[visualized by Ralf Kaehler]

Modeling Dark Matter Distributions

Yao-Yuan Mao   @yaoyuanmao   stanford.edu/~yymao

with Louie Strigari, Marc Williamson, and Risa Wechsler

KIPAC/Stanford/SLAC

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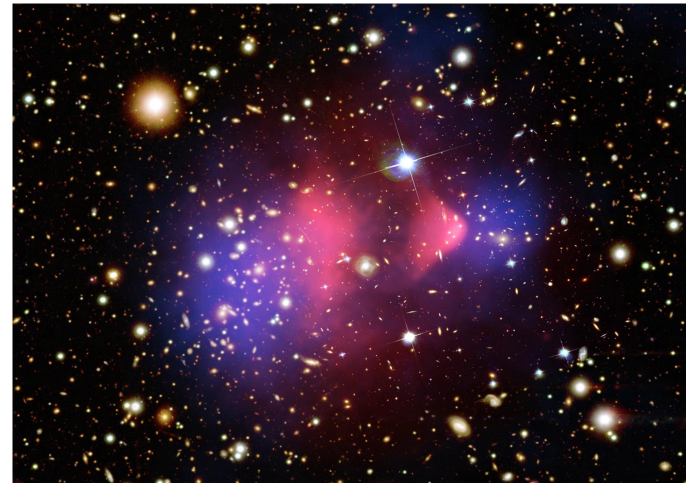
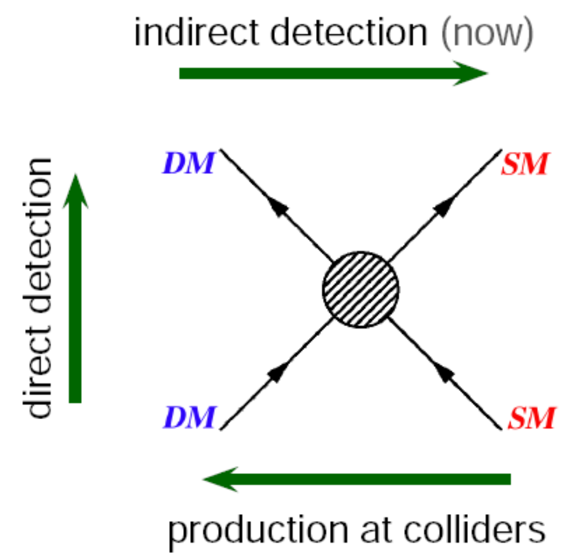
Hunting for dark matter





Outline

How do cosmologists provide better models for dark matter experiments?

Velocity distribution of dark matter

Relevant for direct detection

[See YYM+ (ApJ 2013) **1210.2721** and YYM+ (PRD 2013) **1304.6401**]

Dark matter subhalo abundance

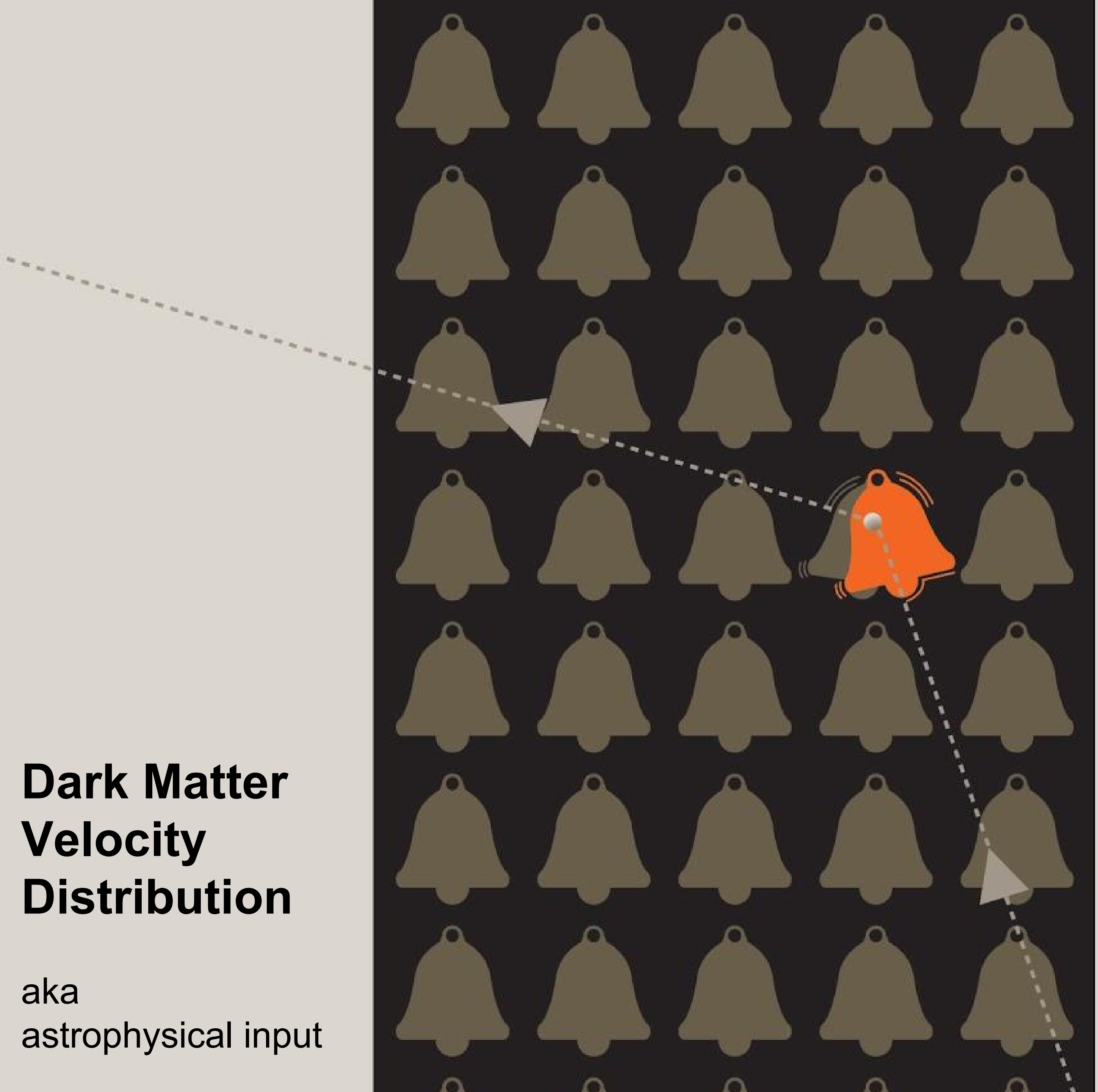
Relevant for indirect detection and astrophysical observations

[See YYM+ **1503.02637**]

Results are based on dissipationless CDM N-body simulations.

Dark Matter Velocity Distribution

aka
astrophysical input



[Symmetry Magazine]

Velocity Distribution Function (VDF) in direct detection

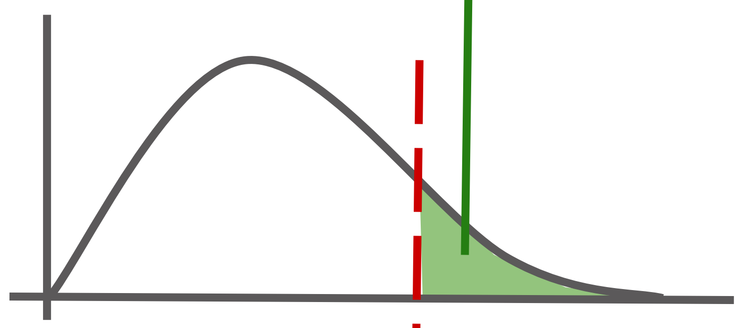
- The differential event rate of the DM-nucleon collision depends on the Galactic Velocity Distribution Function (VDF).

$$\left.\frac{dR}{dQ}\right|_Q = \frac{\rho_0}{m_{\rm dm} m_N} \int_{v_{\rm min}(Q)} d^3v \, v \, f(\mathbf{v}+\mathbf{v}_{\rm e}) \frac{d\sigma}{dQ}$$

$$= \frac{\rho_0 \sigma_0}{2\mu^2 m_{\rm dm}} A^2 |F(Q)|^2 \int_{v_{\rm min}(Q)} d^3v \, \frac{f(\mathbf{v}+\mathbf{v}_{\rm e})}{v}$$

- The relevant quantity:

$$g(v_{\rm min}, \mathbf{v}_{\rm e}) =$$

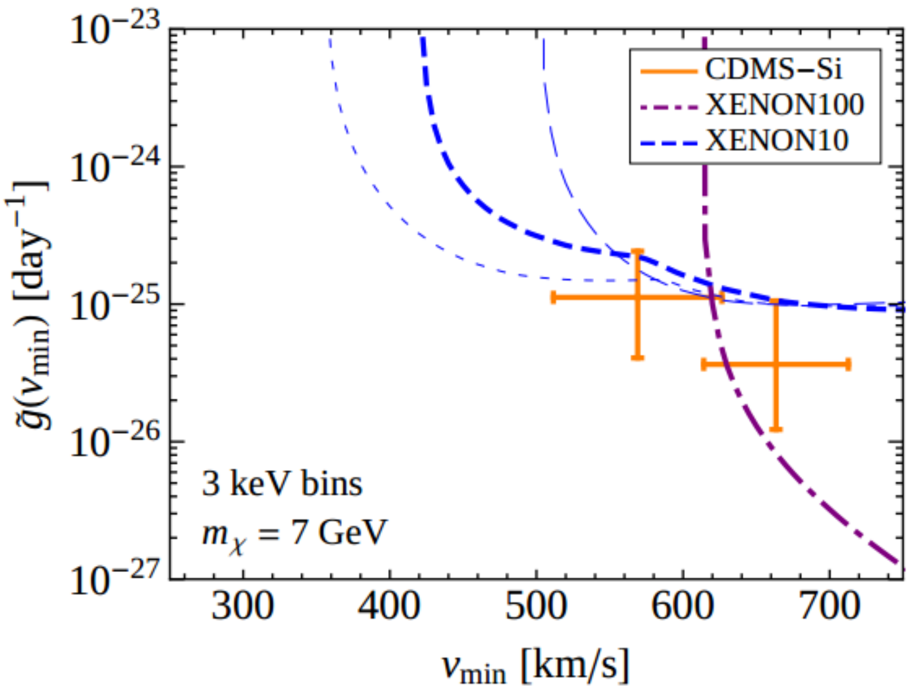


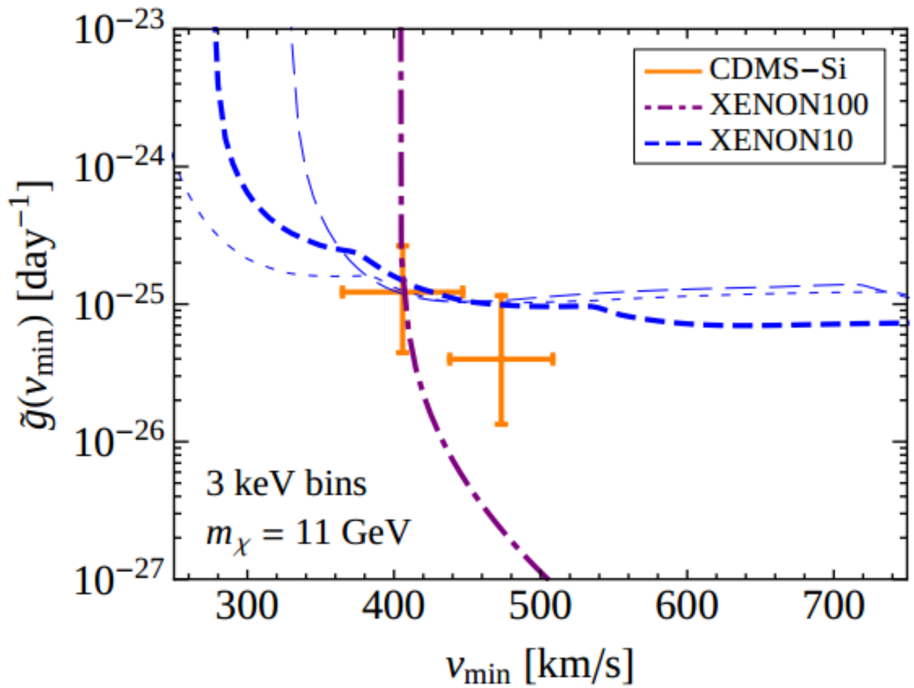
The $g(v_{min})$ method

Fox+, PRD (2011)
Frandsen+, JCAP (2012)

Instead of comparing experimental results in the plane of cross section vs. WIMP mass, compare the results in the plane of $g(v_{min})$ and v_{min}, with a WIMP mass assumed.

[Frandsen+ 2013]

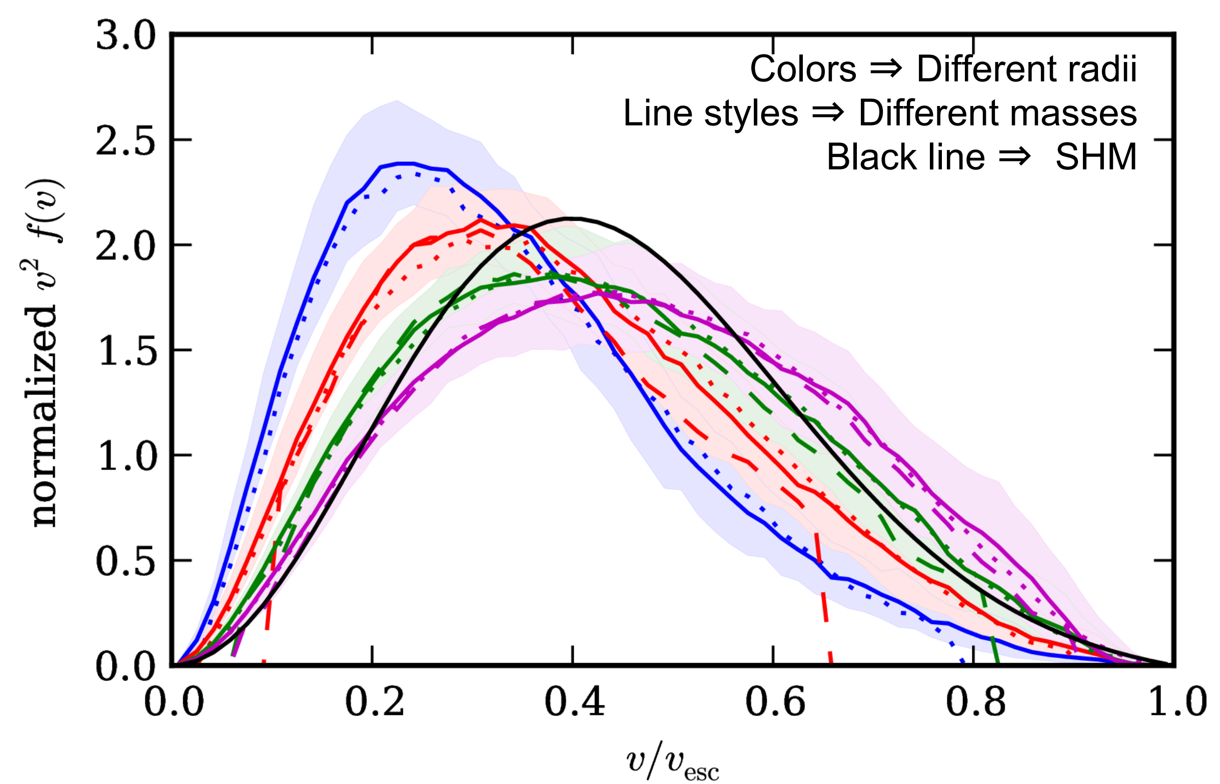




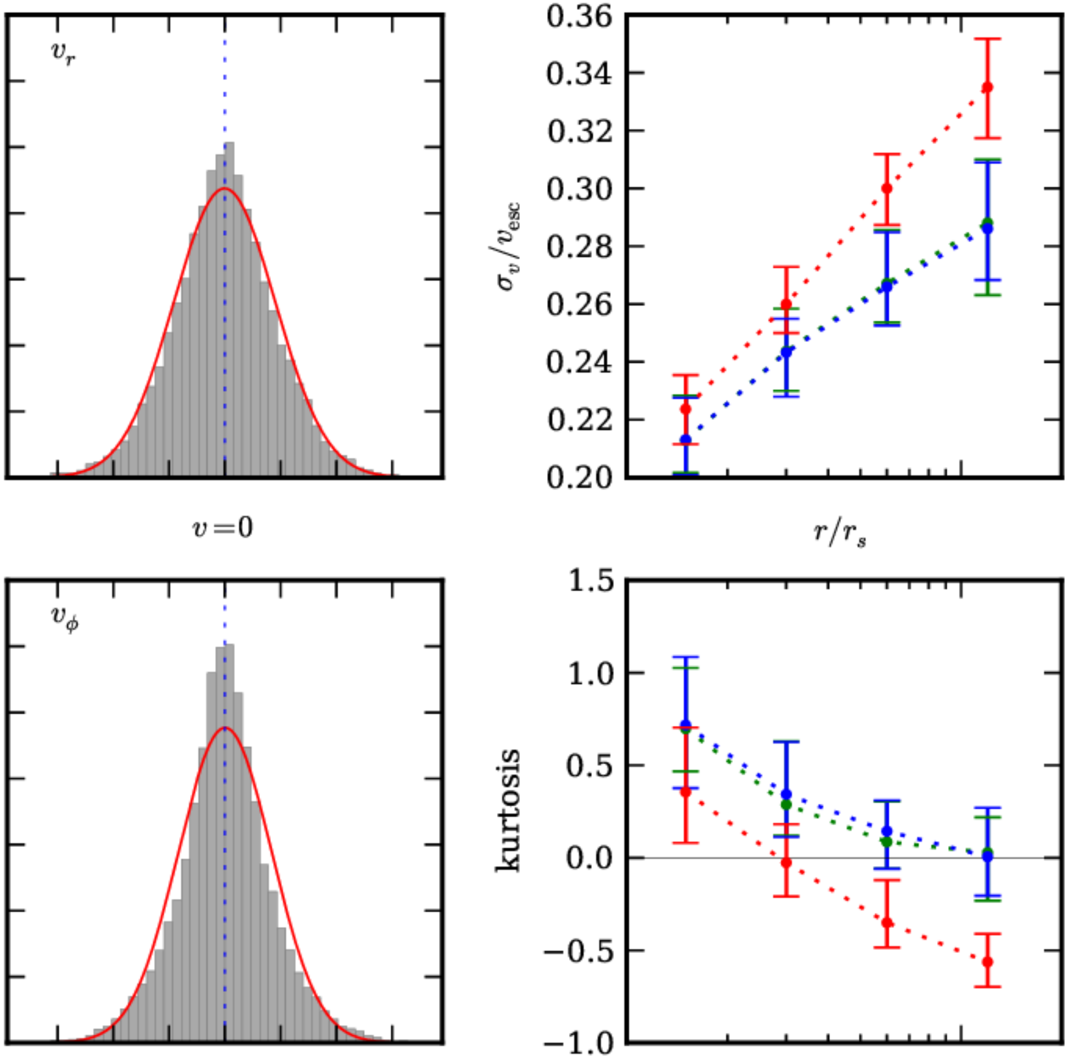
"Standard Halo Model"

$$f(v) \propto \exp\left(-\frac{v^2}{v_0^2}\right)$$

- Maxwell-Boltzmann distribution + unphysical cutoff.
- The parameter v_0 is determined by the circular velocity.
- There's no physical reason for the DM VDF to be like a M-B distribution.



Why doesn't DM follow the Maxwell-Boltzmann distribution ?



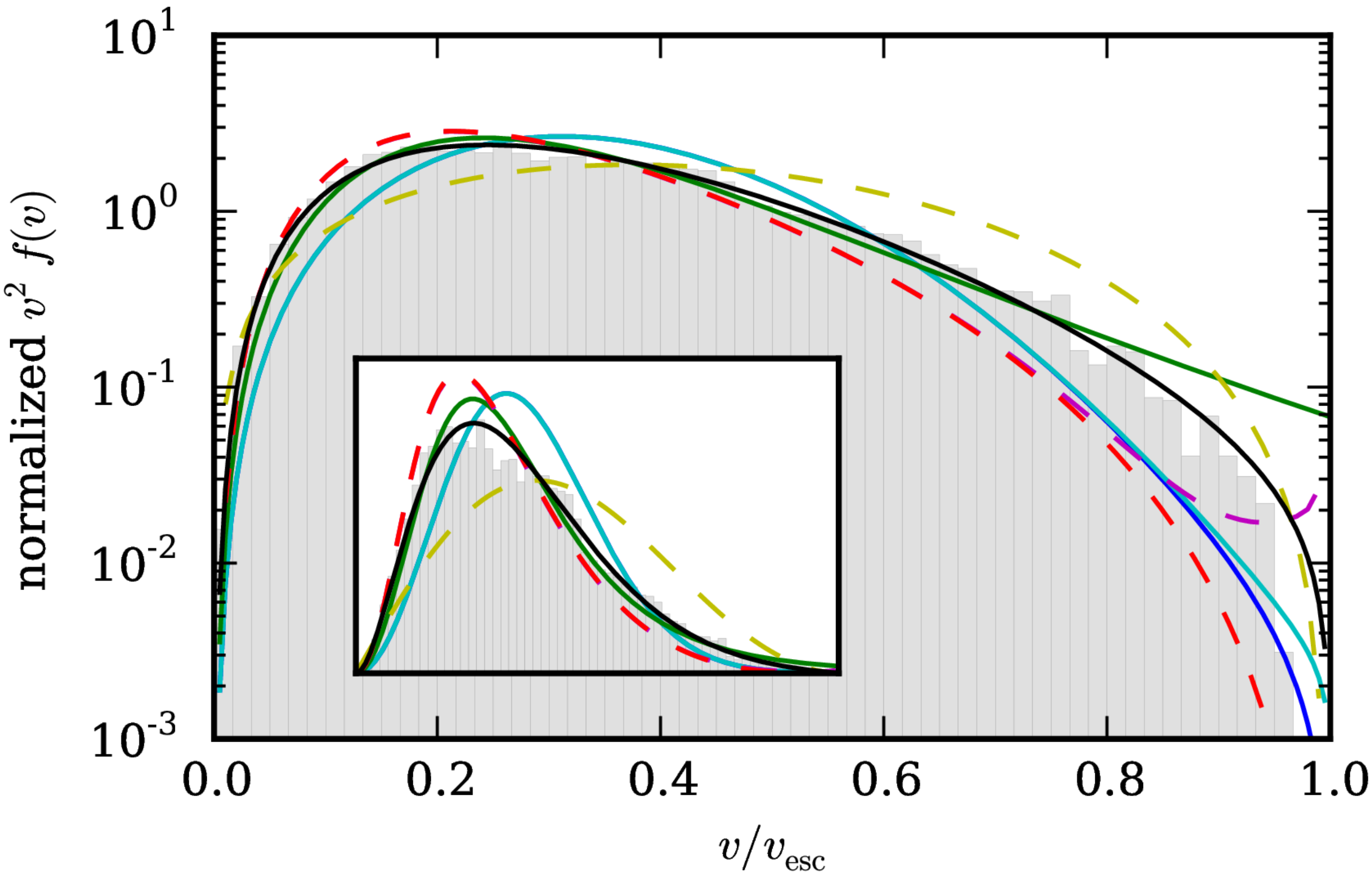
Is the equilibrium state really isotropic?

Even if the anisotropy parameter is zero, there still exists anisotropy in the velocity space.

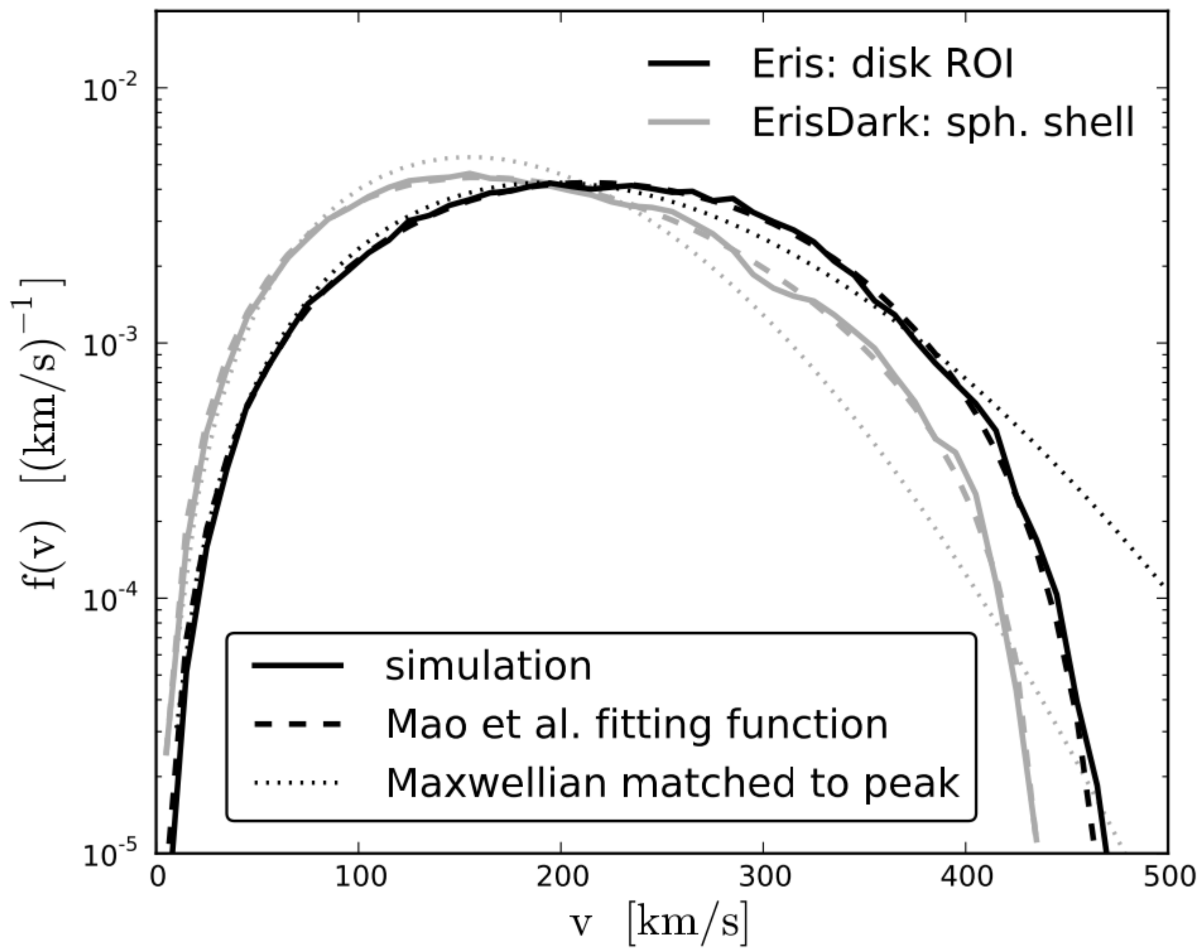
An accurate model of VDF

$$f(v) \propto \exp\left(-\frac{v}{v_0}\right)\left(v_{\rm esc}^2 - v^2\right)^p, \quad v \in [0, v_{\rm esc}]$$

- Two parameters: $\boldsymbol{v_0}$ and $\boldsymbol{p}$
- NOT a variant of a Maxwell-Boltzmann distribution (eg. Standard Halo Model)
- Based on an exponential distribution (flattened shape): could be due to the velocity anisotropy (ellipsoid)
- Tail modified by a power-law cutoff in energy



Comparing VDF models with DM-only simulation.



Comparing VDF models with hydro simulation.

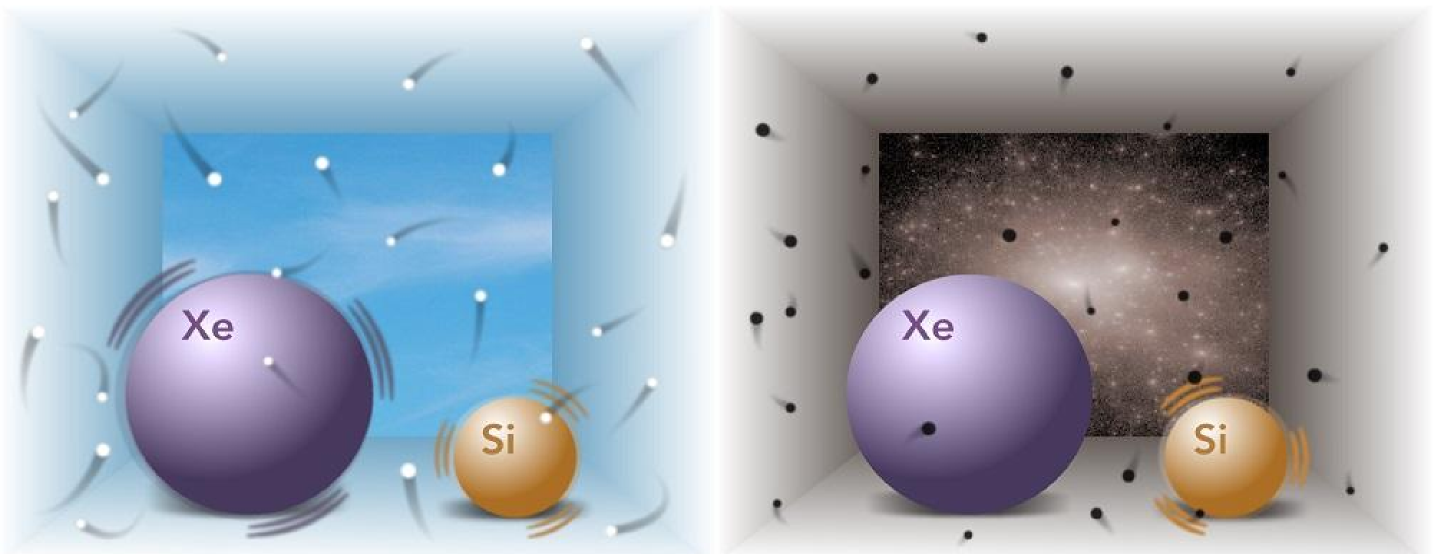
[Kuhlen+ 2013]

Does the VDF really matter for experiments?

Yes, especially for larger v_{min}

(light WIMP, heavy target, high recoil energy)

$$v_{\min} = \sqrt{\frac{E_{nr} m_n}{2\mu^2}}$$



[Greg Stewart/SLAC National Accelerator Laboratory]

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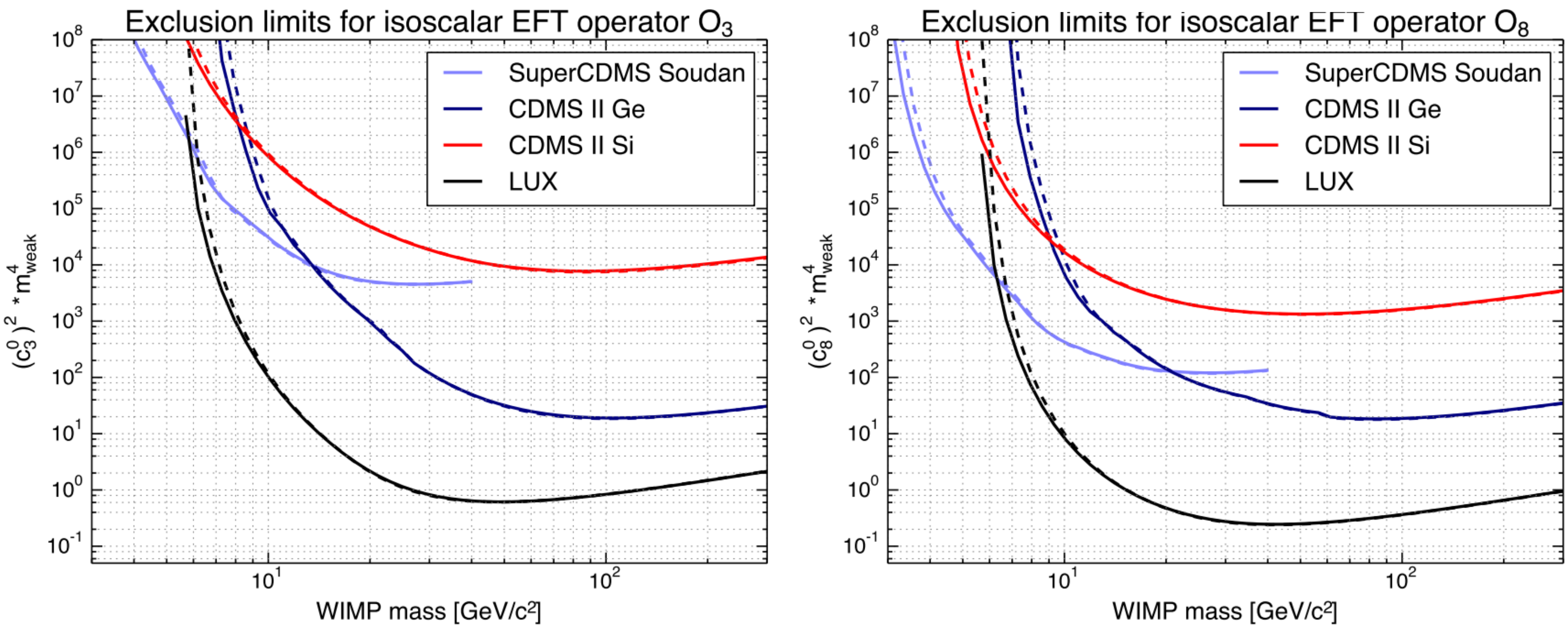
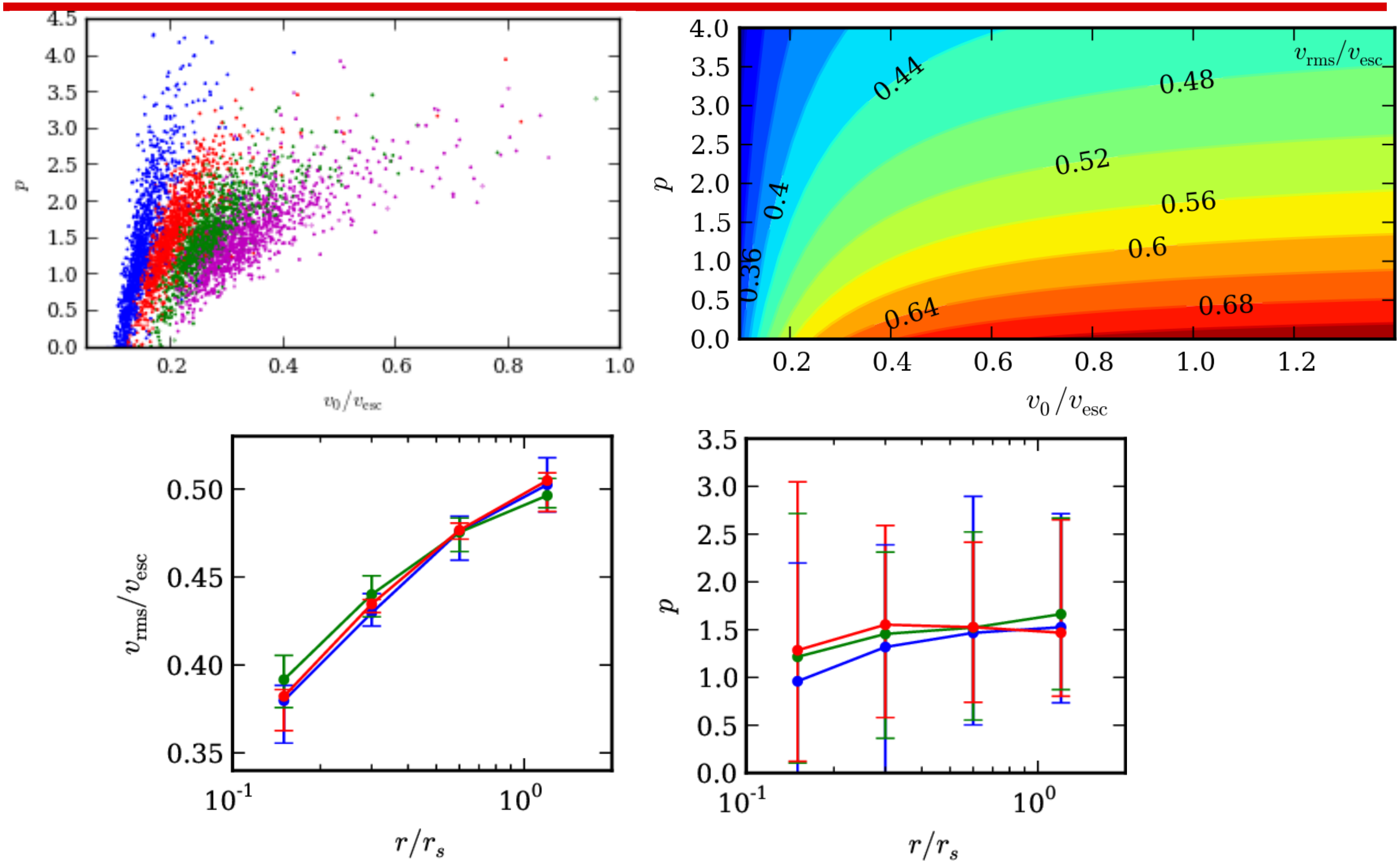


[Schneck+ (SuperCDMS Collab.) 2015]

Prior distributions of VDF parameters



Quantify the impact of VDF on the energy spectrum

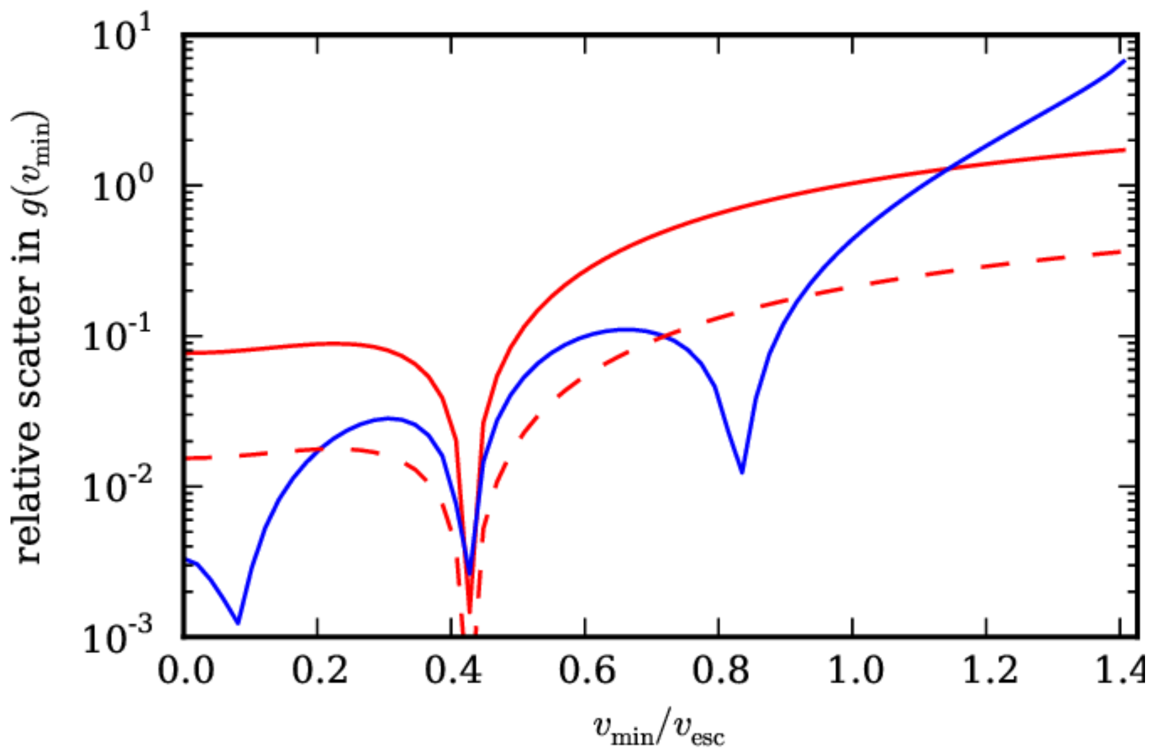
The relative scatter (range) of $g(v_{min})$ for:

v_{rms} in [0.38, 0.48] (p = 1.5)

v_{rms} in [0.42, 0.44] (p = 1.5)

p in [0, 3] (v_{rms} = 0.43)

$$g(v_{\min}, \mathbf{v}_\mathbf{e}) \equiv \int_{v_{\min}} d^3v \, \frac{f(\mathbf{v} + \mathbf{v}_\mathbf{e})}{v}$$



v_{rms} ⇨ *the overall shape*

p ⇨ *detailed shape and the asymptotic tail*

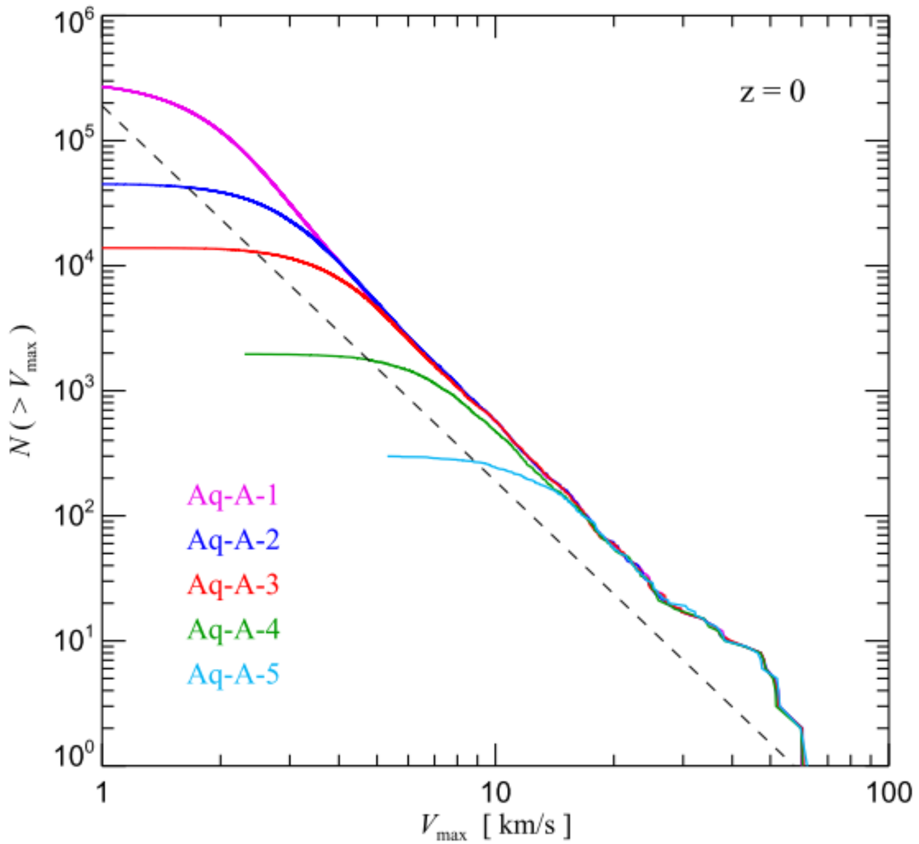
Half-time summary

- We propose a flexible, parameterized VDF model, along with the priors on the parameters, based on cosmological simulations.
- Future experiments should include the VDF in the analysis, preferably by marginalizing over the VDF parameters.
- When *real* DM signals start to be found in direct detection experiments, realistic VDF models can provide insights to the properties of the MW halo.
- The mechanism of non-Maxwellian VDF and its relation to the equilibrium state of the DM halos are still unclear and need to be understood theoretically.

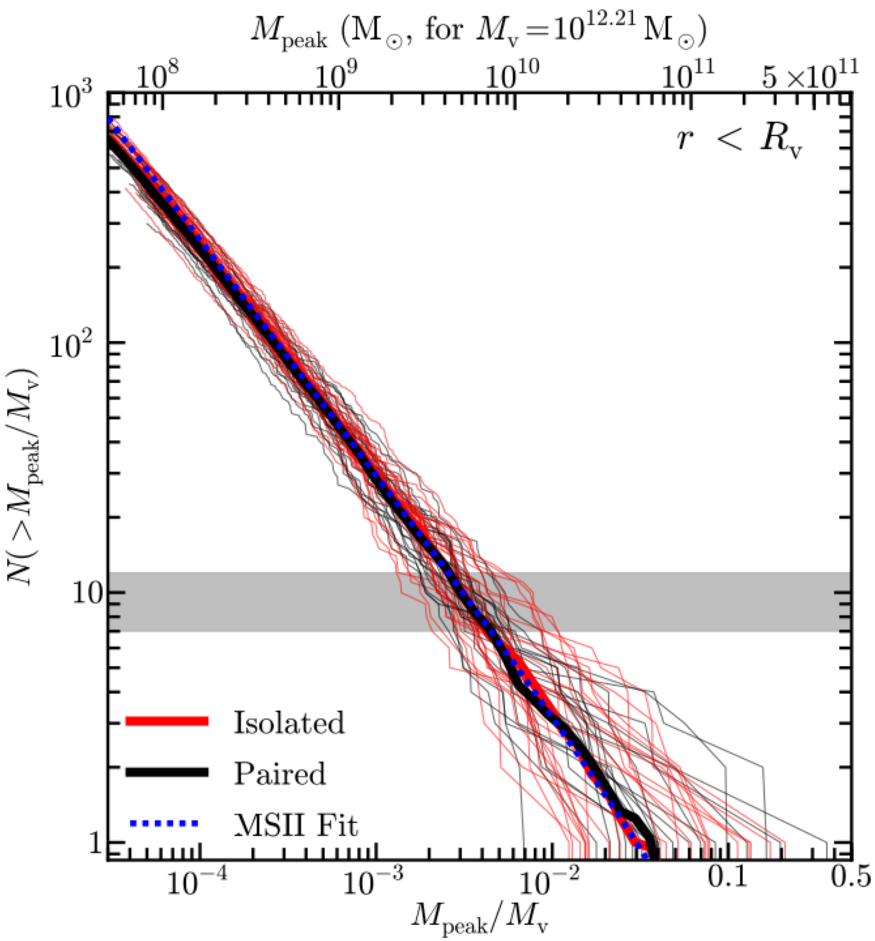
Dark Matter Substructures

[Symmetry Magazine]

What are subhalo abundance functions and what do we know about them?

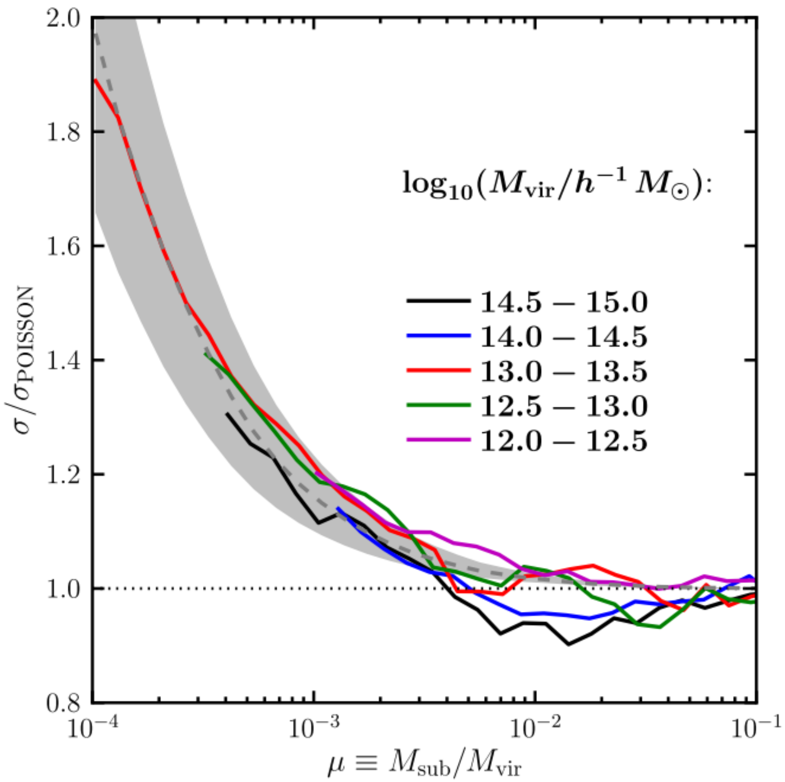


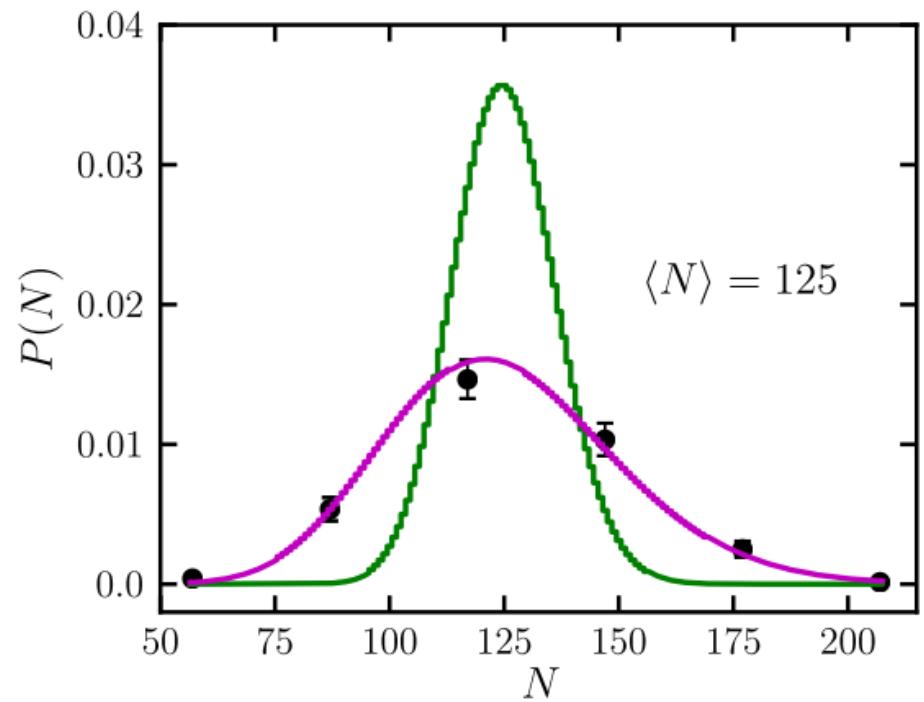
Aquarius [Springel+ 2008]



ELVIS [Garrison-Kimmel+ 2014]

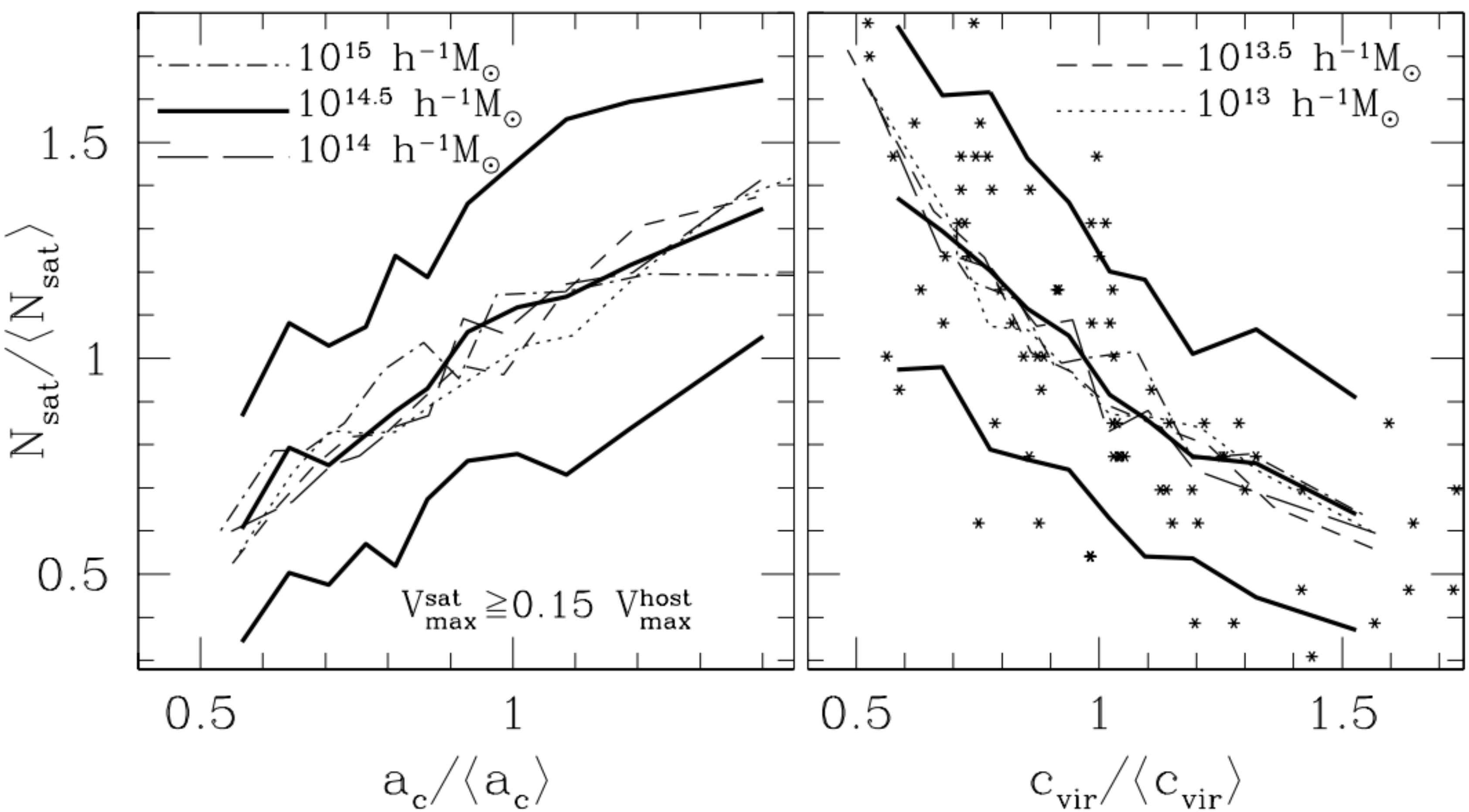
The halo-to-halo scatter?





The scatter in subhalo occupation at a fixed halo mass is **larger** than Poisson scatter.

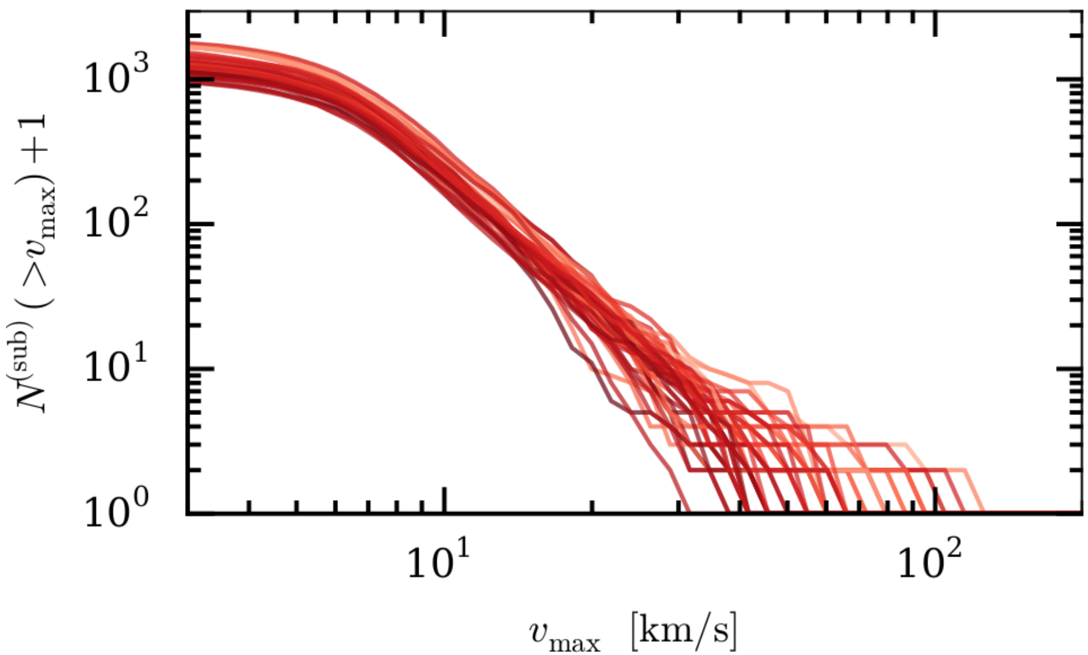
[Boylan-Kolchin+ 2010]



Correlation between subhalo abundance and halo formation time/concentration

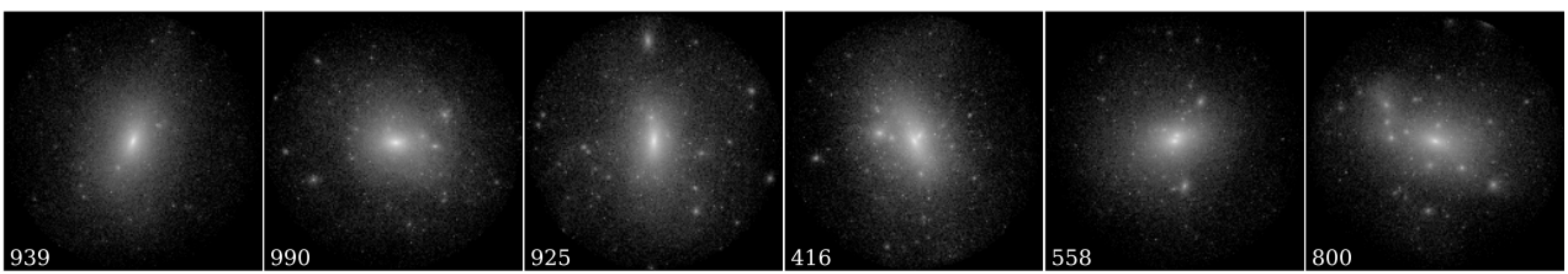
[Zentner+ 2005]

How to model the subhalo abundance function and its halo-to-halo scatter?

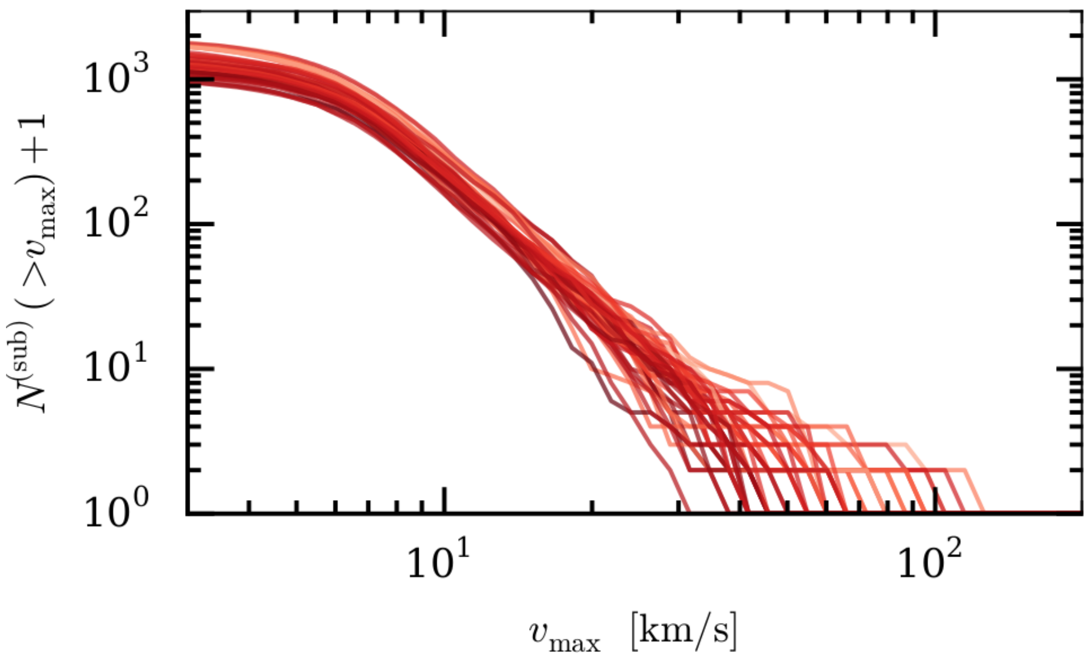


Zoom-in simulations of Milky Way-like halos

- mass resolution ~ 3 x 10^5 $M_{\rm sun}$
- subhalo resolved down to 8 km/s



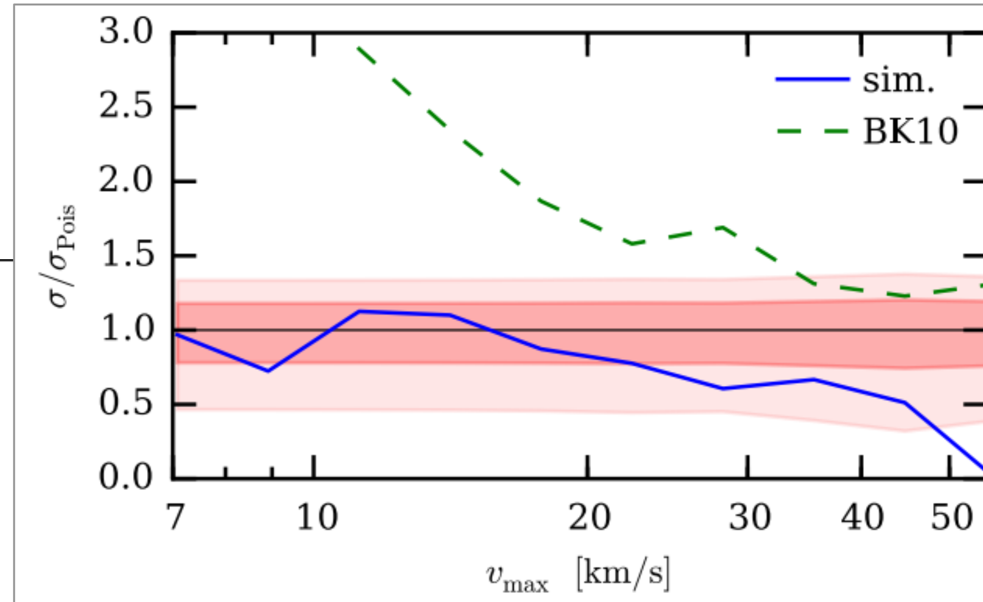
How to model the subhalo abundance function and its halo-to-halo scatter?

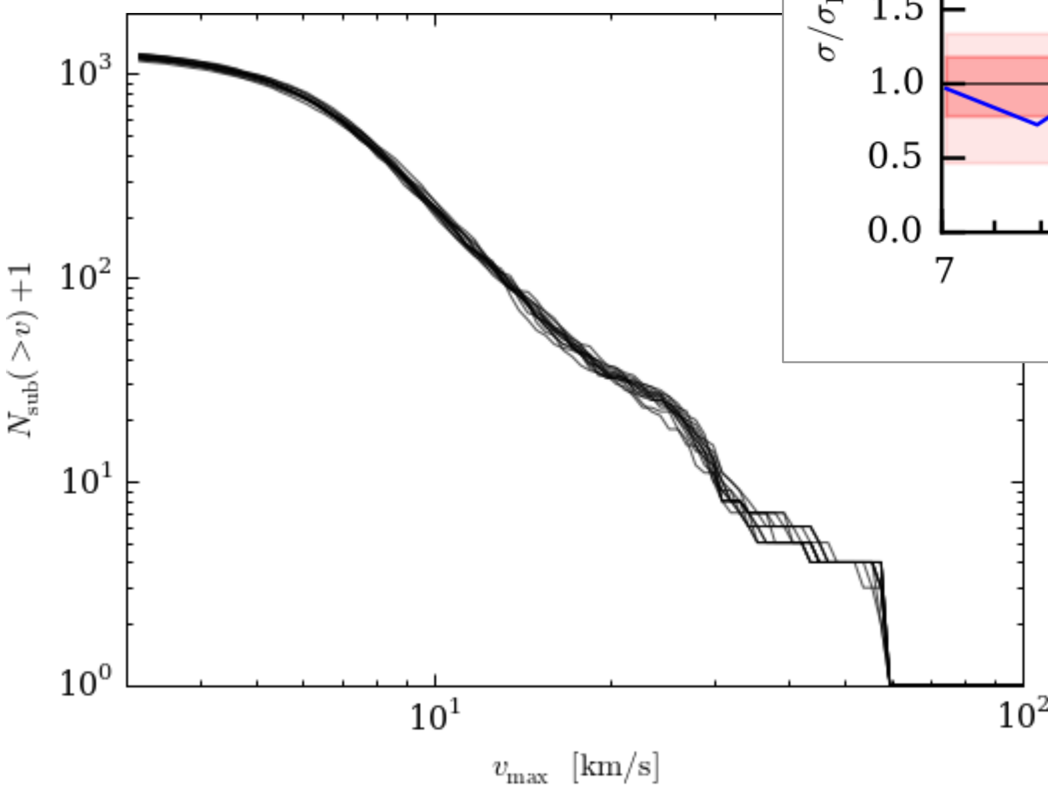


1. Halo-to-halo scatter affects mostly the normalization of the SAF
2. Normalization and host concentration are (anti-)correlated
3. The power-law index is constant (at least in a narrow mass bin)

Poisson Point Process (PPP) for a single halo

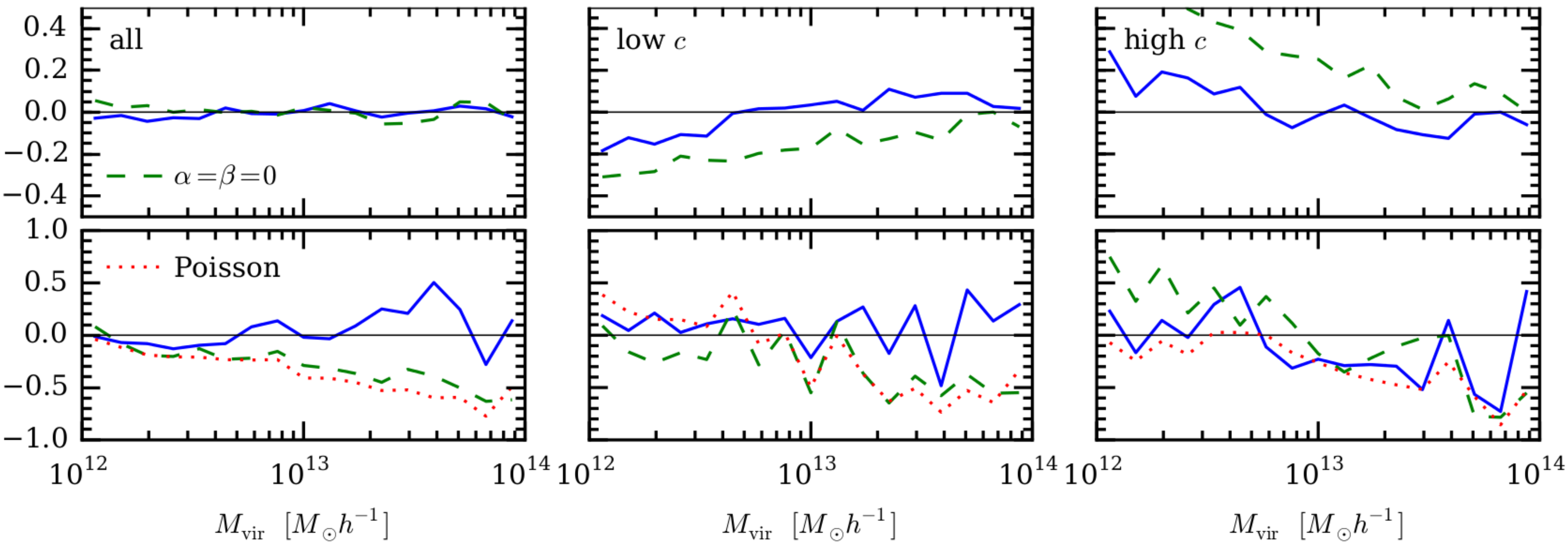
Re-simulate one single host halo with different small-scale modes.



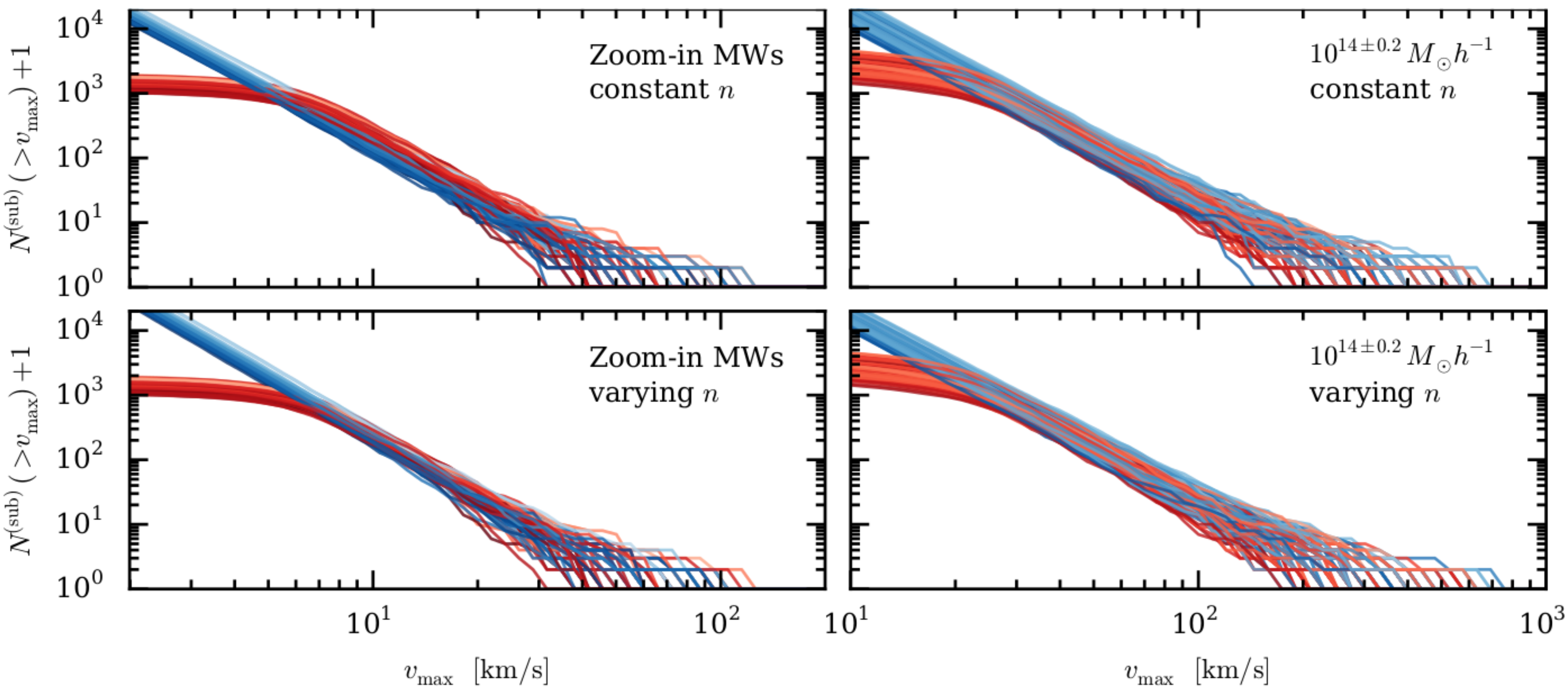


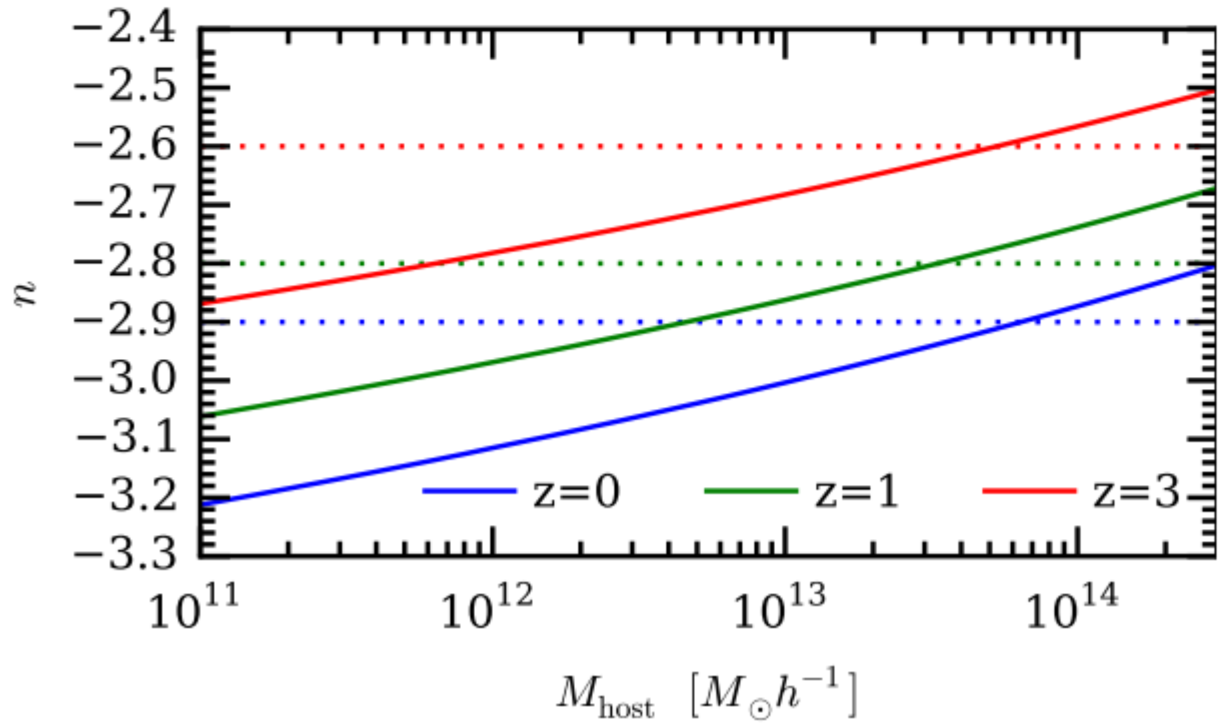
An accurate subhalo abundance model

$$\langle N(v) \rangle = \left(\frac{v}{v_0}\right)^n - \left(\frac{v_{\rm cut}}{v_0}\right)^n \qquad \begin{aligned} v_0 &= a\, v_{\rm vir} \\ v_{\rm cut} &= b\, v_{\rm vir} \\ n &= n_0 \end{aligned} \qquad \begin{aligned} a &:= a_0 \left(\frac{v_{\rm max}}{v_{\rm vir}}\right)^\alpha \\ b &:= b_0 \left(\frac{v_{\rm max}}{v_{\rm vir}}\right)^\beta \end{aligned}$$



Is the power-law index constant?





$$n = -3.05\,\nu(M,z)^{-0.1} \qquad \nu(M,z) = \frac{\delta_c}{\sigma(M)D(z)}$$

Possible mass/redshift-dependence of the power-law index

Summary

1. Scatter in subhalo abundance = halo-to-halo scatter in the sample + Poisson scatter for each individual halo
2. Halo-to-halo scatter comes from scatter in halo mass and concentration

The model can successfully reproduce the mean and the scatter of subhalo occupation in simulations.

It also provides a convenient method to sample a sequence of v_{max} that represents the subhalos of a given host halo.

Halo mass and concentration characterize subhalo abundance. Knowing the prior of MW concentration is essential for statistical analysis.

Final take-home messages

How do cosmologists provide better models for dark matter experiments?

Velocity distribution of dark matter

Relevant for direct detection

[See YYM+ (ApJ 2013) **1210.2721** and YYM+ (PRD 2013) **1304.6401**]

Realistic VDF models (ie. *not* standard halo model) are needed for accurate analysis and for extracting info of MW halos.

Dark matter subhalo abundance

Relevant for indirect detection and astrophysical observations

[See YYM+ **1503.02637**]

High-concentration halos have fewer subhalos. This model can predict the expected number of subhalos and its scatter.

Results are based on dissipationless CDM N-body simulations.