Supernovae Feedback II: Impact on Galaxies and Host Halos

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Lecture Notes for Advanced Cosmology 2019
Hebrew University of Jerusalem

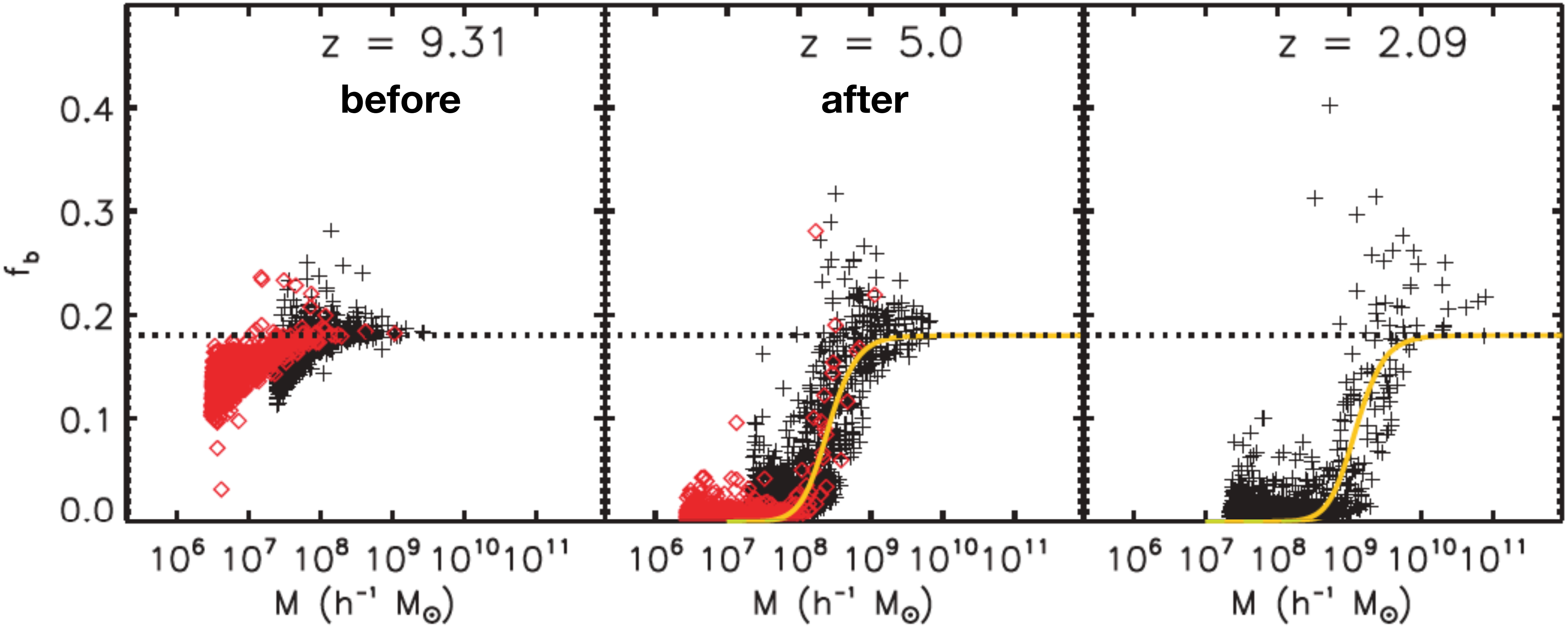
Outline

- What is “feedback”?
- Why do we need feedback?
- How does SN feedback work? (analytic arguments, simulations)
- Impact on galaxies (ultra-diffuse galaxies)
- Impact on dark-matter halos (cusp-core issue)

What is feedback?

Feedback (fdbk) is a process that regulates the growth of galaxies, suppressing (negative fdbk) or boosting (positive fdbk) star formation

- Photoheating (UV background) fdbk:
  - Reionization heats the gas in the IGM to ~10^4K
  - DM halos with a “virial temperature” less than 10^4K cannot retain baryons. ($T=10^4$K ~ $V=20$km/s at $z_{\mathrm{reionization}}$)



- SN fdbk: SN goes off, heats the ISM, halts further star formation
- AGN fdbk: AGN releases energy that couples to gas, prevents star formation

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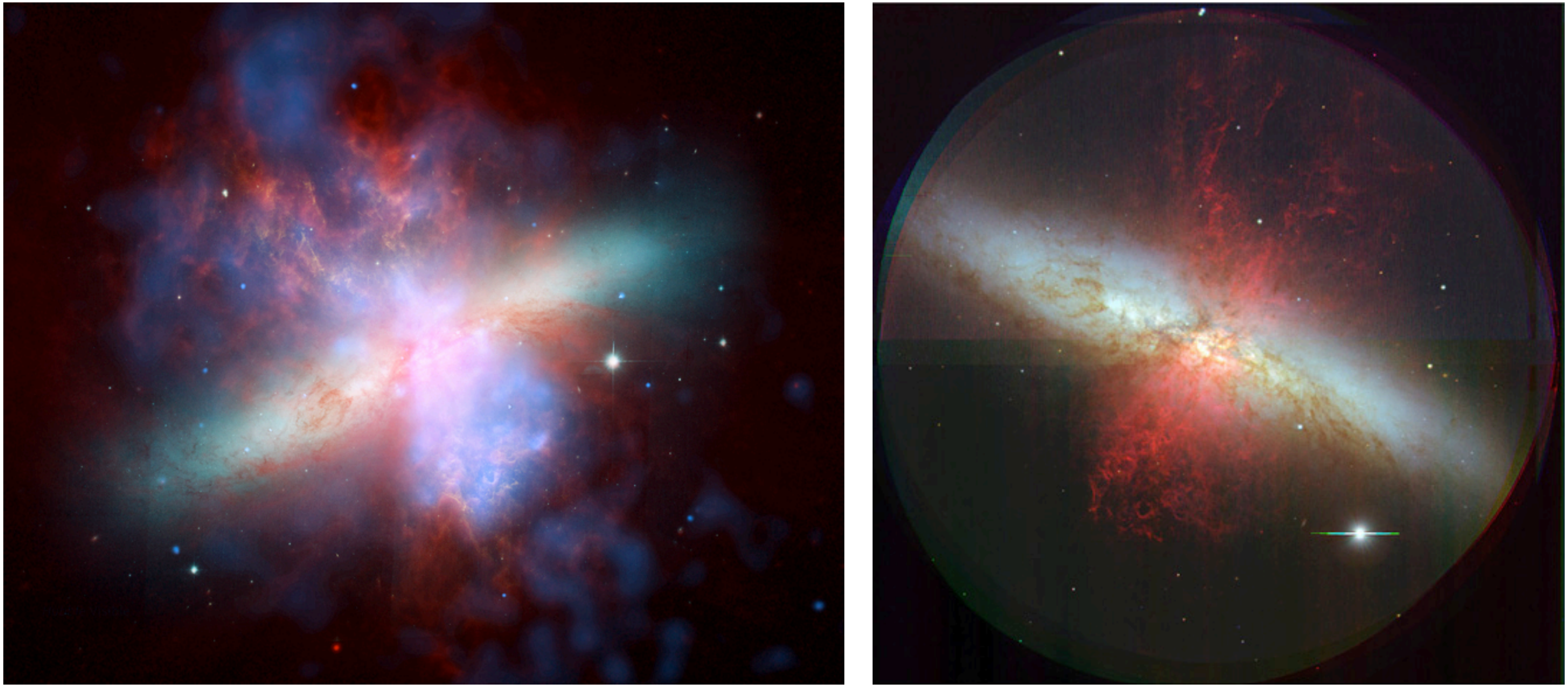
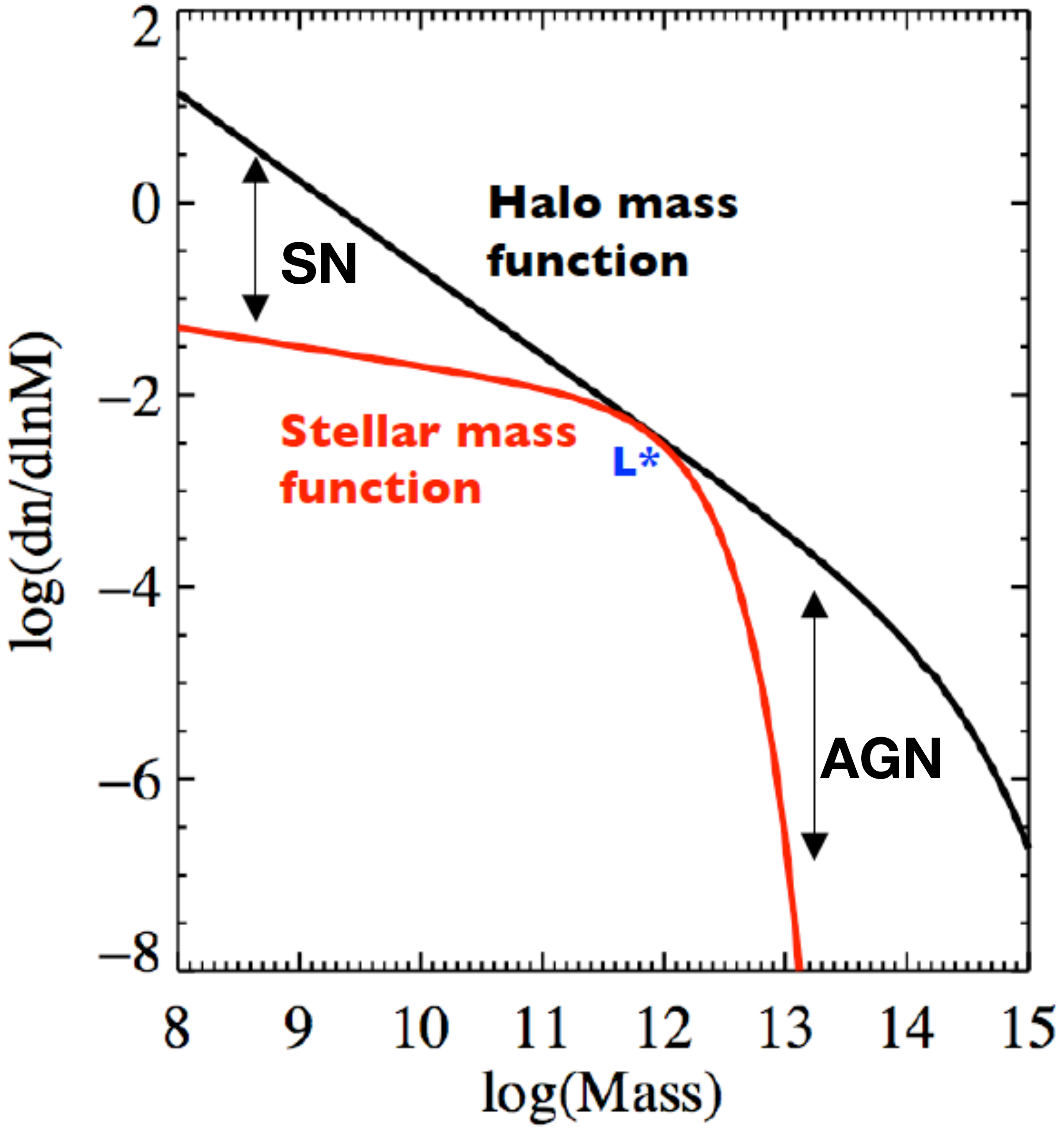


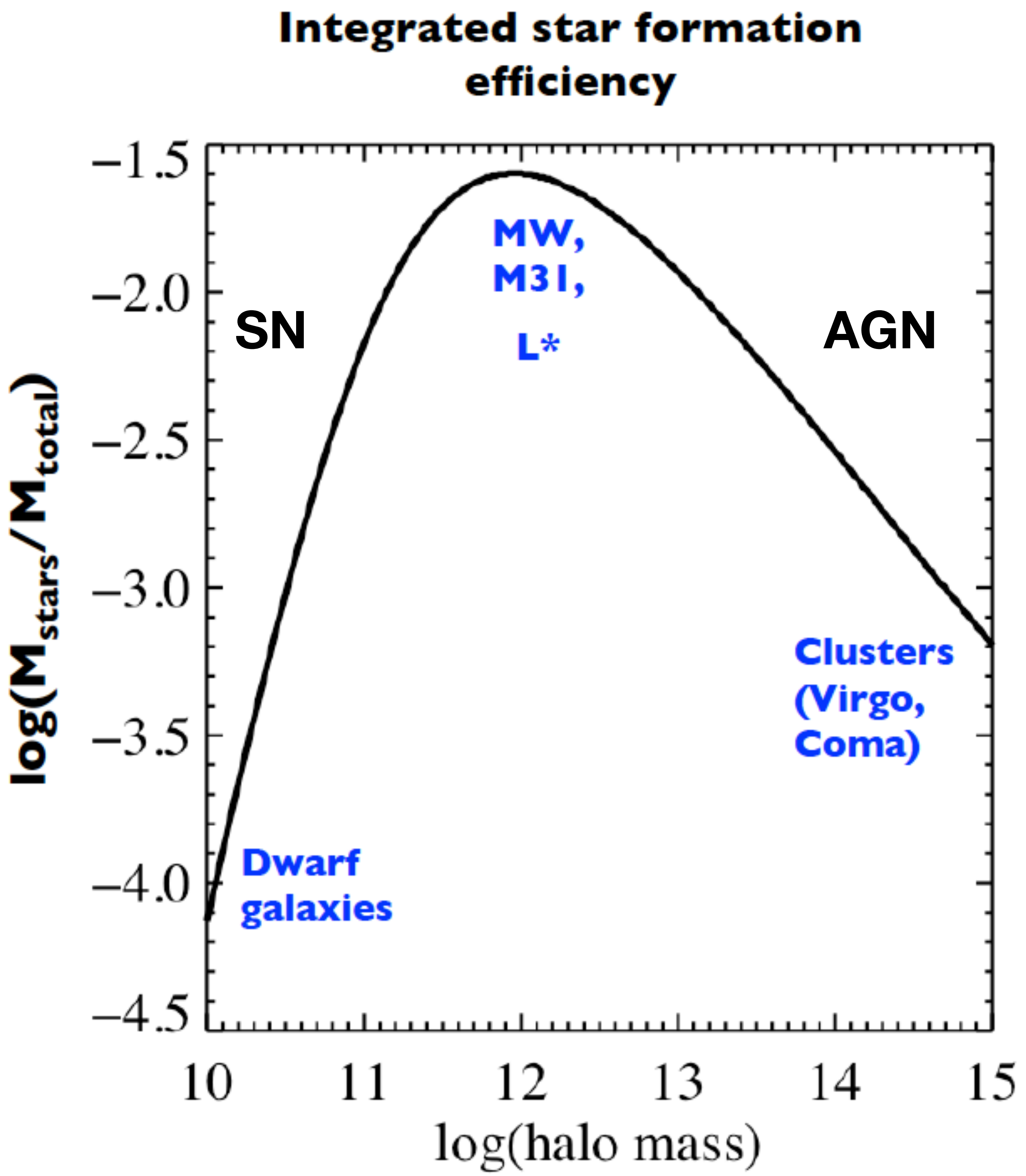
X-ray

Hα

M82: a massive starburst galaxy with obvious outflow

Why do we need feedback?




Integrated star formation efficiency

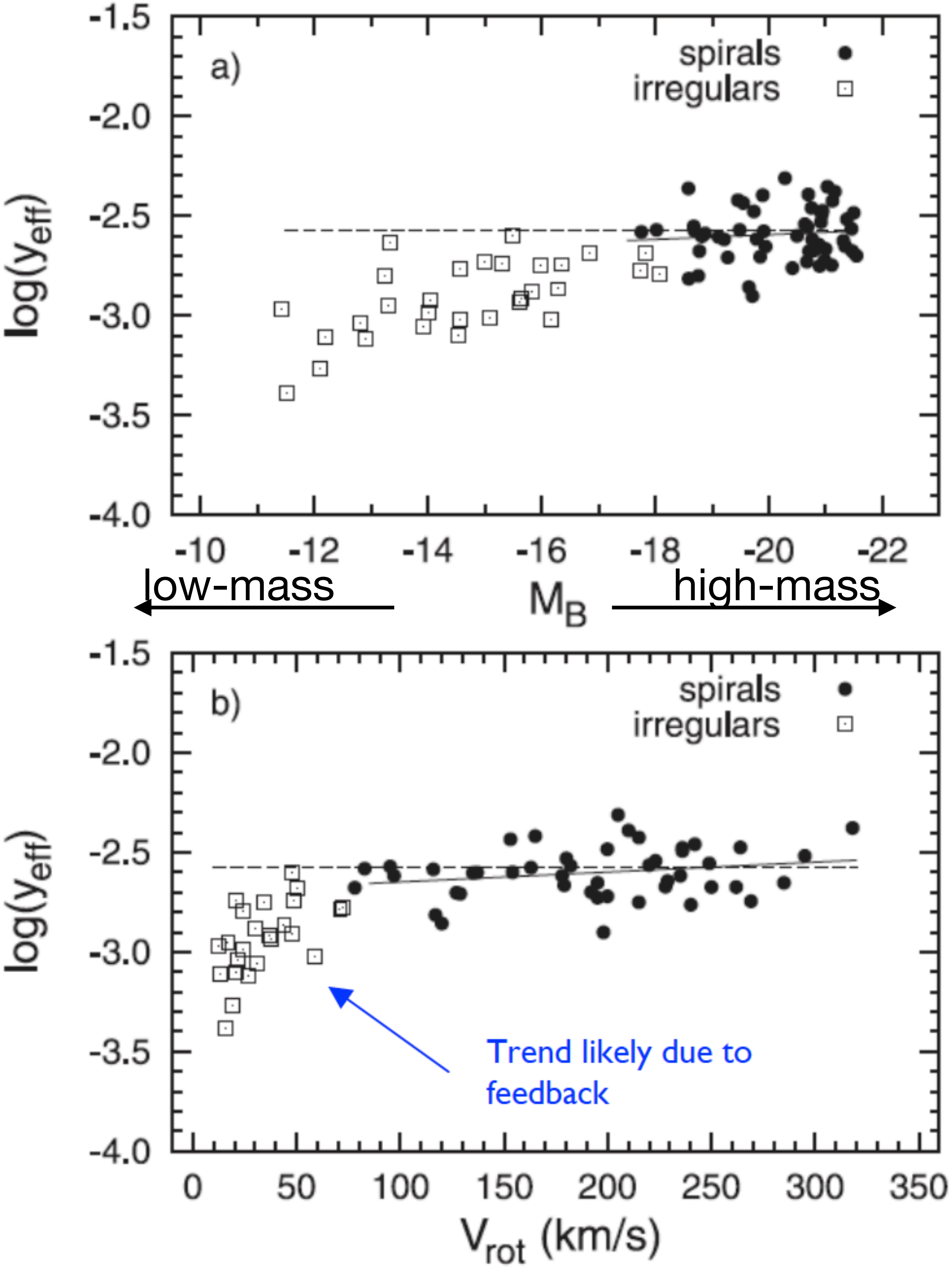
SN fdbk is believed to be responsible for suppressing star formation in dwarf galaxies ($M_{vir} < 10^{11} M_{sun}$, $V_{vir} < 100$km/s)

Observational evidence

$$\text{yield} = \frac{\text{mass of new metals added to ISM by SNe}}{\text{mass of ISM converted to long}-\text{lived stars}}$$

The effective metallicity yield,
$y_{eff} = - Z_{gas} / \ln(f_{gas})$,
is constant for a closed box model of galactic chemical evolution

Lower y_{eff} in low mass galaxies means metal-enriched outflows



low-mass

high-mass

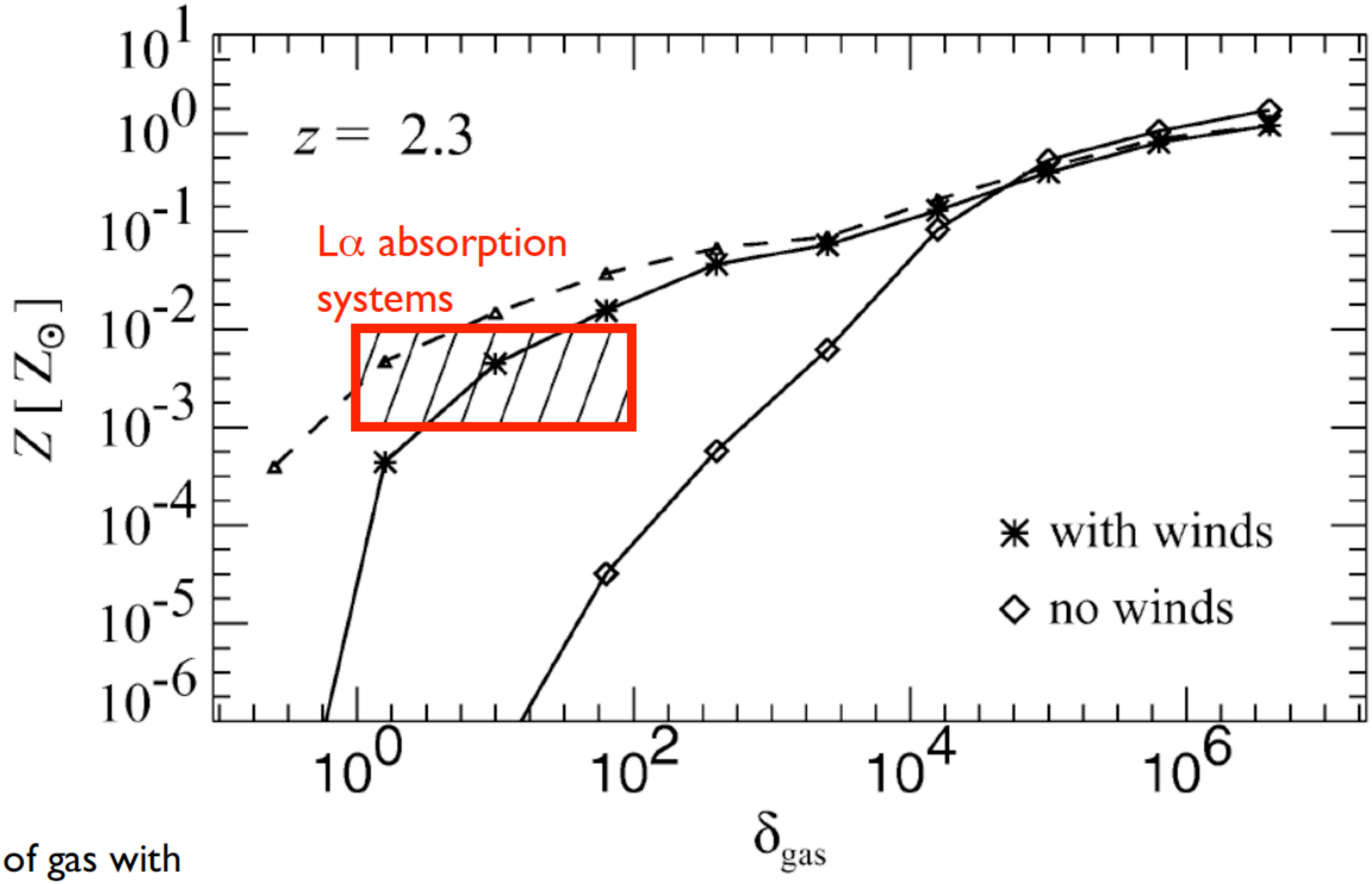
Trend likely due to feedback

Pilyugin et al. 2004

Observational evidence

Moderate density regions of the Universe (e.g. the IGM) are metal enriched. But there is no star formation in such regions. — Metal-enriched winds can deposit metals into the IGM.

Probing the importance of winds and feedback at high redshift (z~2)



δ_{gas} = overdensity of gas with respect to the mean density

Springel & Hernquist 2003

SN feedback on galactic scales: numerology

Energy released by a type II SN: $E_{SN} \sim 10^{51}$ ergs

10^{49} ergs deposited into ISM per 1 M_{sun} of stars formed
(recall that for a standard IMF, 1 SN per 100 M_{sun})

$E_{bind} \sim M_{gas} V_{vir}^2 \sim G\ M_{gas}\ M_{vir} / R_{vir}$

- For a giant molecular cloud (GMC),

  $M_{gas} \sim 10^5\ M_{sun}$, $R \sim 50$pc $\quad$ $E_{bind} \sim 10^{49}$ ergs

  so a single SN can in principle unbind a typical GMC.

- For a L* galaxy,

  $M_{vir}=10^{12}\ M_{sun}$, $M_{gas}=10^{10}$ Msun, $R_{vir}=300$kpc $\quad$ $E_{bind} \sim 10^{57}$ ergs

  a single SN will not unbind the galaxy

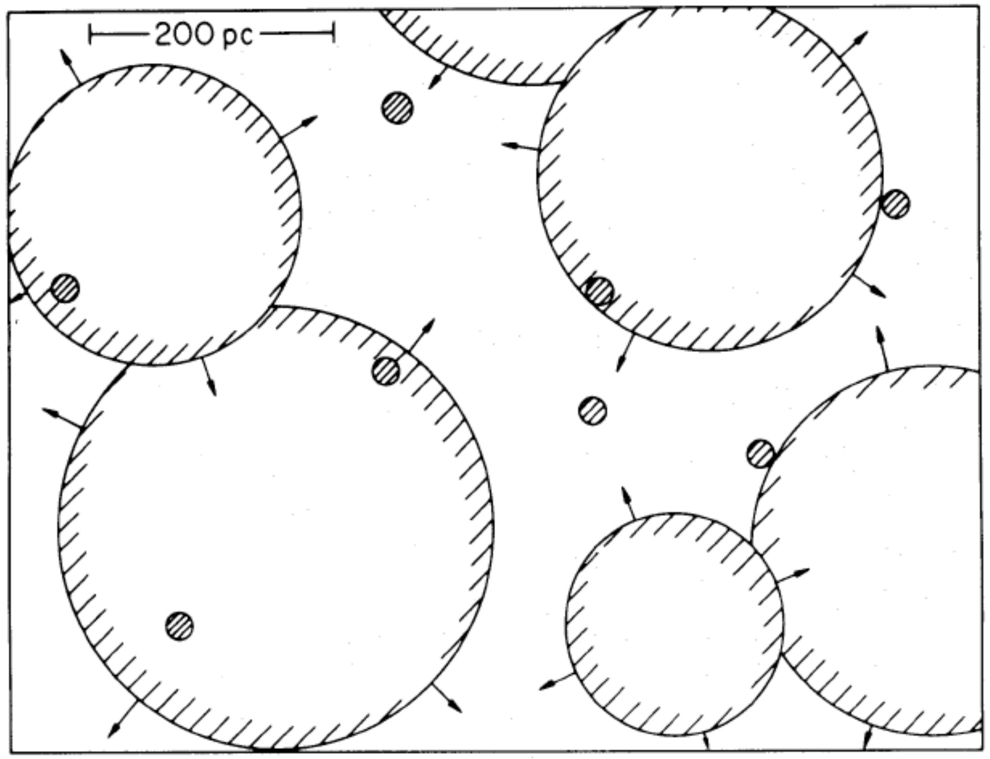
SN feedback on galactic scales

Recap: the standard picture for isolated SN evolution

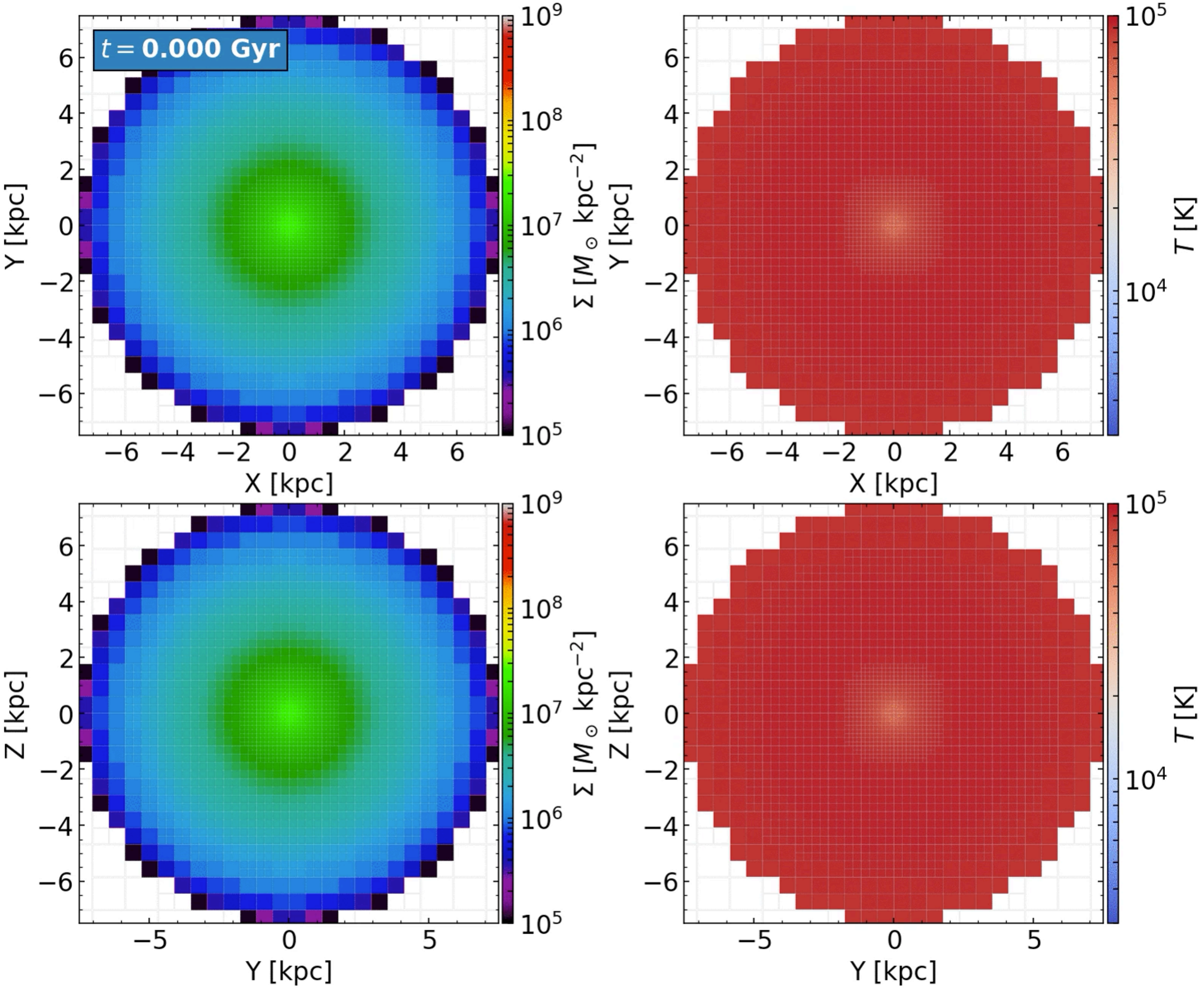
- **Free expansion**: ends when $M_{swept} \sim M_{eject}$, (**t~200 yr, R~1pc**)
- **Adiabatic** (Sedov-Taylor) phase: ends when radiative losses become important (**t~$10^{4\text{-}5}$yr, R~30pc**)
- **Snowplow** phase (approximately momentum conserving): ends when when the shock velocity is comparable to the local sound speed (**t~10^6 yr, R~100pc**)

However, Within 10^6yr, another SN is likely to go off within 100pc, for MW SNR

Therefore, within ~Myr, every point in the ISM will have experienced a SN blastwave (McKee & Ostriker 1977)



SN feedback on galactic scales



SN feedback on galactic scales

Total SN energy deposited into ISM:

$E_{SN,tot} = E_{SN}\ \mathrm{SFR}\ t_{rad}$

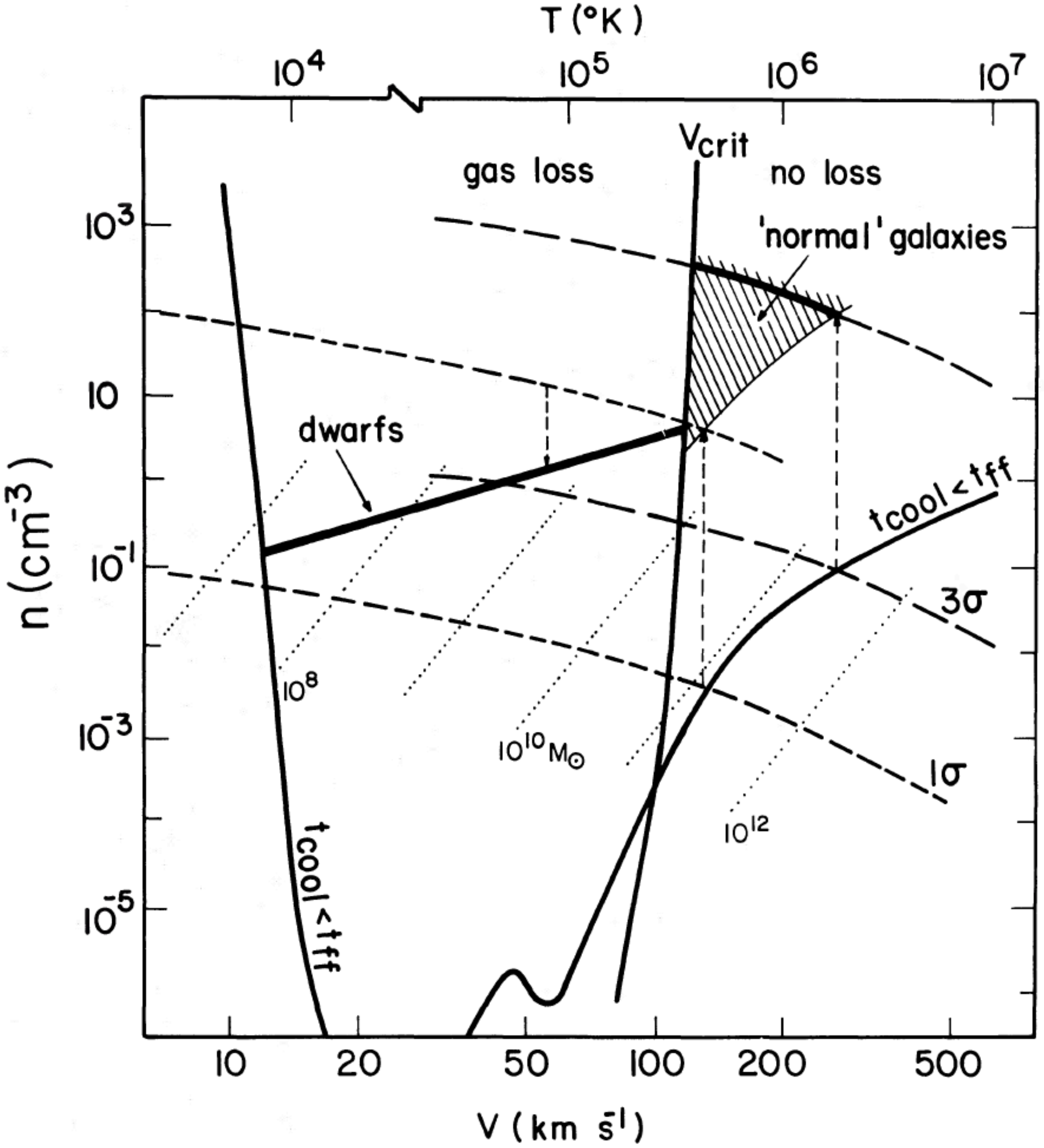
t_{rad} : time when SNR radiates away a significant fraction of its initial energy, $\propto n^{-9/17}$, ~ SN overlap time for the assumed SFR

$\mathrm{SFR} \sim M_{gas} / t_{ff}$

$t_{ff} = (6\pi G\rho)^{-1/2} \propto n^{-1/2}$

Condition for gas removal:

$E_{SN,tot} > E_{bind} \sim M_{gas} V_{vir}^2$



$V_{vir} < V_{crit} \sim 120\ f(E_{SN}$, gas fraction, Z, halo density profile, etc) km/s

Dekel & Silk 86

SN feedback on galactic scales: in simulations

Hydrodynamic simulations of the formation and evolution of galaxies cannot simultaneously resolve the SN blastwave (pc scales), galactic structures (kpc scales), and the cosmological environment (Mpc scales) — “subgrid” recipes are required.

Early hydrodynamic simulations of galaxy formation attempted to model SN feedback by dumping 10^{51} ergs of thermal energy into the nearest grid cell (or SPH particle), e.g. Katz 1992

- The cells nearest to the SN are the densest (a necessary condition for star formation), and so the cooling rate, which scales as n^2, is very large

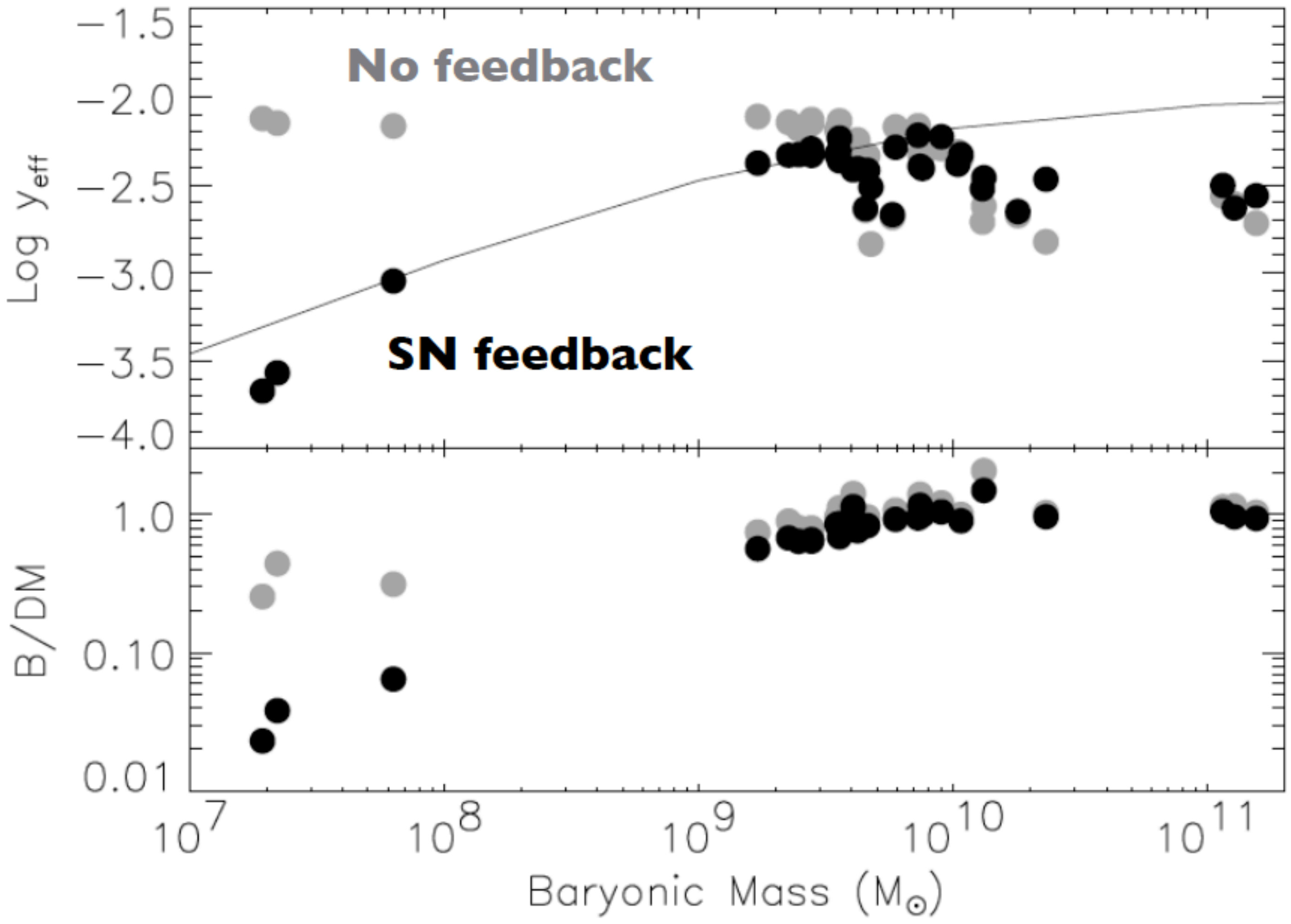
- The net result is that the SN energy is radiated away instantly, and therefore has no effect on the ISM — “cooling catastrophe”, i.e., too many stars form

SN feedback on galactic scales: in simulations

Ad hoc prescriptions were then adopted to fix the overcooling problem:

- Dump the SN energy into kinetic energy (e.g. Navarro & White 1993)
- turn off cooling for some amount of time, until the SN energy diffuses over a large enough volume to act as feedback
- Simplistic recipes for a multiphase ISM (e.g. Yepes et al. 1997, Springel & Hernquist 2003): SN energy is shared between the hot and cold components; hot component is susceptible to thermal feedback (b/c it is of low density and high temperature), so SN feedback can be effective at reducing the growth of the cold component

cosmological hydro simulation



Brooks et al. 2007

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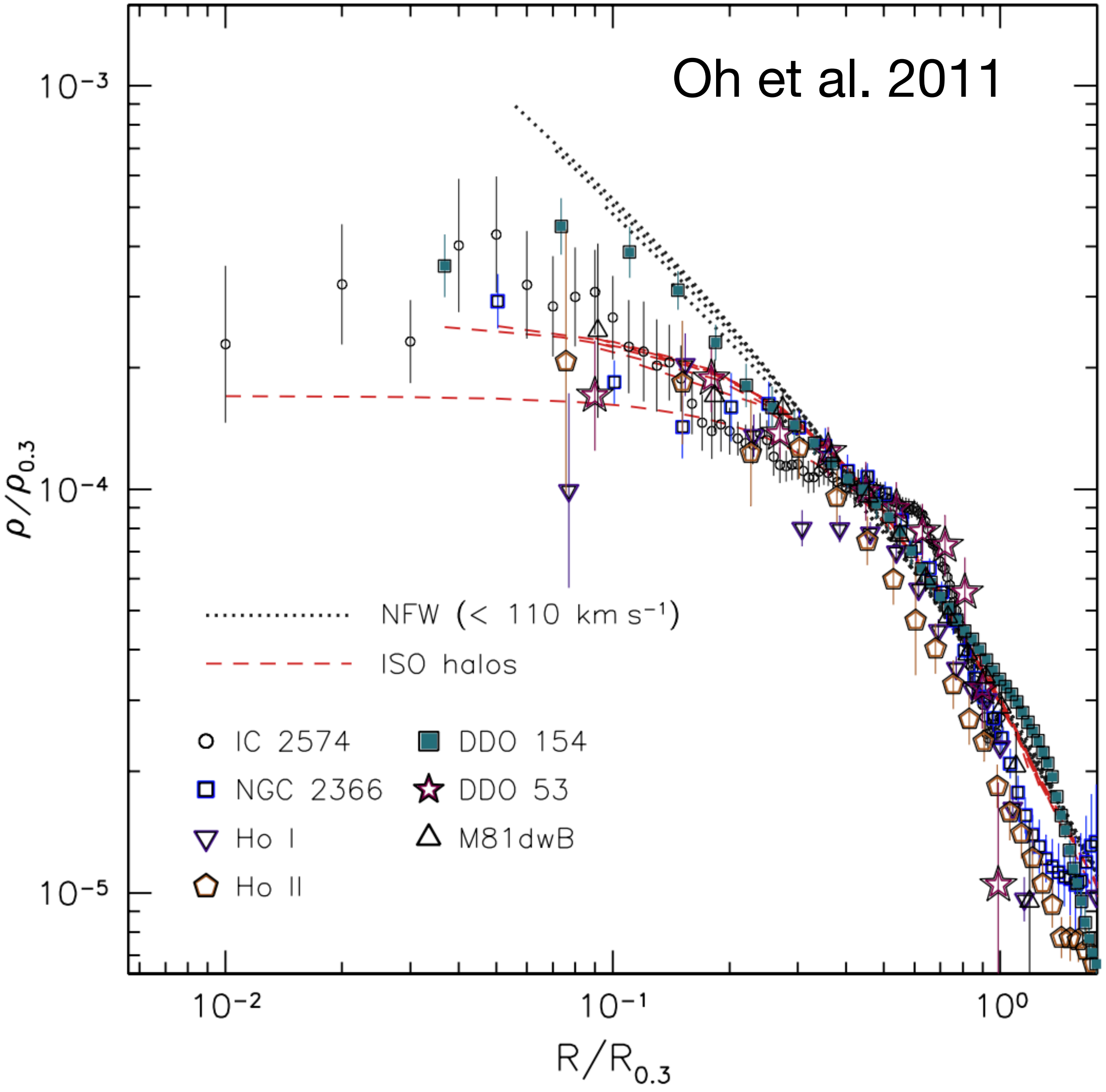
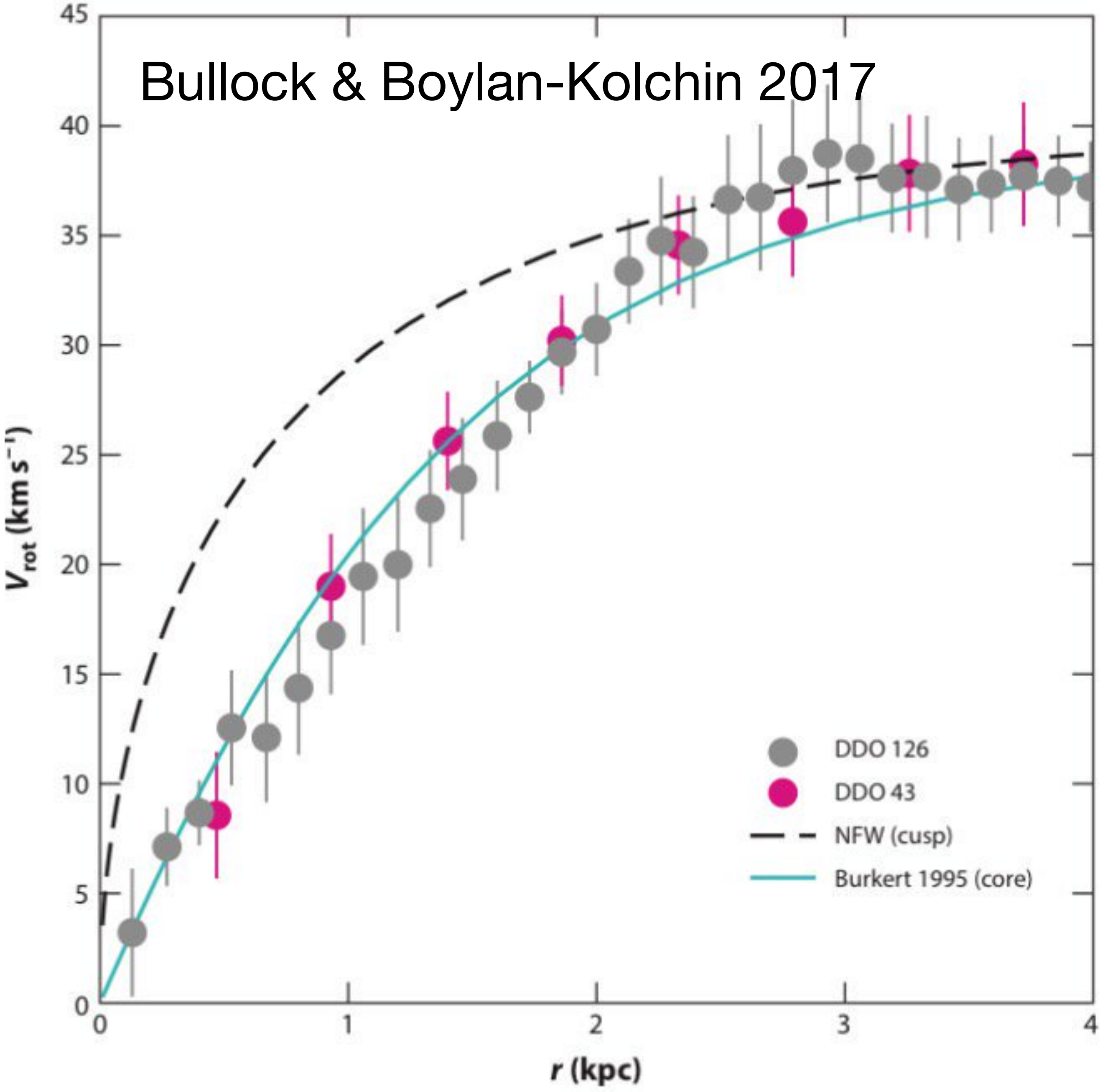
The Cusp-Core Problem

DM-only cosmological simulations predict steep DM density profiles $\rho \propto r^{-1}$ in the center (cusps)

DM inner density slopes inferred from gas/stellar kinematics range from -1 to 0 (cores)

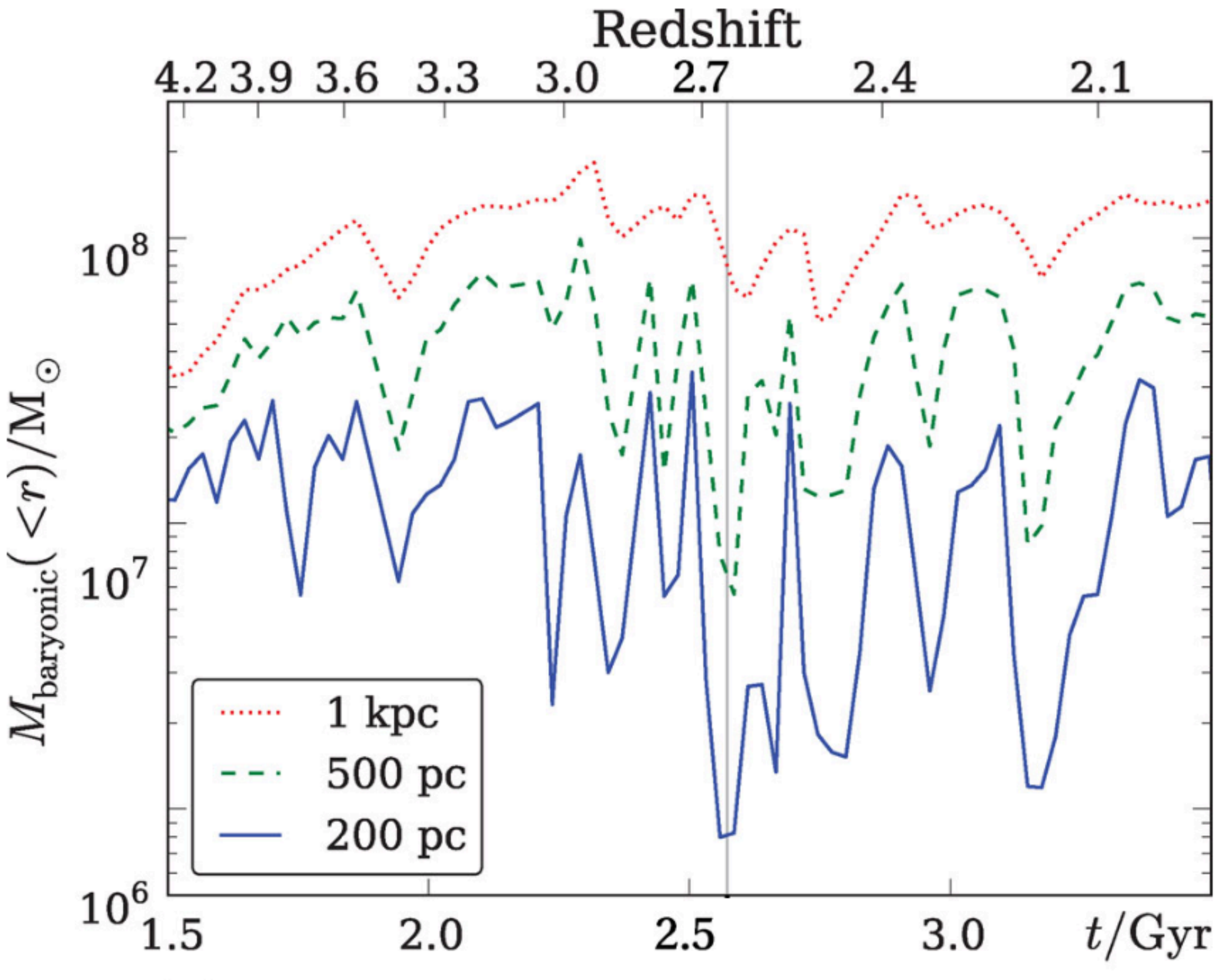


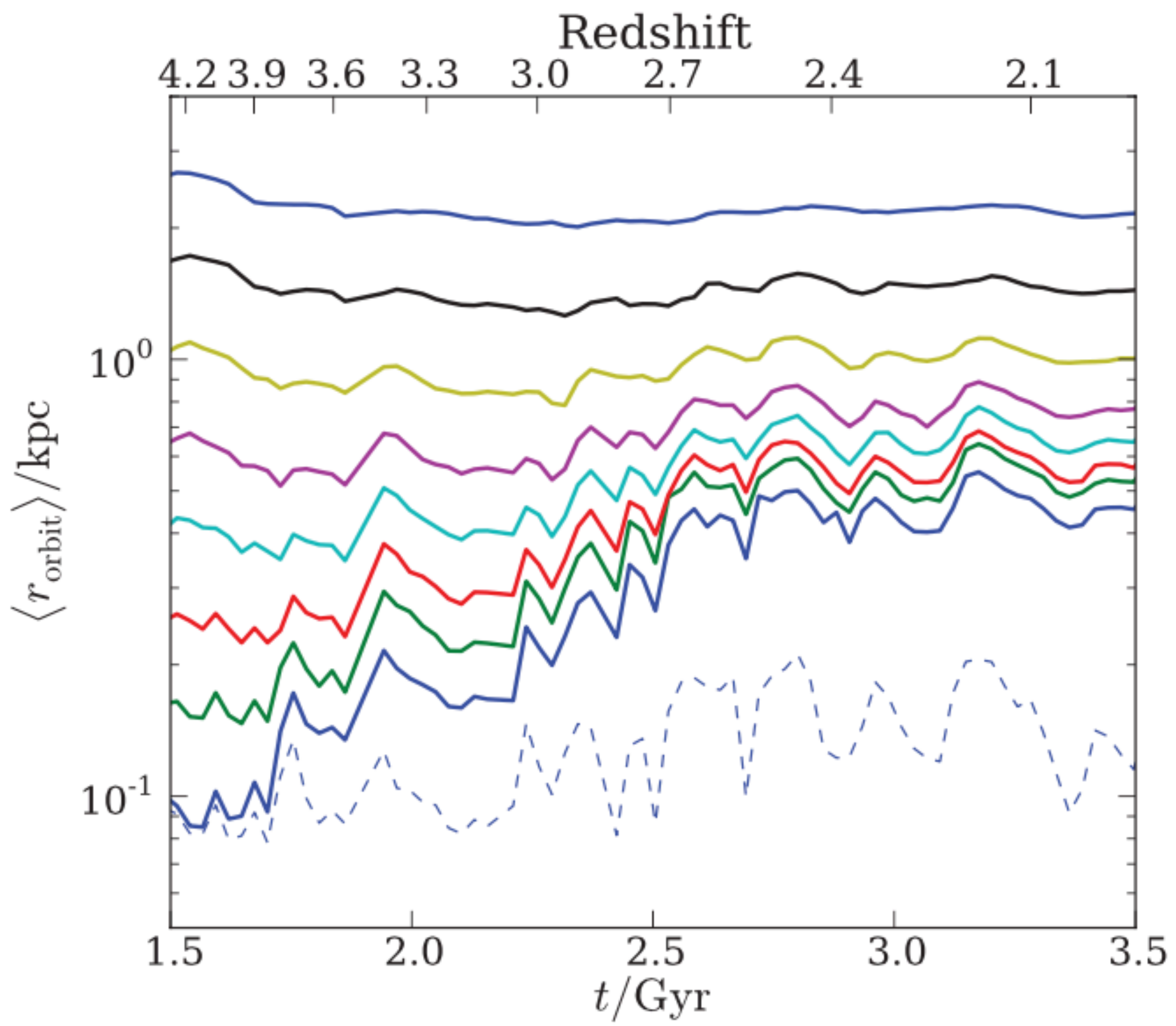


The Cusp-Core Problem

Baryonic effects modifies the DM density profile:

- Adiabatic contraction (conservation of the angular momentum on circular orbits): $J \propto r V \propto (M(<r)\, r)^{1/2}$ is invariant —> more cuspy
- Repeated potential fluctuations due to gas inflows (accretion) and outflows (SN fdbk) “pushes” DM particles to orbits of larger radii, forming cores (Pontzen & Governato 2012)





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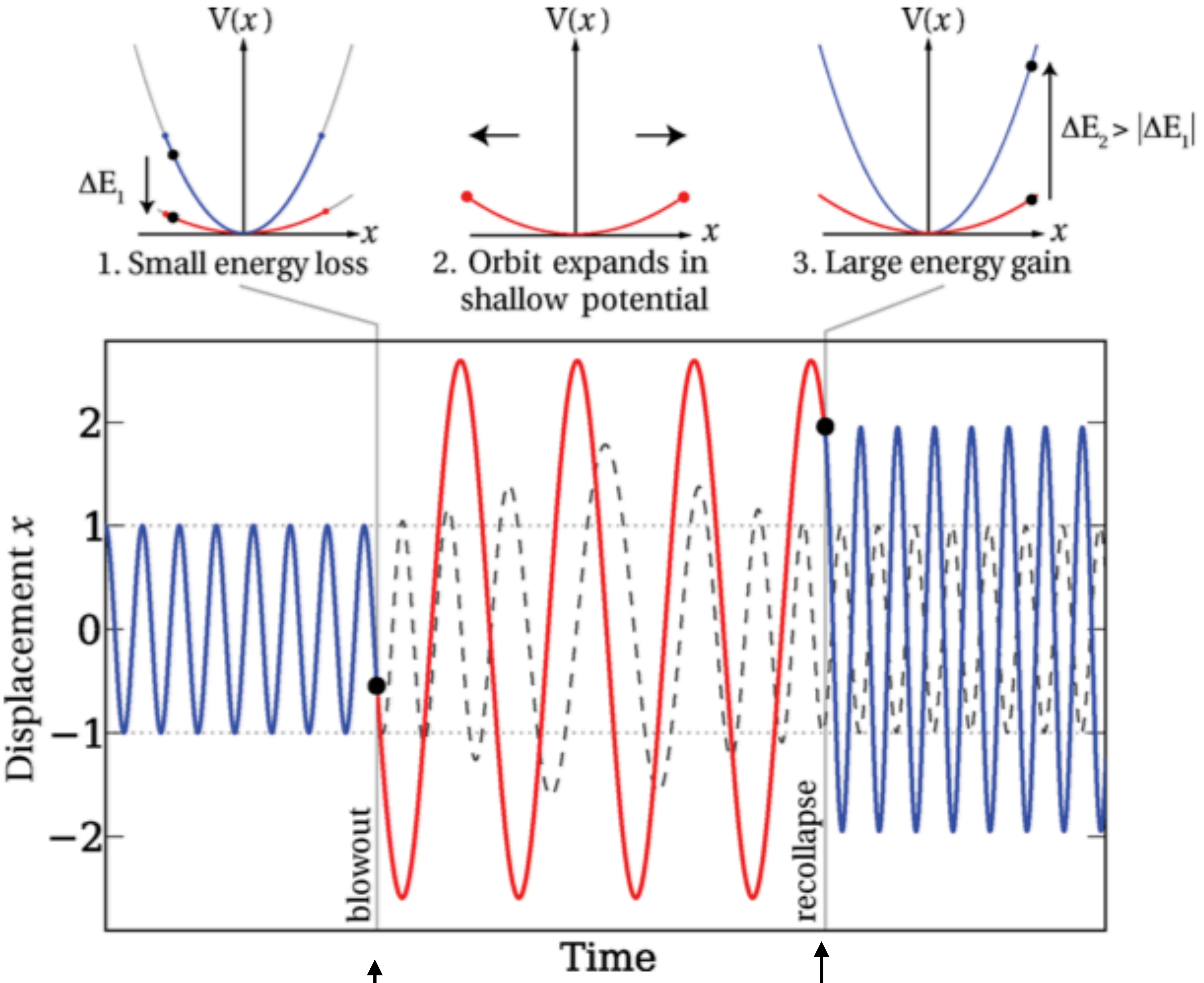


SN

accretion / gas fall back

The Cusp-Core Problem

Toy model: consider an instant mass decrement from the galaxy center (e.g. f=m/M=-0.02)

1) Initial conditions at equilibrium

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

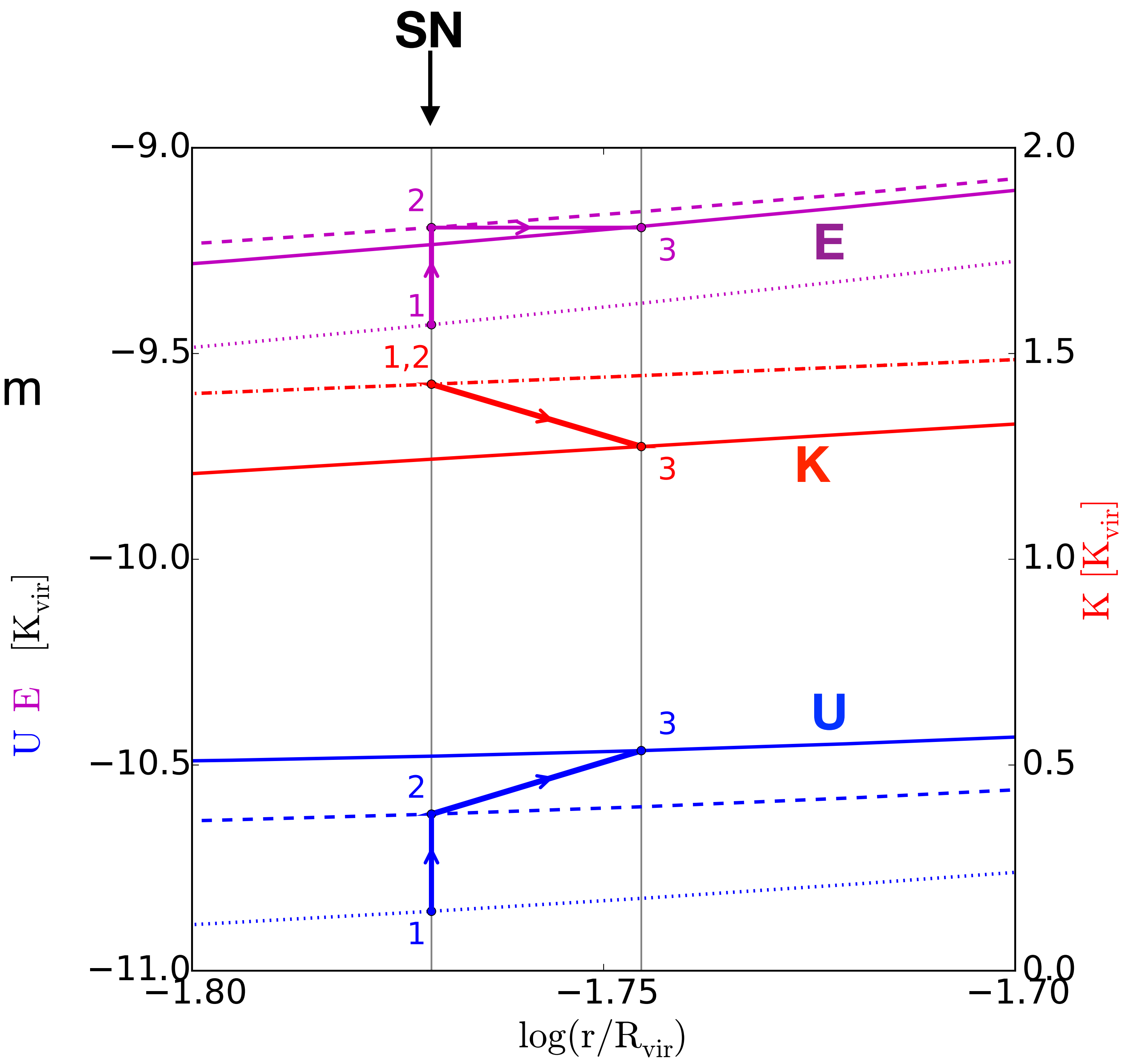
2) Immediately after the mass change

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

3) The system relaxes to a new equilibrium

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

Given functional forms U(r) and K(r), energy conservation $E_f(r_f) = E_t(r_i)$ yields the final state



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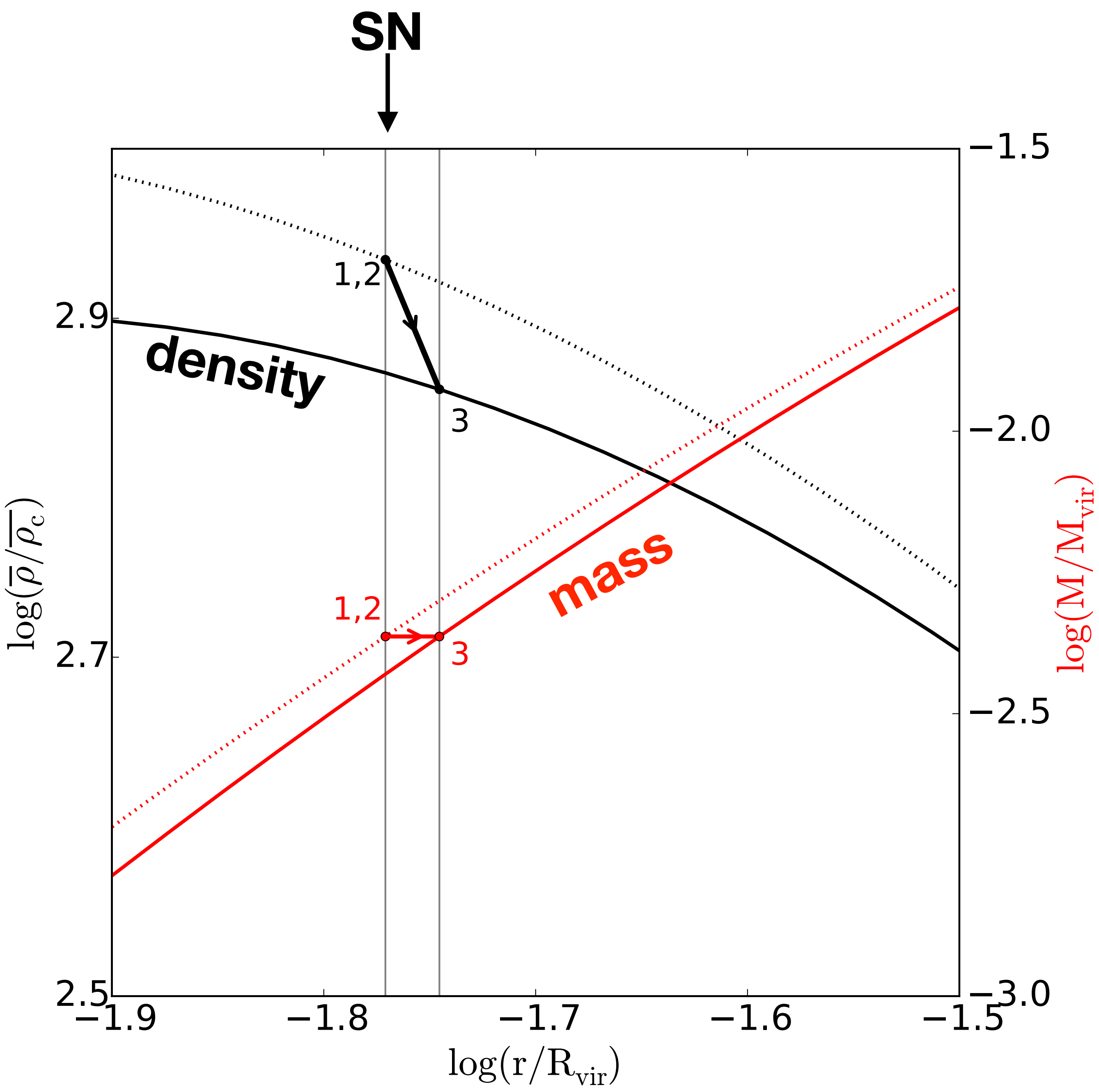

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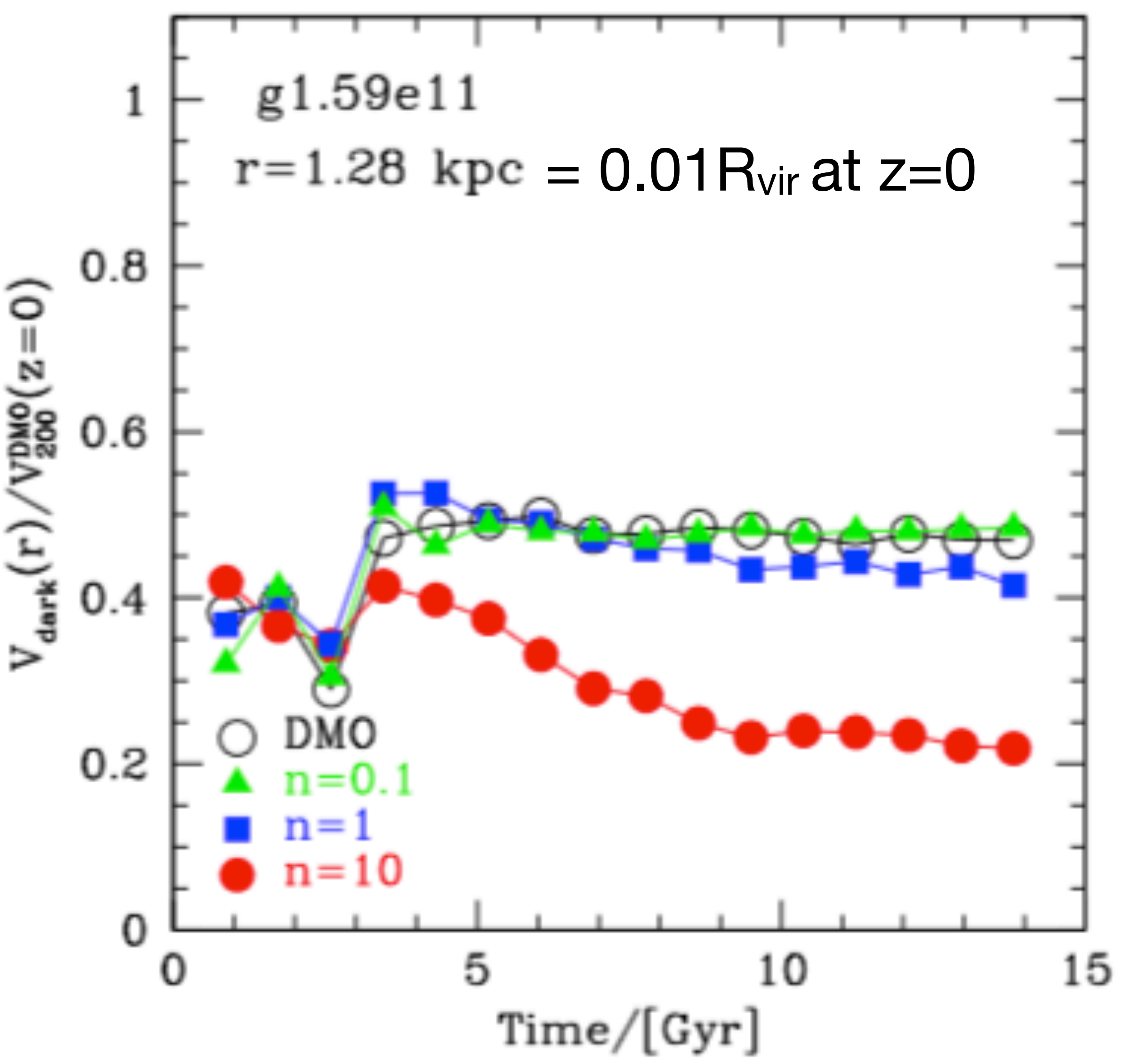
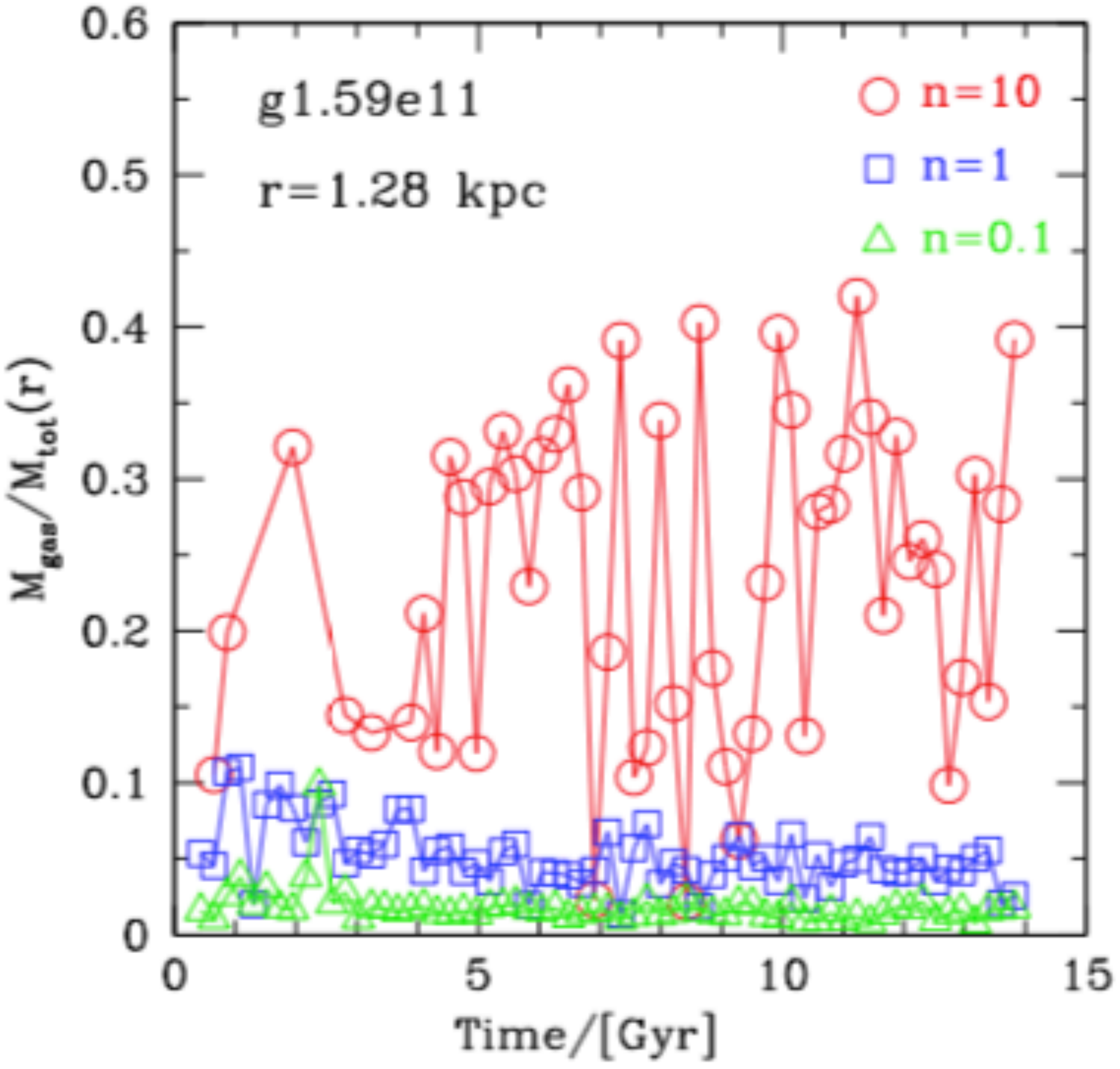
The Cusp-Core Problem

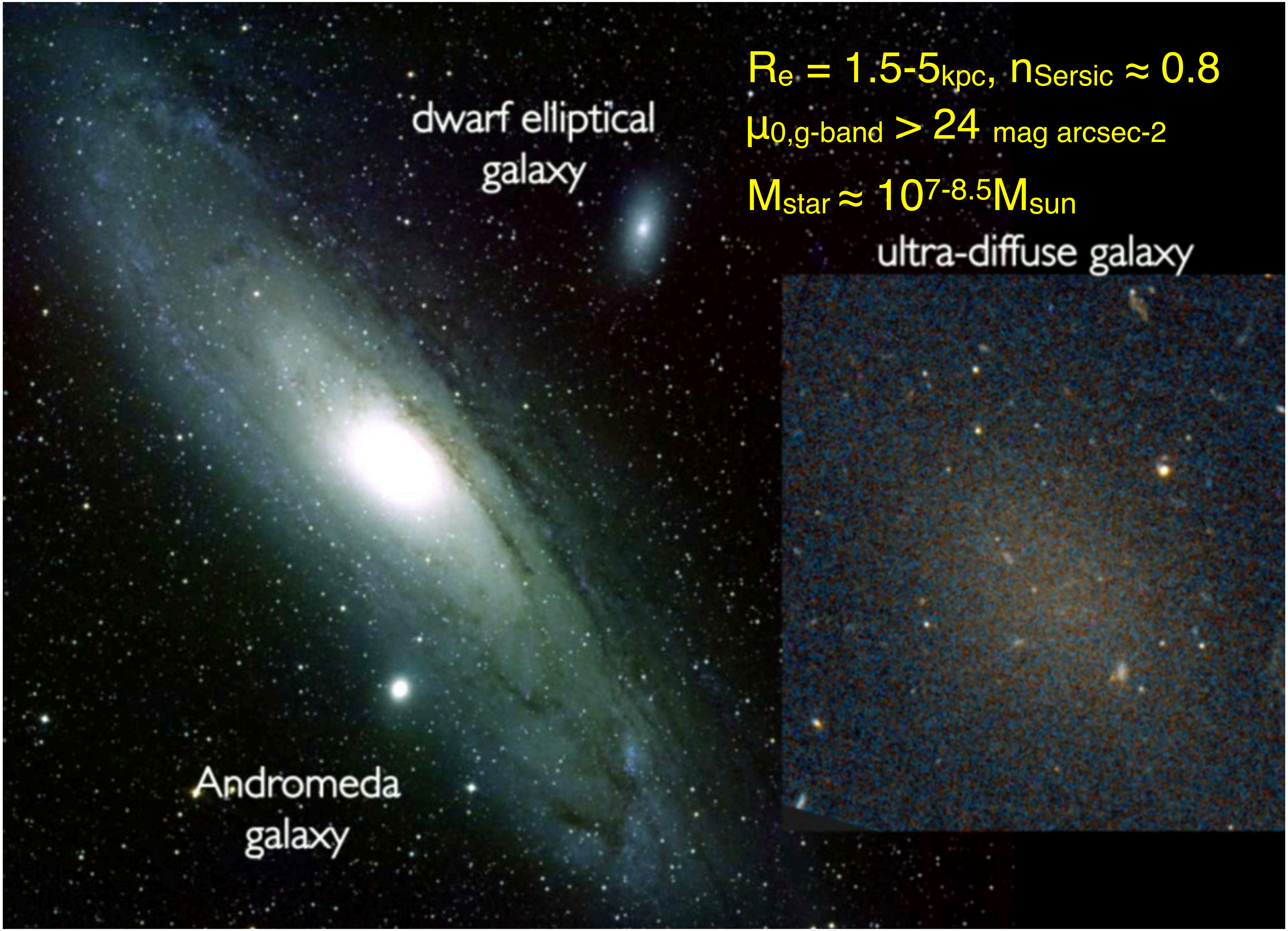
Condition for this process (i.e., the drastic potential-well fluctuations) to happen:

Significant amount of gas condenses to the innermost few kpc, before the SNe pushes the gas out impulsively





Ultra-diffuse galaxies (UDGs)

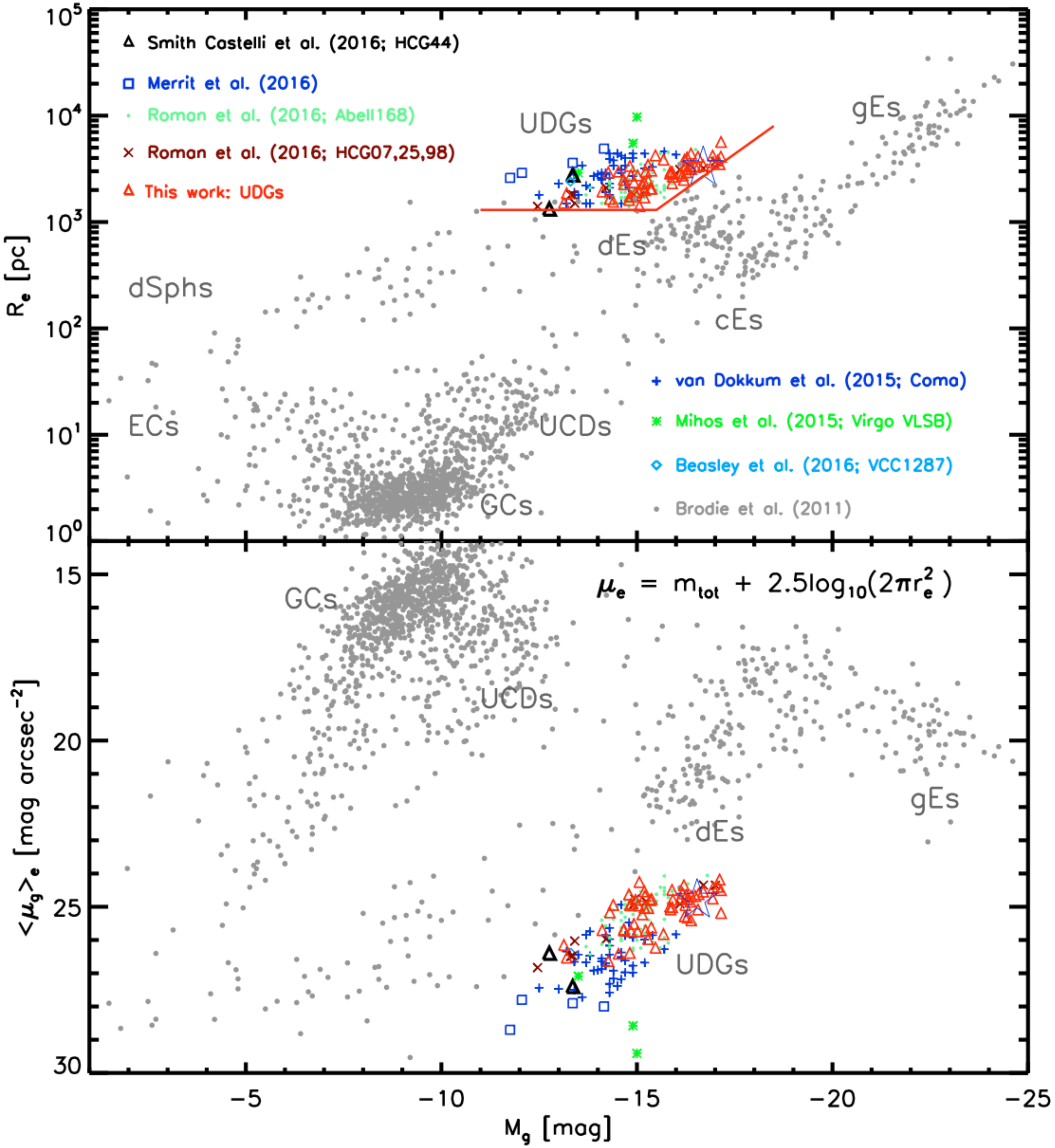


$R_e = 1.5\text{-}5_{\text{kpc}}$, $n_{\text{Sersic}} \approx 0.8$

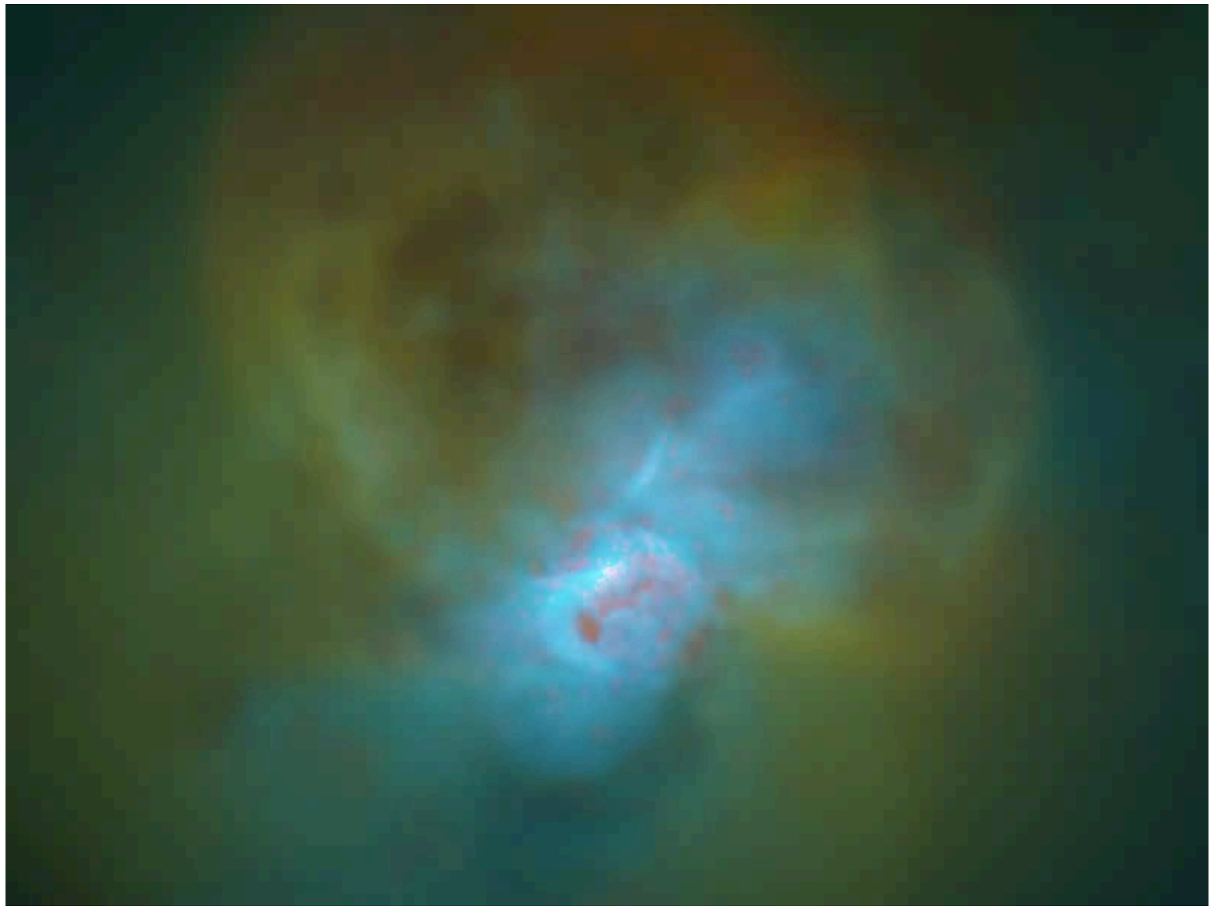
$\mu_{0,\text{g-band}} > 24$ mag arcsec-2

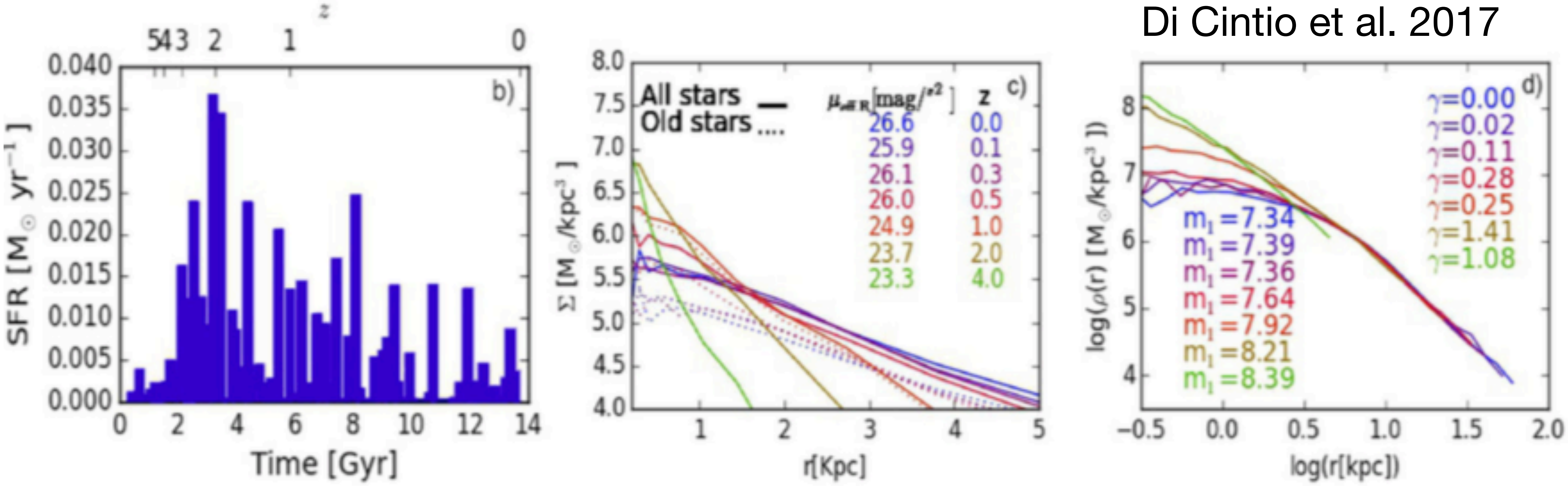
$M_{\text{star}} \approx 10^{7\text{-}8.5} M_{\text{sun}}$

Ultra-diffuse galaxies



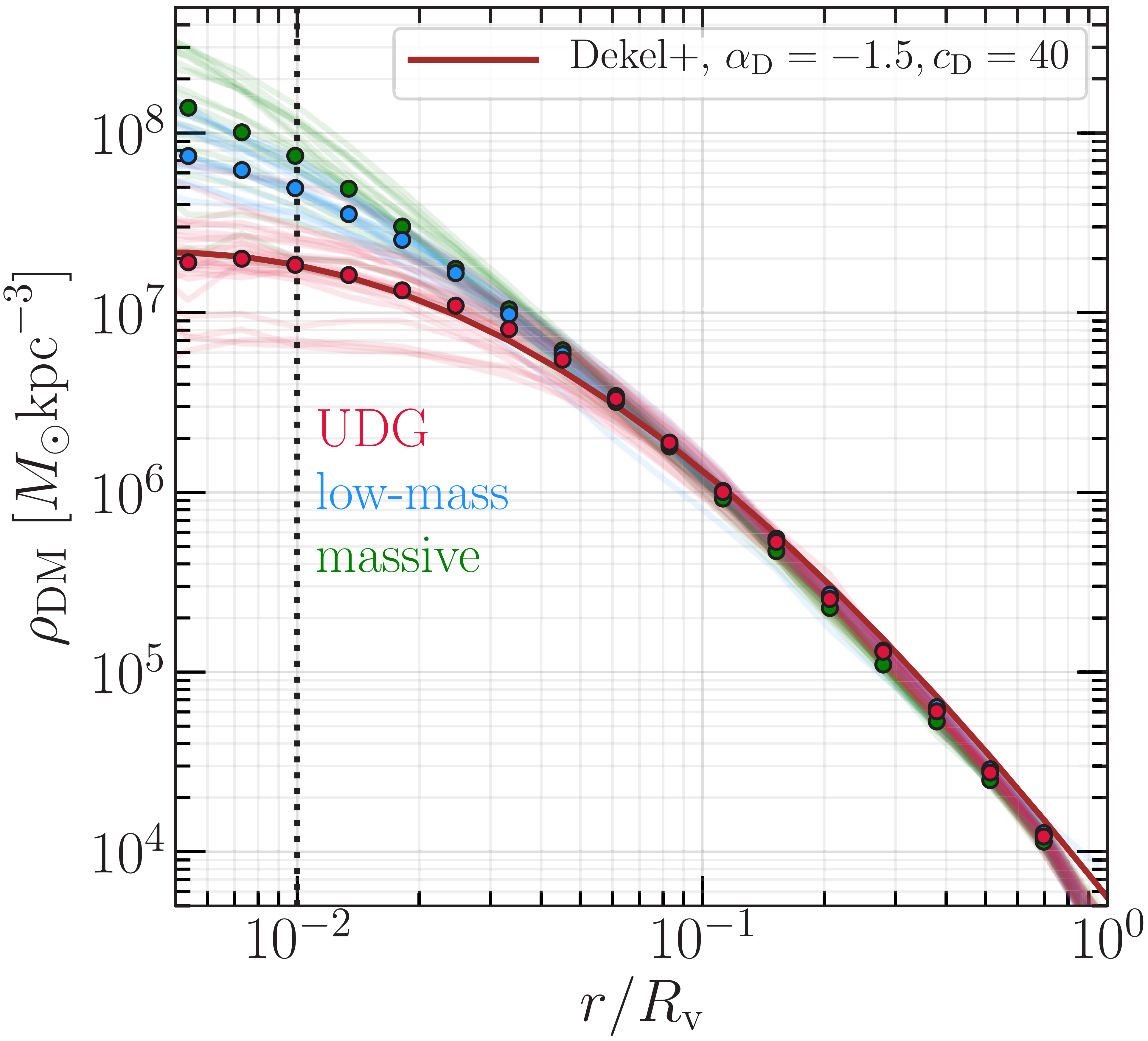
Ultra-diffuse galaxies





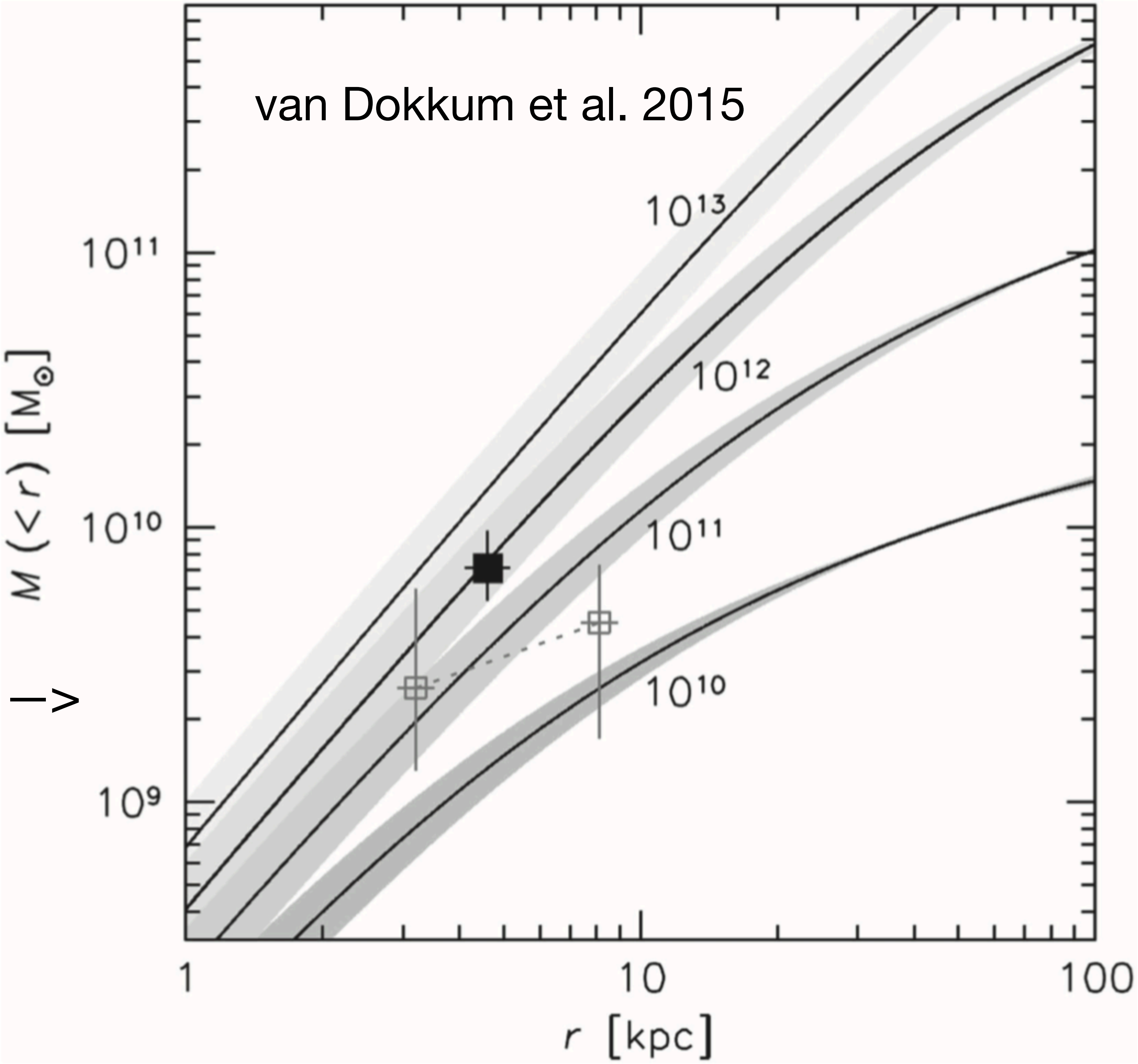
Di Cintio et al. 2017

Ultra-diffuse galaxies



Ultra-diffuse galaxies

Debate on the UDG halo mass: Puffed-up dwarf or failed L* galaxy

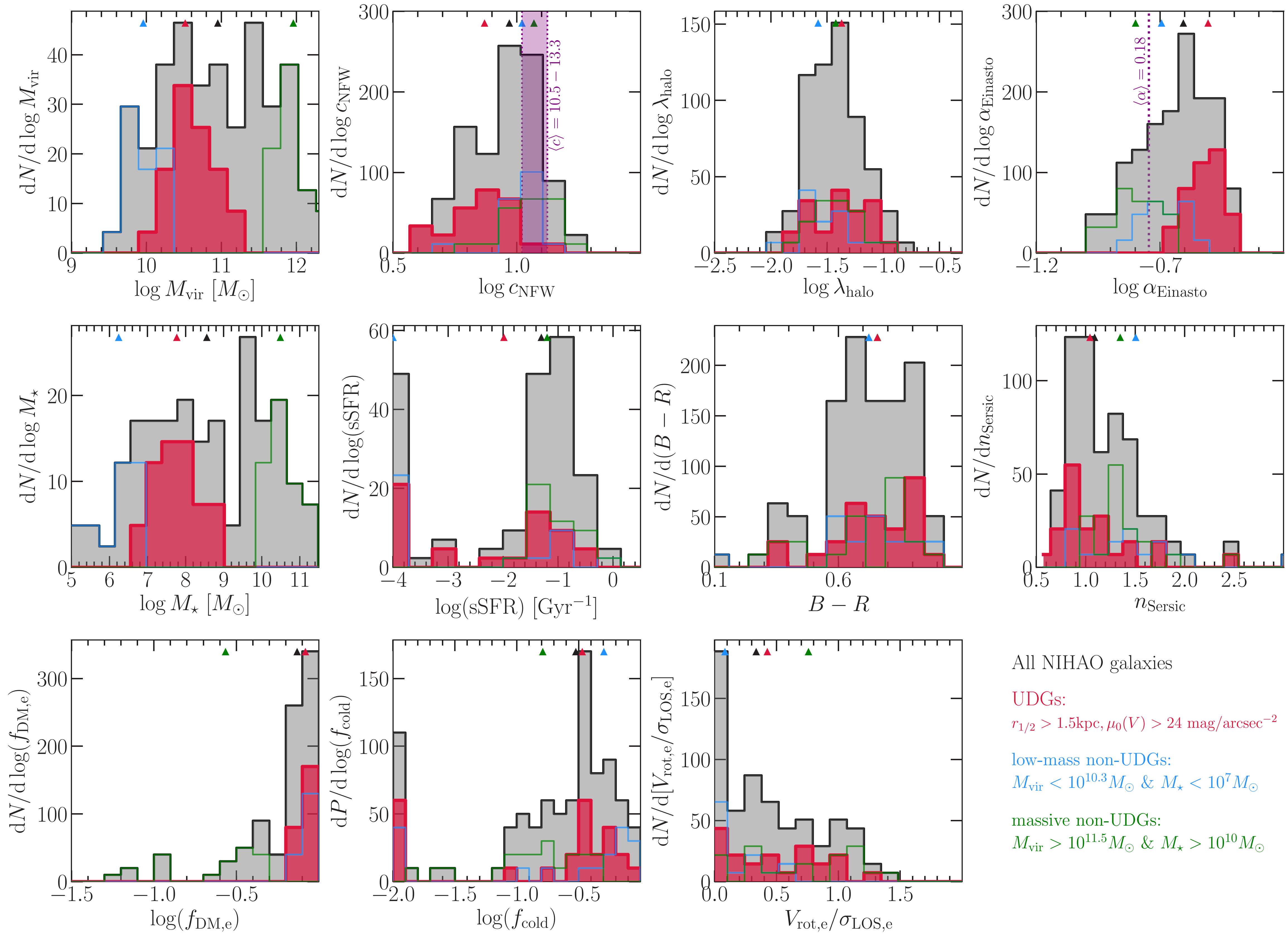


Evidence for failed L* —>

However, this Rvir estimate relies on extrapolating the density profile from ~2kpc to ~200 kpc, and assuming a cuspy NFW profile.

Ultra-diffuse galaxies

Simulations show that UDGs are dwarf galaxies puffed up by SN fdbk: e.g., Di Cintio et al. 2017, Jiang, Dekel, Freundlich et al. 2018



Summary

- What is “feedback”? — a process that regulates the growth of galaxies, suppressing or boosting star formation

- Why do we need feedback? — to reconcile the halo mass function and galaxy stellar mass function (i.e., to explain the low SF efficiency in dwarf gaaxies), to explain the drop of metallicity yield in dwarf galaxies

- How does SN feedback work? — injects energy to the ISM —> pushes gas out, or remove gas completely conditioning on the host-halo potential —> most efficiently for dwarf galaxies with $V_{vir} <\approx 120$ km/s

- Impact on dark-matter halos (cusp-core issue) — impulsive gas removal from the central few kpcs of a dwarf galaxy causes potential fluctuations —> dark matter cusps transform into cores

- Impact on galaxies (ultra-diffuse galaxies) — the same process is believed to be responsible for the formation of UDGs in the field.