Can we measure the Milky Way mass accurately?

— a lesson from steady-state dynamics

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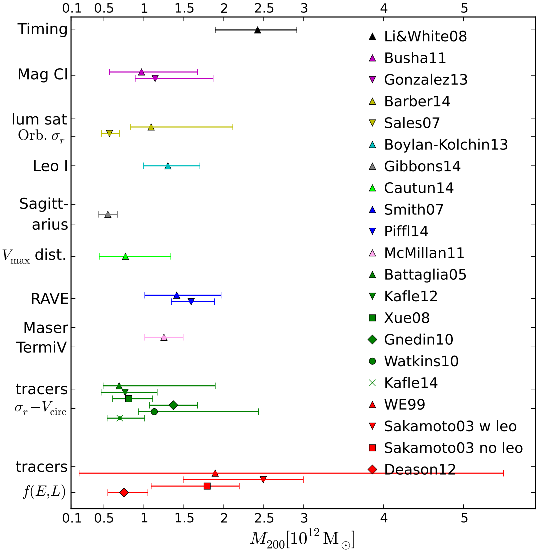
References

arxiv:1502.03477, 1507.00769, 1507.00771, and Wang et al. (2016 in prep)

Milky Way mass divergence



Different methods disagree by $\sim \times 5$: A problem with methods?

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

Testing a state-of-the-art $f(E, L)$ method

$$\left.\begin{array}{l} f(E,L) = L^{-2\beta}F(E) \\ \text{NFW potential } (M, c) \end{array}\right\} \Rightarrow$$

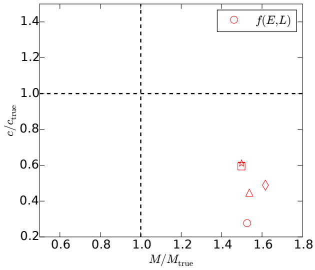
$$P(r, v_r, v_t|\rho_s, r_s, \beta, \alpha, \gamma, r_0) = f(E,L) =$$

$$-\frac{r_s^{-\alpha-\gamma} l^{-2\beta}}{2^{3/2-\beta}\pi^{3/2}v_s^3\Gamma(\beta+1/2)\Gamma(1-\beta)} \times \int_{R_{\rm inner}}^{R_{\rm max,t}} dR(\epsilon-\phi(R))^{\beta-1/2}\times$$

$$\left\{\frac{(2\beta+1)R^{2\beta}\left(\frac{R}{1+R}-\ln(1+R)\right)-\left[\frac{1}{(1+R)^2}-\frac{1}{1+R}\right]R^{2\beta+1}}{\left[\frac{R}{1+R}-\ln(1+R)\right]^2}\times\frac{(2\beta-\alpha)\left(\frac{R}{r_0}\right)^{\alpha}r_s^{-\gamma}+(2\beta-\gamma)\left(\frac{R}{r_0}\right)^{\gamma}r_s^{-\alpha}}{\left[\left(\frac{R}{r_0}\right)^{\alpha}r_s^{-\gamma}+\left(\frac{R}{r_0}\right)^{\gamma}r_s^{-\alpha}\right]^2}+\right.$$

$$\frac{R^{2\beta+1}}{\left[\frac{R}{1+R}-\ln(1+R)\right]\left[\left(\frac{R}{r_0}\right)^{\alpha}r_s^{-\gamma}+\left(\frac{R}{r_0}\right)^{\gamma}r_s^{-\alpha}\right]^2}\times\left[(2\beta-\alpha)r_s^{-\alpha-\gamma}\left(\frac{\alpha}{r_0}-\frac{2\gamma}{r_0}\right)\left(\frac{R}{r_0}\right)^{\alpha+\gamma-1}+\right.$$

$$\left.\left.(2\beta-\gamma)r_s^{-\alpha-\gamma}\left(\frac{\gamma}{r_0}-\frac{2\alpha}{r_0}\right)\left(\frac{R}{r_0}\right)^{\alpha+\gamma-1}-(2\beta-\alpha)r_s^{-2\gamma}\frac{\alpha}{r_0}\left(\frac{R}{r_0}\right)^{2\alpha-1}-(2\beta-\gamma)r_s^{-2\alpha}\frac{\gamma}{r_0}\left(\frac{R}{r_0}\right)^{2\gamma-1}\right]\right\}$$



Fits to Aquarius haloes

The fits are biased!

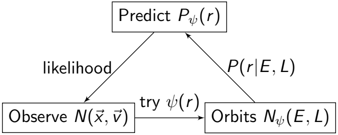
- fail to describe the loosely-bound particles

the orbital Probability Distribution Function (oPDF)

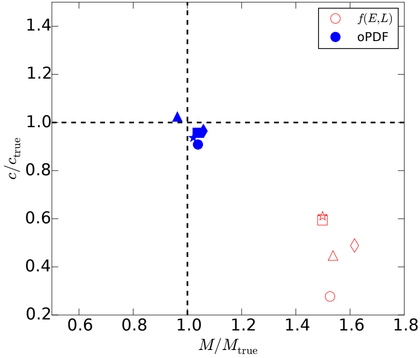
Steady-state solution to collisionless Boltzmann equation:

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

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

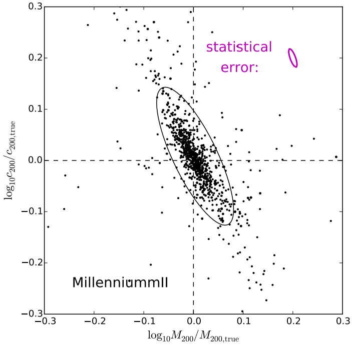


oPDF: Fits to Aquarius haloes



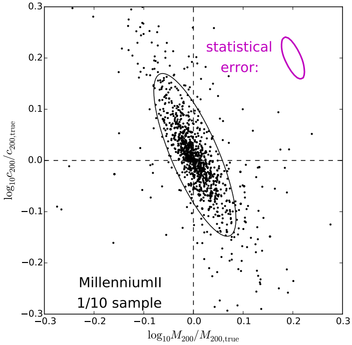
- no global systematic bias using oPDF: main source of bias removed

oPDF: Fits to many haloes



- Ensemble-unbiased
- Significant irreducible individual bias
  - $\sigma_M \sim 0.1$ dex (20%) for DM

oPDF: Fits to many haloes



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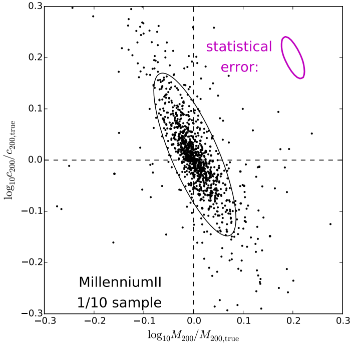
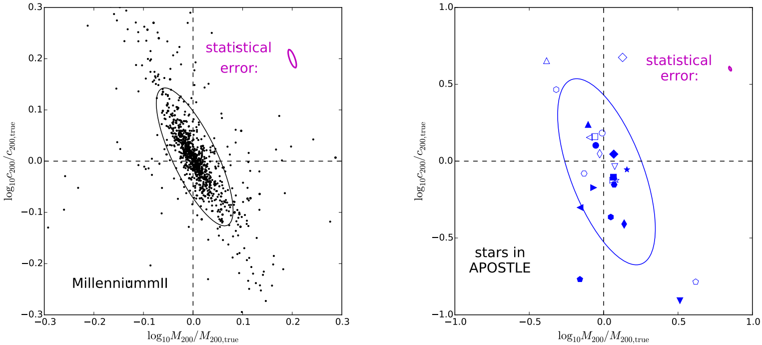
oPDF: Fits to many haloes



- Ensemble-unbiased
- Significant irreducible individual bias
  - $\sigma_M \sim 0.1$ dex (20%) for DM
  - correlate similarly as the statistical noises
  - Interpretation: correlated phase-space structure reduces $N_{\rm eff}$

oPDF: Fits to many haloes



- Stars are less in equilibrium than DM
  - DM: $\sigma_M \sim 0.1$ dex (20%)
  - Star: $\sigma_M \sim 0.3$ dex ($\sim \times 2$)

Summary and Conclusions

- Hand-made distribution functions (DF) are usually not general enough to describe the real halo
  - Unjustified assumptions $\Rightarrow$ biased fits
- oPDF is a minimal assumption method
  - steady-state assumption alone $\Rightarrow$ ensemble-unbiased fits
- Simulated haloes are approximately steady-state systems
  - correlated phase-space structure violates steady-state assumption, leading to irreducible stochastic bias
  - Intrinsic $\sigma_M \sim 20\%$ (DM) or $\sim \times 2$ (stars): a lower limit to any steady-state method!

open questions

Is a precise mass worth it?

- Which mass? For example, does the outer mass profile matter? For objects with the same inner profile but different outer profile, do they have different subhalo population?
- More generally, what is an intrinsic property of halo that really matters?