# The relationship between quenching and structural and morphological evolution

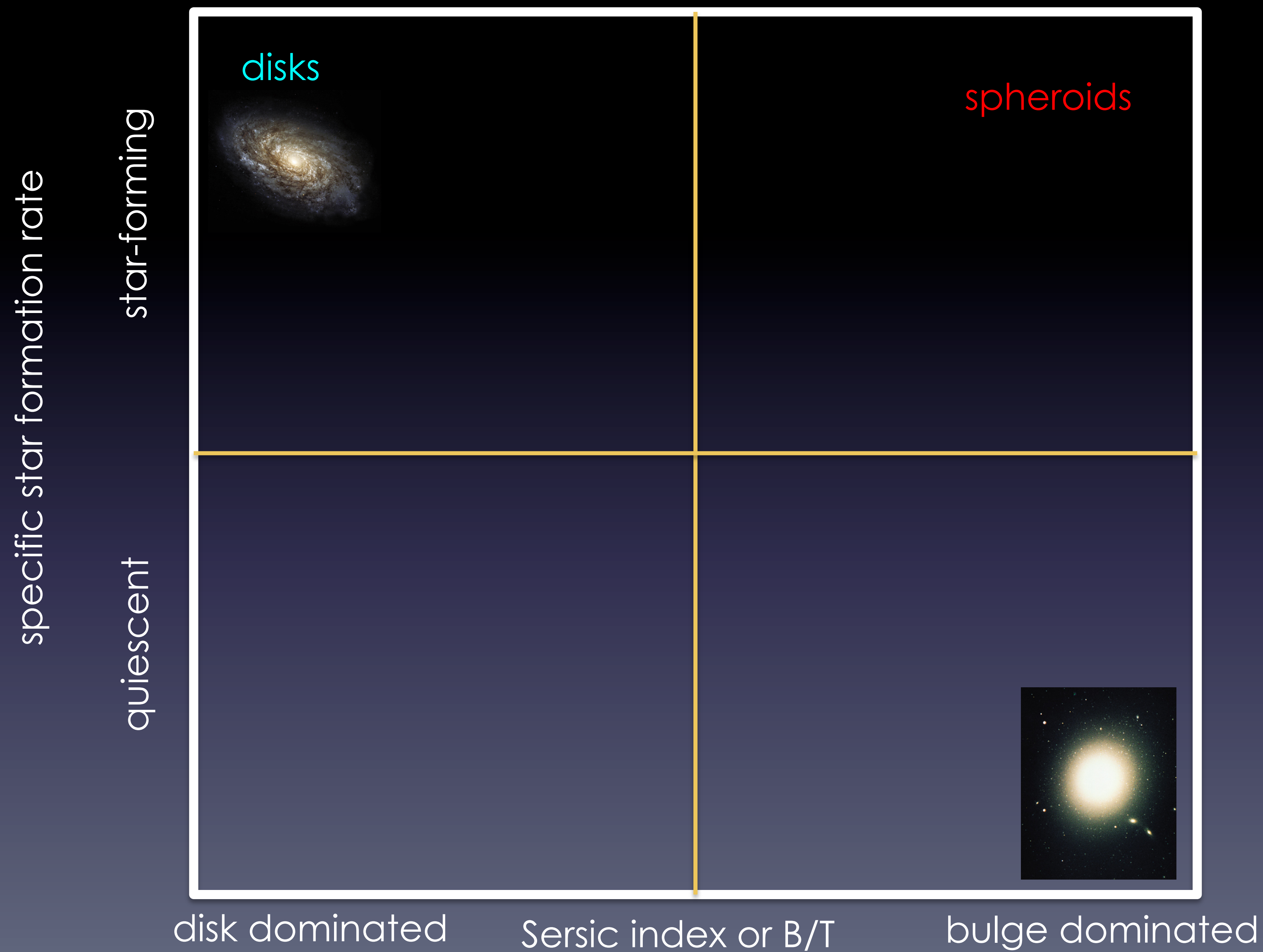

*rachel somerville*
*Rutgers University*

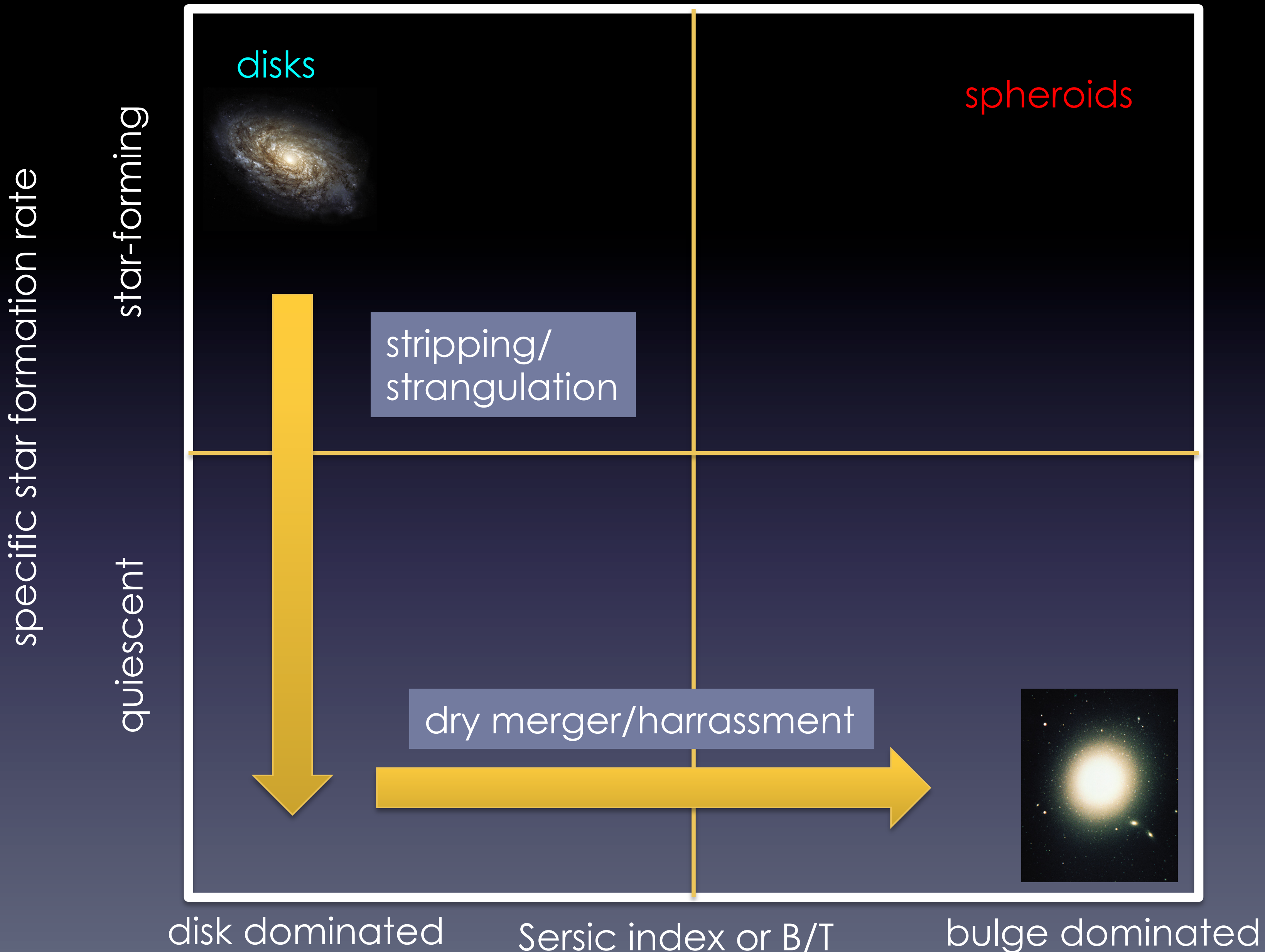

with thanks to: Ryan Brennan, Viraj Pandya, Ena Choi
Guillermo Barro, Stijn Wuyts, Dale Kocevski, Arjen van der Wel
& the CANDELS team

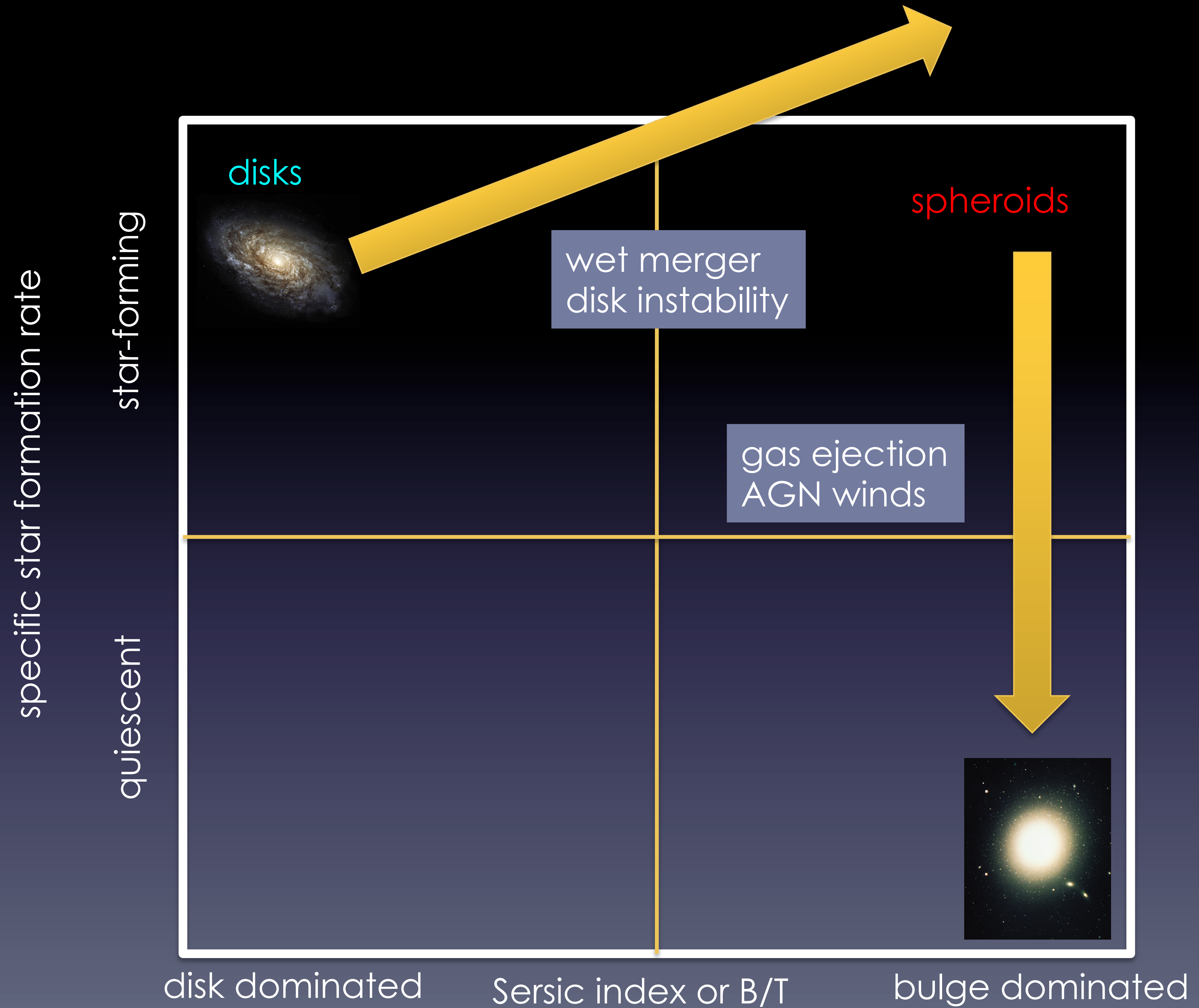
Quenching & Quiescence
Heidelberg, July 14-18 2014

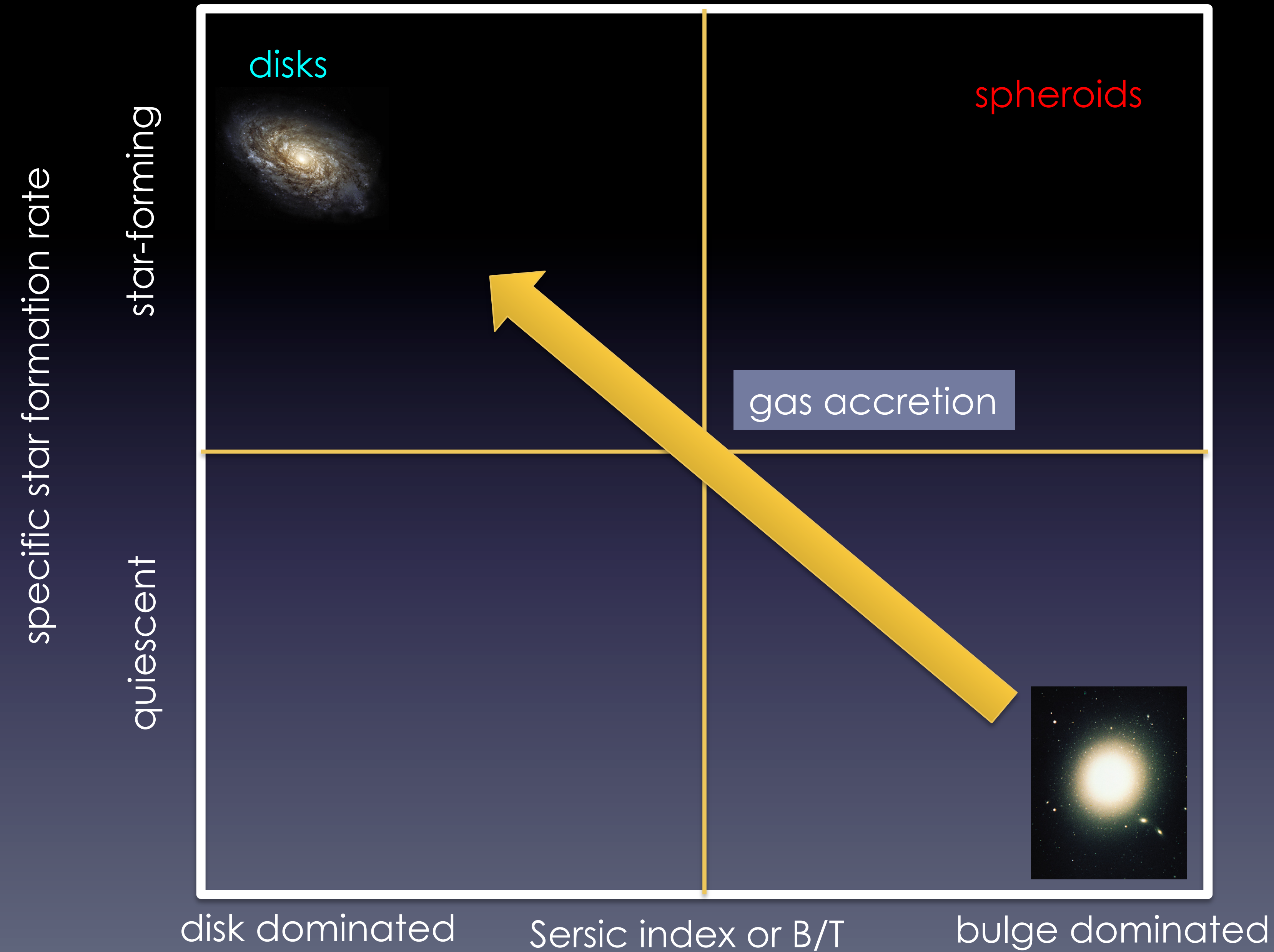
# Quenching Questions and Conundra

- quiescence and galaxy morphology (internal density) are linked – at all epochs since z~3 (E. Bell talk)
- fraction of galaxies (by number or mass) in 'quiescent' population has grown substantially since z~3 (Bell, etc.)
- quiescent galaxies are always more compact than SF galaxies (at a given stellar mass) at all epochs since z~3 (Bernardi, vdW talks)
- sizes of quiescent galaxies evolve much faster than SF-ers (vdW talk)
- how are quenching, morphological transformation, and structural evolution connected? → this talk!


disks
spheroids
star-forming
quiescent
specific star formation rate
disk dominated
Sersic index or B/T
bulge dominated

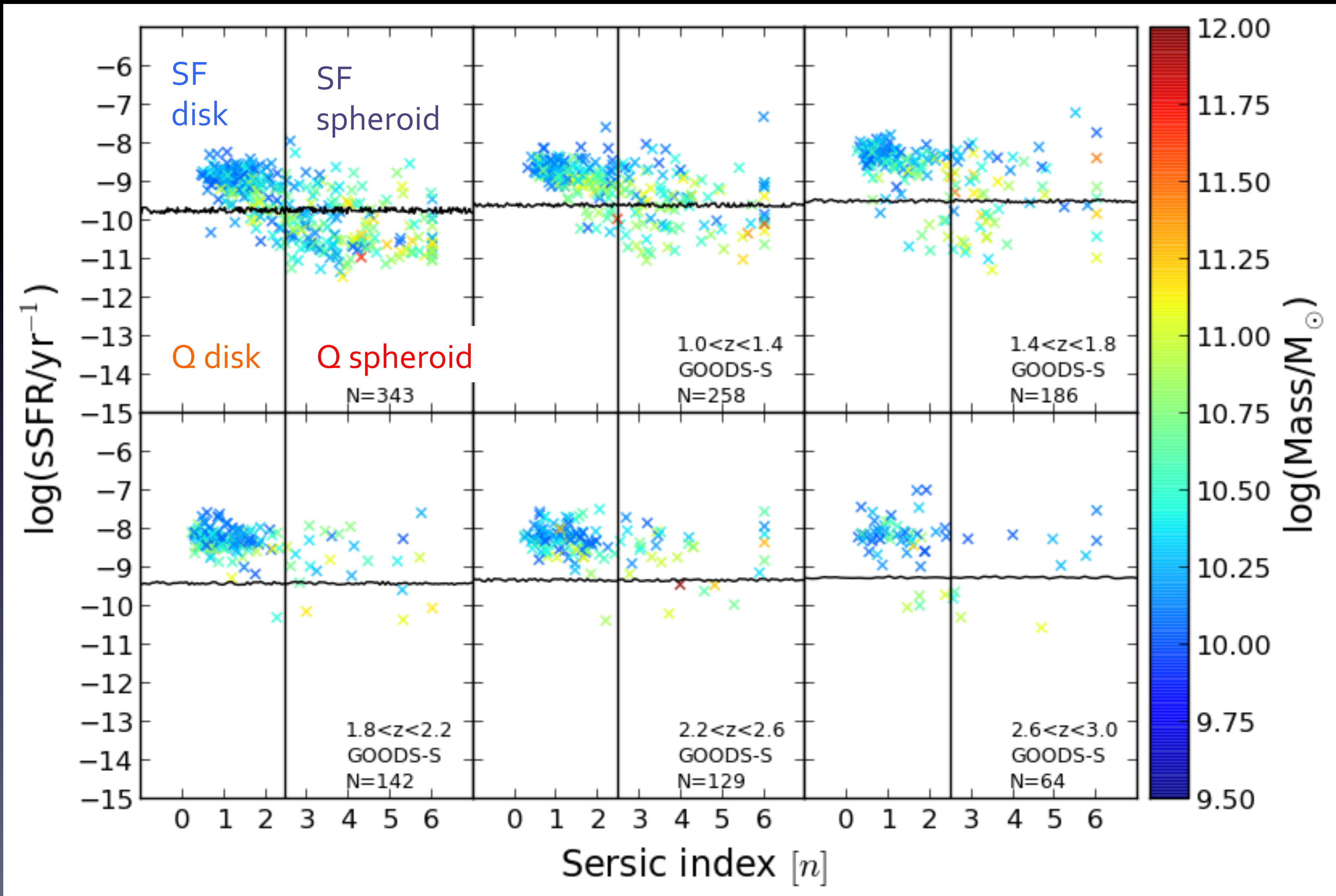

specific star formation rate
star-forming
quiescent
disks
spheroids
stripping/
strangulation
dry merger/harrassment
disk dominated
Sersic index or B/T
bulge dominated


disks
spheroids
wet merger
disk instability
gas ejection
AGN winds
specific star formation rate
star-forming
quiescent
disk dominated
Sersic index or B/T
bulge dominated

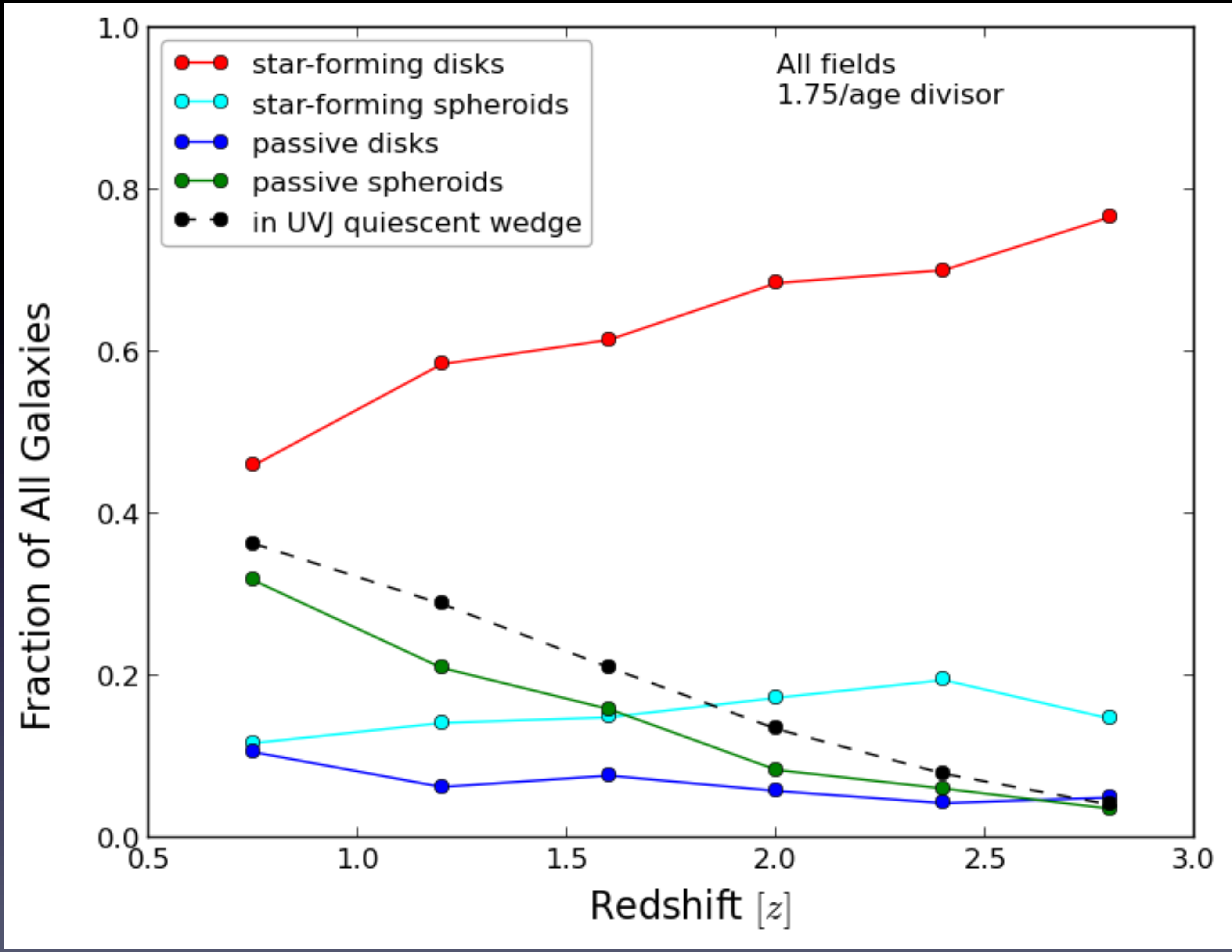

disks
spheroids
gas accretion
star-forming
quiescent
specific star formation rate
disk dominated
Sersic index or B/T
bulge dominated

$sSFR_{crit} = 1.75/age(z)$

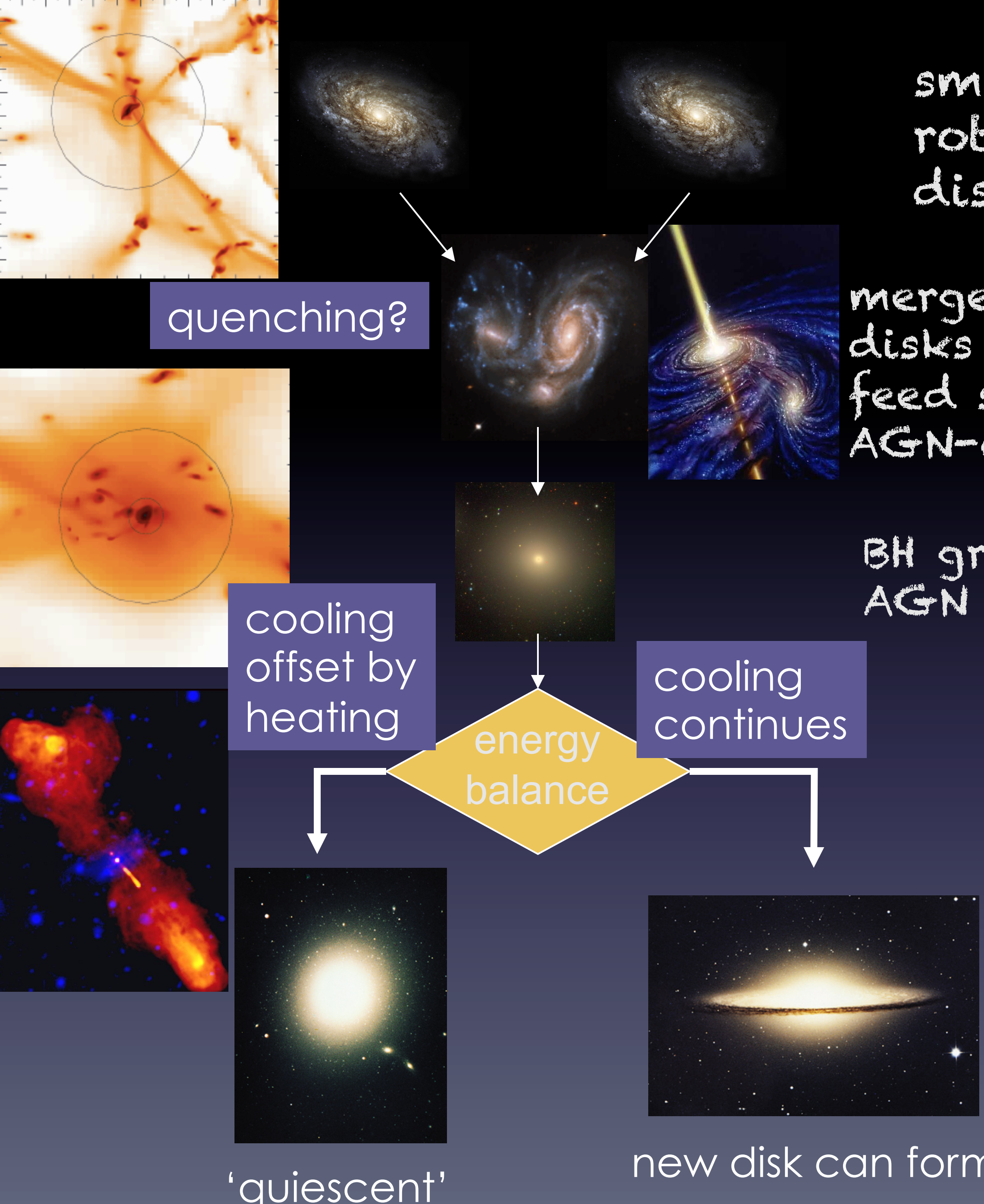
preliminary data from CANDELS – Brennan, Pandya, rss et al. in prep



CANDELS




Brennan, Pandya, rss et al. in prep

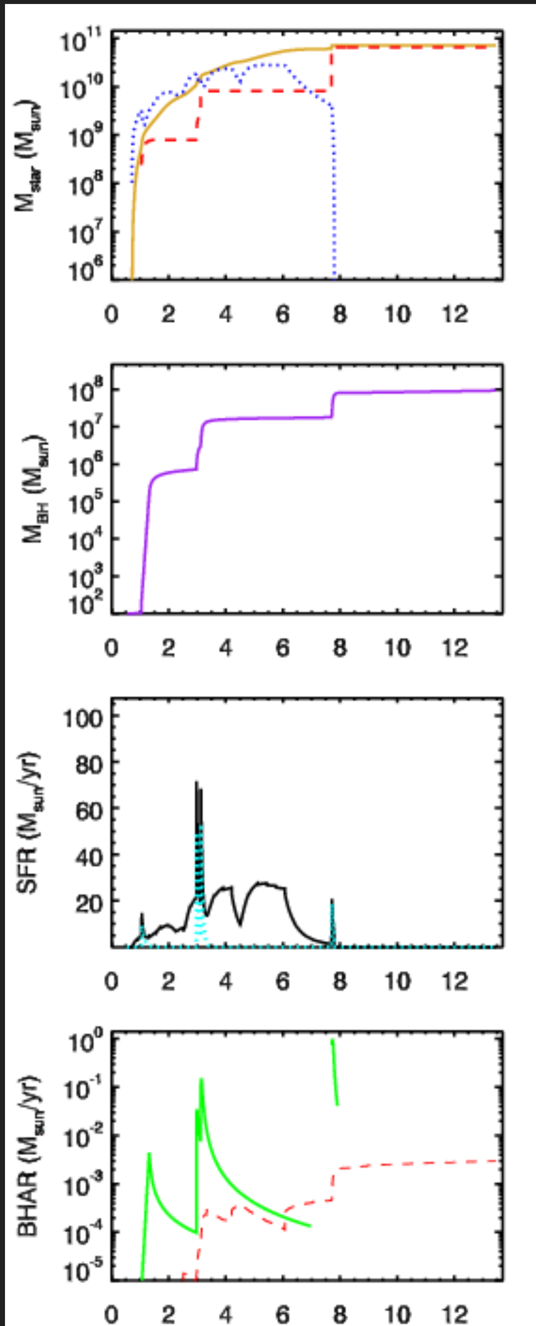



smooth accretion forms rotationally supported disks, stars form

mergers (or DI?) transform disks into spheroids and rapidly feed supermassive blackholes -- AGN-driven winds eject gas

BH growth self-regulated by AGN feedback on 'small scales'

diffuse halo gas heated by radio jets (+?) ('maintenance mode')

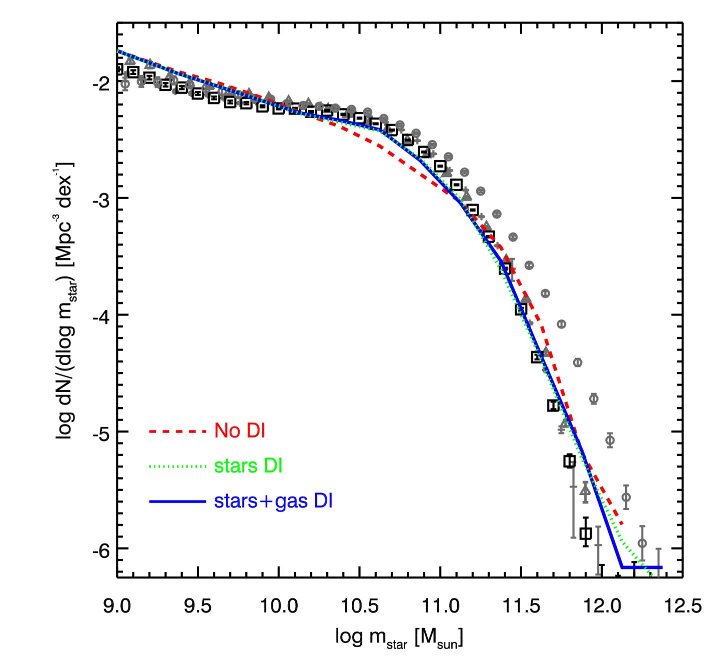


time (Gyr)

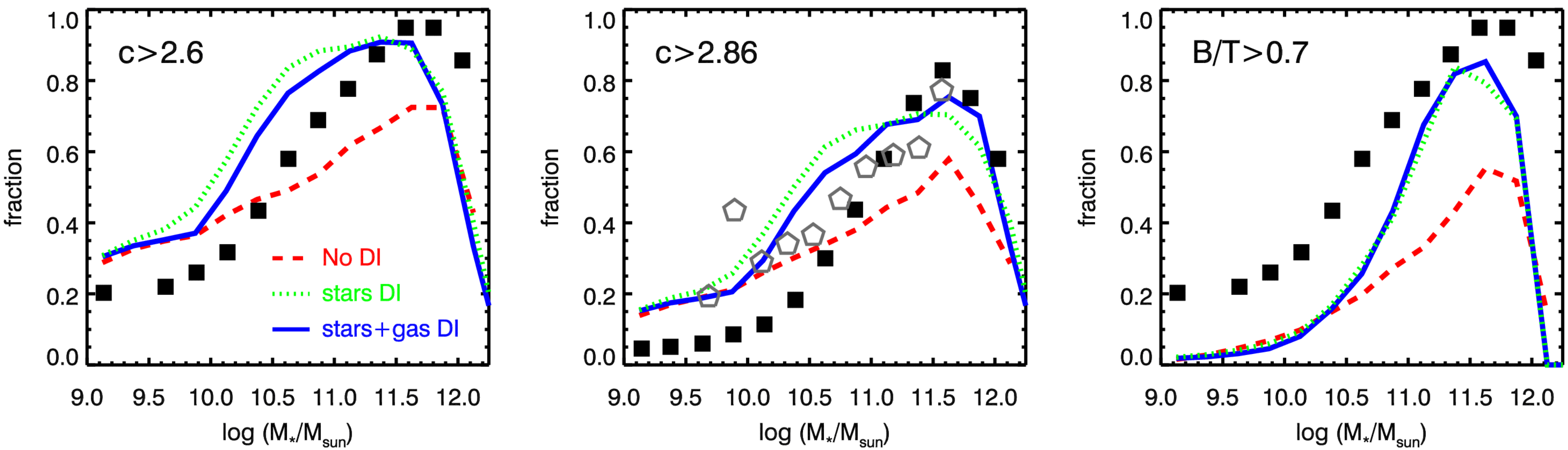
# model for the co-evolution of galaxies, black holes, and AGN

- top-level halos start with a ~100-$10^4$ $M_{sun}$ seed BH
- mergers trigger bursts of star formation and accretion onto BH, and scatter disk stars into a spheroidal component. parameterized based on hydrodynamic merger simulations (Cox et al., Robertson et al.)
- following a merger, BH accrete at Eddington until they reach 'critical mass', then enter 'blowout' (power-law decline) phase (Hopkins et al. lightcurves)
- energy released by "bright mode" BH accretion drives a 'momentum driven' wind
- 'Bondi' accretion mode fed by hot halo gas; powers radio jets that offset cooling flow in "hot mode" halos (radiatively inefficient)

rss, Hopkins, Cox, Robertson & Hernquist 2008

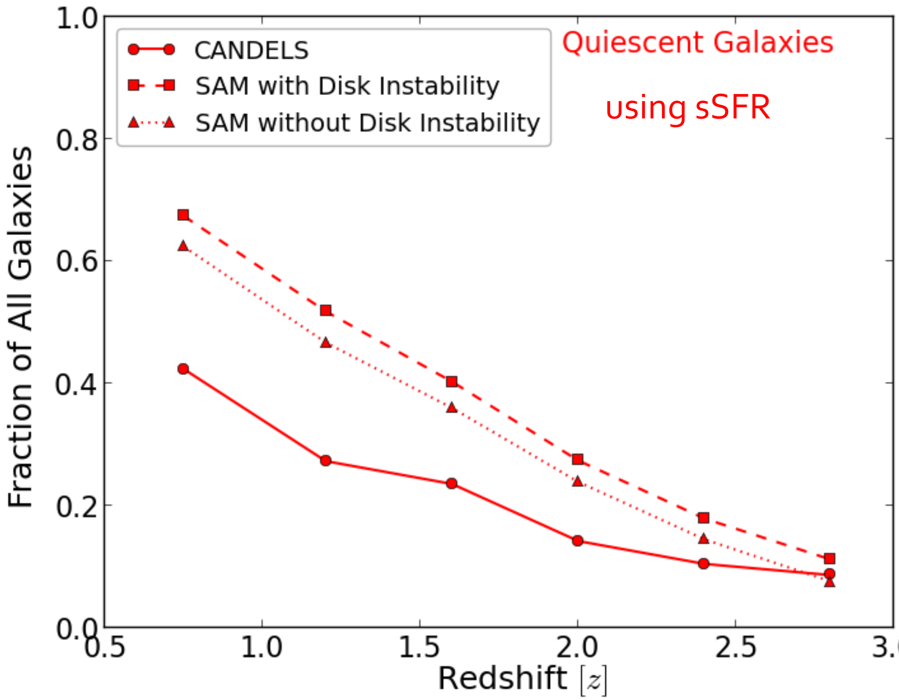


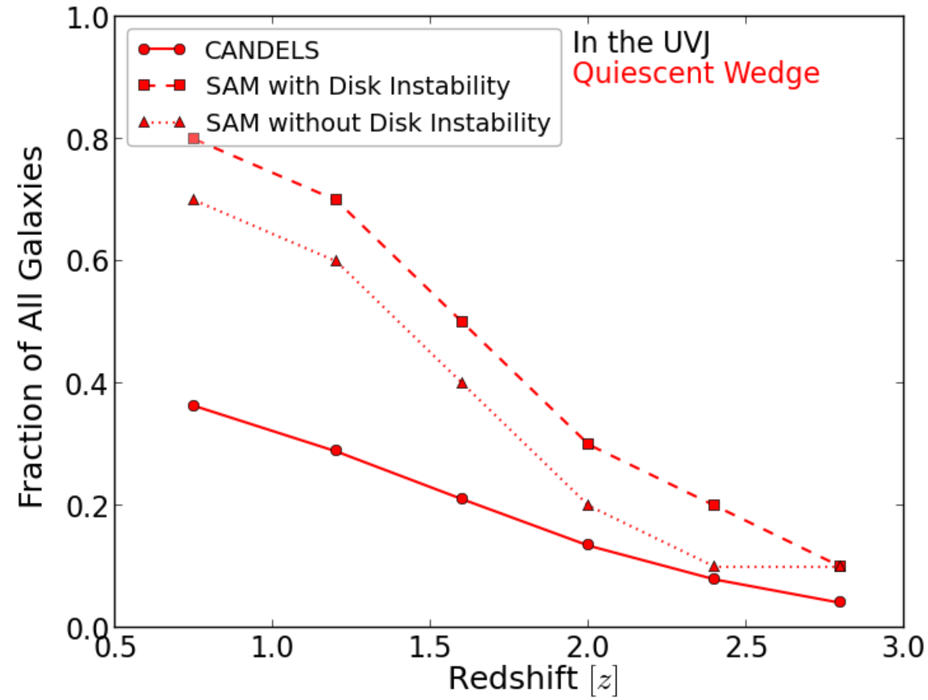

Latest 'Santa Cruz' SAM: Porter, rss, et al. 2014
arXiv:1407.0594
-run in 'ROCKSTAR+consistent trees' from Bolshoi
-model in which spheroids grow via mergers only did not produce enough intermediate mass early-type galaxies
-introduced two 'Disk Instability' recipes: stars only and stars+gas
-coupling of radio mode FB tuned to match high-mass end of SMF




symbols are observations from Bernardi et al. 2010; Cheng et al. 2011

SAMs produce about the right fraction of quiescent galaxies, or slightly too many (excess is probably mostly satellites; depends on how one defines `quiescent')




stellar mass >1.0E10 Msun

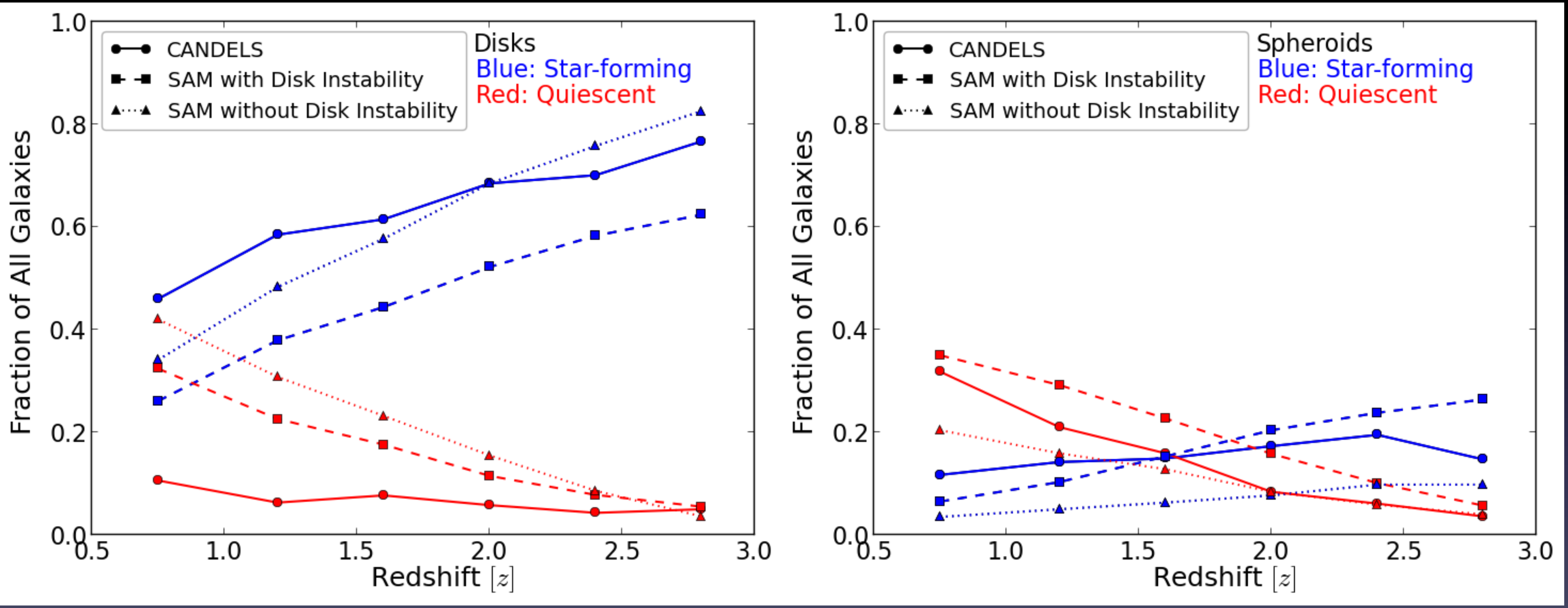
also qualitatively reproduce dependence of quiescent fraction on stellar or bulge mass up to z~3 – Lang et al. 2014

Brennan, Pandya, rss et al. in prep

SAMs produce too many quiescent disks

not enough SF spheroids in the model w/o DI

still, overall, the qualitative trends are not too bad…




Brennan, Pandya, rss et al. in prep

# simple model for disk sizes

$$r_d \sim \lambda\, r_H\, f(c, \lambda, f_d)$$

- smoothly accreted gas ~ conserves its specific angular momentum
- disks form with exponential radial profiles
- density profile gets modified a bit by 'baryonic contraction'

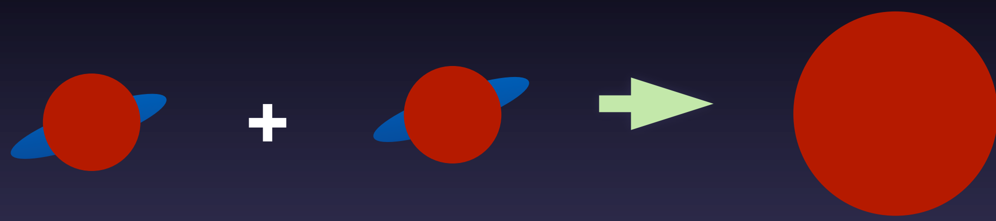
Blumenthal et al. 1986
Dalcanton et al. 1997
Mo, Mao & White 1998
Somerville et GEMS 2008

# New Model for spheroid sizes and velocity dispersions

$$C_{\rm int} E_{\rm int,remn} = C_{\rm int} E_{\rm int,prog} + C_{\rm rad} E_{\rm rad}$$

Orbital parameters, gas fraction, mass ratio

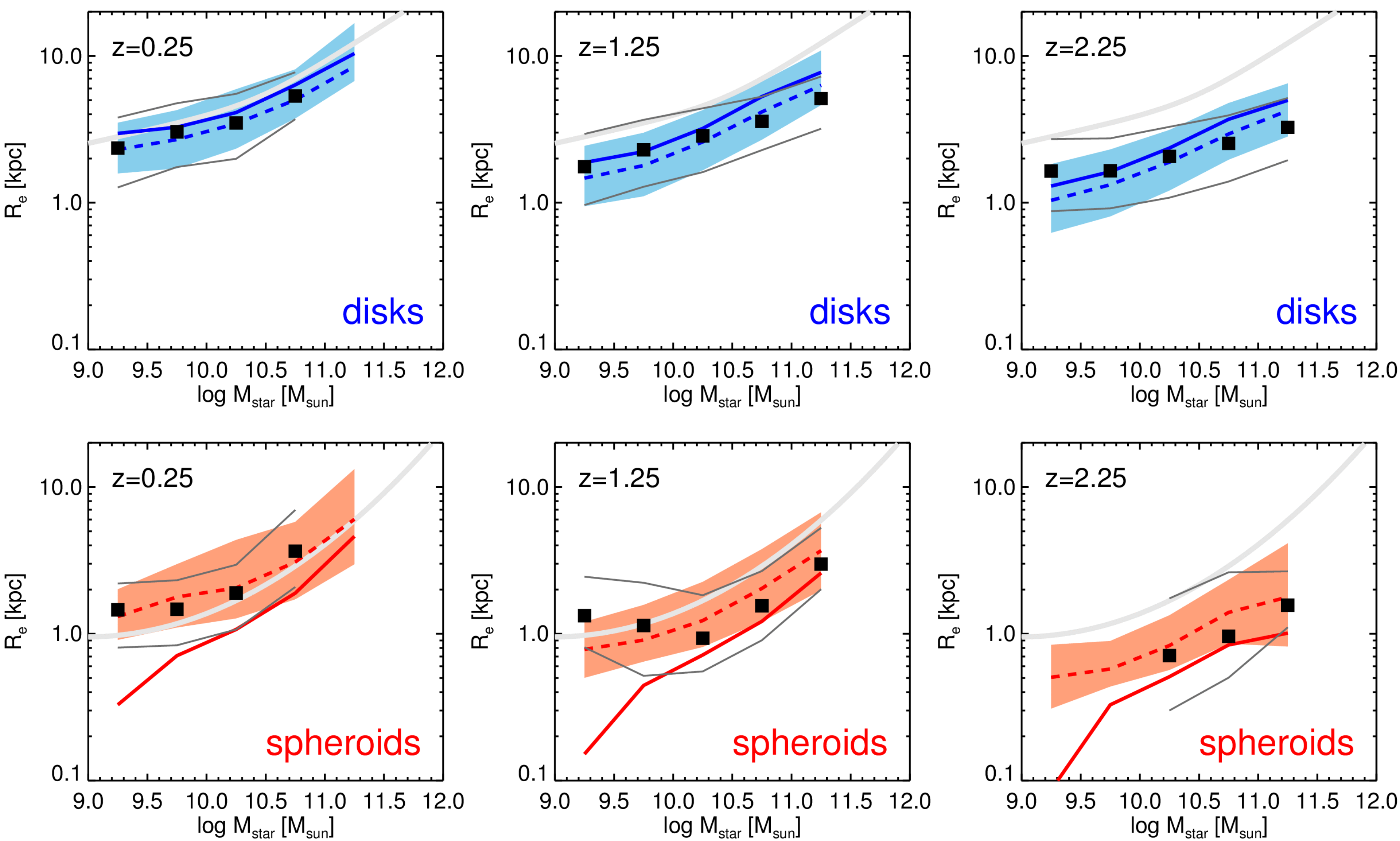
form factors calibrated from SPH simulations of binary idealized galaxy mergers (Cox et al.; Johansson et al. 2009) including mixed-morphology mergers




'dry' mergers produce remnants that are larger in radius than their progenitors


'wet' mergers produce remnants that are more compact than their progenitors

Porter, rss et al. 2014; see also Covington et al. 2008; 2011 solid lines: size of disk or spheroid component; dashed: size of composite galaxy

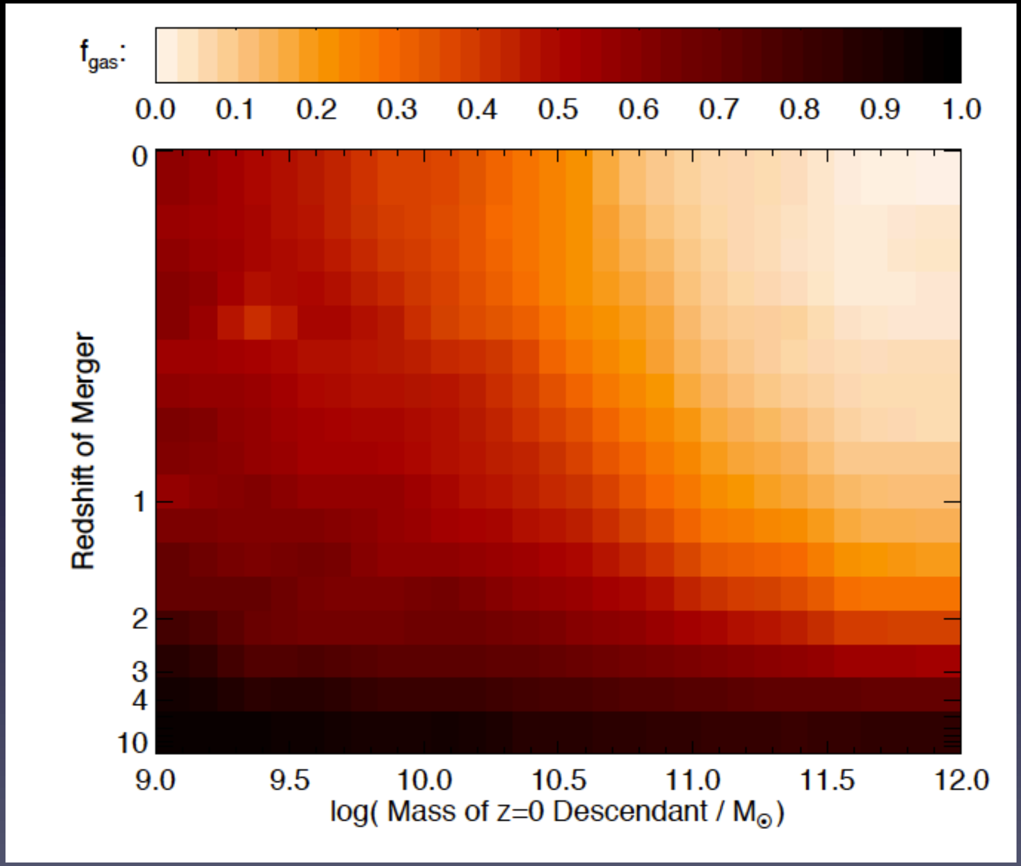



rss, Porter+CANDELS in prep; observations from van der Wel et al. 2014

# quenching and size evolution

- mergers are more gas-rich at high z
- low-mass galaxies have higher gas fractions at all z (set by SF efficiency/ feedback)
- the more gas, the more dissipation, the more compact the remnant
- massive galaxies become quenched at z~2 → transition from predominantly wet to predominantly dry (gas-poor) mergers above the critical (quenching) mass

gas fraction in mergers

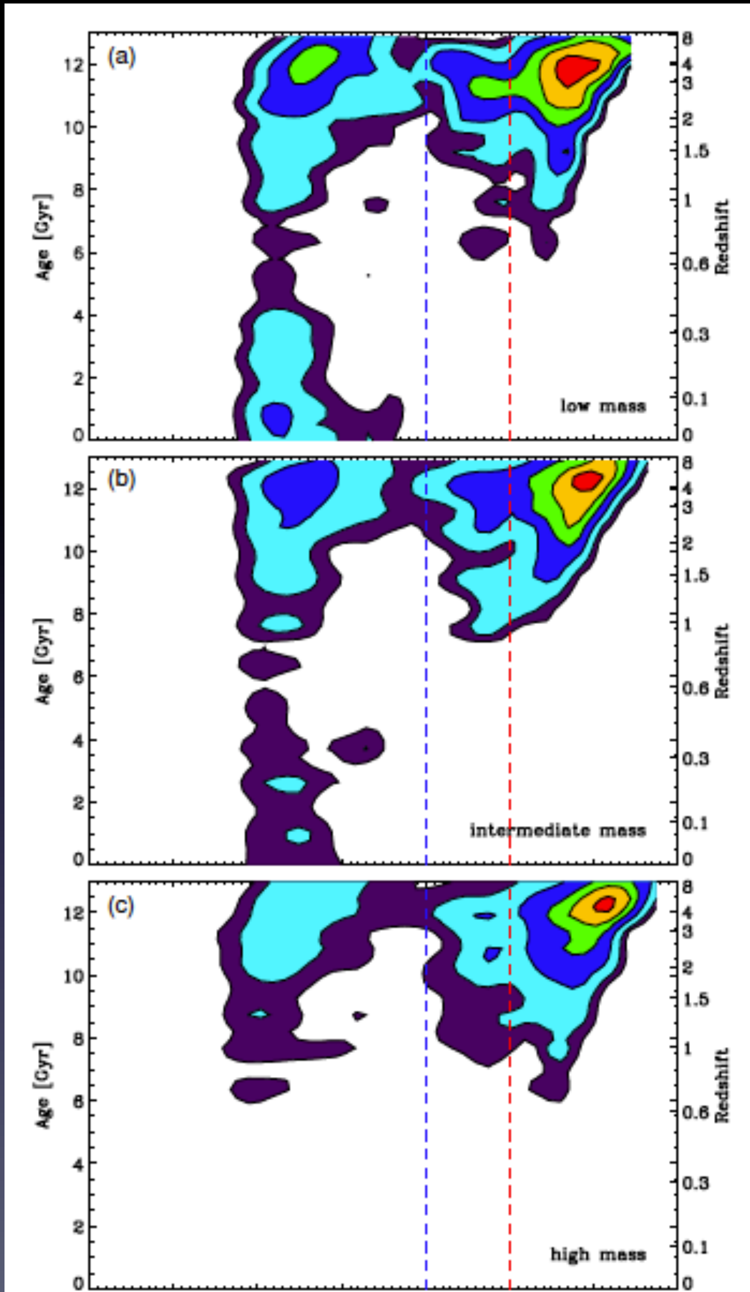



P. Hopkins, rss et al. 2009

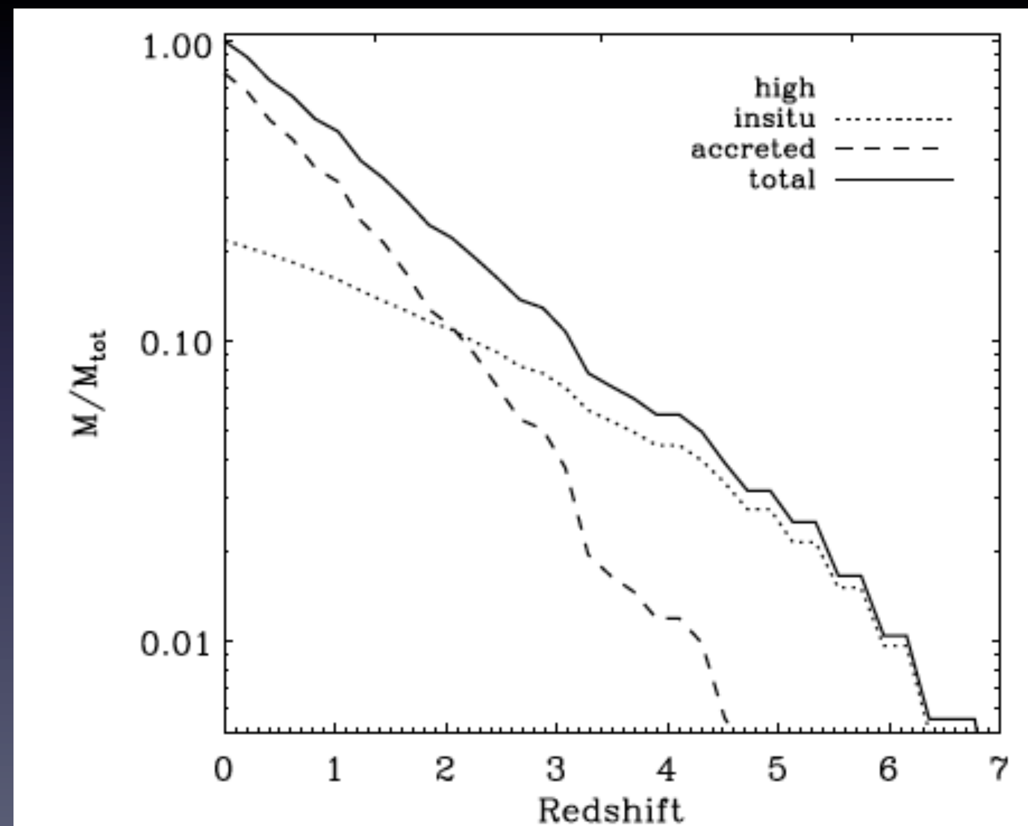
# ‘Two-phase’ galaxy assembly

Oser, Naab et al. 2010, 2012

growth of early types dominated by ‘accreted mass’ at late times
[more so for more massive systems]



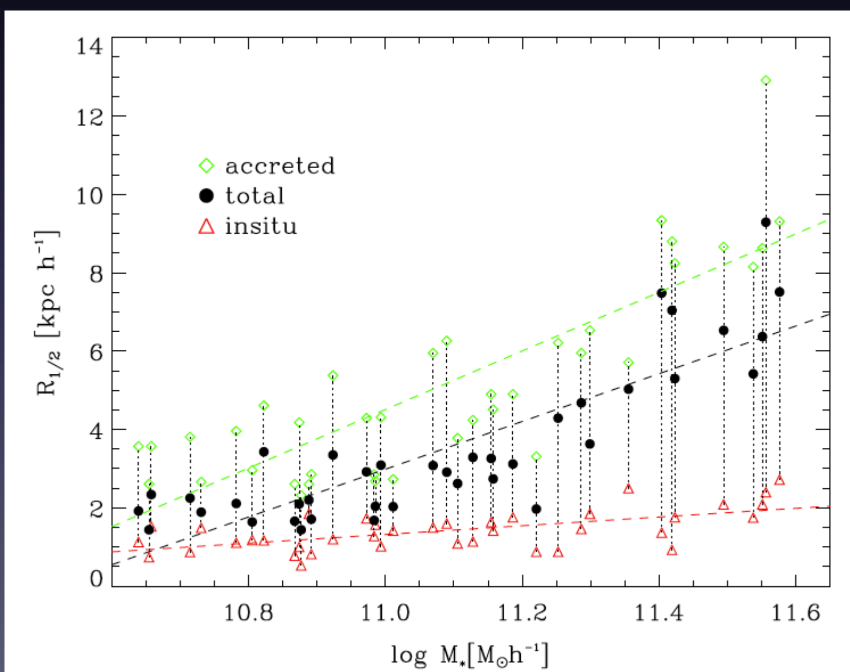

-5 -4 -3 -2 -1 0 log $R/R_{vir}$

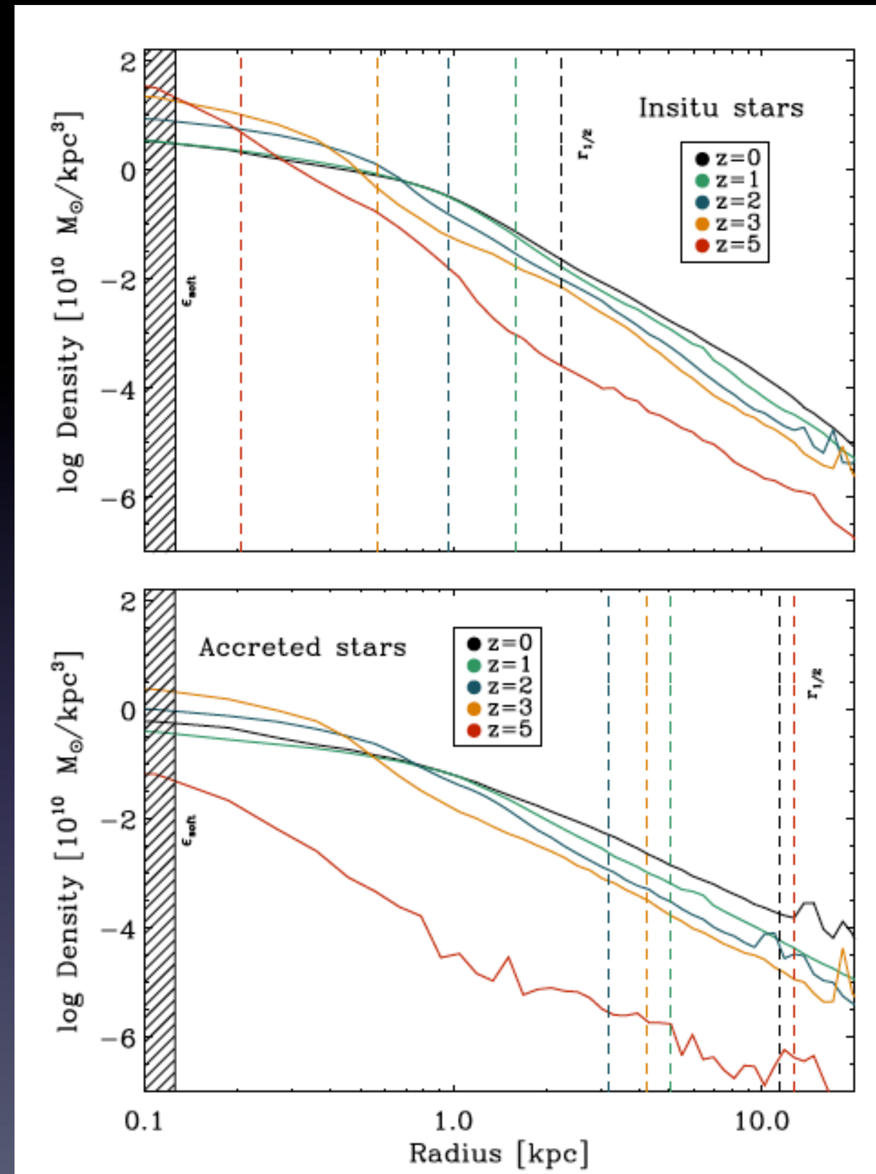



Oser et al. 2010

a relatively small number of dry minor or intermediate mergers (1:5-1:10) can significantly increase radius; accompanied by much smaller increase in mass and velocity dispersion; $R_{1/2} \sim M_{acc}/M_{ins}$

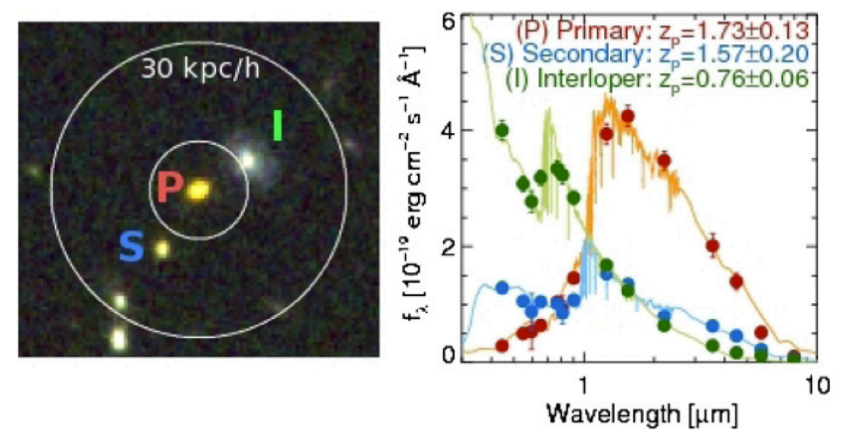
Naab et al. 2009; Hilz et al. 2012
see also Hopkins et al. 2009, 2010

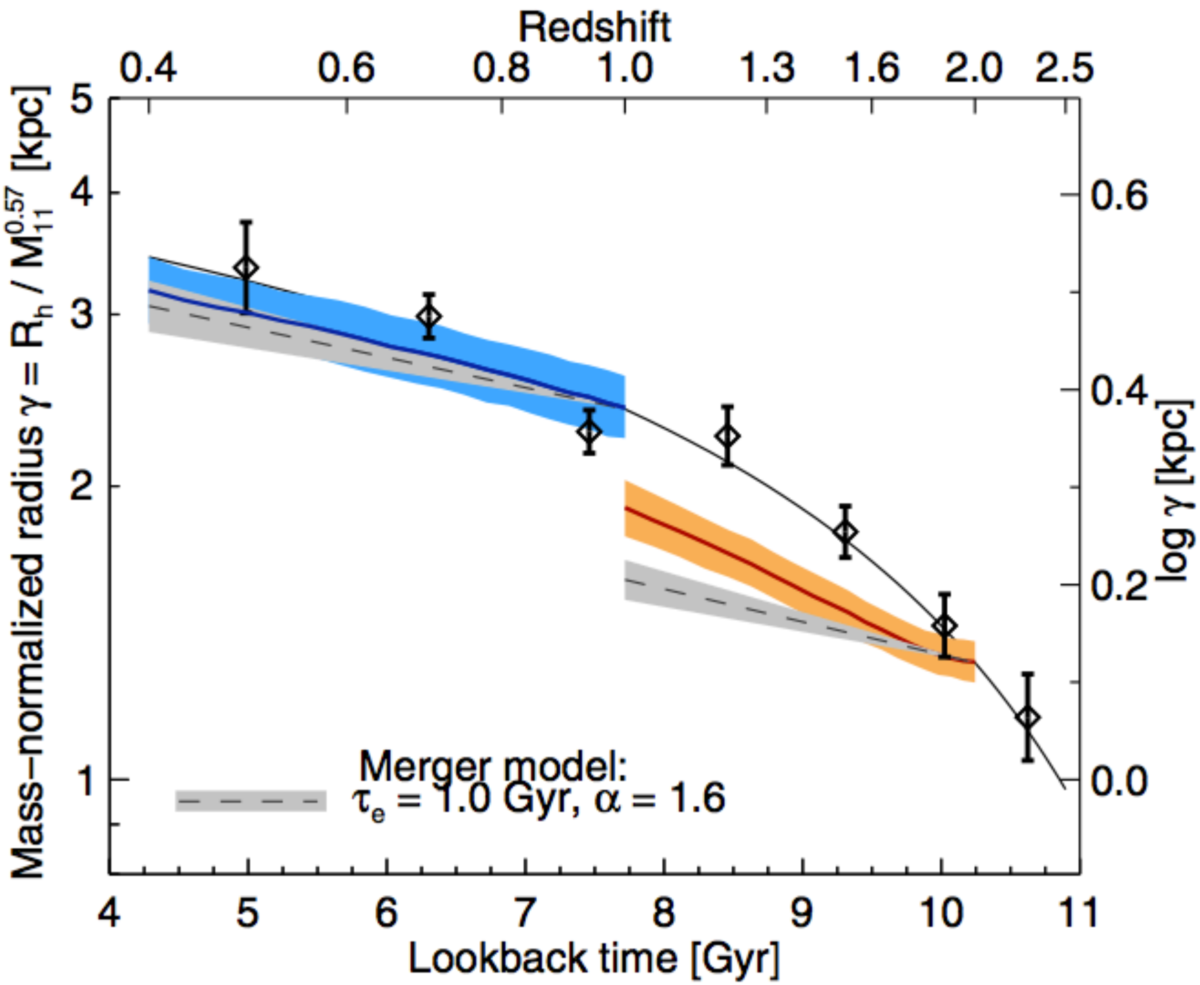


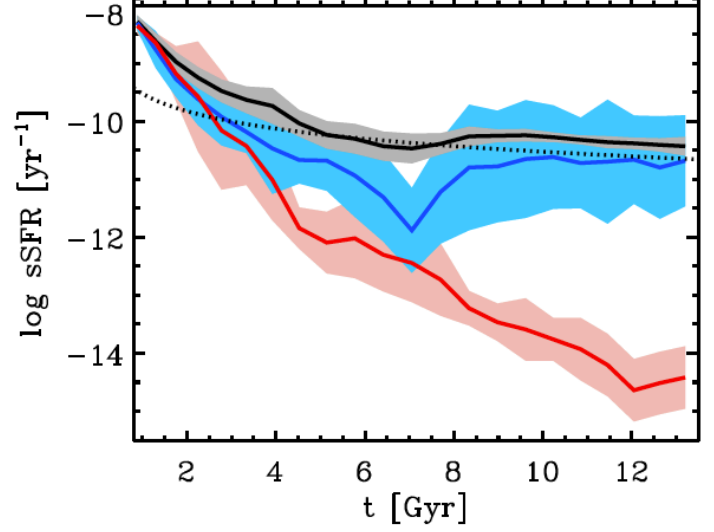

Oser et al. 2010

Newman et al. 2012: study of pair fractions around quiescent galaxies in UDS+GOODS-S



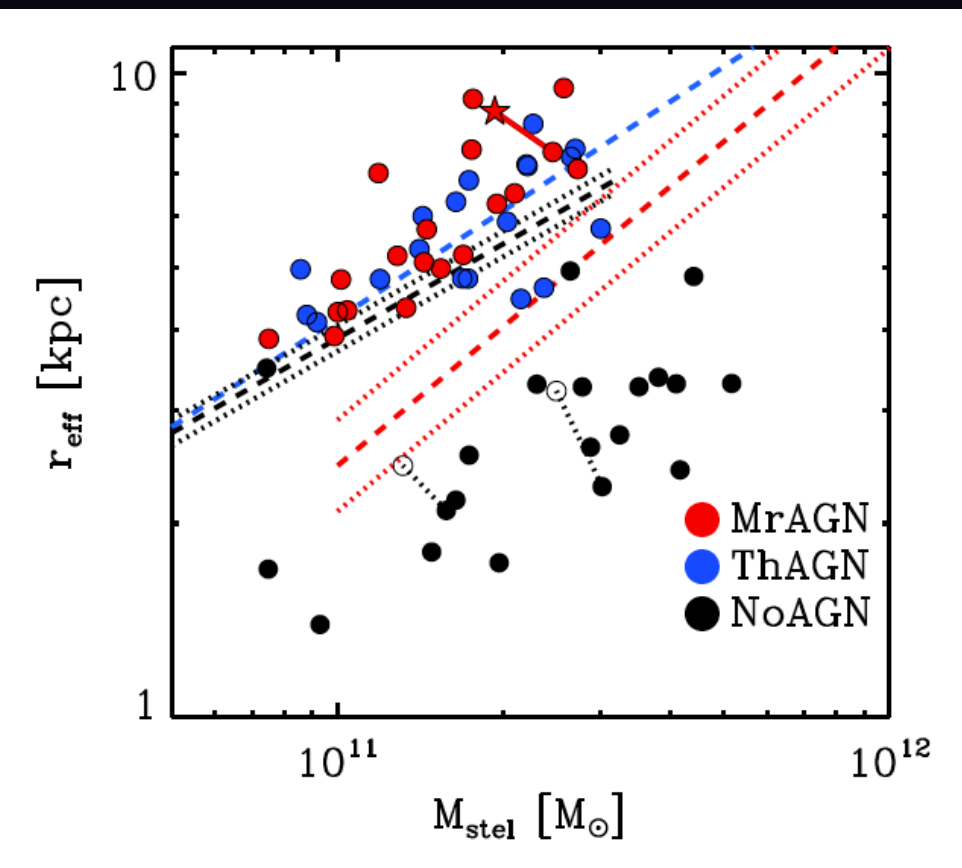




concluded observed pair fractions consistent w/ minor mergers driving size growth at z<~1 but not at z>1




Cosmological hydrodynamical “zoom-in” simulations
including AGN feedback
(thermal, radiative, and mechanical)

20 halos
$(1.1E12 < M_h(z=0) < 1.0E13)\ M_{sun}$
$(8.9E10 < M_*(z=0) < 1.0E12)\ M_{sun}$
star and gas particles 6E06 $M_{sun}$
DM particles 3.6E07 $M_{sun}$
comoving softening 571 pc

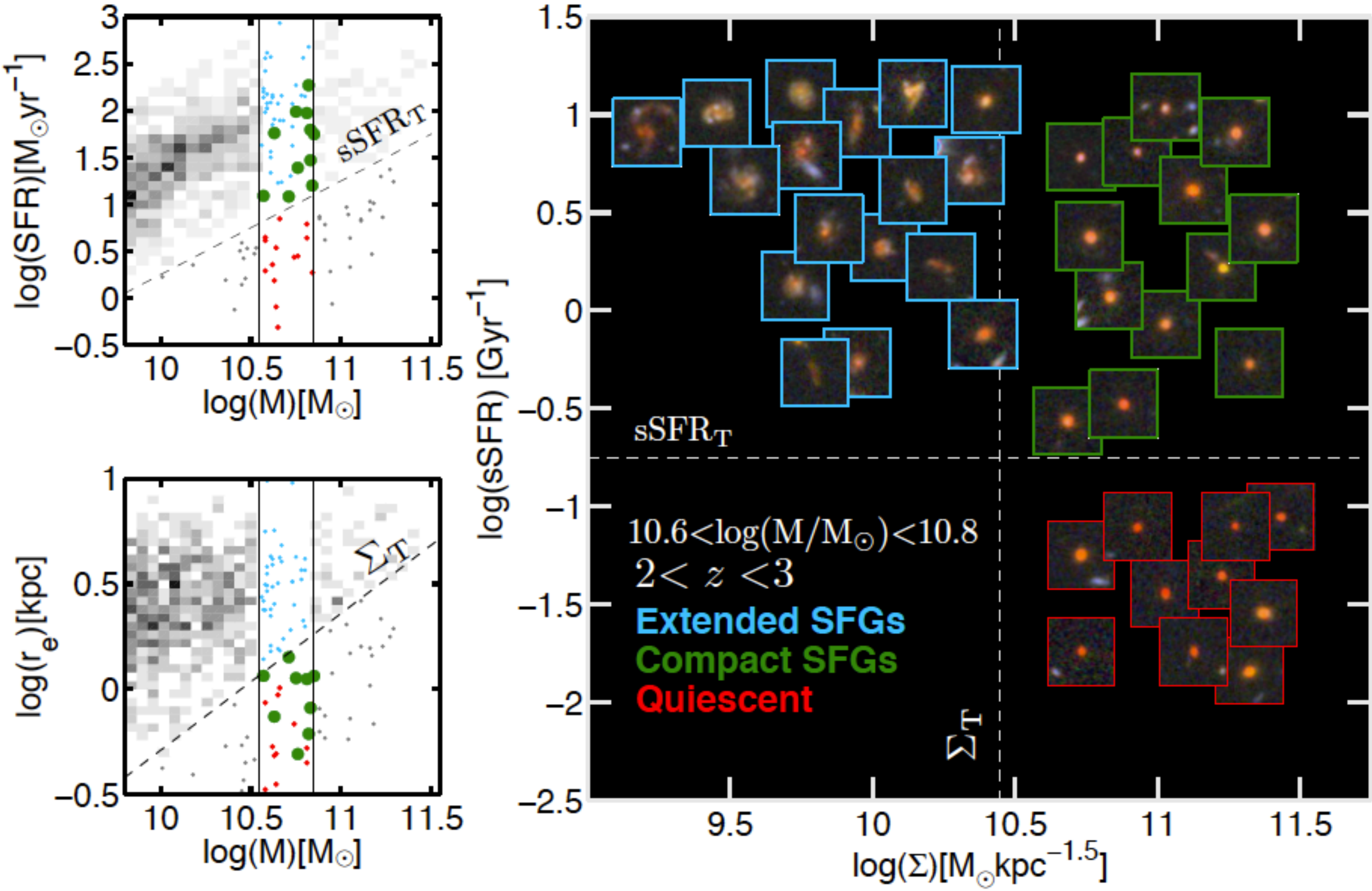



- size-mass scaling relations
- size evolution
- fraction of accreted/in situ

*all very sensitive to details of stellar and AGN feedback! (and also to numerics)*

E. Choi et al. arXiv:1403.1257
+work in prep w/ Naab, J. Ostriker
Oser, Hu, Moster, rss

# Introducing the “Barro” plot

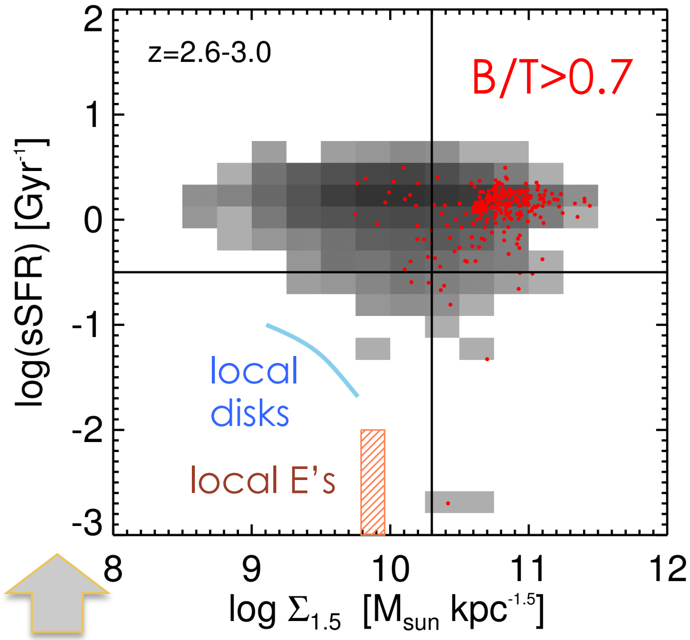



Barro et al. arXiv/1311.5559; see also Barro et al. 2013

How do galaxies evolve in internal density and specific star formation rate?

Viraj Pandya & Ryan Brennan
w/ G. Barro & the CANDELS team
work in prep

z=2.6-3

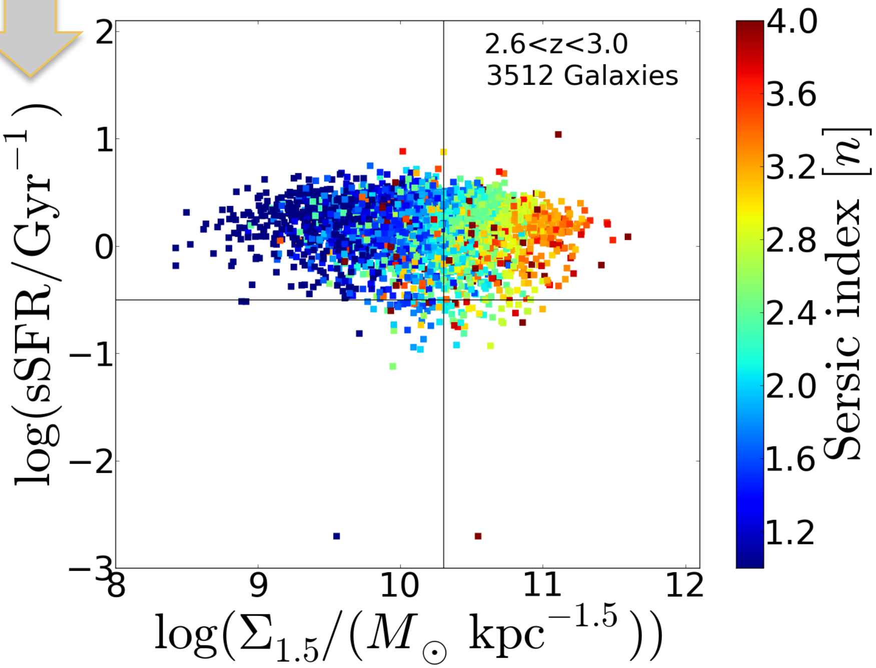


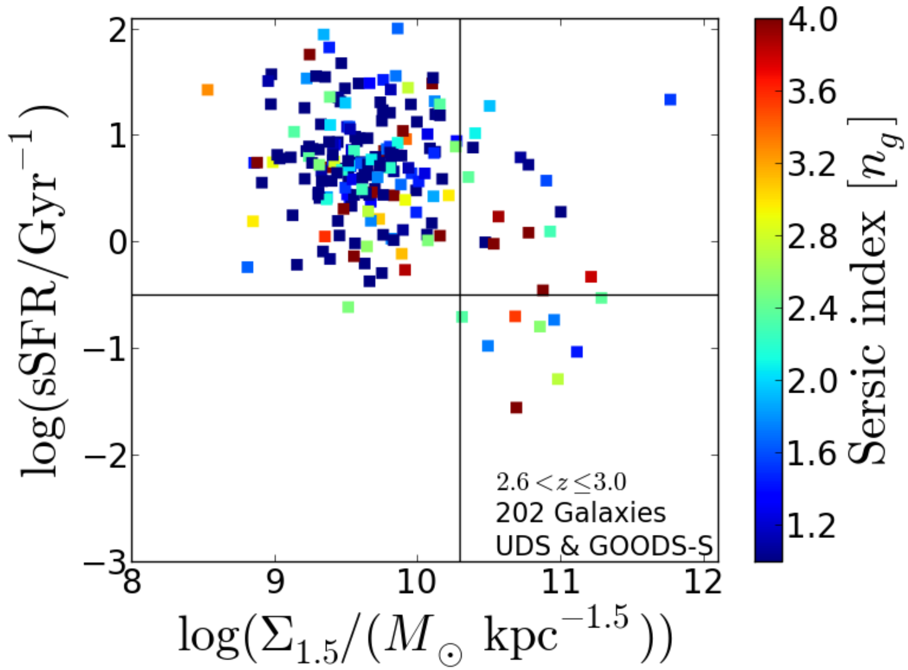

model

log $M_*/M_{sun}$ > 10

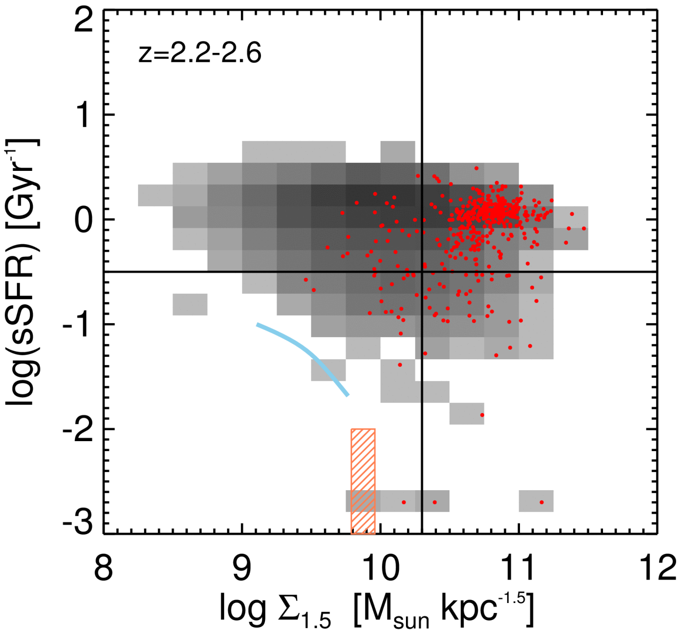
CANDELS observations

spheroid-like



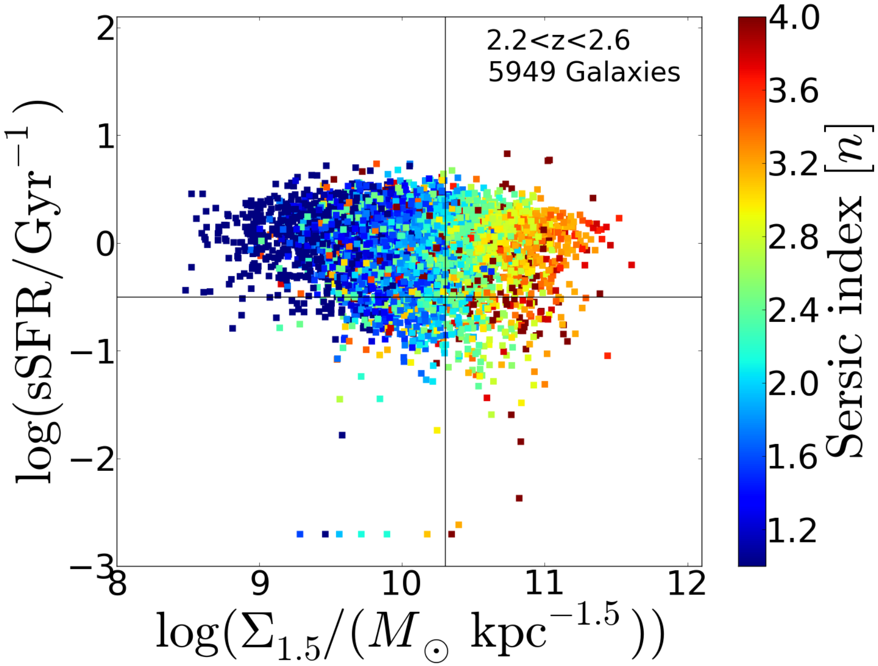
z=2.2-2.6

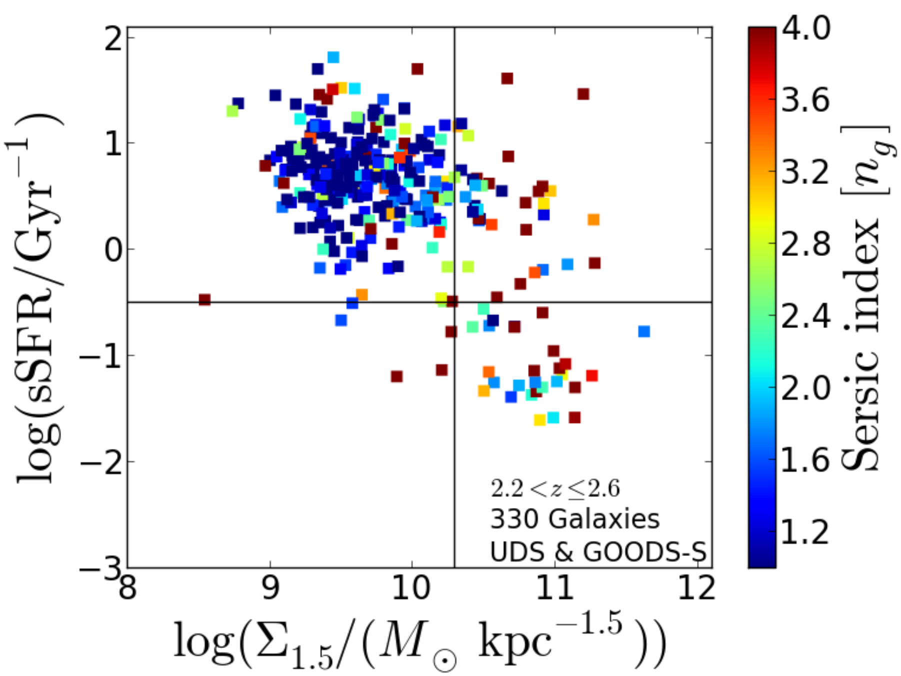



quenching

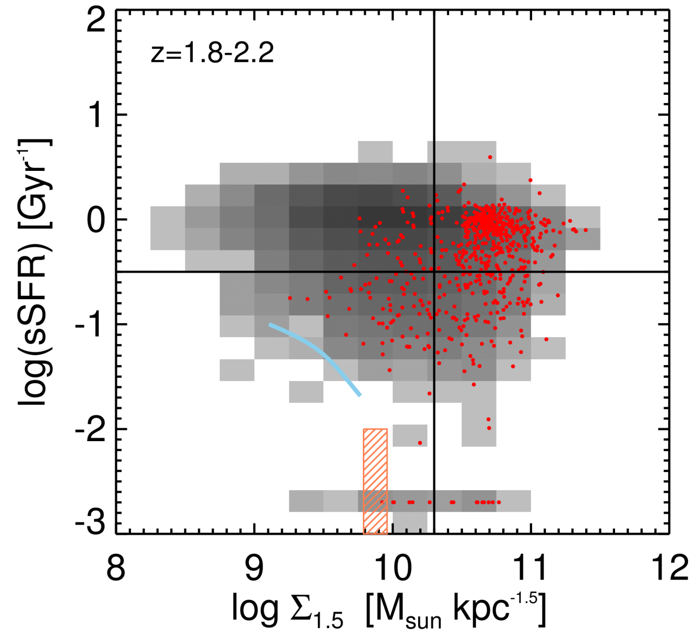
CANDELS
observations

model



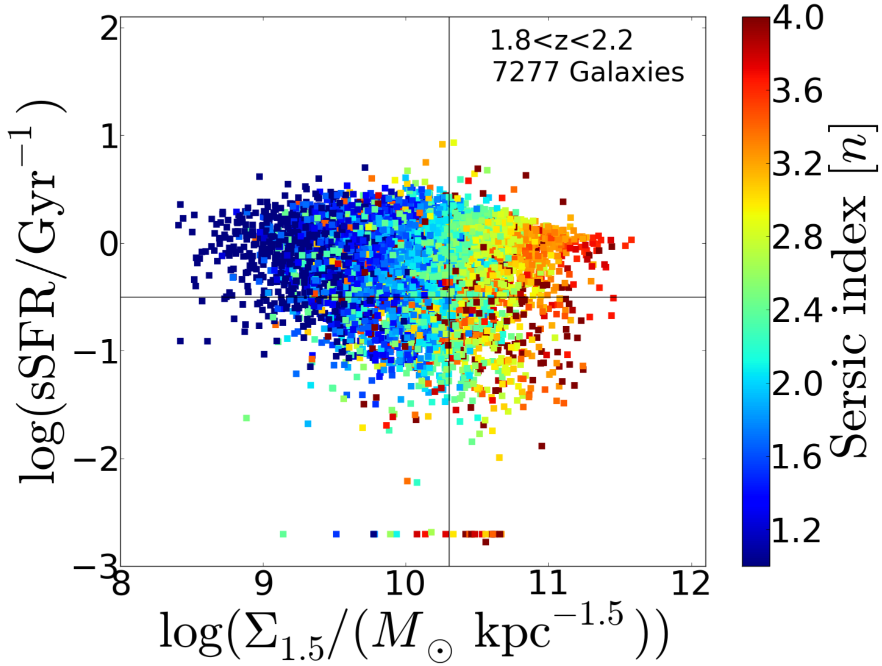
z=1.8-2.2

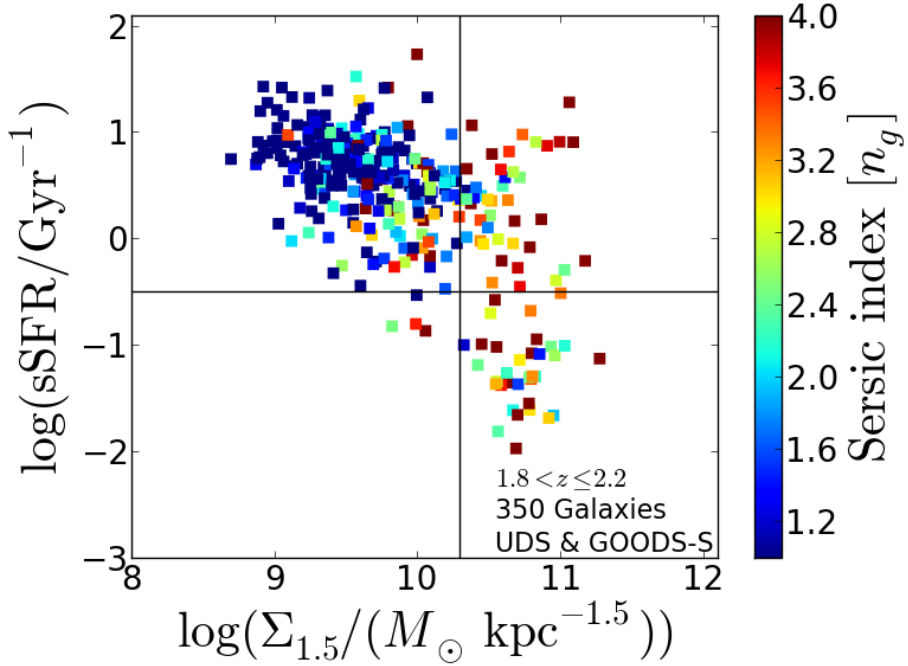


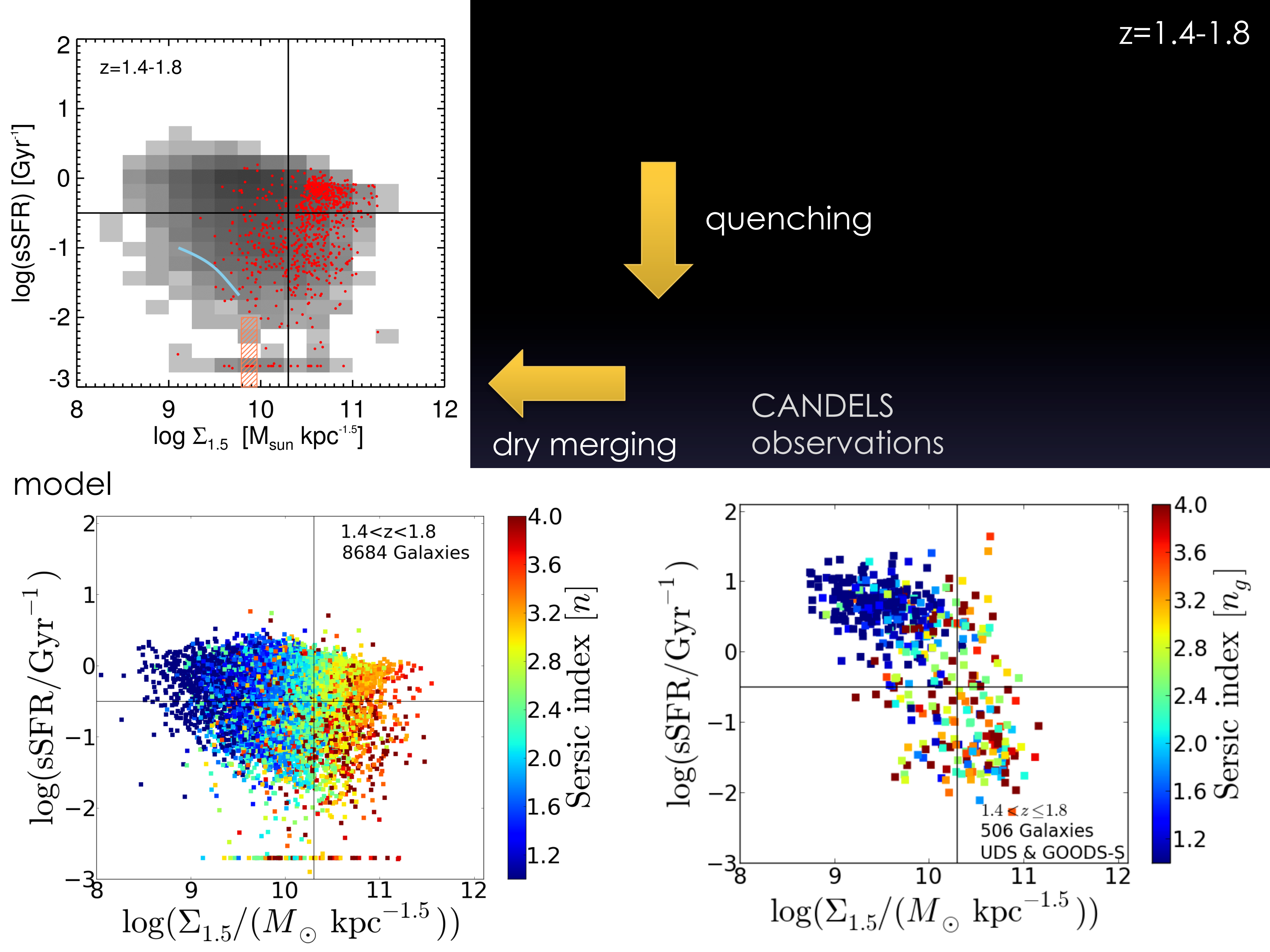

quenching

CANDELS observations

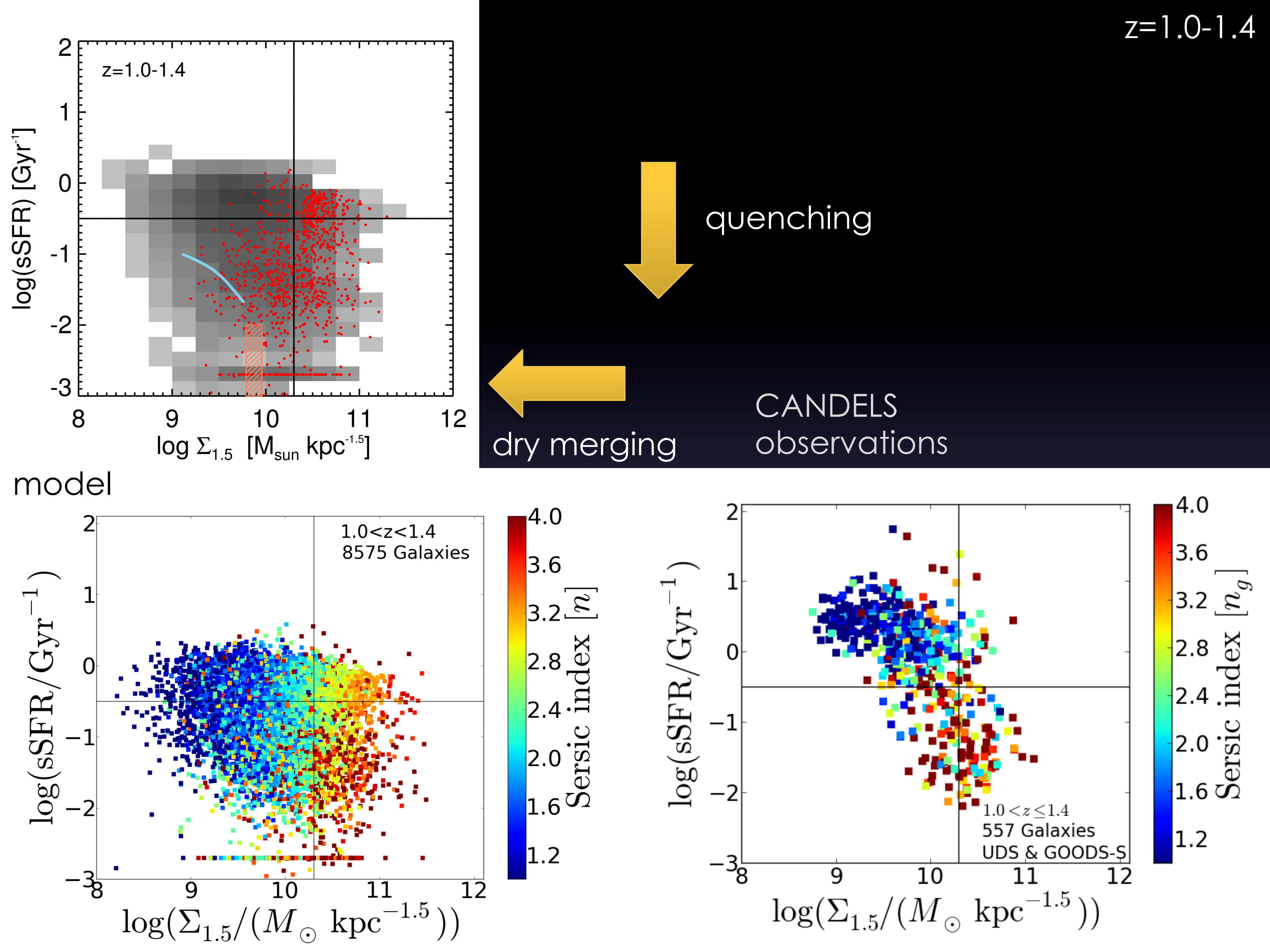
model

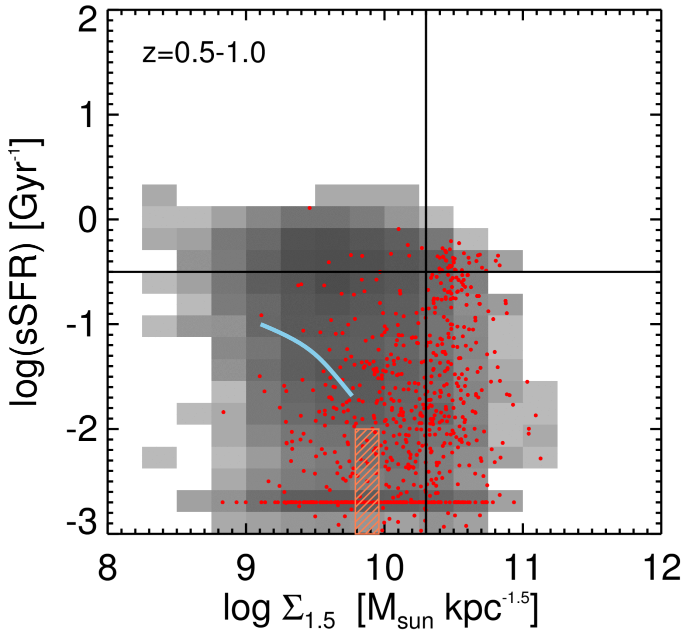


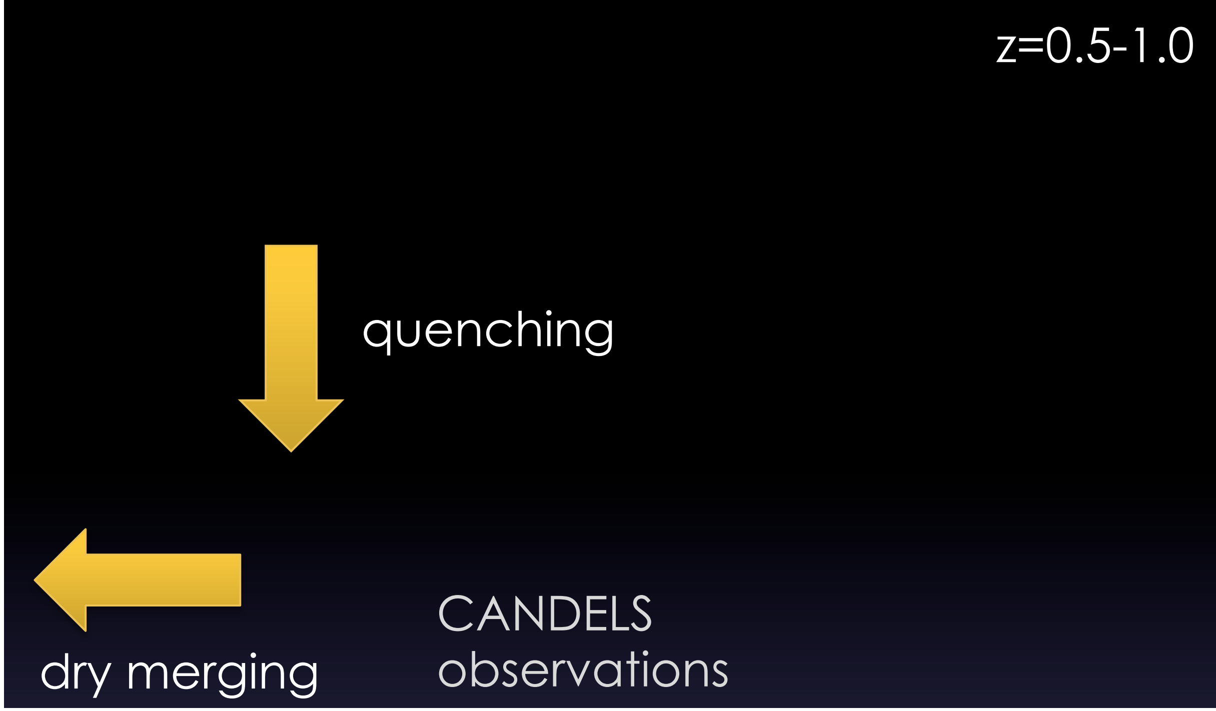





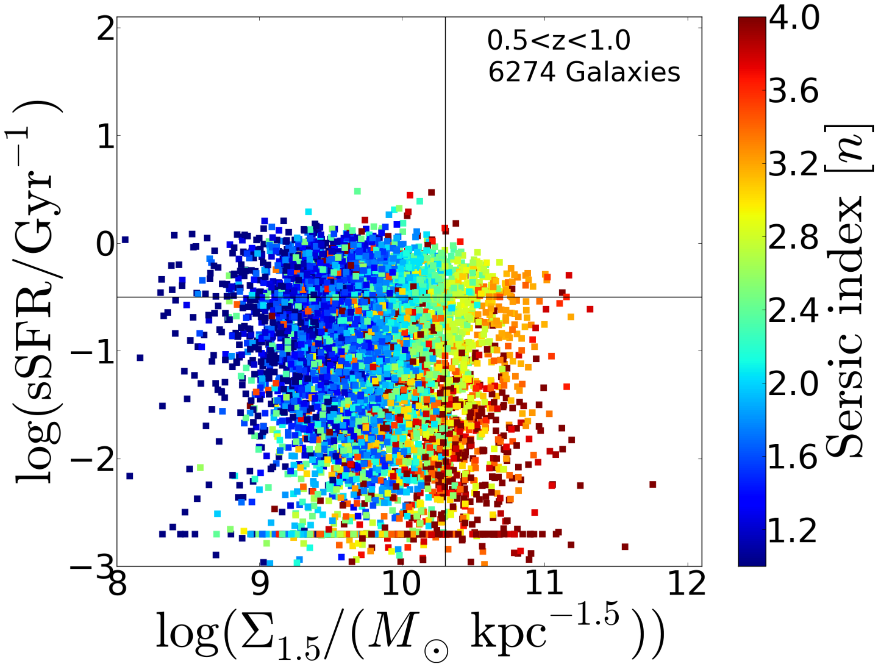
z=1.4-1.8
log(sSFR) [Gyr⁻¹]
log Σ1.5 [Msun kpc-1.5]
quenching
dry merging
CANDELS
observations
model
1.4<z<1.8
8684 Galaxies
log(sSFR/Gyr⁻¹)
log(Σ1.5/(M⊙ kpc⁻¹·⁵))
Sersic index [n]
1.4<z≤1.8
506 Galaxies
UDS & GOODS-S
Sersic index [ng]

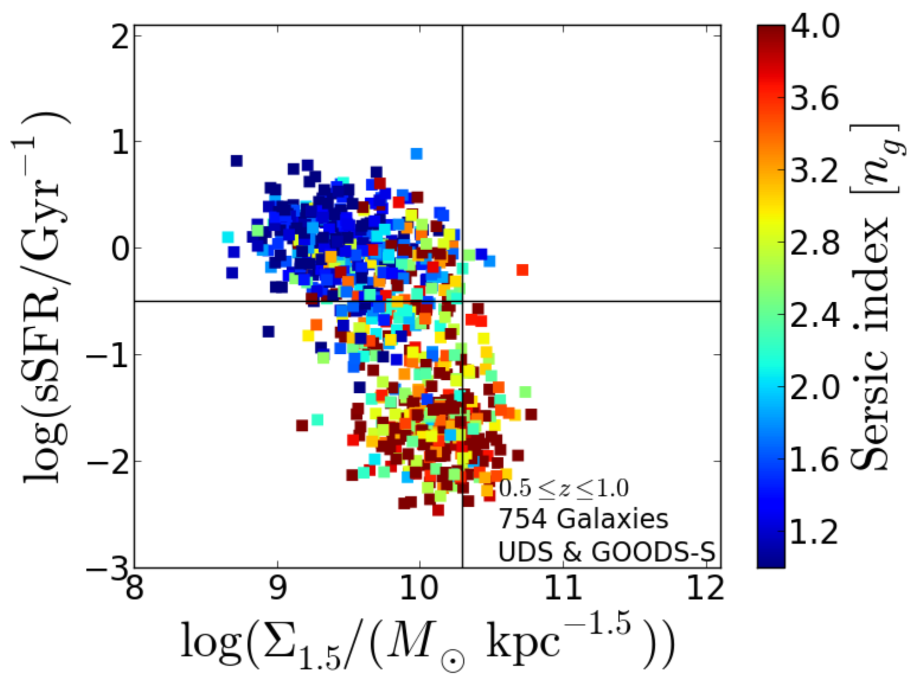

z=1.0-1.4
z=1.0-1.4
log(sSFR) [Gyr$^{-1}$]
log $\Sigma_{1.5}$ [M$_{sun}$ kpc$^{-1.5}$]
quenching
dry merging
CANDELS
observations
model
1.0<z<1.4
8575 Galaxies
$\log(\mathrm{sSFR}/\mathrm{Gyr}^{-1})$
$\log(\Sigma_{1.5}/(M_\odot\ \mathrm{kpc}^{-1.5}))$
Sersic index [$n$]
$1.0<z\leq1.4$
557 Galaxies
UDS & GOODS-S
$\log(\mathrm{sSFR}/\mathrm{Gyr}^{-1})$
$\log(\Sigma_{1.5}/(M_\odot\ \mathrm{kpc}^{-1.5}))$
Sersic index [$n_g$]

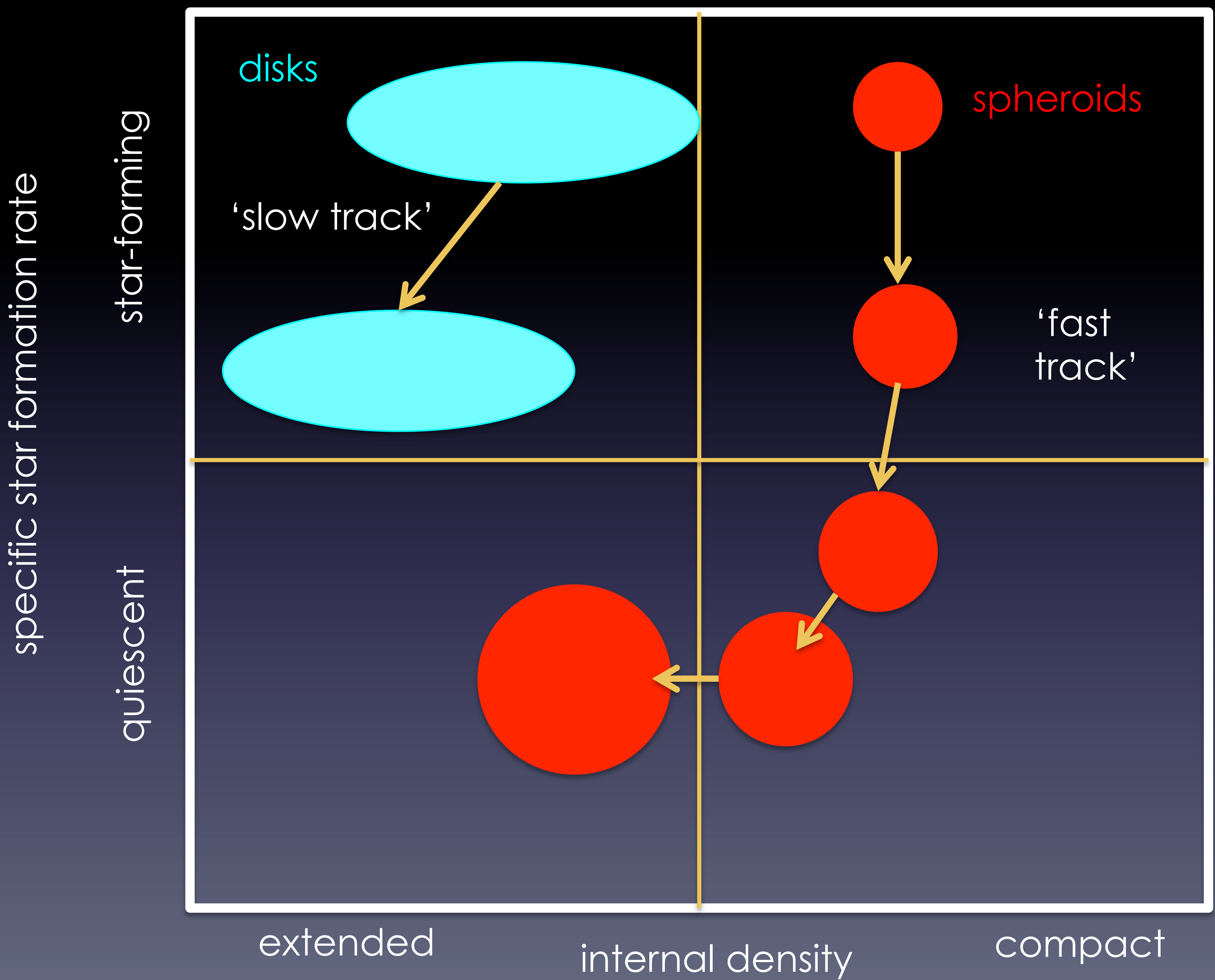

z=0.5-1.0
log(sSFR) [Gyr⁻¹]
log Σ1.5 [Msun kpc⁻¹·⁵]
8
9
10
11
12
2
1
0
-1
-2
-3

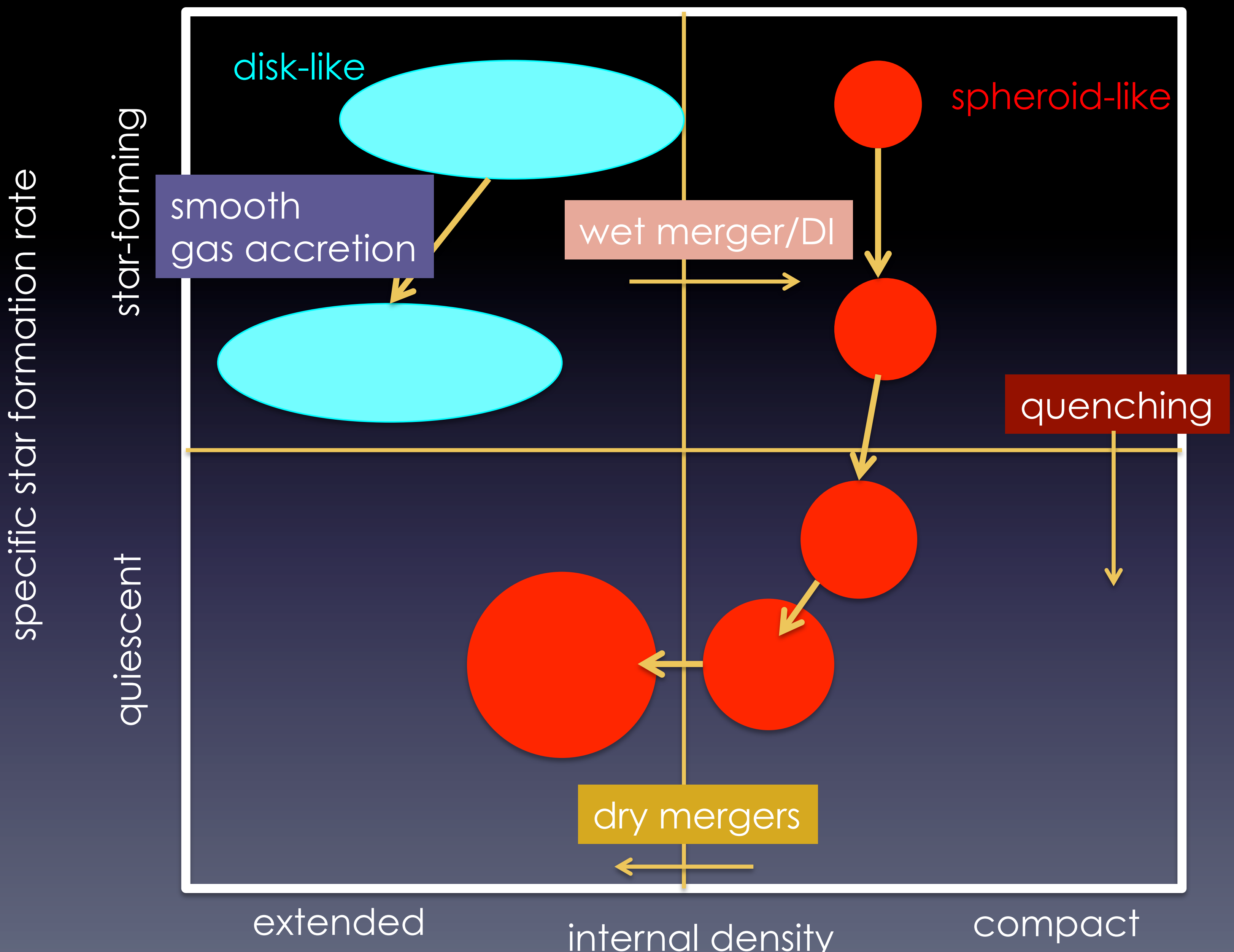

z=0.5-1.0
quenching
dry merging
CANDELS
observations

model

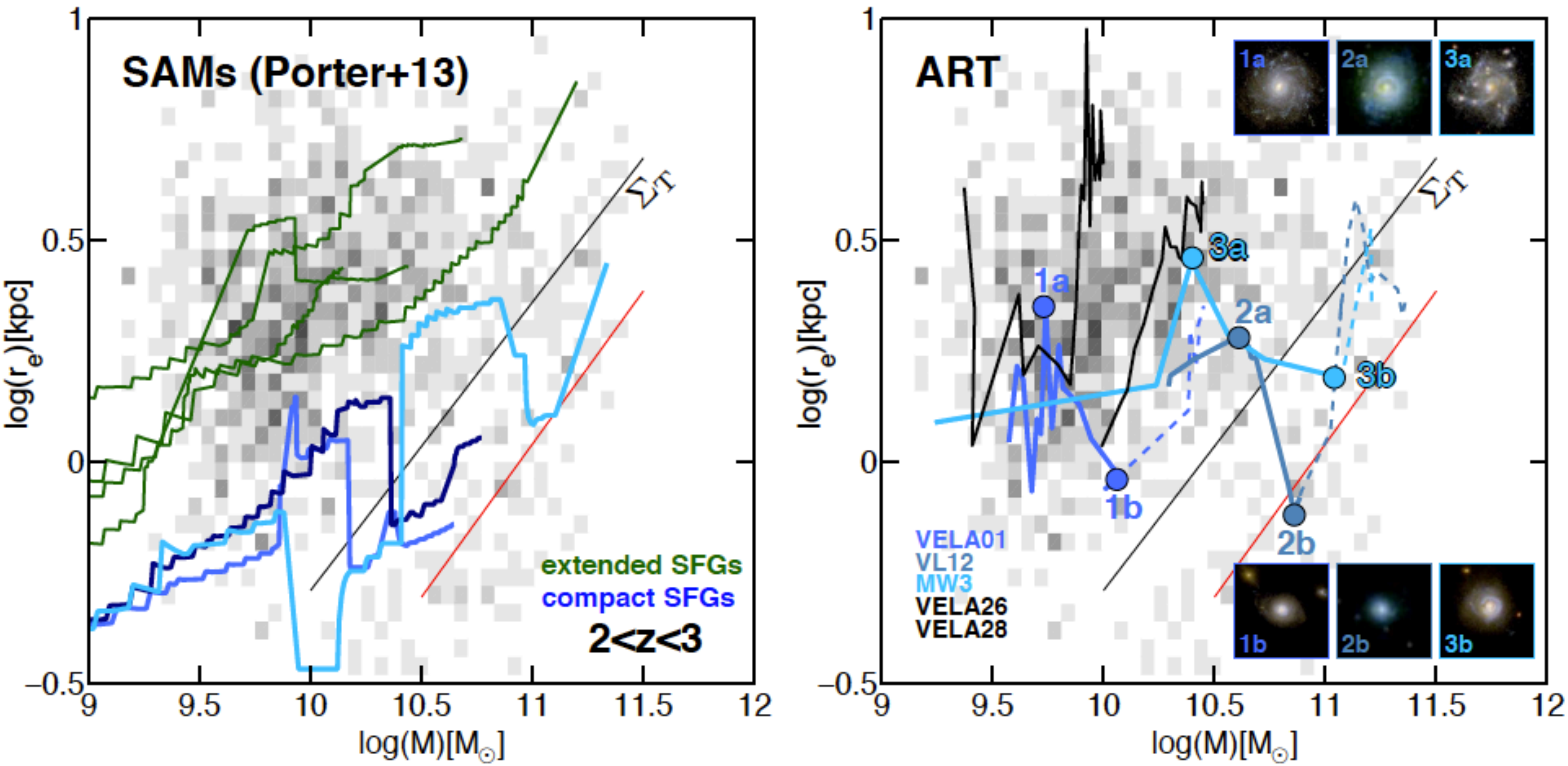

0.5<z<1.0
6274 Galaxies
log(sSFR/Gyr⁻¹)
log(Σ1.5/(M⊙ kpc⁻¹·⁵))
Sersic index [n]
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2


0.5≤z≤1.0
754 Galaxies
UDS & GOODS-S
log(sSFR/Gyr⁻¹)
log(Σ1.5/(M⊙ kpc⁻¹·⁵))
Sersic index [ng]
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2


specific star formation rate
star-forming
quiescent
disks
'slow track'
spheroids
'fast track'
extended
internal density
compact


disk-like
spheroid-like
smooth
gas accretion
wet merger/DI
quenching
dry mergers
specific star formation rate
star-forming
quiescent
extended
internal density
compact

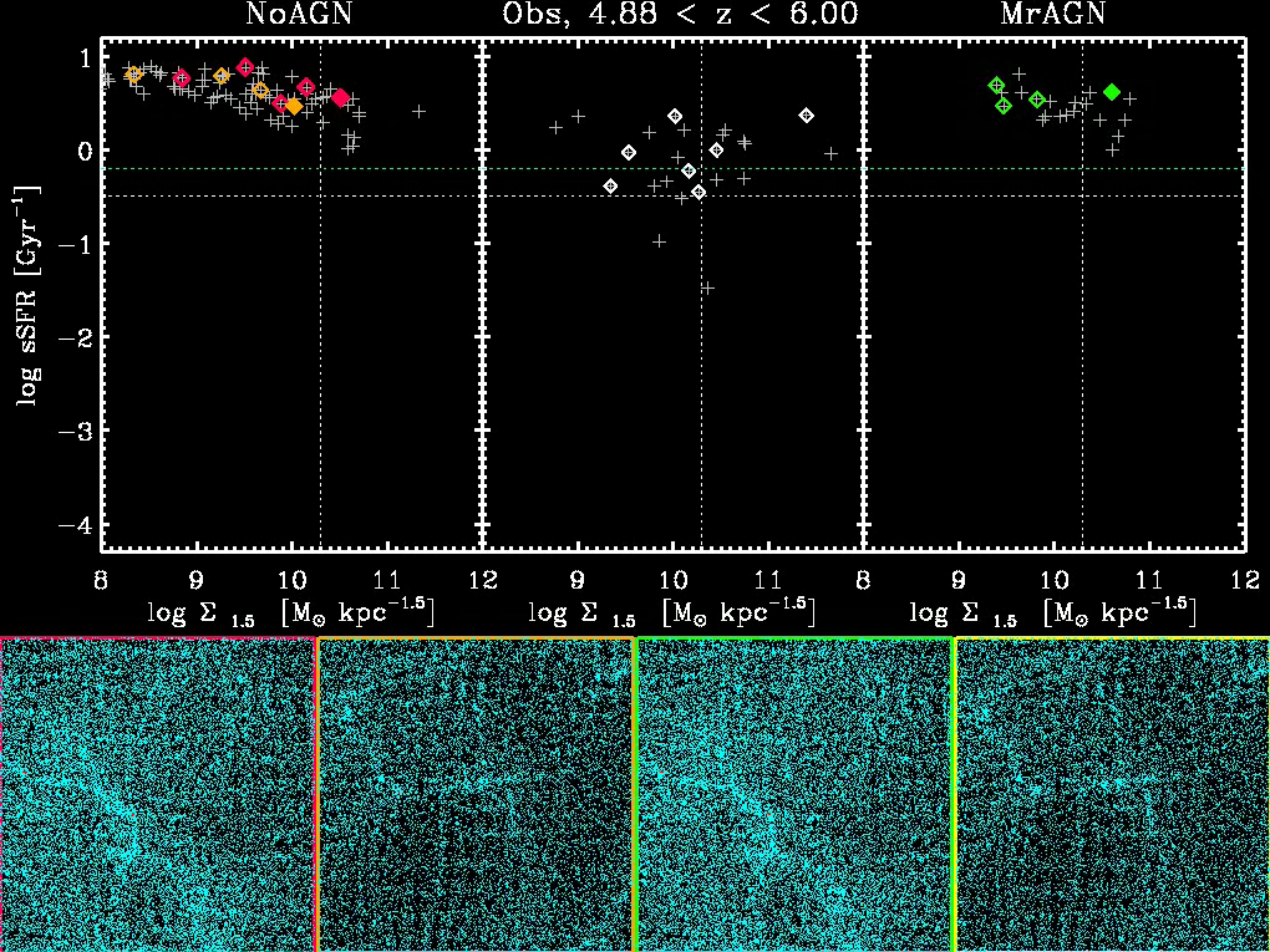
# how do galaxies become compact? tracks of individual galaxies in simulations



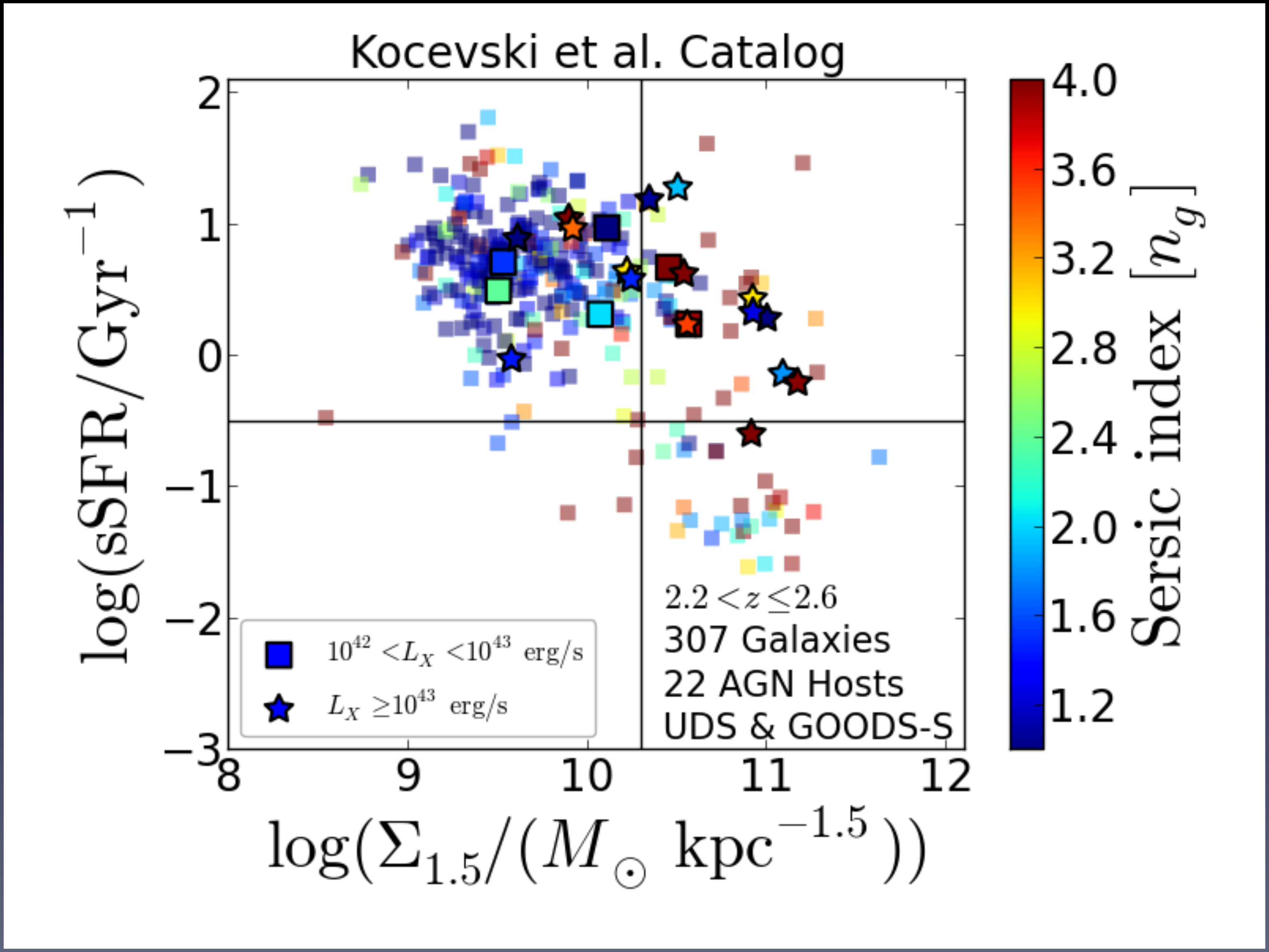

40% of galaxies become compact due to mergers
60% become compact due to disk instabilities (Porter et al. 2014)

"Violent Disk Instabilities" seen in hydrodynamical simulations (Ceverino et al. 2011)

Barro et al. arXiv/1311.5559


NoAGN
Obs, 4.88 < z < 6.00
MrAGN
log sSFR [Gyr$^{-1}$]
1
0
−1
−2
−3
−4
8
9
10
11
12
log Σ 1.5 [M⊙ kpc$^{-1.5}$]

work in progress: where and when do we see "radiative mode" AGN?



# Conclusions

- deep multi-wavelength surveys like CANDELS now allow us to simultaneously study the evolution of quenching, morphology and structure since ‘cosmic high noon’ – promising way to constrain physical mechanisms
- galaxies cannot just ‘fade out’ – morphological and structural transformation must accompany quenching
- our work suggests most galaxies first become compact and spheroid dominated in a \`wet’ (dissipational) process *then* quench
- size evolution of early types caused by combination of 1) late→early type transformation 2) transition from wet→ dry mergers 3) transition from in situ → accretion