The low surface brightness Universe with cosmological simulations

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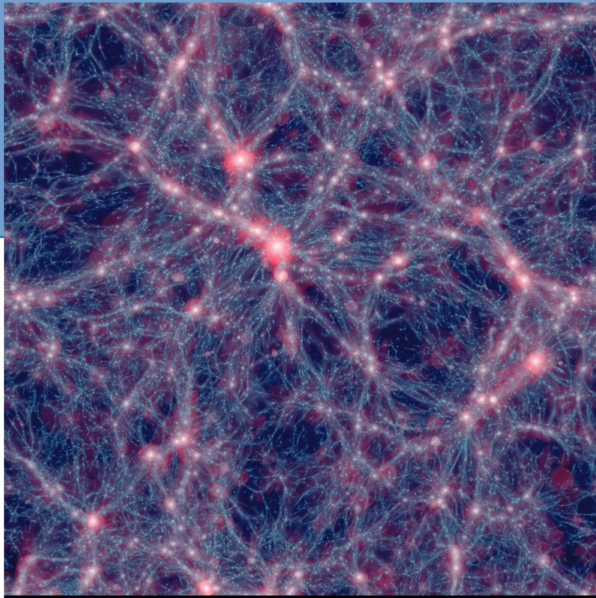
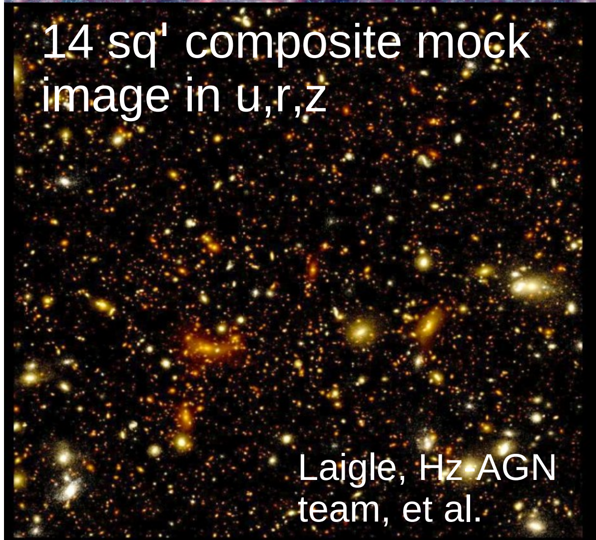
The low surface brightness universe

- We should keep in mind that observational studies are surface brightness limited as well as magnitde limited
- Studies of galaxy evolution are dominated by high-surface-brightness ($\mu_e < 23$ mag arcsec^{-2}) galaxies, below which e.g. SDSS starts to become incomplete **(e.g. Kniazev +04, Bakos +12, Williams +16)**
  - But deep surveys show a rich LSB population lies just below current detection limits **(e.g. Kaviraj 14, van Dokkum+15, Venhola +17, Román +17, +18)**
- Our inability to study the majority of low mass galaxies biases our understanding of the Universe
- Cosmological ΛCDM simulations can be used to predict the properties of faint populations that are currently invisible to us.

Modelling the LSB population





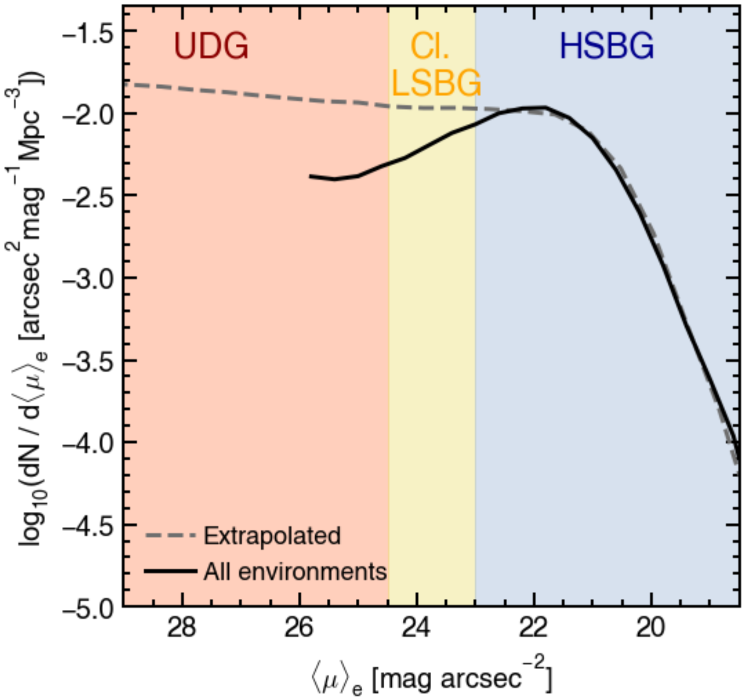
Horizon-AGN (Dubois+16)

- ~100h^{-1} CoMpc box length.
- Minimum 1kpc resolution – we can probe intermediate mass (M* > 10^9) LSB galaxies.
- Good agreement with observed bulk properties of the Universe **(Dubois+14, +16, Volonteri+17, Kaviraj+17)**.

Modelling the LSB population

Split galaxies at z = 0 in the population into 3 groups:

- High SB galaxies (**HSBGs**): μ_e < 23 mag arcsec^{-2}
- Classical LSB galaxies (**Cl. LSBGs**): 24.5 > μ_e > 23 mag arcsec^{-2} **(e.g Van der Hulst+93)**
- Ultra-diffuse galaxies (**UDGs**): μ_e > 24.5 mag arcsec^{-2} **(e.g. Sandage+Bingelli+84, VanDokkum+15,Koda+15)**



Plot: Surface brightness function

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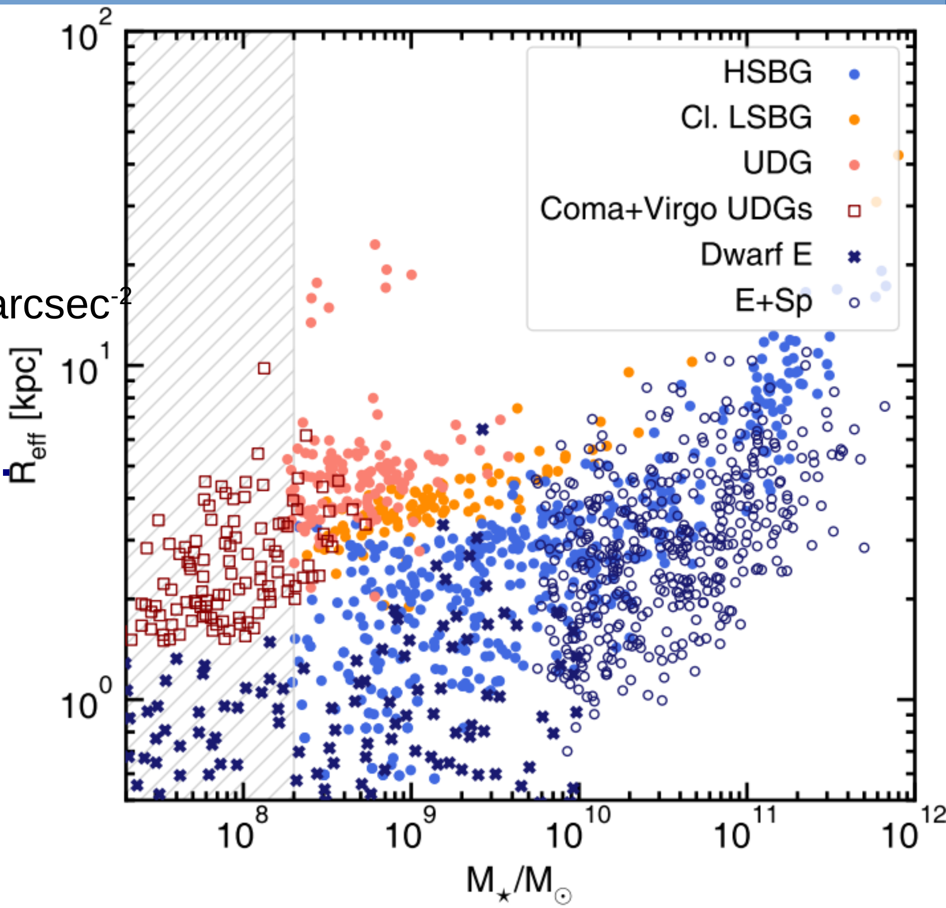
- Ultra-diffuse galaxies (**UDGs**): μ_e > 24.5 mag arcsec^{-2} **(e.g. Sandage+Bingelli+84, VanDokkum+15,Koda+15)**
- <u>What properties do LSBGs have at z = 0?</u>
- <u>Where do their properties diverge from HSBGs?</u>
- <u>What drives this divergence?</u>



How significant are low-surface-brightness galaxies?

- LSBGs account for most of the number density budget, but a fairly small proportion of the stellar mass and luminosity budgets

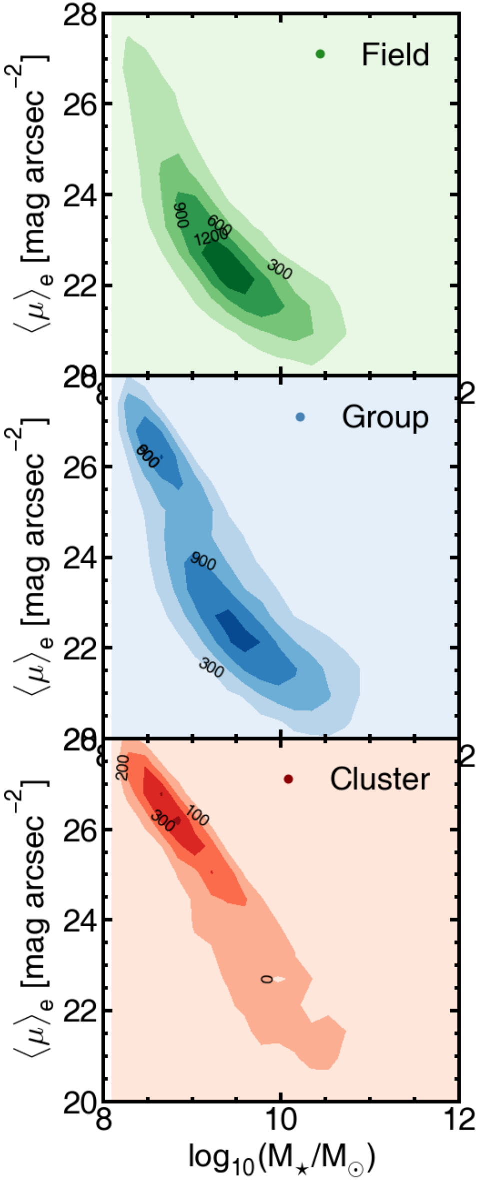
	$\langle\mu\rangle_e < 23$	$24.5 > \langle\mu\rangle_e > 23$	$\langle\mu\rangle_e > 24.5$
f_{M_*}	0.924 (0.902)	0.059 (0.067)	0.014 (0.030)
f_L	0.939 (0.892)	0.049 (0.071)	0.012 (0.037)
f_N	0.534 (0.145)	0.214 (0.093)	0.252 (0.762)

- LSBG populations outside of cluster environments currently poorly understood
  - Limited samples of UDGs discovered in groups **(e.g. Romain+Trujillo 2016, Merritt 2016)** and the field **(e.g. Papastergis+2017)**
  - We will have to wait for deep-wide surveys (e.g. LSST, EUCLID) in order to get significant samples of LSBGs / UDGs

How significant are low-surface-brightness galaxies?

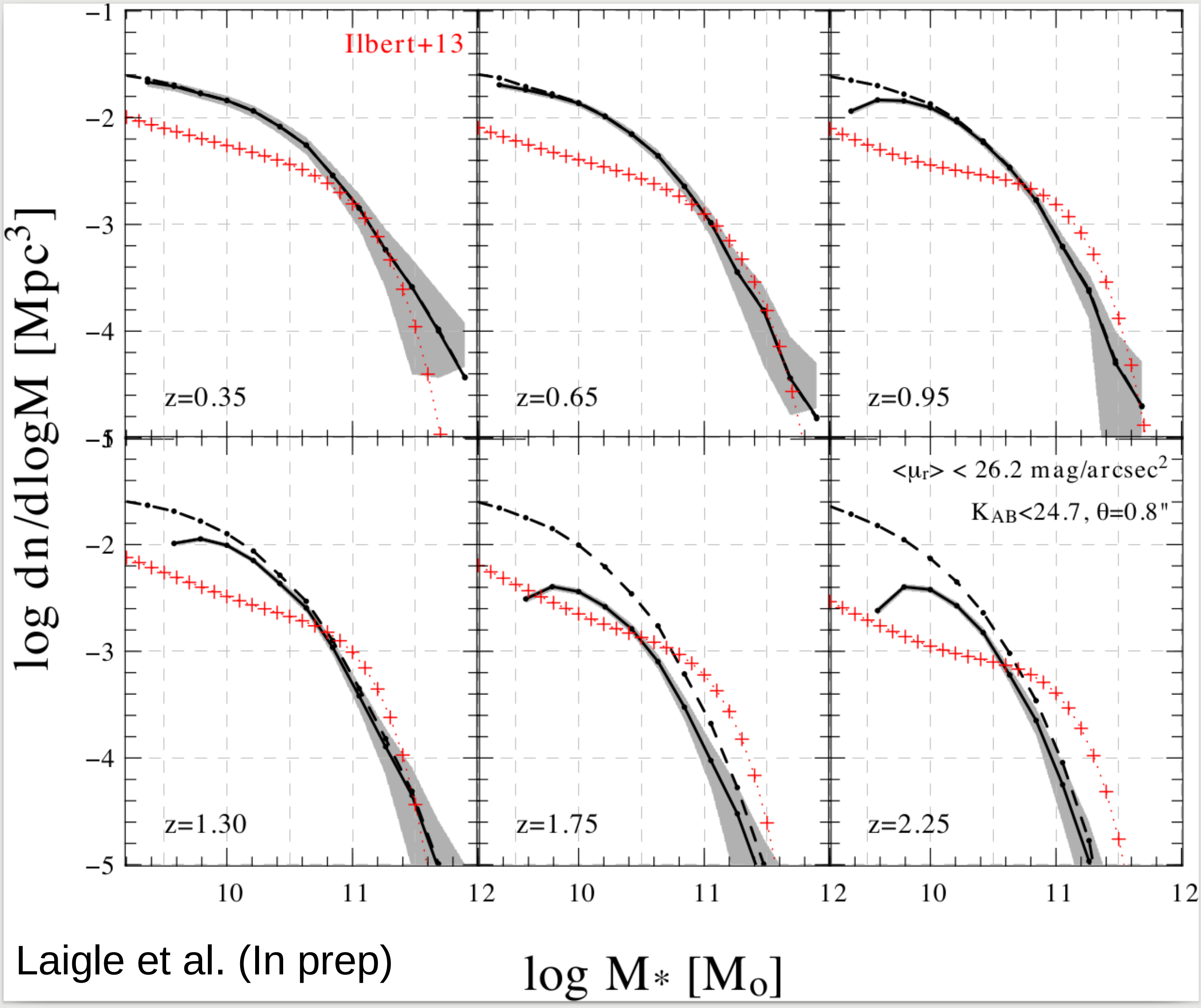
	$f(24.5 > \langle\mu\rangle_e > 23)$	$f(\langle\mu\rangle_e > 24.5)$	$N(24.5 > \langle\mu\rangle_e > 23)$	$N(\langle\mu\rangle_e > 24.5)$
Low density (Field)	0.23 (0.09)	0.18 (0.77)	10760	5634
Intermediate density (Groups)	0.21 (0.09)	0.27 (0.74)	12691	12119
High density (Clusters)	0.19 (0.07)	0.46 (0.83)	2310	4572

- We find significant numbers of LSB galaxies in less extreme environments
- More LSBGs at fixed stellar mass in denser environments
- But only 10% of galaxies are in clusters
- The aggregate number of LSBGs is greater in the field than in clusters, even if the fraction galaxies that are LSB in clusters is significantly higher.



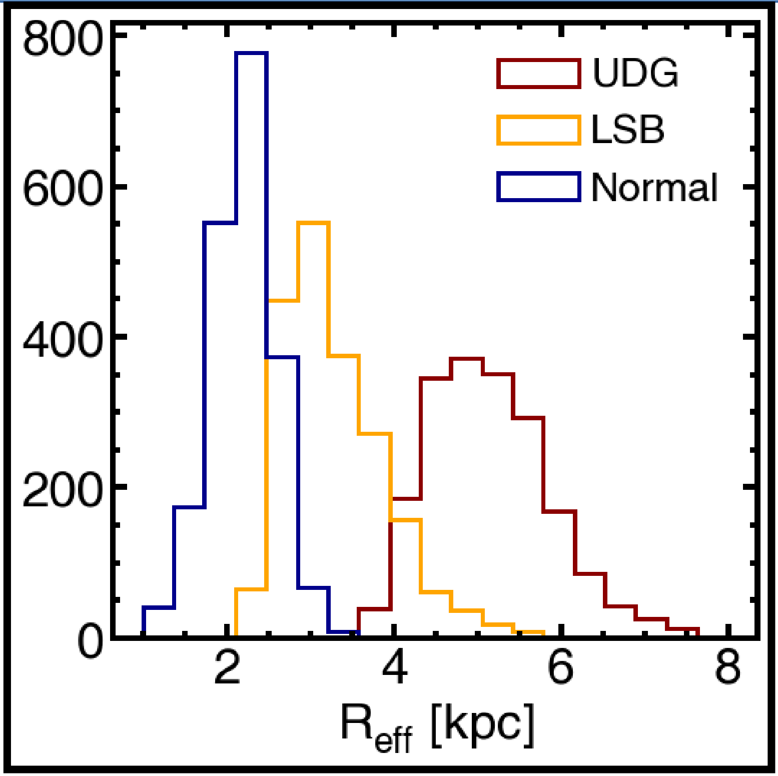
What does this mean for comparisons with observations?

SB limits (not just magnitude limits) must be taken into account when we compare simulations with observations.



Laigle et al. (In prep)

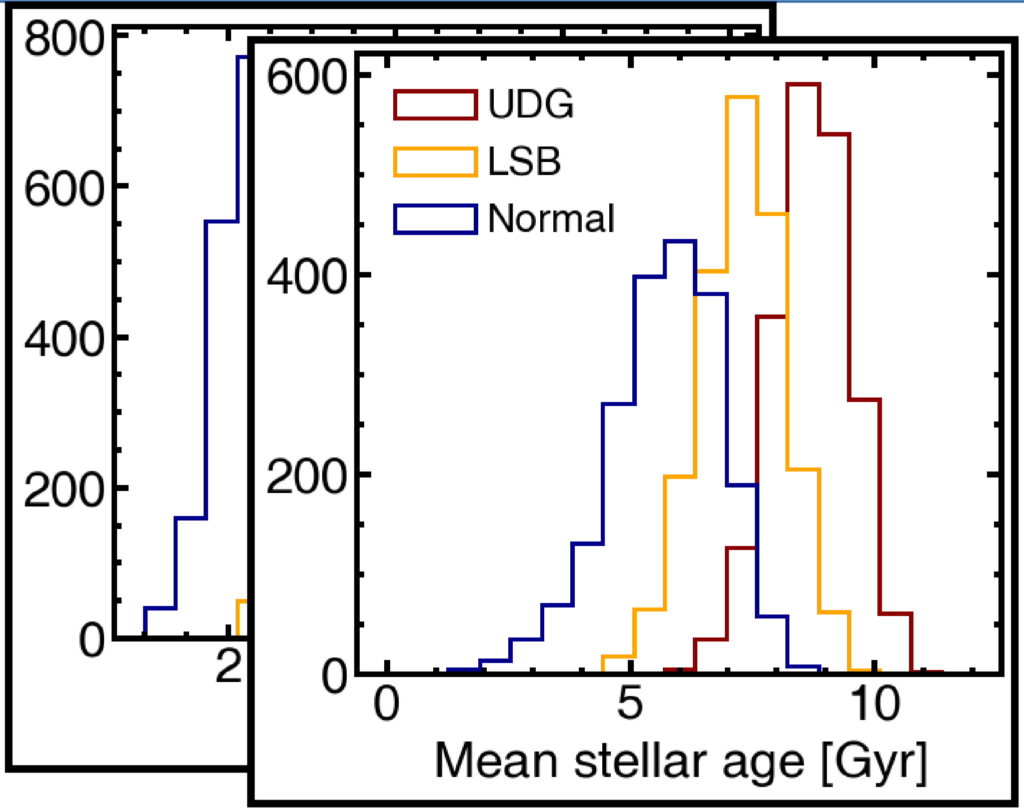
The properties of LSB galaxies



Plots: distribution of properties for a mass matched sample

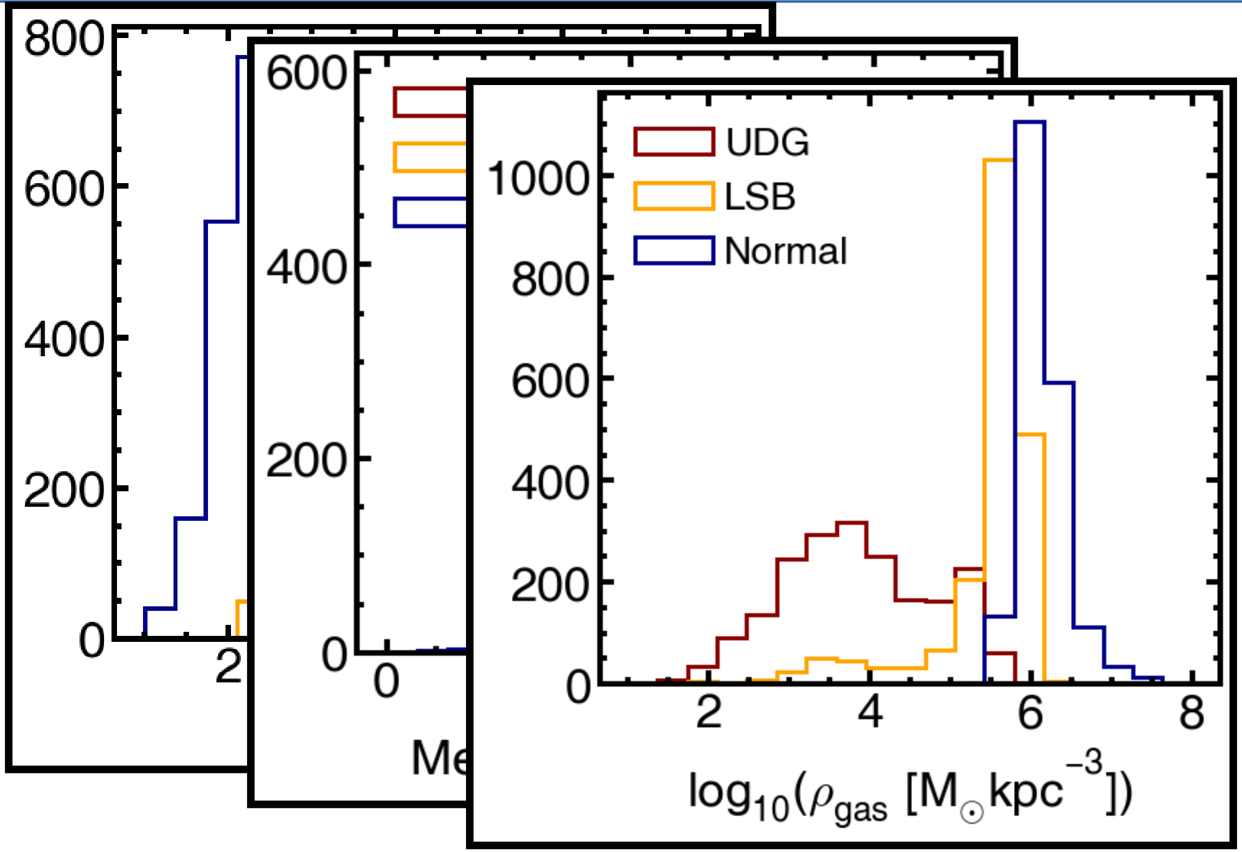
- Large Radii

The present day properties of LSB galaxies



- Large Radii
- Old / faint stellar populations – generally red

The present day properties of LSB galaxies



- Large Radii
- Old / faint stellar populations
- Low gas masses / star formation rates

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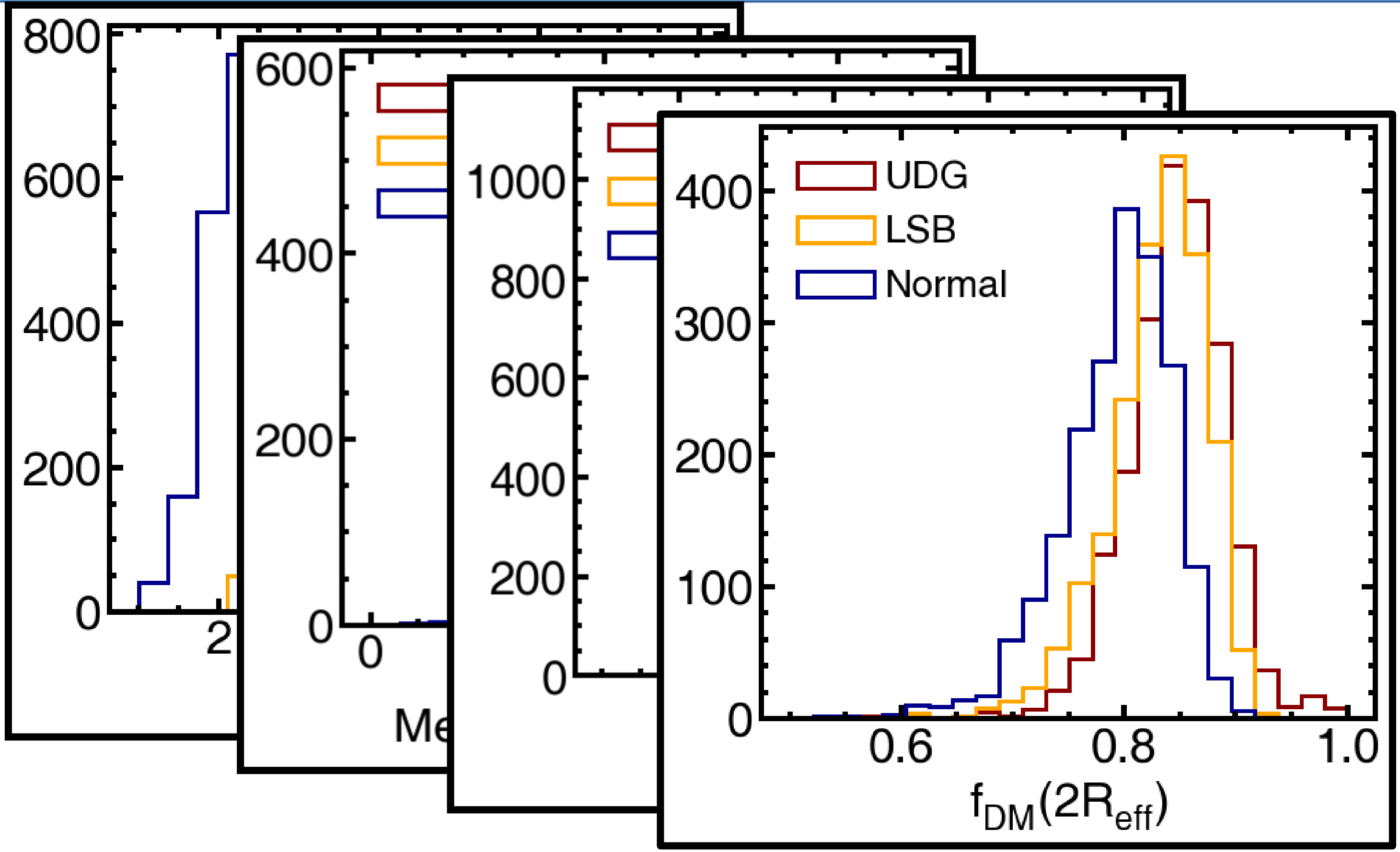


- Large Radii
- Old / faint stellar populations
- Low gas masses / star formation rates
- DM fractions of LSB and normal galaxies are similar – not failed L* galaxies

The evolution of the LSBG population

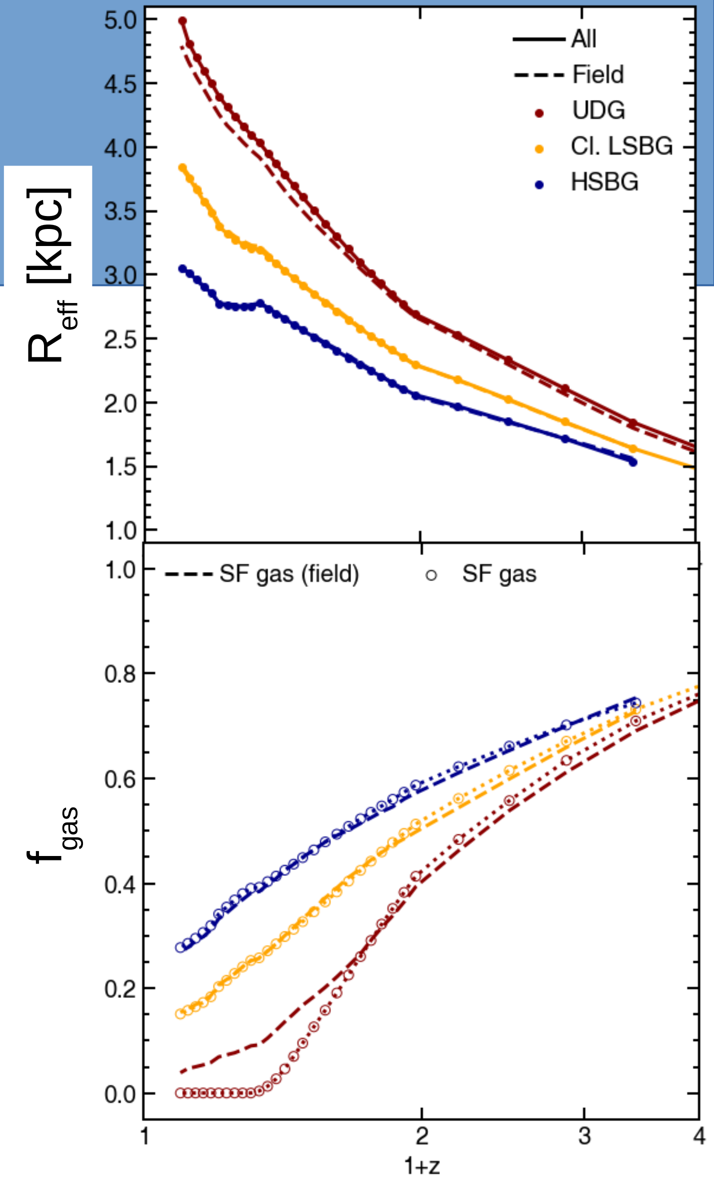
- Radii of LSBGs (especially UDGs) increase faster than HSBs – particularly after z = 1

- Field (dashed line) and cluster galaxies evolve similarly in terms of radius

- Although gas fractions evolve differently, field and cluster UDGs end up with similar levels of **star forming** gas by z = 0

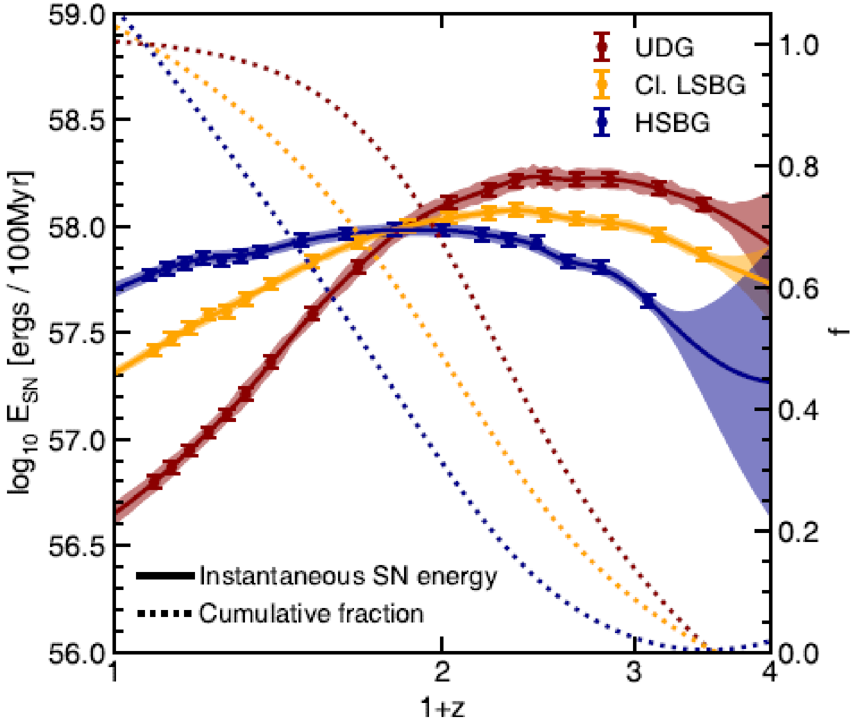
- <u>Main creation process is not cluster specific</u>

- <u>So, why have the relatively homogenous z = 3 – 2 populations diverged by z=0?</u>



The origin of UDGs: Stellar Feedback

- Star formation in UDGs is more 'bursty'
- UDGs (and Cl. LSBGs to some extent) are assembled very rapidly, forming 75% of their stellar mass before z = 1
- Rapid SF leads to <u>large instantaneous SN energy injection</u>



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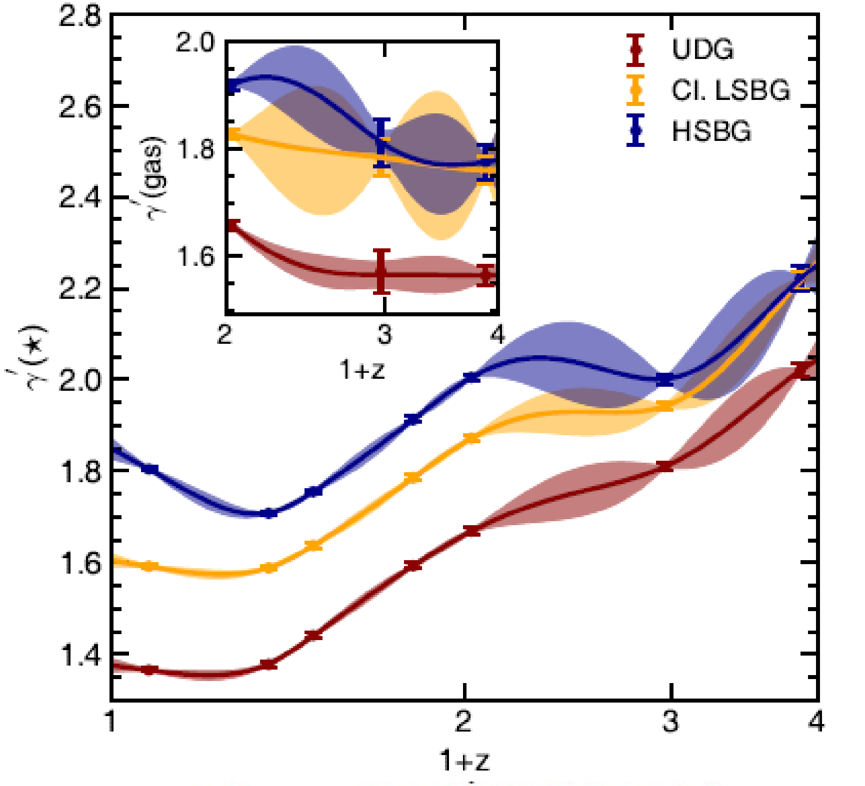
- Rapid SF leads to <u>large instantaneous SN energy injection</u>
- Feedback leads to <u>shallower gas density profiles</u> **(e.g. Peirani +17)**, leading to shallower stellar profiles
- Should also produce a central core in the DM density profile **(e.g. Di Cintio +16)**, but we do not resolve these processes (more on this later)

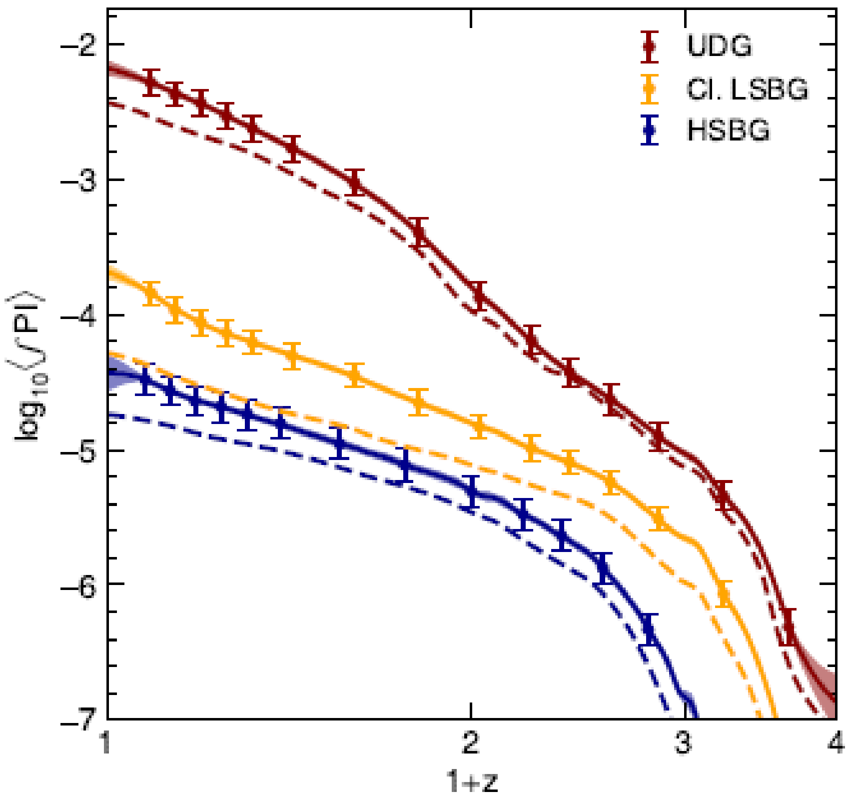


$$\gamma = -d\log(\rho)/d\log(r)$$

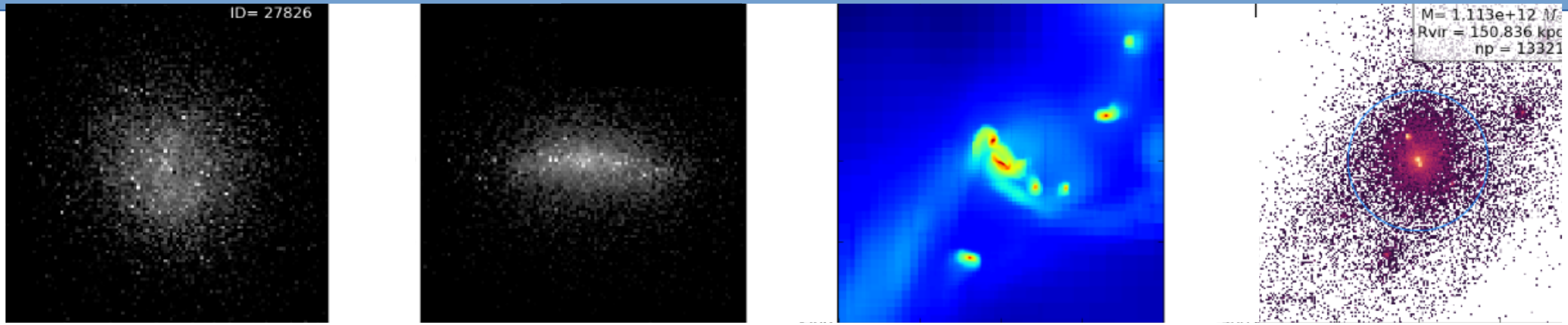
The main driver of UDG evolution: The tidal field and interactions

$$PI = \int_{t_1}^{t_2} \sum \left(\frac{M_{p,i}}{M_{gal}}\right) \times \left(\frac{R_{gal}}{d_{p,i}}\right)^3 dt$$ **(Bryd+Valtonen90)**

- Cumulative perturbations experienced by UDGs is 3 orders of magnitude higher than for HSBGs
- The tidal field heats the gas and stellar components
- PI is similar, regardless of environment
- Tidal perturbations likely the main driver of (high mass) LSBG formation after z = 1
- But their formation is triggered by high-z flattening of the density profile by feedback (reduced binding energy)



Future work



(Min Jung, Yonesi)

- We need higher resolution to study processes during the trigger epoch of LSBGs (z = 1 – 3)
- **New-Horizon** is a zoom-in of a region of Horizon-AGN with a 35 pc resolution
- Now we can <u>resolve the processes that flatten the galaxy density slope</u>, including DM density profiles **(e.g. Brook+11+12,Di Cintio+14+17)**.
- Do minor mergers play a role **(e.g. Naab+09,Hopkins+10,Bedorf+13)**?
- Are the causes of lower mass LSBs the same as intermediate mass ones?

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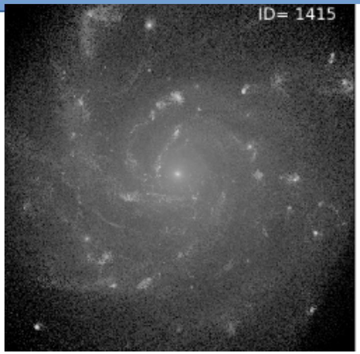

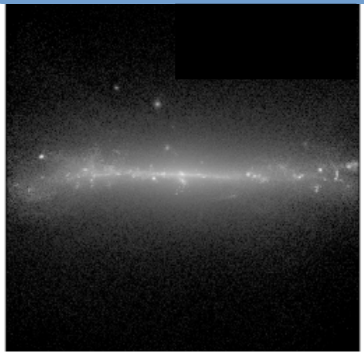
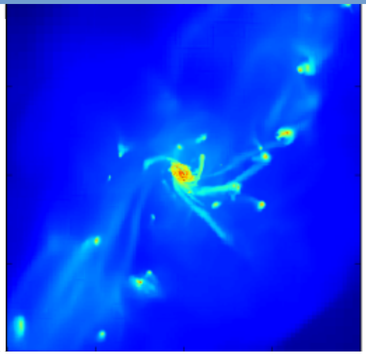
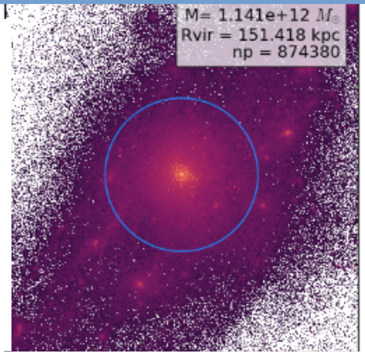

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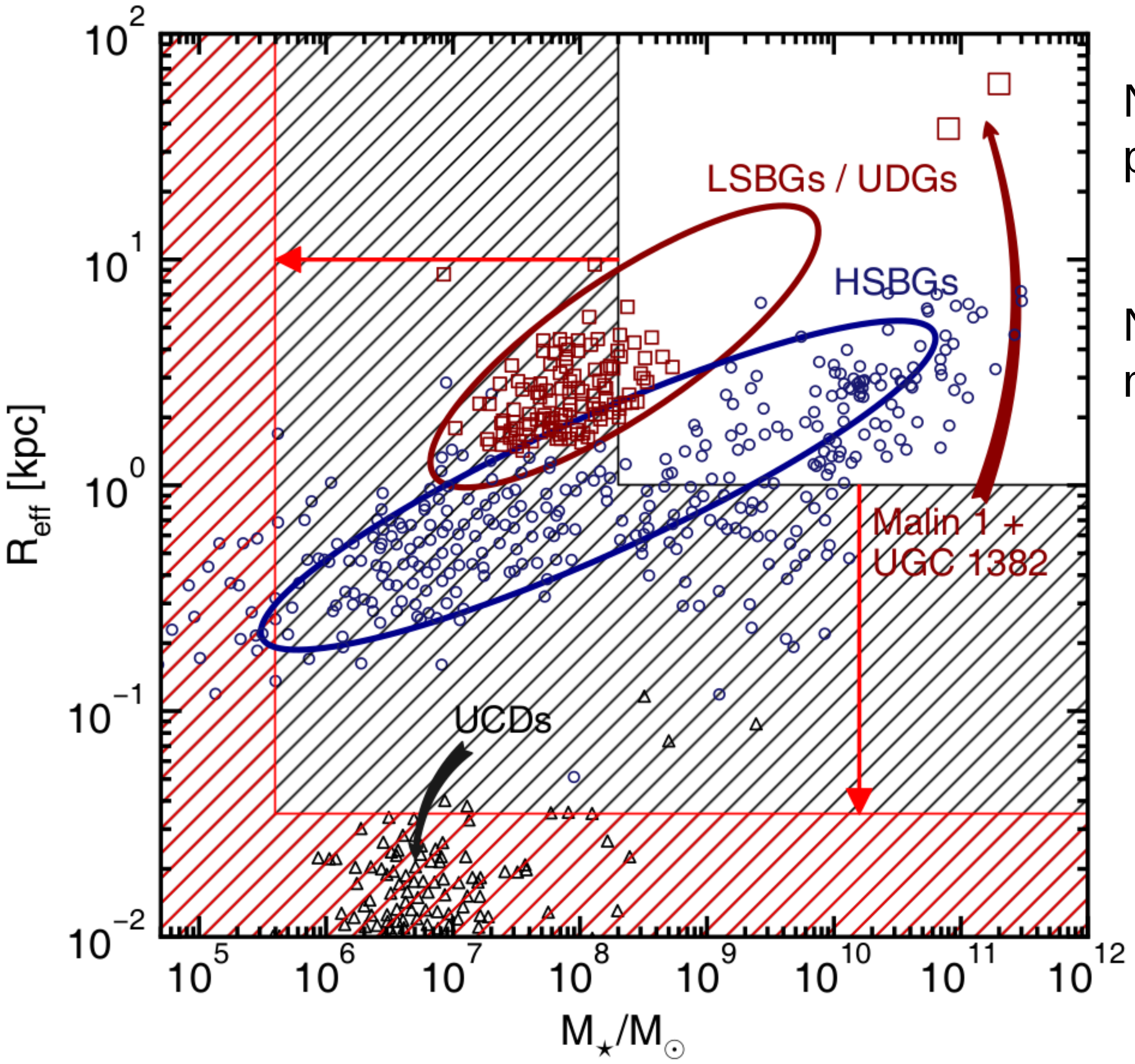

New-Horizon vs Horizon-AGN parameter space

New-Horizon at z=0 would be even more useful

Summary

- Low surface brightness galaxies dominate galaxy number density in all environments. We need to understand the LSBG population if we want to understand galaxy evolution
- Their formation is triggered by large instantaneous SN energy injection at high redshift, which is the result of rapid star formation history
- Feedback creates shallow density slopes, making galaxies more susceptible to tidal processes
- Galaxy radii increase and star-forming gas is heated by the tidal field
- Similar processes produce the (generally red) UDGs we see in clusters and the field – but we do not probe typical UDG masses (do different formation mechanisms dominate for field galaxies at high mass?)
- The cosmological volume of Horizon-AGN allows us to compare the predicted abundances and properties of UDGs with future observations (e.g. LSST)
  - Since the UDG population is especially sensitive to SN feedback and this is potentially useful for constraining sub-grid recipes