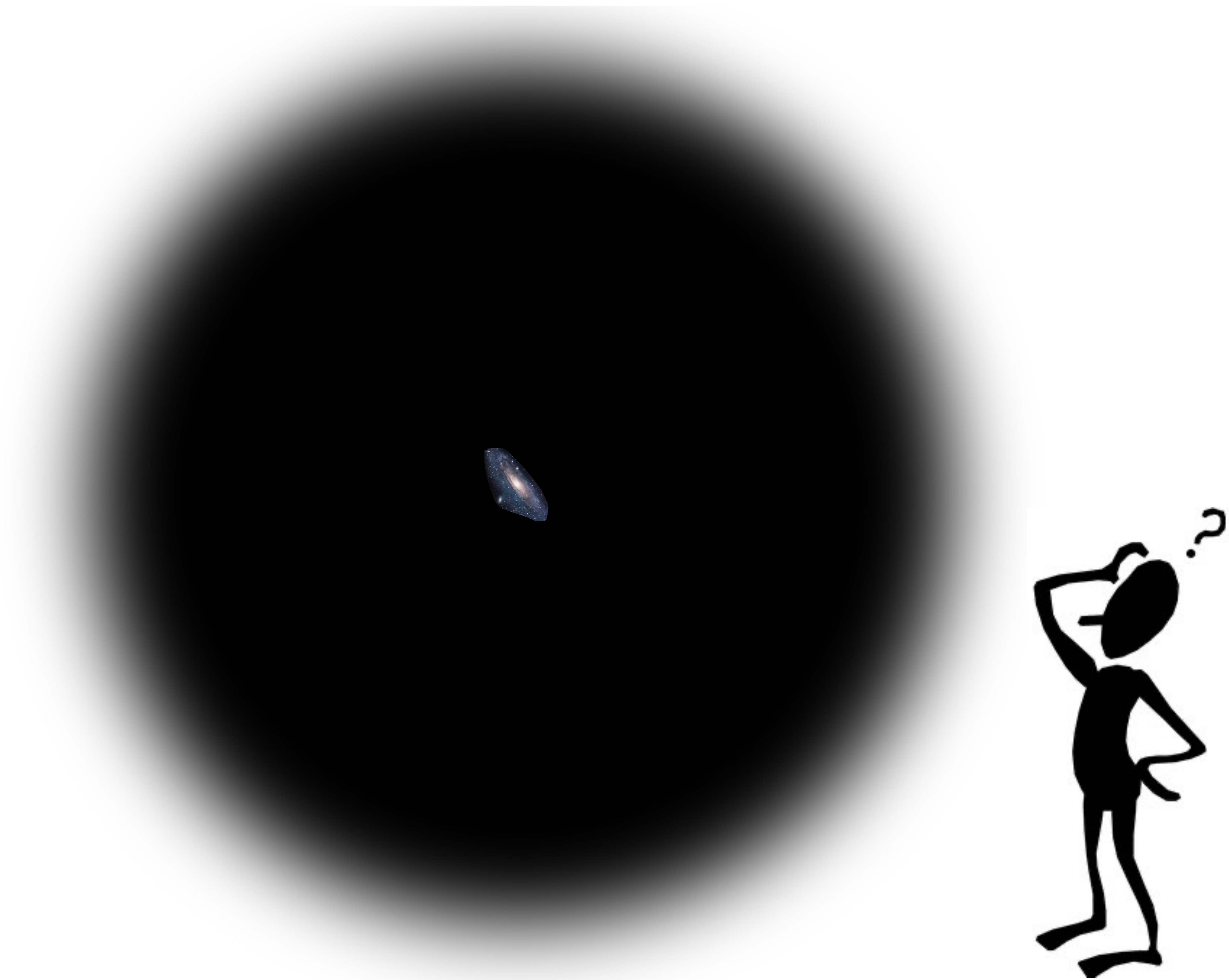
Observatoire astronomique de Strasbourg | ObAS

On the diversity of dark matter haloes

Jonathan Freundlich

With: Françoise Combes, Amr El-Zant, Avishai Dekel, Fangzhou Jiang, Anaelle Hallé, Benoit Famaey, Thibaut François, Zhaozhou Li, Srikanth Nagesh, Nicolas Bouché, Bianca Ciocan…



ΛCDM challenges at galaxy scales

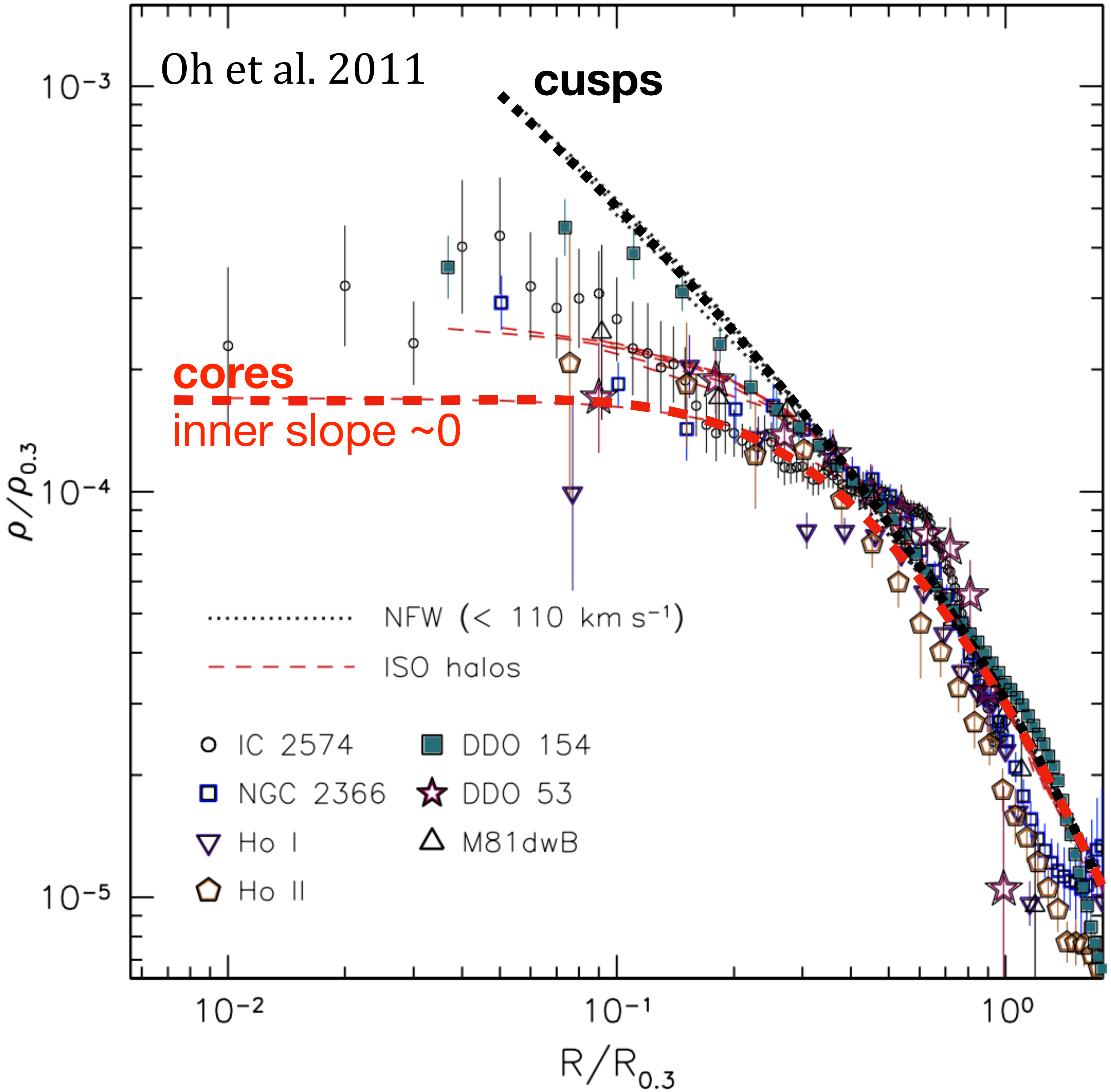
ΛCDM challenges at galaxy scales

No tension	Uncertain	Weak tension	Strong tension
Missing satellites	$M_\star$-$M_{\rm halo}$ relation	Too big to fail	Diversity of rotation curves
	Core-cusp	Diversity of dwarf sizes	Satellite planes
	Correlations between dynamics and baryons (baryonic Tully Fisher, radial acceleration relation, "Renzo's rule")	Quiescent fractions	
	Bar, gas, and disk fractions in cosmological simulations		

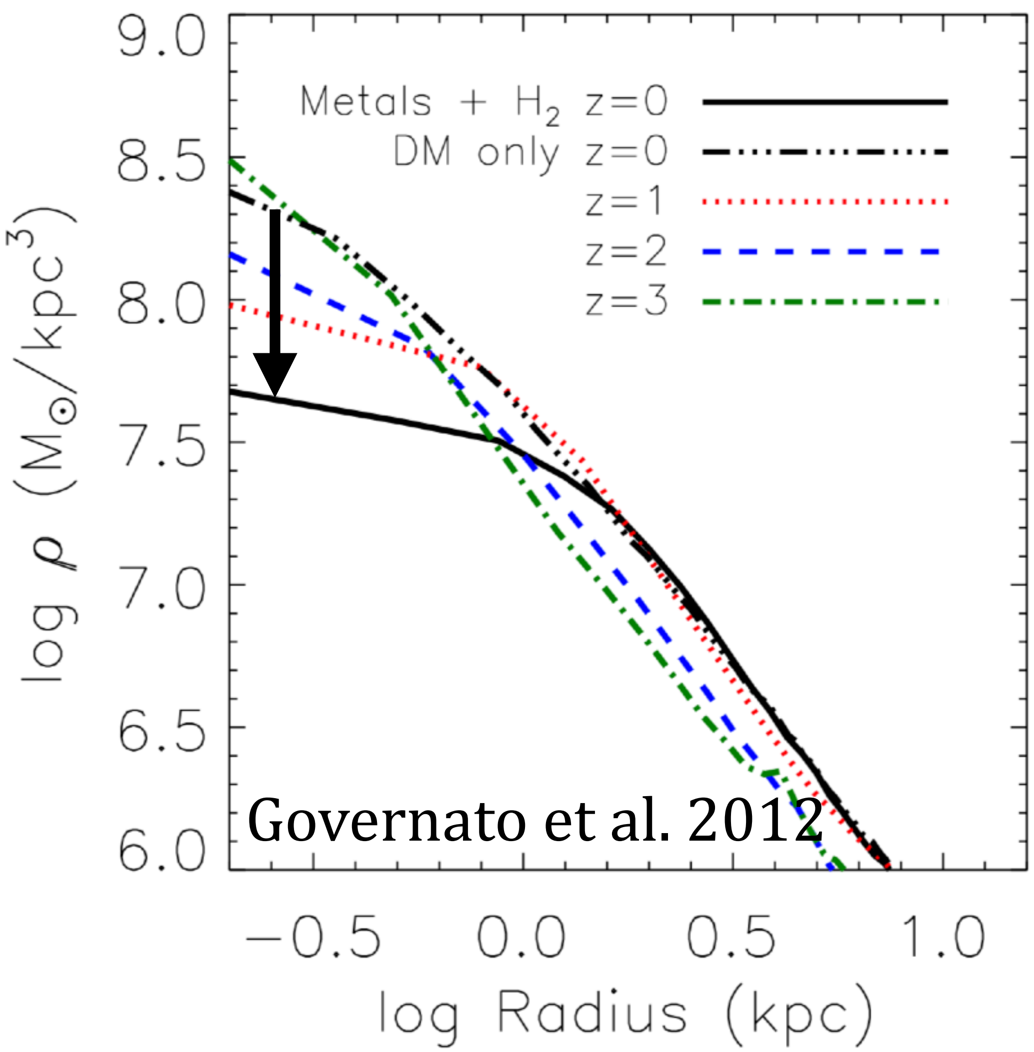
Sales, Wetzel & Fattahi (2022)

The cusp-core discrepancy

Observations:



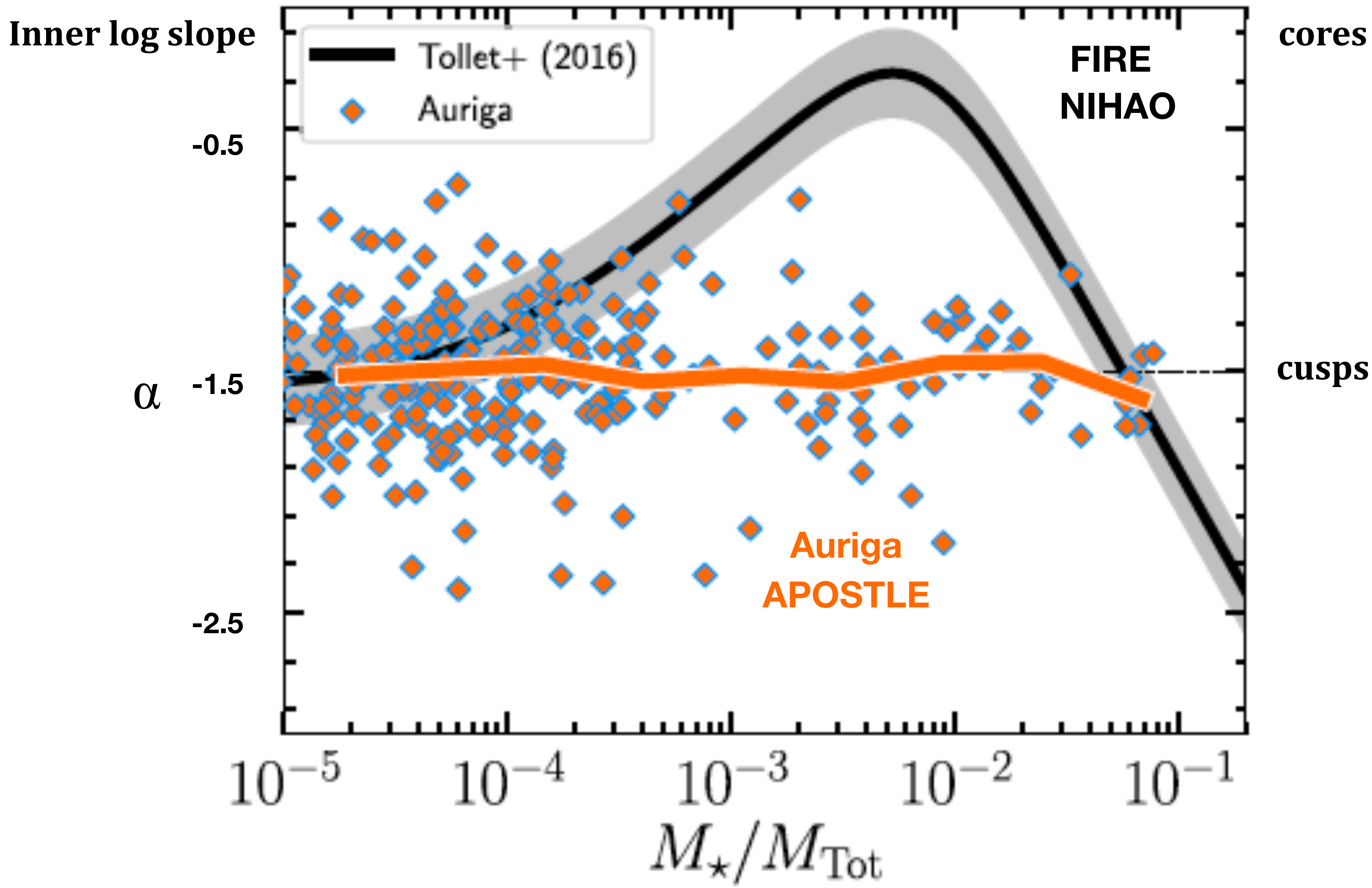
Simulations:



➡ **Baryonic processes (i.e. feedback) within ΛCDM?**

➡ **Alternative cosmological models?**

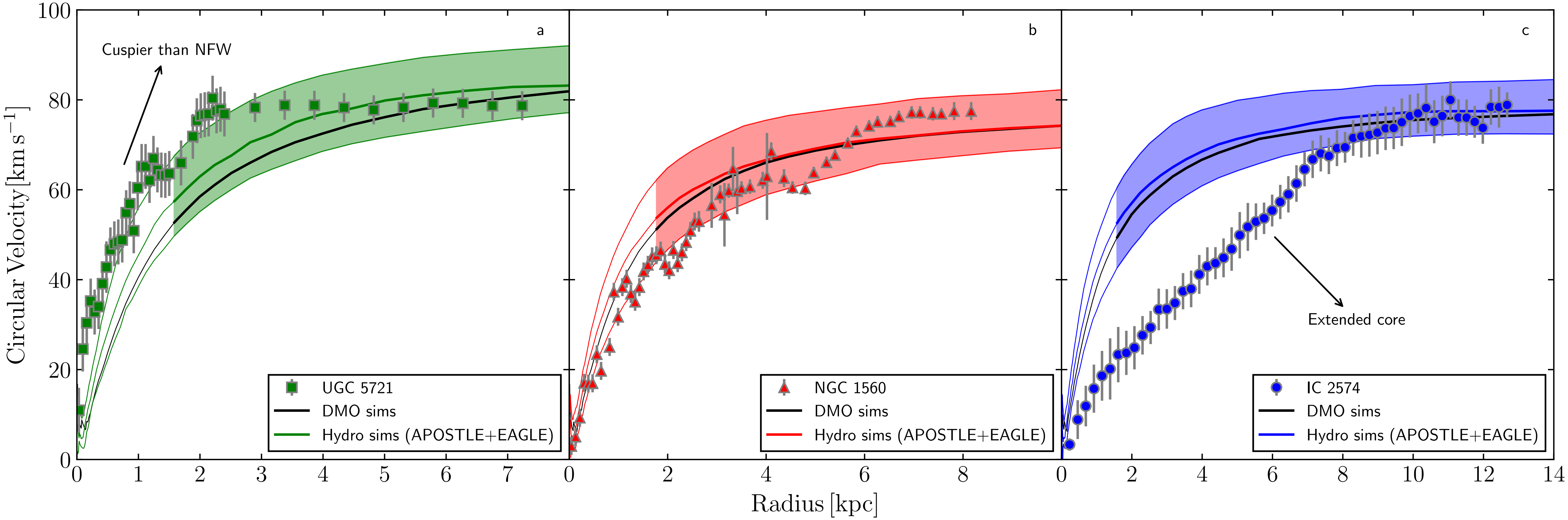
Different predictions for the halo response



Bose et al. 2019

The diversity of rotation curves

Dwarf galaxies with similar outer rotation velocity but distinct inner behavior:



Oman et al. 2015, adapted by Sales et al. 2022

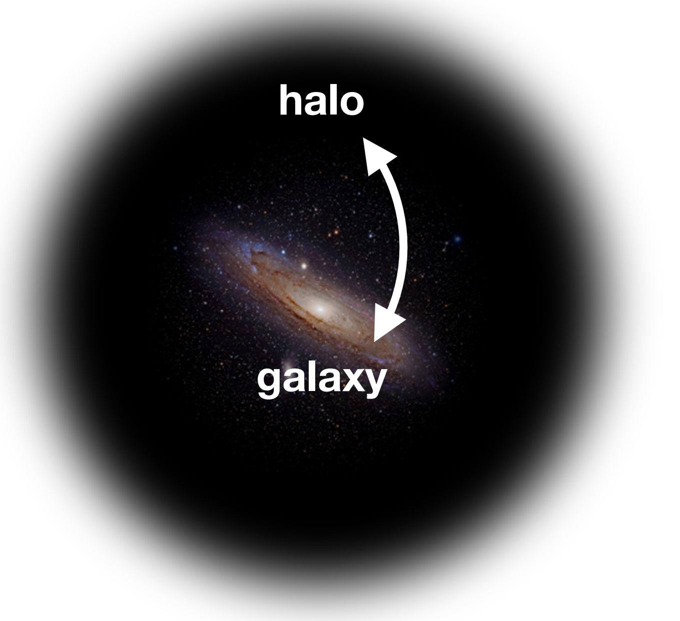
Modeling core formation from feedback processes

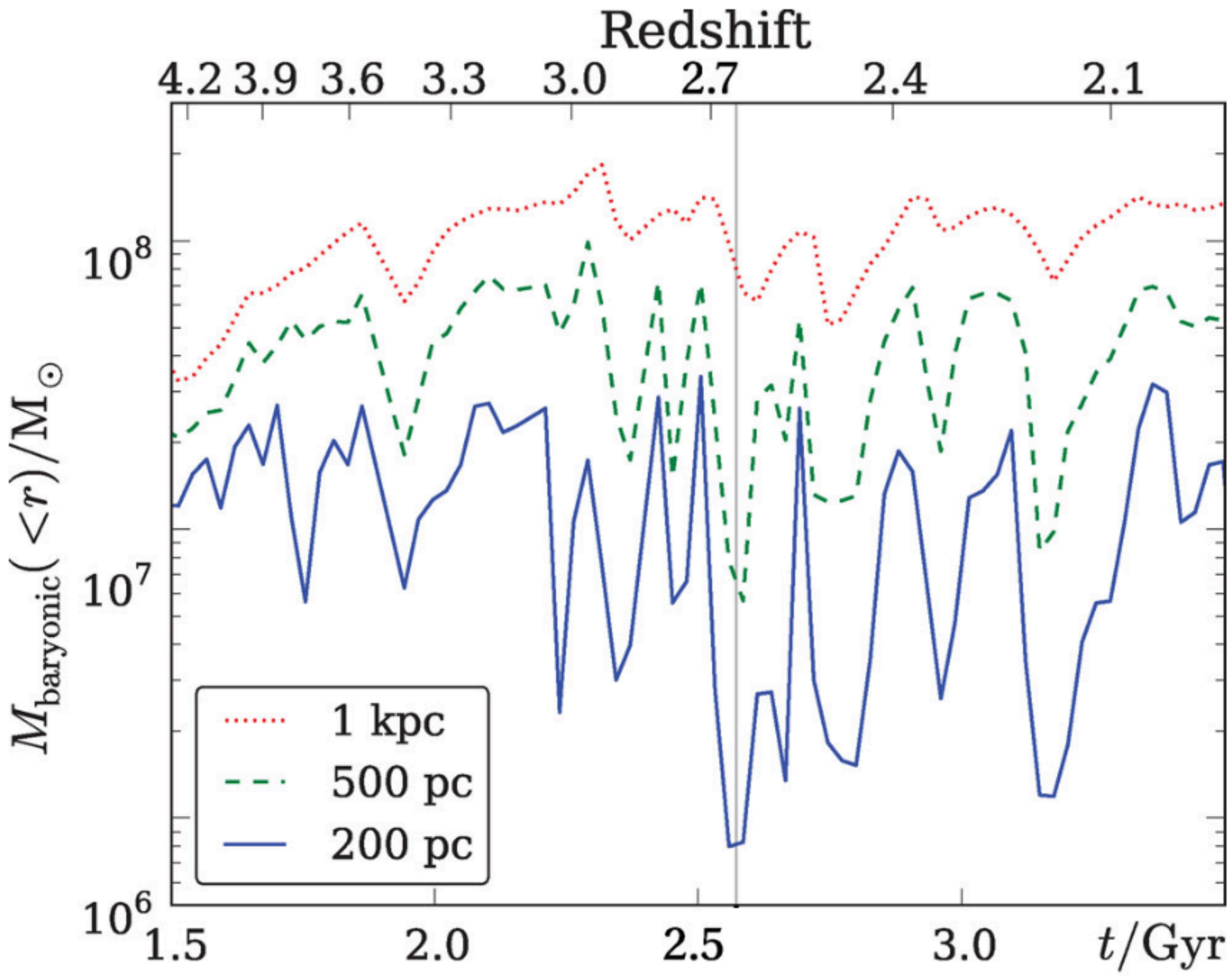
How can baryons affect dark matter haloes?

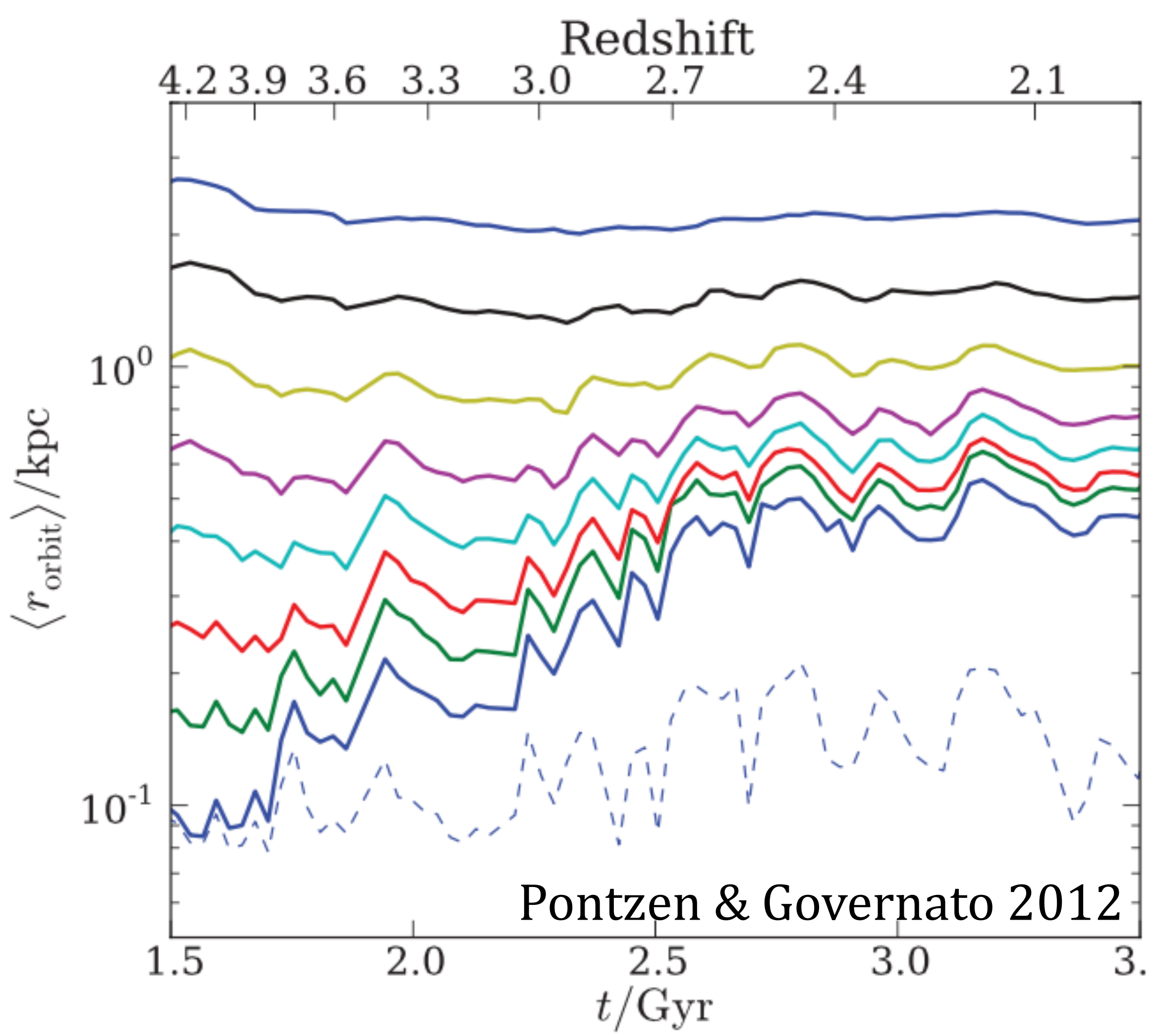
✦ **Adiabatic contraction** (Blumenthal+1986)

✦ **Dynamical friction** (El-Zant+2001, 2004)

✦ **Repeated potential fluctuations from feedback processes** (Pontzen & Governato 2012)







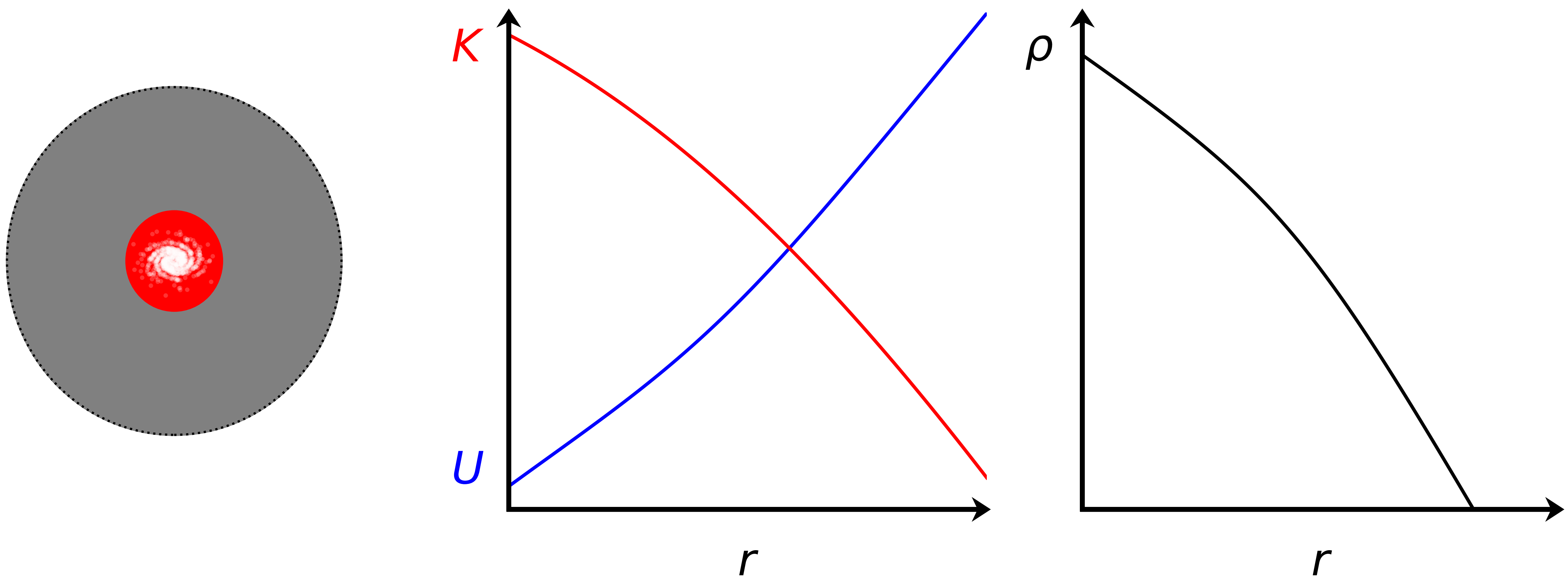
Pontzen & Governato 2012

Model I: Core formation from bulk outflows

Evolution of a spherical shell encompassing a collisionless mass M when a baryonic mass m is removed (or added) *instantaneously* at the center, using an impulse approximation.

① Initial equilibrium

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

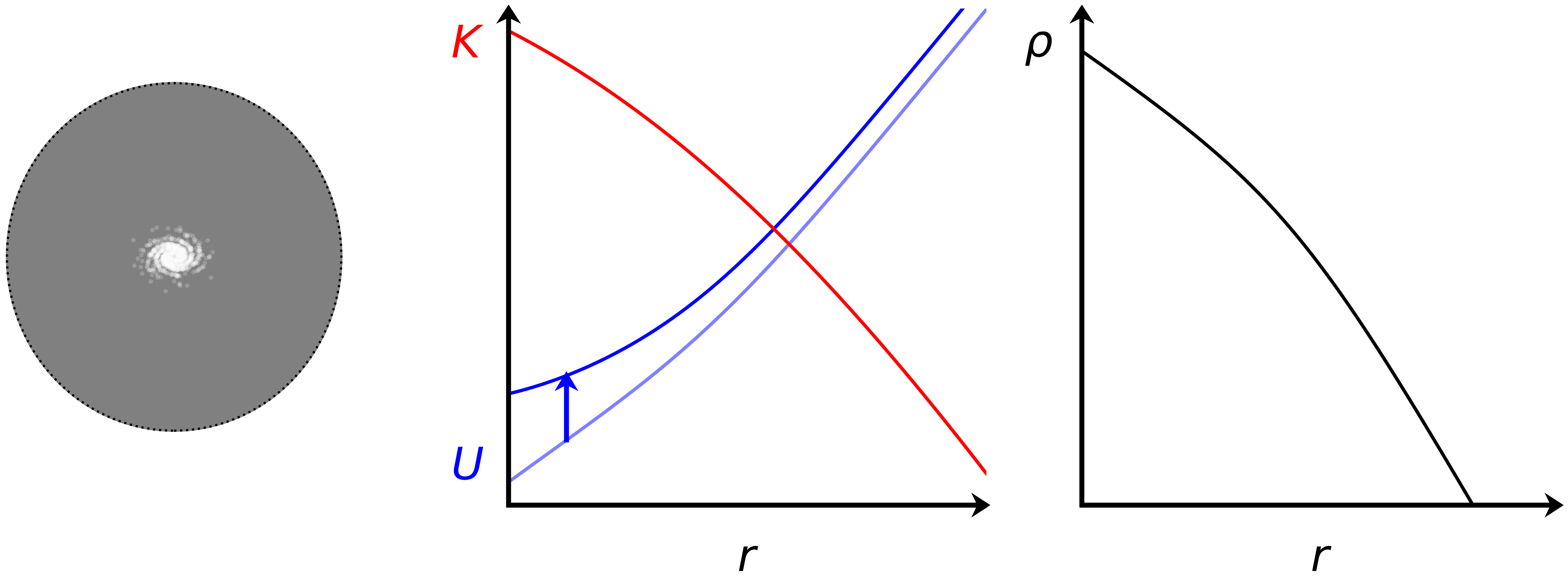


Freundlich et al. (2020a)

Model I: Core formation from bulk outflows

Evolution of a spherical shell encompassing a collisionless mass M when a baryonic mass m is removed (or added) *instantaneously* at the center, using an impulse approximation.

② Sudden gas removal $E_t(r_i) = U_i(r_i) - Gm/r_i + K_i(r_i)$



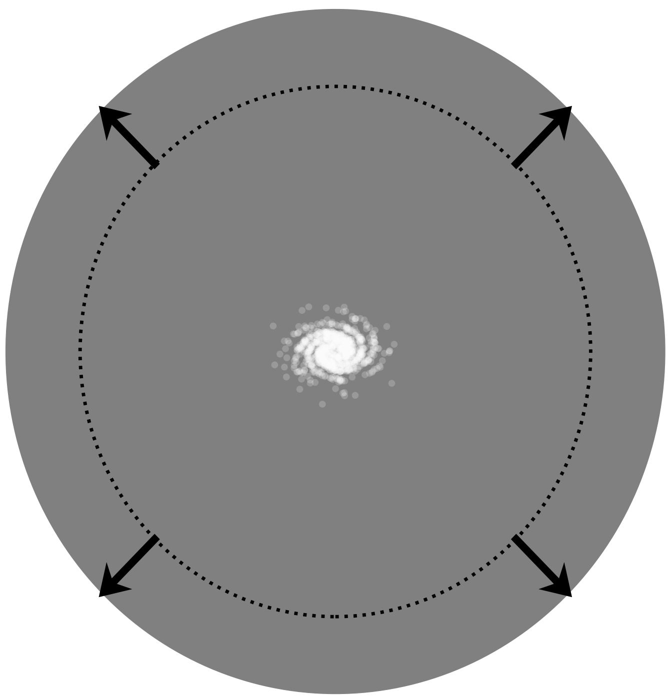
Freundlich et al. (2020a)

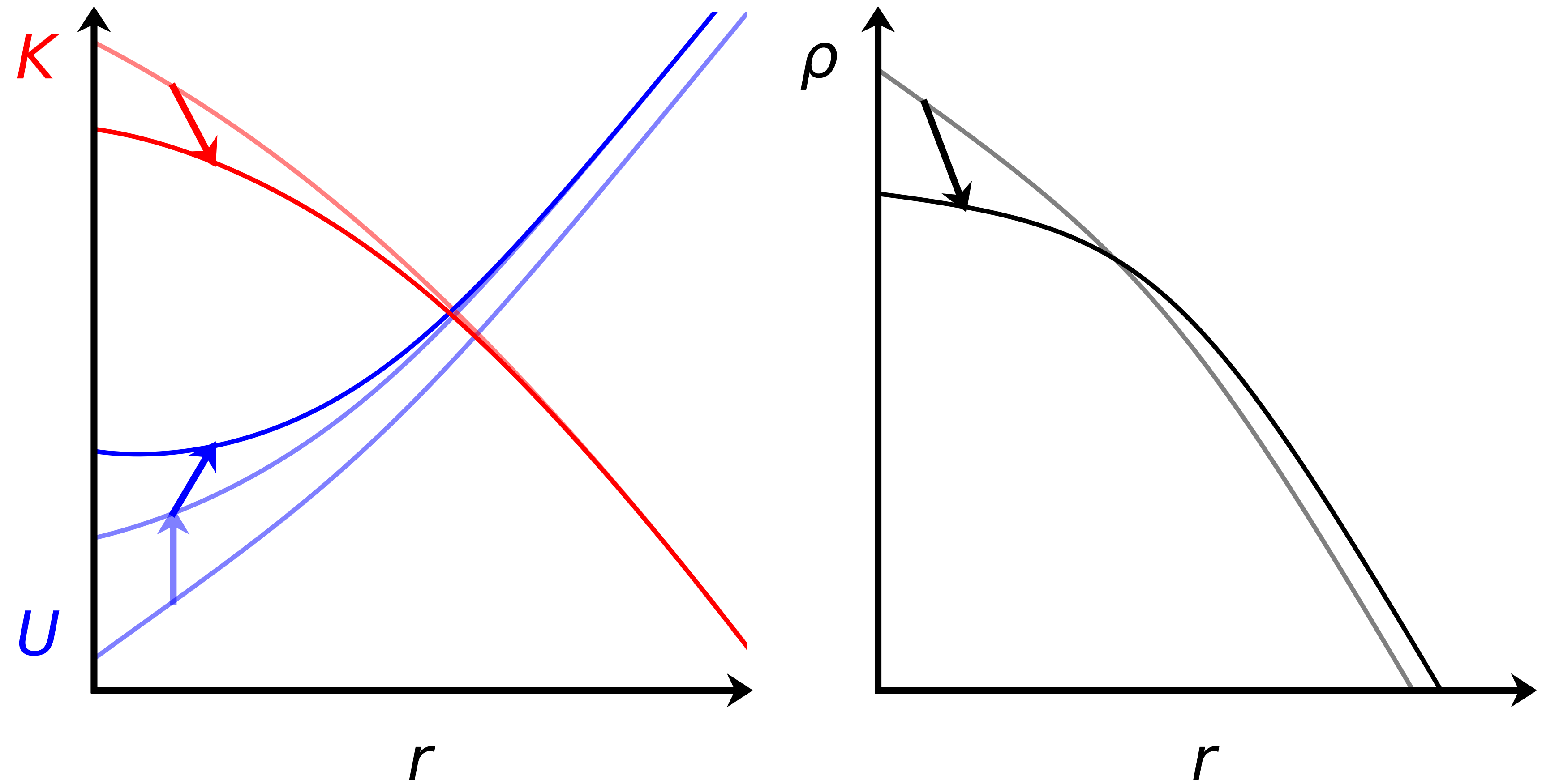
Model I: Core formation from bulk outflows

Evolution of a spherical shell encompassing a collisionless mass *M* when a baryonic mass *m* is removed (or added) *instantaneously* at the center, using an impulse approximation.

③ Relaxation

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





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

Freundlich et al. (2020a)

Along the way: a new dark matter halo parameterization

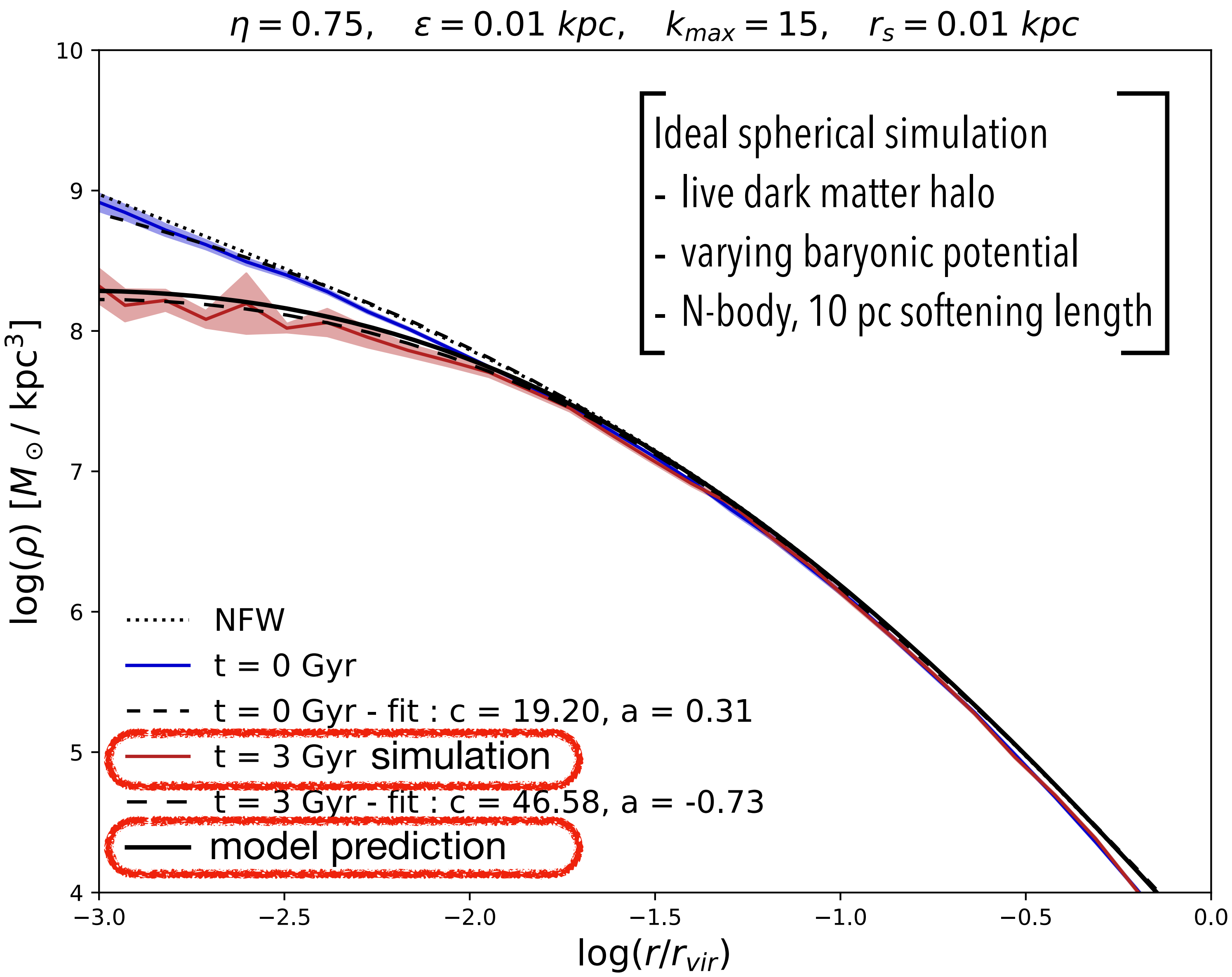
	Profile	Expression & shape parameters		Analytic expressions c_2	$M(r)$	$V(r)$	$\sigma_r(r)$	$\Phi(r)$	$\Sigma(r)$	$\overline{\Sigma}(r)$	$f(\mathscr{E})$	Mass-dependence
cusps	NFW NFW 1996 An & Zhao 2013	$\rho = \dfrac{\rho_c}{x(1+x^2)}$	c	✓	✓	✓	(✓)	✓	✓	✓	(✓)	$c(M_{\rm halo})$
cusps	superNFW Lilley+2018	$\rho = \dfrac{\rho_c}{x(1+x)^{5/2}}$	c	✓	✓	✓	✓	✓	(✓)	✗	(✓)	✗
cores	pISO	$\rho = \dfrac{\rho_c}{1+x^2}$	c	✓	✓	✓	✓	✓	✓	✓	(✓)	✗
cores	Burkert Burkert 1995	$\rho = \dfrac{\rho_c}{(1+x)(1+x^2)}$	c	✓	✓	✓	(✓)	✓	✗	✗	✗	✗
cores	Lucky13 Li+2020	$\rho = \dfrac{\rho_c}{(1+x)^3}$	c	✓	✓	✓	(✓)	✓	(✓)	(✓)	(✓)	✗
variable inner slope	Einasto Einasto 1965 An & Zhao 2013	$\rho = \rho_c \exp\left[-\dfrac{2}{\alpha}\left(x^\alpha - 1\right)\right]$	c, α	✓	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)	✗	✗
variable inner slope	coreEinasto Lazar+2020	$\rho = \rho_c \exp\left[\dfrac{-2}{\alpha}\left(\left(x+x_c\right)^\alpha - 1\right)\right]$	c, x_c, α	✗	(✓)	(✓)	✗	(✓)	✗	✗	✗	$r_c(x_M), c_2(x_M)$ with $\alpha = 0.16$
variable inner slope	$\alpha\beta\gamma$/Di Cintio Zhao 1996 Di Cintio+2014	$\rho = \dfrac{\rho_c}{x^a(1+x^{1/b})^{b(g-a)}}$	c, a, b, g	✓	(✓)	(✓)	(✗)	(✗)	(✗)	(✗)	✗	$a(x_M), b(x_M), g(x_M), c_2(x_M)$
variable inner slope	gNFW	$\rho = \dfrac{\rho_c}{x^a(1+x)^{3-a}}$	c, a	✓	(✓)	(✓)	(✓)	(✓)	(✗)	(✗)	✗	✗
variable inner slope	coreNFW Read+2016	$M = f^n M_{\rm NFW}, f = \tanh\left(r/r_c\right)$	c, r_c, n	✗	✓	✓	✗	✗	✗	✗	✗	$c(M_{\rm halo})$
variable inner slope	Dekel-Zhao Zhao 1996 Dekel+2017 Freundlich+2020b	$\rho = \dfrac{\rho_c}{x^a(1+x^{1/2})^{2(3.5-a)}}$	c, a (or c_2, s_1)	✓	✓	✓	✓	✓	(✓)	(✓)	✗	$c_2(x_M), s_1(x_M)$

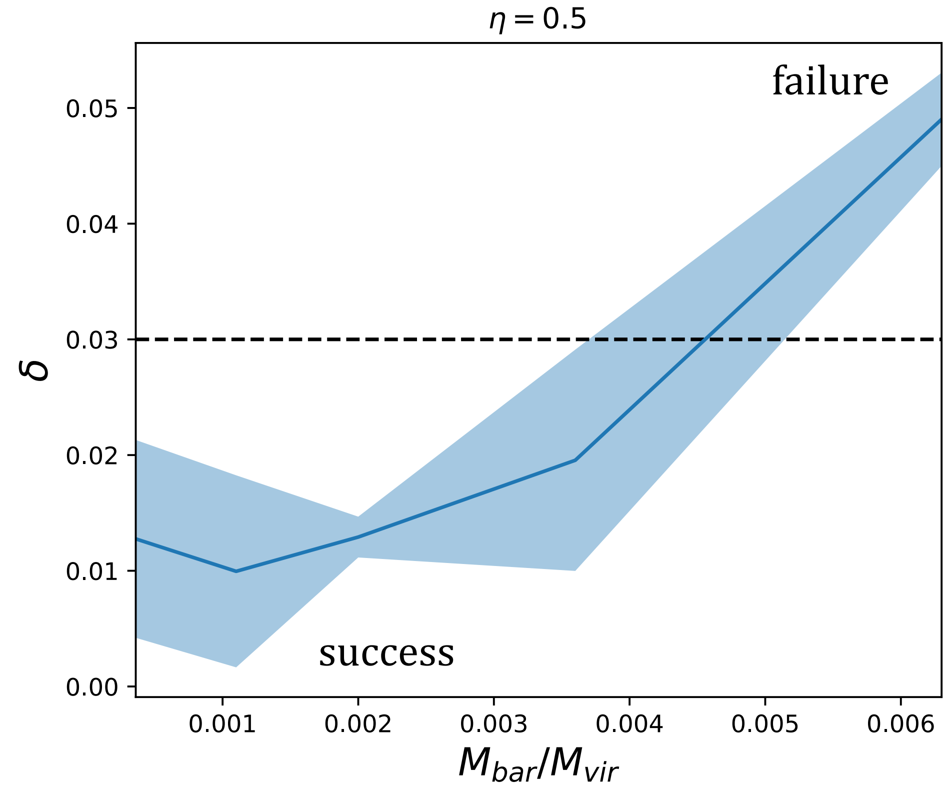
$x = r/r_s$ $c = R_{\rm vir}/r_s$ $x_M = M_{\rm star}/M_{\rm halo}$ $c_2 = R_{\rm vir}/r_{-2}$ ✓ available (✓) non-elementary functions ✗ not available (✗) only certain cases

*for the $\alpha\beta\gamma$ profile, $M(r)$, $V(r)$, $\sigma_r(r)$, and $\Phi(r)$ can be expressed using elementary functions in certain cases (in particular when $\alpha = n, \beta = 3 + k/n$ with $k, n \in N$)

Shortcomings

The model is extremely successful in certain cases… … but fails when too much mass is removed





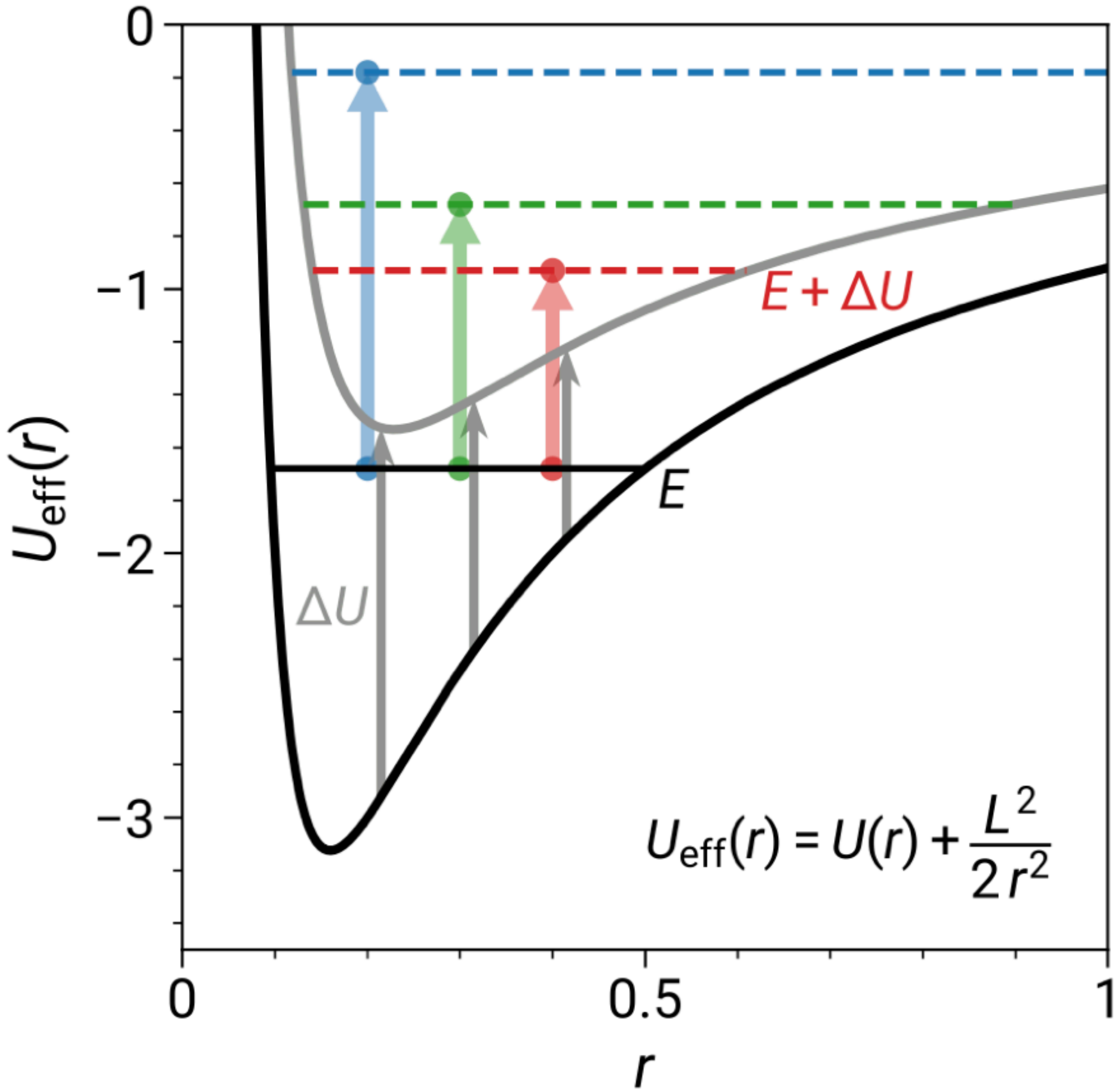
δ difference between outcome and prediction

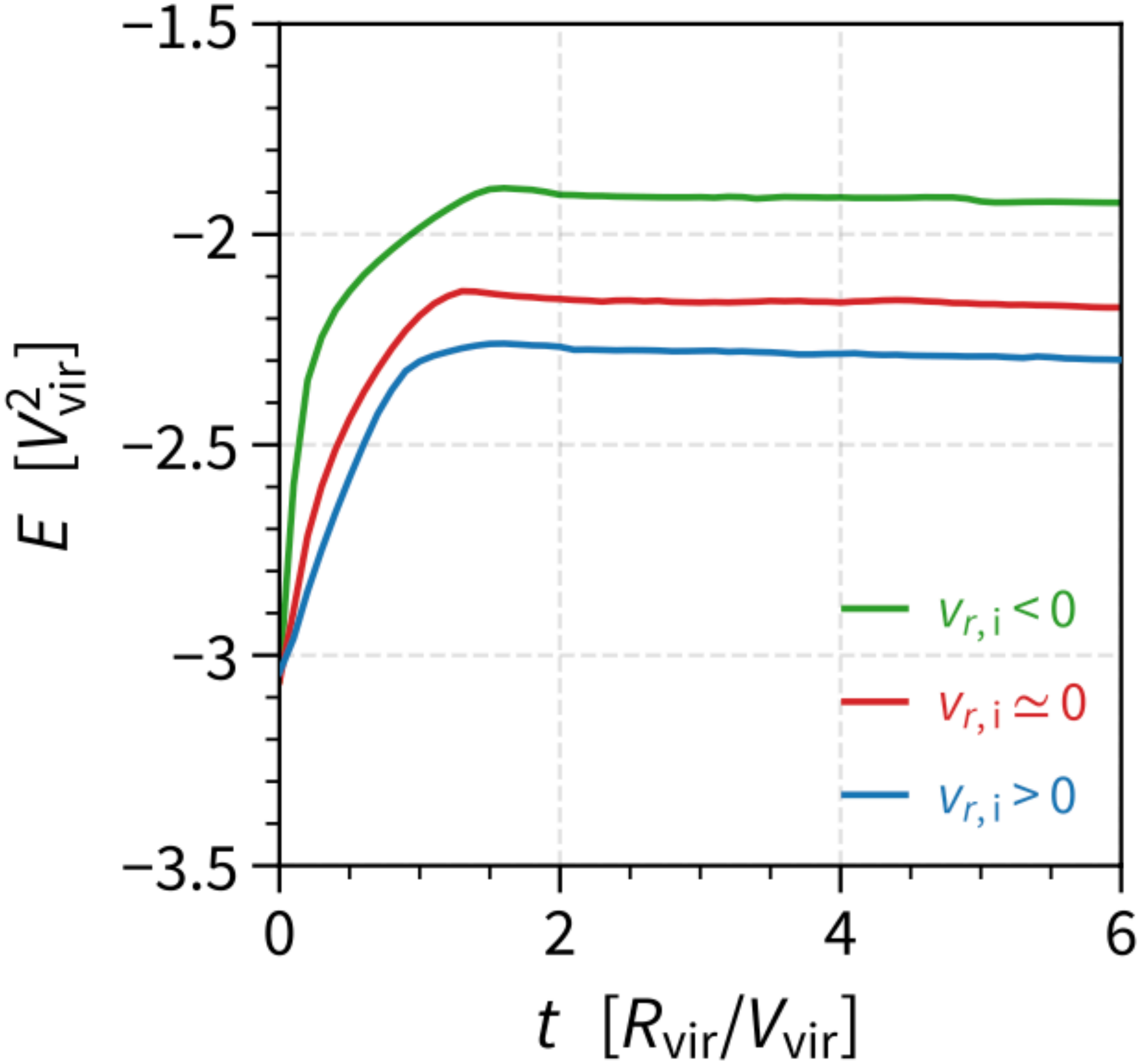
$\eta = \Delta M_{\rm bar}/M_{\rm bar}$

M2 internship of Thibaut François
co-supervised with Benoit Famaey

Shortcomings

- ✦ **Energy diffusion:** particles on the same orbit experience different energy gains depending on their orbital phase
- ✦ **Violent relaxation** followed by **phase mixing**





Li et al. 2022 (incl. Freundlich)

Model I, version 2: iteratively updating the distribution function

① Initial equilibrium

$$U_0 = U_{\rm g,i} + U_{\rm dm,i}$$

$$f_0(E) = \frac{1}{\sqrt{8}\pi^2} \int_E^0 \frac{d^2 \rho_{\rm dm,i}}{dU_0^2} \frac{dU_0}{\sqrt{U_0 - E}}$$

② Sudden gas removal/addition

$$U_1 = U_{\rm g,f} + U_{\rm dm,i}$$

$$\Delta U(r) = U_1(r) - U_0(r)$$

③ Relaxation to new equilibrium

New distribution function for $E \to E + \Delta U(r)$

$$f_k(E) = \frac{\int_0^{r_E} f_{k-1}(E - \Delta U(r)) \sqrt{E - U_k(r)} r^2 \, dr}{\int_0^{r_E} \sqrt{E - U_k(r)} r^2 \, dr}$$

Equilibrium density in *static* U_k

$$\rho'_{{\rm dm},k}(r) = 4\sqrt{2}\pi \int_{U_k(r)}^0 f_k(E) \sqrt{E - U_k(r)} dE$$

Evolve $\rho_{\rm dm}$ towards $\rho'_{{\rm dm},k}$ with a finite step

$$\rho_{{\rm dm},k}(r) = \mu \rho'_{{\rm dm},k}(r) + (1 - \mu) \rho_{{\rm dm},k-1}(r)$$

Update potential

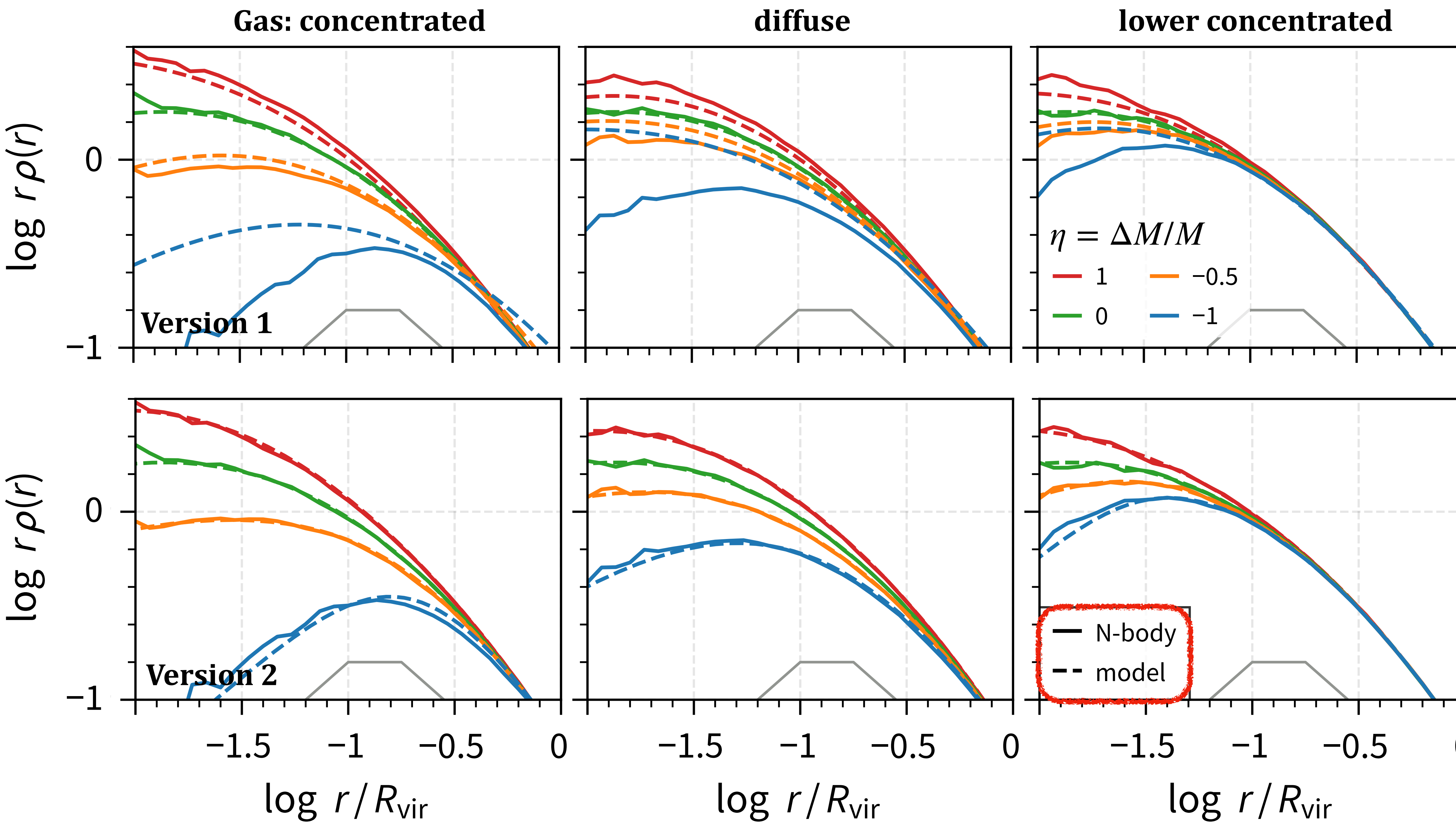
$$U_{k+1}(r) = U_{\rm g,f}(r) - 4\pi G \int_r^\infty \frac{dy}{y^2} \int_0^y \rho_{{\rm dm},k}(x) x^2 \, dx$$

$$k \mathrel{+}= 1$$

$$\Delta U(r) = U_k(r) - U_{k-1}(r)$$

Li et al. 2022 (incl. Freundlich)

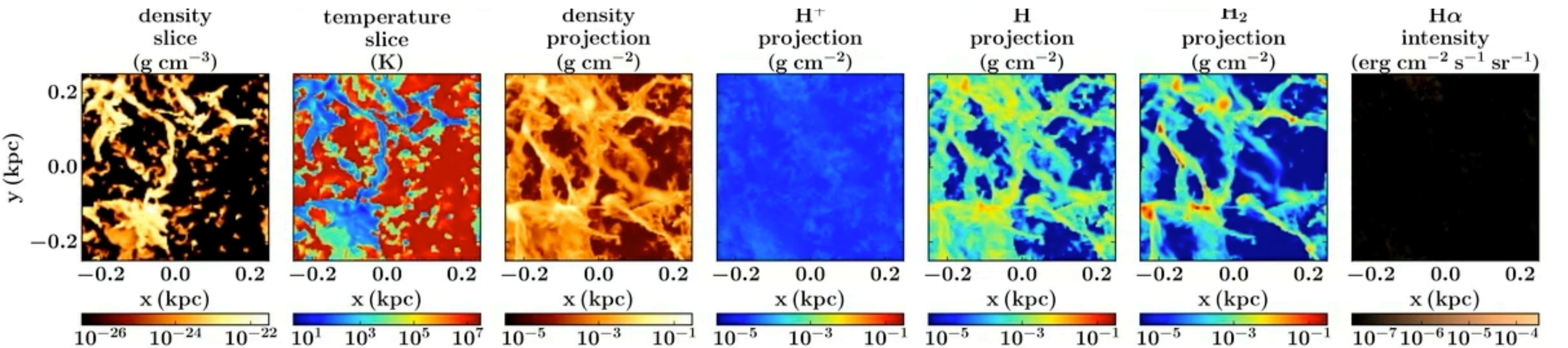
Model I, version 2: numerical tests



Li et al. 2022 (incl. Freundlich)

Model II: core formation from stochastic density fluctuations

✦ **Effects of radiation, stellar winds and supernovae on the interstellar medium** (e.g., SILCC Peters+17)



✦ **Stochastic gas density fluctuations in an unperturbed homogeneous medium**

— Density contrast

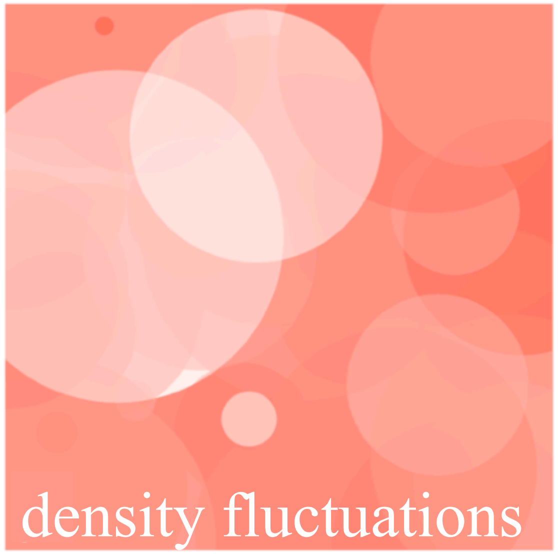
$$\delta(\mathbf{r}) = \frac{V}{(2\pi)^3} \int \delta_{\mathbf{k}}\, e^{i\mathbf{k}.\mathbf{r}}\, d^3\mathbf{k}$$

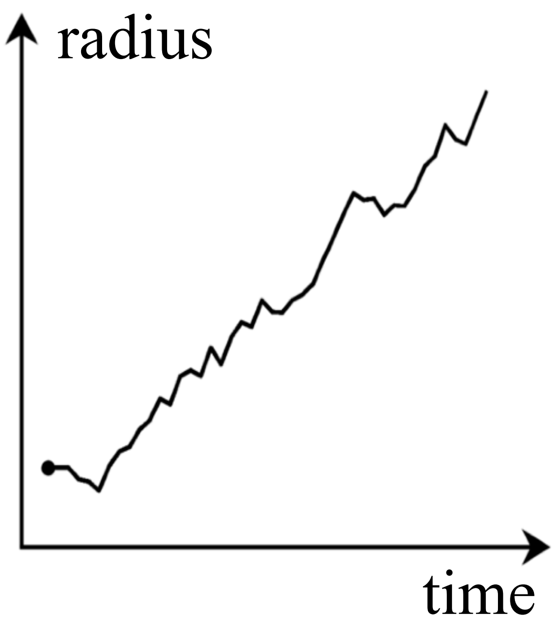
— Each mode induces a 'kick'

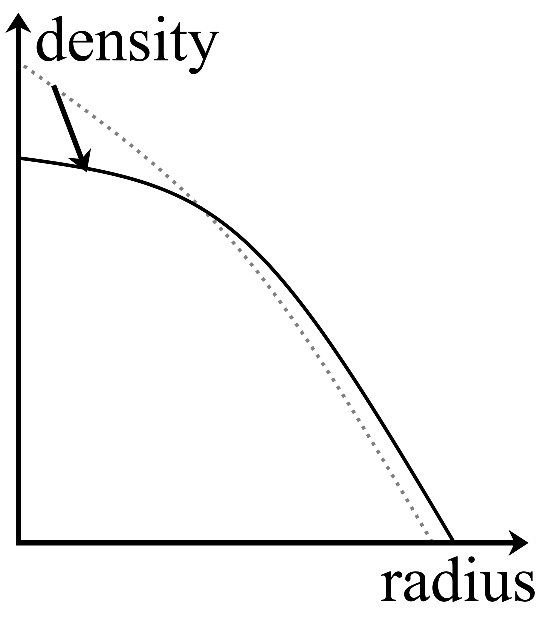
$$\mathbf{F}_{\mathbf{k}} = 4\pi i\, G\rho_0\, \mathbf{k}\, k^{-2}\, \delta_{\mathbf{k}}$$

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

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



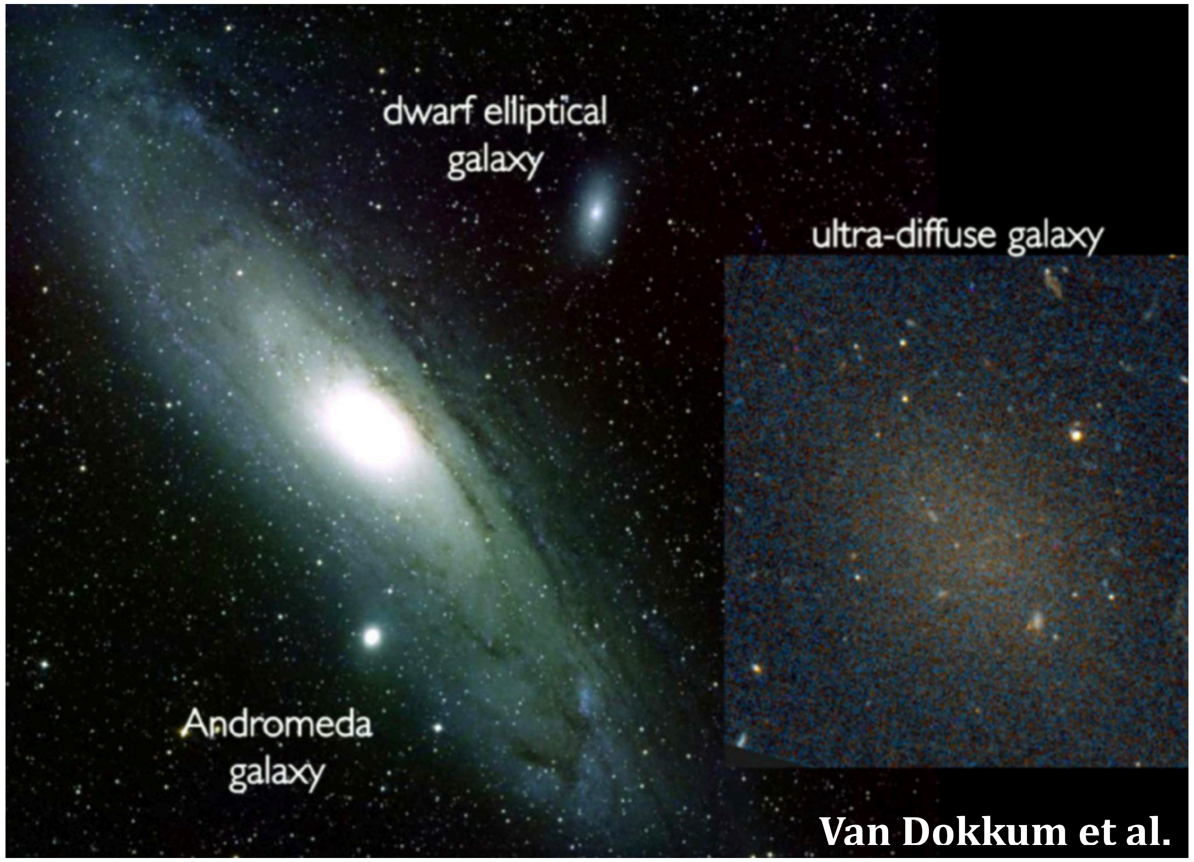




El-Zant, Freundlich & Combes 2016, Hashim, El-Zant, Freundlich et al. 2023

Some implications

The same process at stake in ultra-diffuse galaxies?

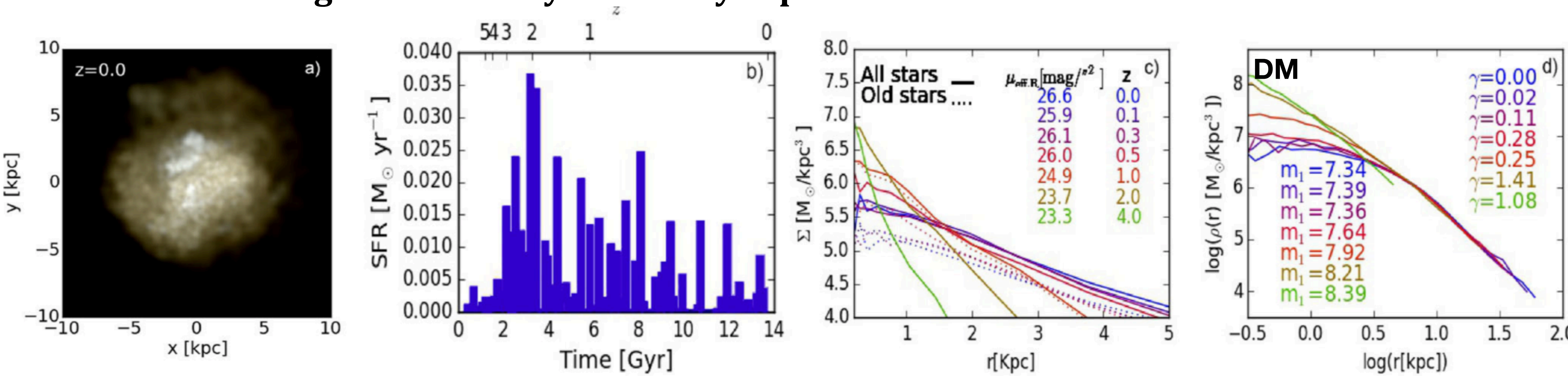


- ✦ **Stellar masses of dwarf galaxies**
  $7 < \log(M_{\rm star}/M_{\odot}) < 9$
- ✦ **Effective radii of MW-sized objects**
  $1 < r_{\rm eff}/{\rm kpc} < 5$

Possible formation scenarii:

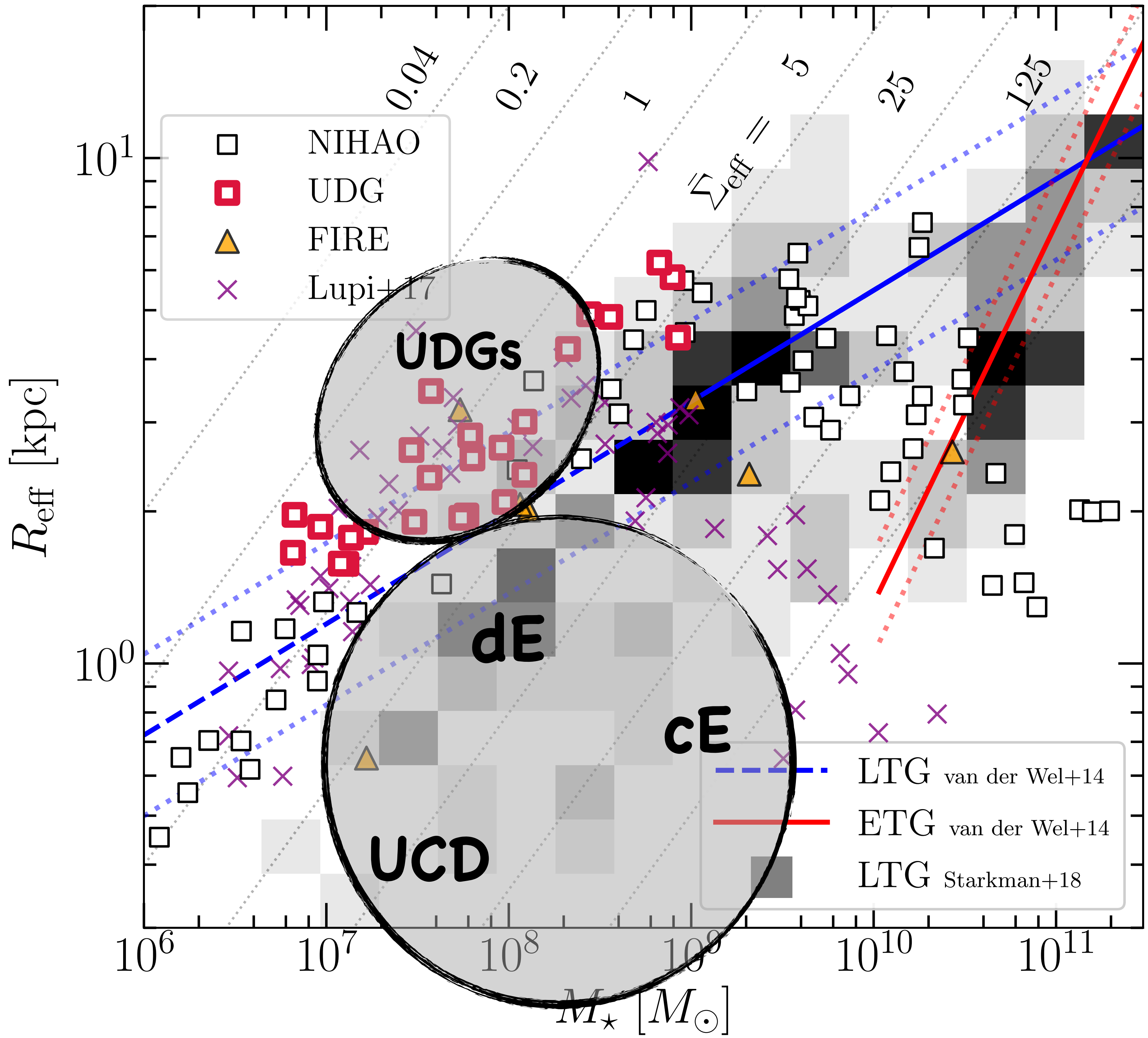
- ✦ **Failed MW-like galaxies** (Van Dokkum+2015)
- ✦ **High-spin tail** (Amorisco & Loeb 2016)
- ✦ **Tidal debris** (Greco+2017)
- ✦ **Stellar feedback outflows** (Di Cintio+2017)

Outflows resulting from a bursty SF history expand both the stellar and the DM distributions



Di Cintio et al. 2017

A dwarf galaxy diversity problem in simulations



Jiang, Dekel, Freundlich et al. 2019

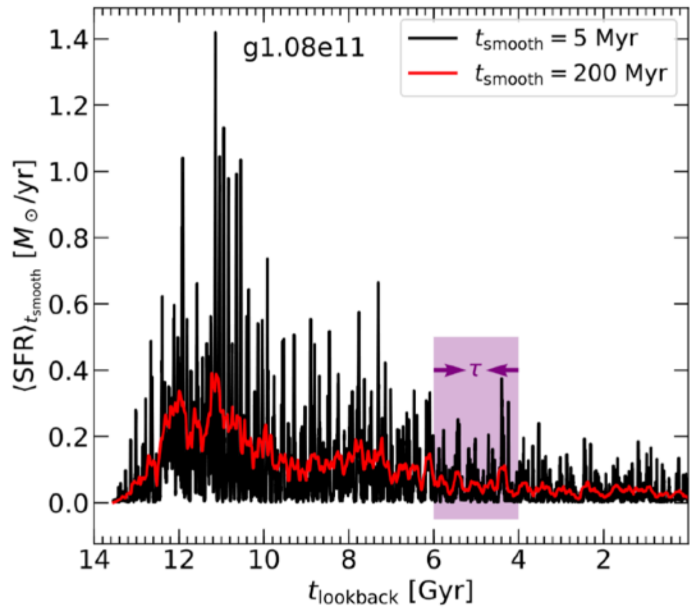
Towards observational tests?

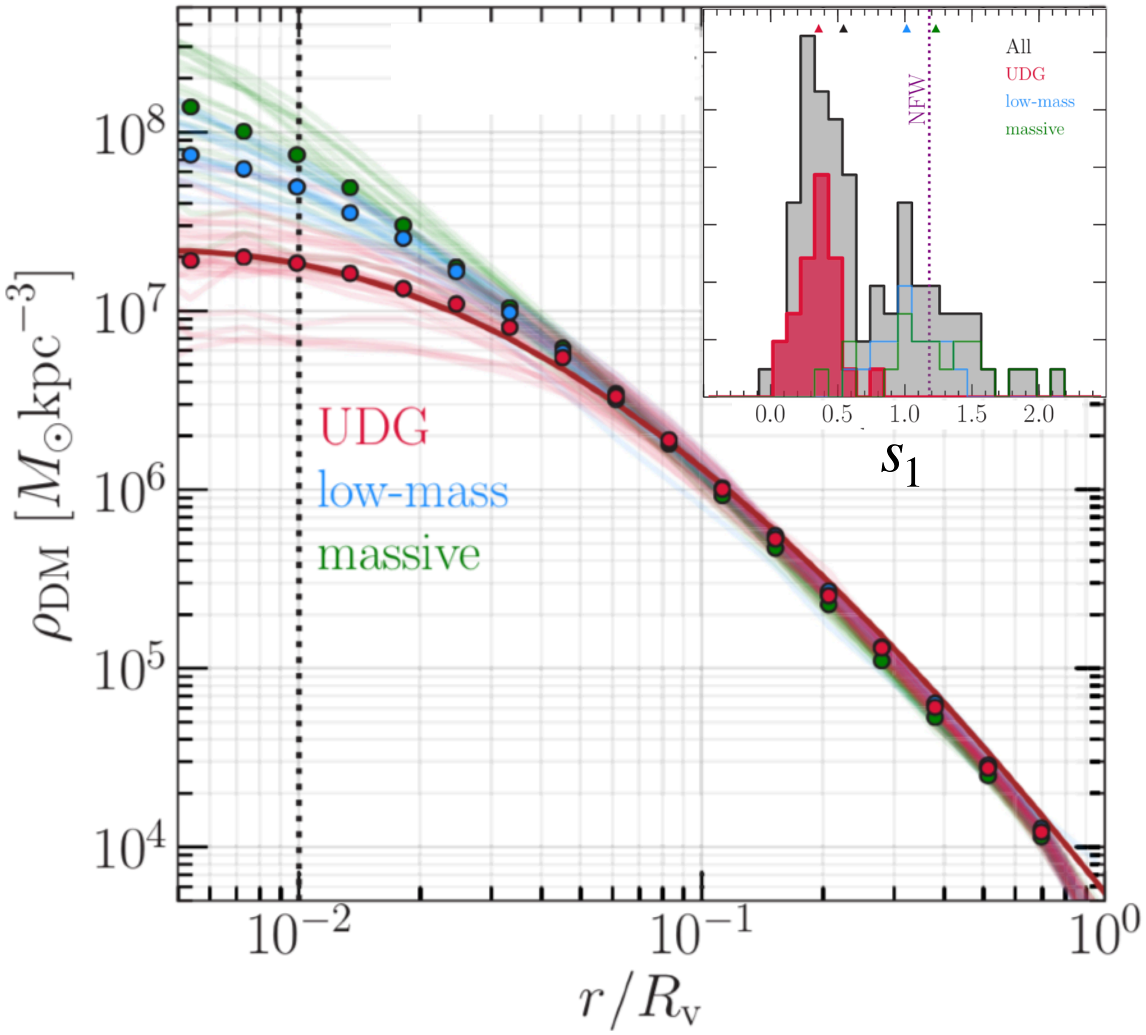
Consequences of such models:

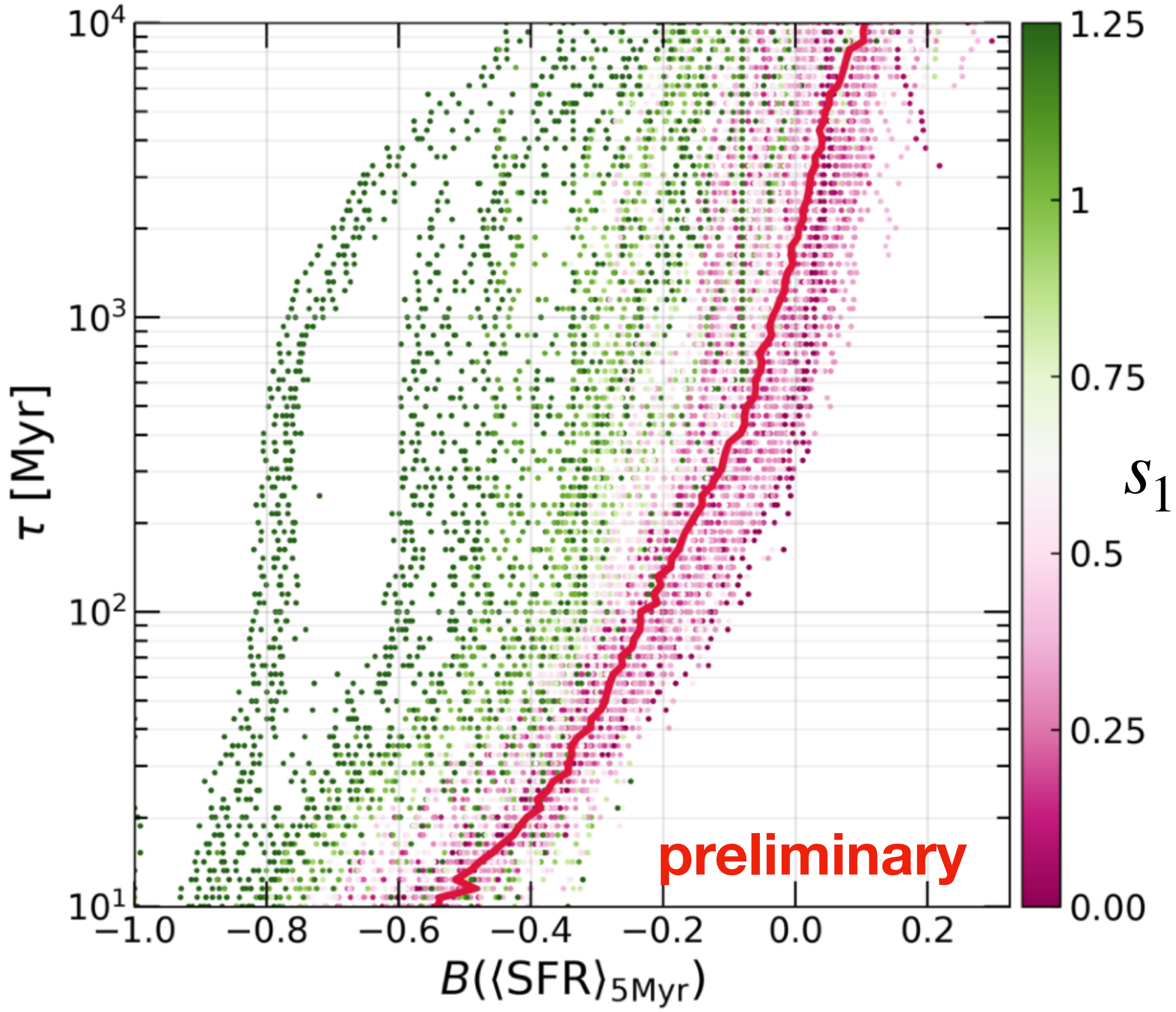
— UDGs should have **cored** dark matter density profiles

— Inner slope s_1 should be related to the **burstiness** of the SFR history

$$B(\tau) = \frac{\sigma_{\rm SFR}/\mu_{\rm SFR} - 1}{\sigma_{\rm SFR}/\mu_{\rm SFR} + 1}$$

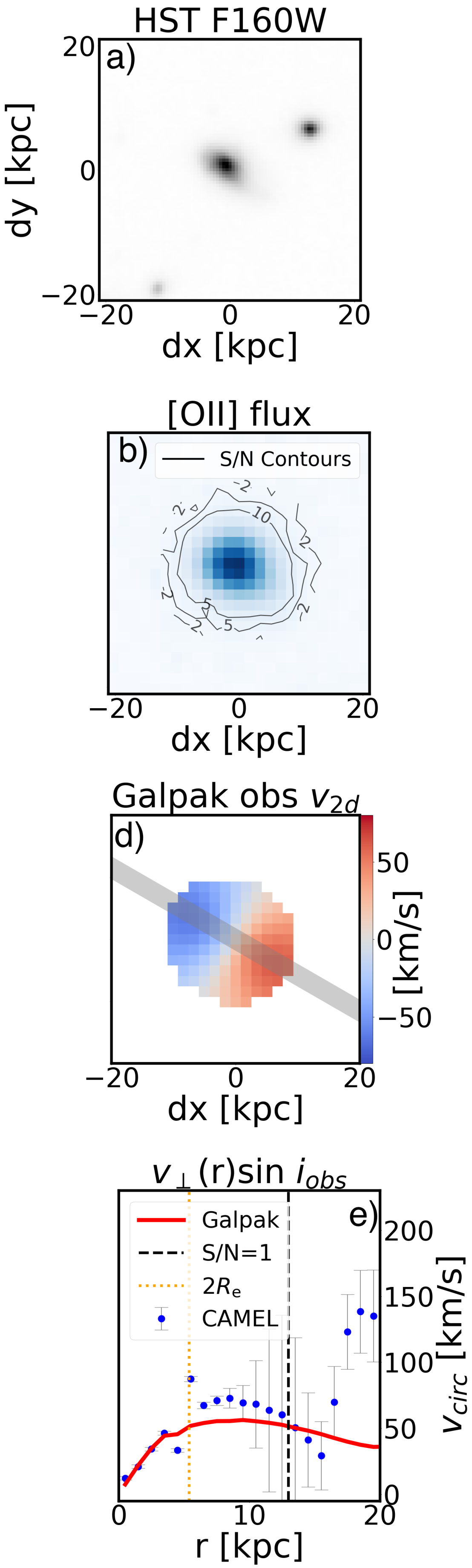


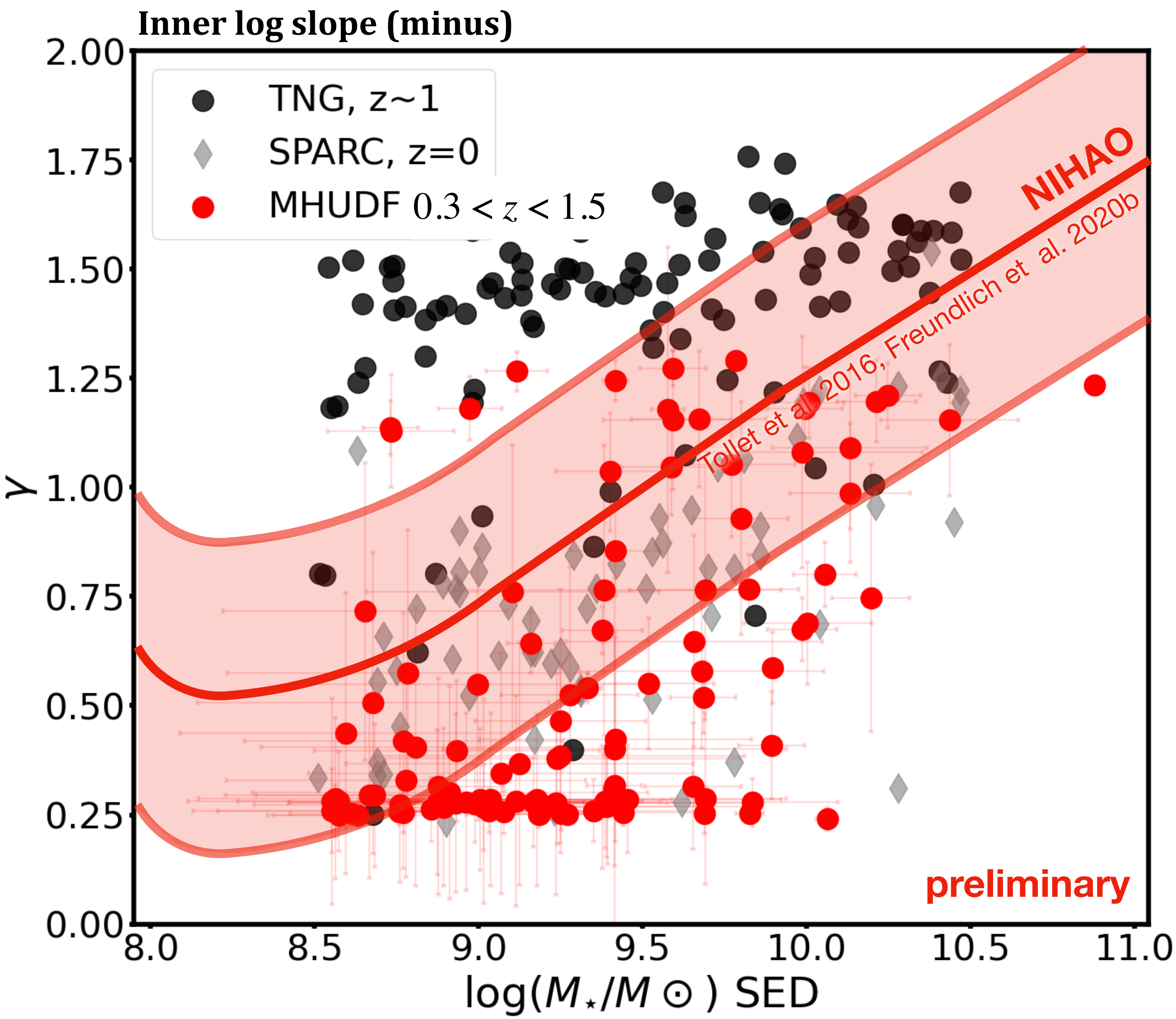




Jiang, Dekel, Freundlich et al. 2019, He, Jiang et al. in prep.

Where do observations lie?





Ciocan, Bouché et al., submitted

Perspectives with SKA

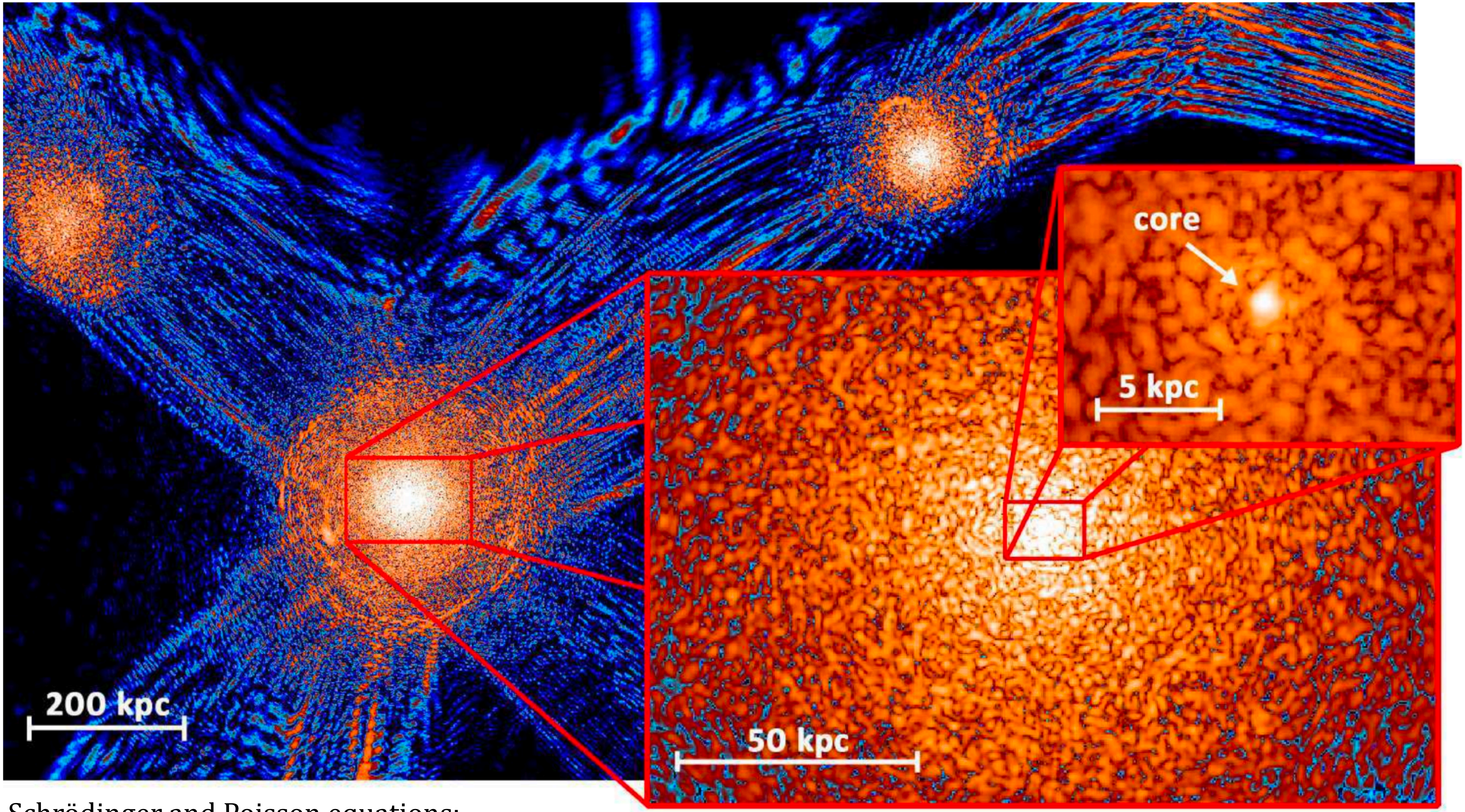
- ➡ **Testing** the different **core formation** models, e.g. focussing on UDGs and their HI gas
- ➡ Observational constraints on **dark matter haloes across cosmic time** through HI rotation curves (in fact probably only until z~1)
- ➡ Indirectly constraining **feedback processes** through the diversity of halo shapes

Annonce :

Grande conférence nationale SKA pilotée par la CSAA à l'intention de l'ensemble de la communauté INSU en mai 2026 à Paris

Alternatives to cold dark matter

A non-standard dark matter candidate: fuzzy dark matter (FDM)



Schrödinger and Poisson equations:

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r},t) = -\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r},t) + m\ \Phi_s(\mathbf{r},t)\psi(\mathbf{r},t)$$

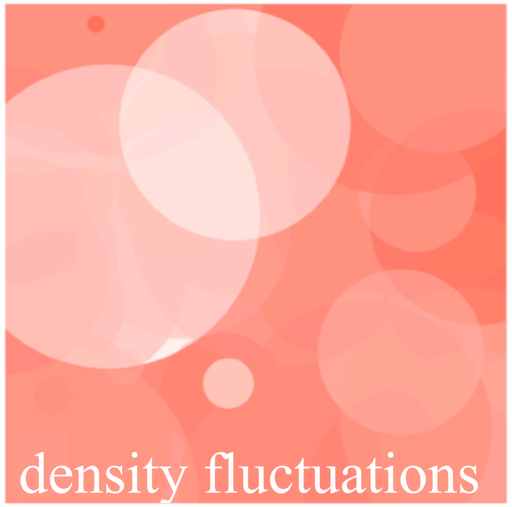
$$\nabla^2\Phi_s(\mathbf{r},t) = 4\pi G\ |\psi(\mathbf{r},t)|^2$$

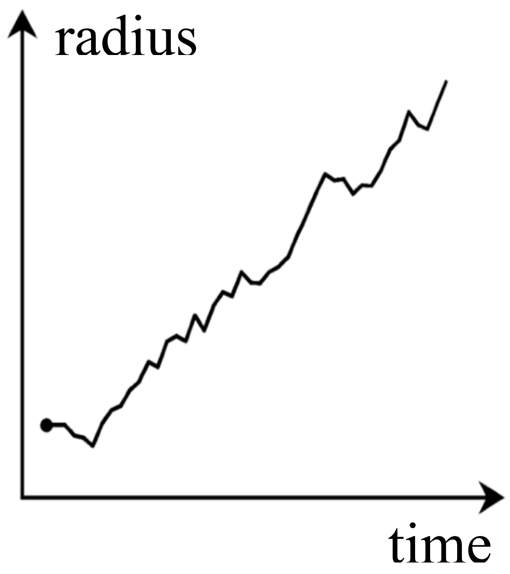
Interferences, granules, core

Schive et al. (2014)

Constraining fuzzy dark matter: dynamical heating

Marsh & Niemeyer 2019: Fuzzy dark matter (FDM) halo density fluctuations should heat up stellar structures, such as the old stellar cluster at the center of Eridanus II dwarf galaxy

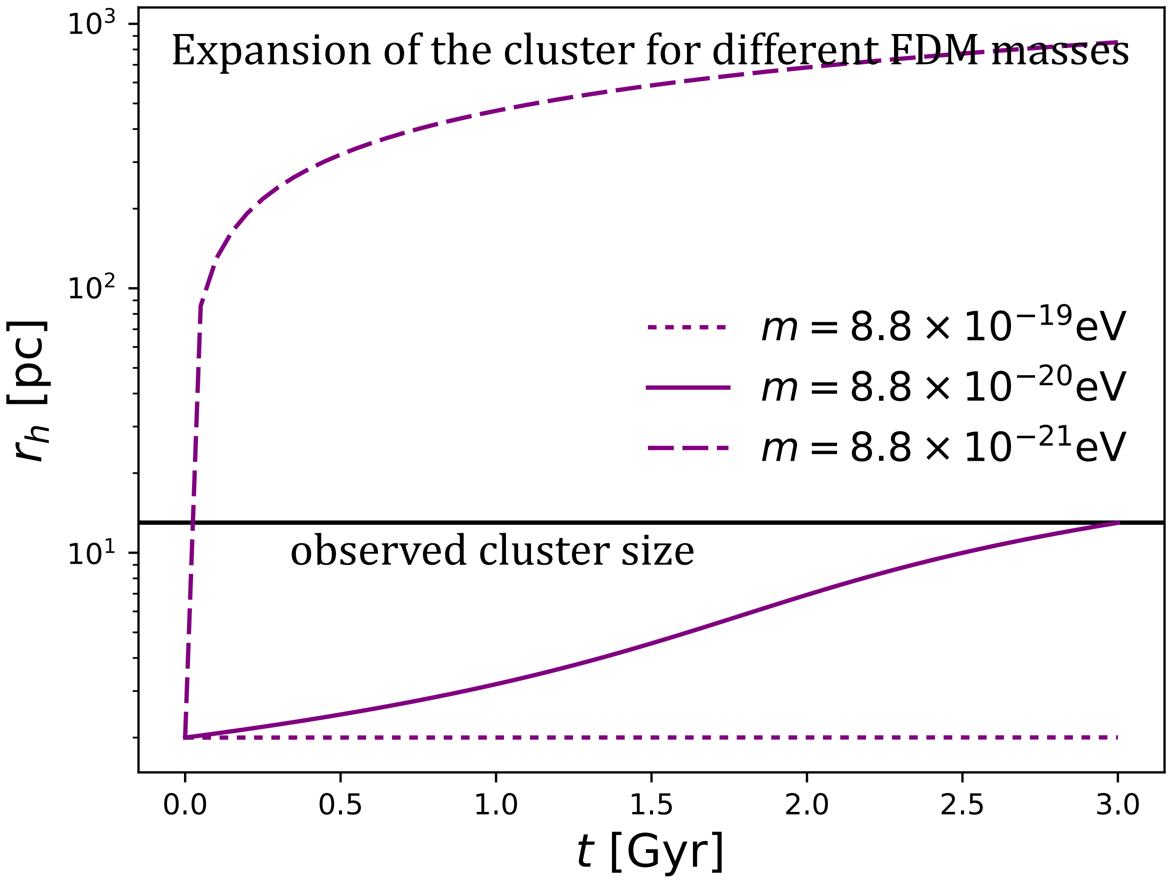


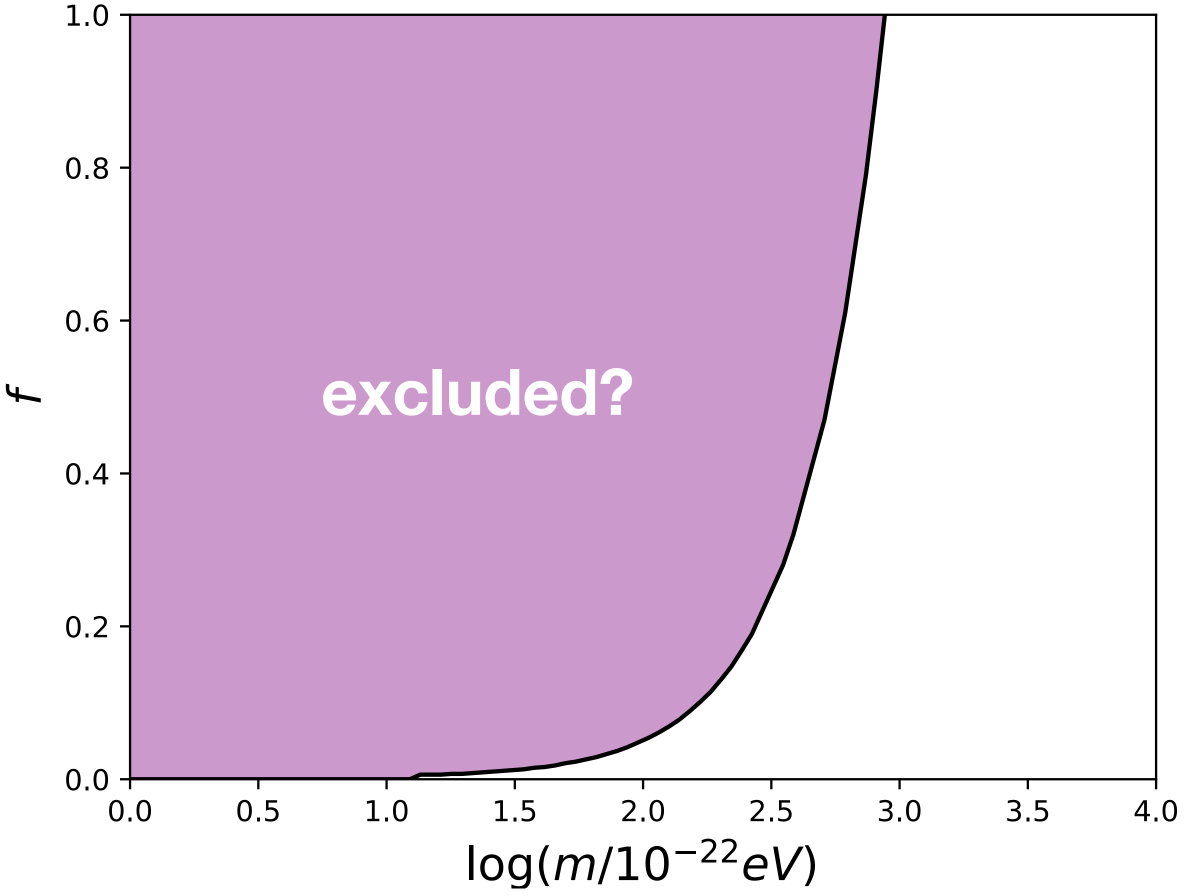


El-Zant, Freundlich, Combes & Hallé (2020): Adapting the formalism of El-Zant, Freundlich & Combes (2016), we derive the effect FDM halo fluctuations on test particles.

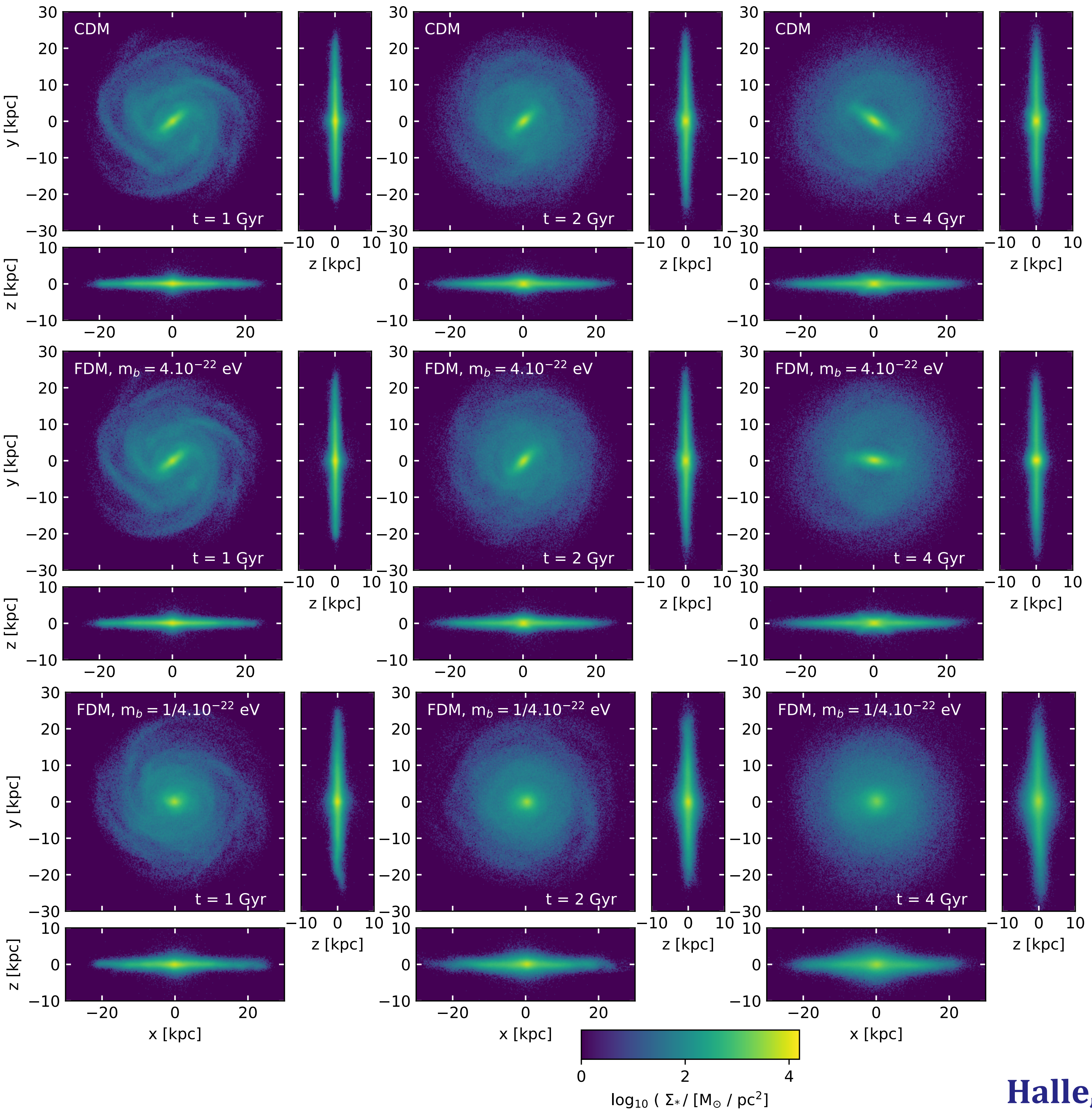
➡ FDM particle mass m>2x10^{-22} eV from the local velocity dispersion in the Milky Way

➡ Stronger constraints can in principle be obtained, but some caveats.





Effect of FDM fluctuations on galactic disks



Isolated disk + halo simulation
- Gadget-2 N-body code
- 80 pc softening length
- Additional force from FDM fluctuations (from El-Zant, Freundlich, et al. 2020)

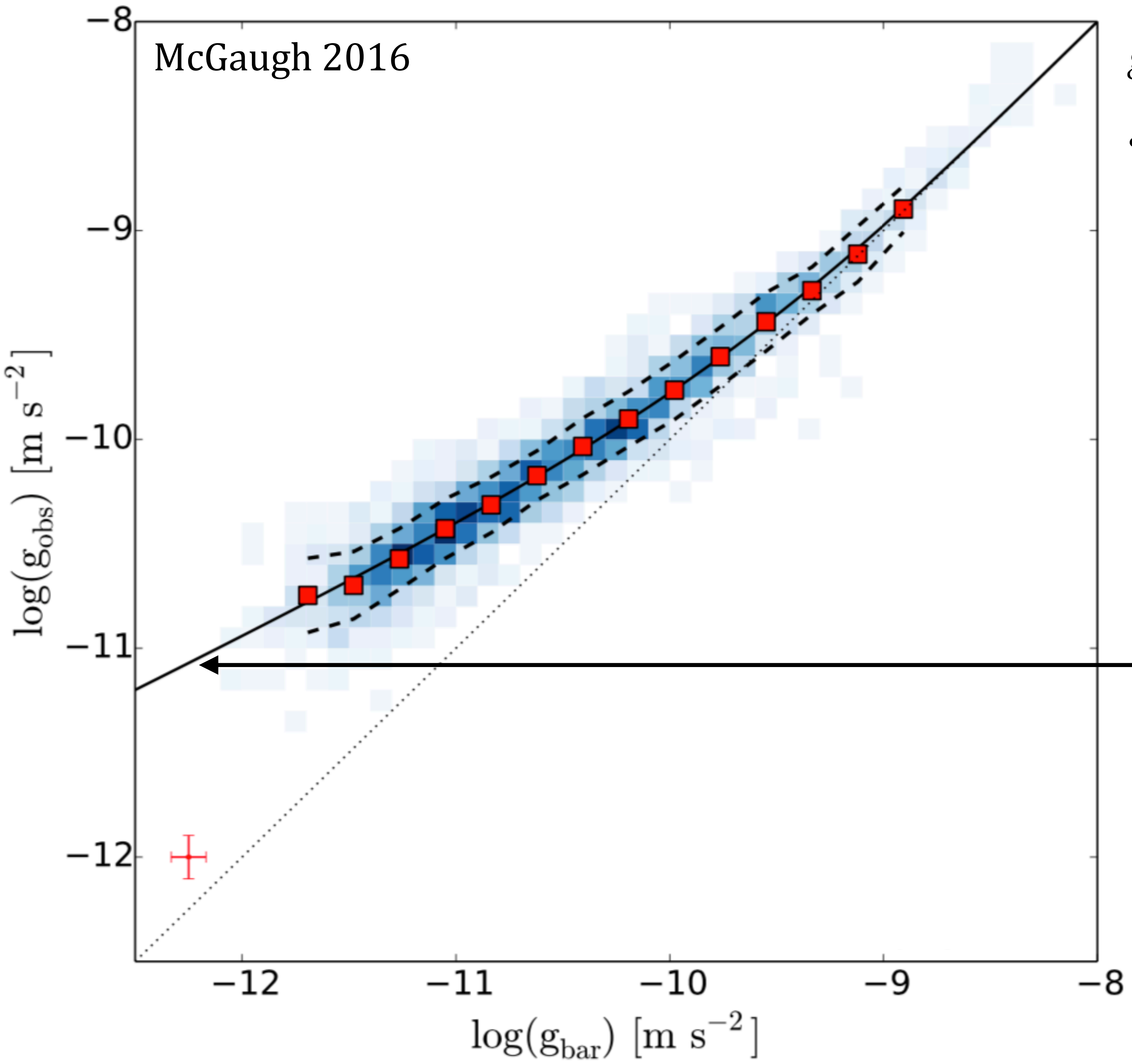
Halle, El-Zant, Freundlich & Combes in prep.

ΛCDM challenges at galaxy scales

No tension	Uncertain	Weak tension	Strong tension
Missing satellites	$M_{\star}$-$M_{\rm halo}$ relation	Too big to fail	Diversity of rotation curves
	Core-cusp	Diversity of dwarf sizes	Satellite planes
	Correlations between dynamics and baryons (baryonic Tully Fisher, radial acceleration relation, "Renzo's rule")	Quiescent fractions	
	Bar, gas, and disk fractions in cosmological simulations		

Sales, Wetzel & Fattahi (2022)

The radial acceleration relation (RAR)



g_{obs} from the observed velocity

g_{bar} from the baryonic mass distribution

$$g_{\text{obs}} = \frac{g_{\text{bar}}}{1 - e^{-\sqrt{g_{\text{bar}}/a_0}}}$$

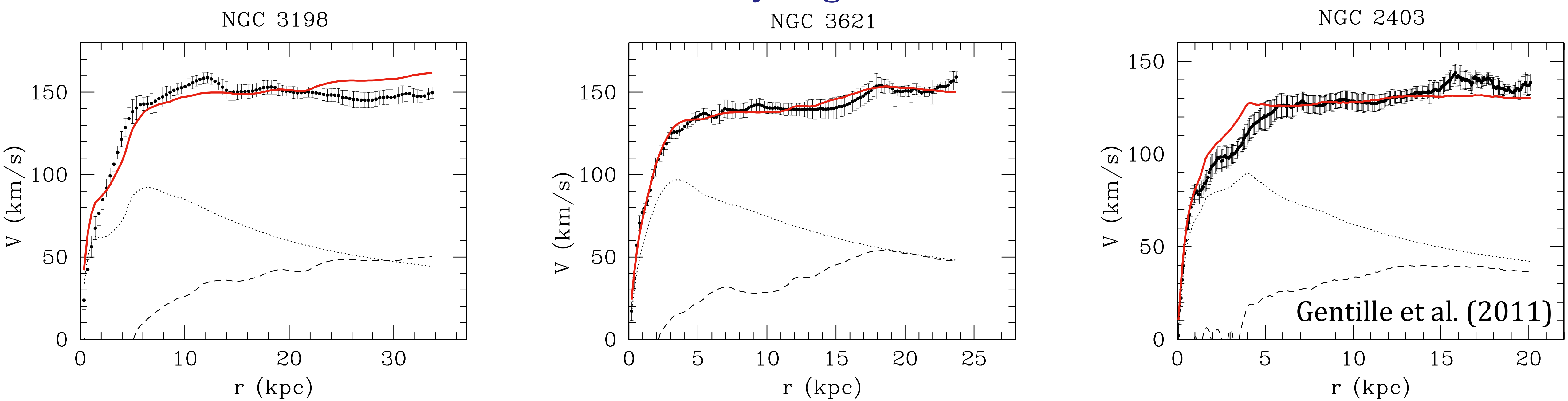
$$a_0 = 1.2 \times 10^{-10}\ \text{m s}^{-2}$$

- Particularly small scatter
- The dark matter distribution seems to be fully specified by the baryons

Modified Newtonian Dynamics (MOND)

Milgrom (1983): $\begin{cases} g = g_N & \text{when } g \gg a_0 \\ g = \sqrt{g_N a_0} & \text{when } g \ll a_0 \end{cases}$ $\quad a_0 \approx 10^{-10}\ \mathrm{m\ s^{-2}}$

➡ Predicts the rotation curve of a wide variety of galaxies

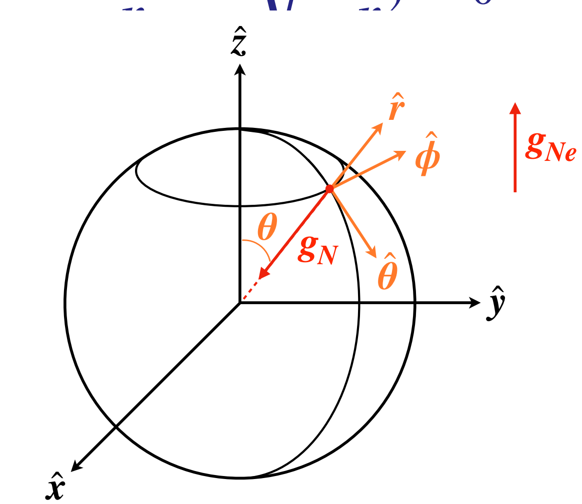


➡ The weak acceleration regime lead to the baryonic Tully Fisher relation: $\frac{V^2}{r} = \sqrt{\frac{GM}{r^2} a_0}$

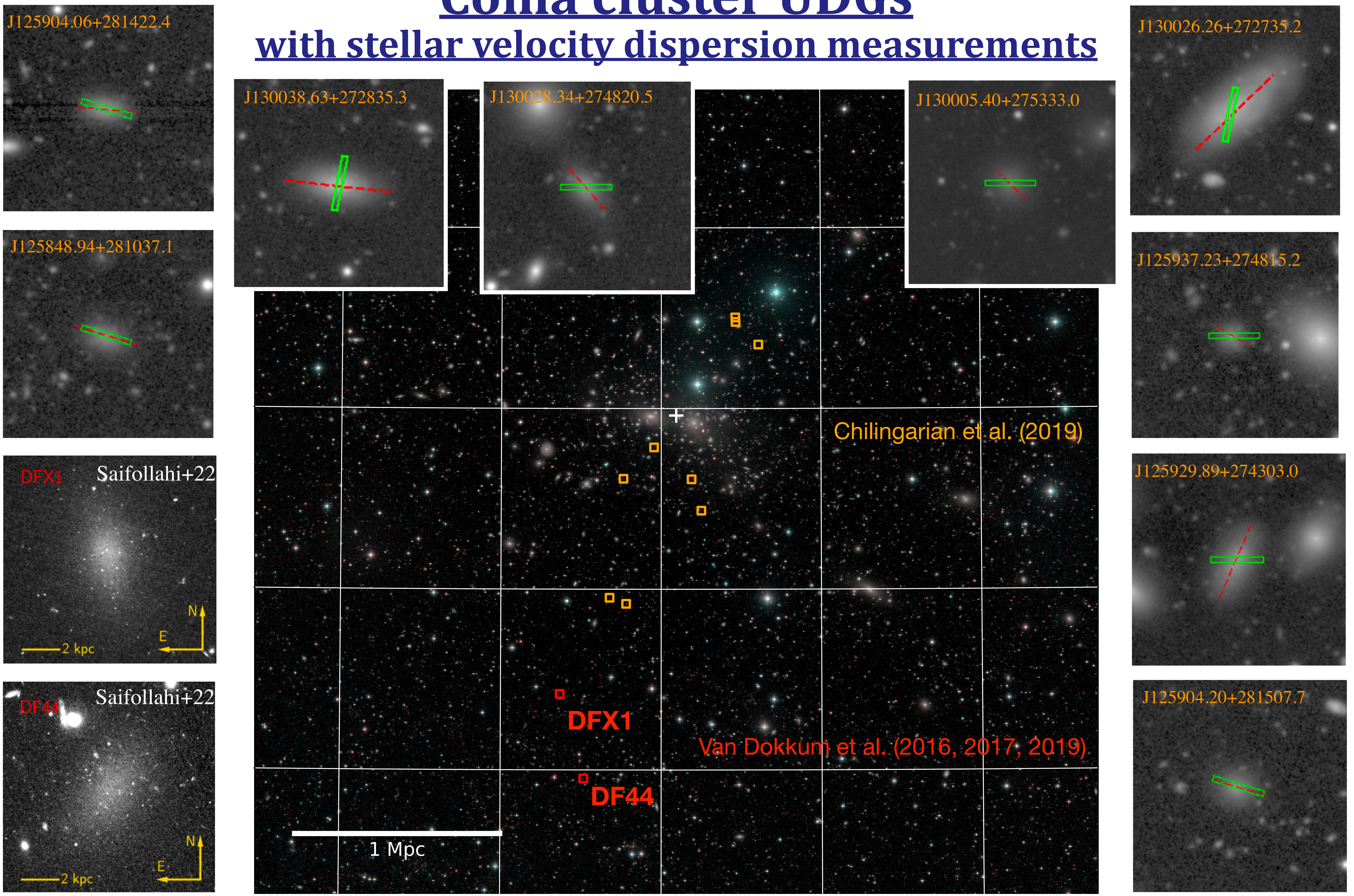
➡ The RAR is a consequence of the modified gravity

➡ But **External Field Effect (EFE)**: internal dynamics of a self-gravitating system in a constant external field *depend on the external field* (violation of the strong equivalence principle)

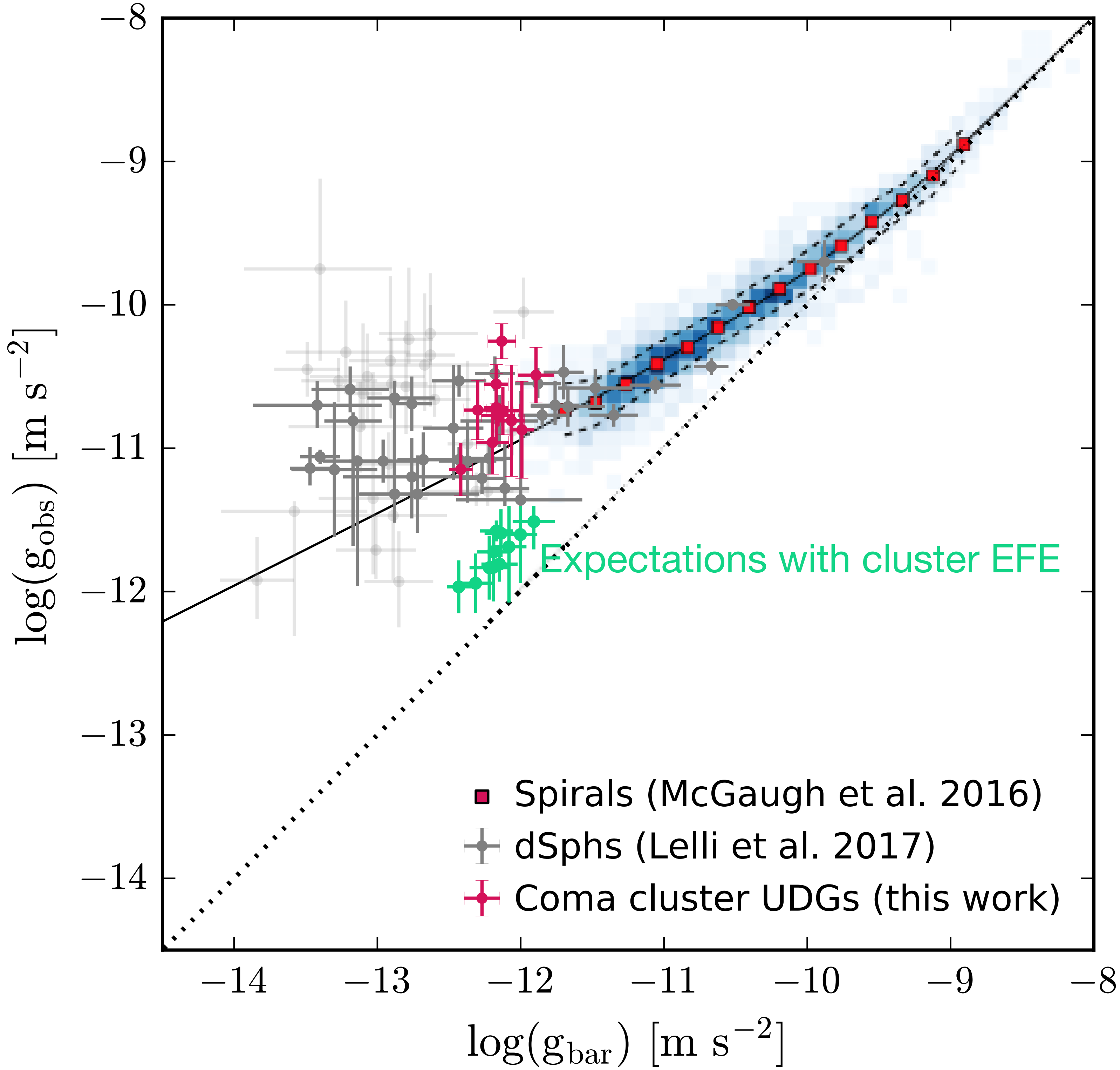
Consequence: galaxies in clusters should have lower velocity dispersion than in isolation



Coma cluster UDGs
with stellar velocity dispersion measurements



RAR in tension with MOND expectations with EFE



$$g_{obs} = \frac{9}{4}\frac{\sigma_{eff}^2}{R_e}$$

(cf. Wolf et al. 2010)

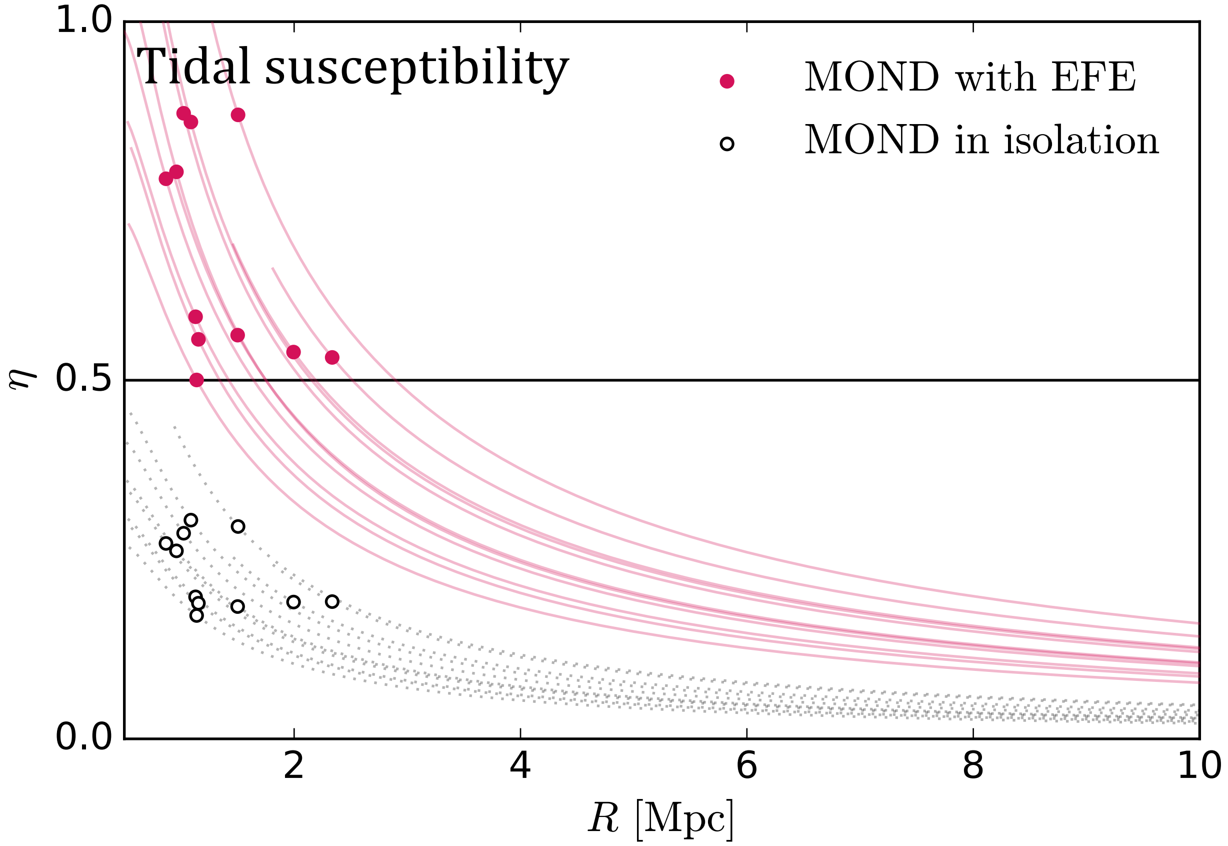
$$g_{bar} = \frac{GM(r_{1/2})}{r_{1/2}^2}$$

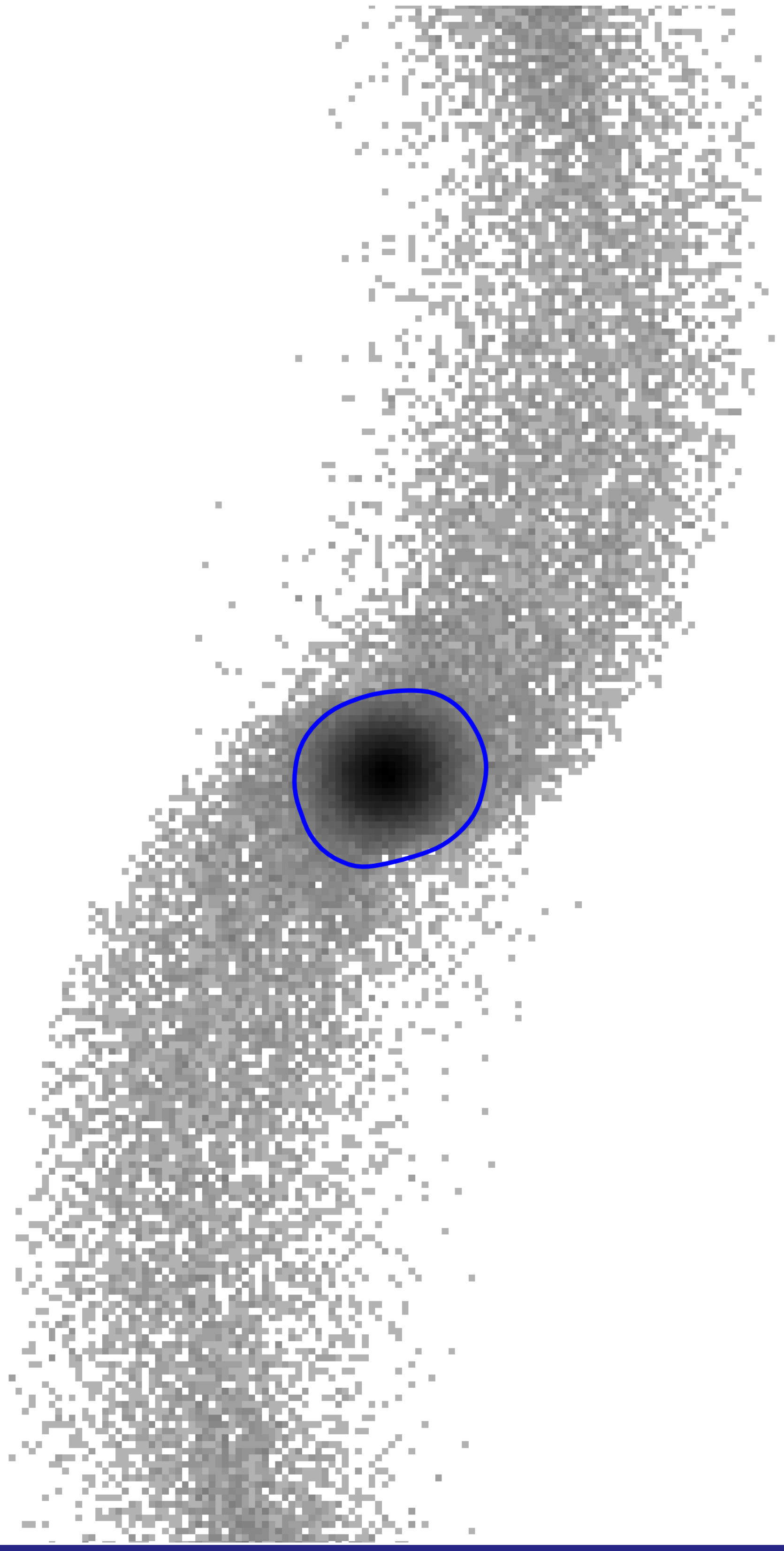
$r_{1/2} \approx (4/3)R_e$
$M(r)$ deprojected Sersic
(Lima Neto et al. 1999)

Freundlich, Famaey et al. 2022

UDGs tidally heated or on their first infall (survivor bias)?

UDGs could be tidally disrupted or tidally heated (elongated morphologies, tidal susceptibility)





Nagesh, Freundlich, Famaey et al. 2024:

✦ Tides not sufficient to increase the velocity dispersion

✦ Recent infall onto the cluster possible but constrained

UDG N-body simulations
- Phantom of RAMSES (QUMOND, Lüghausen et al. 2015, Nagesh et al. 2021)
- Analytic cluster potential
- Resolution 600 Msun, 10^5 particles per UDG

Possible explanations

- ➡ Recent infall (survivor bias)
- ➡ Tidal interactions
- ➡ Higher M/L ratios
- ➡ Cluster baryonic dark matter
- ➡ Modified inertia
- ➡ MOND as a dark matter scaling relation

but why does isolated MOND work so well?

- ➡ **EMOND $A_0(\varphi)$**
- ➡ **Screening the EFE in clusters in theories with additional degrees of freedom?**
  - ↳The tension with the EFE in clusters could guide further theoretical development

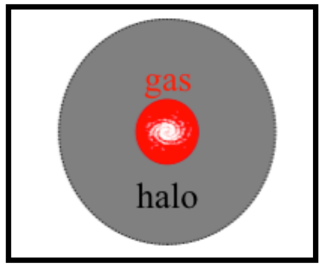
Conclusion

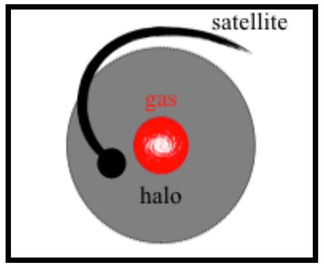
Conclusion

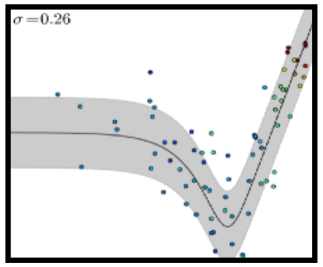
Modeling core formation from feedback processes

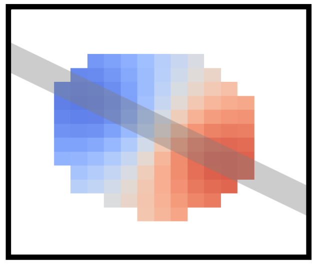
- A new mass-dependent **dark matter halo profile**
- Three **core formation models**: from stochastic density fluctuations, from bulk outflows, from dynamical friction + outflows

Perspectives:
➡ **Testing** the different models in simulations and observations (e.g. **UDGs**)
➡ Observational constraints on **dark matter haloes across cosmic time**
➡ Constraining **feedback processes** through the diversity of halo shapes



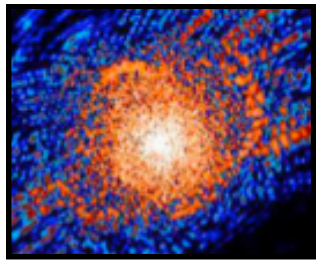
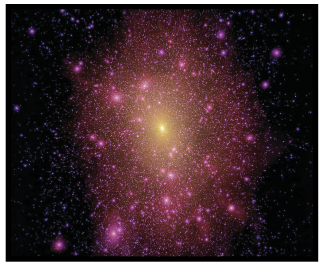
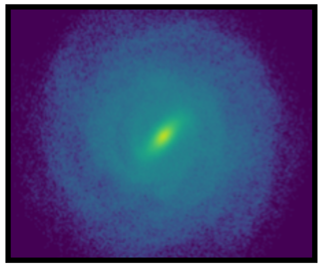
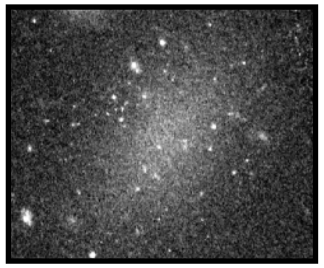
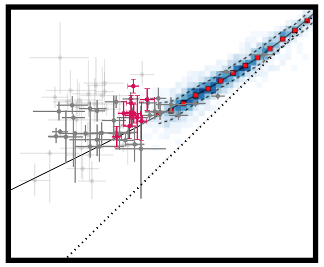
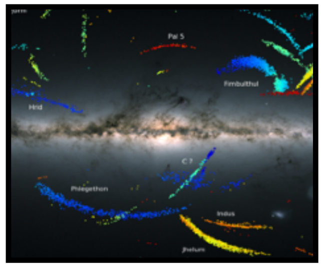





Alternatives to cold dark matter

- Describing the effect of **fuzzy dark matter halo fluctuations** on test particles
- Testing **MOND and the external field effect** in cluster UDGs

Perspectives:
➡ **Testing fuzzy dark matter** (e.g. stellar streams, Milky Way disk)
➡ More constraints on **MOND at galaxy scales** (Milky Way substructures and satellites, other cluster UDGs, rotation curves)
➡ Other cosmologies?

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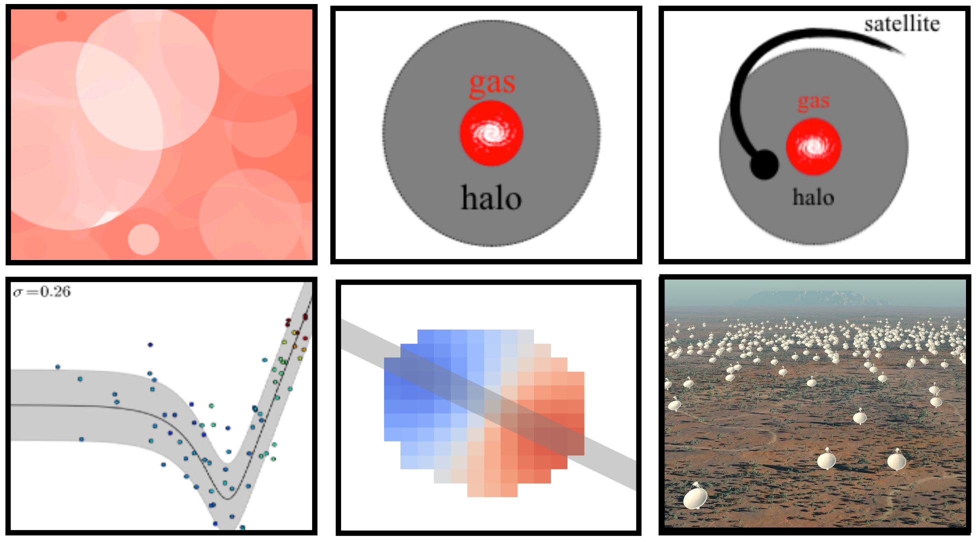

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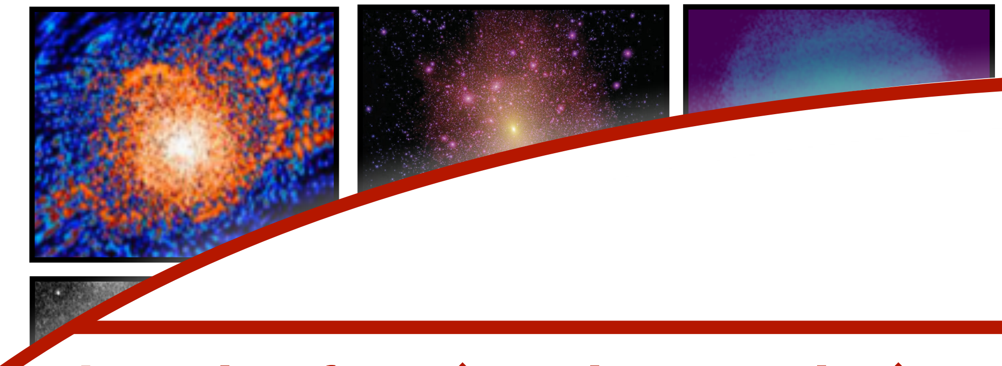
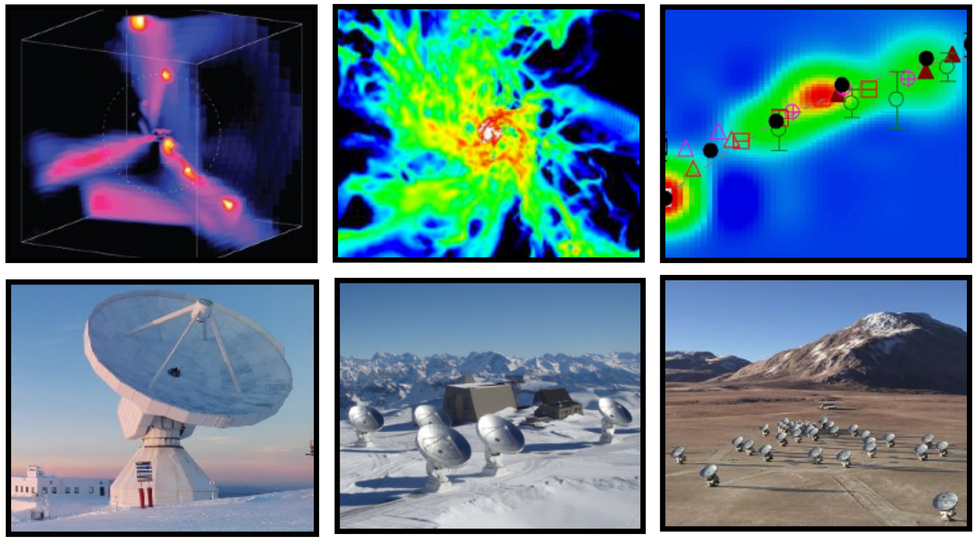


The role of gas in galaxy evolution



thank you!