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Probing the invisible Universe with simulations:

the abundances and environments of simulated low surface-brightness galaxies

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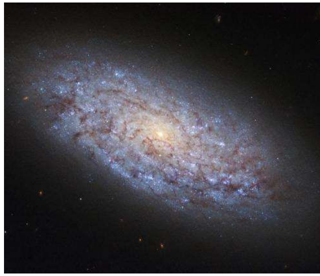
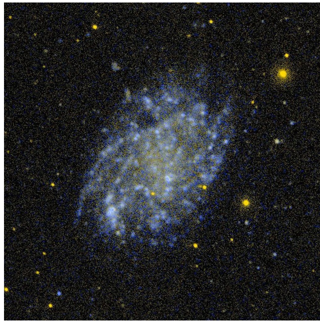
The low surface brightness Universe

- 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)**
- Surface-brightness is a little-explored axis for understanding galaxy formation and evolution
- Galaxy properties appear to vary strongly with surface-brightness
  - Our inability to study the majority of low mass galaxies **biases our understanding of the Universe**





The low surface brightness Universe

- Low surface brightness galaxies probably represent a majority of all galaxies at a wide range of stellar masses.
    - 80% of faint galaxies (M_r = -18 to -15) are may be LSB **(e.g. Dalcanton+1997, Haberzettl+2007)**

- Although recent improvements in instrumentation (e.g. Dragonfly, HSC and soon LSST) mean we can finally start to account account for these faint objects observationally over wide areas of the sky -- a full range of environments remains mostly inaccessible

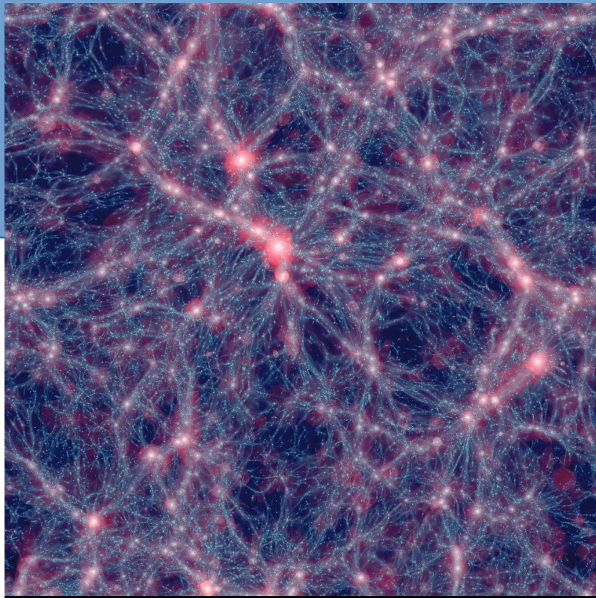
- Cosmological ΛCDM simulations can be used to predict the properties of faint populations that are currently invisible to us

The Simulation

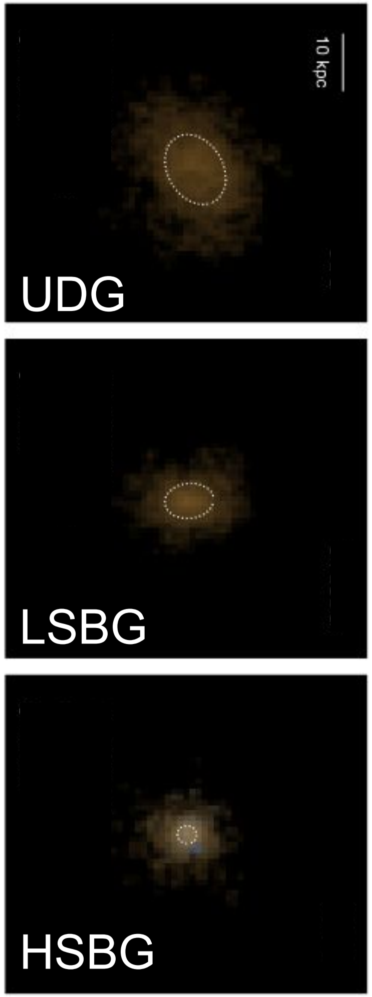
Horizon-AGN **(Dubois+16)**

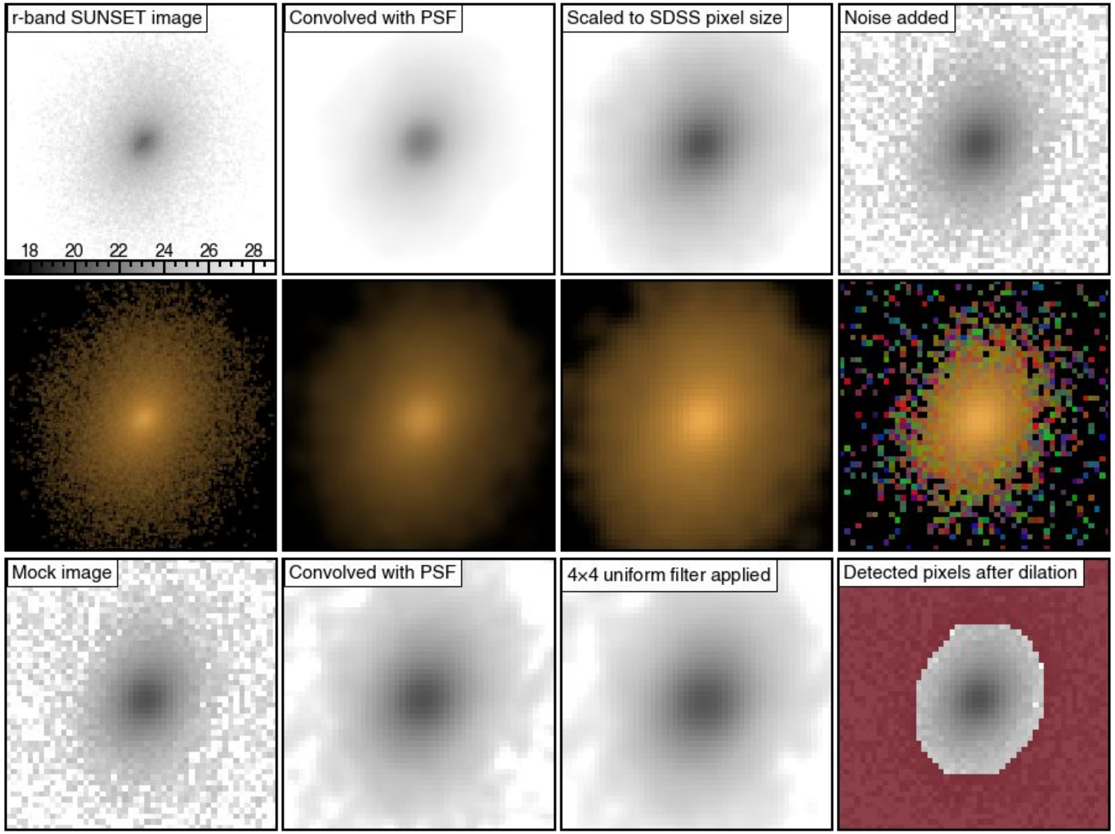
- ~**<u>100h</u>**$^{-1}$ **CoMpc** box length – ~200,000 galaxies at peak.
- Minimum **1kpc** resolution – 5 orders of magnitude range.
- Cosmology corresponding to WMAP7 results **(Komatsu+ 2011).**
- Hz-AGN Provides good agreement with observed bulk properties of the **high surface-brightness** Universe **(Kaviraj+2017)**.
- **We are considering relatively high mass objects only (>10^8.5)**

People: PI – **Yohan Dubois** (IAP), **Julien Devriendt** (Ox), **Christophe Pichon** (IAP)



Modelling the LSB population

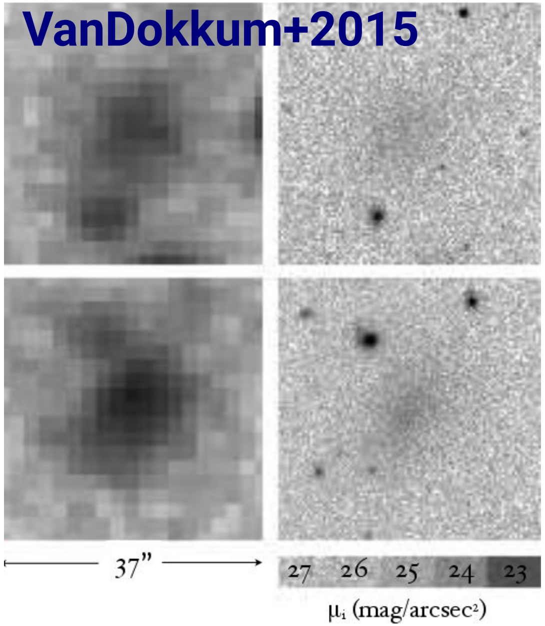


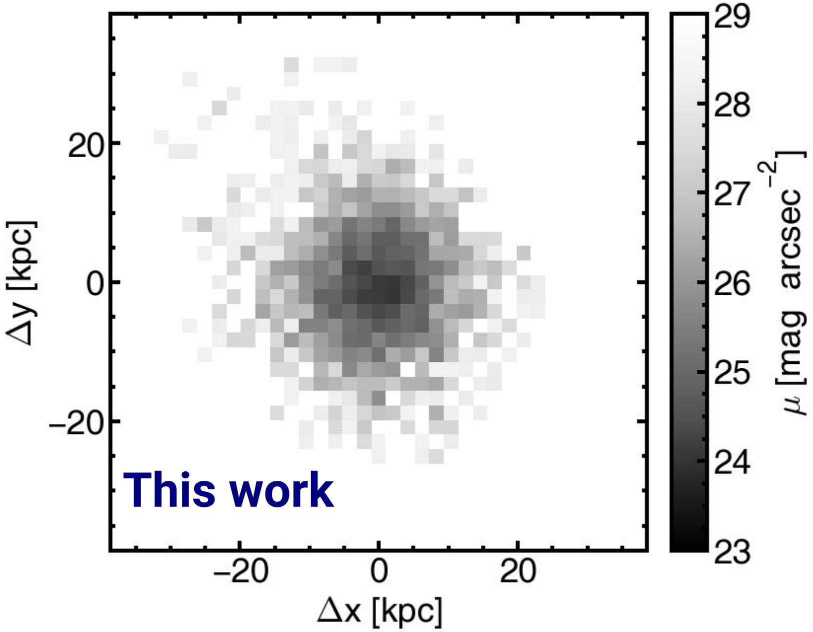


- We observe simulated galaxies, model selection effects and measure properties for SDSS, LSST and other instruments
- Add PSF, noise etc to mock images with dust screen
- Apply SDSS detection pipeline

Our simulated LSB populations

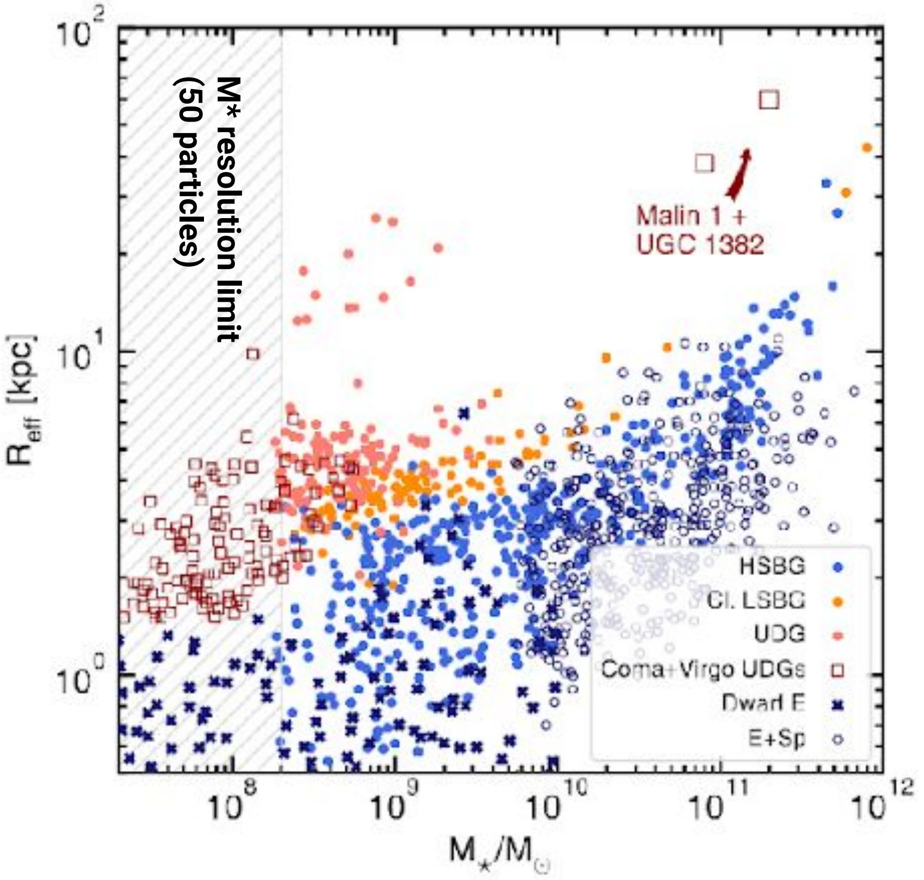
Surface brightness profiles correspond well to observed LSB galaxies (e.g. do not follow the Freeman law or equivalent)





Modelling the LSB population

Position of objects of different surface brightness on the M*-R_{eff} plane corresponds well to observations



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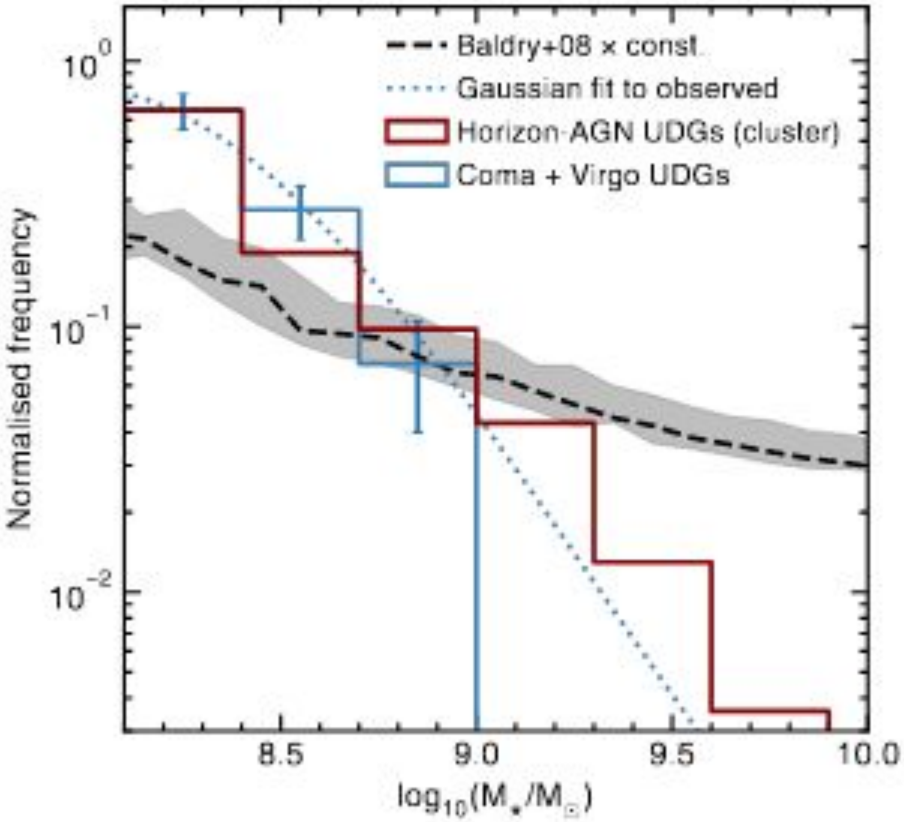
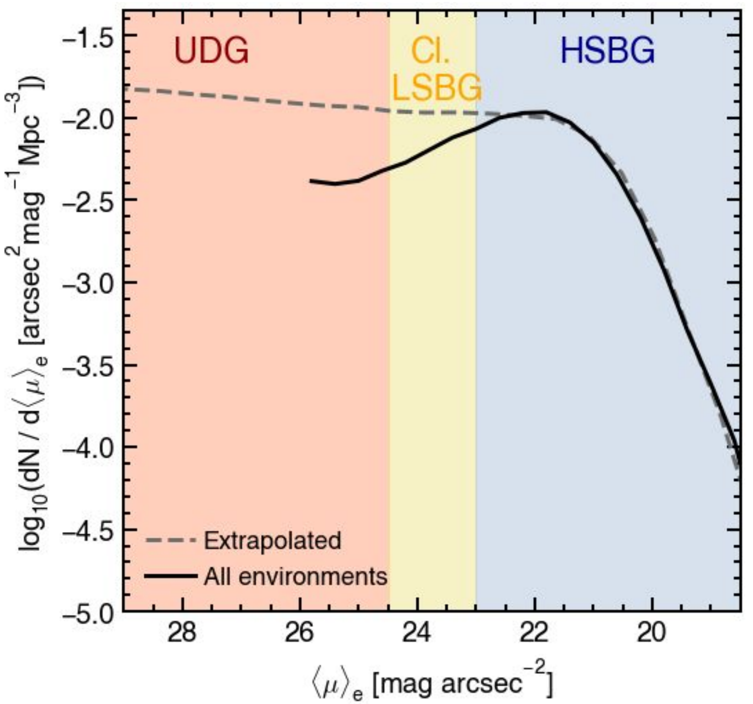


- Also reproduces observed abundances in clusters from recent surveys **(e.g. van Dokkum et al. 2015; Mihoset al. 2015; Yagi et al. 2016; Gu et al. 2018)**.

Modelling the LSB population

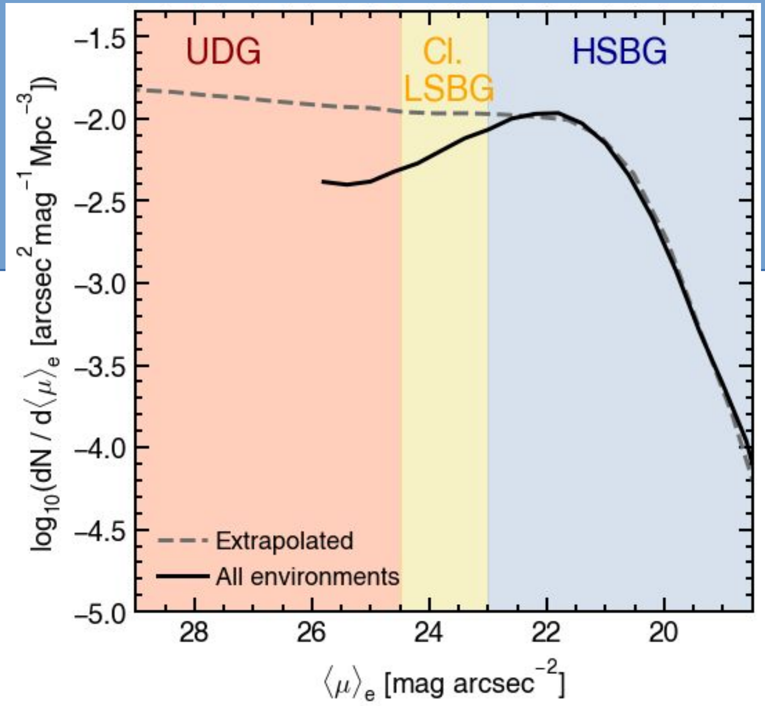
Split galaxies at z = 0 in the population into 3 groups:

- 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

Modelling the LSB po



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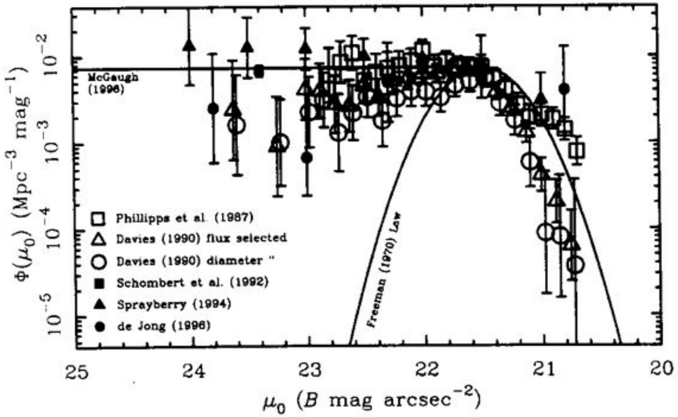
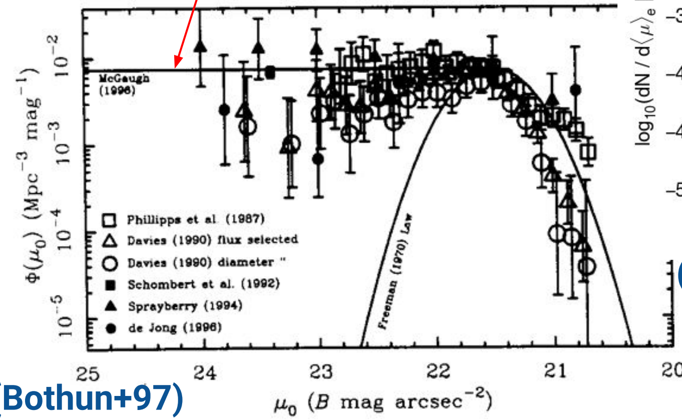
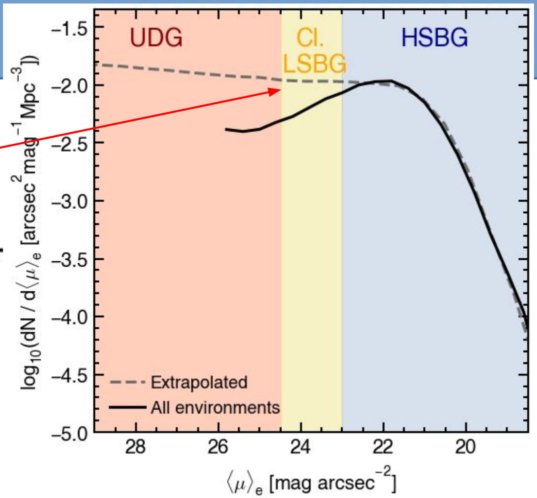
Horizon-AGN reproduces the predicted LSB tail **(e.g. Bothun+97 -- observations, McGaugh+96 -- theory)**



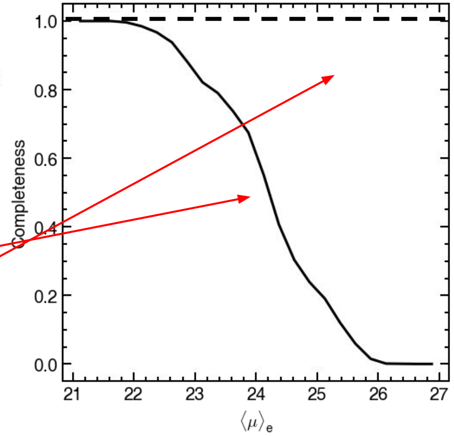
Expect a continuous tail of (resolved) low surface-brightness objects



(Bothun+97)

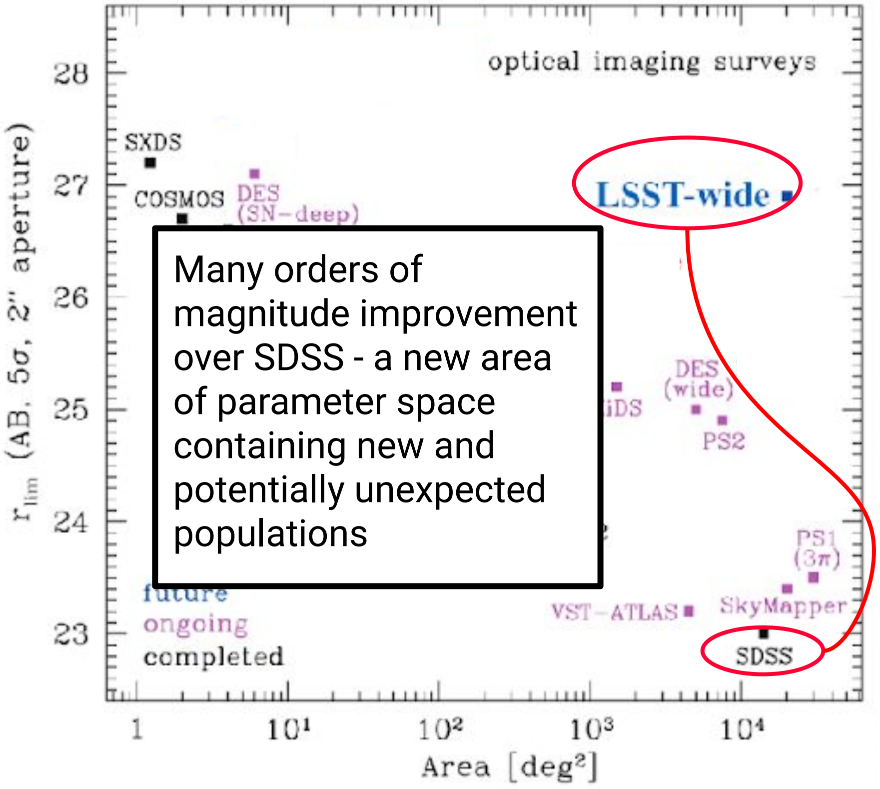


(Martin+2019)



SDSS-like completeness

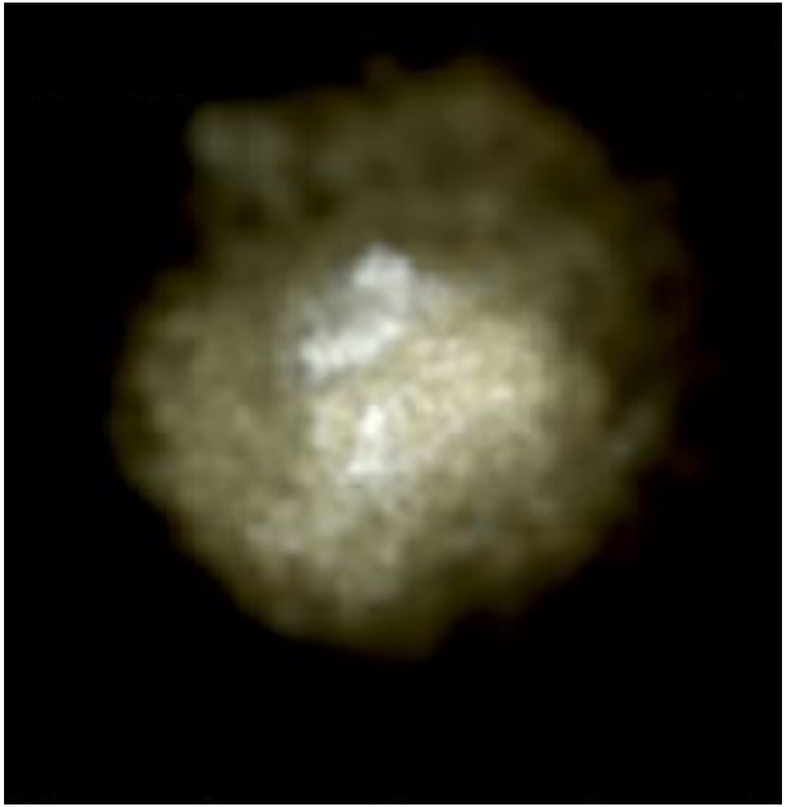
LSST-like completeness (hopefully)



Many orders of magnitude improvement over SDSS - a new area of parameter space containing new and potentially unexpected populations

The low surface brightness universe

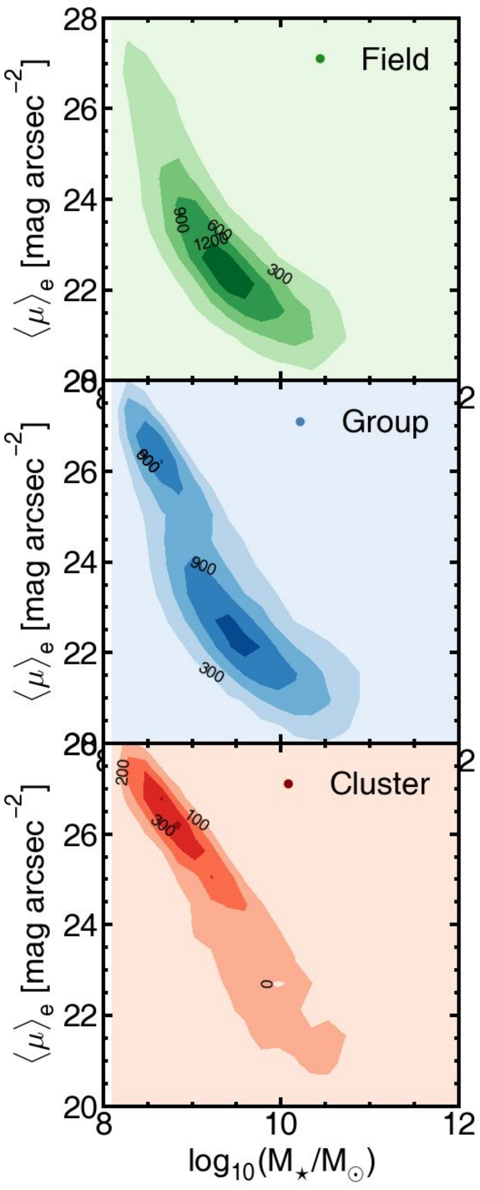
- UDGs are commonly observed in clusters (**VanDokkum+15,Koda+15**)
- Inefficient to observe in the field without deep wide-field instruments like Hyper suprime-cam, LSST ComCam (e.g. **Greco+2018**)
- However, theoretical predictions indicate that UDGs should also be common in the field and groups (e.g. **Jiang+2019, Di Cintio+2019, Di Cintio+2017**)



The low surface brightness universe

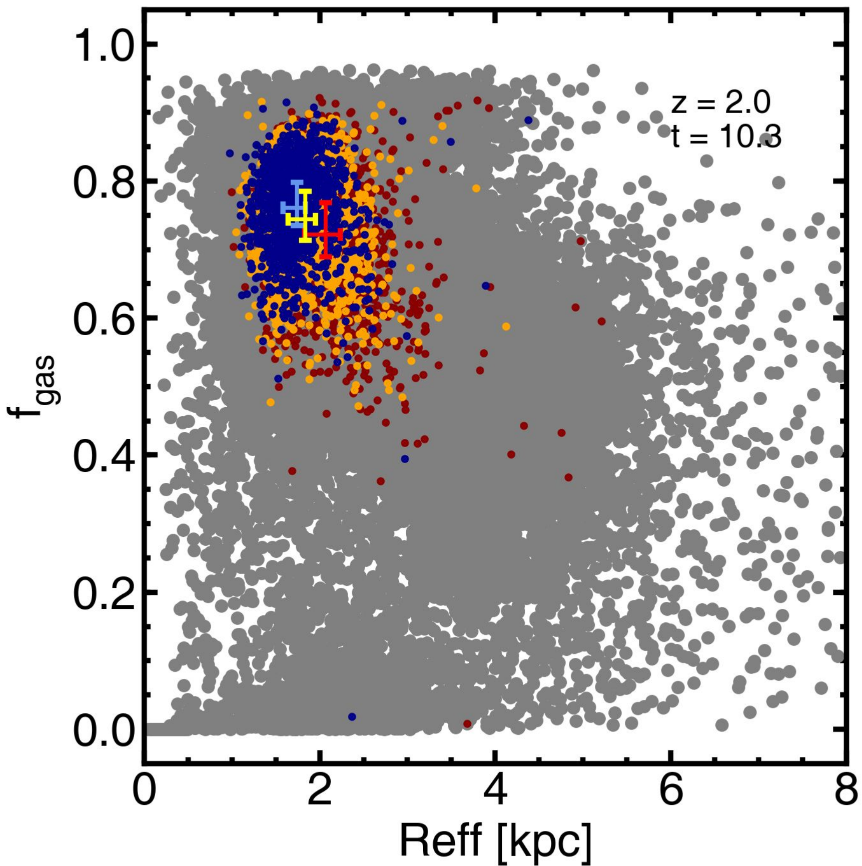
	f_{LSB}	f_{UDG}	n_{LSB}	n_{UDG}
Field	20%	3%	6800	900
Group	27%	7%	11600	3100
Cluster	48%	23%	4100	1900

- We find significant numbers of LSB galaxies in less extreme environments
- Aggregate numbers are similar between environments, even if the fraction galaxies that are LSB in clusters is significantly higher.



LSB populations appear at the tail end of the $R_{eff} - f_{gas}$ distribution

- Progenitors of **HSB**, **LSB** and **UDG** galaxies are plotted as a function of their effective radius and gas fraction.
- At z = 2, the populations are almost homogeneous.



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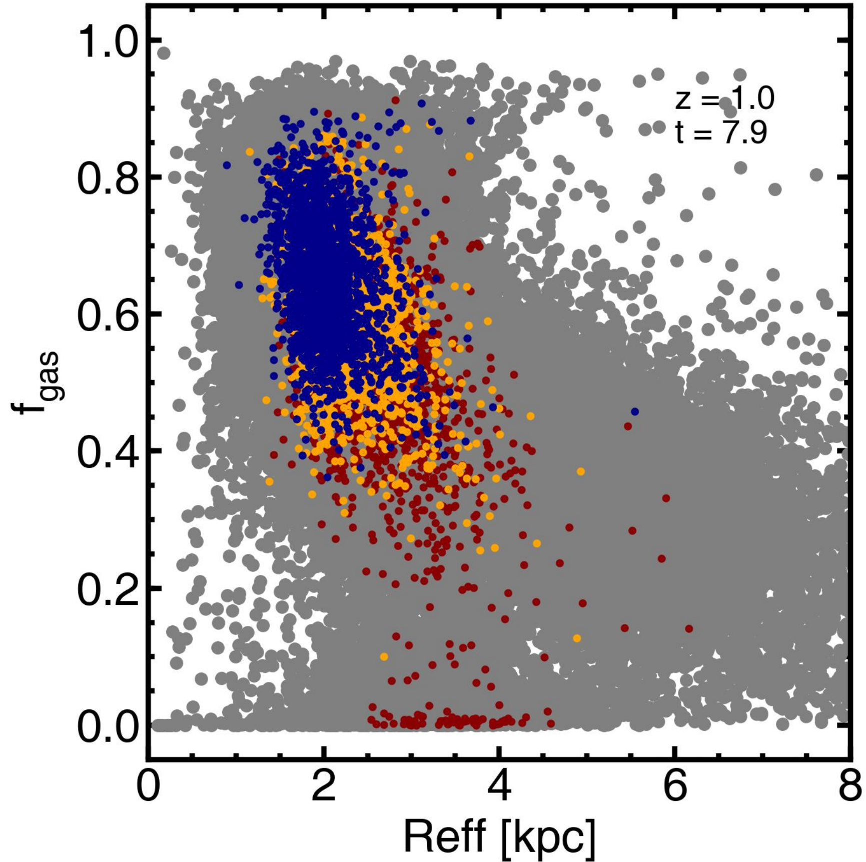

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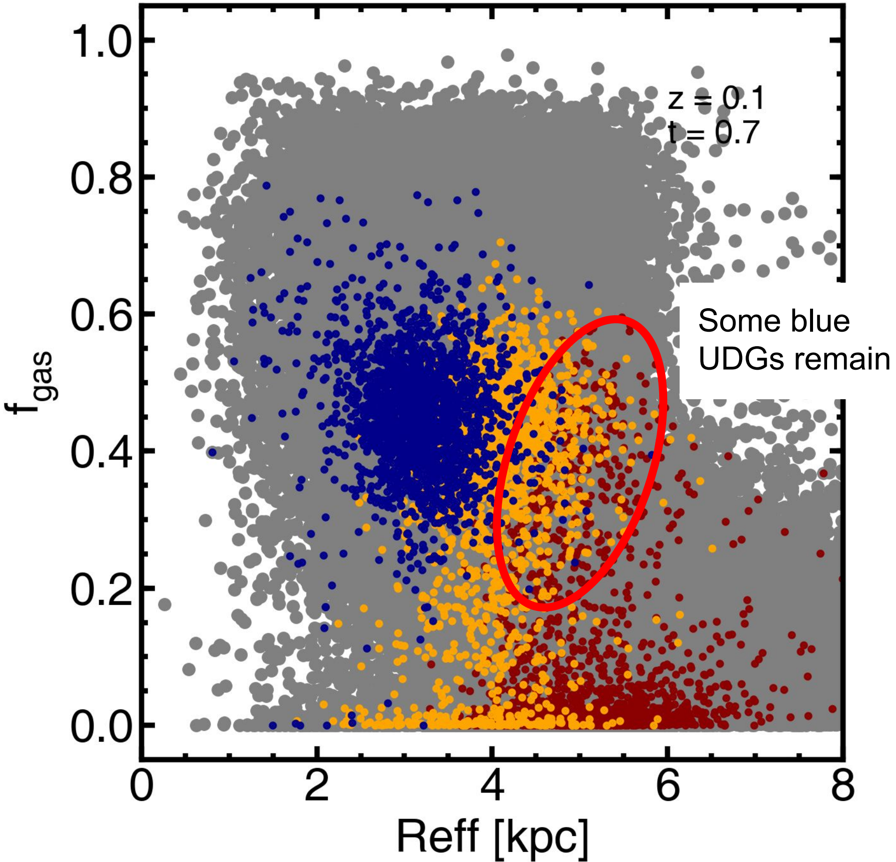
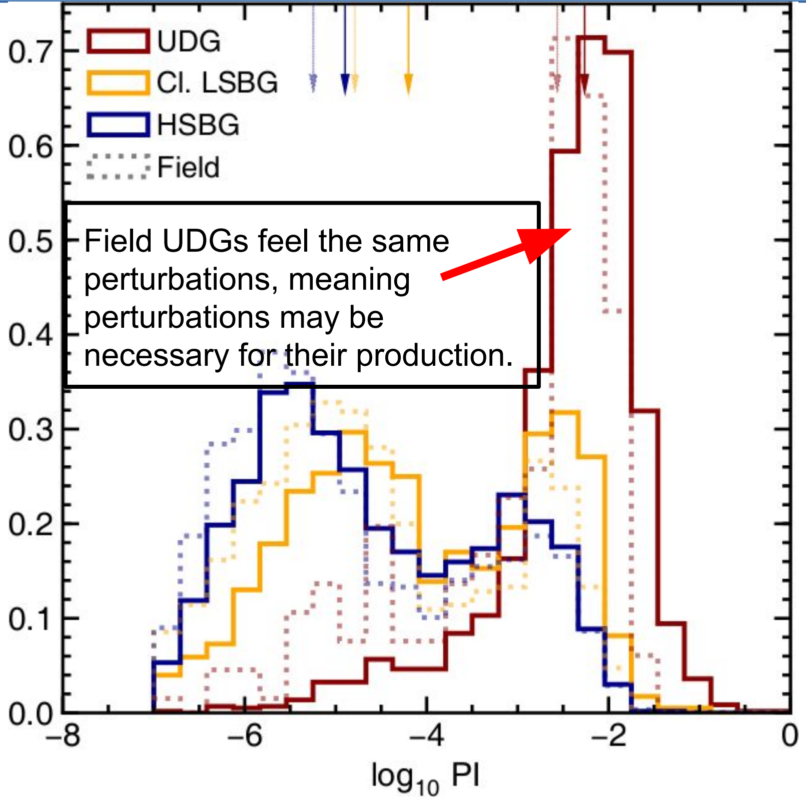
- Progenitors of **HSB**, **LSB** and **UDG** galaxies are plotted as a function of their effective radius and gas fraction.
- At z = 2, the populations are almost homogeneous.
- By z = 0, most UDGs and significant proportion of LSB galaxies have lost significant amounts of gas
- Does this correspond to observations? Galaxies may be over-quenched



The origin of UDGs: environment

- The faintest galaxies have to have undergone catastrophic gas loss at some point in their evolution.
- All UDGs experience more violent encounters.
  - $PI = \int_{t_1}^{t_2} \sum \left(\frac{M_{p,i}}{M_{gal}}\right) \times \left(\frac{R_{gal}}{d_{p,i}}\right)^3 dt$
- And are more likely to have undergone ram-pressure stripping.

  We calculate the ρv^2, where v is the relative velocity between the ICM/IGM and each galaxy
- Need to appeal to external processes to explain the majority of UDGs

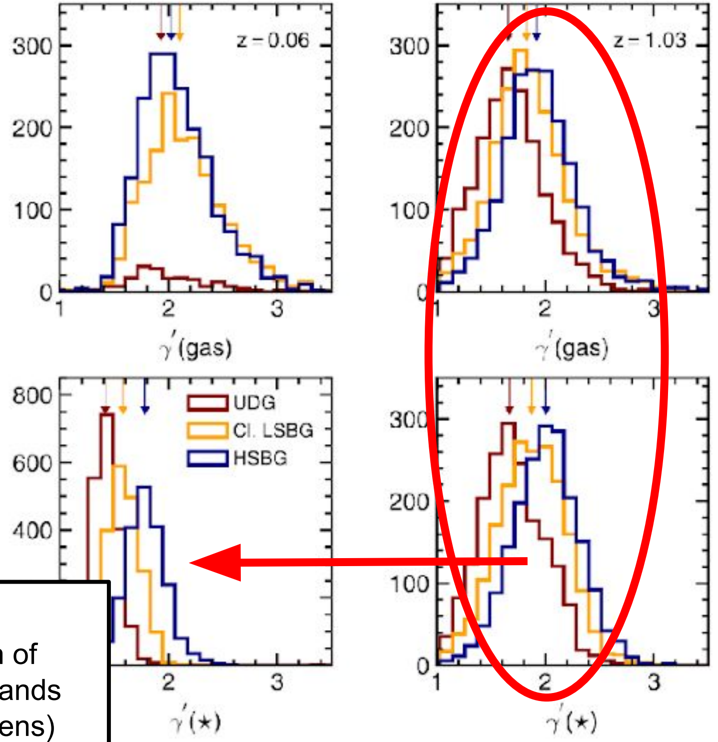


Plot: Integrated perturbations felt by UDGs, LSBs and HSB galaxies

The origin of UDGs: SN feedback

High redshift progenitors share the same distribution of density profile slopes

- Star formation is significantly more bursty than normal counterparts
- Stars forming from flat gas profile, stellar density profile closely matches the gas density profile by z=1
- As a result, binding energy is also small – due to consistently flatter density profiles in LSBs.
- Stellar density slope becomes much flatter by the present day due to environmental effects



Stellar distribution of UDGs expands (slope flattens)

Plot: evolution of gas and stellar density profile slope distributions

- LSB and UDG galaxies are not special objects: they form the tail of a smooth distribution and have similar ancestors to normal galaxies

- 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,

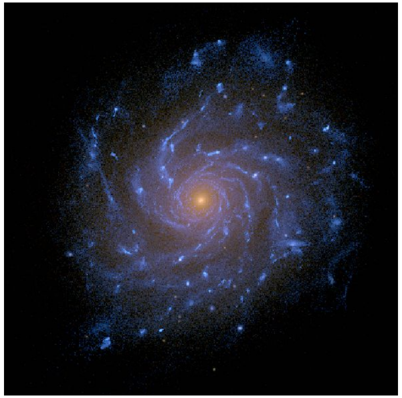
- But this isn't sufficient to fully reproduce the LSB population: shallow density profiles also make galaxies more susceptible to tidal processes and encounters

- Galaxy radii increase and star-forming gas is heated by the tidal field or fly-bys

- At lower masses than we probe (<10^8.5), feedback alone may be sufficient to produce UDGs

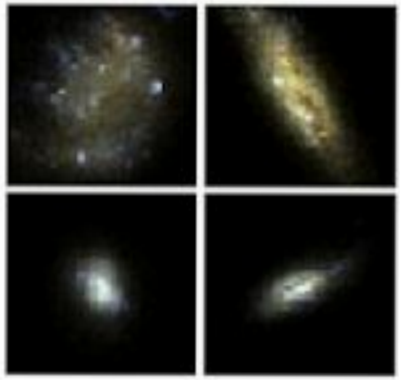
The New Horizon Simulation

Plot:full resolution u, r, Ks images using SUNRISE RT code

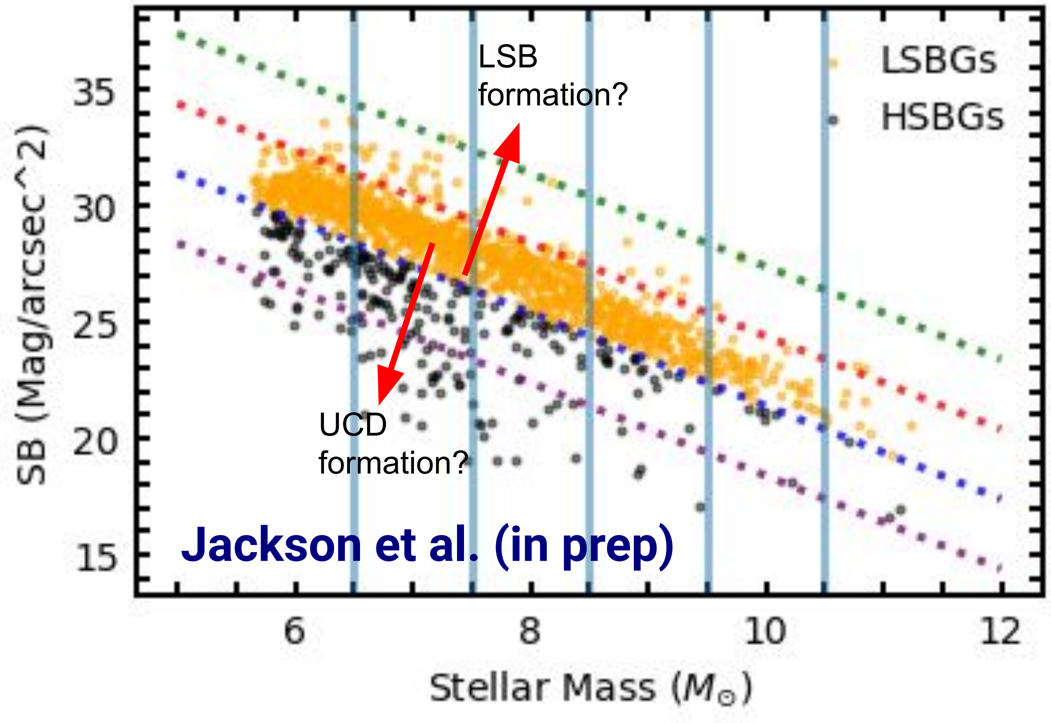


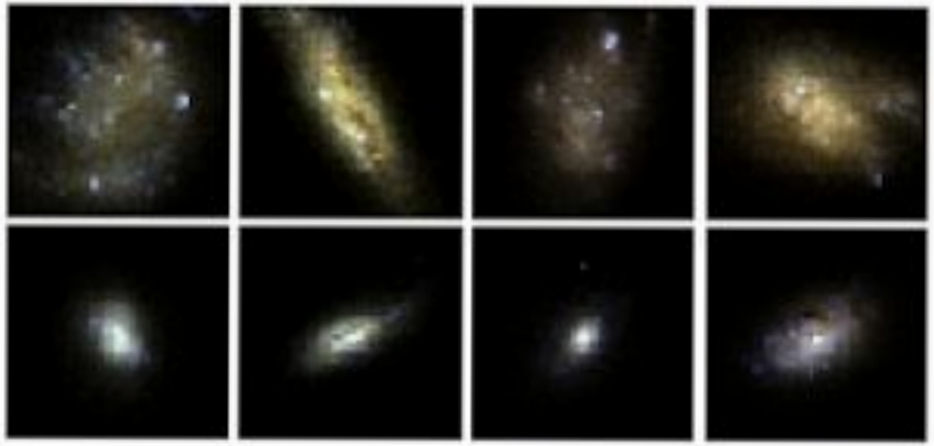
Plot: g, r, z. Dust screen only

JWST mocks using SKIRT RT code

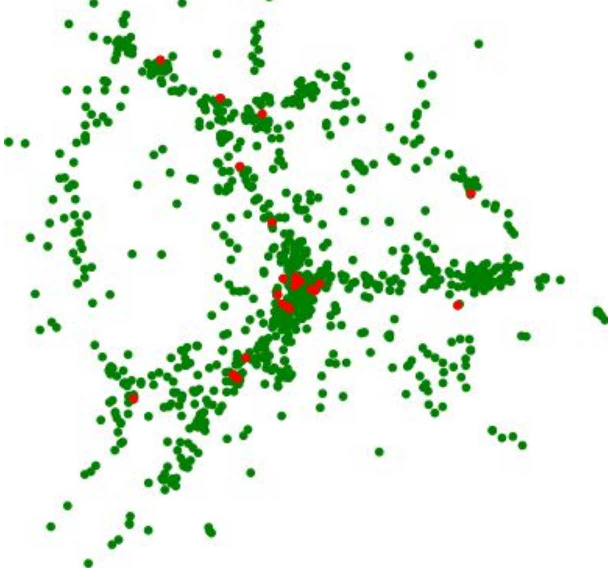


- A zoom-in of a large region of Horizon-AGN with 35pc / 10^4 Msun resolution, 4000 Mpc^3 volume (10 Mpc radius sphere)
    - Possible to study both realistic, unbiased statistical populations of galaxies and details of the environment and filamentary structure on all scales
- Study, in detail, the processes that lead to flattening of gas profiles of LSB progenitors at high redshift
- Quantify the relative contribution of these processes as a function of cosmic environment
- Predictions for future instruments (JWST, E-ELT, LSST, EUCLID etc)
    - Including kinematics, morphology, observable signatures of formation mechanisms





Top: LSB and HSB progenitors at z=1.
Left: SB vs M* distribution at z=1



- We can now do a much better job resolving low-mass galaxies and the processes that lead to their evolution but still retain a significant sample of galaxies across a variety of environments
- Also: Dwarf AGN? DM deficient galaxies? Creation of tidal dwarfs? Gas properties? Colours? Formation of UCDs? Transience of LSB/UCD/DM deficient galaxies?

Conclusions I

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- 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

  Horizon-AGN appears to be capable of reproducing statistical trends in the intermediate-to-low mass LSB population

- We don't seem to need to invoke any additional physics or mechanisms to reproduce many of the bulk properties of the LSB population

- LSB predicted to exist in field and group environments in large numbers -- aggregate numbers comparable or exceed those in clusters

- New simulations will allow us to probe these populations down to the low mass regime where the majority of such objects reside