The depletion radius of dark matter halo

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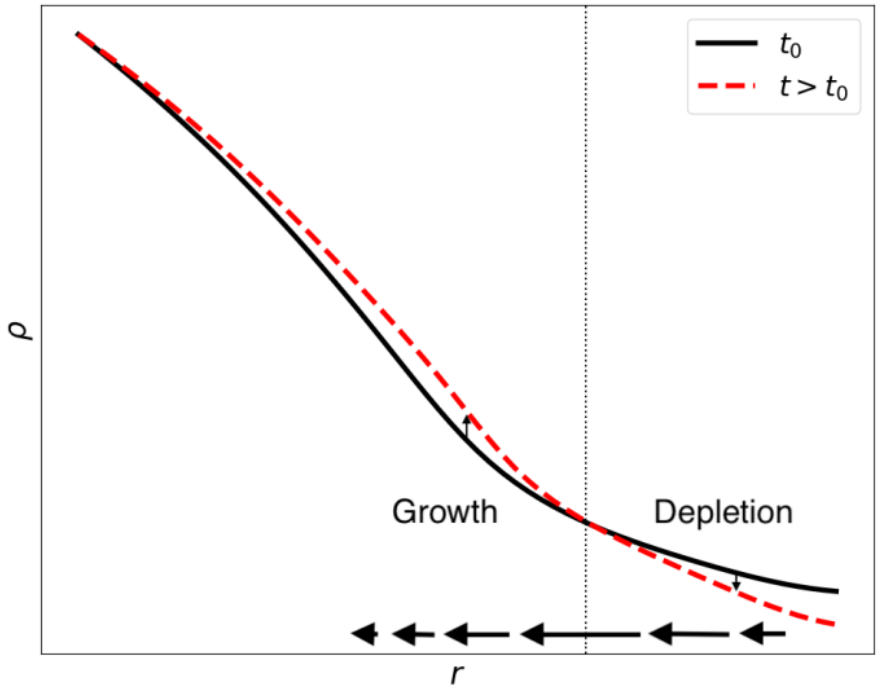
Arxiv: 2008.03477，2105.04978，2205.01816，2303.10886，2303.10887

The depletion radius: definition

- Growth of a halo ➔➔ depletion of environment
  - Maximum infall rate location: inner depletion radius

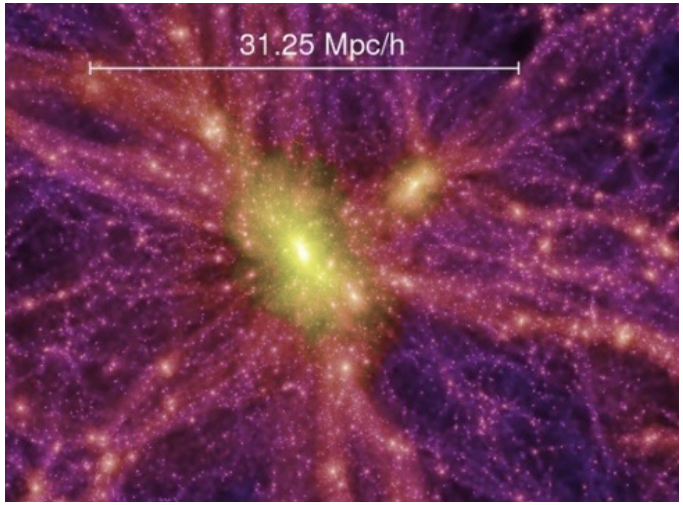


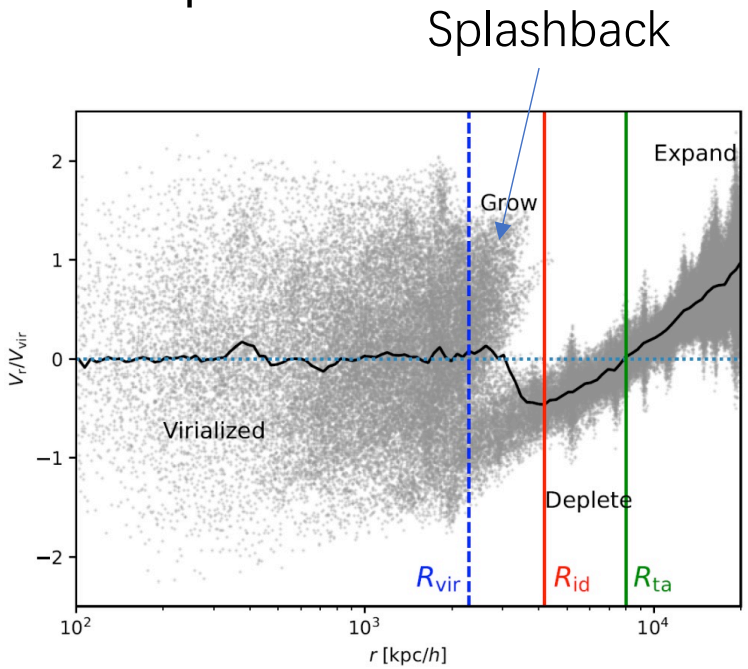
Mass Conservation

$$\dot{\rho}\, 4\pi r^2 \mathrm{d}r = -\mathrm{d}MFR$$

Fong & Han 2021

The depletion radius: example





The depletion radius defines a more complete halo in both spatial coverage and physical processes

Halo Model

Evolution Probe

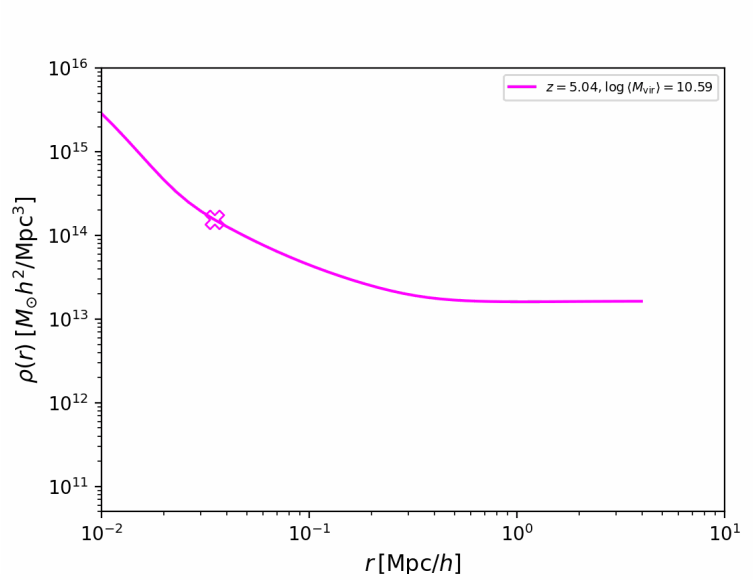
The process of depletion

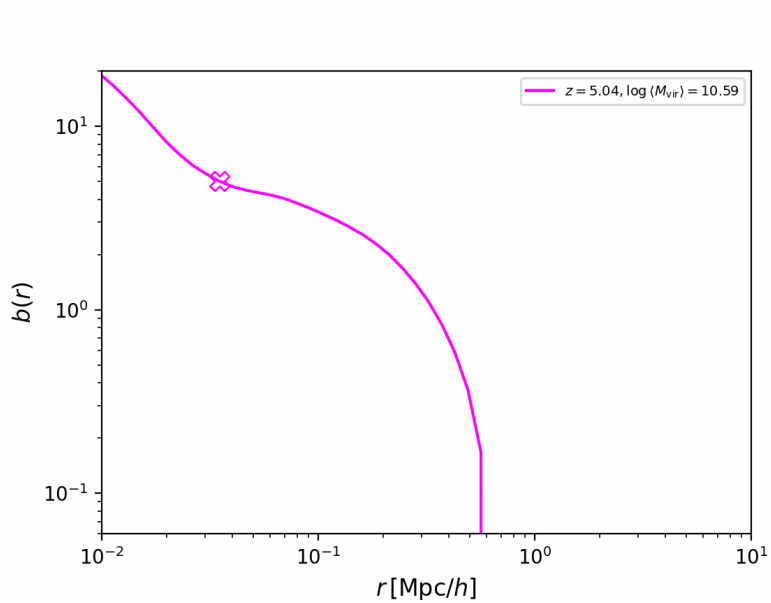
- Expanding universe—background density also receding
- Halo growth – neighborhood extra depletion
- Relative density profile unveils depleted region

$$b(r) = \frac{\xi_{\rm hm}(r)}{\xi_{\rm mm}(r)} = \frac{\langle \delta(r) \rangle}{\xi_{\rm mm}(r)}$$

- Characteristic depletion radius:

(relative) **clustering is the weakest**: region of influence





Gao, Han+, 2023

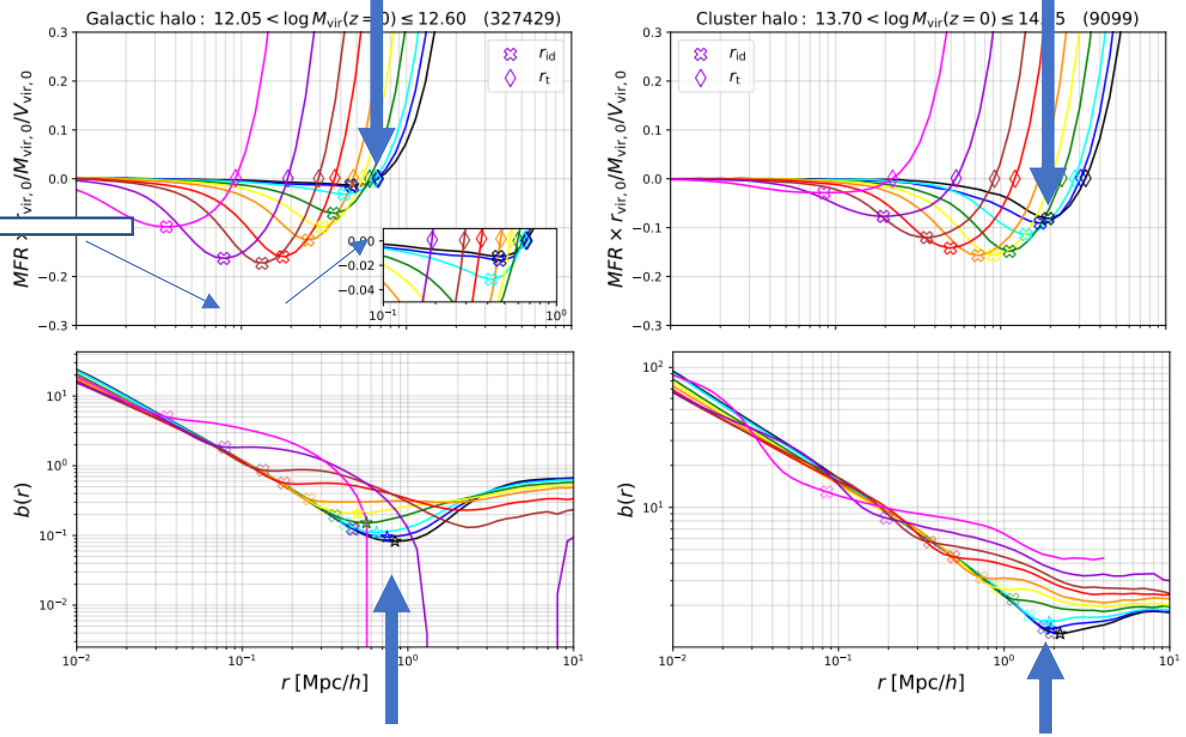
Depletion radius as a halo evolution probe

- Galactic halos form/deplete earlier

Galactic halos have almost exhausted the surrounding material at z=0

Cluster halos are still actively depleting

depletion rate first increases then decreases

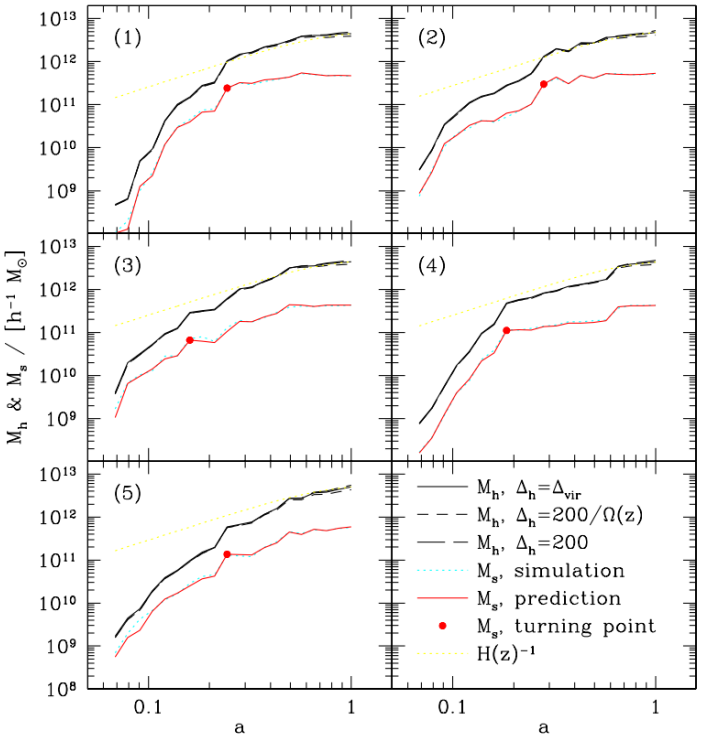


More depleted

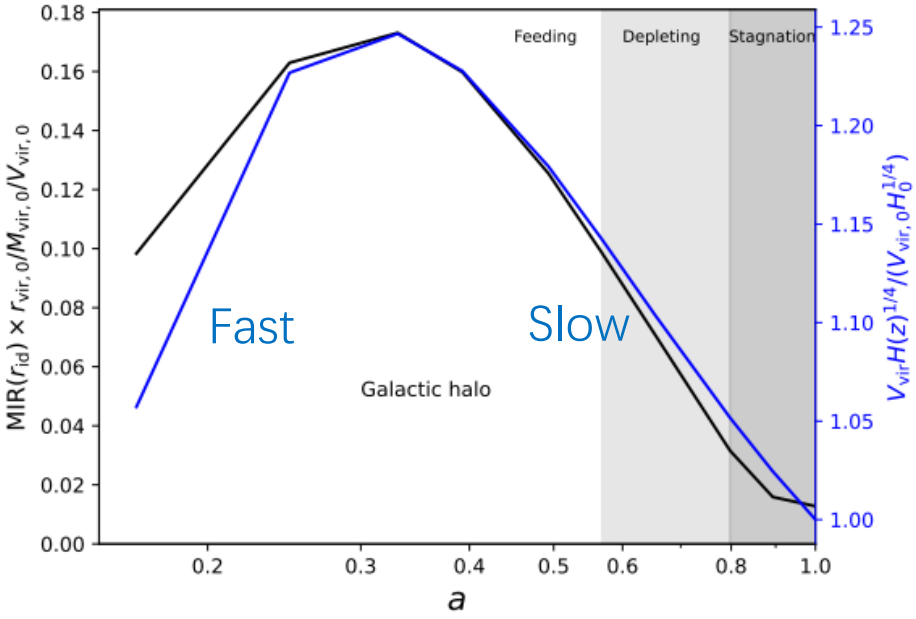
Less depleted

Depletion radius as a halo evolution probe

- Halo evolution undergoes fast & slow accretion phases (Zhao et al. 2003)
- The transition determines halo concentration



- The depletion rate provides a more objective diagnostic
  - Accelerated Depletion
  - Decelerated Depletion



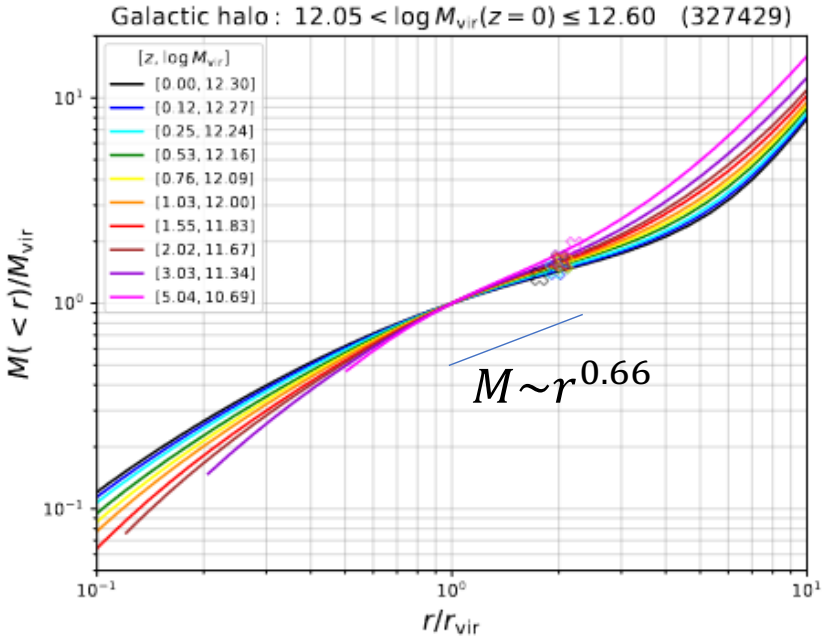
Depletion radius evolution

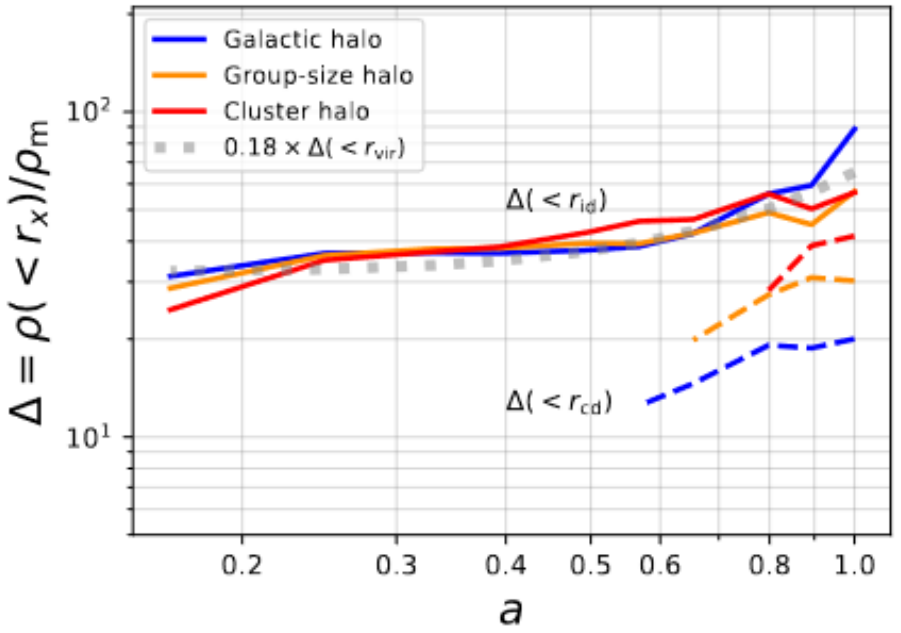
- Well proportional to virial quantities across redshift

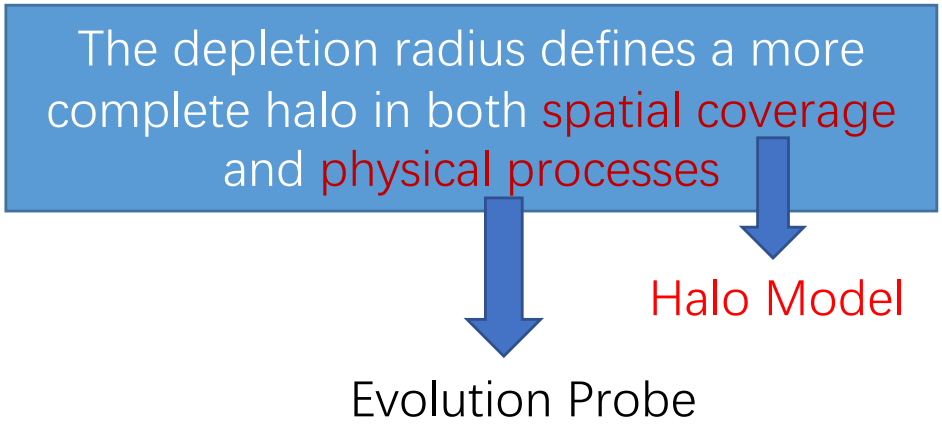
Why?

$$r_{\rm id} \simeq 2.0 \times r_{\rm vir}.$$

$$\Delta(r_{\rm id}) \simeq 0.18\Delta(r_{\rm vir}).$$

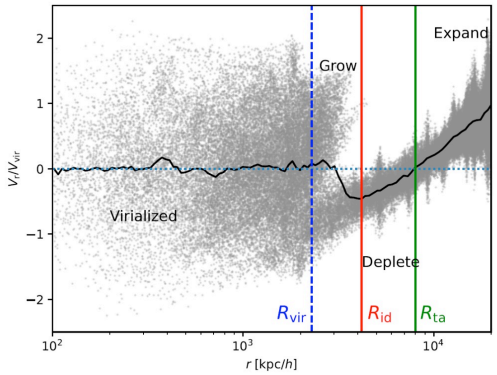





The depletion radius defines a more complete halo in both spatial coverage and physical processes
Halo Model
Evolution Probe

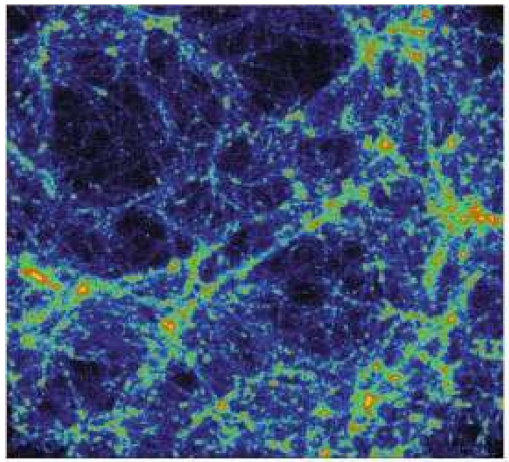
The classical halo model is not self-consistent

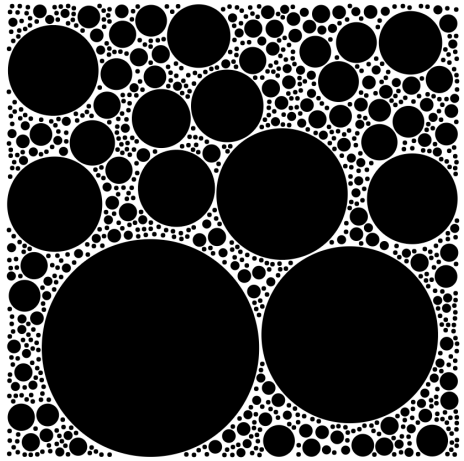
- Classical model: virialized halo
  - Missing the non-virialized envelope

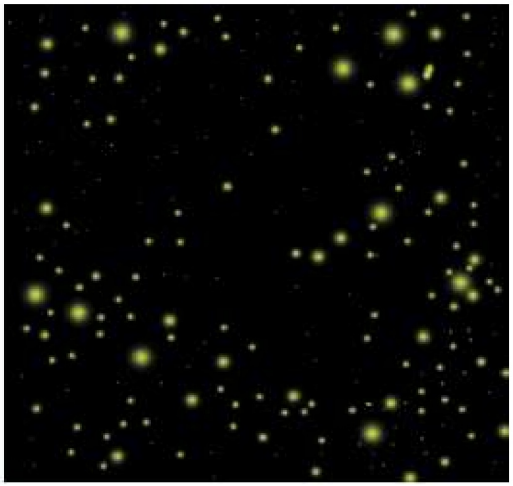


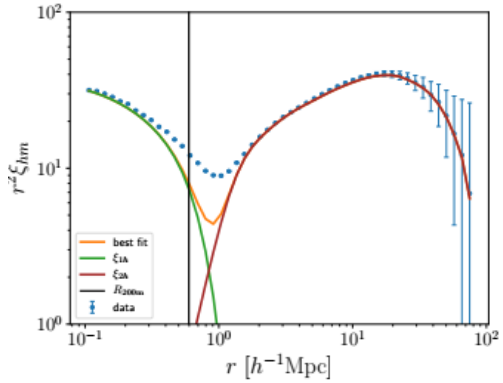
- Problems
  - Mass not counted:
    mass conservation violated
  - Space not covered: Incorrect intermediate scale clustering

Density field=packed halos





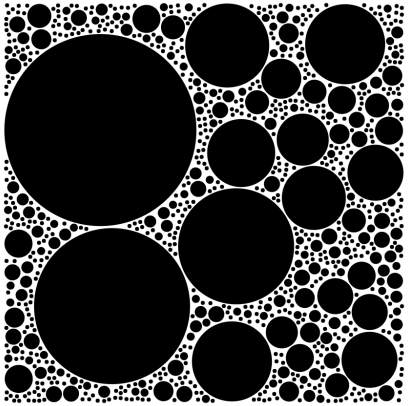


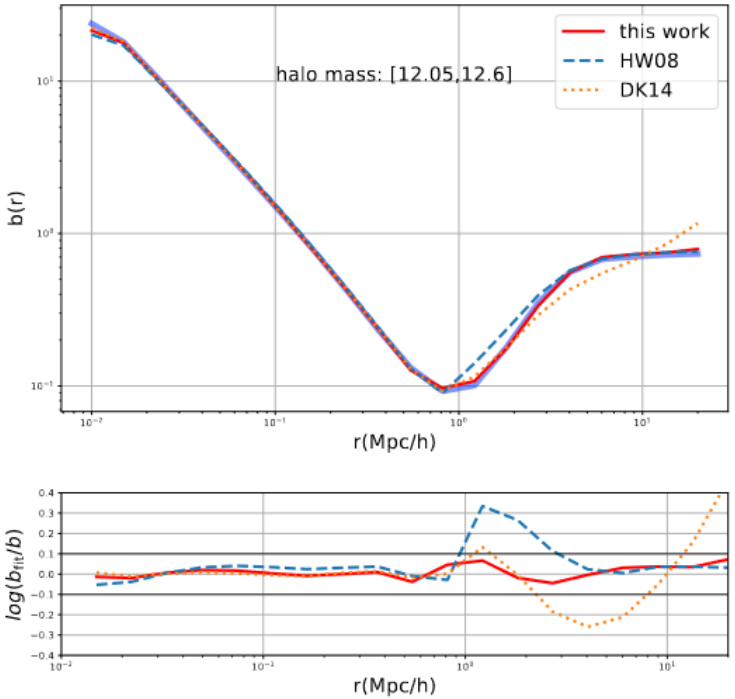


Garcia et. al. 2020

Depletion radius as the **exclusion radius**

- Define halos according to depletion radius
- First principle model
  - Simple/natural model components
  - Single free parameter for unresolved halos
- Percent level accuracy across scales





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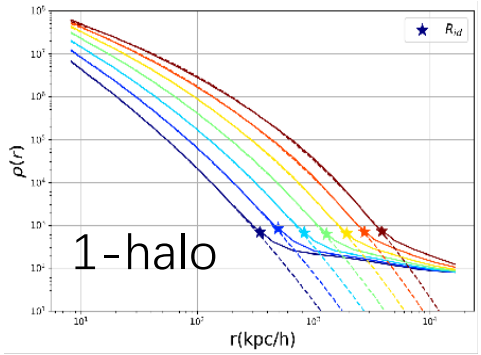

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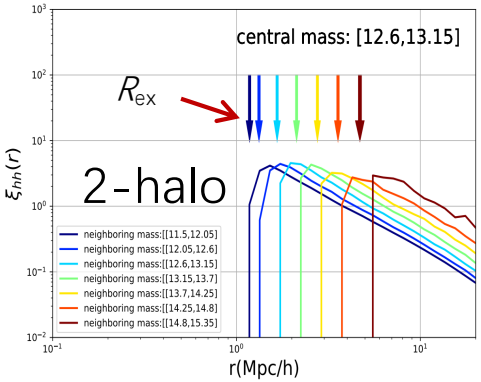
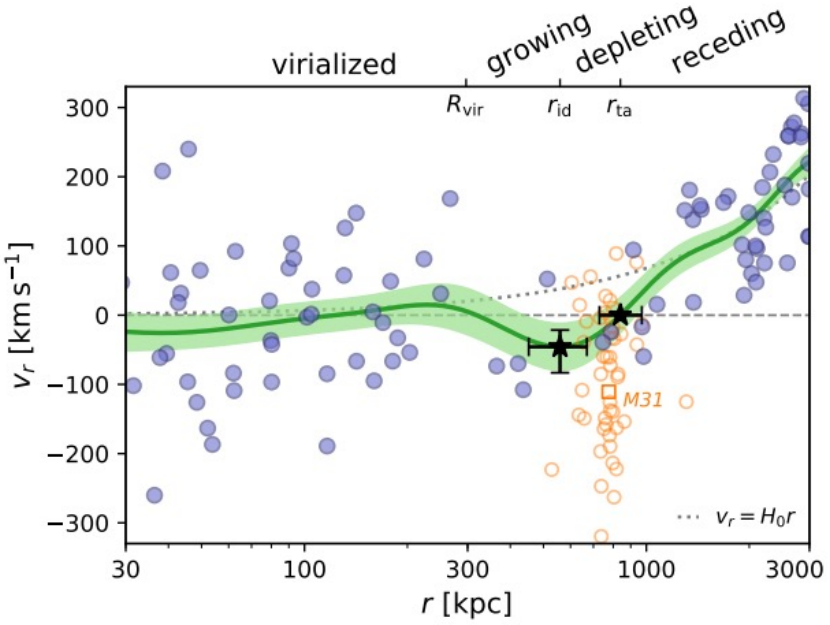


Self-similar

Zhou & Han, 2023

Measuring the depletion radius in our MW



Li & Han 2021, ApJL
arXiv: [2105.04978]

- Radial velocities of dwarf galaxies within 3Mpc of MW
  - Exclude satellites within 600kpc from M31
- Iterative Gaussian process
  - Velocity Dispersion
  - Average radial velocity
- MaxInfall detected at ~2σ for our MW

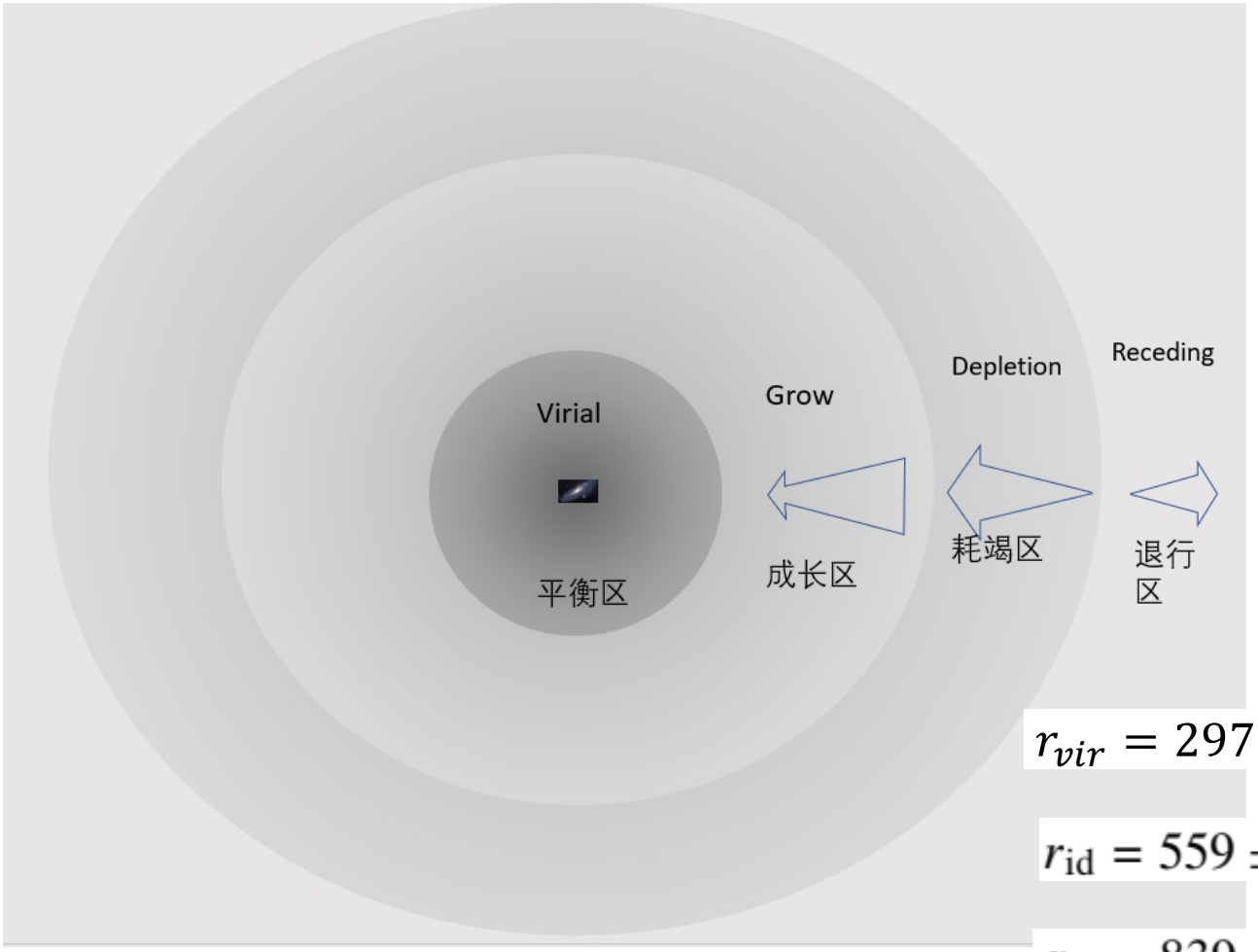
$$v_{\rm inf,max} = -46^{+24}_{-39}\,{\rm kms}^{-1}$$

$$r_{\rm id} = 559 \pm 107\,{\rm kpc}$$

$$r_{\rm ta} = 839 \pm 121\,{\rm kpc}$$

Outermost edges of MW!

Landscape of our MW



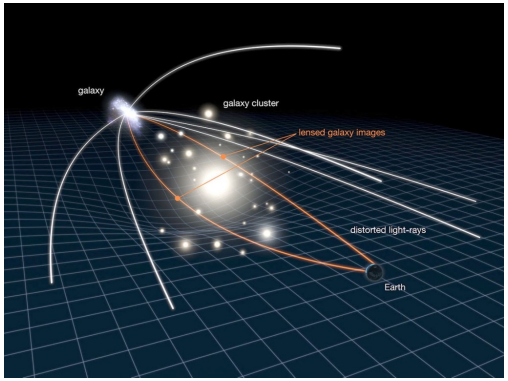
$r_{vir} = 297 \pm 16$ kpc

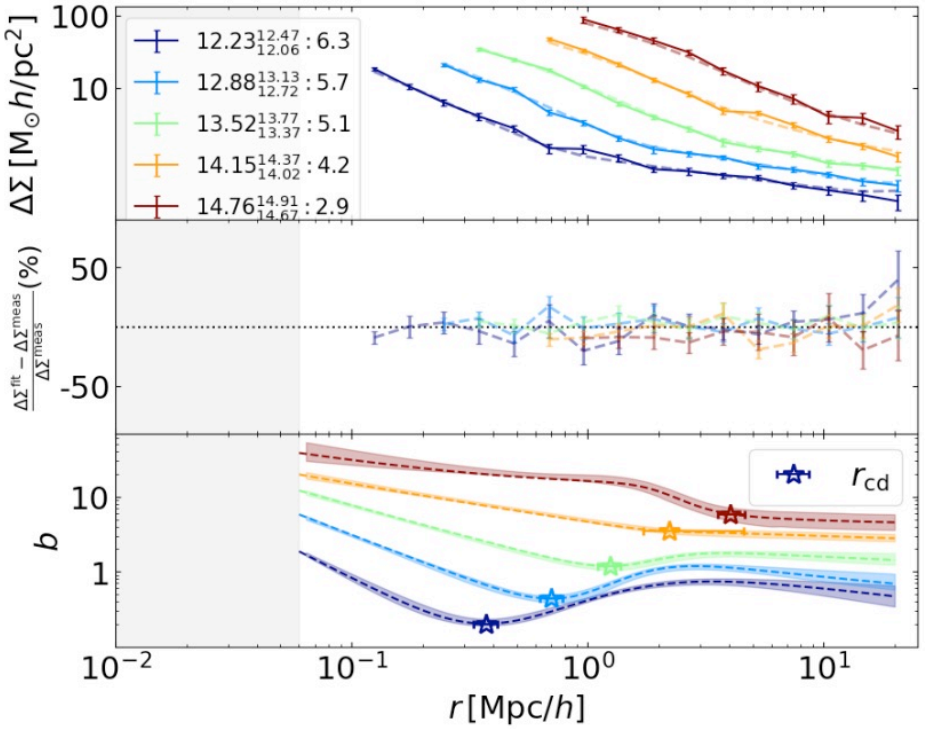
$r_{\mathrm{id}} = 559 \pm 107$kpc

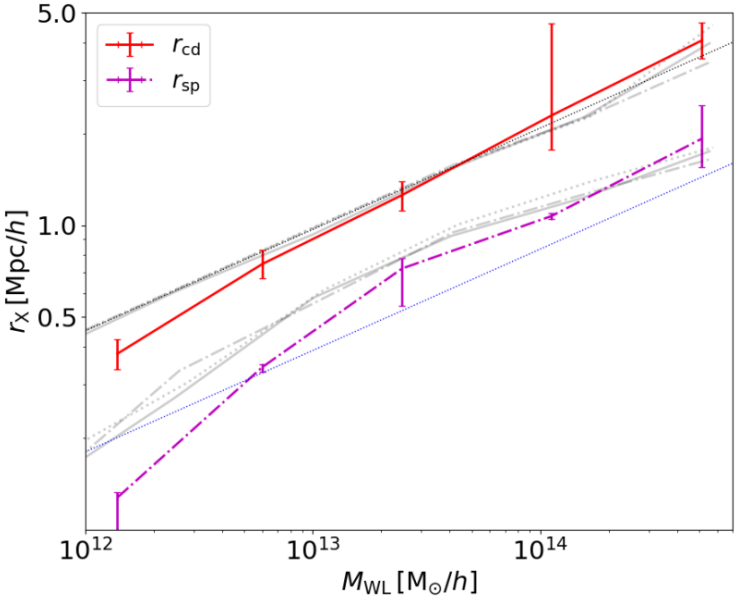
$r_{\mathrm{ta}} = 839 \pm 121$kpc.

Weak lensing measurement of the depletion radius

DECALS DR8 shear and group catalog
Measure Projected Density Filed
—Fit for 3D density/bias field

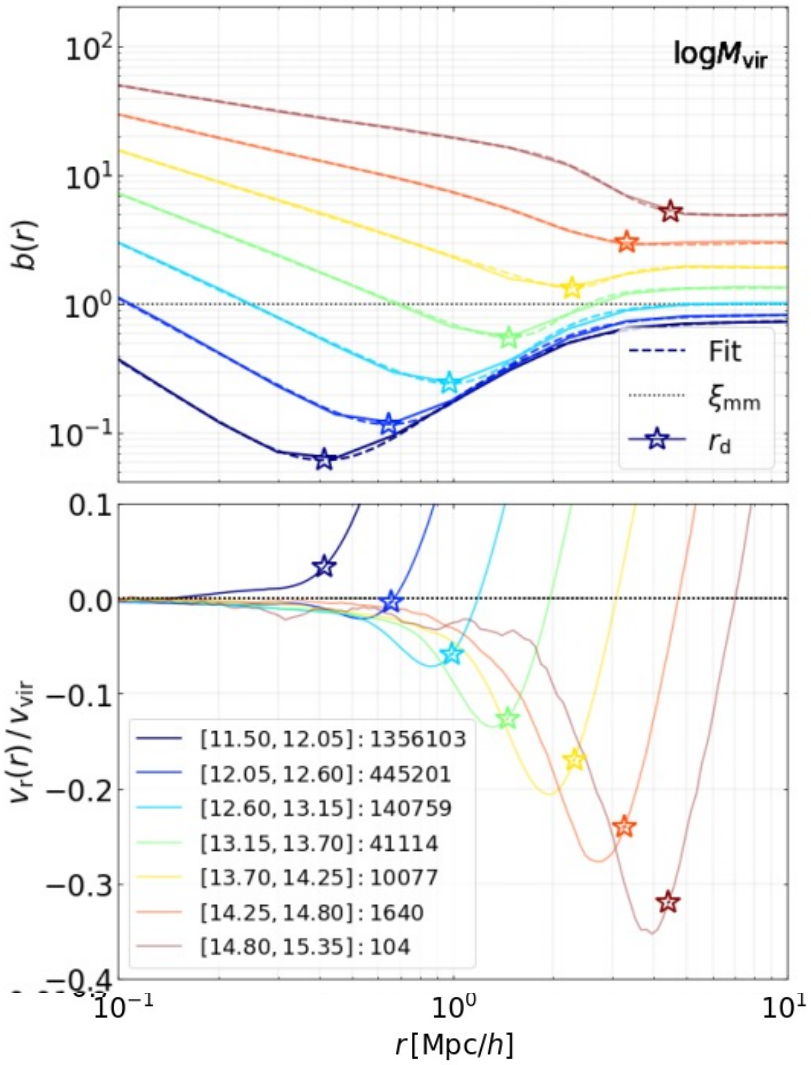




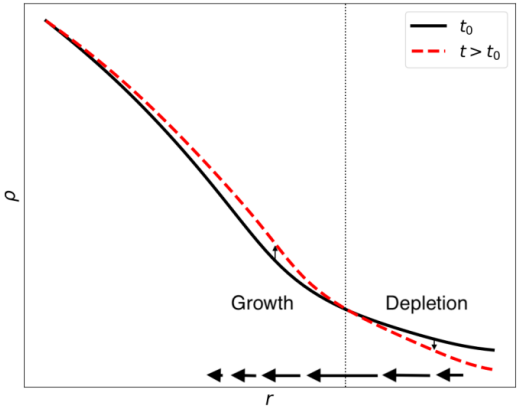


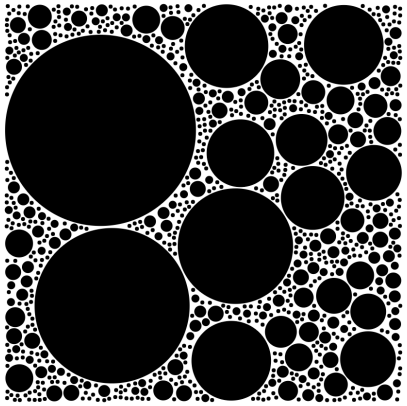
Fong, Han+, 2022., MNRAS

Summary



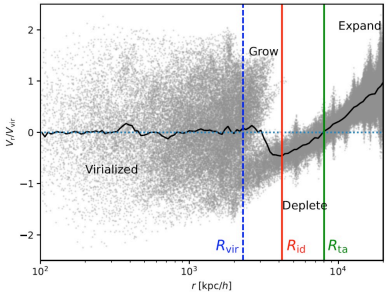
- Representation
  - Maximum infall location
  - Minimum bias location
- Meaning
  - Growth boundary
  - Depletion boundary
  - Clustering boundary
  - Exclusion boundary
- Basis for more physical and concise halo models





The extended halo model

Growing multi-layer dark matter condensation

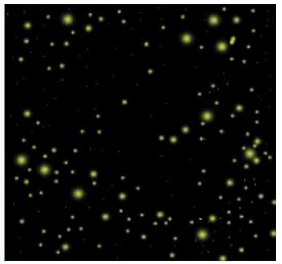


Exclusion radius (Zhou & Han 23)

Growing envelope

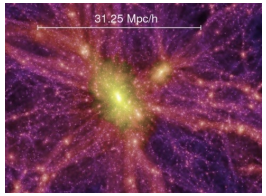
- Depletion radius (Fong &Han 20; Li & Han 21; Fong, Han+22)

Special largescale locations

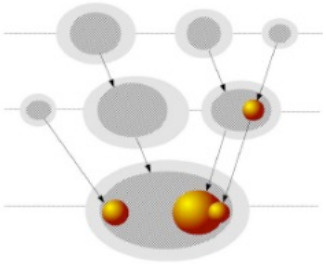


Growth radius (Gao,Han+23)

Quasi-equilibrium structure

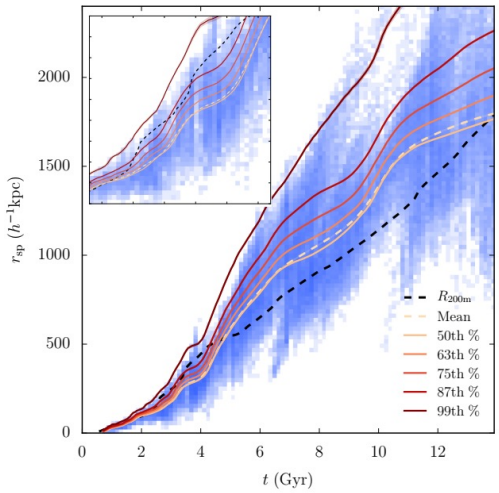


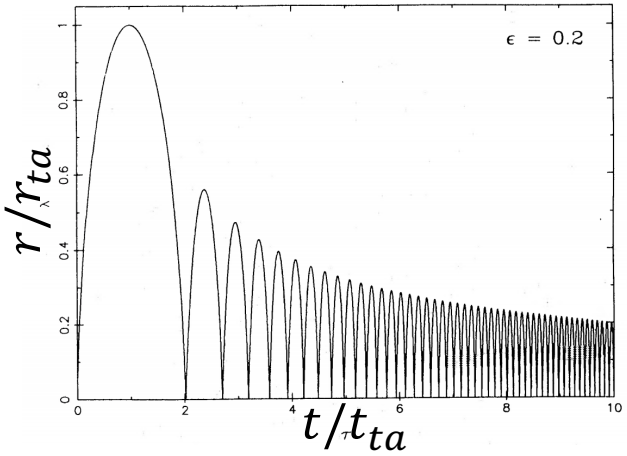
Hierarchical buildup



Connection to splashback

Diemer et al. 2017





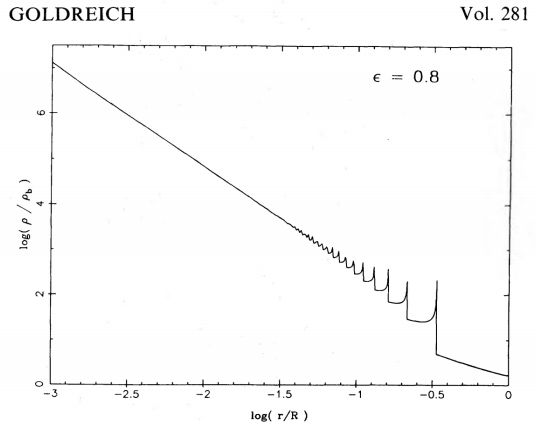


FIG. 11.—Spherical symmetry: ratio of actual to background density for $\epsilon = 0.8$.

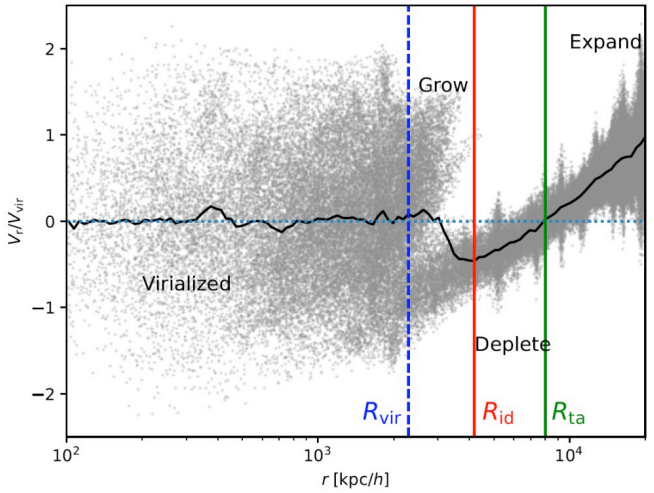
Wide spread in splashback radii of different particles

- Ambiguity in defining the splashback radius

Splashback creates density caustics

- Steepest slope location as one representative
- ~Certain percentile in splashback population

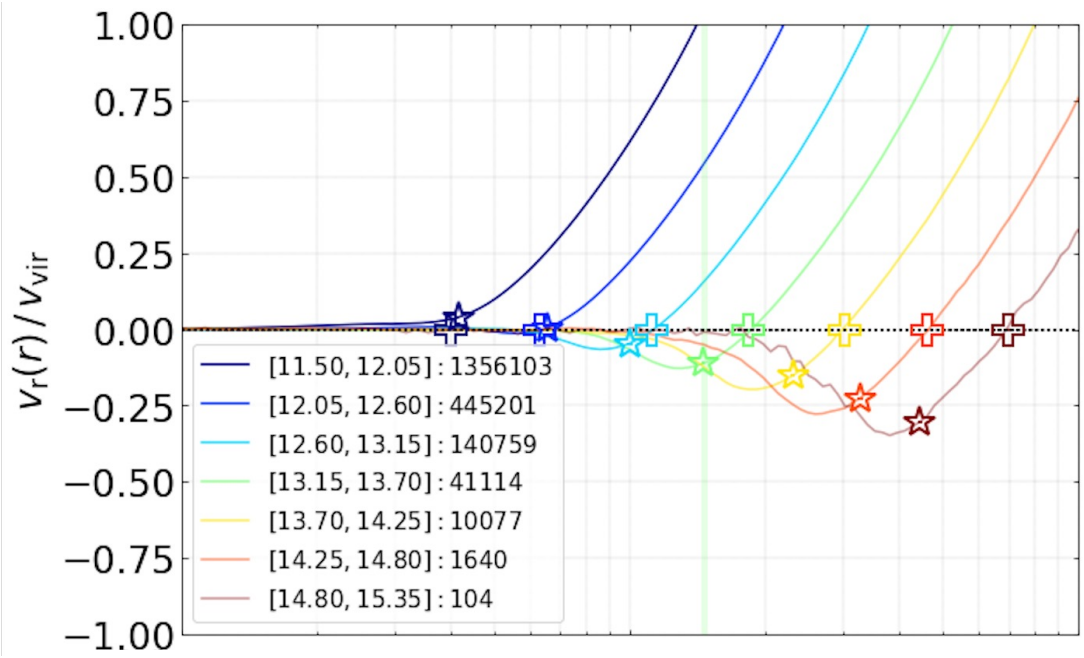
Depletion: a highly complete percentile in splashback



Depletion radius v.s. Turnaround radius

$$v_r = v_p + v_H$$

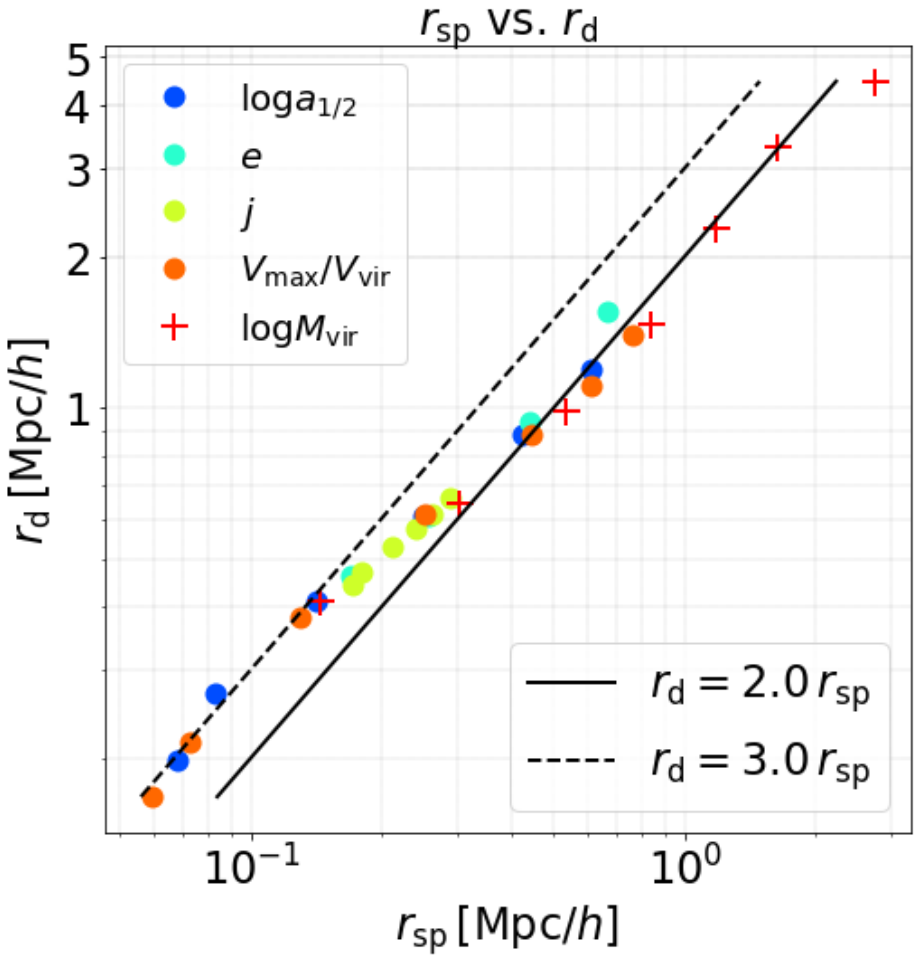
v_H = Hubble Flow



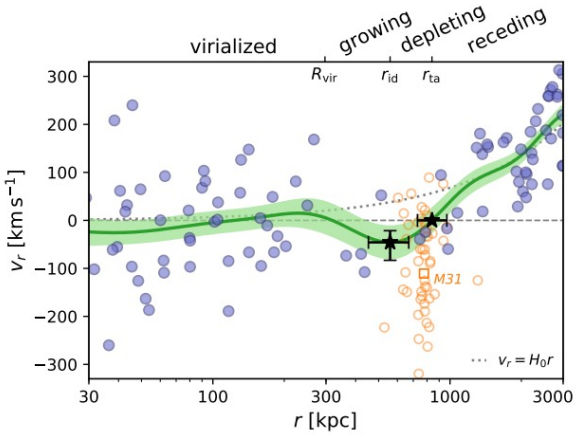
- Low mass halos: depletion radius catch up with turnaround, growth have saturated
- Turnaround radius have also reached maximum (Tanoglidis et al. 2015), so that depletion radius can catch up

Depletion radius v.s. Splashback radius

- Much (~2-3 times) larger than conventional splashback radius



Measuring the depletion radius in our MW



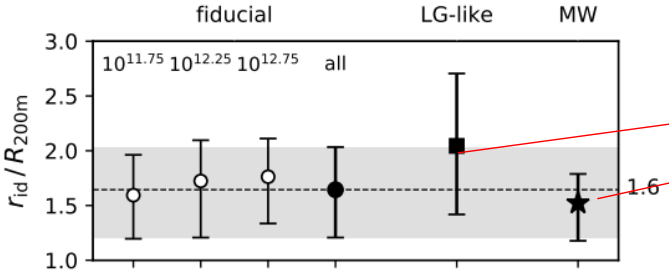
Li & Han 2021, ApJL
arXiv: [2105.04978]

- detected at ~2σ for our MW

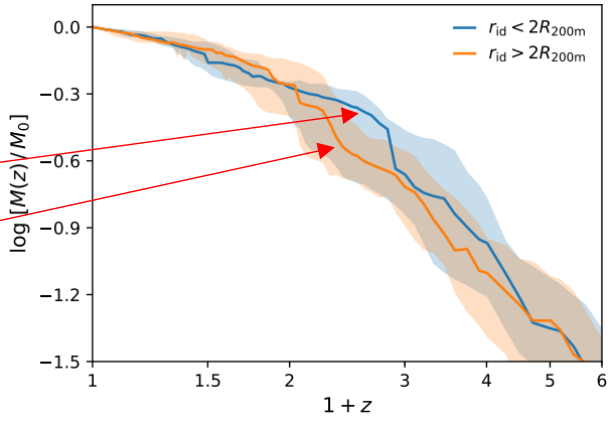
$$r_{\rm id} = 559 \pm 107 {\rm kpc}$$

$$r_{\rm ta} = 839 \pm 121 {\rm kpc}$$

- Slight inconsistency with virial radius measurement

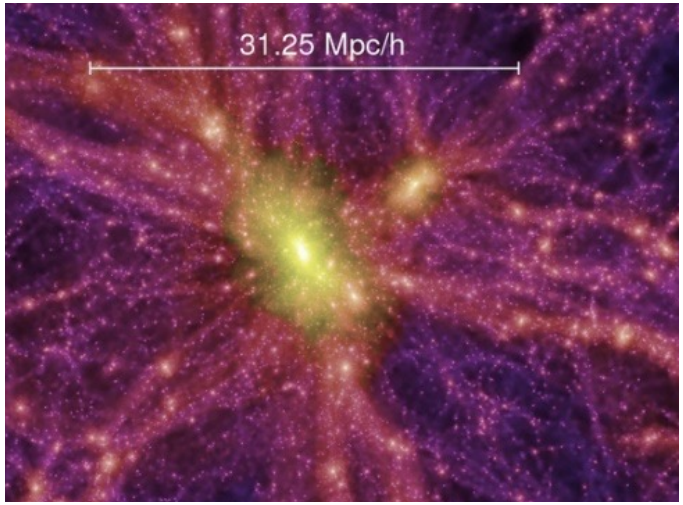


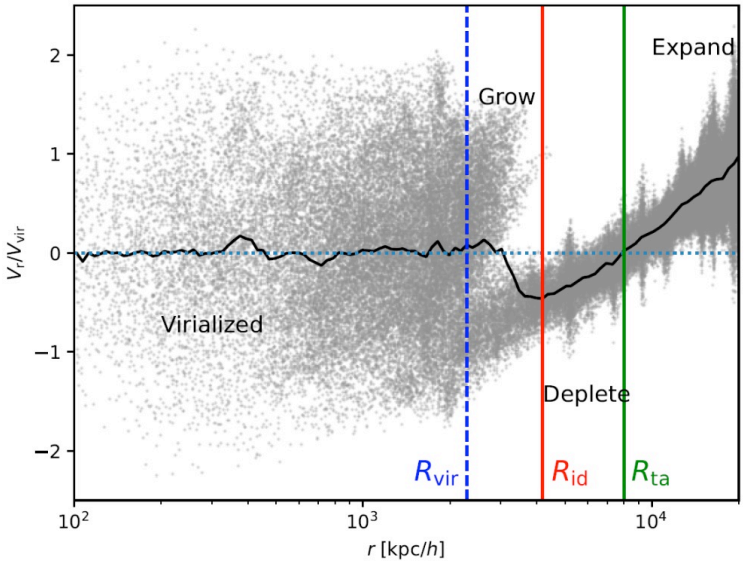
Measured depletion to virial ratio (~1.6) in slight tension with LG-analogos in Illustris



Hints for unique growth history of the MW?

The depletion radius: example



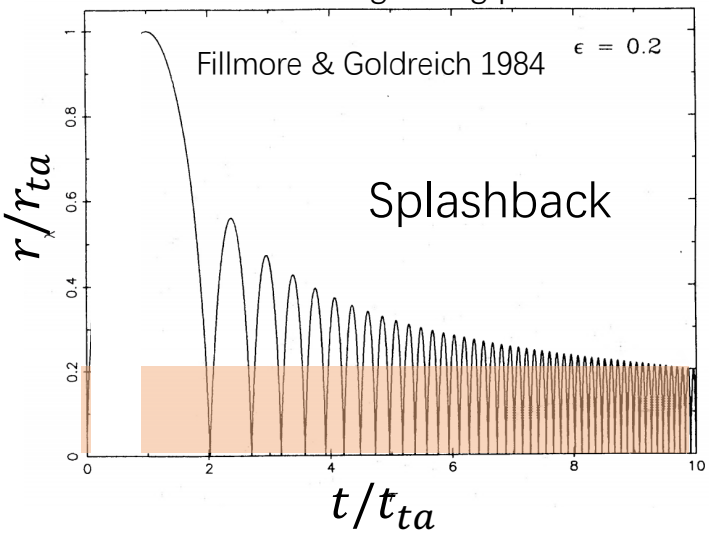


The depletion radius defines a more complete halo in both spatial coverage and physical process

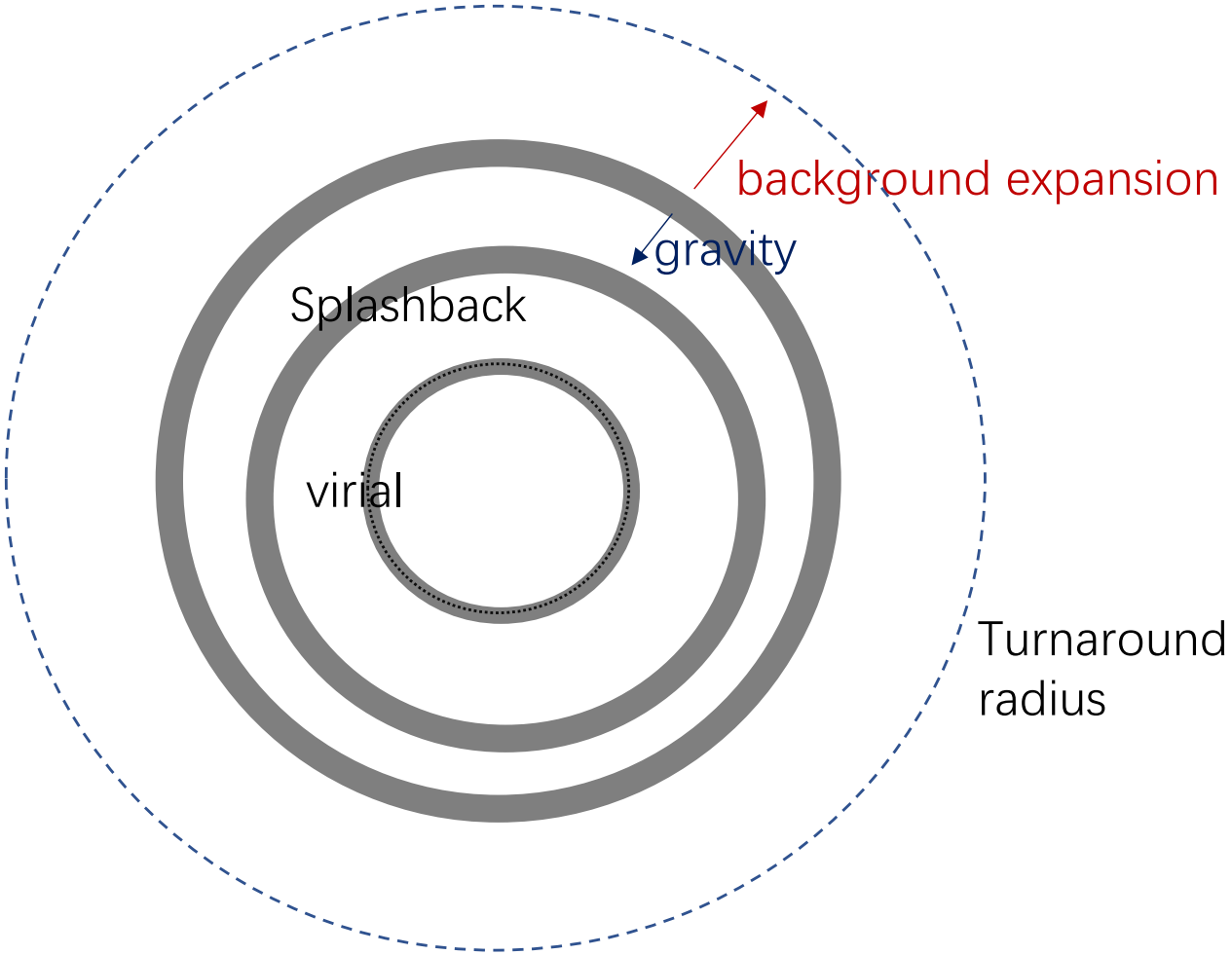
Halo Model

Evolution Probe

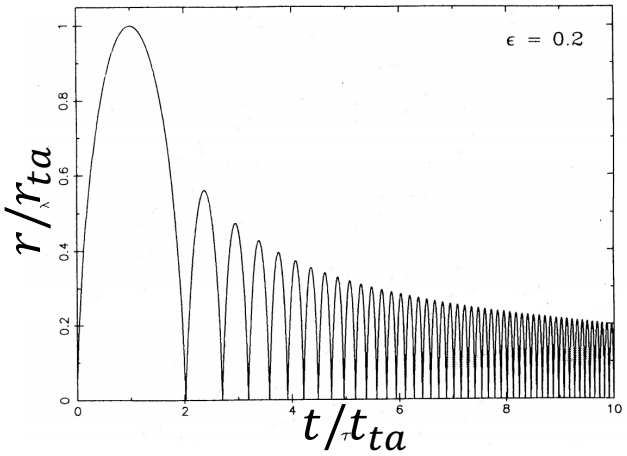
Particle orbit in a growing potential



Characterizations of halo boundary in spherical collapse



Existing characterizations of halo boundary



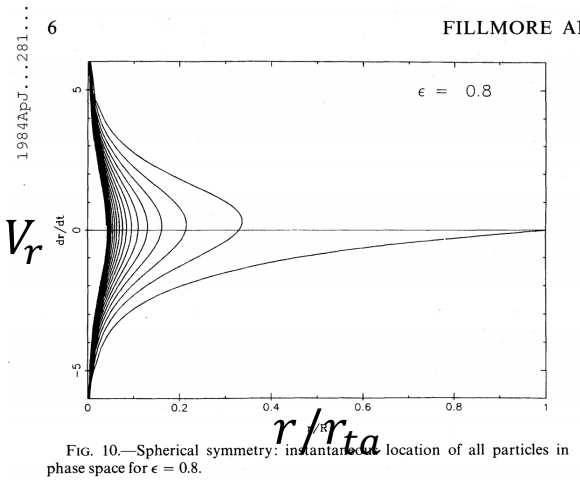


FIG. 10.—Spherical symmetry: instantaneous location of all particles in phase space for $\epsilon = 0.8$.

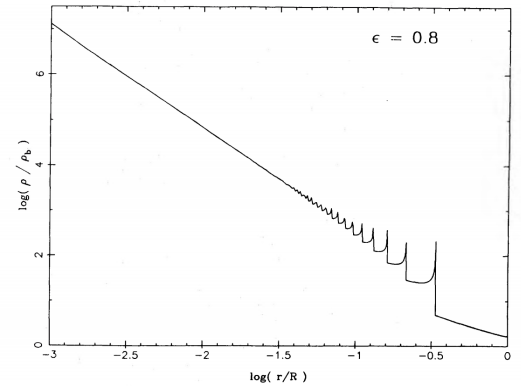
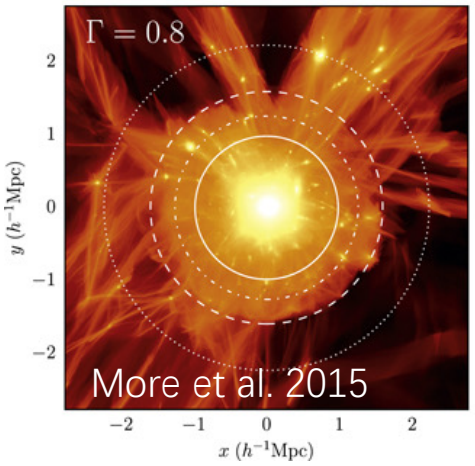
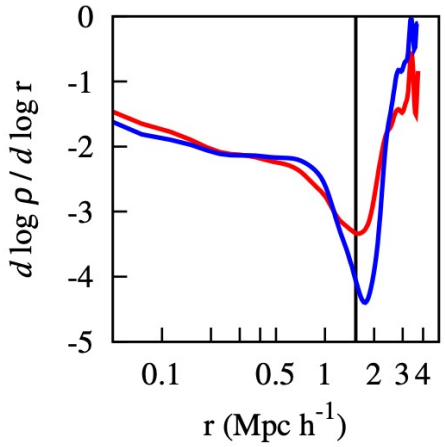


FIG. 11.—Spherical symmetry: ratio of actual to background density for $\epsilon = 0.8$.

- virial radius: equilibrium region
- turnaround radius: collapsing region
- Splashback radius: first apocenter in accreting halo





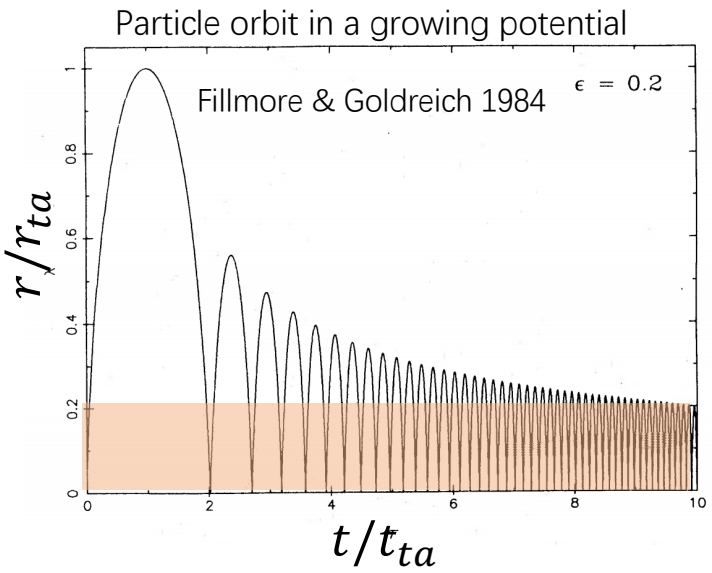
Adhikari et al. 2014

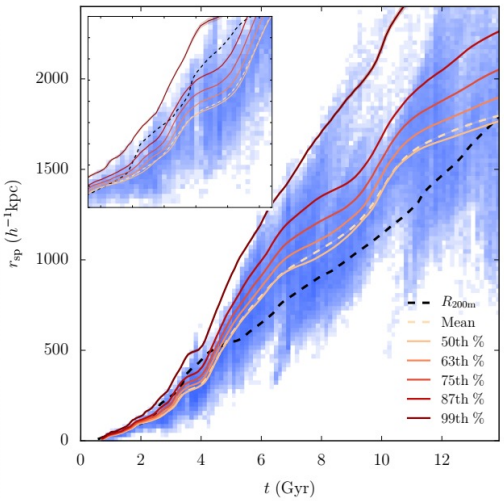
The splashback radius

- Pros:
  - A dynamical characterization of halo
  - Sensitive to halo growth rate: new window to observe halo

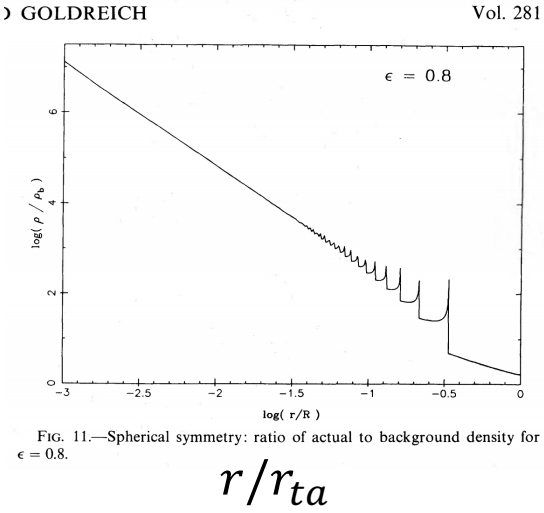
Cons:

- Wide distribution in splashback radius of different particles
  →Ambiguity in defining the splashback radius
- Density slope difficult to measure





Diemer et al. 2017



Fillmore & Goldreich 1984