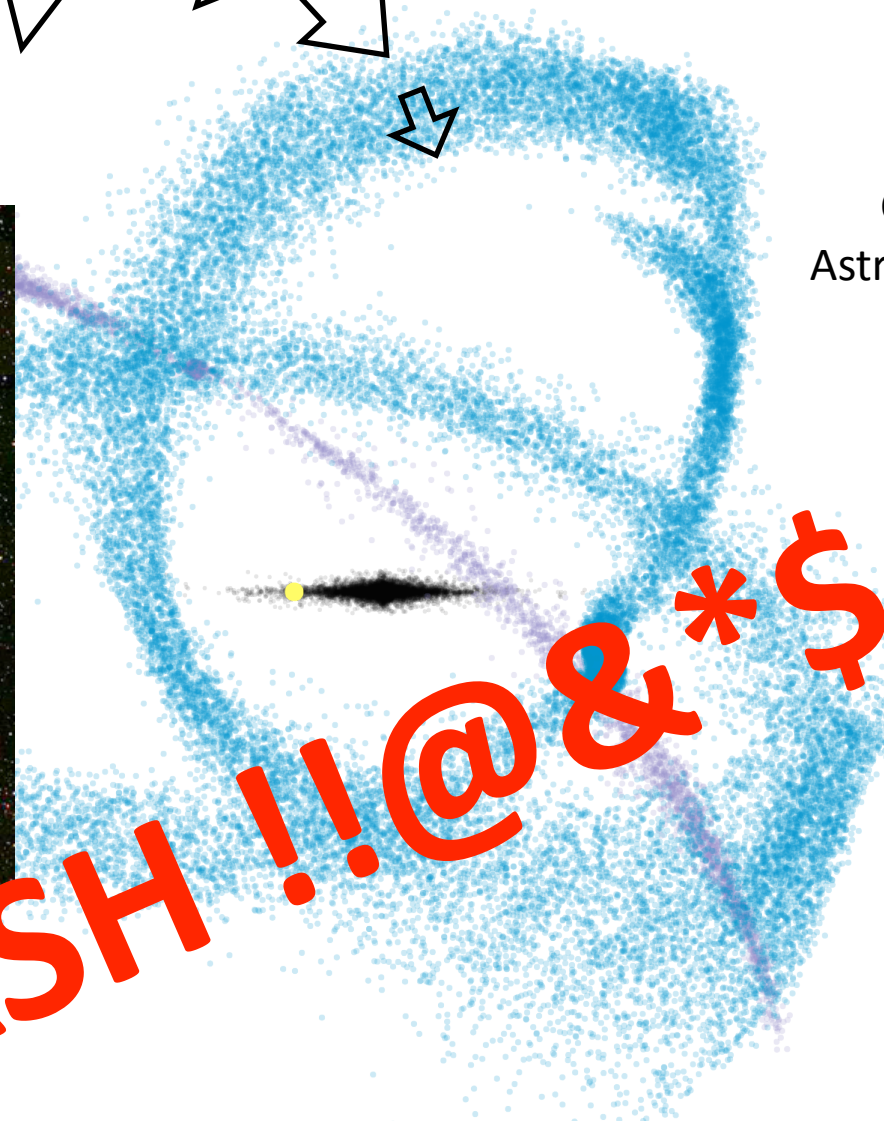
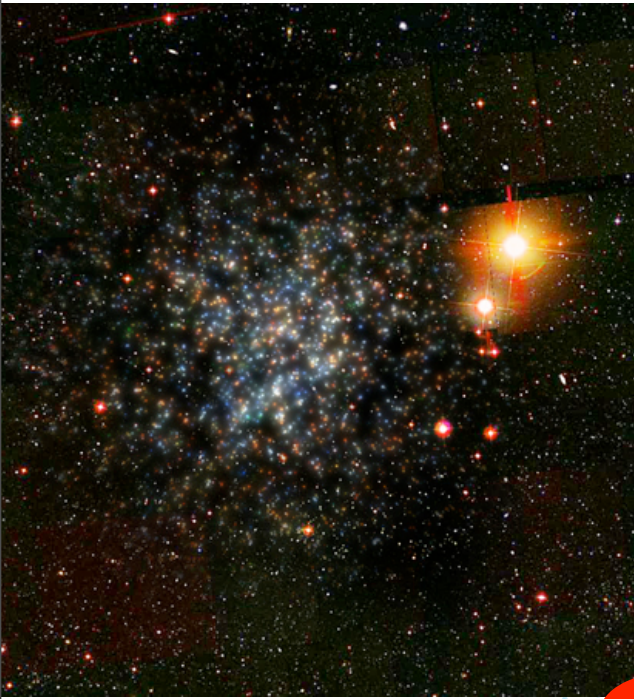
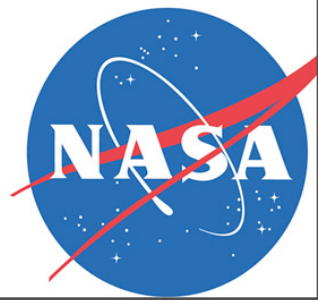




Kathryn V Johnston
Columbia University
Astronomy Department



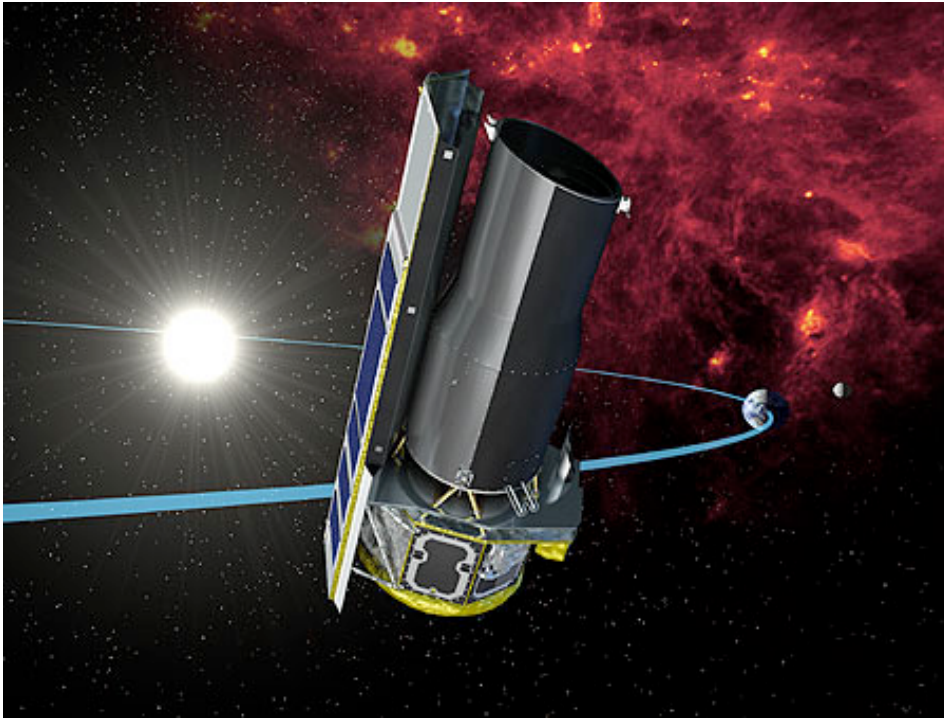
SMHASH !! @ & * \$ @ ??



Research supported by the
National Science Foundation and NASA

SMHASH

Spitzer Merger History And Shape of the Halo

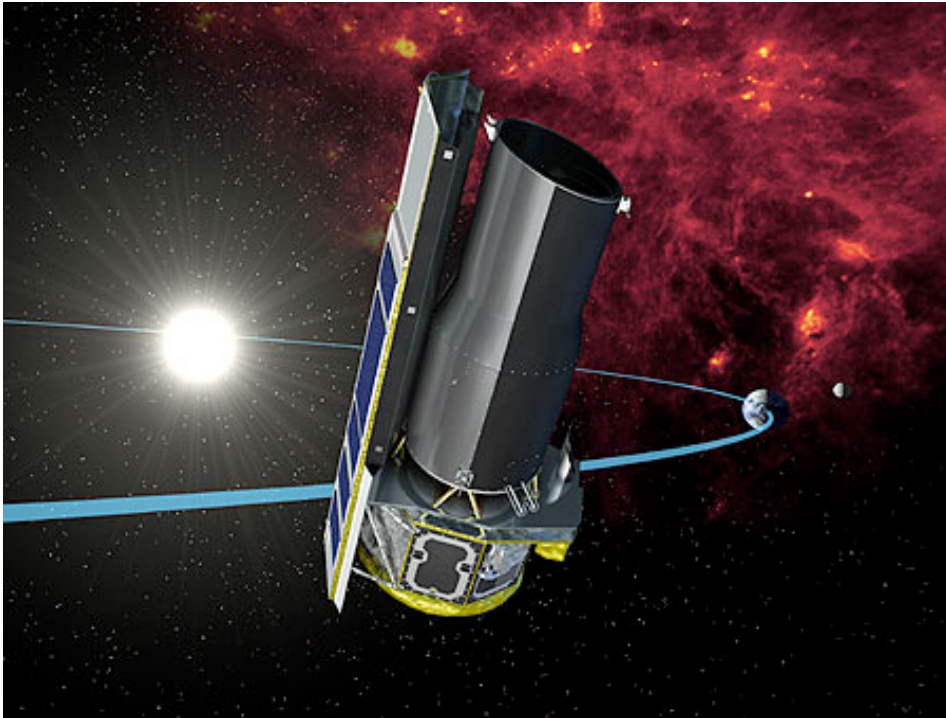


- RR Lyraes: intrinsic 2% scatter in P-L relation in IR (Madore & Freedman 2012 and Spitzer Cycle 9 work)

Johnston, Madore, Majewski, Besla, Bono, Clementini, Cioni, Cohen, Cusano, Freedman, Garofalo, Grillmair, Hendel, Kallivayalil, Kollmeier, Law, Marengo, Mondon, Moretti, Nidever, Pietrzynski, Persson, Price-Whelan, Rich, Scowcroft, Seibert, Smith, Sesar, Soszynski, Thompson, Udalski, van der Marel

SMHASH

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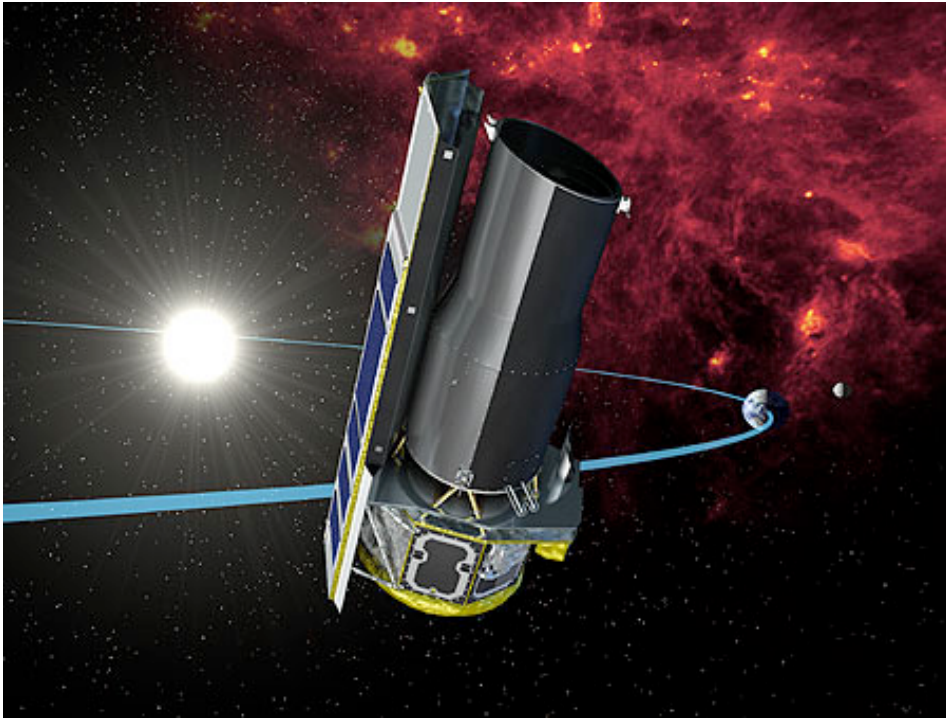


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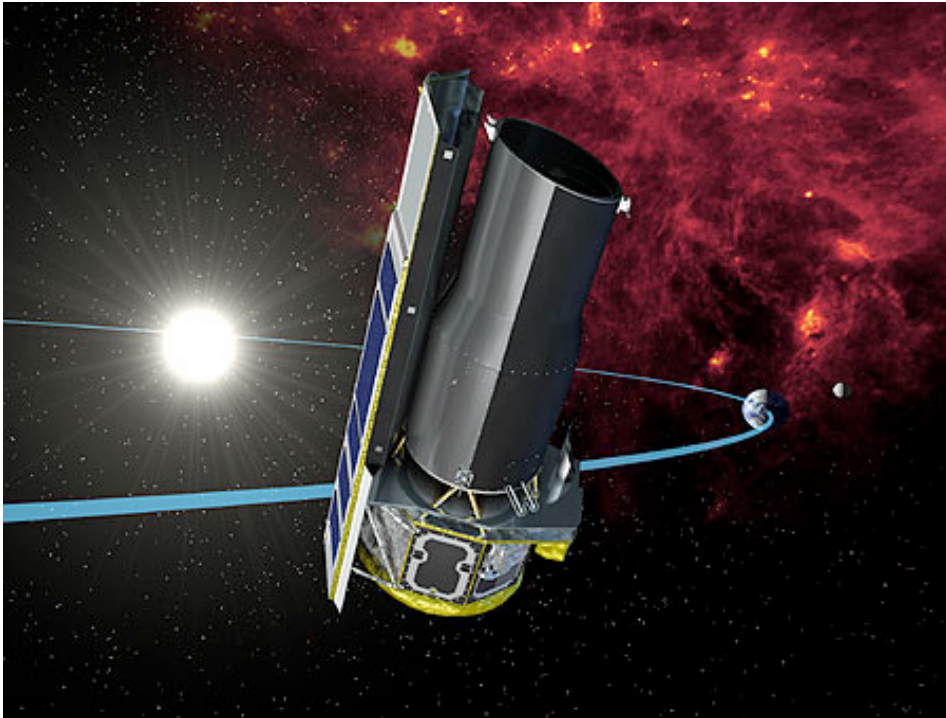


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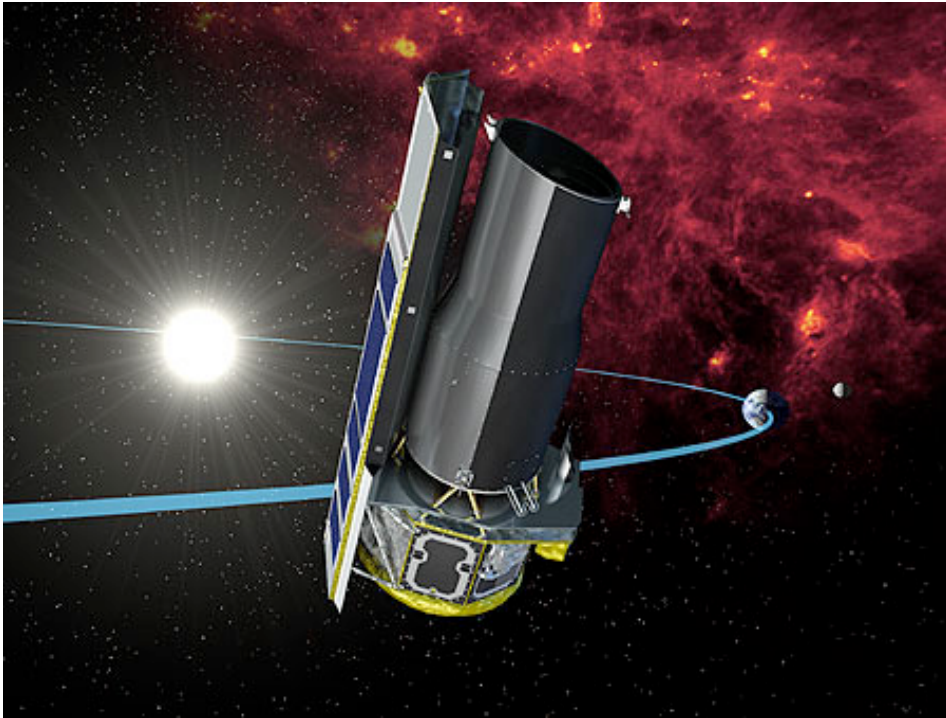


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SMHASH

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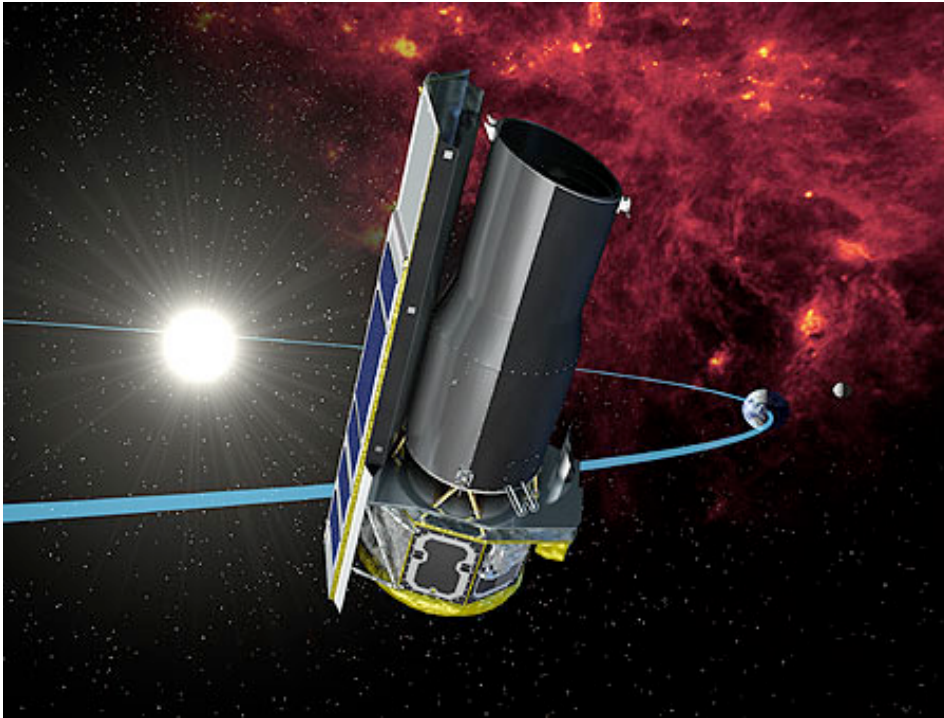


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SMHASH

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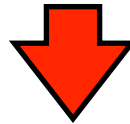
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SMHASH Overview

- Targets: dwarfs(Sgr, Umin, Car, Scul, Boo); streams (Sgr, Orphan)
- Idea

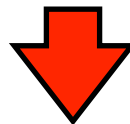
distances/structure of dwarfs and streams



potential of MW

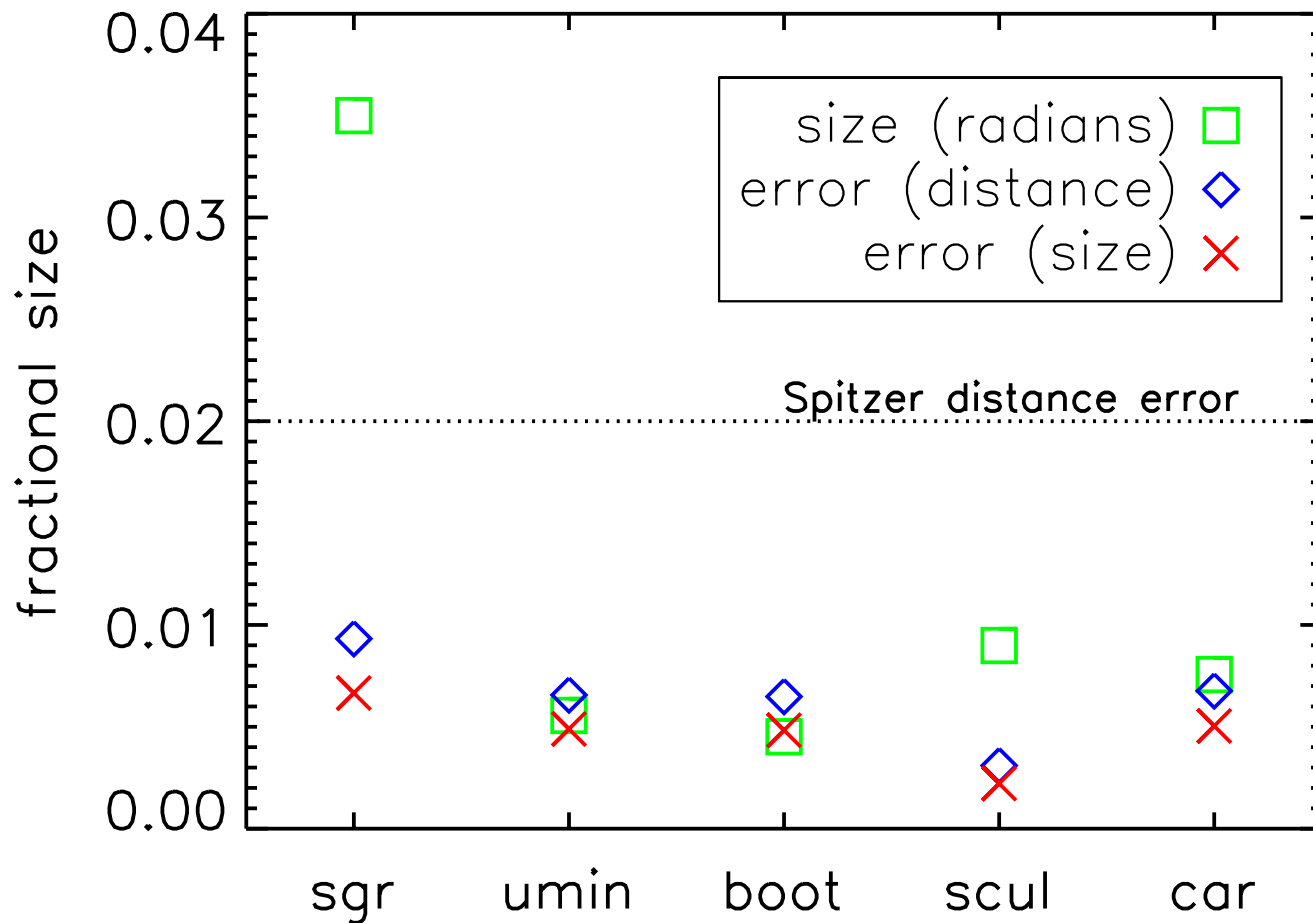


orbits

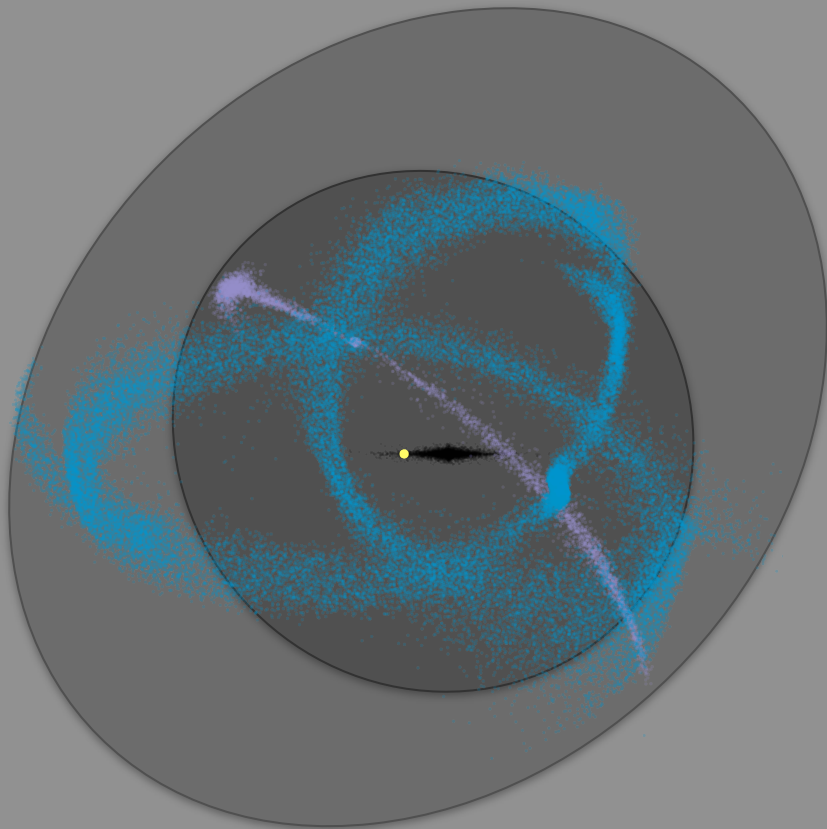


evolution of sats, MW gas halo

e.g. Satellites



Where's the Matter?



STREAM

With: the Stream Team

Ana Bonaca, David Hendel, Marla Geha, David Hogg,
Andreas Kuepper, Sarah Pearson, Adrian Price-Whelan
(Robyn Sanderson) and Allyson Sheffield

TEAM

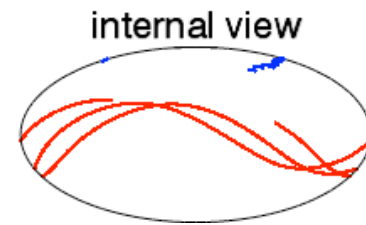
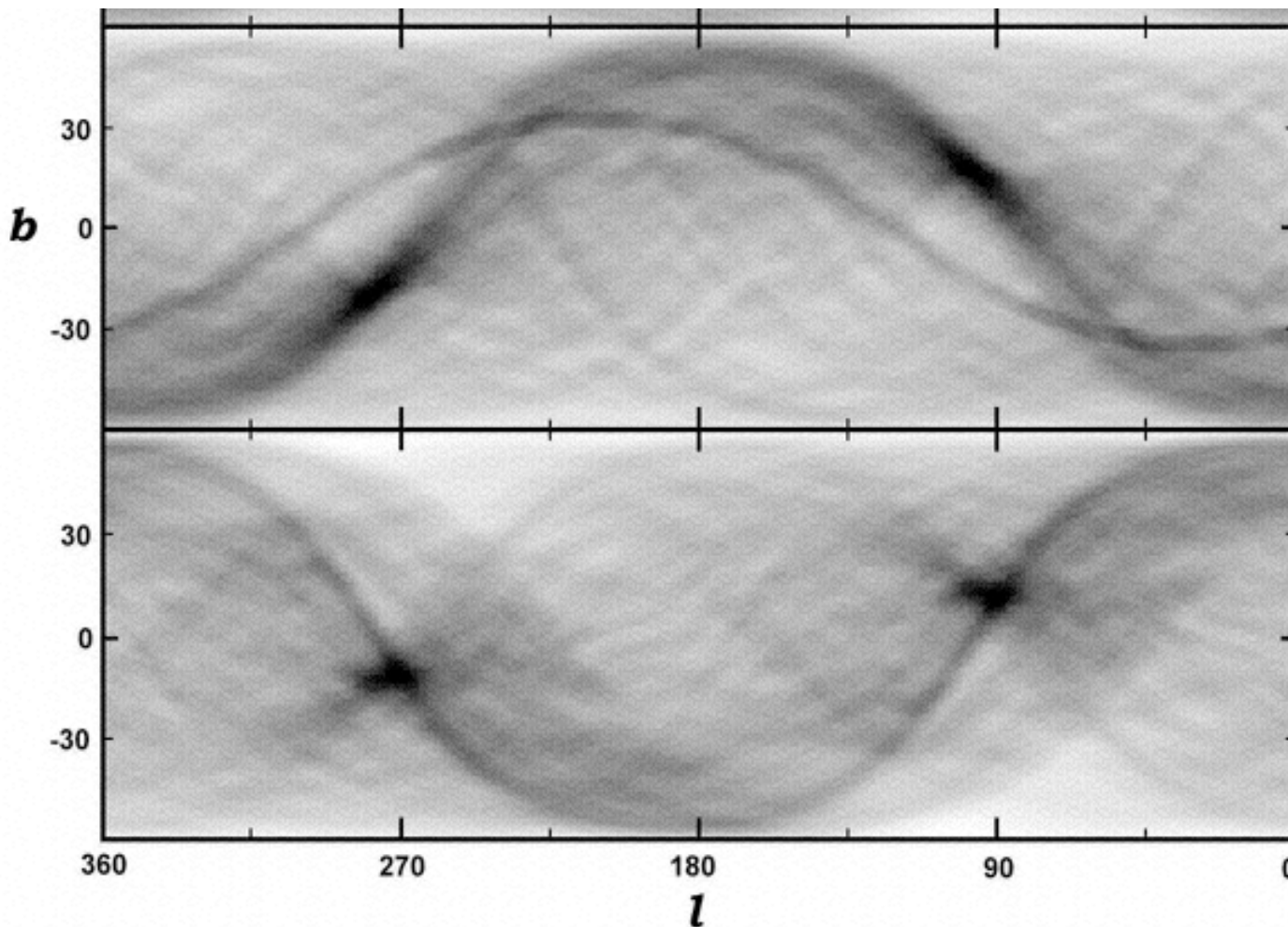
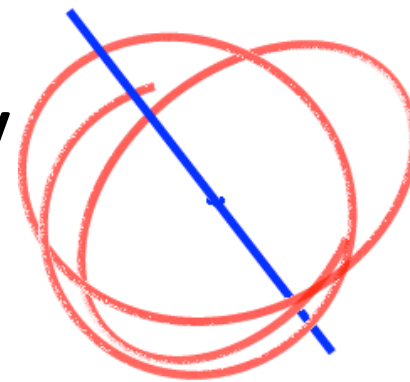


...see also work by

- Talks coming up: **Adam Bowden, Carlos Vera-Ciro**
- Poster: **Gibbons** et al (2014)
- Others at conference
 - Sanderson, **Helmi** & Hogg (2014)
 - **Penarrubia**, Kozlov & **Walker** (2012)
- Other work: Jo Bovy (IAS), Jason Sanders (Oxford/Cambridge)

e.g. Sagittarius Dwarf Galaxy

orbital plane precession \leftrightarrow shape

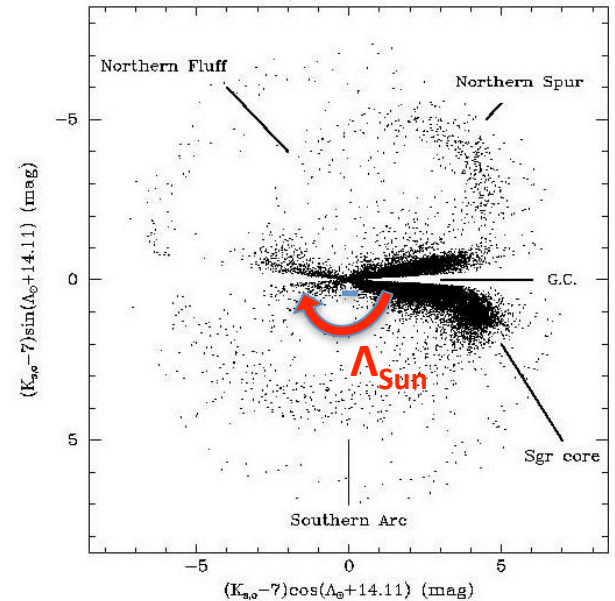
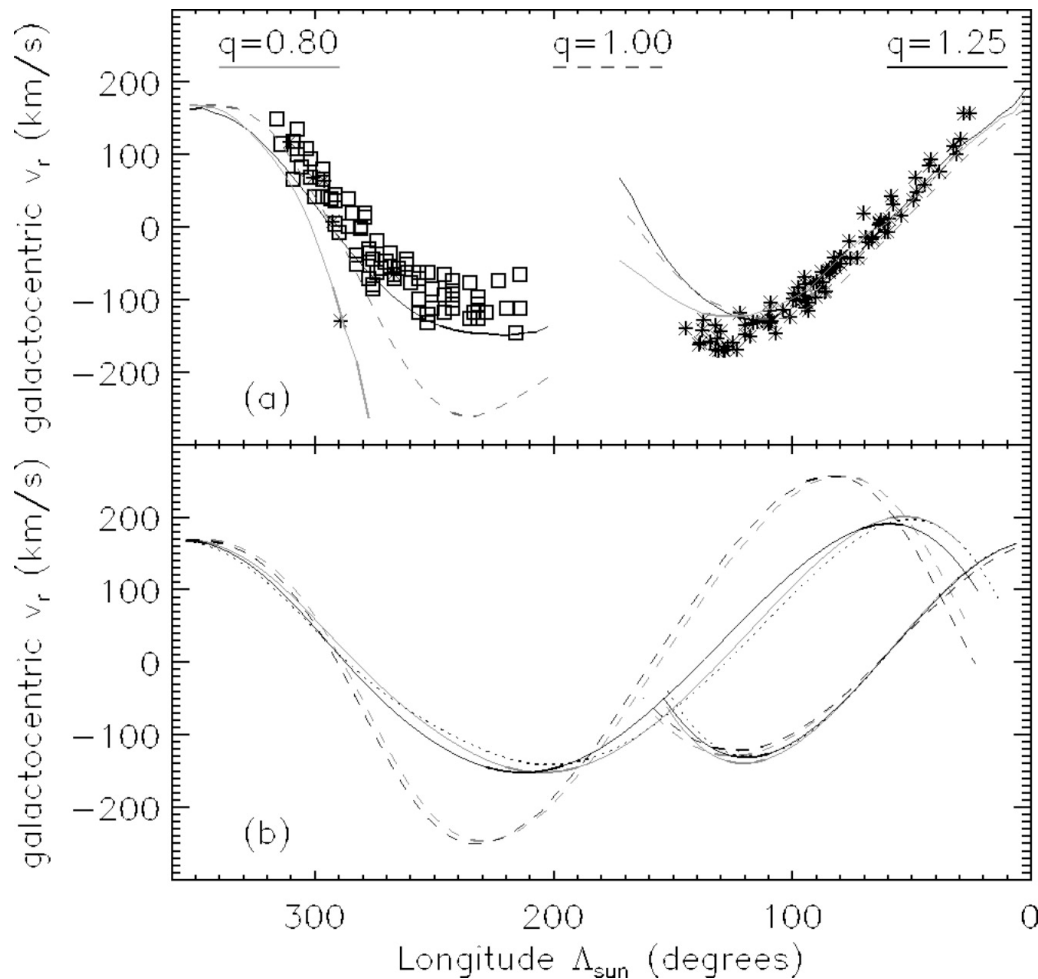


Majewski et al, 2003

Ibata et al 2000;
Johnston, Law &
Majewski, 2005;
Fellhauer et al 2006

e.g. Sagittarius Dwarf Galaxy

velocity trends \leftrightarrow depth of potential

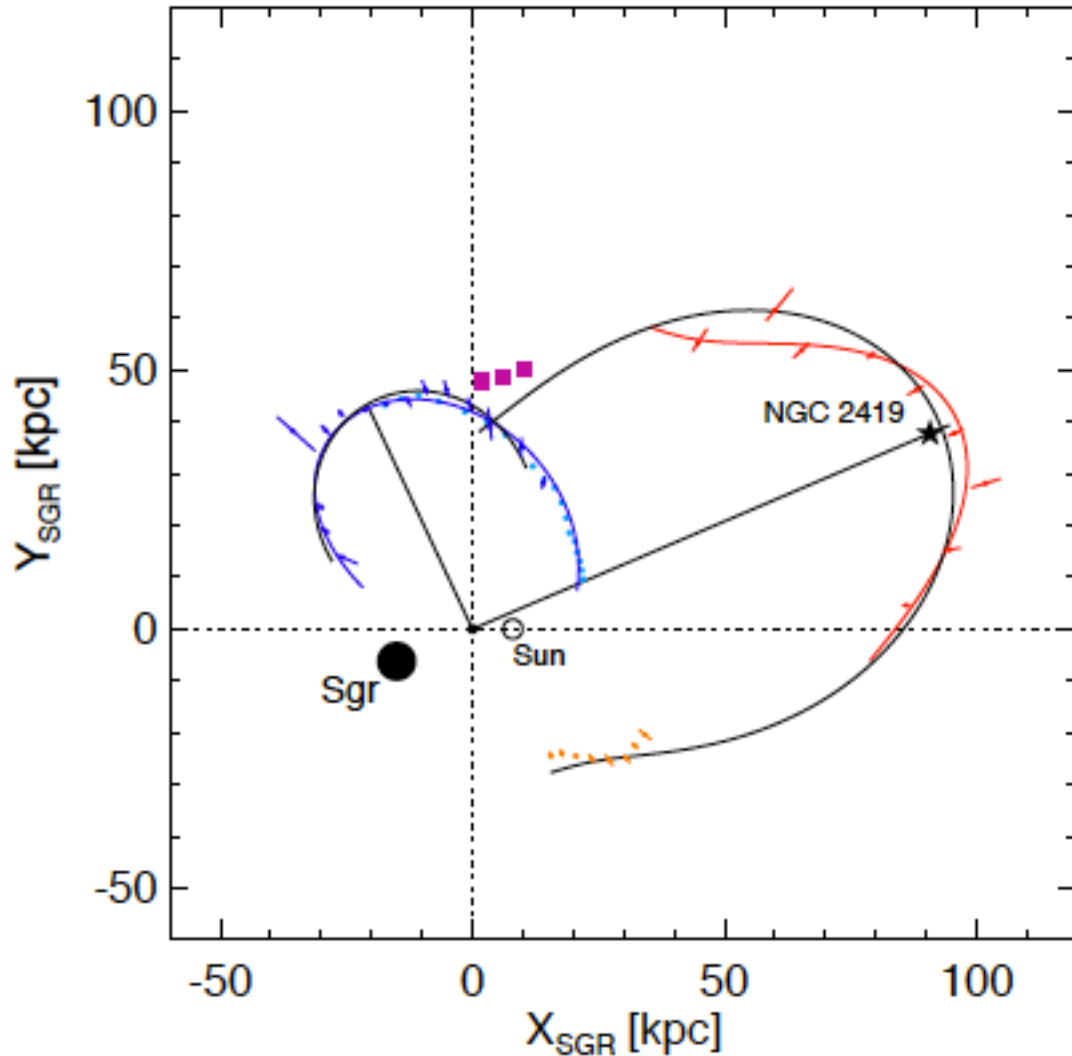


Majewski et al, 2004

Helmi, 2004

e.g. Sagittarius Dwarf Galaxy

precession angle of turning points \leftrightarrow density profile

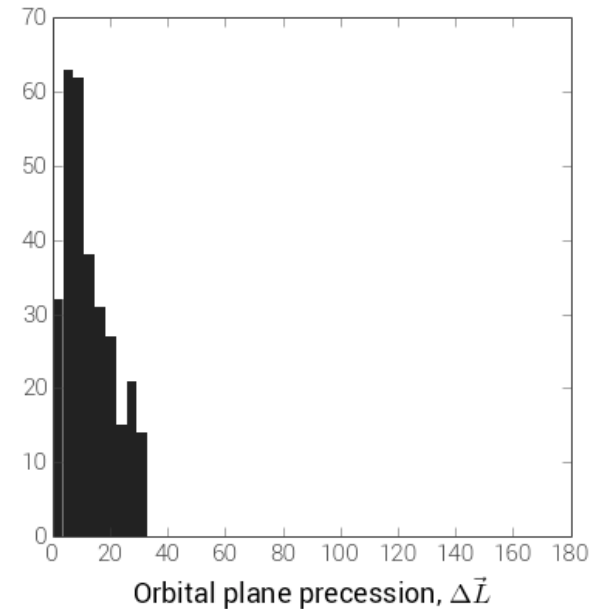
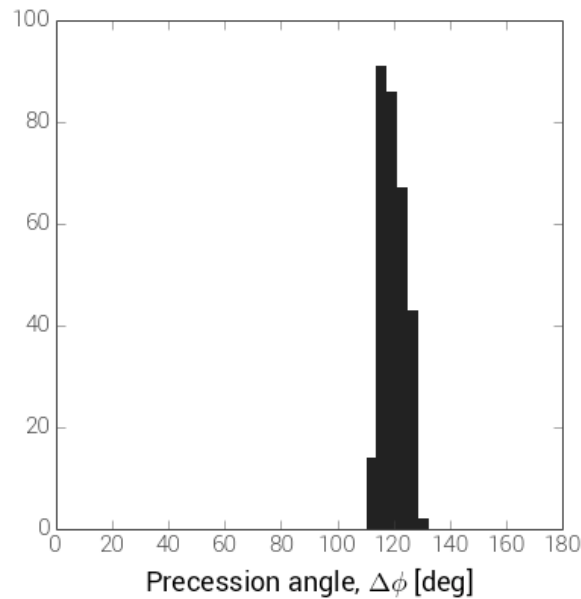
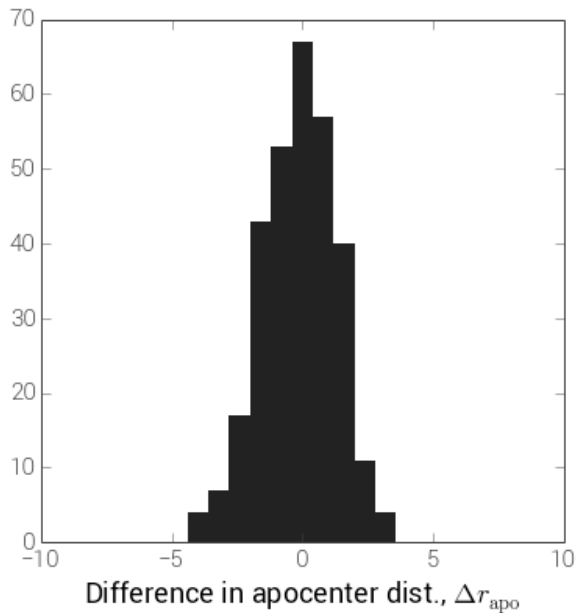


Belokurov et al
2013

See poster by
[Simon Gibbons](#) on
modeling this data

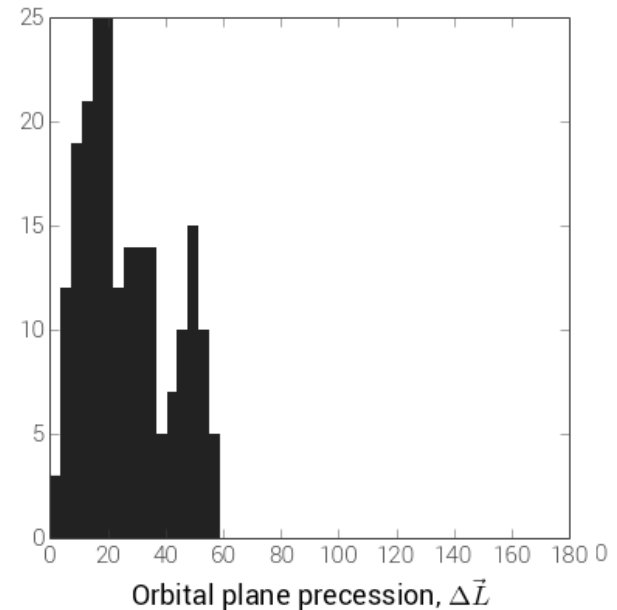
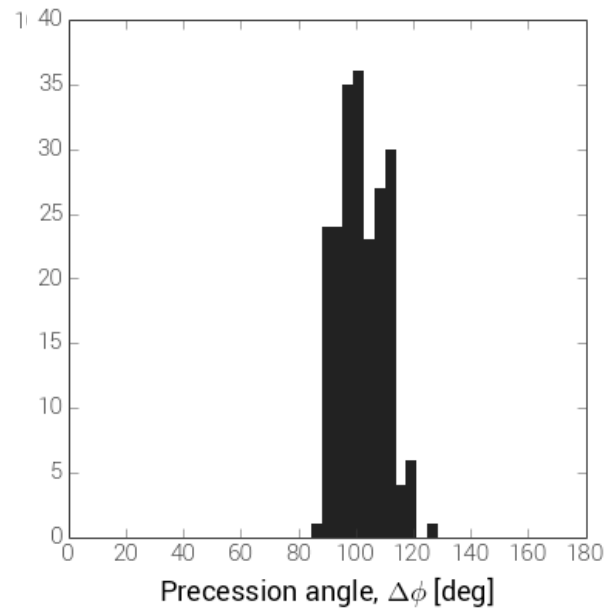
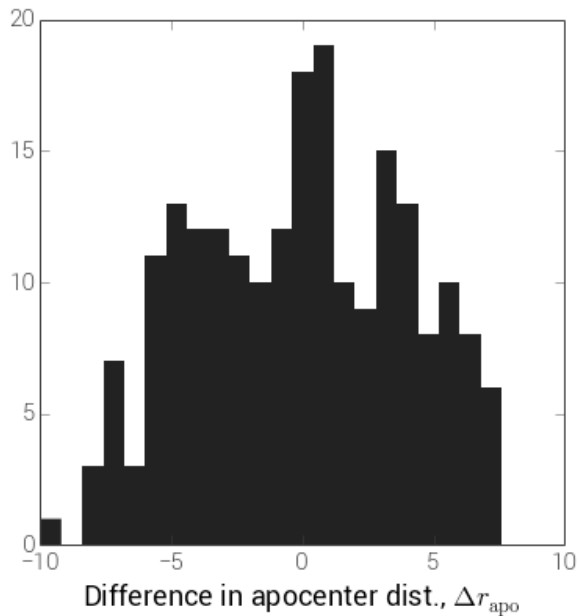
Triaxiality confuses everything!

(plots from Adrian Price-Whelan)



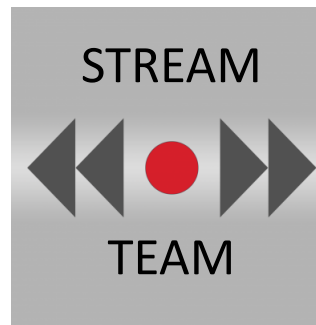
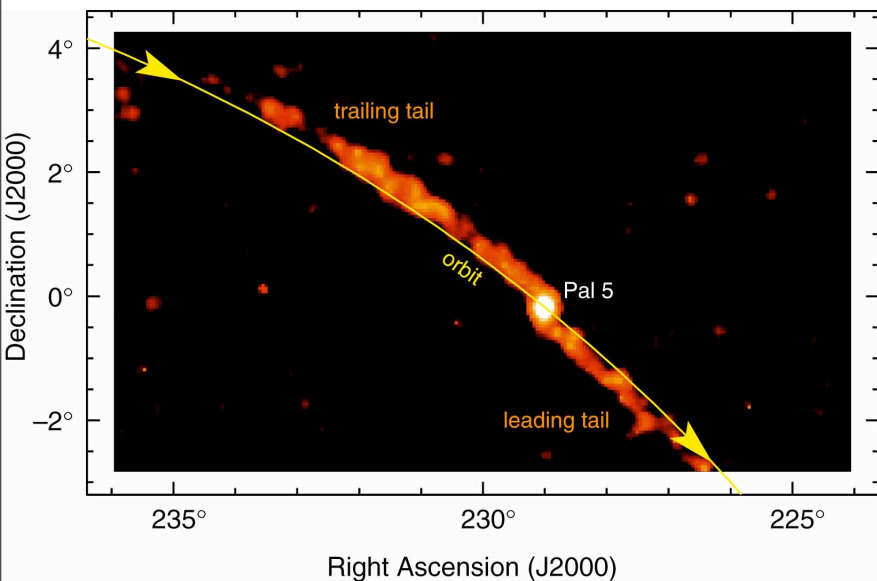
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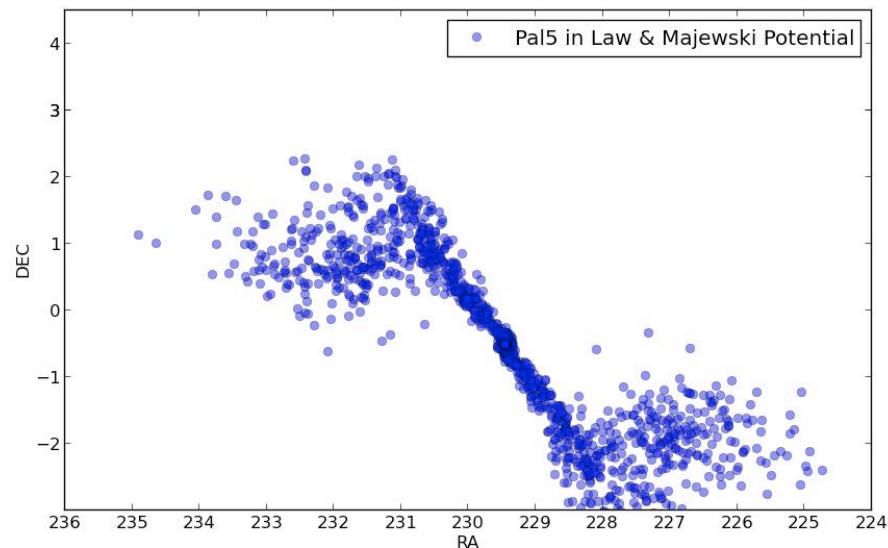
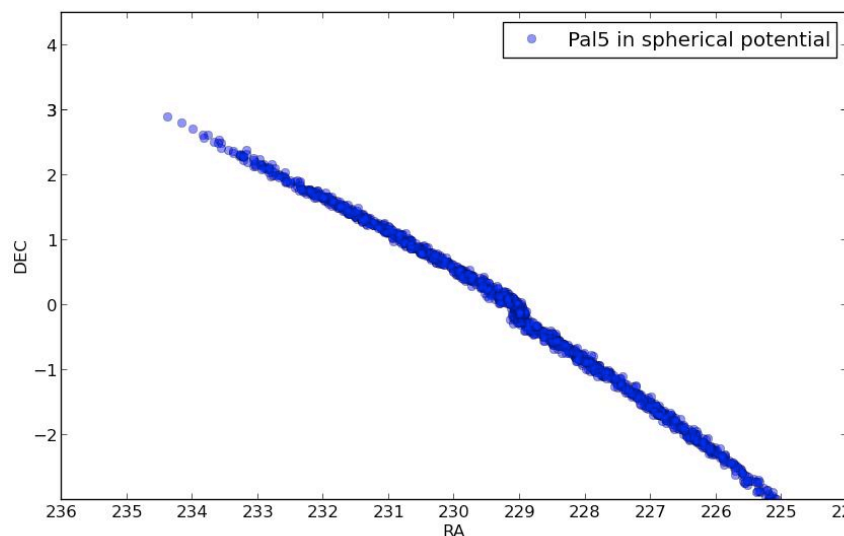


Aside: Palomar 5?

Odenkirchen et al (2002)



Andreas Kuepper and Sarah Pearson

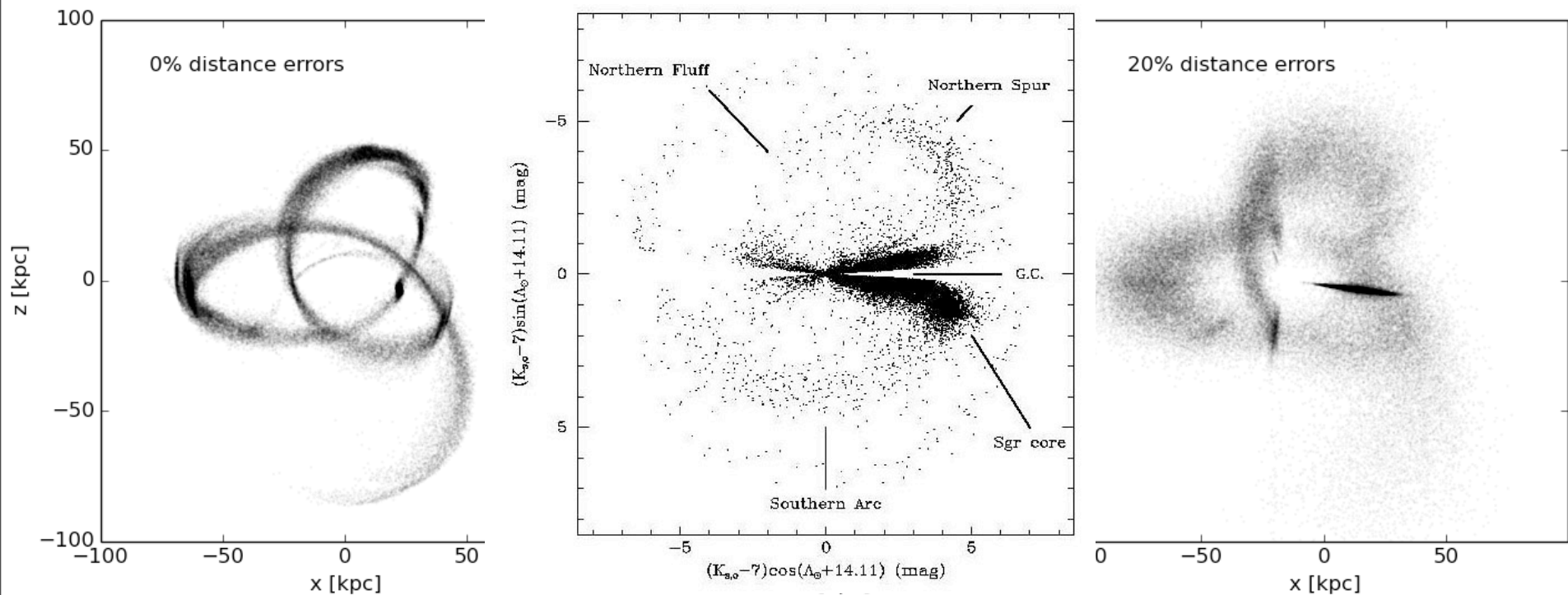


SMHASH!!!!@&*^\$@????

2% distances



position within tidal streams

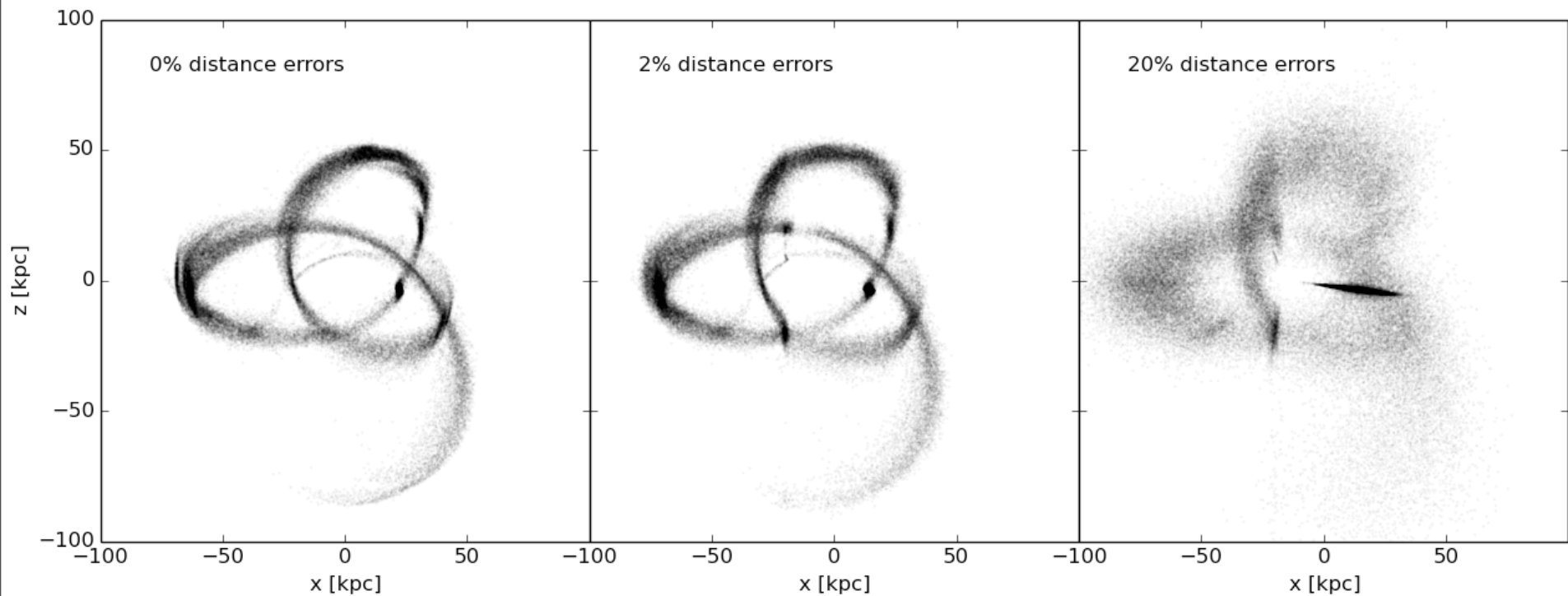


SMHASH!!!!@&*^\$@?????

2% distances



position within tidal streams



Gaia!

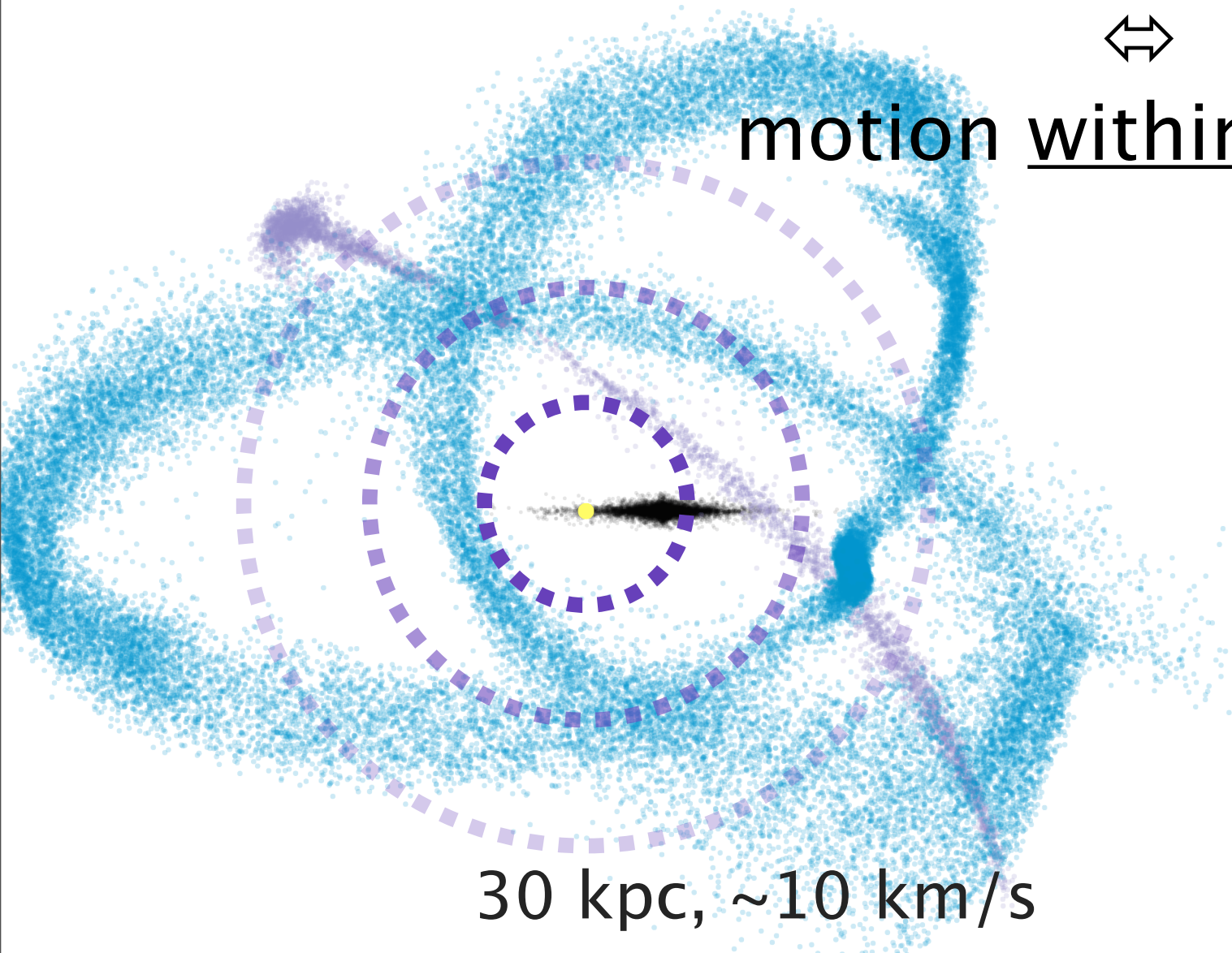


Gaia:

proper motion error



motion within stream



30 kpc, ~ 10 km/s



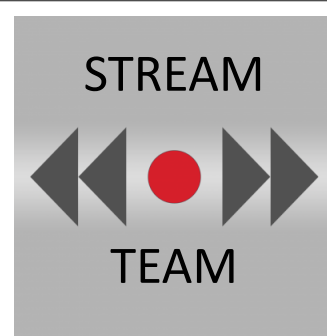
Adrian
Price-Whelan

e.g. **REWINDER**

(Johnston, Zhao, Spergel & Hernquist, 1999)

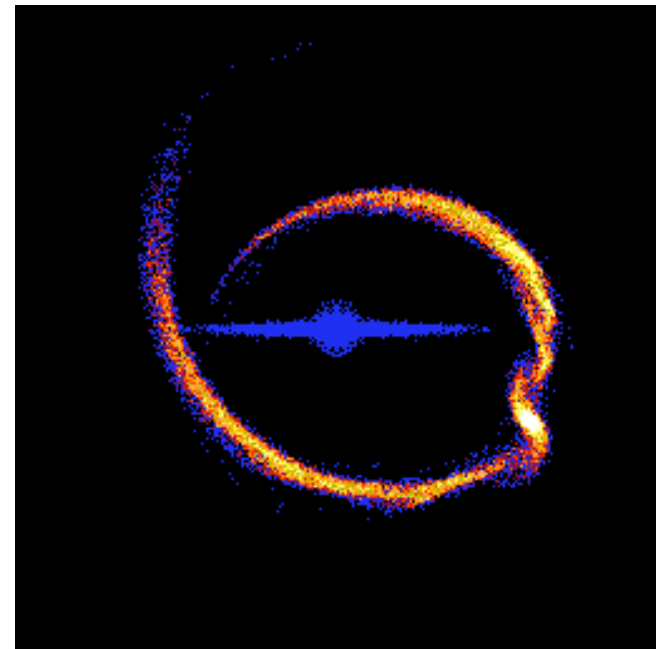
(Price-Whelan & Johnston, 2013)

(Price-Whelan, Hogg, Johnston & Hendel, 2014)

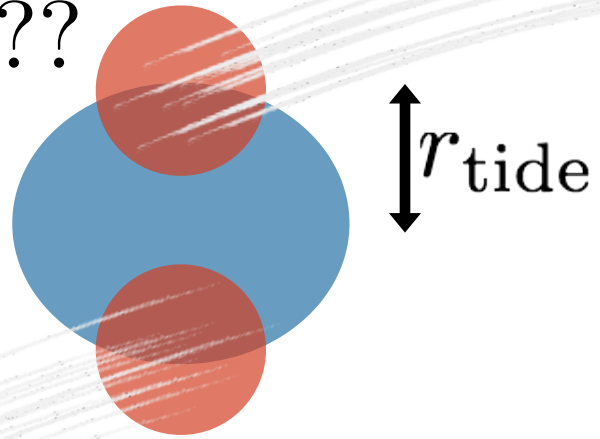


“debris once all part of same object”

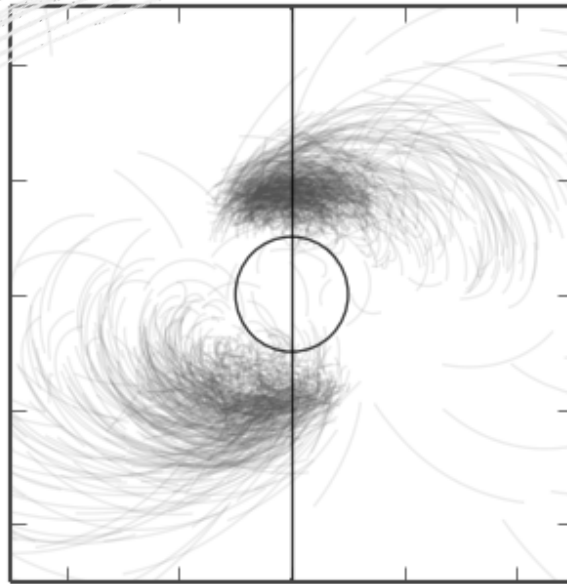
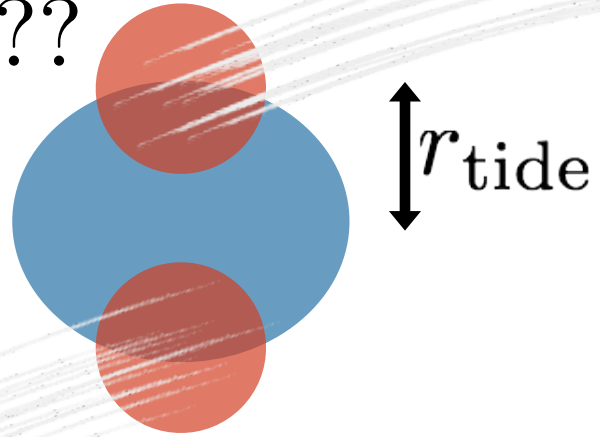
- Assume full phase-space info
 $\Leftrightarrow (x, y, z, v_x, v_y, v_z)$
- Integrate these “final conditions” *backwards*
- In correct potential, stars recombine with satellite



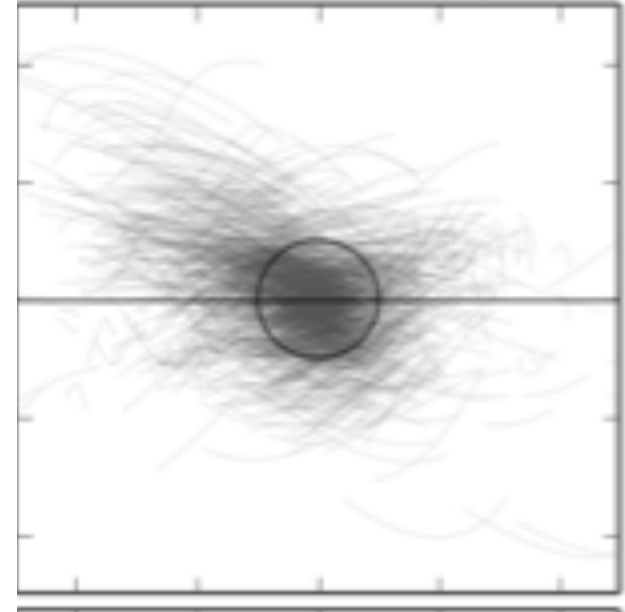
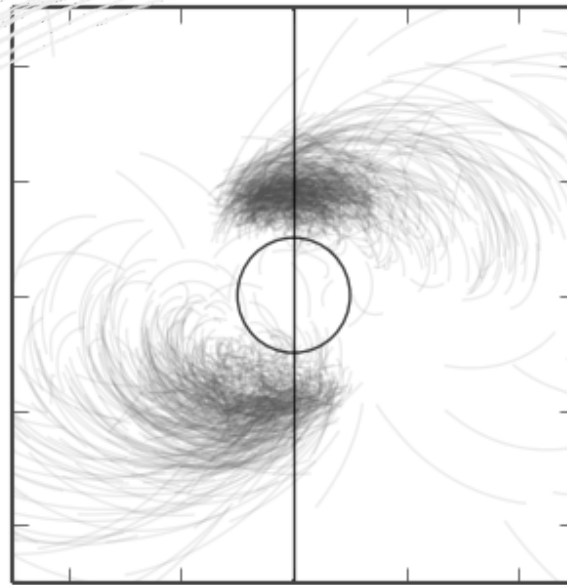
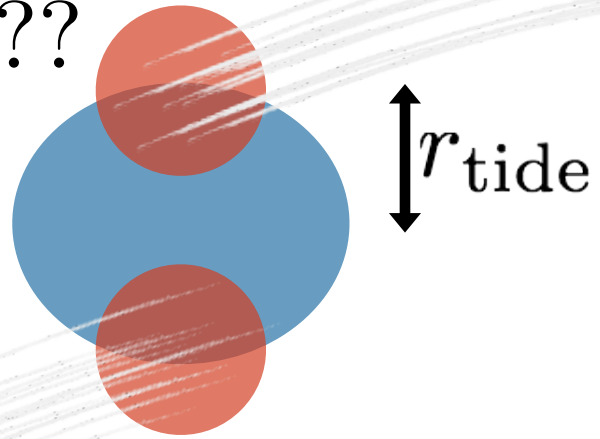
$$p(W|W_p, \Phi, K)????$$



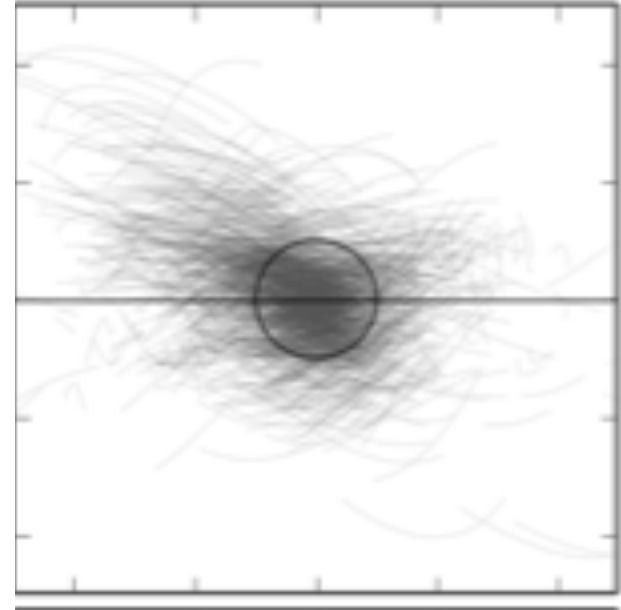
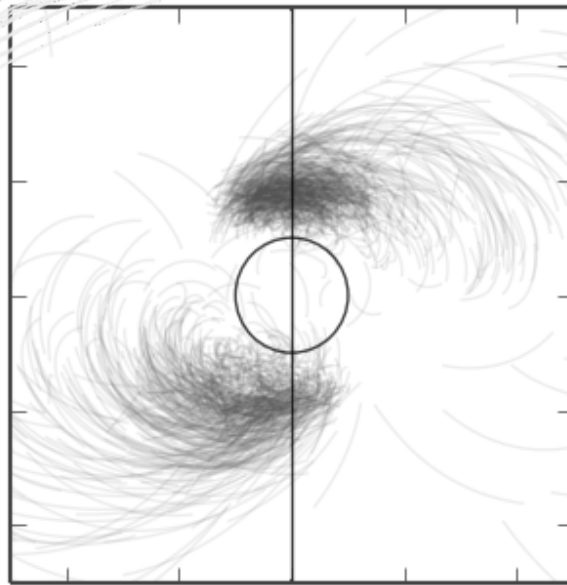
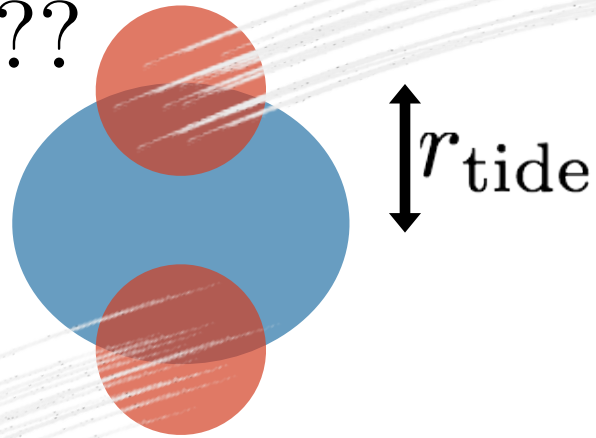
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$$p(W|W_p, \Phi, K)????$$



$$p(W|W_p, \Phi, K)????$$



$$p(W|W_p, \Phi, K) = \int p(W, \tau|W_p, \Phi, K) d\tau$$

$$p(W, \tau|W_p, \Phi, K) \sim \exp \left[-(\mathbf{x} - \mathbf{x}_p)_\tau^2 / 2r_{\text{tide}}^2 \right] \times \exp \left[-(\mathbf{v} - \mathbf{v}_p)_\tau^2 / 2\sigma^2 \right]$$

OBSERVATIONS

Each star:

$D = (l, b, d, \mu_l, \mu_b, v_r)$ → observed position,
errors or missing
dimensions

Progenitor:

$D_p = (l, b, d, \mu_l, \mu_b, v_r)$ → observed 6D
position

PARAMETERS

Each star:

$\mathbf{W} = (l, b, d, \mu_l, \mu_b, v_r)$ \longrightarrow true 6D position

K \longrightarrow leading/trailing tail

Progenitor:

$\mathbf{W}_p = (l, b, d, \mu_l, \mu_b, v_r)$ \longrightarrow true 6D position

M \longrightarrow mass today

Potential:

Φ \longrightarrow anything!

the Posterior

$$\begin{aligned} & p(\Phi, W, W_p, K | D, D_p) \\ &= \frac{1}{Z} p(D | W) p(D_p | W_p) \quad \text{Gaussian errors} \\ &\quad \times p(W | W_p, \Phi, K) \quad \text{Likelihood} \\ &\quad \times p(\Phi) p(K) \quad \text{Priors} \end{aligned}$$

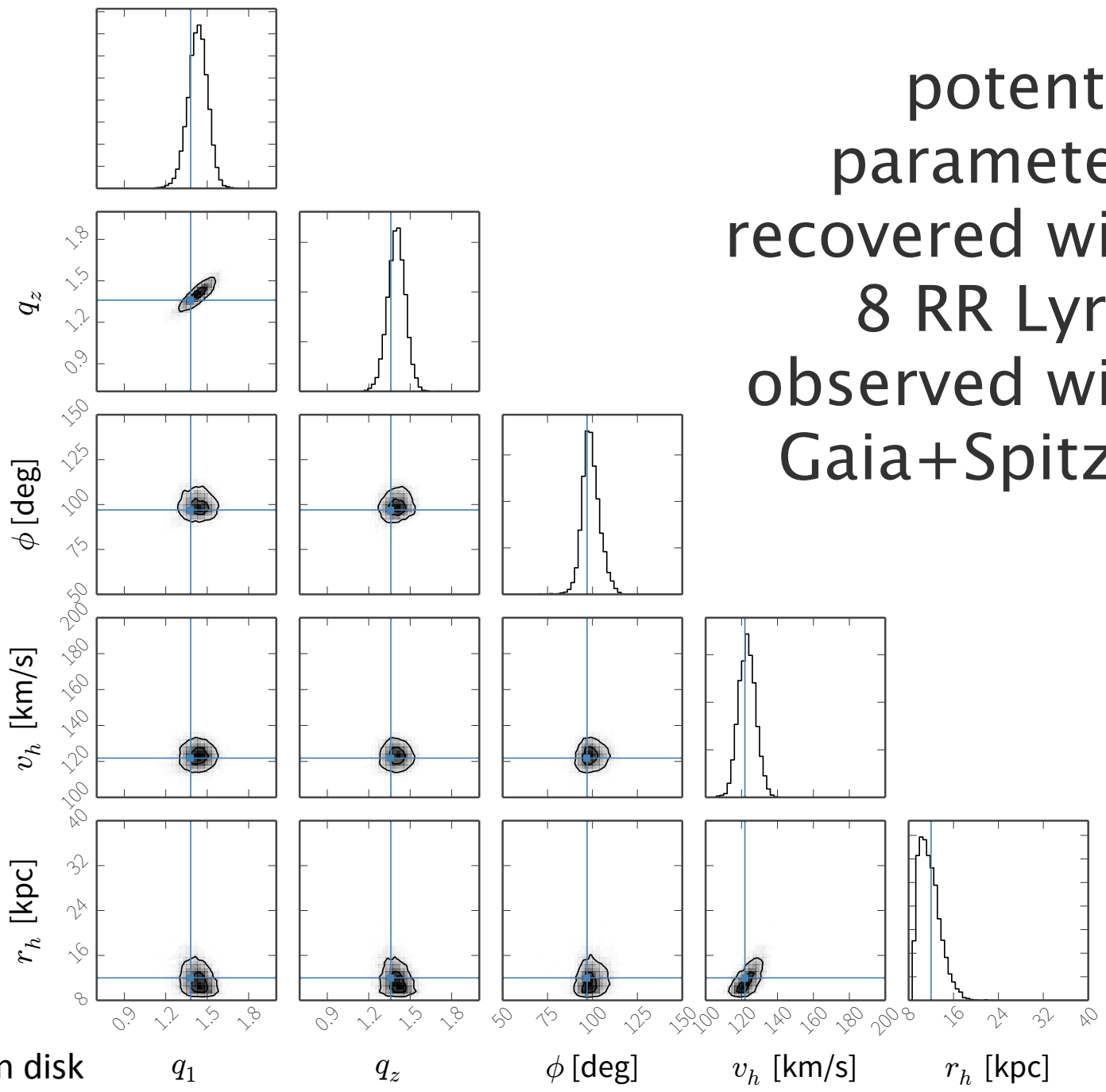
potential parameters recovered with 8 RR Lyrae observed with Gaia+Spitzer

Flattening perpendicular to disk

Orientation in disk plane

Velocity scale of halo

length scale of halo



axis ratio in disk

q_1

q_z

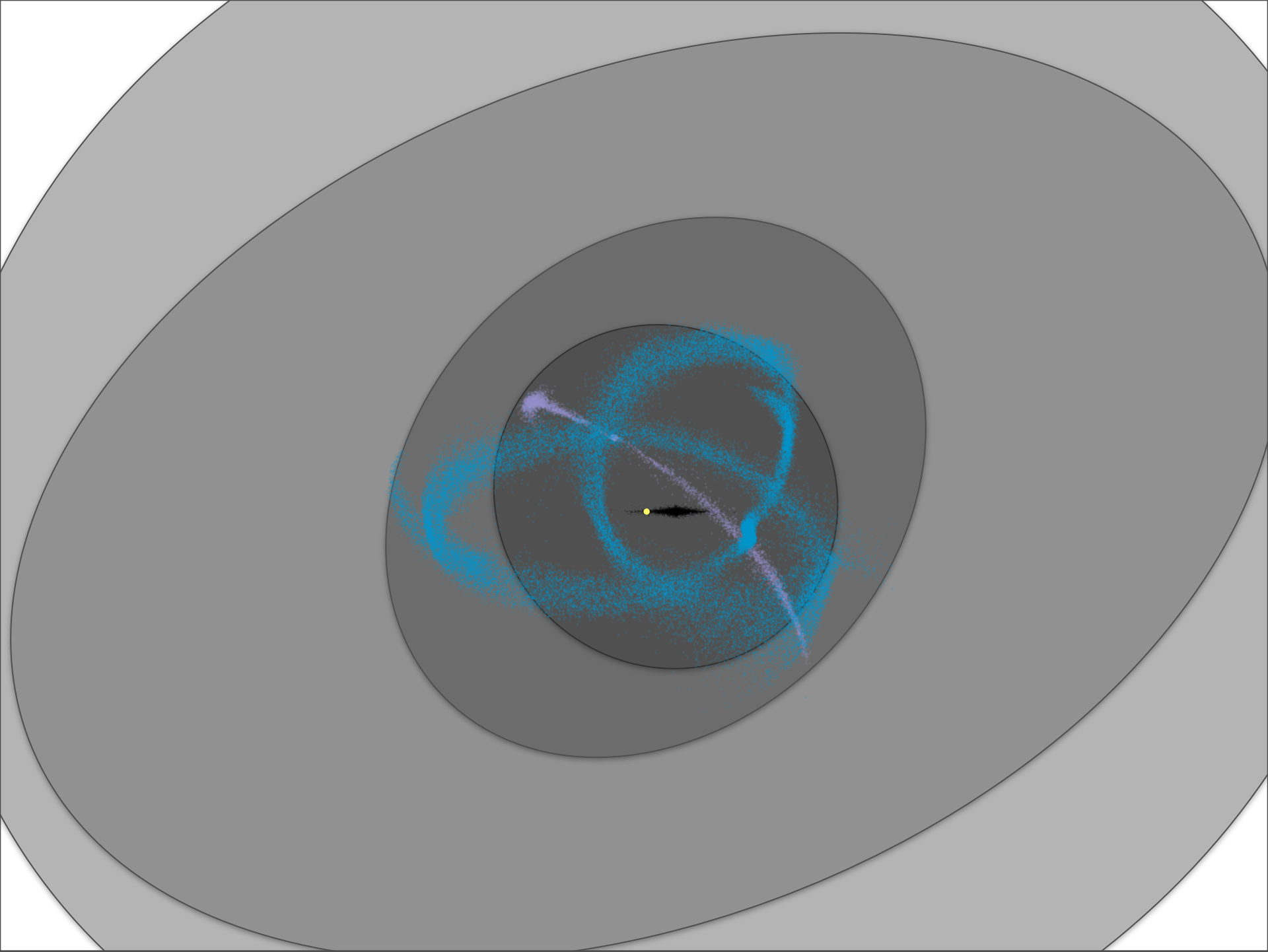
ϕ [deg]

v_h [km/s]

r_h [kpc]

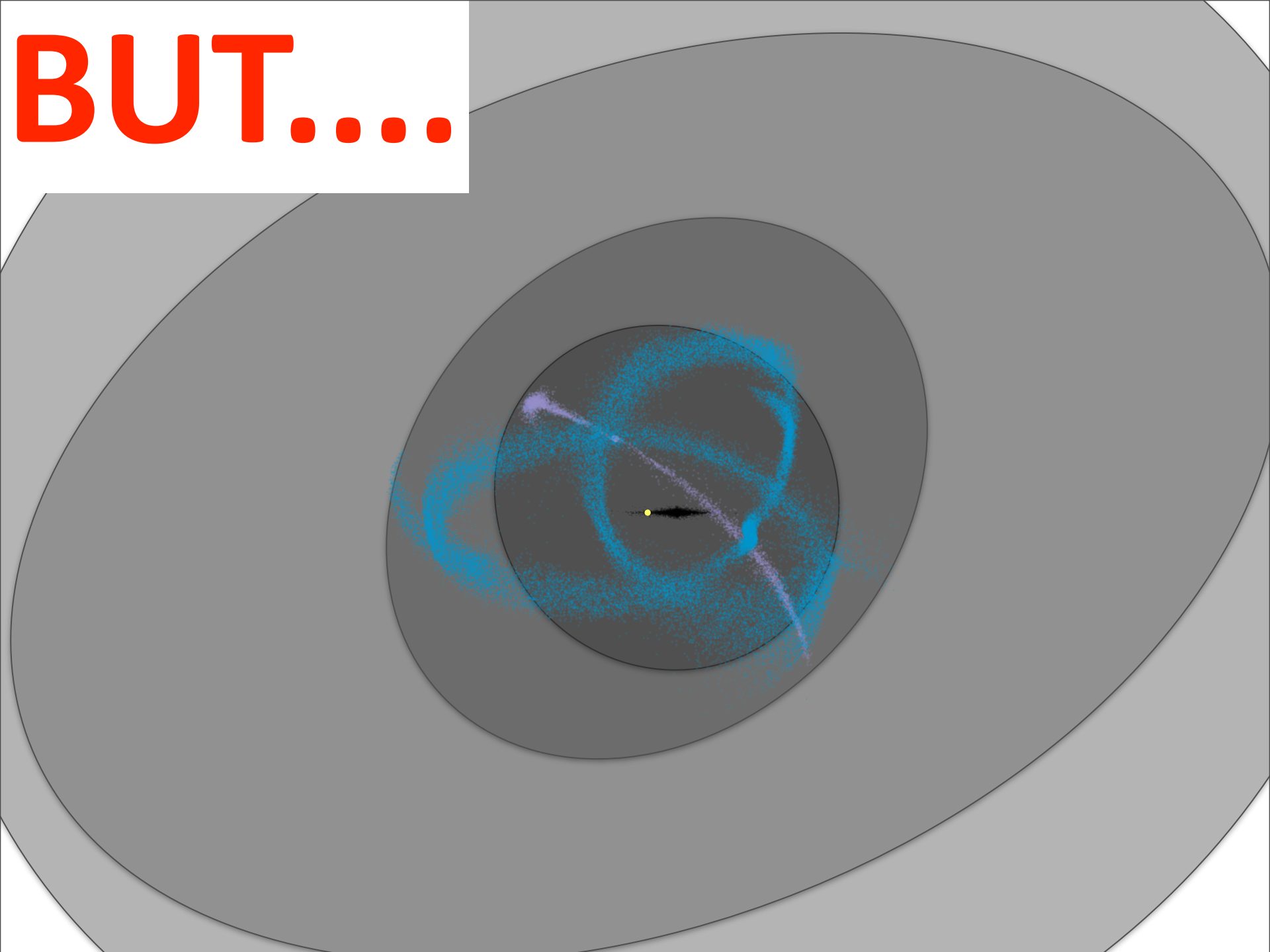
dead/dying satellites
+ *Gaia*
+ **SMHASH!!@#%??**
=
3-D map
of the
dark matter halo

..... with some caveats still to be addressed



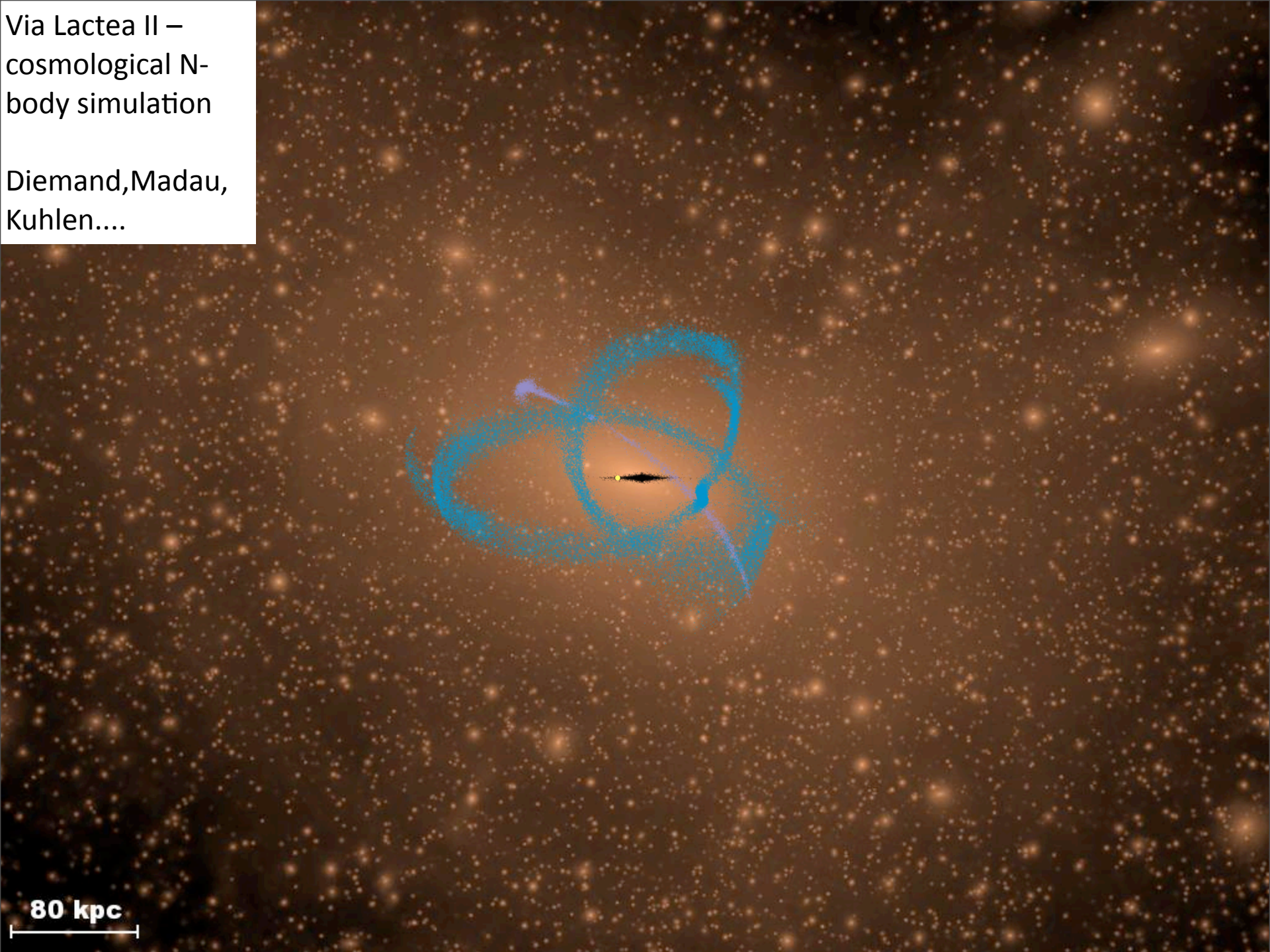
Tuesday, August 26, 14

BUT....



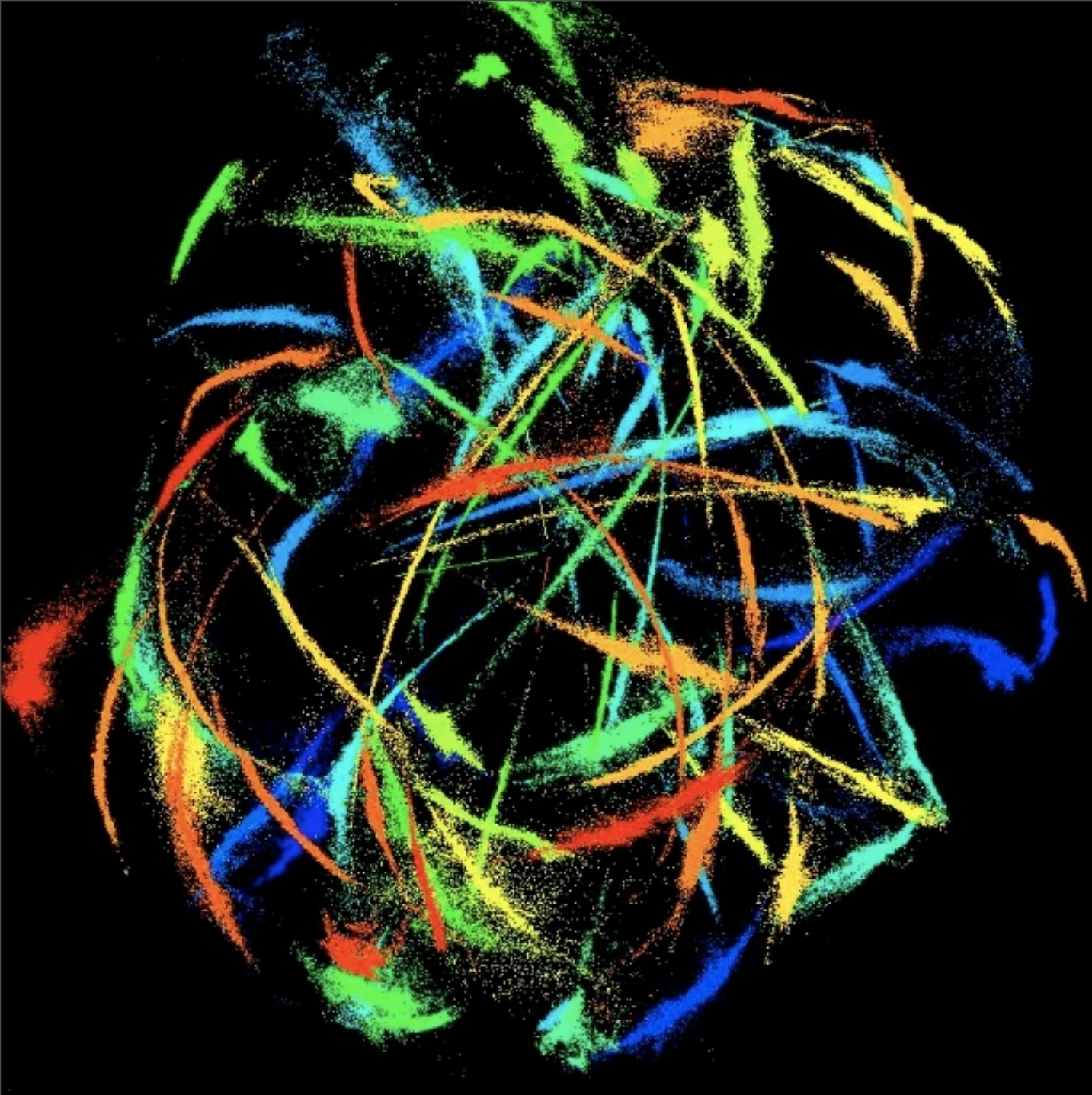
Via Lactea II –
cosmological N-
body simulation

Diemand, Madau,
Kuhlen....



80 kpc

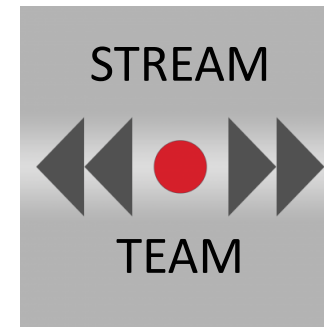
Tuesday, August 26, 14



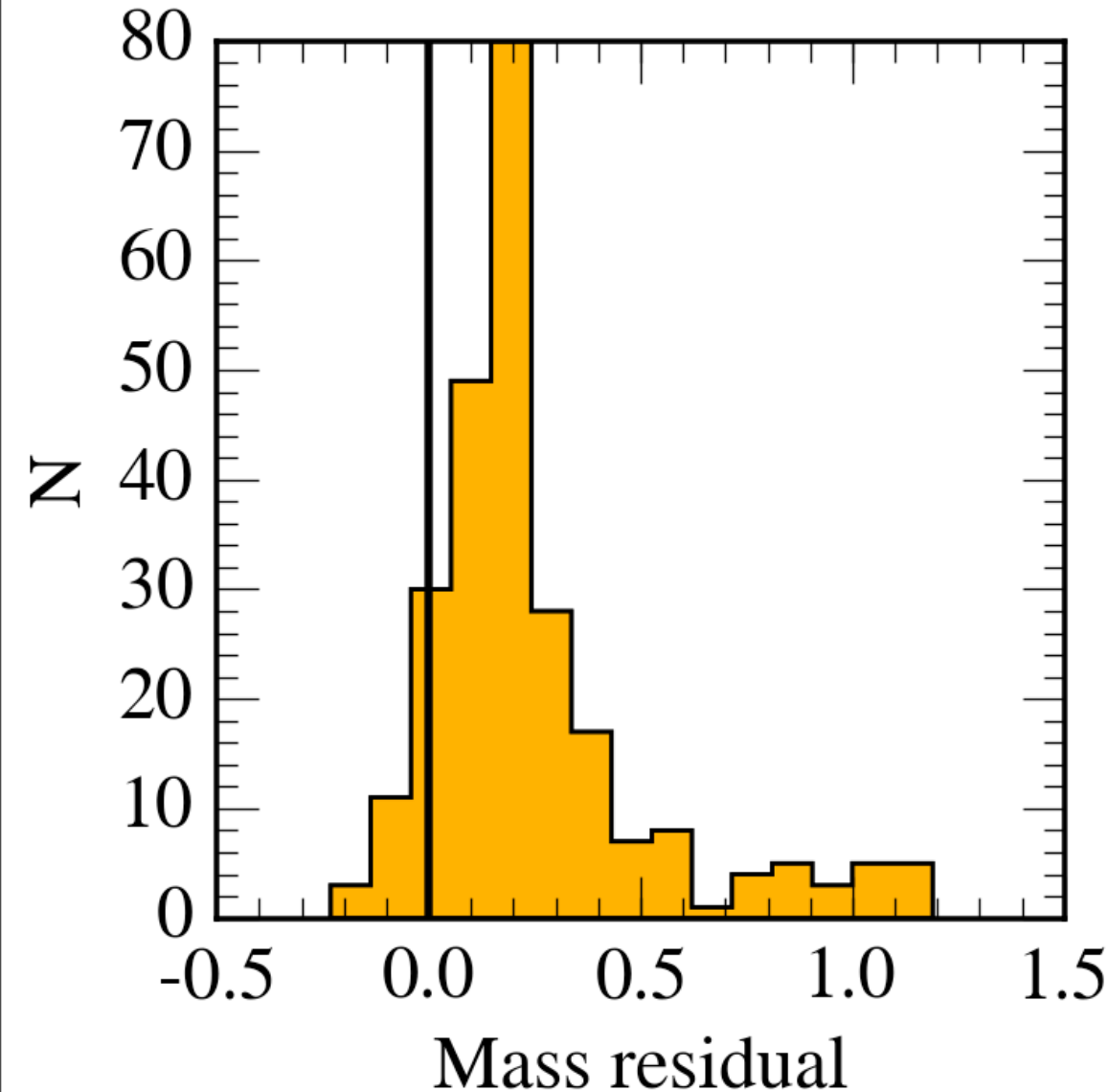
Test data set:
12,000
globular
cluster
streams
simulated in
Via Lactea II
potential
(Kuepper &
Diemand)

FAST FORWARD

fitting using *streakline* (Kuepper 2012)



Ana Bonaca (Yale)



Fractional error
on estimates of
mass within
150kpc in the VLII
halo with 256
different streams

dead/dying satellites
+ *Gaia*
+ **SMHASH!!@#%??**
=
3-D map
of the
dark matter halo

..... with some caveats still to be addressed