האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

A simulation view on the formation of ultra-diffuse galaxies in the field and in galaxy groups

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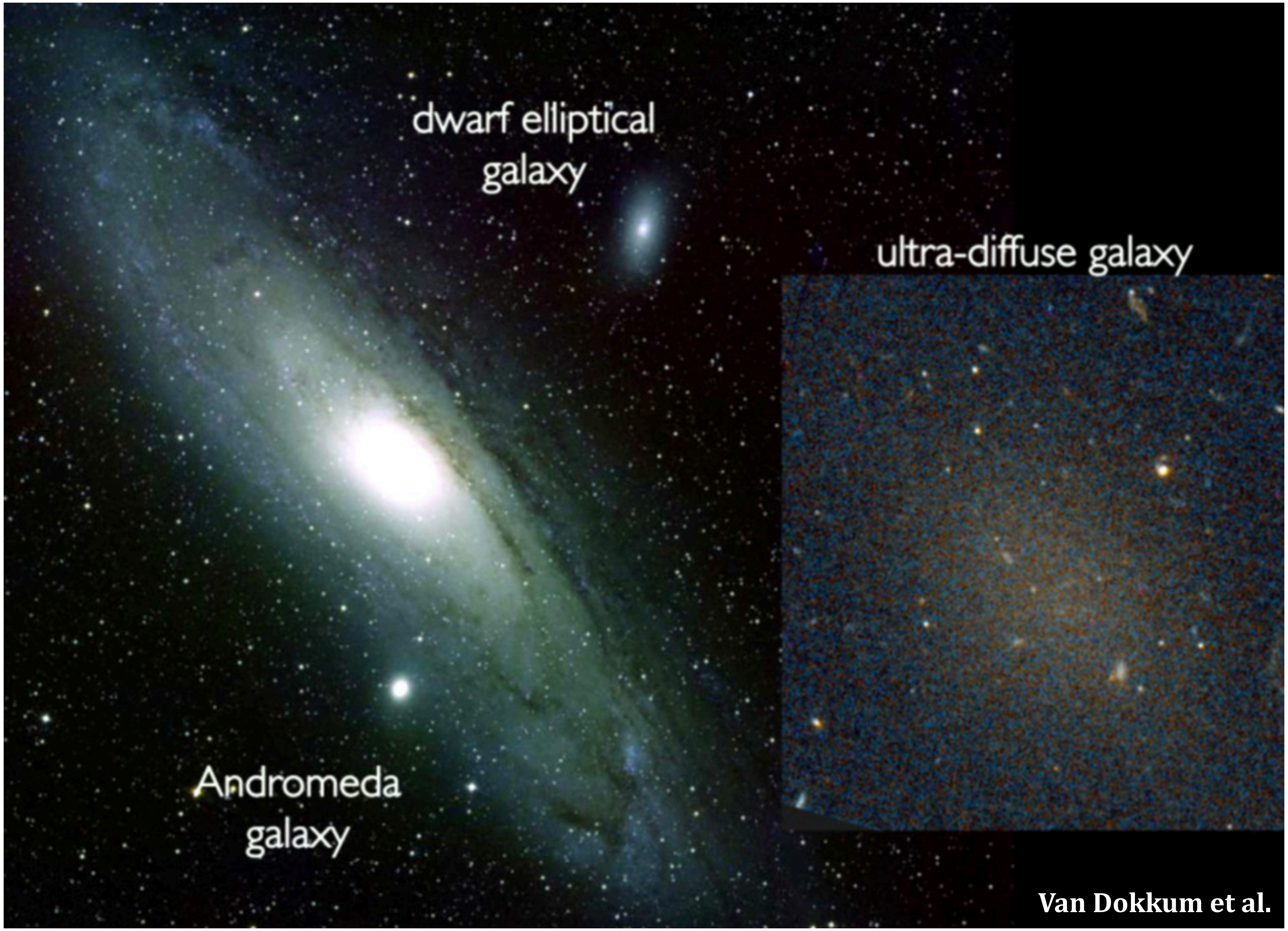
Ultra Diffuse Galaxies (UDGs)



✦ **Low surface brightness**
$\mu_0 > 24 \text{ mag . arcsec}^{-2}$

✦ **Stellar masses of dwarf galaxies**
$7 < \log(M_{\rm star}/M_\odot) < 9$

✦ **Effective radii of MW-sized objects**
$1 < r_{\rm eff}/\text{kpc} < 5$

Some facts about UDGs

Spatial distribution of UDGs

✦ Ubiquitous in clusters

✦ Present in the field
(e.g. van Dokkum+15, Koda+15, Martinez-Delgado+16, Leisman+17, Shi+17, Greco+17)

Shape

✦ $n_{\text{Sérsic}} \sim 0.8$
(e.g. van Dokkum+15, Mowla+17)

Stellar age

✦ Intermediate to old in groups

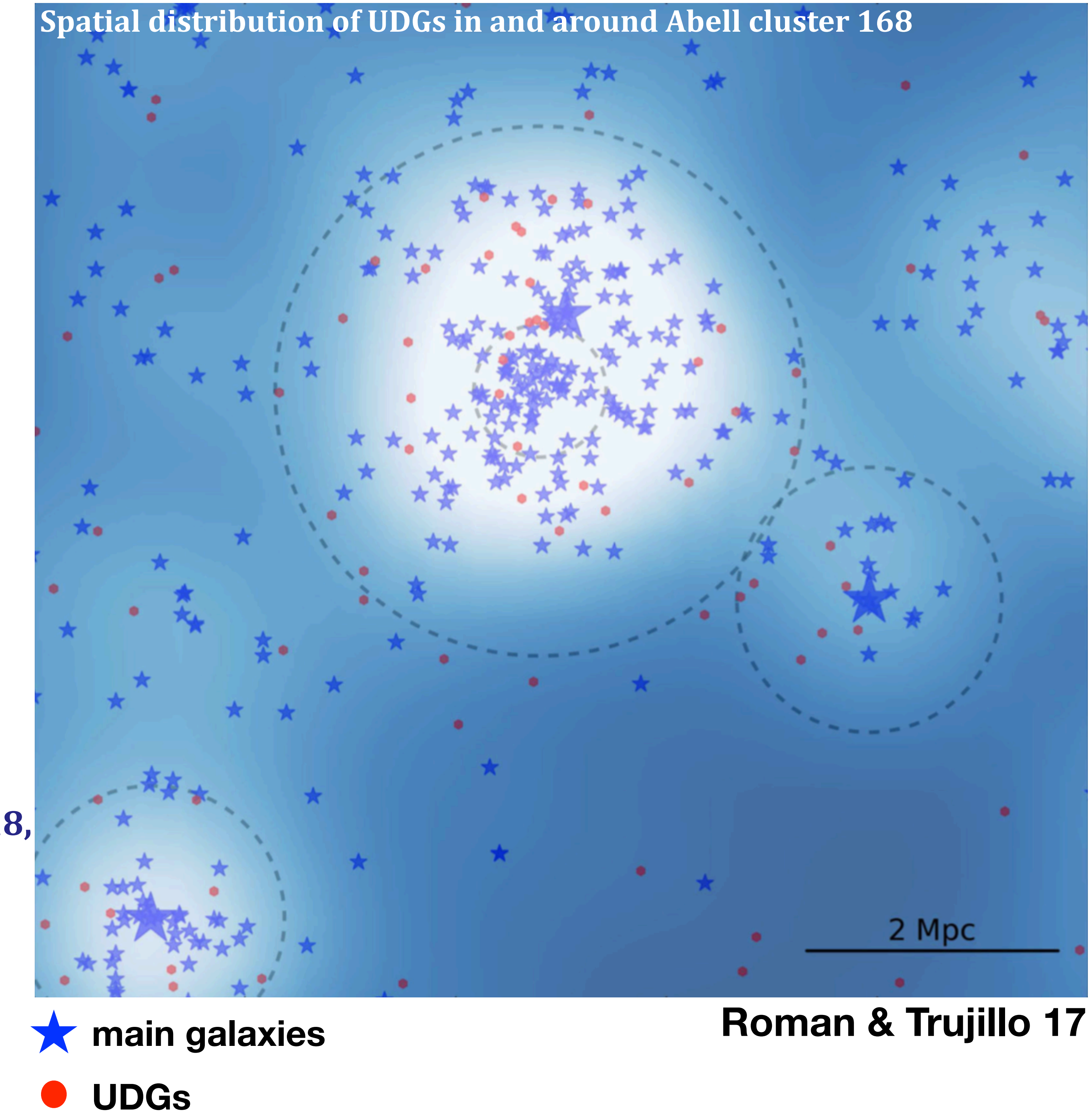
✦ Possibly younger in the field

✦ Older & redder towards the center
(e.g. Gu+17, Pandya+17, Alabi+18, Ferre-Mateu+18, Ruiz-Lara+18)

Star formation

✦ Possible recent or ongoing star formation

✦ Possible significant HI content
(e.g. Janowiecki+15, Leisman+17 with ALFALFA, Trujillo+17, Shi+17, Pandya+17)

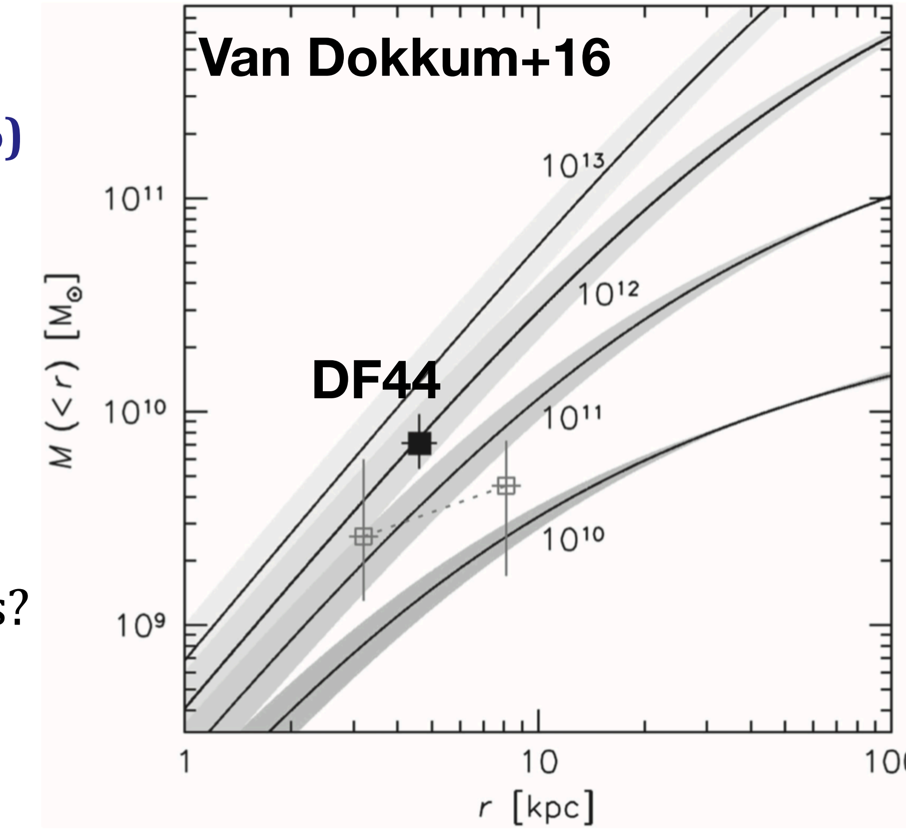


Roman & Trujillo 17

Some questions about UDGs

✦ **Are UDGs puffed-up dwarfs or failed L* galaxies?**

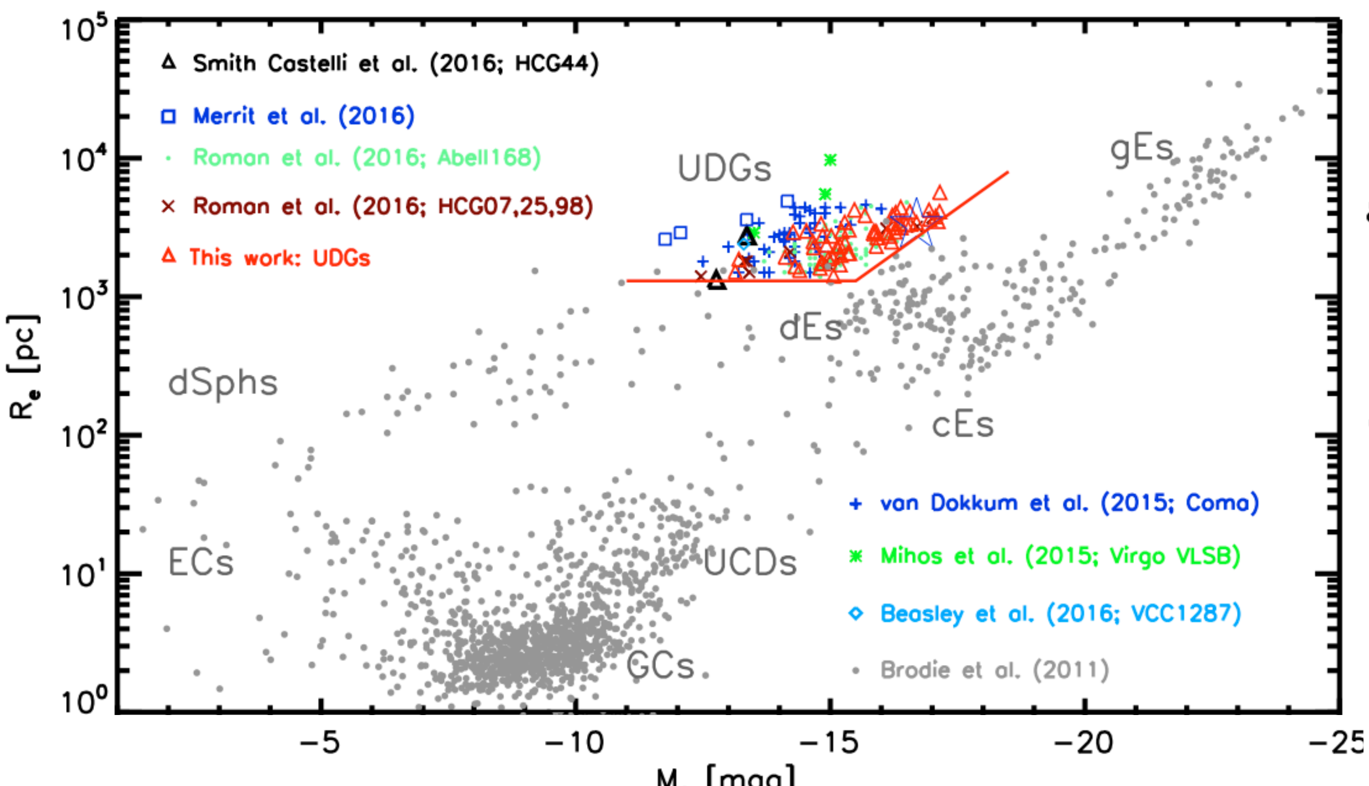
- DF44 halo mass compatible with a **MW-like halo mass** **(van Dokkum+16)**
- **High globular cluster abundance** **(Harris+17)**
- But **variability in the number of globular clusters** **(Lim & Peng 18)**

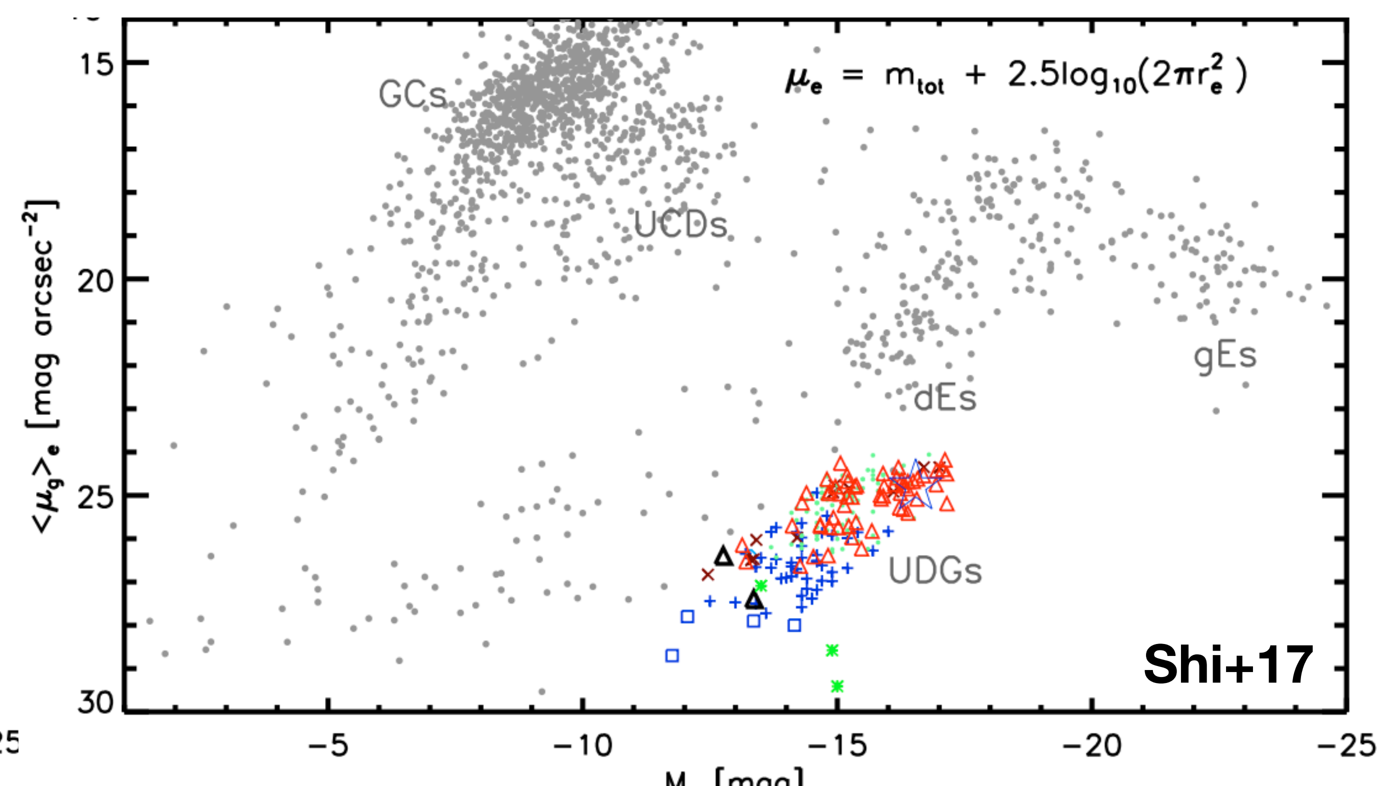


✦ **Are UDGs distinct from the overall galaxy population?**

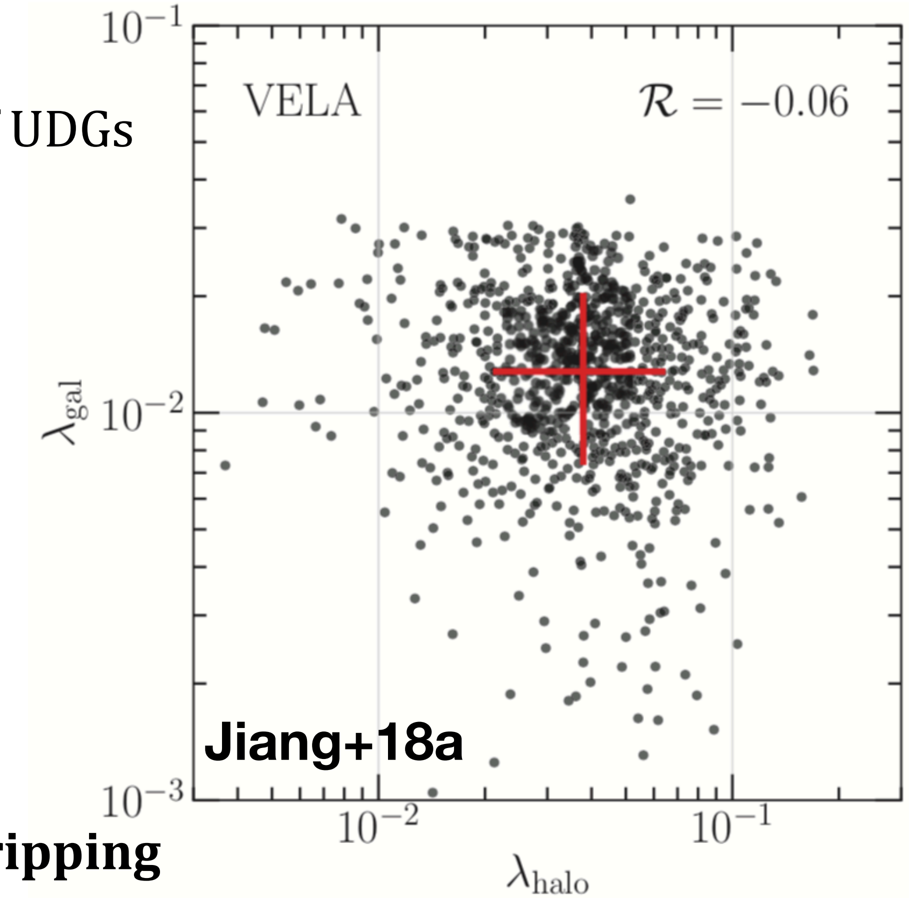
✦ **How do UDGs form and evolve?**

- **Failed MW-like galaxies** that lost their gas after forming their first stars? **(van Dokkum+15)**
- **High-spin tail** of the dwarf galaxy population **(Amorisco & Loeb 16)**
- **Tidal debris** from mergers or tidally-disrupted dwarfs **(Greco+17)**
- **Outflows from stellar feedback** **(Di Cintio+17)**





UDGs in semi-analytical models and simulations



✦ Semi-analytical models

- **Amorisco & Loeb 16**: the high halo spin tail reproduces the abundance of UDGs
- **Rong+17**: UDGs have larger spin and later formation
- But **you get what you put in** and λ_{gal} may not be proportional to λ_{halo} **(cf. Jiang+18a)**

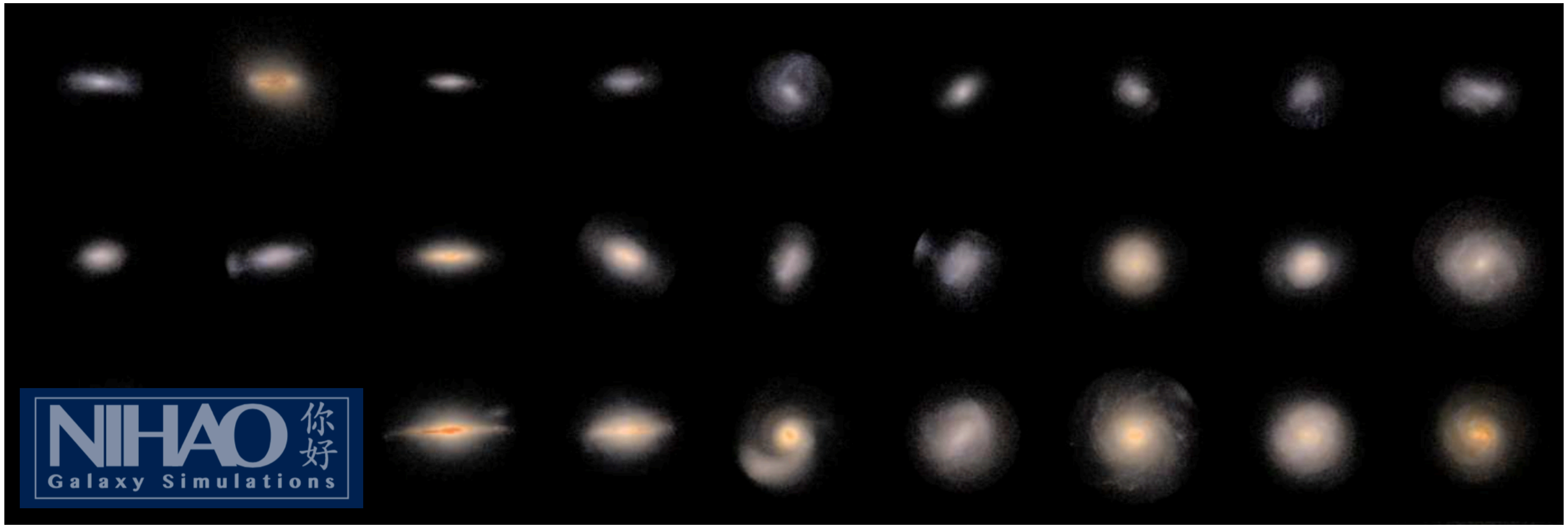
✦ Simulations of UDGs in the field

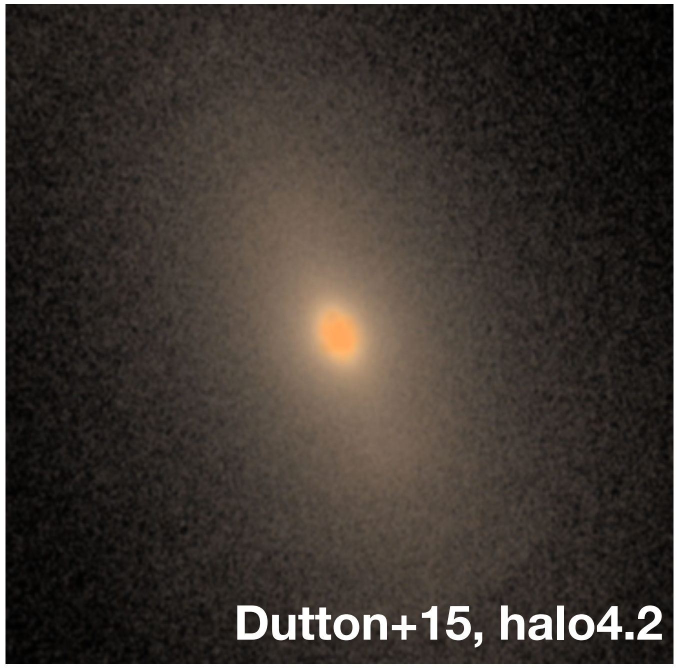
- **Di Cintio+17** and **this work*** with the NIHAO simulations **(Wang+15)**
- **Chan+18** with post-processed FIRE simulations
- **Field UDG formation from outflow episodes**

✦ Simulations of UDGs in groups

- **This work*** with a NIHAO-like group **(Dutton+15)**
- **UDG formation from tidal heating and quenching by ram-pressure stripping**

***Jiang, Dekel, Freundlich et al. 2018, arXiv:1811.10607**
Freundlich, Dekel, Jiang et al. 2019, in prep.





NIHAO UDGs in the field

✦ **The NIHAO simulations**

- About 90 cosmological zoom-in hydrodynamical simulations of galaxies
- Smoothed Particle Hydrodynamics code Gasoline2
- ΛCDM cosmology (Planck collaboration 2014)
- Turbulent mixing, cooling, UV background, star formation, chemical enrichment
- **Ionizing feedback from massive stars and blast-wave SN feedback**
- With and without baryons
- **Spatial resolution 1% of the virial radius**
- **logMvir = 9.5-12.3**

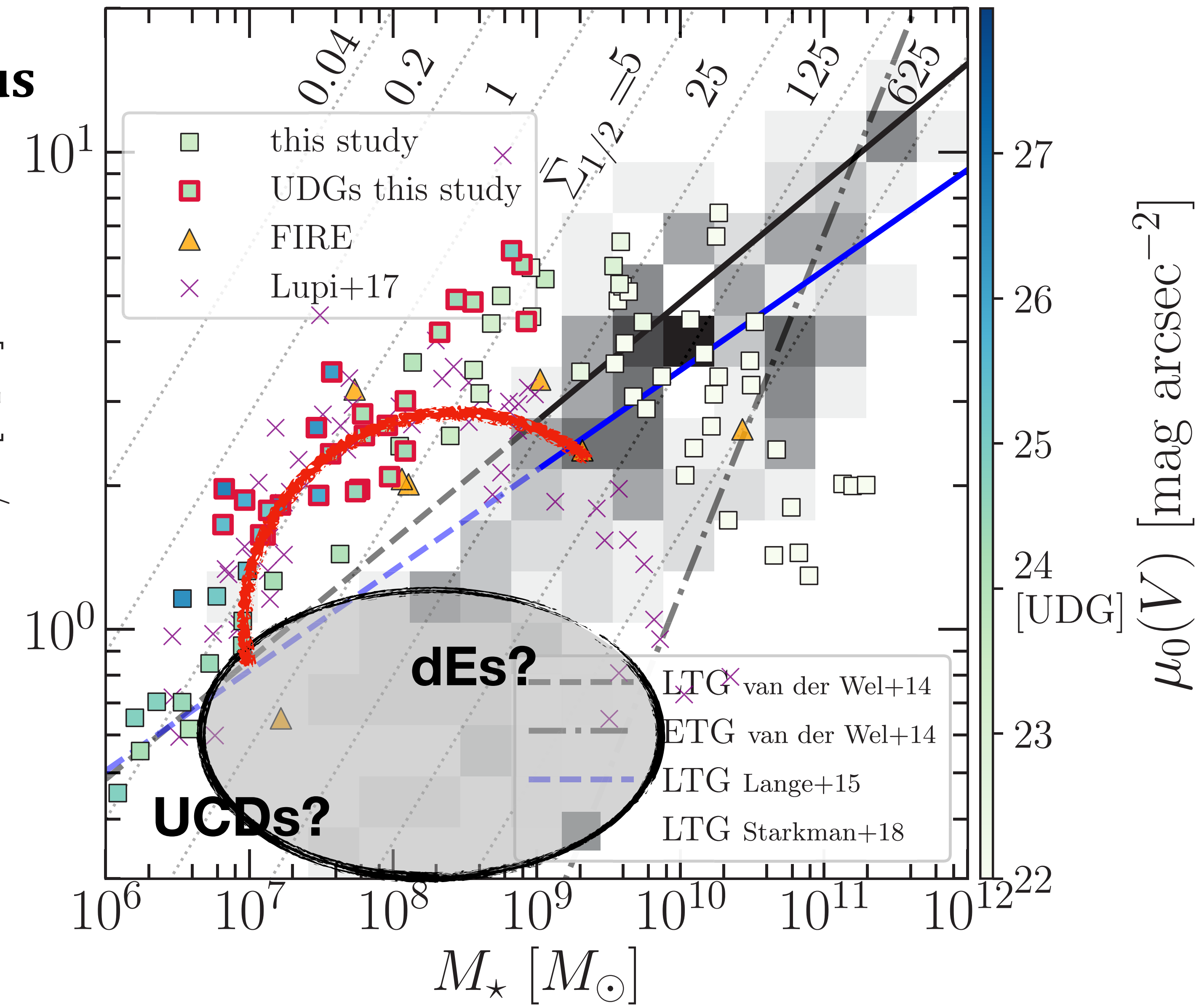
✦ **UDG definition**

$\mu_{0(V)}$ >24 mag/arcsec²
r_e > 1.5 kpc

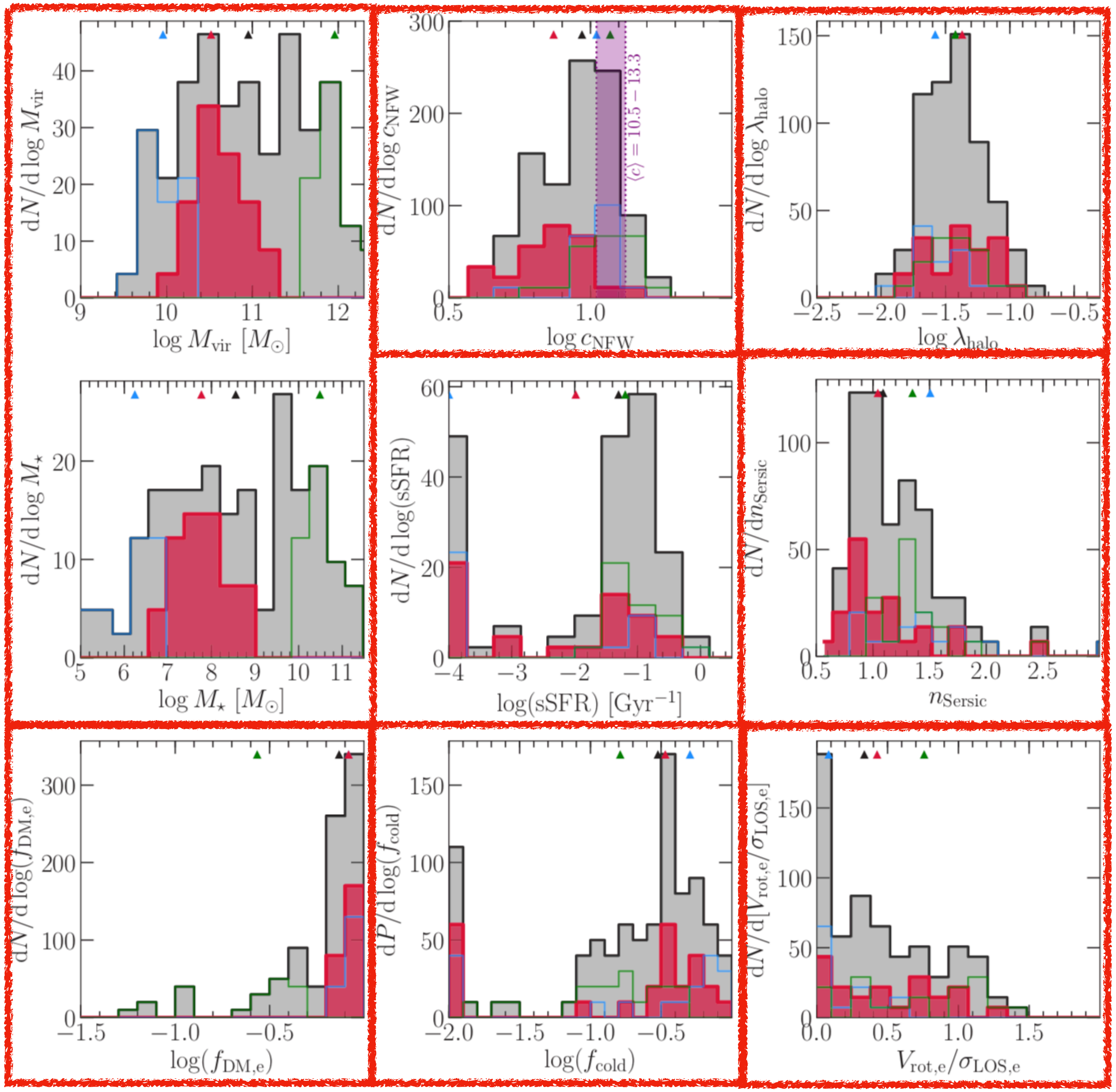
- At least 250 DM particles
- At least 50 stellar particles

✦ **Mass range: logMstar=7-9**

- Dominated by diffuse systems, no compact dwarfs: too strong feedback? flawed star formation recipe? (not just for NIHAO)



NIHAO UDGs in the field



- ✦ **Relatively narrow range in Mvir, Mstar**
- ✦ **Average halo spin**
- ✦ **Lower halo concentration**
- ✦ **High DM fraction**
- ✦ **$n_{Sérsic}$ ~ 1 lower than non-UDGs**
- ✦ **Average v/σ**
- ✦ **High cold gas fraction (T<1.5 10^4 K)**
- ✦ **Wide range in sSFR & color**

All NIHAO galaxies

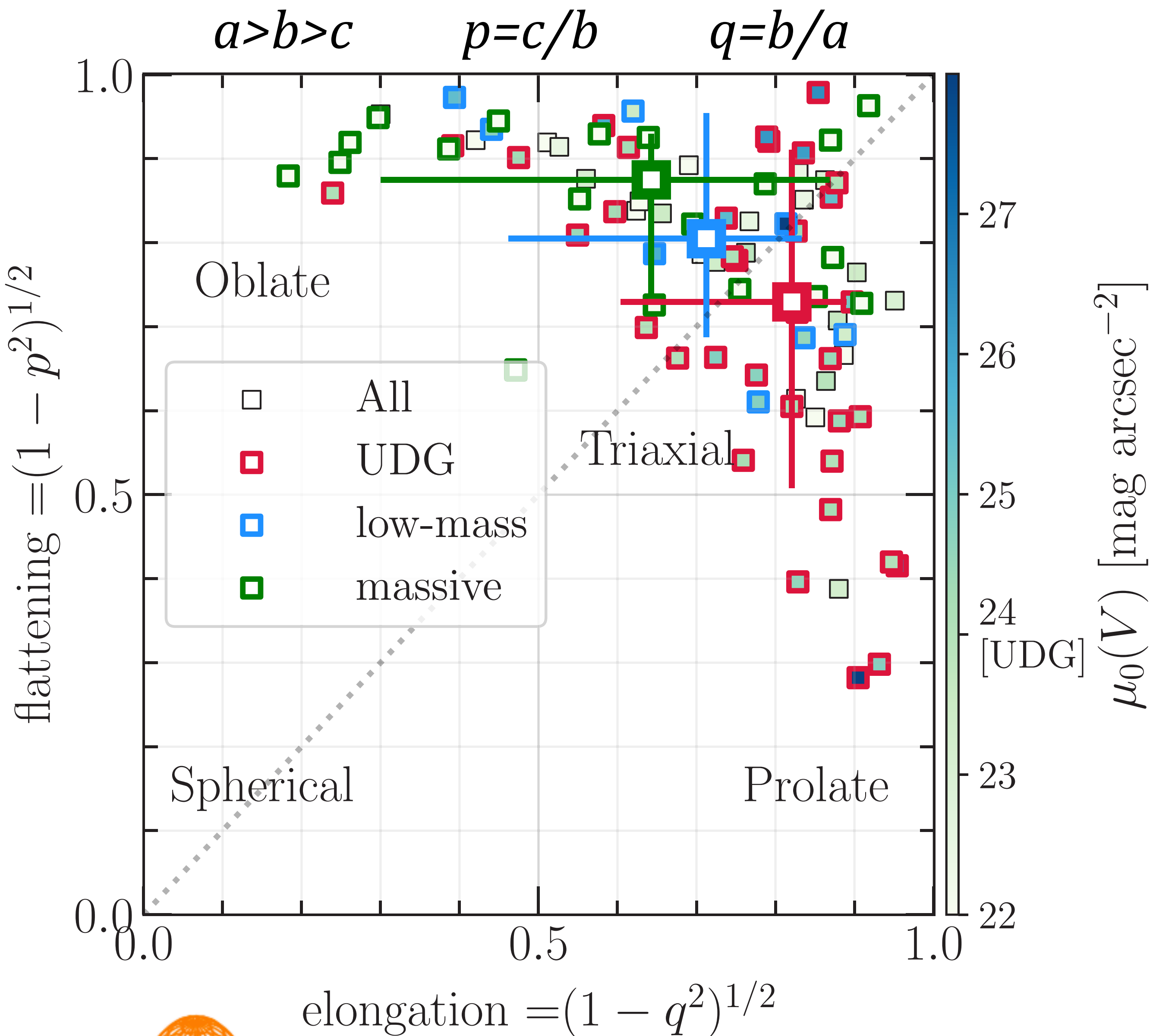
UDGs:
$r_{1/2} > 1.5\text{kpc}, \mu_0(V) > 24$ mag/arcsec^{-2}

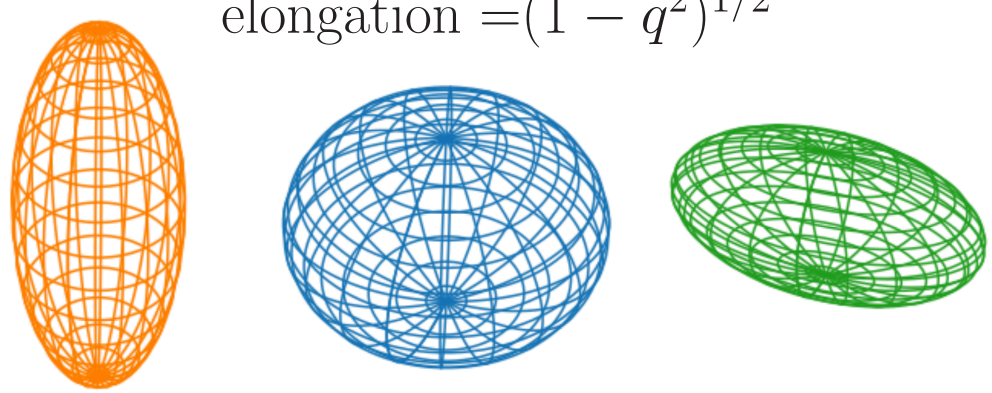
low-mass non-UDGs:
$M_{vir} < 10^{10.3} M_\odot$ & $M_\star < 10^7 M_\odot$

massive non-UDGs:
$M_{vir} > 10^{11.5} M_\odot$ & $M_\star > 10^{10} M_\odot$

NIHAO UDGs in the field

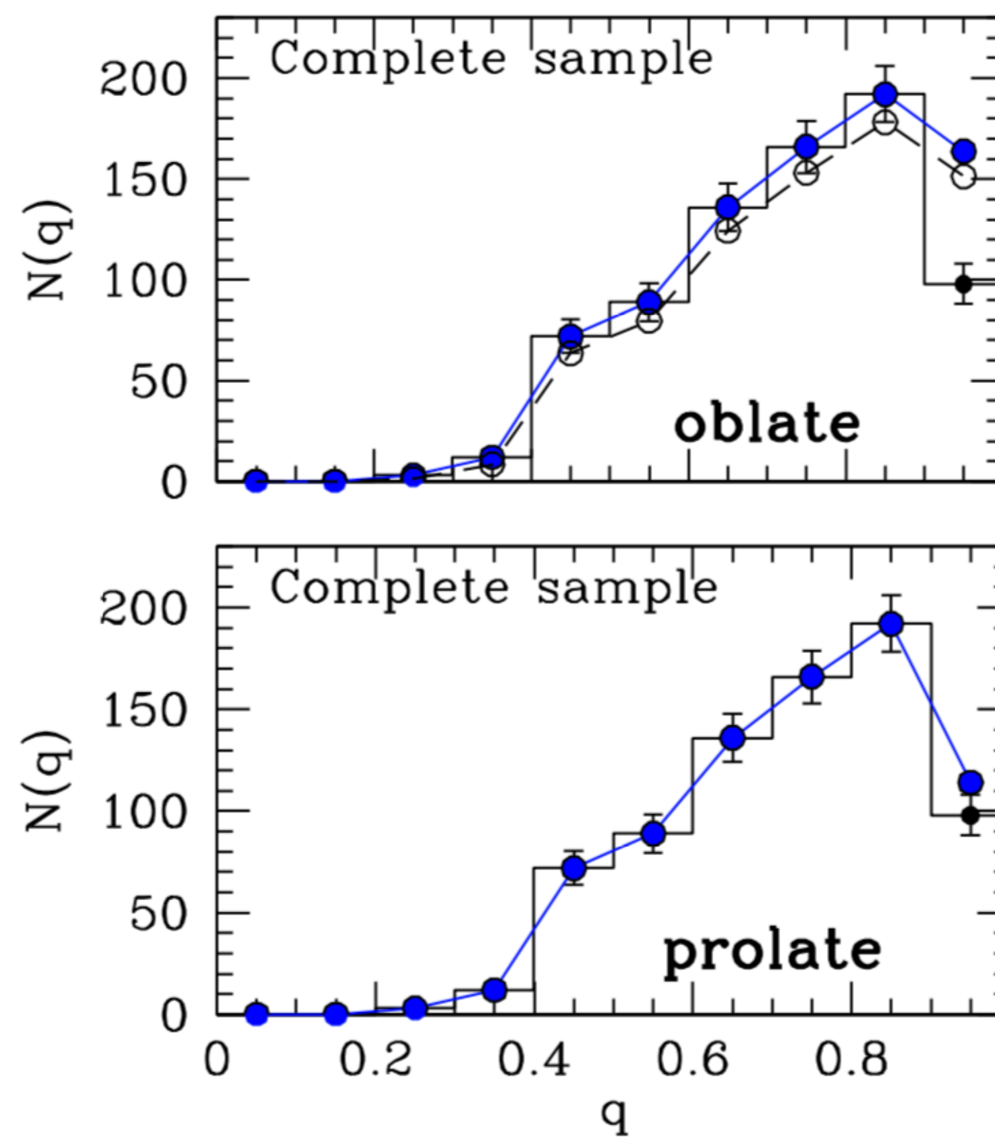
✦ **UDGs have a slightly more prolate stellar distribution**





prolate oblate triaxial

✦ **Burkert 17:** the distribution of axis ratios in Coma UDGs favours prolate systems

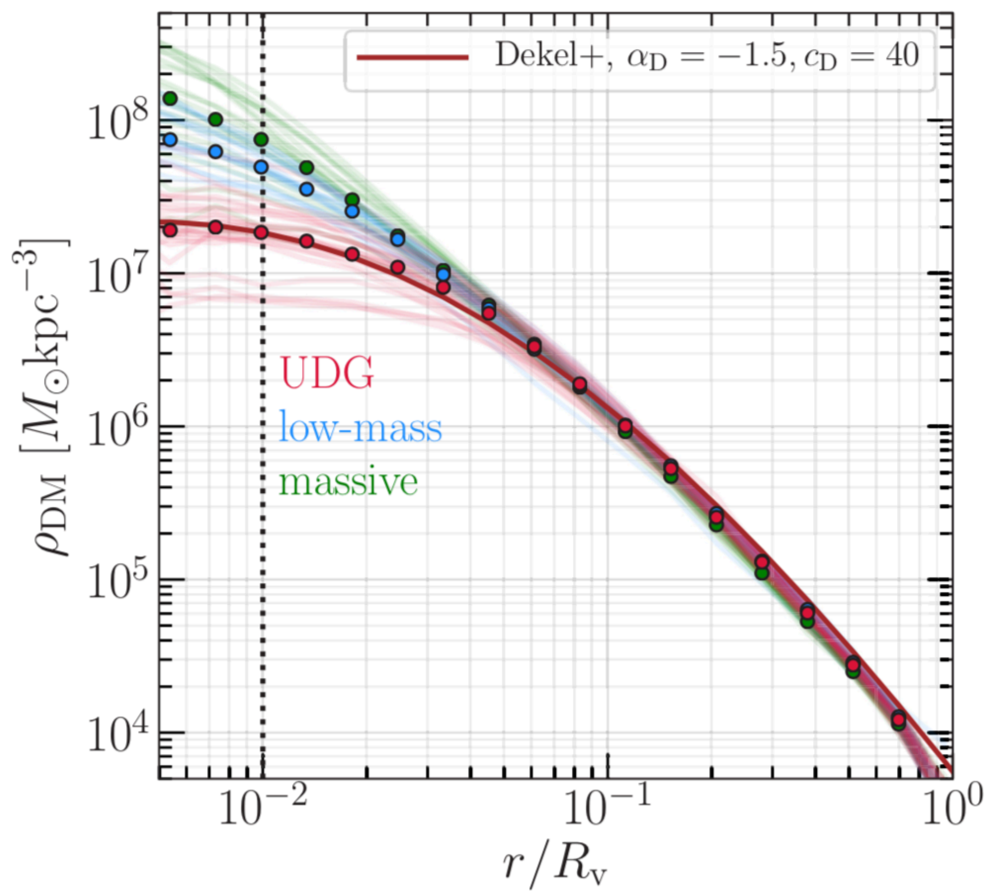


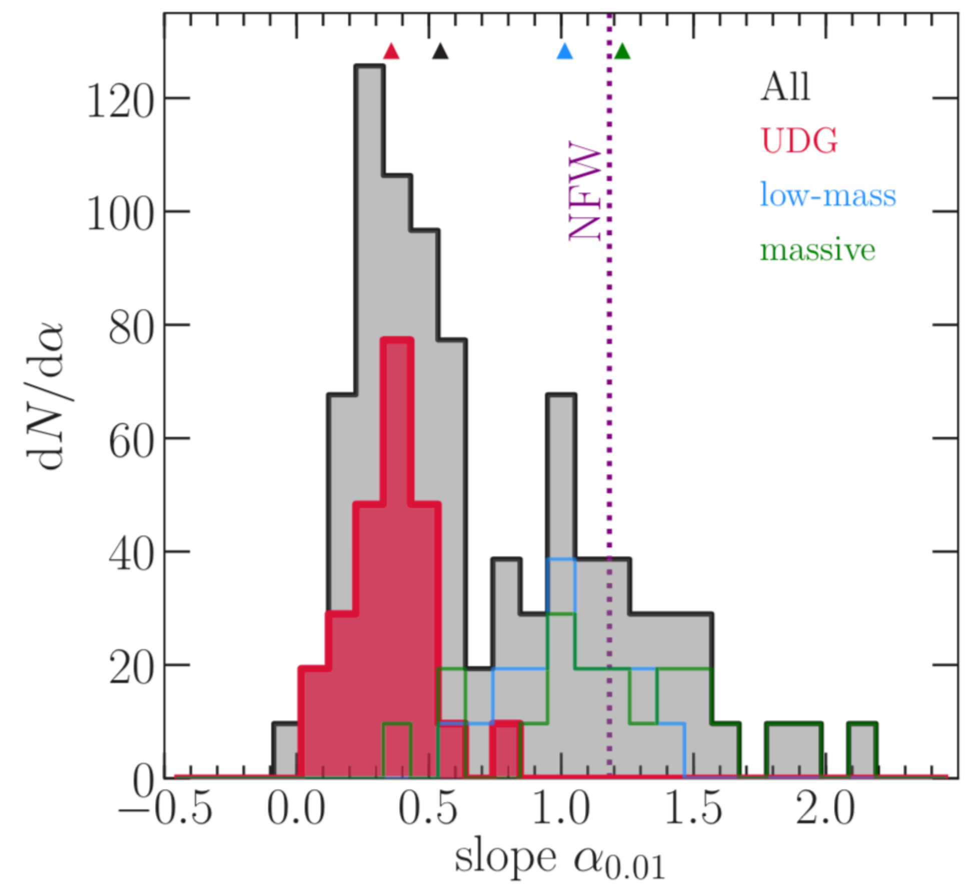
✦ **Why prolate?**

- Dispersion dominated?
- Anisotropic velocity dispersion?
- Puffed-up disk?
- Prolate DM halo?
- Tidal effects? (cf. Martinez-Delgado+16)

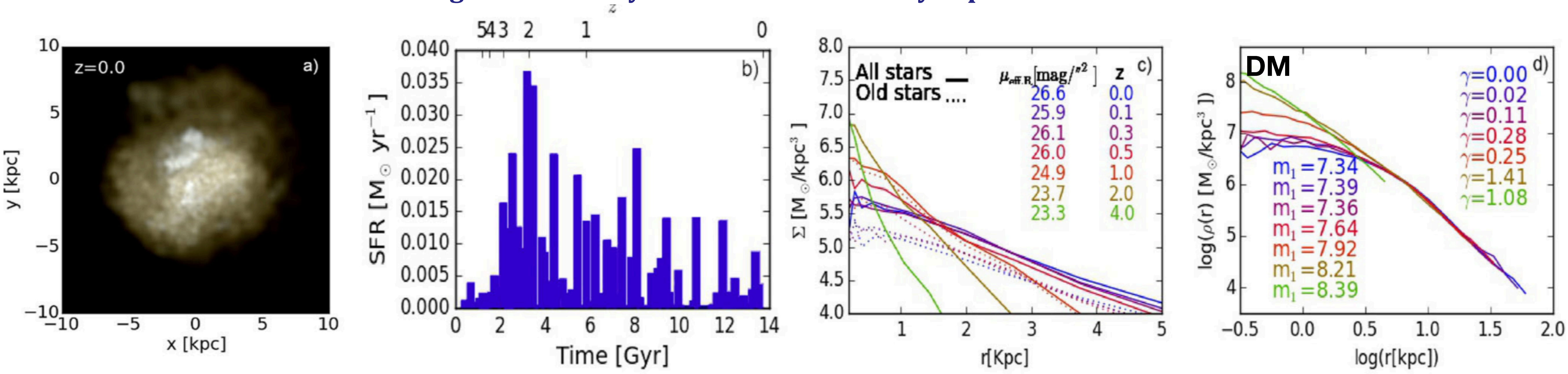
NIHAO UDGs in the field

✦ **Cored DM density profile**





✦ **Di Cintio+17: Outflows resulting from a bursty star formation history expand both the stellar and the DM distributions**



NIHAO UDGs in the field

A toy model for core formation from outflow episodes (Freundlich, Dekel, Jiang+ in prep.)

Evolution of a spherical shell encompassing a collisionless mass M when a baryonic mass m is removed (or added) at the center

- **Adiabatic mass change**
  Conservation of the angular momentum on circular orbits $L \propto rv = \sqrt{GMr}$

$$\frac{r_f}{r_i} = \frac{M}{M+m} = \frac{1}{1+f} \quad \text{with} \quad f = \frac{m}{M}$$

cf. Presentation on Friday

- **Instant mass change**

1) Initial conditions at equilibrium

$$E_i(r_i) = U_i(r_i) + K_i(r_i)$$

2) Immediately after the mass change

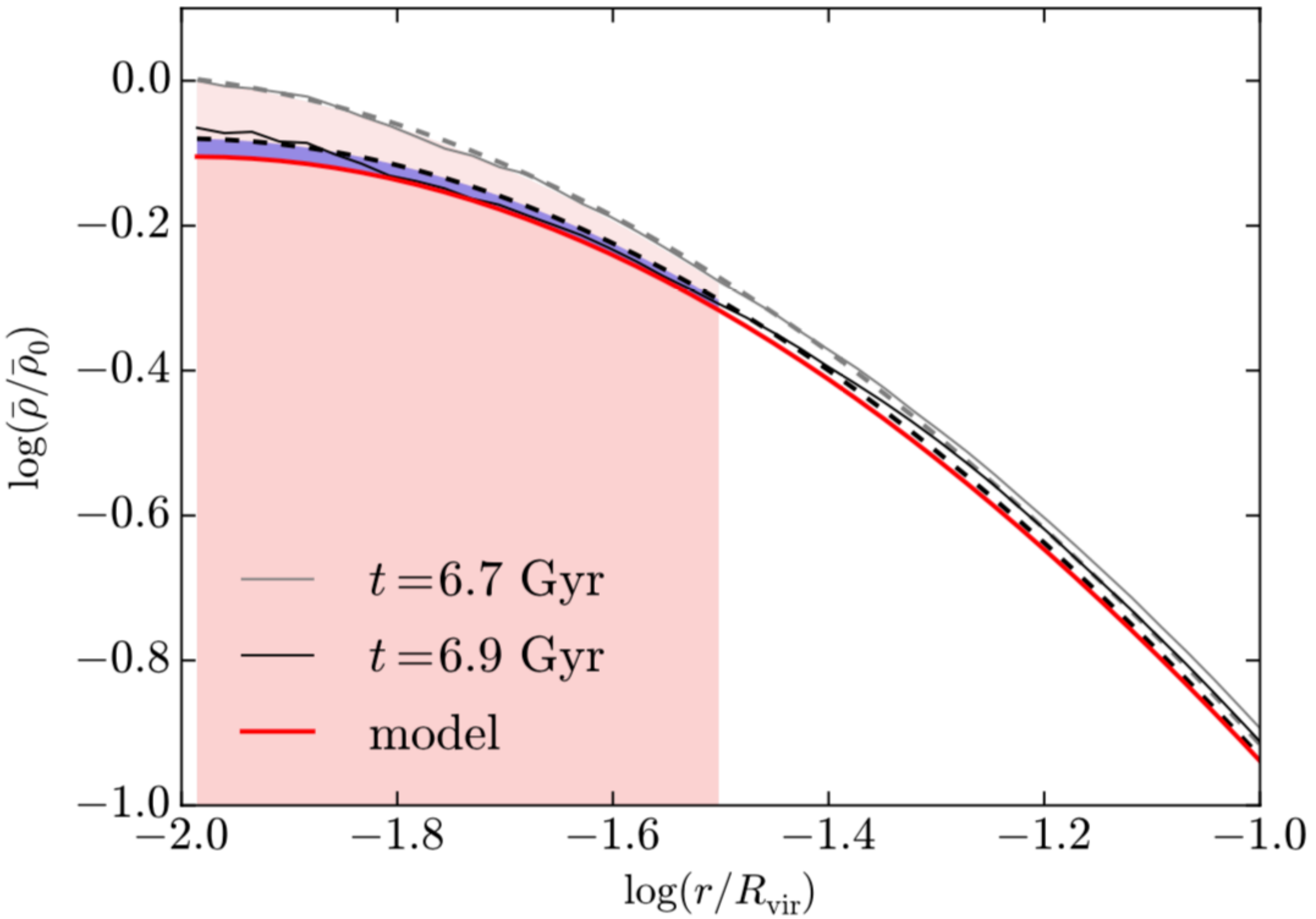
$$E_t(r_i) = U_i(r_i) - Gm/r_i + K_i(r_i)$$

3) The system relaxes to a new equilibrium

$$E_f(r_f) = U_f(r_f) - Gm/r_f + K_f(r_f)$$

where K can be expressed from the mass distribution through the Jeans equation

Given functional forms *U(r;p)* and *K(r;p,m)*, energy conservation $E_f(r_f) = E_i(r_i)$ yields the final state



NIHAO UDGs in the field

A toy model for core formation from stochastic density fluctuations (El-Zant, Freundlich & Combes 16)

The gravitational potential fluctuations arise from feedback-induced stochastic density fluctuations and deviate DM particles from their trajectories as in a diffusion process.

Fourier decomposition of the density contrast:

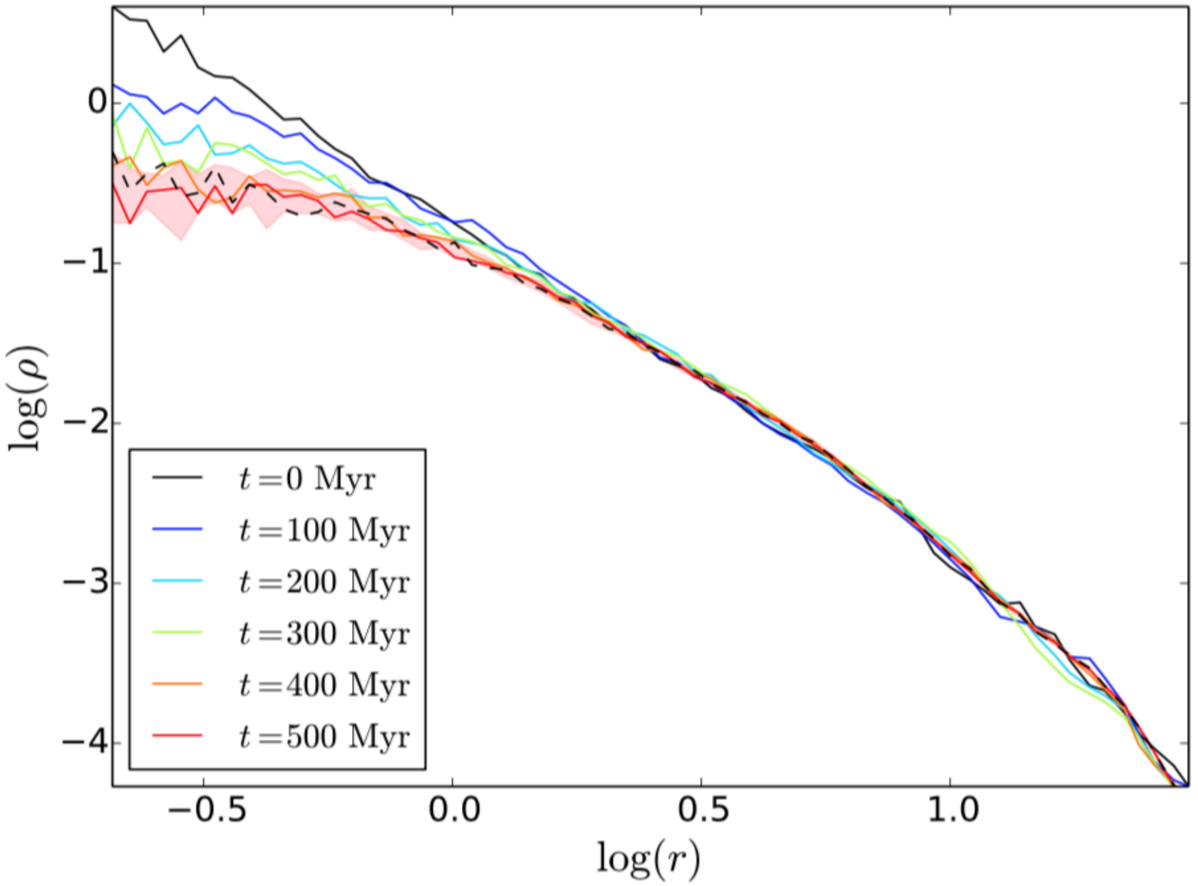
$$\delta(\vec{r}) = \frac{V}{(2\pi)^3} \int \delta_{\vec{k}} \, e^{i\vec{k}.\vec{r}} \, d^3\vec{k}$$

Each perturbation $\delta_{\vec{k}}$ induces a **'kick'**

$$\vec{F}_{\vec{k}} = 4\pi i \; G\rho_0 \; \vec{k} \; k^{-2} \; \delta_{\vec{k}}$$

Which cumulatively induces the dark matter particles to deviate from their trajectories by

$$\langle \Delta v^2 \rangle = 2 \int_0^T (T-t) \, \langle F(0)F(t) \rangle \; dt.$$



✦ **Assumptions:**

- Unperturbed homogeneous gaseous medium ρ_0
- Isotropic & stationary density fluctuations within d
- Power-law power spectrum $\langle |\delta_{\vec{k}}|^2 \rangle \propto k^{-n}$
- Minimum and maximum cutoff scales $\lambda_{min} \ll \lambda_{max}$

✦ **In the diffusion limit $\lambda_{max} \ll R$ we obtain the relaxation time**

$$t_{\rm relax} = \frac{n v_r \langle v \rangle^2}{8\pi (G\rho_0)^2 V \langle |\delta_{k_{min}}|^2 \rangle}$$

v_r: average DM velocity/fluctuating field;
$\langle v \rangle$: initial orbital velocity of the particle;
$V = d^3$; $k_{min} = 2\pi/\lambda_{max}$.

Cf. also **Bar-Or, Fouvry & Tremaine 18** and **El-Zant, Freundlich & Combes, in prep.** in the context of fuzzy dark matter.

UDGs in a NIHAO-like group

✦ Halo4.2 from Dutton+15

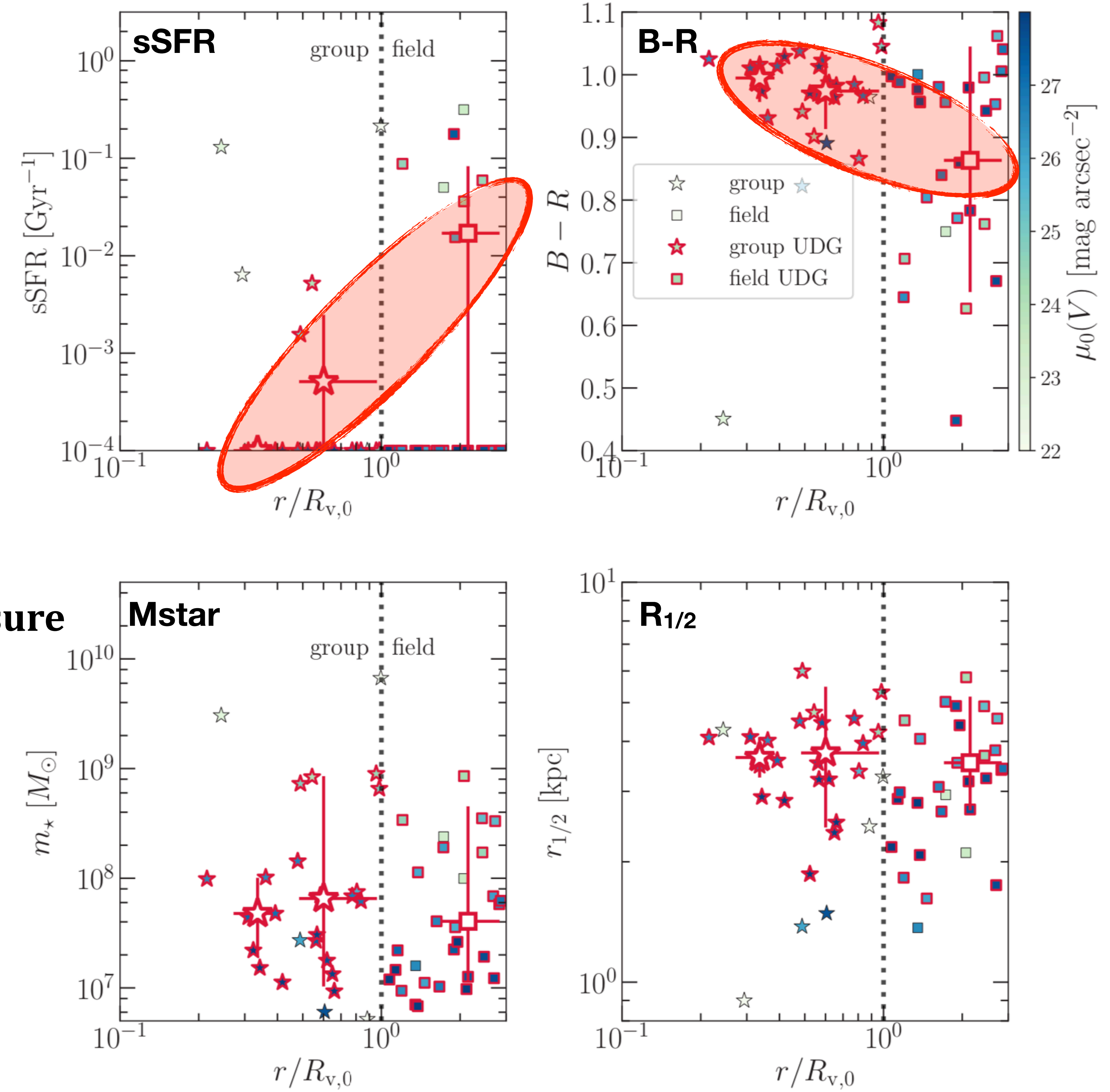
- logMvir = 13.3; Rvir=572 kpc
- Central galaxy logMstar=11.4
- Star formation and feedback similar to NIHAO
- 600 pc com. spatial resolution
- UDGs only marginally resolved at logMstar=7/logMvir=9

✦ Radial trends at *z=0*

- Color gradient as observed
- Strong sSFR gradient
- No trends in Mstar, $R_{1/2}$

✦ Tidal stripping vs. ram-pressure

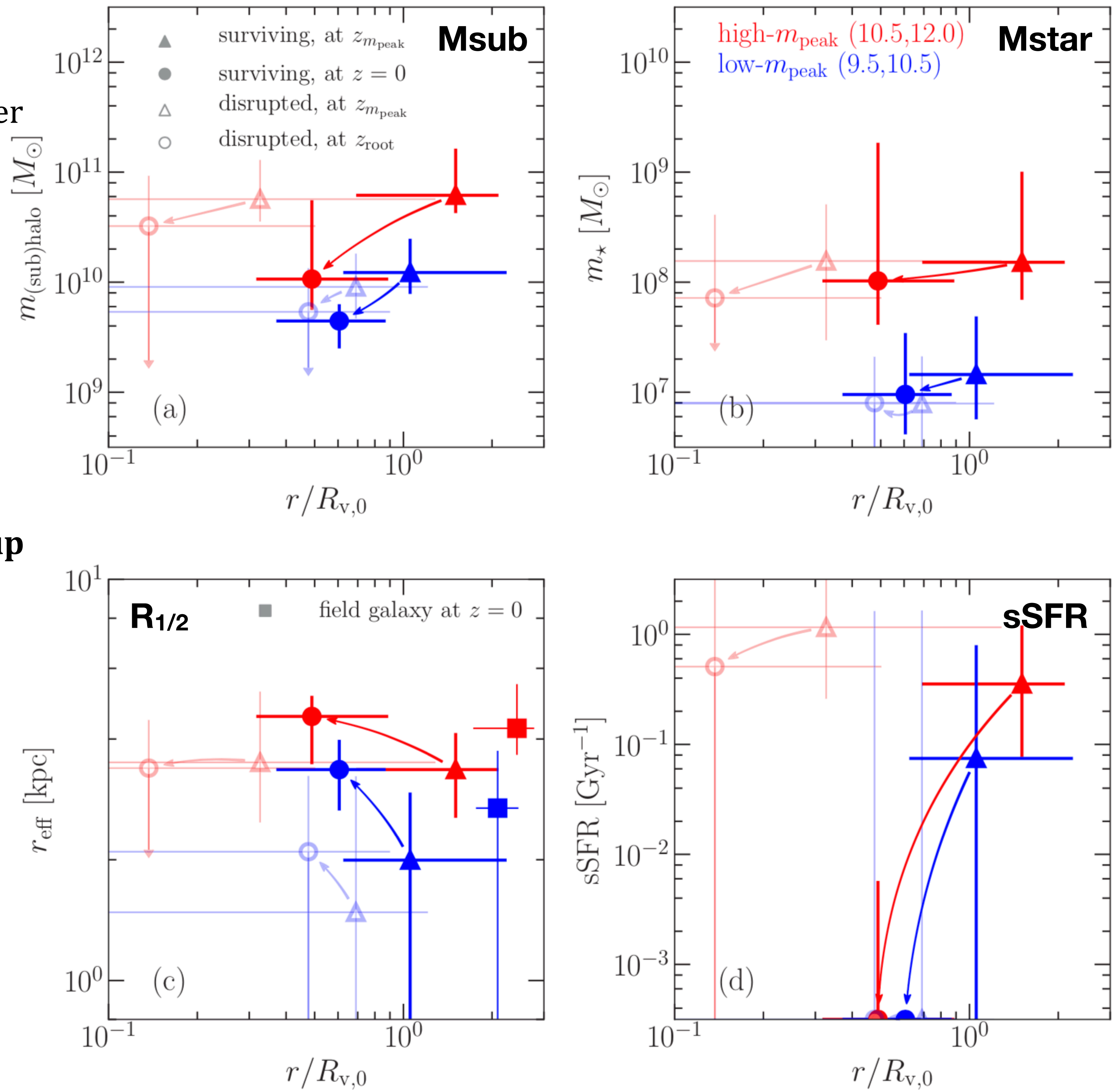
- sSFR trend from gas loss
- Tidal stripping would also affect Mstar
- Ram pressure stripping may be dominant to quench UDGs



UDGs in a NIHAO-like group

✦ **Average evolution from infall to *z=0* or disruption**
- Disruption occurs closer to the center
- High mass satellites more disrupted (dynamical friction stronger)
- **Weak stellar mass loss**
- **Size growth** (but progenitor bias)
- **Strong environmental quenching**

✦ **About 20% of all group UDGs survive,** out of which:
- **50% were accreted as UDGs**
- **50% became UDGs inside the group**

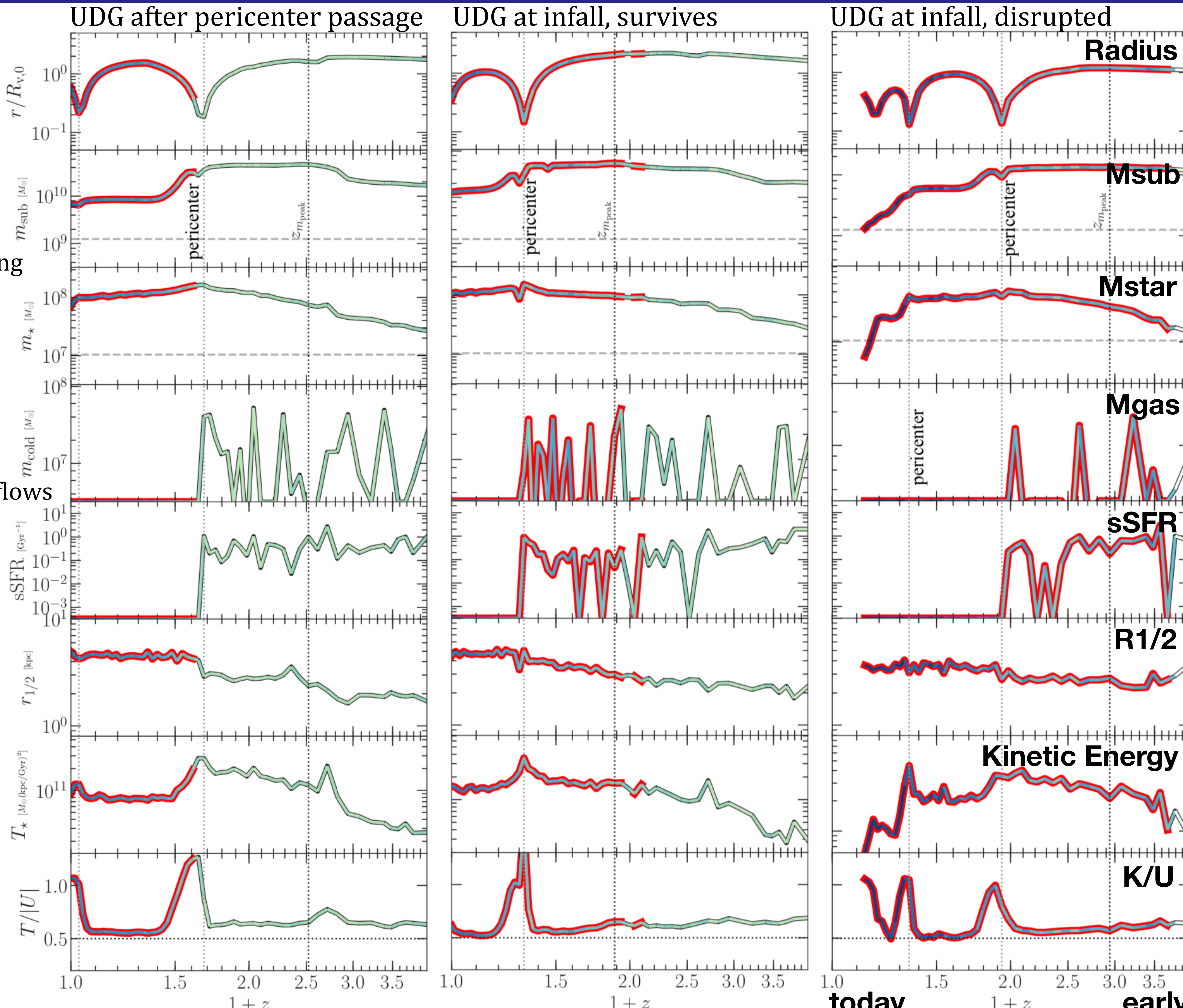


▲ infall
● *z=0*
○ disruption

✦ Exemples

UDG after pericenter:
- DM loss
- Gas removal
- Small Mstar change (ram pressure)
- Size growth
- Impulsive tidal heating

UDG at infall:
- Similar trends at pericenter
- Formed from SN outflows as field UDGs?



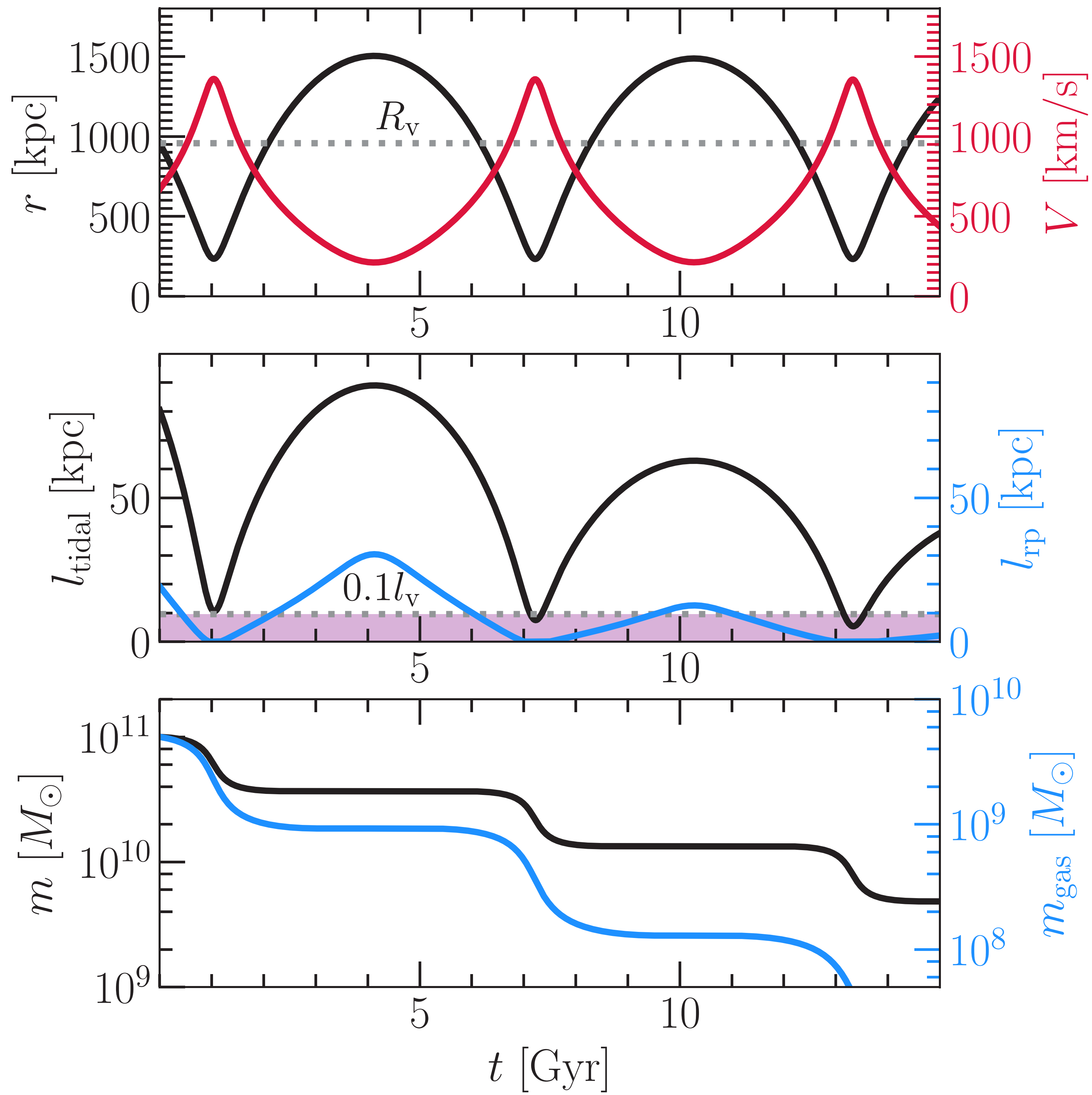
UDGs in a NIHAO-like group

✦ Tidal stripping vs. ram-pressure (model)

- **Tidal radius (l_{tidal}):** where self-gravity is balanced by the tidal force
- **Ram-pressure radius (l_{rp})**: where the self-gravity restoring force per unit area is equal to the ram pressure

A UDG-sized NFW satellite (logMvir=11, c=10) orbiting a massive host (logMvir=13, c=5) on a typical orbit.

- **The ram-pressure radius is always smaller than the tidal radius**
- **Ram pressure stripping dominant for quenching satellites**



Summary

✦ **How do UDGs form (in the NIHAO simulations)?**

- **In the field:**
  bursty star formation > repeated SN outflows/density fluctuations > stellar expansion
  Consequence: field UDGs should have cored DM distributions

- **In groups:**
  field UDGs can survive + tidal puffing-up at pericenter
  And quenching due to ram-pressure stripping

✦ **Are UDGs special (in the NIHAO simulations)?**

- **Not in halo spin**
- **But they reside in cored DM haloes, have more triaxial or prolate shape and a high DM fraction**

Jiang, Dekel, Freundlich et al. 2018, arXiv:1811.10607
Freundlich, Dekel, Jiang et al. 2019, in prep.