A Bayesian Analysis of a Milky Way Ultra-faint Satellite

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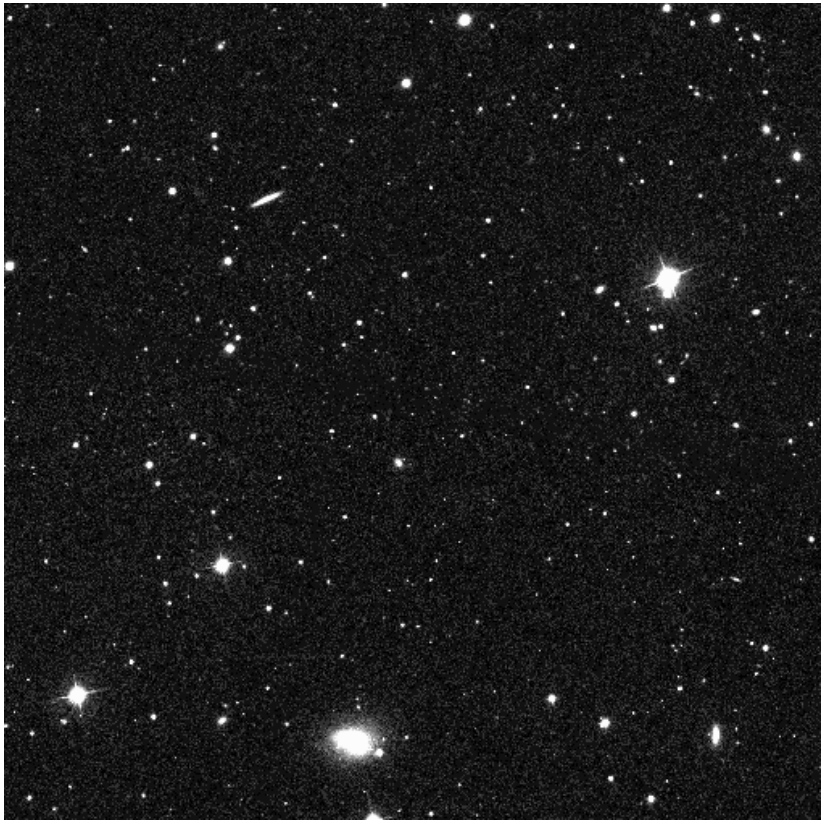
Roberto Trotta, *Imperial College*
Josh Simon, *Carnegie*
Marla Geha, *Yale*

Image: Marla Geha



It's a galaxy, I swear!?

CENTER FOR COSMOLOGY

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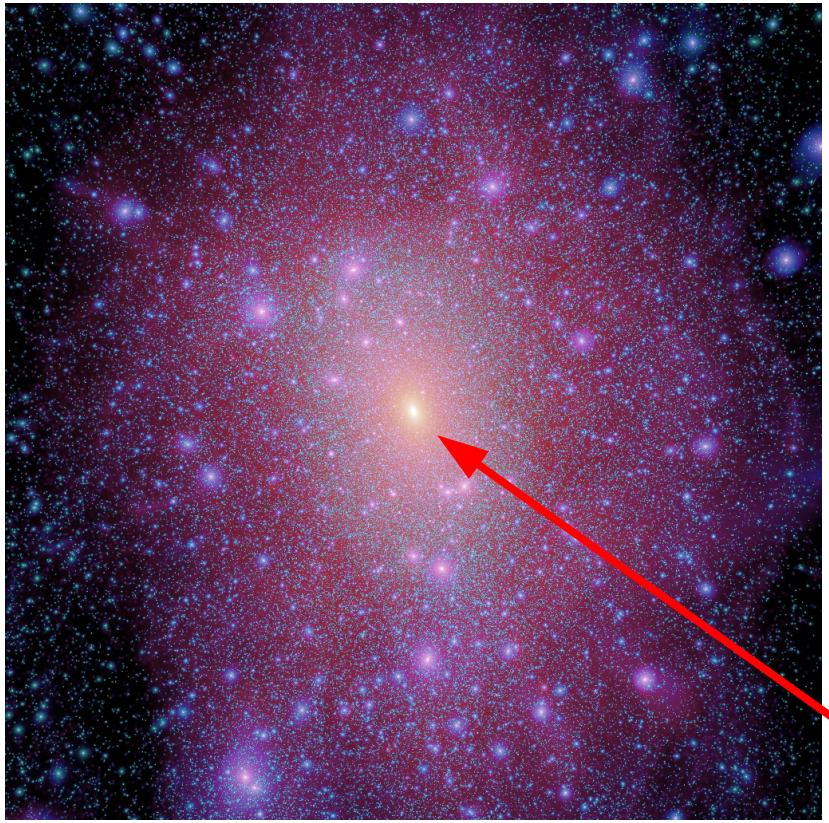
Greg's Talk in a Nutshell

- Motivation: Why bother with Milky Way Sats?
- Methodology
  - Membership Issues
  - Binaries Effects
- Indirect DM detection description
  - boost derivation
- Conclude.

Motivation



Springel et. al. '08

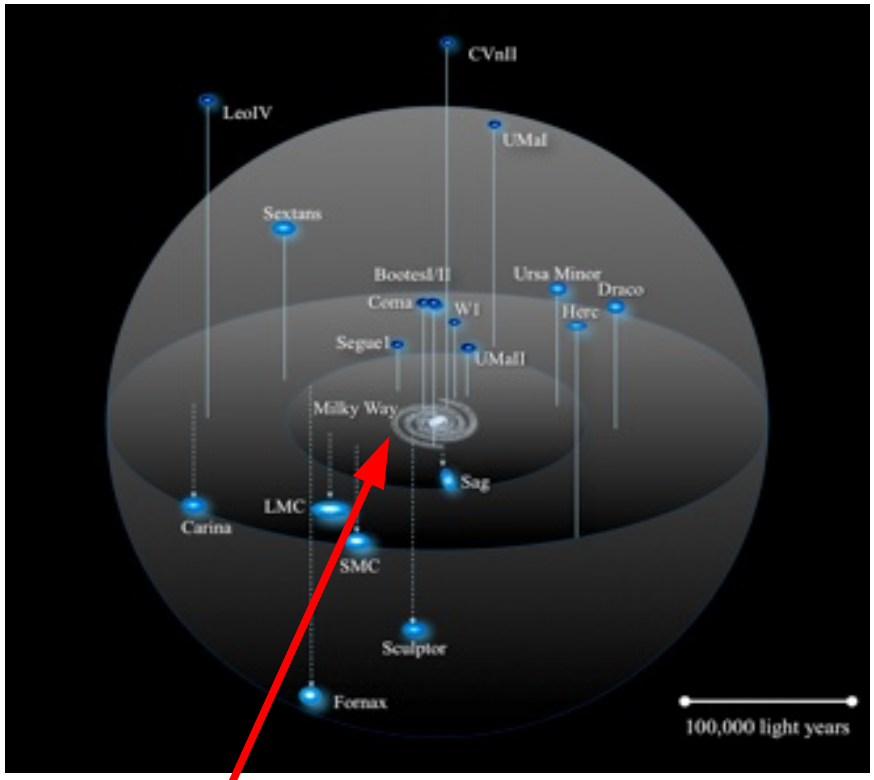
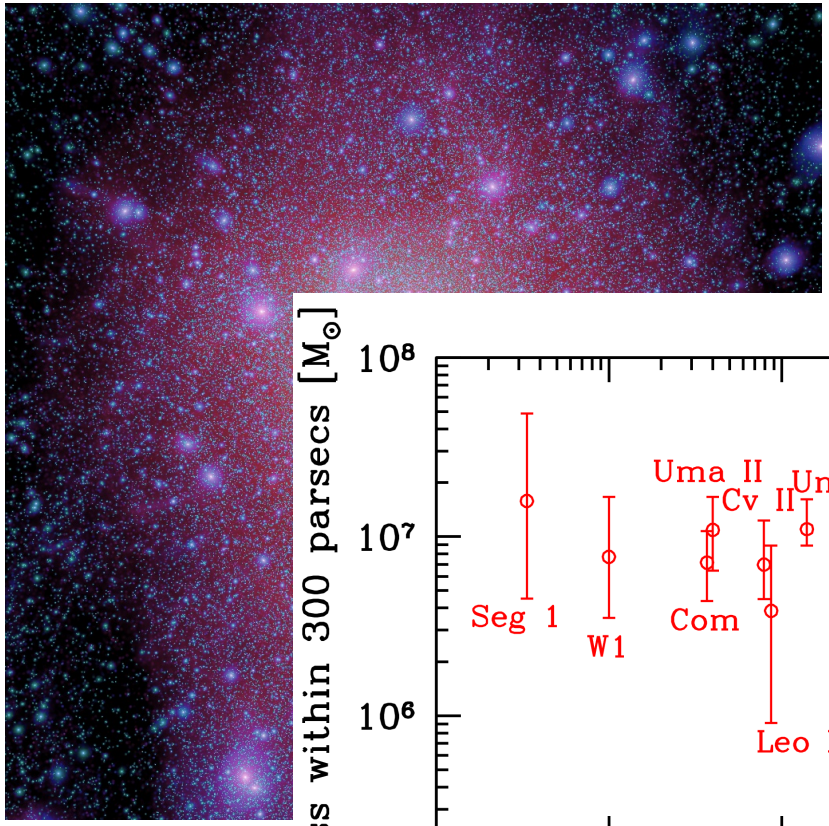


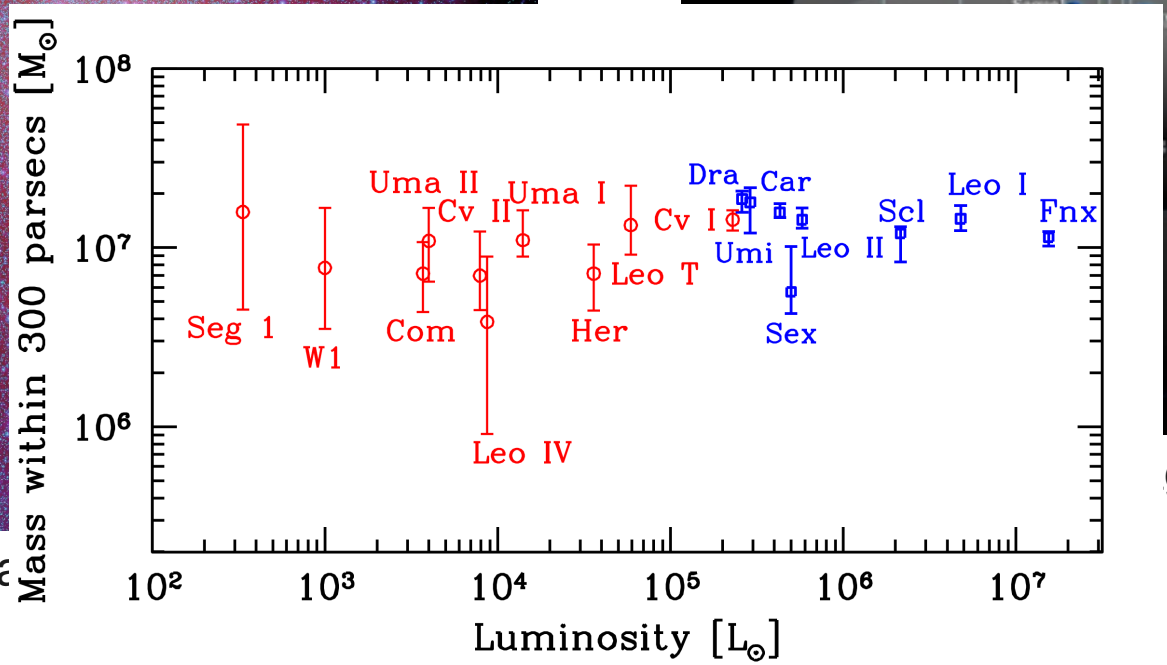
Image: Marla Geha

You are here

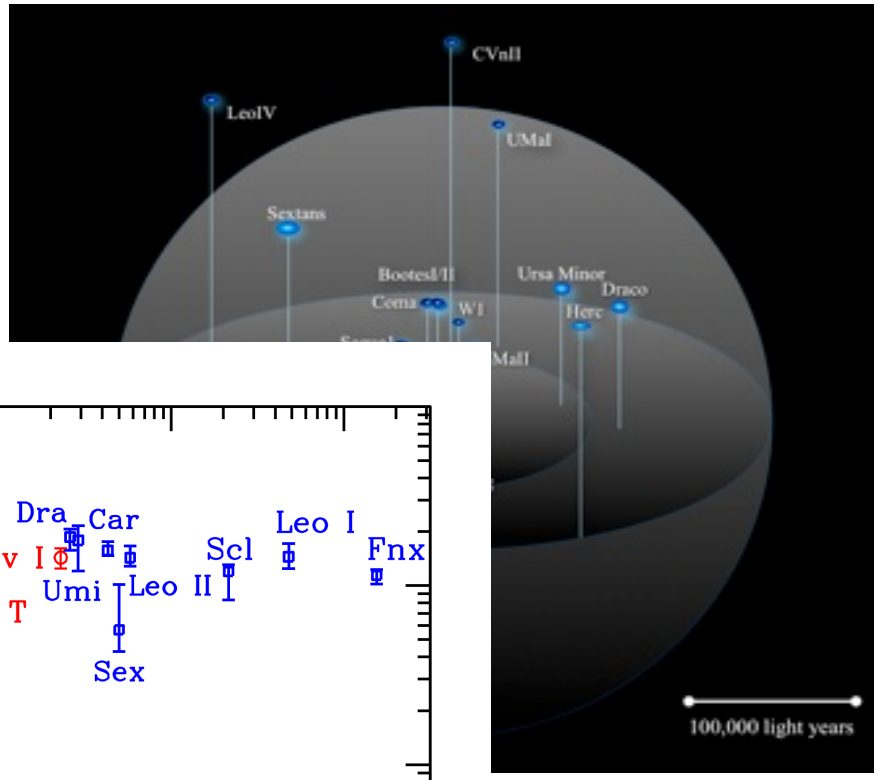
Motivation



Springel et. a

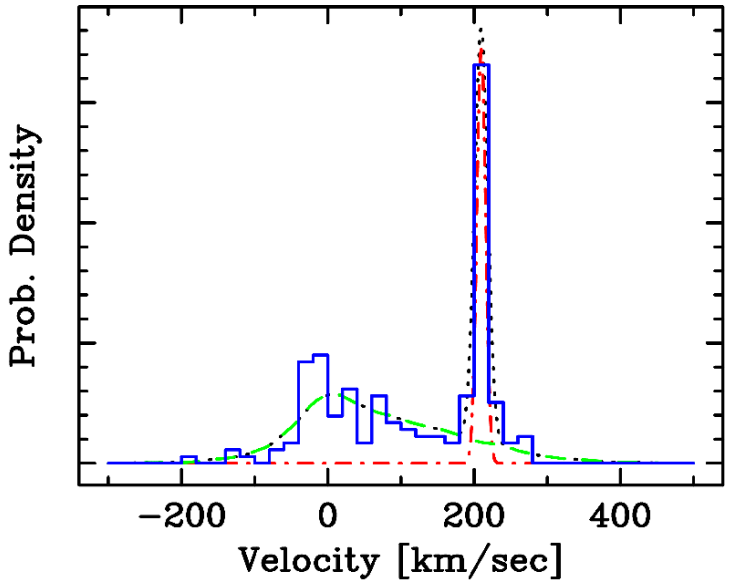


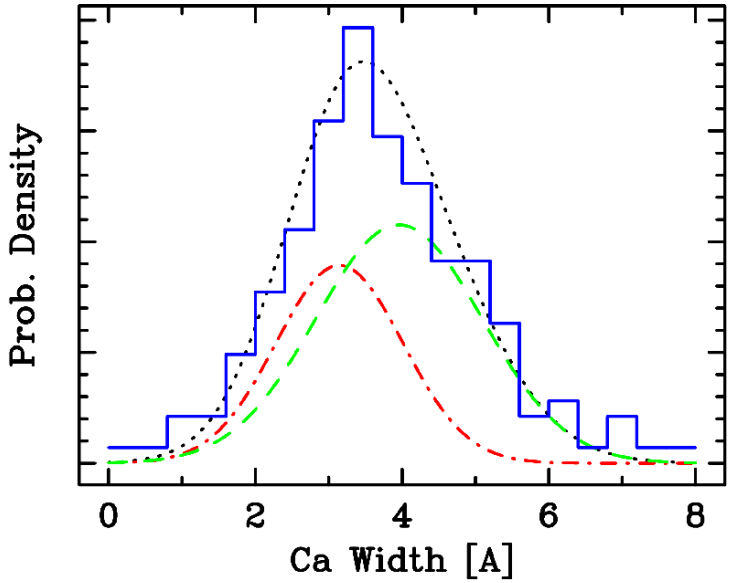
Strigari et. al. '07



ge: Marla Geha

Methodology





Membership Issues

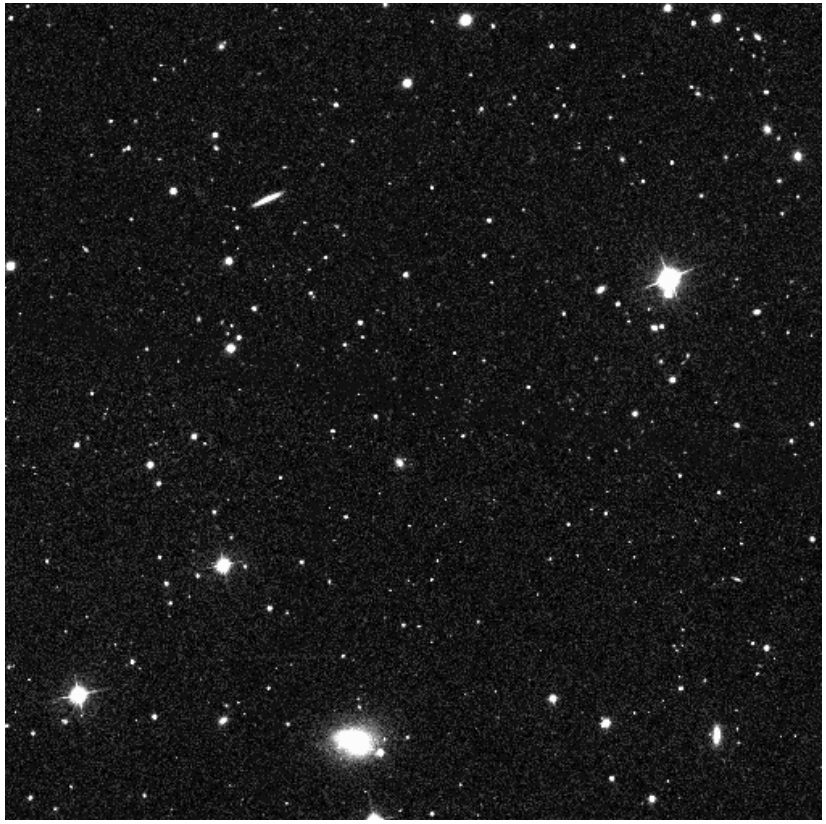
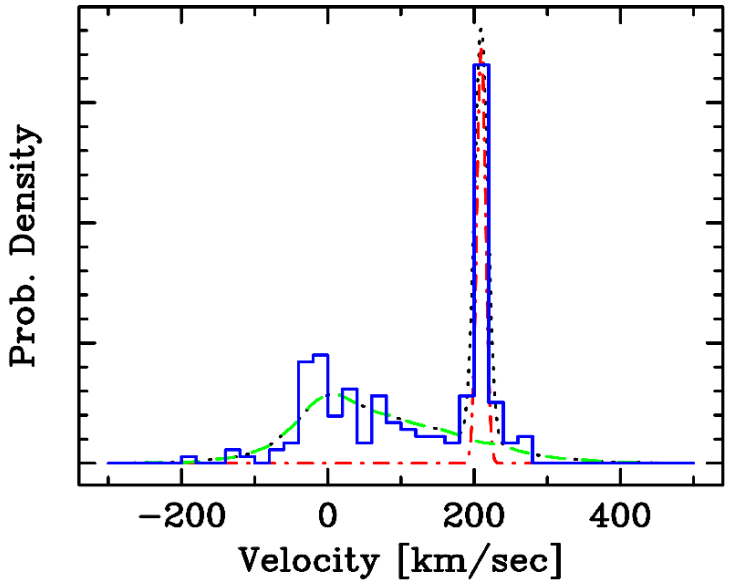
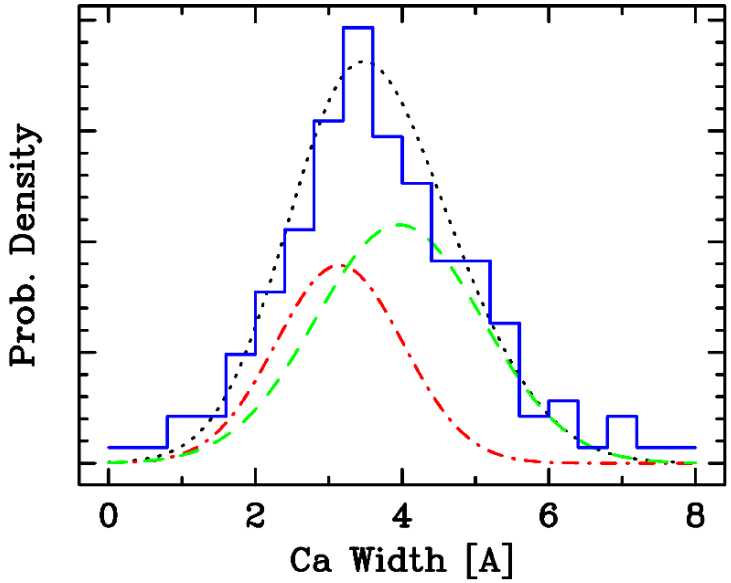


Image: Marla Geha

Martinez, Minor et. al. '10 (arXiv:1008.4585)
Minor, Martinez et. al. '10 (arXiv:1001.1160)

Methodology





Membership Issues

- Currently, membership is inferred by the ratio of the best fit Milky Way and Galaxy Probably Distributions (see Walker et. al. '09 and '07).

- But to obtain proper errors, more than just the best fit solution is needed.

- Our method uses the Milky Way and Galaxy Probability Distributions Directly. While proper statistics can be obtained, calculations require the integration of large parameter spaces (>20) – this can be done!

Methodology

What Probability function, *L(v, w, r)*, to use?

$$L(v, w, r) = ?$$

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- Assumption 1: There are two distinct Populations

$$L(v,w,r) = F \times L_{gal}(v,w,r) + (1-F) \times L_{MW}(v,w,r)$$

Methodology

What Probability function, *L(v, w, r)*, to use?

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- Assumption 1: There are two distinct Populations

$$L(v,w,r) = F \times L_{gal}(v,w,r) + (1-F) \times L_{MW}(v,w,r)$$

- Assumption 2: The metallicity pdf is independent of the other parameters

Interpreted as the density

$$L(v,w,r) = F L_{gal}(w) \times L_{gal}(v|r) \times L_{gal}(r) + (1-F) L_{gal}(w) \times L_{gal}(v|r) \times L_{gal}(r)$$

Methodology

What Probability function, *L(v, w, r)*, to use?

$$L(v,w,r) = L(v,w|r) \times Density(r) \times Bias(x,y)$$

Lets take only the first part

Methodology

What Probability function, *L(v, w, r)*, to use?

$$L(v,w|r) = f(r)\times L_{gal}(w)\times L_{gal}(v|r)$$
$$+(1-f(r))\times L_{gal}(w)\times L_{gal}(v|r)$$

$$f(r) = \frac{Density_{gal}(r)}{Density_{gal}(r)+Density_{MW}(r)}$$

- **The subsample of stars is still collisionless therefore still obeys Boltzmann equation.**

- **The fraction is not affected by selection bias if bias affects galaxy and Milky Way densities the same**

Methodology

What Probability function, *L(v, w, r)*, to use?

$L(w)_{gal} \rightarrow$ Gaussian

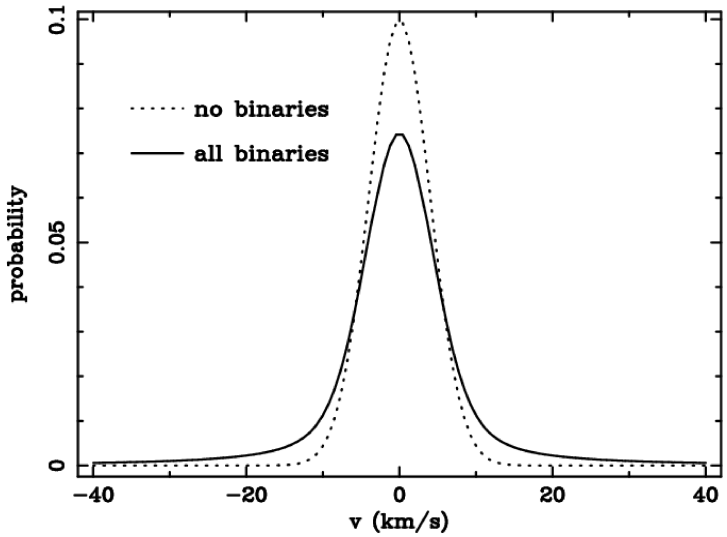
$L(w)_{MW} \rightarrow$ Gaussian

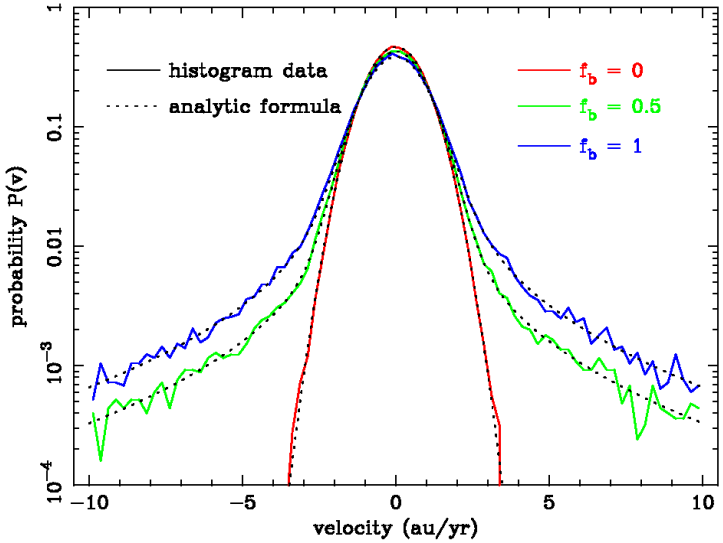
$L(v|r)_{gal} \rightarrow$ Gaussian (for now)

$L(v|r)_{MW} \rightarrow$ Besancon Model

Methodology

Binary Effects





- Orbital motion of binaries can inflate dispersion.
- Effect greater for small dispersion galaxies and data with large errors.
- In ultra-faint dwarfs, small sample sizes, few RGB stars, dominance of main sequence stars in sample, and large measurement errors make binaries hard to account for (see Minor et. al. in prep.)

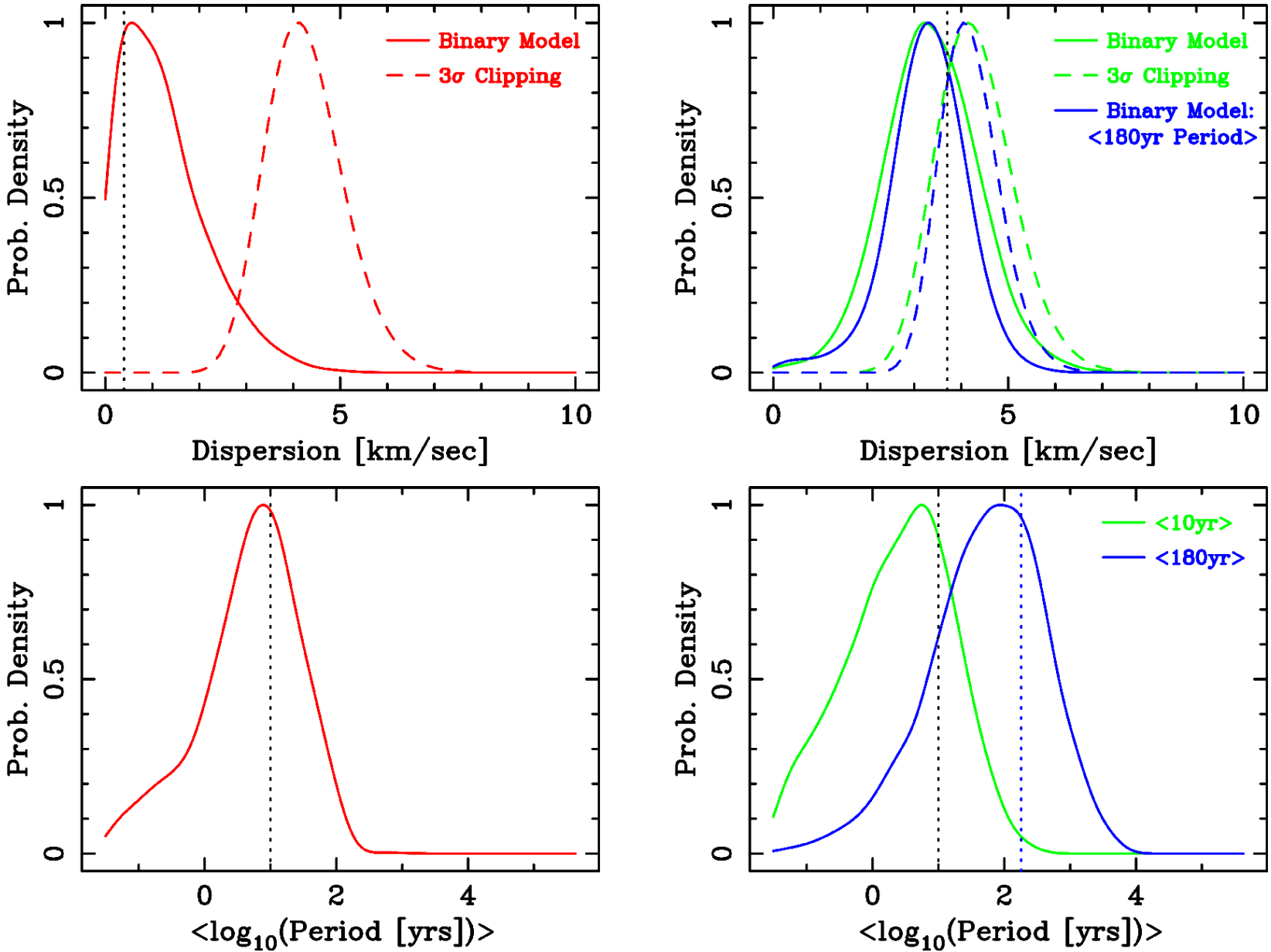
Methodology

Binary Effects

- Log-normal distribution of periods for field binaries (Duquennoy 1991)
- Mass ratio distribution
  - follows Salpeter IMF for long periods ($q > 0.5$)
  - roughly uniform for short periods (Mazeh 1992)
- Eccentricity distribution from Duquennoy (1991)
- Stars with orbits smaller than their stellar radii suffer Roche lobe overflow

Methodology

Martinez et. al. '10



Berkeley '10

Statistical Methods

Bayesian Analysis Methods

Integration
Monte Carlo Integration
Rejection Method
Barker-Hastings Algorithm
Metropolis-Hastings Algorithm
Slice Sampling
Nested Sampling
MultiModal Nested Sampling
Metropolis Nested Sampling
Hamiltonian Sampling
Diffusive Nested Sampling

Method Complexity

"Sure, I'll do it"

↓

"You want me to do what?"

↓

"I have no clue what's going on?"

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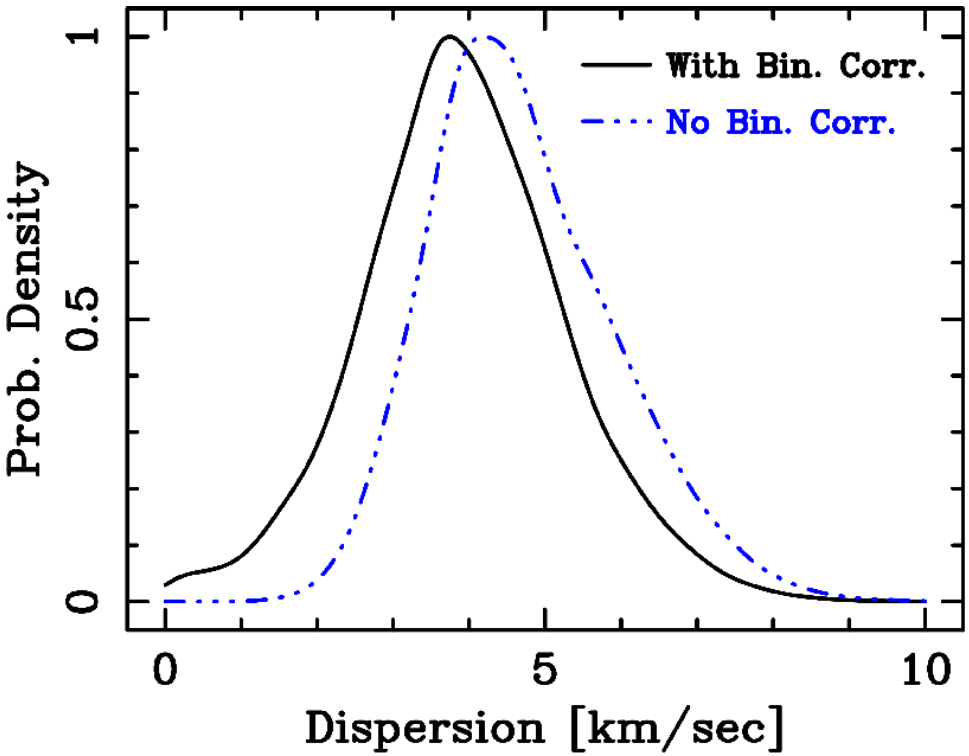
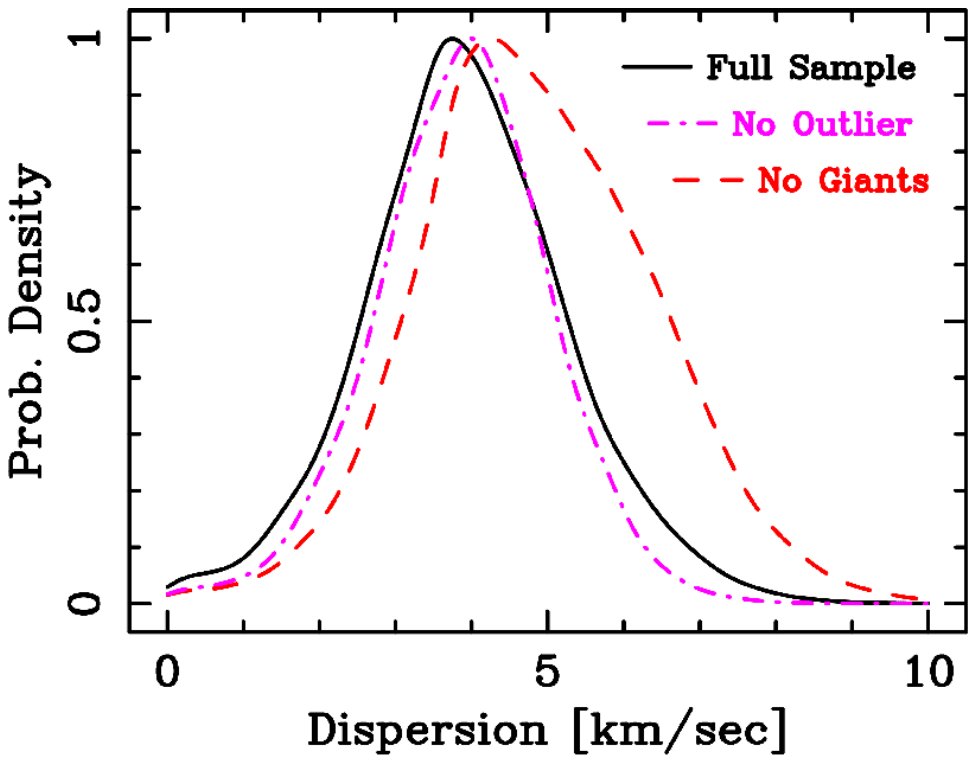
Segue 1 Results

Martinez et. al. '10





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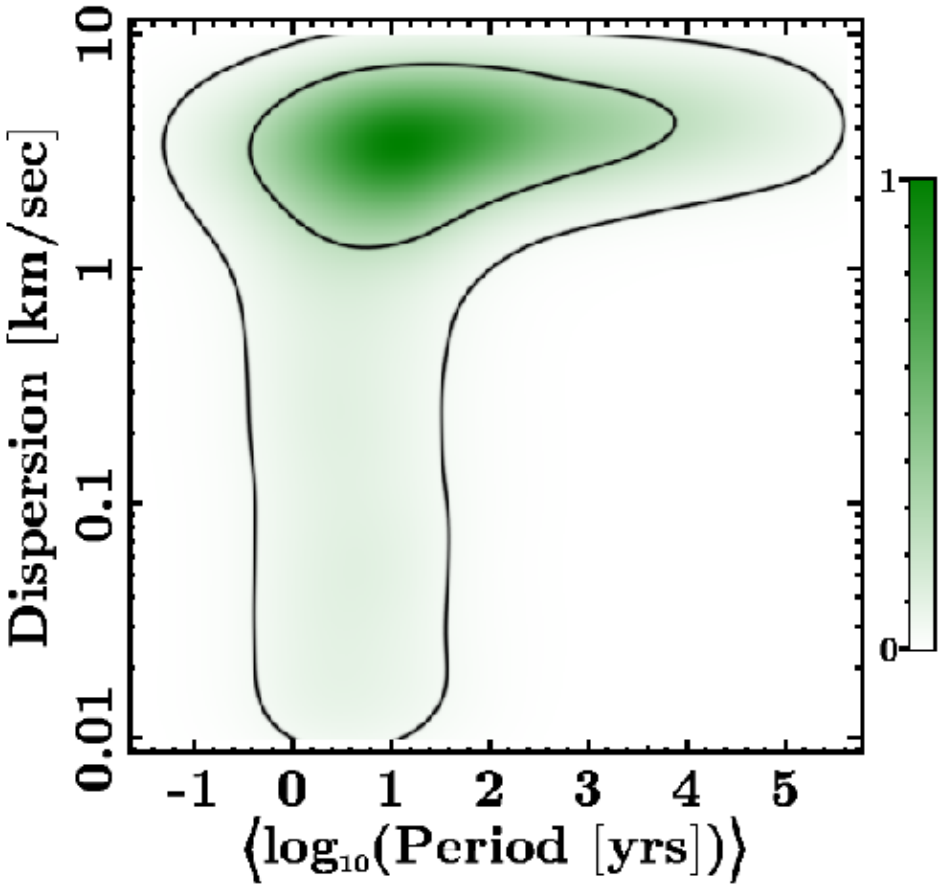
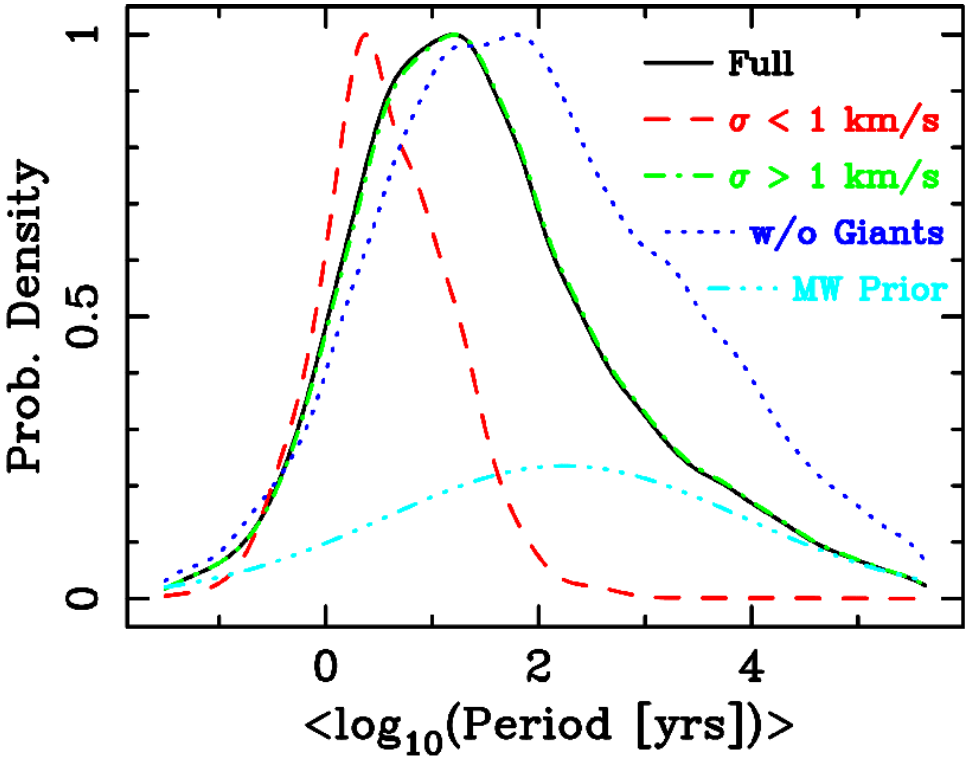


Martinez et. al. '10



Segue 1 Results

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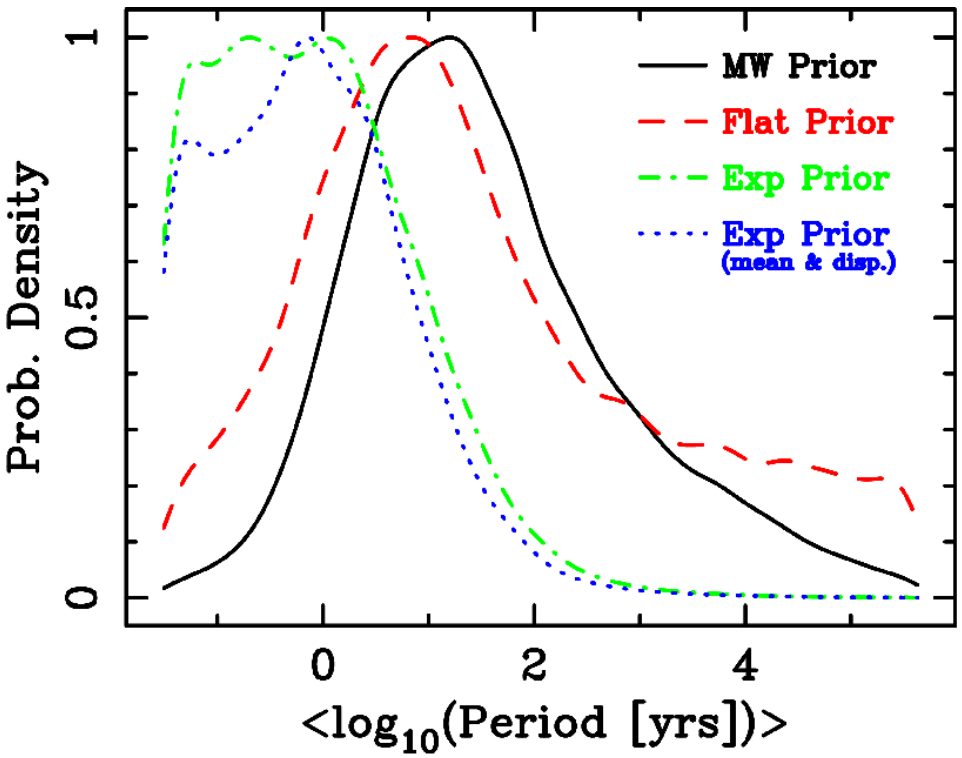

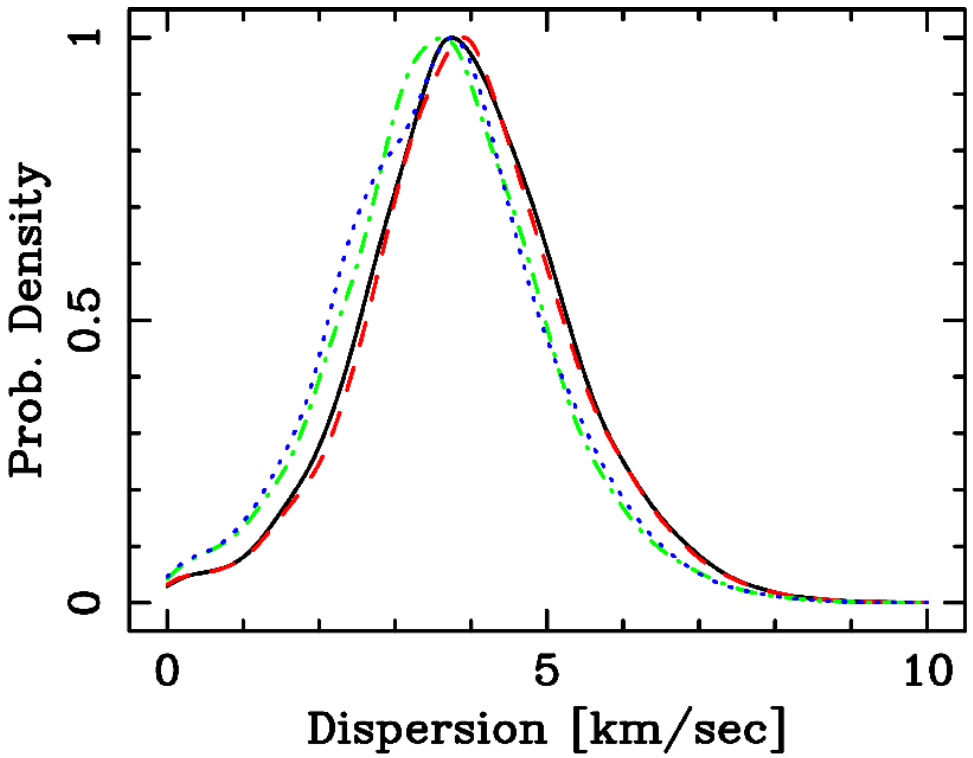

Jeans (Mass) Modeling

- Dispersion supported galaxies are supported by the randomness of stellar orbits.

- Line-of-sight motions are measured.
- Dynamical mass is inferred from the dispersion.

$$\frac{\partial(\rho\sigma_r^2)}{\partial r} + 2\beta\frac{\rho\sigma_r^2}{r} = -G\frac{M}{r^2}$$

$$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}$$

- But, there is a degeneracy between the dispersion anisotropy and the mass.

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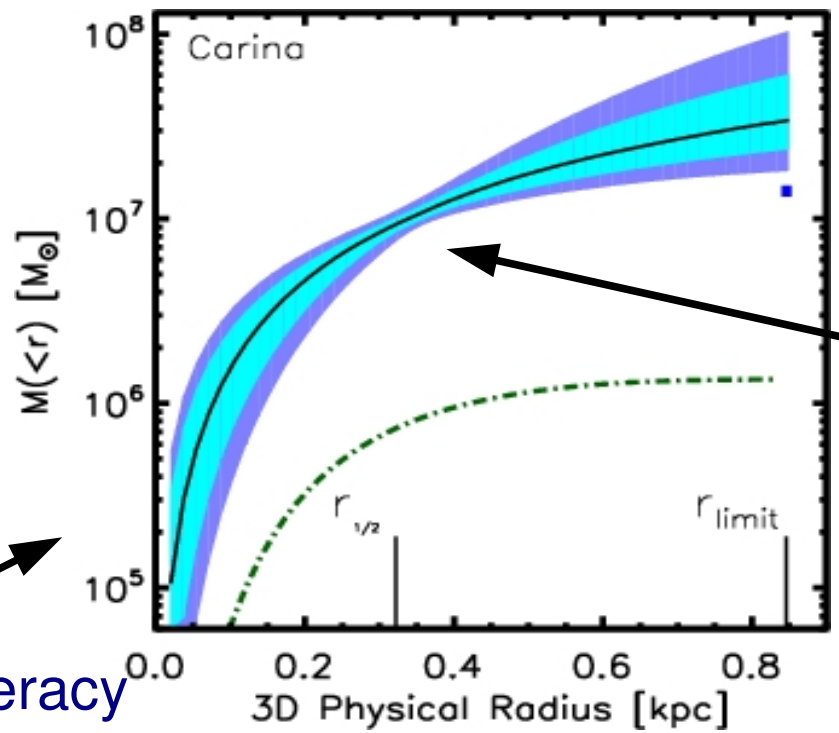


Degeneracy minimized at one point!

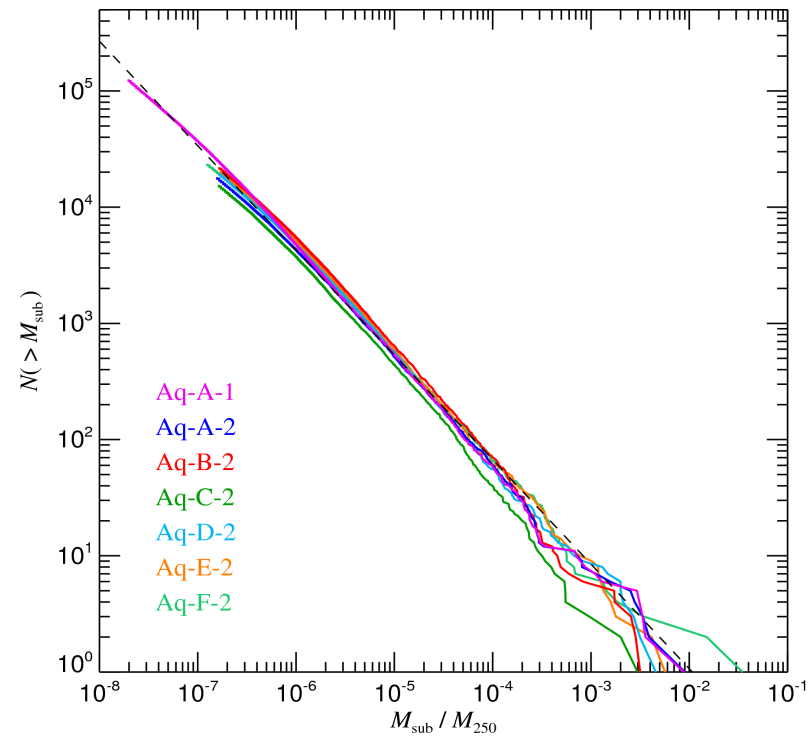
- But, there is a degeneracy between the dispersion anisotropy and the mass.

Wolf, Martinez et. al. '10

CDM Prior

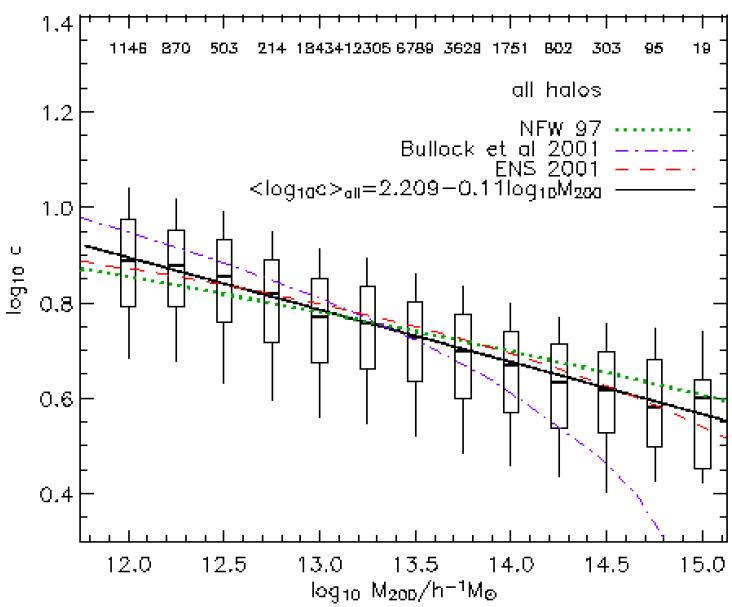
Prior on Total Mass

Springel et. al. '08



- Simulations infer probability of halo shape and mass.

Neto et al. '07



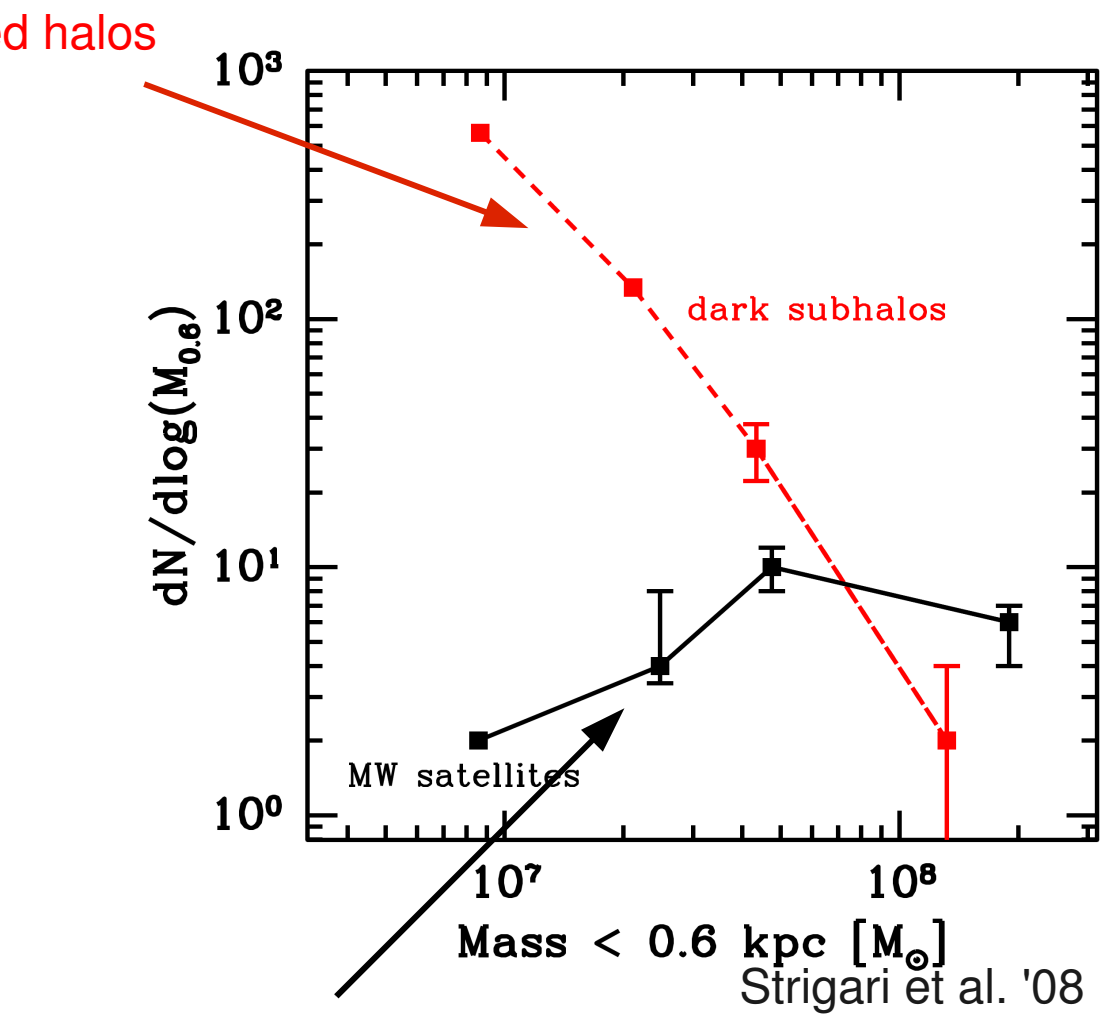
$$P(c, M) = P(c|M)\,P(M)$$

Total Prior

Prior on Profile

CDM Prior

- Simulations infer probability of halo shape and mass.
- Predicted mass probability is over conservative – not all halos host galaxies.



Strigari et al. '08

Observed halos (pre-SDSS)

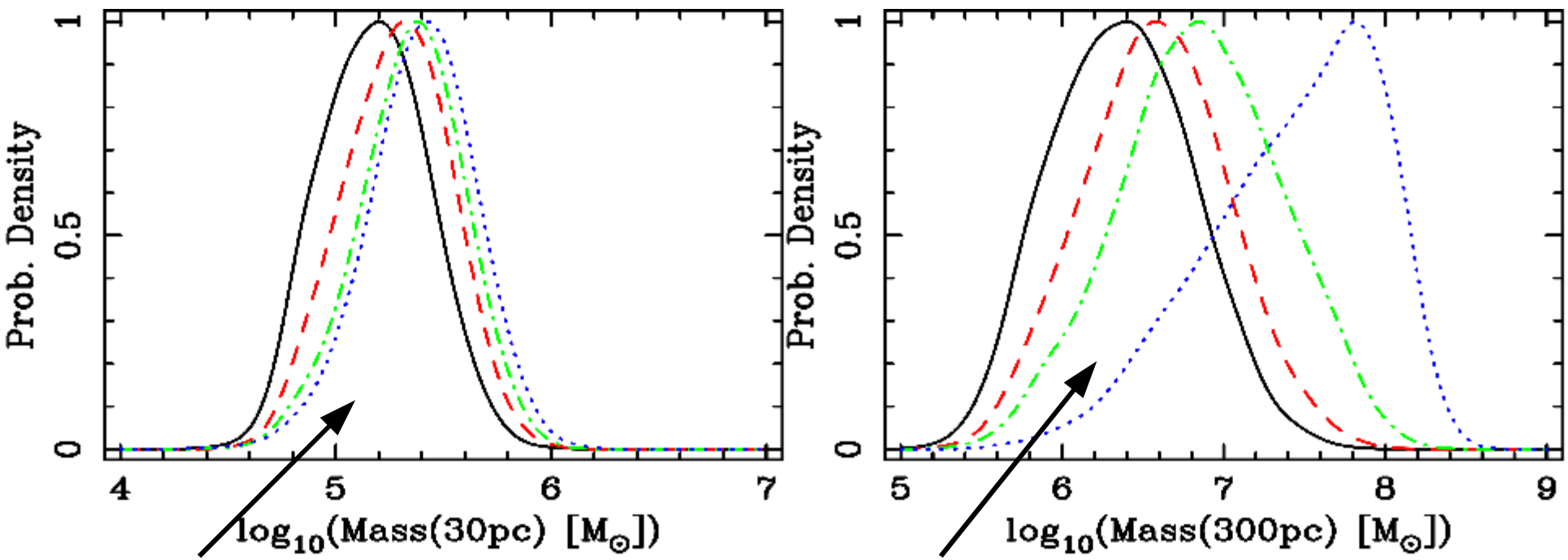
Segue – How Massive?

CDM prior biases the mass the most and limits amount of prior dominated parameter space.

Mass within half-light radius

Mass outside tidal radius

Martinez et al. '09



Data Dominated

Prior Dominated

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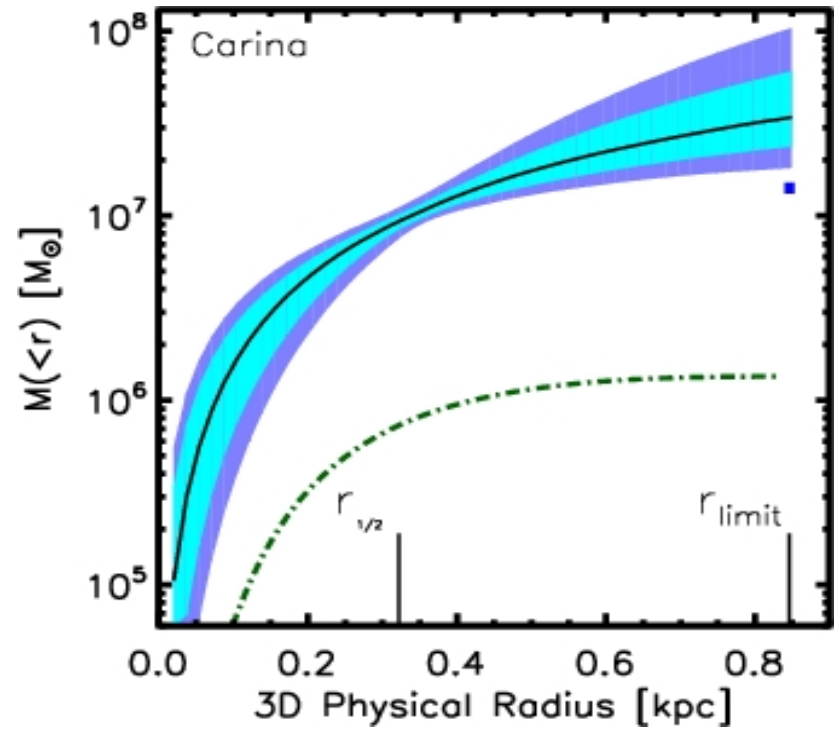
Segue 1 Results

$$M(r < r_{1/2}) = \frac{3 r_{1/2} \langle \sigma^2_{\rm LOS} \rangle}{G}$$

$$= \frac{3 \times 38\mathrm{pc} \times (3.8\mathrm{km/s})^2}{0.0043\,\mathrm{pc}\,\mathrm{M}_\odot^{-1}(\mathrm{km/s})^2}$$

$$= 3.8 \times 10^5\,\mathrm{M}_\odot$$

$$\rho(r < r_{1/2}) = 1.7\,\frac{\mathrm{M}_\odot}{\mathrm{pc}^3}$$



Wolf, Martinez et. al. '10

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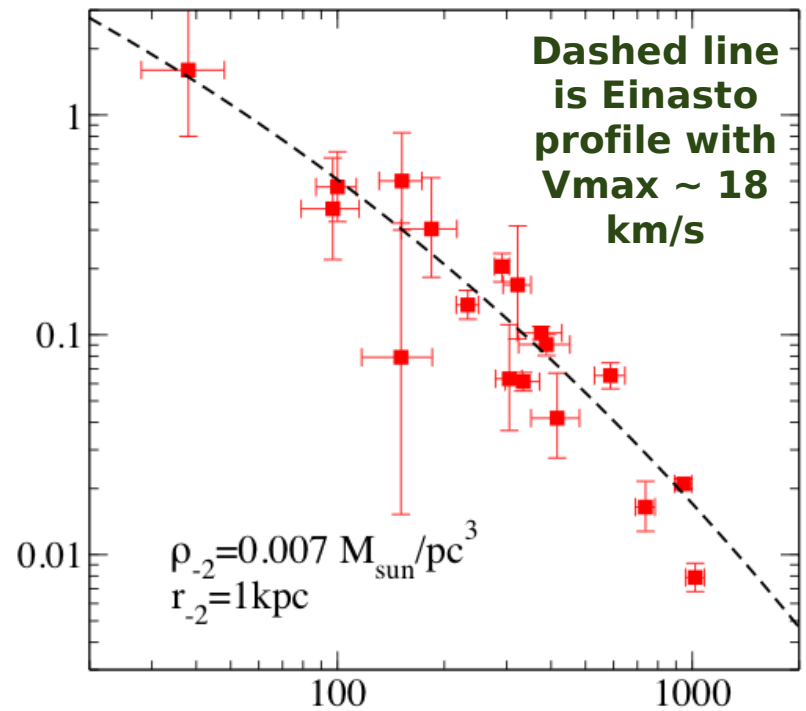
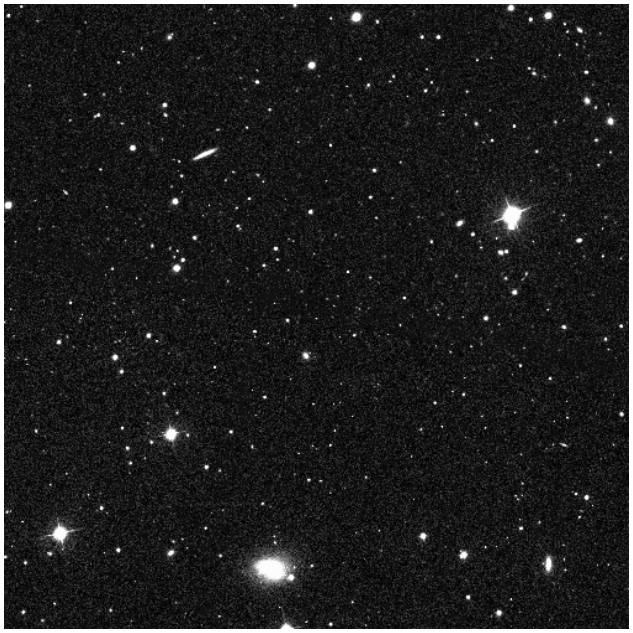
Density of dark matter at half light radius



Half light radius in parsec

Wolf, Martinez et. al. '10

Calculating Flux



Near-by Milky Way dwarf galaxies:

- Low intrinsic gamma ray flux
- Dark matter dominated
- Close-by

Detection of dark matter annihilation gamma-rays can constrain/rule-out dark matter theories!

Martinez et. al. '09 (arXiv:0902.4715)
Fermi Collab. '10 (arXiv:1001.4531)

Calculating Flux

Substructure Enhancement:

- Minimum halo size
- Subhalo concentration

$$Flux \propto (B+1) \times \int <\sigma v> \frac{\partial N}{\partial E} dE \times \int \rho^2(l)\, dl\, d\Omega$$

Particle Physics Properties:

- Annihilation cross section
- Photon yield
- DM mass

Dark Matter Halo Properties:

- Halo density profile

Calculating Flux

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Calculating Flux

Particle Physics Properties:

Constrained Minimal Supersymmetry Model (CMSSM)

- Only 4 free parameters (8 total)!

- Pre-existing code to determine model properties:
  - SoftSusy: (Allanach '07)
  - DarkSusy: (Gondolo et al. '04)
  - SuperBayes: (de Austri et al. '06)

- Effect of priors: Not well understood: see Trotta et al. '06

- Constrained from collider and CMB data.

Calculating Flux

$$Flux \propto (B+1) \times \int <\sigma v> \frac{\partial N}{\partial E} dE \times \boxed{\int \rho^2(l)\, dl\, d\Omega}$$

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Calculating Flux

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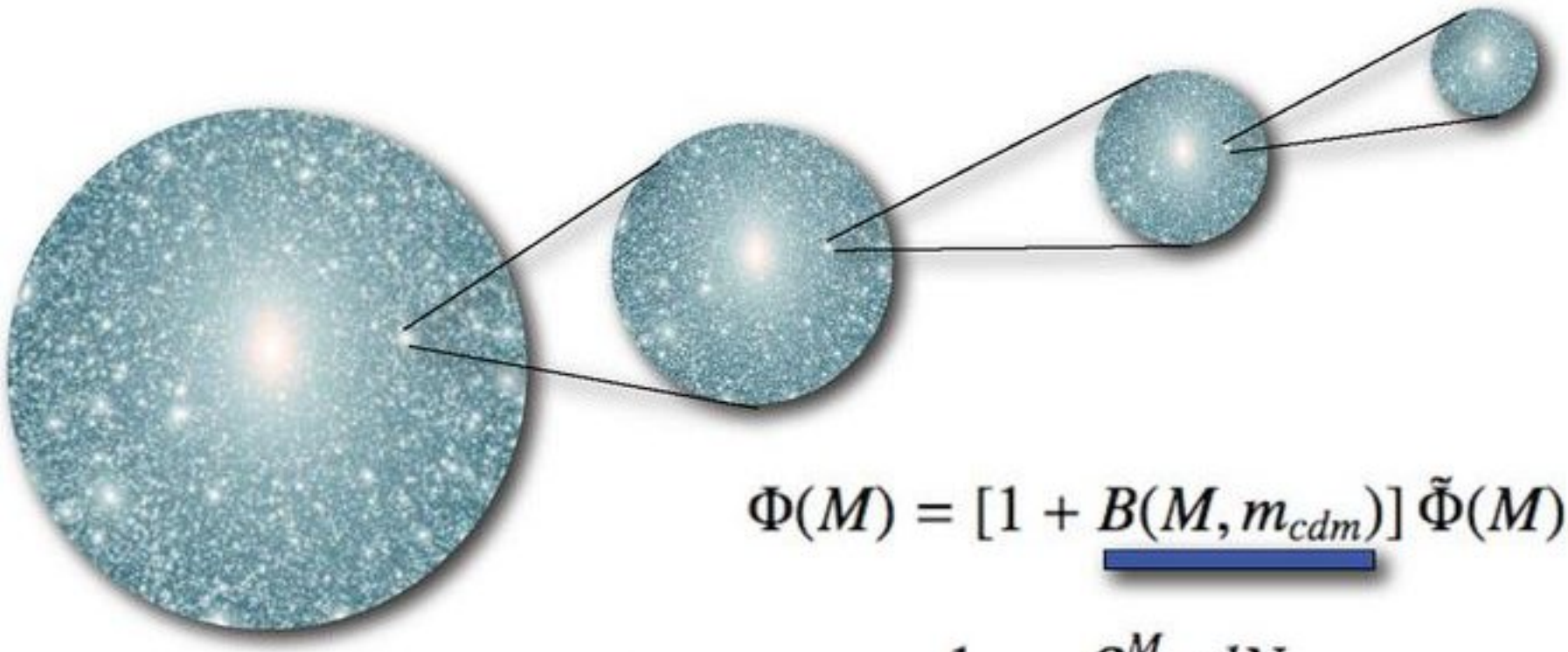
Calculating Boost

Enhancement due to substructure:



$$\Phi(M) = [1 + B(M, m_{cdm})]\,\tilde{\Phi}(M)$$

$$B(M, m_{cdm}) = \frac{1}{\tilde{\Phi}(M)} \int_{m_{cdm}}^{M} \frac{dN}{dm} \Phi(m) dm$$

Martinez et al. '09; Strigari et. al. '07;
Diemand et. al. '08

Calculating Boost

Enhancement due to substructure:

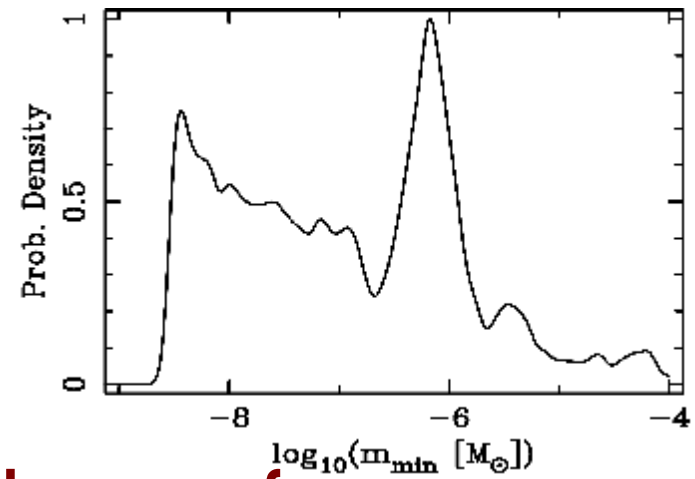
- Dependent on both particle and astrophysics
- Dependent on micro-halo luminosity.
  - Determined by concentration and mass function
- Dependent on the minimum halo mass
  - Determined by era of kinetic decoupling
    - Determined on the lepton scattering cross section.

Calculating Boost

Enhancement due to substructure: Kinetic Decoupling

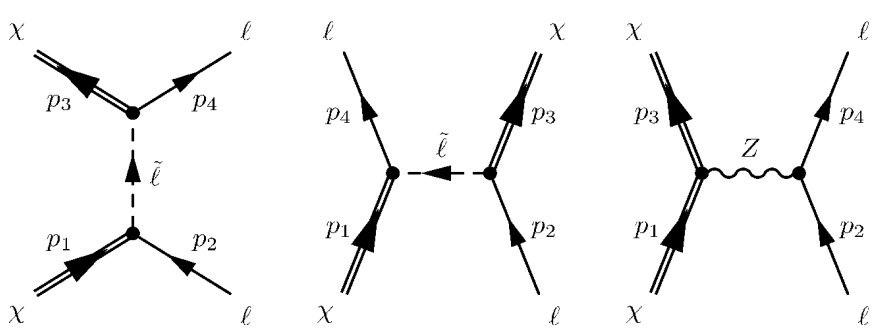
- **Neutralinos elastically scattered with SM leptons that are still in thermal bath.**

Bertschinger, '06; Profumo, '06;
Green et. al. '04;



Martinez et al. '09

- **Minimum halo mass is determined by era of kinetic decoupling which in turn depends on the lepton scattering cross section:**



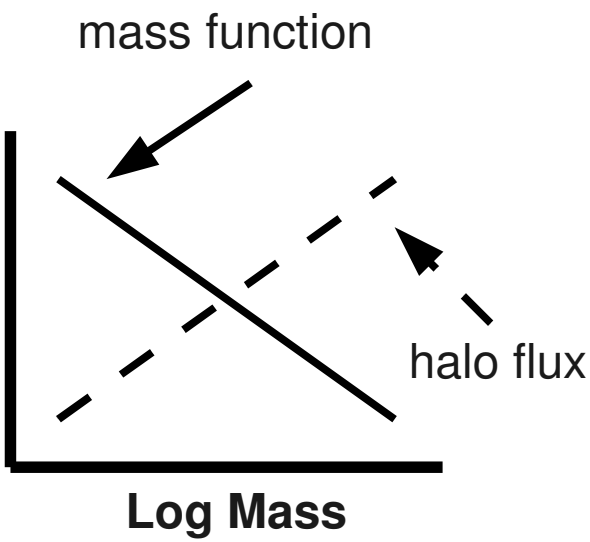
= Really Big Equation

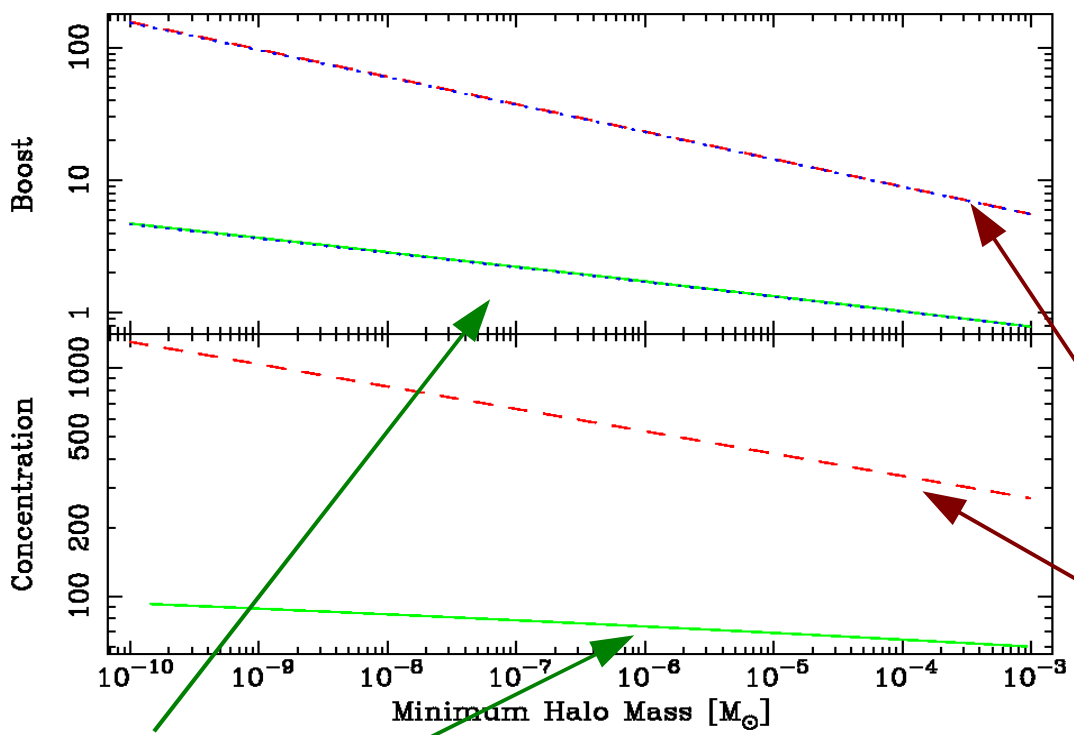
Berkeley '10

Calculating Boost

Enhancement due to substructure: Halo Dependence

- Small mass halos dominate boost.
  - Smaller, but more numerous.





Self similar model
High concentration

Bullock et al. Model
Low concentration

Martinez et al. '09

Calculating Boost

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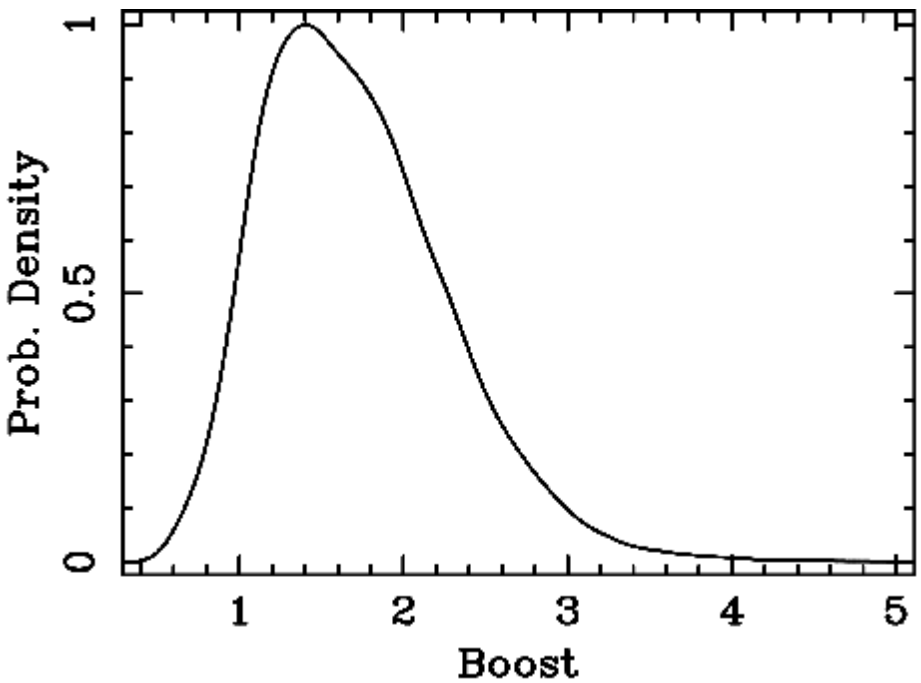
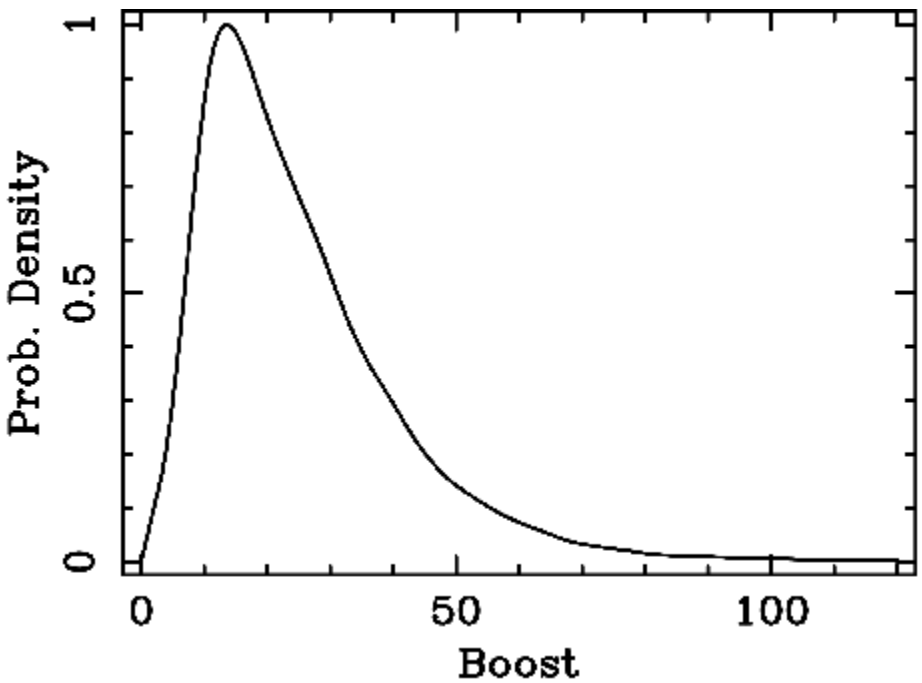
Martinez et al. '09



Low concentration



High concentration

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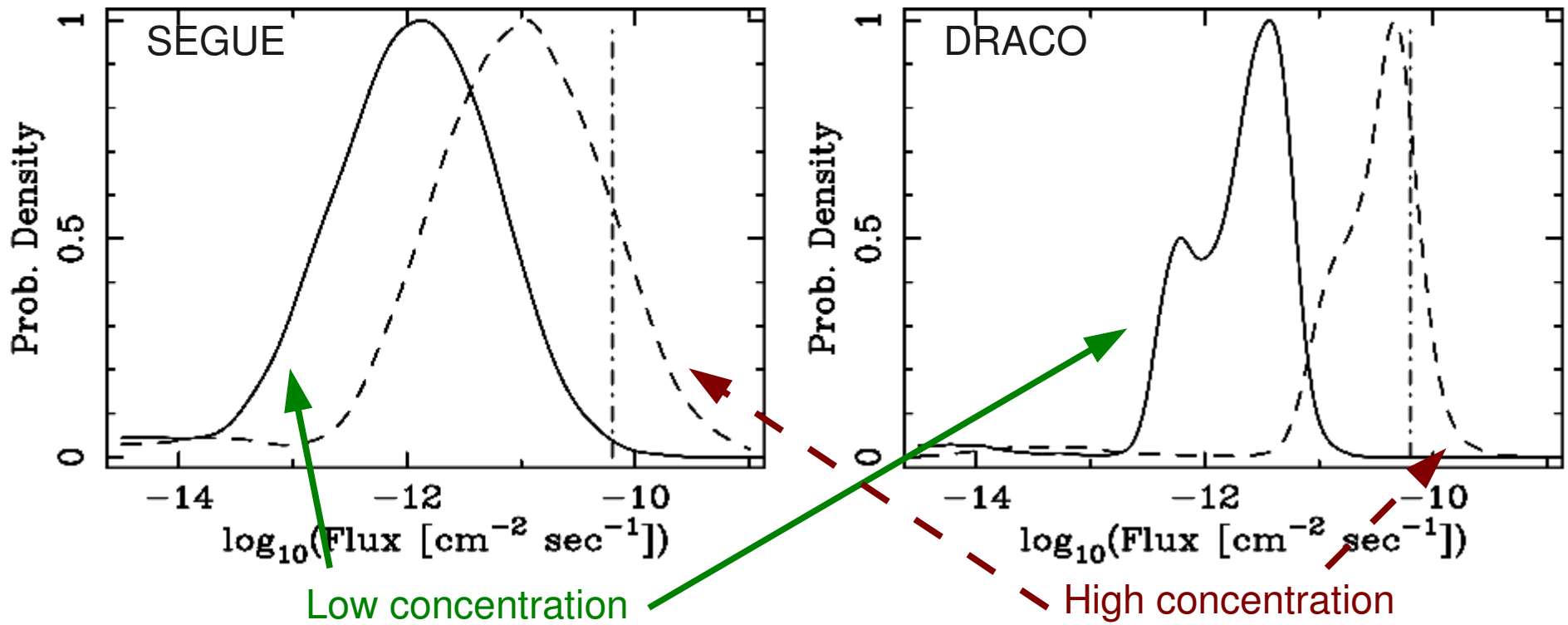
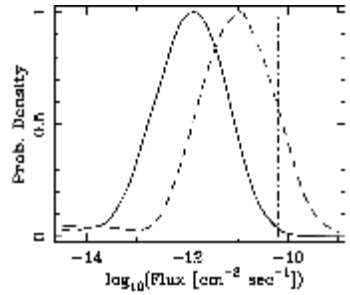
Martinez et al. '09

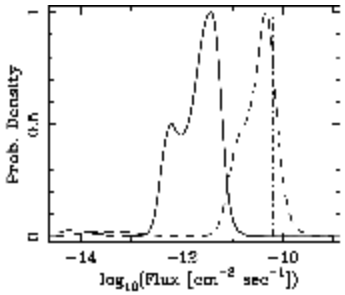


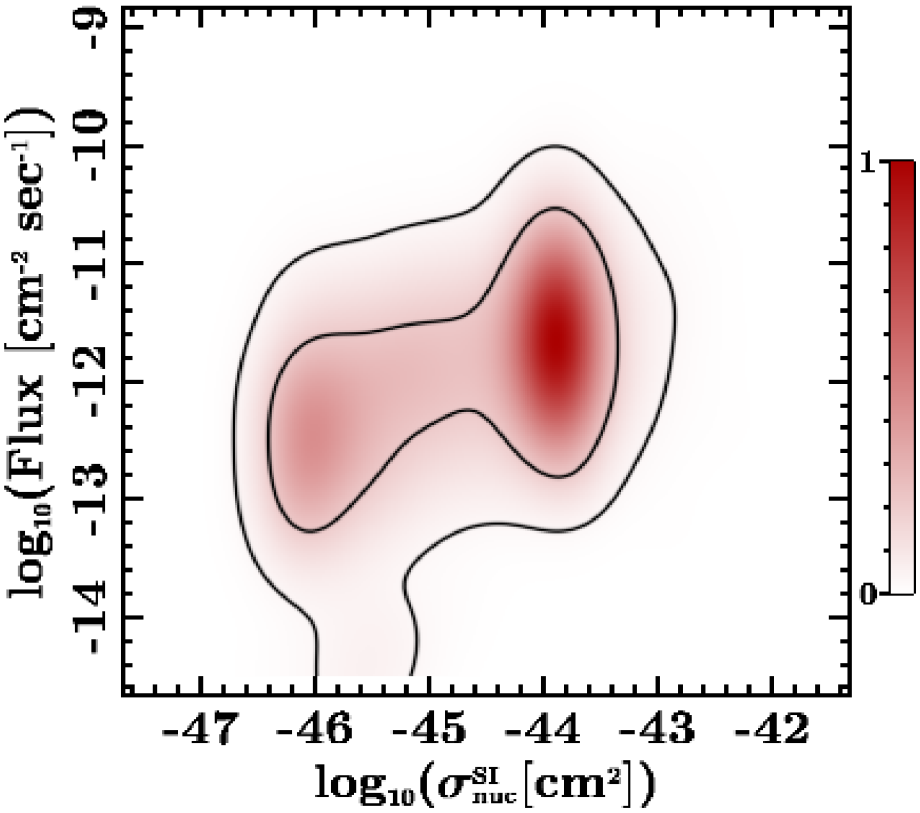
Predicting Flux

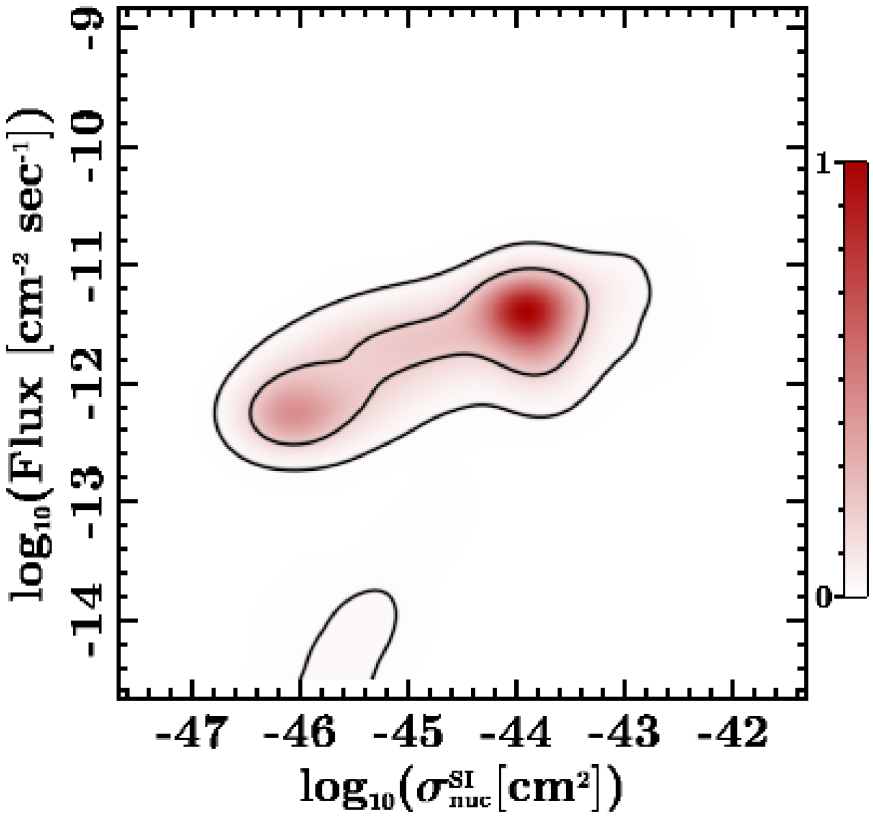
SEGUE



DRACO







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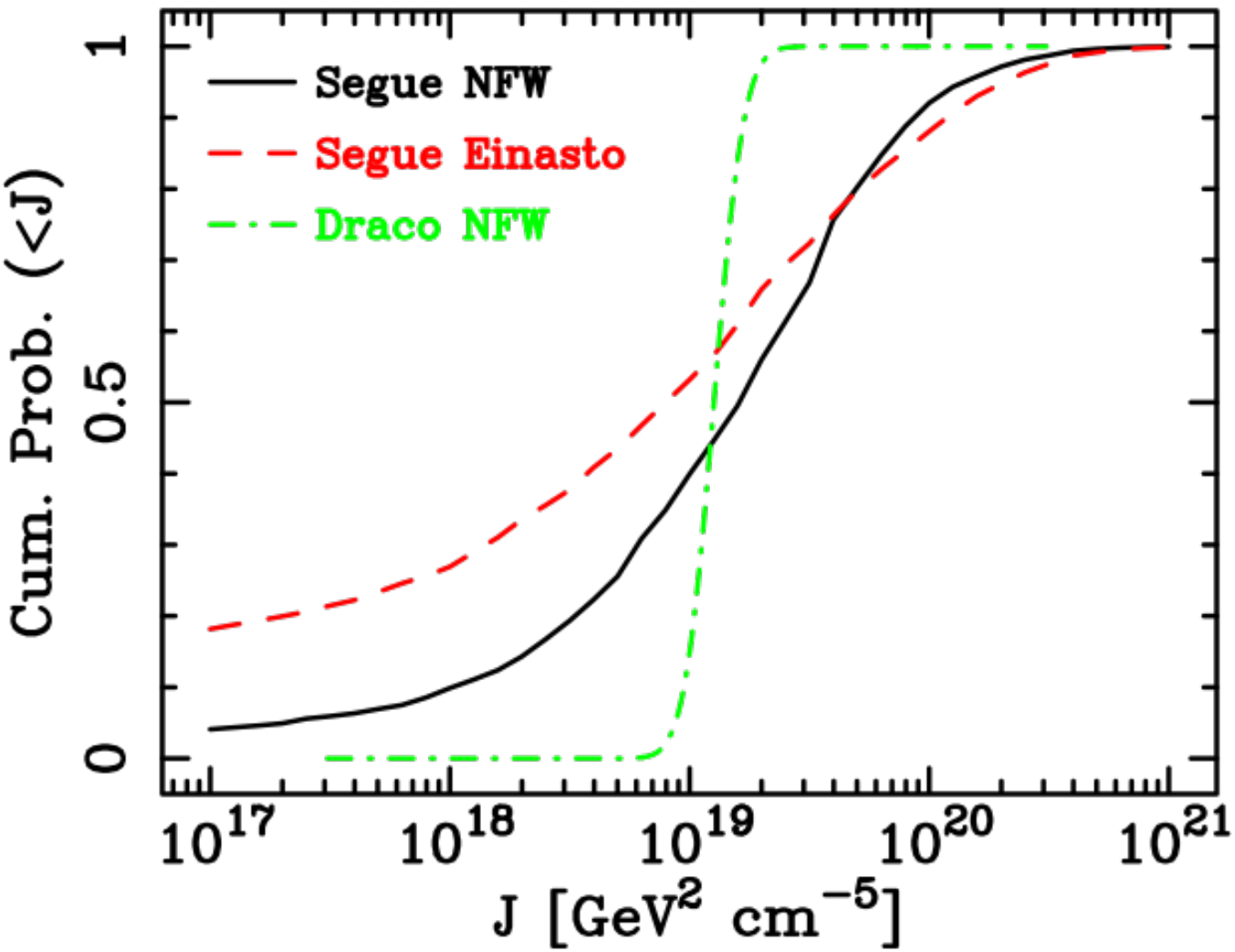
Preliminary Segue 1 Flux



Summary

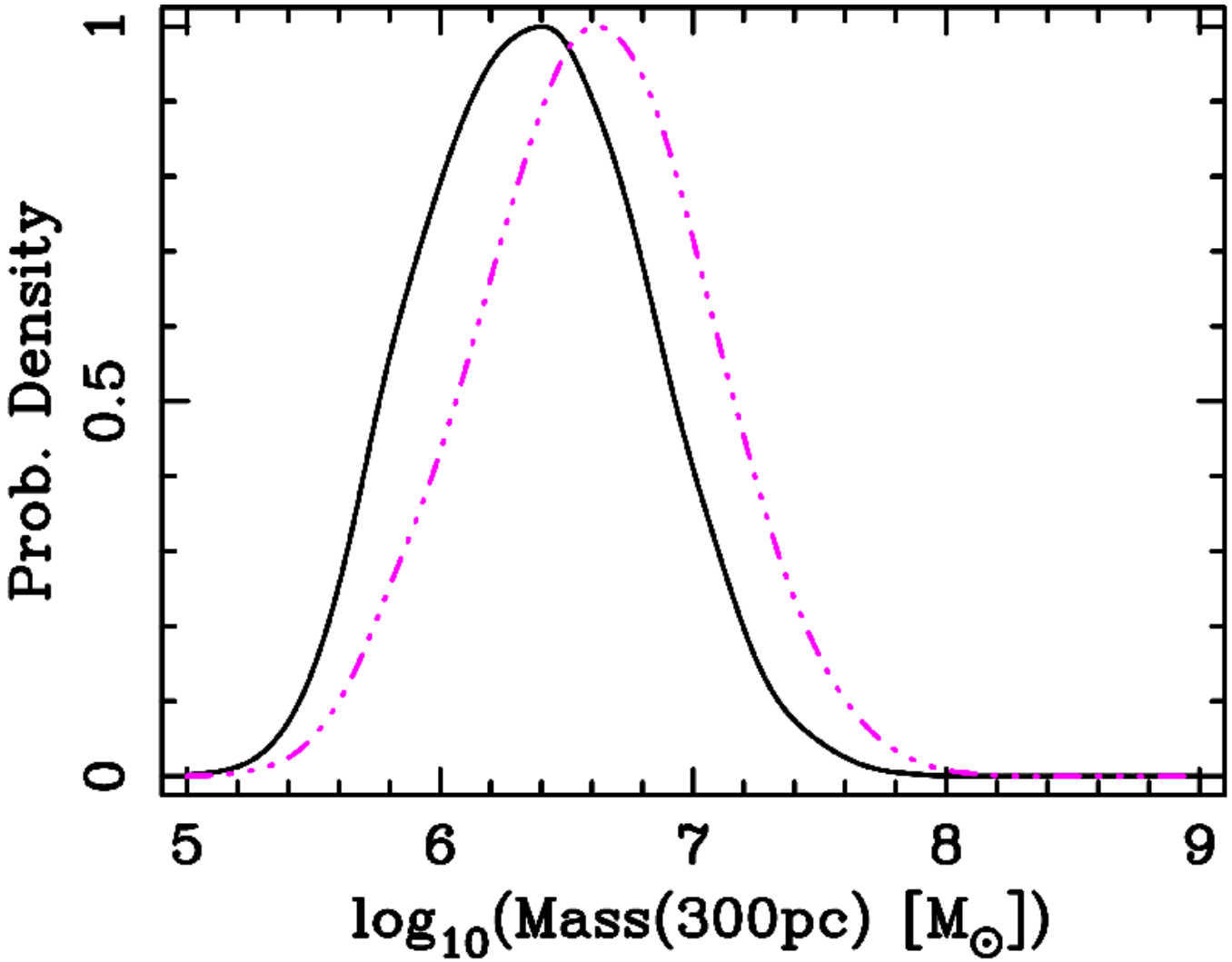
- MW satellites, especially the newly discovered ultra-faint Milky Way satellites, provides a means to test dark matter theories.

- Current analysis strongly suggests Segue 1 lives in a large dark matter halo that is similar to the dark matter halos of other dwarfs.

- Data analysis methods are quickly evolving, but work is needed.

- Using current data, dark matter properties can be inferred such as halo mass within the half light radius and predictions for gamma ray fluxes from dark matter annihilations in MW dwarf galaxies.

Calculating Flux



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