Clustering in the phase space of dark matter haloes: relevance for dark matter annihilation

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SUMMARY

- A different perspective on DM clustering (in phase space) using the Particle Phase Space Average Density (**P^2SAD**)
- DM annihilation can be computed directly from the **P^2SAD** for arbitrary velocity-dependent $(\sigma v)_{ann}$
- The **P^2SAD** at small separations (in phase space) is (quasi) universal in time and across divergently assembled haloes
- A plausible model motivated by the stable clustering hypothesis and by tidal disruption
- One application: subhalo boost to annihilation in a MW-size halo down to ~free-streaming mass ~20 (not ~200!)

preliminary!

Dark matter annihilation

Annihilation rate (# of events per unit time in a region of volume V)

- Standard definition:

$$R_{\rm ann} = \frac{1}{2m_\chi^2}\int_V d^3\mathbf{x}\,\rho^2(\mathbf{x})\langle\sigma v\rangle_{\rm ann}$$

"thermal" average

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"thermal" average

- In terms of the phase space distribution function:

$$R_{\rm ann} = \lim_{\Delta x\to 0}\left[\frac{1}{2m_\chi^2}\int_V d^3\mathbf{x}\int d^3\mathbf{v}d^3\mathbf{\Delta v}(\sigma v)_{\rm ann}f(\mathbf{x},\mathbf{v})f(\mathbf{x}+\mathbf{\Delta x},\mathbf{v}+\mathbf{\Delta v})\right]$$

total DM mass within V

$$= \frac{1}{2m_\chi^2}\int d^3\mathbf{\Delta v}(\sigma v)_{\rm ann}M_V\lim_{\Delta x\to 0}\Xi(\Delta x,\Delta v)$$

$$\text{Particle Phase Space Average Density }(P^2SAD)$$

$$\Xi(\Delta x,\Delta v)\propto \text{2D phase}-\text{space 2PCF}$$

Spatial dark matter clustering

smooth distribution + substructures

Aquarius project Springel+08

- Smooth spherical dist. (NFW or Einasto profile)

$$\ln\left(\frac{\rho(r)}{\rho_{-2}}\right) = \left(\frac{-2}{\alpha}\right)\left[\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right]$$

- Collection of subhaloes with a given:
  - Abundance (mass function)

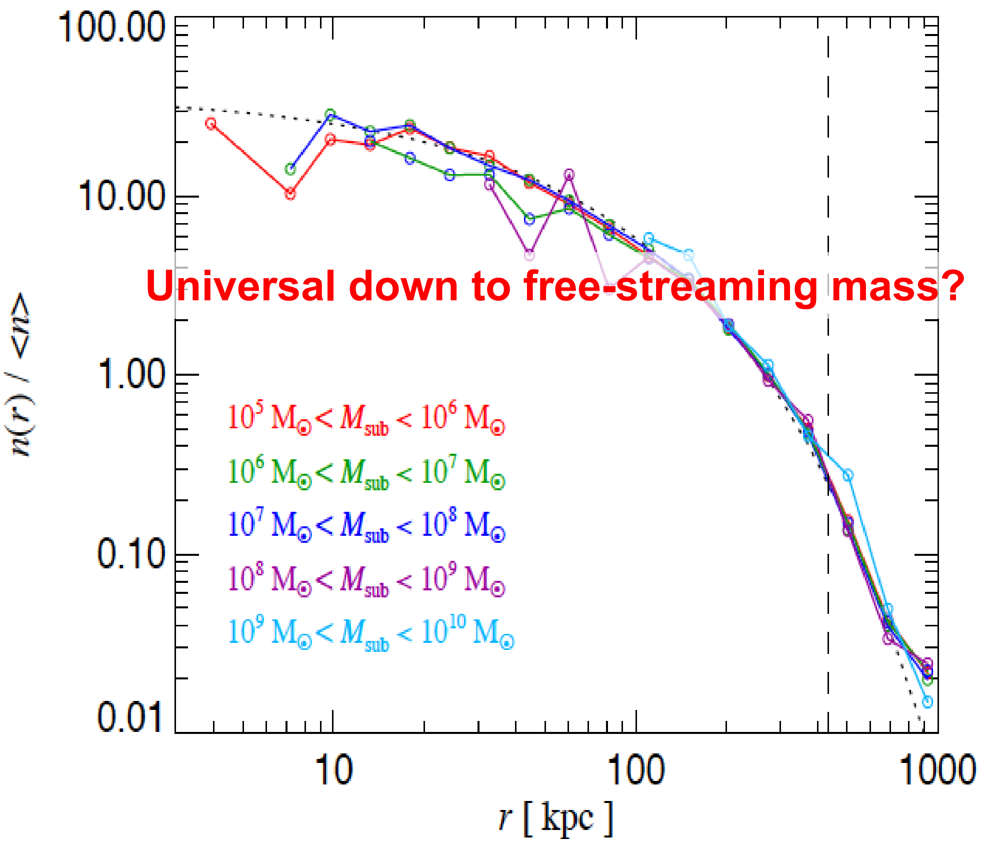
$$\frac{\mathrm{d}N}{\mathrm{d}M} = a_0 \left(\frac{M}{m_0}\right)^{n} \quad n = -1.9$$

Spatial dark matter clustering

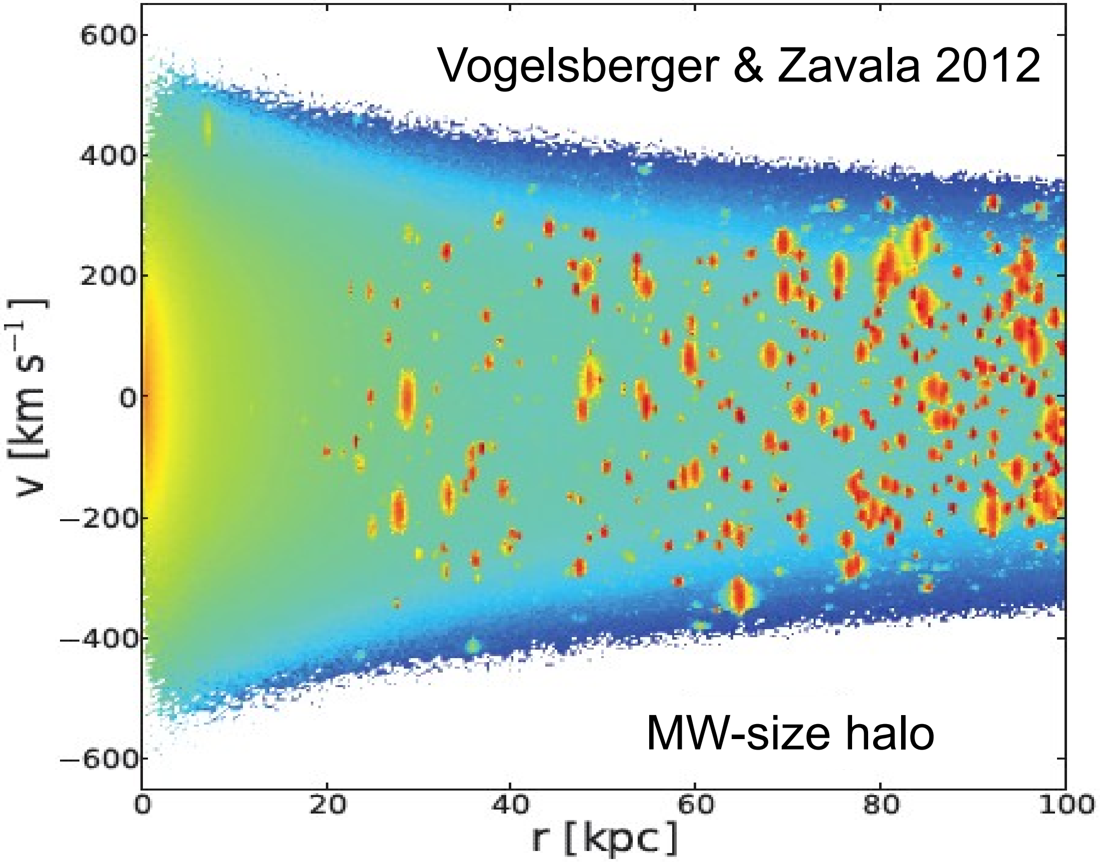
smooth distribution + substructures

Aquarius project Springel+08

- Smooth spherical dist. (NFW or Einasto profile)
- Collection of subhaloes with a given:
  - Abundance (mass function)
  - Density profile (NFW or Einasto)
  - Radial distribution (“cored” Einasto)



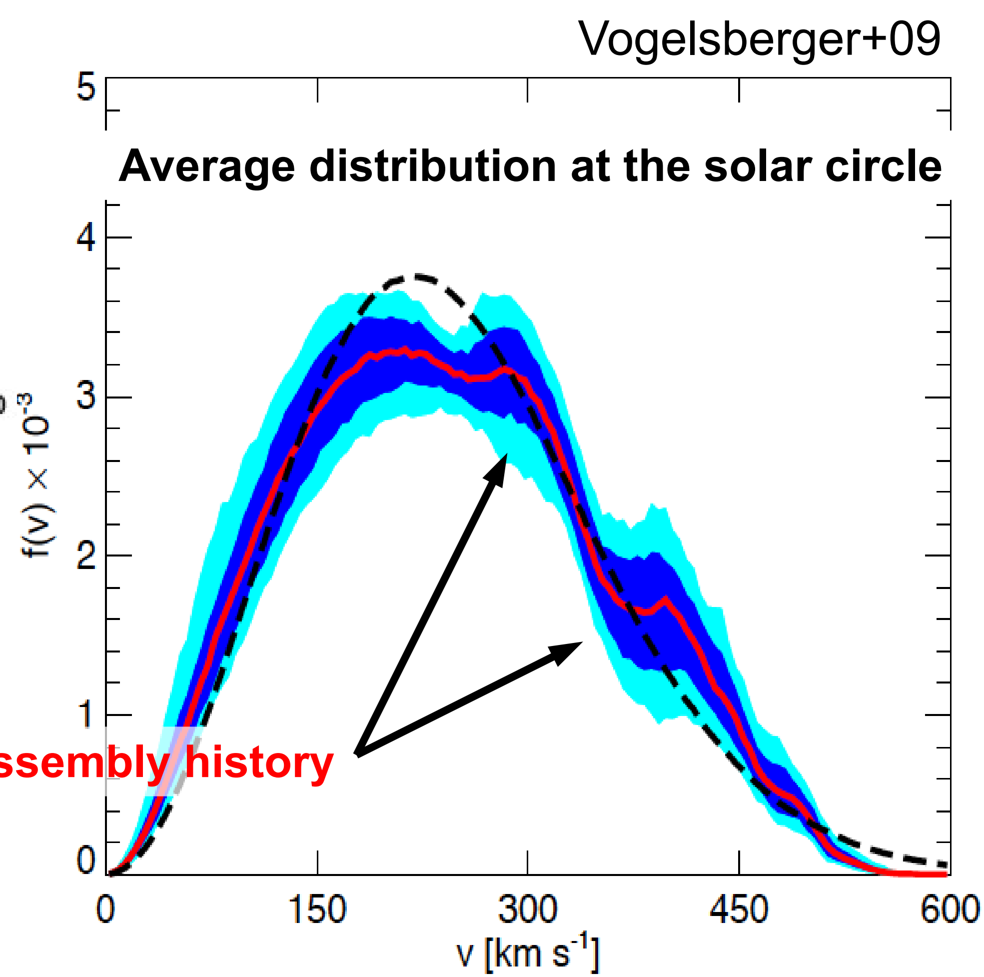
Clustering in the phase space of DM haloes



Particles weighted by the local pseudo phase space density

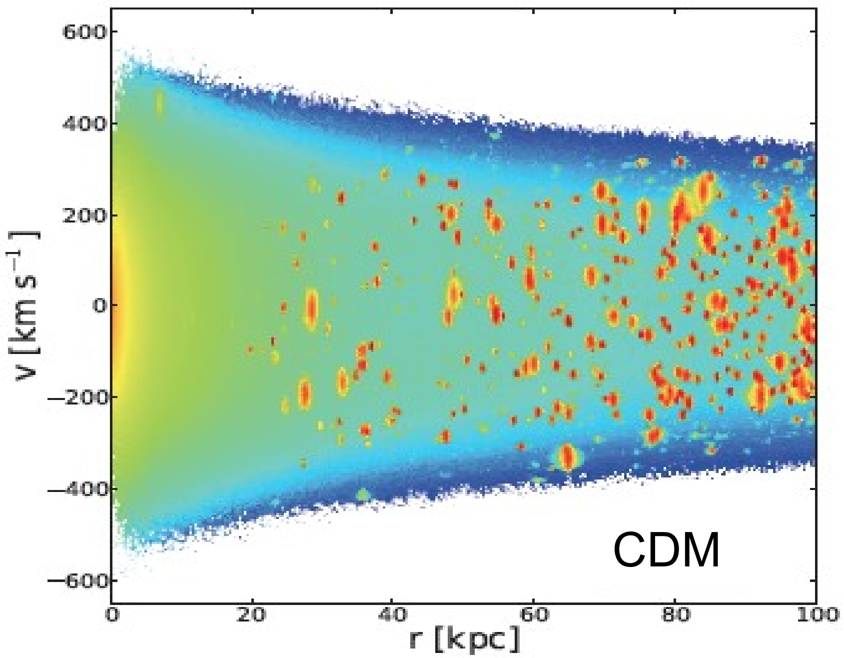
$$\rho/\sigma^3$$

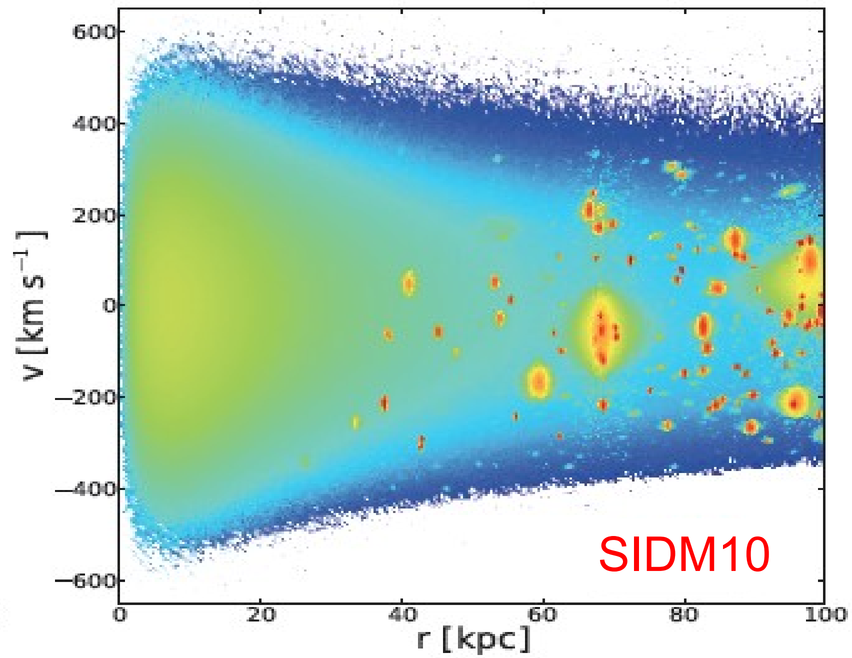
Velocity distribution is not truly Maxwellian (influence on direct detection rates)



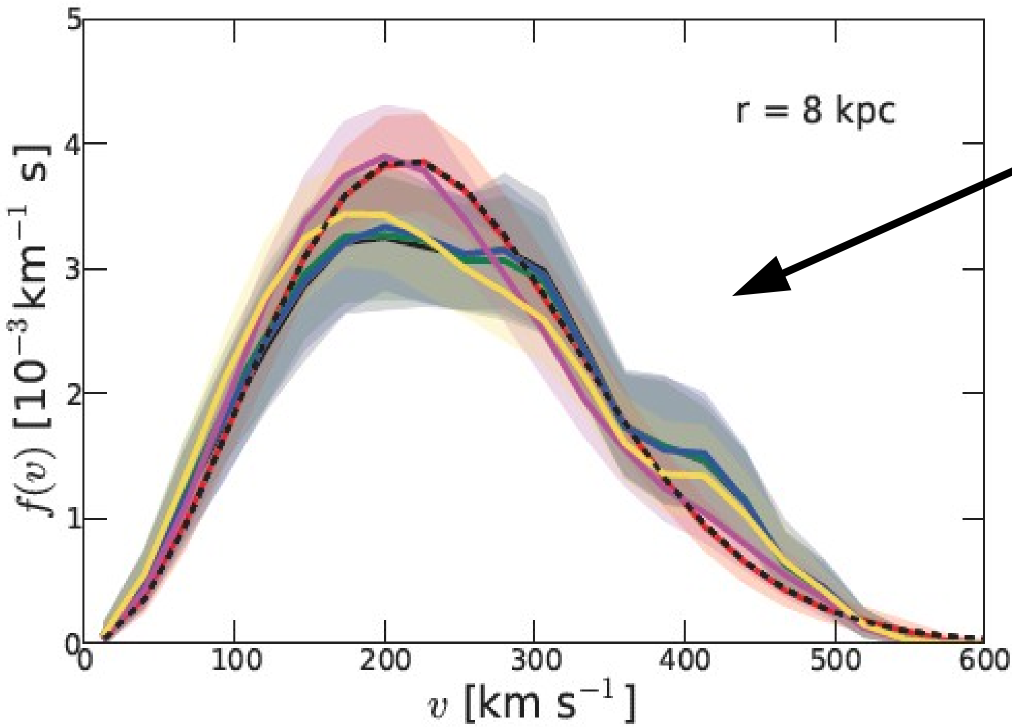
Related to individual assembly history

(Self-Interacting(collisional) dark matter)





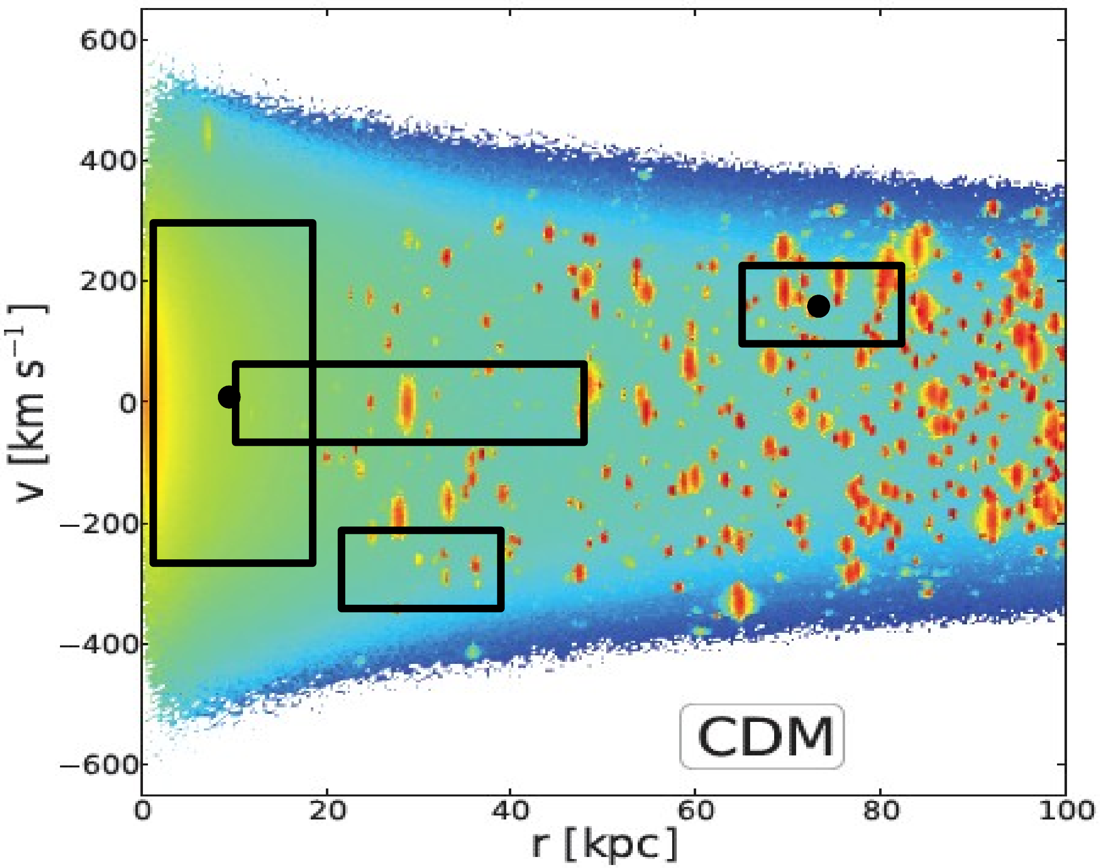
Vogelsberger & Zavala 2012



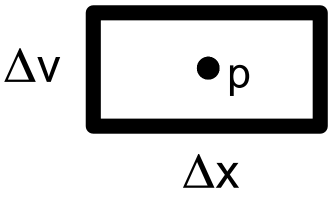
"Local" DM velocity distribution for observers at the solar circle

DM self-scattering affects predictions from direct detection experiments (~20% effect)

Particle phase space average density (P^2SAD) in DM haloes



Estimate of P^2SAD in a simulation:

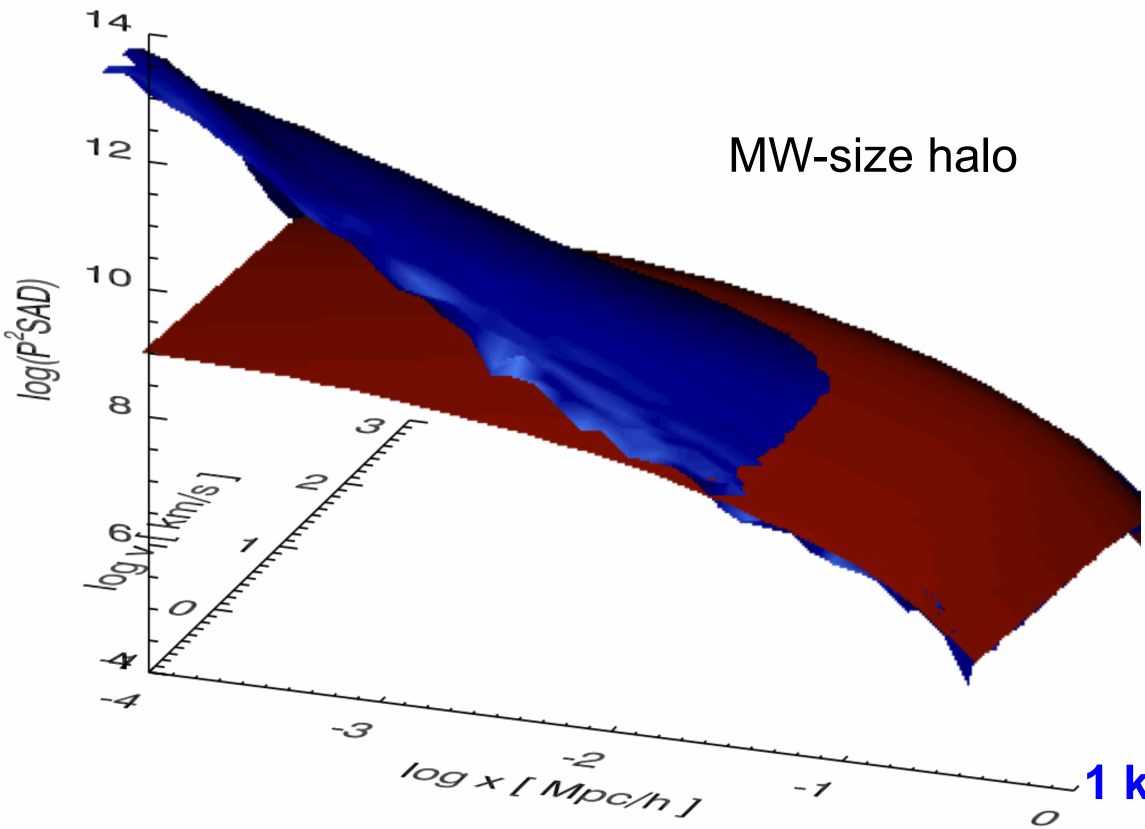


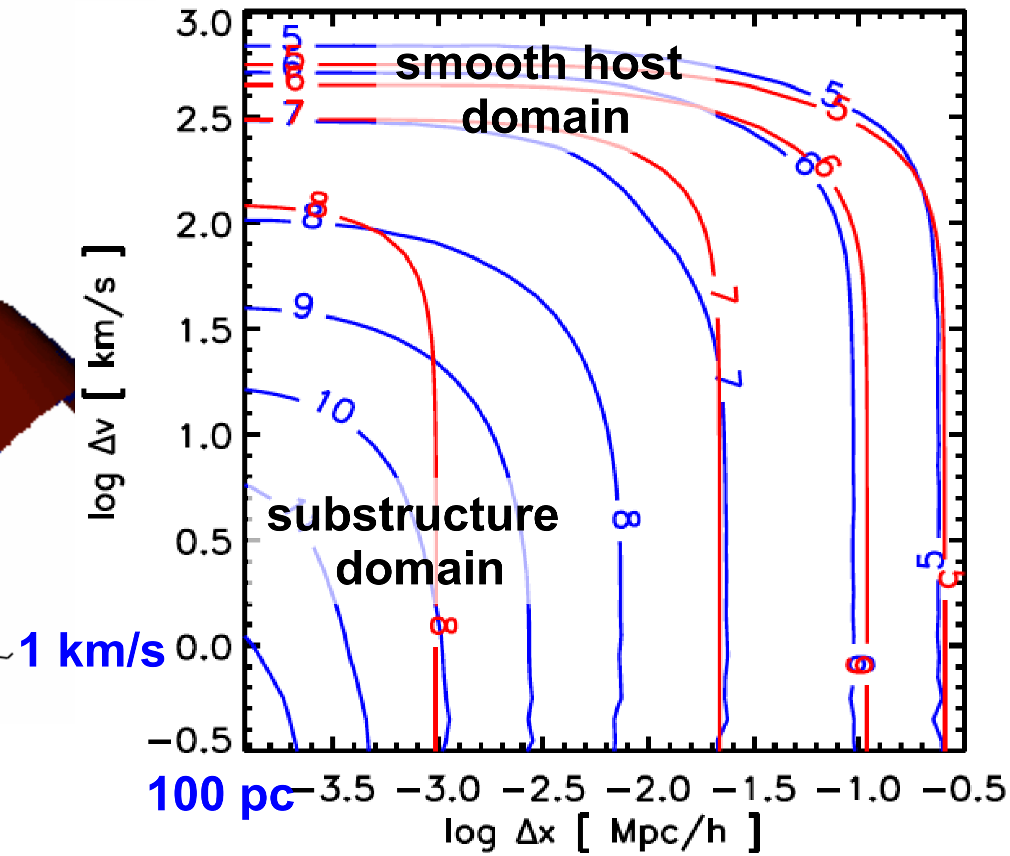
Average over a sample of particles across the volume of interest

$$\Xi(\Delta x, \Delta v)_{\rm sim} = \frac{m_p \langle N_p(\Delta x, \Delta v)\rangle}{V_6(\Delta x, \Delta v)}$$

V_6 is volume of the shell

Particle phase space average density (P^2SAD) in DM haloes





Smooth distribution (fit to simulation)

Full distribution (simulation data)

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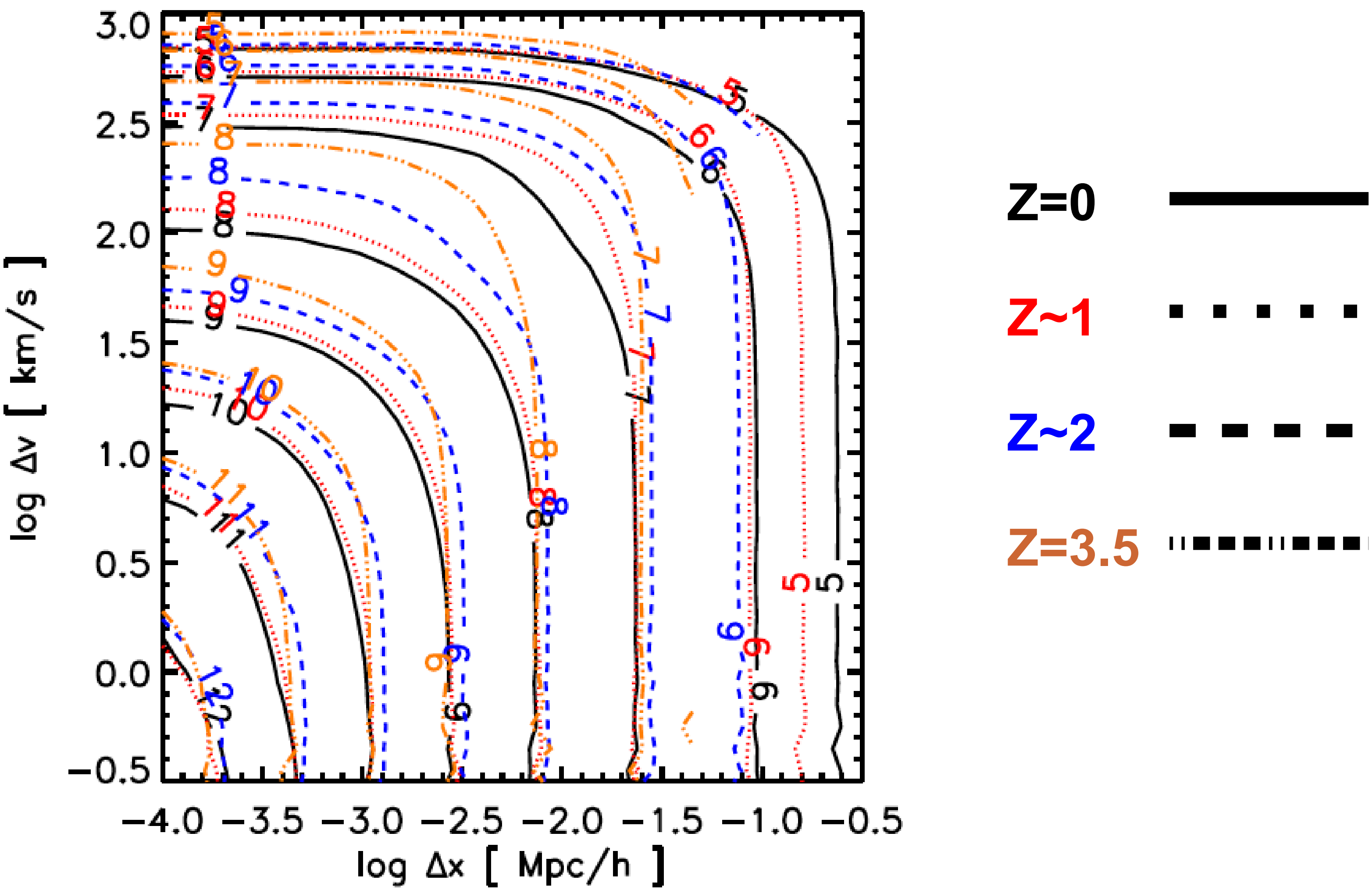
(quasi)Universality of P^2SAD at small scales

Redshift variation up to z=3.5



Changes in the smooth component explained by "inside-out" growth

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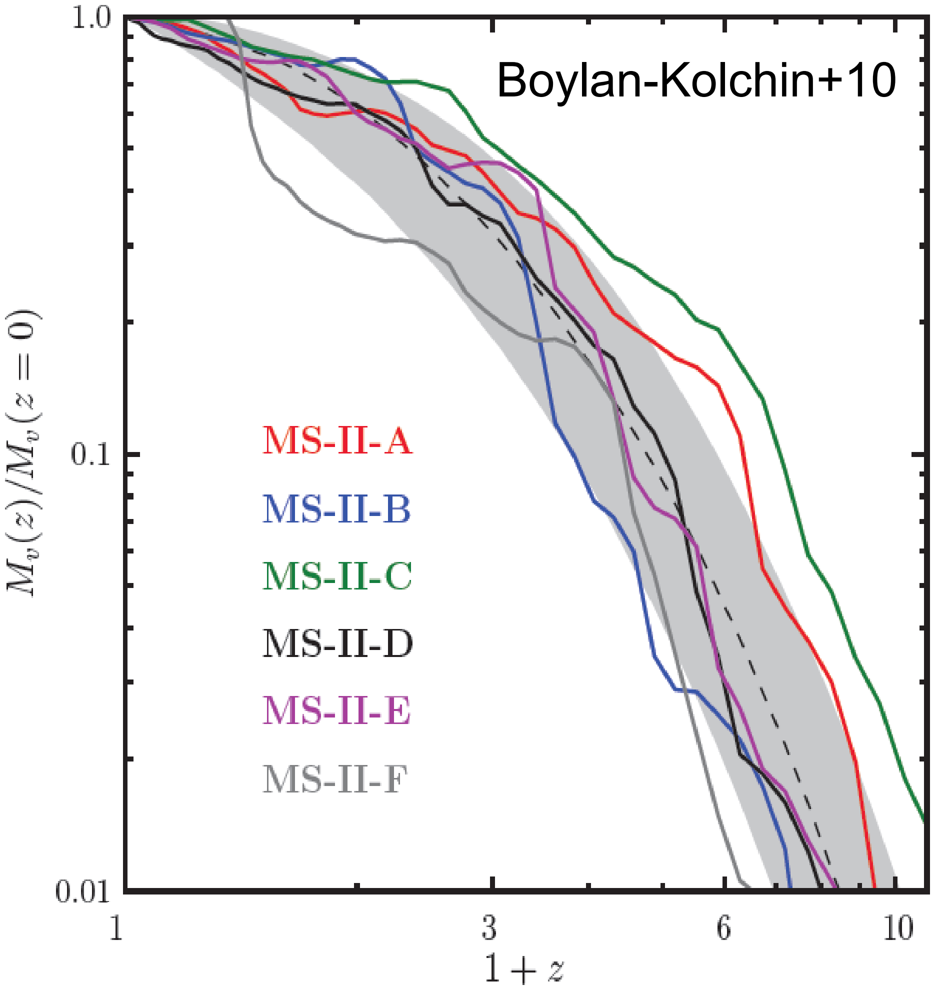
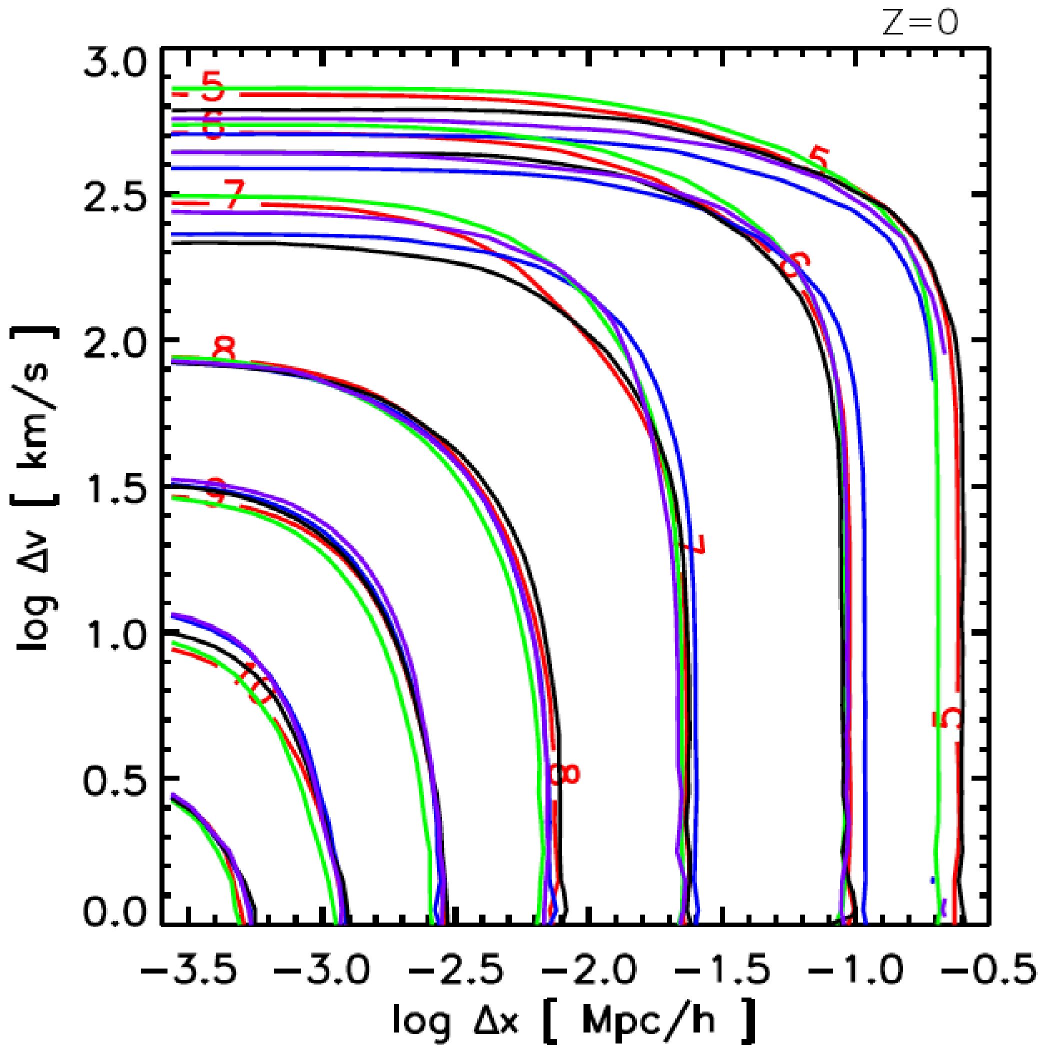
(quasi)Universality of P²SAD at small scales

Different mass assembly history





5 MW-size haloes with different accretion histories (differ in mass and concentration by up to ~2)

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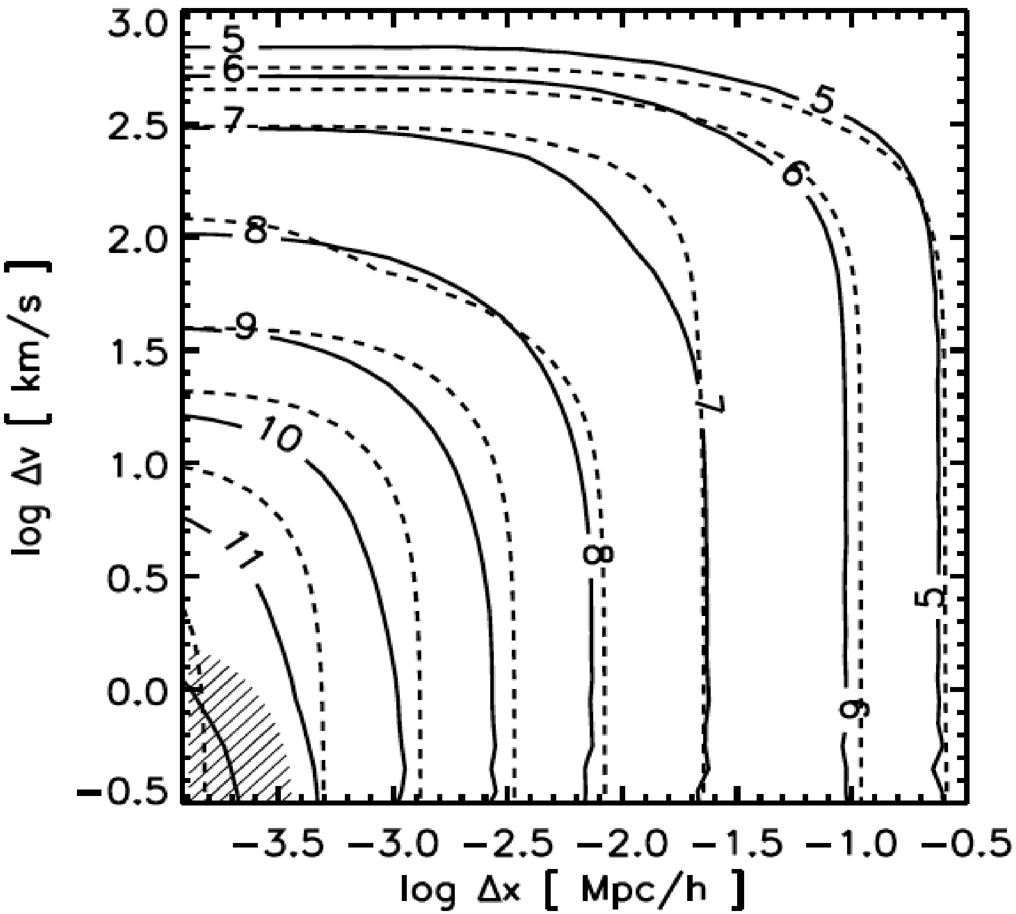
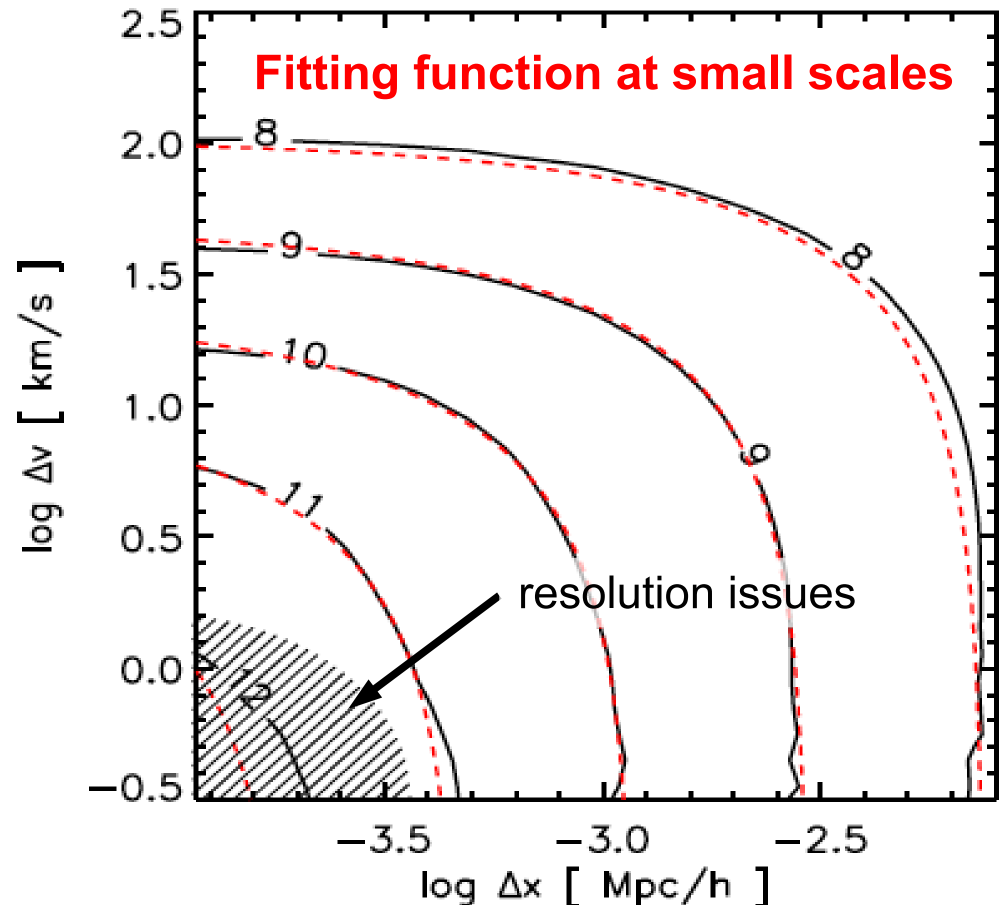
Descriptive modelling of the P^2SAD



Sim. data —— Model - - -



$$\left(\frac{\Delta x}{\mathcal{X}(\Xi)}\right)^{\beta} + \left(\frac{\Delta v}{\mathcal{V}(\Xi)}\right)^{\beta} = 1$$

$$\mathcal{X}(\Xi) = q_X \Xi^{\alpha_X}$$

$$\mathcal{V}(\Xi) = q_V \Xi^{\alpha_V}$$

Halo model: smooth + substructures
(works at large separations, problems at small scales
-**specially If one wishes to extrapolate**-)

β, q's and α's, slowly varying functions of redshift to accommodate variations

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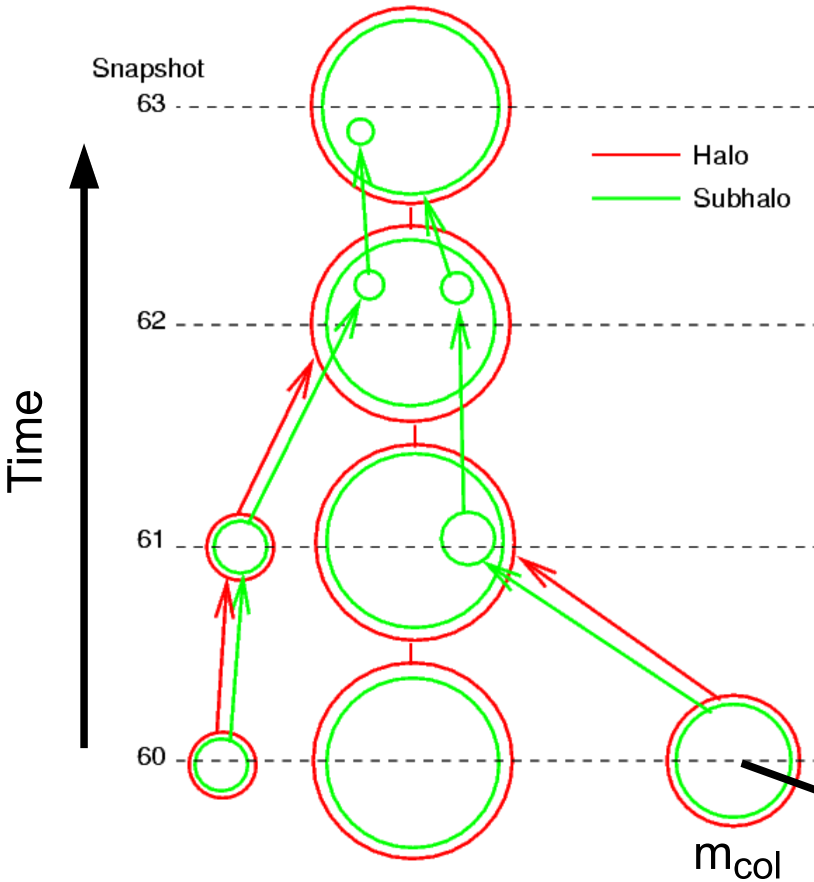
Model inspired by stable clustering

Hypothesis originally proposed by Davis & Peebles 1977. Extension to phase space: “the number of particles within the physical velocity Δv and physical distance Δx of a given particle does not change with time for small enough Δv and Δx”

Model inspired by stable clustering

Hierarchical assembly



spherical collapse

z_{col}

$$\xi_s = \frac{\rho_{\rm char}}{\sigma_{\rm vir}^3}$$

collisionless Boltzmann eq.

+

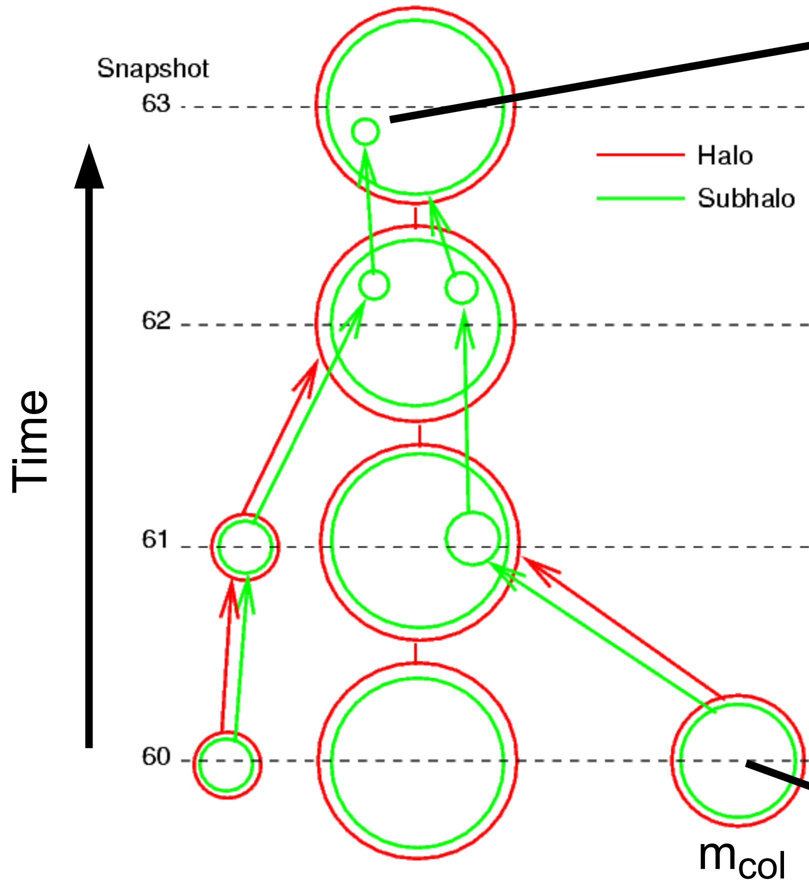
stable clustering

$$\Xi(\Delta x, \Delta v) \equiv \xi_s = F\left((\mathbf{\Delta v})^2 + (4\pi/3)G\rho_{\rm char}(\mathbf{\Delta x})^2\right)$$

Afshordi, Mohayaee & Bertschinger 2010

Model inspired by stable clustering

Hierarchical assembly



Tidal disruption

$$\Xi(\Delta x, \Delta v) \equiv \mu\xi_s = F\left((\mathbf{\Delta v})^2 + (4\pi/3)G\rho_{\rm char}(\mathbf{\Delta x})^2\right)$$

stable clustering

+

collisionless Boltzmann eq.

spherical collapse

z_{col}

$$\xi_s = \frac{\rho_{\rm char}}{\sigma_{\rm vir}^3}$$

Afshordi, Mohayaee & Bertschinger 2010

Model inspired by stable clustering

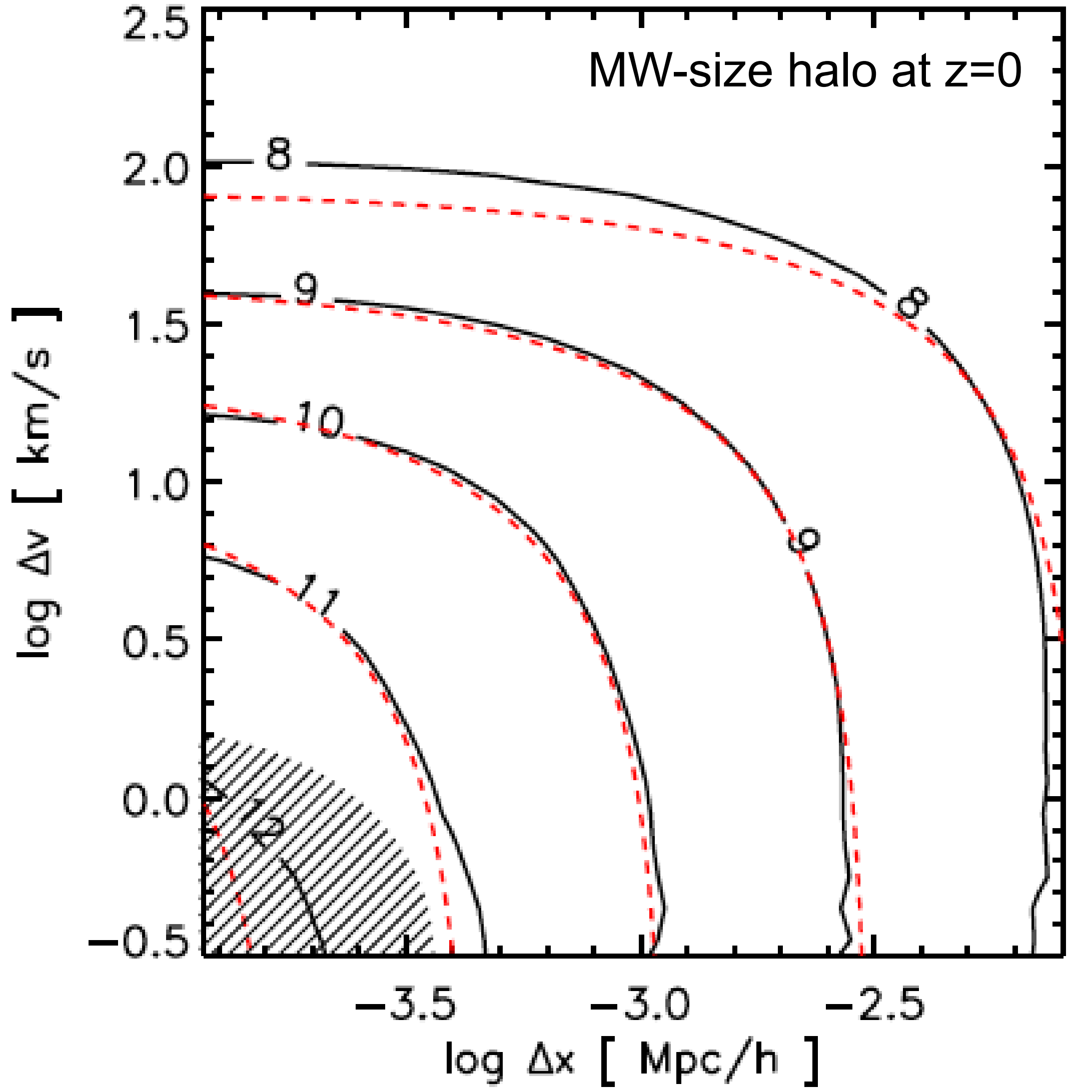
$$\left(\frac{\Delta x}{a\lambda(m_{\rm col})}\right)^{\beta} + \left(\frac{\Delta v}{b\zeta(m_{\rm col})}\right)^{\beta} = 1$$

λ and ζ are given by spherical collapse

a, b and β slowly varying functions of redshift of order 1 (**deviations from stable clustering**)

We propose a tidal disruption model

$$\mu(m_{\rm col}; z)\xi_s = \Xi(\Delta x, \Delta v)$$



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Global substructure boost to annihilation

(example $(\sigma v)_{ann}$ = cte)

$$R_{\rm ann} \propto \int d^3\mathbf{\Delta v} \lim_{\Delta x \to 0} \Xi(\Delta x, \Delta v)$$

fitting function →

$$R_{\rm ann} \propto q_v^3 \ln\left(\frac{\Xi_{\rm max}}{\Xi_{\rm min}}\right)$$

valid away from smooth component dominion

model →

$$R_{\rm ann} \propto b^3 \int_{\rm M_{min}}^{\rm M_{max}} \mu(m_{\rm col}) d(m_{\rm col}\sigma^3(m_{\rm col}))$$

mass variance (↑ σ^3)

Global substructure boost to annihilation

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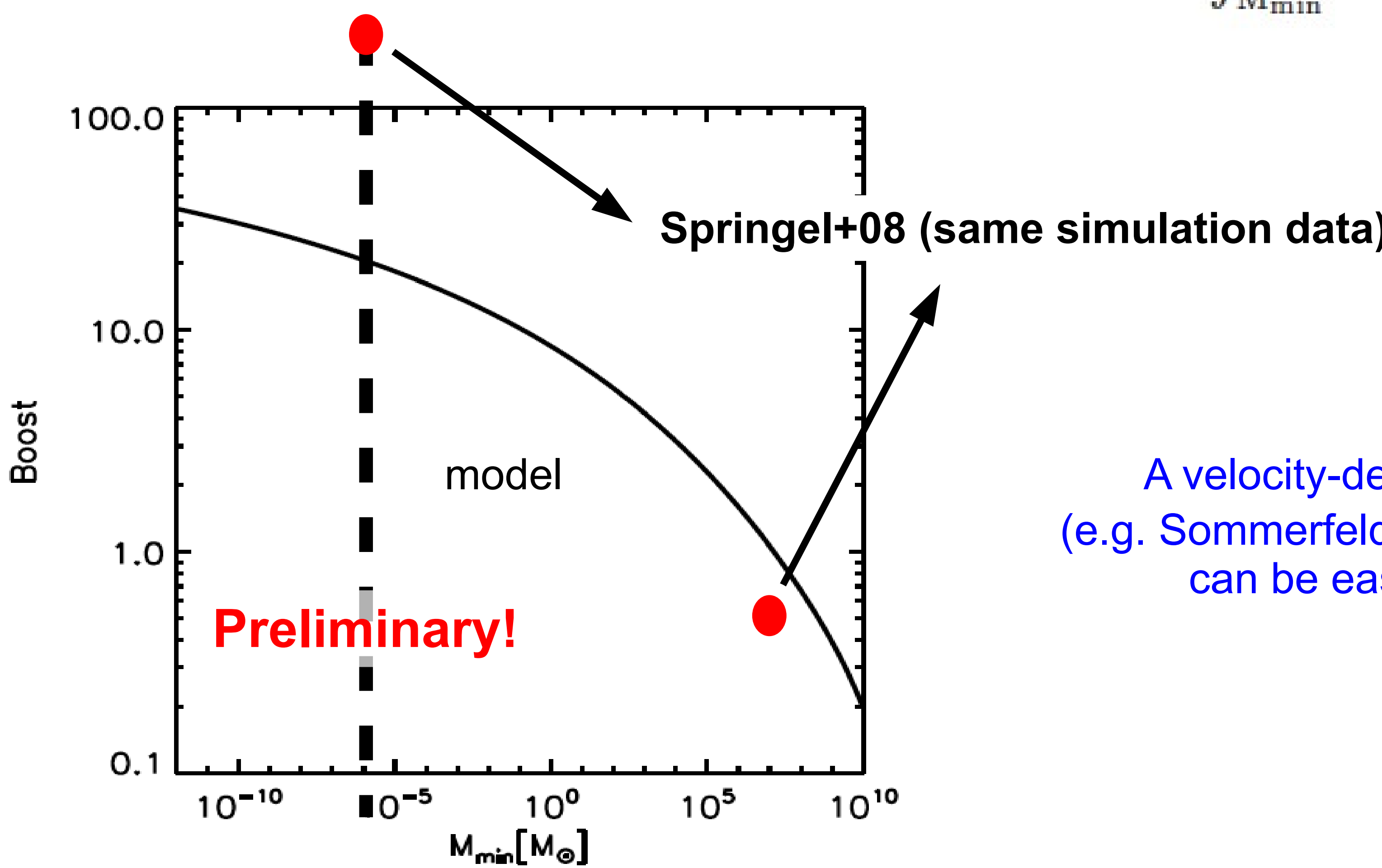

A velocity-dependent $(\sigma v)_{ann}$
(e.g. Sommerfeld-enchanced models)
can be easily introduced

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