An Observational View of the Relative Growth of BHs and Galaxies

Kevin Schawinski
Einstein Fellow
Yale Center for Astronomy & Astrophysics
Department of Physics
Yale University

At what stage in their lives do galaxies feed their black holes?

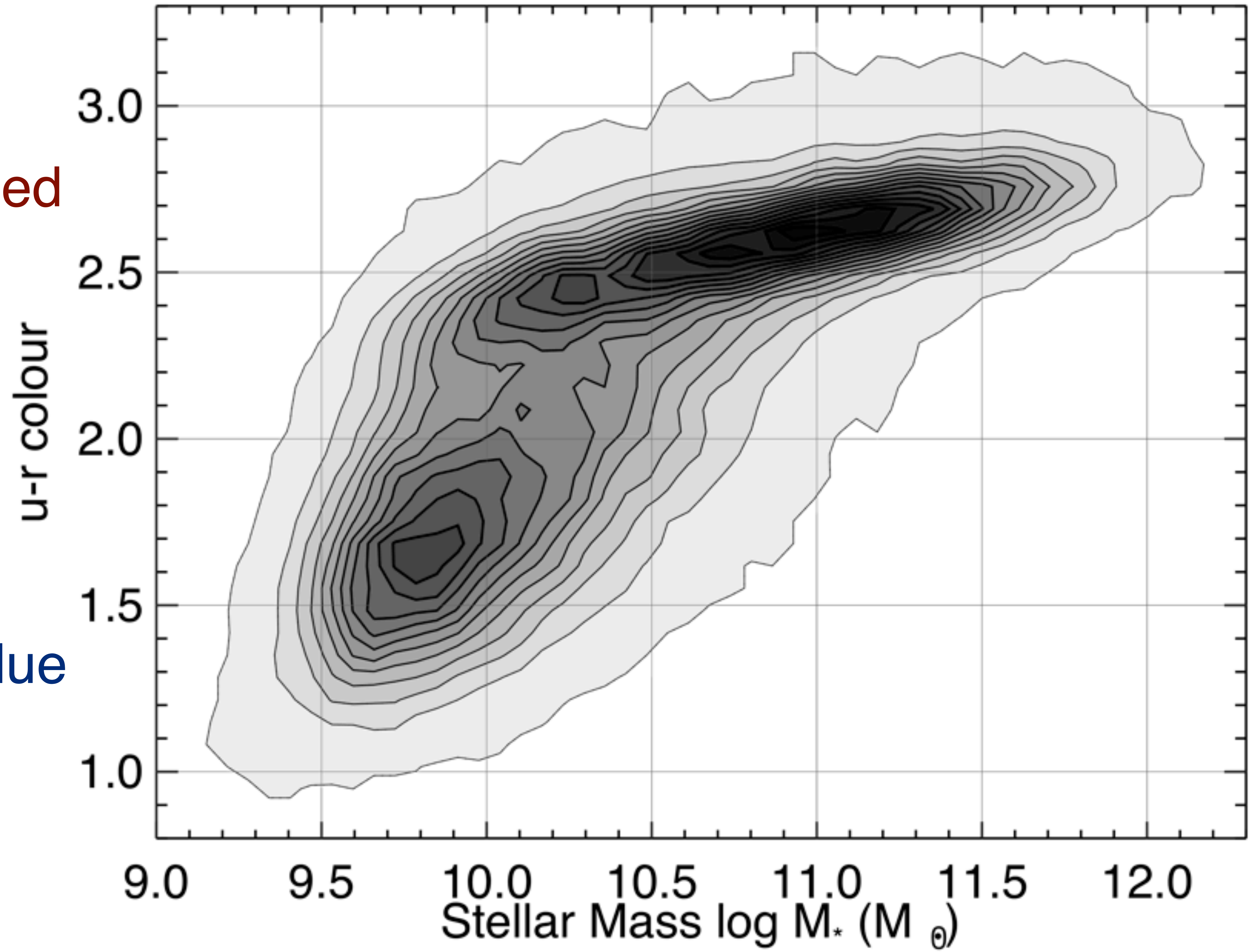
What effect does black hole growth have on the evolutionary trajectory of galaxies?

4 Msec CDF-S

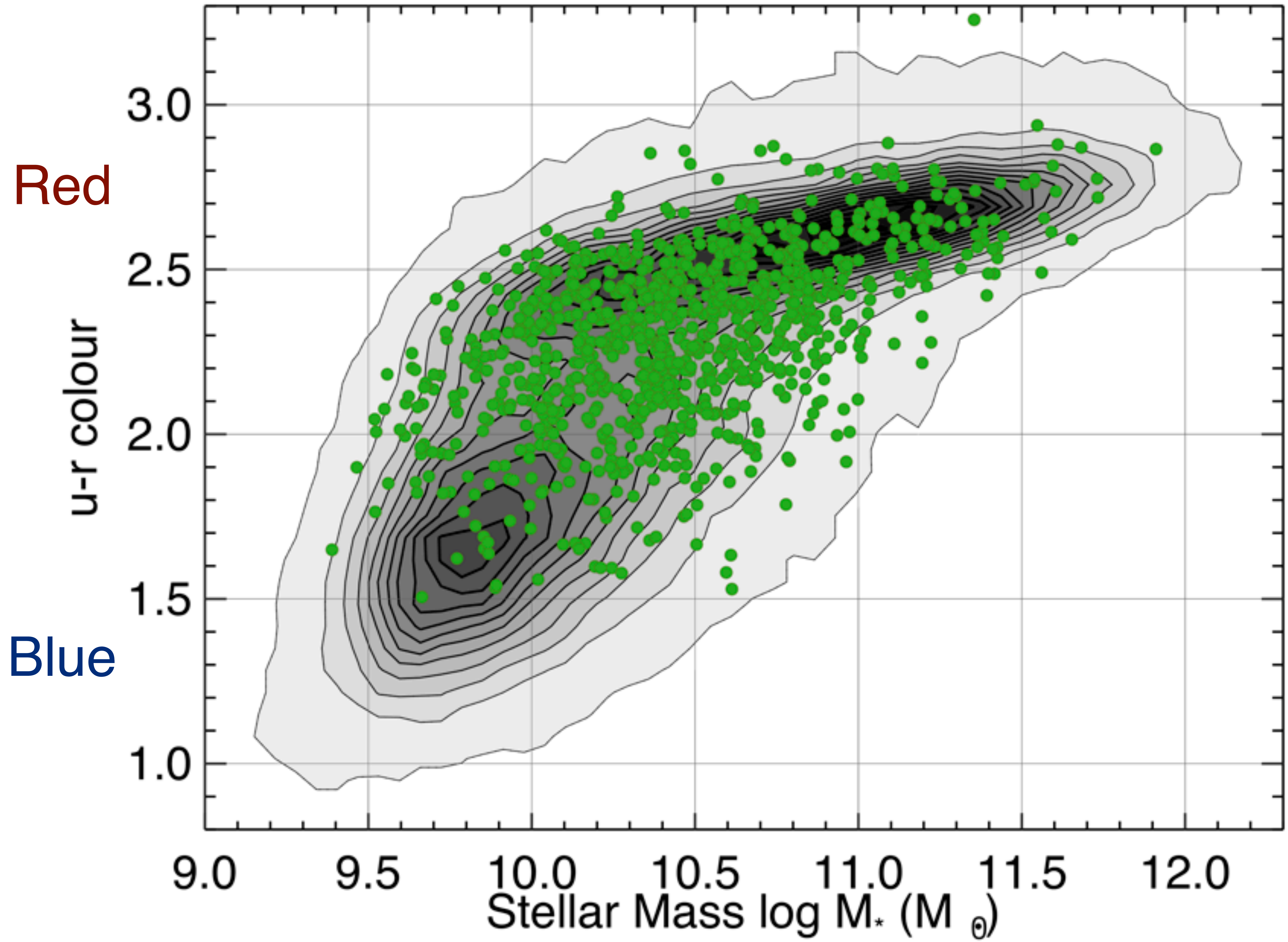
Which galaxies are feeding their black holes at z~0?

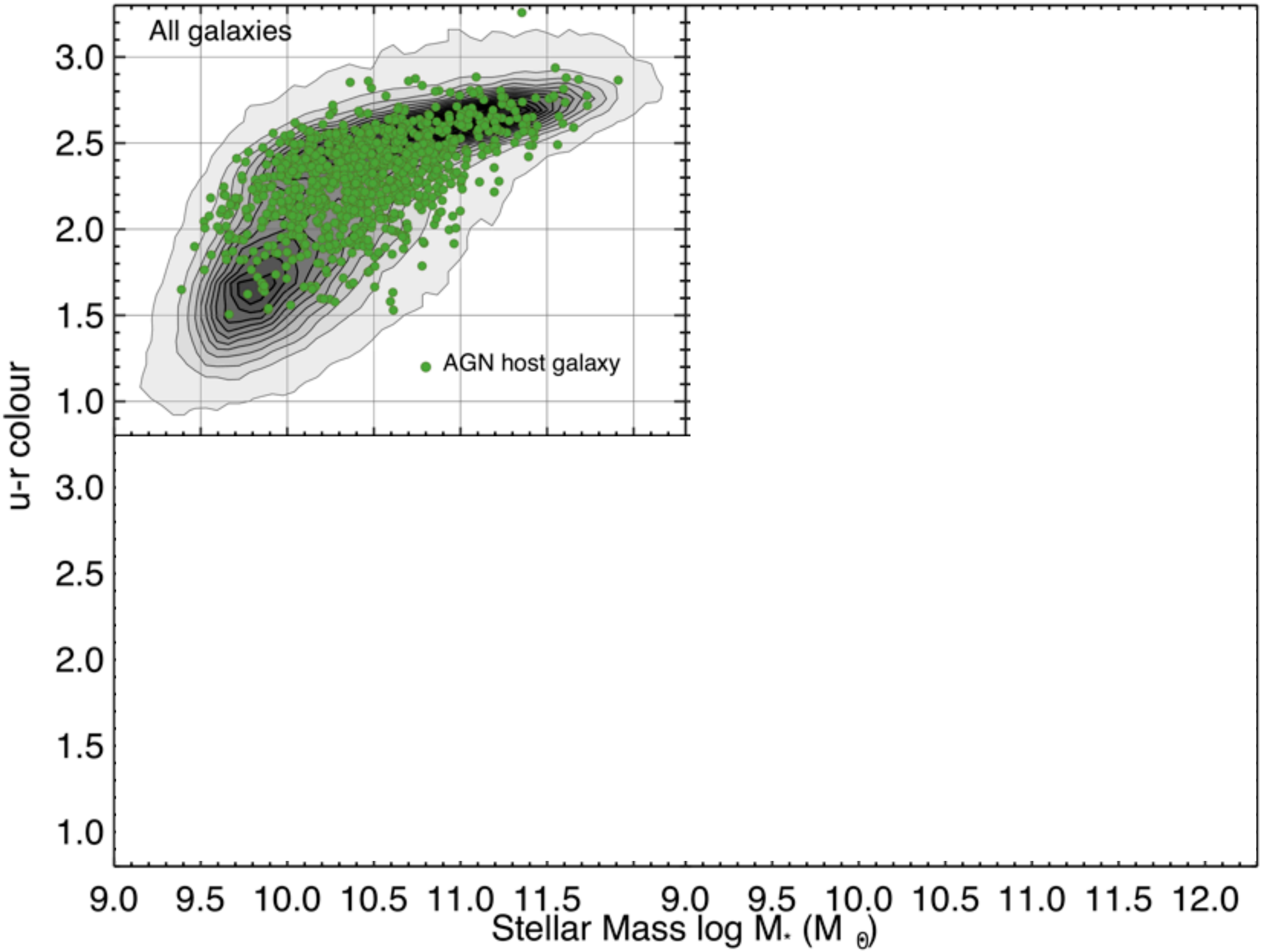
Red

Blue

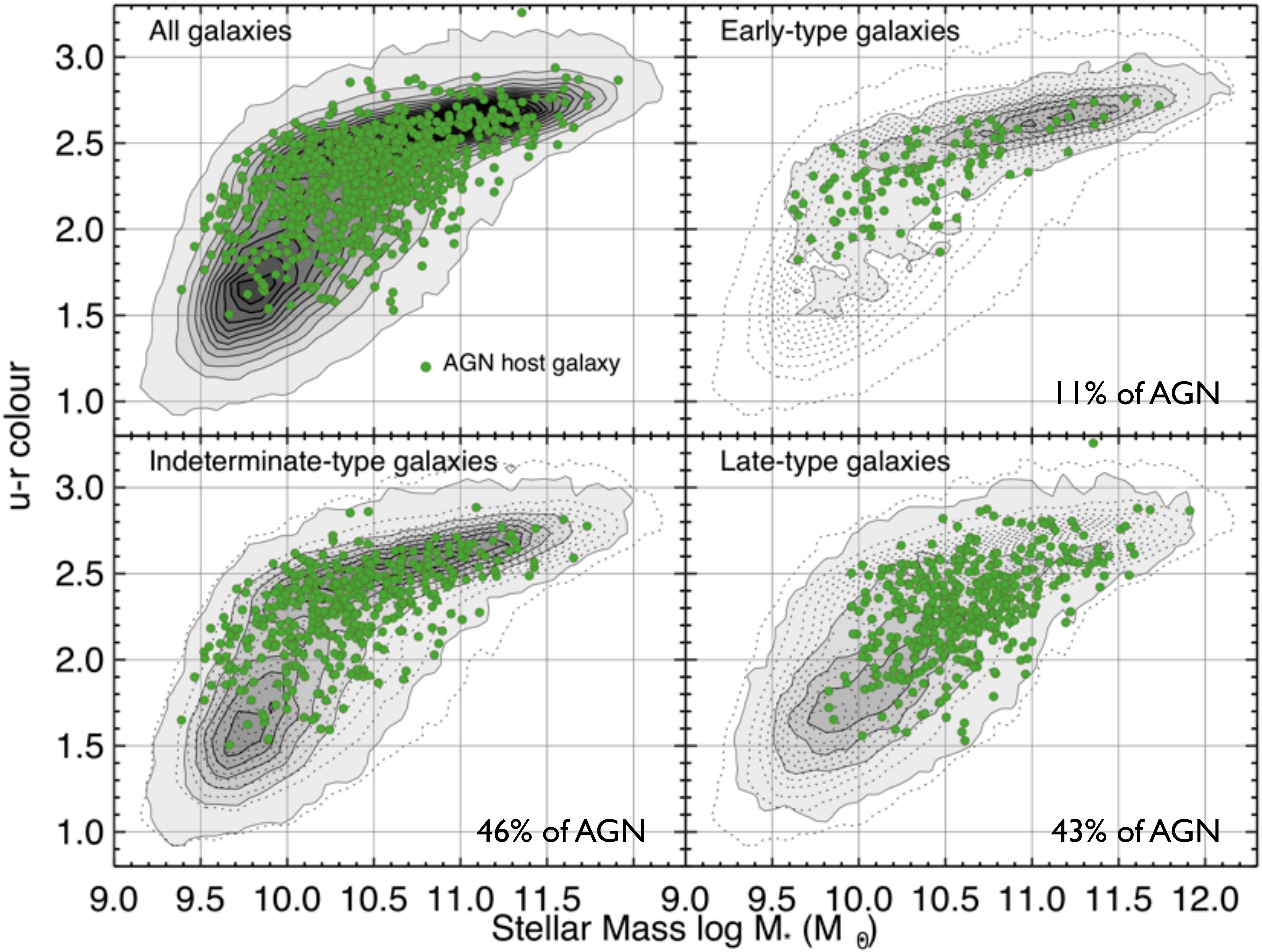


Which galaxies are feeding their black holes at z~0?

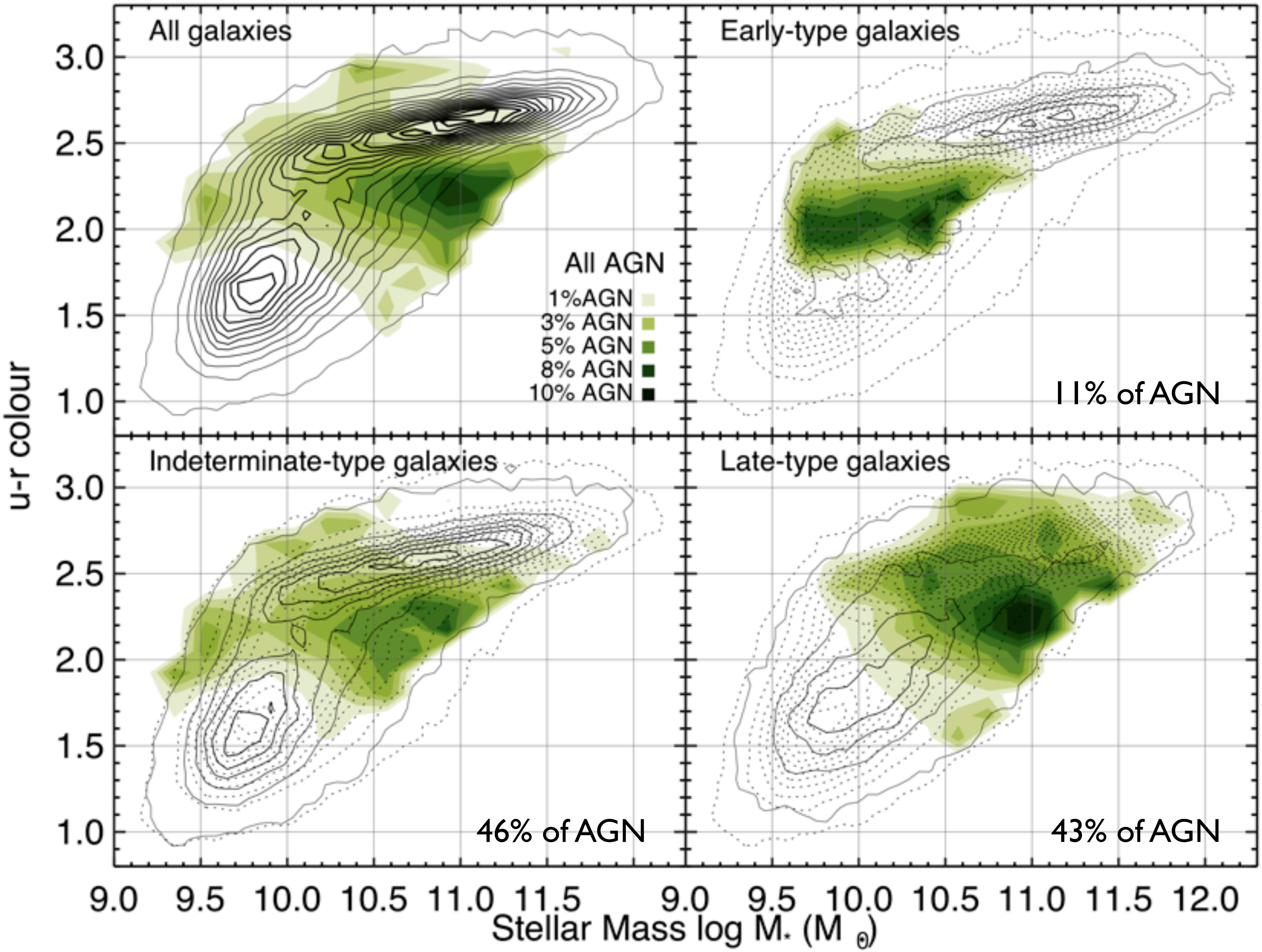


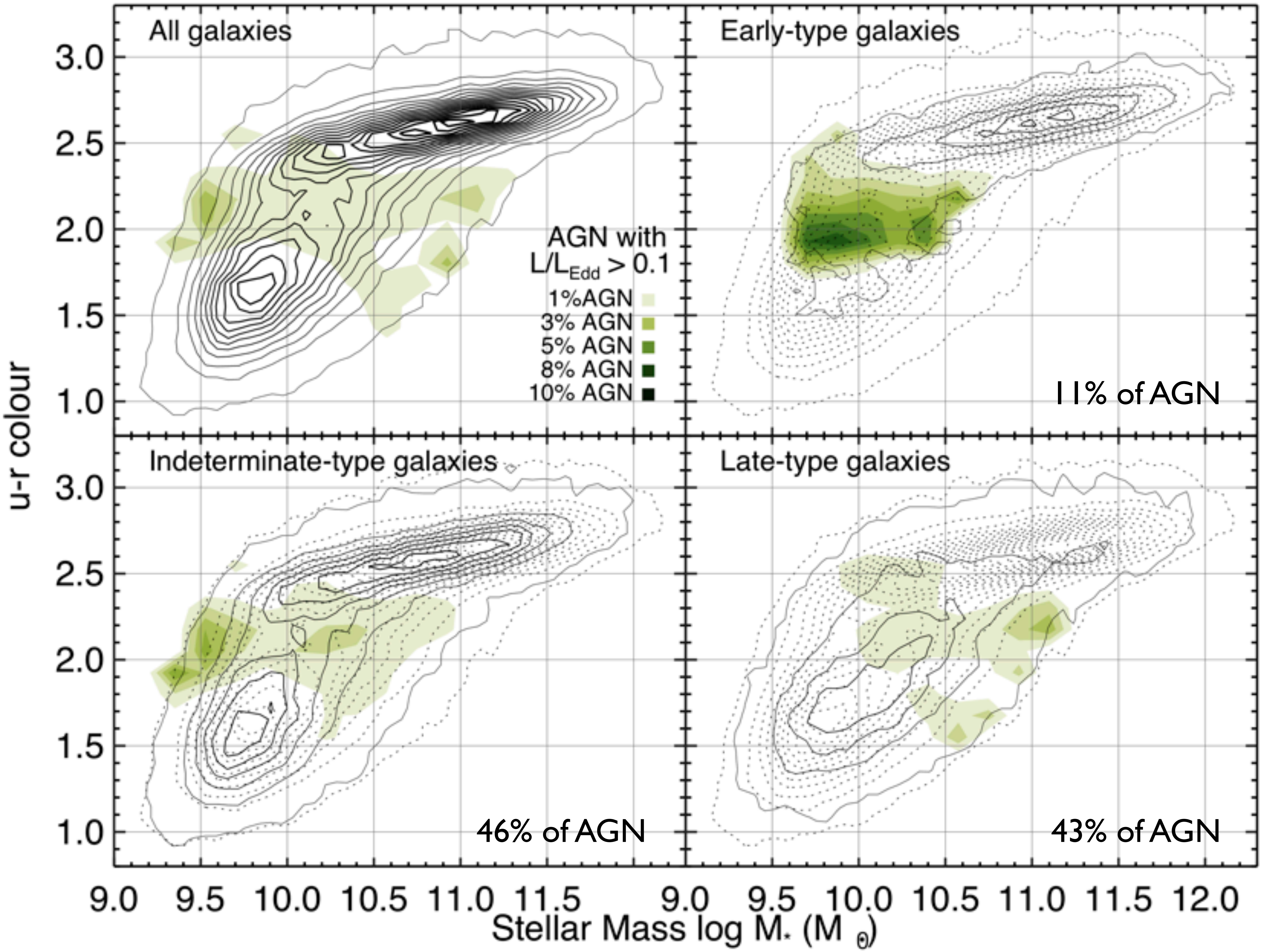


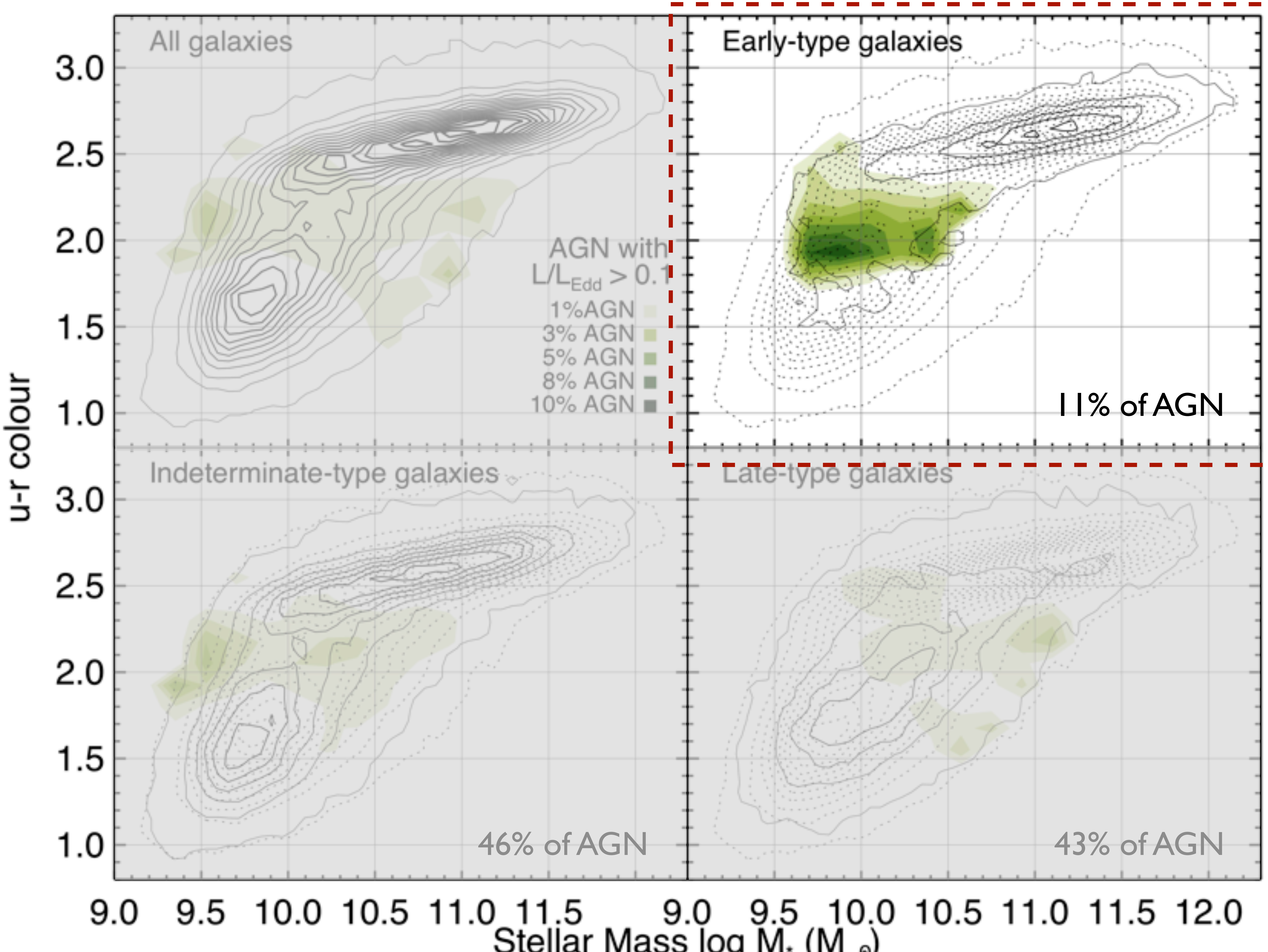
Mergers are rare, but interesting; see Mike Koss's talk!

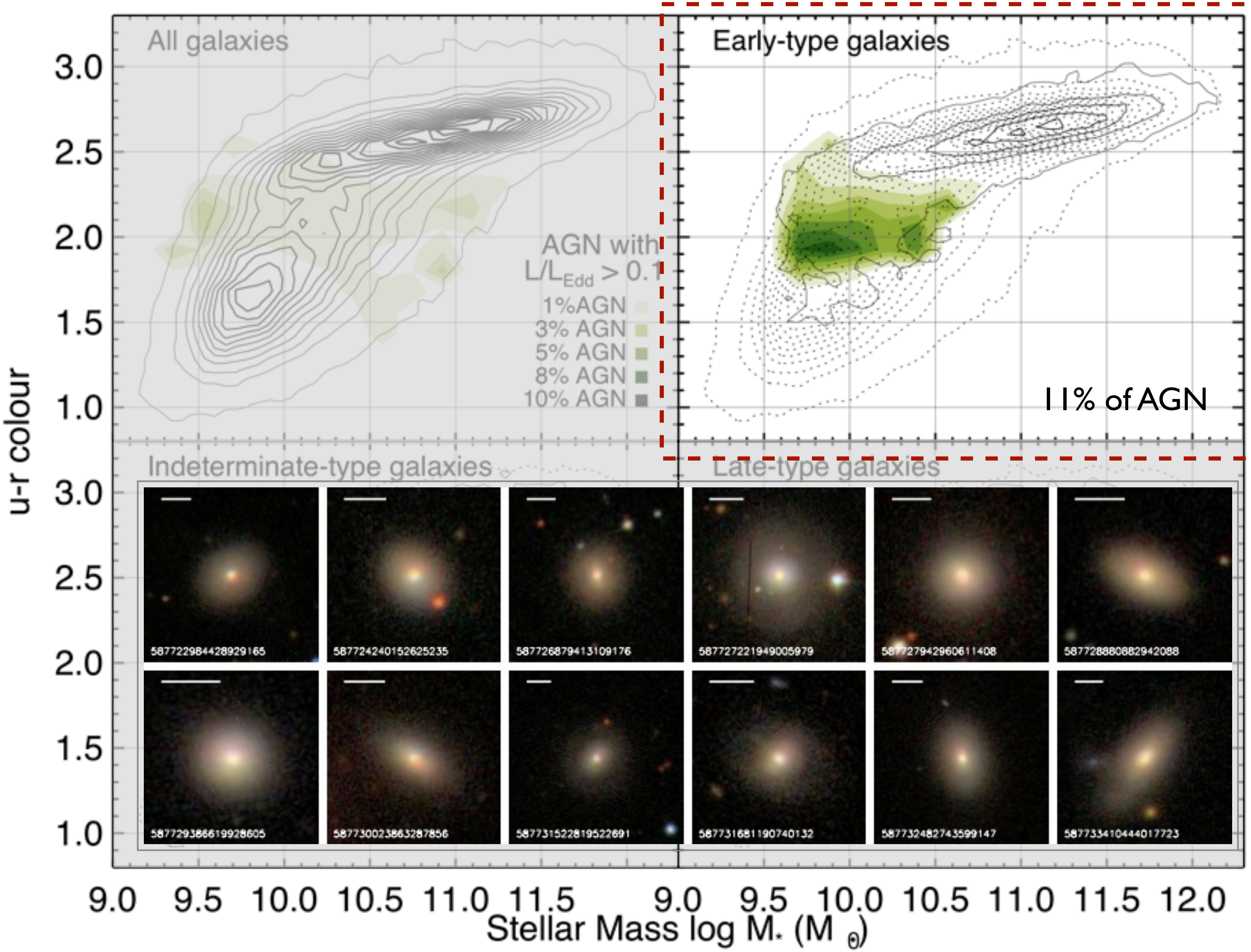


Mergers are rare, but interesting; see Mike Koss's talk!


All galaxies
Early-type galaxies
Indeterminate-type galaxies
Late-type galaxies
All AGN
1%AGN
3% AGN
5% AGN
8% AGN
10% AGN
11% of AGN
46% of AGN
43% of AGN
u-r colour
Stellar Mass log M* (M ⊙)
3.0
2.5
2.0
1.5
1.0
9.0
9.5
10.0
10.5
11.0
11.5
12.0

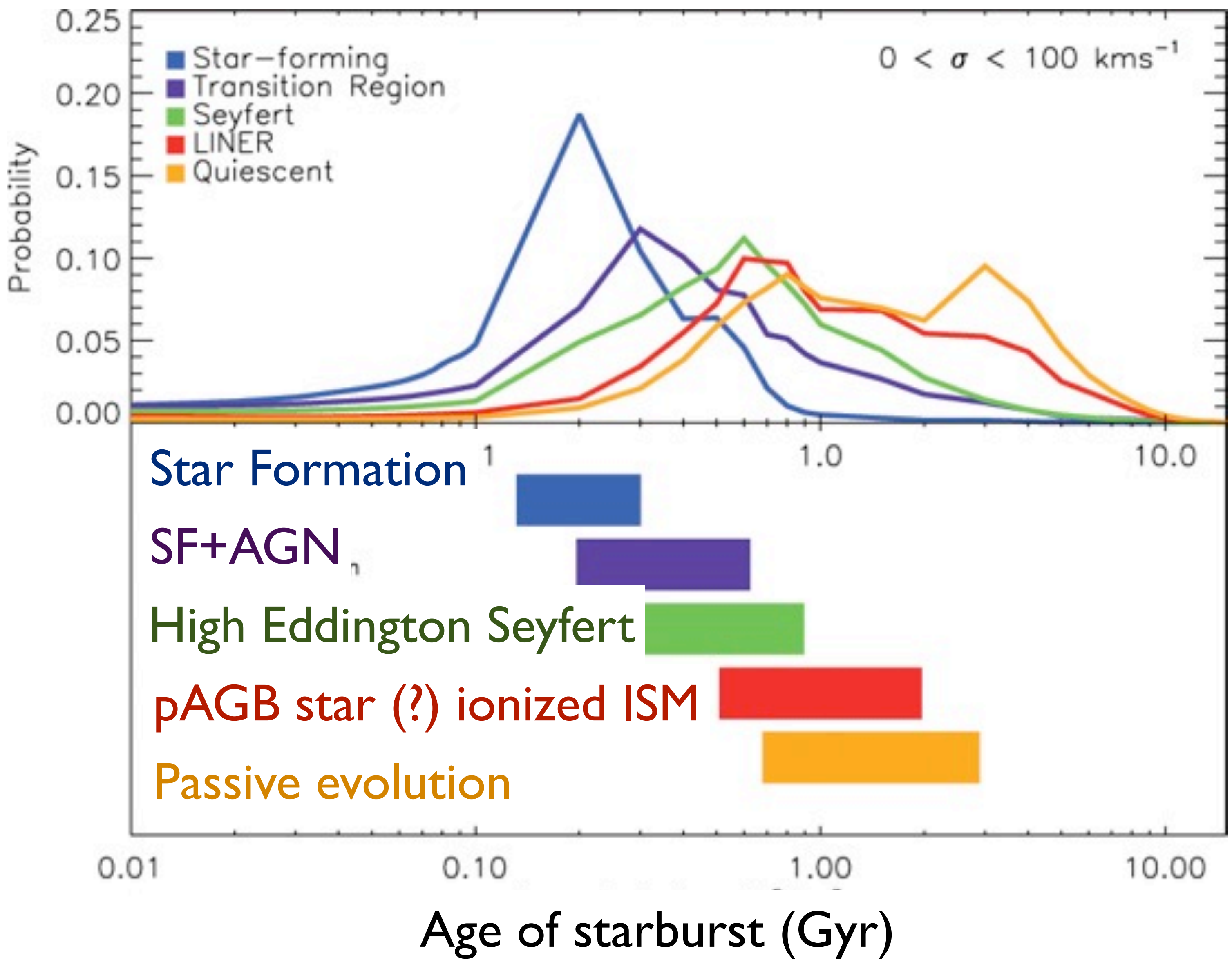

All galaxies
Early-type galaxies
Indeterminate-type galaxies
Late-type galaxies
AGN with
L/L$_{Edd}$ > 0.1
1%AGN
3% AGN
5% AGN
8% AGN
10% AGN
11% of AGN
46% of AGN
43% of AGN
u-r colour
Stellar Mass log M* (M ⊙)
3.0
2.5
2.0
1.5
1.0
9.0
9.5
10.0
10.5
11.0
11.5
12.0

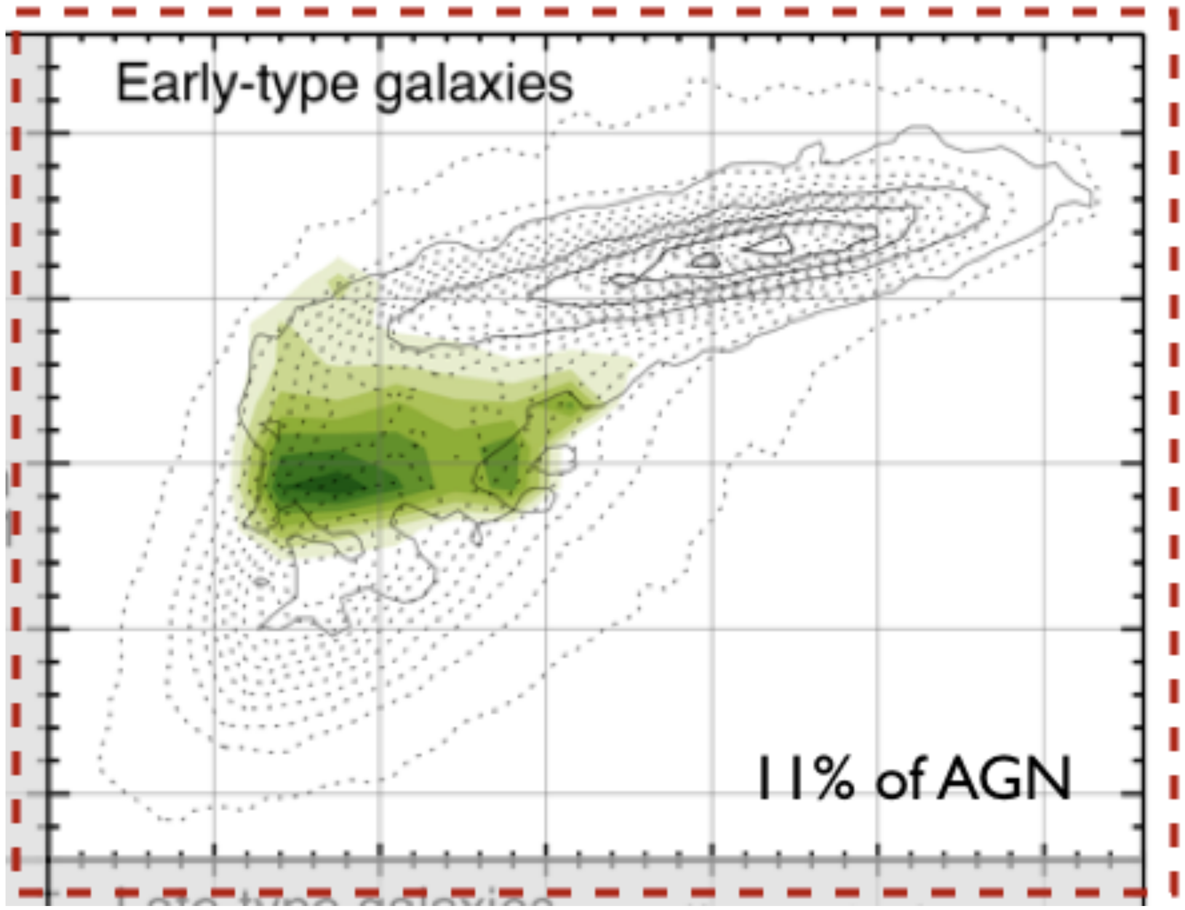

All galaxies
Early-type galaxies
Indeterminate-type galaxies
Late-type galaxies
AGN with
L/L_Edd > 0.1
1%AGN
3% AGN
5% AGN
8% AGN
10% AGN
11% of AGN
46% of AGN
43% of AGN
u-r colour
Stellar Mass log M* (M☉)
3.0
2.5
2.0
1.5
1.0
9.0
9.5
10.0
10.5
11.0
11.5
12.0


All galaxies
Early-type galaxies
Indeterminate-type galaxies
Late-type galaxies
AGN with L/L_Edd > 0.1
1%AGN
3% AGN
5% AGN
8% AGN
10% AGN
11% of AGN
u-r colour
Stellar Mass log M* (M ☉)
587722984428929165
587724240152625235
587726879413109176
587727221949005979
587727942960611408
587728880882942088
587729386619928605
587730023863287856
587731522819522691
587731681190740132
587732482743599147
587733410444017723

SDSS reveals an evolutionary sequence:

Low-mass early-types migrate to the red sequence



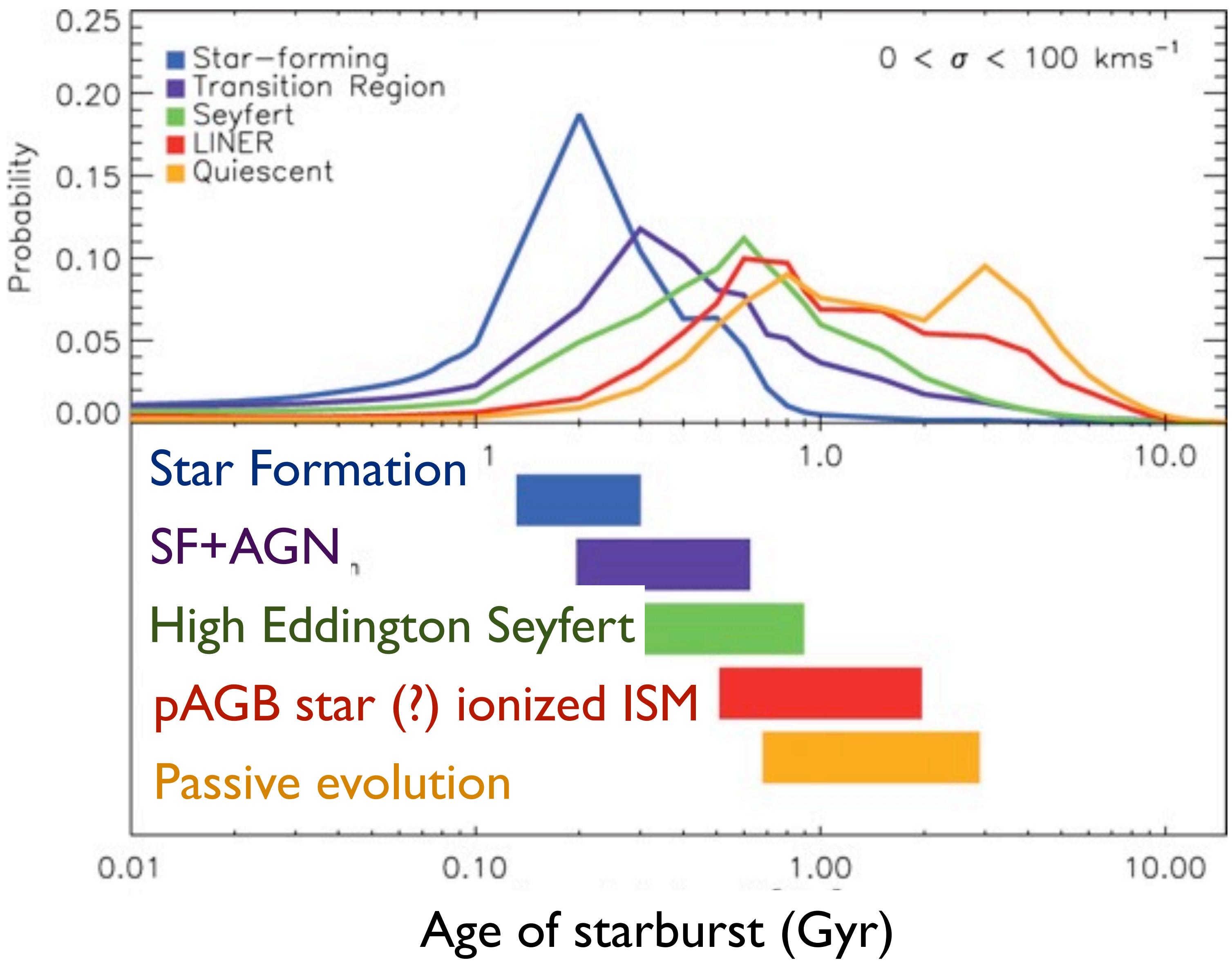


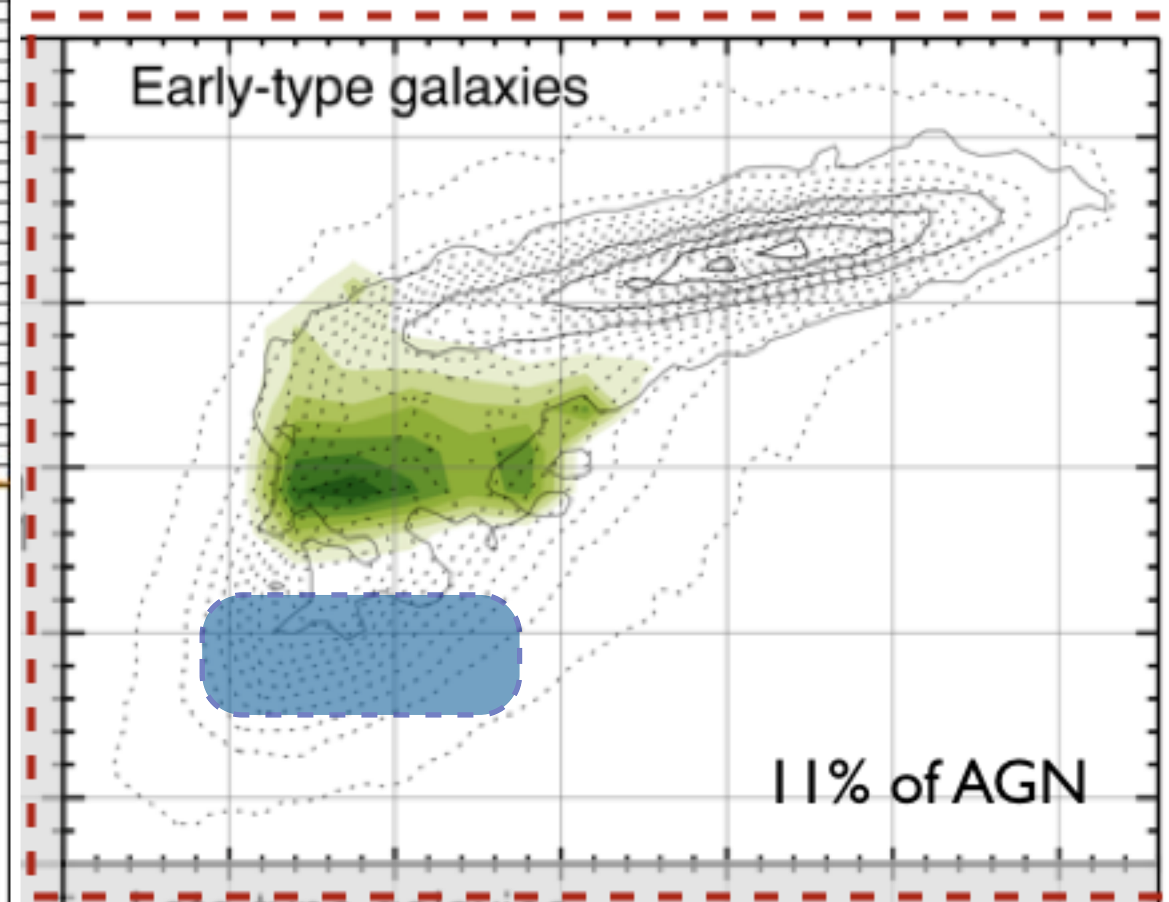
Input: GALEX+SDSS+2MASS photometry, SDSS spectroscopy (Lick indices)
Result: **1-10% of stellar mass** formed in most recent burst; leads to **rapid quenching** on ~100 Myr timescale and **migration to red sequence**

Output: the green valley conundrum!

SDSS reveals an evolutionary sequence:

Low-mass early-types migrate to the red sequence



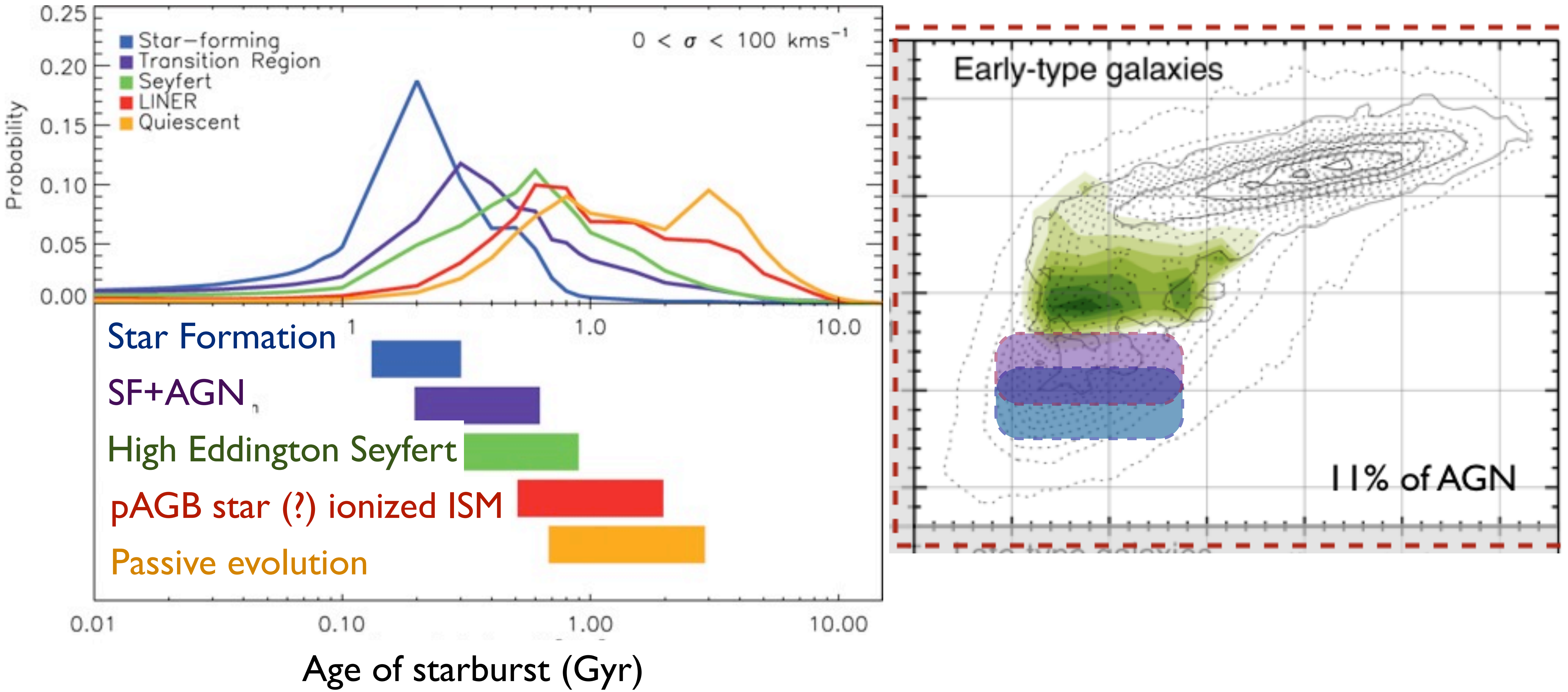


Input: GALEX+SDSS+2MASS photometry, SDSS spectroscopy (Lick indices)
Result: **1-10% of stellar mass** formed in most recent burst; leads to **rapid quenching** on ~100 Myr timescale and **migration to red sequence**

Output: the green valley conundrum!

SDSS reveals an evolutionary sequence:

Low-mass early-types migrate to the red sequence

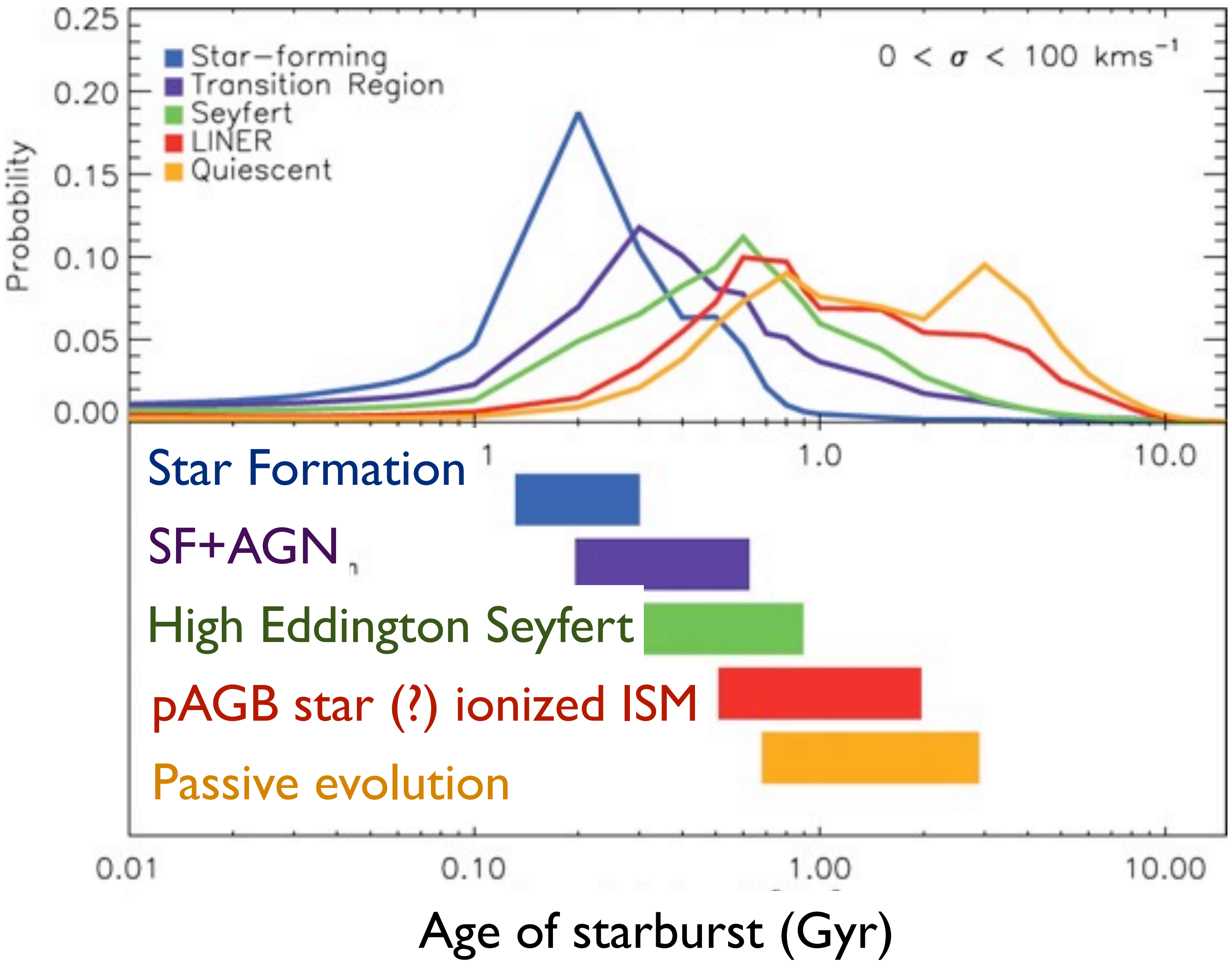


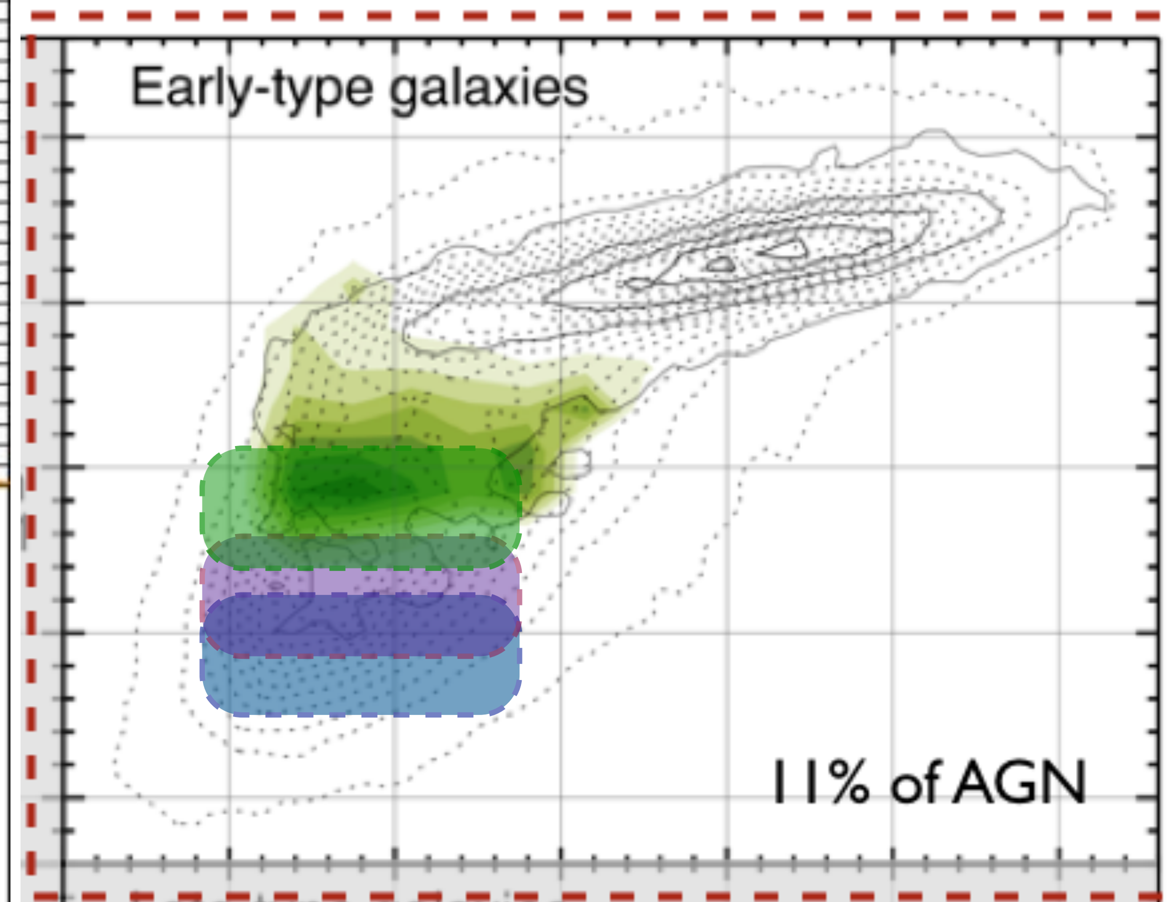
Input: GALEX+SDSS+2MASS photometry, SDSS spectroscopy (Lick indices)
Result: **1-10% of stellar mass** formed in most recent burst; leads to **rapid quenching** on ~100 Myr timescale and **migration to red sequence**

Output: the green valley conundrum!

SDSS reveals an evolutionary sequence:

Low-mass early-types migrate to the red sequence



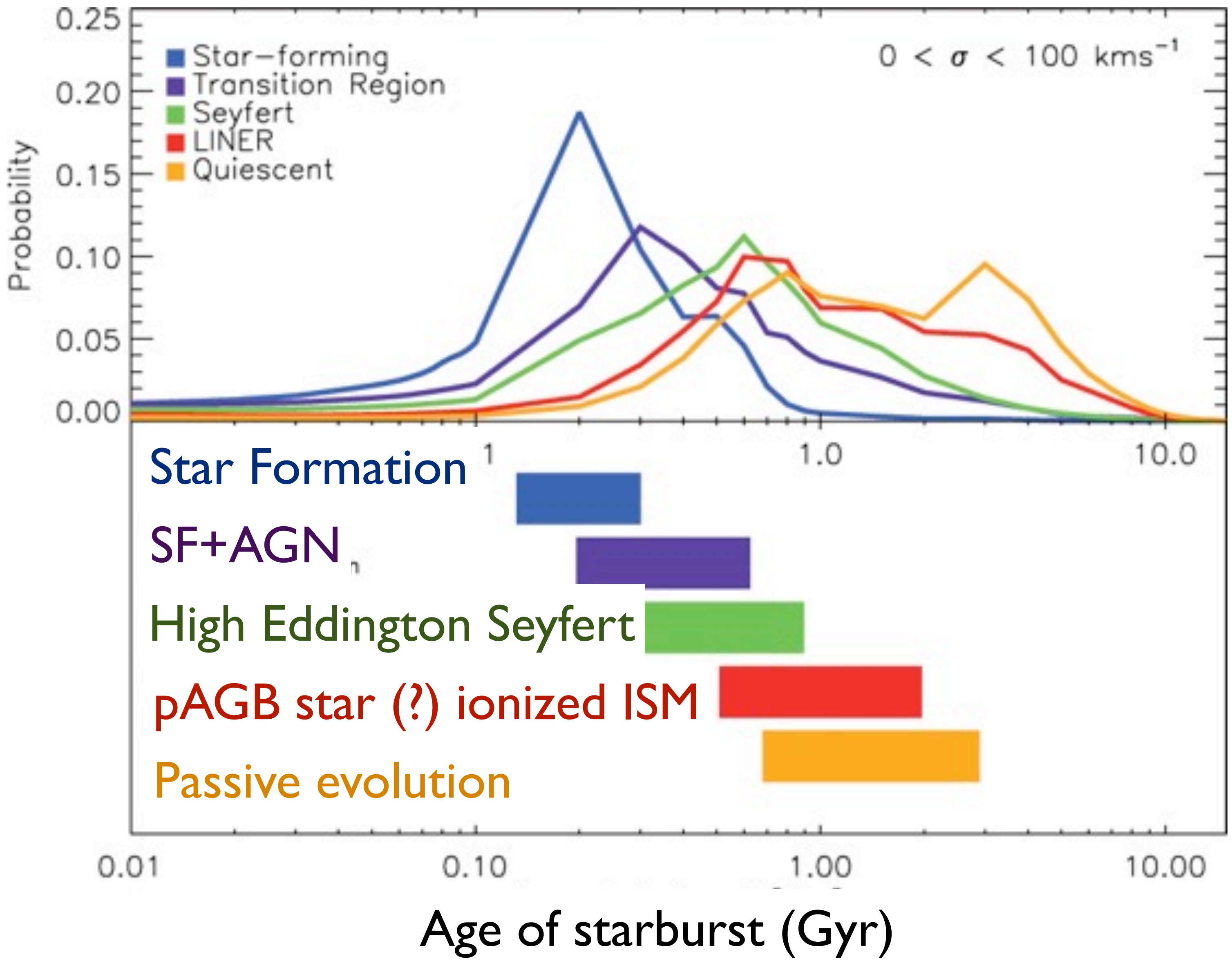


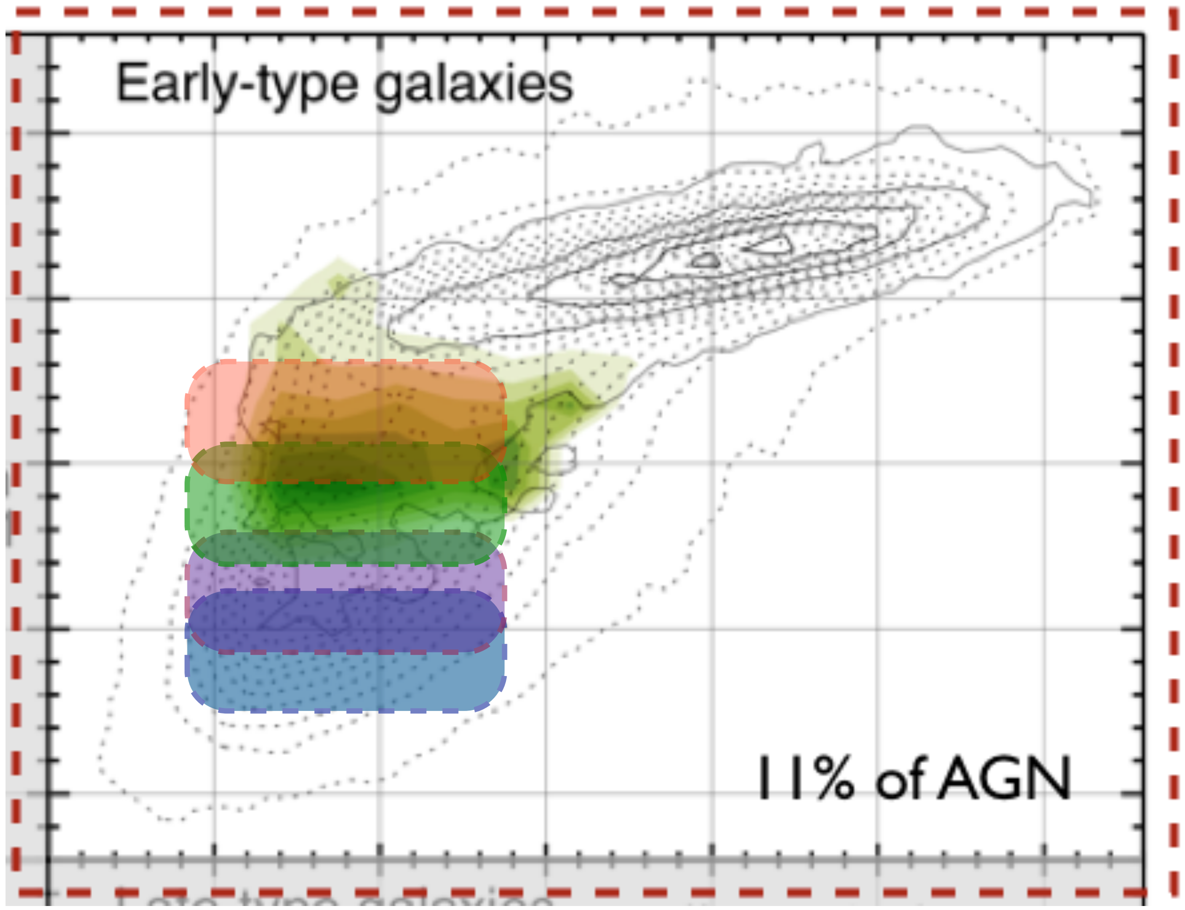
Input: GALEX+SDSS+2MASS photometry, SDSS spectroscopy (Lick indices)
Result: **1-10% of stellar mass** formed in most recent burst; leads to **rapid quenching** on ~100 Myr timescale and **migration to red sequence**

Output: the green valley conundrum!

SDSS reveals an evolutionary sequence:

Low-mass early-types migrate to the red sequence



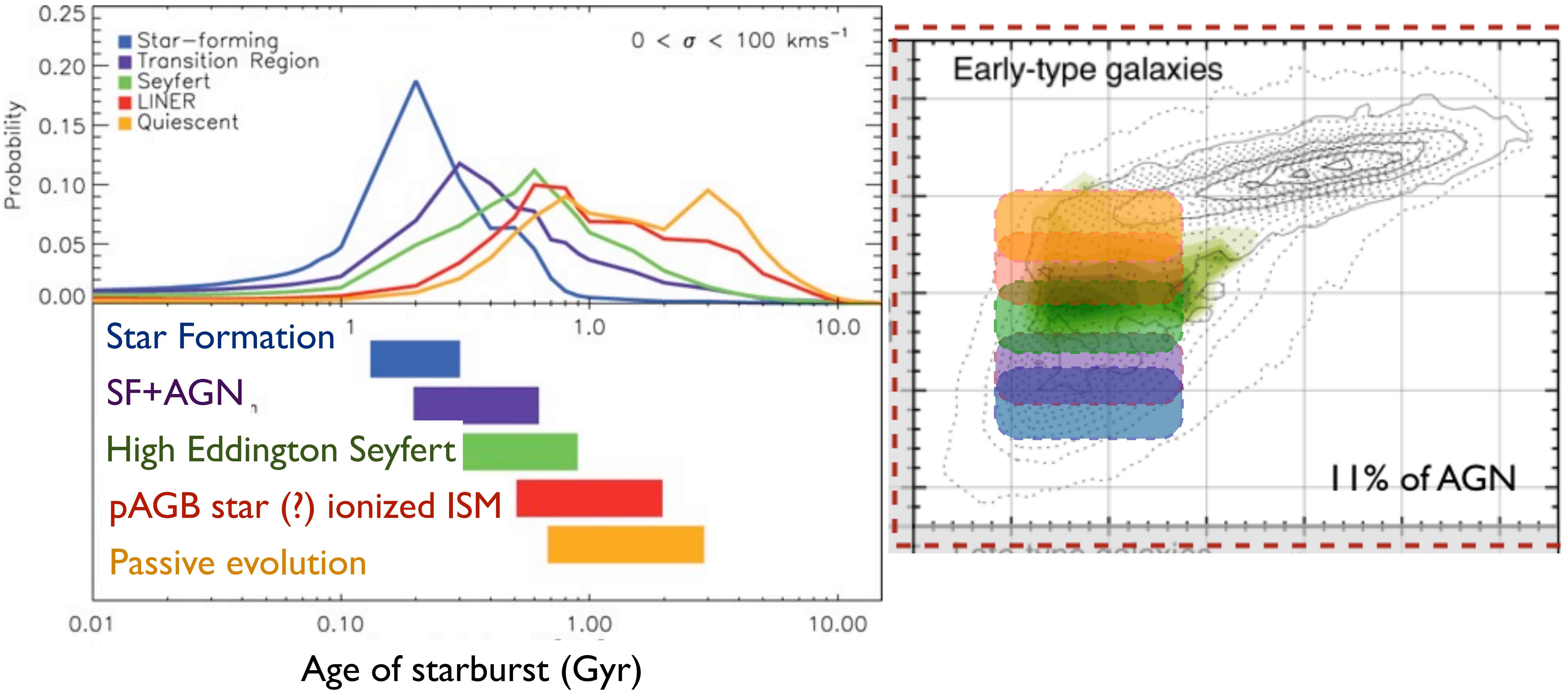


Input: GALEX+SDSS+2MASS photometry, SDSS spectroscopy (Lick indices)
Result: **1-10% of stellar mass** formed in most recent burst; leads to **rapid quenching** on ~100 Myr timescale and **migration to red sequence**

Output: the green valley conundrum!

SDSS reveals an evolutionary sequence:

Low-mass early-types migrate to the red sequence

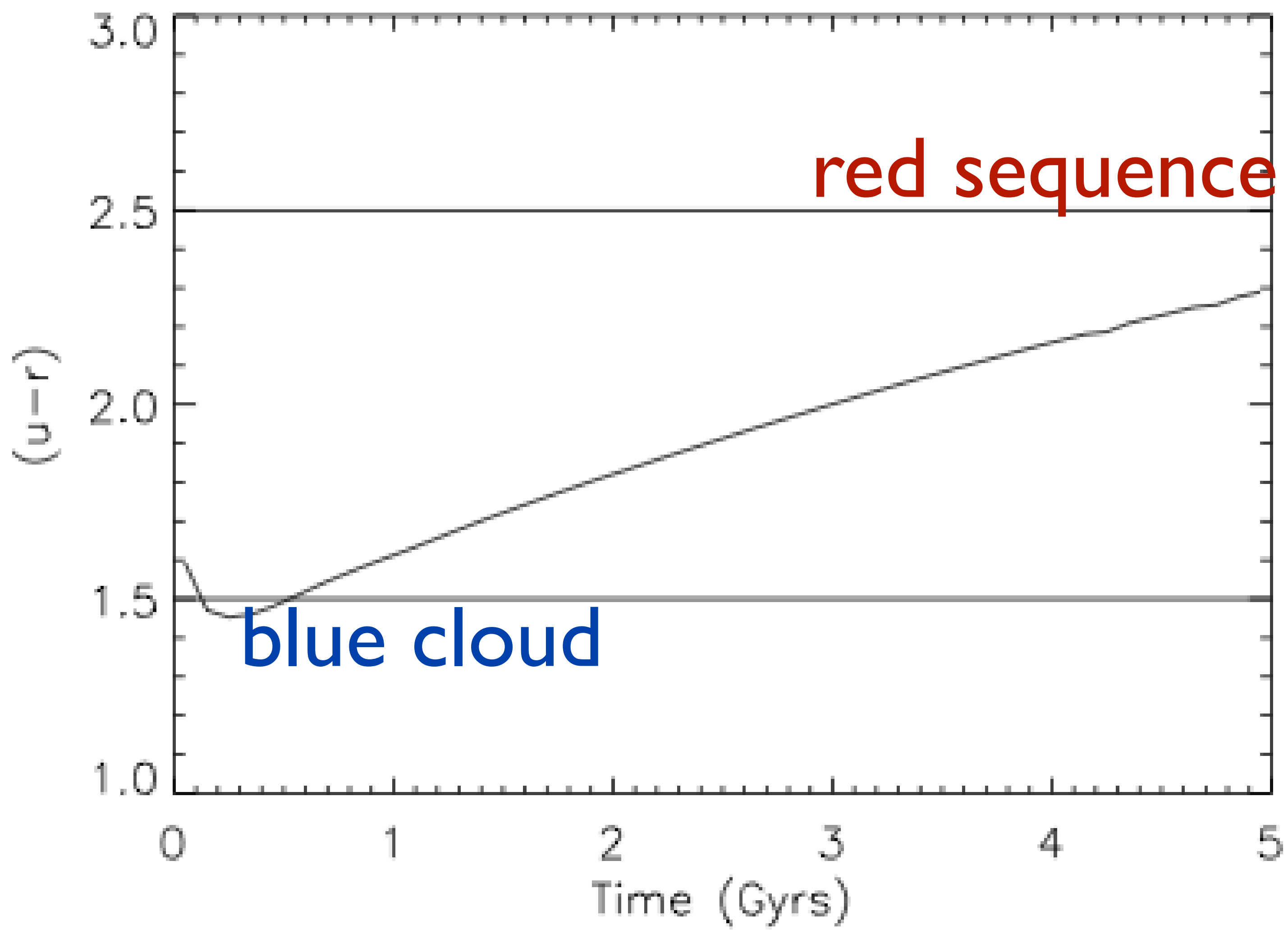


Input: GALEX+SDSS+2MASS photometry, SDSS spectroscopy (Lick indices)
Result: **1-10% of stellar mass** formed in most recent burst; leads to **rapid quenching** on ~100 Myr timescale and **migration to red sequence**

Output: the green valley conundrum!

Deviations from the Schmidt Law: Clues to Feedback

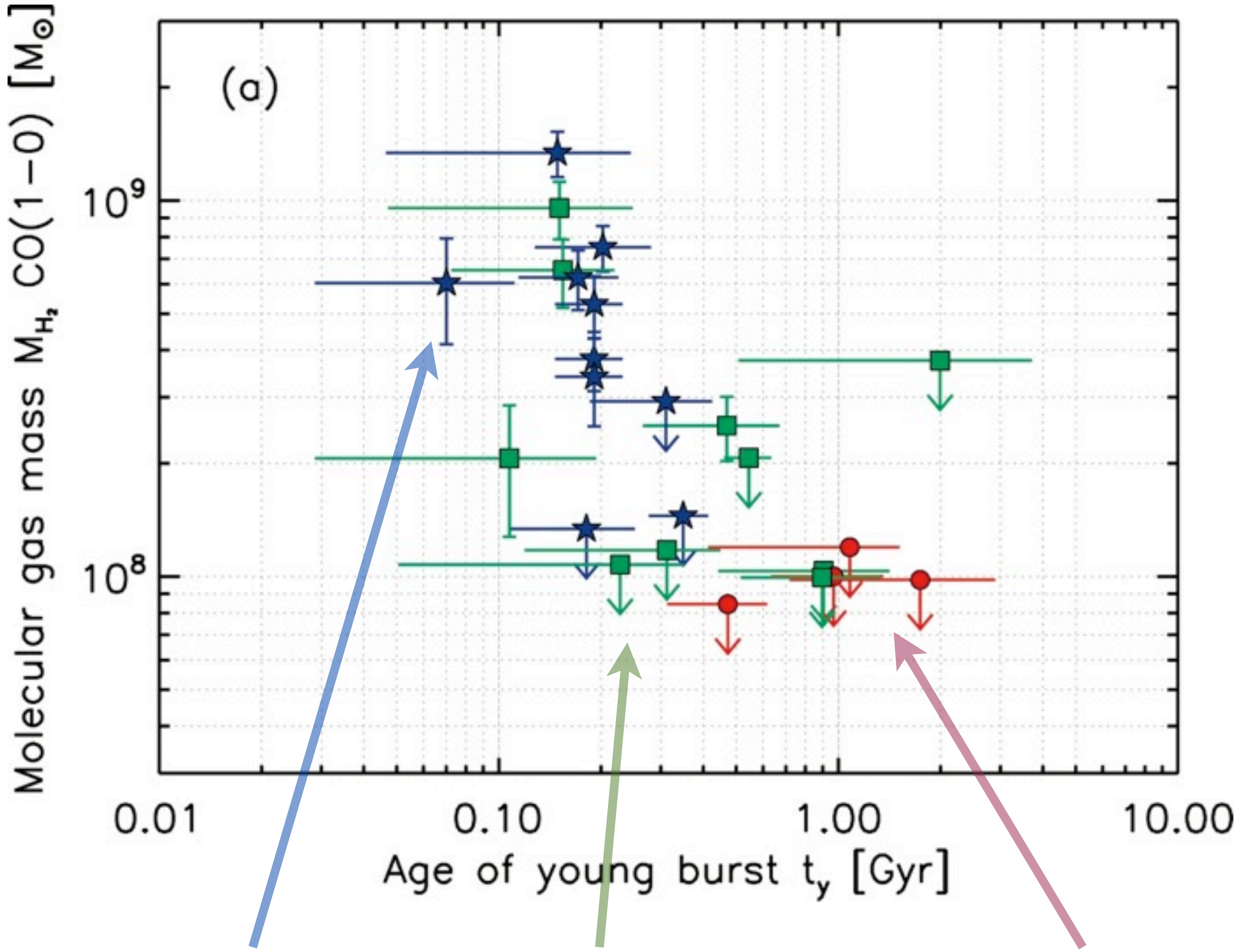
SFR = $\varepsilon M_{gas}/t_{dyn}$



Evolution of an (early-type) galaxy following the Schmidt Law with typical dynamical time and gas fraction and a standard efficiency of 2%. No further outside gas accretion, no minor mergers and no mass loss allowed to replenish the gas reservoir.

Schawinski+09a, Kaviraj, Schawinski, Silk & Shabala 2010

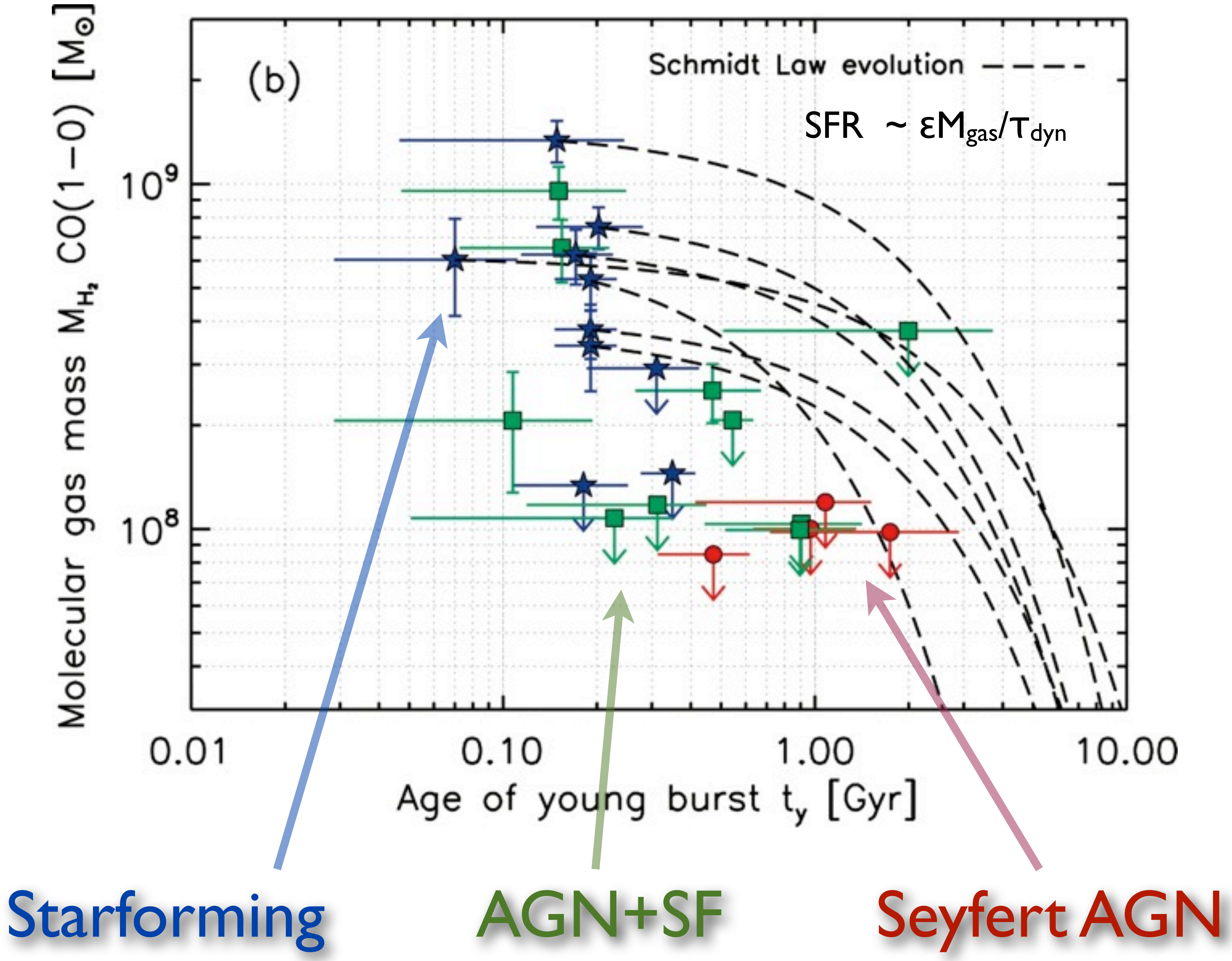
Deviations from the Schmidt Law: Clues to Feedback



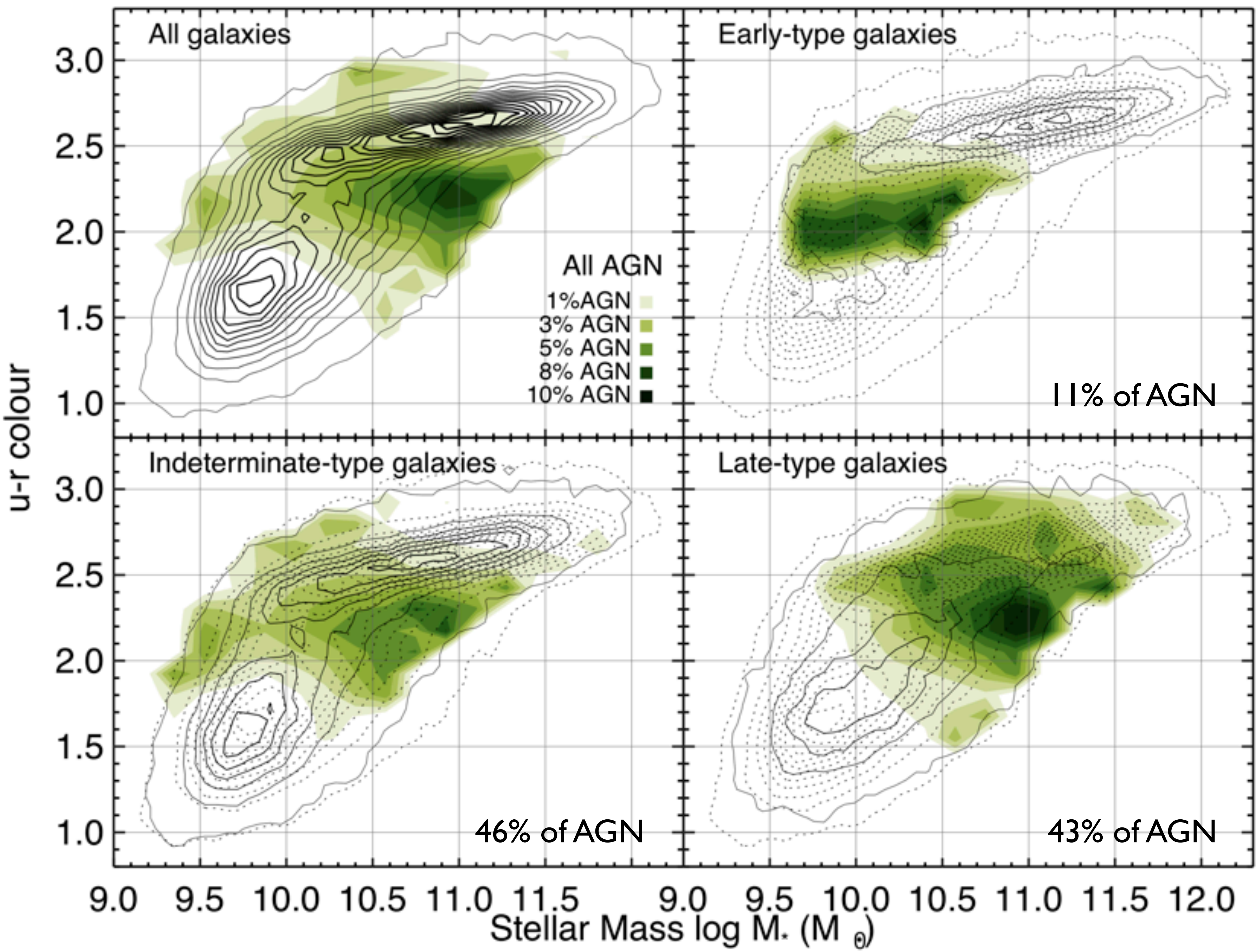
Starforming AGN+SF Seyfert AGN

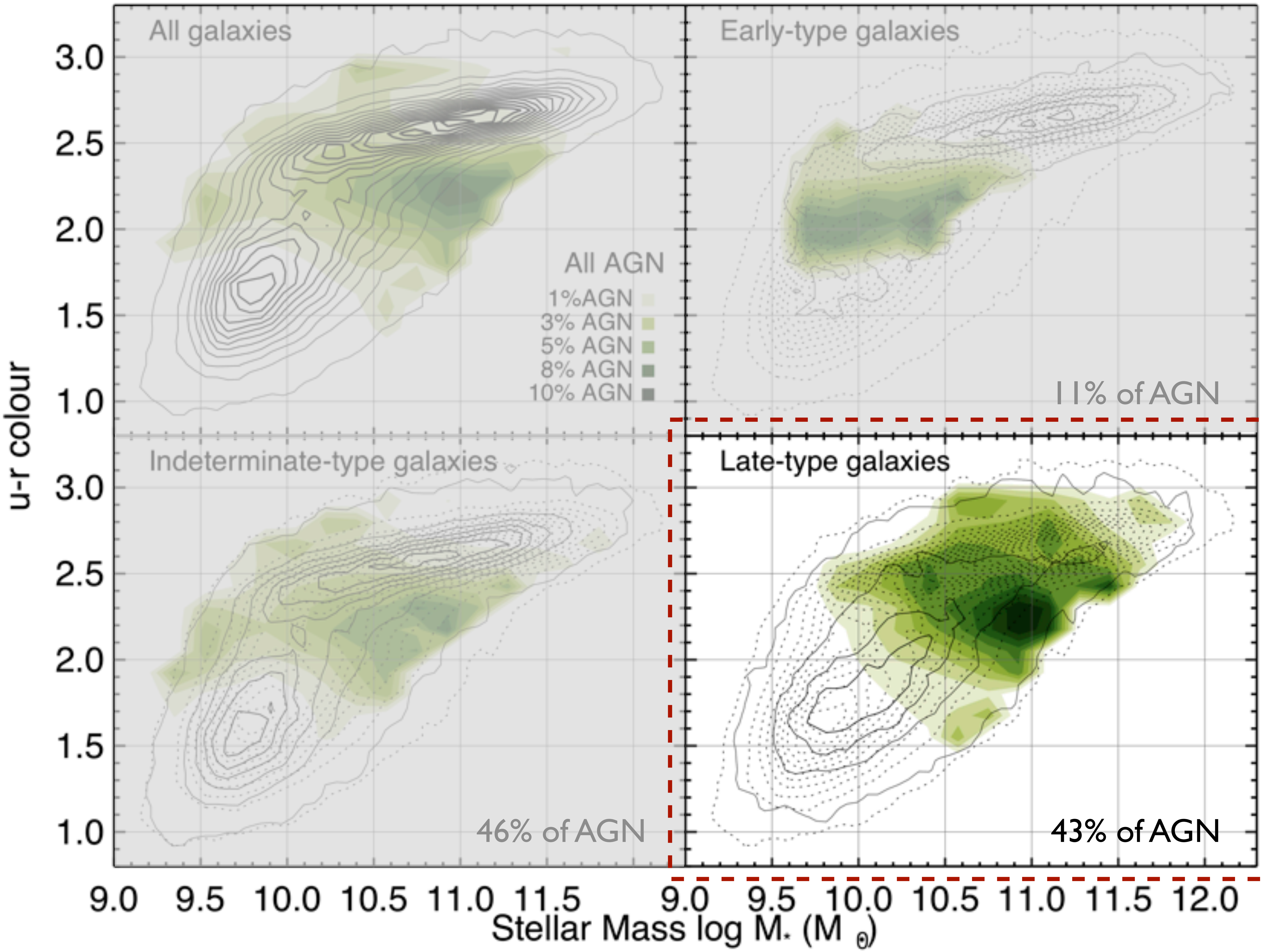
Schawinski+09a, Kaviraj, Schawinski, Silk & Shabala 2010

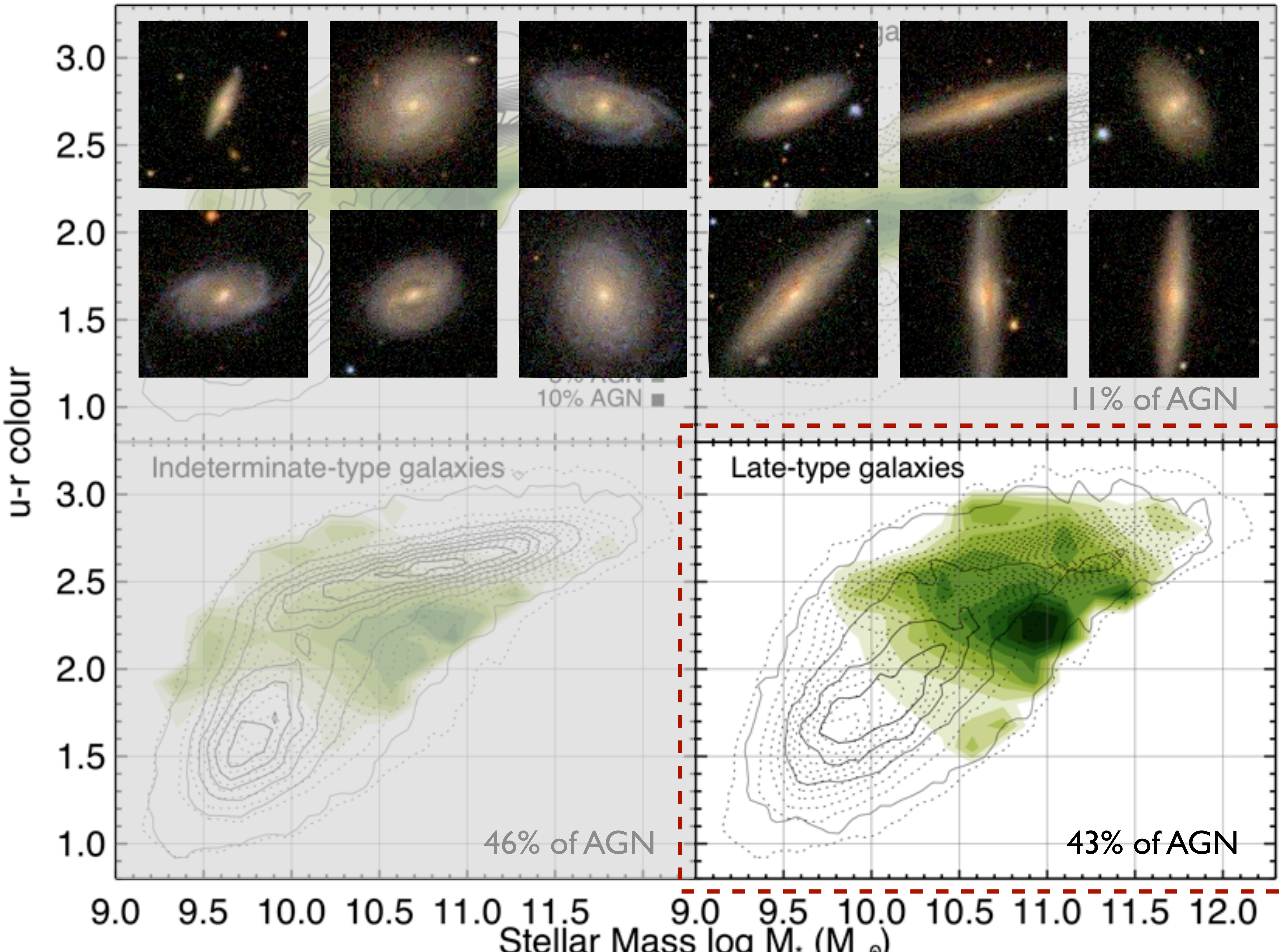
Deviations from the Schmidt Law: Clues to Feedback



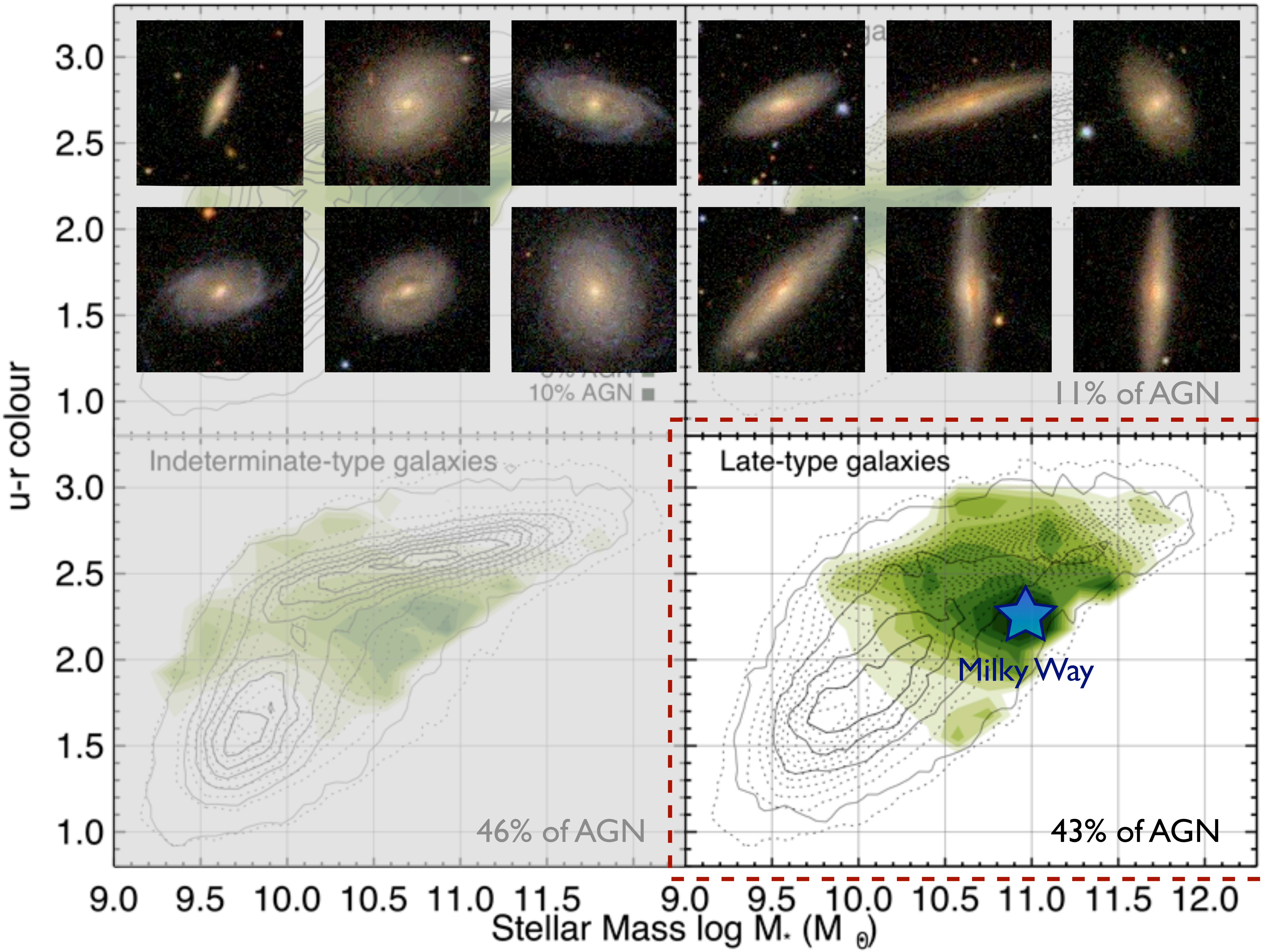
Schawinski+09a, Kaviraj, Schawinski, Silk & Shabala 2010


All galaxies
Early-type galaxies
Indeterminate-type galaxies
Late-type galaxies
All AGN
1%AGN
3% AGN
5% AGN
8% AGN
10% AGN
11% of AGN
46% of AGN
43% of AGN
u-r colour
Stellar Mass log M* (M ⊙)


All galaxies
Early-type galaxies
Indeterminate-type galaxies
Late-type galaxies
All AGN
1%AGN
3% AGN
5% AGN
8% AGN
10% AGN
11% of AGN
46% of AGN
43% of AGN
u-r colour
Stellar Mass log M* (M ☉)
3.0
2.5
2.0
1.5
1.0
9.0
9.5
10.0
10.5
11.0
11.5
12.0



u-r colour
10% AGN
11% of AGN
Indeterminate-type galaxies
46% of AGN
Late-type galaxies
43% of AGN
Stellar Mass log M* (M⊙)


3.0
2.5
2.0
1.5
1.0
10% AGN
11% of AGN
u-r colour
Indeterminate-type galaxies
46% of AGN
Late-type galaxies
Milky Way
43% of AGN
9.0 9.5 10.0 10.5 11.0 11.5
9.0 9.5 10.0 10.5 11.0 11.5 12.0
Stellar Mass log M* (M ⊙)

Two modes of black hole growth:

Post-starburst early-types

Early-type galaxies
(11% of AGN)

- Least massive black holes most likely to accrete.
- Triggered (indirectly) by (major?) merger.
- Host galaxies have post-starburst stellar populations (blue>green>red).
- Are building low-mass end of the red sequence.
- Phasing with merger/starburst still hard to understand.

Two modes of black hole growth:

Post-starburst early-types vs. secular late-types

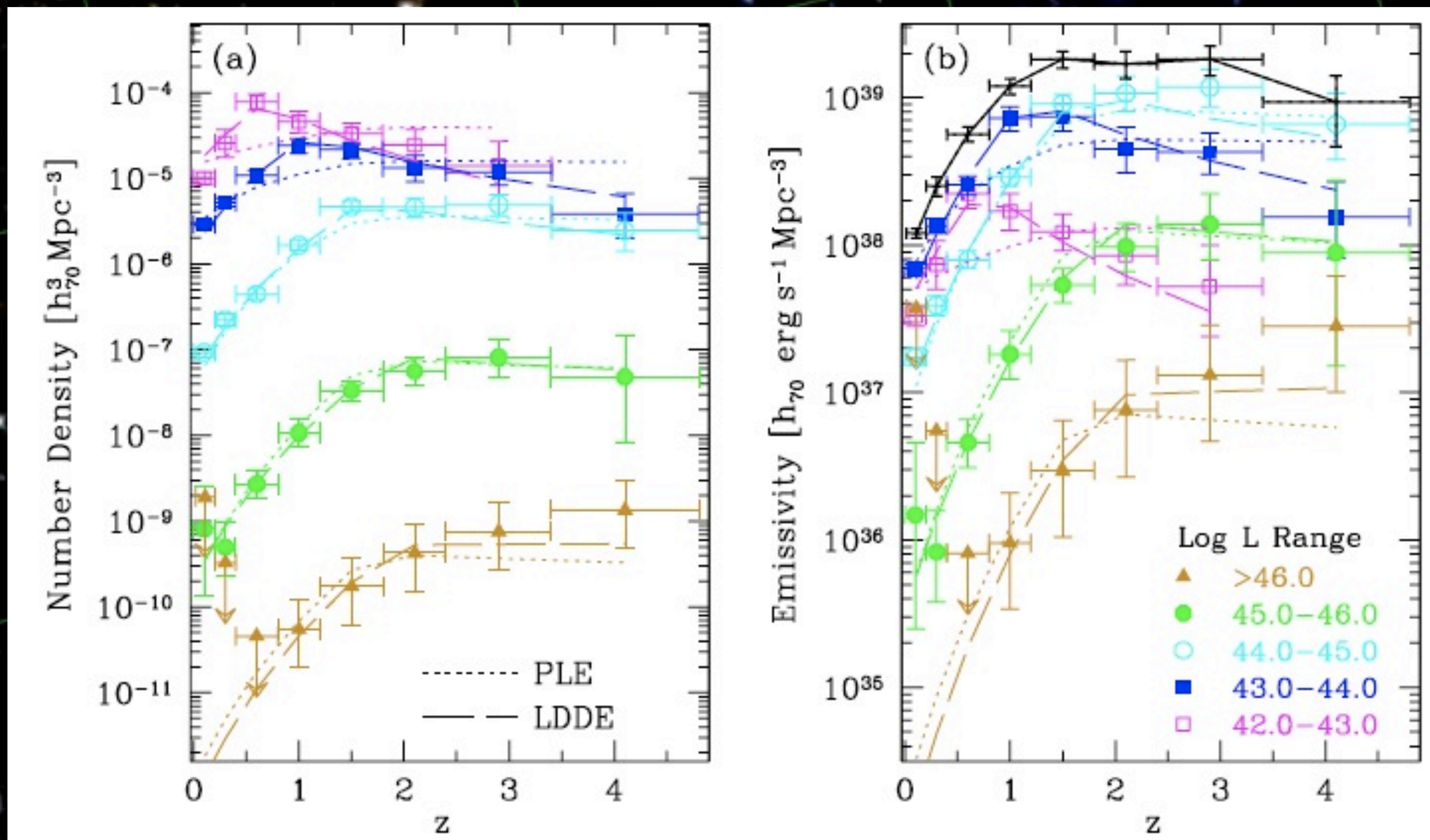
Early-type galaxies
(11% of AGN)

- Least massive black holes most likely to accrete.
- Triggered (indirectly) by (major?) merger.
- Host galaxies have post-starburst stellar populations (blue>green>red).
- Are building low-mass end of the red sequence.
- Phasing with merger/starburst still hard to understand.

Late-type galaxies
(43% of AGN +46% indeterminates?)

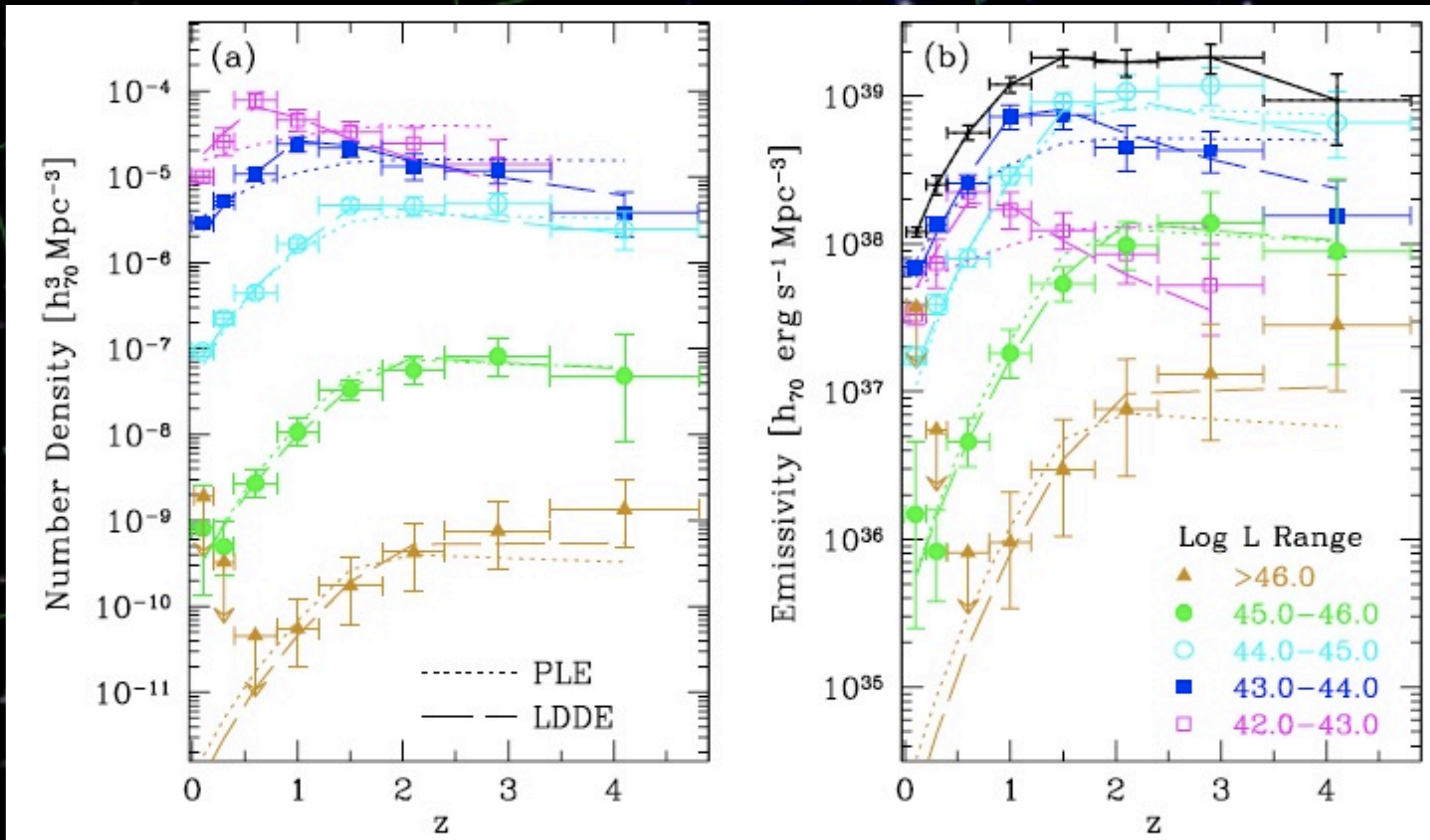
- Most massive black holes most likely to accrete.
- Unlikely to be triggered by merger - disks are stable.
- Host galaxies do NOT post-starburst stellar populations, but low SSFR?
- Are not transitioning from blue to red.
- Fuelling likely to be stochastic.
- Milky Way is archetype.

WFC3/IR (*YJH*) imaging of *Chandra* X-ray AGN



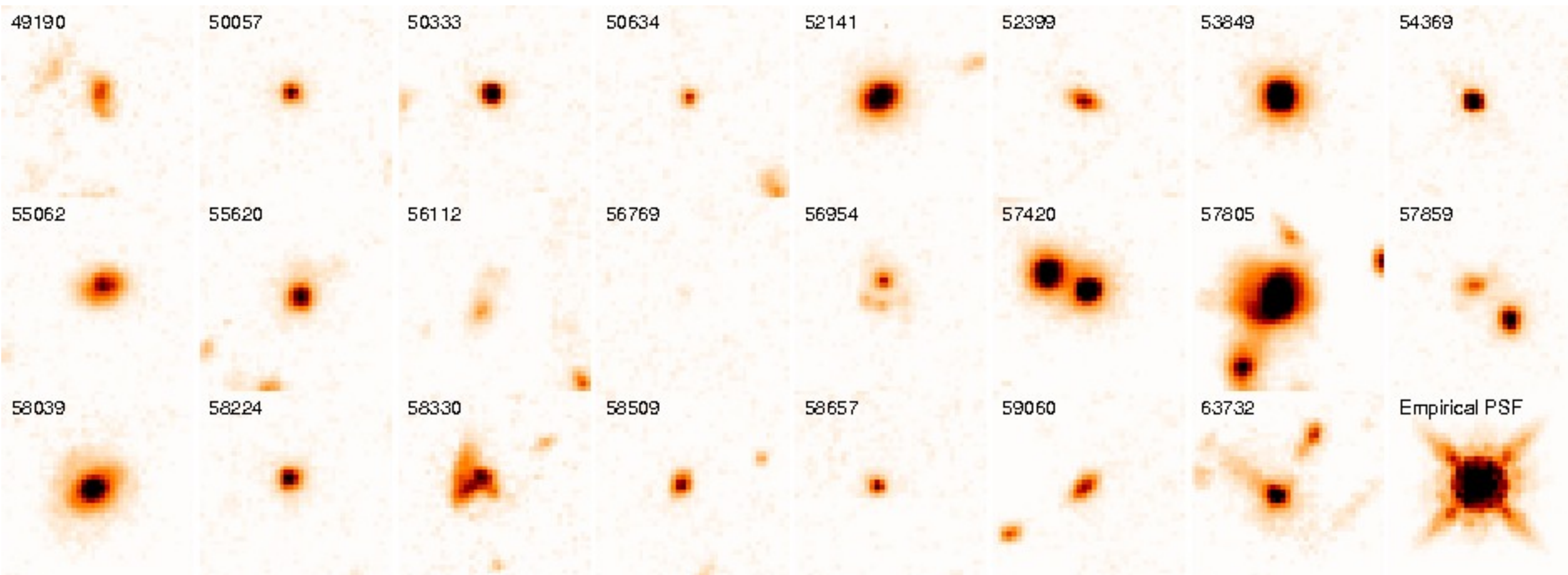
Hasinger, Miyaji & Schmidt (2005)

WFC3/IR (*YJH*) imaging of *Chandra* X-ray AGN

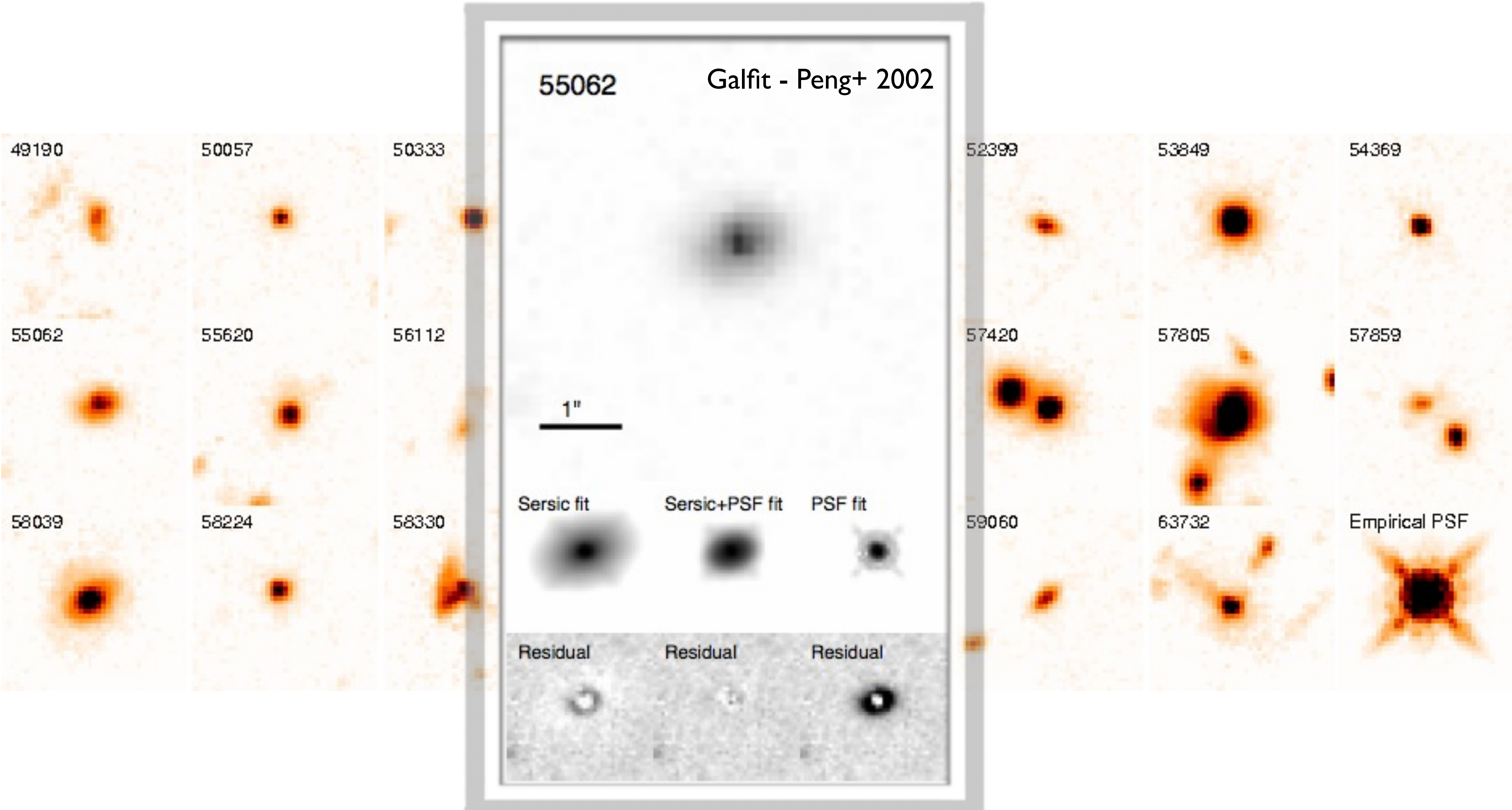


Hasinger, Miyaji & Schmidt (2005)

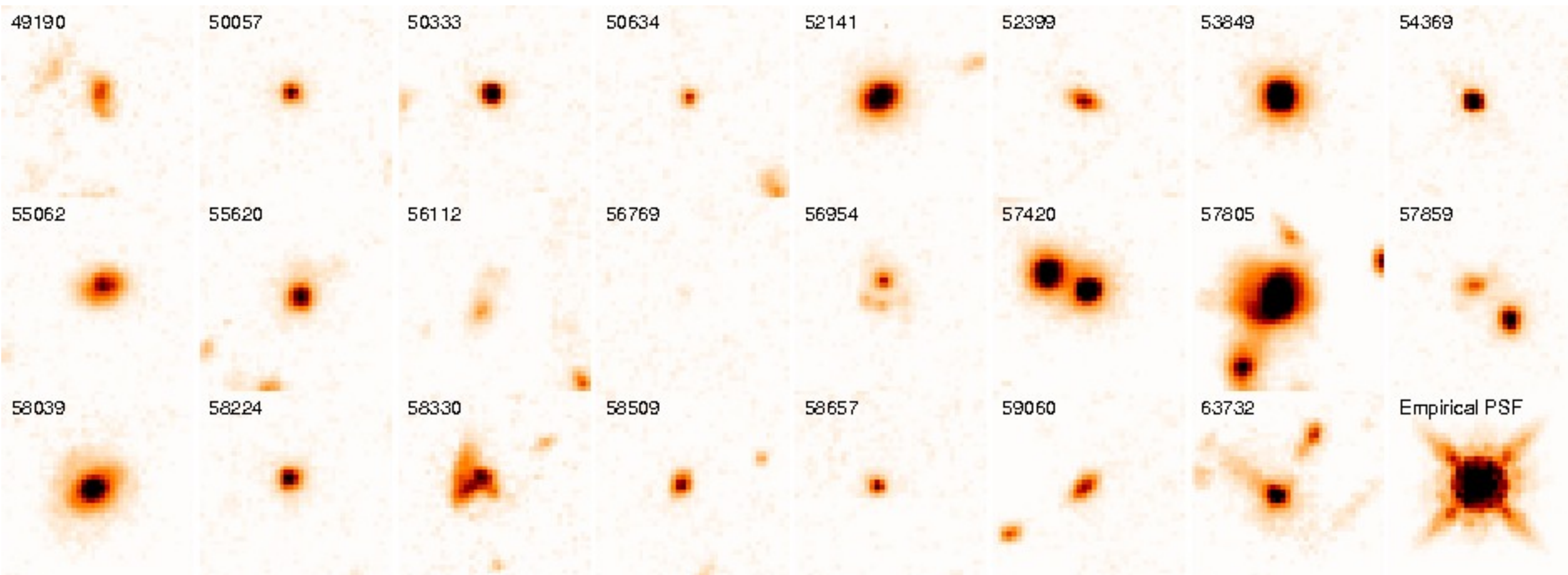
Typical AGN host galaxies at z ~ 2



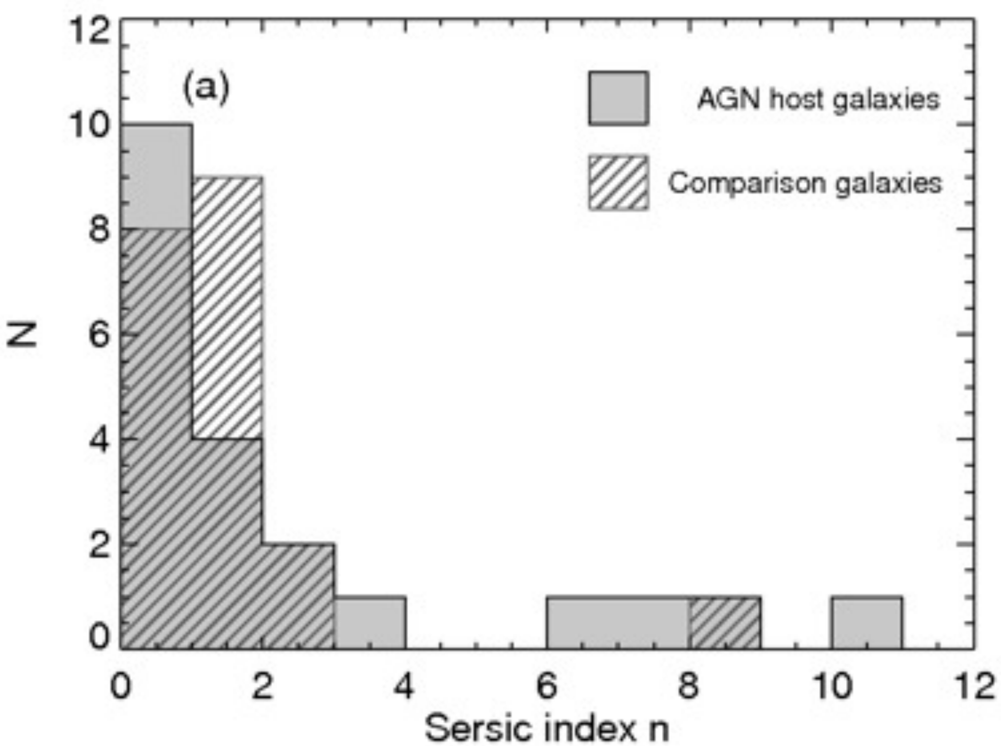
Typical AGN host galaxies at z ~ 2



Typical AGN host galaxies at z ~ 2



Typical AGN host galaxies at z ~ 2

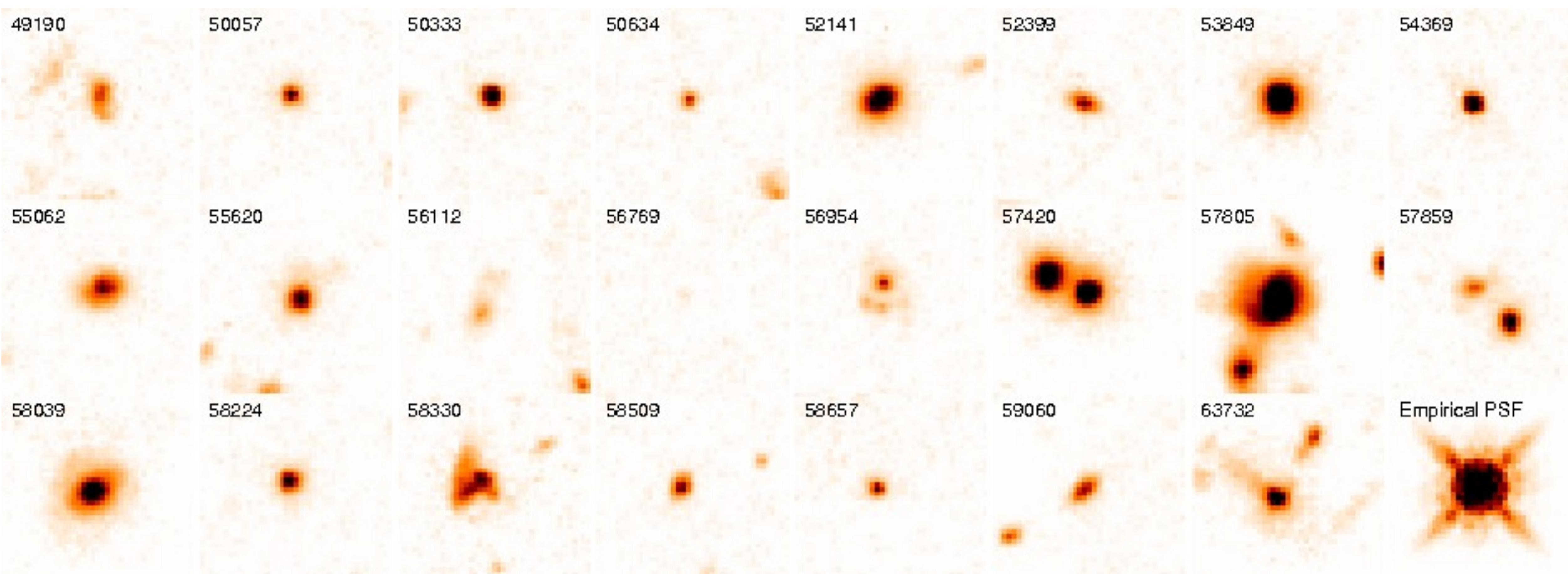


80% have low Sersic indices - disk-dominated, not bulges, not mergers.

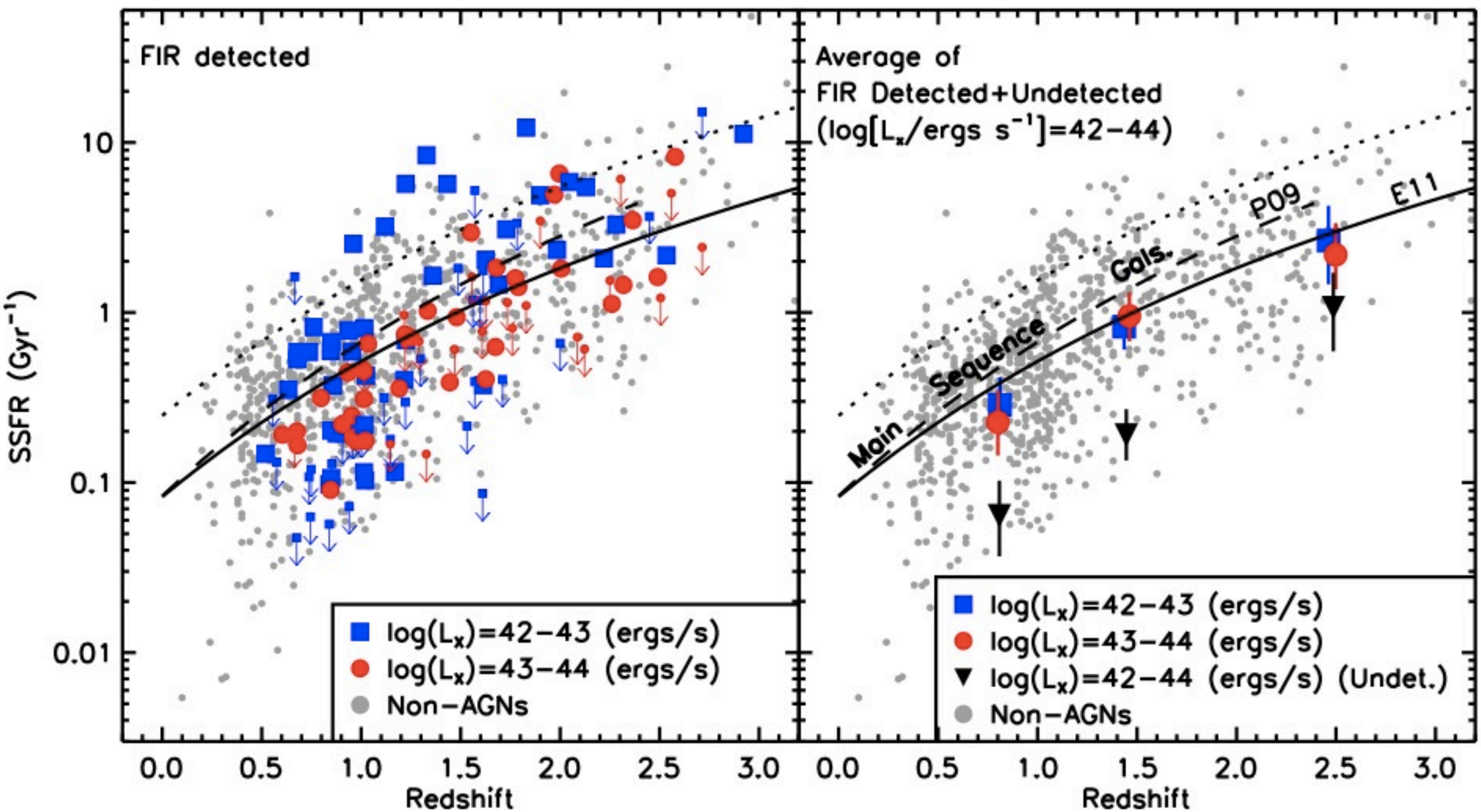
Possibly high Eddington ratios!

Very similar morphological mix as at z~0 - but *caveat emptor*!

Similar to Cisternas+11 at z<1
Now also Allevato+11(clustering), Mullaney+11, Kocevski, CANDELS+11 (submitted)



Typical AGN host galaxies at z ~ 2



Mullaney+11 - SSFR of X-ray selected AGN indistinguishable from galaxies

No link to mergers? Not so fast...
Mid-IR-selected CT-quasars at z>2 are a mess

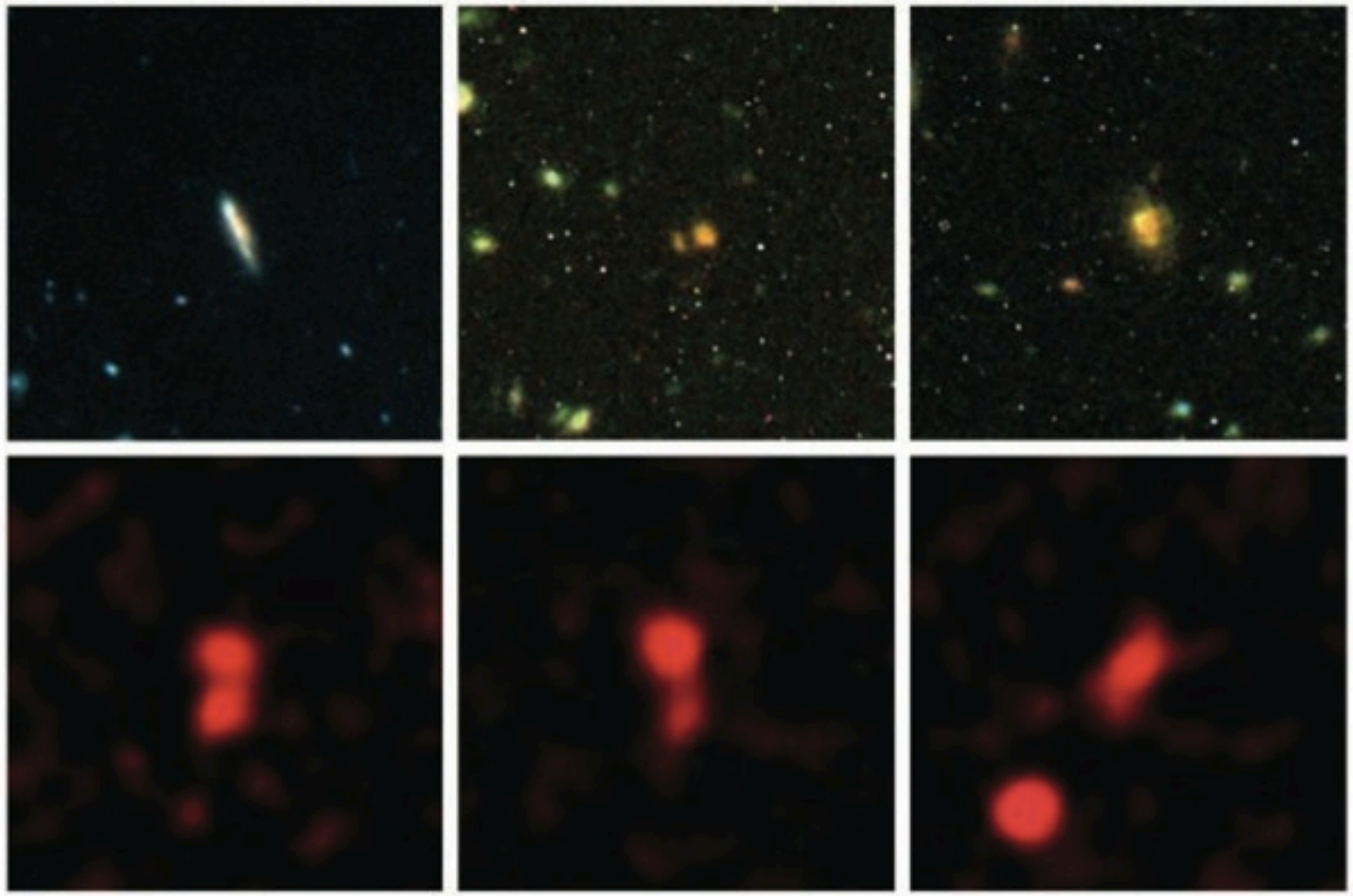


Fig. 3. Rest-frame optical images of six mid-IR–selected heavily obscured quasars at $z \sim 2$ in the Extended Chandra Deep Field-South region. Top images were obtained with the HST-WFC3 (Wide Field Camera 3) camera using the *Y*, *J*, and *H* observations of the Ultra-Deep (left) and GOODS fields. The bottom images were made by combining data in the *R*, *J*, and *K* bands obtained from ground-based telescopes, hence with a spatial resolution about 10 times as large as that of the HST images. All images are 15 arc sec by 15 arc sec.

Treister, Schawinski+10, *Science*

No link to mergers? Not so fast...
Mid-IR-selected CT-quasars at z>2 are a mess

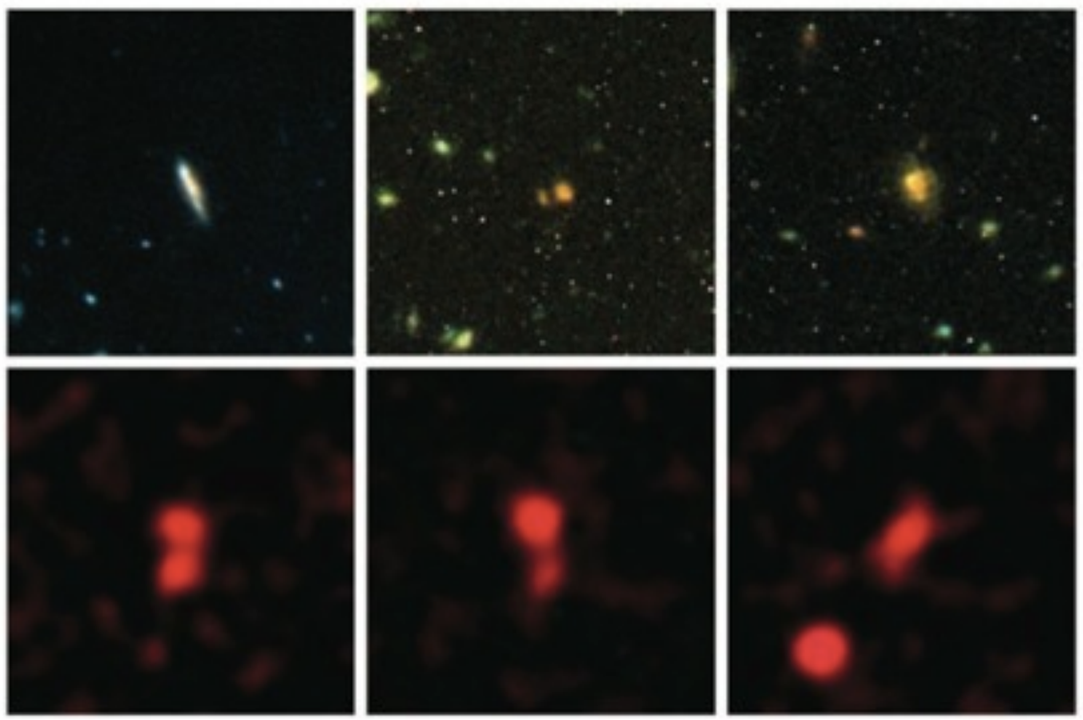


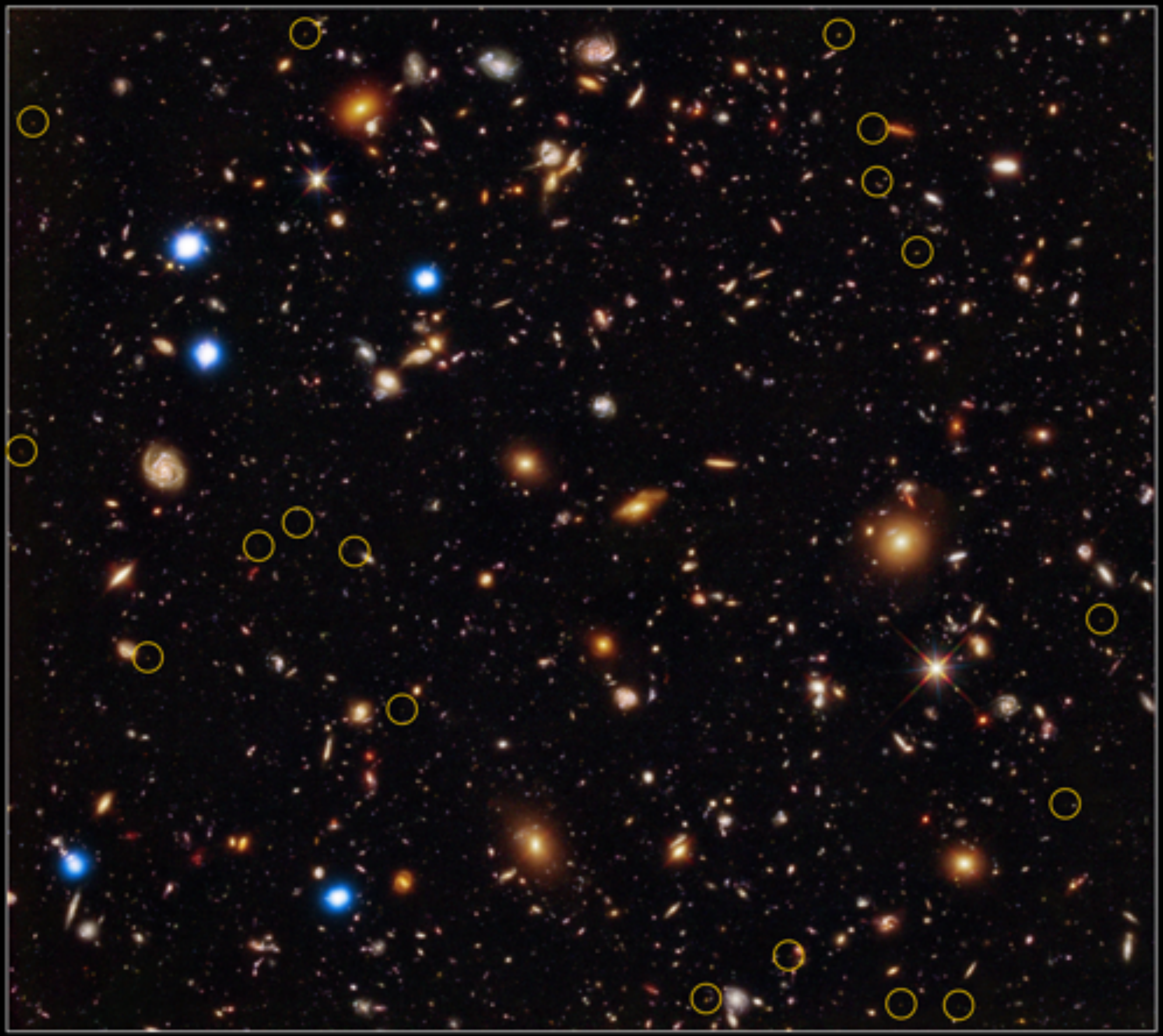
Fig. 3. Rest-frame optical images of six mid-IR–selected heavily obscured quasars at $z \sim 2$ in the Extended Chandra Deep Field-South region. Top images were obtained with the HST-WFC3 (Wide Field Camera 3) camera using the *Y*, *J*, and *H* observations of the Ultra-Deep (left) and GOODS fields. The bottom images were made by combining data in the *R*, *J*, and *K* bands obtained from ground-based telescopes, hence with a spatial resolution about 10 times as large as that of the HST images. All images are 15 arc sec by 15 arc sec.

z>2 AGN hosts still very poorly understood and high-z universe just opening up:

* *HST*/IR (imaging & grism)
* ALMA
* *Chandra* deep fields
* Near-IR MOSs

Do we even capture all black hole growth? High obscuration a major problem and mid-IR selection still difficult and low-L systems still basically impossible to detect...

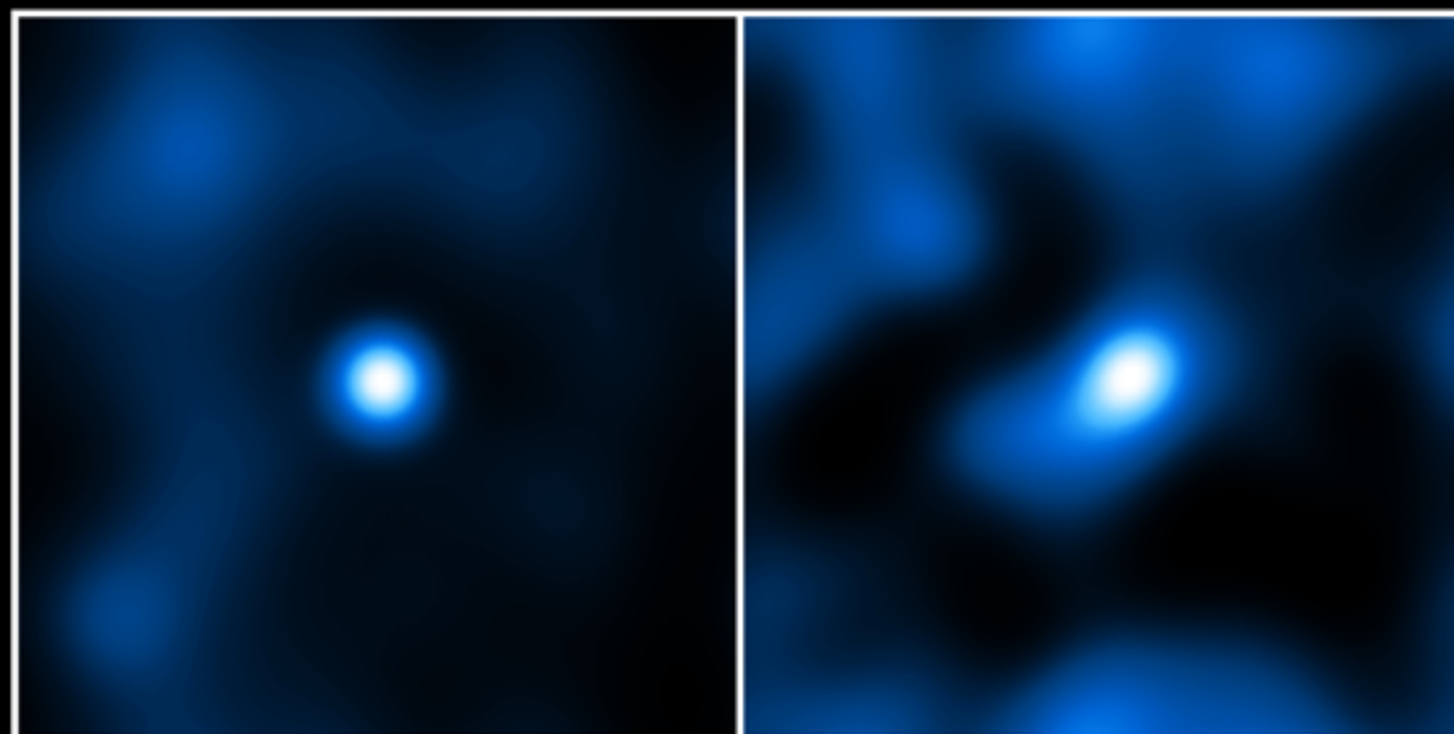
Search for z>6 AGN



z=6,7,8 drop-outs seen by HST, Bouwens+06,10a,10b

Chandra stack of z=6 galaxies

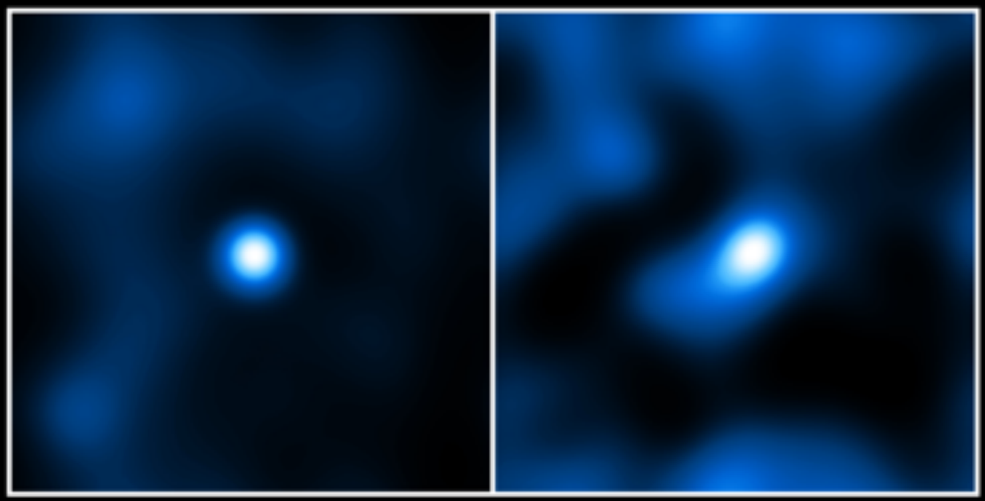
Effective 23 years of Chandra time!



Hard band	Soft band
Significance: 6.8σ	5σ
Observed: 2-10 keV	0.5-2 keV
Rest: 14-56 keV	3.5-14 keV

30%+ of z=6 galaxies host a growing black hole

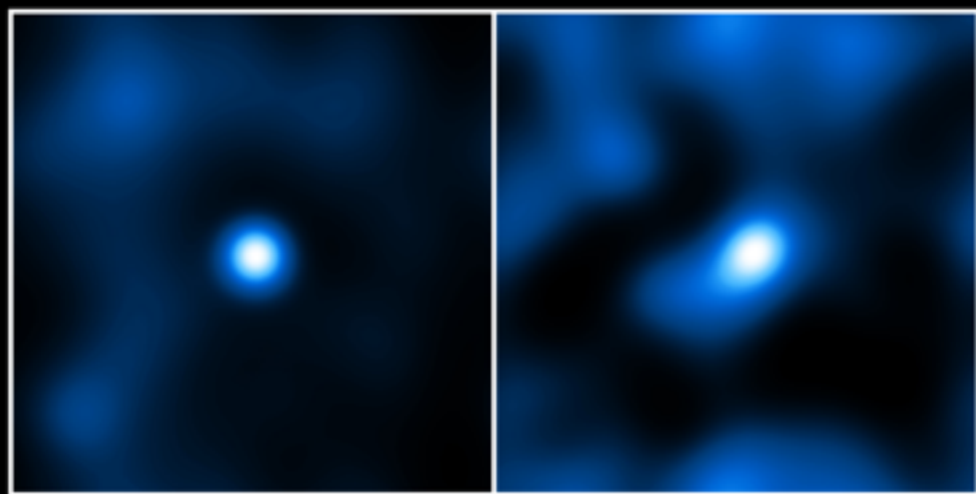
Chandra stack of z=6 galaxies



Hard band	Soft band
Significance: 6.8σ	5σ
Observed: 2-10 keV	0.5-2 keV
Rest: 3.5-14 keV	14-56 keV

197 z=6 dropout galaxies
Average Luminosity:
$L_{X,hard} = 8.4 \times 10^{42}$ erg s^{-1}
$L_{X,soft} = 9.1 \times 10^{41}$ erg s^{-1}

Chandra stack of z=6 galaxies

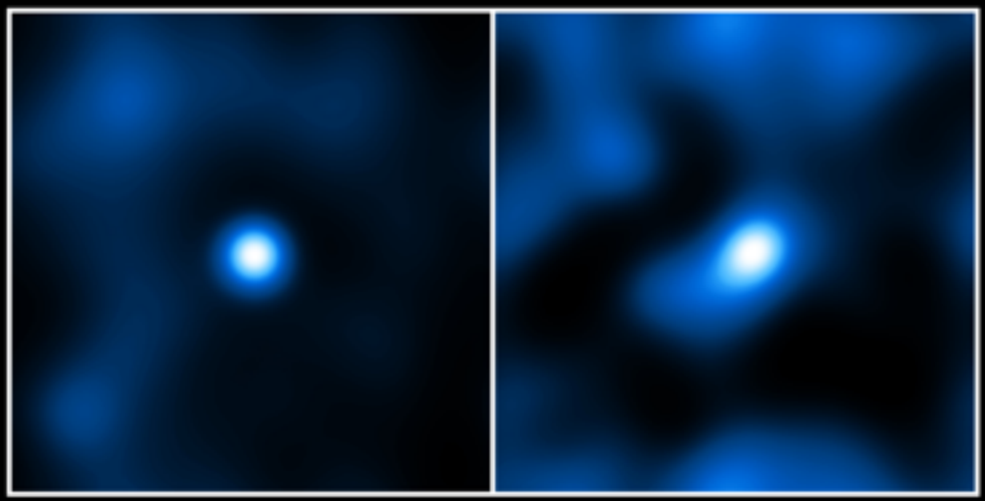


Hard band	Soft band
Significance: 6.8σ	5σ
Observed: 2-10 keV	0.5-2 keV
Rest: 3.5-14 keV	14-56 keV

197 z=6 dropout galaxies
Average Luminosity:
$L_{X,hard} = 8.4 \times 10^{42}$ erg s^{-1}
$L_{X,soft} = 9.1 \times 10^{41}$ erg s^{-1}

Factor ~9 difference implies large absorbing column: $N_H > 1.6 \times 10^{24}$ cm^{-2}

Chandra stack of z=6 galaxies



Hard band	Soft band
Significance: 6.8σ	5σ
Observed: 2-10 keV	0.5-2 keV
Rest: 3.5-14 keV	14-56 keV

197 z=6 dropout galaxies
Average Luminosity:
$L_{X,hard} = 8.4 \times 10^{42}$ erg s^{-1}
$L_{X,soft} = 9.1 \times 10^{41}$ erg s^{-1}

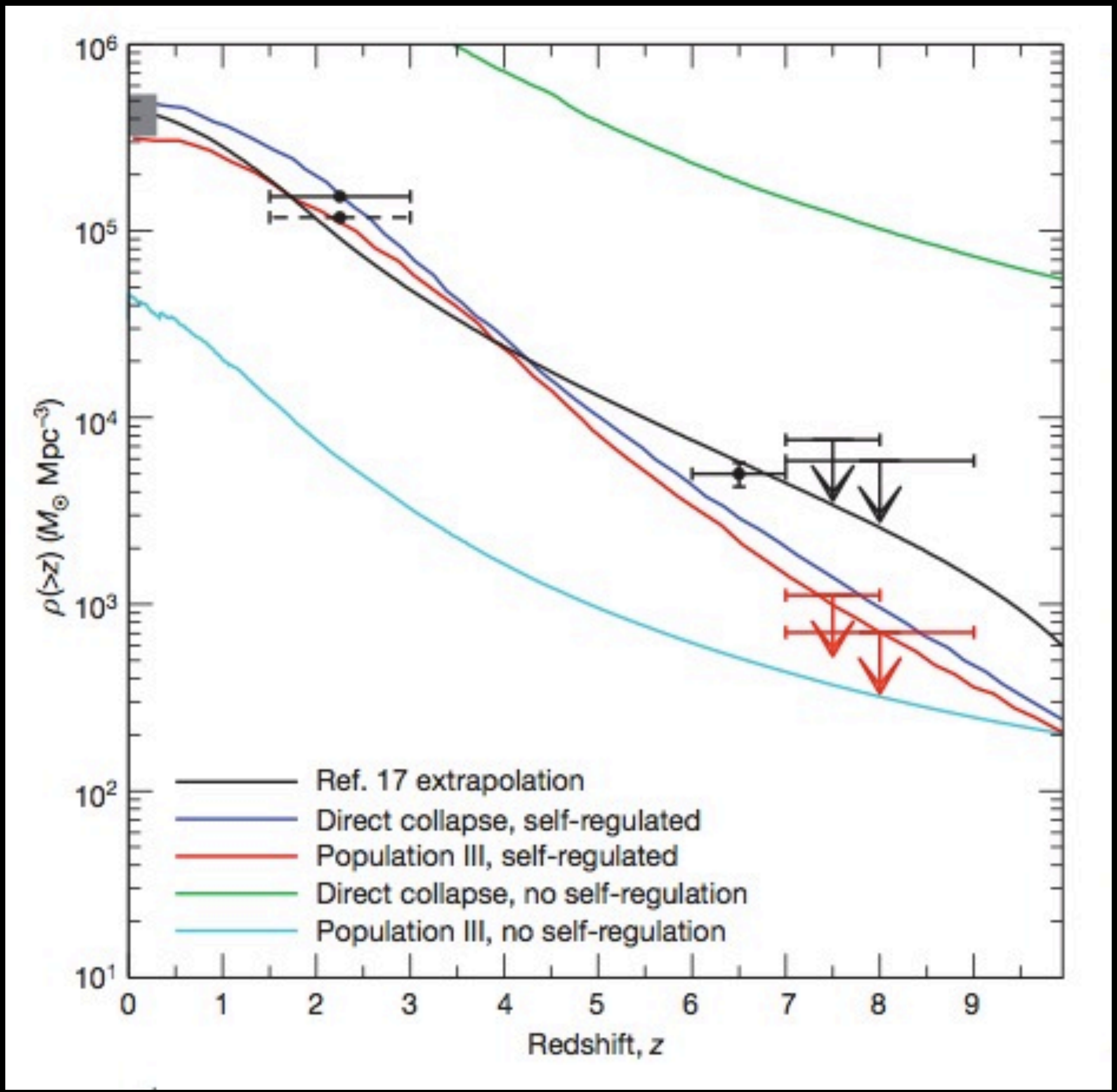
Factor ~9 difference implies large absorbing column: $N_H > 1.6 \times 10^{24}$ cm^{-2}

Very few if any sources can have lower obscuring colums, so (almost) all AGN at z=6 are Compton-thick at all viewing angles.

Black Hole Growth at z=6-8 is Self-Regulated

models by Marta Volonteri and Priya Natarajan

Accreted black hole mass density

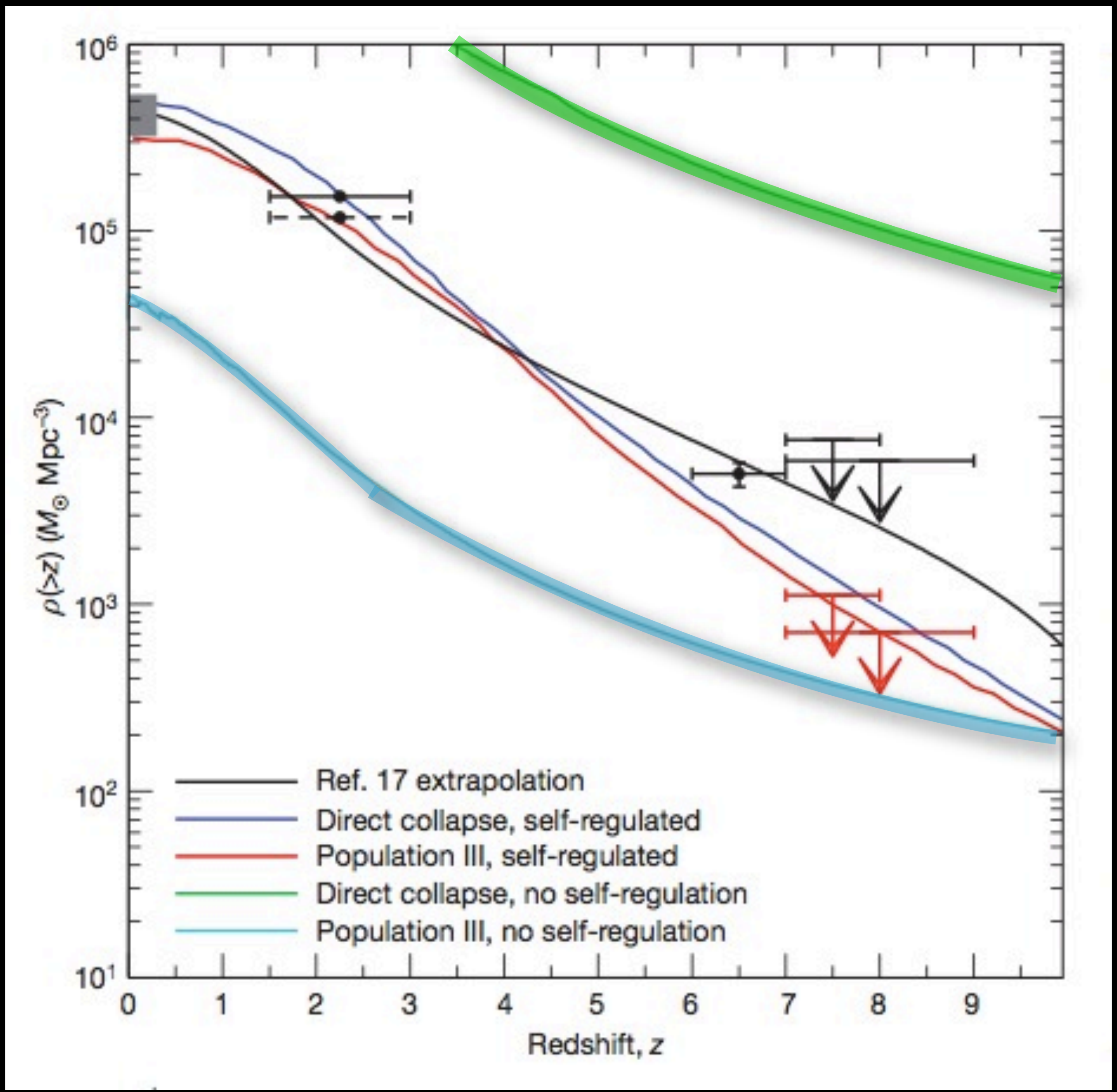


Redshift

Black Hole Growth at z=6-8 is Self-Regulated

models by Marta Volonteri and Priya Natarajan

Accreted black hole mass density



Redshift

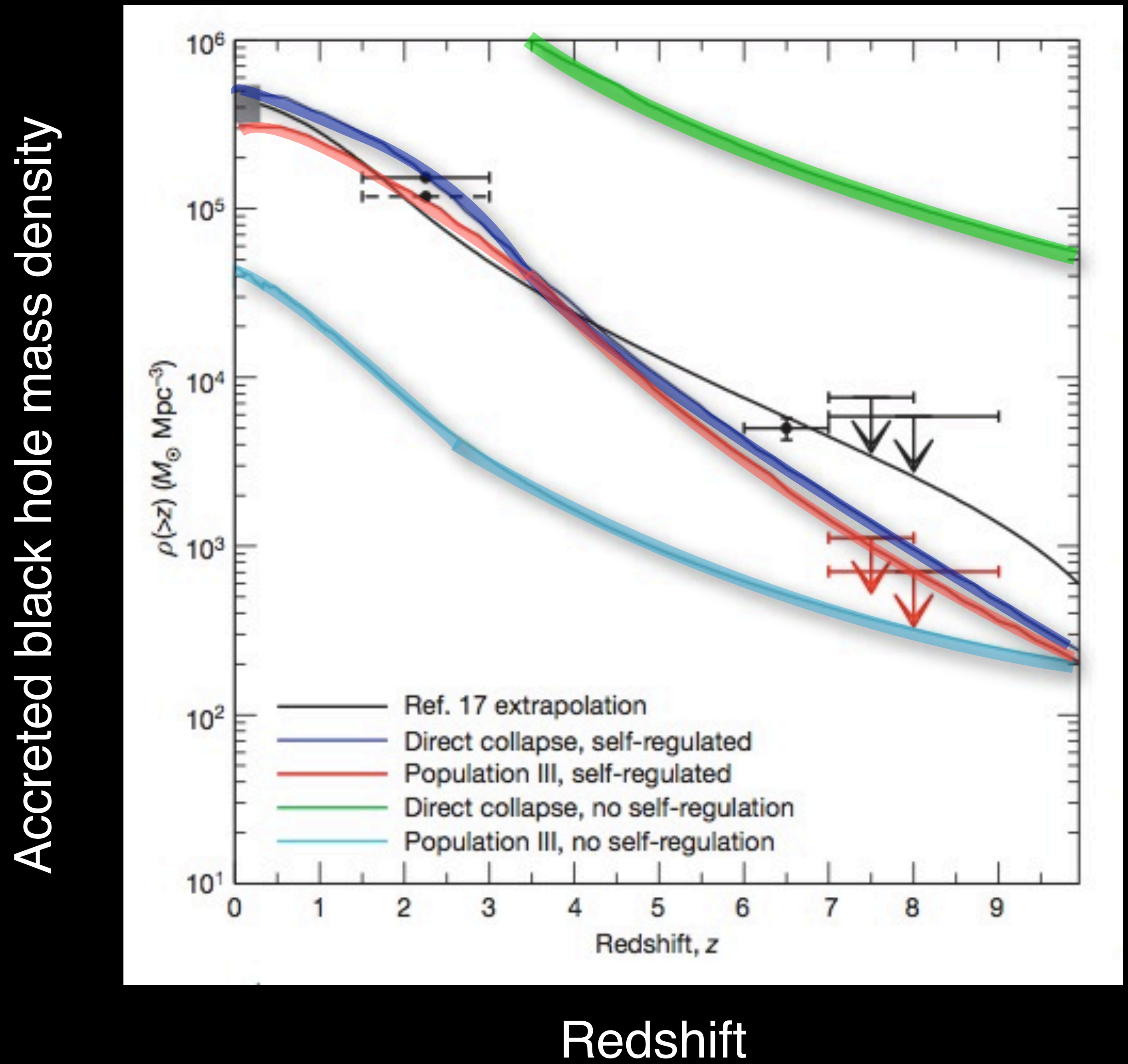
Models without self-regulation result in growth histories incompatible with the 6<z<8 observations.

Direct collapse, no self-regulation

Pop III, no self-regulation

Black Hole Growth at z=6-8 is Self-Regulated

models by Marta Volonteri and Priya Natarajan



Models without self-regulation result in growth histories incompatible with the 6<z<8 observations.

Direct collapse, no self-regulation

Pop III, no self-regulation

Models with self-regulation match the 6<z<8 observations.

Direct collapse, self-regulation

Pop III, self-regulation

Self-regulation = explicit link between accreted black hole mass and halo circular velocity

Summary

1. There are two fundamentally different black hole growth modes in early- and late-type galaxies.

2. Secular processes in disk galaxies may govern a large fraction of cosmic black hole growth.

3. Black hole growth appears to be self-regulated even at z=6-8.

Summary

1. There are two fundamentally different black hole growth modes in early- and late-type galaxies.

2. Secular processes in disk galaxies may govern a large fraction of cosmic black hole growth.

3. Black hole growth appears to be self-regulated even at z=6-8.

Summary

1. There are two fundamentally different black hole growth modes in early- and late-type galaxies.

2. Secular processes in disk galaxies may govern a large fraction of cosmic black hole growth.

3. Black hole growth appears to be self-regulated even at z=6-8.

Questions:

* Are there really multiple modes of co-evolution, and if so, why do they give the same result (scaling relations)?

* If a large fraction of black hole mass is accreted in disk galaxies, why do we have an M-sigma relation, rather than an M-disk mass or M-total mass relation?

* The "green valley conundrum": If there is such a large time lag between starburst and black hole accretion, how can we have feedback?