Observatoire astronomique de Strasbourg | ObAS

Dynamical studies of dark matter

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

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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
		Quiescent fractions	

Sales, Wetzel & Fattahi (2022)

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The cusp-core discrepancy

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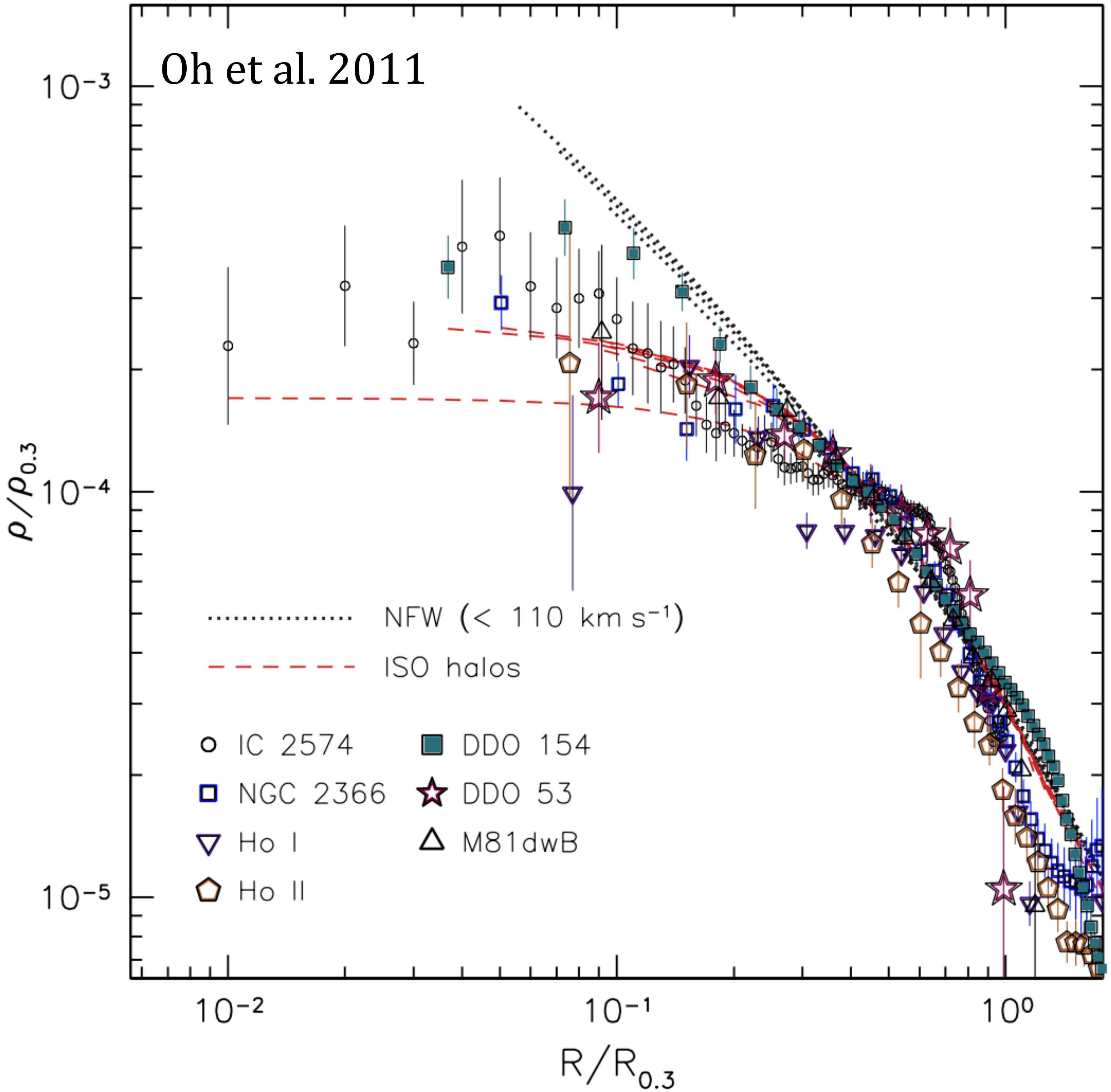

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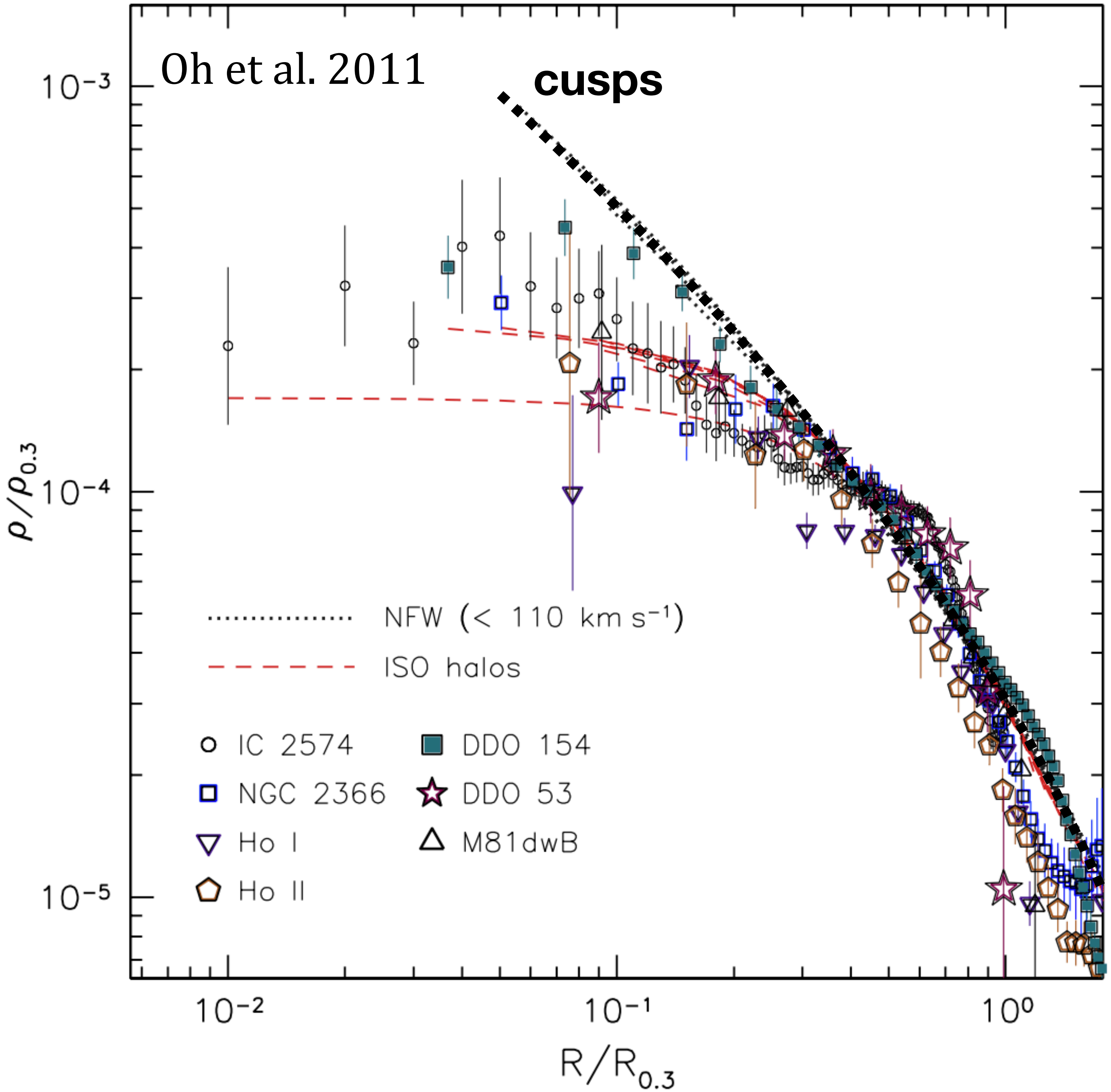

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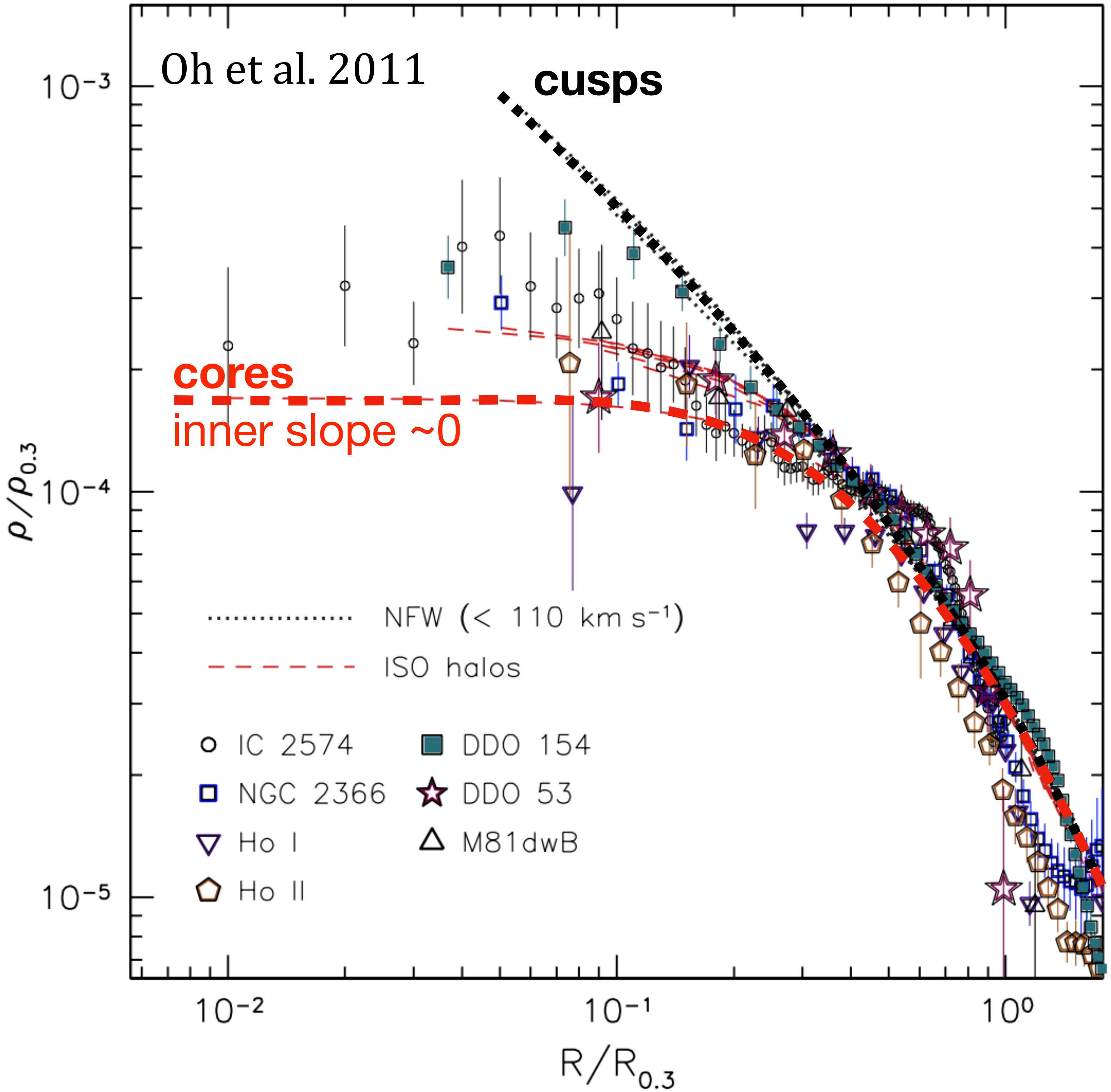

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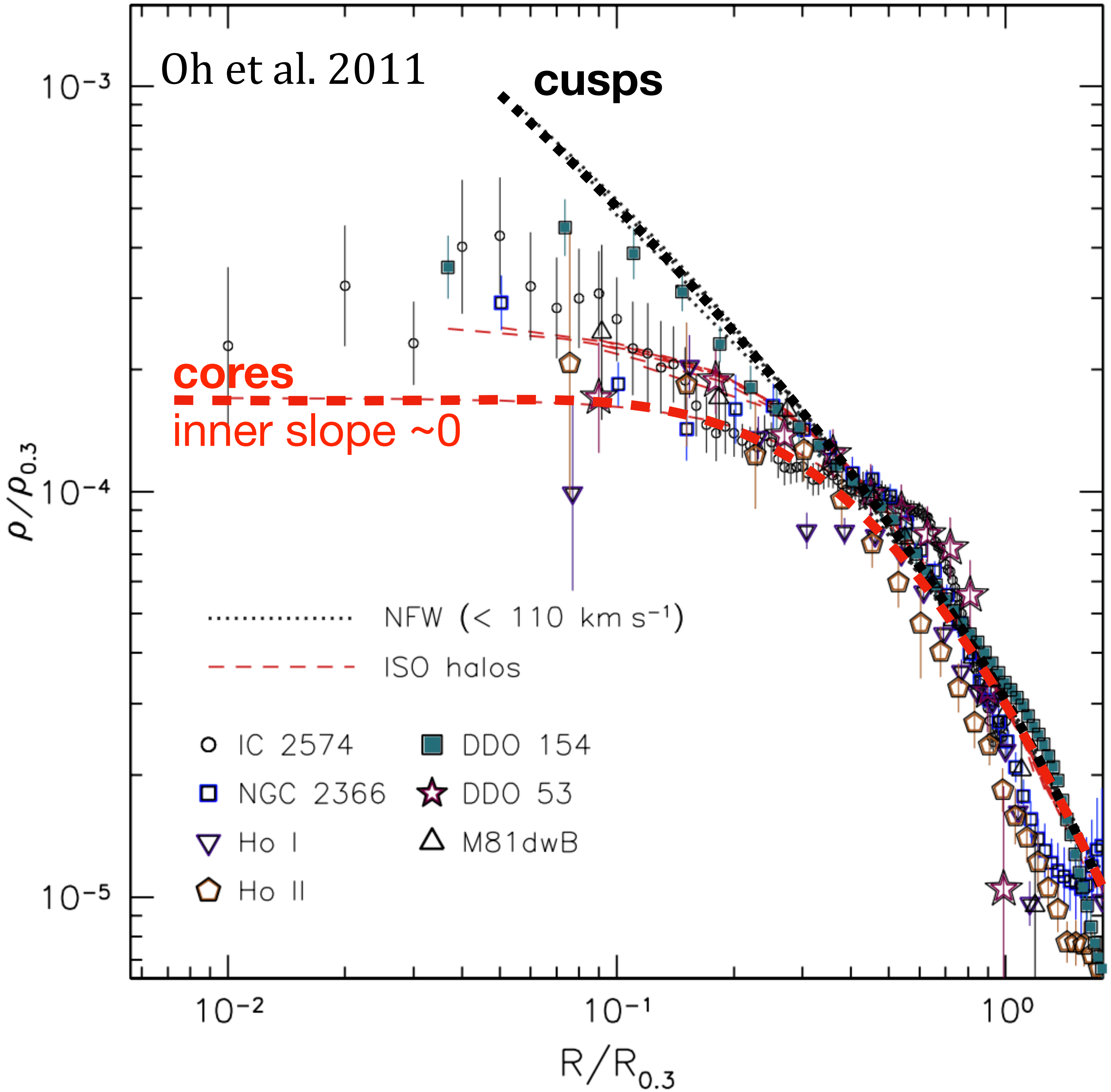

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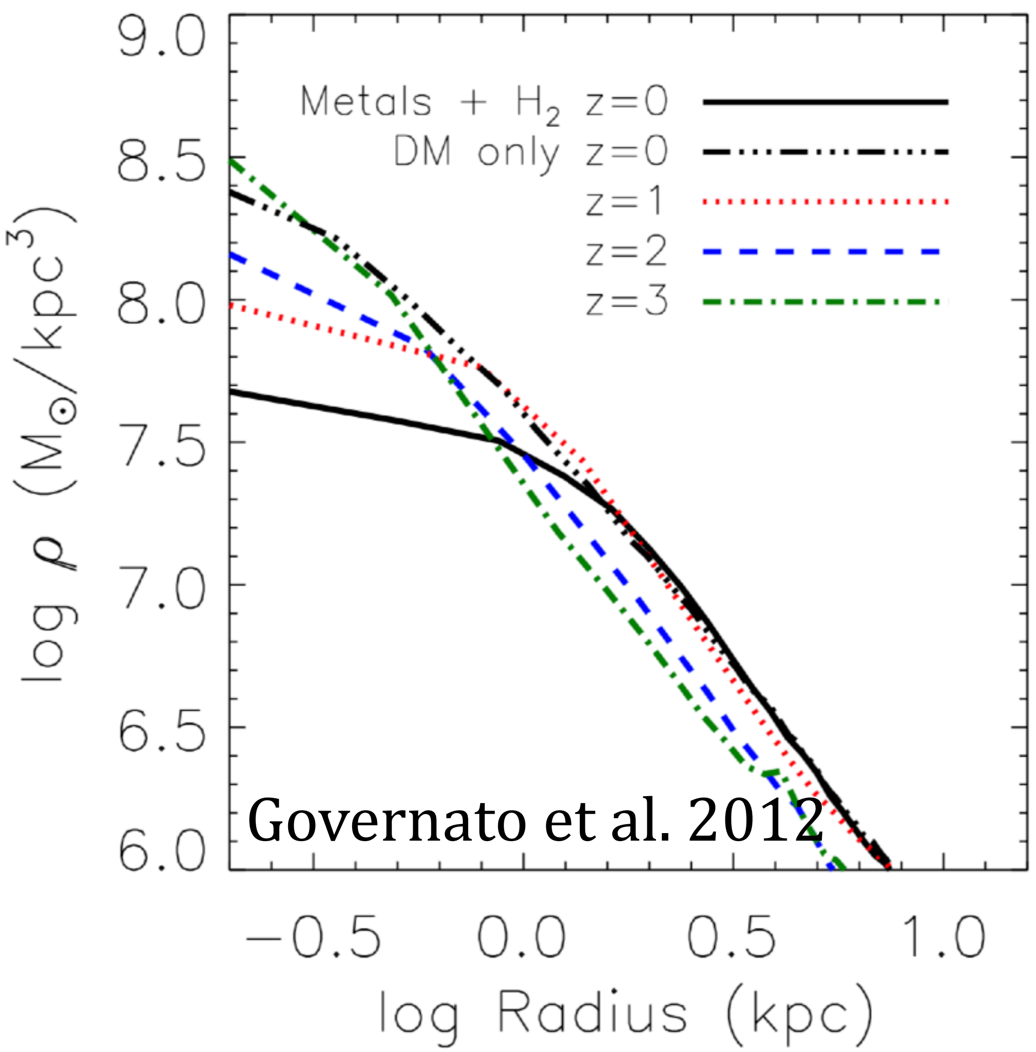

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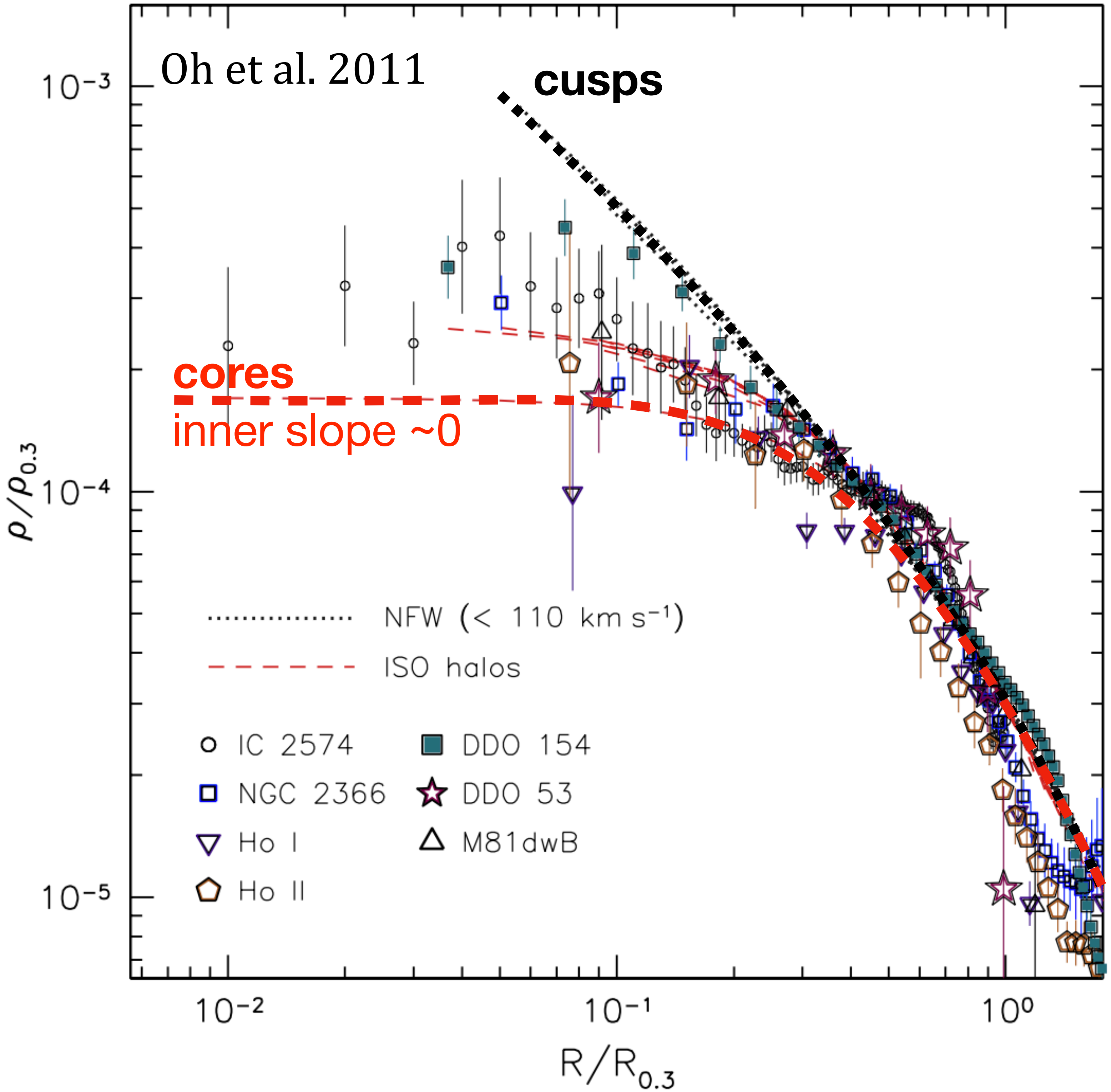

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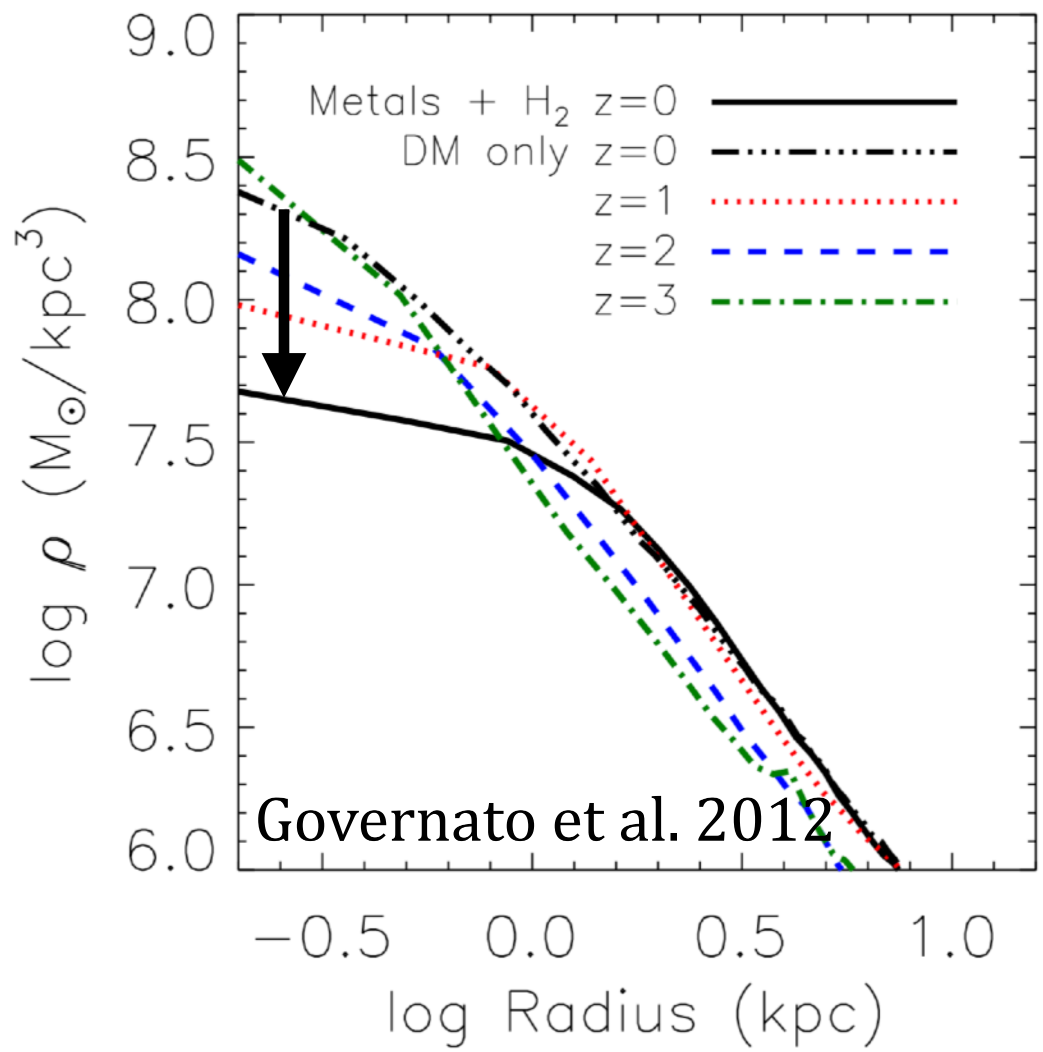

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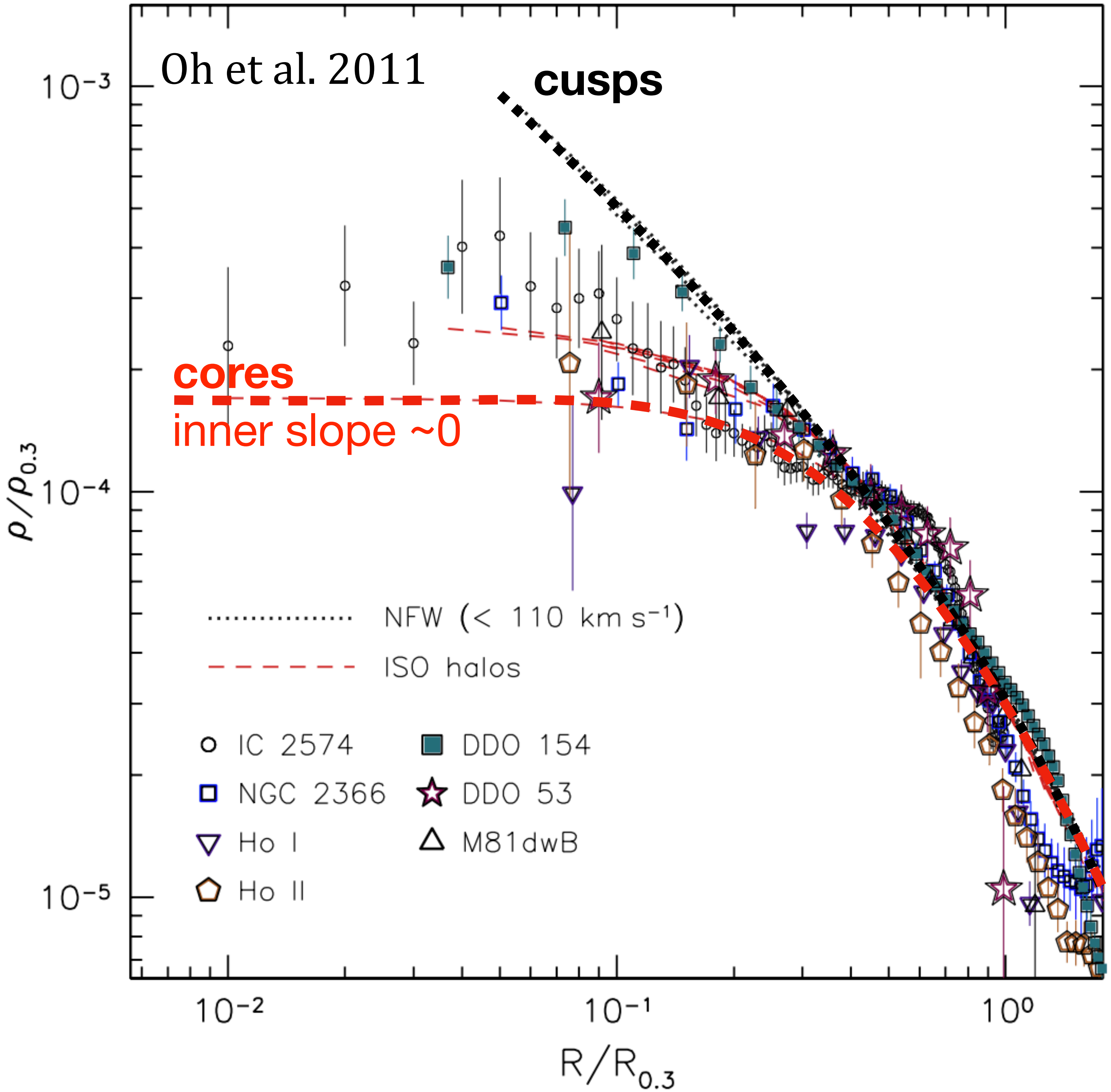

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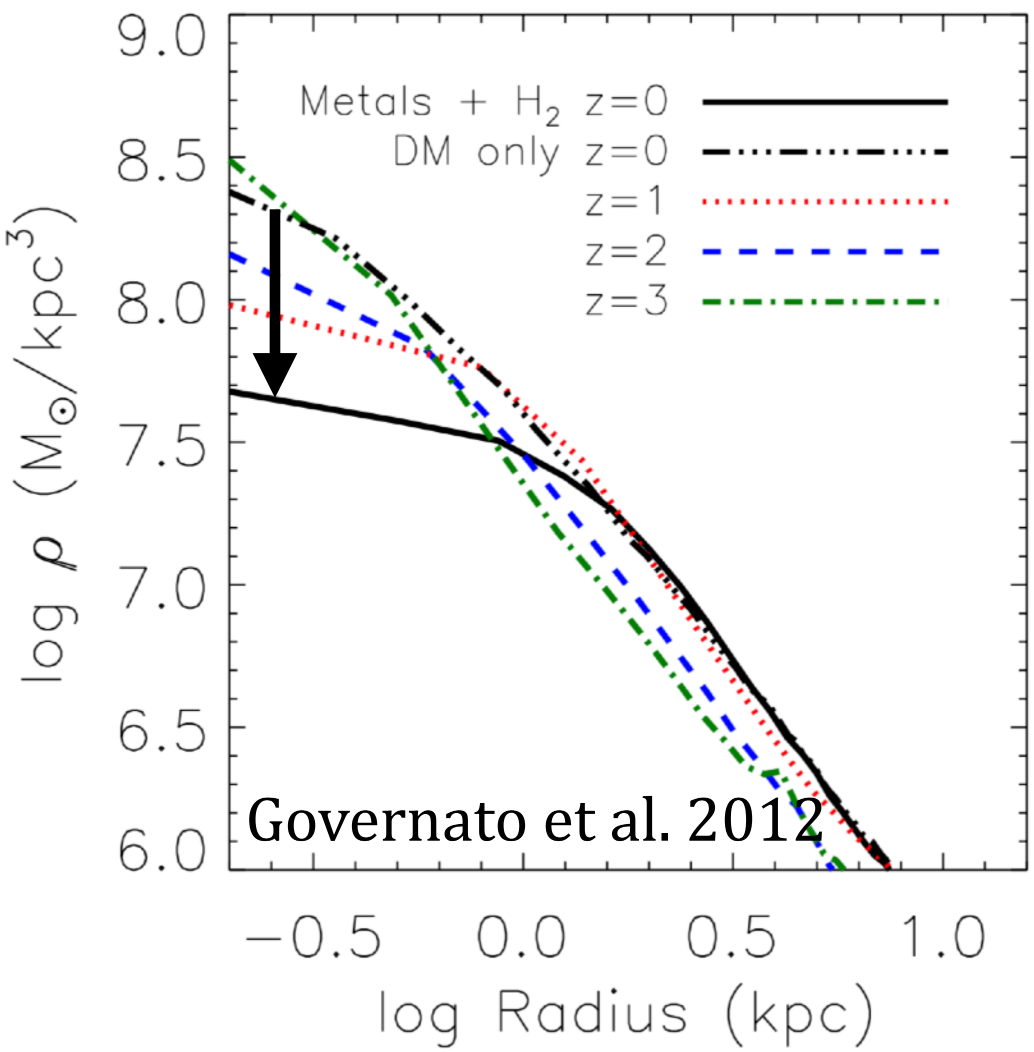

➡ **Baryonic processes (i.e. feedback) within ΛCDM?**

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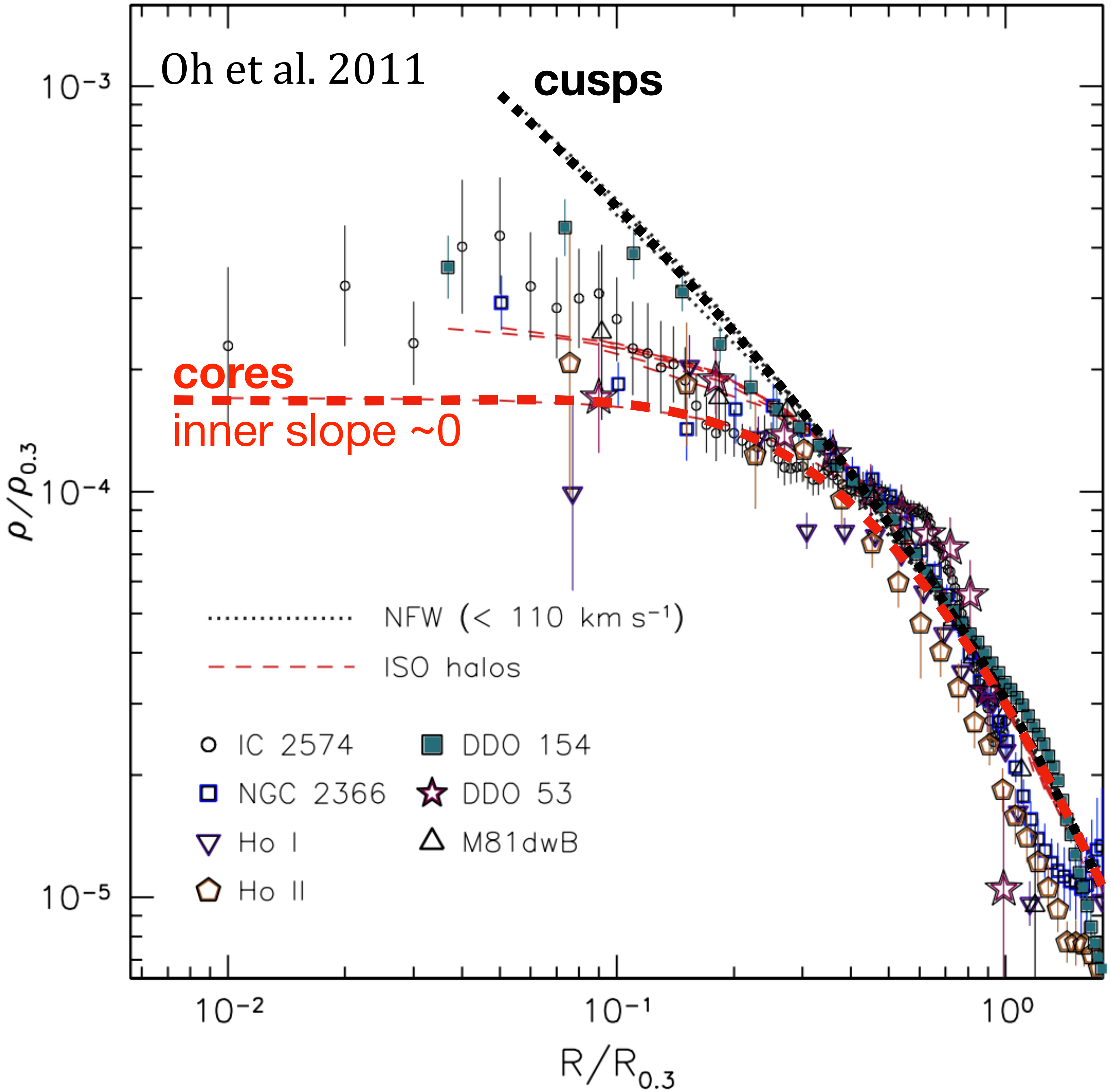

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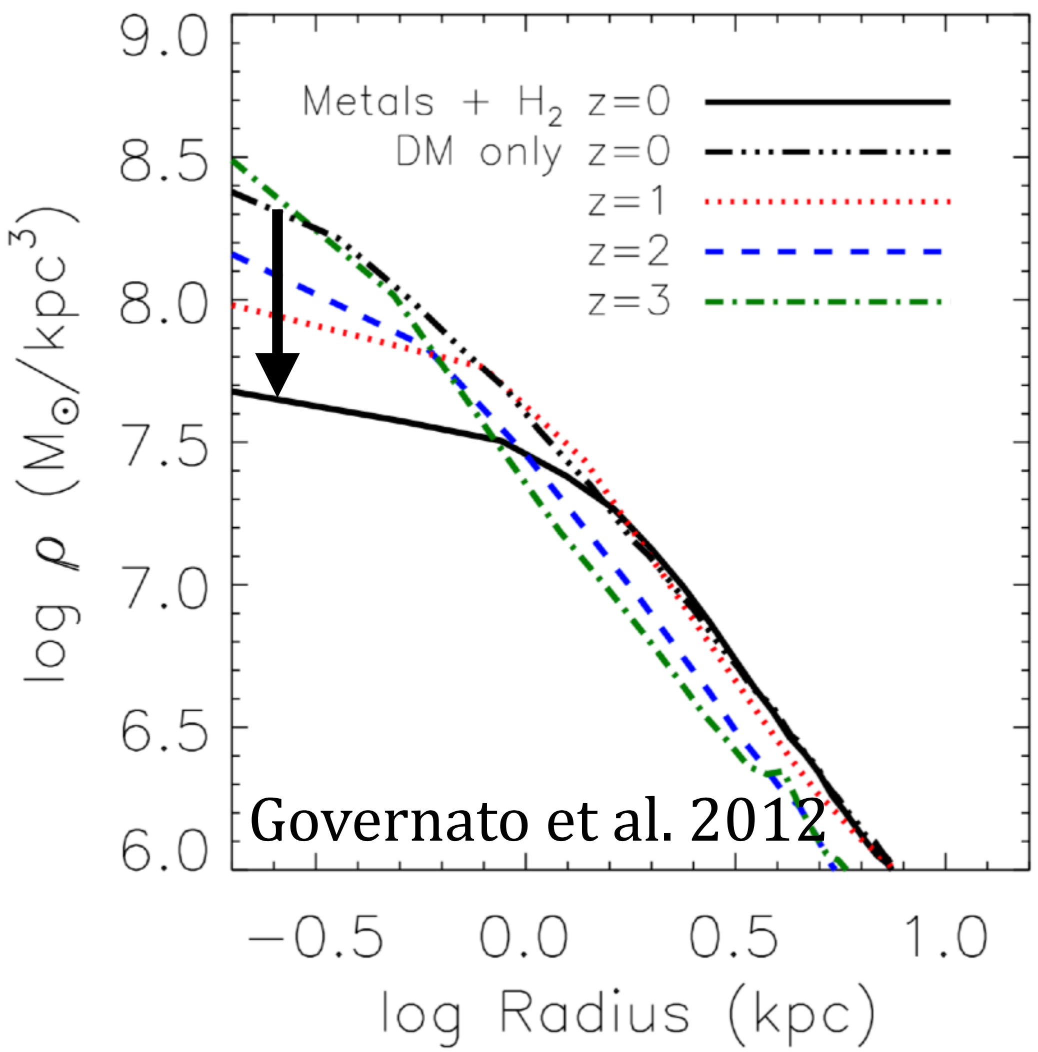
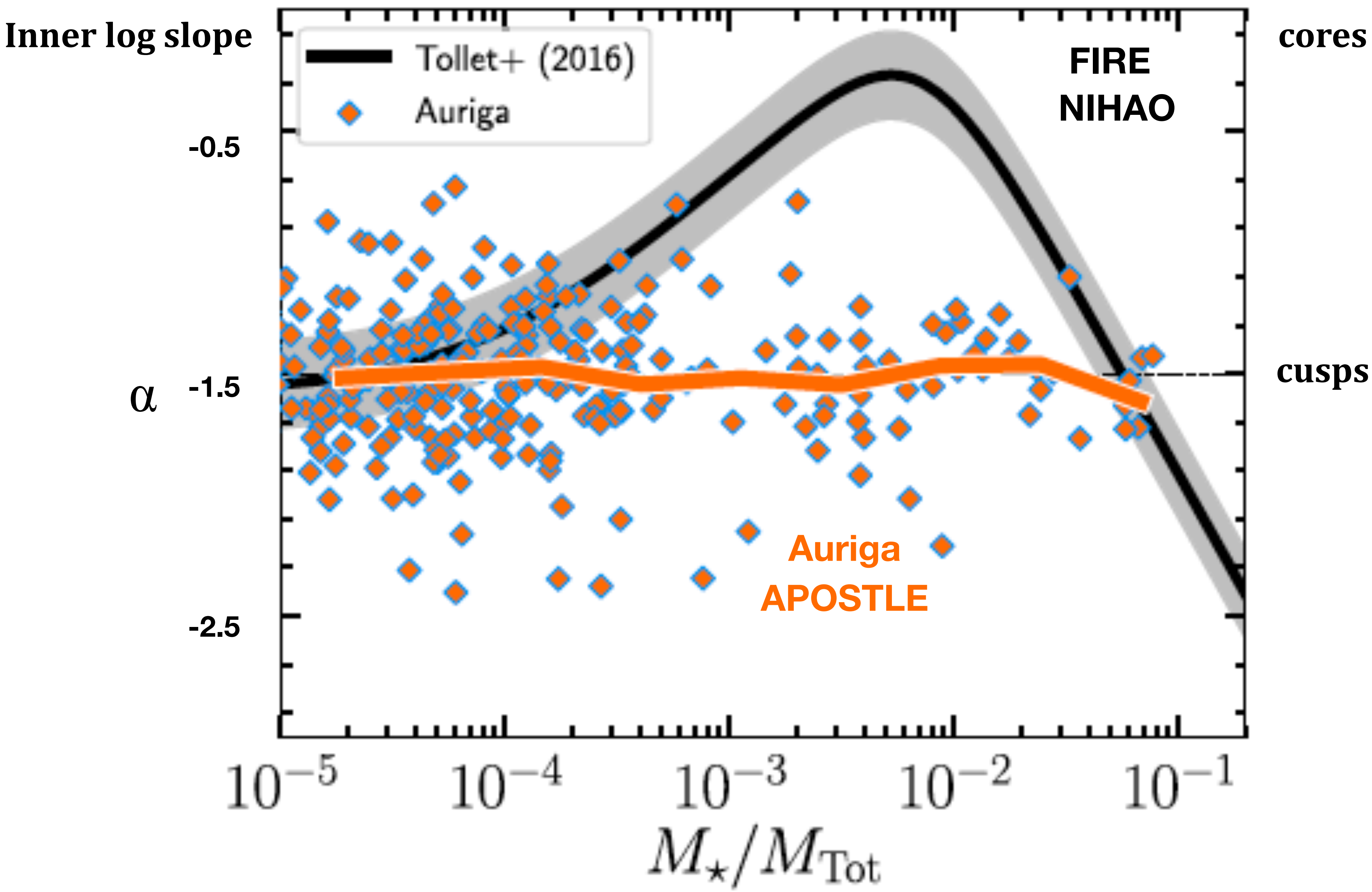


➡ **Baryonic processes (i.e. feedback) within ΛCDM?**

➡ **Alternative cosmological models?**

Different predictions for the halo response

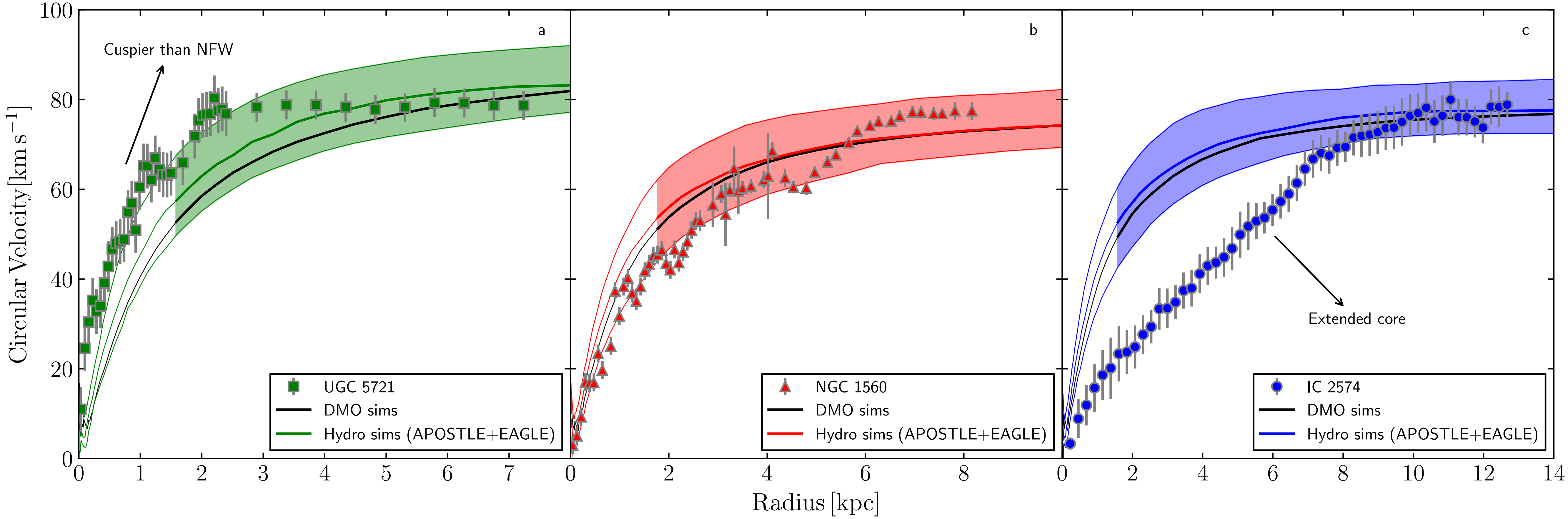
A simulation issue: different simulation suites predict different halo responses.



Bose et al. 2019

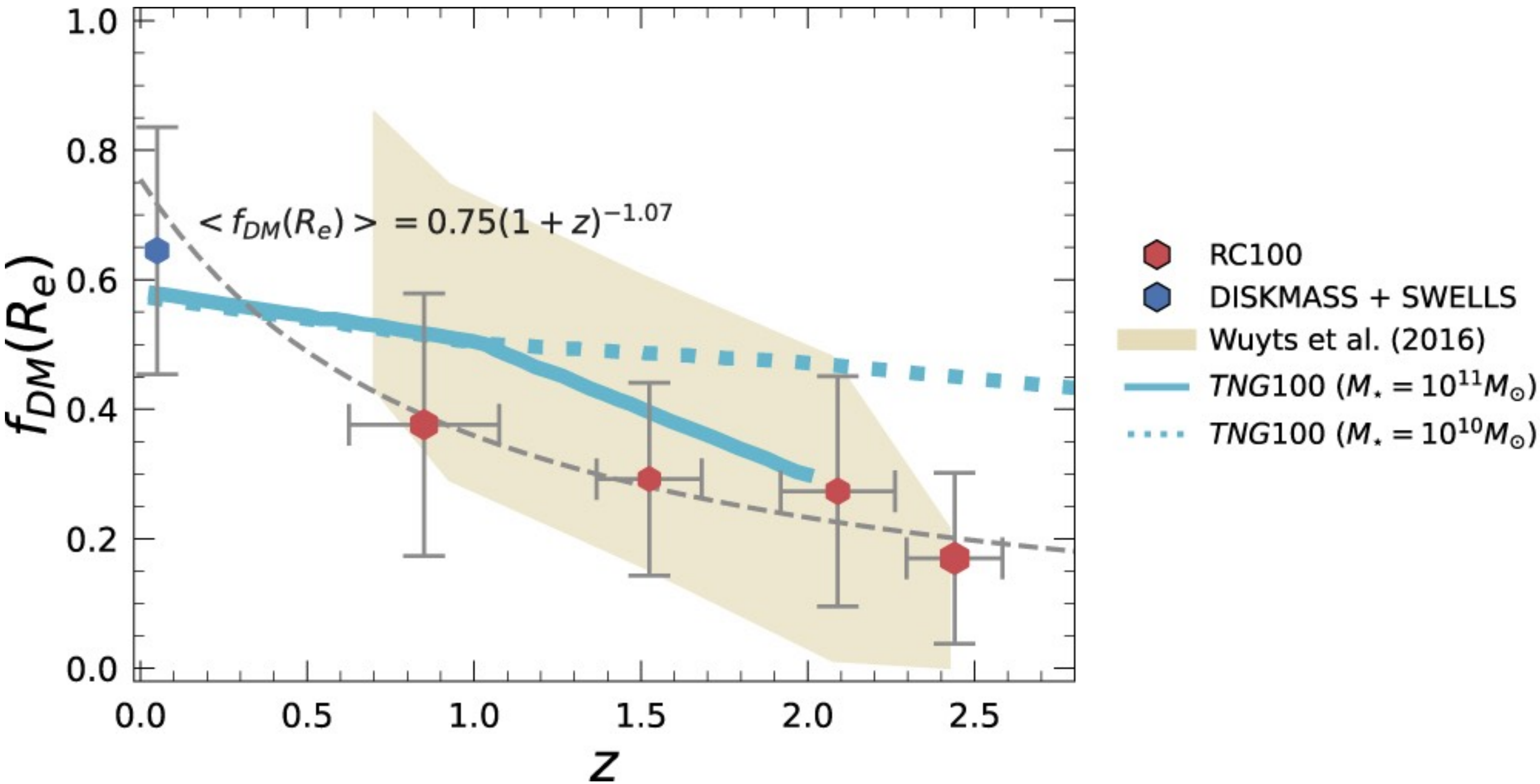
The diversity of rotation curves

An observational issue: dwarf galaxies with similar outer rotation velocity but distinct inner behavior.



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

Dark matter deficient galaxies in the early Universe?



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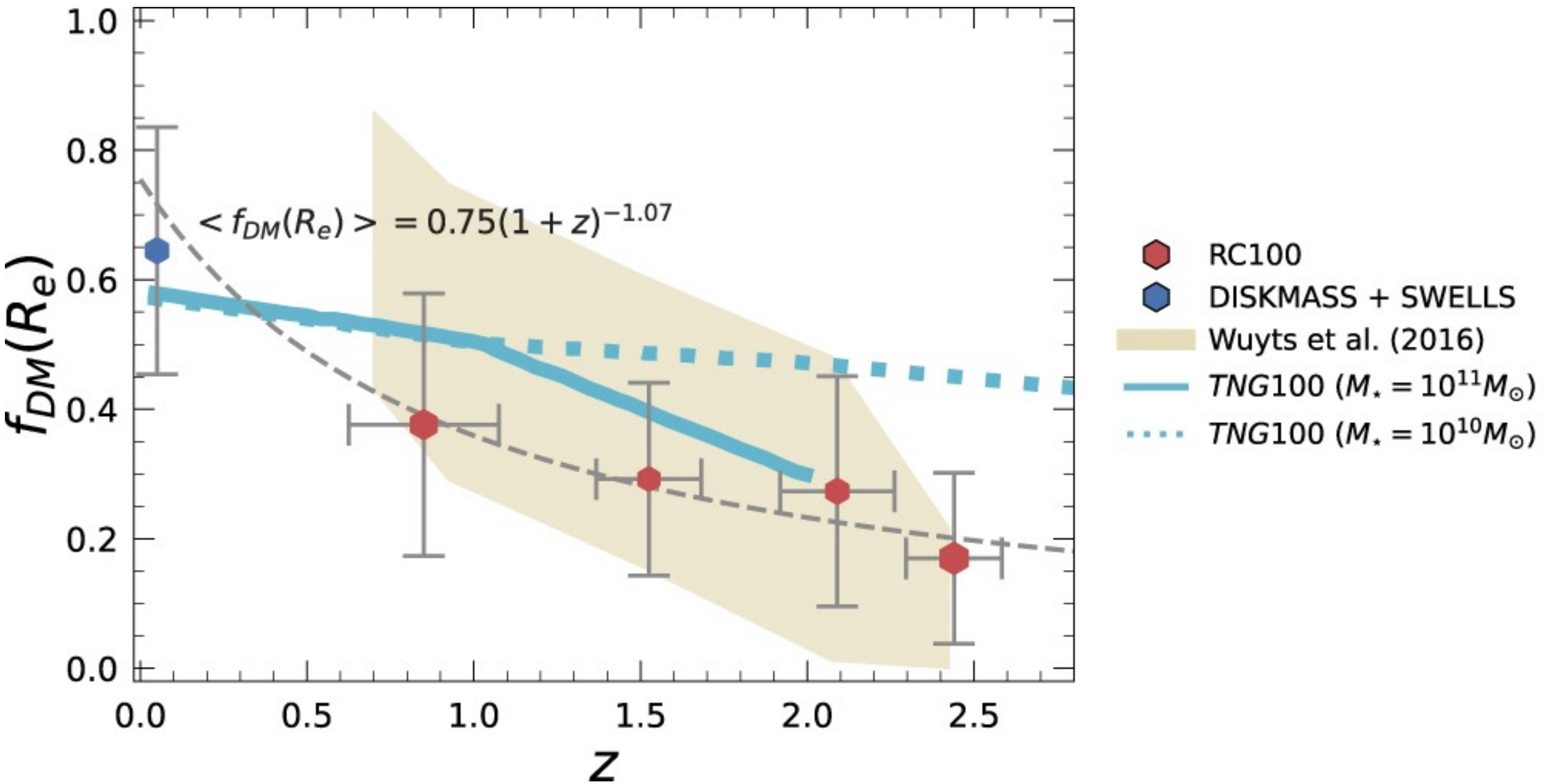

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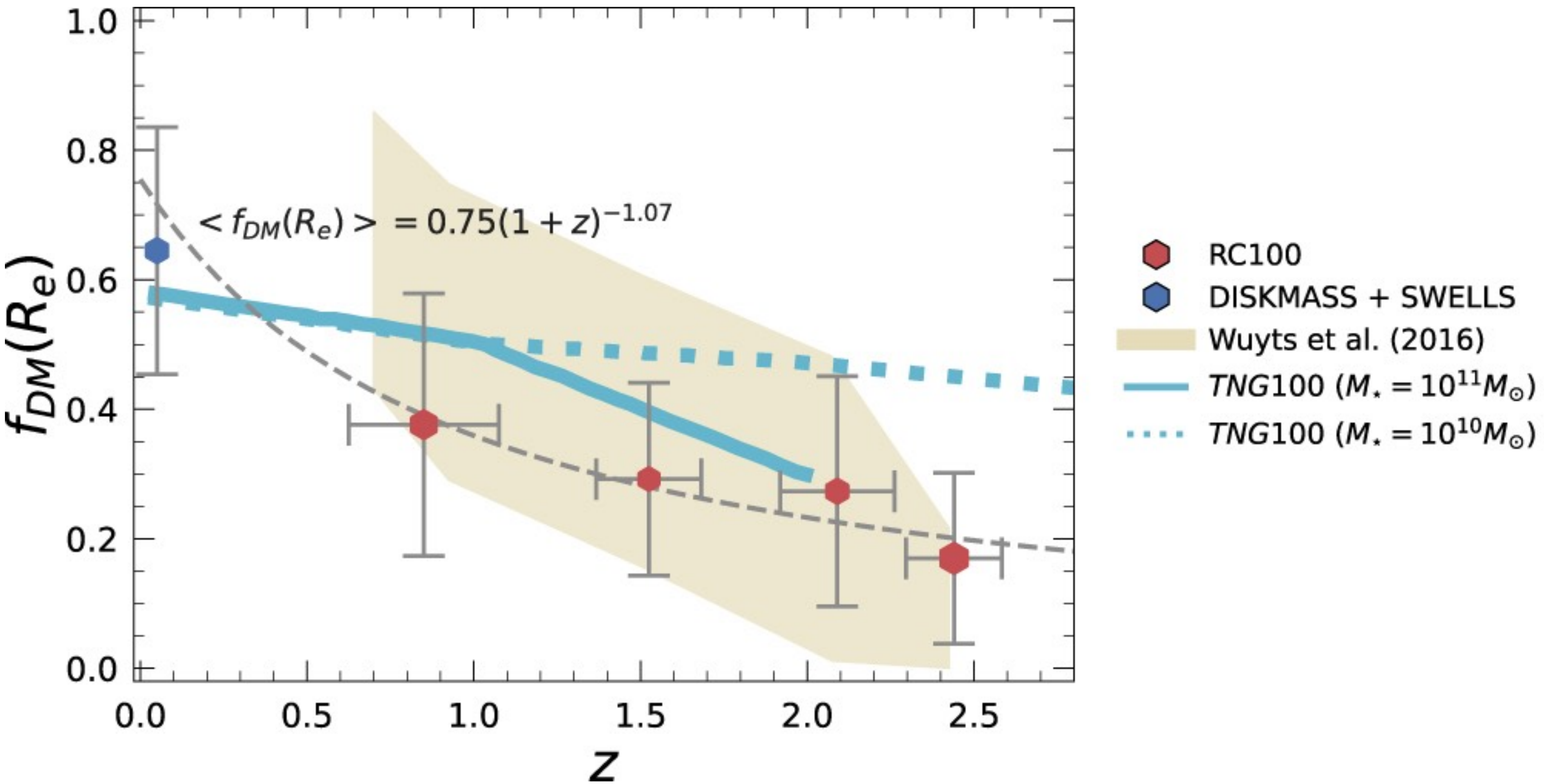


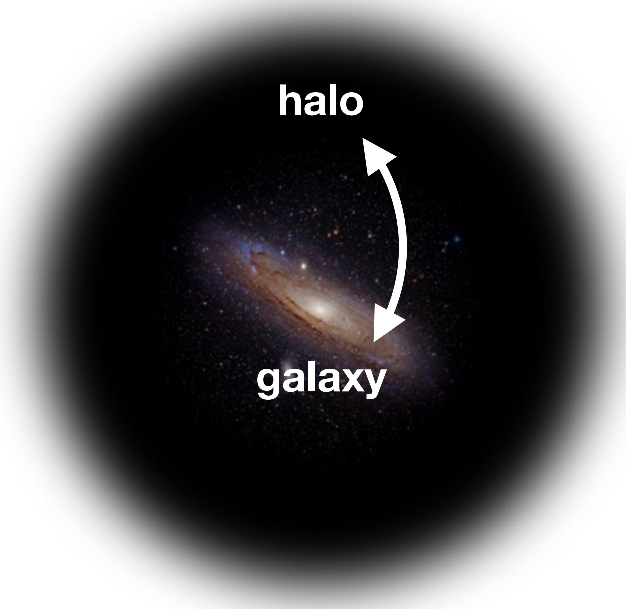
➡ Evidence for cores in the early Universe?

➡ If yes, how can they form so quickly?

Genzel et al. 2017, 2020, Price et al. 2021, Nestor Shachar et al. 2023

Modeling core formation from feedback processes

How can baryons affect dark matter haloes?



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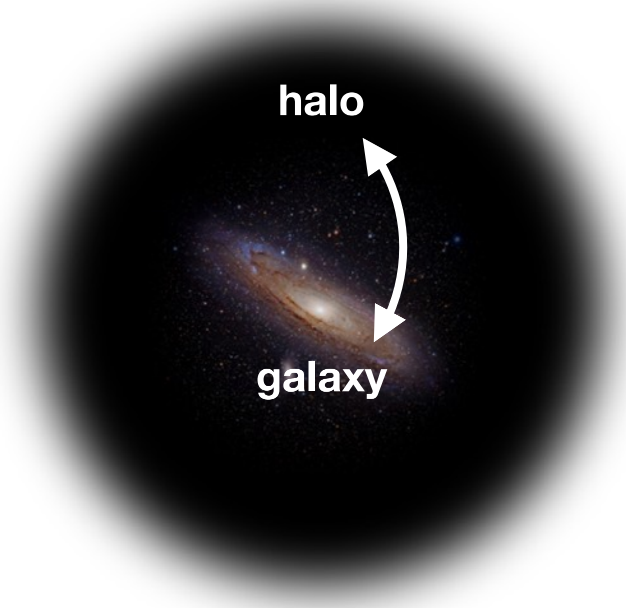
✦ **Adiabatic contraction** (Blumenthal+1986)



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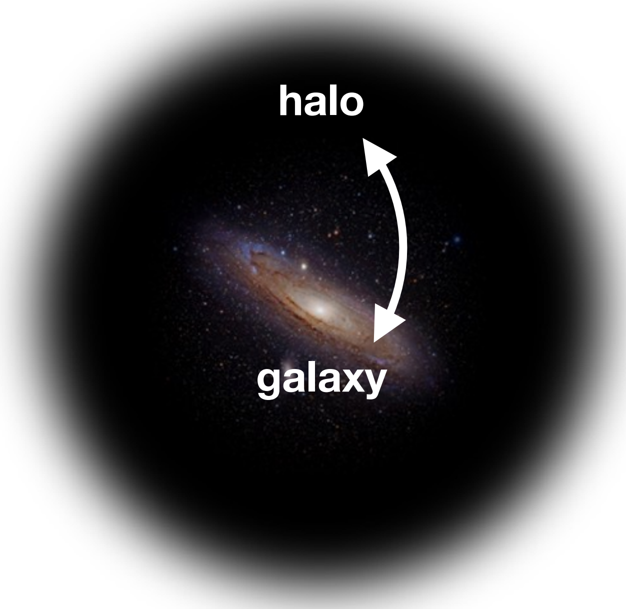

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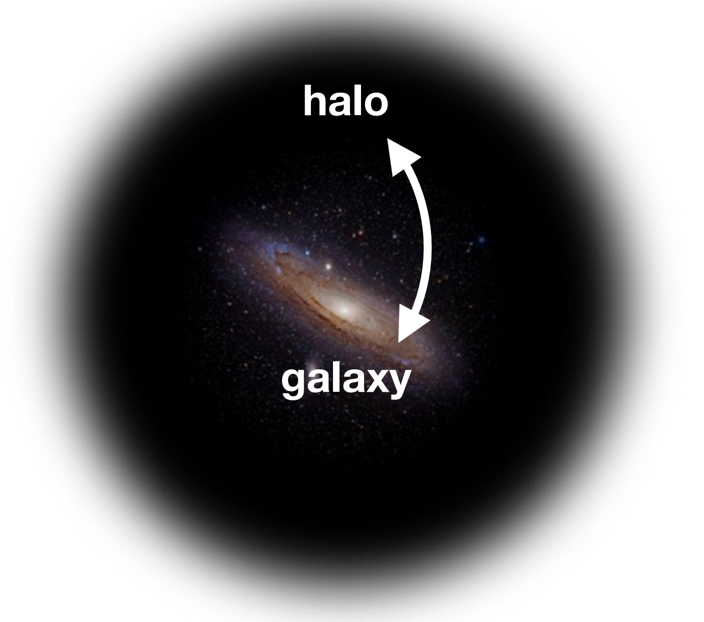

- ✦ **Adiabatic contraction** (Blumenthal+1986)
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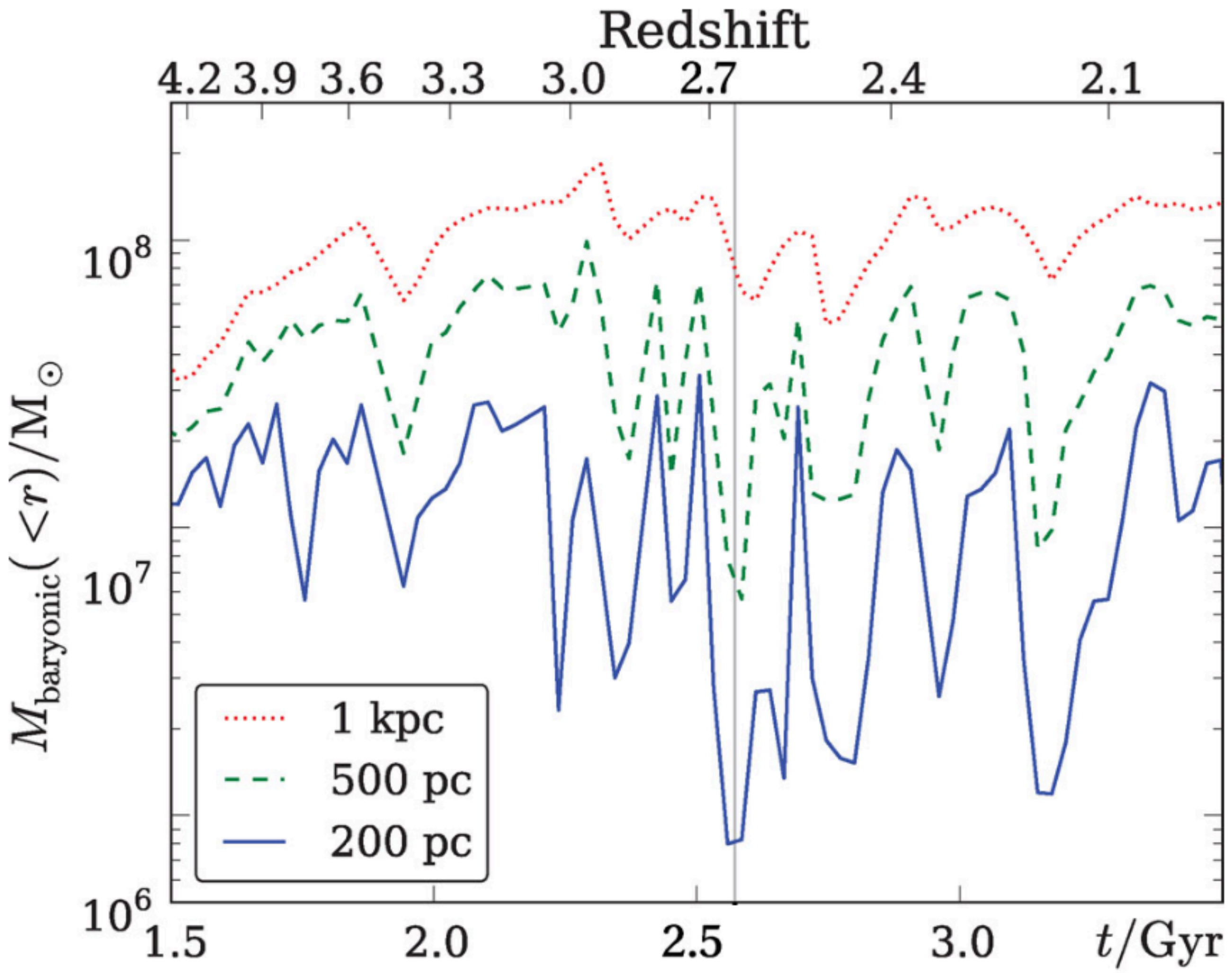
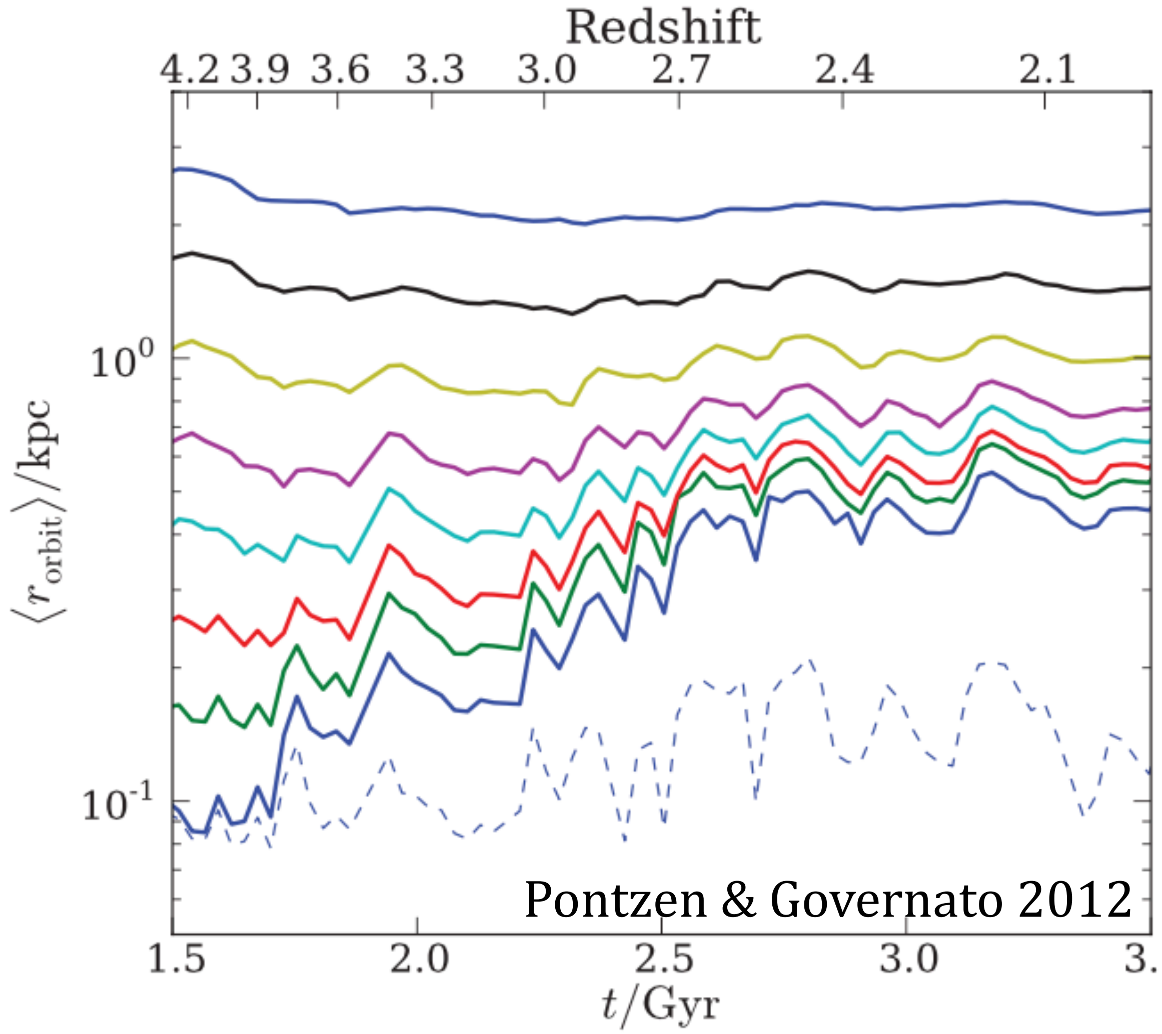
- ✦ **Repeated potential fluctuations from feedback processes** (Pontzen & Governato 2012)





Feedback processes

The gas in the interstellar medium is constantly renewed, recycled, or put in motion by radiation, stellar winds, supernova explosions, and **active galactic nuclei**. These **feedback phenomena** generally inhibit the formation of stars.

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✦ **Effects of Radiation**

- **UV radiation** from young, ionizing stars: heats the gas up to 10^4 K, photodissociates H_2
- **Photoevaporation**: the surface of a heated cloud can expand and disperse into the surrounding medium.
- **Radiation pressure**: can eject gas and slow down accretion.

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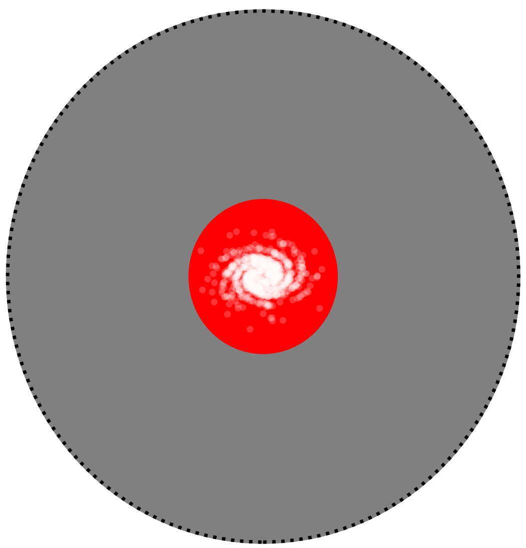
✦ **Active Galactic Nuclei**

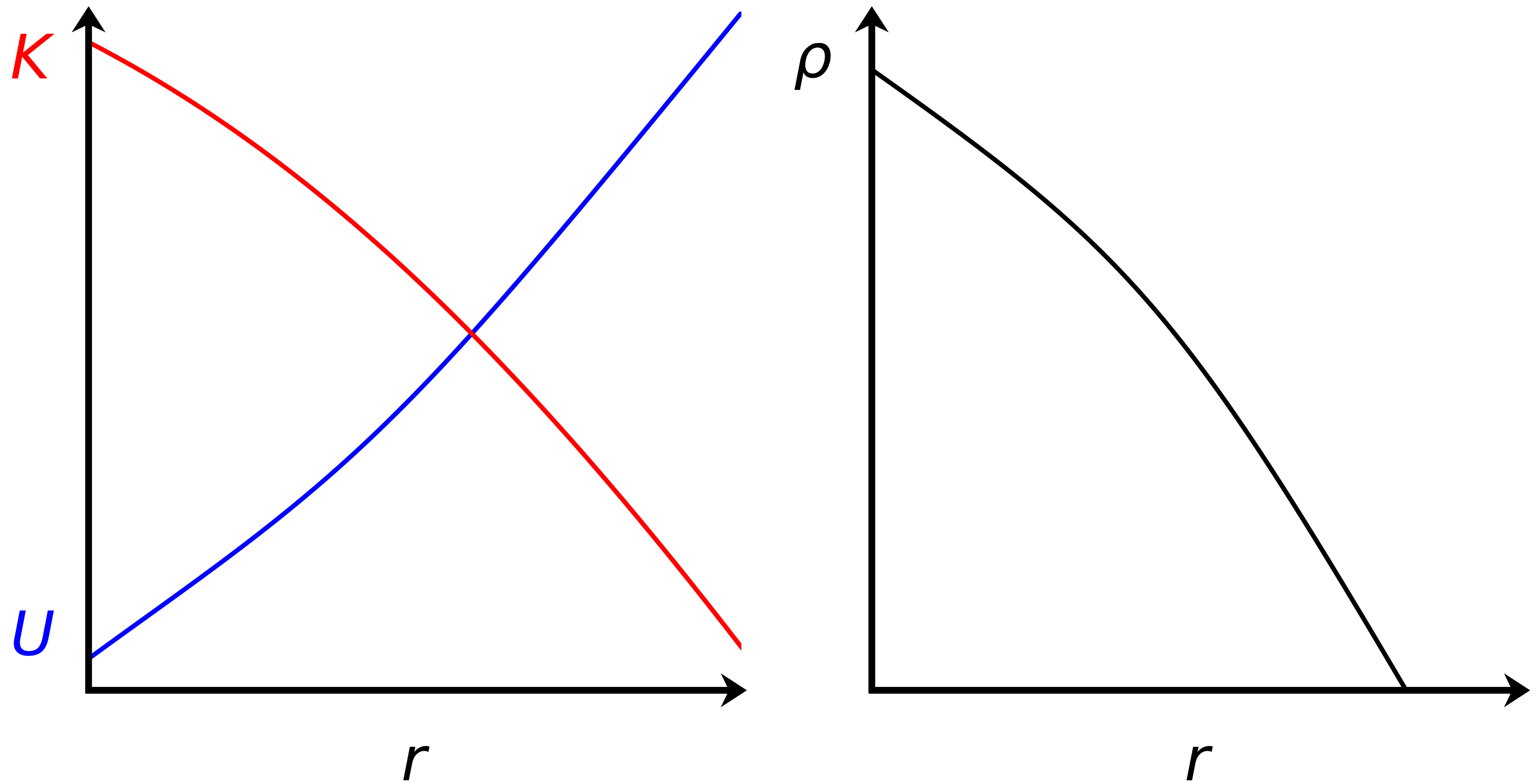
The accretion disks around supermassive black holes are highly energetic, producing intense radiation, stellar winds, and also collimated **relativistic jets**.

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)

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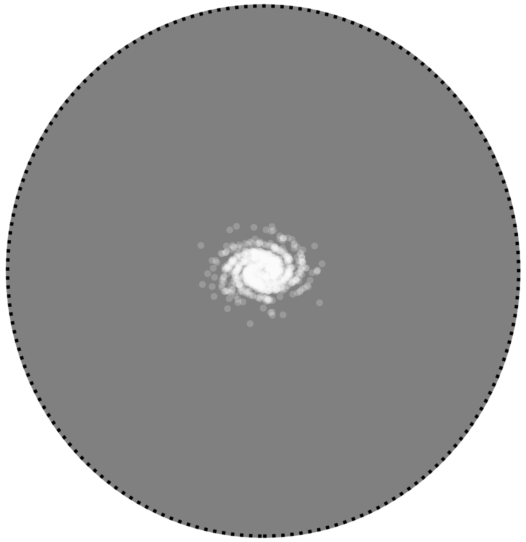
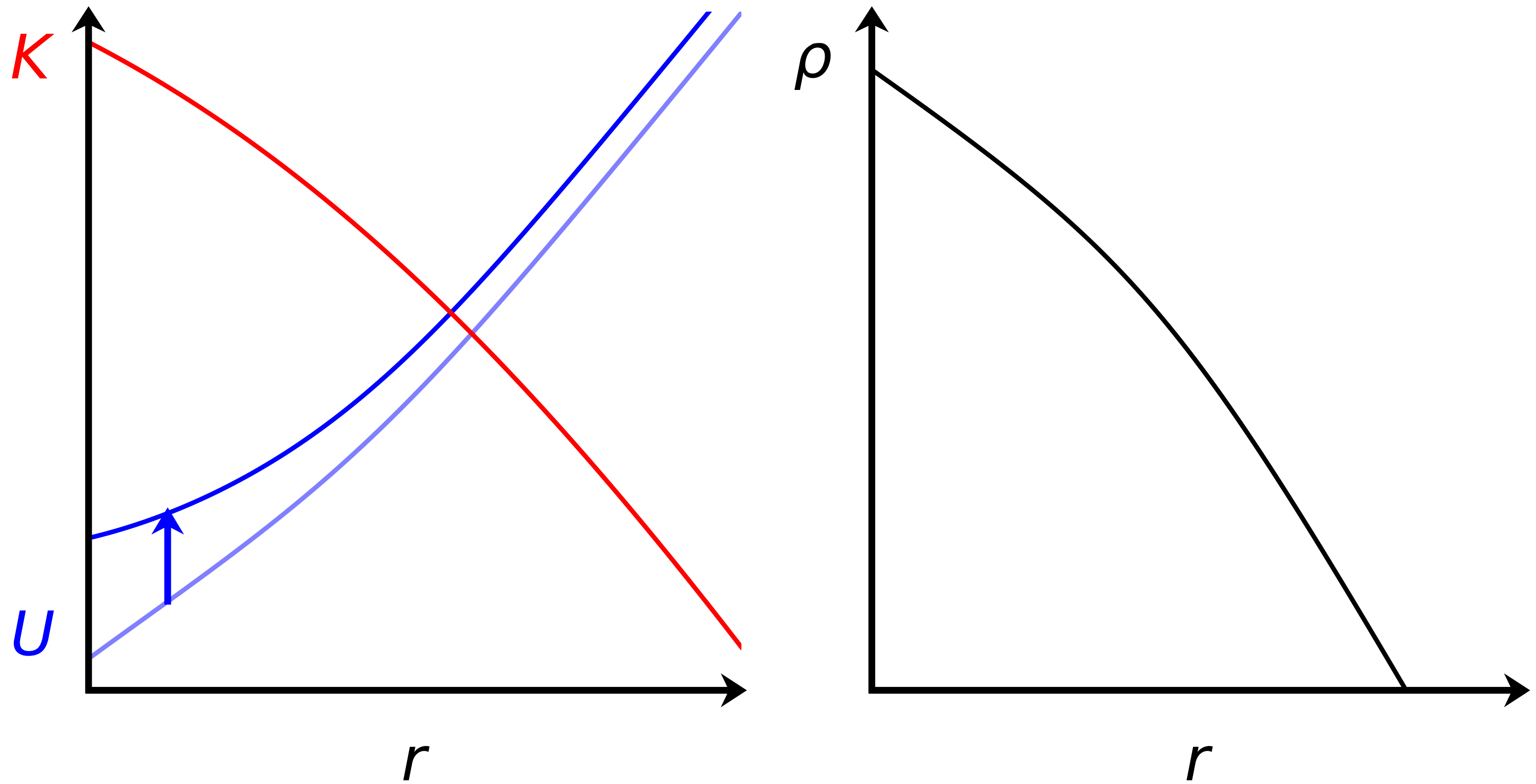
② Sudden gas removal $E_t(r_i) = U_i(r_i) - Gm/r_i + K_i(r_i)$





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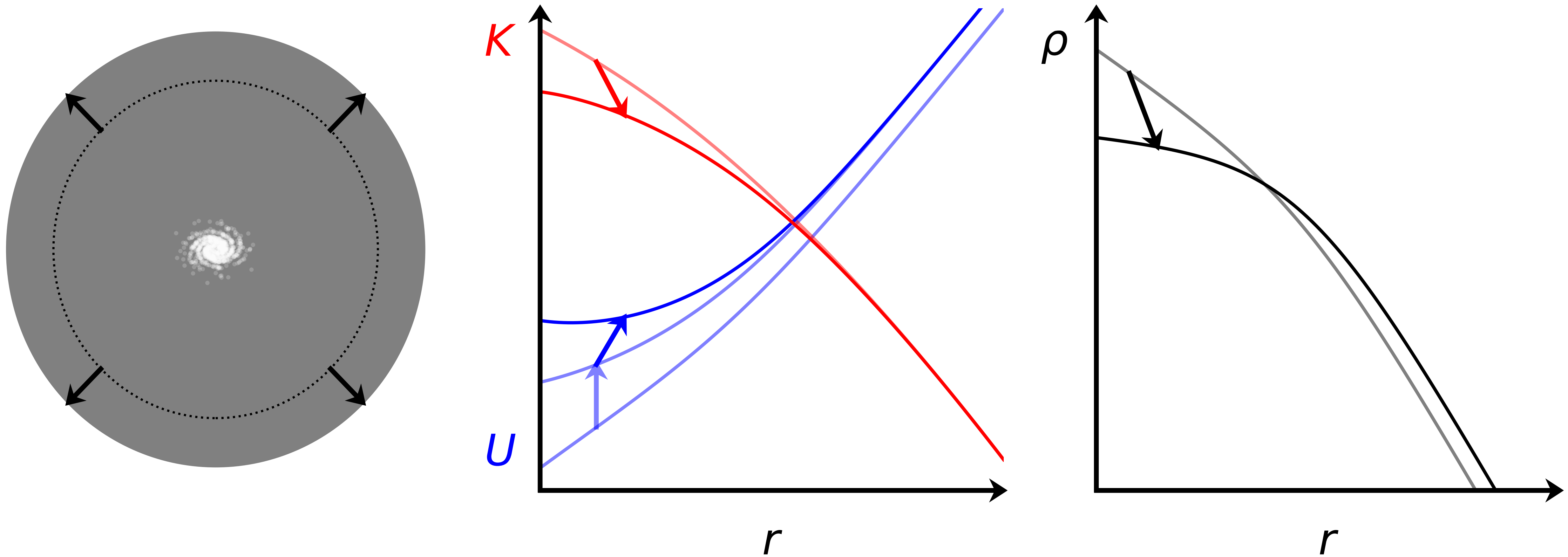
③ Relaxation

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



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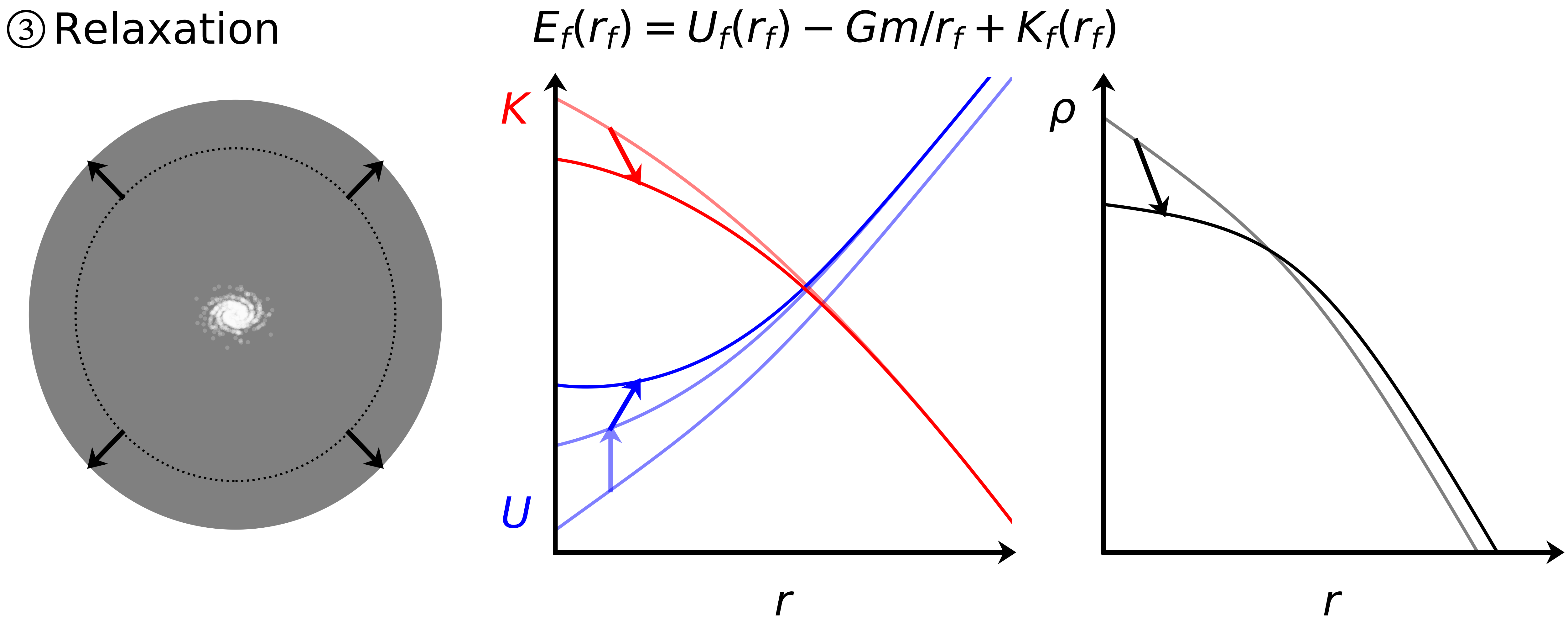


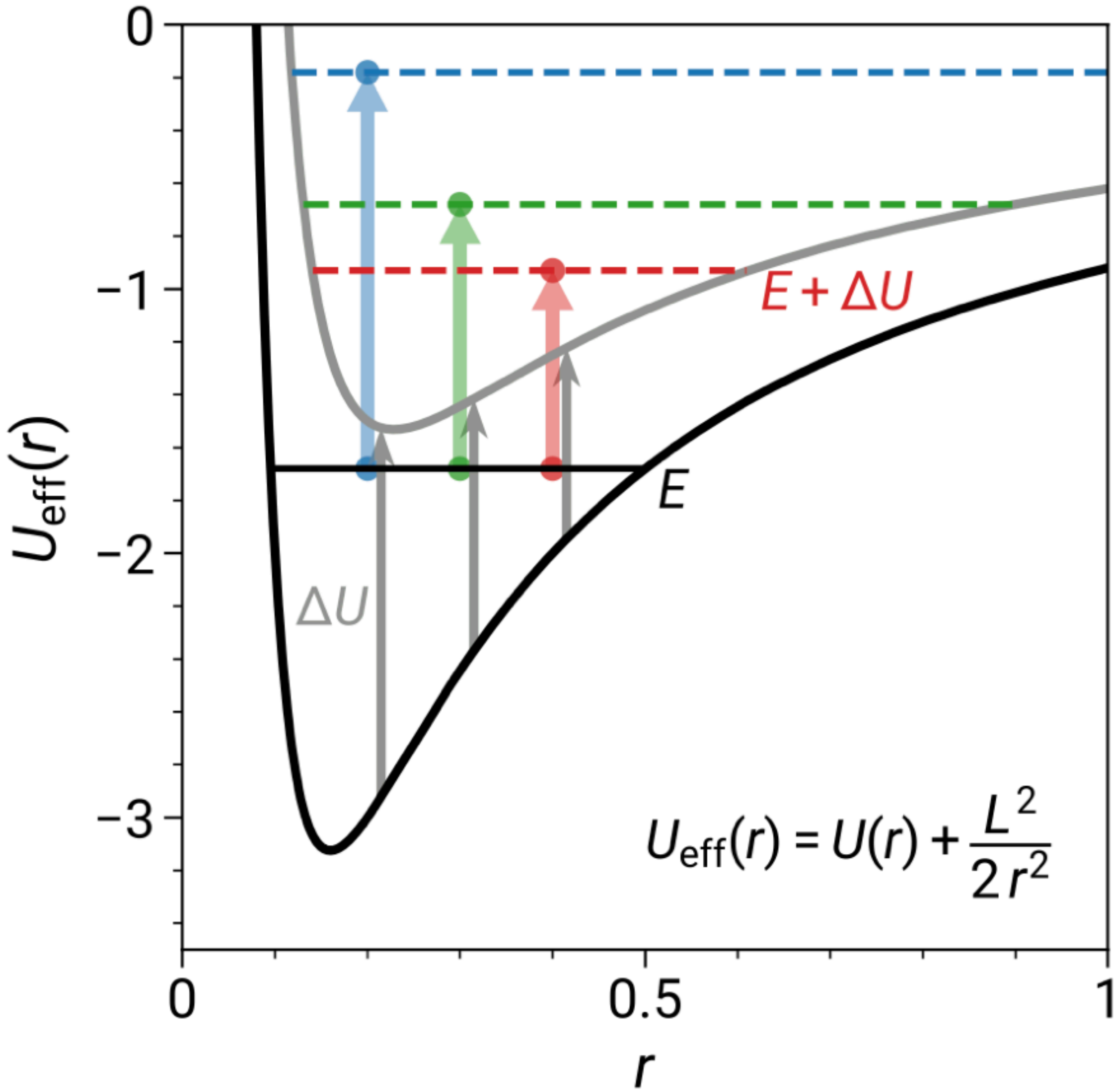
Given functional forms ***U(r;p,m)*** and ***K(r;p,m)***, **energy conservation** $E_f(r_f) = E_t(r_i)$ during relaxation yields the final state (*CuspCore I*)

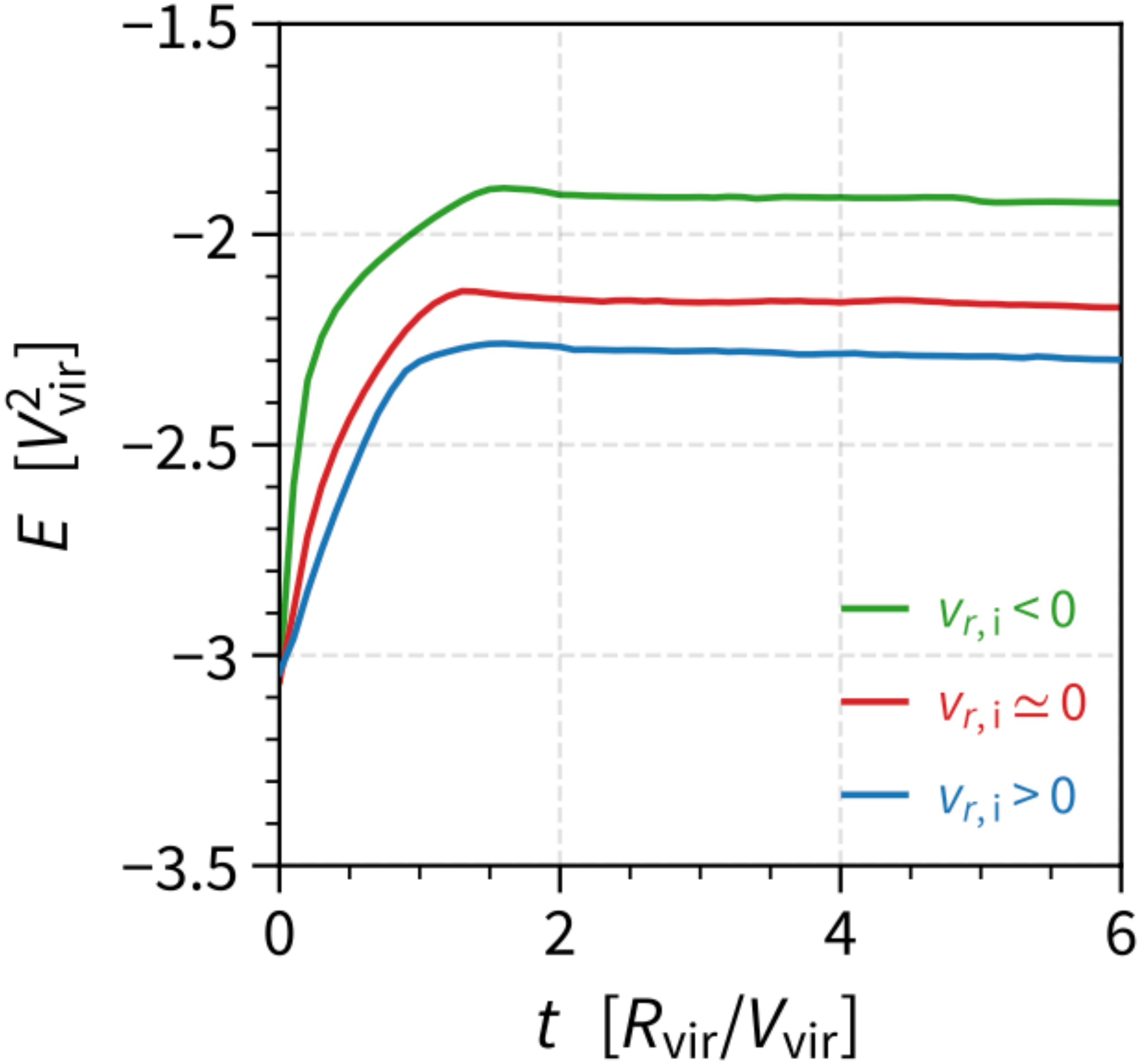
Freundlich et al. (2020a)

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

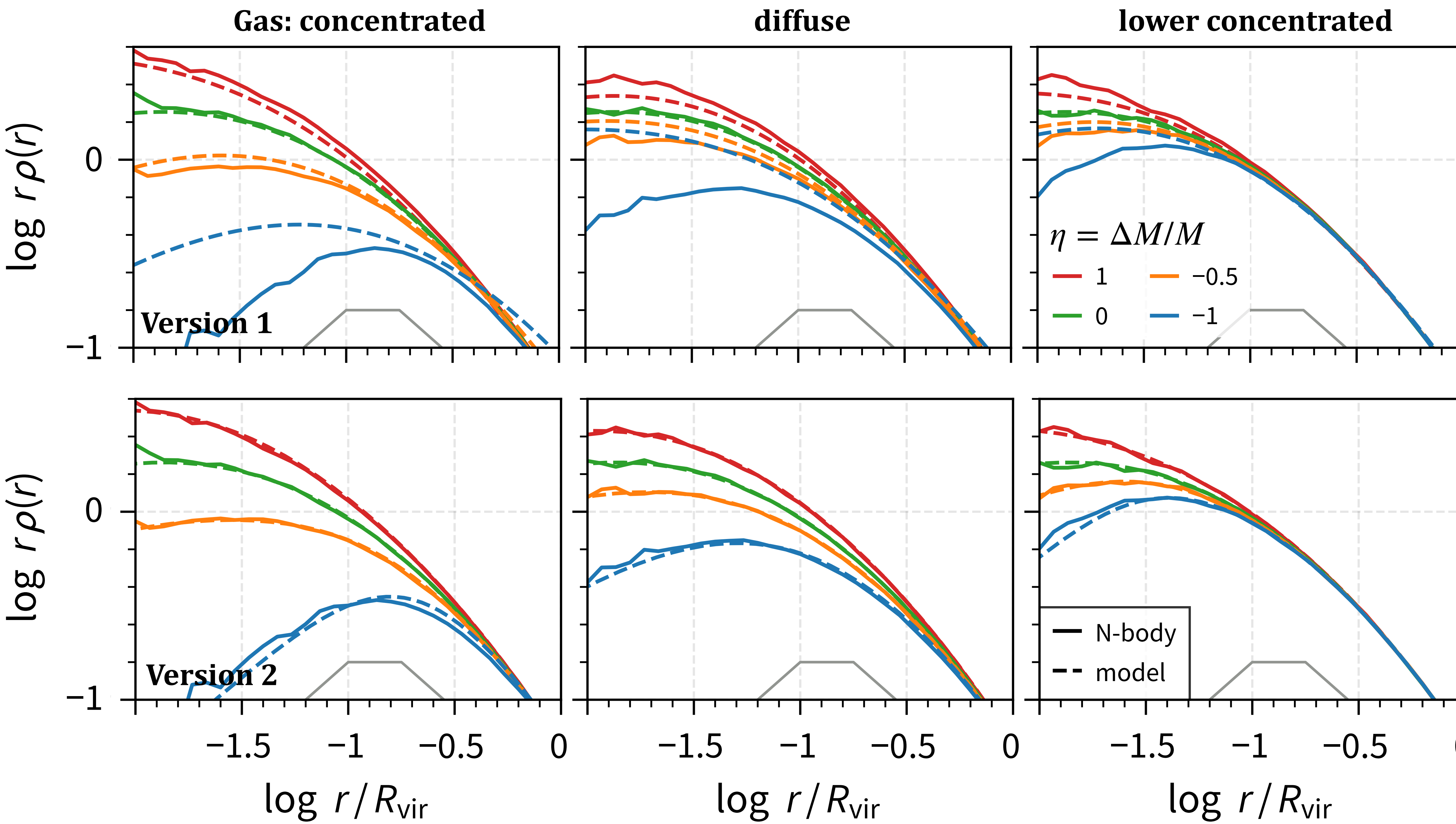
$$U_{k+1}(r) = U_{\rm g,f}(r) - 4\pi G\int_r^\infty \frac{dy}{y^2}\int_0^y \rho_{{\rm dm},k}(x)x^2\,dx$$

$k \mathrel{+}= 1$

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

Li et al. 2022 (incl. Freundlich)

Model I, version 2: numerical tests



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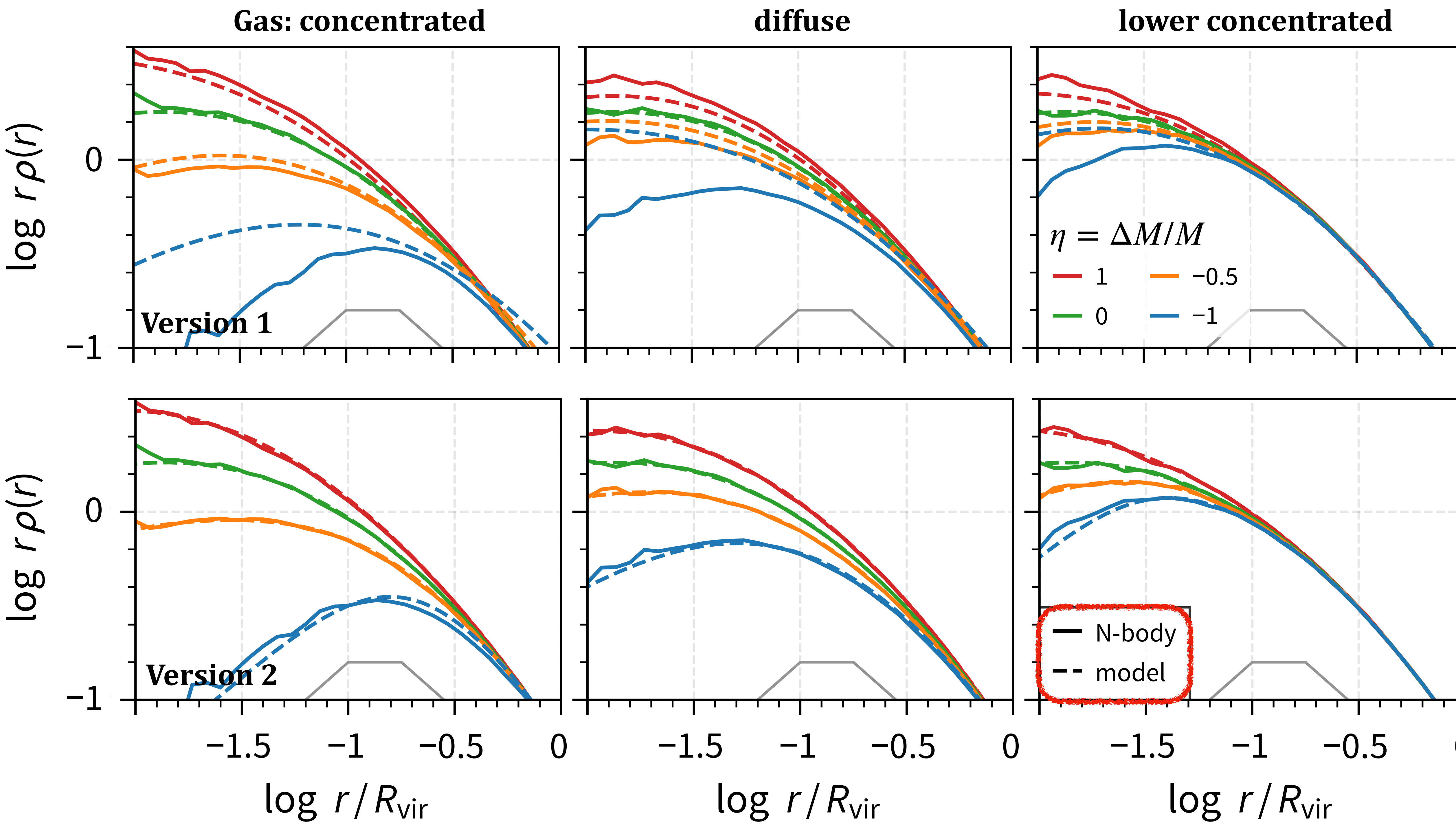

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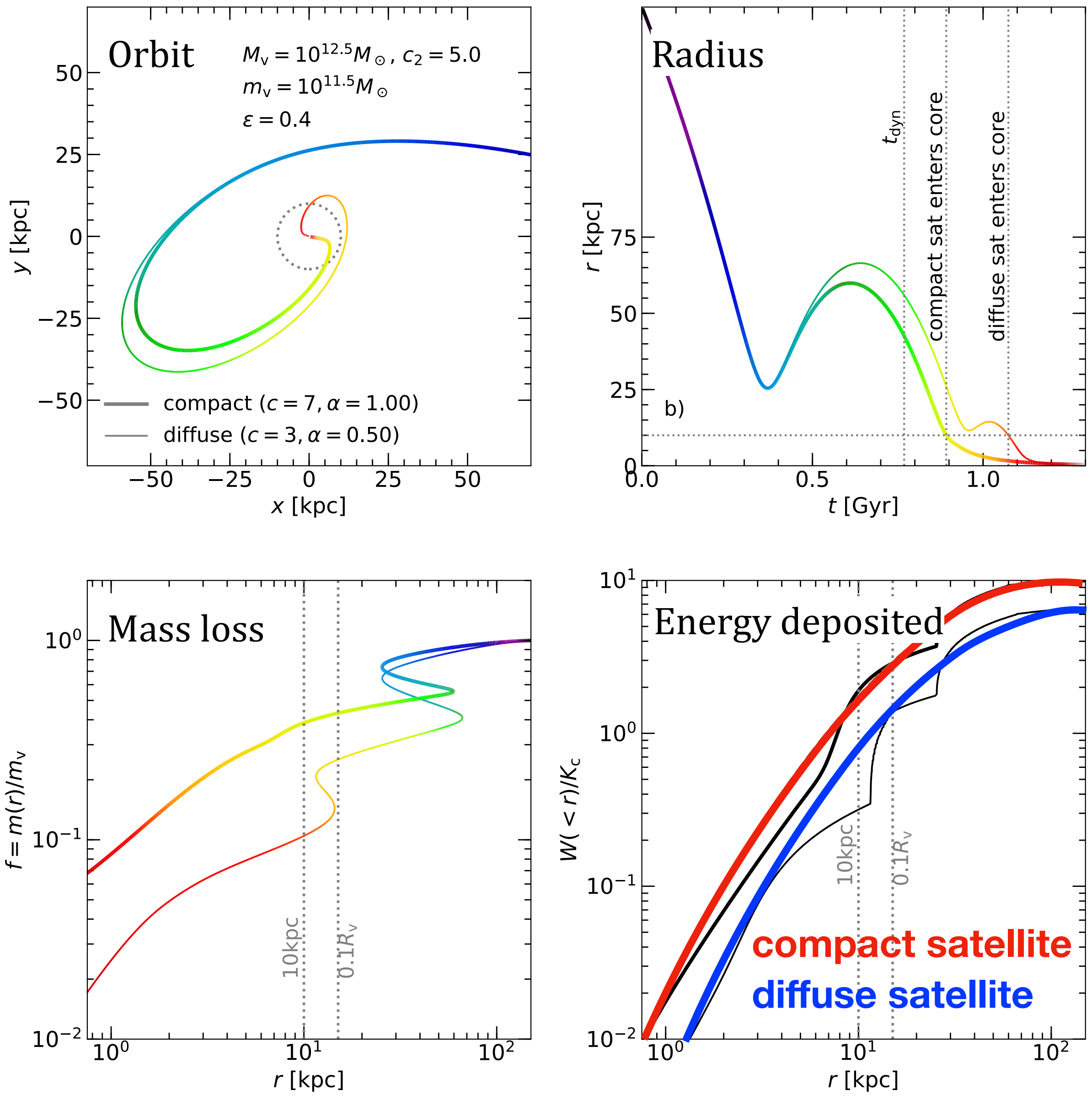
Model Ibis: Enhanced core formation with dynamical heating

Energy deposited through dynamical friction…



Dekel, Freundlich, Jiang et al. 2021

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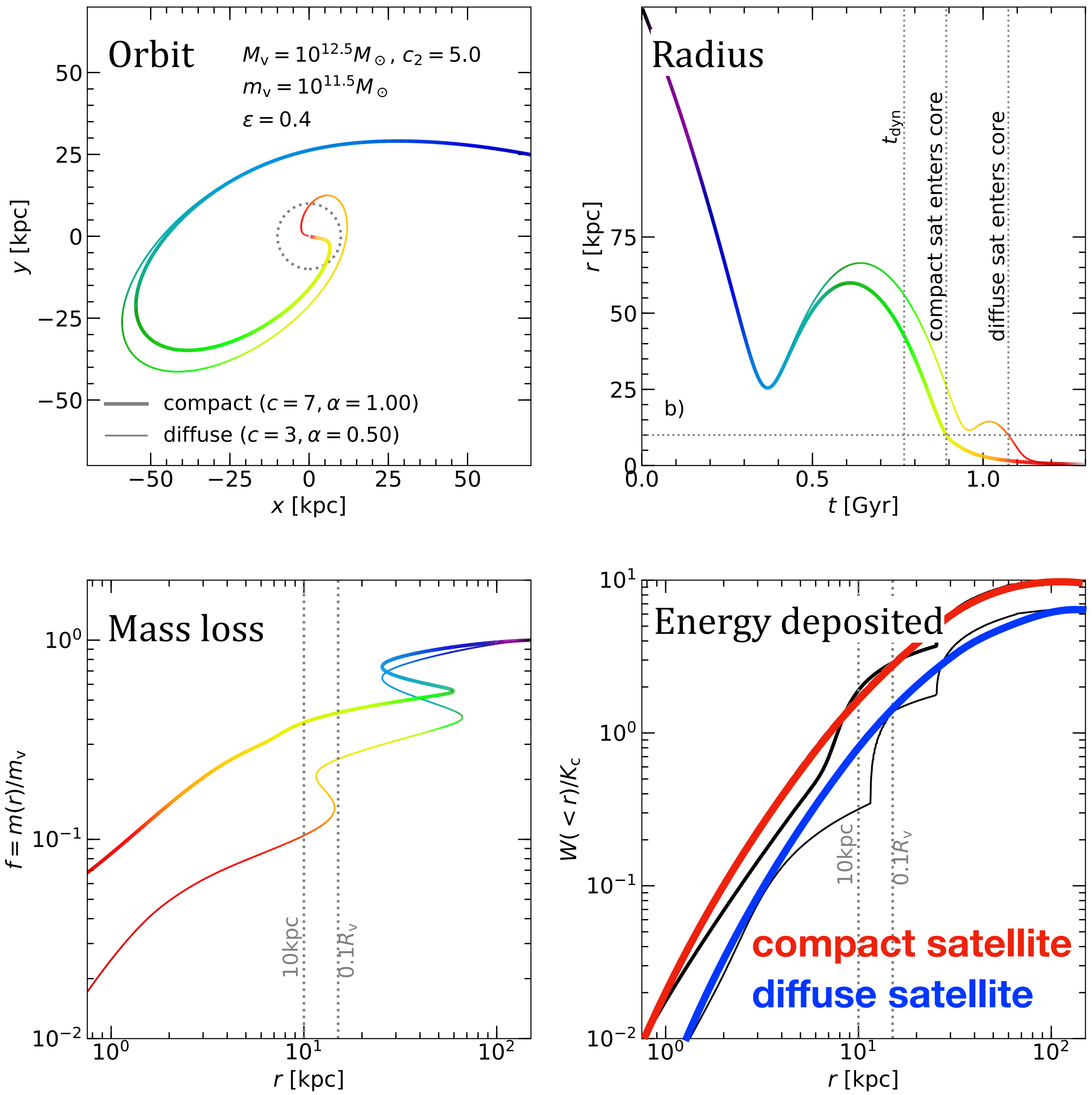
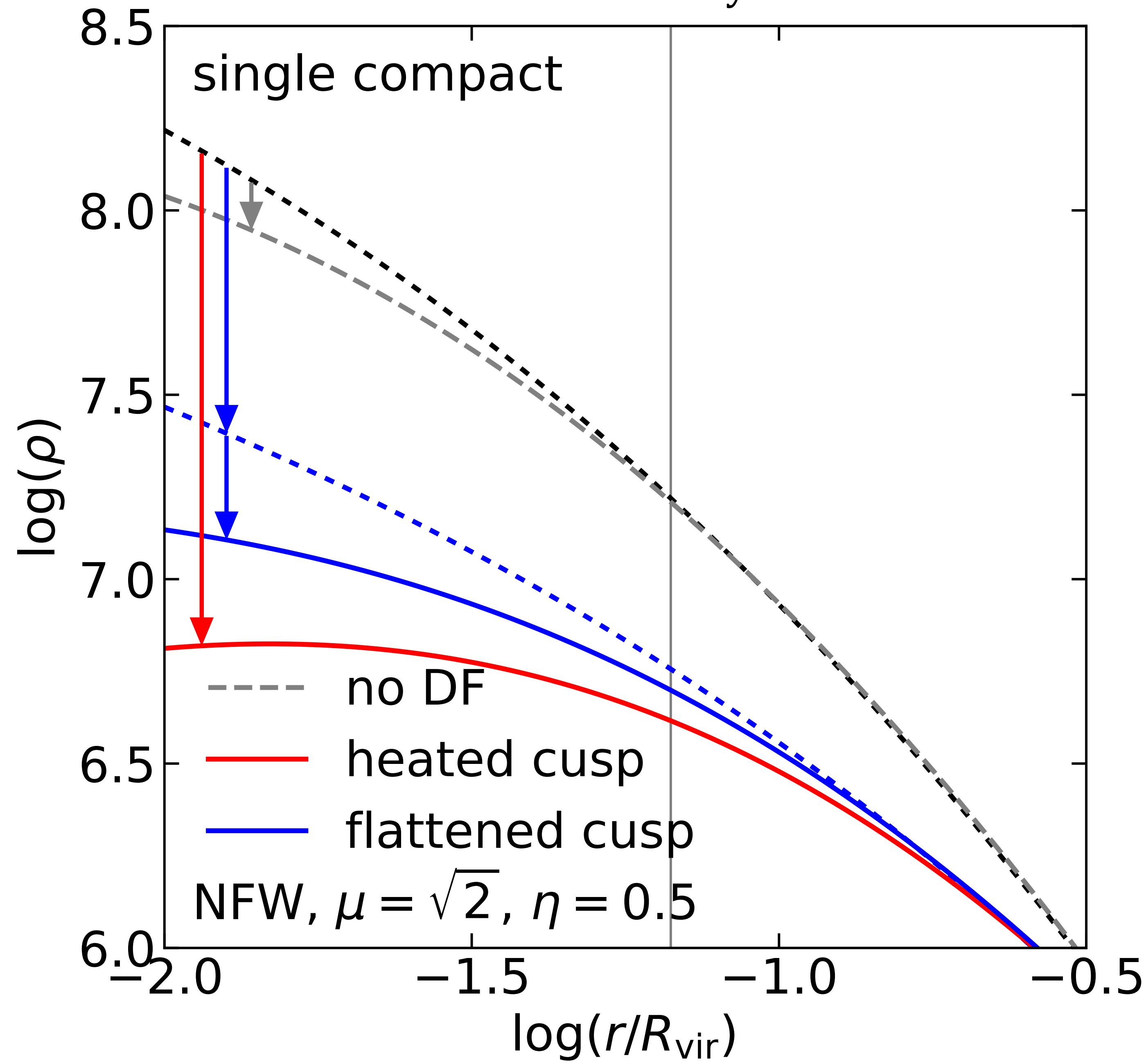


…followed by a sudden outflow



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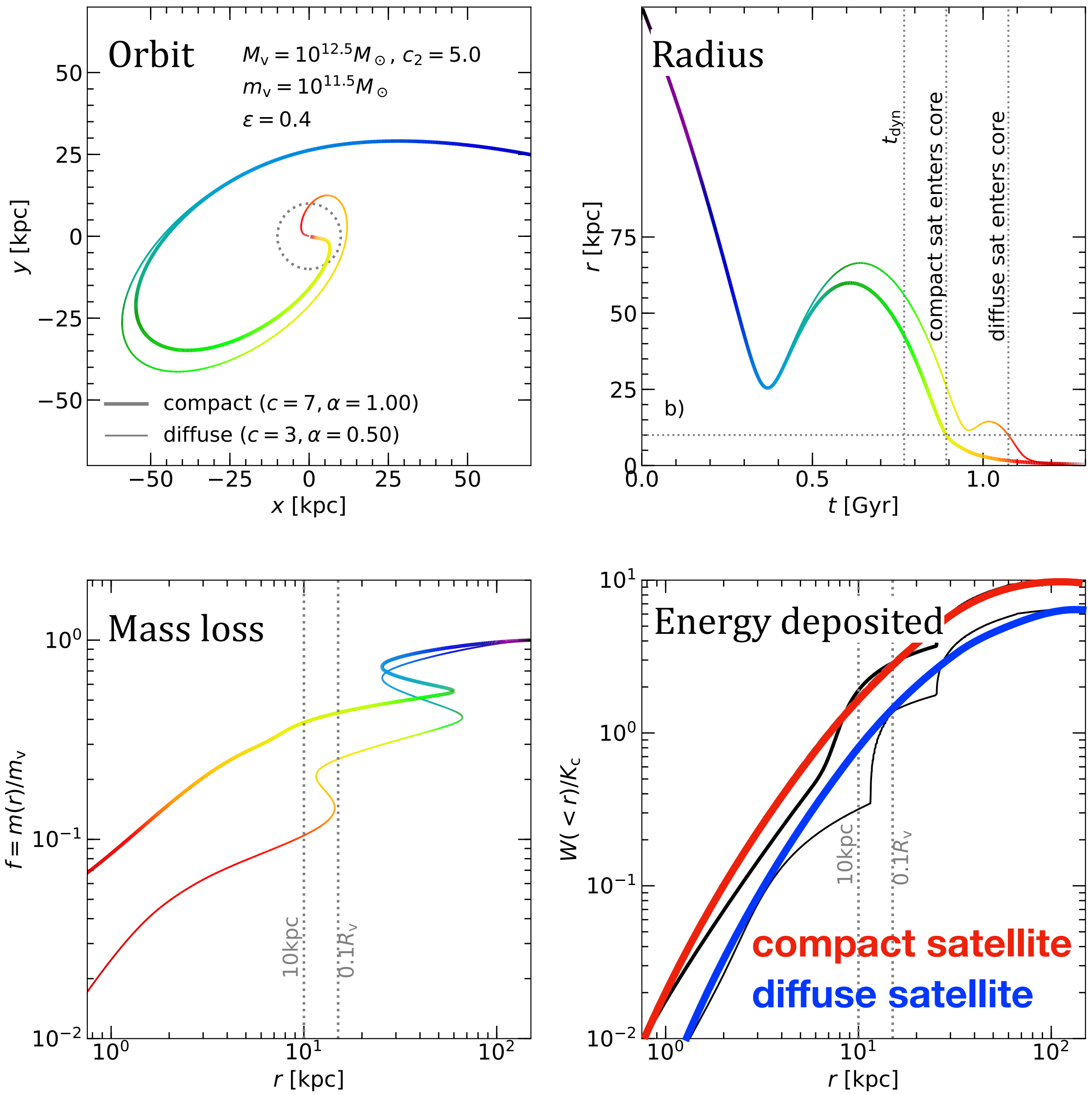

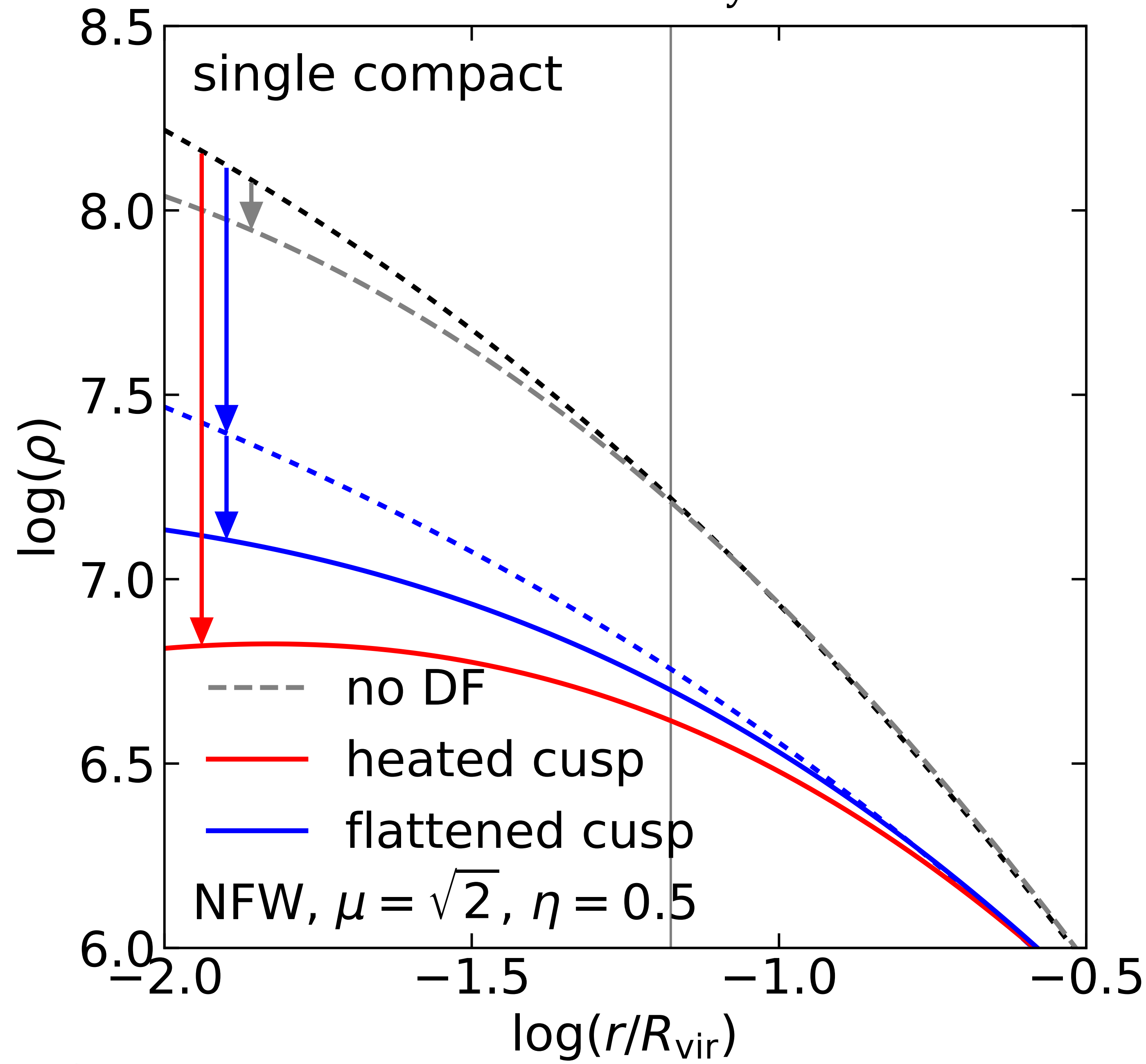

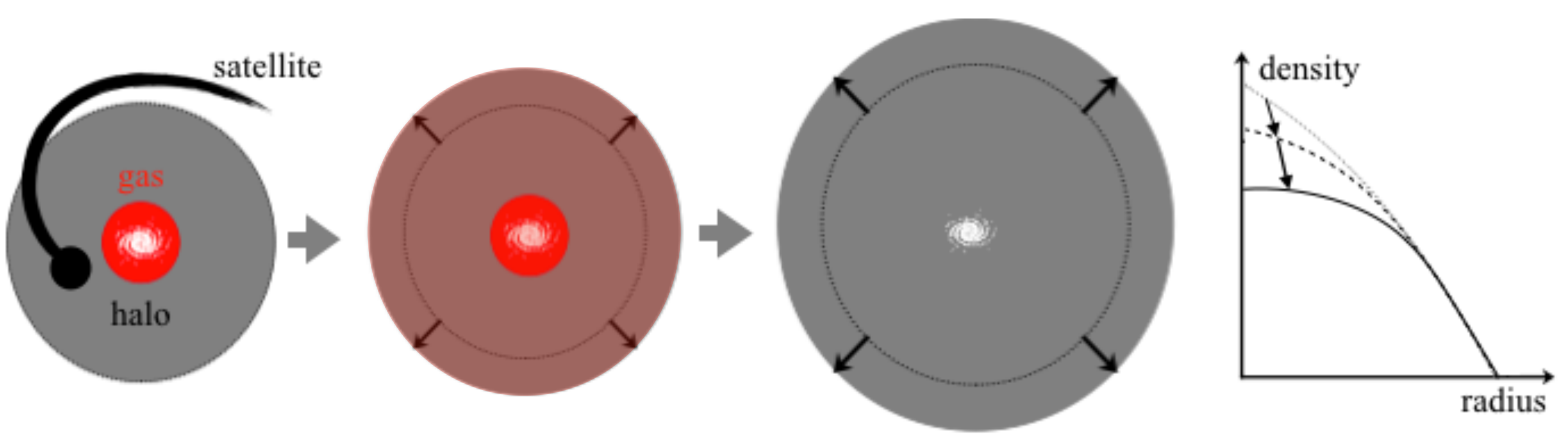

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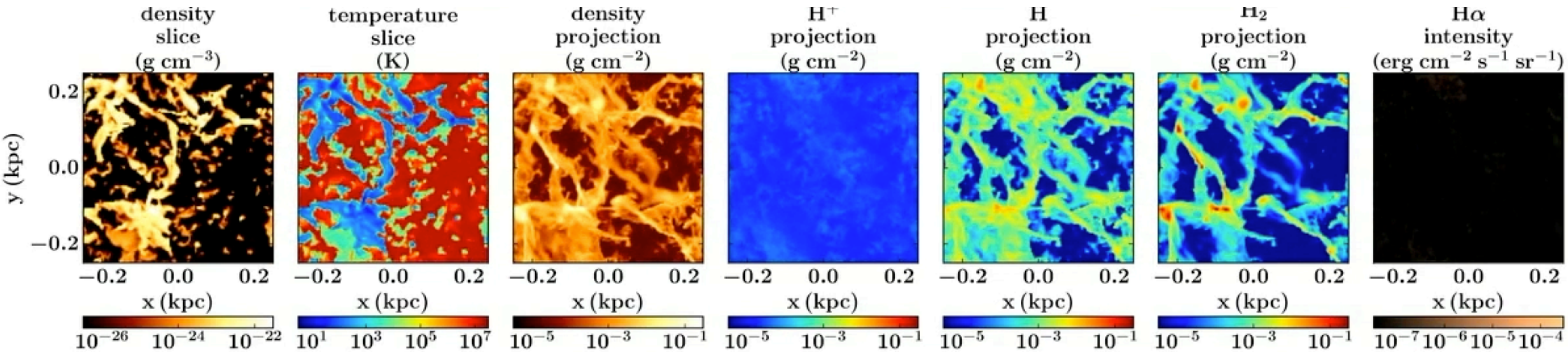
Model II: core formation from stochastic density fluctuations

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



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

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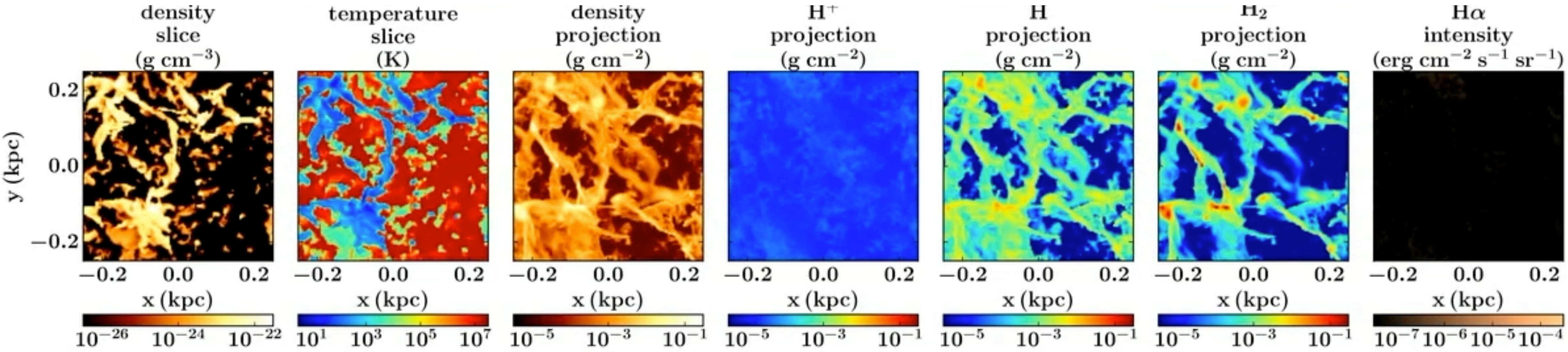

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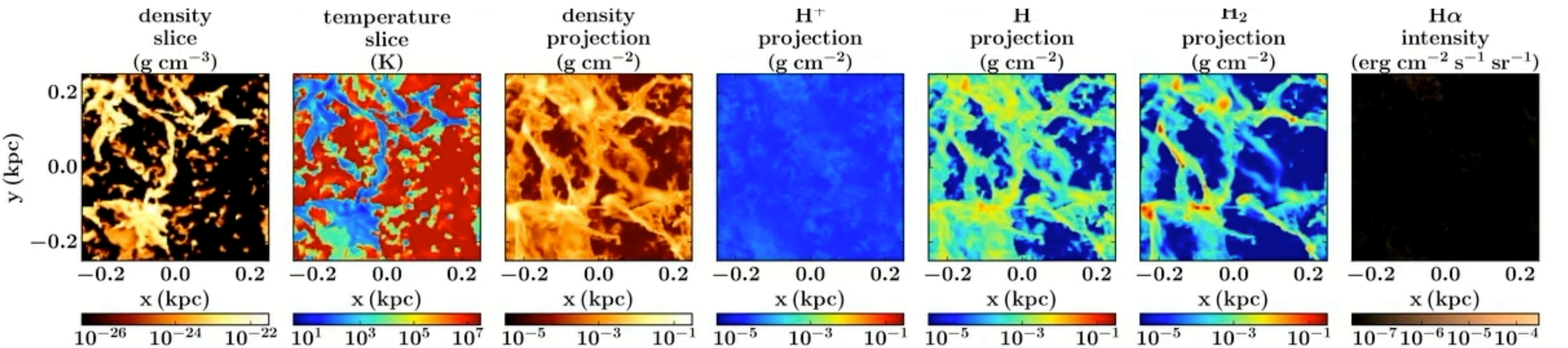


✦ **Stochastic gas density fluctuations in an unperturbed homogeneous medium**

— Density contrast

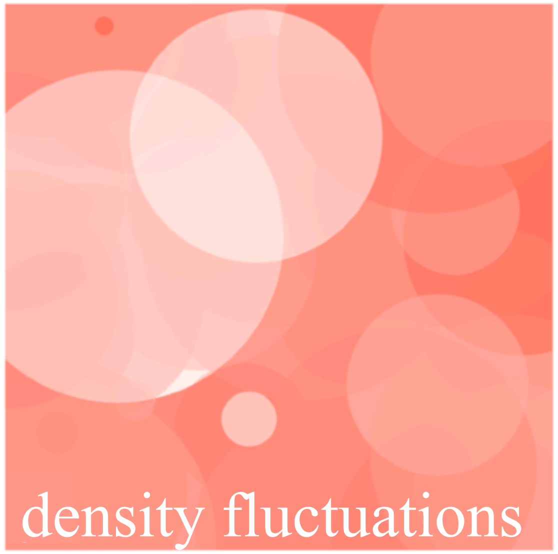
$$\delta(\mathbf{r}) = \frac{V}{(2\pi)^3} \int \delta_{\mathbf{k}}\, e^{i\mathbf{k}.\mathbf{r}}\, d^3\mathbf{k}$$

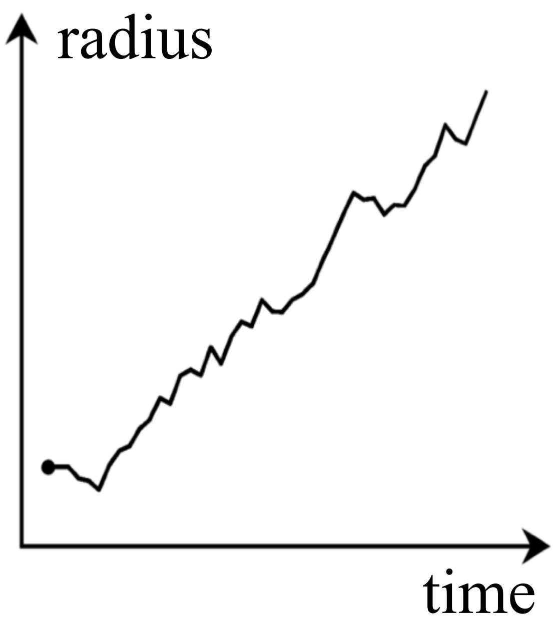
— Each mode induces a ‘kick’

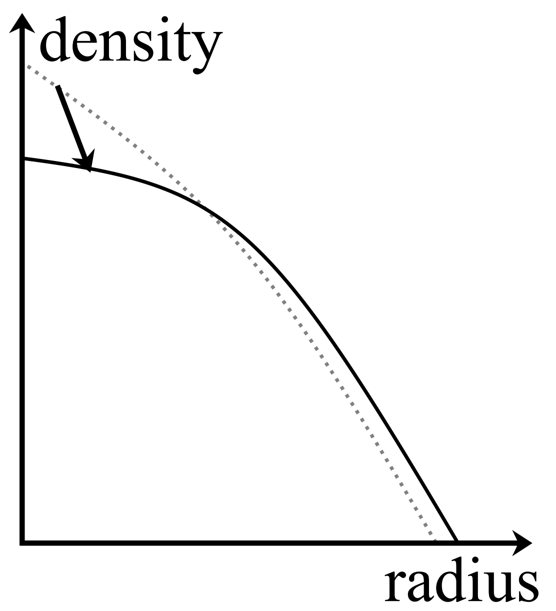
$$\mathbf{F}_{\mathbf{k}} = 4\pi i\, G\rho_0\, \mathbf{k}\, k^{-2}\, \delta_{\mathbf{k}}$$

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

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



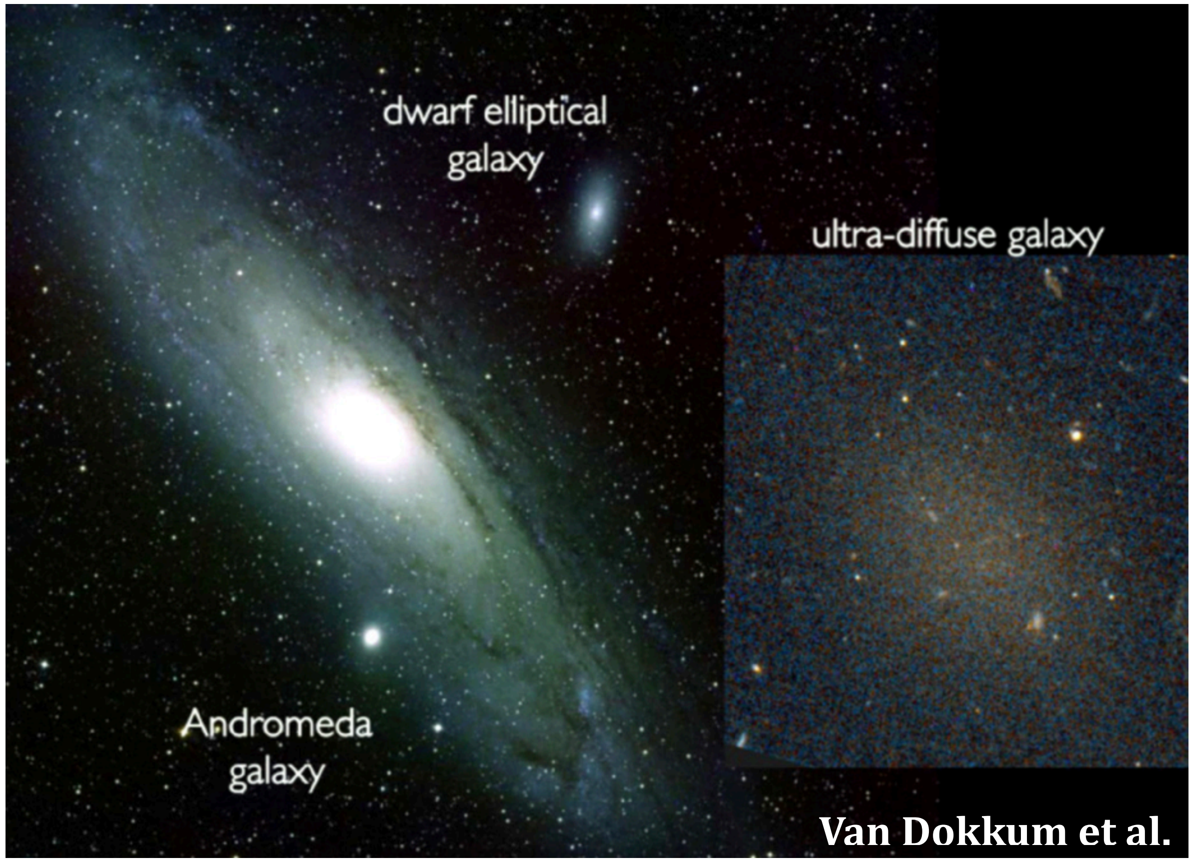




El-Zant, Freundlich & Combes 2016, Hashim, El-Zant, Freundlich et al. 2023

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**
  $1 < r_{\rm eff}/{\rm kpc} < 5$

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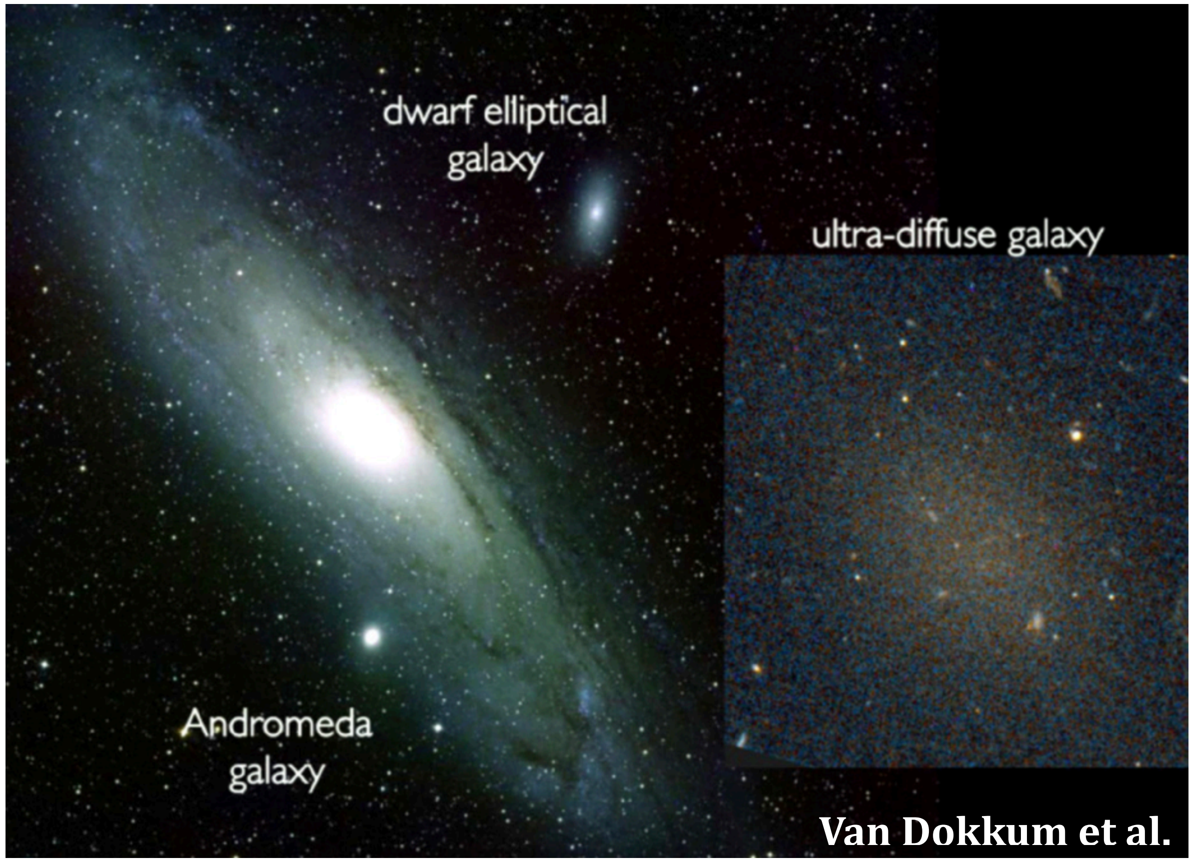

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✦ **High-spin tail** (Amorisco & Loeb 2016)

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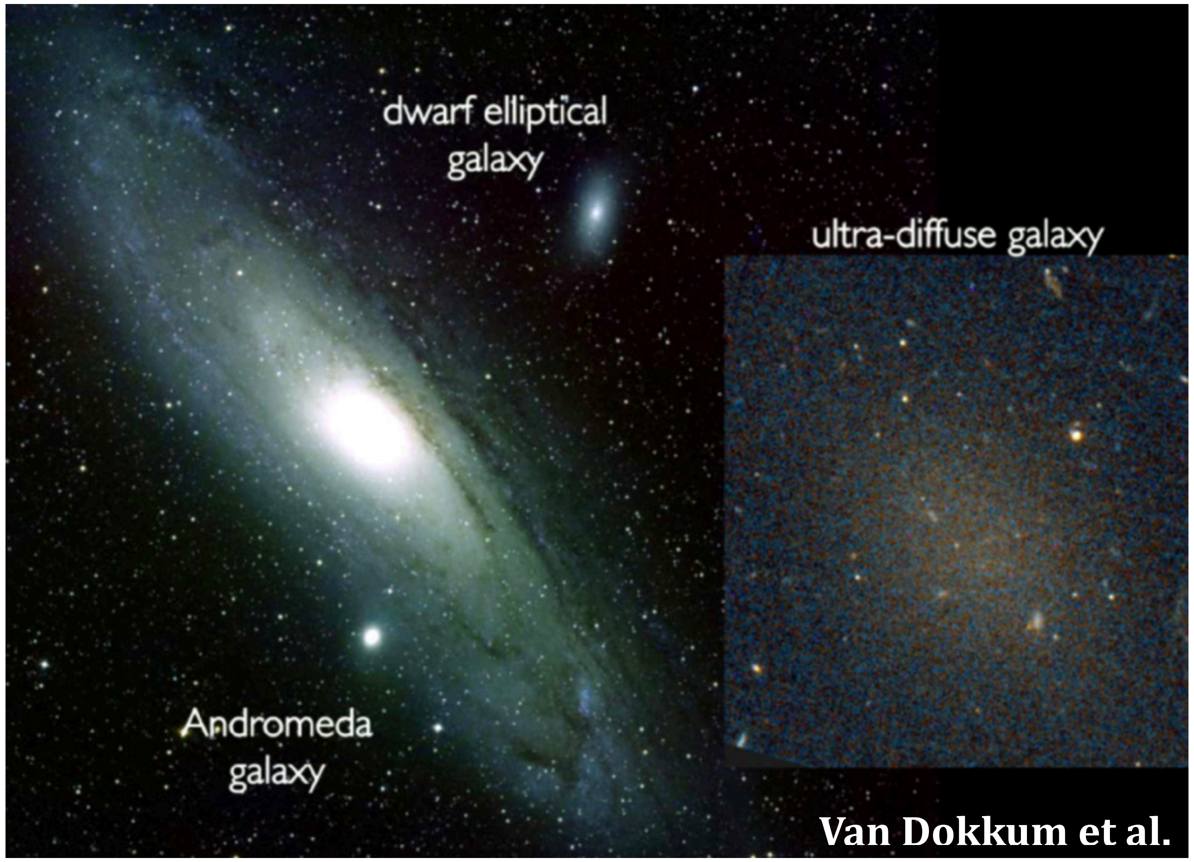

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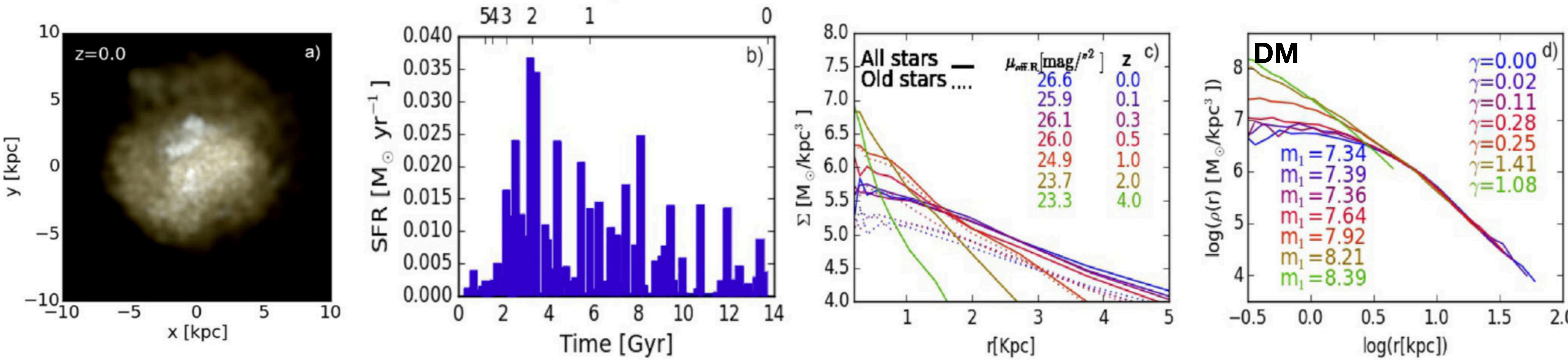
Outflows resulting from a bursty SF history expand both the stellar and the DM distributions



Di Cintio et al. 2017

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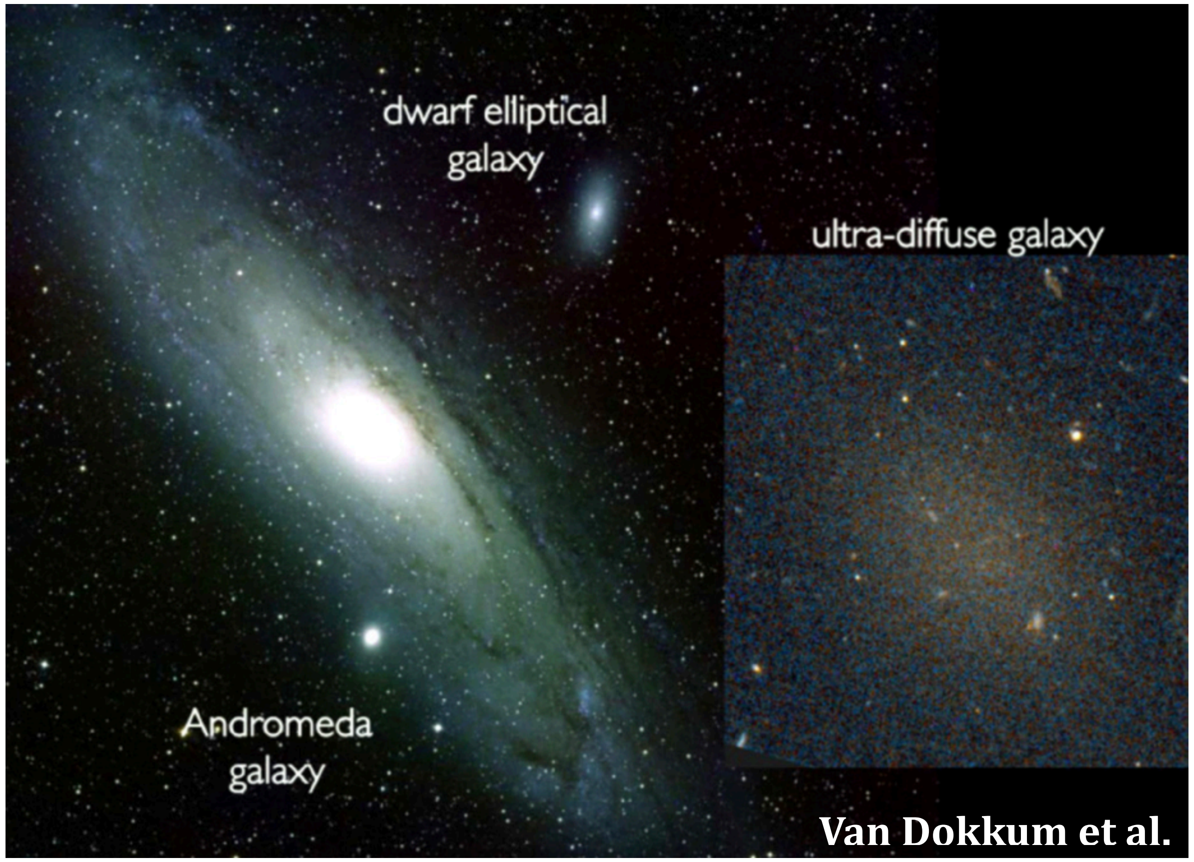

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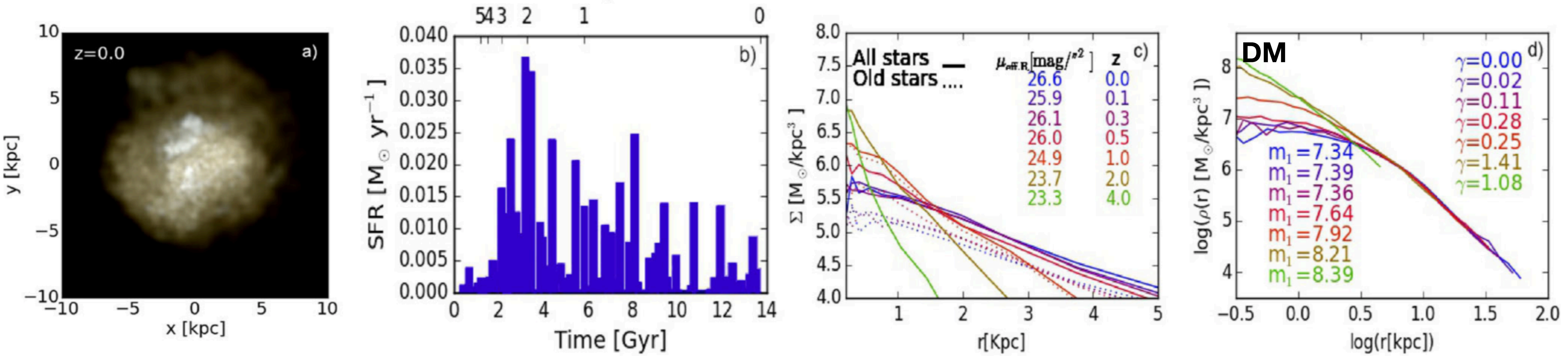


➡ UDGs could be used as tests for core formation models.

Di Cintio et al. 2017

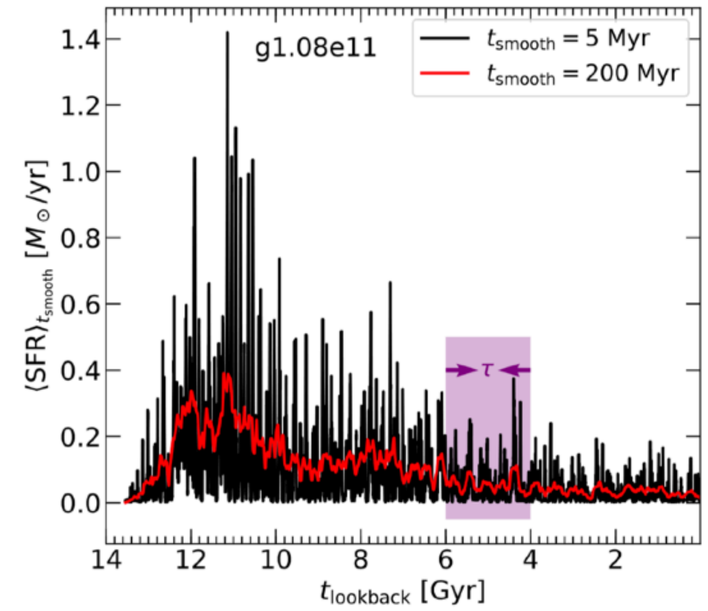
Towards observational tests?

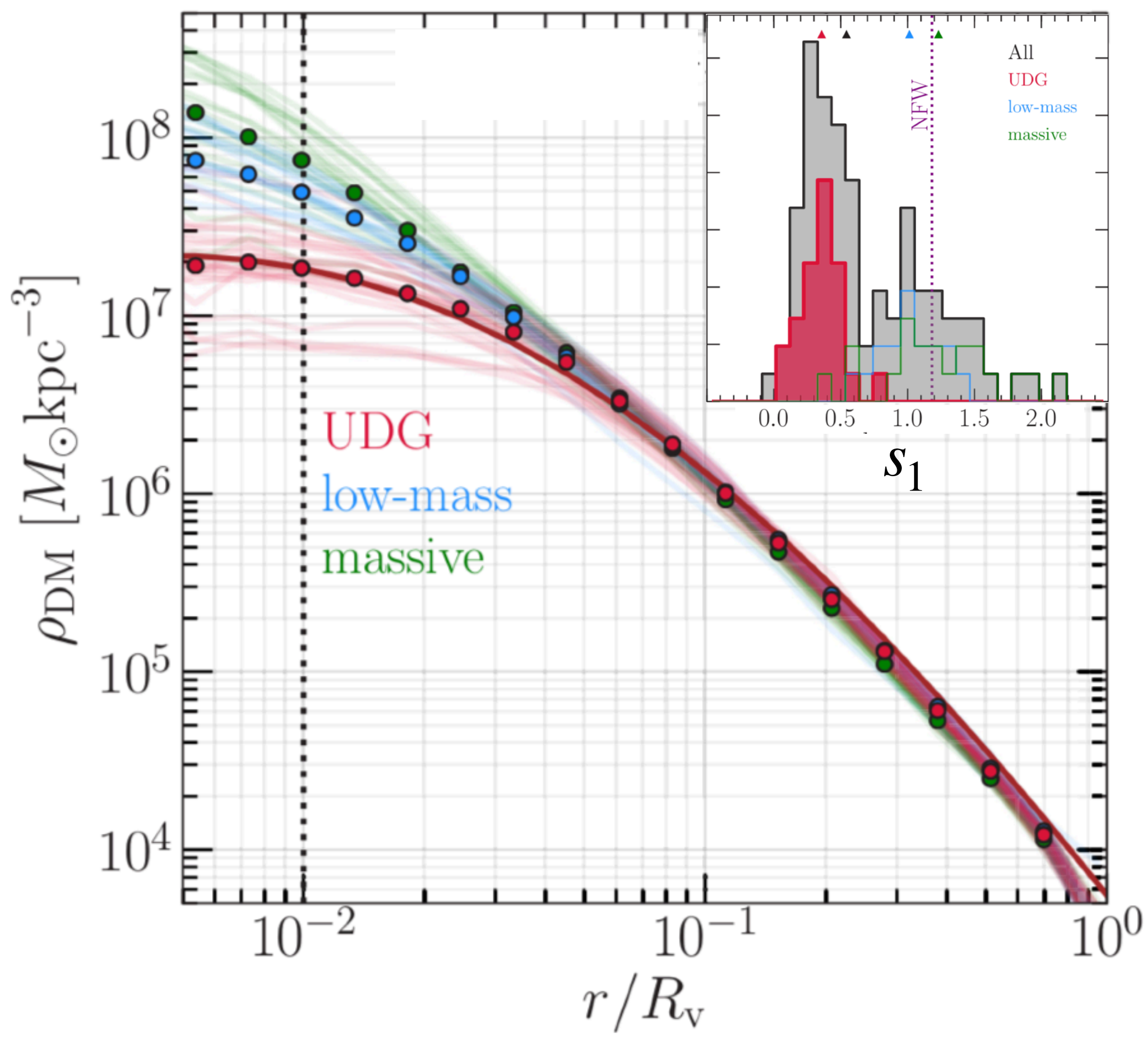
Consequences of feedback-induced core formation:

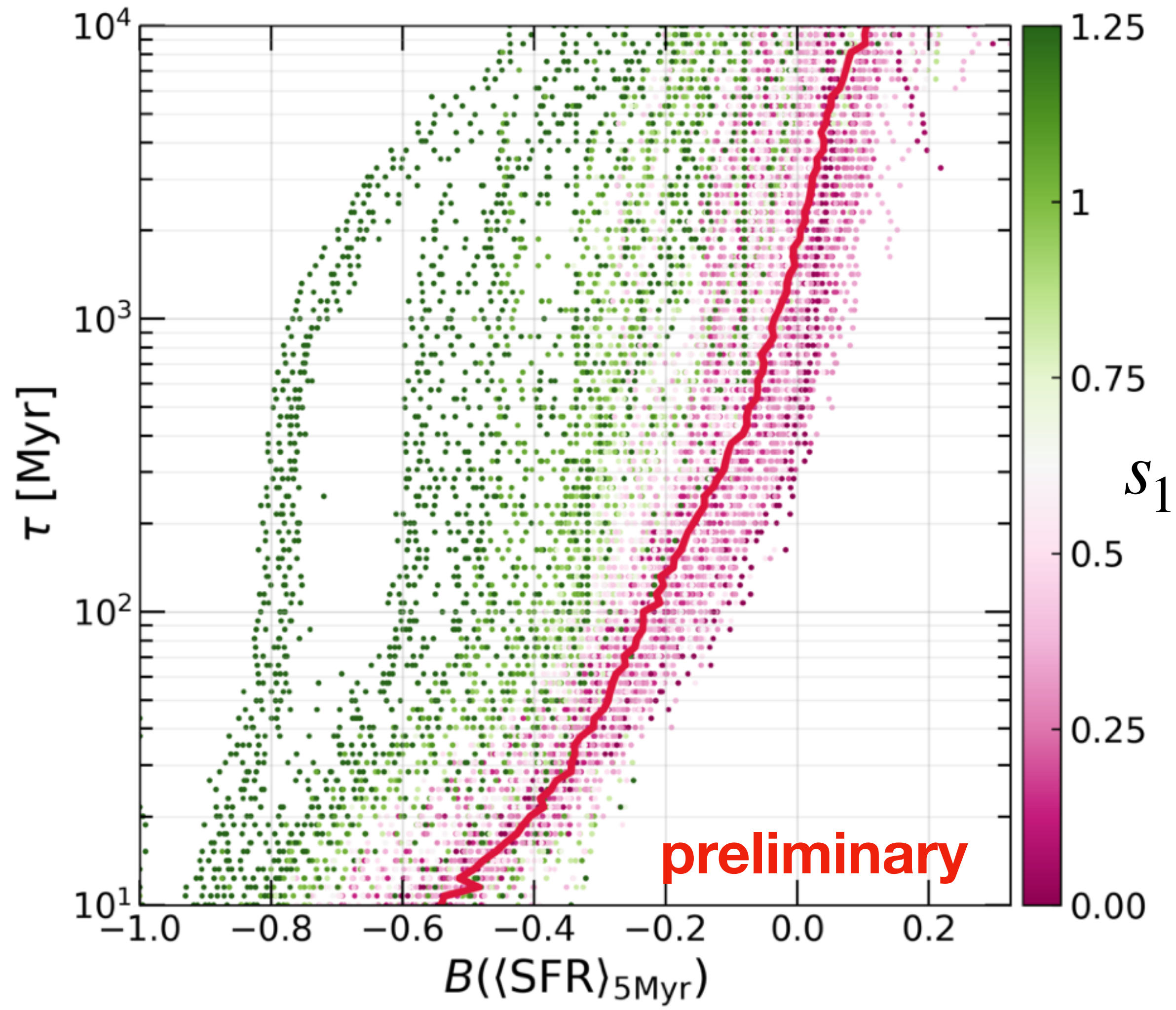
— UDGs should have **cored** dark matter density profiles

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

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

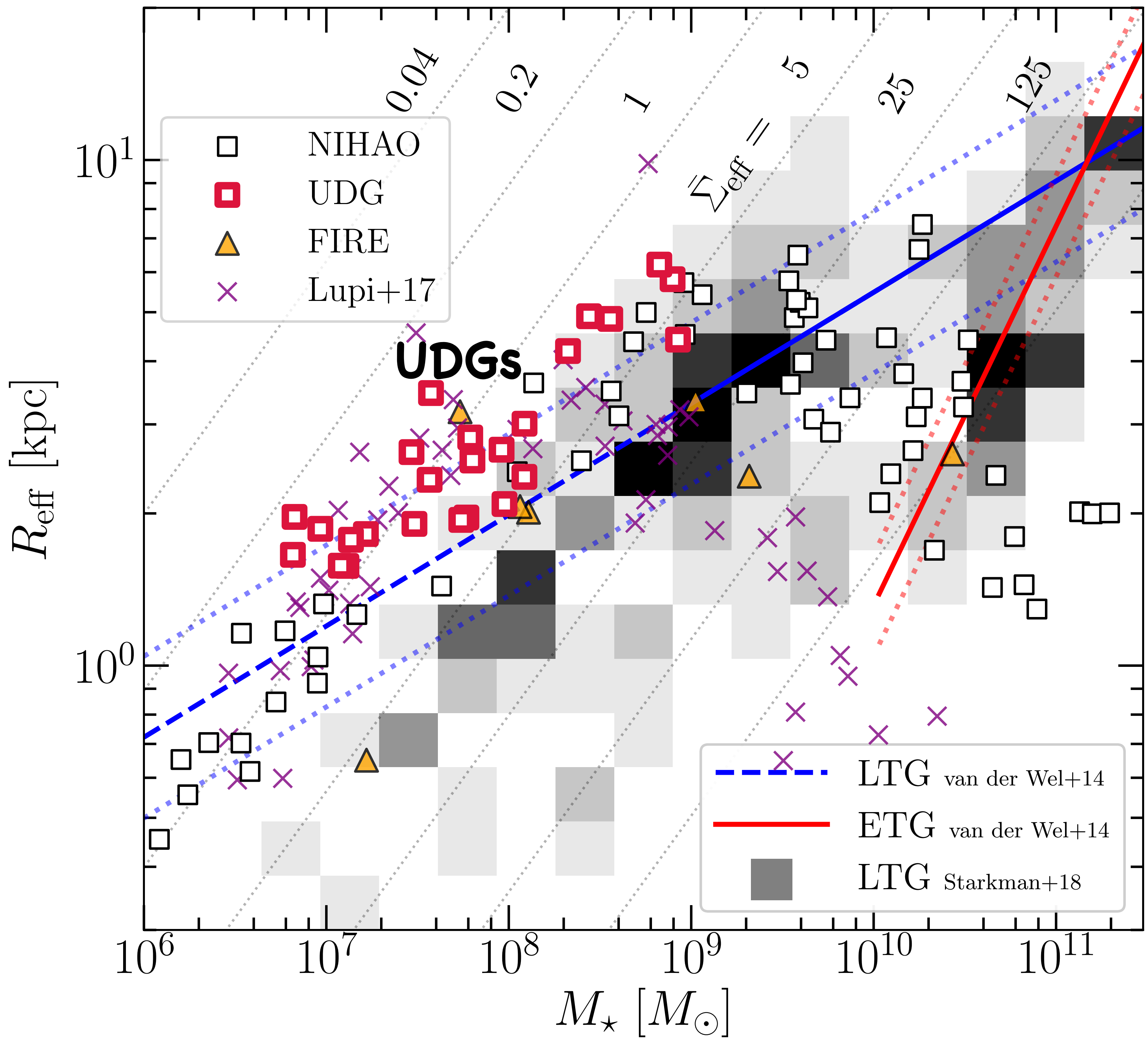






Jiang, Dekel, Freundlich et al. 2019, He, Jiang et al. in prep.

A dwarf galaxy diversity problem in simulations



Jiang, Dekel, Freundlich et al. 2019

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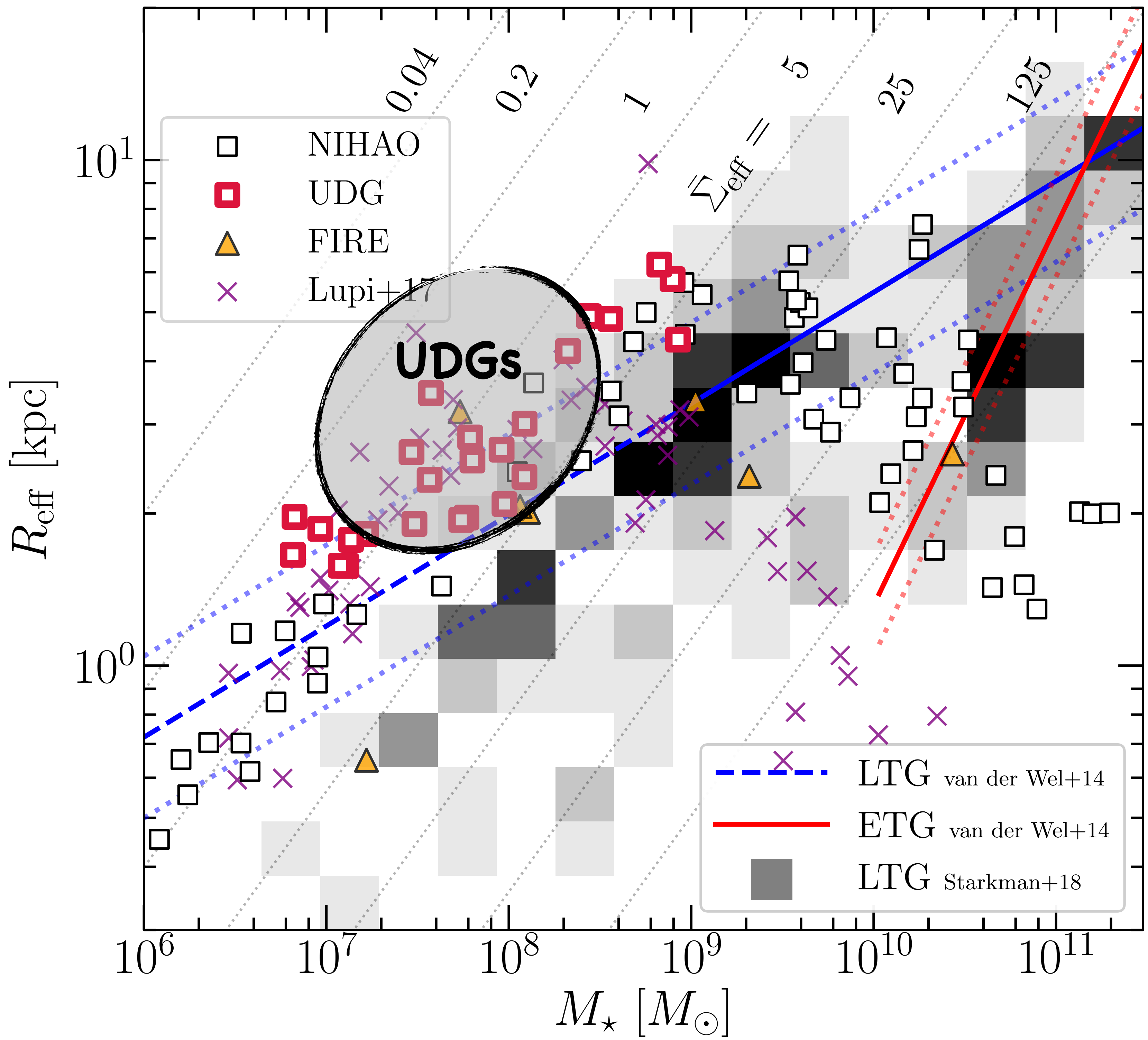

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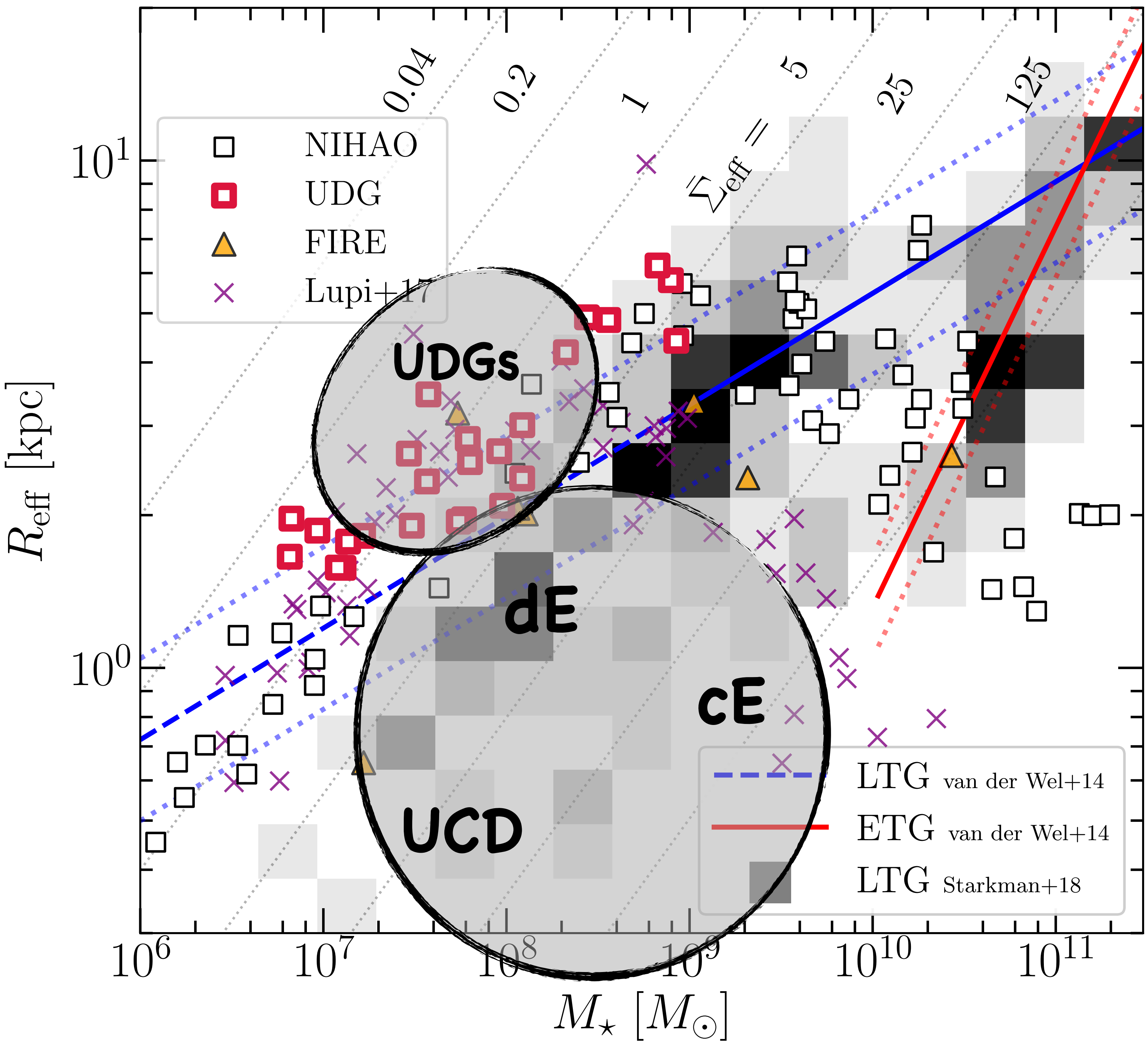

Jiang, Dekel, Freundlich et al. 2019

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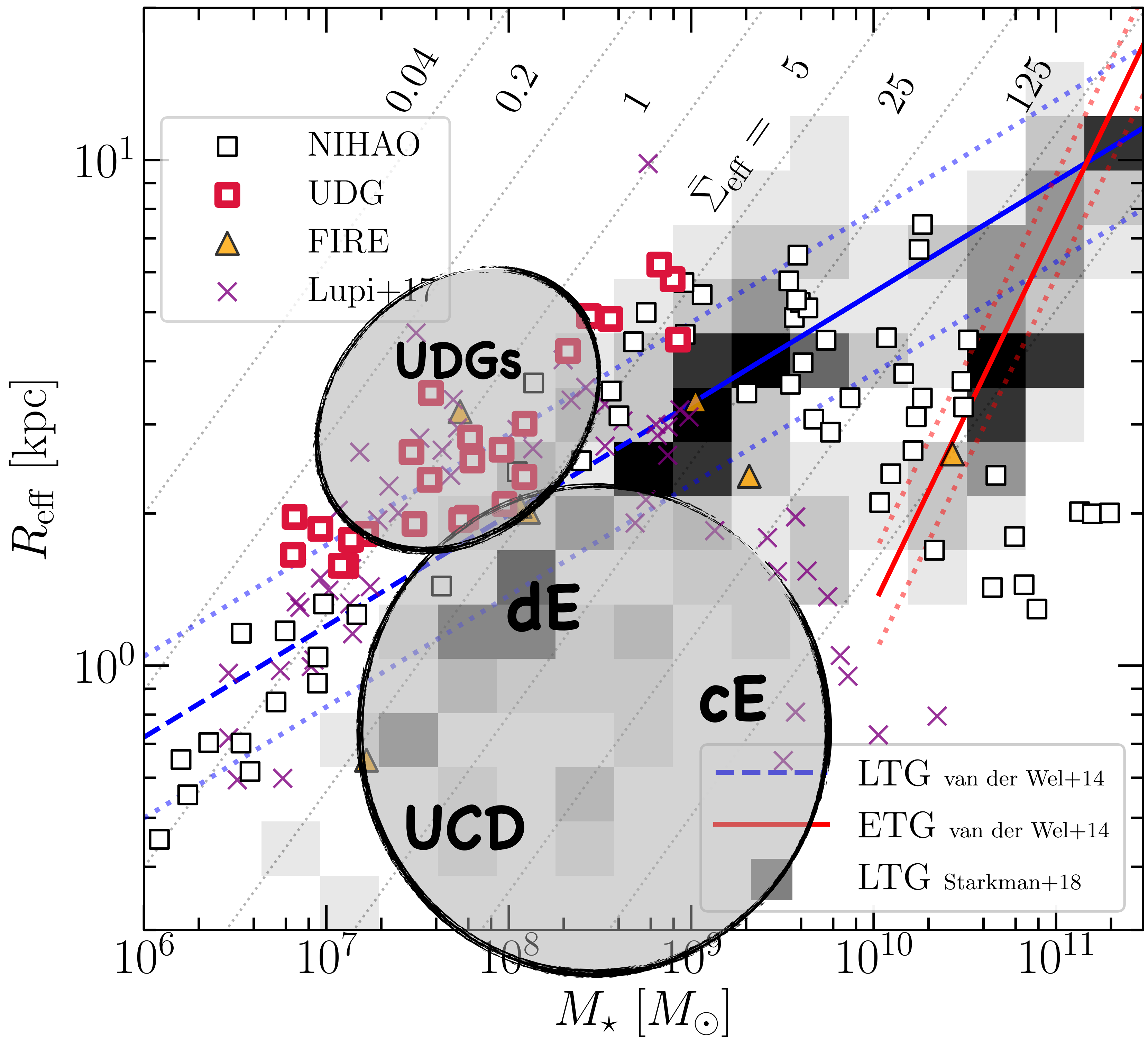
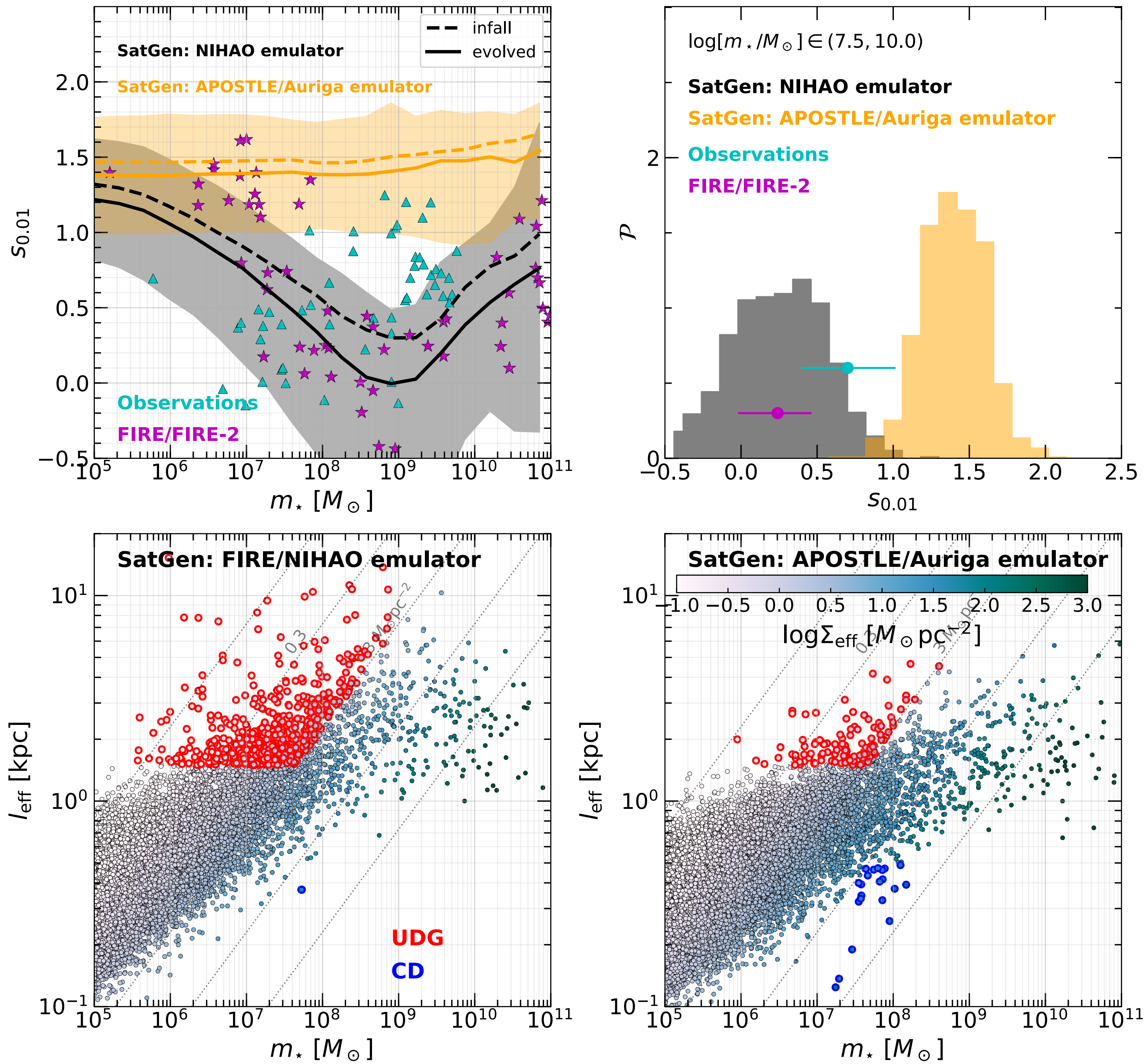


A simulation issue: simulations that form UDGs may not form compact dwarfs.

Jiang, Dekel, Freundlich et al. 2019

Distinguishing halo response (feedback) models with dwarfs



Credits: F. Jiang

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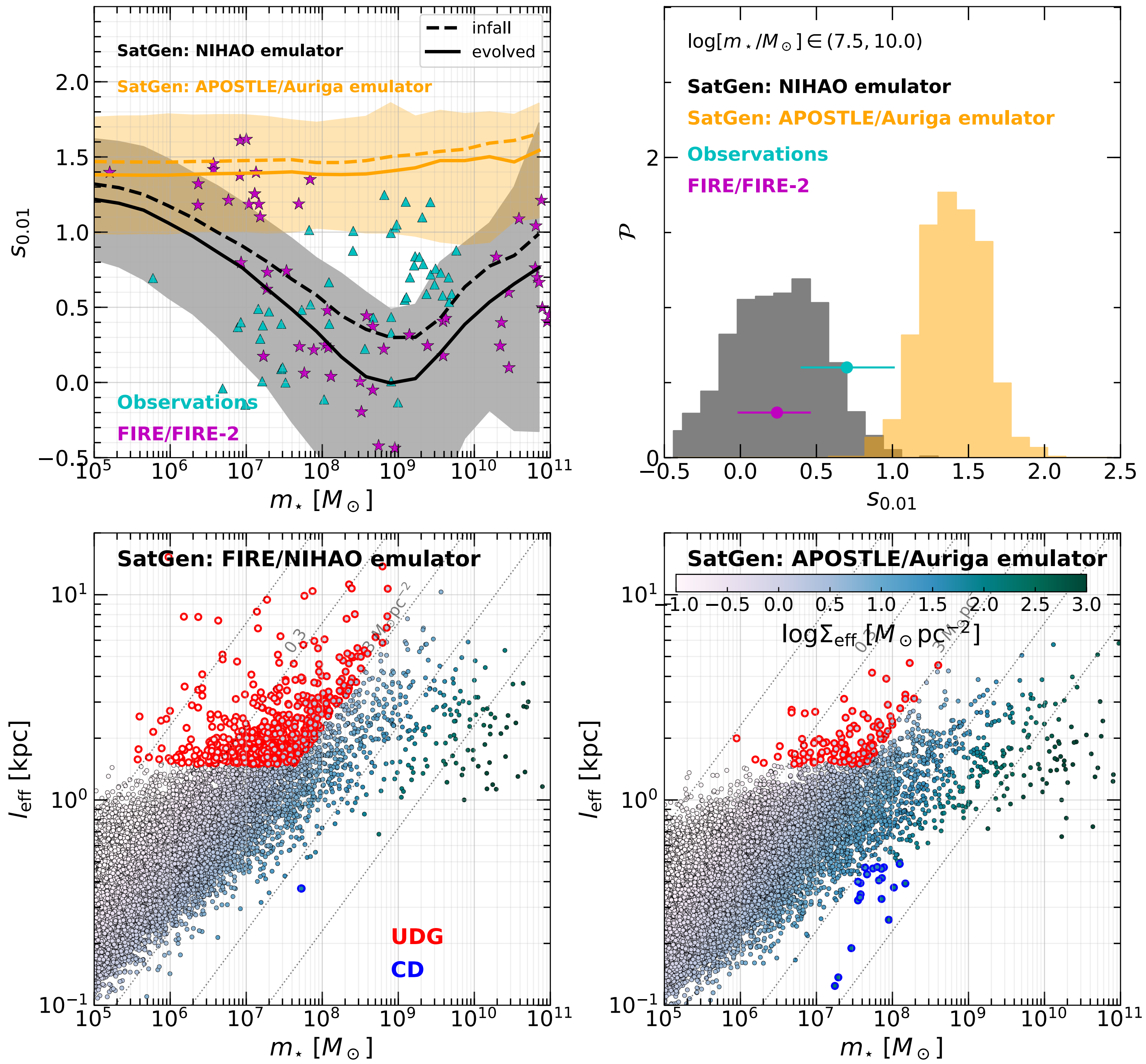
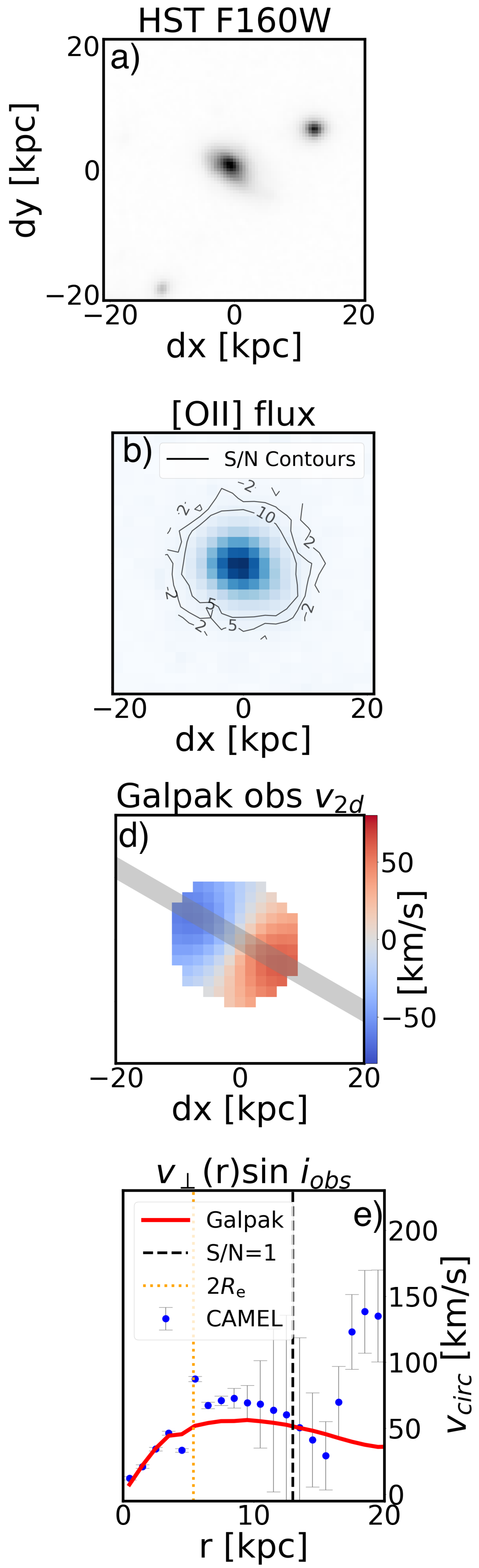
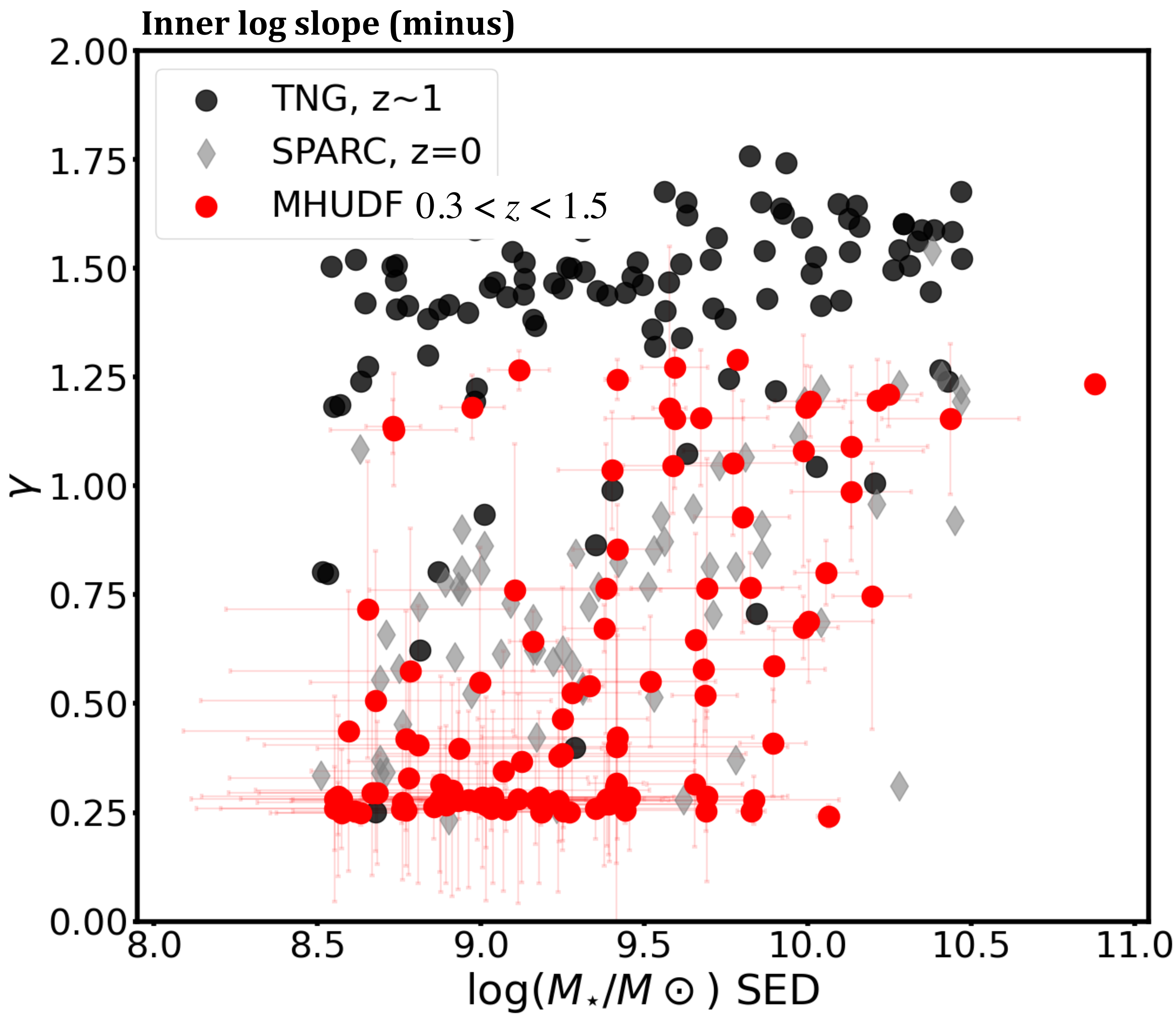


Dwarf galaxy populations in simulations may help distinguish halo response and/or feedback models.

Credits: F. Jiang

Where do observations lie?





Ciocan et al. 2025

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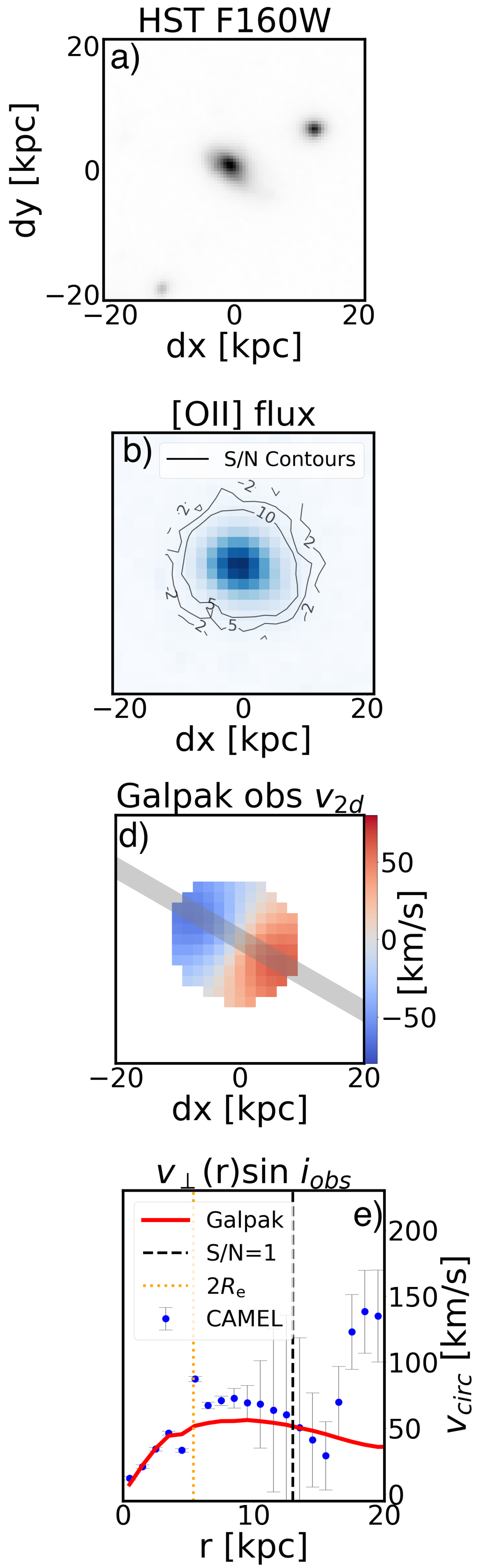
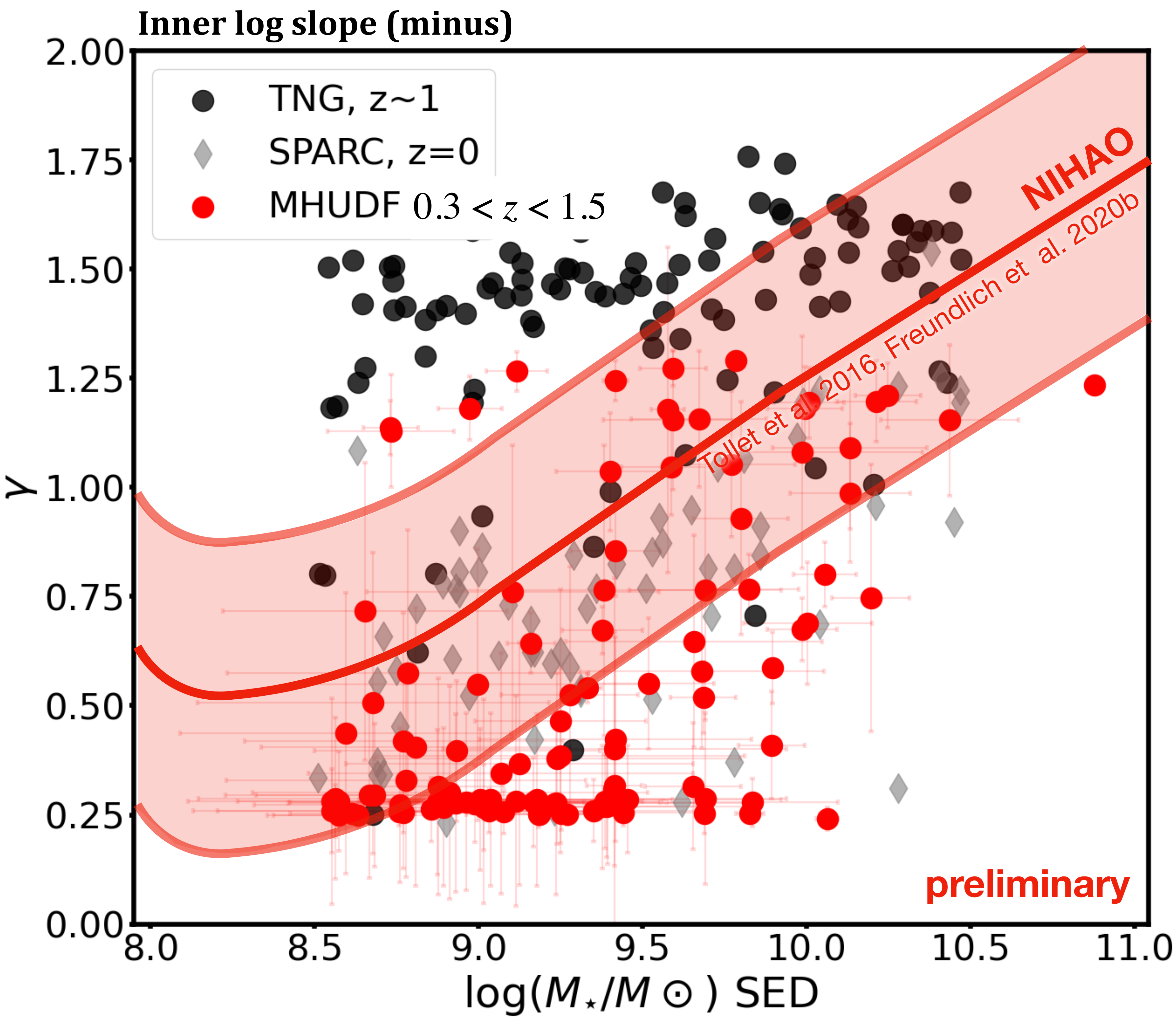




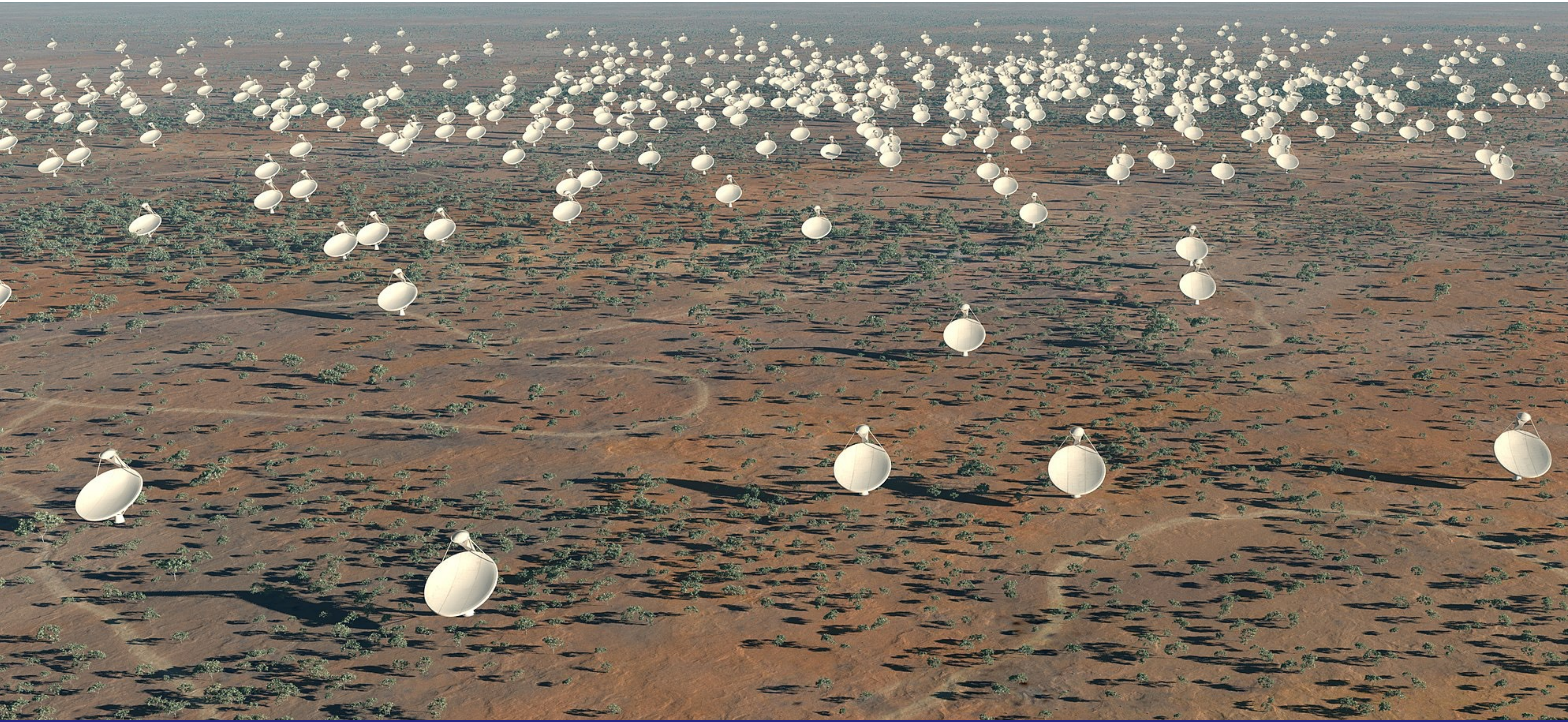
Ciocan et al. 2025

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 (up to z~1)

➡ Indirectly constraining **feedback processes** through the diversity of halo shapes



FR EN

Jonathan Freundlich

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- Registration management ▾
- Website ▾

SKA: AN OBSERVATORY FOR THE ENTIRE COMMUNITY

The Square Kilometre Array (SKA) opens up new horizons that could revolutionize our understanding of the Universe, from the cosmic dawn, large structures, and galaxies to the Solar System, and through the interstellar medium, stars, (exo)planets, the Sun, and transient astrophysical phenomena. As we approach full operationality, it is crucial for the French astrophysics community to consolidate its expertise, foster synergies among researchers from different fields, and strategically prepare for the scientific opportunities this instrument will bring.

This conference, led by the CSAA, aims to be widely accessible to the entire community that could be interested in using the SKA observatory, and non-experts in radio astronomy are particularly welcome. The goal is to bring together the entire French community that could benefit from the SKA. The first day (Tuesday 19 May) will introduce methods and infrastructures, including usage demonstrations; the second day (Wednesday 20 May) will present the scientific opportunities offered by SKA for each relevant Action Thematique with dual talks aiming at bridging the gap between experts in radio astronomy and non-experts; and the third day (Thurstay 21 May) will focus on synergies with existing and upcoming instruments. There will be no contributed talks, but ample time for discussions. Postdoctoral researchers and doctoral students are especially welcome.

INVITED SPEAKERS

TBA

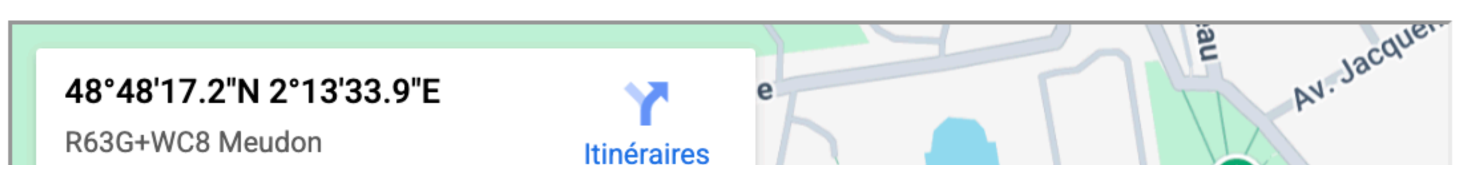
LOCATION

The conference will take place in the **amphithéâtre Evry Schatzman** in the Meudon campus of the Paris Observatory, building 18.

Pedestrian access: 5, place Jules Janssen, 92195 Meudon

Vehicule access: 1, avenue Marcelin Berthelot, 92195 Meudon

Standard : +33 1 45 07 74 60



KEY DATES

May 19th 2026: beginning of the conference

May 21st 2026: end of the conference

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C. Briand
P. Charlot
B. Famaey
C. Ferrari
J. Freundlich
B. Godard
A. Gorce
A. Gusdorf
F. Le Petit
B. Magnelli
N. Meunier
M.-A. Miville-Deschenes
C. Ng-Guiheneuf
V. Hue
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LOC

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Announcement :

Large SKA conference led by the CSAA
for the entire INSU community
19-21 May 2026, Paris

https://ska-meudon2026.sciencesconf.org/

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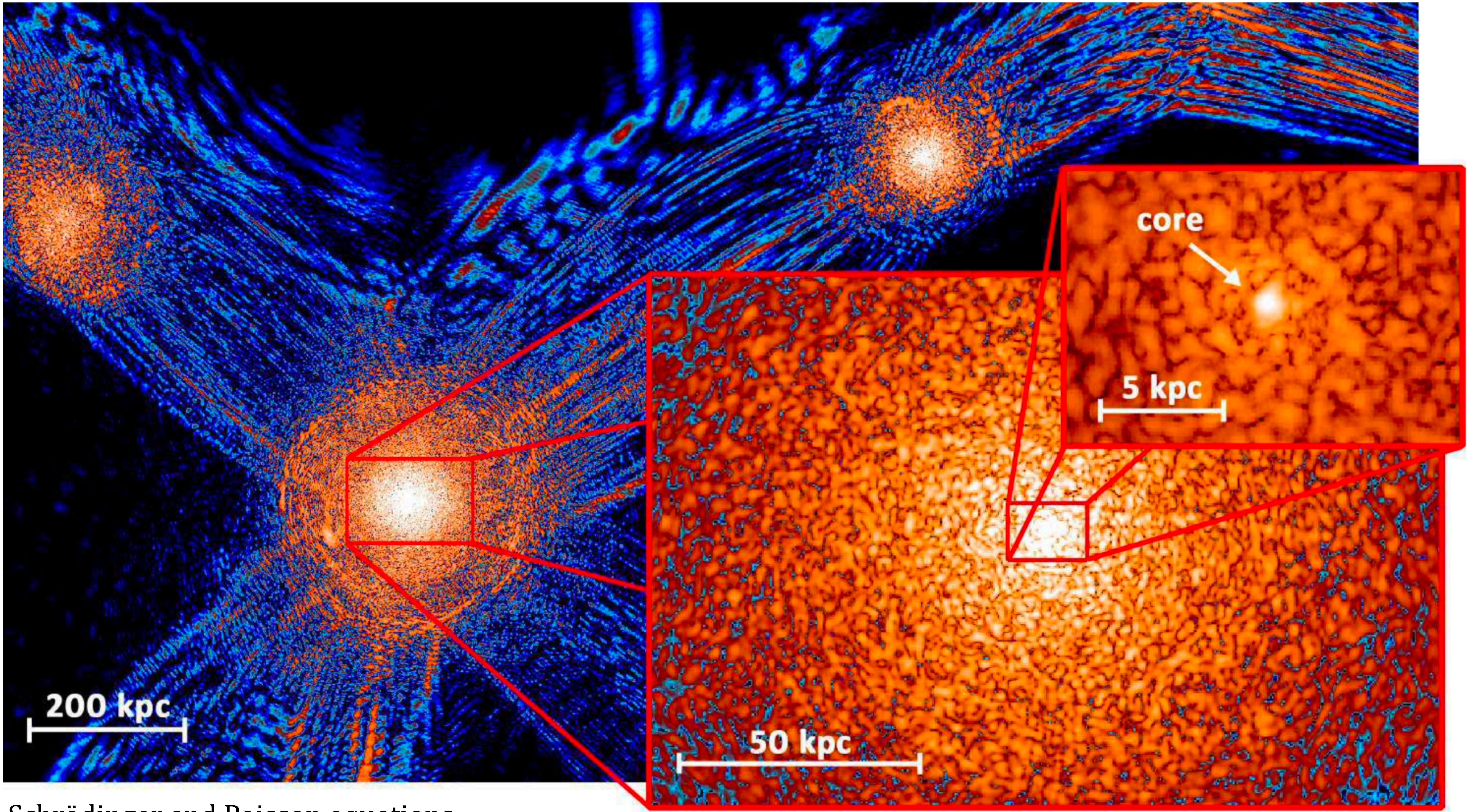
A non-standard dark matter candidate: fuzzy dark matter (FDM)



Schrödinger and Poisson equations:

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

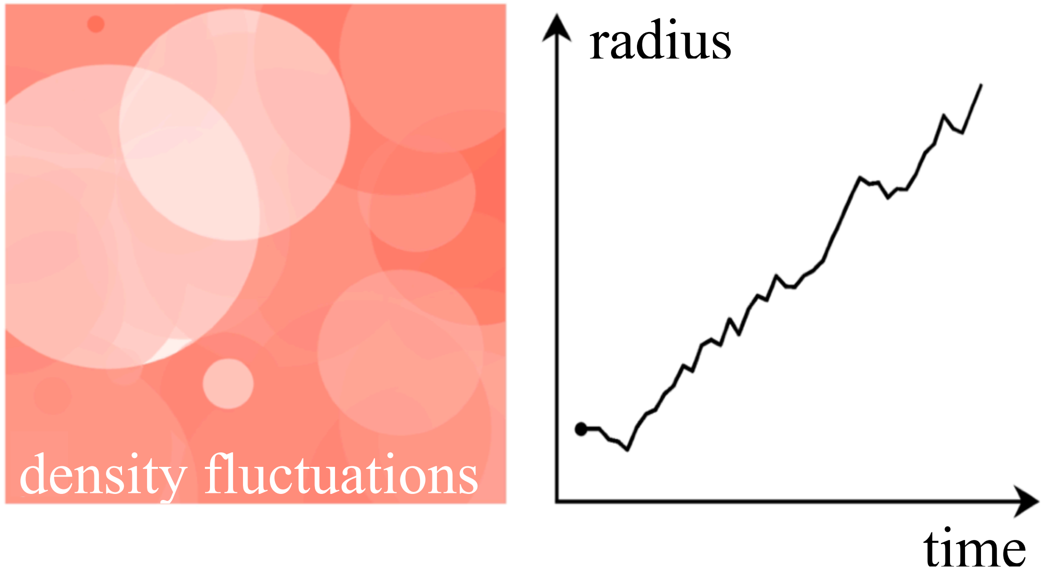
$$\nabla^2\Phi_s(\mathbf{r},t) = 4\pi G\ |\psi(\mathbf{r},t)|^2$$

Interferences, granules, core

Schive et al. (2014)

Constraining fuzzy dark matter through 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



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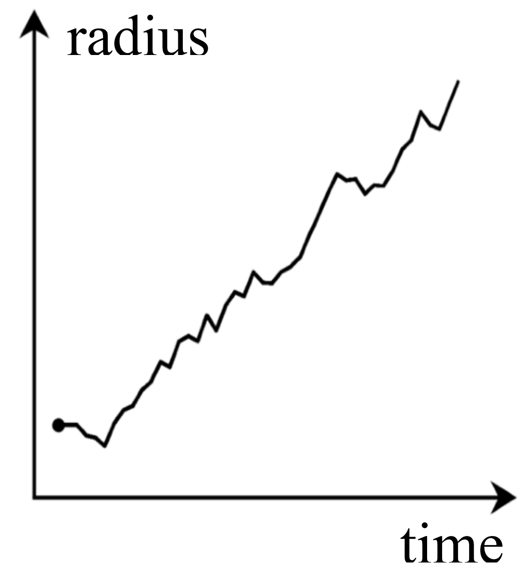

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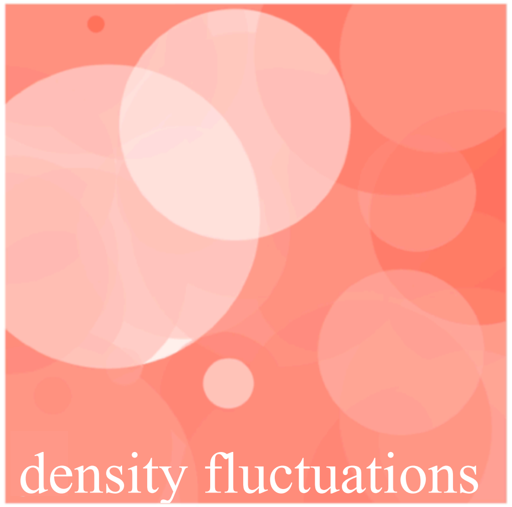
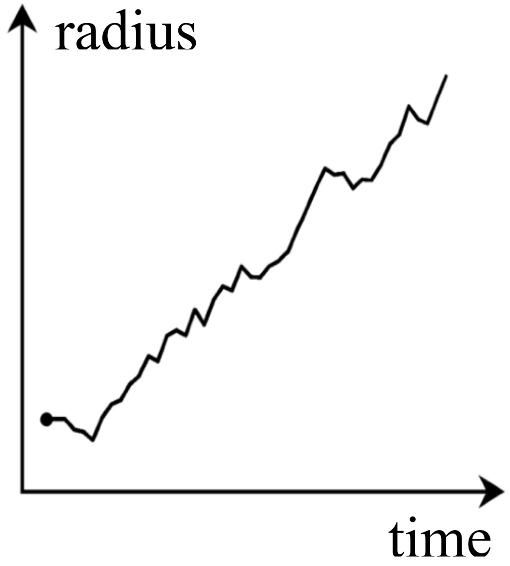
➡ FDM particle mass $m > 2 \times 10^{-22}$ eV from the local velocity dispersion in the Milky Way





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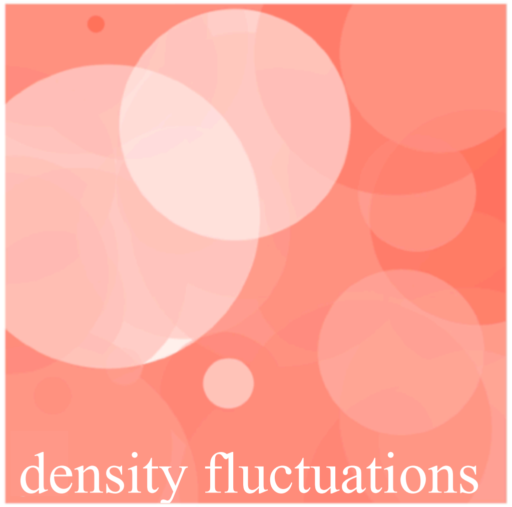
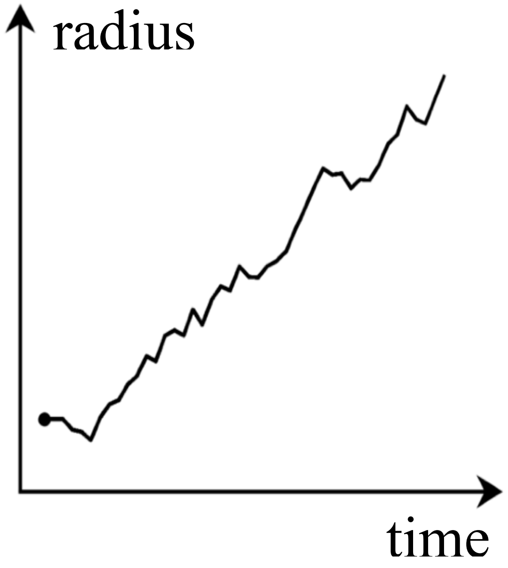
➡ Stronger constraints can in principle be obtained, but some caveats.





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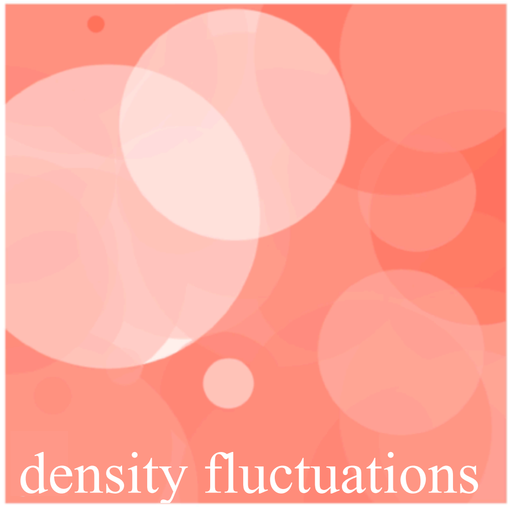
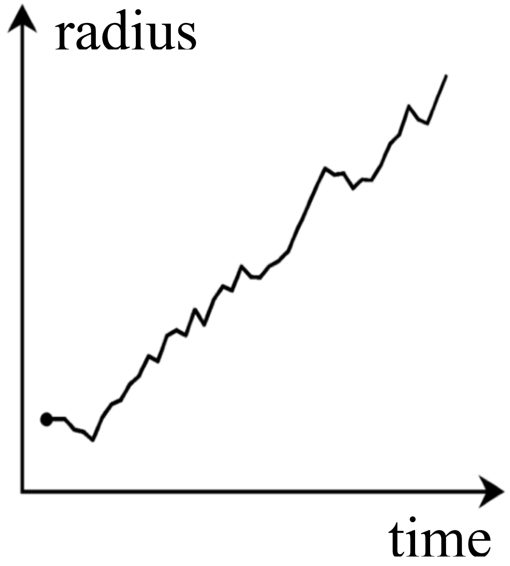
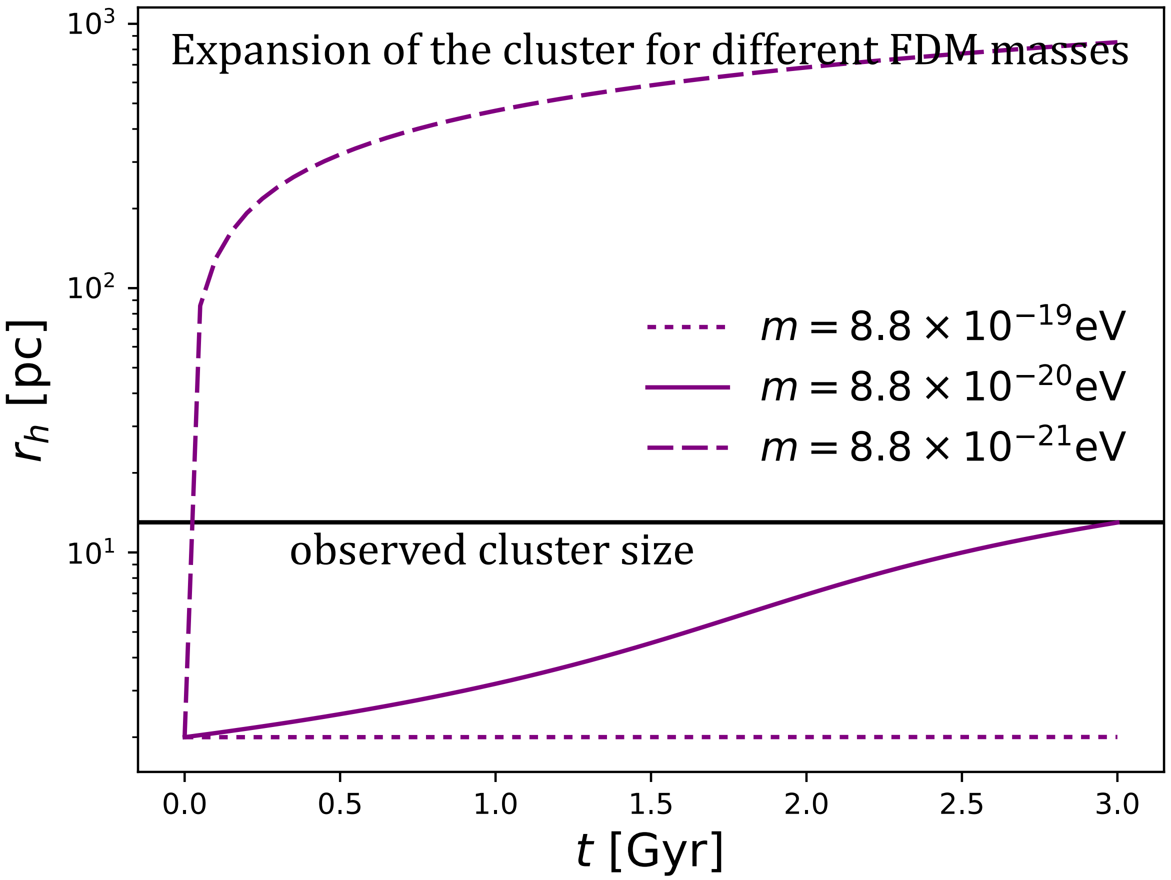
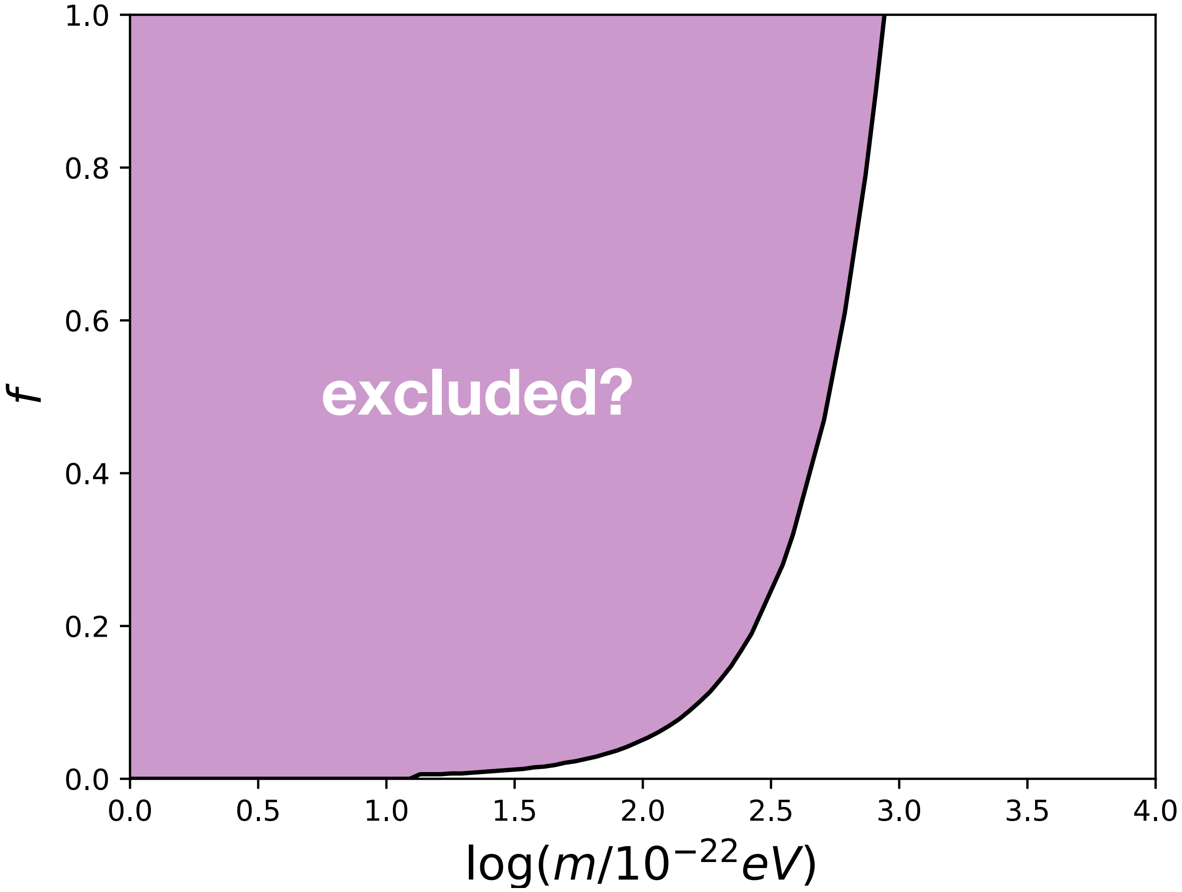
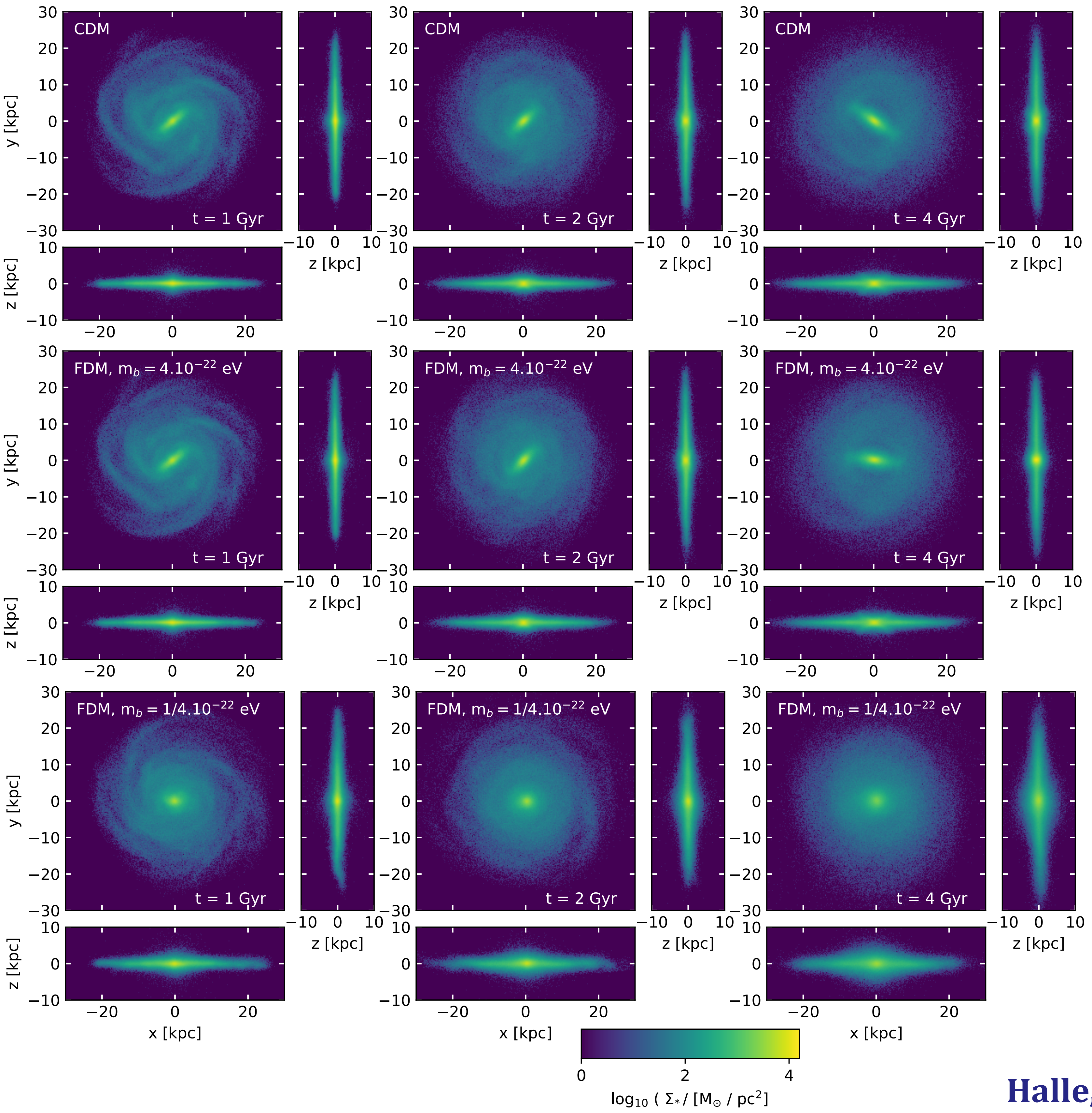








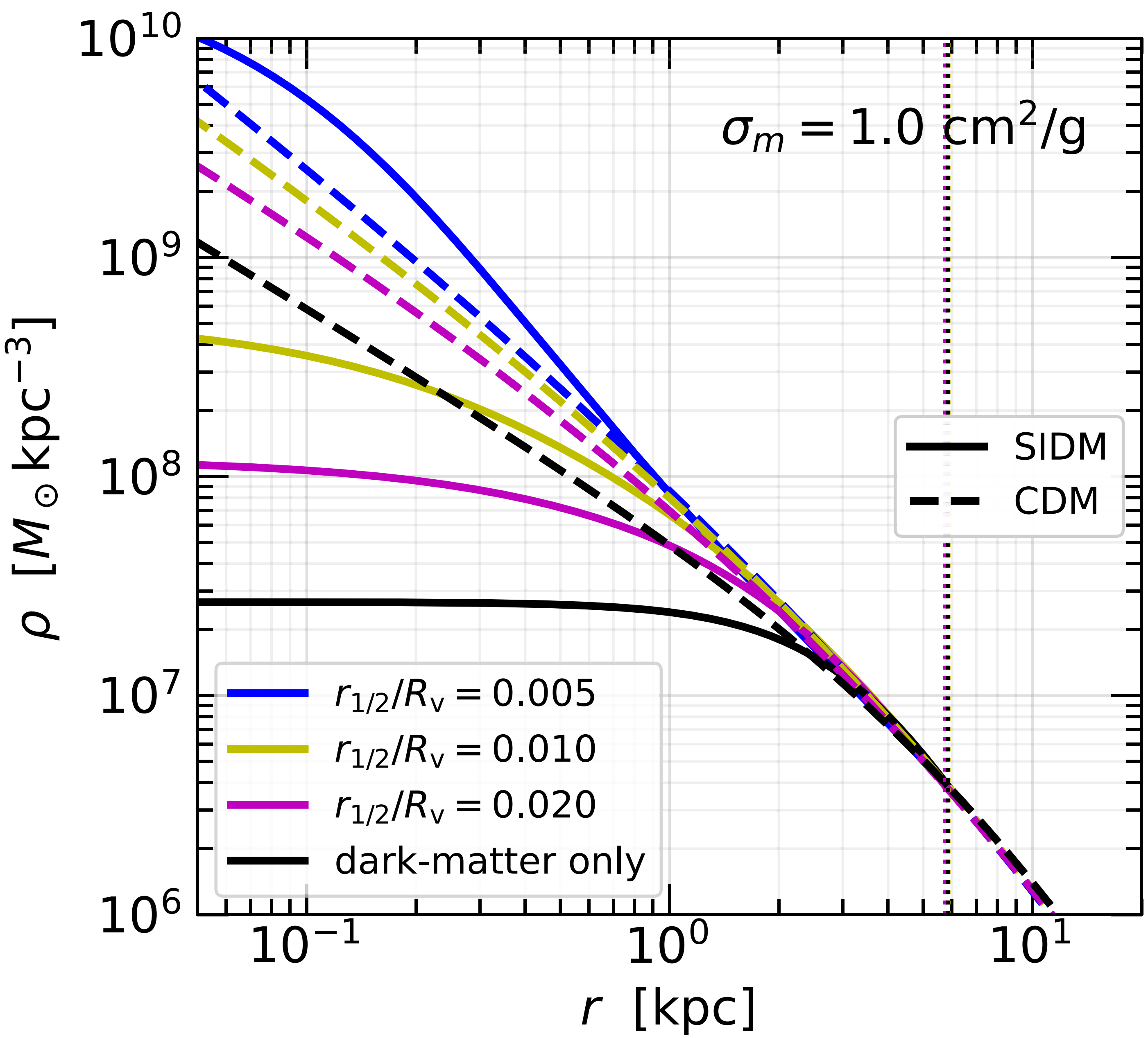
Effect of FDM fluctuations on galactic disks



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.

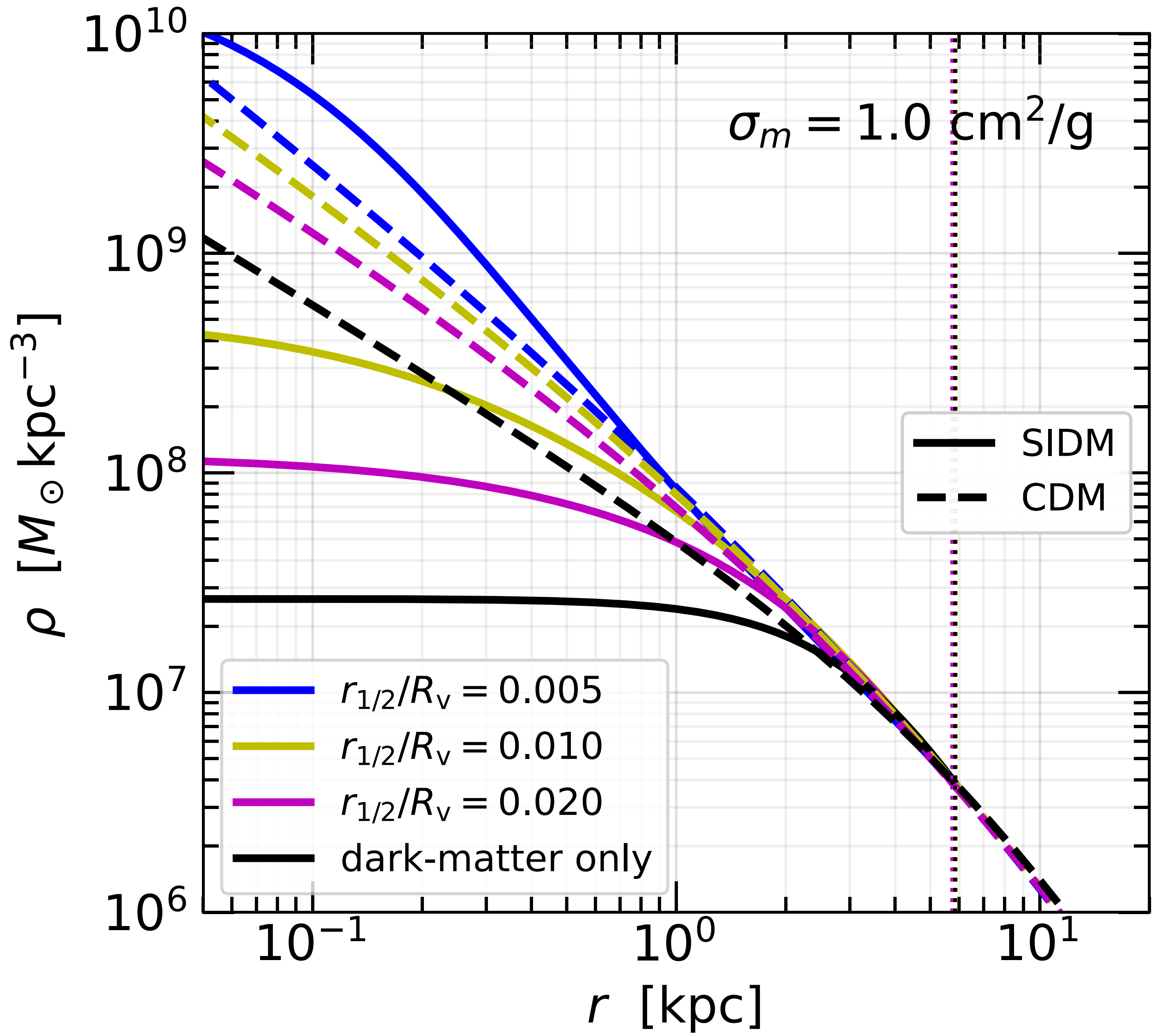
Effect of baryons on self-interacting dark matter (SIDM) haloes?



Jiang et al. (2023)

Effect of baryons on self-interacting dark matter (SIDM) haloes?

- Self-interactions of dark matter heat up the central region, inducing cores.



Jiang et al. (2023)

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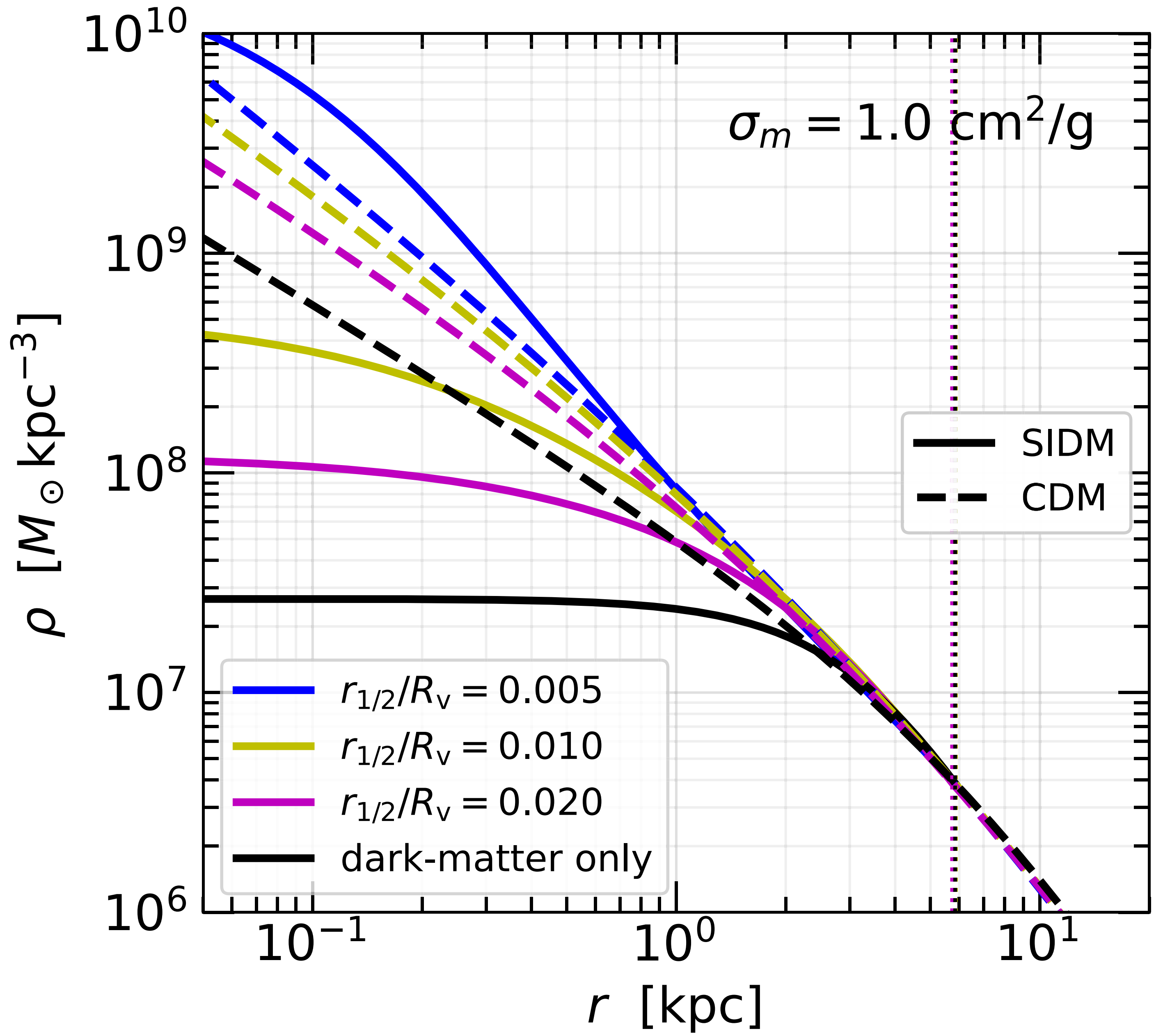

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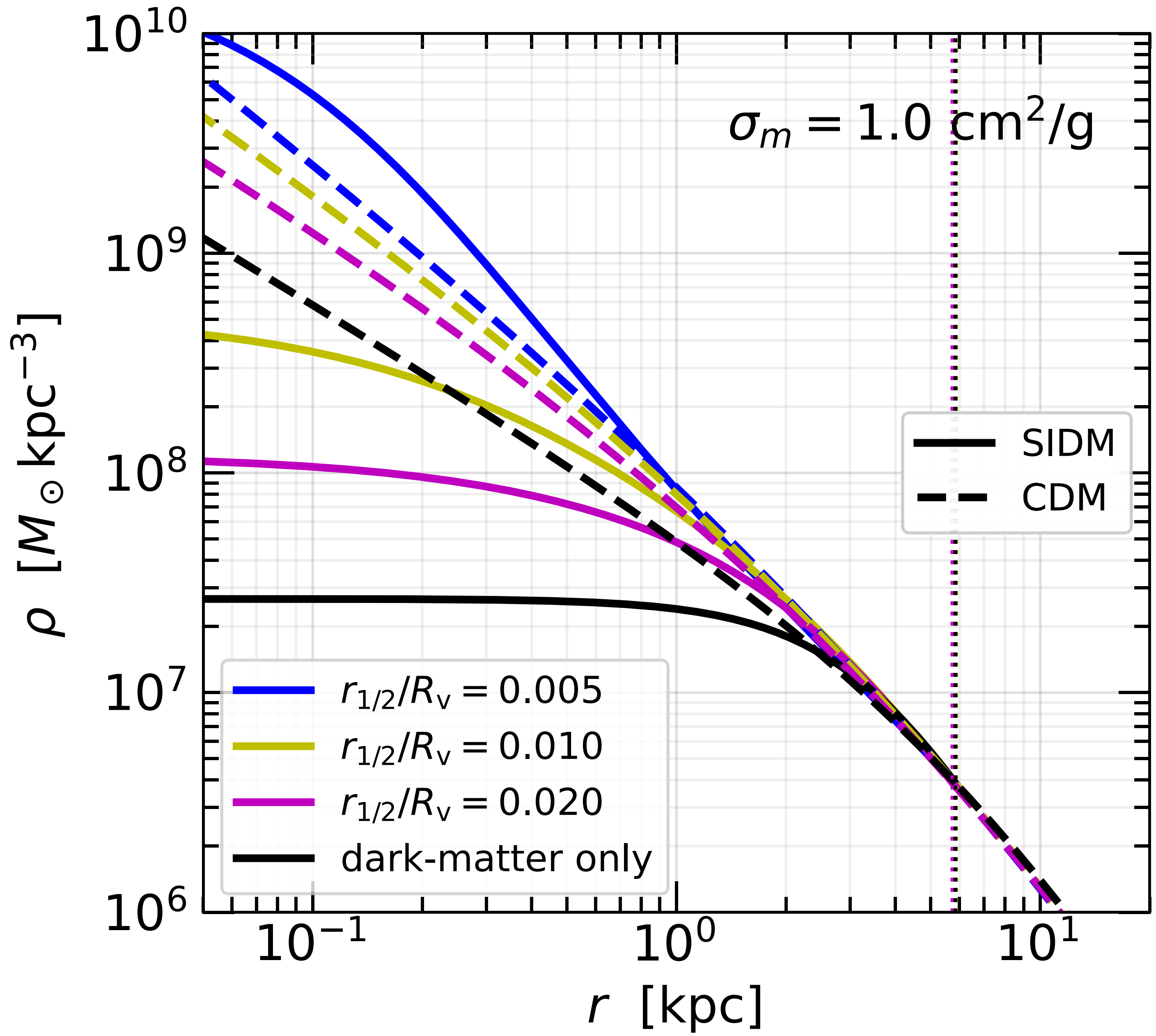
- SIDM haloes may be more responsive to baryons, leading to a diversity of dark matter halo profiles.
- Is feedback less relevant than adiabatic contraction?



Jiang et al. (2023)

Conclusion

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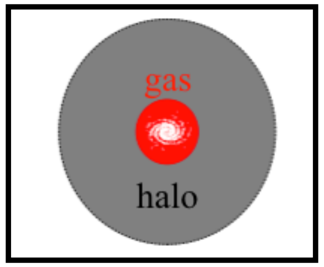
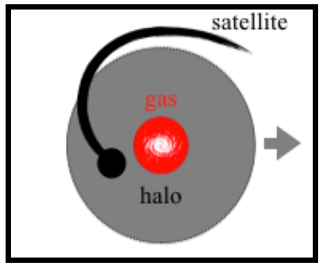
Conclusion

Modeling core formation from baryonic feedback processes

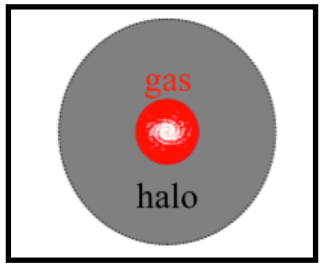
- Feedback effects modeled as **bulk gas outflows**
- Feedback effects modeled as **stochastic density fluctuations** in the interstellar medium
- Combined effect of bulk outflows and **dynamical friction** (which can in itself contribute to core formation)

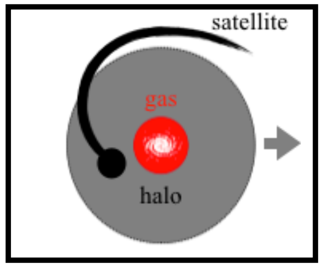




Conclusion

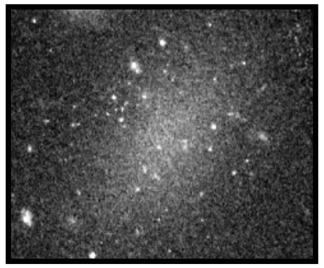
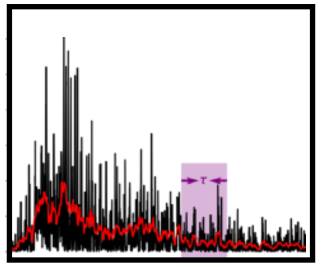
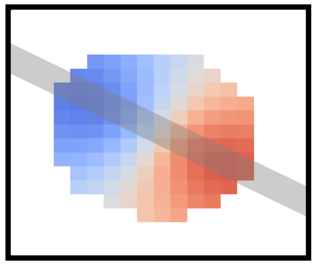
Modeling core formation from baryonic feedback processes



- Feedback effects modeled as **bulk gas outflows**
- Feedback effects modeled as **stochastic density fluctuations** in the interstellar medium
- Combined effect of bulk outflows and **dynamical friction** (which can in itself contribute to core formation)

Implications and perspectives

- **Testing** feedback-induced core formation in simulations and observations **UDGs, burstiness of the star formation history, dwarf galaxy population**
- Observational constraints on **dark matter haloes across cosmic time**
- **Constraining feedback** processes through the diversity of halo shapes

Conclusion

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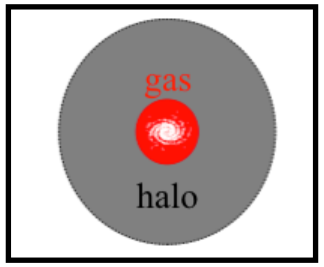

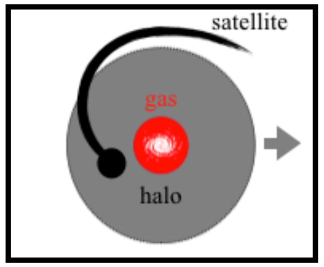

Implications and perspectives

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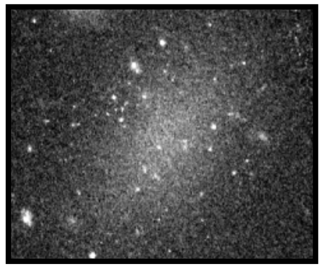
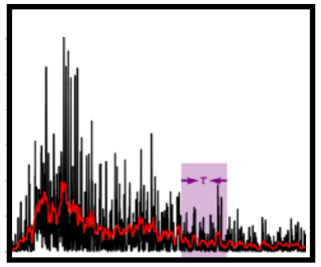
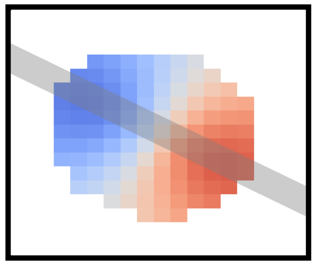
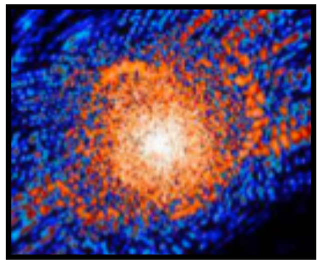


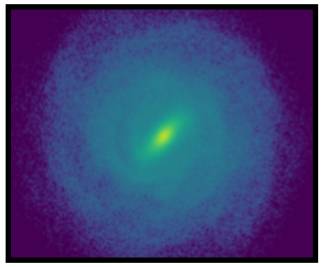


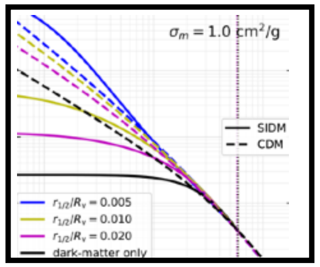


Alternatives to cold dark matter

- Constraining **fuzzy dark matter** owing to dynamical heating
- What about feedback effects in **self-interacting dark matter** haloes?
- ...







Conclusion

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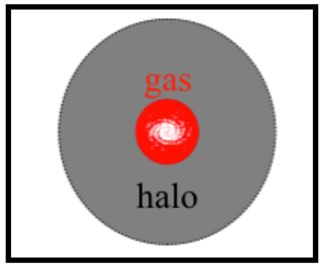

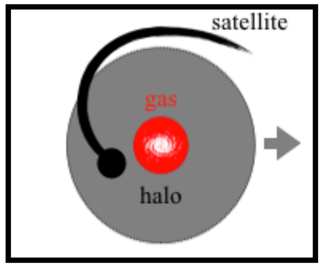

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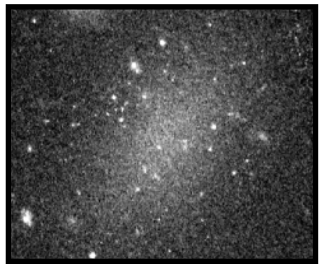

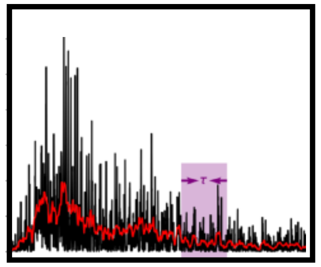

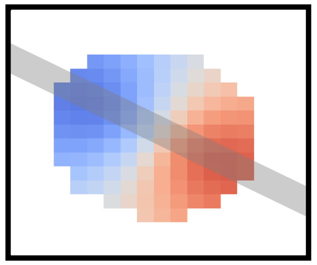

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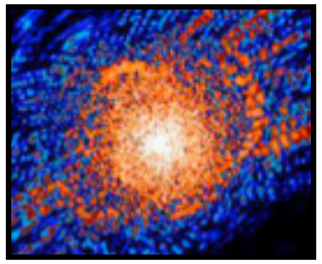

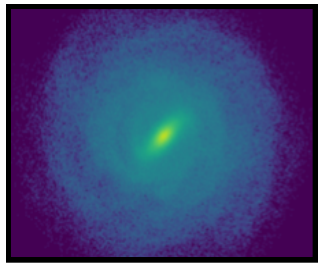

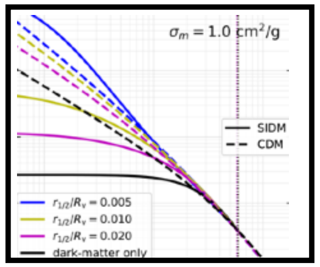

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thank you!