The quasi-equilibrium structure of dark matter halos

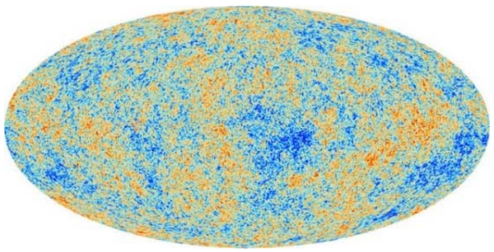
--from simulations to observations

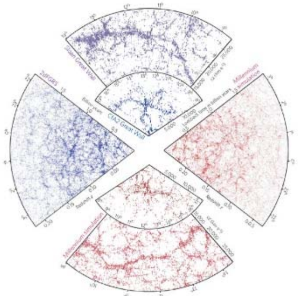
Jiaxin Han

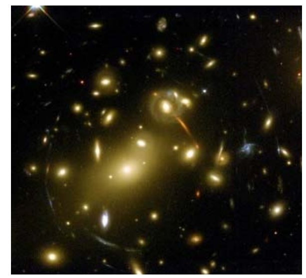
Shanghai Jiao Tong University

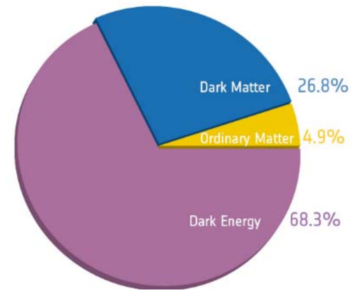
Collaborators: Wenting Wang (SJTU), Shuan Cole (Durham), Carlos Frenk (Durham), Yipeng Jing (SJTU), Zhaozhou Li (SJTU)

The cold dark matter paradigm

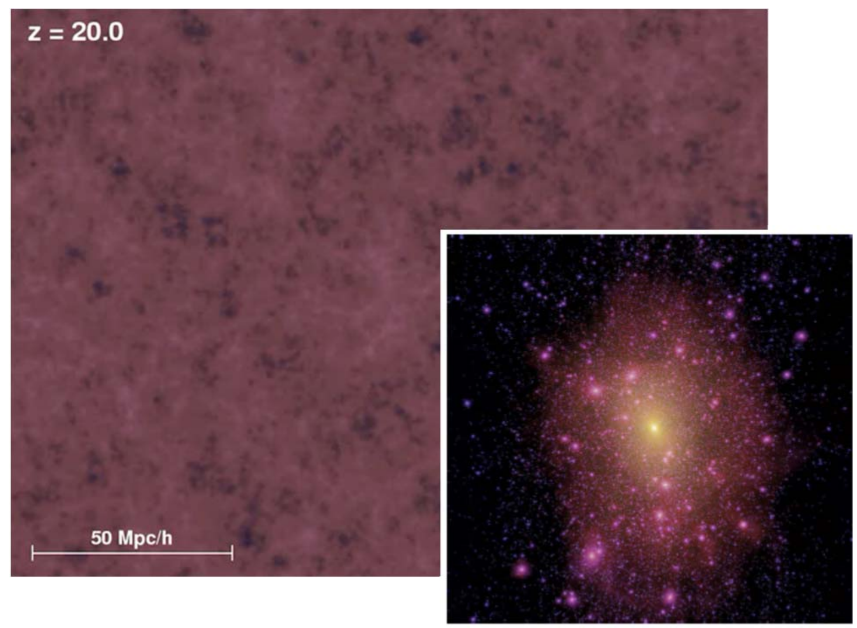






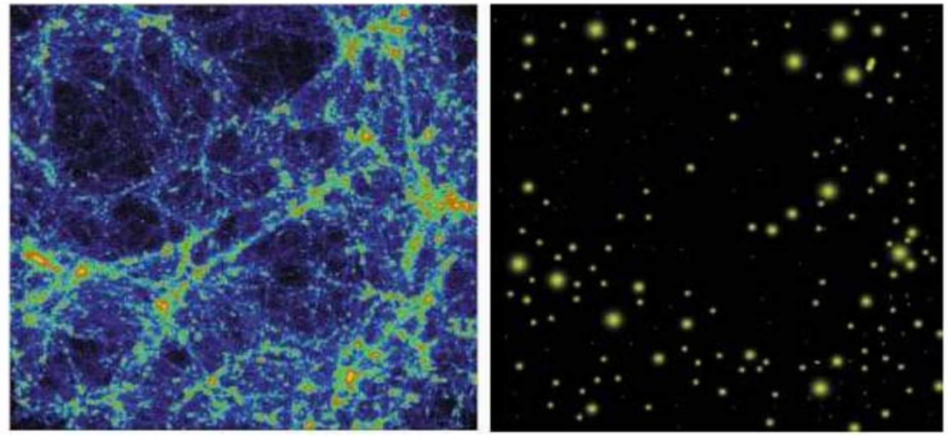


- Concordance cosmology
  - 85% cold dark matter
  - Only gravity, no other interaction
- Numerical simulation
  - Detailed prediction about the distribution of dark matter
- Dark matter halo
  - Approximately virialized objects
  - Numerical simulation←→Analytical understanding

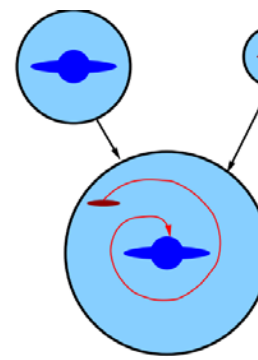


Dark Matter Halos

- Decomposing largescale structure
  - Largescale distribution of halos
  - Internal structure of halos

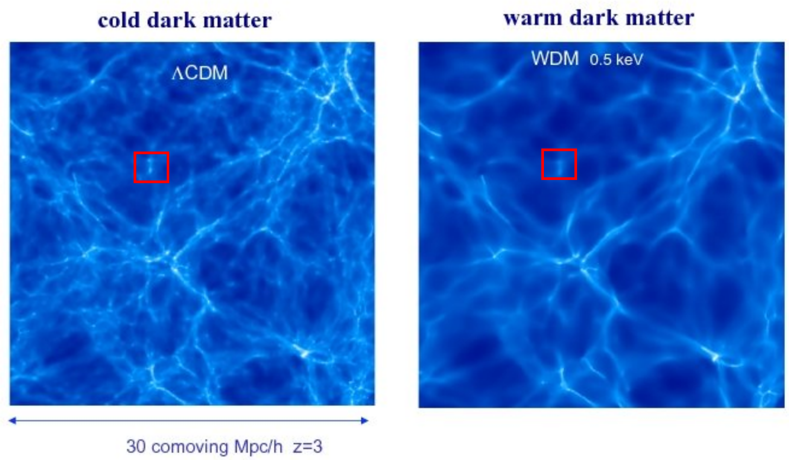


- Decomposing galaxy formation/distribution
  - Galaxies form within halos
  - Halo formation history→ galaxy formation history
  - Halo distribution→galaxy distribution

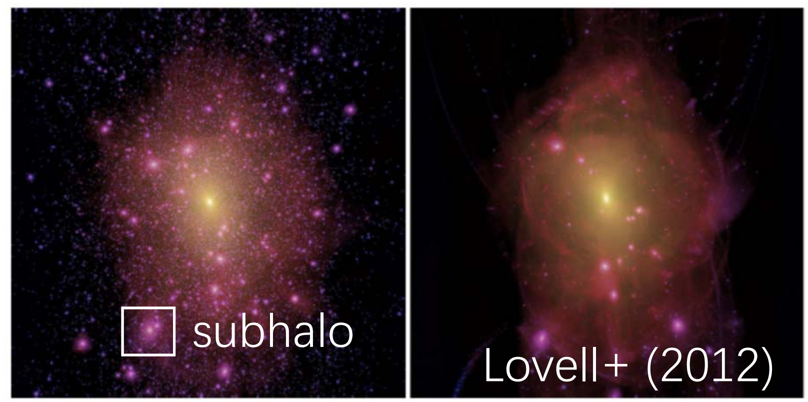


Why the halo structure?

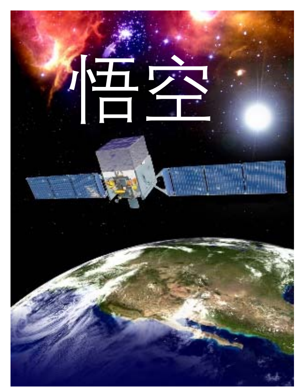
- How cold is dark matter?
  - Different small scale structure
  - Various small-scale crisis

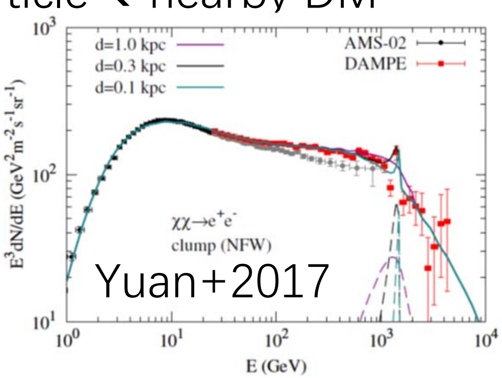


Halo



- What is dark matter?
  - catch DM particle ←nearby DM distribution
    - Direct: pha
    - Indirect: de substructu





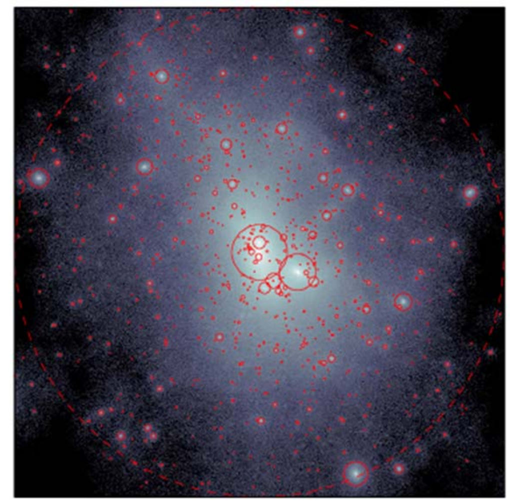
Outline

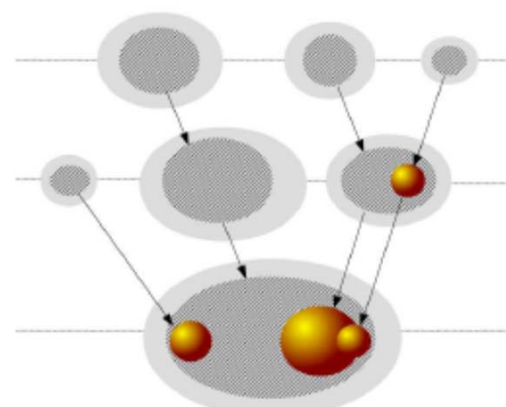
- The clumpy structure of DM halos
- The dynamical state of DM halos

Part I. the clumpy structure of dark matter halos

Subhalo Identification with HBT

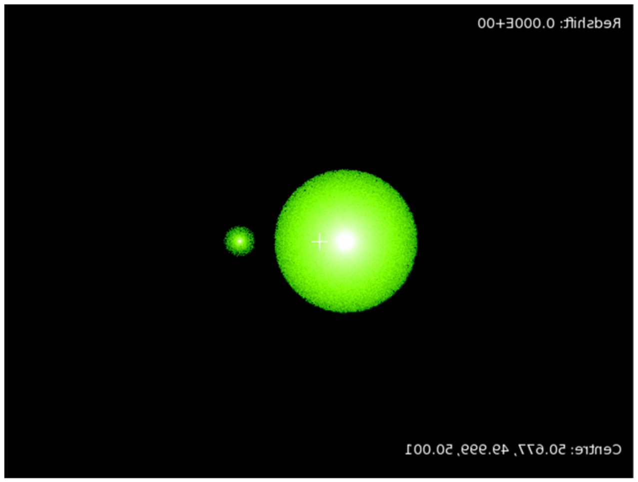
- Subhalos are blended with the high density background, difficult to resolve
- HBT: From movie to code
  - Birth->accretion->stripping->sink/disrupt

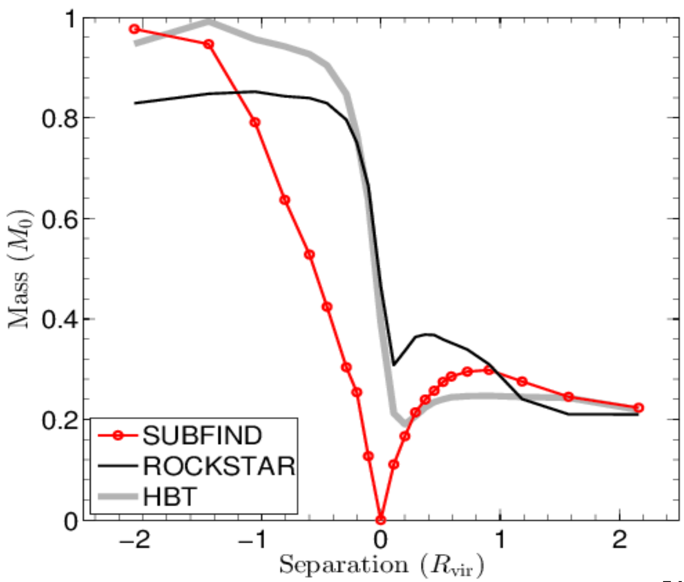




JH+13, 18

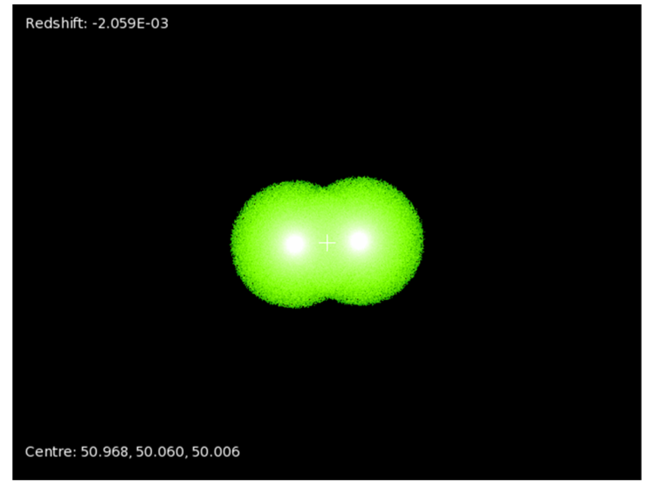
persistent

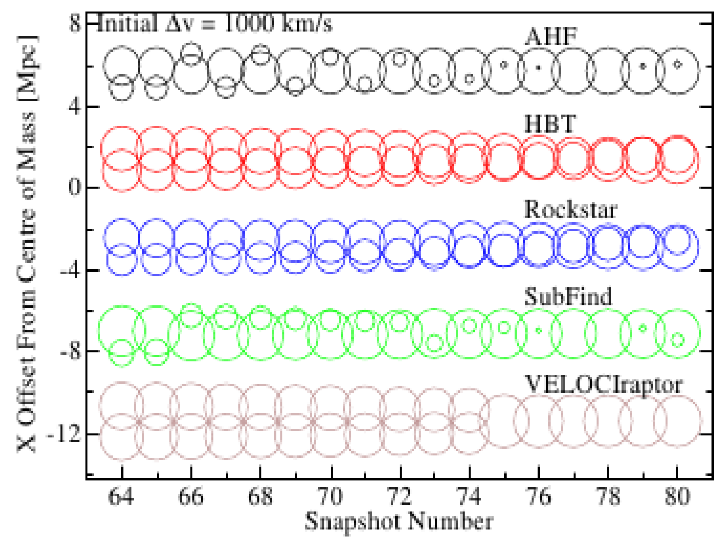




JH+ 13

consistent





Behroozi, JH+ 15

Massive subhalos—central excess

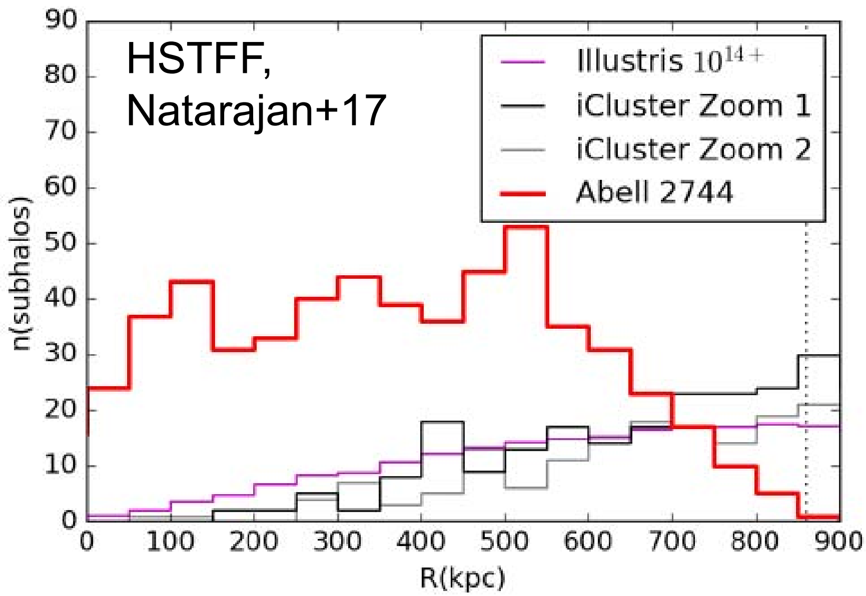
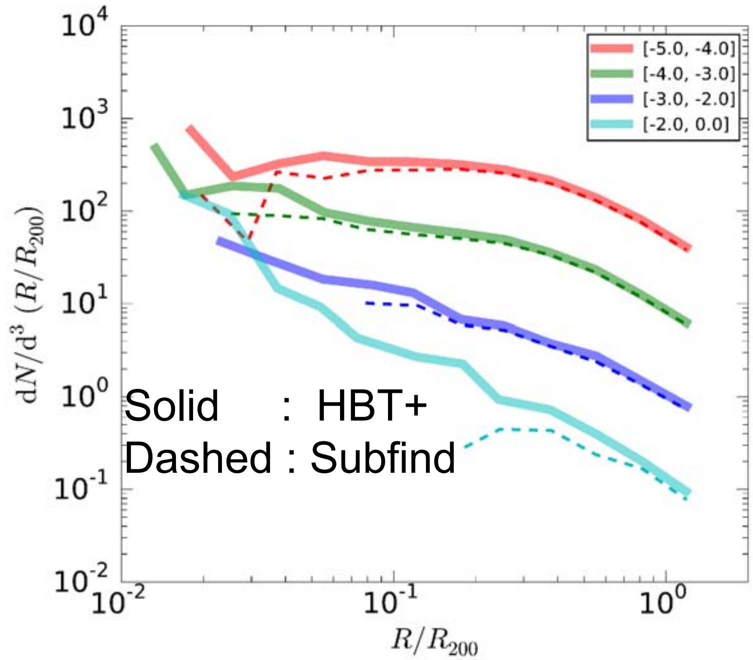
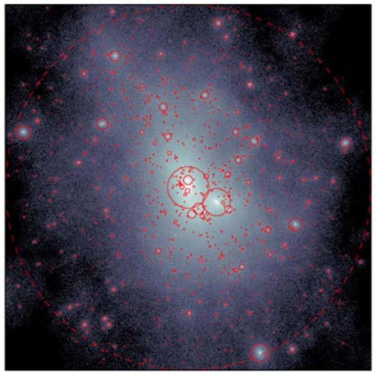


Figure 10. Radial distribution of the SHMF derived from *iCluster Zoom 1* compared to that of the lensing derived SHMF for Abell 2744 from the HST FF data (red histogram). The snapshot was selected from the full physics run of *iCluster Zoom 1*. We clearly see that galaxies in *iCluster Zoom 1* are not as centrally concentrated as Abell 2744.

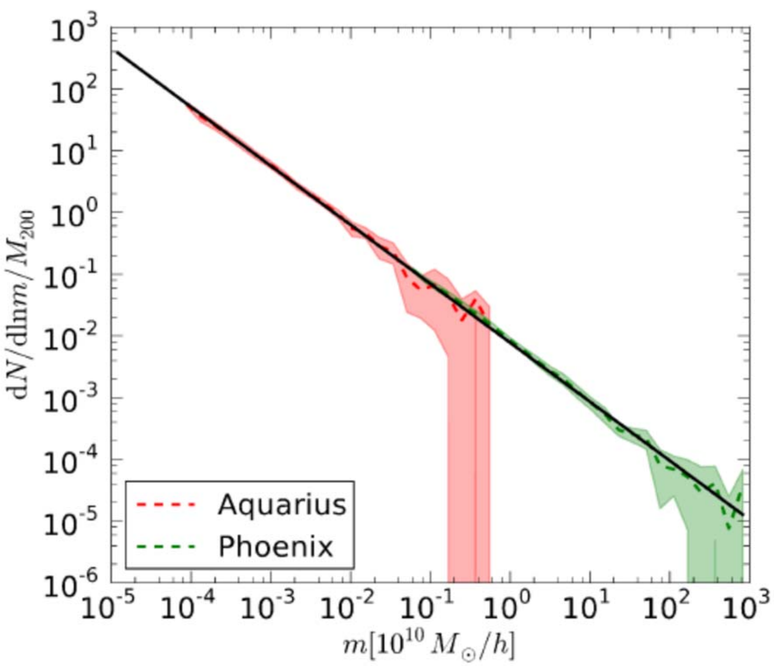


JH+2018

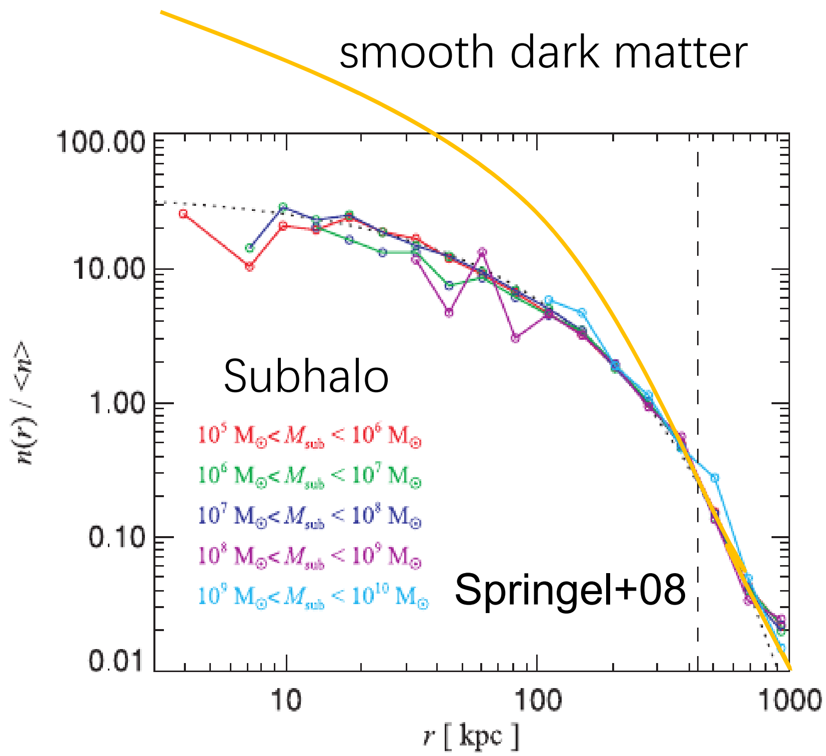
Low mass subhalos: universal distribution



$$\frac{\mathrm{d}N}{\mathrm{d}^3R\,\mathrm{d}\ln m} \propto \rho_{\mathrm{sub}}(R)m^{-\alpha}$$



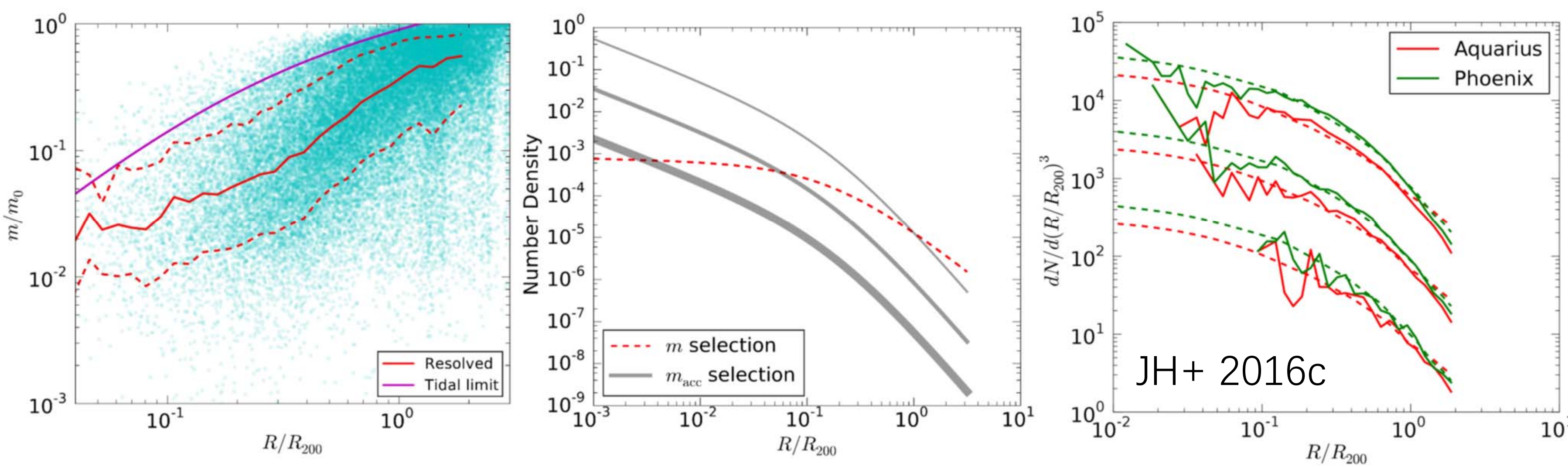
$\rho_{\mathrm{sub}} \neq \rho_{\mathrm{NFW}}$



Low mass subhalo: unified model

- Subhalo as a dark matter particle with an evolving mass
  - unbiased accretion: same dynamics as DM particles→distribution following DM
    - Abundance
    - Spatial distribution
  - mass evolution: radial selection
    - Flattened profile
    - conserved mass function shape

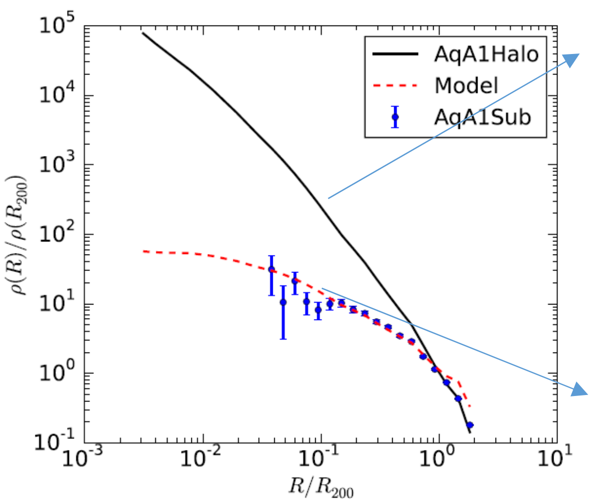
$$\frac{\mathrm{d}N(m,R)}{\mathrm{d}\ln m \mathrm{d}^3 R} = \int \frac{\mathrm{d}N(m, m_{\rm acc}, R)}{\mathrm{d}\ln m \mathrm{d}^3 R \mathrm{d}m_{\rm acc}} \mathrm{d}m_{\rm acc}$$
$$= A_{\rm acc} B f_{\rm s} e^{\sigma^2 \alpha^2/2} m^\alpha \bar{\mu}(R)^{-\alpha} \rho(R)$$

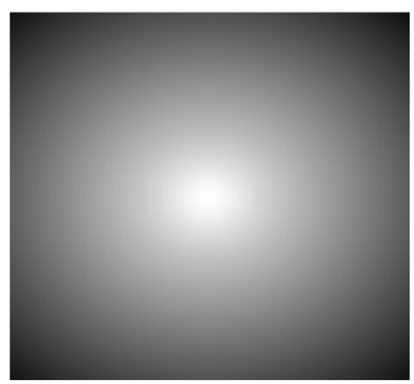


Application of subhalo model

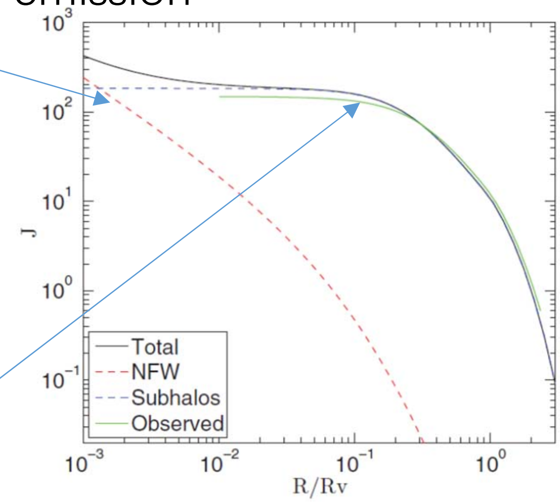
- Gamma-ray detection of annihilating DM
  - Sensitive to density clumps → subhalos

$$\boldsymbol{I} \propto \int_{l.o.s.} \boldsymbol{\rho}^2 \mathrm{d}\boldsymbol{l}$$



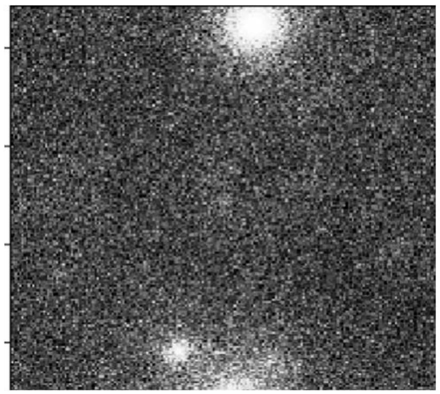


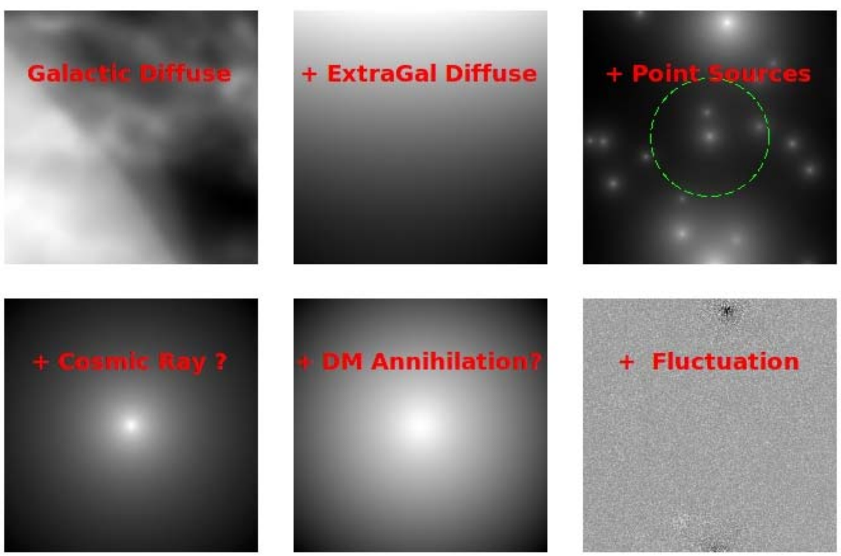
Subhalo dominated emission



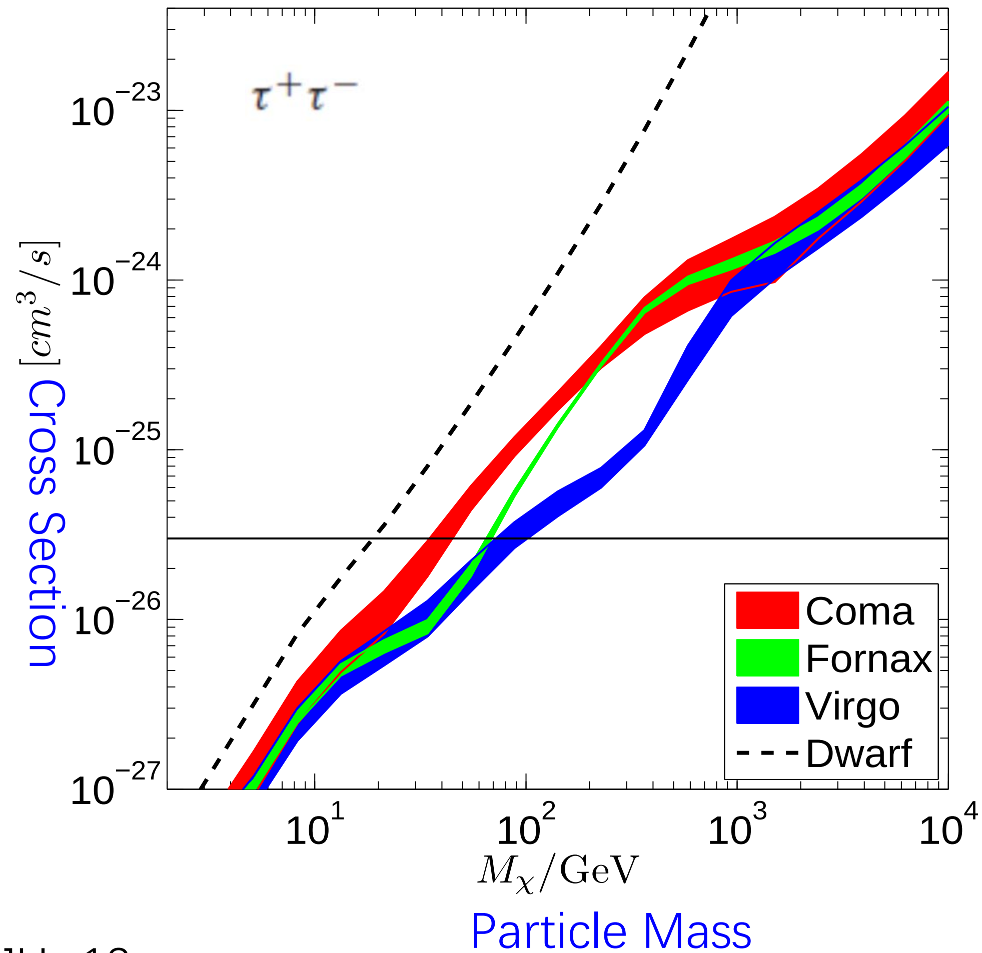
Application of subhalo model: indirect DM detection

Virgo Cluster





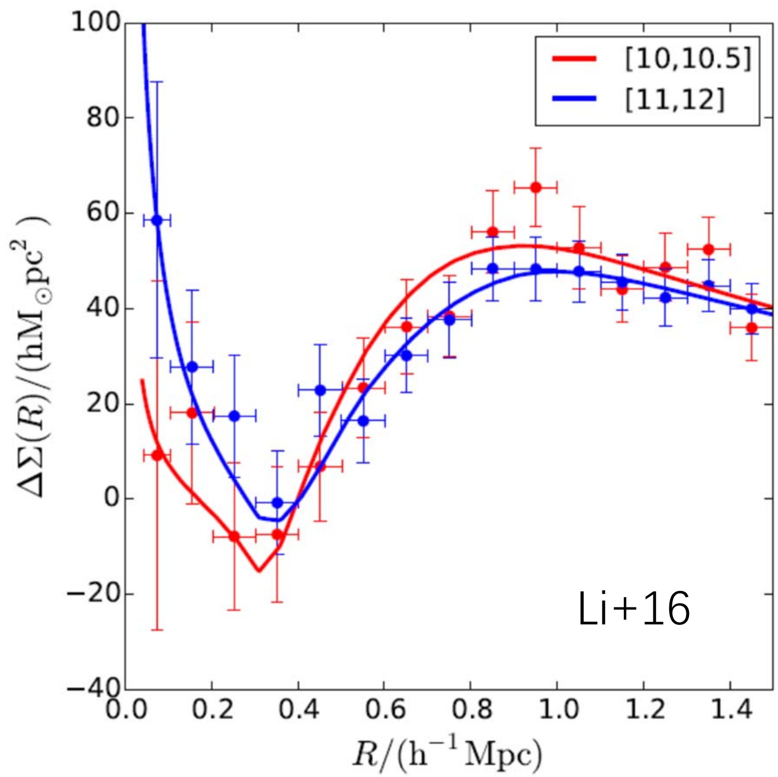
Strongest constraint on DM particle property

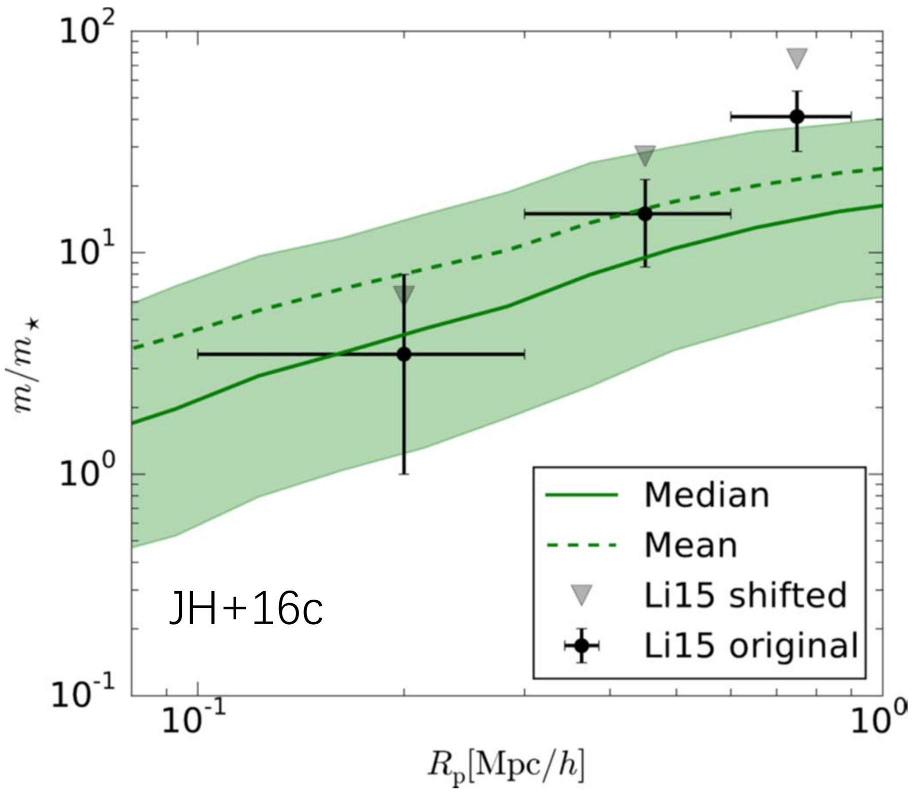


JH+13

Application of subhalo model: weak lensing interpretation

- Lensing directly probes the spatial and mass distribution of subhalos

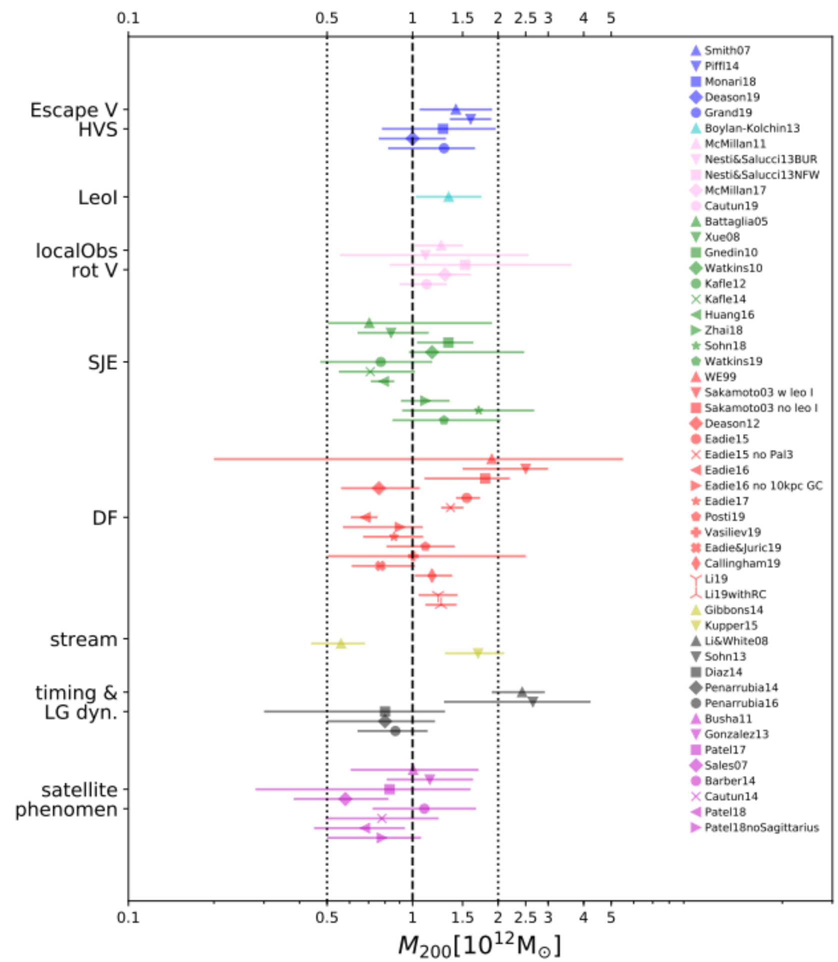




Part II: The dynamical state of DM halos

MW halo mass

- Why we haven't reach a convergence in MW mass measurements?
  - Is the MW halo in a steady-state?



Wang, JH+ 2015, 2019

Steady-state methods

- time independent tracer distribution function (DF)

$$P_\psi(\vec{x},\vec{v}) \Rightarrow \psi$$

  - Jeans theorem:

$$\frac{\partial P}{\partial t} = 0 \Leftrightarrow P(\vec{x},\vec{v}) = f(J_1, J_2, J_3 ...)$$

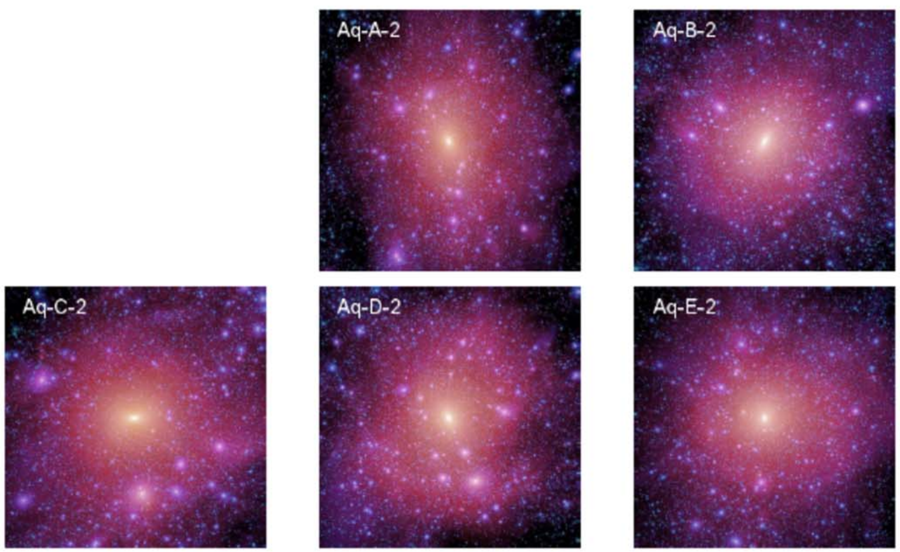
    - $J_1, J_2, J_3...$: integrals of motion
    - additional assumptions about functional form required

Steady state methods: conventional approach

- Constructing (guessing) a DF function

$$\left.\begin{aligned} &f(E,L) = L^{-2\beta}F(E) \\ &\text{NFW potential } (M, c) \\ &\int f(E,L)d^3v = \rho(r) \end{aligned}\right\} \Rightarrow$$

$$P(r, v_r, v_t | \rho_s, r_s, \beta, \alpha, \gamma, r_0) = f(E,L) = \frac{r_s^{-\alpha-\gamma} J^{-2\beta}}{2^{3/2-\beta}\pi^{3/2} v_s^2 \Gamma(\beta+1/2)\Gamma(1-\beta)} \times \int_{R_{max}}^{R_{max,\epsilon}} dR(\epsilon - \phi(R))^{\beta-1/2} \times$$
$$\left\{ \frac{(2\beta+1)R^{2\beta}\left(\frac{R}{1+R} - \ln(1+R)\right) - \left[\frac{1}{(1+R)^2} - \frac{1}{1+R}\right]R^{2\beta+1}}{\left[\frac{R}{1+R} - \ln(1+R)\right]^2} \times \frac{(2\beta-\alpha)\left(\frac{R}{r_0}\right)^{\alpha} r_s^{-\gamma} + (2\beta-\gamma)\left(\frac{R}{r_0}\right)^{\gamma} r_s^{-\alpha}}{\left[\left(\frac{R}{r_0}\right)^{\alpha} r_s^{-\gamma} + \left(\frac{R}{r_0}\right)^{\gamma} r_s^{-\alpha}\right]^2} + \right.$$
$$\frac{R^{2\beta+1}}{\left[\frac{R}{1+R} - \ln(1+R)\right]\left[\left(\frac{R}{r_0}\right)^{\alpha} r_s^{-\gamma} + \left(\frac{R}{r_0}\right)^{\gamma} r_s^{-\alpha}\right]^2} \times \left[(2\beta-\alpha)r_s^{-\alpha-\gamma}\left(\frac{\alpha}{r_0} - \frac{2\gamma}{r_0}\right)\left(\frac{R}{r_0}\right)^{\alpha+\gamma-1} + \right.$$
$$\left.\left.(2\beta-\gamma)r_s^{-\alpha-\gamma}\left(\frac{\gamma}{r_0} - \frac{2\alpha}{r_0}\right)\left(\frac{R}{r_0}\right)^{\alpha+\gamma-1} - (2\beta-\alpha)r_s^{-2\gamma}\frac{\alpha}{r_0}\left(\frac{R}{r_0}\right)^{2\alpha-1} - (2\beta-\gamma)r_s^{-2\alpha}\frac{\gamma}{r_0}\left(\frac{R}{r_0}\right)^{2\gamma-1}\right]\right\}$$



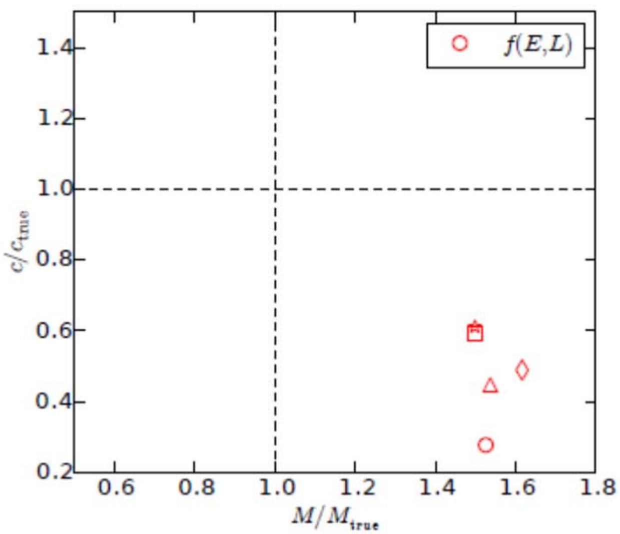
Fit $P_\psi(x, v)$ to Aquarius halos

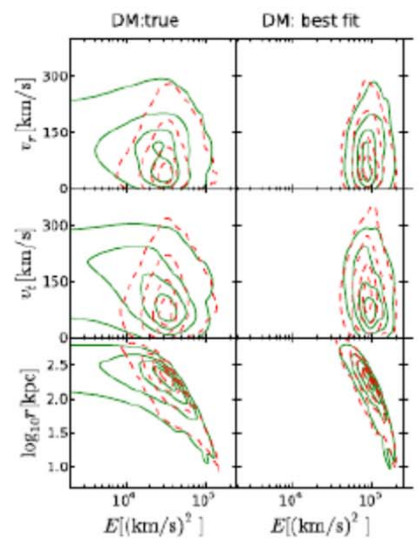
(Subhalos removed)

Wang, JH+ 2015

Testing a conventional DF method

$$\left.\begin{array}{l} f(E,L) = L^{-2\beta}F(E) \\ \text{NFW potential } (M,c) \\ \int f(E,L)d^3v = \rho(r) \end{array}\right\} \Rightarrow P(x,v|\psi(M,c))$$





The fits are biased!

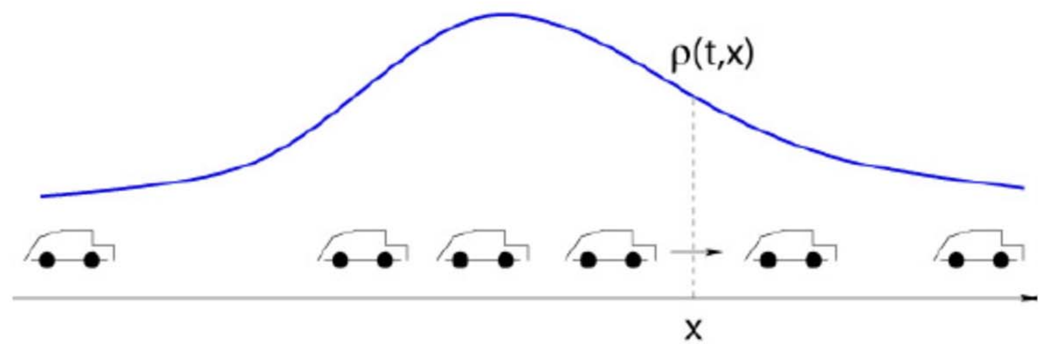
- fail to describe the loosely-bound particles

Wang, JH+ 2015

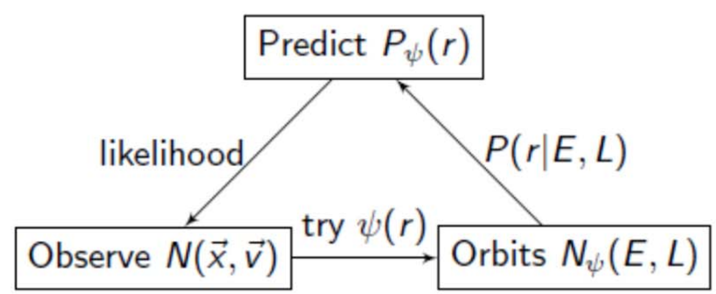
oPDF: a minimal assumption method

Steady-state solution to collisionless Boltzmann equation:

$$dP(x|\mathrm{orbit}) \propto dt$$

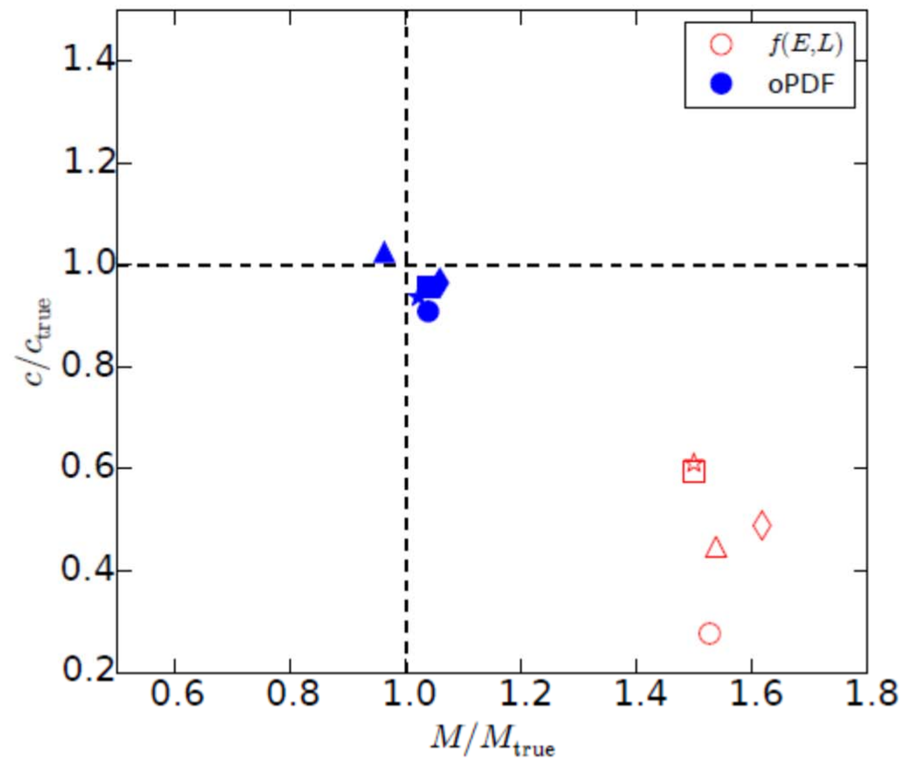


$$dP(r|E,L) = \frac{dr}{v_r(E,L,r)T(E,L)}$$



JH+2016a

oPDF: Fits to Aquarius haloes

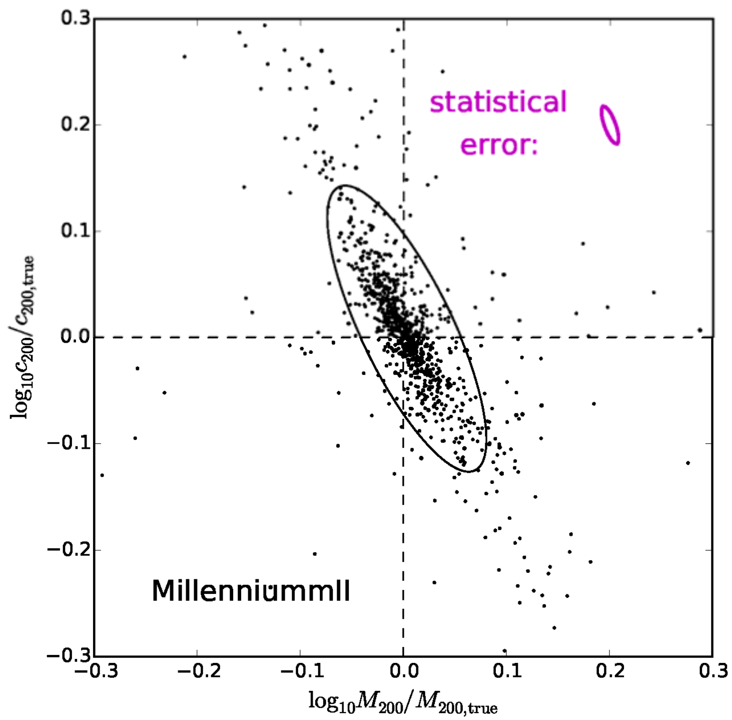


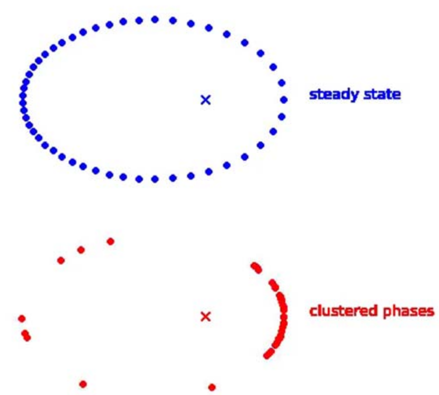
JH+2016b

- no global systematic bias using oPDF: main source of bias removed
- still significant and *correlated* individual biases?

oPDF: fits to many halos

- Significant irreducible bias
  - limiting precision $\sigma_M \sim 0.1$ dex (20%) for DM
  - Deviations from steady-state

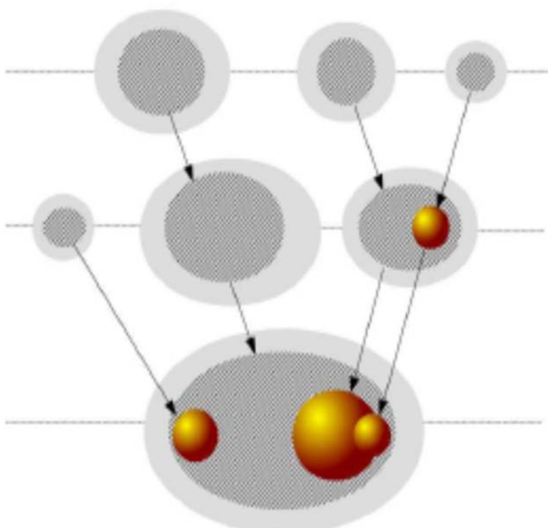




Wang, JH+ 2017

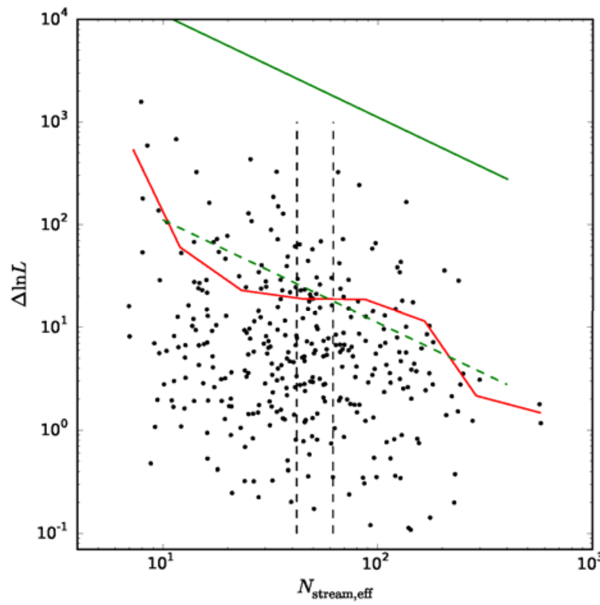
What determines the bias

- MAH-> stream->dynamics->bias



$$N_{\rm stream,eff} = \frac{(\sum n_i)^2}{\sum n_i^2} \in [1, m]$$

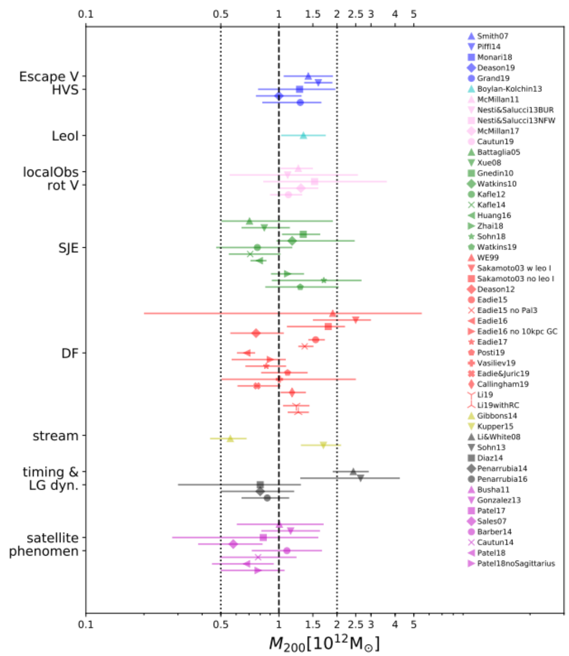
$$\Delta \ln L \sim \frac{N}{N_{\rm eff}} \chi^2(2)$$

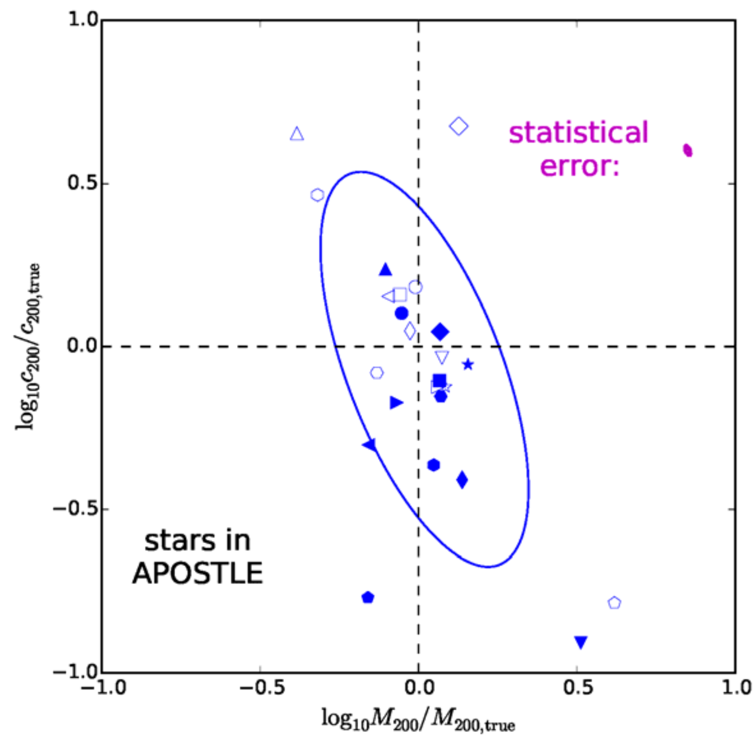


Wang, JH+ 2017

oPDF: fits to stars

- Stars deviate more from steady state
  - 0.3 dex scatter in mass (x2)
  - Comparable to the x5~=2x2 observational scatter!

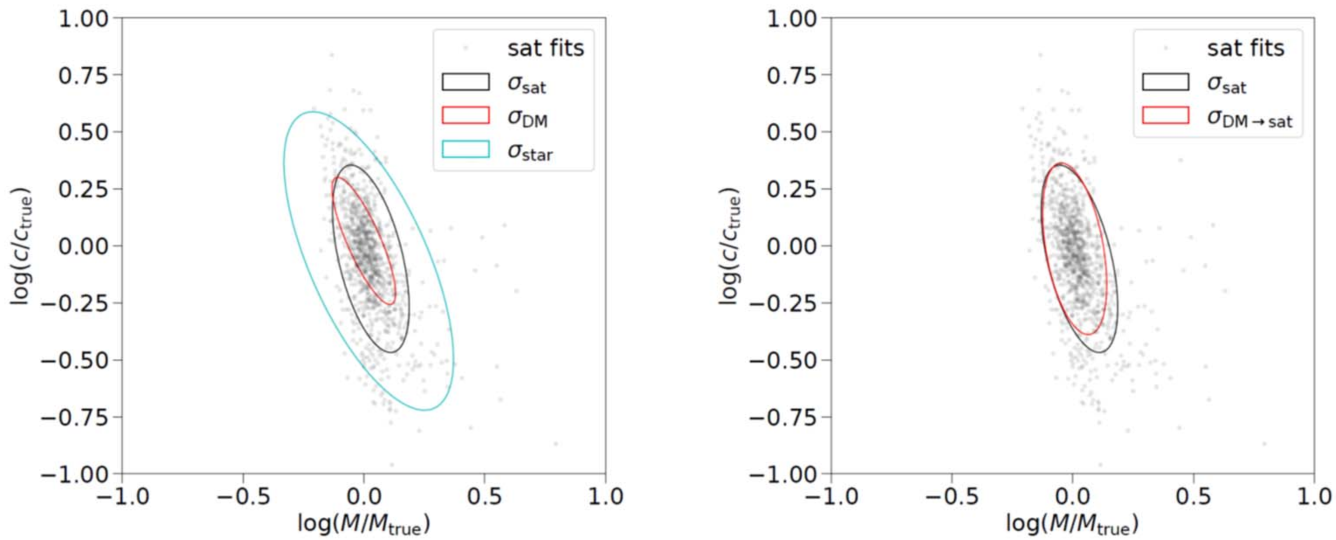




Wang, JH+ 17

Same result from Jeans Eq. (Wang, JH+18)

Improving the limiting precision: Satellites as better tracers



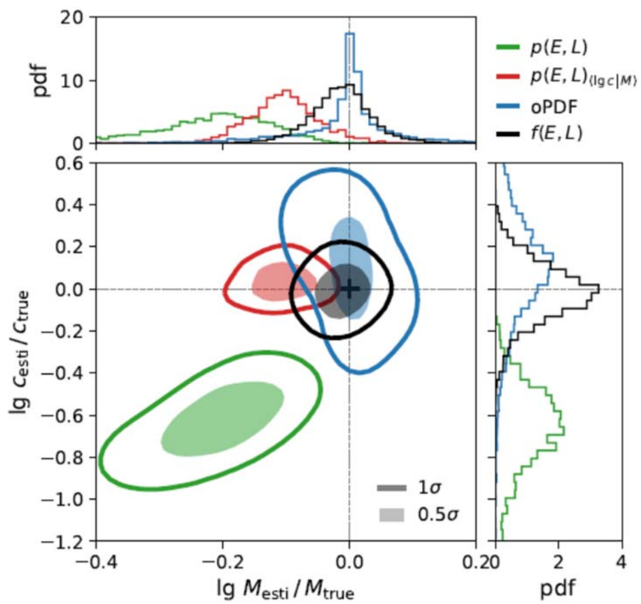
- Satellites are better tracers than stars
- Dynamical state of satellite tracers are close to DM

JH+. 2019

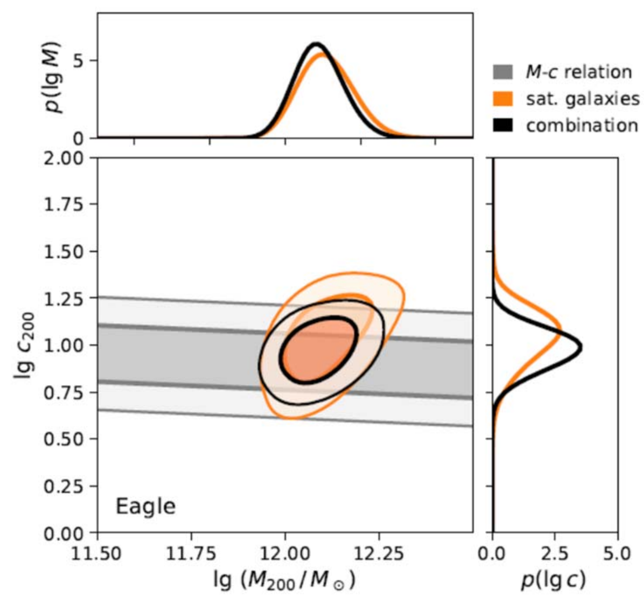
Improving the limiting precision: using non-steady-state information

$$f(\boldsymbol{r}, \boldsymbol{v}) = \frac{|v_r|}{8\pi^2 L} p(r|E, L) p(E, L),$$

Mock tests



Observations of 28 Satellites



$M = 1.23^{+0.21}_{-0.18} \times 10^{12} M_\odot$ $\quad c = 9.4^{+2.8}_{-2.1}$

Li, Qian, JH+ 2019a

Li, Qian, JH+ 2019b

Summary

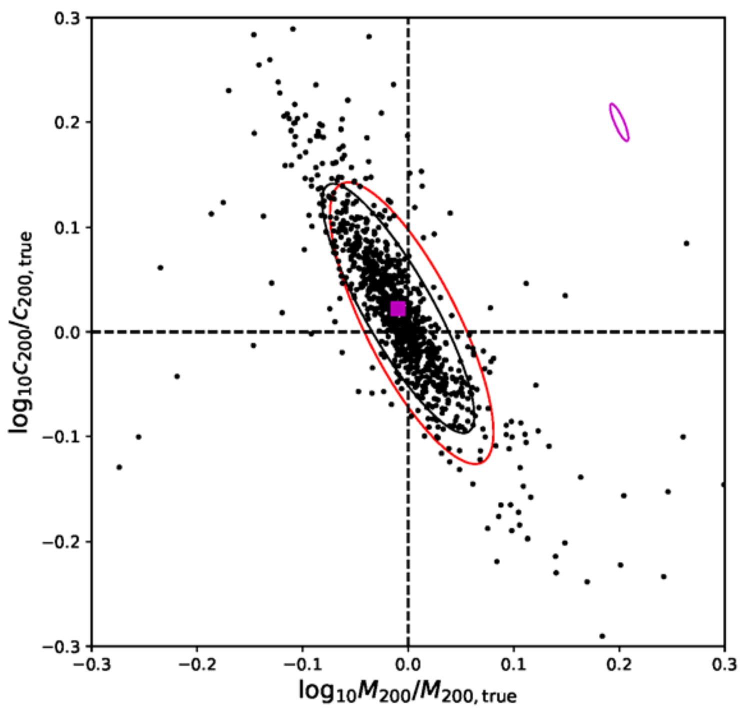
- DM halo is clumpy
  - Hierarchical merging leads to formation of subhalos
  - This formation mechanism can be utilized to identify and model subhalos in simulations
  - Subhalos play a vital role in the observational signals of DM, including indirect detection and lensing
- The smooth halo is not in a steady-state
  - The phase-space structure is too complex to guess its distribution function
  - Deviations from steady-state lead to an intrinsic limiting precision for pure steady-state methods
  - The precision can be improved by using satellite dynamics, and going beyond steady-state

Alternative method: Jeans equation

- Momentum equation of steady-state DF
  - Dynamical pressure=Gravity

$$\frac{1}{\rho_*}\frac{\mathrm{d}(\rho_*\sigma_{r,*}^2)}{\mathrm{d}r}+\frac{2\beta\sigma_{r,*}^2}{r}=-\frac{\mathrm{d}\phi}{\mathrm{d}r}$$

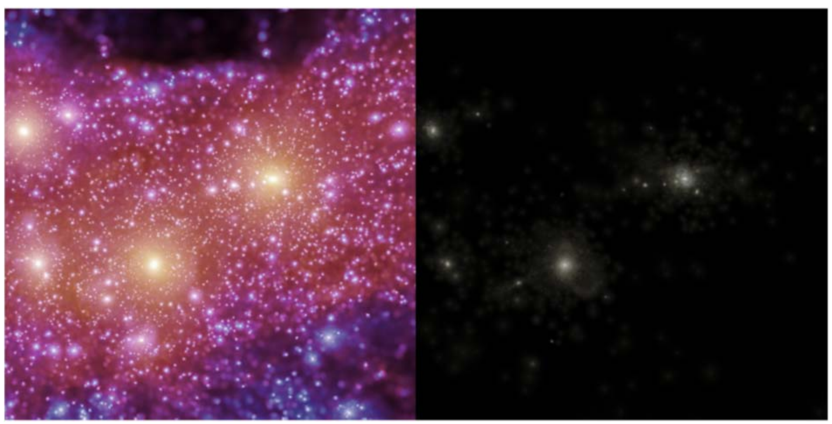
  - Steady-state and spherical assumptions alone
- The limiting precision applies to any steady-state methods



Wang, JH+, 2018

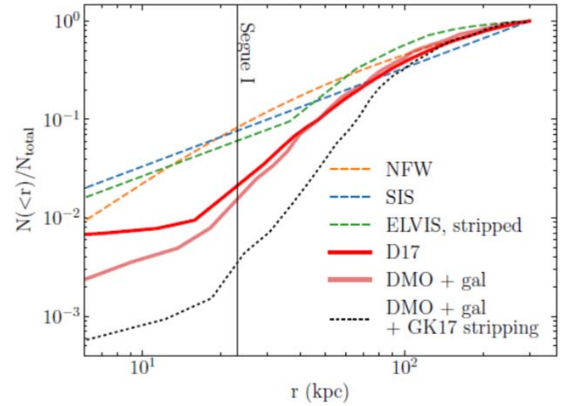
Small scale crisis?

- Missing Satellite?
  - Too many satellites? Selection function?
- Too big to fail?
  - Fair comparison? Poor statistics?
- Core-cusp?
  - Robust prediction? Observational systematics?
- Baryonic physics?



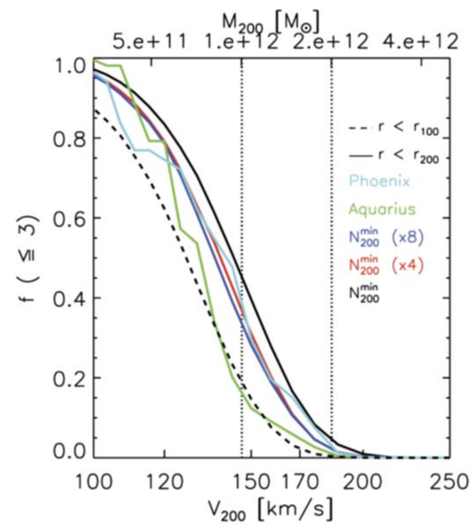
Sawala et al. 2016, APOSTLE simulation

Radial distribution of satellites



Kim et al. 2018

Fraction of allowed halos



Wang et al. 2012