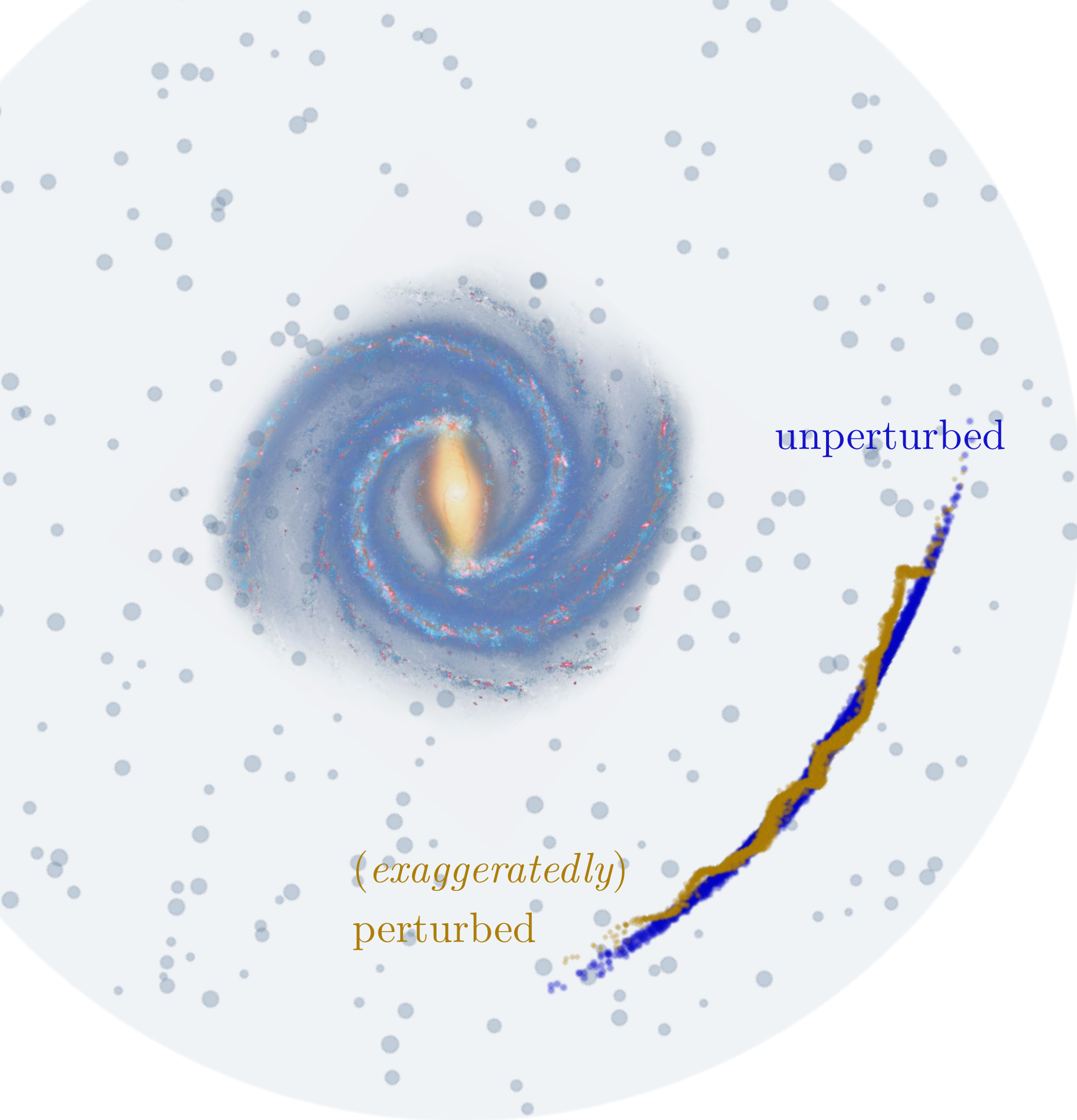
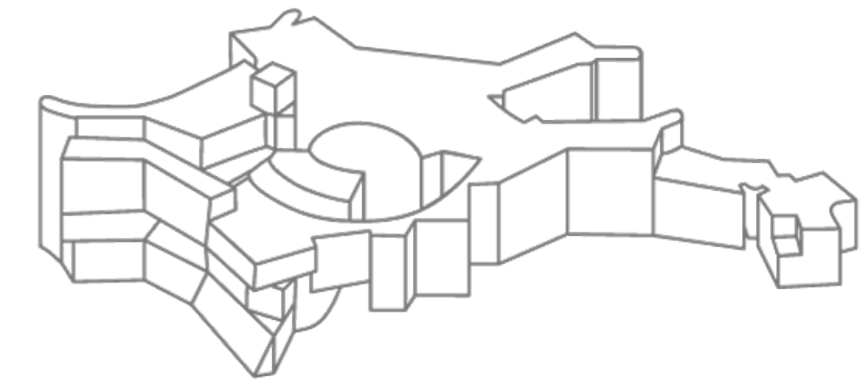




Stellar streams in the diffusion regime: a fast differentiable forward model for dark matter substructure inference

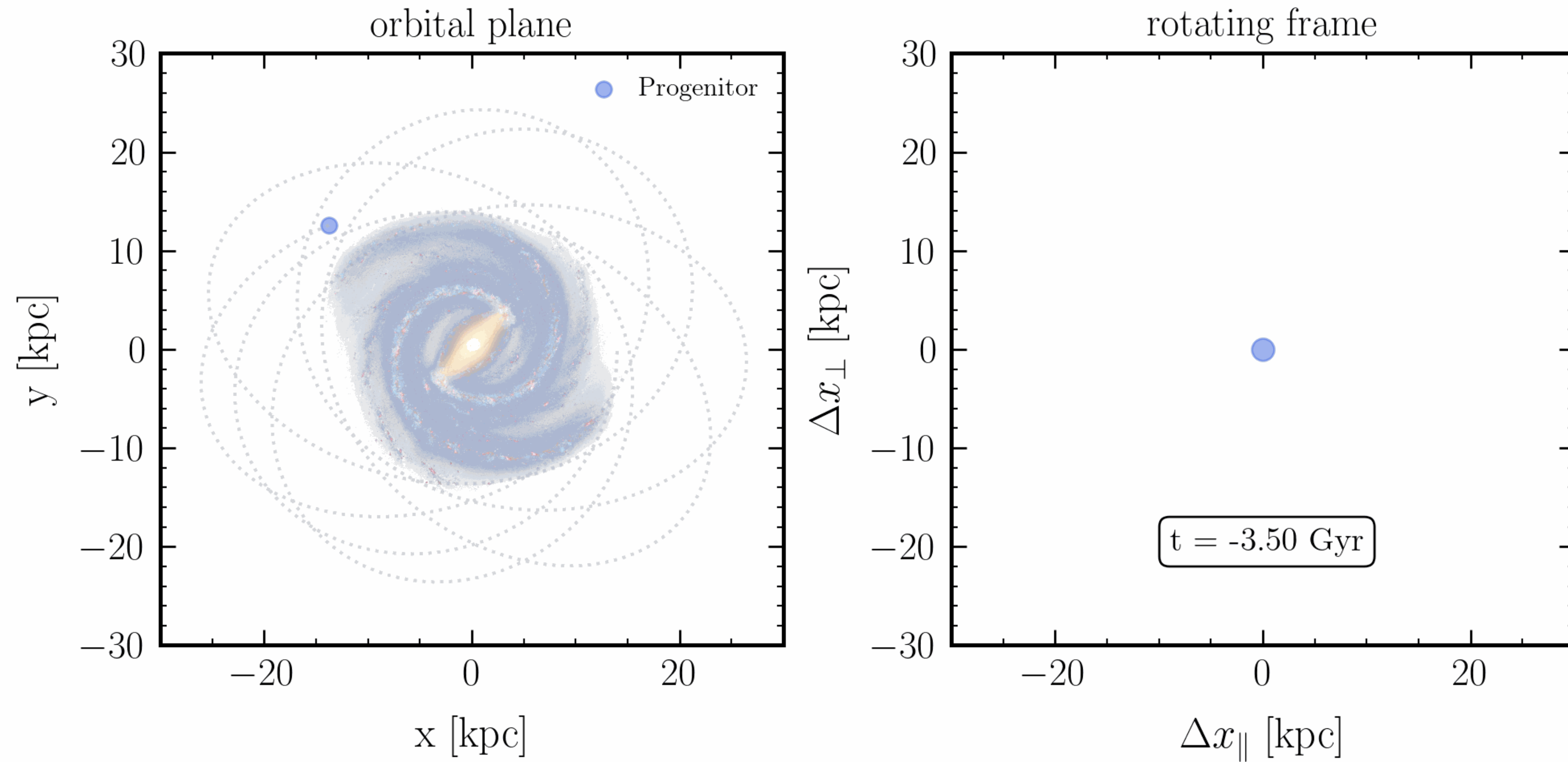
Noemi Anau Montel

with Fabian Schmidt

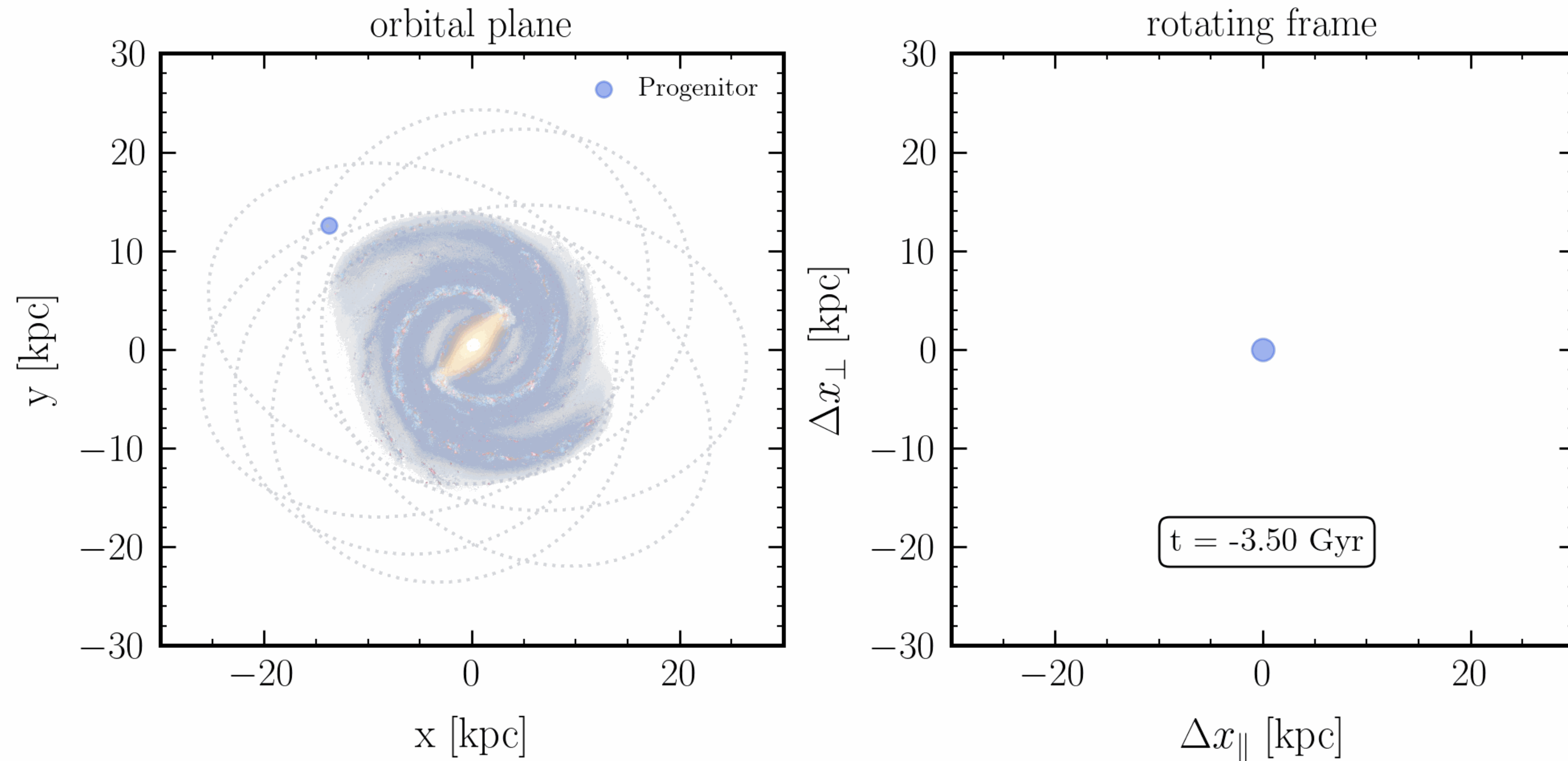
based on [arXiv:2606.09629](https://arxiv.org/abs/2606.09629)



What is a stellar stream?



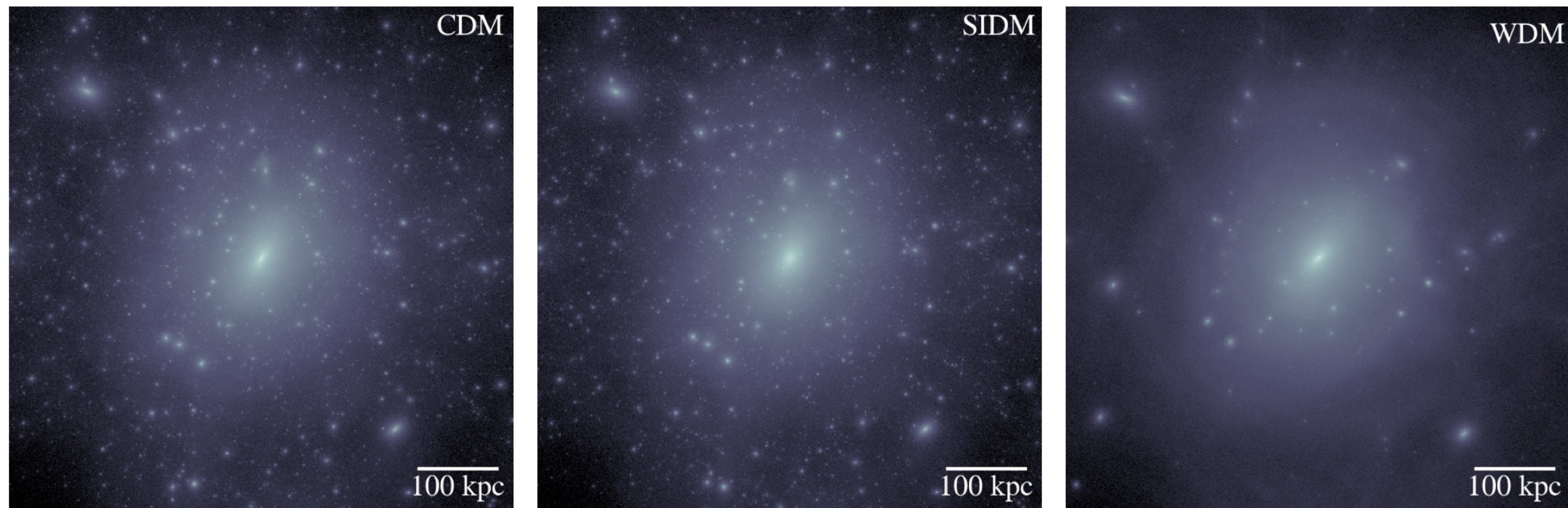
What is a stellar stream?



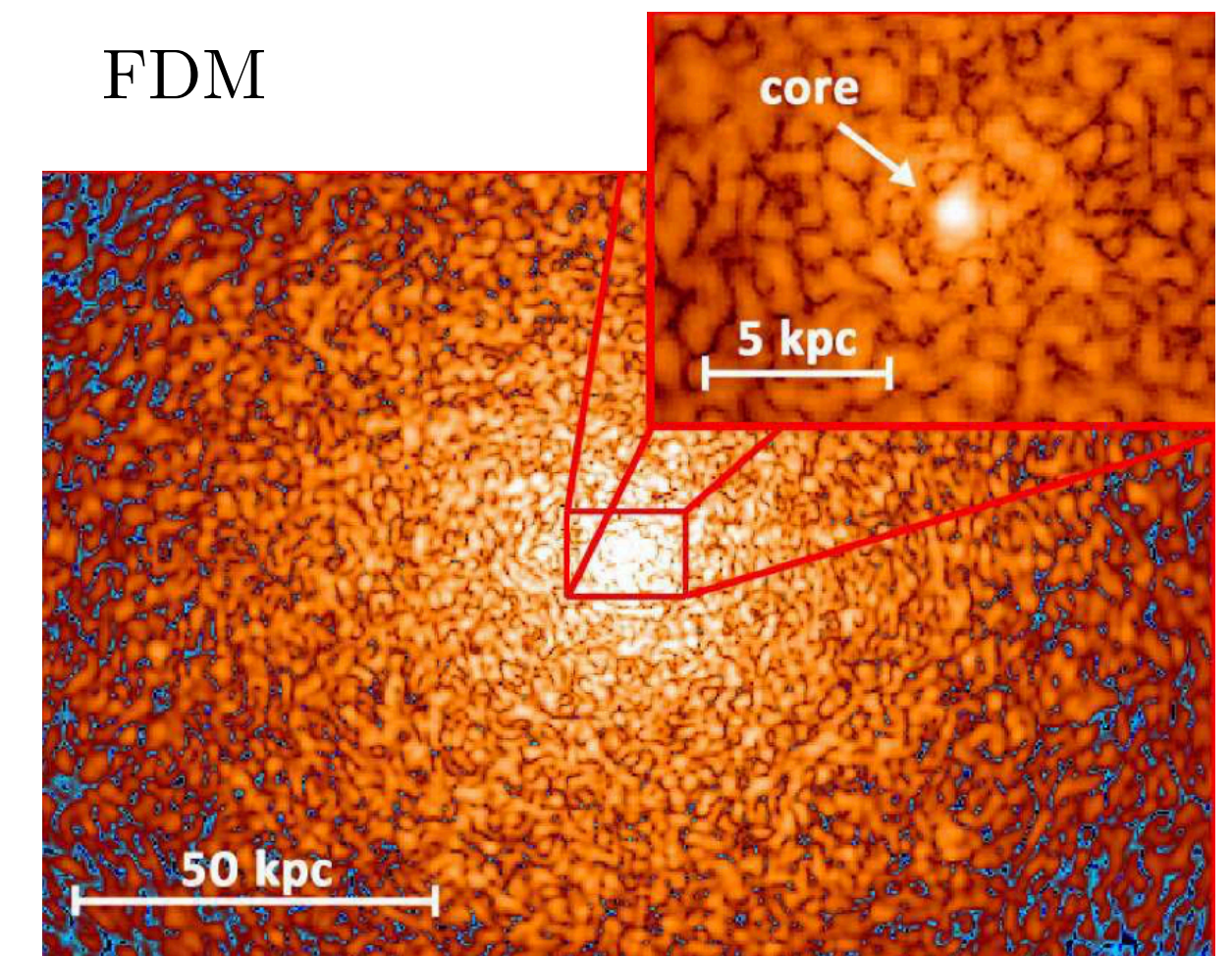
Stellar streams have **negligible self-gravity** and are **dynamically cold**

→ They are sensitive to, and retain a sharp memory of, any gravitational perturbations

Dark matter physics is encoded in halos' density structure



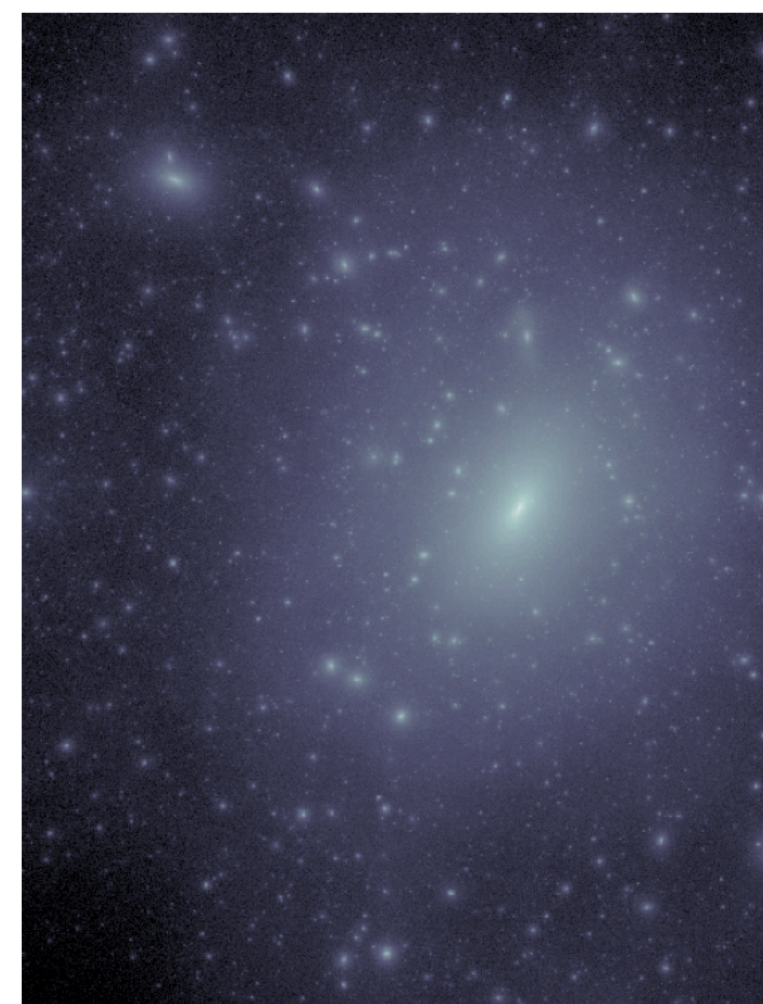
[Bullock & Boylan-Kolchin \(2017\)](#)



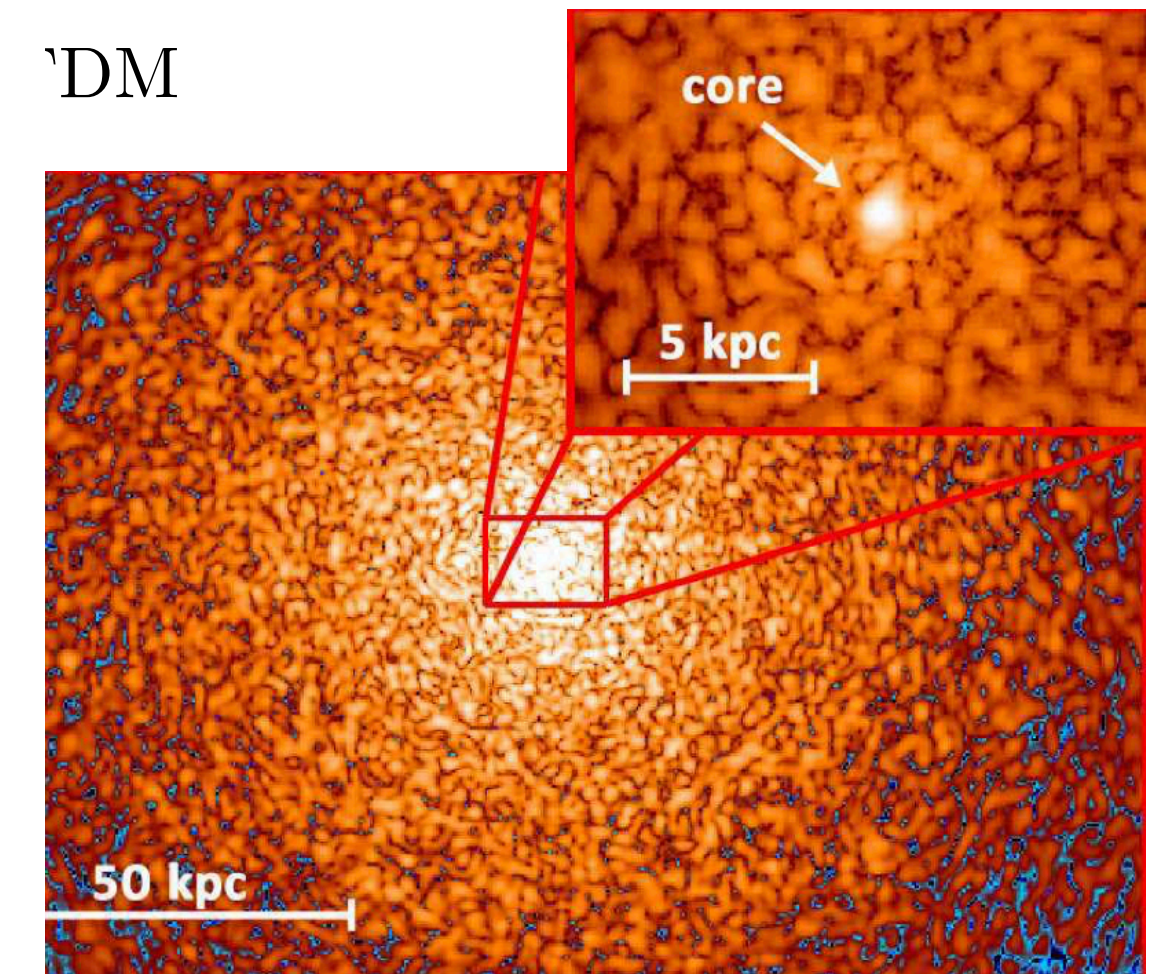
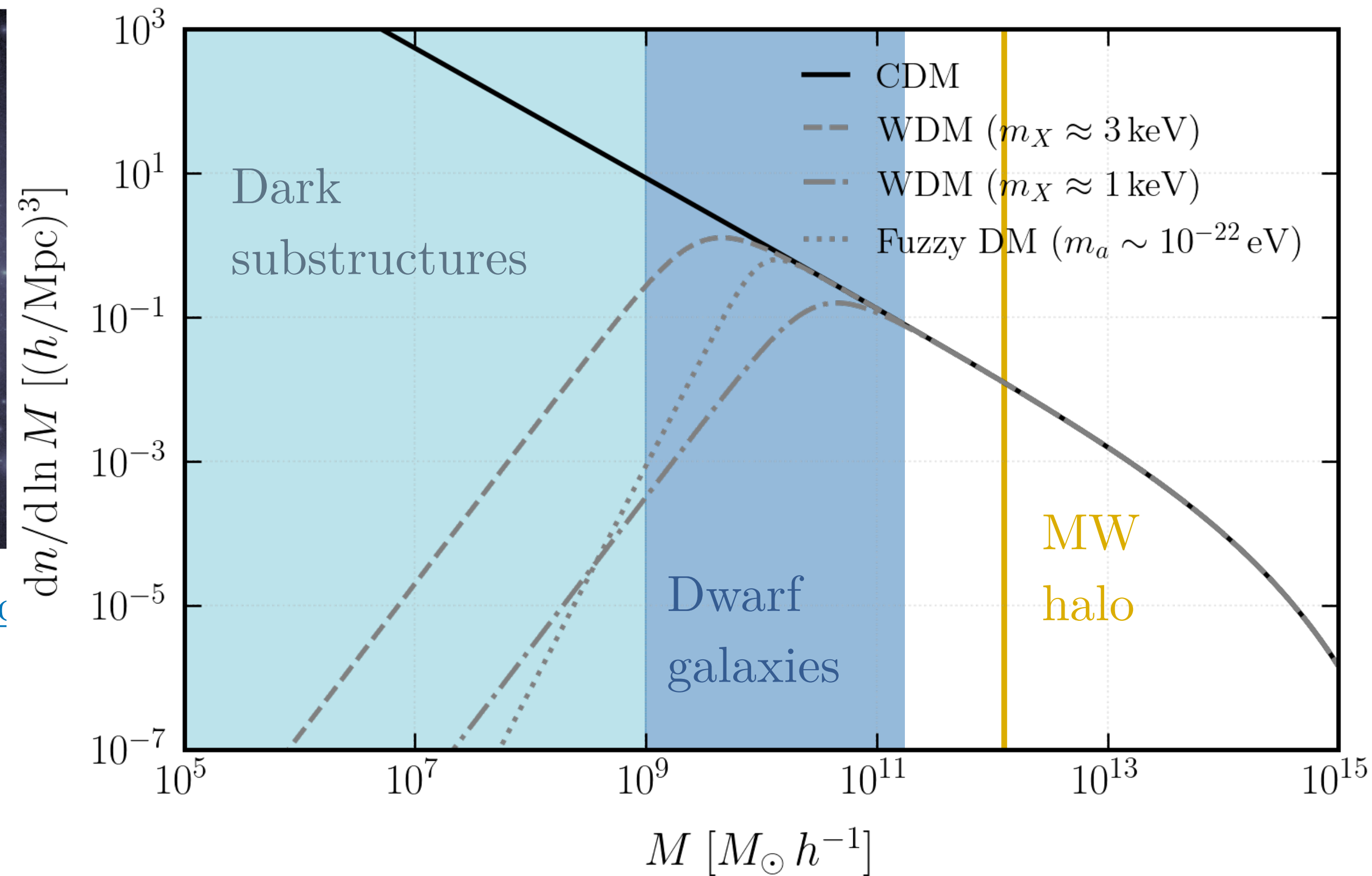
[Schive+ \(2014\)](#)

Dark matter physics is encoded in halos' density structure

Abundance of DM substructure



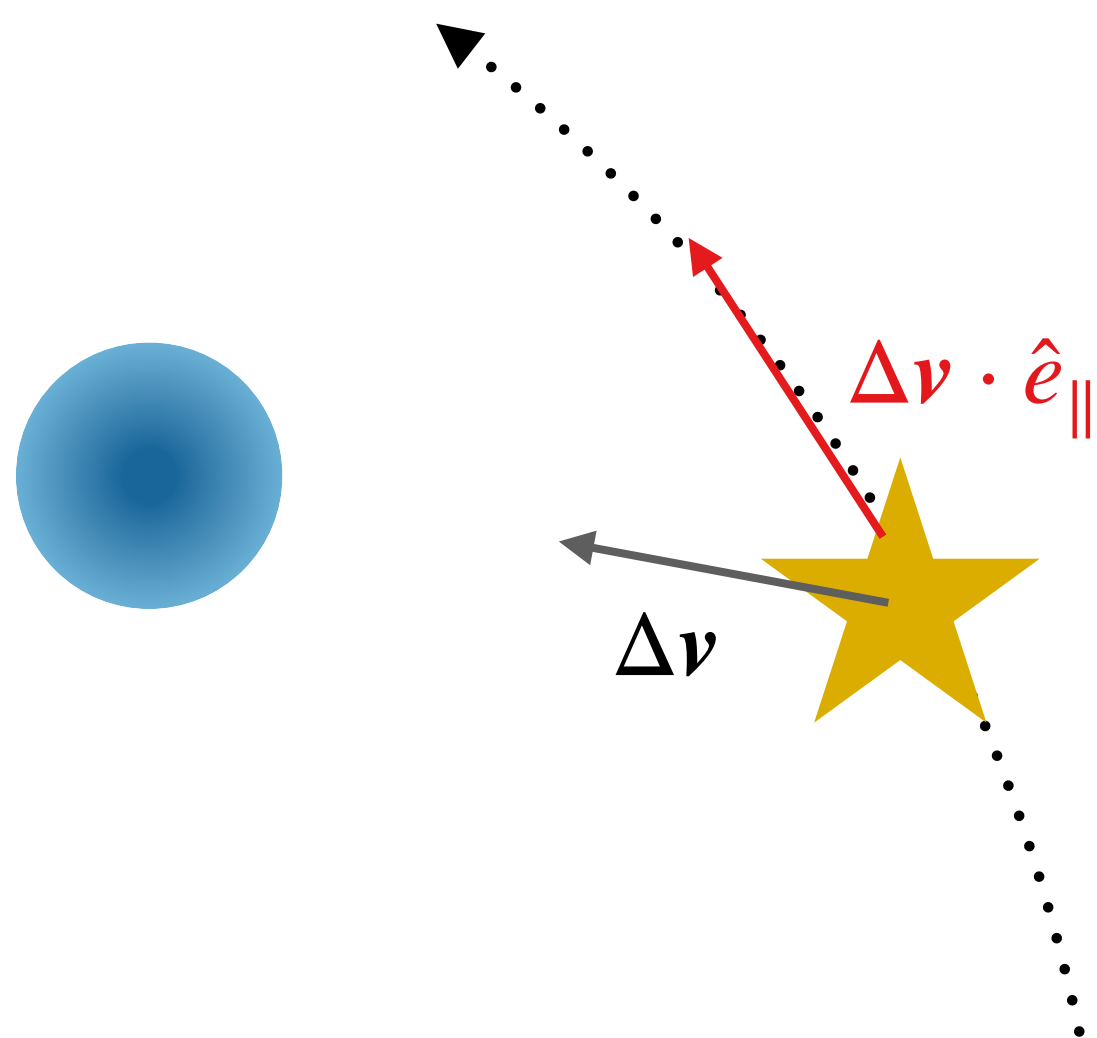
[Bullock & Boylan-Kolchin \(2005\)](#)



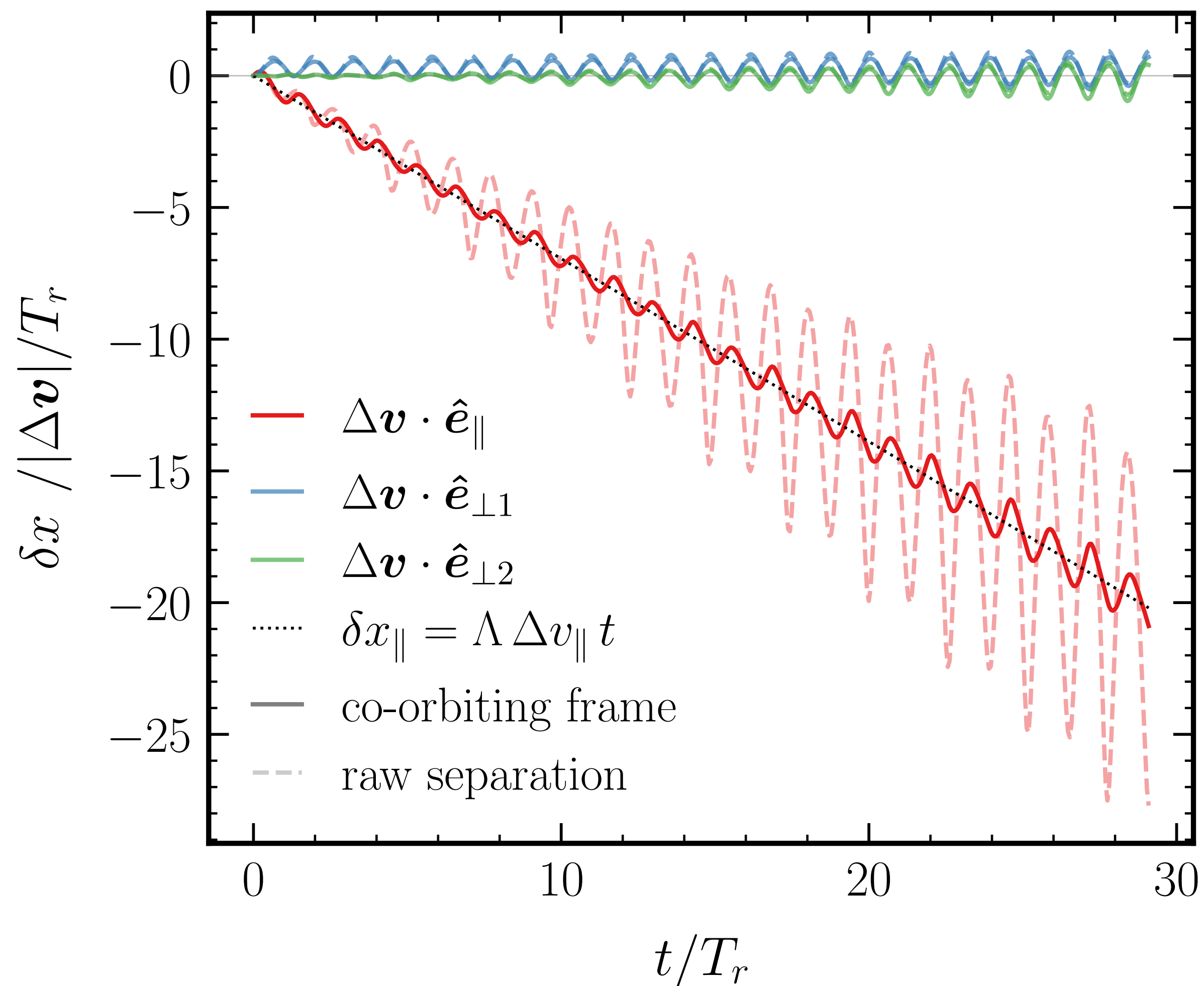
[Shive+ \(2014\)](#)

Orbit response to a substructure velocity kick

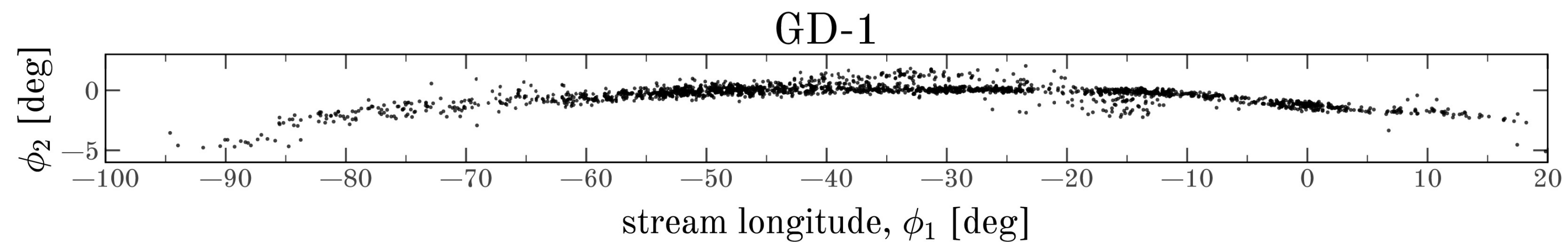
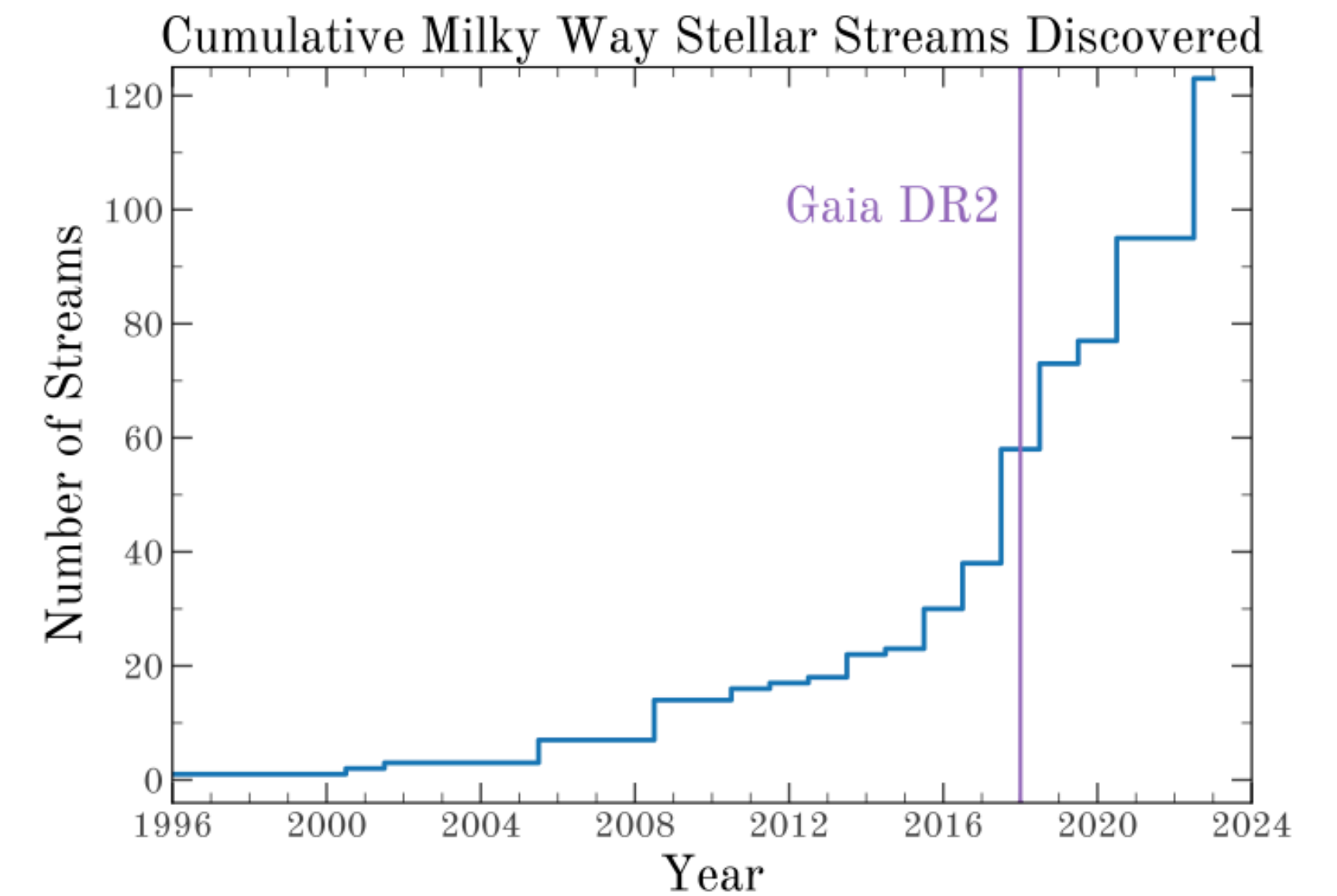
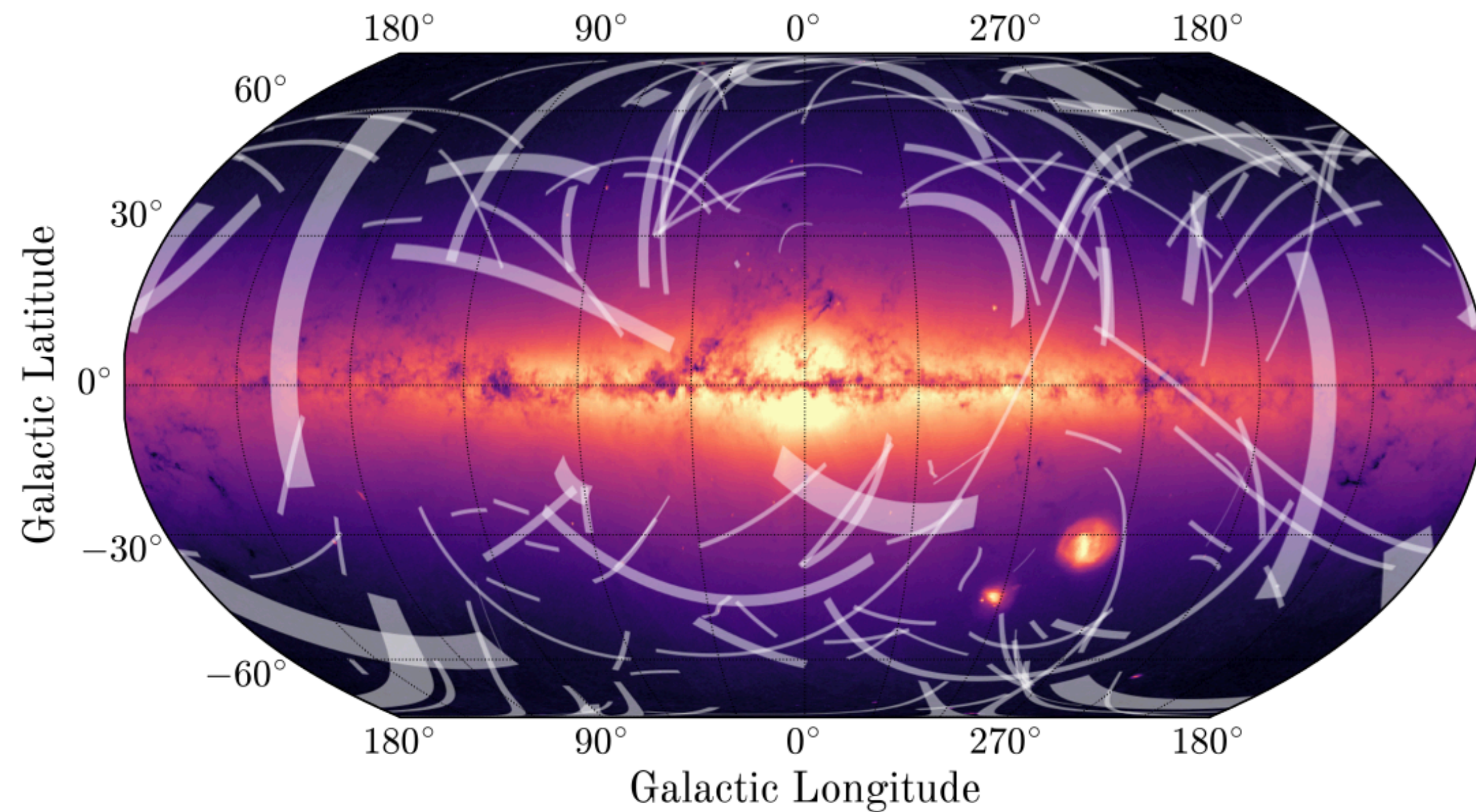
A dynamics detour



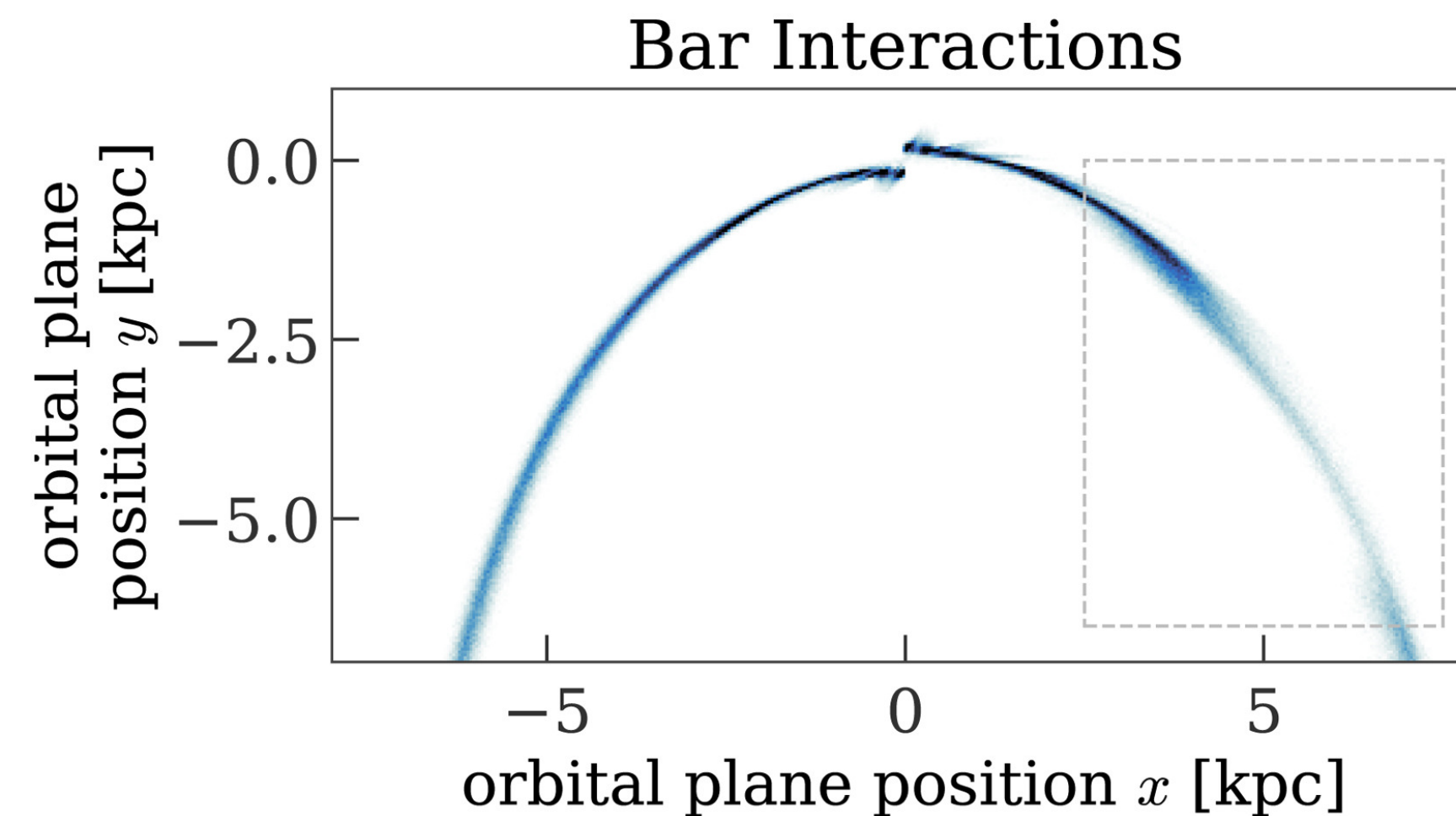
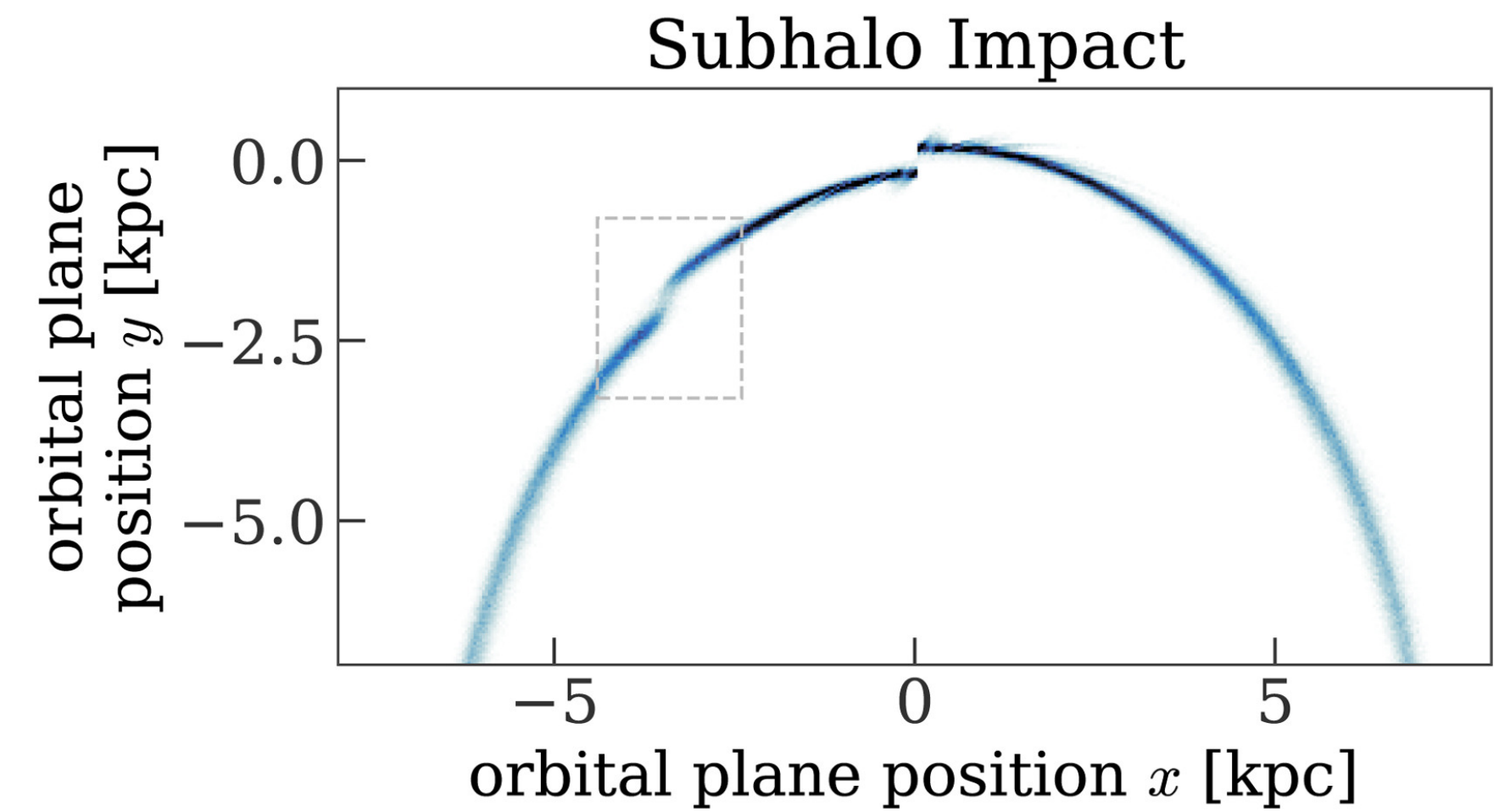
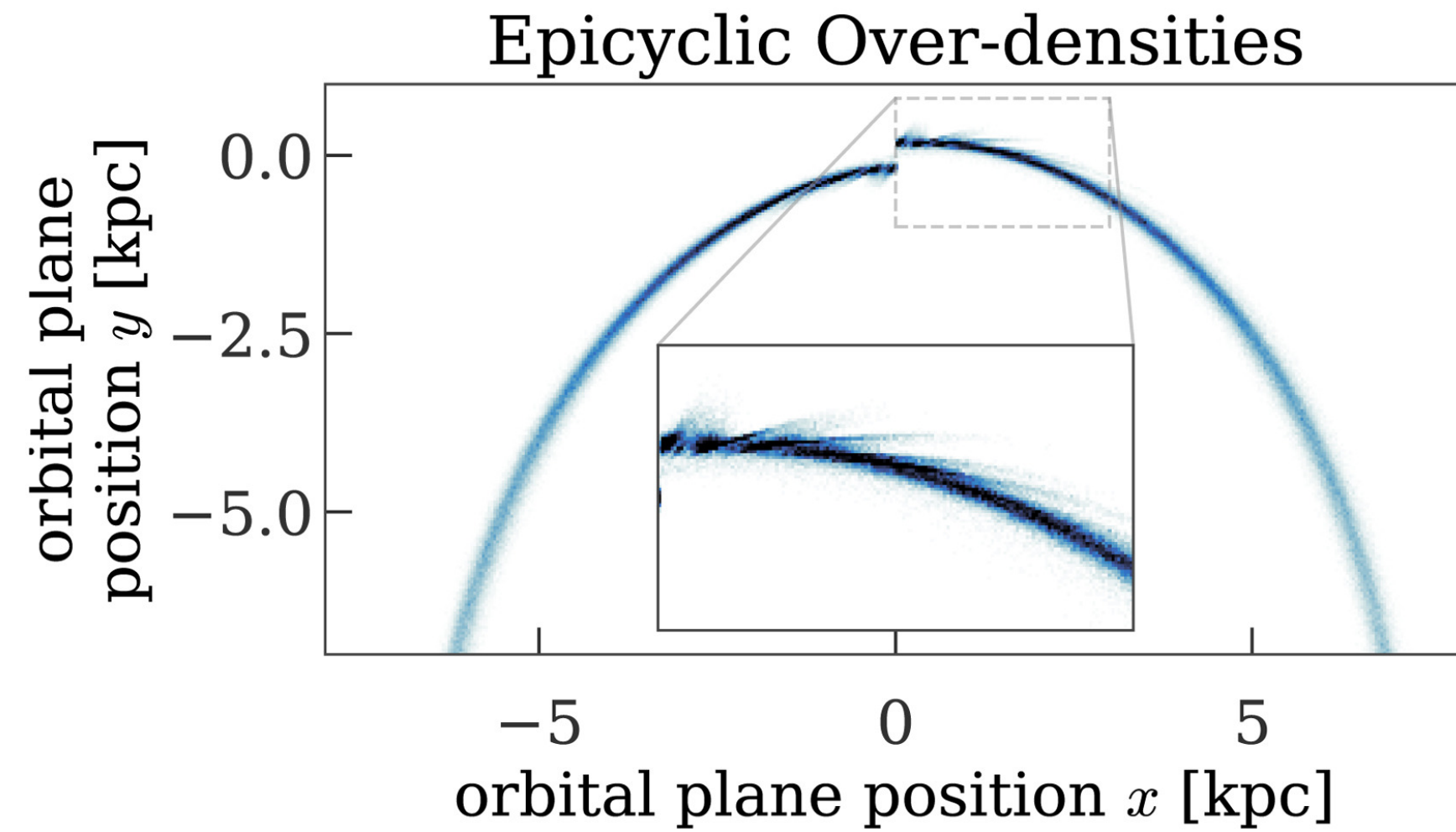
A velocity kick perturbs the orbit's energy and angular momentum, producing a secular drift along the stream that grows with time.



Stellar streams in the Milky Way

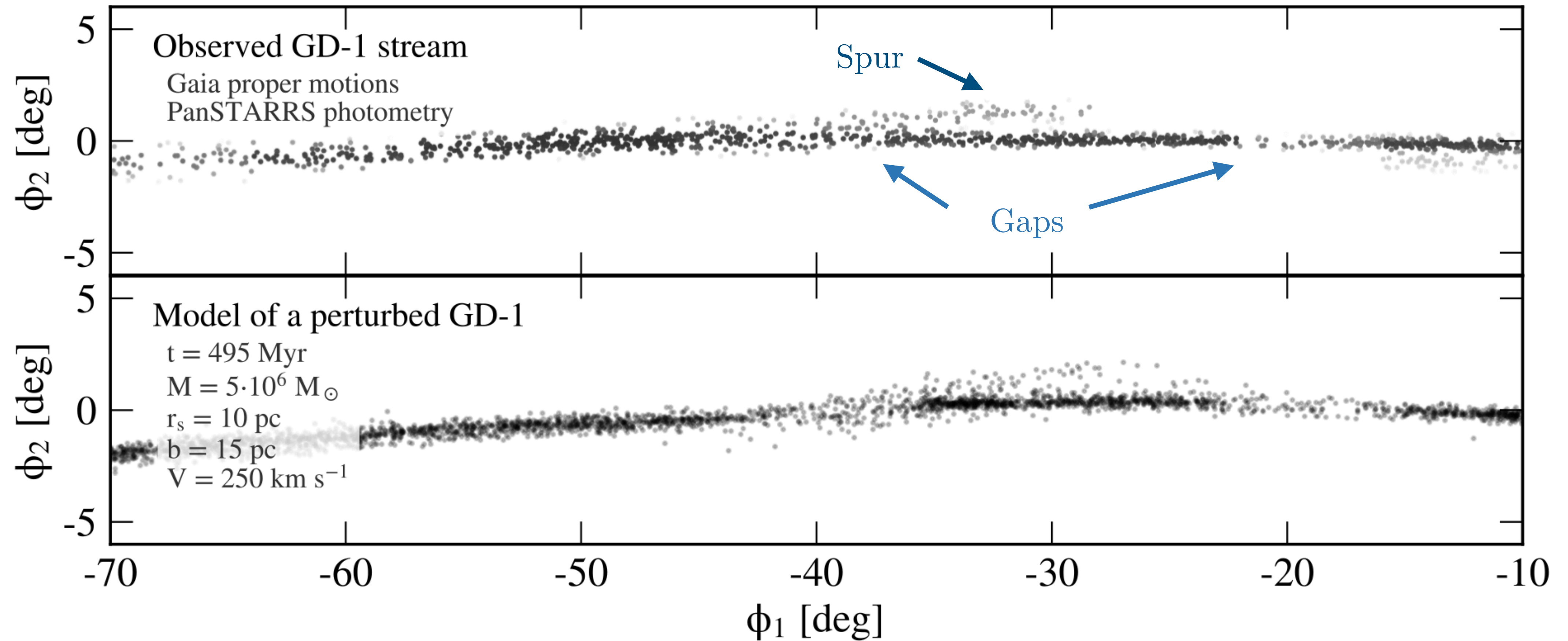


What effects can impact stream density variations?



Current analysis status

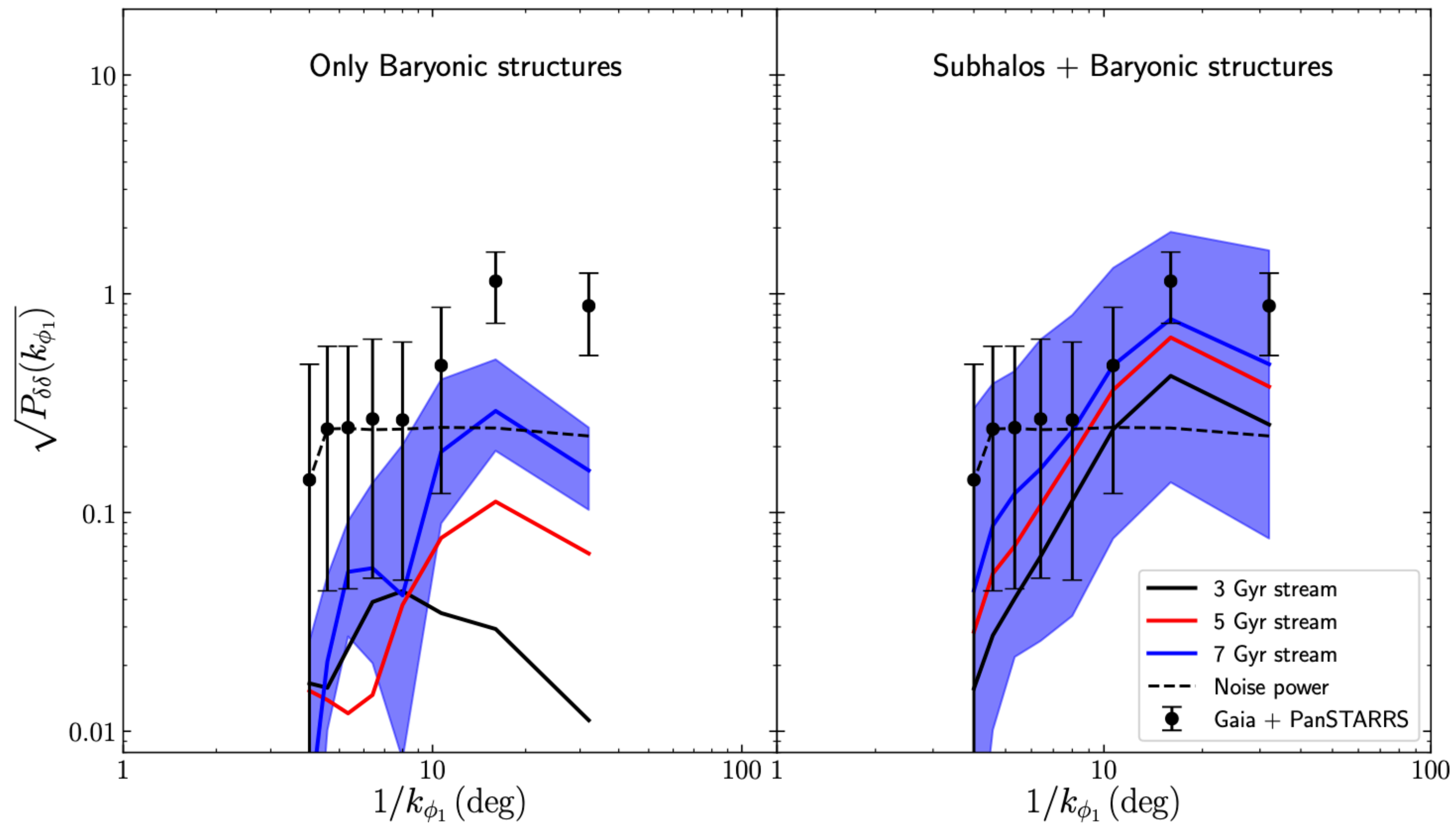
1. Comparing individual features between data and simulations



[Bonaca+ \(2018\)](#)

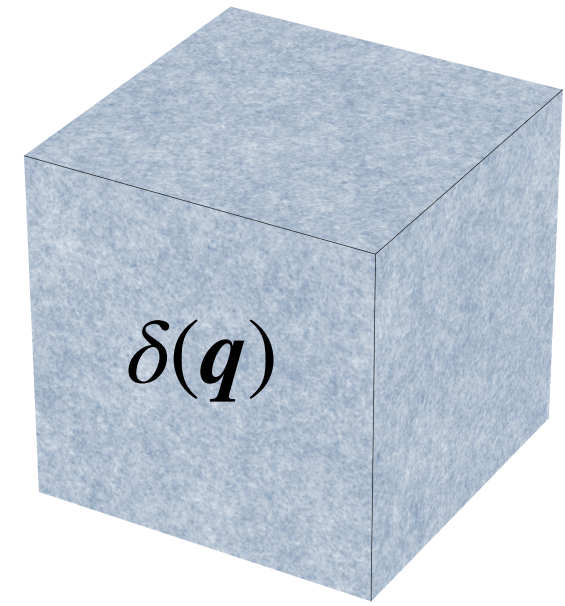
Current analysis status

2. Statistical approach using the power spectrum of stream density variations



[Banik+ \(2019\)](#)

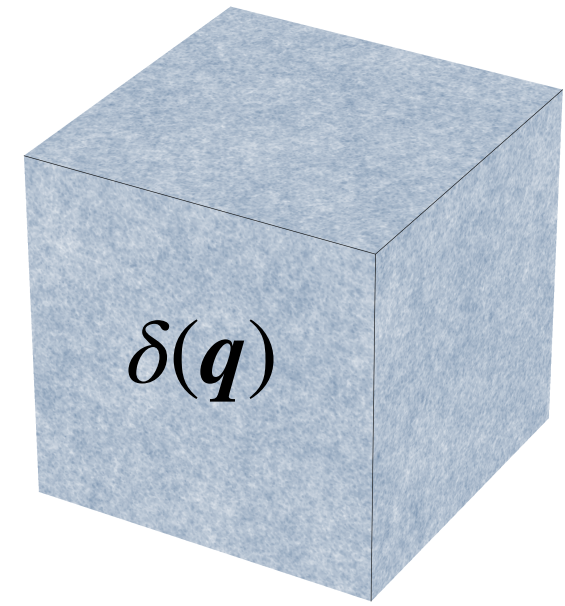
Stellar streams in the diffusion regime



The **diffusion regime**:

Many small kicks, not rare
strong flybys ($< 10^8 M_\odot$) $\rightarrow$
random walk in phase space

Stellar streams in the diffusion regime



Substructure power

$$\mathcal{P}(q)$$



Velocity kicks power

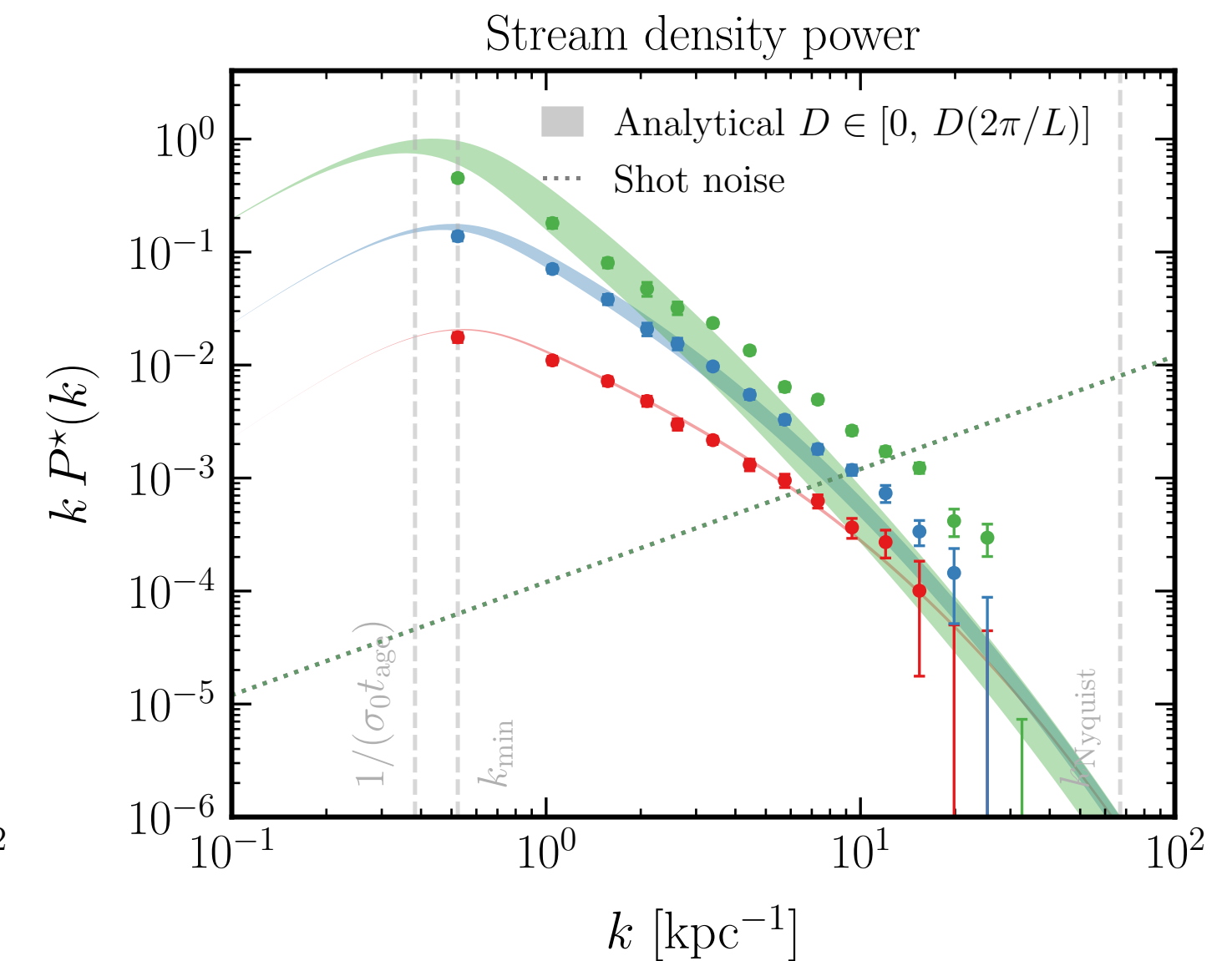
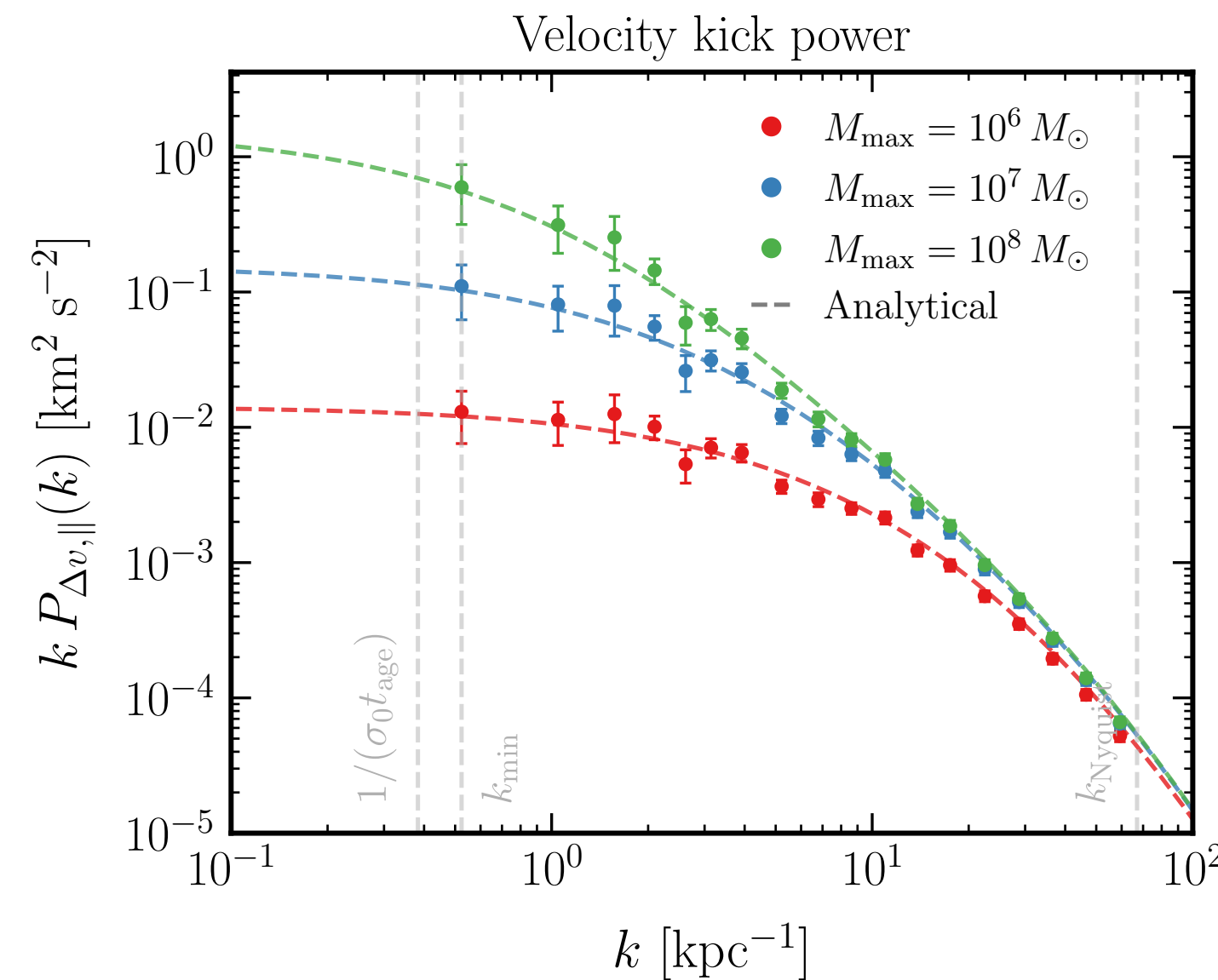
$$P_{\Delta v}(k, t)$$



Stream density power

$$P_*(k, t)$$

The diffusion regime:
Many small kicks, not rare strong flybys ($< 10^8 M_\odot$) $\rightarrow$ random walk in phase space



In the **absence of orbital dynamics**, this mapping is one-to-one and analytic.
We need to forward model stream formation and orbital dynamics.

JAX-based simulations of stellar streams in the diffusion regime



- Just-in-time compilation
- GPU support
- **Autodifferentiable**
- Parallelisable with vmap



Gradient-based inference or use additional information from gradients for ML methods.

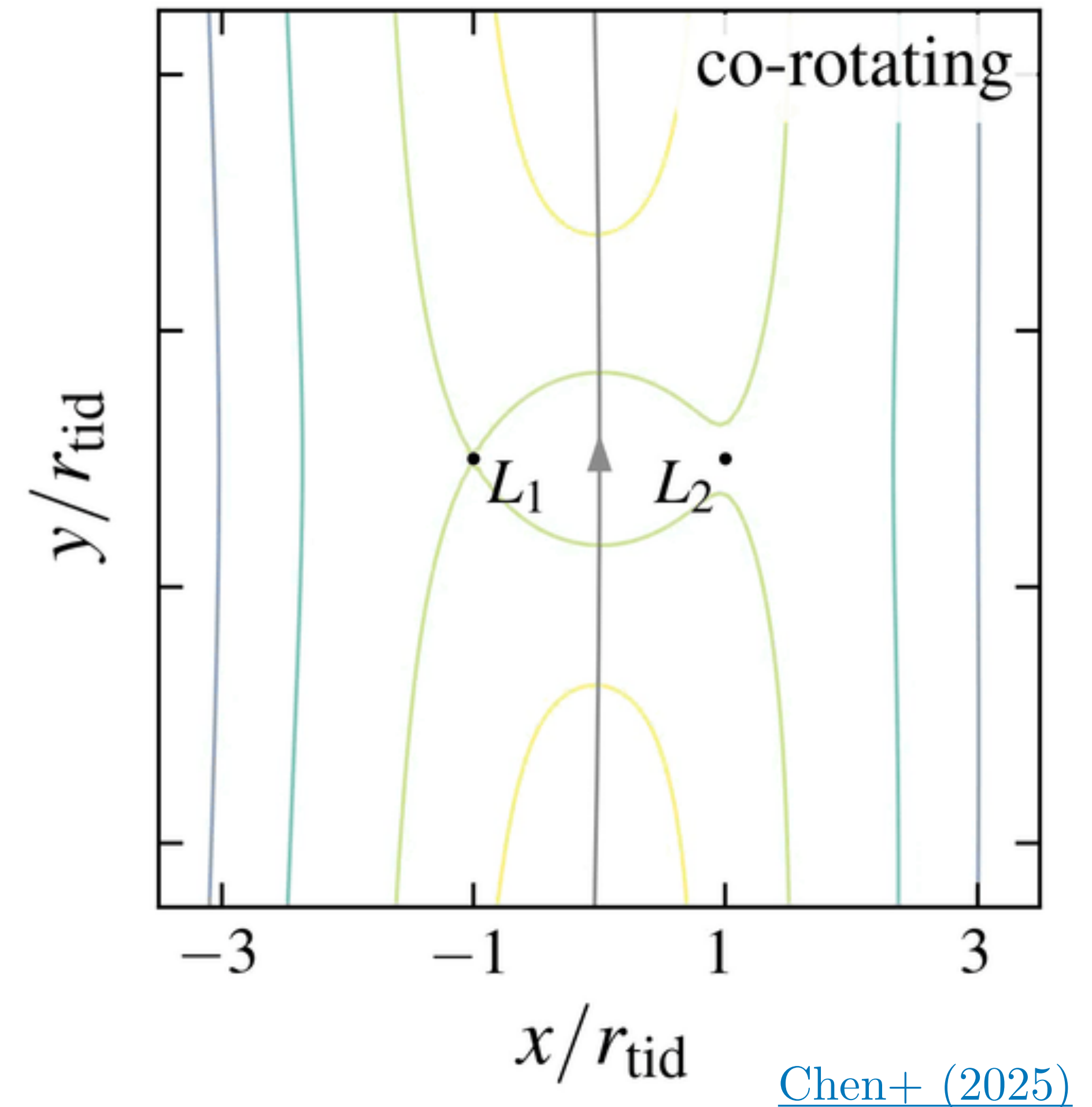
JAX-based simulations of stellar streams in the diffusion regime

1. Progenitor cluster dynamics sets stellar initial conditions

Particle-spray model: ejects stars with positions and velocities offset from the progenitor's Lagrange points and orbital velocity at a rate determined by the progenitor's properties and mass loss rate. [e.g. [Fardal+2015](#), [Chen+2025](#)]



Differentiable w.r.t. mass loss rate parameters and the progenitor's properties.



JAX-based simulations of stellar streams in the diffusion regime

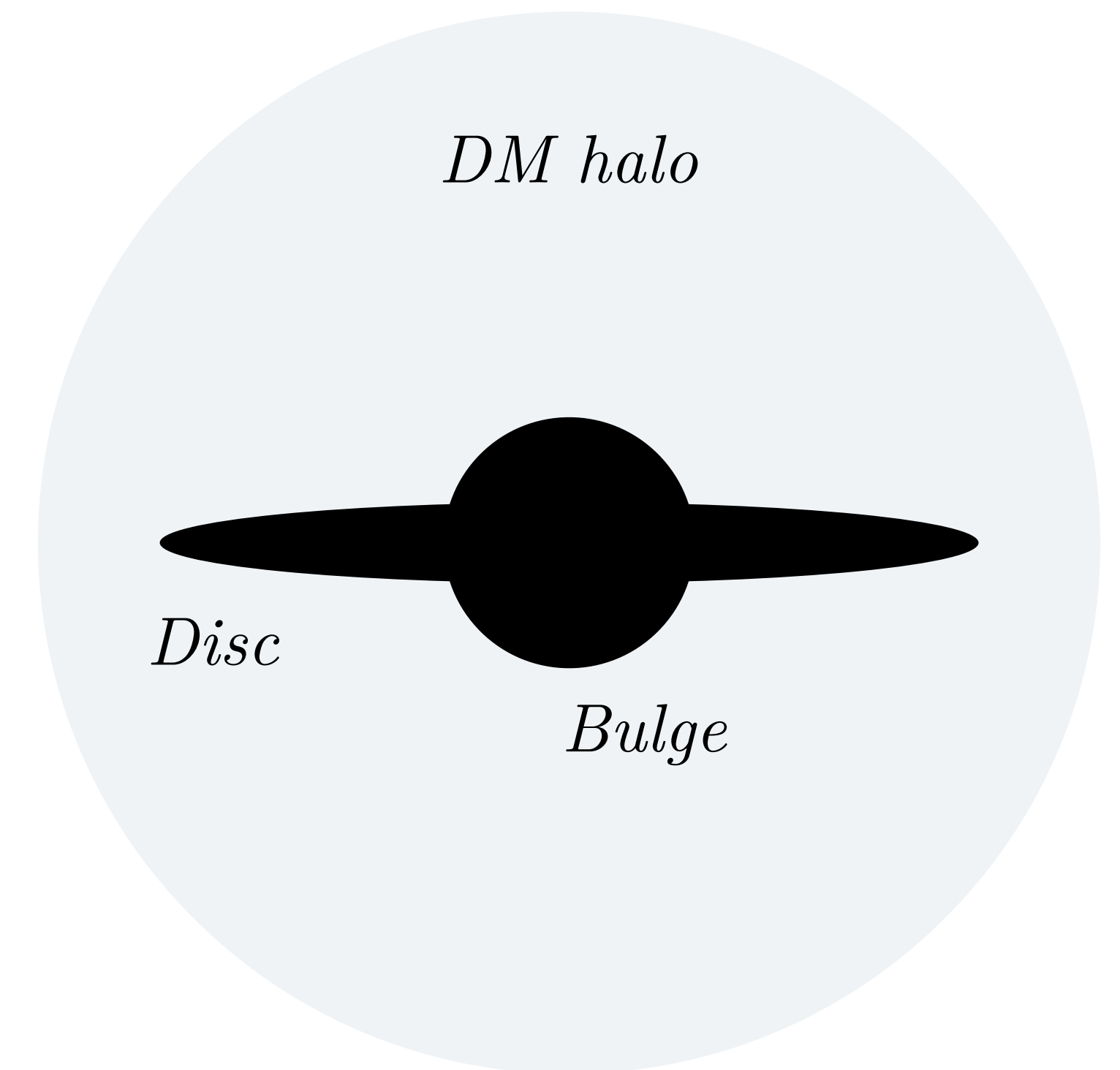
2. Orbital dynamics

Integrate stellar orbits in the host galaxy potential. We use a JAX-based version of the galactic dynamics package `gala` [[Price-Whelan+2017](#)].



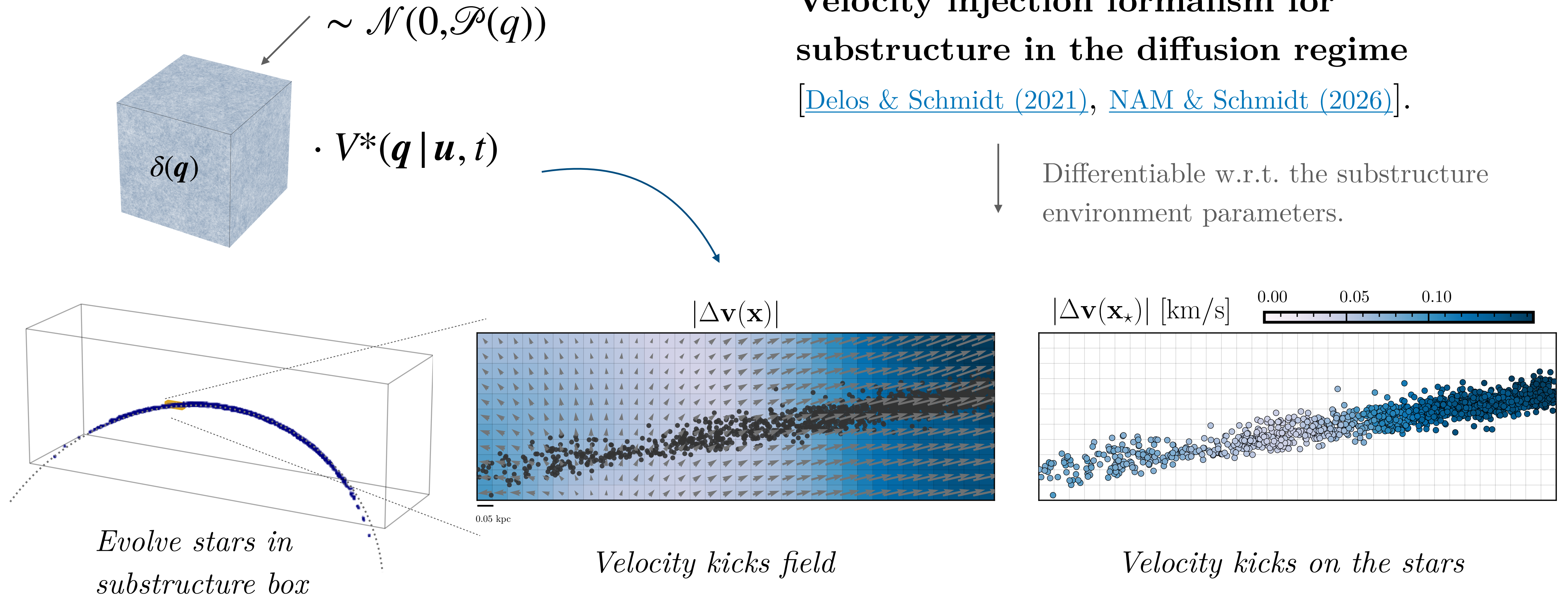
Differentiable w.r.t. the galactic potential parameters.

$$\ddot{\mathbf{x}} = -\nabla\Phi(\mathbf{x})$$

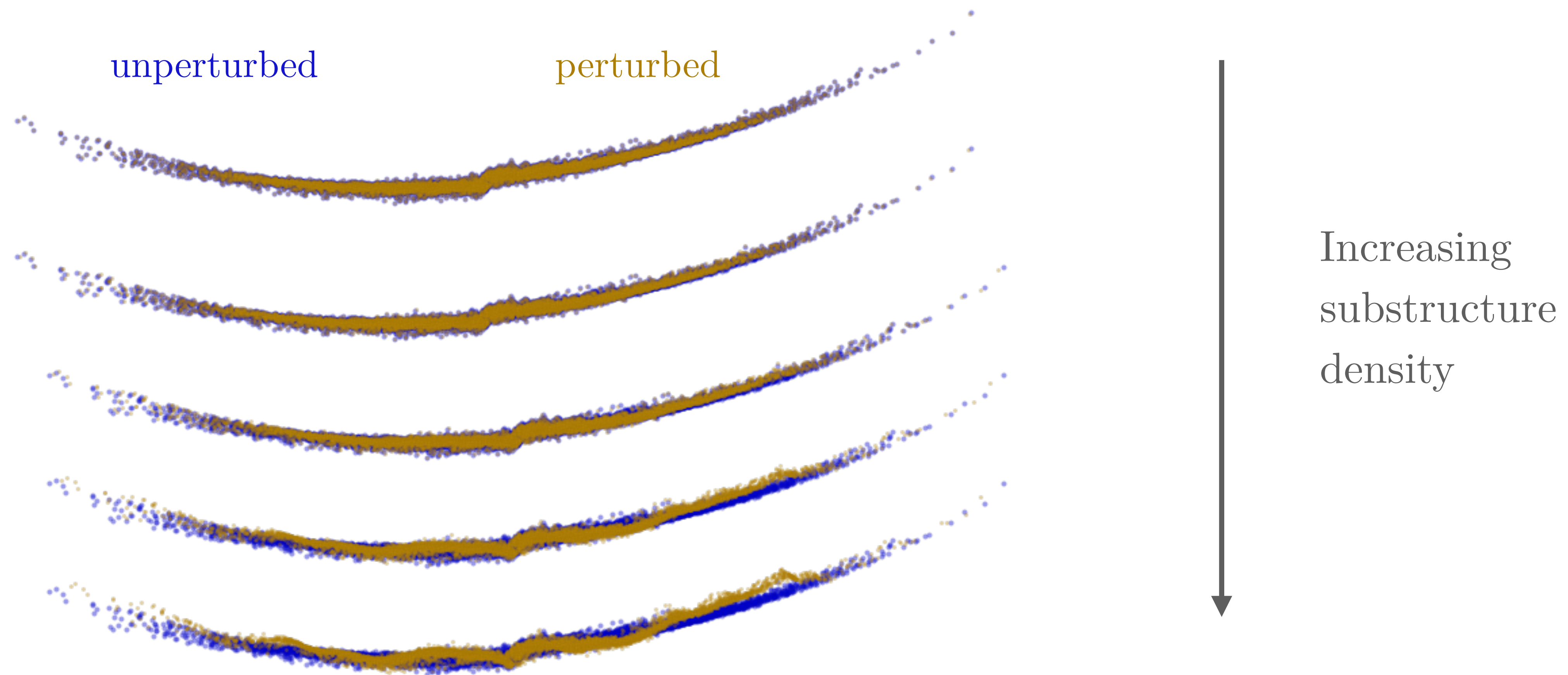


JAX-based simulations of stellar streams in the diffusion regime

3. Velocity kicks due to substructures

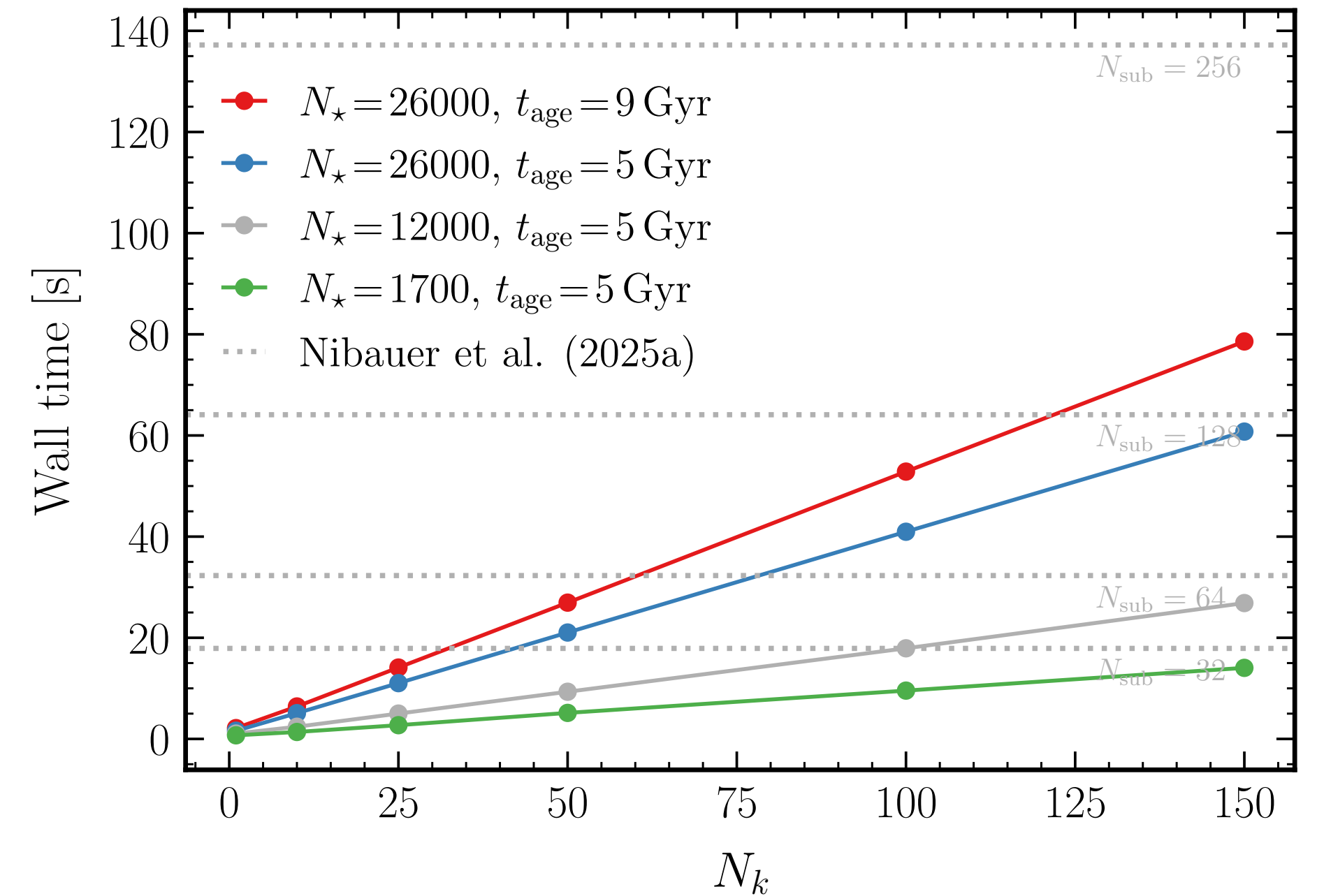


JAX-based simulations of stellar streams in the diffusion regime



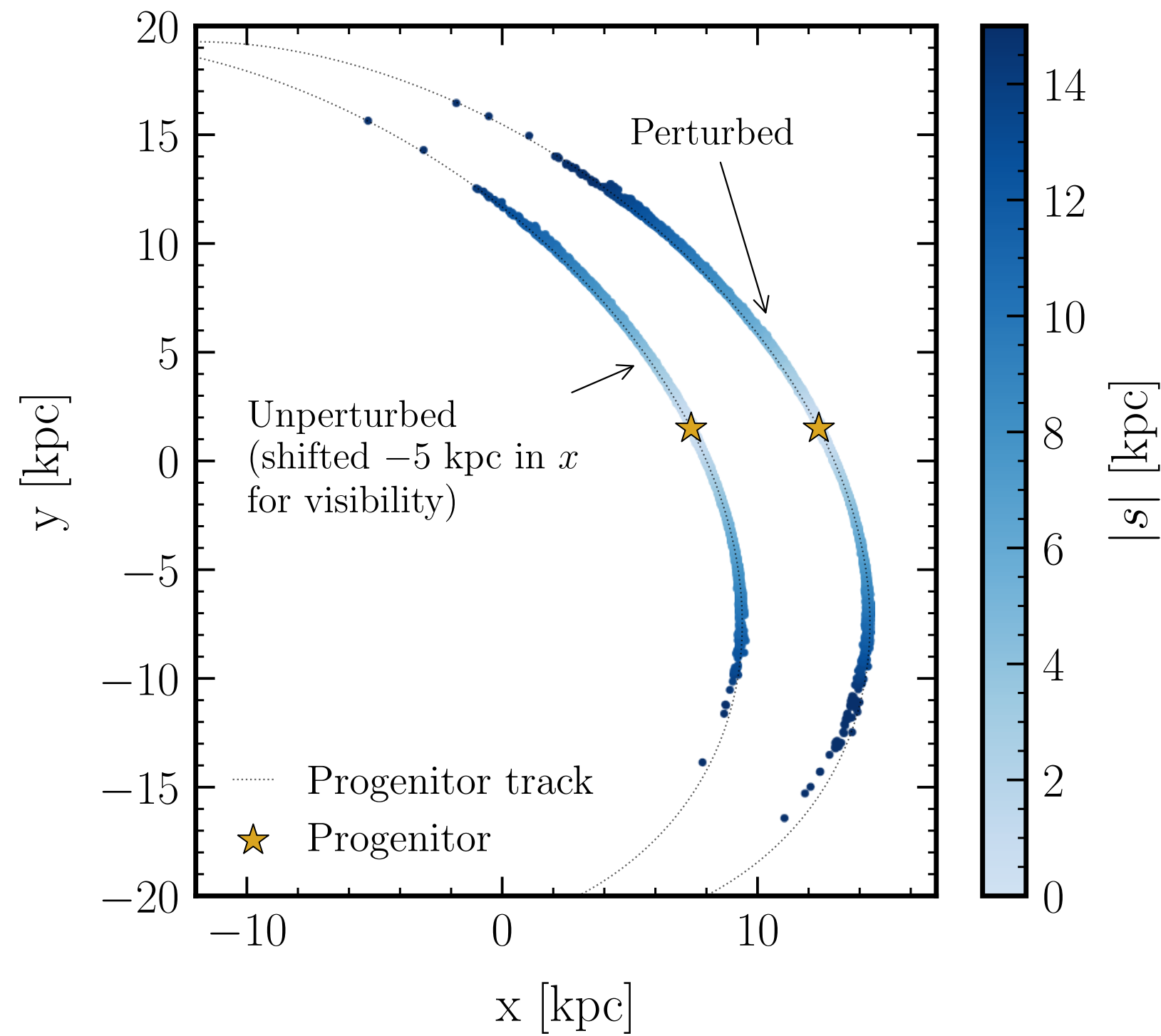
What this buys us

- **Approximate dynamics $\rightarrow$ 3D integration.** We integrate orbits fully in 3D with self-consistent stream formation, which also gives access to kinematic observables (proper motions, radial velocities).
- **Resolved encounters $\rightarrow$ statistical field.** Cost of resolving individual subhalos grows prohibitively as $M_{\min}$ decreases. Sampling $\delta(q)$ in a box makes the cost independent of substructure number.
- **Discrete subhalos $\rightarrow$ continuous perturbations.** Non-standard DM (e.g. FDM) produces density fluctuations (e.g. interference patterns) that are not discrete objects. A field-level description handles them naturally.

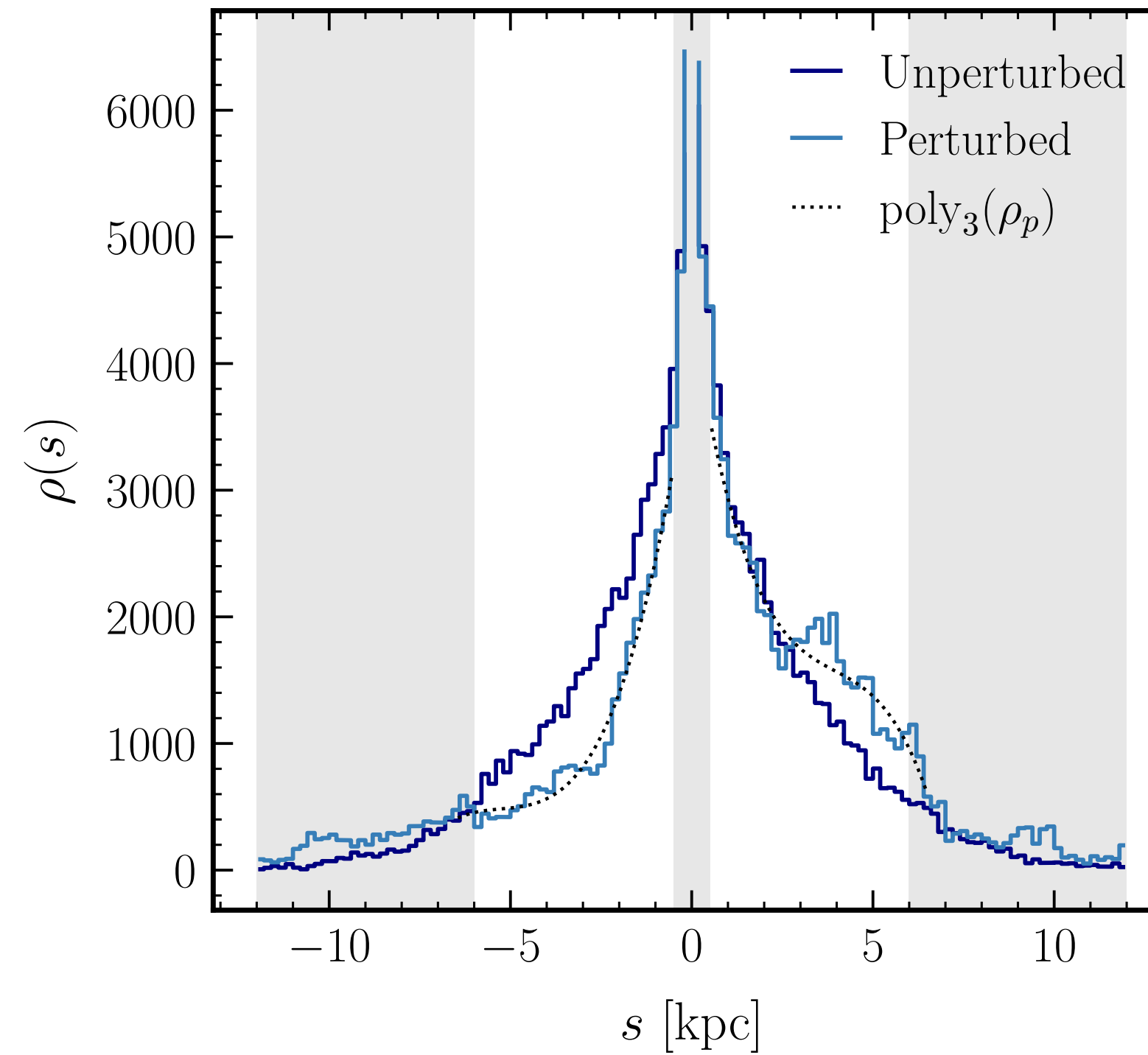


Observable: stream linear density

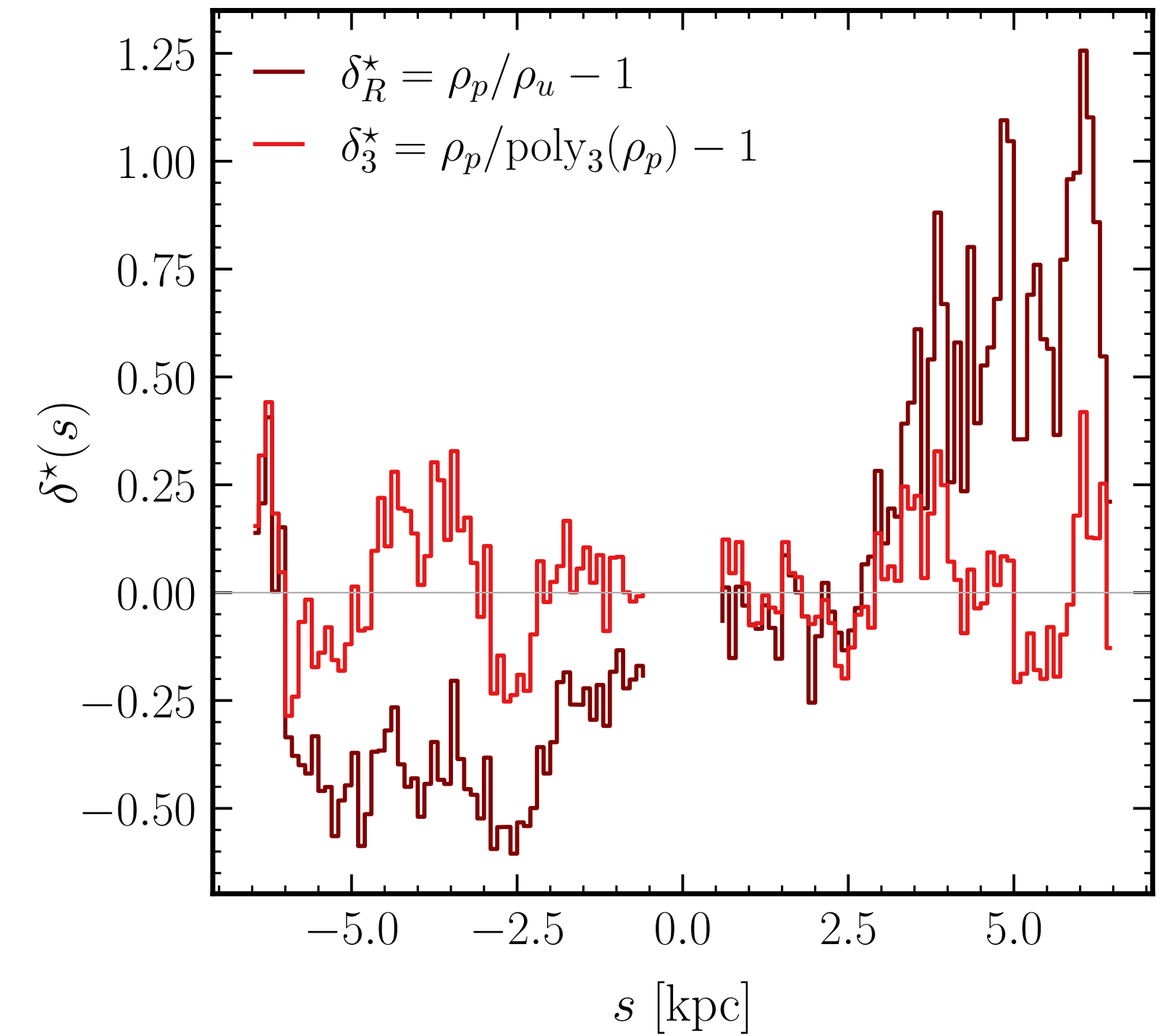
GD1-like stream



Density



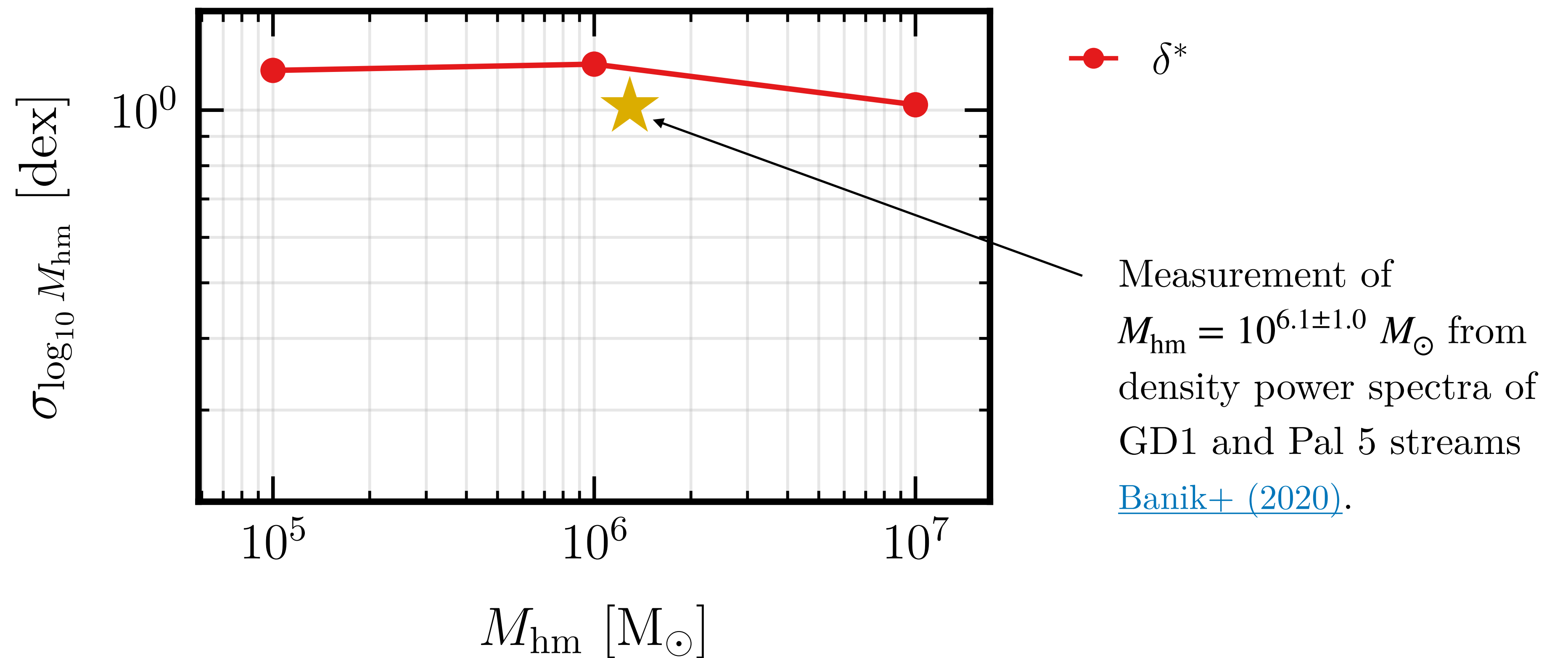
Density contrast



Fisher forecasts on a GD1-like stream

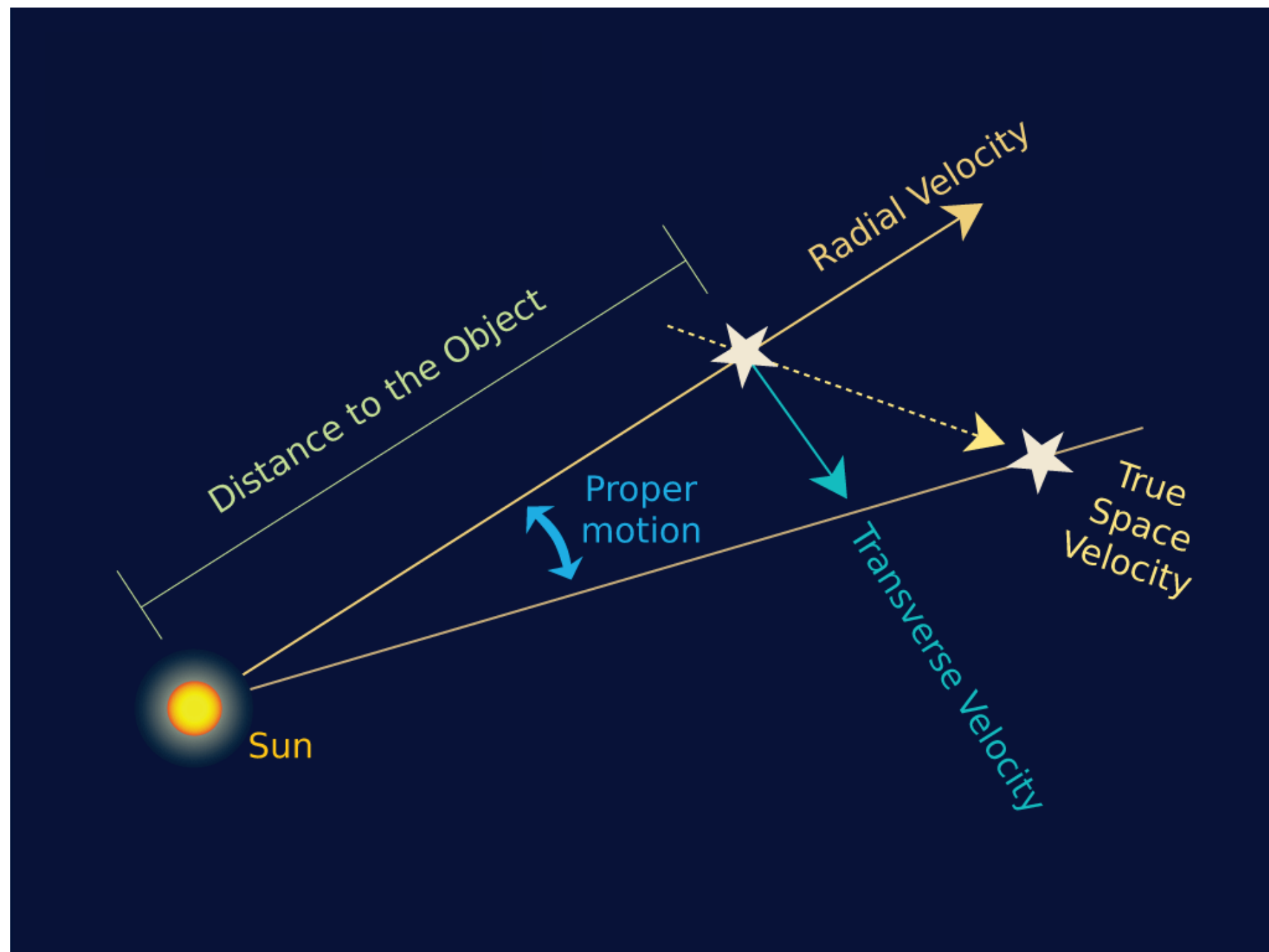
How well can we constrain parameters of the substructure environment?

$N_{\star} = 1700$
 $t_{\text{age}} = 5 \text{ Gyr}$



Other observables

How well can we constrain parameters of the substructure environment?



- Stream density power spectrum $P^\star(k)$
- Proper motions power spectra $P_{\mu_{\phi_1}}(k)$ and $P_{\mu_{\phi_2}}(k)$

$$\mu_{\phi_1} = \frac{\mathbf{v} \cdot \hat{\mathbf{e}}_{\phi_1}}{r} \text{ and } \mu_{\phi_2} = \frac{\mathbf{v} \cdot \hat{\mathbf{e}}_{\phi_2}}{r}$$

Positions
and proper
motions
from
astrometry
(GAIA)

- Radial velocity power spectrum $P_{v_r}(k)$

$$v_r = \mathbf{v} \cdot \hat{\mathbf{n}}$$

Radial velocities from
spectroscopy
(e.g. DESI, upcoming
VIA Project...)

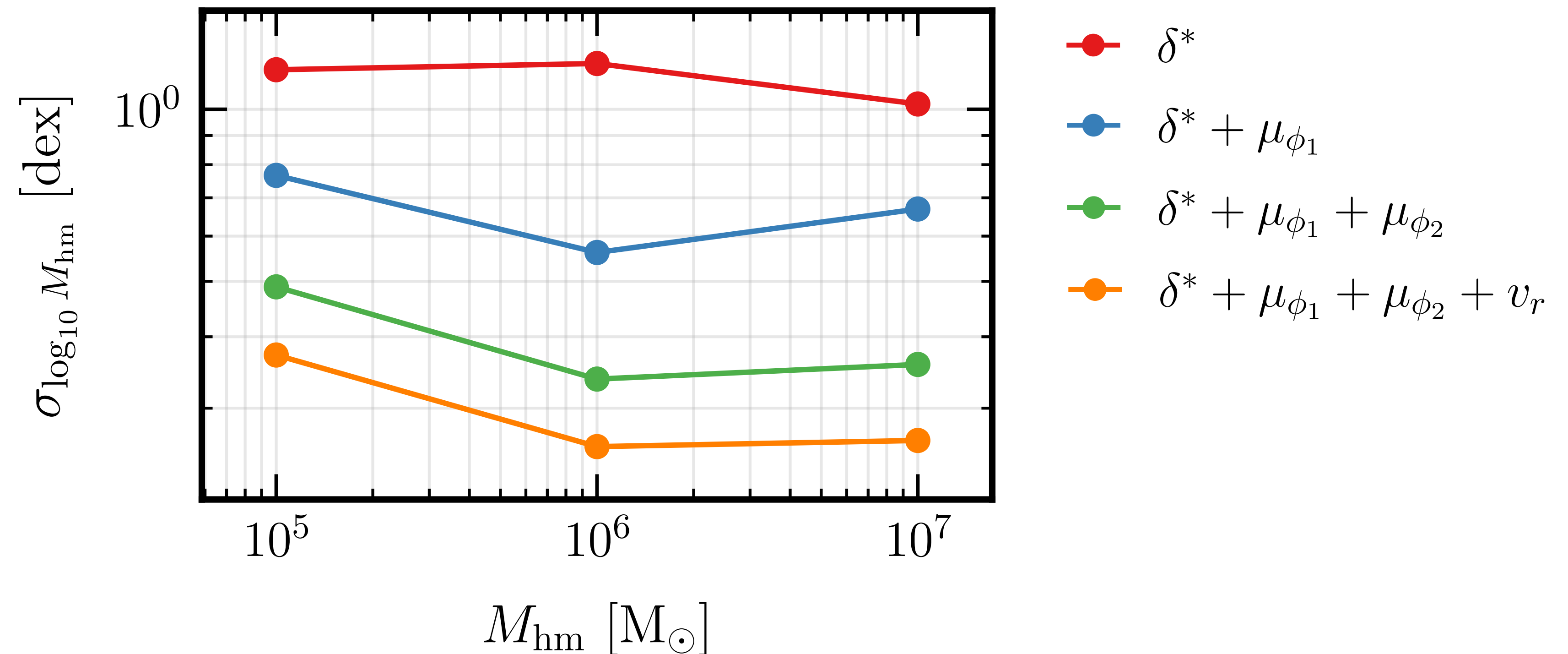
Fisher forecasts on a GD1-like stream

How well can we constrain parameters of the substructure environment?

$$N_{\star} = 1700$$

$$t_{\text{age}} = 5 \text{ Gyr}$$

Including
information from
kinematics
observables improves
the constraints!

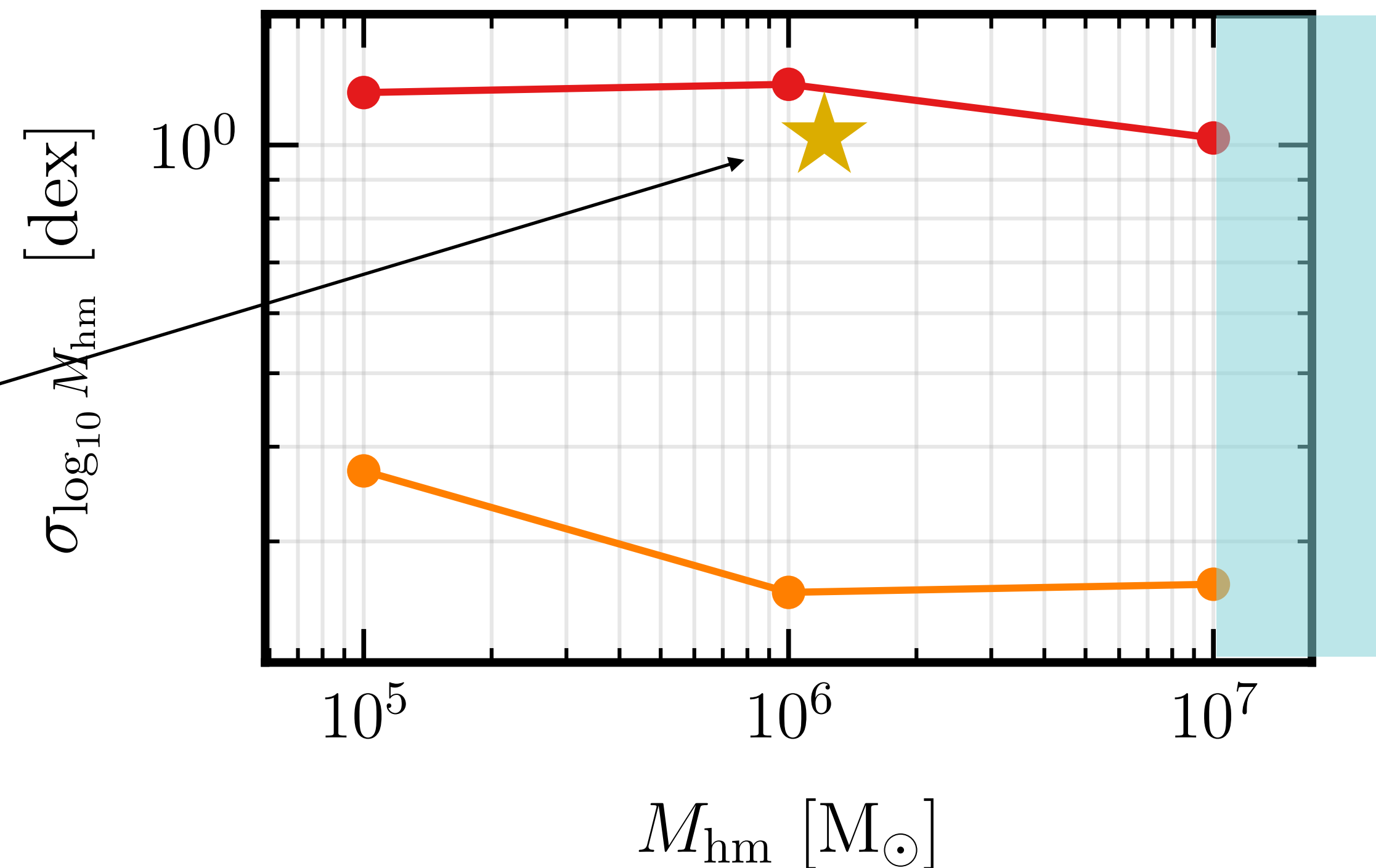


Fisher forecasts on a GD1-like stream

How well can we constrain parameters of the substructure environment?

- δ^*
- $\delta^* + \mu_{\phi_1} + \mu_{\phi_2} + v_r$

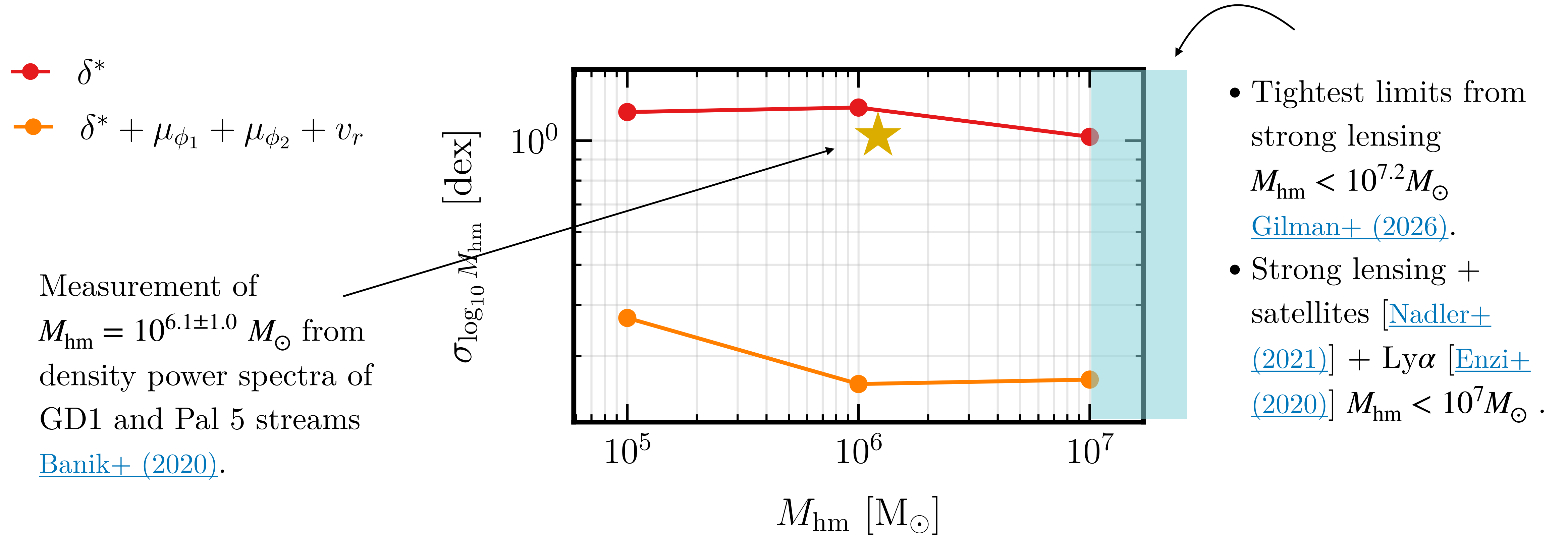
Measurement of
 $M_{\text{hm}} = 10^{6.1 \pm 1.0} M_{\odot}$ from
 density power spectra of
 GD1 and Pal 5 streams
[Banik+ \(2020\)](#).



- Tightest limits from strong lensing
 $M_{\text{hm}} < 10^{7.2} M_{\odot}$
[Gilman+ \(2026\)](#).
- Strong lensing + satellites [[Nadler+ \(2021\)](#)] + Ly α [[Enzi+ \(2020\)](#)] $M_{\text{hm}} < 10^7 M_{\odot}$.

Fisher forecasts on a GD1-like stream

How well can we constrain parameters of the substructure environment?



A single well-measured stream with full kinematic information could constrain M_{hm} at least as well as other probes, providing a local, purely gravitational measurement with independent systematics.

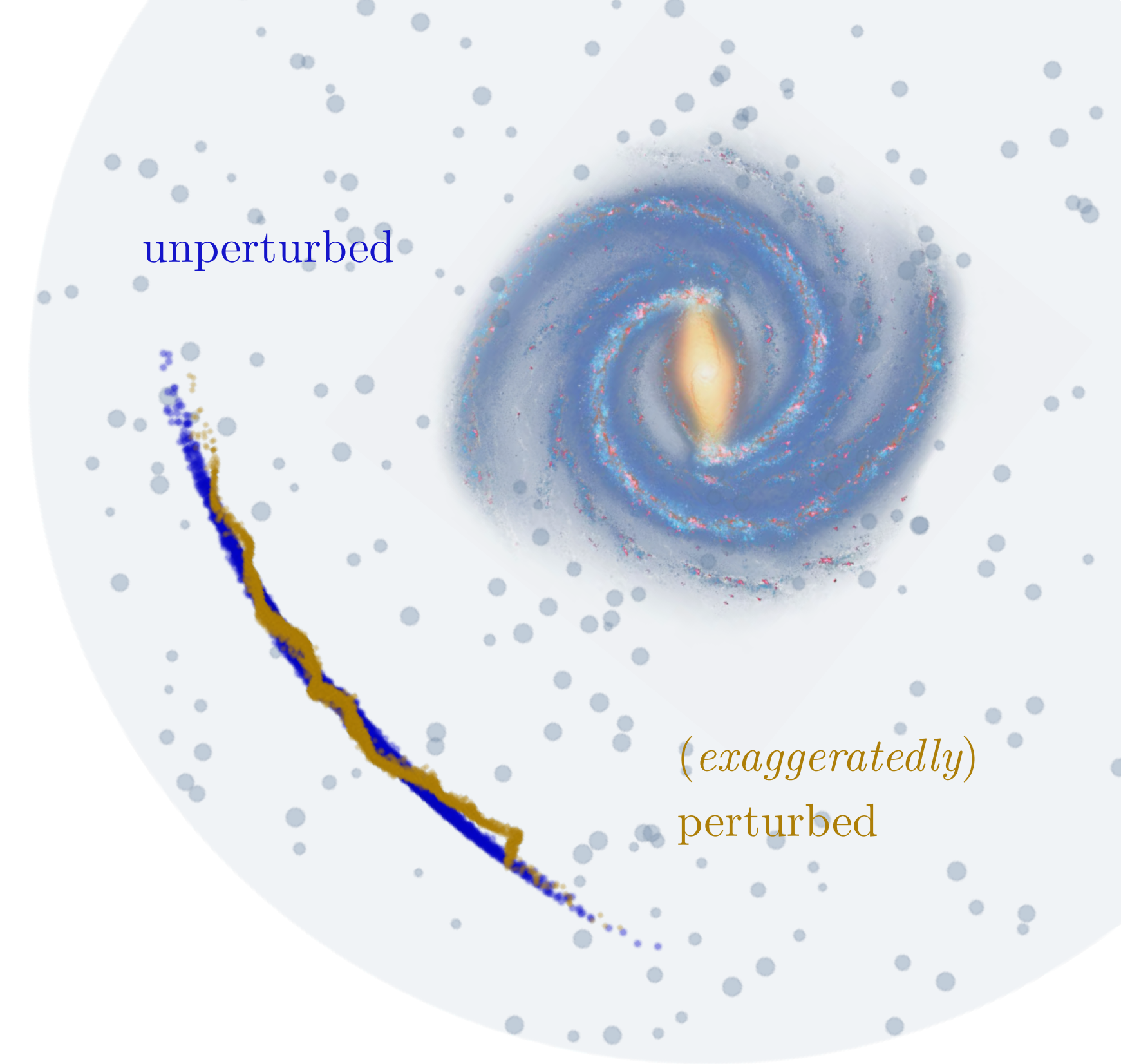
Next steps

From forecasts to measurements:

- **Add complexity to the forward model:** time varying host potential, epicyclic perturbations, observational noise...
- **Baryonic substructure** (a genuine open problem): include as an extra density field, or as deterministic perturbations when the perturber is known. Key need: a prior over plausible baryonic contributions to marginalize over.
- **Beyond the power spectrum:** the differentiable model predict other summary statistic — bispectrum, wavelets, or learned/neural compression could extract more information.

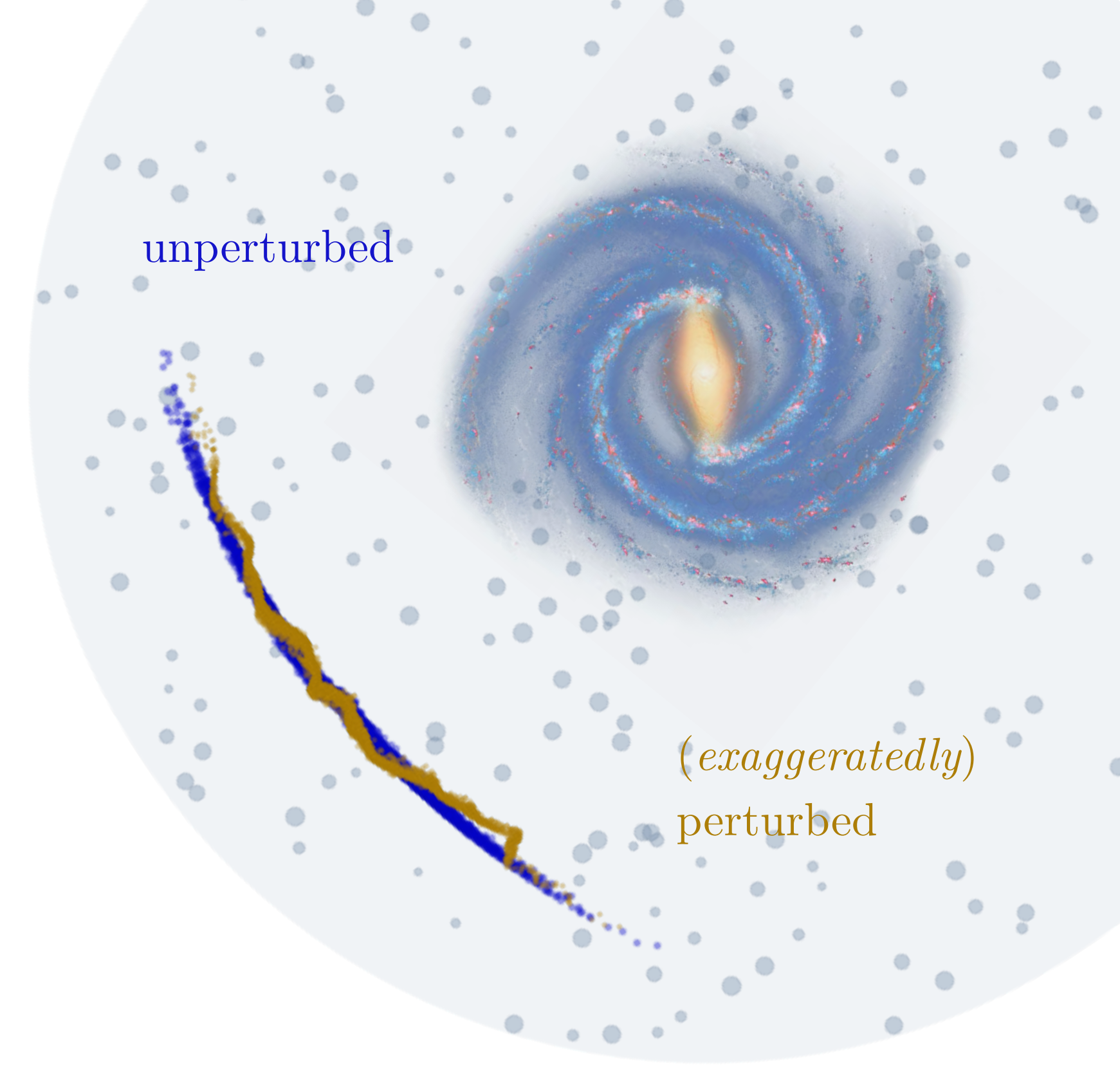
Summary

- **Stellar streams are a sensitive probe of dark matter** in the Milky Way (and beyond).
- They remain underexploited: **progress is limited more by modelling and inference than by data**, and a few well-characterized streams could already give competitive constraints.
- We have developed a *fast and differentiable JAX-based forward model for stellar streams in the diffusion regime*, that can be used for Bayesian inference.
- **Combining multiple stream observables** (available from upcoming data) sharpens constraining power on DM.



Summary

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Thank you!