15th May 2019

Resonant instabilities in cosmology and their observational consequences

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Probing dark matter from nonlinear structure formation of the Universe

Atsushi Taruya (YITP)

Papers related to parametric instabilities

PHYSICAL REVIEW D, VOLUME 59, 103505

Parametric amplification of density perturbations in the oscillating inflation model

A. Taruya*
Department of Fundamental Sciences, FIHS, Kyoto University, Kyoto 606-8501, Japan
(Received 11 December 1998; published 20 April 1999)

We study the adiabatic density perturbation in the *oscillating inflation* model, proposed by Damour and Mukhanov. T
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ELSEVIER Physics Letters B 428 (1998) 37–43

Cosmological perturbation with two scalar fields in reheating after inflation

A. Taruya [1], Y. Nambu [2]
Department of Physics, Nagoya University, Chikusa-ku, Nagoya 464-01, Japan

Abstract

We investigate th
the exact solution of
analyze the behavior
massless scalar field
Elsevier Science B.V

PACS: 98.80.-k; 98.80.
Keywords: Cosmologic

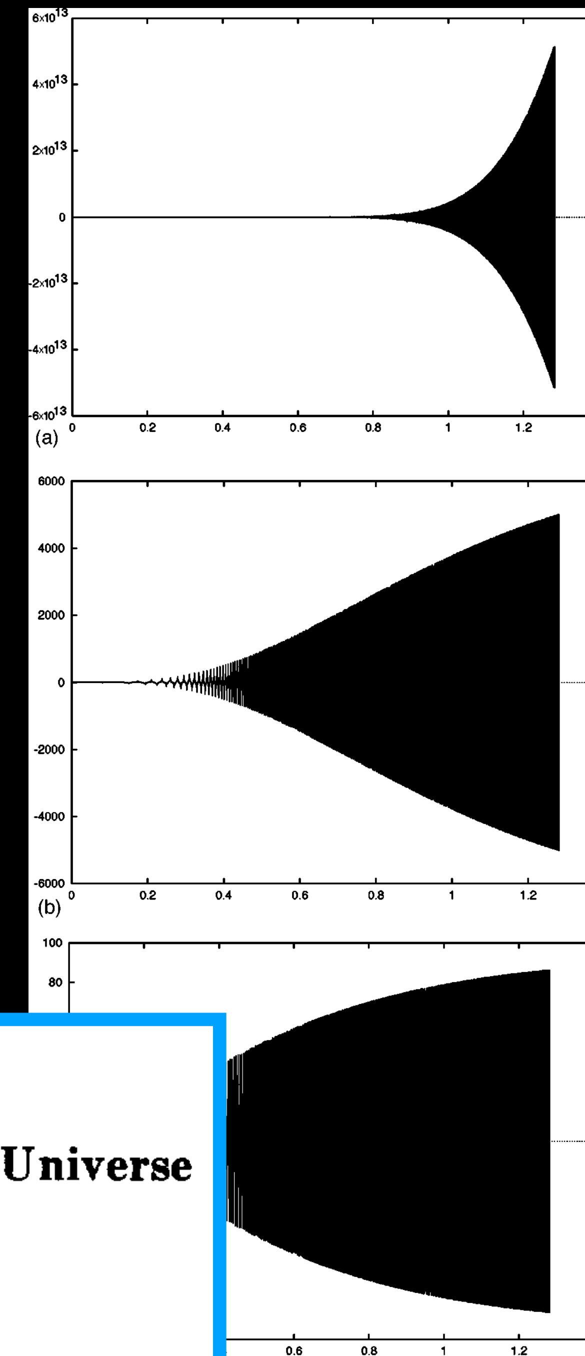
Progress of Theoretical Physics, Vol. 97, No. 1, January 1997

Evolution of Cosmological Perturbation in Reheating Phase of the Universe

Yasusada NAMBU and Atsushi TARUYA
Department of Physics, Nagoya University, Nagoya 464-01

(Received September 13, 1996)

The evolution of the cosmological perturbation during the oscillatory stage of the scalar field is investigated. For the power law potential of the inflaton field, the evolution equation of Mukhanov's gauge invariant variable is reduced to the Mathieu equation, and the density perturbation grows due to parametric resonance.



Contents

Nonlinear structure formation as a probe of dark matter : phase-space properties of cold dark matter (CDM) halos

- Introduction
- Phase-space structures of CDM halos
- Summary and prospects

In collaboration with

Yann Rasera
(Observatoire de Paris)

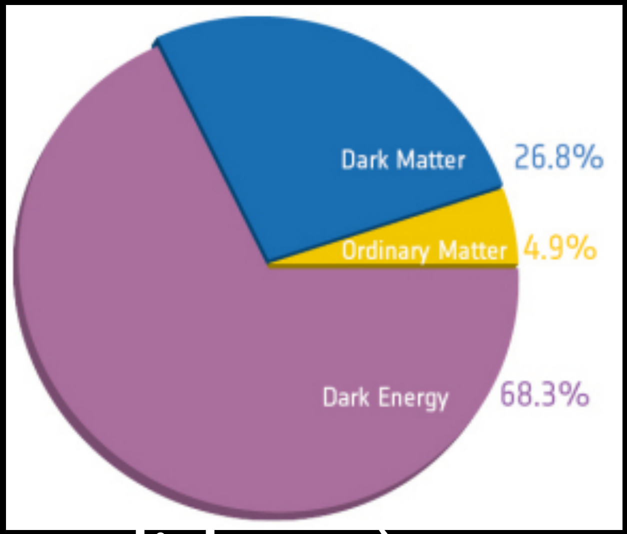
Hiromu Sugiura
(Dept. Phys. Kyoto U)

Takahiro Nishimichi
(YITP)

Dark matter & structure formation

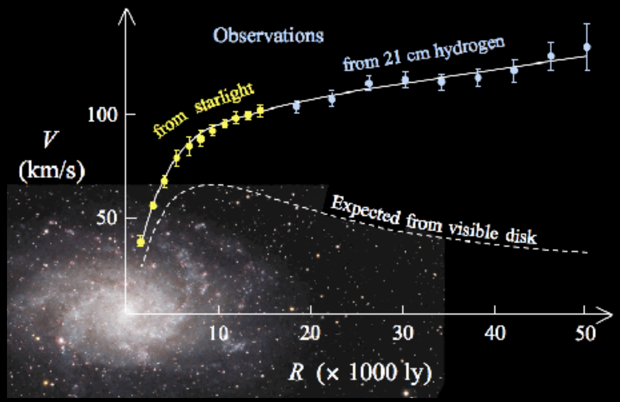
Dark matter (DM)

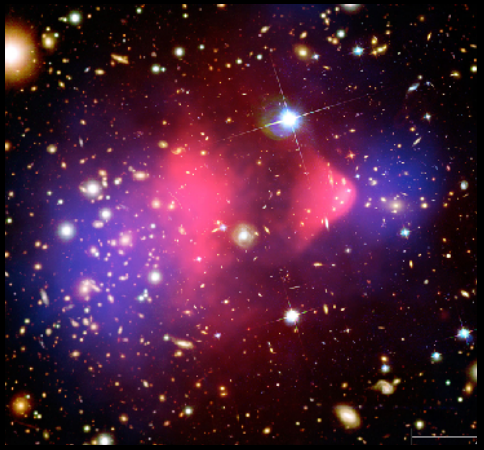
- Hypothetical *invisible* massive particles
- ~30 % of the energy density of the Universe
- Unknown microscopic origin (though many candidates)



Observational evidences:

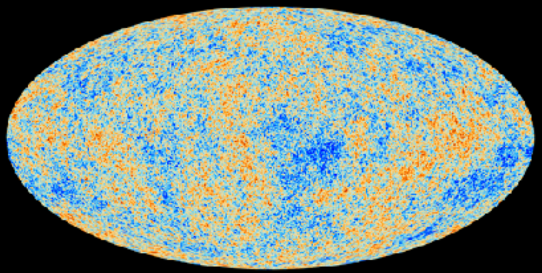
Flat rotation curves

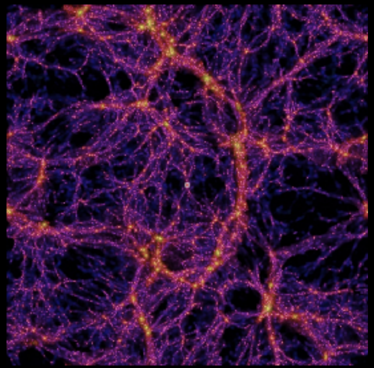




Weak lensing observations (e.g., Bullet clusters)

CMB & large-scale structure





DM is an important building block in cosmic structure formation

Nature of dark matter

In structure formation,

of particular importance is *cold* nature of DM

velocity distribution was virtually null at an early stage of structure formation

→ *Cold dark matter (CDM)*

e.g., Peebles ('82), Blumenthal et al. ('82), Bond et al. ('82), …

- Early growth of CDM fluctuations   Baryon "catch up"
- Hierarchical clustering of structure formation (cuspy halos / substructure)

Irrespective of microscopic origin,

Such a system is macroscopically described by Vlasov-Poisson equation starting with cold initial condition

Cosmological Vlasov-Poisson system

Vlasov-Poisson system in a cosmological background:

Distribution function

$$\left[\frac{\partial}{\partial t} + \frac{\boldsymbol{p}}{ma^2}\frac{\partial}{\partial \boldsymbol{x}} - m\frac{\partial \Phi}{\partial \boldsymbol{x}}\frac{\partial}{\partial \boldsymbol{p}}\right] f(\boldsymbol{x},\boldsymbol{p}) = 0,$$

Collisionless Boltzmann eq.

$$\nabla^2\Phi(\boldsymbol{x}) = 4\pi\, G\, a^2 \left[\frac{m}{a^3}\int d^3\boldsymbol{p}\, f(\boldsymbol{x},\boldsymbol{p}) - \rho_{\rm m}\right]$$

Newton potential

a(t) : scale factor of the Universe

= Large-*N* limit (*N* → ∞) of *N*-body simulation

Cold initial flow (or single-stream flow):

Dirac's delta function

$$f(\boldsymbol{x},\boldsymbol{p}) = \overline{n}\, a^3\ \{1+\delta_{\rm m}(\boldsymbol{x})\}\ \delta_{\rm D}\left[\boldsymbol{p} - m\, a\, \boldsymbol{v}(\boldsymbol{x})\right]$$

Mass density field

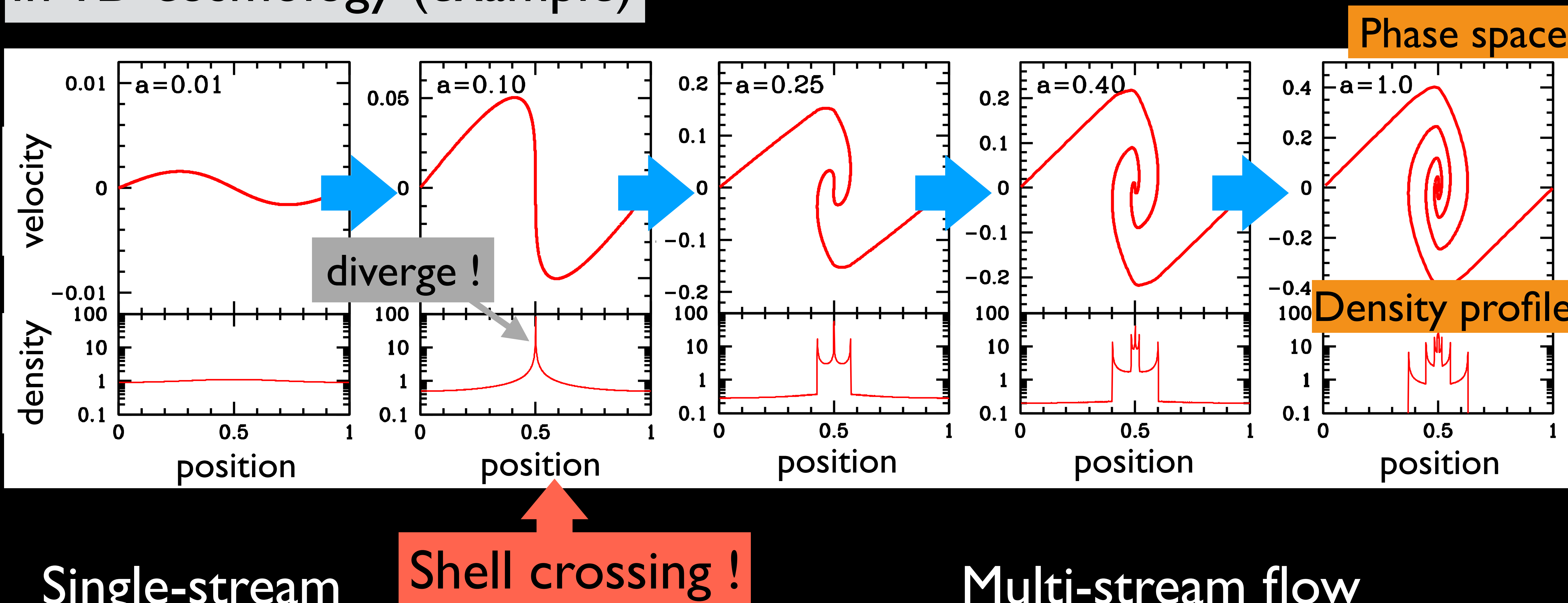
Velocity field

System at an early phase is reduced to pressureless fluid system

→ foundation of (Eulerian) perturbation theory

Fate of cold initial condition

In 1D cosmology (example)



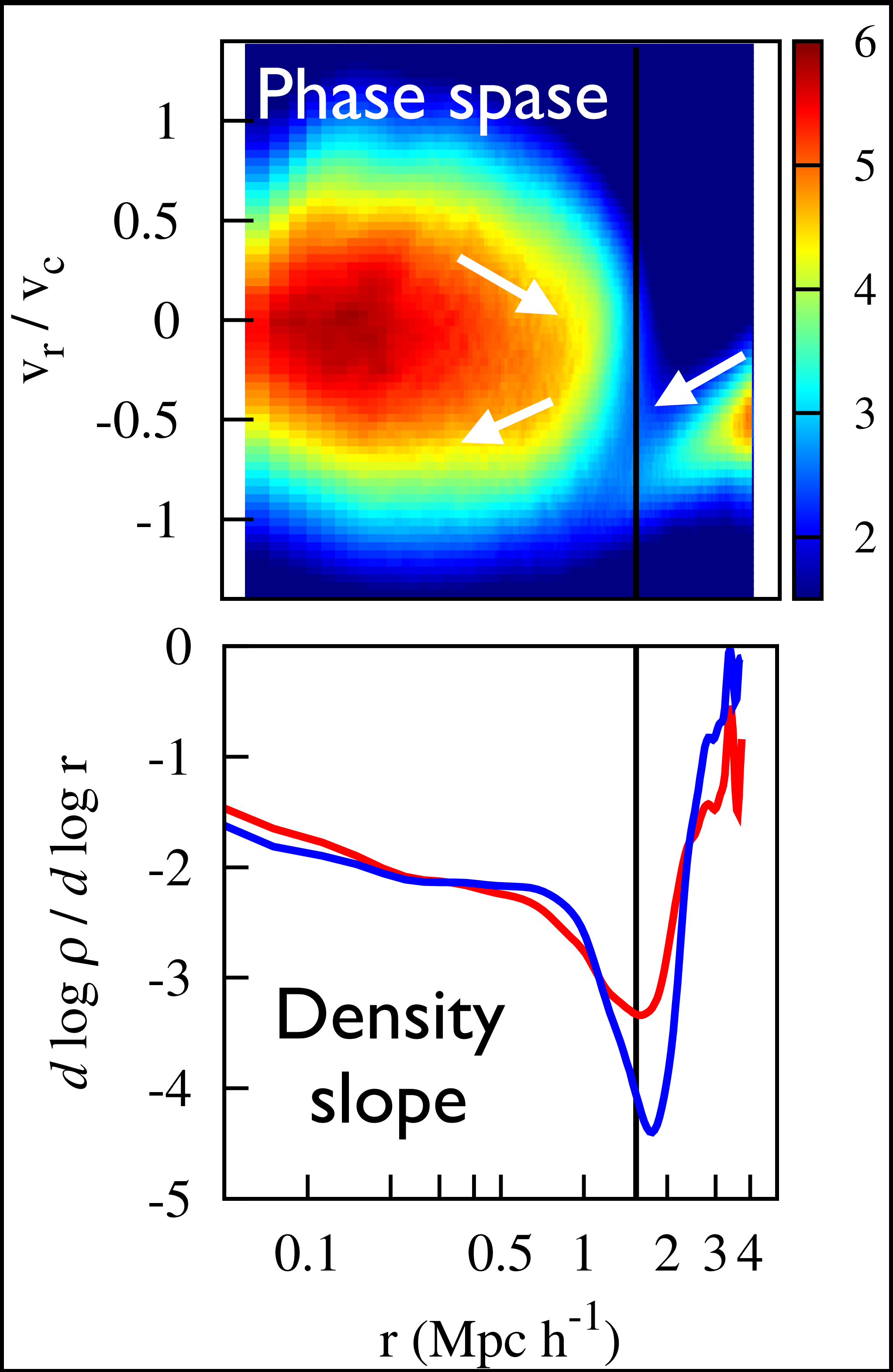
Single-stream

Multi-stream flow

(= formation of dark halo)

Shell-crossing & multi-stream flows are natural outcome of nonlinear structure formation in CDM cosmology → Test for CDM paradigm

Boundary of CDM halos



Diemer & Kravtsov ('14)

Adhikari et al. ('14)

Outskirt of density profile is found to significantly deviate from NFW profile:

$$\rho_{\rm halo}(r) \propto \frac{1}{(r/r_s)(1+r/r_s)^2} \xrightarrow{r\to\infty} r^{-3}$$

(Navarro et al. '97)

This exactly happens at the boundary of single-/multi-stream flow (≠viral radius)

→ splashback radius

Detection of splashback signature

- SDSS DR8 phot-z gals

  More et al. ('16), Baxter et al. ('17)

- DES Y1 photo-z gals & weak lensing

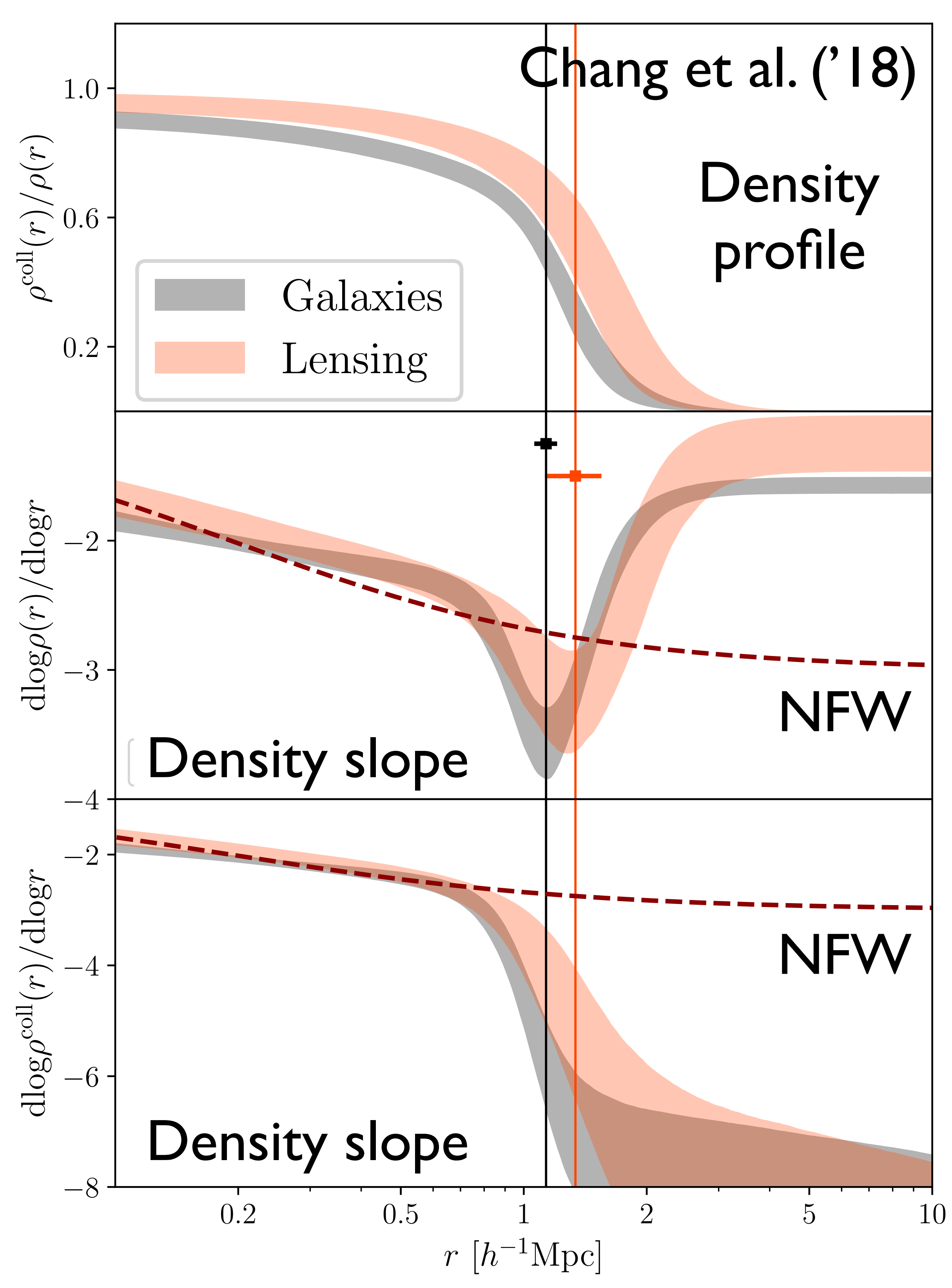
  Chang et al. ('18)

  Clusters identified with redMaPPer algorithm

- Planck SZ clusters
  + Pan-STARRS photo-z galaxies

  Zurcher & More ('18)

Detection is at high-stat. significance, but the results are still controversial

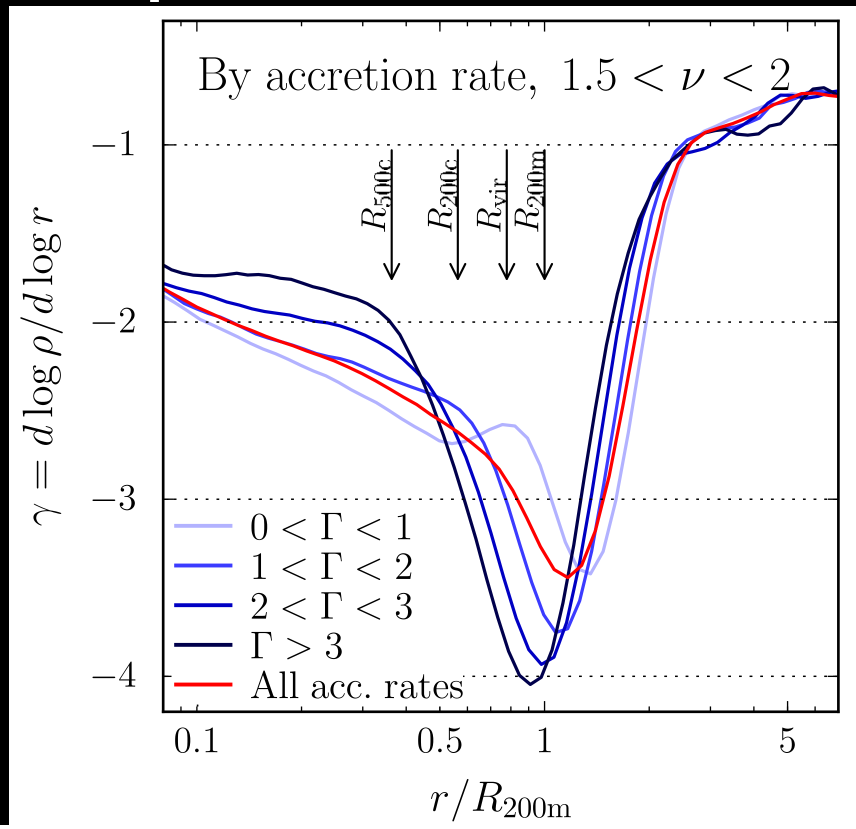


Splashback radius: theoretical aspects

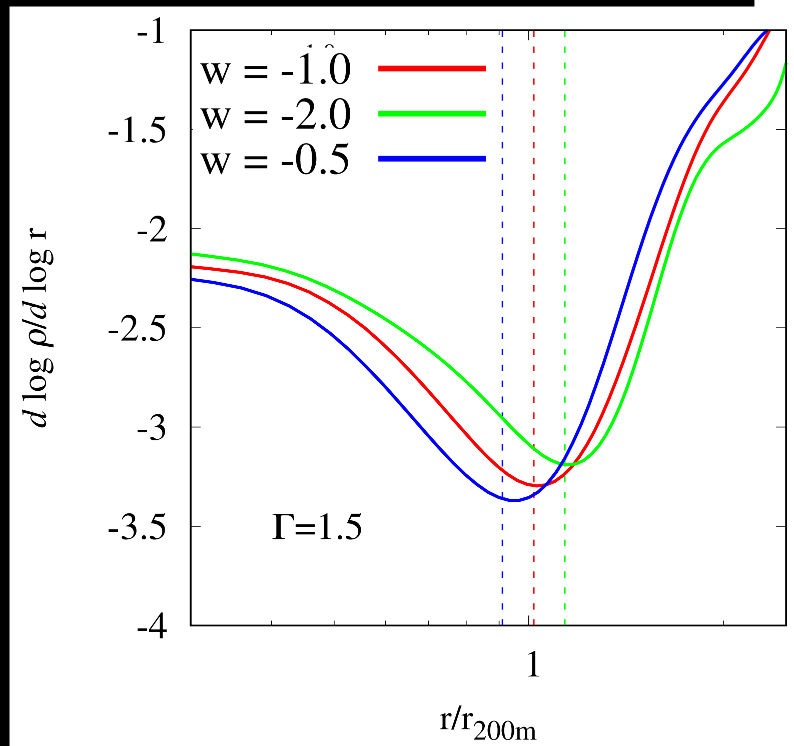
Dependence of outer environment is important

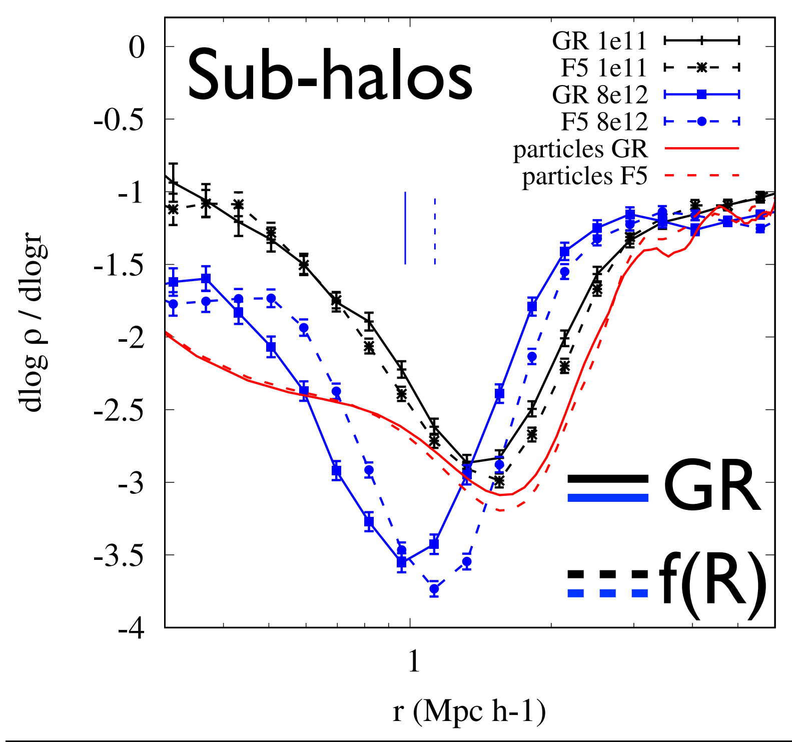
- Mass accretion rate : $\Gamma \equiv \dfrac{\Delta \log(M_{\mathrm{vir}})}{\Delta \log(a)}$

(Diemer & Kravstov '14)



- Dark energy & modified gravity





Adhikari et al. '18

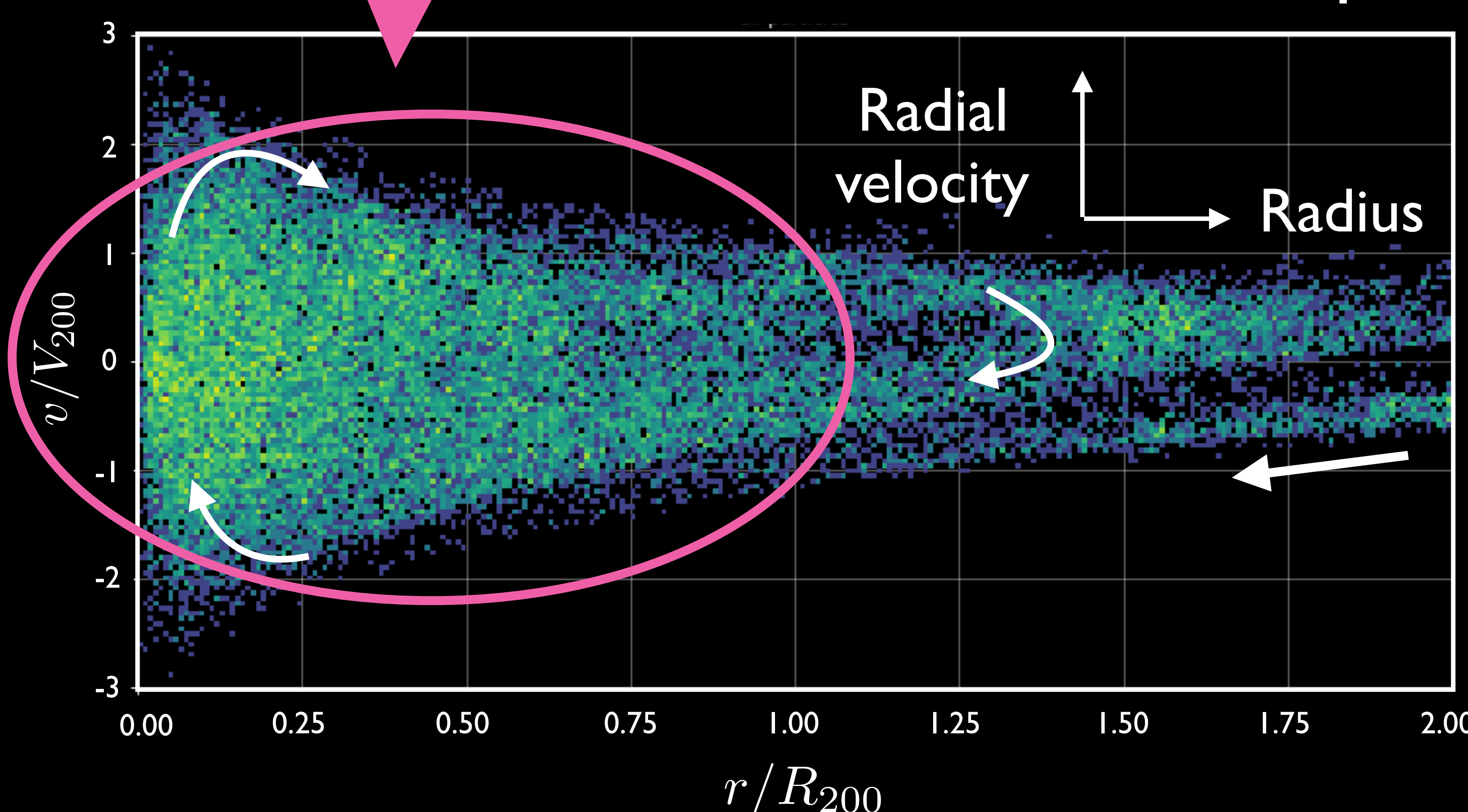
Beyond splashback radius

Splashback radius is just one of the rich CDM characteristics

Beyond splashback radius,

<u>Multi-stream structure</u> is supposed to be developed

→ Alternative probe of dark matter

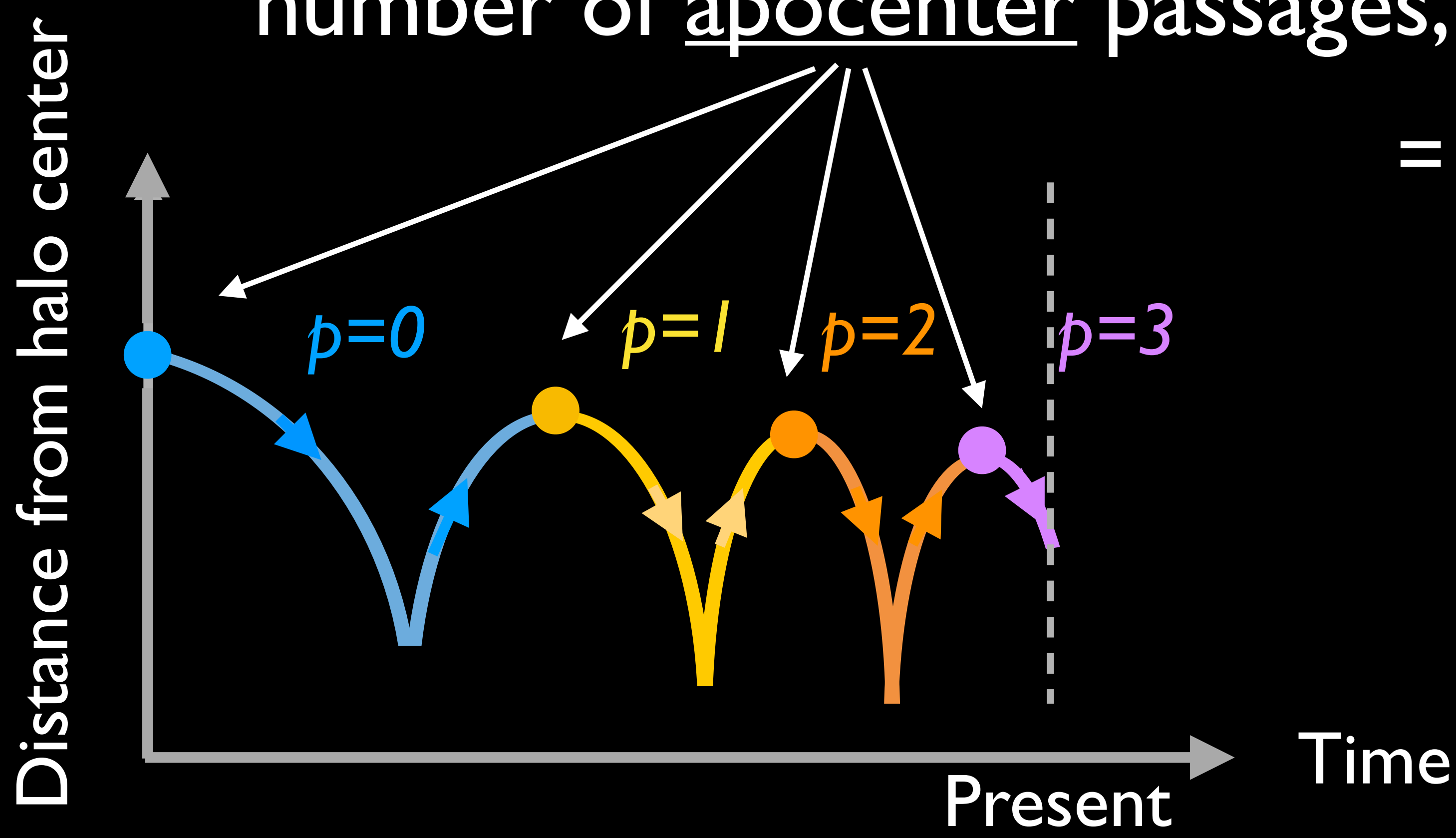


How can we look at multi-stream ?

Tracing multi-stream flow with particle trajectories in *N*-body simulation

H. Sugiura, AT, Yann & Nishimichi (in prep.)

Keeping track of apocenter passage(s) for particle trajectories,
number of apocenter passages, *p*, is stored for each particle



= SPARTA algorithm + α
(Diemer'17; Diemer et al.'17)

Tiling phase-space streams with *p*

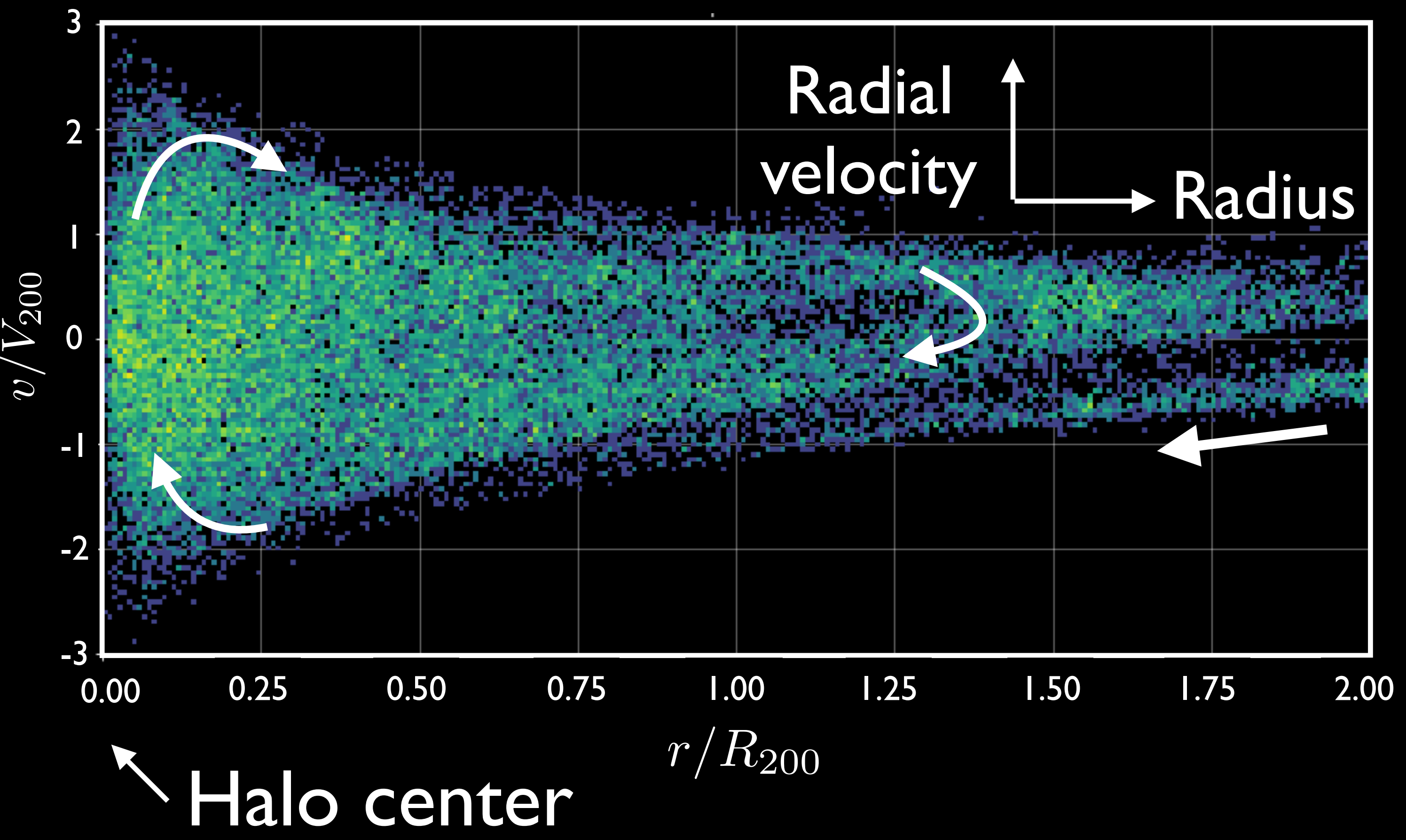
N-body simulation
by Y. Rasera
(Observatoire de Paris)

- L=316Mpc/h, N=512^3
- 60 snapshots at 0<z<1.43
- Einstein-de Sitter universe $(\Omega_{\rm m}=1, \Omega_\Lambda=0)$

11,000 halos
$(M_{200} \geq 10^{13} M_\odot)$

Multi-stream flow in CDM halo

H. Sugiura, AT, Yann & Nishimichi (in prep.)



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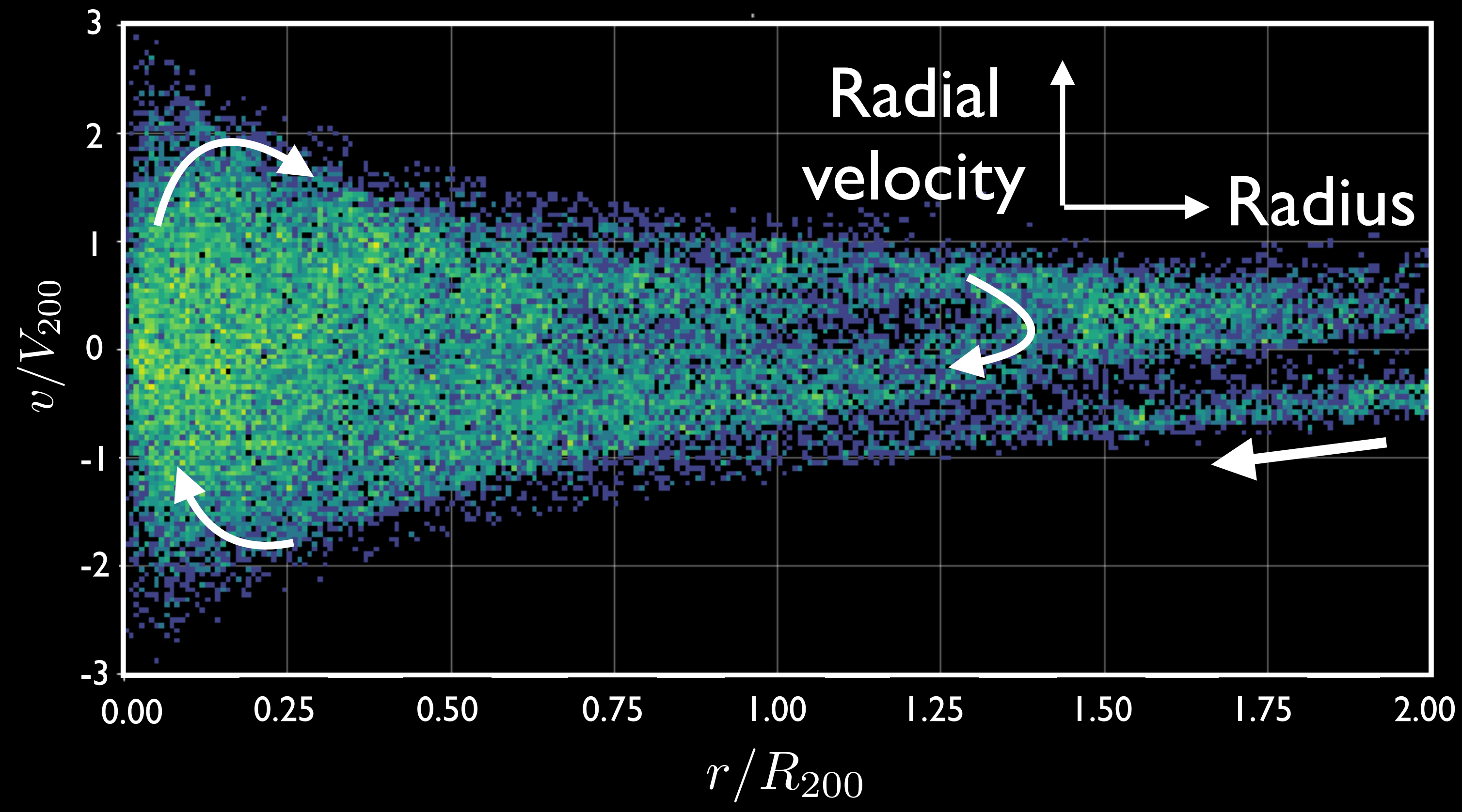
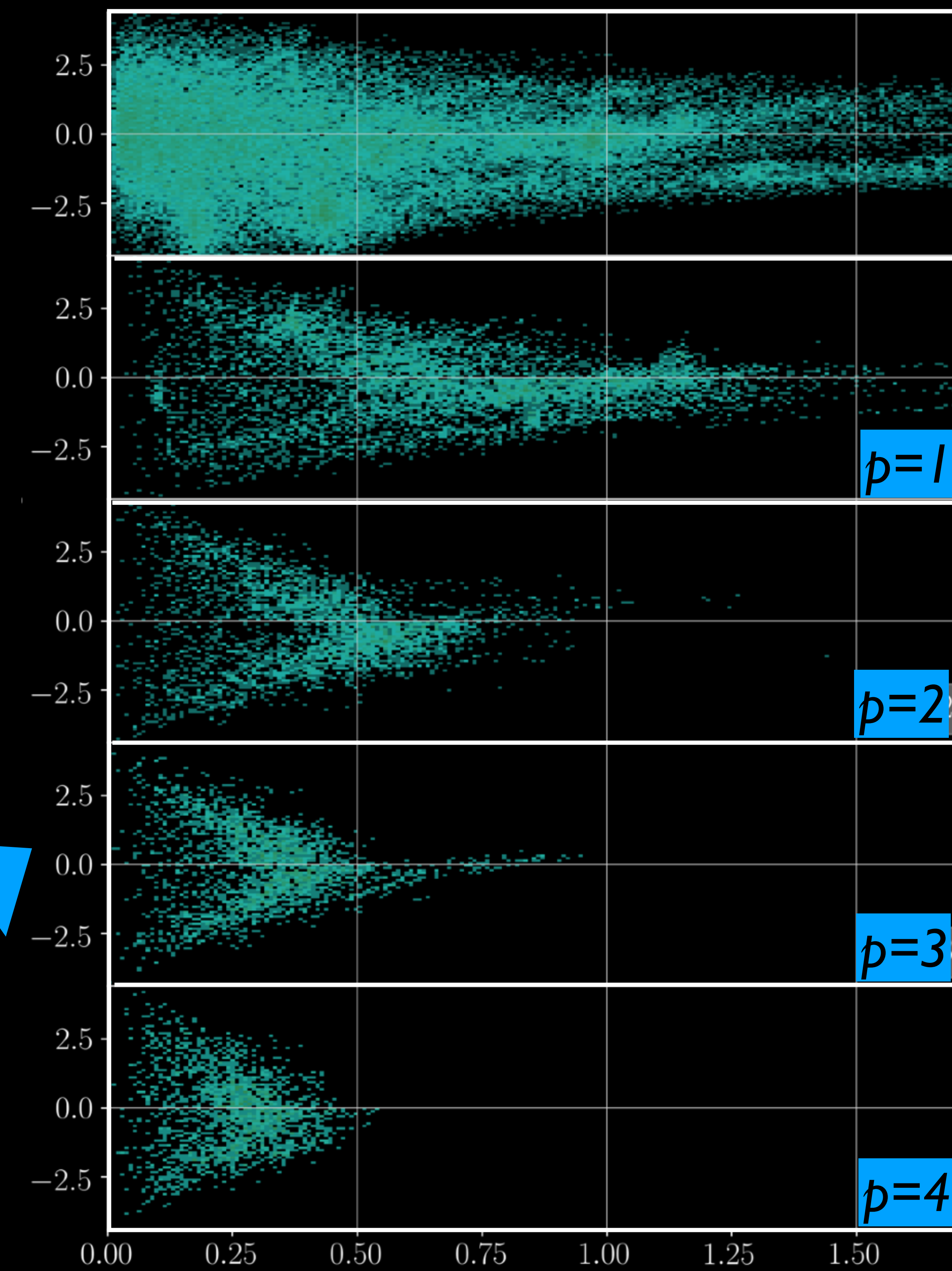




Phase-space distribution of particles classified by # of apocenter passage, *p*

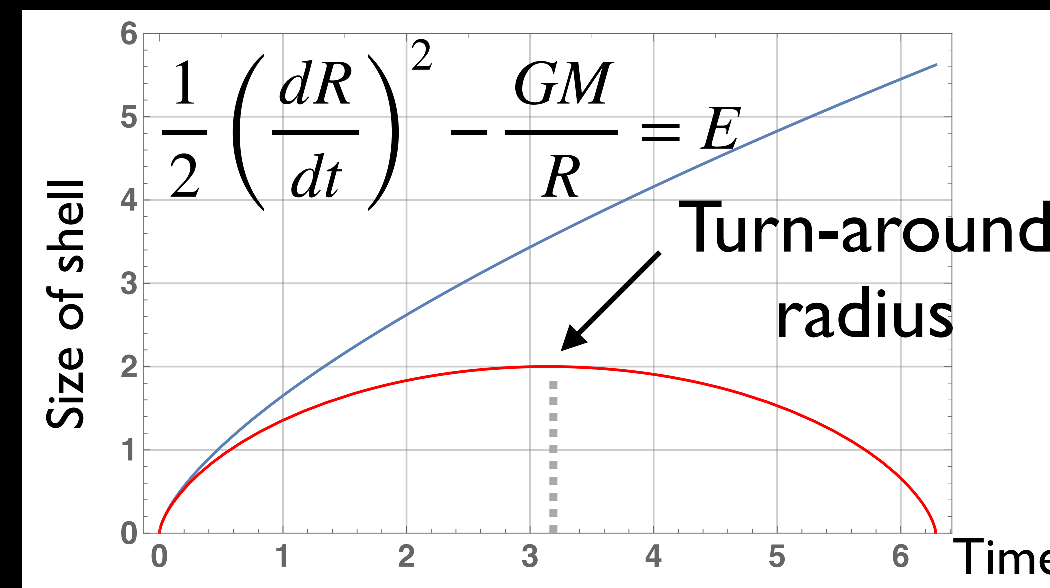
Are these really multi-stream flow ?

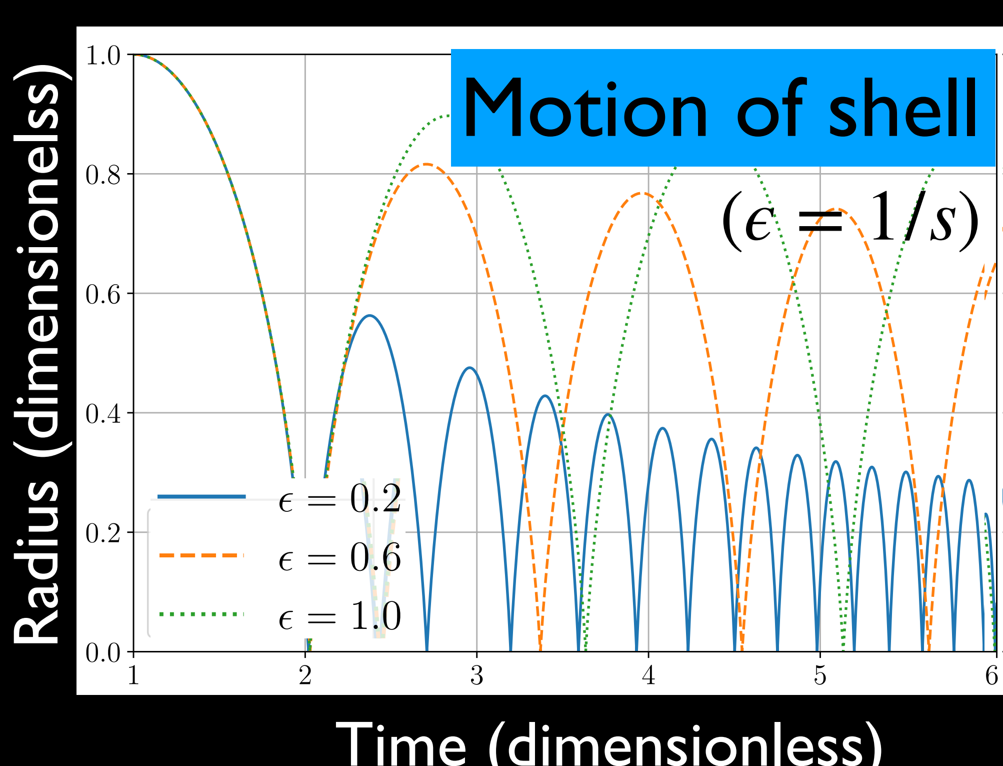
Comparing self-similar solution

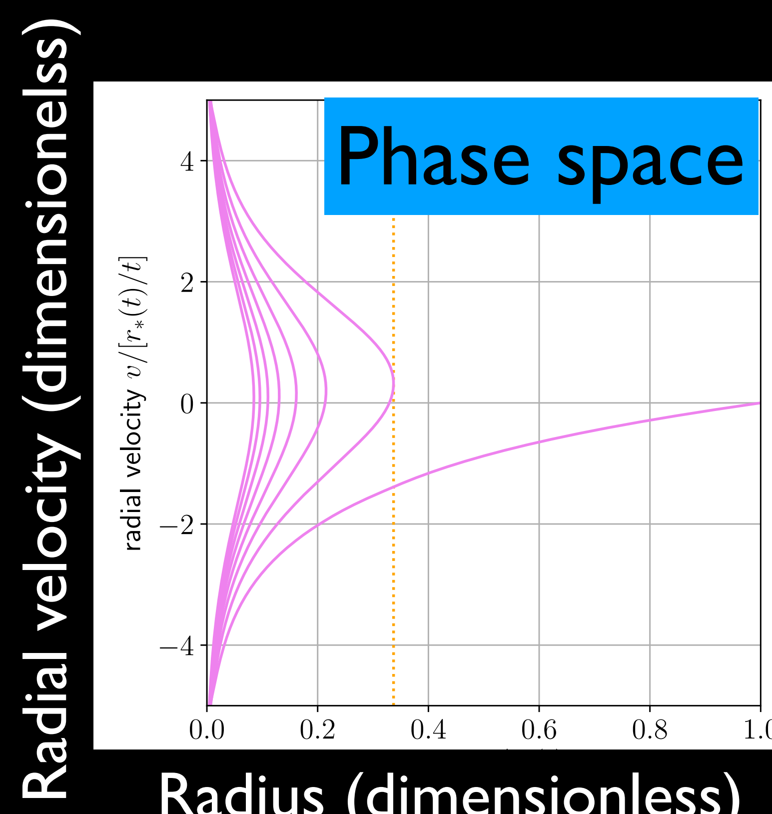
Fillmore & Goldreich ('84)

(see also Bertschinger '85)

- Extension of top-hat spherical model
- Describe motion of collisionless dark matter shell under stationary accretion







# of parameter : 3

- Mass acrretion rate : s

$$M_{\mathrm{halo}} \propto \{a(t)\}^s$$

- Scaling parameters of velocity & radius

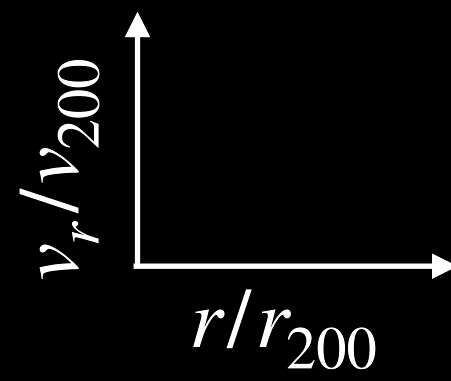
Comparison with *self-similar solution*

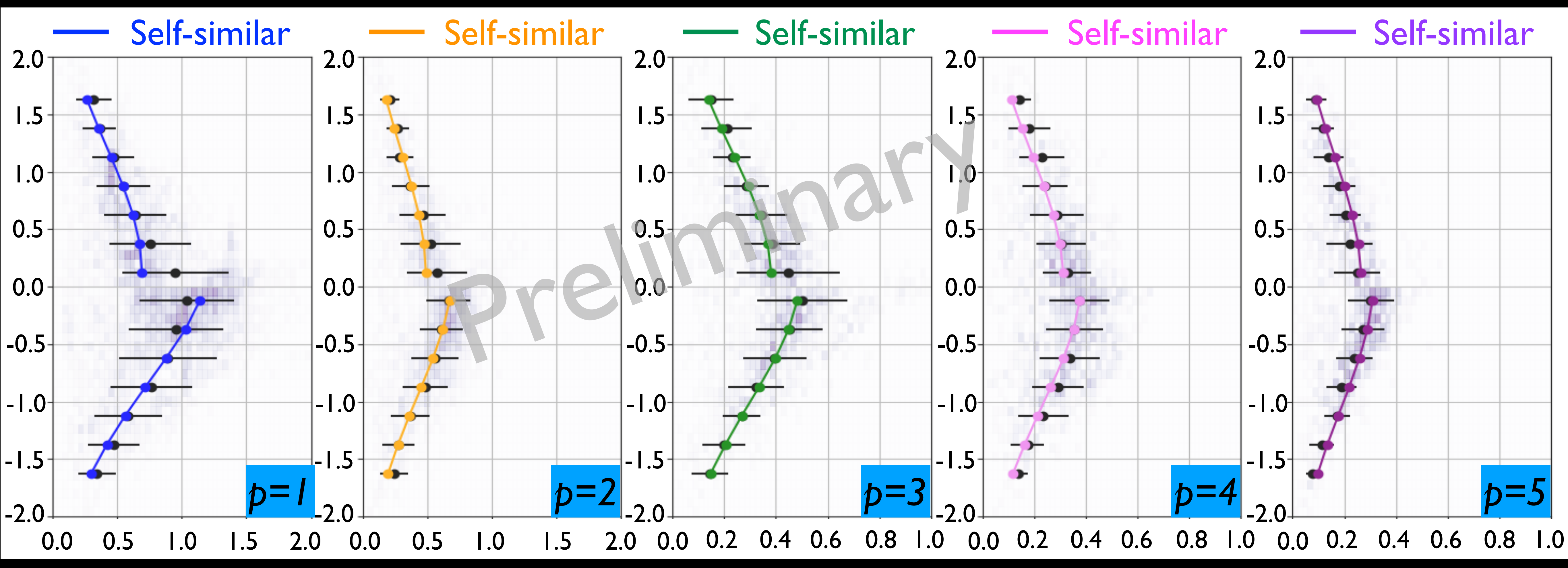
Sugiura et al. (in prep.)

Using particles with *p*=1~5 (# of apocenter passage) to fit:

An example

to show a good agreement





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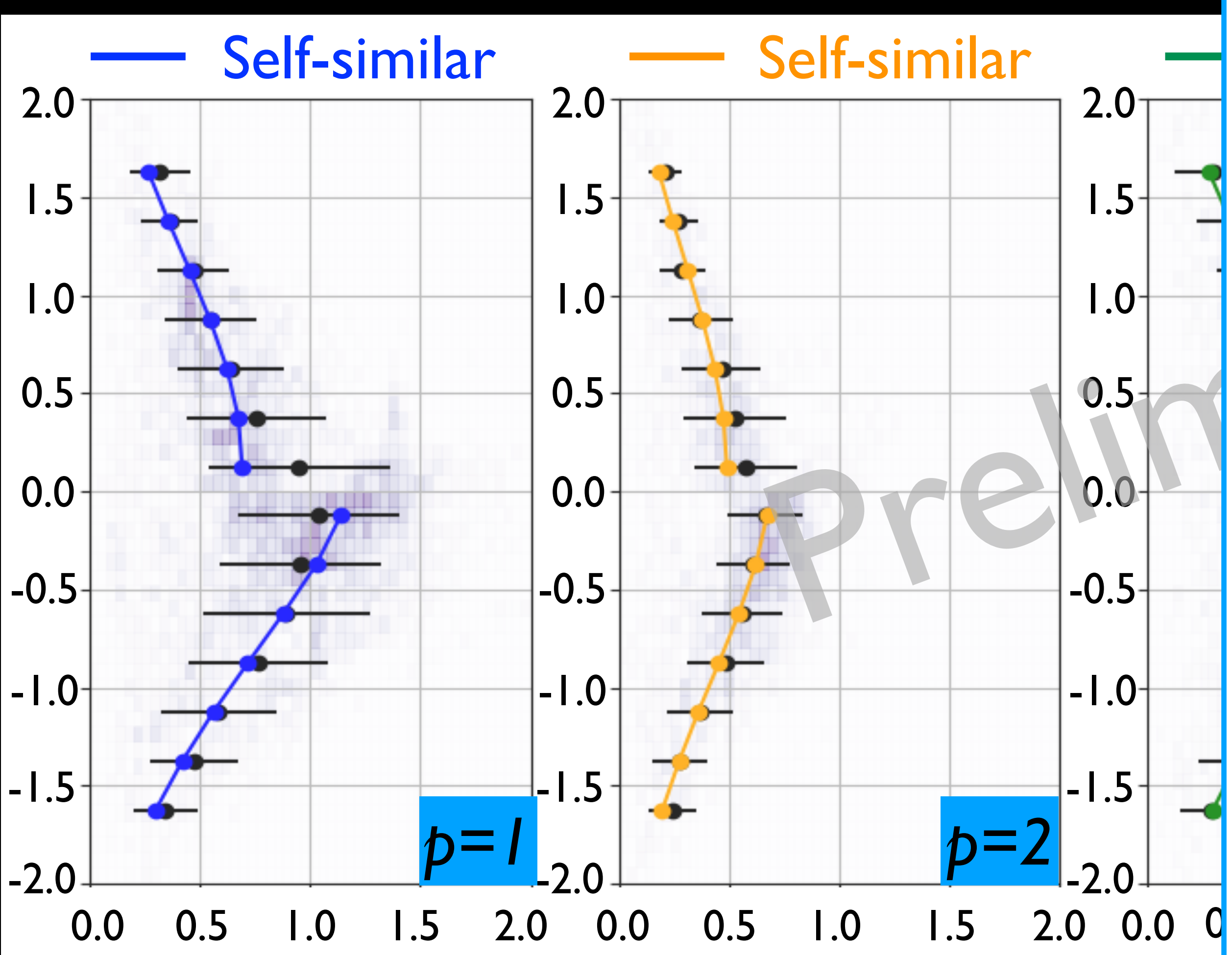
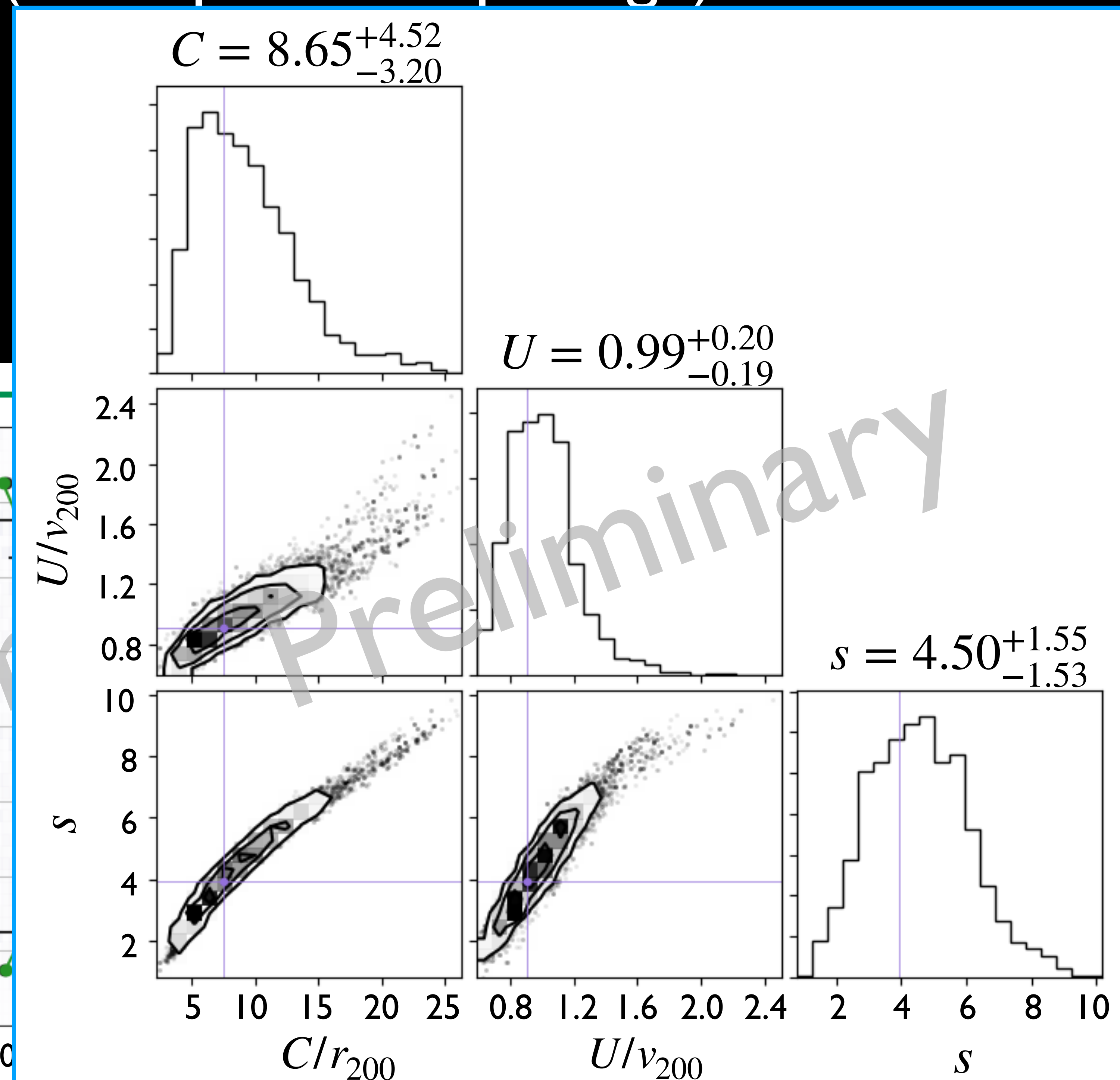
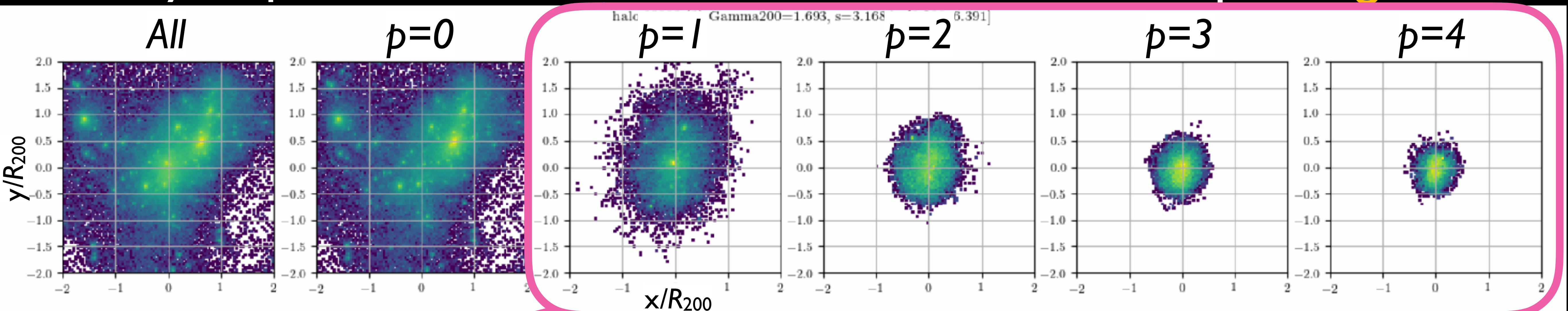




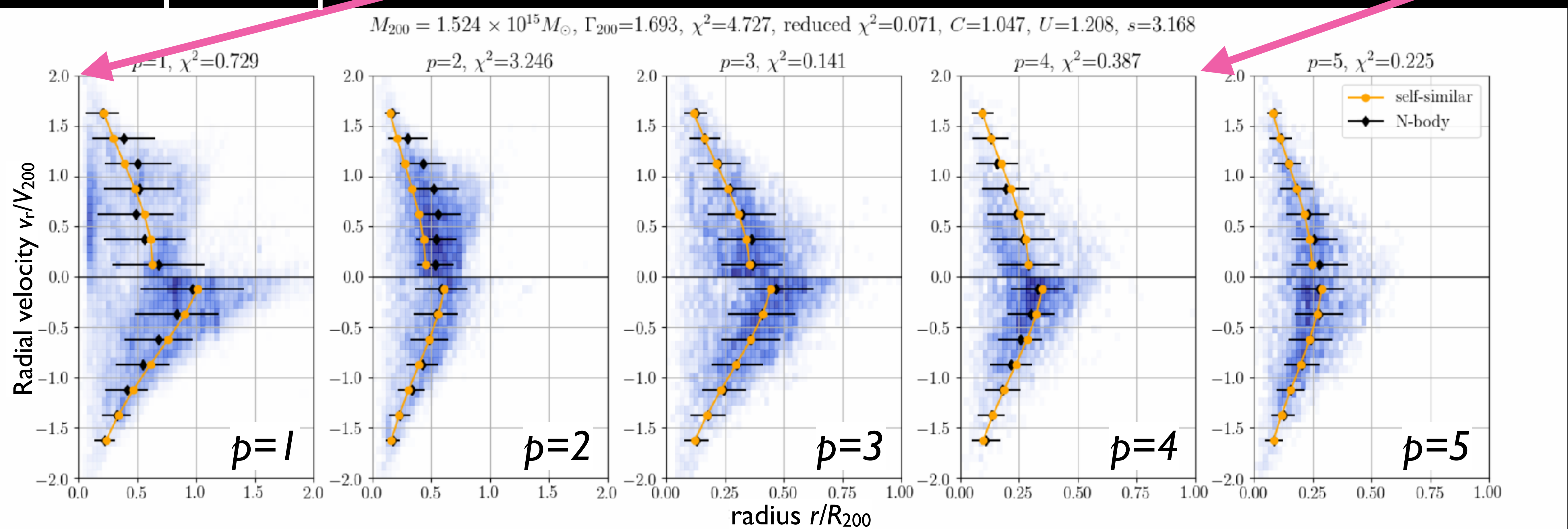
Comparison with *self-similar solution*

Density map

Example of good fit



Radial phase space



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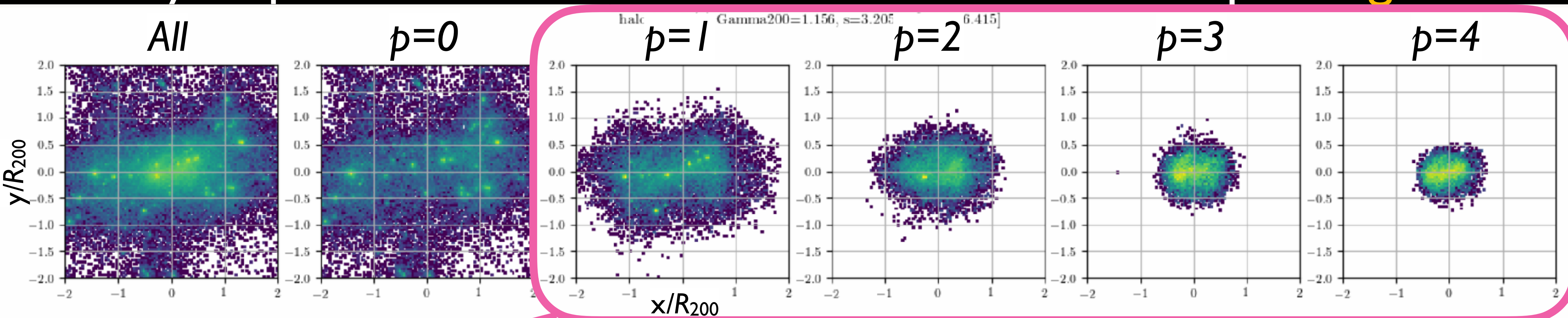
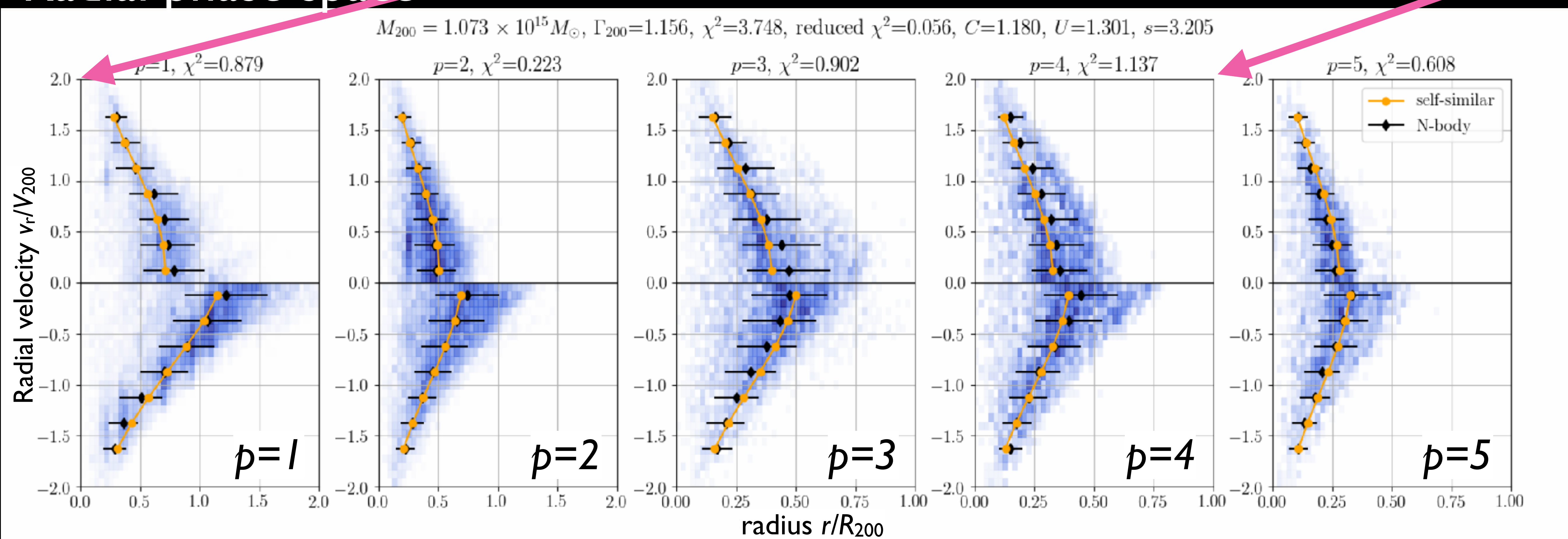


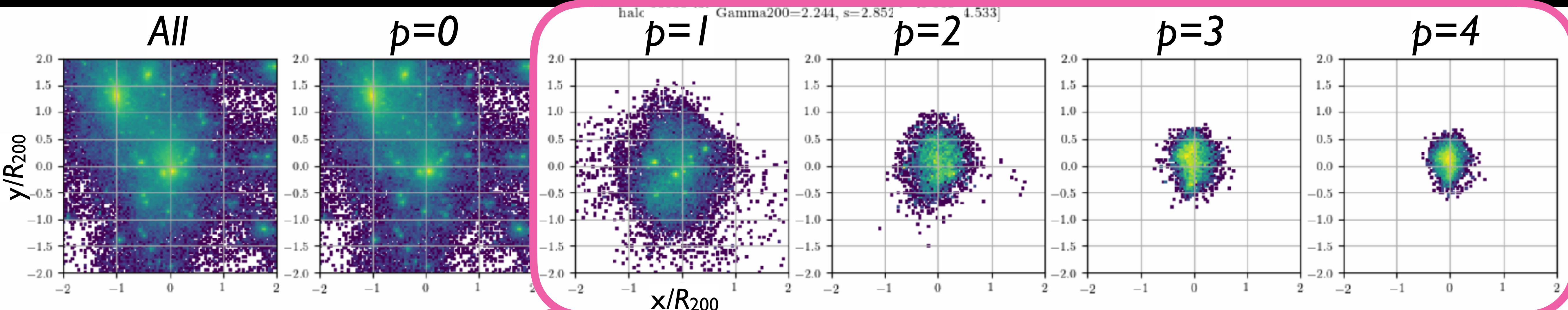
Radial phase space



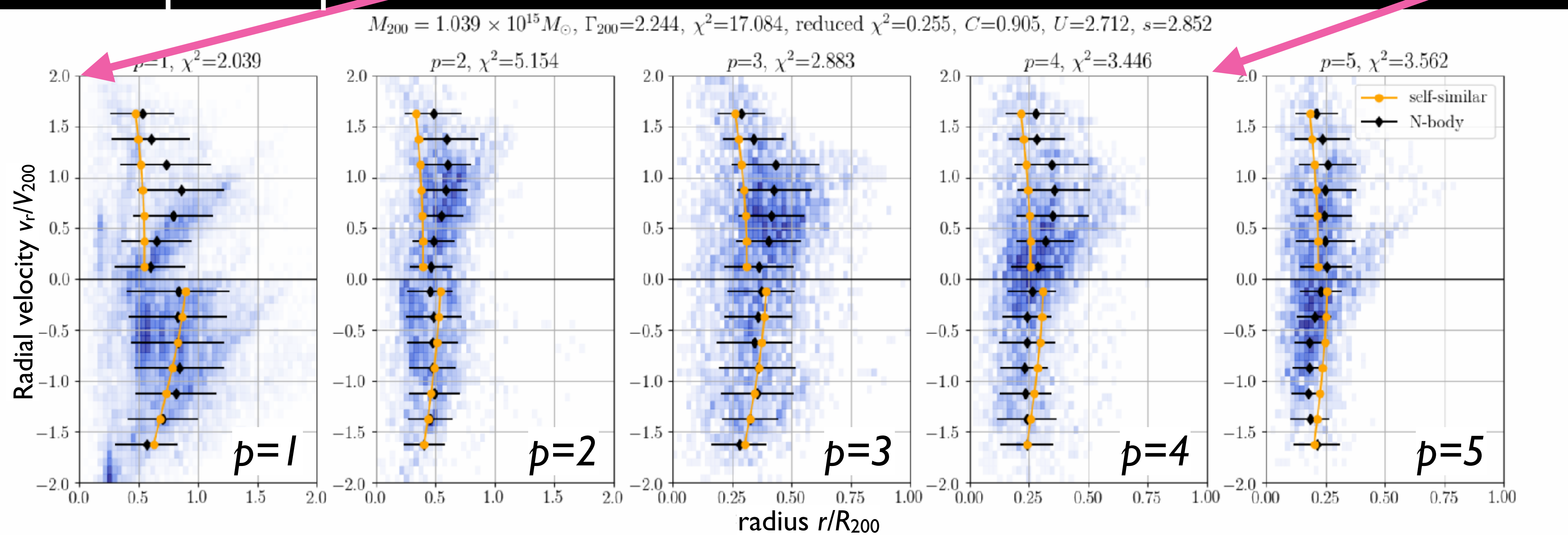
Comparison with *self-similar solution*

Density map

Example of bad fit



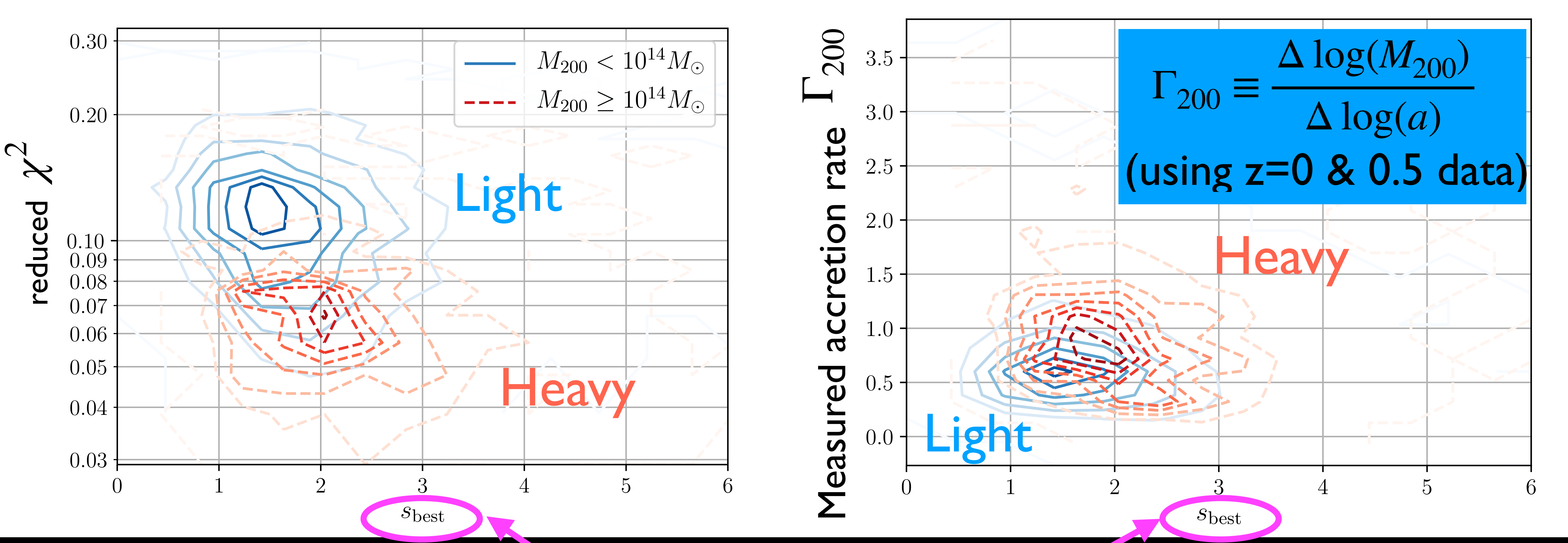
Radial phase space



Statistical properties

~40% of halos are found to be better fitted to self-similar solution (with s_{best} = 1~3)

- Massive halos tend to give a better fit to self-similar solution
- A large scatter between fitting parameter **s** and Γ_{200} (Best-fit) (Measured)



Best-fit accretion rate in self-similar solution $(M \propto a^s)$

Summary

Dark matter halo as cosmological probe of dark matter & fresh look at its phase-space properties

- Distinctive feature of cold dark matter in phase space
  - Multi-stream structure
  - Sharp divergence in density （shell-crossing）

Outskirts of halo → Splashback radius

- Tracing multis-dream flow with particle trajectories

$\cdots$ comparison with self-similar solution

~40% of halos are better fitted to self-similar solution

Investigation of phase-space properties of dark matter are fun, and would help clarifying the origin of dark matter