Semi-Analytic Models of Galaxy Formation II — BH Growth & AGN Feedback

Dwarf Galaxies — Impact of Baryonic Processes on Galaxies and Host Halos

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Lecture Notes for Advanced Cosmology 2019
Hebrew University of Jerusalem

SMBH growth & AGN fdbk

Henriques et al. 2015

- Quasar mode : BH growth

pre-existing BHs merge as soon as their host galaxies do — the main channel by which BHs gain mass, not associated with feedback beyond that from the starbursts which accompany gas-rich mergers.

satellite baryon mass

central baryon mass

$$\Delta M_{\mathrm{BH,Q}} = \frac{f_{\mathrm{BH}}(M_{\mathrm{sat}}/M_{\mathrm{cen}})\,M_{\mathrm{cold}}}{1+(V_{\mathrm{BH}}/V_{200\mathrm{c}})^2},$$

central cold-gas mass

fraction of cold gas that goes into BH (free param)

a threshold host-halo virial velocity above which BH accretion is suppressed (free param)

- Radio mode (maintenance mode): AGN feedback

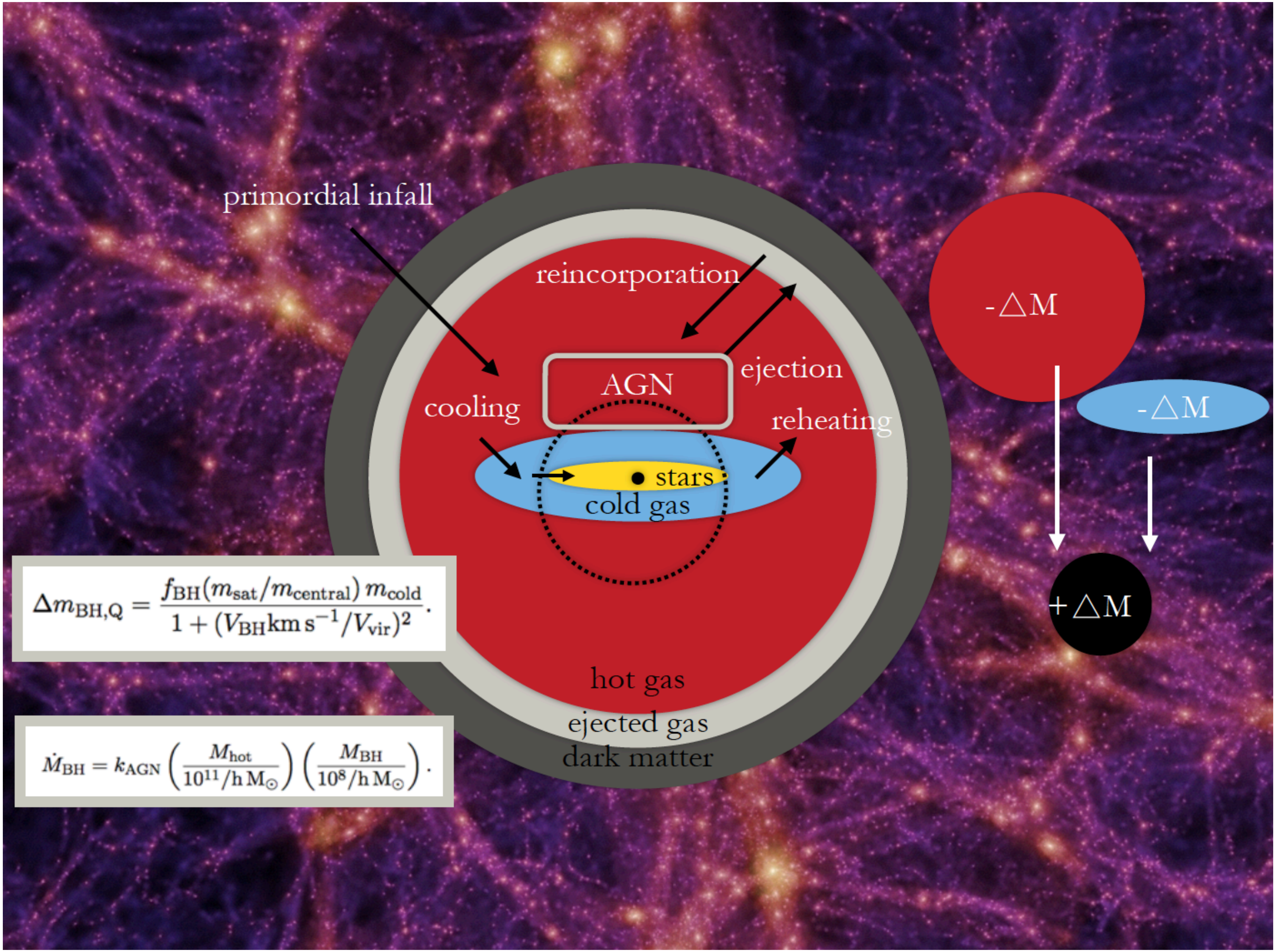
Black holes are also allowed to accrete gas from the hot gas atmospheres of their galaxies — this is assumed to generate jets and bubbles which produce “radio mode” feedback, suppressing cooling onto the galaxy and so eliminating the supply of cold gas and quenching star formation.

$$\dot{M}_{\mathrm{BH}} = k_{\mathrm{AGN}}\left(\frac{M_{\mathrm{hot}}}{10^{11}\,\mathrm{M}_\odot}\right)\left(\frac{M_{\mathrm{BH}}}{10^{8}\,\mathrm{M}_\odot}\right)$$

$$\dot{E}_{\mathrm{radio}} = \eta \dot{M}_{\mathrm{BH}} c^2,$$

$$\dot{M}_{\mathrm{cool,eff}} = \max\left[\dot{M}_{\mathrm{cool}} - 2\dot{E}_{\mathrm{radio}}/V_{200\mathrm{c}}^2,\ 0\right]$$

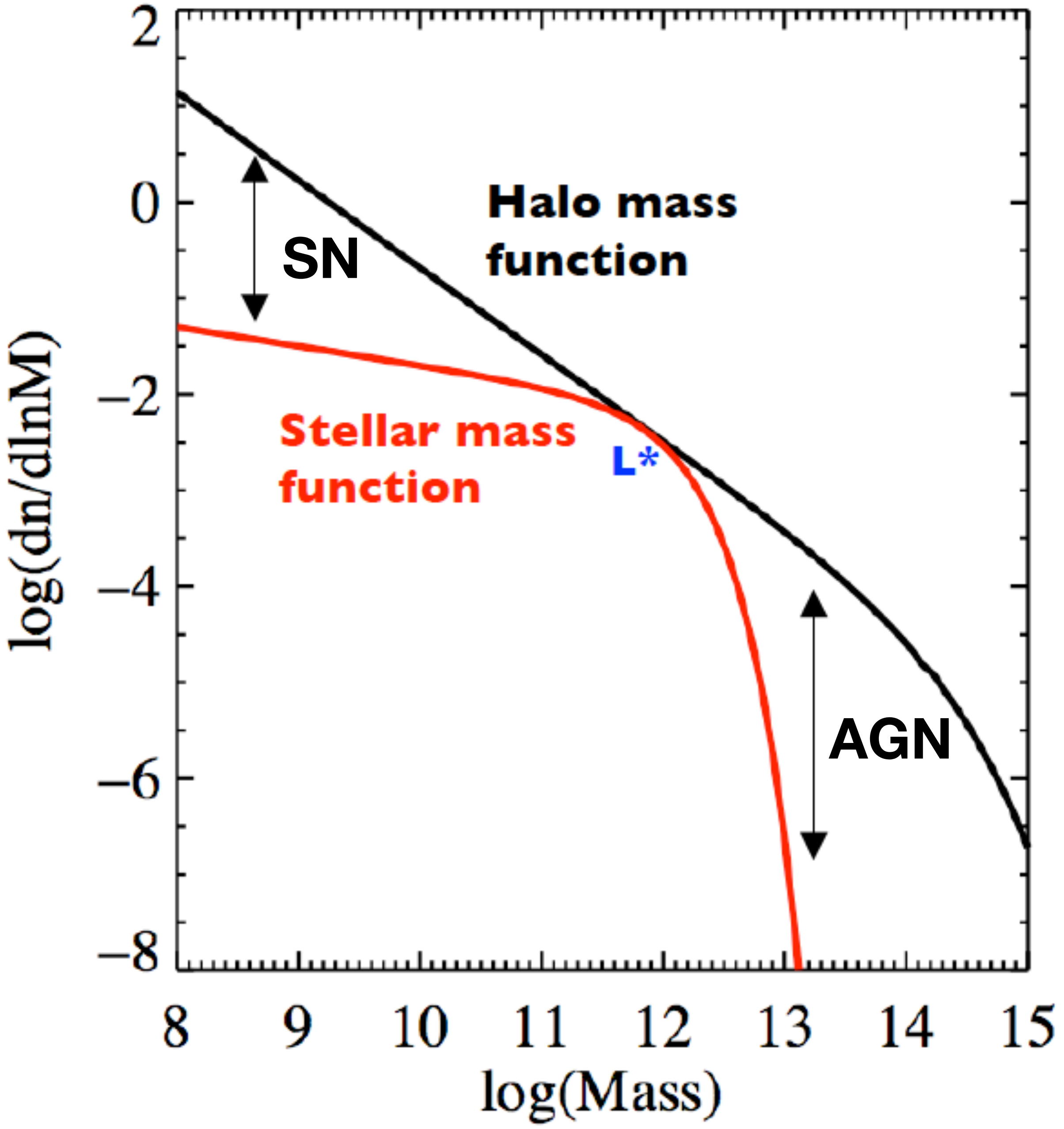
Putting everything together

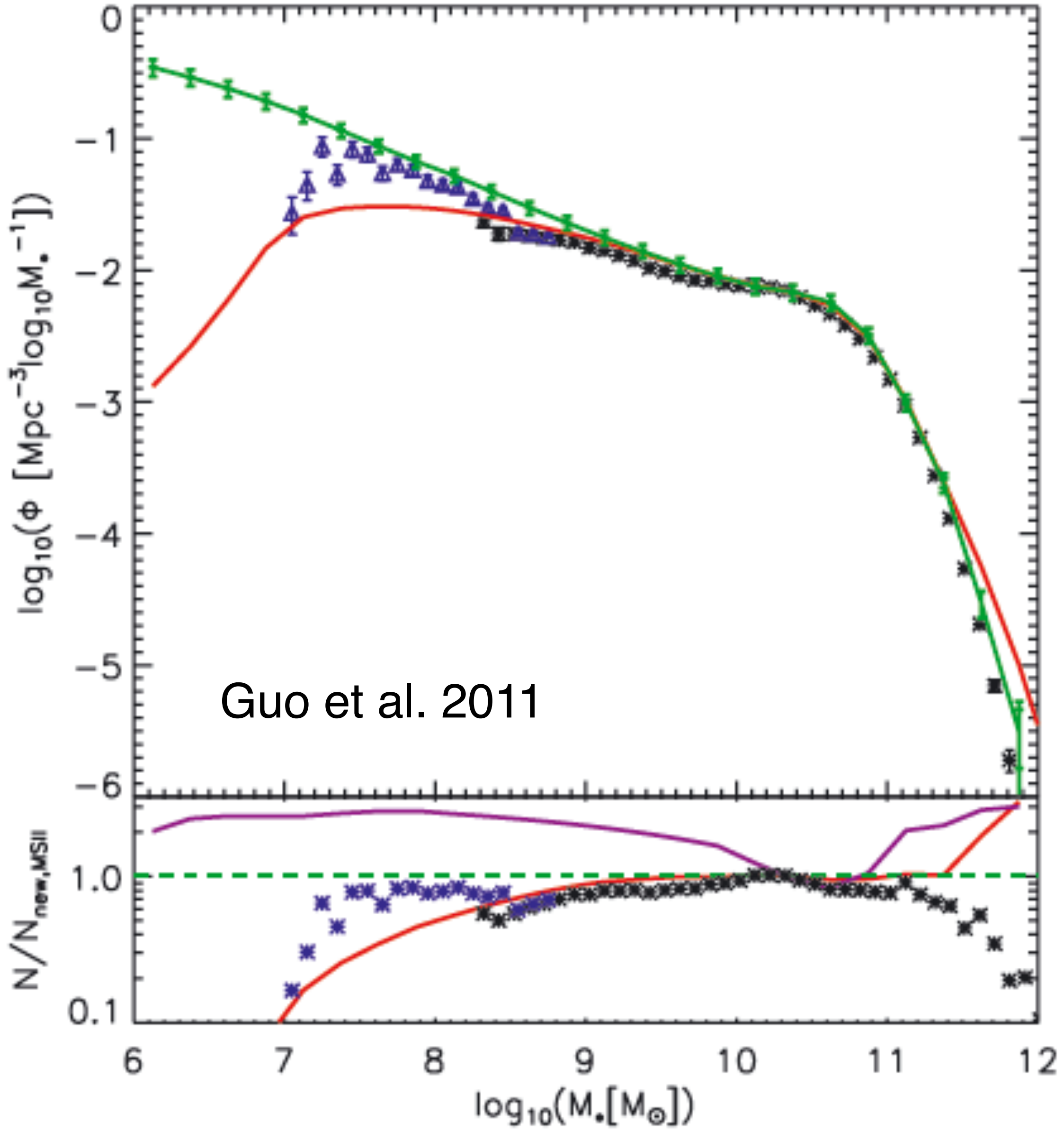


$$\Delta m_{\rm BH,Q} = \frac{f_{\rm BH}(m_{\rm sat}/m_{\rm central})\, m_{\rm cold}}{1+(V_{\rm BH}{\rm km\,s^{-1}}/V_{\rm vir})^2}.$$

$$\dot{M}_{\rm BH} = k_{\rm AGN}\left(\frac{M_{\rm hot}}{10^{11}/{\rm h\,M_\odot}}\right)\left(\frac{M_{\rm BH}}{10^{8}/{\rm h\,M_\odot}}\right).$$

SAM predictions: galaxy stellar mass functions




Guo et al. 2011

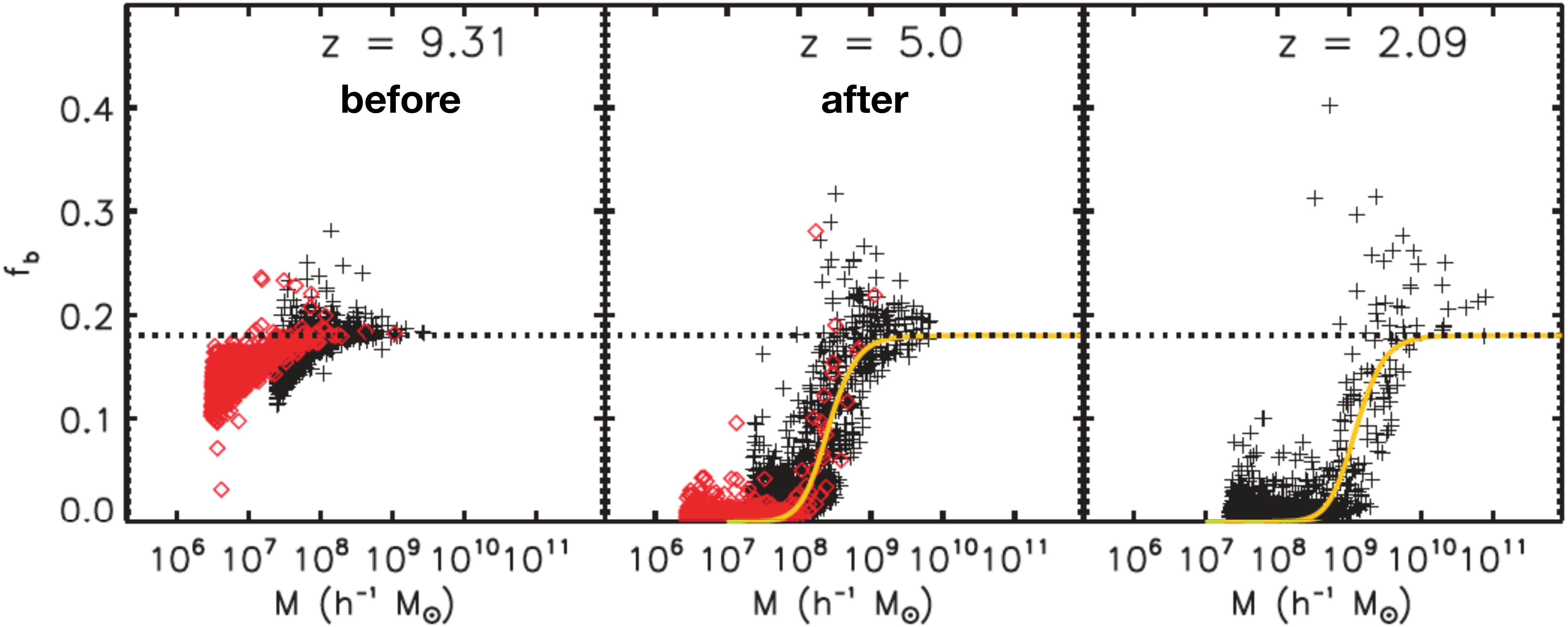
Dwarf Galaxies — Impact of Baryonic Processes on Galaxies and Host Halos

- Recap: baryonic feedback
- Small-scale issues of the LCDM paradigm
- Impact of fdbk on galaxies (ultra-diffuse galaxies) and 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 $z_{\text{reionization}}$)



- 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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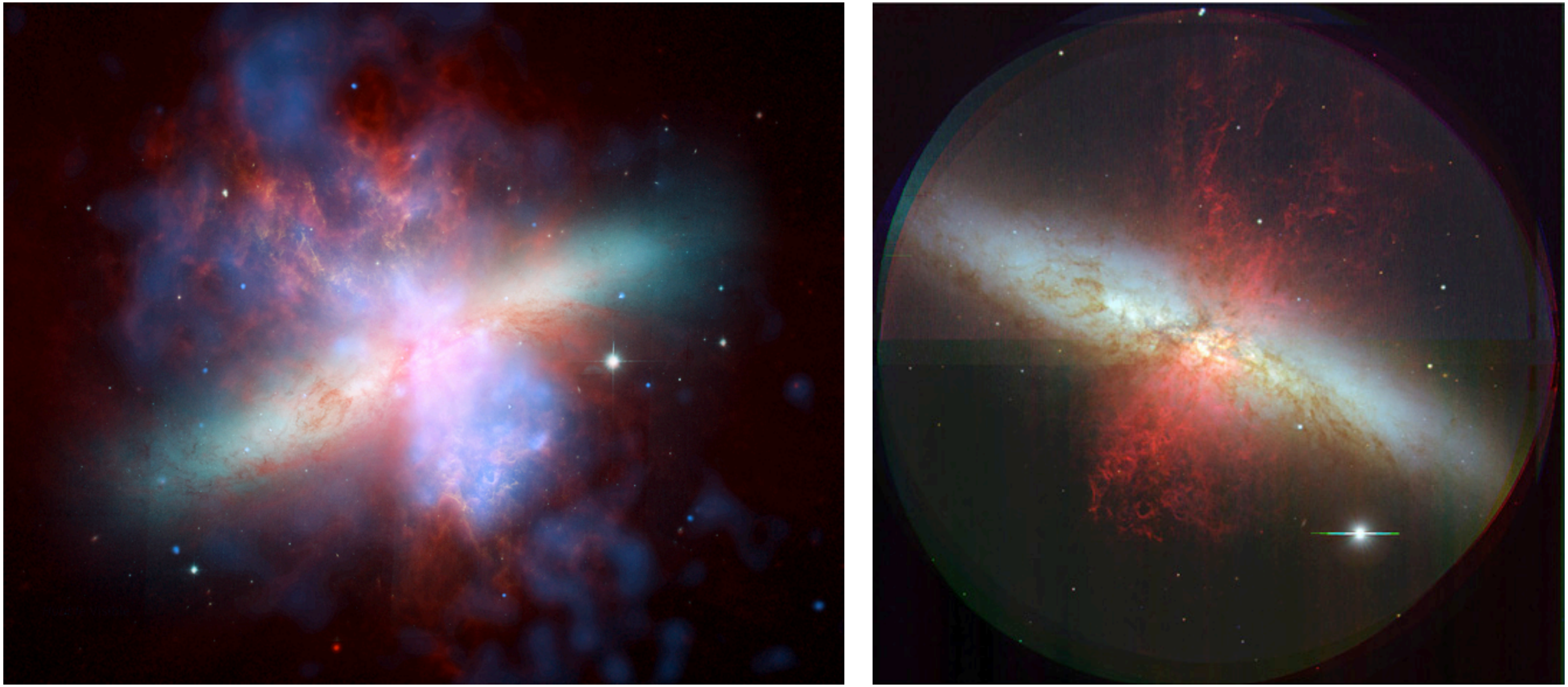
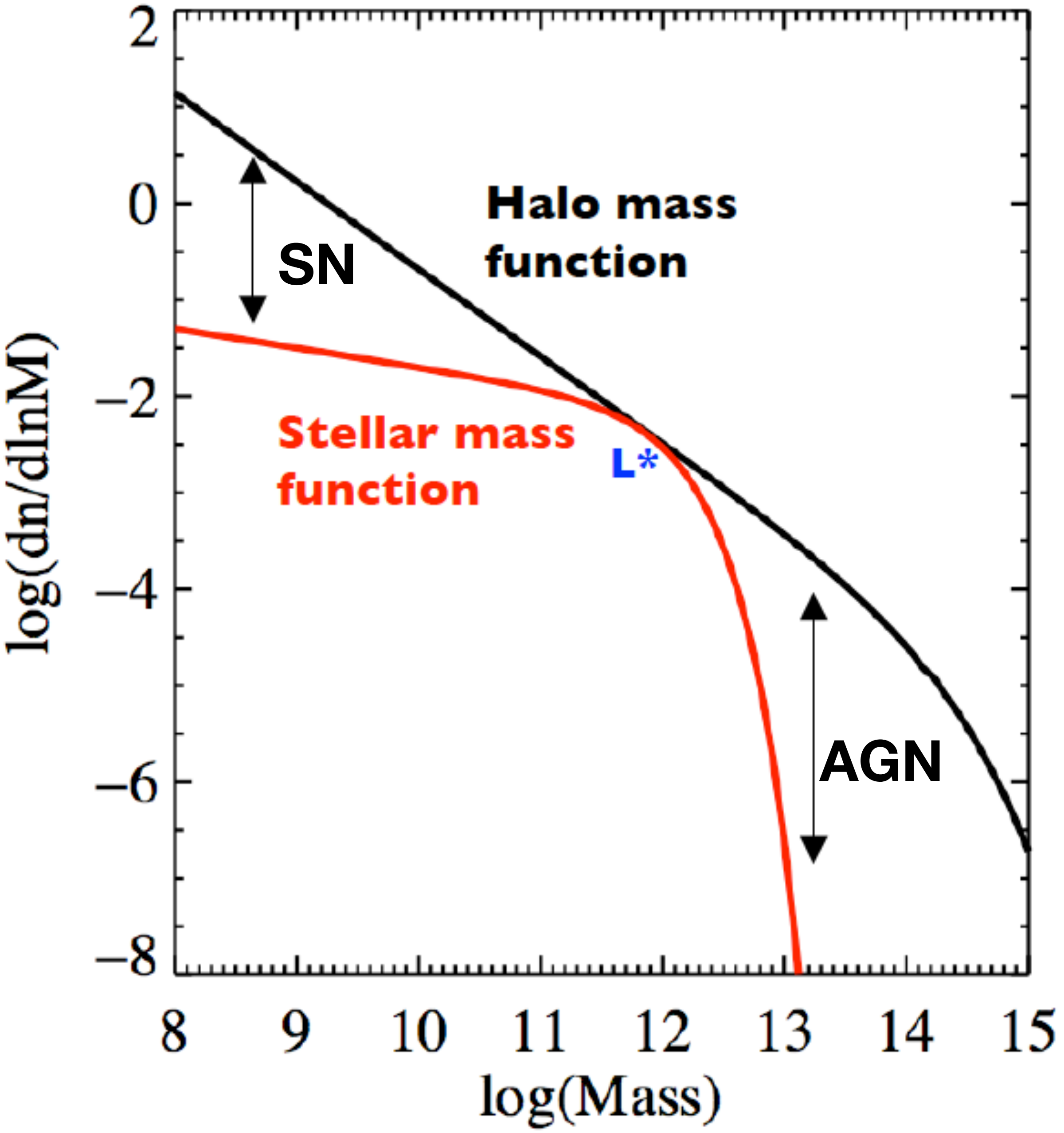


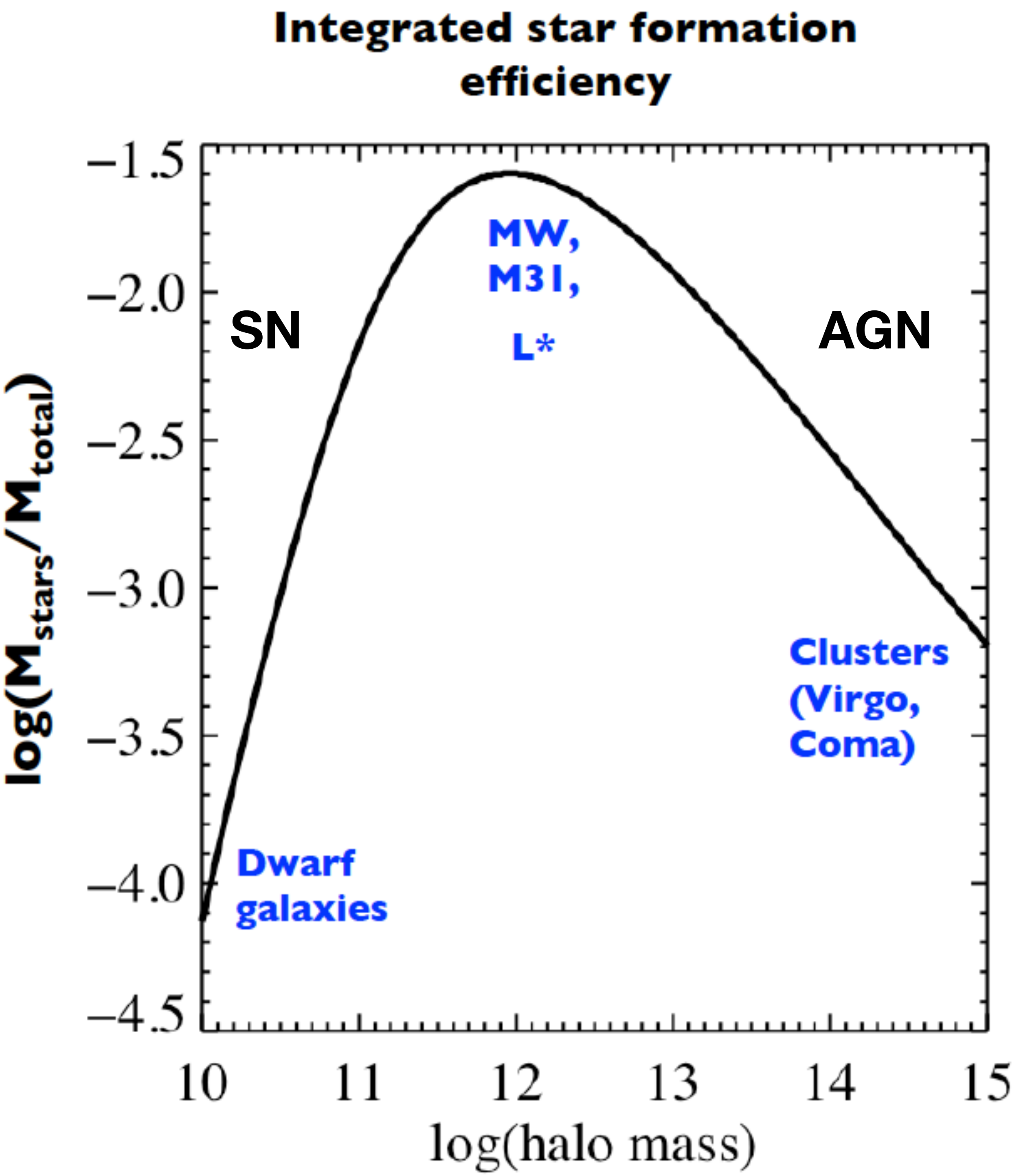
X-ray

Hα

M82: a massive starburst galaxy with obvious outflow

Why do we need feedback?





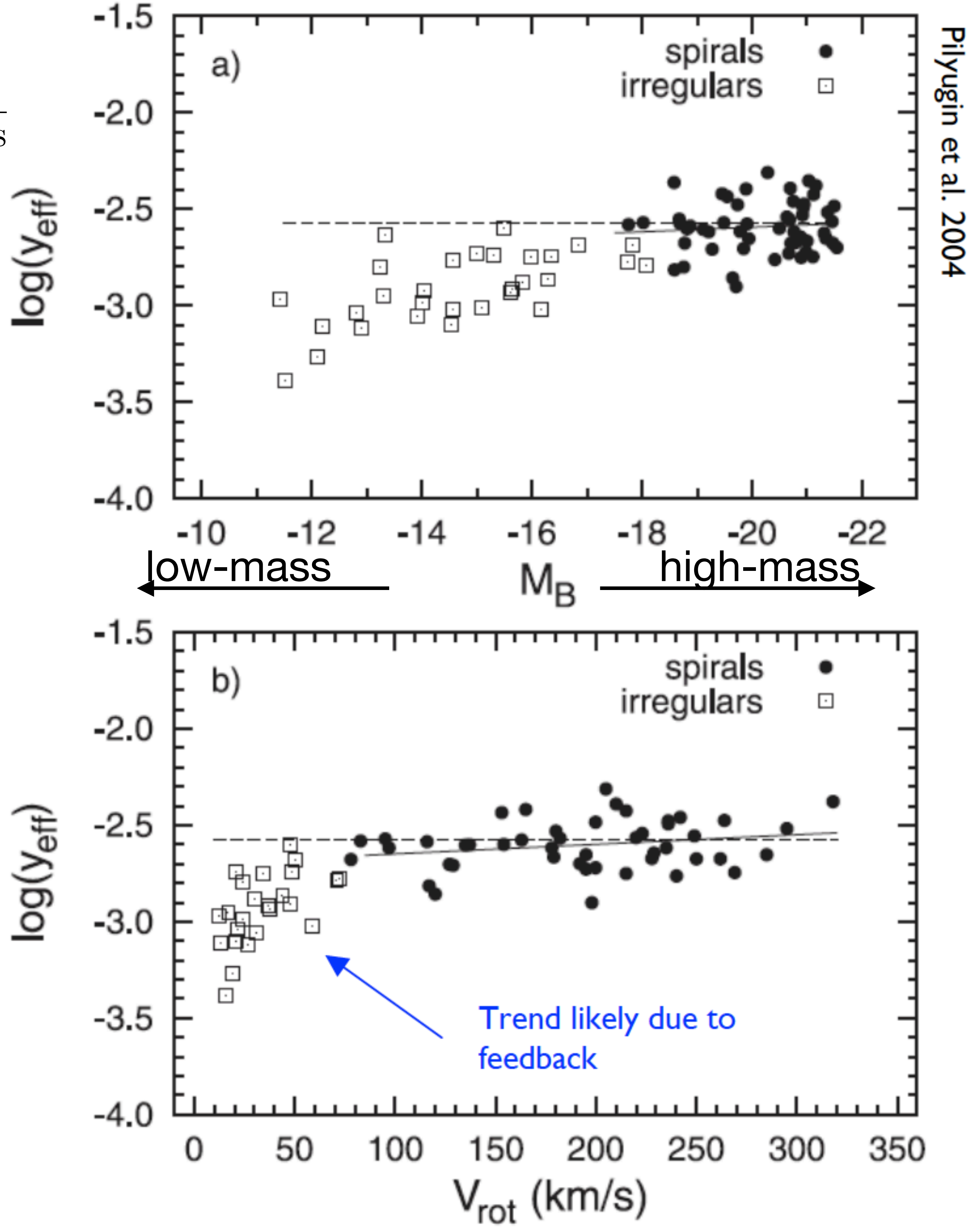
SN fdbk is believed to be responsible for suppressing star formation in dwarf galaxies ($M_{vir} < 10^{11} M_{sun}$, $V_{vir} < 100$km/s)

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

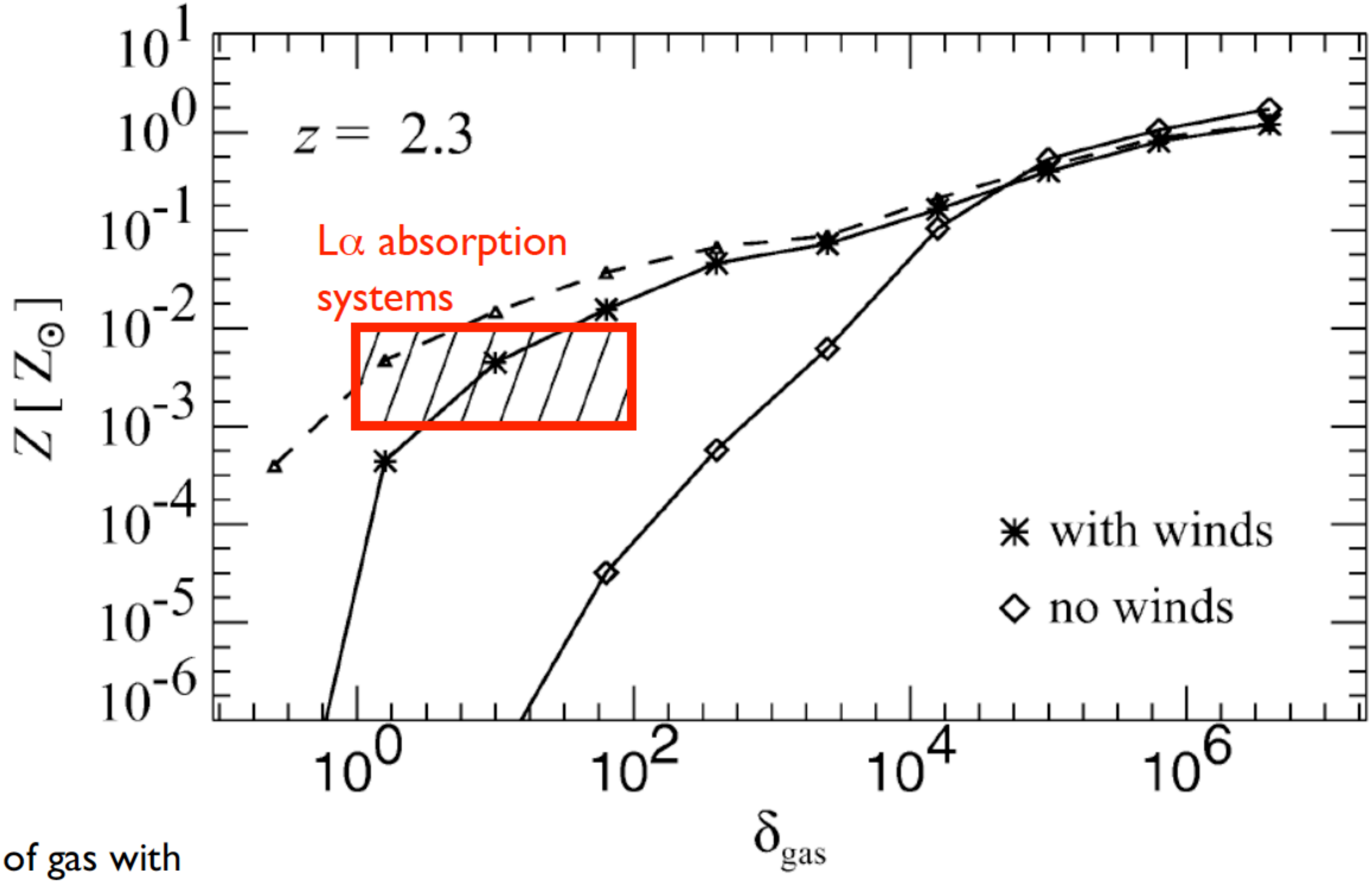
Trend likely due to feedback

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 $\qquad E_{bind} \sim 10^{49}$ 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 $\qquad E_{bind} \sim 10^{57}$ ergs

  a single SN will not unbind the galaxy

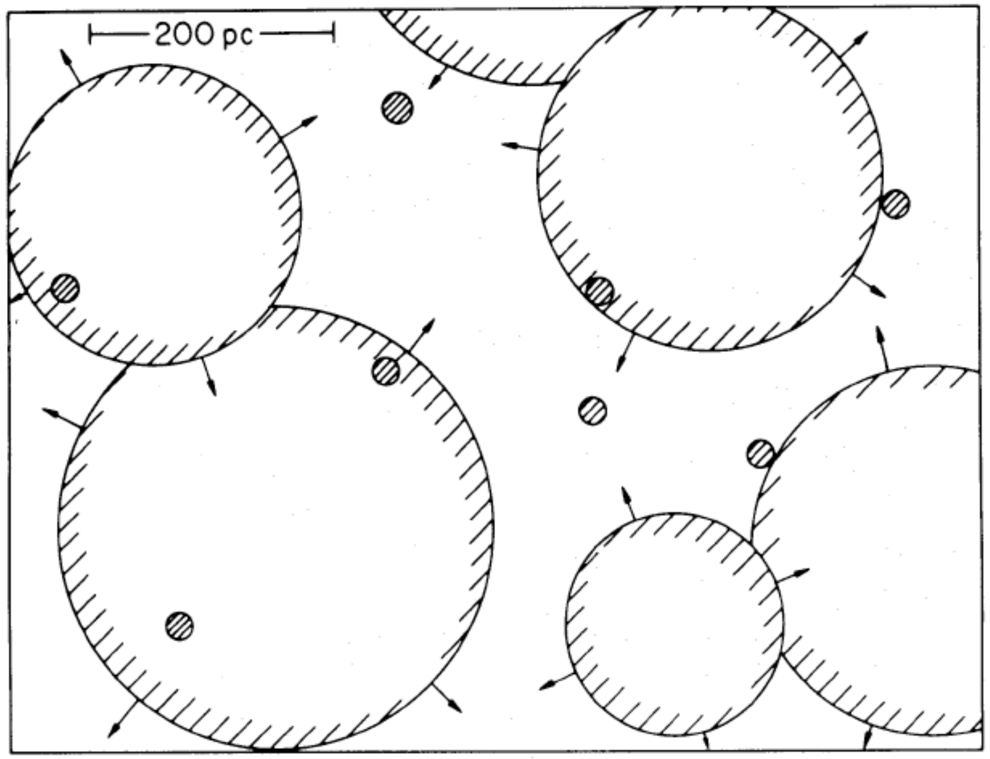
SN feedback on galactic scales

Recap: the standard picture for isolated SN evolution

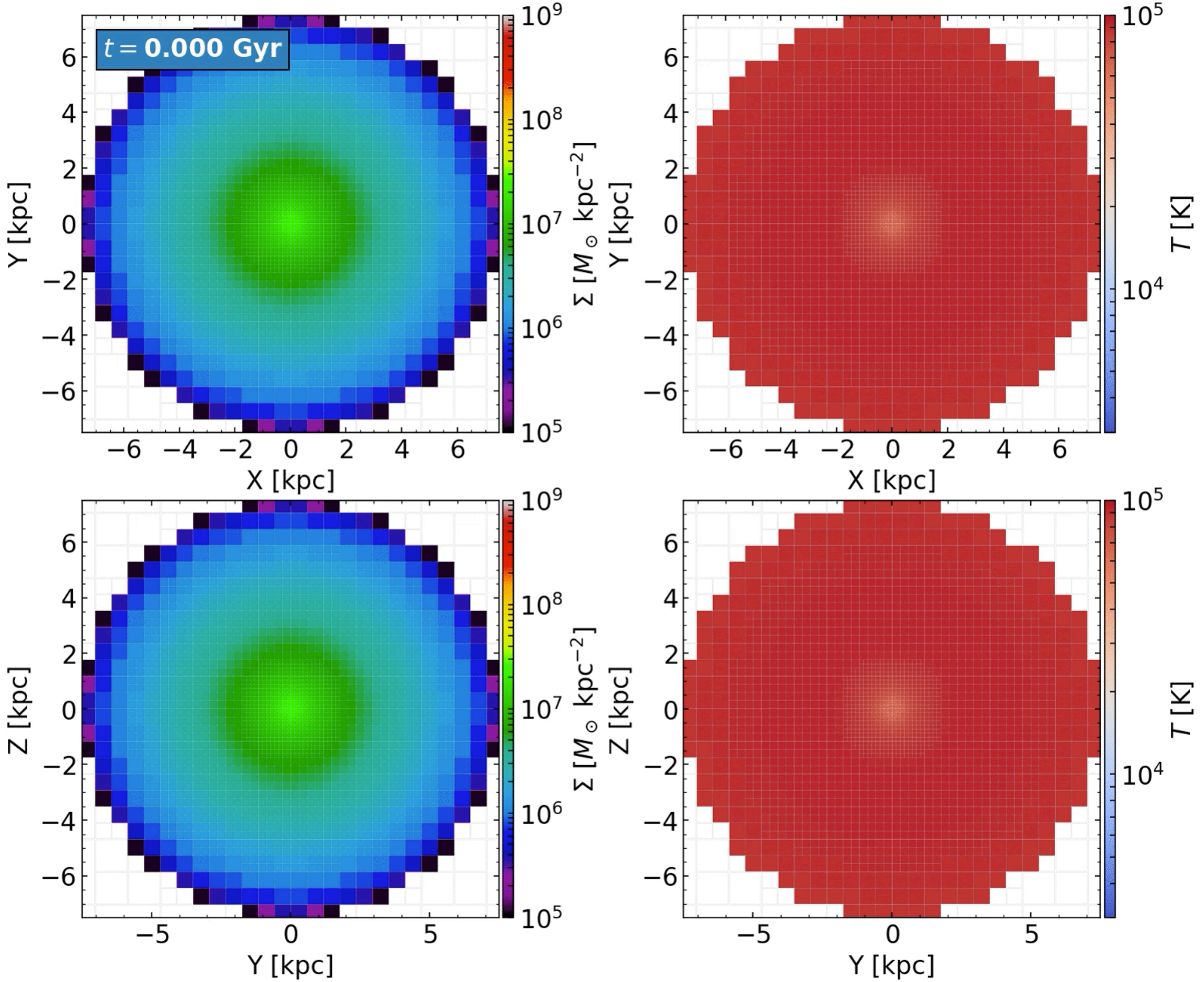
- **Free expansion**: ends when $M_{swept} \sim M_{eject}$, (**t~200 yr, R~1pc**)
- **Adiabatic** (Sedov-Taylor) phase: ends when radiative losses become important (**t~10^{4-5}yr, R~30pc**)
- **Snowplow** phase (approximately momentum conserving): ends when when the shock velocity is comparable to the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

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

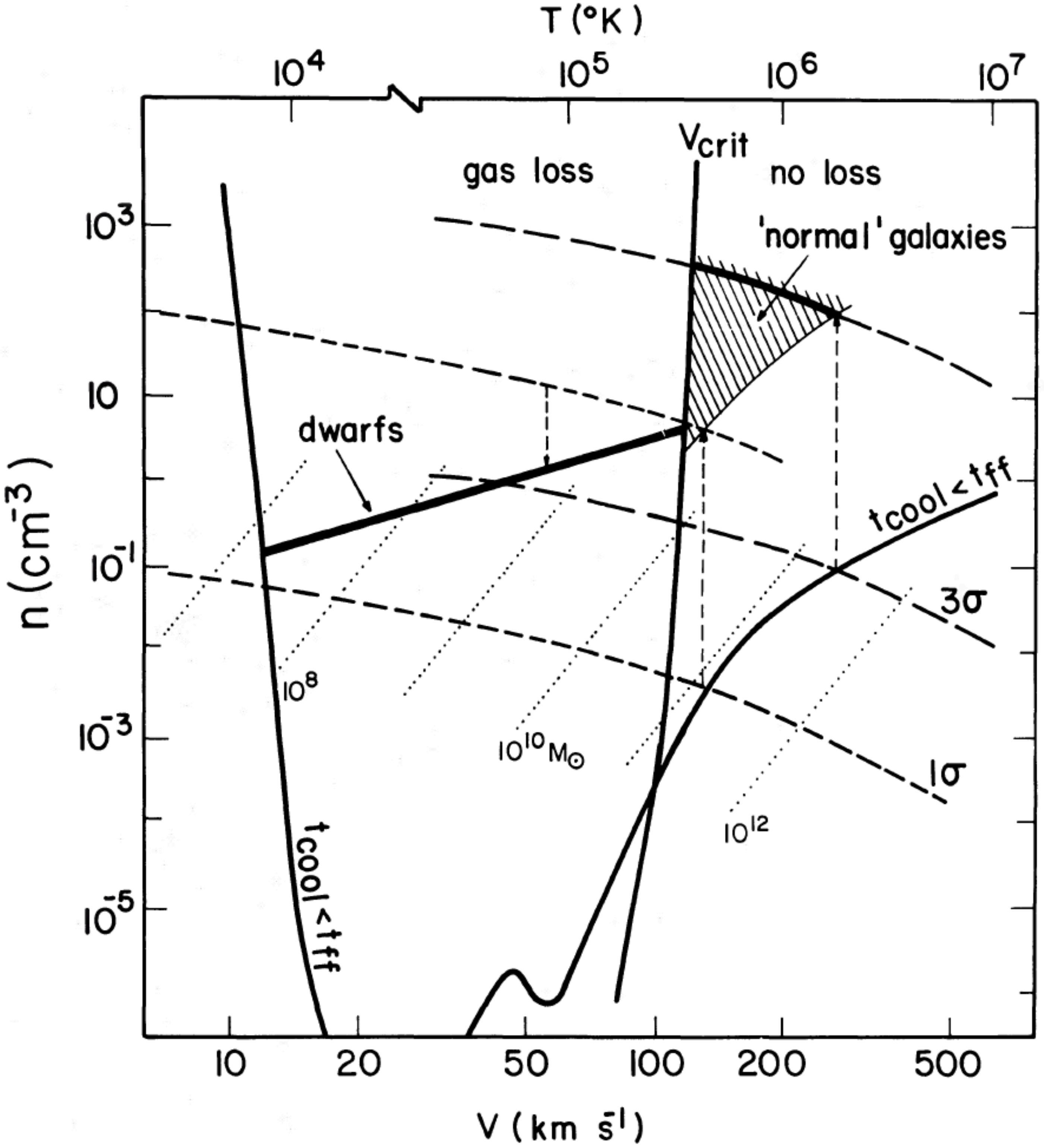
t_{rad} : time when SNR radiates away a significant fraction of its initial energy, $\propto n^{-9/17}$, ~ SN overlap time for the assumed SFR

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

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

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

We worked out the energetics of SN fdbk, and showed that they can expel gas and suppress SF. However, 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” (semi-analytic) 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

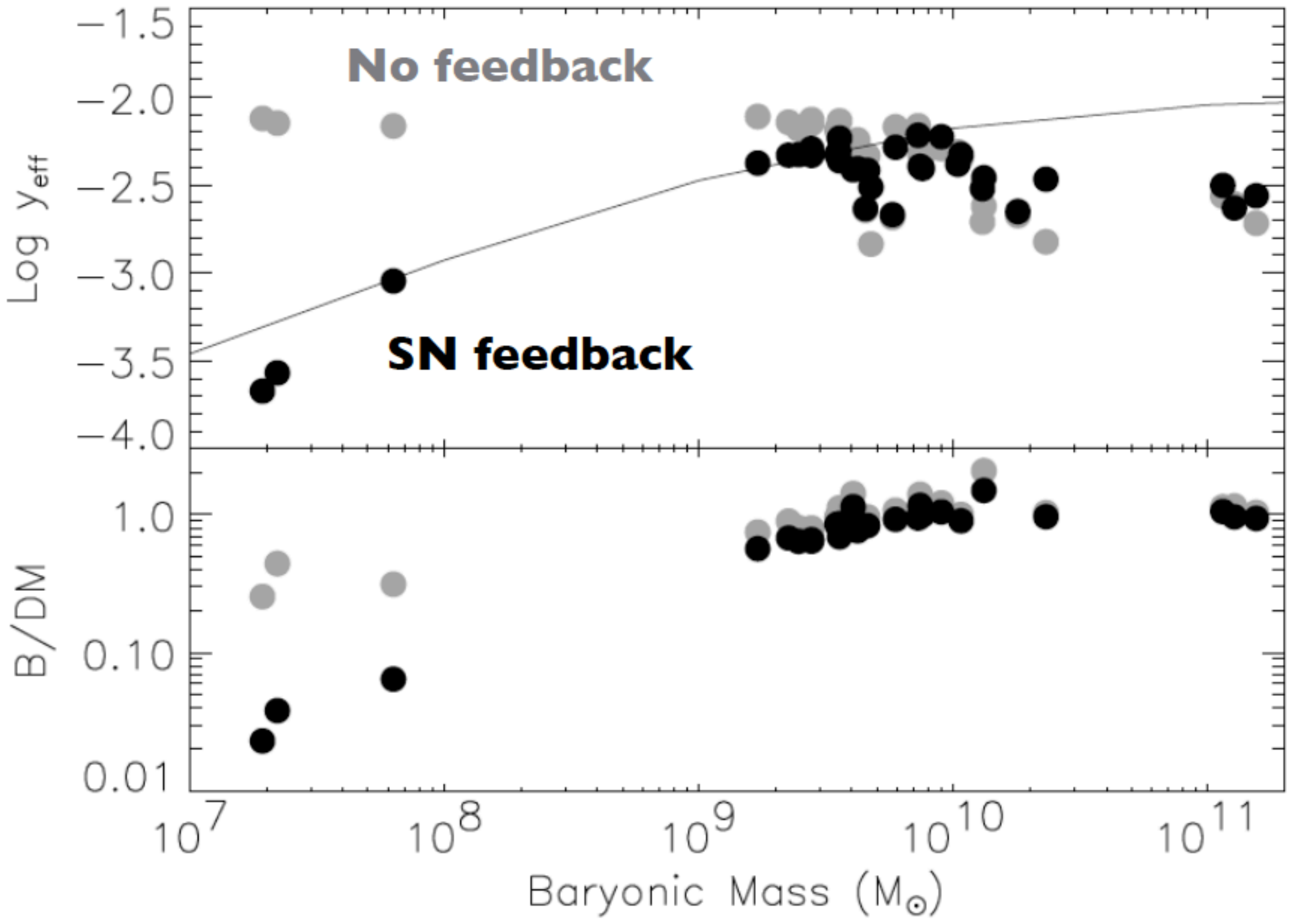
- The net result is that the SN energy is radiated away instantly, and therefore has no effect on the ISM —> “cooling catastrophe”, i.e., too many stars formed

SN feedback on galactic scales: in simulations

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

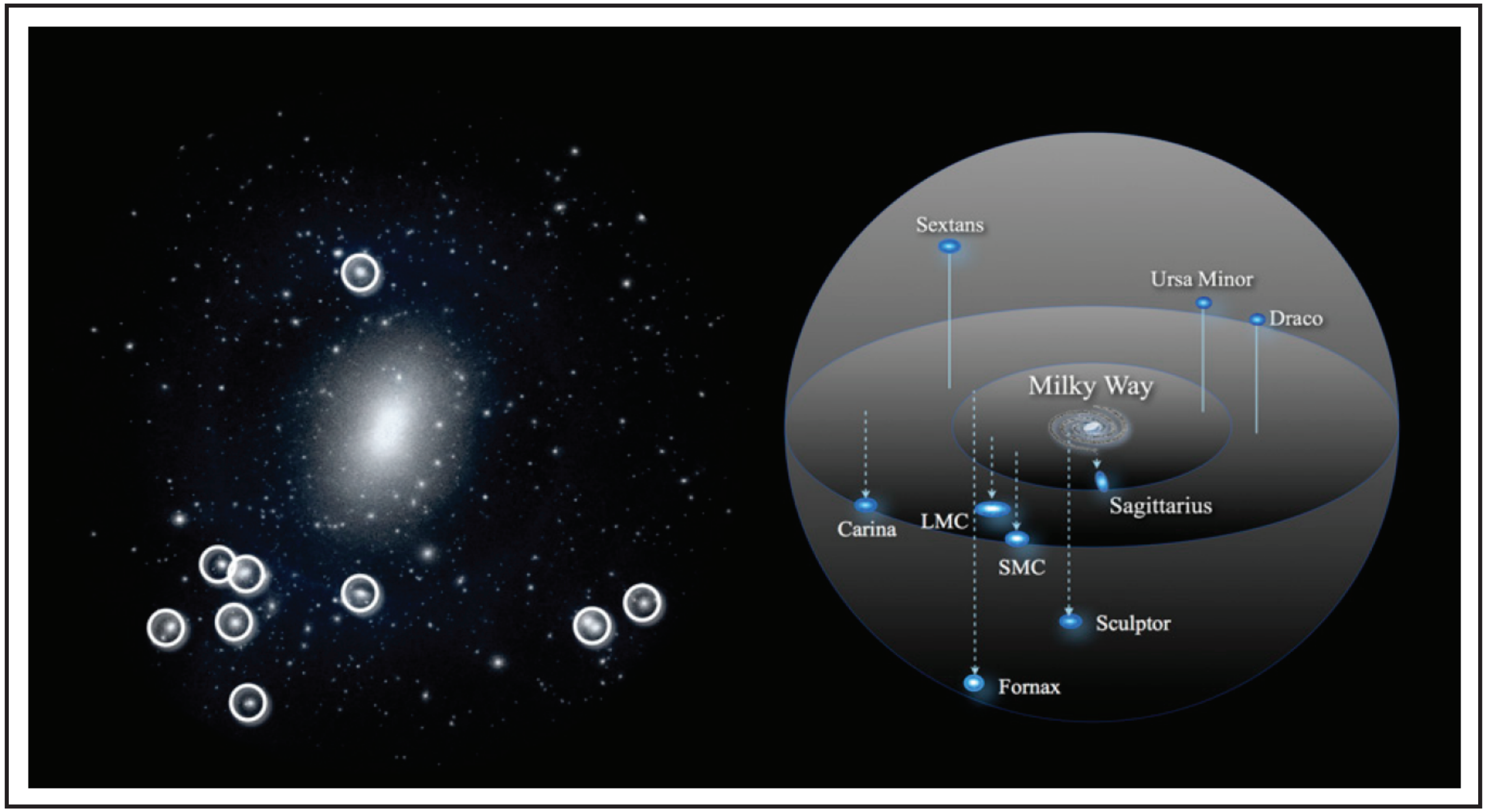
- Dump the SN energy into kinetic energy (e.g. Navarro & White 1993)
- turn off cooling for some amount of time, until the SN energy diffuses over a large enough volume to act as feedback
- Simplistic recipes for a multiphase ISM (e.g. Yepes et al. 1997, Springel & Hernquist 2003): SN energy is shared 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

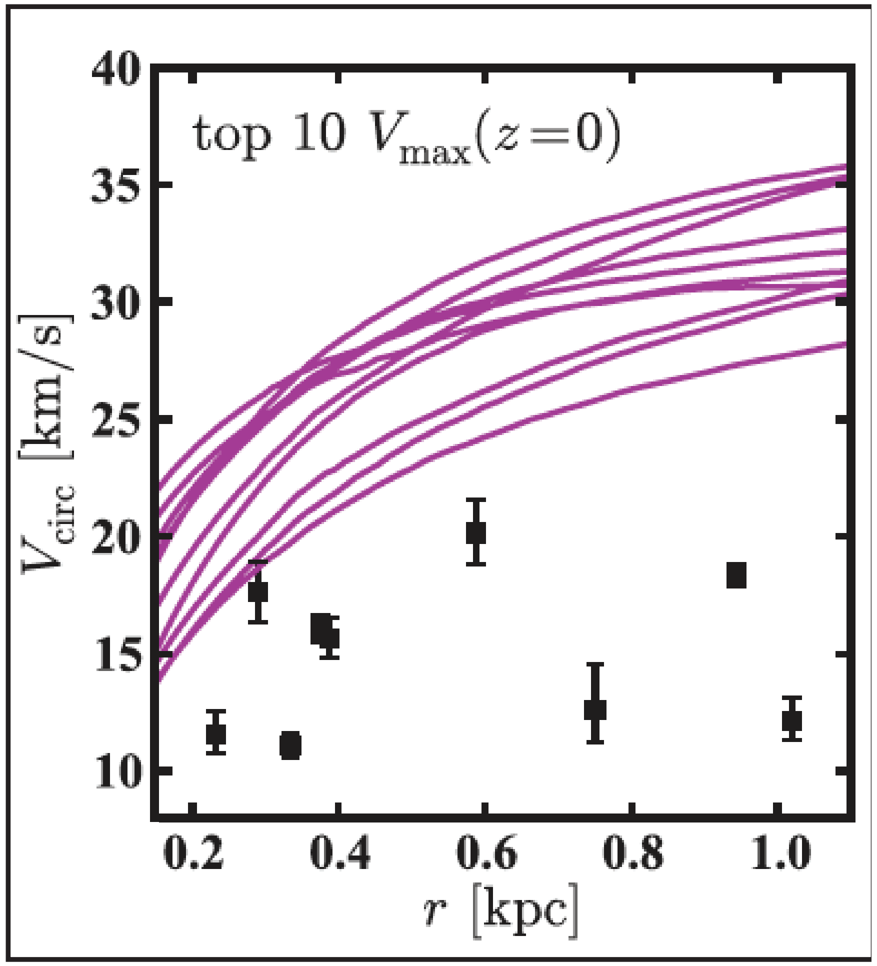


Brooks et al. 2007

Small-scale issues of LCDM: “missing satellite” and “too-big-to-fail”



Weinberg+2015



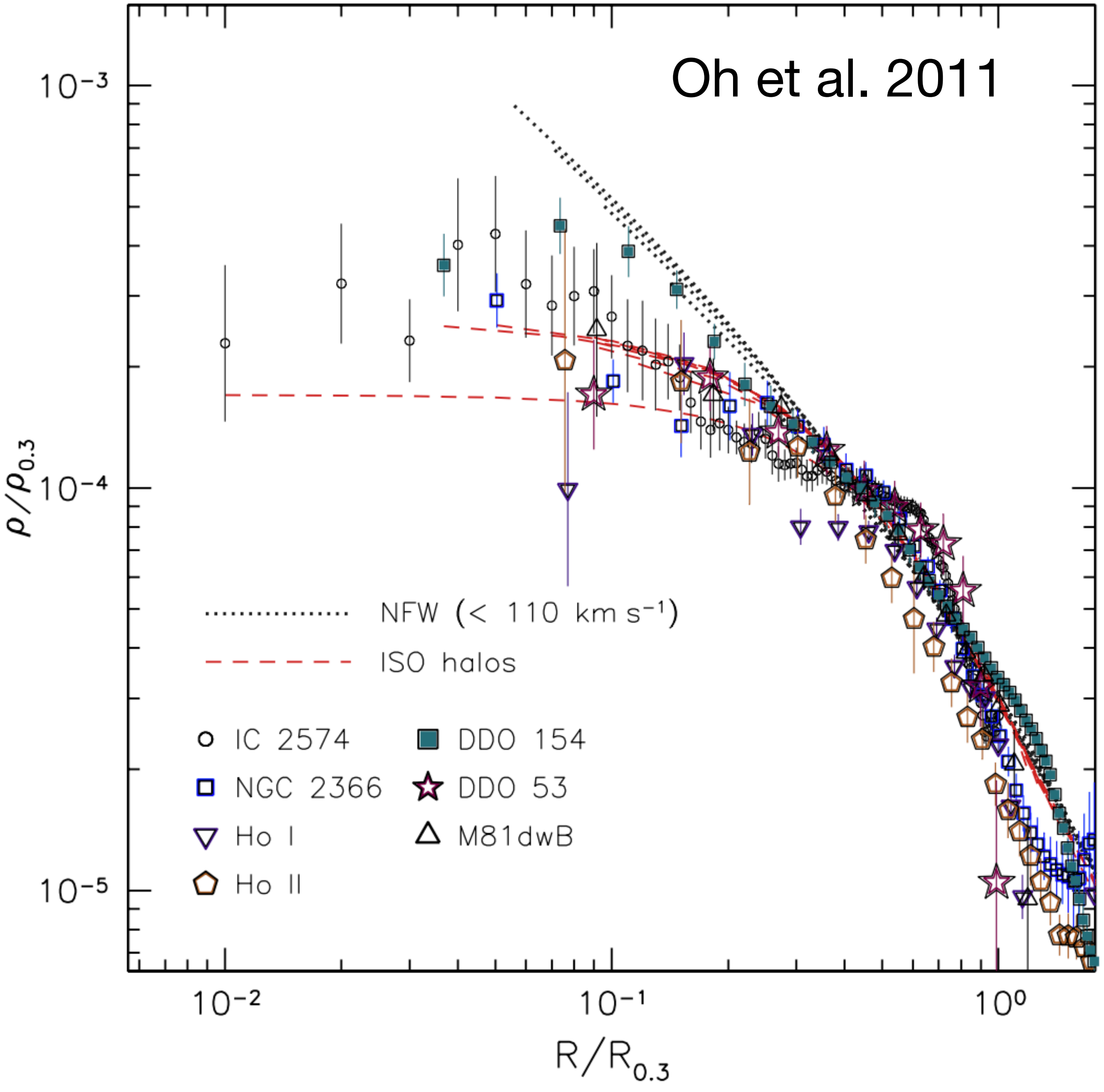
Boylan-Kolchin+2011

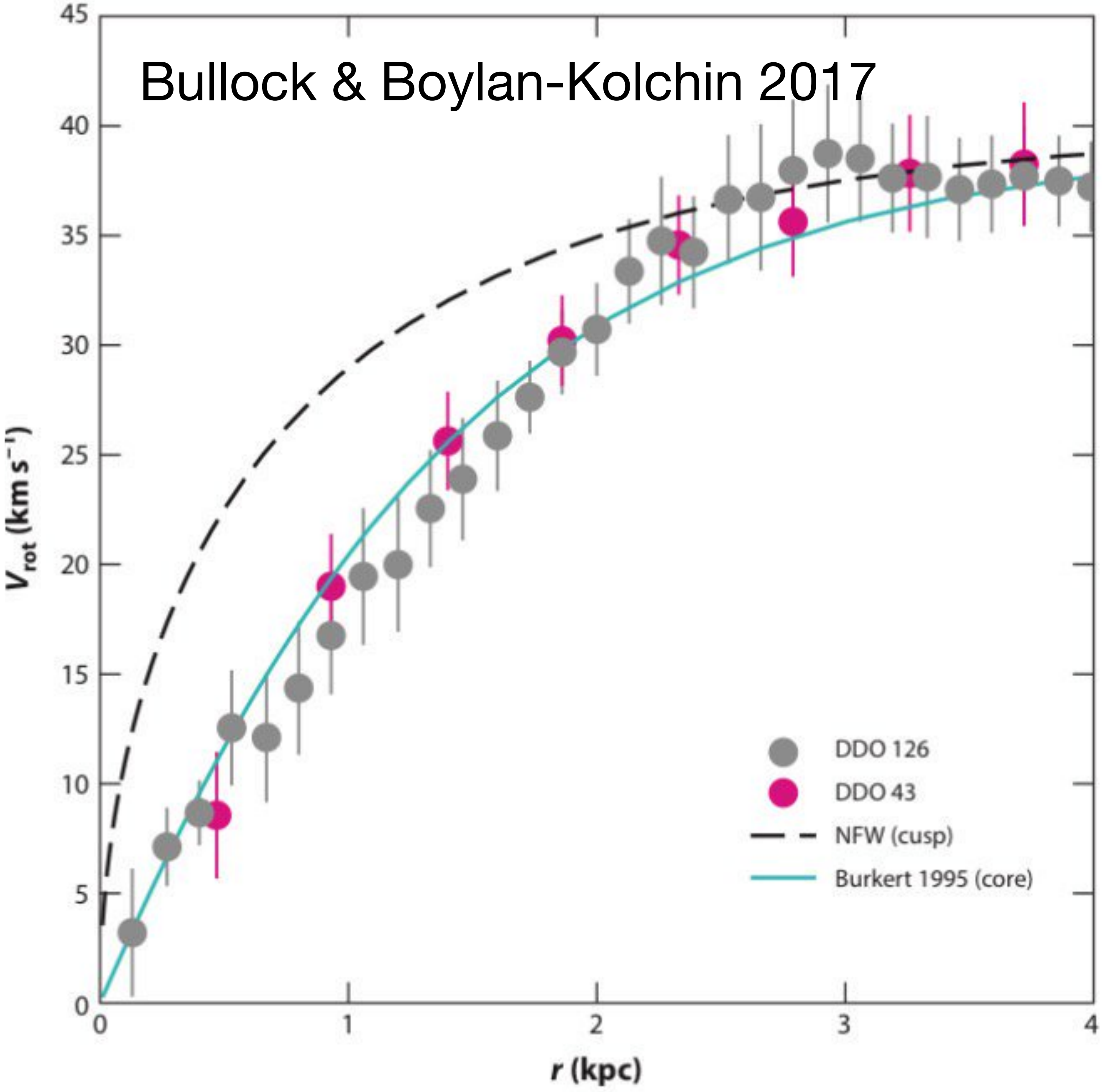
- “**missing satellites**”: too many satellites in simulations — solved
- “**too big to fail**” : too many <u>massive and dense</u> satellites in simulated Milky Way
- “**cusp-core**”: massive dwarfs are “cuspy” in cosmological N-body simulations, while observed ones are consistent with a blend of “cores” and “cusps”

Small-scale issues of LCDM: “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**)

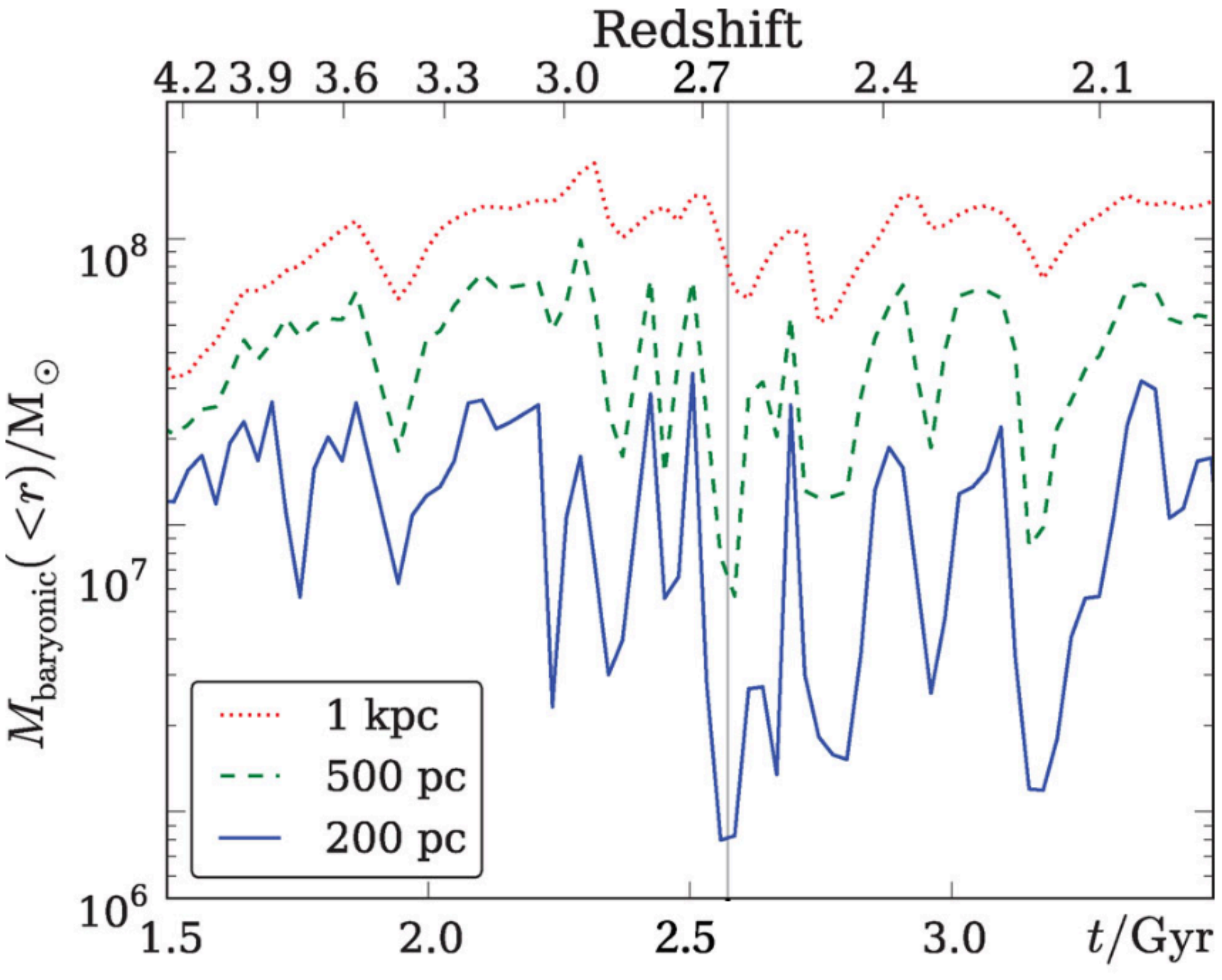

Oh et al. 2011

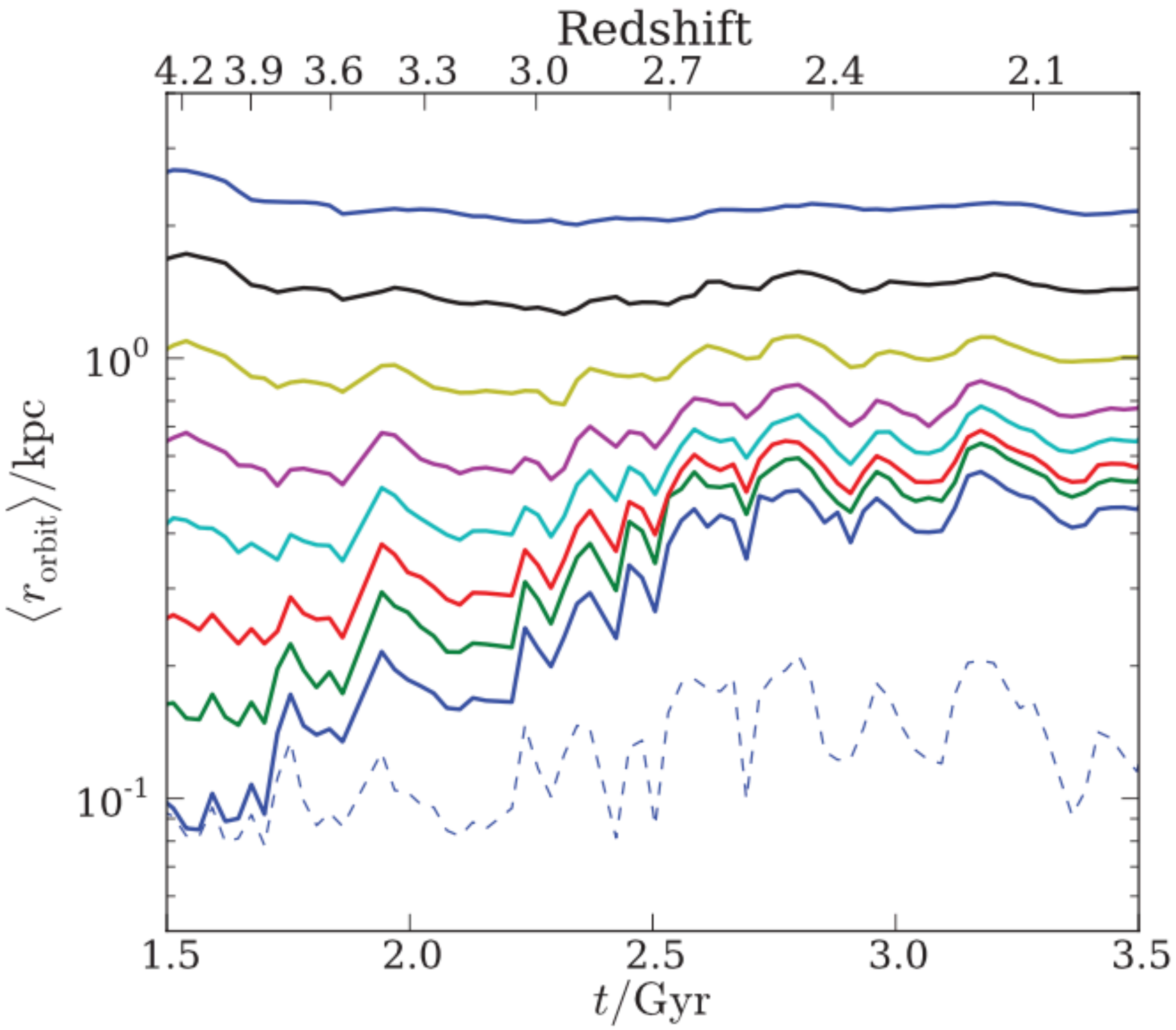

Bullock & Boylan-Kolchin 2017

Cusp-Core transformation

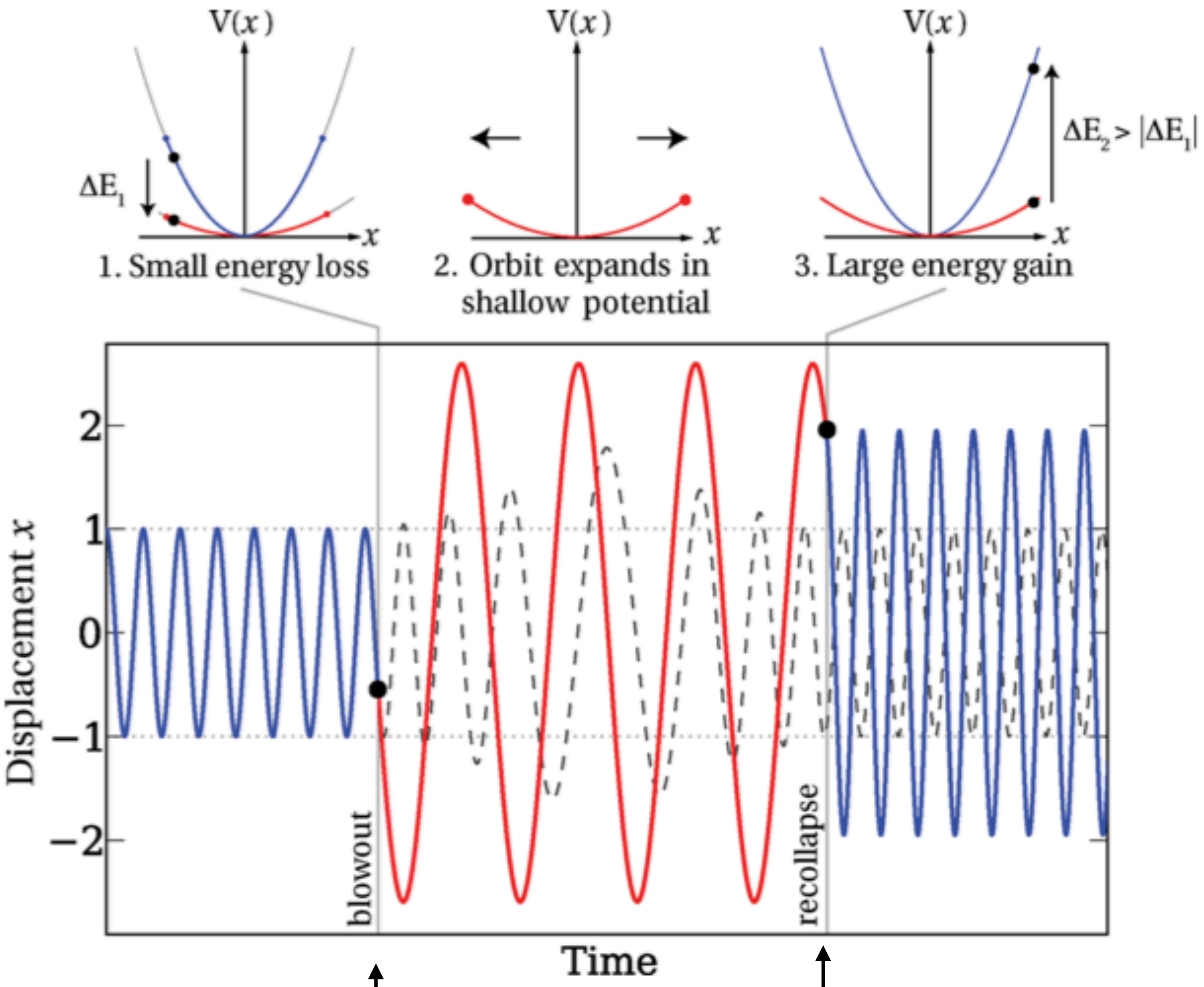
Baryonic effects modifies the DM density profile:

- 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)





Cusp-Core transformation



SN

accretion / gas fall back

Cusp-Core transformation

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

1) Initial conditions at equilibrium

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

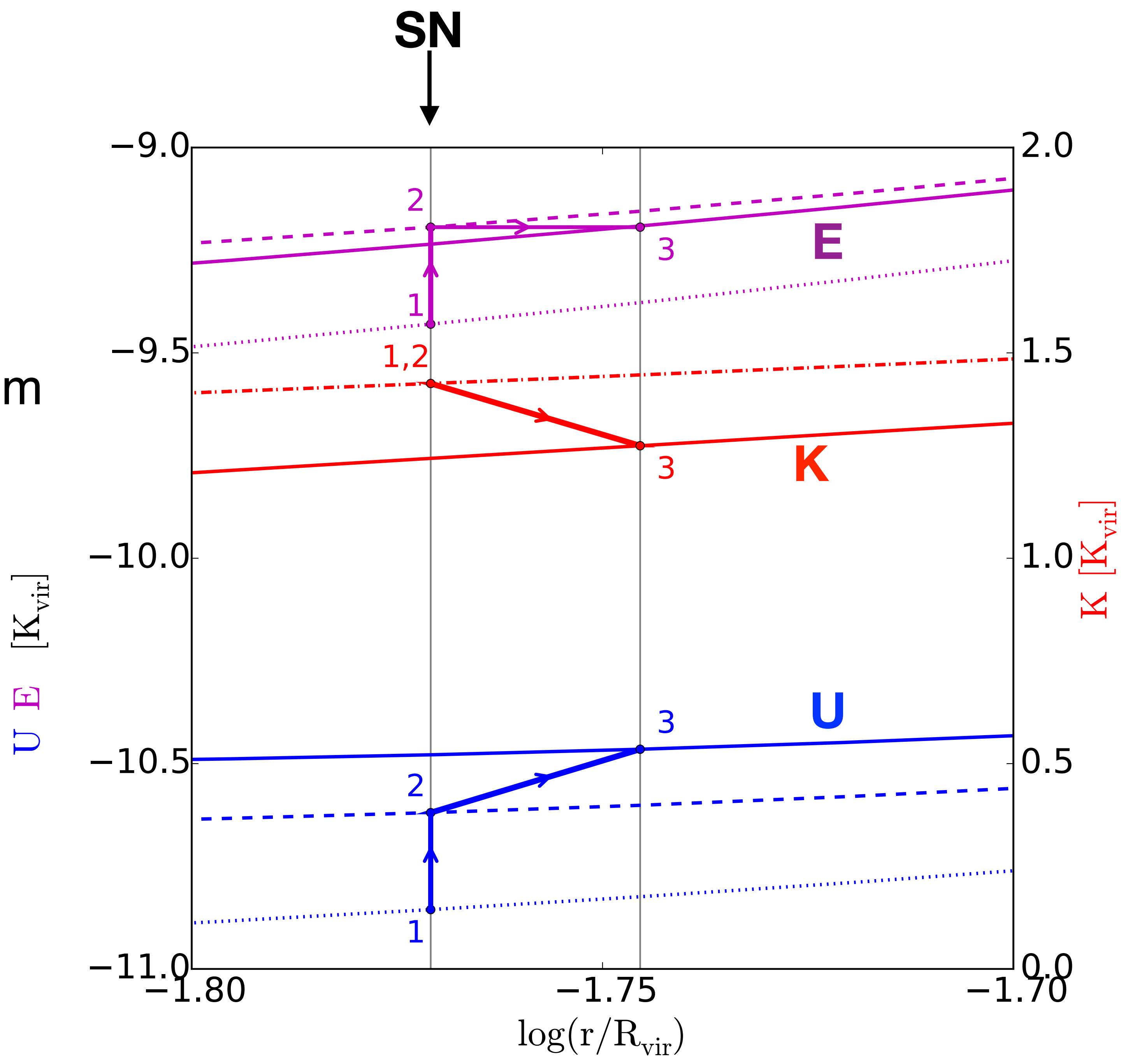
2) Immediately after the mass change

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

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



Freundlich, Dekel, Jiang+2020

Cusp-Core transformation

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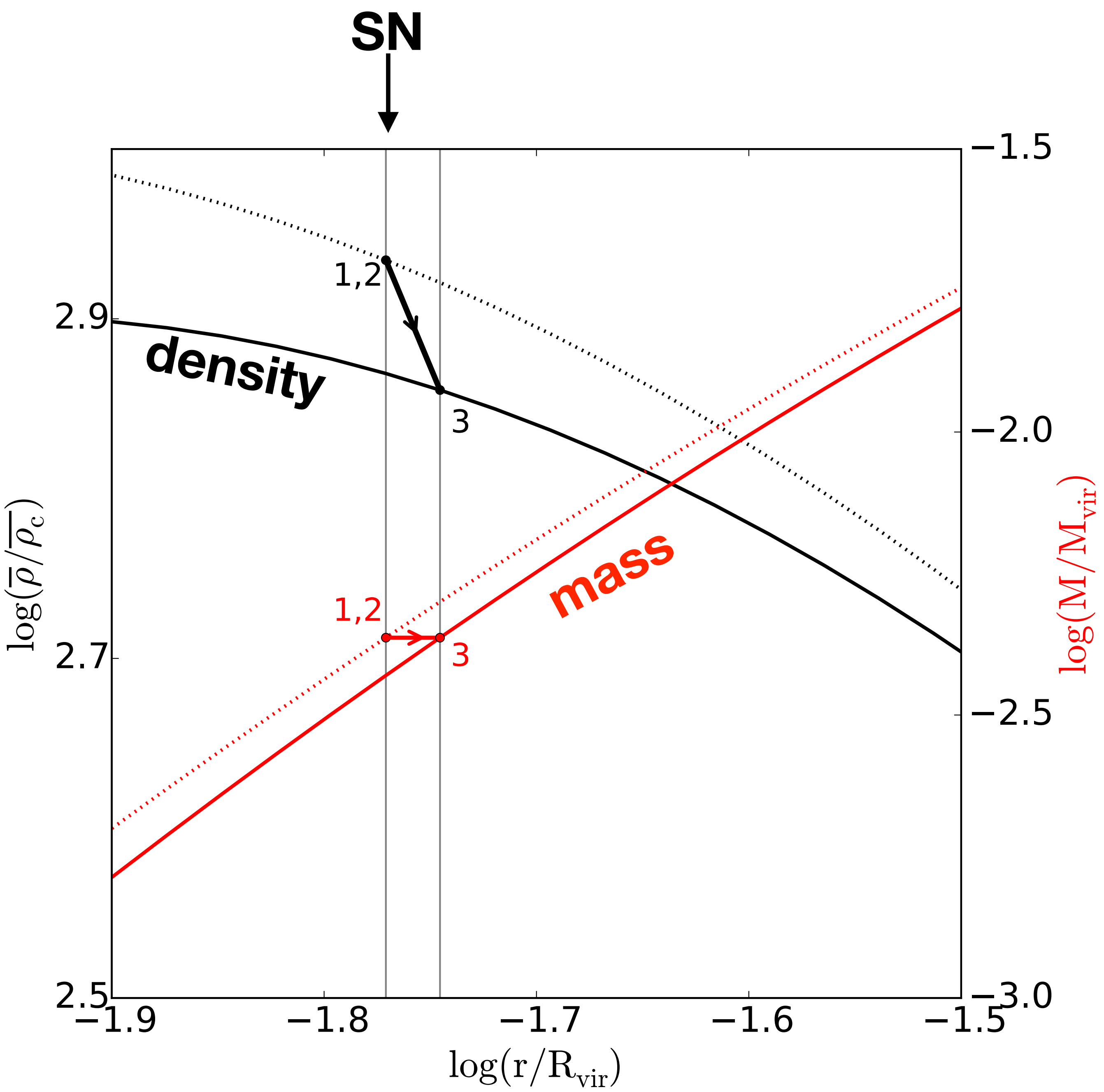
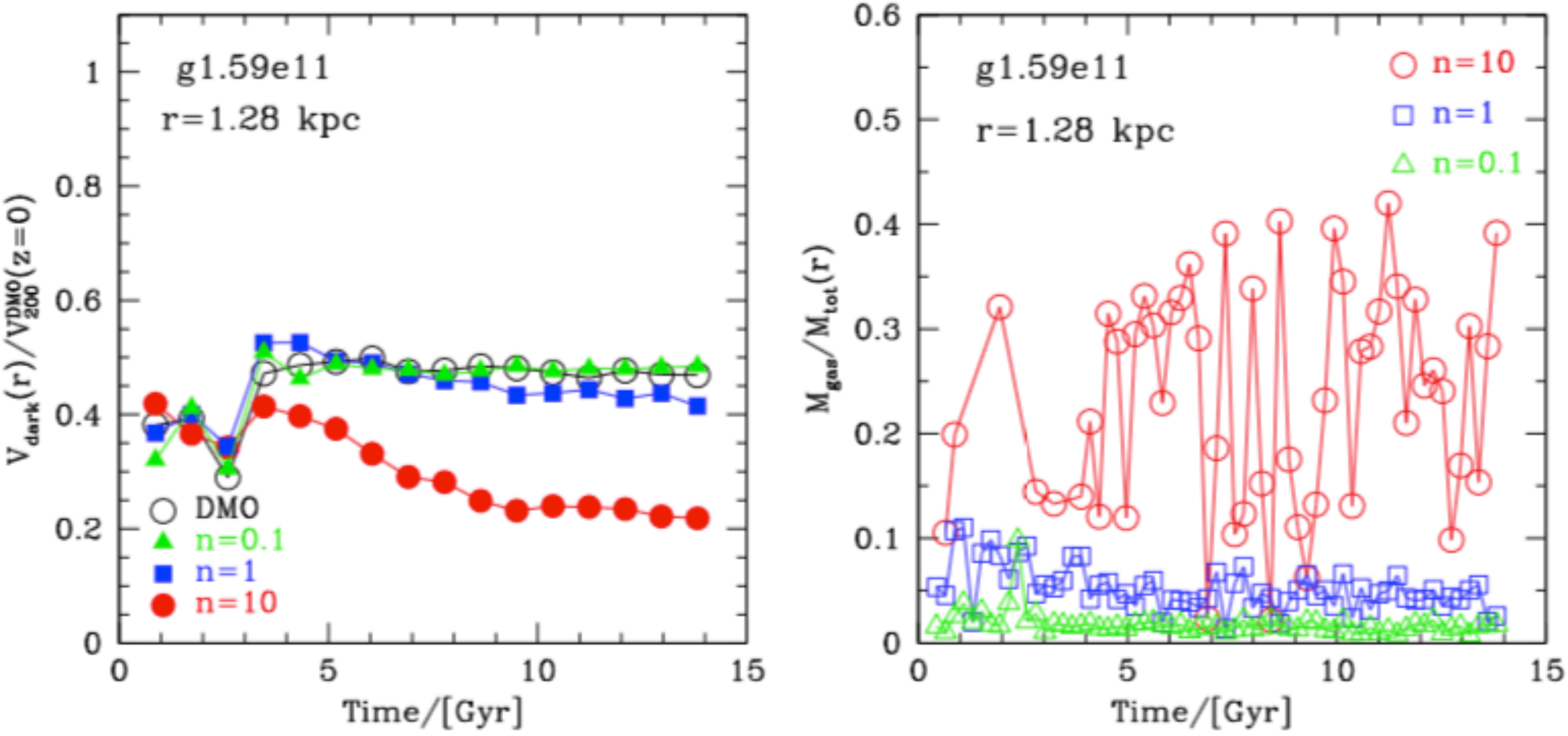


Freundlich, Dekel, Jiang+2020

Cusp-Core transformation

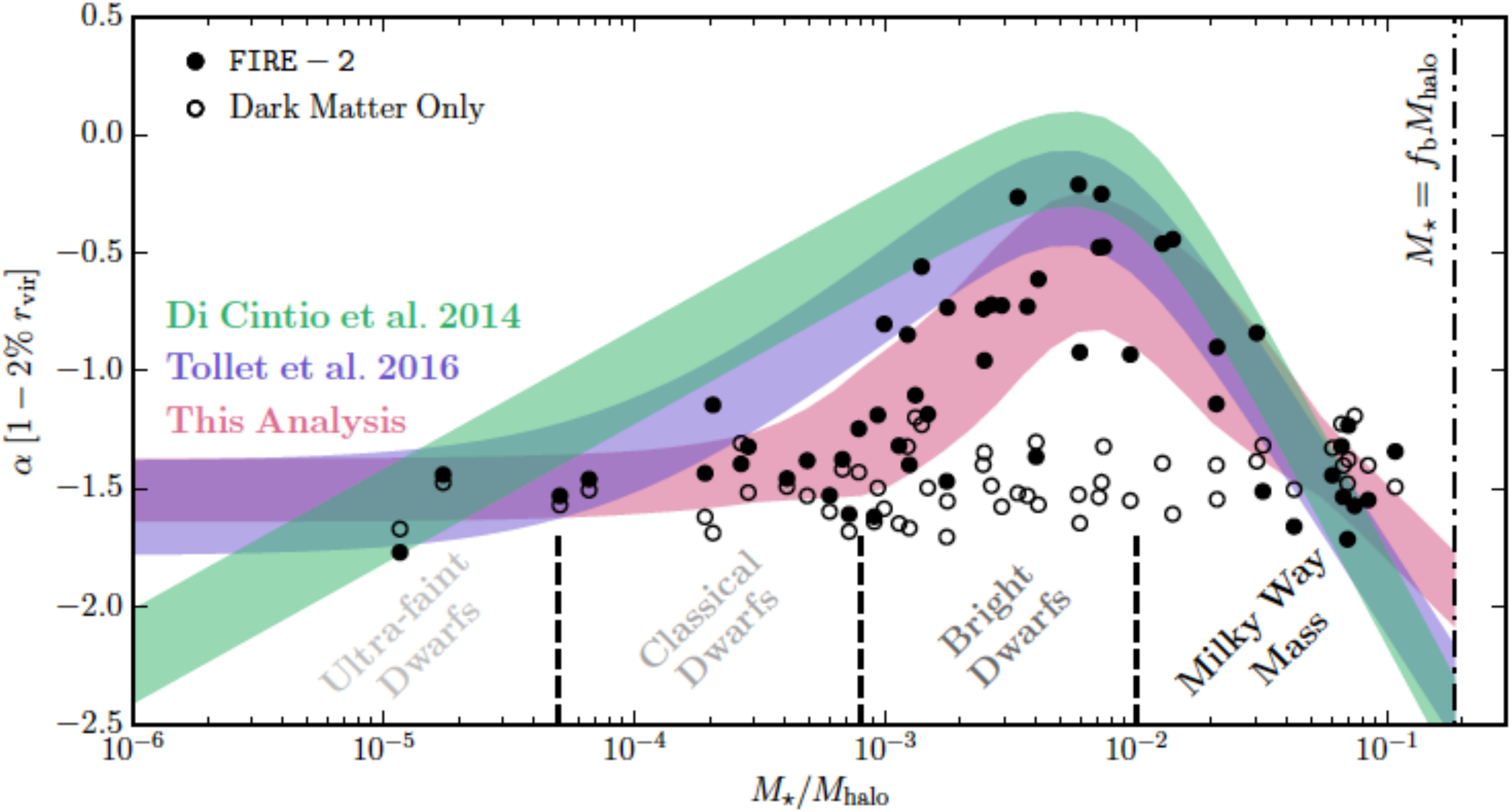
Condition for this process (i.e., the drastic potential-well fluctuations) to happen:

Significant amount of gas condenses to the innermost few kpc, before the SNe pushes the gas out impulsively — this happens when the density threshold for SF is higher than ~10 a.m.u./cm^3



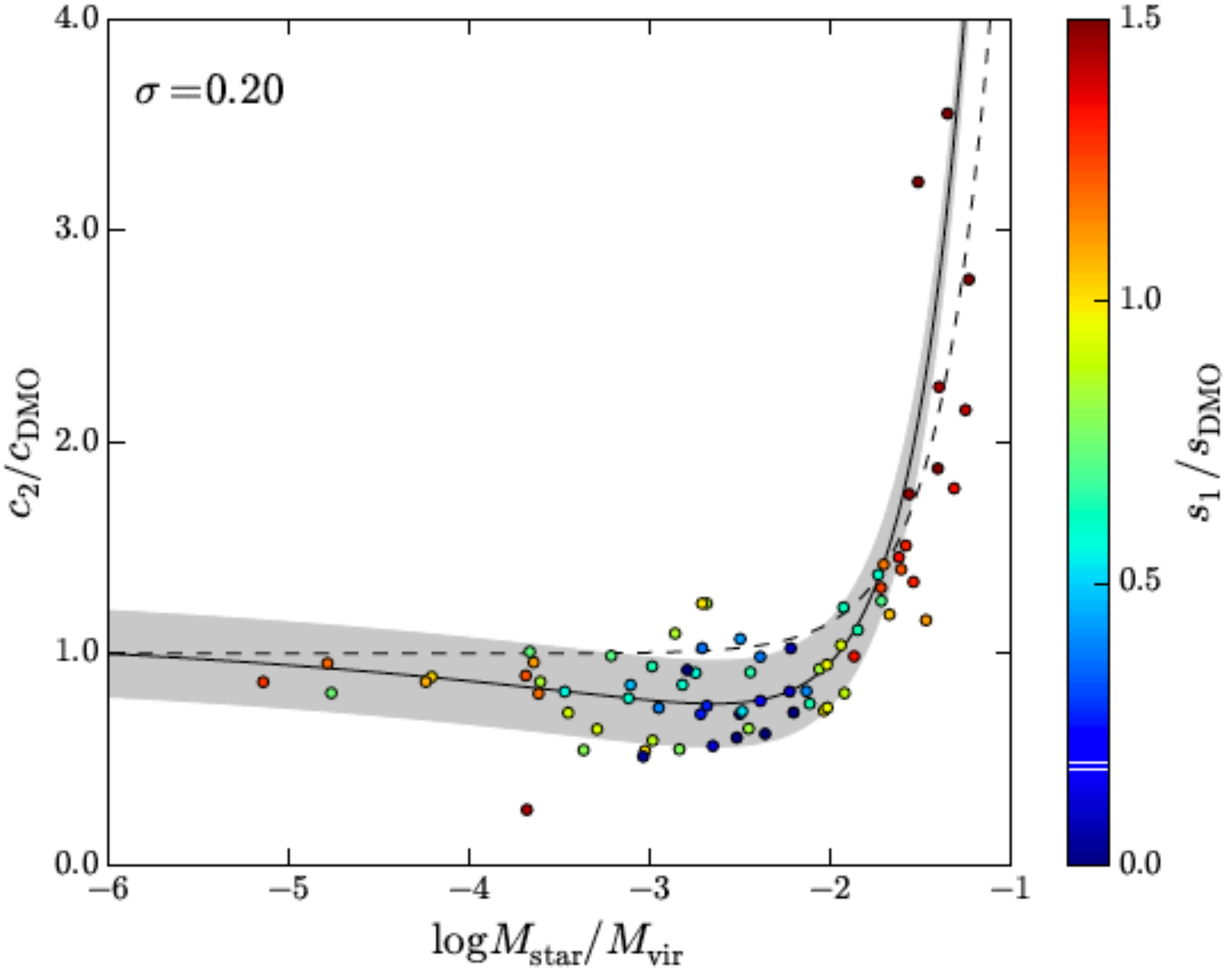
Dutton+2019

"Halo response" to feedback



Lazar+2020

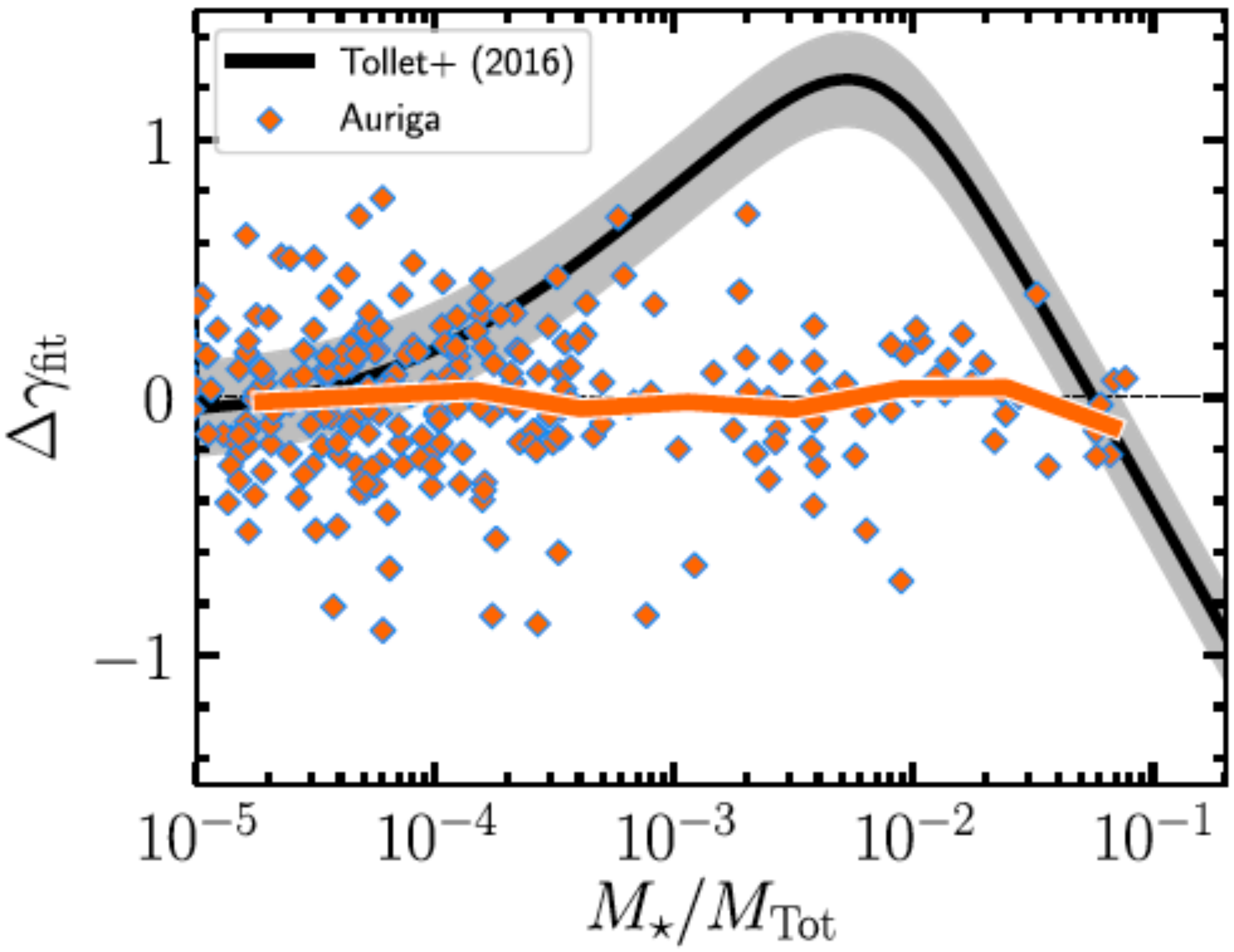
"Halo response" to feedback



Freundlich, Jiang, Dekel+2020

Halo response is maximized in the regime of massive dwarf galaxies ($M_{\rm star}$ ~$10^{7\text{-}9}$ $M_{\rm sun}$ or $M_{\rm vir}$~$10^{10\text{-}11}M_{\rm sun}$)

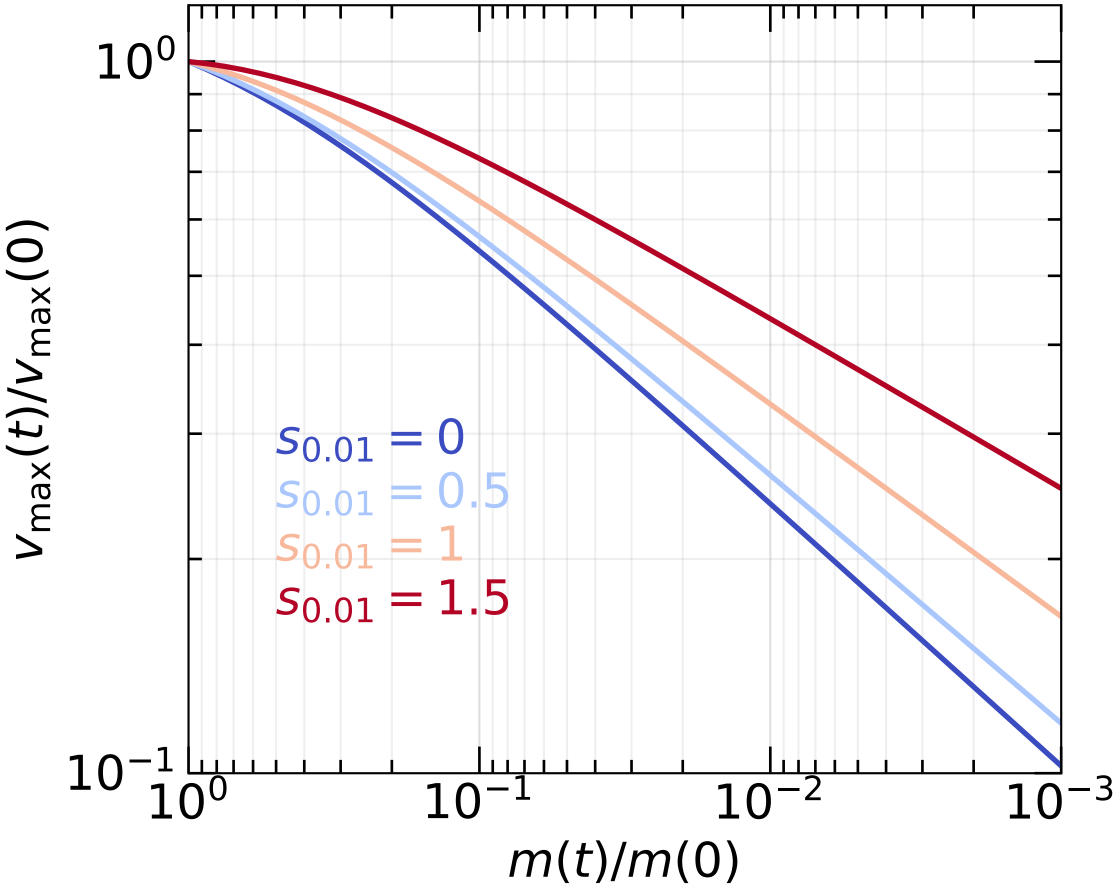
“Halo response” to feedback



Bose+2019

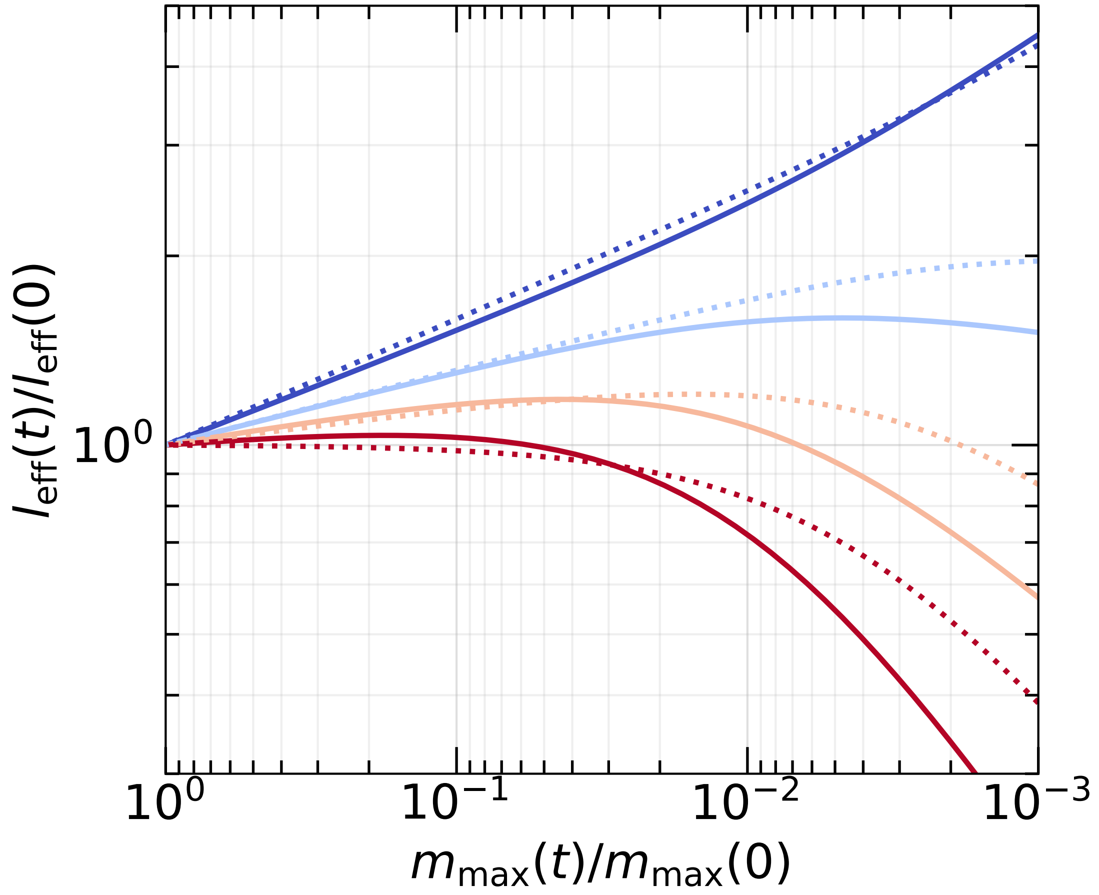
Caveat: the strength of halo response depends on sub-grid physics (e.g., SF density threshold) — with no consensus in simulations, to be tested by kinematics observations or weak lensing

Halo response: impact on satellite galaxies



instant halo mass / initial halo mass

galaxy size

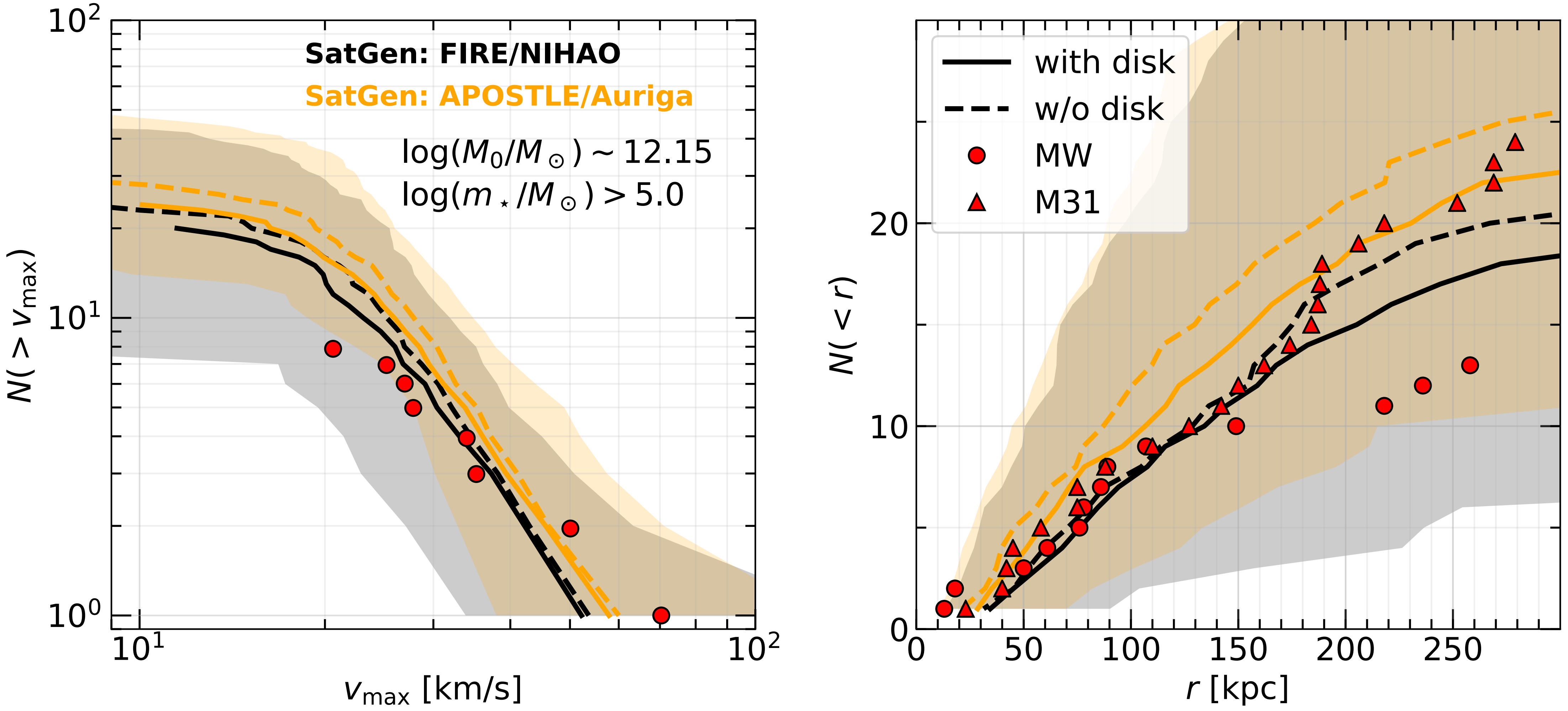


halo mass within V_{max} radius

Penarrubia+2010, Errani+2018

Cored satellites are more prone to environmental effects (tidal stripping, tidal heating, and ram-pressure), and are therefore more disrupted or puffed up

Halo response: impact on satellite galaxies



Jiang, Dekel, Freundlich +2020

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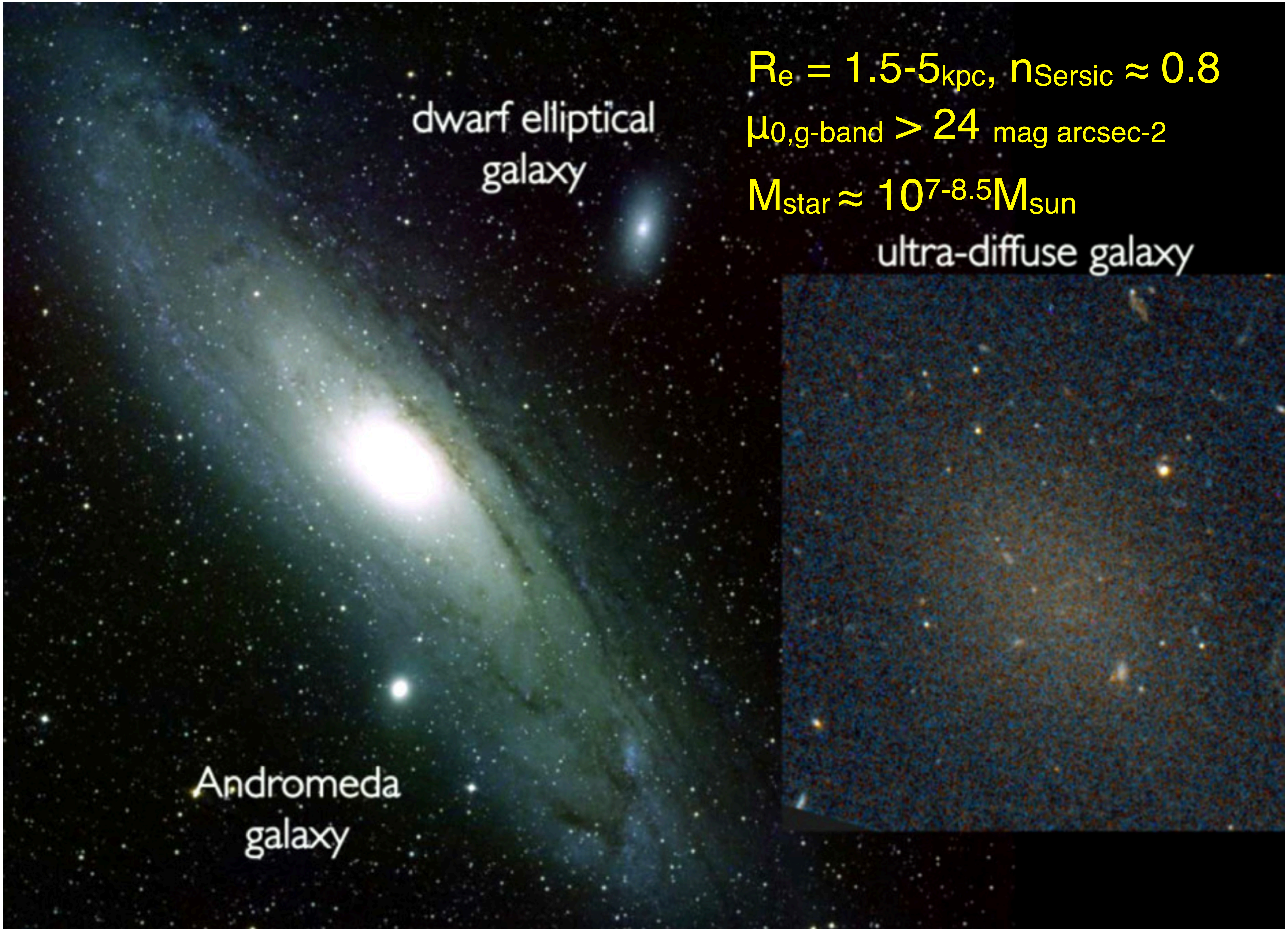
Ultra-diffuse galaxies (UDGs)

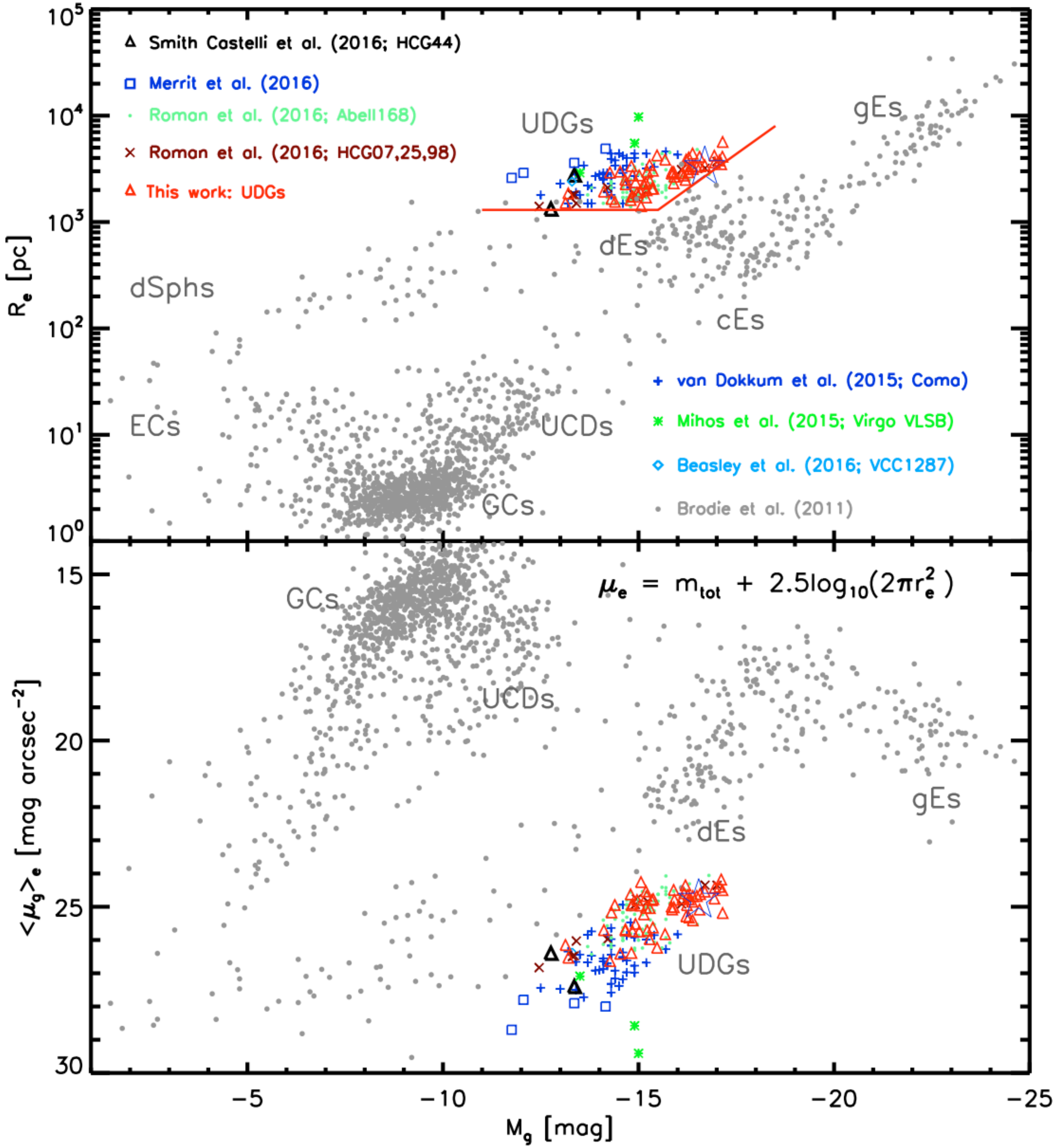


$R_e = 1.5\text{-}5_{\text{kpc}}$, $n_{\text{Sersic}} \approx 0.8$

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

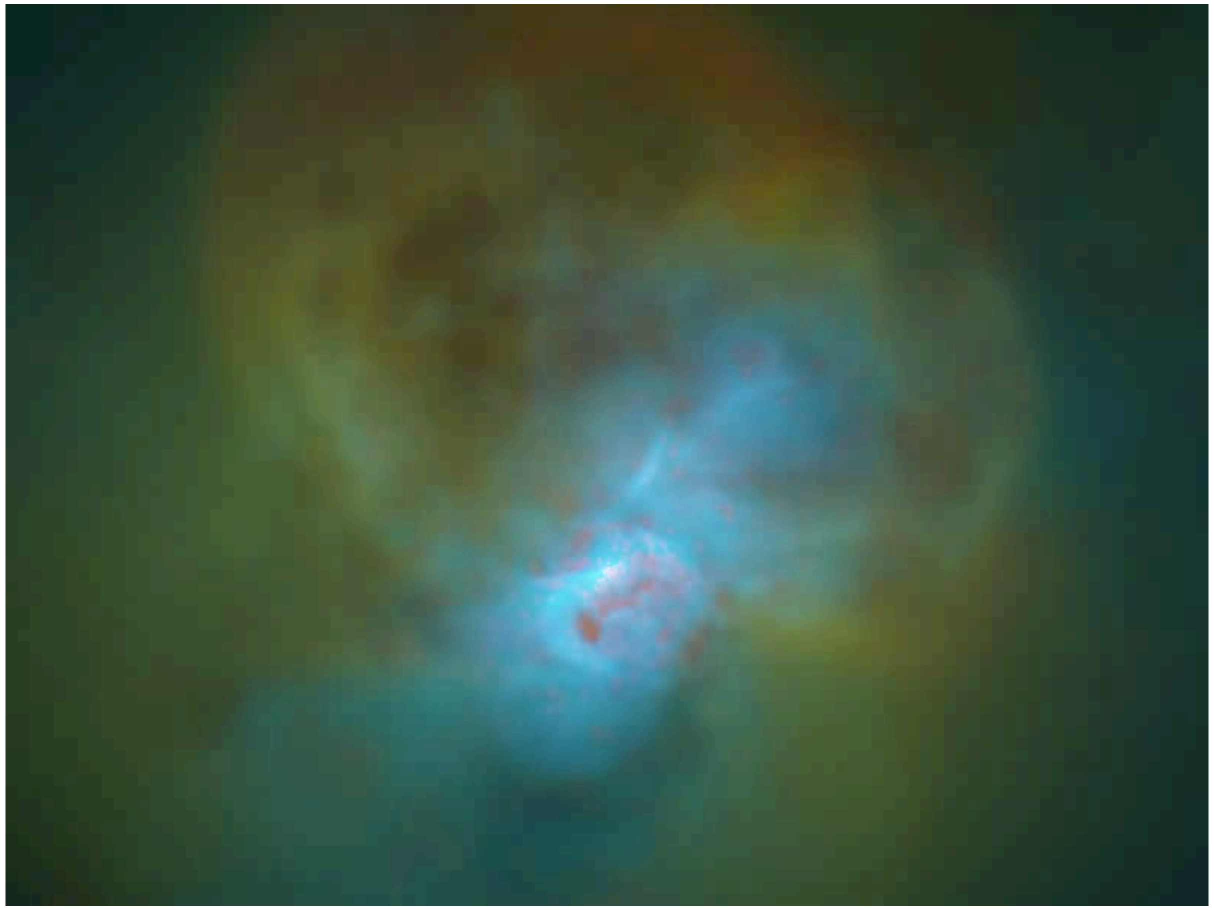
$M_{\text{star}} \approx 10^{7\text{-}8.5} M_{\text{sun}}$

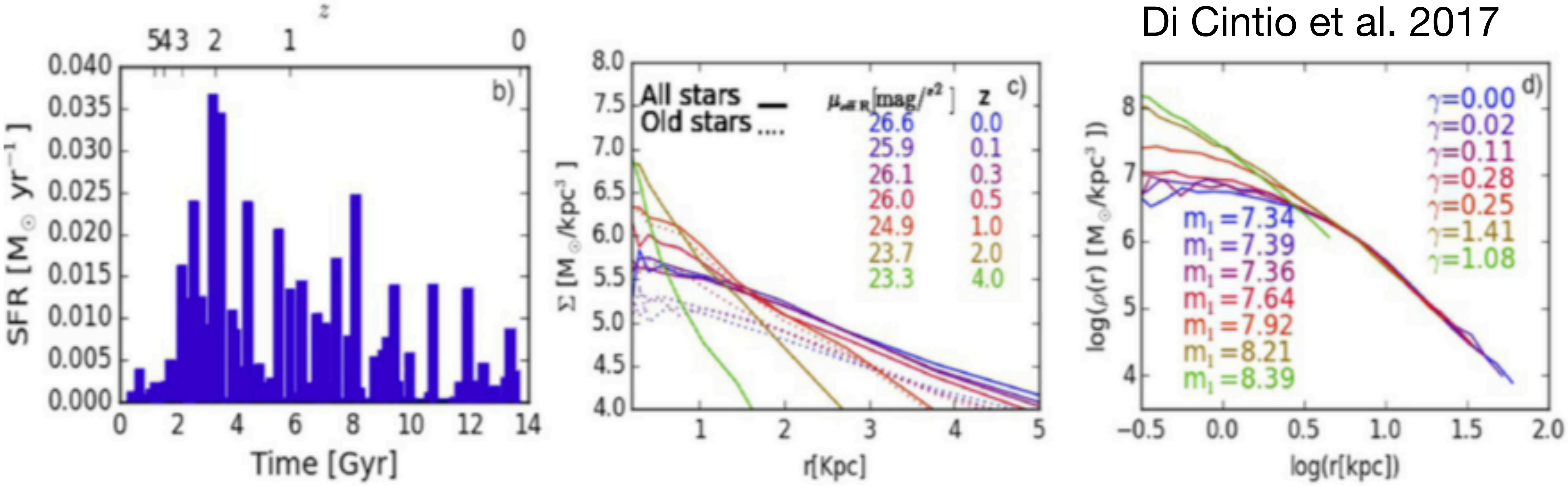
Ultra-diffuse galaxies



Shi et al. 2017

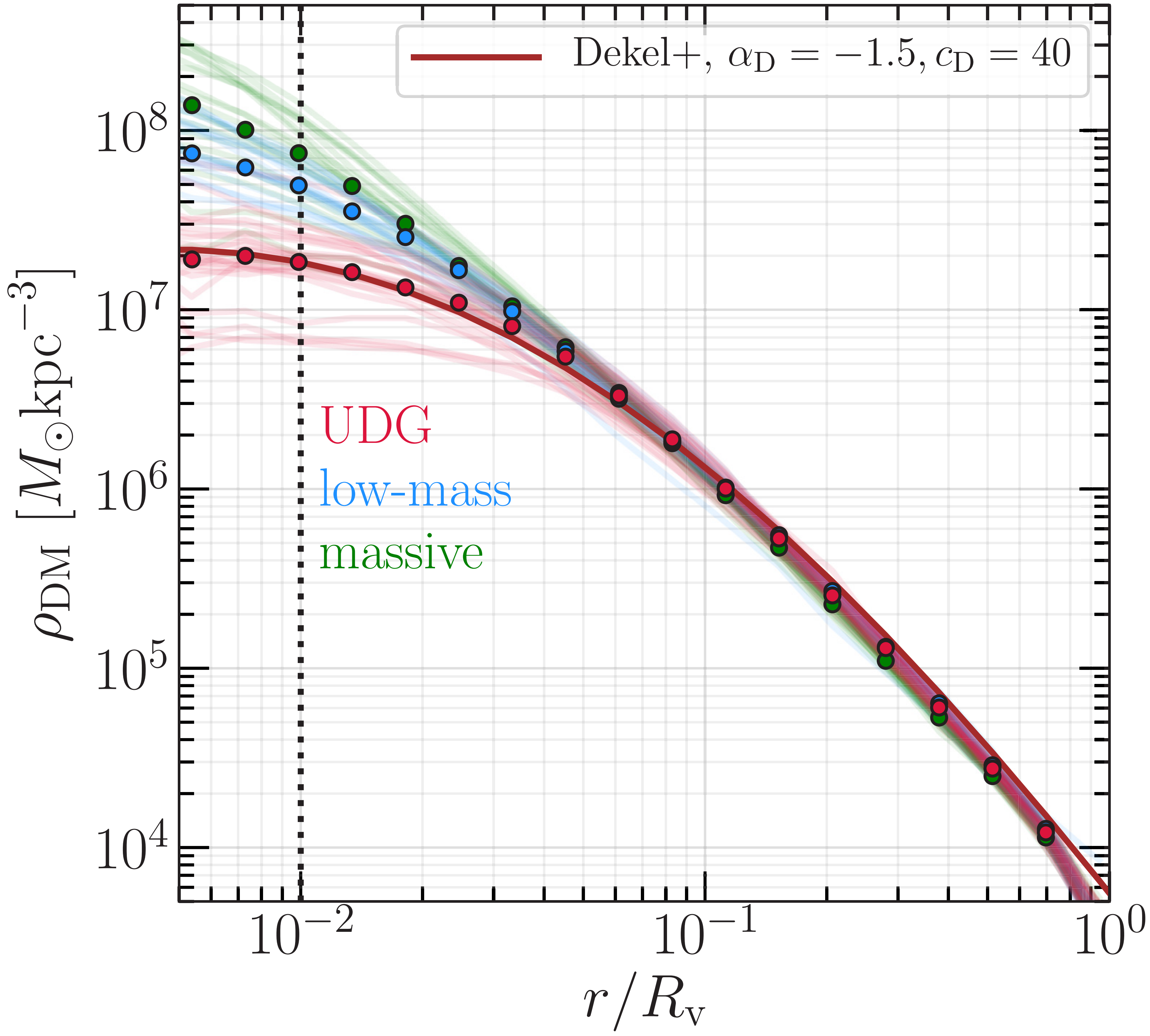
Formation of ultra-diffuse galaxies due to SN fdbk associated with bursty star formation





Di Cintio et al. 2017

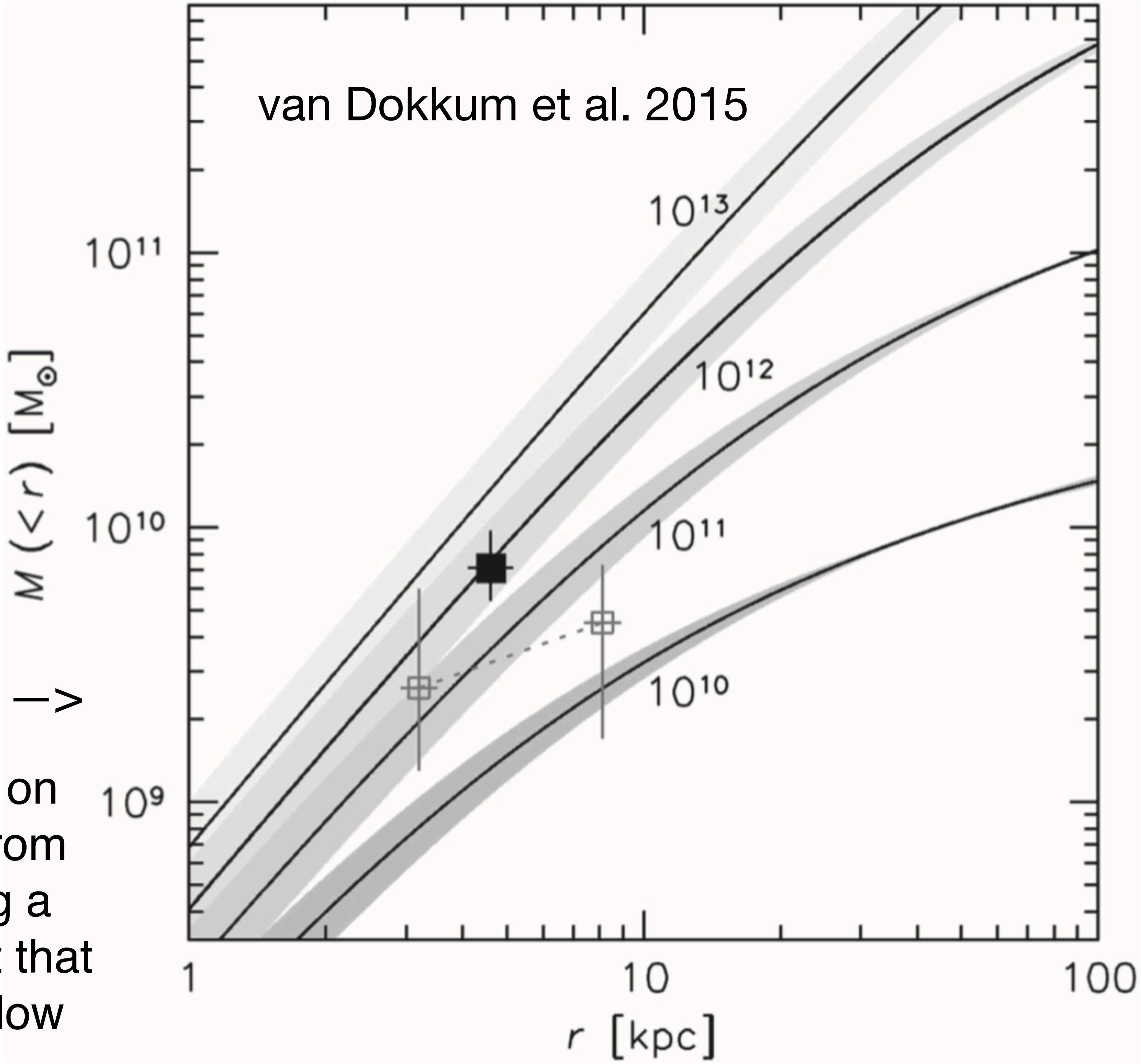
Host halos of ultra-diffuse galaxies



(Simulated) UDGs live in cored DM halos.

Ultra-diffuse galaxies

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

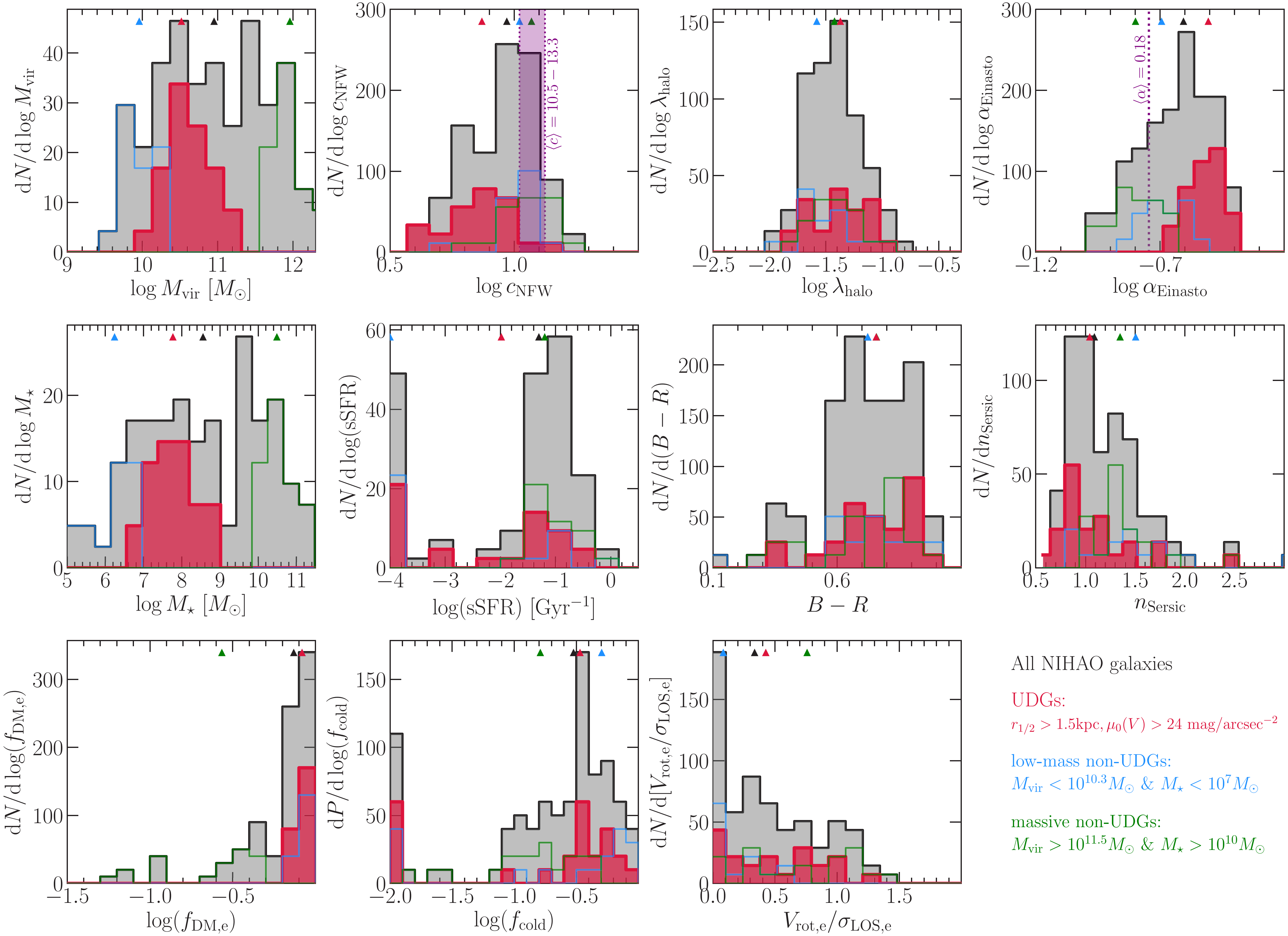


van Dokkum et al. 2015

Evidence for failed L* —>

However, this M_{vir} estimate relies on extrapolating the density profile from ~2kpc to ~200 kpc, and assuming a cuspy NFW profile, and we learnt that UDG hosts do not necessarily follow NFW profiles.

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. 2019), not L* galaxies failed forming sufficient stars or high-spin systems.

Summary

- Baryonic “feedback” are processes that regulate the growth of galaxies, suppressing or boosting star formation — they reconcile the halo mass function and galaxy stellar mass function, and explain the drop of metallicity yield in dwarf galaxies, among many other things

- 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 of SN fdbk on dark-matter halos (cusp-core issue) — impulsive gas expulsion from the center a dwarf galaxy causes potential fluctuations —> dark matter cusps transform into cores

- Impact of SN fdbk on galaxies (ultra-diffuse galaxies) — the same process is believed to be responsible for the formation of UDGs in the field. (UDGs in galaxy clusters or groups can also form from tidal puffing up, not shown here)

- Satellite galaxies living in cored and cuspy halos have different tidal evolution tracks (affecting the missing satellite issue and the too-big-to-fail issue).