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THE HEBREW UNIVERSITY OF JERUSALEM

SF2A

Dark matter core formation from outflow episodes induced by feedback

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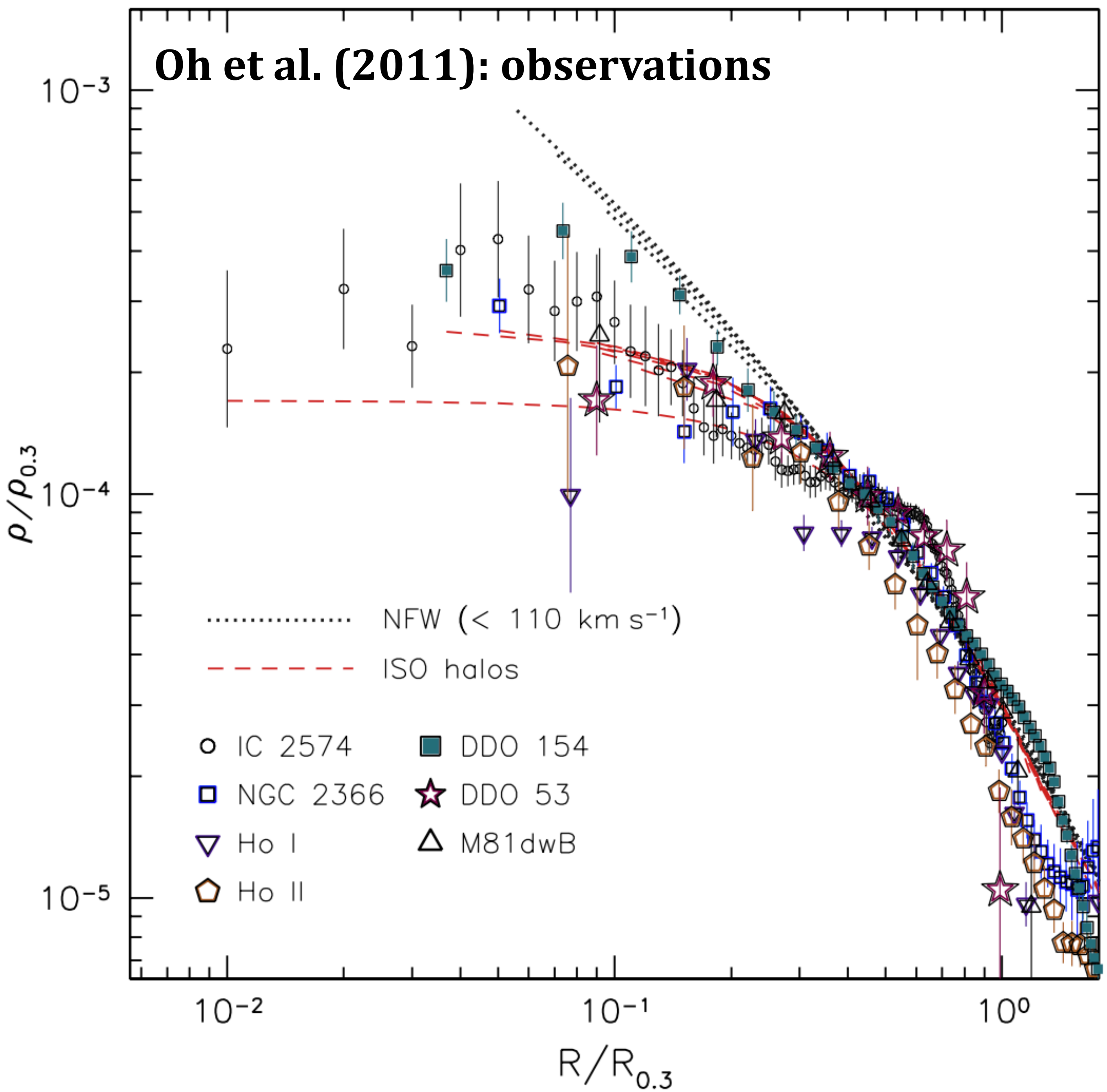
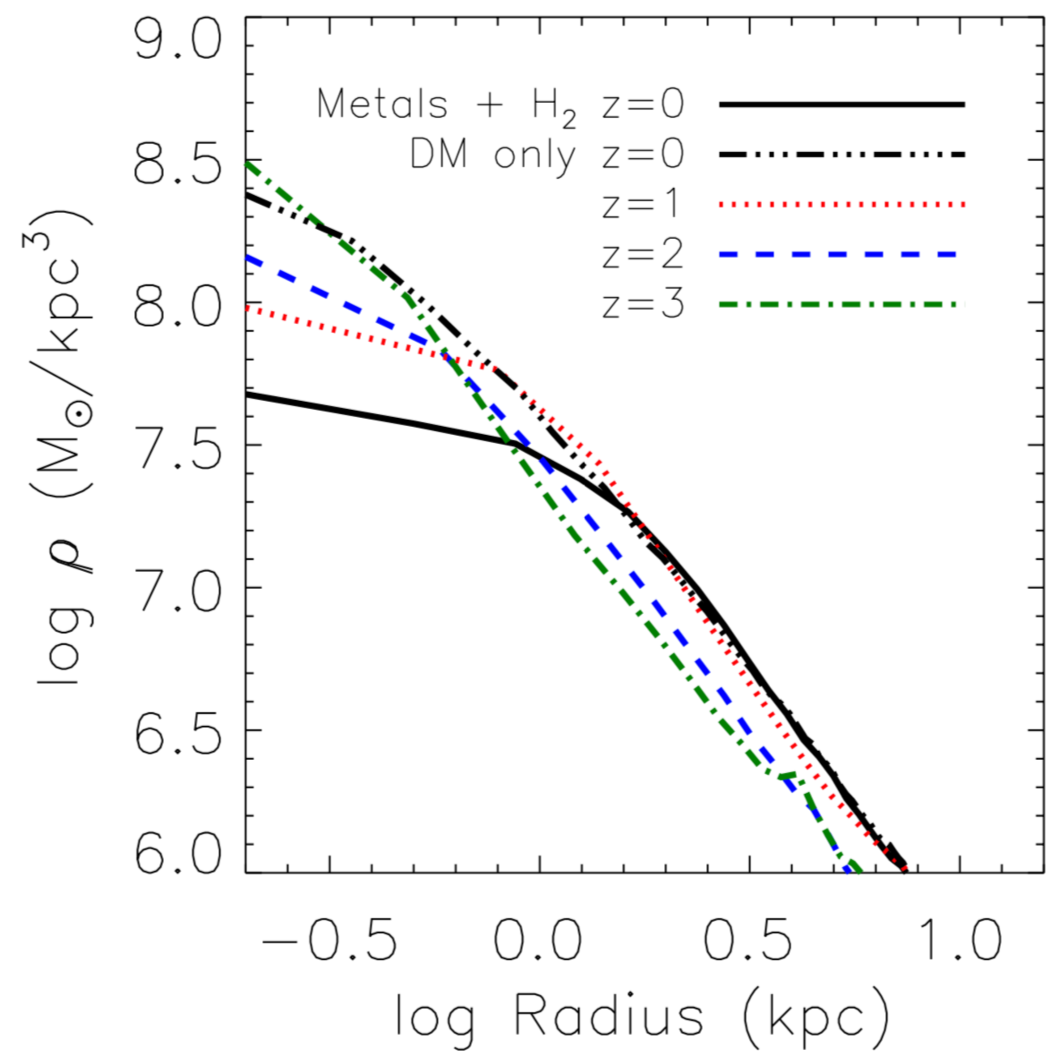
The cusp-core discrepancy

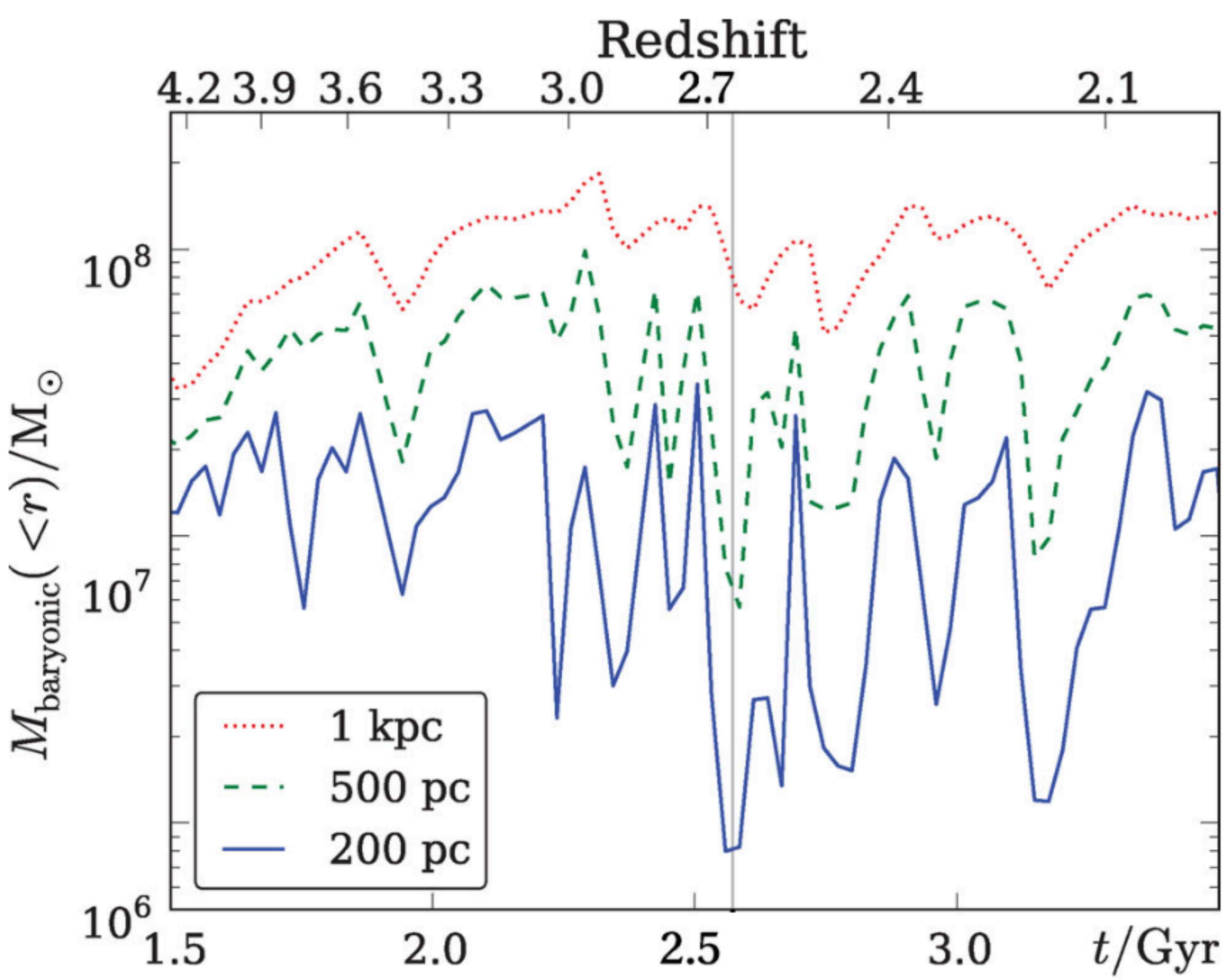


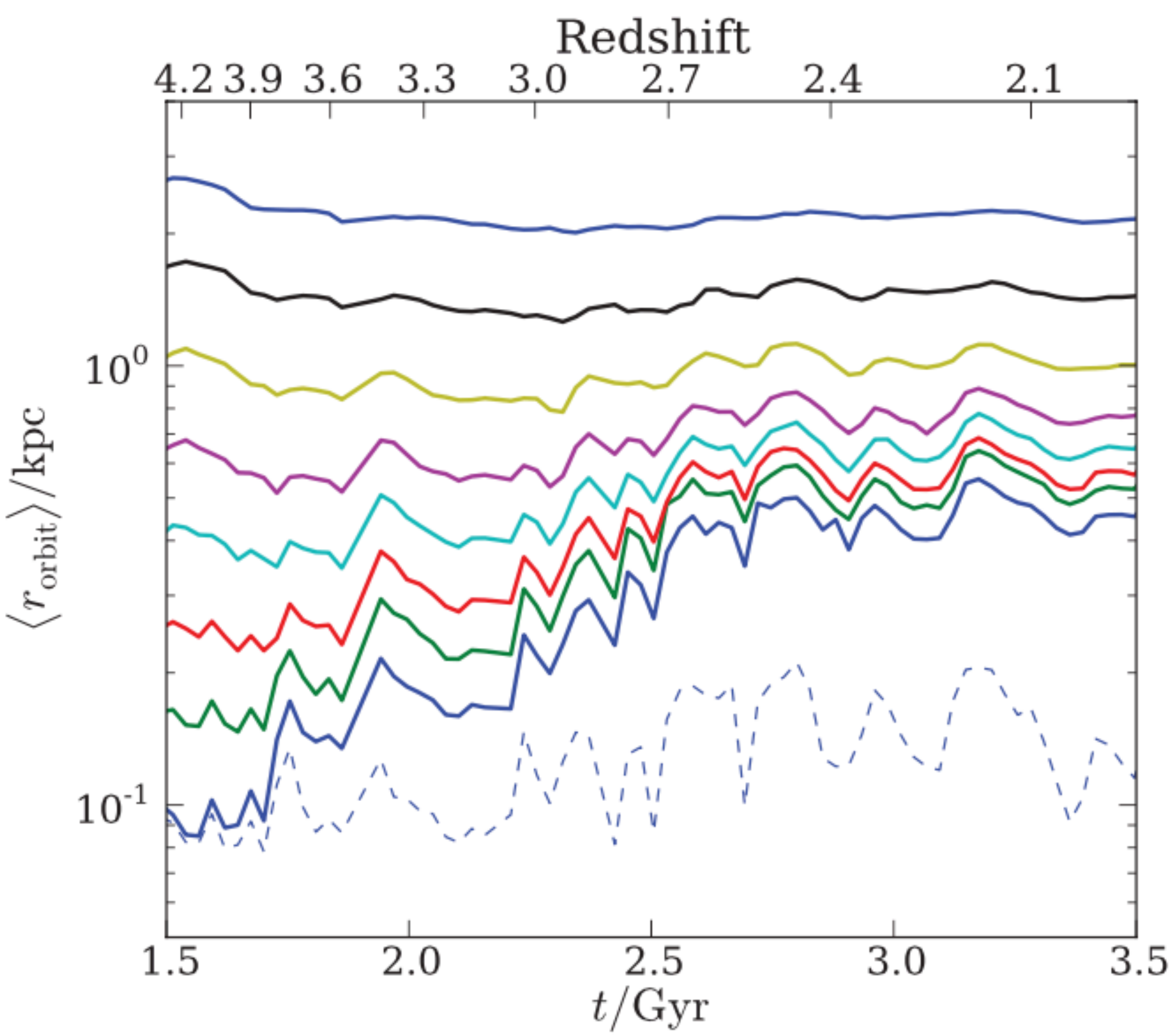
Governato et al. (2012): simulations



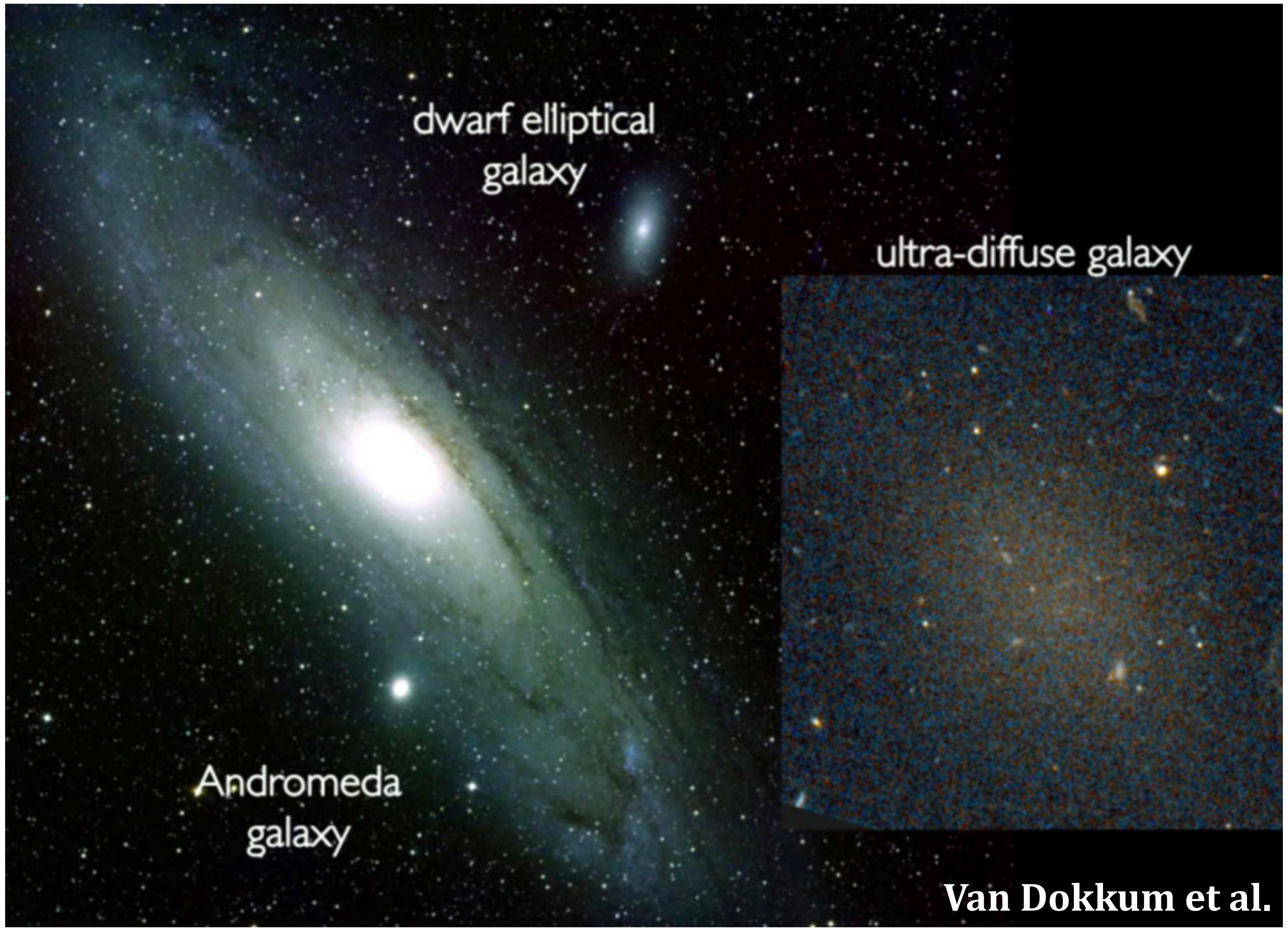
How can baryons affect the dark matter halo

- ✦ Adiabatic contraction (Blumenthal et al. 1986)
- ✦ Dynamical friction (El-Zant et al. 2001, 2004)
- ✦ **Repeated potential fluctuations from feedback processes (Pontzen & Governato 2012)**





Ultra Diffuse Galaxies (UDGs)

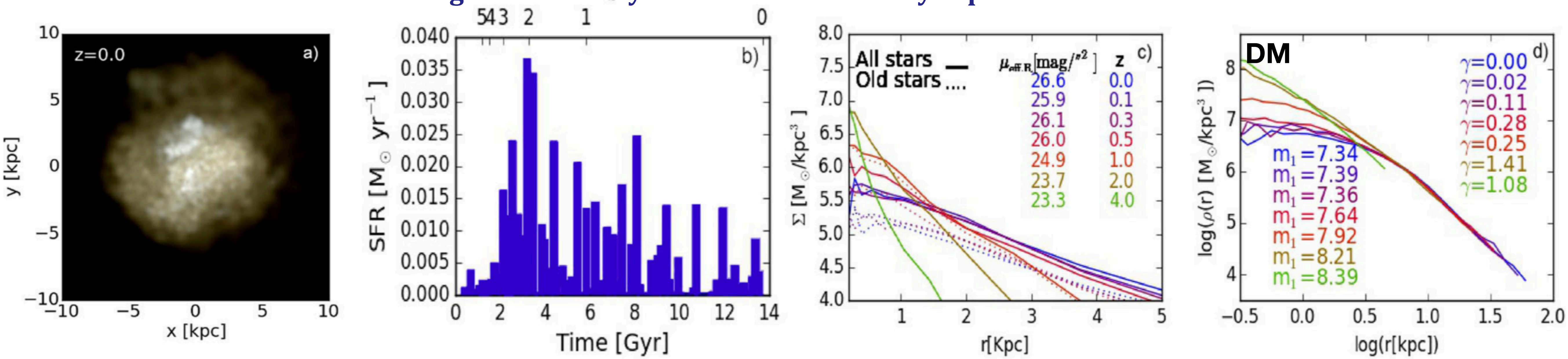


- ✦ **Stellar masses of dwarf galaxies**
  $7 < \log(M_{\rm star}/M_\odot) < 9$
- ✦ **Effective radii of MW-sized**
  $1 < r_{\rm eff}/\mathrm{kpc} < 5$

Possible formation scenarii:

- ✦ **Failed MW-like galaxies** that lost their gas after forming their first stars (Van Dokkum et al. 2015)
- ✦ **High-spin tail** of the dwarf galaxy population (Amorisco & Loeb 2016)
- ✦ **Tidal debris** from mergers or tidally disrupted dwarfs (Greco et al. 2017)
- ✦ **Episodes of inflows and outflows from stellar feedback** (Di Cintio et al. 2017)

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



cf. also Jiang, Dekel, Freundlich et al. 2018, arXiv:1811.10607

A toy model based on cycles of inflows and outflows

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

✦ **Slow mass change**

Conservation of the angular momentum on circular orbits $L \propto rv = \sqrt{GMr}$

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

✦ **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

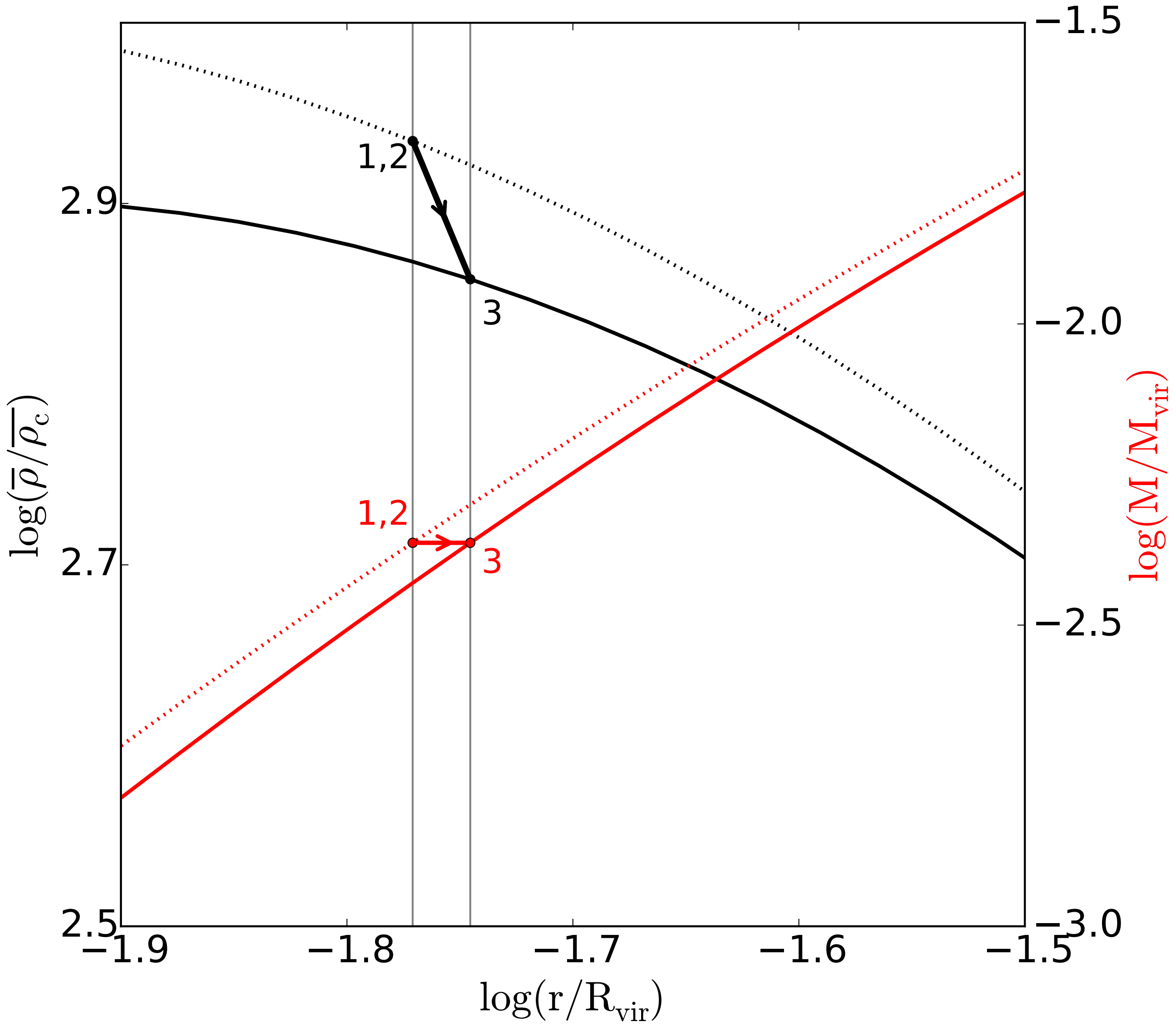
$$E_t(r_i) = U_i(r_i) - Gm/r_i + K_i(r_i)$$

3) The system relaxes to a new equilibrium

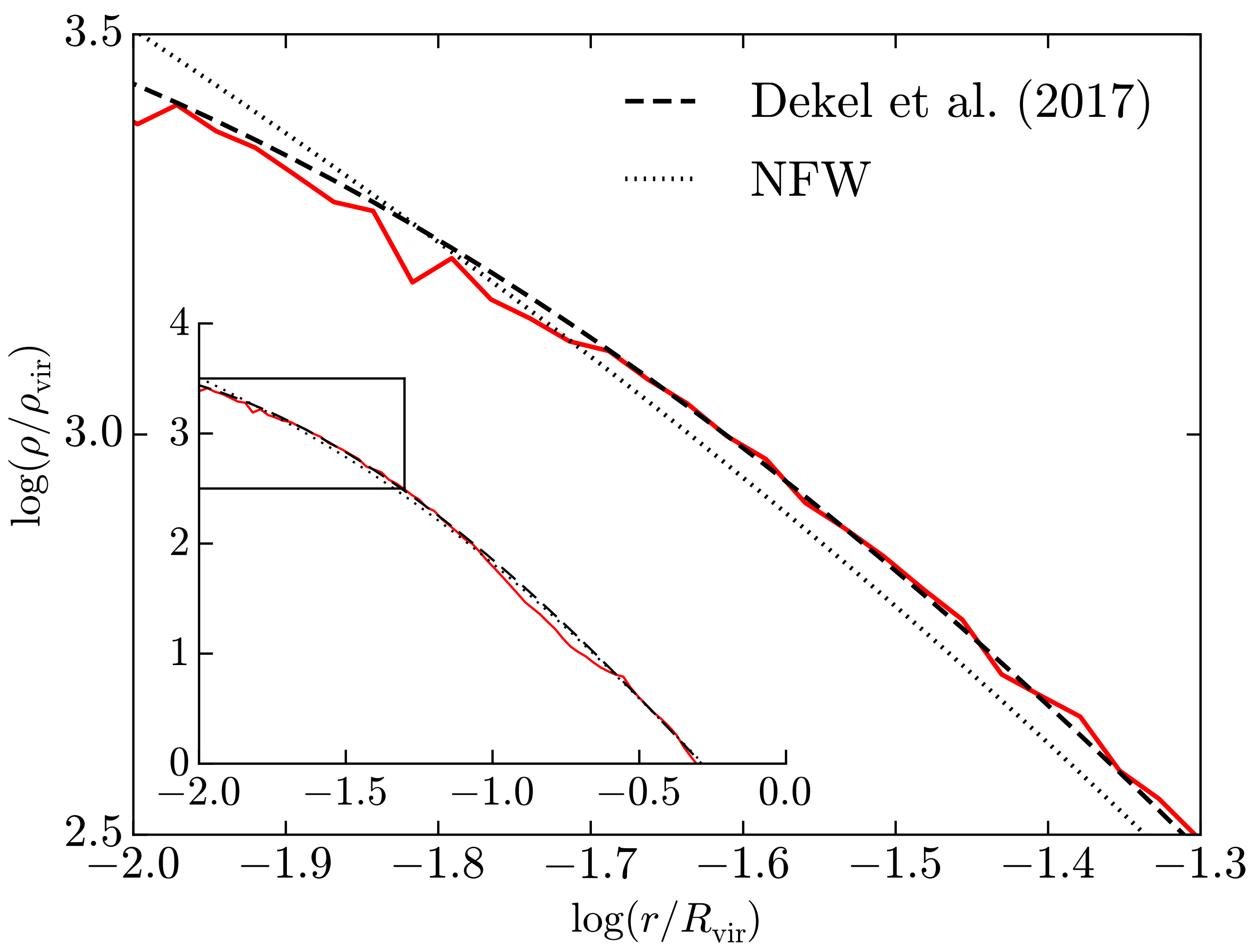
$$E_f(r_f) = U_f(r_f) - Gm/r_f + K_f(r_f)$$

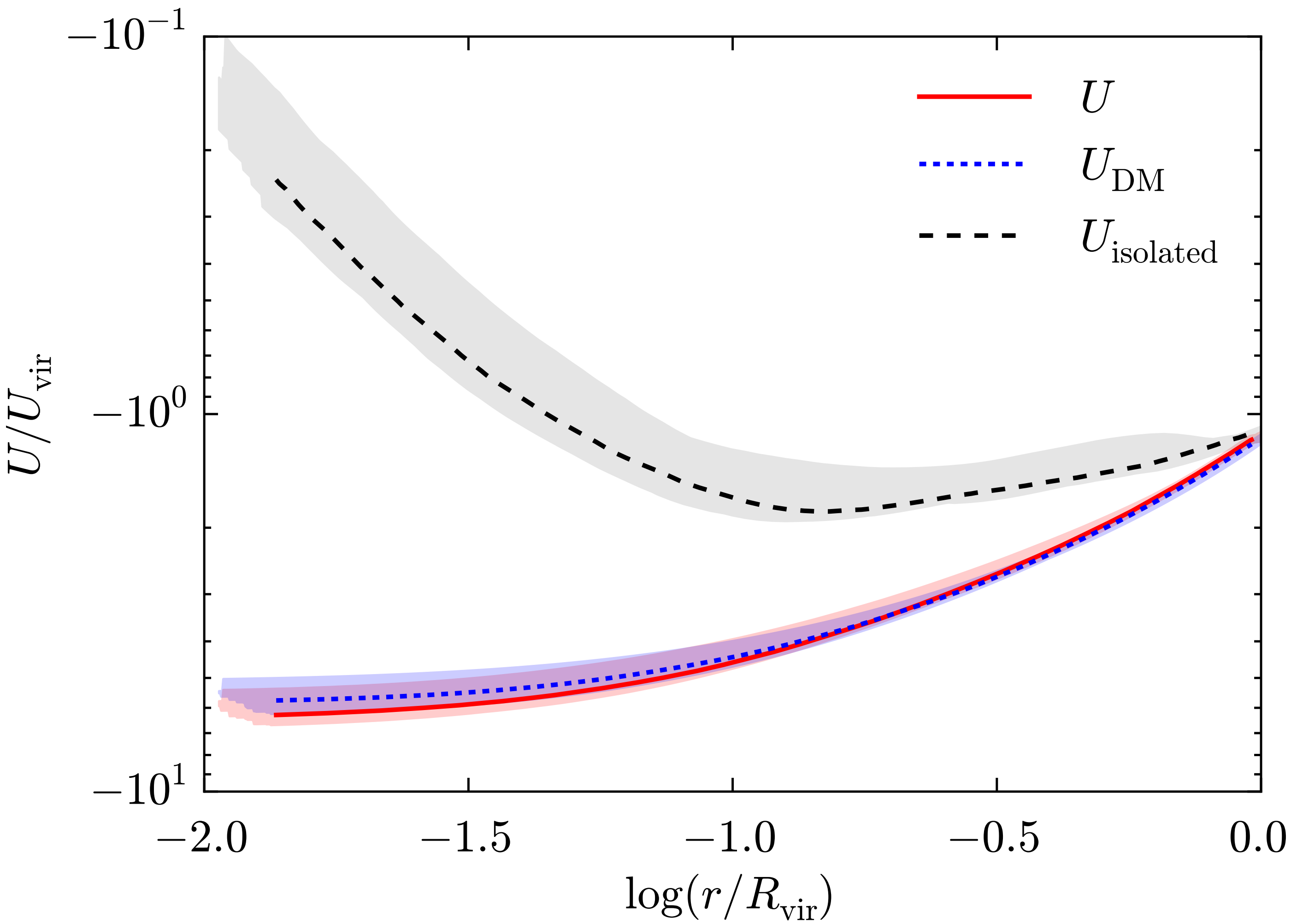
where K can be expressed from the mass distribution through the Jeans equation

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



Parametrization of the density profile





Dekel et al. (2017) parametrization:

✦ $\rho(r) \propto \dfrac{1}{x^a(1+x^{1/2})^{2(3.5-a)}}$ with $x = cr/R_{\rm vir}$

✦ Analytical potential

✦ Free inner slope

✦ Inner logarithmic slope: $s_0 = s(0.01R_{\rm vir})$

with $s(r) = \dfrac{d\ln\rho}{d\ln r} = \dfrac{a+3.5x^{1/2}}{1+x^{1/2}}$

✦ Effective concentration

$$c_{\rm max} = \frac{r_{\rm max}}{R_{\rm vir}} = \frac{c}{(2-a)^2}$$

Parametrization of the local kinetic energy

✦ Spherical symmetry and anisotropy

$$K(r) = 1.5\sigma_r^2$$

✦ Jeans equilibrium

$$(\alpha + \gamma - 2\beta)\sigma_r^2 = V_c^2$$

$$\frac{d(\rho\sigma_r^2)}{dr} + \cancel{\frac{2\beta}{r}\rho\sigma_r^2} = -\rho\frac{d\phi}{dr}$$

$$\sigma_r^2(r) = \frac{G}{\rho(r)}\int_r^\infty \rho(r')M(r')r'^{-2}\mathrm{d}r'$$

✦ **Dekel et al. (2017)** parametrization

$$K(r) \propto \left[\mathscr{B}(4(1-a),9,\zeta)\right]_\chi^1$$

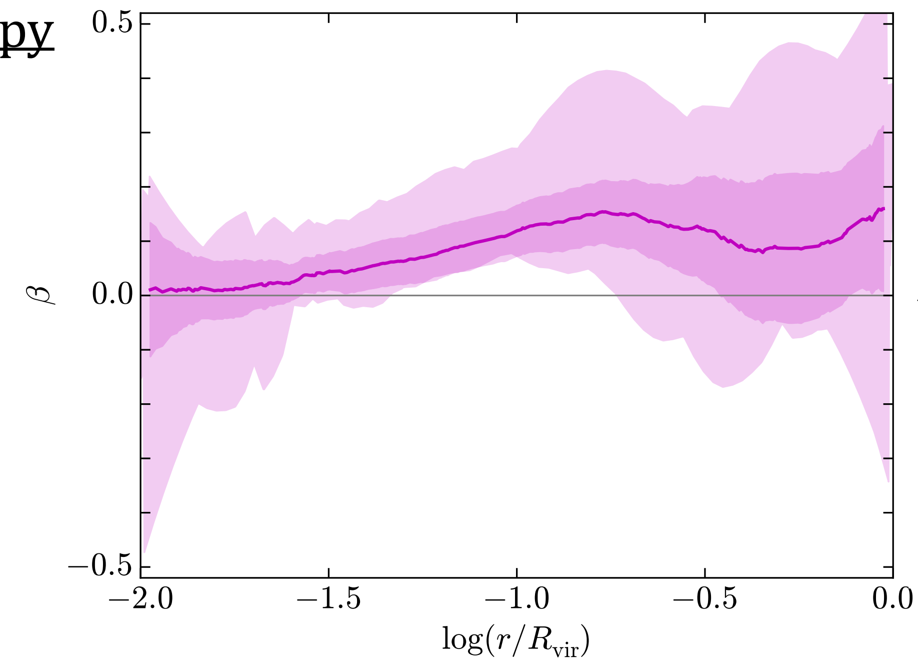
with $\mathscr{B}(a,b,x) = \int_0^x t^{a-1}(1-t)^{b-1}dt$

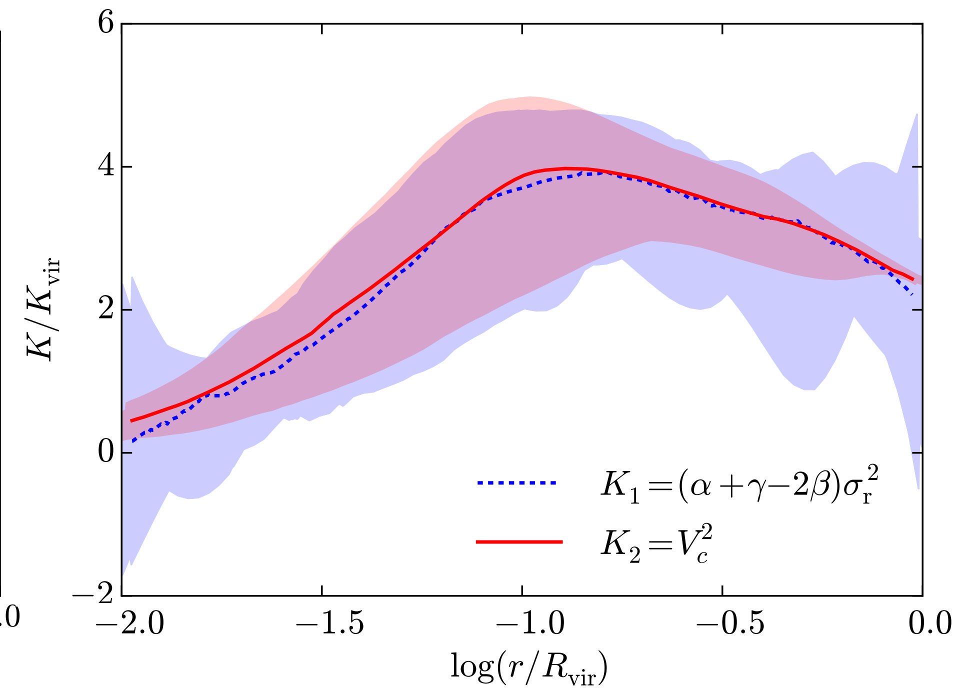
and $\chi = \dfrac{x^{1/2}}{1+x^{1/2}}$

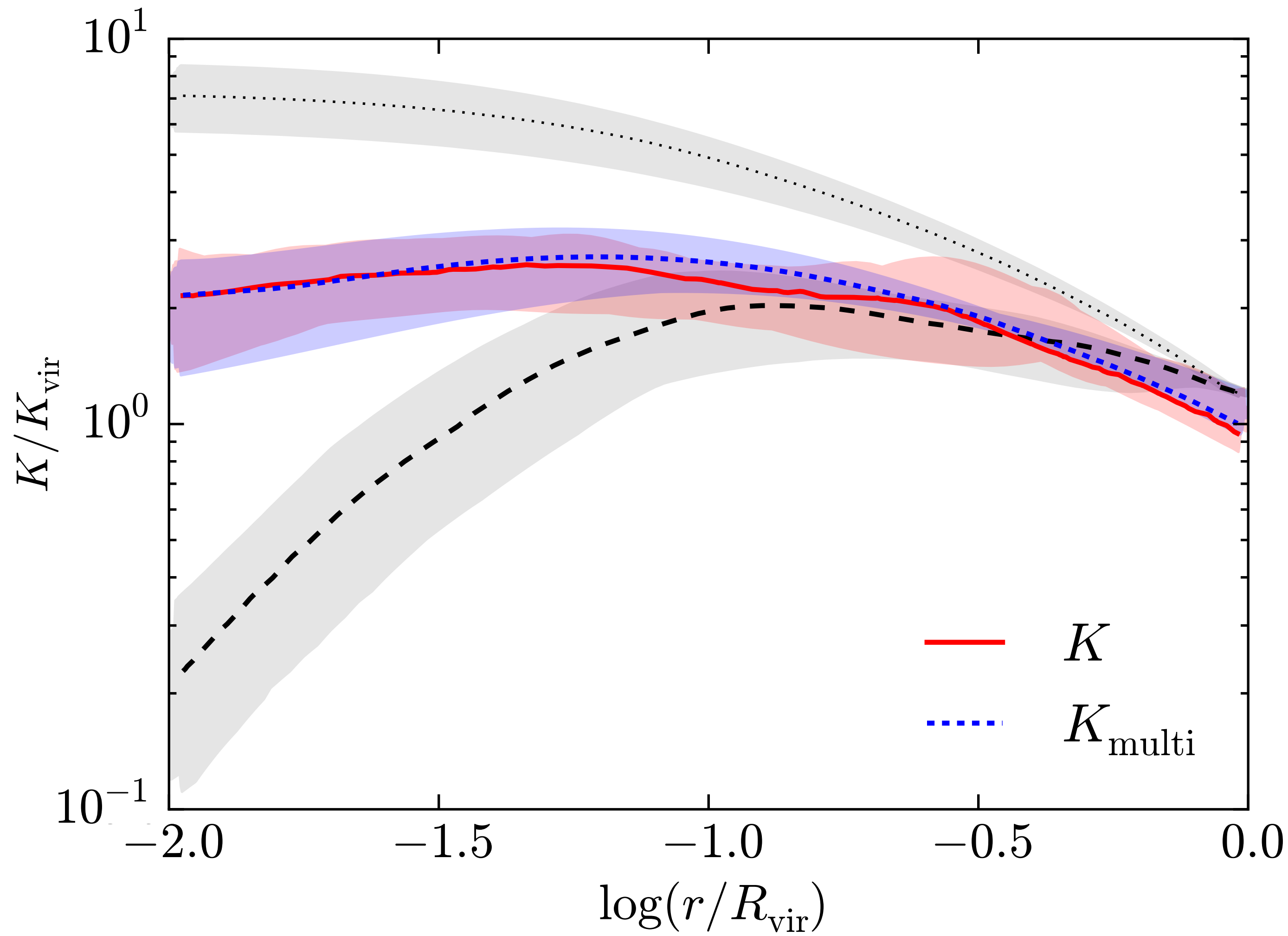
✦ Multi-component halo

$$\frac{M_{\rm tot}}{M} = X_M\left(\frac{r}{R_{\rm vir}}\right)^{-n}$$

$$K(r) \propto \left[\mathscr{B}(4(1-a)-2n,9+2n,\zeta)\right]_\chi^1$$





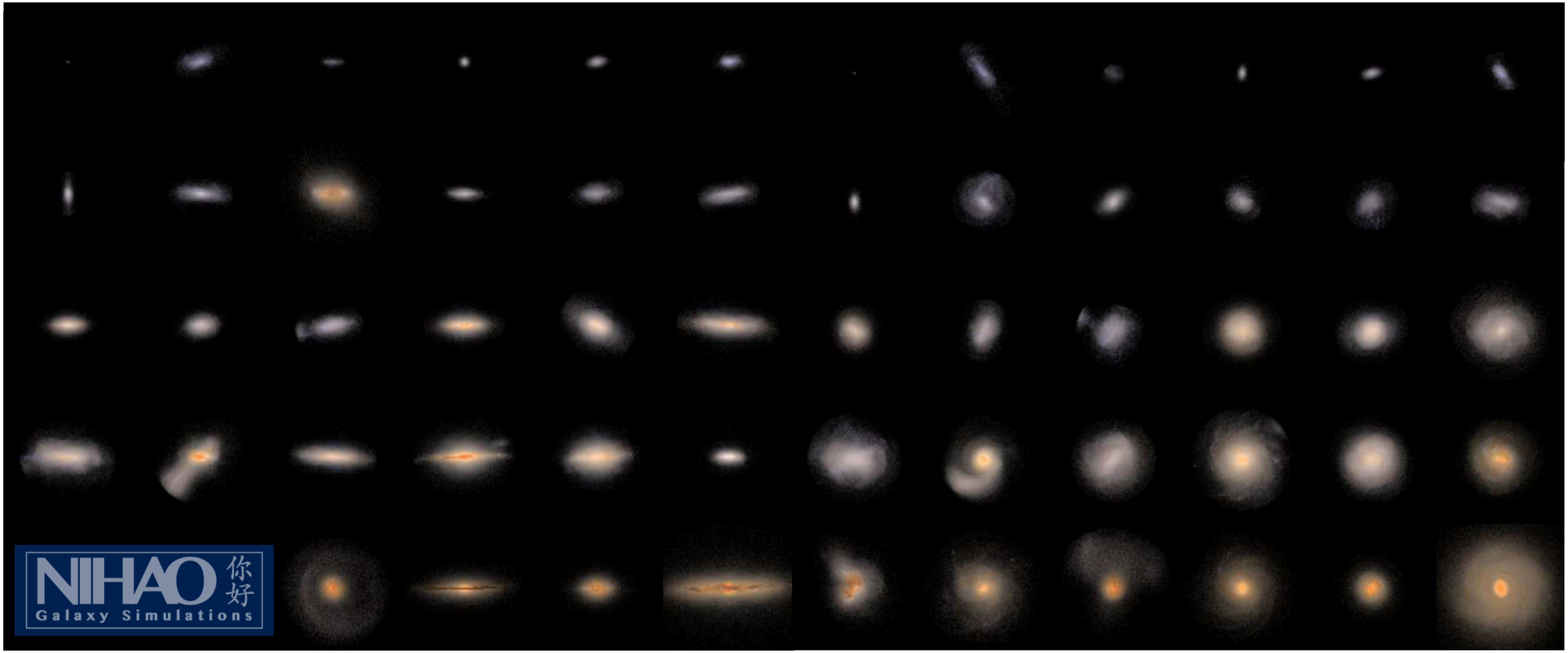


Test with the NIHAO simulations

A set of ~100 cosmological zoom-in hydrodynamical simulations of galaxies

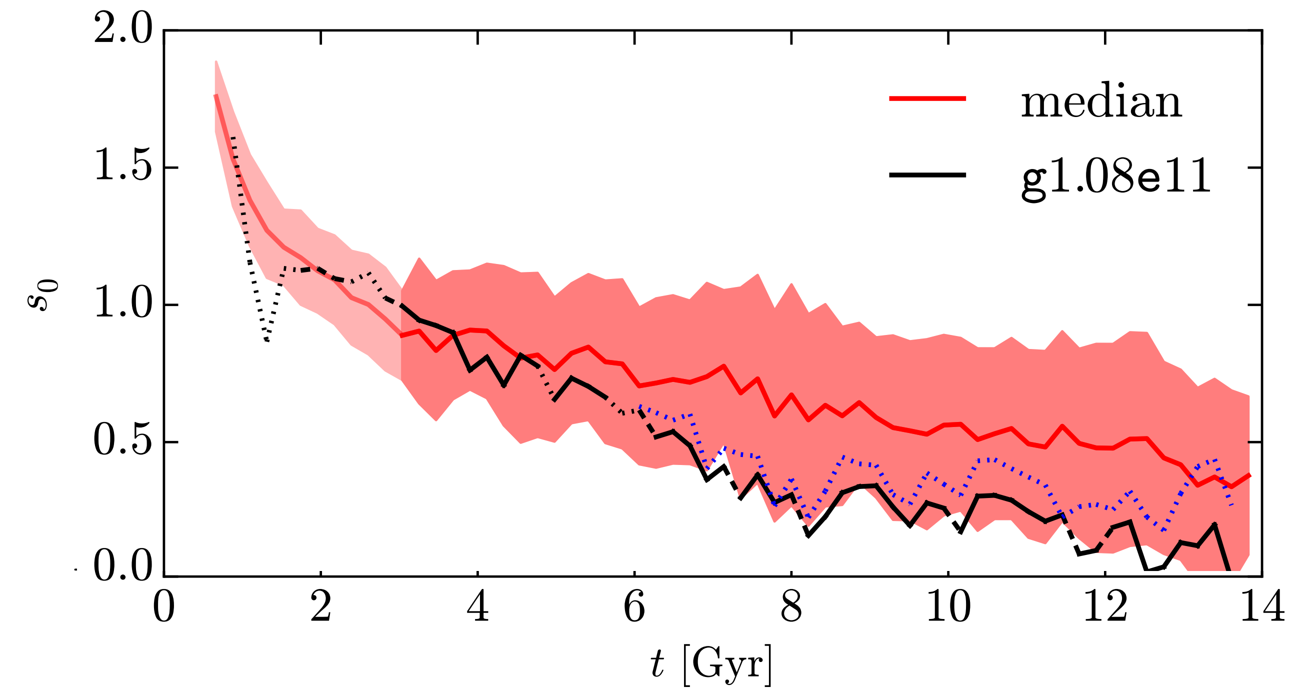
- ✦ Smoothed Particle Hydrodynamics code Gasoline2
- ✦ ΛCDM cosmology (Planck collaboration 2014)
- ✦ Turbulent mixing, cooling, UV background, star formation, chemical enrichment
- ✦ **Ionizing feedback from massive stars and blast-wave SN feedback**
- ✦ With and without baryons
- ✦ **Spatial resolution 1% of the virial radius**

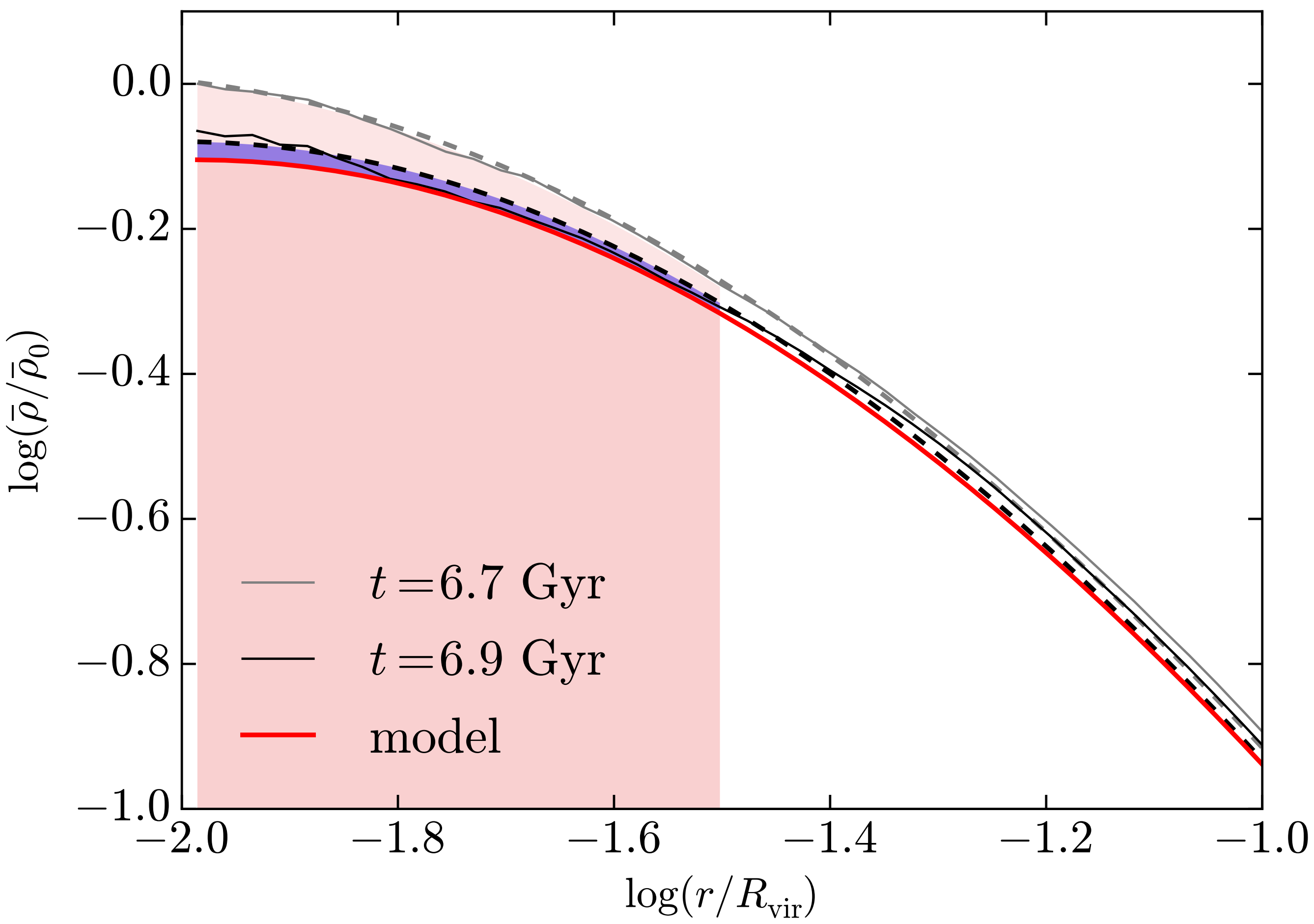
Wang et al. (2015)

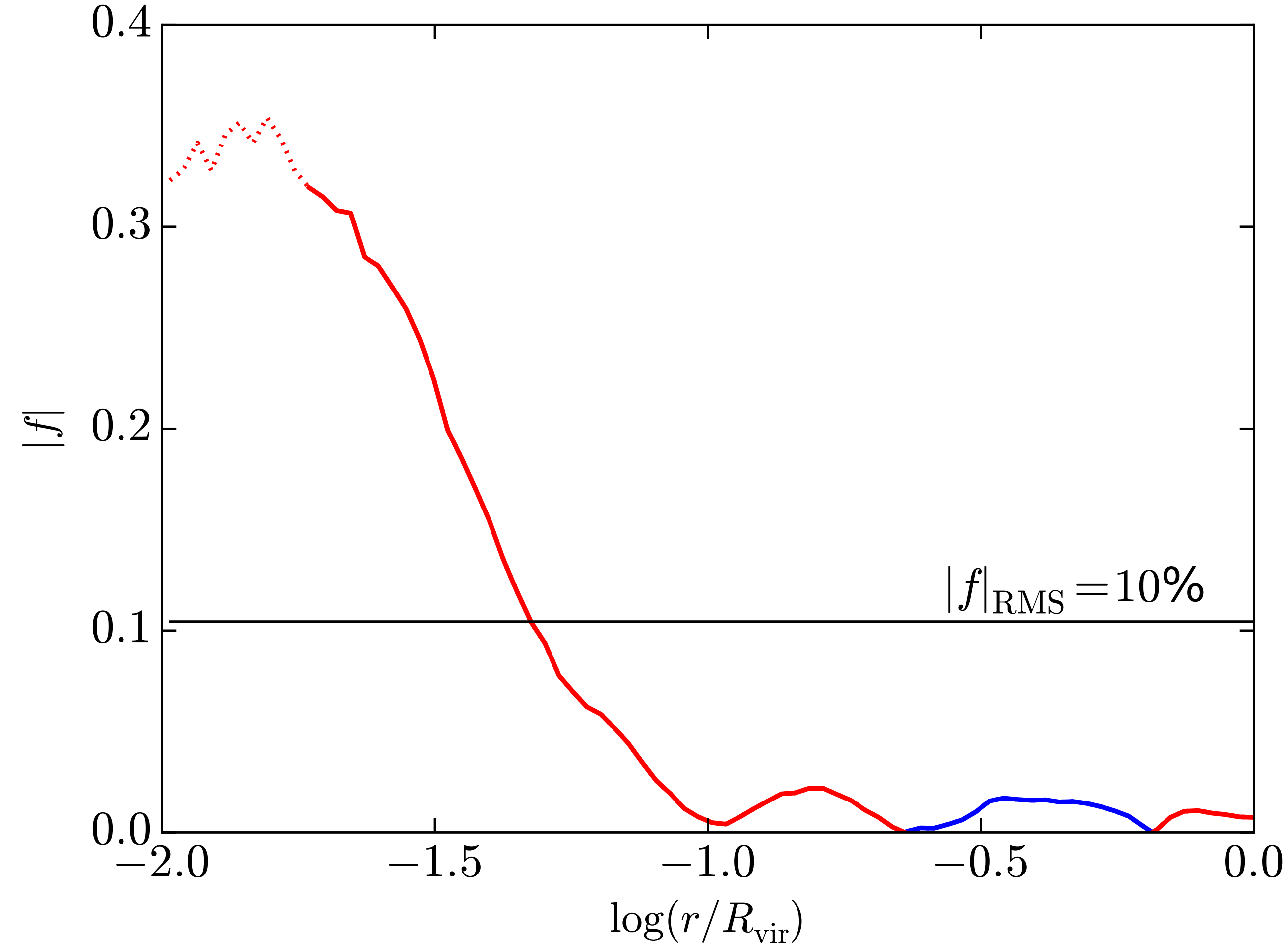


Test with the NIHAO simulations

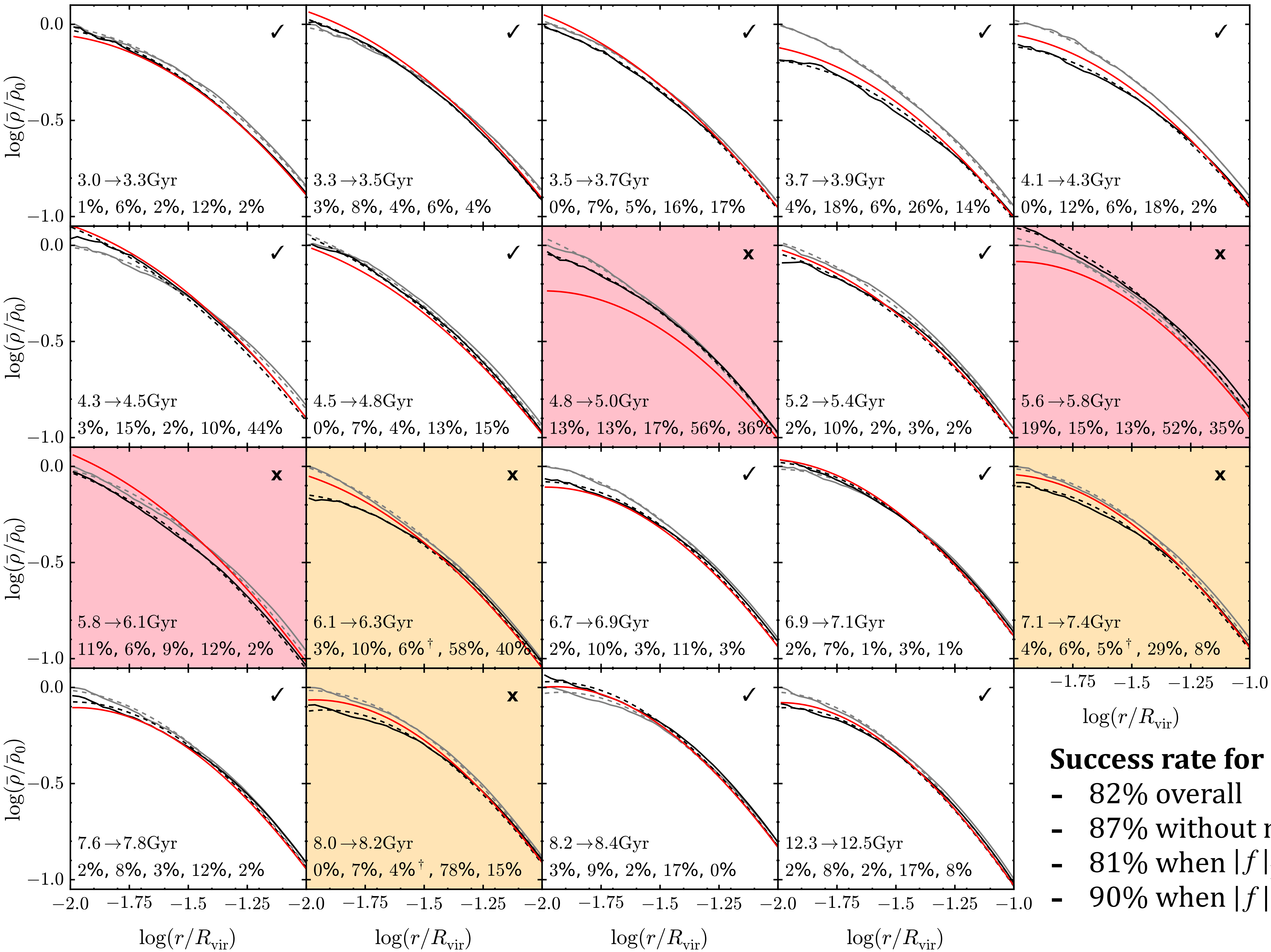
- ✦ **33 galaxies with M_{star}=10^7-10^9 M_{sun} at z=0**
- ✦ Specific mass range for core formation **(Di Cintio+14, Oh+15, Tollet+16, Dutton+16)**
- ✦ A fiducial example: **g1.08e11**







Test with the NIHAO simulations



Success rate for g1.08e11:

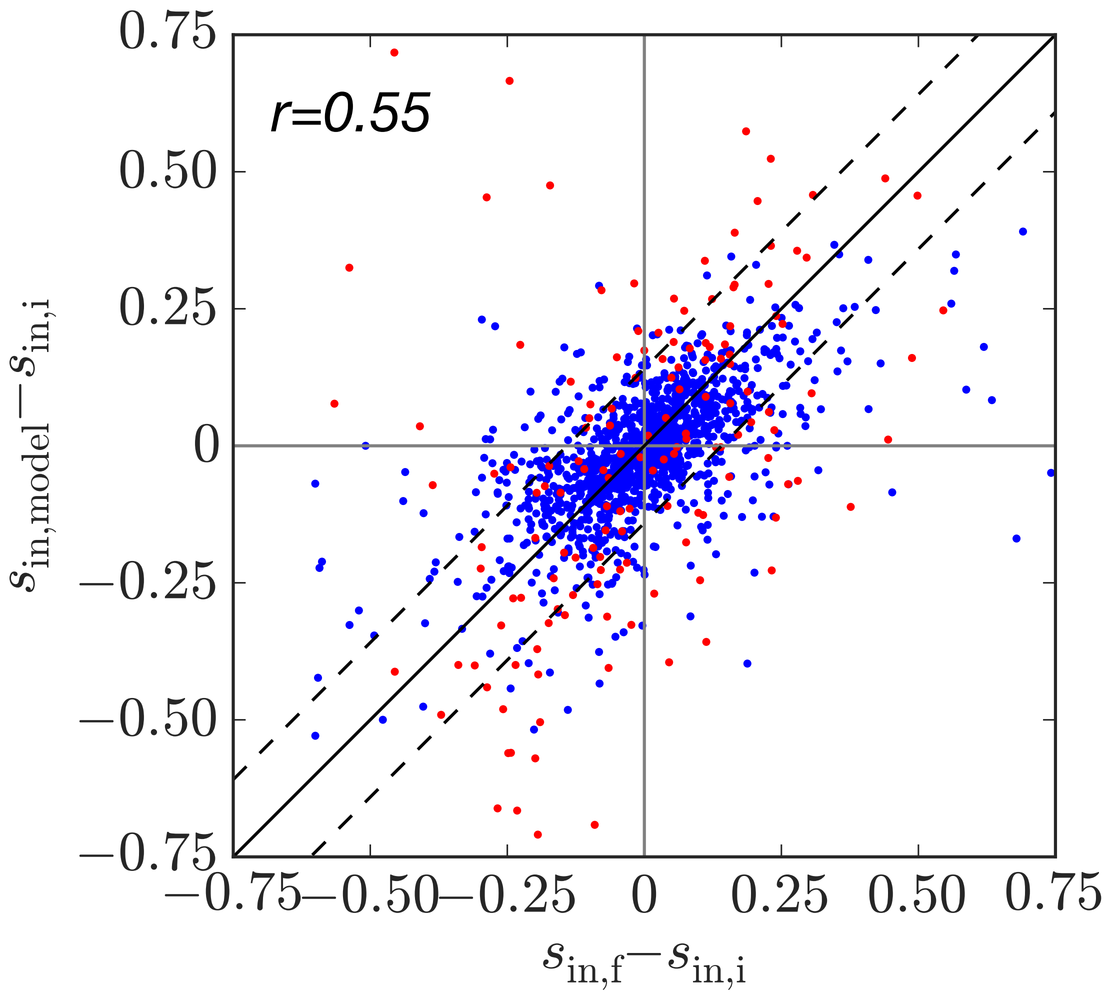
- 82% overall
- 87% without mergers
- 81% when $|f|_{\rm RMS} > f_{\rm min} = 6\,\%$
- 90% when $|f|_{\rm RMS} < f_{\rm min}$

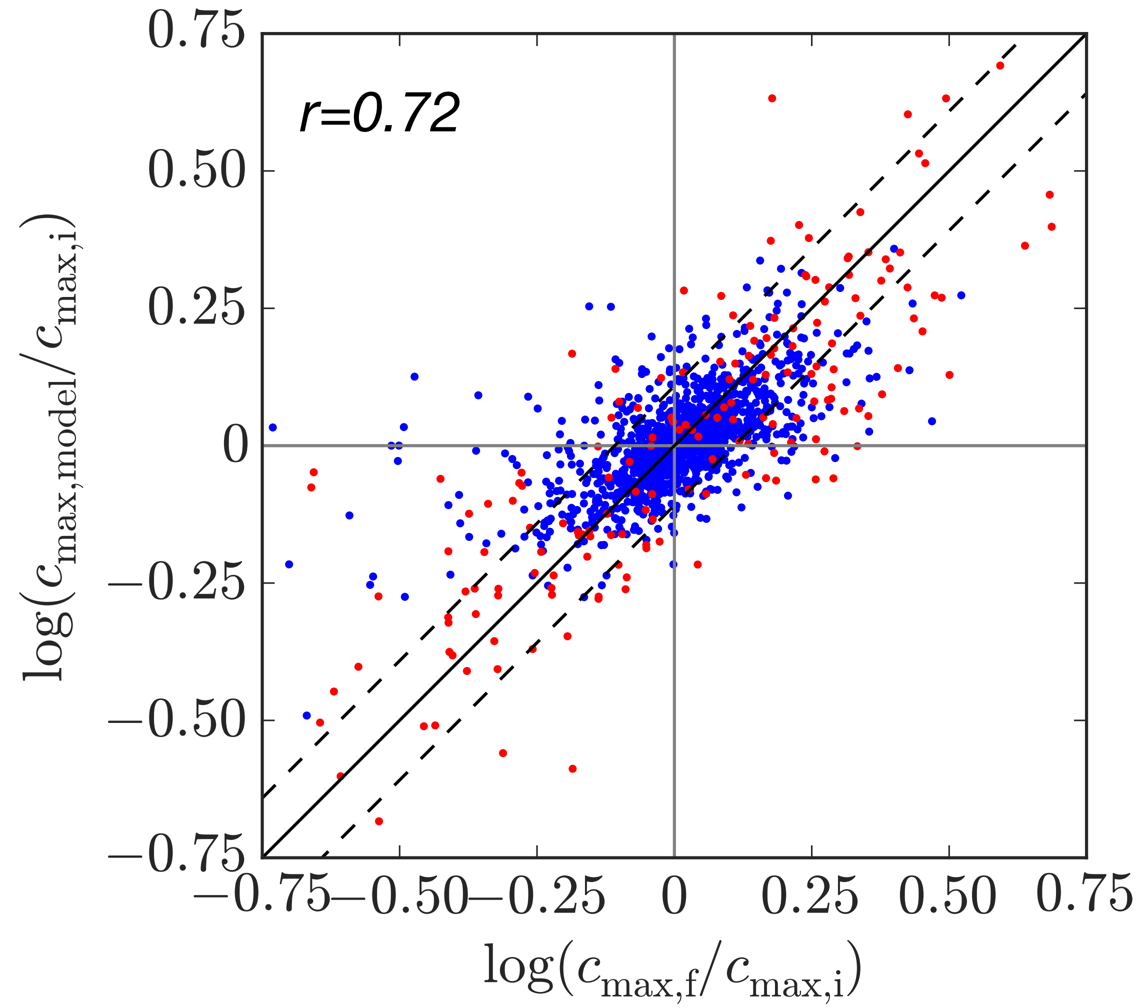
Test with the NIHAO simulations

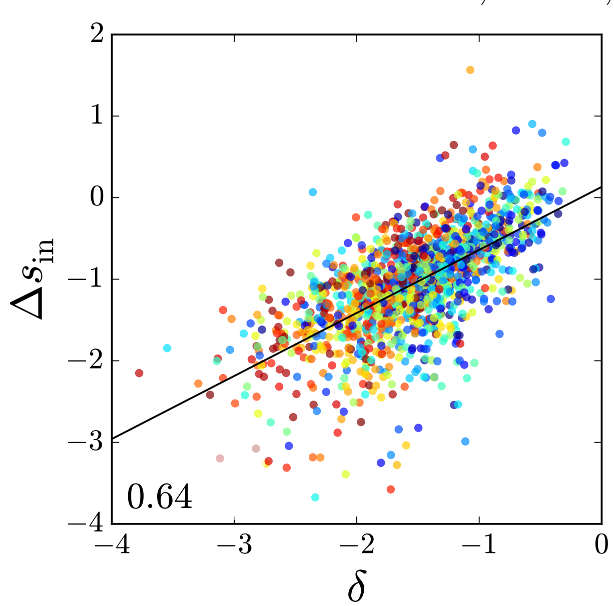
Simulation ID	M_{vir} [$M_\odot$]	$M_\star$ [$M_\odot$]	r_e [kpc]	$\mu_{0,V}$ [mag.arcsec^{-2}]	p_{all}	$p_{no\ mergers}$	$p_{>f_{min}}$	$p_{<f_{min}}$
g1.57e11	1.58×10^{11}	1.15×10^9	5.42	23.62	29/50 = 58%	24/36 = 67%	19/27 = 70%	05/09 = 56%
g4.99e10†	4.9×10^{10}	1.22×10^8	3.01	24.16	31/43 = 72%	31/42 = 74%	14/24 = 58%	17/18 = 94%
g3.21e11	3.03×10^{11}	3.67×10^9	4.88	21.29	25/48 = 52%	25/39 = 64%	19/31 = 61%	06/08 = 75%
g3.44e10†	4.88×10^{10}	6.32×10^7	2.54	24.43	21/33 = 64%	19/26 = 73%	15/18 = 83%	04/08 = 50%
g3.59e11	3.49×10^{11}	4.36×10^9	5.10	21.76	26/46 = 57%	24/33 = 73%	18/23 = 78%	06/10 = 60%
g6.12e10†	4.97×10^{10}	9.13×10^7	2.67	24.03	27/33 = 82%	27/30 = 90%	11/12 = 92%	16/18 = 89%
g2.04e11	2.09×10^{11}	4.7×10^9	3.07	20.18	43/50 = 86%	43/46 = 93%	20/23 = 87%	23/23 = 100%
g4.27e10†	4.25×10^{10}	6.15×10^7	2.83	24.21	15/20 = 75%	15/19 = 79%	12/14 = 86%	03/05 = 60%
g4.94e10	5.26×10^{10}	1.11×10^8	2.42	23.89	25/38 = 66%	25/33 = 76%	07/13 = 54%	18/20 = 90%
g5.05e10†	4.29×10^{10}	9.47×10^7	2.09	24.28	27/38 = 71%	26/33 = 79%	10/13 = 77%	16/20 = 80%
g2.19e11	1.31×10^{11}	9.27×10^8	4.52	23.01	27/47 = 57%	27/41 = 66%	23/35 = 66%	04/06 = 67%
g6.37e10†	1.15×10^{11}	2.11×10^8	4.19	24.10	17/41 = 41%	16/30 = 53%	10/19 = 53%	06/11 = 55%
g3.49e11	4.33×10^{11}	3.96×10^9	5.23	22.02	39/50 = 78%	39/49 = 80%	09/15 = 60%	30/34 = 88%
g1.08e11†	$\mathbf{1.2 \times 10^{11}}$	$\mathbf{8.47 \times 10^8}$	**4.41**	**24.10**	**41/50 = 82%**	**41/47 = 87%**	**13/16 = 81%**	**28/31 = 90%**
g1.64e11	1.93×10^{11}	9.12×10^8	5.72	22.41	10/33 = 30%	08/21 = 38%	07/16 = 44%	01/05 = 20%
g2.54e11	2.67×10^{11}	3.5×10^9	3.60	19.84	28/46 = 61%	27/38 = 71%	19/28 = 68%	08/10 = 80%
g4.48e10	6.04×10^{10}	1.37×10^8	3.62	23.92	16/31 = 52%	16/24 = 67%	07/12 = 58%	09/12 = 75%
g9.59e10†	8.84×10^{10}	2.75×10^8	4.91	24.48	15/50 = 30%	13/39 = 33%	13/36 = 36%	00/03 = 0%
g2.94e10†	3.22×10^{10}	5.86×10^7	1.96	24.26	22/27 = 81%	22/27 = 81%	08/11 = 73%	14/16 = 88%
g4.90e11	3.25×10^{11}	3.43×10^9	5.77	22.95	37/50 = 74%	34/43 = 79%	11/15 = 73%	23/28 = 82%
g5.46e11	3.25×10^{11}	3.77×10^9	5.29	22.47	37/48 = 77%	36/43 = 84%	12/15 = 80%	24/28 = 86%
g4.86e10†	5.16×10^{10}	1.22×10^8	2.36	24.37	45/50 = 90%	45/50 = 90%	01/03 = 33%	44/47 = 94%
g6.91e10	7.08×10^{10}	2.5×10^8	2.54	23.49	39/50 = 78%	39/49 = 80%	11/17 = 65%	28/32 = 88%
g6.96e10	8.95×10^{10}	3.64×10^8	3.49	23.34	34/47 = 72%	34/42 = 81%	18/22 = 82%	16/20 = 80%
g2.41e11	2.53×10^{11}	4.1×10^9	3.97	21.48	36/49 = 73%	34/43 = 79%	16/19 = 84%	18/24 = 75%
g6.77e10	9.28×10^{10}	4.83×10^8	4.37	23.22	24/42 = 57%	21/35 = 60%	19/28 = 68%	02/07 = 29%
g8.89e10	9.22×10^{10}	4.02×10^8	3.12	23.10	42/50 = 84%	42/48 = 88%	09/13 = 69%	33/35 = 94%
g3.55e11	4.23×10^{11}	3.85×10^9	6.48	22.44	19/43 = 44%	16/33 = 48%	13/27 = 48%	03/06 = 50%
g1.37e11	1.48×10^{11}	2.02×10^9	3.46	22.51	44/50 = 88%	44/50 = 88%	05/08 = 62%	39/42 = 93%
g1.59e11†	1.68×10^{11}	6.69×10^8	6.21	24.97	39/50 = 78%	39/48 = 81%	21/26 = 81%	18/22 = 82%
g3.23e11†	8.93×10^{10}	3.6×10^8	4.85	24.05	25/49 = 51%	24/43 = 56%	22/36 = 61%	02/07 = 29%
g1.52e11†	1.57×10^{11}	7.9×10^8	5.81	24.29	32/50 = 64%	32/50 = 64%	05/12 = 42%	27/38 = 71%
g1.05e11	1.18×10^{11}	5.66×10^8	4.99	23.39	25/44 = 57%	24/38 = 63%	16/28 = 57%	08/10 = 80%
All					**962/1446 = 67%**	**932/1268 = 74%**	**433/655 = 66%**	**499/613 = 81%**

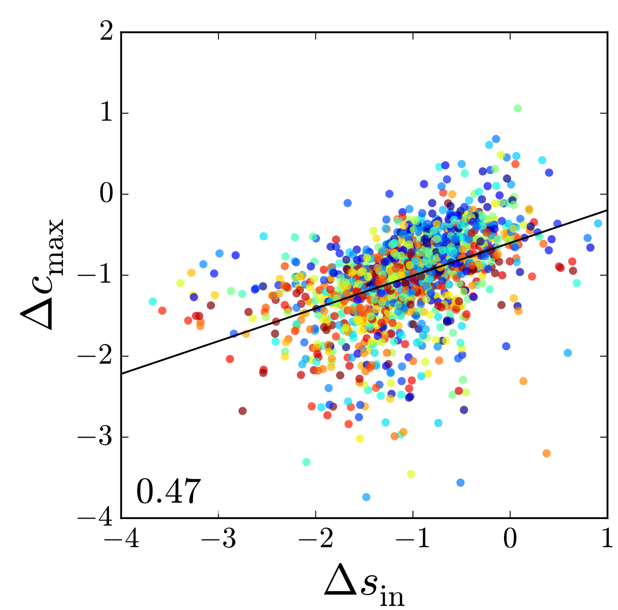
Test with the NIHAO simulations

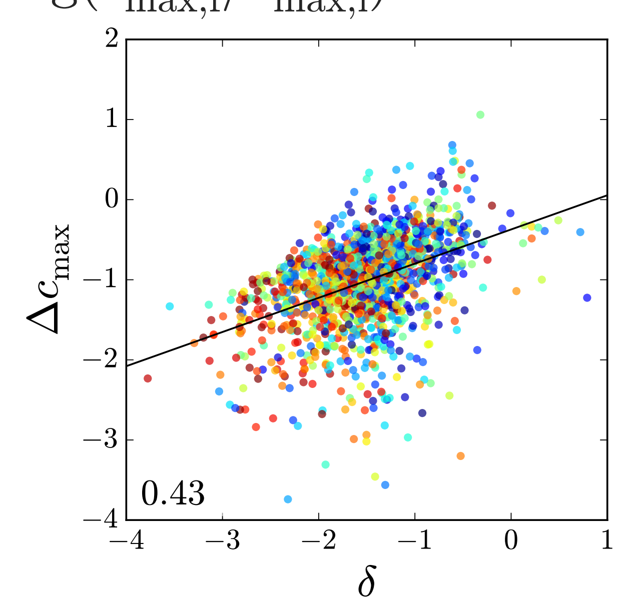
✦ **Predicted vs. actual inner slope and concentration**



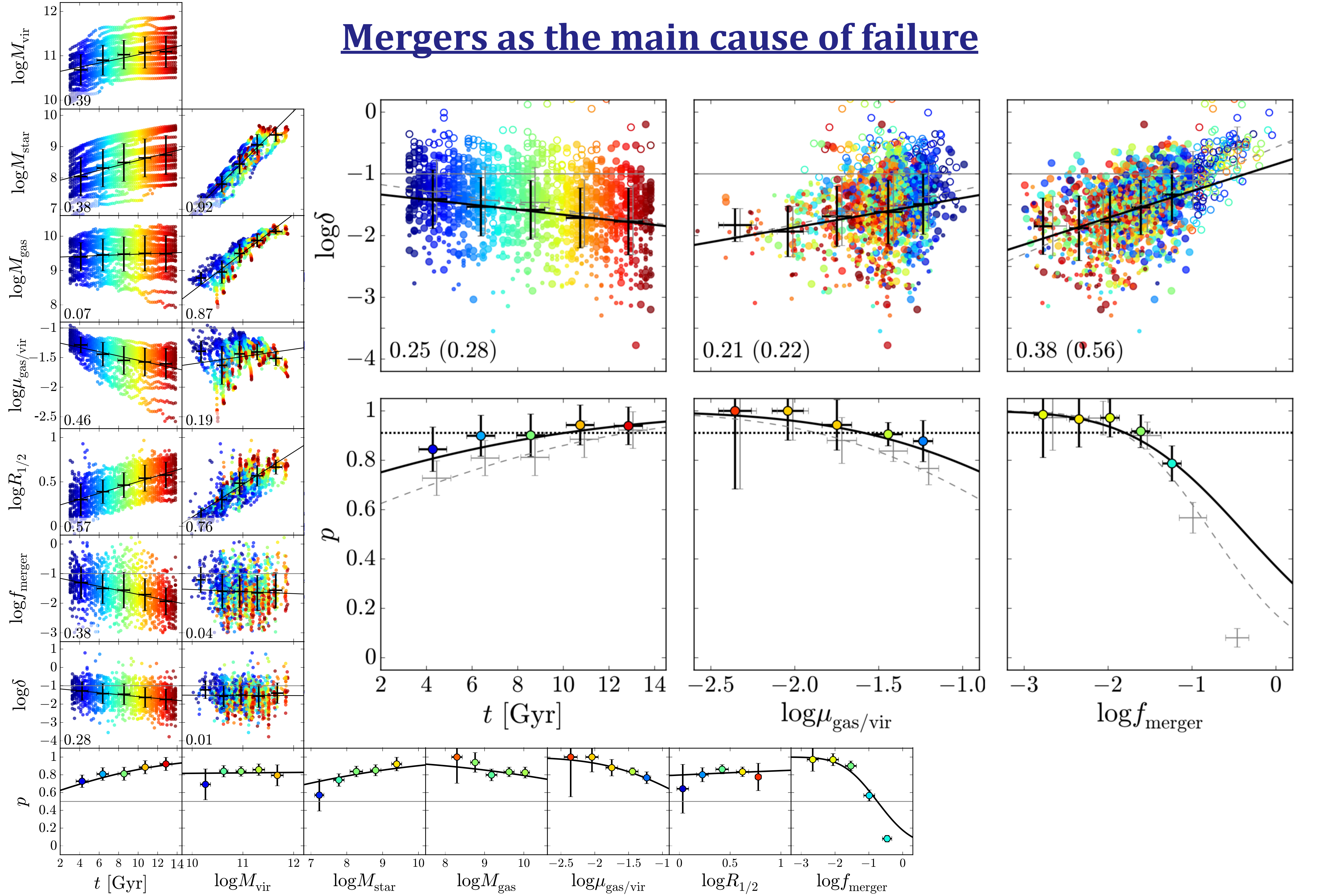




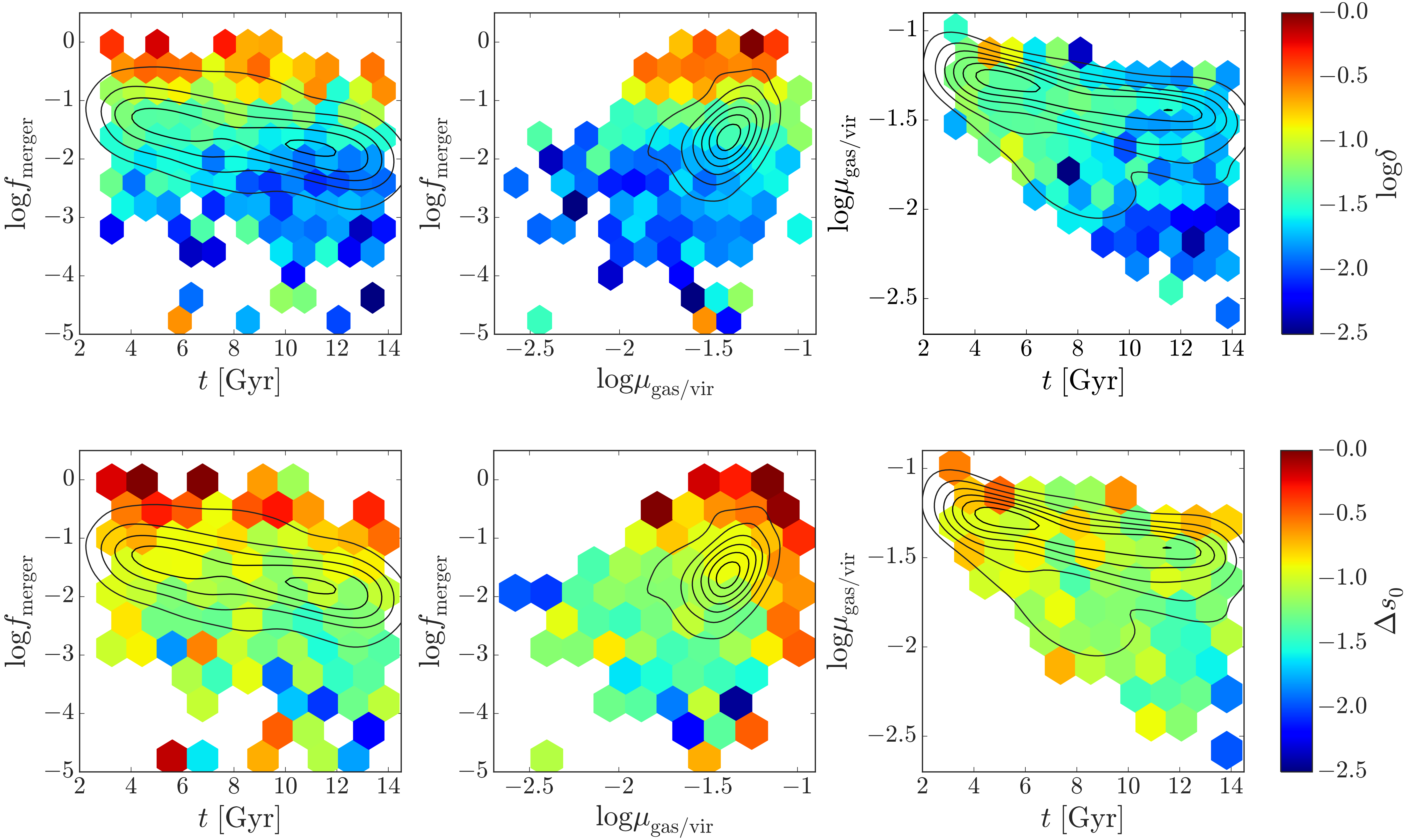




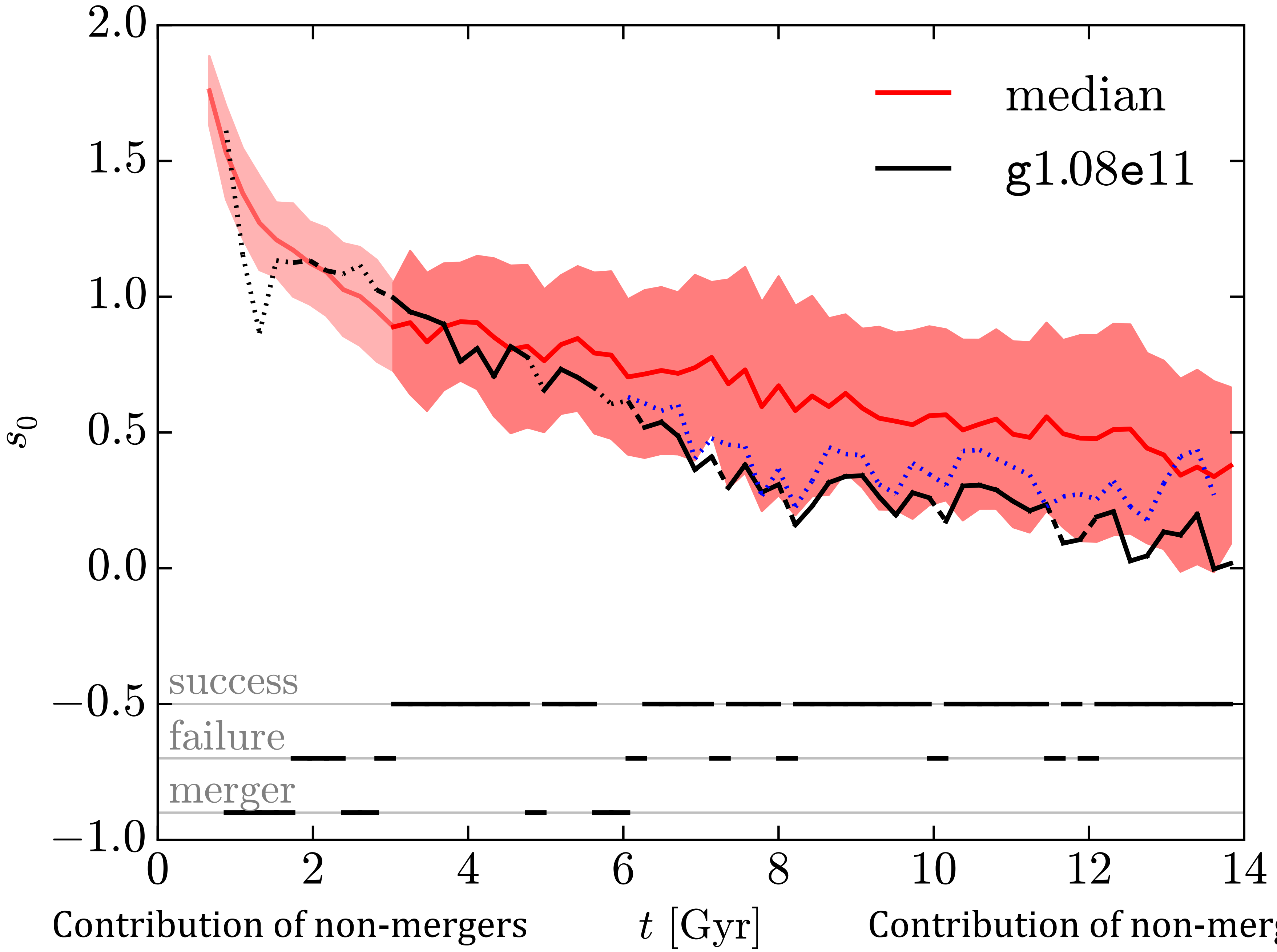
Mergers as the main cause of failure



Mergers as the main cause of failure



Contribution to the evolution of the inner density slope



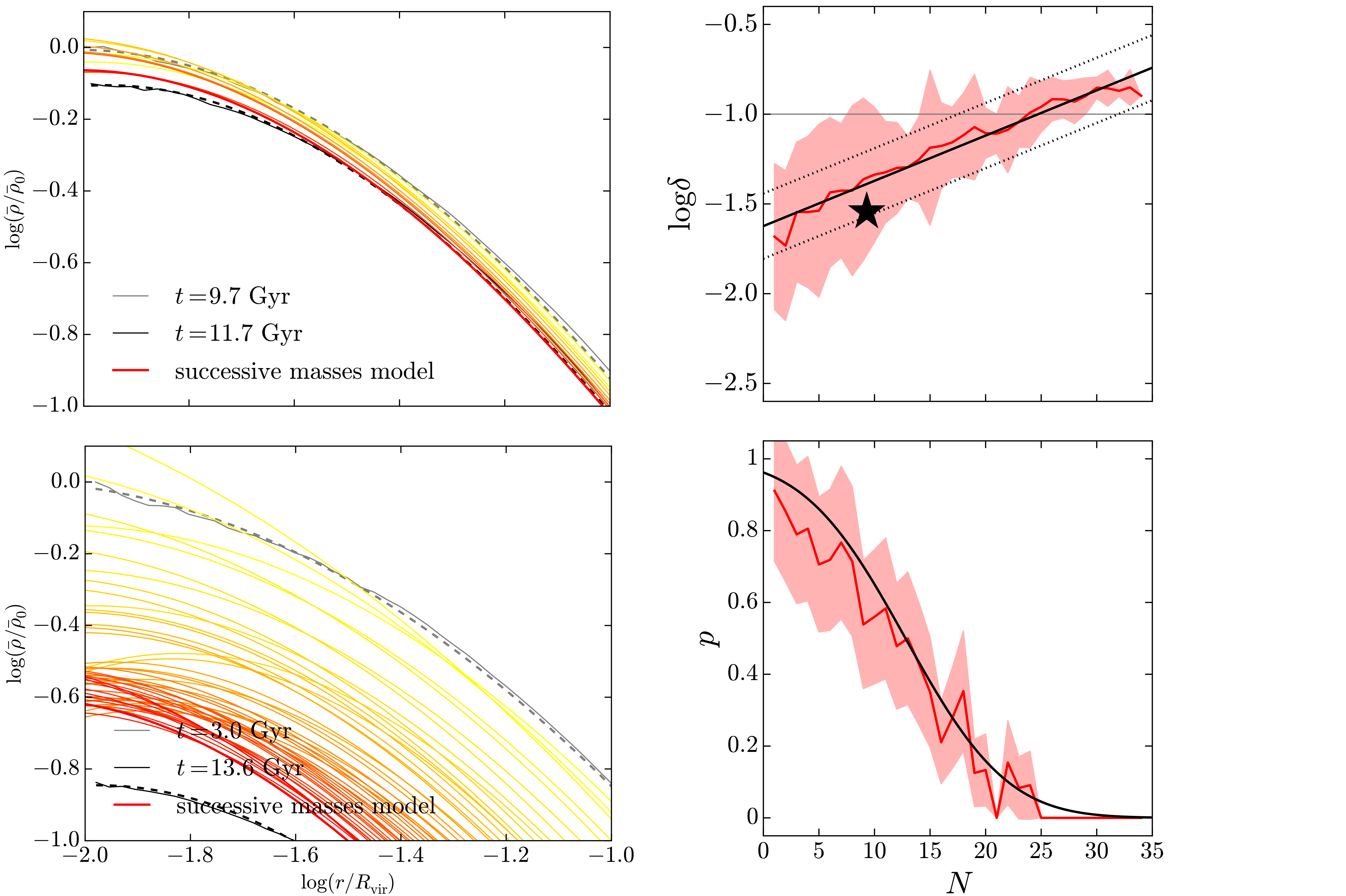
Contribution of non-mergers to $\Sigma\Delta s_0$ after 3 Gyr:
- g1.08e11: 83%
- all: 81%

Successful non-mergers:
- g1.08e11: 36%
- all: 50%

Contribution of non-mergers to $\Sigma|\Delta s_0|$ after 3 Gyr:
- g1.08e11: 94%
- all: 70%

Successful non-mergers:
- g1.08e11: 78%
- all: 59%

Multiple episodes (preliminary)



Another model for core formation

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:

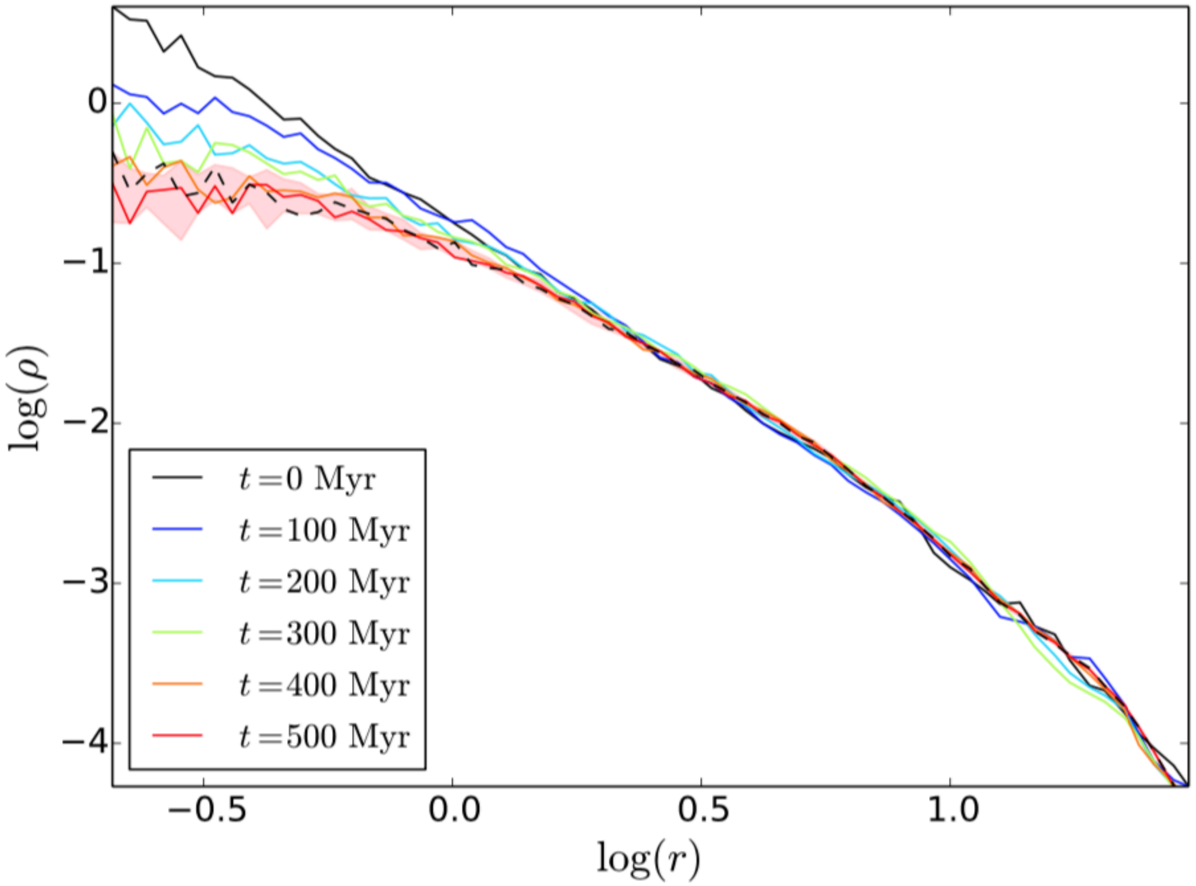
$$\delta(\vec{r}) = \frac{V}{(2\pi)^3} \int \delta_{\vec{k}} \, e^{i\vec{k}.\vec{r}} \, d^3\vec{k}$$

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
- **Marsh & Niemeyer 18**,
- **Bar-Or, Fouvry & Tremaine 18** and
- **El-Zant, Freundlich & Combes 19**, in prep.

in the context of fuzzy dark matter.

Conclusion

Freundlich, Dekel, Jiang et al., in prep.:

- ✦ A simple theoretical model based on **outflow episodes** to explain both the **formation of dark matter cores and UDGs**.
- ✦ Possible improvements: Mtot/M, non-spherical systems (stellar distribution of UDGs)
- ✦ Controlled experiments: Warrener, van den Bosch et al. in prep.
- ✦ Comparison with other models: **El-Zant, Freundlich & Combes (2016)**, Bar-Or, Fouvry & Tremaine (2018)

thanks