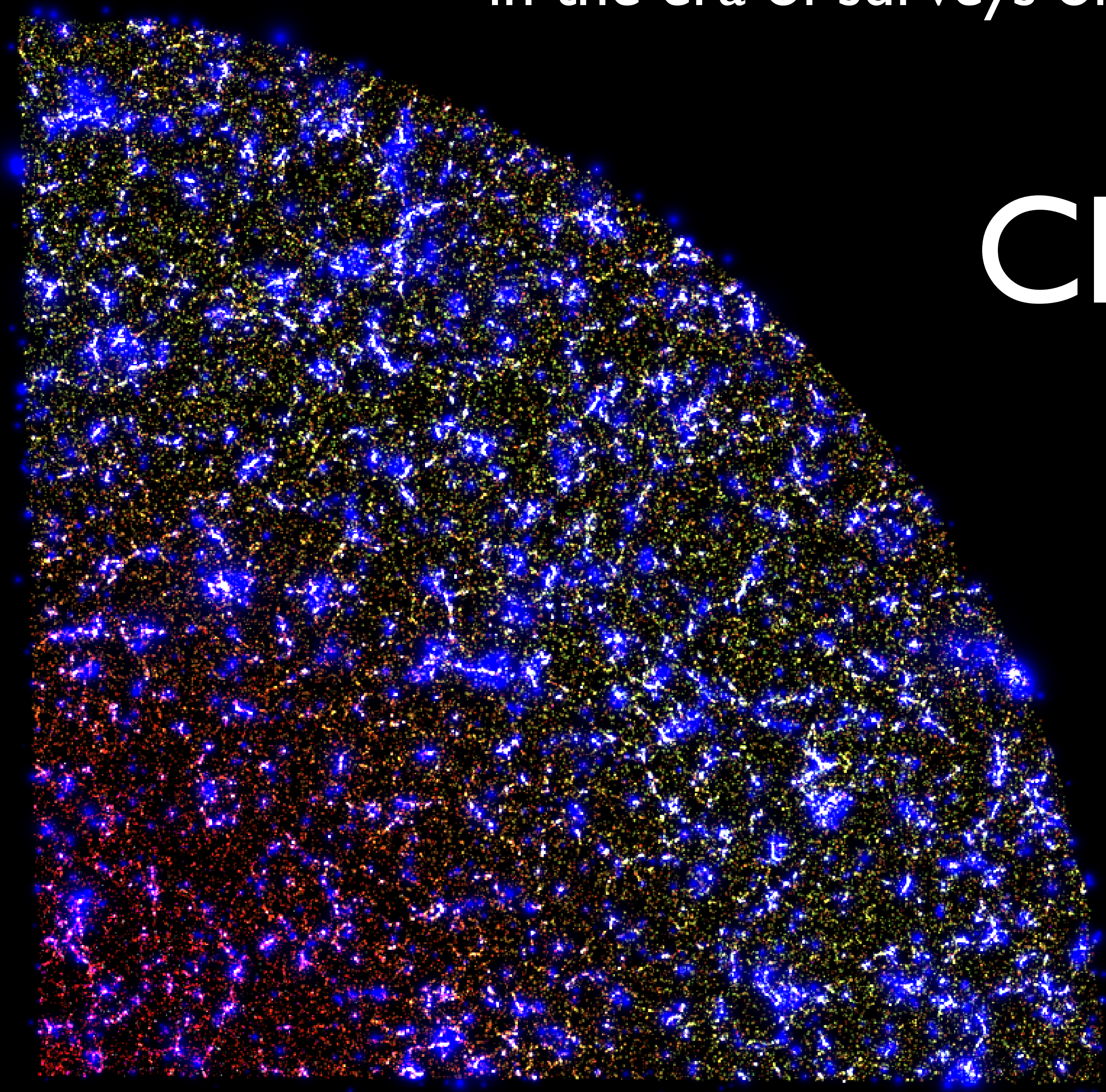
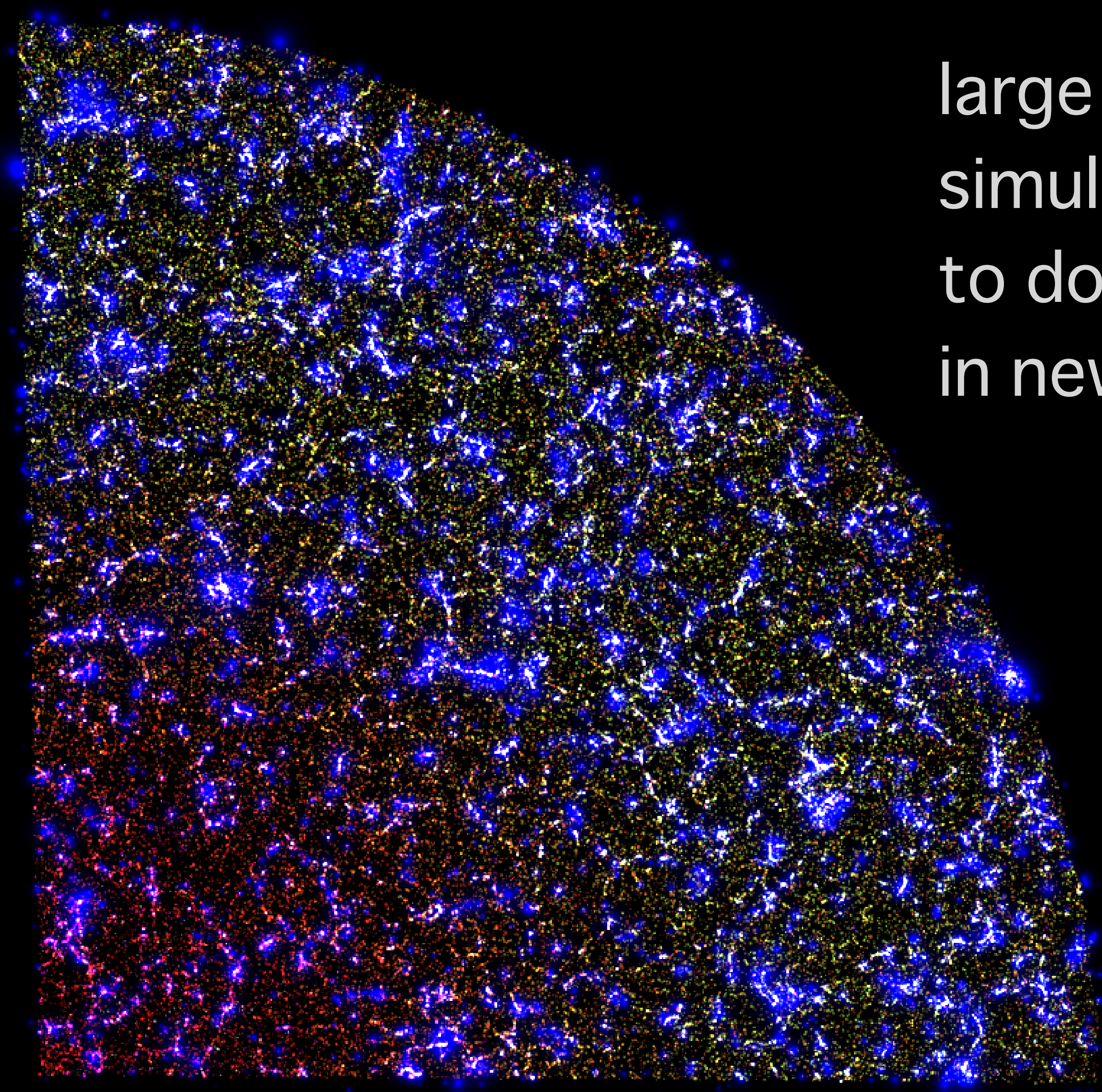
Creating, Testing, and Using
Simulations of the Galaxy Population
in the era of surveys of 10 billion galaxies



# Chapter 3:
# Using.

Risa Wechsler
KIPAC @ Stanford & SLAC



large cosmological simulations allow you to do many analyses in new ways

Inference from the Prior PDF of Cosmological Simulations.

# basic idea:

- let's say you have an object (or objects) that you observe.
- you know some of its observed properties.
- you have a cosmological simulation that you think reproduces those properties well.
- your simulation has a lot of volume, so that you would statistically expect to find many objects with these observed properties.

# basic idea: continued

- (for simplicity, consider the case where the cosmological model in your simulation is identical to the true cosmological model of our universe)
- Catalogs from this cosmological simulation can be thought of as the prior PDF on the properties of your object.
- You then importance sample this prior PDF with your observable data, to get the posterior PDF of some underlying property of the object in question.

# example

What is the mass of the Milky Way?

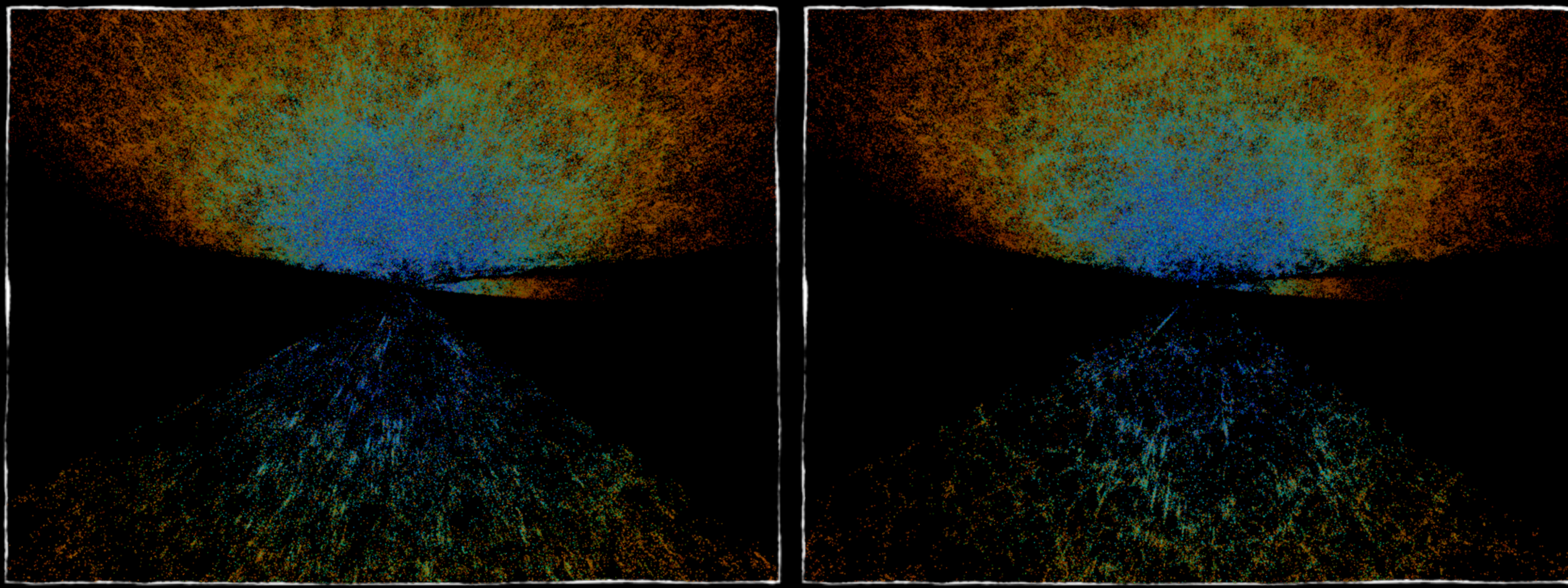
Busha, Marshall et al (2011); Marshall, Busha, RW 2012 in prep

# What observable information might tell us about this?

- the rotation curve, as traced by stellar halo stars
- the properties of the MW satellites: positions, masses, proper motions
- motion with respect to Andromeda
- etc...

- Large cosmological simulations contain millions of dark matter halos
- We know the position mass, velocity, motions, internal properties of each one at every output time, plus their assembly histories
- A halo catalog can be thought of as a set of samples drawn from our prior probability density function for galaxy halos

# Bolshoi vs SDSS



- Reproduces small and large scale clustering of galaxies
- 100,000 halos have at least one sub-halo

- The Milky Way has two large satellite galaxies, the LMC and SMC

What can the existence and properties of these galaxies teach us about the properties and history of the MW?

# Observational Constraints on the Milky Way

- Not a “satellite” of a larger structure
- Has exactly two satellites with $v_{max}$ > 50 km/s
- No other substructures within 300 kpc with $v_{max}$ > 25km/s

Sagittarius is next brightest with $v_{max}$ ~ 20 km/s (Strigari et al 10)

| | LMC | SMC |
|---|---|---|
| $v_{max}$ | ~65 km/s | ~60 km/s |
| $r_0$ | 50 kpc | 60 kpc |
| $v_{rad}$ | 89 ± 4 km/s | 23 ± 7 km/s |
| Speed | 378 ± 18 km/s | 301 ± 52 km/s |

Watkins, Evans, & An 2010;
Kallivayalil, van der Marel, & Alcock 06;
Krachentsev et al 04;
van der Marel et al 02

# What people often do:

- very difficult measurement (e.g. proper motion of the MCs: observing the motion of stars relative to background quasars over a baseline of several years)
- interpret in the context of simplified dynamical models
- better: model the dynamics of halos in their true cosmological context; dynamics generated by an LCDM universe

- The Milky Way has exactly two satellite galaxies with $v_{max}$ > 50 km/s, the LMC and SMC

- 36000 halos in Bolshoi have exactly two satellite galaxies with $v_{max}$ > 50 km/s.

# Constrained halo catalogs

- We have some intrinsic halo properties {x} e.g. mass, concentration, assembly history...
- We have some data [d] for these objects.
- What is the posterior for these intrinsic properties, given the data?
- $P(\{x\}|[d]) \sim P([d]|\{x\})P(\{x\})$

# Constrained halo catalogs

- Subhalos in Bolshoi catalog

  Prior PDF: $P_1$ ( $\{M_{host}, r_1, v_1, r_2, v_2, \ldots\}$ | H )

- Observations of Magellanic Clouds:

  Likelihood $P_2$ ( $[r_{1,obs}, v_{1obs}, r_{2,obs}, v_{2,obs}]$ | $\{x\}$, H)

- New measurements:

  Posterior PDF $P_3$ ( $\{x\}$ | $[d]$, H ) $\alpha$ $P_1 \times P_2$

# Constrained halo catalogs

- Posterior PDF $P_3$ ( {x} | [d], H ) $\alpha$ $P_1$ x $P_2$
- We want samples from P3, but we … have samples from P1. Look at i…

  <x> = \int x $P_3$ d…

  … dx

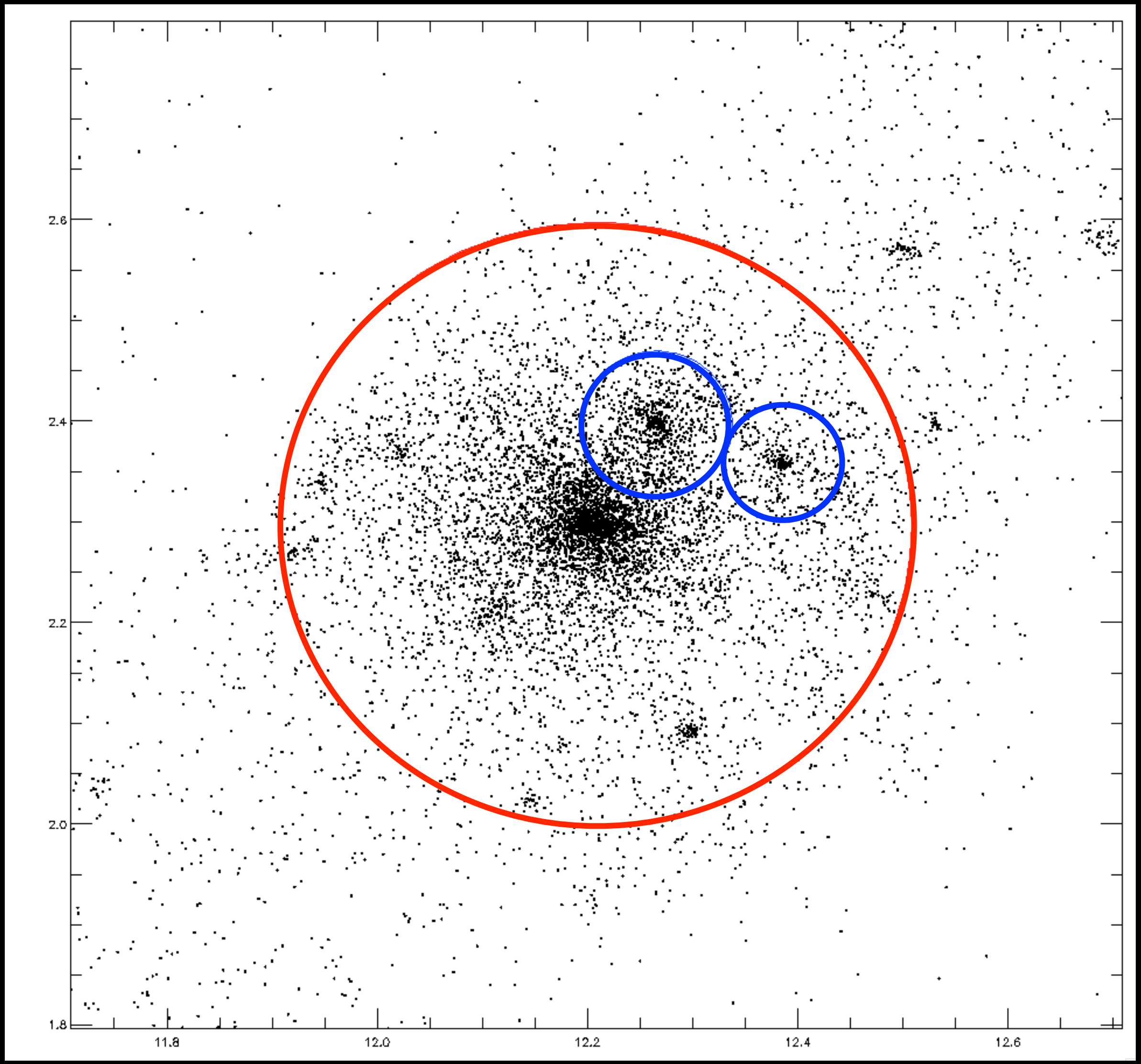
  … $P_1$ dx

  ~ \sum{ x $P_2$ }

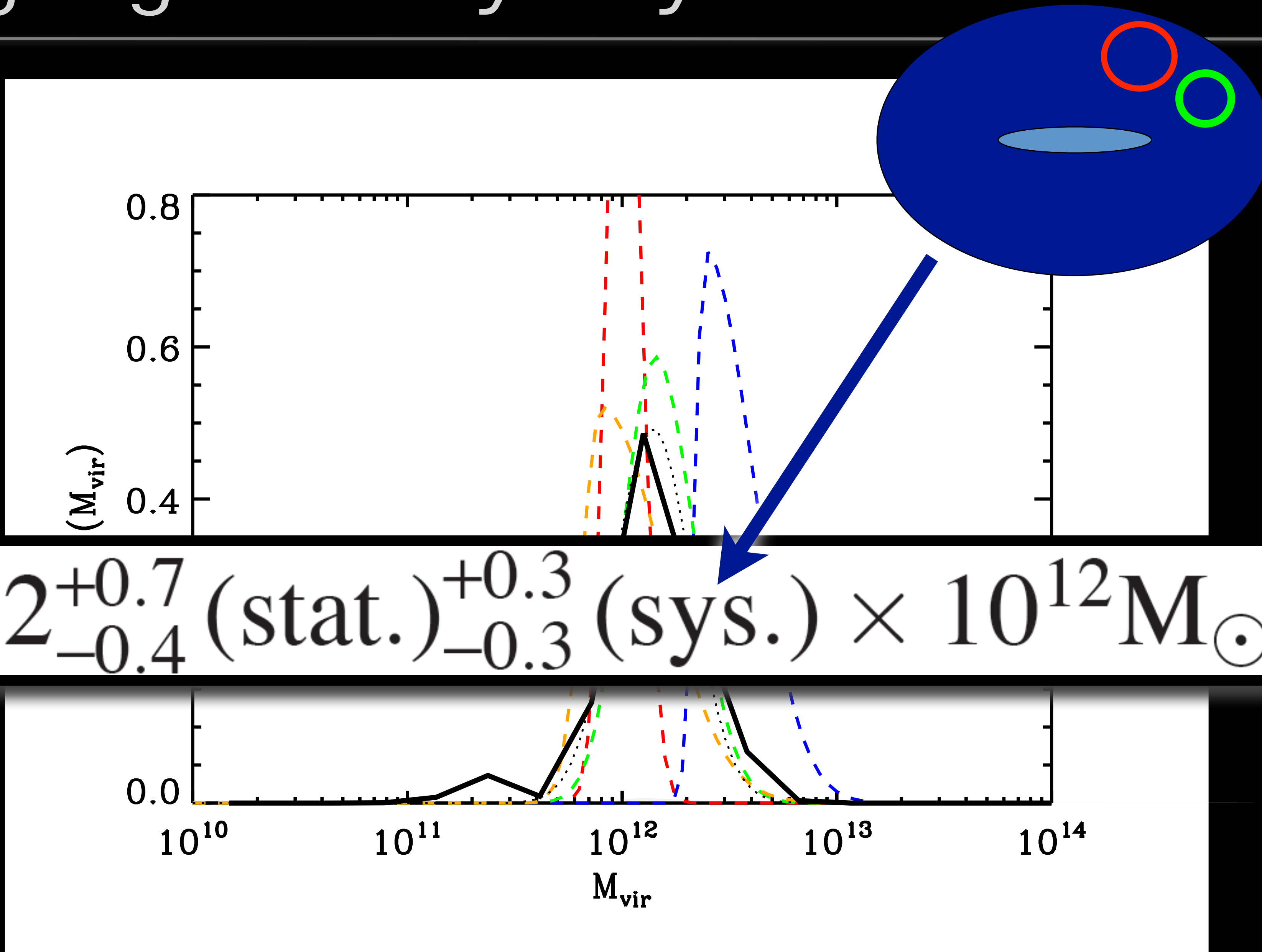
**Importance Sampling**

- Inferences are sums over prior samples, weighted by the likelihood

# one of the “MW-like” halos

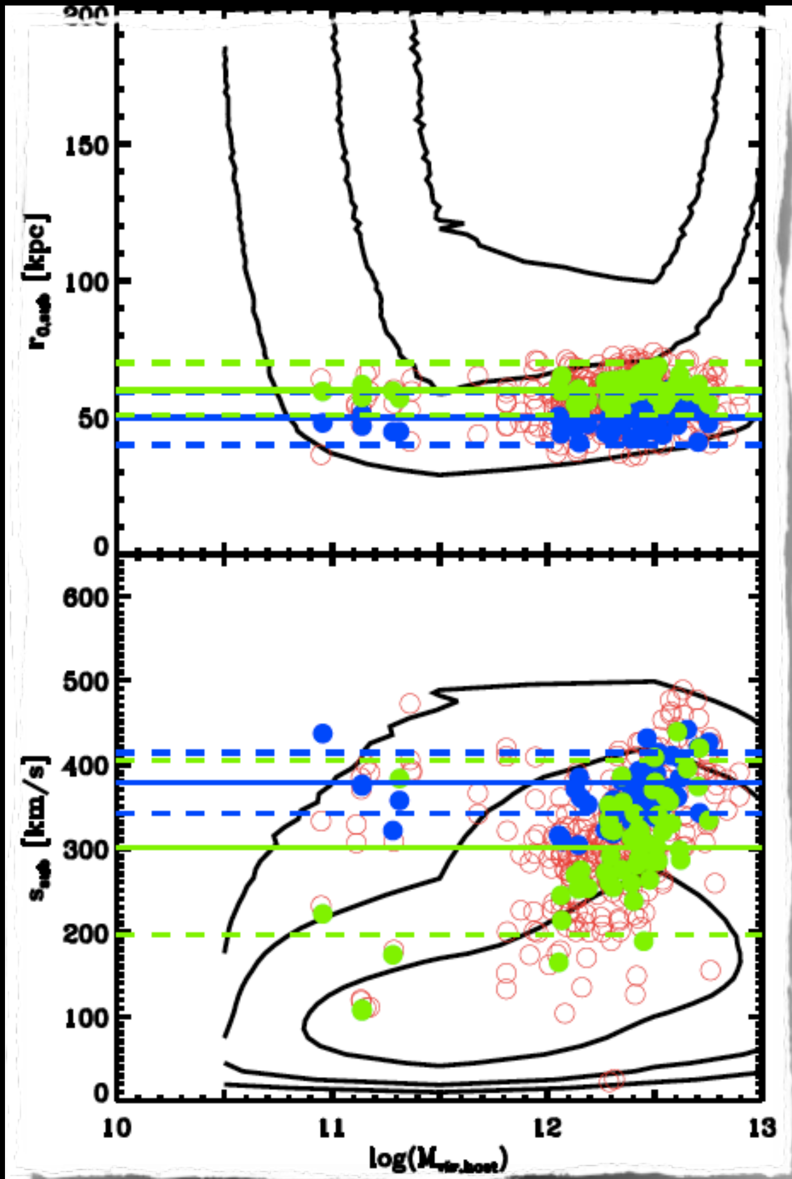


# Weighing the Milky Way



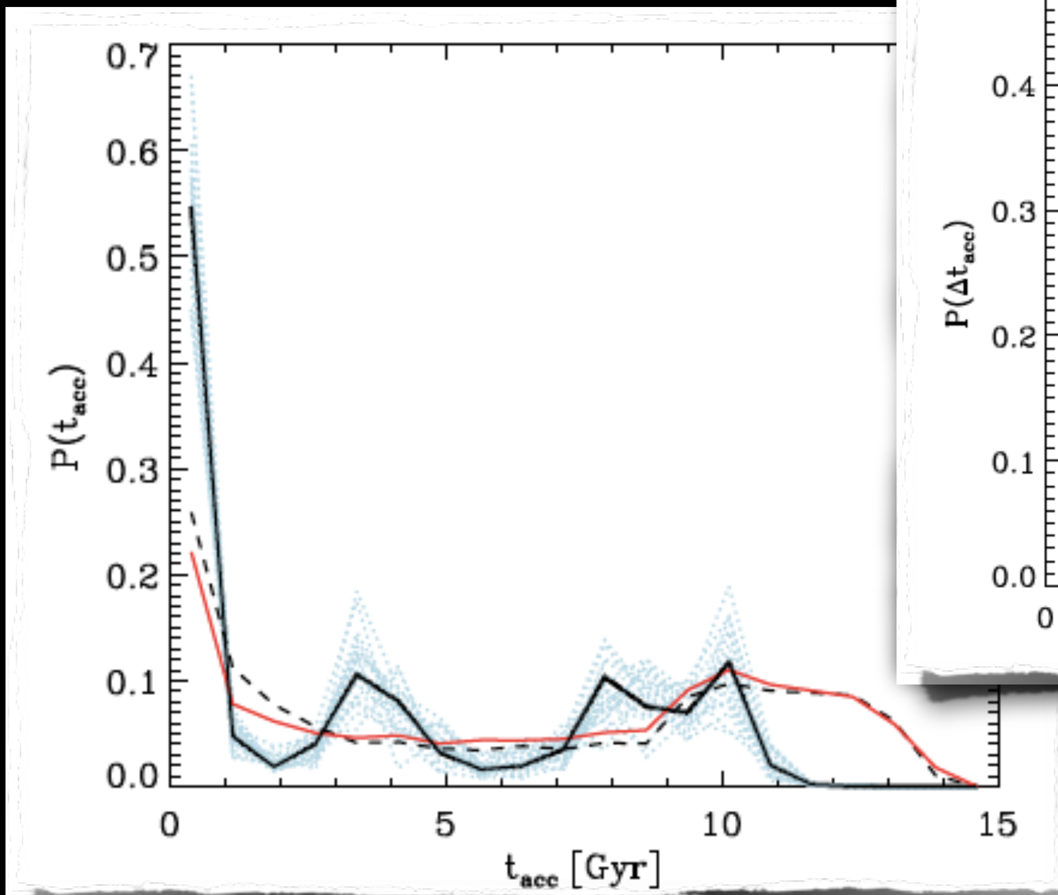

$$1.2^{+0.7}_{-0.4}\,(\mathrm{stat.})^{+0.3}_{-0.3}\,(\mathrm{sys.}) \times 10^{12} M_{\odot}$$

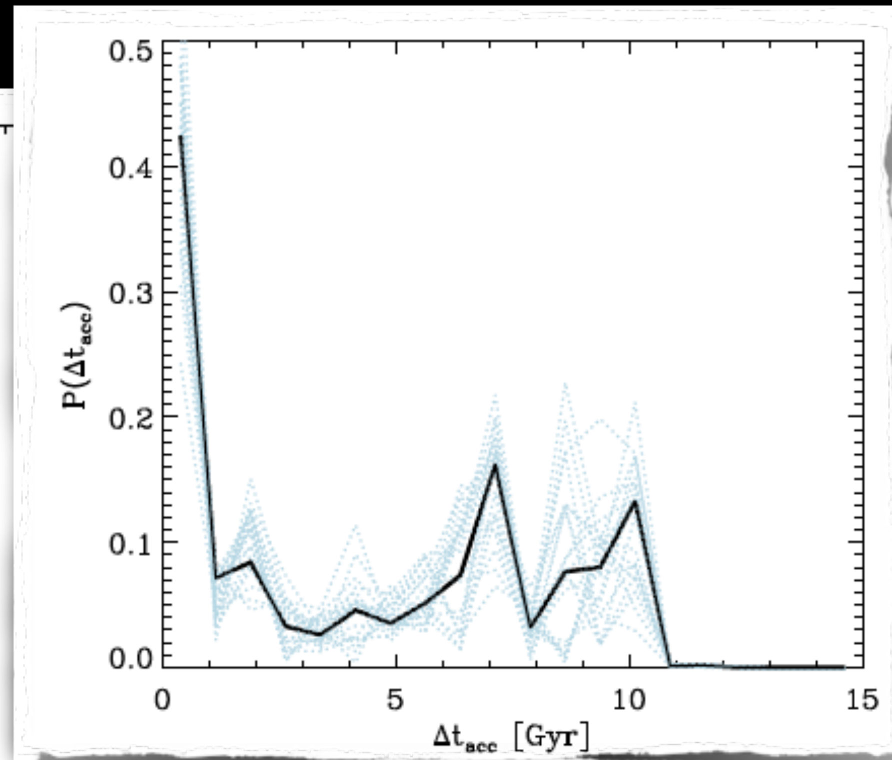
# How unusual is the MW halo?




- Around 1 in 20 Milky Way-like galaxies have two Magellanic clouds (Busha et al 2011b)
- The Magellanic Clouds are surprisingly close, and are moving surprisingly fast! What else can we learn?

# When did the Magellanic Clouds arrive?




- 72% chance they arrived within the last billion years,
- and 50% chance they arrived together

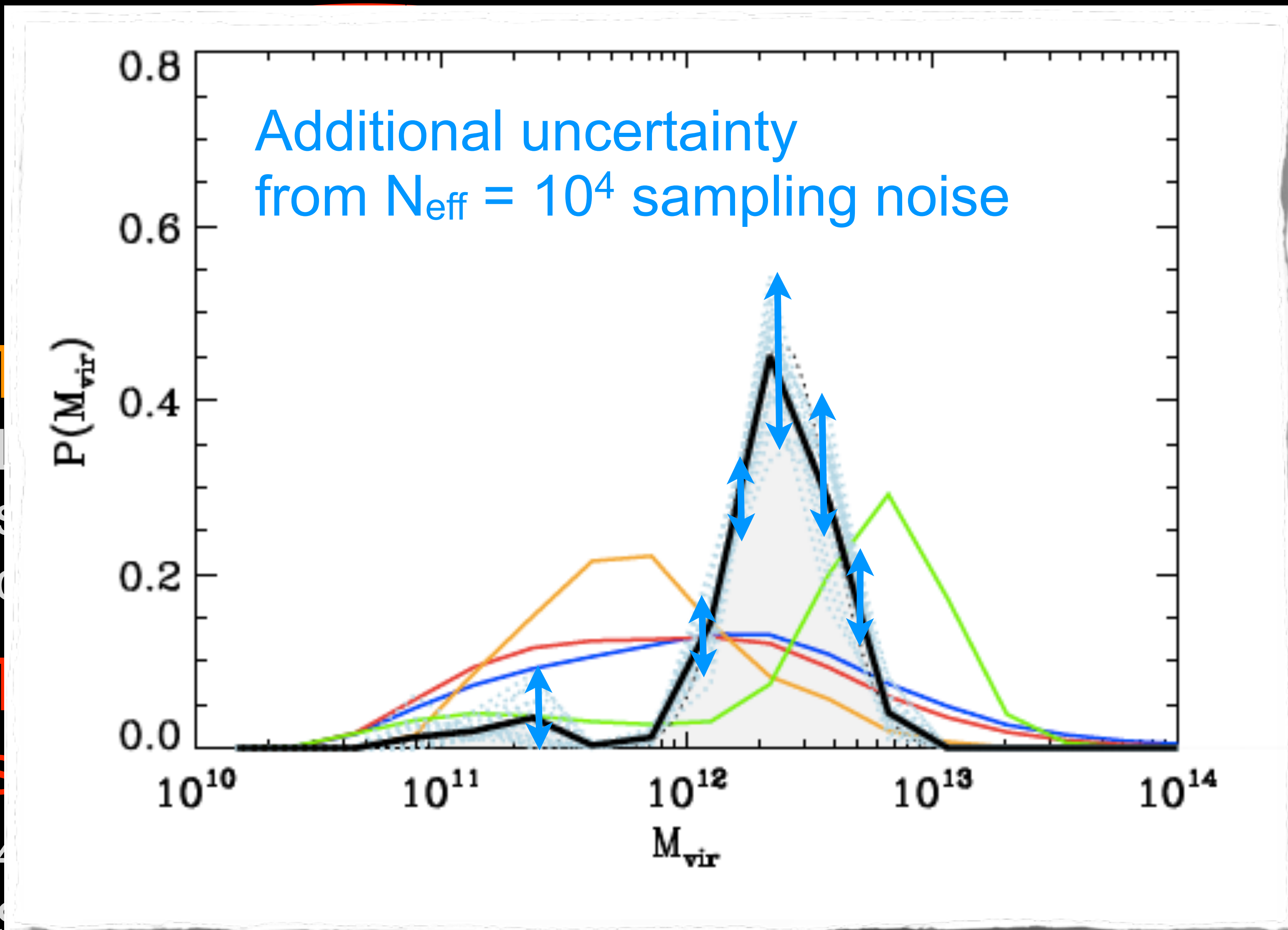
see also Boylan-Kolchin, Besla & Hernquist 2010

# When did the Magellanic Clouds arrive?

Visualization: Ralf Kaehler

see Sky & Telescope cover, October 2012!

# Importance sampling failure modes




1. T … d

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2. T …

s … or

bars, estimated by bootstrap resampling

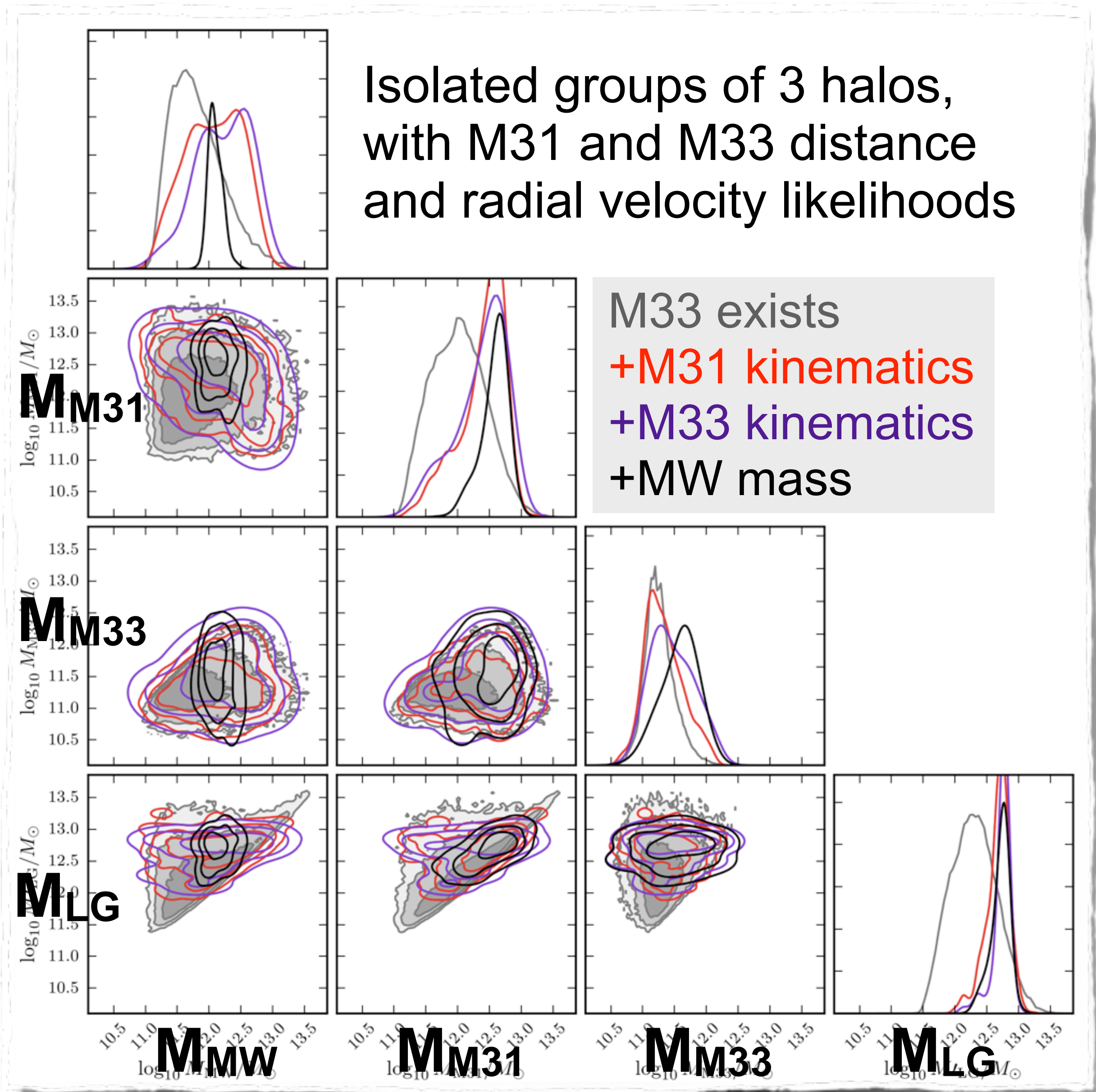
# Many possible applications

- In this case:
  - apply more/tighter priors (e.g. new measurements of the LMC proper motions!)
  - look at the posterior distribution of other intrinsic properties, and learn more about the MW (e.g. satellite population, distribution and speeds of dark matter particles, etc.)
- Many other interesting examples!

# Weighing galaxies with halo catalogs

- Can we measure the Local Group mass and history in the same way? *Consuelo: ~100x Bolshoi volume*

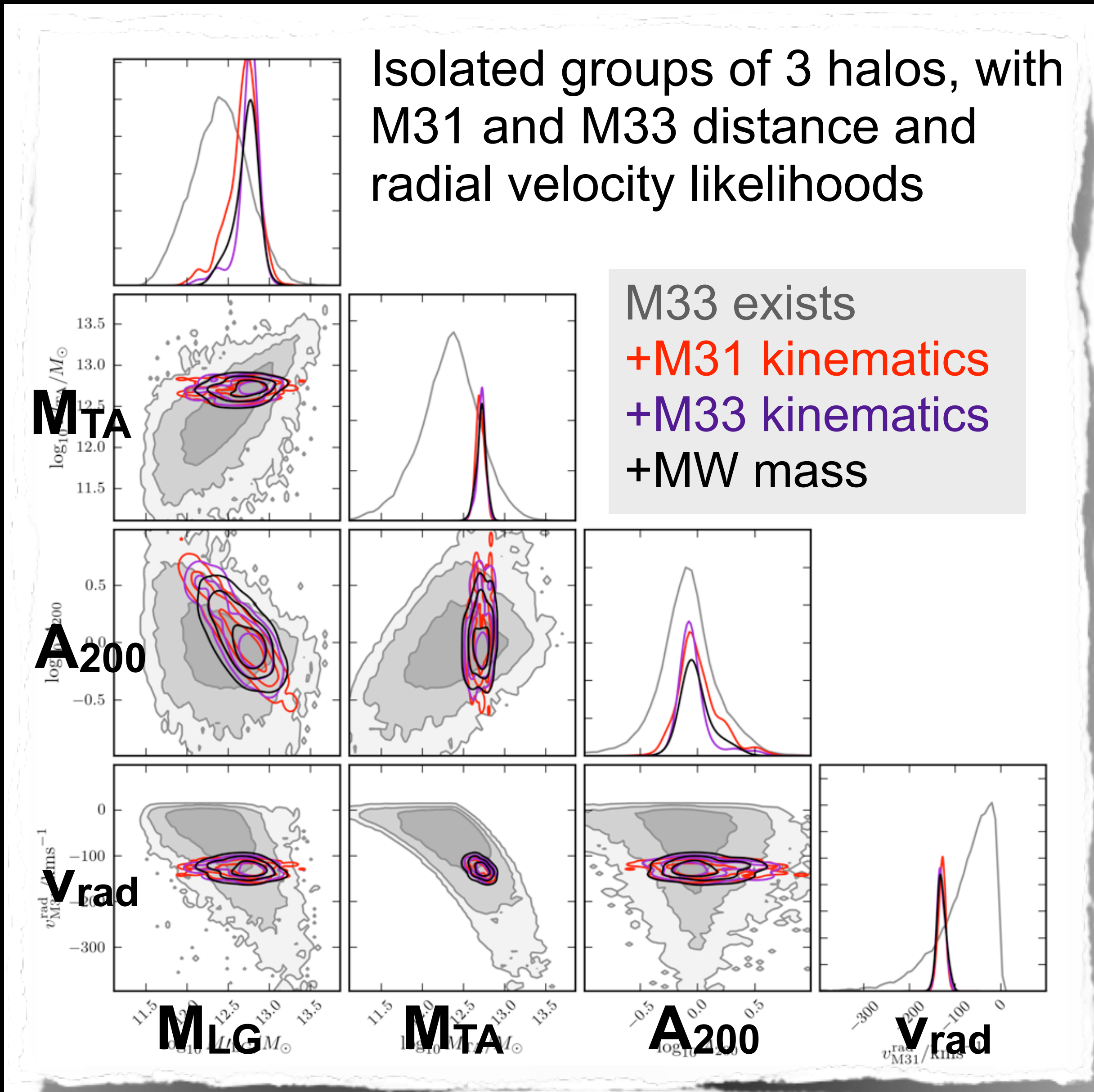
# Preliminary results on the Local Group




Local group masses are dominated by M31 (around 3 times heavier than MW): formal uncertainty around 50%

log M200 estimates:
MW: 12.0 +/- 0.1 prior
M31: 12.66 +/- 0.15
M33: 11.7 +/- 0.3
LG: 12.8 +/- 0.1
(errors are correlated)

# The Timing Argument




M31's radial orbit suggests a simple toy model for the Local Group collapse (Kahn & Woltjer 1959)

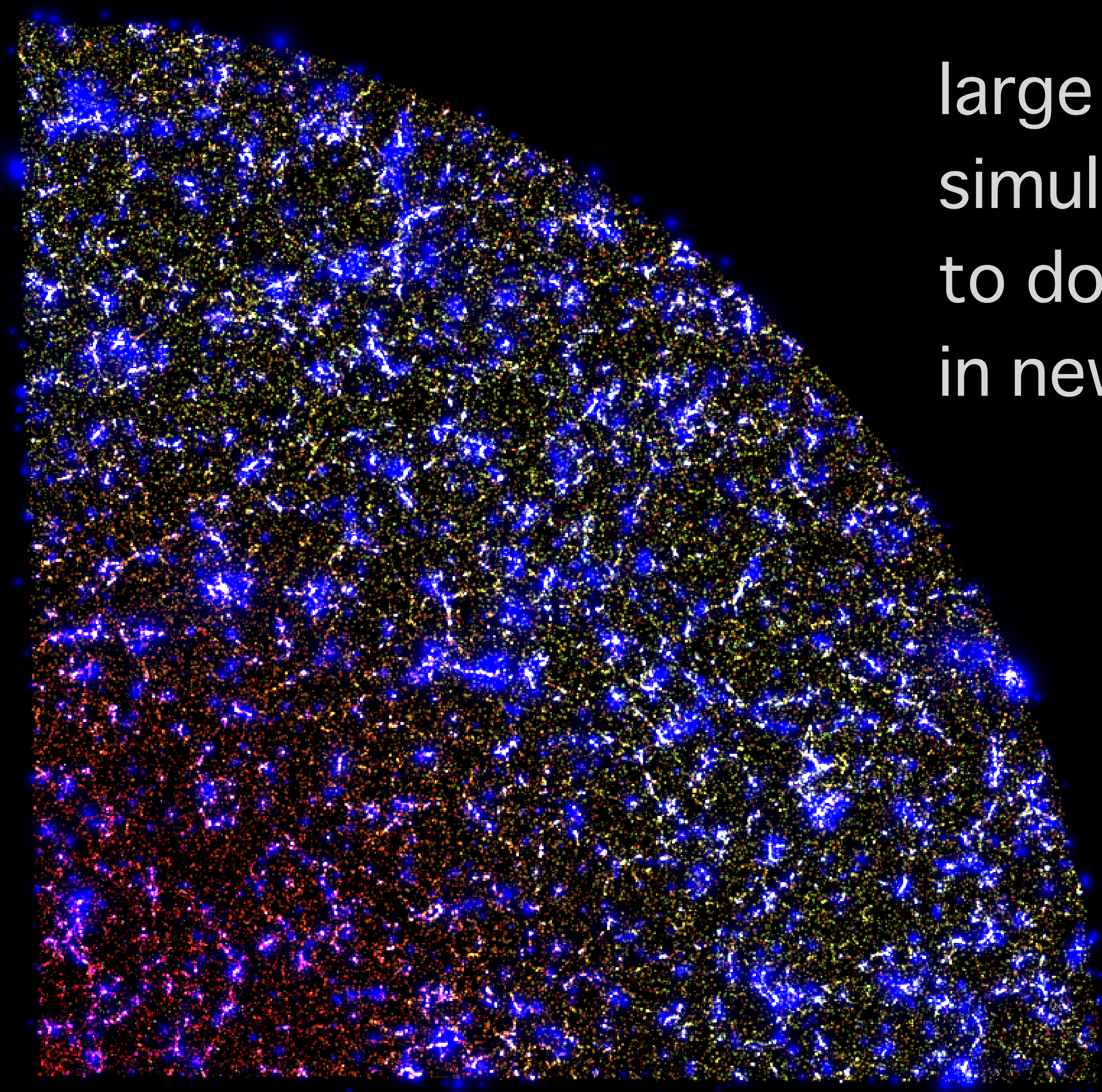
# Weighing galaxies with halo catalogs

- Can we measure the Local Group mass and history in the same way? *Consuelo: ~100x Bolshoi volume*
- What is the shape of the Milky Way halo? What "missing satellite" population do we predict?
- What is the distribution of dark matter in the Milky Way?
- How could we include more satellites? When will importance sampling break down? How can we sample PDFs in (100 epochs x 100 parameters*) = 10000D? *Importance sampling is very inefficient (need large volumes), but constrained realizations are expensive... Middle ground?*

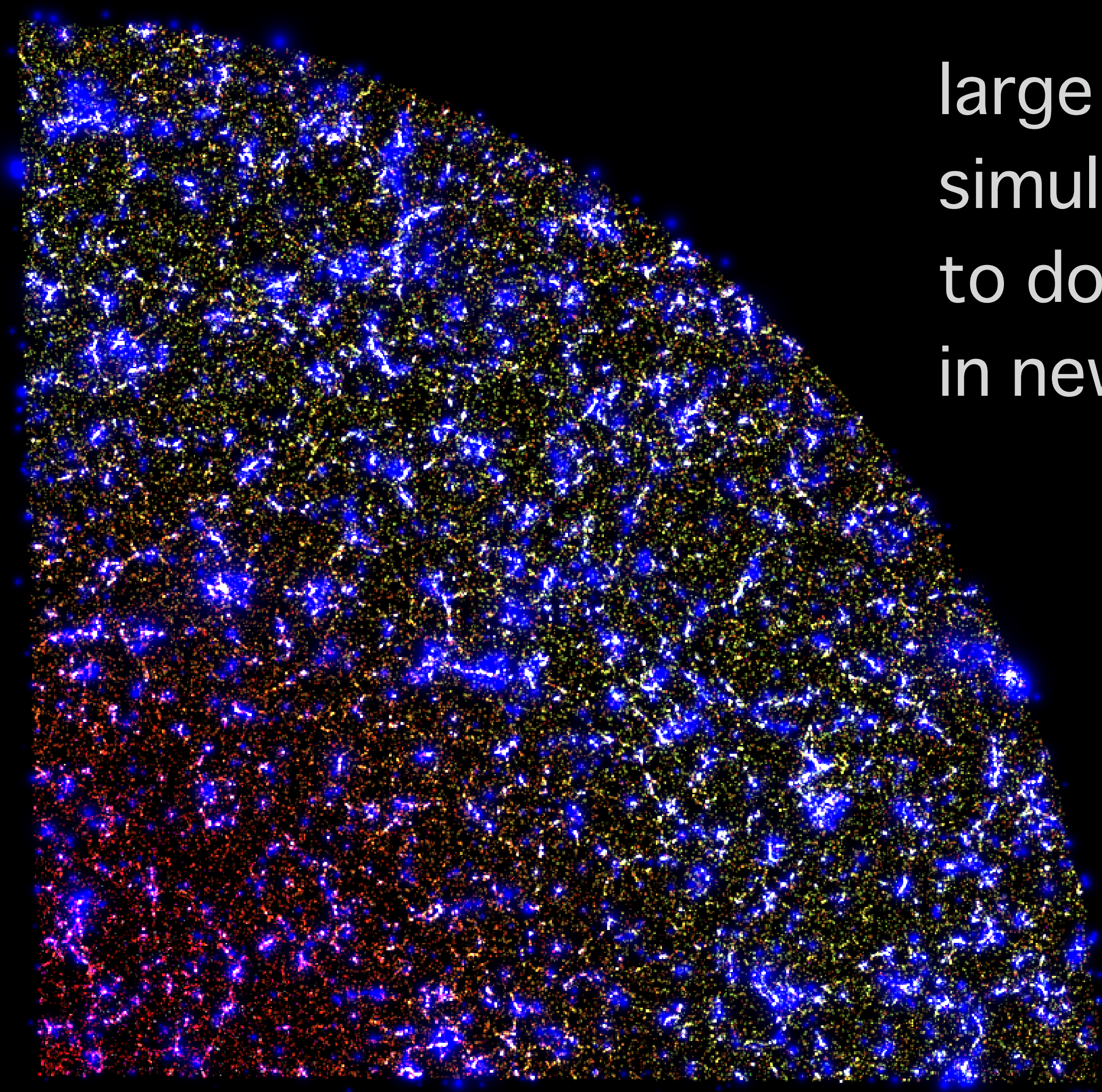
* e.g. 2 mass profile params, 6D phase space, 3 angular momentum vector, 6 inertia tensor = 17 per halo x 5-6 halos ~ 100

# Many possible applications

- Velocities of galaxies in clusters? And in the large scale structure?
- Motions of massive clusters (e.g. Bullet cluster)
- Anything else where you have observations that relate to properties well predicted in simulations, and some intrinsic property you are interested in!



large cosmological simulations allow you to do many analyses in new ways



large cosmological simulations allow you to do many analyses in new ways...

but care must be taken to properly estimate the impact of uncertainties

# Example in galaxy cluster cosmology

- two key steps in cluster cosmology:
  - find the clusters
  - weigh the clusters
- cosmological analysis:
  - depends on relating these observed objects to predictions of the mass function of halos in a given cosmological model