The response of dark-matter halos/subhalos to baryons and environmental effects — ΛCDM and SIDM

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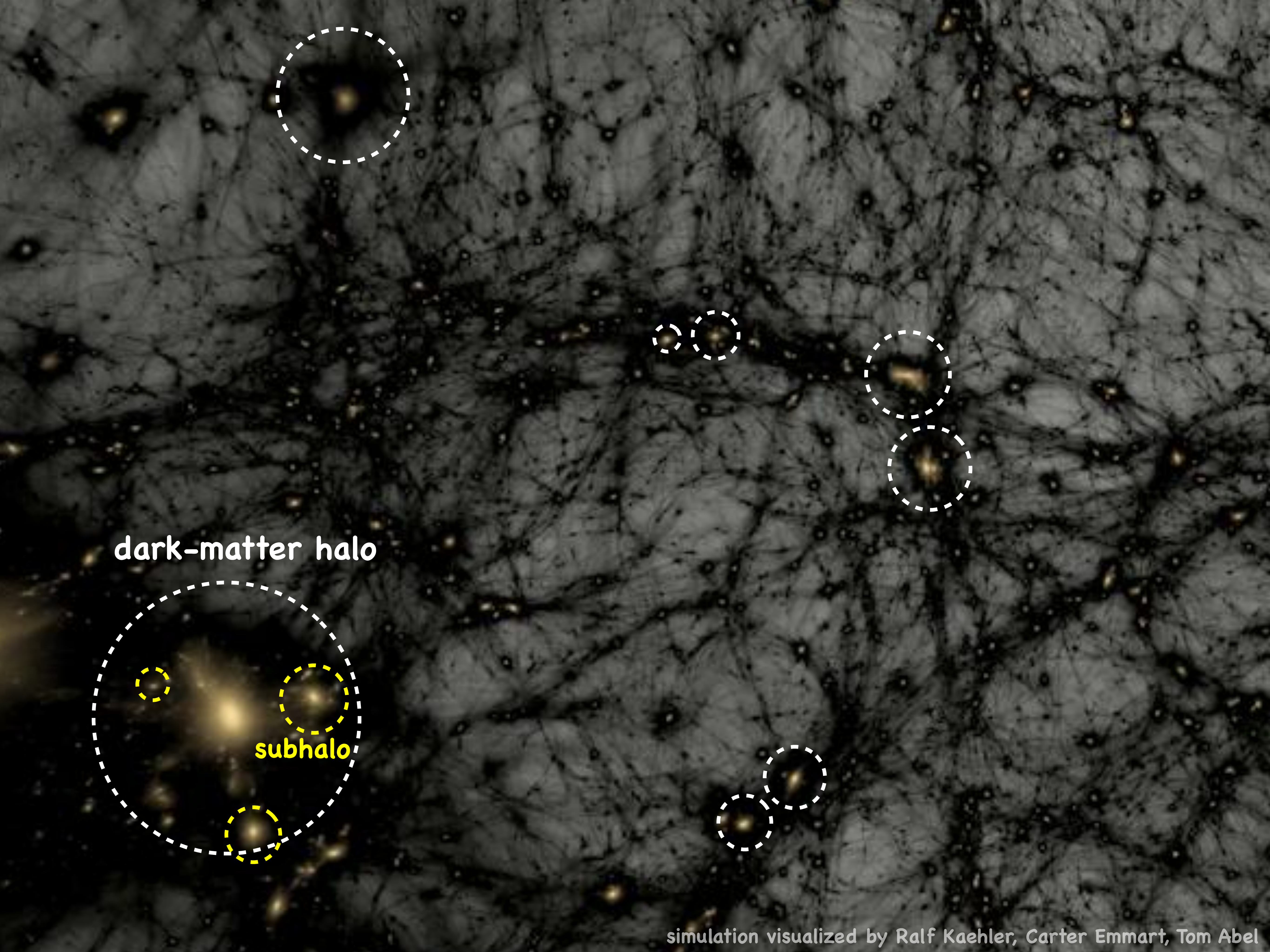
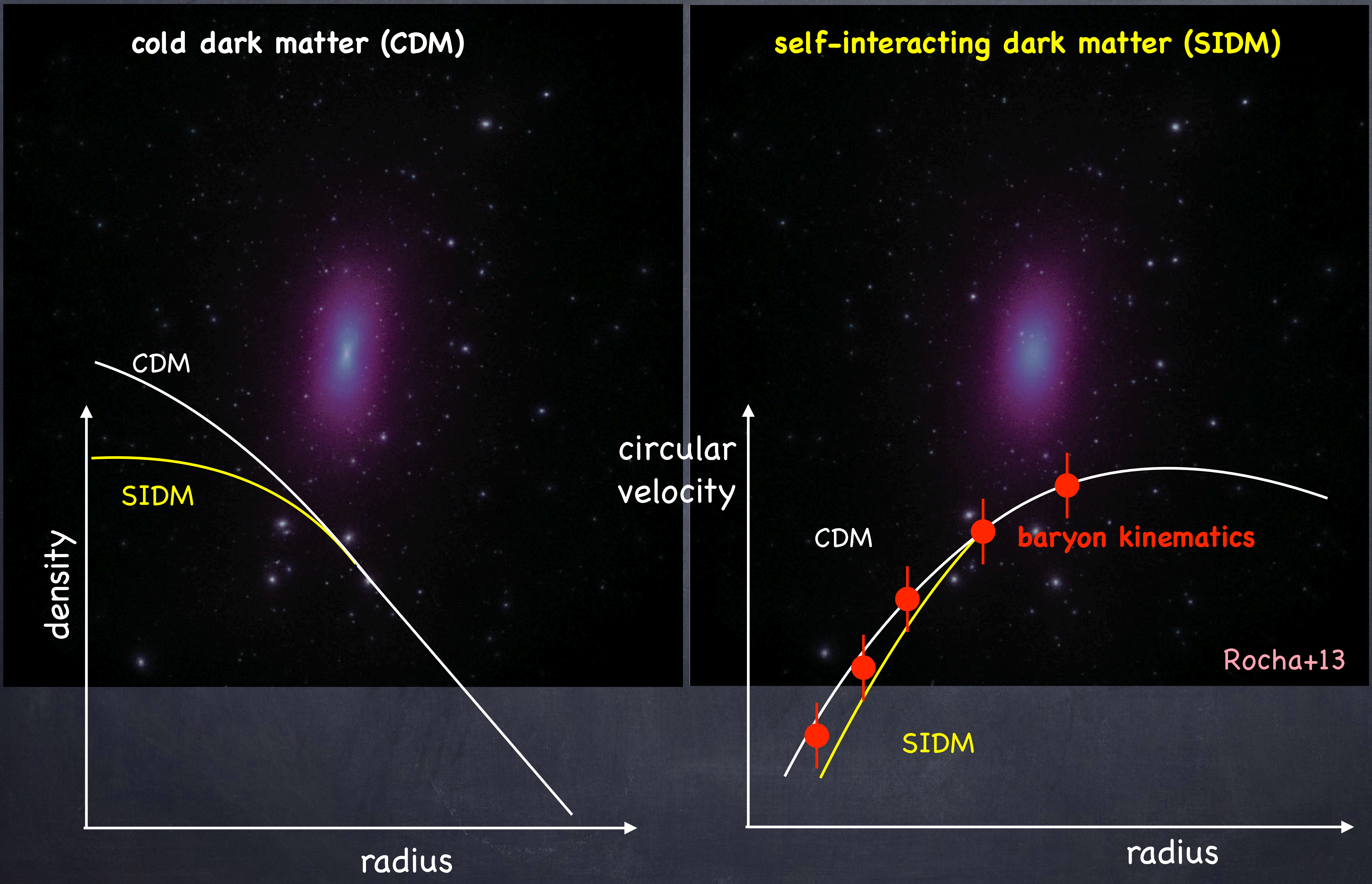
FIRE, NIHAO, VELA simulation collaborations ...

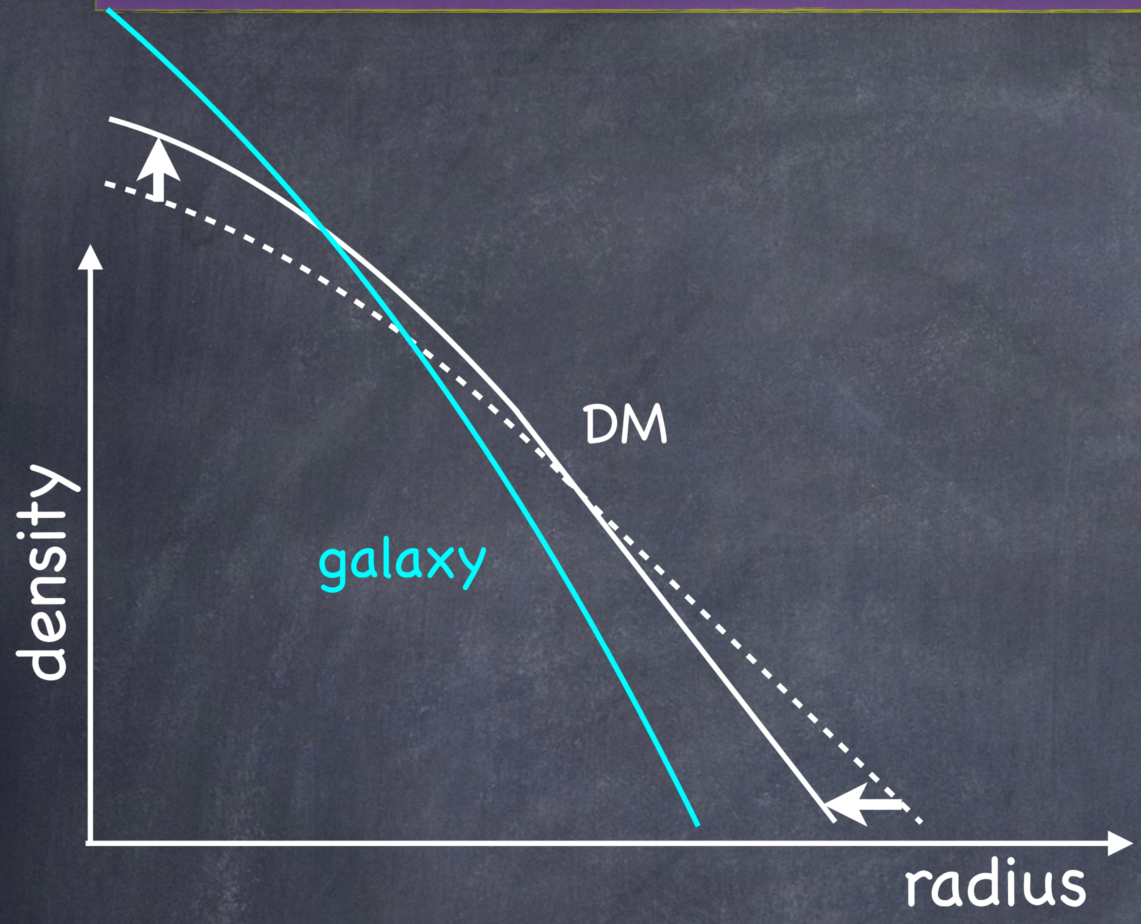
simulation visualization by Ralf Kaehler, Carter Emmart, Tom Abel

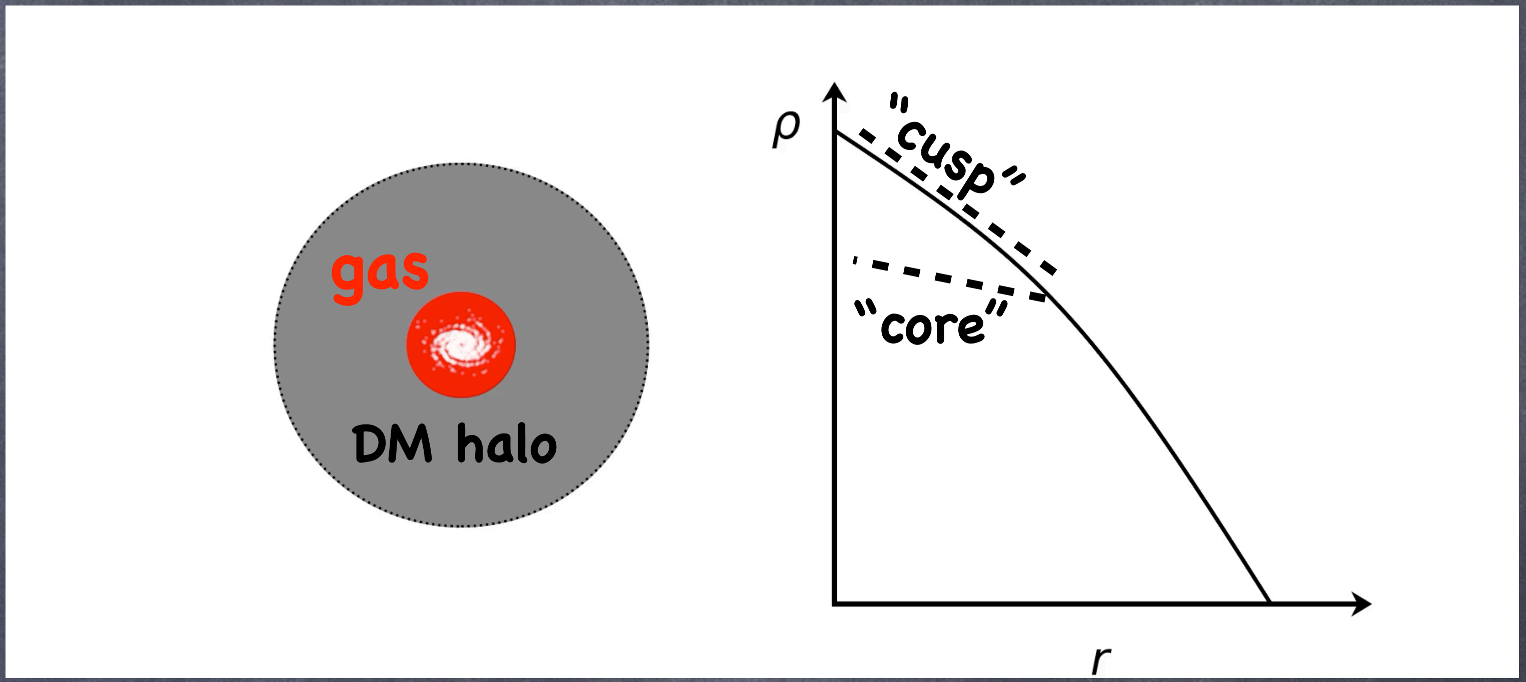

dark-matter halo
subhalo
simulation visualized by Ralf Kaehler, Carter Emmart, Tom Abel

DM halo structure contains information of cosmology



Halo structure is influenced by baryonic processes





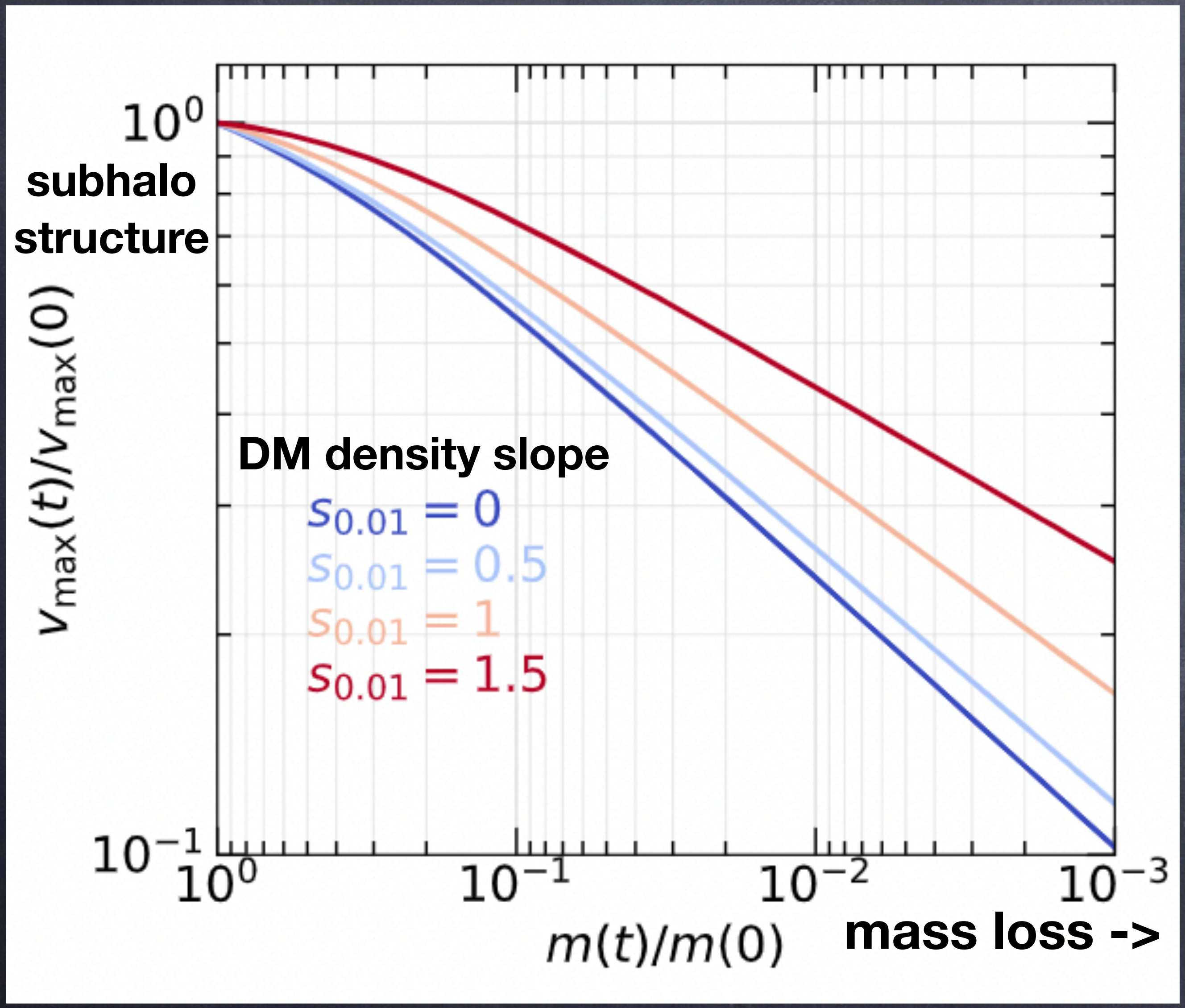
- Baryonic potential —> adiabatic contraction
- SN / AGN driven gas outflows —> expansion and cusp-core transformation

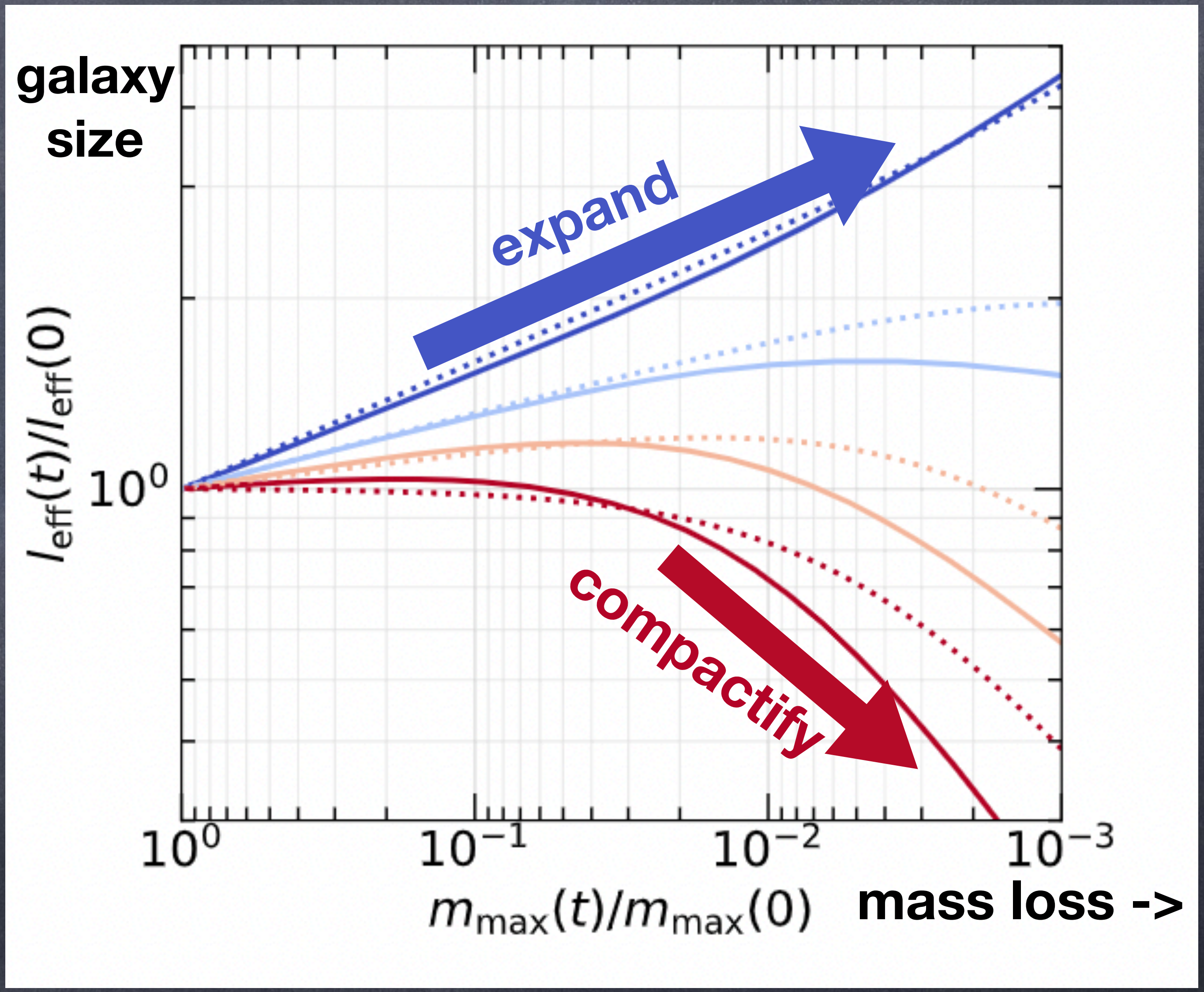
Need to understand the halo response to baryons before using halo structure to constrain cosmology

"Halo response" is amplified in dense environments -> solve small-sale issues of LCDM?

- The "**tidal evolution tracks**" depend on the initial structures and **diverge** as the satellites evolve

Hayashi+03; Penarrubia+08,10; Errani+15,18 ...
Stucker+22; Benson & Du 22





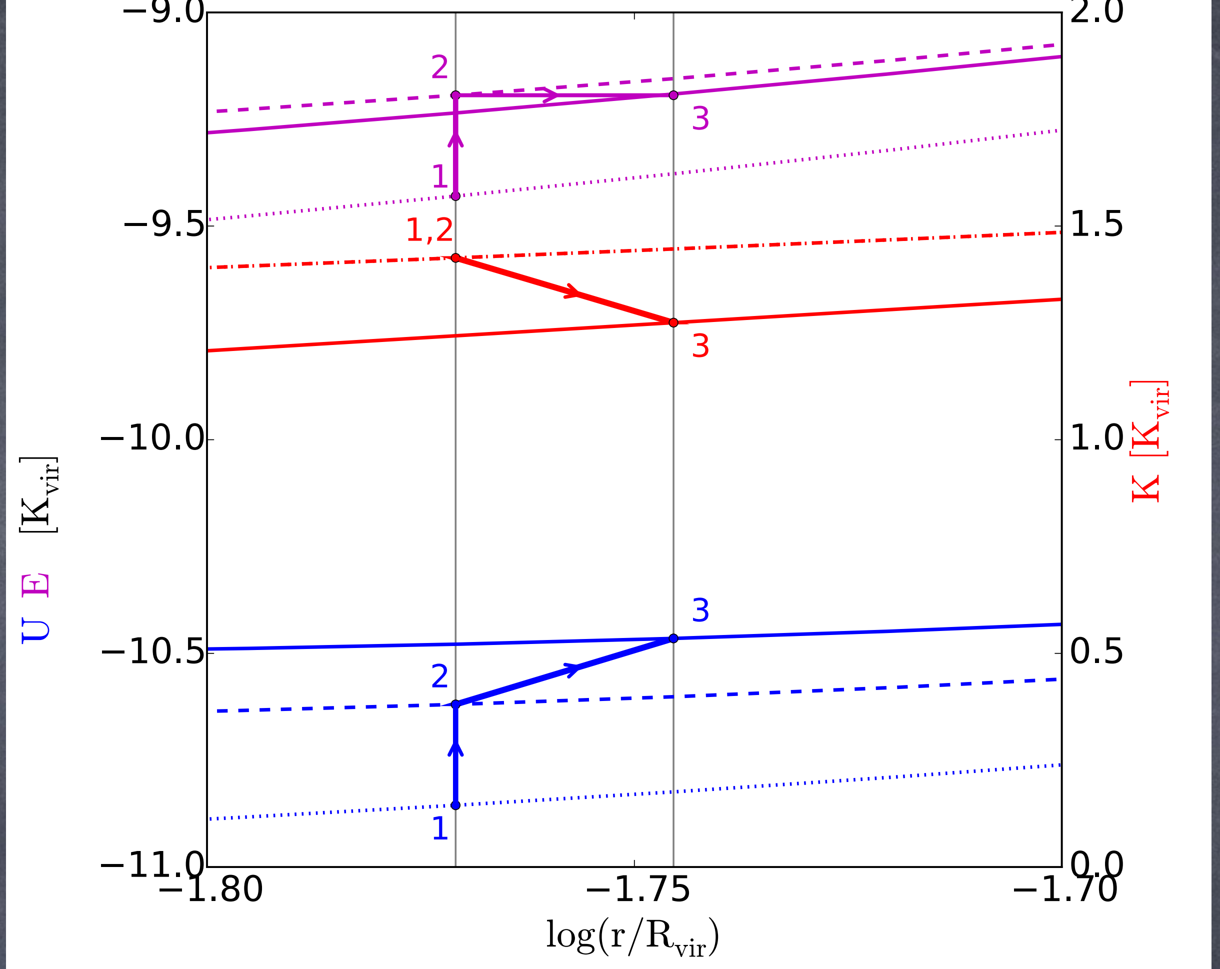
Analytical descriptions of halo response

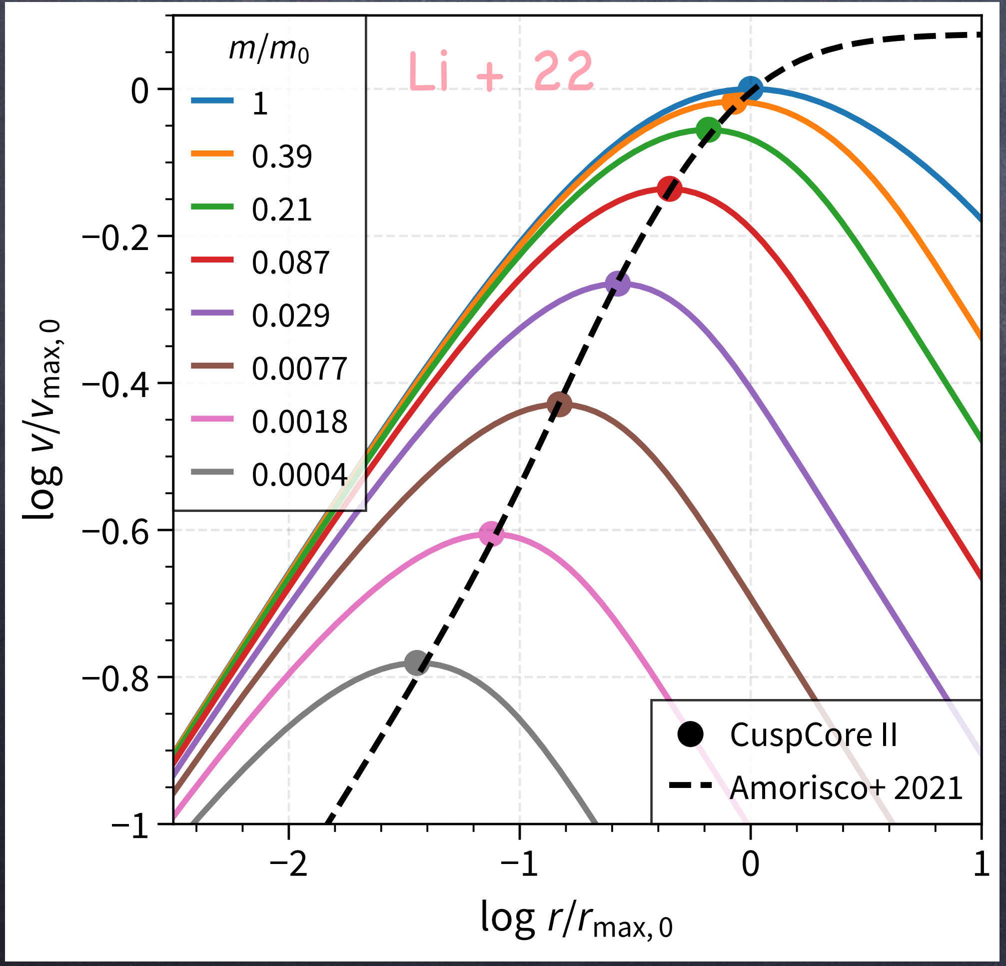
- **CuspCore** model for describing halo response to gas removal/ inflow

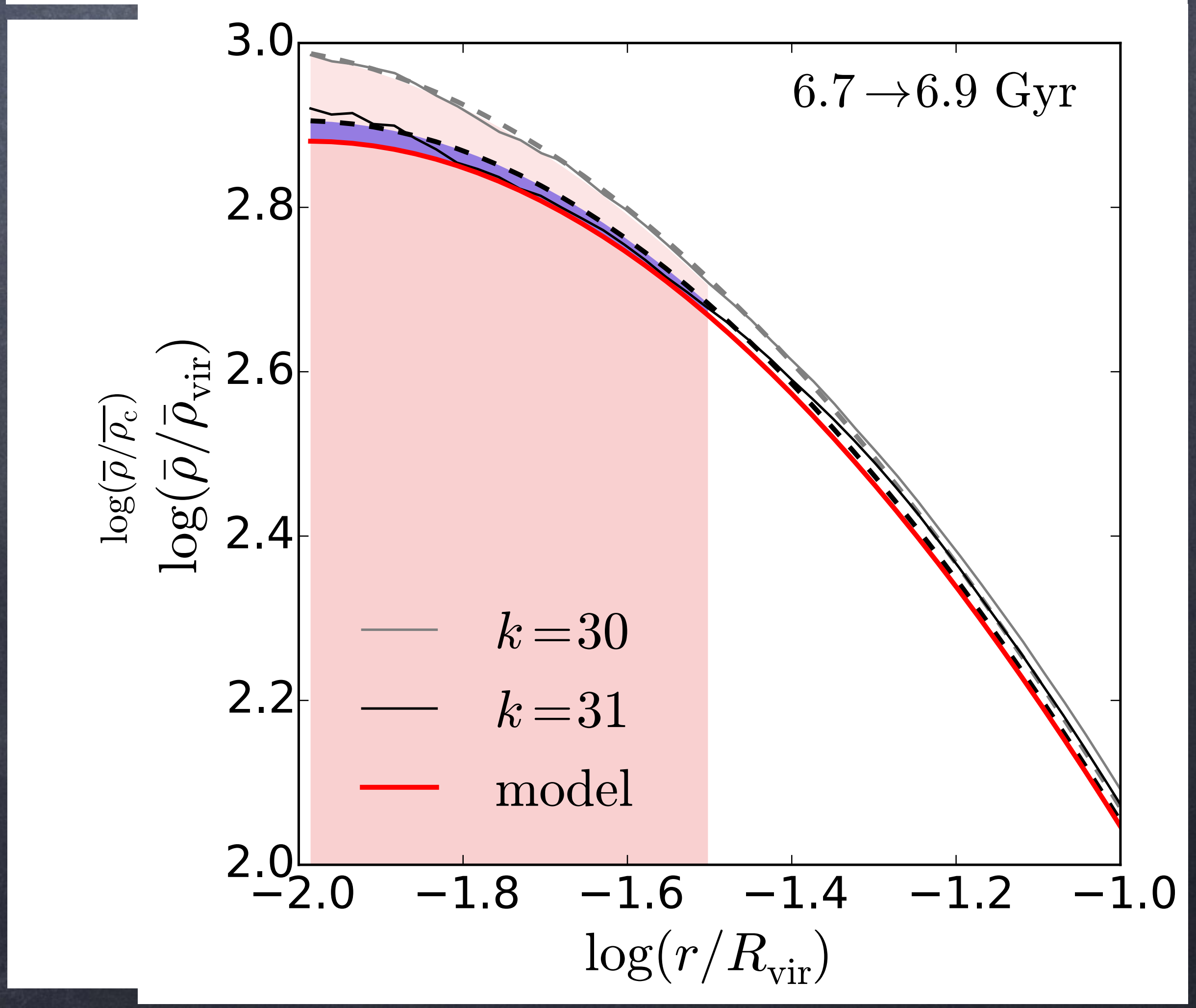
  Freundlich, **Jiang**, Dekel + 20, MN, 499,2912

  Freundlich, Dekel, **Jiang** + 20, MN, 491,4523

- **CuspCoreII** model can be generalized to describe tidal tracks



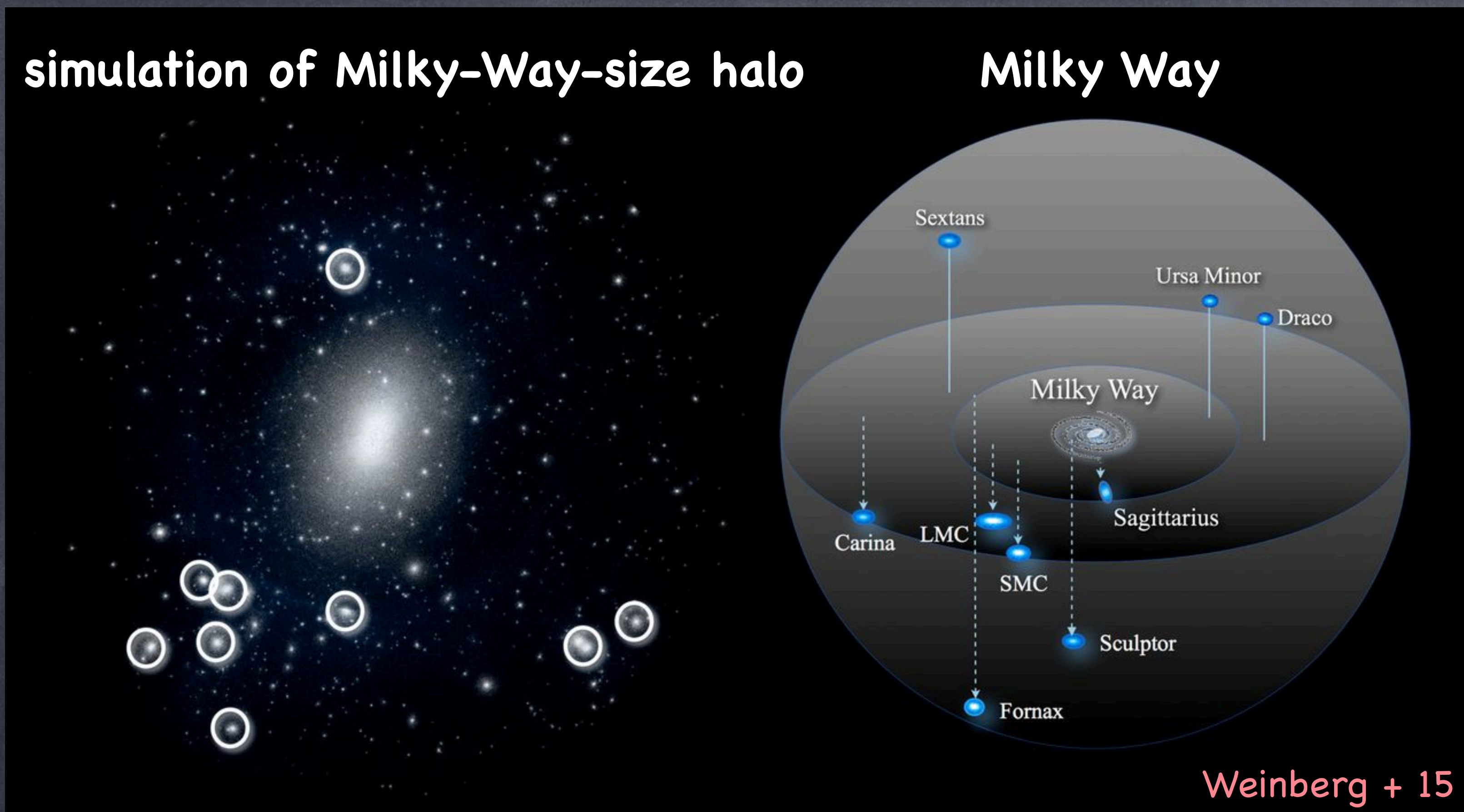


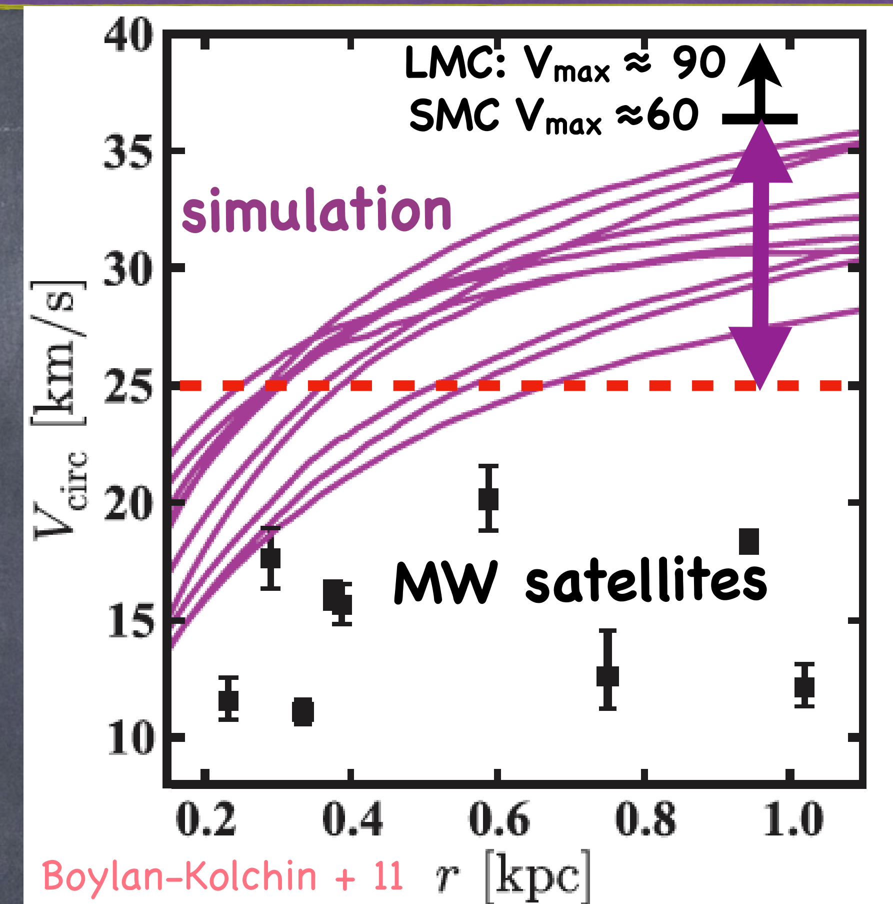


I. Can we solve the small scale issues within ΛCDM,

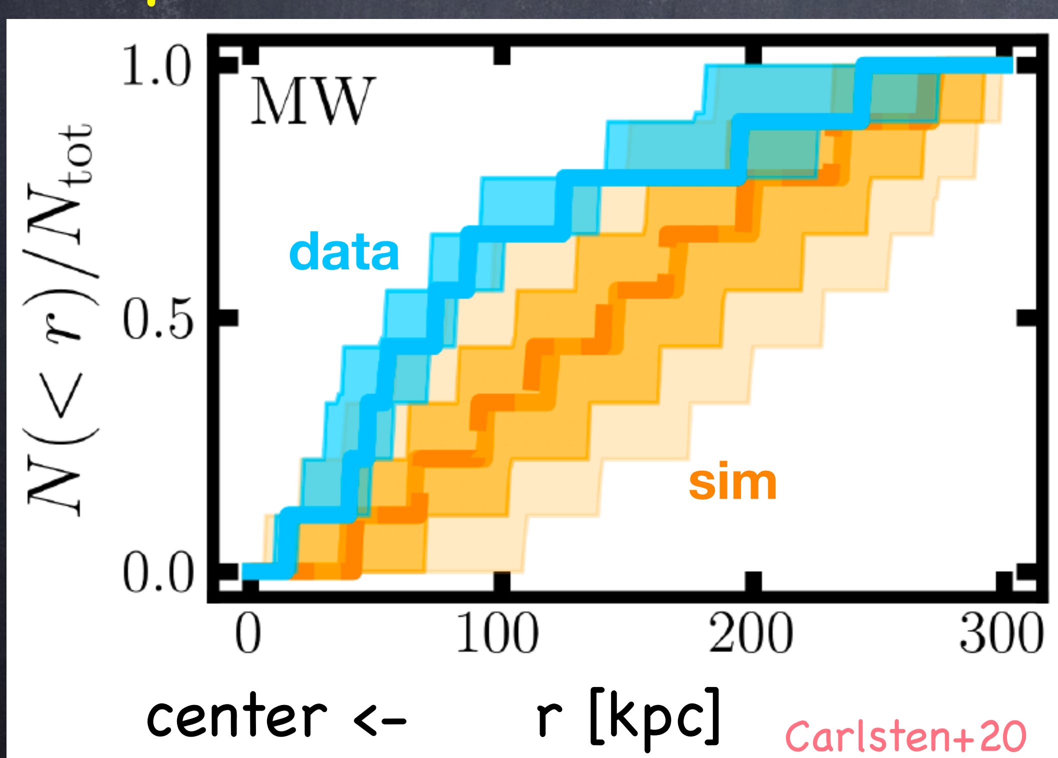
accounting for the halo response?

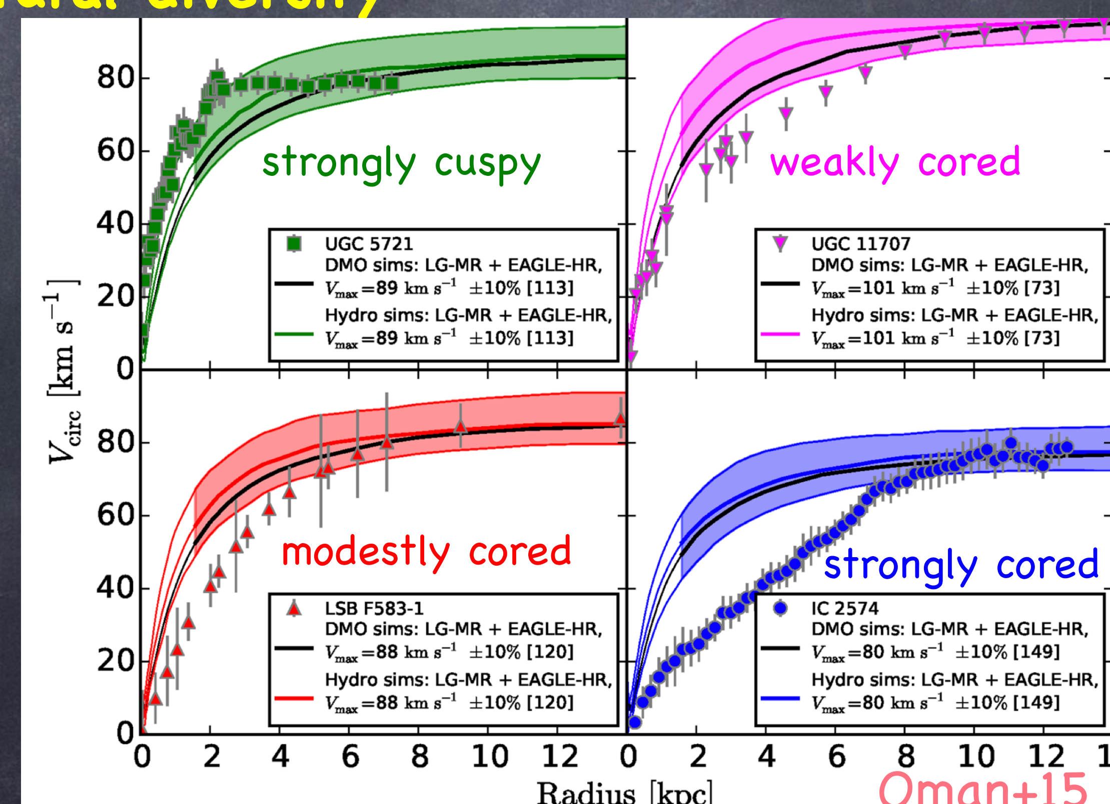
Cosmological small-sale issues I





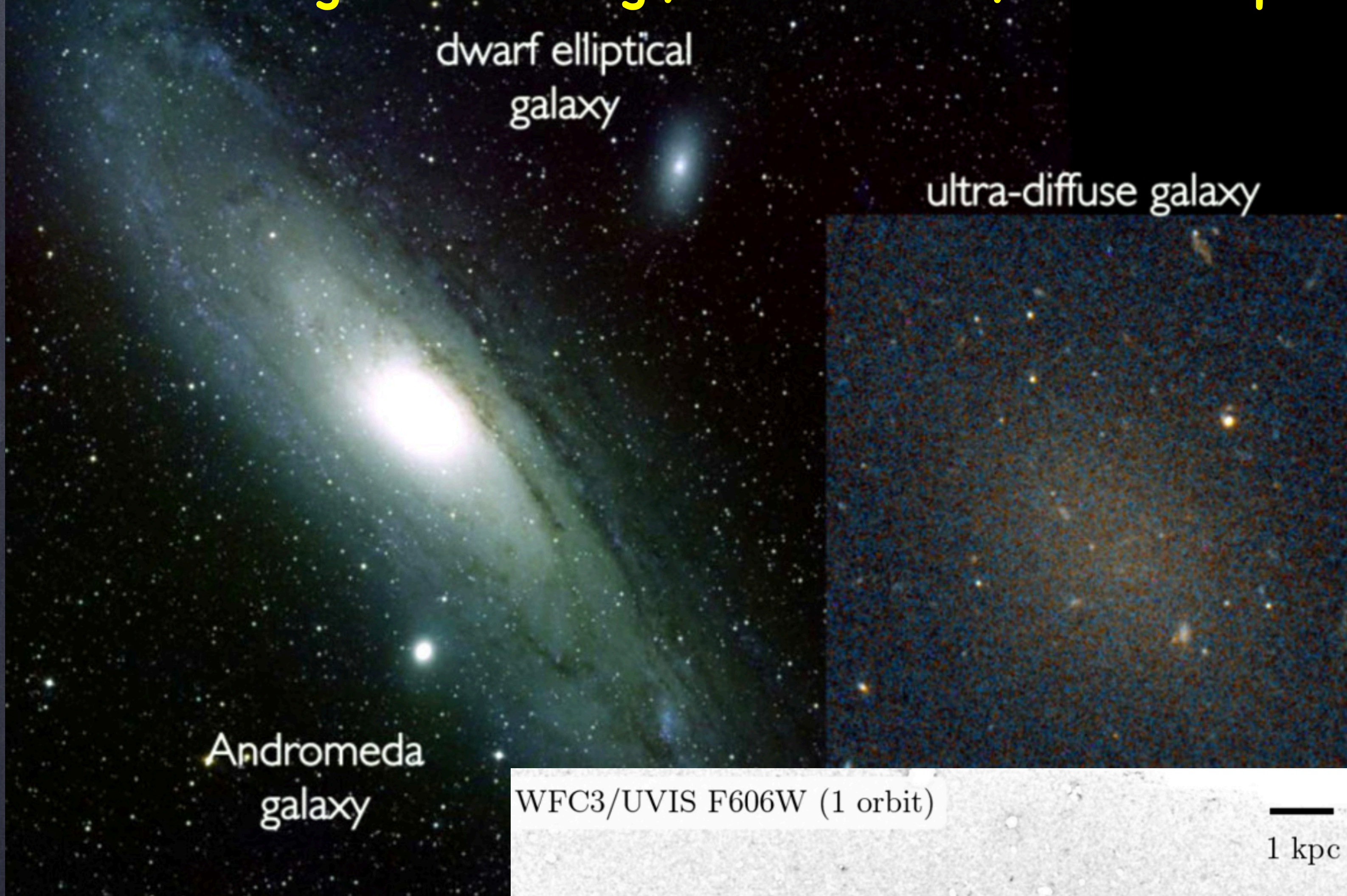
- missing satellites
- spatial distribution
- too big to fail — also a diversity issue, or the gap issue
- structural diversity



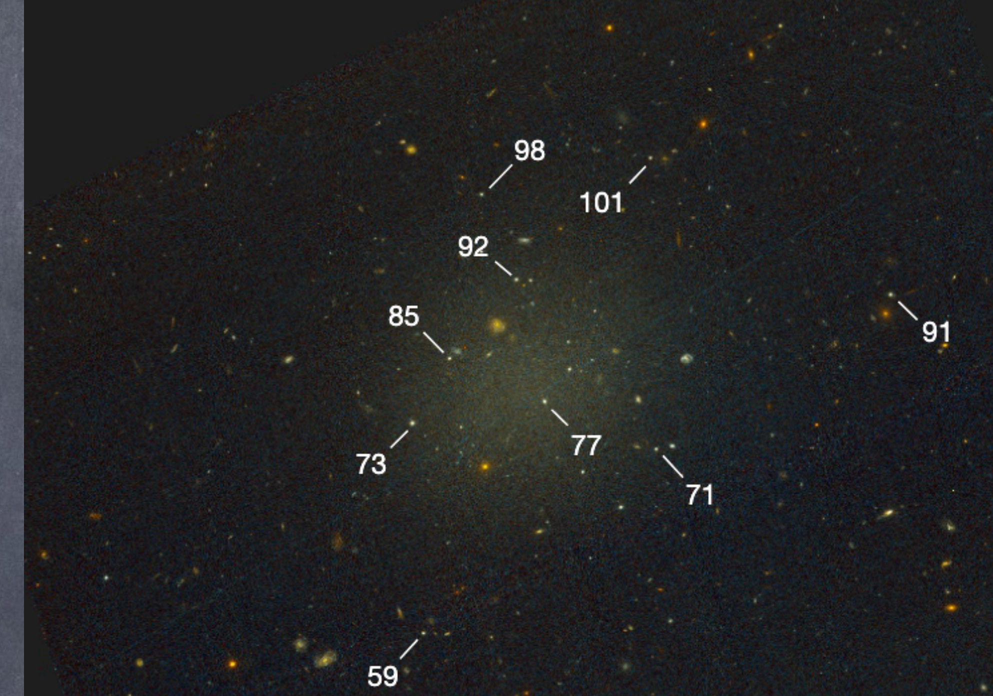


Cosmological small-sale issues II

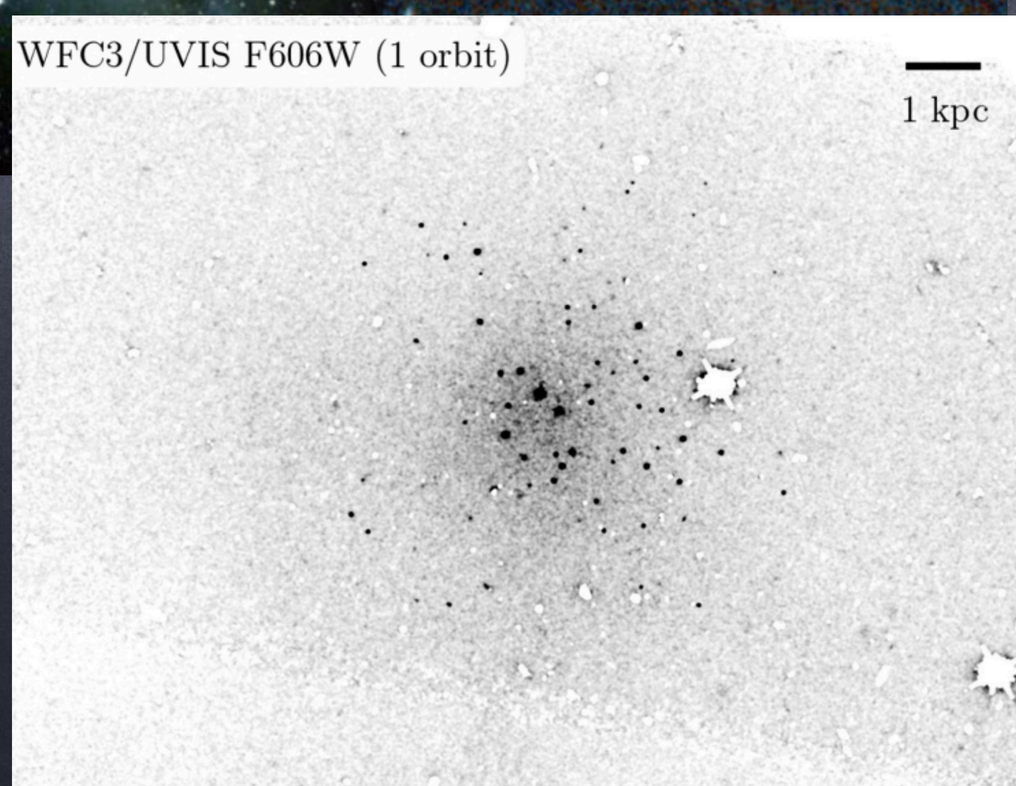
- Extreme galaxies — e.g., ultra diffuse, ultra-compact



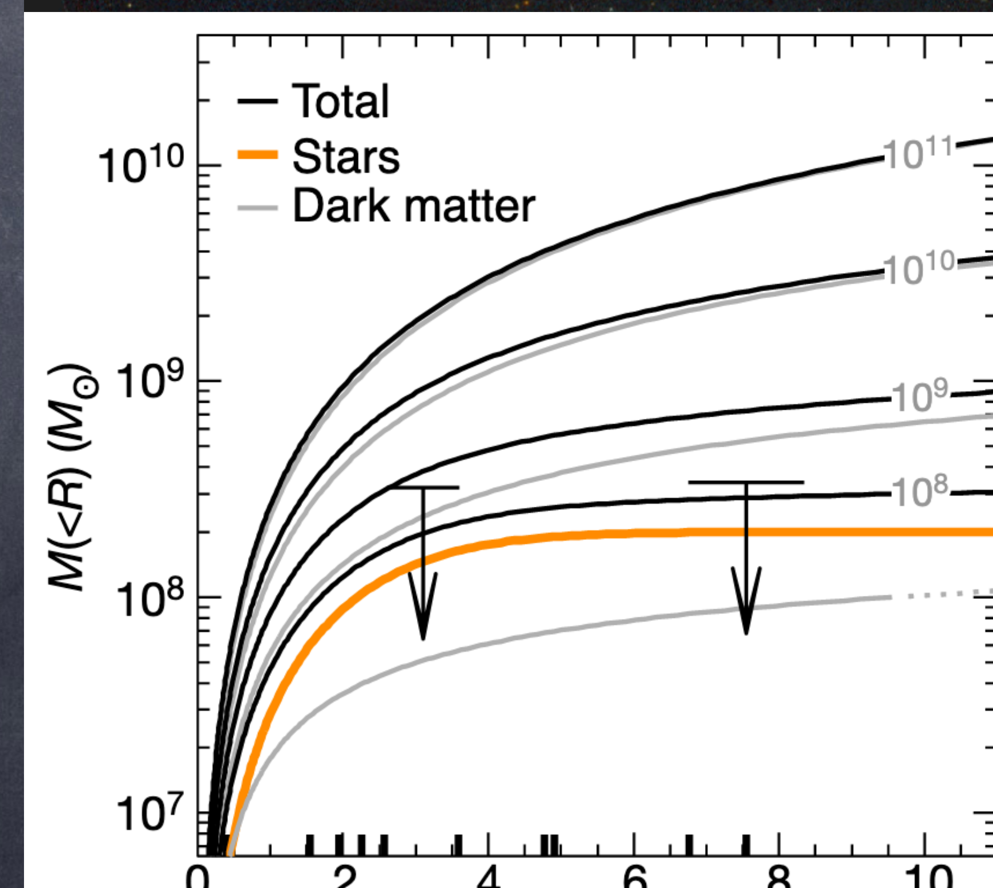
- dark-matter deficient dwarfs



- Some UDGs show mass-segregated GCs or even nuclear star clusters

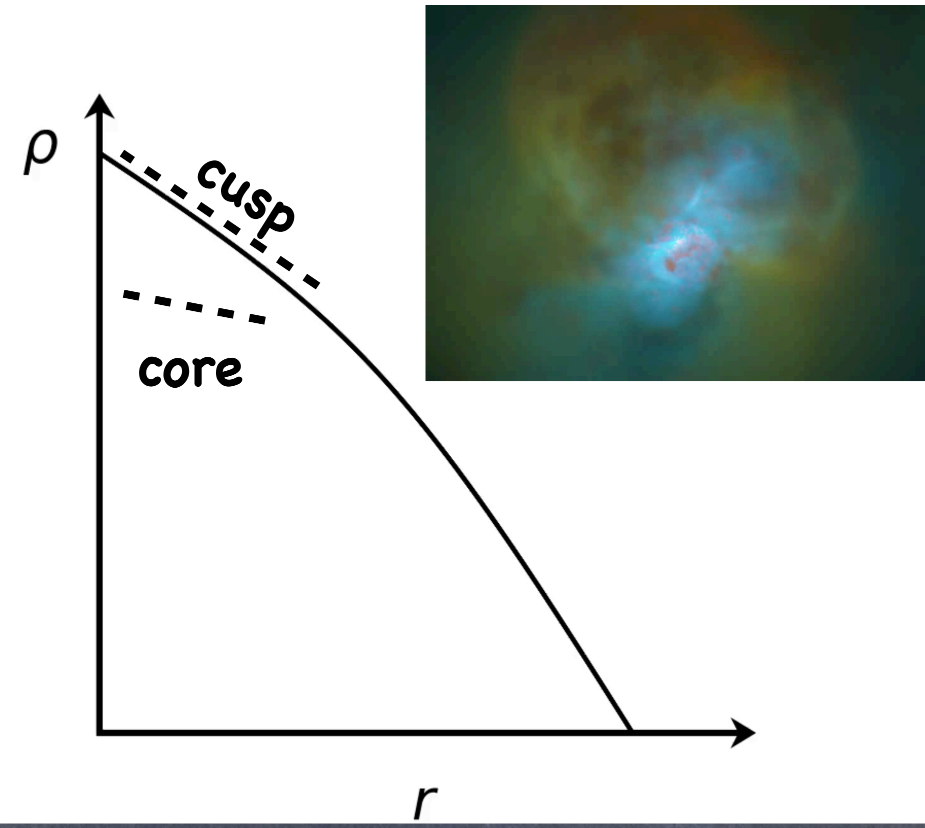


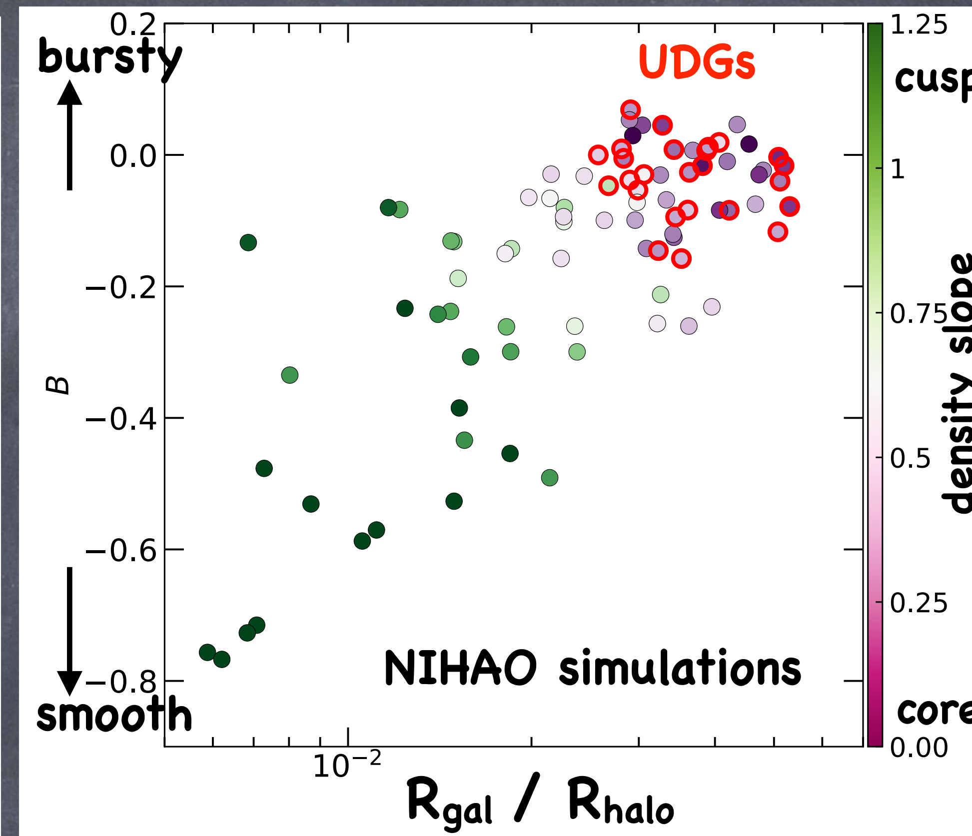
Danieli + 21



van Dokkum + 18

Formation of extreme galaxies: bursty star formation and SNe outflows

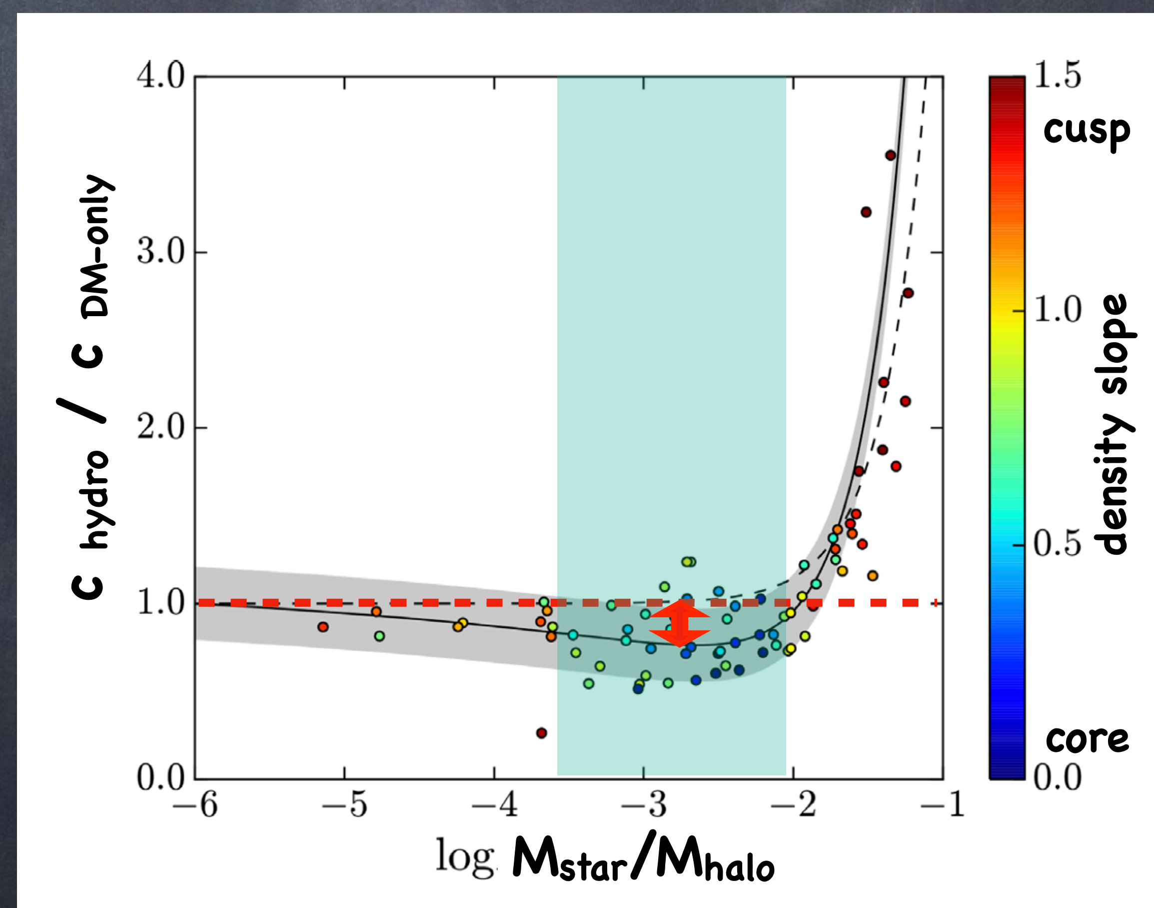




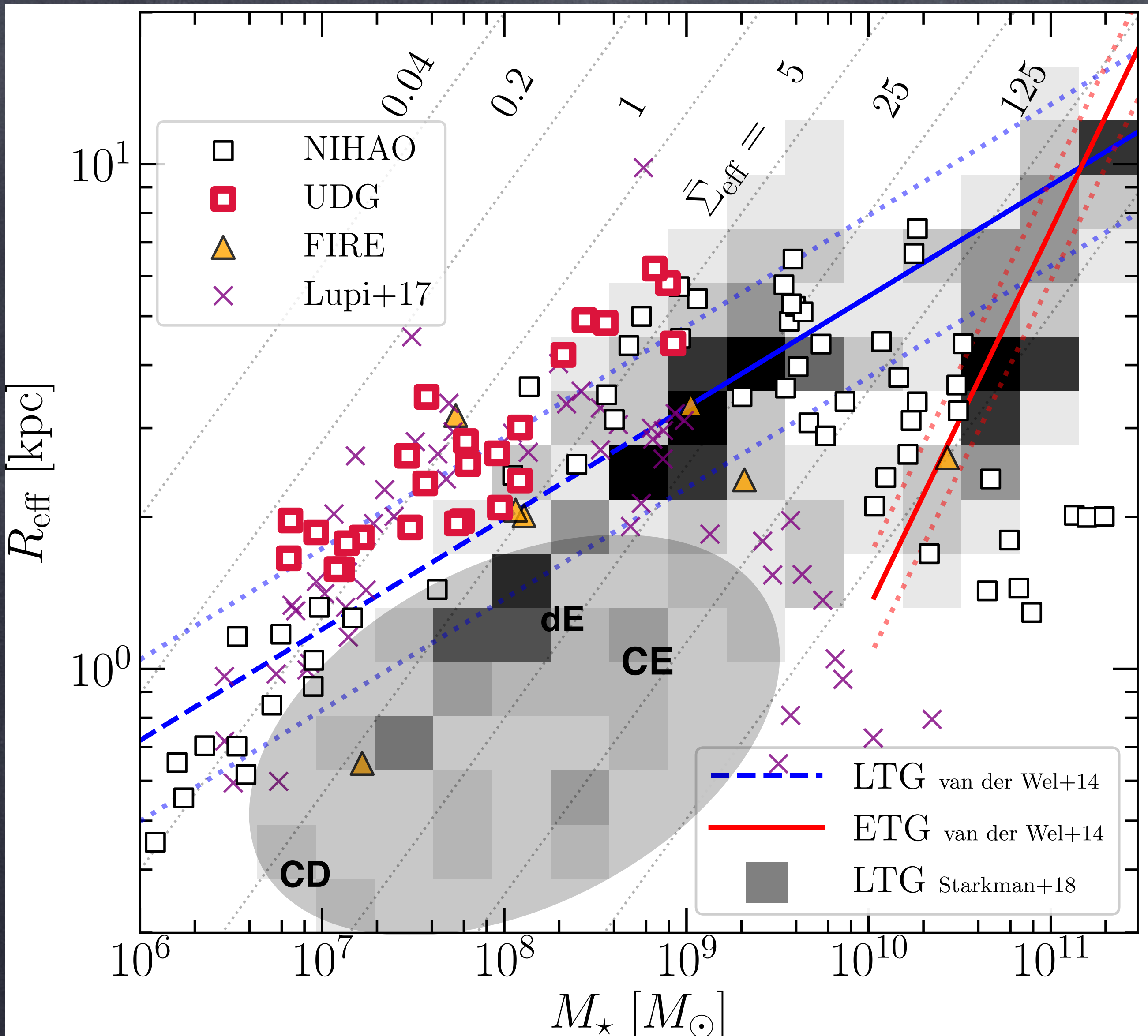
- UDGs are puffed up by repeated SN-driven gas outflows — the same process that transforms DM cusps to cores

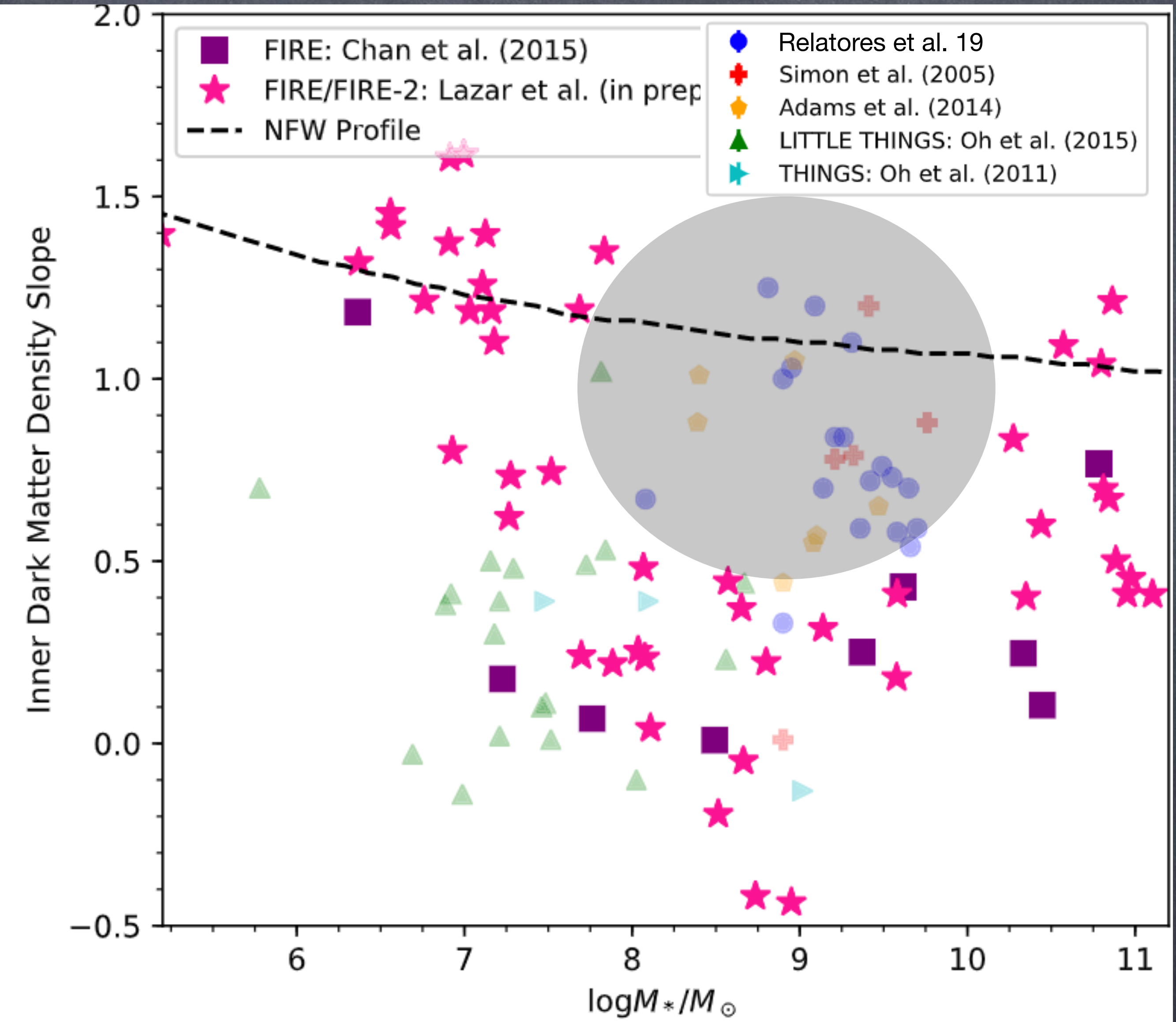
- The halo response to the bursty SF and SN feedback is maximized in massive dwarf halos of $M_{halo} \approx 10^{10-11} M_{sun}$ or $M_{star}/M_{halo} \approx 10^{-3.5} - 10^{-2}$

Freundlich, **Jiang**, Dekel + 20, MN, 499,2912
Freundlich, Dekel, **Jiang** + 20, MN, 491,4523



However, structural diversity not fully reproduced in simulations ...





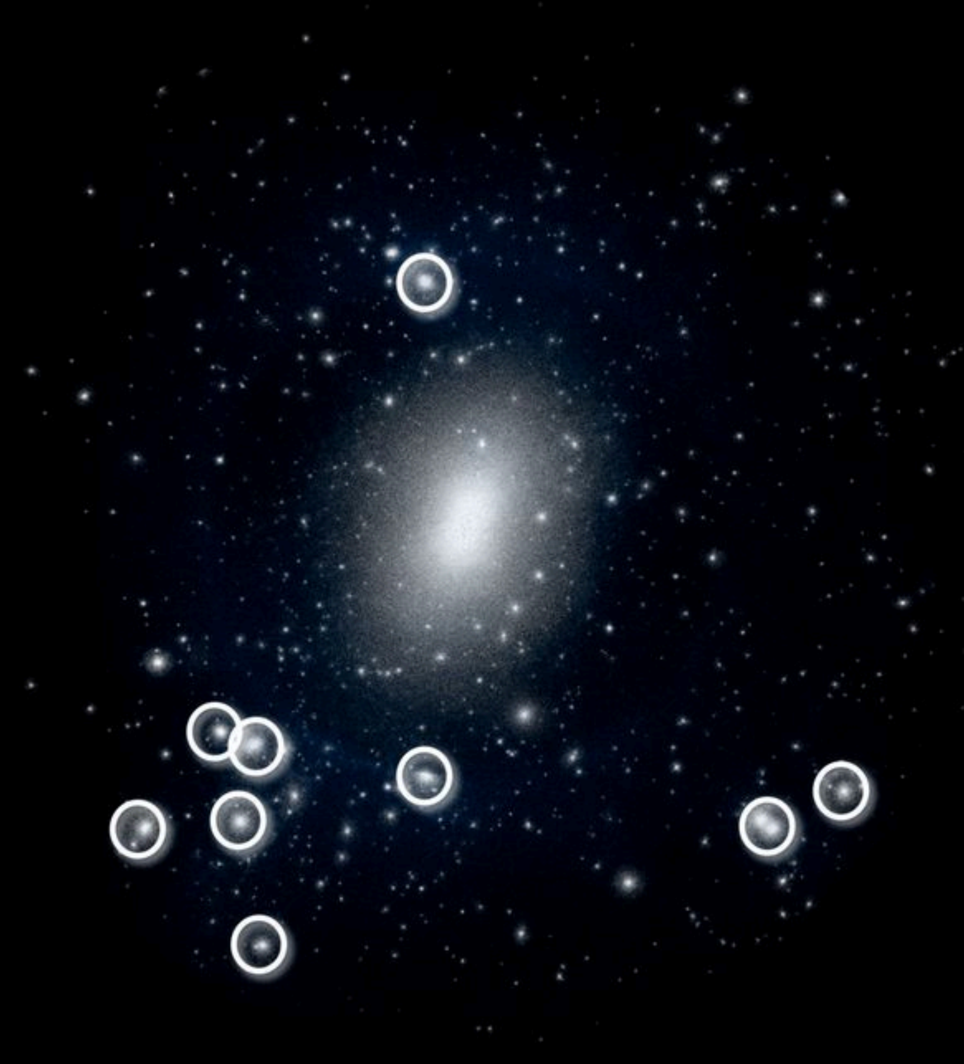
Jiang + 19a MN, 487, 5272

Relatores + 19

- Star-formation recipe flawed?
- Feedback too strong/bursty?
- Splash-back satellites?
- AGN play a role in bright dwarfs?
- SIDM ?

To address satellite issues: numerical vs semi-analytical simulations

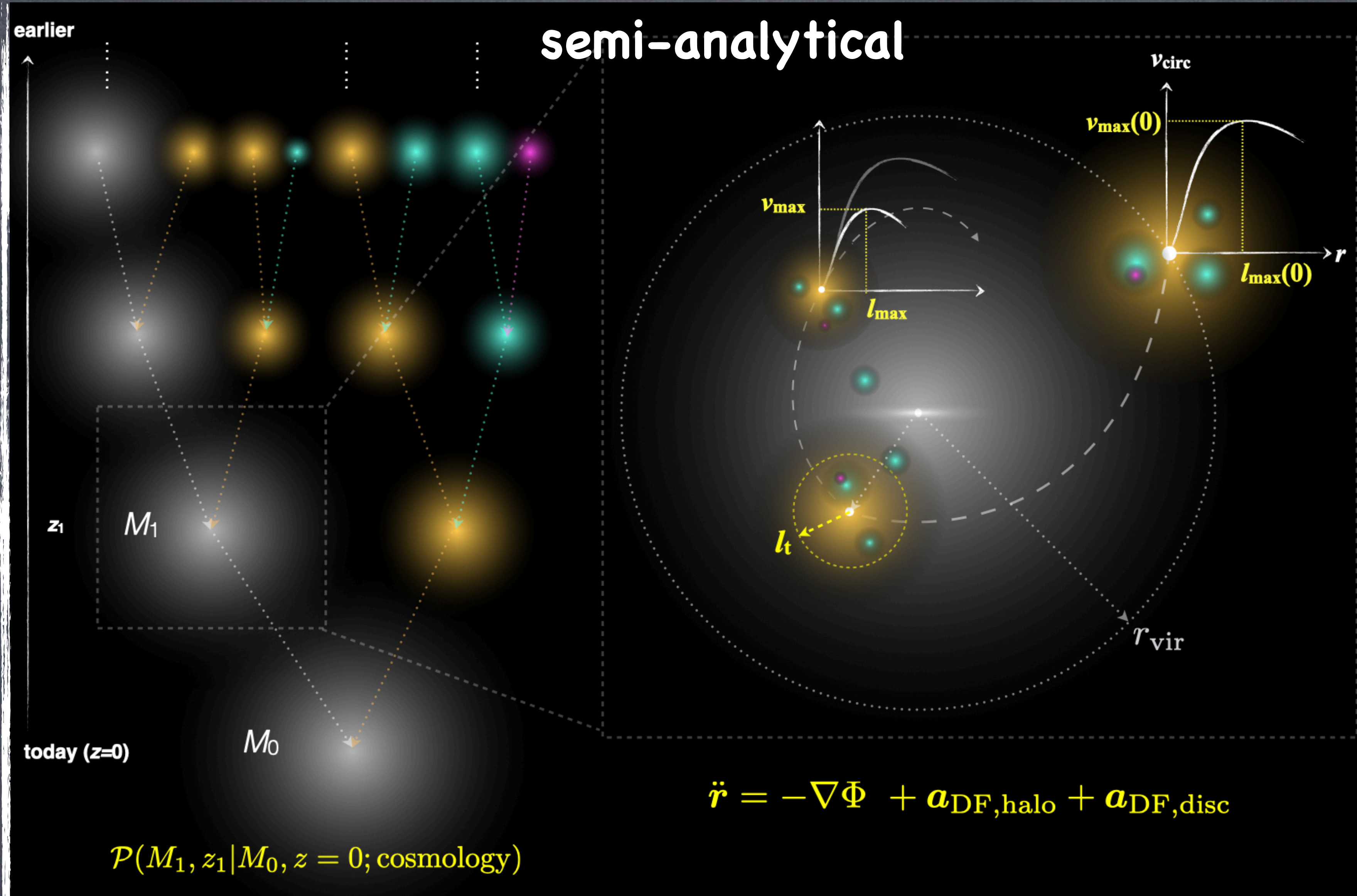
simulation



ELVIS simulation (Garrison-Kimmel+14)

- operate on <u>particles/cells</u>: gravity + hydrodynamics + subgrid recipes

semi-analytical



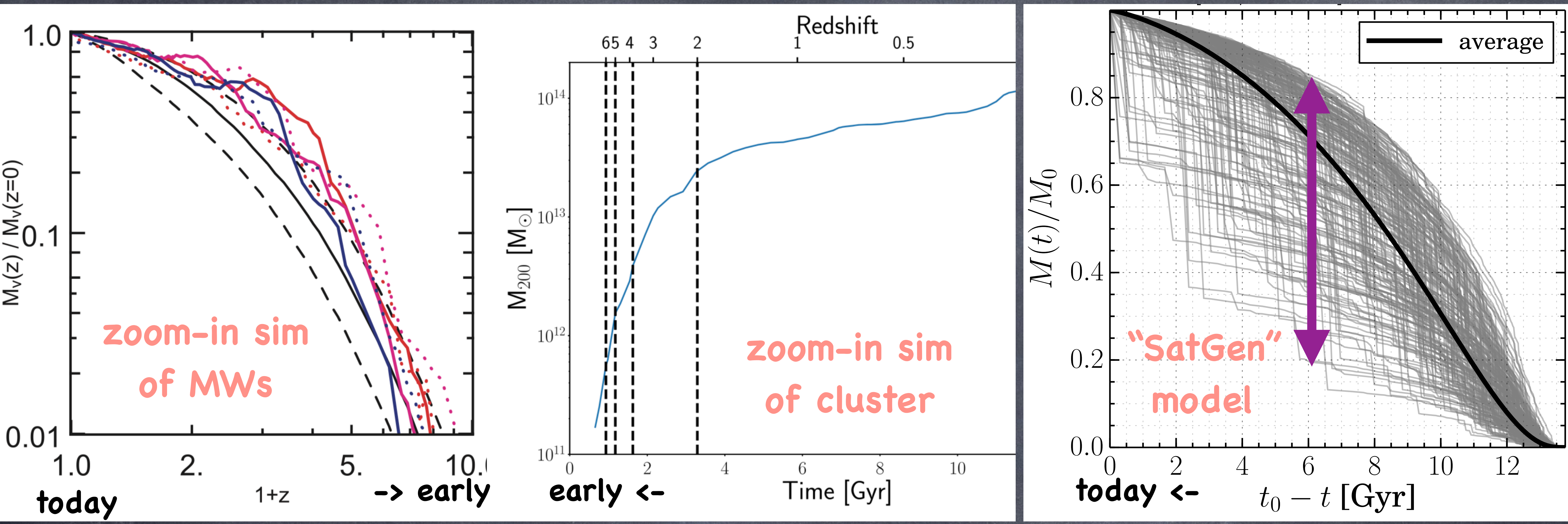
"SatGen" (Jiang & van den Bosch 14,15,16,17; Jiang+21)

- operate on <u>halo merger trees</u>: assign galaxies to halos according to empirical/analytical galaxy-halo connections —> evolve satellites using empirical/analytical recipes for dense environments

https://github.com/JiangFangzhou/SatGen

Comparison of methods: simulation versus semi-analytical model

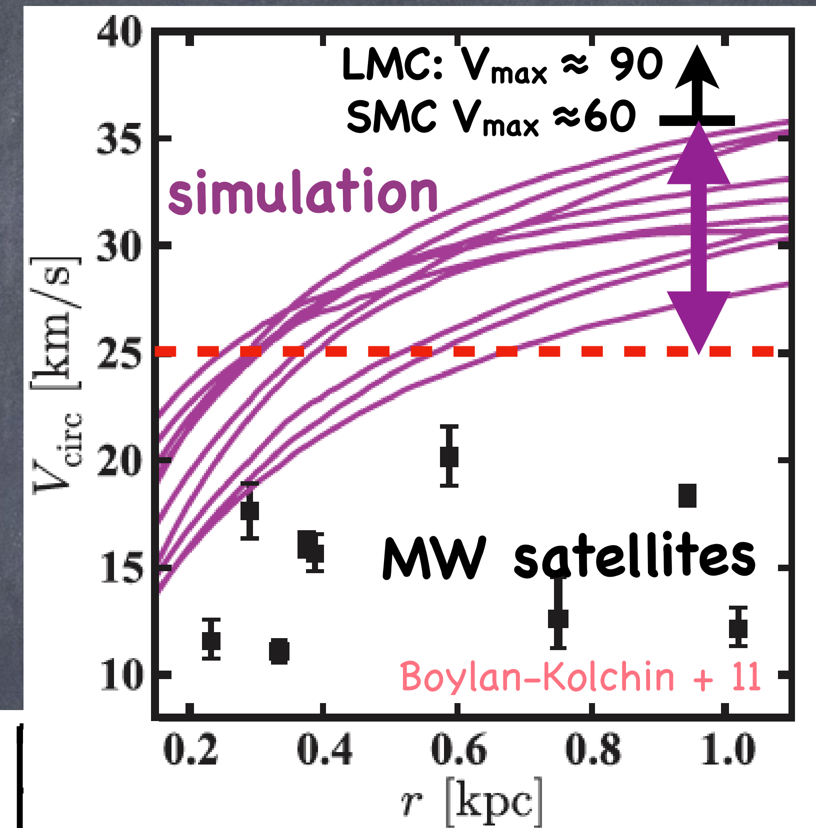
Halo mass assembly histories



- A zoom-in simulation suite has ≈10 MWs or ≈1 cluster
- Adequate sampling of the cosmic halo-to-halo variance requires a sample of >100

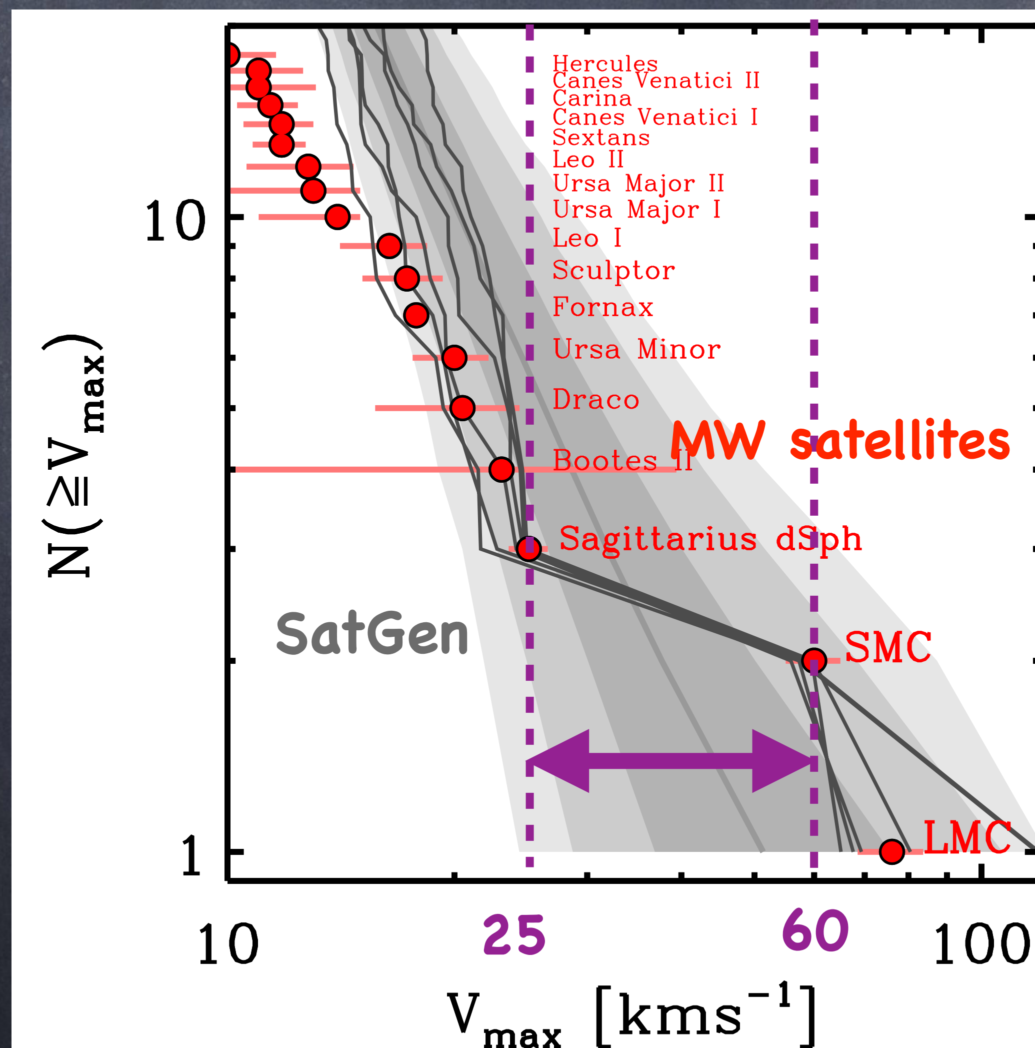
SatGen: evaluating the "too-big-to-fail" problem

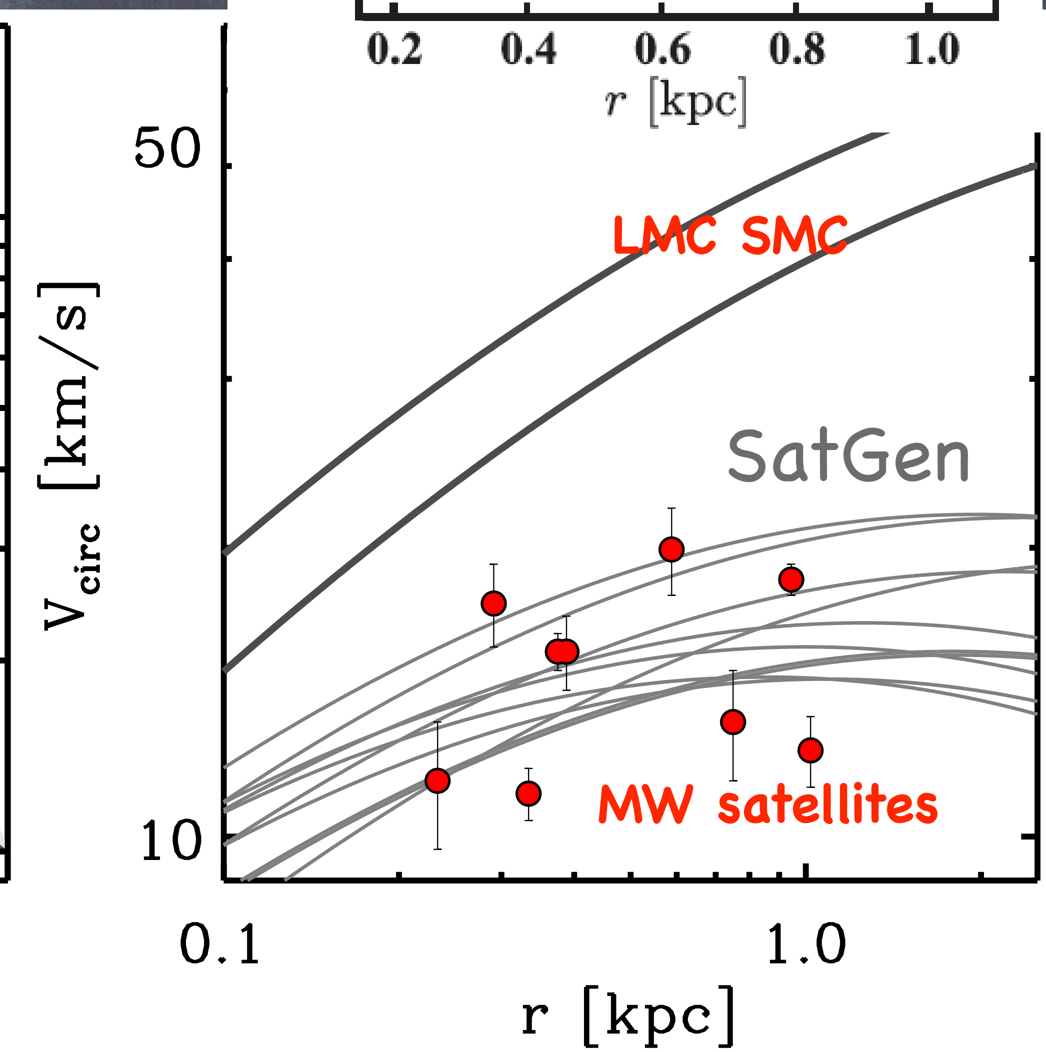
TBTF: a V_{max} gap between LMC, SMC and the other MW satellites



- Among thousands of MWs "simulated" by **SatGen**, 1% are free from TBTF — only from accounting for the cosmic variance of merging histories

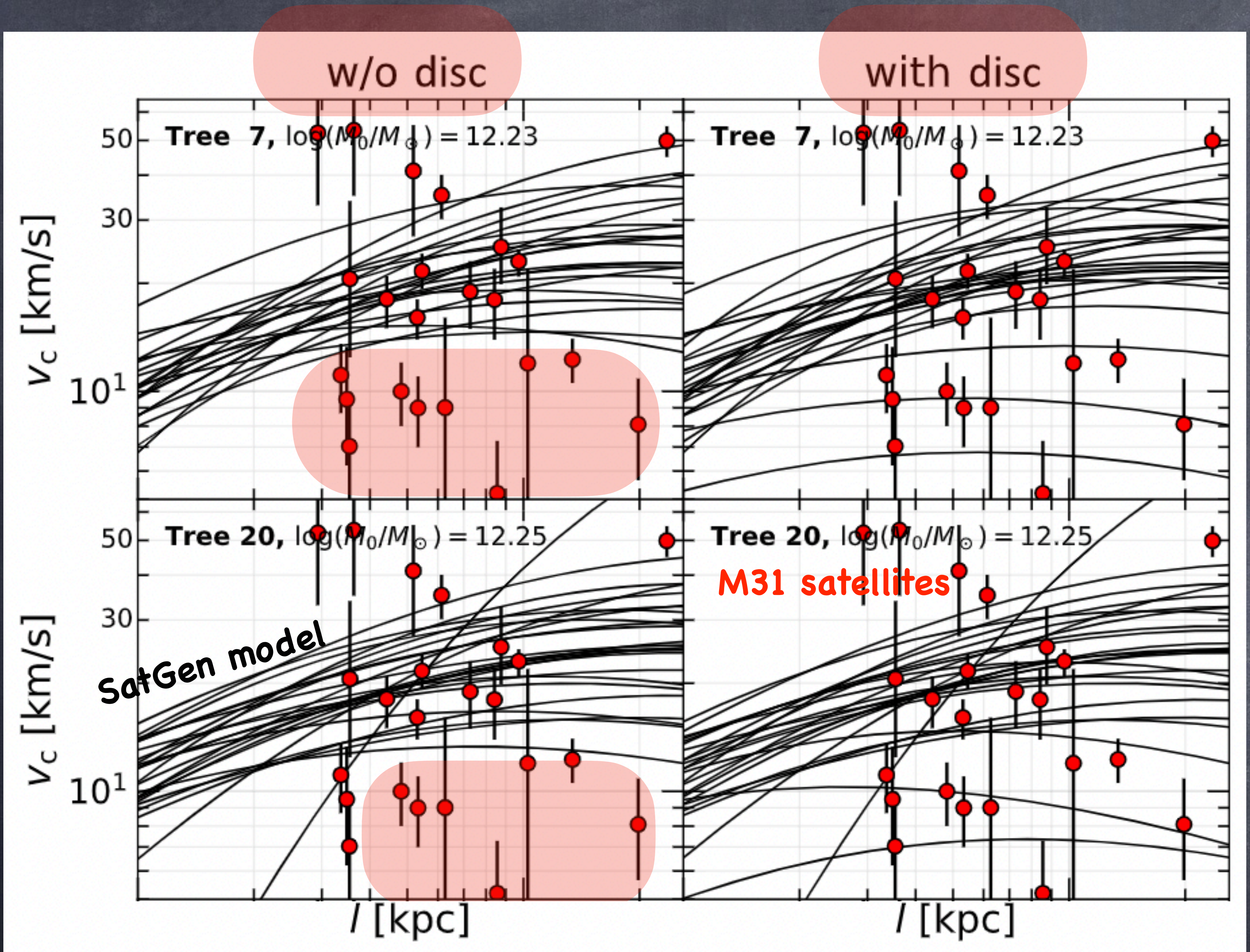
- taking baryonic effect into account can further alleviate the tension …





Jiang & van den Bosch 15, MN, 453, 3575

SatGen: TBTF, as a rotation-curve diversity issue, is alleviated by host disk

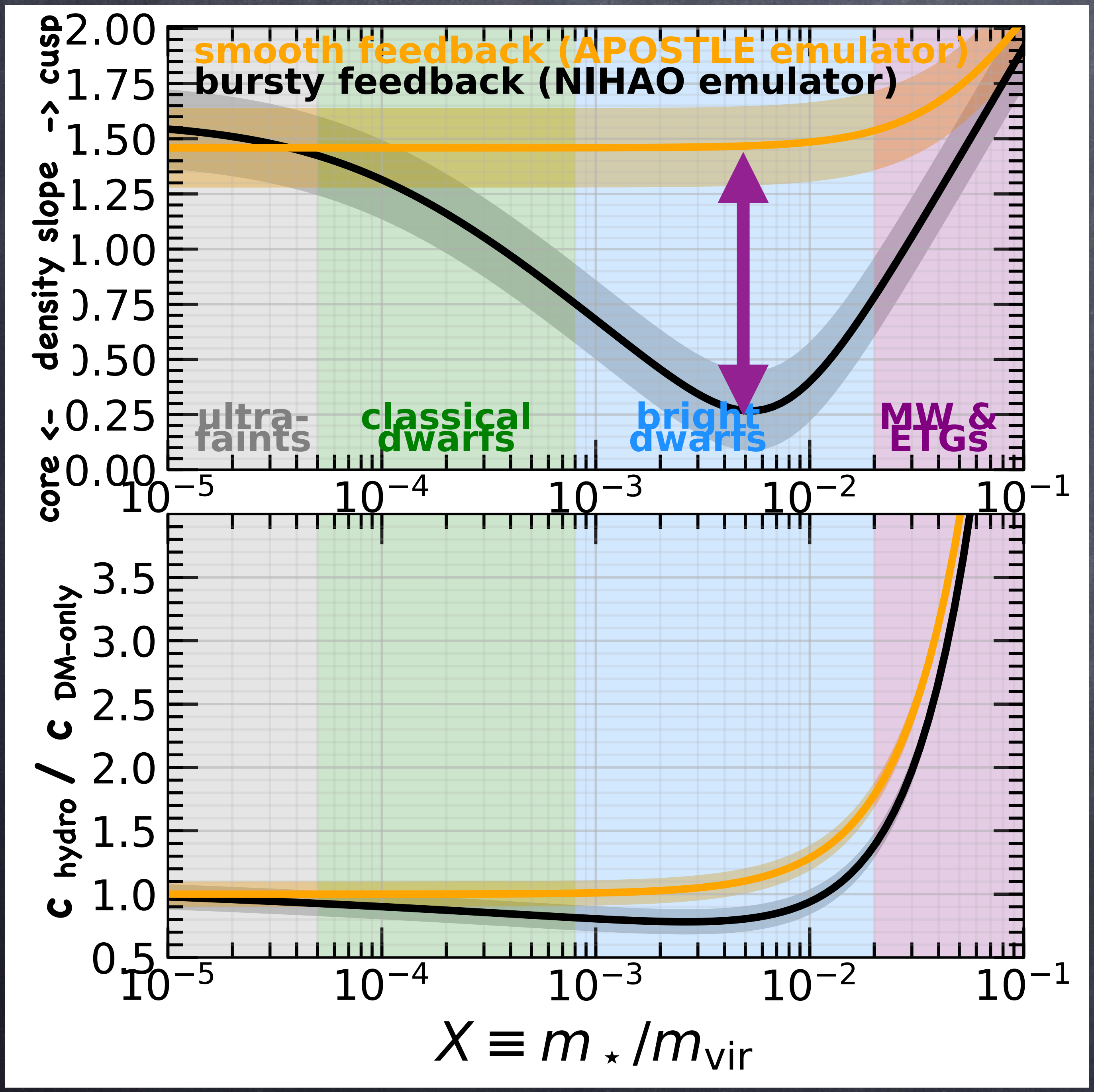


Jiang + 21, MN,502,621

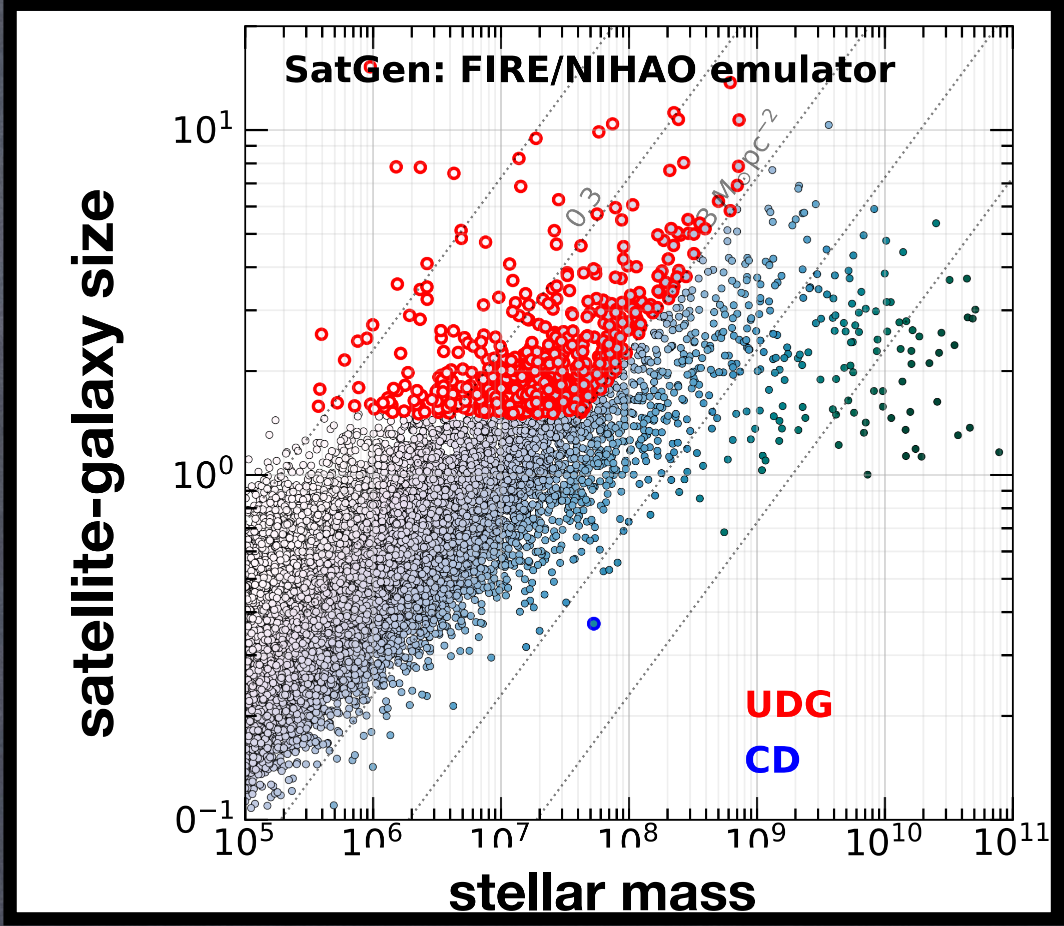
- Simulation studies (e.g., **Phat-ELVIS**) have shown this before; **SatGen** offers more agility and larger statistical samples

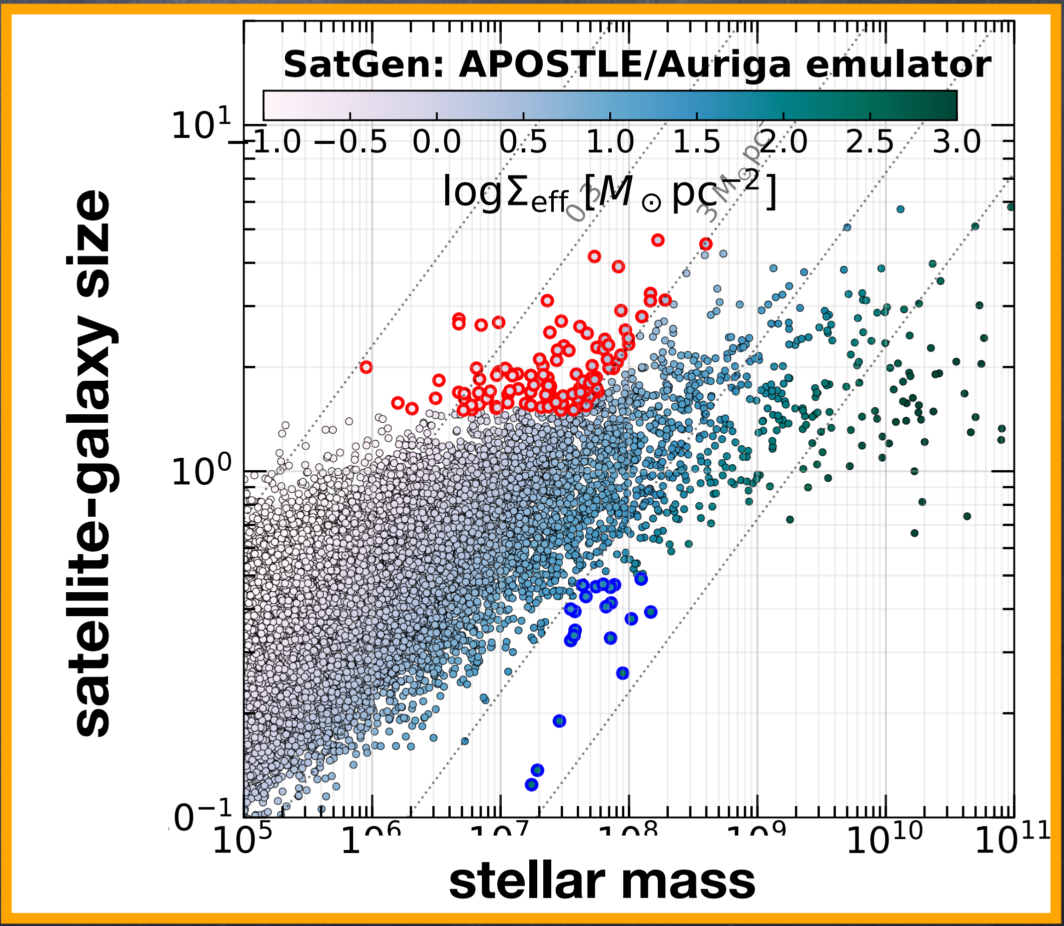
Distinguish halo-response schemes with satellite statistics

- Simulations disagree in feedback strength and therefore the halo responses !

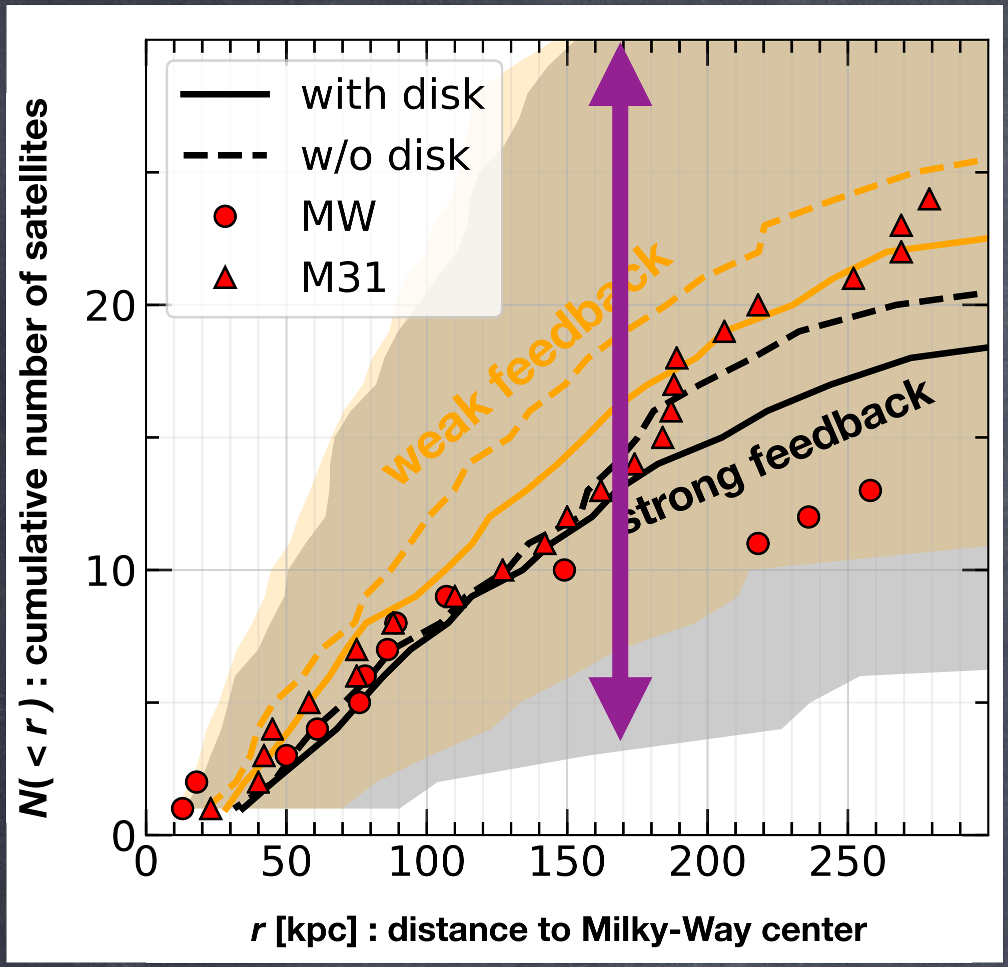


SatGen





Evaluating the satellite spatial distribution issue

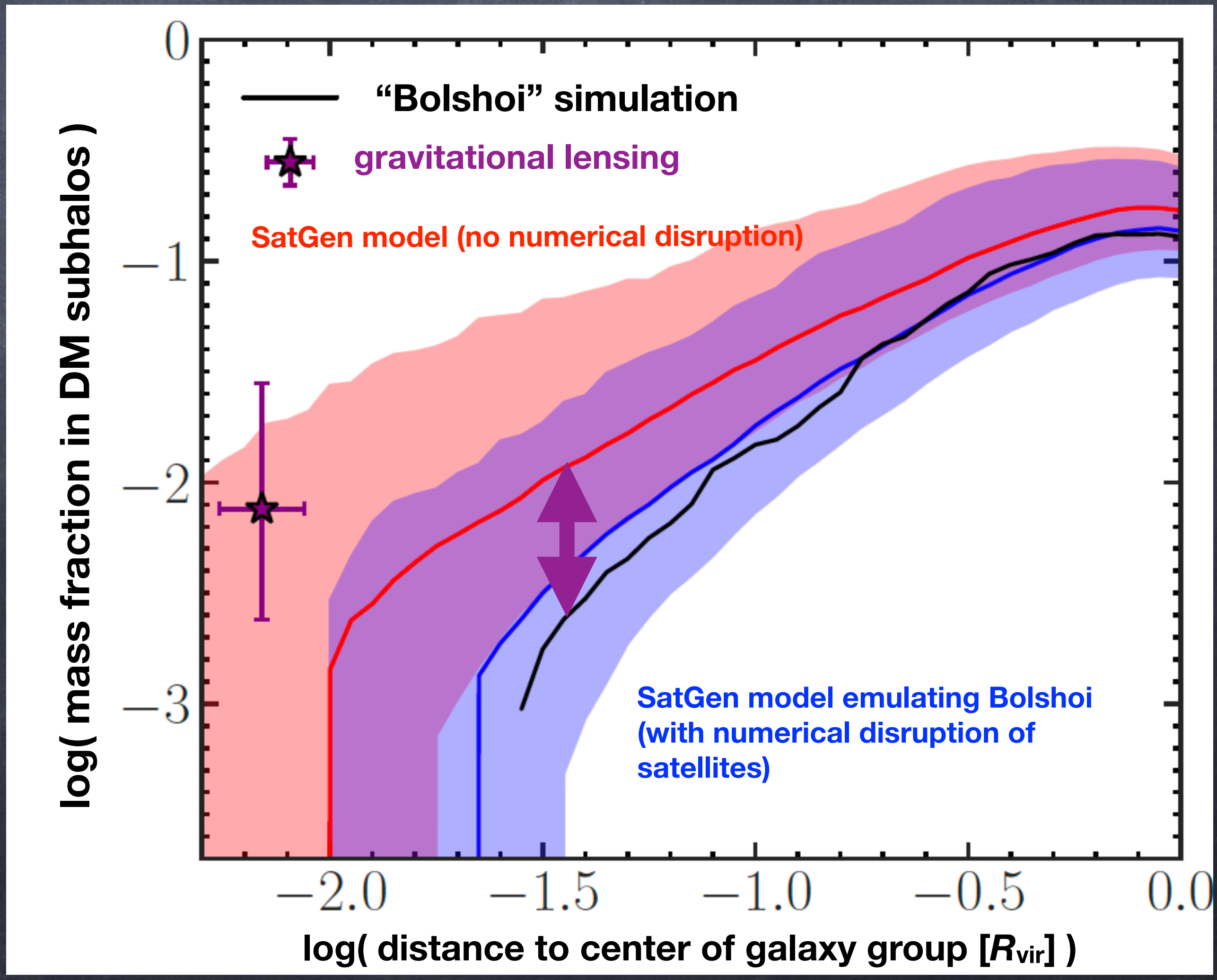


Jiang + 21, MN, 502,621

- Different feedback schemes yield different spatial distributions
- Halo-to-halo scatter is dramatic! — statistical sample of 100 satellite populations are needed to distinguish different models (e.g., the **SAGA** survey, the **ELVES** survey)

- Significant artificial disruption still exists in simulations !
- Without numerical disruption, gravitational lensing estimate of subhalo mass fraction is reconciled

Sheridan Green, van den Bosch, **Jiang** 21a, MN, 503, 4075



I. Can we solve the small scale issues within ΛCDM?

- Extreme galaxies can be produced, but structural diversity is still challenging, even accounting for environmental effects

- For satellite statistics, we resort to the specialty in the MW/Local-Group assembly history, or some fine-tuning of feedback and environmental processes

- Satellite issues can be efficiently evaluated using semi-analytic frameworks

II. SIDM halos and subhalos: towards a semi-analytical description

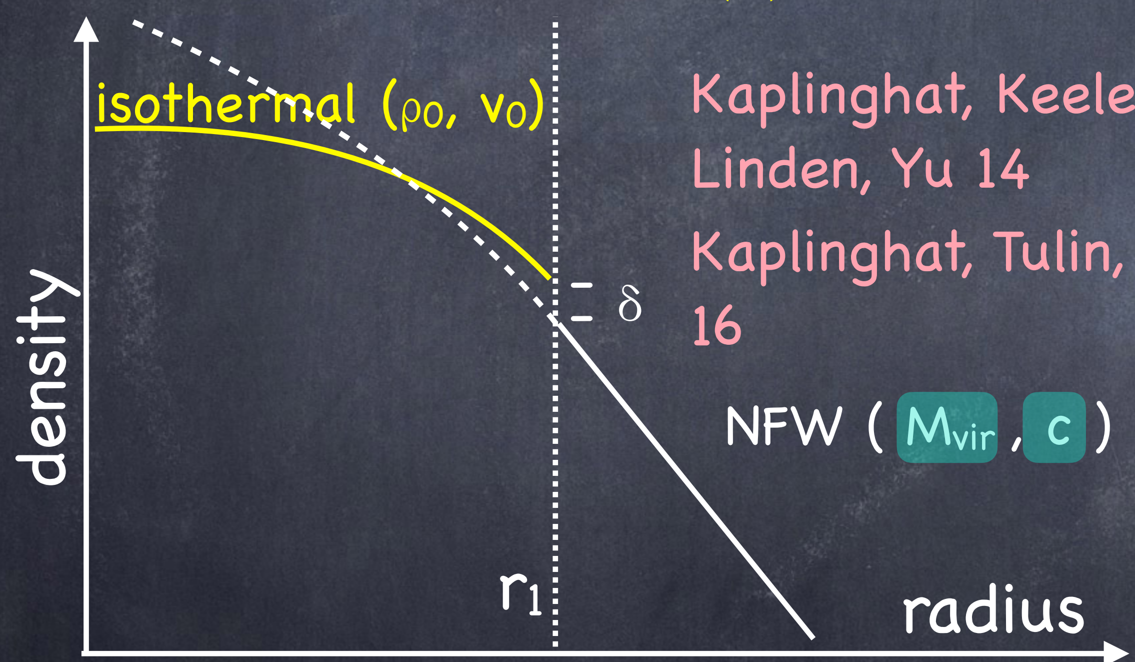
Field SIDM halos — two analytical descriptions: gravothermal fluid equations vs isothermal Jeans Equilibrium

- isothermal Jeans-Poission

$$\Gamma(r_1) = \rho_{\rm CDM}(r_1) v_{\rm CDM}(r_1) \sigma_m = \frac{1}{t_{\rm age}}$$

$$\nabla^2 \ln \rho(r) = -\frac{4\pi G}{v_0^2}\rho(r)$$

$$\rho(r) = \rho_0 e^{-\phi(r)/v_0^2}$$



Kaplinghat, Keeley, Linden, Yu 14

Kaplinghat, Tulin, Yu 16

- gravothermal fluid description

$$\frac{\partial \tilde{M}}{\partial \tilde{r}} = \tilde{r}^2 \tilde{\rho}, \quad \text{mass conservation}$$

$$\frac{\partial(\tilde{\rho}\tilde{v}^2)}{\partial \tilde{r}} = -\frac{\tilde{M}\tilde{\rho}}{\tilde{r}^2}, \quad \text{hydro equilibrium}$$

$$\frac{\partial \tilde{L}}{\partial \tilde{r}} = -\tilde{r}^2 \tilde{\rho}\tilde{v}^2 \left(\frac{\partial}{\partial \tilde{t}}\right)_{\tilde{M}} \ln\left(\frac{\tilde{v}^3}{\tilde{\rho}}\right), \quad \text{1st law}$$

$$\text{flux} \quad \tilde{L} = -\frac{3}{2}\tilde{r}^2 \tilde{v}\left(\frac{a}{b}\tilde{\sigma}_m^2 + \frac{1}{C\tilde{\rho}\tilde{v}^2}\right)^{-1} \frac{\partial \tilde{v}^2}{\partial \tilde{r}}.$$

e.g., Lynden-Bell & Eggleton 80; Balberg & Shapiro 02; Pollack + 15

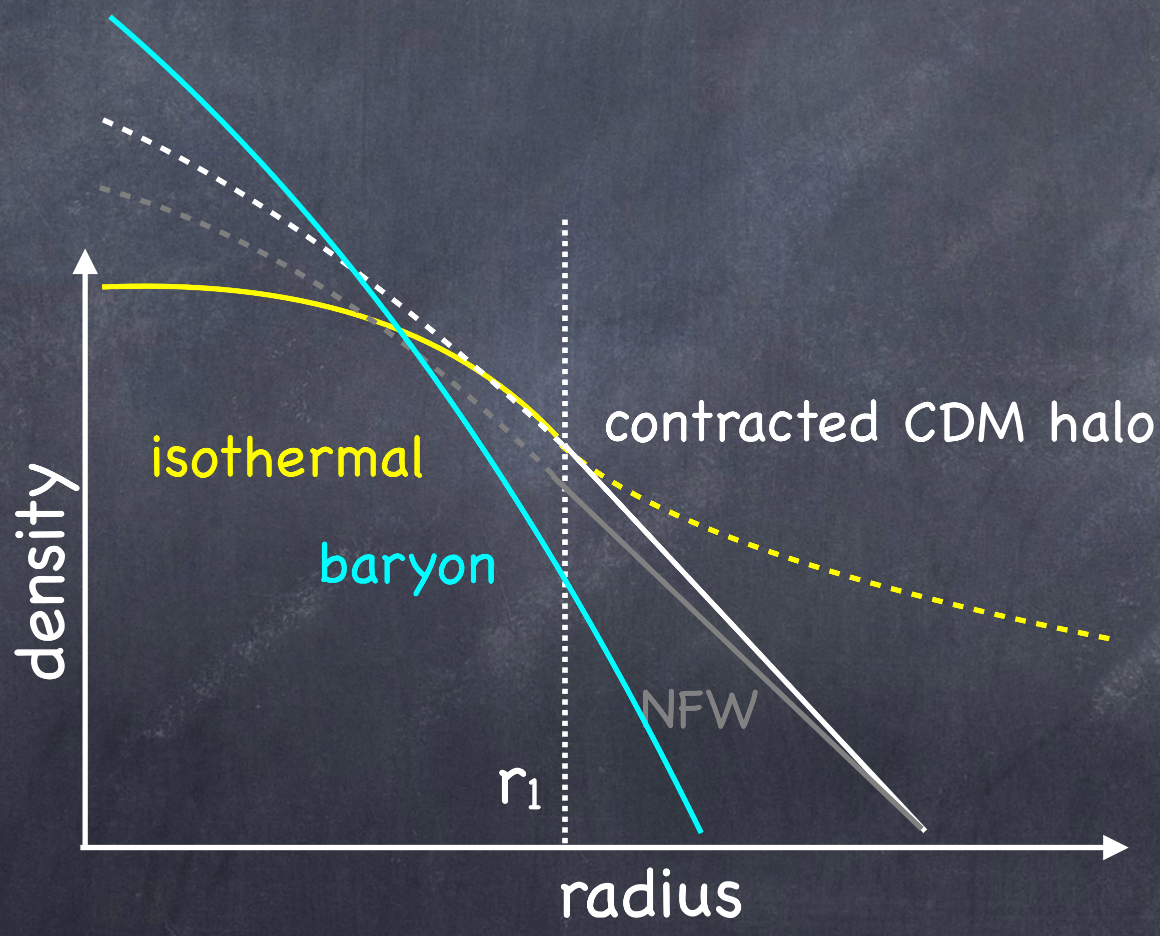
Both methods treat SIDM as a modification to a target CDM halo — the isothermal method uses CDM halo for boundary condition; while the fluid method uses the CDM halo for initial condition

Isothermal Jeans model — adding inhabitant galaxy

$$\nabla^2 \ln \rho_{\rm dm}(r) = -\frac{4\pi G}{v_0^2}\left[\rho_{\rm dm}(r) + \rho_{\rm b}(r)\right]$$

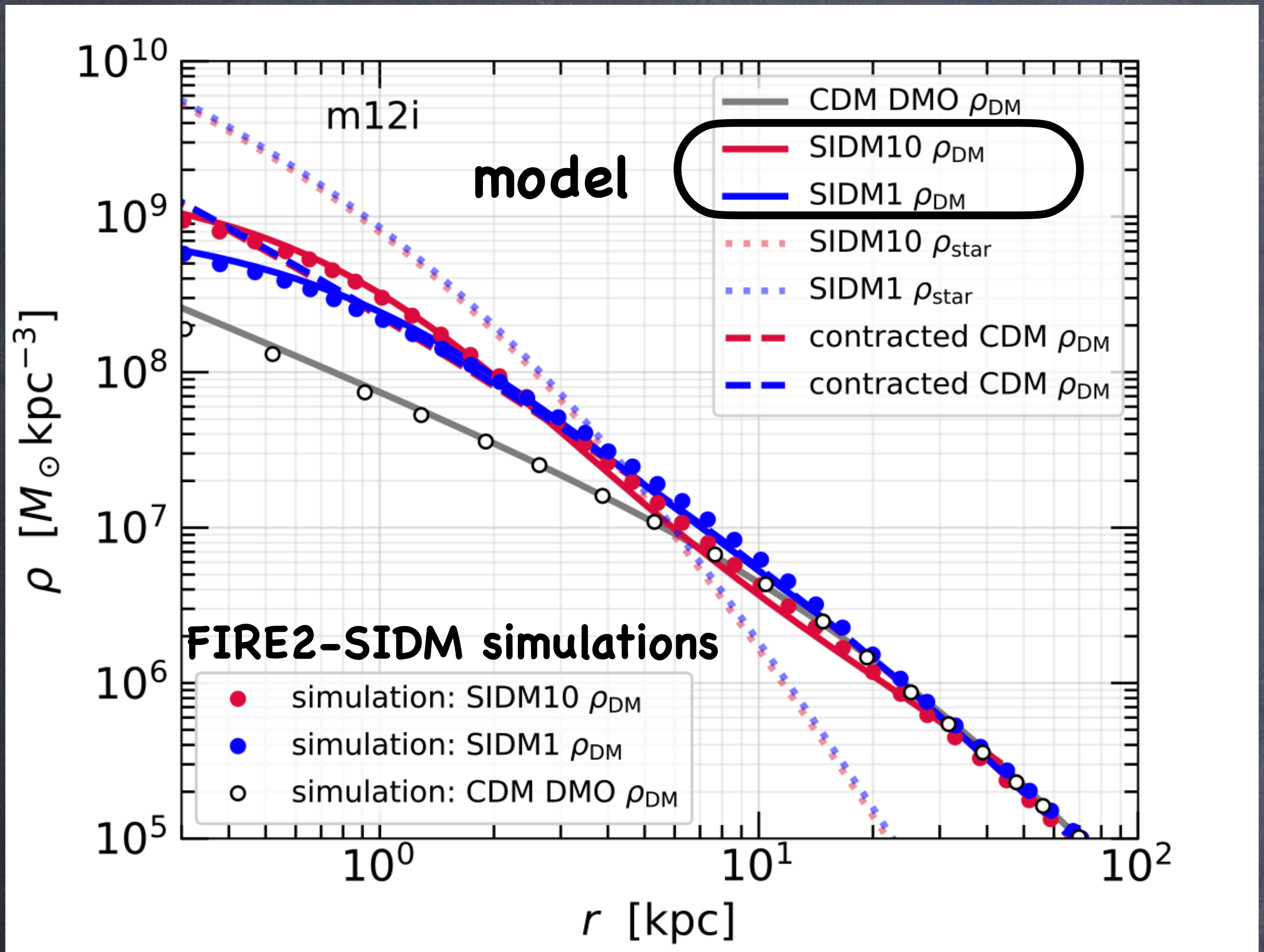
- given a baryon distribution ρ_b
- consider adiabatic contraction due to the baryonic potential
- evaluate r_1 using the contracted CDM halo
- other steps remain the same

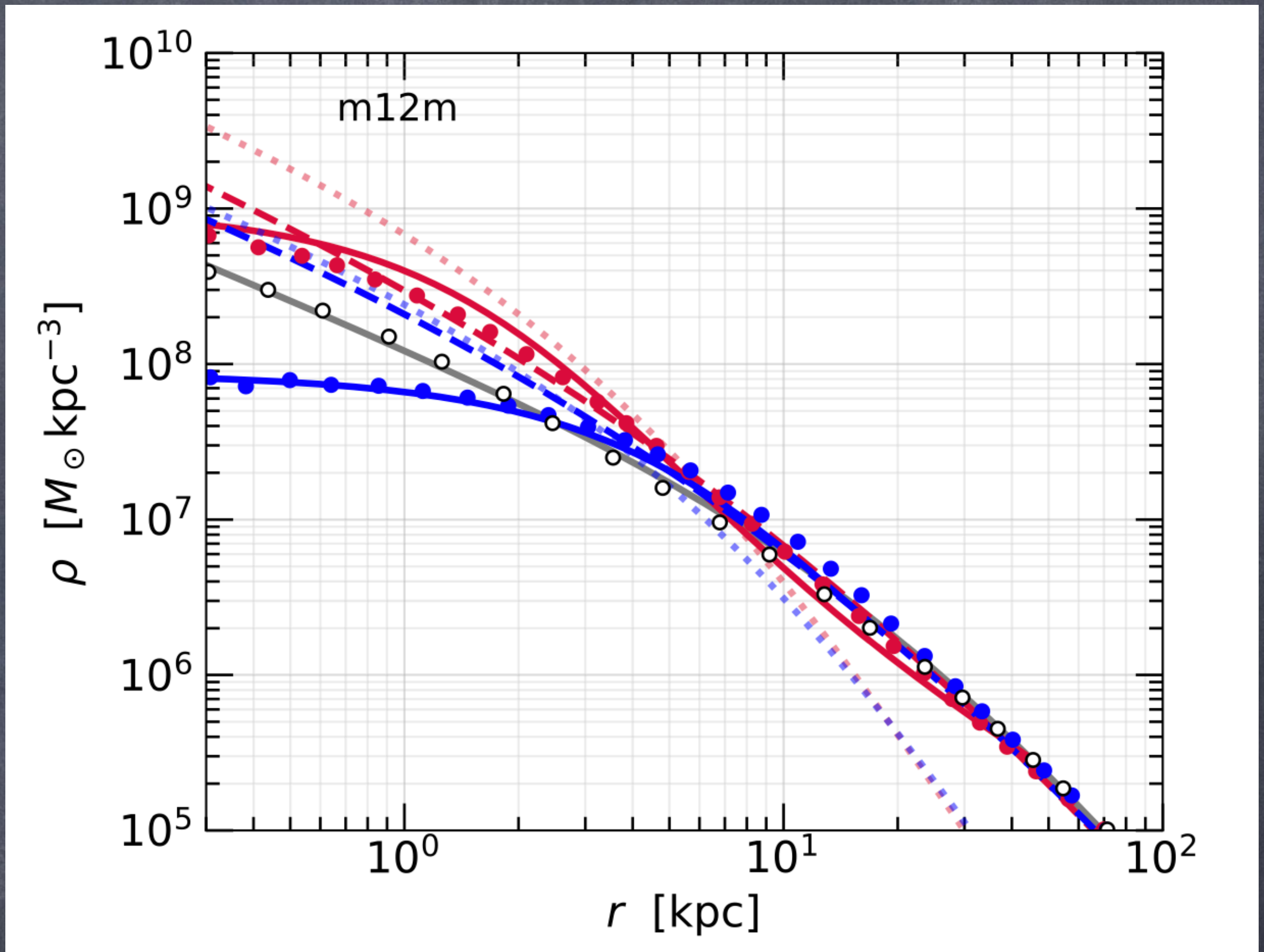
Gnedin + 04,11



Isothermal Jeans model — adding inhabitant galaxy

- comparison with cosmological FIRE2-SIDM simulations

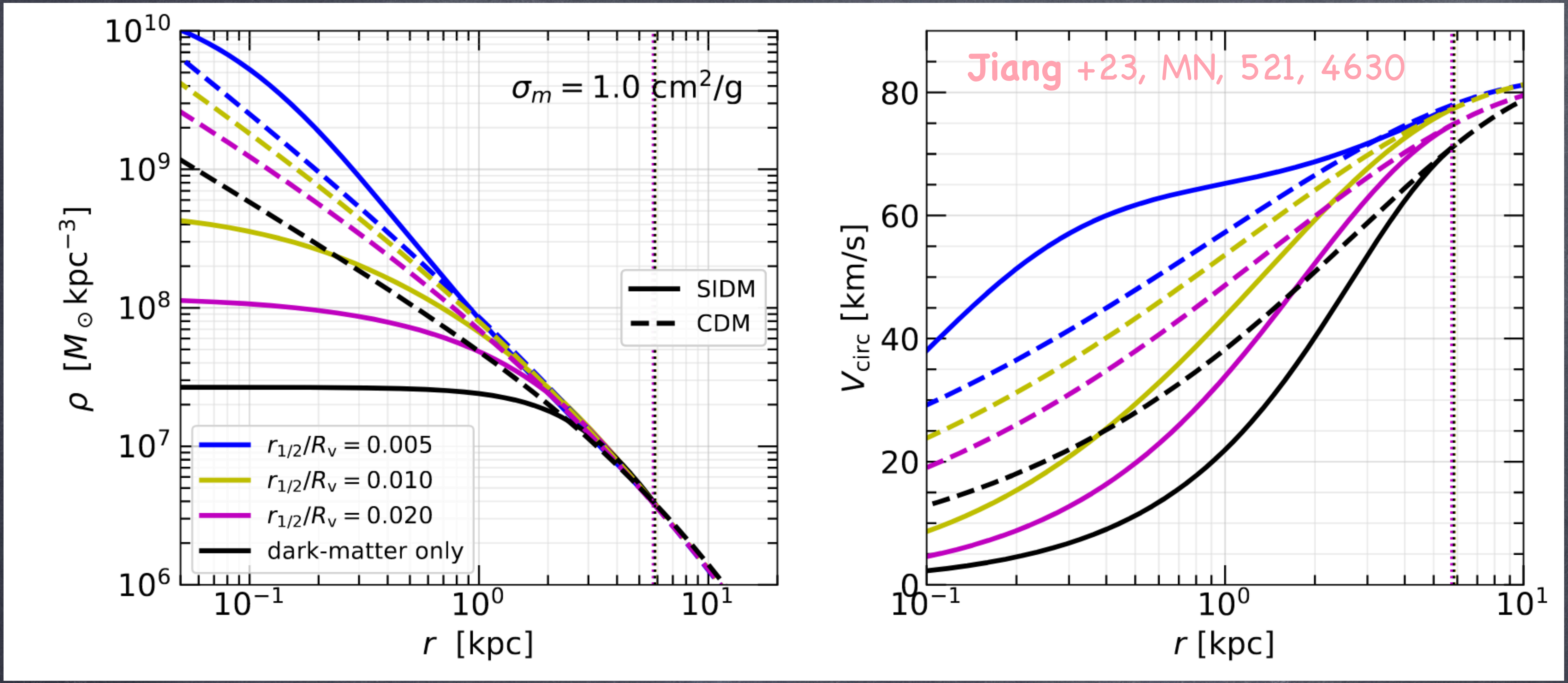




Jiang +23, MN, 521, 4630

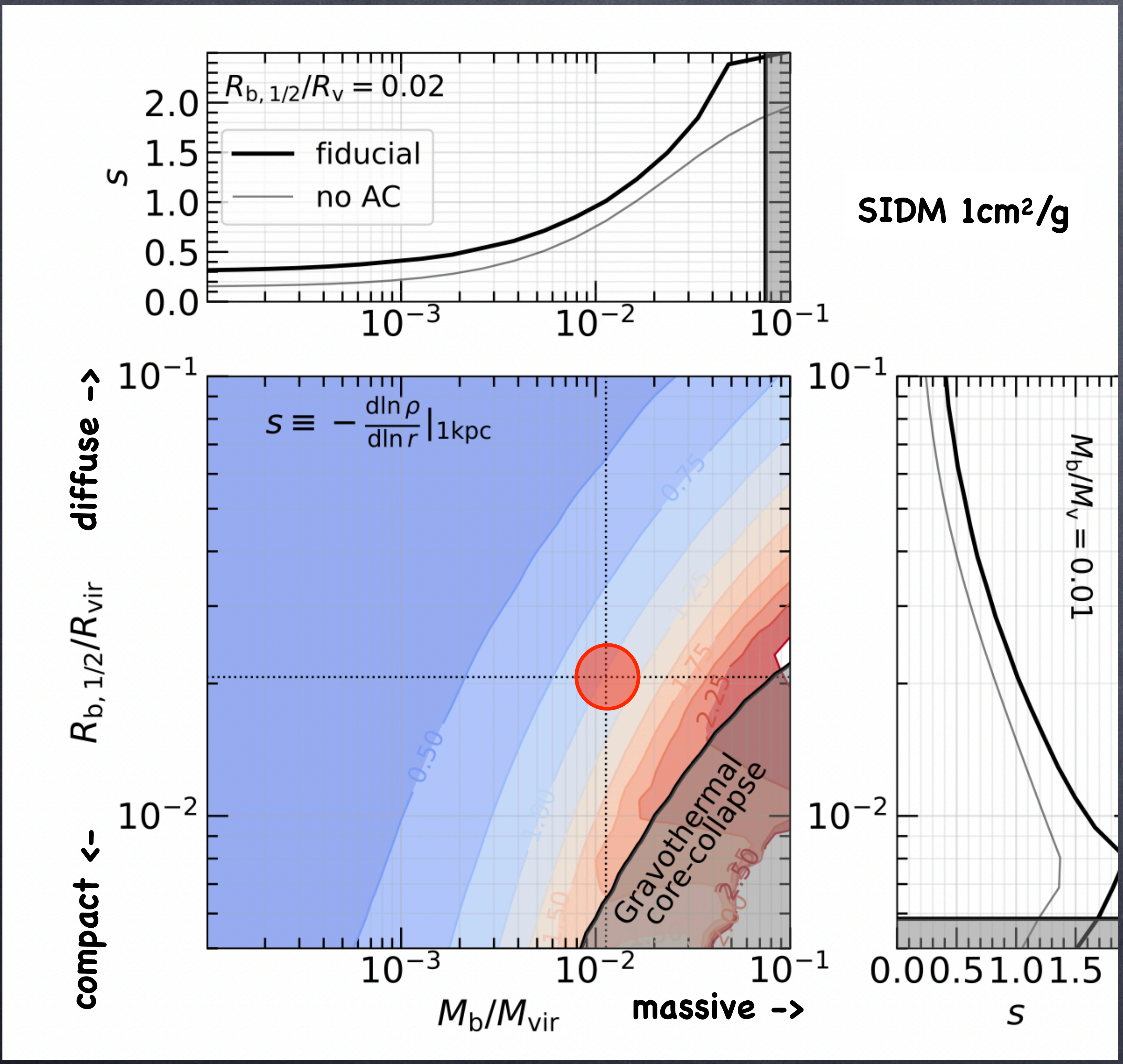
https://github.com/JiangFangzhou/SIDM

SIDM halo response to inhabitant galactic potential



- SIDM halo response more sensitive than CDM — depending on galaxy compactness, SIDM halo can be cored, as cuspy, or cuspier than CDM counterpart
- not necessarily a solution to the diversity problem, but SIDM makes the two perspectives of the diversity issue strongly coupled — if there is an explanation for the size diversity, it explains automatically the range of DM density slopes

SIDM halo response to inhabitant galactic potential



- For MW-like galaxies, R_e/R_v~0.015, M_s/M_v~0.01, SIDM halos are similar to CDM counterparts
- Gravothermal core-collapse is facilitated by massive and compact inhabitant galaxies
- Adiabatic contraction (AC) cannot be neglected

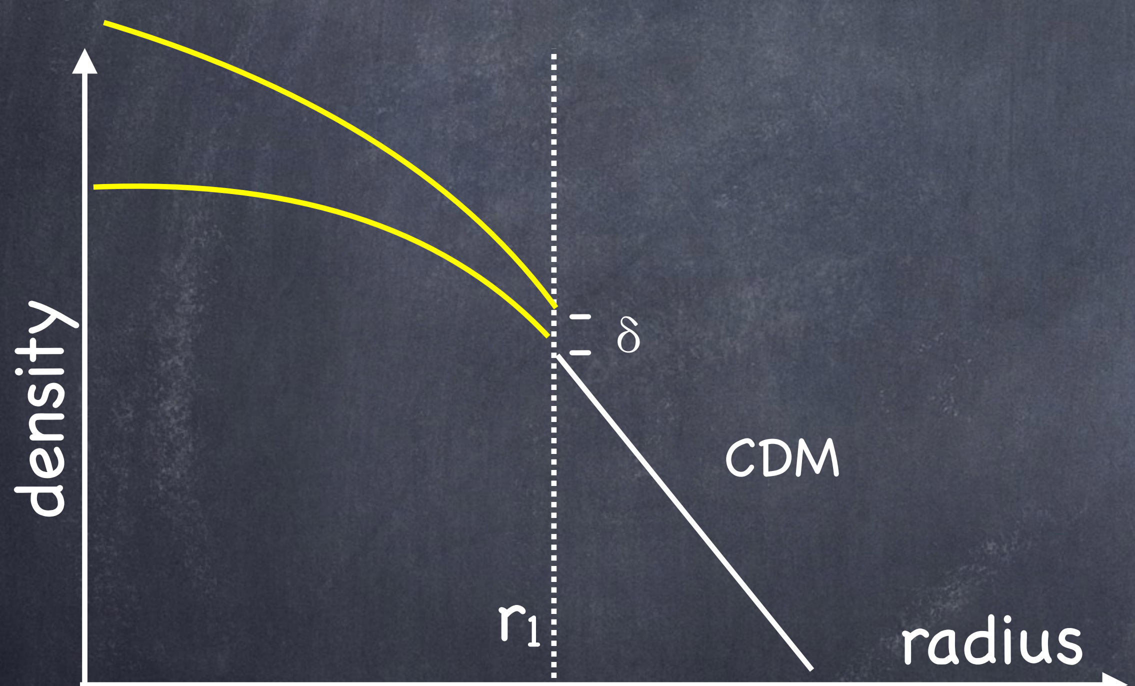
Jiang +23, MN, 521, 4630

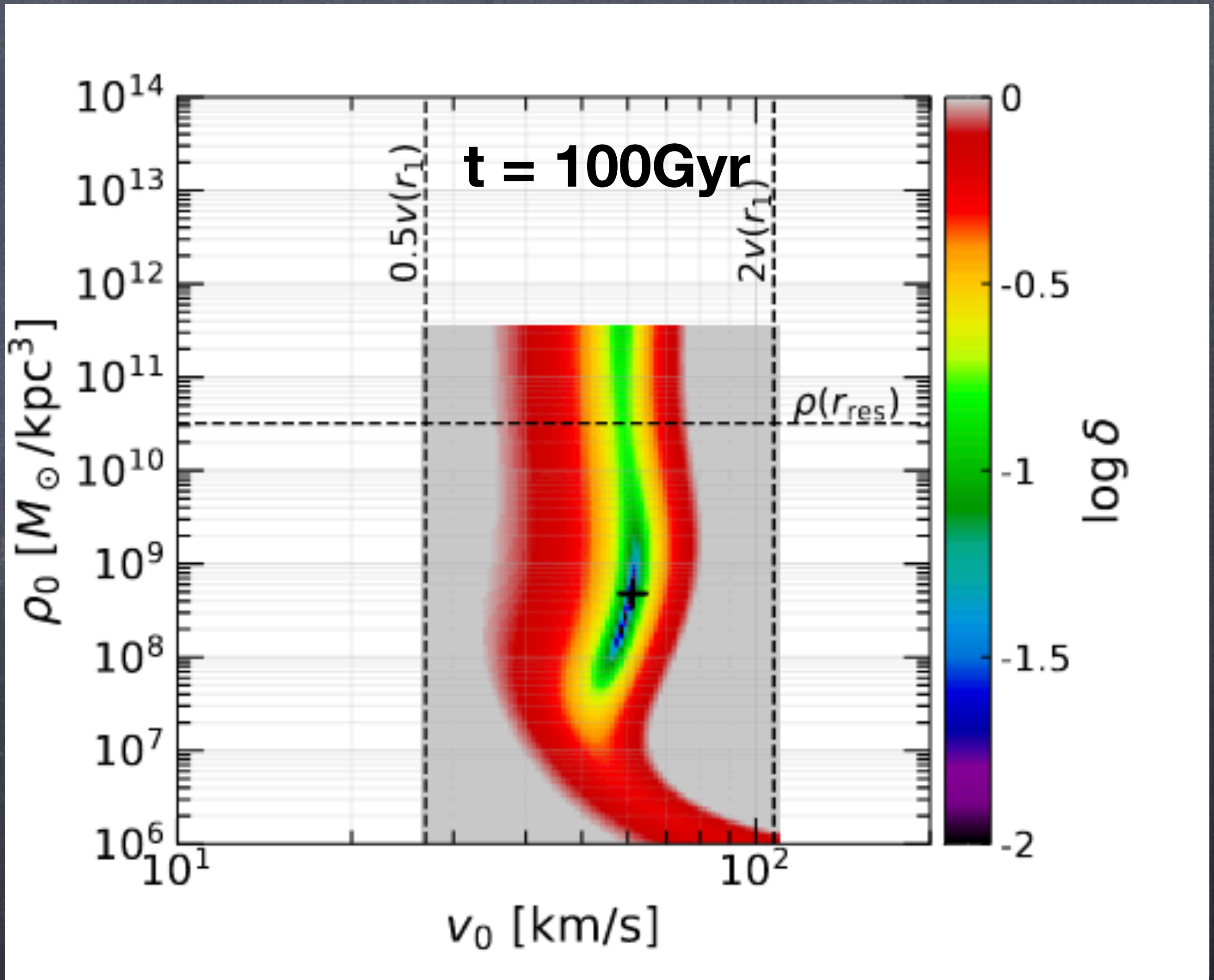
SIDM halo response to inhabitant galactic potential

- How do we capture core-collapse with the isothermal model?

there are two solutions of the isothermal core — both are physical, but the lower-density solution is closer to target CDM halo — when the two solutions merge, the isothermal assumption breaks, manifesting the onset of core collapse

two isothermal solutions of (ρ_0, v_0)





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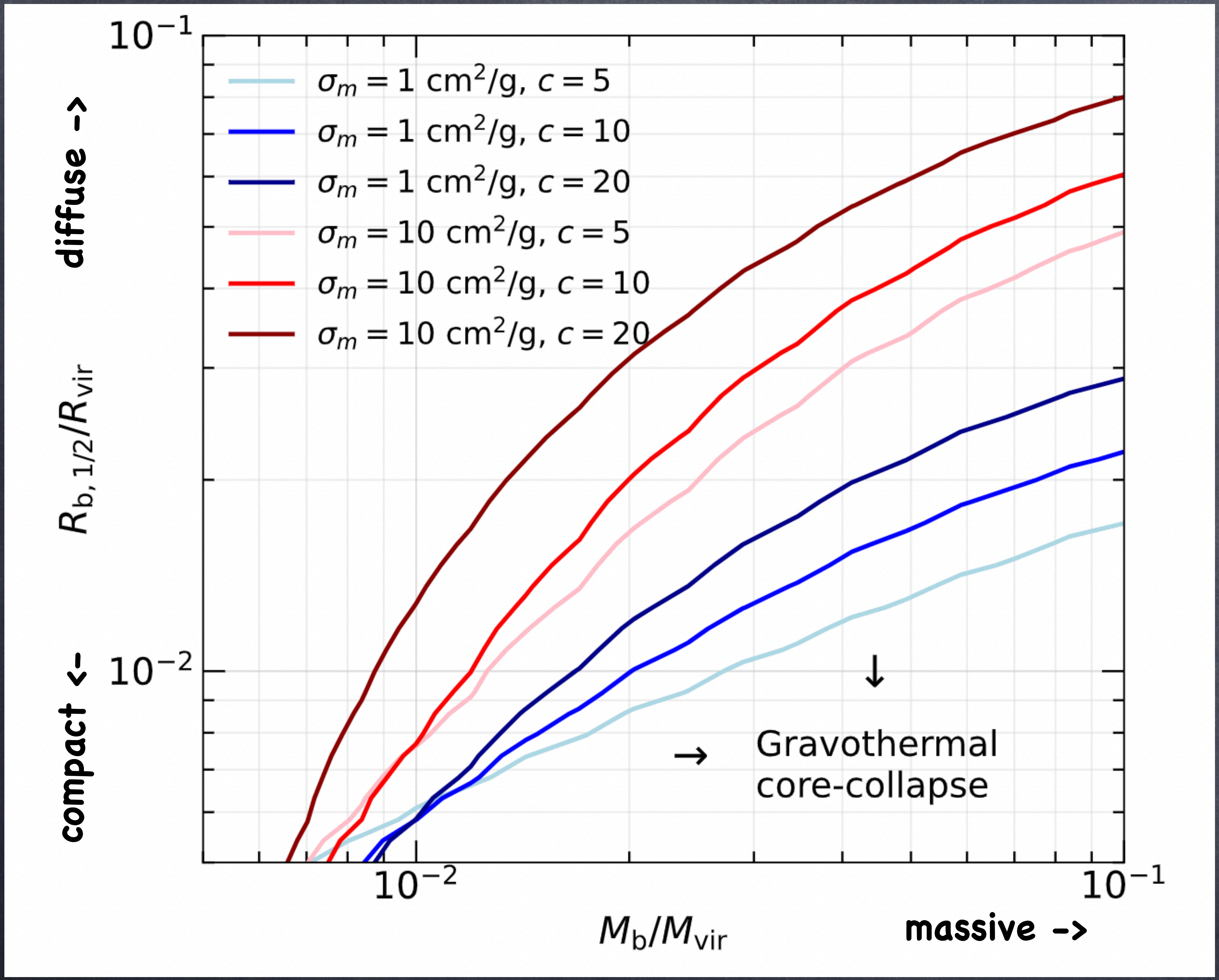
core-collapse regime in the galaxy compactness-mass plane



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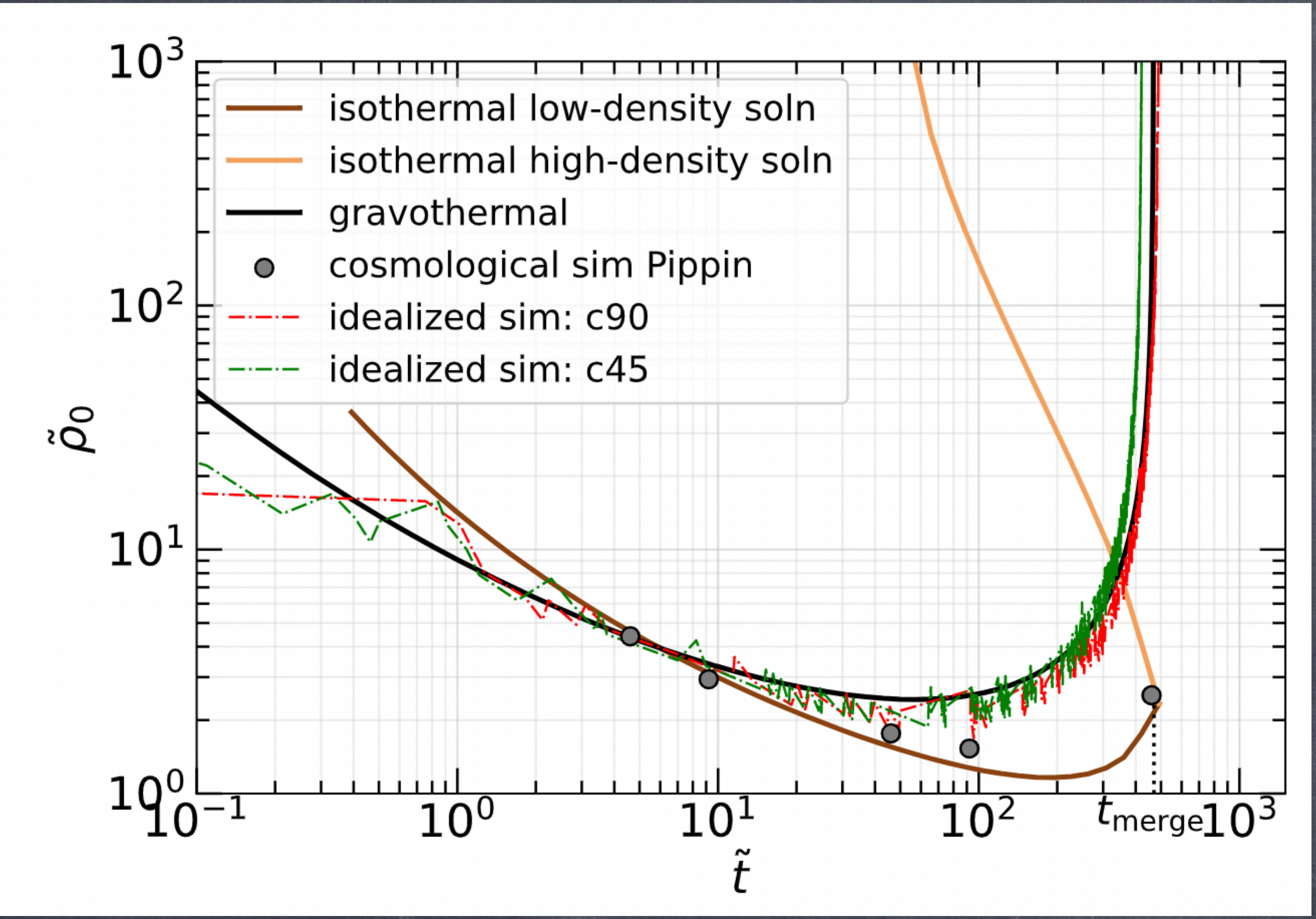
- the core-collapse threshold in the galaxy compactness-mass plane depends on the cross section and the profile of the (target) halo

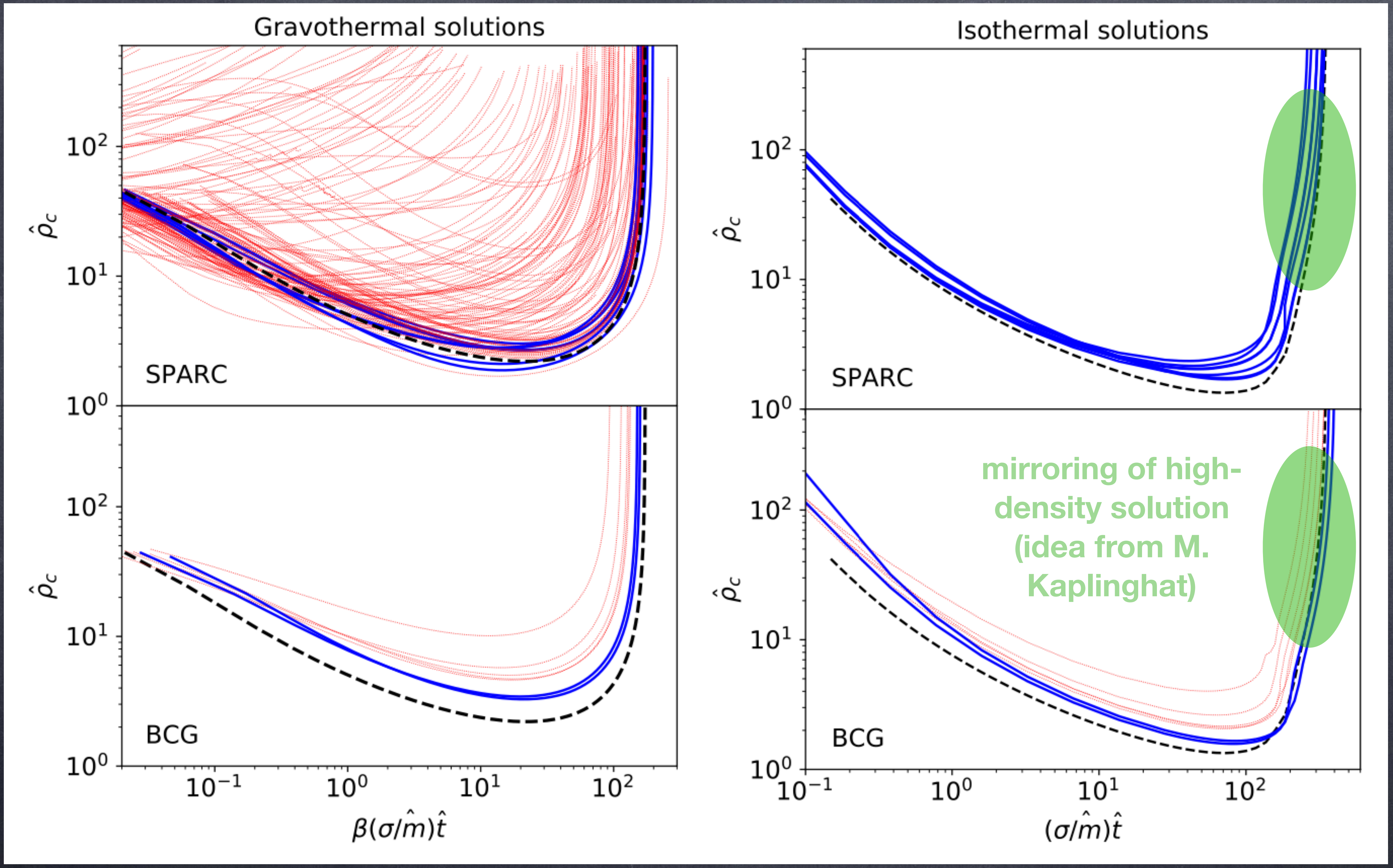
Comparison of methods: isothermal vs gravothermal



Jiang +23, MNRAS, 521, 4630

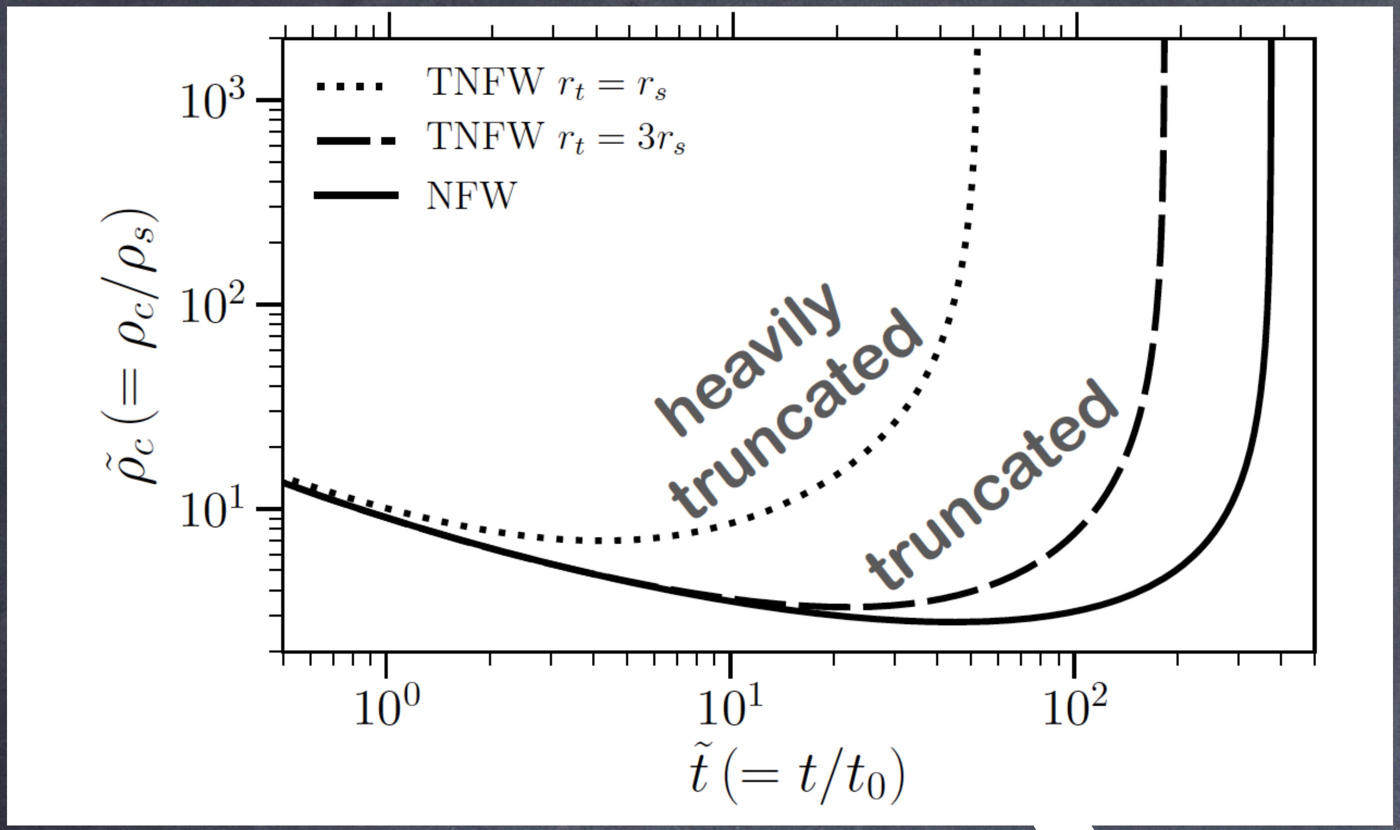
- The gravothermal fluid model uses CDM halo as **IC**, and thus agrees with idealized simulations, as intended
- The isothermal Jeans model uses CDM halo for **BC**, and since the CDM profile implicitly contains the assembly-history information, it agrees better with cosmological simulations

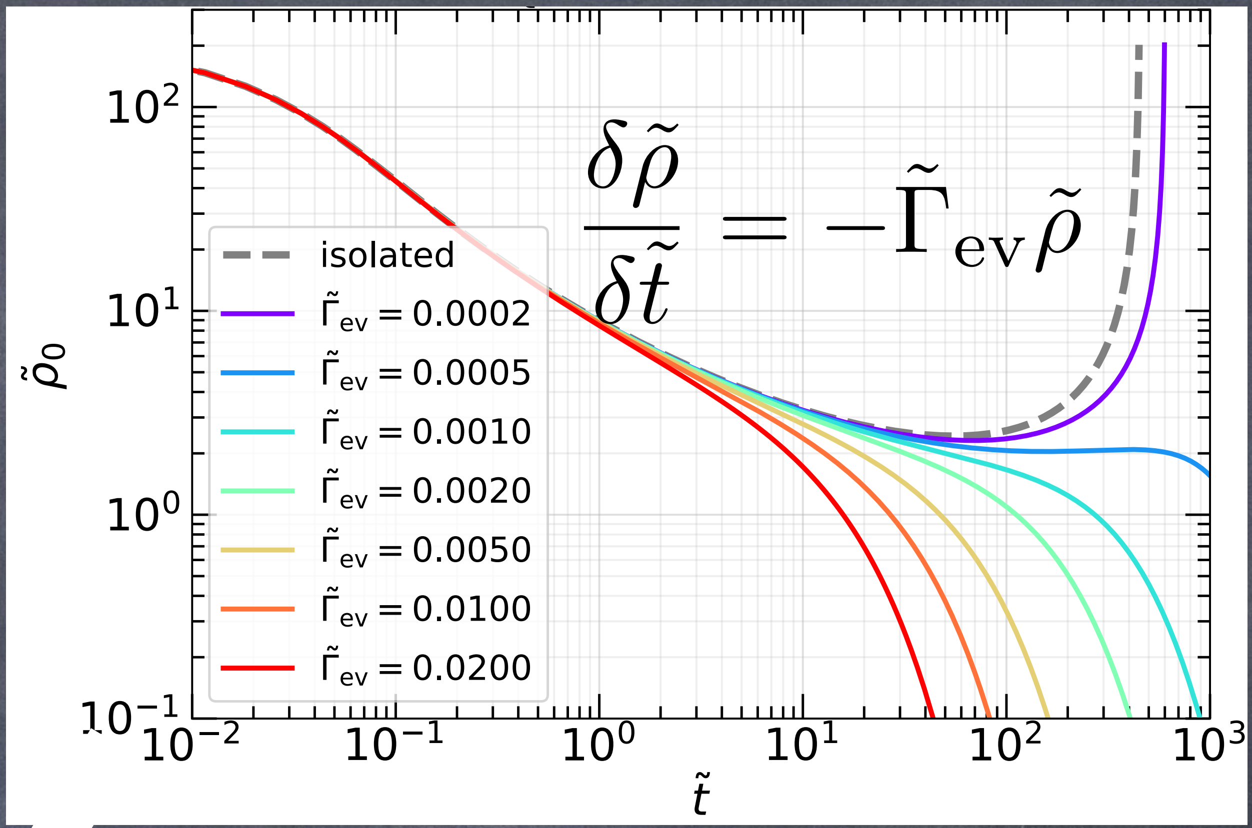
Comparison of methods: isothermal vs gravothermal



Yang*, **Jiang***, Benson + arXiv: 2305.05067

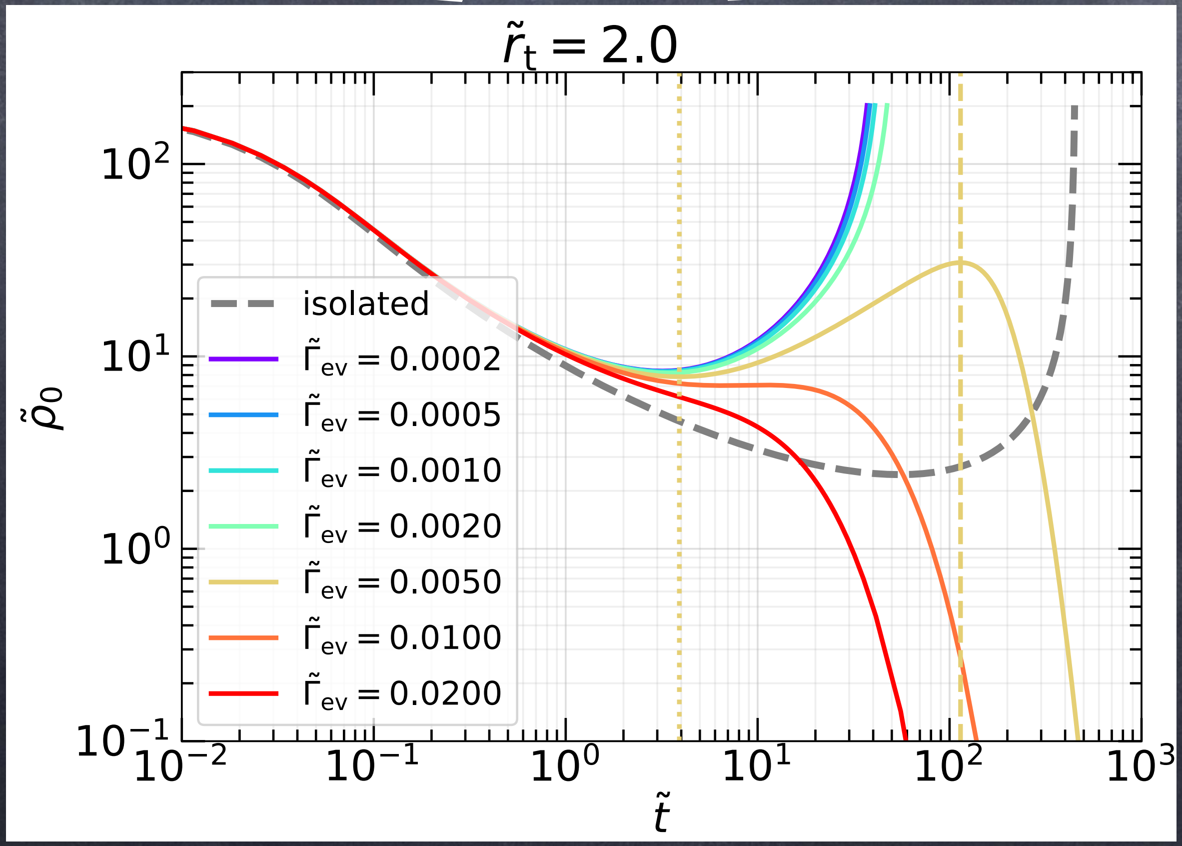
SIDM subhalos: tides versus ram pressure



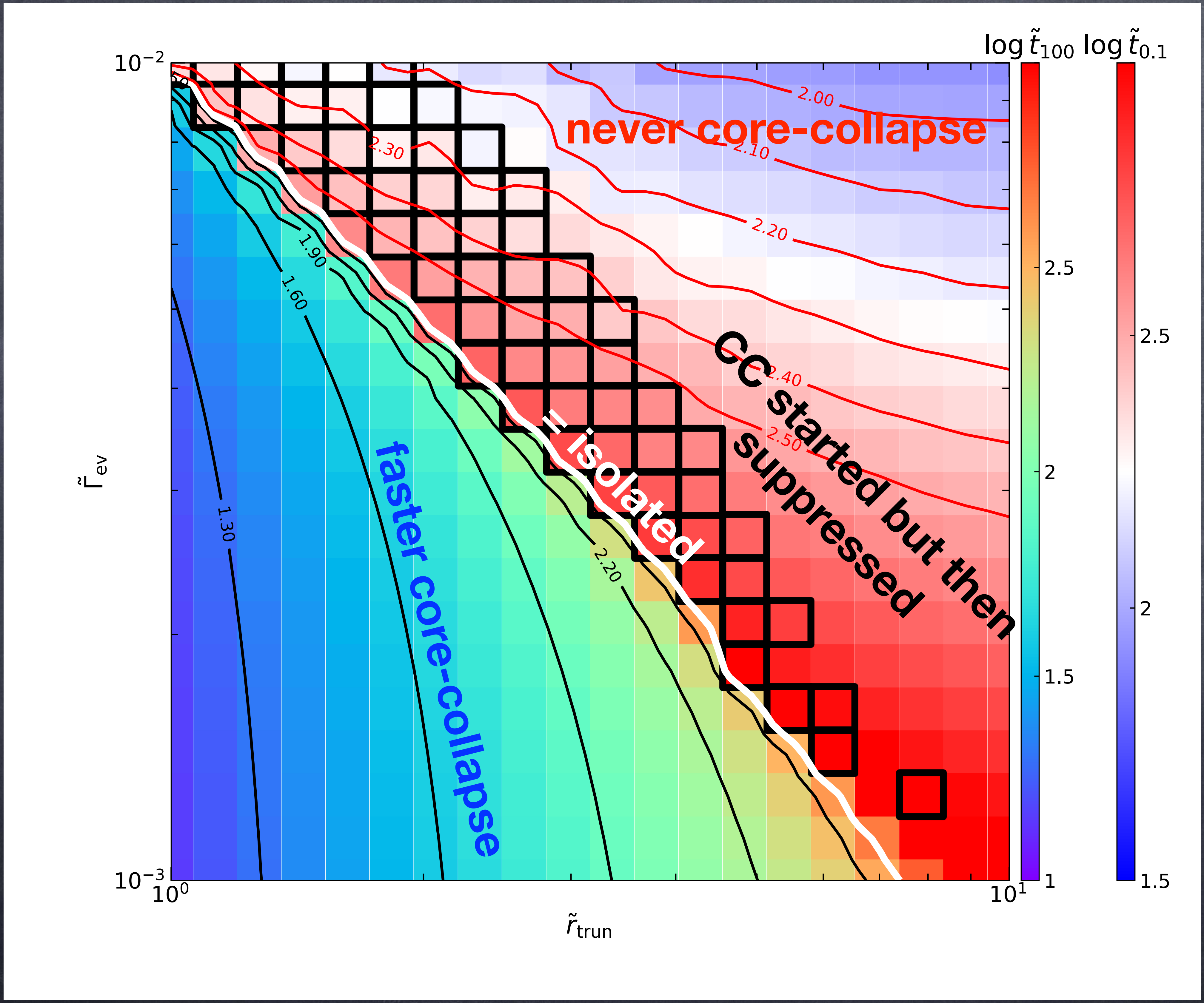


Nishikawa + 21

Slone, **Jiang**, van den Bosch + in prep



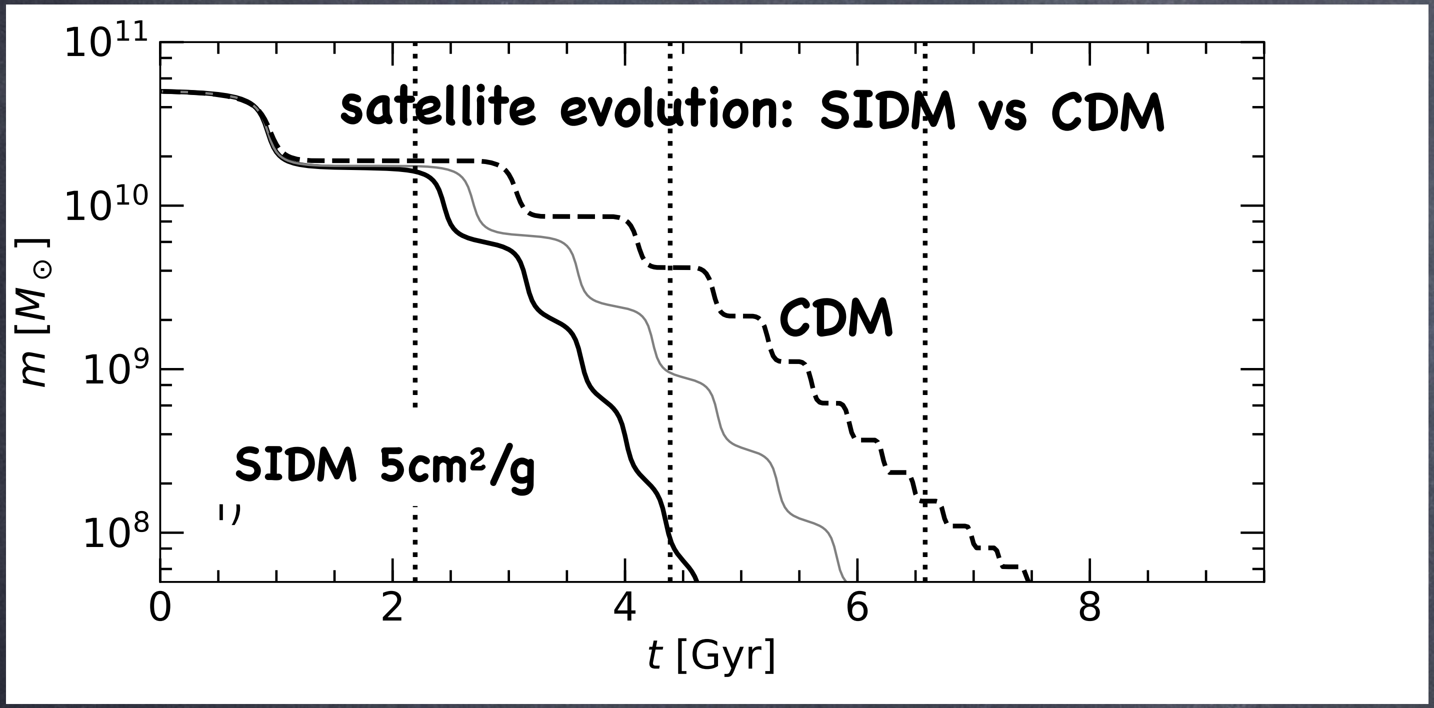
SIDM subhalos: tides versus ram pressure



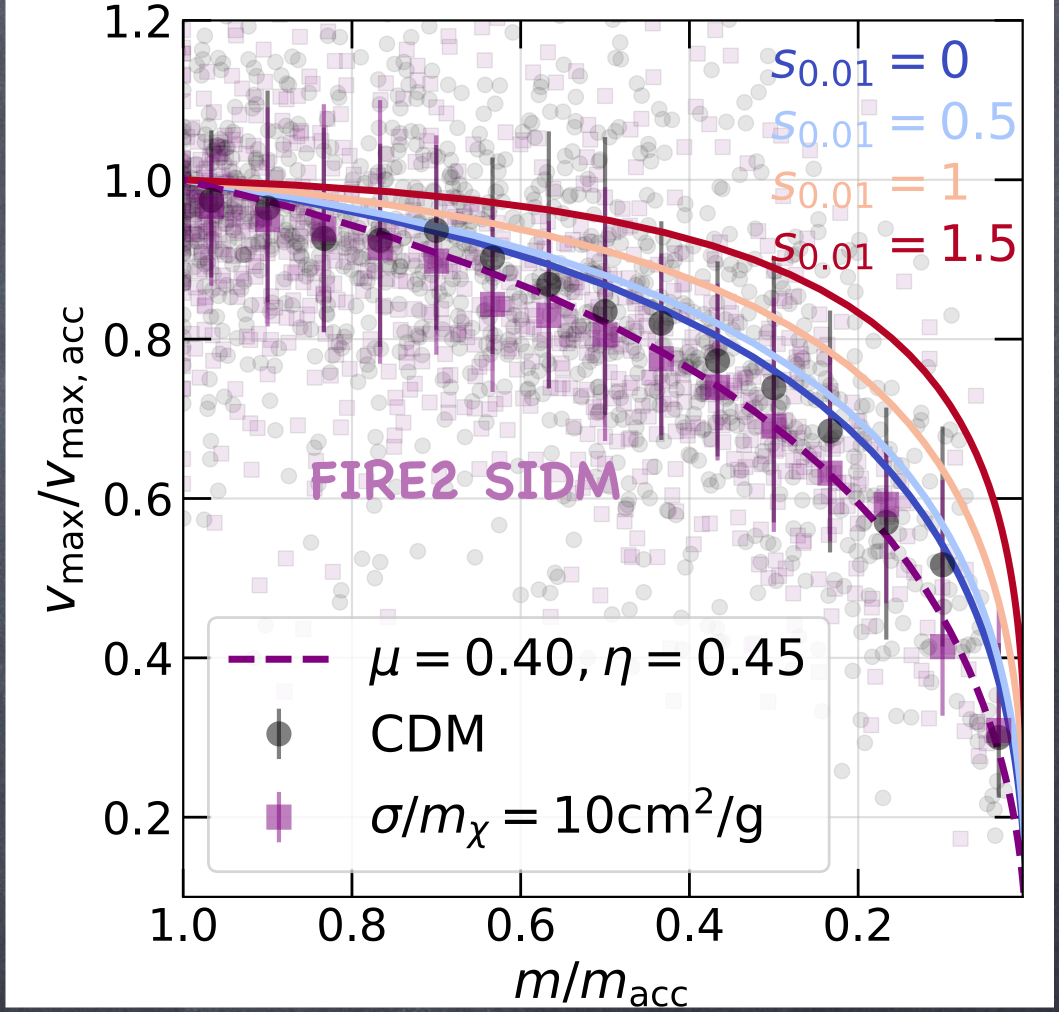
Slone, **Jiang**, van den Bosch + in prep

Evolution of SIDM subhalos: upgrading SatGen

- enhanced mass loss and RP deceleration



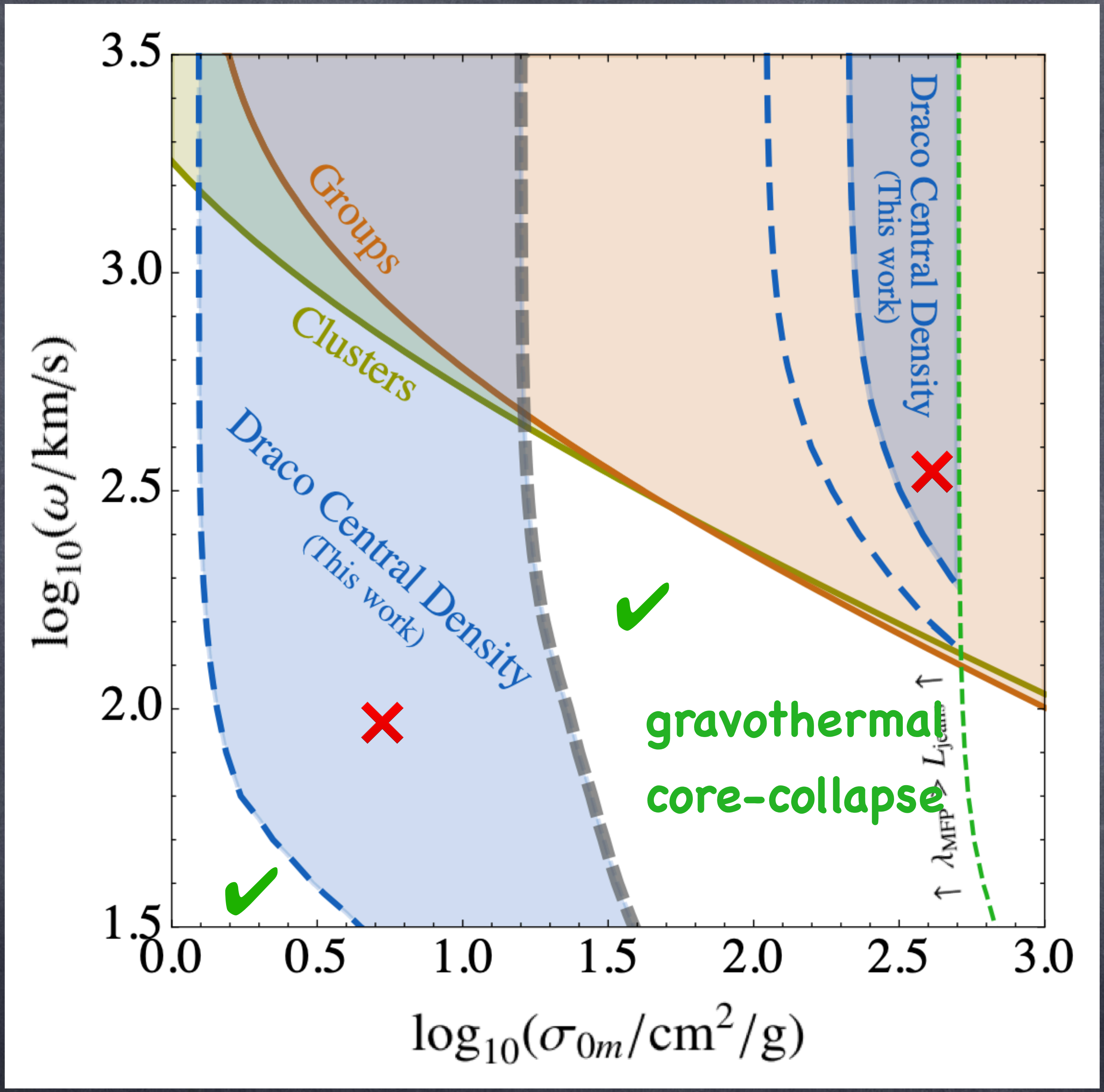
- different tidal tracks



Jiang + in prep

Constrain self-interacting DM using halo structures and satellite statistics

SatGen-SIDM proof-of-concept



Slone, **Jiang**, Lisanti, Kaplinghat, 23, PRD, 107, 4

Summary

- **Halo response in ΛCDM alleviates small-scale issues, but structural diversity is arguably still not fully reproduced**

  Jiang + 19b MN, 488,4801

  Freundlich, **Jiang**, Dekel+ 20, MN, 499,2912

- **SatGen: a semi-analytical framework for satellite galaxies** https://github.com/JiangFangzhou/SatGen
  - Satellite issues (TBTF, radial distribution, structural diversity) can be efficiently assessed
  - propagates halo-response patterns from field to dense environment

  Jiang + 21, MN, 502, 621

  Green, van den Bosch, **Jiang** 21a,b

  Dekel, Freundlich, **Jiang** + 21

- **SIDM: halo response is more diverse and subhalos evolve differently than CDM** https://github.com/JiangFangzhou/SIDM
  - The simple isothermal stitching + adiabatic contraction model performs amazingly well and quantifies halo response in galaxy compactness-mass plane

    Jiang + 23, arXiv: 2206.12425 Yang*, **Jiang***, Benson + arXiv:2305.05067
  - SatGen-SIDM: in development — proof-of-concept study shows that constraints of SIDM with MW satellite observations is feasible

    Slone, **Jiang**, Lisanti, Kaplinghat, 23, arXiv: 2108.03243

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