Painting on the Perturbations

Differentiable Models for Stellar Streams in the Evolving Milky Way

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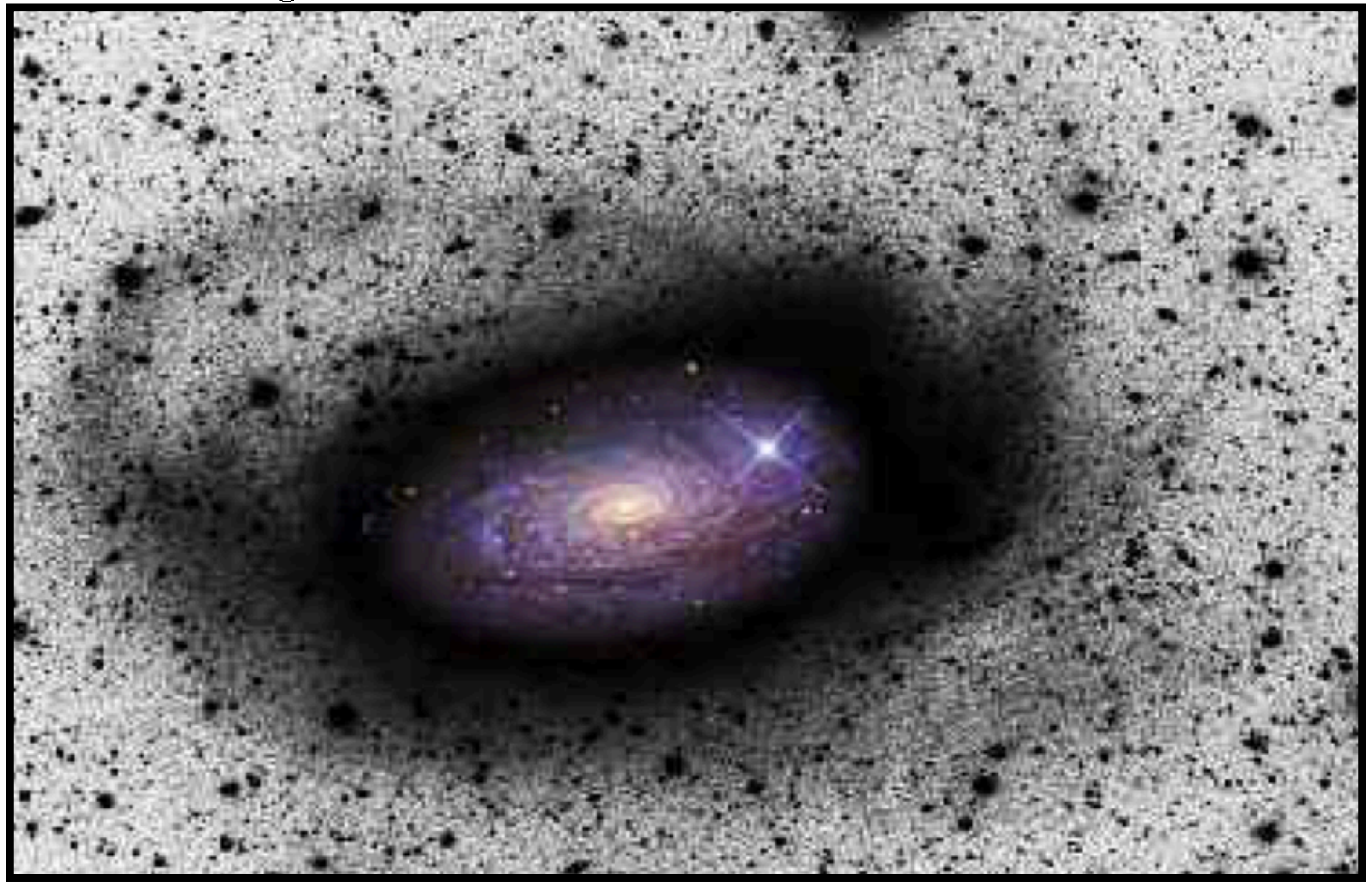
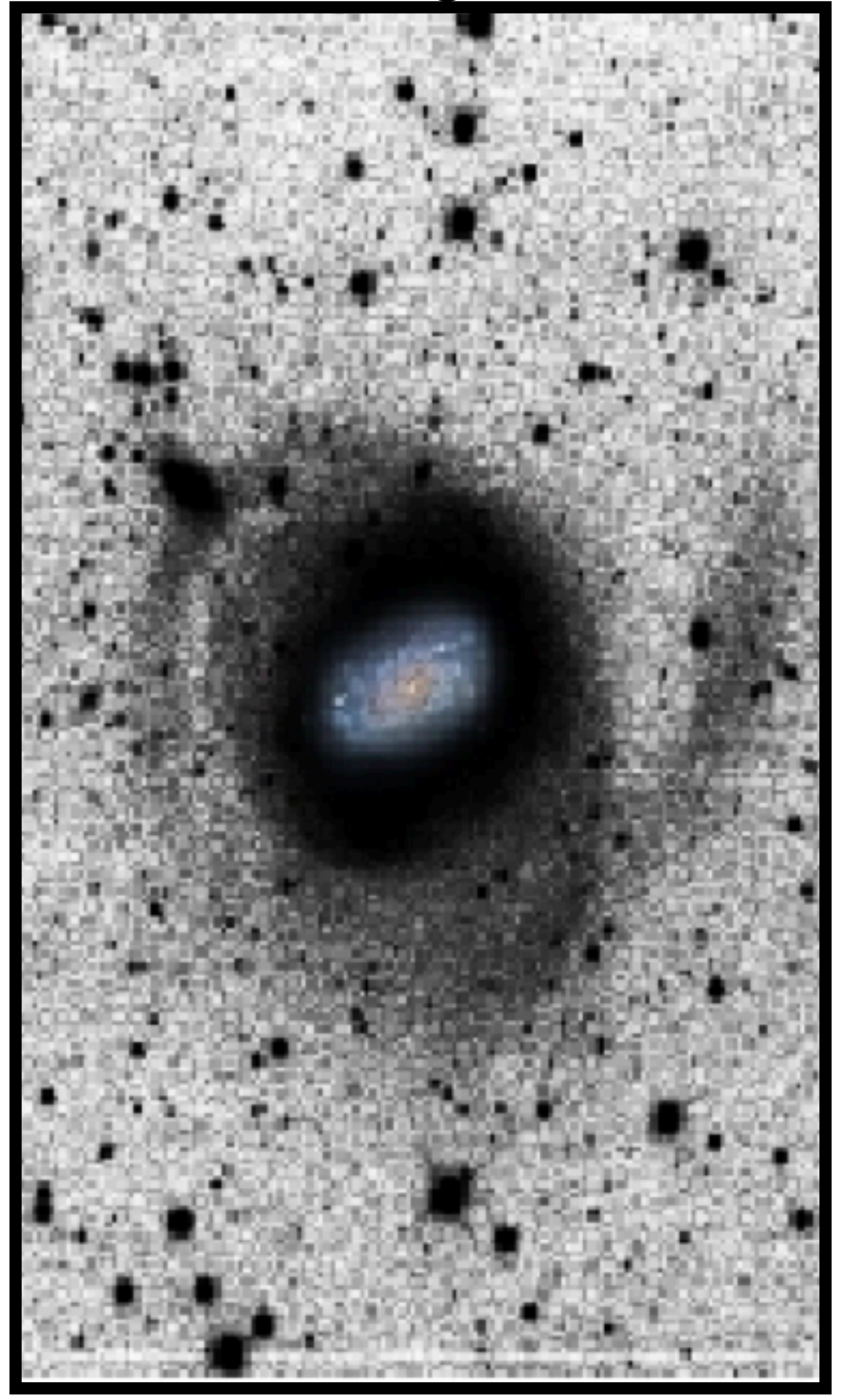
PRINCETON UNIVERSITY

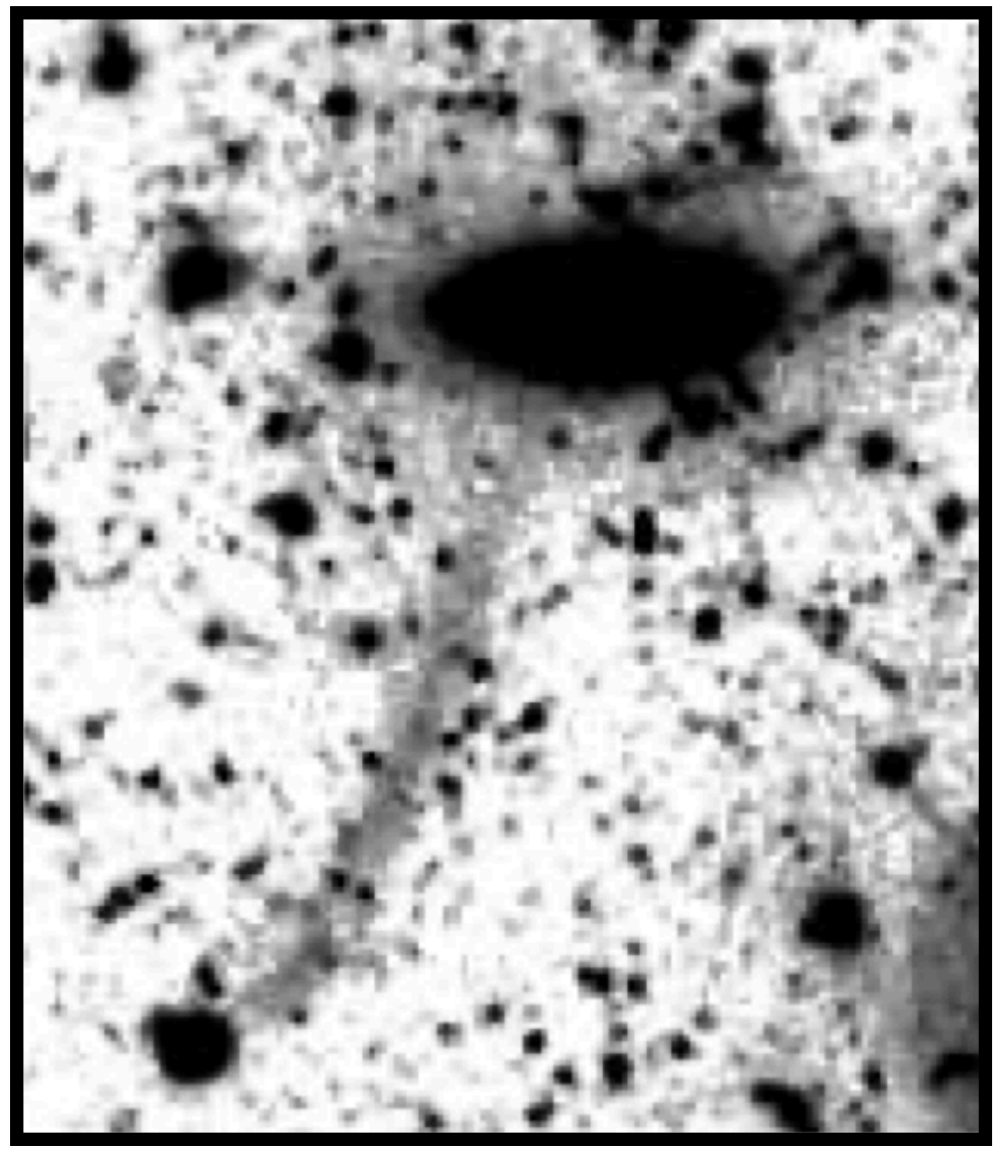
DGSCS
Chicago 2024

Martínez-Delgado+2010

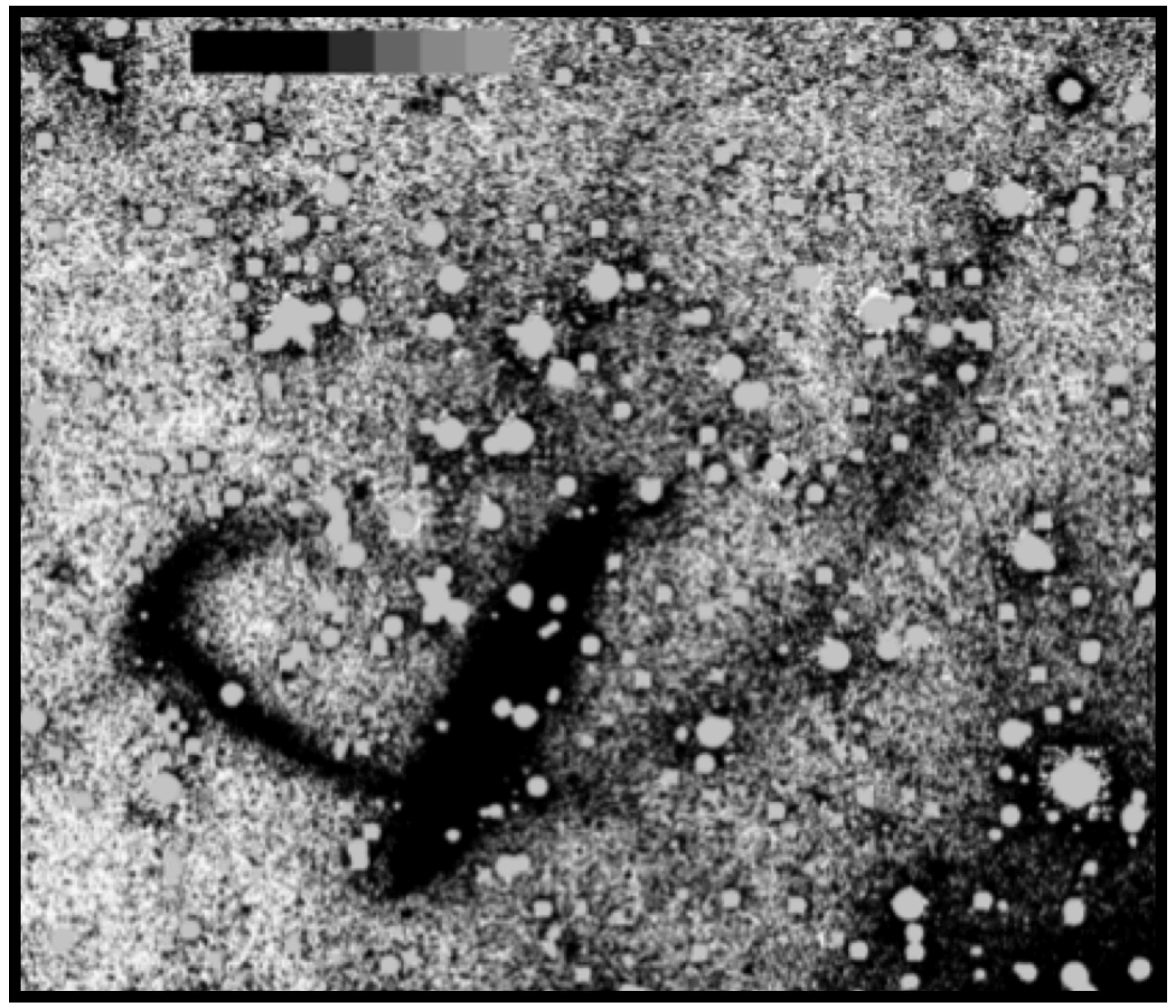


Martínez-Delgado+2009

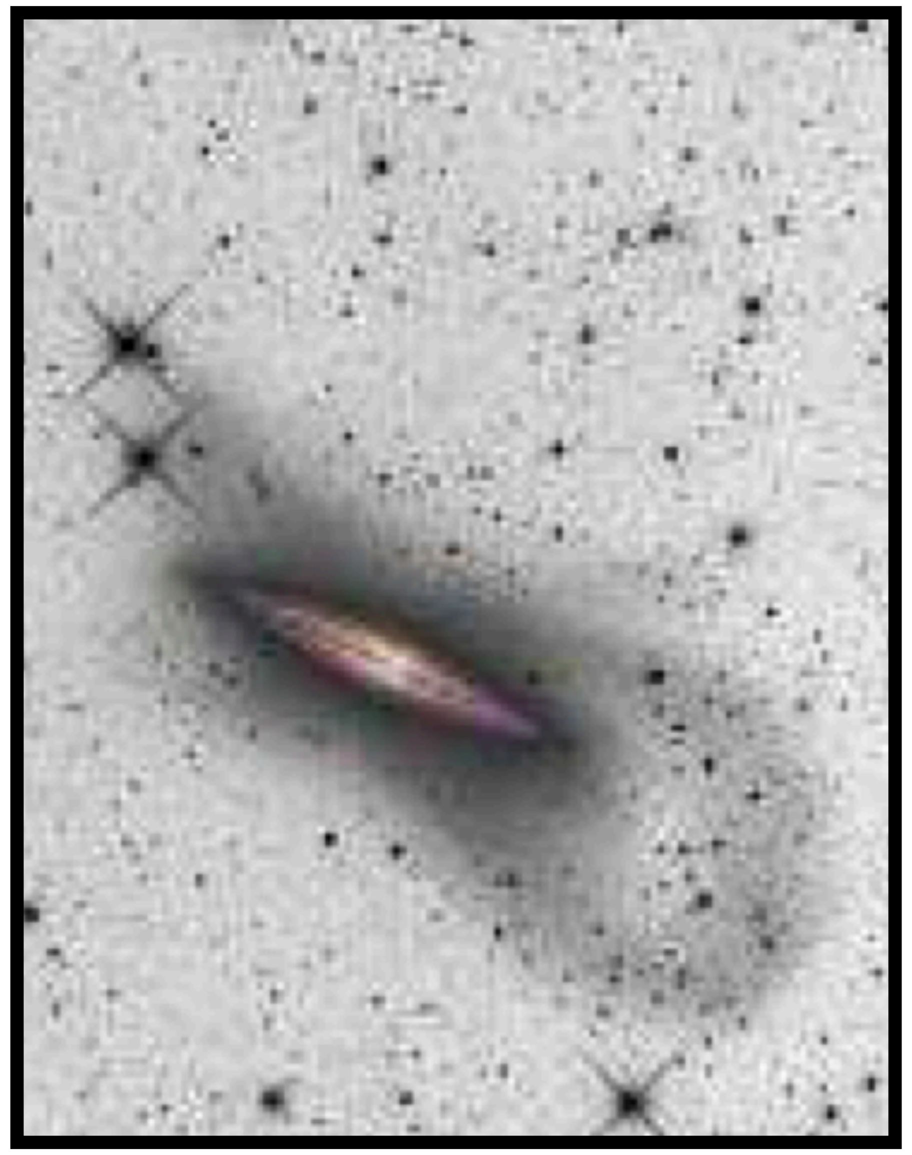




Pohlen+2004



Van Dokkum+2019



Martínez-Delgado+2010

Stellar Streams around external galaxies

- Many 10000s+ of tidal features with Rubin, Roman
- d_{obs} = Photometry [2d Image, surface brightness]

Q: How to convert stream morphology

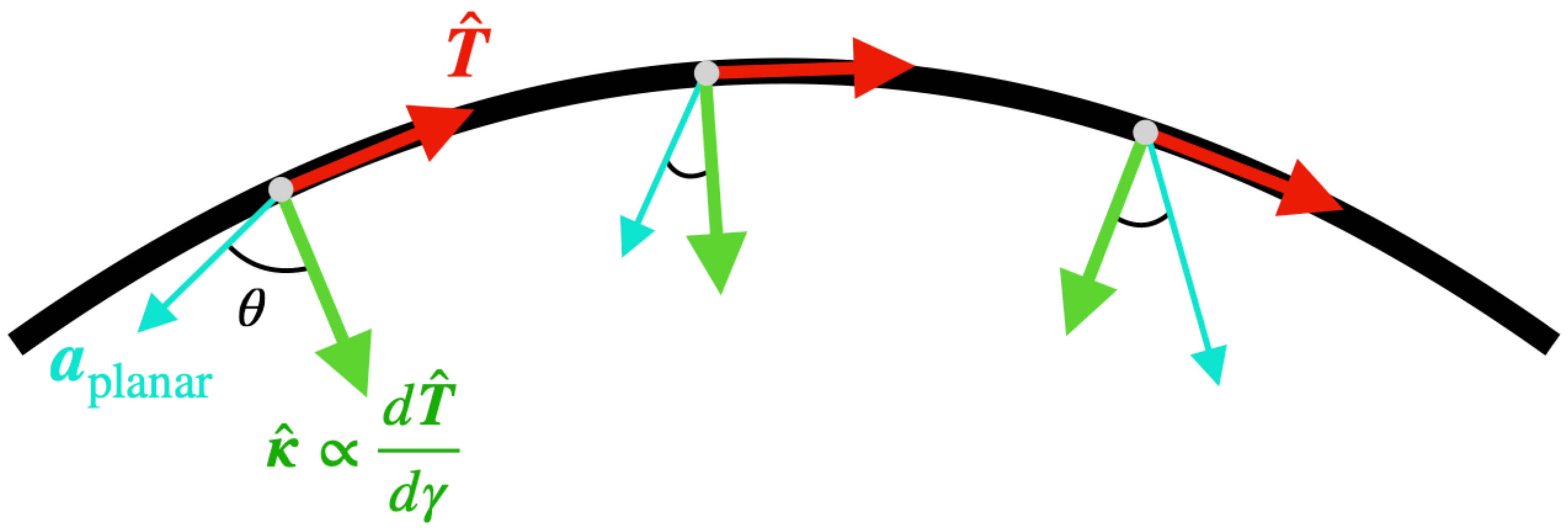
↓ ?

Physical Constraints on DM Distribution

What can projected stream morphology tell us?

1. Decompose the acceleration (along stream + perpendicular to stream)

$$\boldsymbol{a}_{\text{planar}} \equiv \frac{d\boldsymbol{v}_{\text{planar}}}{dt} = \underbrace{\left[\dot{v}_T \hat{\boldsymbol{T}} + v_\kappa \frac{d\hat{\boldsymbol{\kappa}}}{dt}\right]}_{\boldsymbol{a}_T = (\boldsymbol{a}_{\text{planar}} \cdot \hat{\boldsymbol{T}})\hat{\boldsymbol{T}}} + \underbrace{\left[\dot{v}_\kappa \hat{\boldsymbol{\kappa}} + v_T \frac{d\hat{\boldsymbol{T}}}{dt}\right]}_{\boldsymbol{a}_\perp = (\boldsymbol{a}_{\text{planar}} \cdot \hat{\boldsymbol{\kappa}})\hat{\boldsymbol{\kappa}}},$$



2. Perpendicular acceleration depends on curvature

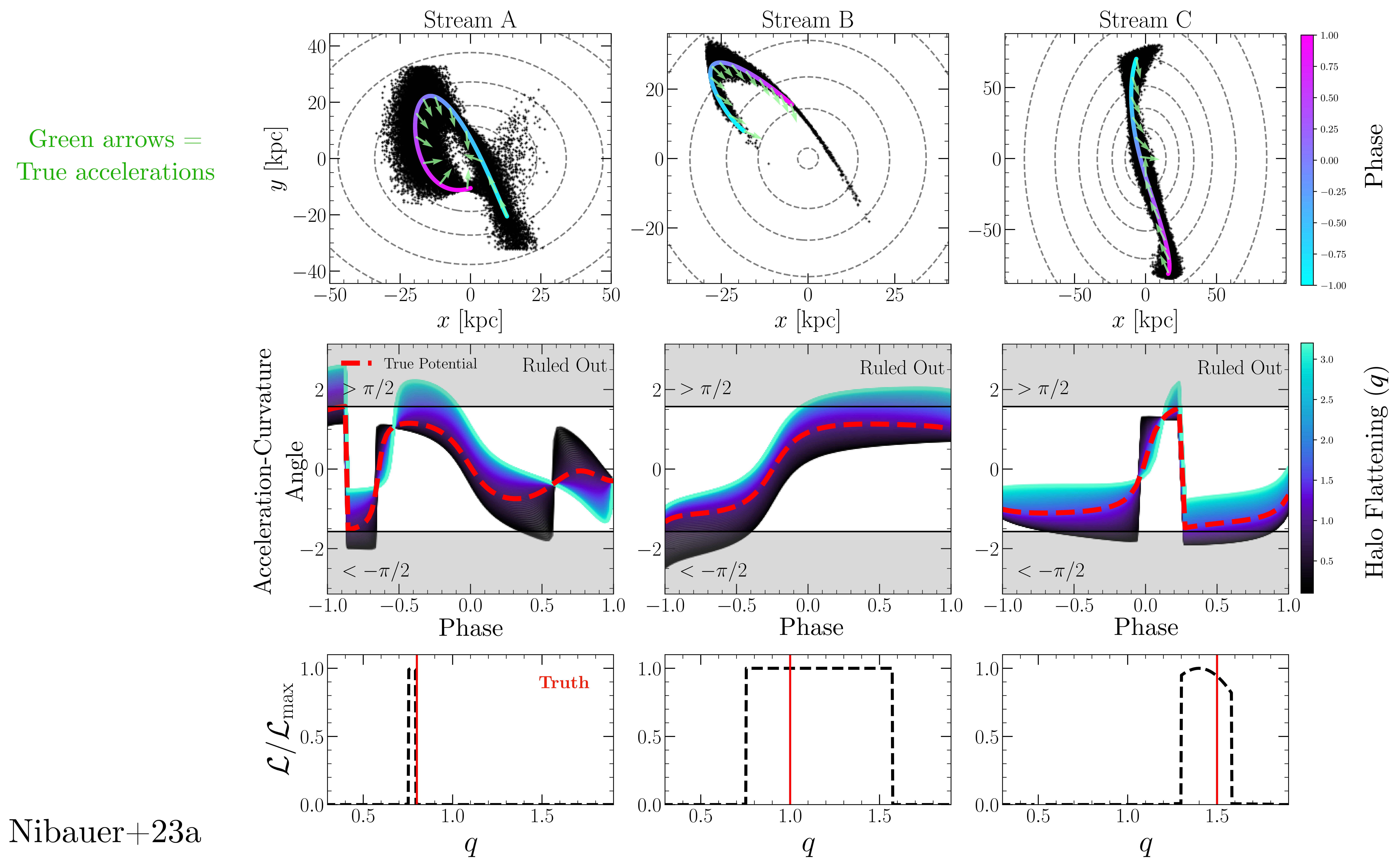
Halo Model — **Observable**

$$\boxed{\boldsymbol{a}_\perp} = \left(\dot{v}_\kappa + v_T \left\|\frac{d\hat{\boldsymbol{T}}}{dt}\right\|\right)\boxed{\hat{\boldsymbol{\kappa}}}$$

What this means: the angle between the stream and acceleration vector should be $< 90°$

Halo models that are inconsistent with this principle can be ruled out

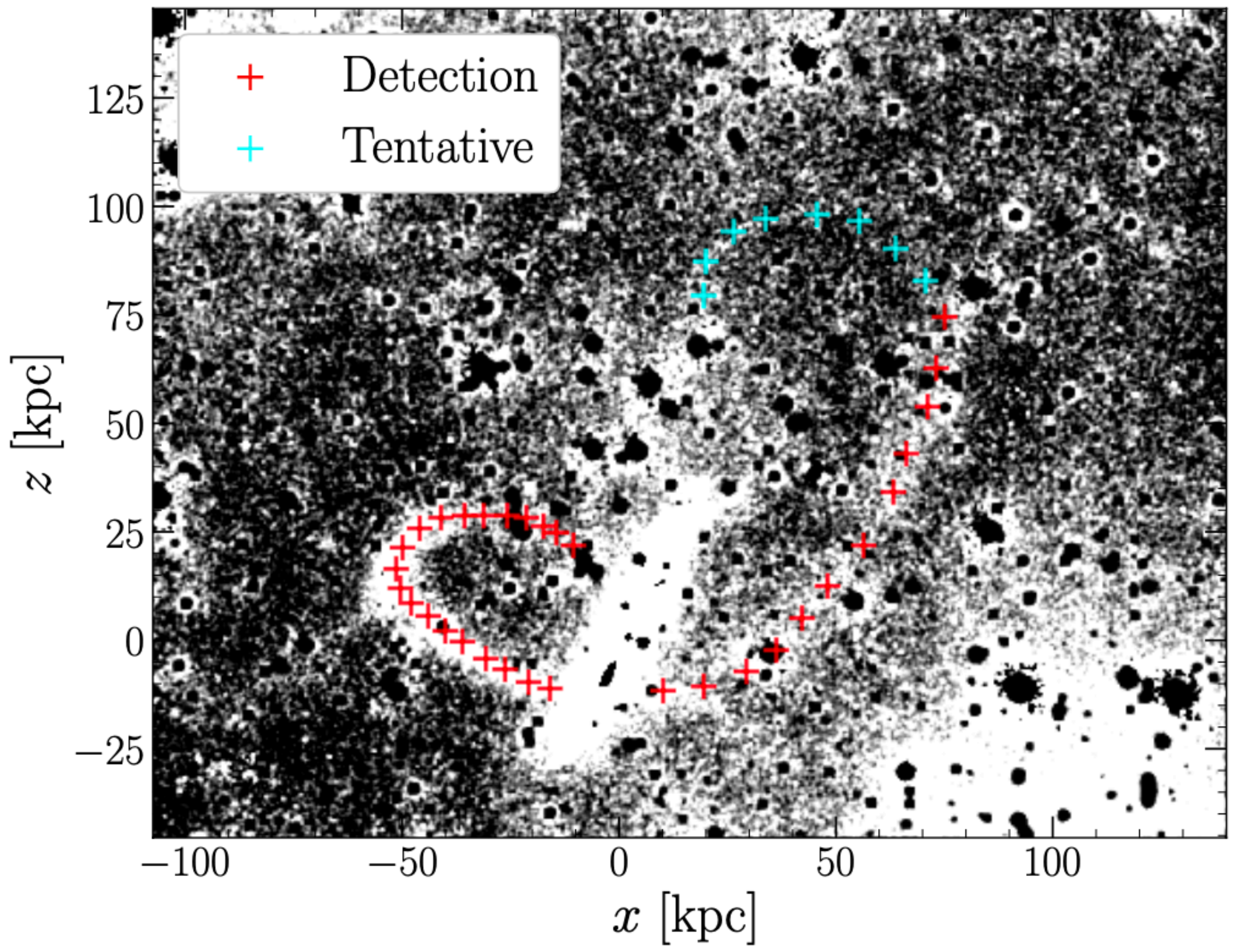
Nibauer+23a



Green arrows =
True accelerations
Stream A
Stream B
Stream C
y [kpc]
x [kpc]
Phase
True Potential
Ruled Out
> π/2
< −π/2
Acceleration-Curvature Angle
Halo Flattening (q)
Truth
ℒ/ℒmax
q

Nibauer+23a

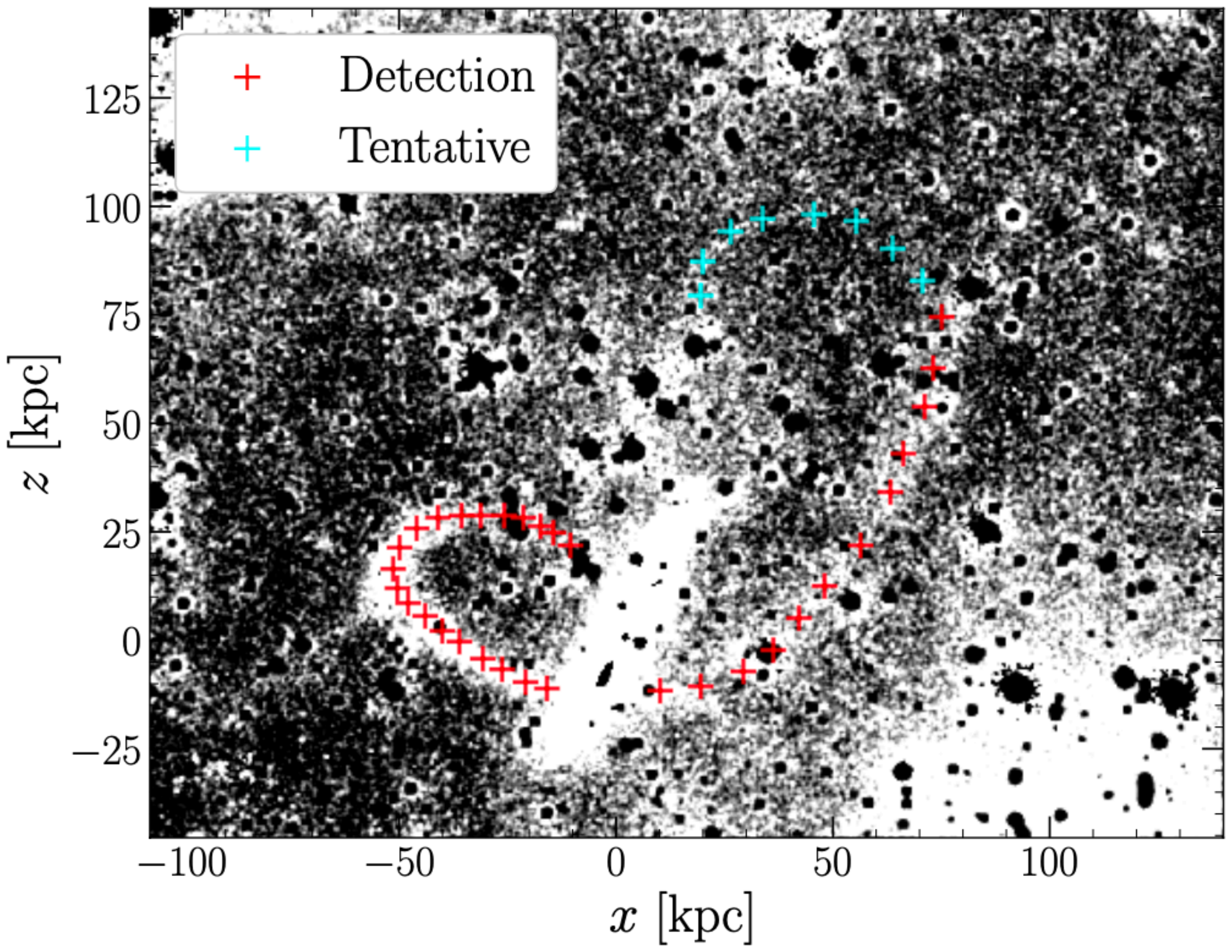
Application: NGC 5907 [Dragonfly Imaging]

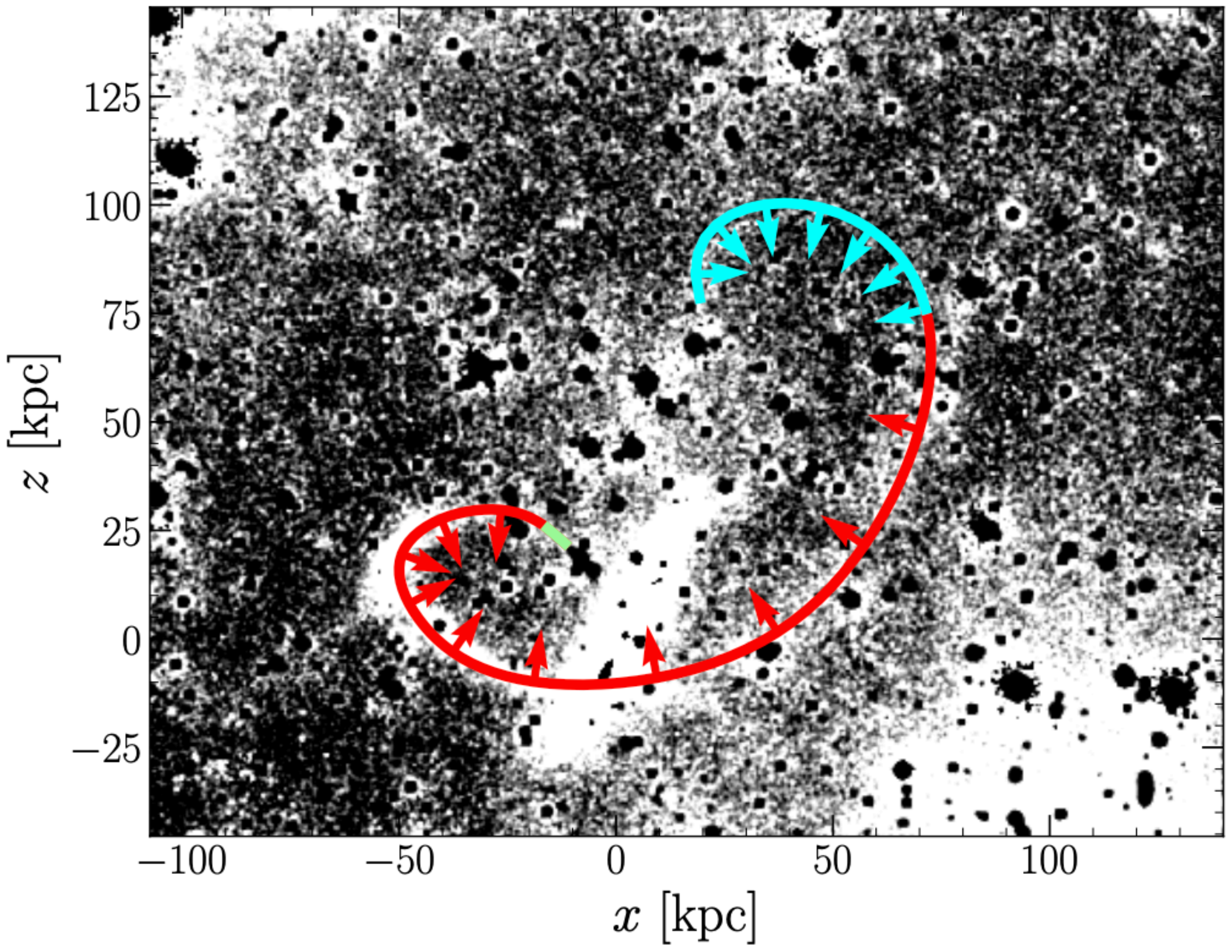


Constrain: **Flattening** (q), **Rotation** (Disk-Halo Angle)

Nibauer+23a

Application: NGC 5907 [Dragonfly Imaging]





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Nibauer+23a

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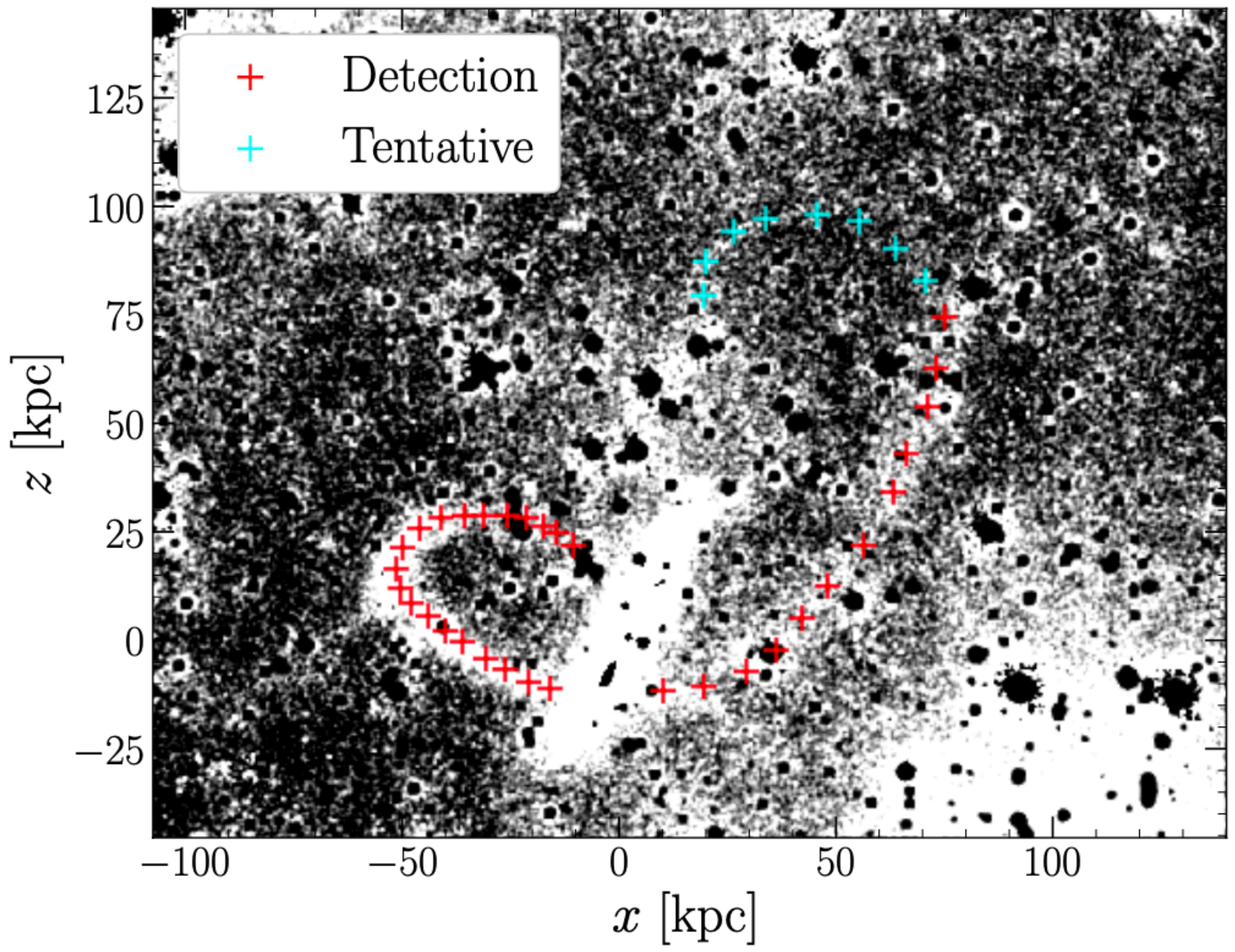
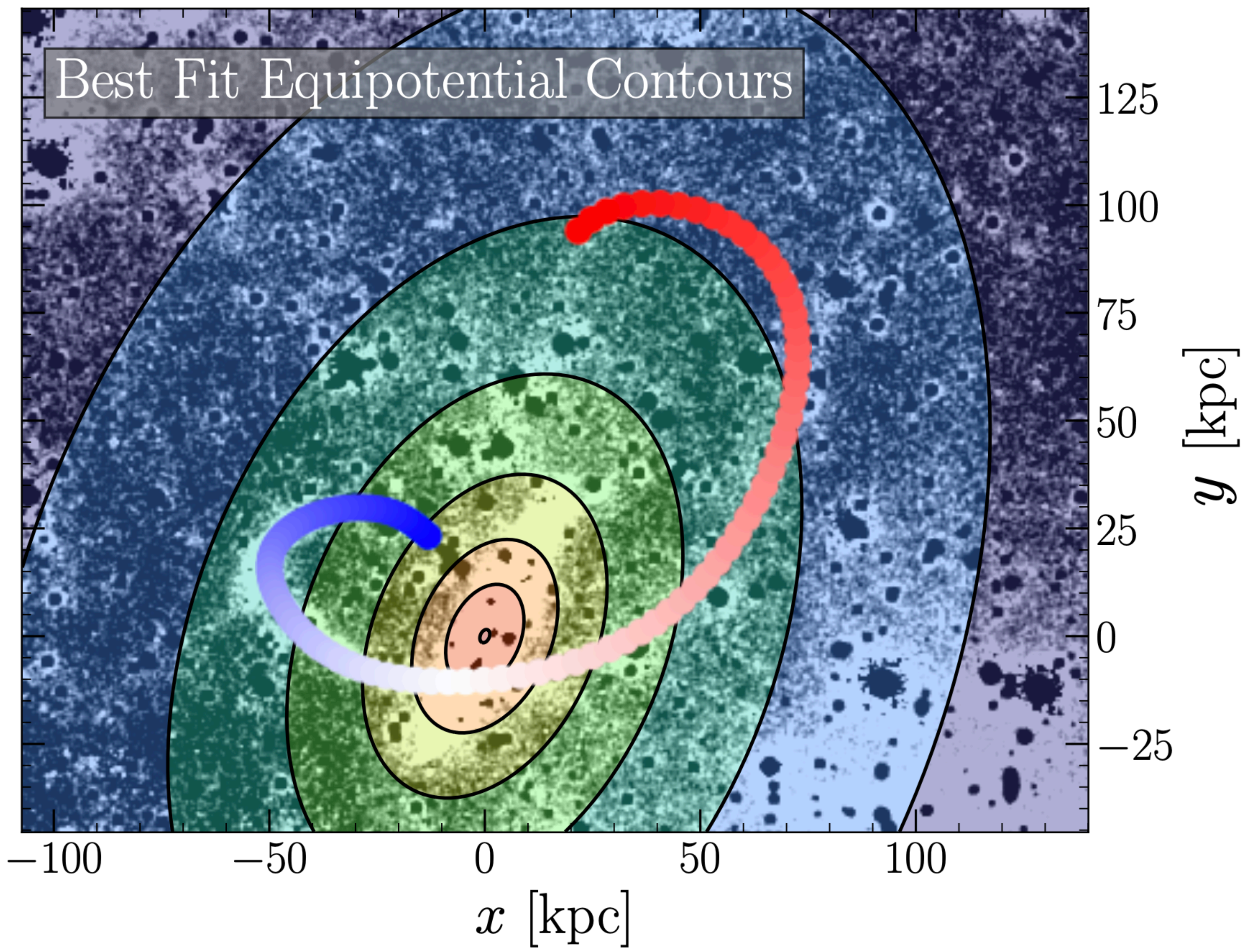
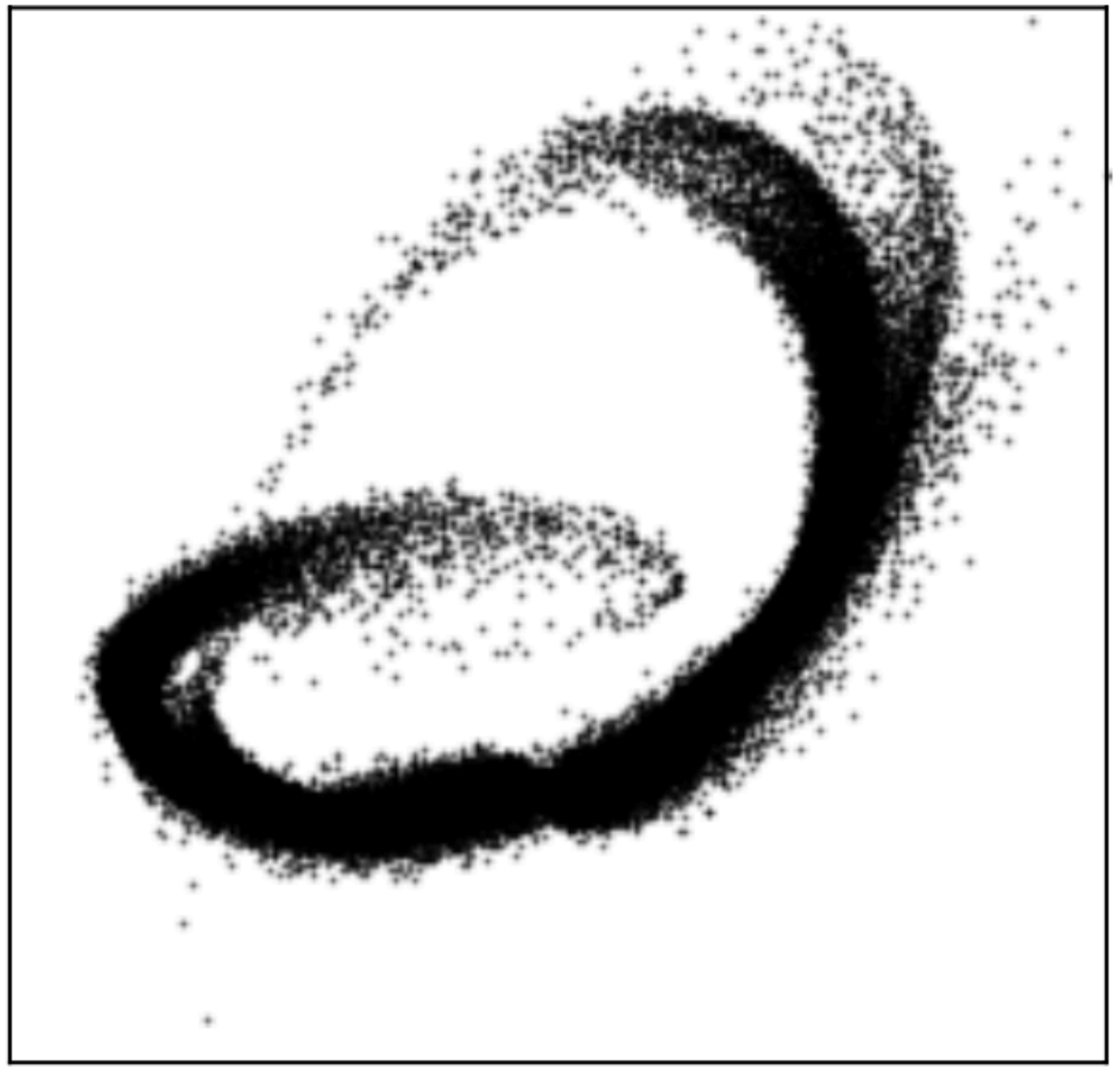




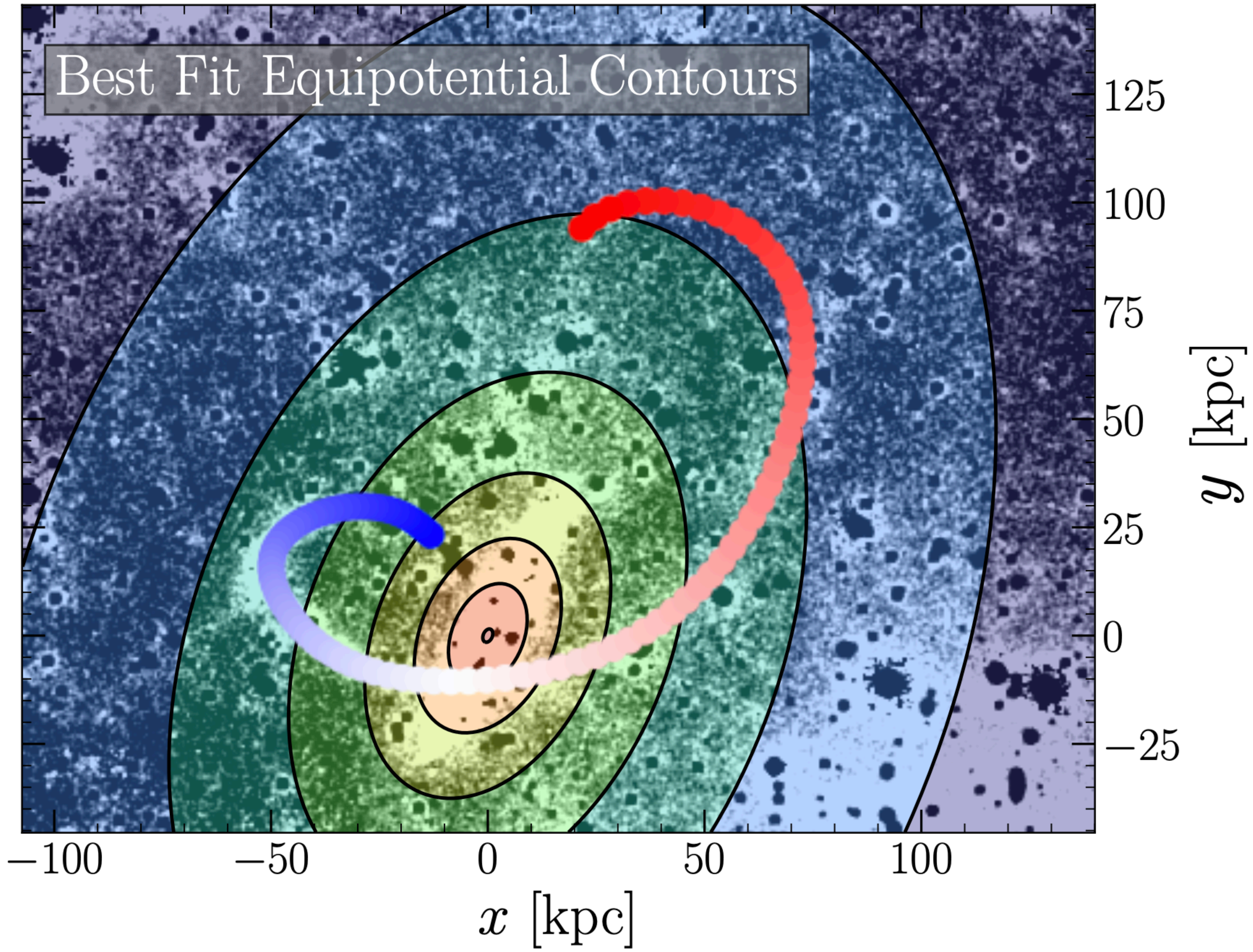
Constrain: **Flattening** (q), **Rotation** (Disk-Halo Angle)

Nibauer+23a

Forward model at best fit potential



NGC 5907



Detection

10000s+ tidal features → Automated track characterization → Halo shapes ↔ Cosmological simulations

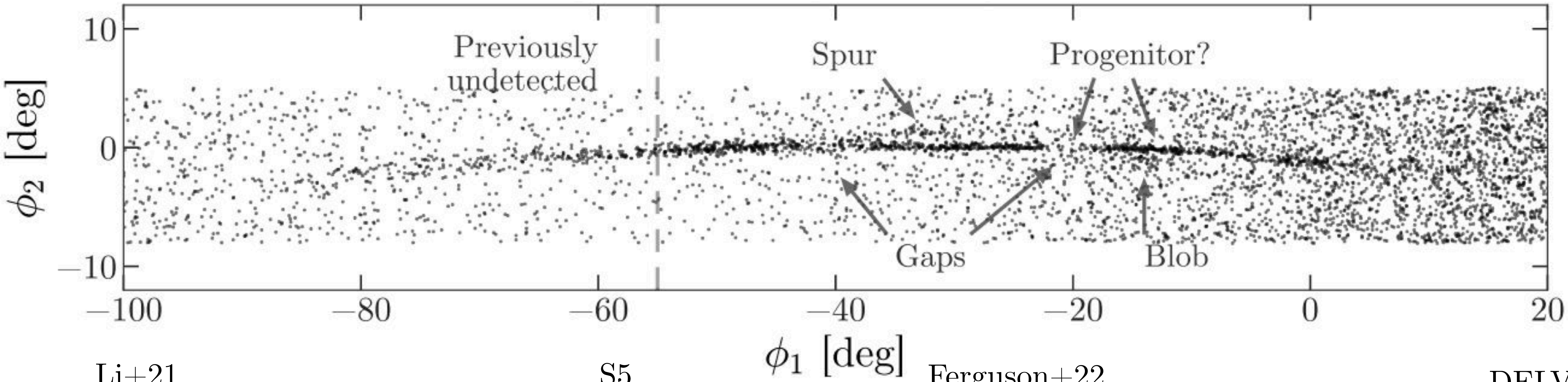
Nibauer+23a


THE MILKY WAY
STREAM ATLAS
May 2024
Legend
Prograde Polar
Planar
Retrograde Polar
-1.0
-0.5
0.0
0.5
1.0
$\mathrm{sgn}(L_z)\ L_\perp/|L|$
Streams
Total number: 87
Typical mass: $9\times10^3\ M_\odot$
Longest stream: Orphan-Chenab [210 deg]
Narrowest stream: C-20 [0.072 deg]
Most member stars: Fimbulthul [3724]
Largest Galactocentric distance: Kwando [53 kpc]
Closest to the Earth: New-3 [1.0 kpc]
Credit
Ana Bonaca & Adrian Price-Whelan
Data: Ibata et al., arXiv:2311.17202
4 kpc
8 kpc
12 kpc
Sun
Outer halo streams (today)
Pearson+24

The known Milky Way streams show rich density structure

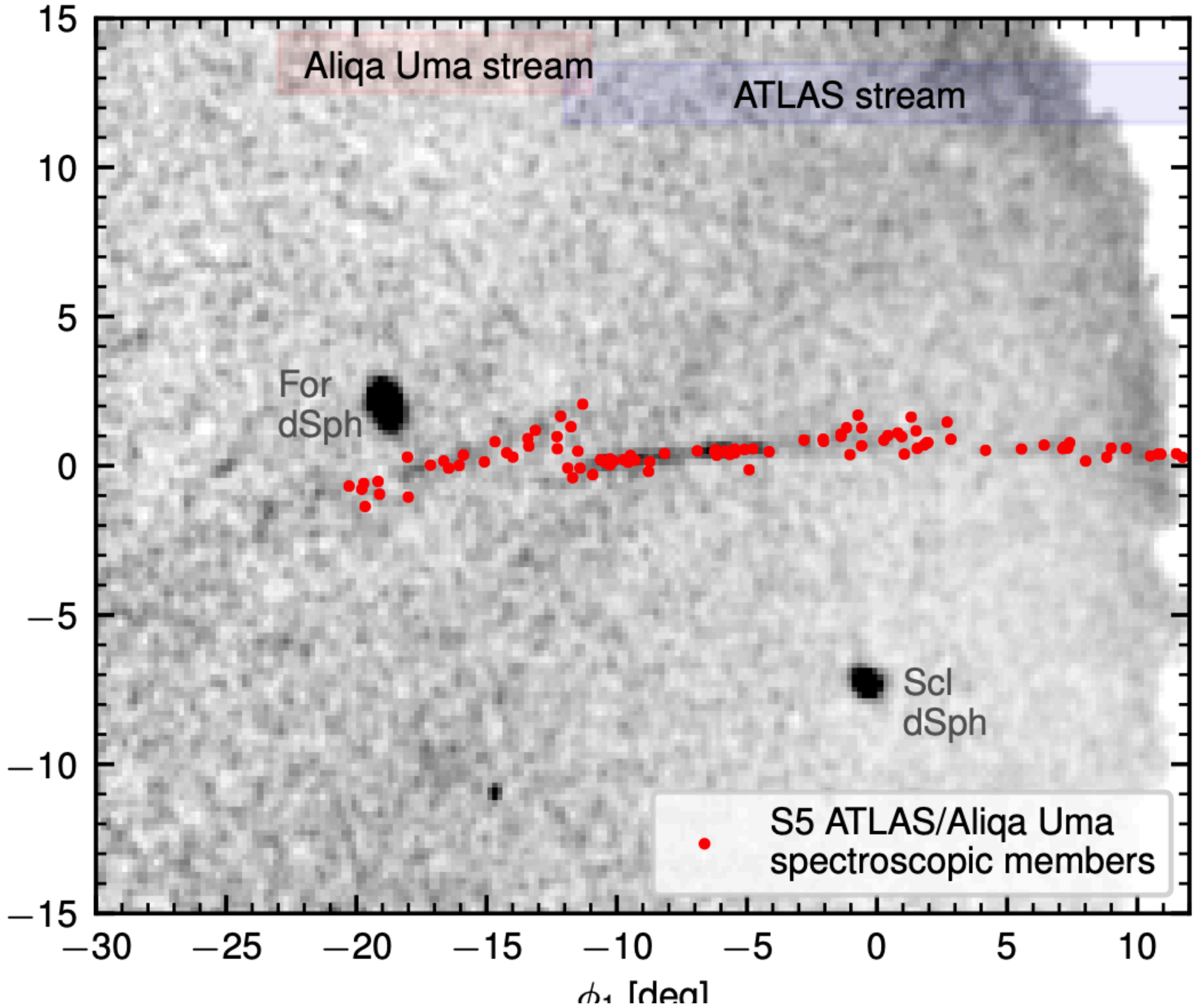
Price-Whelan, Bonaca 2018

Gaia + Pan-STARRS



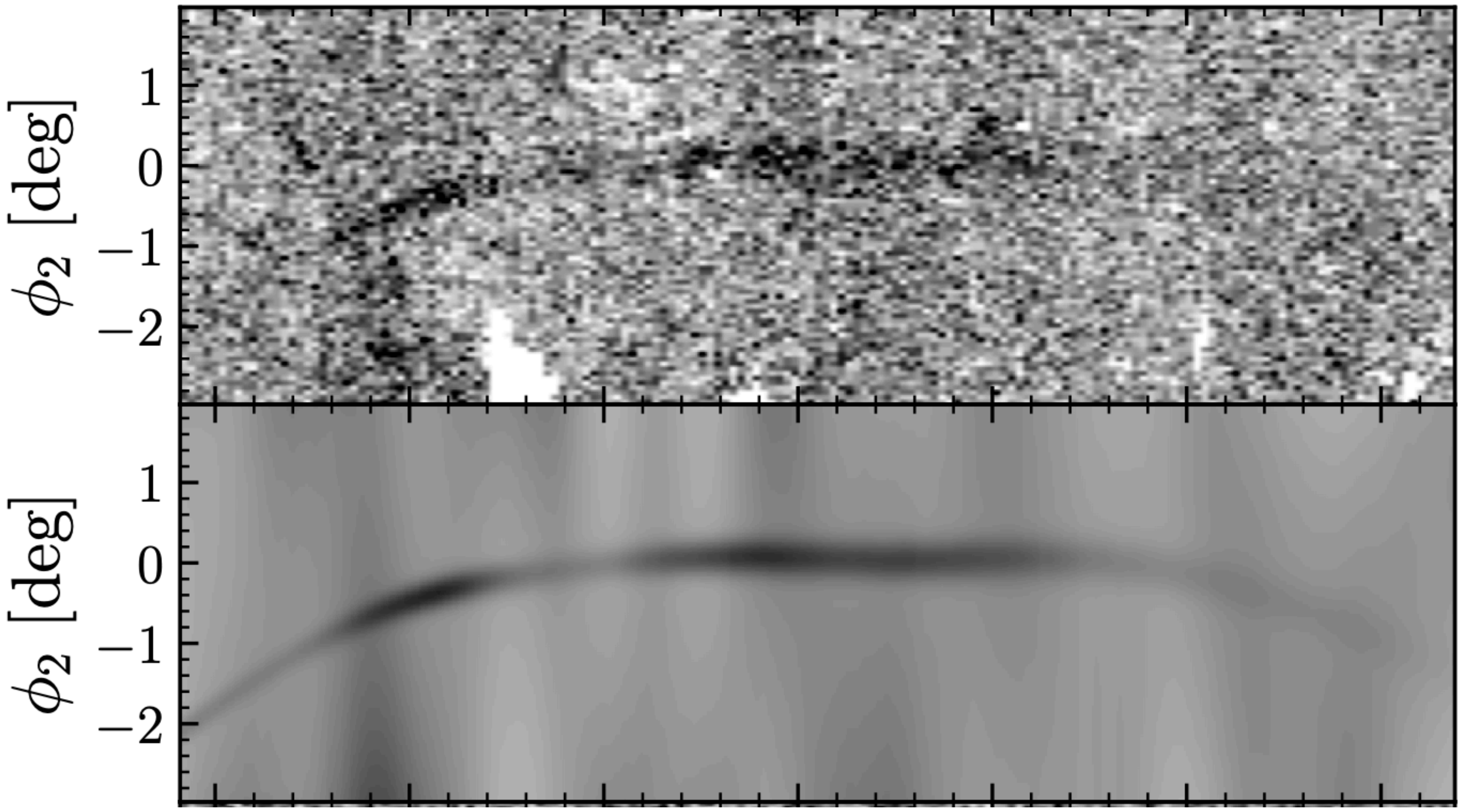
Li+21

S5

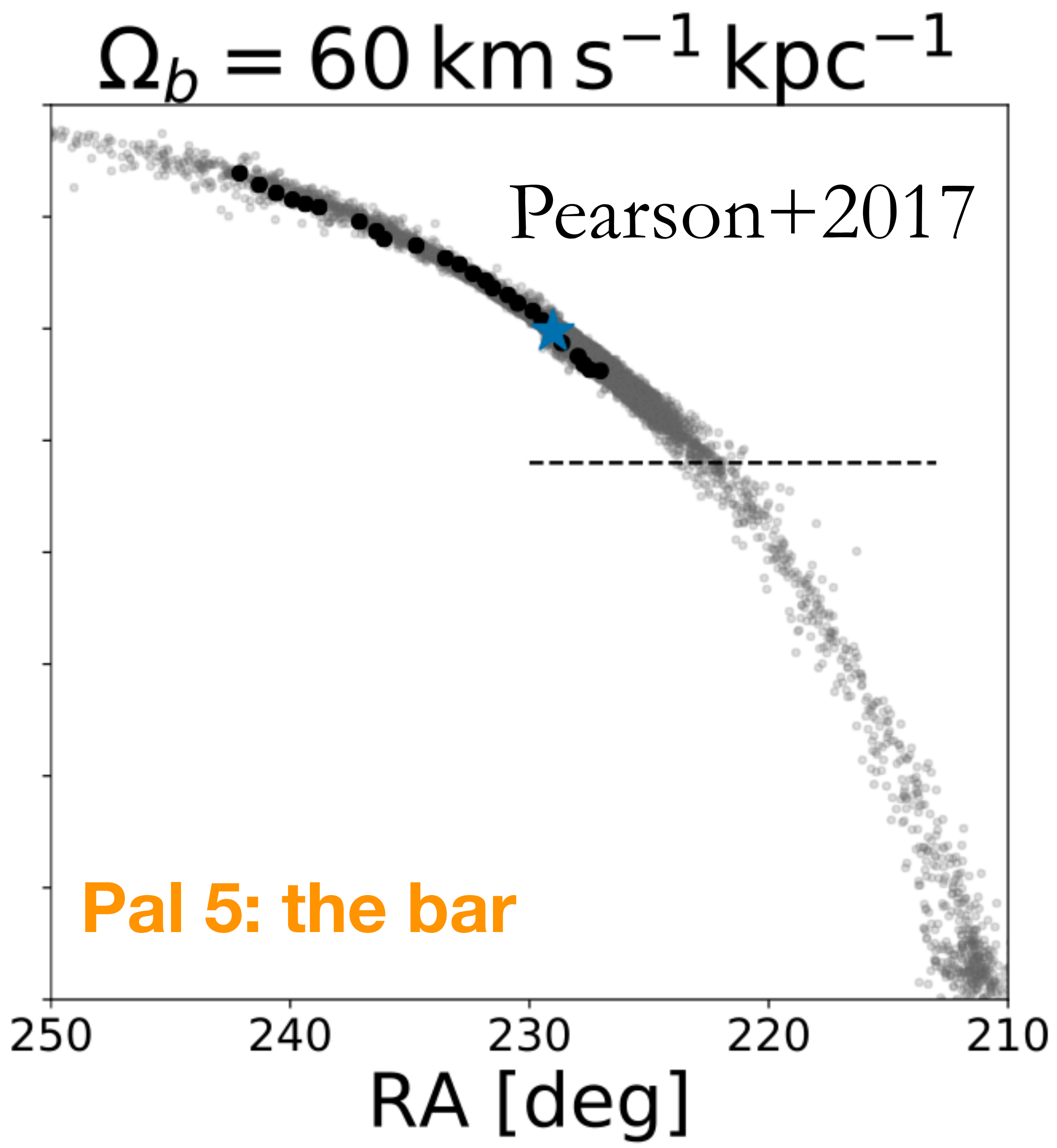


Ferguson+22

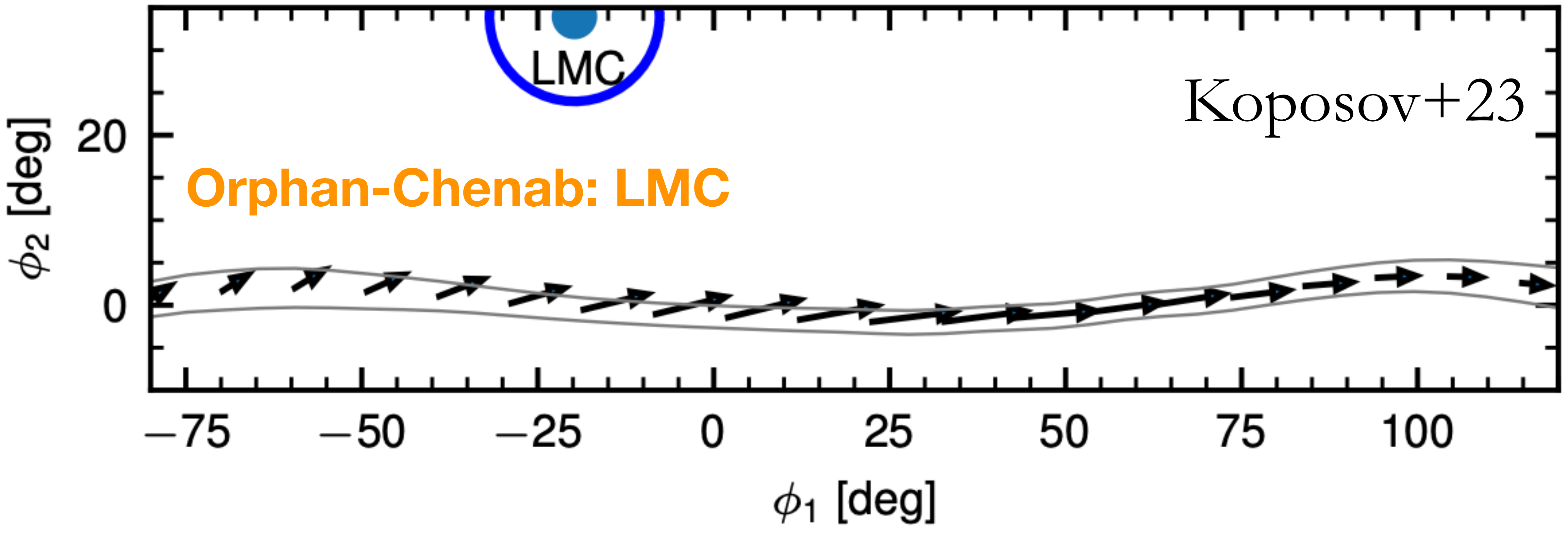
DELVE

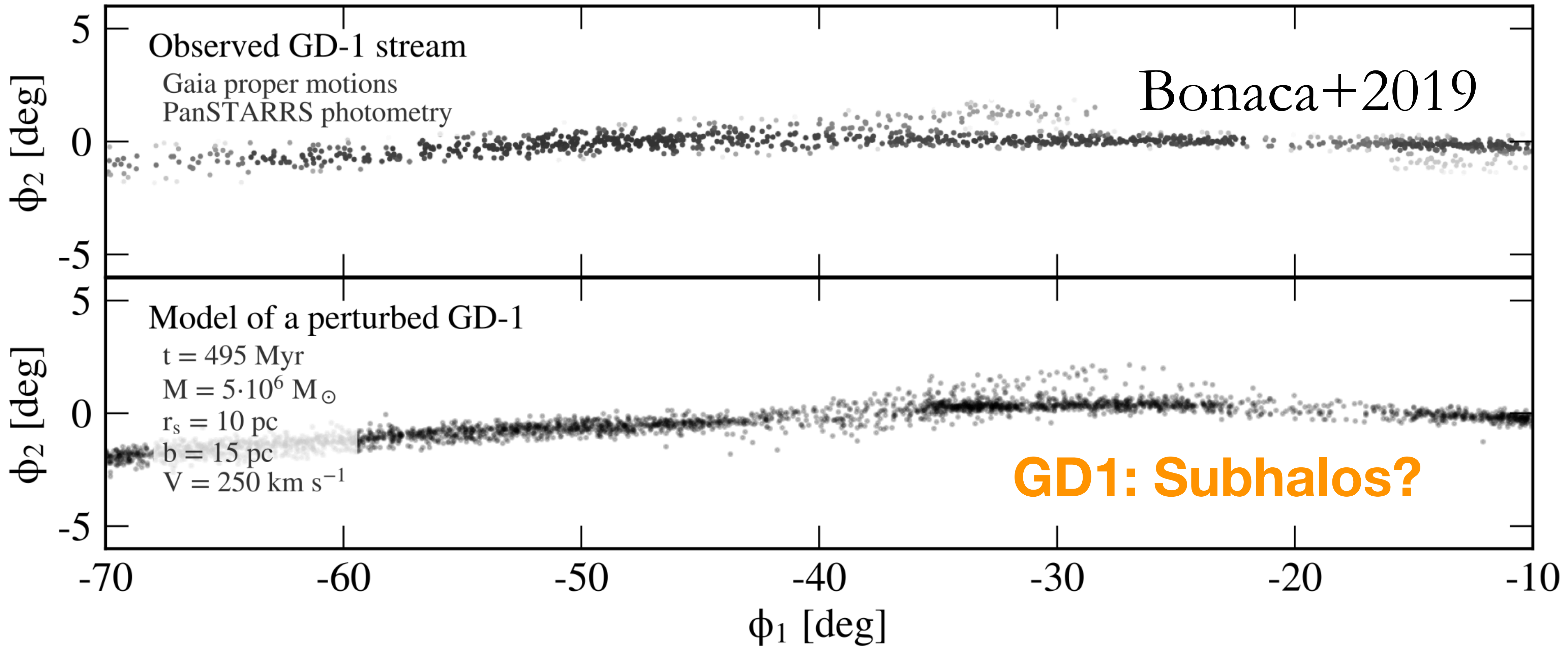


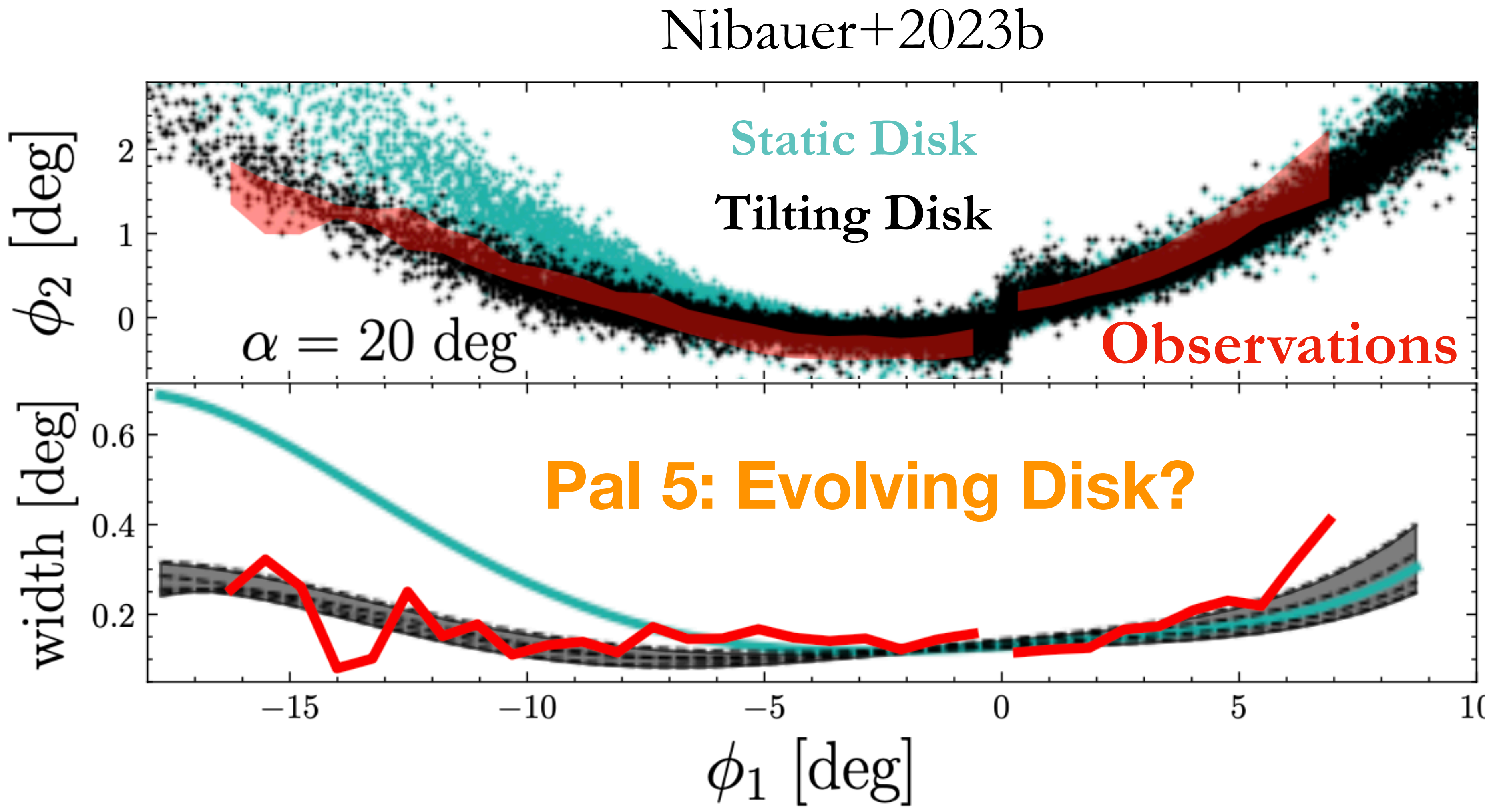
Where do the density variations come from?



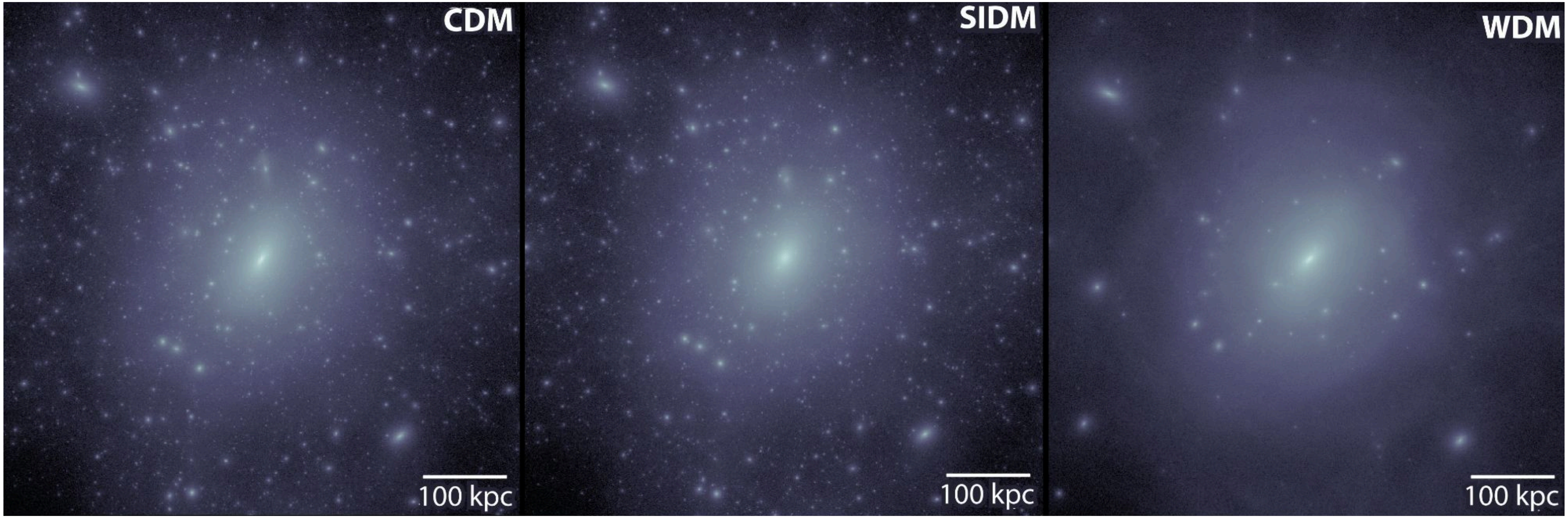
Large range of scales influence stream properties
Small scales: important for competing dark matter models





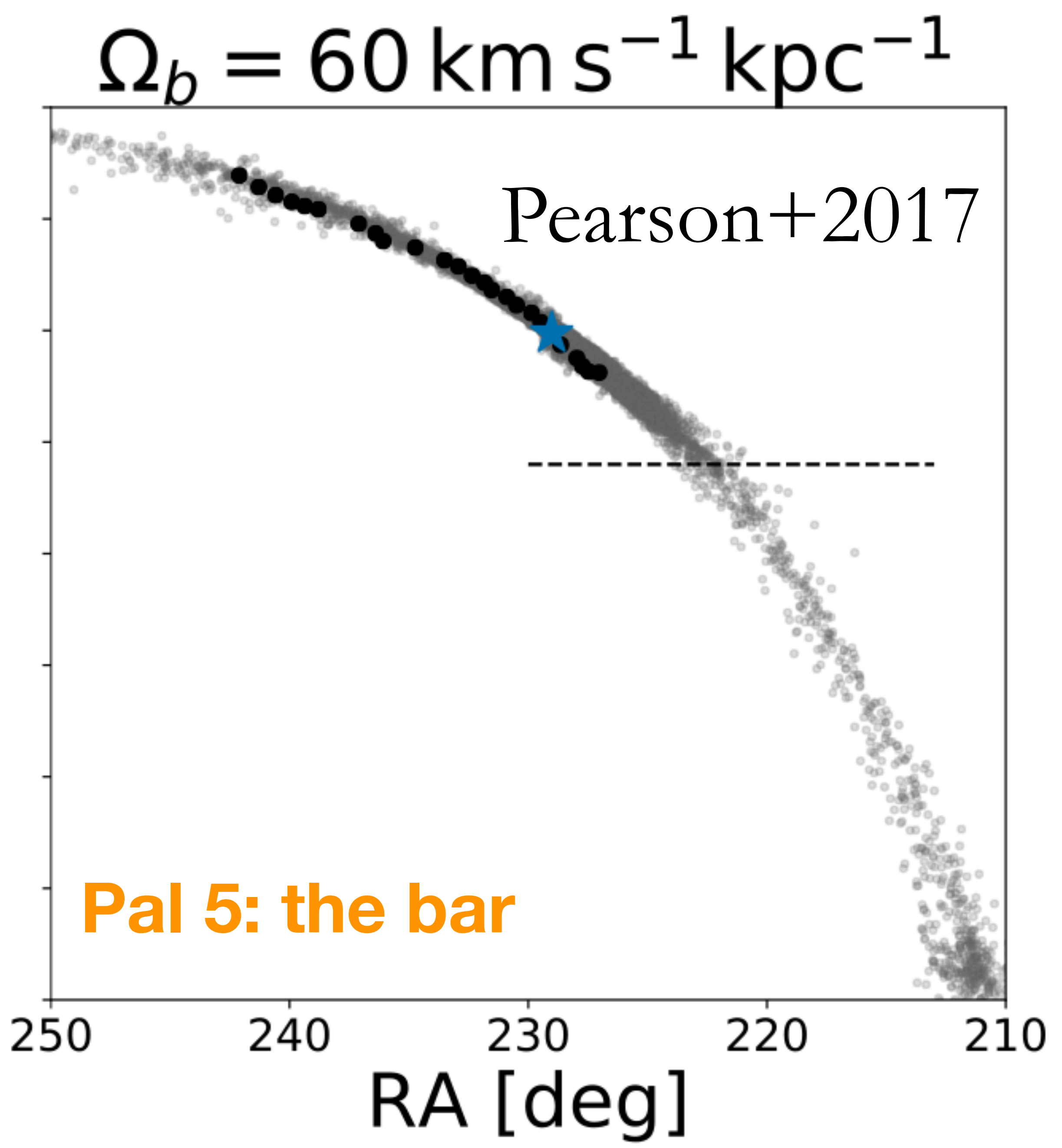


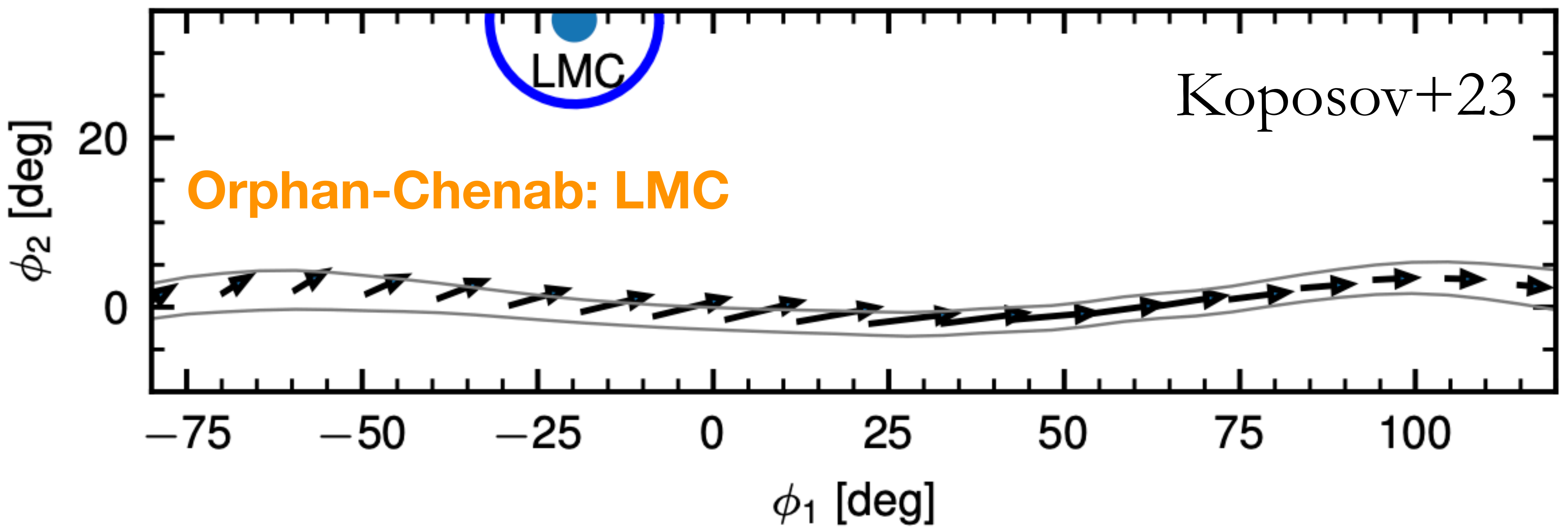
Substructure imprints streams with density/kinematic variations

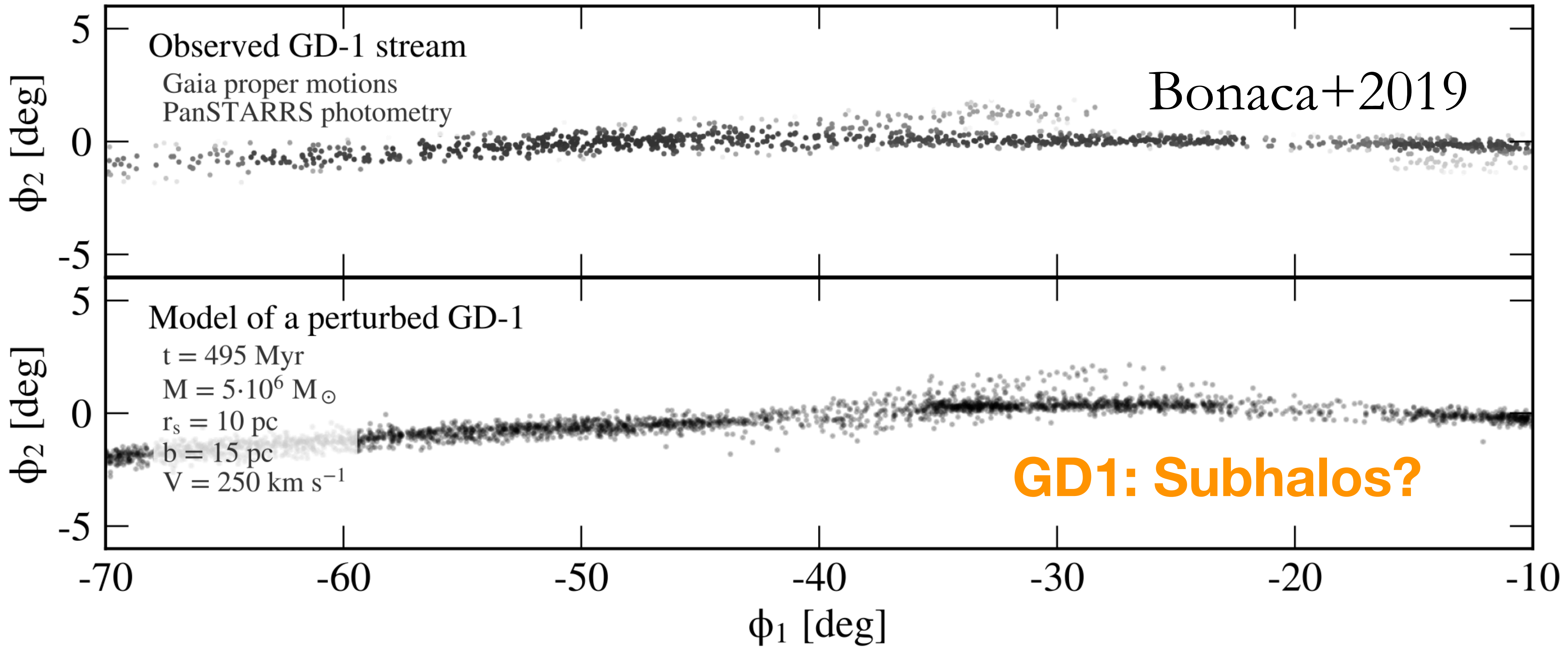


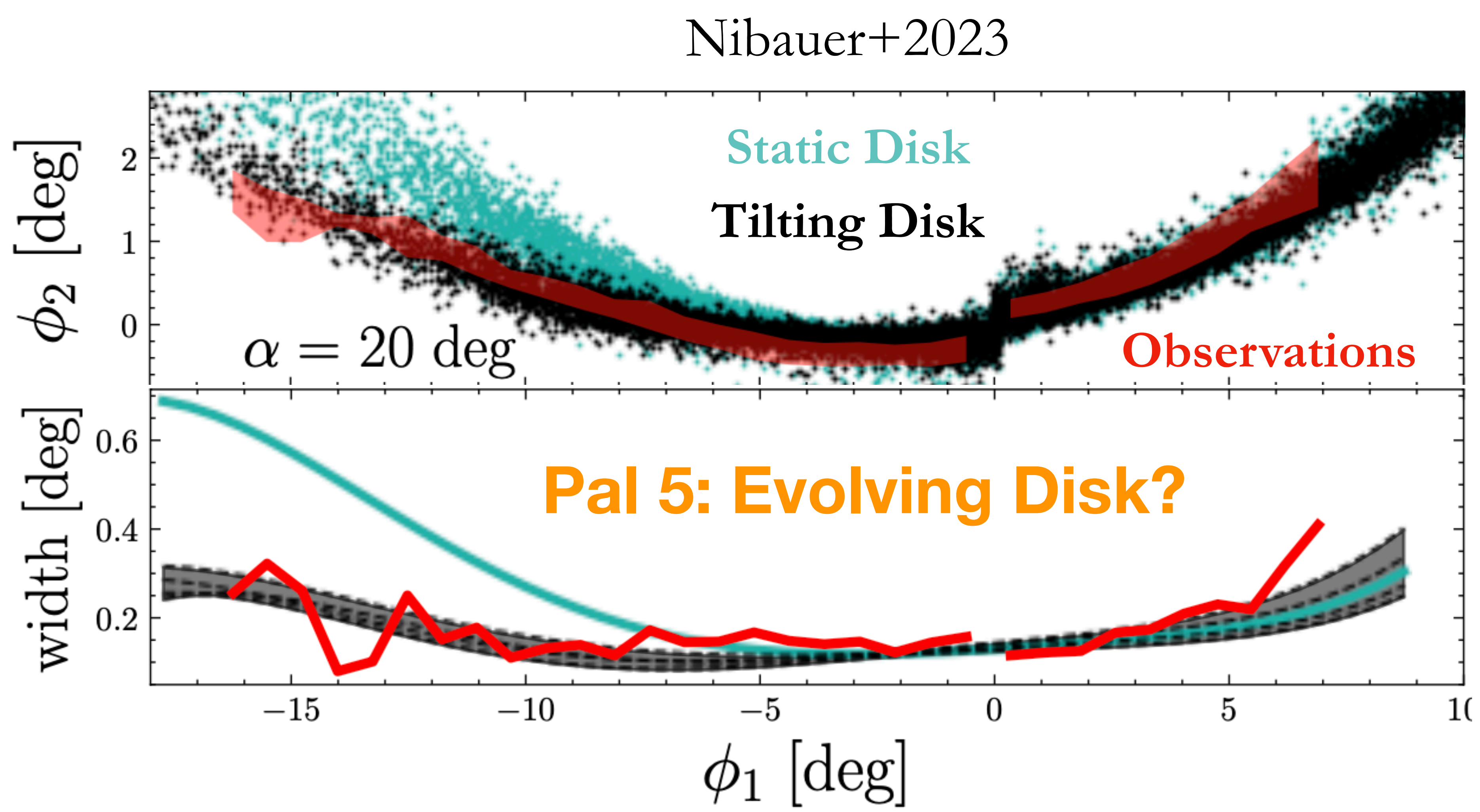
Adapted from Vogelsberger+2014, Bullock+2017

Streams are promising probes of dark substructure, but this is difficult…





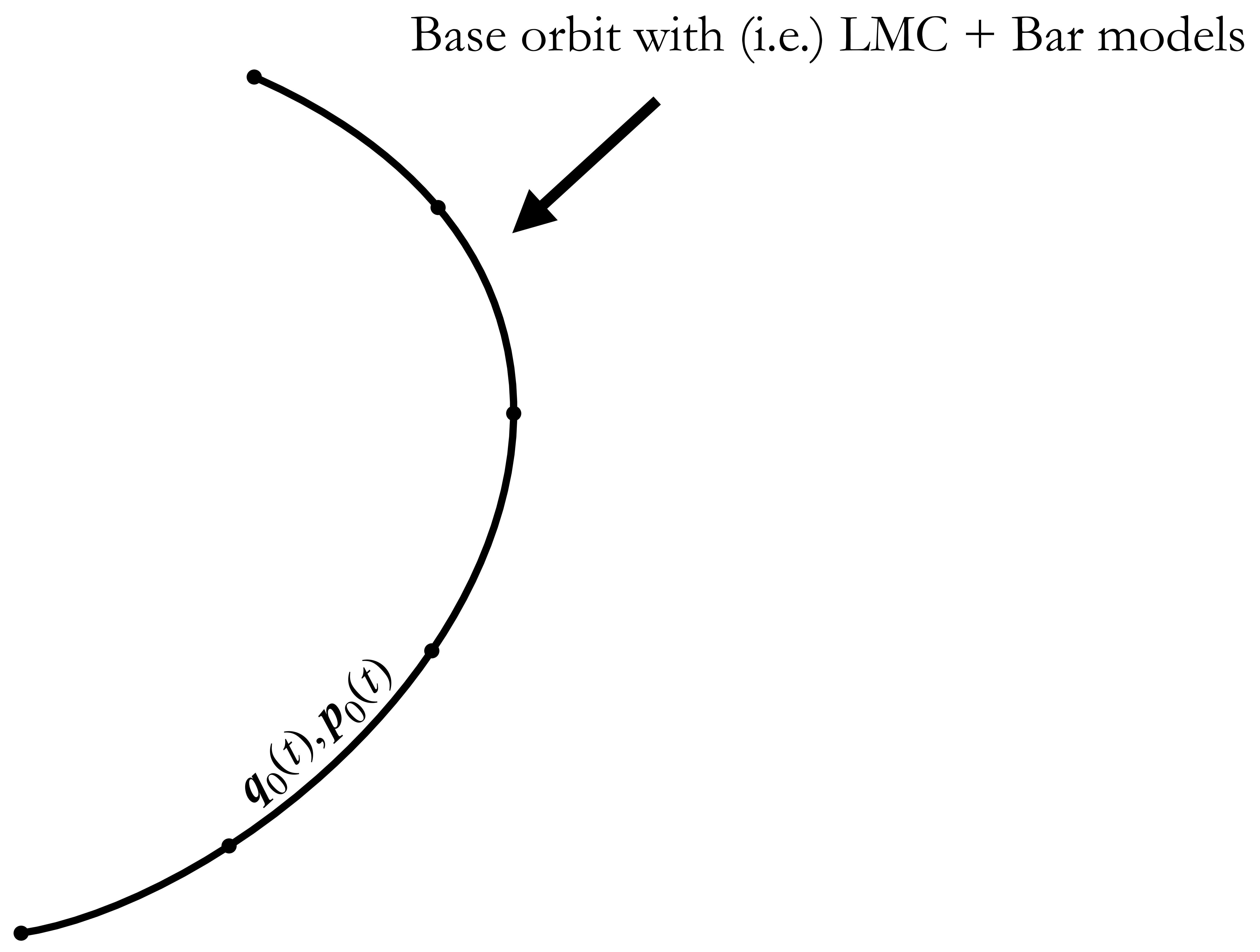




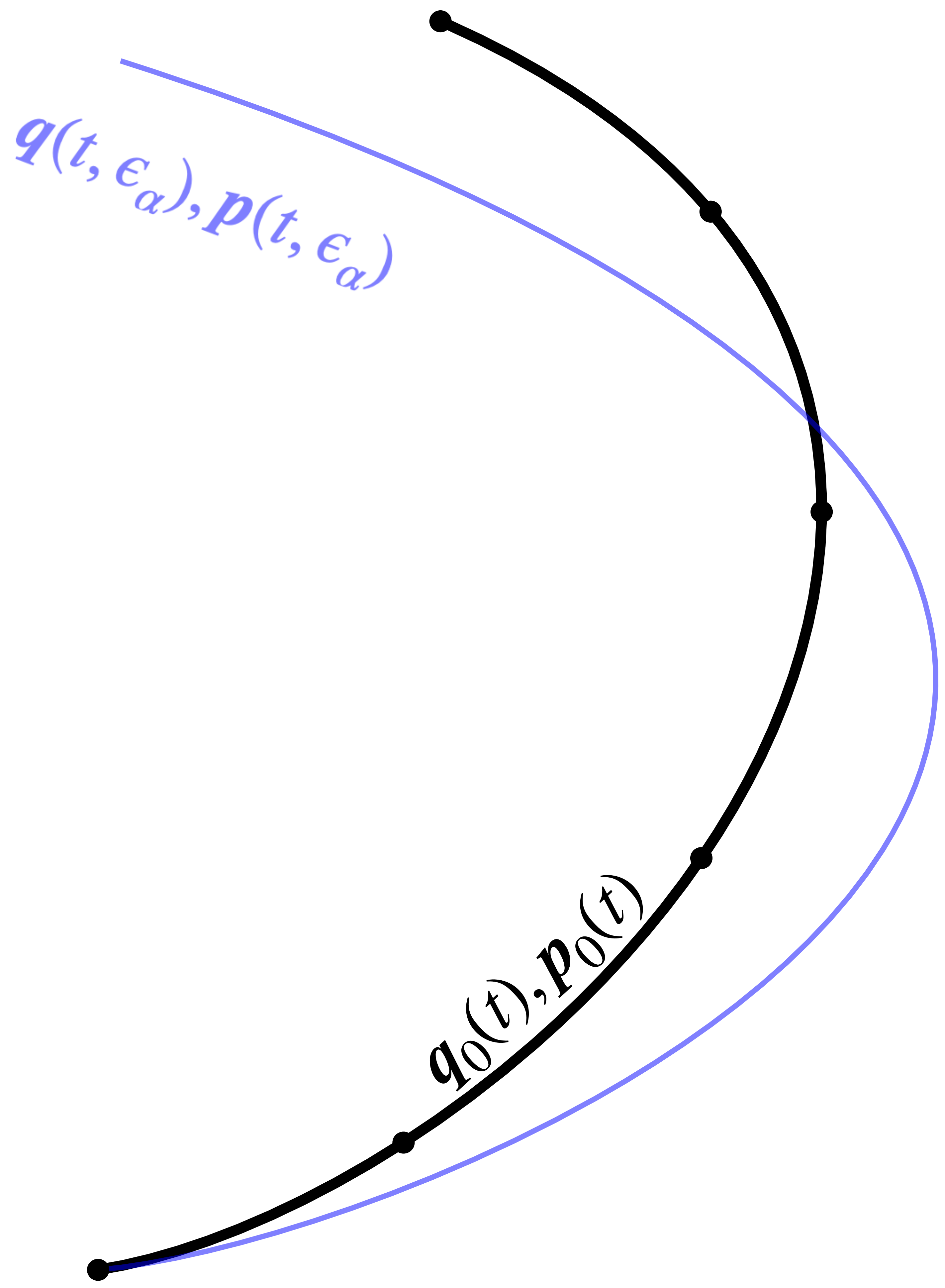
Toward a fast, flexible, stream model

- Observations already show rich density structure
- Many sources of perturbation (known baryonic structures and potentially substructures dark)
- Goal: fast, flexible (time-dependent) method for generating many impacts, incorporating known perturbers as a baseline

Method: treat the subhalos at linear order, simulate everything else at non-linear order

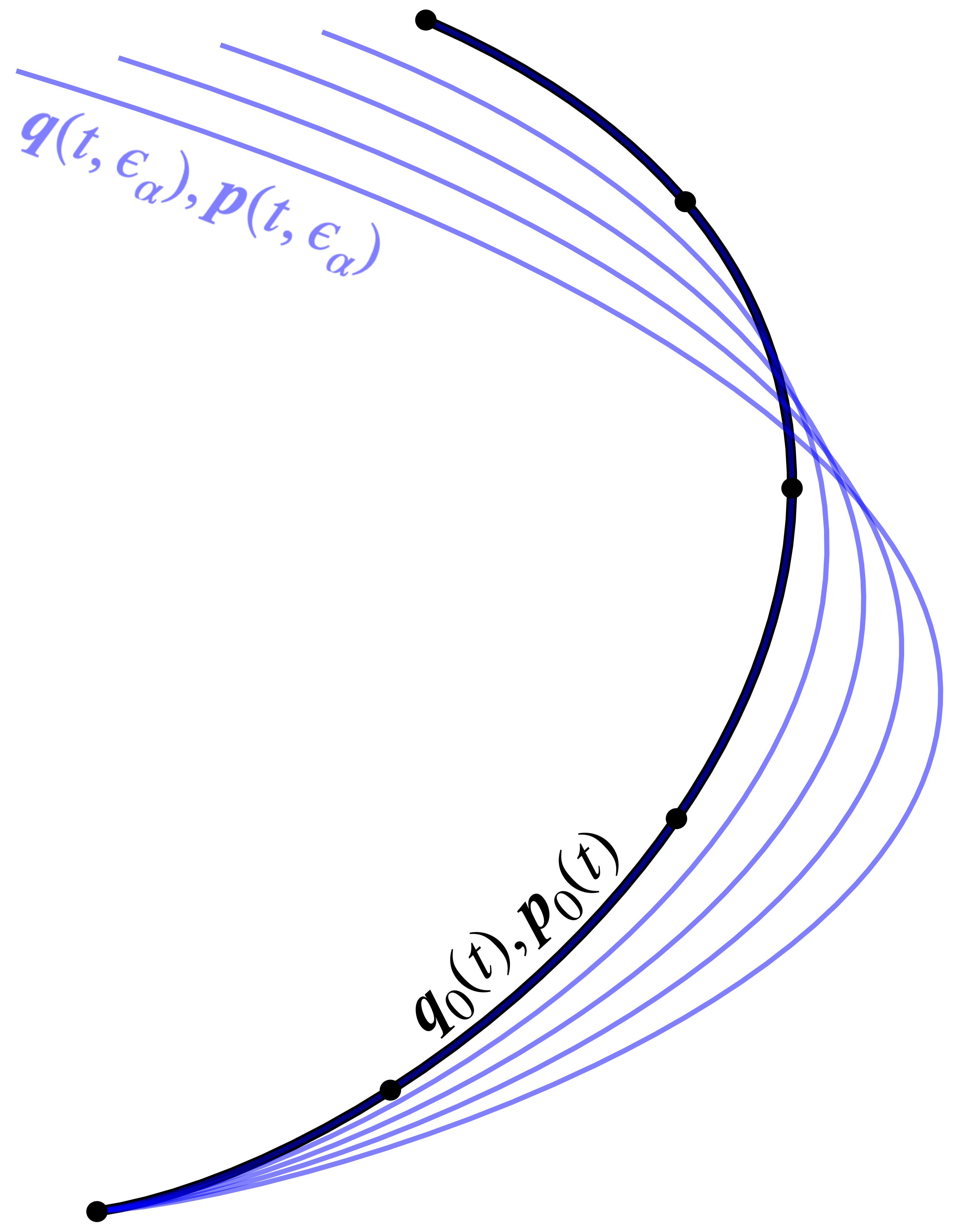


Method: treat the subhalos at linear order, simulate everything else at non-linear order



ϵ : controls perturbation strength (i.e., mass)

Method: treat the subhalos at linear order, simulate everything else at non-linear order



ϵ : controls perturbation strength (i.e., mass)

Method: treat the subhalos at linear order, simulate everything else at non-linear order

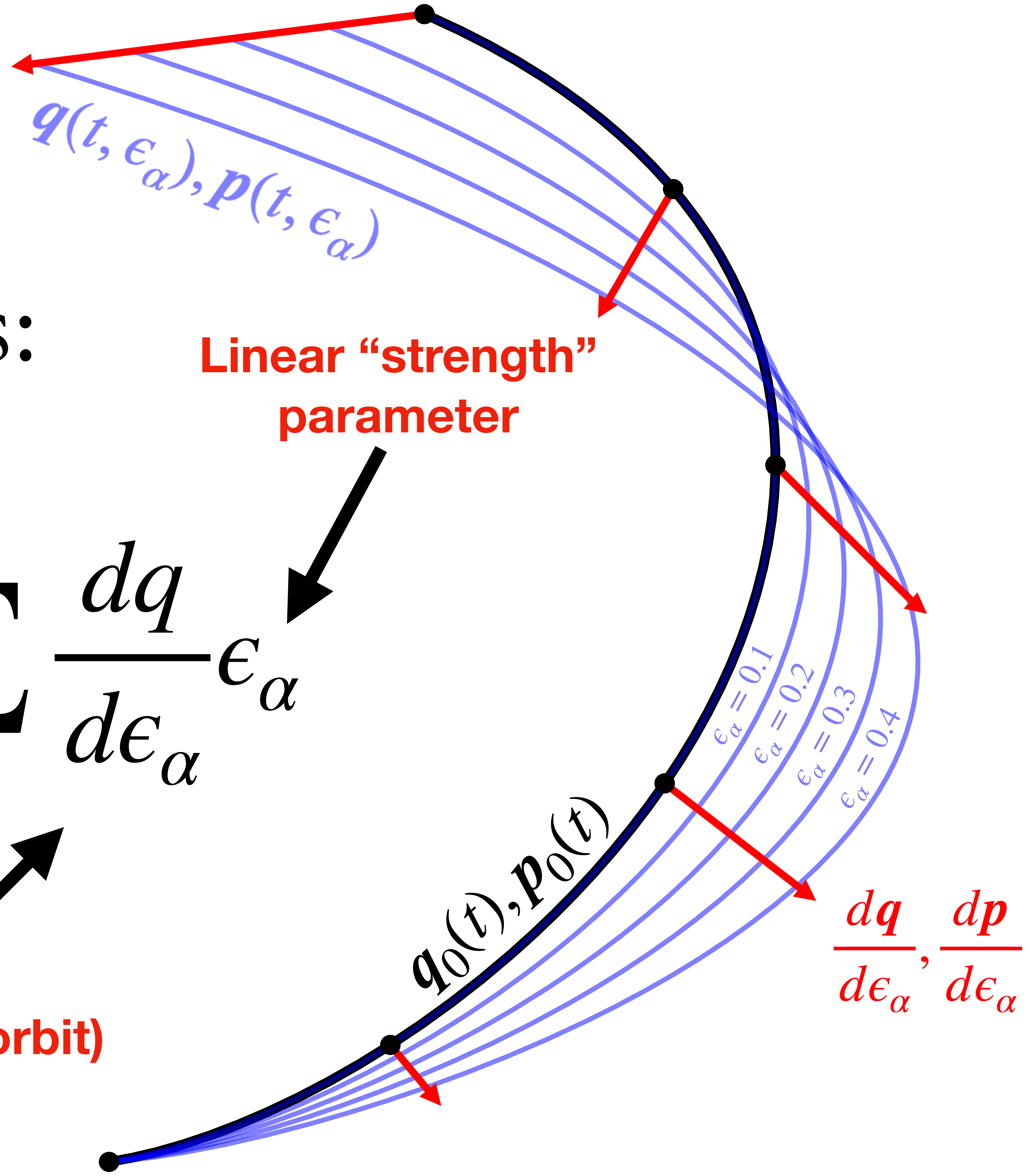
Once you have derivatives:

perturbed stream ≈

unperturbed stream + $\sum_{\alpha} \frac{dq}{d\epsilon_\alpha} \epsilon_\alpha$

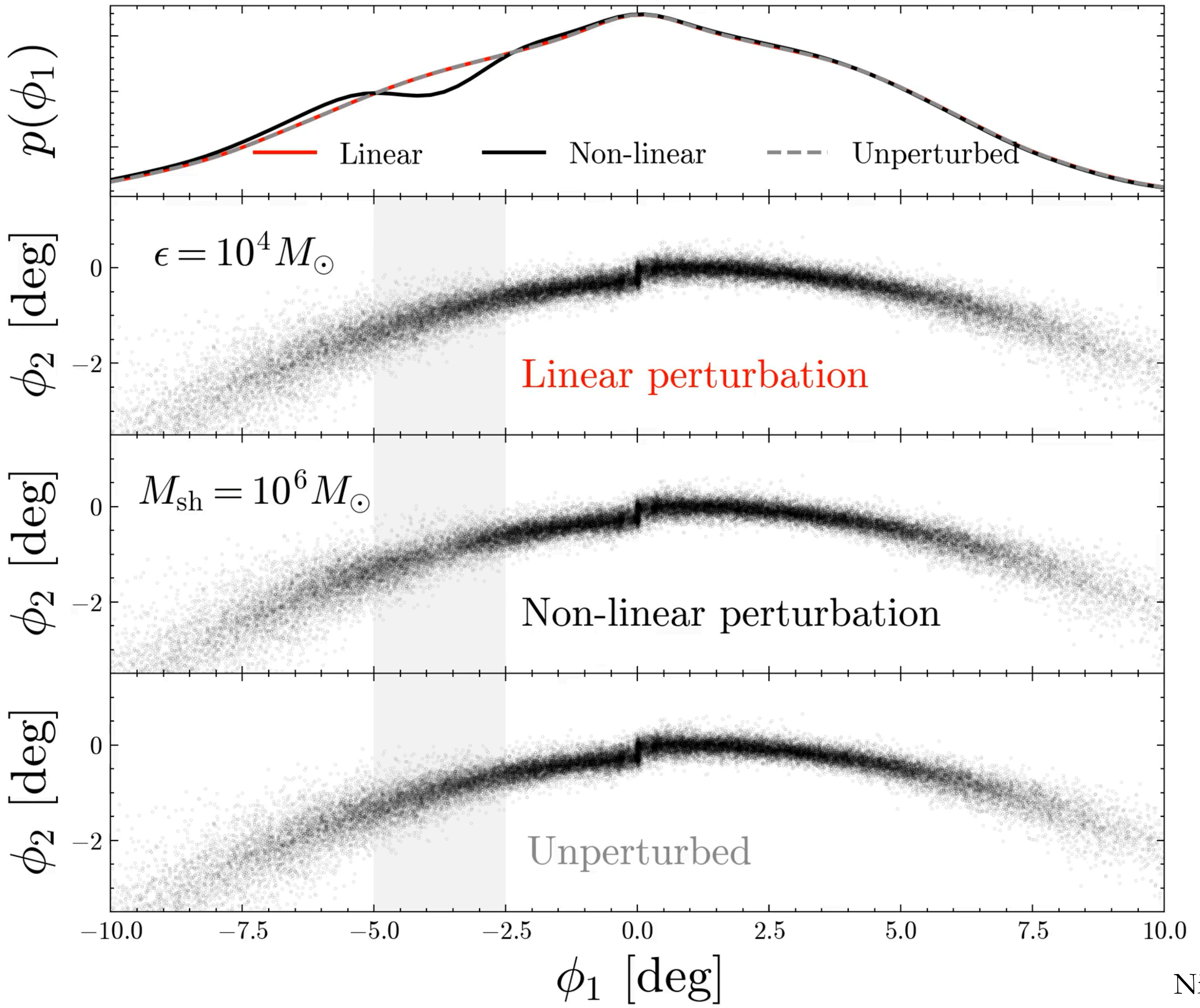
Linear "strength" parameter

Pre-compute 1000s (1 per subhalo orbit)



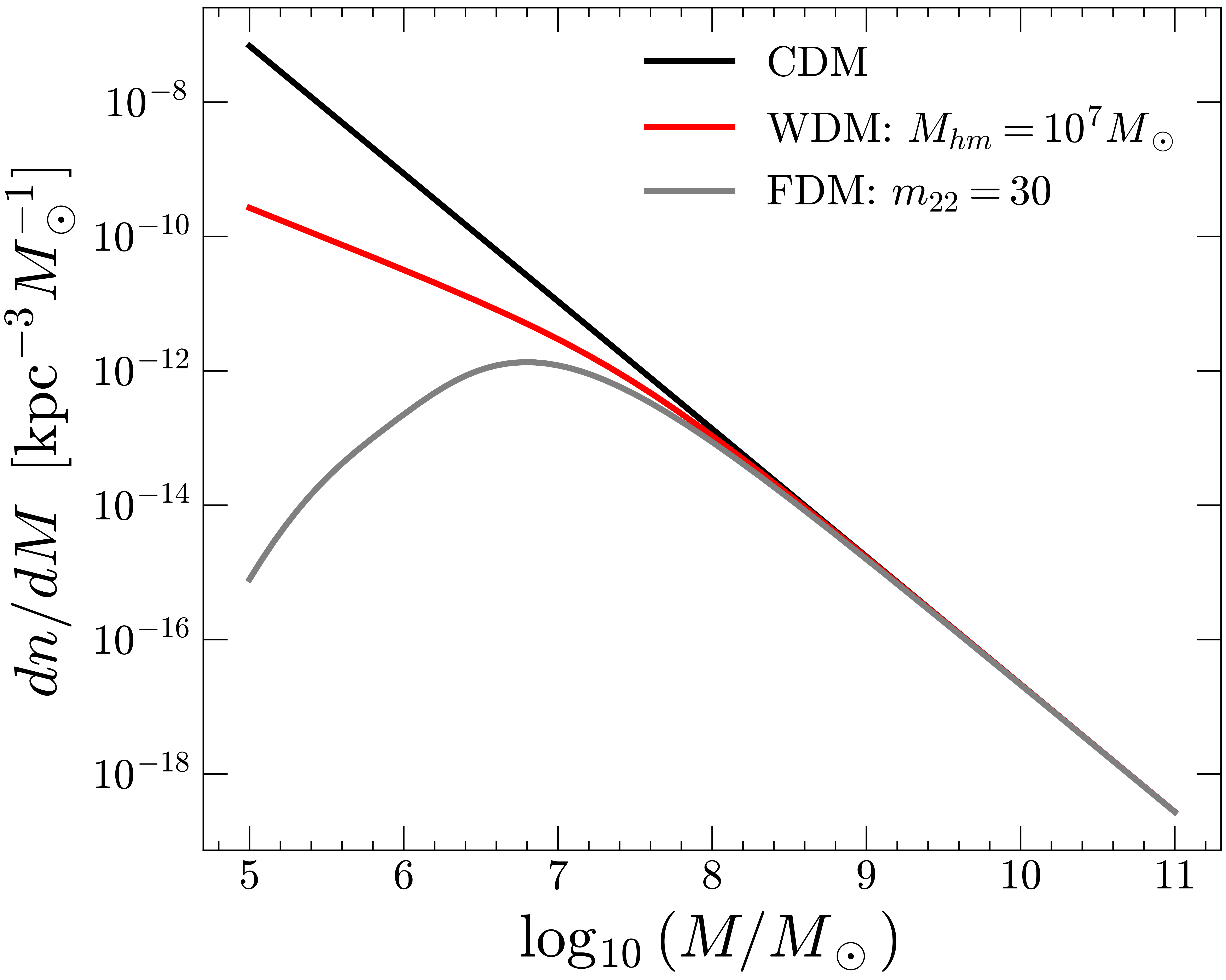
Taylor expanding a simulation!

ϵ : controls perturbation strength (i.e., mass)



(Video)

Nibauer+2024 (In prep.)

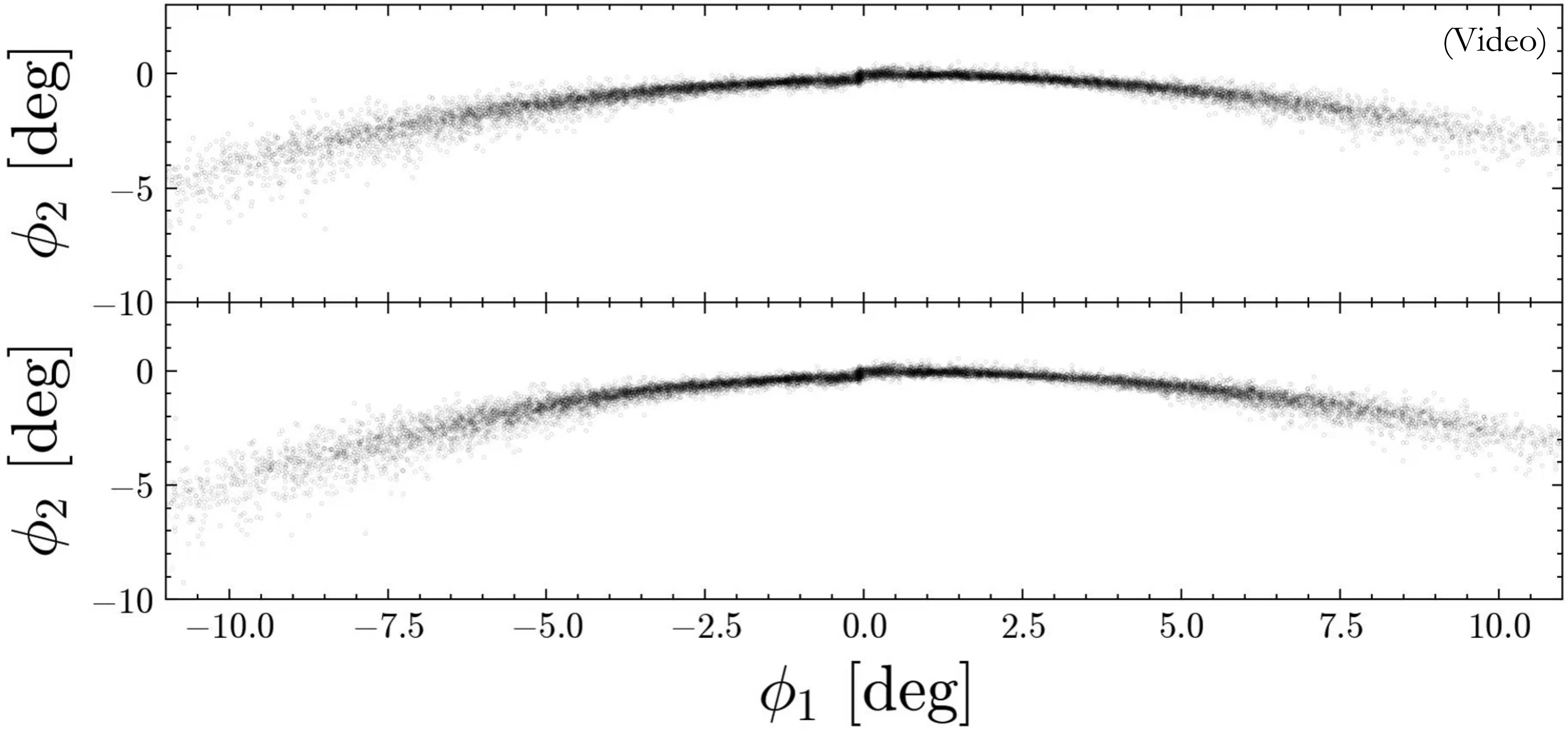


CDM Expectation for GD-1:

$\mathcal{O}(100)$ total impacts

$\mathcal{O}(1)$ major ($> 10^6 M_\odot$) impacts

Continuously deforming a stream due to $\mathcal{O}(100)$ subhalos (CDM impact rate)



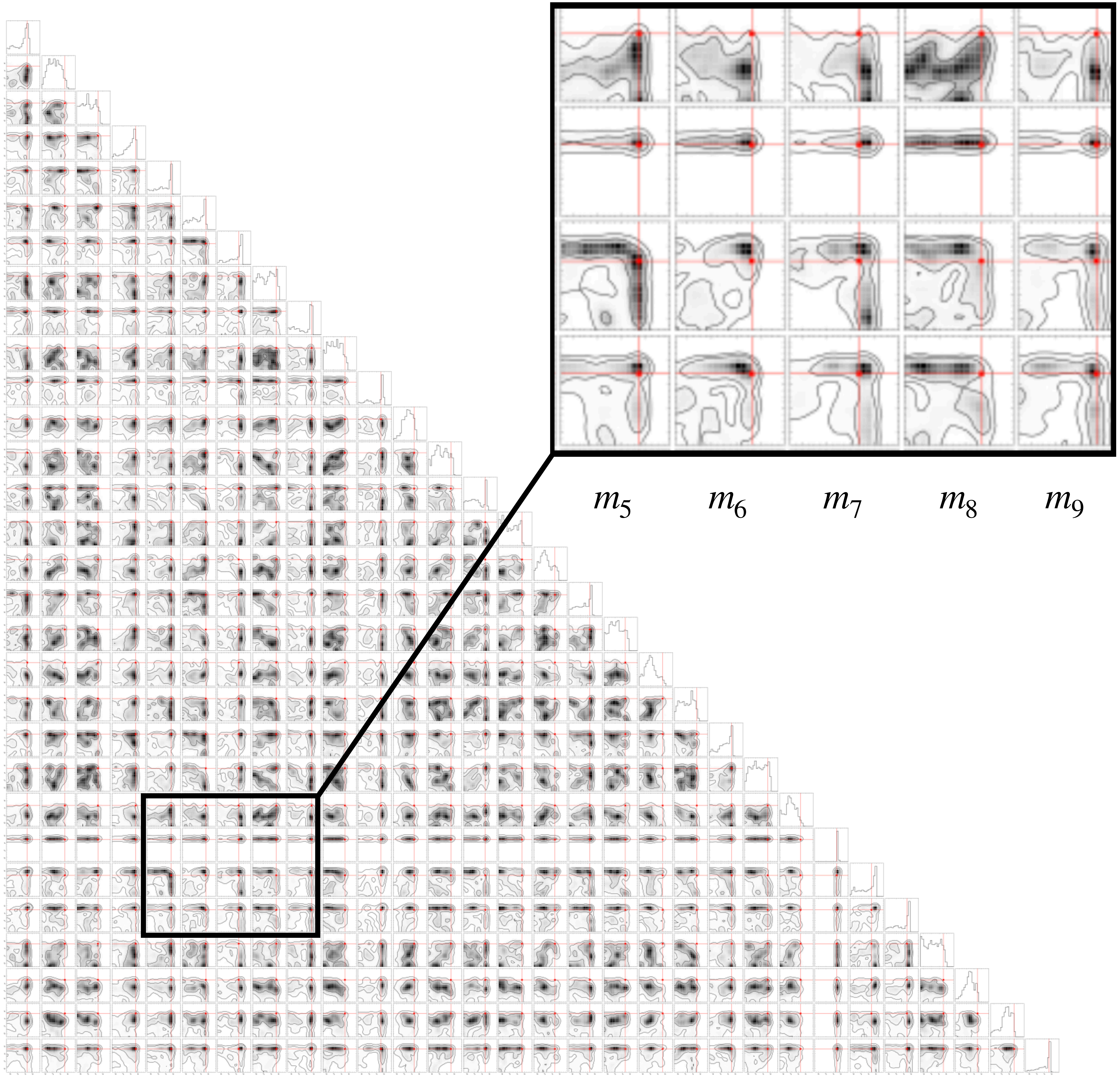
$[10^5, 10^6]\ M_\odot$ subhalos <u>heat</u> the stream (velocity dispersion and width, 10 % density fluctuations)

More massive subhalos → gaps + bifurcations

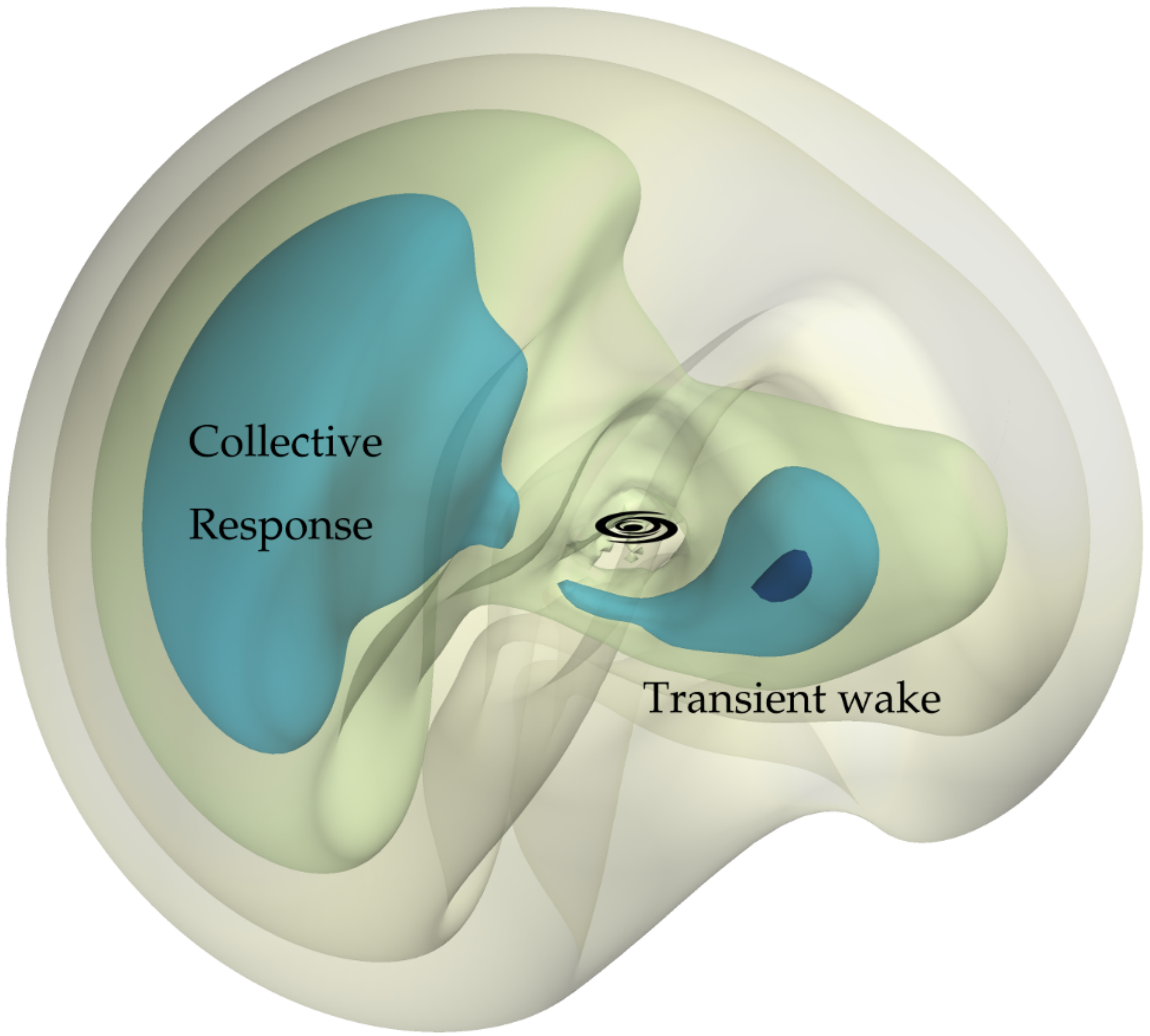
(Ridiculous plot warning)

Sampling the *linear* mass posterior for 30 subhalos on fixed orbits, in ~ 1 minute

Input mock-data: stream density structure

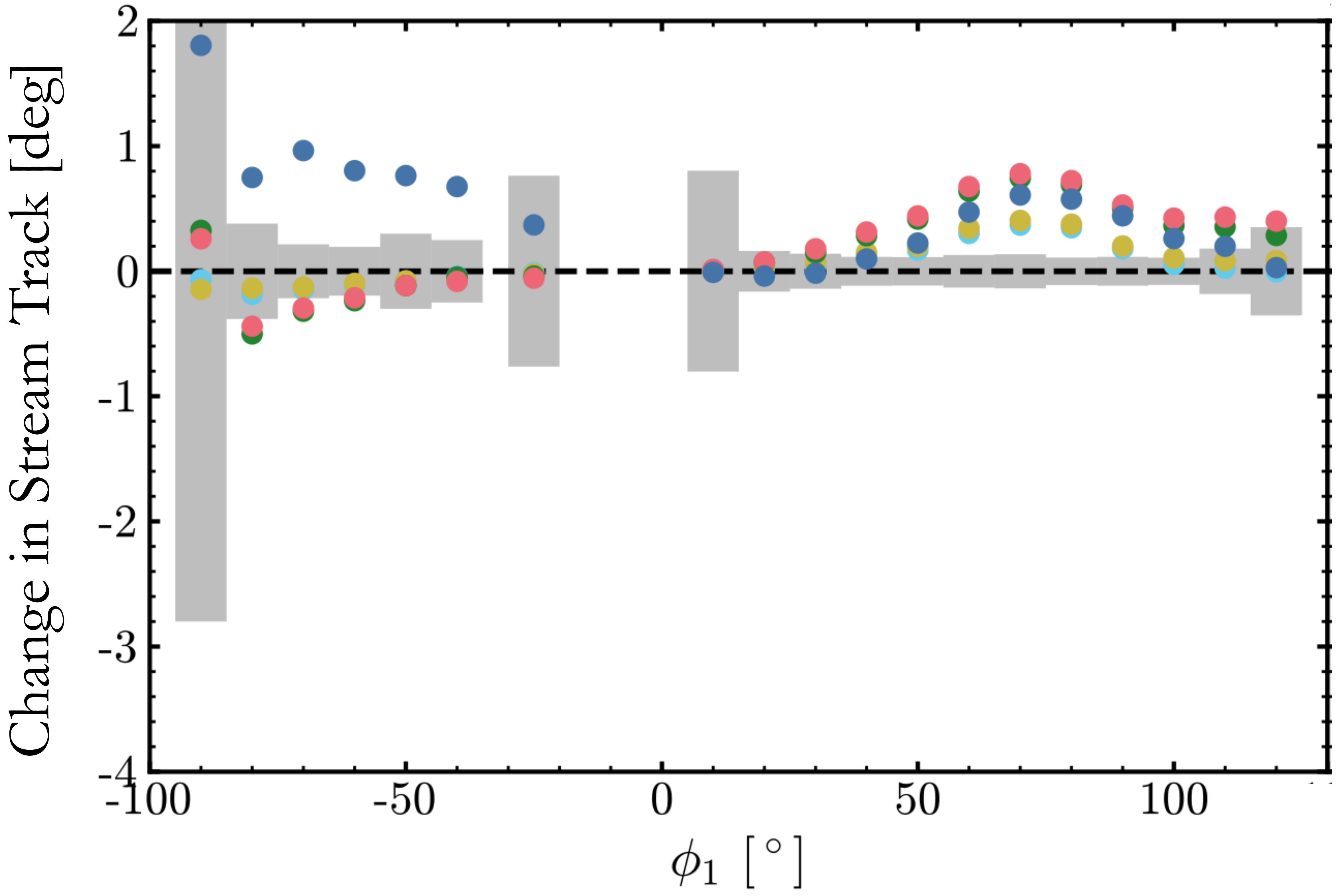


LMC shifts the tracks of some streams (e.g., the OC Stream)

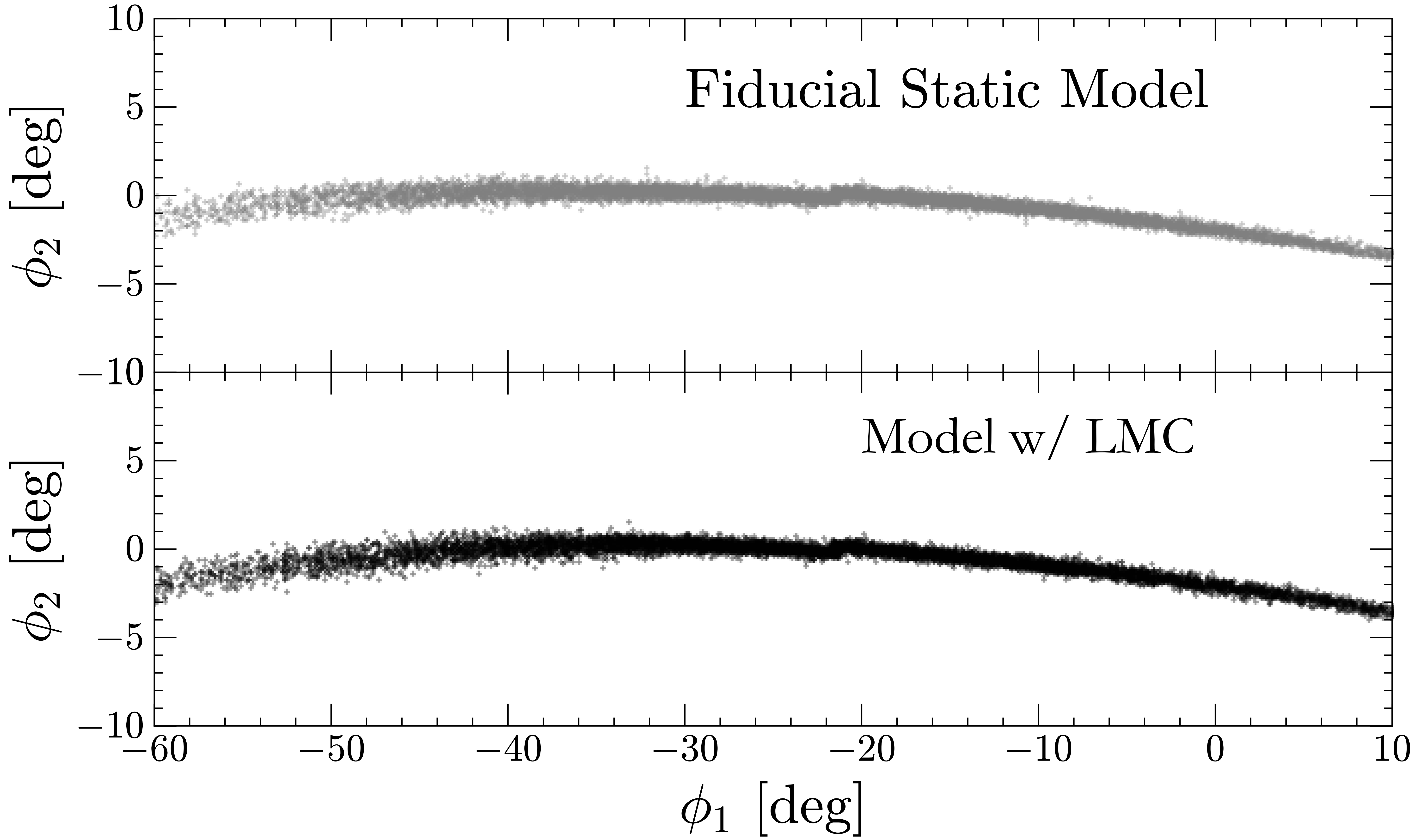


Garavito-Camargo+21

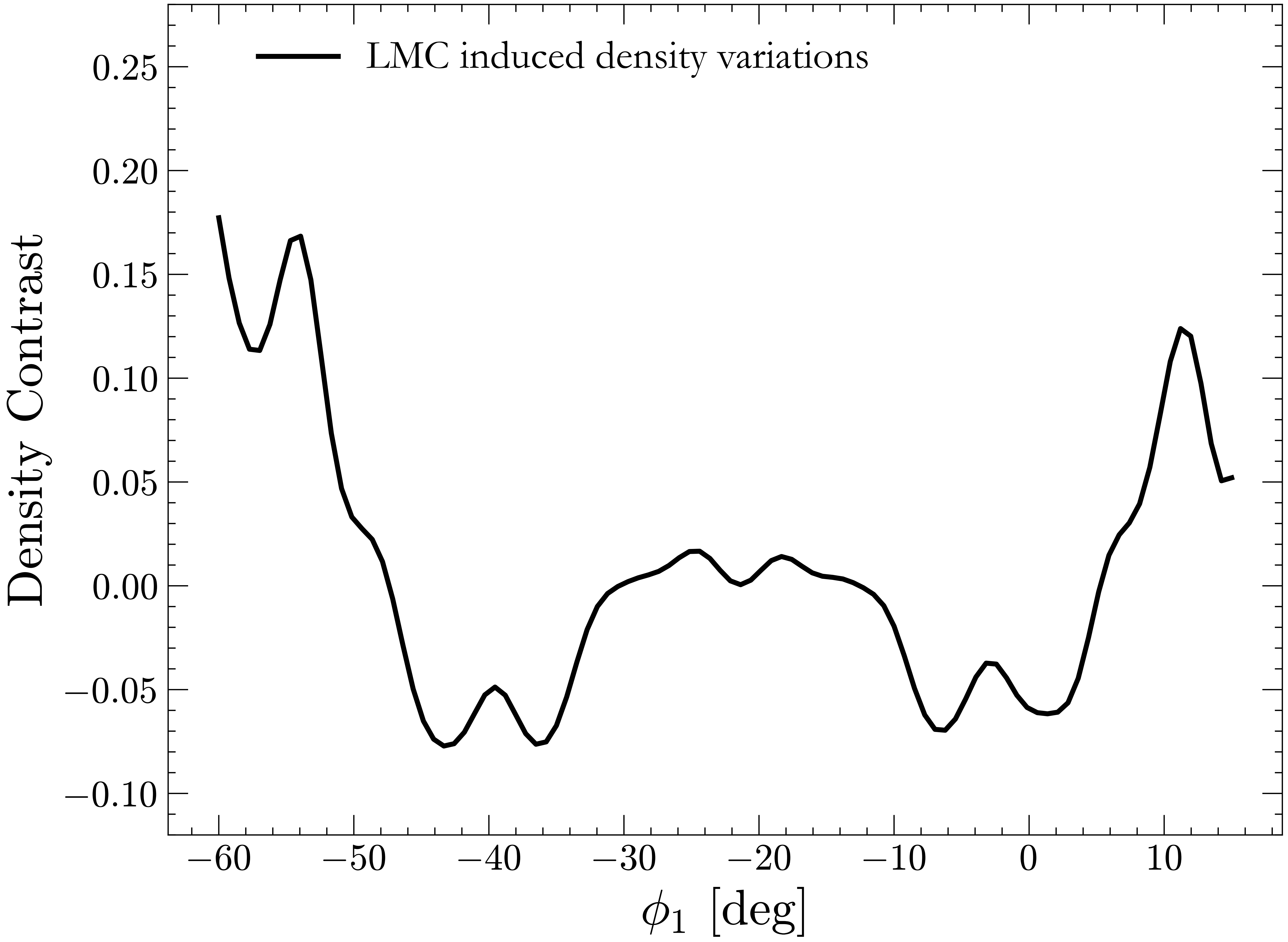
Lilleengen+23



The track of GD-1 is not expected to shift due to the LMC by a detectable amount

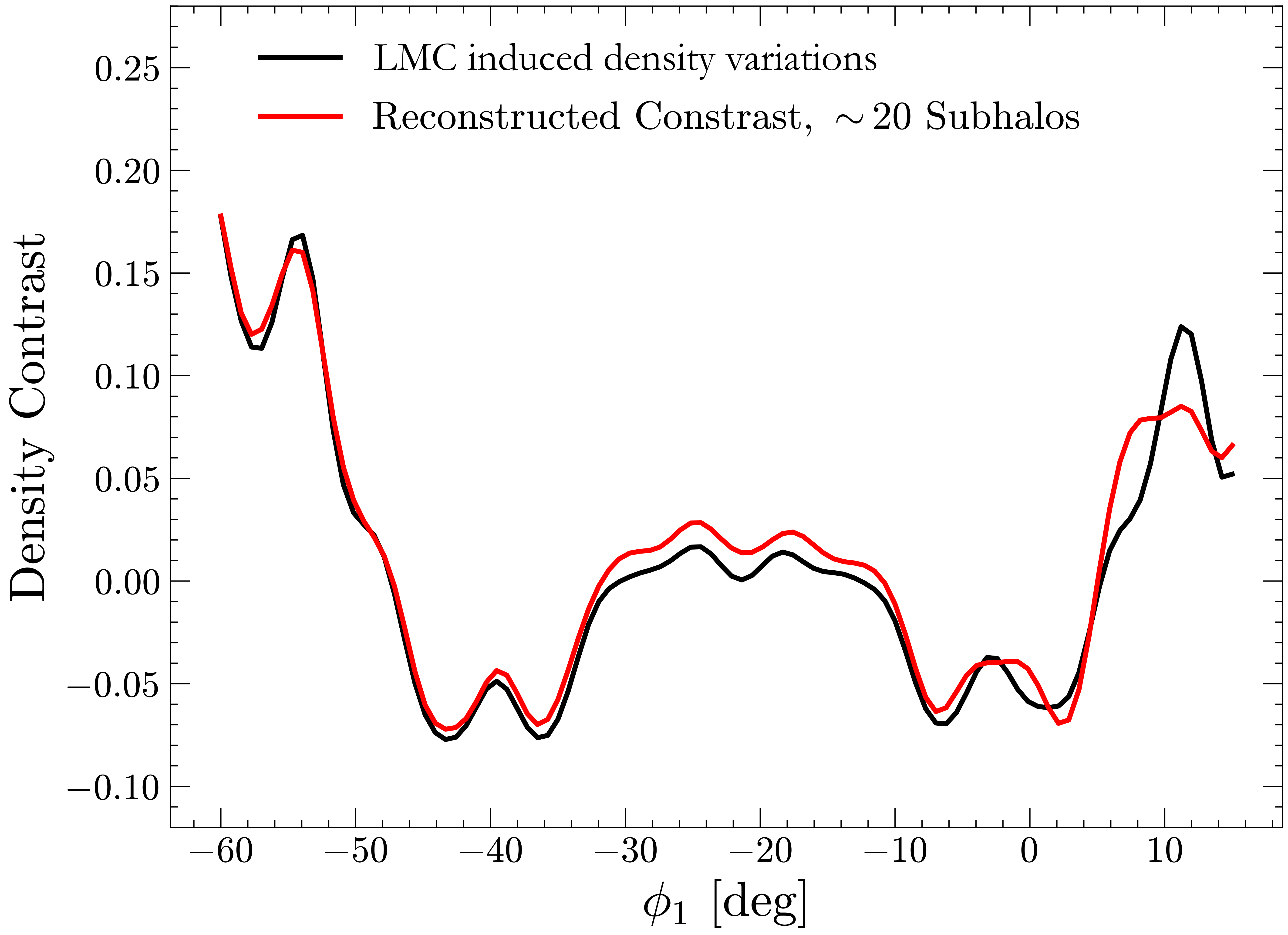


Density Structure?

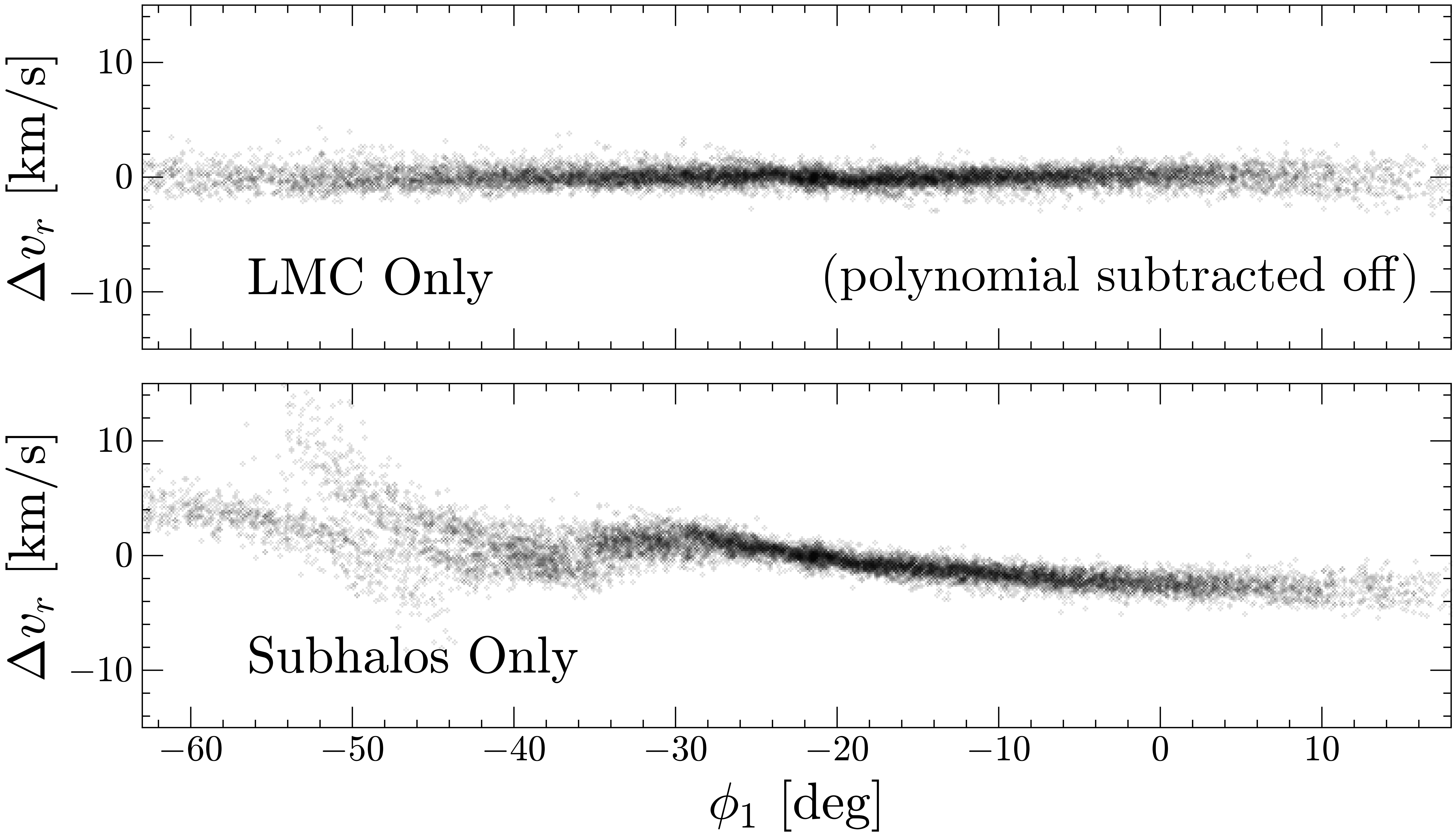


LMC induced density variations
Density Contrast
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−60
−50
−40
−30
−20
−10
0
10
ϕ_1 [deg]

Failure to account for LMC can bias constraints from linear density

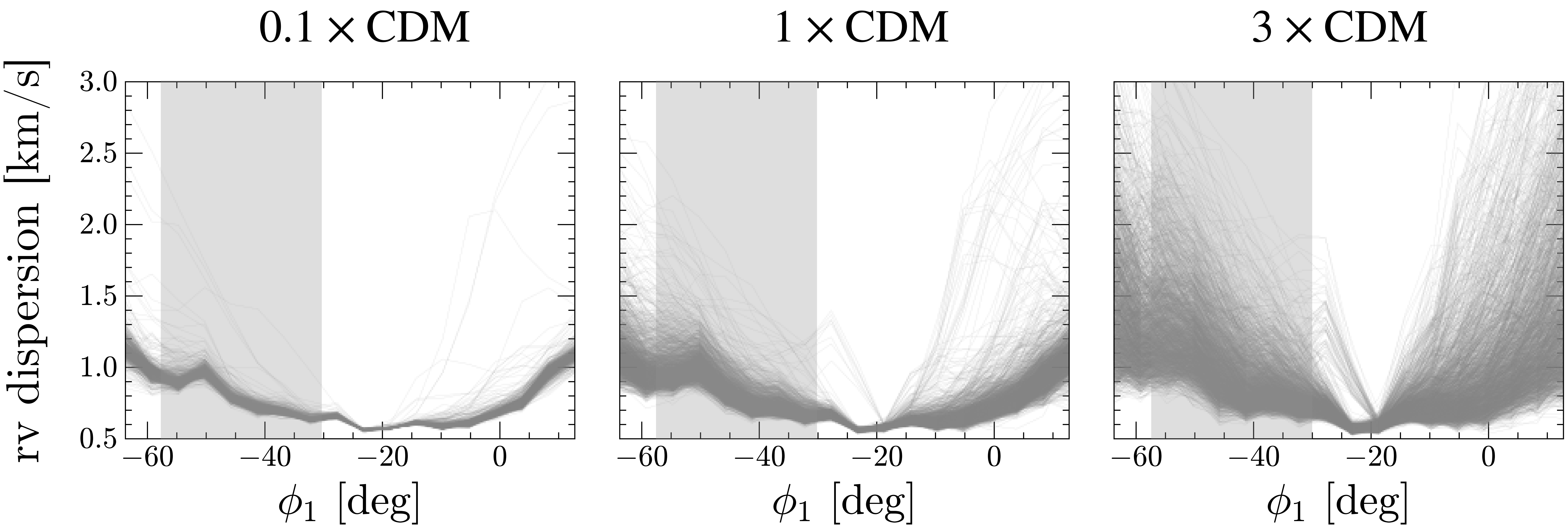


But we can now incorporate known perturbations in the base model

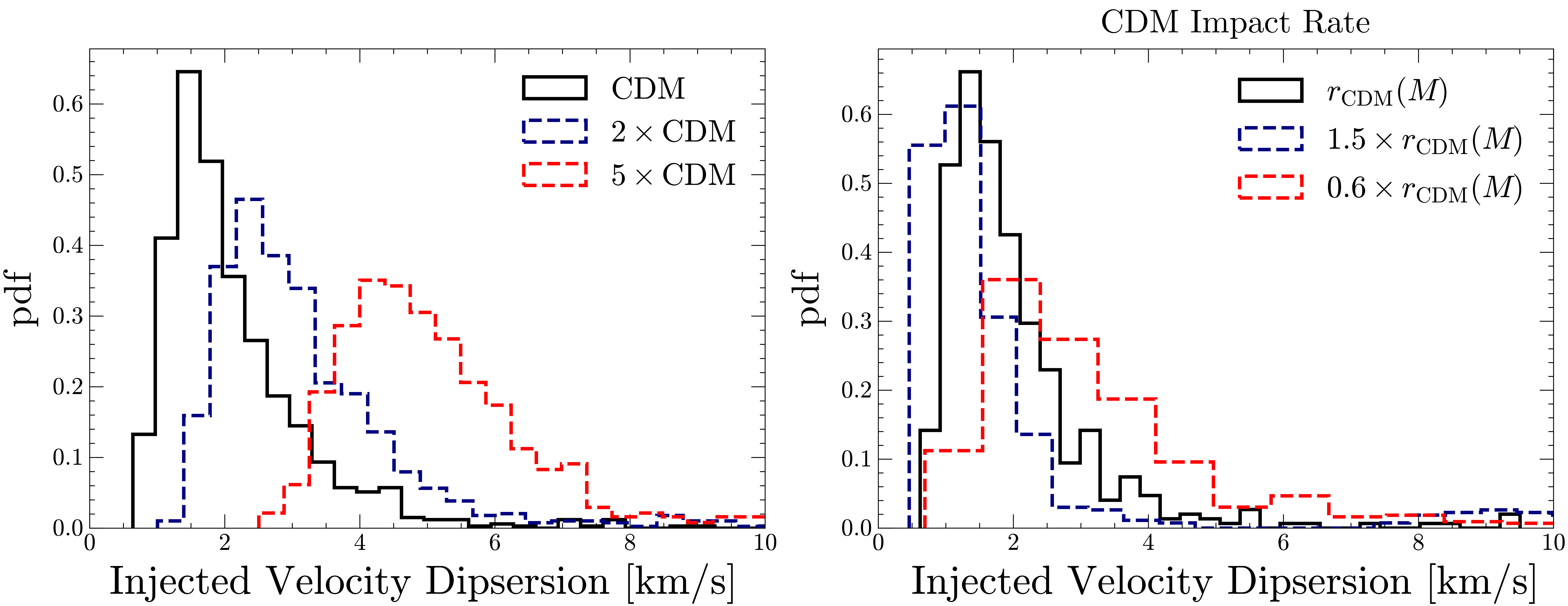


Density structure derived from deep photometry alone will provide constraints, precise ($\lesssim 1$ km/s) radial velocity follow-up provides a crucial cross-check

The effect of ~ 100 subhalos with $M \in [10^5, 10^6]\ M_\odot$ is to increase the stream's velocity dispersion

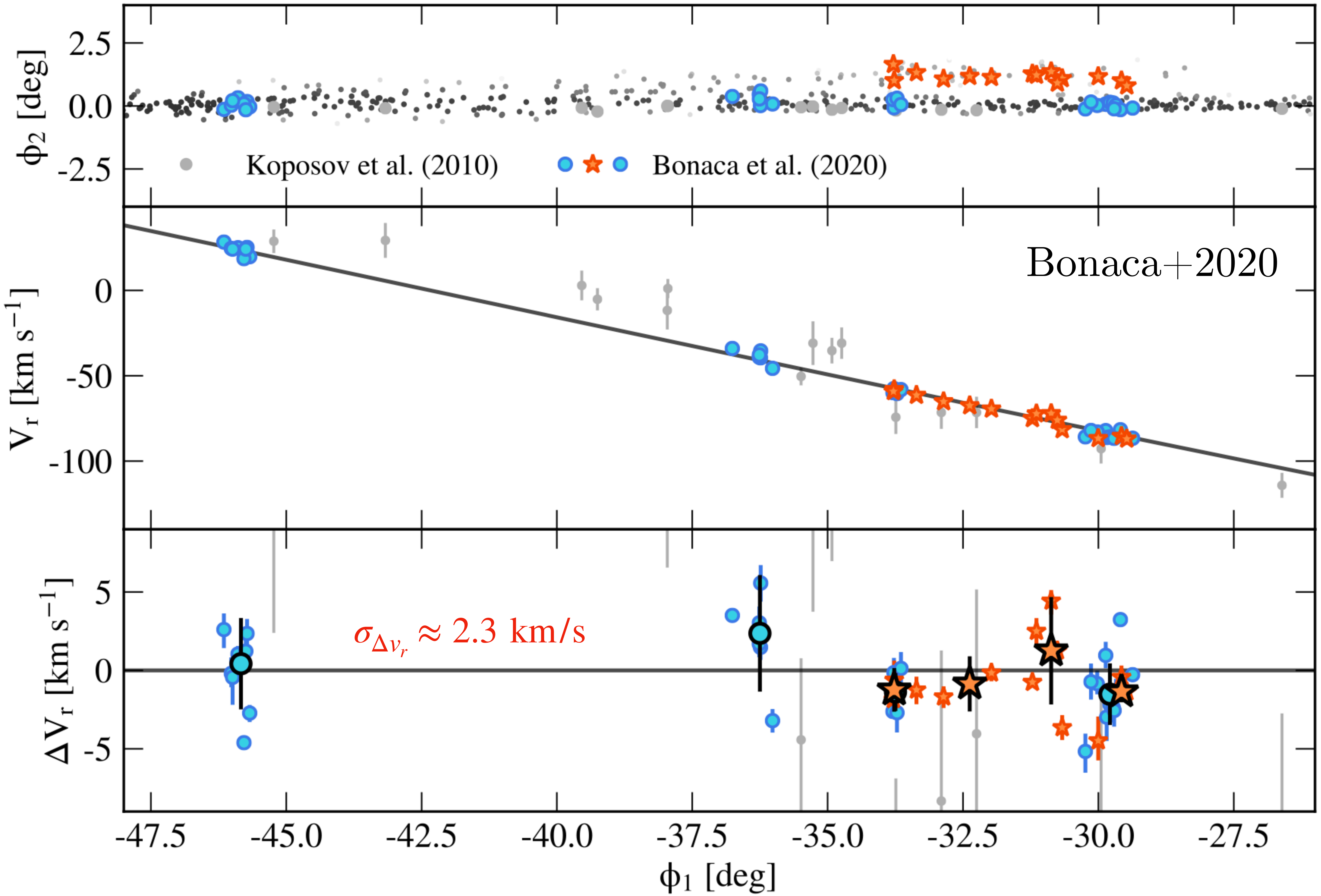


(e.g. if 1 x CDM = 100 impacts, 0.1 x CDM = 10 impacts)



Distributions are taken over ~ 20 deg of the stream

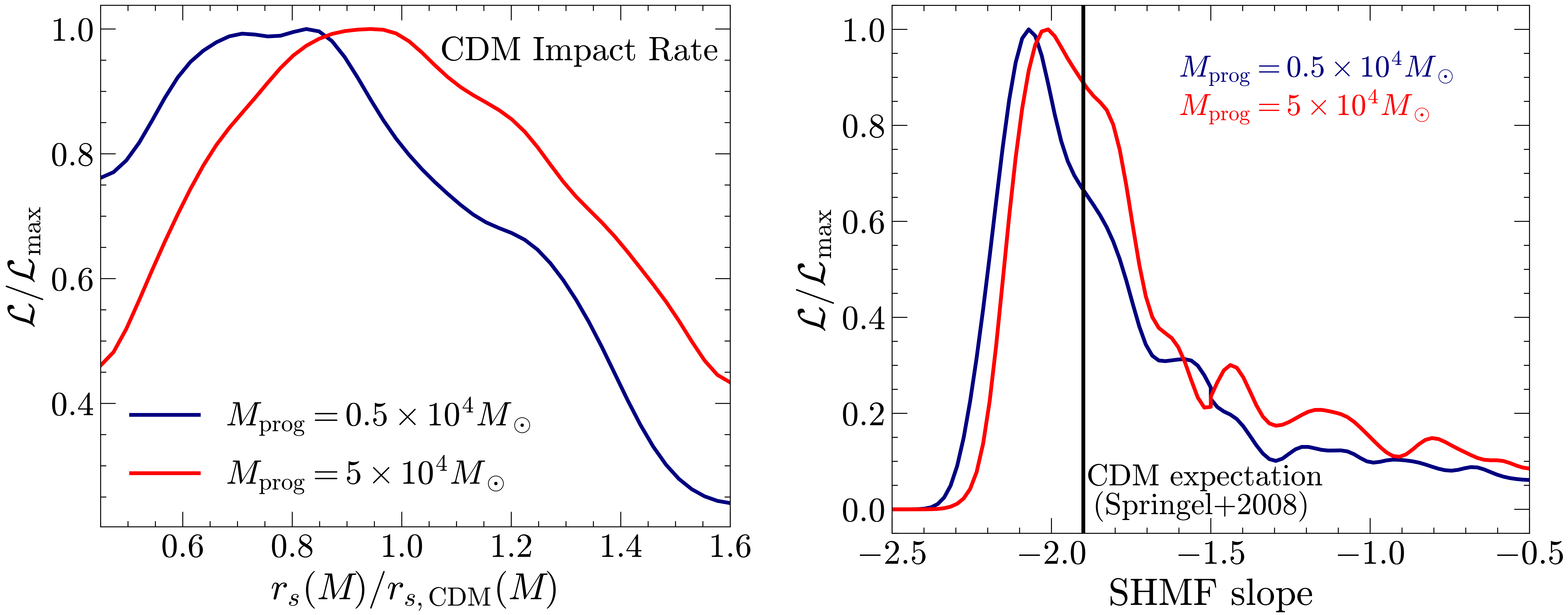
High-resolution spectroscopy of GD-1 reveals a dynamically heated stream



Unperturbed models: $\sigma_{\Delta v_r} \sim$ 0.6-0.8 km/s

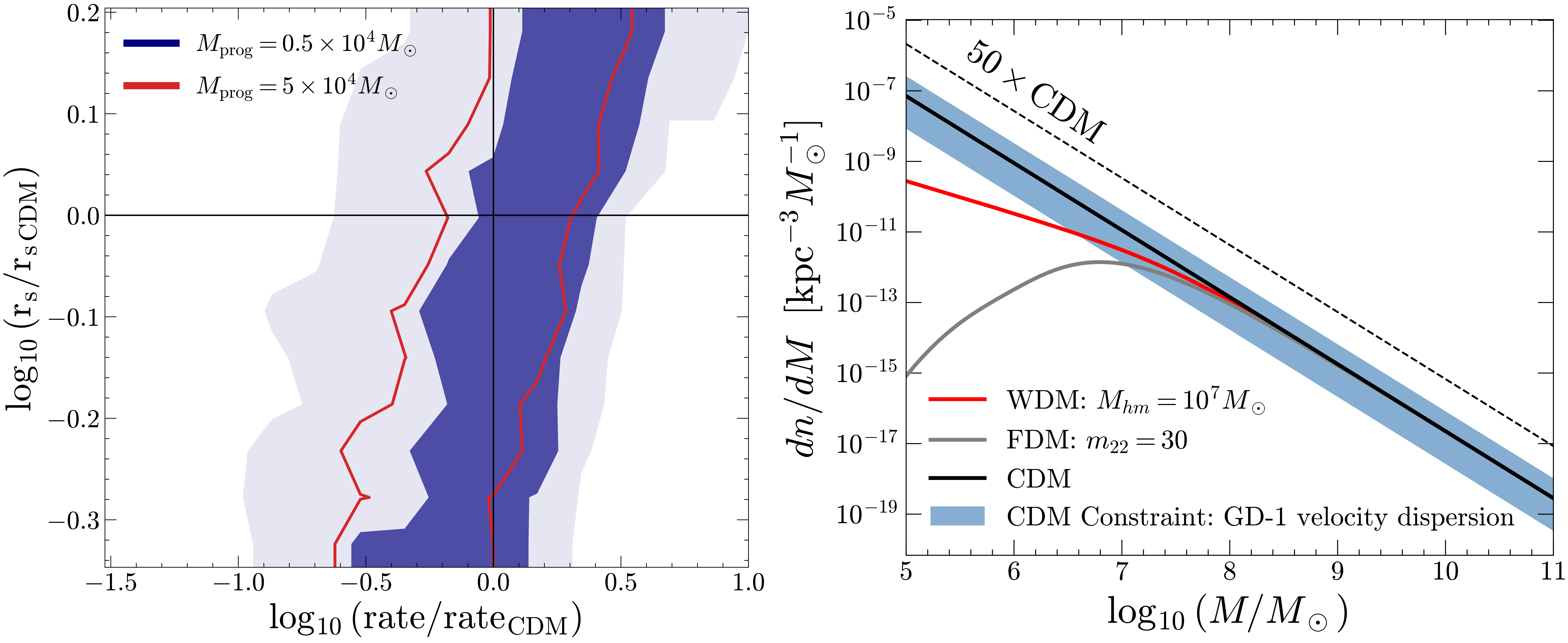
Also see Gialluca+2020

Data: radial velocities of 43 spectroscopically confirmed GD-1 stars



Preliminary

Data: radial velocities of 43 spectroscopically confirmed GD-1 stars



Preliminary

Take-homes

- Stream curvature probes stellar halo shapes (Nibauer+23), an under-explored prediction of ΛCDM. More work needed to characterize stream-tracks with LSST
- Effects of the bar, the LMC, halo shapes, etc. are important when modeling the density structure of streams. Perturbation theory provides a path forward
- Radial velocity followup will be crucial for the rich density structures we are bound to find along streams w/ LSST
  - If density and radial velocities tell a consistent story, this will be compelling
- More work needed: semi-analytic cluster models — beyond particle spray (Thurs?)

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