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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?

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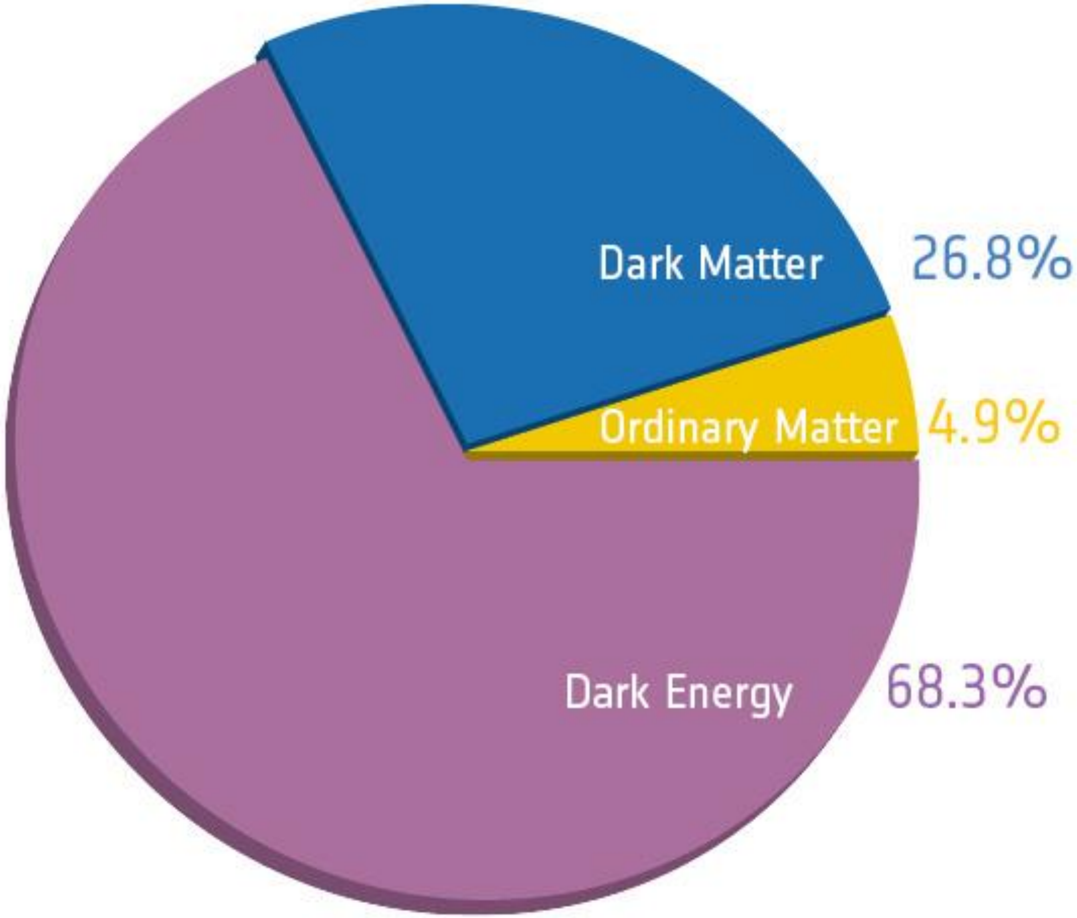
Outline

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

Dark matter in the Universe

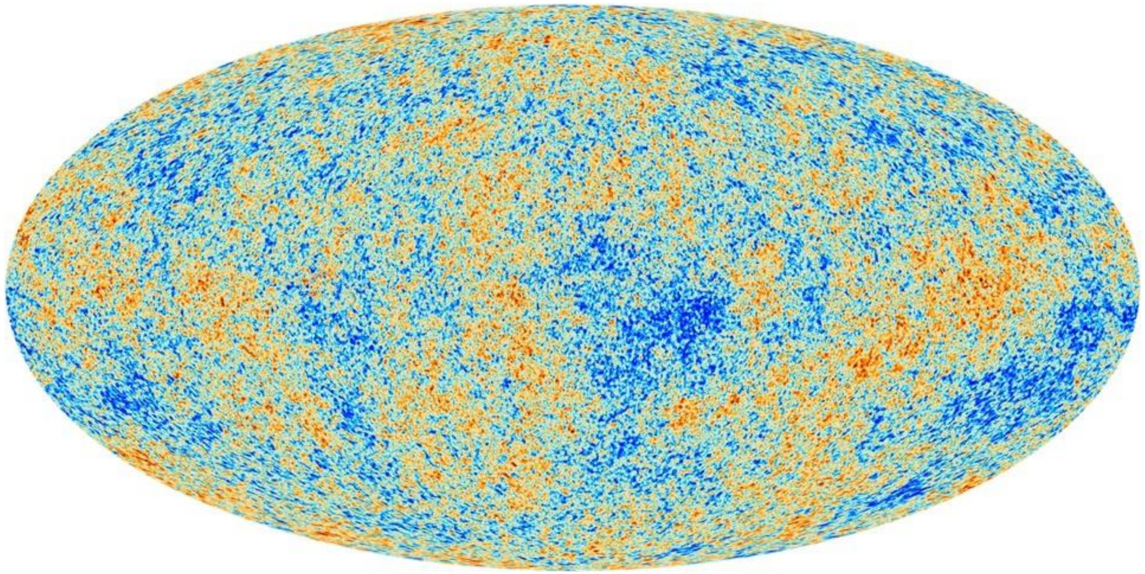
- Dark matter (DM)
  - Interacts only through gravity
    - ✓ (Small cross sections for other interactions)
  - One of main components
    - ✓ 27% of the total energy density
    - ✓ 85% of the total mass

- Bunch of candidates
  - Cold dark matter (CDM)
    - ✓ Weakly interacting massive particle (WIMP), axion
  - Warm dark matter (WDM)
    - ✓ Sterile neutrino
  - Fuzzy dark matter (FDM)
    - ✓ Ultra-light axion
  - Self interacting dark matter (SIDM)
  - Hot dark matter (HDM)
    - ✓ Neutrino
  - Massive compact halo object (MACHO)
    - ✓ Undetectable PBH, BH, WD, NS, planet …



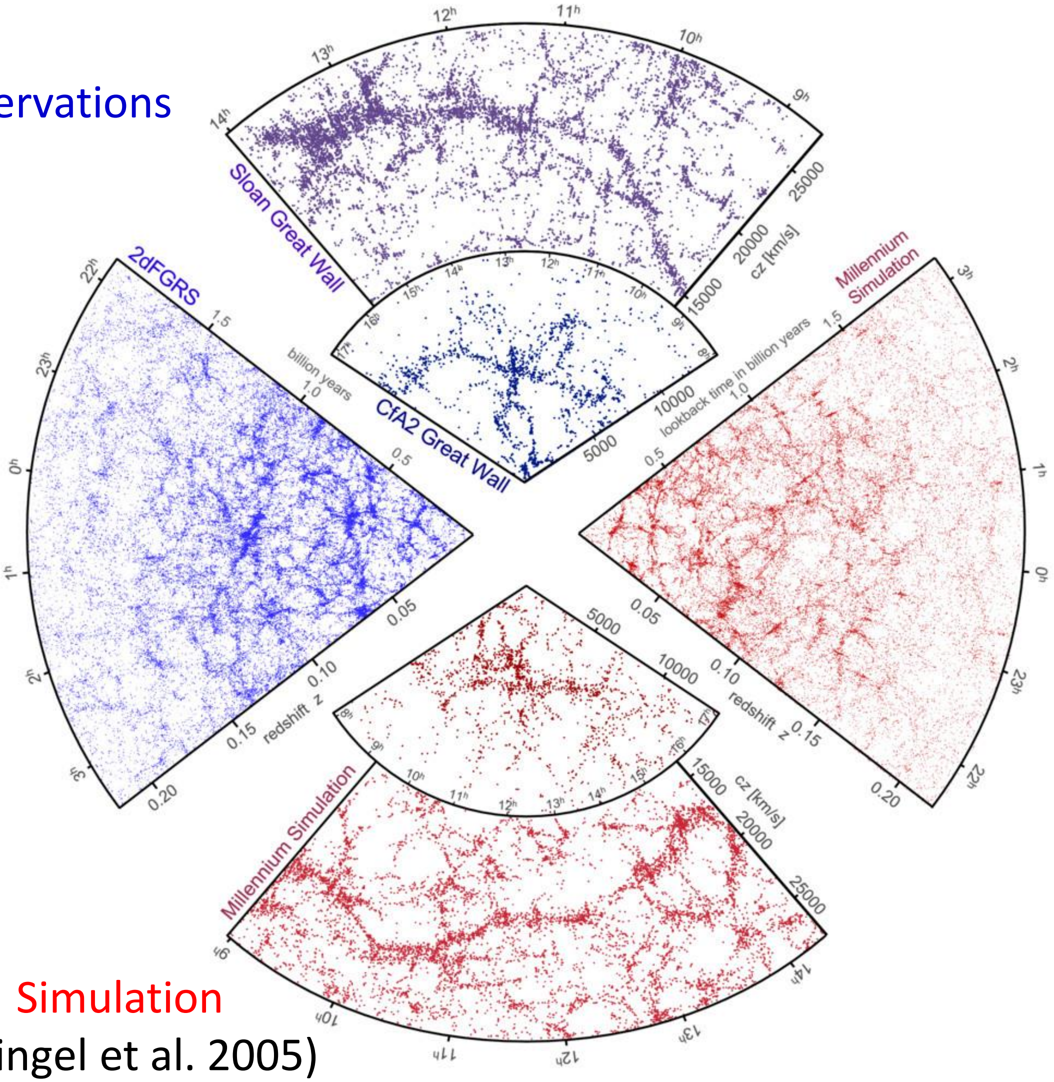
by Planck mission (ESA)

Structure formation in the Universe



Planck satellite (ESA)

Observations



Simulation

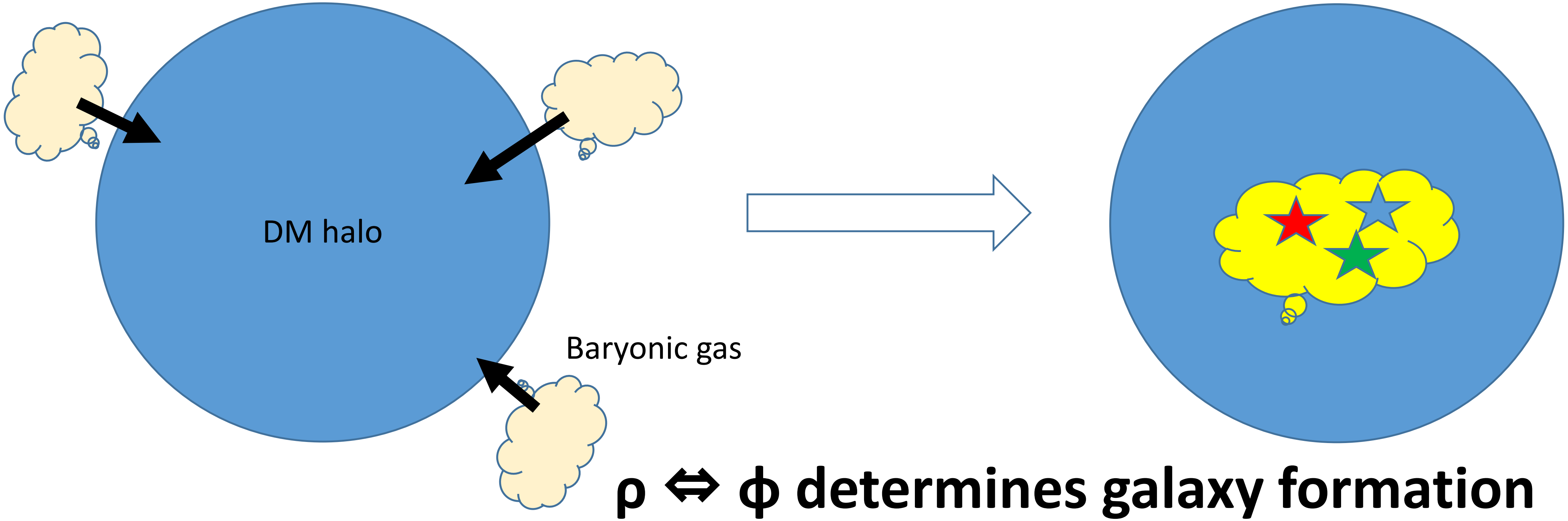
(Springel et al. 2005)

Why DM density profile, ρ?

- DM halo = driver of galaxy formation and evolution

Attracting baryonic gas

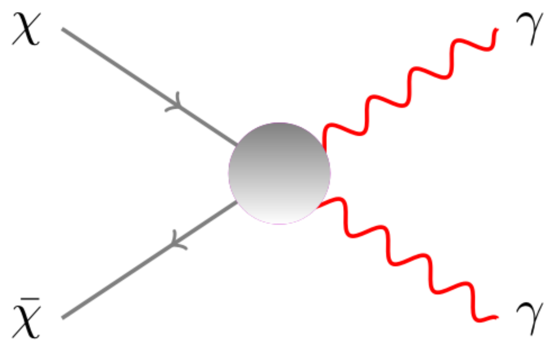
Star formation in the condensed gas



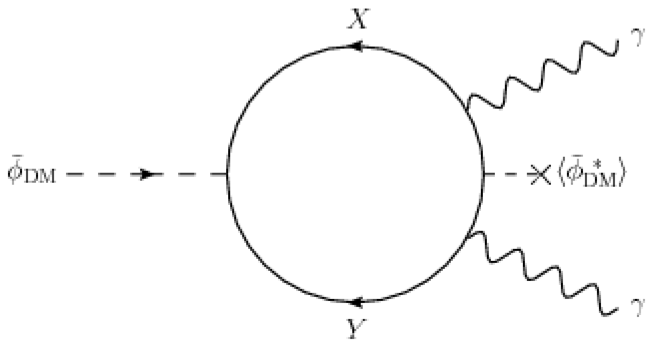
ρ ⇔ ϕ determines galaxy formation

Why DM density profile, ρ?

- Indirect search of DM in astronomical obs.
  - Annihilation signal ∝ ρ^2



  - Decay signal ∝ ρ

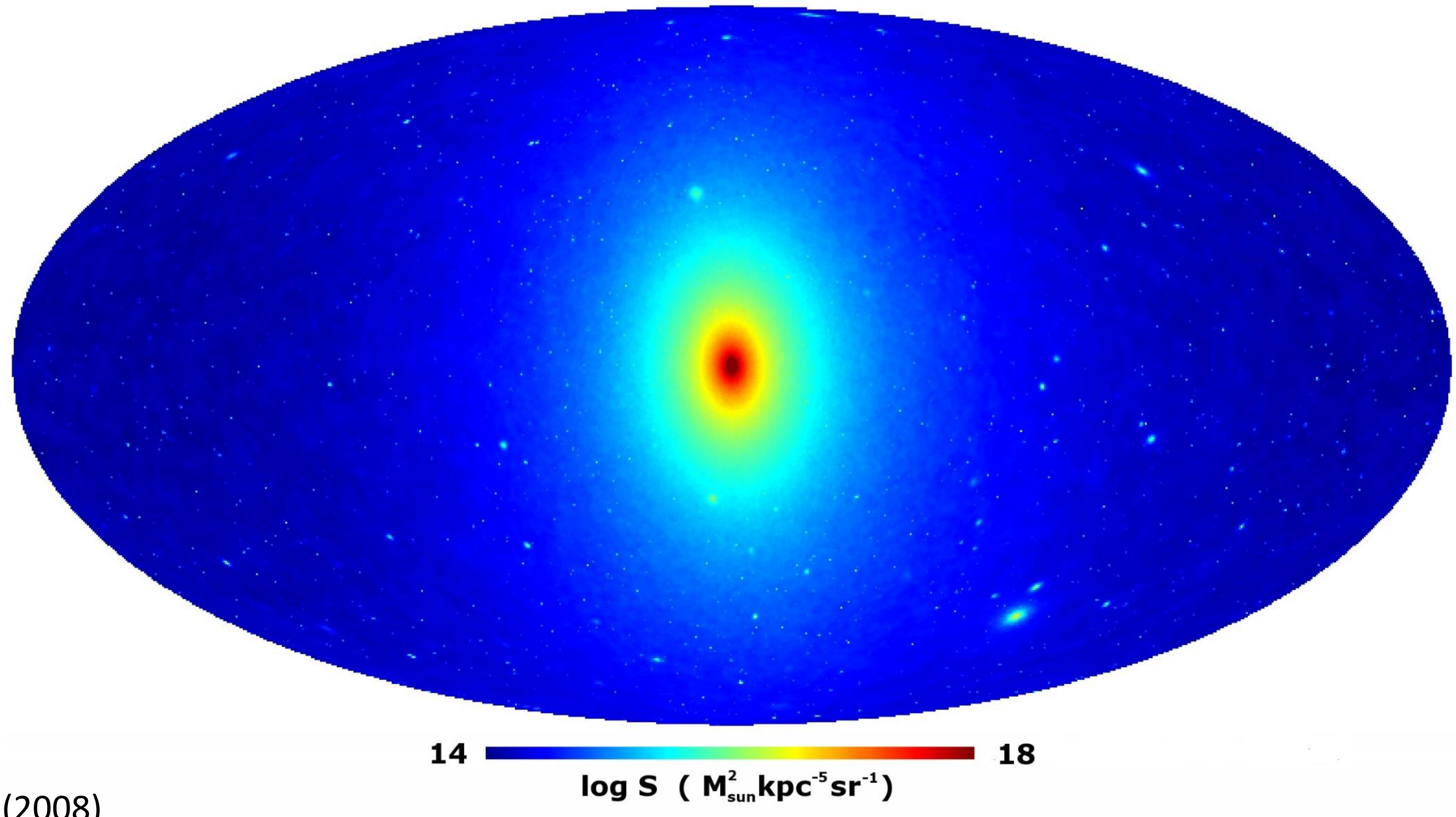


Important for estimating the detectability

DM distribution in a Milky Way sized region

Springel et al. (2008)

Expected annihilation signal ∝ ρ^2



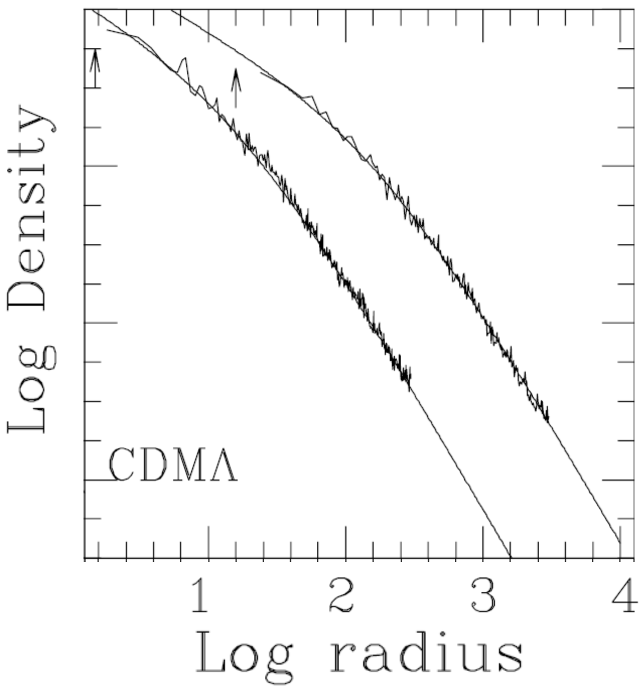
Springel et al. (2008)

NFW density profile

➢Navarro, Frenk & White (NFW)

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

- 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

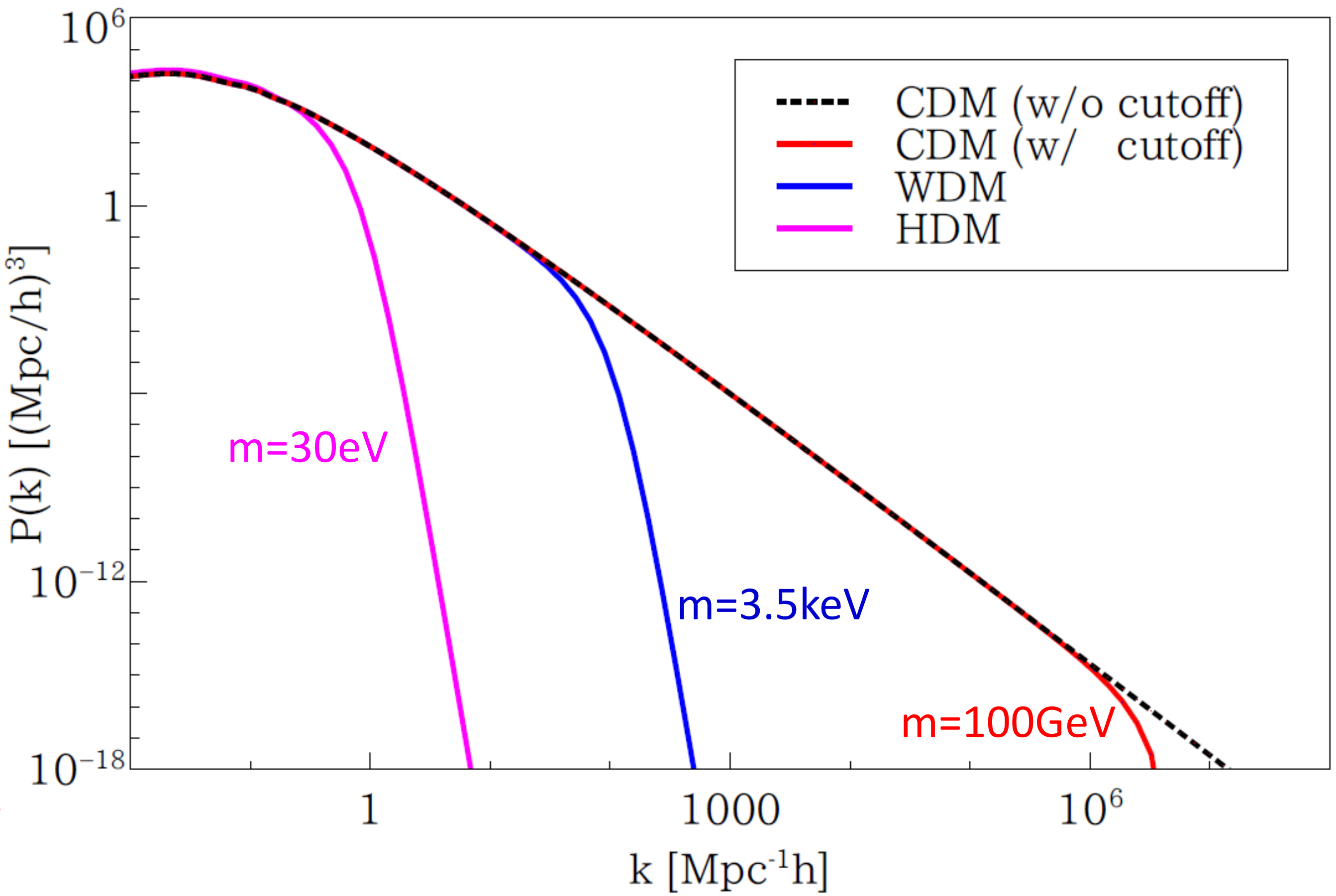
- Power spectrum, P(k) = How much of density fluctuations at the scale of the wave num., k

- 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

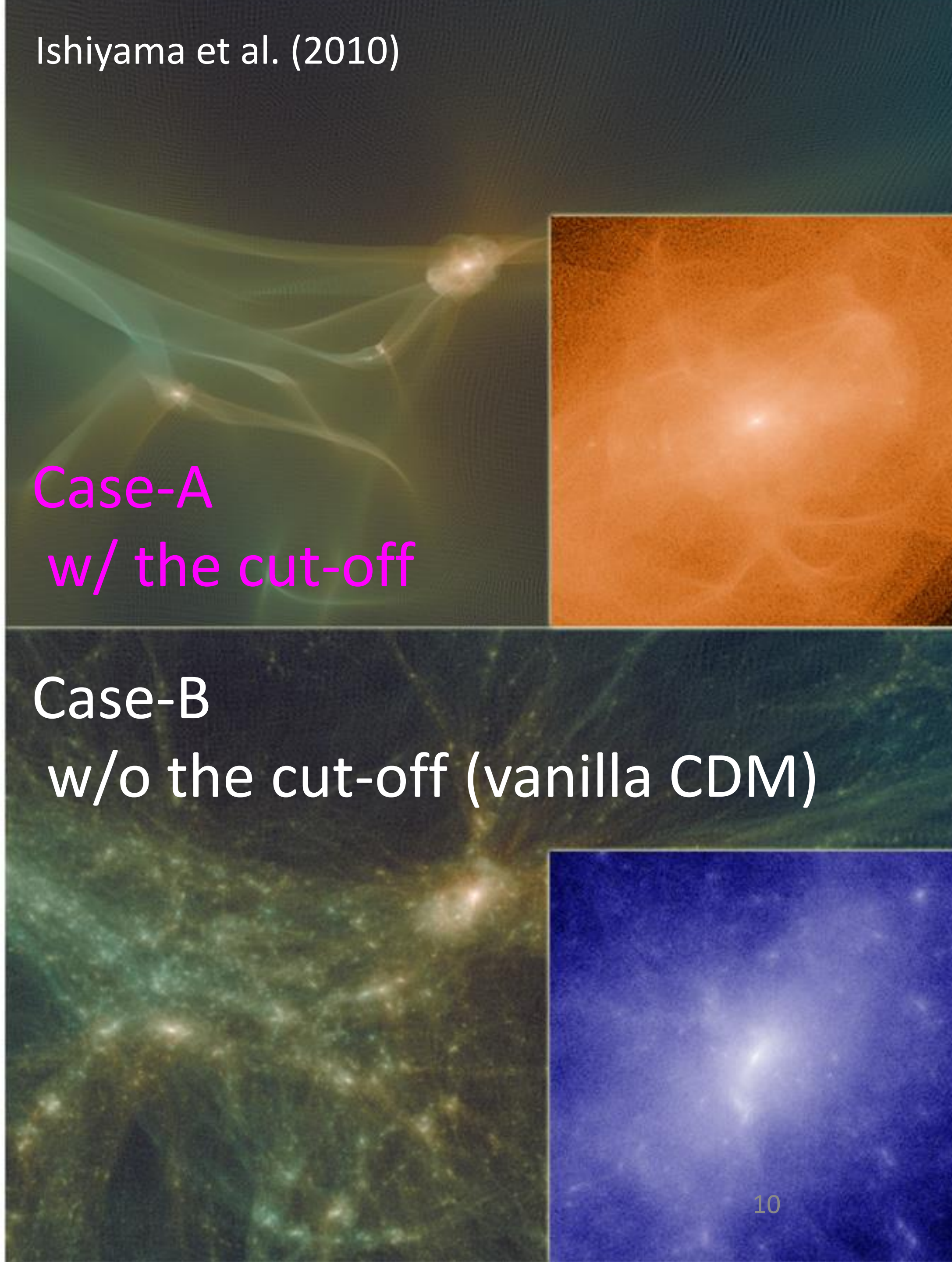
= Seeds of larger ones



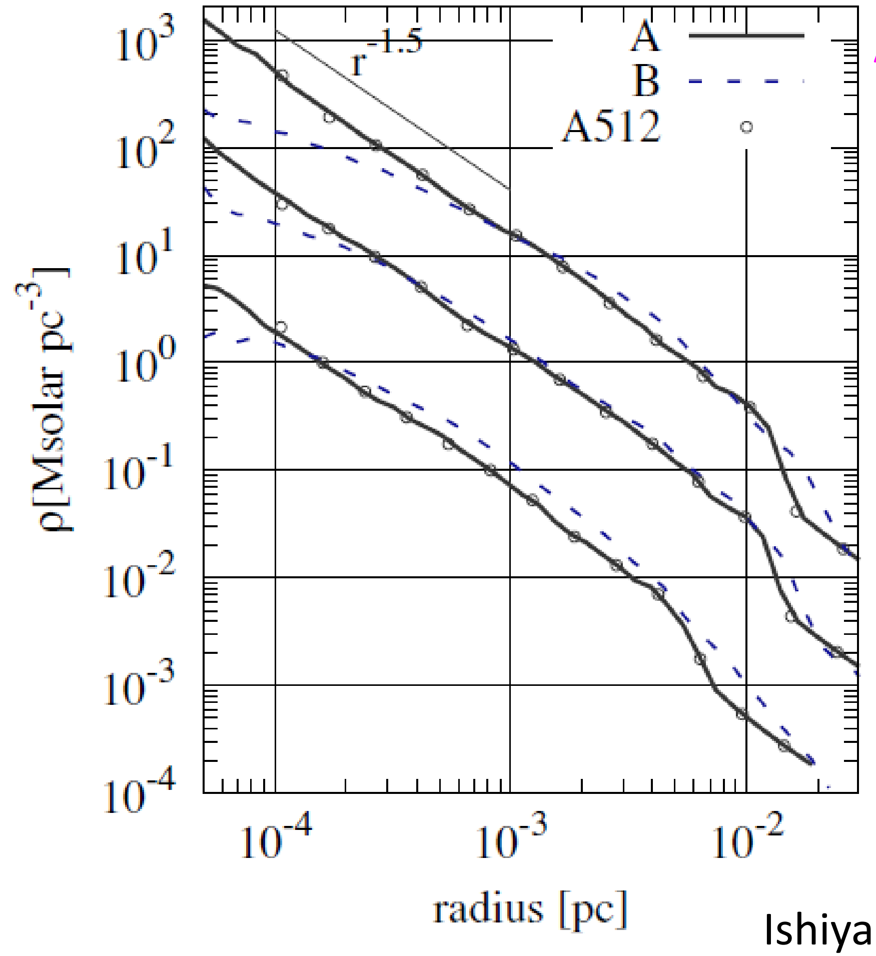
Cosmo. sims of ‘microhalos’

- 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

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

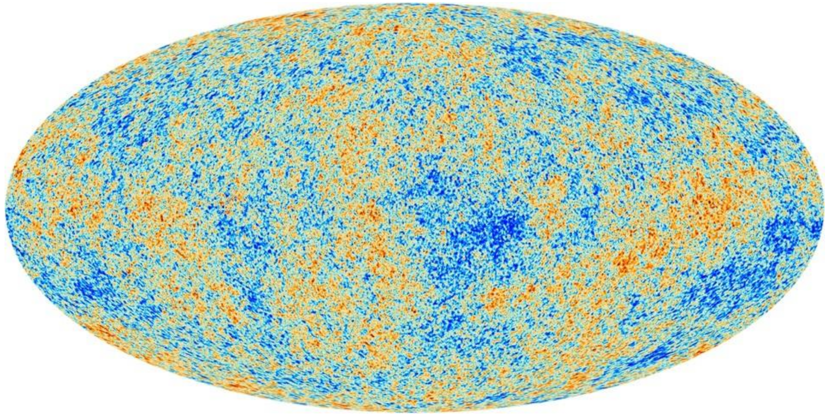
- Case-A: α=1.5
- Case-B: α=1 (NFW)

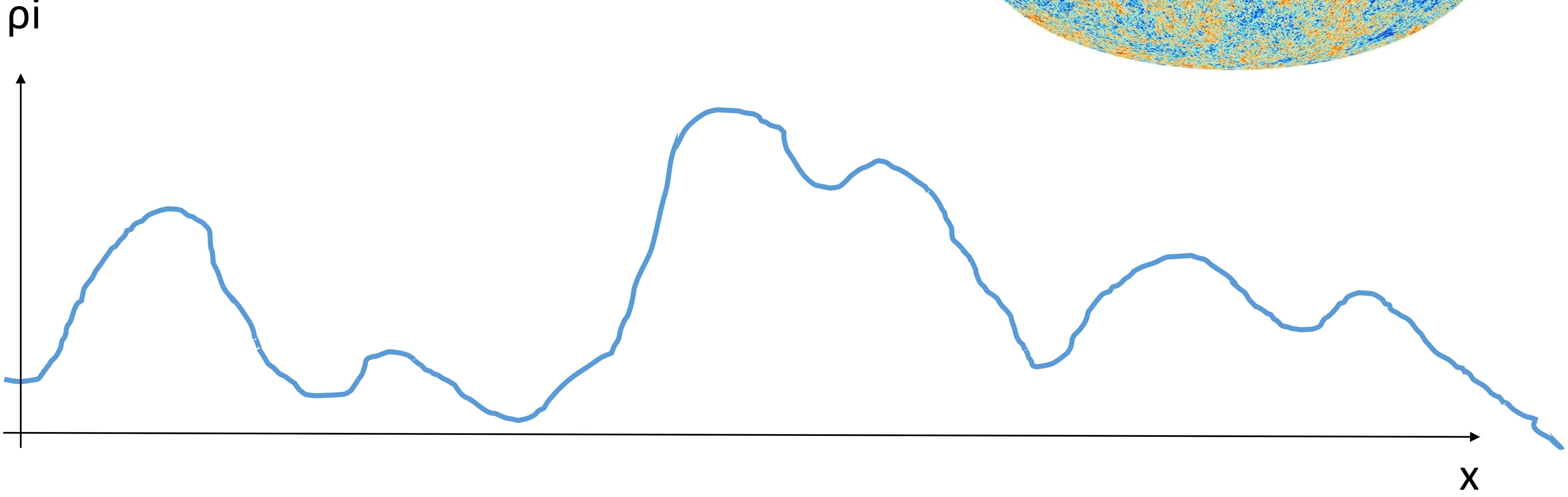
➢***Why do the halos in Case-A have the steeper slope?***

➢Case-A = DM halos of the 1st gen.

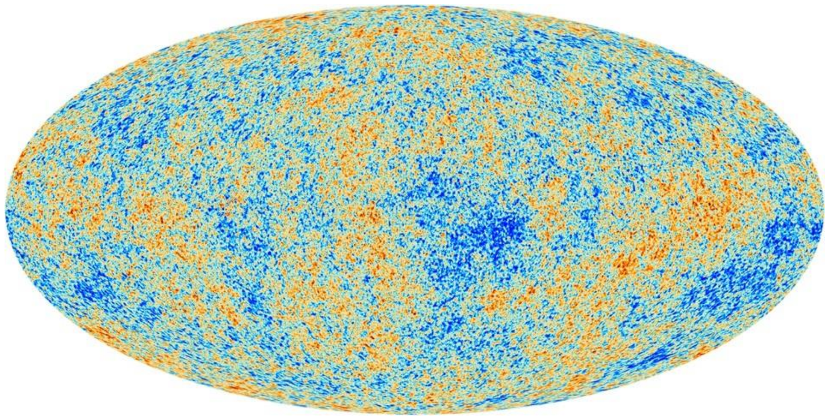
- **Formed through monolithic collapse**
- **Not experienced any mergers**

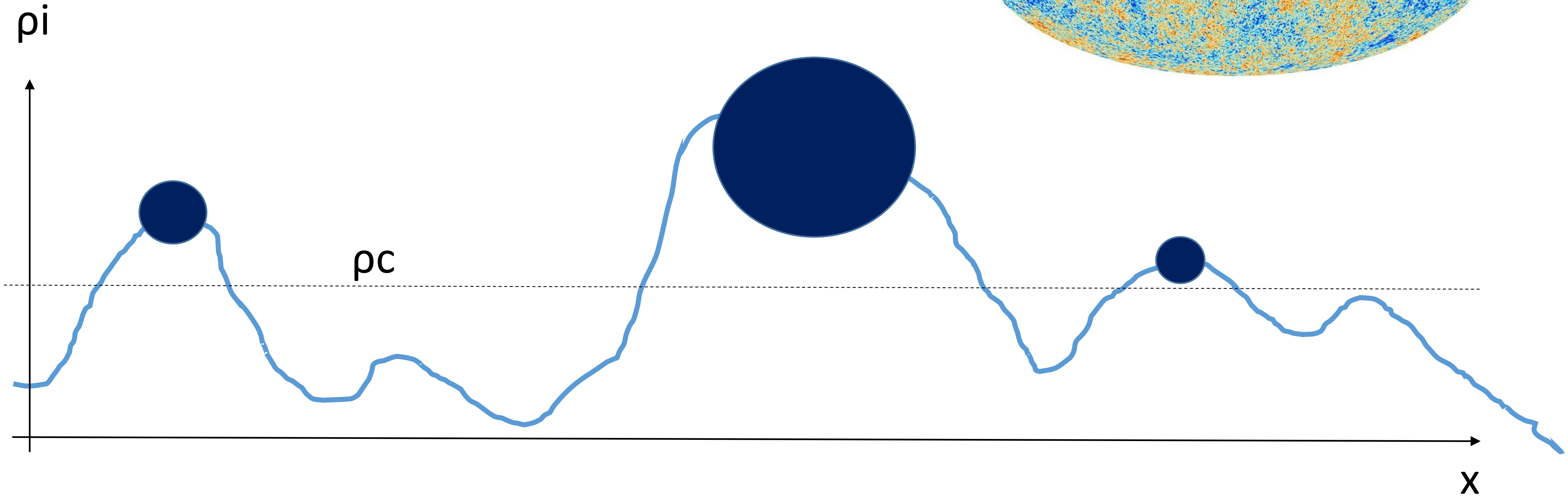
Sites of halo formation





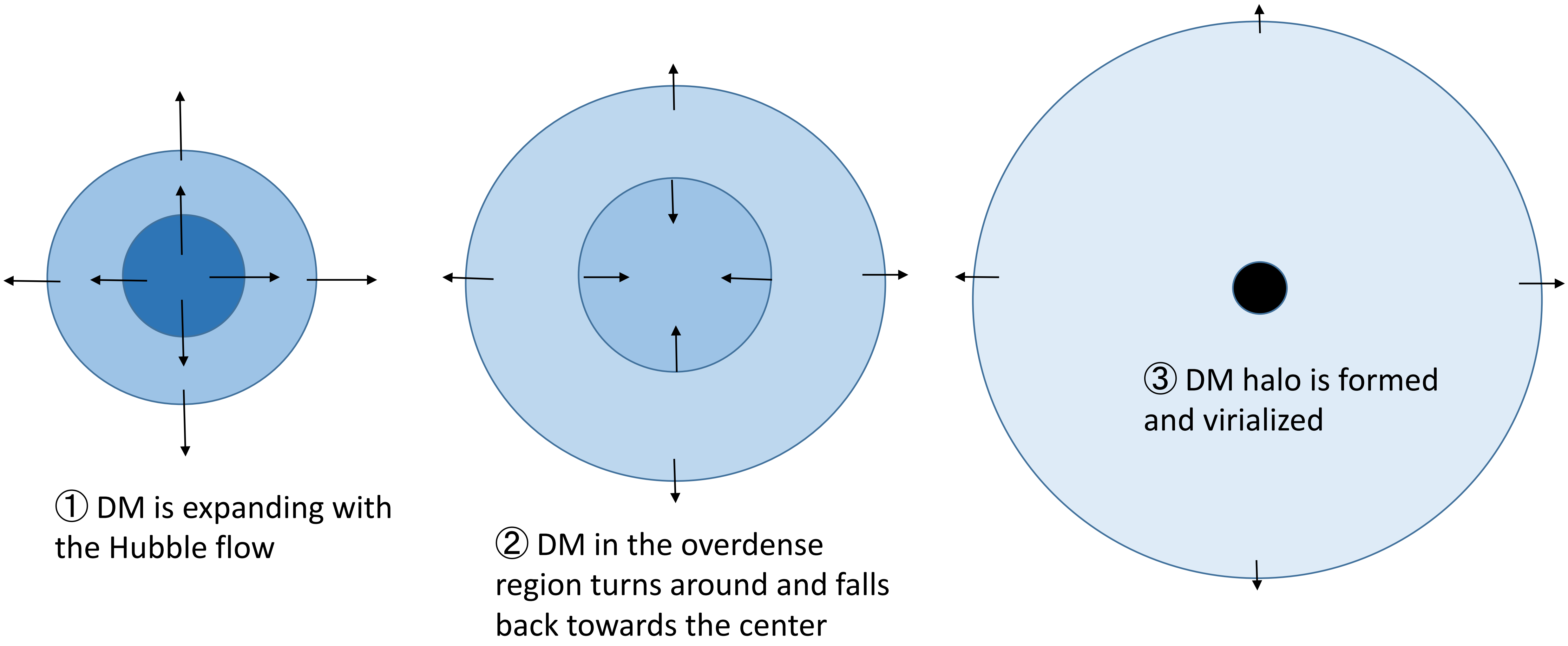
Sites of halo formation



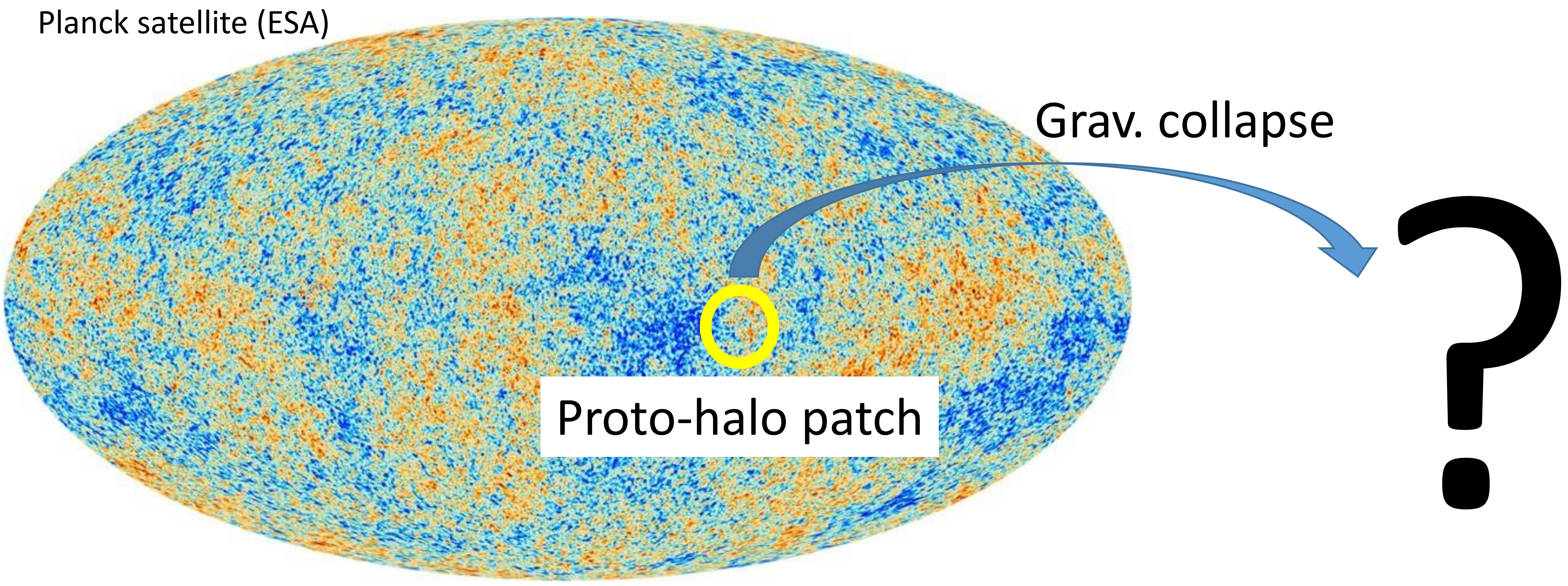


DM halos are formed at points where ρi exceeds ρc

Formation of DM halos through collapse



What we'd like to know = first halo formation

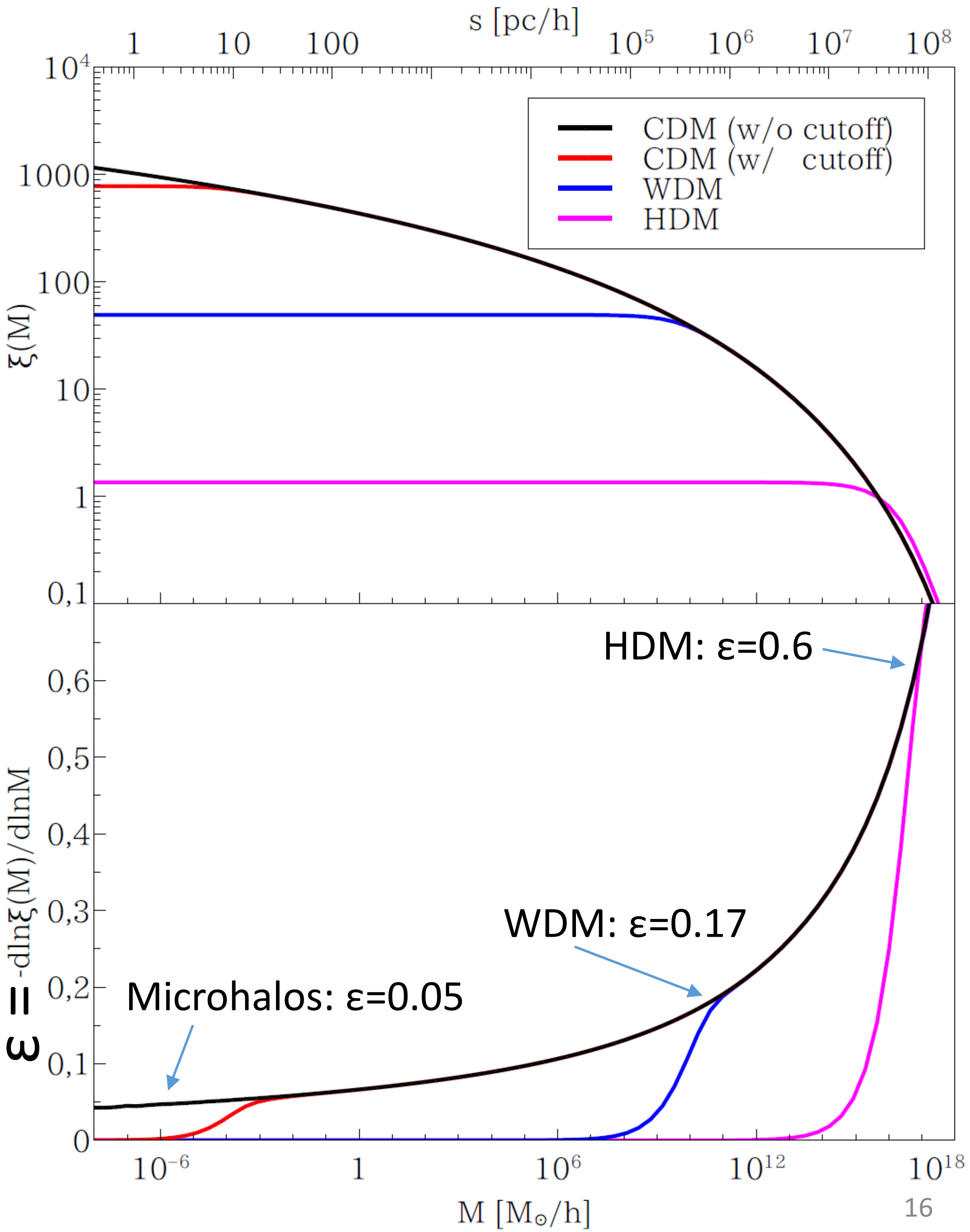


Structure of proto-halo patches

- Assumption: $\rho_{\mathrm{i}}(r) \propto \xi(r)$
- **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

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

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



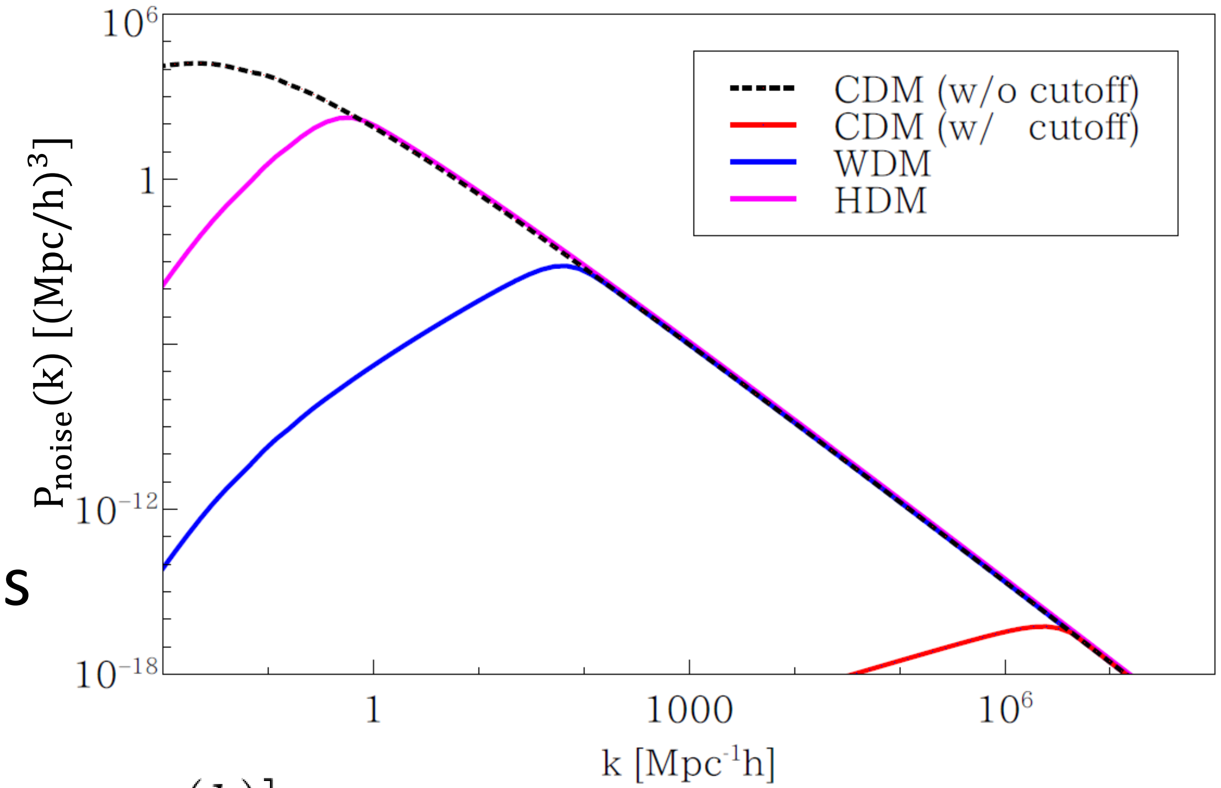
Role of 'Noises'

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

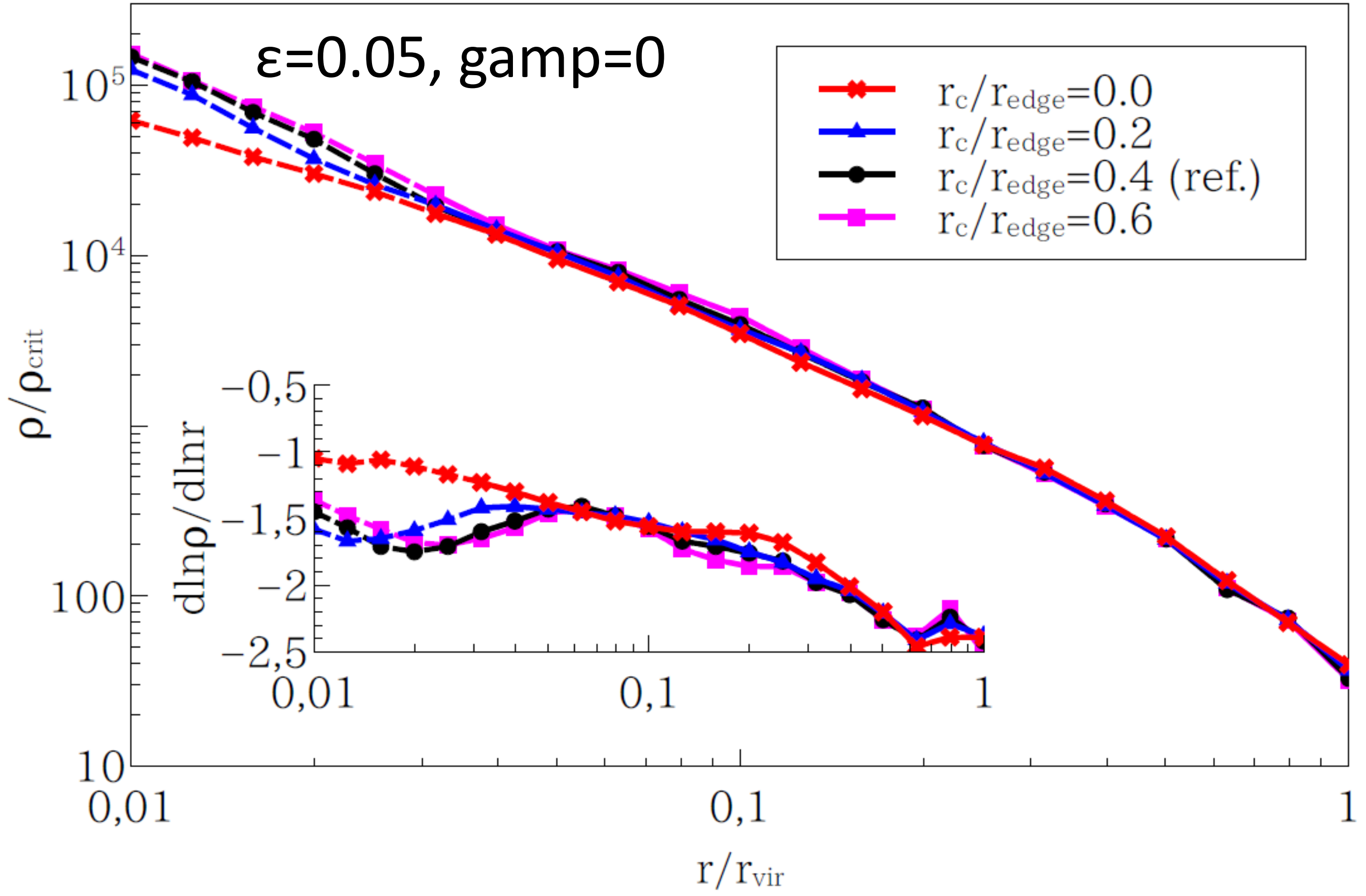
No physical noise is included, but numerical ones always exist
-> + Non-spherical perturbation; to avoid numerical issues

  - 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

Impact of the initial core

$$\rho_i(r) \propto (r^2 + r_c^2)^{-3\epsilon/2}$$



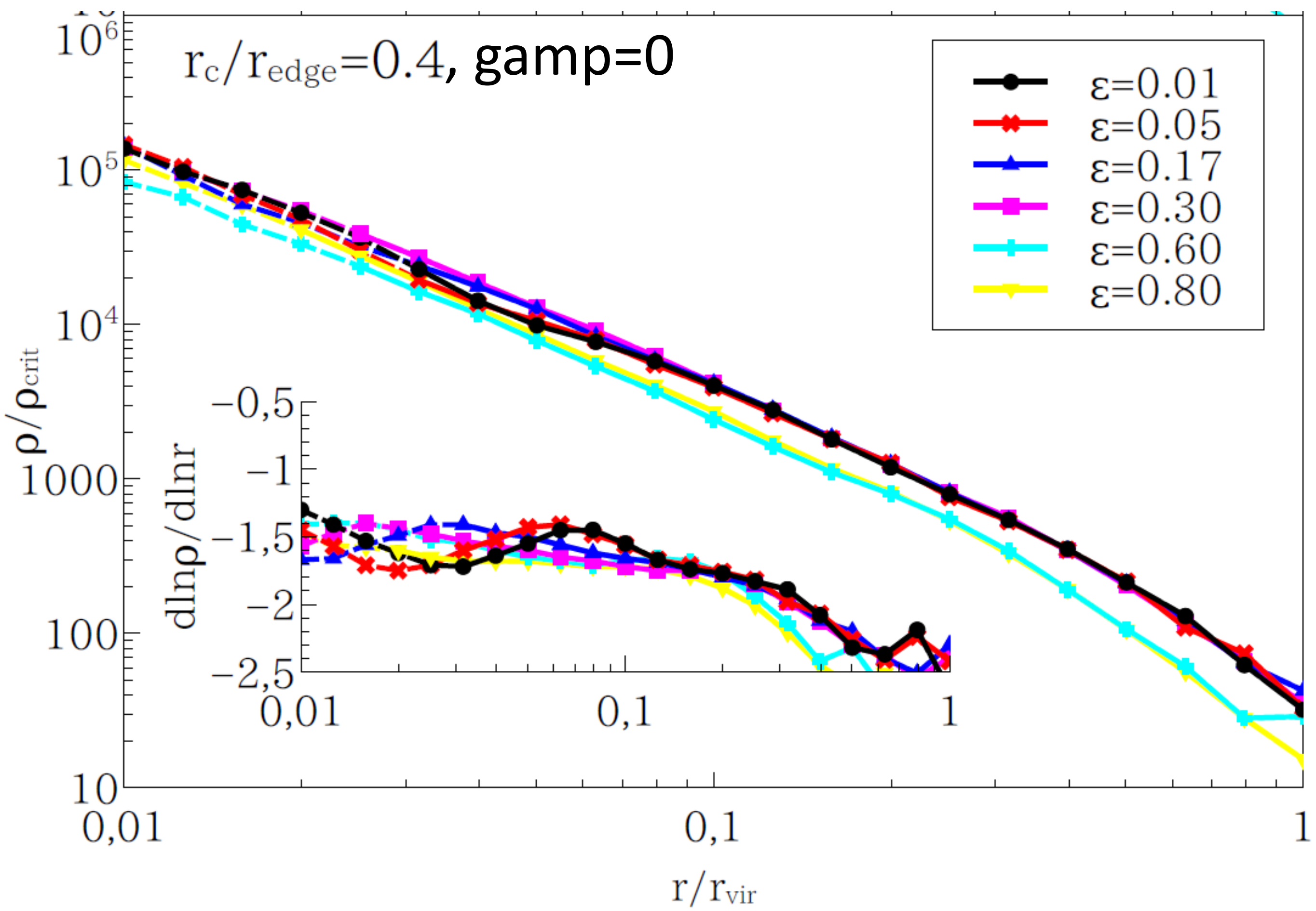
- Density at the outskirts is the same
- In runs with larger rc,
  - Higher central density
    -> Steeper cusps
  - α ~ 1.5 in runs with the core

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

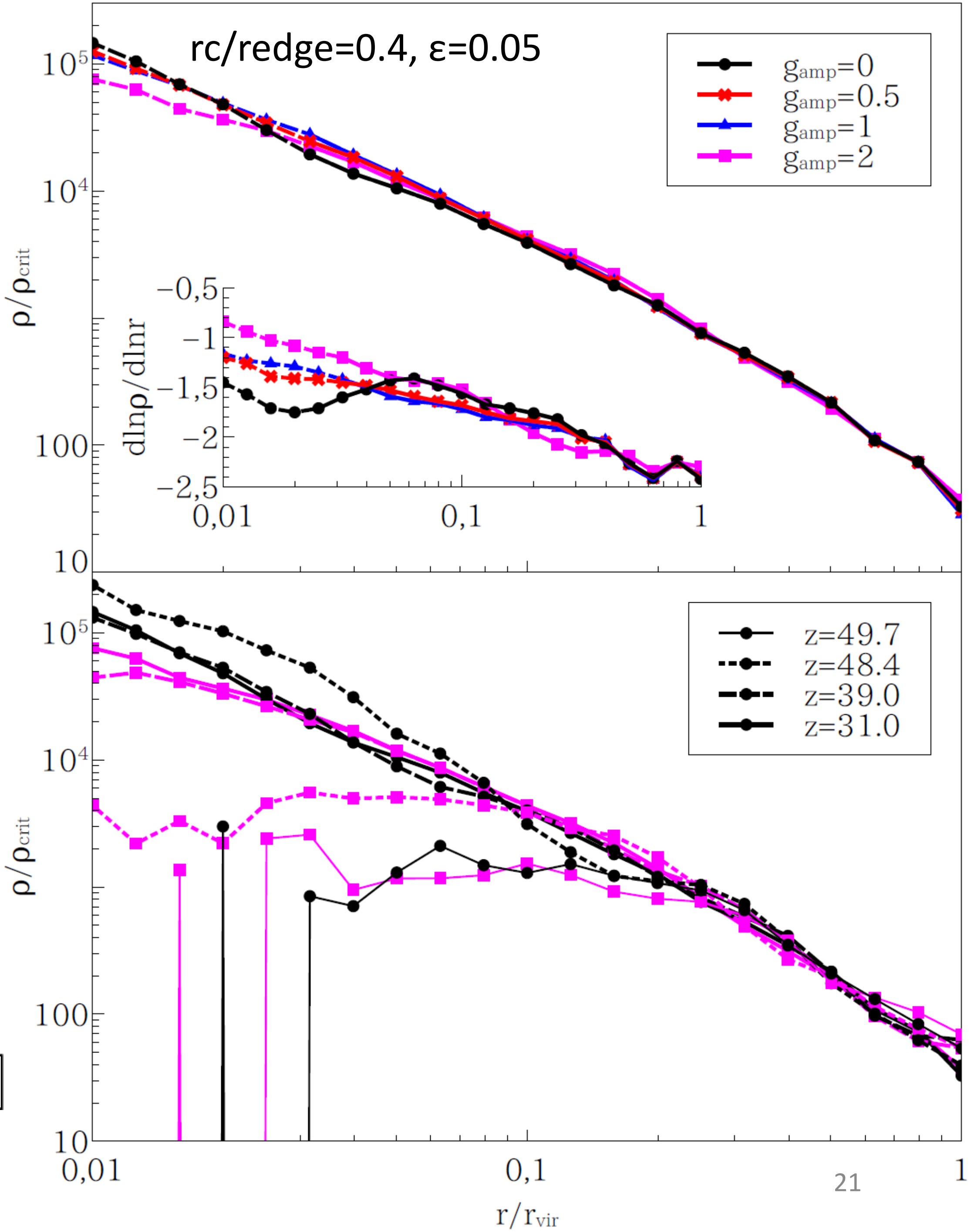
Impact of the noise

- [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

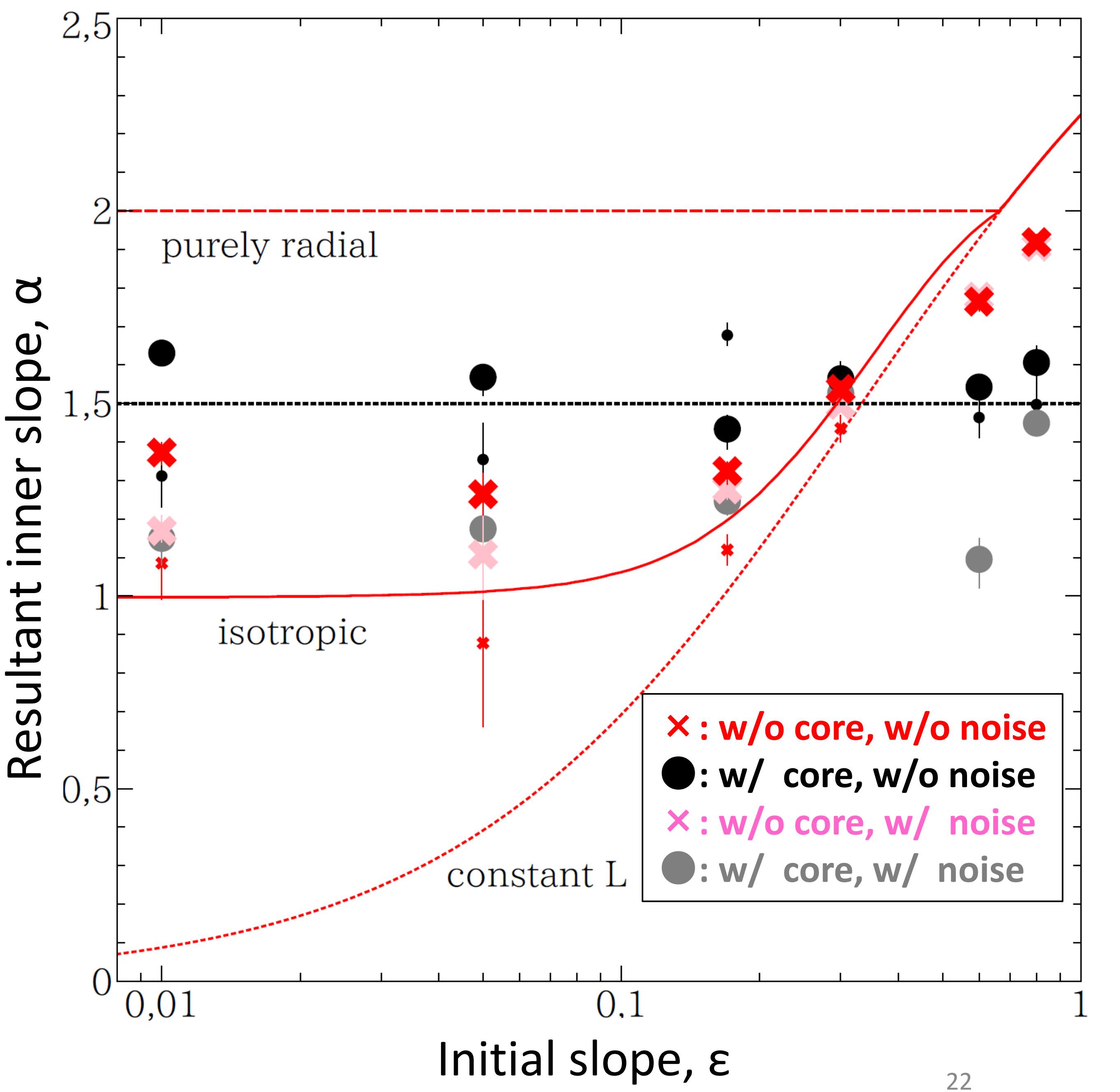
$$P_{\rm noise}(k) = g_{\rm amp}[P_{\rm w/o\ cut-off}(k) - P_{\rm w/\ cut-off}(k)]$$



Overview

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

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

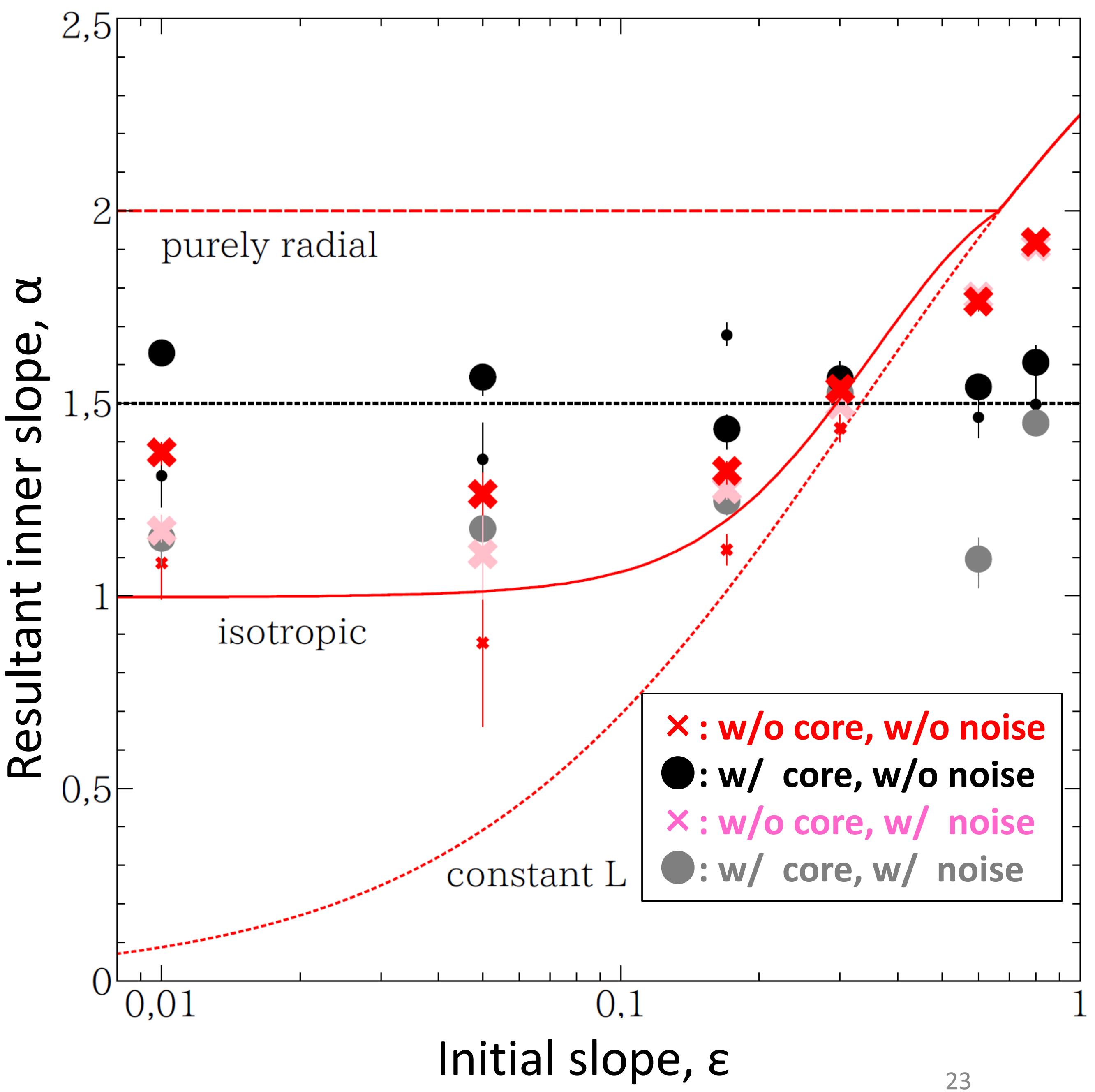


Overview

➢Runs w/ the noise

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

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

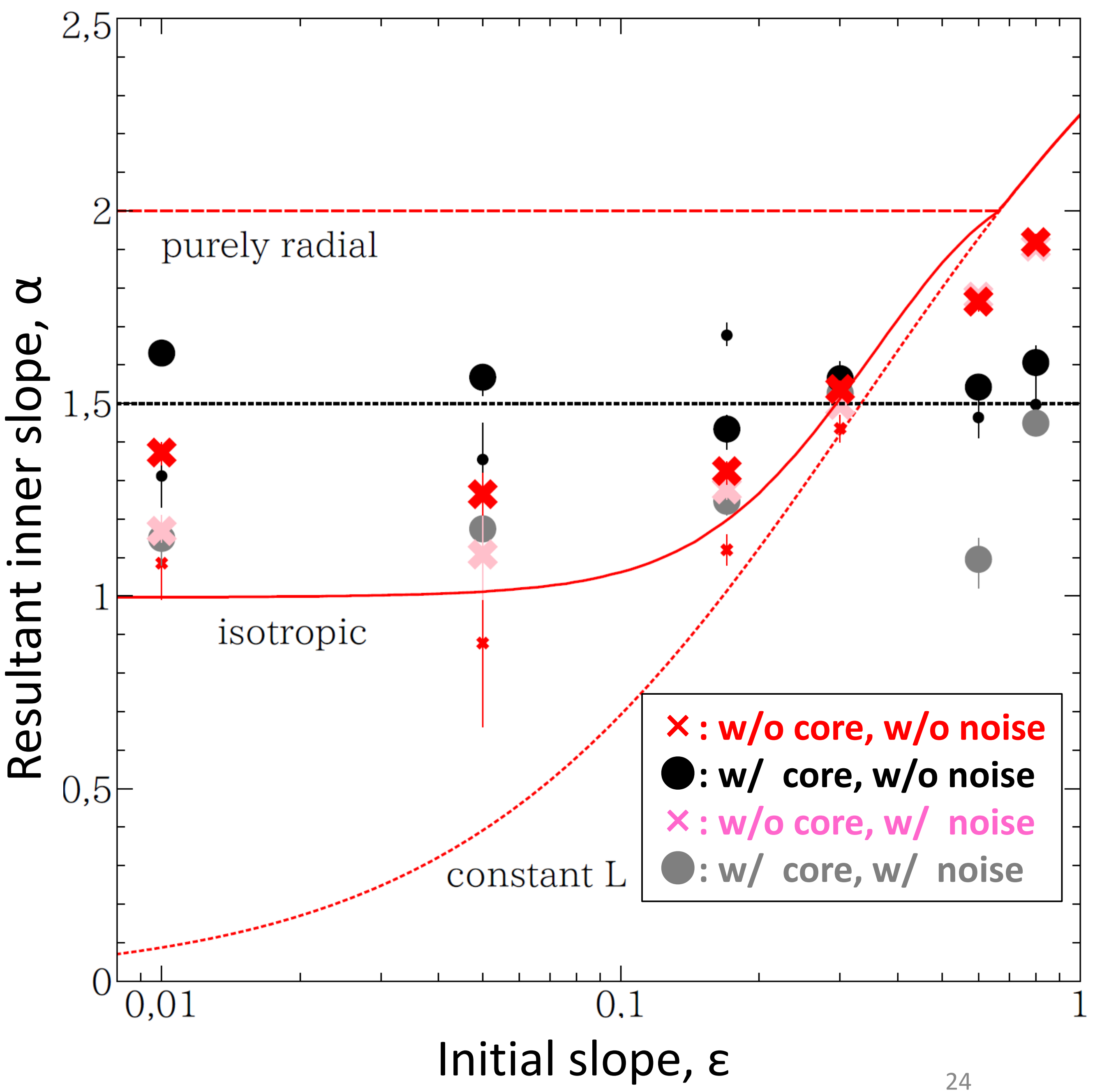


GO & Hahn, arXiv:1707.07693

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)

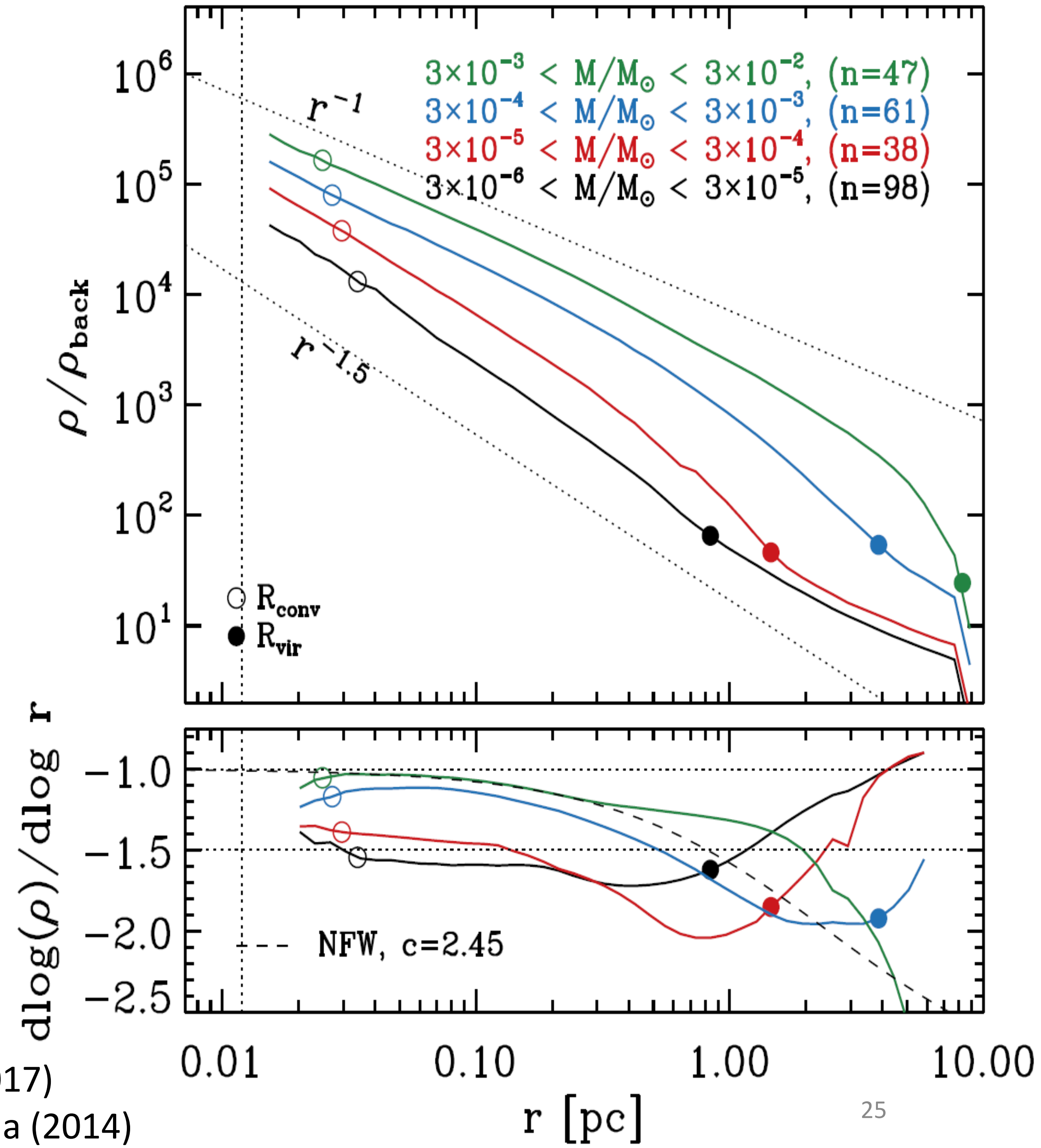


Halos of the 2^{nd}, 3^{rd} … gens

- ➢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



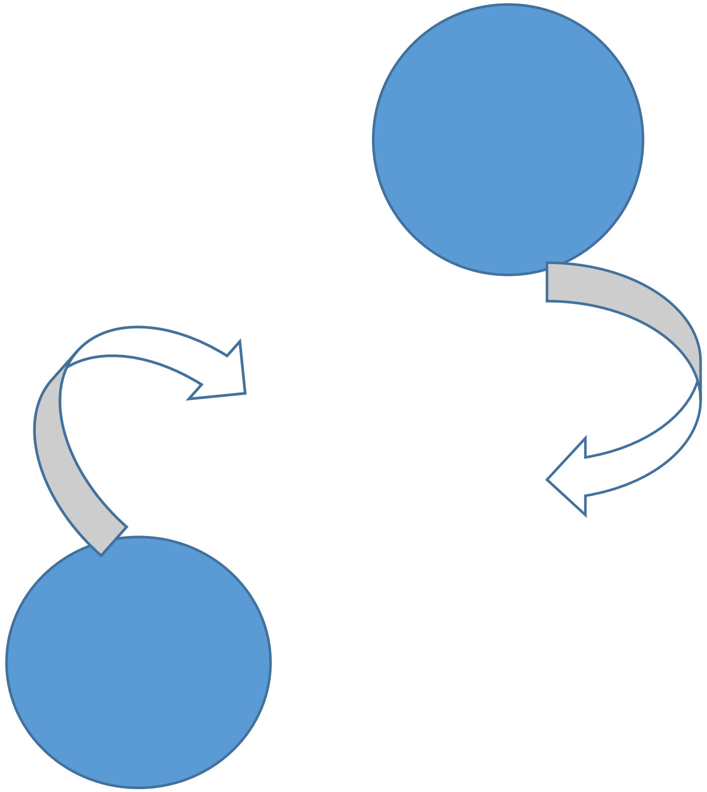
Angulo et al. (2017)
See also Ishiyama (2014)

Persistence of cusps

- Merger progenitors

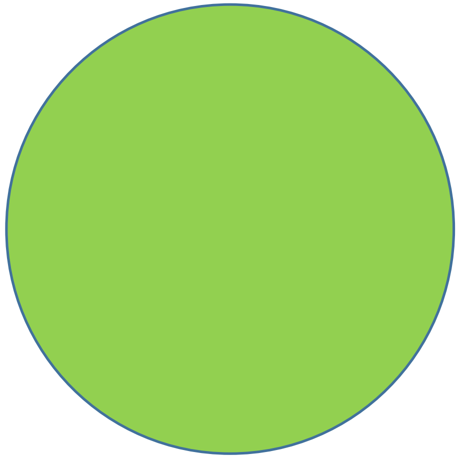
$$\rho(r) = \frac{\rho_0 r_0^3}{r^\alpha (r + r_0)^{3-\alpha}}$$

- Typical orbit in cosmo sims
  - e.g. Khochfar & Burkert (2006); Wetzel (2011)



Persistence of cusps

- Consecutive mergers
  - e.g. Progenitors of 2nd merger = remnant of 1st merger
  - Typical orbit



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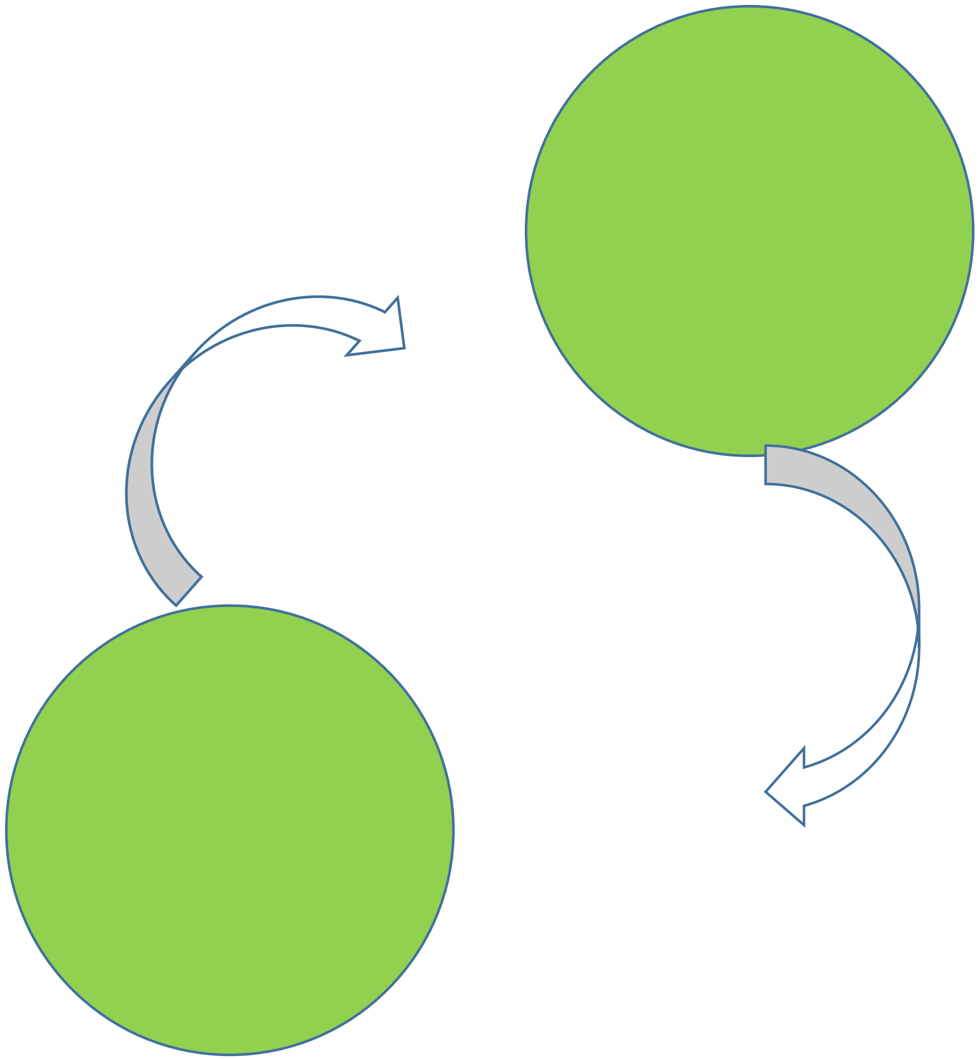

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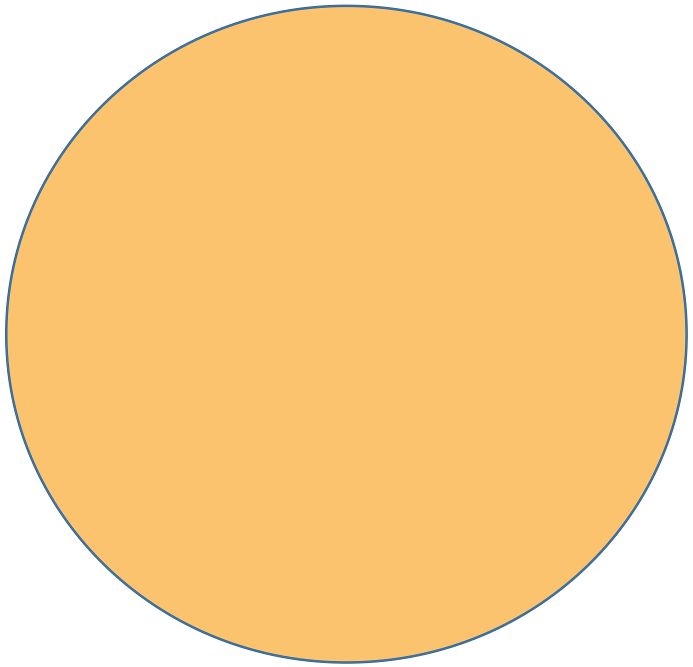
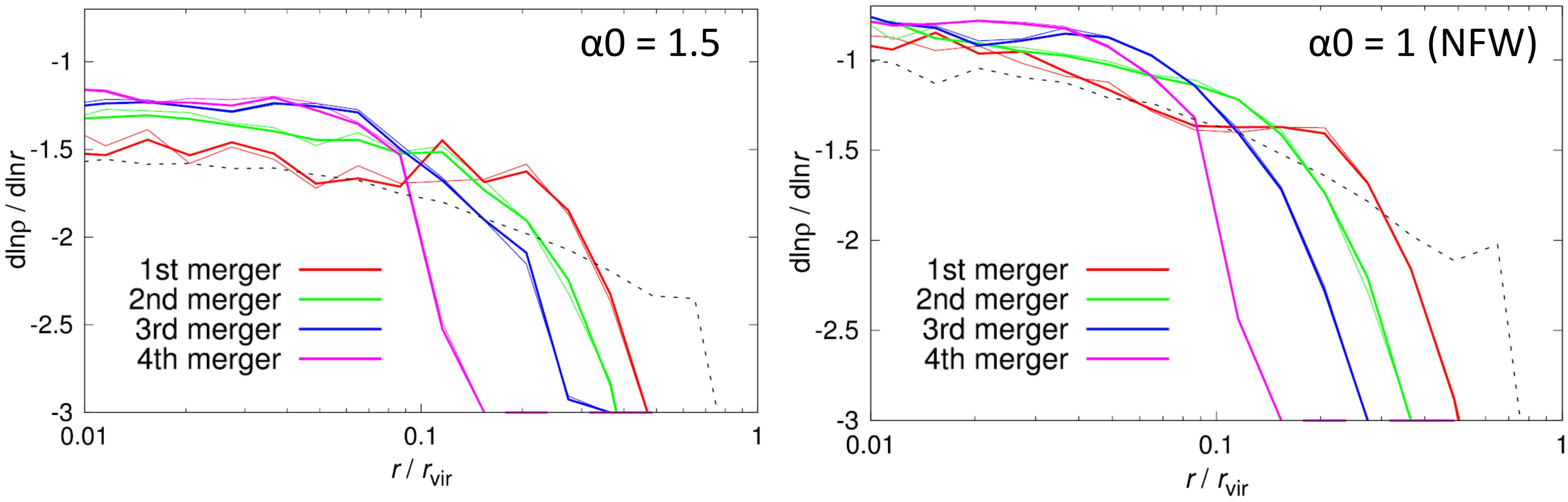


GO, Nagai & Ishiyama, arXiv:1604.02866

Persistence of cusps

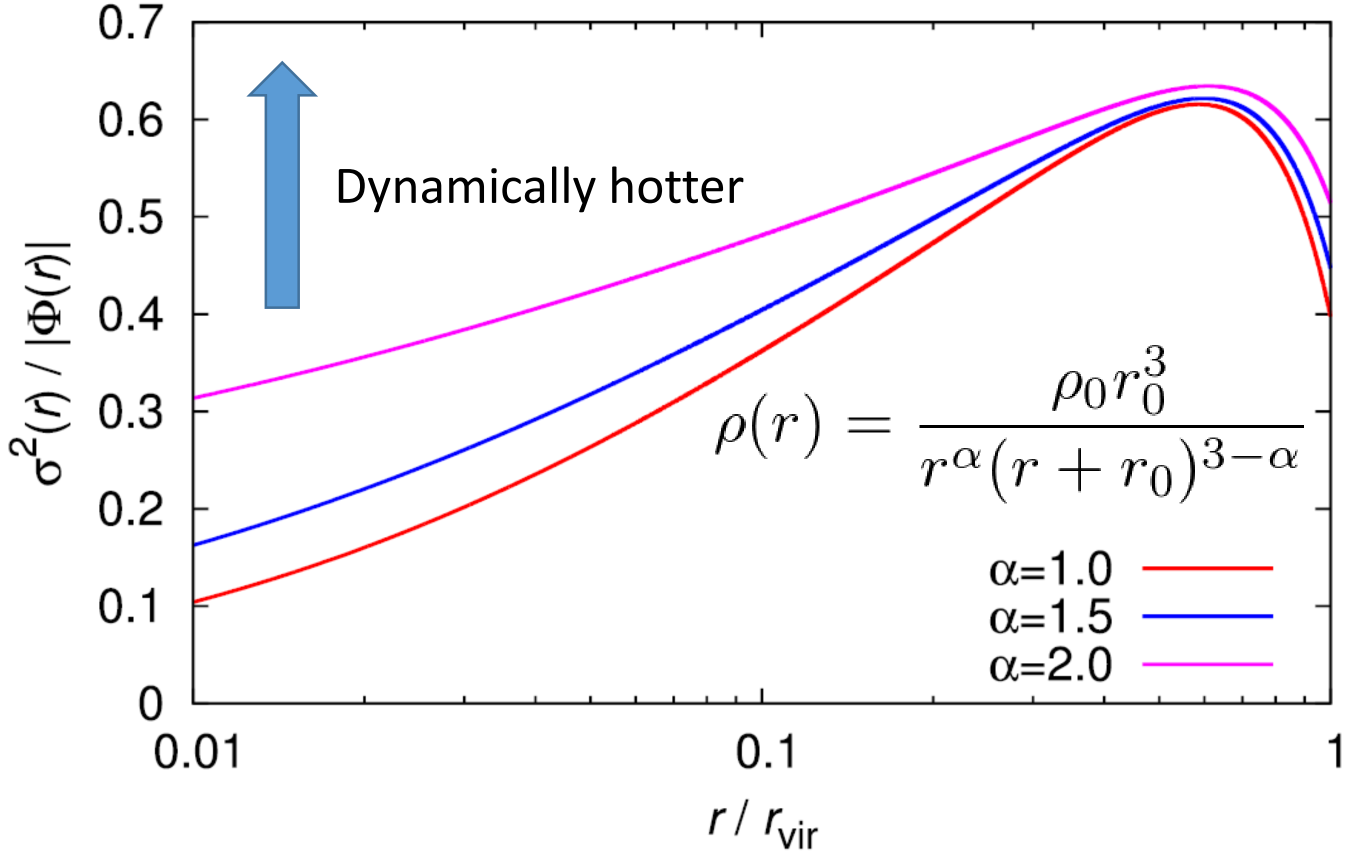
$$\rho(r) = \frac{\rho_0 r_0^3}{r^{\alpha}(r + r_0)^{3-\alpha}}$$



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

GO, Nagai & Ishiyama, arXiv:1604.02866

Why is the NFW halo more resilient?

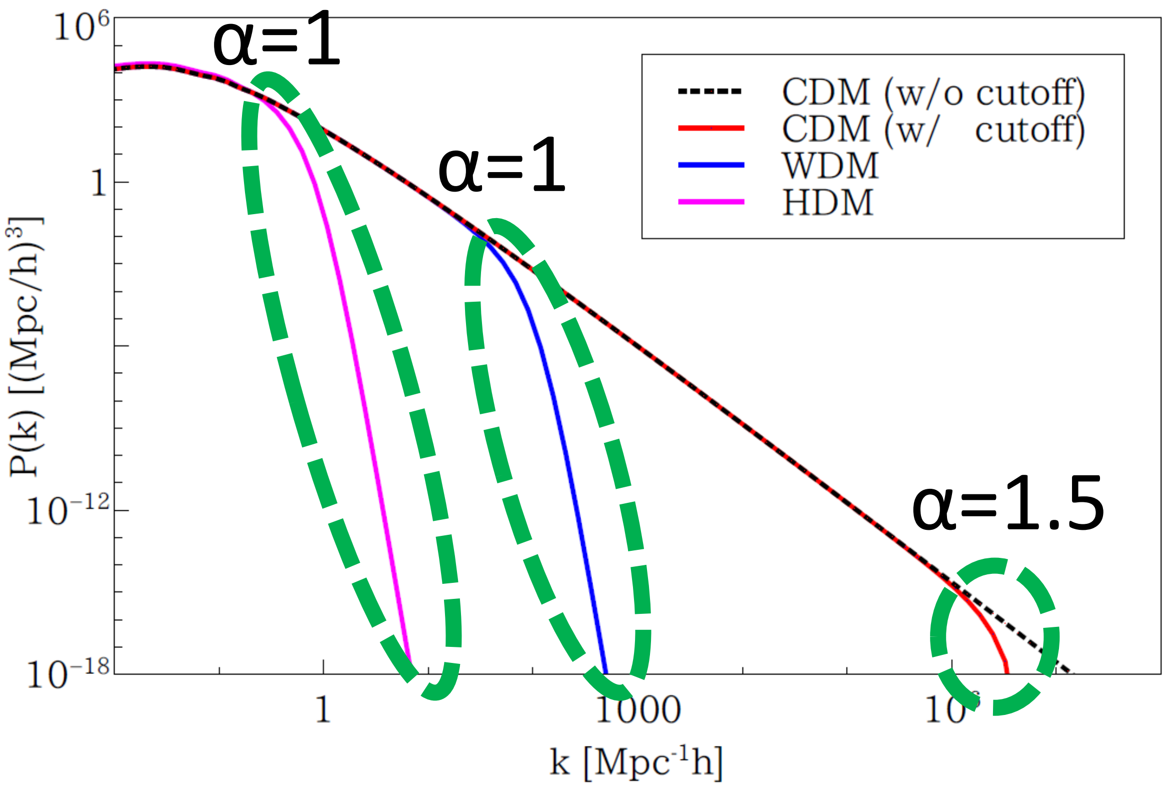


- ➢Major mergers lead significant changes in potential
  - Violent relaxation (Lynden-Bell 1967)
  - Particles exchange energy
  - Orbits of a fraction of particles expand
  - Lower central density and shallower slope
- ➢Would work more efficiently in dynamically hotter systems

  -> α=1 (NFW) is more resilient

  -> *Universality?*

What about WDM and HDM halos?



- They are halos of the 1st gen. as well
- But the NFW profile (α=1) works well for WDM and HDM halos
  - WDM: Bode et al. (2001); Avila-Reese et al. (2001); Busha et al. (2007); Lovell et al. (2014); but see also *Polisensky & Ricotti (2015; α=1.5)*
  - HDM: Wang & White (2009)

- ***Cusps may have been made shallower by***
  - ***Discreteness noises?***
  - ***Mergers?***
    - ✓ WDM works studied MW sized halos, > 1000 times greater than the smallest mass scale

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

Thank you for your attention!