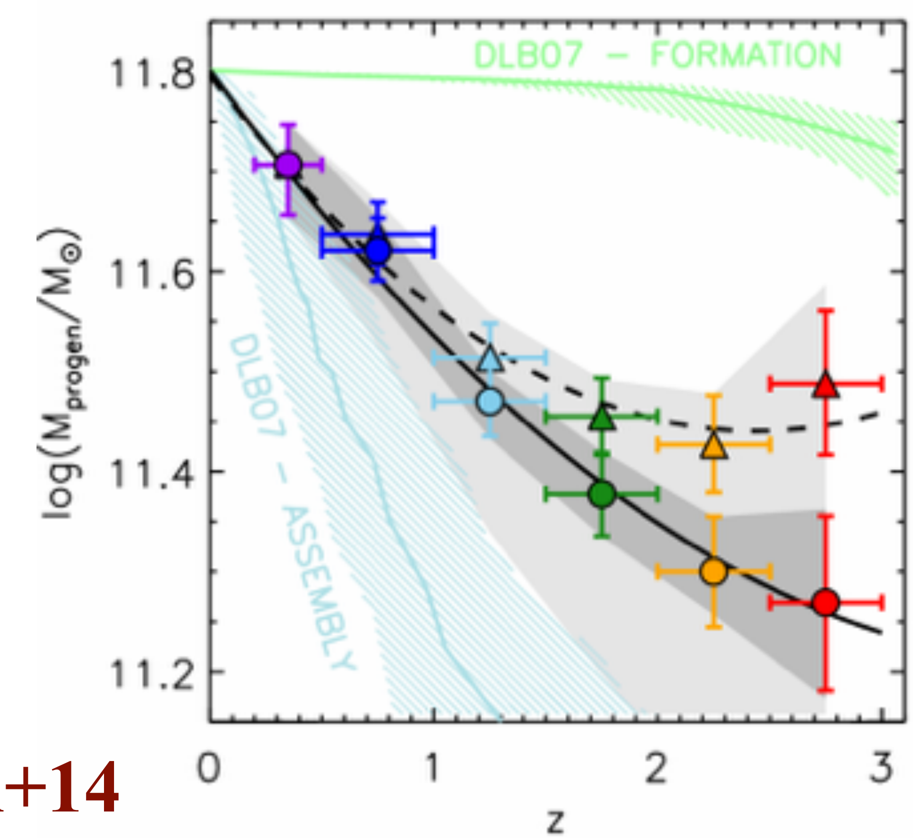


Dekel+09



Ilbert+13

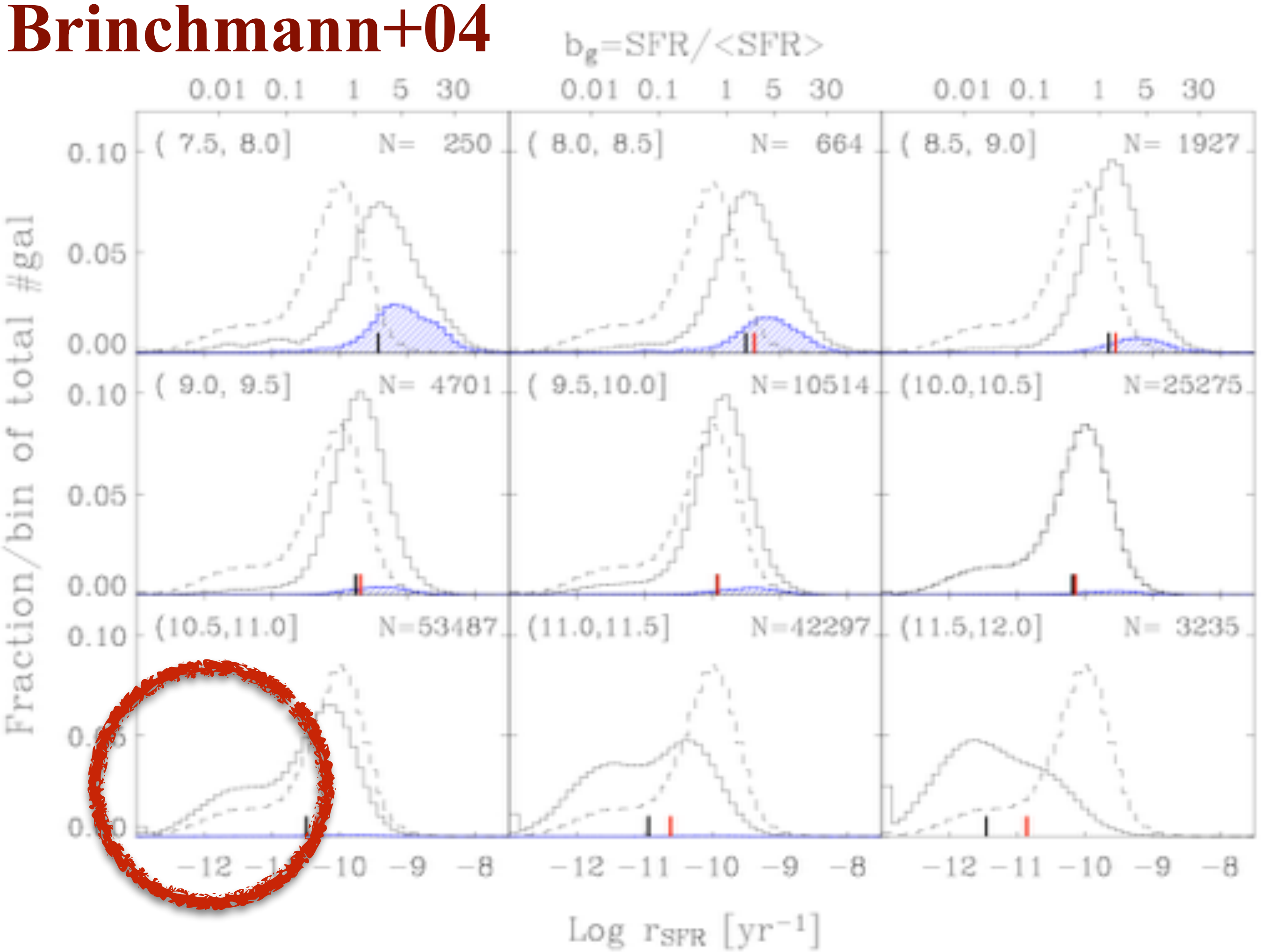
continuous mass build-up



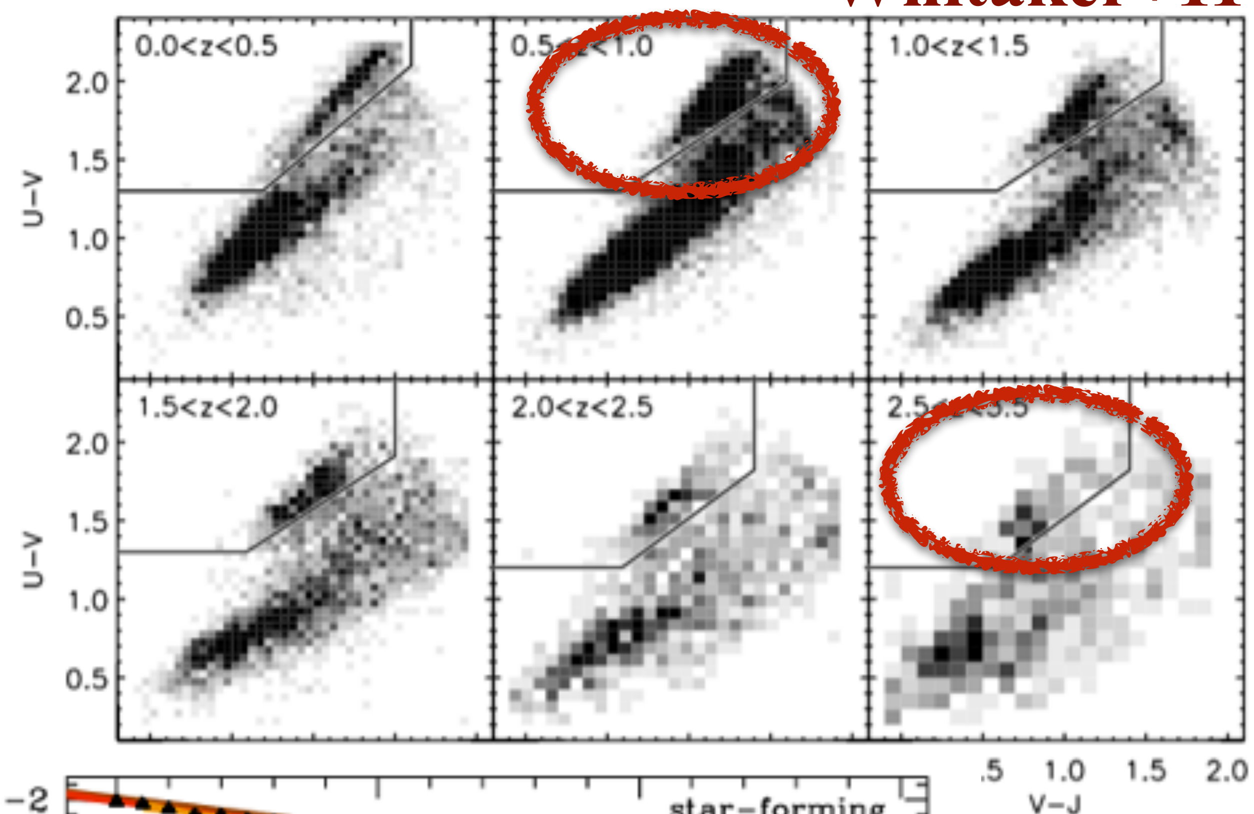
Marchesini+14

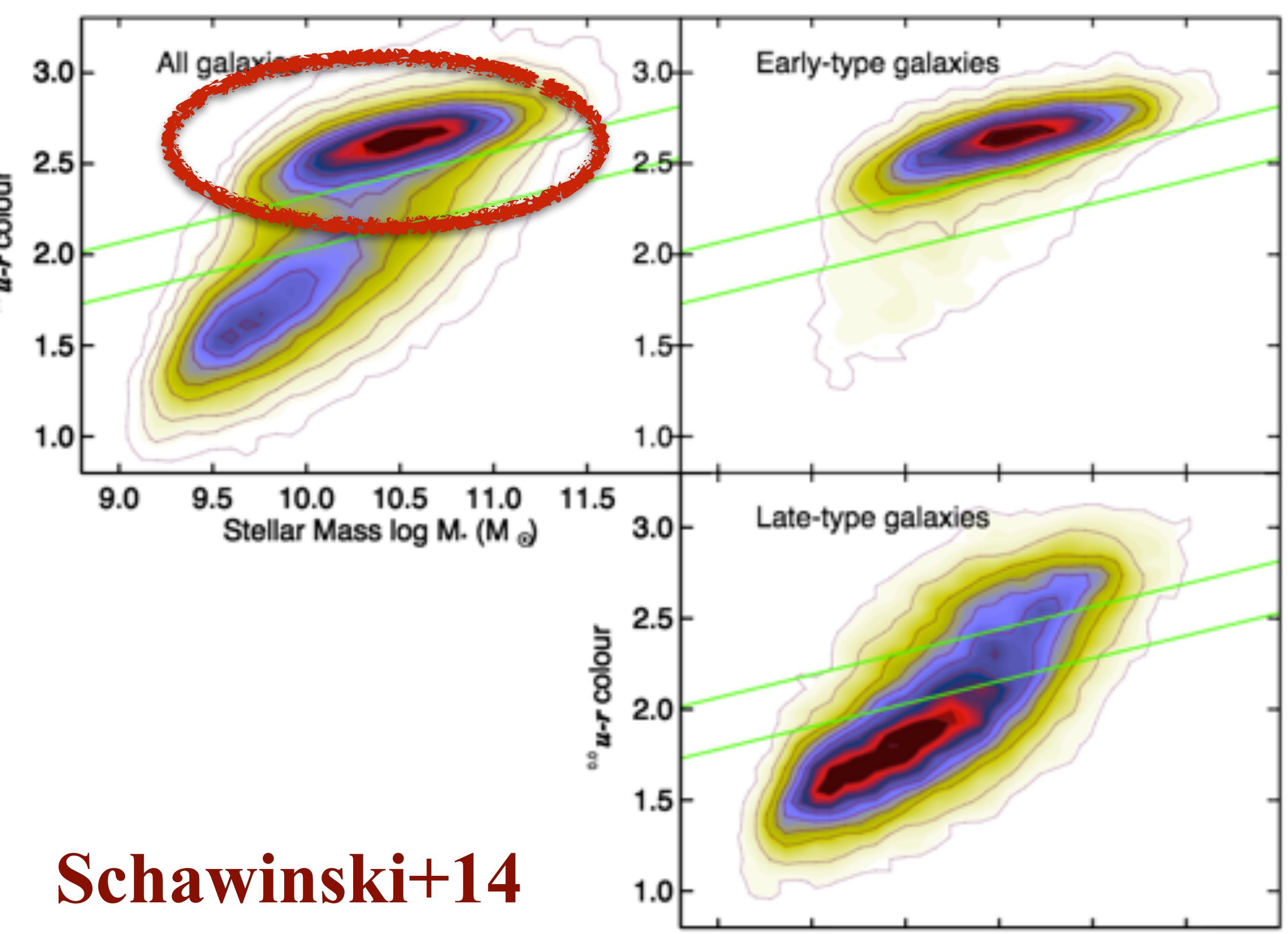
GALAXY BIMODALITY FROM z~3

Brinchmann+04

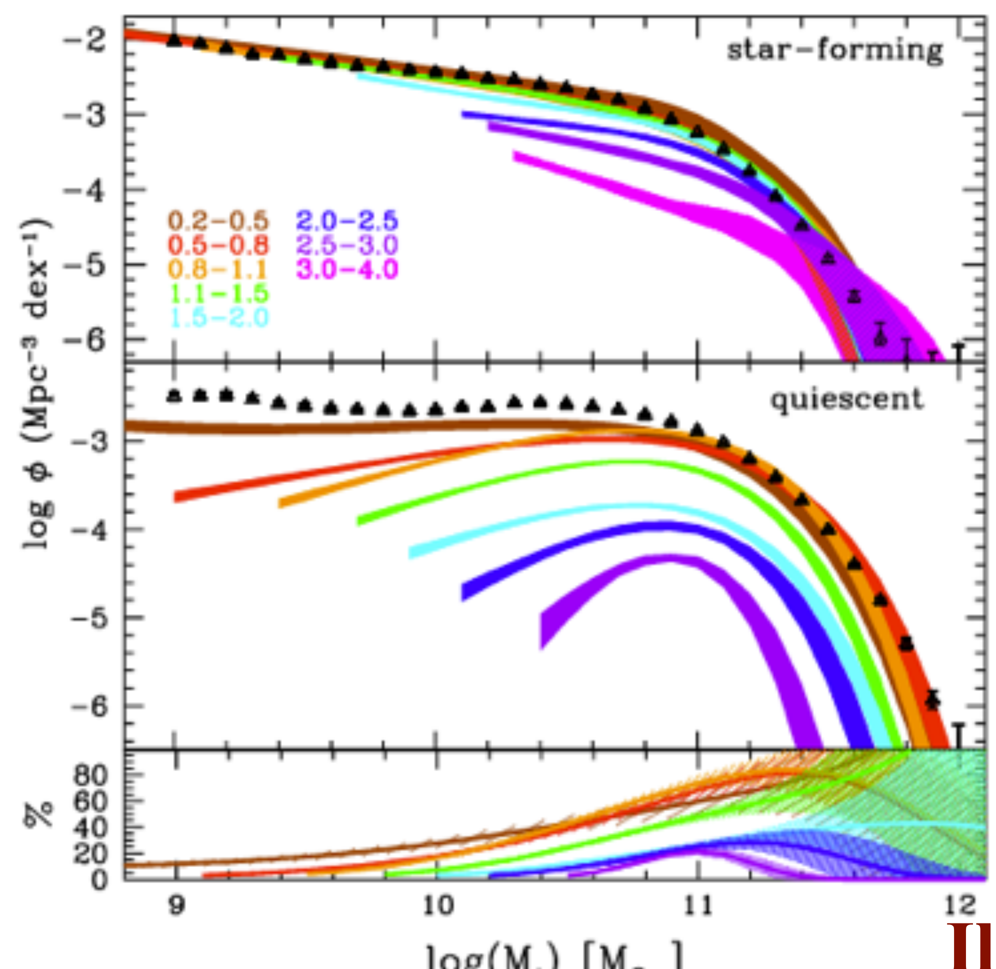


Whitaker+11



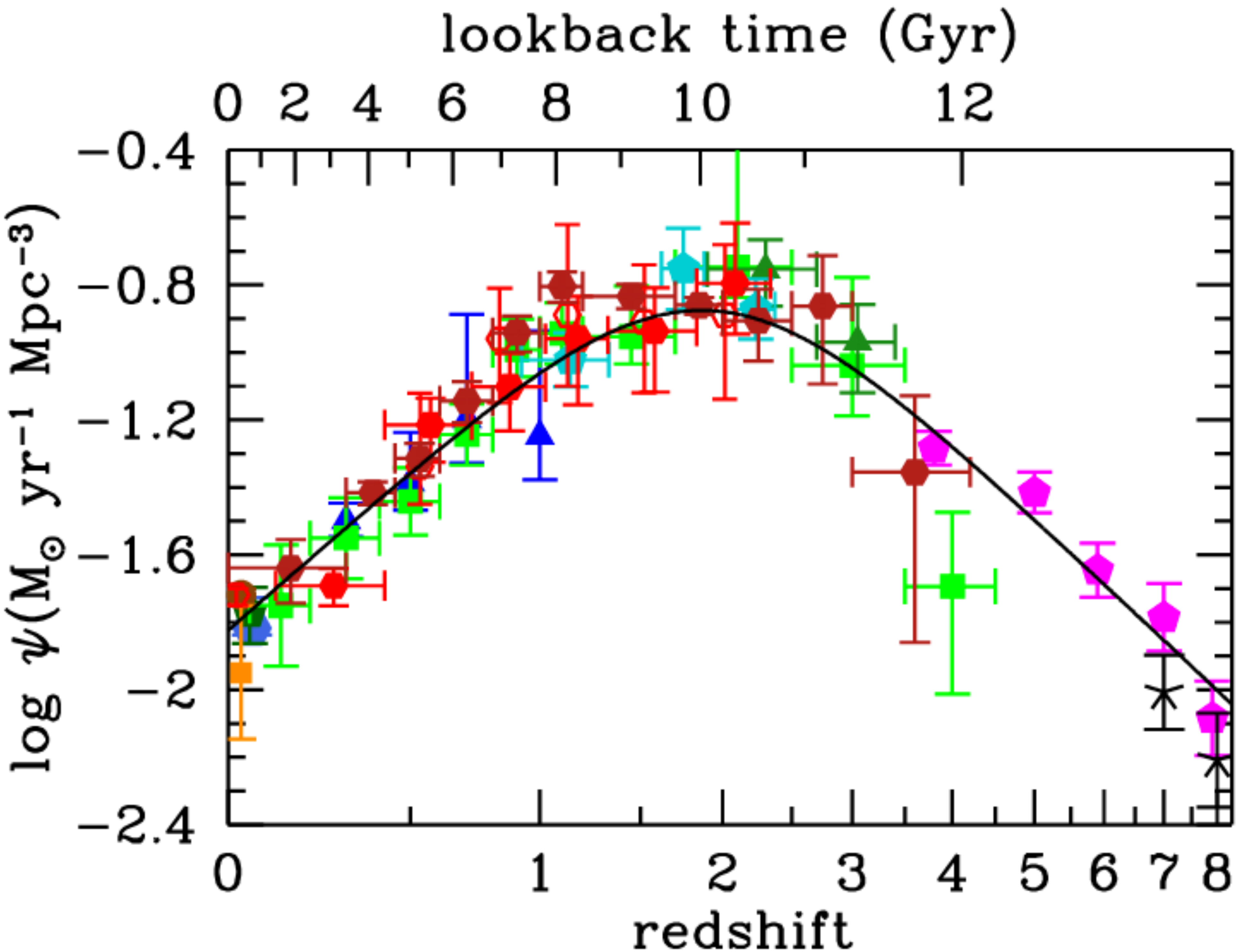


Schawinski+14



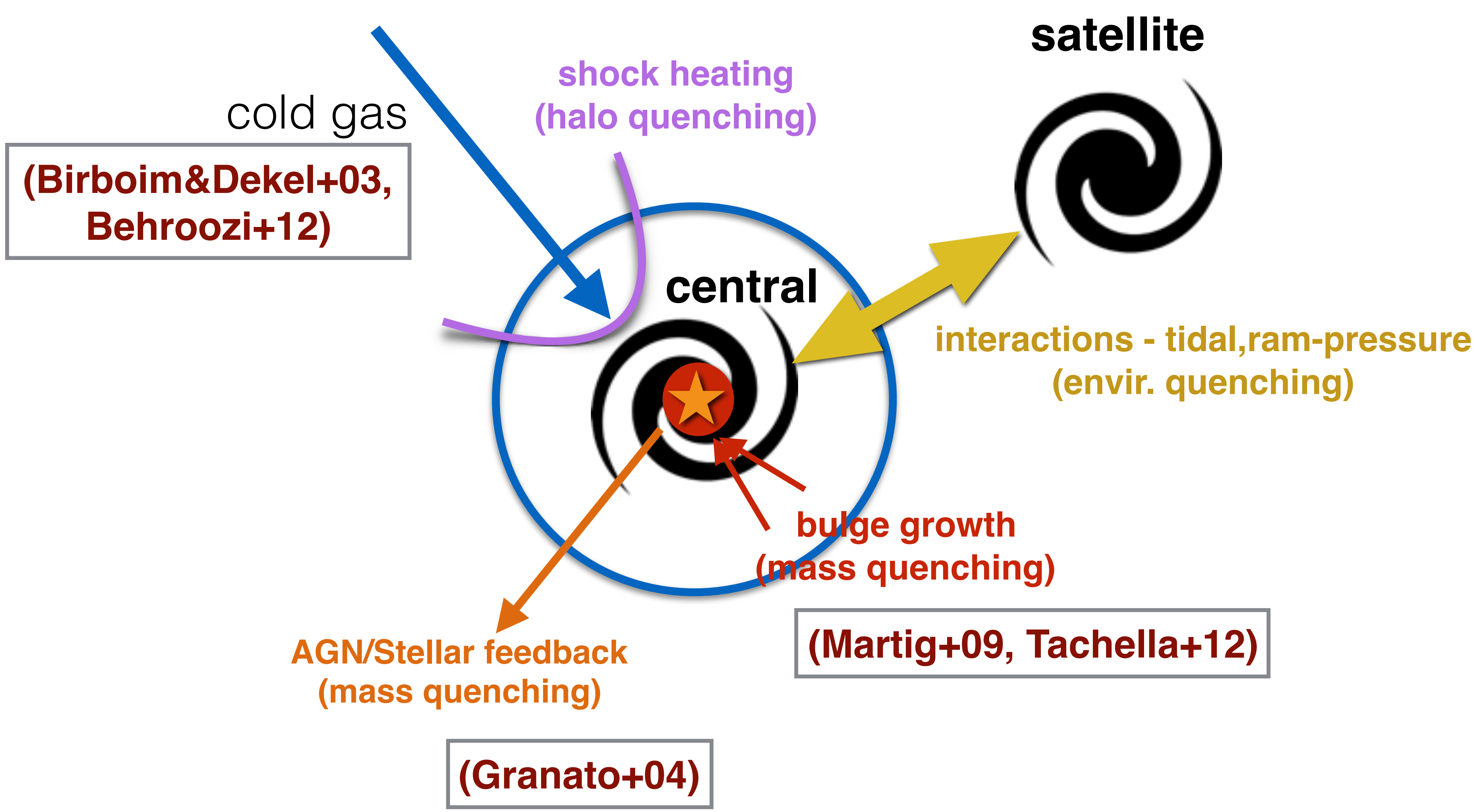
Ilbert+13

<u>Quenching:</u> a key event in a galaxy's life and a fundamental property of our universe?



Madau&Dickinson+14

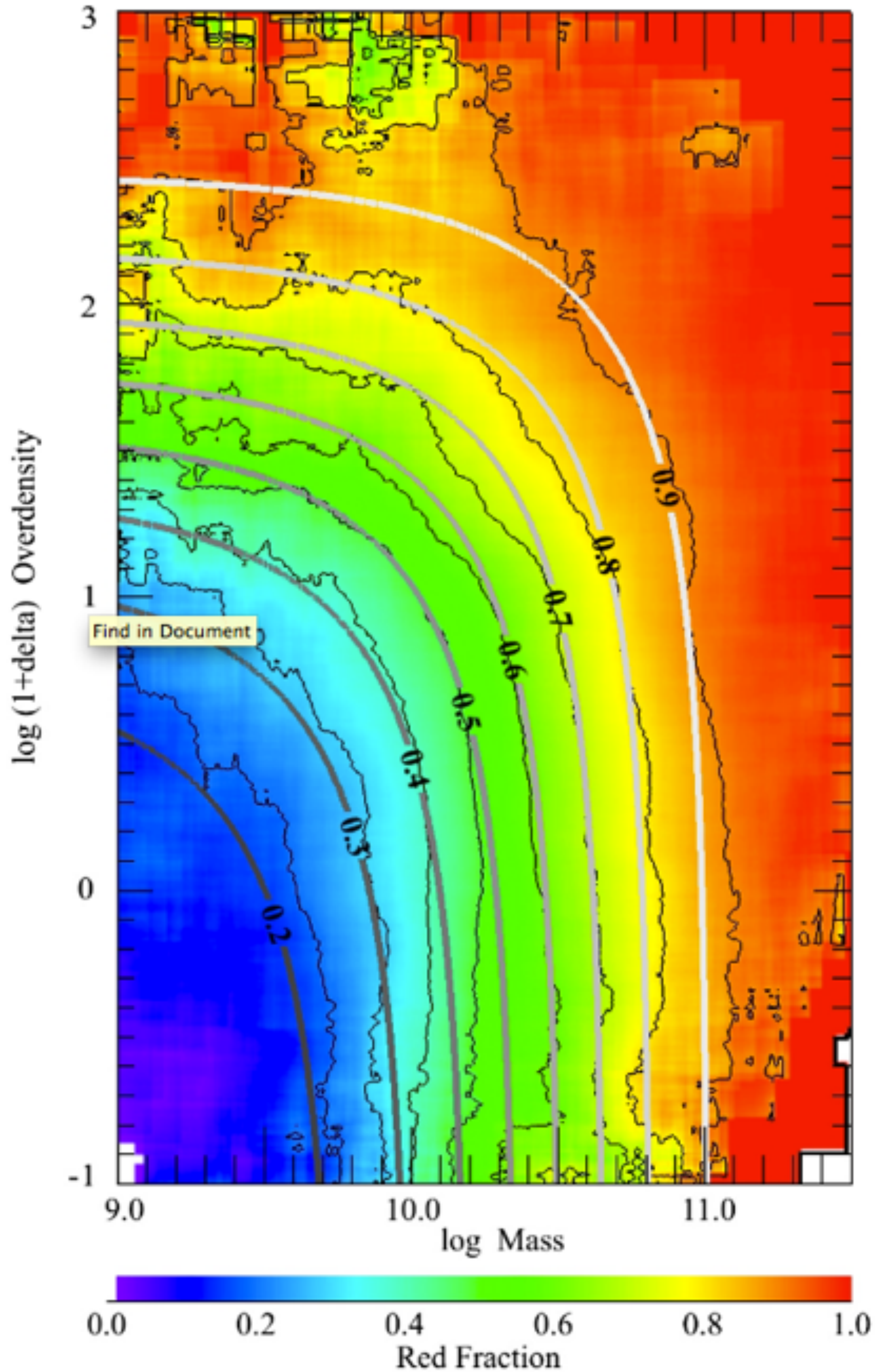
How to stop forming stars? (quench)



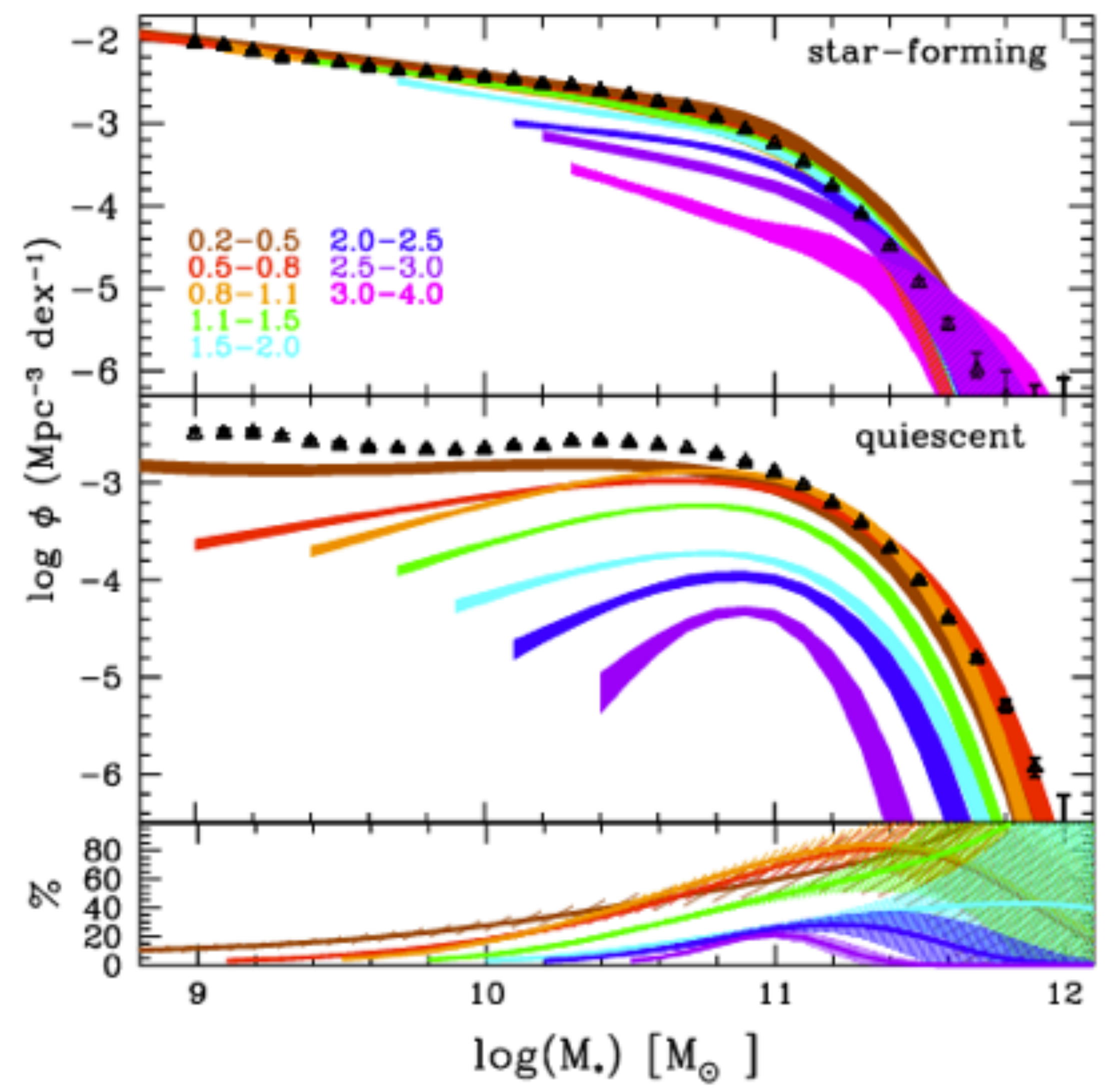
See also Lilly+13

Mass and environment both contribute to quenching

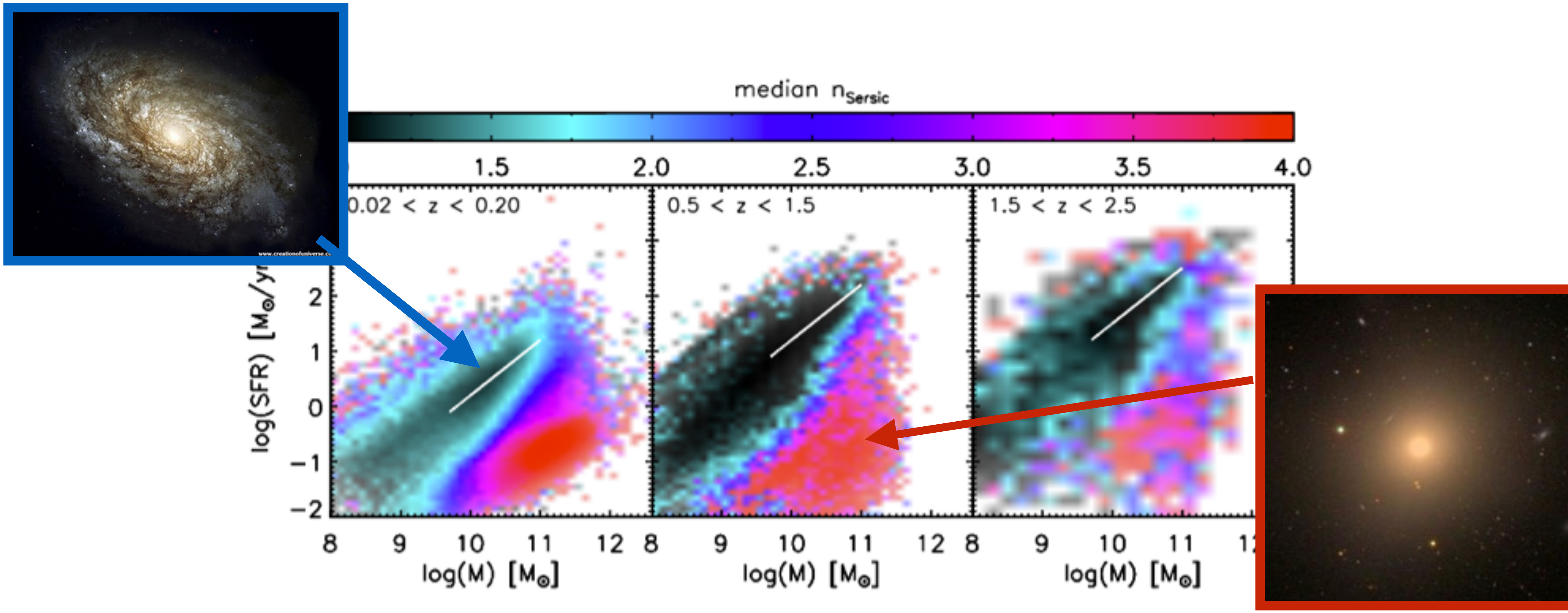
Peng+10



Ilbert+13



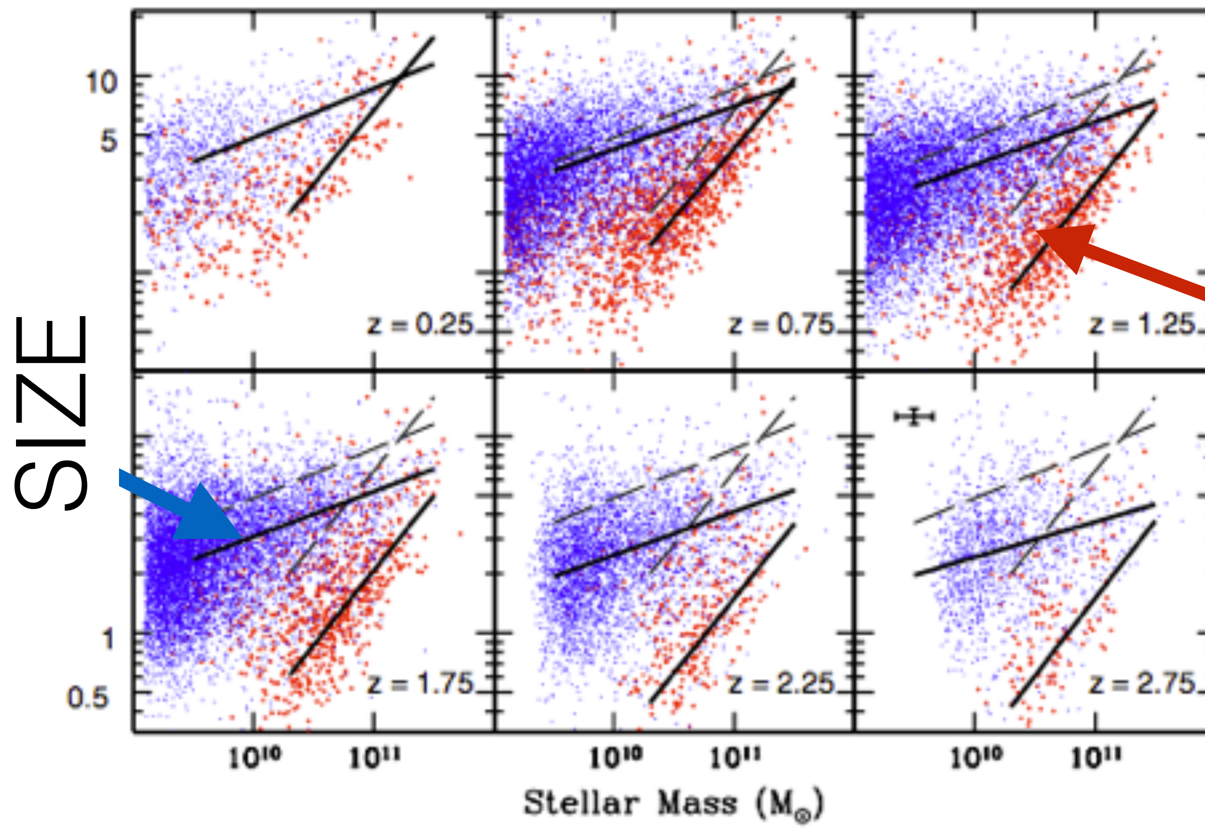
Halo or baryonic physics?



Wuyts+11

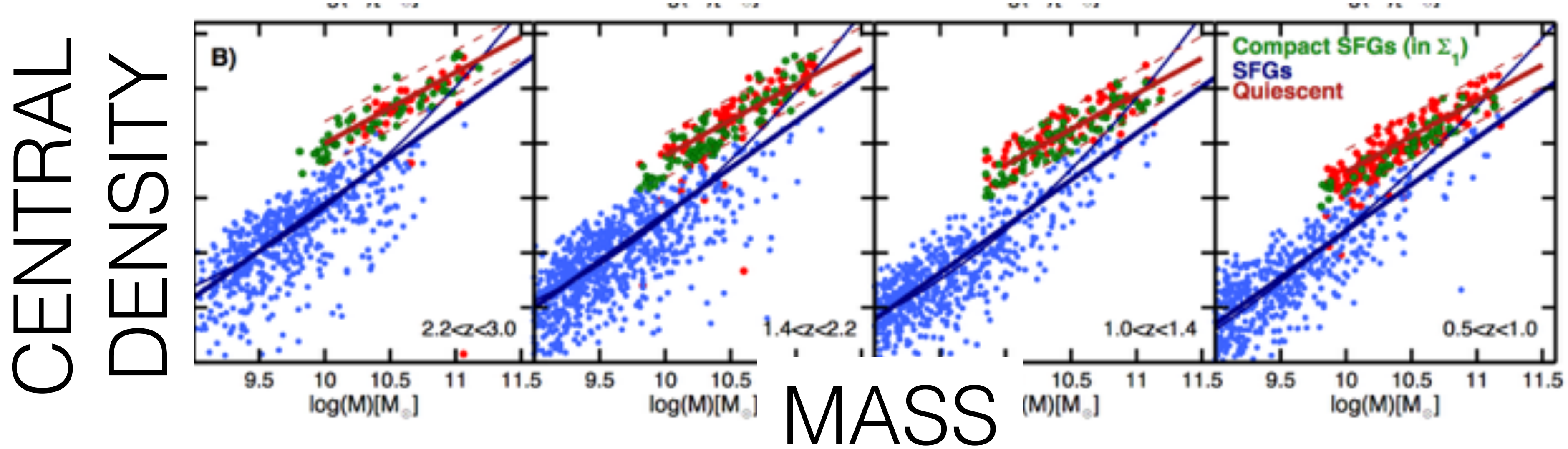
Quenched/SF galaxies have different morphologies

Halo or baryonic physics?



van der Wel+13

Barro+15



Imprint in the central 1Kpc!

Inside-out growth/quenching?

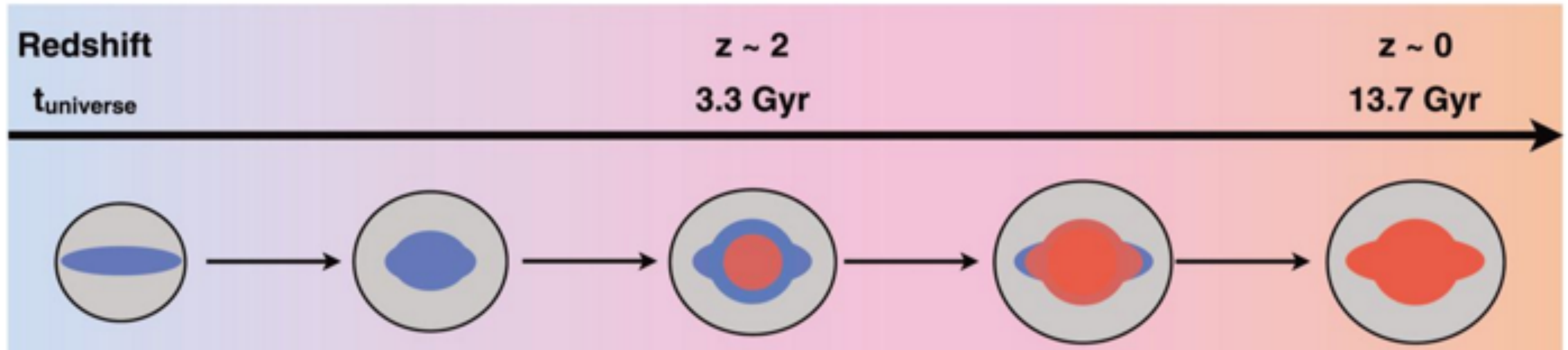
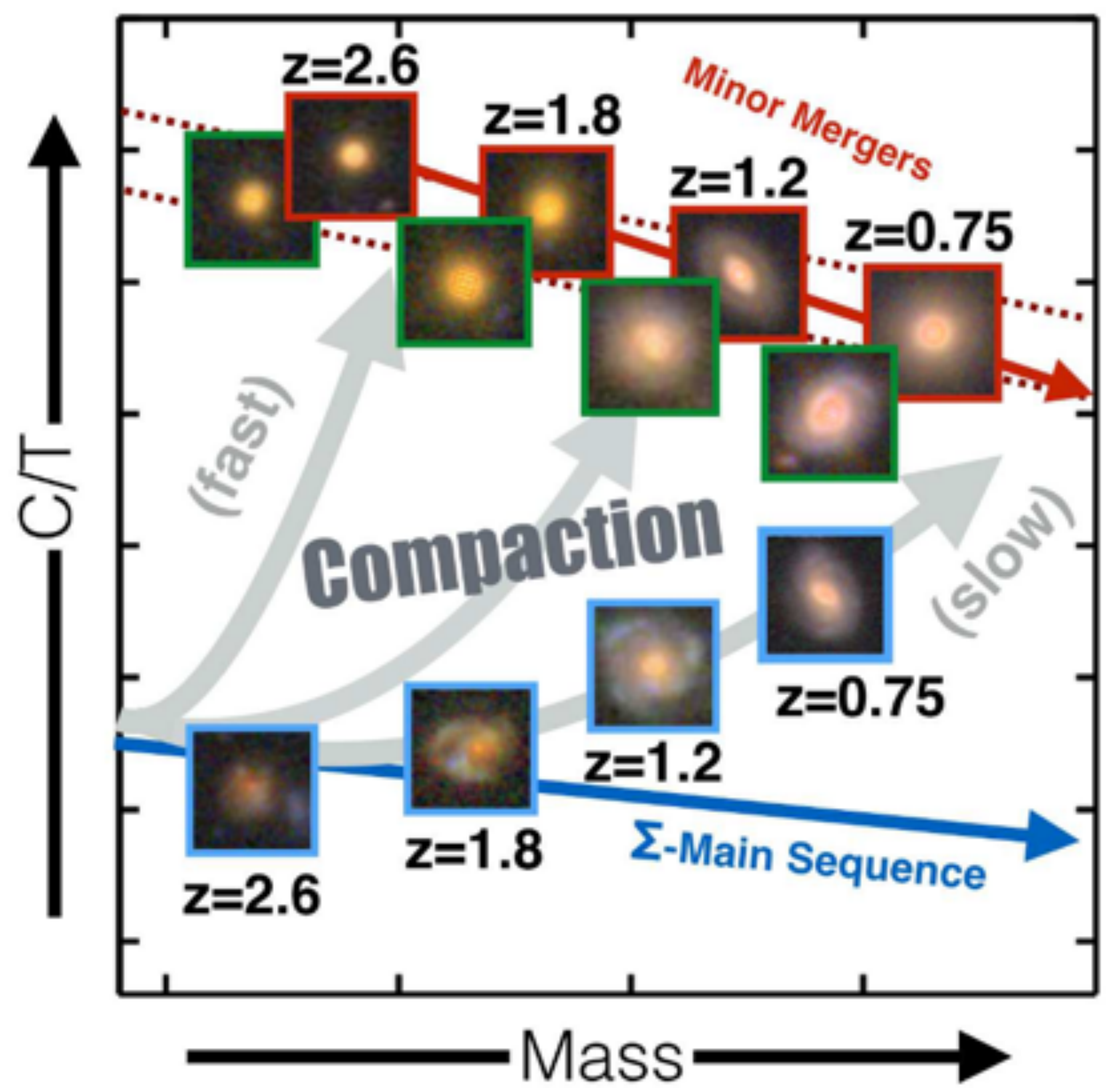


Fig. 4 Proposed sketch of the evolution of massive galaxies.
Our results suggest a picture in which the total stellar mass and bulge mass grow synchronously in z ~ 2 main sequence galaxies, and quenching is concurrent with their total masses and central densities approaching the highest values observed in massive spheroids in today's universe.

Tacchella+15

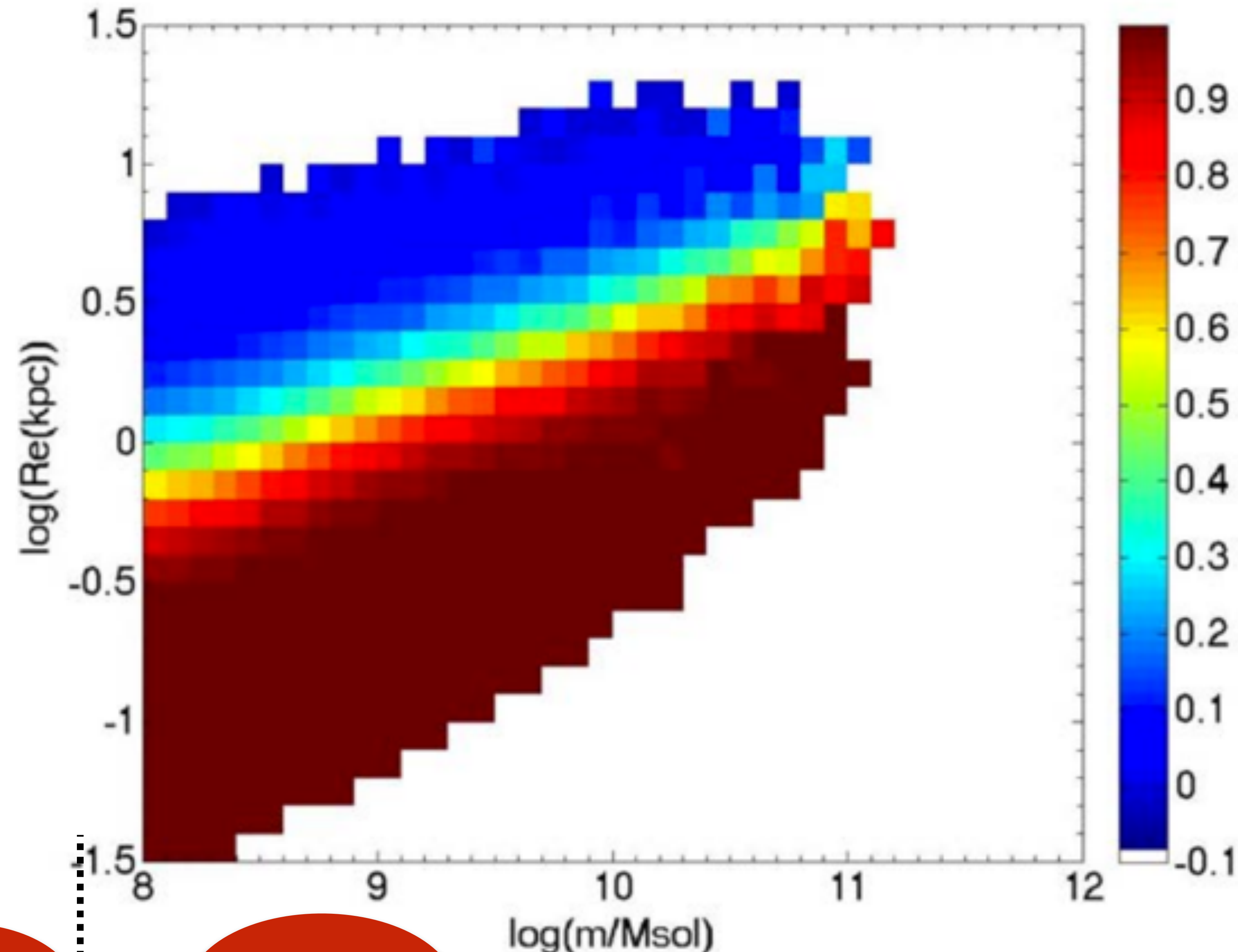


Barro+15

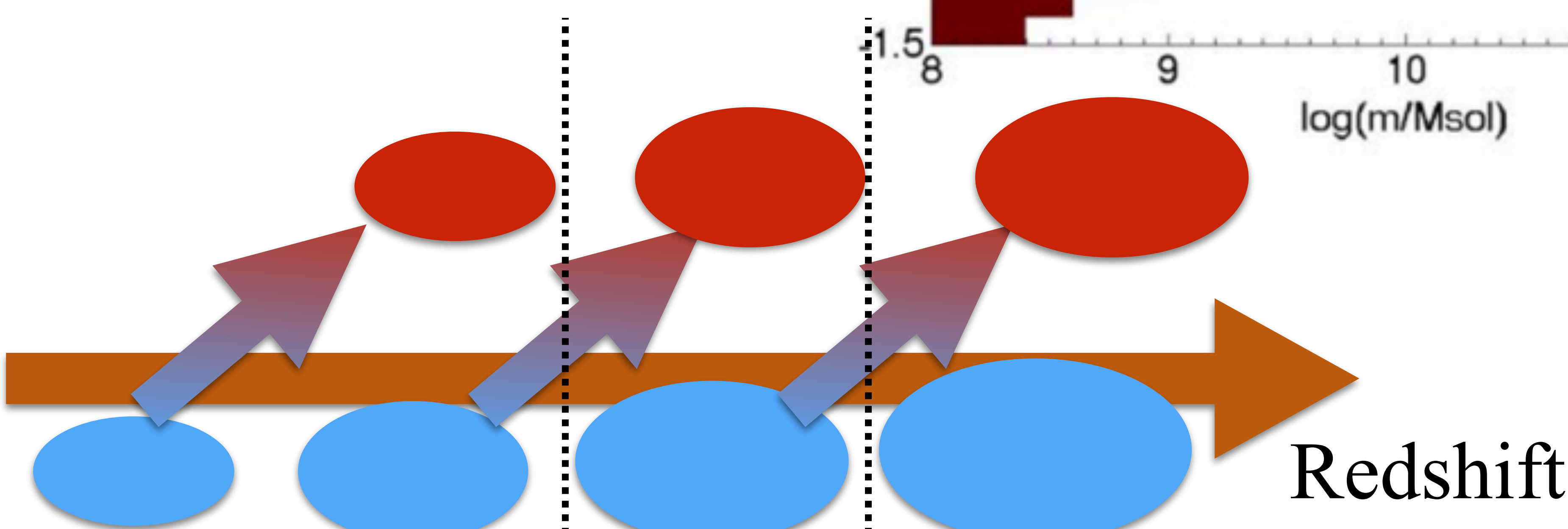
Compaction and quenching: whenever a central density threshold is reached, a quenching event follows

Progenitor bias can also explain the observed correlations

Quenched galaxies at a given epoch appear smaller because they quenched earlier



Lilly&Carollo+16



QUENCHING ⟷ MORPHOLOGY

remains an open question

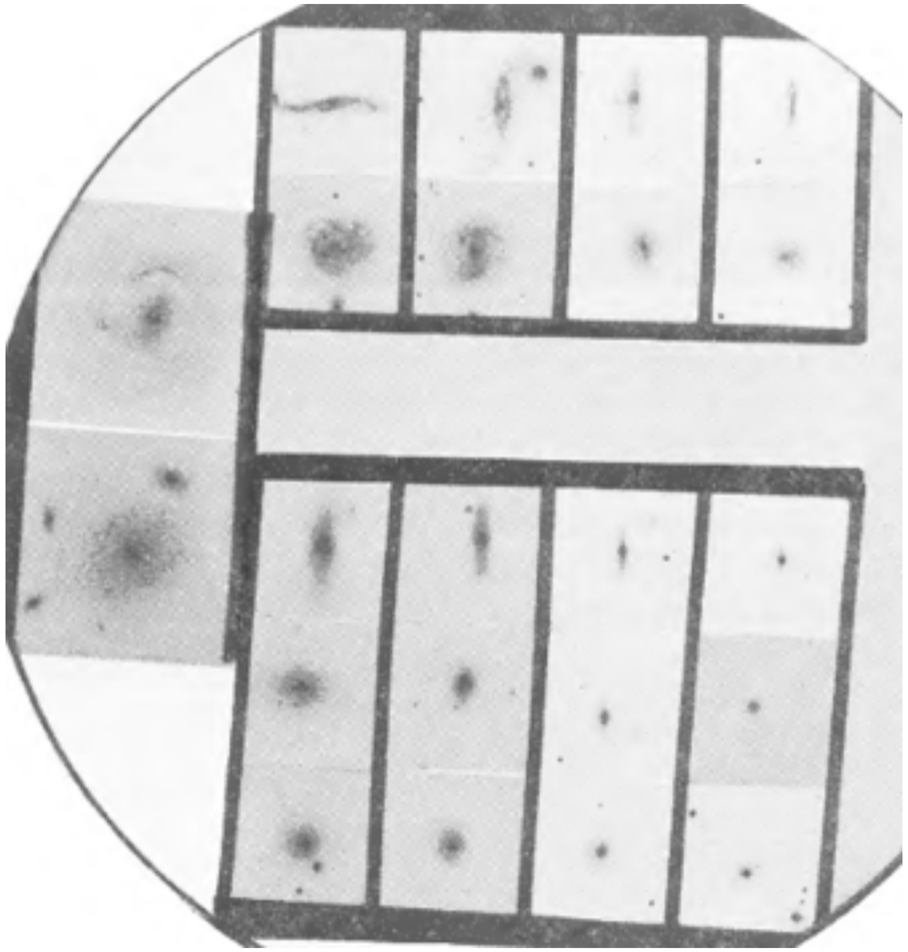
This will be the main topic of this talk

Can we get additional clues by analyzing detailed morphologies?

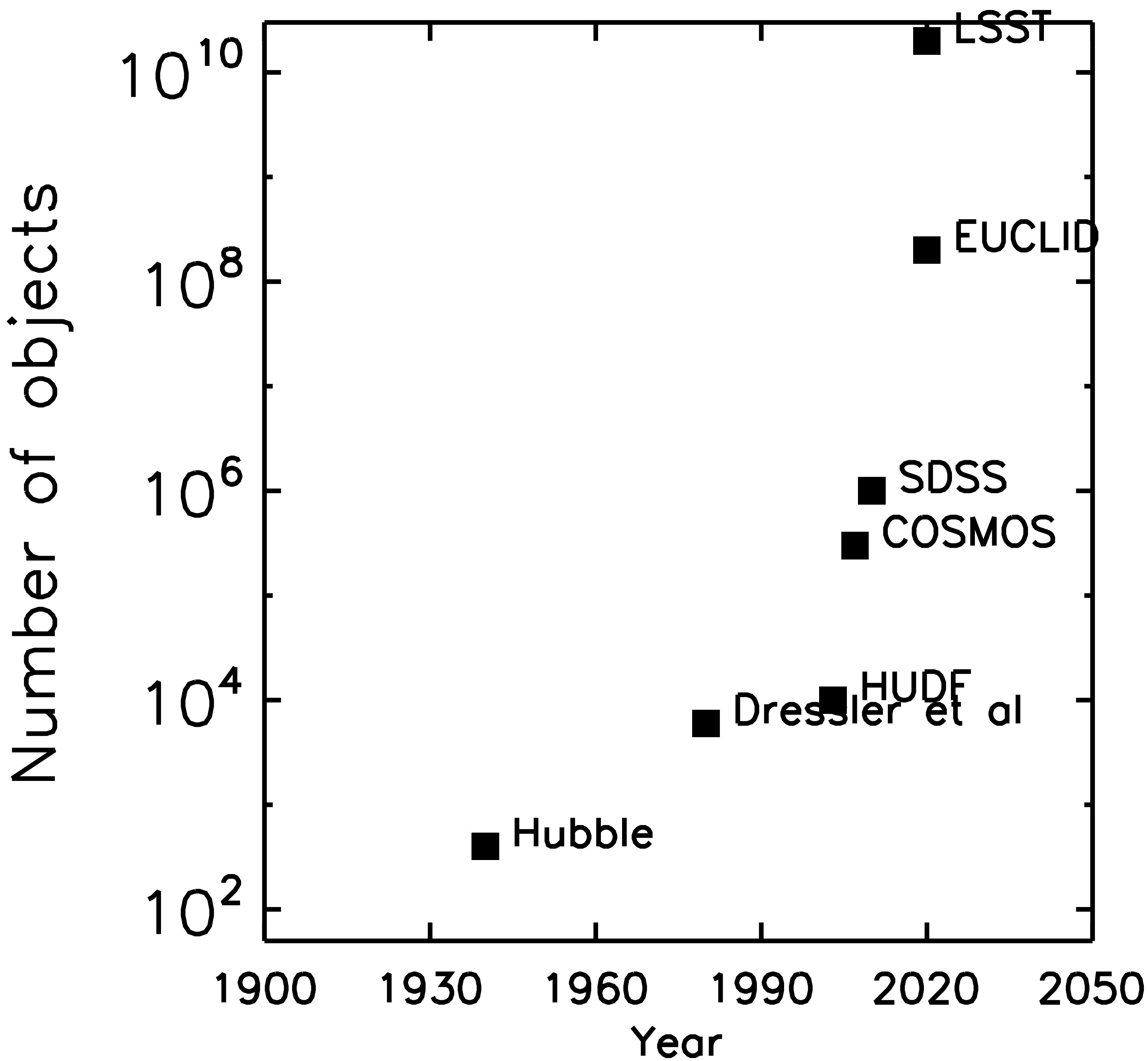
Estimating galaxy morphologies from large surveys

Early ages - Before deep surveys

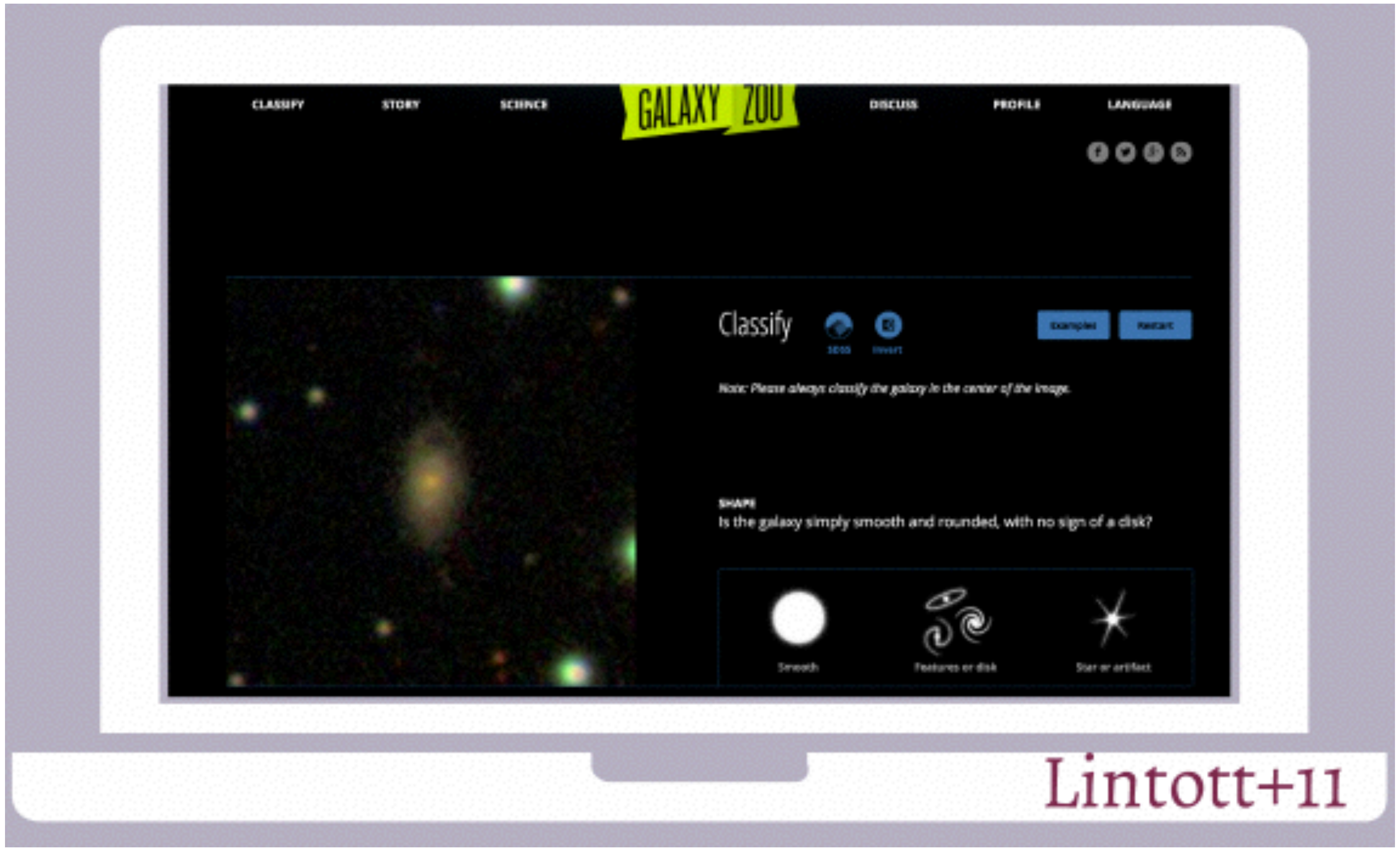
visual classifications
by individual researchers
[e.g. Dressler+80, Postman+05]



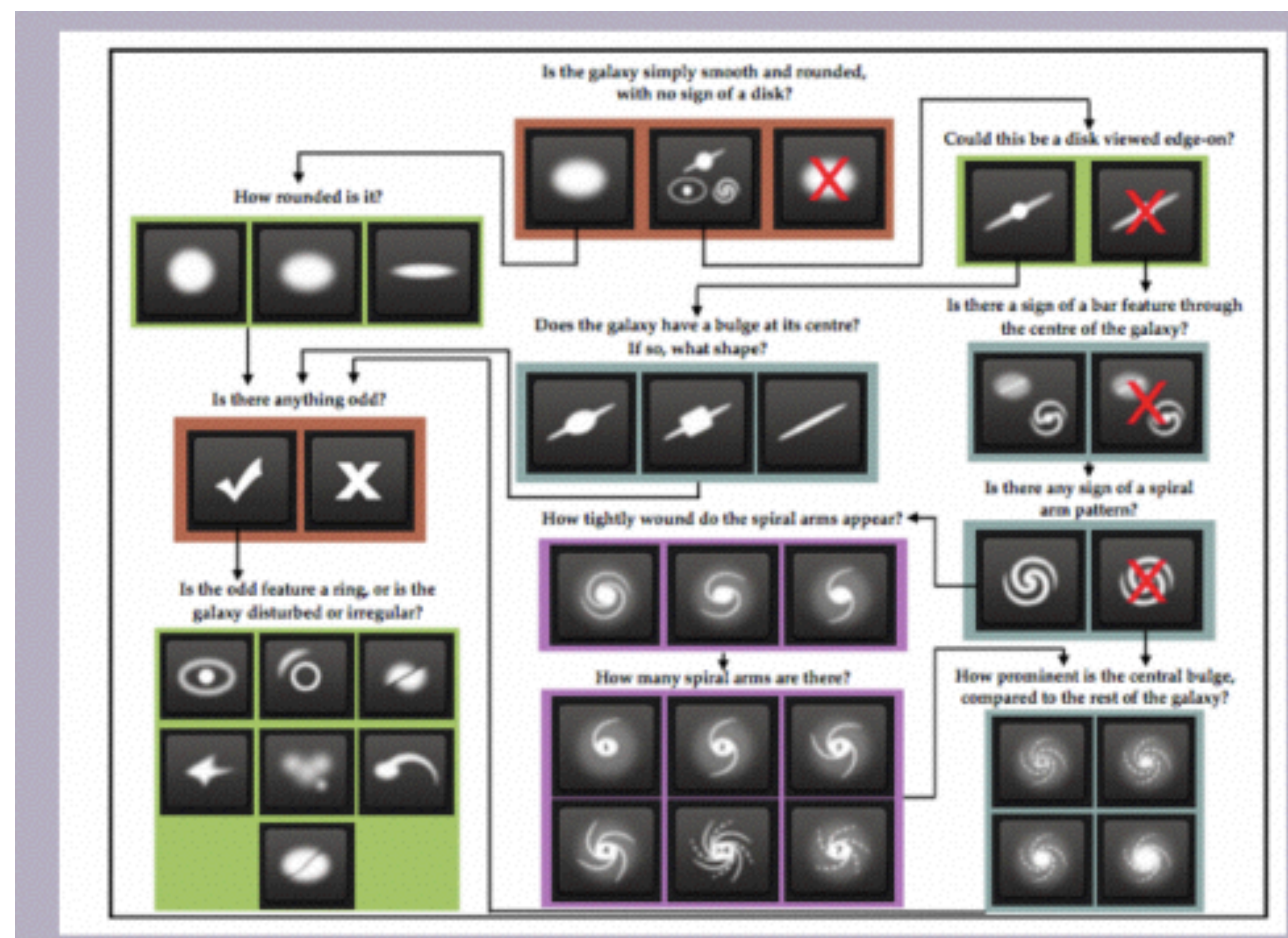
THE BIG-DATA ERA IN ASTRONOMY



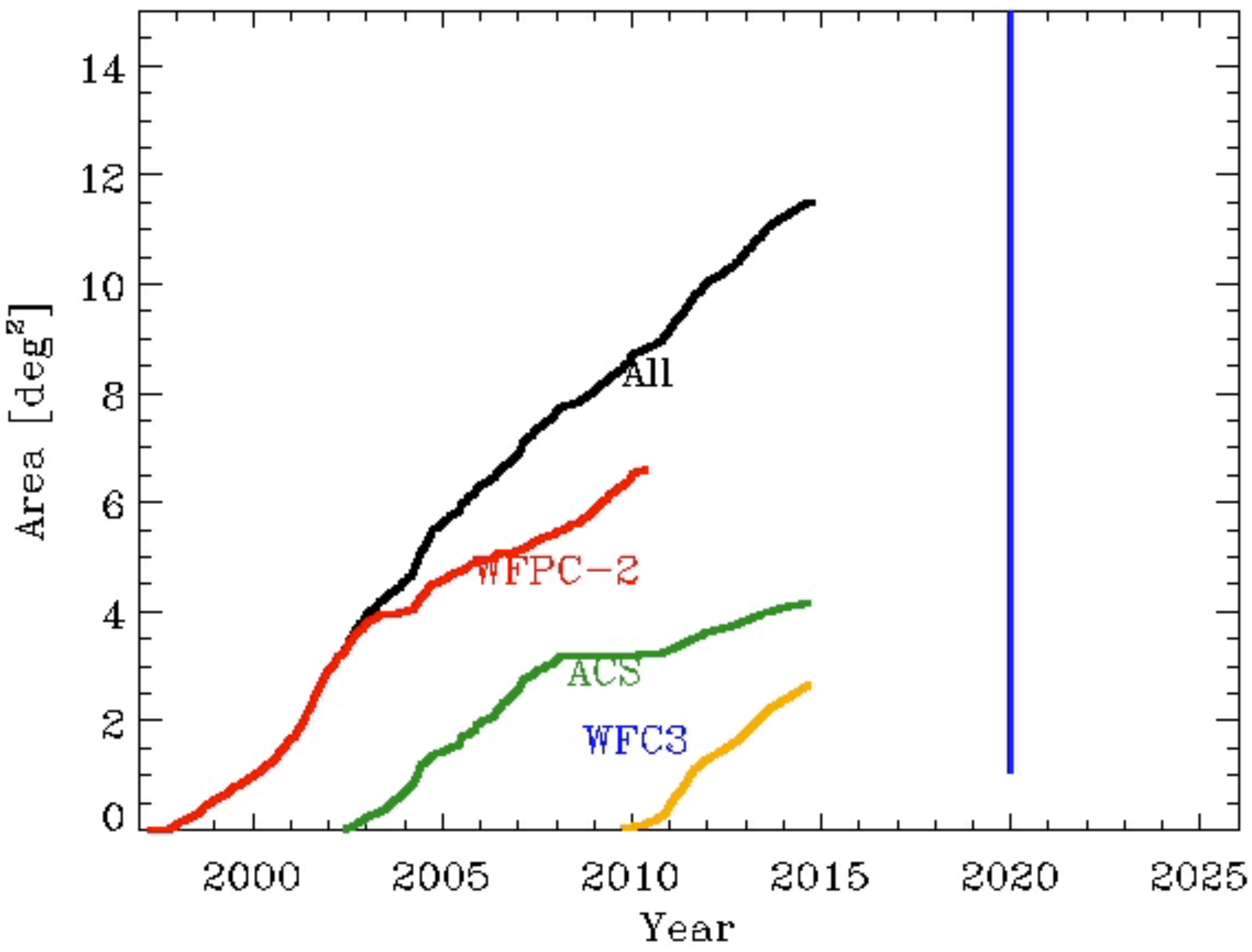
GALAXY ZOO PROJECT



INCREASE THE NUMBER OF CLASSIFIERS

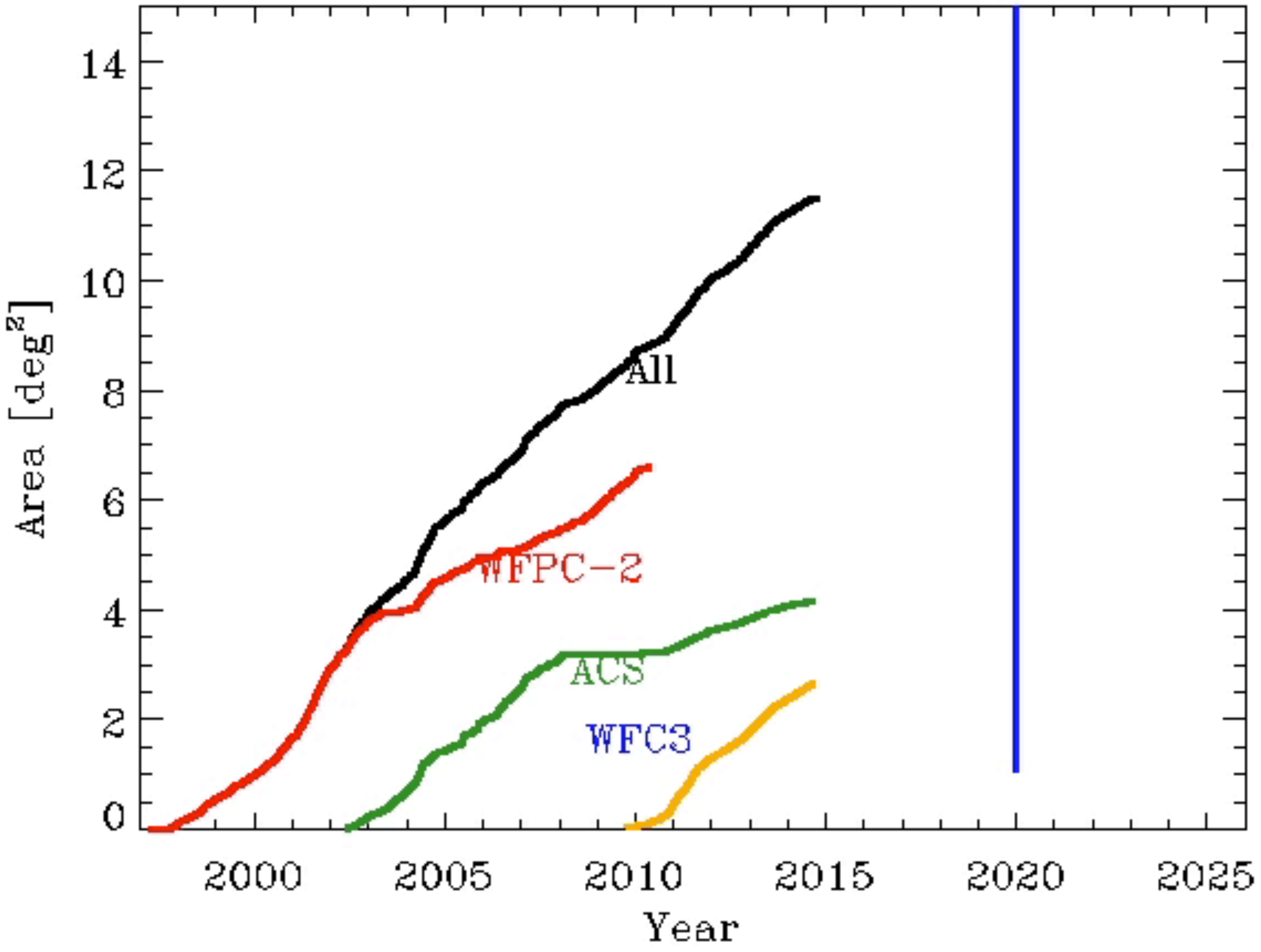


The big-data revolution in astronomy, e.g. EUCLID



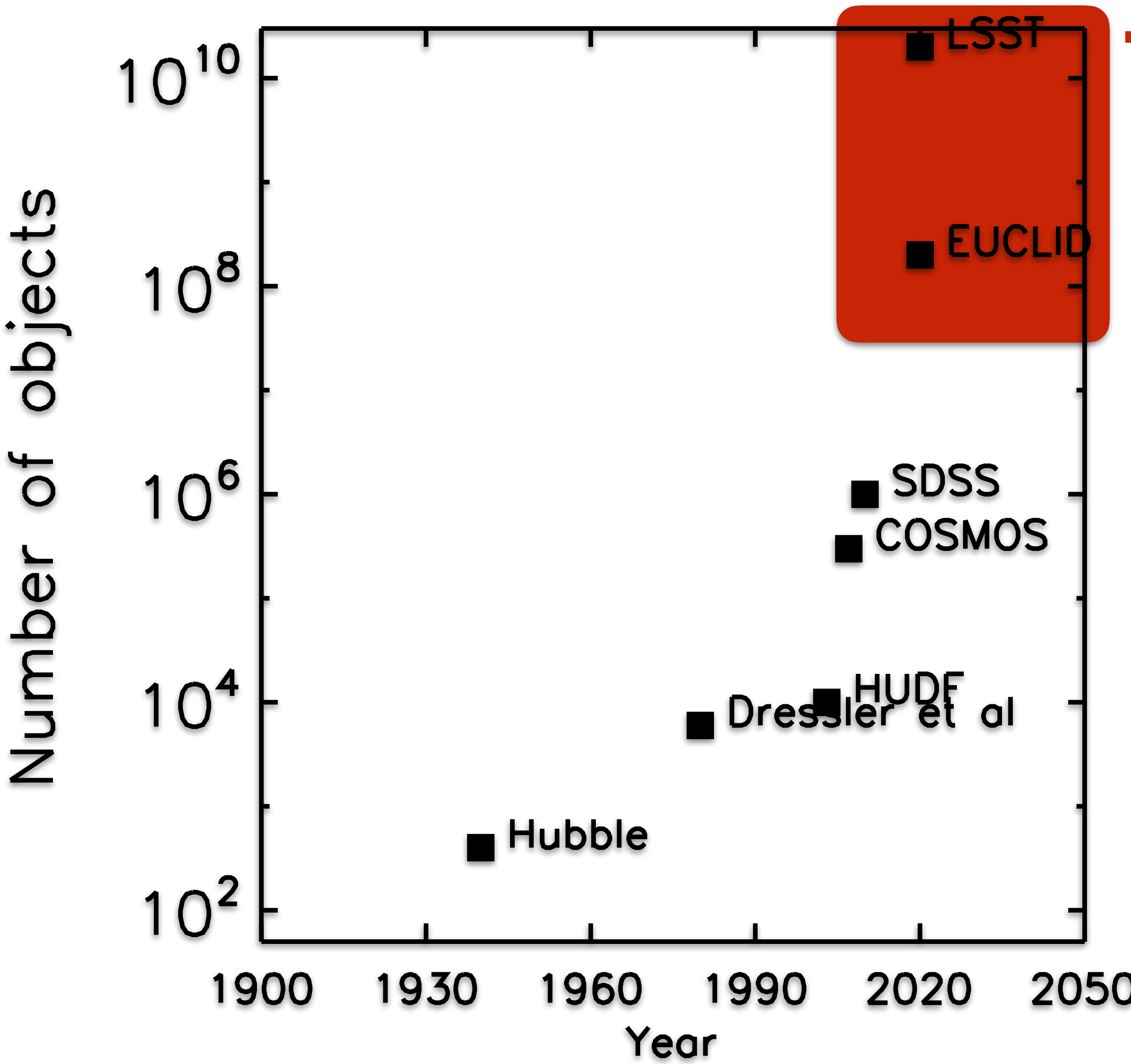
(Thanks to J. Brinchmann)

The big-data revolution in astronomy, e.g. EUCLID



(Thanks to J. Brinchmann)

Big-Data era



Galaxy Zoo on EUCLID would take ~70yrs

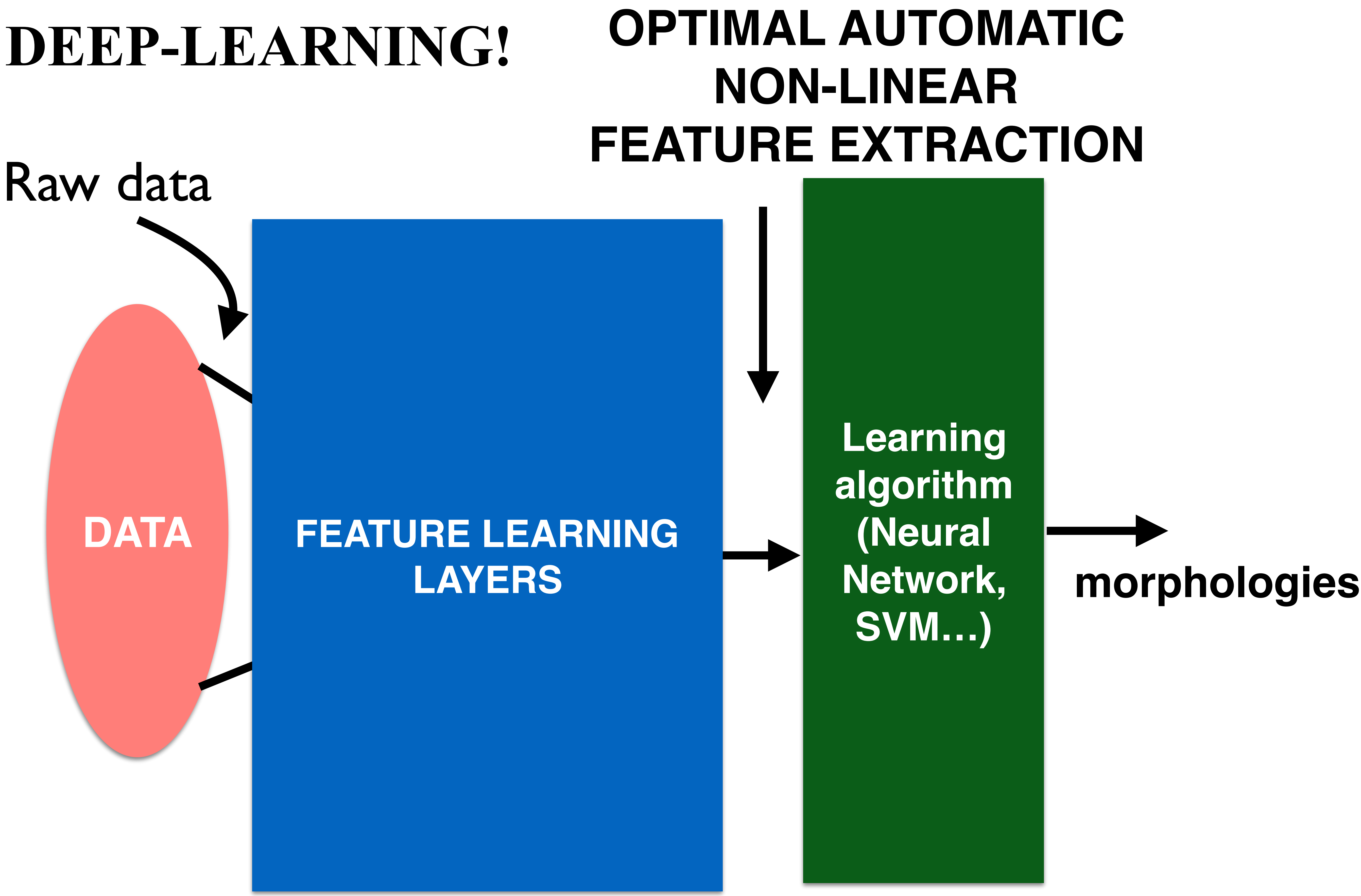
Artificial intelligence is required in the near future

▶ 99.2% accuracy

"Deep learning is killing every problem in AI."

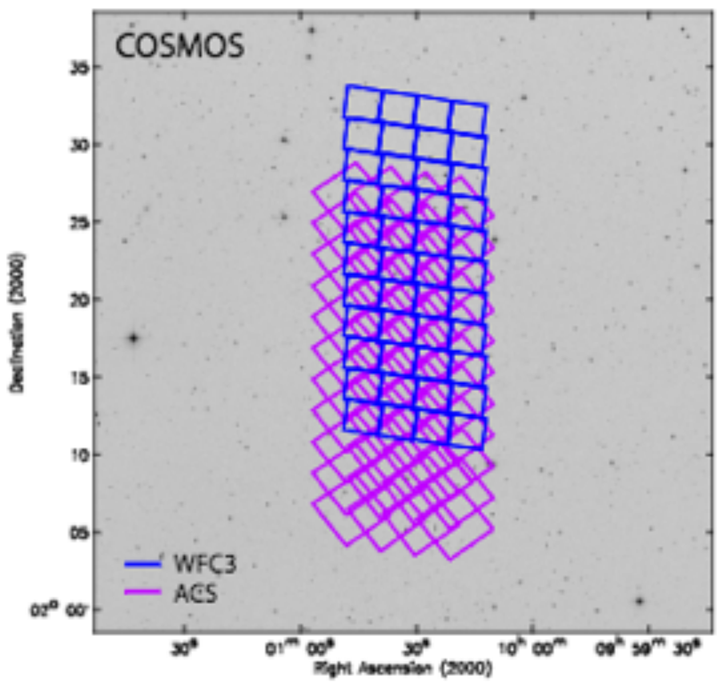
(Nature, 01/2016)

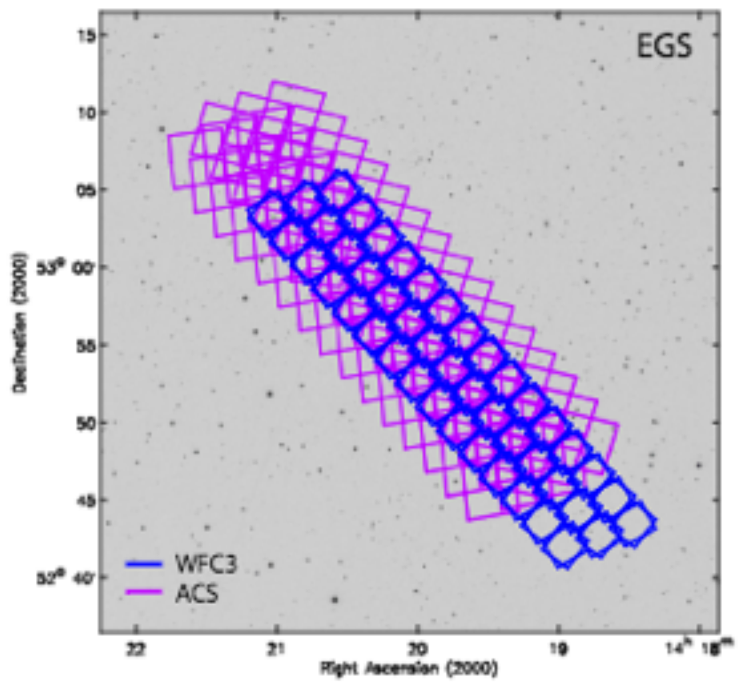
▶ 94.3 % accuracy

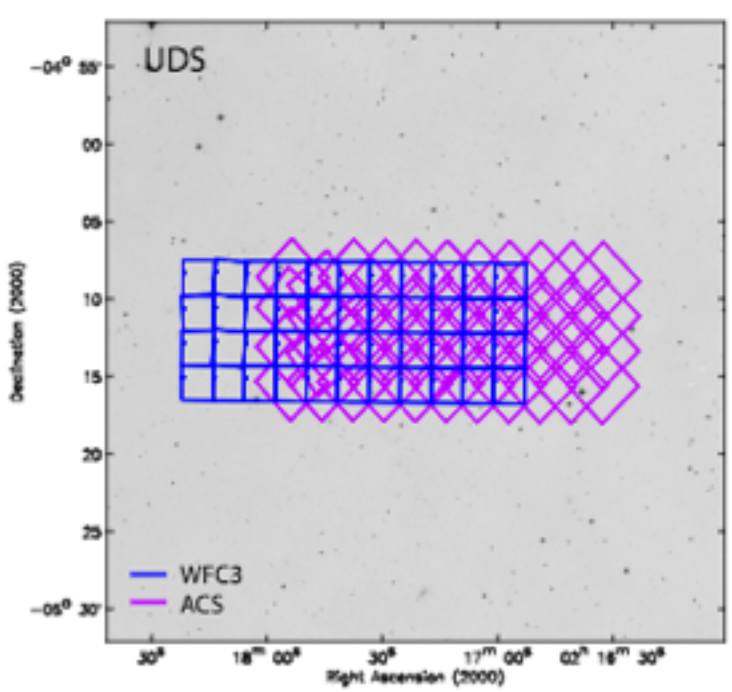

DEEP-LEARNING!
OPTIMAL AUTOMATIC
NON-LINEAR
FEATURE EXTRACTION
Raw data
DATA
FEATURE LEARNING
LAYERS
Learning
algorithm
(Neural
Network,
SVM…)
morphologies

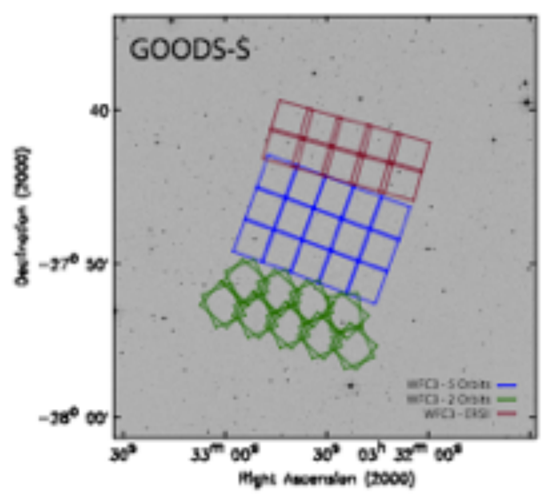
CANDELS survey

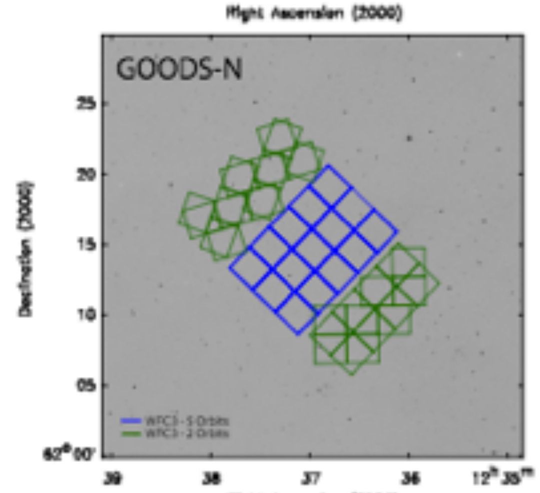
[PI - Faber/Ferguson]







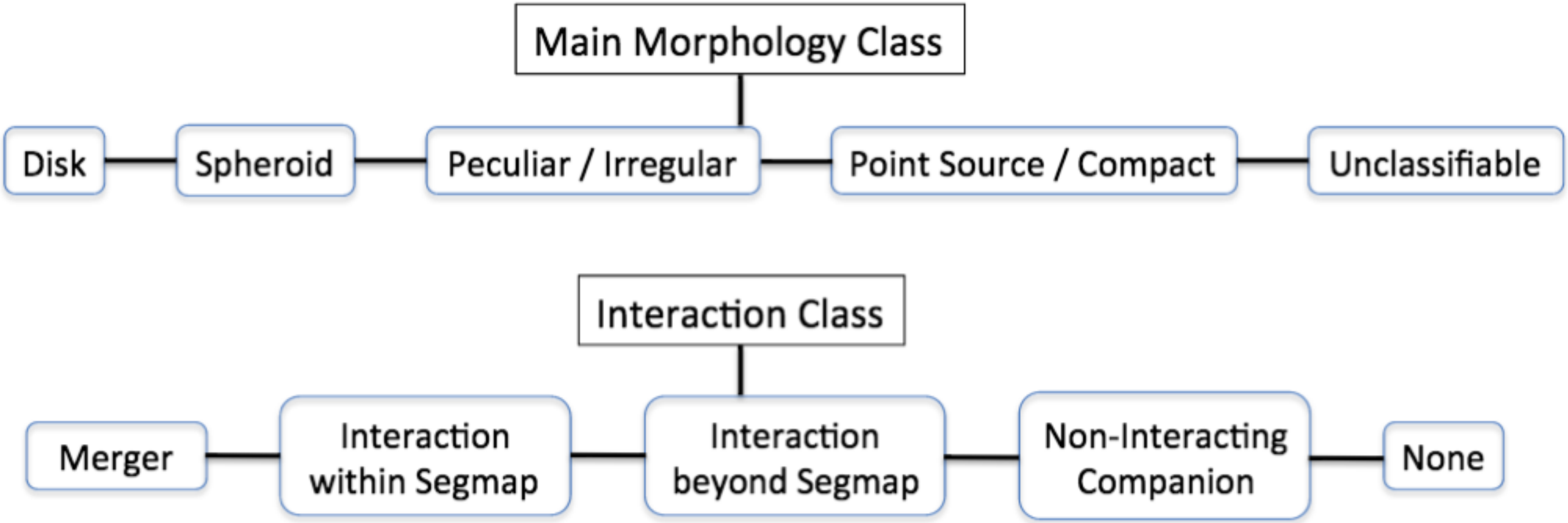




HST NIR survey of 4 cosmological fields

Rest-frame optical high-resolution morphologies at $1<z<3$

CANDELS visual classification tree



Kartaltepe+15

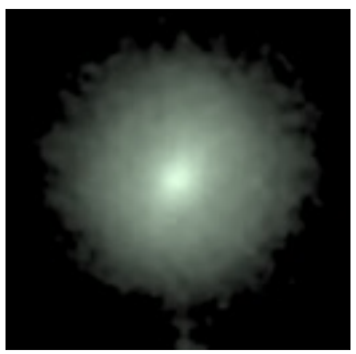
— Classification of galaxies in GOODS-S with **H<24.5**
— Each galaxy is classified by 3-5 experts
— Fractions for ~8000 galaxy in GDS
— Classification done in F160 (+F125,F105)

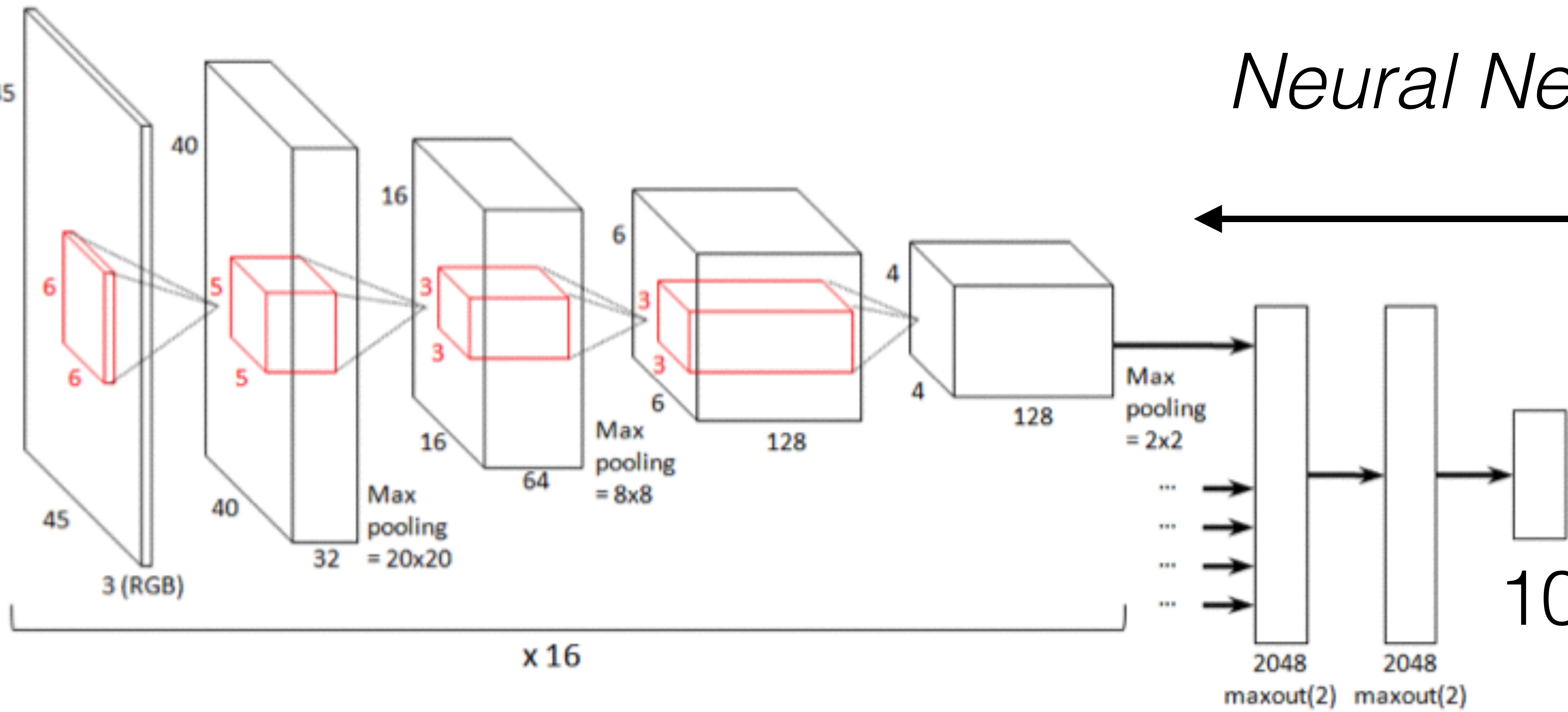
CONVNET for CANDELS

- **TRAIN**: ~50.000 redundant galaxies in GDS (~10 days)
- **CLASSIFY**: GDN, COSMOS, UDS, GDS, EGS (~8h/field)

Feature learning

Neural Network

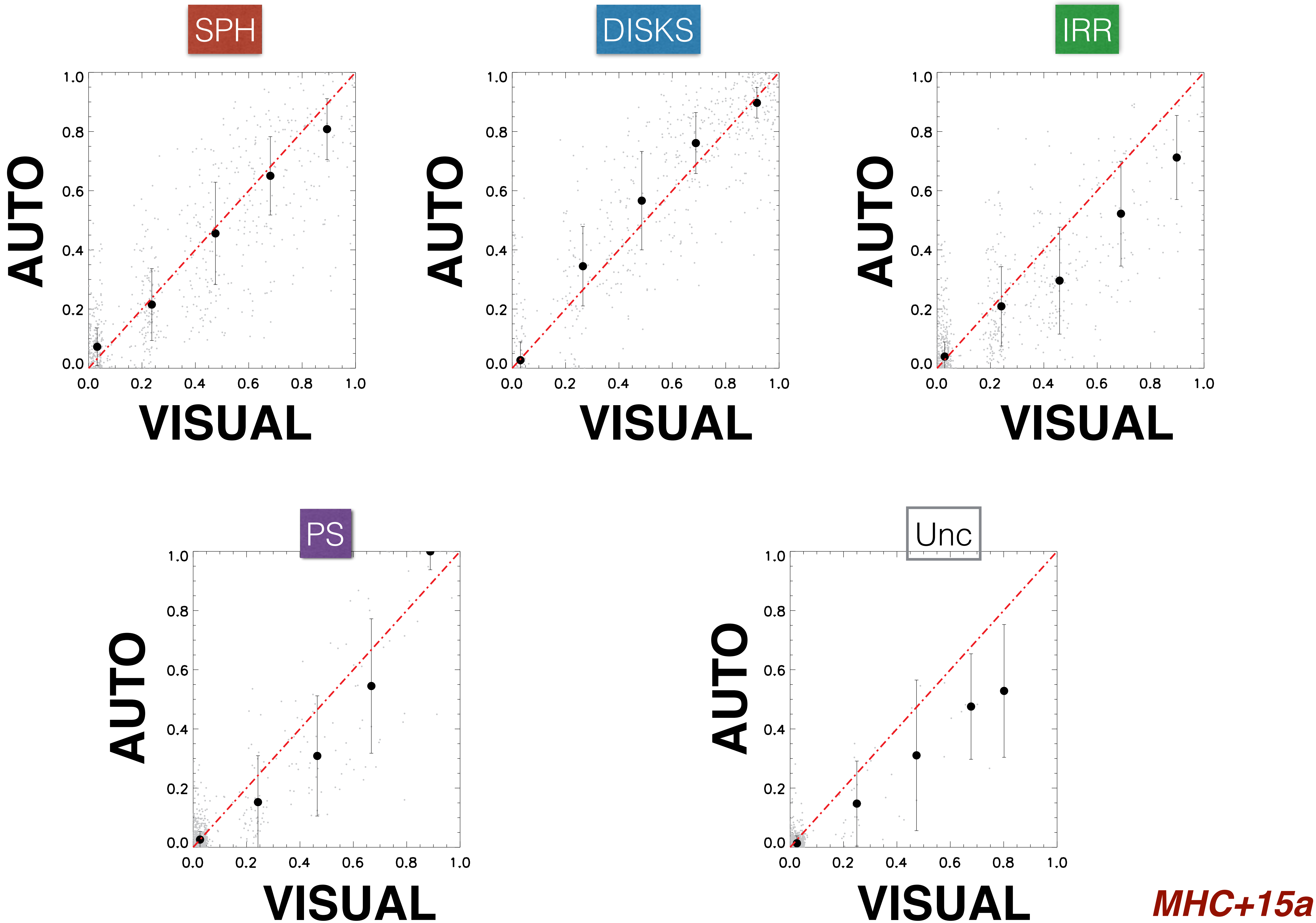




Dielman+14, MHC+15a

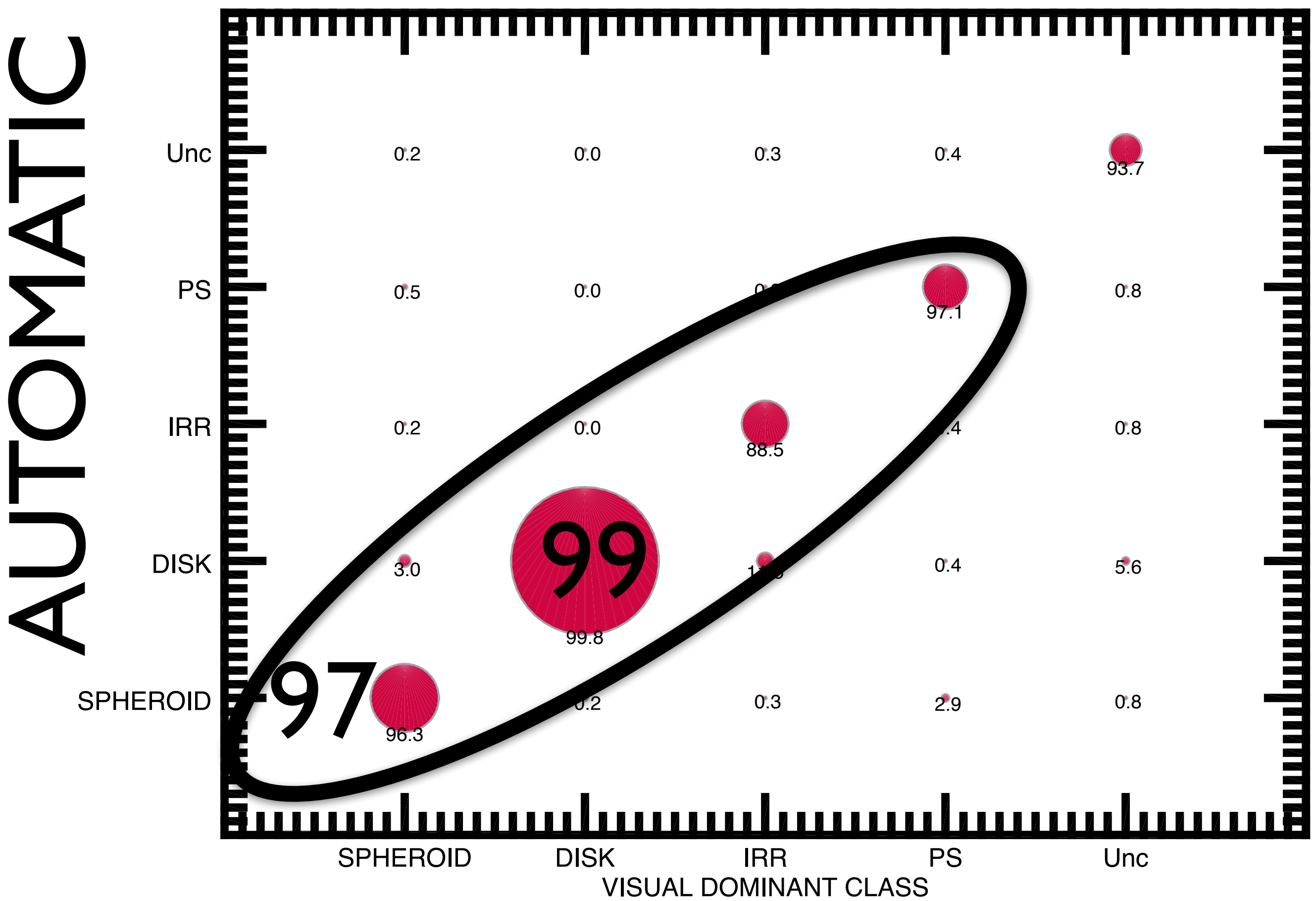
***INPUT**: RGB JPEG GDS snapshots*

***OUTPUT**: 10 probs.*



SPH
DISKS
IRR
PS
Unc
AUTO
VISUAL
0.0
0.2
0.4
0.6
0.8
1.0
MHC+15a

DEEP-LEARNING APPLIED TO MORPHOLOGY

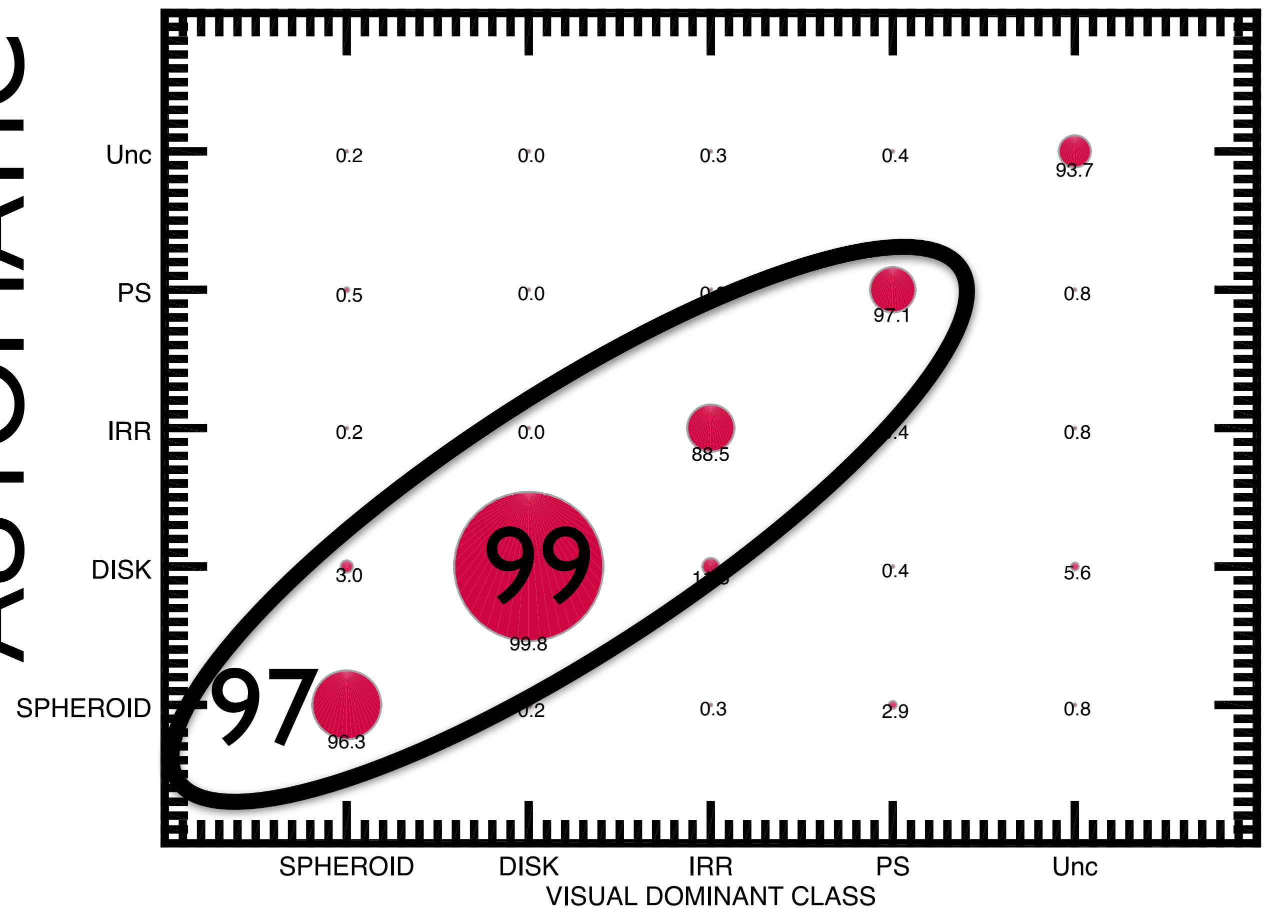


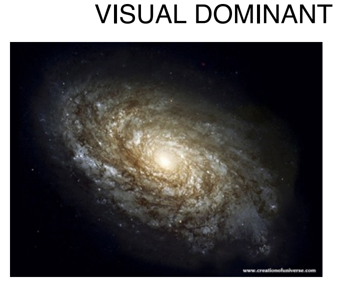
VISUAL

MHC+15b

DEEP-LEARNING APPLIED TO MORPHOLOGY

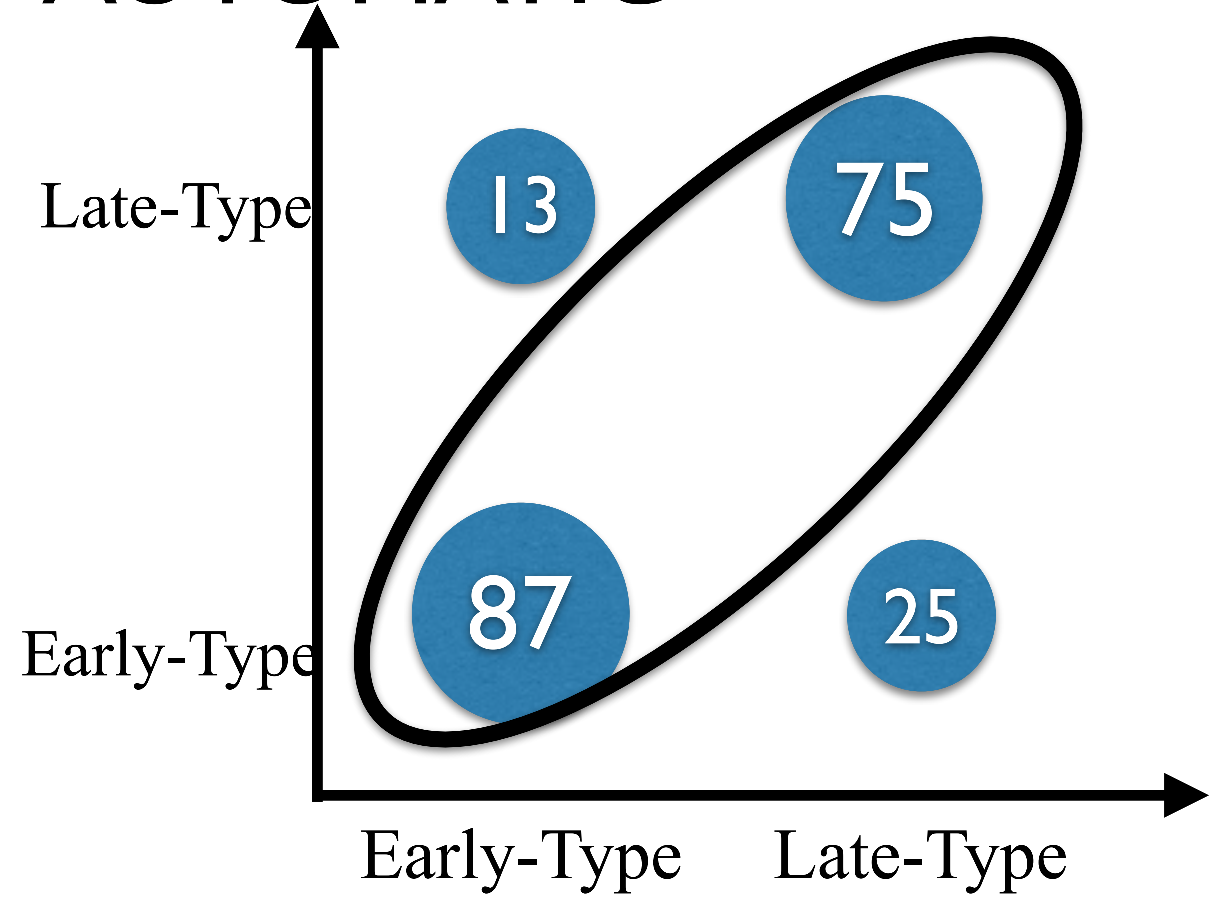
AUTOMATIC





VISUAL

AUTOMATIC



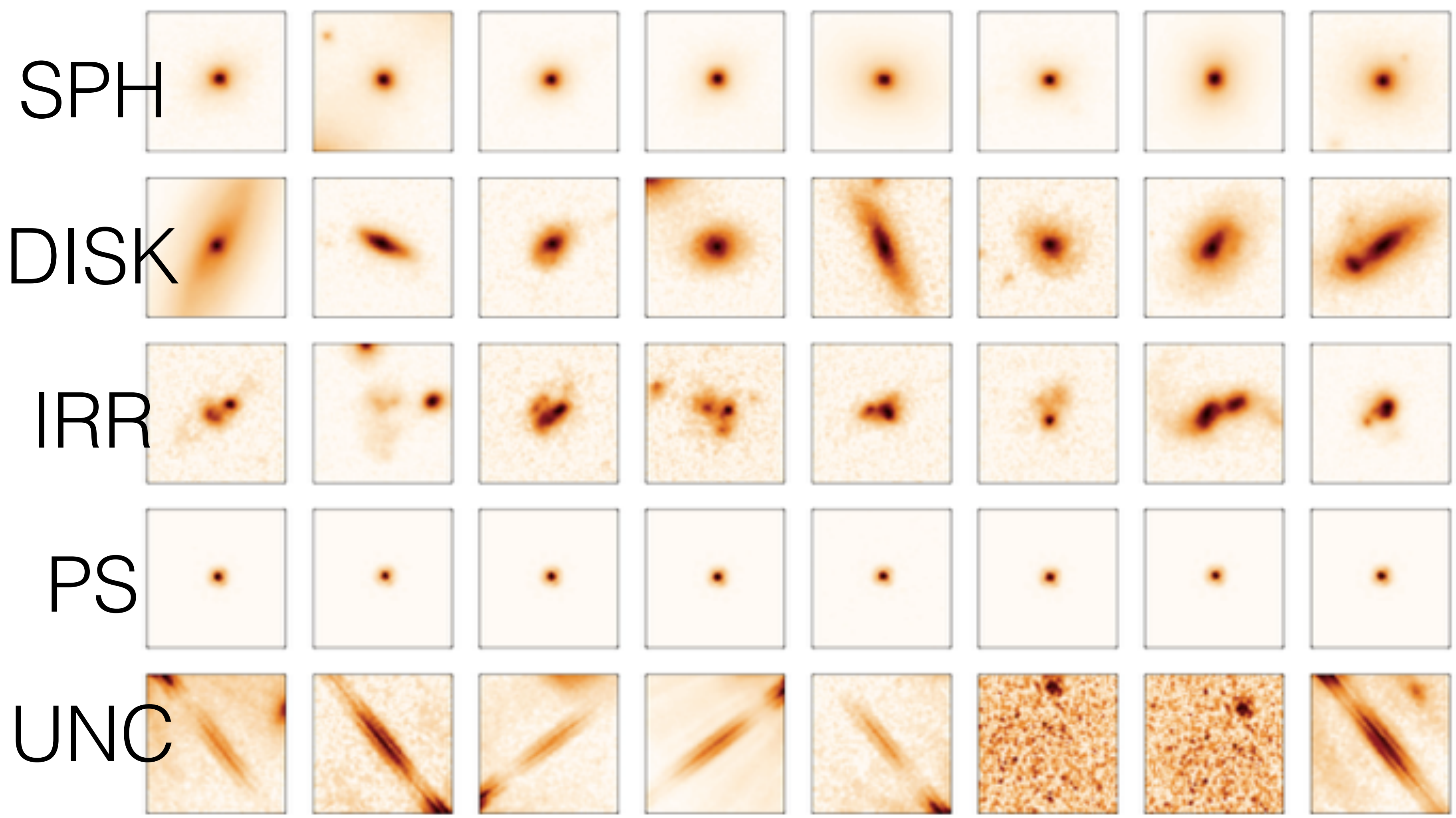
MHC+15b

Public catalog released

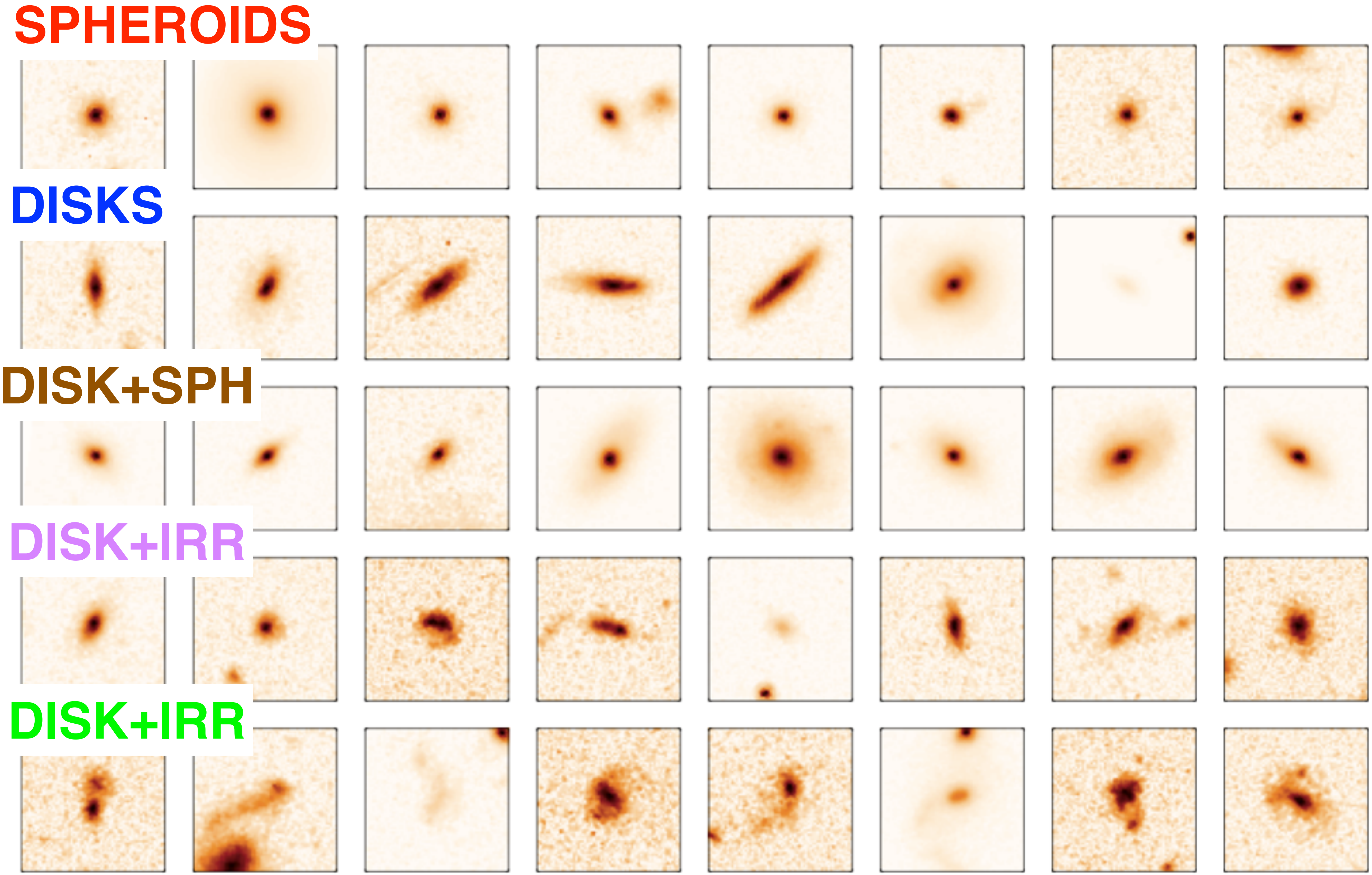
- ~ **50.000** galaxies in **5 CANDELS fields** (GDN, GDS, COSMOS, UDS, EGS)
- 10 probabilities (fractions for each galaxy)
- **H < 24.5**
- **<z>= 1.25**
- Optical rest-frame morphology at 1<z<3
- ~80% complete at Mstar>10^10 Msol @ z~3

Available @
Rainbow Database

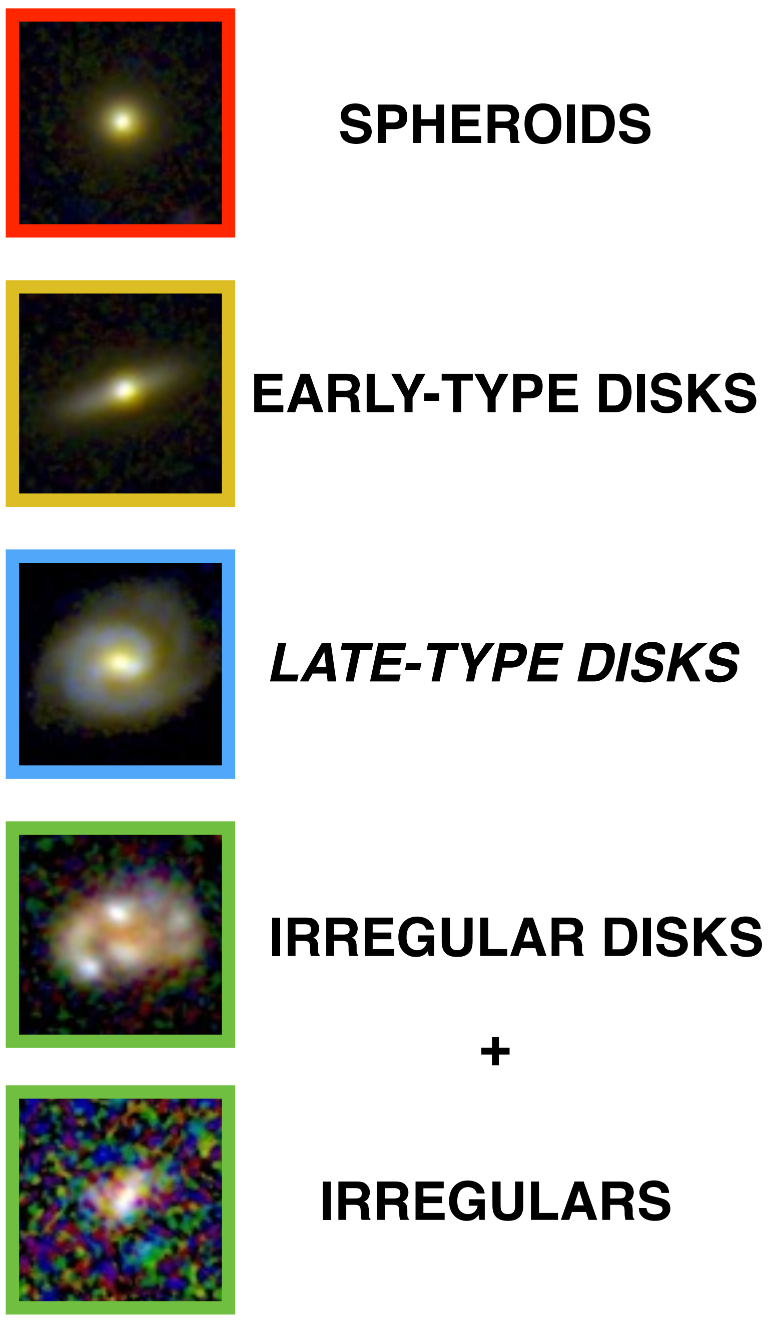
http://rainbowx.fis.ucm.es/Rainbow_navigator_public/

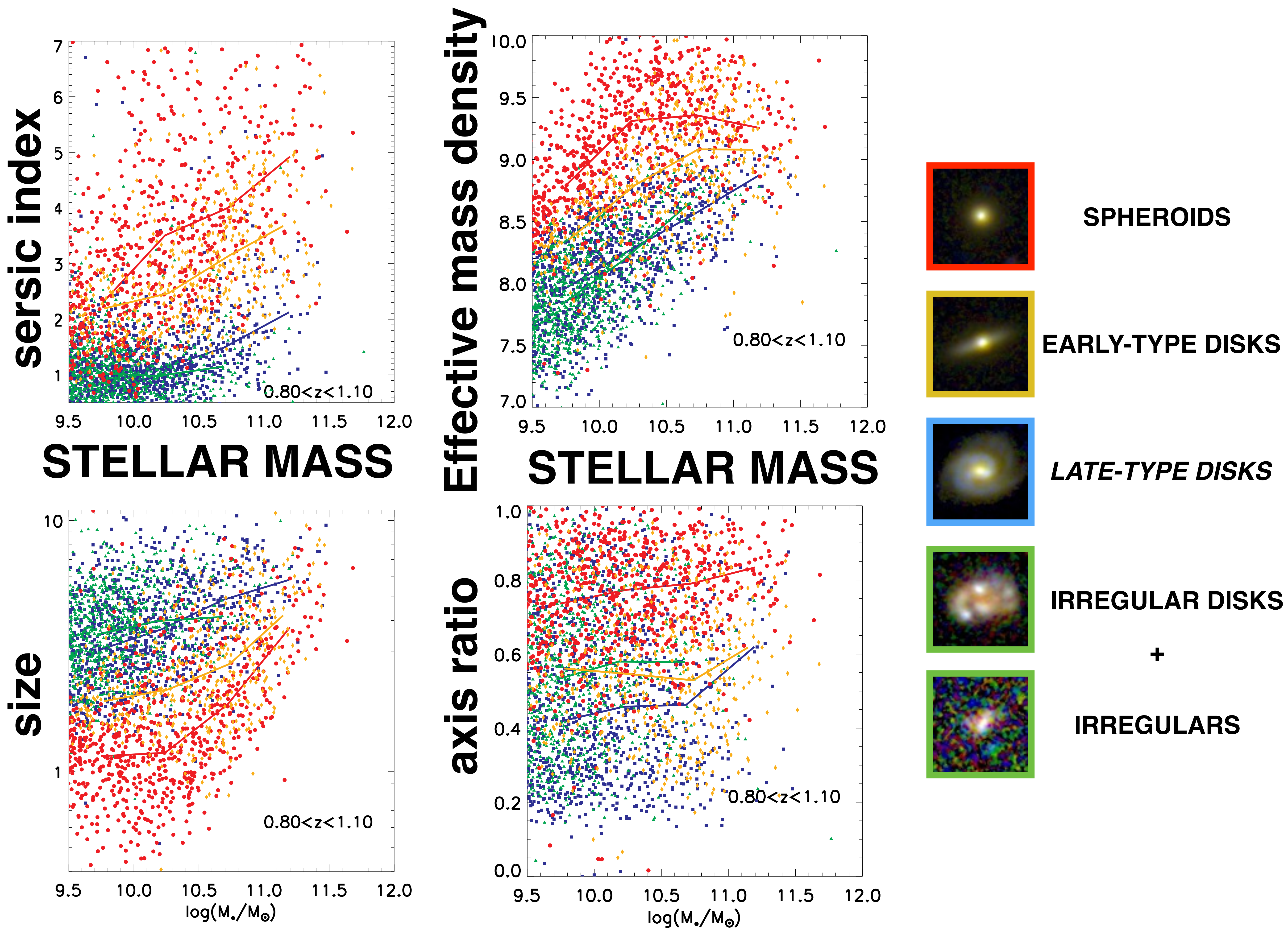


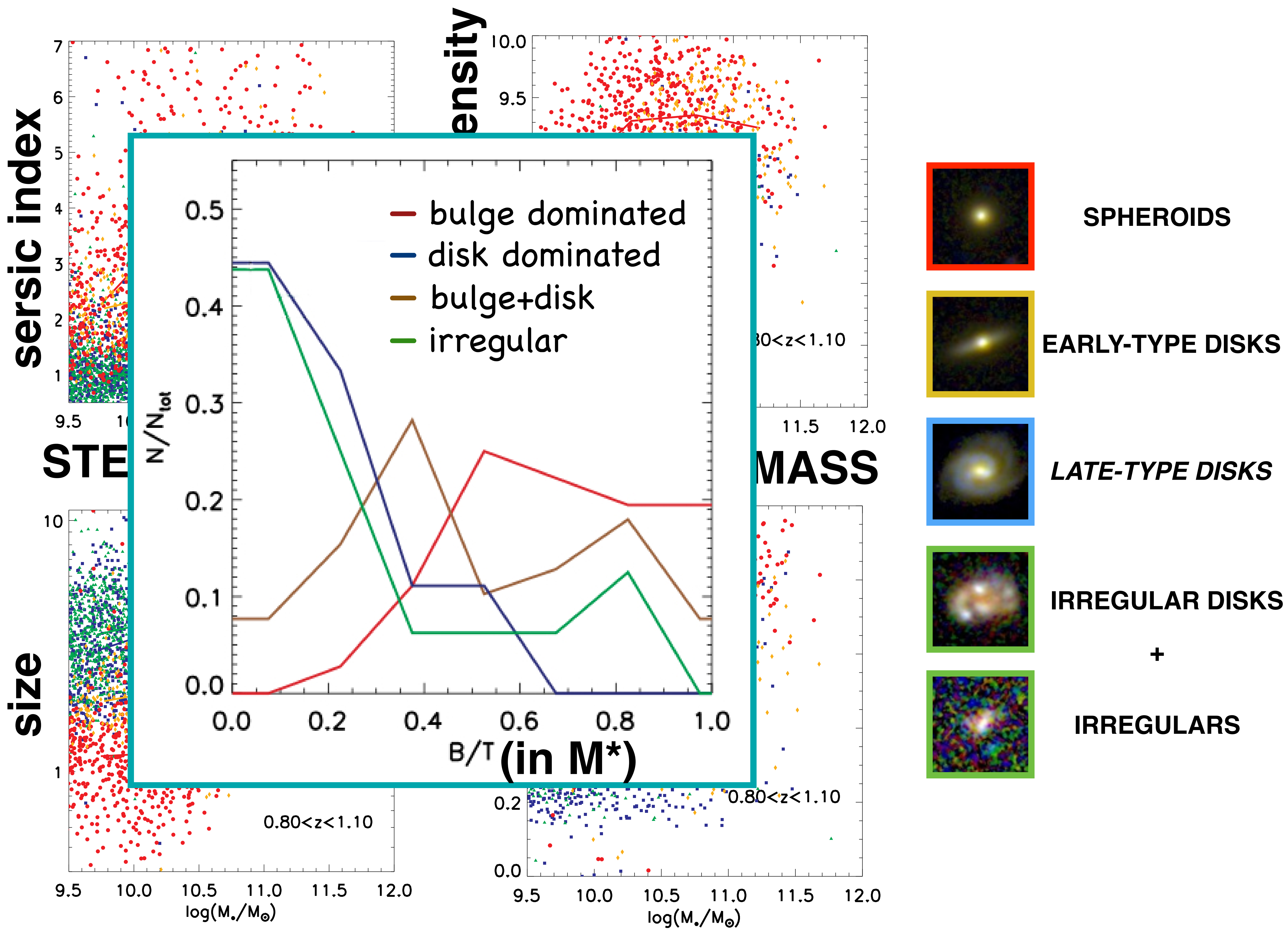
MHC+15b



SPHEROIDS
DISKS
DISK+SPH
DISK+IRR
DISK+IRR

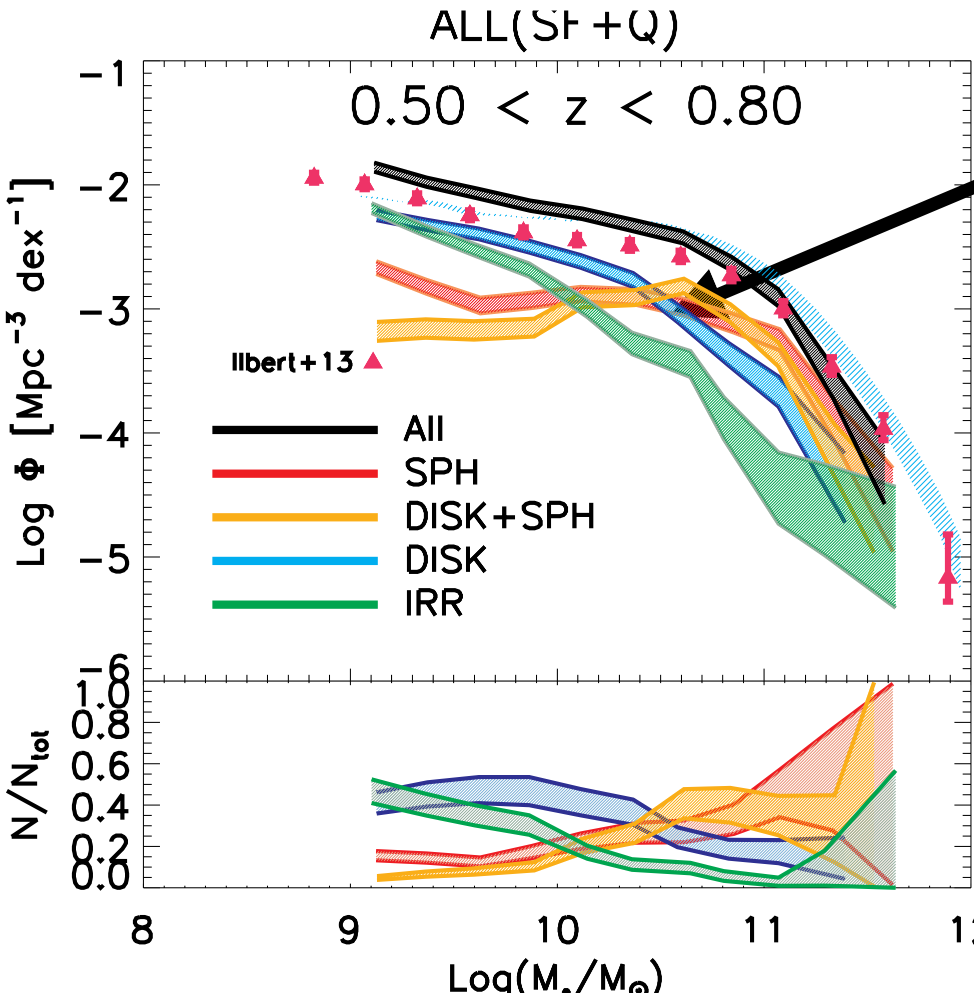

SPHEROIDS
EARLY-TYPE DISKS
LATE-TYPE DISKS
IRREGULAR DISKS
+
IRREGULARS

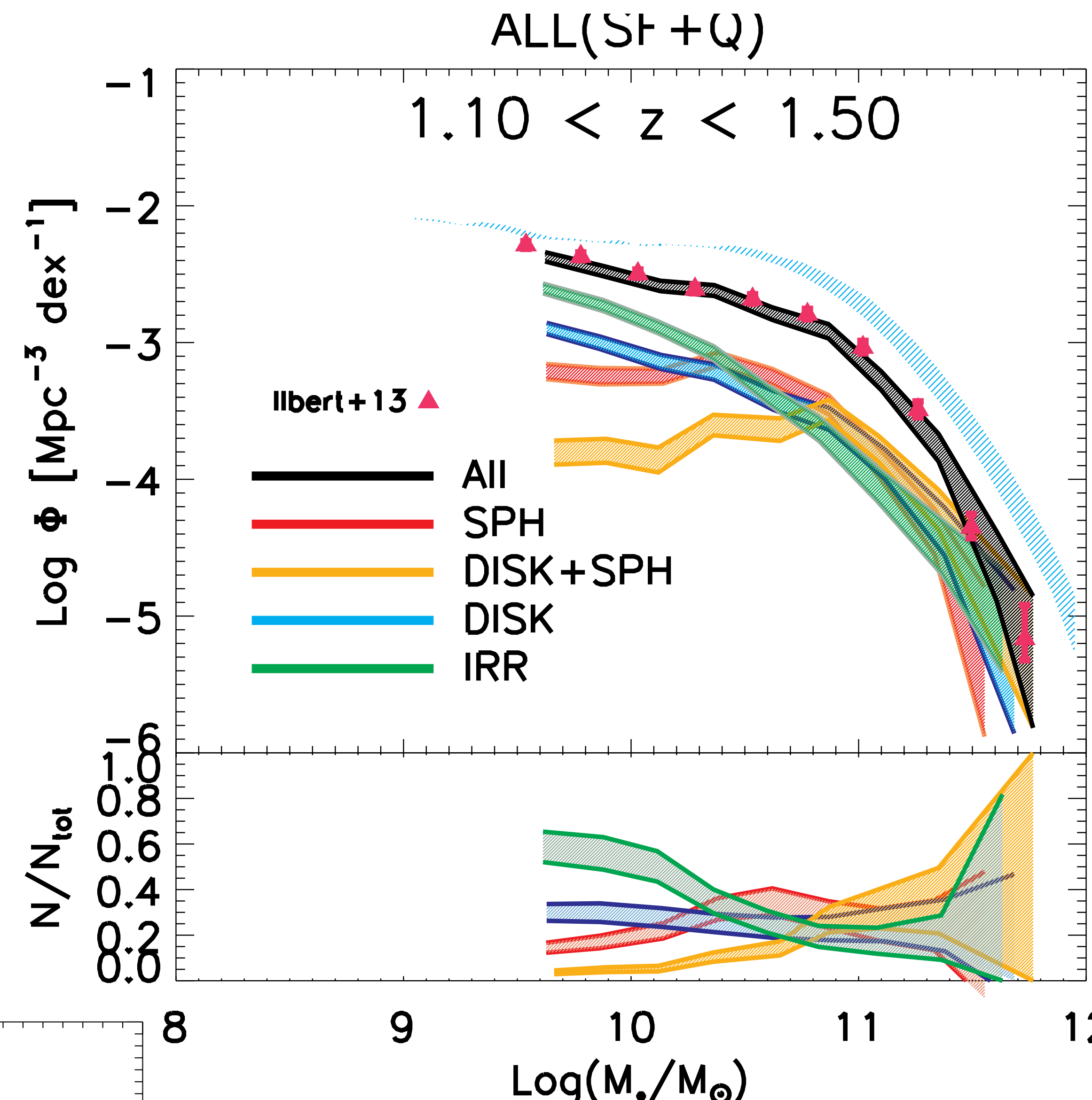

sersic index
STELLAR MASS
0.80<z<1.10
Effective mass density
STELLAR MASS
0.80<z<1.10
size
log(M*/M⊙)
0.80<z<1.10
axis ratio
log(M*/M⊙)
0.80<z<1.10
SPHEROIDS
EARLY-TYPE DISKS
LATE-TYPE DISKS
IRREGULAR DISKS
+
IRREGULARS

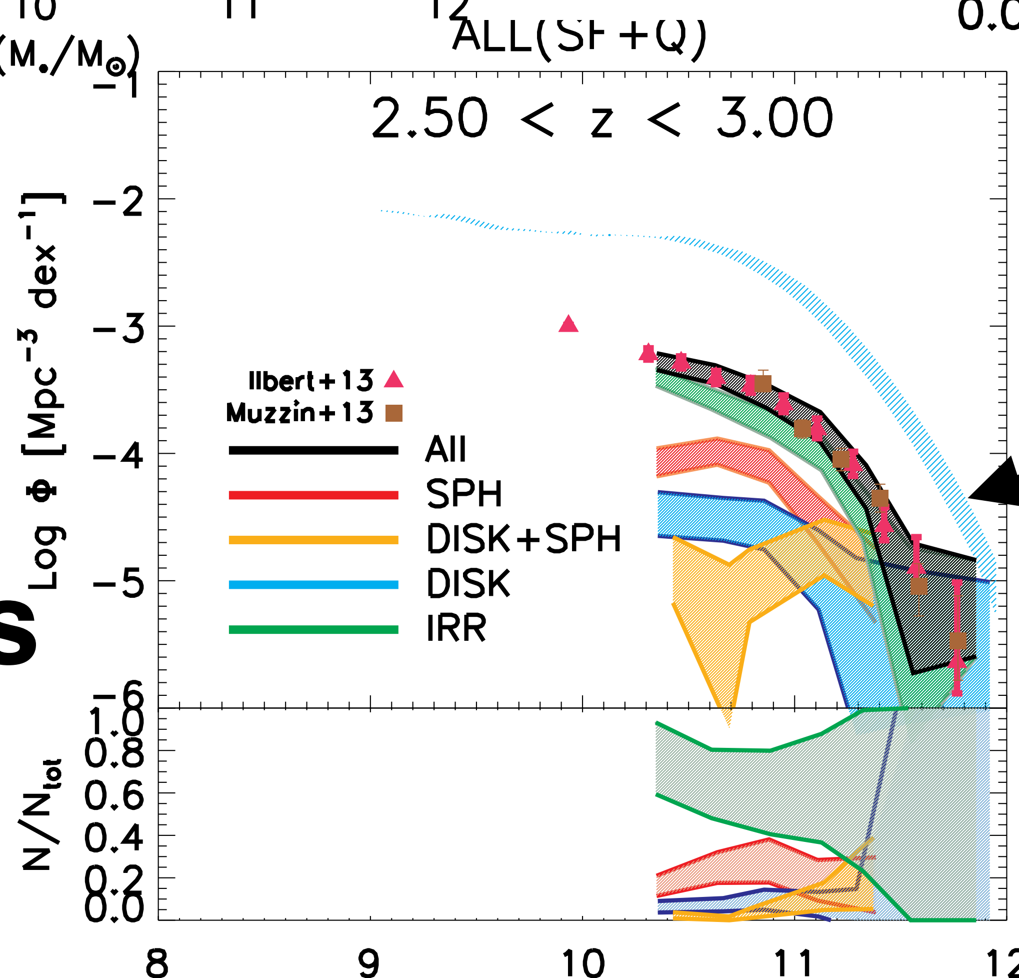

sersic index
ensity
STE
MASS
size
bulge dominated
disk dominated
bulge+disk
irregular
N/N_tot
B/T (in M*)
0.80<z<1.10
log(M*/M⊙)
SPHEROIDS
EARLY-TYPE DISKS
LATE-TYPE DISKS
IRREGULAR DISKS
+
IRREGULARS

Let’s do some science!

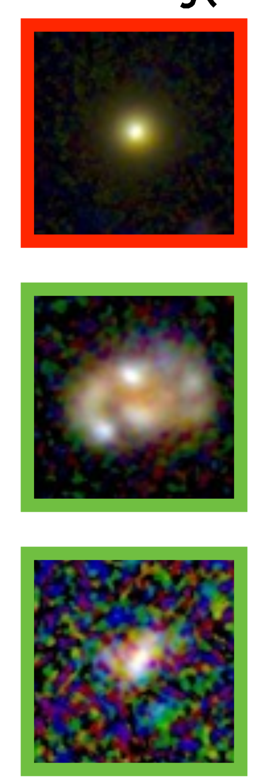
ALL





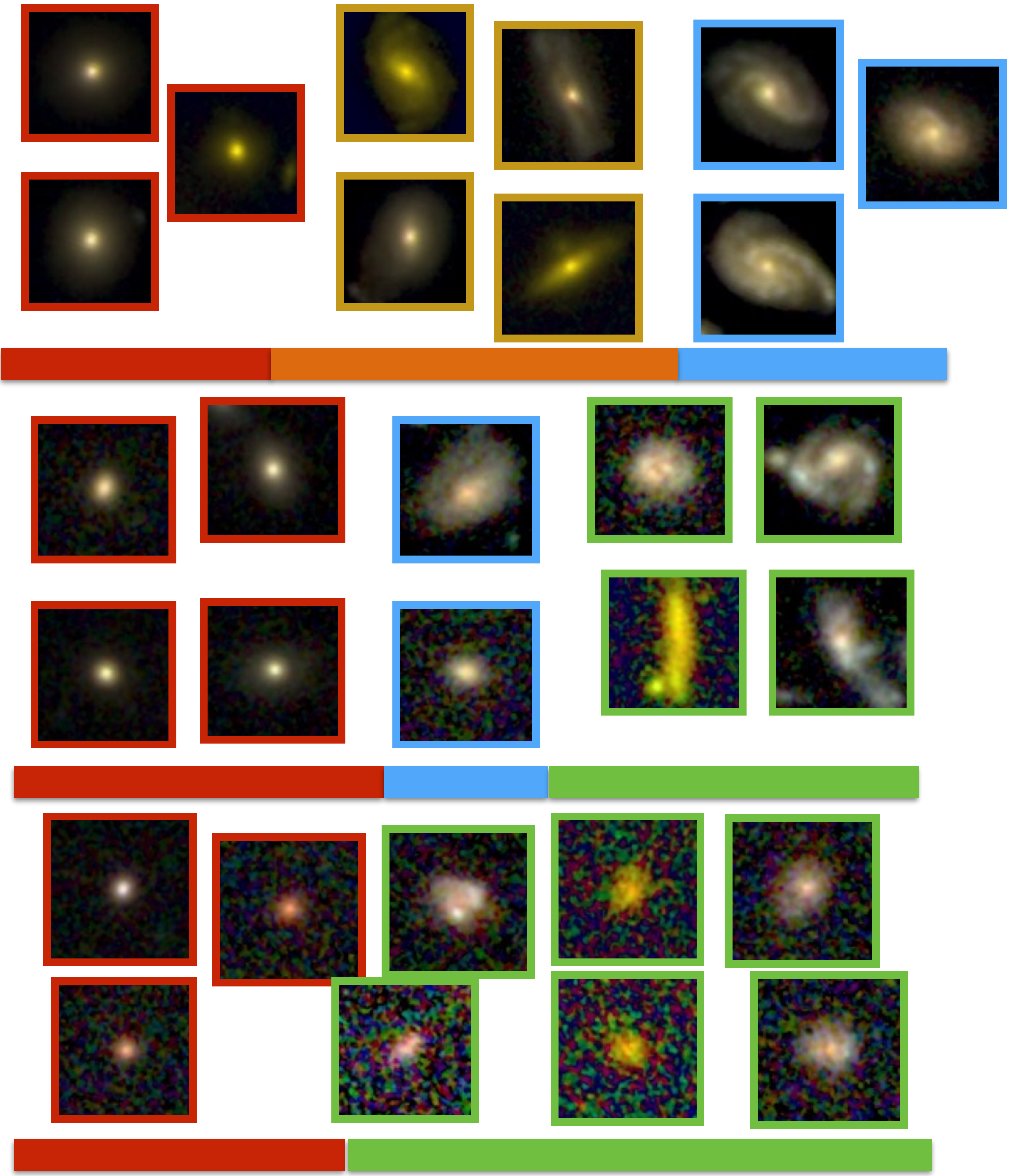


Mass Functions

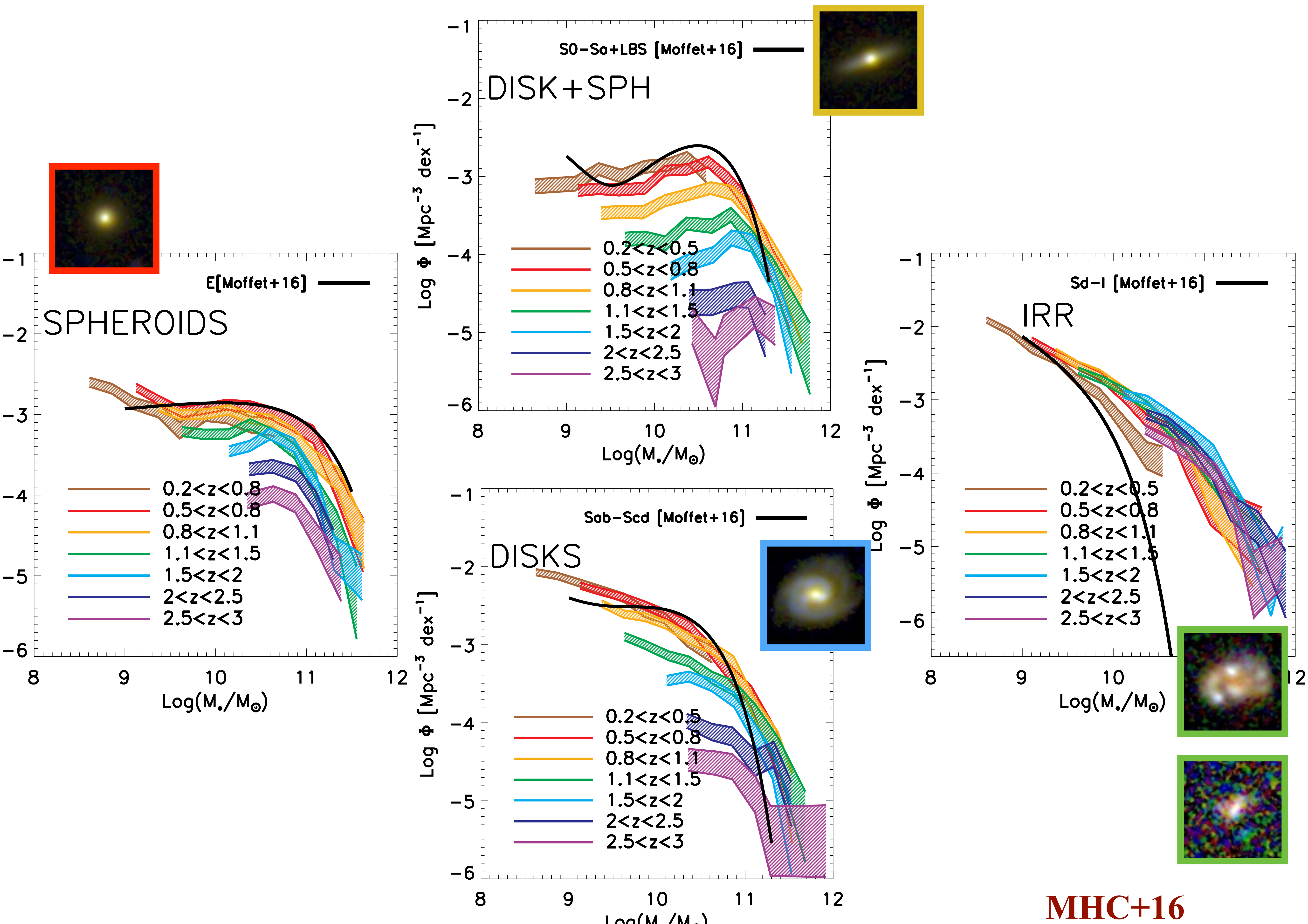


MHC+16

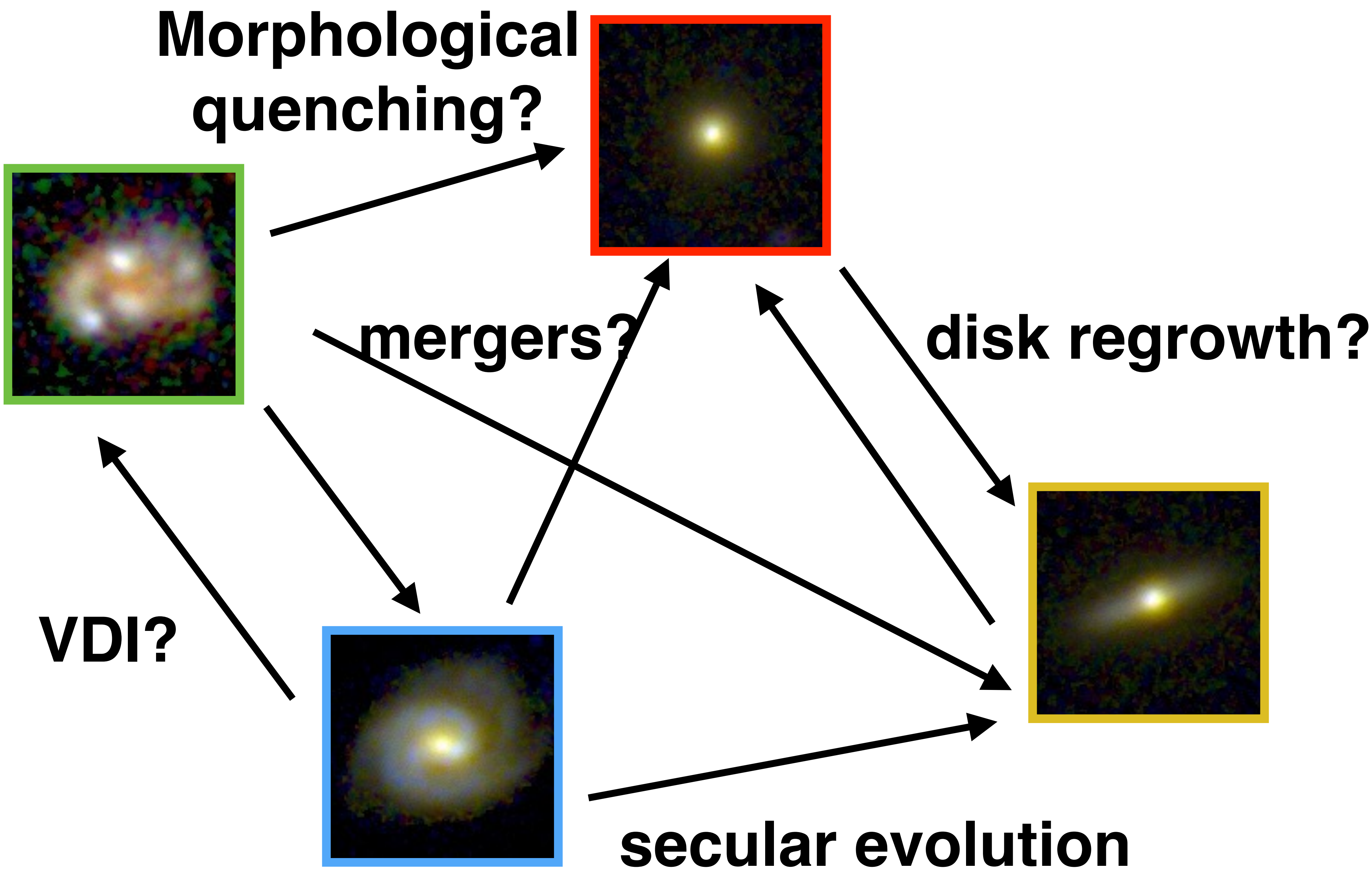
~M* galaxies



MHC+16

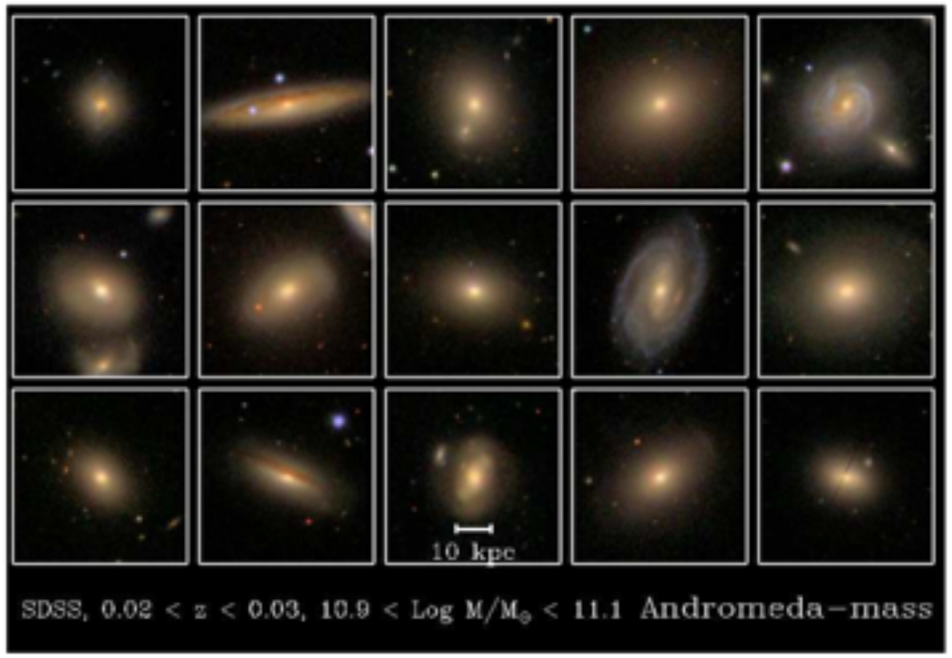

SPHEROIDS
E[Moffet+16]
0.2<z<0.8
0.5<z<0.8
0.8<z<1.1
1.1<z<1.5
1.5<z<2
2<z<2.5
2.5<z<3
DISK+SPH
S0−Sa+LBS [Moffet+16]
0.2<z<0.5
0.5<z<0.8
0.8<z<1.1
1.1<z<1.5
1.5<z<2
2<z<2.5
2.5<z<3
DISKS
Sab−Scd [Moffet+16]
0.2<z<0.5
0.5<z<0.8
0.8<z<1.1
1.1<z<1.5
1.5<z<2
2<z<2.5
2.5<z<3
IRR
Sd−I [Moffet+16]
0.2<z<0.5
0.5<z<0.8
0.8<z<1.1
1.1<z<1.5
1.5<z<2
2<z<2.5
2.5<z<3
Log Φ [Mpc^{-3} dex^{-1}]
Log(M$_*$/M$_\odot$)
MHC+16

The challenges of interpreting these trends…



How to find the progenitors of z=0 galaxies?

z=0

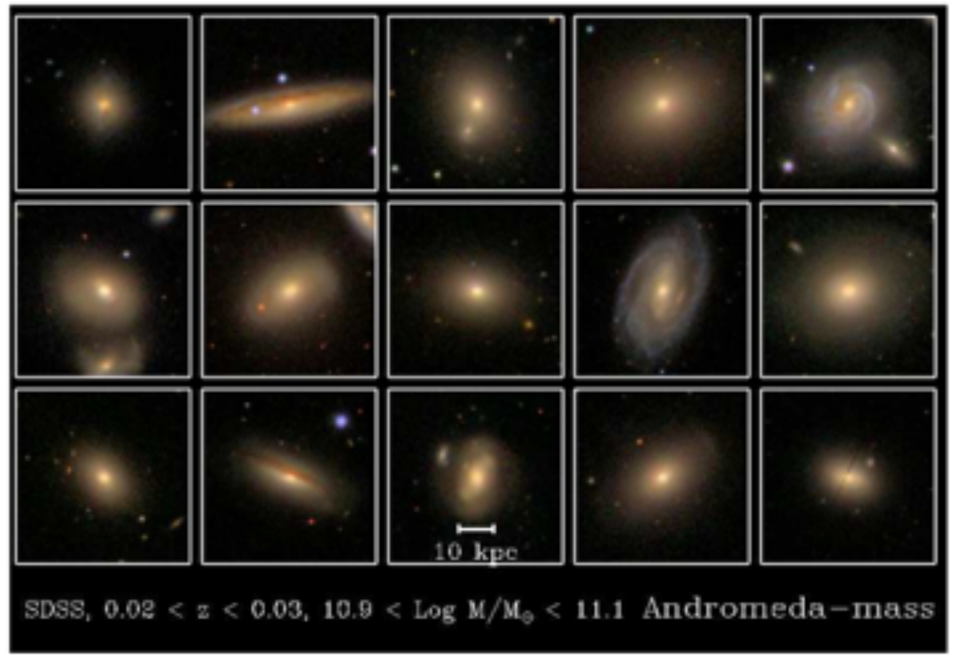


Papovich+15

See Mundy+15

How to find the progenitors of z=0 galaxies?

z=0



Papovich+15

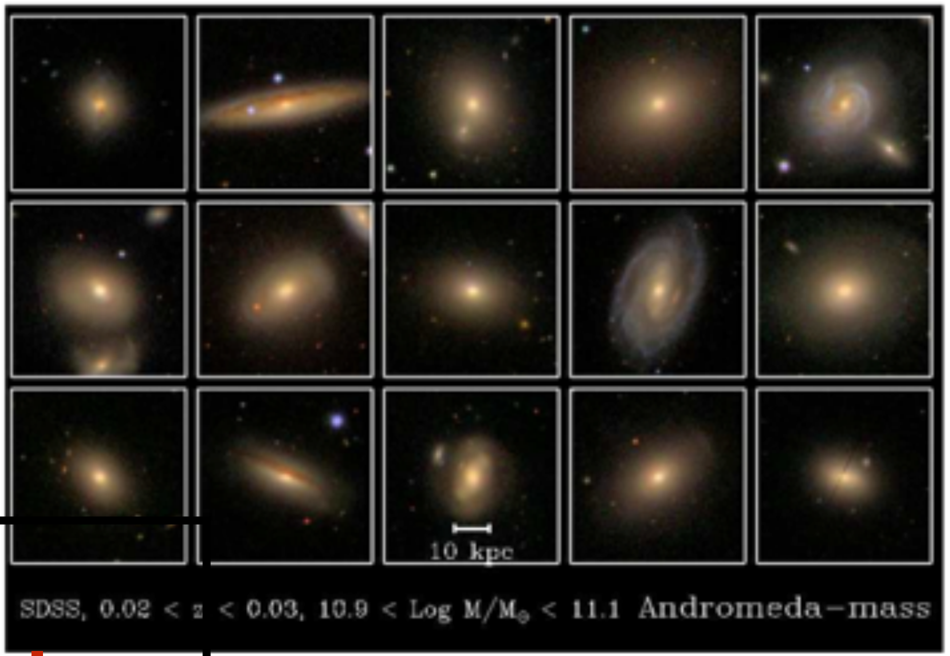
z~3

?

See Mundy+15

How to find the progenitors of z=0 galaxies?

z=0



Papovich+15

Quenching
(feedback, passive evol., cold flows…)

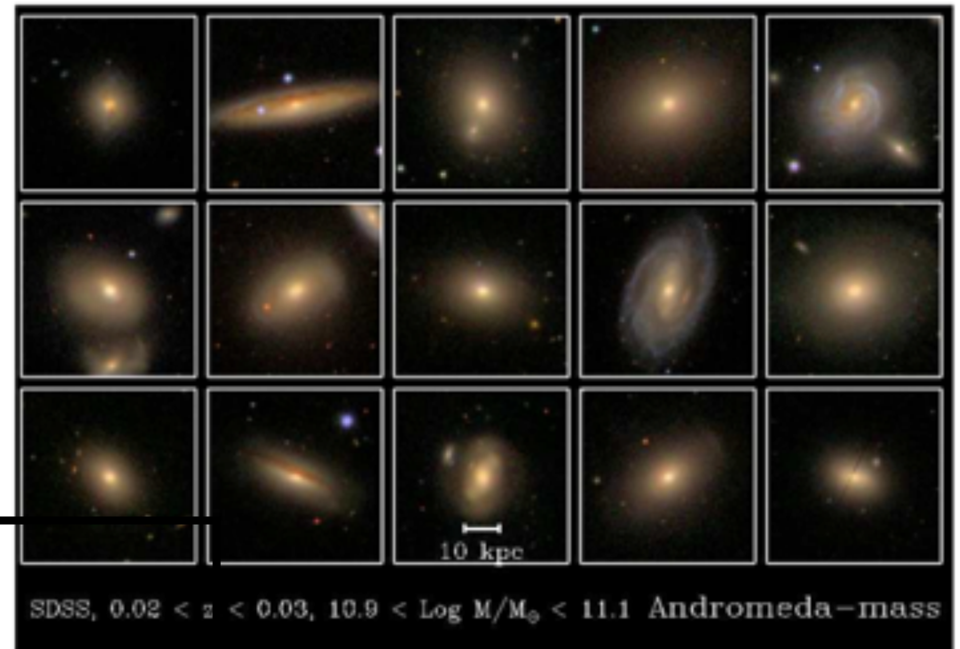
z~3

?

See Mundy+15

How to find the progenitors of z=0 galaxies?

z=0



Papovich+15

Quenching
(feedback, passive evol., cold flows…)

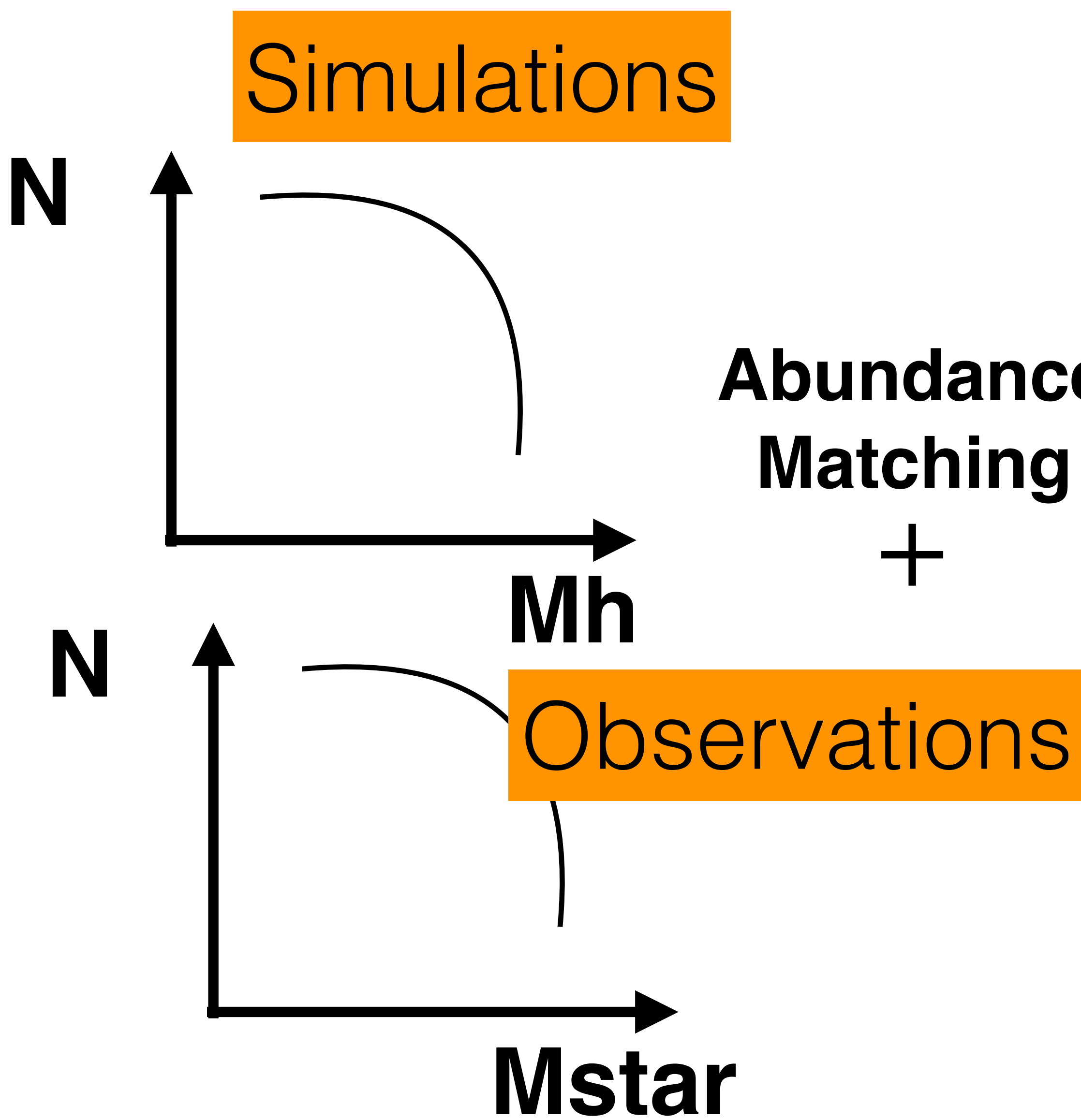
Mass growth
(SF, mergers…)

z~3

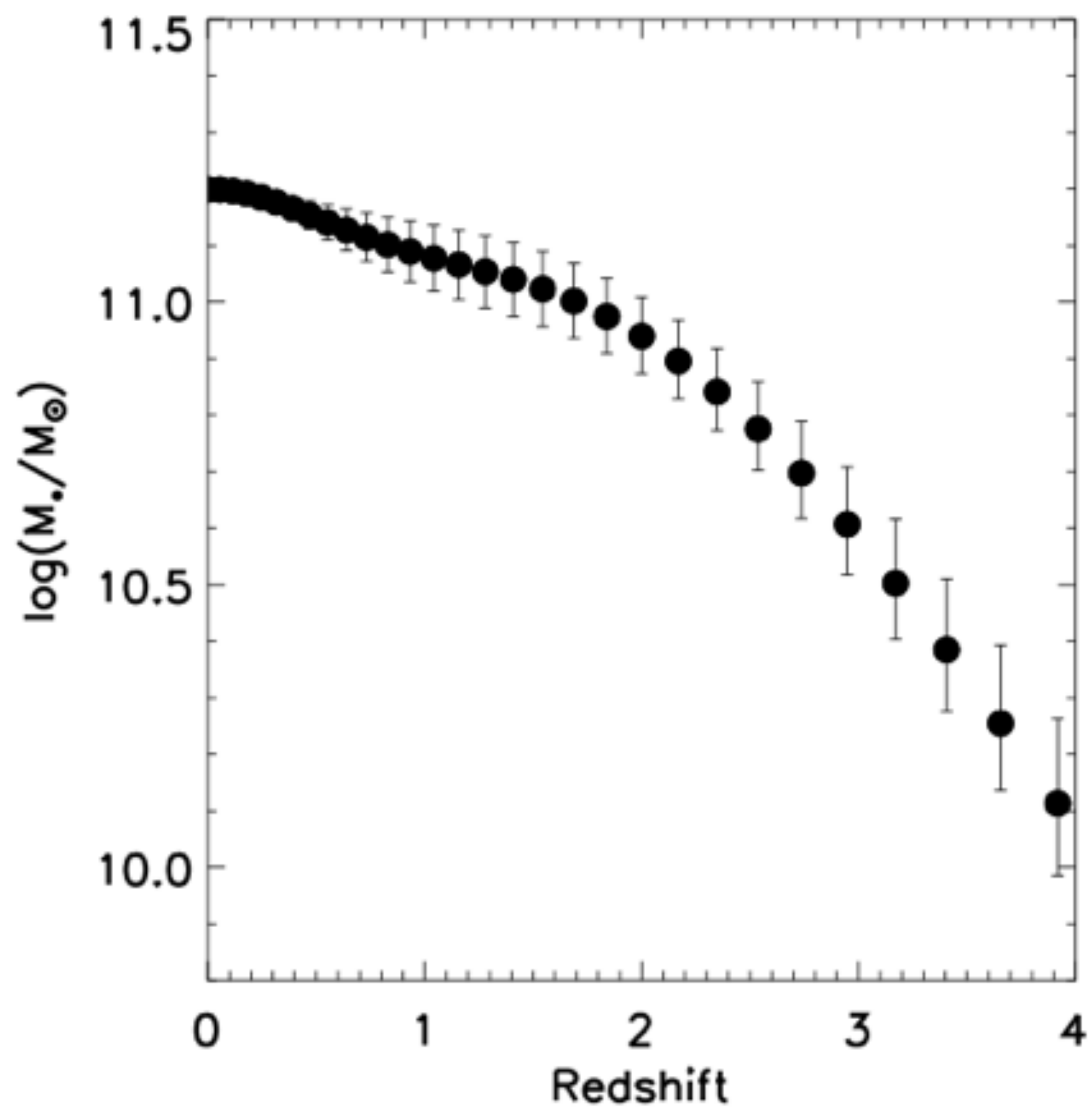
?

See Mundy+15

Following mass growth

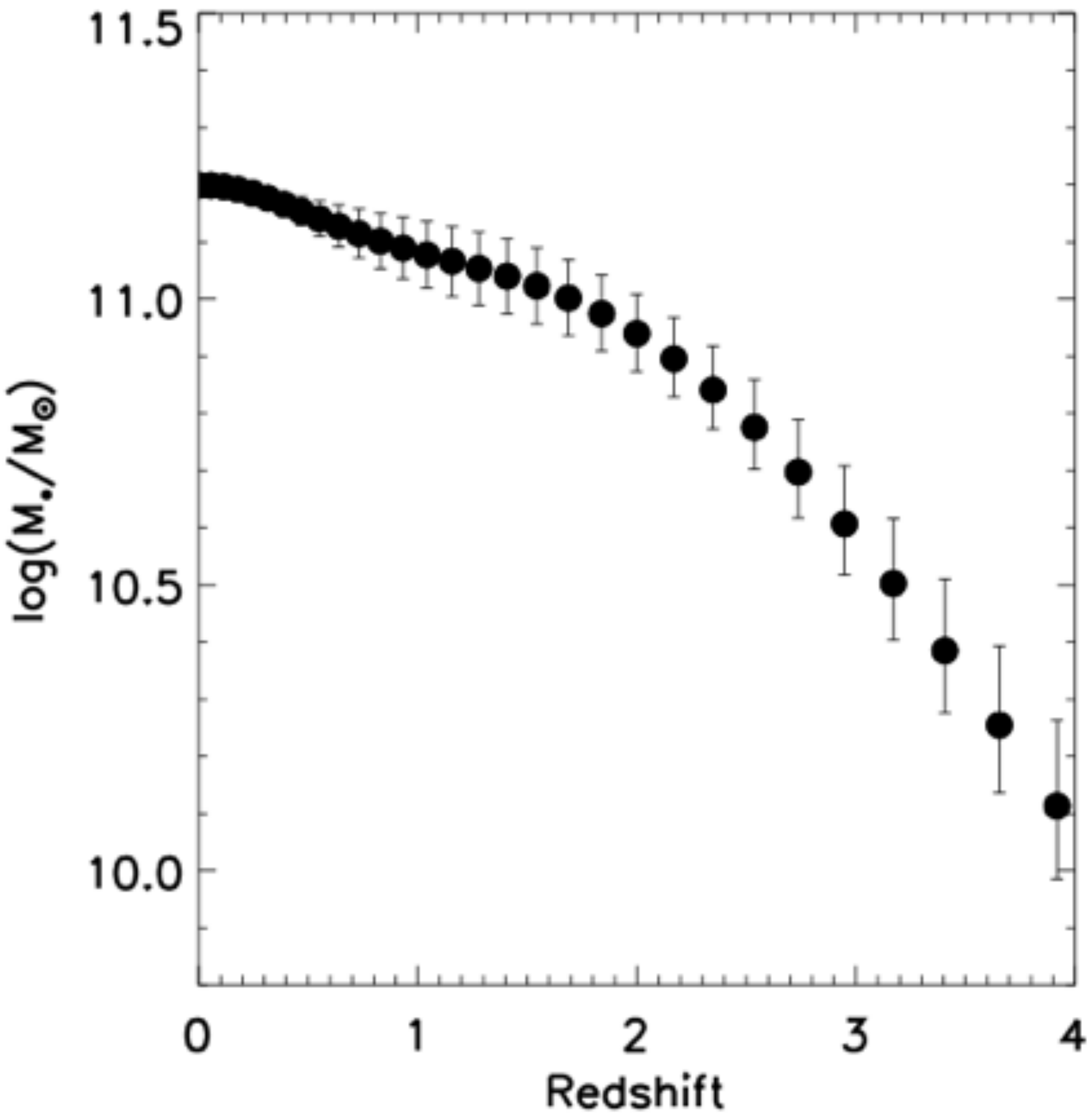


Abundance Matching
+



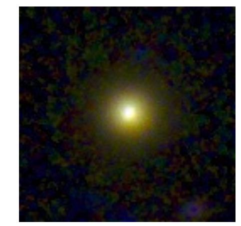
Adapted from Behroozi+13

Selection along the progenitors

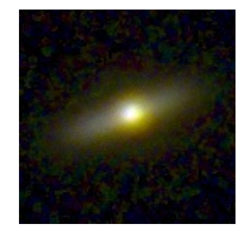


optical rest-frame morphology quantification

+

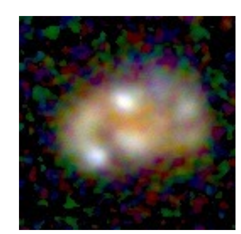


***Pure* SPHEROIDS**

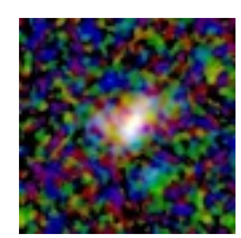


BULGE + DISK

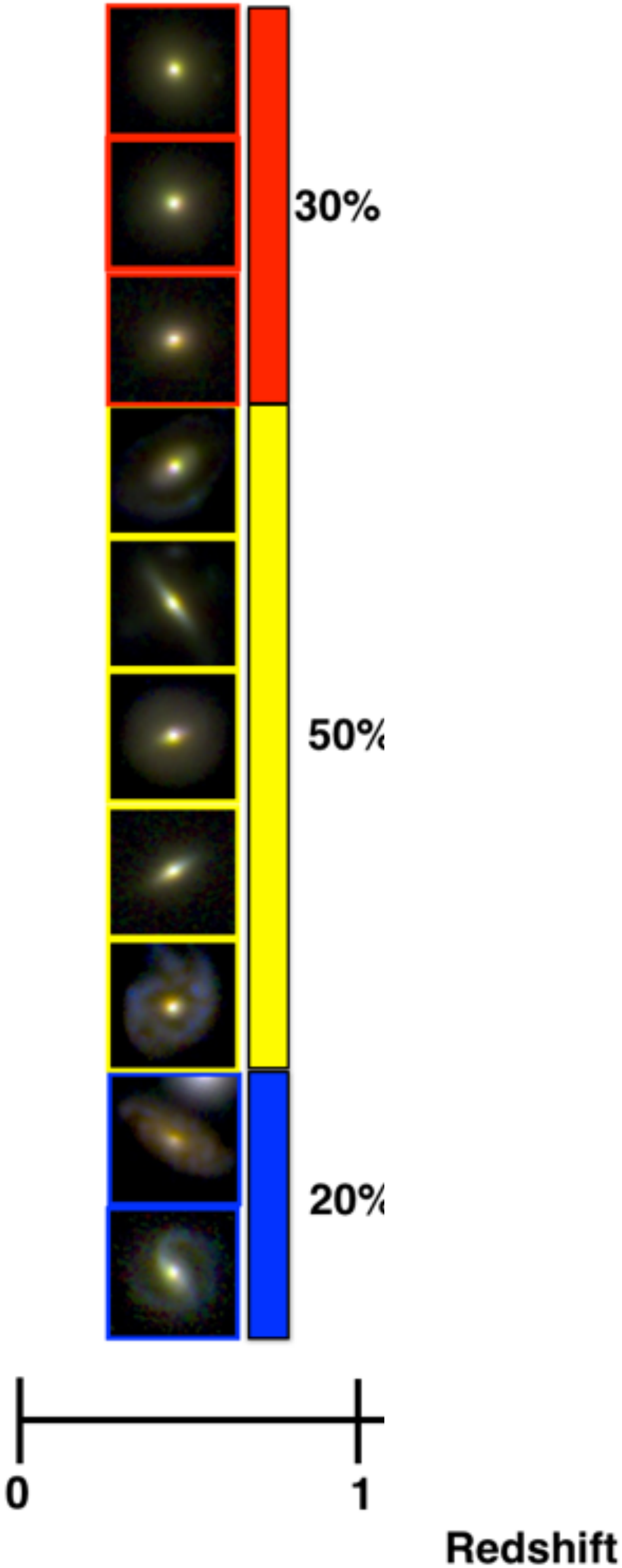
***Regular* DISKS**



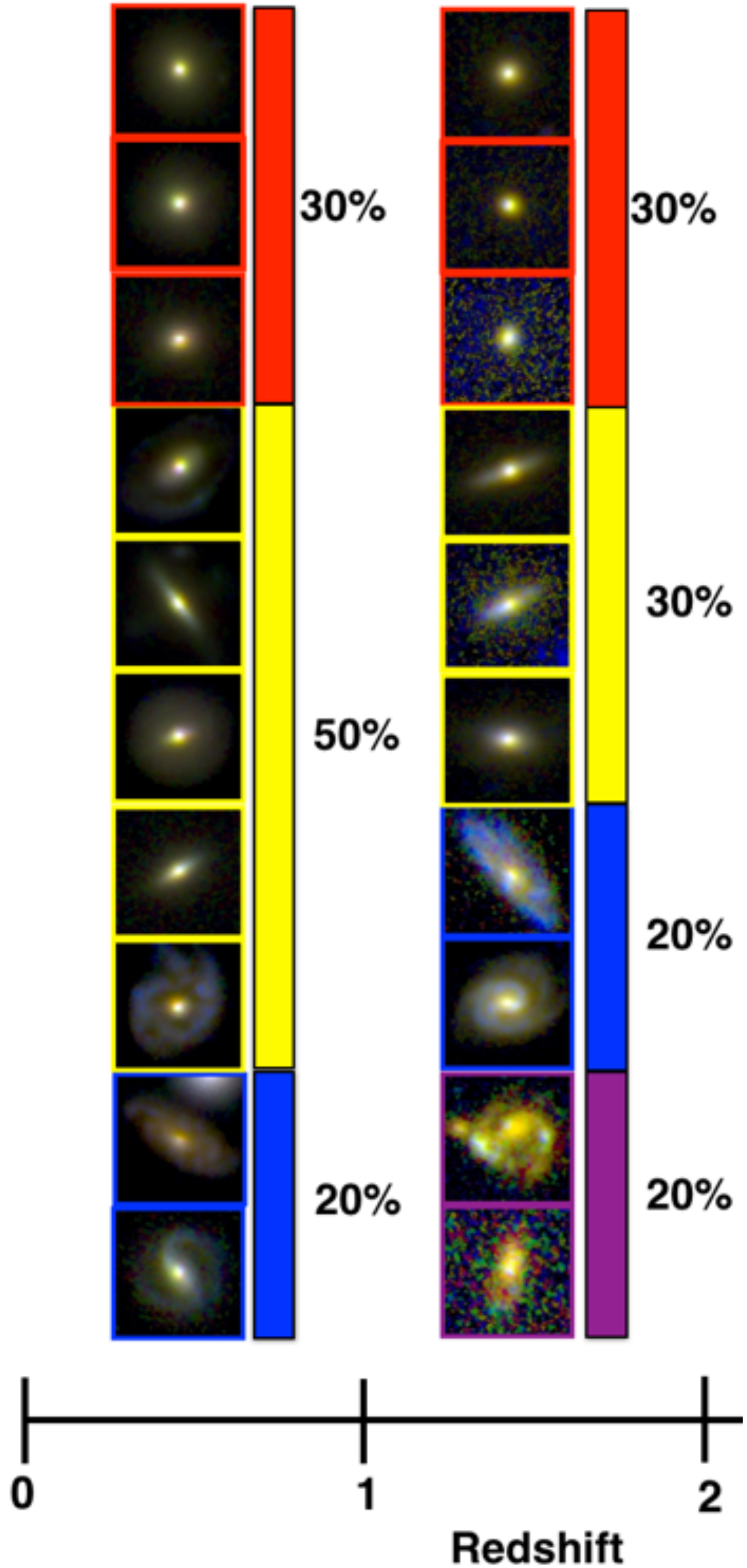
Irr*egular* DISKS



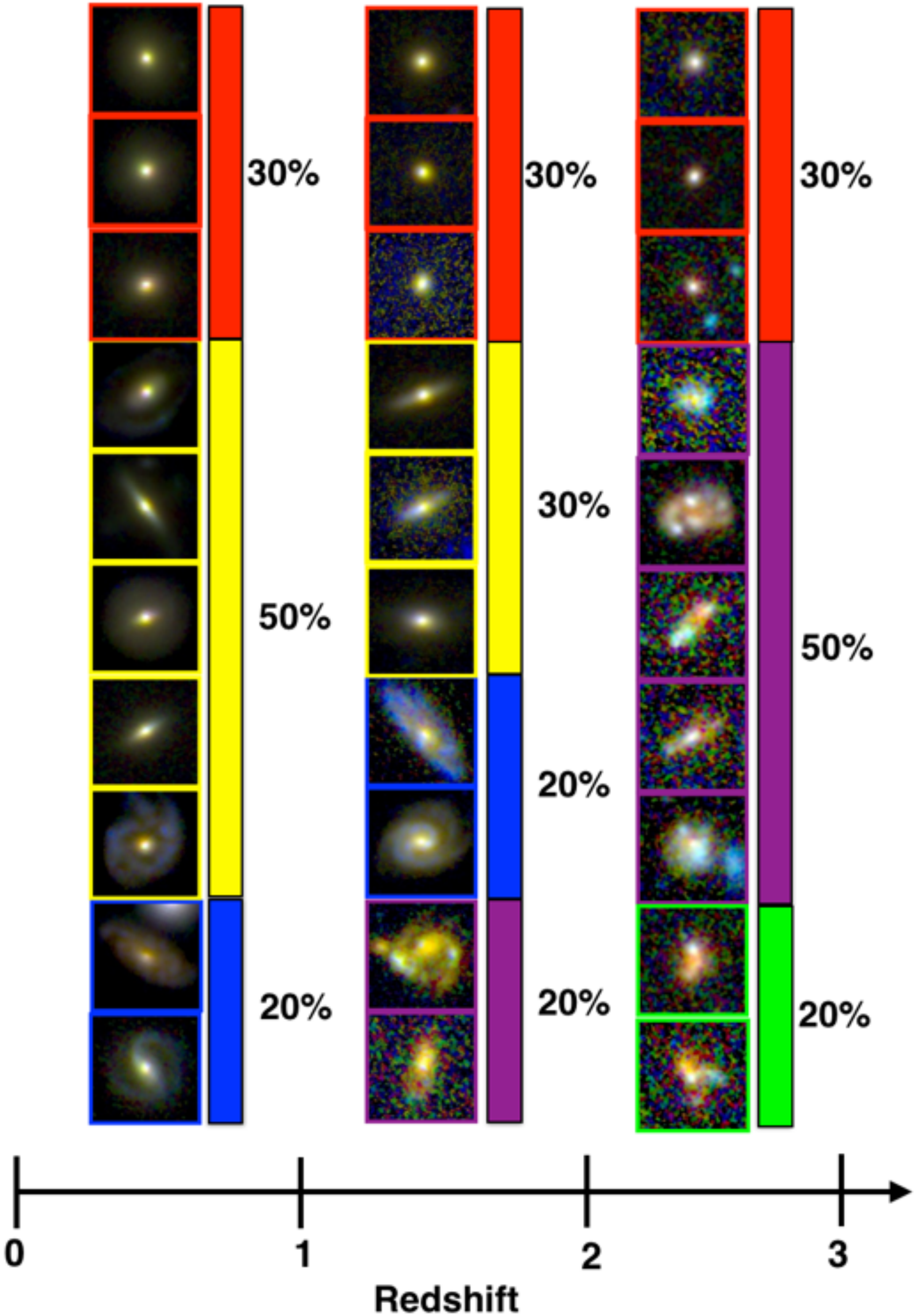
Irr*egulars*



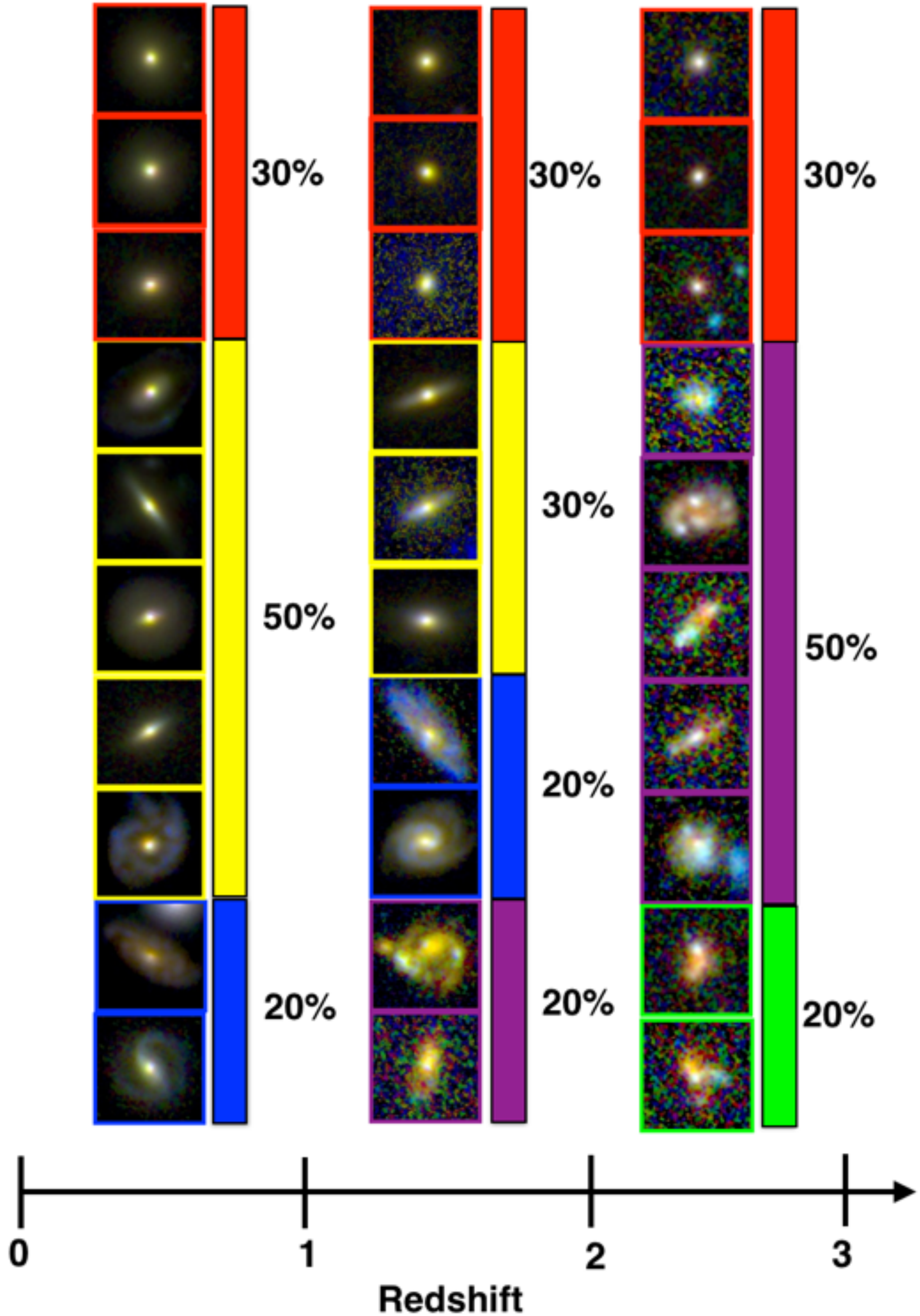
MHC+15b



MHC+15b

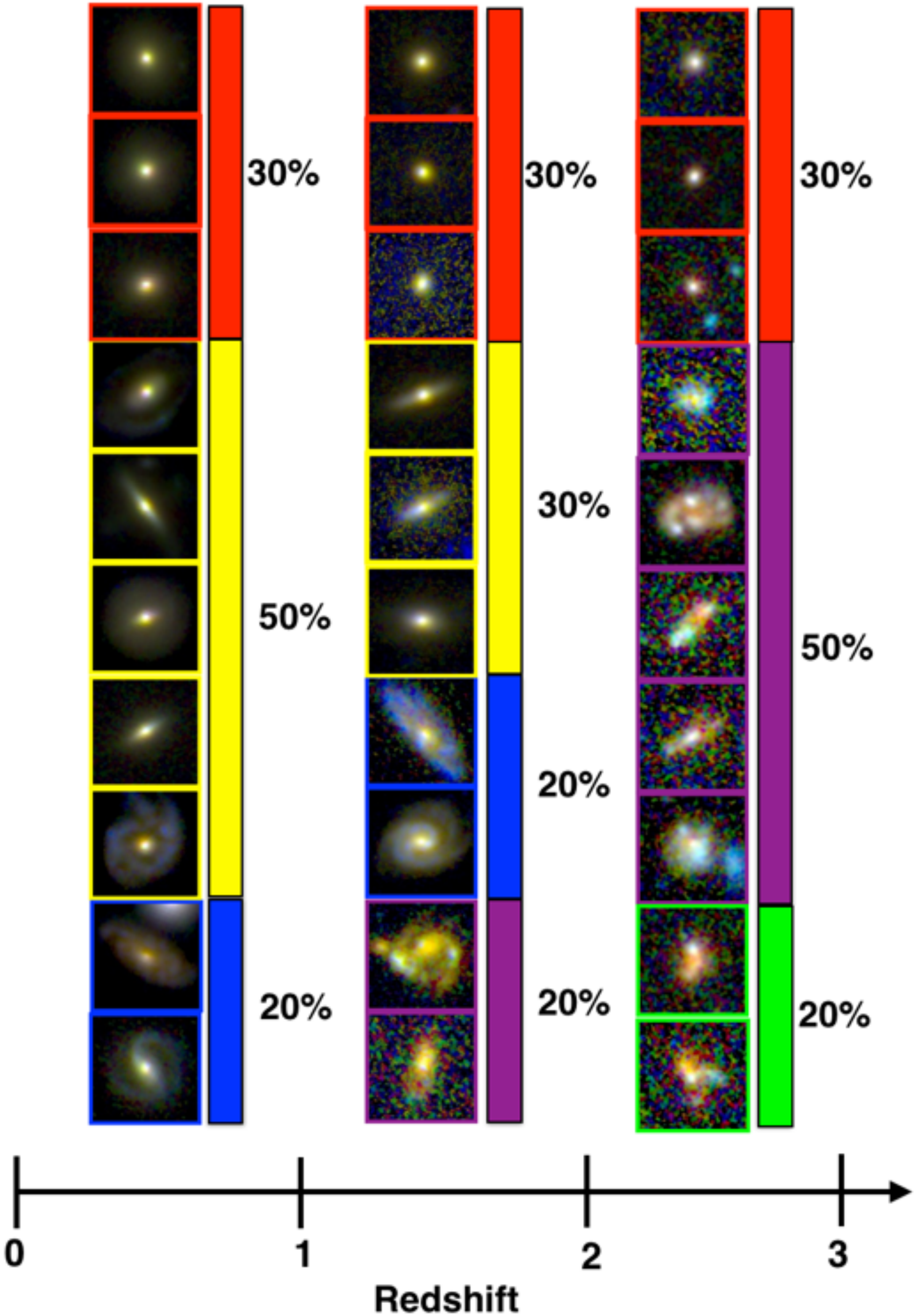


MHC+15b



~70% of the progenitors of massive galaxies at z~3 were irregular

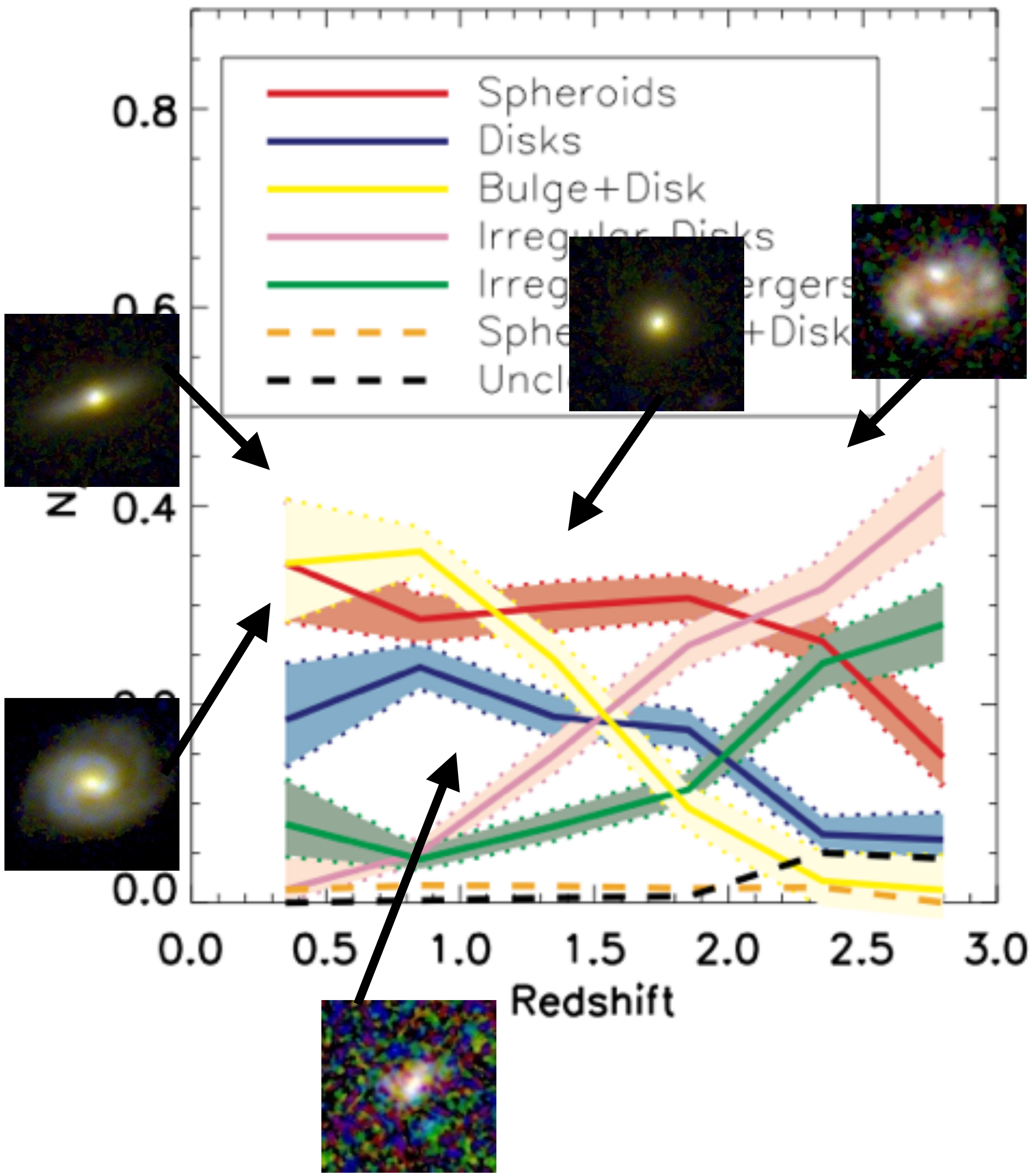
MHC+15b



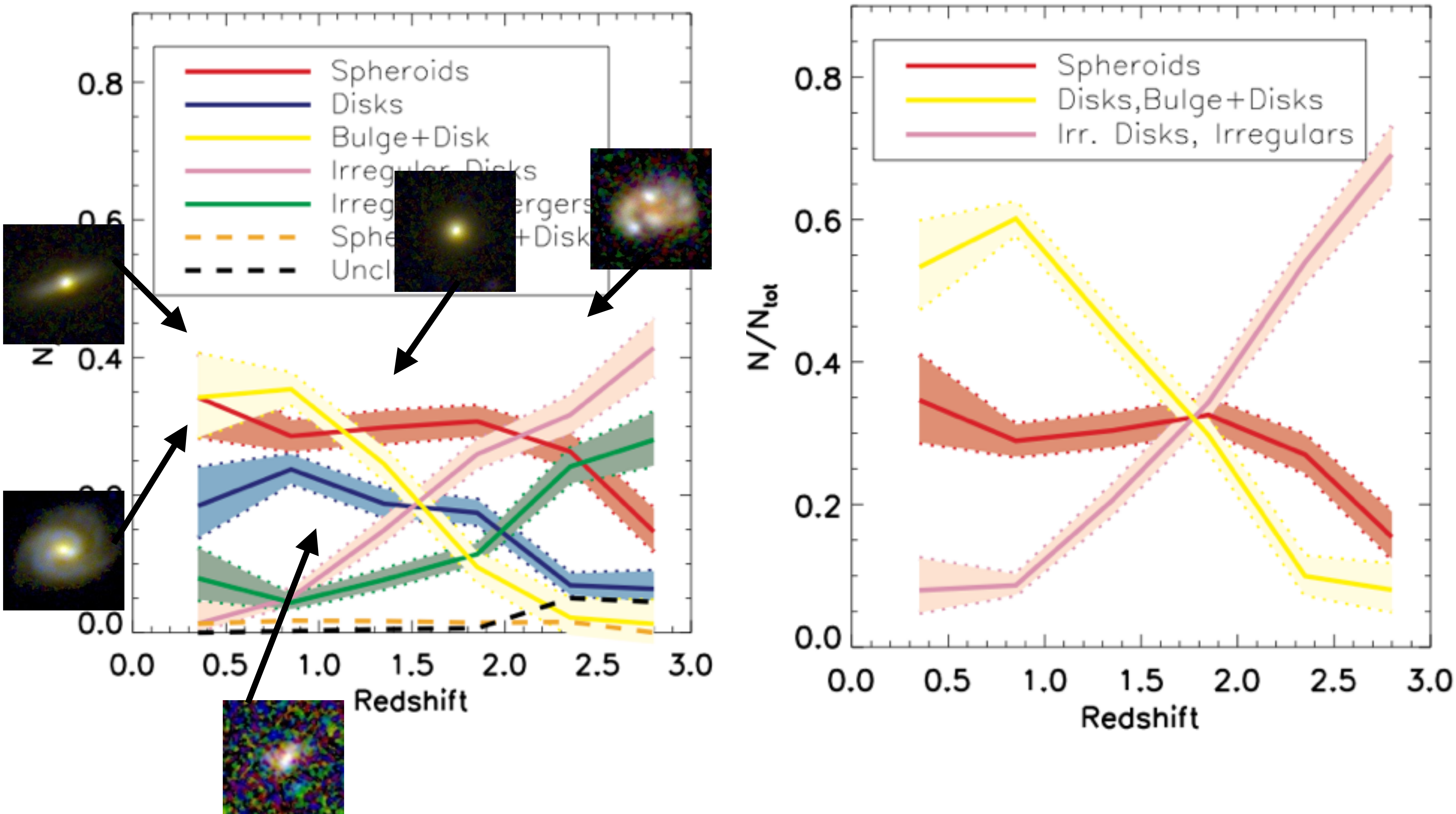
A constant fraction of "pure bulges"

~70% of the progenitors of massive galaxies at z~3 were irregular

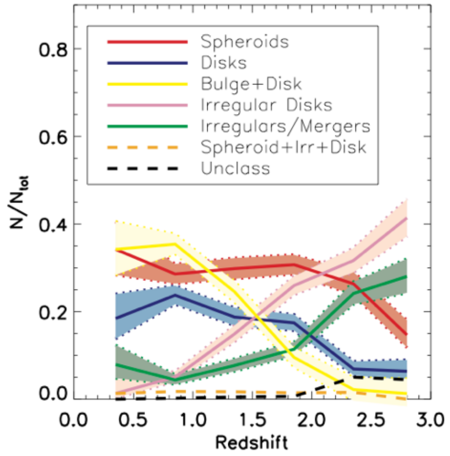
MHC+15b

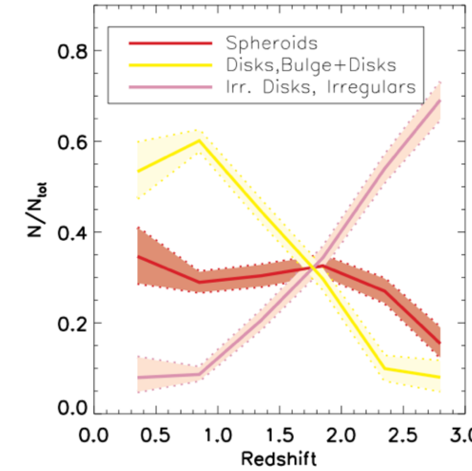

Spheroids
Disks
Bulge+Disk
Irregular Disks
0.8
0.6
0.4
0.0
N
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Redshift

MHC+15b

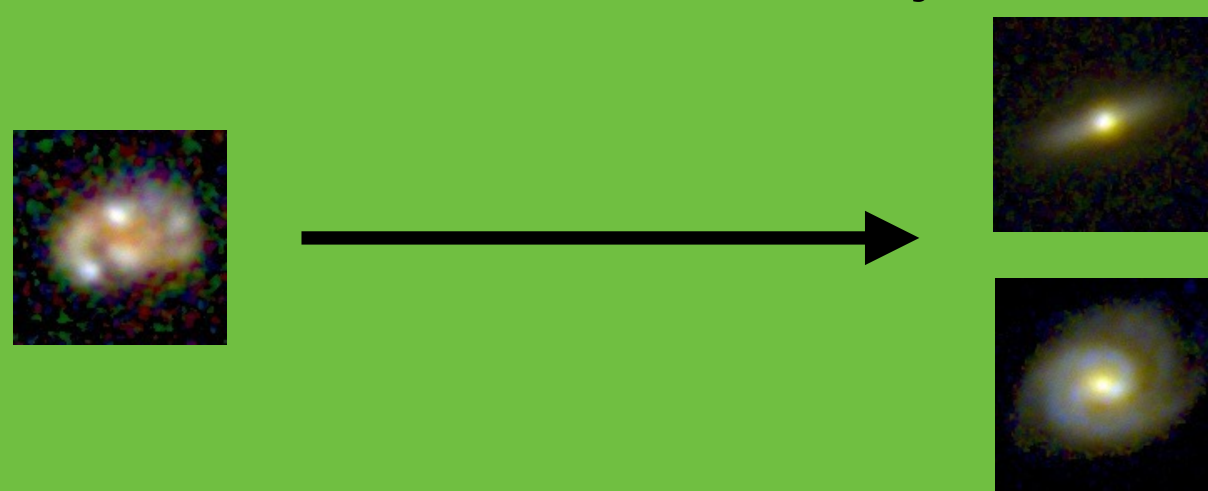

Spheroids
Disks
Bulge+Disk
Irregular Disks
Unclassified
0.0
0.4
0.6
0.8
N
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Redshift
Spheroids
Disks,Bulge+Disks
Irr. Disks, Irregulars
N/N_{tot}
0.0
0.2
0.4
0.6
0.8
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Redshift

MHC+15b



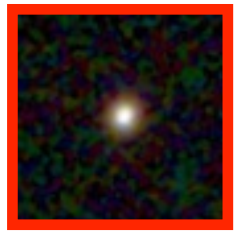


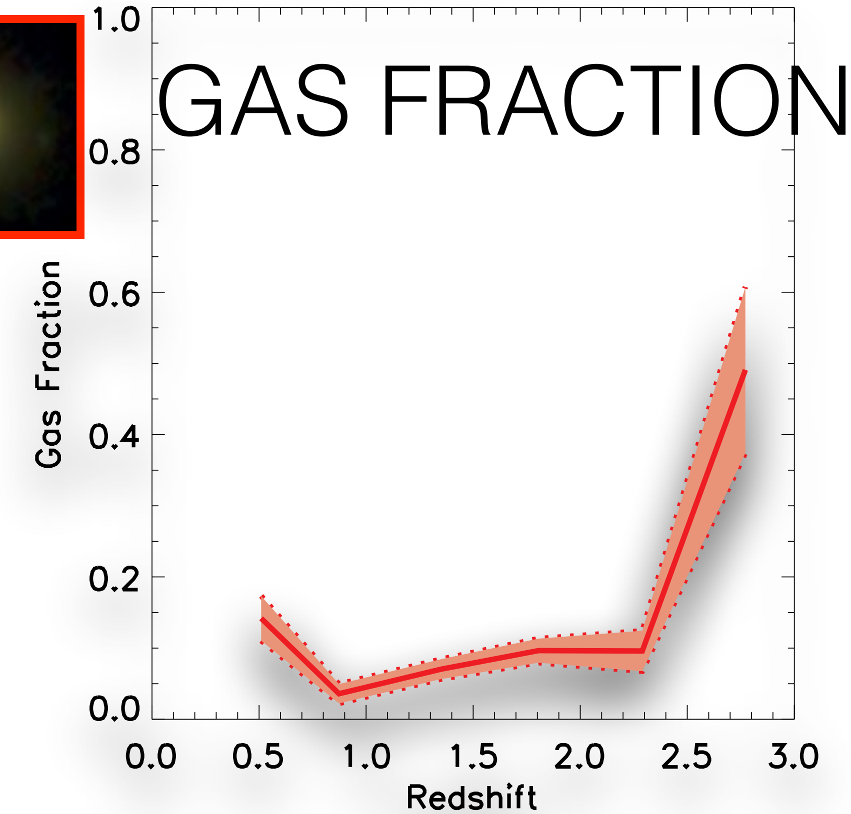
1. **"A clumpy track"** : A morphological transformation at z>1 from clumpy/irregular disky galaxies into regular disk+bulge systems

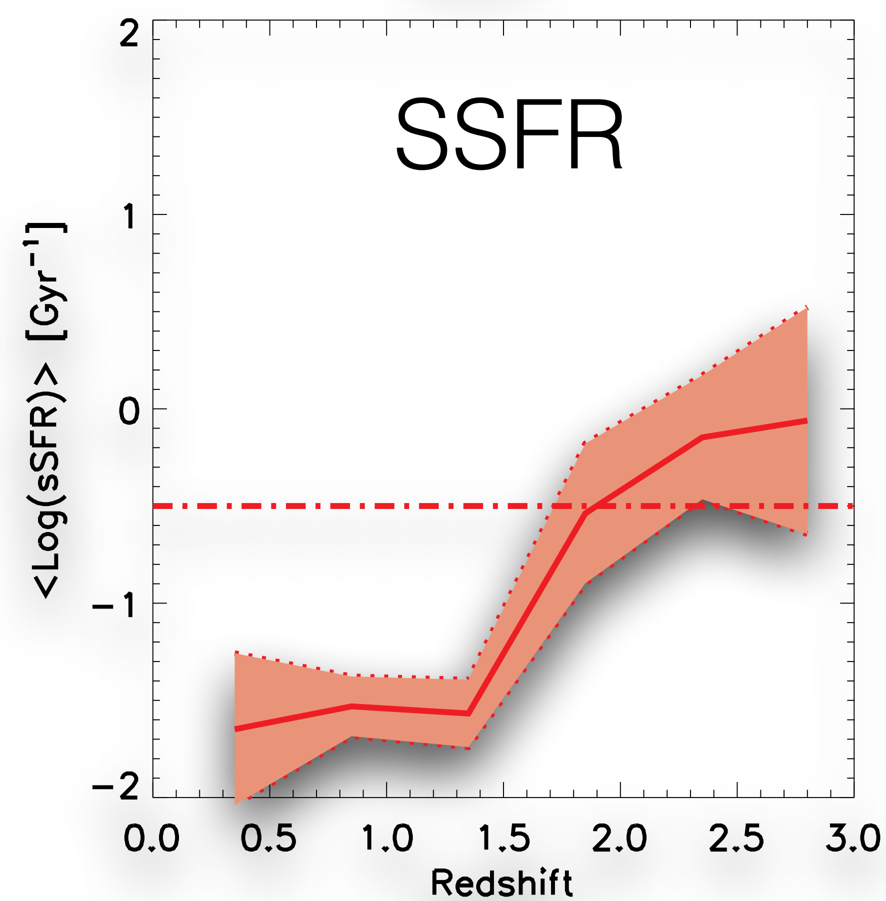


2. "A nugget track" : Bulges rapidly formed at z>2.5

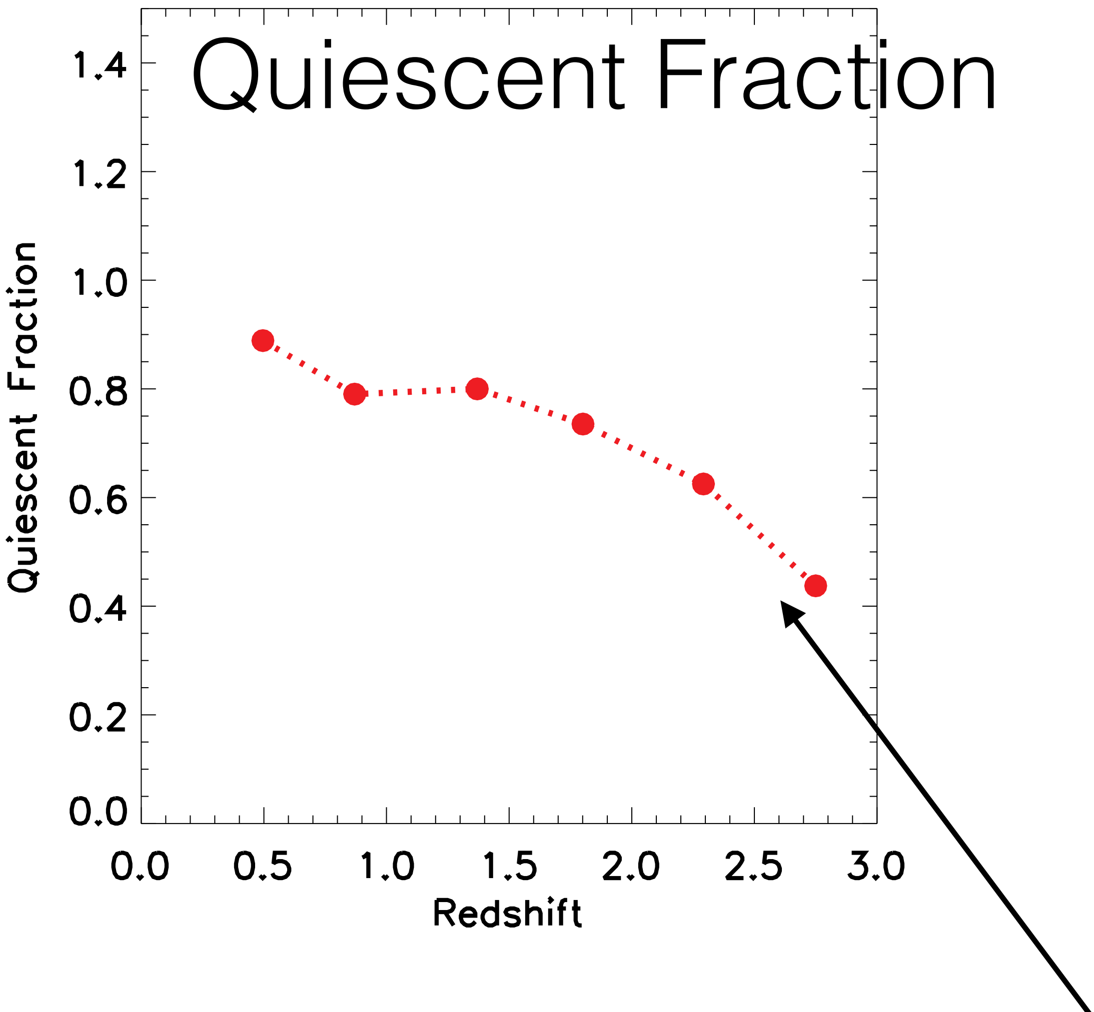
Fast quenching

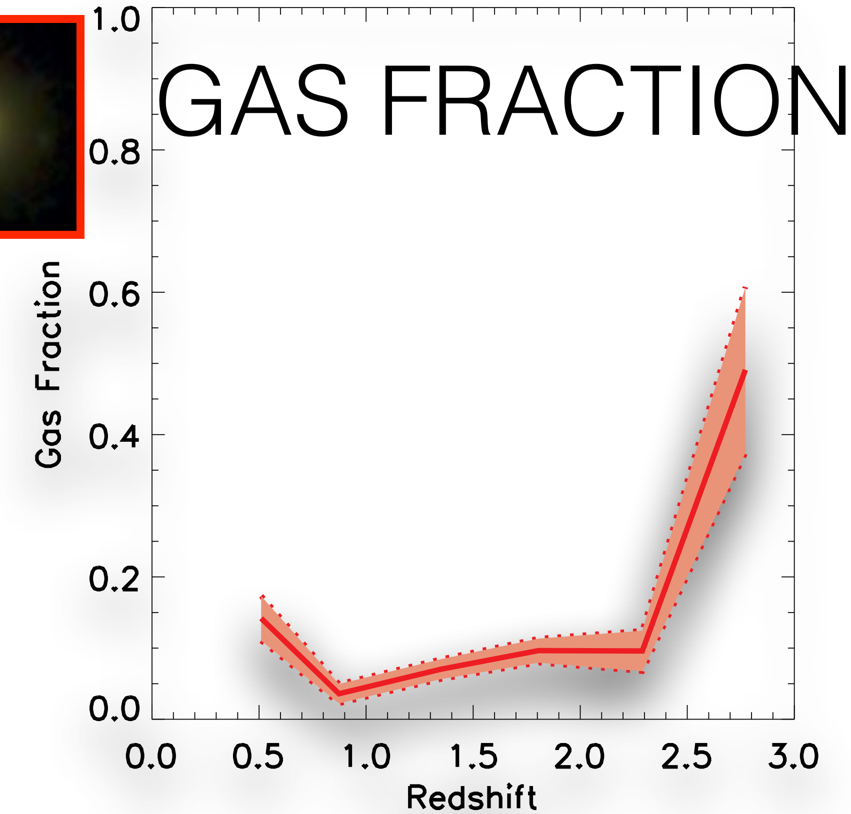


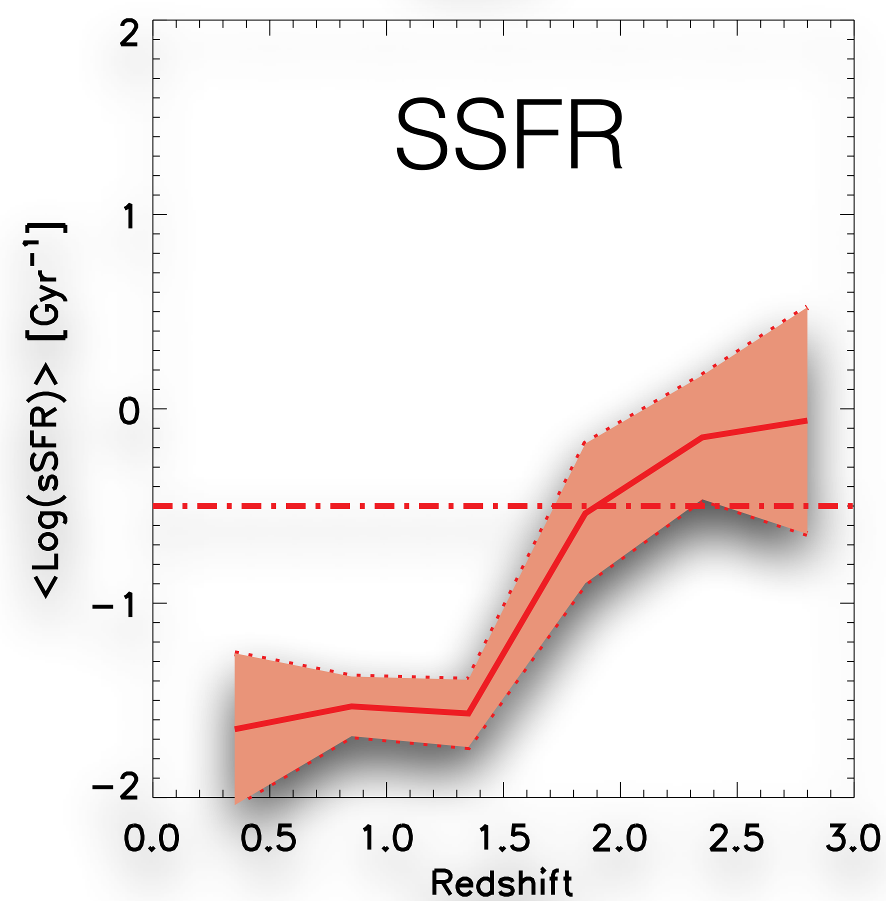




Fast quenching

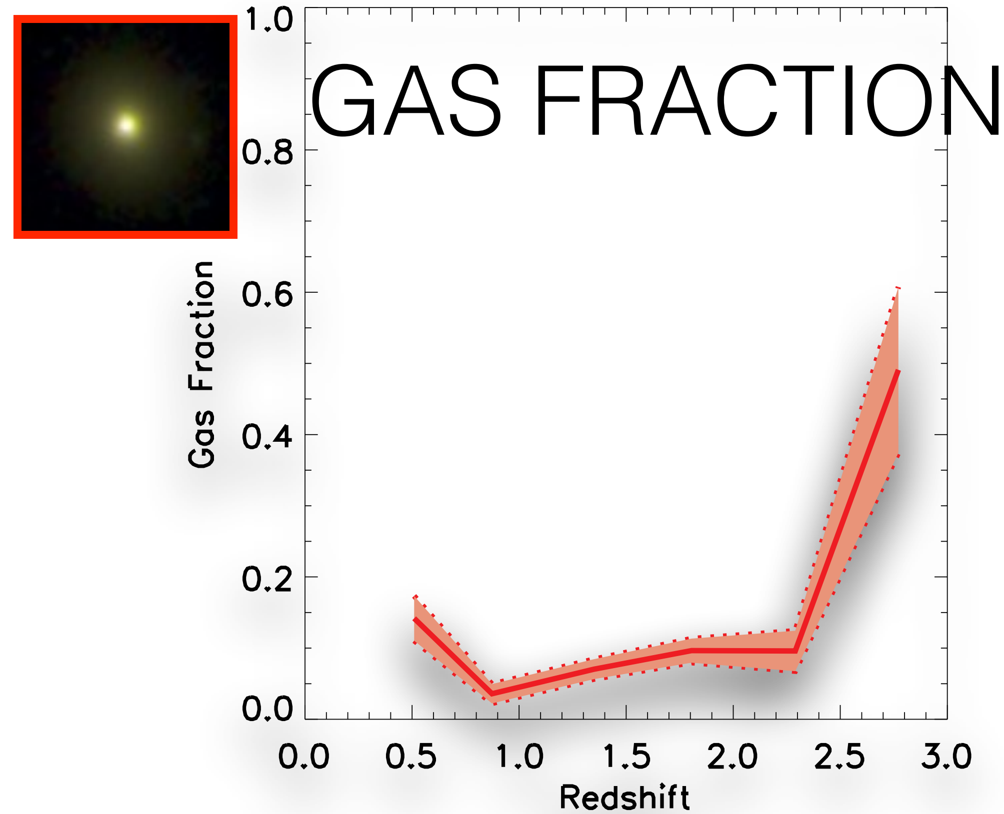


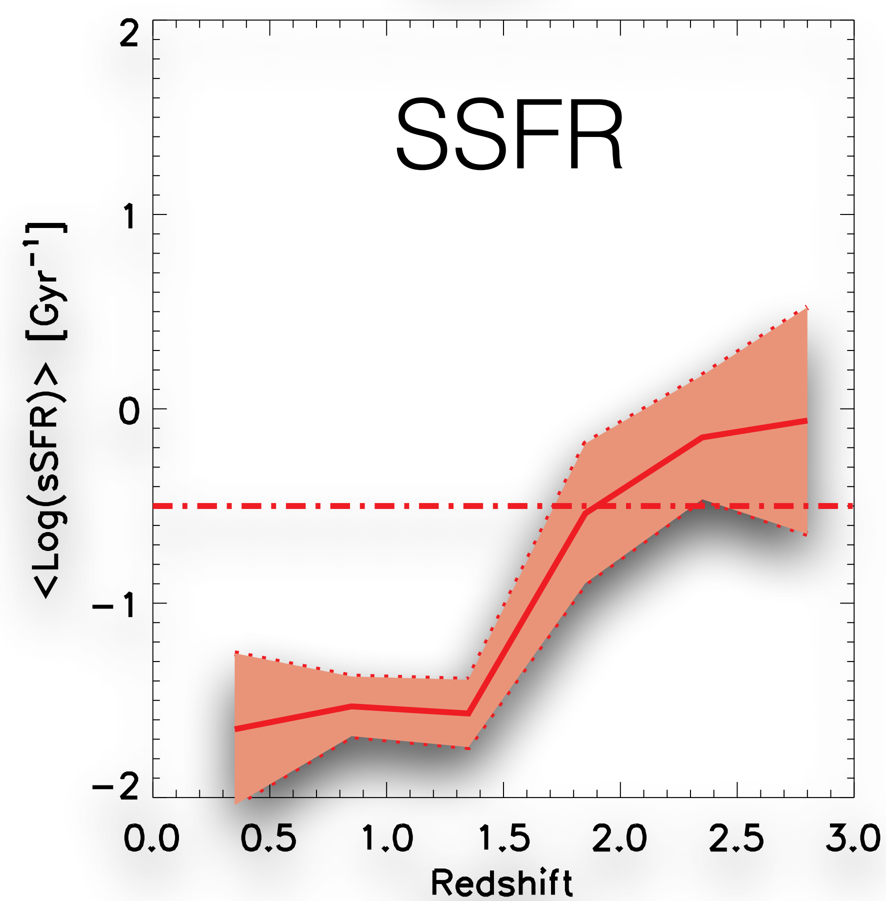




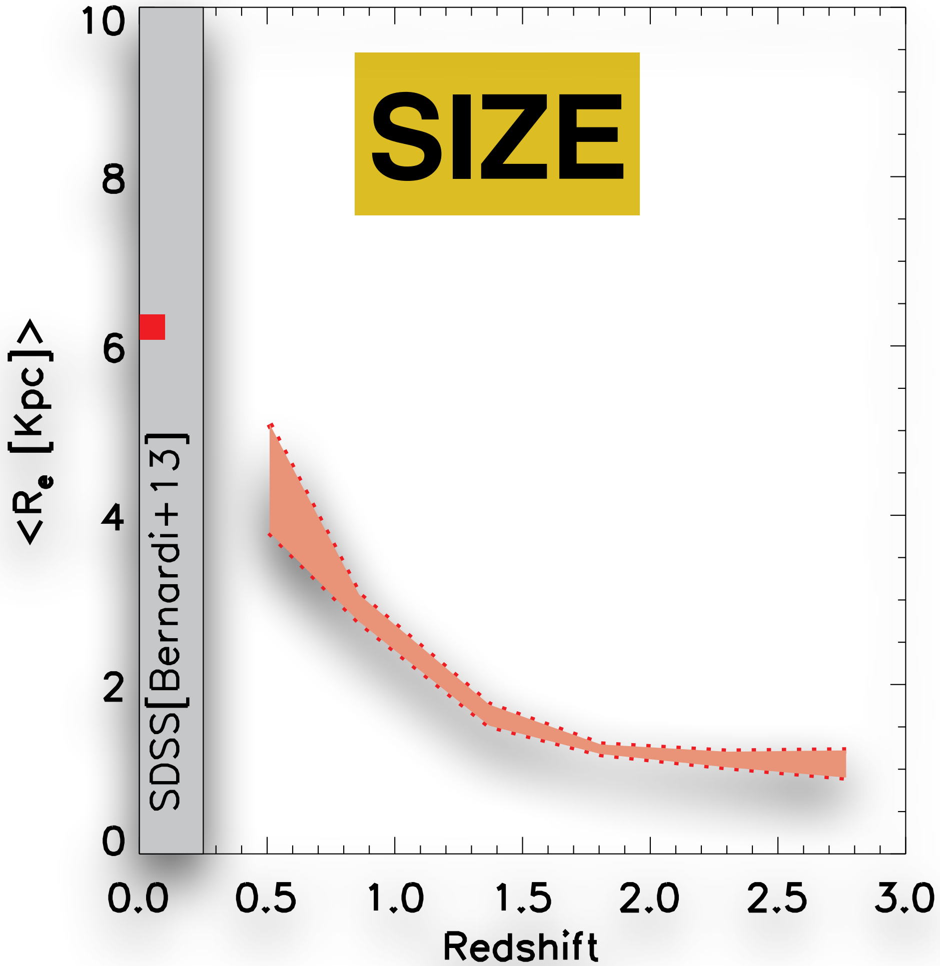
~50% of bulges at z~3 are SF

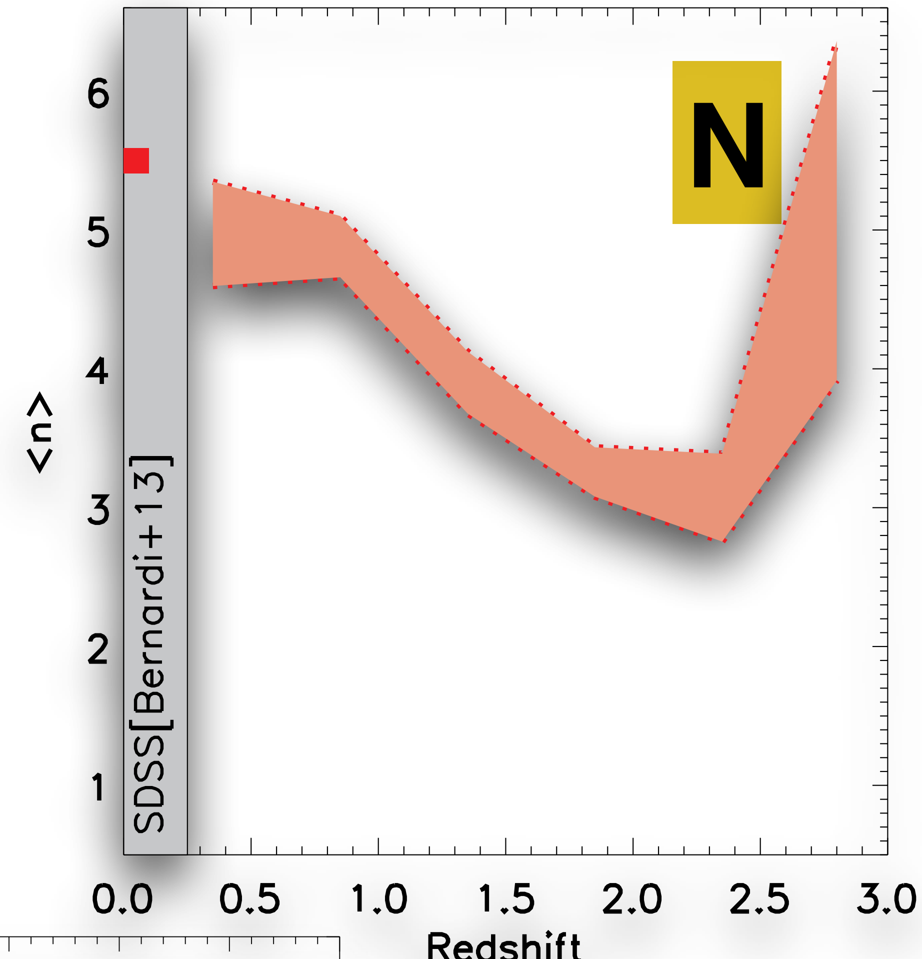
Fast quenching

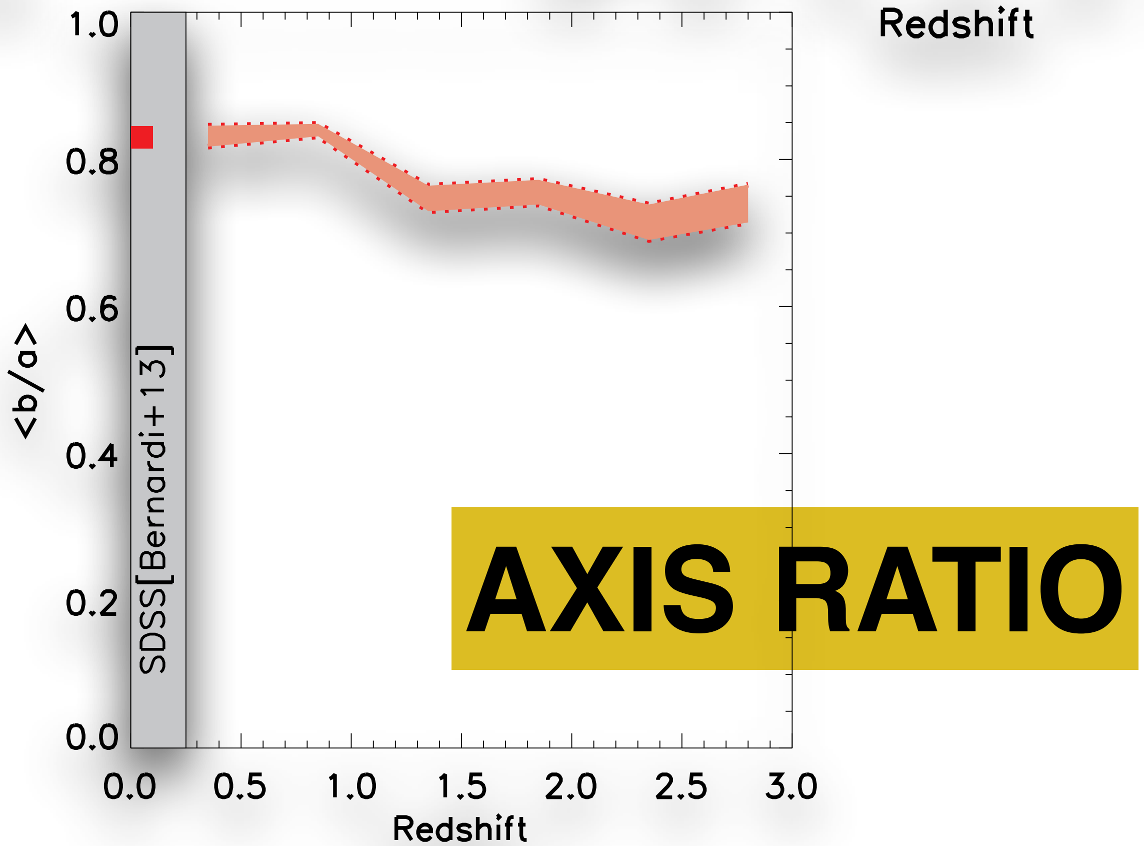




Structure

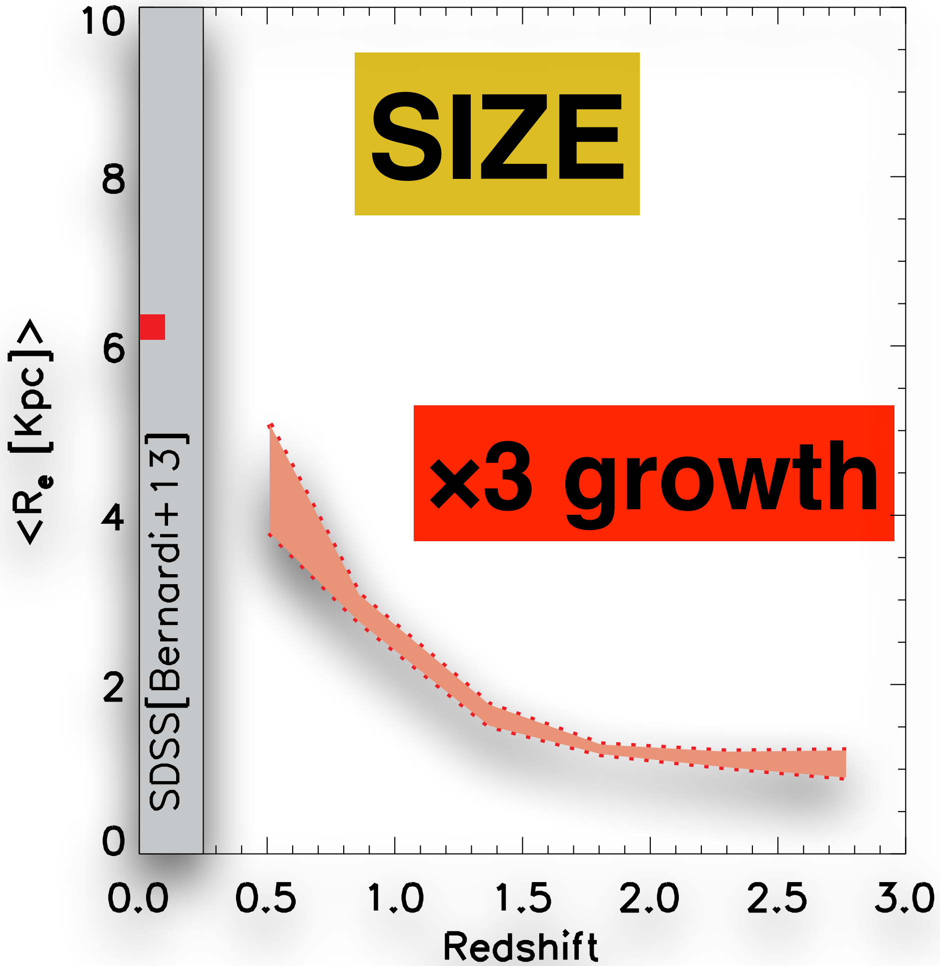


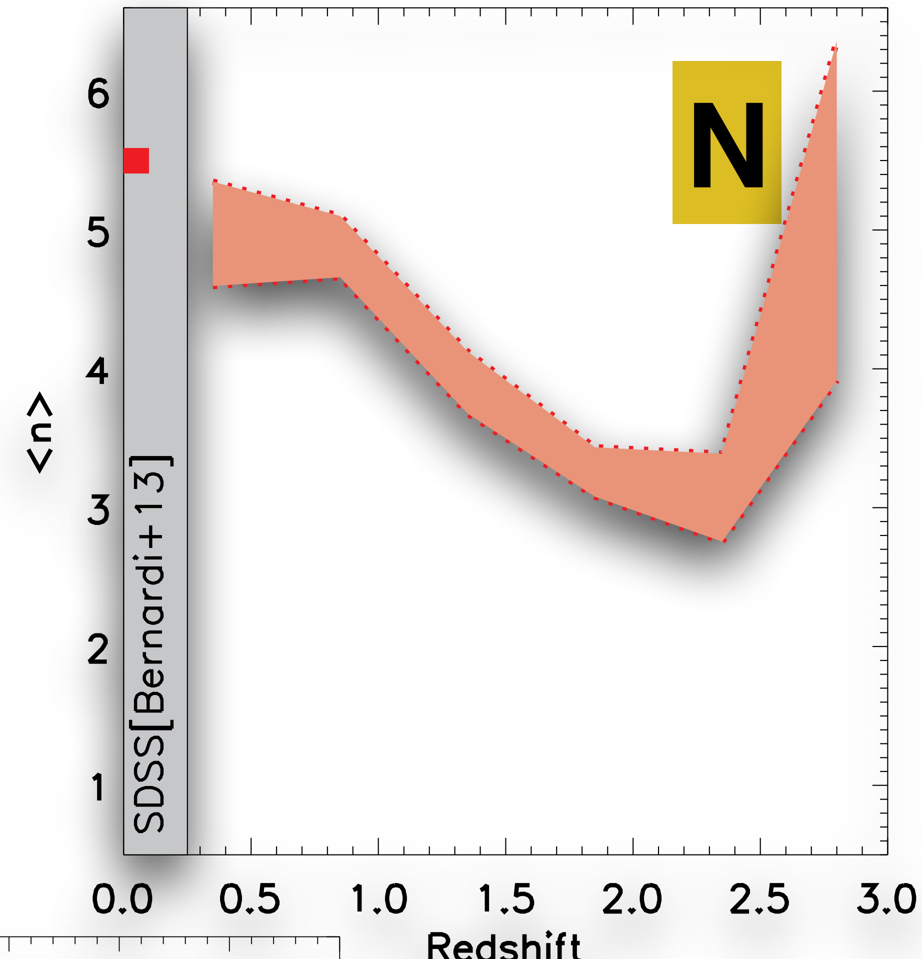


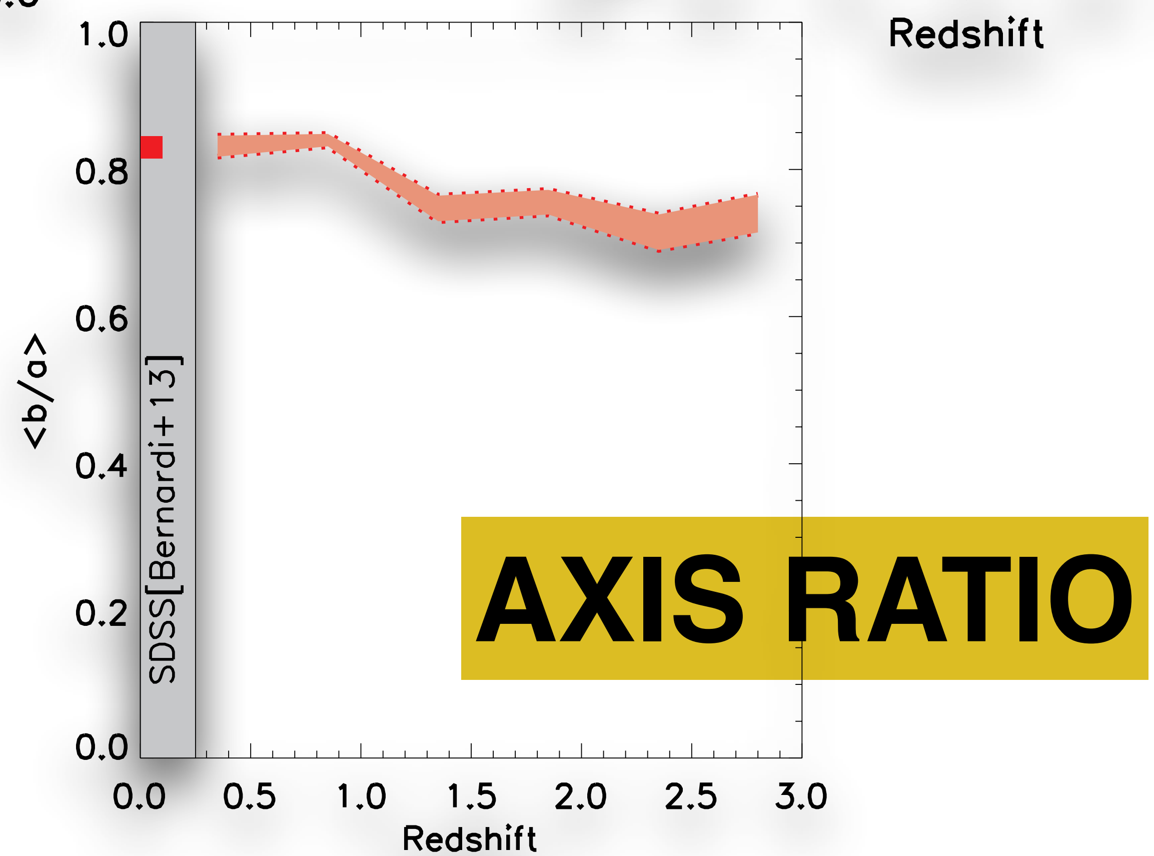


MHC+15b

Structure

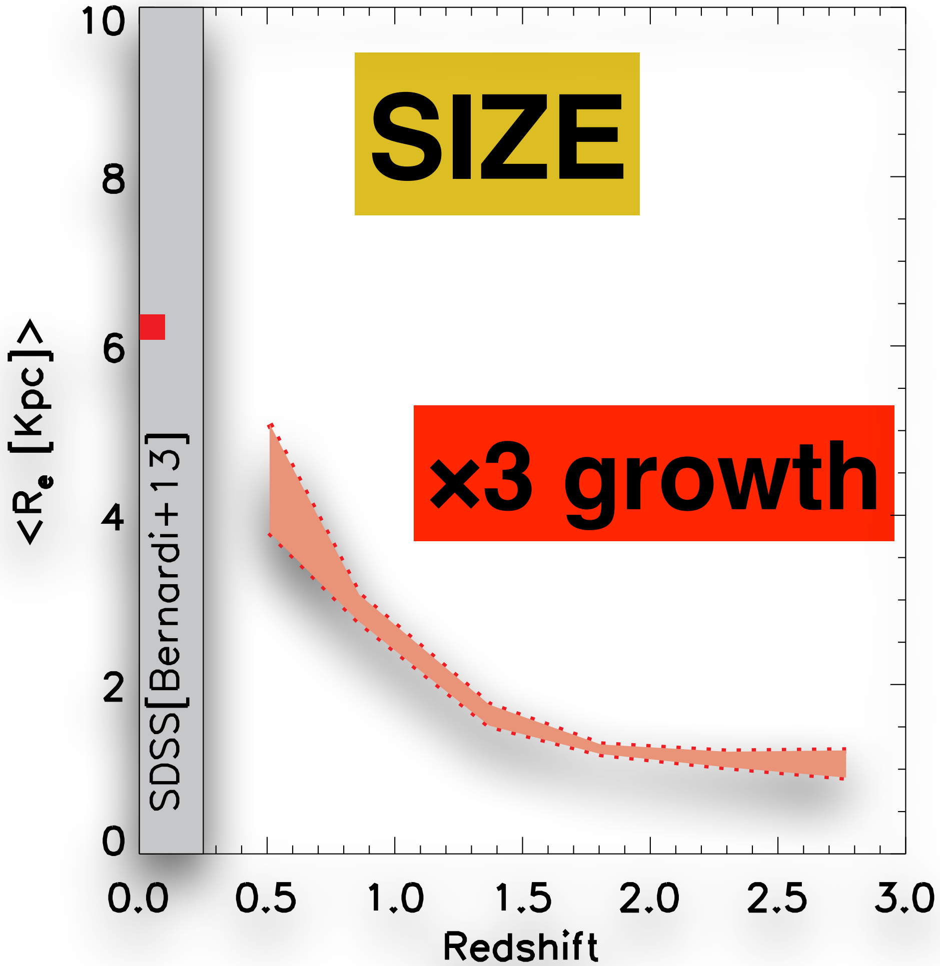


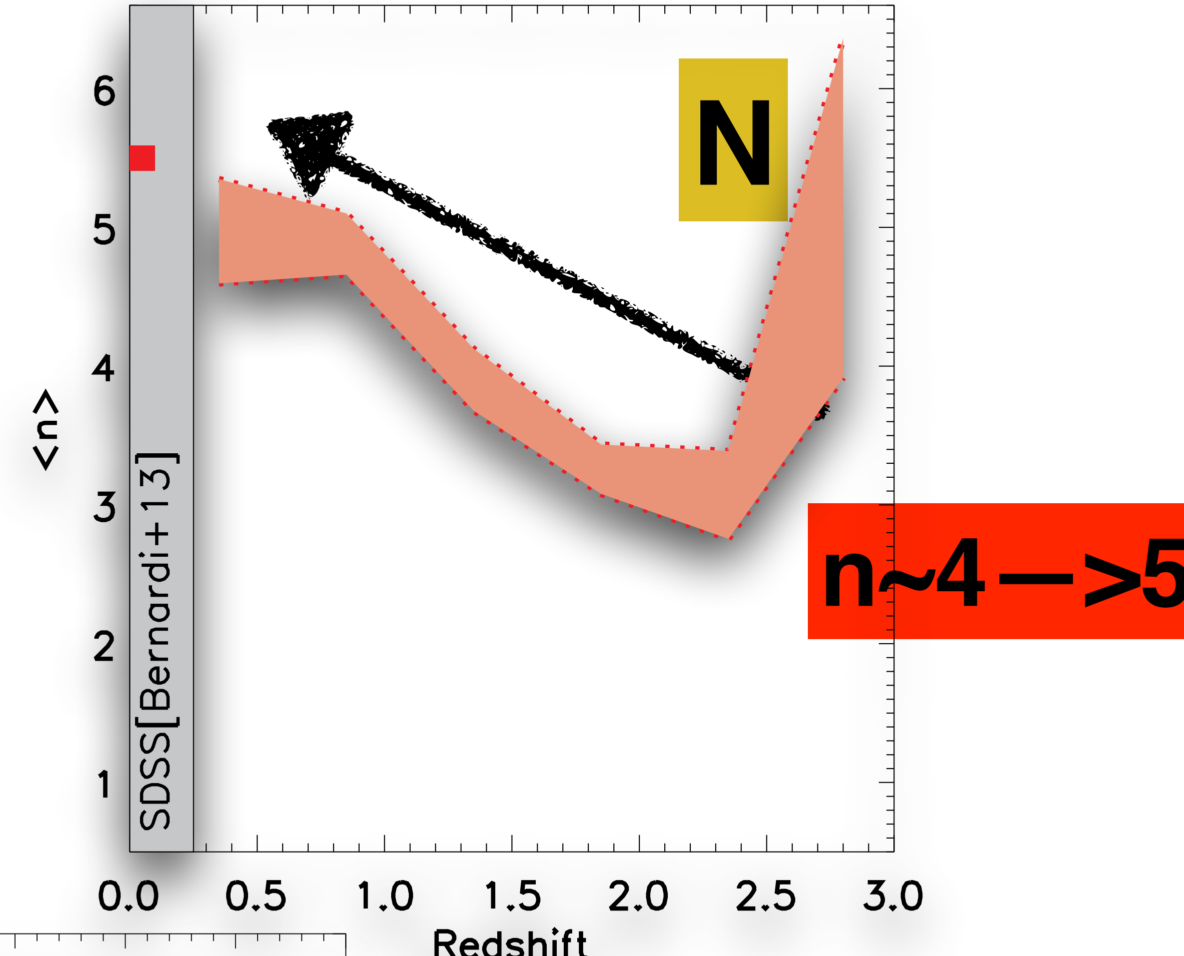


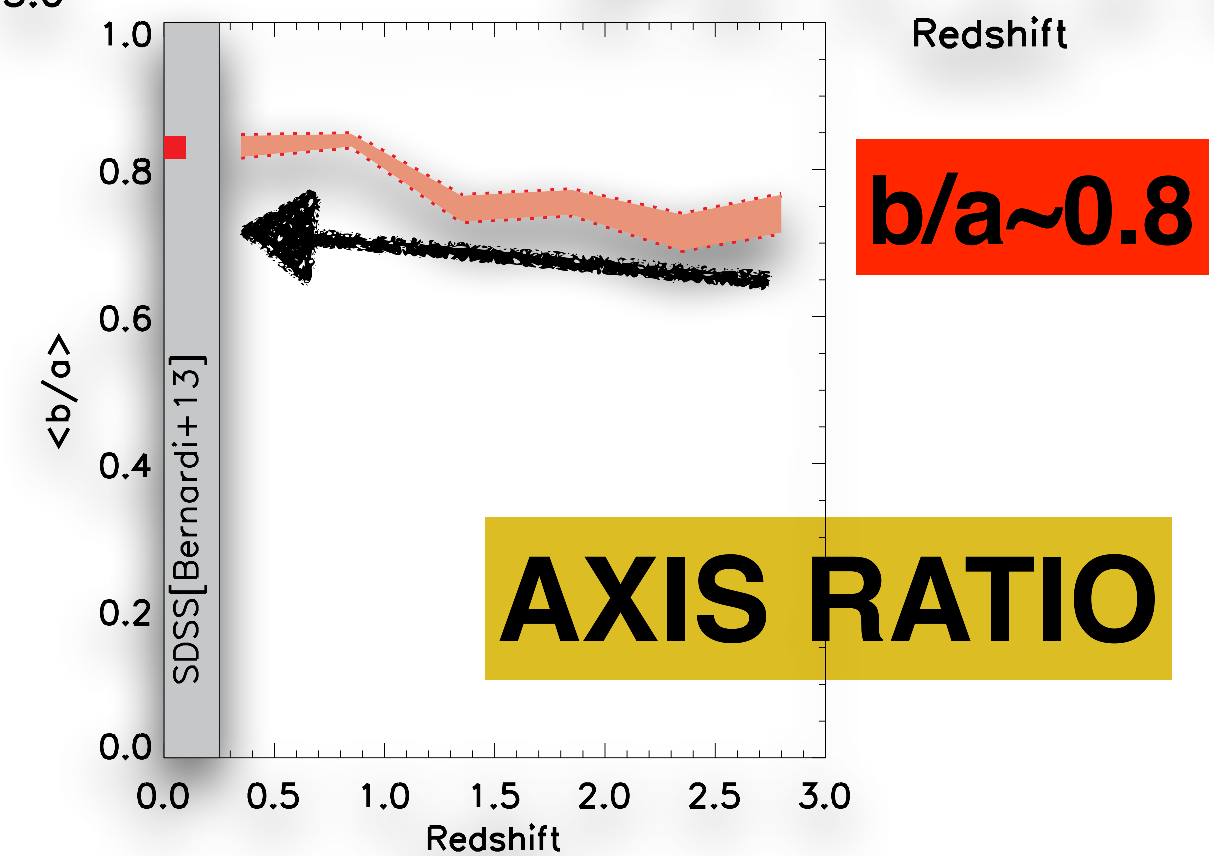


MHC+15b

Structure

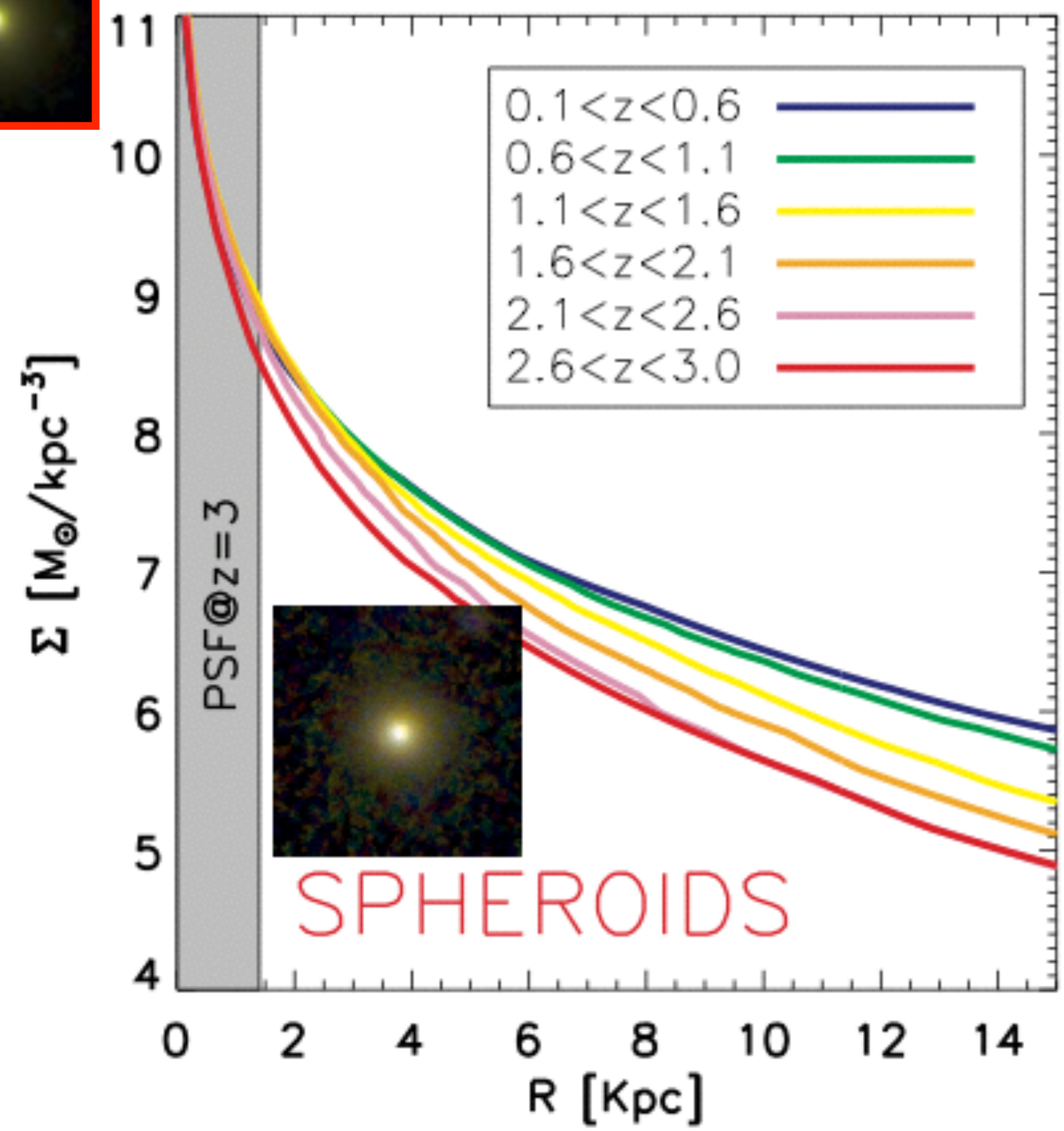


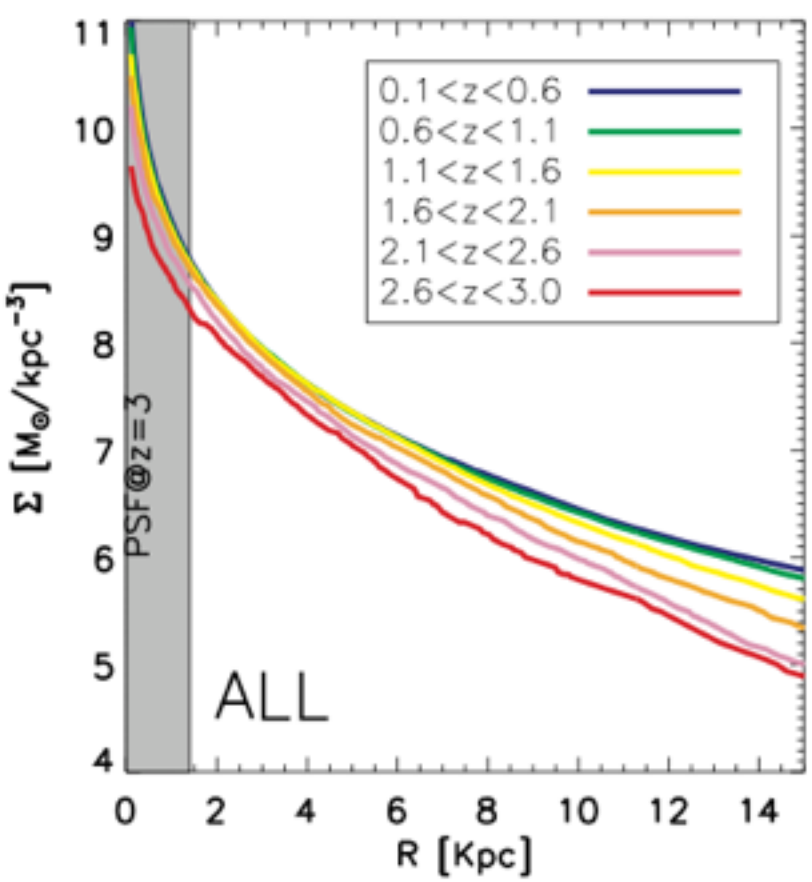




MHC+15b

Mass density profiles



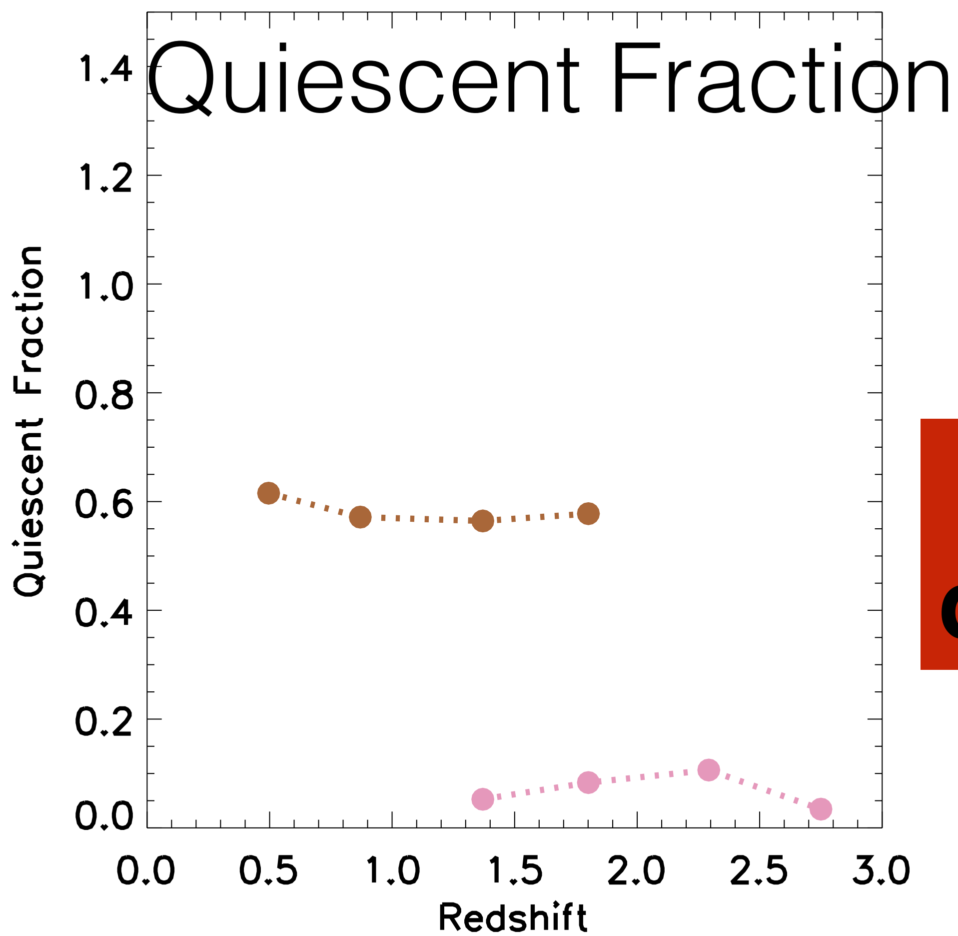


inside-out growth

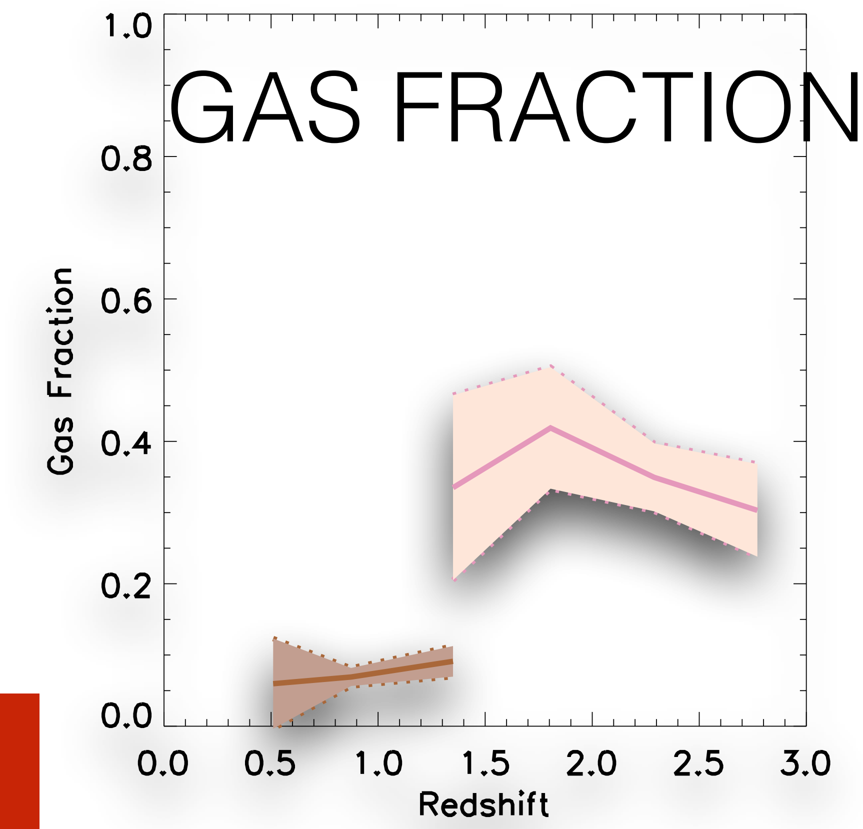
MHC+15b

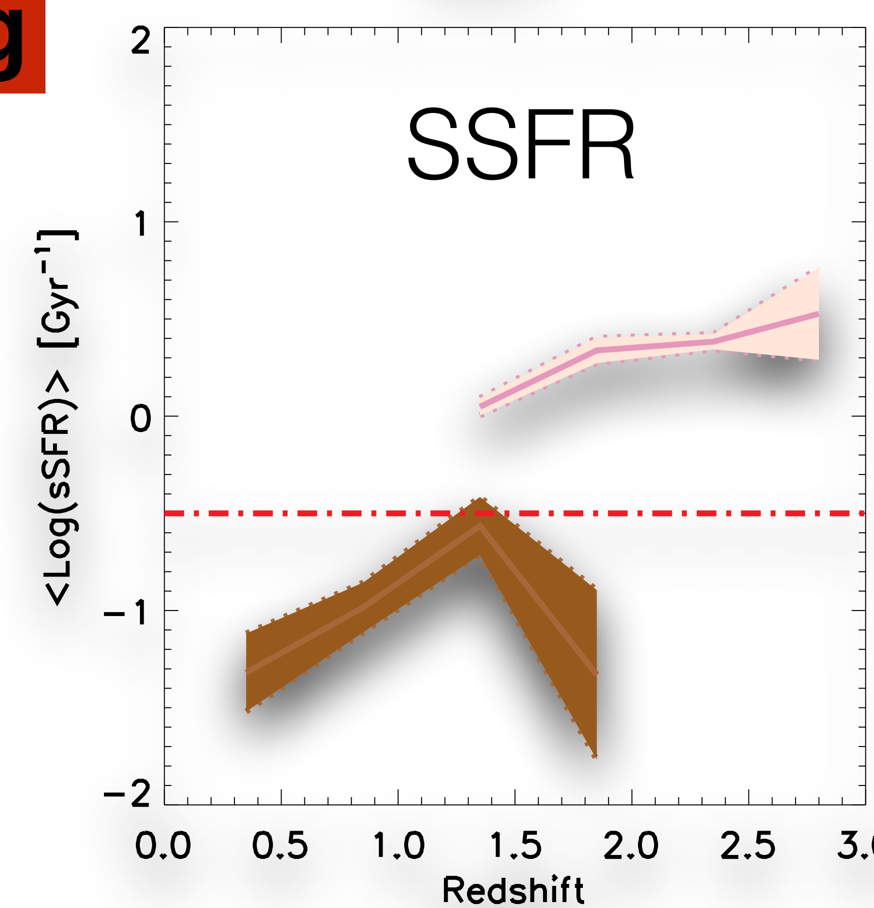
(Pattel+13,Tacchella+15…)

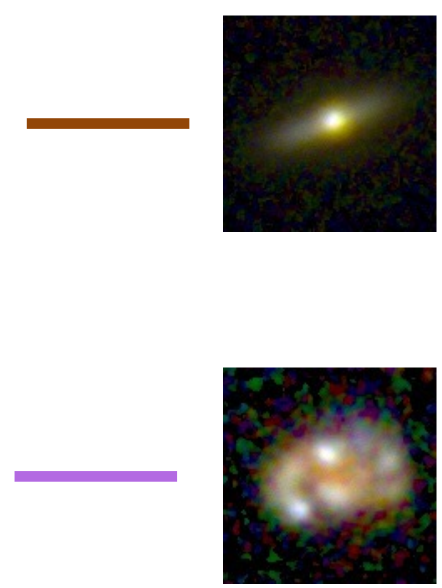
Slow quenching



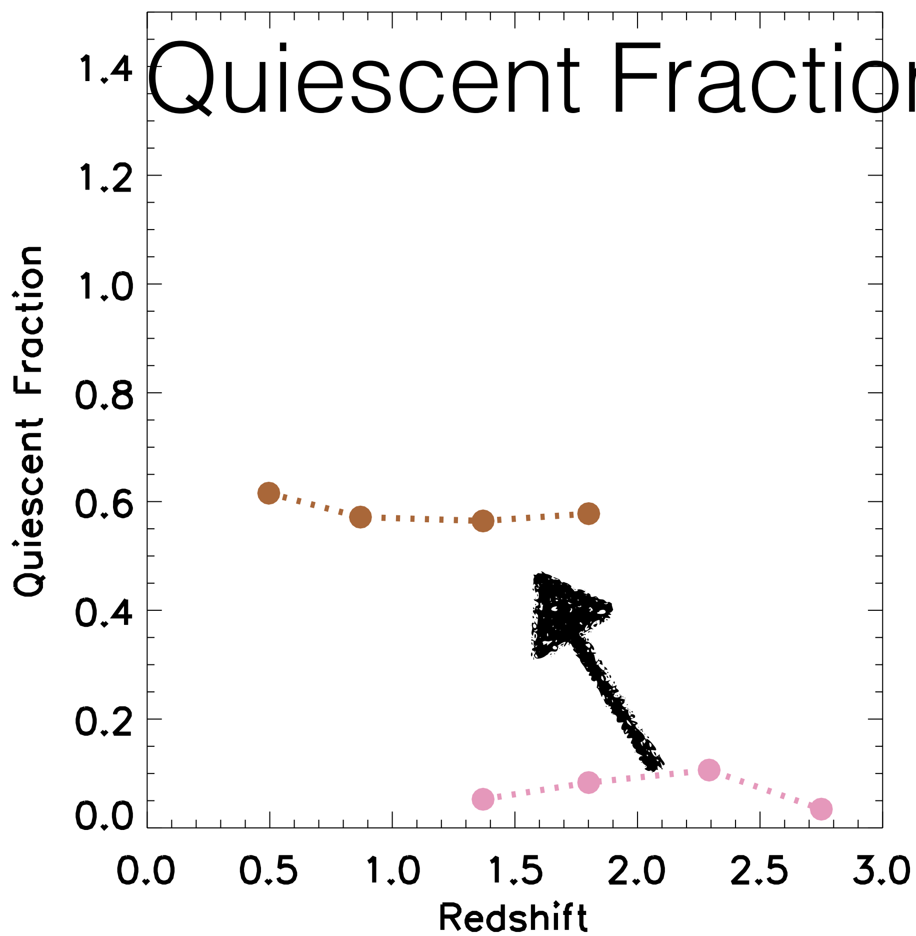
bulge growth driven quenching



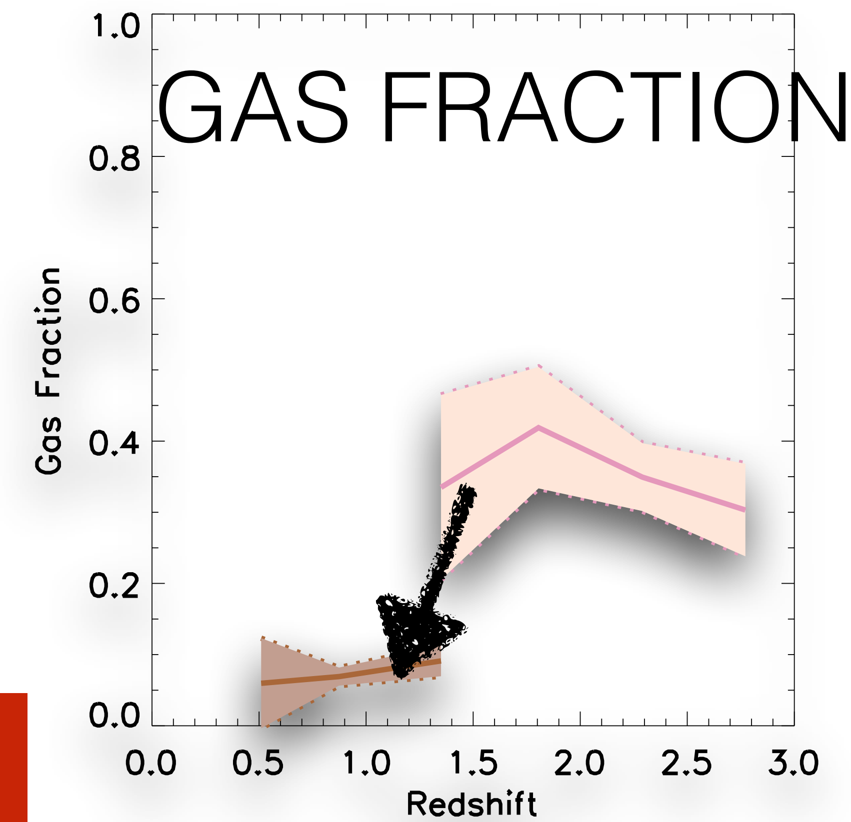


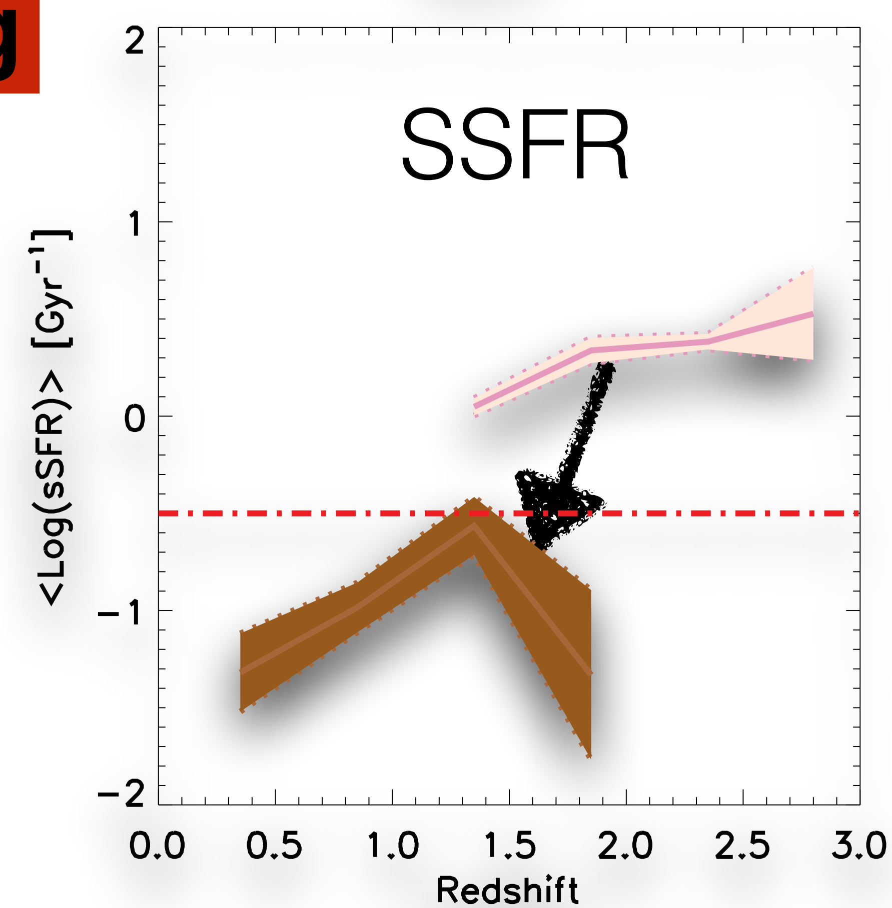


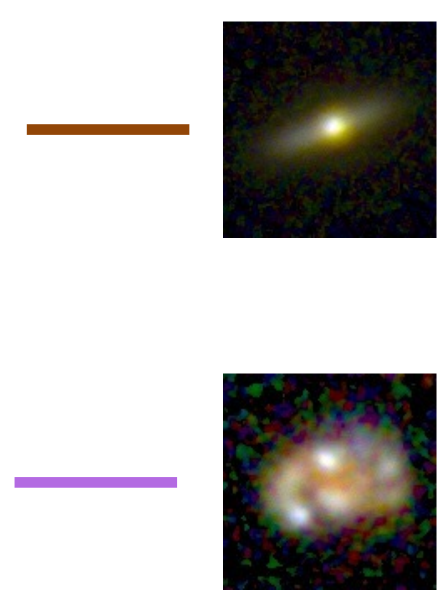
Slow quenching



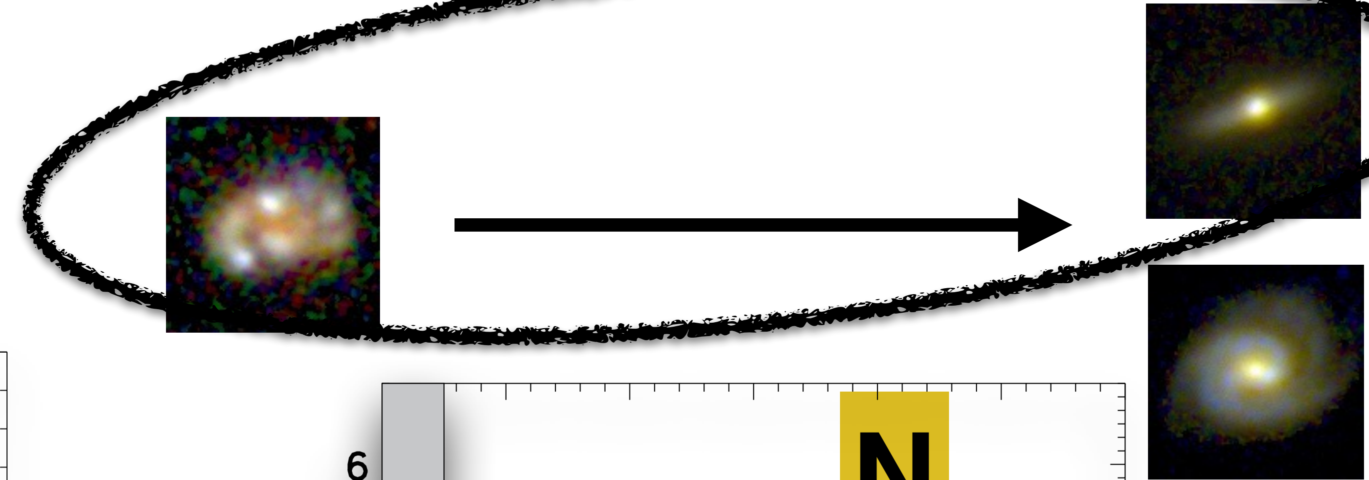
bulge growth driven quenching

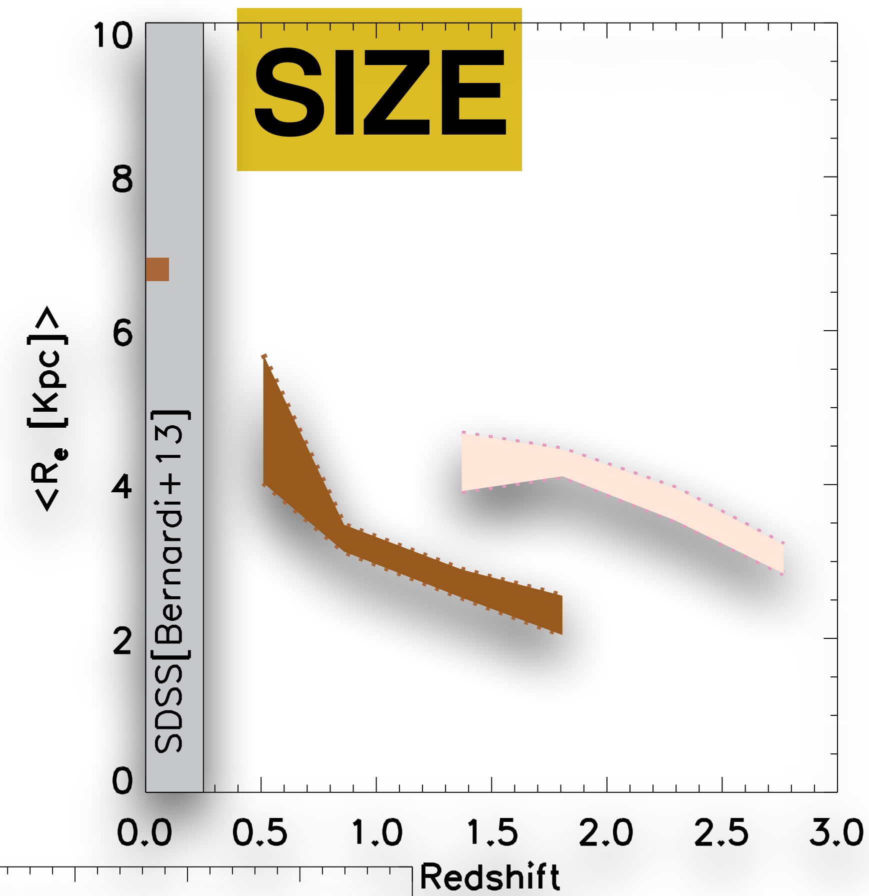


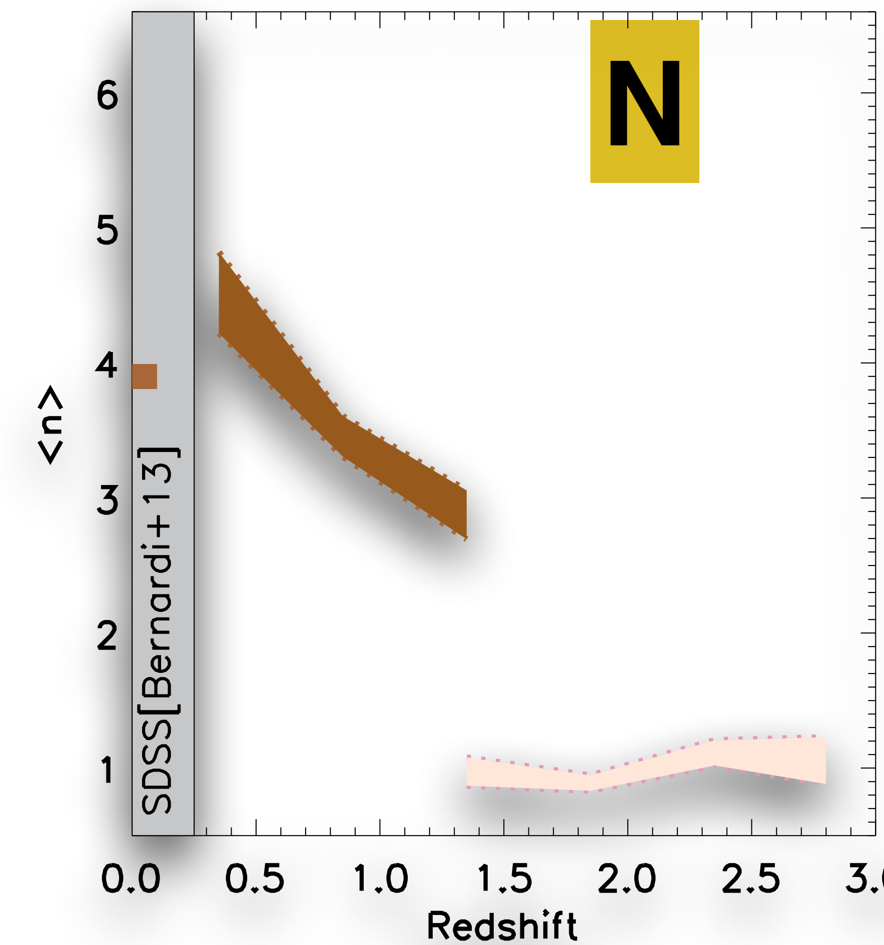


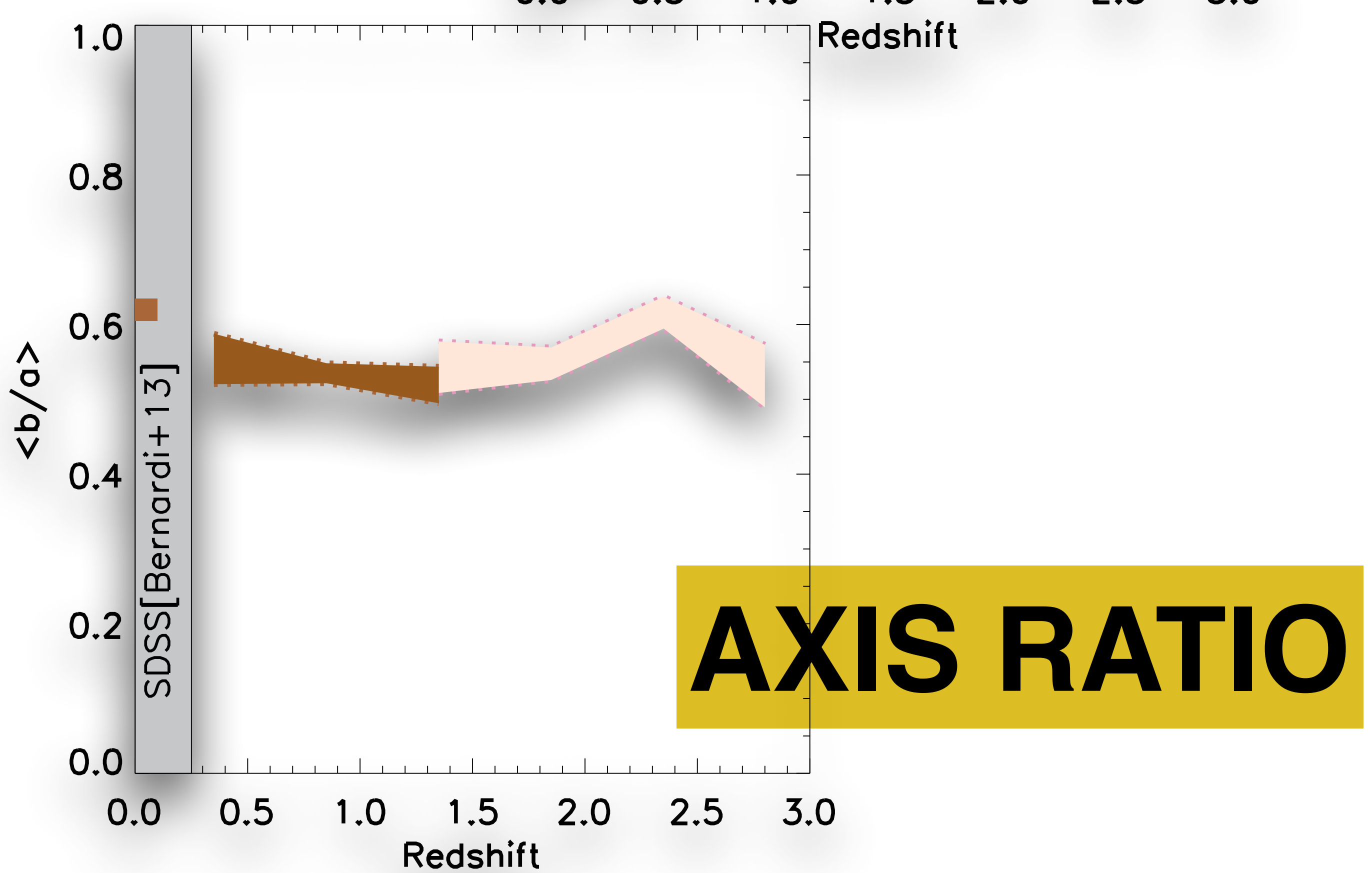


Structure



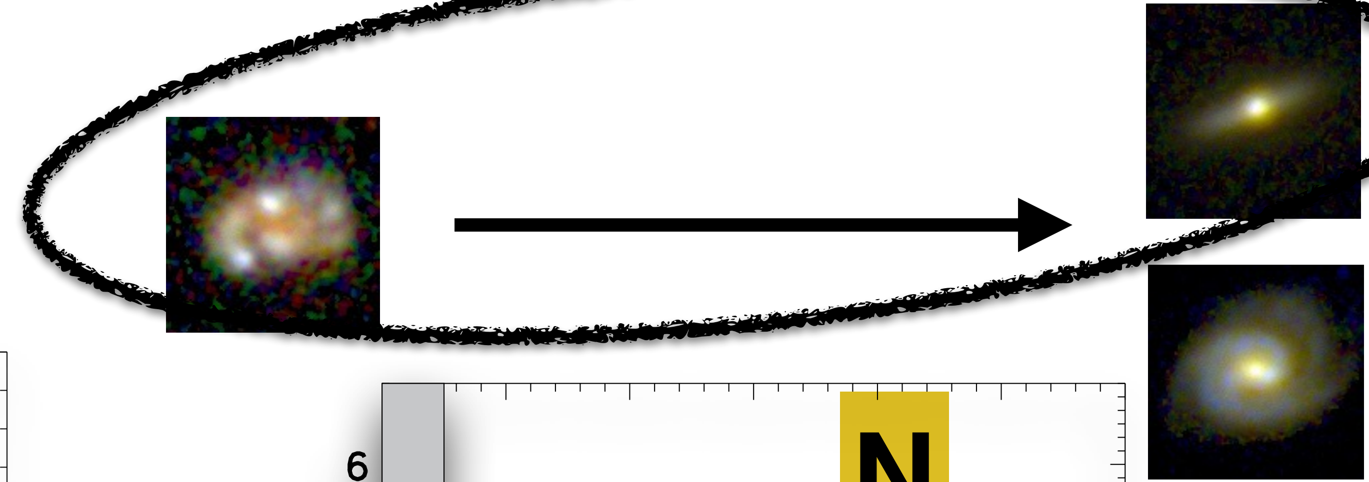


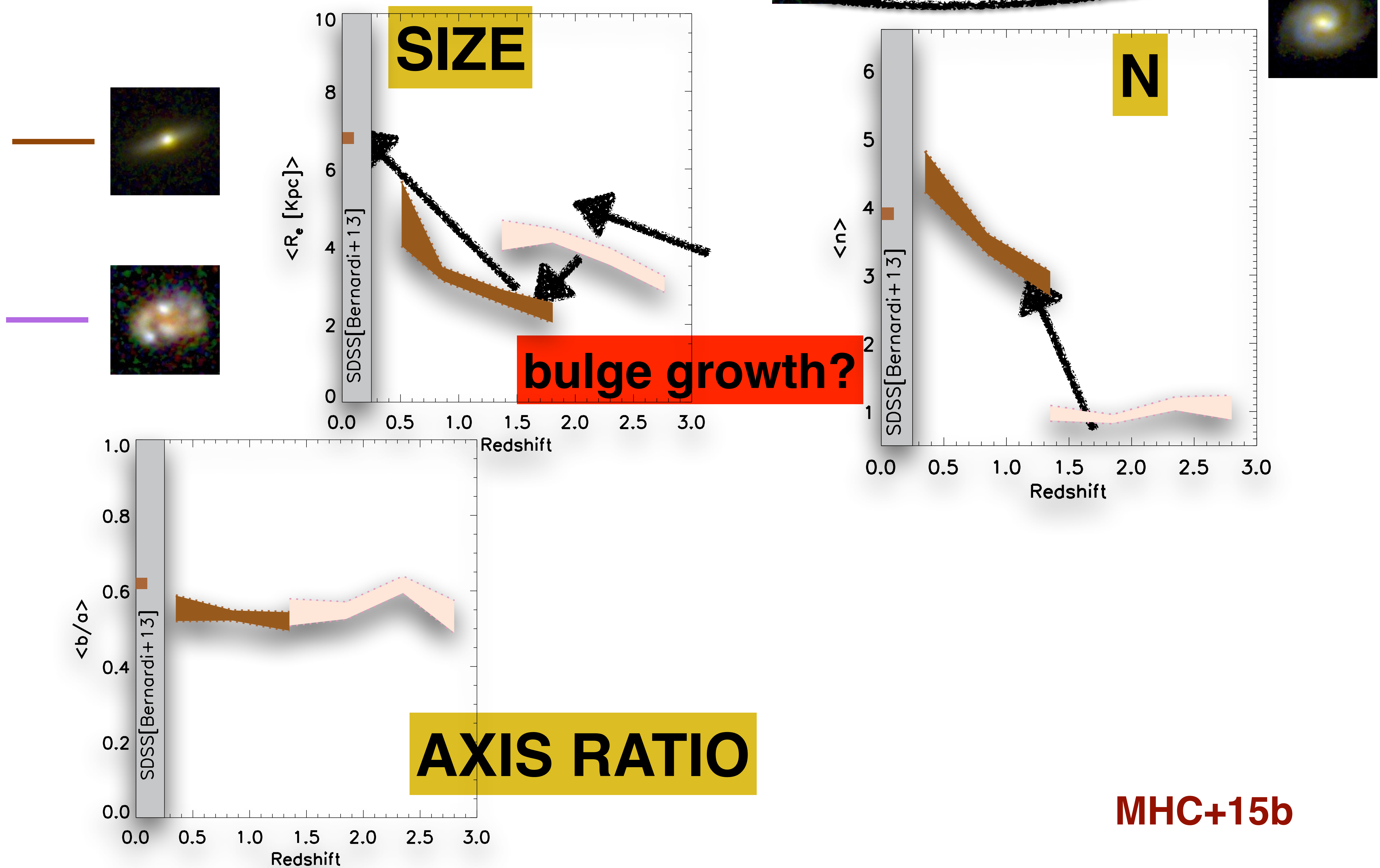




MHC+15b

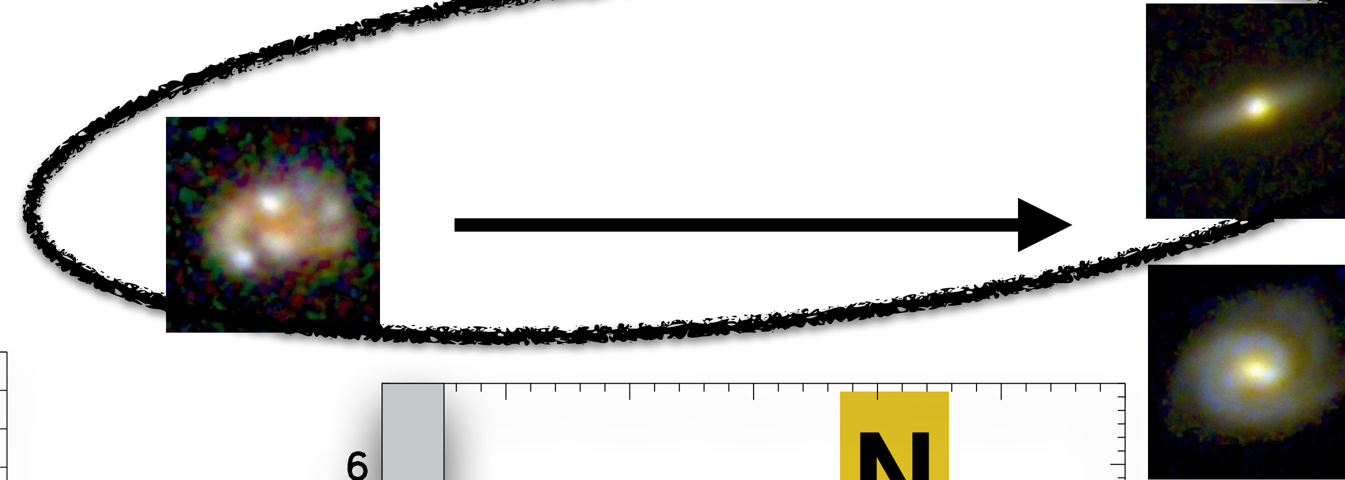
Structure

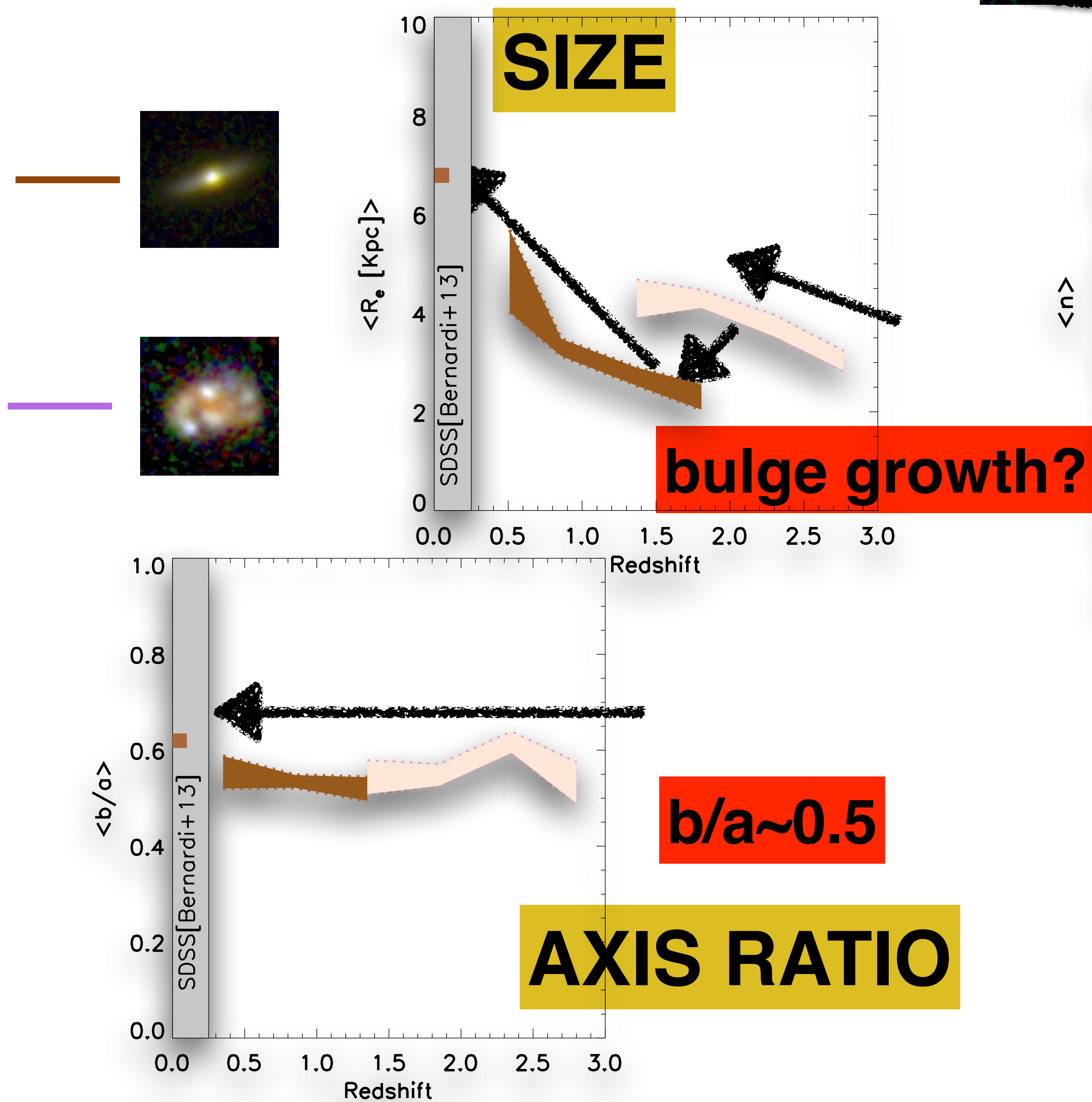


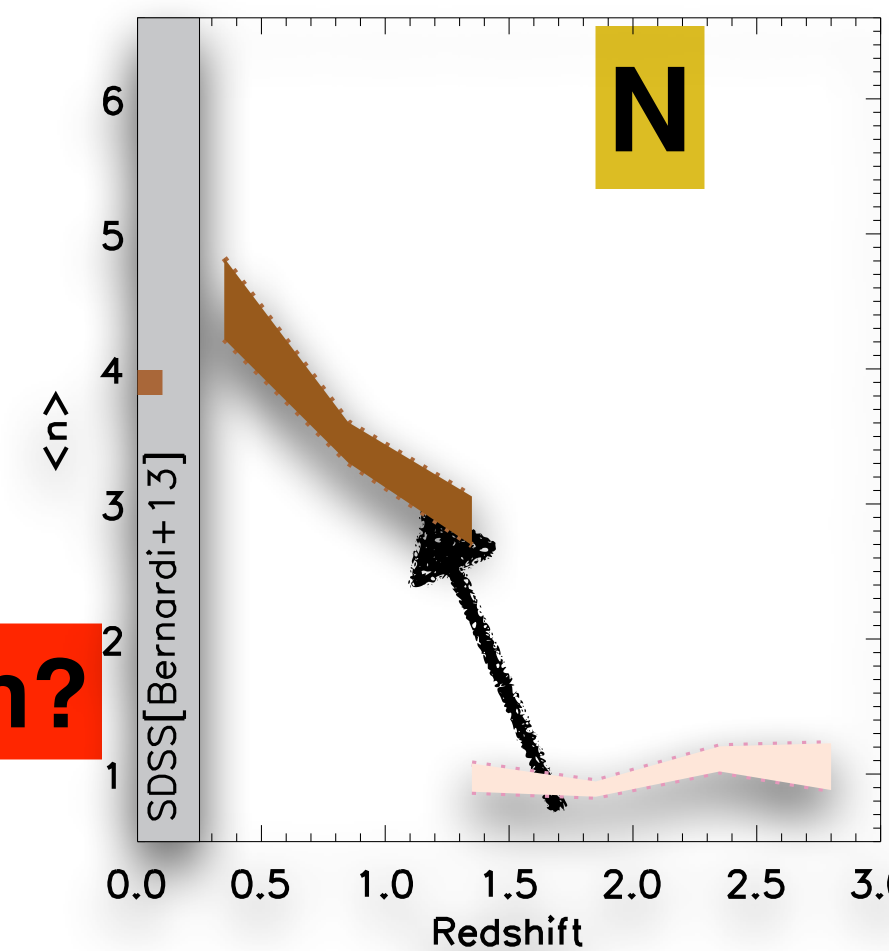


MHC+15b

Structure

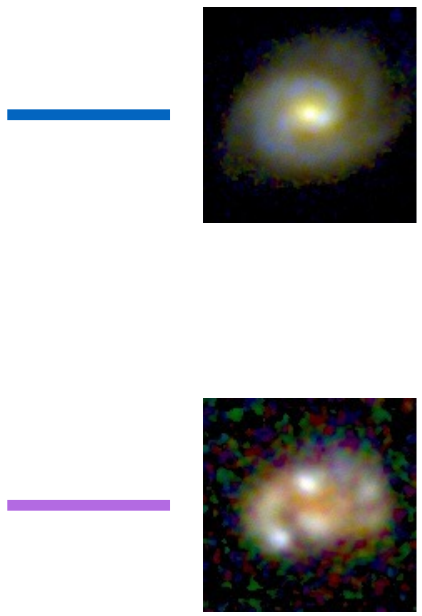


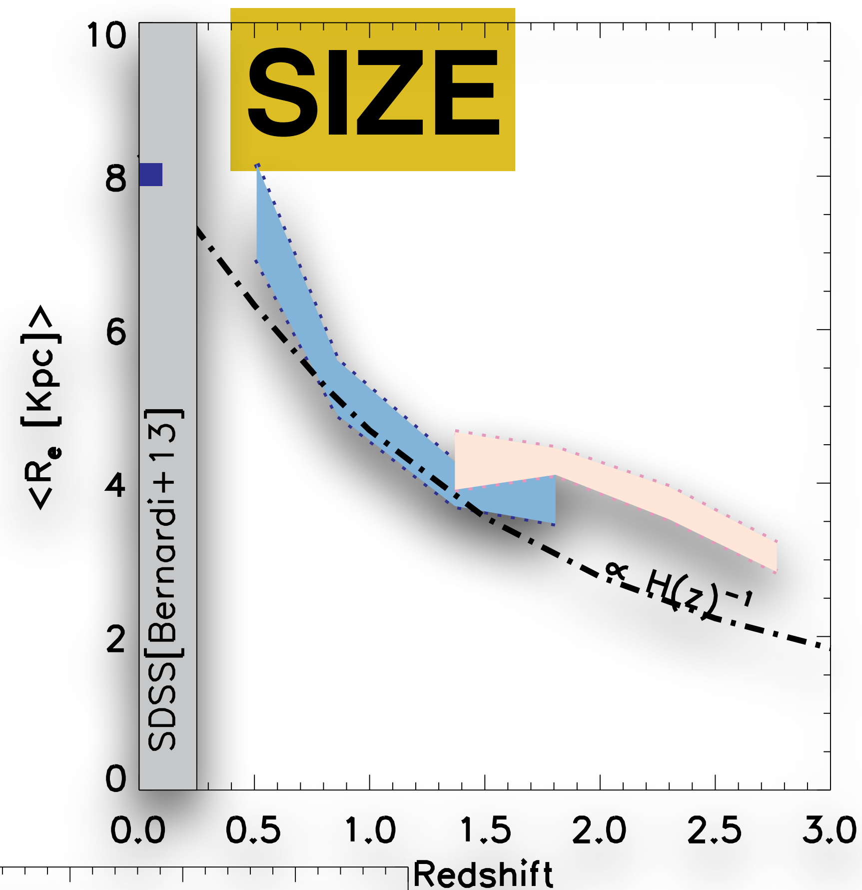


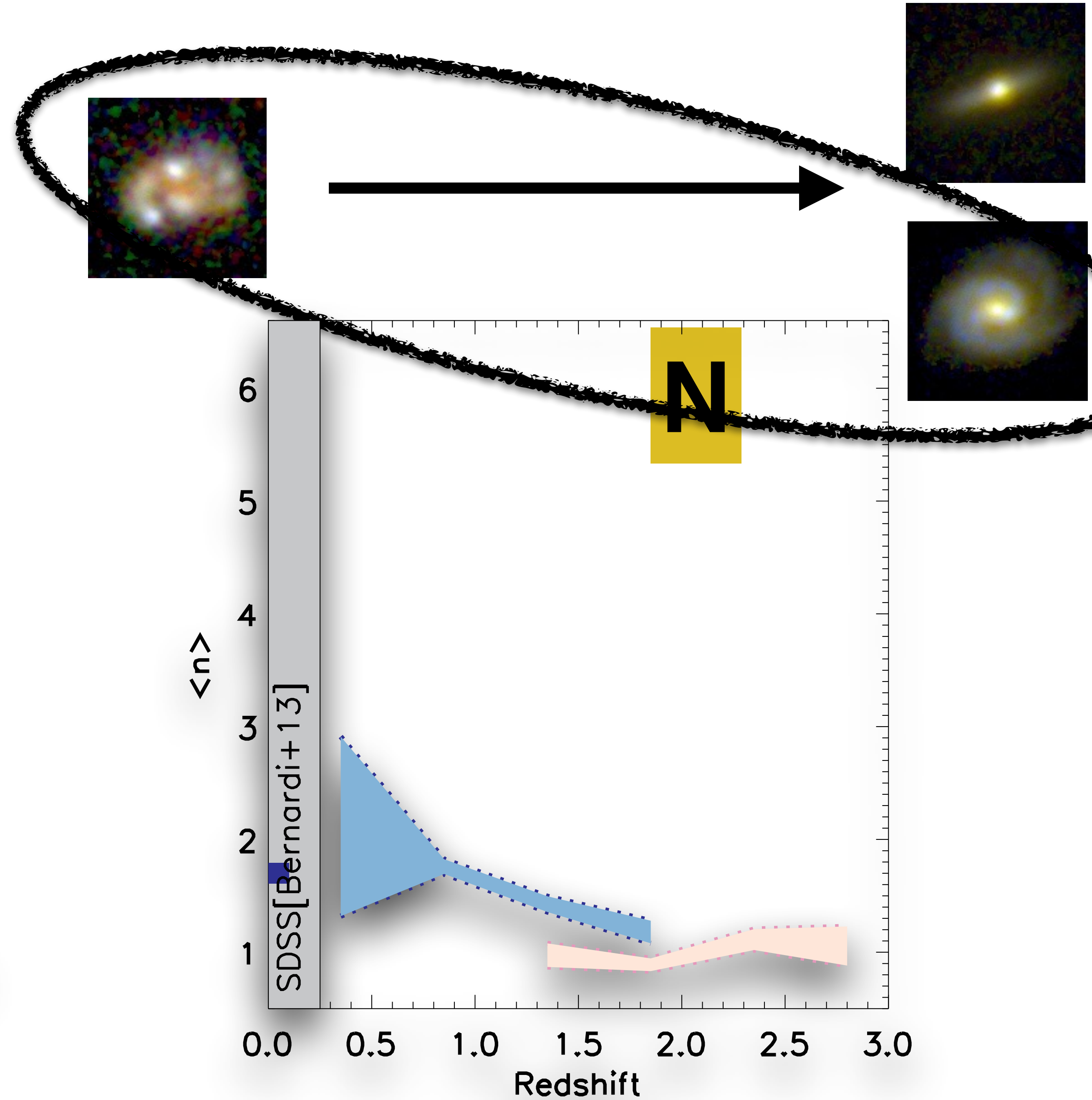


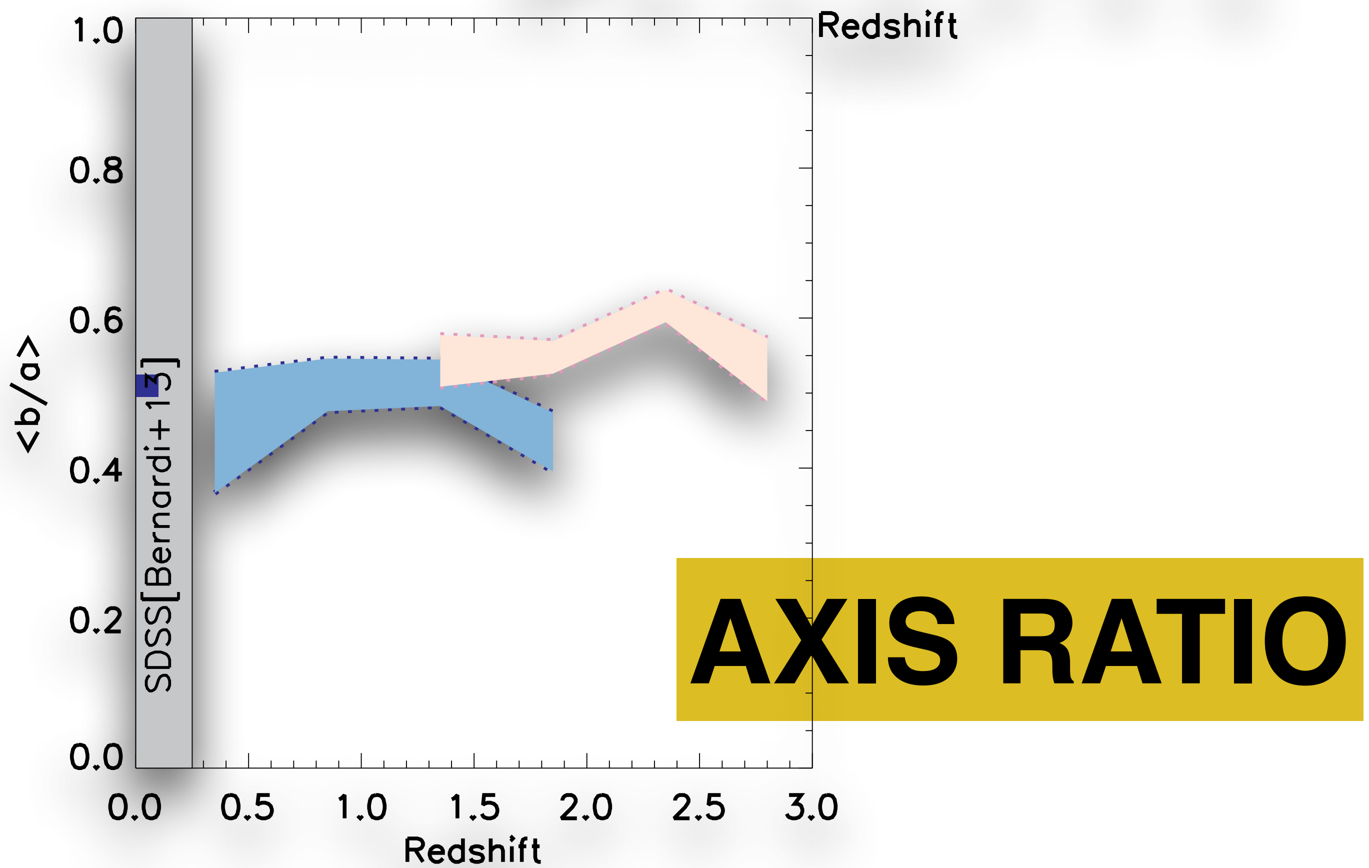
MHC+15b

Structure



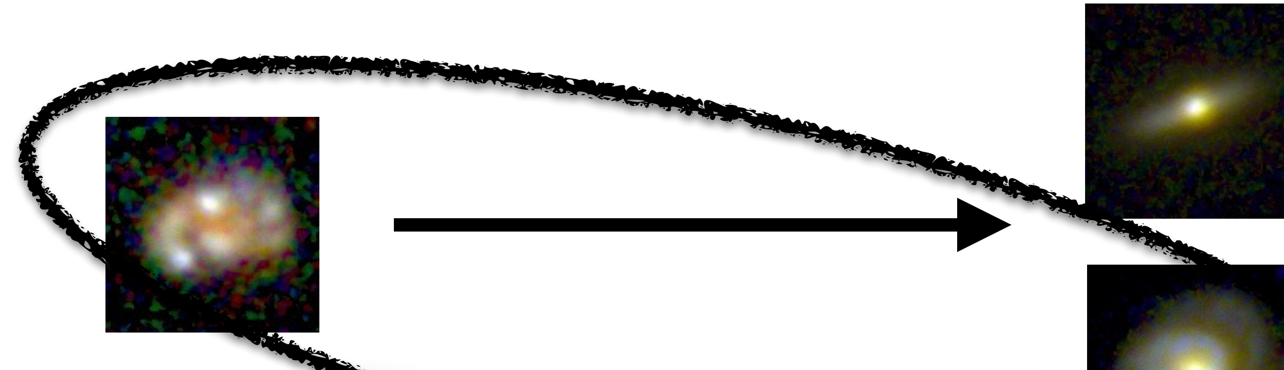


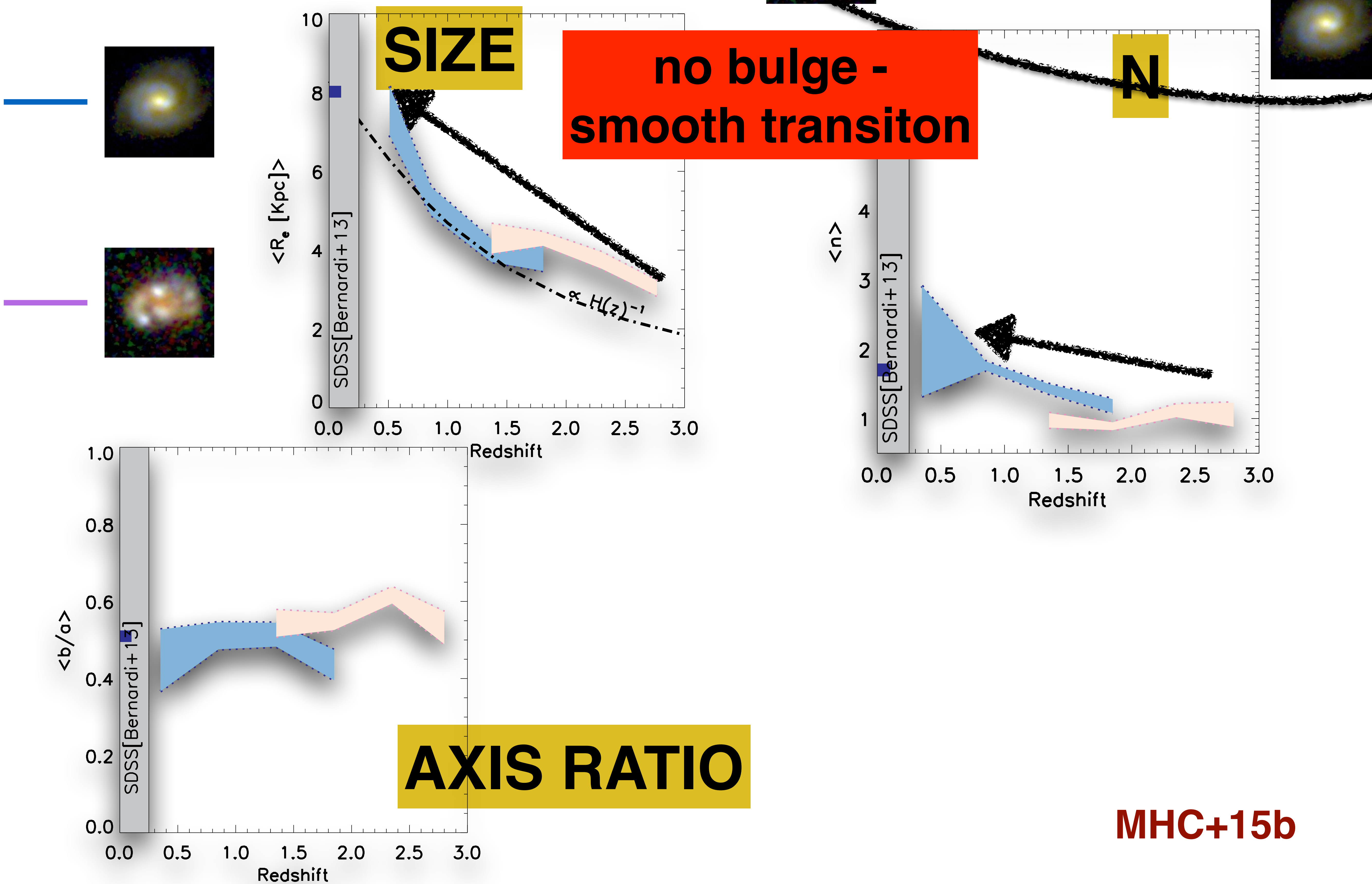




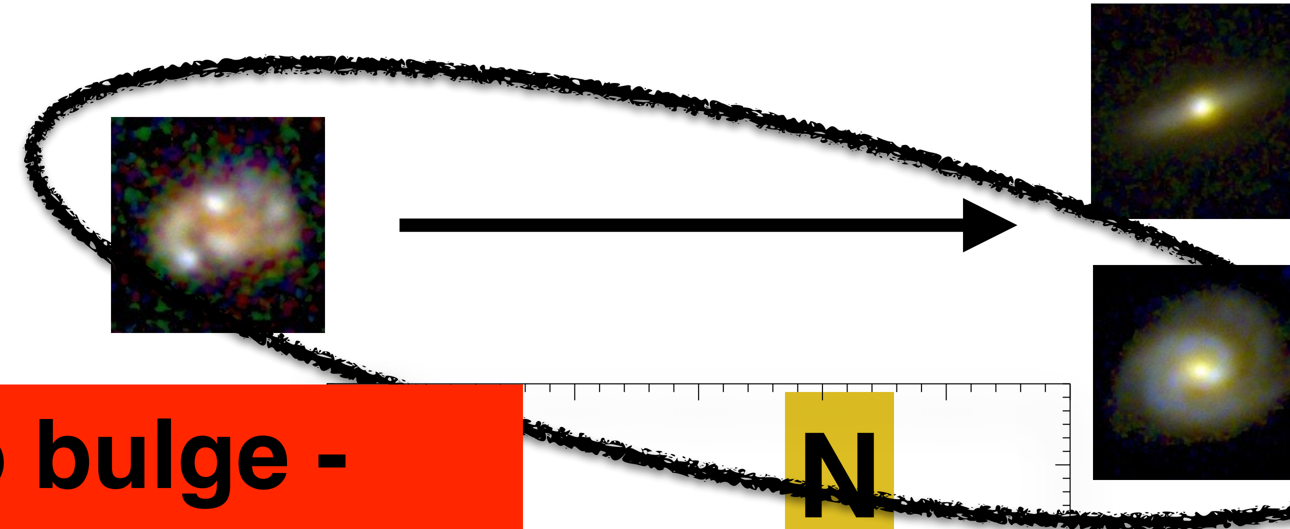
MHC+15b

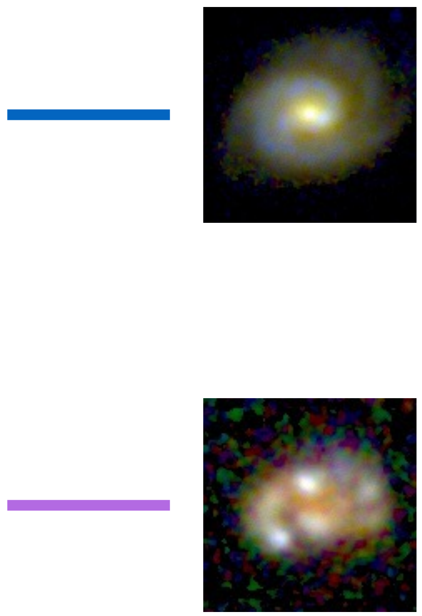
Structure

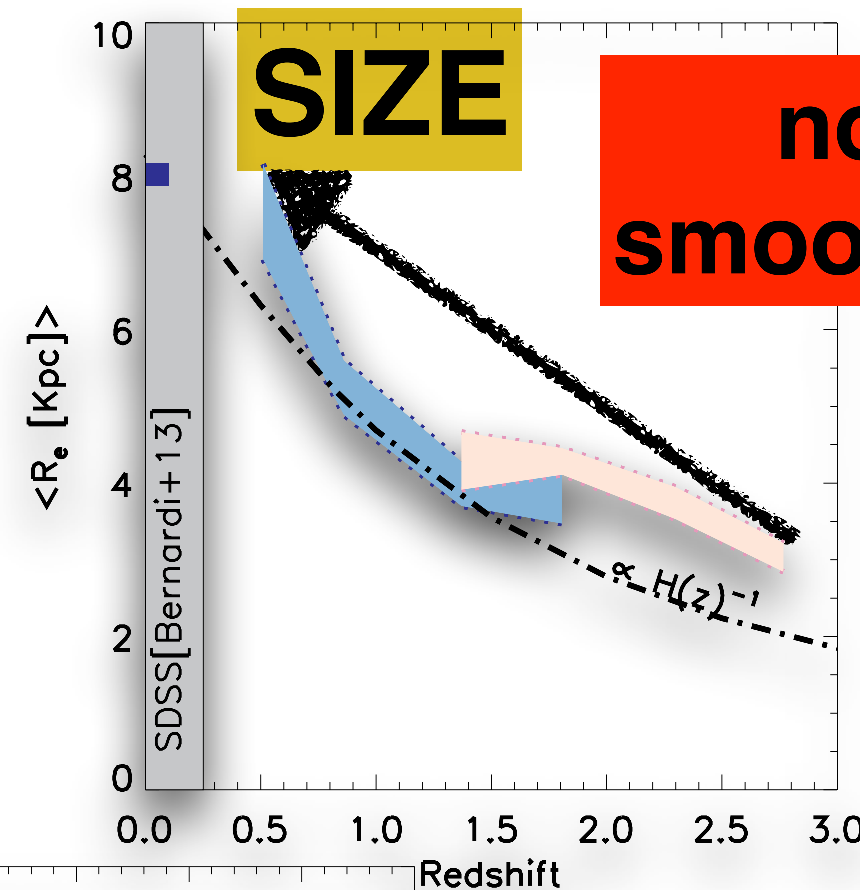



SIZE
no bulge - smooth transiton
N
AXIS RATIO
<R_e [Kpc]>
Redshift
SDSS[Bernardi+13]
∝ H(z)^-1
<n>
<b/a>
MHC+15b

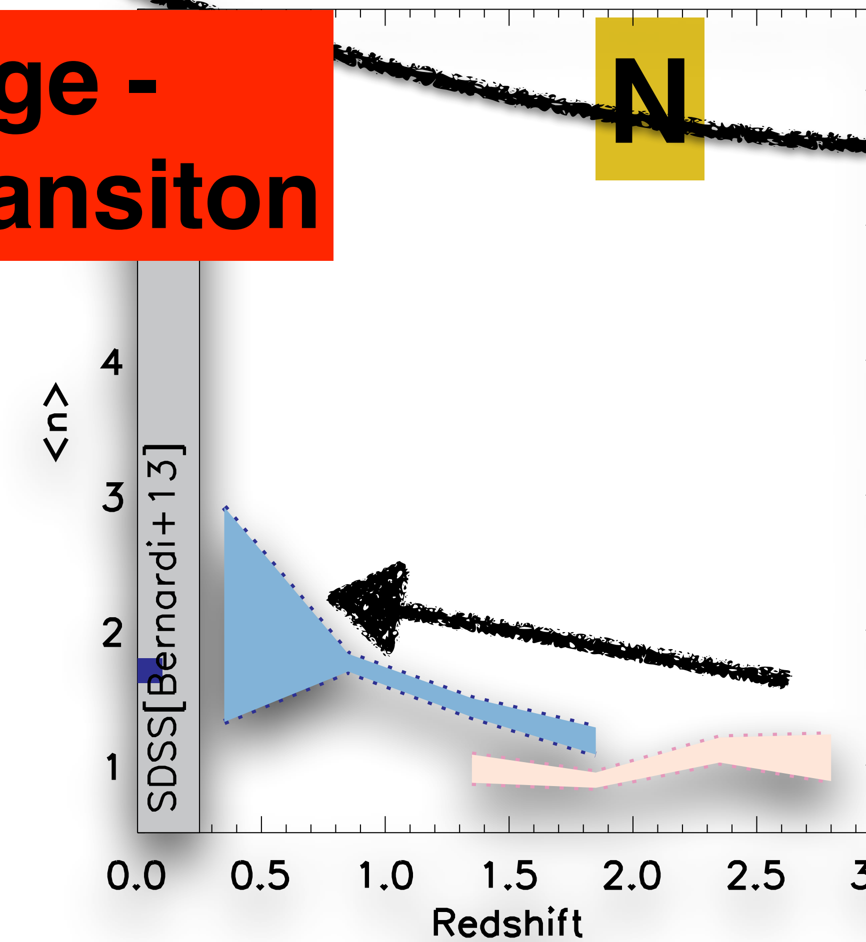
Structure

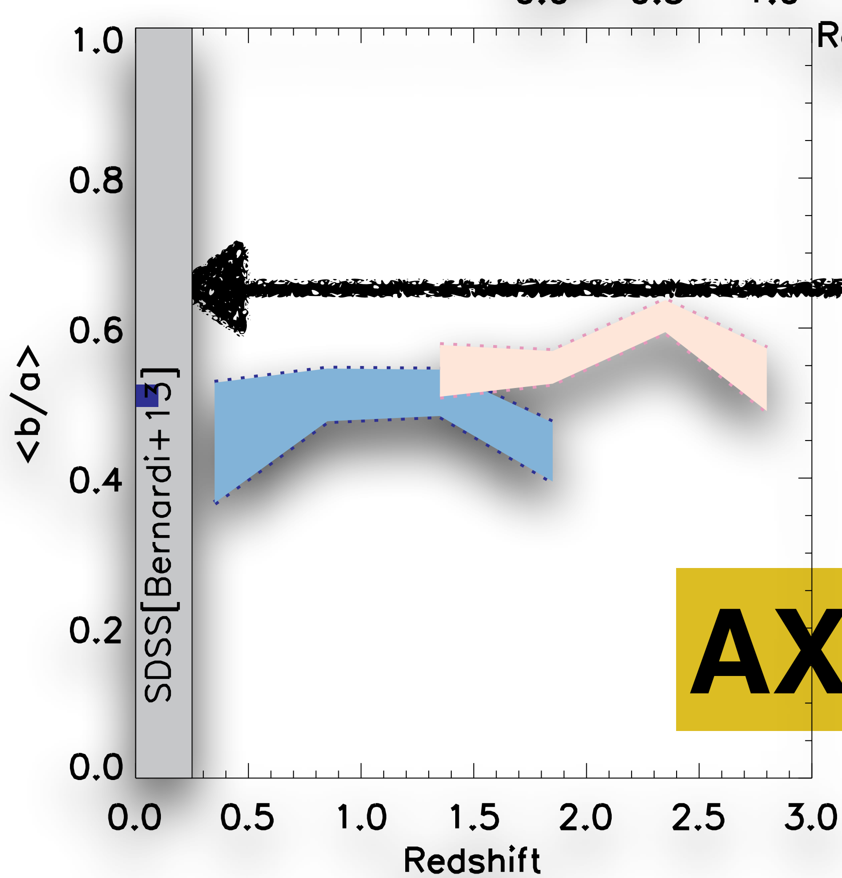






no bulge - smooth transiton



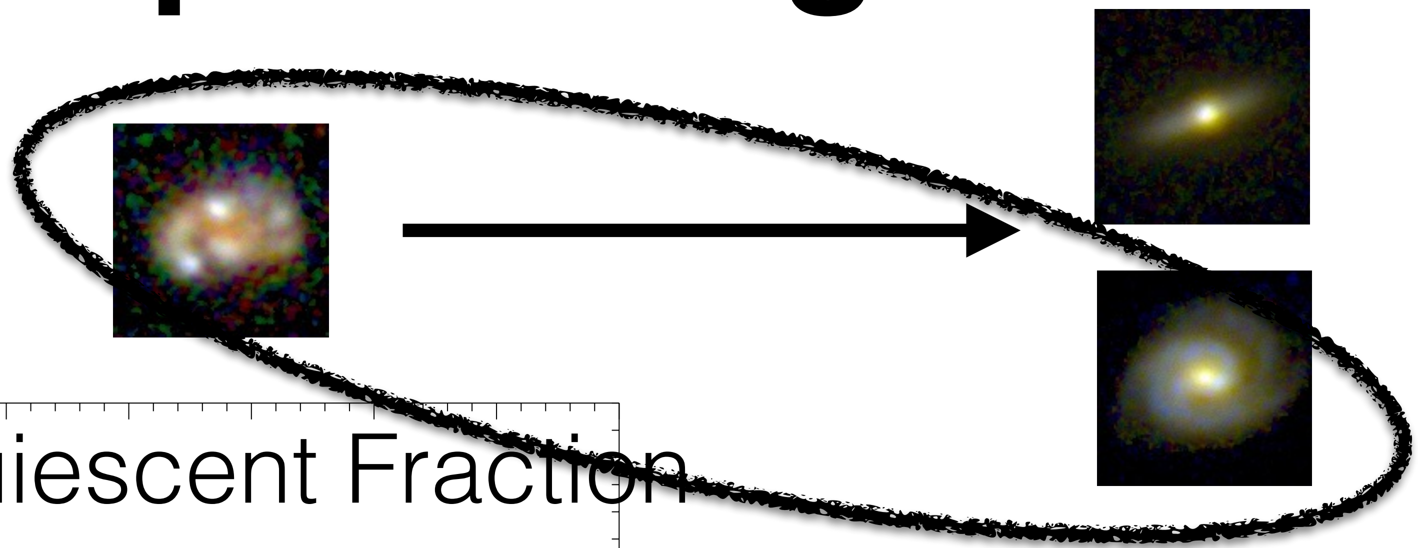


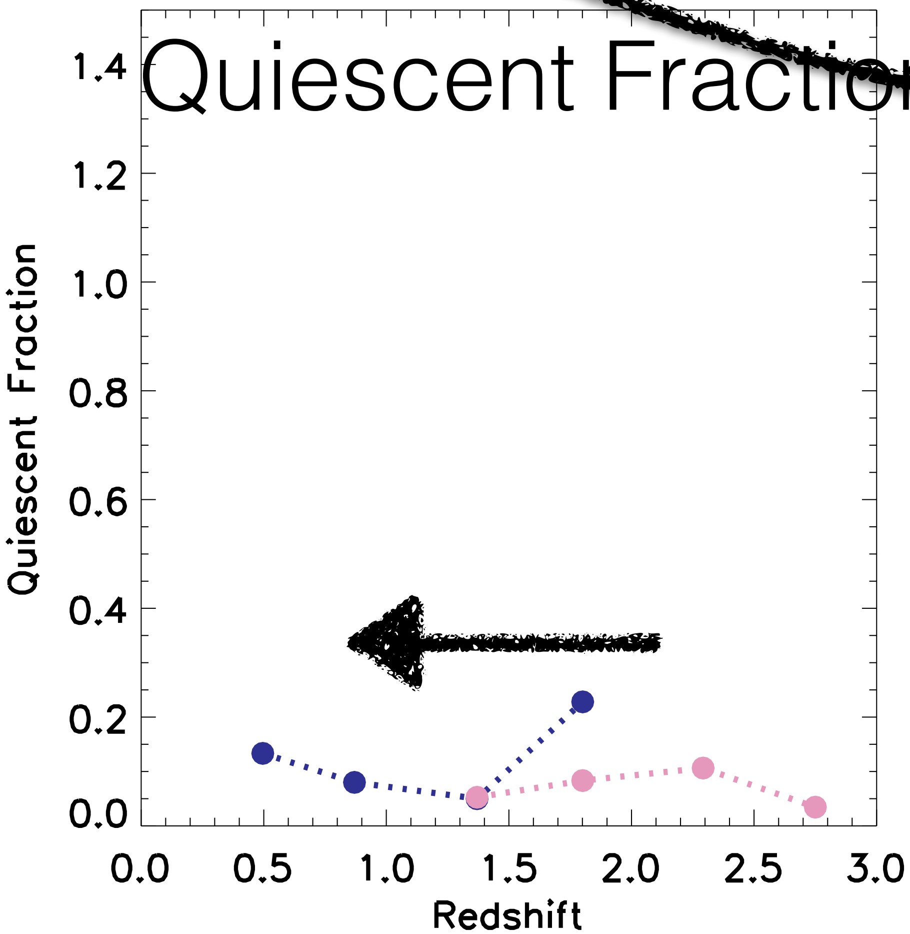
b/a~0.5

AXIS RATIO

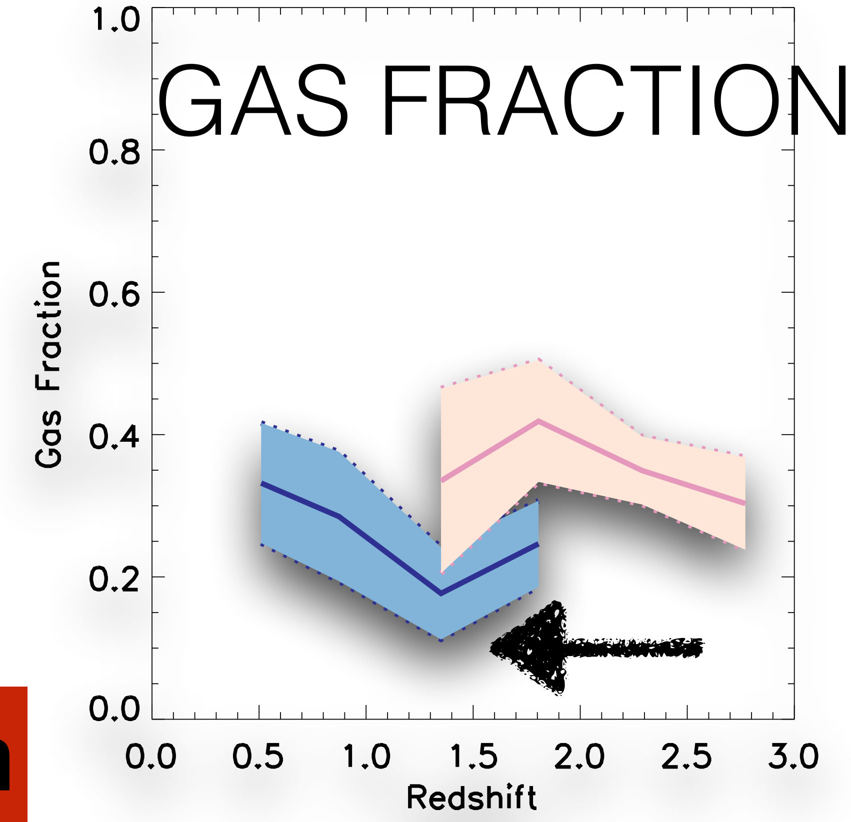
MHC+15b

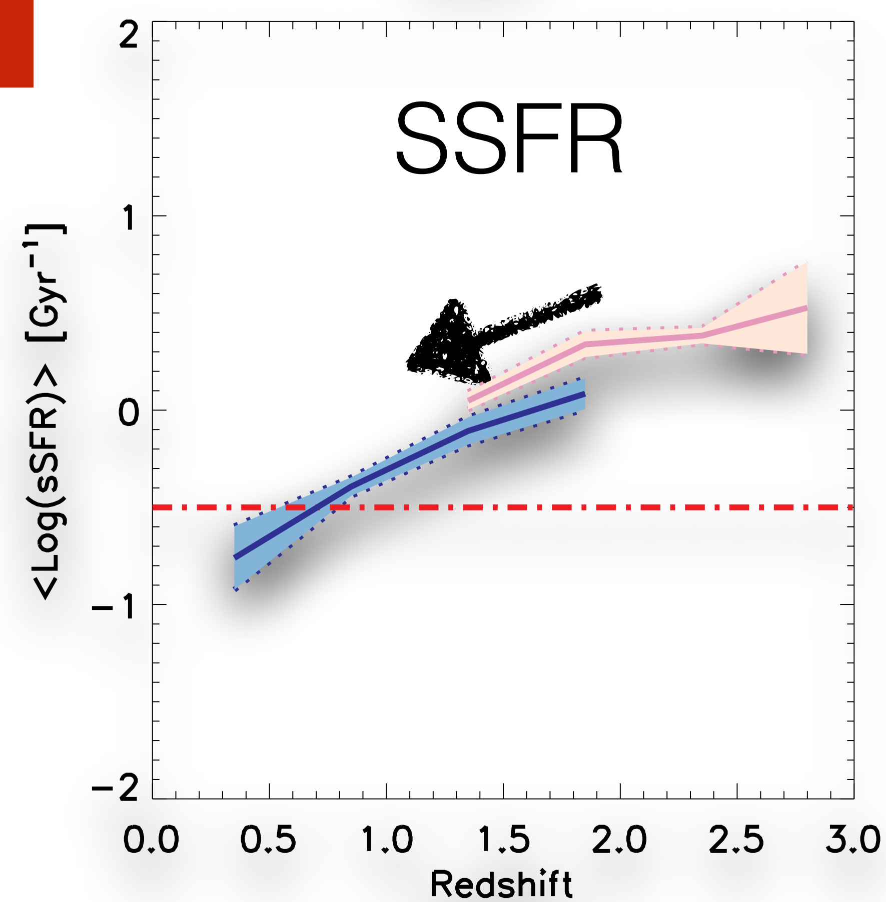
Slow quenching

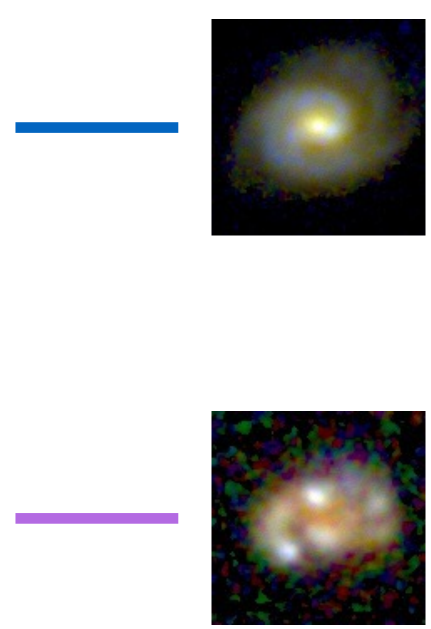


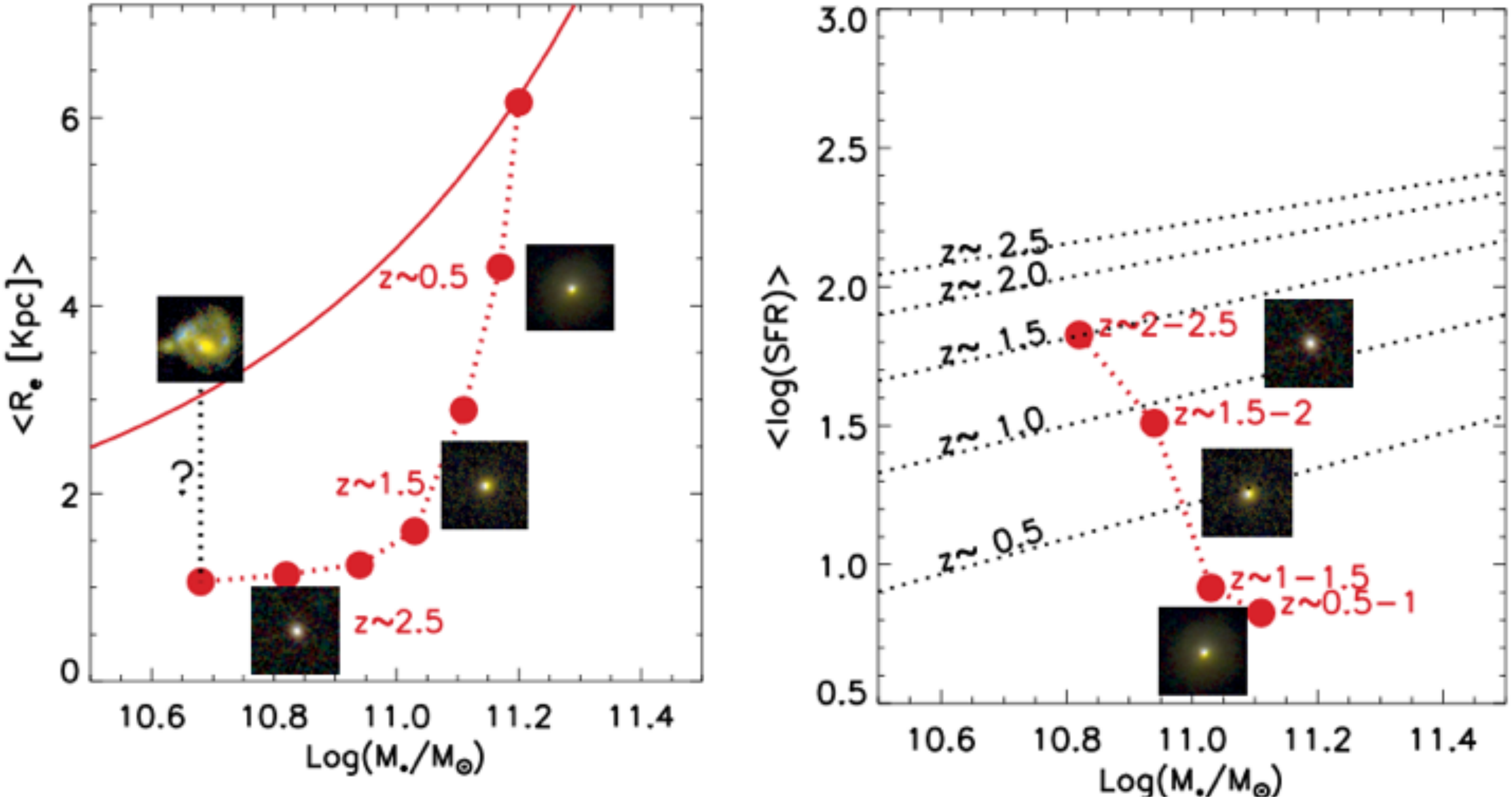


smooth transition / no bulge



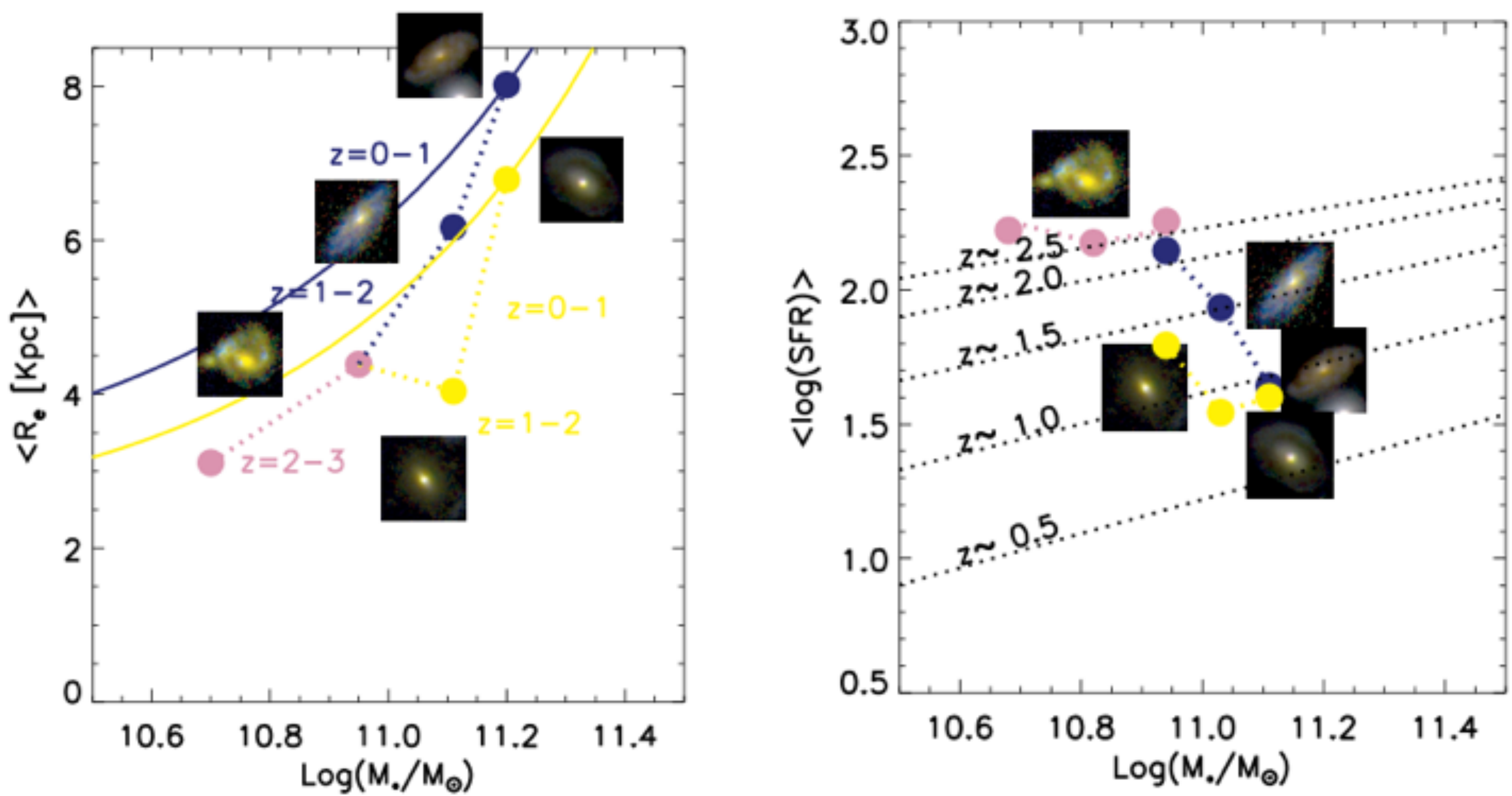






"FAST"

- fast assembly at z>2
- steep growth with low SFRs at z<2
- morphology unaltered



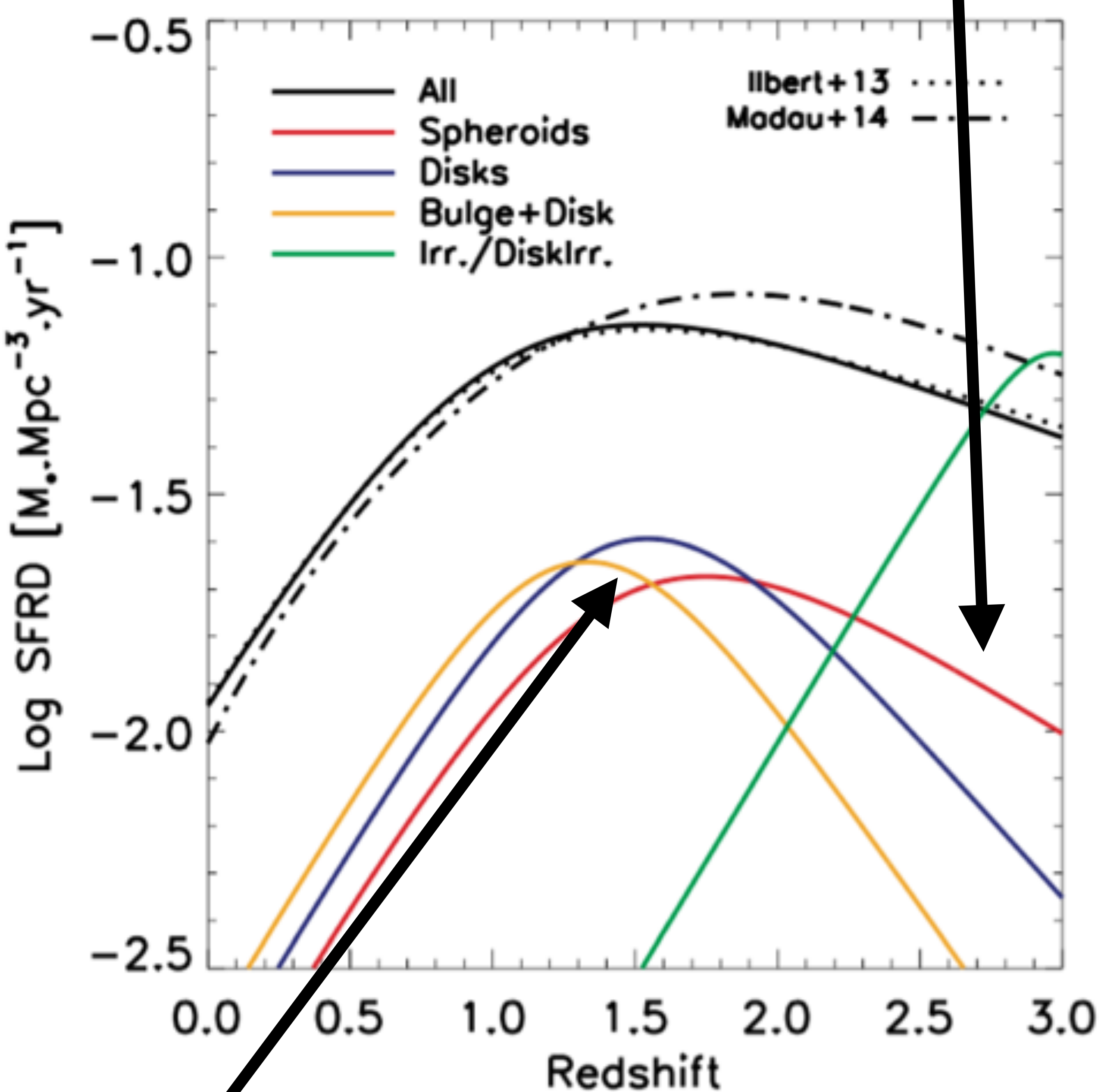
"SLOW"

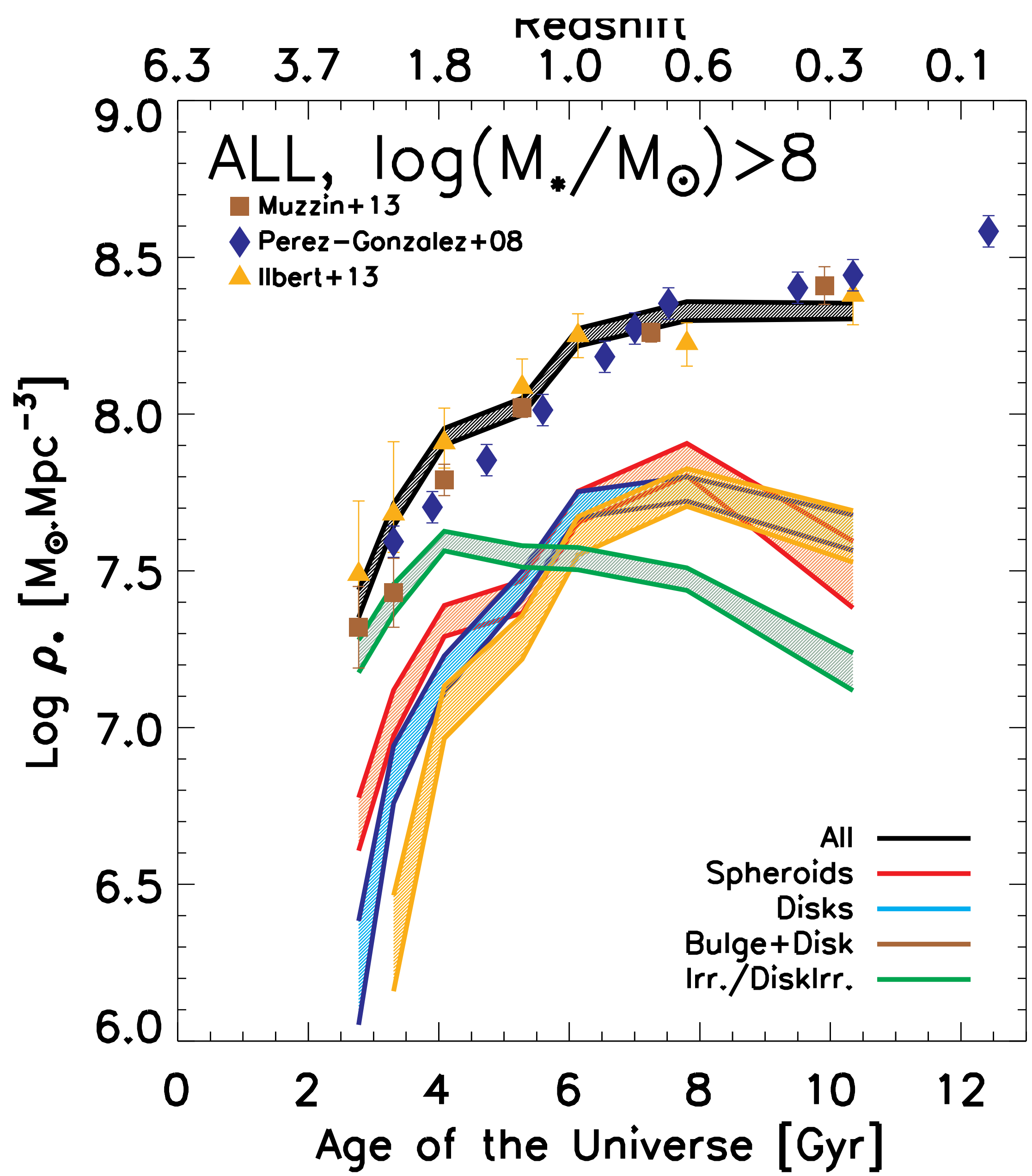
- morphological transformation of disturbed systems at z>1
- 2/3 experience bulge growth + quenching
- 1/3 smooth transition

Log(M)>8

Lilly-Madau plot

spheroids+irregulars dominate the SFRD

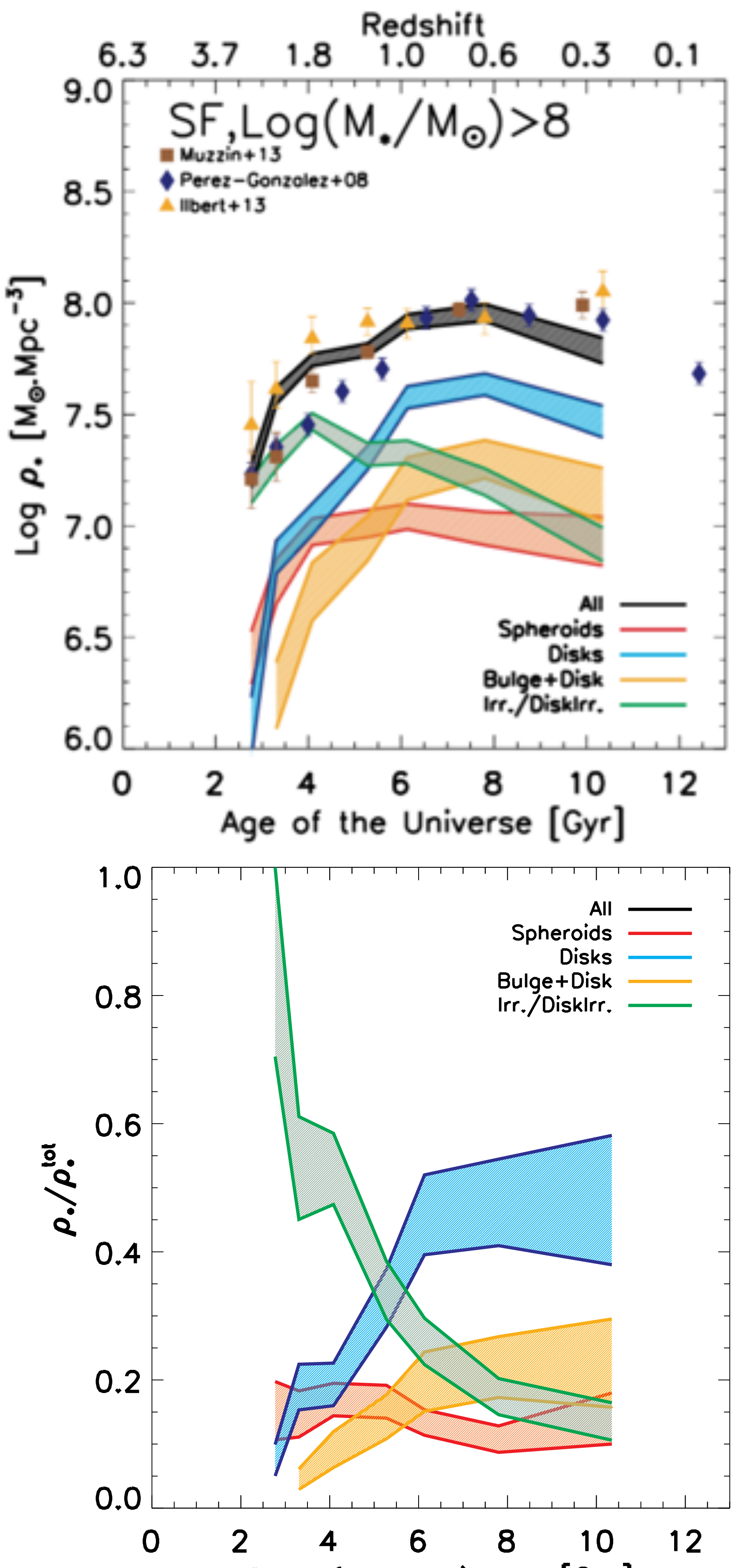




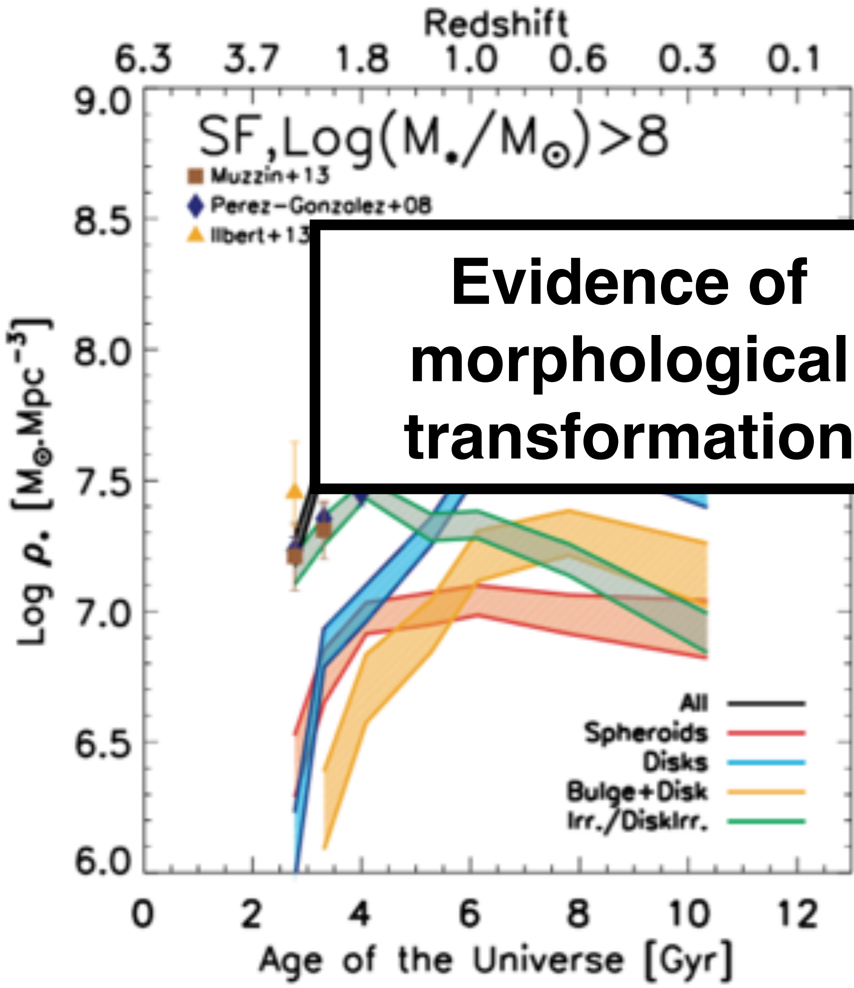
SFRD in disks

MHC+16

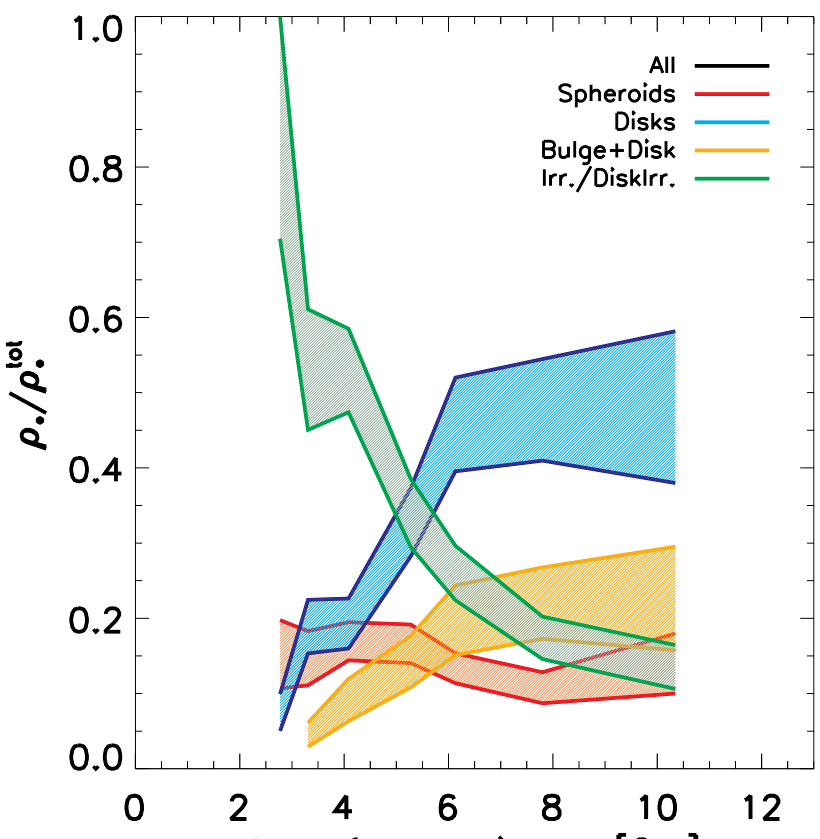
STAR-FORMING GALAXIES



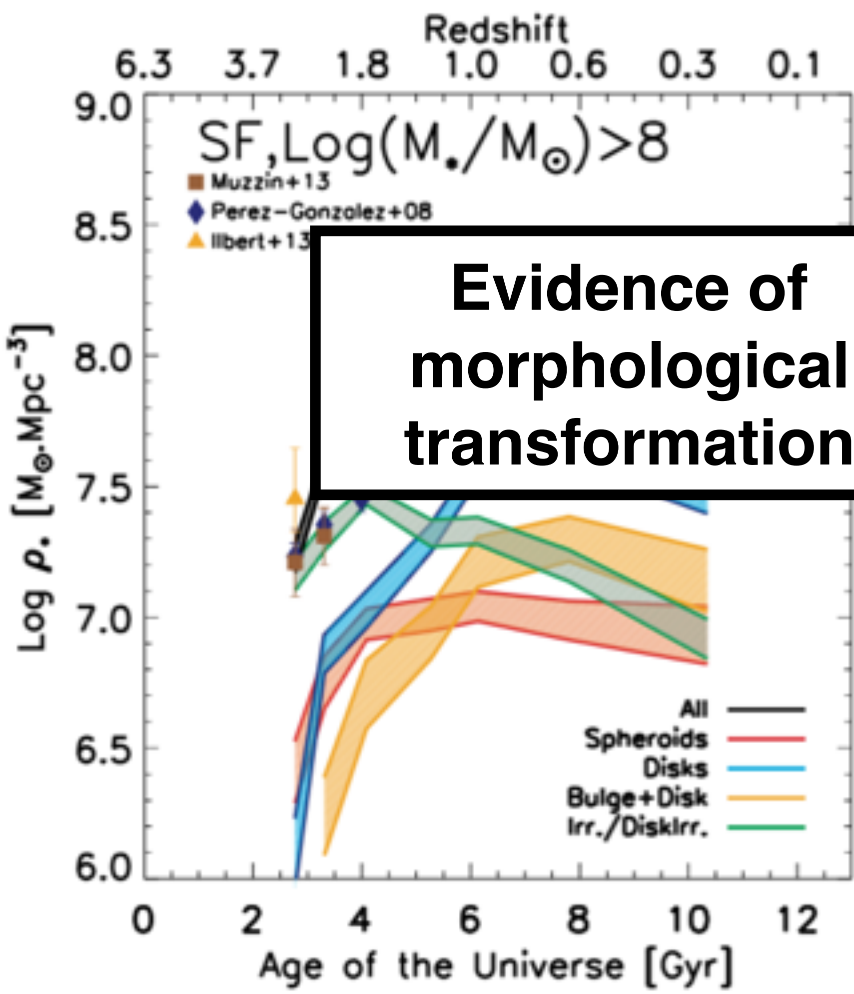
STAR-FORMING GALAXIES



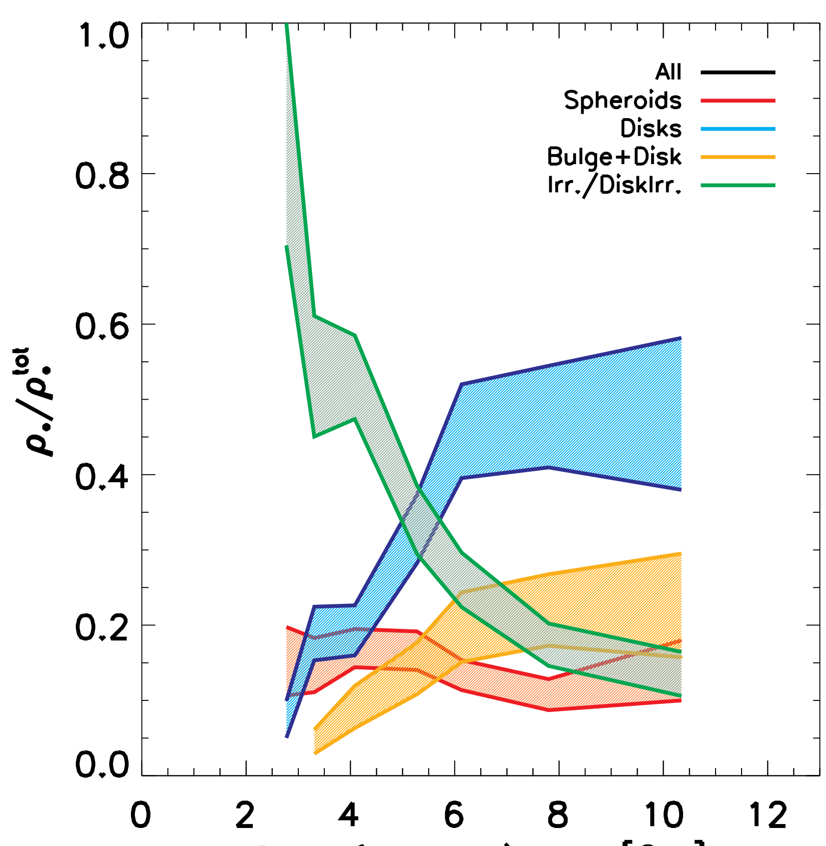
Evidence of morphological transformation

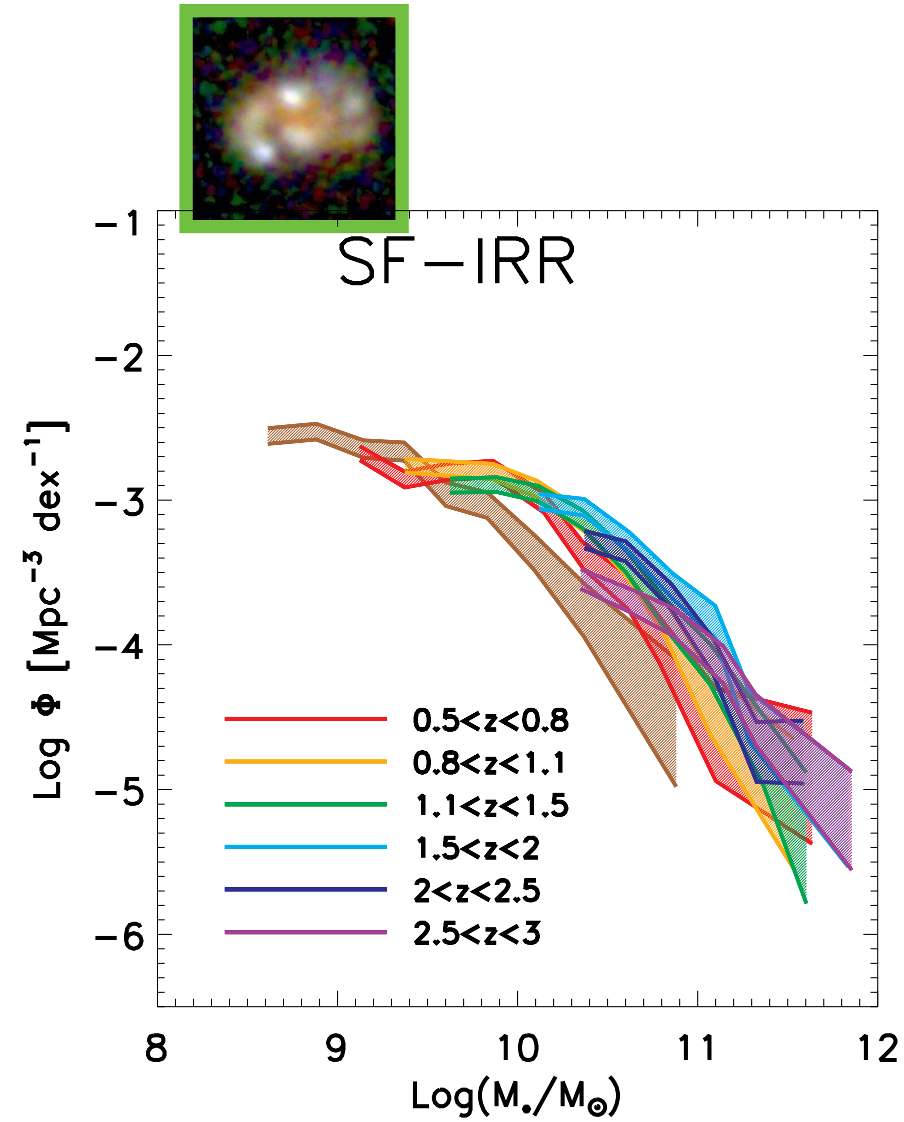


STAR-FORMING GALAXIES

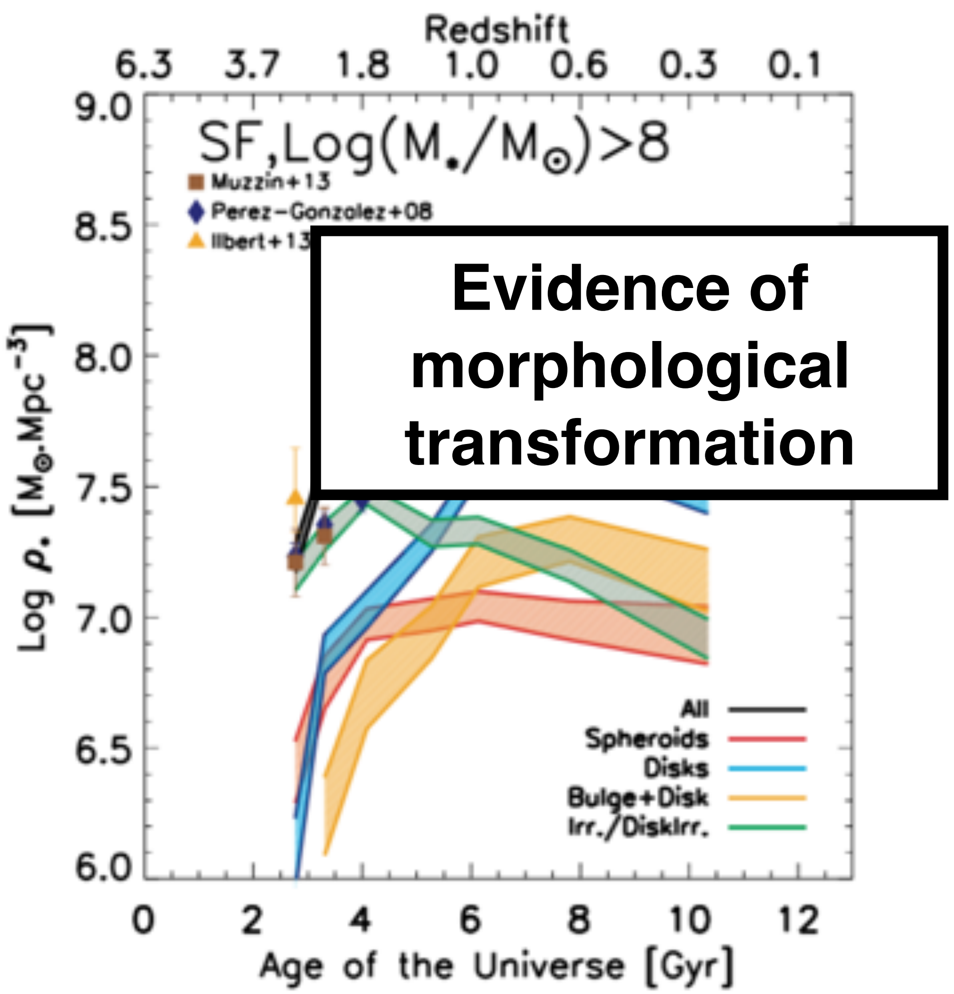


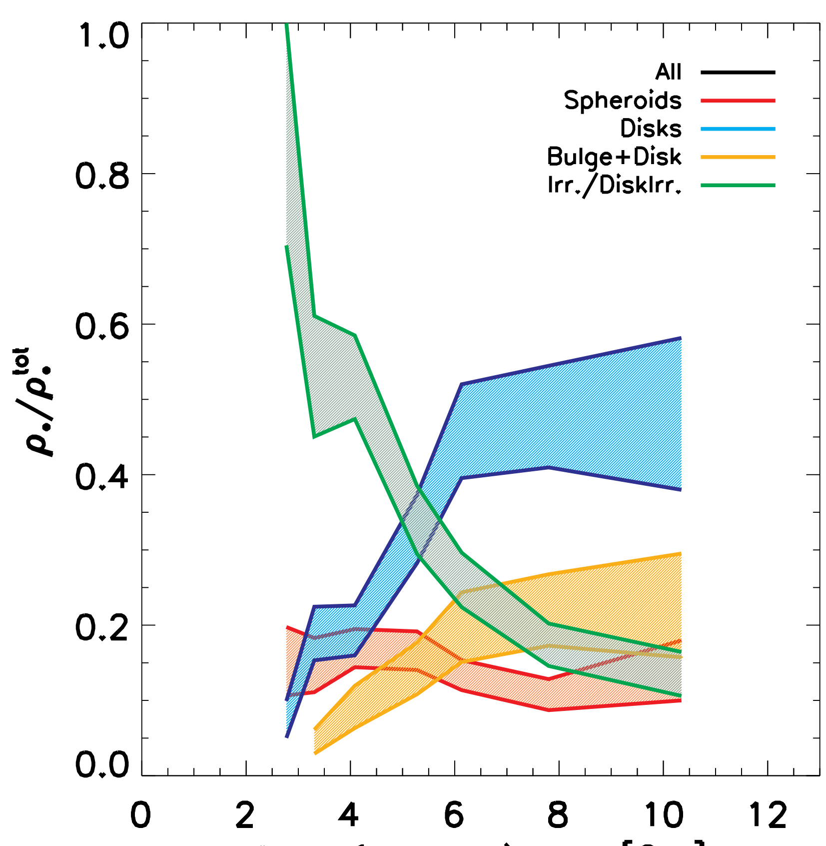
Evidence of morphological transformation

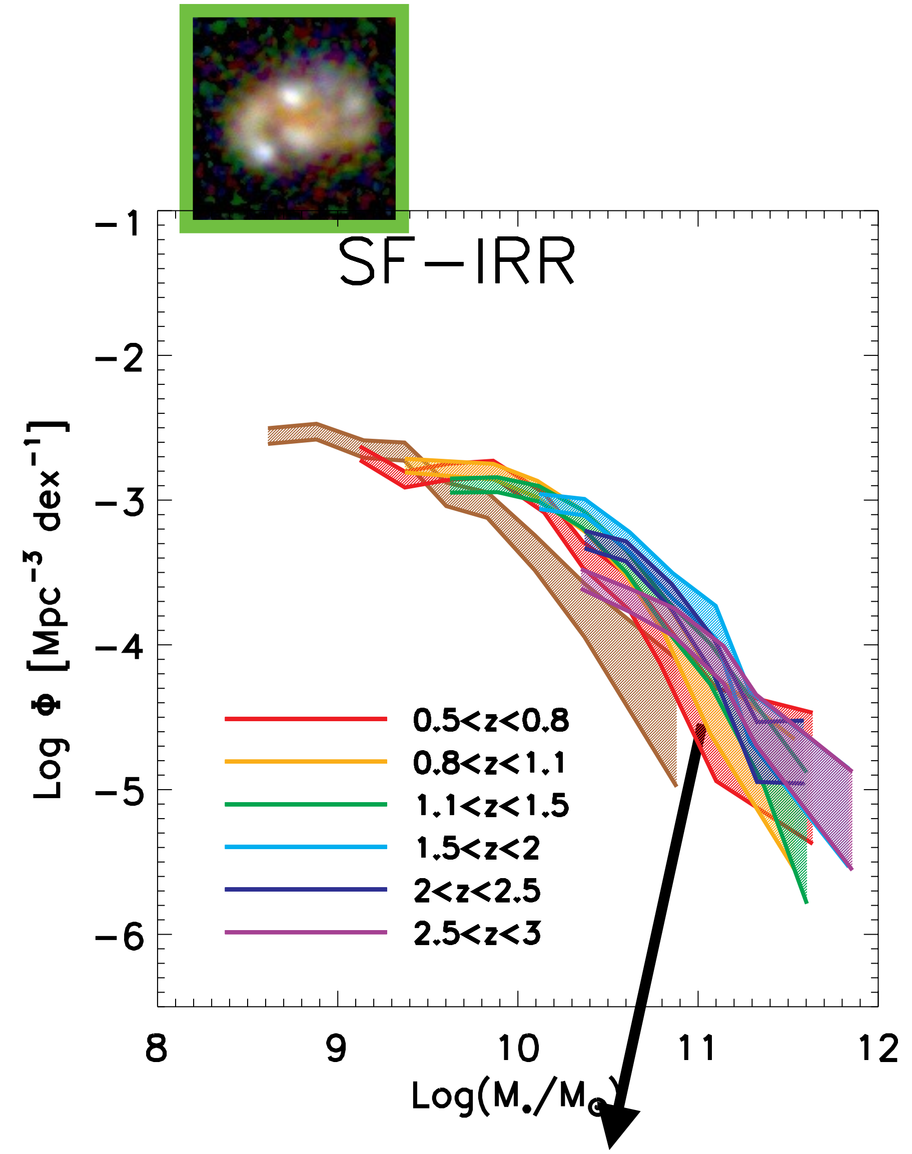




STAR-FORMING GALAXIES

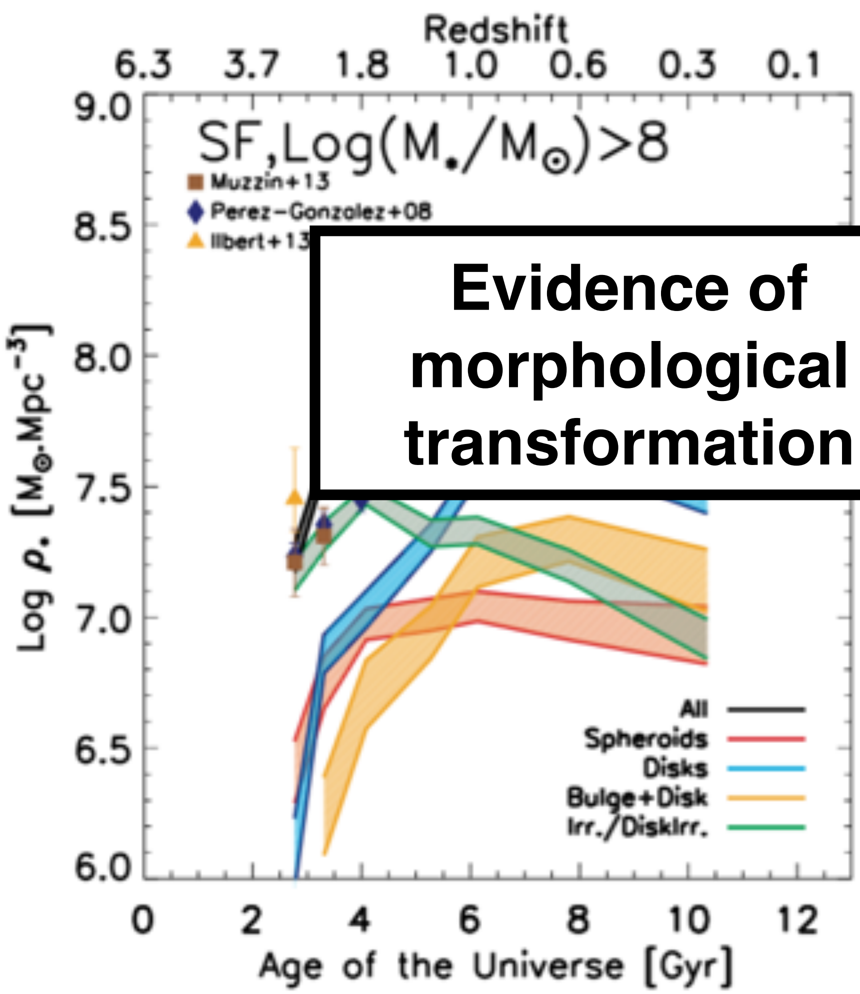




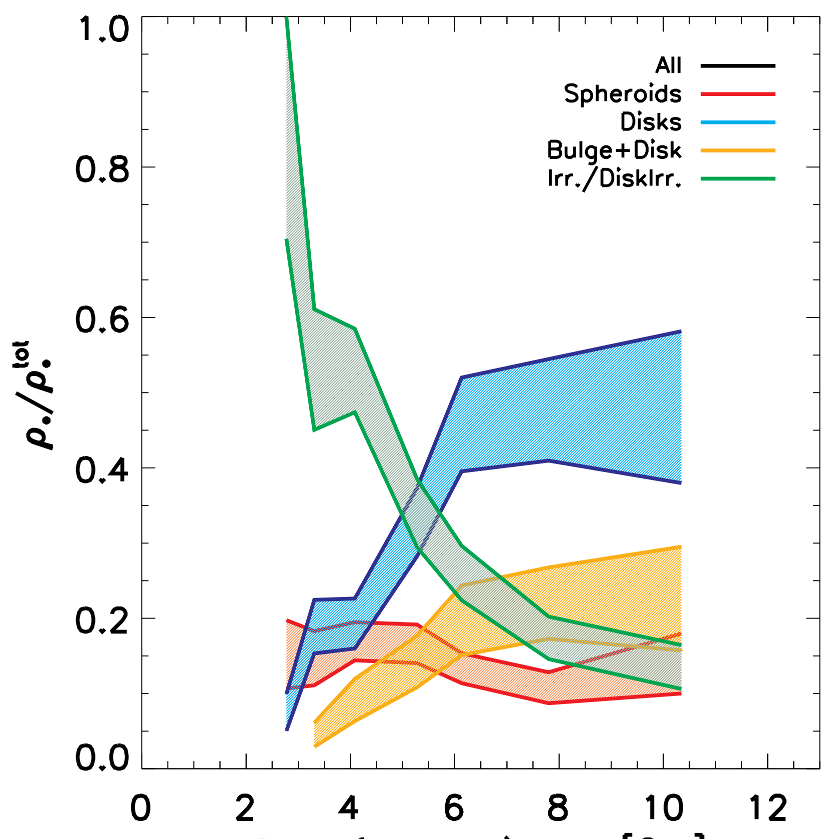


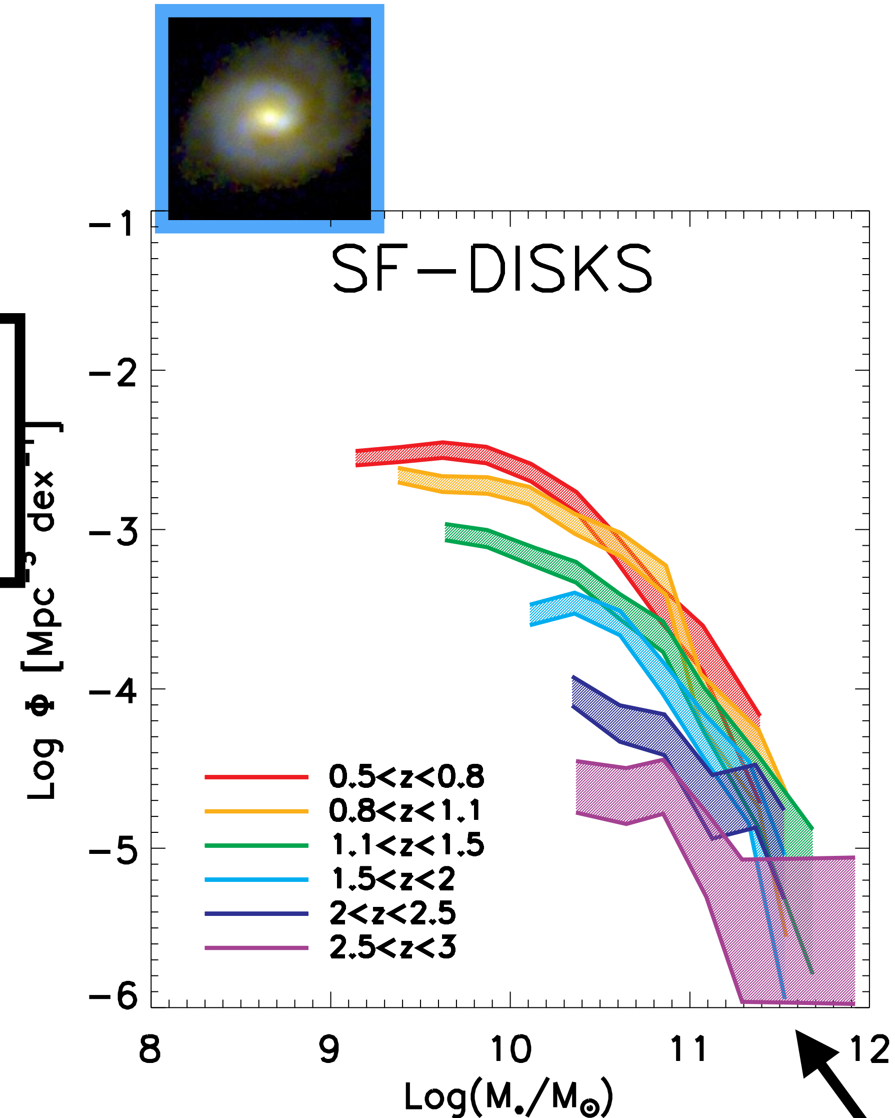
Morphological transformations

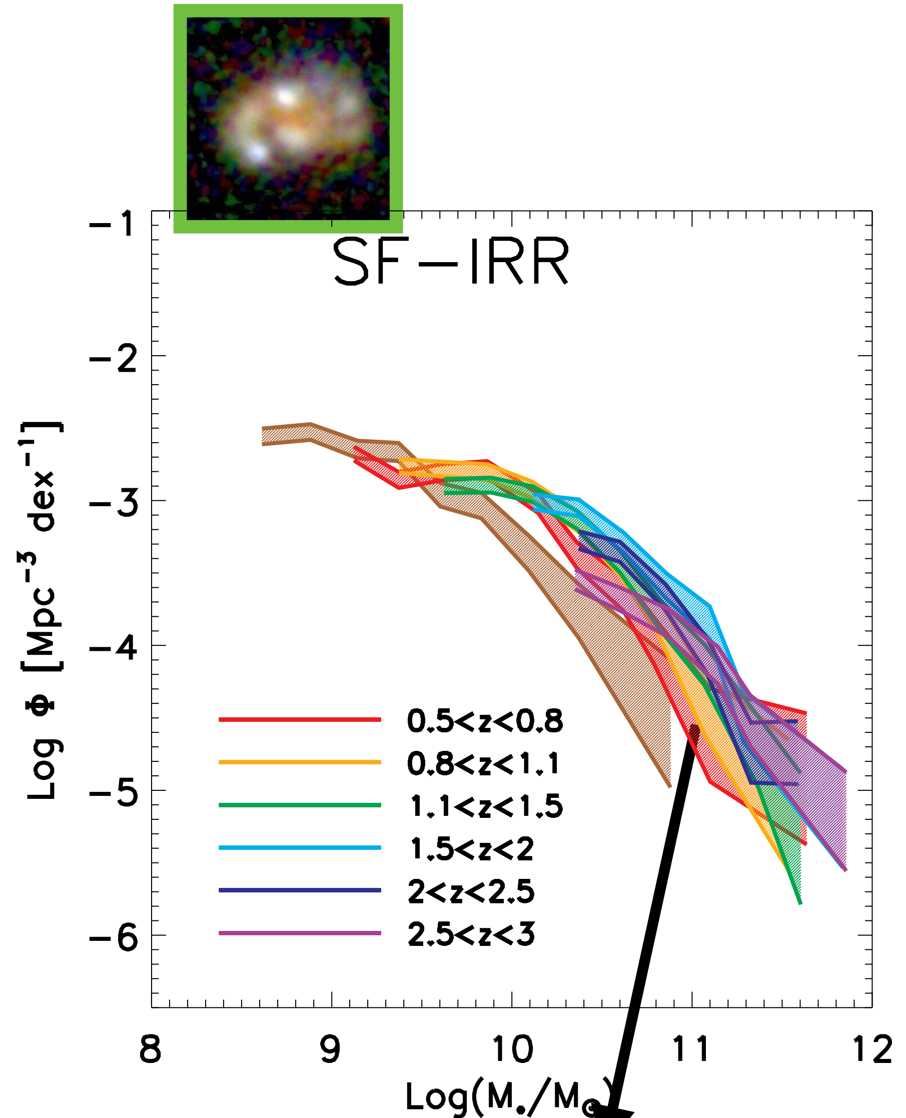
STAR-FORMING GALAXIES



Evidence of morphological transformation

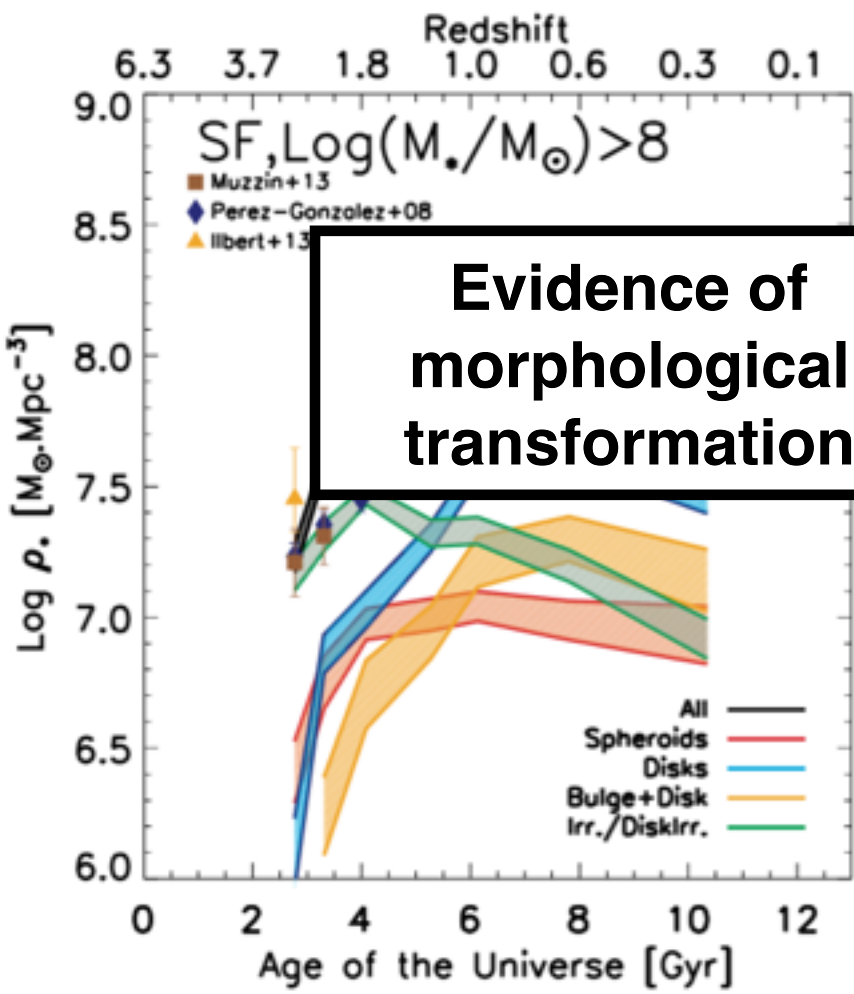




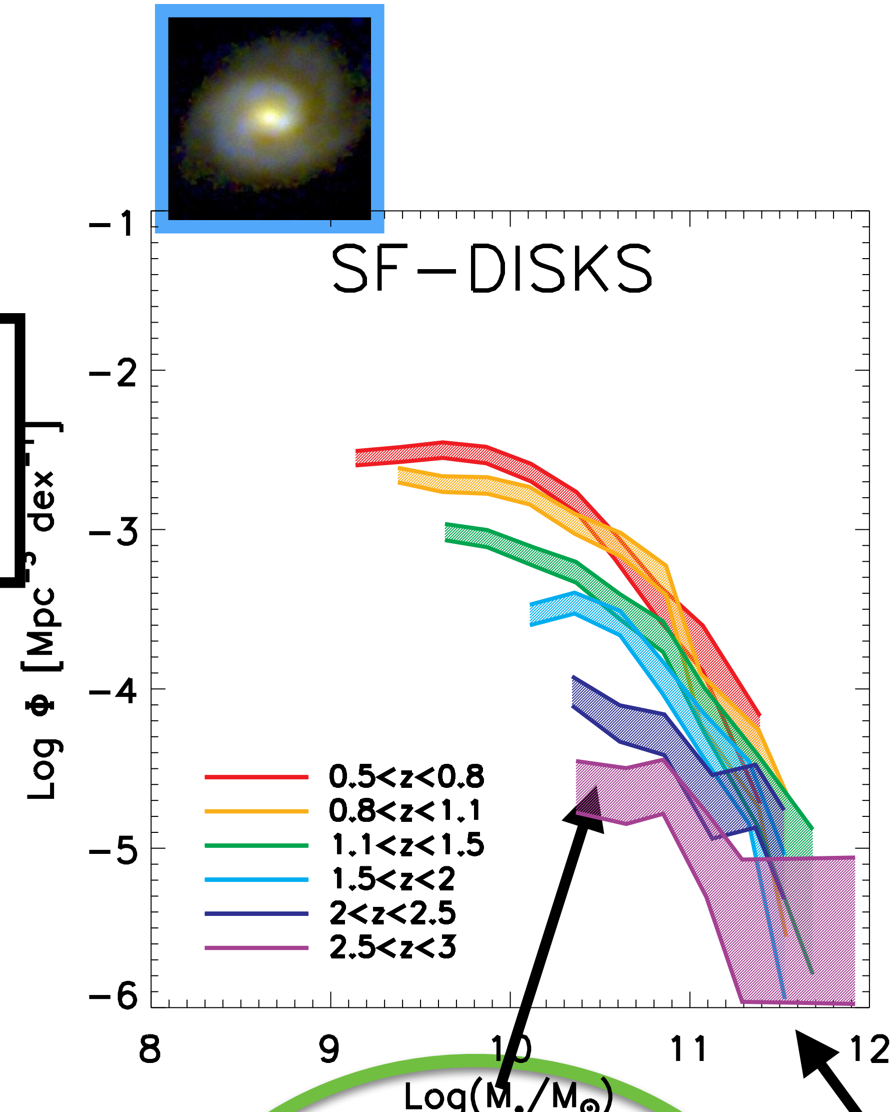


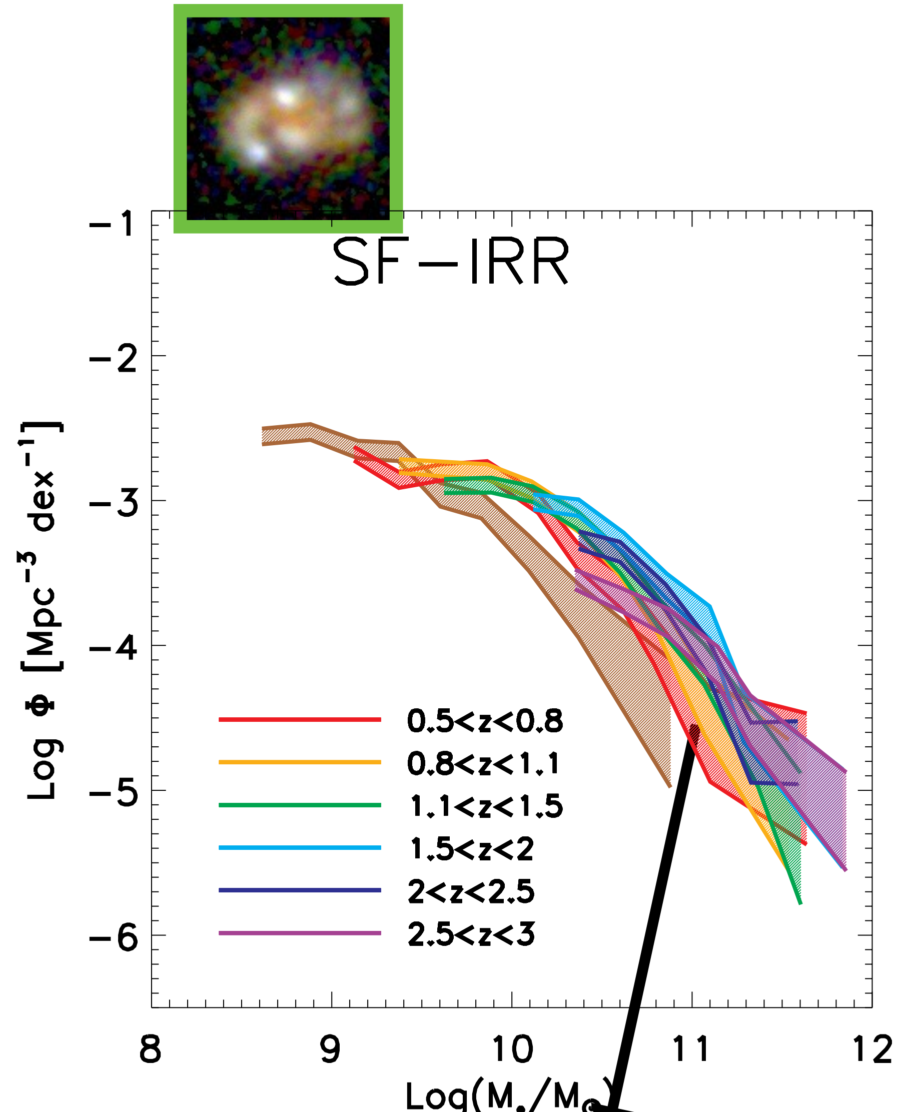
Morphological transformations

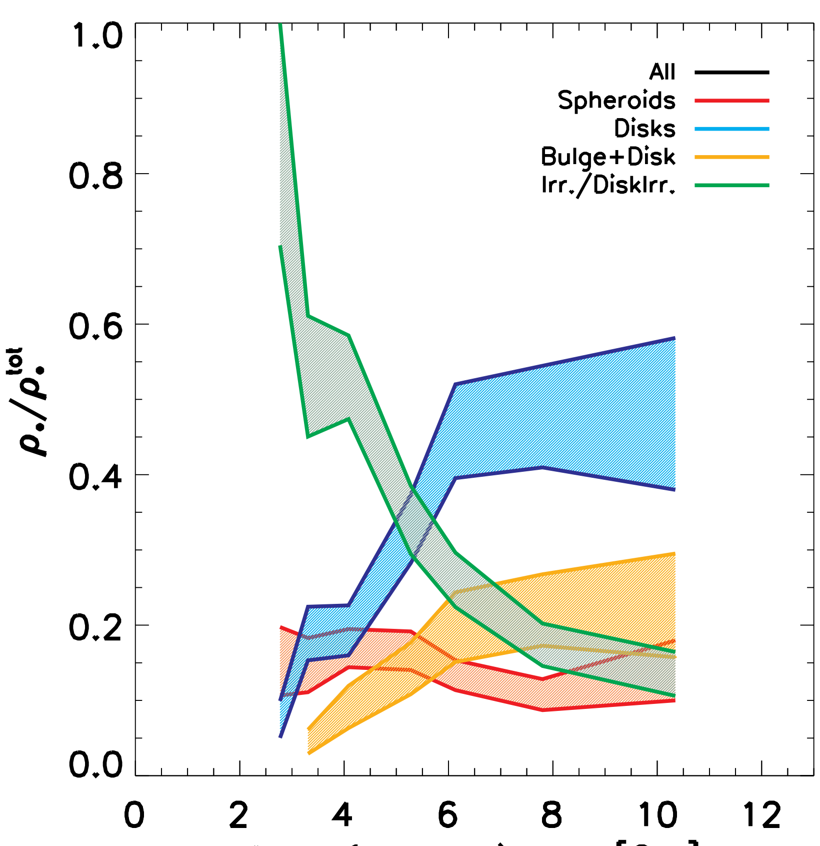
STAR-FORMING GALAXIES



Evidence of morphological transformation



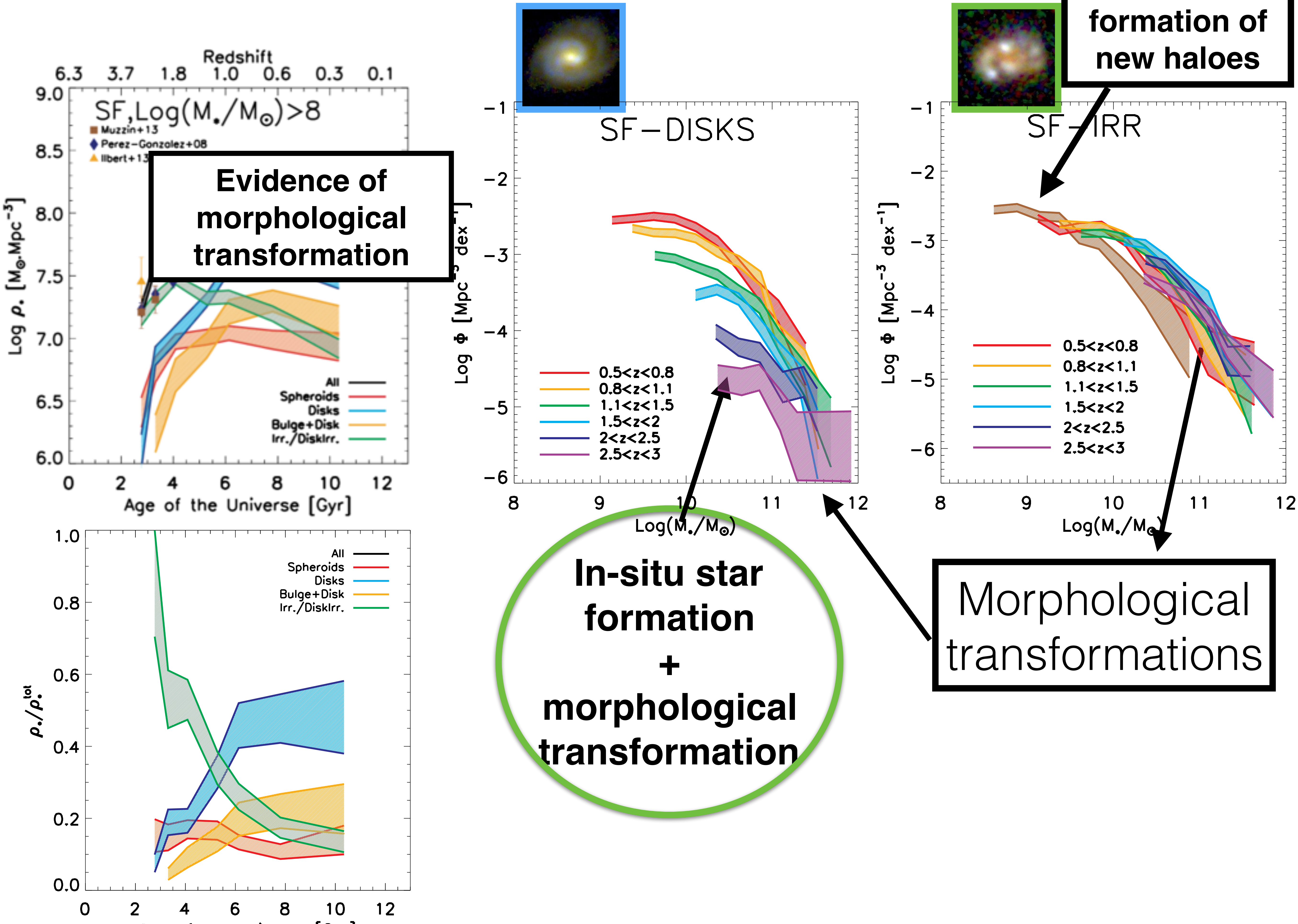




In-situ star formation + morphological transformation

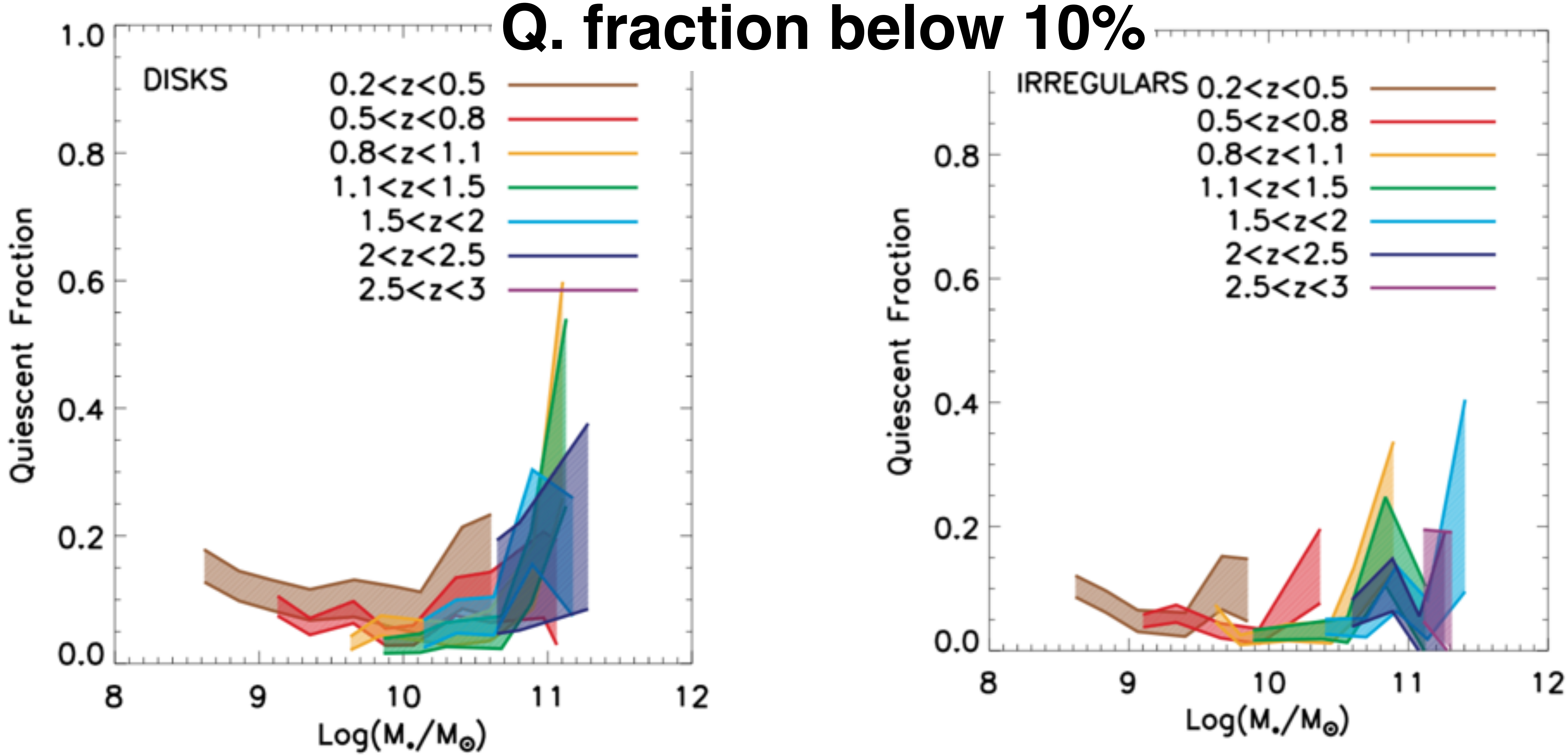
Morphological transformations

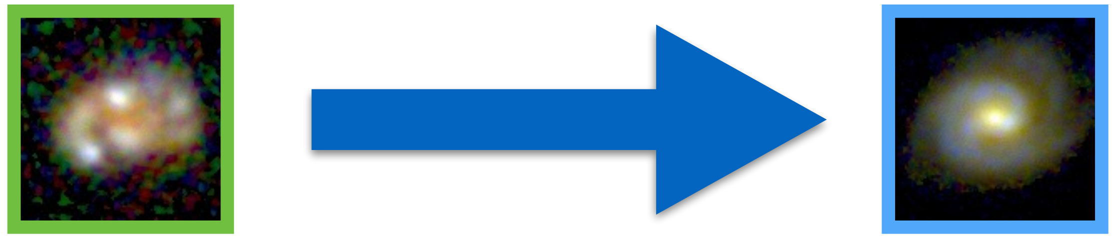
STAR-FORMING GALAXIES



Transformation **mainly** without interruption of star-formation (statistically speaking)

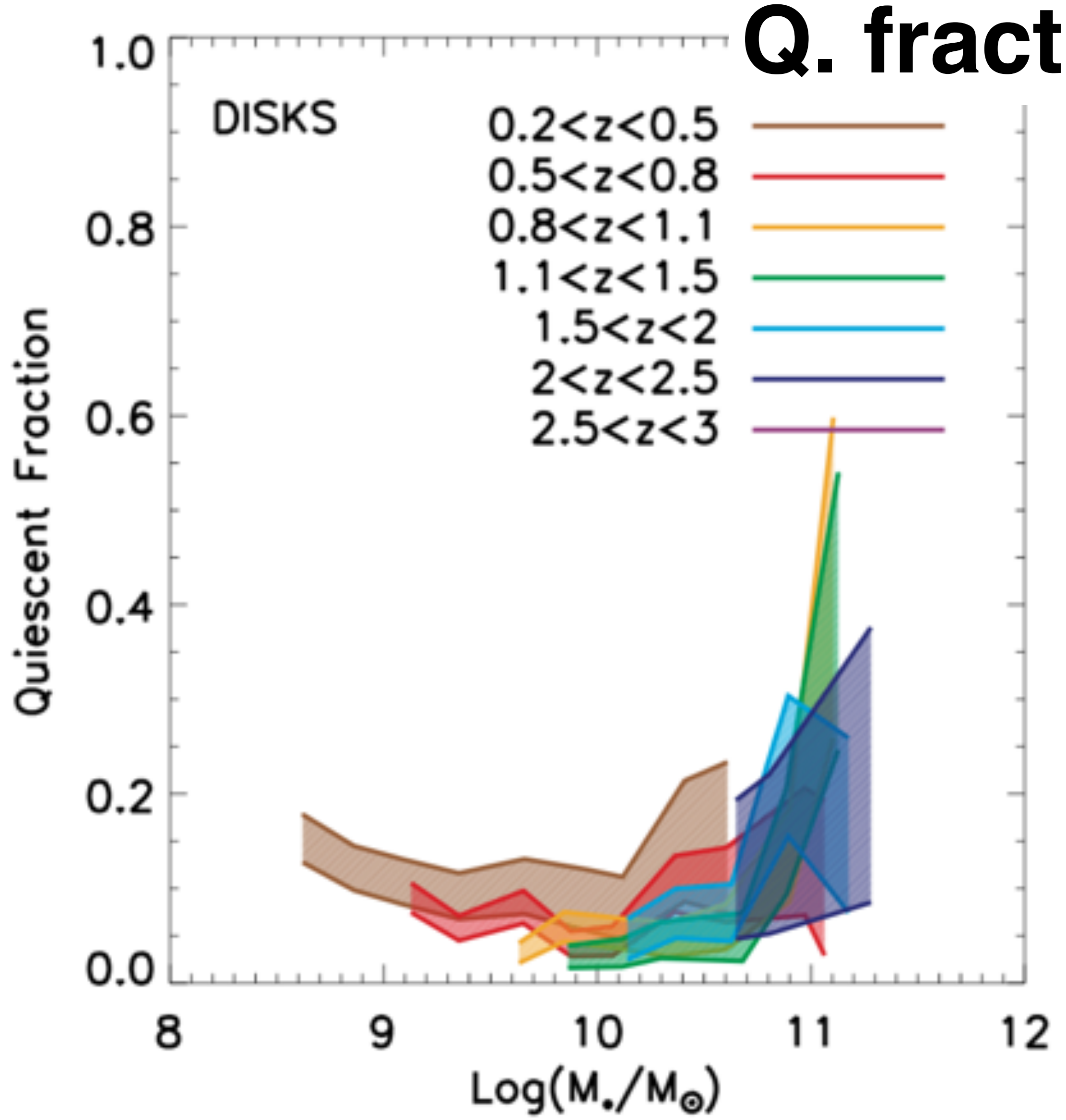
Q. fraction below 10%

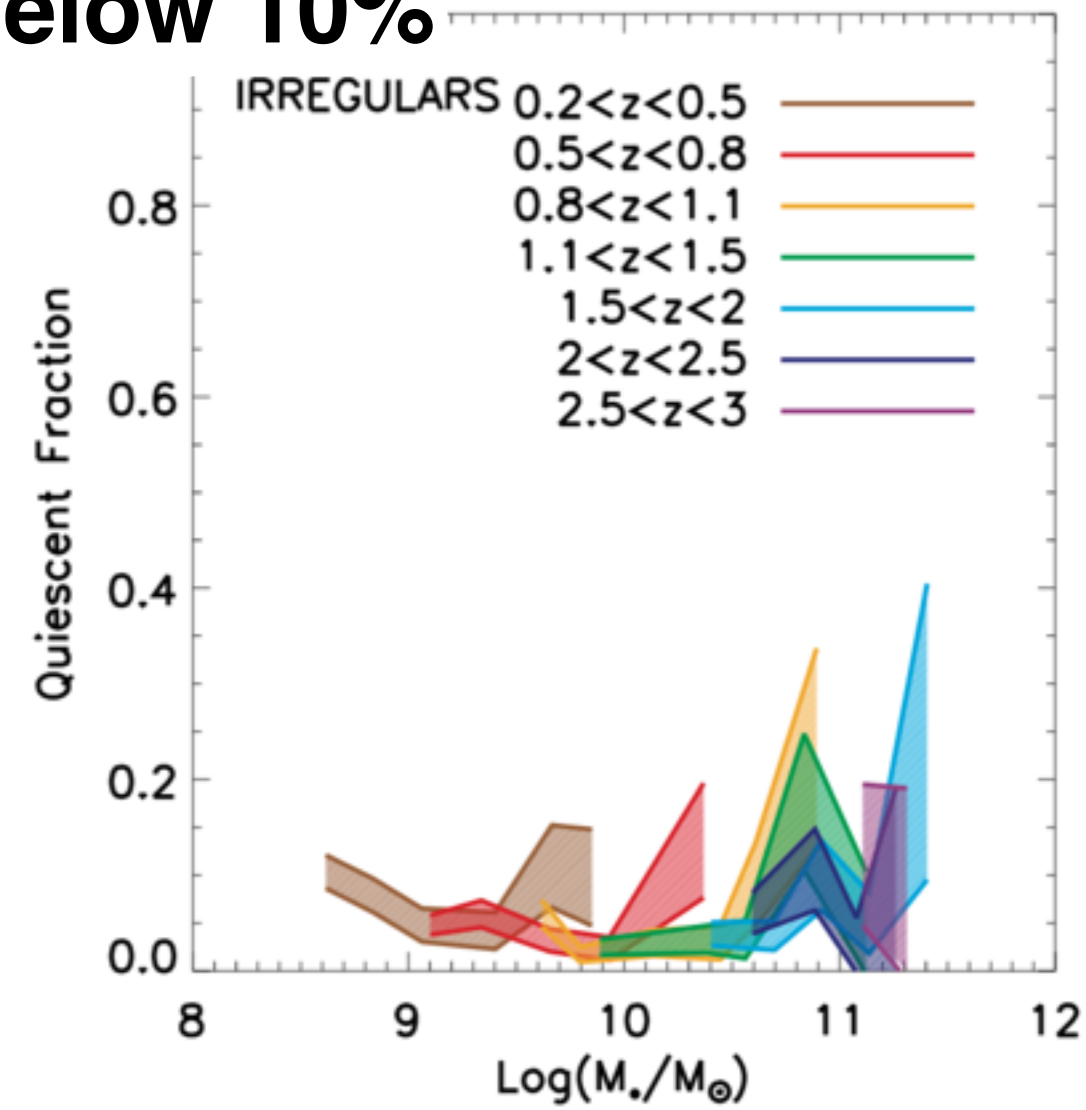




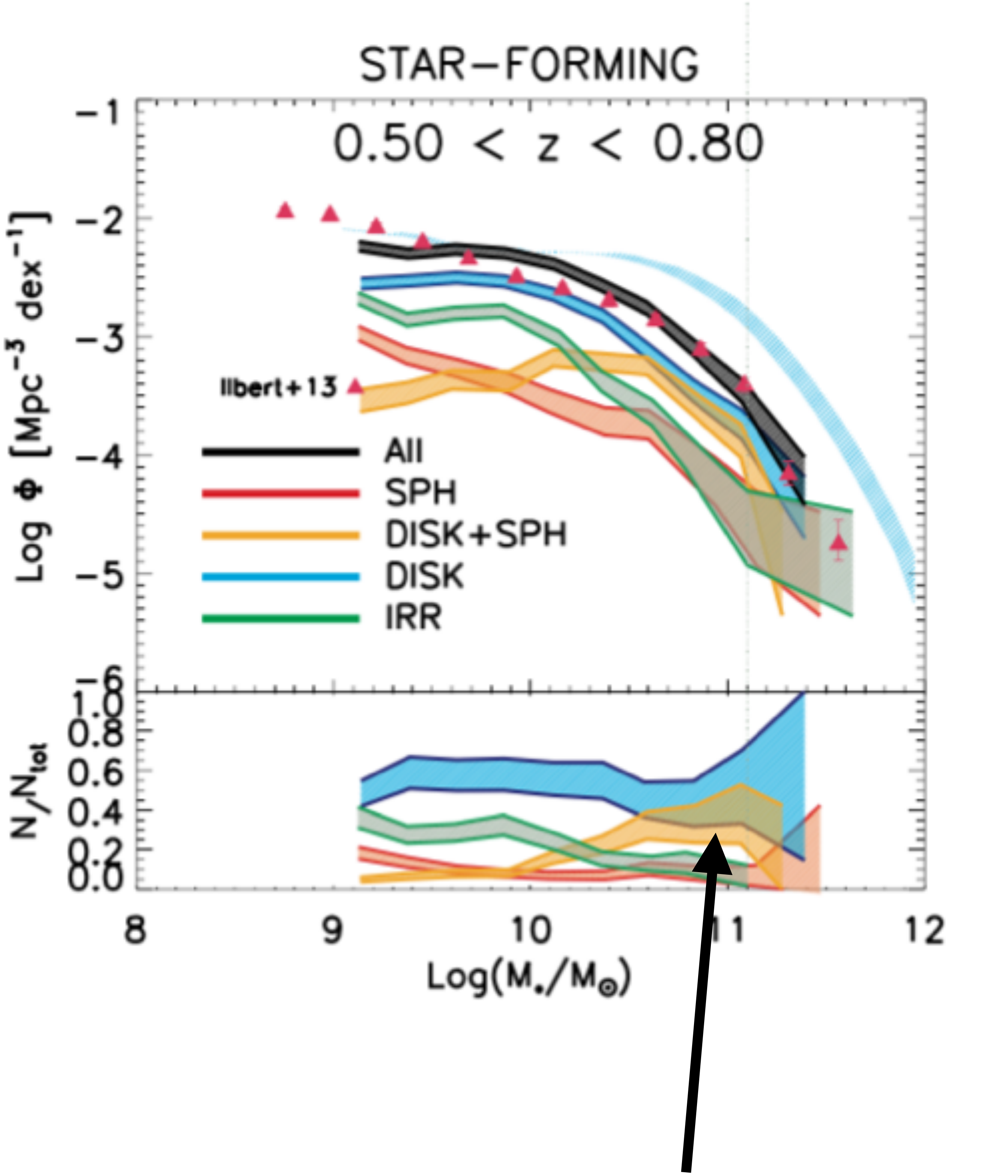
Transformation **mainly** without interruption of star-formation (statistically speaking)

Q. fraction below 10%



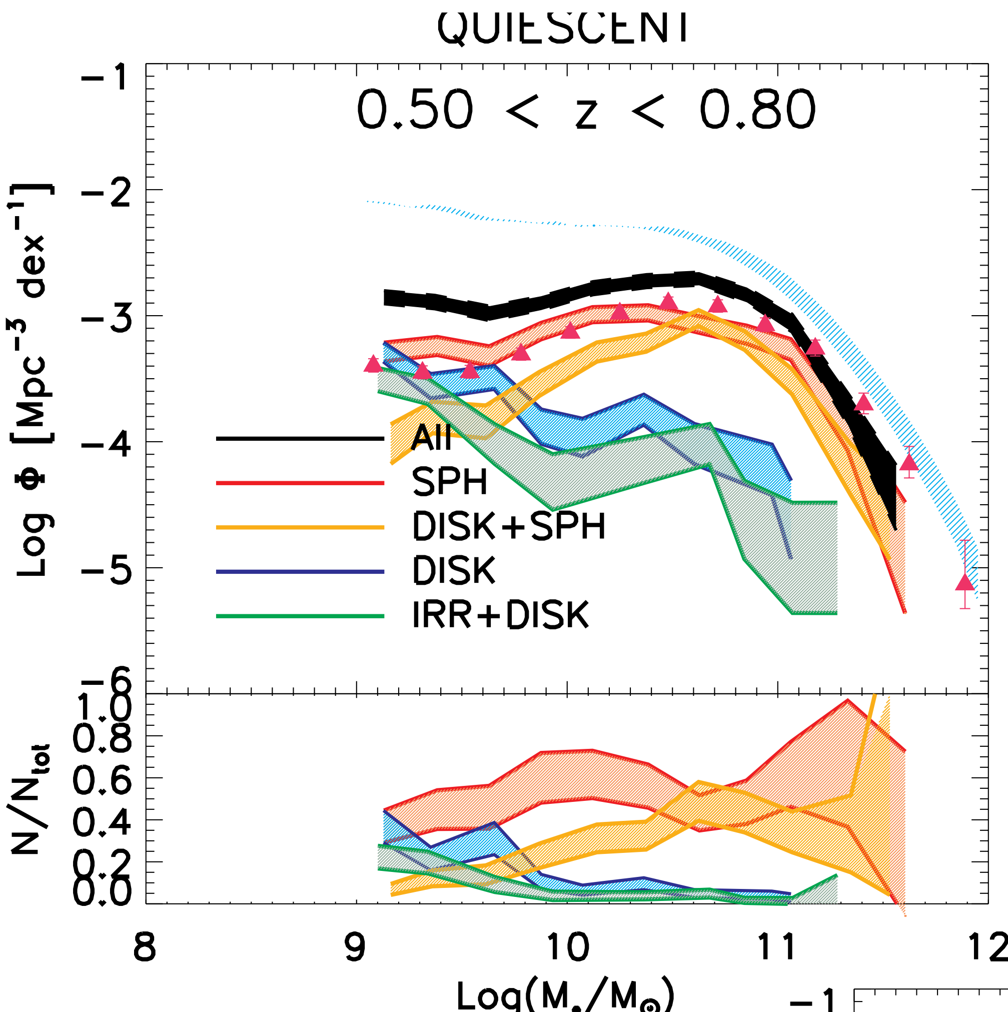


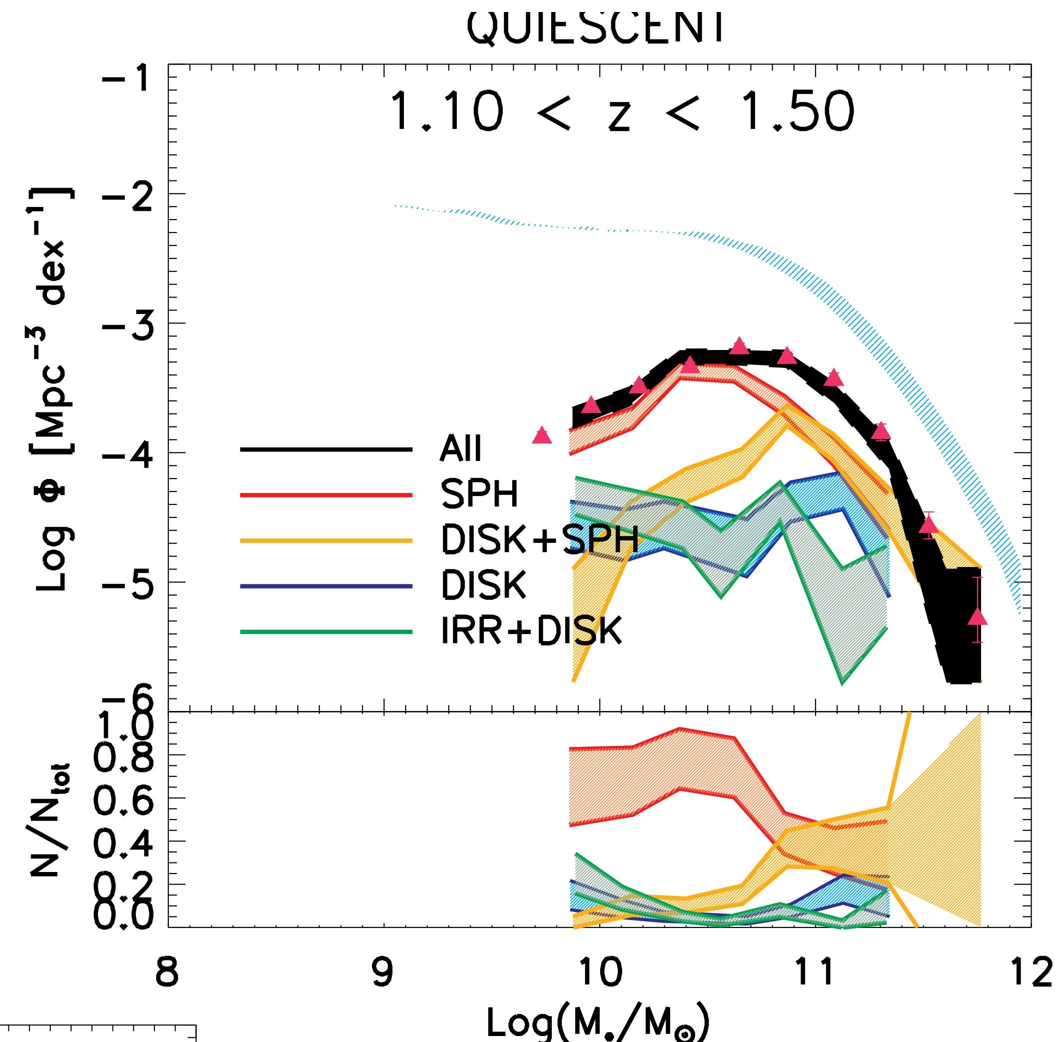
Central star-formation suppression?

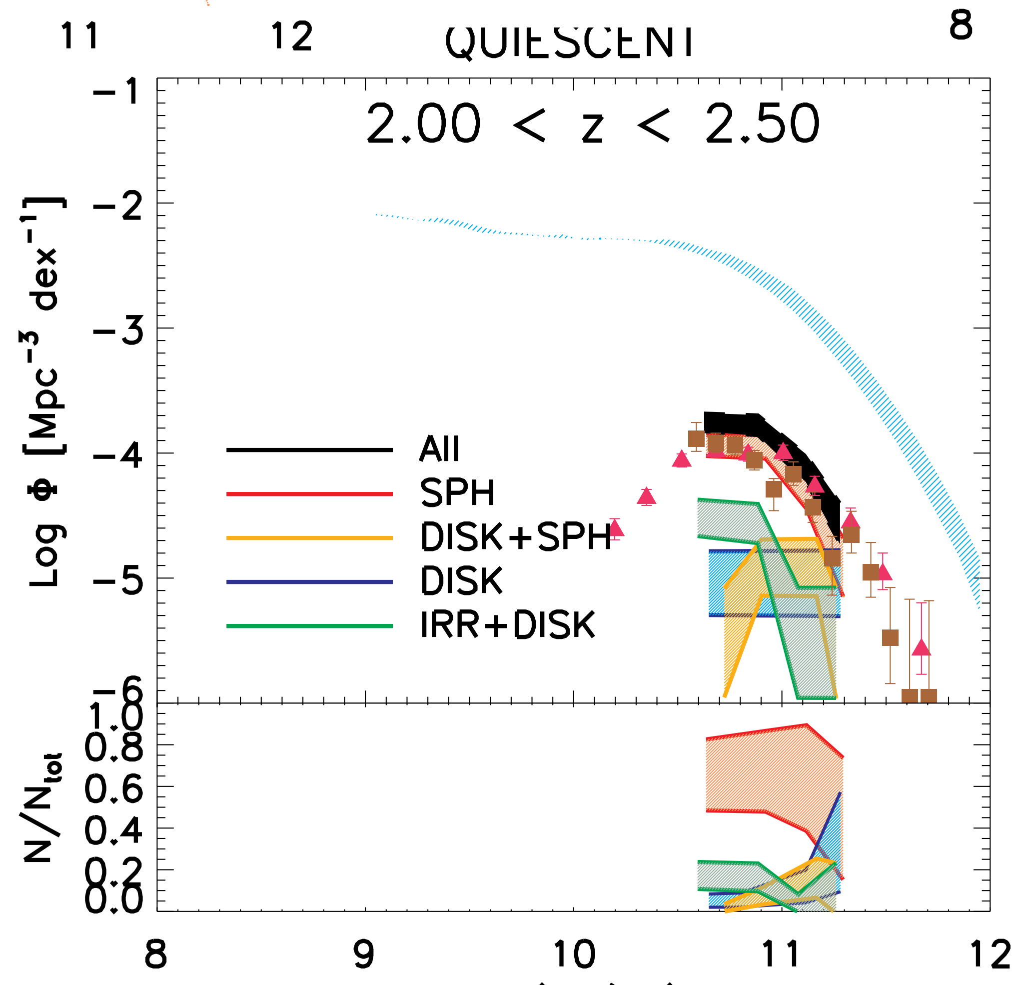


SF with prominent bulges represent ~20%-40% of SF galaxies @ log(M*) > 10.5

QUIESCENT

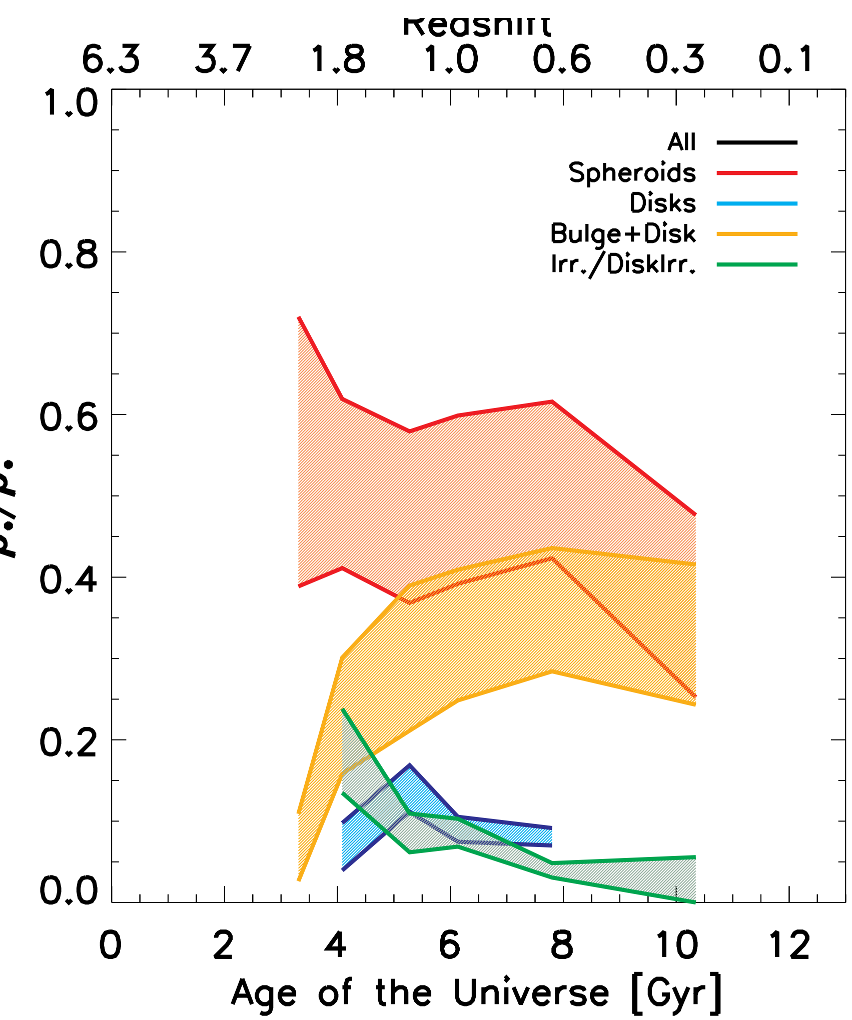


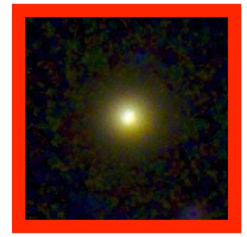




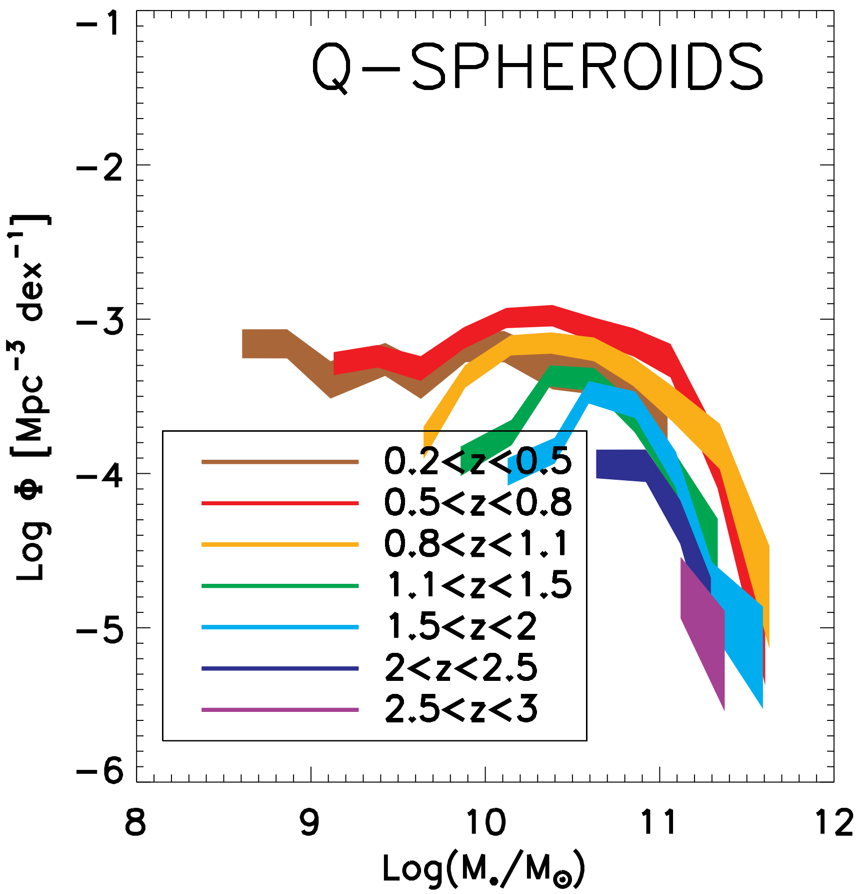
MHC+16

QUIESCENT

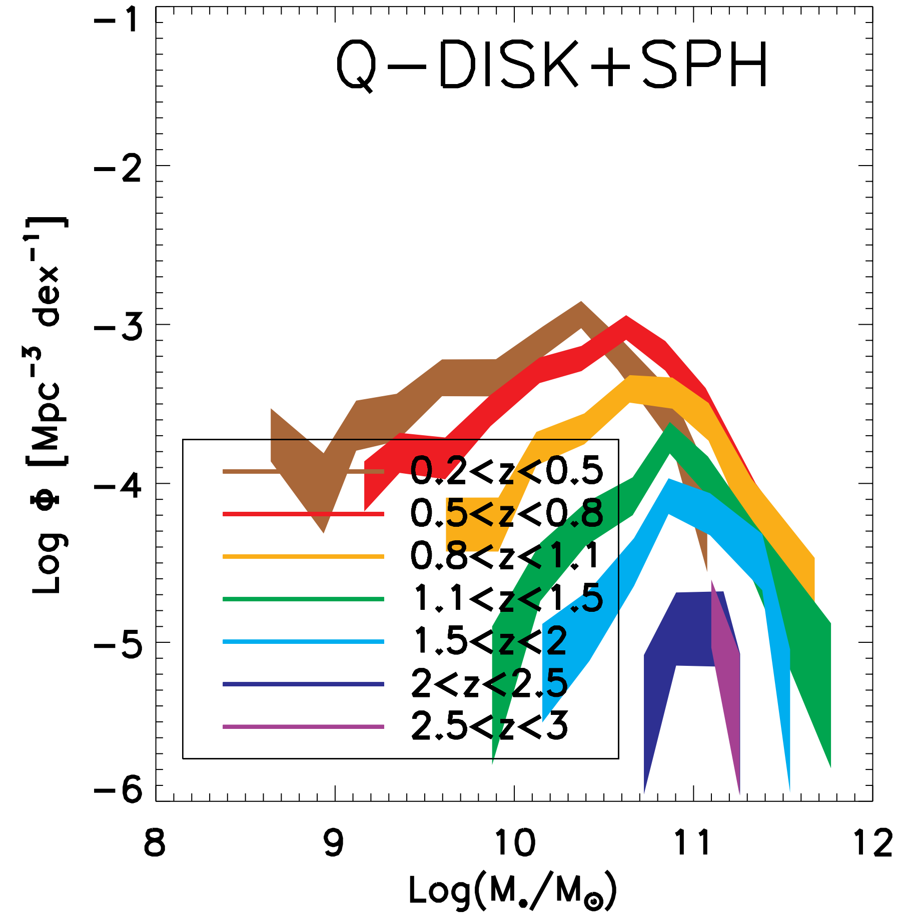




n~3-5
b/a~0.8
Re~1-2Kpc



n~2-3
b/a~0.5
Re~4Kpc



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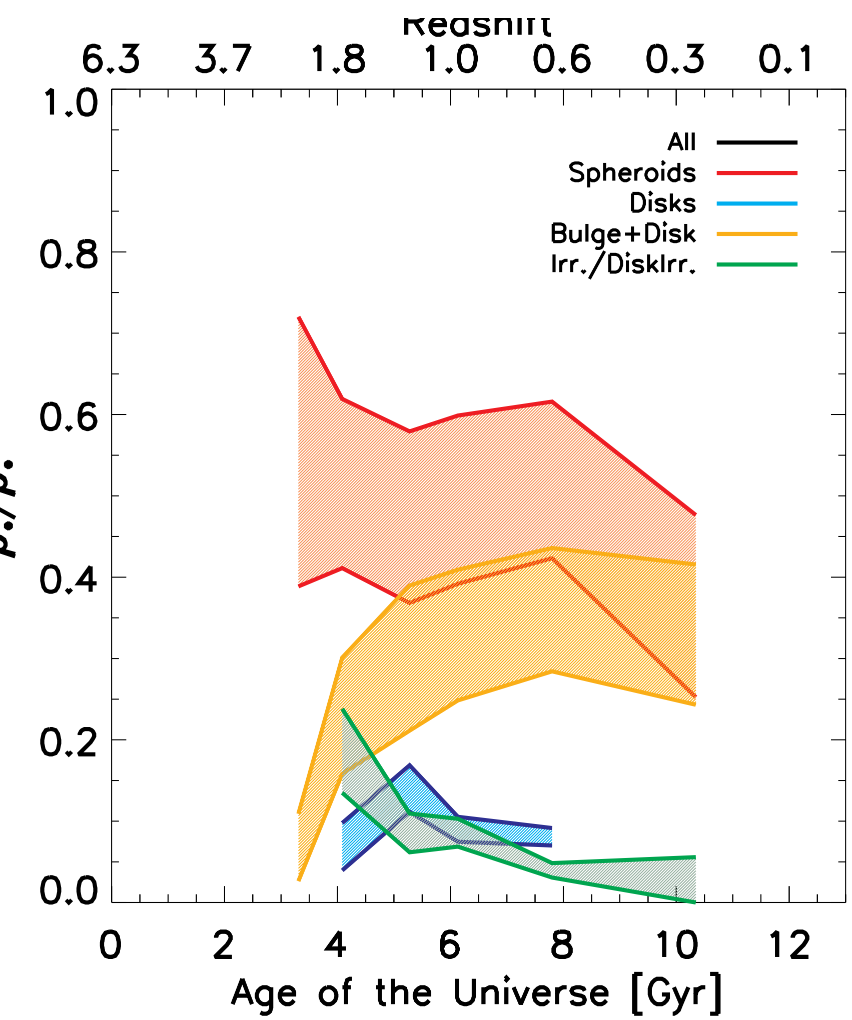
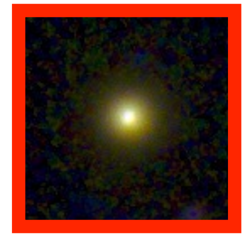
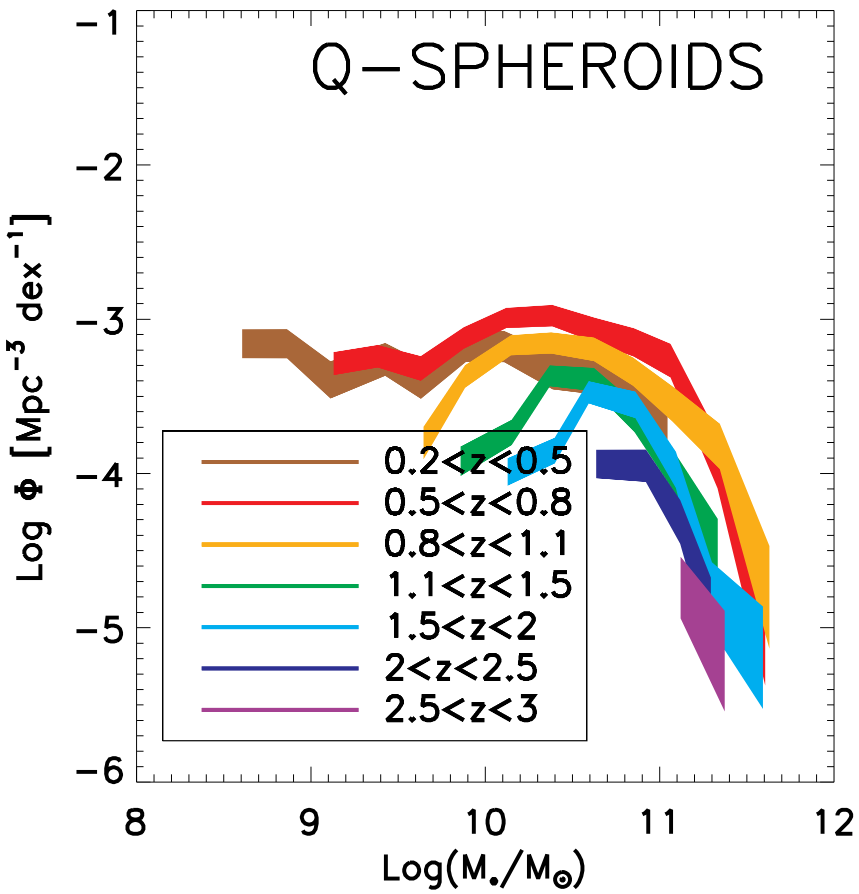
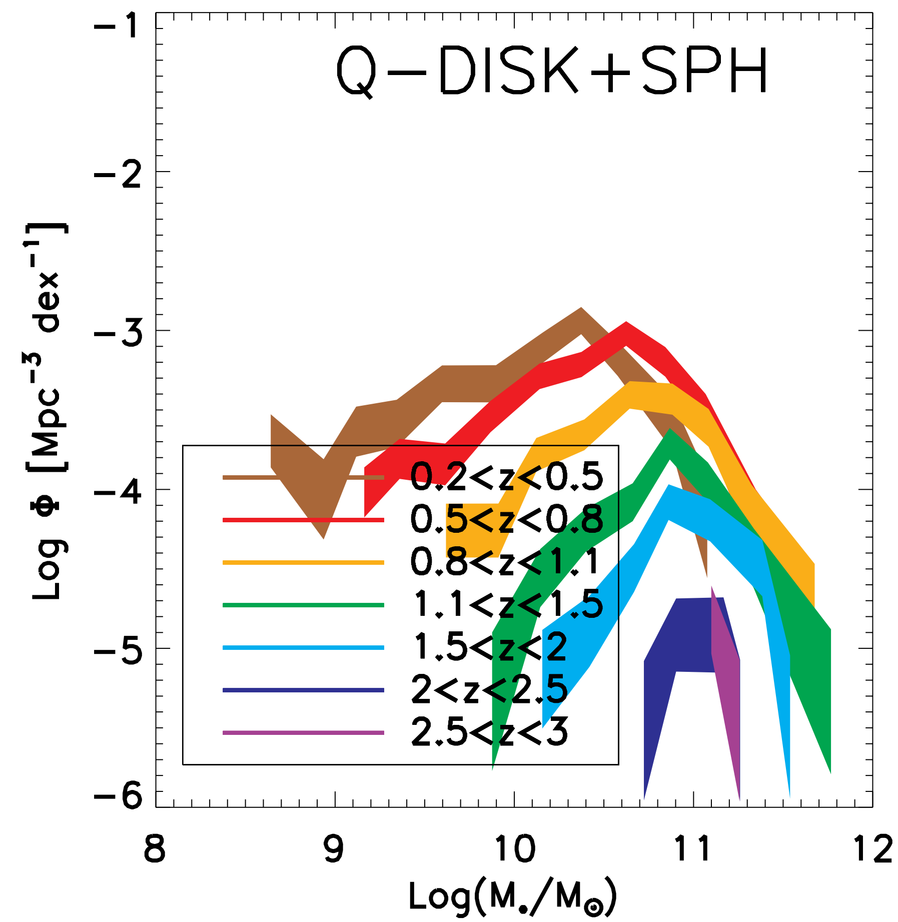




n~3-5
b/a~0.8
Re~1-2Kpc

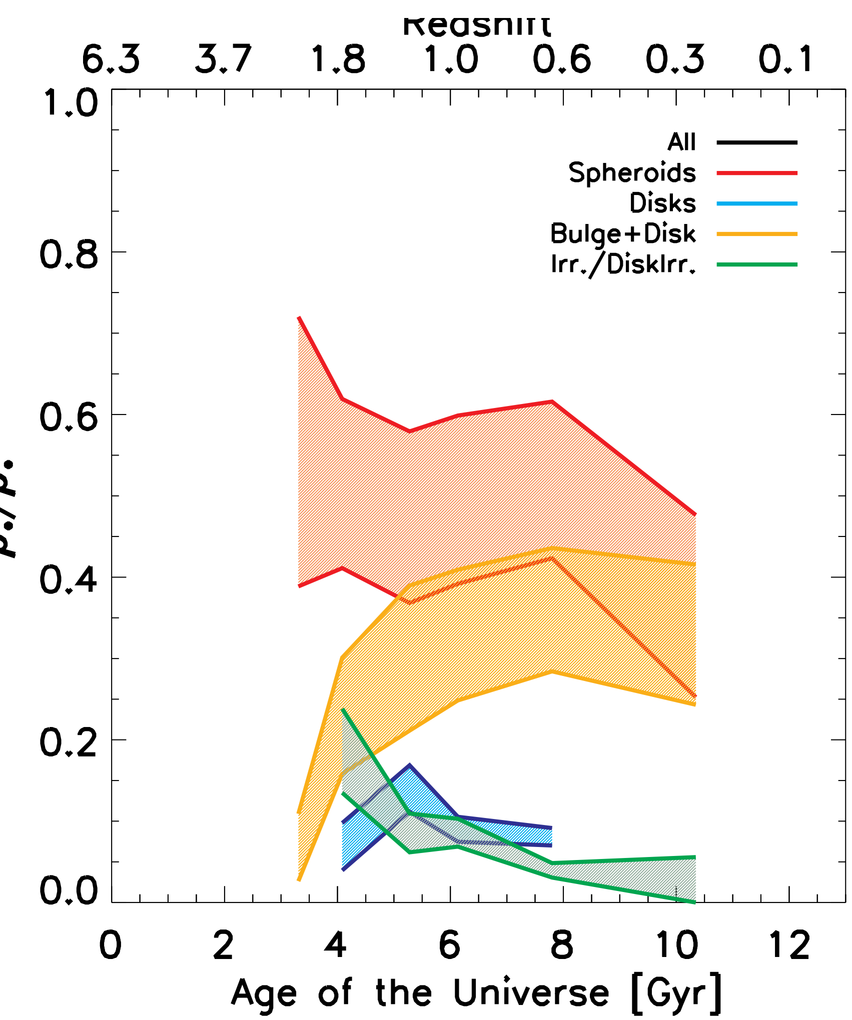
n~2-3
b/a~0.5
Re~4Kpc

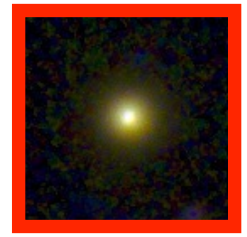




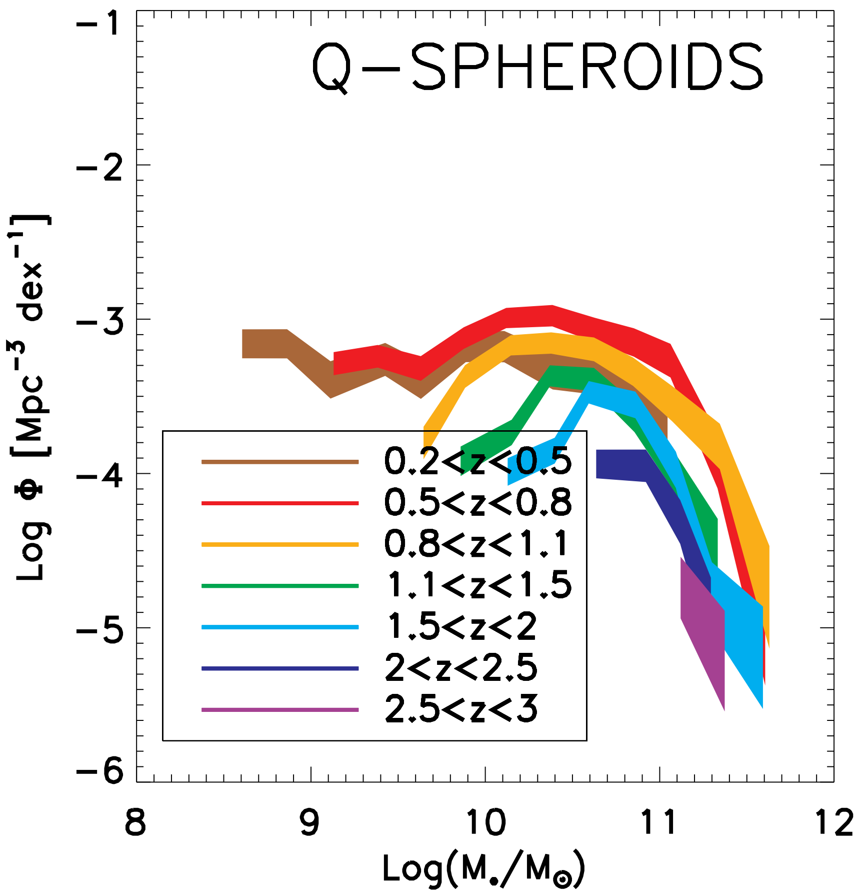
H: Dissipative, violent formation
VDIs
gas-rich - Mergers

QUIESCENT



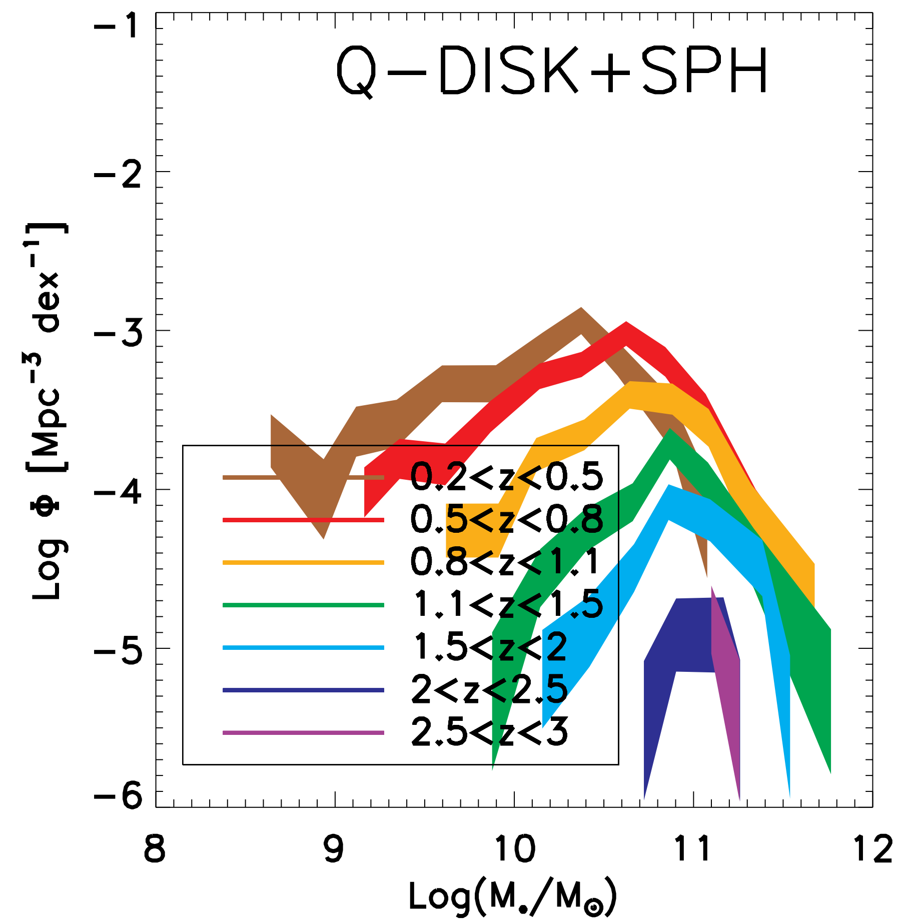


n~3-5
b/a~0.8
Re~1-2Kpc



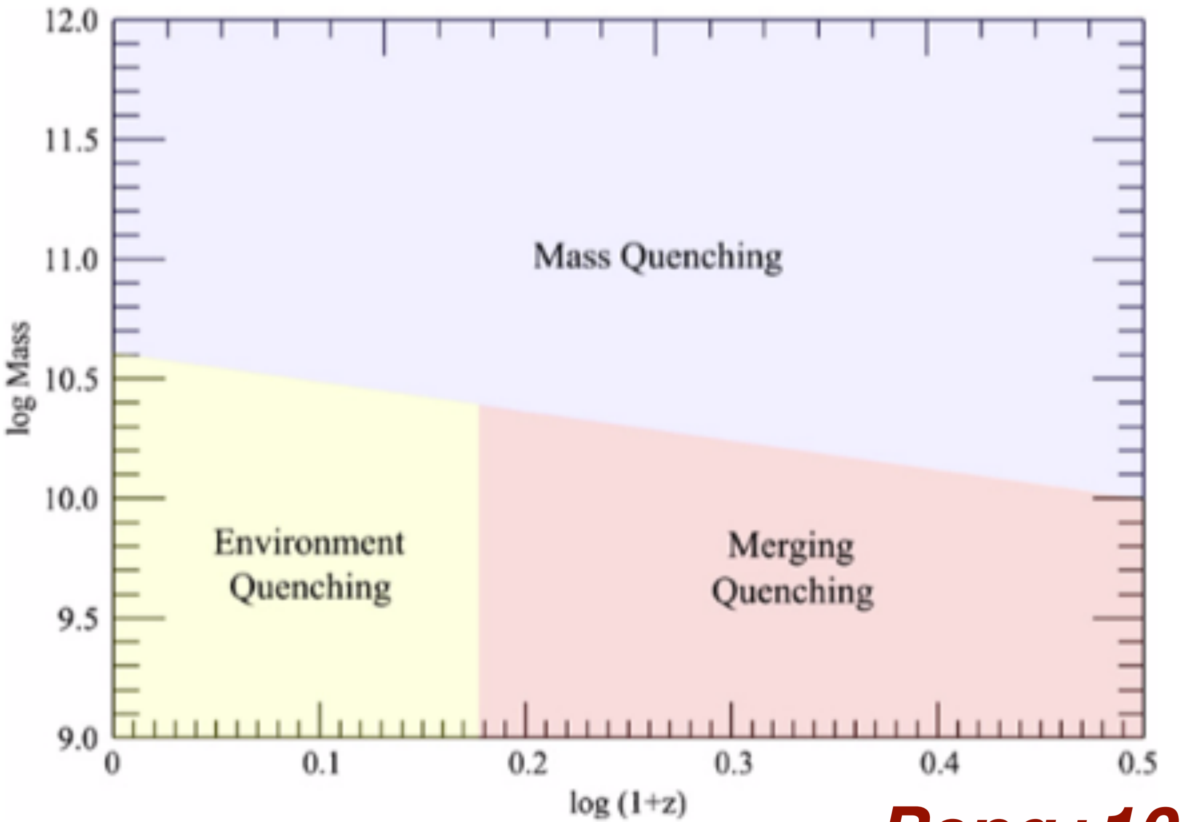
H: Dissipative, violent formation
VDIs
gas-rich - Mergers

n~2-3
b/a~0.5
Re~4Kpc

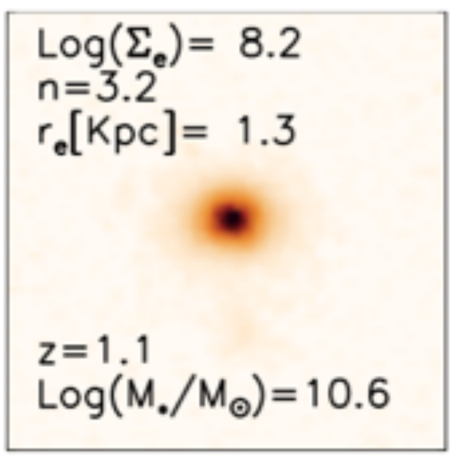


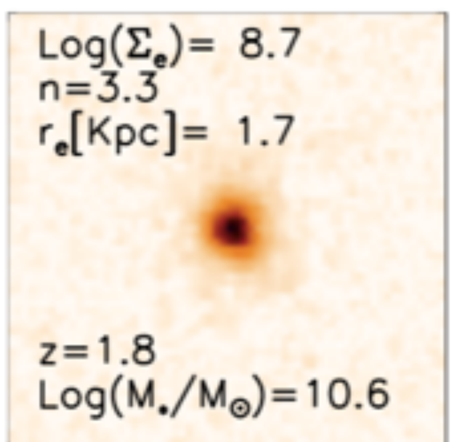
H: “gentle-quenching” - disk not destroyed
strangulation, morphological quenching

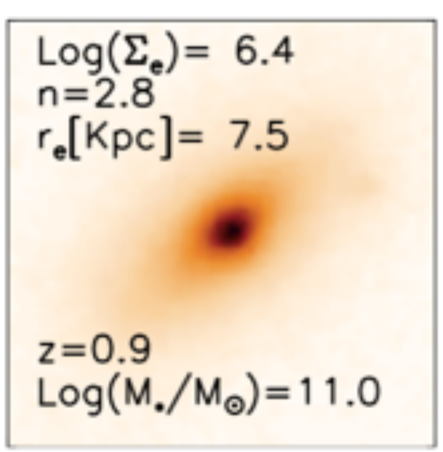
MASS QUENCHING

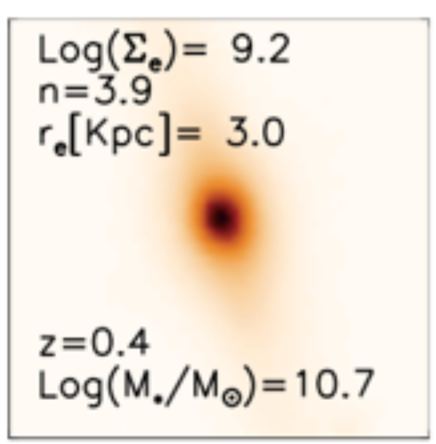


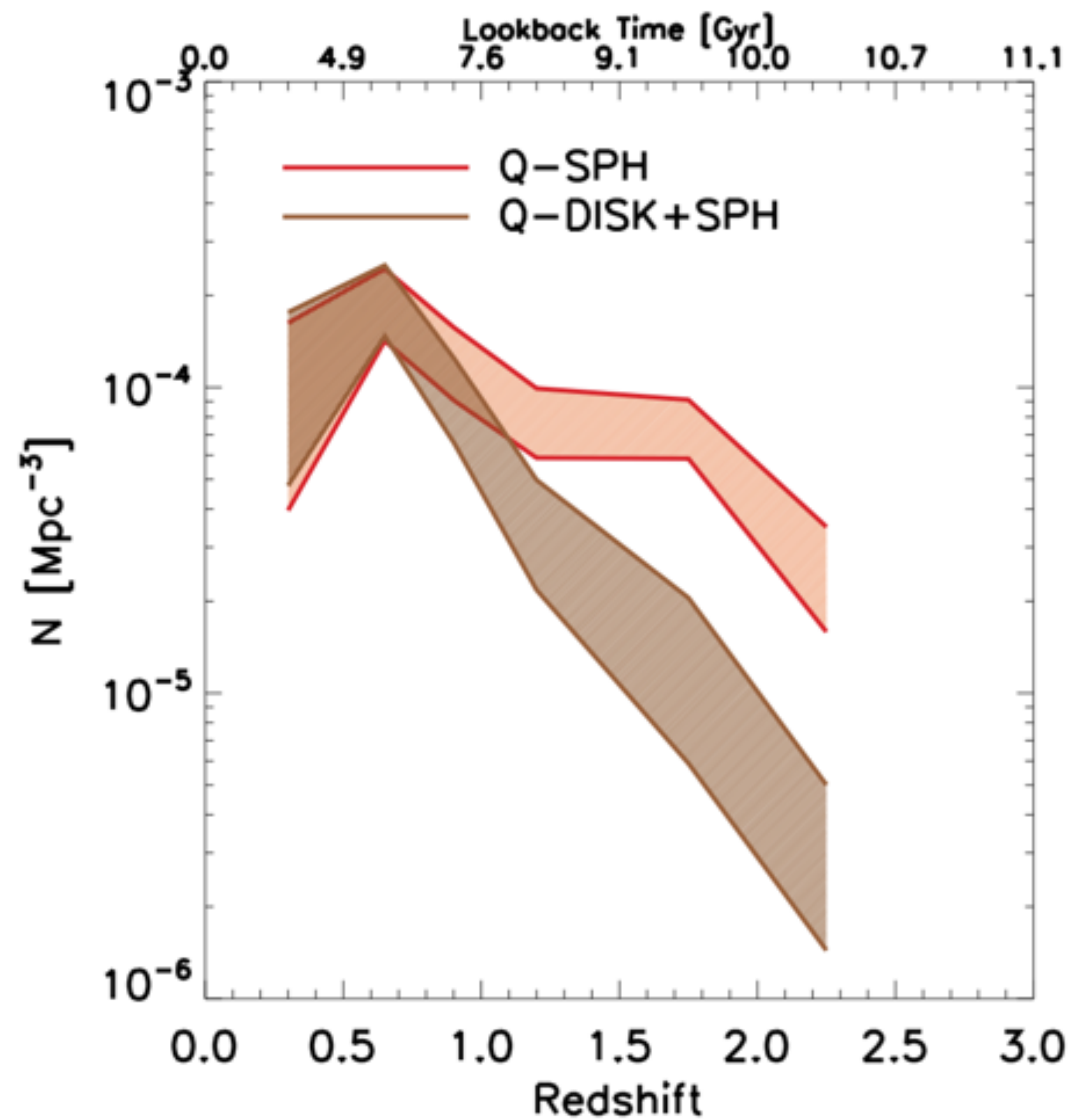
Peng+10



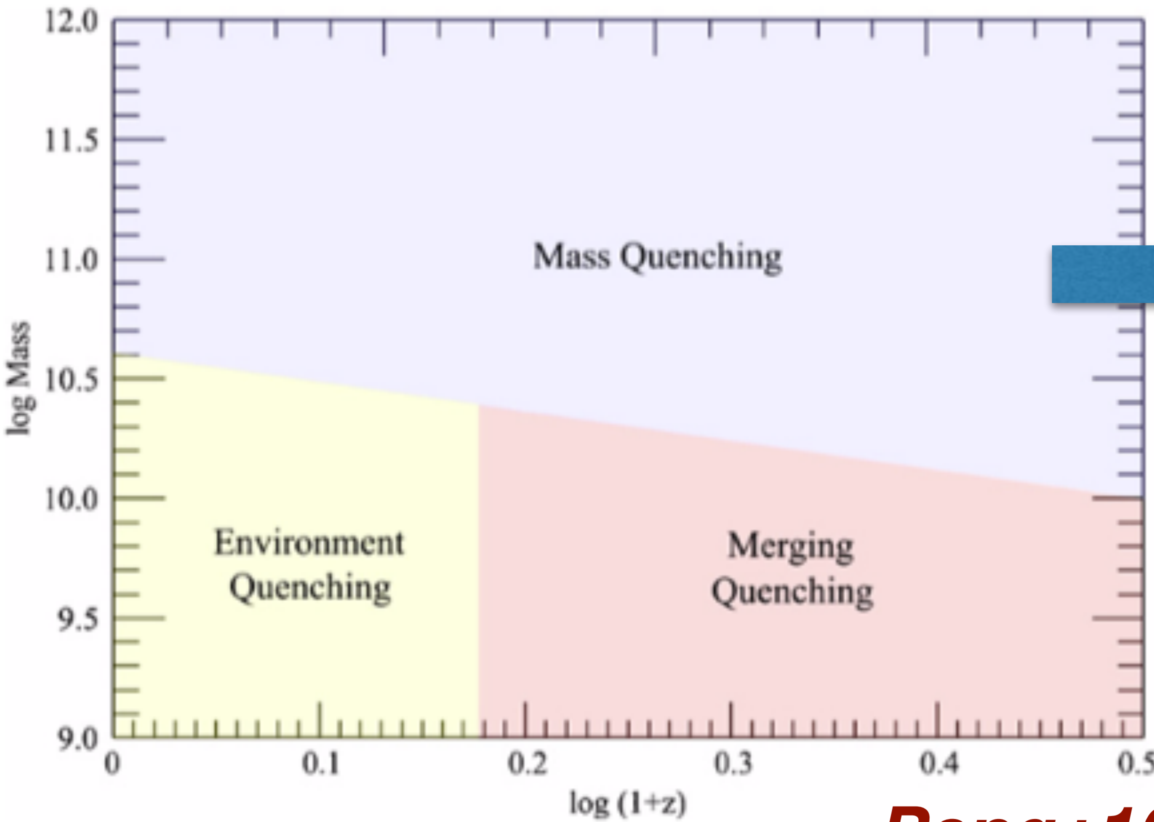






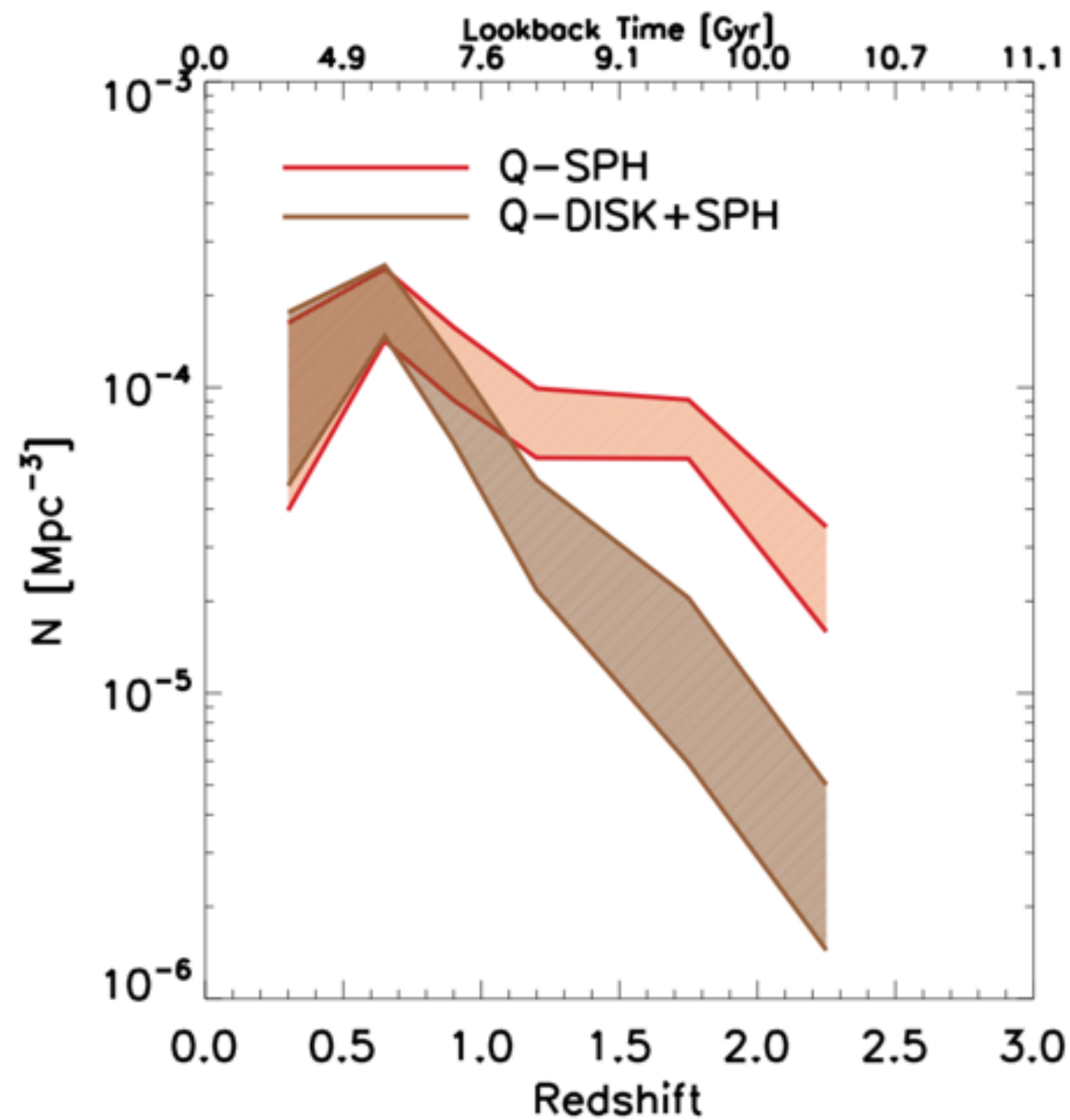


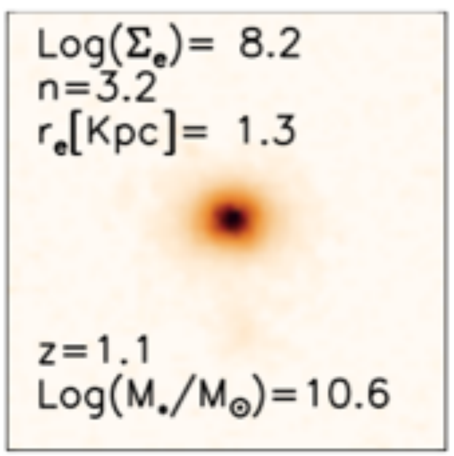
MASS QUENCHING

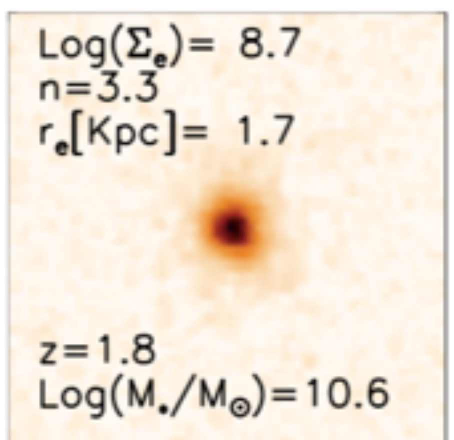


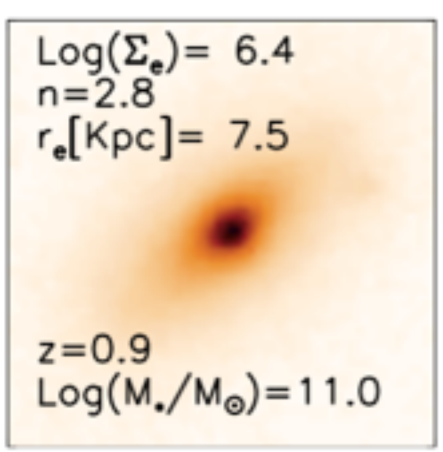
Peng+10

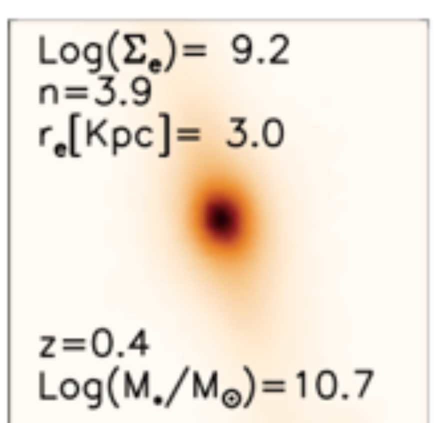
Number density @ M*



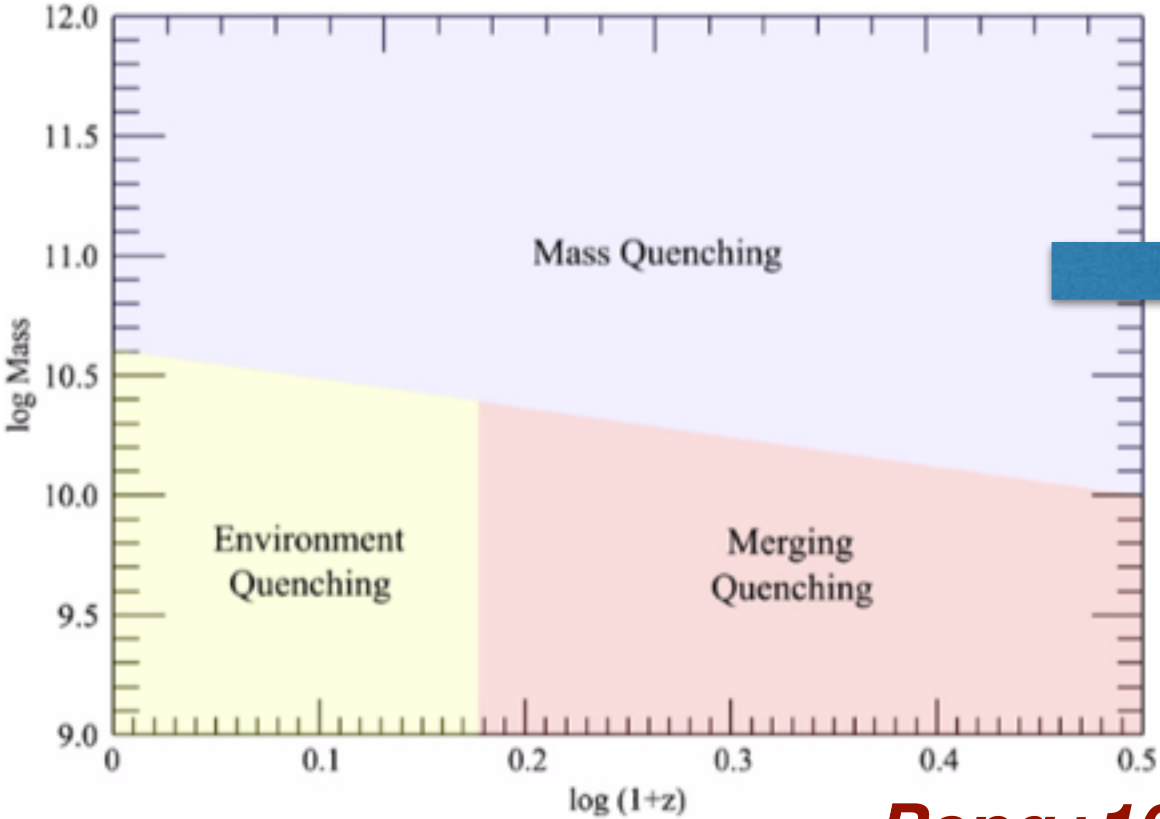








MASS QUENCHING



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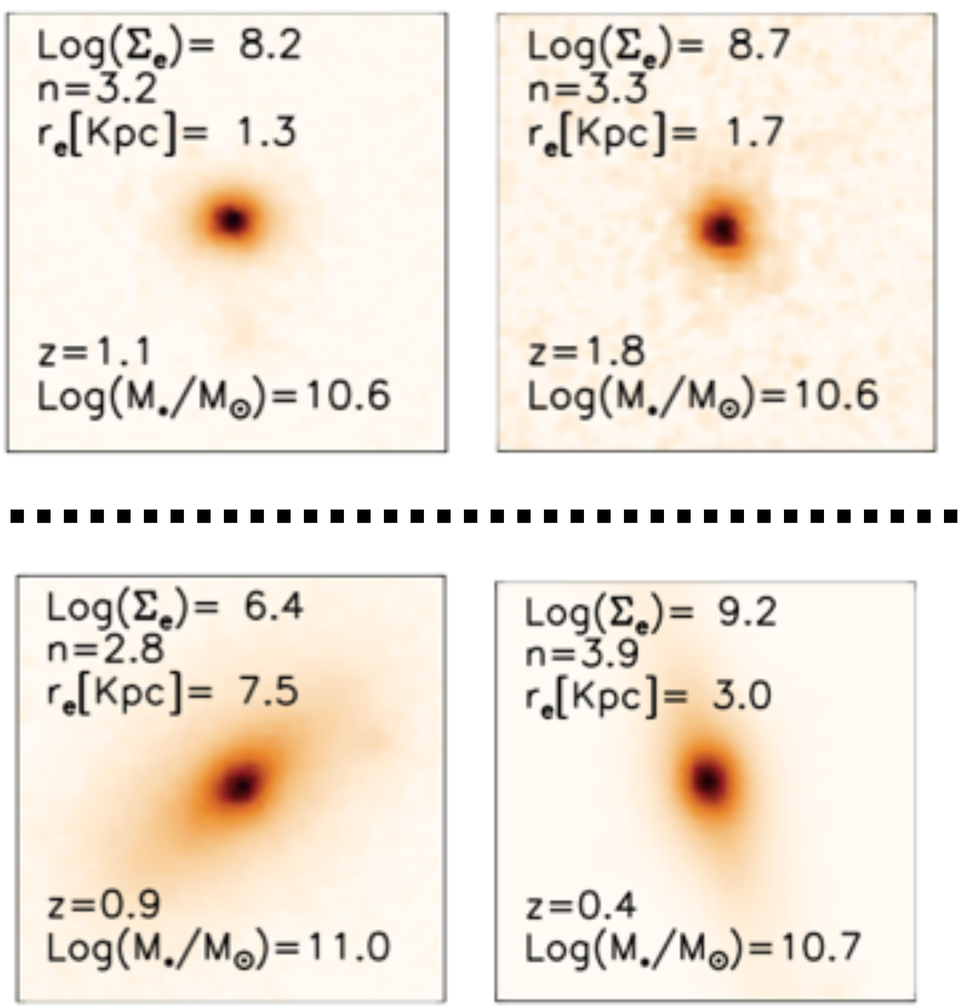
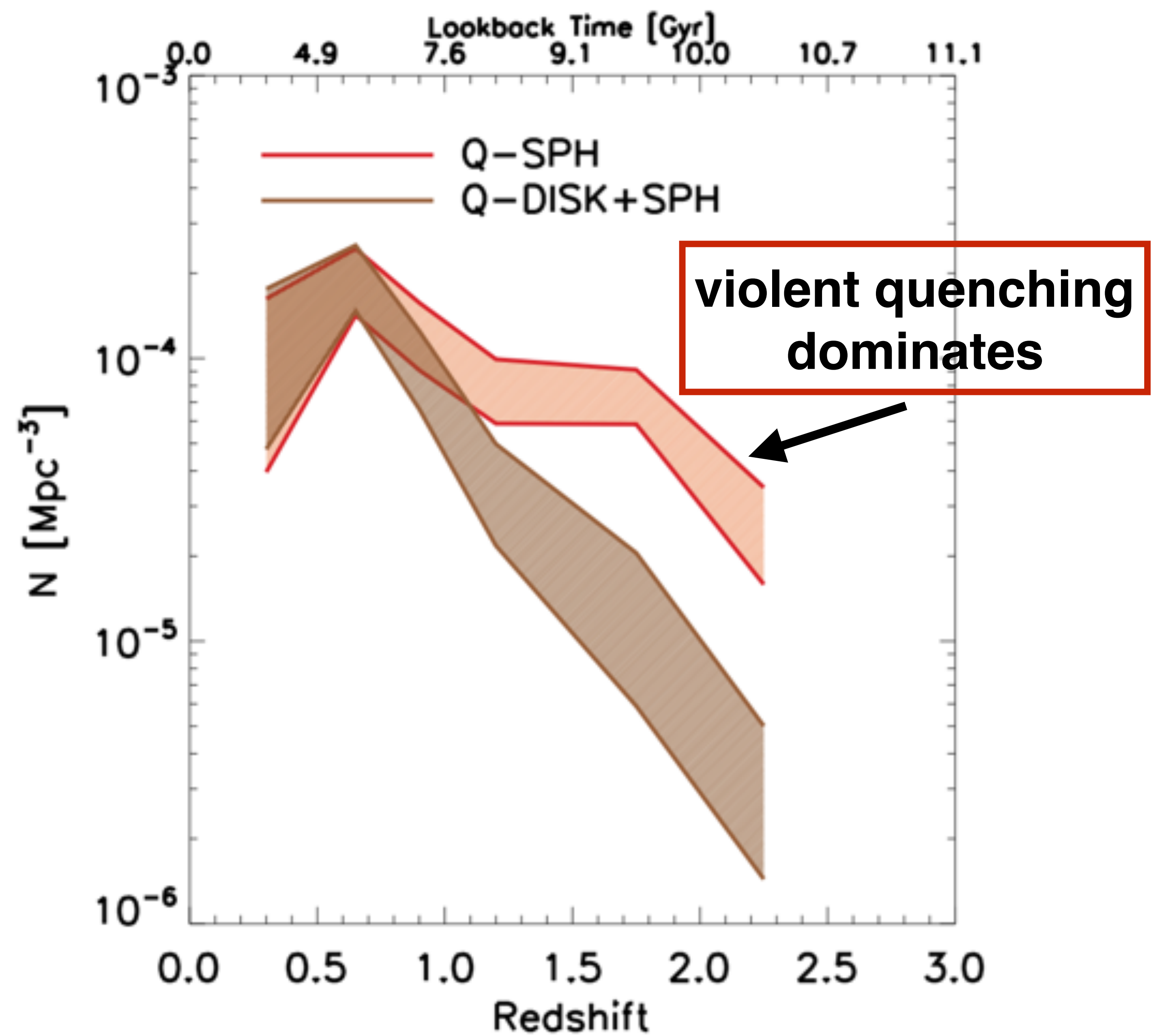
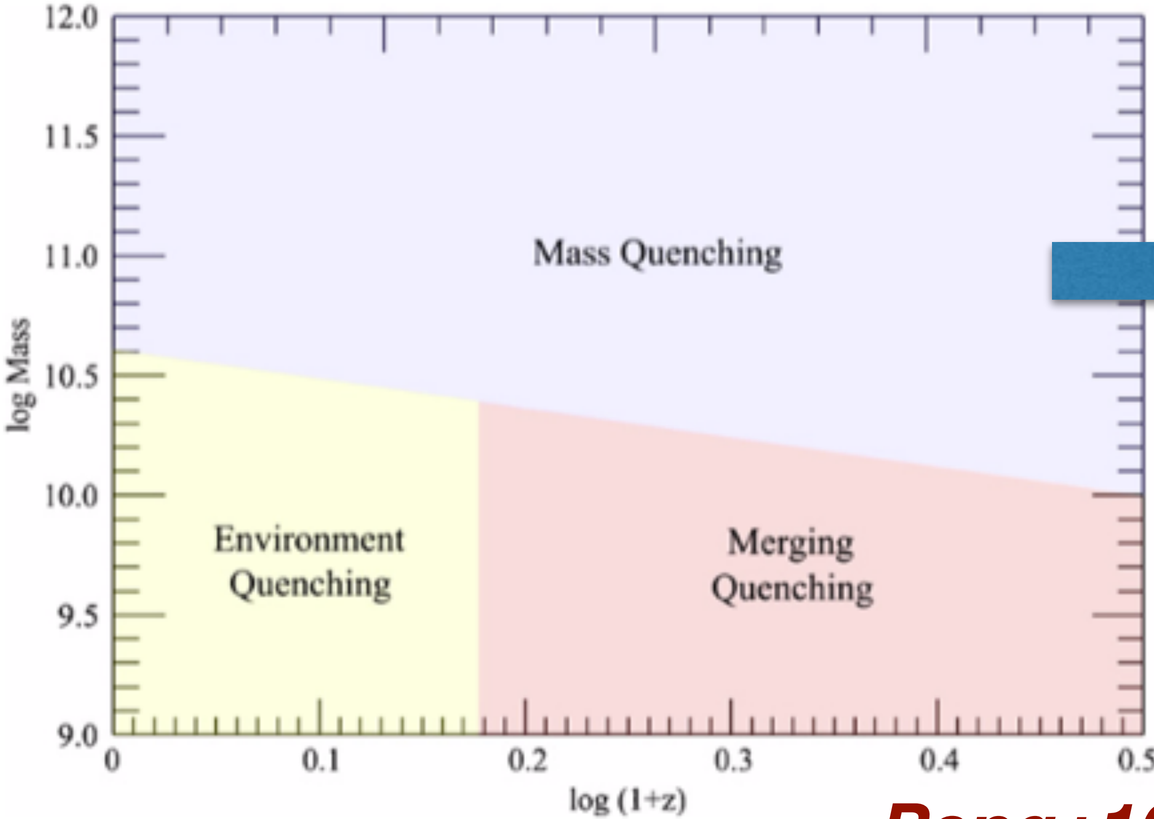


Number density @ M*

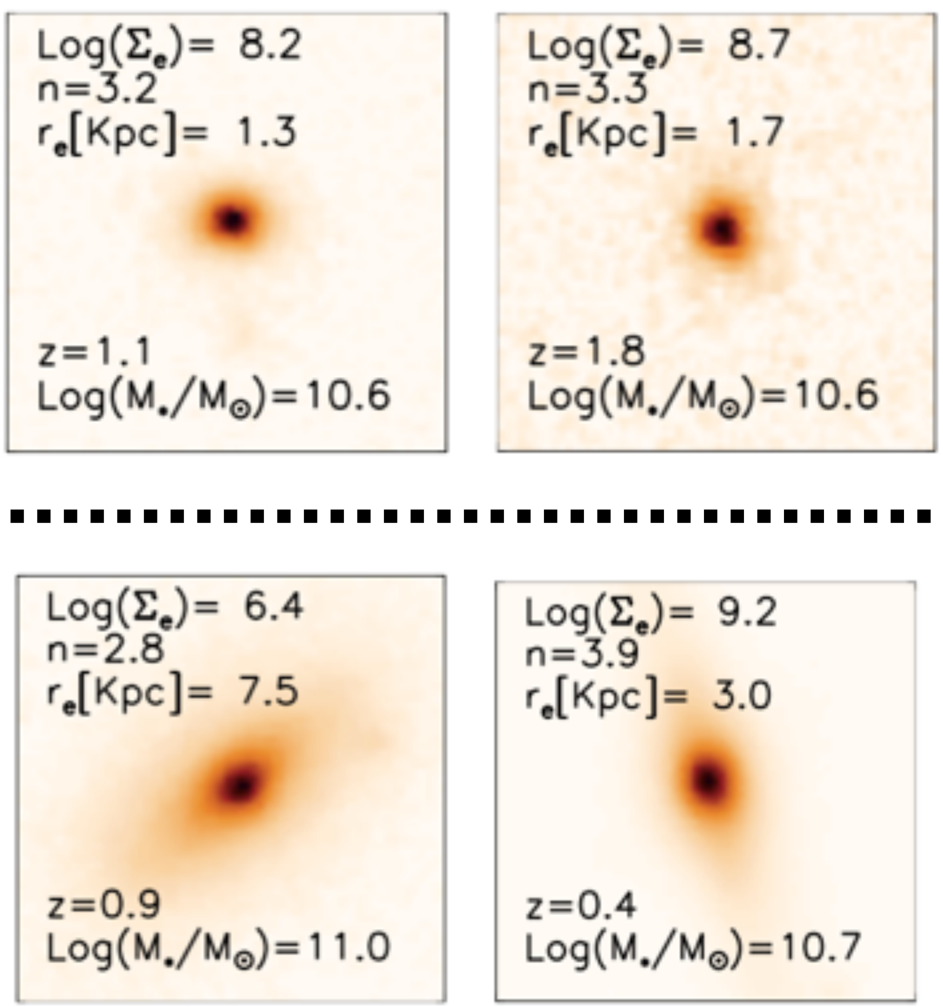


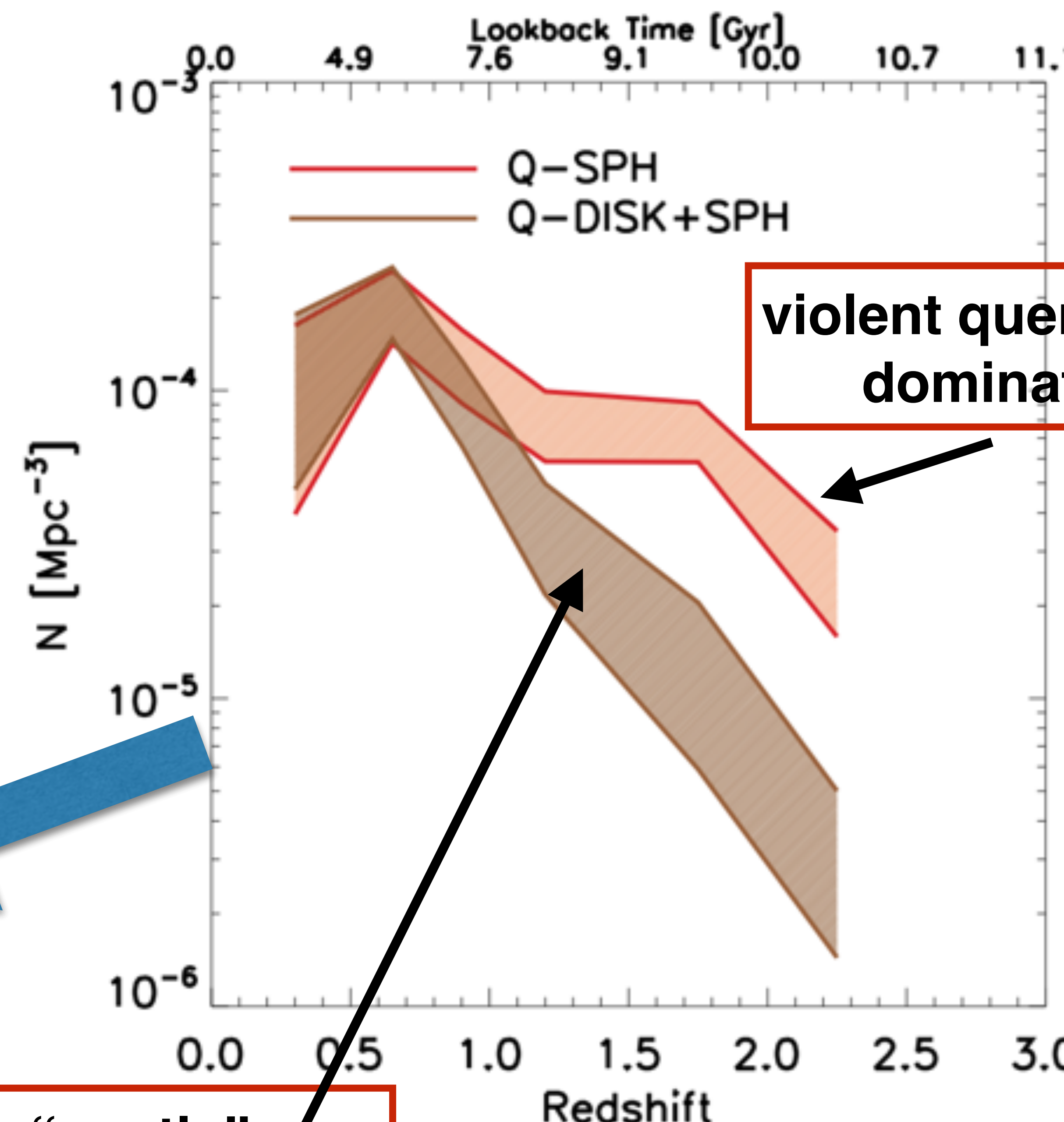


MASS QUENCHING

Number density @ M*

Peng+10

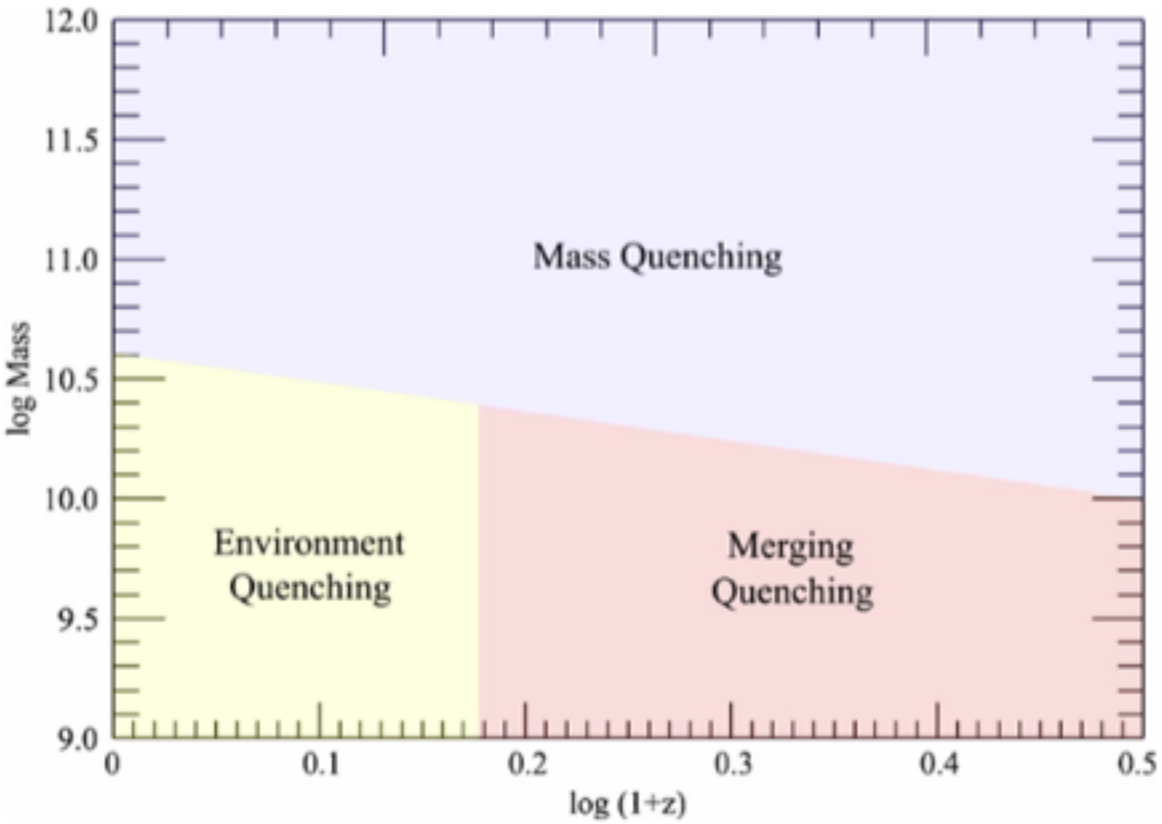




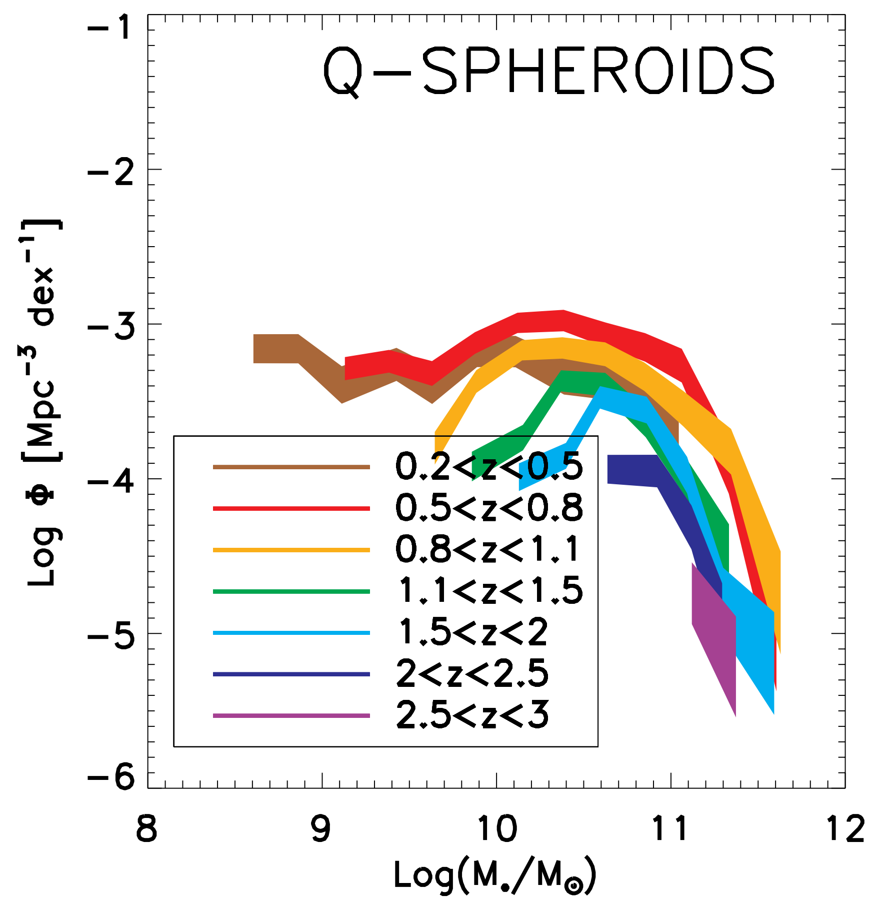
violent quenching dominates

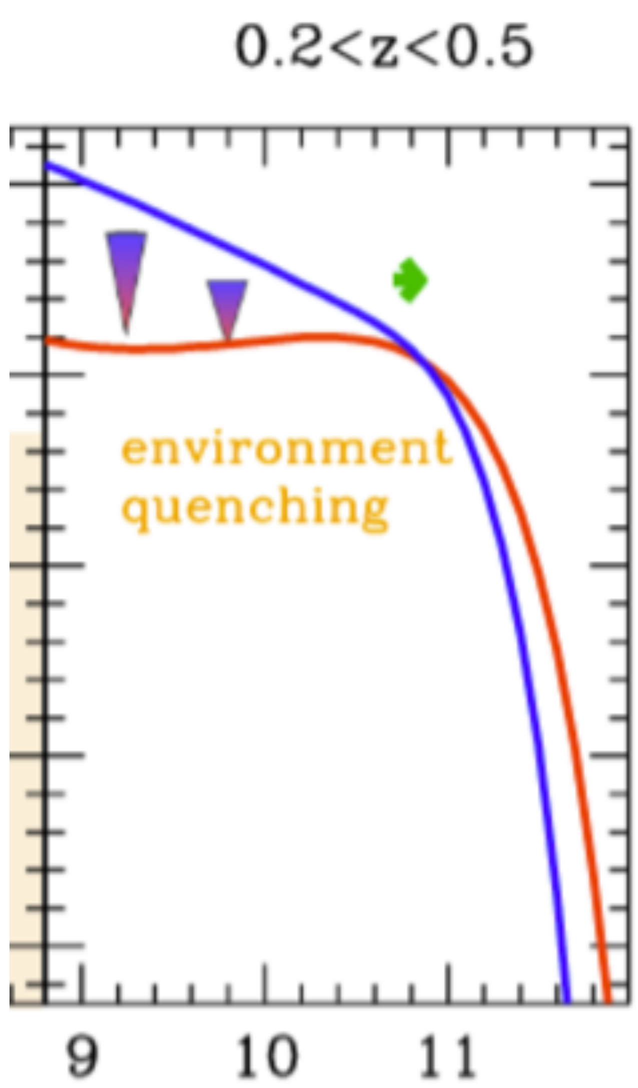
"gentle" quenching more efficient

ENVIRONMENT QUENCHING

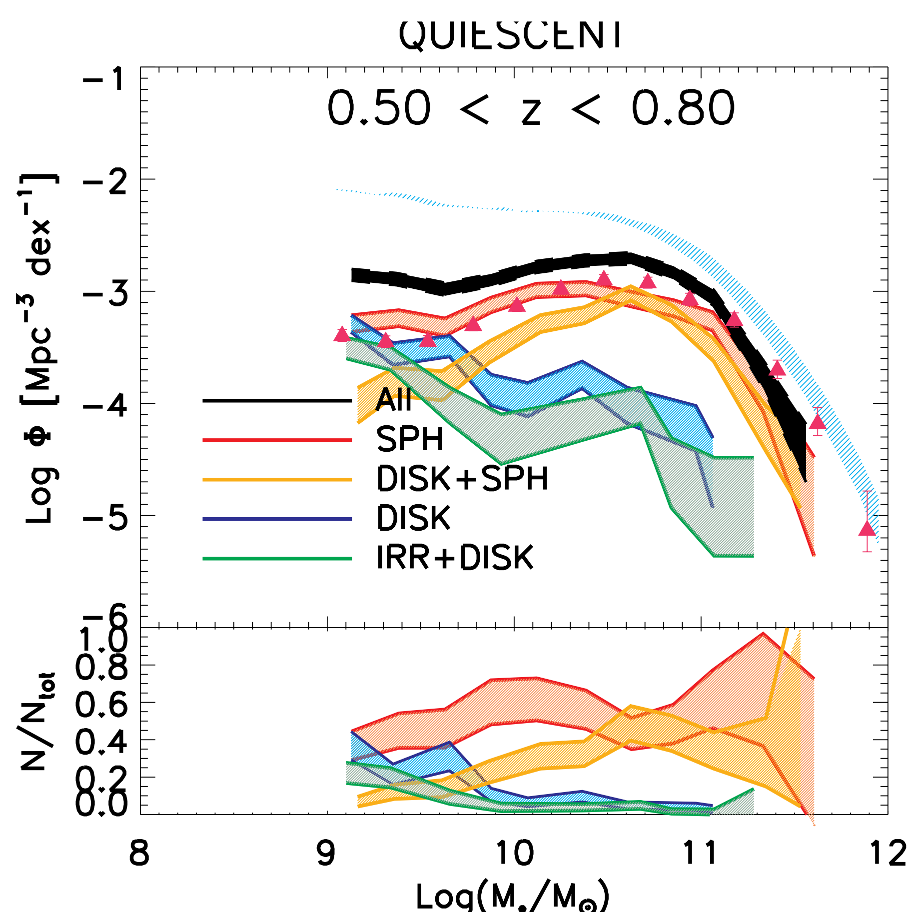


Peng+10

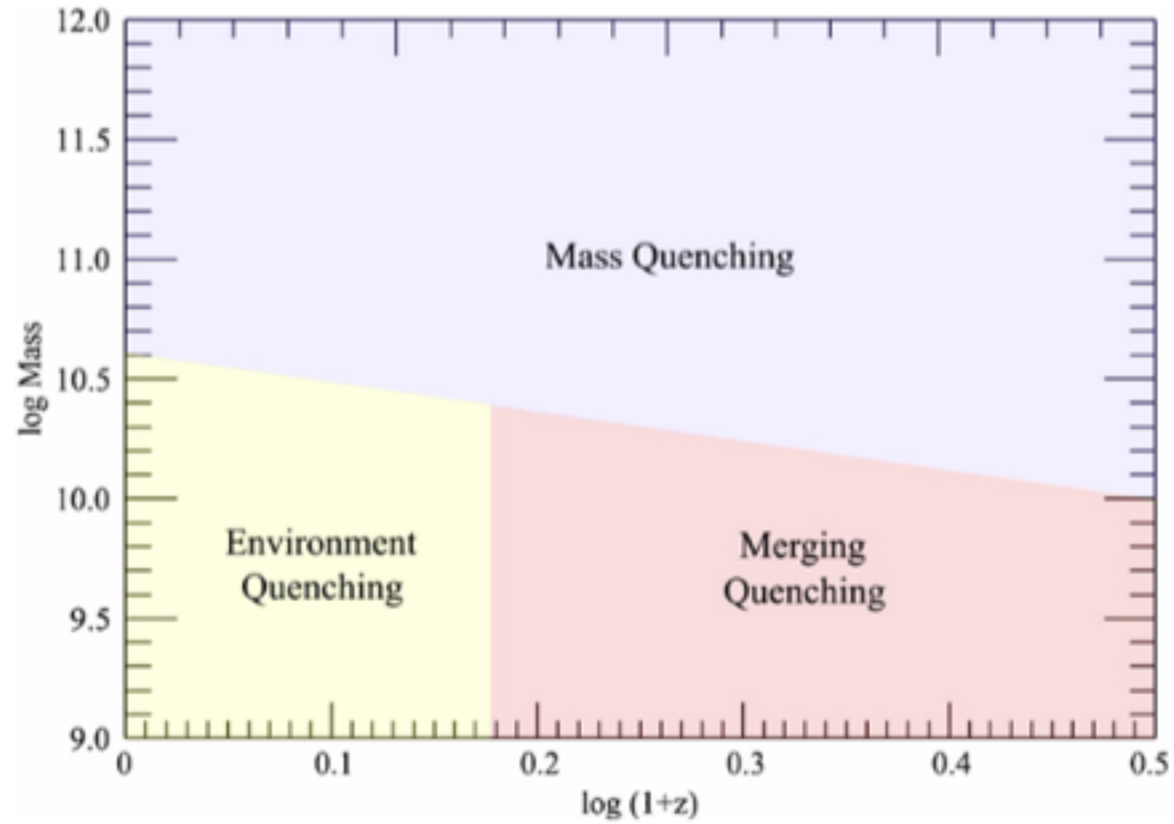




Ilbert+13



ENVIRONMENT QUENCHING



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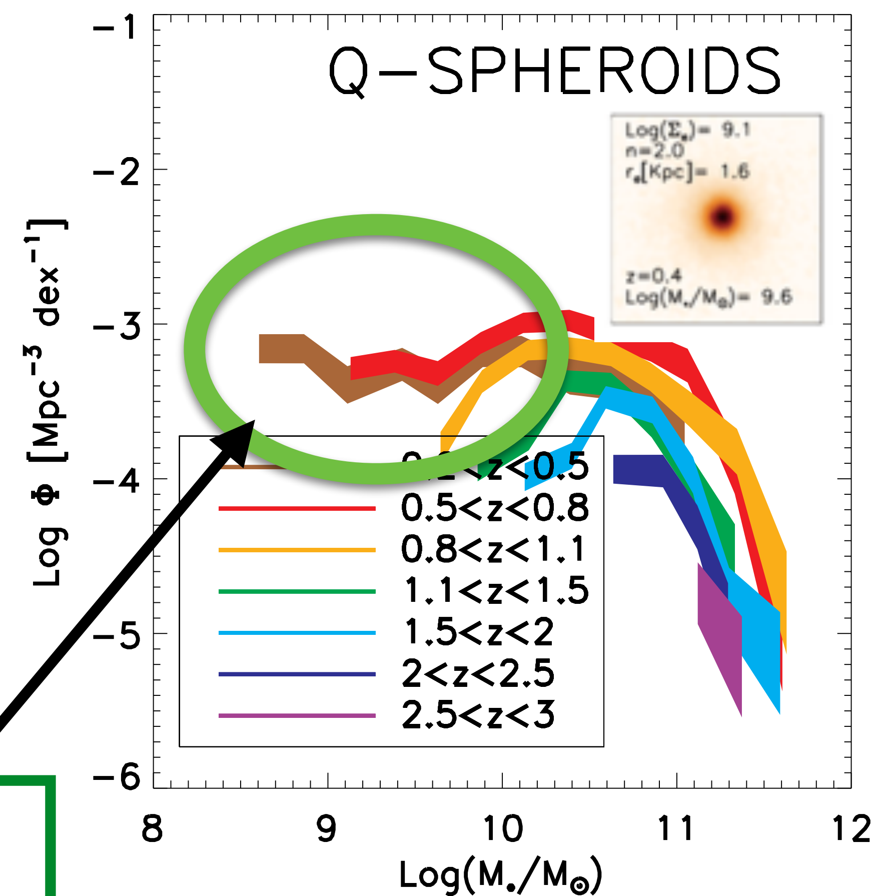
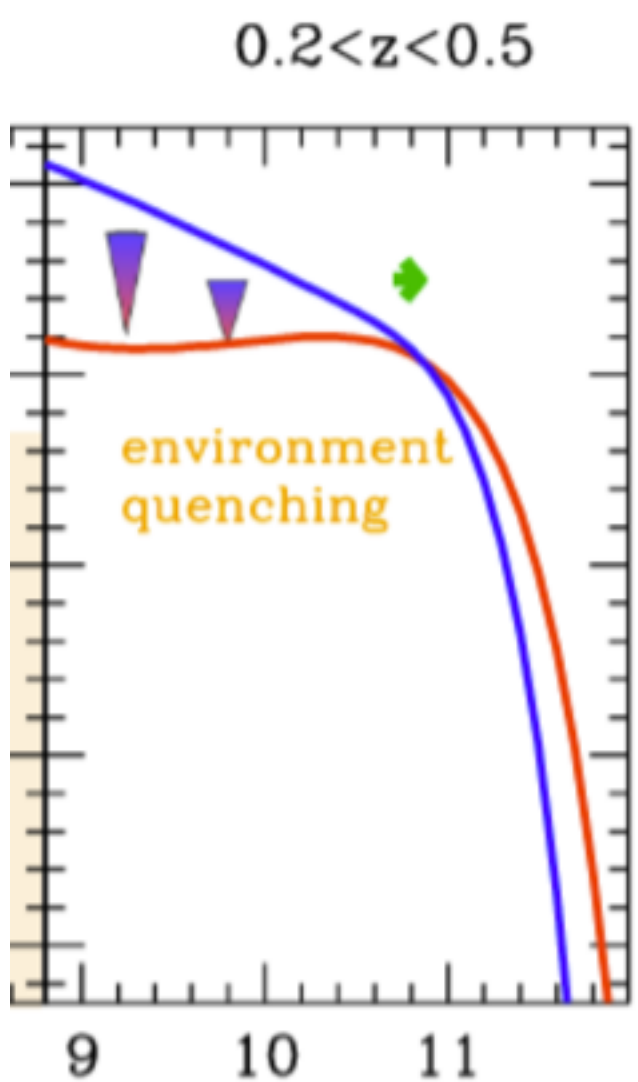
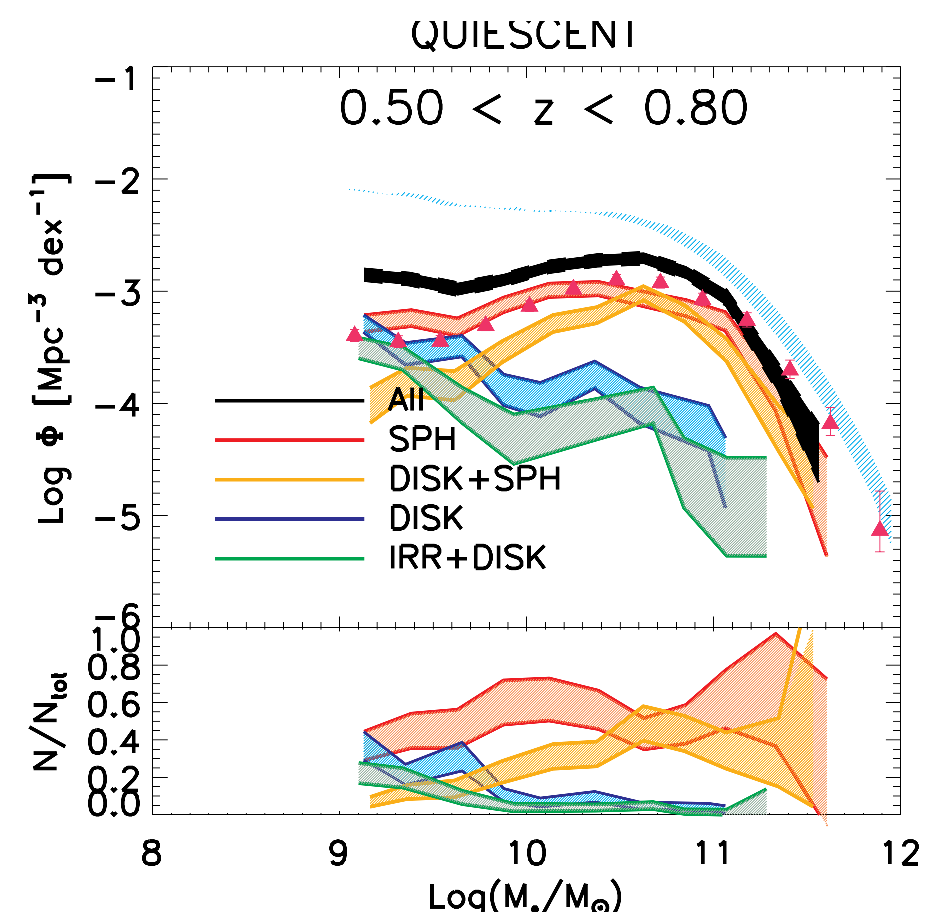


environment quenching predominantly destroys the disk Ram-pressure

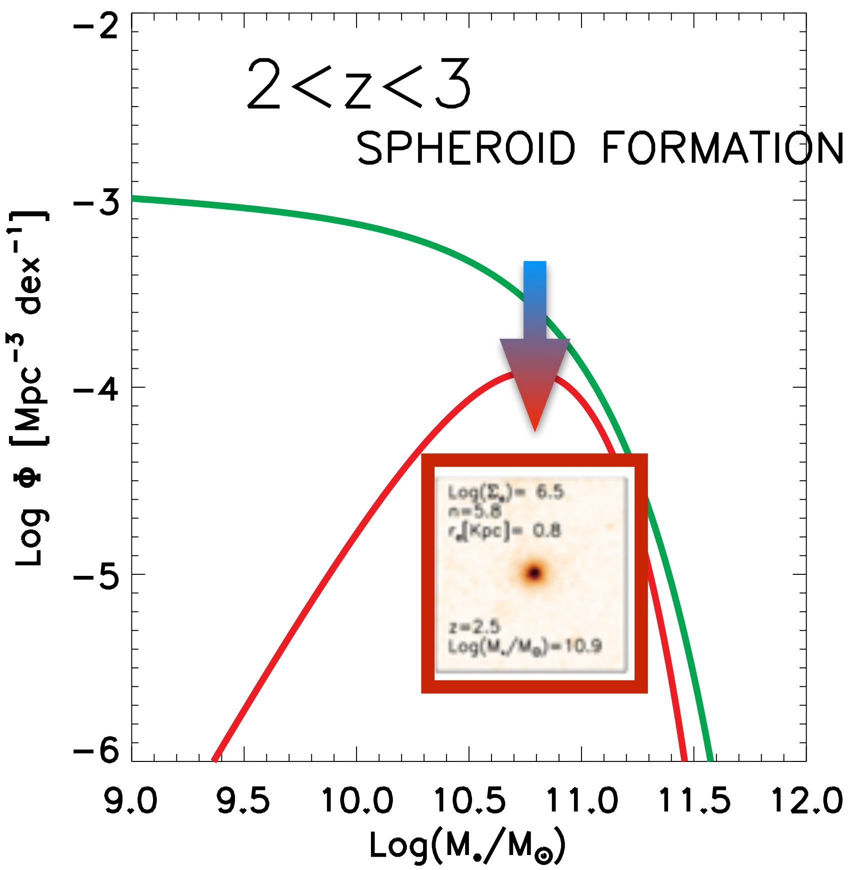


Ilbert+13



see also MHC+15a

SPHEROID FORMATION



Violent quenching:

Rapid spheroid formation

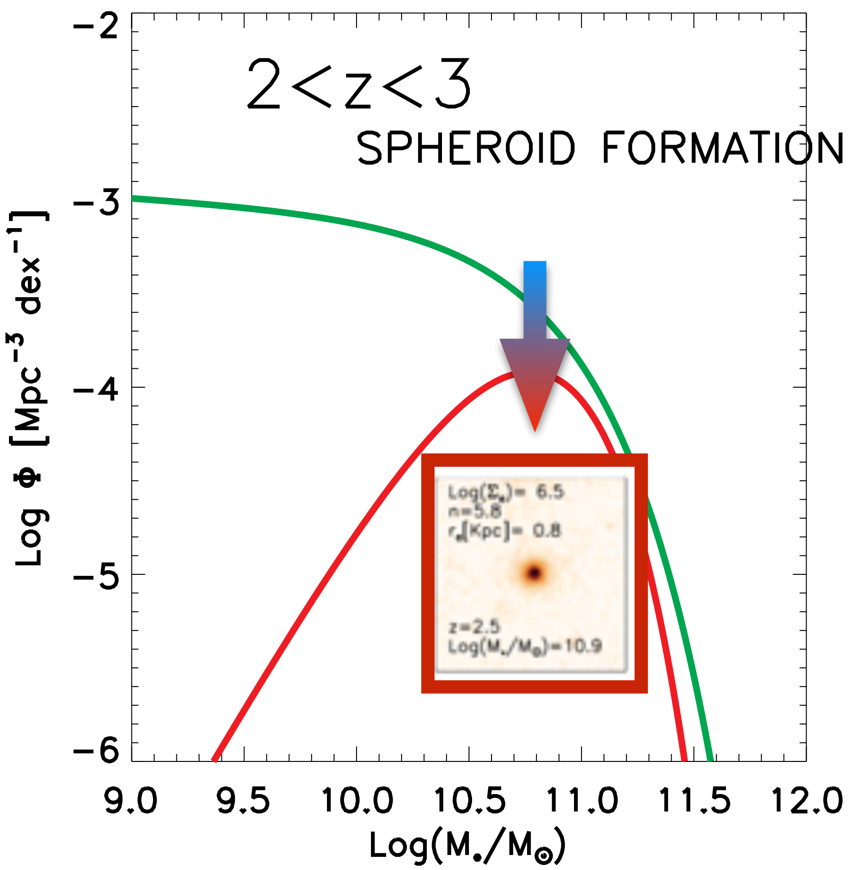
Violent quenching

Fast gas consumption

Compact and dense remnant (Dekel+,Barro +13)

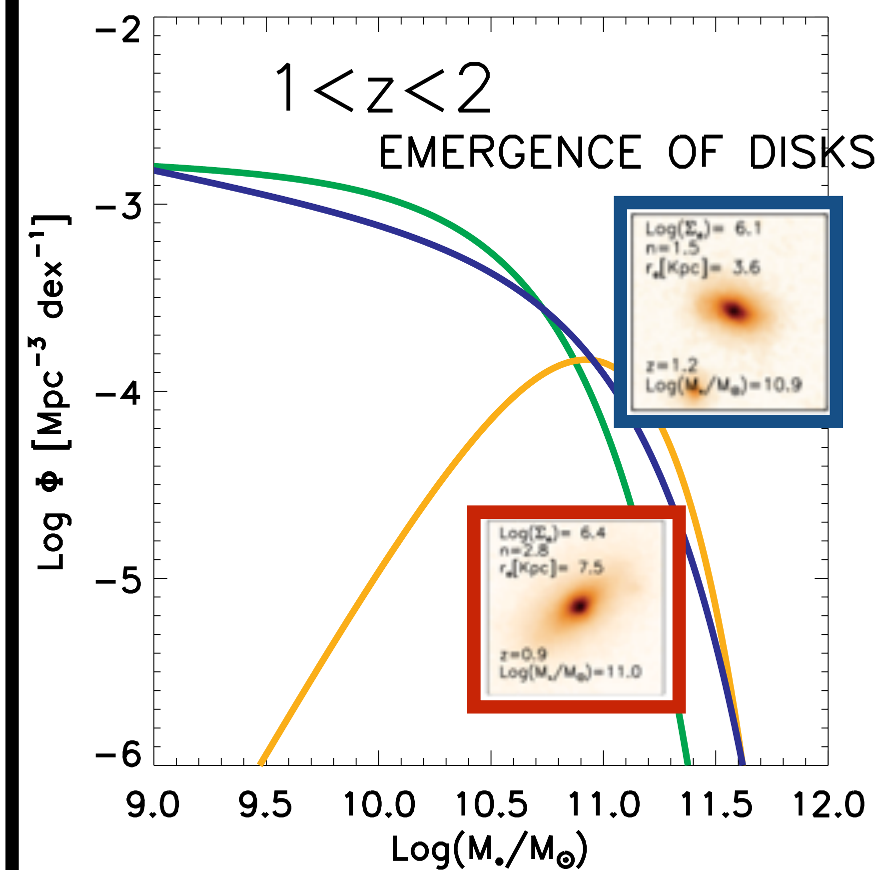
see also MHC+15a

SPHEROID FORMATION



Violent quenching:
Rapid spheroid formation
Violent quenching
Fast gas consumption
Compact and dense remnant (Dekel+,Barro +13)

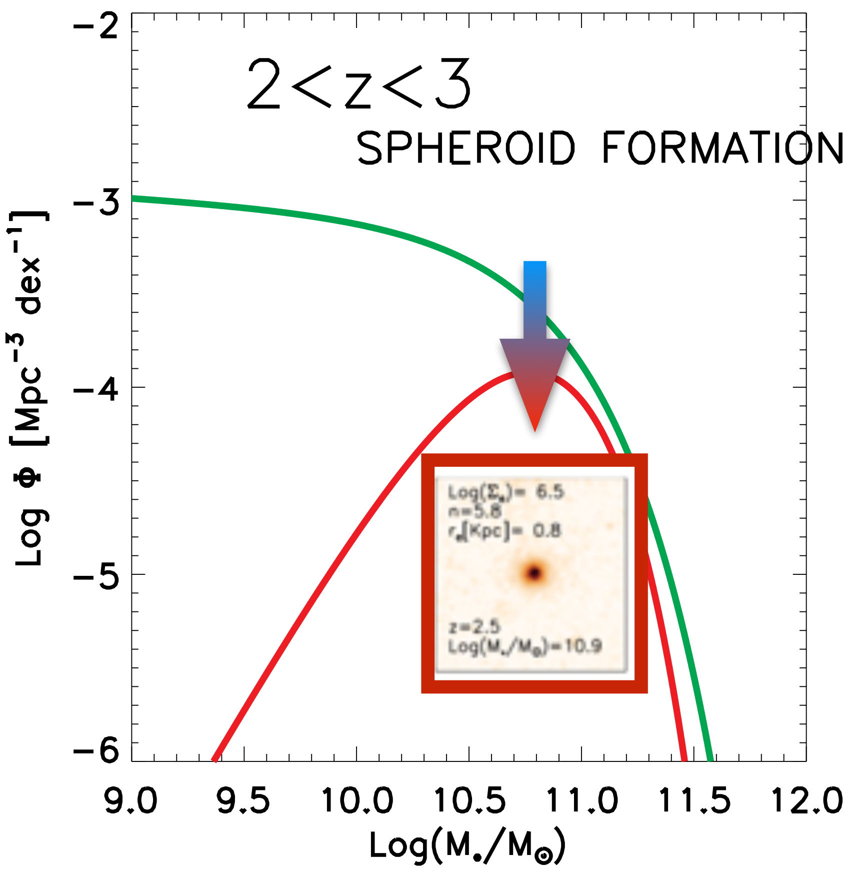
EMERGENCE OF DISKS



Gentle quenching:
Normal disks dominate (disk stabilization)
"Quiet" quenching that preserves the disk - see Peng+15

see also MHC+15a

SPHEROID FORMATION



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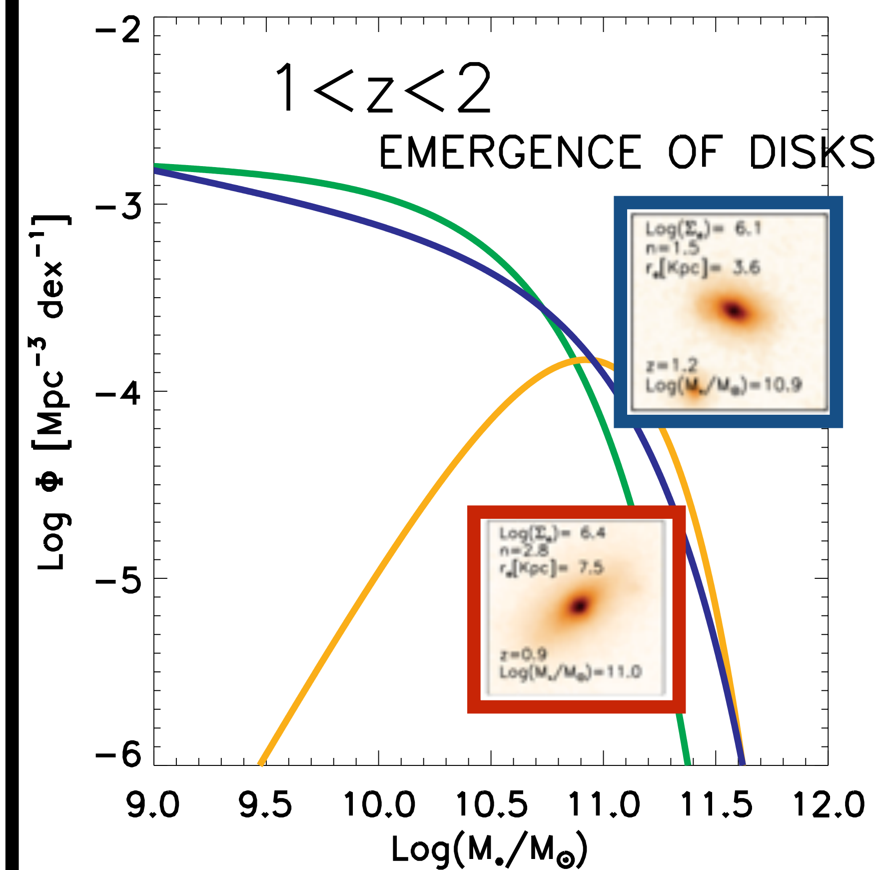
EMERGENCE OF DISKS



Gentle quenching:
Normal disks dominate (disk stabilization)
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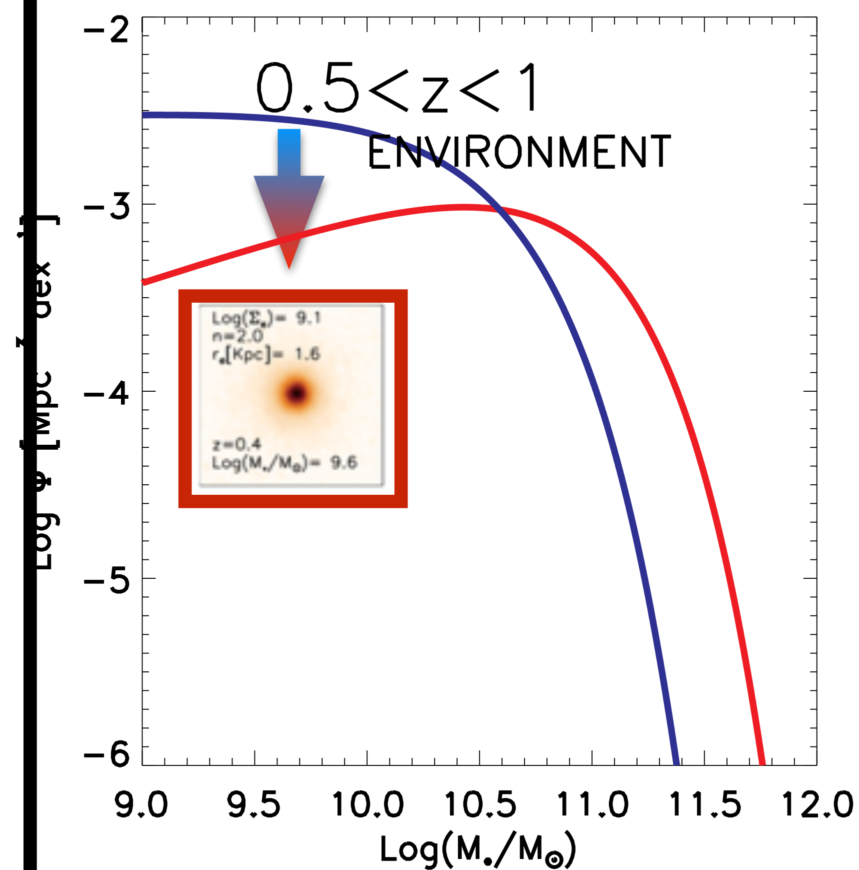
ENVIRONMENT



Environment quenching dominates at the low mass end
Disks statistically destroyed - Ram-pressure?

see also MHC+15a