measuring the

Galactic Potential

with 6D information

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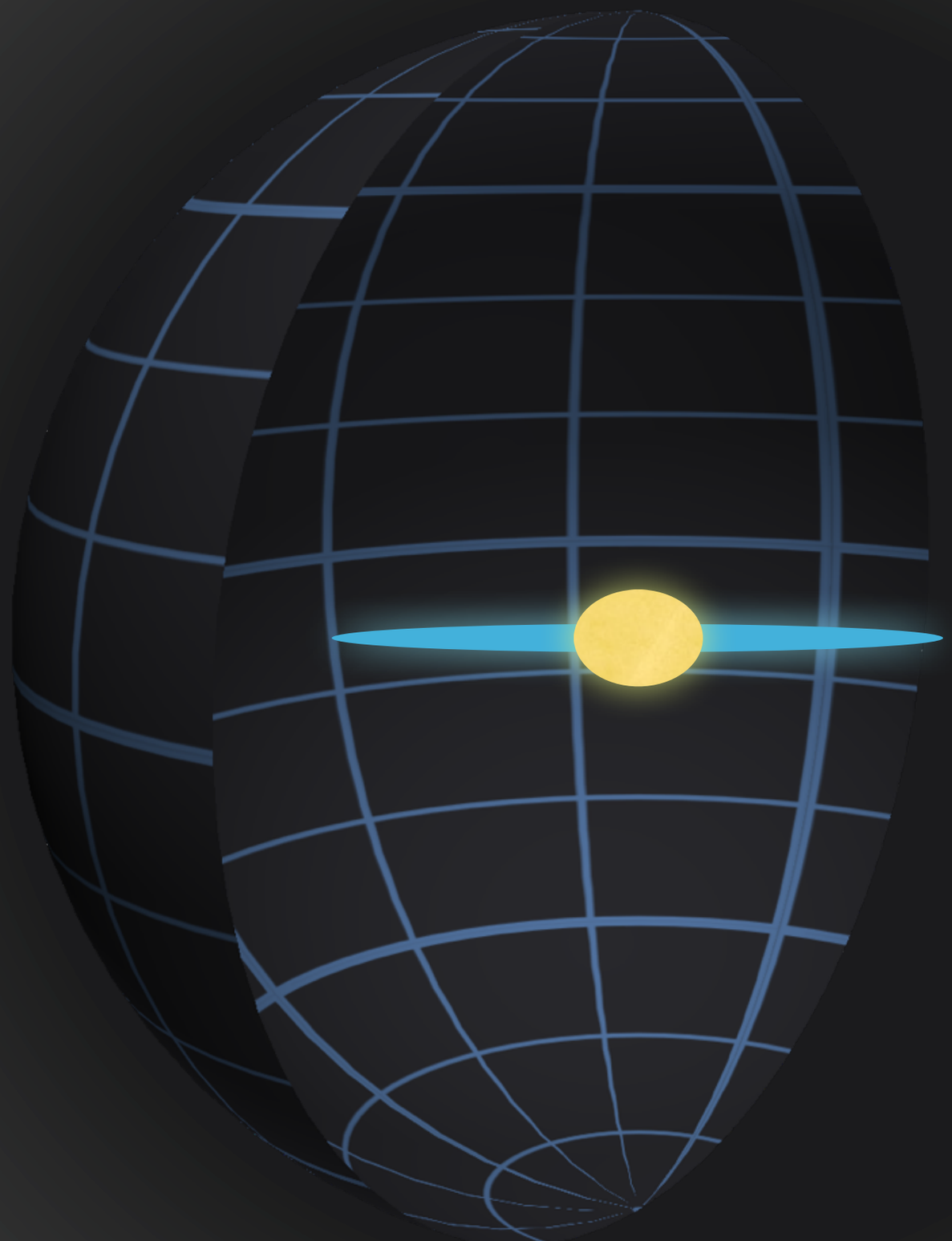
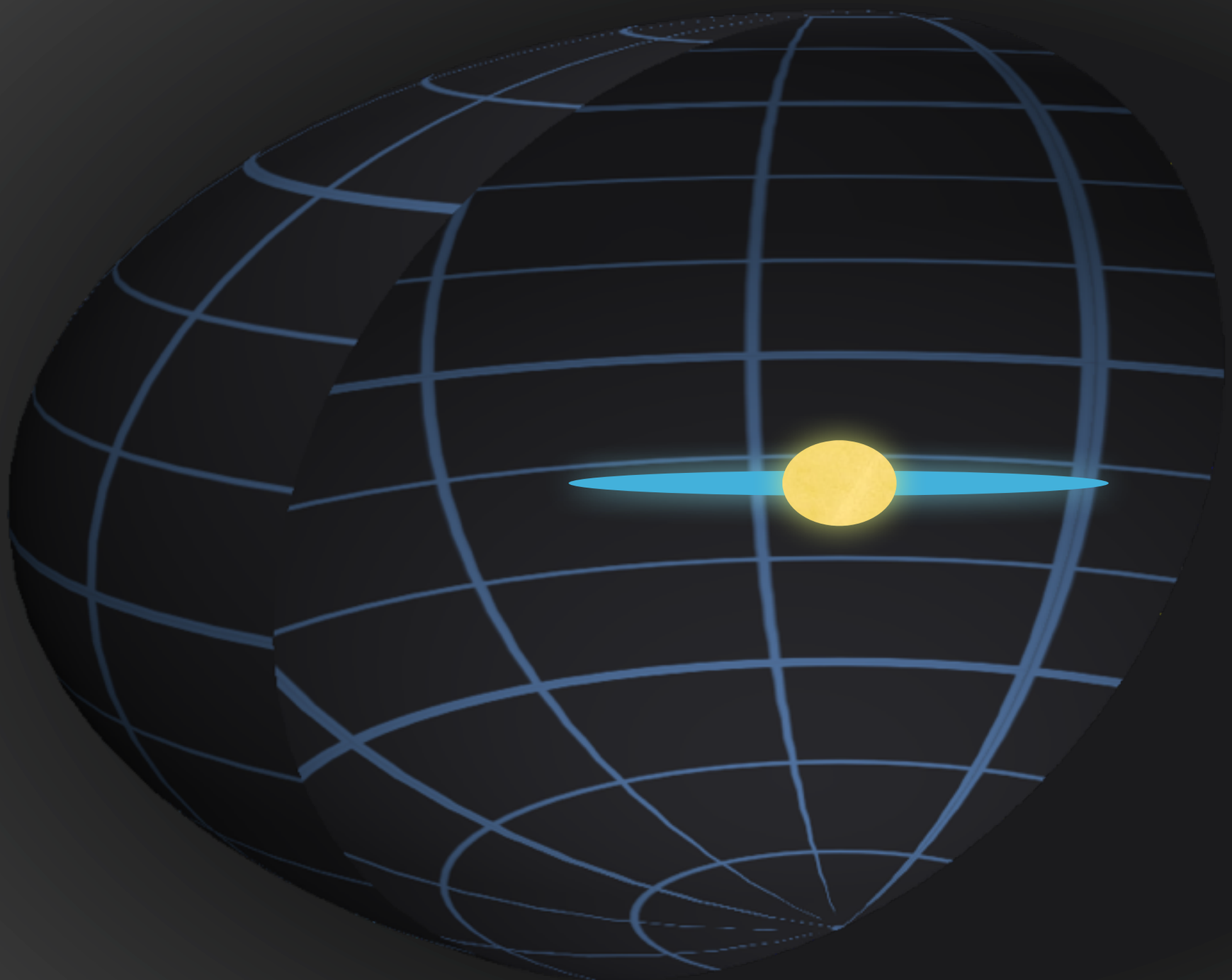
+ Kathryn Johnston

adrn/streams

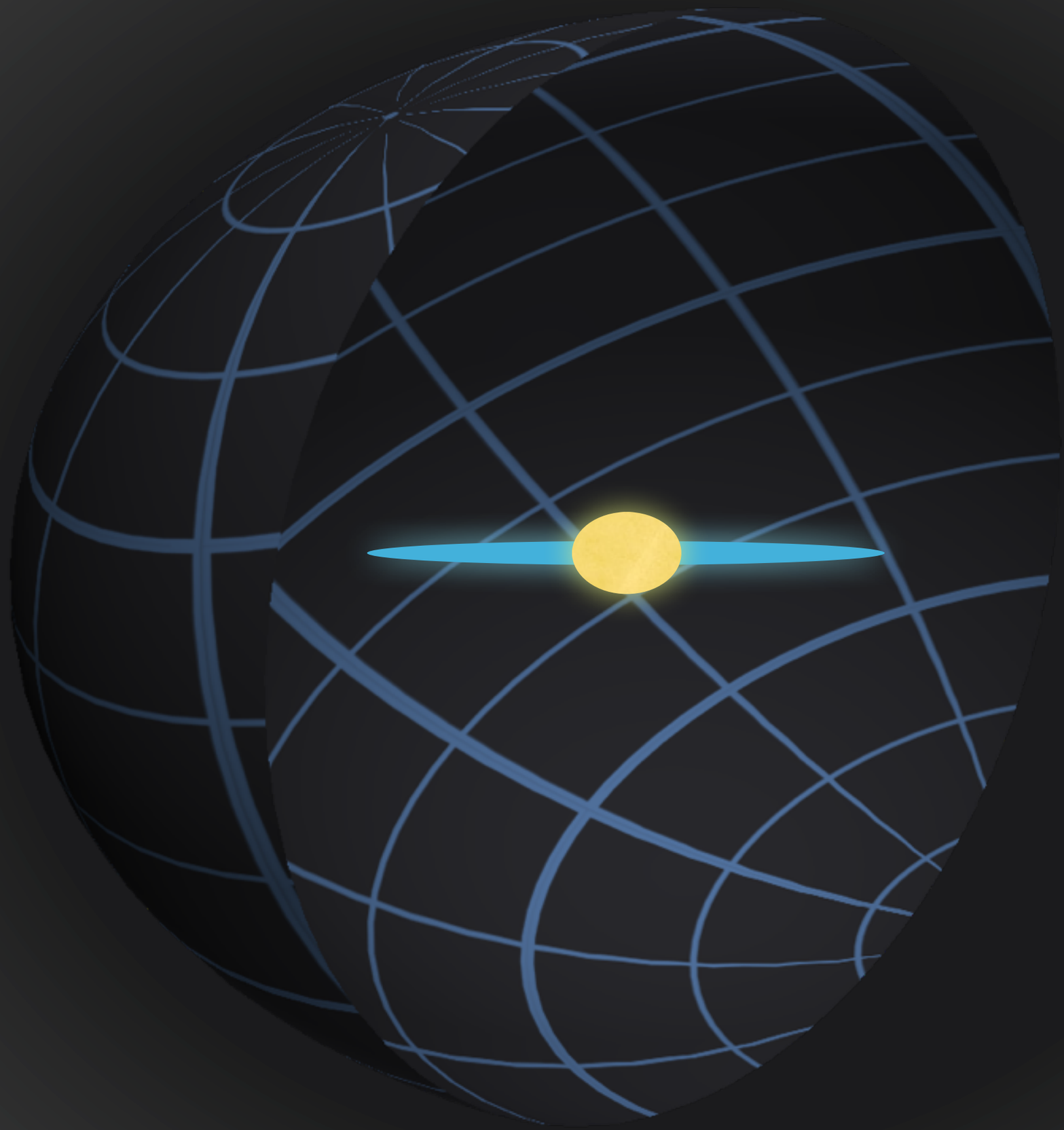
The Motivation



?

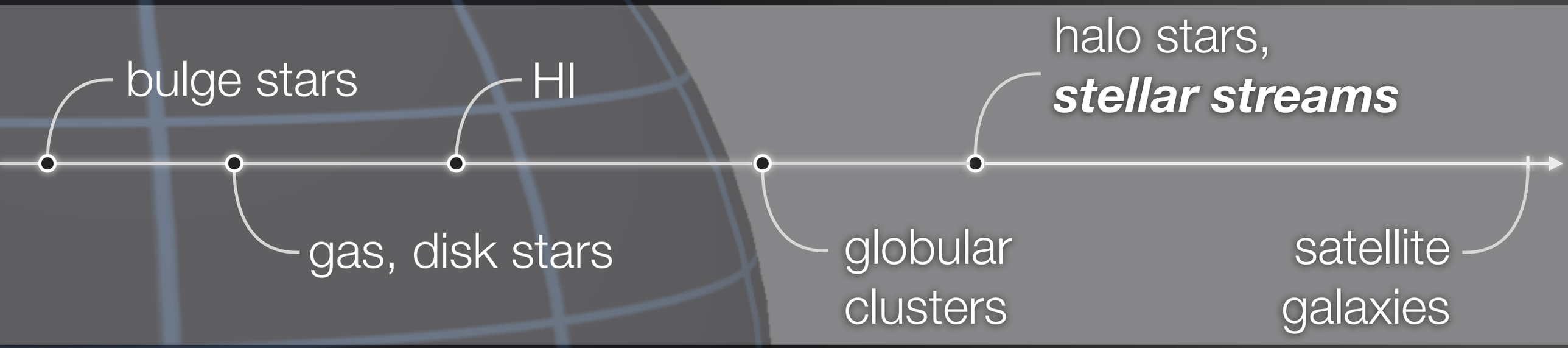


?



2?

kinematic tracers



kinematic tracers

bulge stars

HI

halo stars,

stellar streams

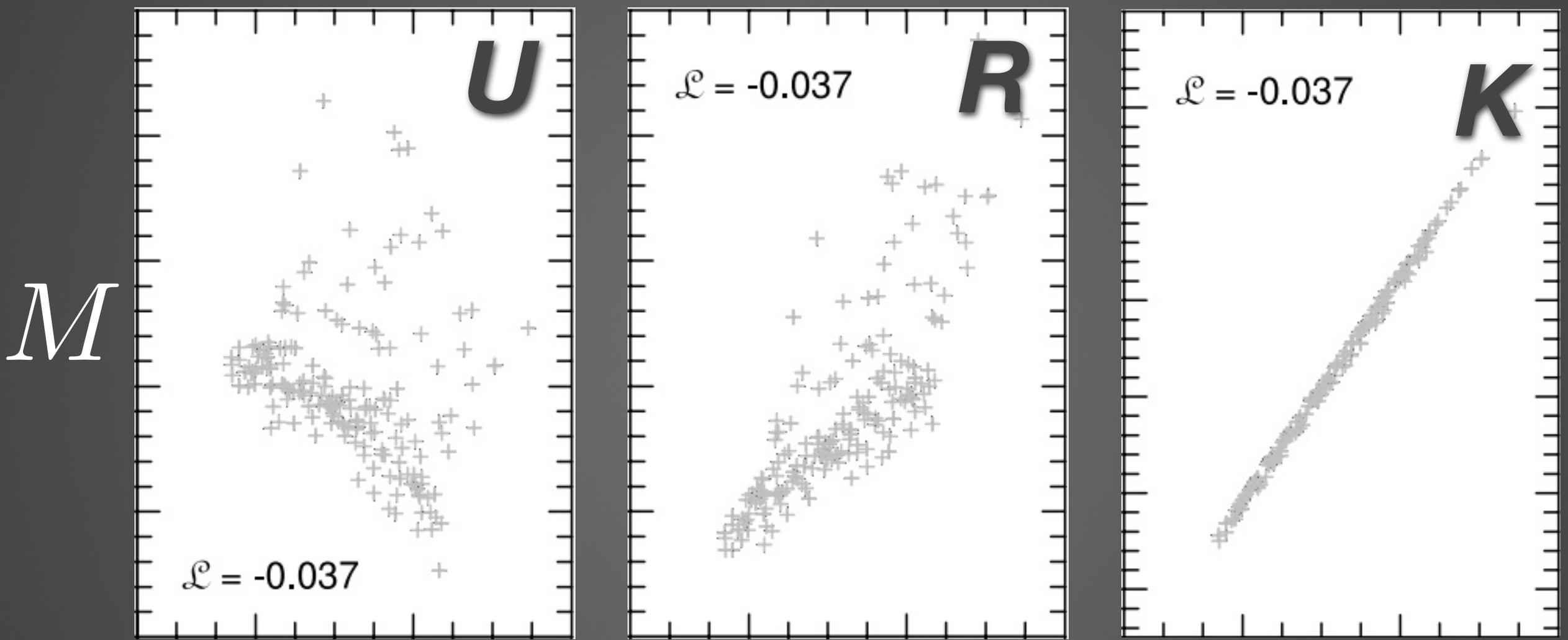
gas, disk stars

globular clusters

satellite galaxies

$$\not{\alpha} \quad \not{\delta} \quad D \quad \mu_l \quad \mu_b \quad \not{v_r}$$

P-L relation for RR Lyrae

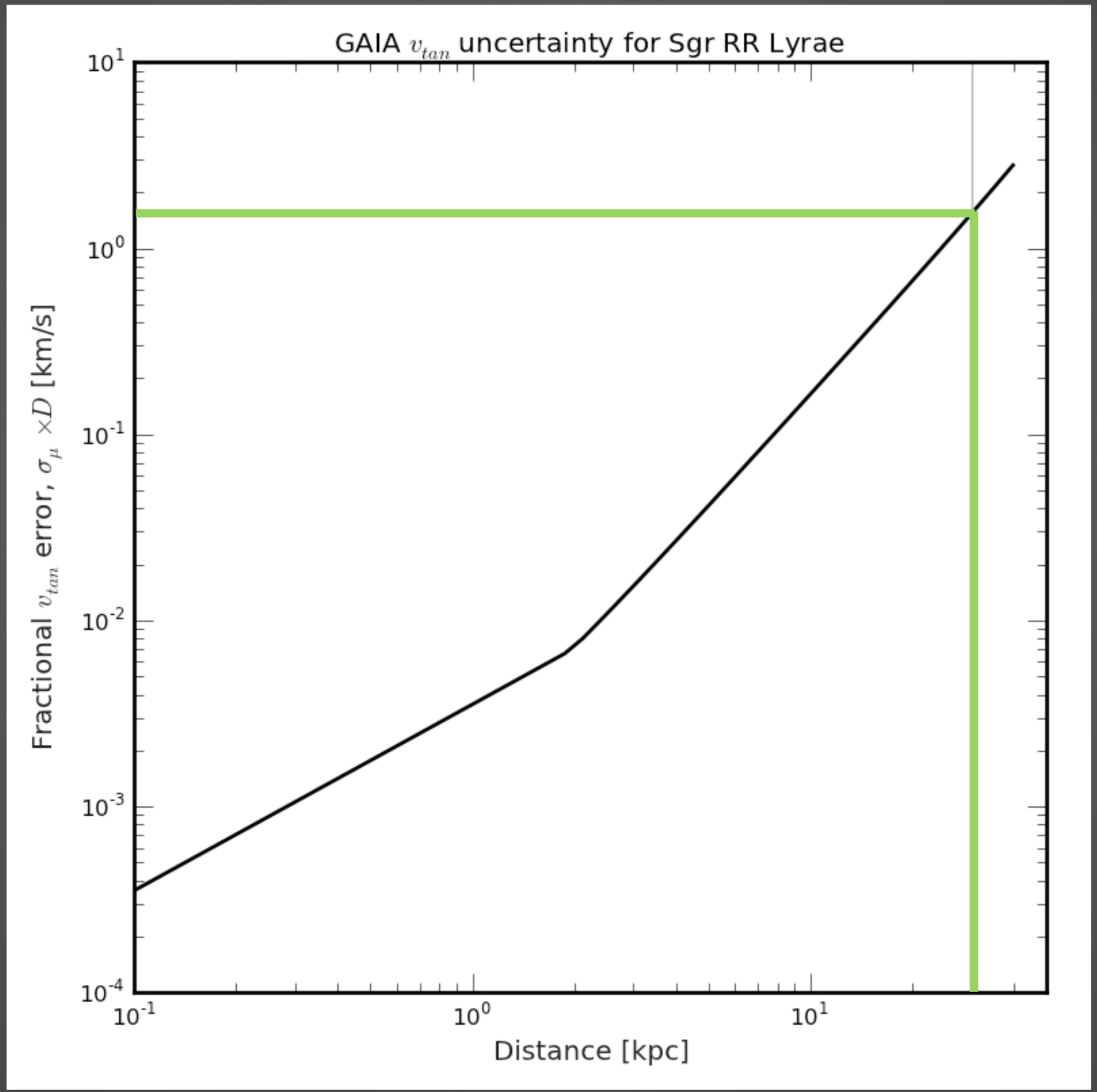


Catelan et al. 2004
Madore & Freedman 2012

OBSERVATIONAL

$$\cancel{\alpha} \quad \cancel{\delta} \quad \cancel{D} \quad \mu_l \quad \mu_b \quad \cancel{v_r}$$

GAIA


GAIA v_{tan} uncertainty for Sgr RR Lyrae
Fractional v_{tan} error, $\sigma_\mu \times D$ [km/s]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
10^{0}
10^{1}
Distance [kpc]

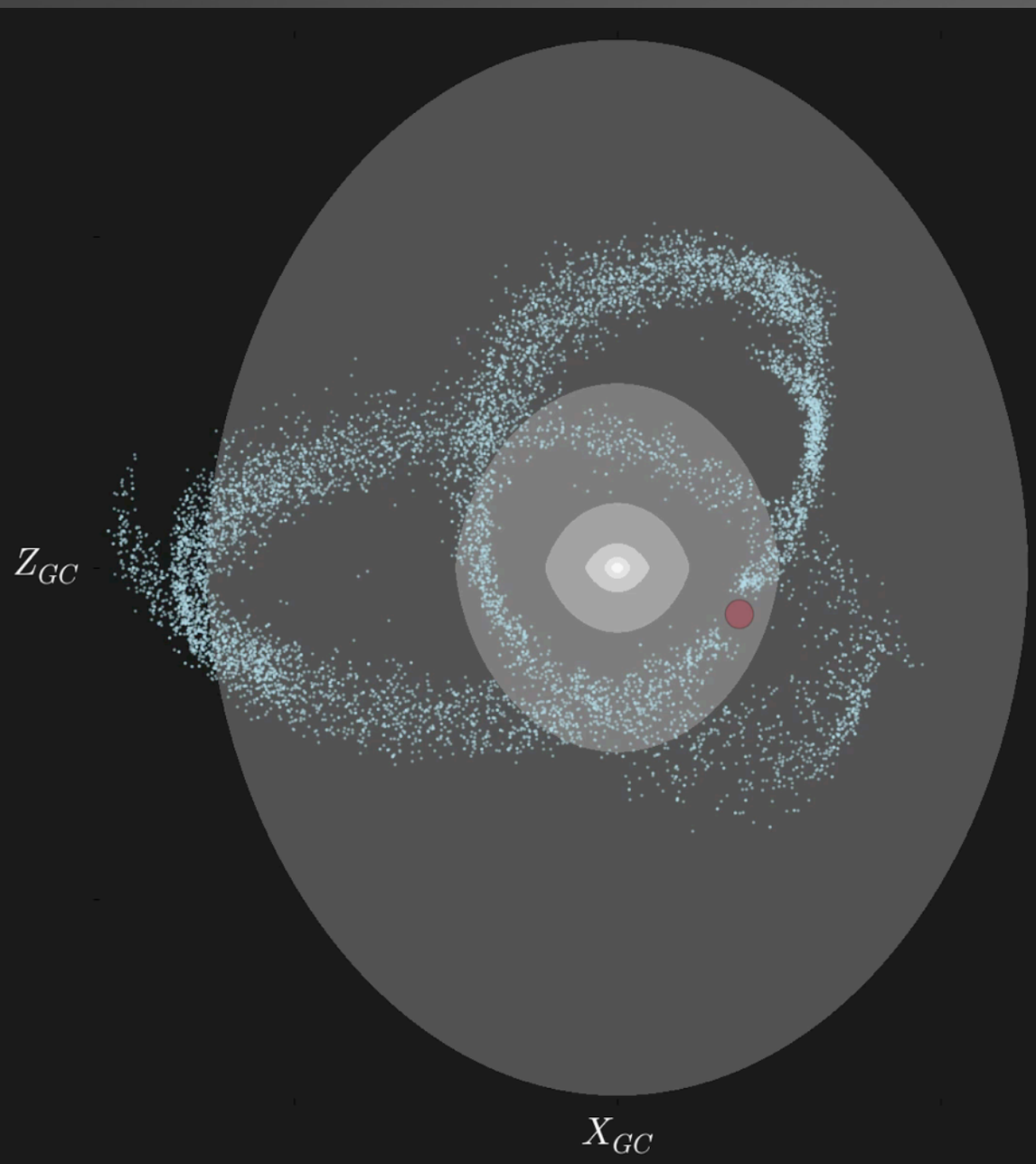
OBSERVATIONAL

$$\cancel{\alpha} \quad \cancel{\delta} \quad \cancel{D} \quad \cancel{\mu_l} \quad \cancel{\mu_b} \quad \cancel{v_r}$$

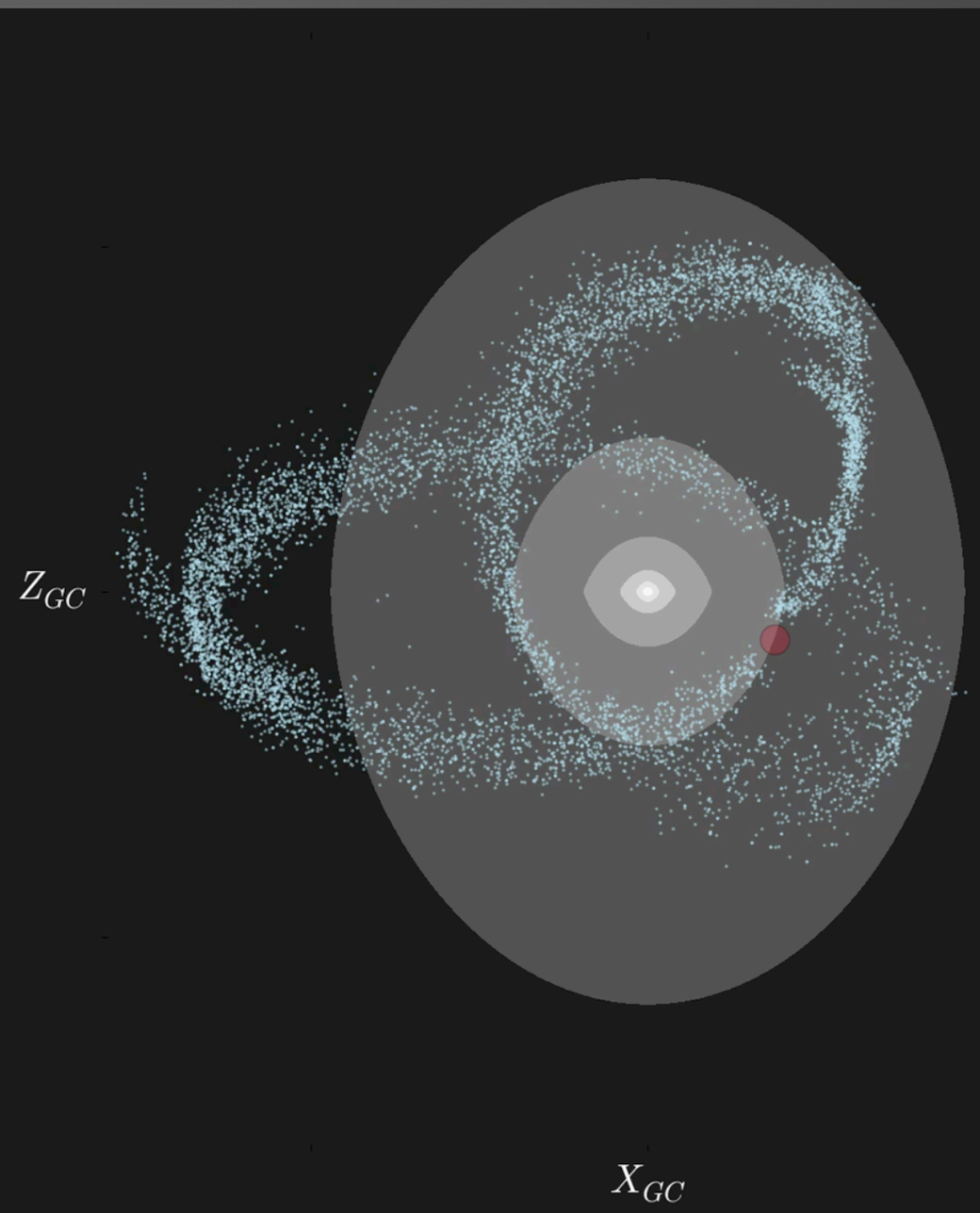
What can we do with 6D information?

The Method

correct



5% wrong



streams / debris

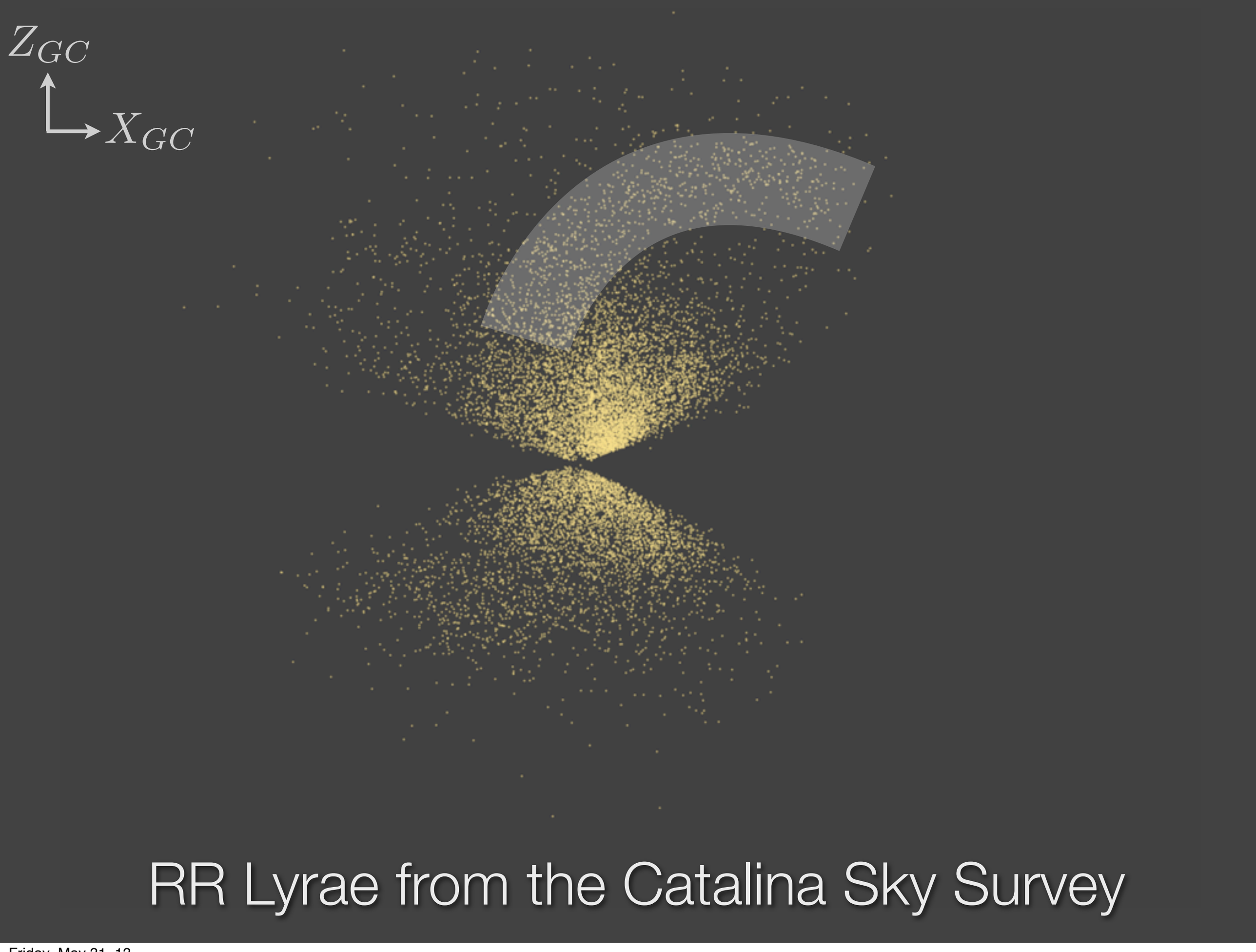
+

6D kinematics

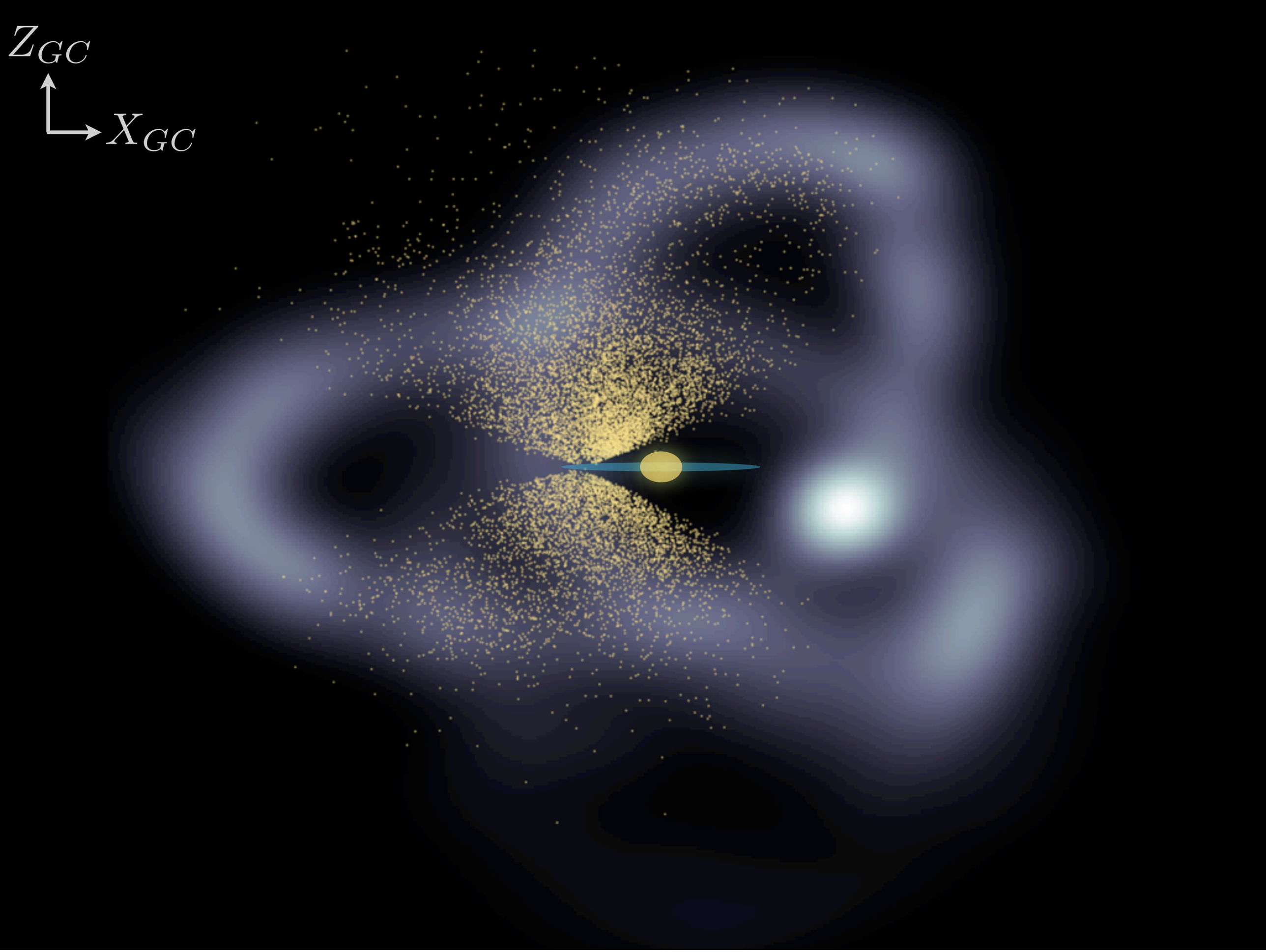
+

*progenitor orbit**

** maybe not necessary...stay tuned*



RR Lyrae from the Catalina Sky Survey

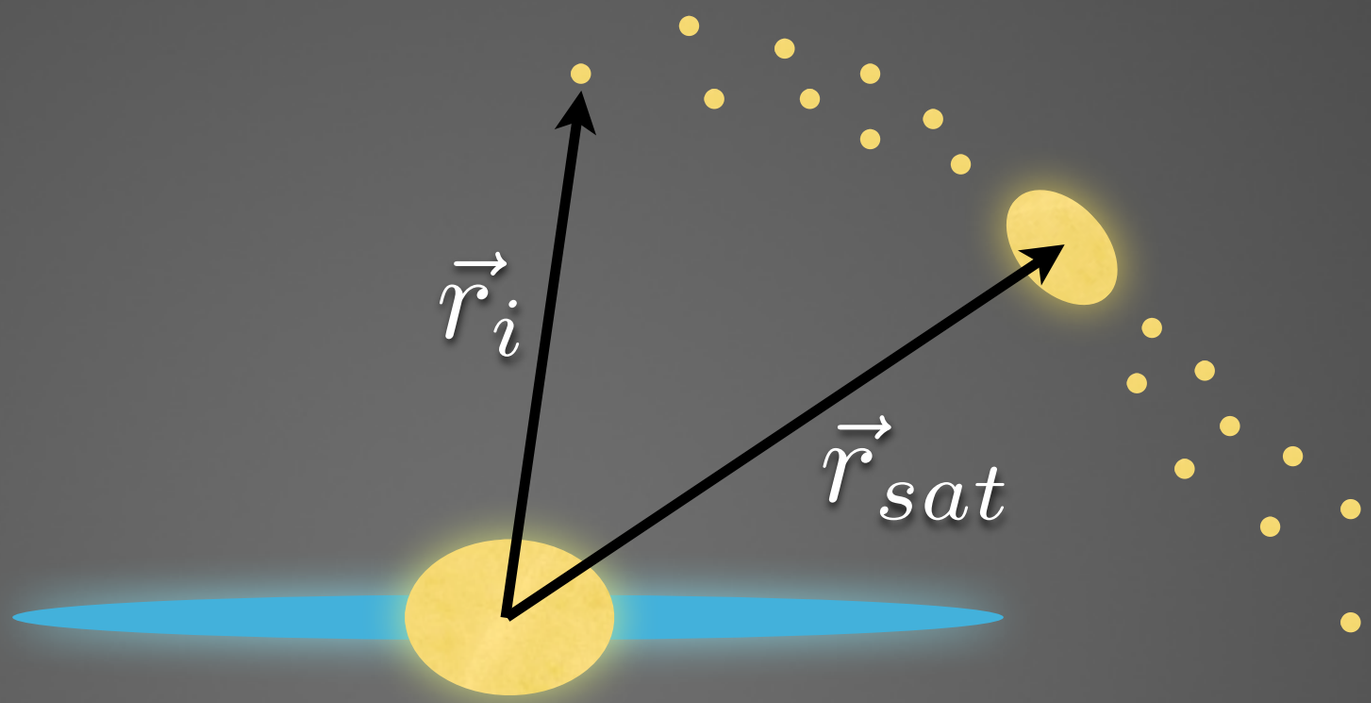

Z_{GC}
X_{GC}

Sgr as a test bed

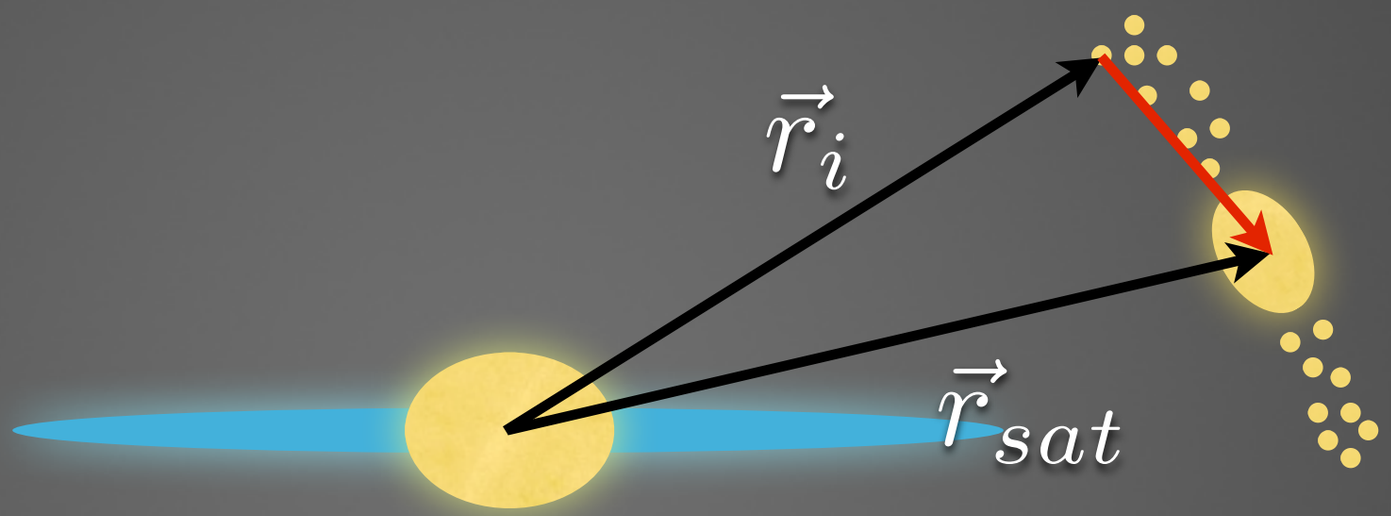
+ thick
+ known progenitor
+ well-studied
+ simulated

Law & Majewski 2010

t = 42



t = 31



$$\vec{p}_i(t) = \frac{|\vec{v}_i - \vec{v}_{sat}|}{V_{esc}}$$

$$\vec{q}_i(t) = \frac{|\vec{r}_i - \vec{r}_{sat}|}{R_{tide}}$$

for a given star...

time

$$\left(\begin{array}{c|c} \vec{p}^{(0)} & \vec{q}^{(0)} \\ \vec{p}^{(1)} & \vec{q}^{(1)} \\ \vdots & \vdots \\ \vec{p}^{(N)} & \vec{q}^{(N)} \end{array}\right)$$

"phase space distance"

$$\left(\begin{array}{c} ||\vec{p}^{(0)}||^2 + ||\vec{q}^{(0)}||^2 \\ ||\vec{p}^{(1)}||^2 + ||\vec{q}^{(1)}||^2 \\ \vdots \\ ||\vec{p}^{(N)}||^2 + ||\vec{q}^{(N)}||^2 \end{array}\right) = \left(\begin{array}{c} D_{PS}^{(0)} \\ D_{PS}^{(1)} \\ \vdots \\ D_{PS}^{(N)} \end{array}\right)$$

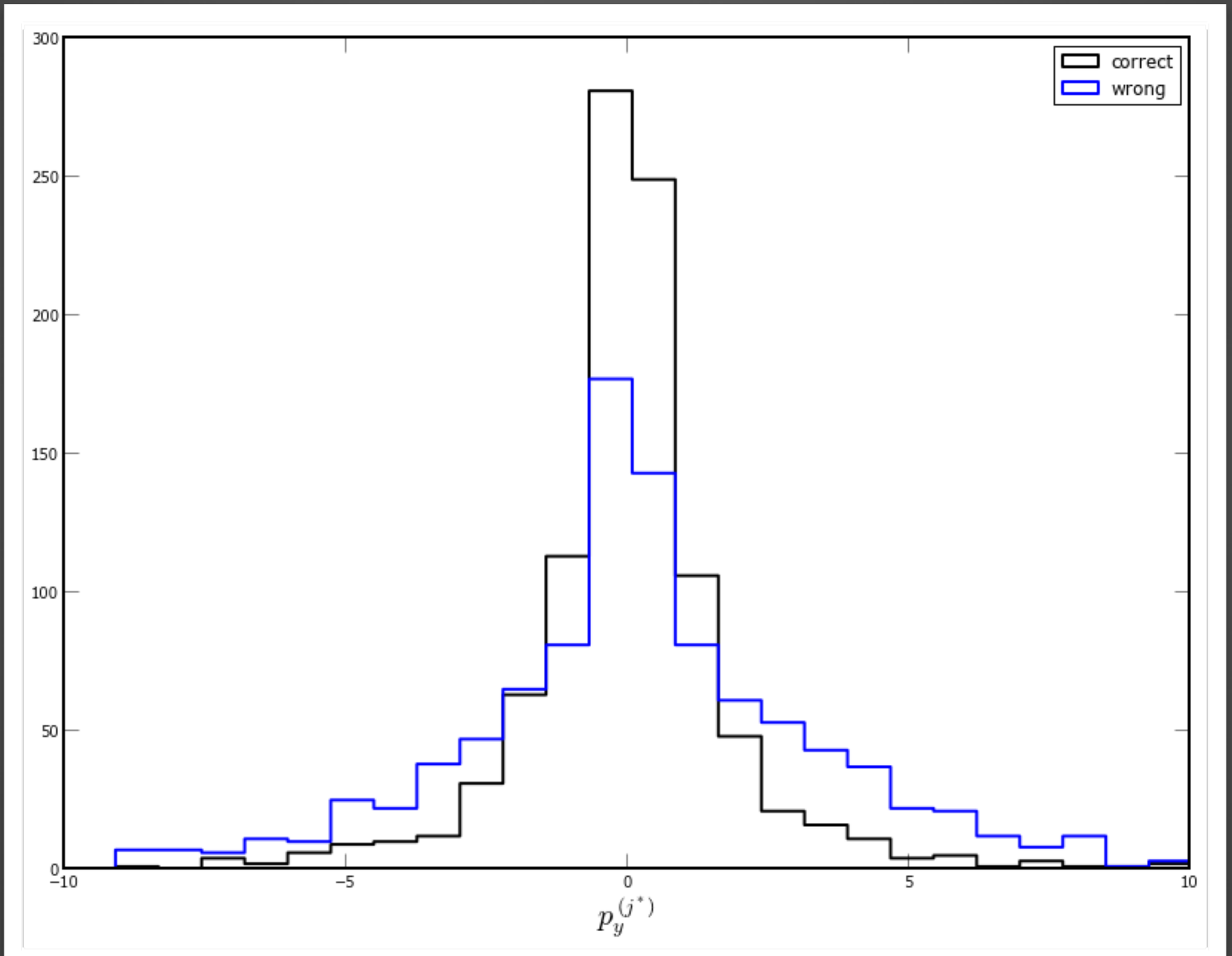
$$\begin{pmatrix} \vec{p}^{(0)} & \vec{q}^{(0)} \\ \vec{p}^{(1)} & \vec{q}^{(1)} \\ \vdots & \vdots \\ \vec{p}^{(j^*)} & \vec{q}^{(j^*)} \\ \vdots & \vdots \\ \vec{p}^{(N)} & \vec{q}^{(N)} \end{pmatrix} \leftarrow j^* = \arg\min_j \begin{pmatrix} D_{PS}^{(0)} \\ D_{PS}^{(1)} \\ \vdots \\ D_{PS}^{(j^*)} \\ \vdots \\ D_{PS}^{(N)} \end{pmatrix}$$

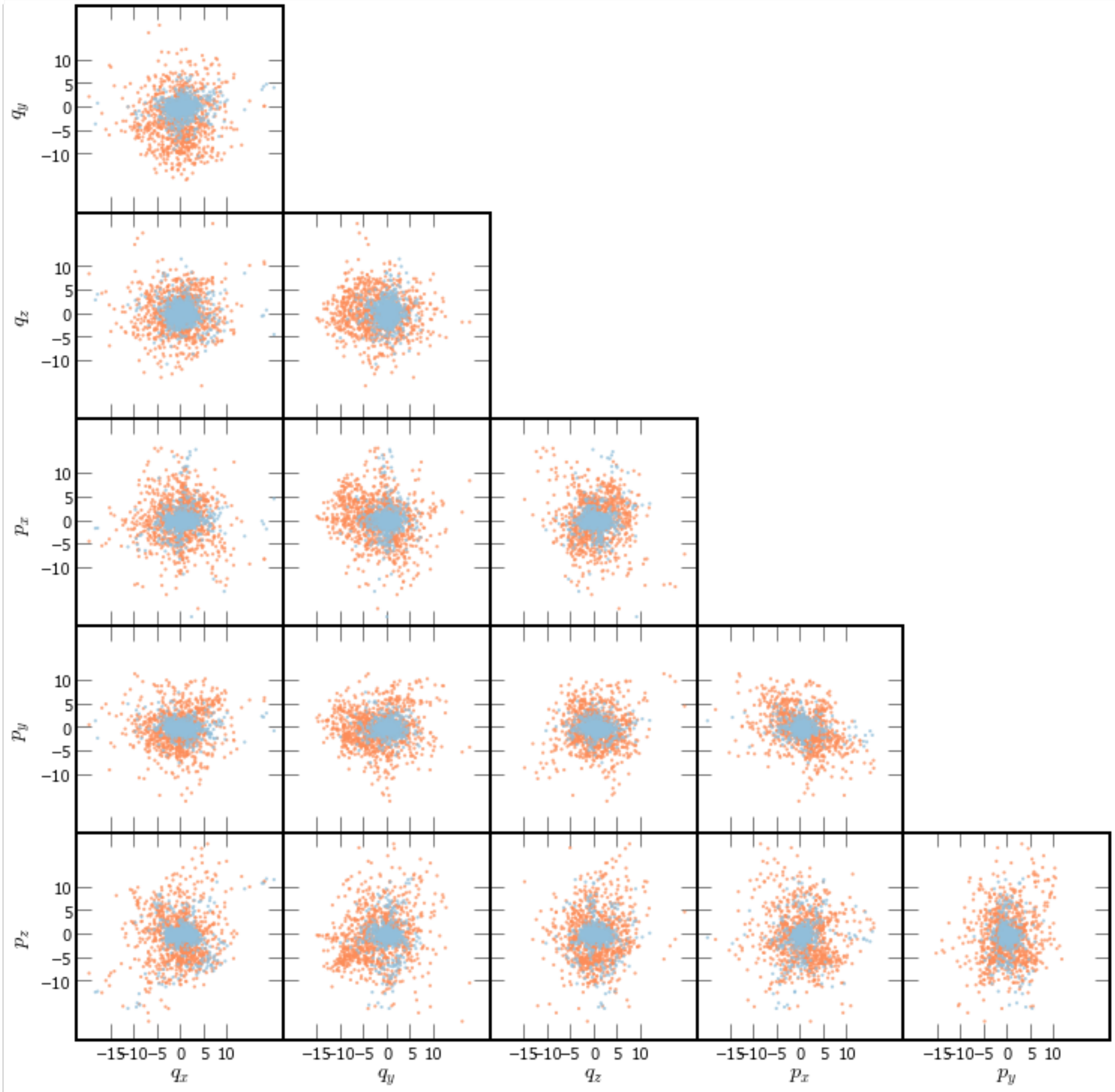
minimum 6D distance vector for each particle

$$\left(\begin{array}{c|c} \vec{p}_0^{(j^*)} & \vec{q}_0^{(j^*)} \\ \vec{p}_1^{(j^*)} & \vec{q}_1^{(j^*)} \\ \vdots & \vdots \\ \vec{p}_M^{(j^*)} & \vec{q}_M^{(j^*)} \end{array}\right)$$

(M particles)

Variance increases in the wrong potential




q_y
q_z
p_x
p_y
p_z
10
5
0
−5
−10
−15
q_x
q_y
q_z
p_x
p_y

$$\begin{pmatrix} \sigma^2_{q_x} & \cdots & \cdots & \mathrm{Cov}[q_x, p_z] \\ & \sigma^2_{q_y} & & \\ \vdots & & \sigma^2_{q_z} & \vdots \\ \vdots & & \sigma^2_{p_x} & \vdots \\ & & & \sigma^2_{p_y} \\ \mathrm{Cov}[p_z, q_x] & \cdots & \cdots & \sigma^2_{p_z} \end{pmatrix}$$

$$\Sigma$$

diagonalize & sum

$$\tilde{\Sigma} = \begin{pmatrix} \tilde{\sigma}^2_{q_x} & & \cdots & \cdots & 0 \\ & \tilde{\sigma}^2_{q_y} & & & \\ \vdots & & \tilde{\sigma}^2_{q_z} & & \vdots \\ & & & \tilde{\sigma}^2_{p_x} & \\ \vdots & & & & \vdots \\ & & & \tilde{\sigma}^2_{p_y} & \\ 0 & & \cdots & \cdots & \tilde{\sigma}^2_{p_z} \end{pmatrix}$$

$$\boxed{\mathrm{Tr}(\tilde{\Sigma})}$$

diagonalize & sum

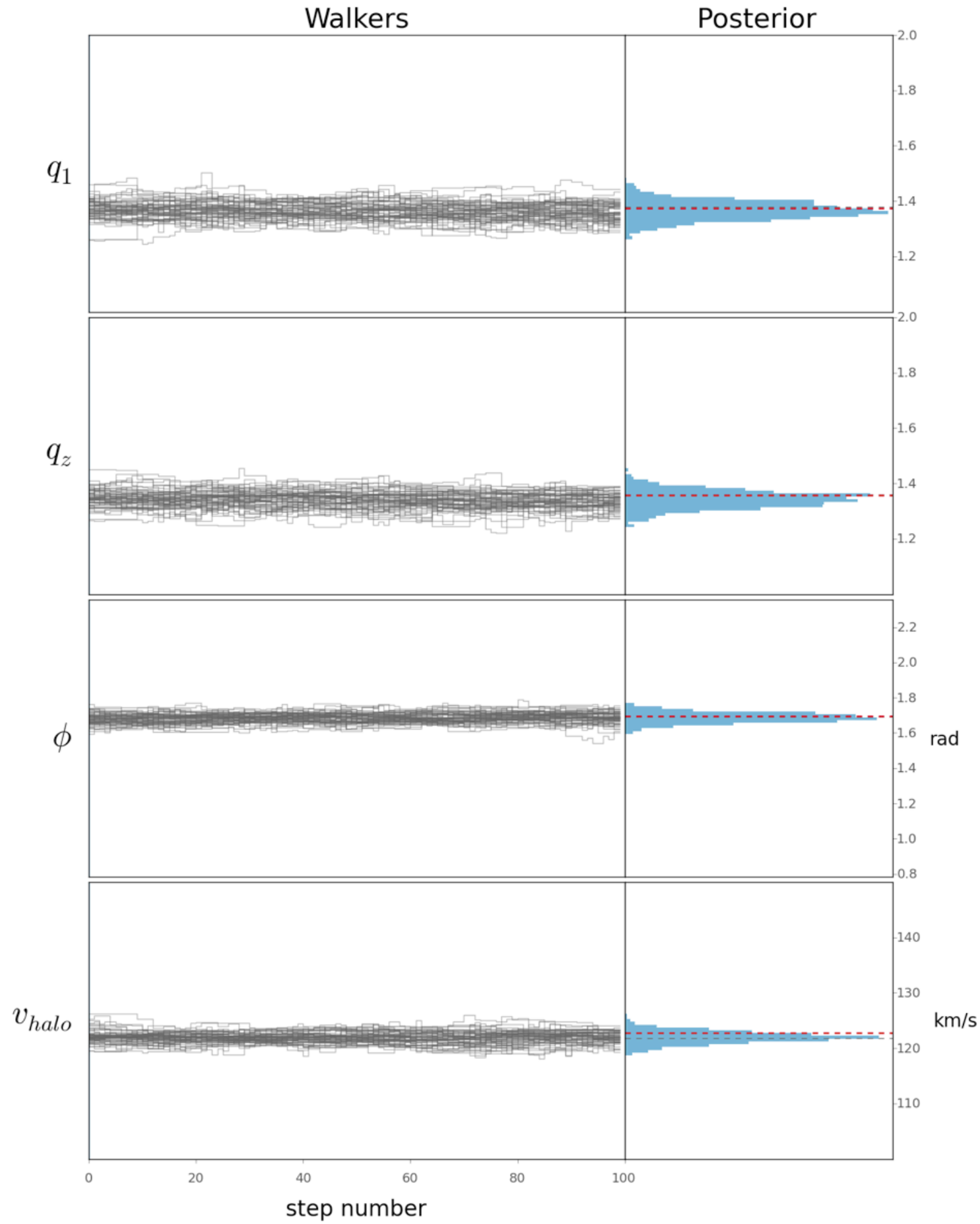
$$\tilde{\Sigma} = \begin{pmatrix} \tilde{\sigma}^2_{q_x} & & \cdots & \cdots & 0 \\ & \tilde{\sigma}^2_{q_y} & & & \\ \vdots & & \tilde{\sigma}^2_{q_z} & & \vdots \\ & & & \tilde{\sigma}^2_{p_x} & \\ \vdots & & & & \vdots \\ & & & \tilde{\sigma}^2_{p_y} & \\ 0 & & \cdots & \cdots & \tilde{\sigma}^2_{p_z} \end{pmatrix}$$

$\mathrm{Tr}(\tilde{\Sigma})$ → finally something we can optimize...

assume a fixed functional form

$$\Phi_{halo} = \frac{1}{2} v_{halo}^2 \ln\left(C_1 x^2 + C_2 y^2 + C_3 xy + (z/q_z)^2 + R_c^2\right)$$

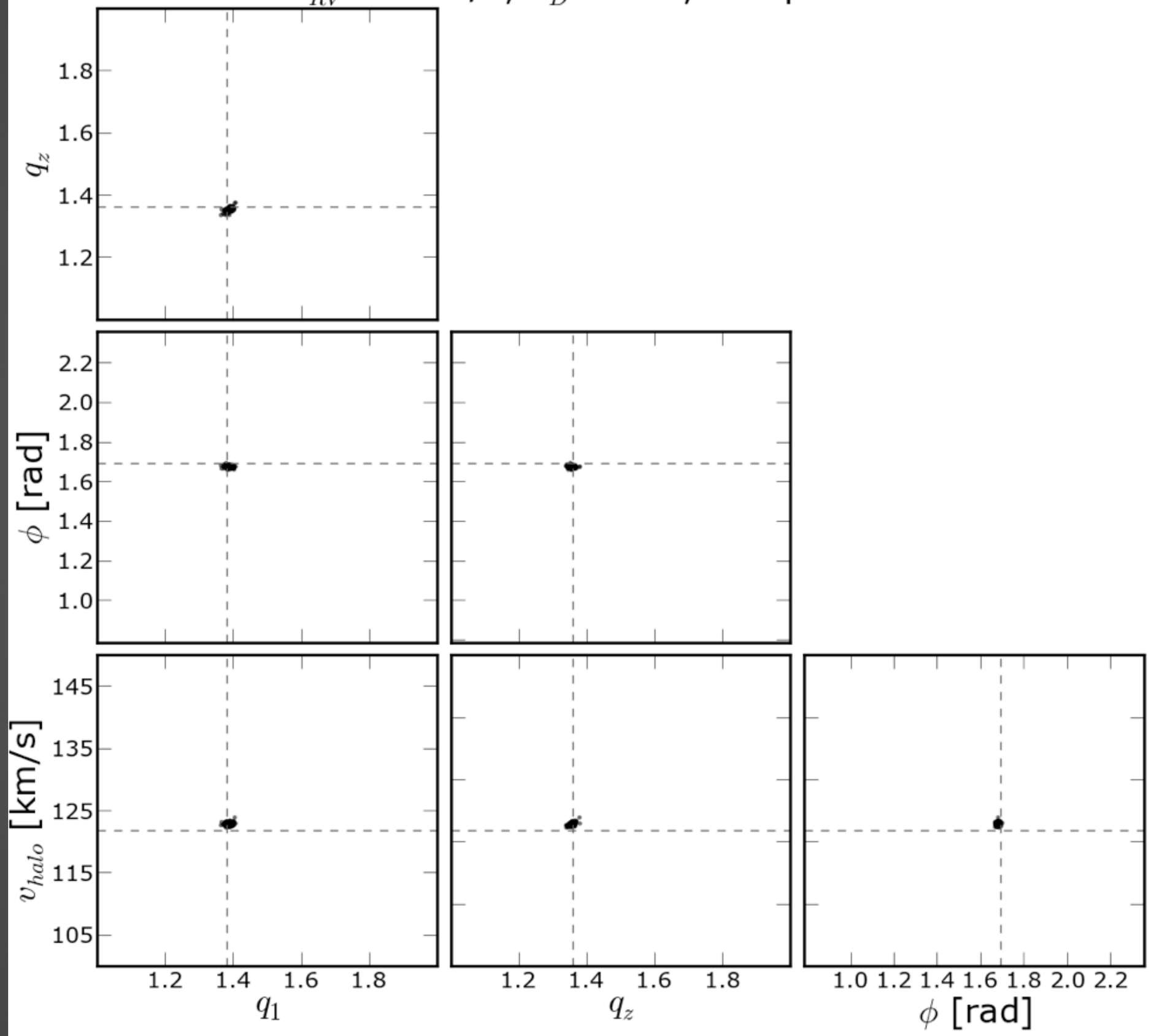
$$C_1, C_2, C_3 \leftrightarrows q_1, q_2, \phi$$



emcee
The MCMC Hammer

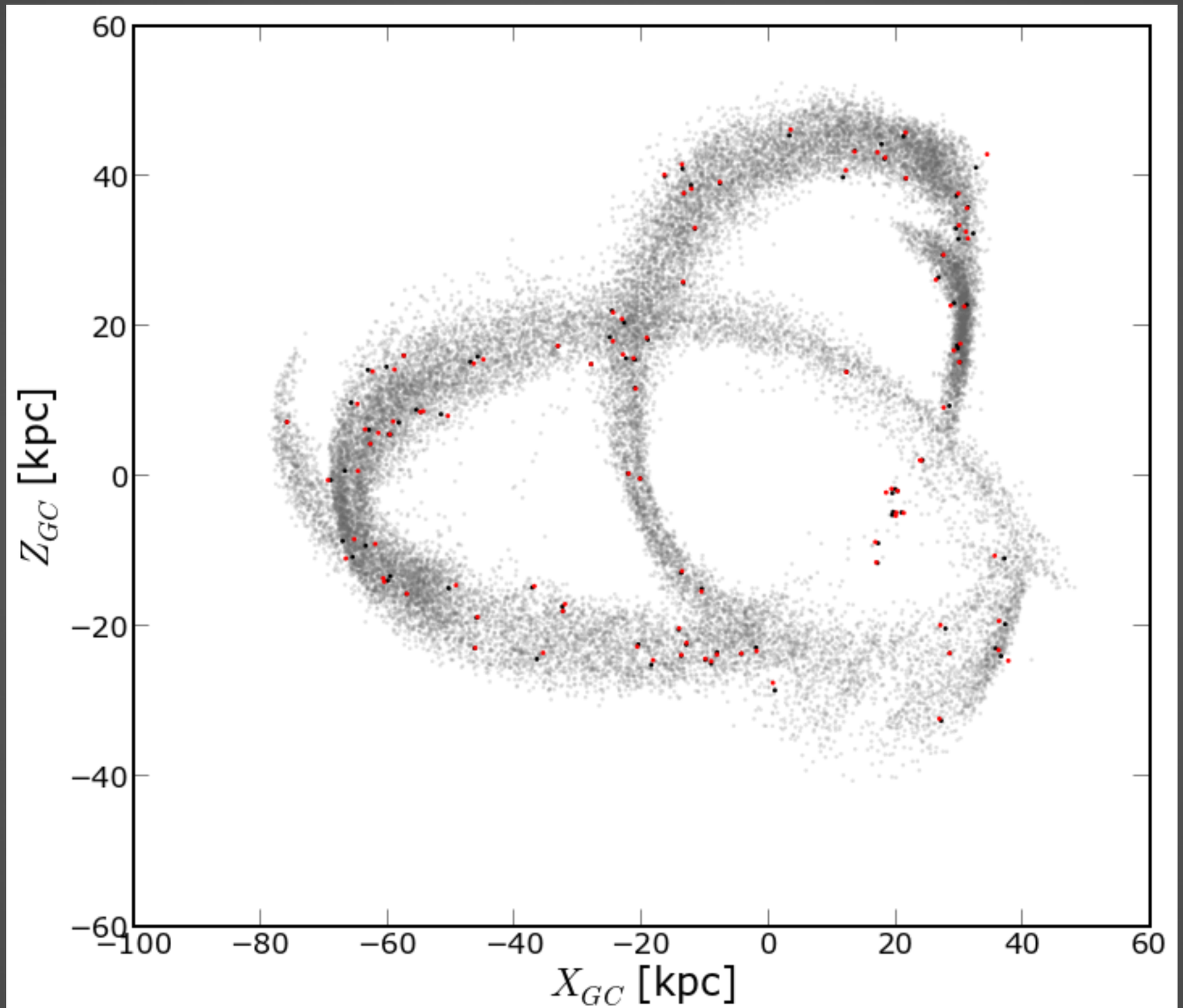
Inferred halo parameters for 100 bootstrapped realizations

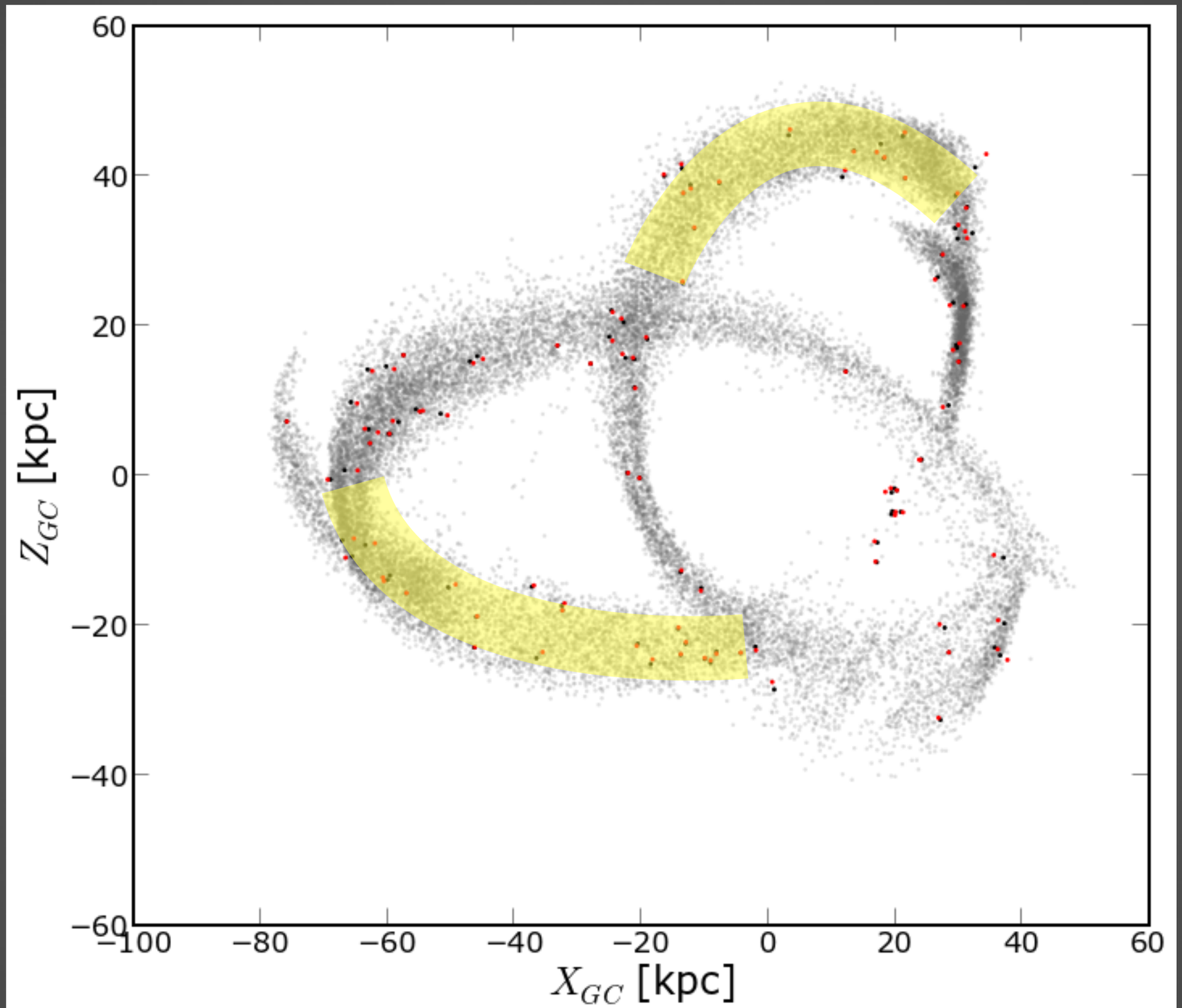
σ_{RV}=15 km/s; σ_D =2%D; 100 particles



Spitzer proposal

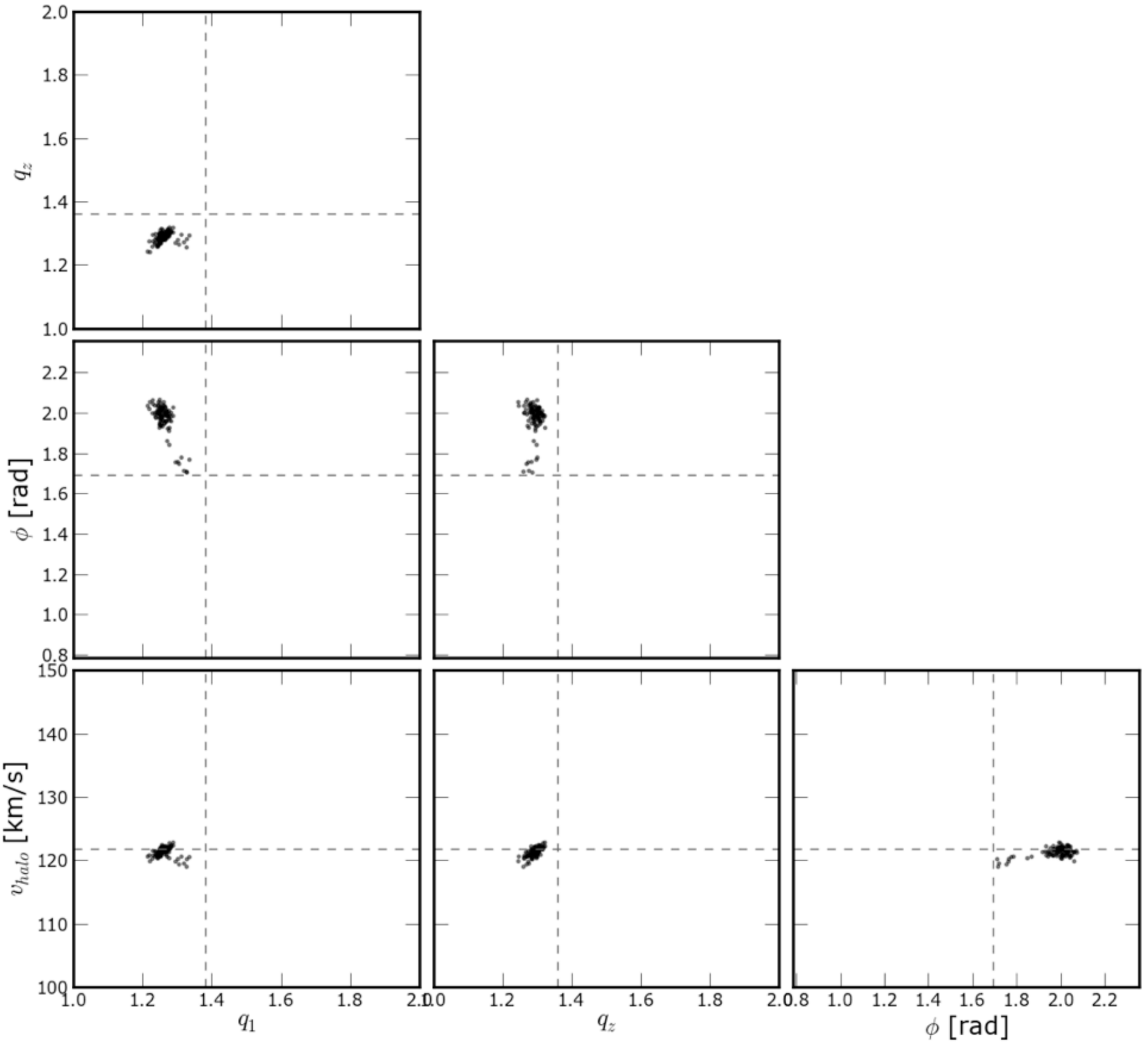
The Future

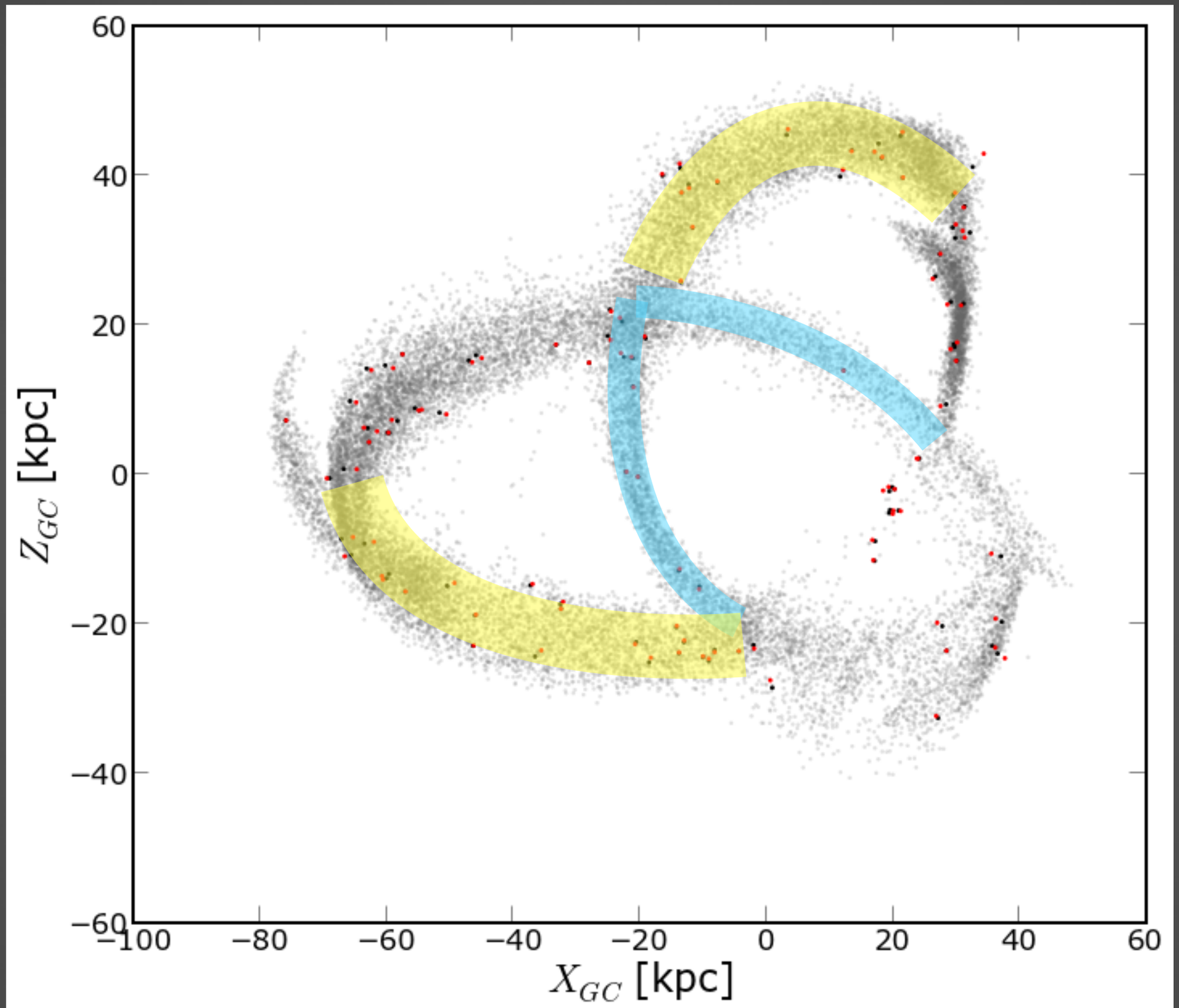

60
40
20
0
−20
−40
−60
−100
−80
−60
−40
−20
0
20
40
60
Z_{GC} [kpc]
X_{GC} [kpc]


60
40
20
0
−20
−40
−60
−100
−80
−60
−40
−20
0
20
40
60
Z_{GC} [kpc]
X_{GC} [kpc]

Inferred halo parameters for 100 bootstrapped realizations

σ_{RV}=15 km/s; σ_D =2%D; 100 known RR Lyrae




60
40
20
0
−20
−40
−60
−100
−80
−60
−40
−20
0
20
40
60
Z_{GC} [kpc]
X_{GC} [kpc]

Inferred halo parameters for 100 bootstrapped realizations

σ_{RV}=15.0km/s km/s; σ_D =2.0%D; 150 particles