Constrain the Milky Way Mass Profile with Phase Space Distribution of Satellite Galaxies

Zhaozhou Li (李昭洲)
Shanghai Jiao Tong University

Collaborators:
Jiaxin Han (SJTU)
Wenting Wang (SJTU)
Ting Li (Carnegie)
Yongzhong Qian (UMN/TDLi)
Yipeng Jing (SJTU)
Why we care about Milky Way mass & profile

‣ Basic properties of our home galaxy
  ‣ Galactic dynamics
  ‣ Formation and assembly history of the MW
‣ Basis for validating theory predictions from local observation
  ‣ Dark matter detection
  ‣ Cosmology, e.g. expected baryon fraction, number of satellites
‣ Gravity Theory
Milky Way (MW) Mass: still very uncertain!

Challenges in data & model
- Virial radius is far beyond tracers like stars
- Poor observations in outer halo
- Model uncertainty: $\beta(r)$, $n(r)$ or form of DF
- Observation error and incompleteness
Milky Way (MW) Mass: still very uncertain!

Challenges in data & model
- Virial radius is far beyond tracers like stars
  Use satellite galaxies instead
- Poor observations in outer halo
  Gaia
  - Model uncertainty: $\beta(r)$, $n(r)$ or form of DF
    Dynamical model based on simulation
- Observation error and incompleteness
  Bayesian statistics
Satellite galaxies: best tracers for MW outer halo

Virtues:
- Extended distribution
  - the only tracers beyond 100 kpc or farther
- Proper motion (pm) available: Gaia
- Well understood population
  - knowledge from theory and simulations
  - well phase-mixed (Han+ 2019)
  ⇒ physical model based on simulation and equilibrium assumption

Data:
- 28 satellites with Gaia DR2 pm
  - 40 kpc < r < 280 kpc
- homogeneous selection function:
  - distant and faint galaxies are missed
  \( N_{\text{star}}(M_V < 20.9) \approx 5 \)
How kinematics reveal mass

Popular methods: Jeans Equation, Distribution Function
Poor observation ⇒ heavier model dependence for outer halo

Extract info from simulations to mitigate model dependence

- orbital distribution: $p(E, L \mid M)$ (Li+ 2017, Callingham+ 2018)
  more efficient use of both data and simulation
  $E$ is not observable ⇒ calibration required

phase space distribution function

$$ p(r, v) = \frac{p(E, L)}{8\pi^2 L T_r(E, L)} \equiv f(E, L) $$

similarity in halo structures ⇒ stacking & scaling

$$ p(r, v \mid M, c) = \frac{1}{r_s^3 v_s^3} \tilde{f} \left( \frac{E}{v_s^2}, \frac{L}{r_s v_s} \right) $$

complete description to satellite kinematics

precise & unbiased
rigorous treatment to observation error and incompleteness
Infer Mass & concentration

Observation $(r, v)$ vs Model $p_{\text{obs}}(r, v \mid M, c)$

\[ M = 0.6 \times 10^{12} M_{\odot} \quad \text{vs} \quad M = 1.2 \times 10^{12} M_{\odot} \]

Likelihood:

\[
p(M, c \mid \{w\}) \propto \left[ \prod_{i=1}^{n_{\text{sat}}} p_{\text{obs}}(w_i \mid M, c) \right] p(c \mid M) p(M)
\]

Observational effects included

Prior information: e.g. $M$-$c$ relation, or other indep. measurements
Test with mock sample from simulation

Example using 40 tracers
~15% precision level for halo mass
well recover the mass profile

\[ \rho(r) \]

\[ M(<r) \]

\[ \Delta \log M(<r) \]

\[ \Delta \log \rho \]

Z.Z. Li et al. submitted
Method comparison: better than Jeans method

- \( p(E, L \mid M, c) \): orbital distribution
  - \( p(E, L \mid M) \): Li+ 2017; Callingham+ 2018; \( M-c \) relation assumed
- oPDF (Han+ 2015): based on steady-state assumption representative to Jeans equation and Schwarzschild modeling
- \( f(E, L \mid M, c) \): phase space distribution (this work)

\[
p(r, v) = \frac{|v_r|}{8\pi^2 L} \left( p(r \mid E, L) \times p(E, L) \right)
\]

Phase space distribution

Radial distribution along one orbit

Orbits distribution

Steady state (oPDF) ⇔

\[
p(r, v) = \frac{p(E, L)}{8\pi^2 L T_r(E, L)} \equiv f(E, L)
\]
Current best estimation to MW halo mass

DF model based on Eagle simulation
28 MW satellites with Gaia measurement
⇒ Constrain total halo mass within 20%

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

Inferred MW mass profile

\[ Z.Z. \text{ Li et al. in prep} \]
Even better: using multiple tracer populations

Satellite Galaxies
\[ \Rightarrow \text{Total halo mass} \]
Satellites + Stars
\[ \Rightarrow \text{Shape of potential} \]

<table>
<thead>
<tr>
<th>Satellites</th>
<th>Satellites + Halo Stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>flat prior</td>
<td>$M$ (-0.24) (0.21)</td>
</tr>
<tr>
<td>$c$</td>
<td>(1.27) (0.15) (0.15)</td>
</tr>
</tbody>
</table>

$^a$ The unit of $M$ is $10^{12} M_\odot$.

M-c relation: Dutton & Macciò 2014

Halo stars: 40 to 80 kpc
 Rotation curve measured by Huang+ 2016

Satellites: 40 to 300 kpc

Z.Z. Li et al. in prep
This work
Hydro simulation matches MW satellites better

The Bayesian Evidence of Eagle is 25 times higher than SAM

Orbits of small pericenter distance
Enhanced satellite disruption due to stellar disc in hydro and real world

Circles: observed satellites
Shade: expected distribution predicted by DF based on simu.

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Mimic the extra disruption by manually remove a fraction of orbits with small $d_{peri}$ in SAM

Hydro simulation

Semi-analytical model on dark simulation with enhanced disruption

Orbits of small pericenter distance
Enhanced satellite disruption due to stellar disc in hydro and real world

Circles: observed satellites
Shade: expected distribution predicted by DF based on simu.

Z.Z. Li et al. in prep
Bonus: reducing uncertainty in satellite orbits

Satellite orbits reveal their infall history and the assembly of MW
The usage is blocked by large uncertainty in proper motion
Using DF model as prior can reduce the uncertainty in satellite orbits
Summary and Outlook

- Current **BEST** estimation to MW halo mass
  - ✓ best tracer for outer halo: satellite galaxies
  - ✓ best data available: 28 satellites with Gaia DR2 proper motion
  - ✓ realistic model: physical DF from simulation → wide usage
  - ✓ rigorous statistics: Bayes for selection function, observational error

  *Li et al. 2019 arxiv:1910.11257*
  *Li et al. 2019 in prep, coming soon!*

- Hydro simulations indeed match satellite dynamics better

- Future improvements in MW mass
  - more satellites
  - combination with other tracers (e.g. halo stars, star clusters)
  - peculiarities of MW and its history

- The DF construction method can apply to other tracers or galaxy groups & clusters

\[
M = 1.23^{+0.21}_{-0.18} \times 10^{12} M_\odot
\]

\[
c = 9.4^{+2.8}_{-2.1}
\]
Supplements
Varying satellite sample selection

The mass estimation is robust against various sample selection criteria.
General performance with mock sample

Varying the number of tracers

- Unbiased
- Low systematics (<10%)
  negligible comparing to current statistical uncertainty level

\[\text{Mass}\]
Enhanced satellite disruption due to stellar disc in hydro simulations

Richings 2018

Garrison-Kimmel 2017, Kelley 2018