Rewinding streams

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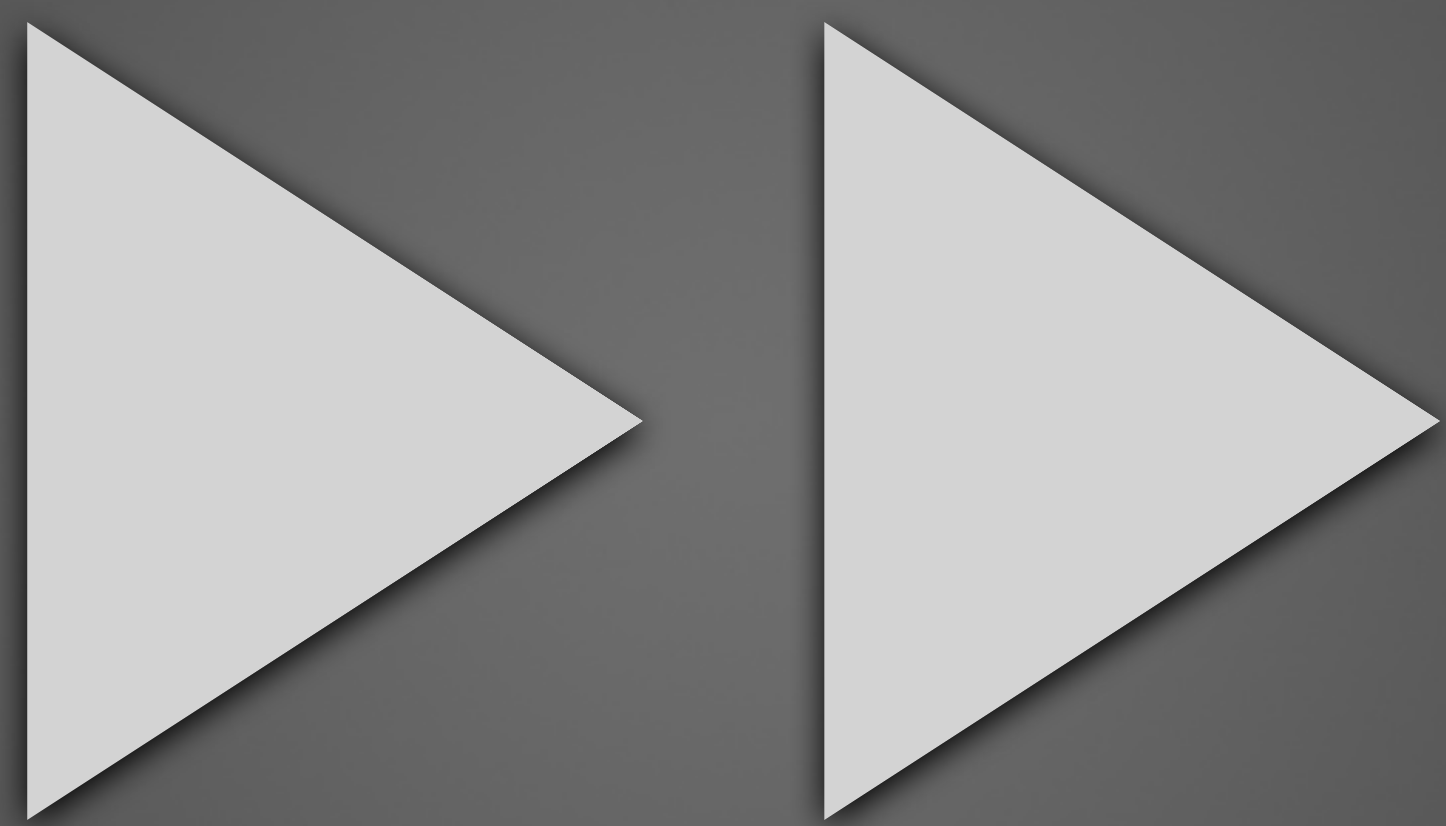
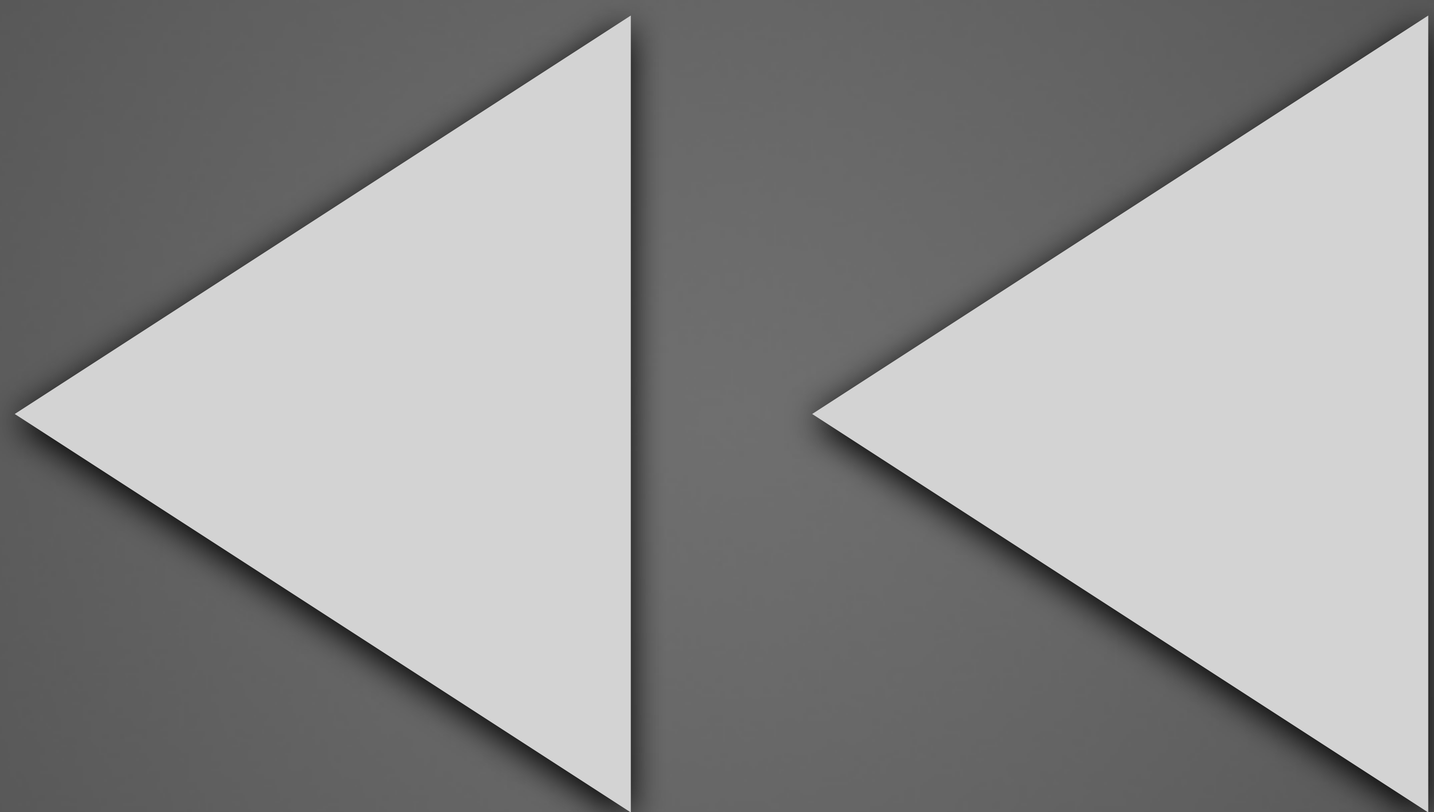
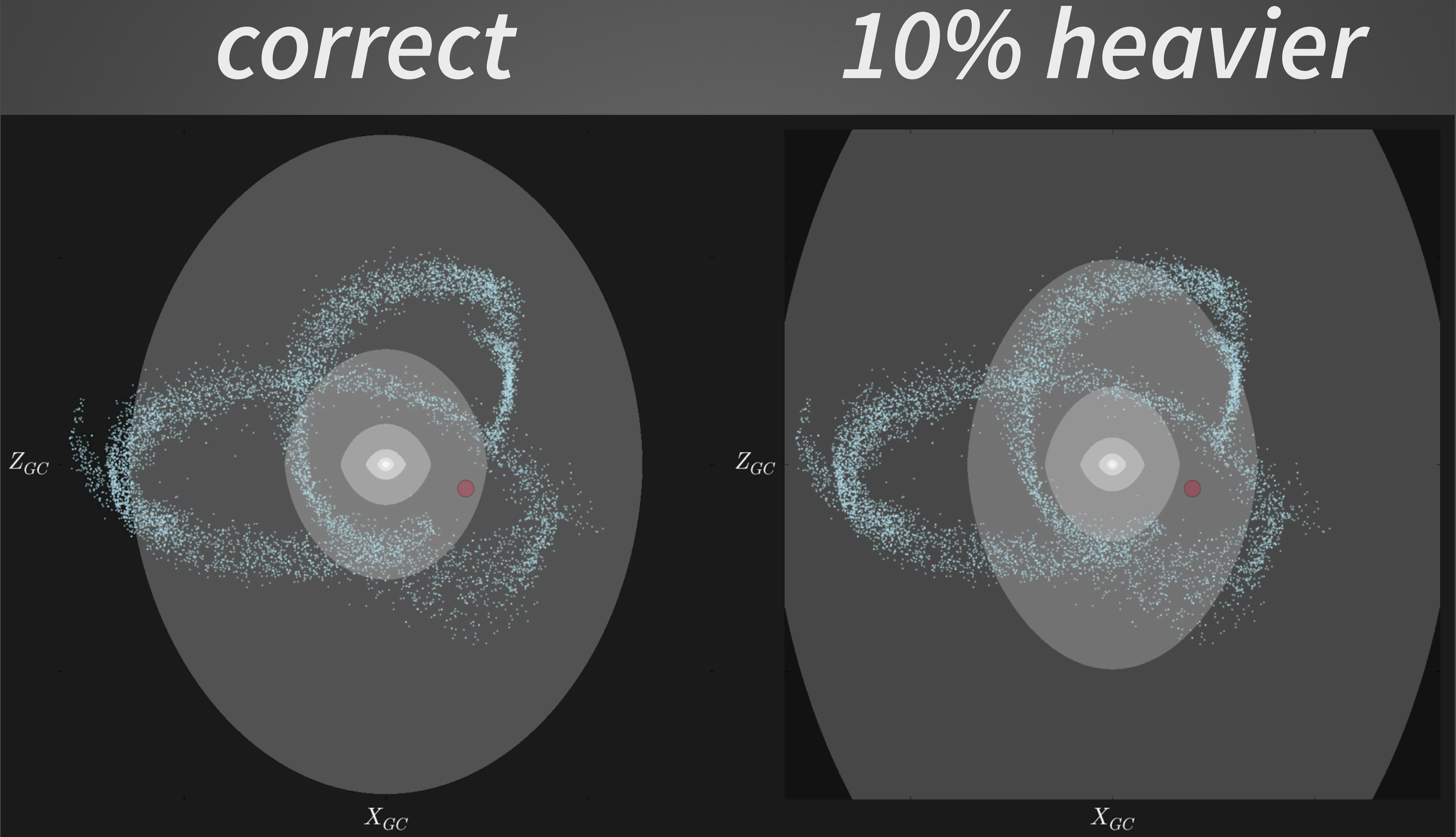
arXiv:1308.2670

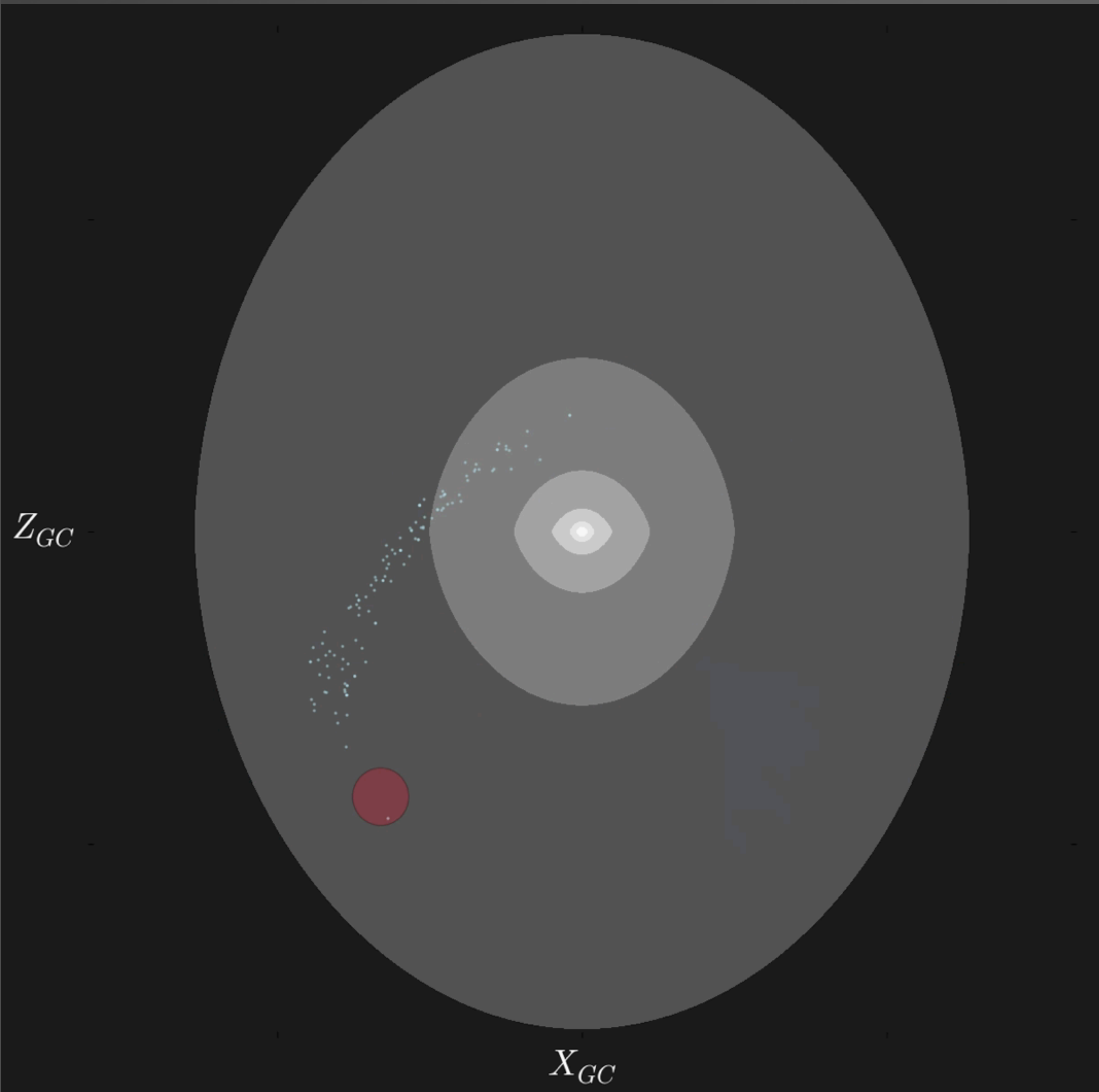
adrn/streams

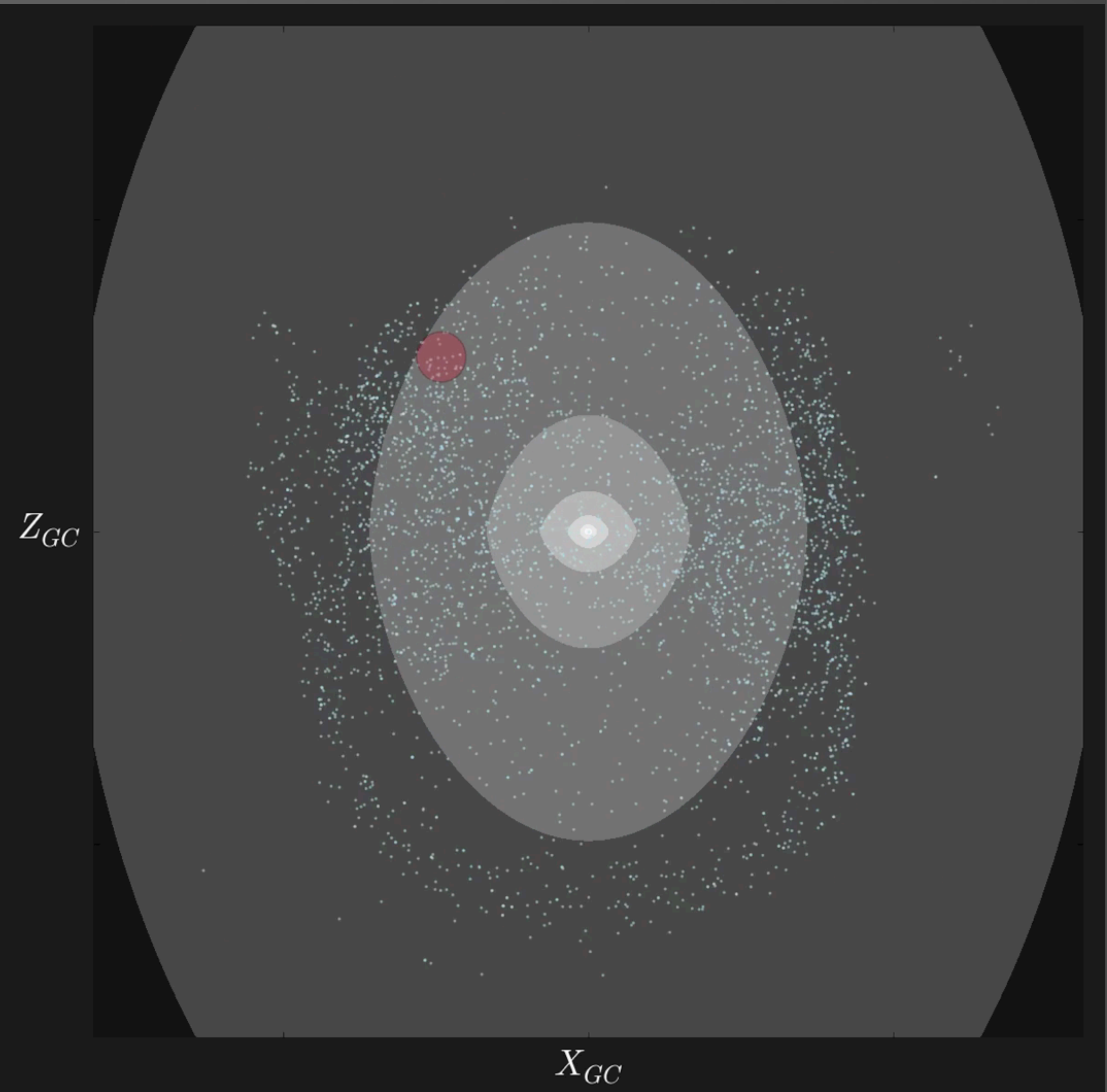


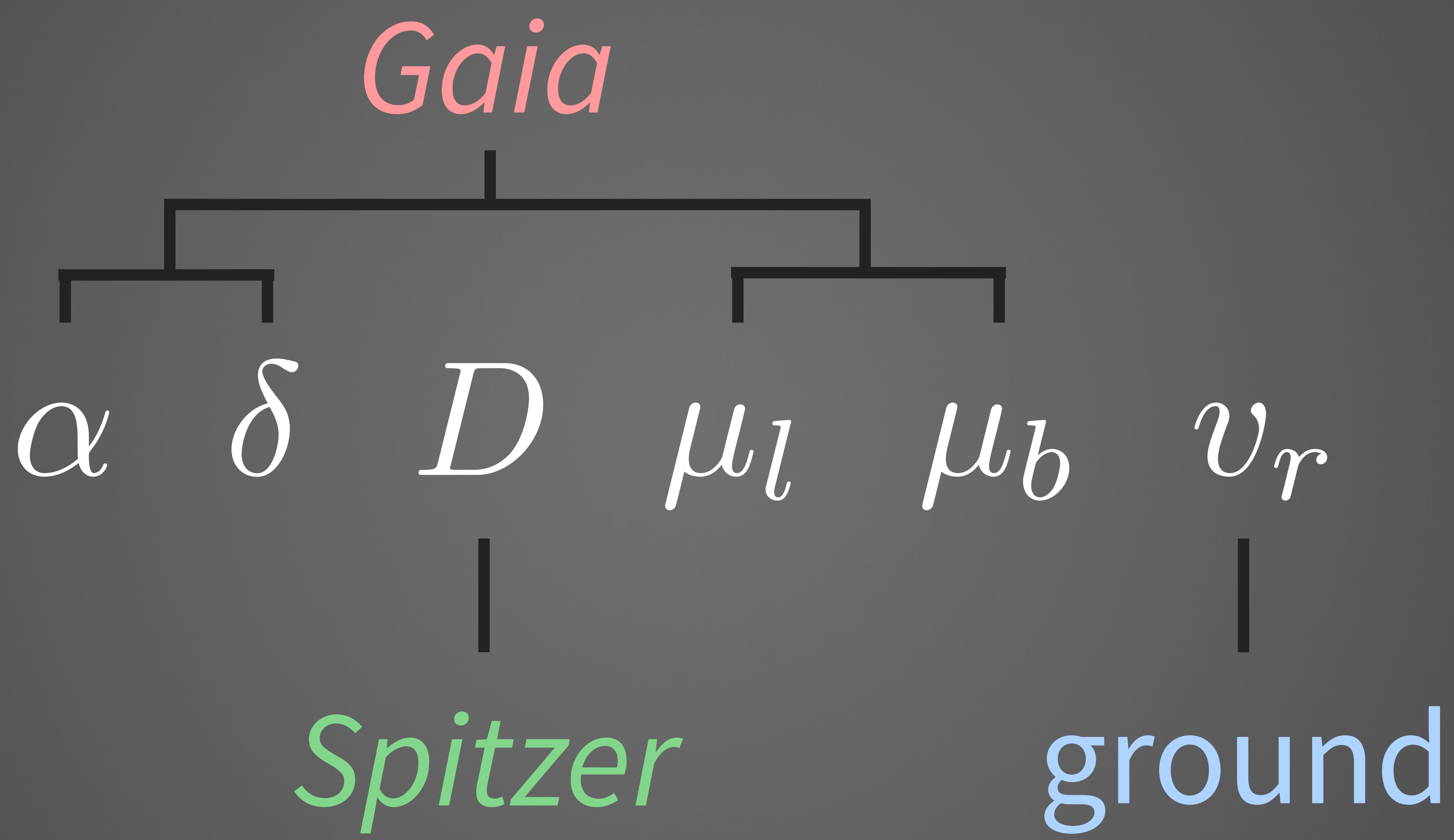



correct
Z_{GC}
X_{GC}
10% heavier
Z_{GC}
X_{GC}

correct   *10% heavier*



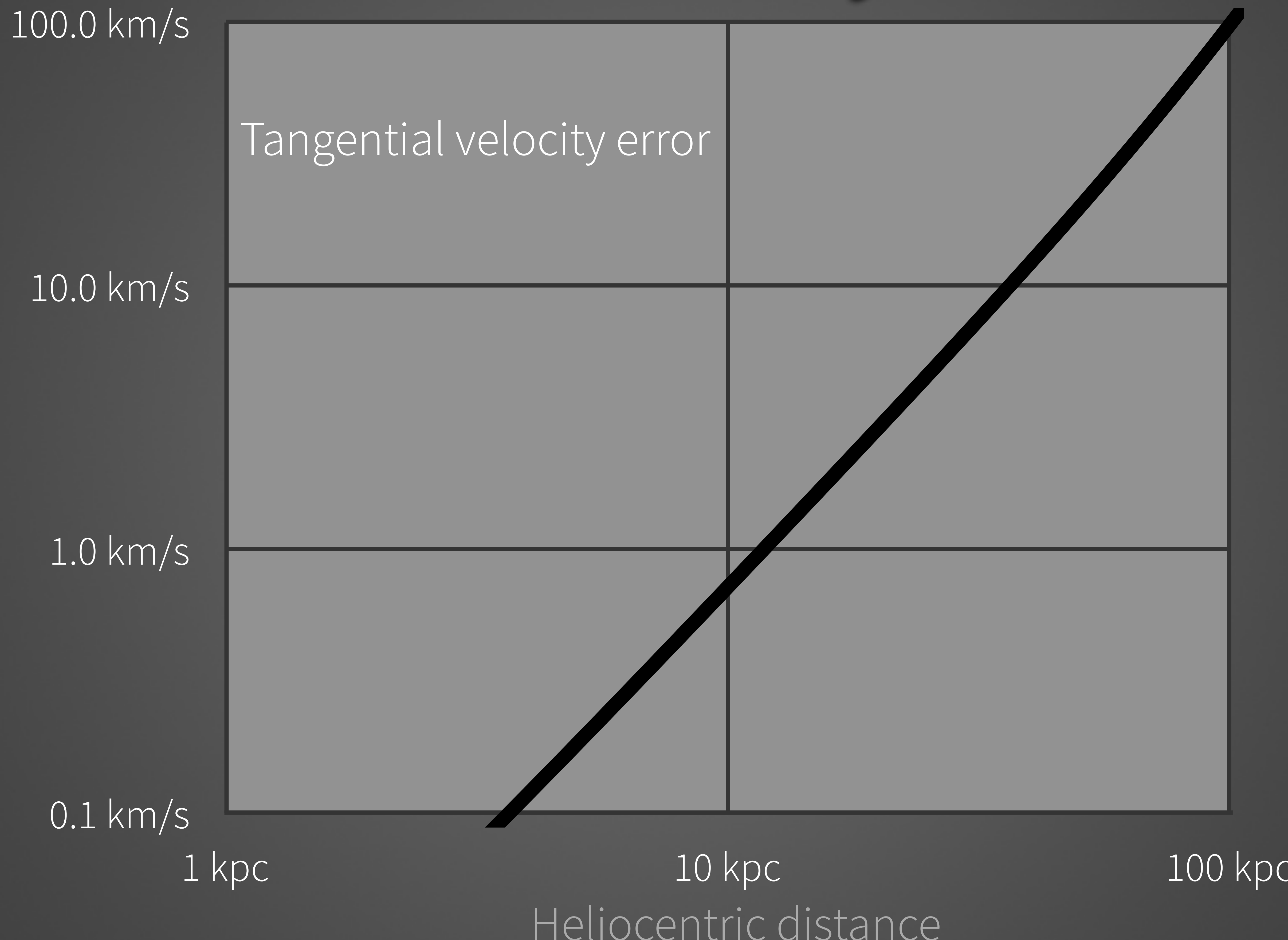



Gaia
α
δ
D
μ_l
μ_b
v_r
Spitzer
ground

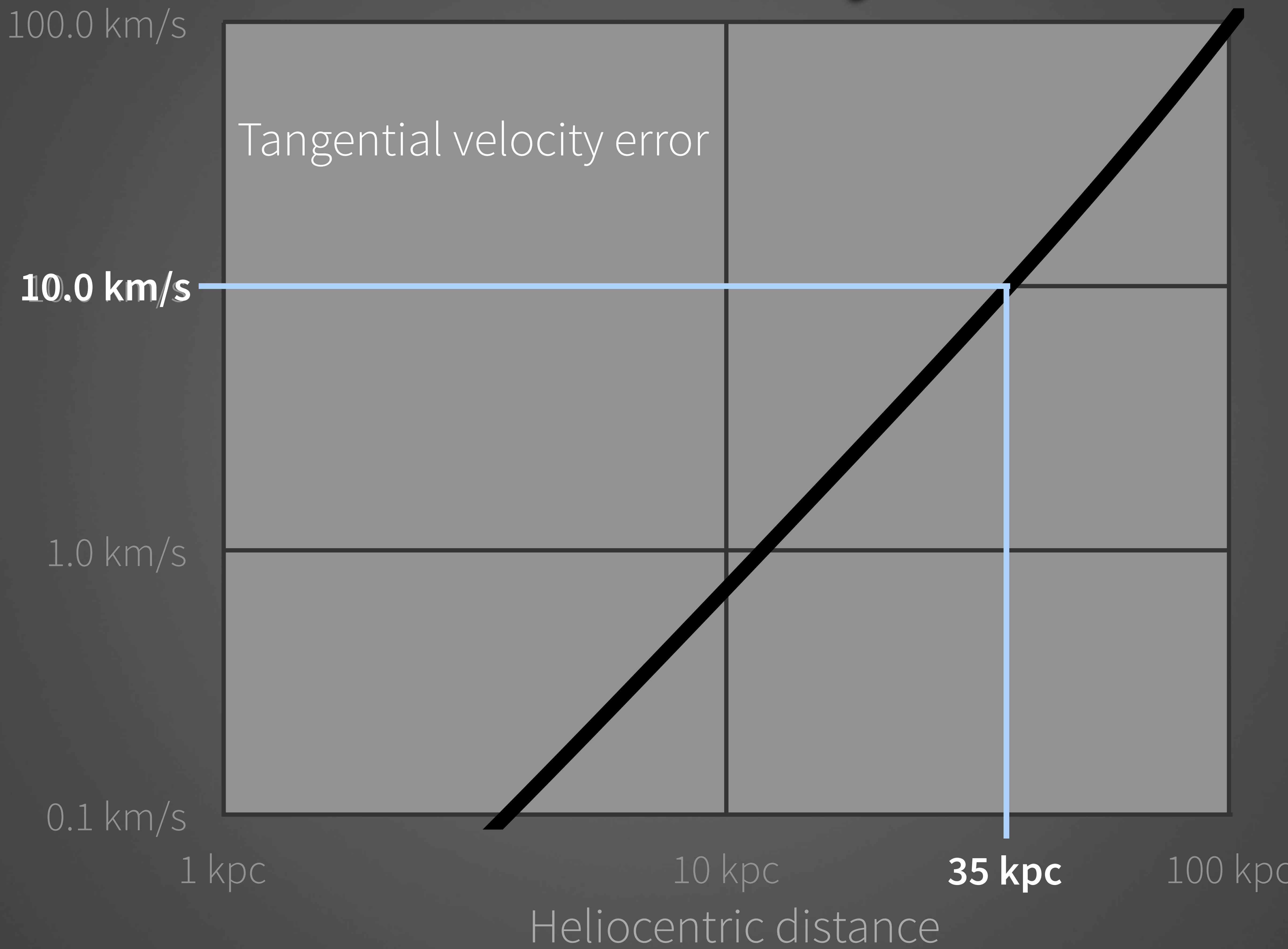
RR Lyrae

- Standard candles
- Bright: ~F/A type, $M_V \sim 0.5$
- Distinct, large-amplitude light curve
- Found in substructure (Sagittarius, Orphan, TriAnd...)
- PL relation in Mid-IR = 2% distance error

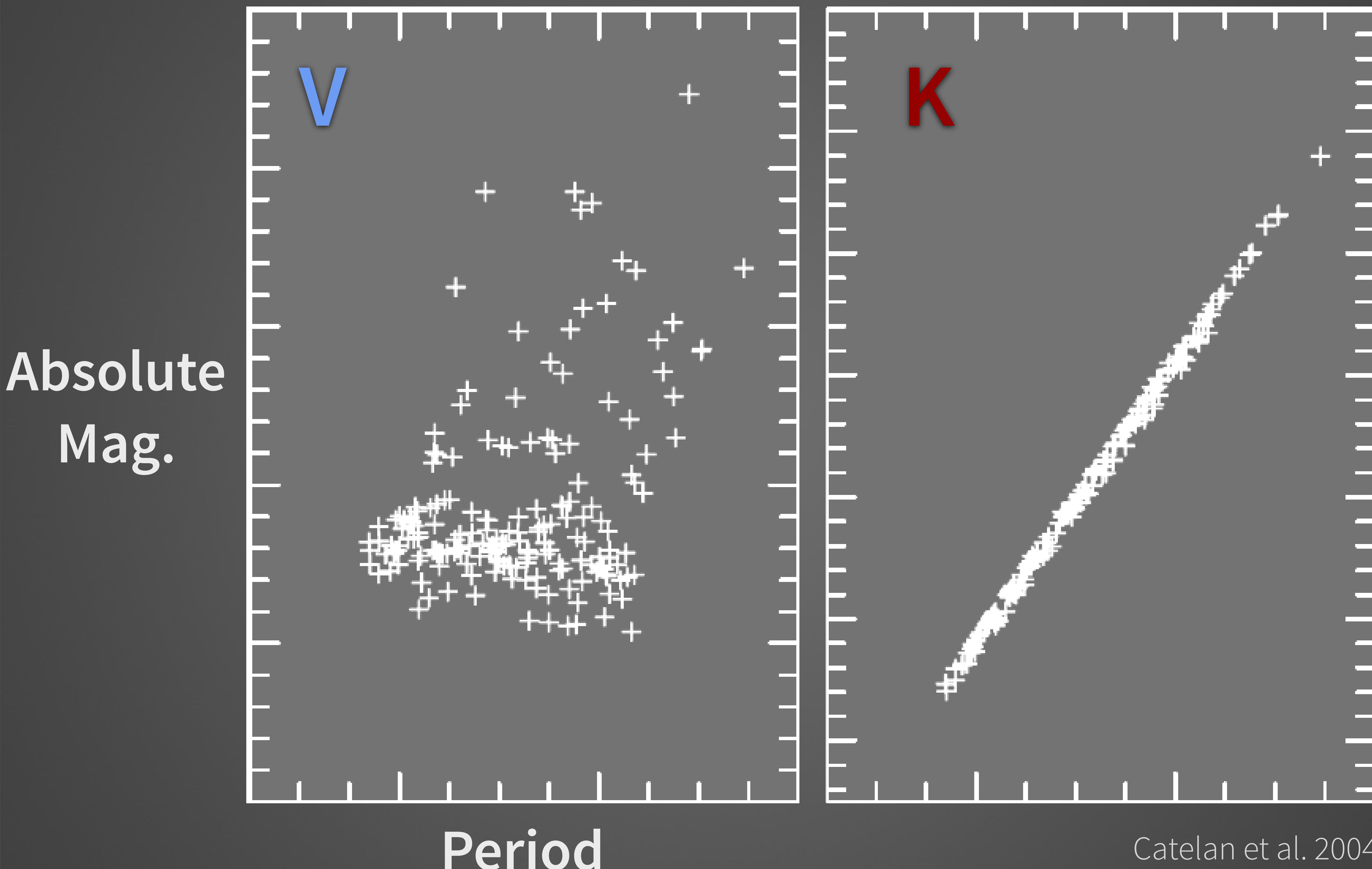
Gaia RR Lyrae



Gaia RR Lyrae



P-L relation for RR Lyrae



Catelan et al. 2004

Madore & Freedman 2012

Ground-based RV

- Correct for pulsation (~100 km/s)

- Take multiple spectra

- Match to ephemeris, e.g. velocity curve

Sesar (2012)

RR Lyrae at 35 kpc

Gaia — $\alpha \;\; \delta$ — $\epsilon \sim$ 80 µas

Gaia — $v_l \;\; v_b$ — $\epsilon \sim$ 10 km/s

Spitzer — $d_\odot$ — $\epsilon \sim$ 700 pc

ground — v_r — $\epsilon \sim$ 10 km/s

6D position
of star

satellite
shape

time star
is unbound

$$p(\vec{X}_0 \mid \vec{\theta}, \bar{\bar{\Sigma}}, \vec{\omega}_0, t^*)$$

potential
parameters

6D position
of satellite

$$p(\vec{X}_0 \mid \vec{\theta}, \bar{\bar{\bar{\Sigma}}}, \vec{\omega}_0, t^*) = \mathcal{N}(\underbrace{\vec{X}}_{\text{full orbit of star}} \mid \underbrace{\vec{\omega}}_{\text{orbit of progenitor}}, \bar{\bar{\bar{\Sigma}}})\Big|_{t^*}$$

Can get orbit of stars & satellite by integrating backwards:

$$\vec{X}_0, \Phi(\theta) \rightarrow \vec{X}(t)$$
$$\vec{\omega}_0, \Phi(\theta) \rightarrow \vec{\omega}(t)$$

Treat stars, satellite as test particles

As an initial test, we assume:

1) we know $\vec{\omega}_0$ *exactly*

2) $t^* = \arg\min_t ||\vec{X}(t) - \vec{\omega}(t)||$

3) satellite is a spherical 6D Gaussian:

$$\bar{\bar{\Sigma}} = \begin{pmatrix} r_{\rm tide}^2 & & & & & \\ & r_{\rm tide}^2 & & & & \\ & & r_{\rm tide}^2 & & & \\ & & & \sigma_v^2 & & \\ & & & & \sigma_v^2 & \\ & & & & & \sigma_v^2 \end{pmatrix}$$

$$r_{\rm tide} = r_{\rm tide}(t = t^*)$$

$$p(\vec{X}_0 \mid \vec{\theta}, \overbrace{\bar{\bar{\Sigma}}, \vec{\omega}_0, t^*}^{\text{assumptions}}) \longrightarrow p(\vec{X}_0 \mid \vec{\theta})$$

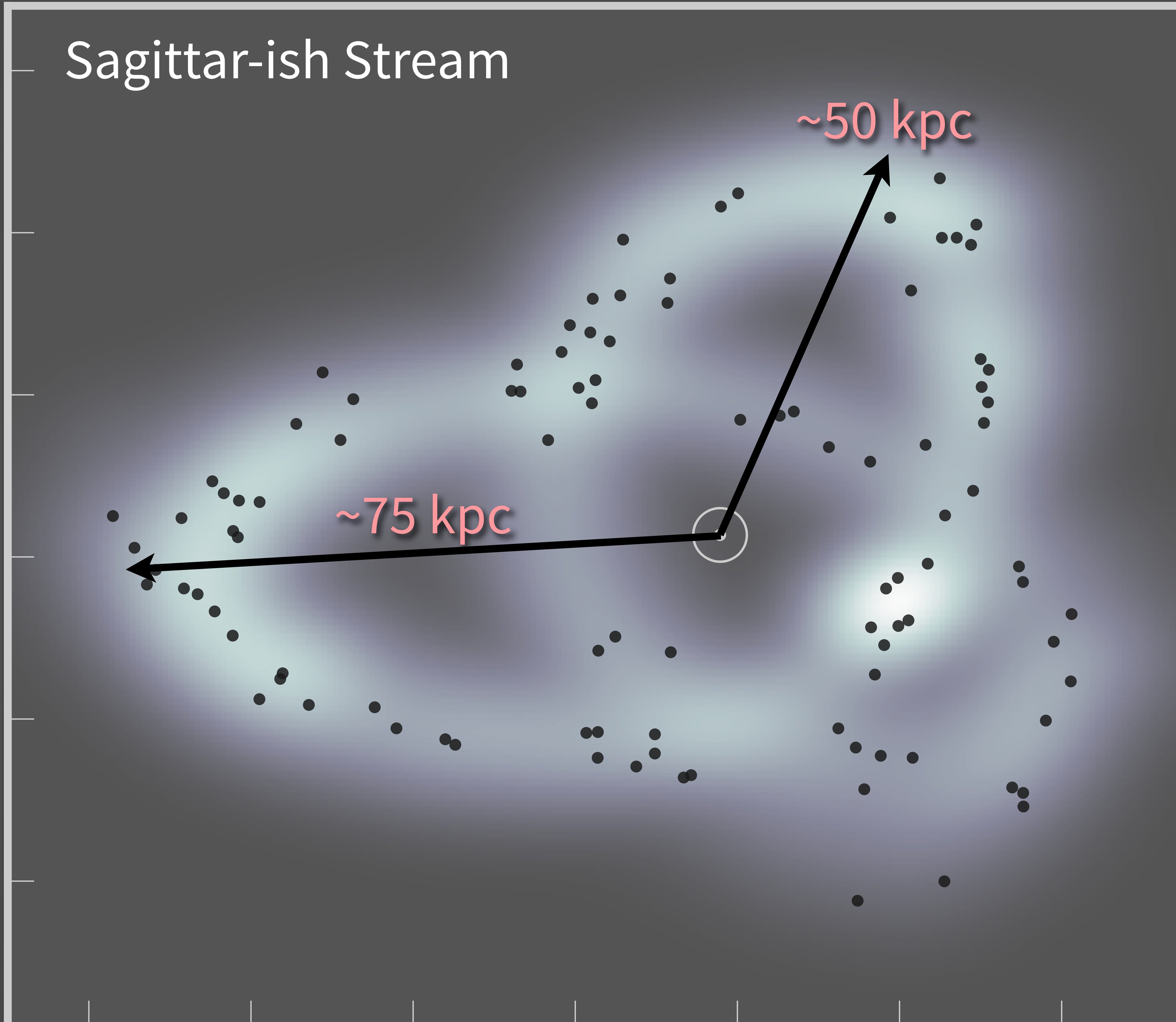
Assumes N-body effects are small

$$p(\vec{X}_0^0, \vec{X}_0^1, \ldots \vec{X}_0^m \mid \vec{\theta}) = \prod_j^m p(\vec{X}_0^j \mid \vec{\theta})$$

$$\boxed{p(\vec{\theta} \mid \vec{X}_0)} \propto p(\vec{X}_0 \mid \vec{\theta})p(\vec{\theta})$$

emcee

The MCMC Hammer

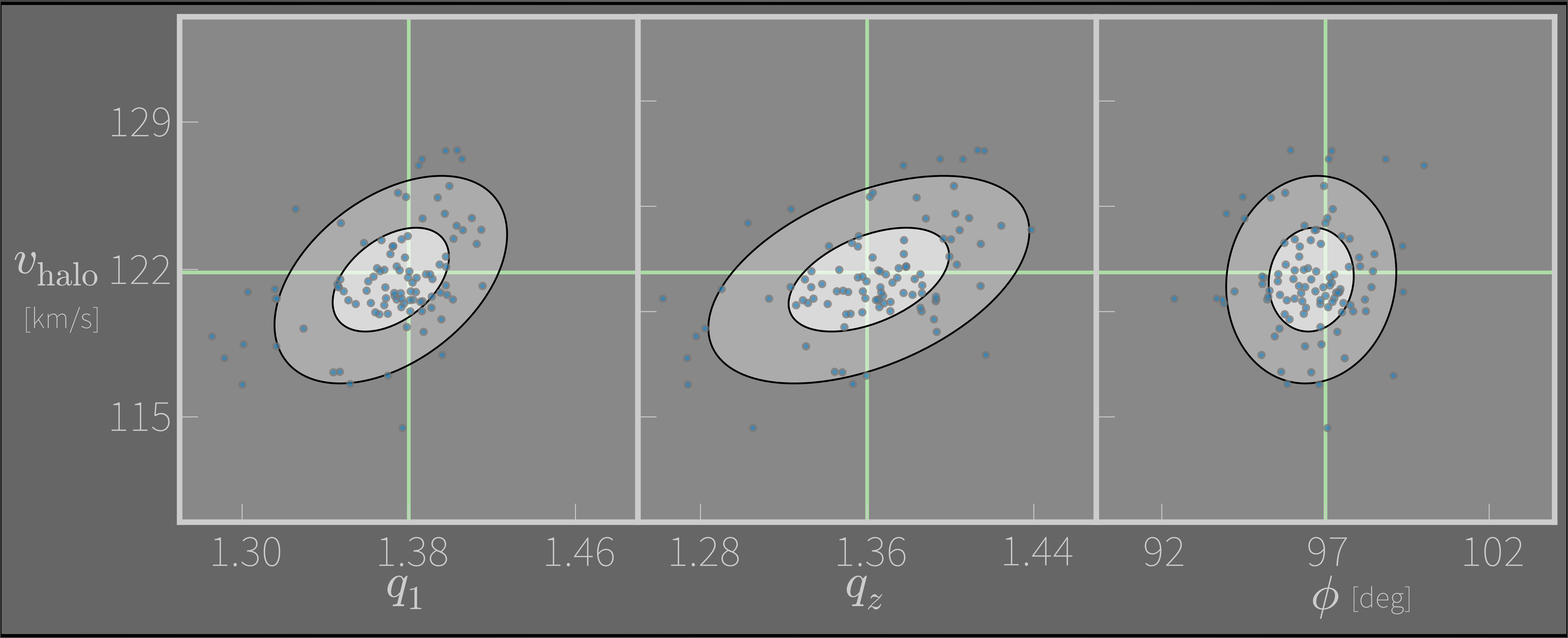


Law & Majewski (2010)

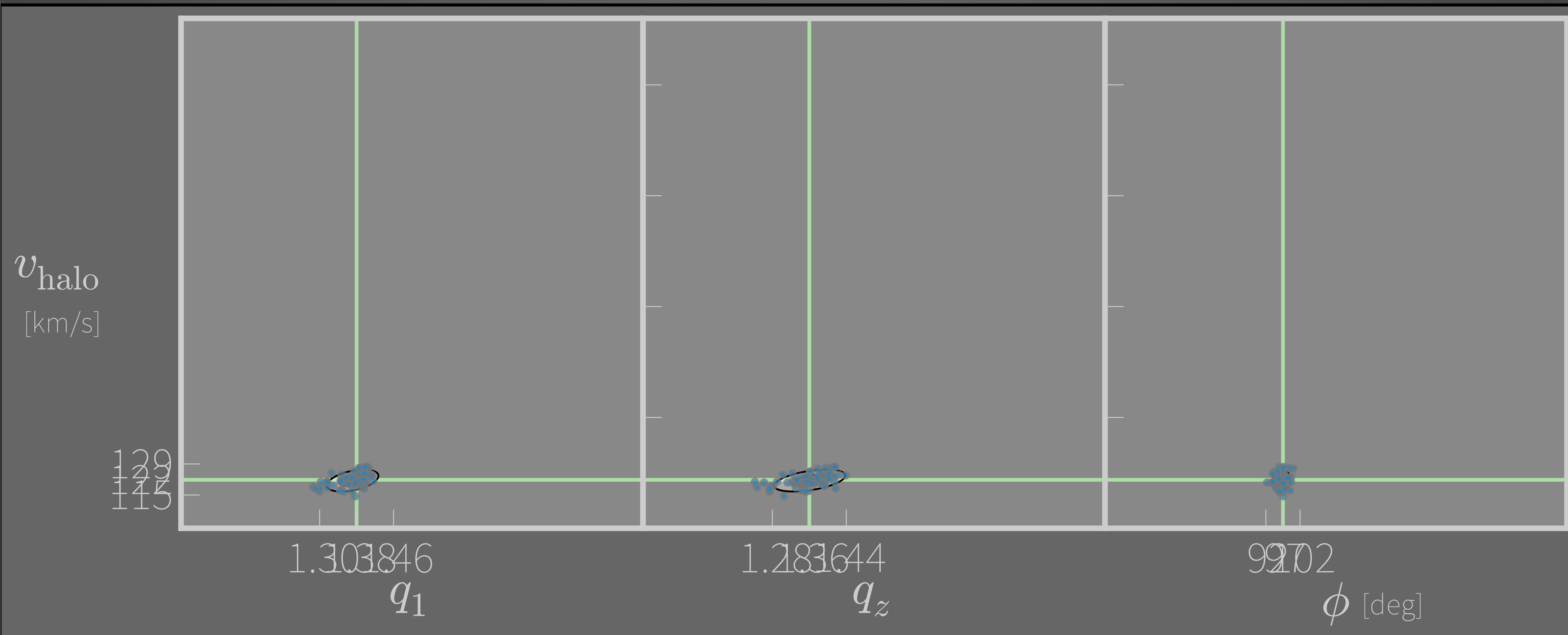
$$\theta_{MAP} = \arg\max_{\theta} p(\theta \mid \{\vec{X}_0\}_m)$$

Find Maximum A Posteriori parameters for many samples

Applied to simulated observations of Law & Majewski 2010



Applied to simulated observations of Law & Majewski 2010



$$q_1 = 1.37 \pm 0.03$$

$$q_z = 1.36 \pm 0.04$$

$$\phi = 96.6 \pm 1.3^\circ$$

$$v_{halo} = 121.5 \pm 2.5 \text{ km/s}$$

streams

↓

debris

Next:

- properly marginalize over unbinding time
- missing data (stars and progenitor)
- inference without a progenitor
- multiple streams
- contamination

Er...the right way

$$p(\vec{X}_0 \mid \vec{\theta}) =$$

$$\int d\vec{\omega}_0 p(\vec{\omega}_0) d\bar{\bar{\bar{\Sigma}}} p(\bar{\bar{\bar{\Sigma}}}) dt^* p(t^*) p(\vec{X}_0 \mid \vec{\theta}, \bar{\bar{\bar{\Sigma}}}, \vec{\omega}_0, t^*)$$

$$\approx \frac{1}{n} \sum_i^n p(\vec{X}_0 \mid \vec{\theta}, t_i^*)$$

$$\ln \mathcal{L} \propto \underbrace{\sum_j^m \ln \sum_i^n}_{\text{ouch}} p(\vec{X}_0^j \mid \vec{\theta}, t_i^*)$$