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Modeling the Tidal Stream of NGC 5466

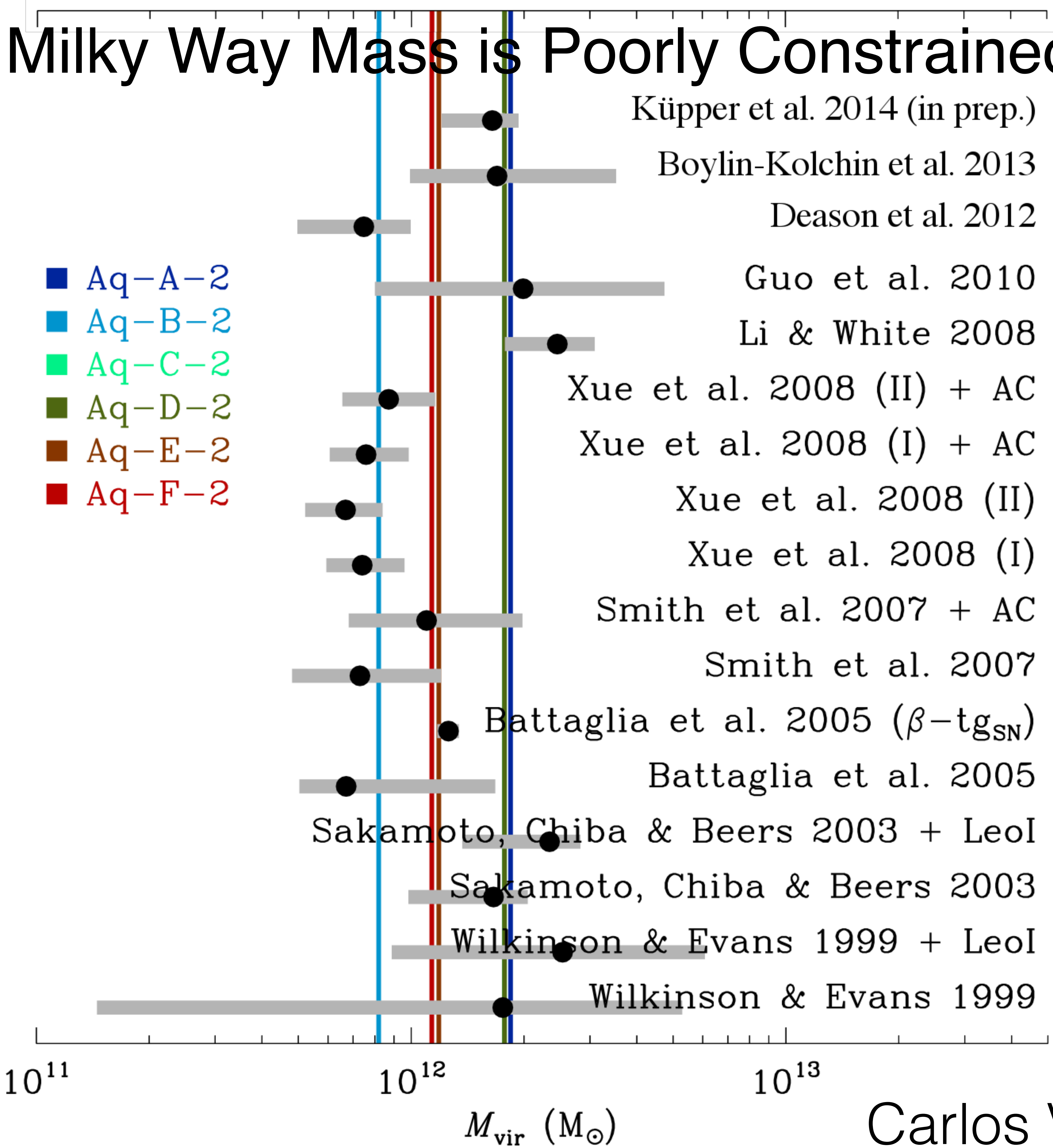
ISIMA - Toronto : August 6, 2014

Image: Spitzer - Caltech

Outline

- Motivation (i.e. why should you care?)
- Theory - Escapers & Streakline Method
- Data - SDSS, Literature Values, Radial Velocities
- Interpretation - Halo Parameters & Cluster Orbit

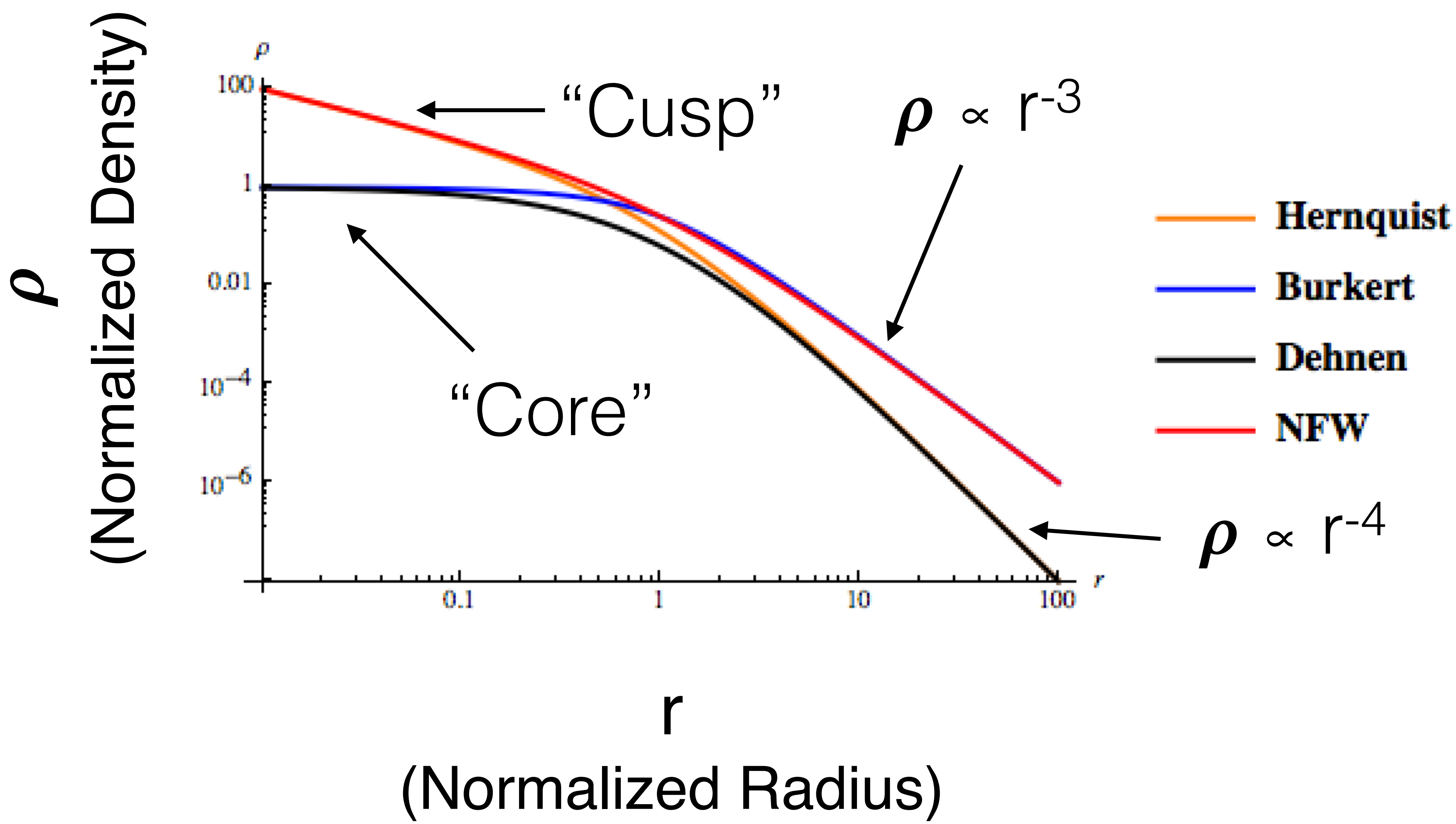
Milky Way Mass is Poorly Constrained



Carlos Vera-Ciro

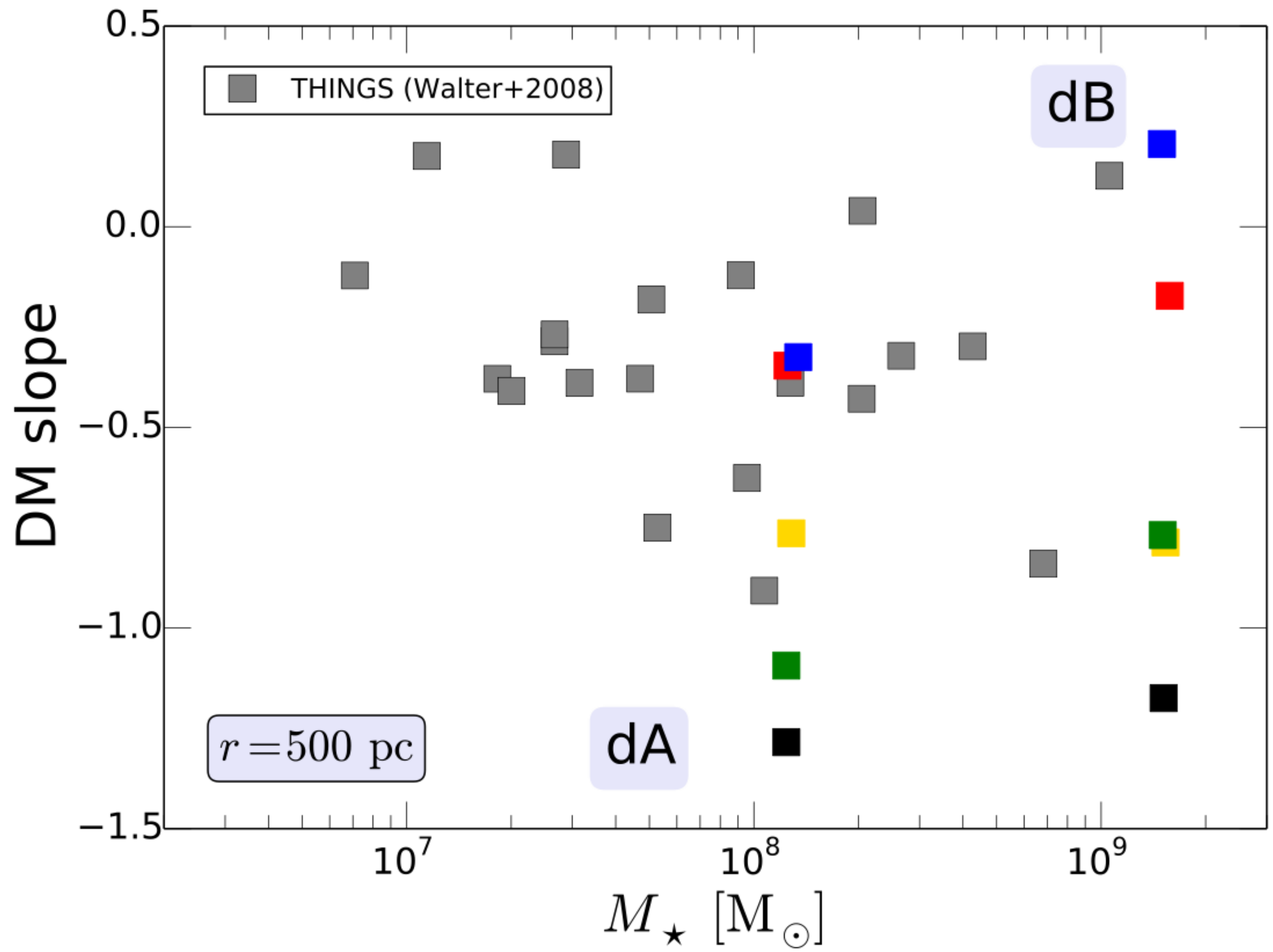
Dark Matter Halos

Spherical Models



Dark Matter Halos

Spherical Models

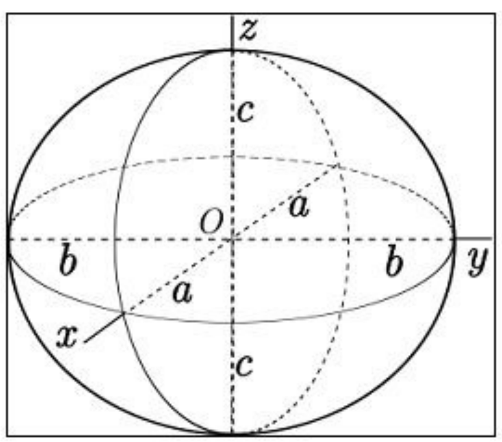


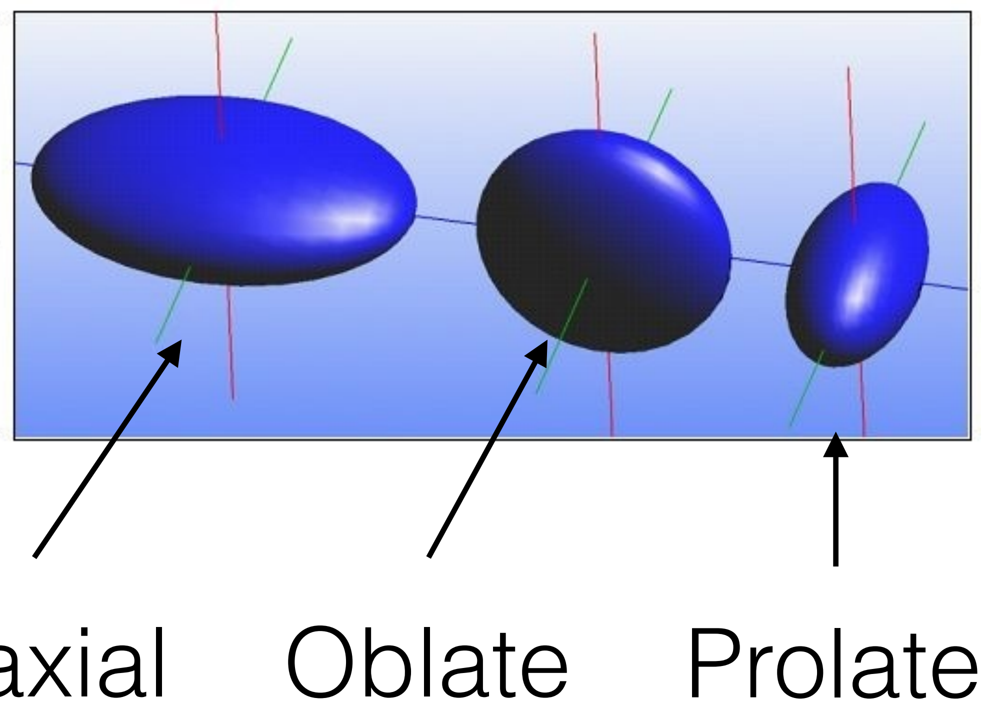
Volgelsberger et al. 2014

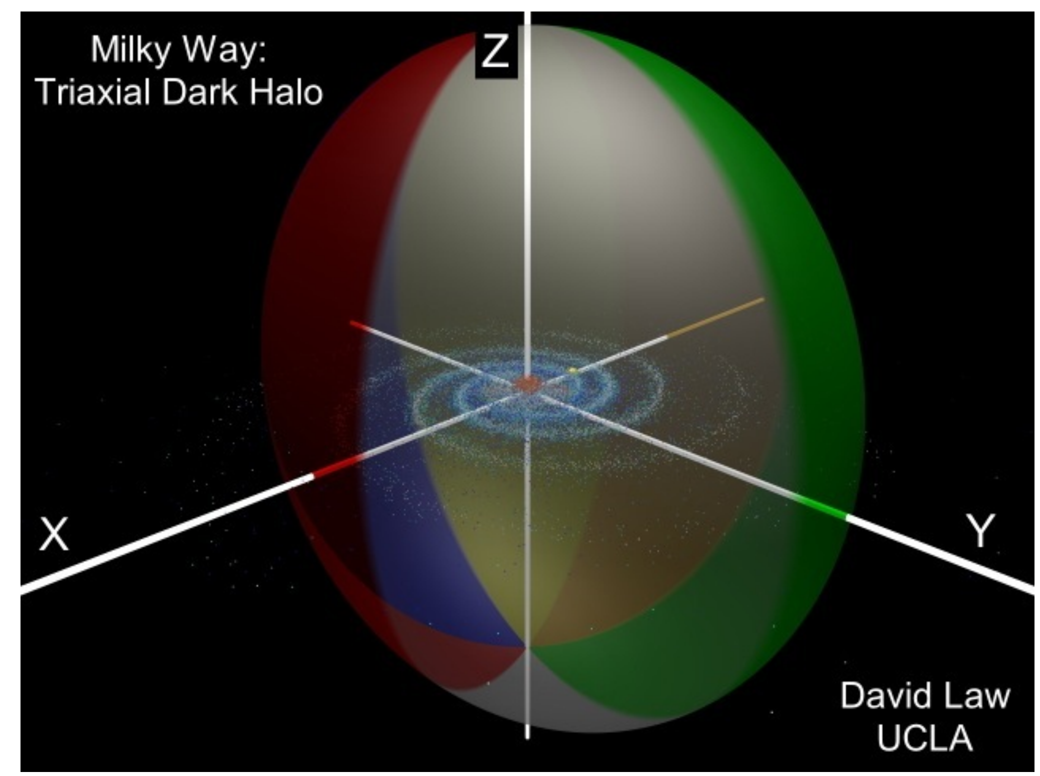
Core vs. Cusp

Dark Matter Halos

Oblate, Prolate, and Tri-axial







Tomas Vydra and Daniel Havelka

http://www.universetoday.com/;
Law & Majewski 2010

Disk and Bulge Models

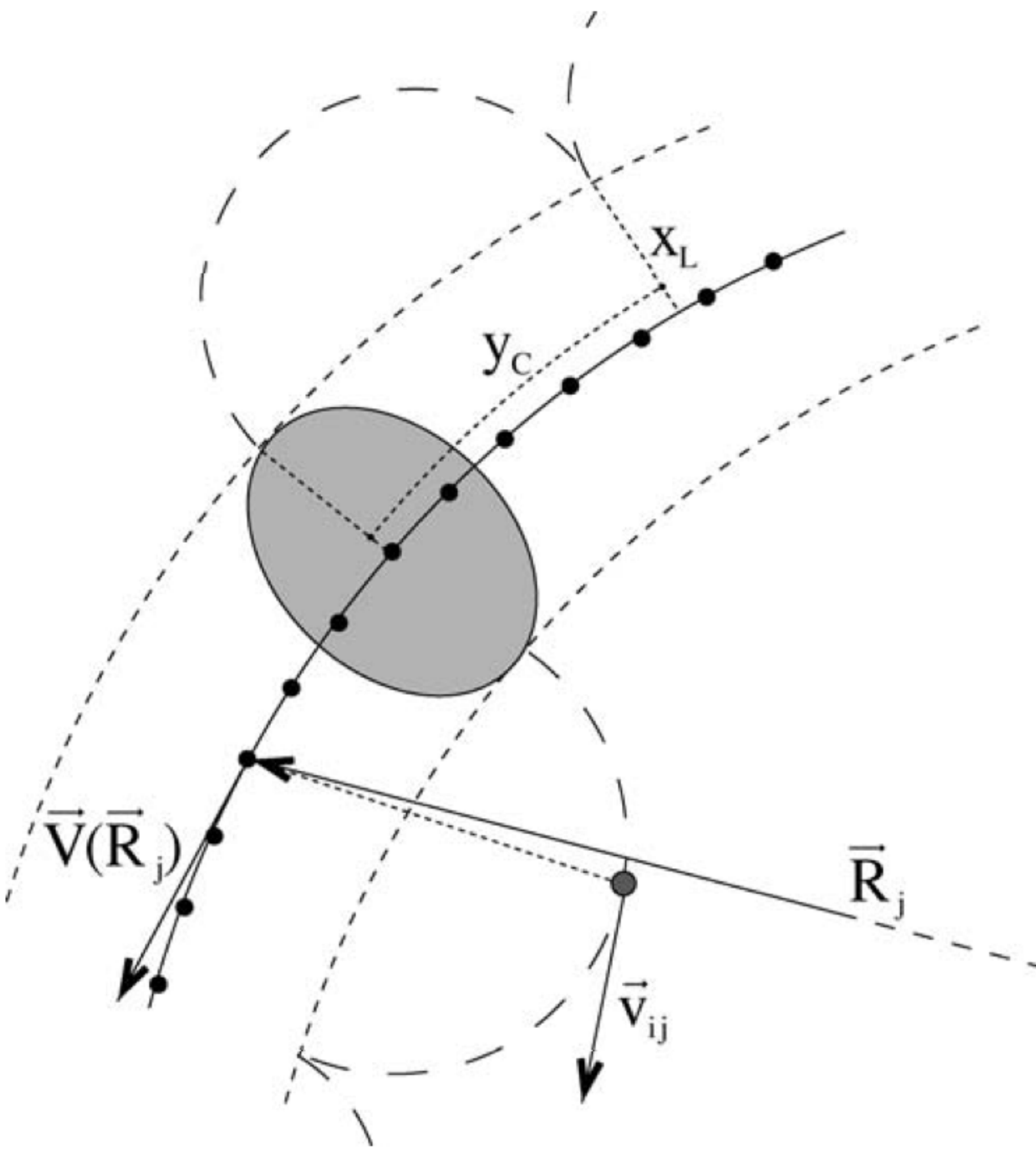
Hernquist (1990) spherical bulge:

$$\Phi_{bulge} = -\frac{GM_{bulge}}{R + a}$$

Miyamoto & Nagai (1975) disk:

$$\Phi_{disk} = -\frac{GM_{disk}}{\sqrt{x^2 + y^2 + (b + \sqrt{z^2 + c^2})^2}}$$

Lagrange Points and Escapers



Küpper et al. 2010

$$r_L = \left(\frac{GM_c}{\Omega_c^2 - \partial^2\Phi/\partial R_c^2} \right)^{1/3}$$

Stars escape:

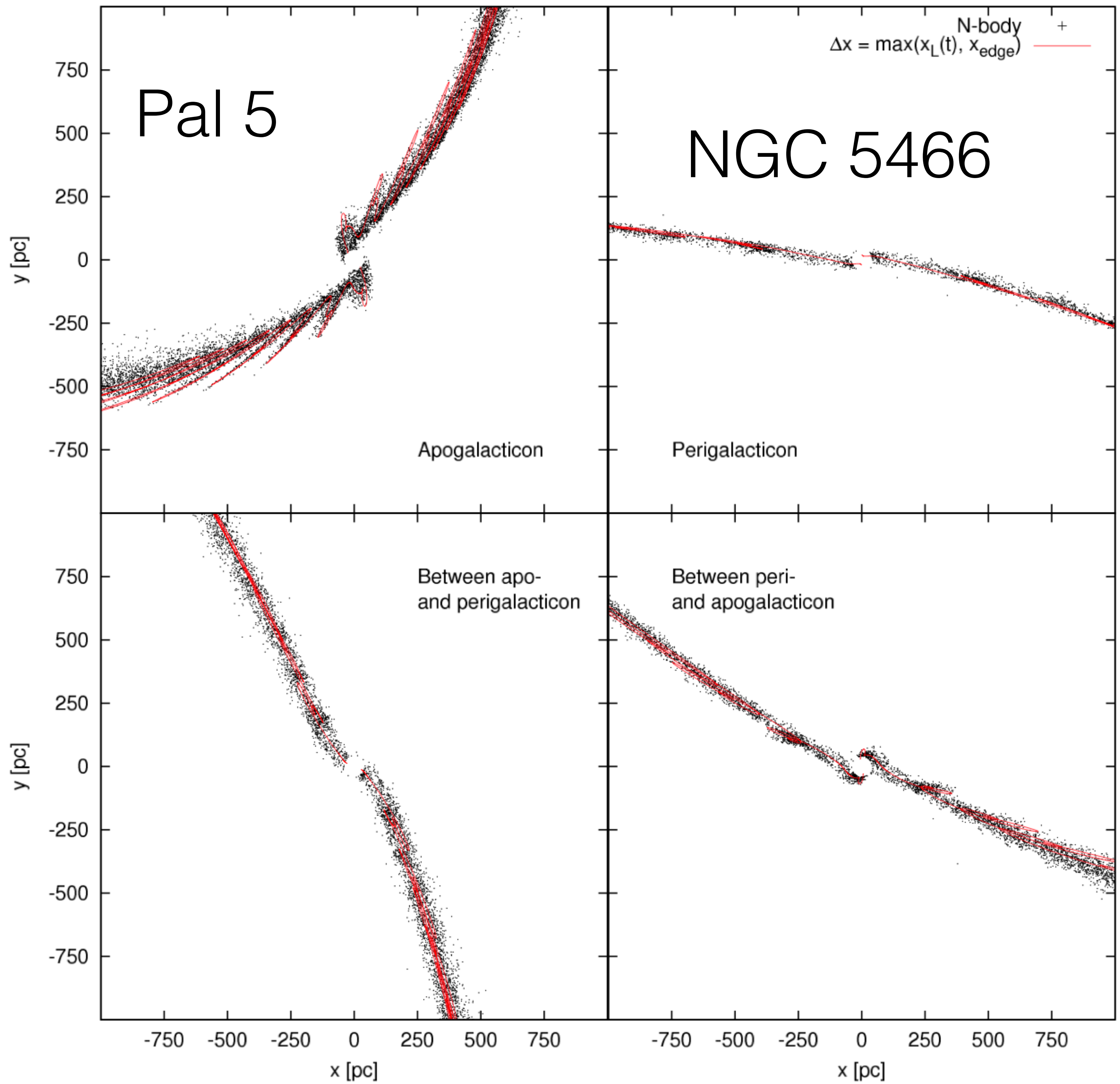
- From Lagrange radius (King 1962)
  - Küpper et al. 2012 set minimum radius to prevent recapture
- At low velocities
  - Modeled as equal the cluster central velocity plus a small offset

$$R^i = \frac{R_c^i}{R_c} \times (R_c \mp r_L) \mp \delta r^i$$

$$V^i = \frac{V_c^i}{V_c} \times (V_c \pm \Omega_L x_L) \pm \delta v^i$$

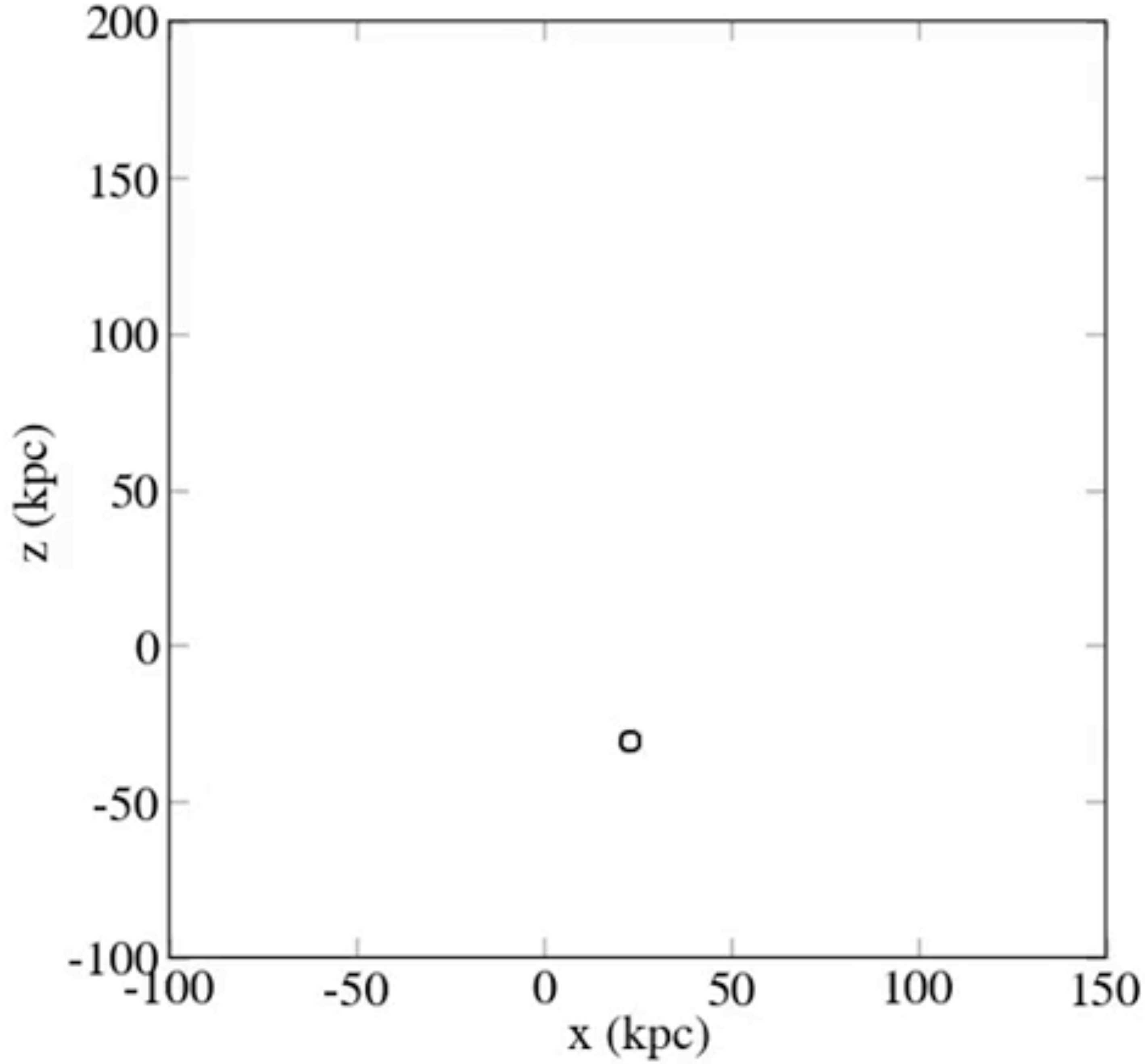
Lagrange Points and Escapers

- Stars on epicyclic orbits create over-densities
- Cluster is stretched and contracted as it goes from pericenter to apocenter
- Reproduce NBody results using streaklines
  - Restricted 3-Body integration - Fast!
  - Test particles are released from cluster at set intervals



Küpper et al. 2012

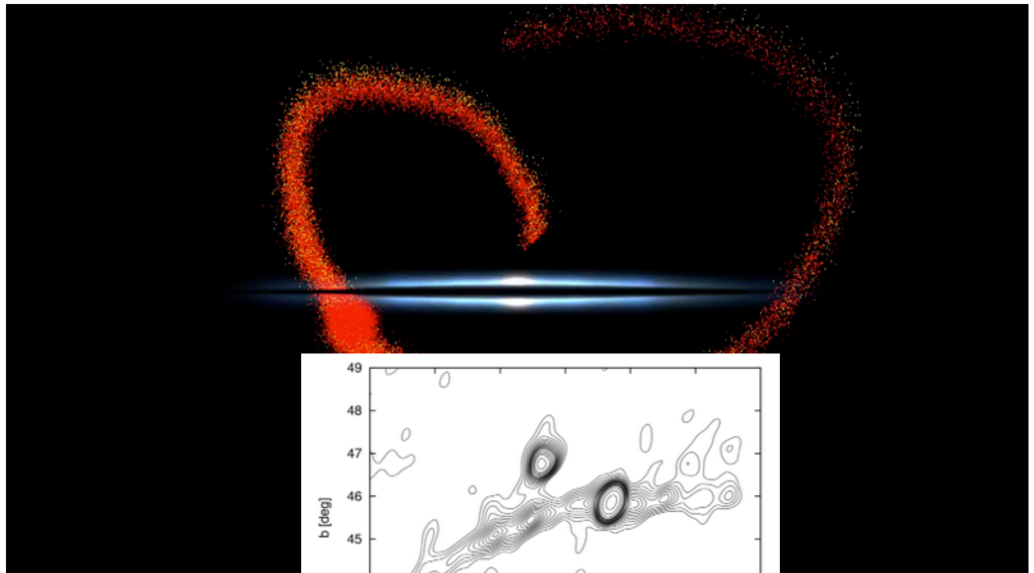
Fast Forward Modeling



Ana Bonaca

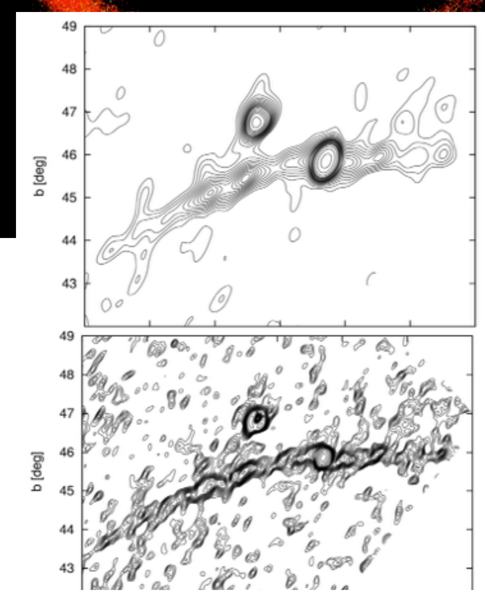
Tidal Streams as Probes of the Galactic Potential

Sagittarius Dwarf



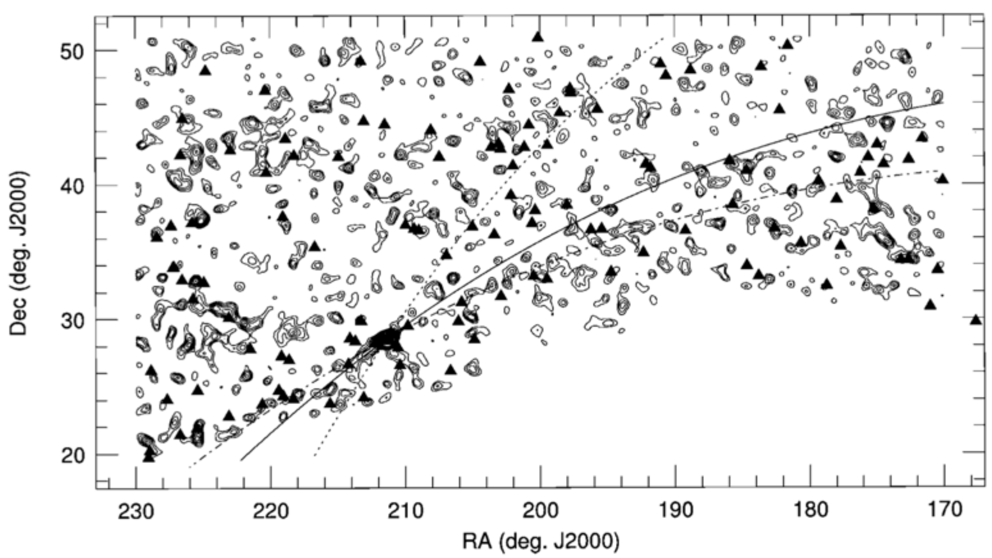
Koposov et al. 2012; Law & Majewski 2010; Gibbons et al. 2014 + Many others

Palomar 5



Küpper et al. 2014 (in prep);
Lux et al. 2013; Dehnen et al. 2004
Odenkirchen et al. 2003 + Many others

NGC 5466



Grillmair & Johnson 2006; Lux et al. 2013;

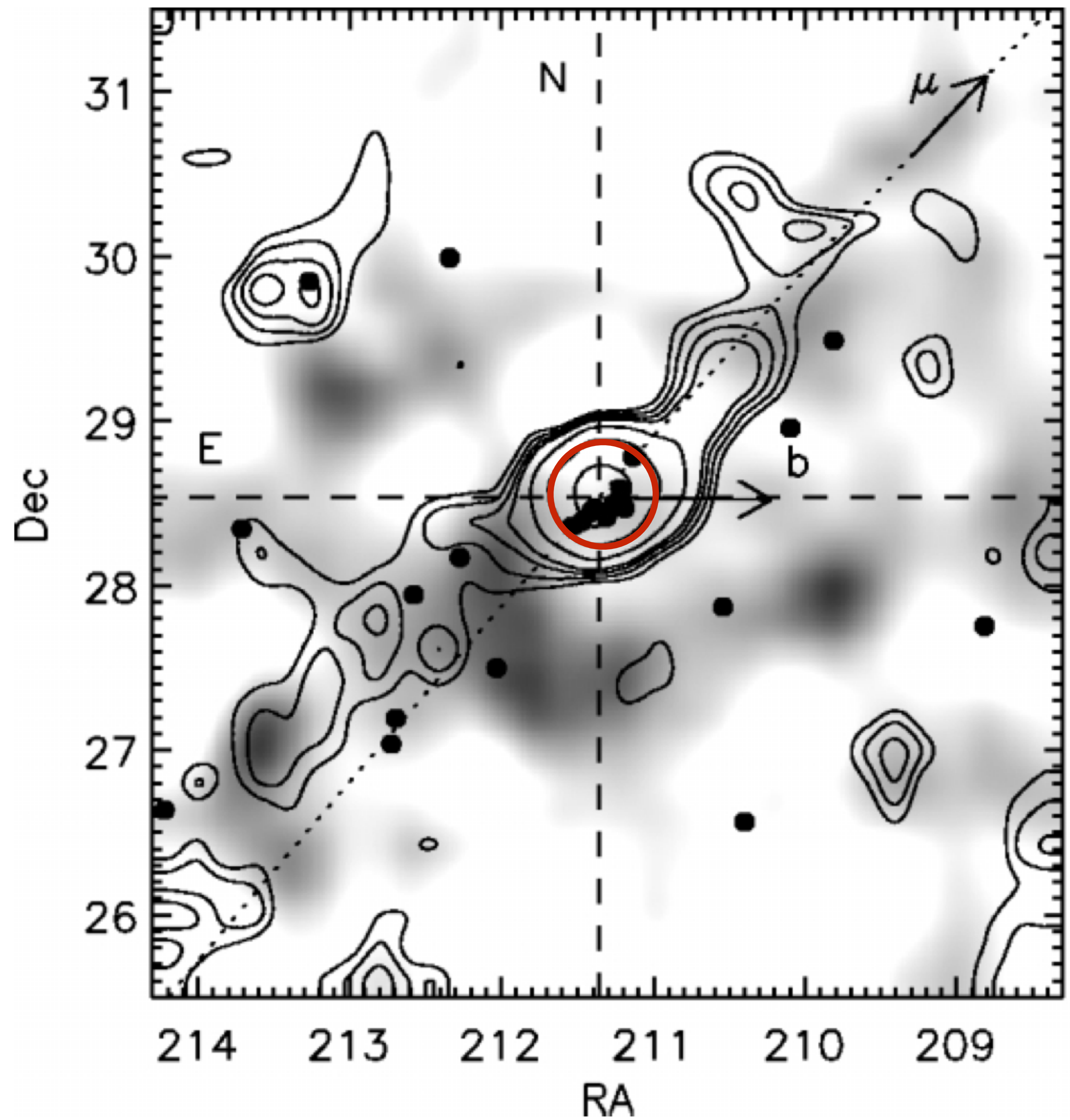
Fellhauer et al. 2007 ; Belokurov et al. 2006

+ Many others

NGC 5466 Stream

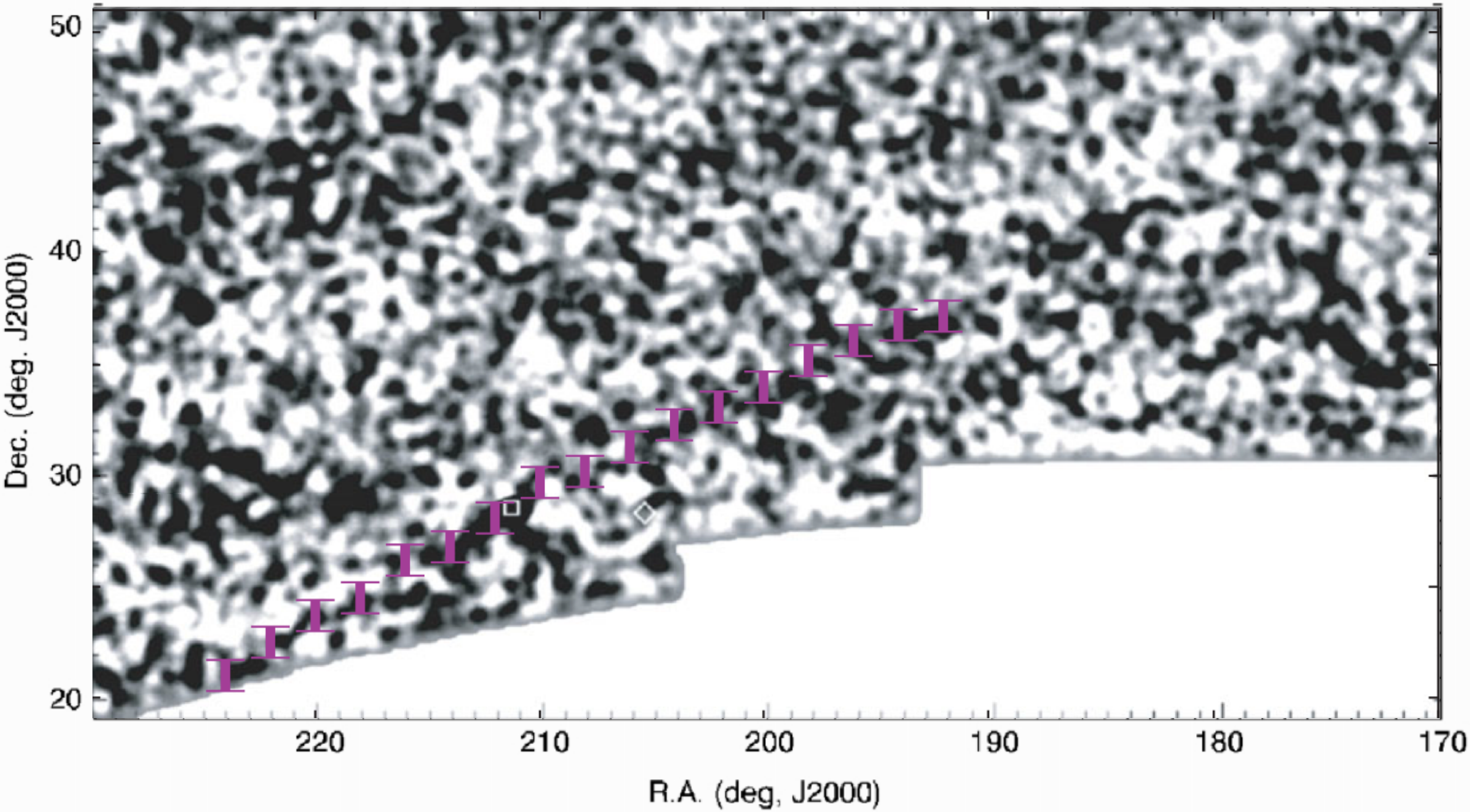
Neural networks detected 4° stream
Belokurov et al. 2006

Tidal Radius ~21arcmin
Lehmann & Scholz 1997



NGC 5466 Stream

Grillmair & Johnson 06 ; Lux+12

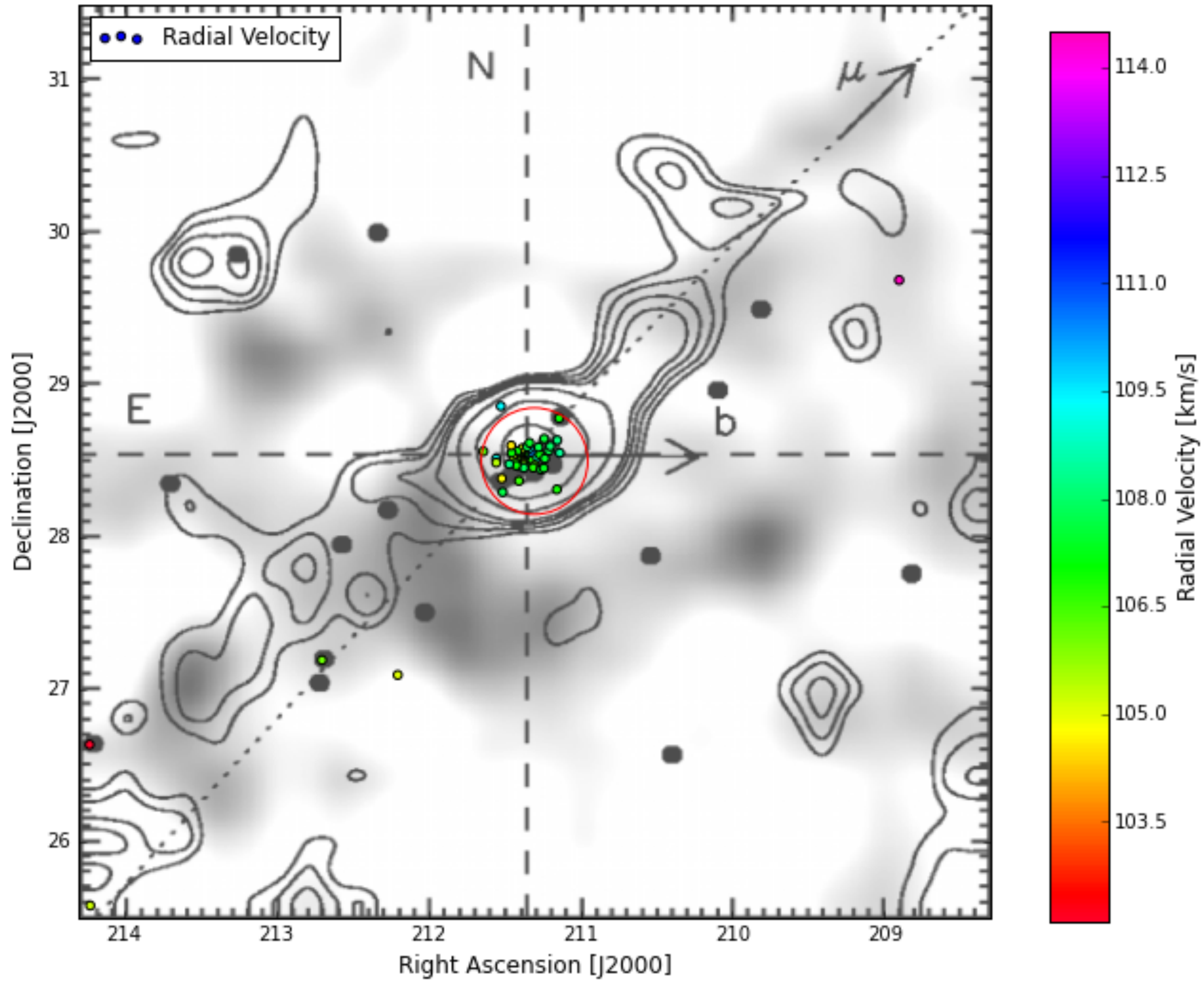


Tentative 45° stream

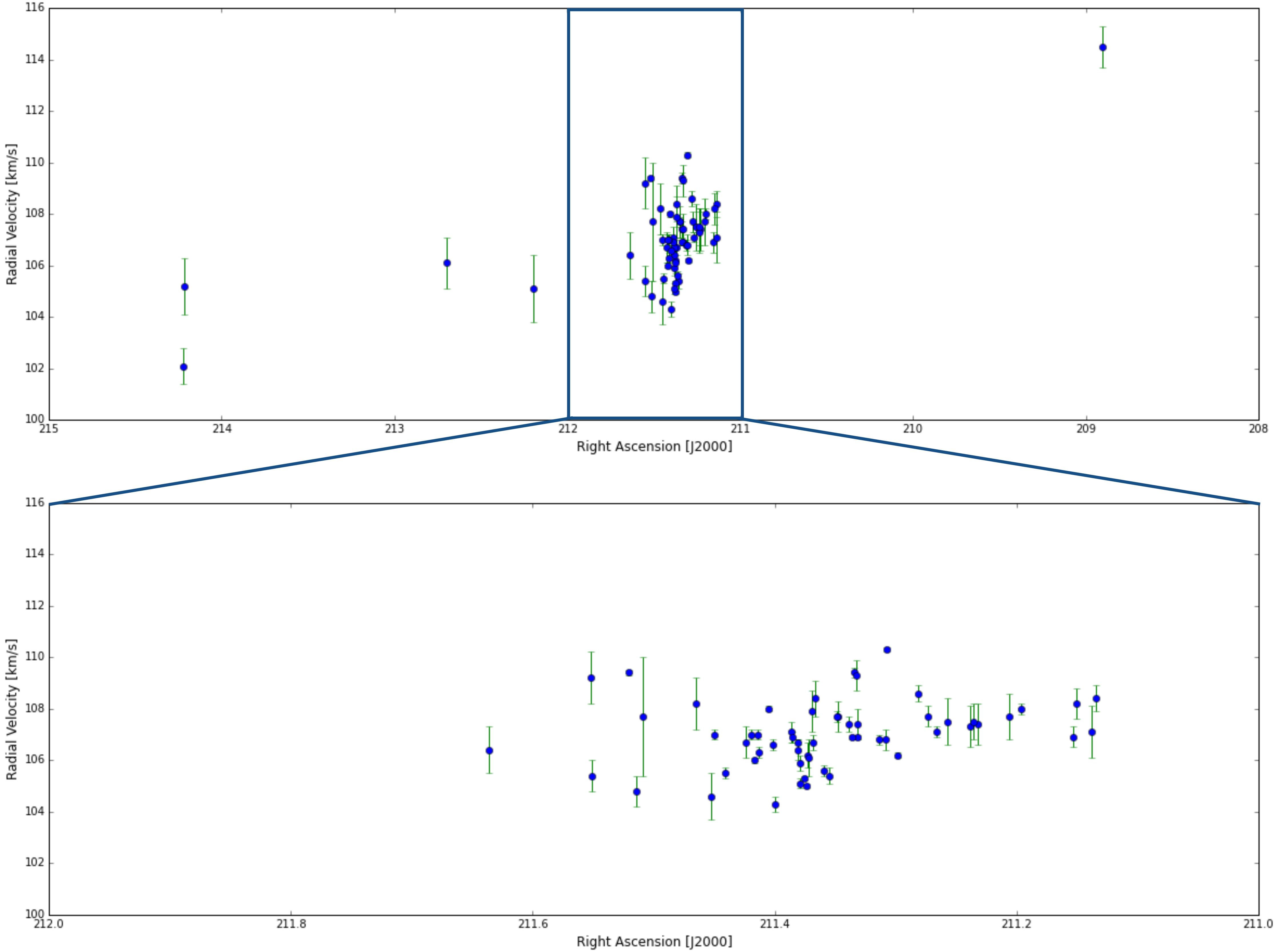
Radial velocity measurements

Data: Jay Strader

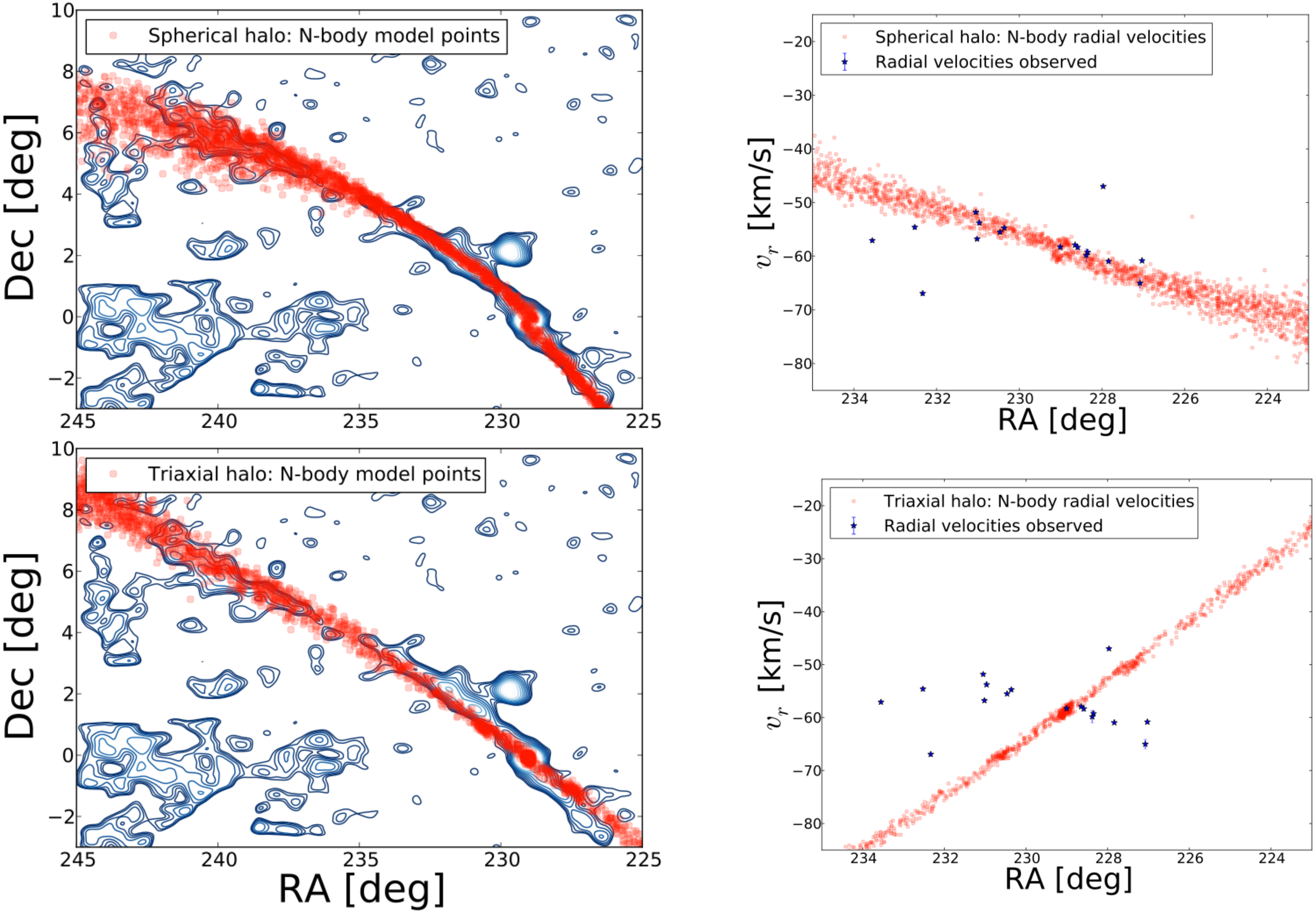
- 309 bright stars observed
- 63 cluster members
- 5 stream members



Radial velocity measurements



Streakline method used to model Palomar 5



Pearson+14

$$\mathrm{LL_{OD}} = \sum_{j}^{N_{OD}} \log\left(\frac{1}{N_{\mathrm{model}}} \sum_{i}^{N_{\mathrm{model}}} \exp^{-\frac{1}{2}\left(\frac{d_{ij}^2}{\Delta d^2}\right)} + \Delta \right)$$

Best fit values use log-likelihood

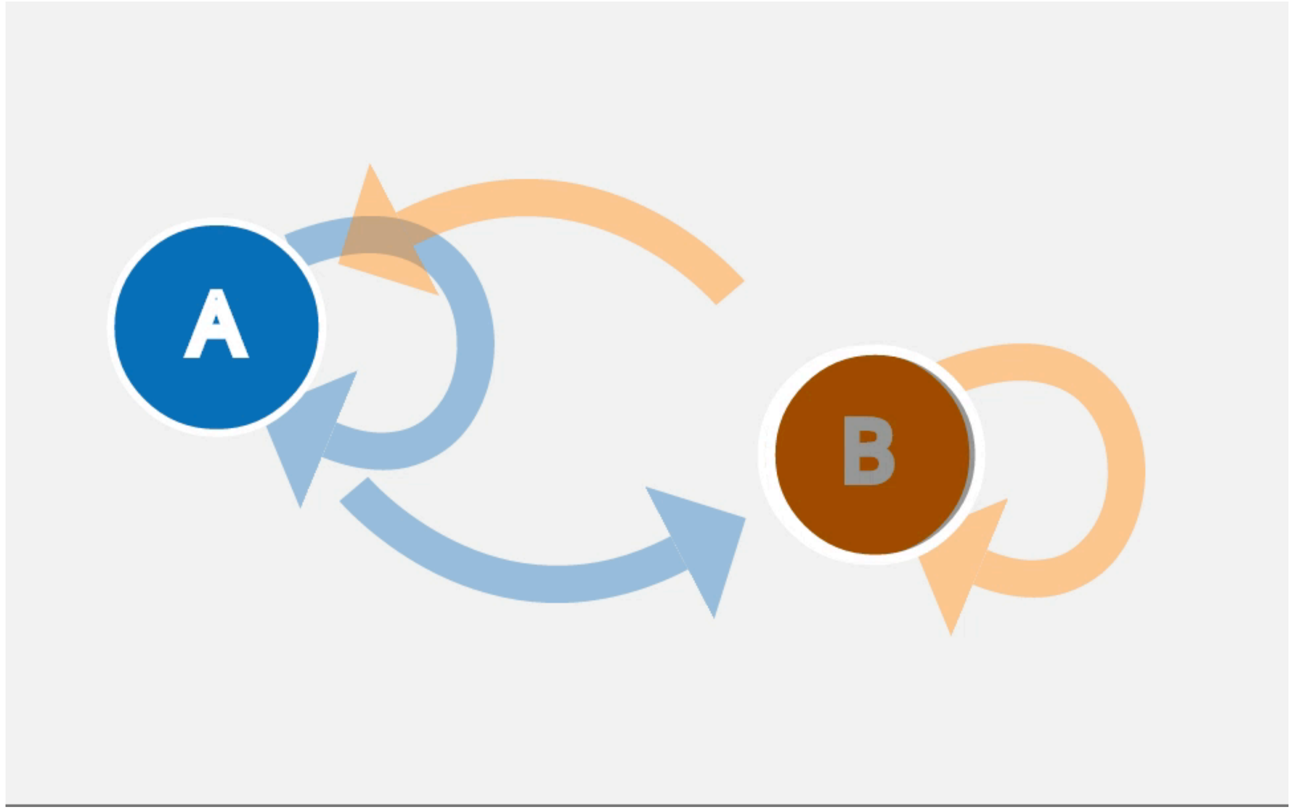
- test particles near data add weight to the model, but…
- data with few test particles do not significantly hurt model

$$\mathrm{LL_{total}} = \log\mathrm{L_{OD}} + \log\mathrm{L}_{v_r}$$

Markov Chain Monte Carlo

Modeling with: *emcee*
http://dan.iel.fm/emcee/

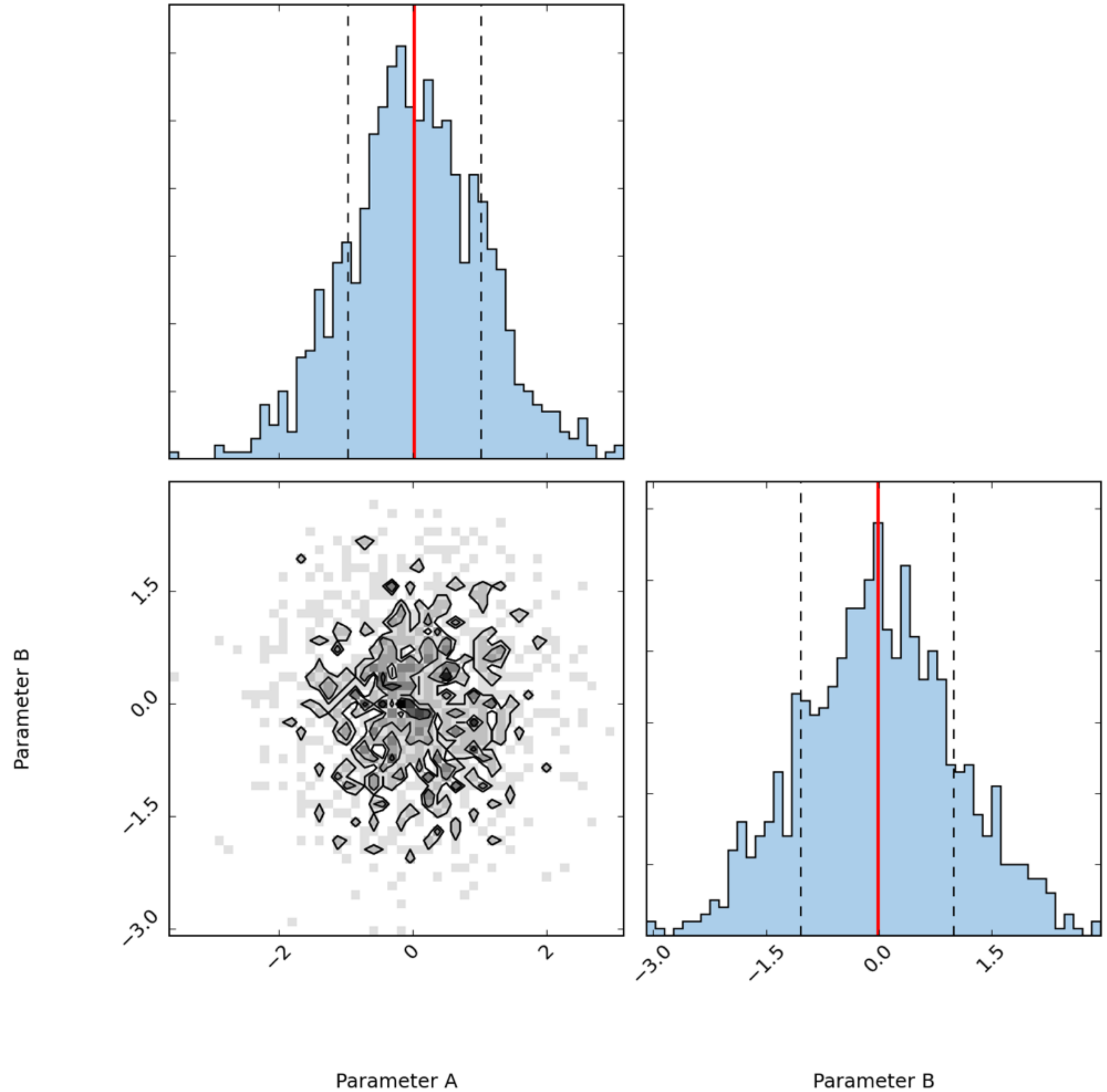
Markov chains move between two (or many) states with a finite probability



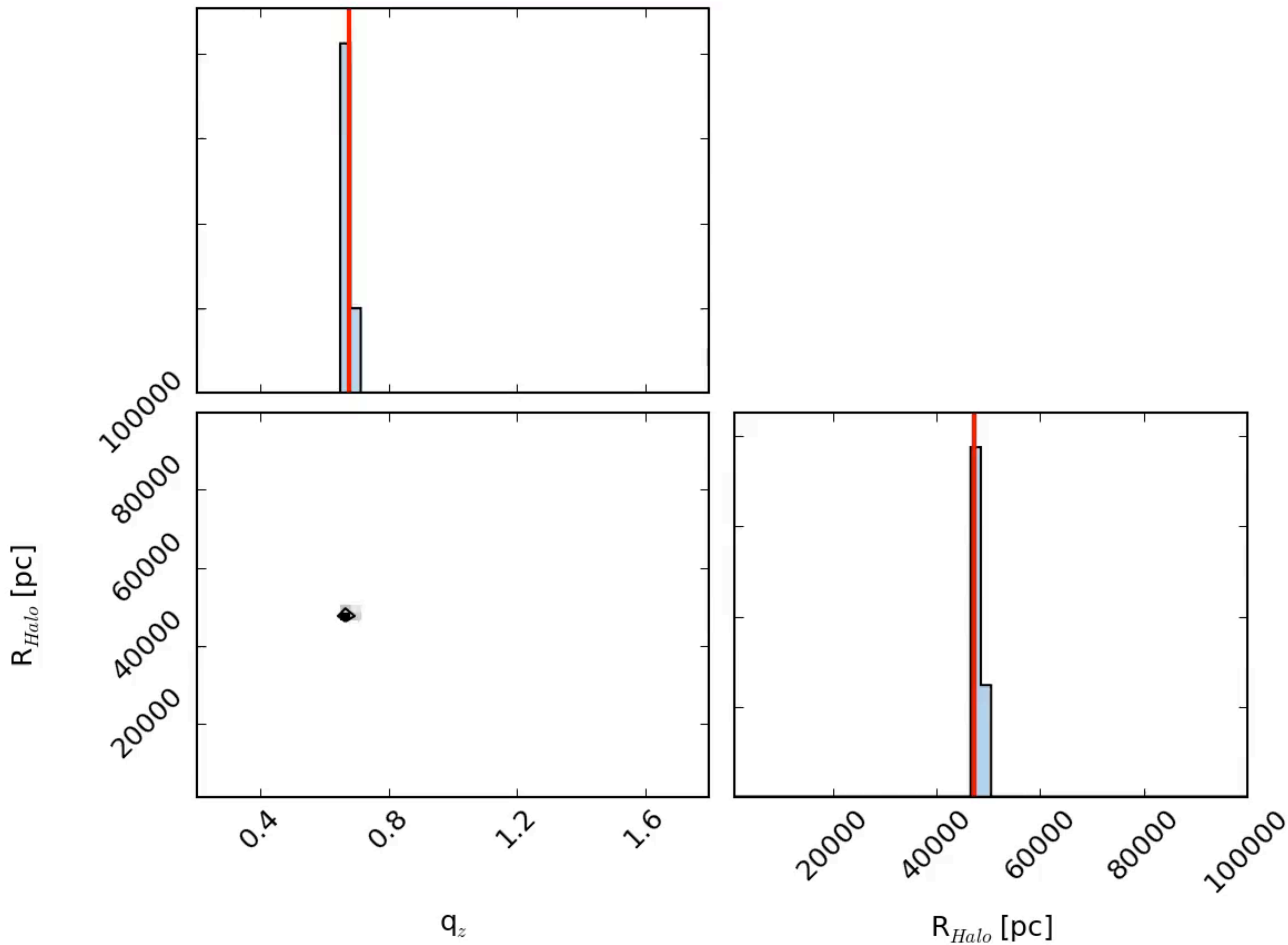
Animation: Victor Powell & Lewis Lehe
setosa.io

Draw new model randomly and test log likelihood

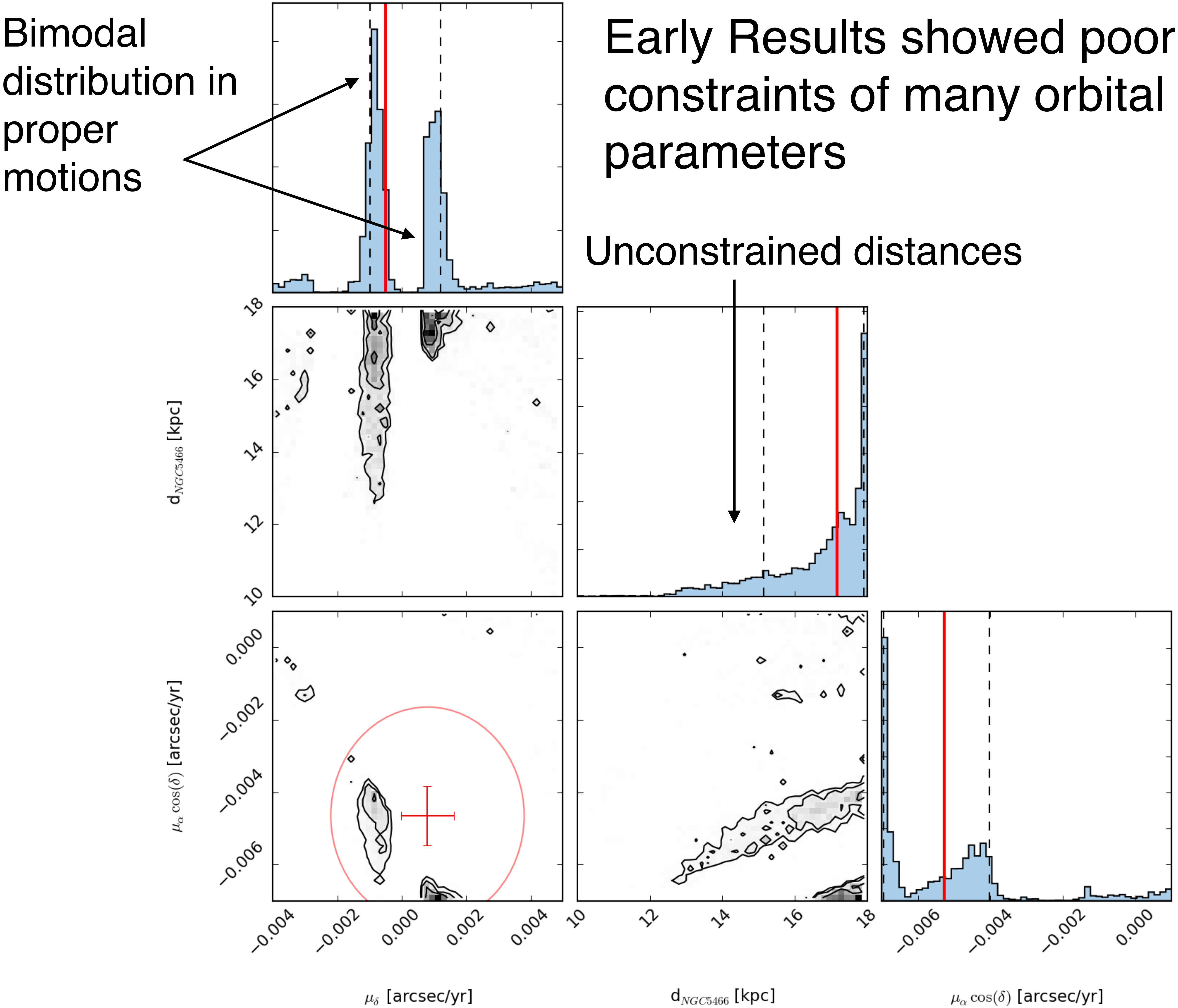
- If better than current - move
- If worse than current - move with some finite probability



Markov Chain Monte Carlo

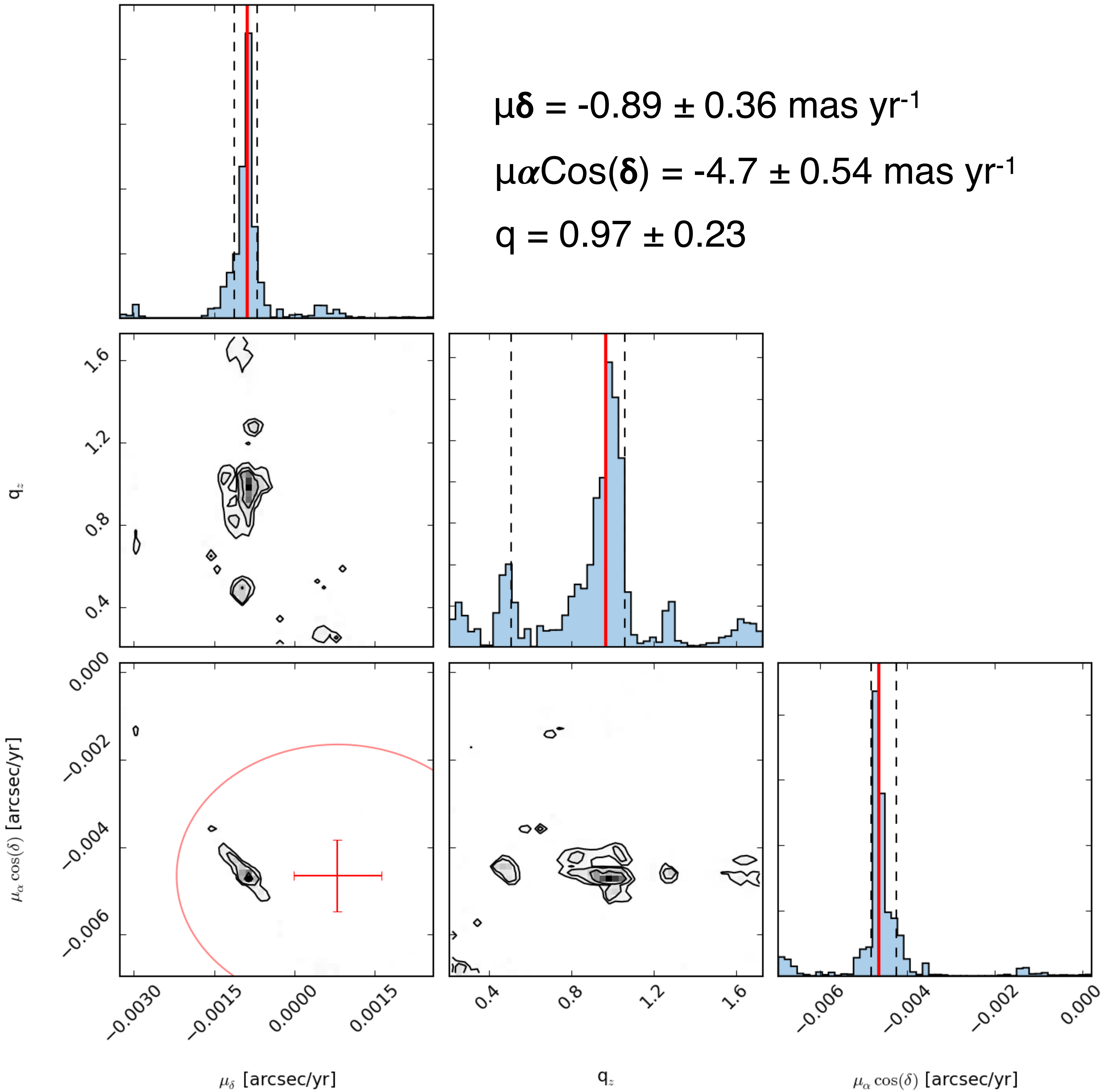


Early Results showed poor constraints of many orbital parameters

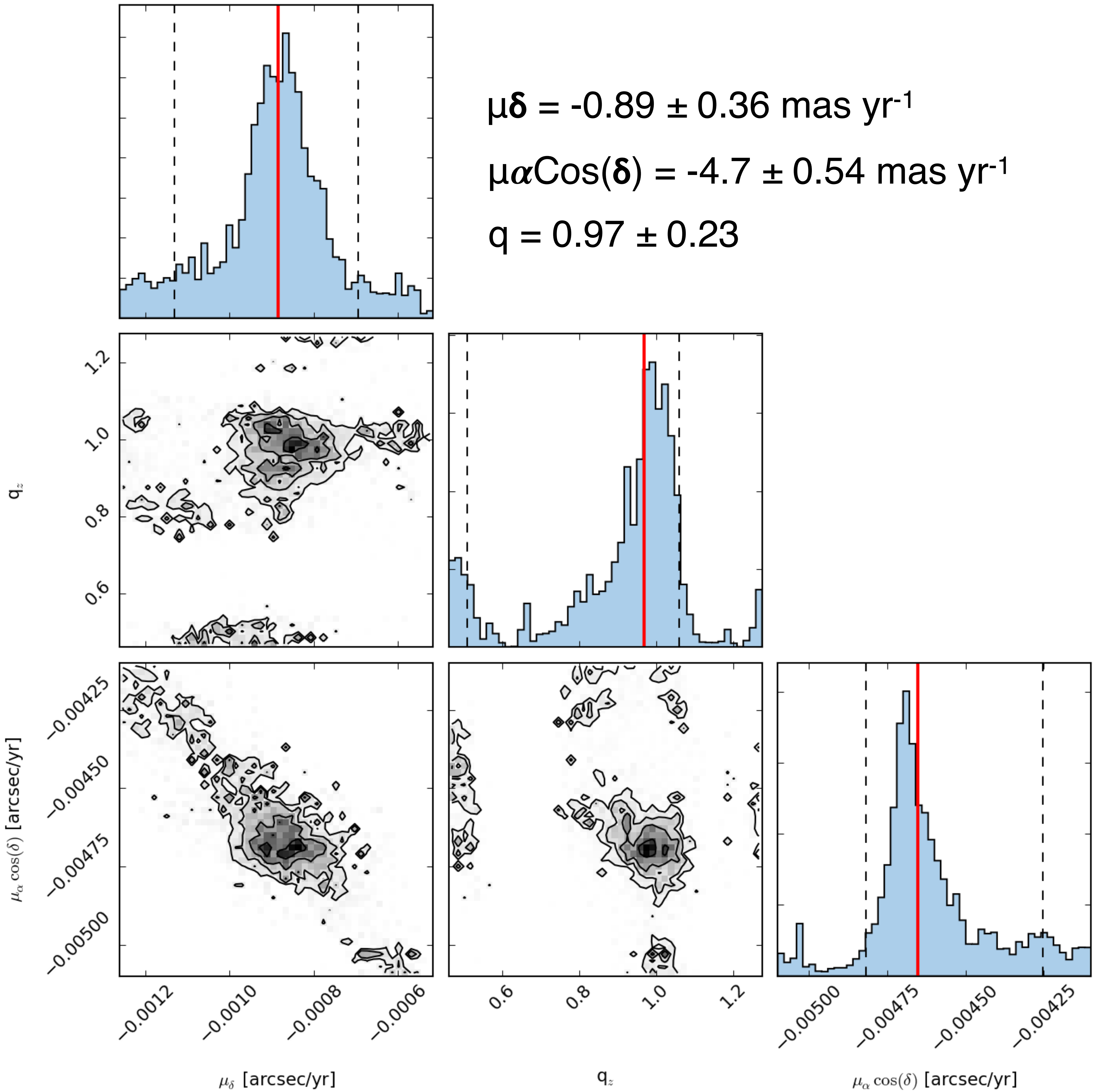


MCMC Priors

Parameter	Distribution	Values	Reference(s)
Halo Mass	Fixed	1.58	Küpper+14
Rh	Fixed	37.9 kpc	Küpper+14
Distance	Fixed	16.0 kpc	Sarajedini+07
Cluster Mass	Fixed	{50, 100, 150, 200}	Pryor+91; Harris96
Rsun	Fixed	8.302 kpc	Küpper+14
VLSR	Fixed	242.05 km s	Küpper+14
Halo Flattening	Flat	[0.5, 1.5)	Küpper+14
$\mu\alpha$Cos(δ)	Flat	[-0.5, -0.3) mas yr	Harris96; Dinescu+97
$\mu\delta$	Flat	[-2, 0) mas yr	Harris96; Dinescu+97
Tpast	Flat	[-5, -4) Gyr	—



μδ = -0.89 ± 0.36 mas yr-1
μαCos(δ) = -4.7 ± 0.54 mas yr-1
q = 0.97 ± 0.23
q_z
μ_α cos(δ) [arcsec/yr]
μ_δ [arcsec/yr]
q_z
μ_α cos(δ) [arcsec/yr]



μδ = -0.89 ± 0.36 mas yr-1
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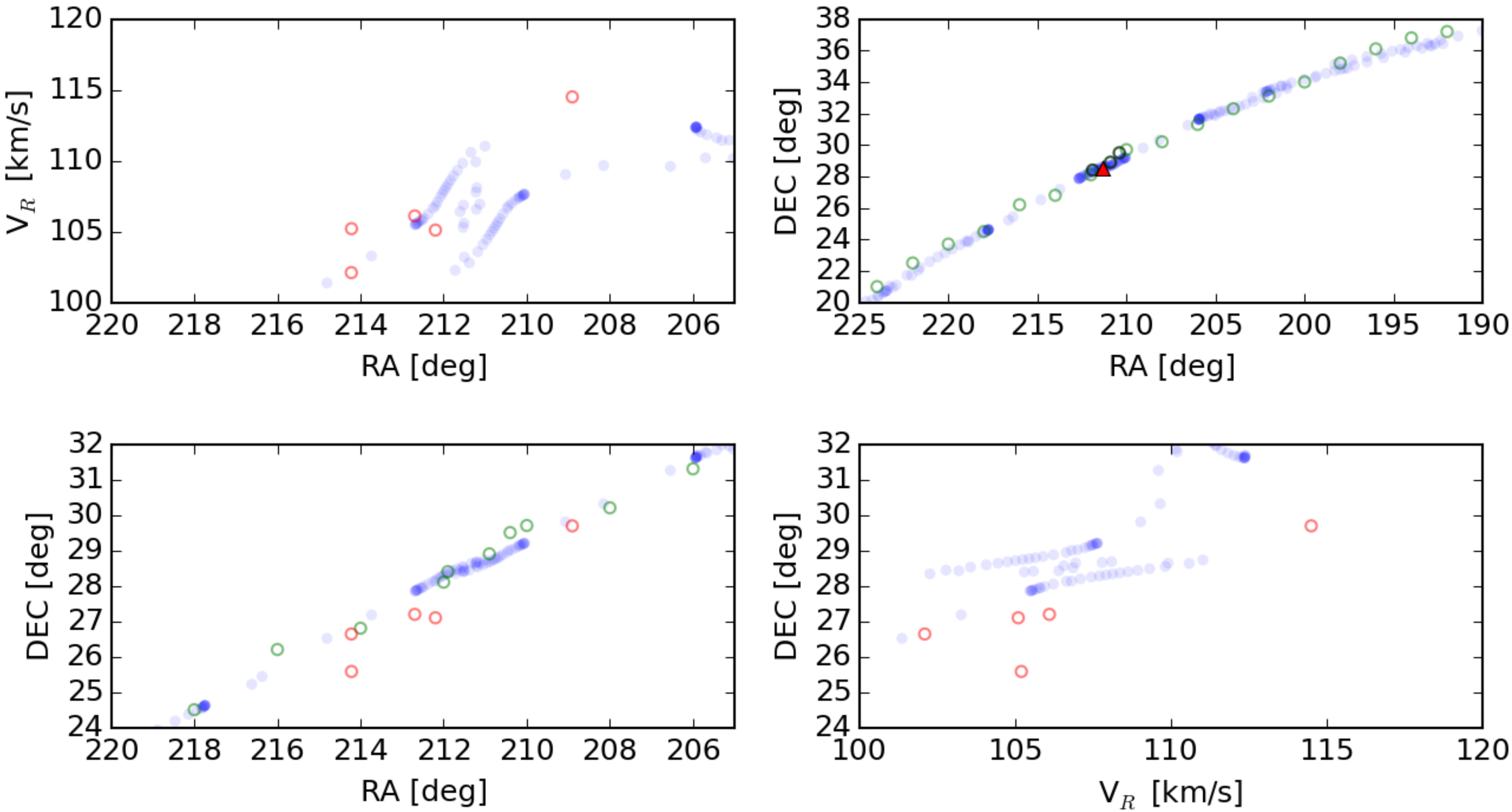
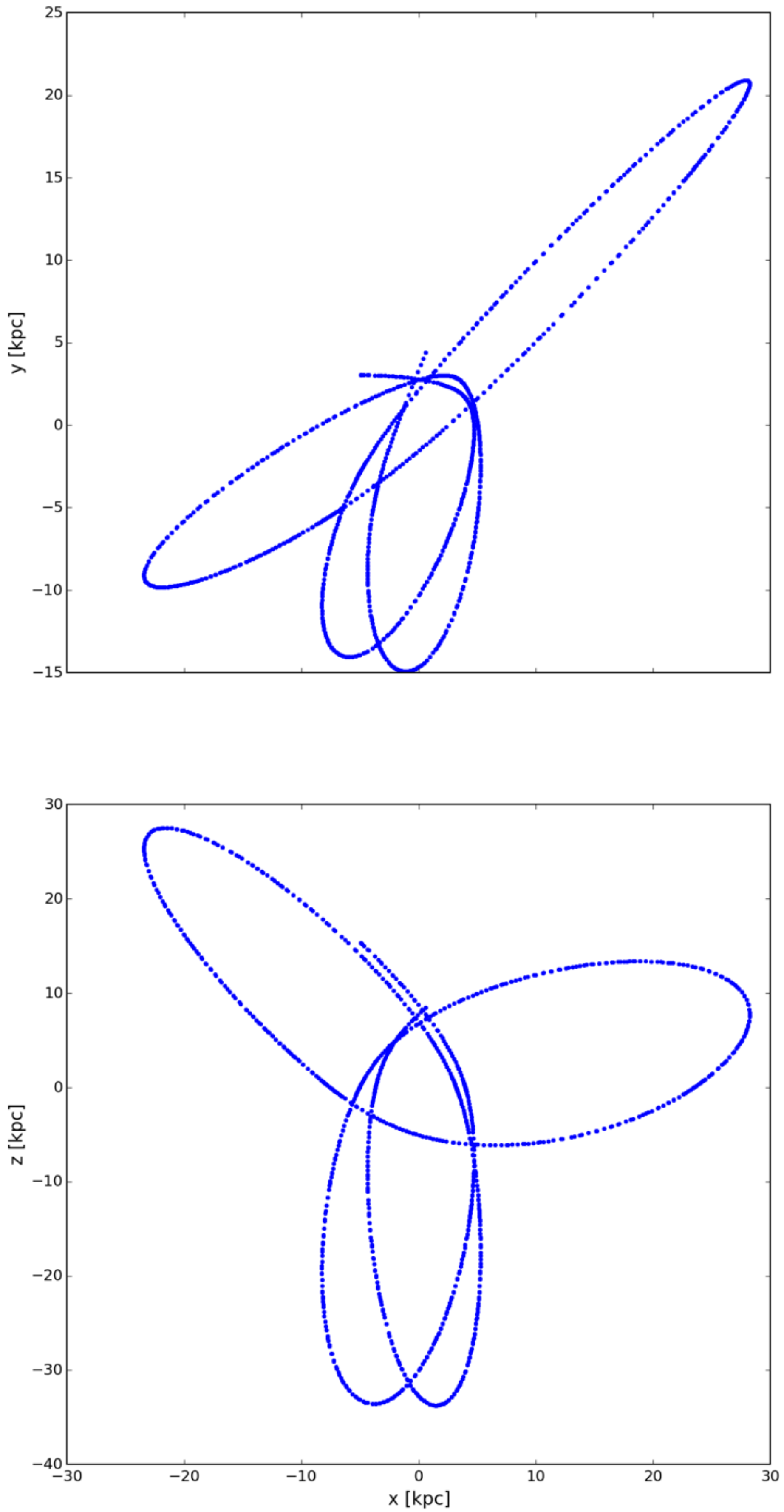
q = 0.97 ± 0.23
q_z
μ_α cos(δ) [arcsec/yr]
μ_δ [arcsec/yr]
q_z
μ_α cos(δ) [arcsec/yr]
−0.0012
−0.0010
−0.0008
−0.0006
0.6
0.8
1.0
1.2
−0.00500
−0.00475
−0.00450
−0.00425

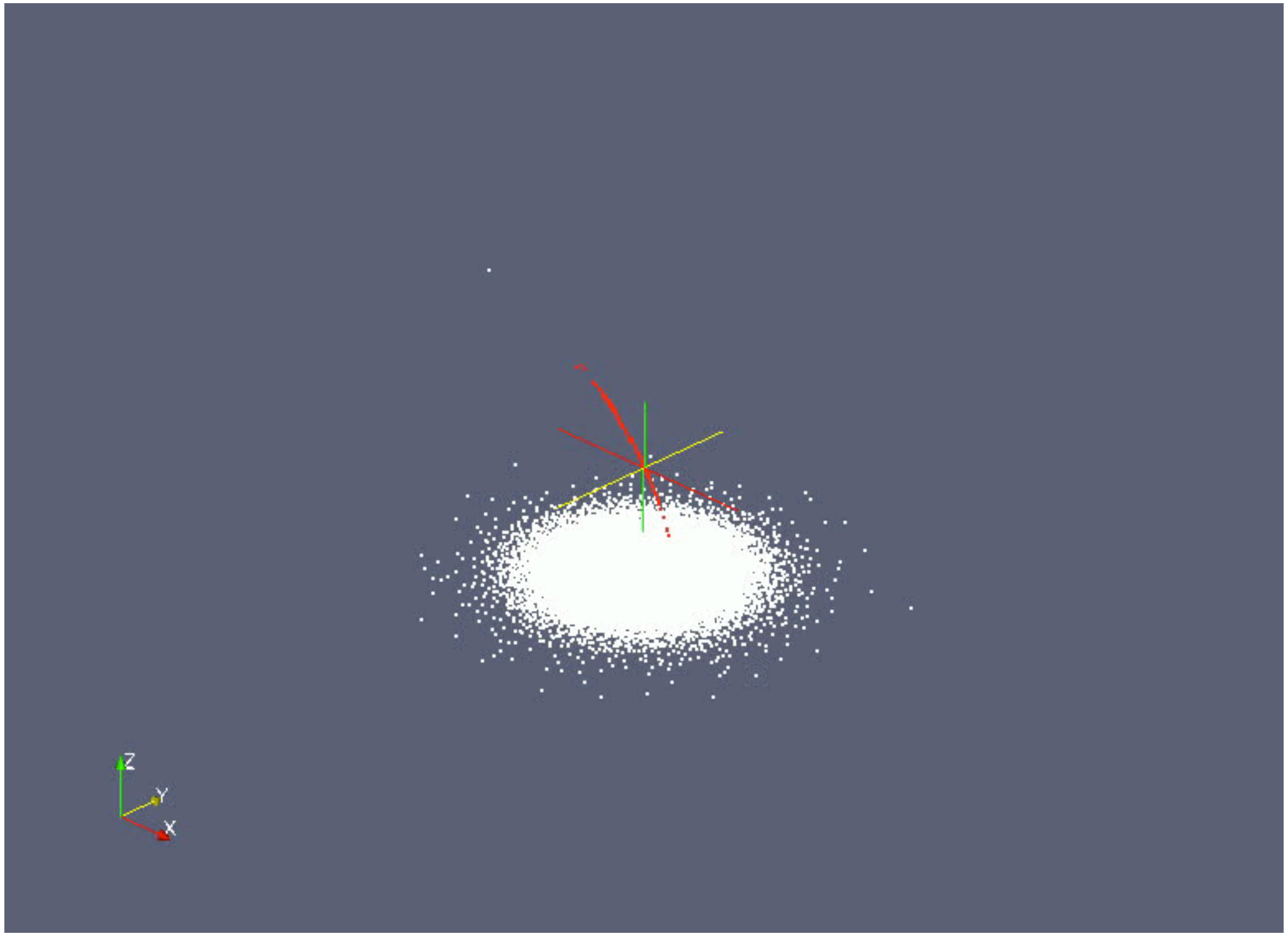
Comparison with Data



Best fit orbit

- Apocenter = 36 kpc
- Pericenter = 4 kpc





Conclusions & Future Work

- Modeling tidal streams can constrain models of the dark matter halo
- Streakline method and MCMC can efficiently search over large parameter space
- Long thin streams are most sensitive to the orbital data and to halo flattening - other parameters require good radial velocity data to constrain

- Gather additional (and better) data for NGC 5466
- Model all tidal streams (Sag., Pal. 5, NGC 5466) simultaneously

    - Tighten constraints on halo parameters
    - Include tests for core/cusp DM profile