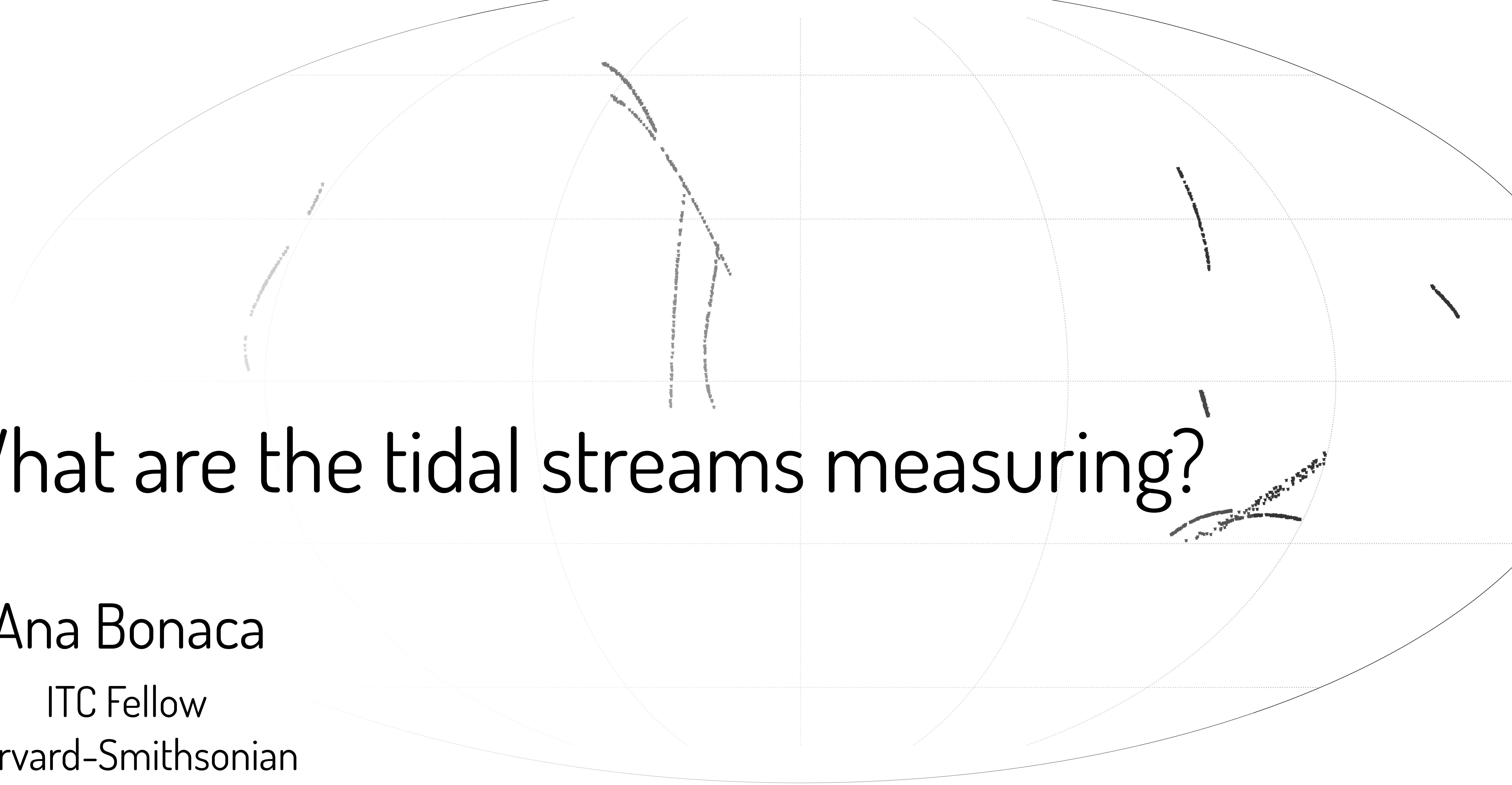


What are the tidal streams measuring?

Ana Bonaca

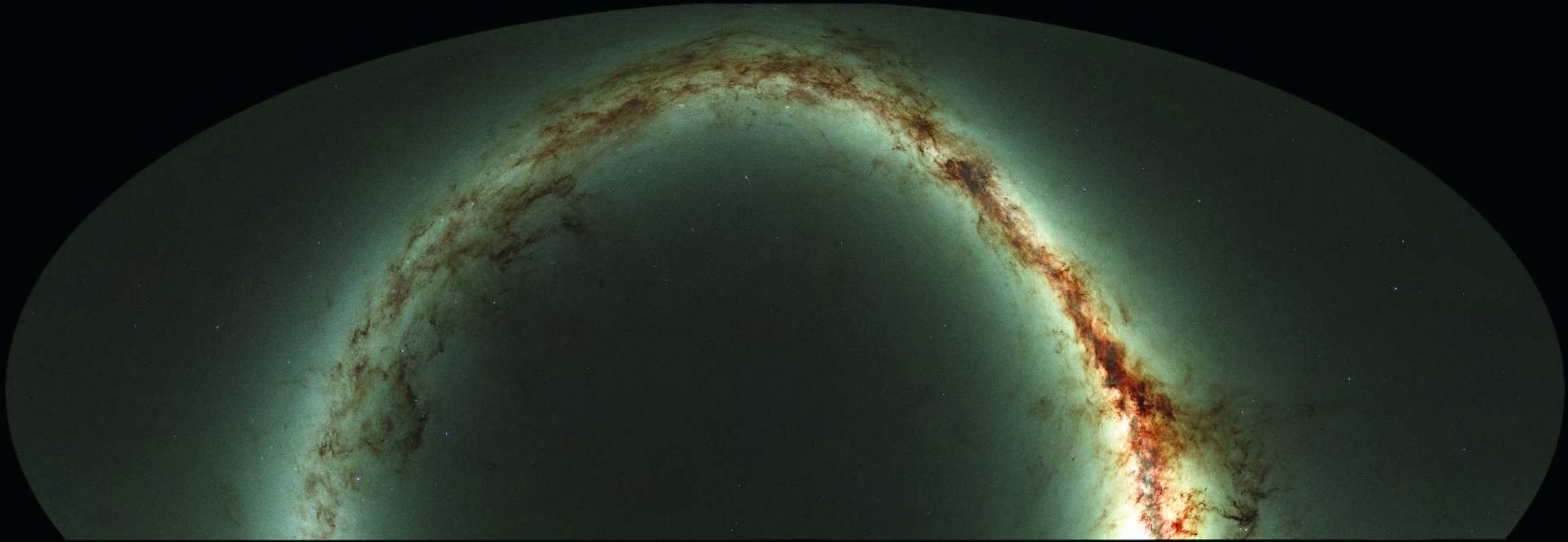
ITC Fellow

Harvard-Smithsonian

Center for Astrophysics

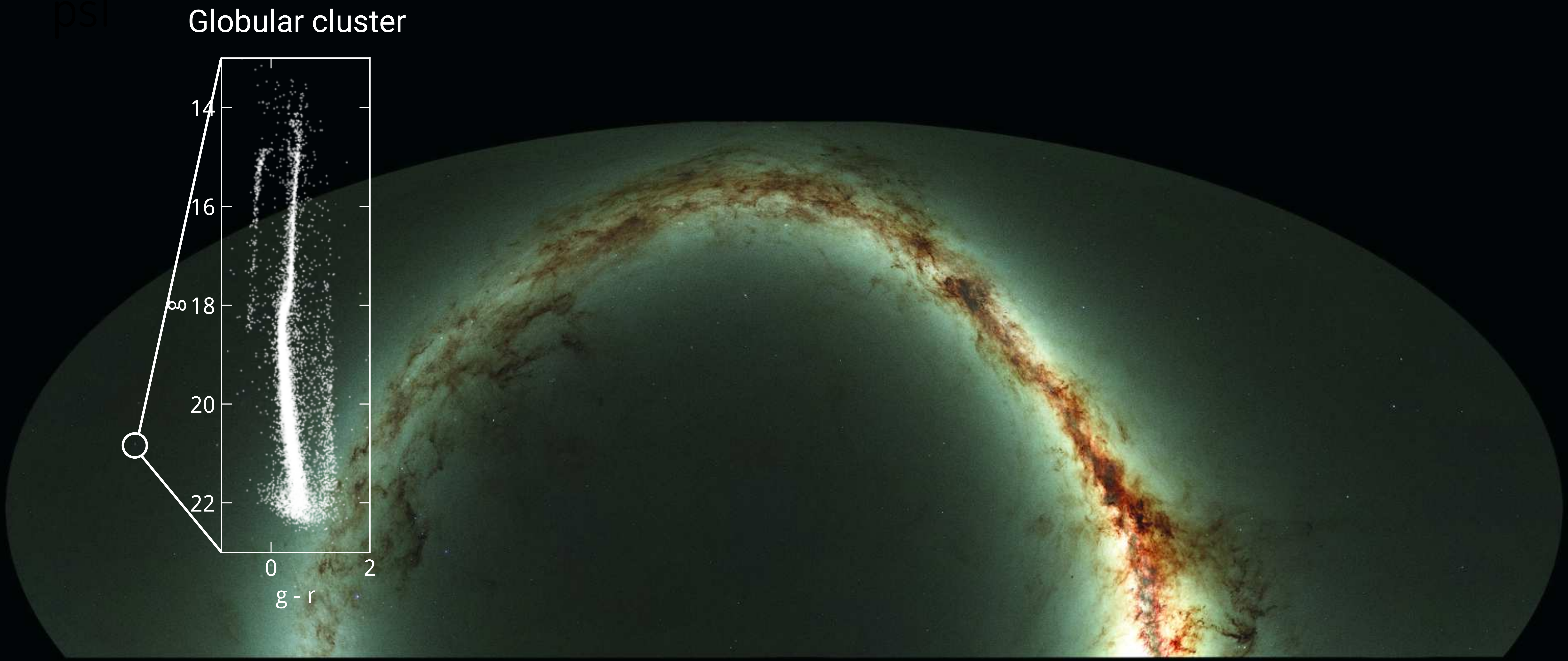
illustris

psl

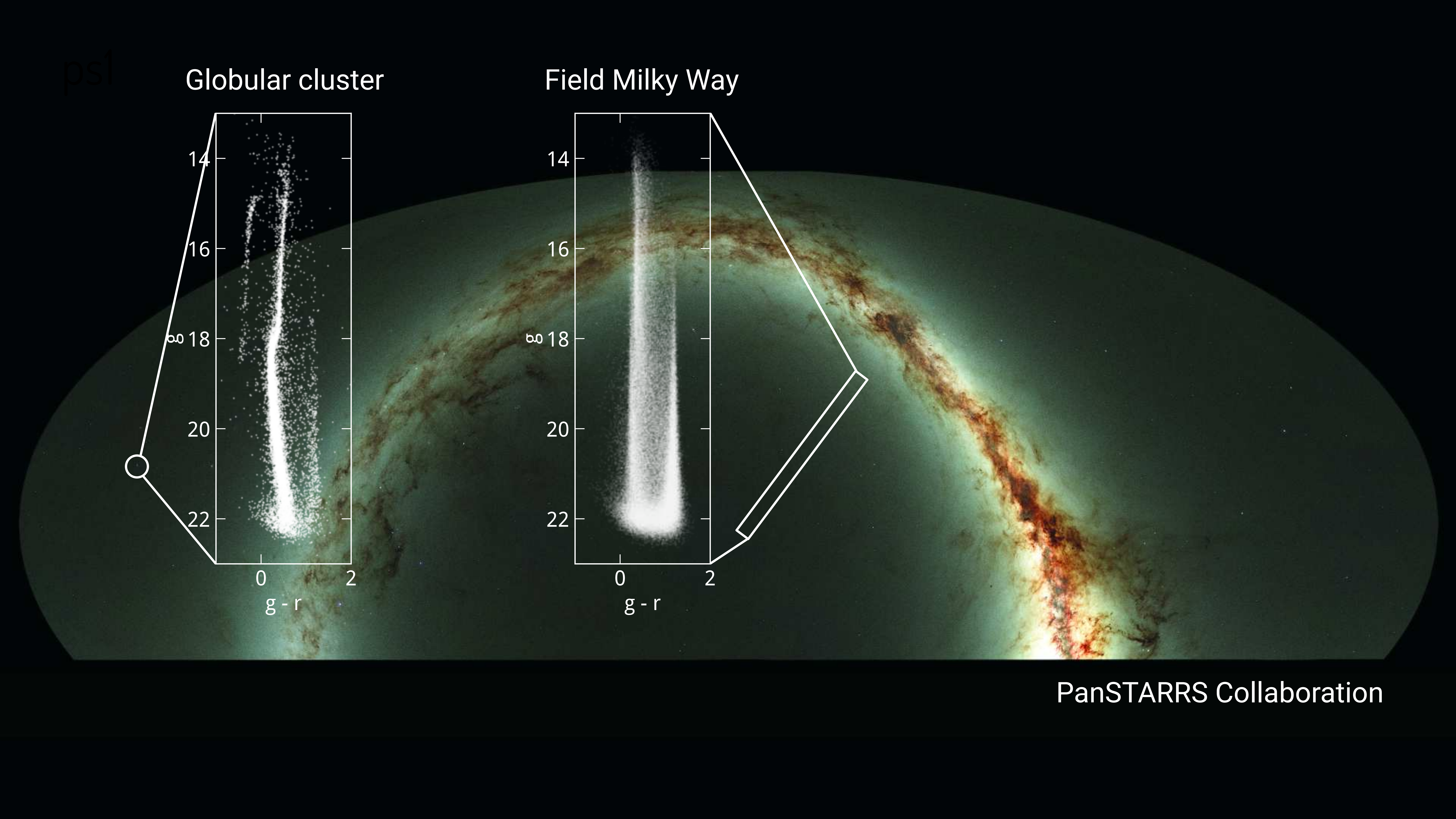


PanSTARRS Collaboration

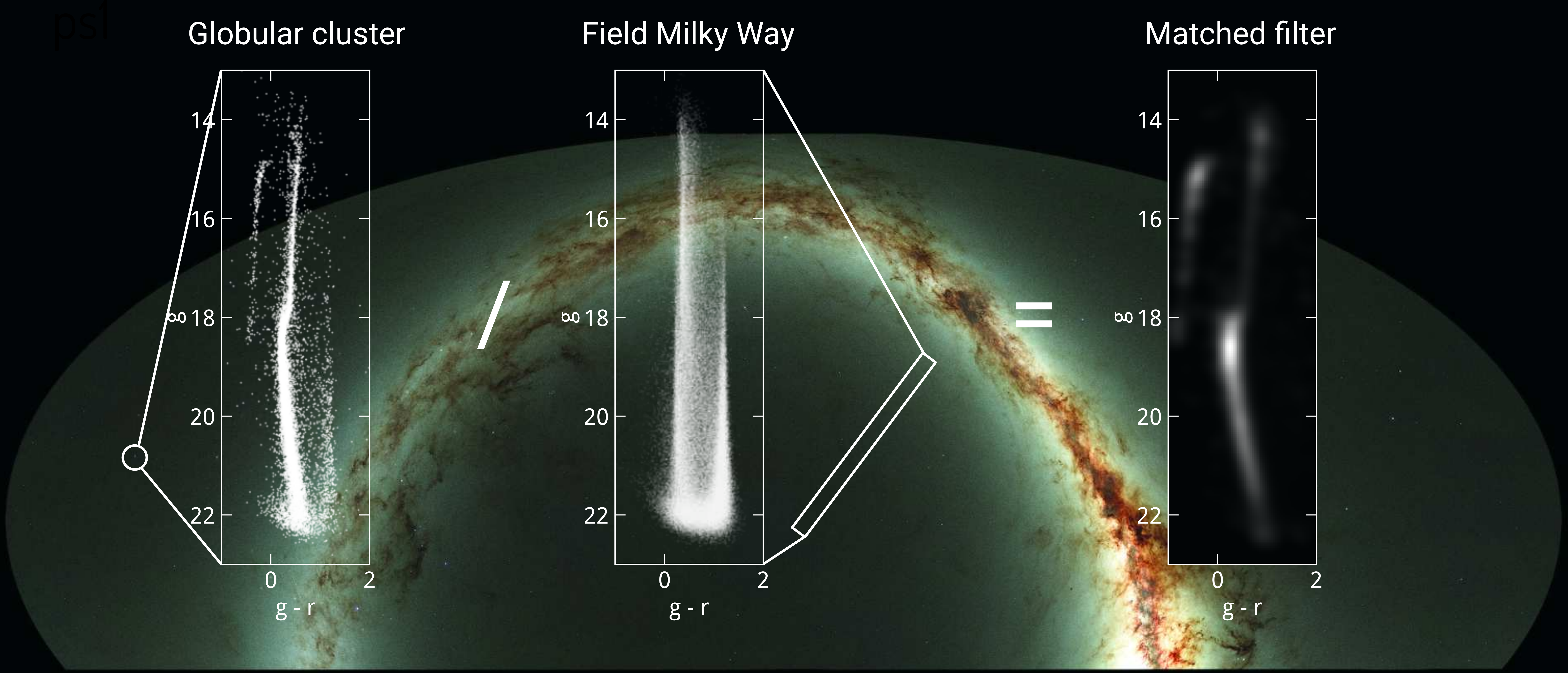
psl



PanSTARRS Collaboration



psl
Globular cluster
Field Milky Way
14
16
g 18
20
22
0
2
g - r
PanSTARRS Collaboration



PanSTARRS Collaboration

Galactic stellar halo is rich with substructure

based on Bernard et al. (2015)

Stellar streams are a direct evidence
of hierarchical formation
of galaxies,

but can they tell us more
about their host galaxy?

Tidal streams are expected to probe the Galactic potential

TIDAL STREAMS AS PROBES OF THE GALACTIC POTENTIAL

KATHRYN V. JOHNSTON,[1] HONGSHENG ZHAO,[2] DAVID N. SPERGEL,[3] AND LARS HERNQUIST[4]

Received 1998 July 22; accepted 1998 December 17; published 1999 January 14

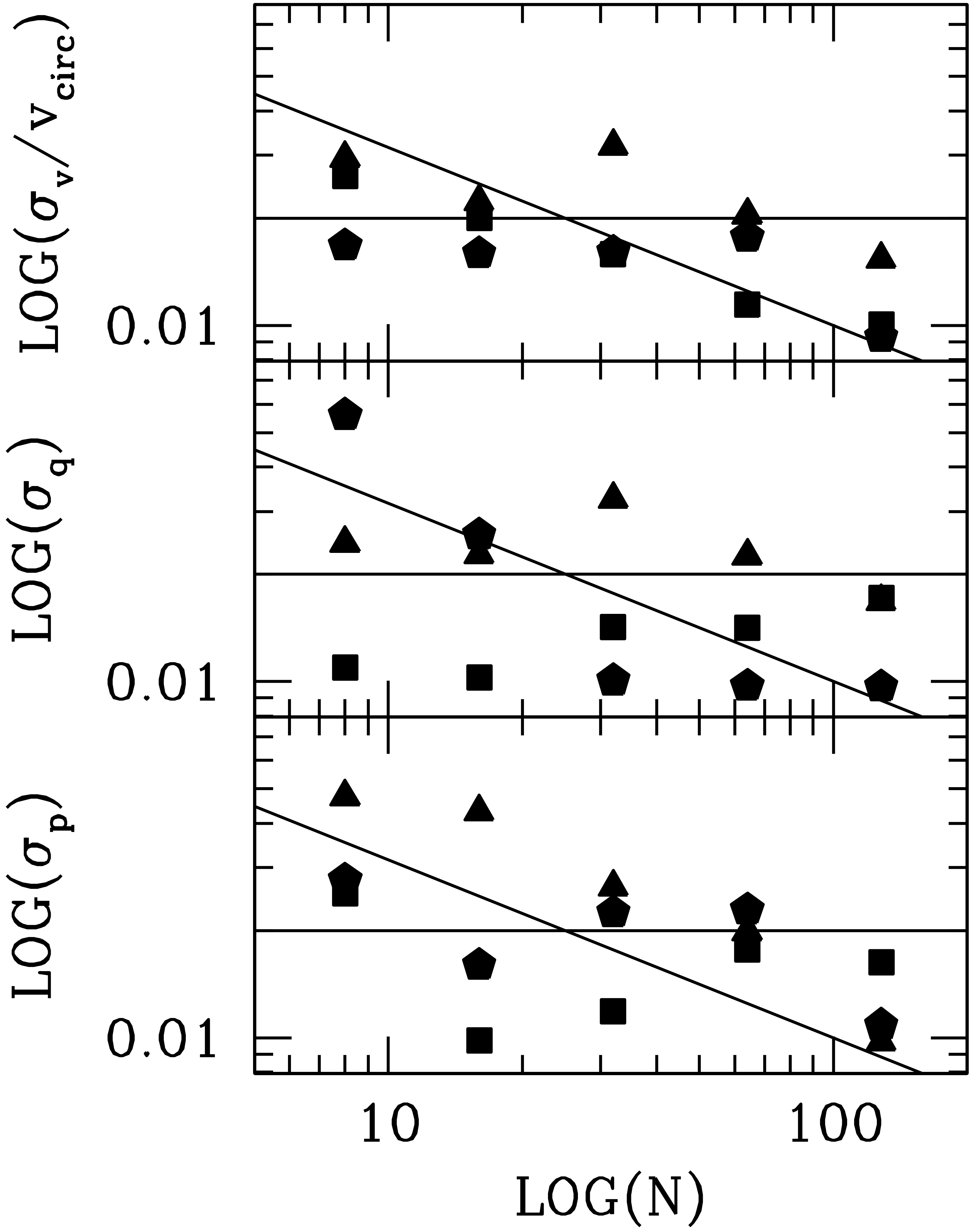
ABSTRACT

We explore the use of tidal streams from Galactic satellites for recovering the potential of the Milky Way. Our study is motivated both by the discovery of the first lengthy *stellar* stream in the halo (Irwin & Totten) and

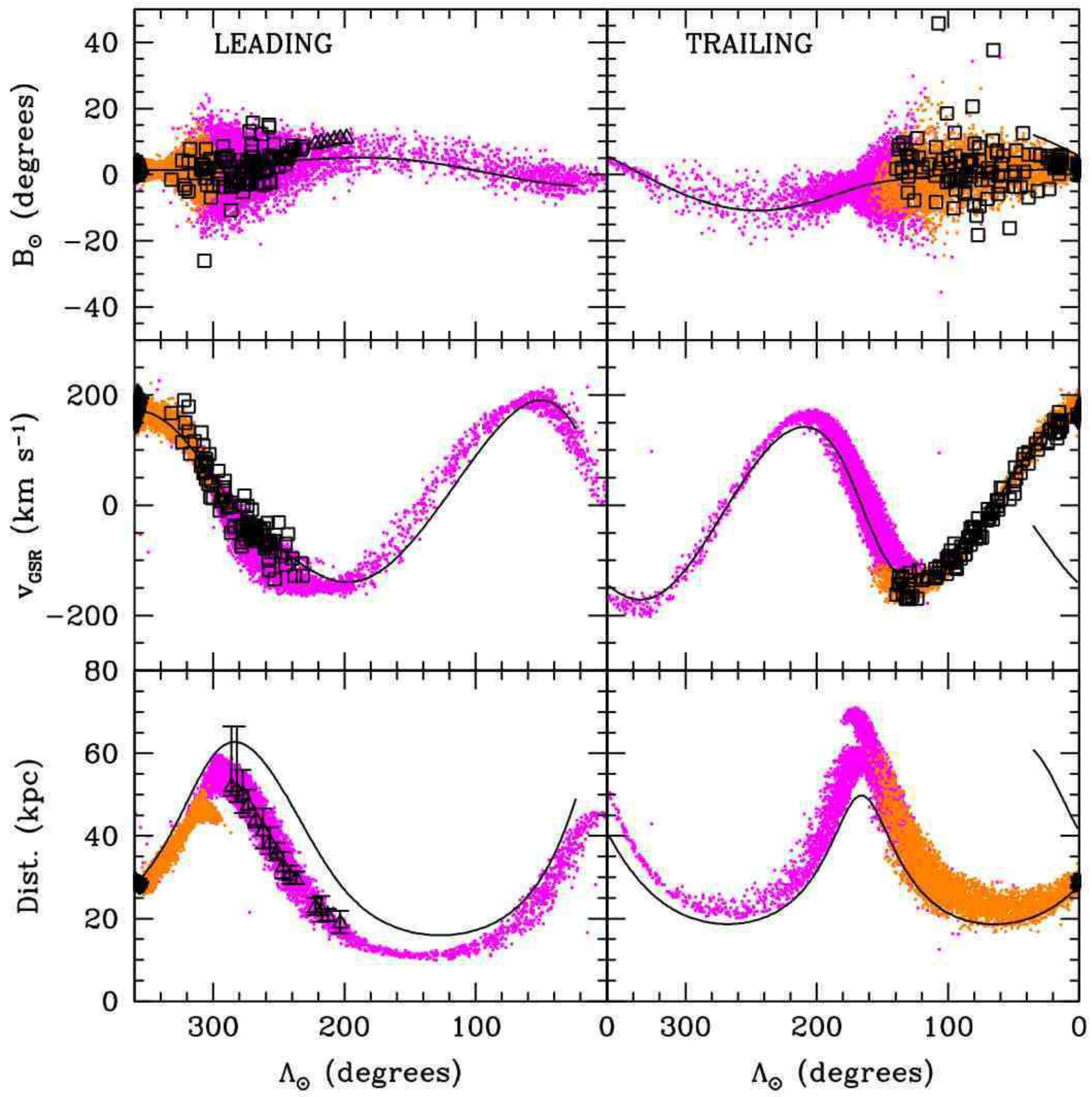
$$\Phi = \frac{V_{circ}^2}{2} \ln\left(x^2 + \frac{y^2}{p^2} + \frac{z^2}{q^2} + c^2\right)$$

4. CONCLUSION: YOU CAN JUDGE A GALAXY BY ITS TAIL

In this Letter, we have explored the use of *SIM* measurements of stars in tidal streams as a probe of the Galactic potential. We find that with five-dimensional phase-space information for only 100 stars, we can determine the circular velocity and shape of the Galactic halo with accuracies of a few percent. This



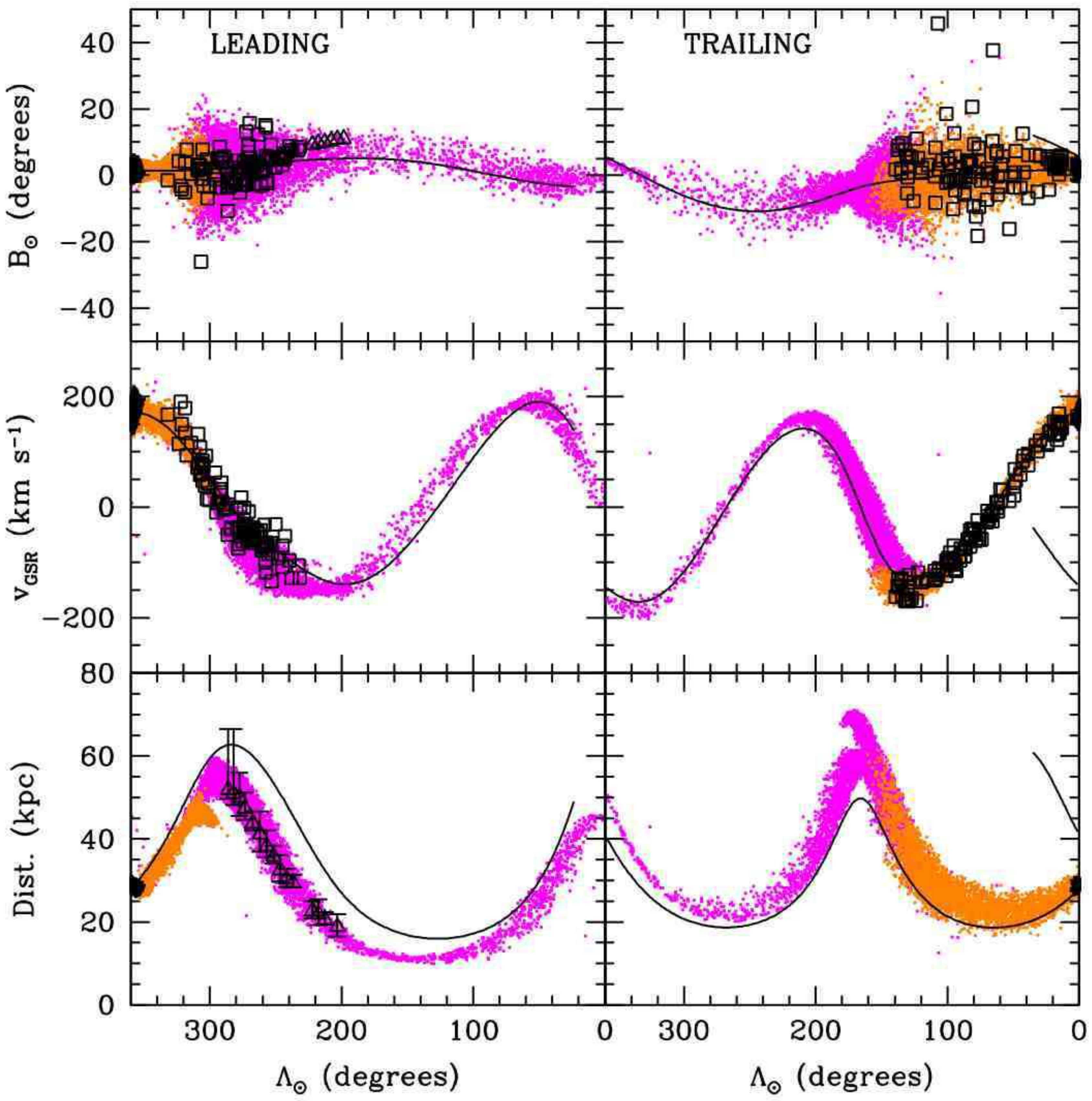
Streams disagree on the shape of the dark matter halo



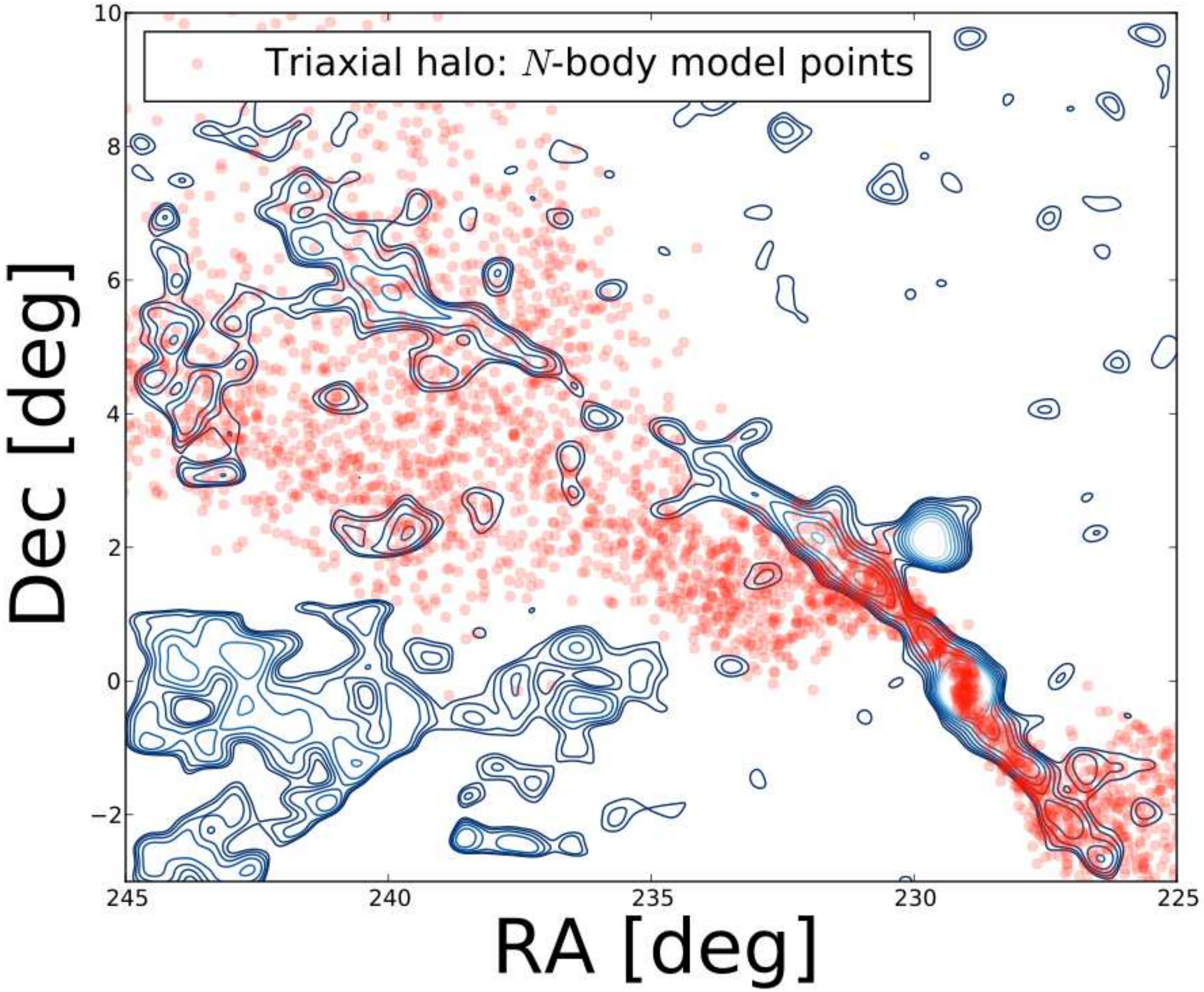
$p = 0.72 \mid q = 0.99$

Sagittarius: Law & Majewski (2010)

Streams disagree on the shape of the dark matter halo



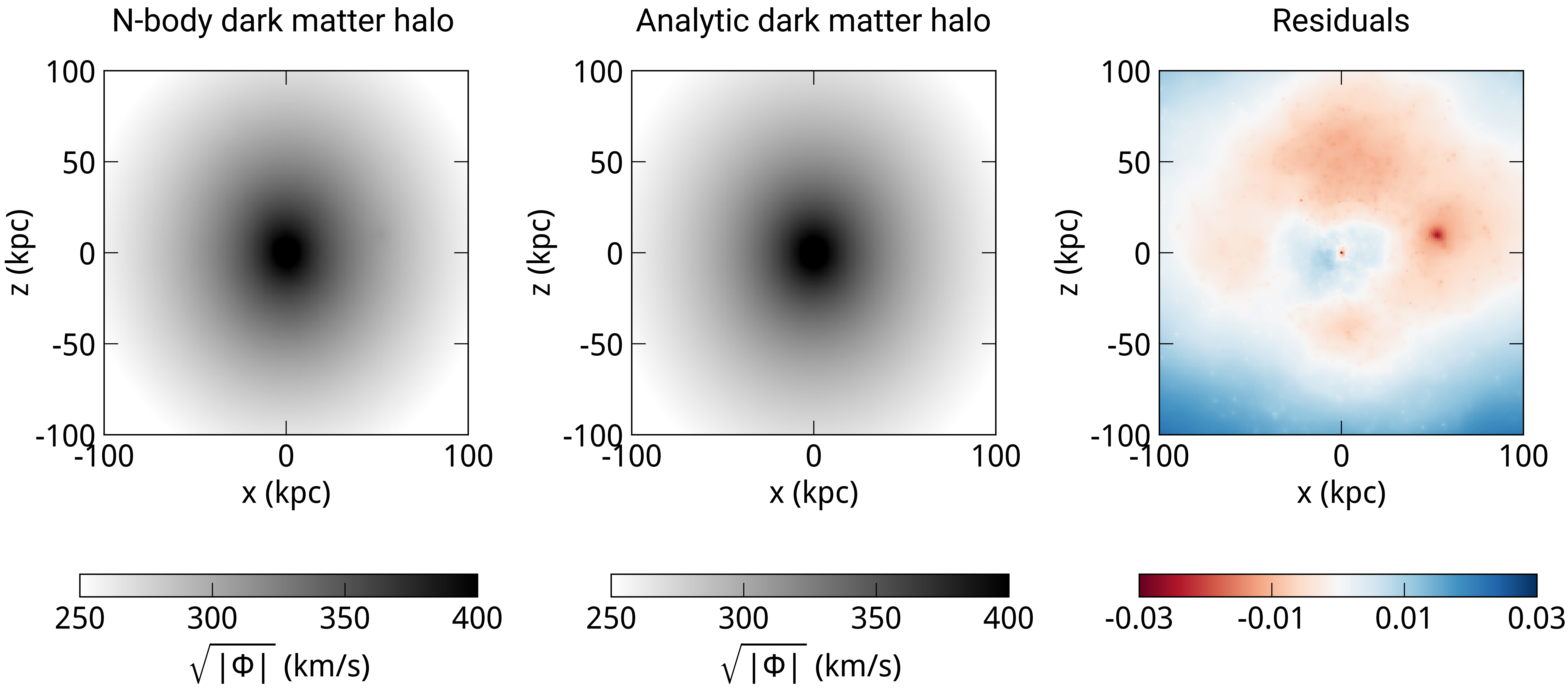
p = 0.72 | q = 0.99 ?



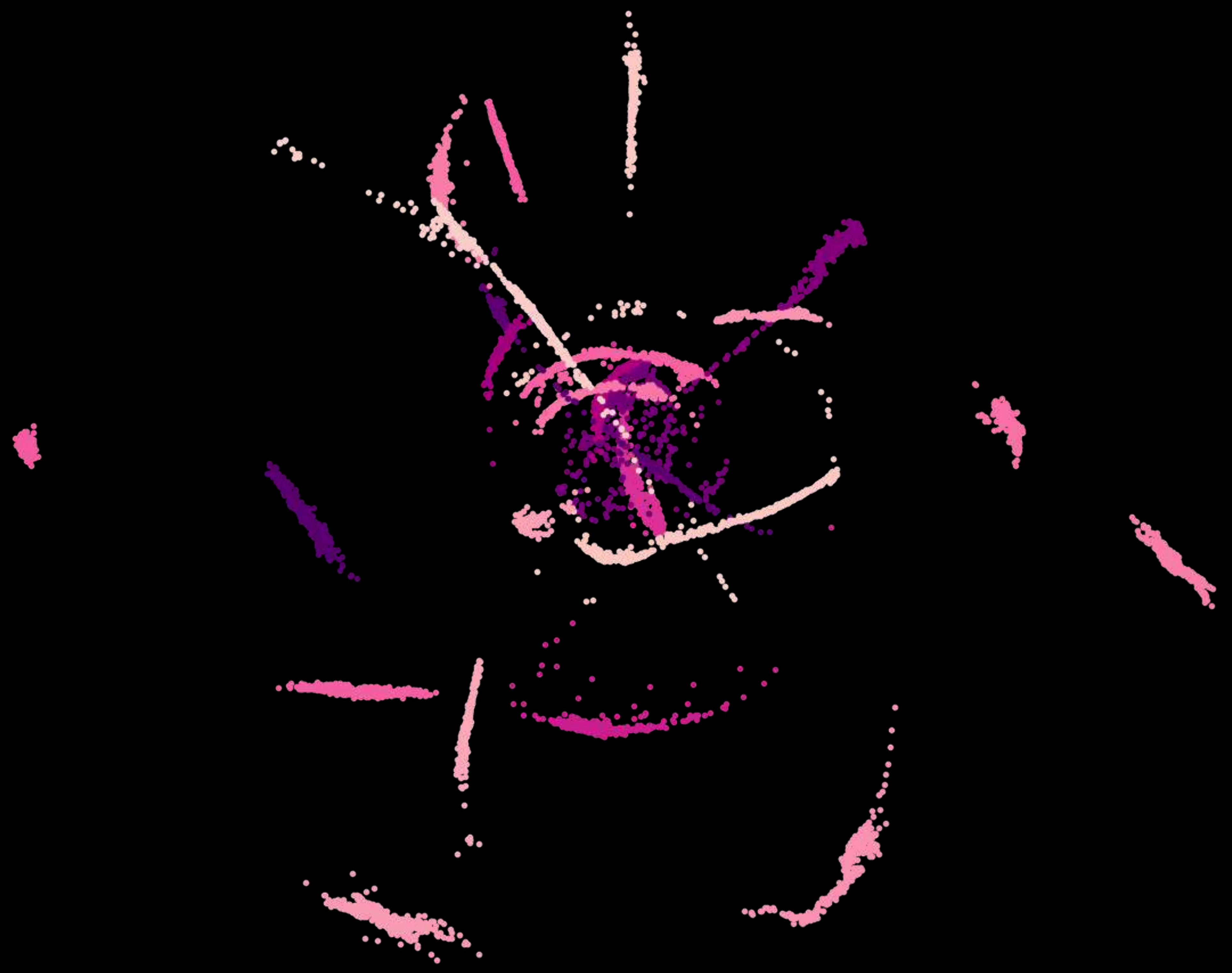
Sagittarius: Law & Majewski (2010)

Palomar 5: Pearson et al. (2015)

Our assumptions about the gravitational potential are idealized

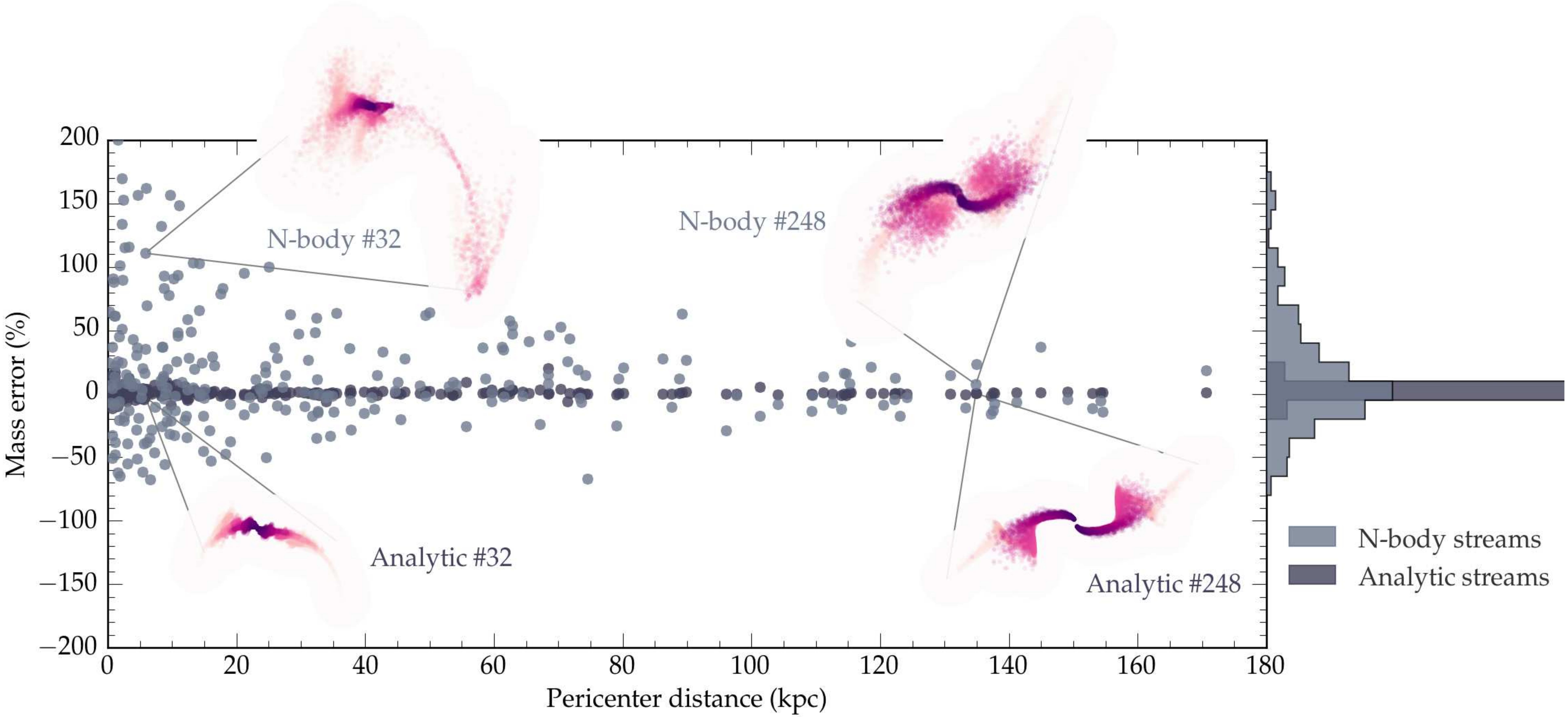


Tidal streams
in an N-body halo



Tidal streams
in an analytic halo

Assumption of an analytic halo can bias the recovery of its mass



Bonaca et al. (2014)

Properties of stellar streams depend
on the underlying gravitational potential,

but what are they actually constraining?

▷ Bonaca & Hogg, in prep

Information content can be quantified with Cramer-Rao bounds

Observational data

(R.A., Dec, distance,
radial velocity, proper motion)

$\vec{y}$

Covariance matrix

(observational uncertainties)

$$C_y = \begin{bmatrix} \sigma_1^1 & \cdots & \\ \vdots & \sigma_2^2 & \\ & & \ddots \end{bmatrix}$$

Information content can be quantified with Cramer-Rao bounds

Observational data $\vec{y}$

(R.A., Dec, distance,
radial velocity, proper motion)

Covariance matrix

(observational uncertainties)

$$C_y = \begin{bmatrix} \sigma_1^1 & \cdots & \\ \vdots & \sigma_2^2 & \\ & & \ddots \end{bmatrix}$$

Model parameters $\vec{x}$

(e.g., dark matter halo parameters)

Covariance (Fisher) matrix

(best attainable constraints)

$$C_x^{-1} = \left[\frac{d\vec{y}}{d\vec{x}}\right]^T C_y^{-1} \left[\frac{d\vec{y}}{d\vec{x}}\right] + V_x^{-1}$$

Cramer-Rao lower bound

$$\sqrt{\mathrm{Diag}\ C_x}$$

Data and model in the context of stellar streams

Generative model for a stellar stream

given gravitational potential, progenitor's
position and stream age

Bonaca et al. (2014)

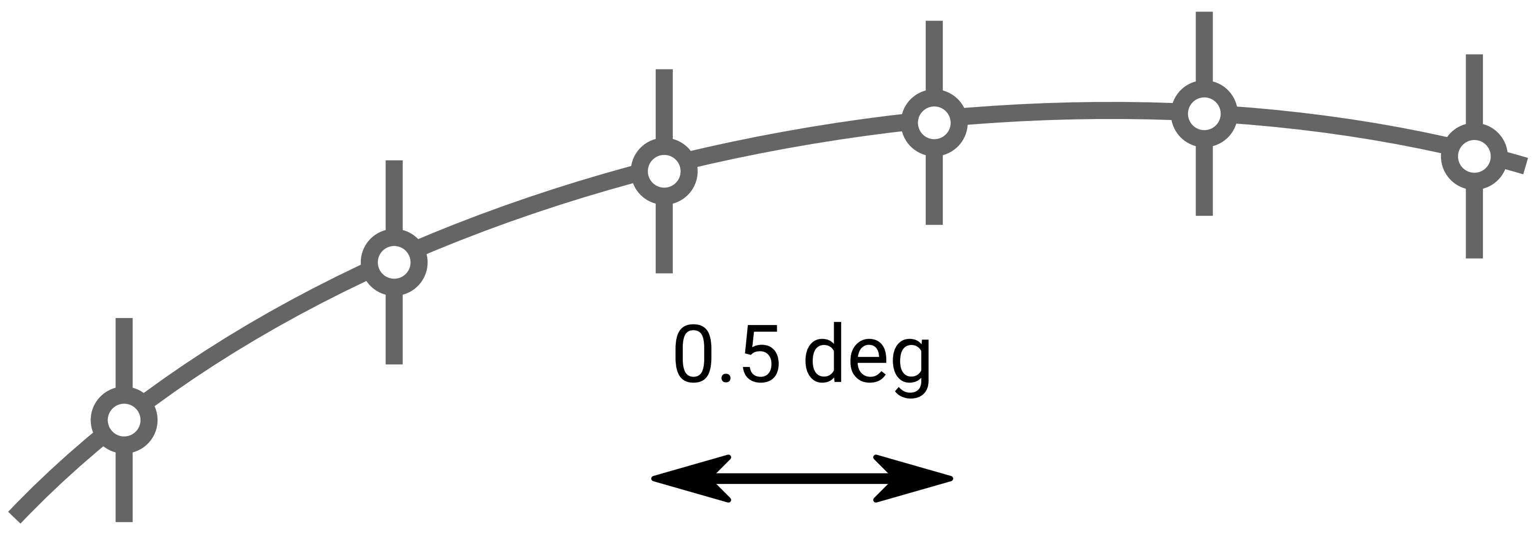
Data and model in the context of stellar streams

Generative model for a stellar stream

given gravitational potential, progenitor's
position and stream age

Stream observationally

a collection of equidistant stars,
with up to 6D positions



Observational uncertainties:

sky position: 0.1 deg

distance: 2 kpc

radial velocity: 5 km/s

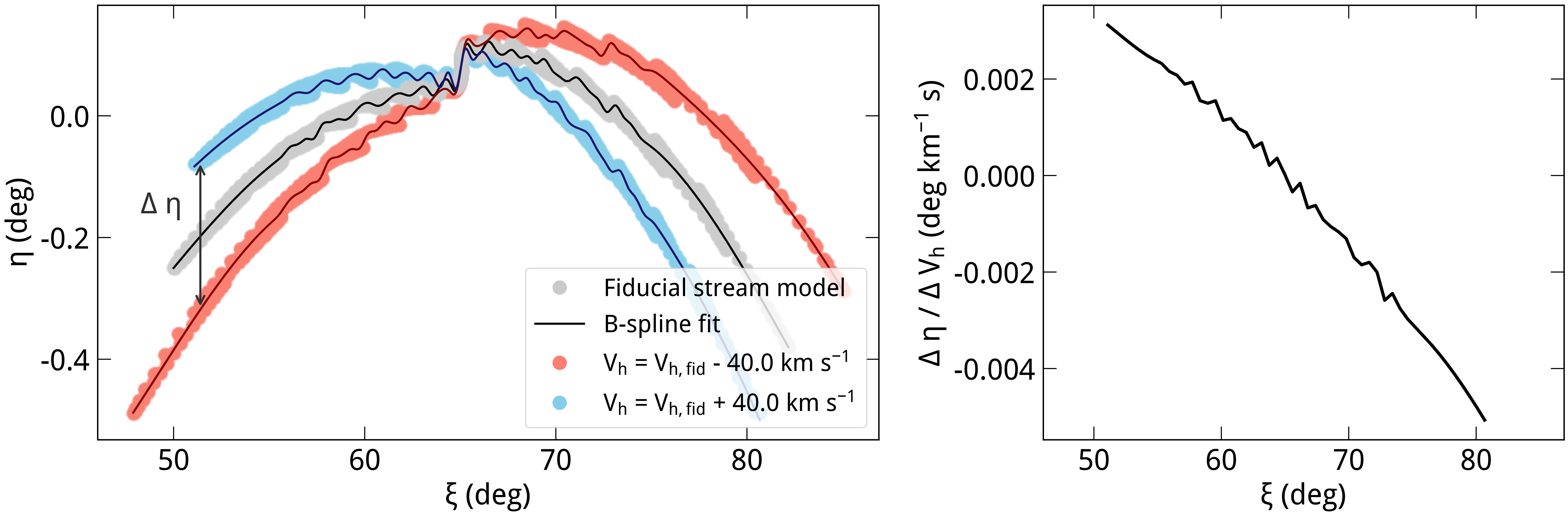
proper motion: 0.1 mas/yr

Bonaca et al. (2014)

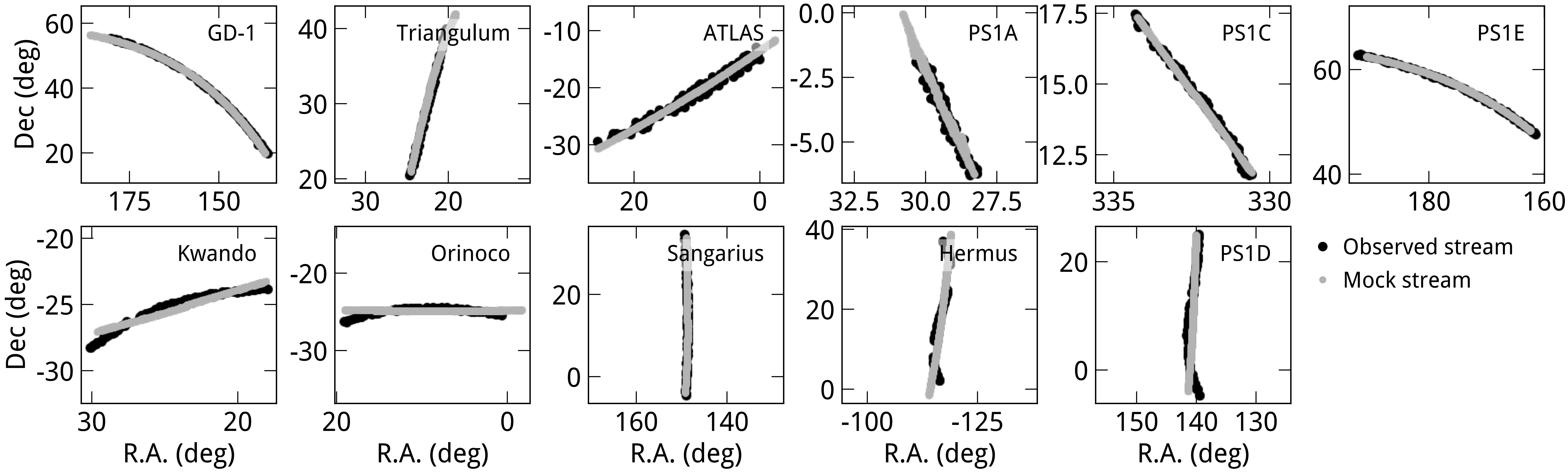
Quantifying how much a stream changes with model variations

A formal derivative is approximated by a numerical derivative:

$$\frac{dy}{dx} \approx \frac{\Delta y}{\Delta x}$$



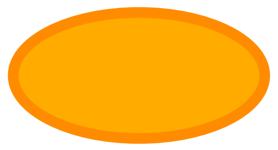
Analysis completed on the following Milky Way-like streams:



Overview of model parameters:

Bulge

mass, scale length



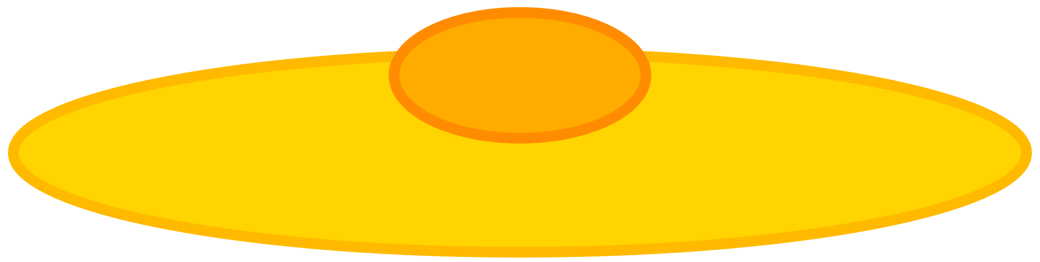
Overview of model parameters:

Bulge

mass, scale length

Disk

mass, scale length, scale height



Overview of model parameters:

Bulge

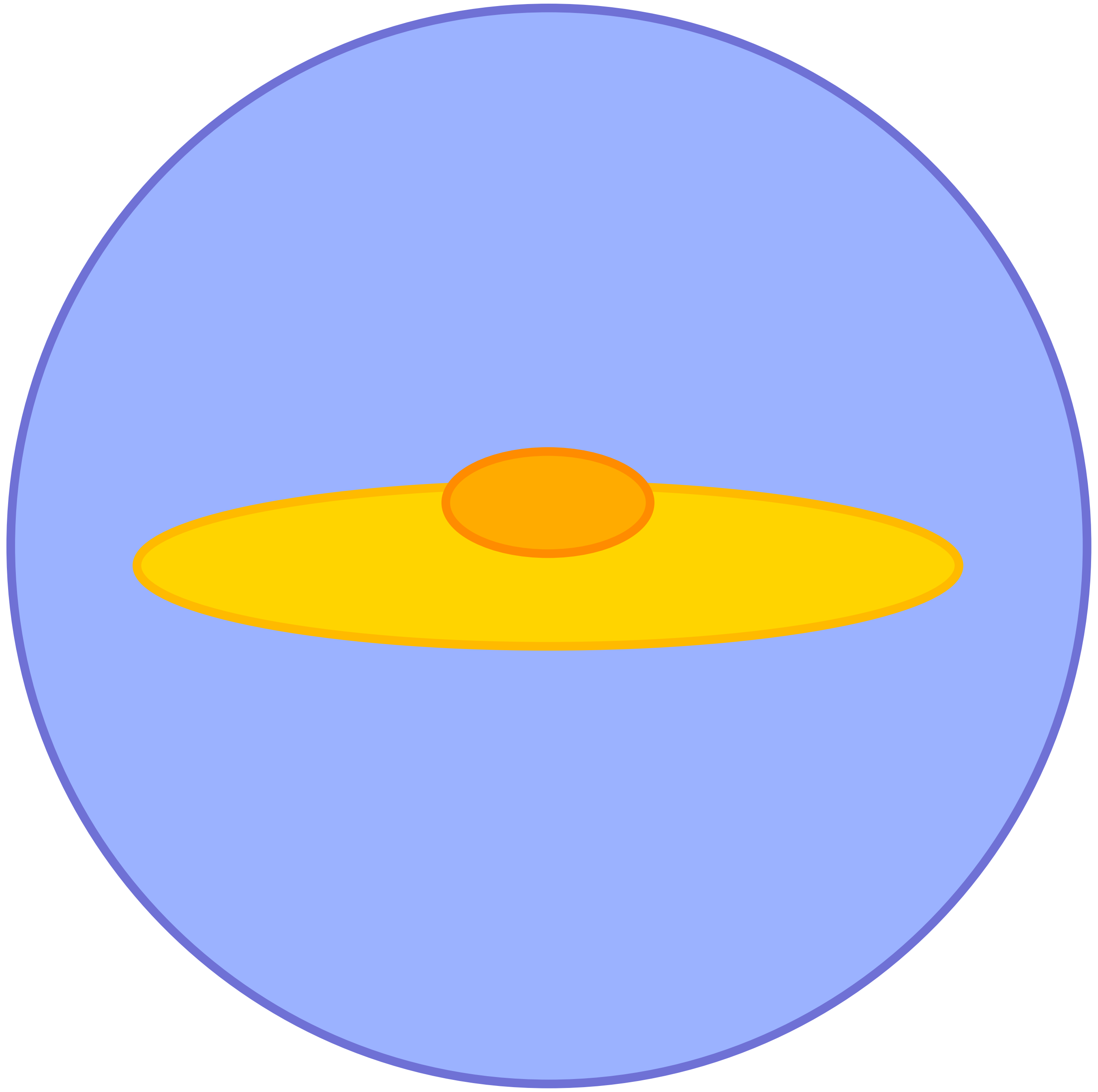
mass, scale length

Disk

mass, scale length, scale height

Dark matter halo

scale velocity, scale radius, x/y axis ratio, z/y axis ratio



Overview of model parameters:

Bulge

mass, scale length

Disk

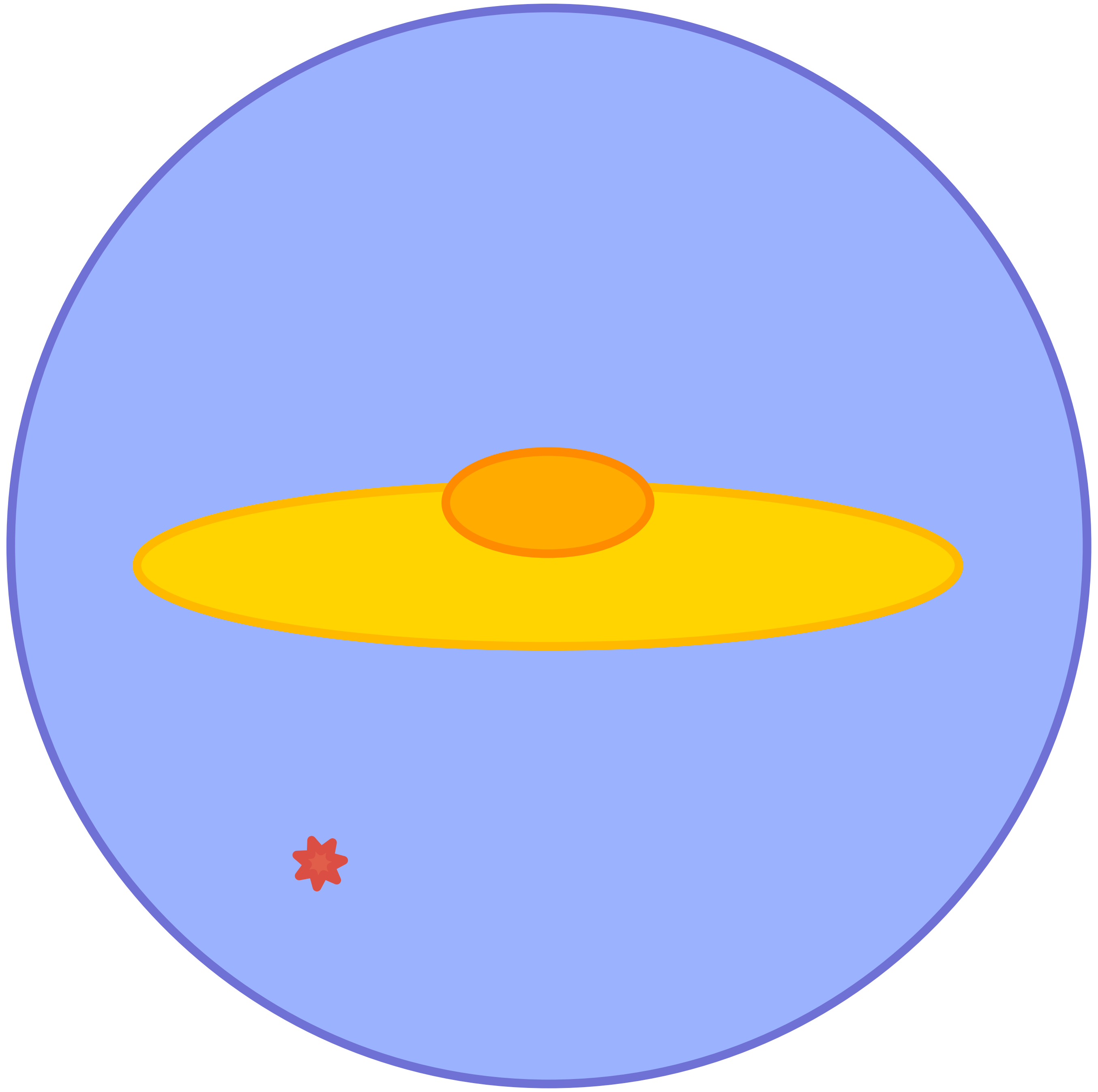
mass, scale length, scale height

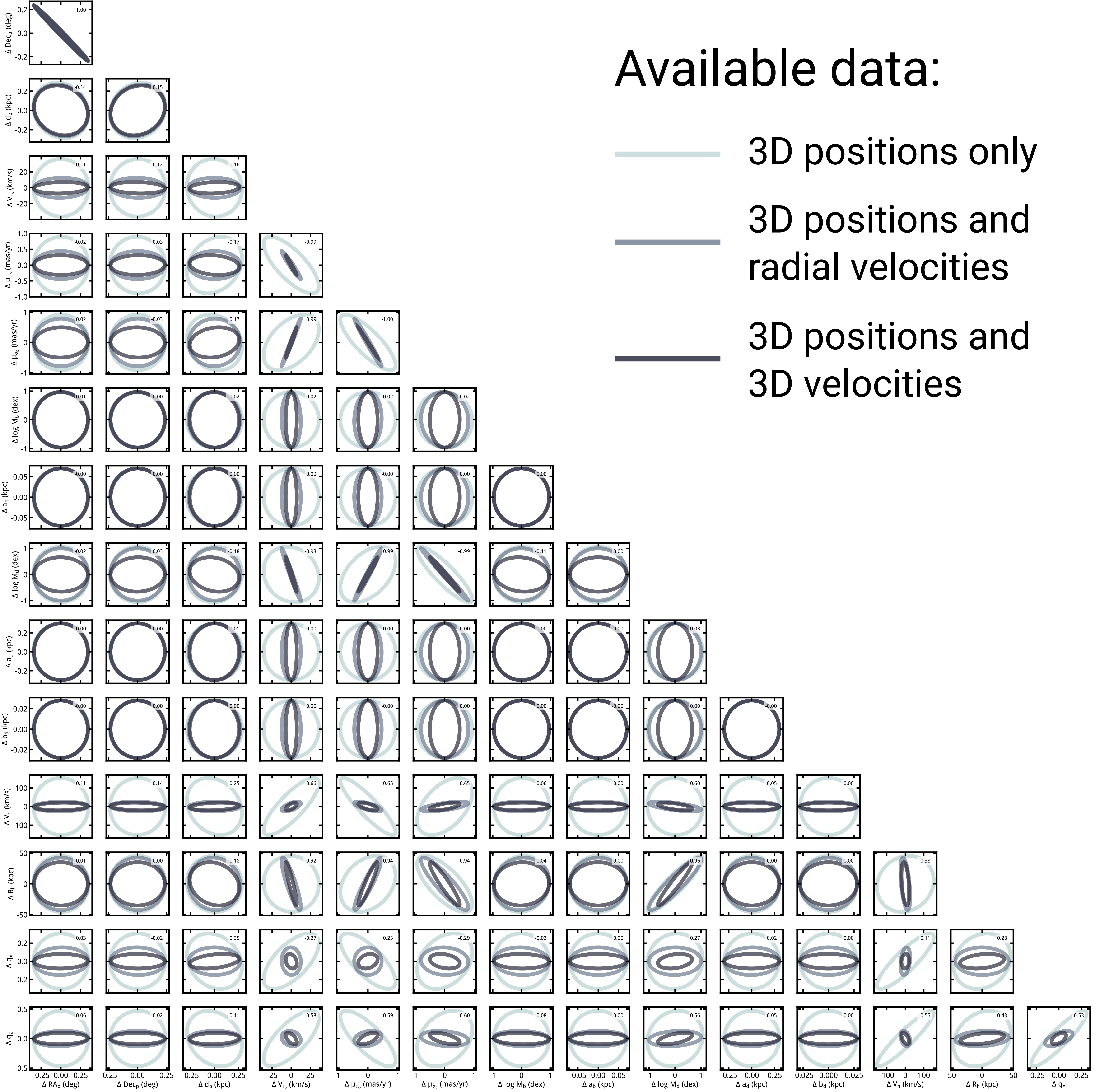
Dark matter halo

scale velocity, scale radius, x/y axis ratio, z/y axis ratio

Progenitor's position

RA, Dec, distance, radial velocity, proper motions





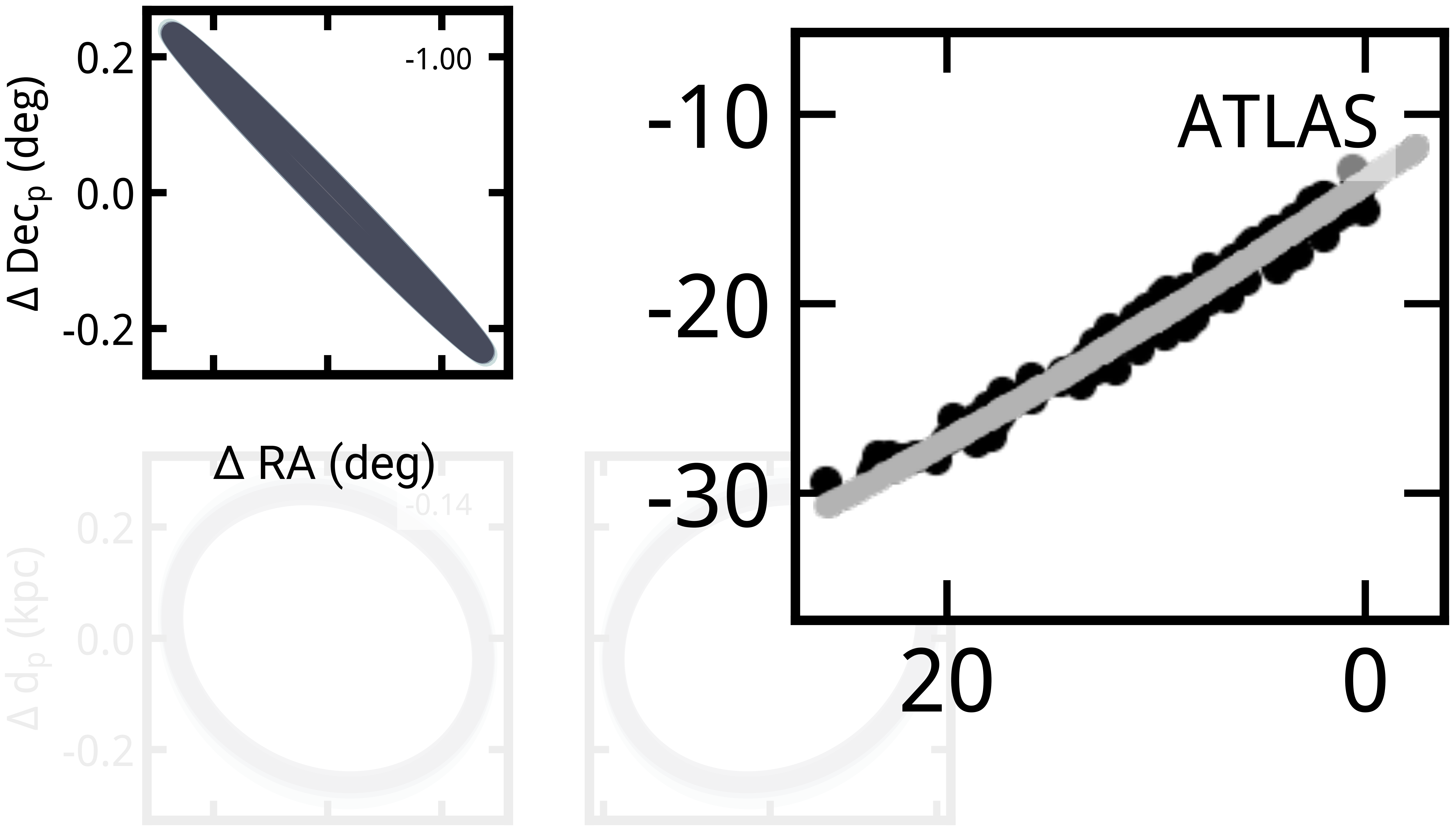
Available data:

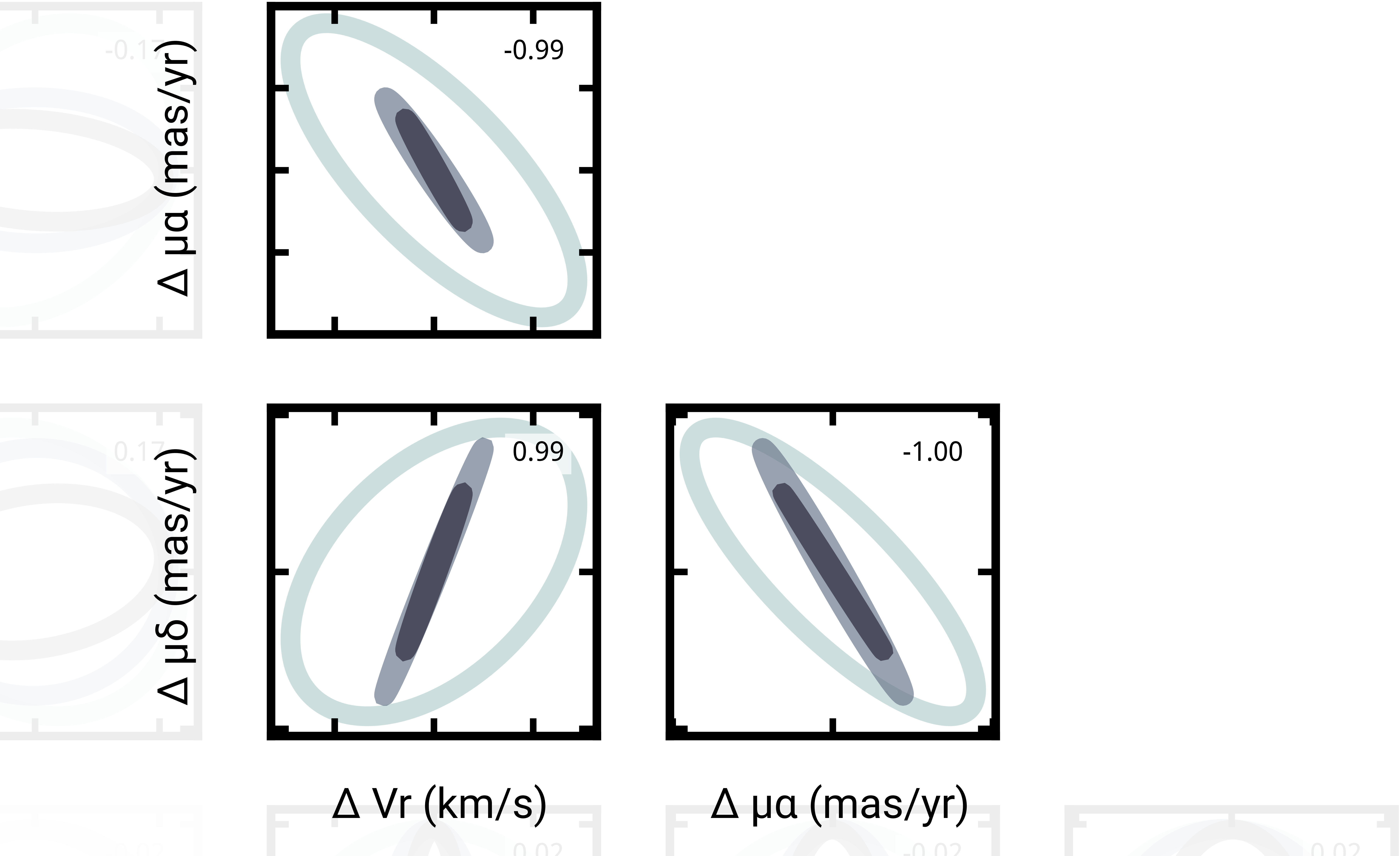
3D positions only

3D positions and radial velocities

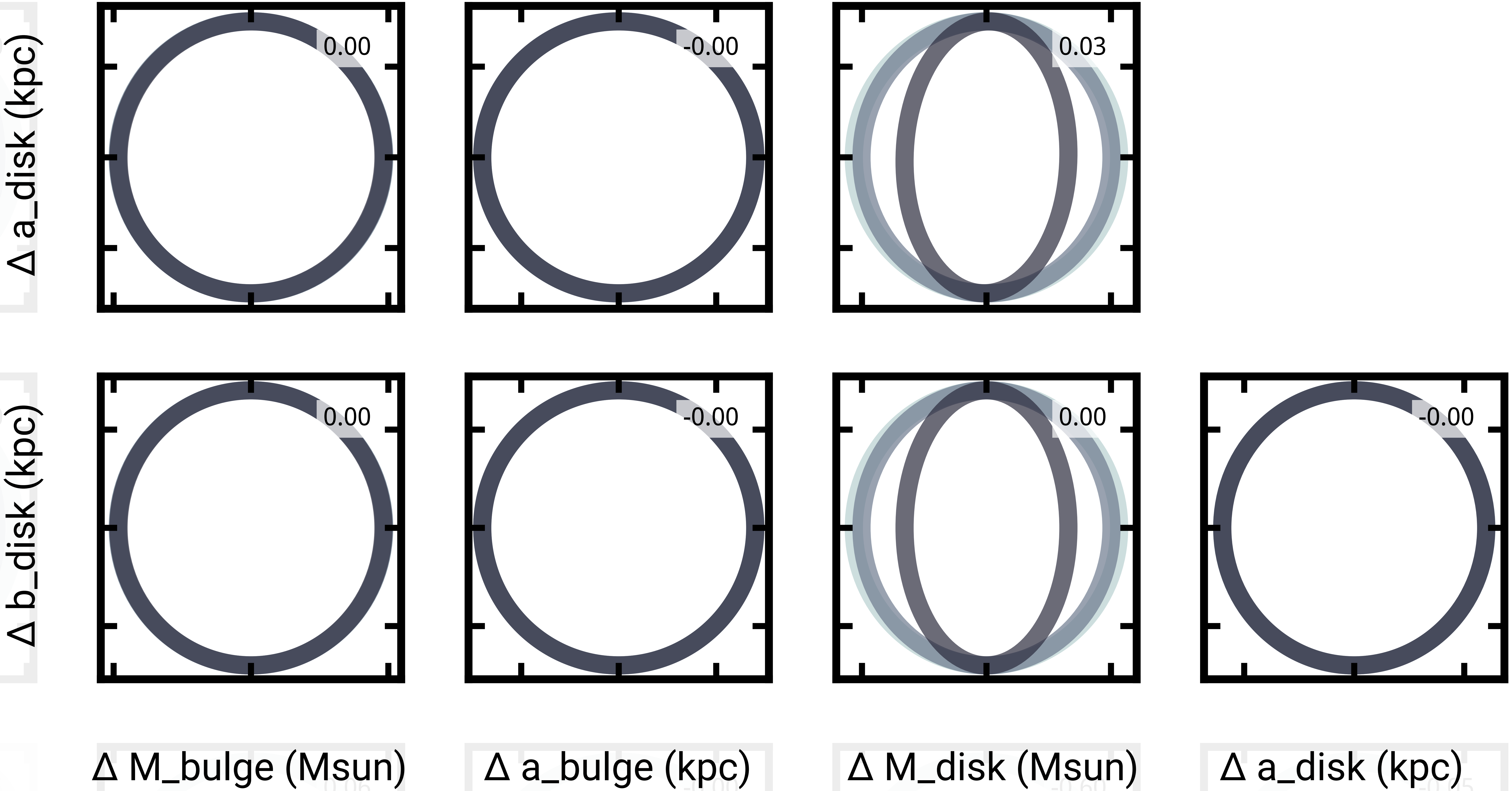
3D positions and 3D velocities

For an individual stream, multiple degeneracies exist between model parameters

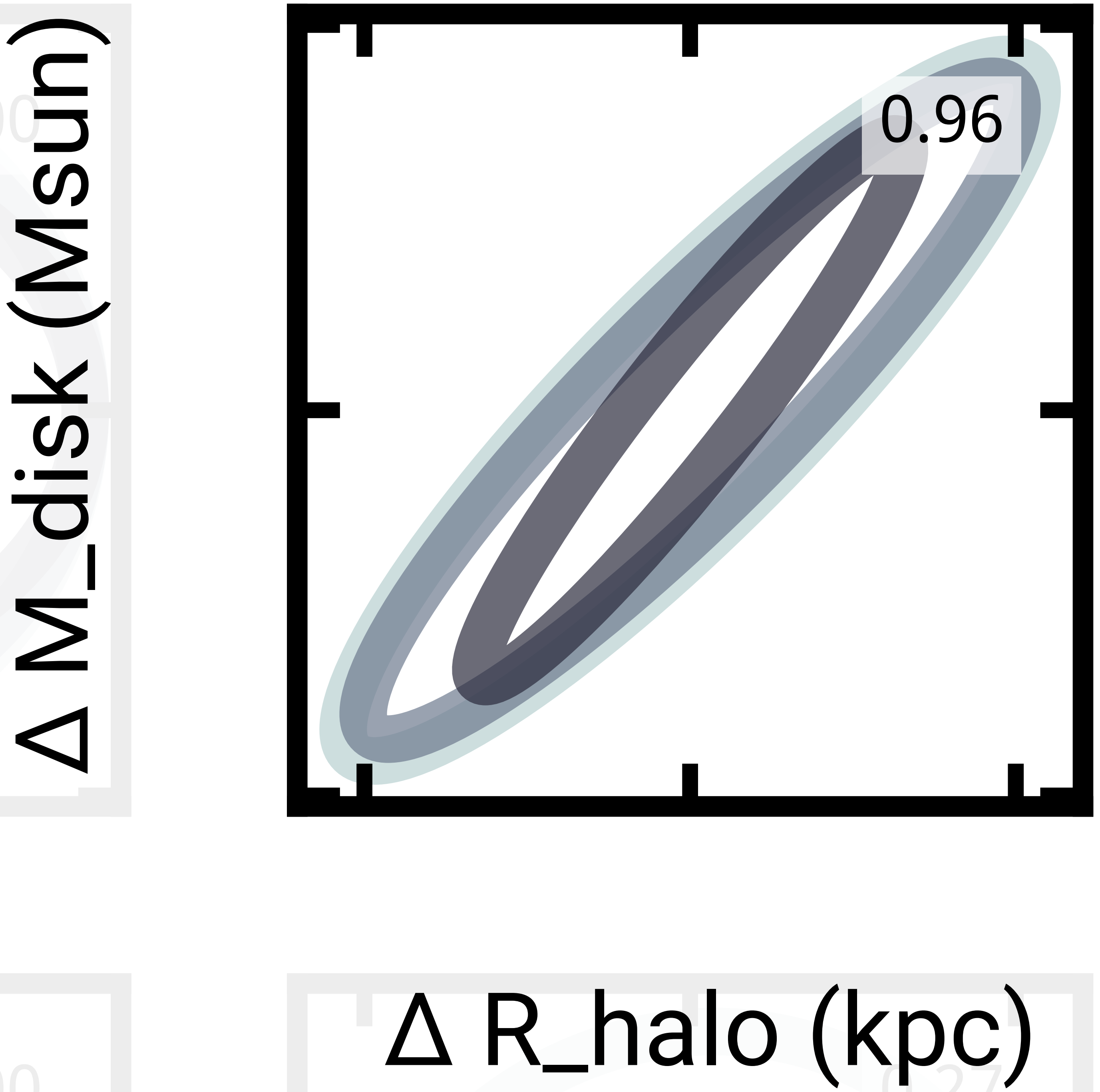

-1.00
0.2
0.0
-0.2
Δ Dec_p (deg)
Δ RA (deg)
-0.14
Δ d_p (kpc)
ATLAS
-10
-20
-30
20
0



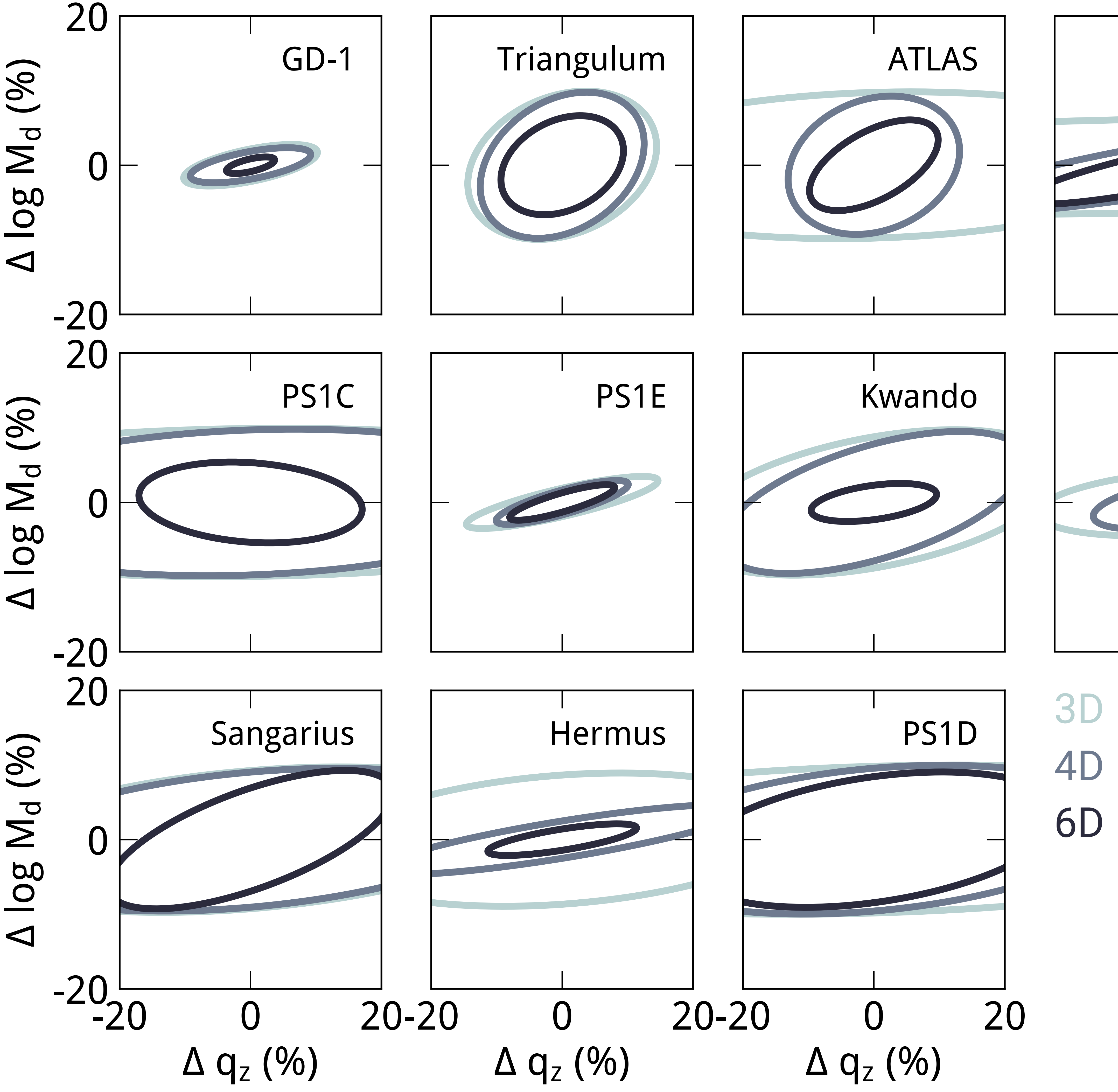
-0.99
0.99
-1.00
Δ μα (mas/yr)
Δ μδ (mas/yr)
Δ Vr (km/s)
Δ μα (mas/yr)



0.00
-0.00
0.03
0.00
-0.00
0.00
-0.00
Δ a_disk (kpc)
Δ b_disk (kpc)
Δ M_bulge (Msun)
Δ a_bulge (kpc)
Δ M_disk (Msun)
Δ a_disk (kpc)



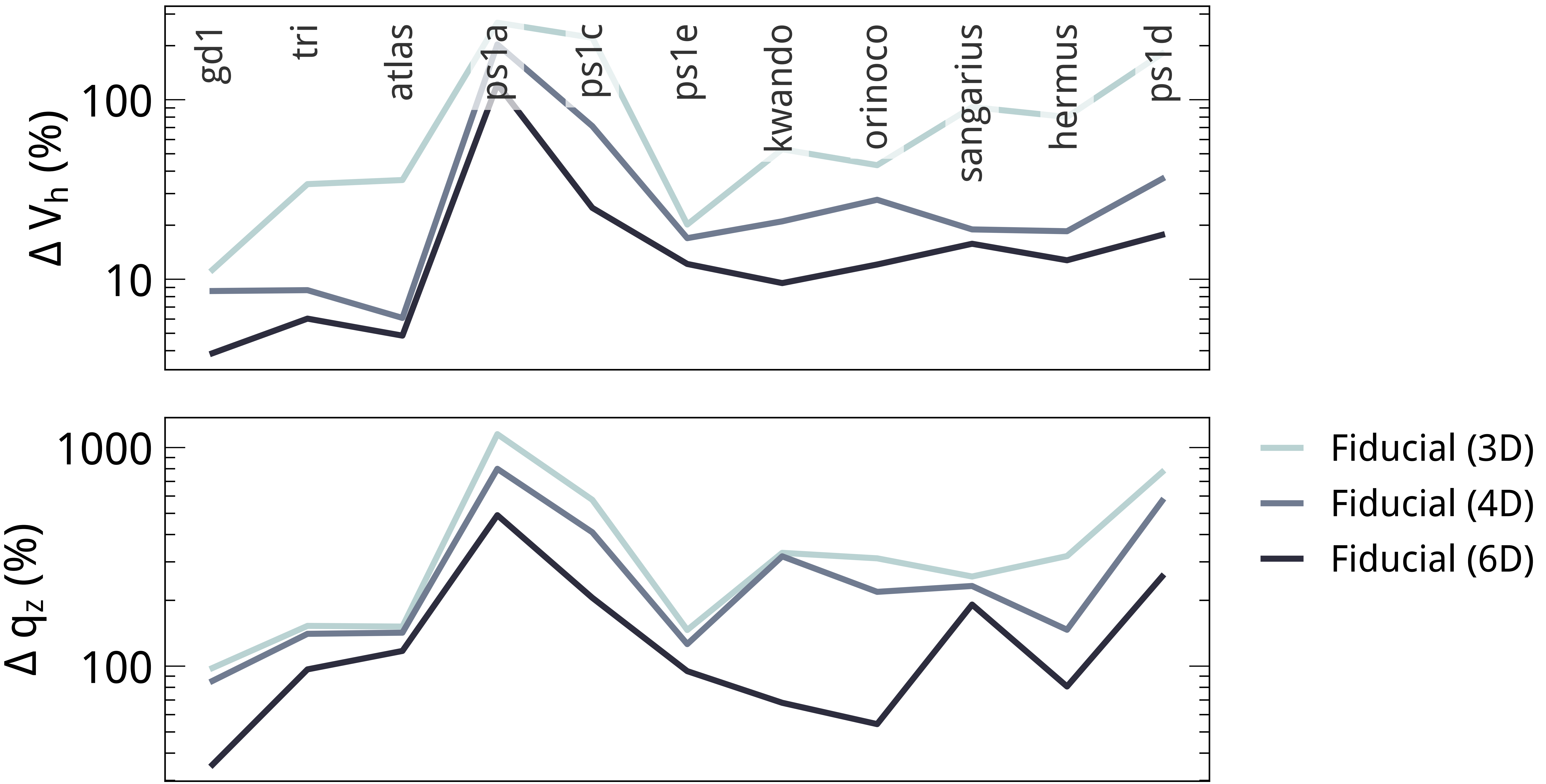
$$M_{inner} \propto M_d + M_h$$



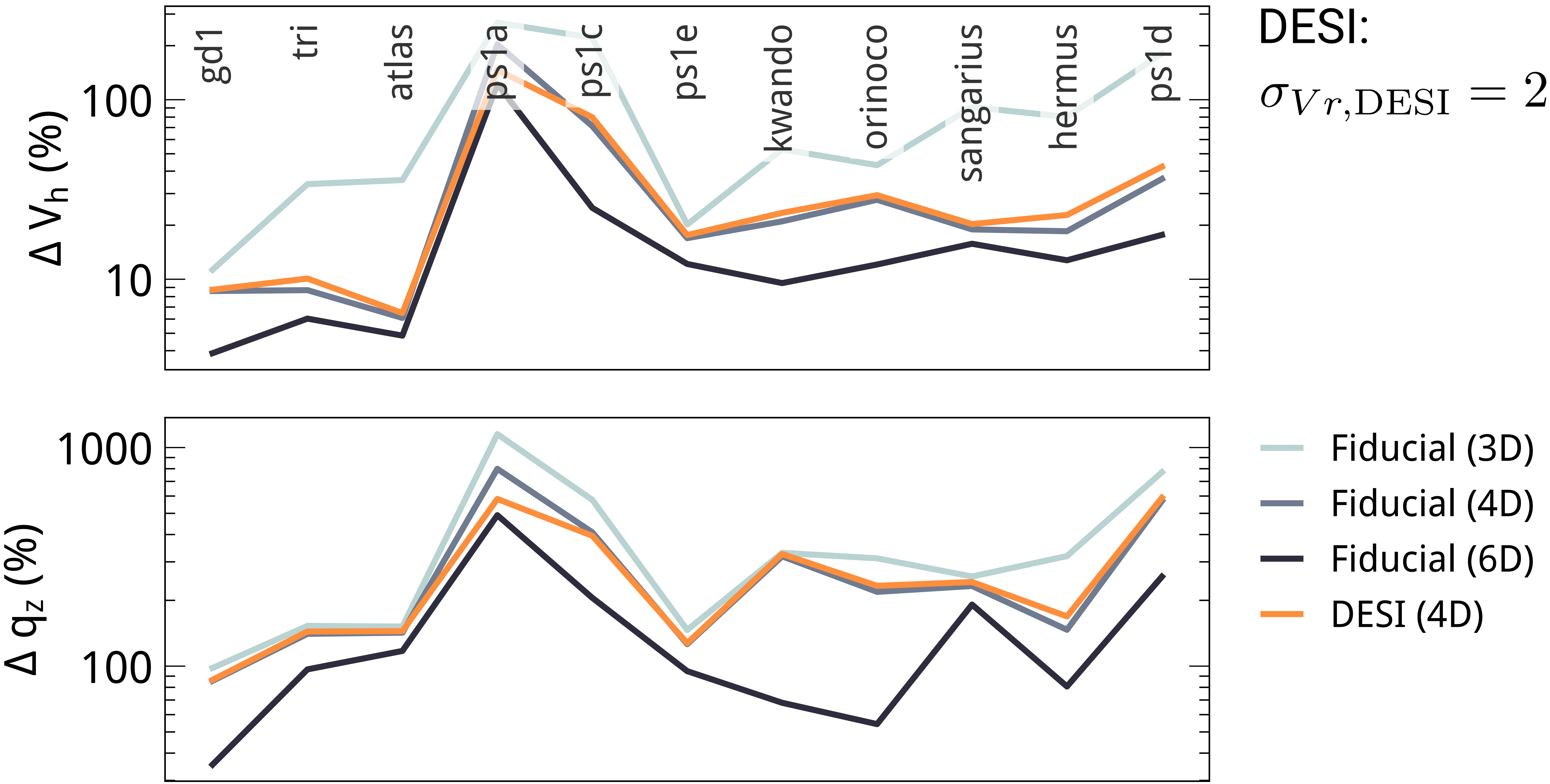
Streams have different:

- sensitivity to Galactic properties
- covariances between different properties, and
- requirements on data quality

Constraints are driven by data dimensionality, not its precision



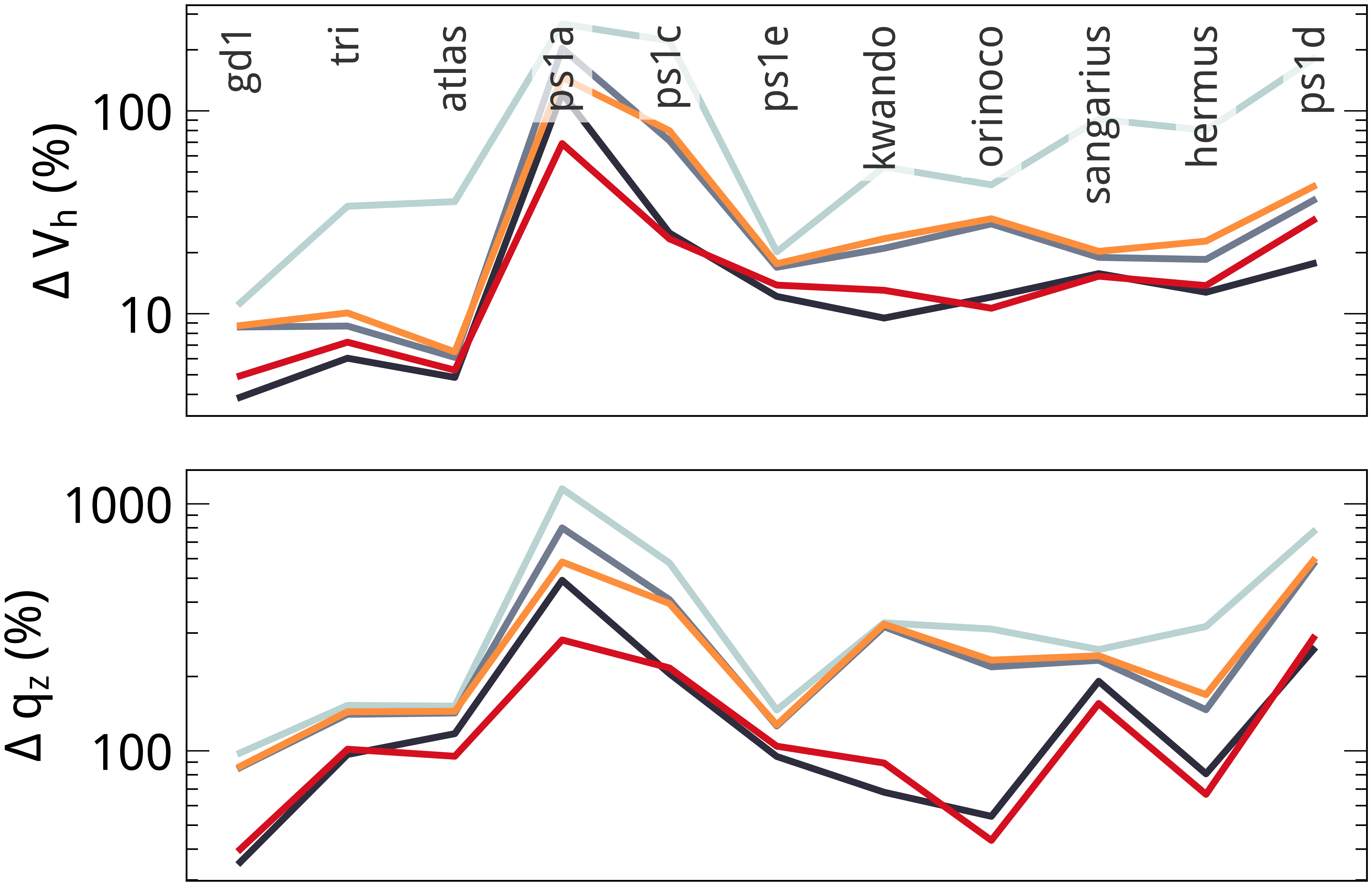
Constraints are driven by data dimensionality, not its precision



DESI:

$$\sigma_{Vr,\mathrm{DESI}} = 2\,\sigma_{Vr,\mathrm{fid}}$$

Constraints are driven by data dimensionality, not its precision



DESI:

$$\sigma_{Vr,\mathrm{DESI}} = 2\,\sigma_{Vr,\mathrm{fid}}$$

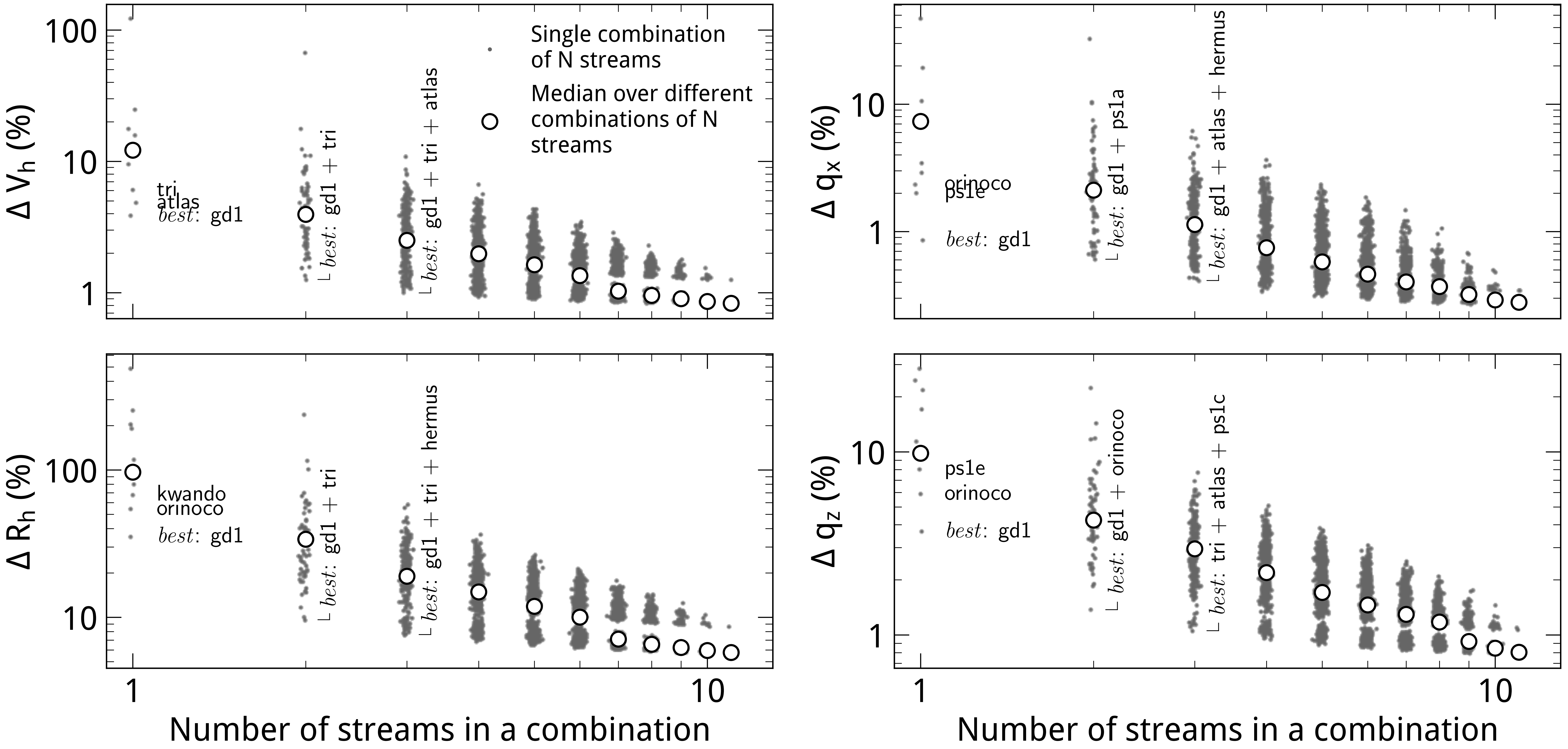
Gaia:

$$\sigma_{d,\mathrm{Gaia}} = 0.1\,\sigma_{d,\mathrm{fid}}$$

$$\sigma_{\mu,Gaia} = 2\,\sigma_{\mu,\mathrm{fid}}$$

Fiducial (3D)
Fiducial (4D)
Fiducial (6D)
DESI (4D)
Gaia (6D)

Multiple streams constrain the dark matter halo to better than 1%



Known stellar streams constrain parameters
of an analytic dark matter halo
to better than a percent,

but how does that map to
physical properties of the halo?

Stream constraints on the potential propagate to physical quantities

Converting from model parameters q to derived quantities p(q):

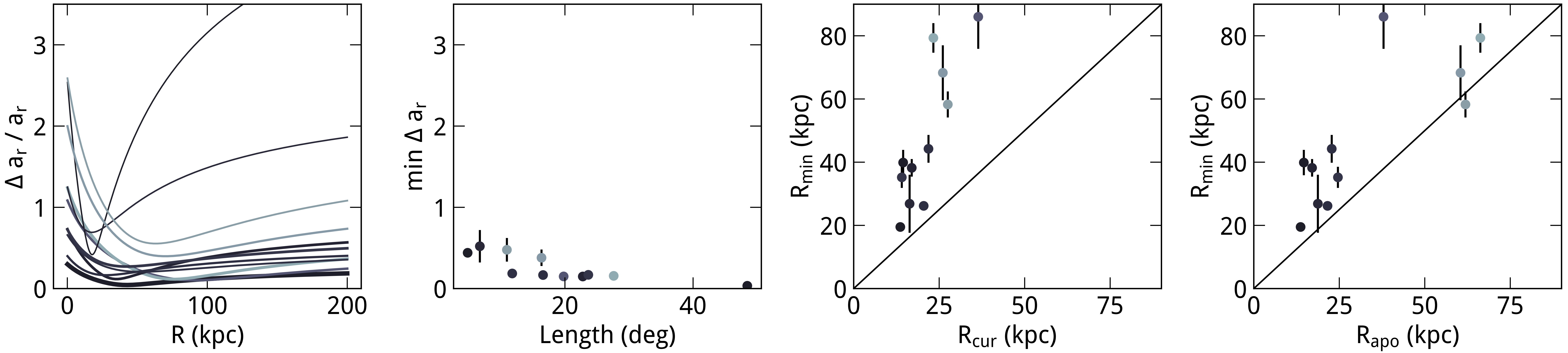
$$C_p = \left(\frac{d\vec{p}}{d\vec{q}}\right)^T C_q \left(\frac{d\vec{p}}{d\vec{q}}\right)$$

Stream constraints on the potential propagate to physical quantities

Converting from model parameters q to derived quantities p(q):

$$C_p = \left(\frac{d\vec{p}}{d\vec{q}} \right)^T C_q \left(\frac{d\vec{p}}{d\vec{q}} \right)$$

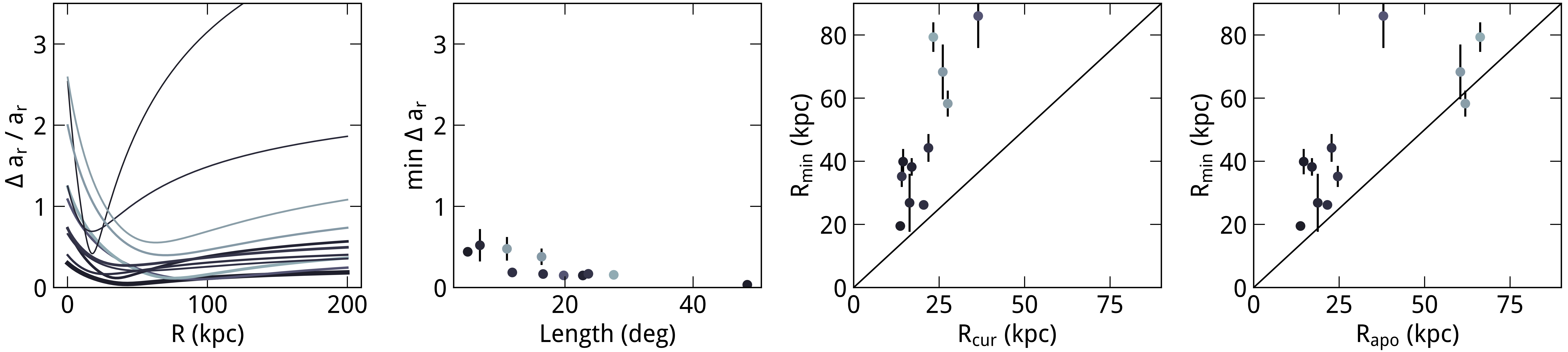
Radial acceleration: $a_r = \frac{\partial \Phi}{\partial r}$



Stream constraints in a more flexible gravitational potential

Fiducial potential: Hernquist bulge + Miyamoto-Nagai disk + NFW halo

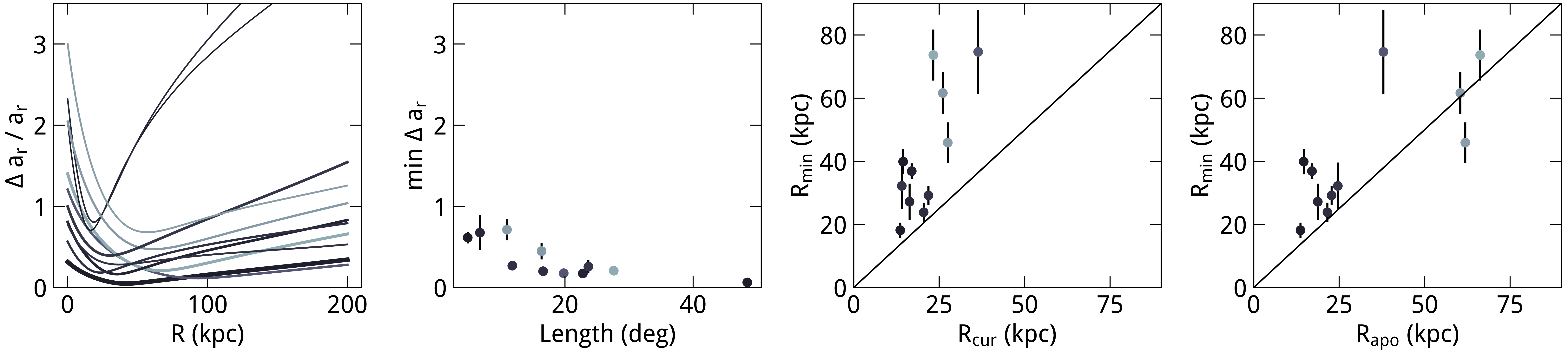
Perturbations:



Stream constraints in a more flexible gravitational potential

Fiducial potential: Hernquist bulge + Miyamoto-Nagai disk + NFW halo

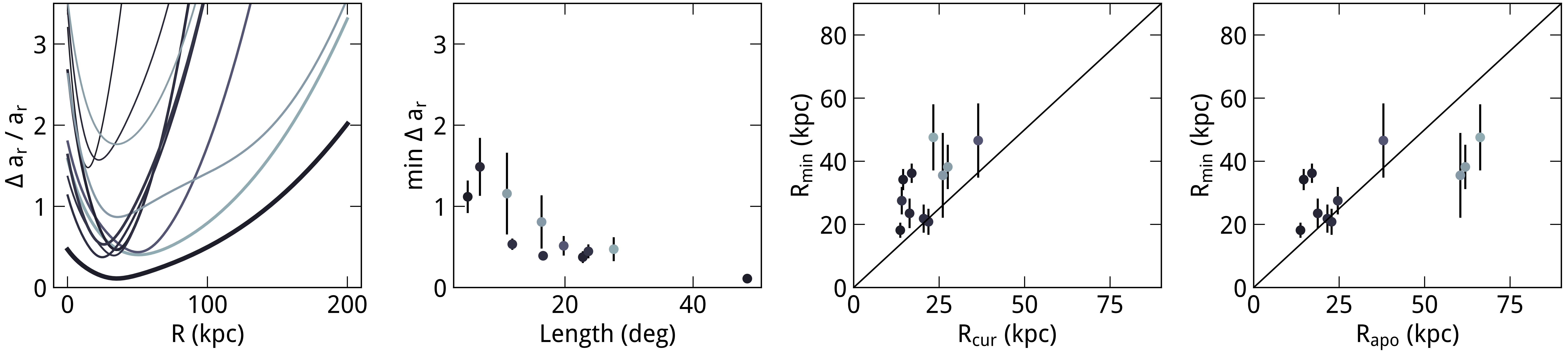
Perturbations: dipole



Stream constraints in a more flexible gravitational potential

Fiducial potential: Hernquist bulge + Miyamoto-Nagai disk + NFW halo

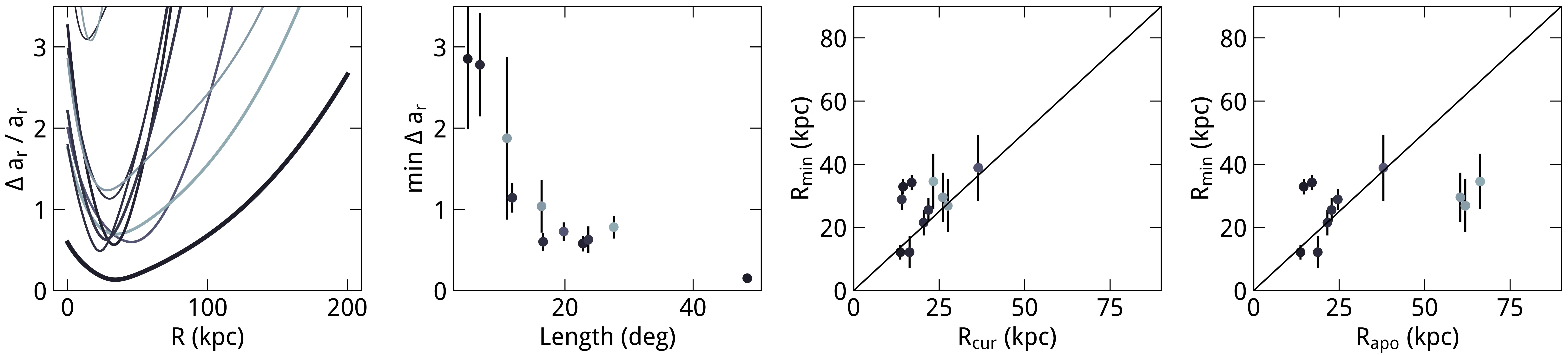
Perturbations: dipole + quadrupole



Stream constraints in a more flexible gravitational potential

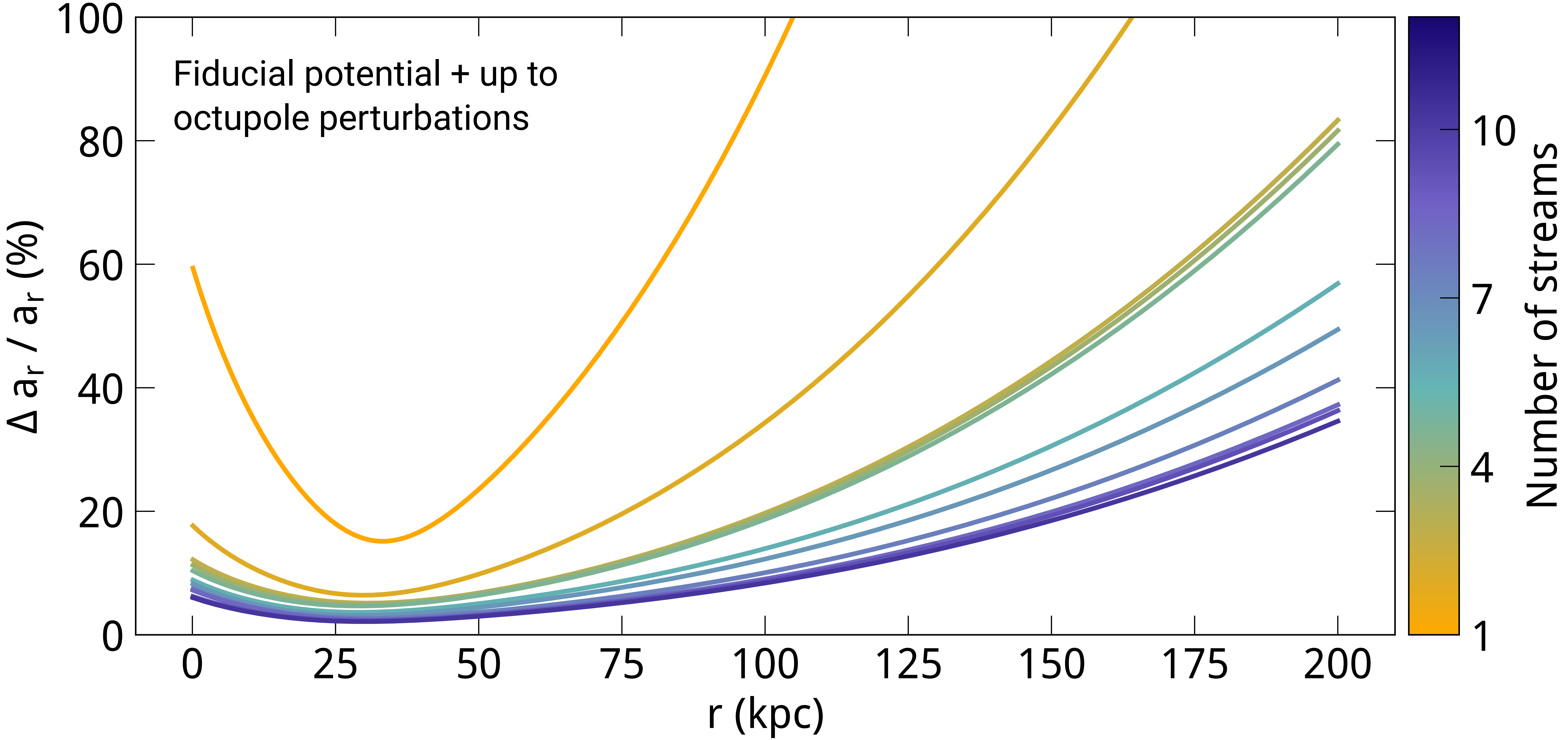
Fiducial potential: Hernquist bulge + Miyamoto-Nagai disk + NFW halo

Perturbations: dipole + quadrupole + octupole

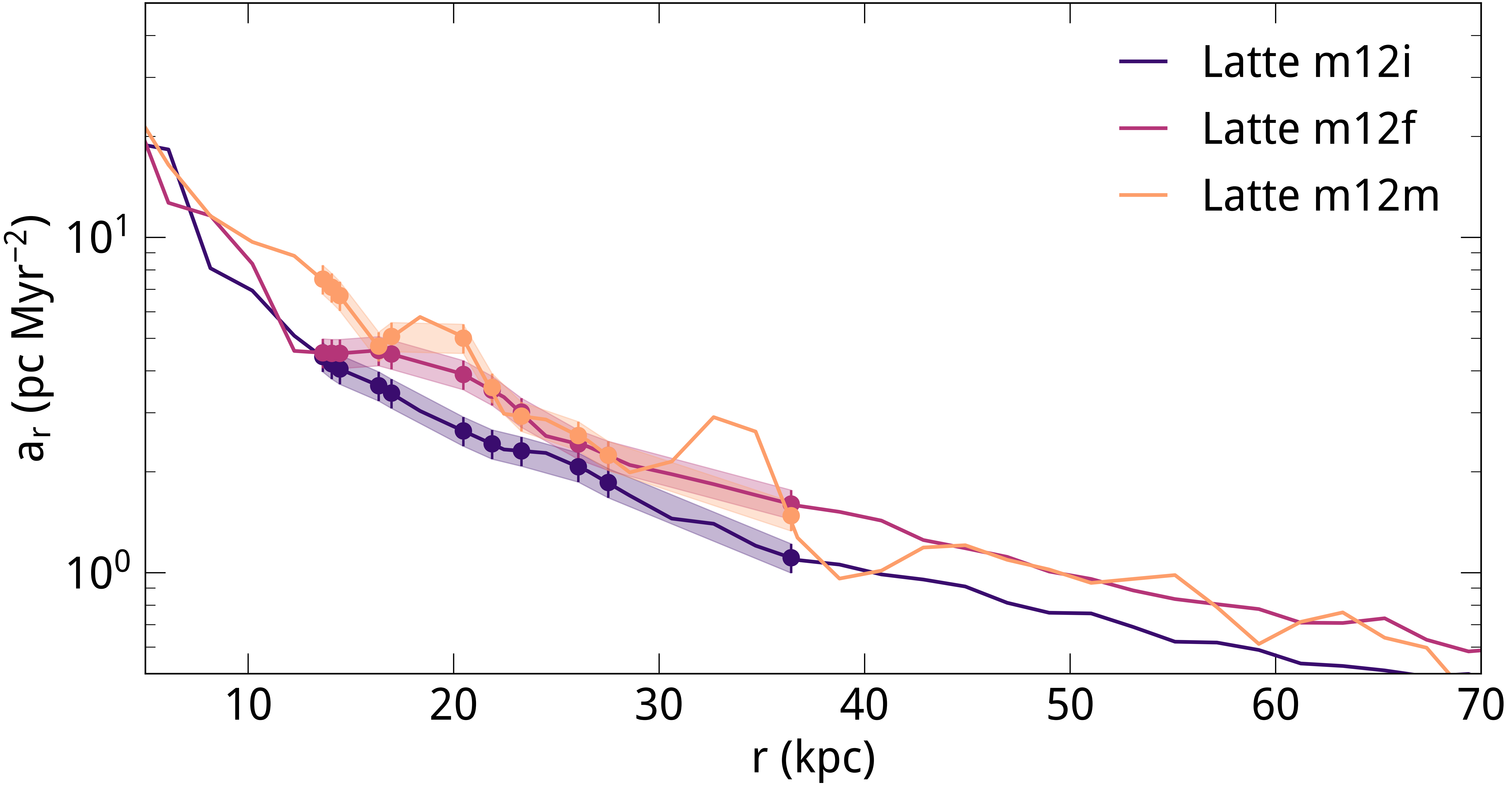


are the best at the stream's current location.

Even in a flexible potential, combined stream constraints are precise



Imprint of different merger histories comparable to stream precision



Latte courtesy A. Wetzel & the FIRE team

In a sufficiently flexible model of the Galaxy,
stellar streams are most sensitive
to the total mass within
their current position.

Combining information from ~10
known streams should constrain
the acceleration field to better than 10%.