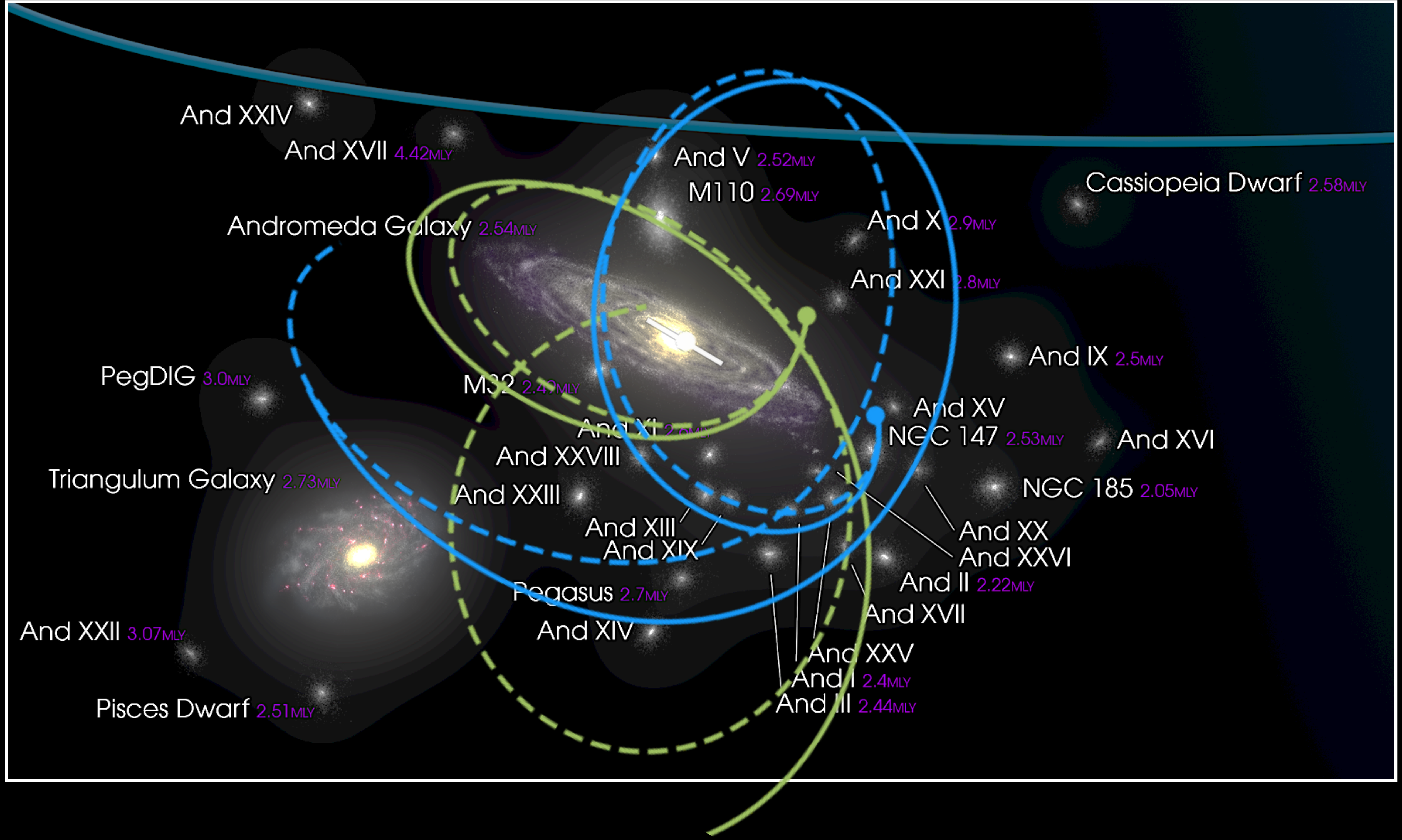
Constraining the Total Mass of Andromeda with Precision Astrometry



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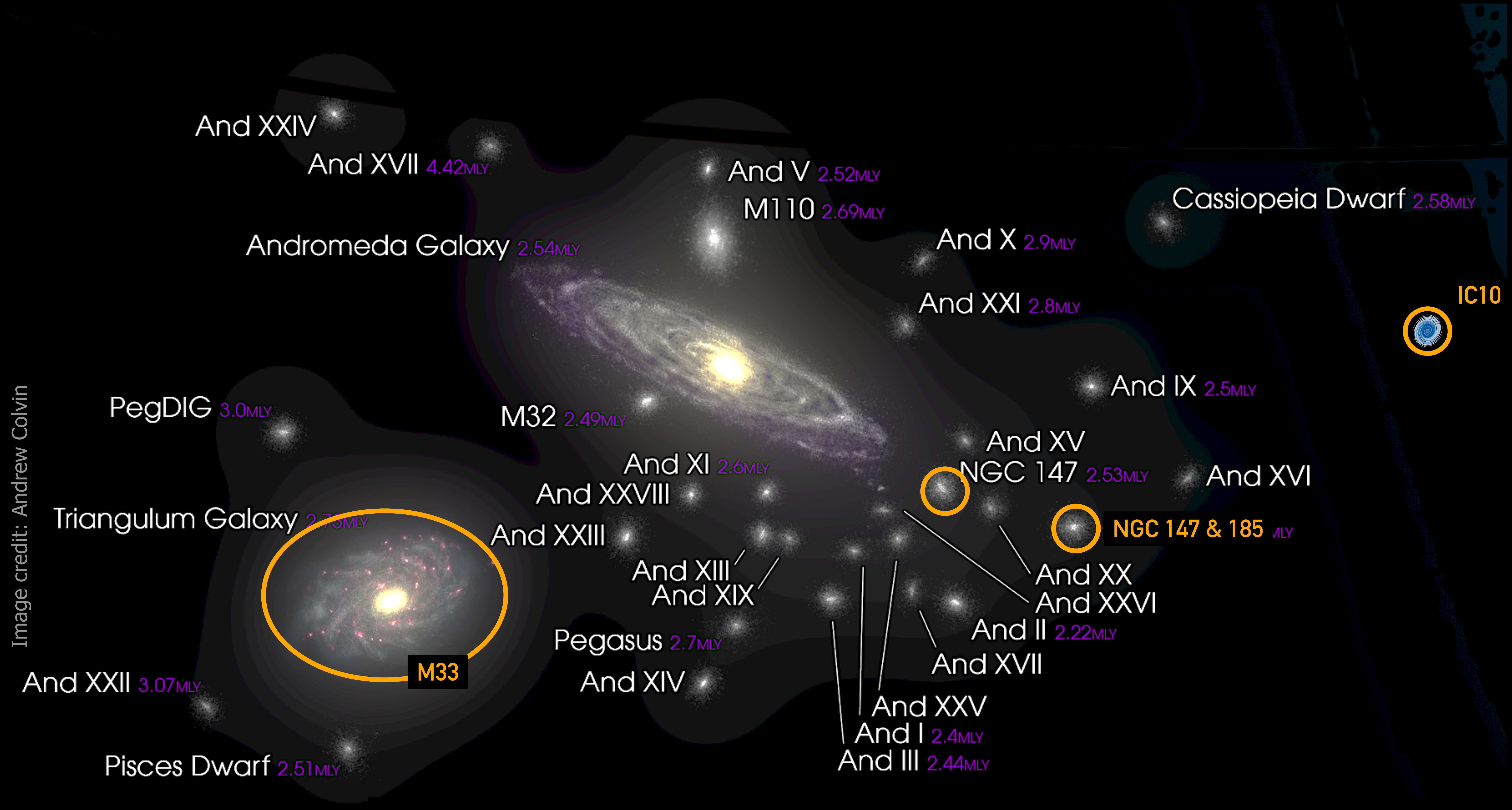
Kaisey Mandel (IoA Cambridge)

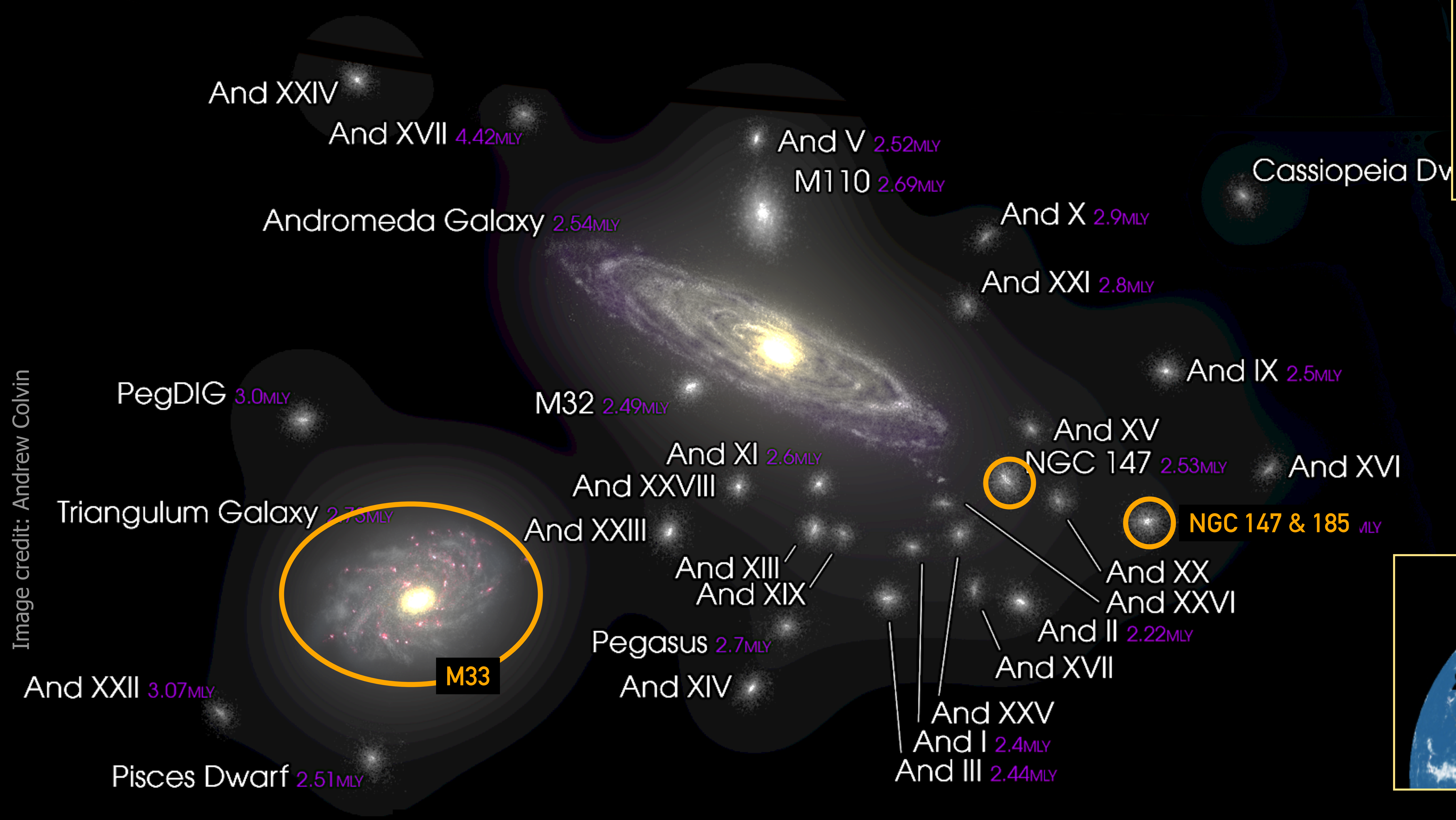
arXiv:2211.15928

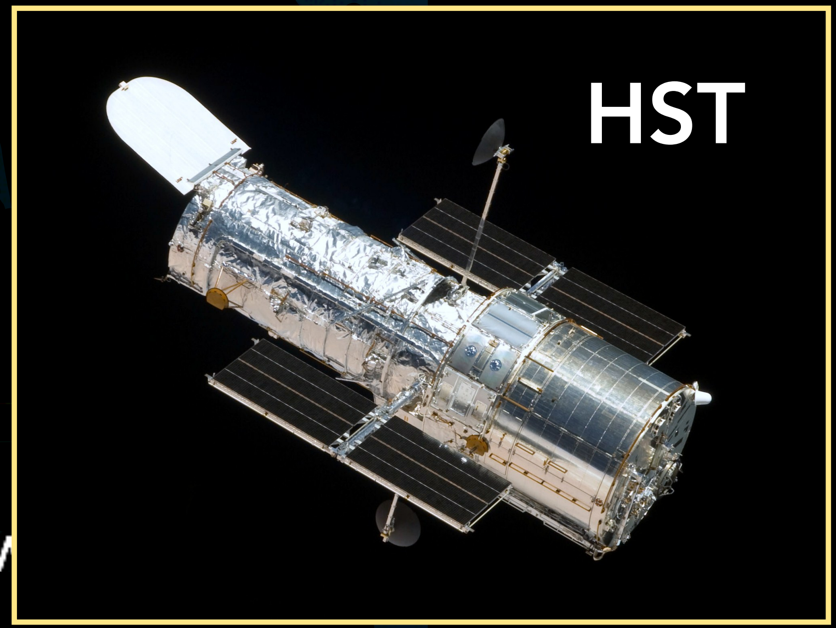
Precision Astrometry and the Andromeda System



As of 2022, full 6D phase space information is available for M31 + 4 satellites!

Precision Astrometry and the Andromeda System





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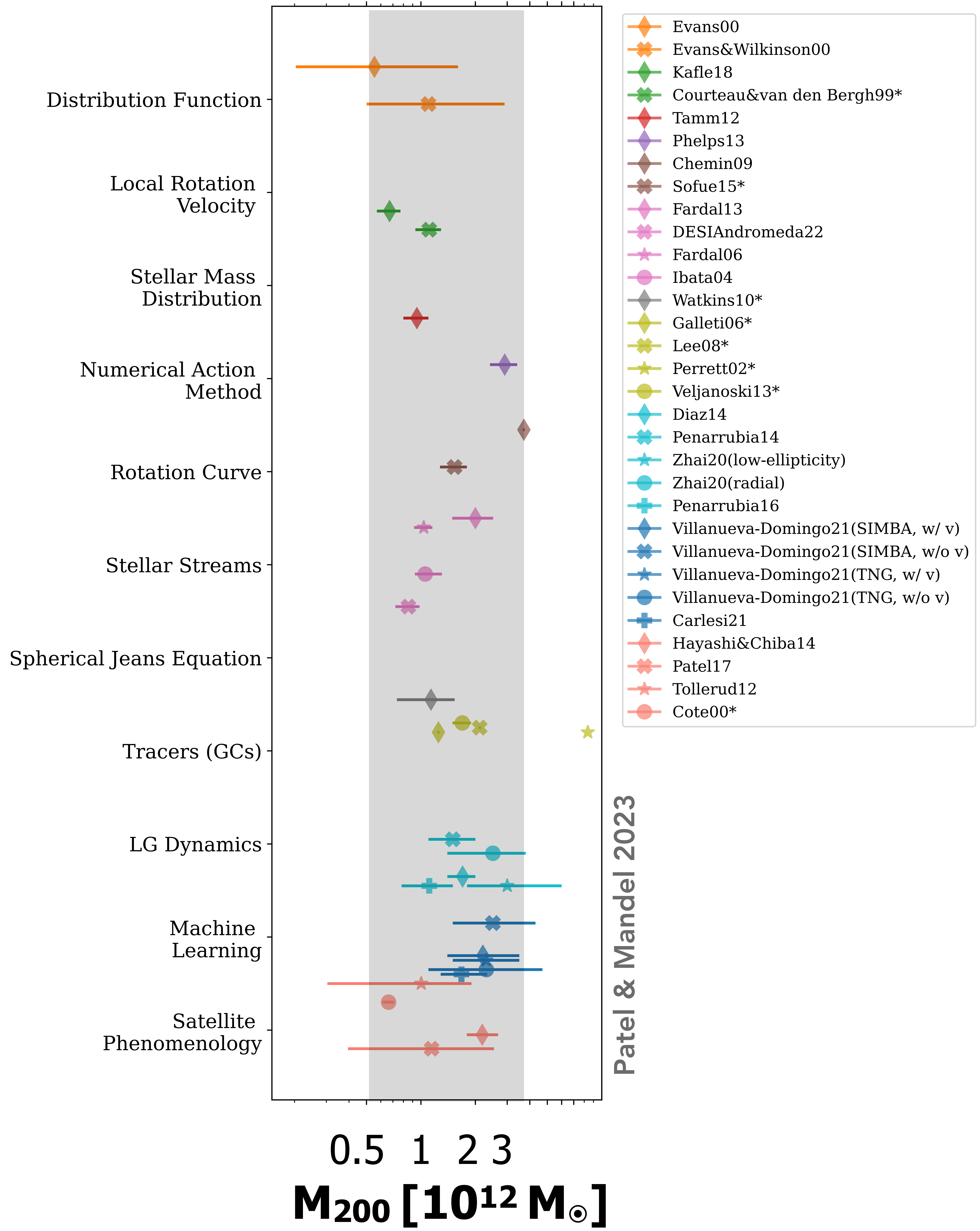
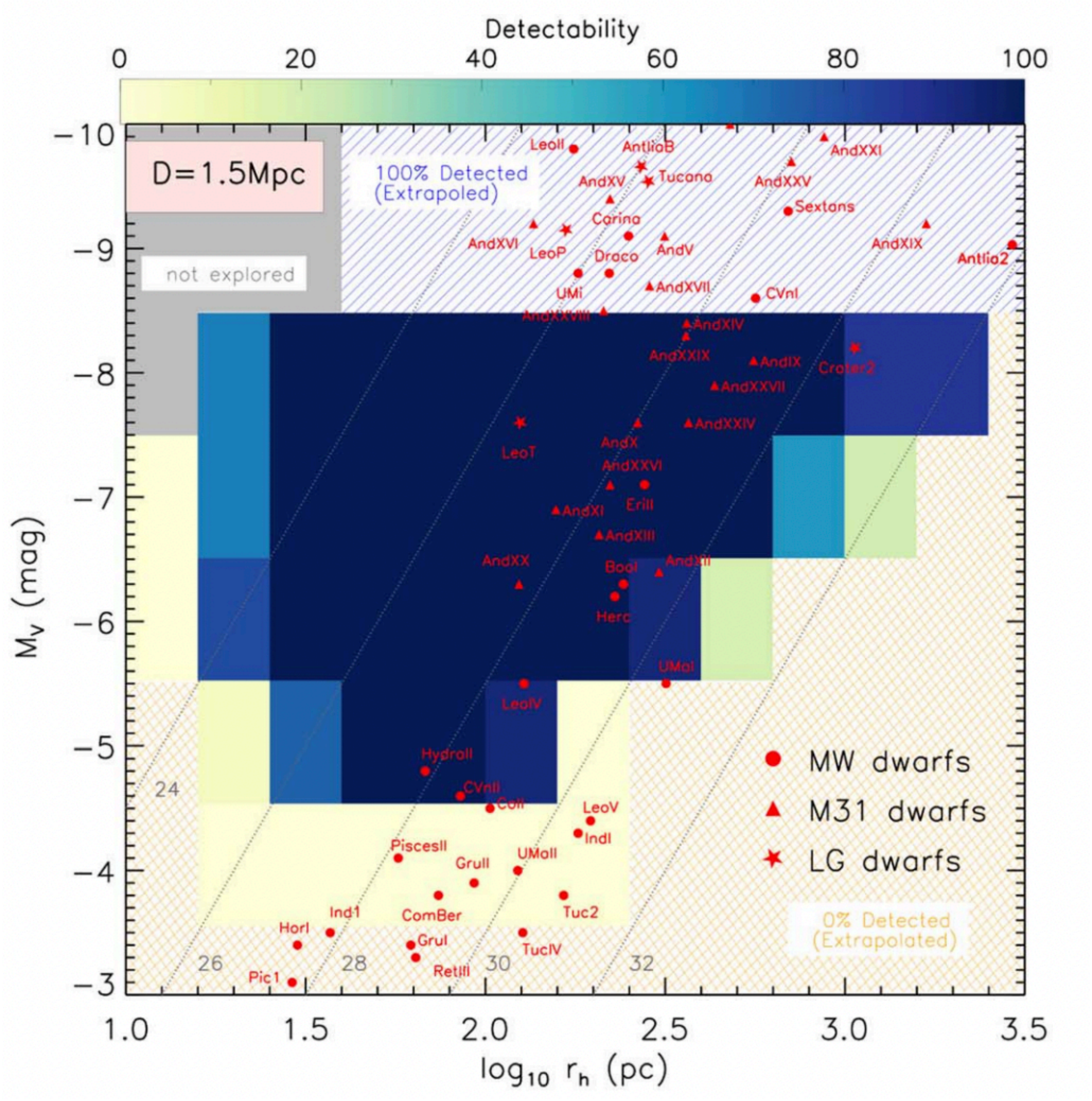


M31 Mass Estimates Since 2000

- Current values for the total mass of M31 range from 0.5−3×10^{12} $M_{\odot}$.
- Many independent mass methods have focused on just 1 tracer (stream, satellite galaxy) or only 1D kinematics (i.e. v_{rad}) when >1 tracers are used.
  - *<u>stellar streams (1 tracer):</u> require assumptions about halo properties (shape, β, etc)*
  - *<u>dynamical tracers (10-30 tracers):</u> only 1D kinematics for globular clusters and satellites*
  - *<u>satellite orbits (1-2 tracers):</u> is the satellite bound? at a unique orbital phase?*
- Halo mass is empirically correlated to a number of galaxy properties, motivating the need for a precise mass (uncertainty ≲ 20%).

Why is a precise mass so important?

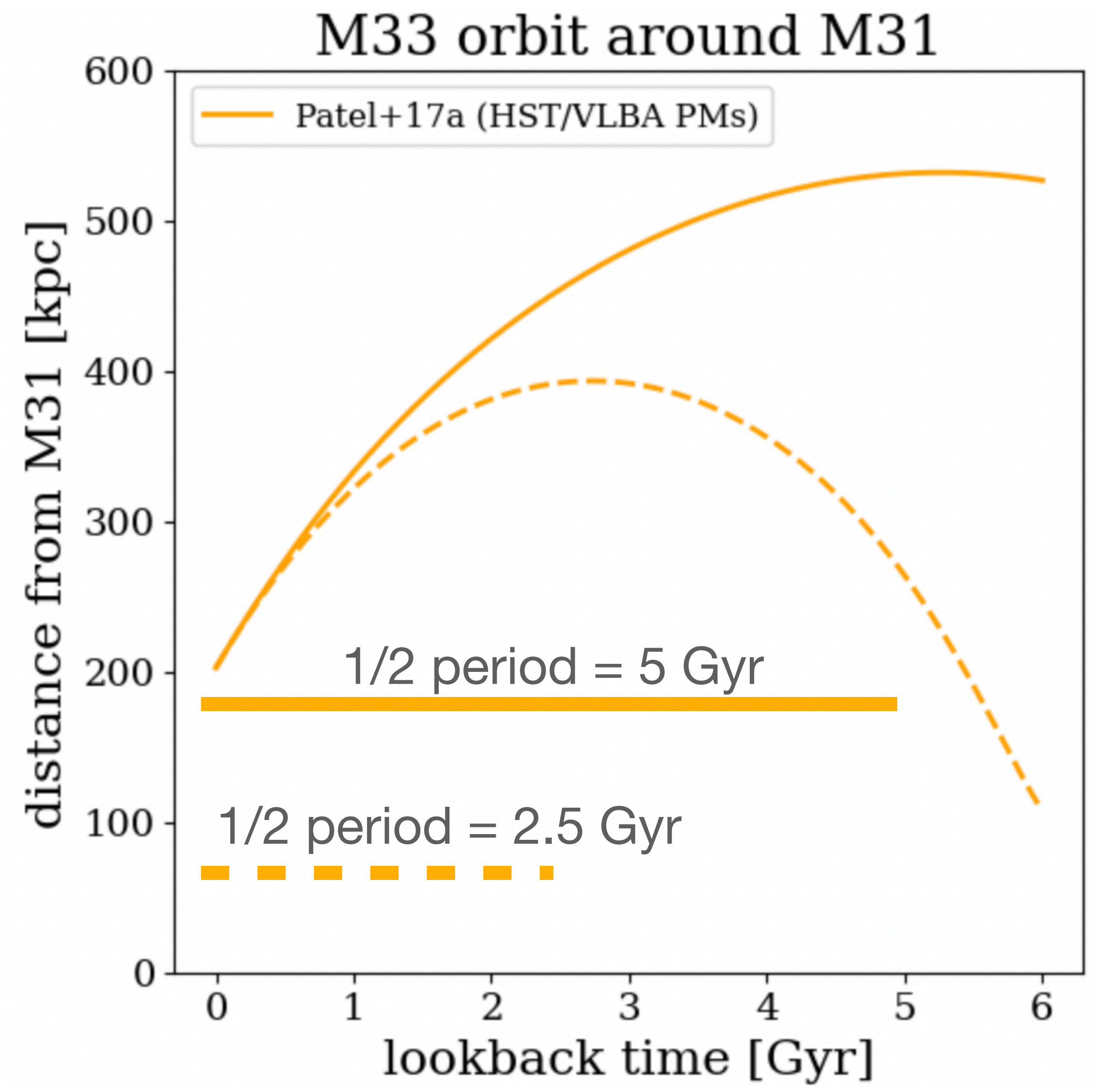
1. total # of expected satellite galaxies



Subaru/SSP and Rubin/LSST will significantly increase the # of known M31 satellites. Roman will yield another influx of discoveries.

(Mutlu-Pakdil+21)

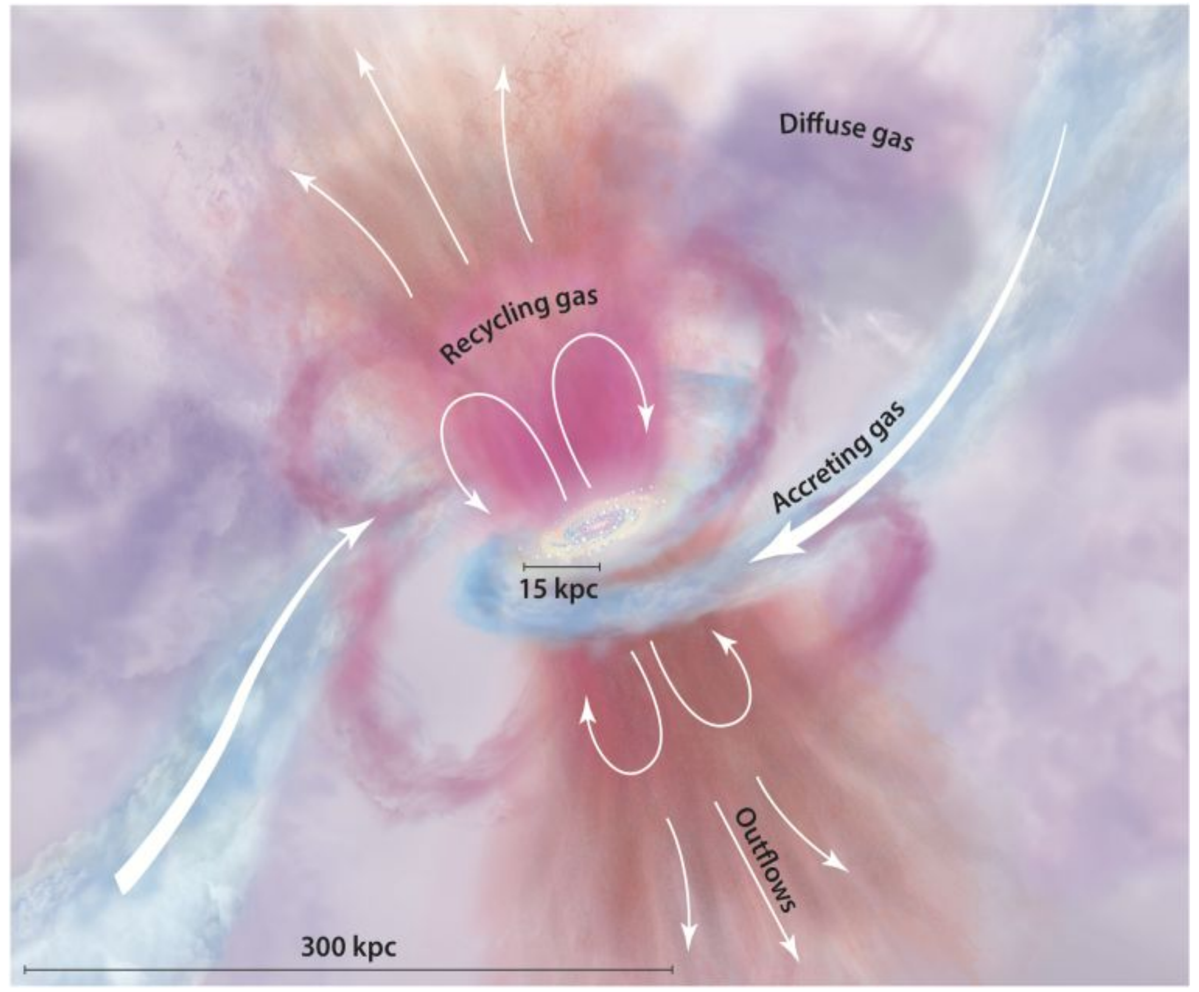
2. orbital parameters of satellite galaxies, streams, and globular clusters



M33's orbital period varies by a factor of ~2 when M31's mass is increased by 50%.

(Patel+17a)

3. the total mass budget and severity of the missing baryons

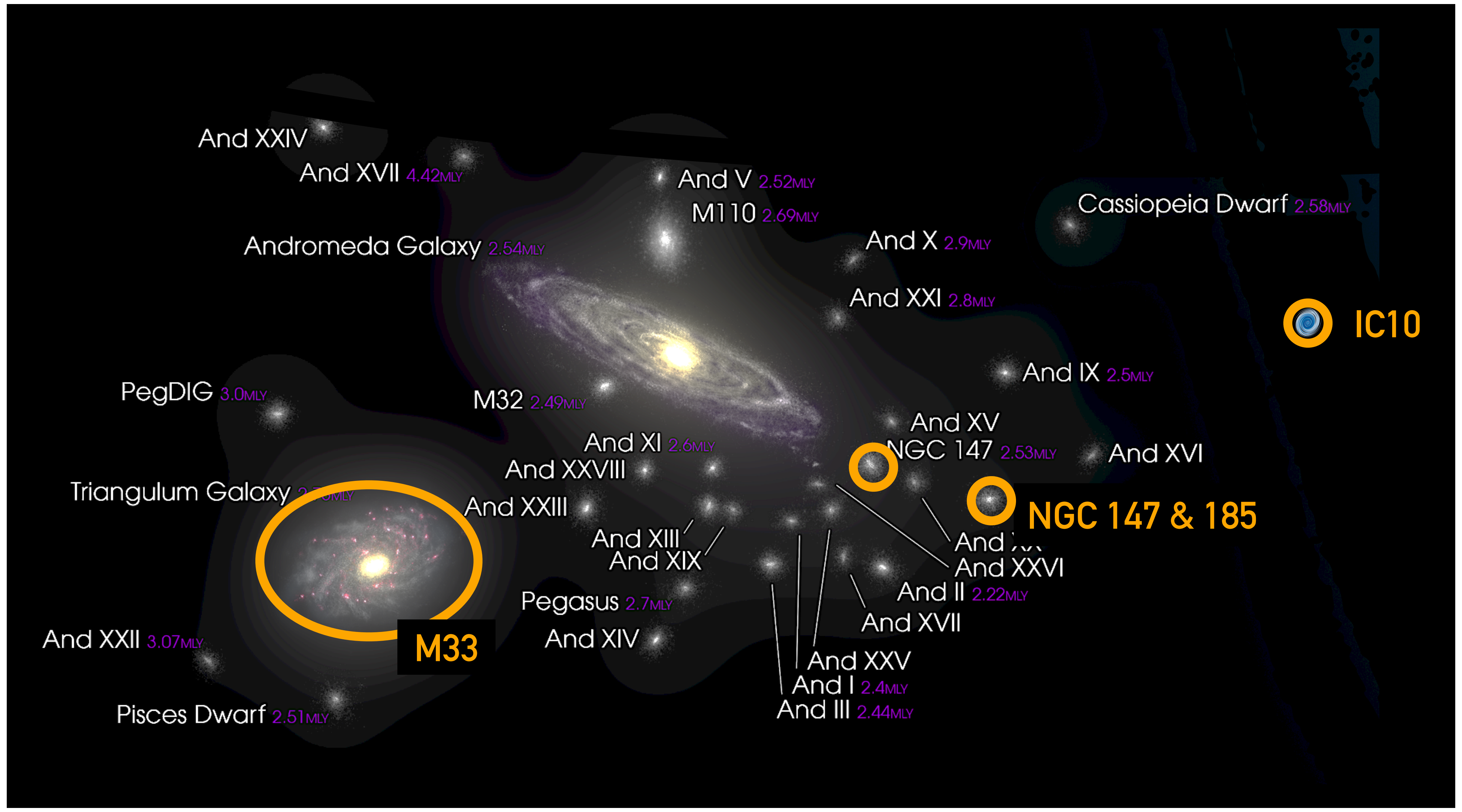


Recent work implies that the CGM of M31 only accounts for ~30% of missing baryons.

(J. Tumlinson/Zhang+21)

Observational Data for 4 Andromeda Satellite Galaxies

proper motion + distance + LOSv → 3D space motion



M33
- **VLBA** Proper Motion (Brunthaler+05)
- **GaiaDR2** Proper Motion (van der Marel w/Patel+19)
- **HST** RR Lyrae Distance (Savino w/Patel+22)

IC 10
- **VLBA** Proper Motion (Brunthaler+07)
- **HST** TRGB Distance (McQuinn+17)

NGC 147 & NGC 185
- **HST** Proper Motion (Sohn, Patel+20)
- **HST** RR Lyrae Distance (Savino w/Patel+22)

M31
- **HST** Proper Motion (Sohn+12, van der Marel+12)
- **GaiaDR2** Proper Motion (van der Marel w/Patel+19)
- **HST** RR Lyrae Distance (Savino w/Patel+22)

All 6D satellite properties are anchored to an M31 v_{tan} zero point.
Two observational data sets are considered in Patel & Mandel 2023:

1) **HST** M31 v_{tan} (denoted as HST+sats)
2) **HST**+**Gaia DR2** M31 v_{tan} (denoted as HST+GaiaDR2)

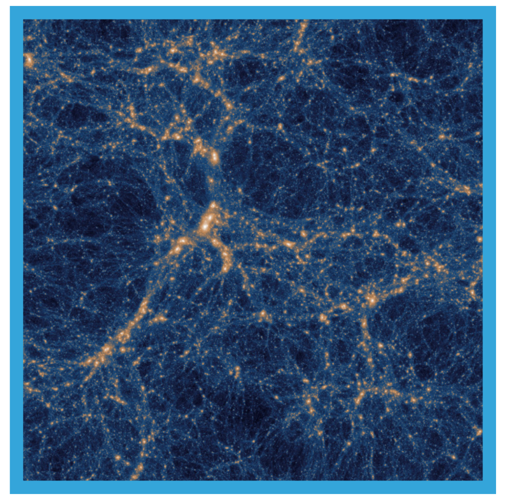
Patel & Mandel 2023

Weighing Andromeda with its Satellite Galaxies

combining precision astrometry (3D motions) with simulated galaxies

PRIOR

Broad selection of simulated LCDM halos and companion subhalos (primary halo's mass: free parameter)



Illustris TNG Simulations
(Springel+, Nelson+, Pillepich+, Naiman+, Marinacci+2018)

DATA

Observed satellite properties derived from 6D phase space

- r_{GC}: distance from COM of host
- v_{tot}: total velocity relative to host
- $j=|r \times v|$: specific orbital angular mom.
- v_{max}: max. circular velocity

LIKELIHOOD

Weights computed for each halo in the prior given a product of normal distributions built around the data

POSTERIOR

Use likelihood weights to calculate the probability density function for host halo mass

(See also Busha+11, Gonzalez+13, **Patel+17b**)

Patel+18a,23

Prior Sample for 4 Andromeda Satellite Galaxies

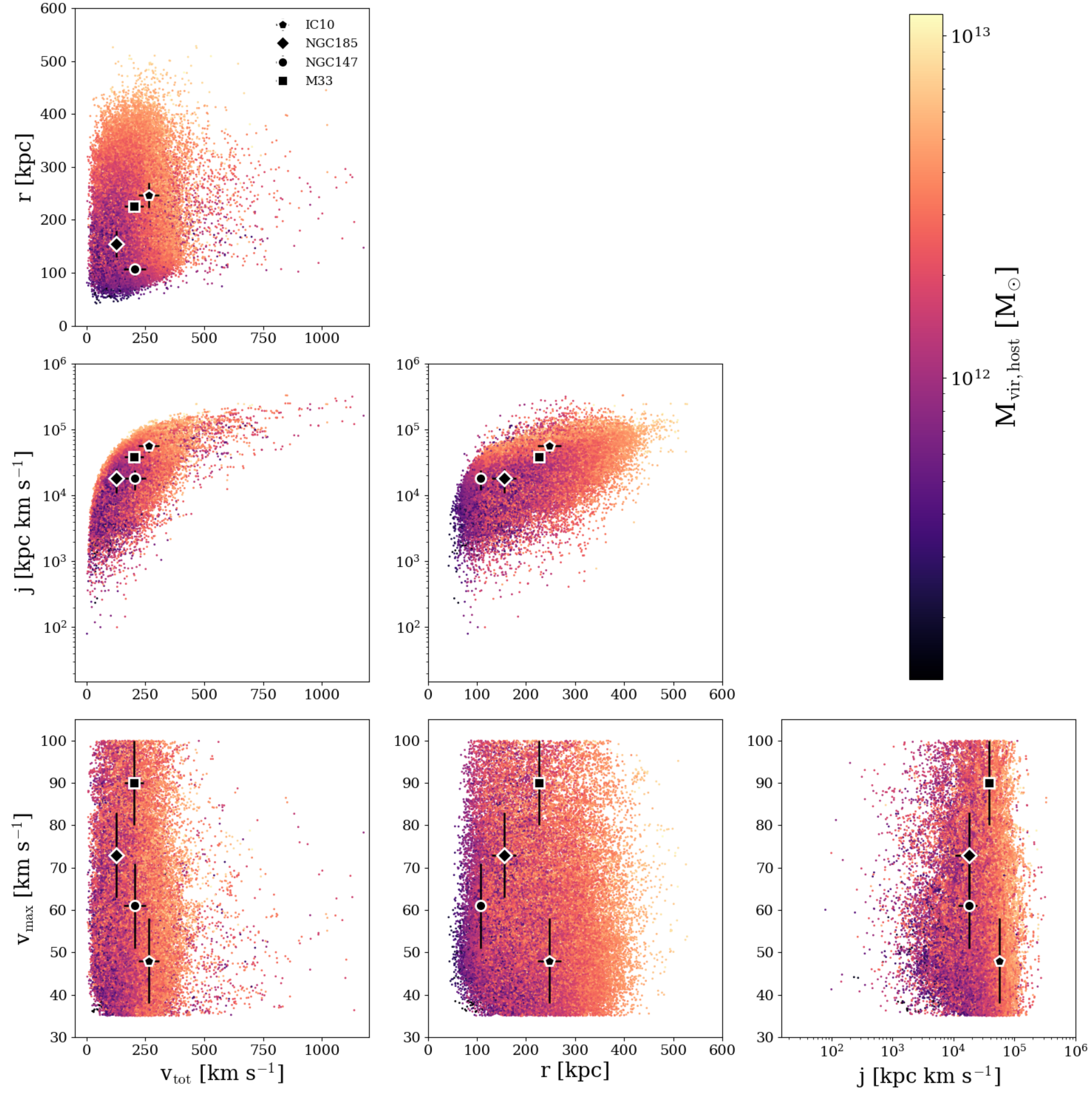
The prior includes all central halos in TNG100 from z=0-0.26 that satisfy:

- Host halo has v_{circ} < 250 km/s

and any subhalos up to N_{sub}=10 where:

- subhalo v_{max} > 35 km/s
- subhalo position < group $0.3R_{vir}$ - R_{vir}
- subhalo mass ≥ 5×10^9 $M_\odot$ at z≈0

group virial mass (M_{vir}) is a free parameter



Patel & Mandel 2023

*only plotting first 4 subhalos in each halo system

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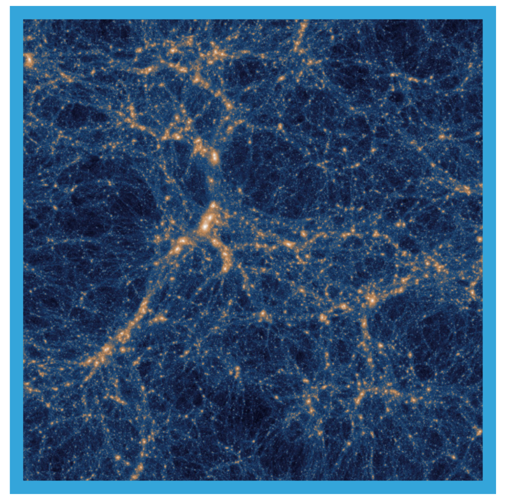

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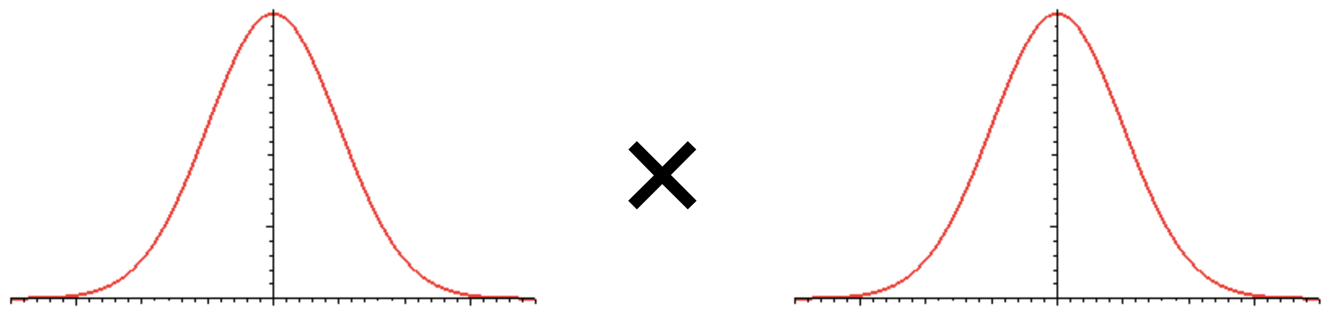


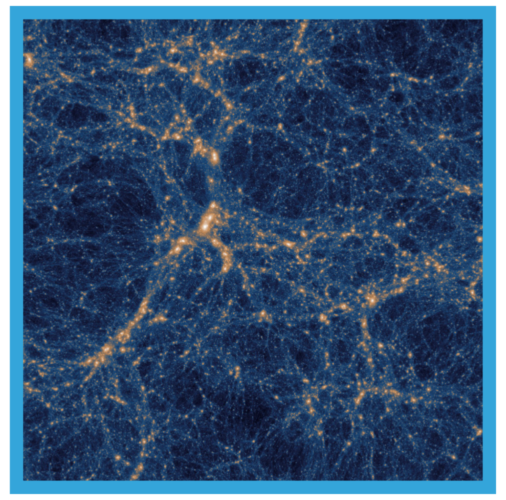
Momentum Method
(j, v_{max})

Patel+18a,23

Weighing Andromeda with its Satellite Galaxies

combining precision astrometry (3D motions) with simulated galaxies

PRIOR — Broad selection of simulated LCDM halos and companion subhalos (primary halo's mass: free parameter)



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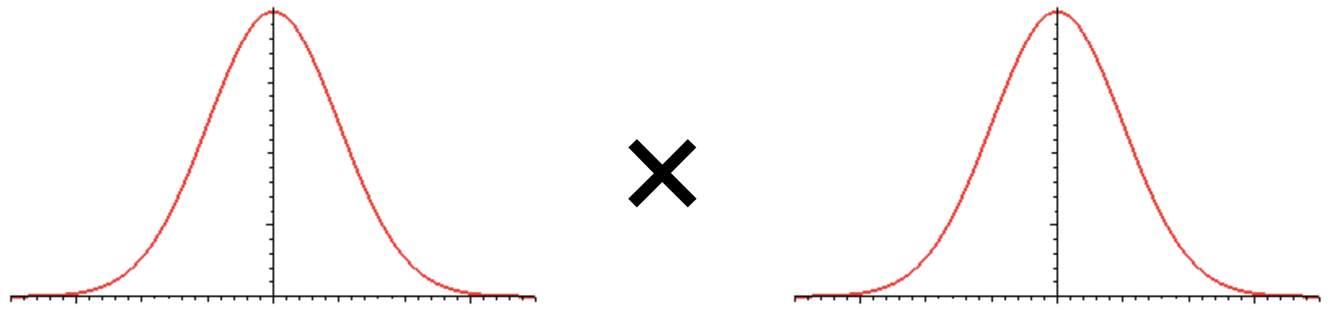


Momentum Method
(j, v_{max})

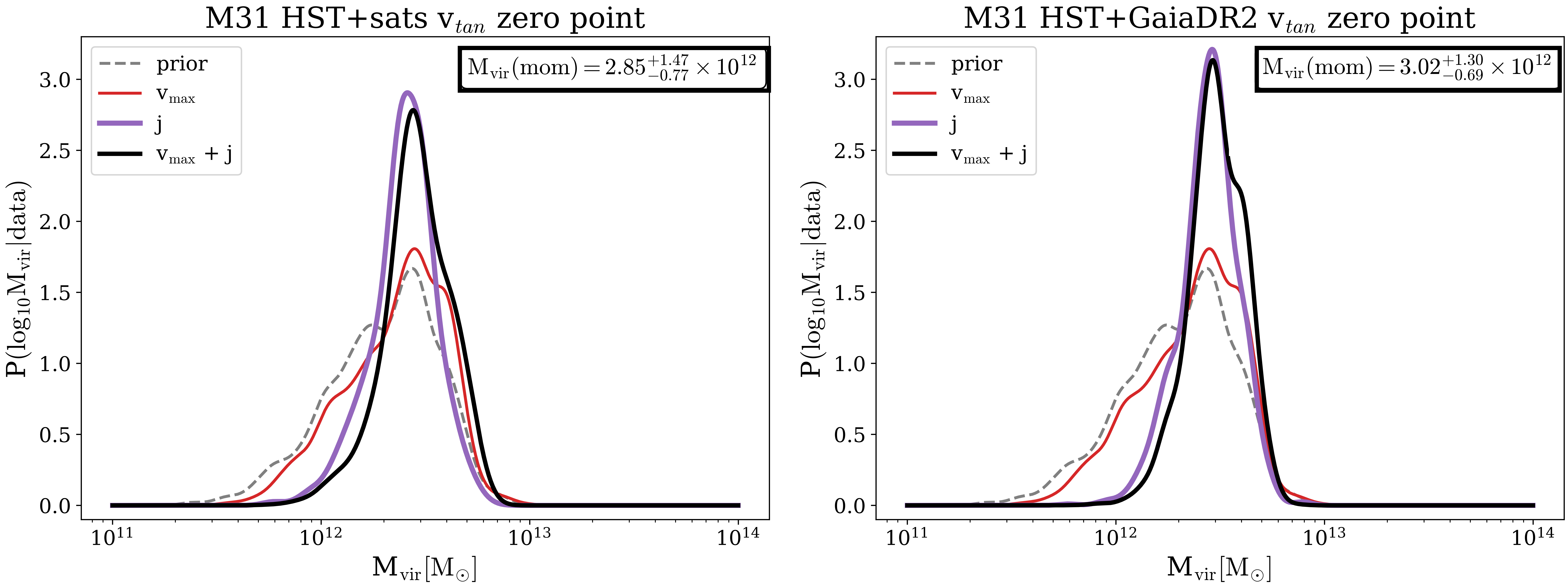
POSTERIOR — Use likelihood weights to calculate the probability density function for host halo mass

$$P(\theta|Data) = \frac{P(\theta)\ P(Data|\theta)}{P(Data)}$$

(See also Busha+11, Gonzalez+13, **Patel+17b**)

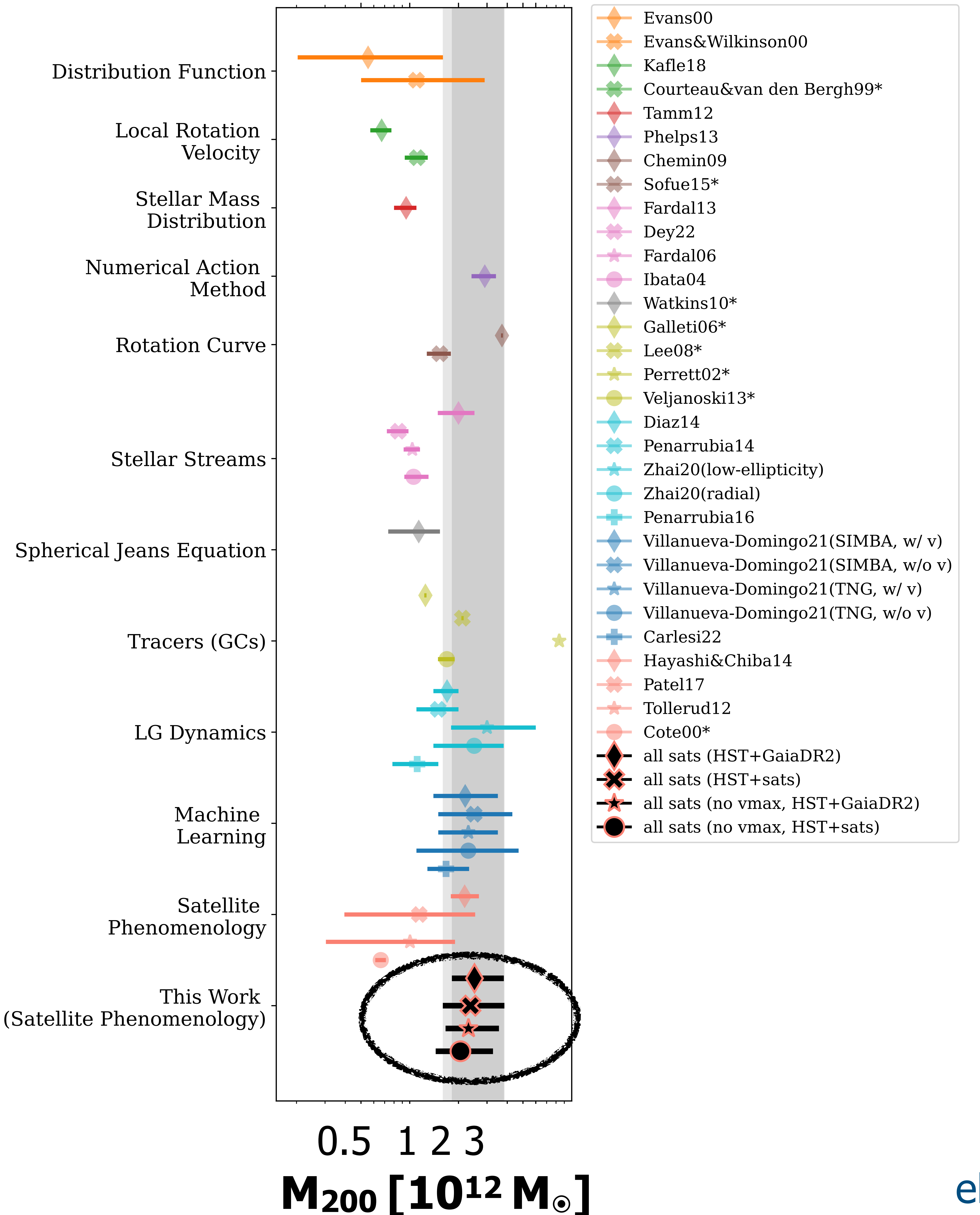
Patel+18a,23

Posterior Mass Estimates for M31 Using 4 Satellite Galaxies



Both M31 v_{tan} zero points yield a minimum of ~2×10^{12} $M_\odot$.
Our new results yield uncertainties of ~20-50% and favor a **high mass** M31.

Patel & Mandel 2023



Summary

1. Previously we showed that the momentum method provides consistent halo mass estimates over time, regardless of satellite orbital phase.

2. The properties of four M31 satellite galaxies used in tandem yield a **high M31 mass** at ~20-50% uncertainty compared to ~50-110% uncertainty from just one satellite galaxy.

3. A high mass has implications for:
(i) modeling the orbits of halo substructures,
(ii) interpreting the merger history of M31,
(iii) the dynamics/timing history of the LG.

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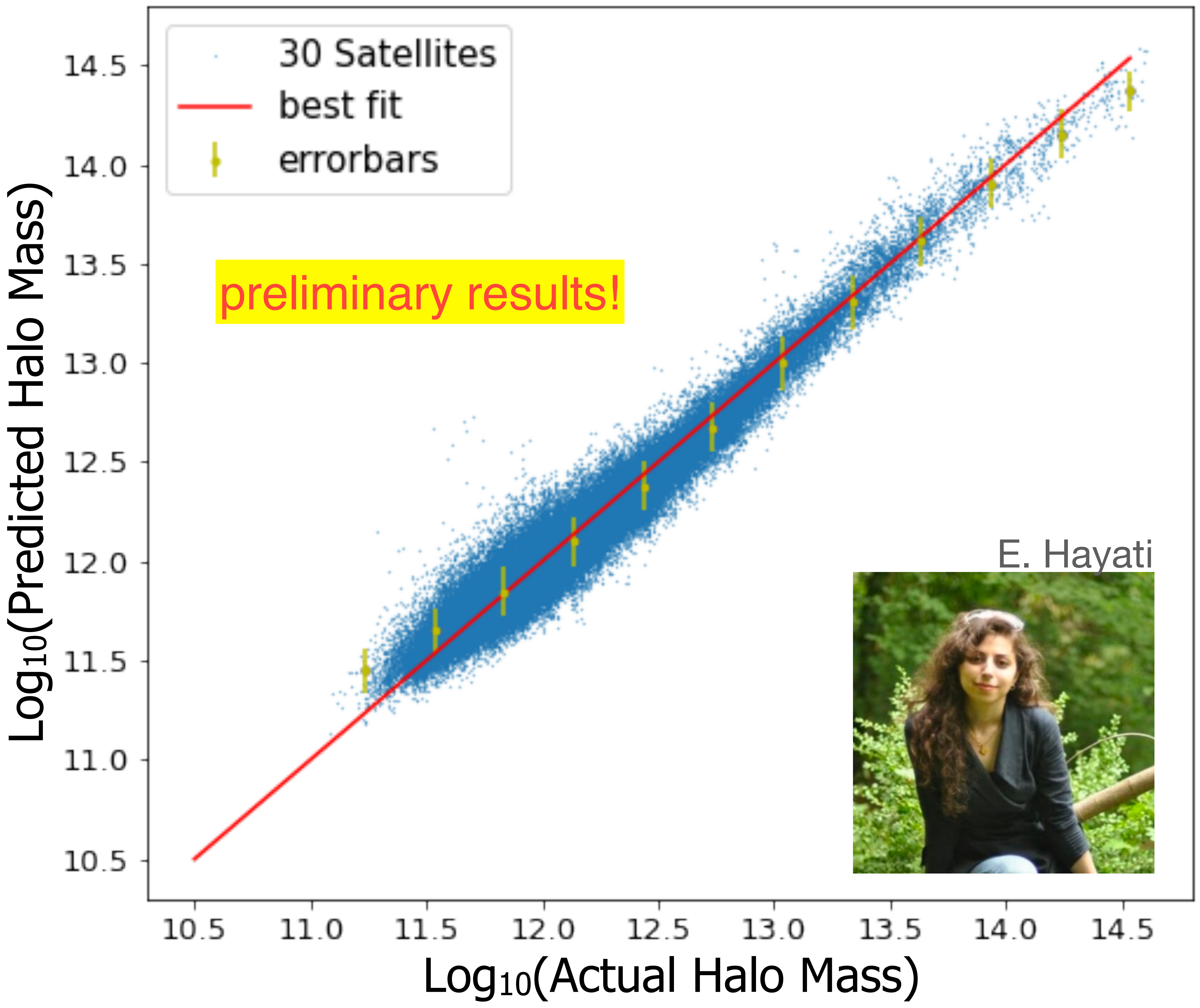
Patel & Mandel 2023

Summary



Using 30 satellite tracers, preliminary results for actual vs. predicted halo masses using neural nets yield uncertainties of **only ~35%**.

1. Previously we showed that the momentum method provides consistent halo mass estimates over time, regardless of satellite orbital phase.

2. The properties of four M31 satellite galaxies used in tandem yield a **high M31 mass** at ~30-60% uncertainty compared to ~50-110% uncertainty from just one satellite galaxy.

3. A high mass has implications for:

(i) modeling the orbits of halo substructures,

(ii) interpreting the merger history of M31,

(iii) the dynamics/timing history of the LG.

4. As more satellite proper motions are measured around M31 and *M33*, neural nets will be used to build prior samples with N $\gtrsim$ 4 satellites (Hayati et al., in prep.).

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