Ultra diffuse and low surface brightness galaxies: observational signatures and dark matter content

In collaboration with C.Brook,
A.Maccio', A.Dutton, S. Cardona-Barrero

Arianna Di Cintio
Marie Curie IF @IAC

DIGESTIVO Project

DIffuse **G**alaxy **E**xpansion **S**igna**T**ures **I**n **V**arious **O**bservables project: understanding the emergence of diffuse, low surface brightness galaxies and the link to their dark matter haloes

DIGESTIVO

30.09.2019

Operational definition

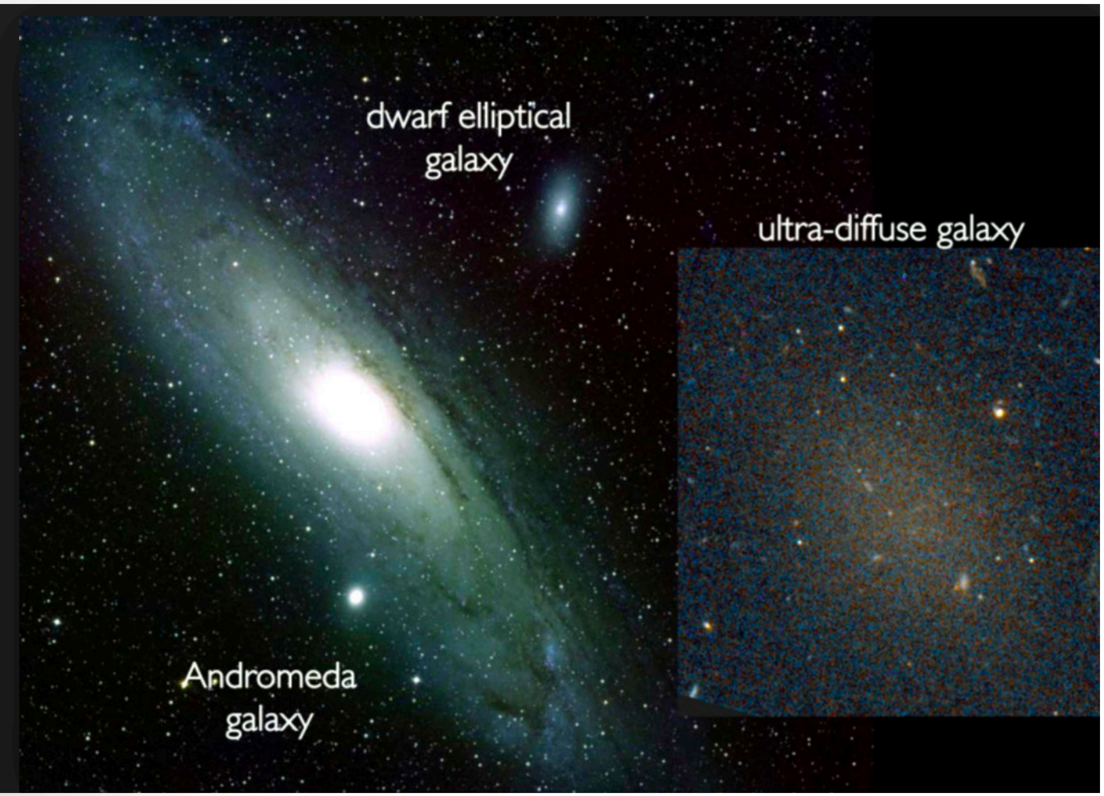
UDGs : Low surface brightness galaxies with $M^{*}\sim10^{7-9}M_{sun}$

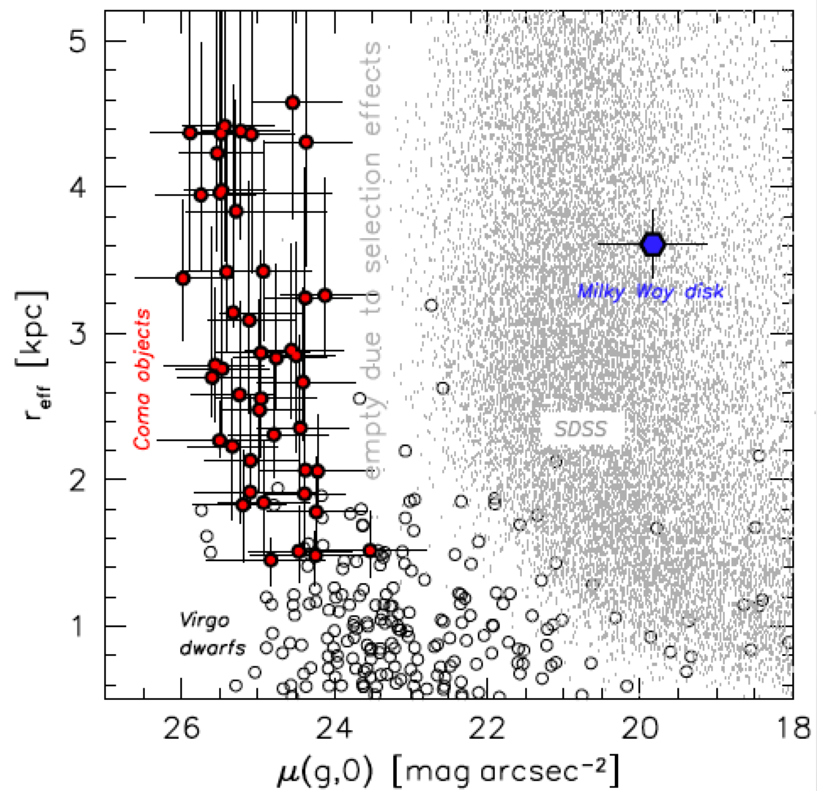
'CLASSIC LSBs': Low surface brightness galaxies with $M^{*}\sim10^{9-10}M_{sun}$

Giant LSBs: LSBs with central [illegible] brightness and $M^{*}>>10^{10}M_{sun}$

~1000 UDGs in Coma cluster

Low surface brightness objects with LUMINOSITY of dwarfs **($M^* = 10^{7-9}$ Msun)** but SIZES of Milky Way-type spirals. **Are they formed outside of clusters?**





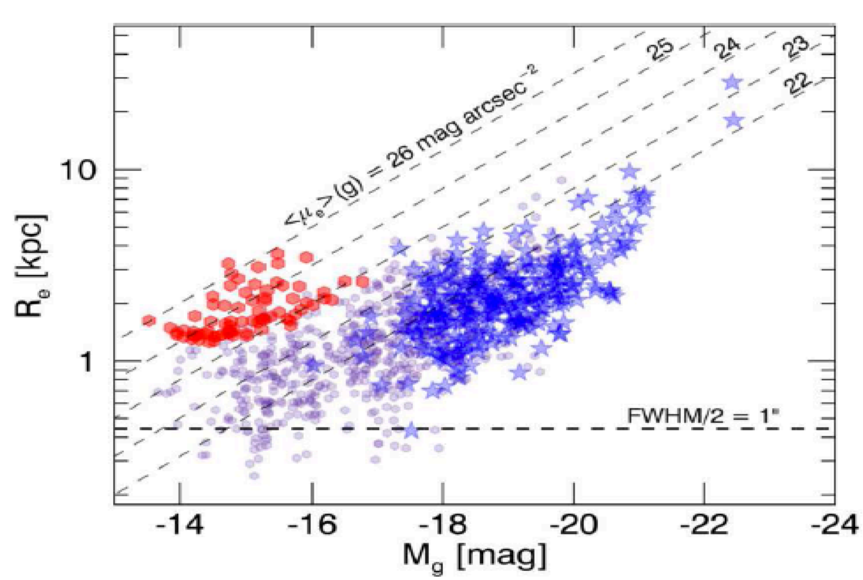
van Dokkum +15 using Dragonfly Telephoto Array
See also Koda +15 using SUBARU Suprime-Cam
Roman & Truijllo 16 using SDSS Stripe82, See also Mihos+15, Van der Burg+16

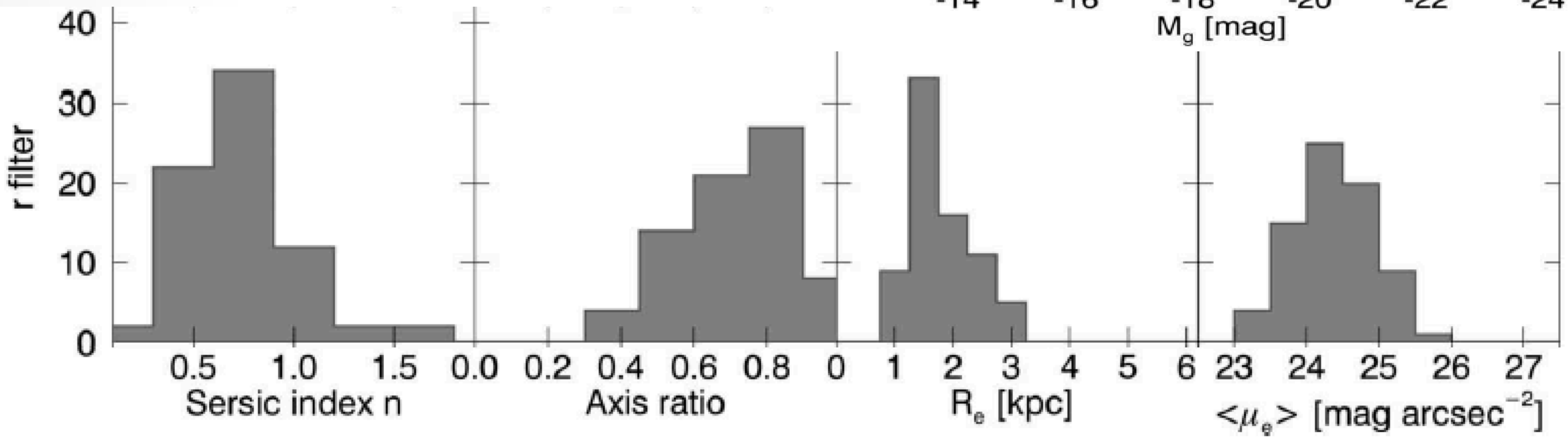
UDGs in/around Abell 168

42% of UDGs inhabit the cluster region

the rest are isolated

Are they formed outside of clusters?

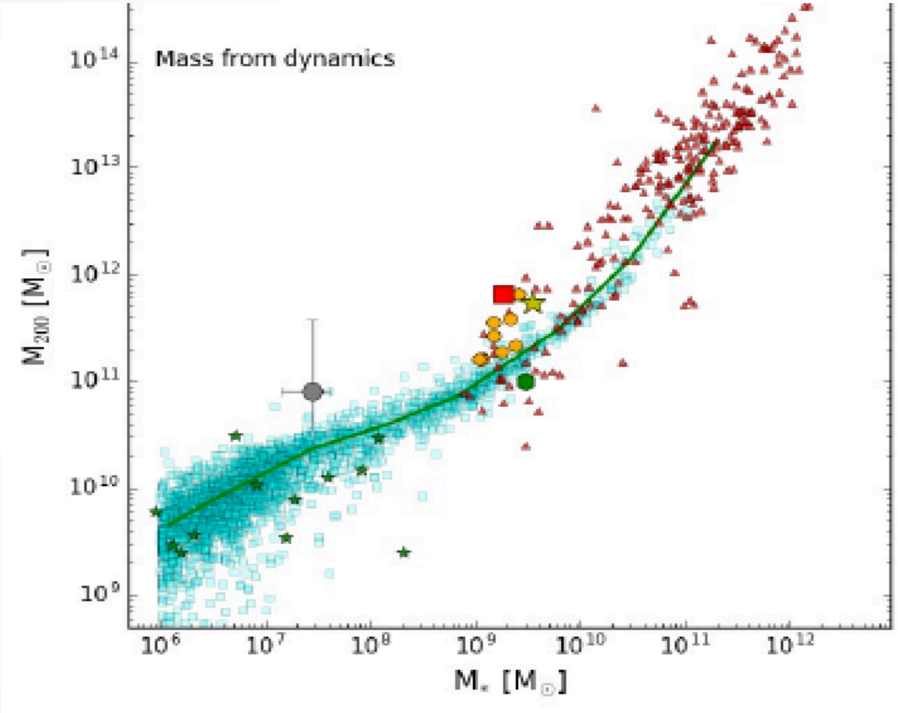




Roman & Truijllo 16 using SDSS Stripe82, See also Mihos+15, Van der Burg+16, Mancera Piña+18

Are UDGs dwarfs of failed L*?

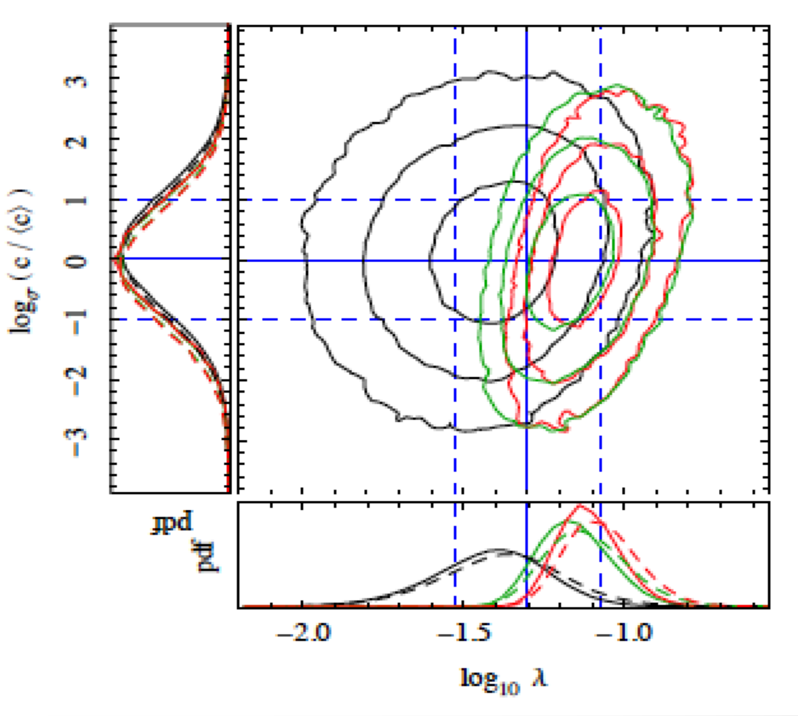
Measured **total mass** of VCC 1287 is (8.0±4.0) x $\mathbf{10^{10}}$ Msun



Beasley +16

They could be the the **high-spin tail** of an abundant dwarf galaxy population

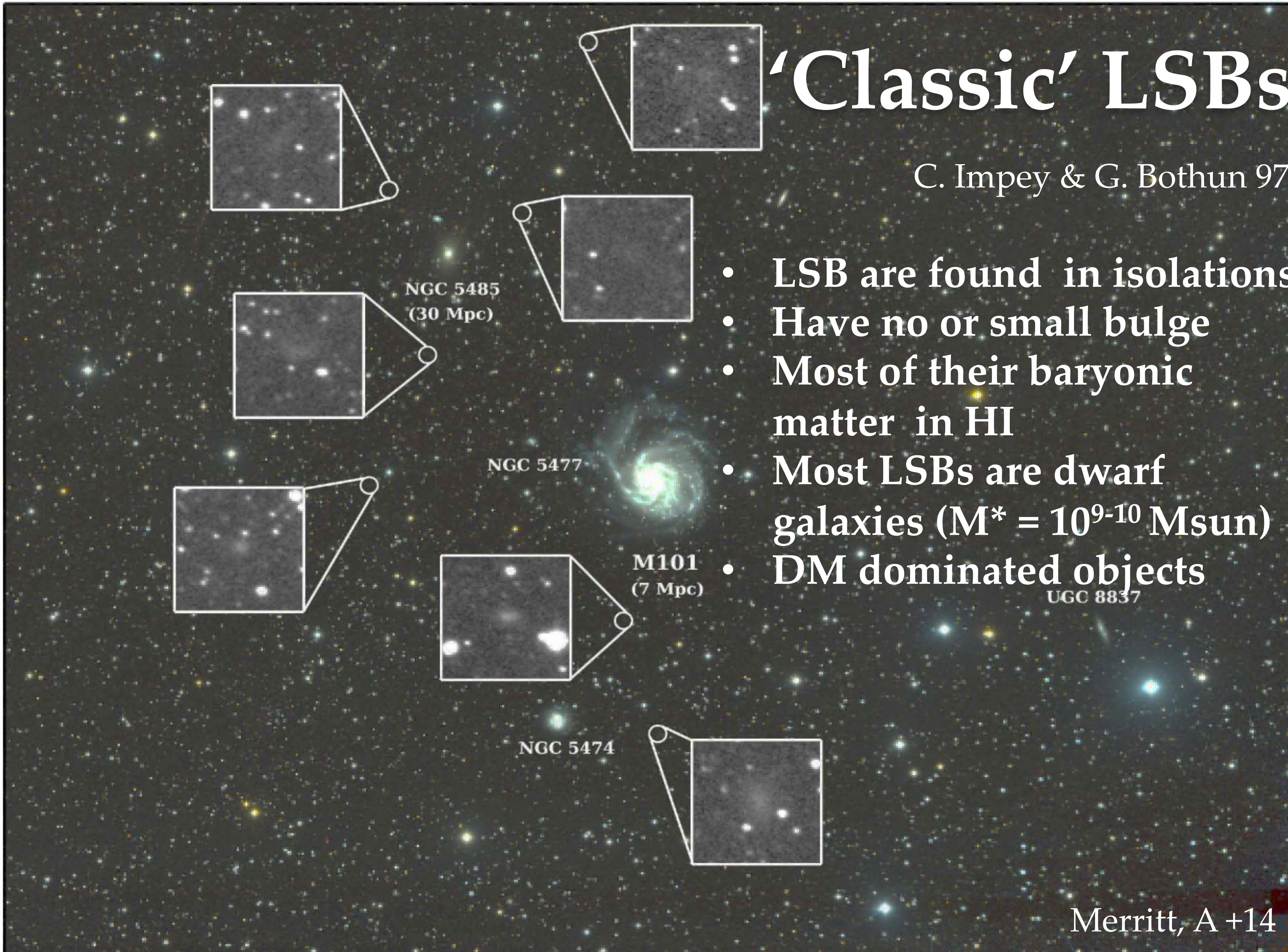
Amorisco & Loeb16



‘Classic’ LSBs

C. Impey & G. Bothun 97

- LSB are found in isolations
- Have no or small bulge
- Most of their baryonic matter in HI
- Most LSBs are dwarf galaxies (M* = 10^{9-10} Msun)
- DM dominated objects



Merritt, A +14

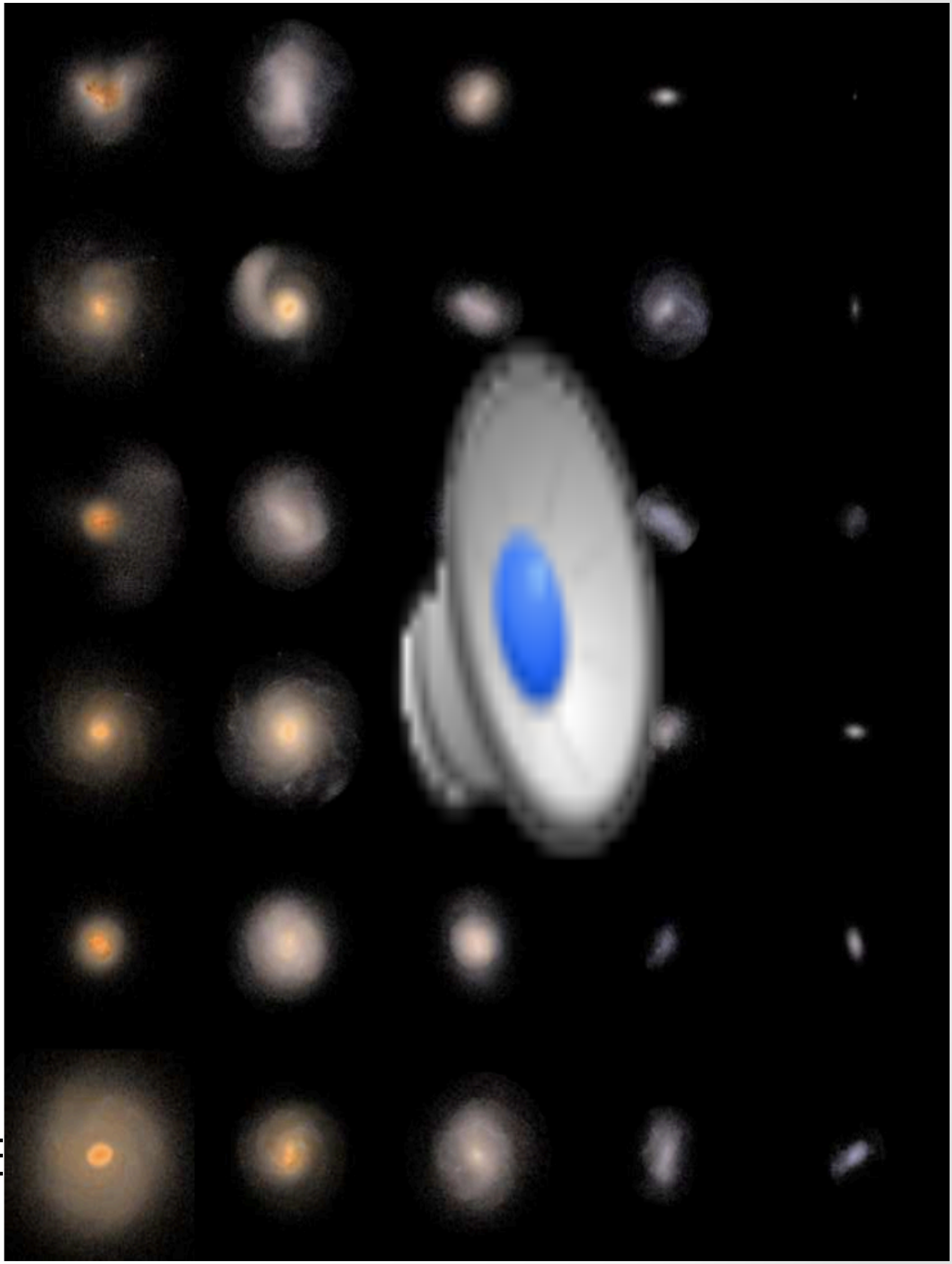
Can LCDM predict and explain the existence of such low surface brightness objects?

NIHAO 你好

Galaxy Simulations

PIs Maccio', Dutton

- Gasoline 2.0-blastwave feedback a la Stinson+06
- Planck Cosmology
- ***125 high resolution (zoomed) galaxies***
- more than $\mathbf{10^6}$ particles in each halo
- $10^5 – 10^{11}\ M_\odot$ stellar mass range ($5\times10^8 – 5\times10^{12}\ M_\odot$)
- 100 times better resolution than ILLUSTRIS
- 50 times better resolution than EAGLE volume
- 10 times more galaxies than FIRE (13 vs. 120)



Gasoline 2

Similar to previous MAGICC galaxies (Brook+12,Stinson+13)

but with improved GASOLINE code,

Smoothed Particle Hydrodynamics (SPH) (Wadsley+06)

New low temperature and Metal Cooling (Shen+ 2010)

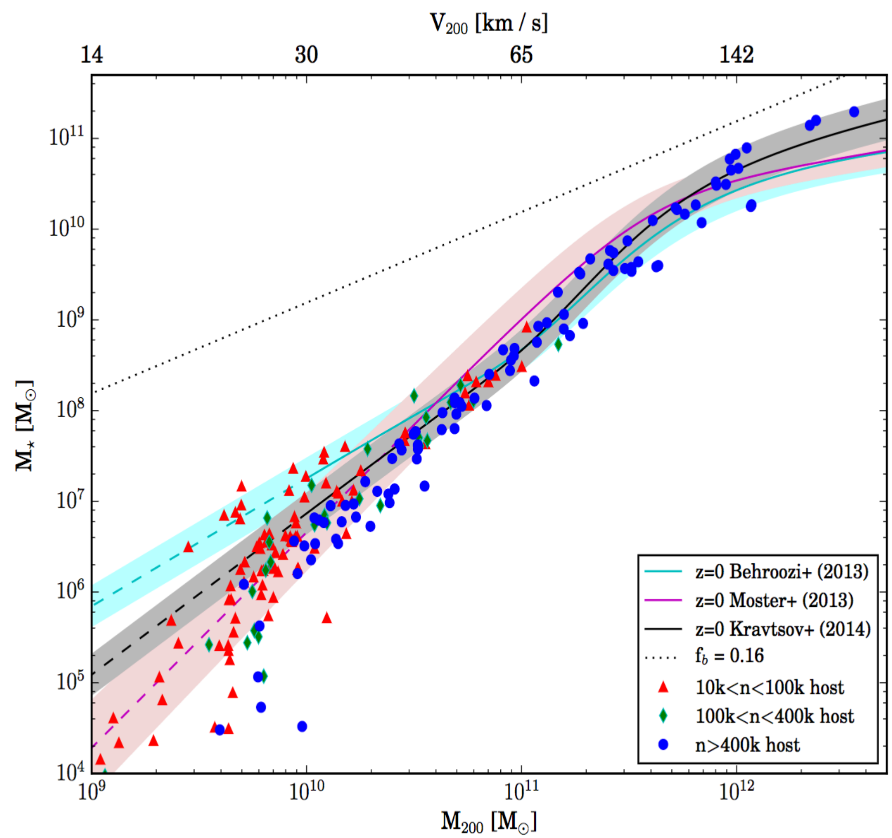
UV heating (Haardt & Madau 2011)

Metal Diffusion (Wadsley+ 2010)

Star Formation and SN feedback (Stinson+06)

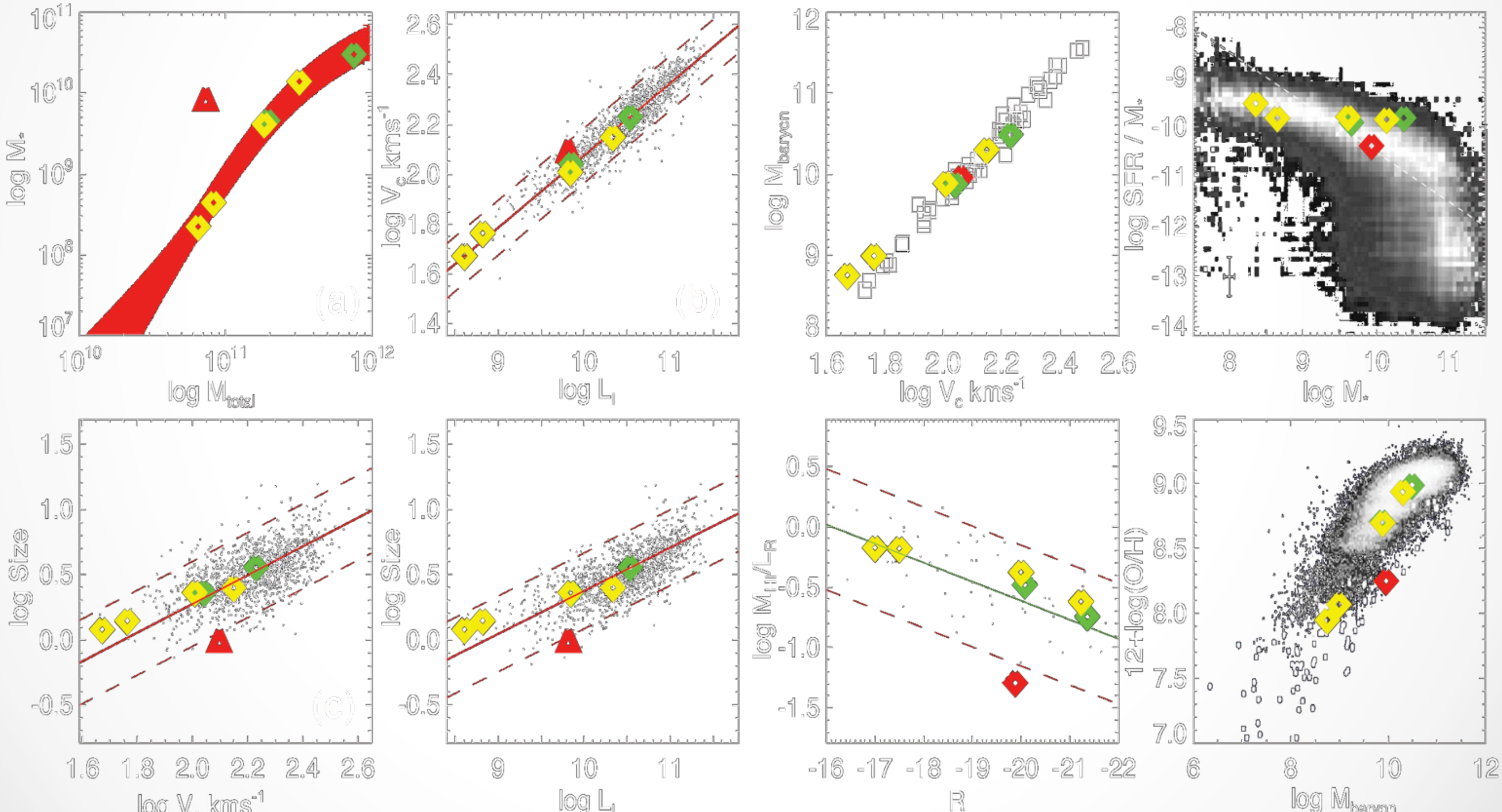
Chabrier IMF & Early Stellar feedback (Stinson, Brook, AM+ 2013)

New SPH implementation (Wadsley+2017)



Wang +15

Gasoline 2

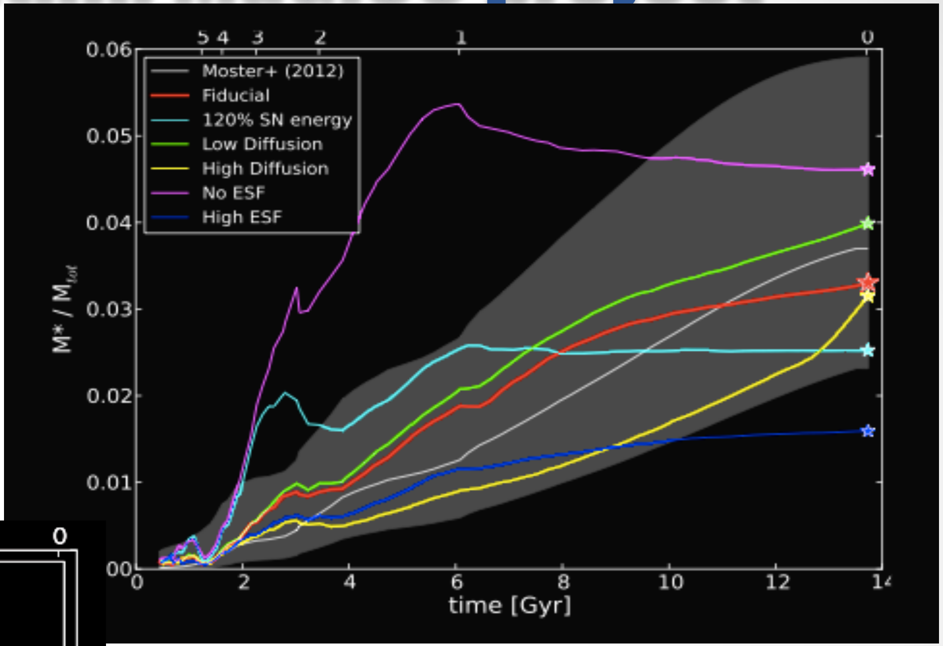


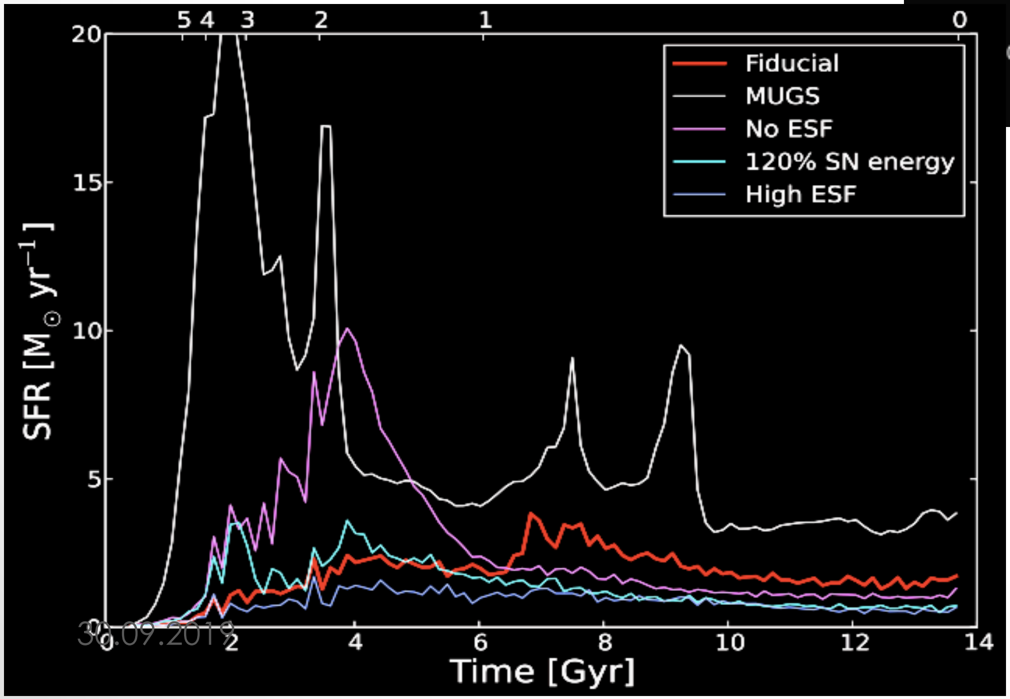
Brook+12

Parameter search within MaGICC project

Stinson et al. 2013

- IMF Kroupa,Chabrier
- $n_{th}[cm^{-3}]$ 0.1,9.3
- $E_{SN}=\varepsilon x 10^{51}$ erg, $\varepsilon=0.4,0.8,1.0,1.2$
- esf=0,0.05,0.1,0.125,0.175

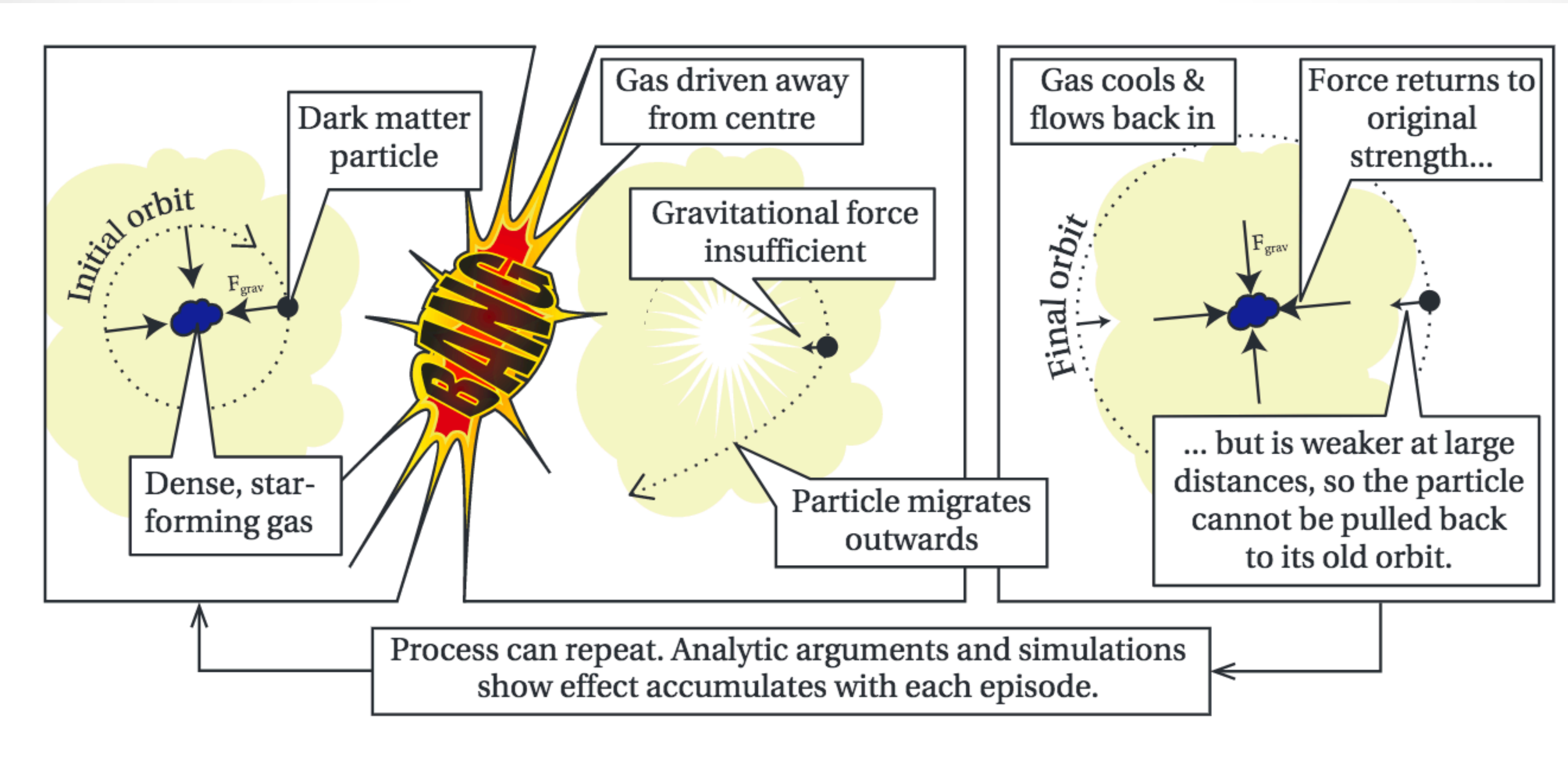




Gas outflows launched by Snae feedback

From gas outflows to DM ‘cores’

Core formation mechanism -> outflows driven by SNae feedback

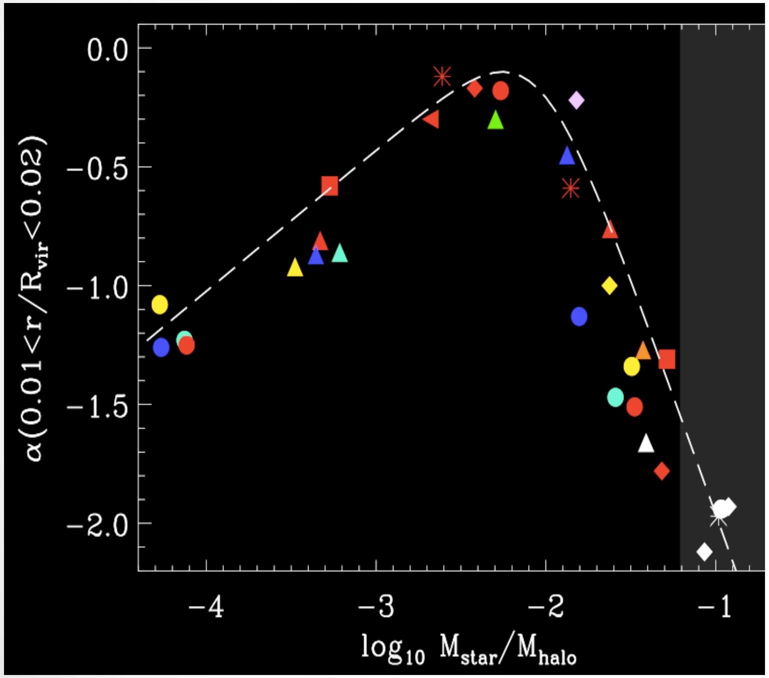


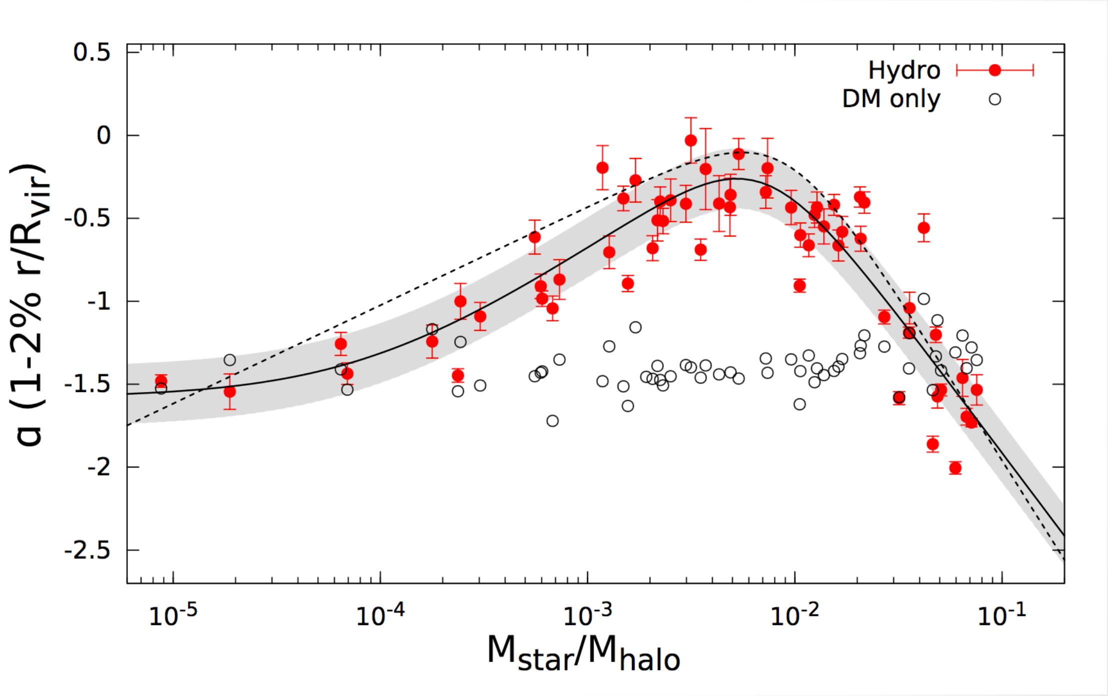
Pontzen & Governato 14
Navarro+96
Governato+10.+12

See Dutton+18 and Benitez-Lllambay+18 for the importance of n_{th} in creating `cores´

NIHAO galaxies form DM cores

Peak of core formation at log(M*/Mhalo)~-2.4 → M*~$10^{8.5}$ Msun (Di Cintio+14a,b)
Core created during starburst events that launch powerful gas outflows

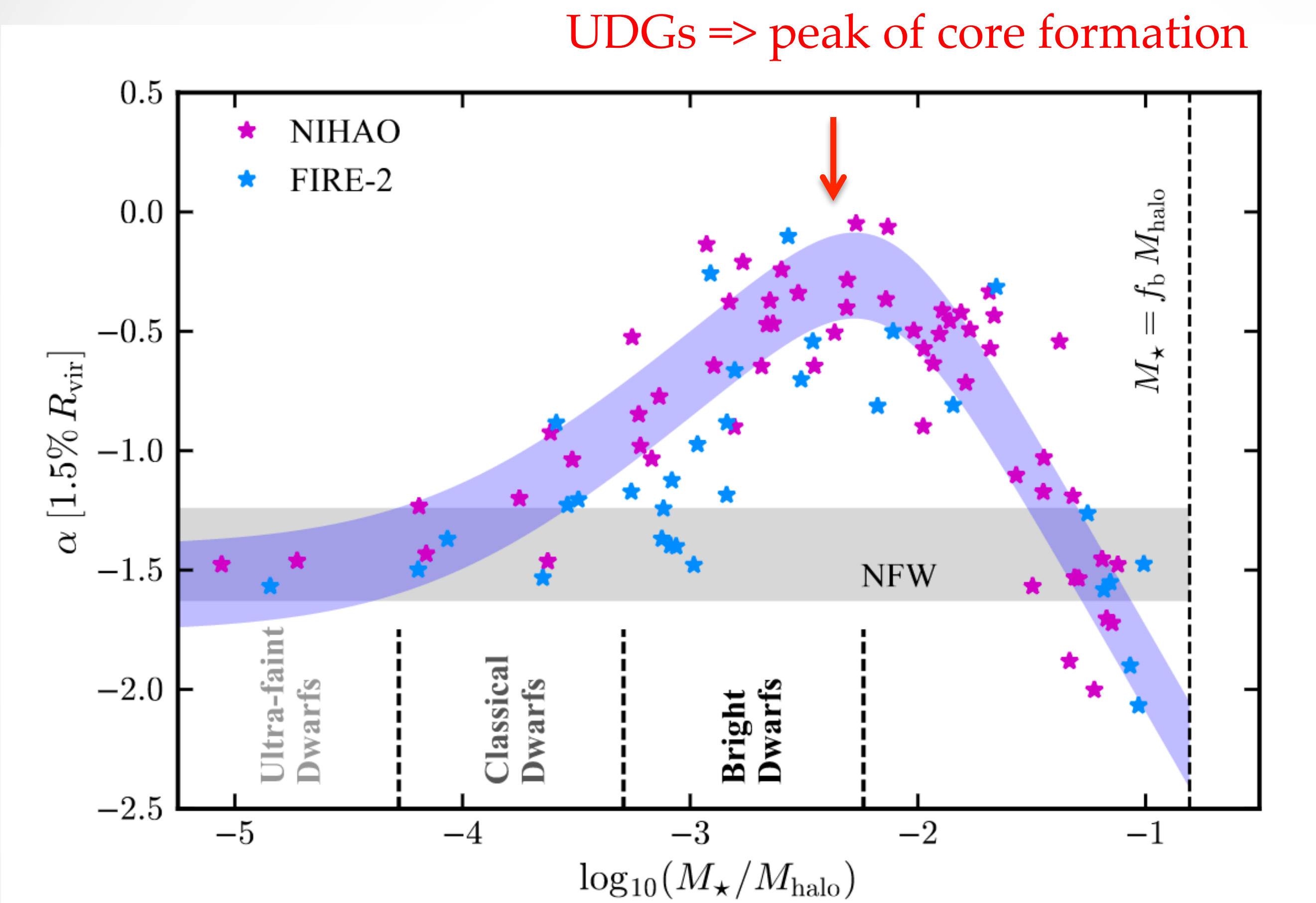




Di Cintio +14 a,b
Chan+15
Tollet+16

Dark matter profiles determined by two opposite effects: energy from Sne vs gravitational potential of the DM halo

Sweet spot of core formation



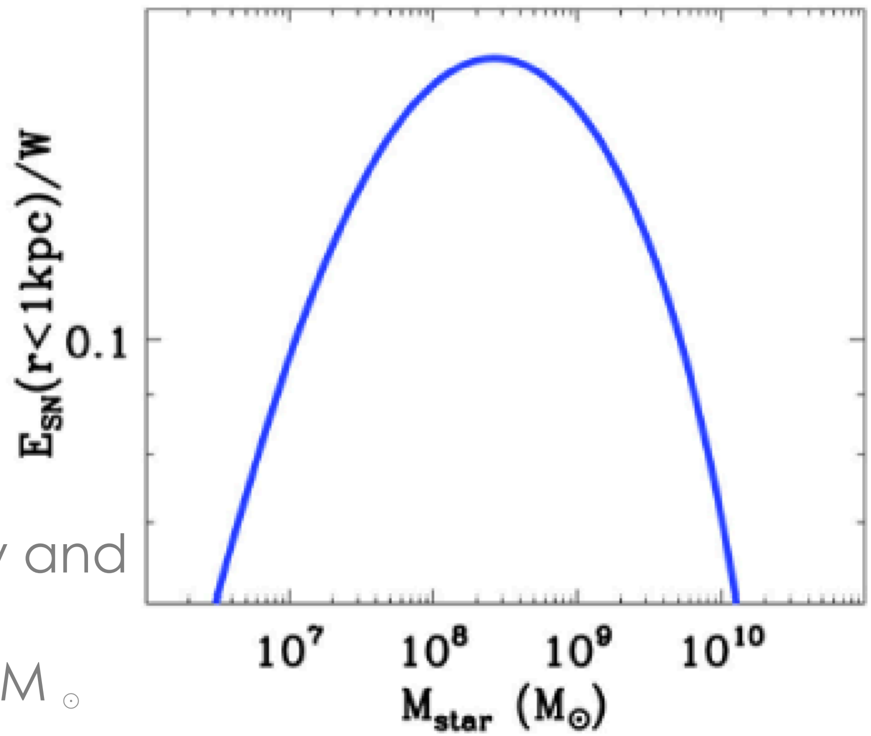
Review by
Bullock & MBK 2017

Data from
Di Cintio+14,
Chan +15,
Tollet+16

Small dwarfs not enough energy from stellar feedback to modify NFW halo
Intermediate dwarfs/LSBs correct amount of energy from Snae
Large spirals can not 'win' the large grav potential of 10^{12} halo with SNae alone

Sweet spot of core formation

$$\frac{E_{SN}}{W} = \frac{M^{\star}(< 1Kpc) \times f_{SN}/\bar{m} \times 10^{51} erg \times \epsilon}{-4\pi G \int_0^{rvir} \rho(r) M(r) r dr}$$



Energy balance between SNe energy and potential energy of NFW halo.
Flattest profiles expected at $M_{*} \sim 10^{8.5} M_{\odot}$

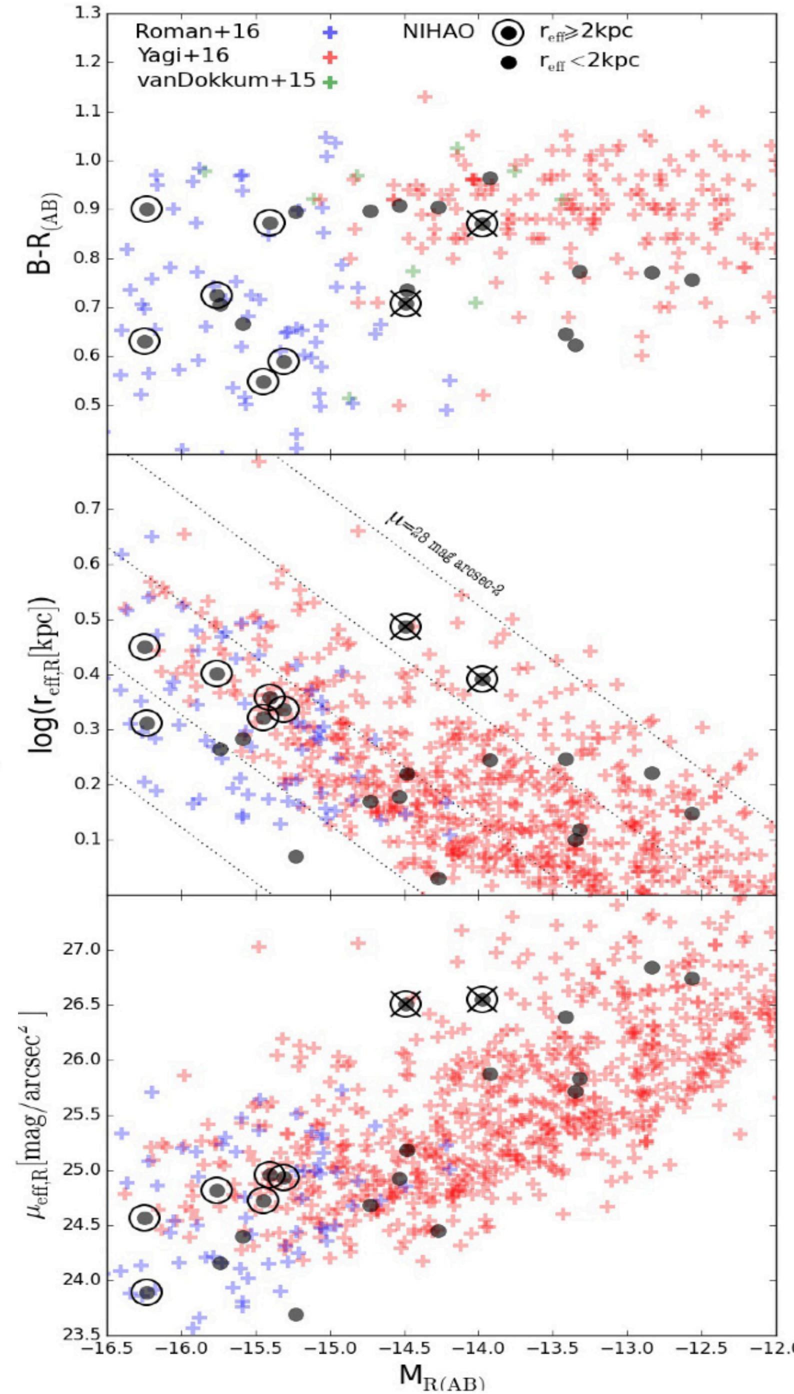
Brook & Di Cintio2015a

Searching for UDGs in NIHAO

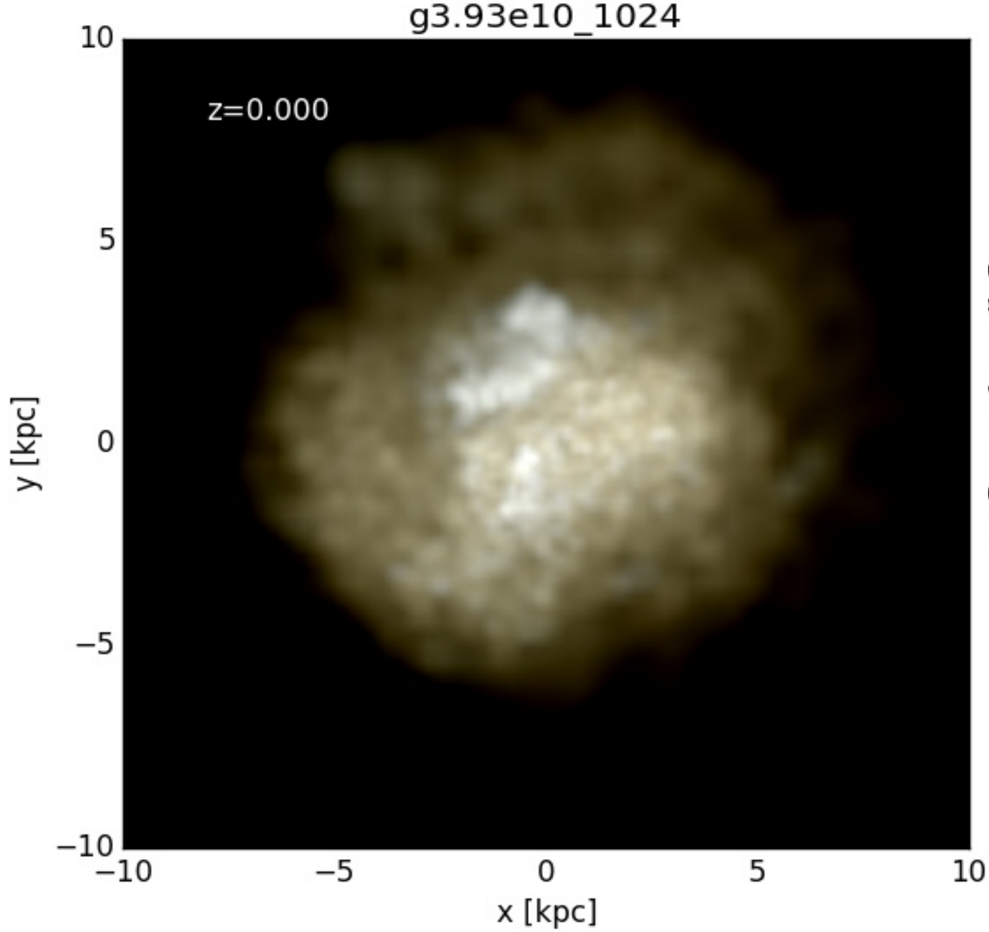
Di Cintio,Brook +17

X	$\overline{X} \pm \sigma$	$X_{min,max}$
$\log(M^{\star}[M_{\odot}])$	7.66 ± 0.42	6.83 , 8.40
$\log(M_{halo}[M_{\odot}])$	10.53 ± 0.18	10.22 , 10.85
r_e[kpc]	1.87 ± 0.53	1.07 , 3.06
μ_e[mag/arcsec^2]	25.23 ± 0.94	23.69 , 26.84
M_R	-14.61 ± 1.07	-16.25 , -12.57
B-R	0.77 ± 0.12	0.54 , 0.97
n_{Sersic}	0.83 ± 0.27	0.31 , 1.46
$\gamma(1\text{-}2\% R_{vir})$	0.37 ± 0.18	0.01 , 0.78
$\log(\lambda)$	-1.48 ± 0.25	-2.04 , -1.17

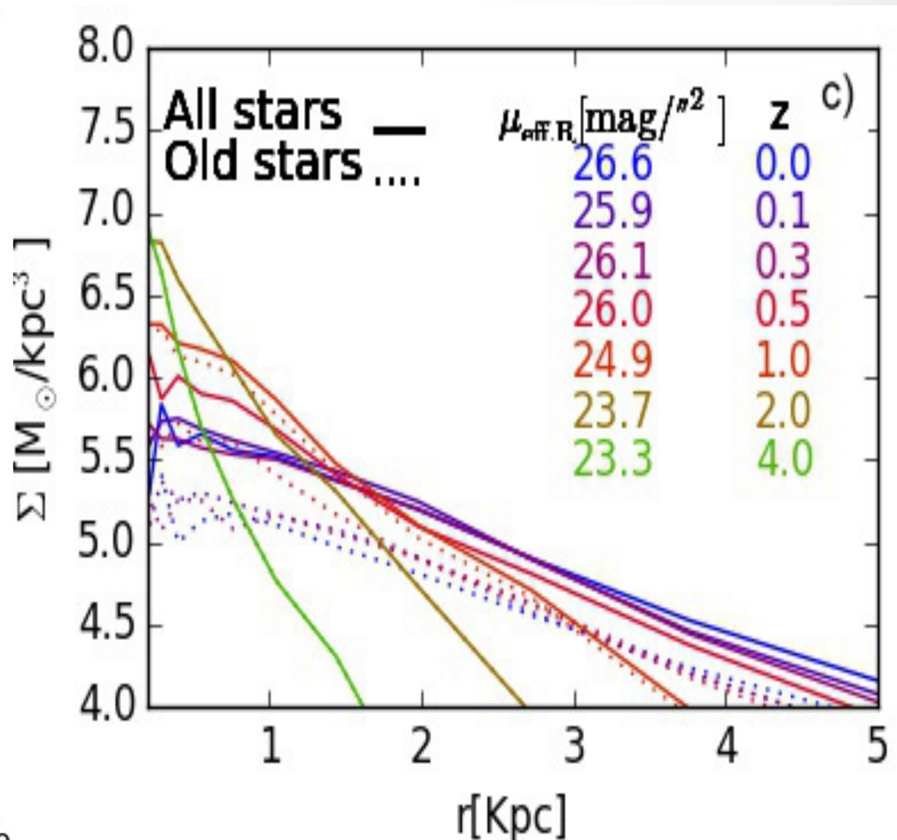
They are dwarfs!
And isolated…



Formation scenario of UDGs



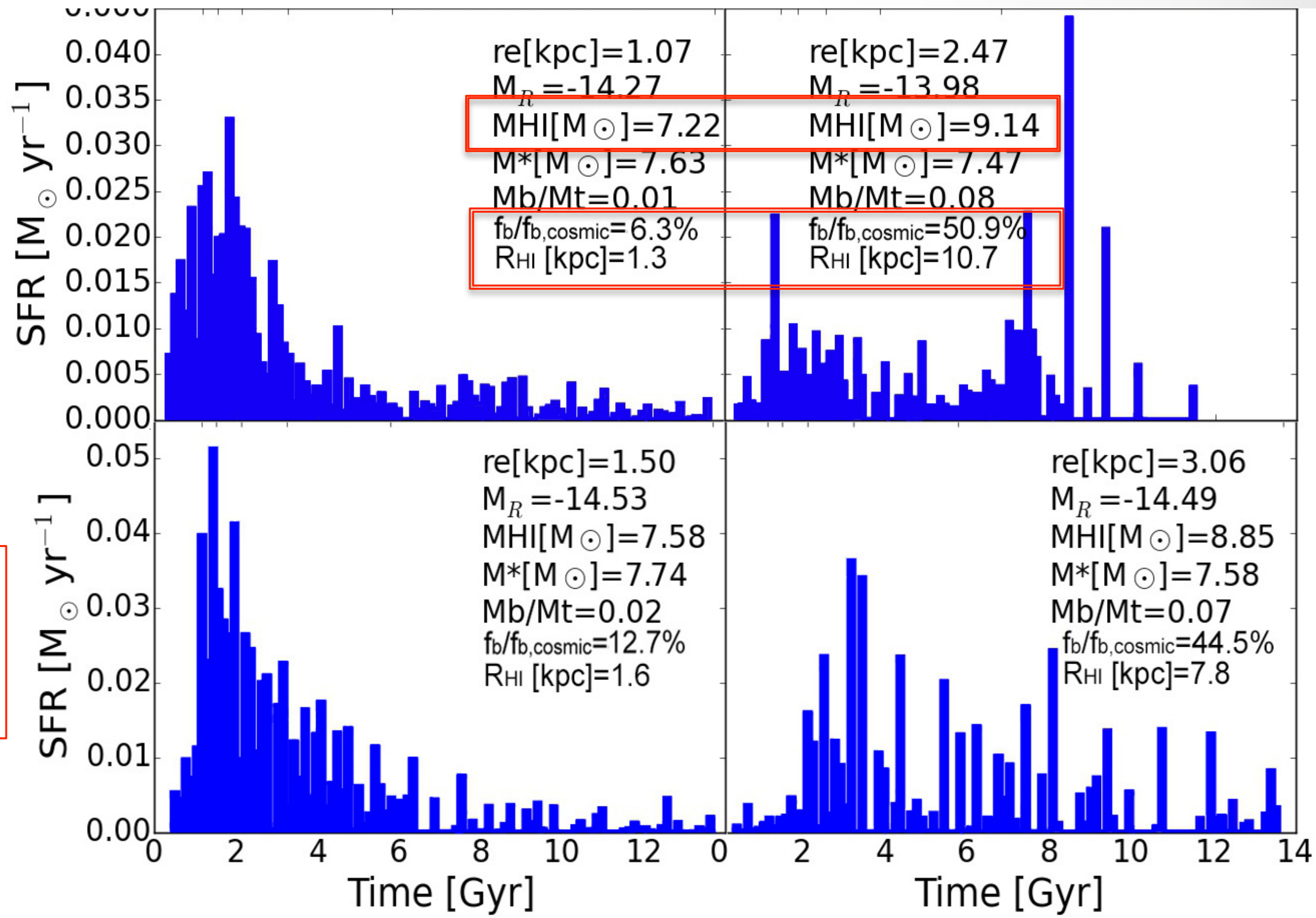
Stellar evolution



Di Cintio,Brook +17

Observational Predictions

The largest isolated UDGs should contain more HI gas, have a larger baryon fraction and a more extended and *bursty* SFH than less extended dwarfs of similar M⋆

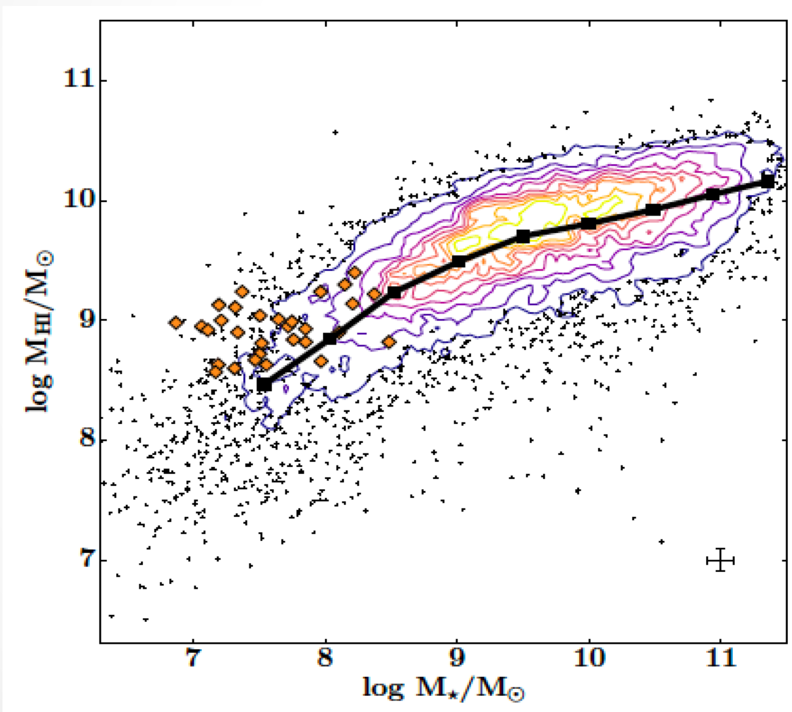


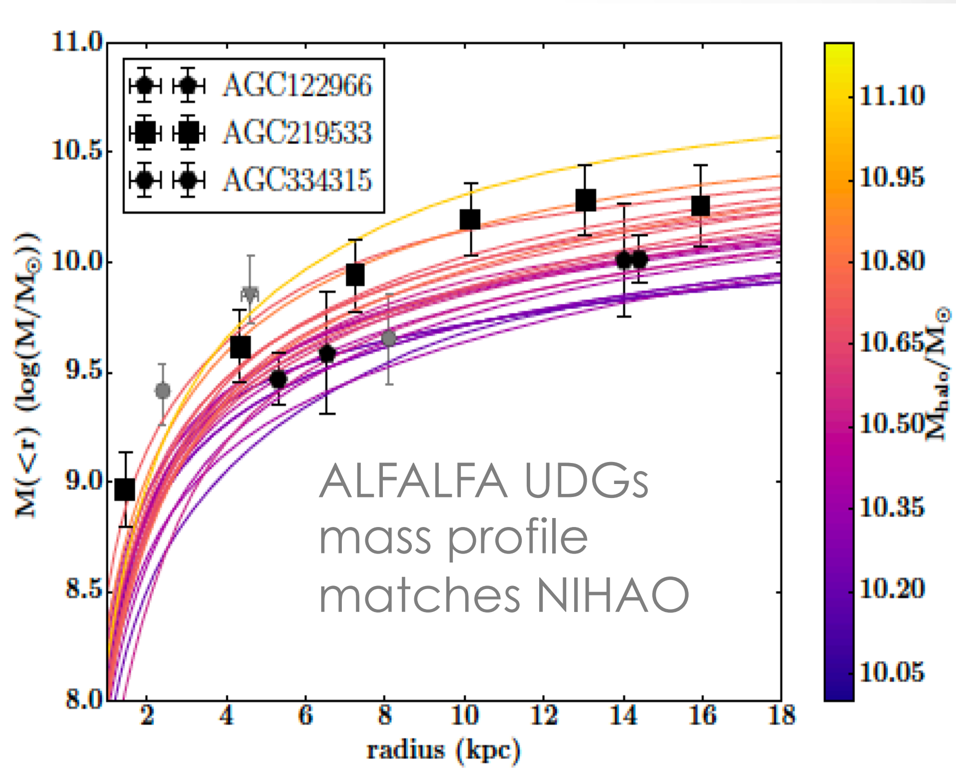
UDGs could be the ***dark galaxies*** of the ALFALFA survey

Di Cintio +17
(see also Onorbe+15, Read+16 for core size dependence on SFH in smaller haloes)

HI-bearing isolated UDGs

115 isolated UDGs found in ALFALFA survey. Bluer than in clusters, supporting scenario in which UDGs form in isolation and then accrete into clusters
Isolated UDGs tend to be HI-rich relative to their stellar mass





Leisman +17 using ALFALFA data

CDM+ baryonic physics Predictions for UDGs!

- Halo mass of dwarfs
- Found in isolation
- Gas rich => the largest ones have higher gas fraction
- Bluer in field than in cluster
- Large gas extent
- ALFALFA dark galaxies can harbor UDGs
- Correlation between SFH and size
- Sersic index n~1
- Dark matter core!

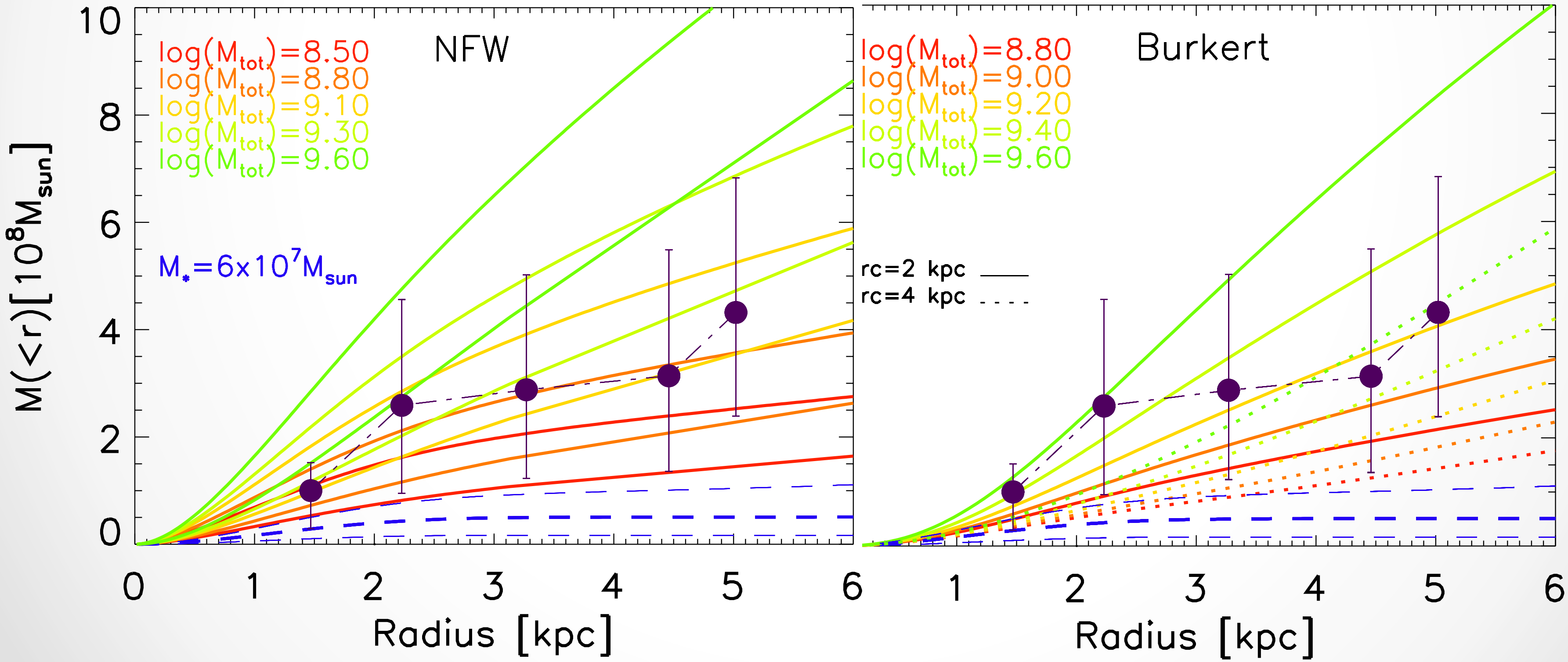
OBS VERIFIED!
WORK IN PROGRESS

The ‘galaxy lacking DM’

NGC1052–DF2, Van Dokkum+18

Trujillo +18 => Mdyn(<5.2kpc) ~4x10^8Msun and M*=6x10^7 Msun by placing the galaxy at D=13 Mpc

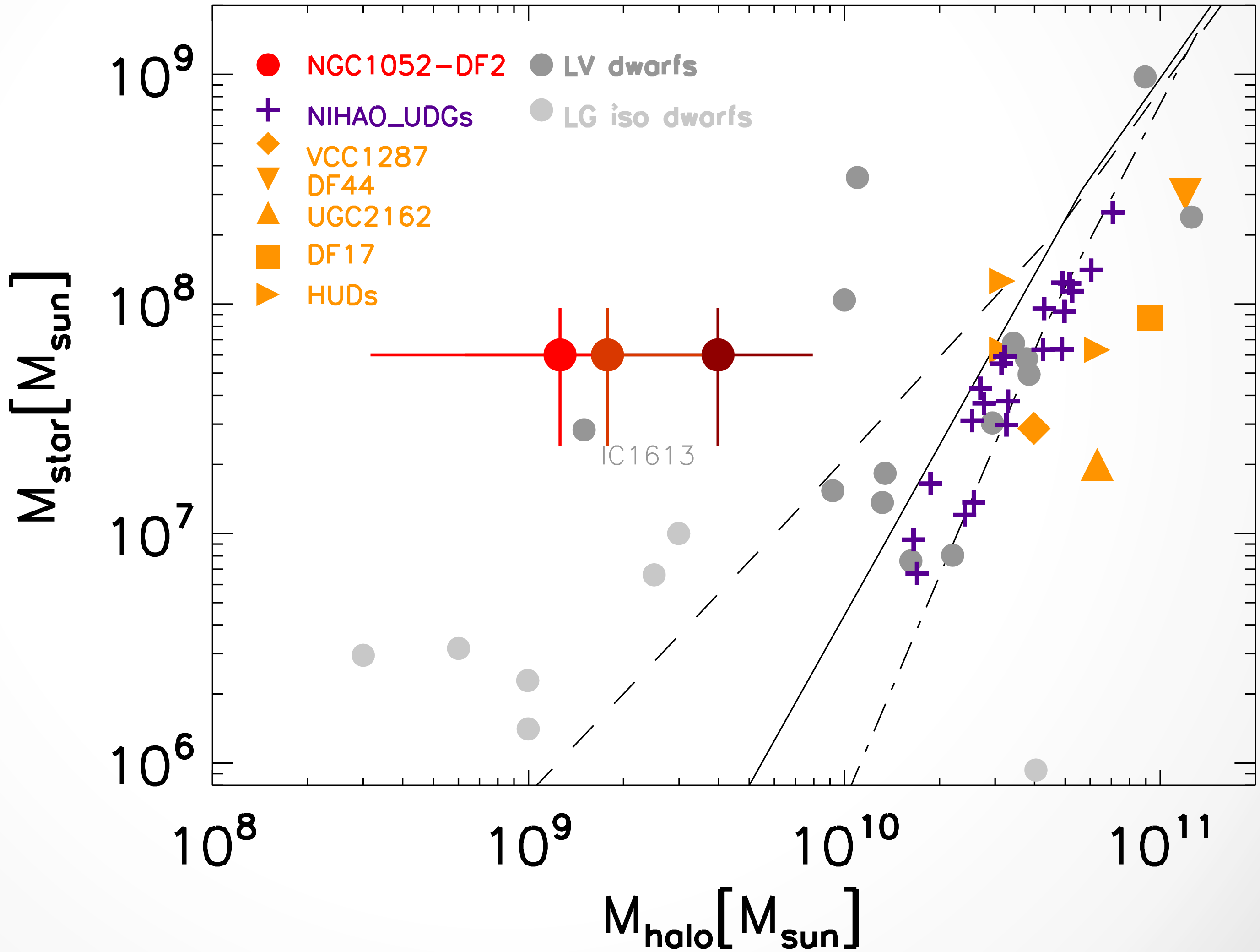
Different profiles (NFW, DC14, Burkert) provide a Mhalo> 10^9 Msun -> Mhalo/M*>20



NGC1052–DF2 M*-Mhalo

Outlier in the M*-Mhalo relation, but definitely not a DM free object.

Other LG dwarfs lie in a similar position In M*-Mhalo space



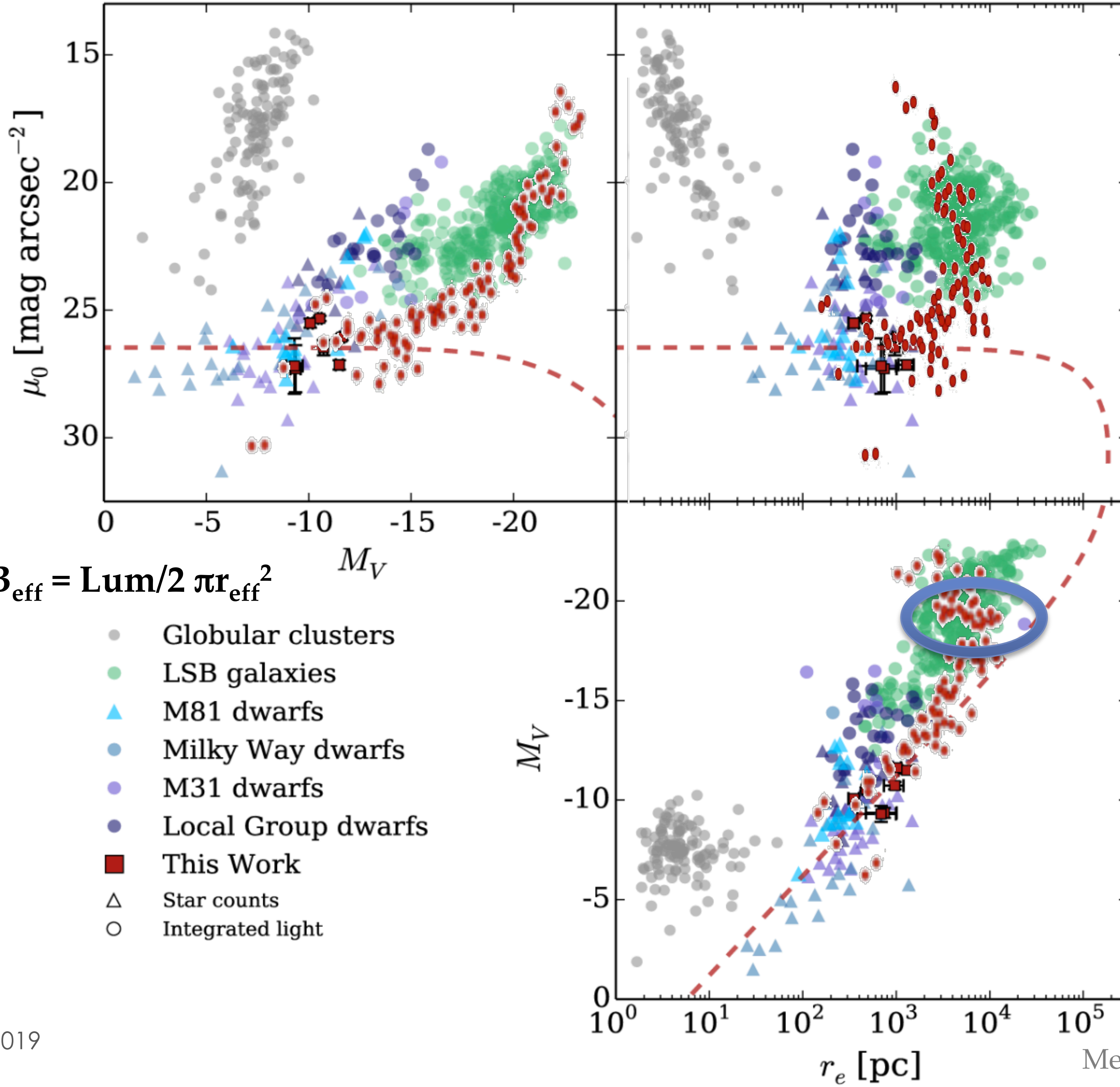
Is the formation mechanism of LSBs the same as the UDGs´one?

- (Surprisingly ?) the formation scenario of large `classic´LSBs (Mstar~$10^{9.5-10}M_{sun}$) is **different** than the one of small UDGs (Mstar~$10^{7-9}M_{sun}$)
- And so are the observational predictions …

What makes LSBs?

- SNae driven Gas outflows => cores in DM and stars?
- Differences in SFHs? Late vs early
- Low concentration haloes?
- Large spin parameter?
- Differences in gas fraction?
- Mergers? Time of last mayor mergers?
- … something else?

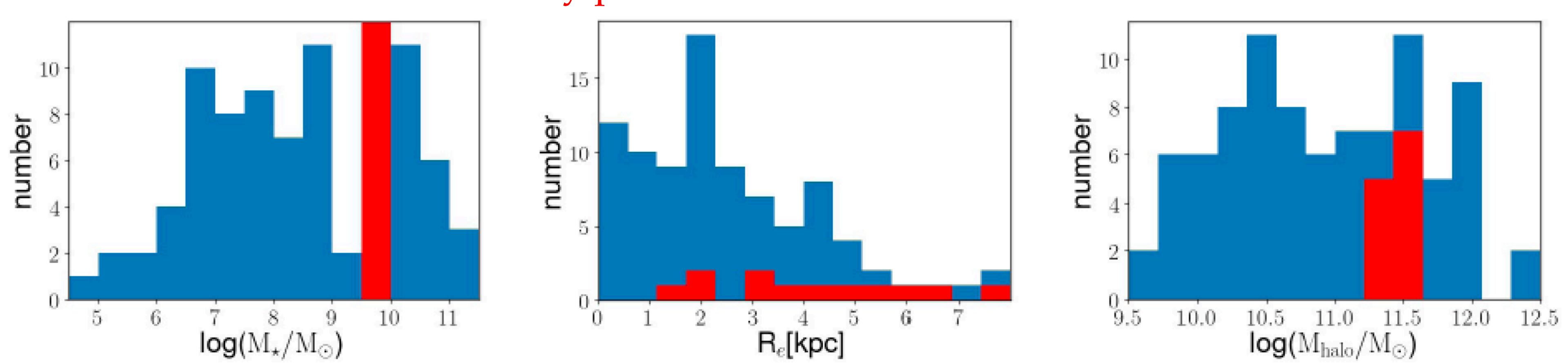
$$SB_{eff} = Lum/2\,\pi r_{eff}^{2}$$

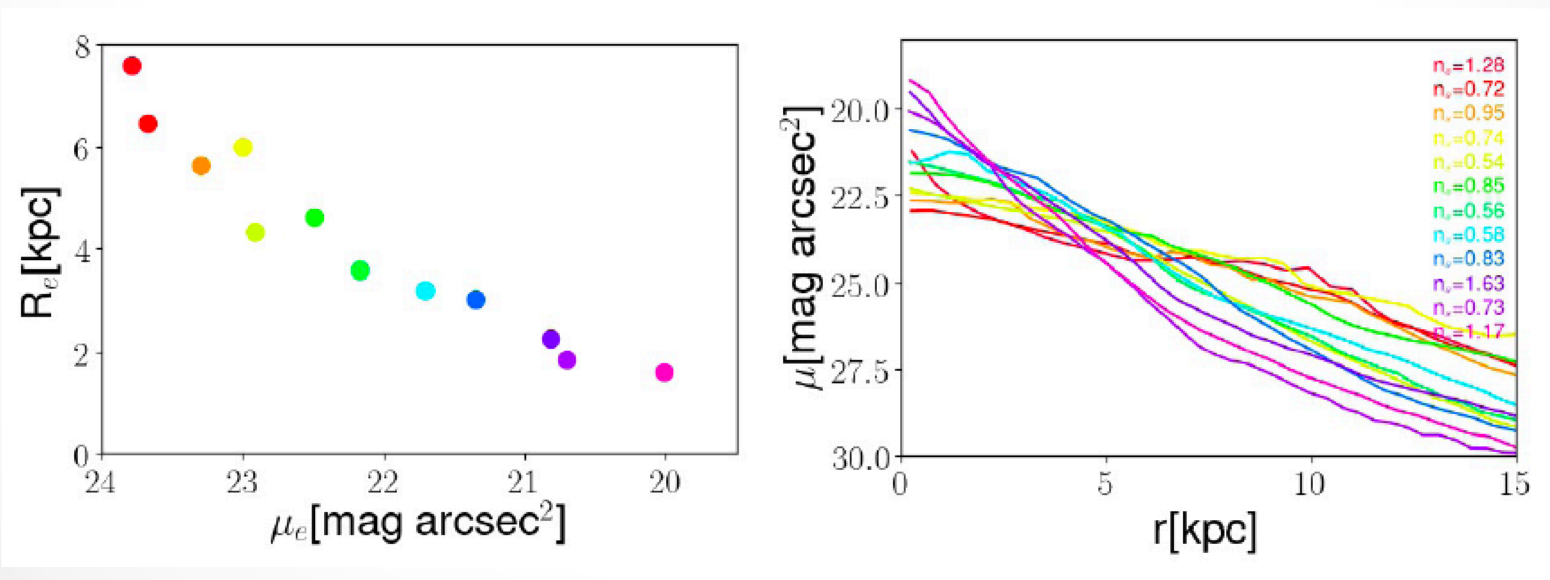


Merritt+14

Selection of LSB/HSBs candidates

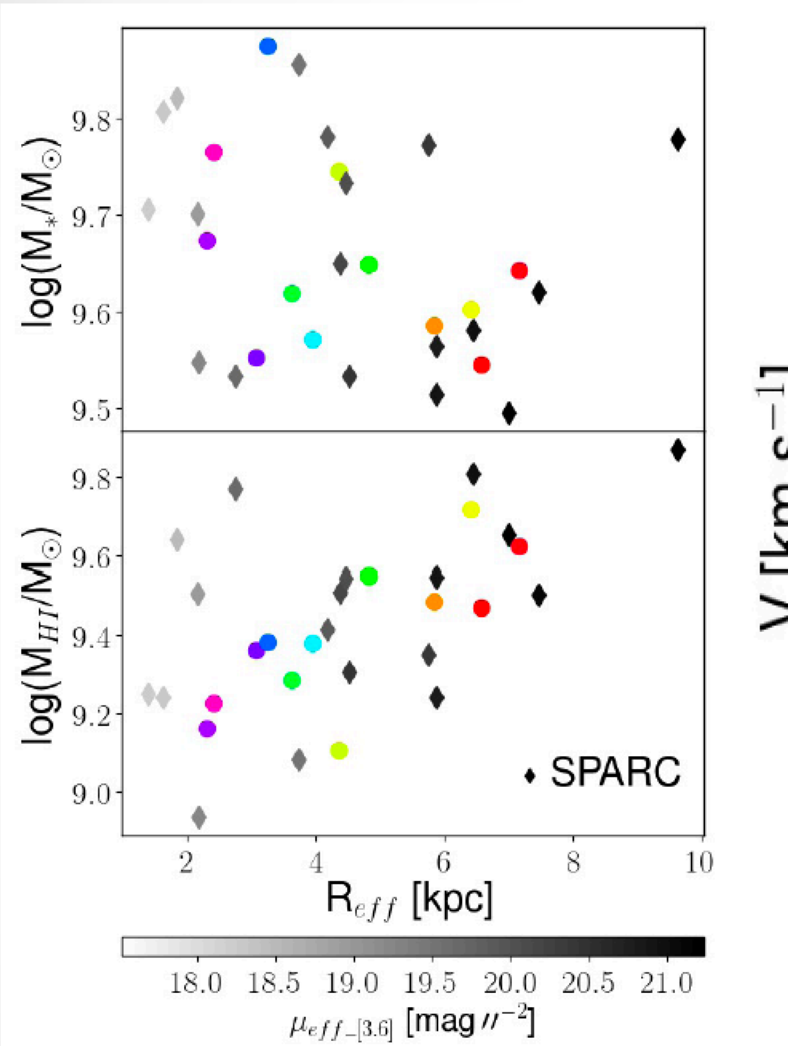
Only possible with NIHAO sims!





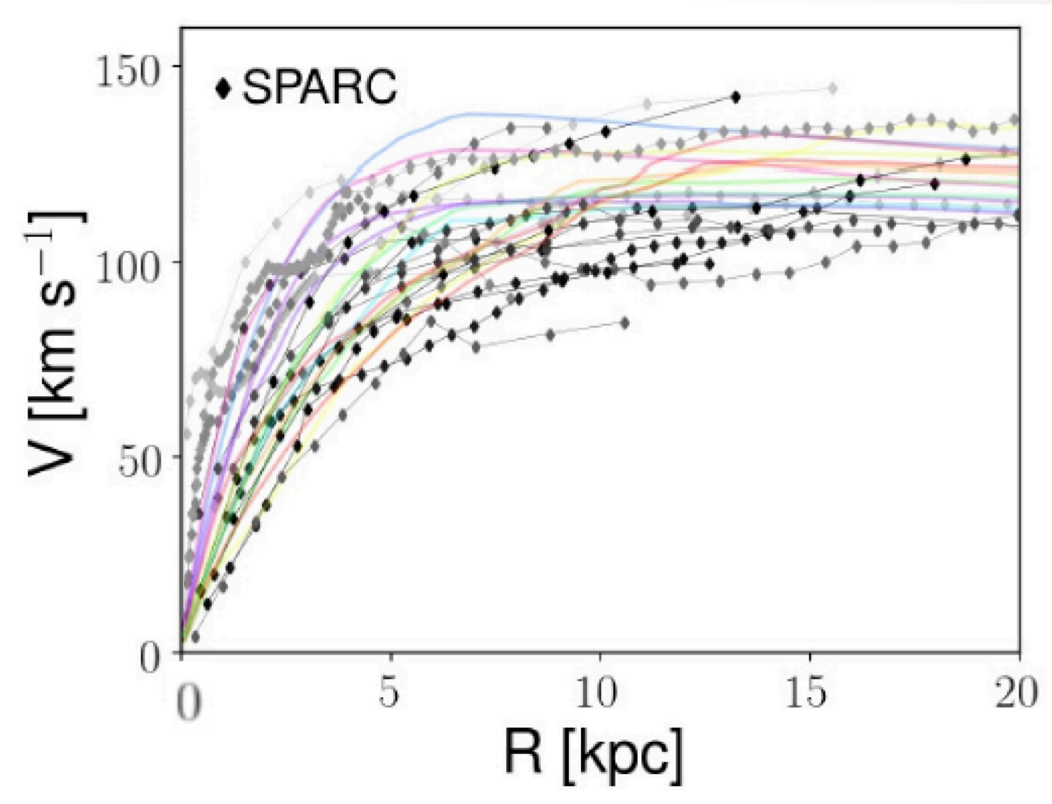
Di Cintio +19

Comparison with obs dataset

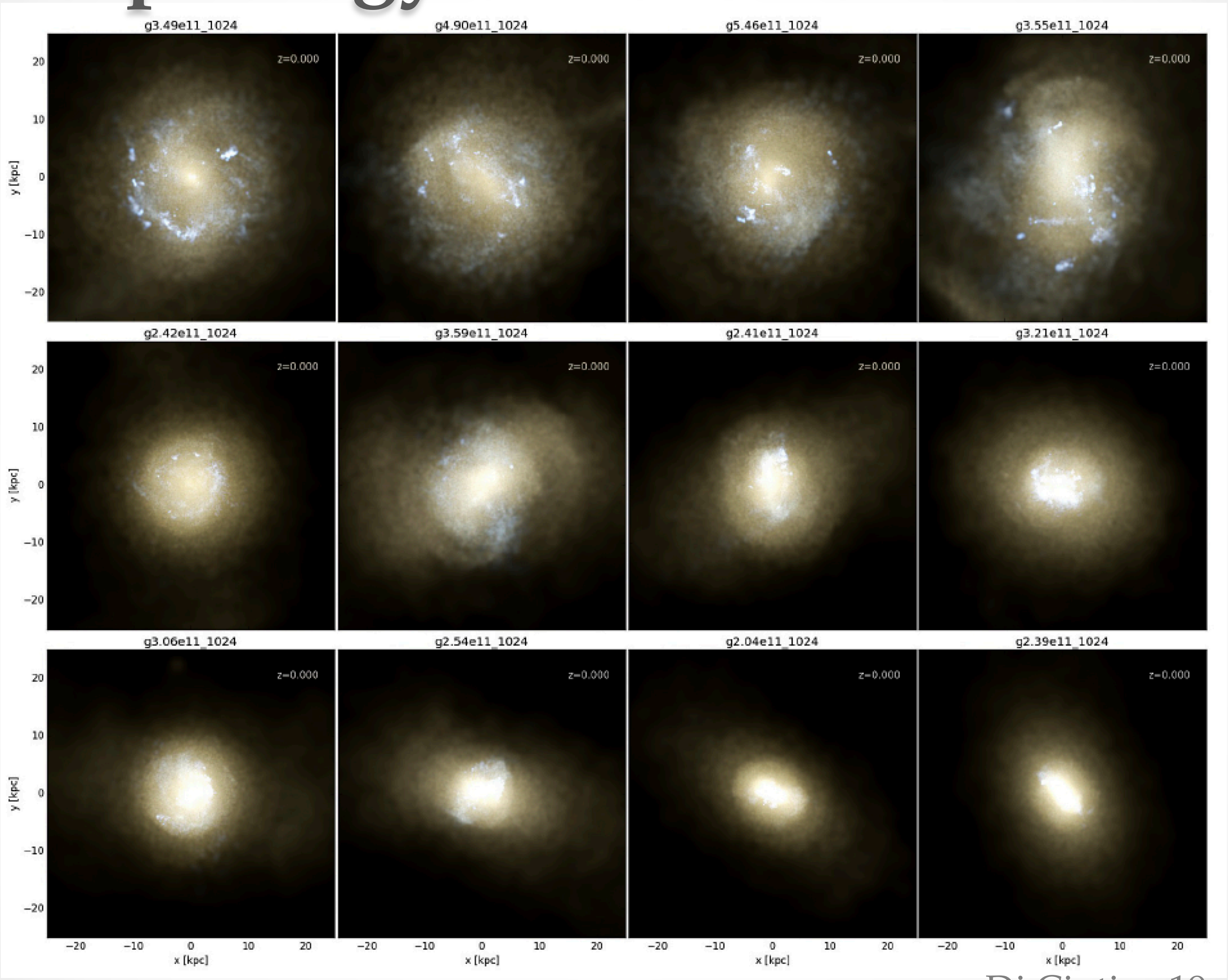


SPARC Spitzer Photometry & Accurate Rotation Curves

Lelli+16

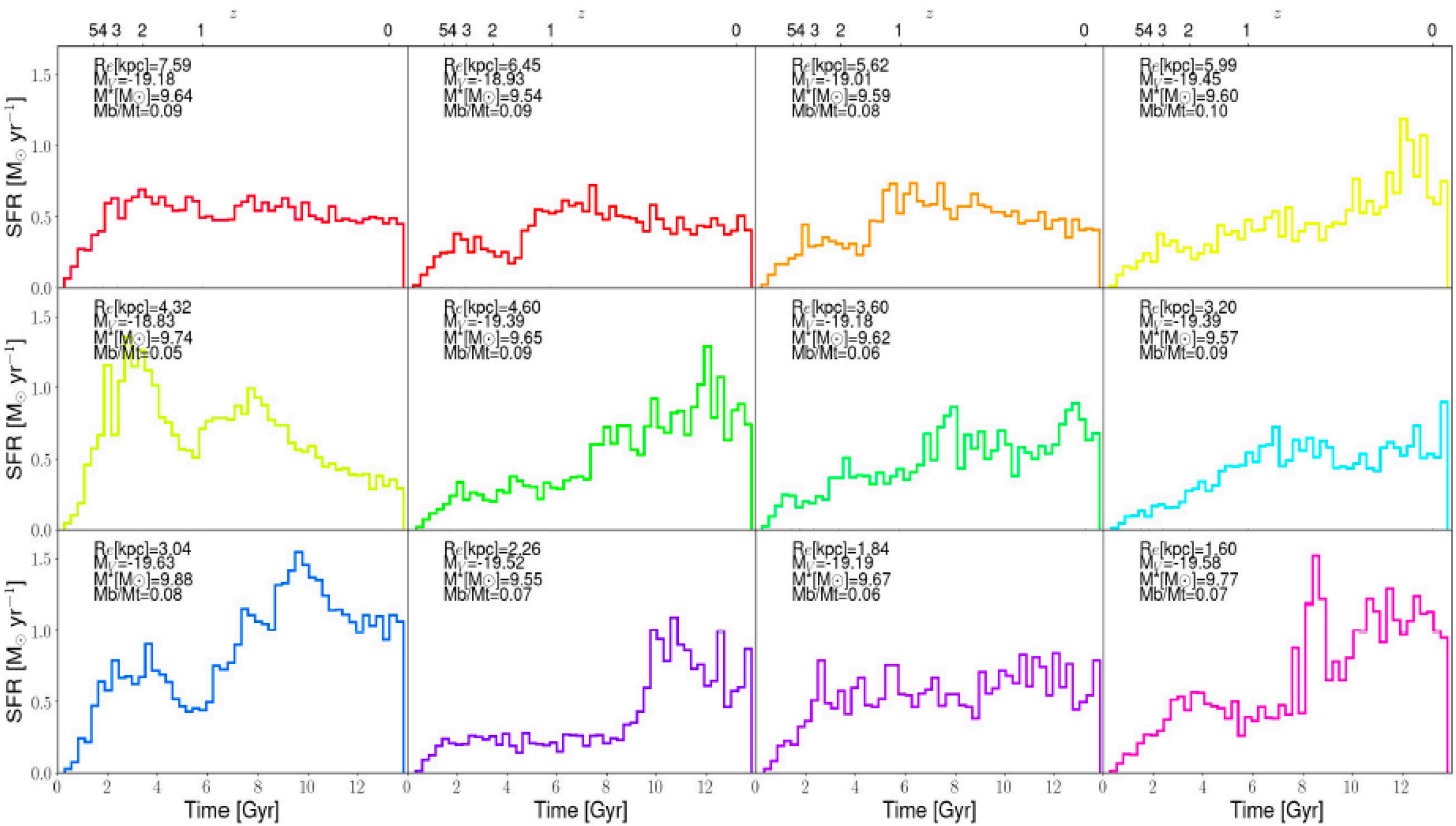


Morphology of LSB/HSBs face-on



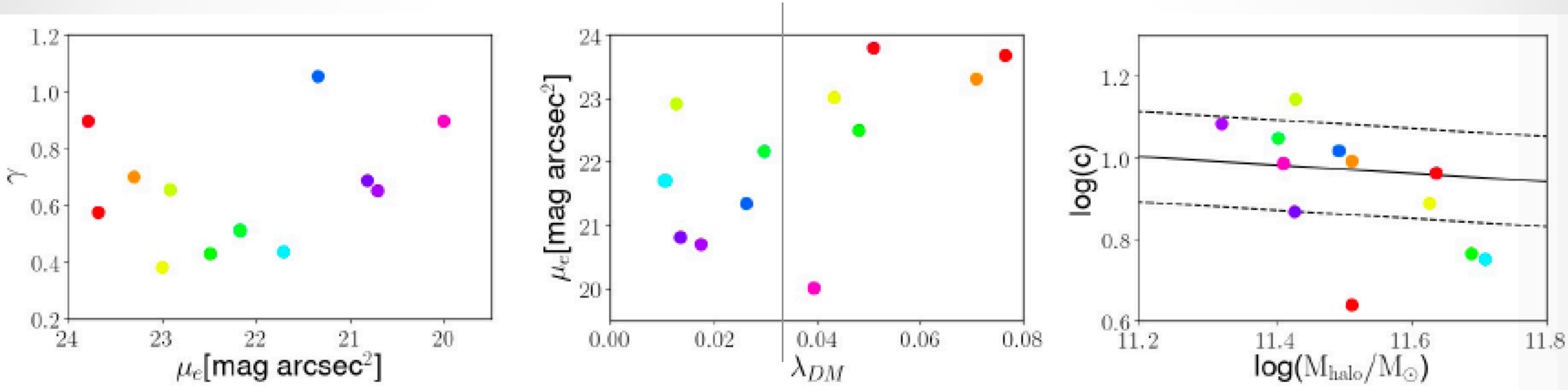
Di Cintio +19

SFHs of LSB/HSBs

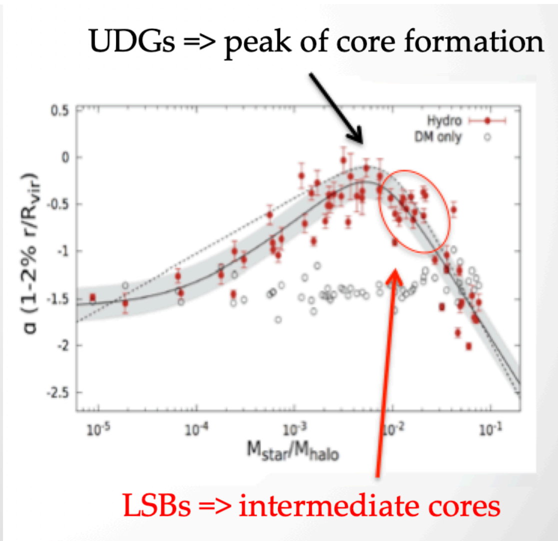


See McGaugh+17, Boissier+08 for current SFRs in LSBs

DM profiles, spin and concentration



$$\Lambda = J/\sqrt{2}MVR$$



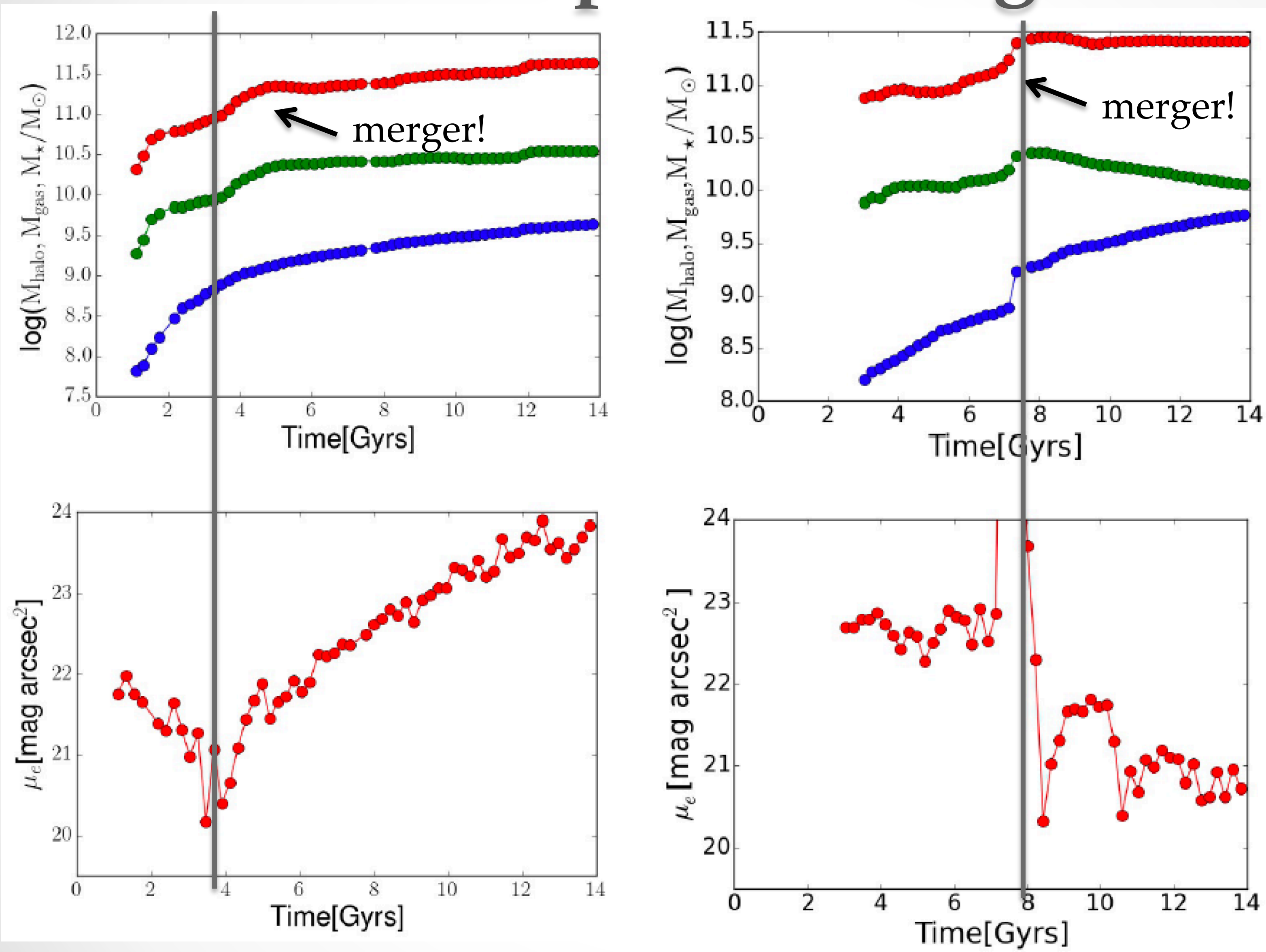
LSBs:

- do not strongly correlate with density slope of their DM halos
- do not live in systematically low concentration halos
- they positively correlates with DM halo spin

Tollet+16,Di Cintio+14

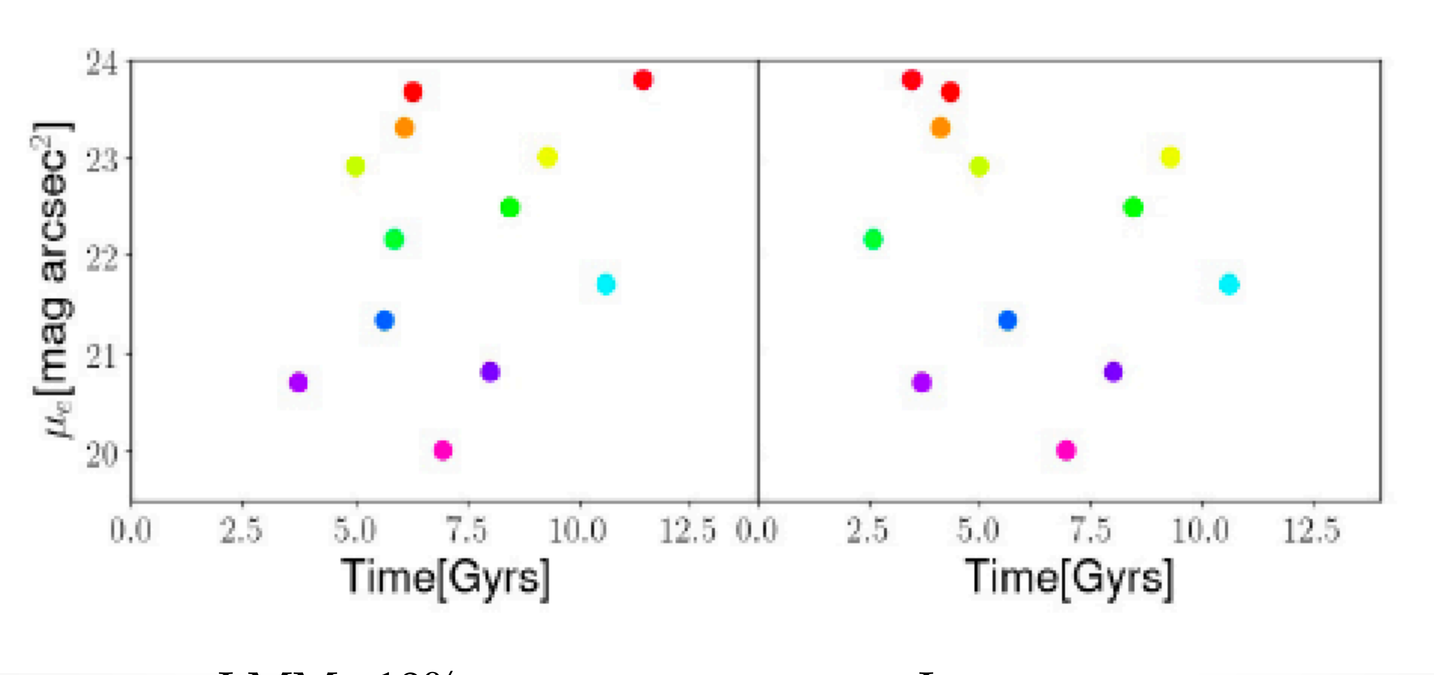
Di Cintio +19

The impact of mergers



Di Cintio +19

LSBs do not correlate with LMM time



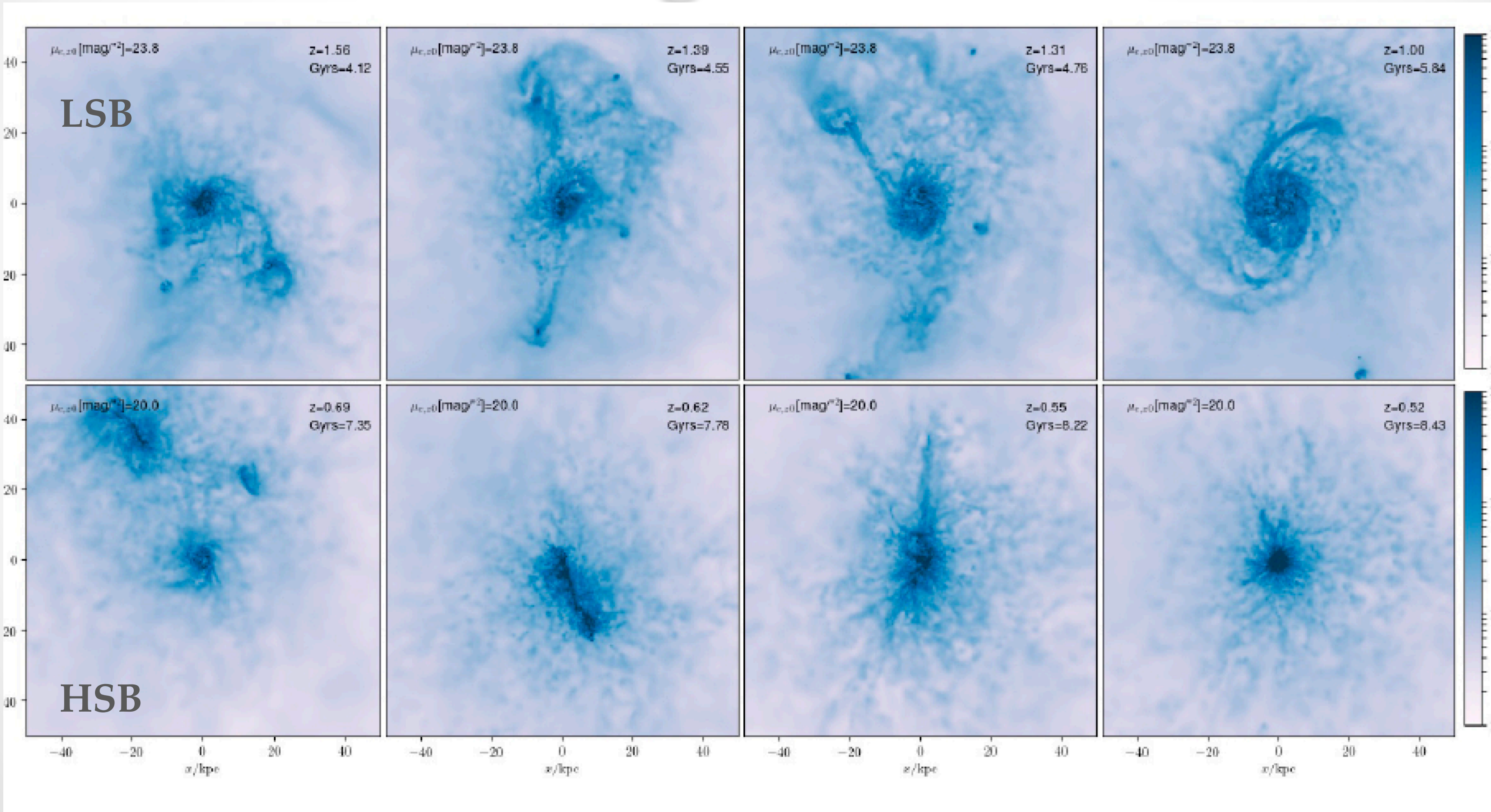
LMM >10%

Largest merger

LSBs => co-planar mergers

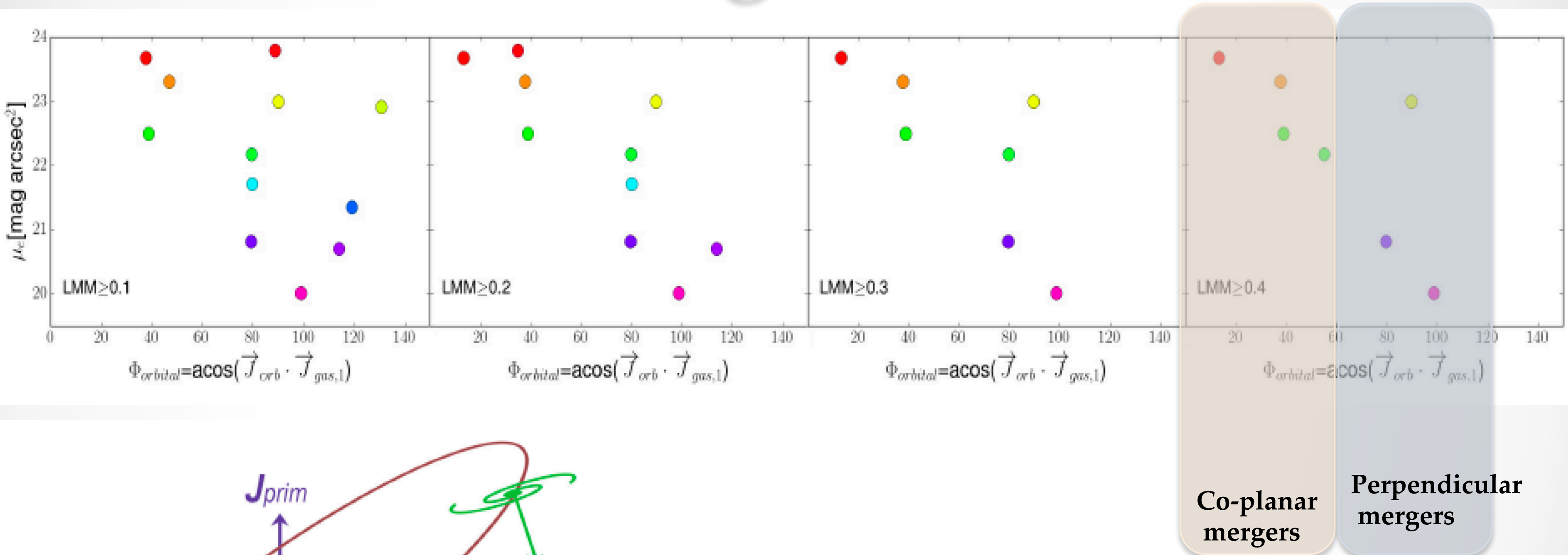
HSBs=>perpendicular mergers

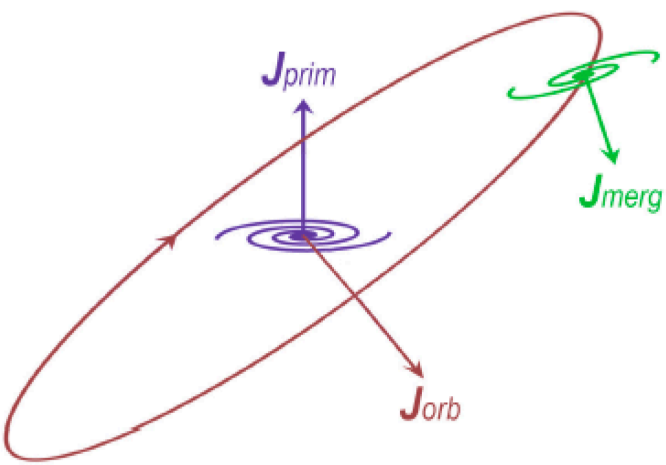
Co-planar vs Perpendicular merger configuration



Di Cintio +19

LSBs do care about orbital alignment at merger time!

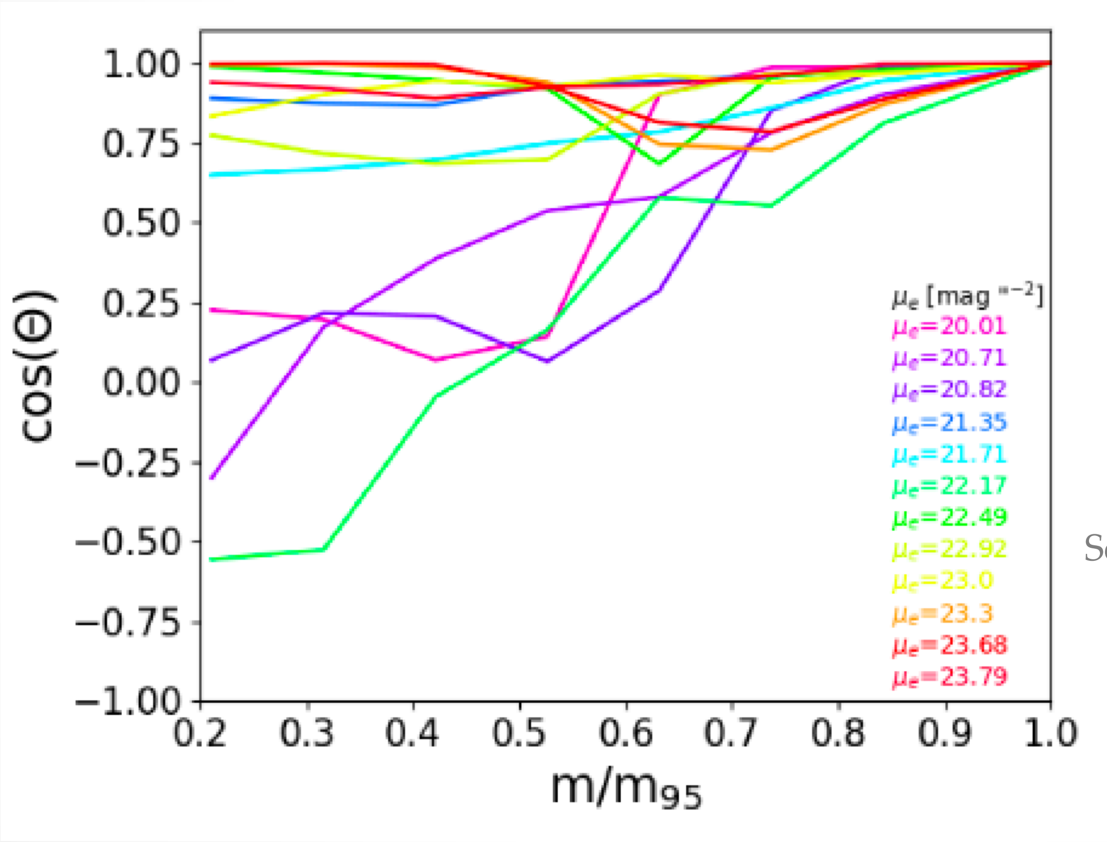




$$\mathrm{Cos}(\phi) = \mathrm{J}_{\mathrm{orb}} \cdot \mathrm{J}_{\mathrm{prim}}$$

$$\mathbf{J} = m_i \sum_{i=1}^{N} \mathbf{r_i} \times \mathbf{v_i}$$

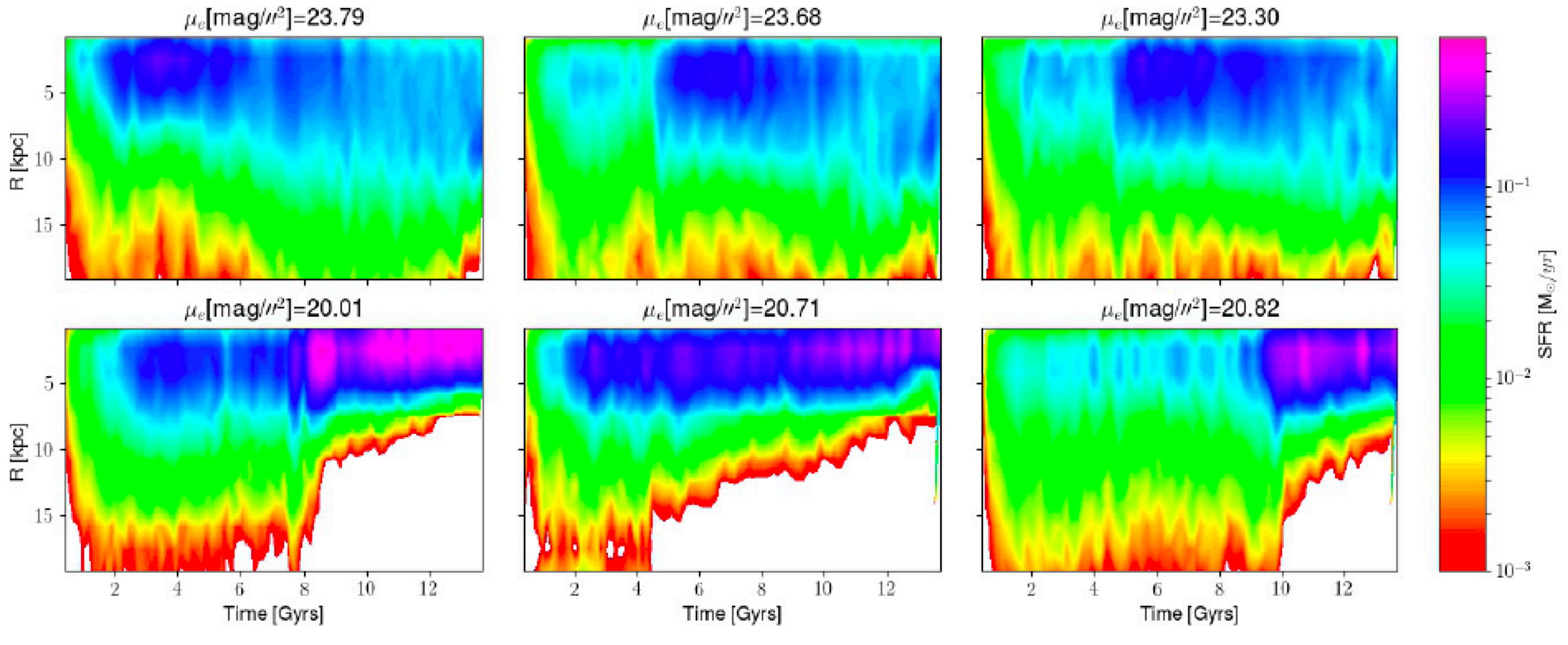
LSBs do care about the alignment of inner and outer gas/baryons at z= $M_{1/2}$

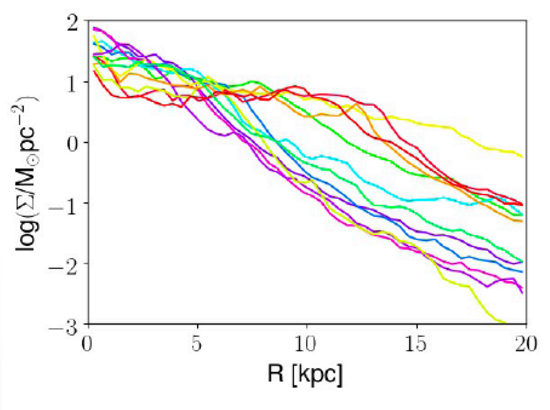


Inner and outer shells of baryons that will make up the galaxy at z=0 are well aligned already at z=$M_{1/2}$

See Sales+12 for similar methodology

Spatially resolved SFR in LSBs





Di Cintio +19

Conclusions

- LSBs are in a mass range where SNae feedback alone is NOT sufficient to "expand" the stellar and gas disks. Prevalent role of mergers: co-planar mergers and aligned inflows of gas add angular momentum and make a large disk, perpendicular mergers and un-aligned accretion cause a higher SB galaxy

- UDGs formation mechanism is solely based on internal feedback driving gas outflows and generating DM and stellar "expansion". Obs signatures: largest gas fraction for largest Reff

- **For LOW SURFACE BRIGHTNESS OBJECTS, Mstar~$10^9 M_{sun}$ represents the transition regime from a "feedback dominated" formation scenario to a "angular momentum dominated" one!**

- Diversity of SBs in the $M^*=10^{9-10} M_{sun}$ regime is a reflection of the variety of mergers and accretion histories of galaxies, on top of mildly expanded DM halos

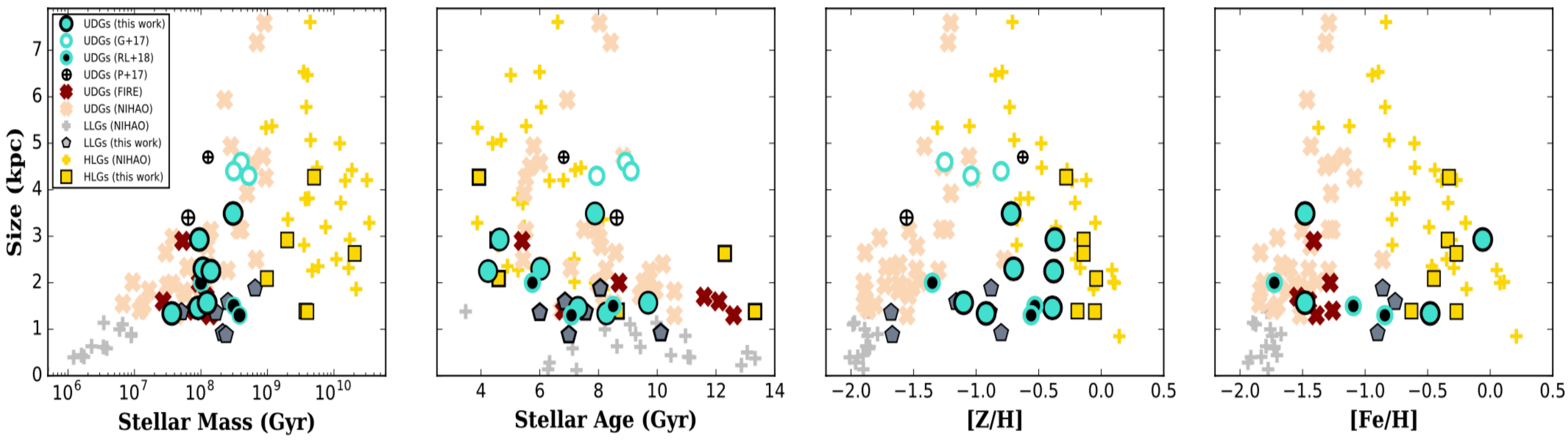
Discussion

- Star formation in dwarf LSBs doesn´t evolve as smoothly and uniformly as it happens for LSB disks (McGaugh & de Blok 97). LSBs dwarfs seem to have higher gas fractions than those of their more massive counterpart (Schombert et al. 01)

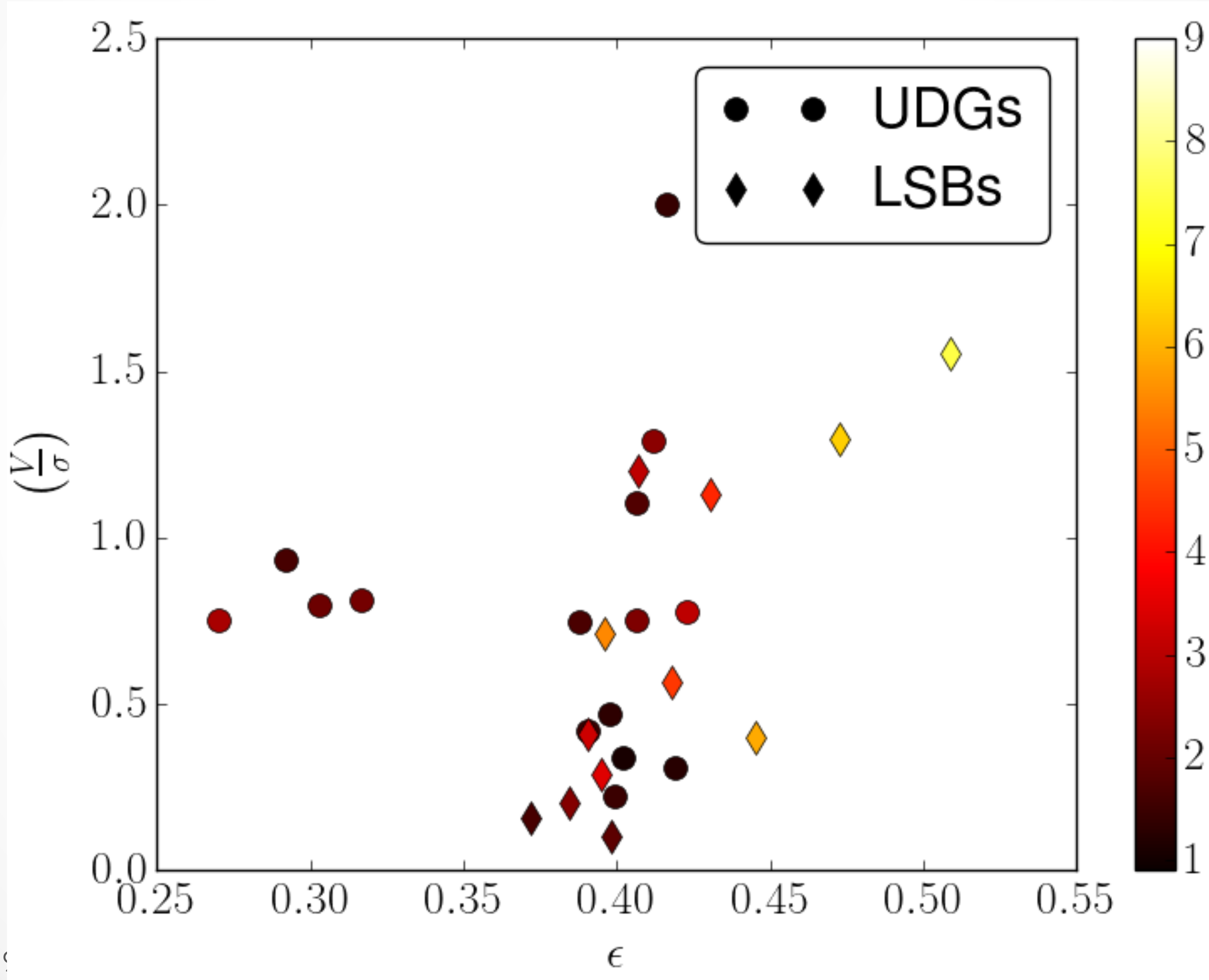
- These aspects are detected in our simulations, with low mass UDGs having bursty-like SFHs and high gas fractions, f_g, up to 97%, while more massive LSBs, from this work, showing continuous SFHs and lower f_g50%.

- Next step… find observational signatures of these two different formation mechanisms, by studying metallicity gradients, V/σ … (Cardona-Barrero's Master Project)

Metallicity



Stellar V/σ


UDGs
LSBs
$\left(\frac{V}{\sigma}\right)$
ϵ
2.5
2.0
1.5
1.0
0.5
0.0
0.25
0.30
0.35
0.40
0.45
0.50
0.55
9
8
7
6
5
4
3
2
1