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COSMO_SIMS

Observatoire de la CÔTE d'AZUR

LAGRANGE

GO & Hahn, arXiv:1707.07693
GO, Nagai & Ishiyama, arXiv:1604.02866

What sets the central density structure of dark matter halos?

Go Ogiya

(Observatoire de la Côte d'Azur, OCA)

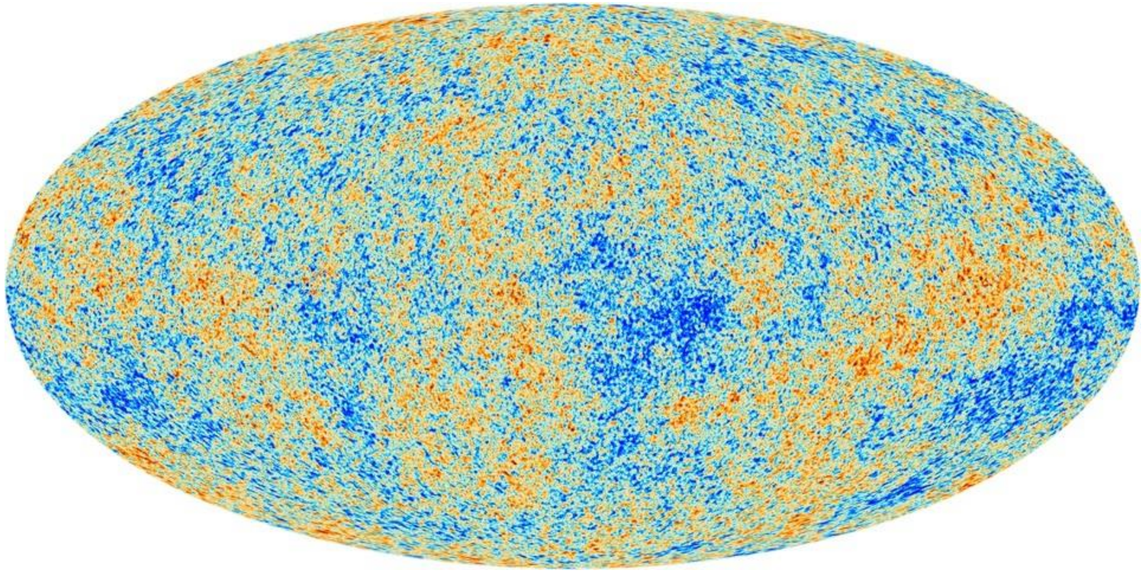
In collaboration with

Oliver Hahn (OCA); Daisuke Nagai (Yale); Tomoaki Ishiyama (Chiba)

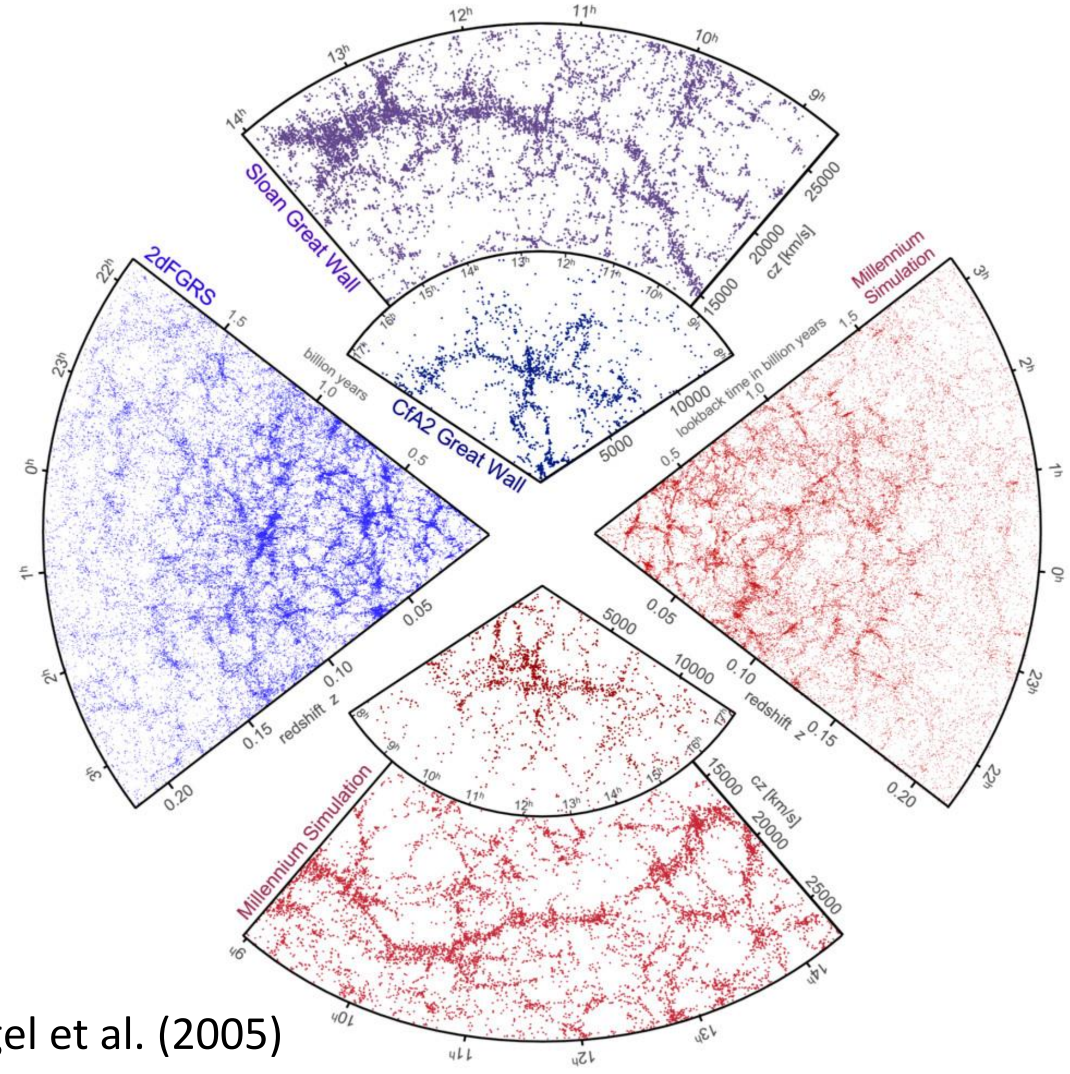
Agenda

- Introduction
- Formation of dark matter halos of the first generation
- Evolution of baby dark matter halos
- Summary

Structure formation in the Universe



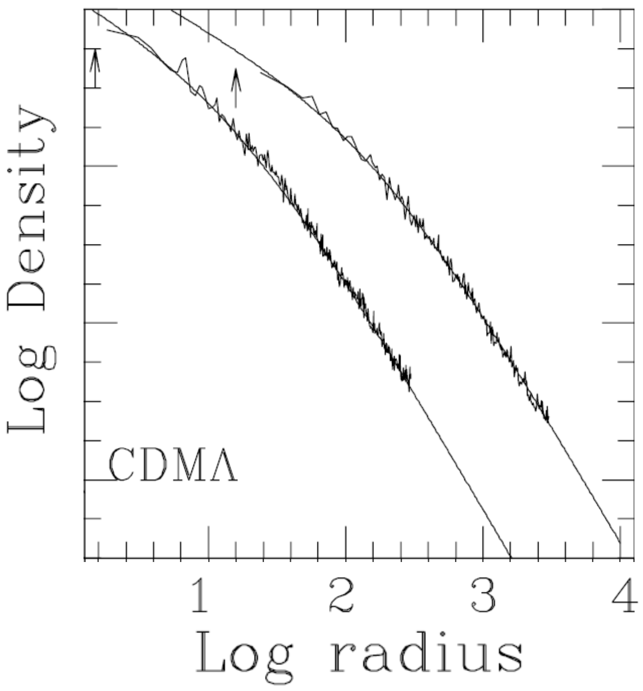
Planck satellite (ESA)



Springel et al. (2005)

Why DM density profile, ρ?

➢Important to
- Understand galaxy formation and evolution
  - ✓ Grav. potential ⇔ ρ
- Estimate the detectability of DM signals
  - ✓ Annihilation signal ∝ ρ^2; Decay signal ∝ ρ



➢Navarro, Frenk & White (NFW)

$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})(1+r/r_{\rm s})^2}$$

- Central cusp of $\rho \propto r^{-1}$
- At outskirts, $\rho \propto r^{-3}$
- Universal in the standard CDM simulations

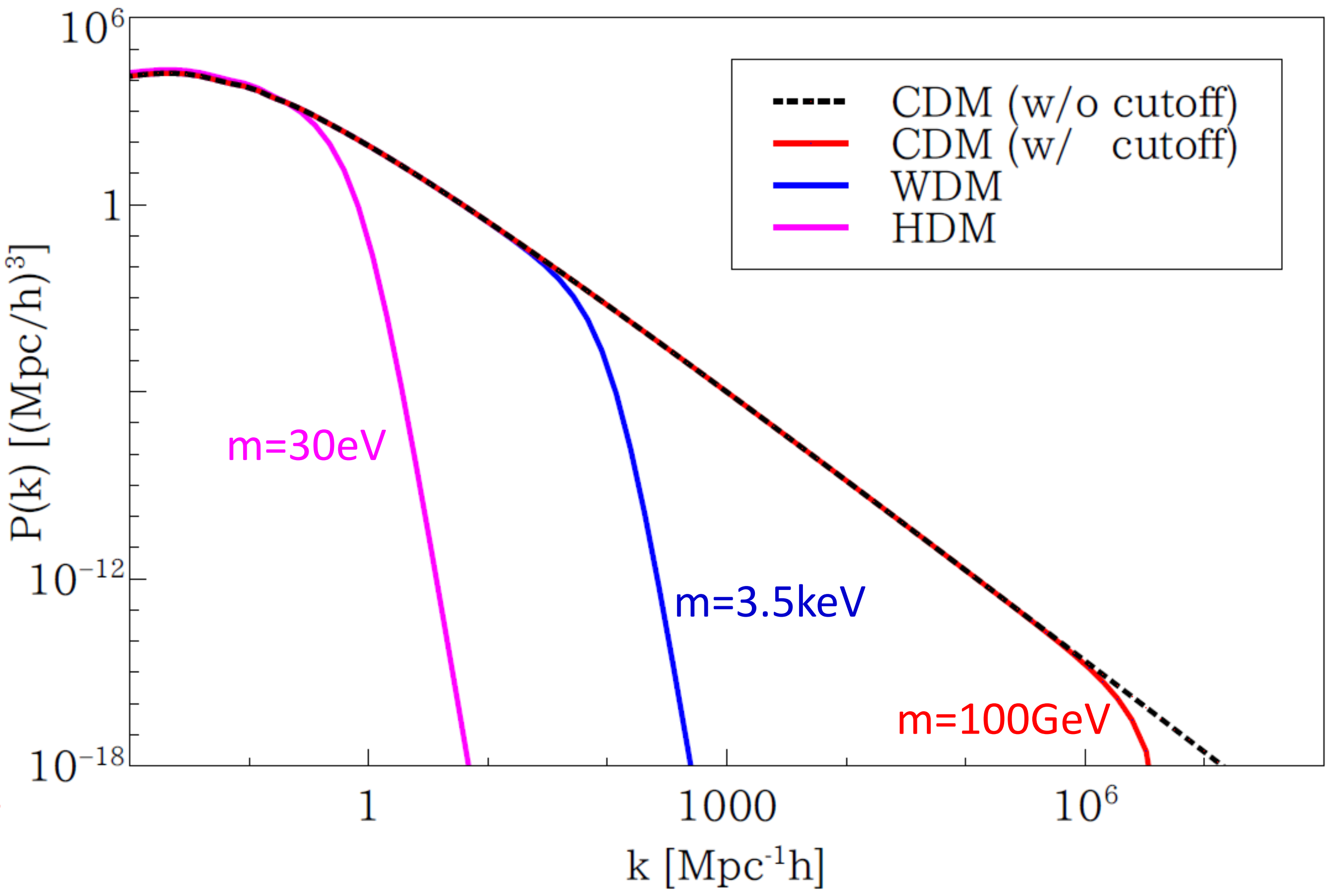
➢Origin is not fully understood yet…

Cosmo. sims with various DM models

- Power spectrum, P(k) = How much of density fluctuations at the scale of the wave num., k
- Vanilla CDM sims assume DM is initially perfectly cold
- Thermally produced DM particles
  - -> Finite T, corr. free-streaming scale
  - -> Erasing fluctuations on the small scales
  - -> Cut-off in the matter power spectrum
  - -> **Structure formation is suppressed beyond the cut-off**

Smallest halos = 1st generation

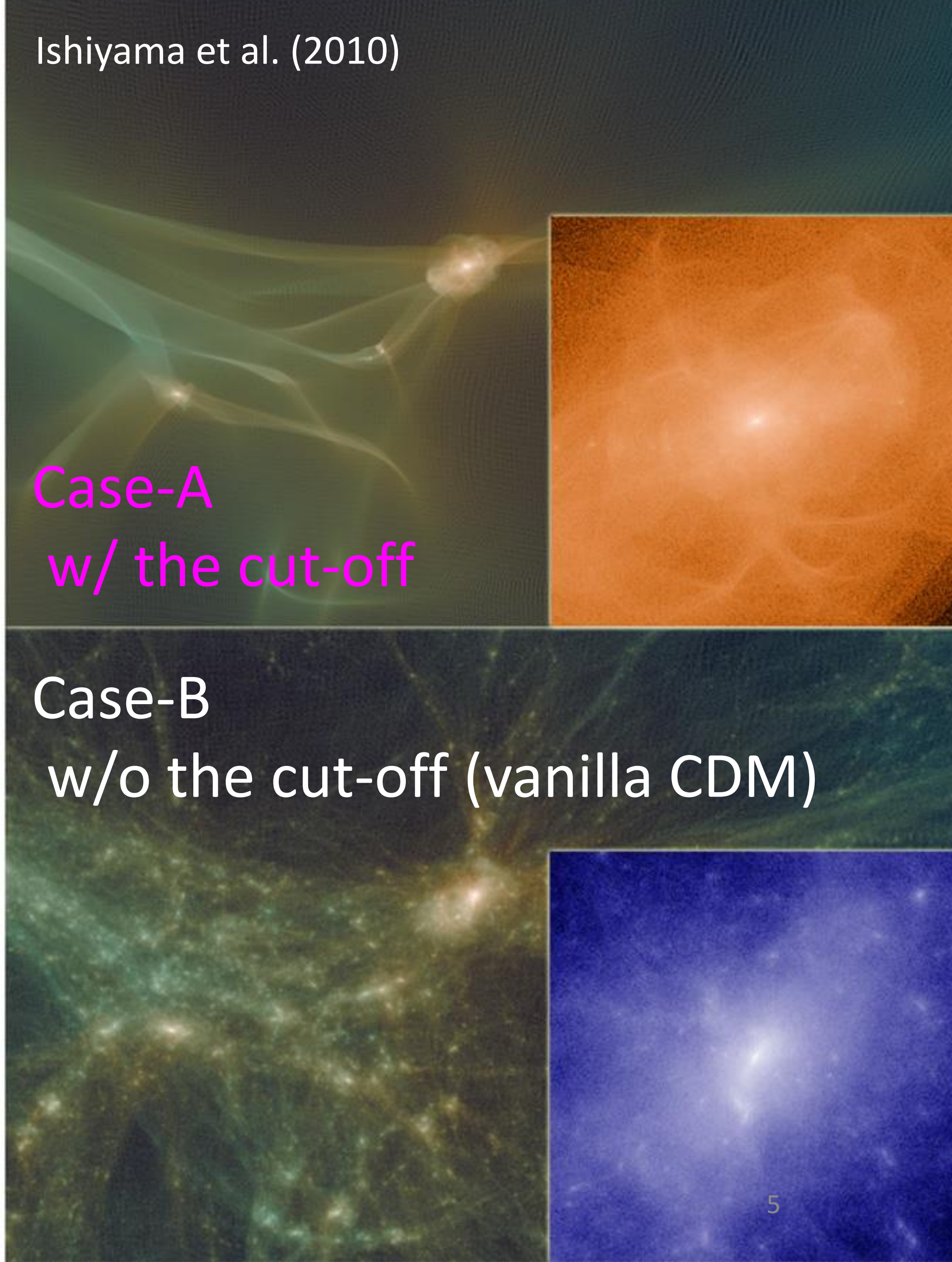
= Seeds of larger ones



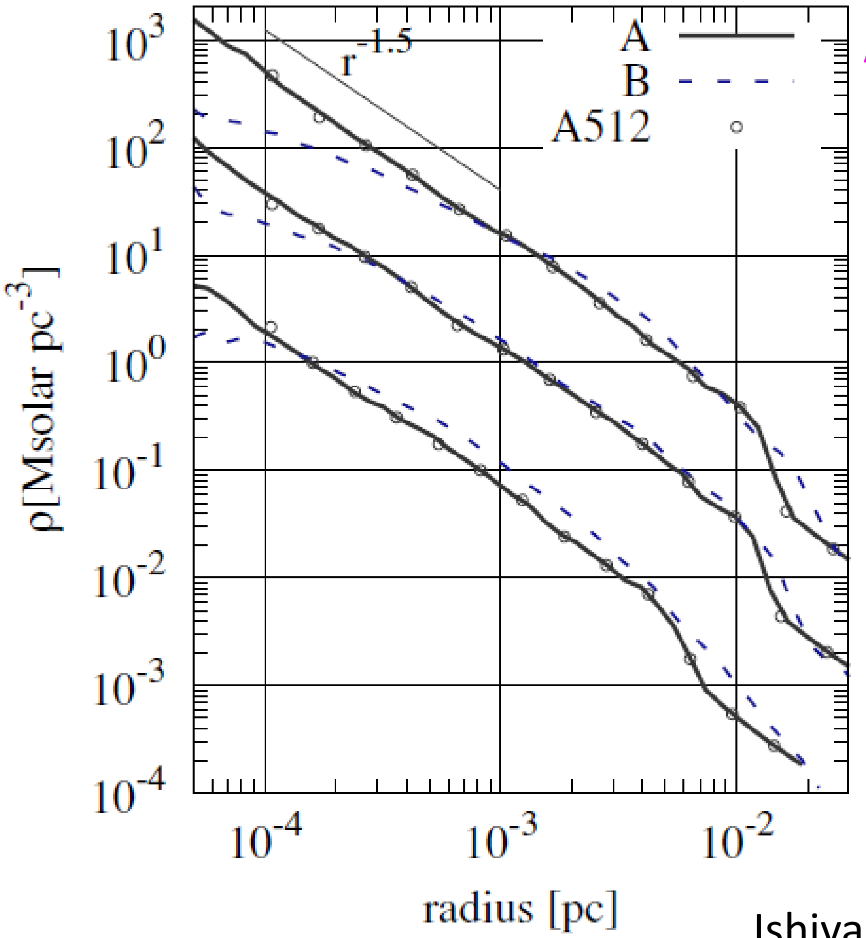
Cosmo. sims of ‘microhalos’

- Assuming CDM particles with a mass of 100GeV, the cut-off arises in the scale of 10^-6Msun, ‘*Microhalos*’

- Case-A
  - No substructure
  - Smooth filaments
- Case-B
  - Lots of substructures
  - Significant graininess



Deviation from the universality



A: w/ cut-off
B: w/o cut-off

Ishiyama et al. (2010)

➢Central density structure of the halo

$$\rho \propto r^{-\alpha}$$

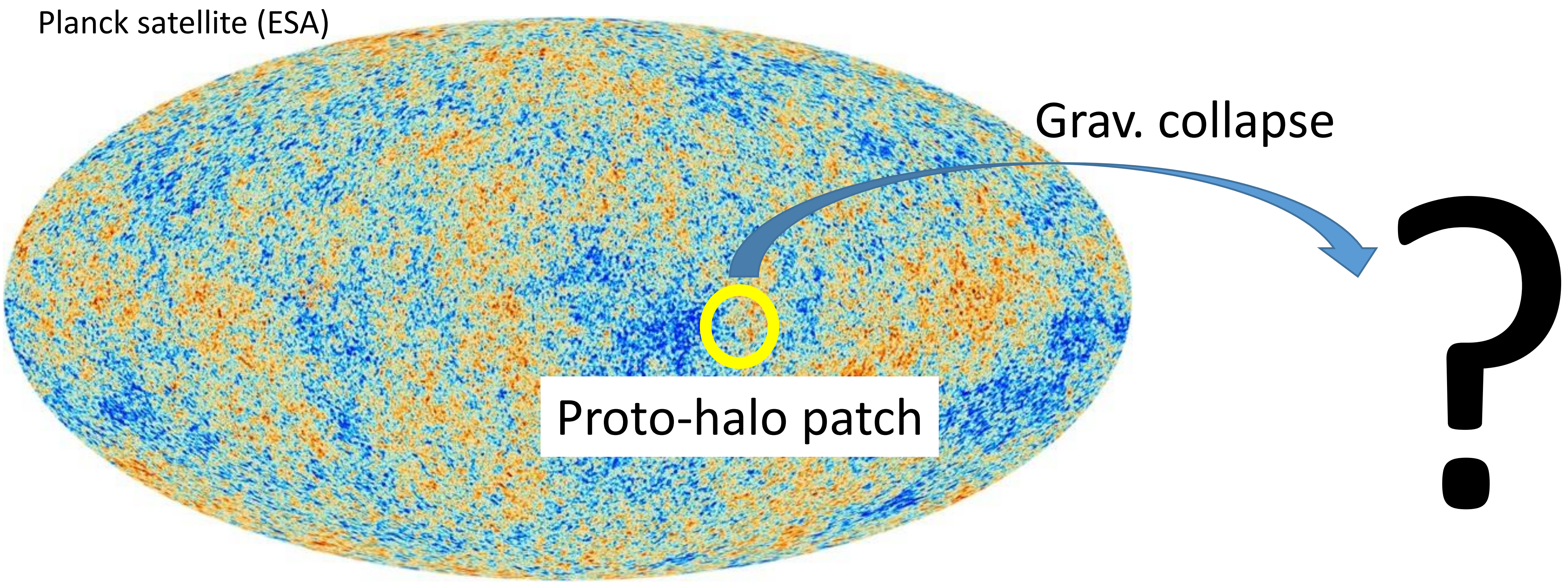
- Case-A: α=1.5
- Case-B: α=1 (NFW)

➢***Why do the halos in Case-A have the steeper slope?***

➢Case-A = DM halos of the 1st gen.

- **Formed through monolithic collapse**
- **Not experienced any mergers**

What we'd like to know = first halo formation

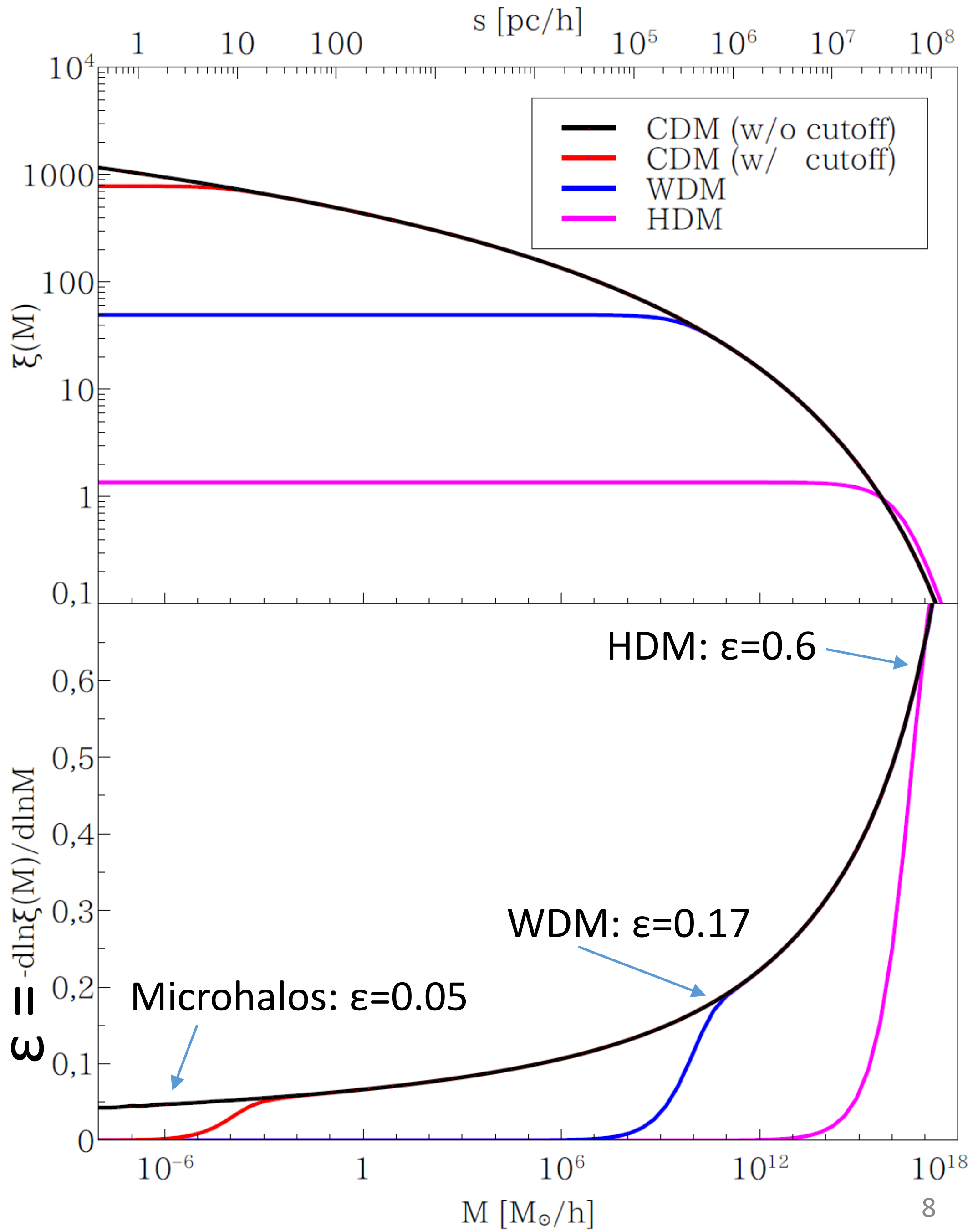


Structure of proto-halo patches

- ➢Assumption: $\rho_{\rm i}(r) \propto \xi(r)$
- ➢**Density core in the models with the cut-off**
  - Fluctuations on the small scales erased
  - Cuspy structure in the model w/o the cut-off
- ➢Generalized spherical infall model

$$\rho_{\rm i}(r) \propto (r^2 + r_{\rm c}^2)^{-3\epsilon/2}$$

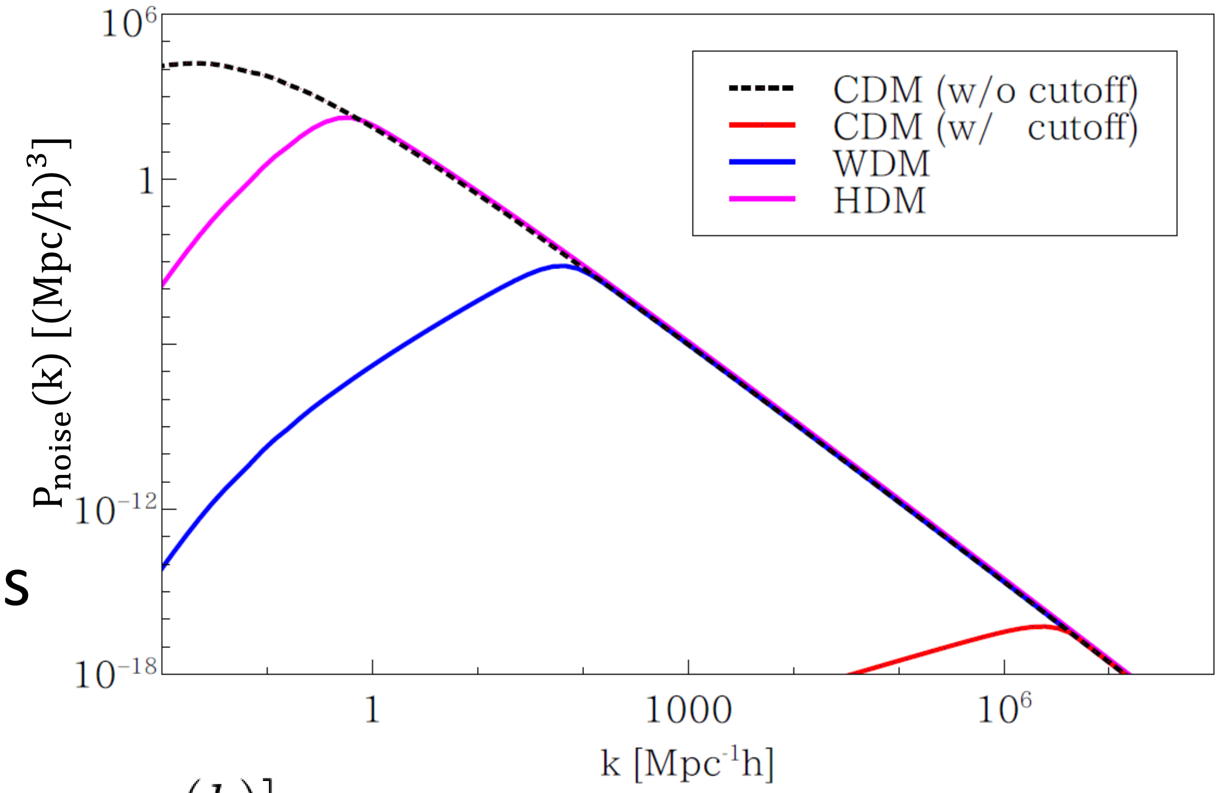
  - rc: core size in the patch
  - ε : slope (func. of mass scale)



Role of ‘Noises’

- ***Noises***
  - Numerically introduced graininess
  - Substructures

- Model them by including the Gaussian noise on the small scales
  - Discuss major mergers later



$$P_{\rm noise}(k) = g_{\rm amp}[P_{\rm w/o\ cut-off}(k) - P_{\rm w/\ cut-off}(k)]$$

Collapse simulations

➢ Initial particle position and velocity

- Zel'dovich approx. (Zel'dovich 1970)
    1. Regular particle lattice
    2. Displacement by following the grav. potential
    3. Follow the profile of $\rho_{\mathrm{i}}(r) \propto (r^2 + r_{\mathrm{c}}^2)^{-3\epsilon/2}$

No physical noise is included, but numerical ones always exist
-> + Non-spherical perturbation; to avoid numerical issues

- Noise on the small scales
- 3 params: $r_{\mathrm{c}}, \epsilon, g_{\mathrm{amp}}$

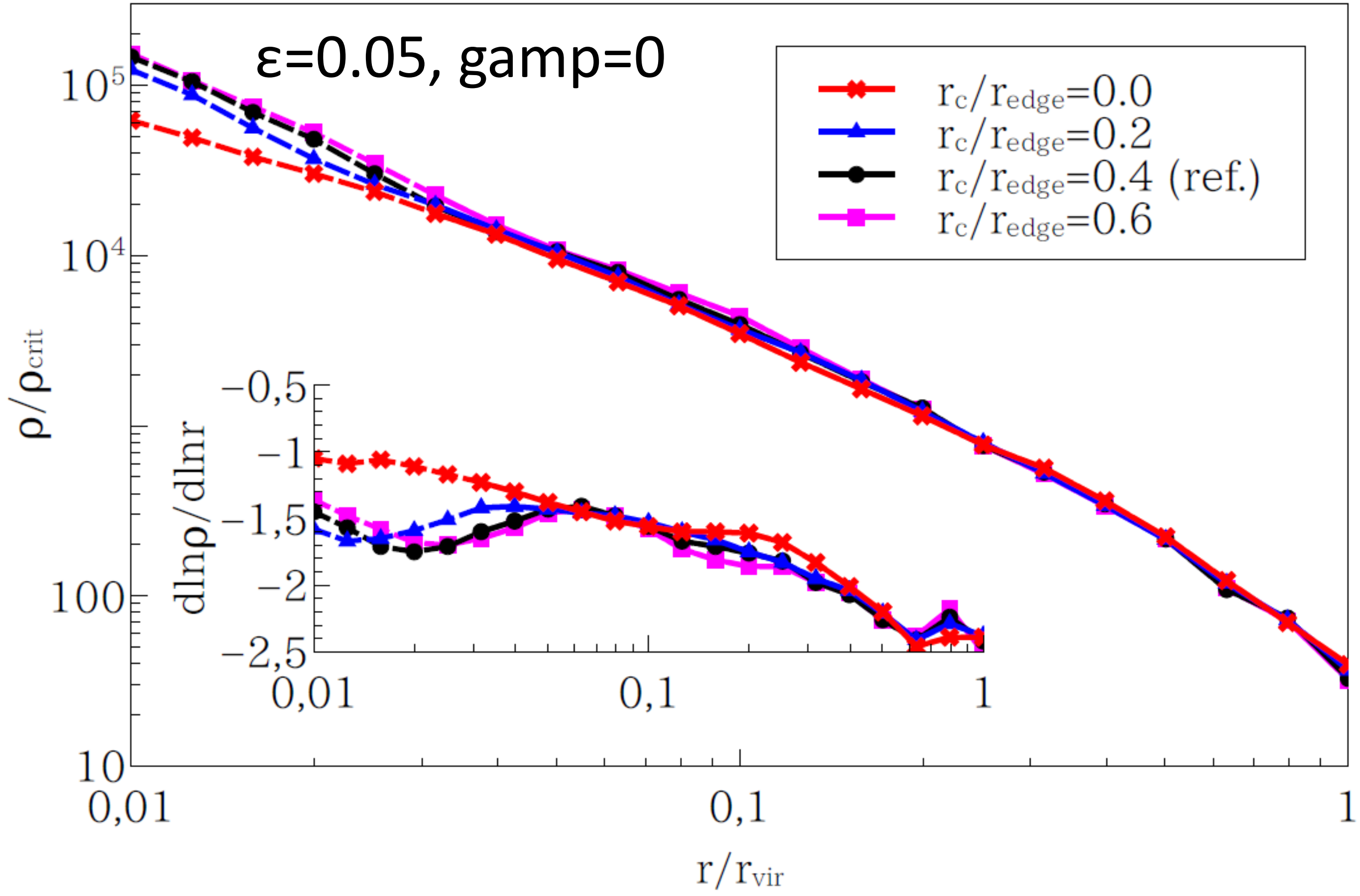
➢ Numerical parameters

- N=8,680,336
- Tree code for GPU clusters (GO et al. 2013, see also Barnes & Hut 1986)
- Params to control the resolution and accuracy are carefully chosen

GO & Hahn, arXiv:1707.07693

Impact of the initial core

$$\rho_{\rm i}(r) \propto (r^2 + r_{\rm c}^2)^{-3\epsilon/2}$$



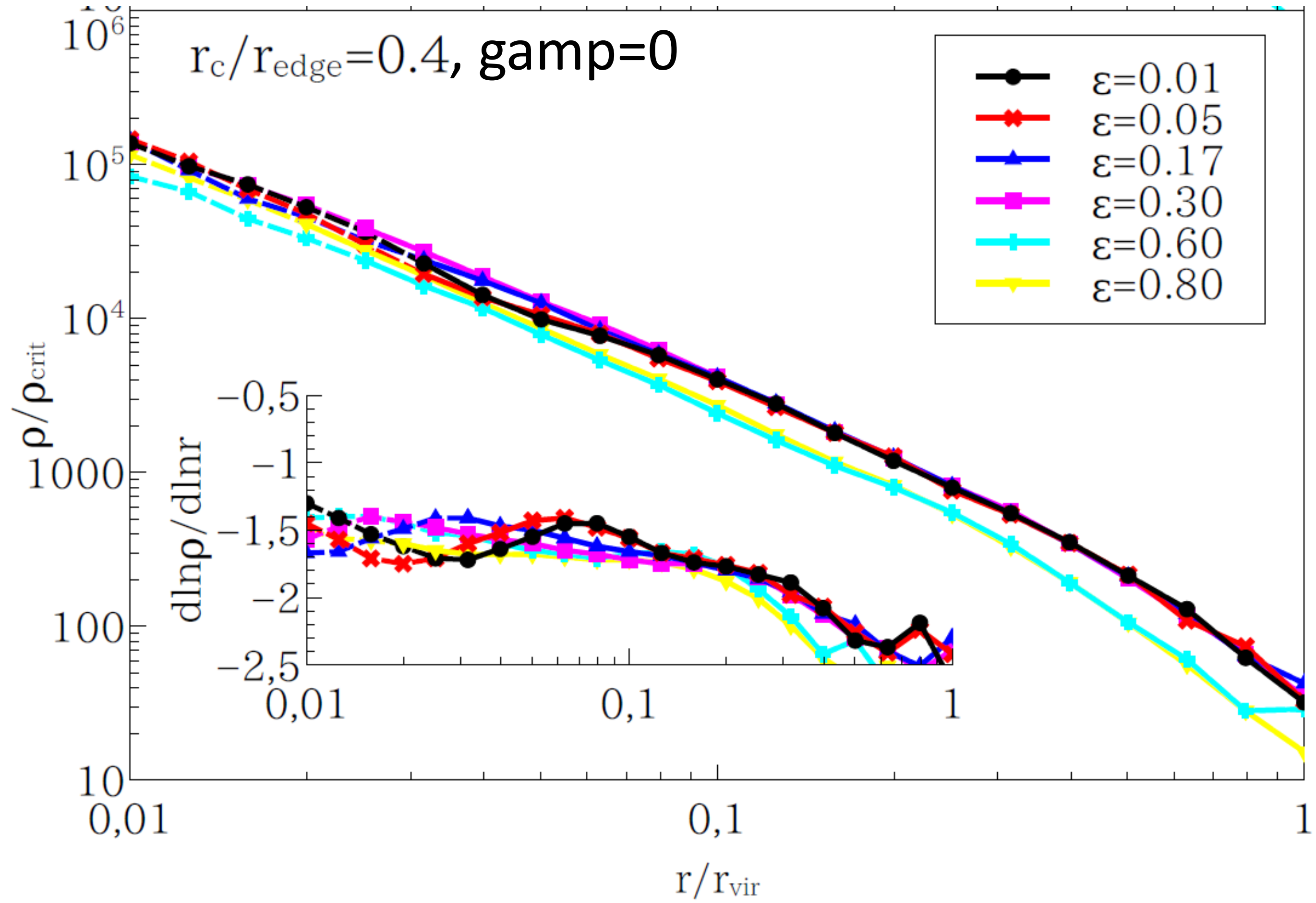
- Density at the outskirts is the same
- In runs with larger rc,
  - Higher central density
    -> Steeper cusps
  - α ~ 1.5 in runs with the core

Consistent with cosmo. sims of microhalos

Ishiyama et al. (2010); Ishiyama (2014); Angulo et al. (2017)

Impacts of the initial slope

$$\rho_{\rm i}(r) \propto (r^2 + r_{\rm c}^2)^{-3\epsilon/2}$$



- ***Profiles of α ~ 1.5 are obtained independently of ε***
- Q. Why α = 1.5?
  - Free-fall motion makes the density profile
    - ✓ Bertschinger (1985); Shu (1977)
  - Because of rapid mass accretion, free-fall motion is kept

GO & Hahn, arXiv:1707.07693

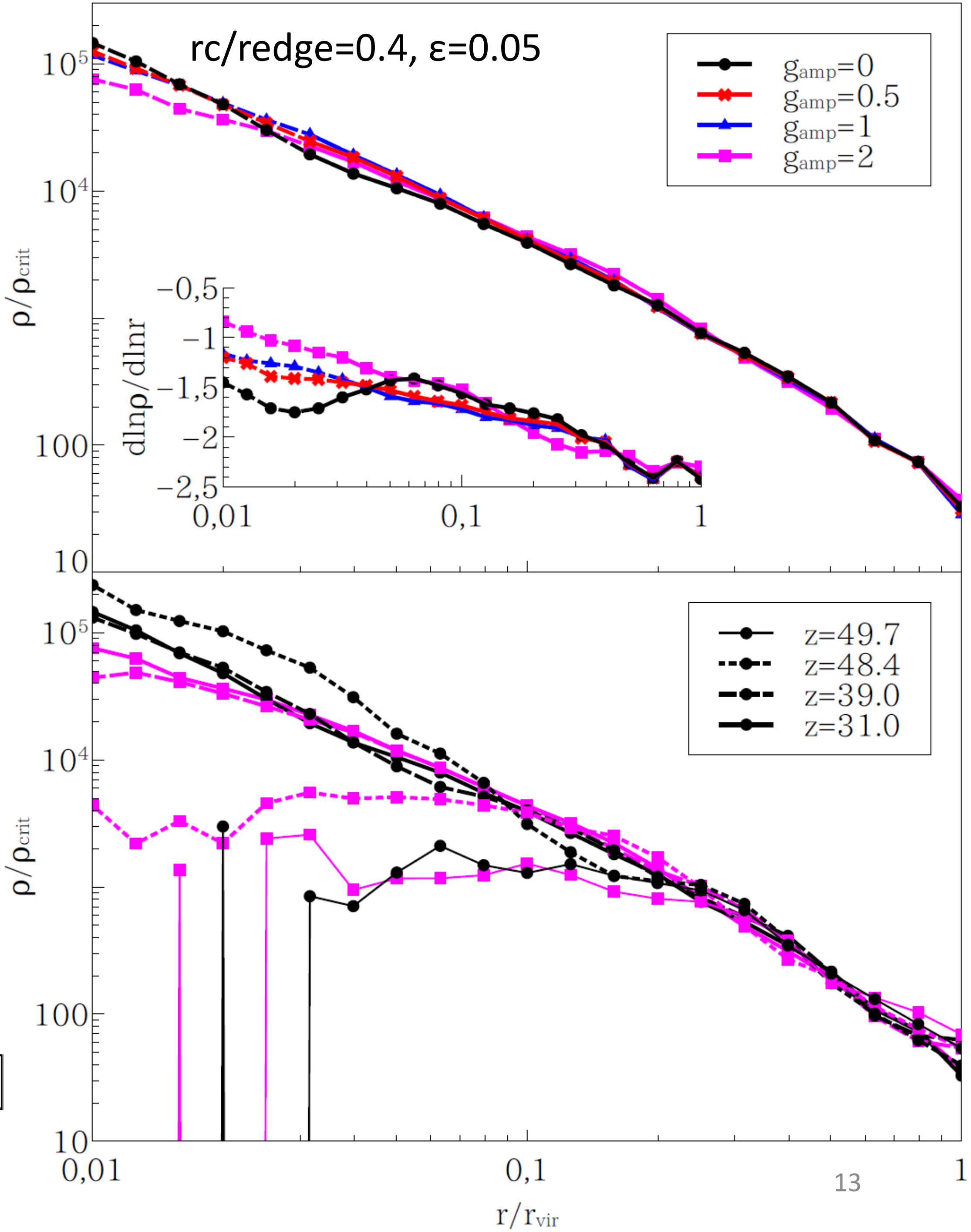
Impact of the noise

- [Upper] Varying gamp

Shallower central cusp in runs with larger gamp

- [Lower] Evolution
  - Noise disturbs the halo formation
  - Halos do not have the high central density and steep slope

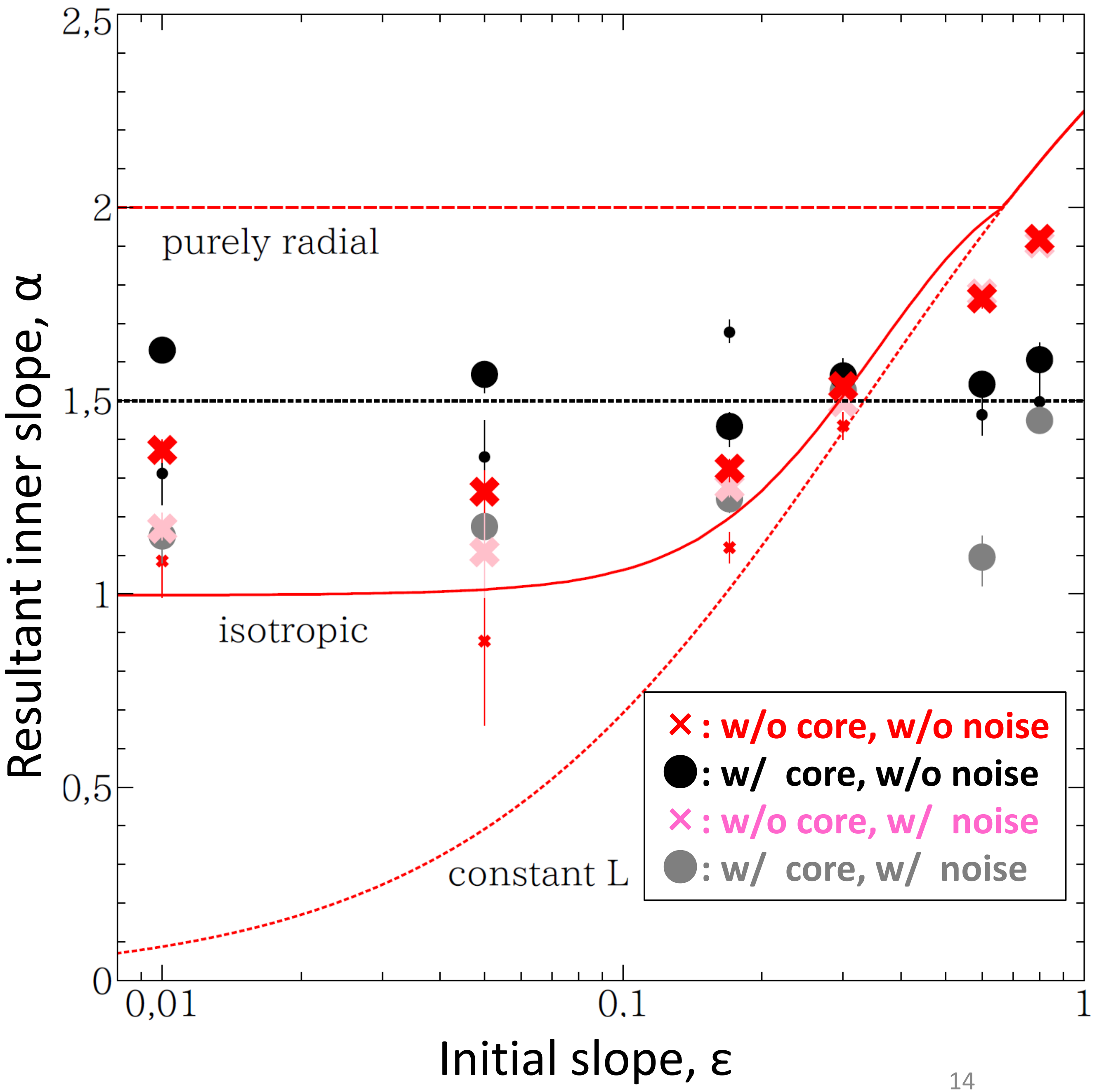
$$P_{\rm noise}(k) = g_{\rm amp}[P_{\rm w/o\ cut-off}(k) - P_{\rm w/\ cut-off}(k)]$$



Overview

- Runs w/o the noise
  - Red points roughly follow solid red line
    - ✓ Fillmore & Goldreich (1984); Bertschinger (1985)
  - Black points: α ~ 1.5

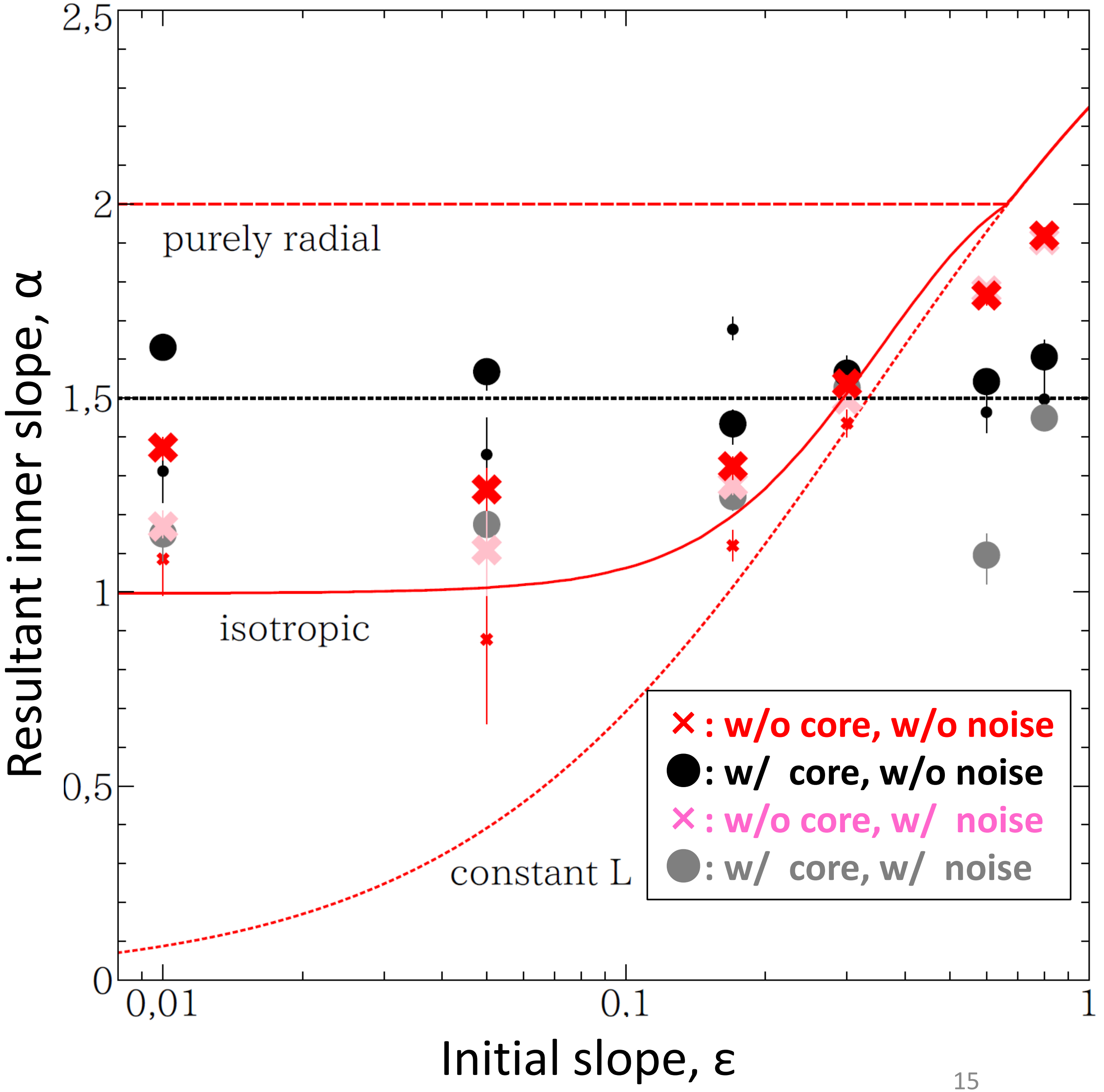
$$\rho_{\rm i}(r) \propto (r^2 + r_{\rm c}^2)^{-3\epsilon/2}$$



Overview

- Runs w/ the noise
  - w/ core: Formation is significantly affected
  - w/o core: Impacts of the noise is weaker

$$P_{\rm noise}(k) = g_{\rm amp}[P_{\rm w/o\ cut-off}(k) - P_{\rm w/\ cut-off}(k)]$$



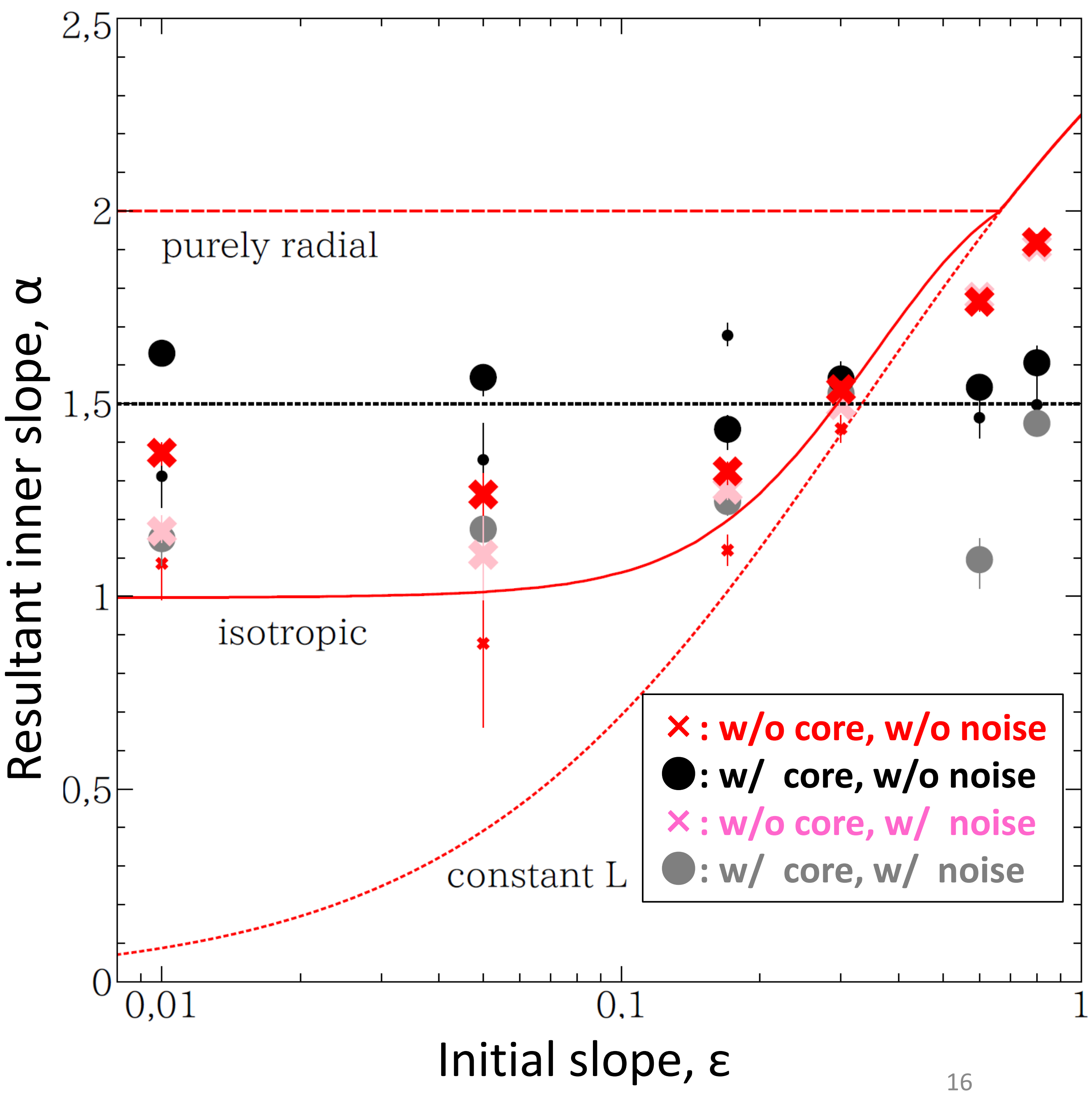
GO & Hahn, arXiv:1707.07693

Overview

- Gray, red and pink ones at ε < 0.3, α ~ 1

- Q. What is the role of the noise?

‘Noises’ in cosmo sims make the cusp shallower and lead to the state of α = 1 (NFW profile)



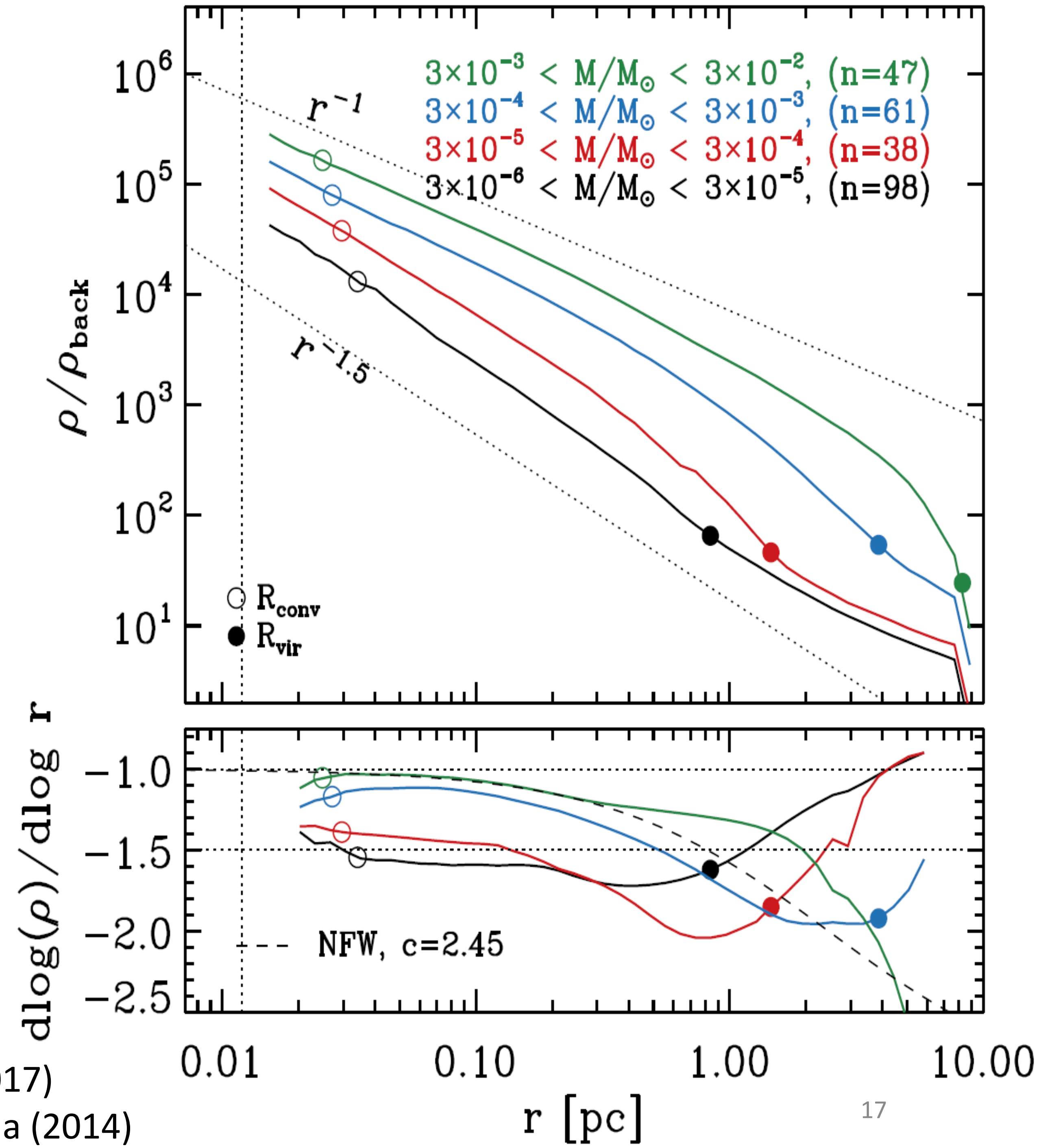
Halos of the 2nd, 3rd … gens

- How do their descendants evolve?

  Inner density slope gets shallower as microhalos grow

- Shallowing central cusps due to ***major mergers***?
  - Because of lack of substructures

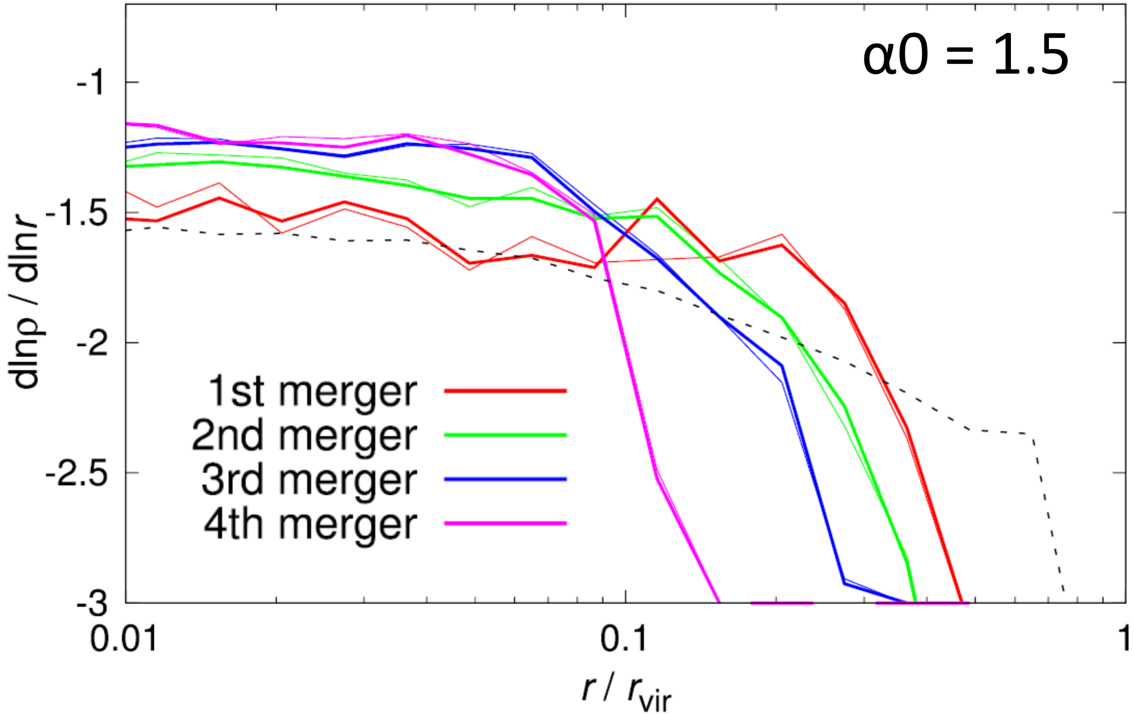
Angulo et al. (2017)
See also Ishiyama (2014)

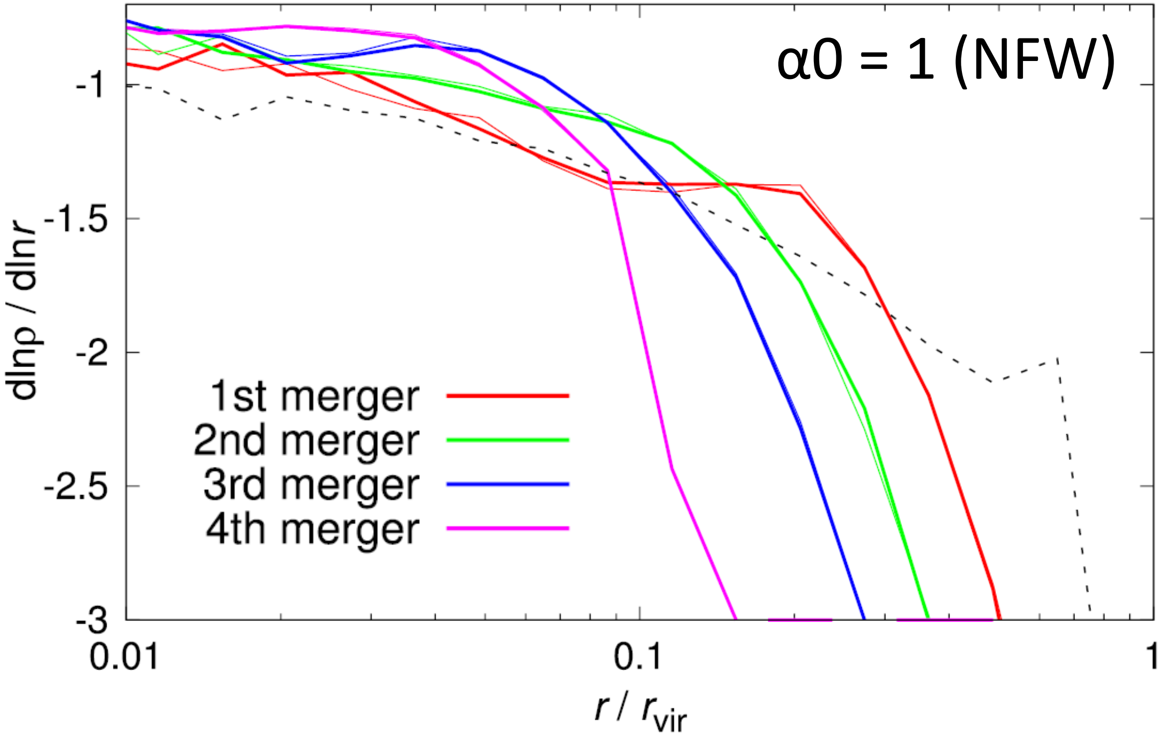


GO, Nagai & Ishiyama, arXiv:1604.02866

Persistence of cusps

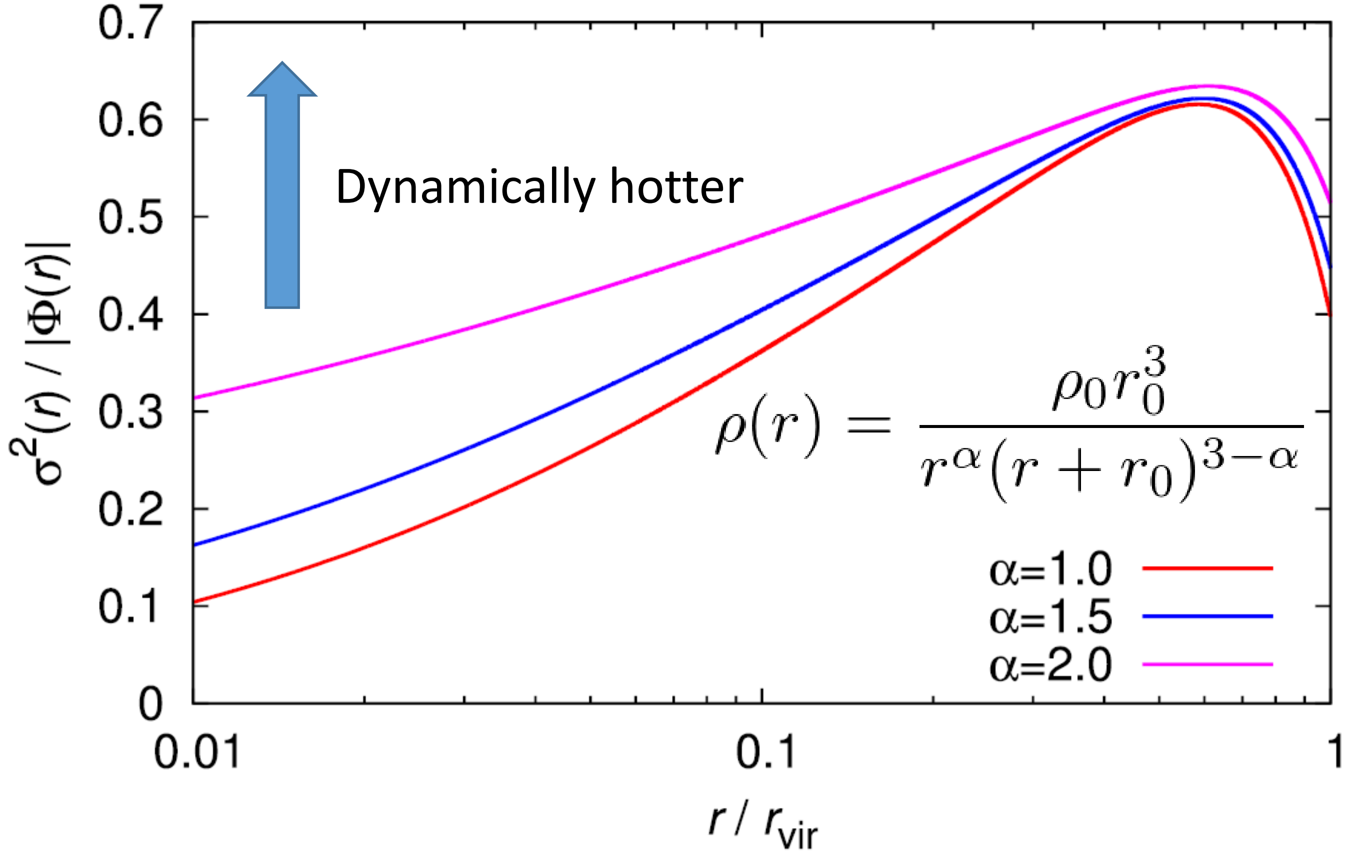
$$\rho(r) = \frac{\rho_0 r_0^3}{r^\alpha (r + r_0)^{3-\alpha}}$$





- *Central cusp gets shallower in each merger event*
- *NFW profile is more resilient*

Why is the NFW halo more resilient?



- Major mergers lead significant changes in potential
  - Violent relaxation (Lynden-Bell 1967)
  - Particles exchange energy
  - Orbits of a fraction of particles expand
  - Lower central density and shallower slope

- Would work more efficiently in dynamically hotter systems

  -> α=1 (NFW) is more resilient

  -> *Universal?*

Summary: an expected story of DM density profile

$$\rho \propto r^{-\alpha}$$

Halos of the 1st generation form with central cusps of α = 1.5

Central slope gets shallower as halos grow and achieves more resilient state of α = 1 (universal NFW)

time

Free streaming motion of DM particles create cored proto-halo patches

Keys = Free-fall motion and rapid mass accretion history (Need to avoid numerical noise)

GO & Hahn, arXiv:1707.07693

Key = Energy exchanging through violent relaxation works more efficiently for halos with larger α

GO, Nagai & Ishiyama, arXiv:1604.02866