Dark matter and tidal streams

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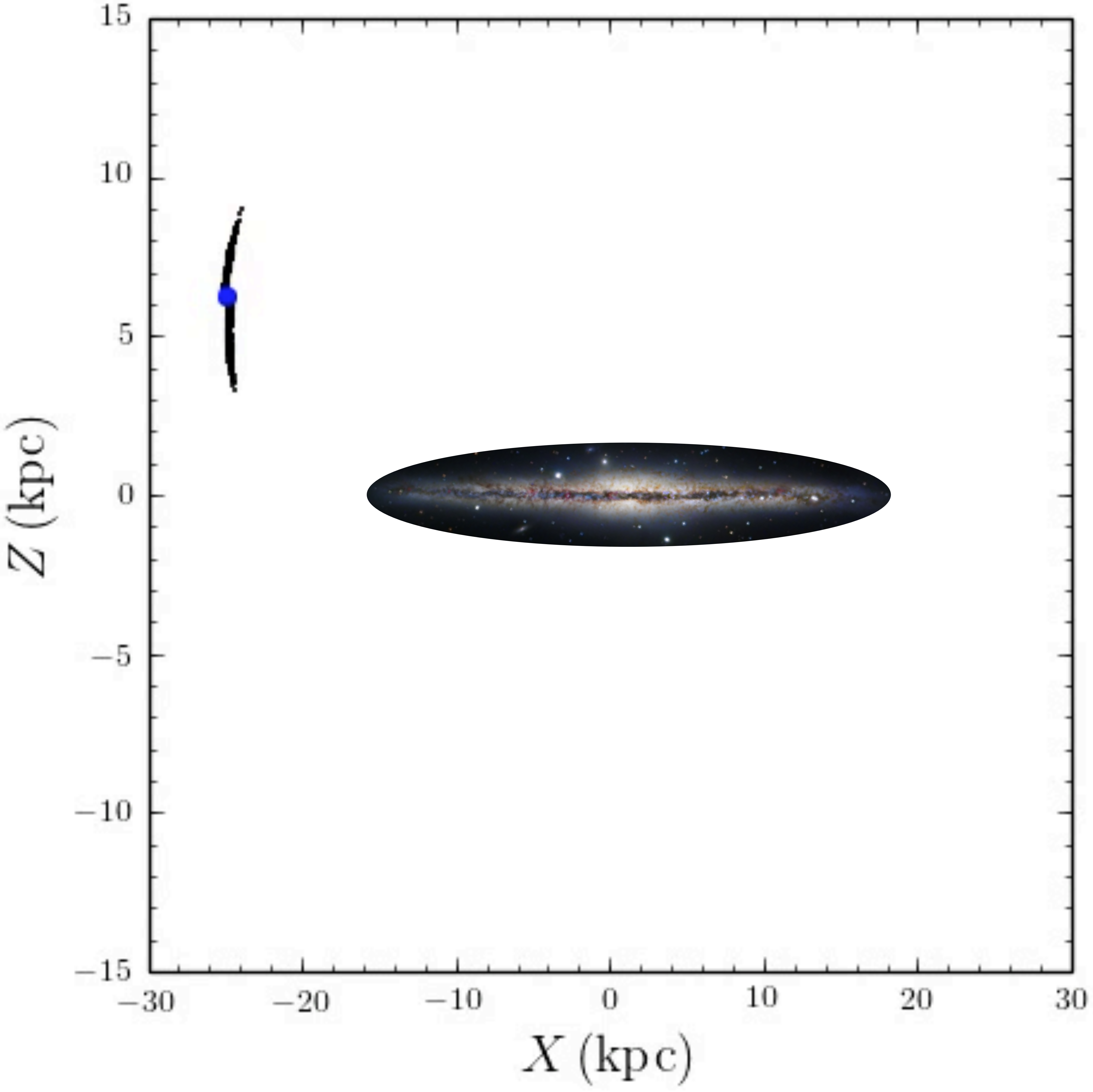

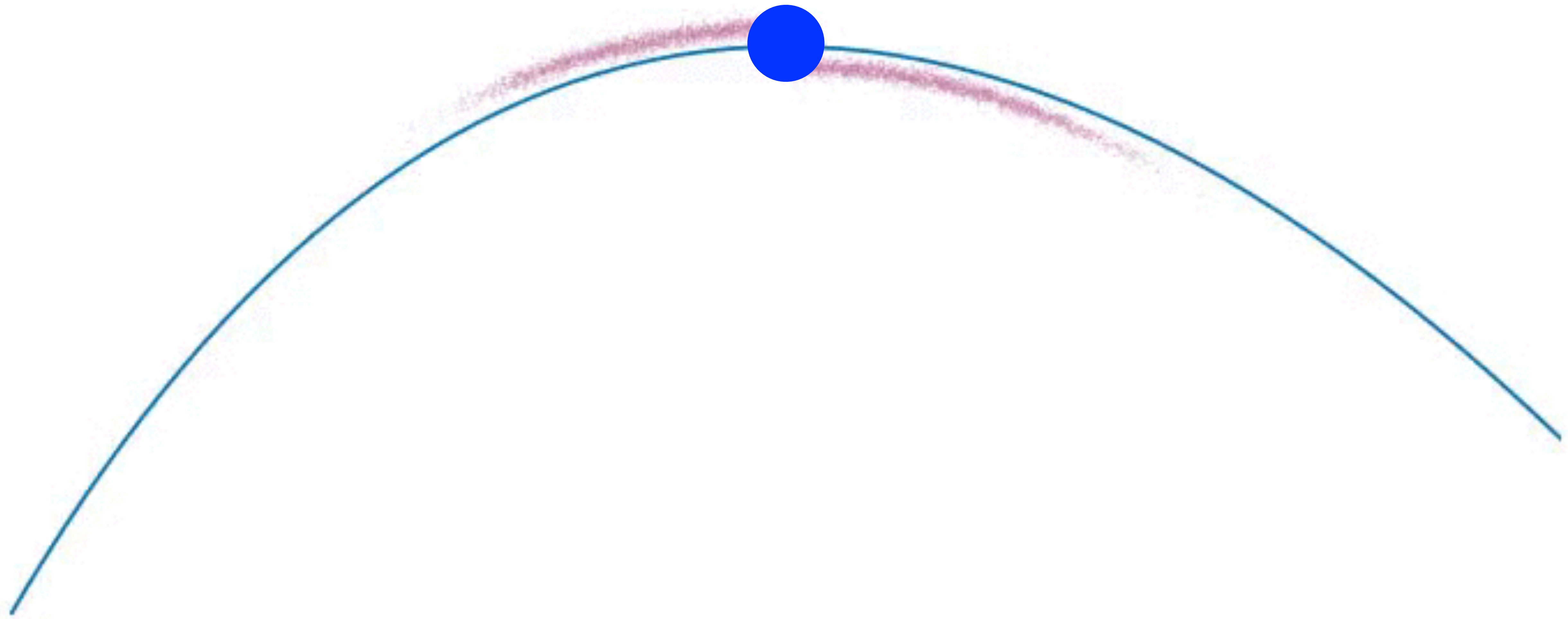

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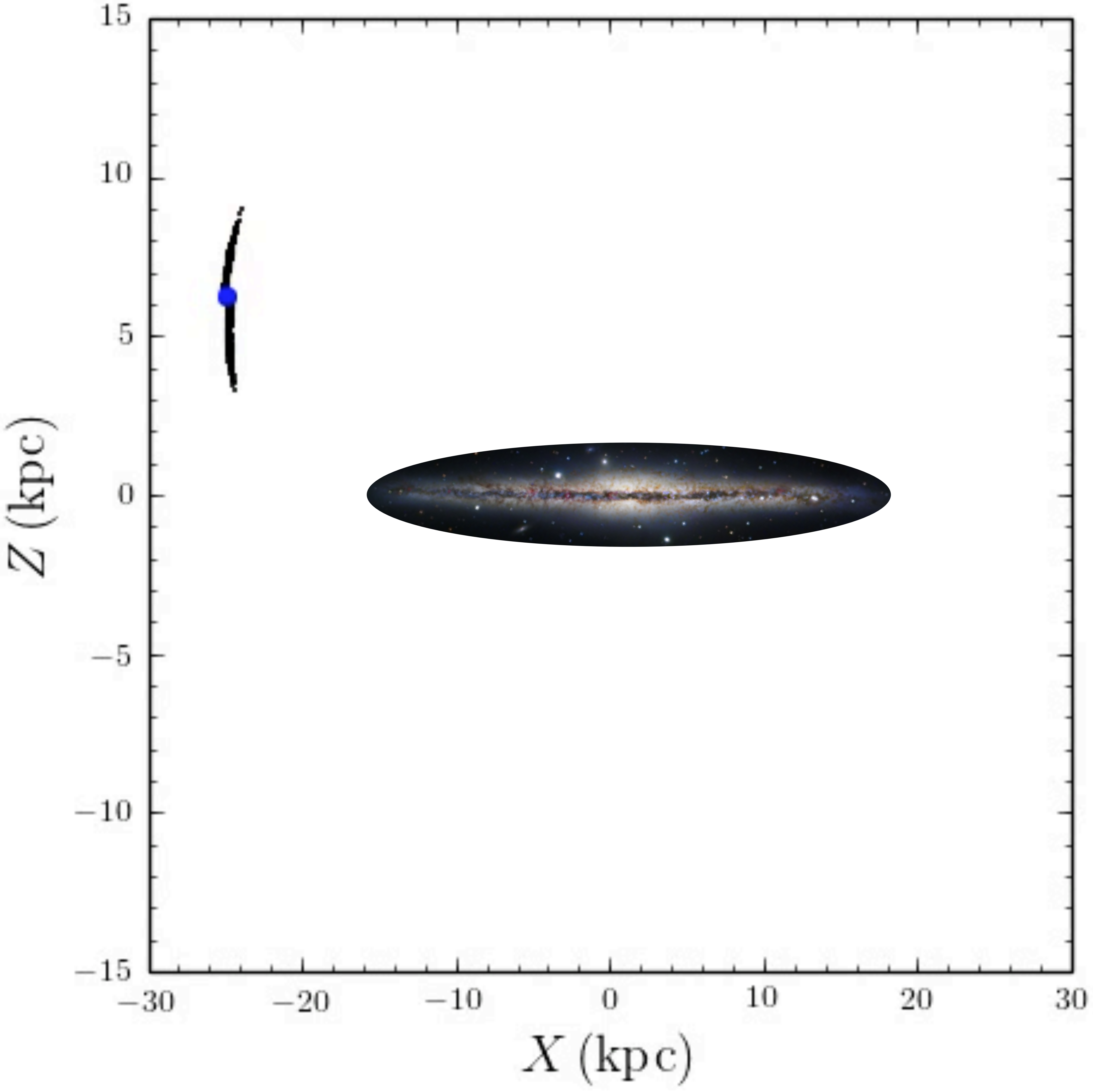

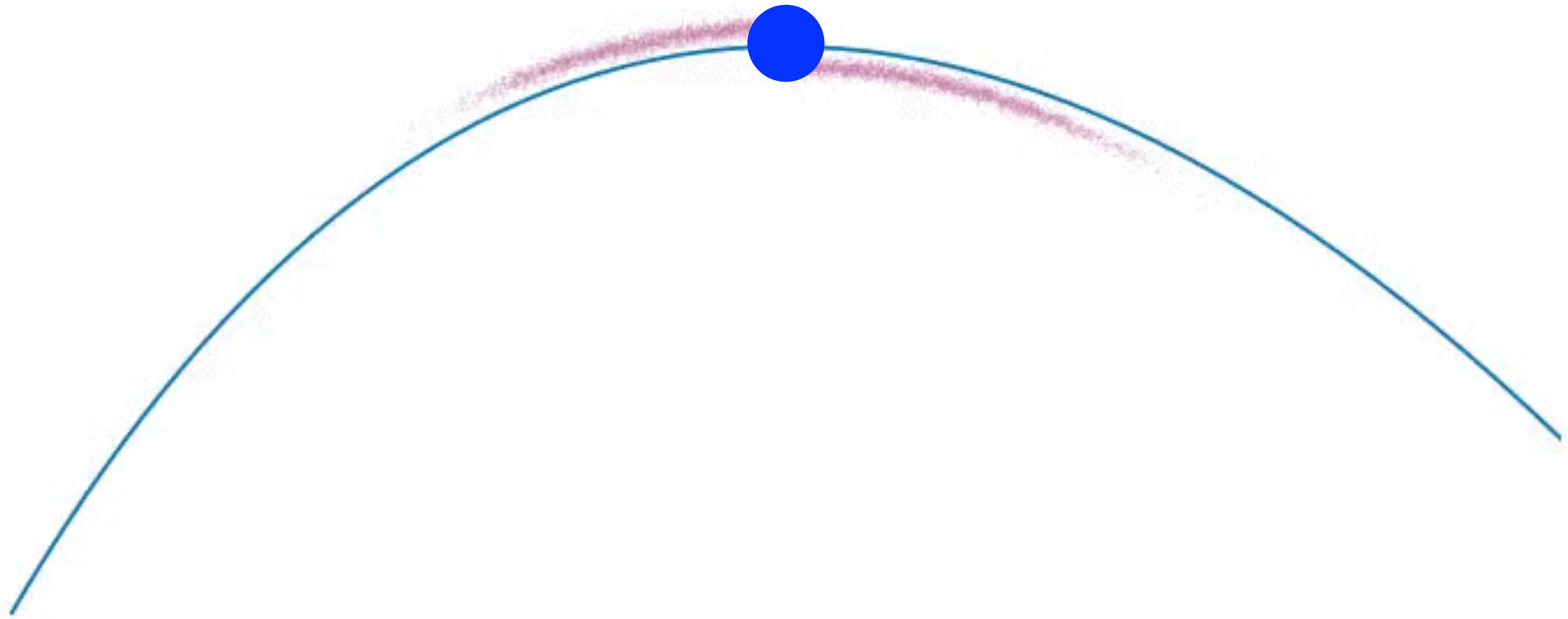

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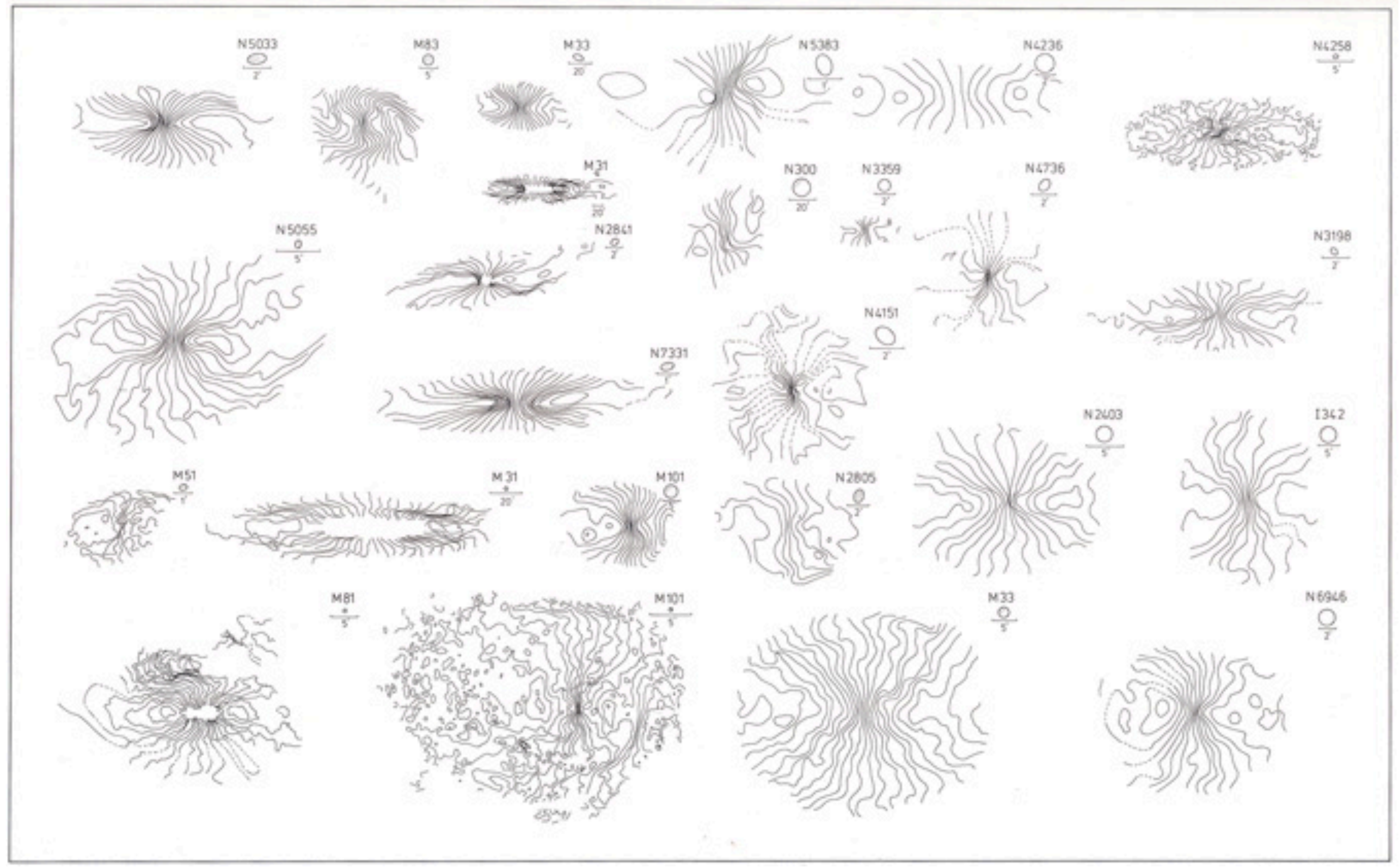
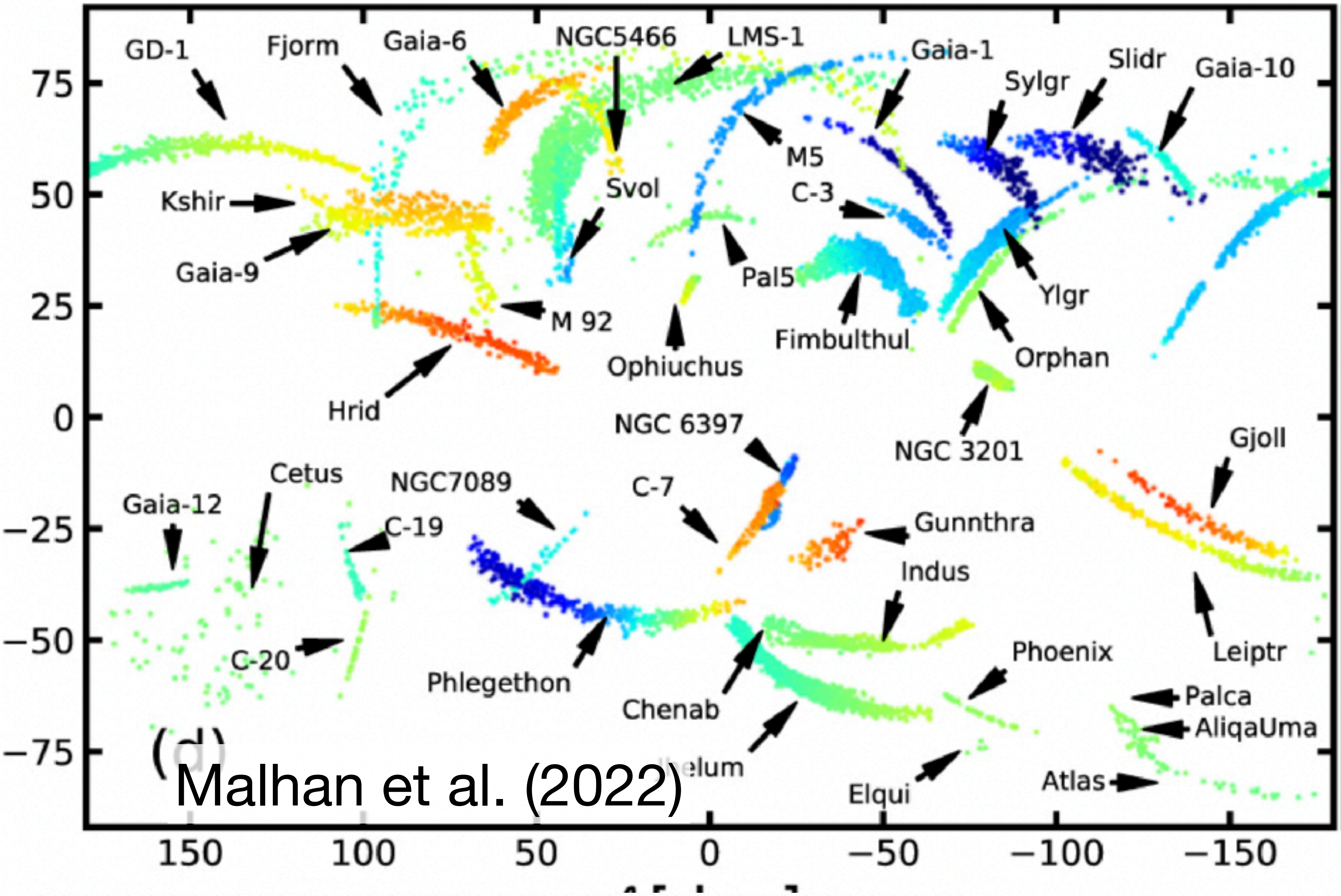
Dark matter and tidal streams

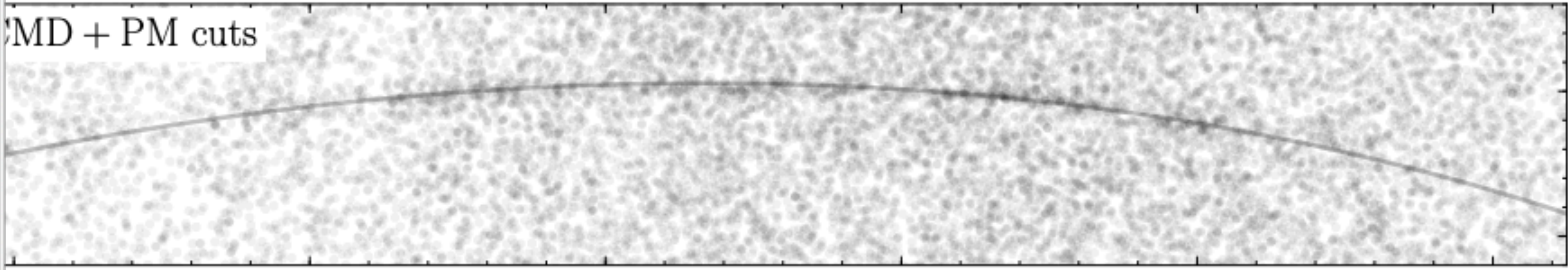
- In the absence of non-gravitational DM interactions,
    - Radial structure
    - Shape
    - Small-scale structure
    - Can tell us about fundamental nature and interactions of DM
- MW and its satellites are one of the best places to study dark matter structure
- And tidal streams are one of the best ways to do that!



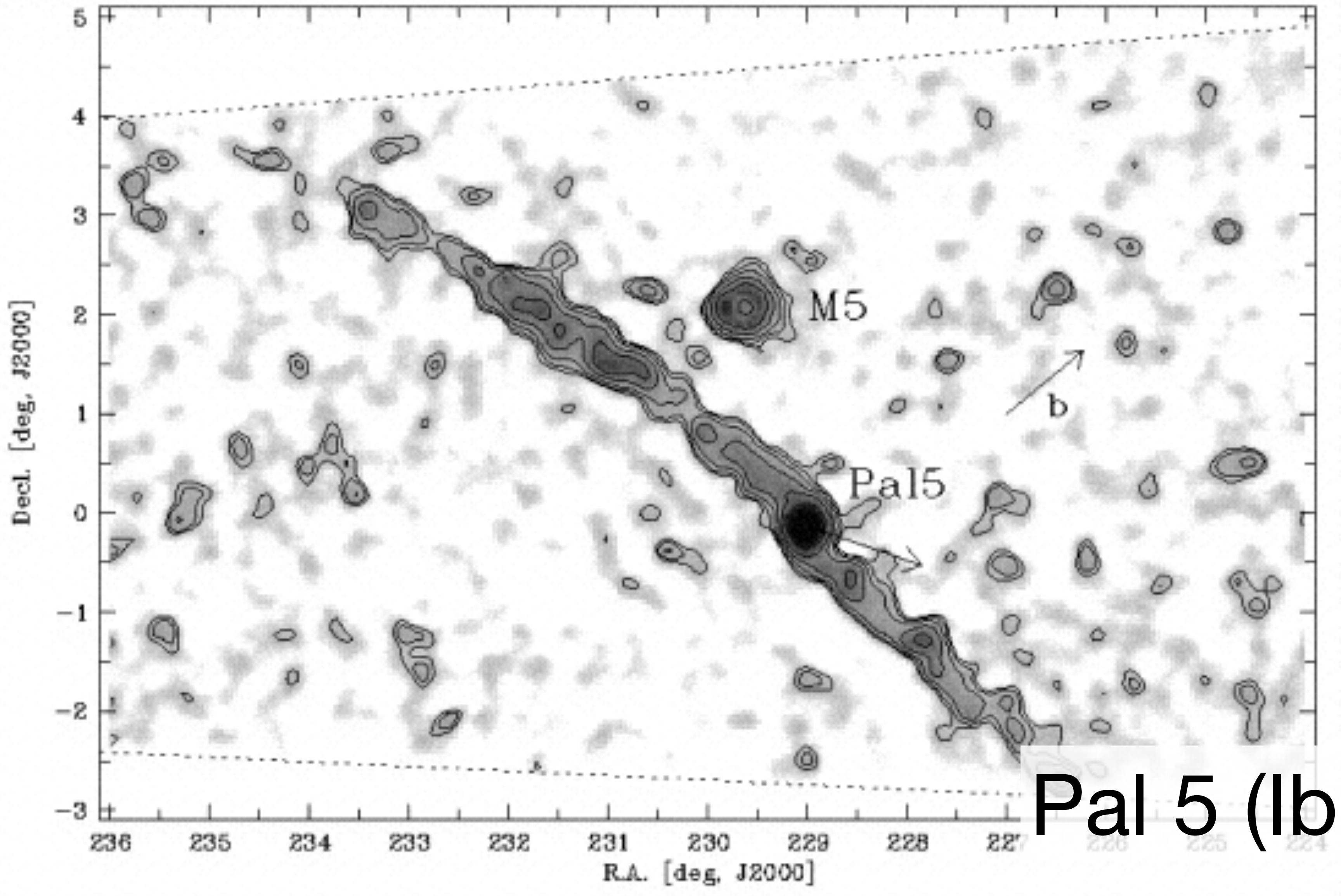
Galaxy rotation curves
(e.g., Bosma 1978, Rubin)



Malhan et al. (2022)

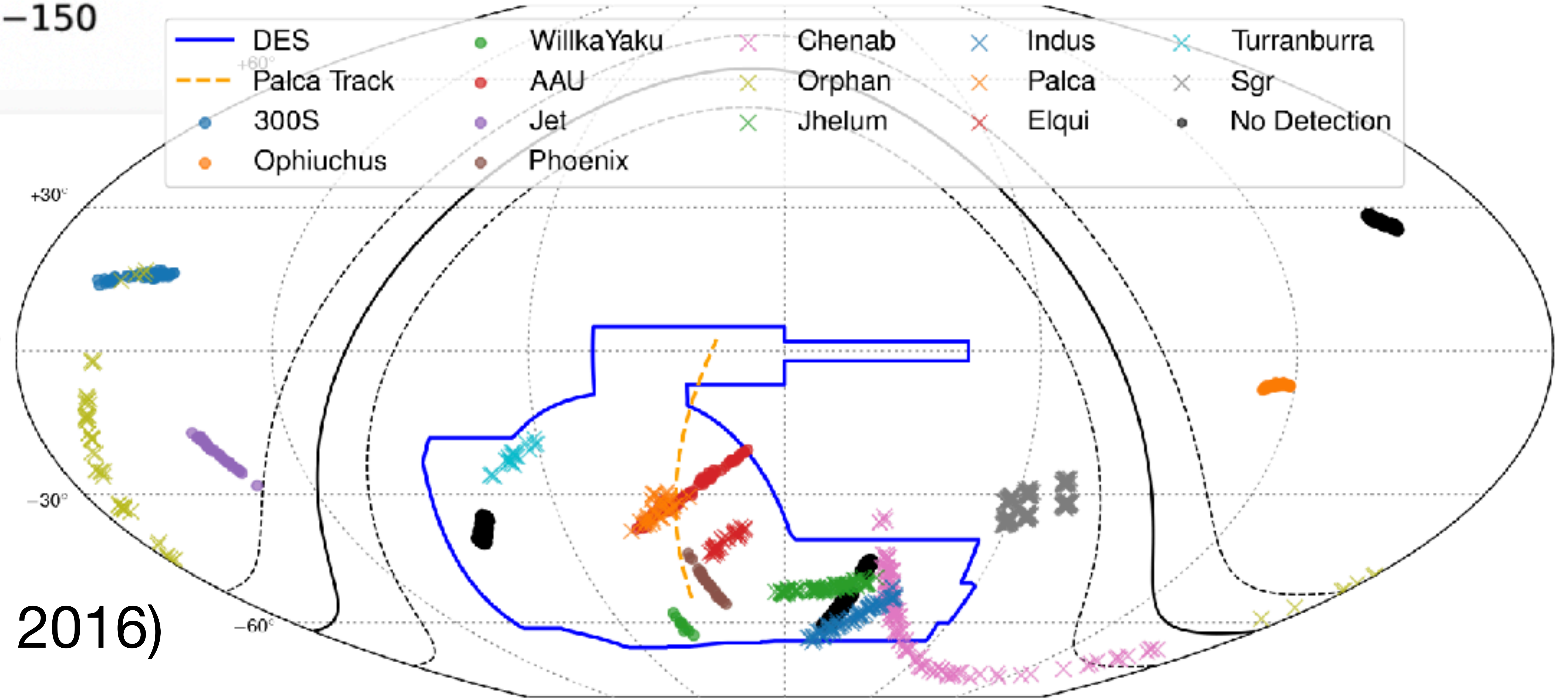


GD-1; Grillmair & Dionatos (2006); Webb & Bovy (2019)



Pal 5 (Ibata et al. 2016)

S5: Li et al. (2022)



Tidal streams and the MW dark matter halo

- Overall curvature of streams —> large-scale gravitational field
    - Dark matter radial profile
    - Dark matter shape
- Small-scale perturbations to density/tidal stream track/kinematics —> small-scale gravitational field
    - Dark matter subhalos to low masses
    - Other small-scale DM structure (PBHs, halo fluctuations of fuzzy DM)
- Both have confounding factors, but small-scale structure less so

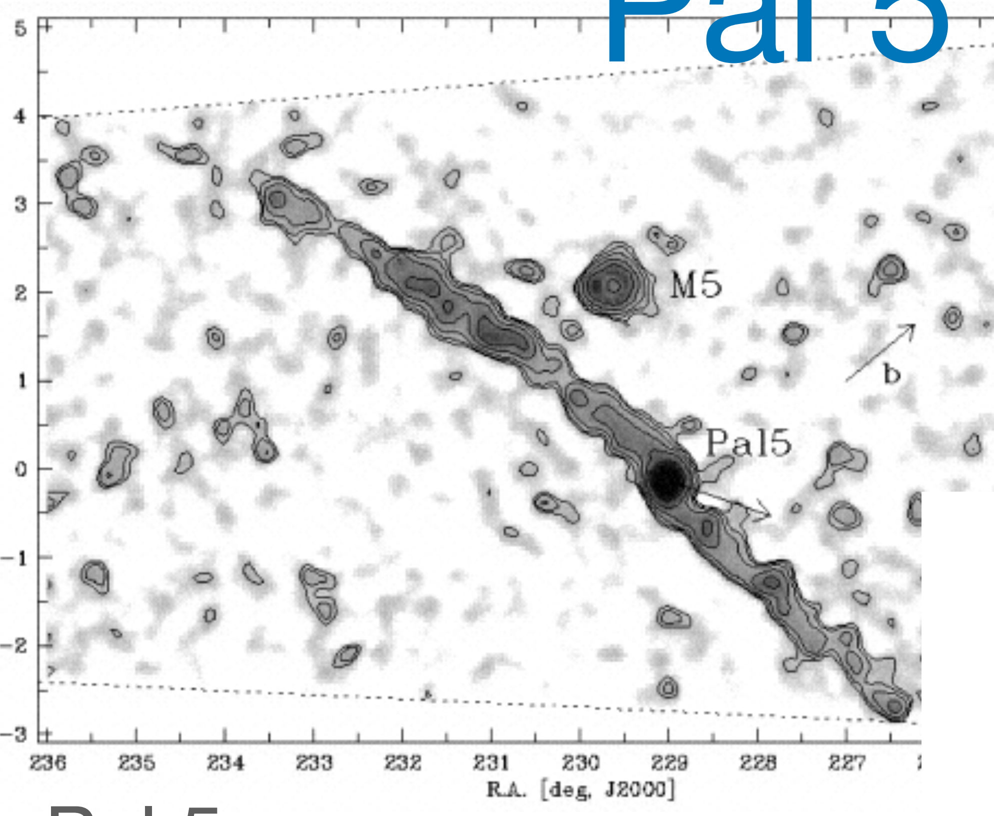
Tidal streams and overall structure of the MW dark-matter halo

Dynamical constraints on the shape of the MW halo

- Numerical simulations: inner halo of MW is slightly flattened, c/a ~ 0.8
- Most dynamical observations are insensitive to the halo shape (rotation curve, vertical force, pretty much any observation involving disk stars)
- Tidal streams result from tidal disruption of a progenitor object and have approx. constant energy
  - ΔE = 0 implies Δϕ = -Δ|v|^2/2 along stream
  - Thus, streams directly measure the local gravitational field
- Streams orbit at large |z|/R, so uniquely sensitive to halo shape

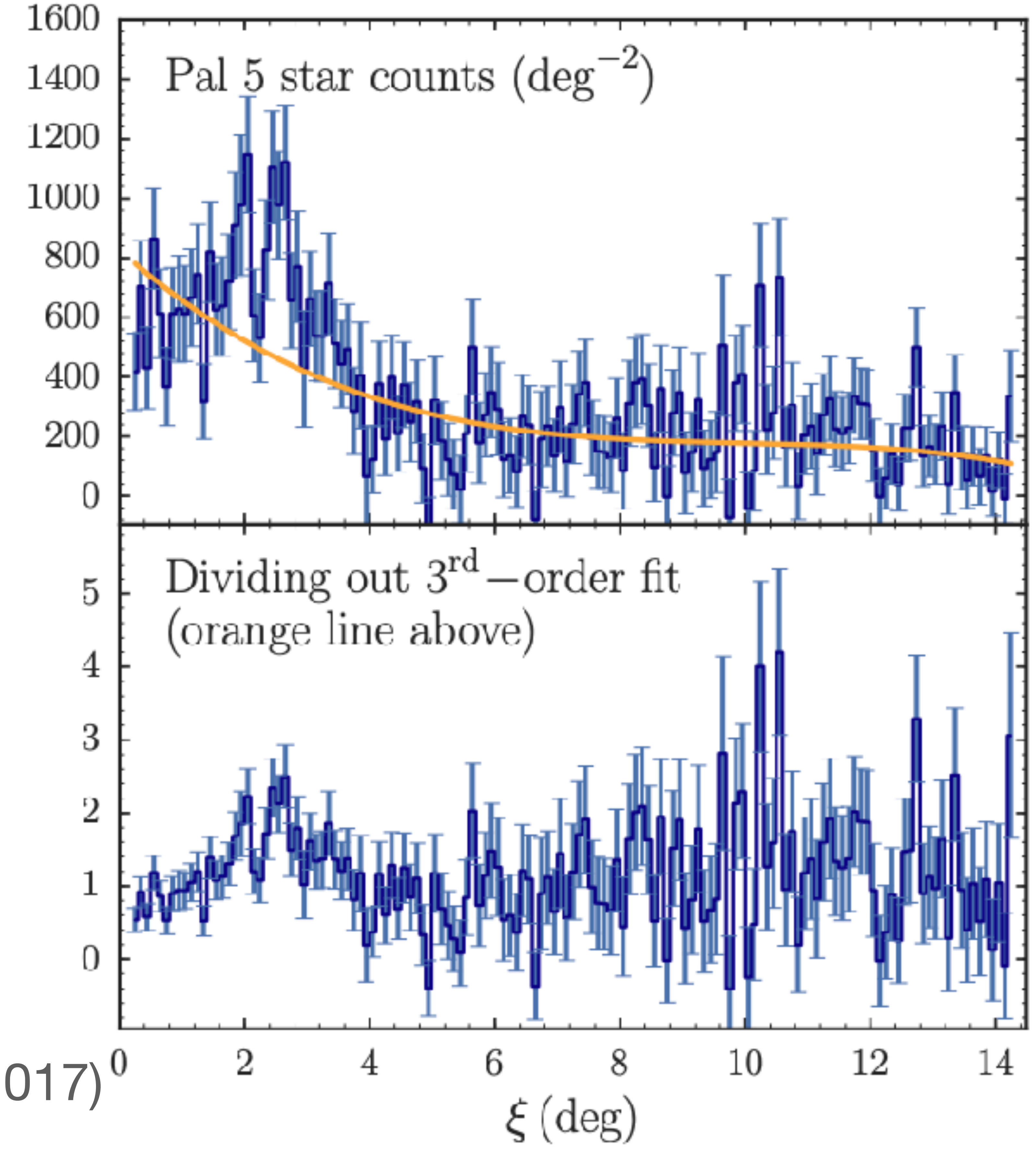
Example: Pal 5 and GD-1

Pal 5



Pal 5: Odenkirchen et al. (2003)

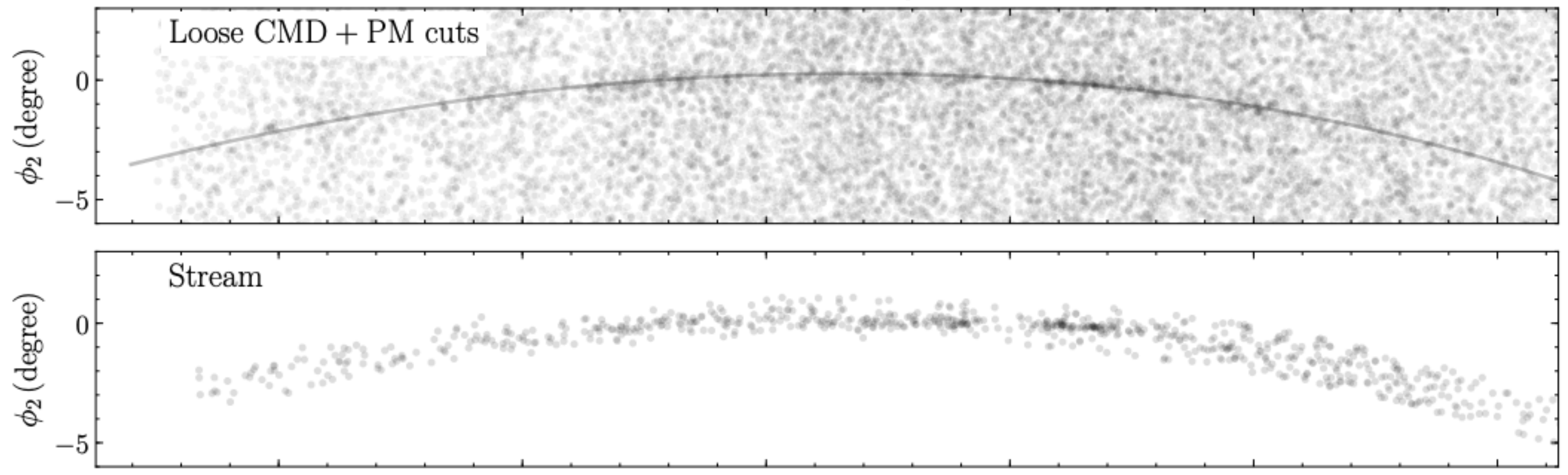
Pal 5: ~30 degree, ~symmetric around Pal 5 cluster (Odenkirchen et al. 2003; Starkman, Bovy, & Webb 2020)



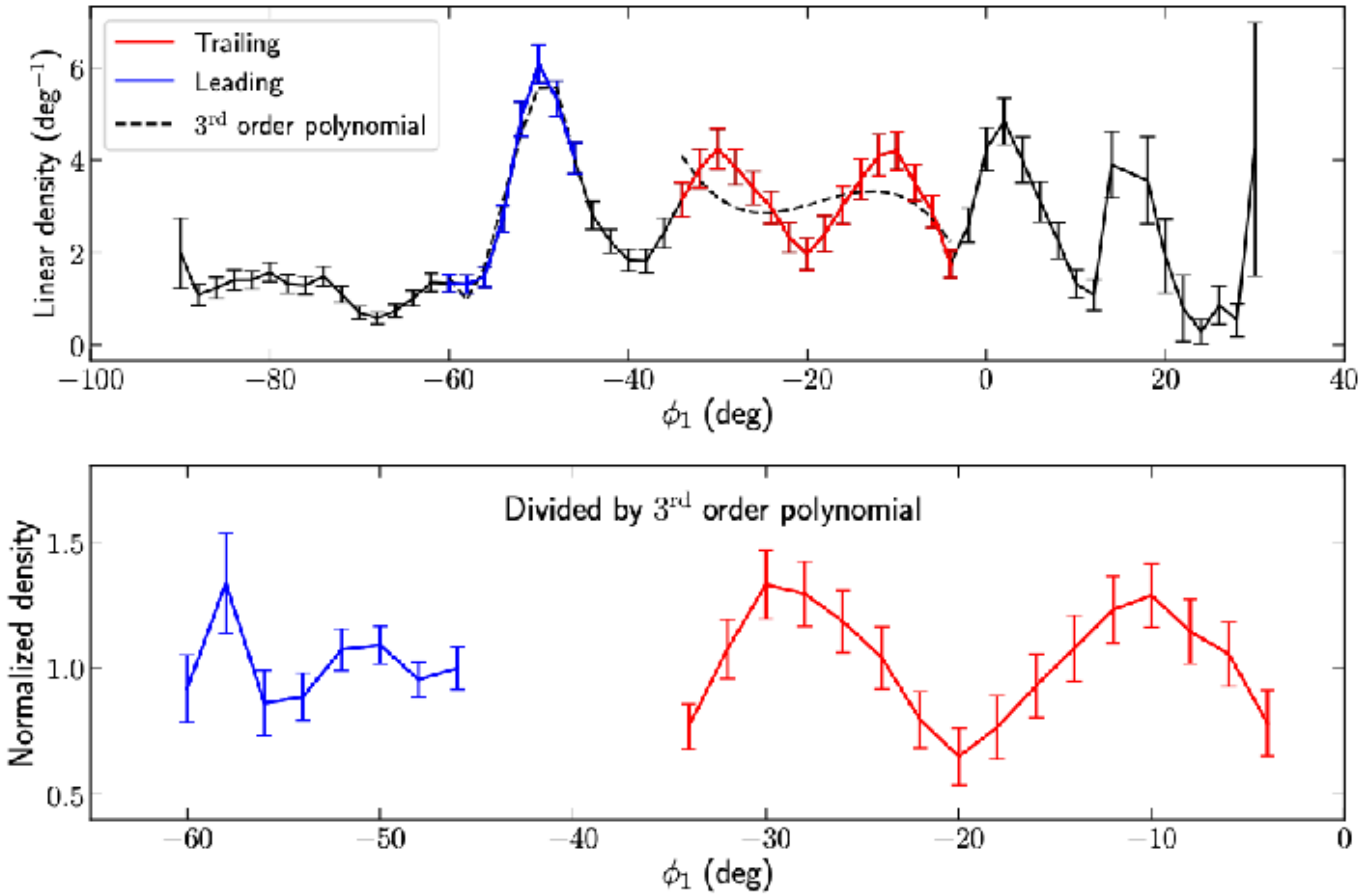
Bovy et al (2017)

GD-1

GD-1: ~100 degree, no known progenitor (Grillmair & Dionatos 2006; Price-Whelan & Bonaca 2018)



Webb & Bovy (2019)

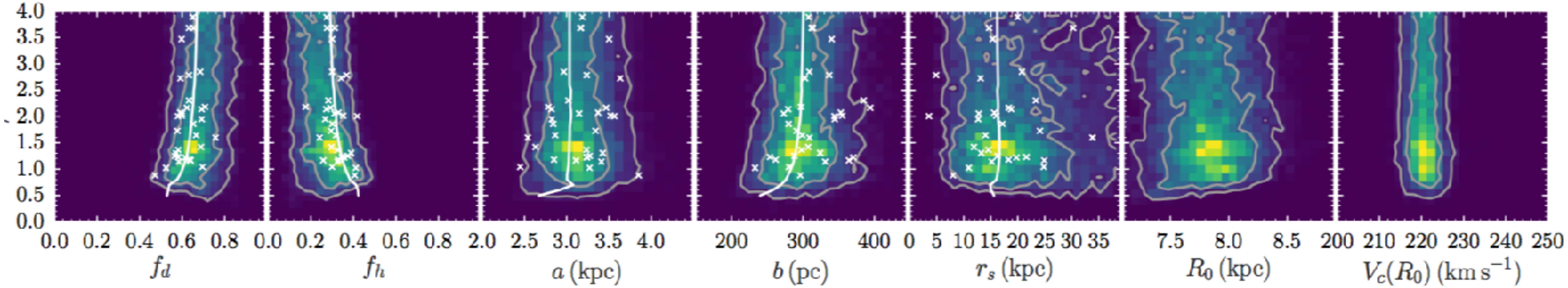


Banik, Bovy, et al. (2021)

Data from Gaia, CFHT, and Pan-STARRS

Example: Pal 5 and GD-1 constraints

- Pal 5 and GD-1 observations measure force at (R,z) ~ (8.4,16.8) kpc and (R,z) ~ (12.5,6.5) kpc, resp.
- Add Pal 5 and GD-1 force measurements to other measurements of the potential of the Milky Way (rotation curve [Bovy et al. 2012, McClure-Griffiths & Dickey 2007/2016], vertical-force disk curve [Bovy & Rix 2013], large R constraints [Xue et al. 2008], bulge constraints,…)
- Previous data essentially has no constraint on halo shape



Halo flattening

Disk fraction **Disk scale length** **halo scale** **Circular velocity**

Halo fraction **Disk scale height** **Distance to GC**

Bovy et al (2016b)

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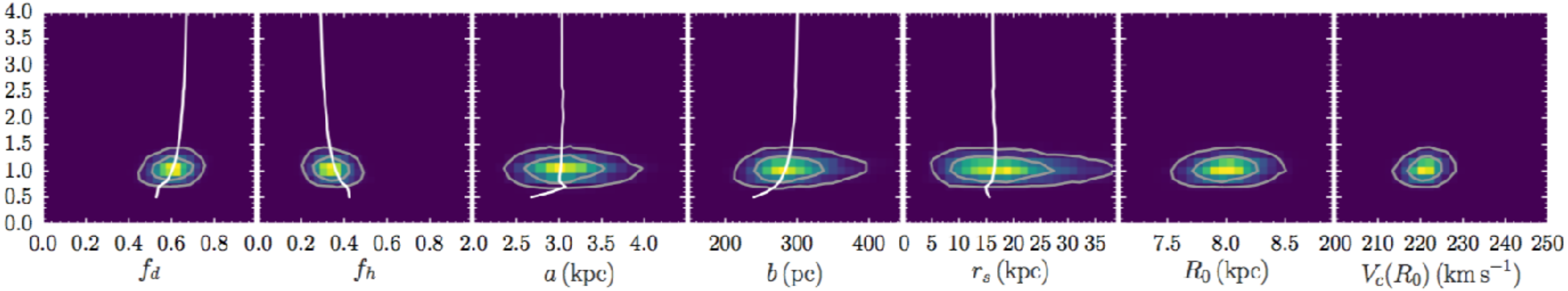
- Adding Pal 5 / GD-1: c/a = 1.05 +/- 0.14

Halo flattening



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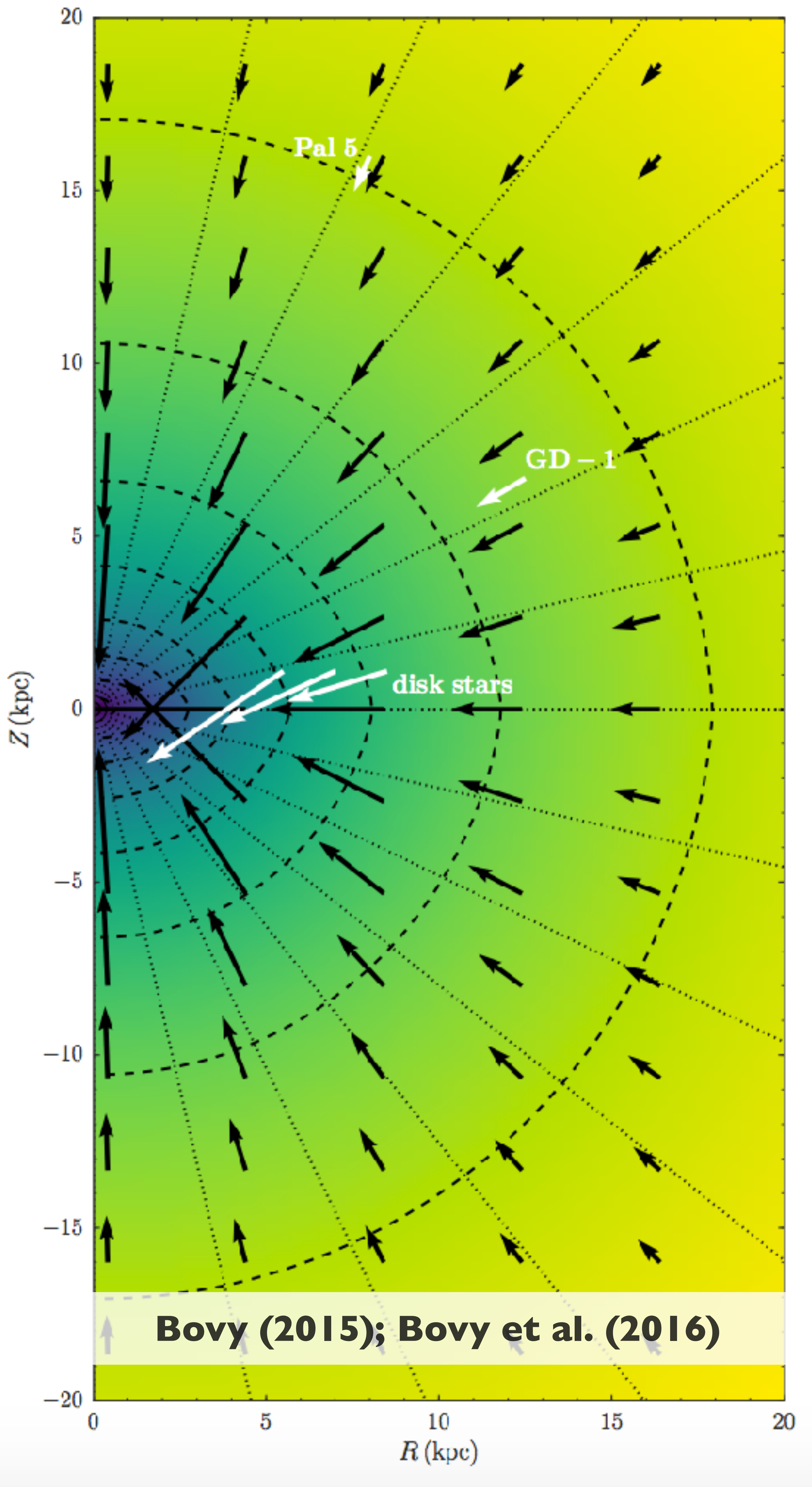
Bovy et al (2016b)

Streams and the dark-matter halo shape

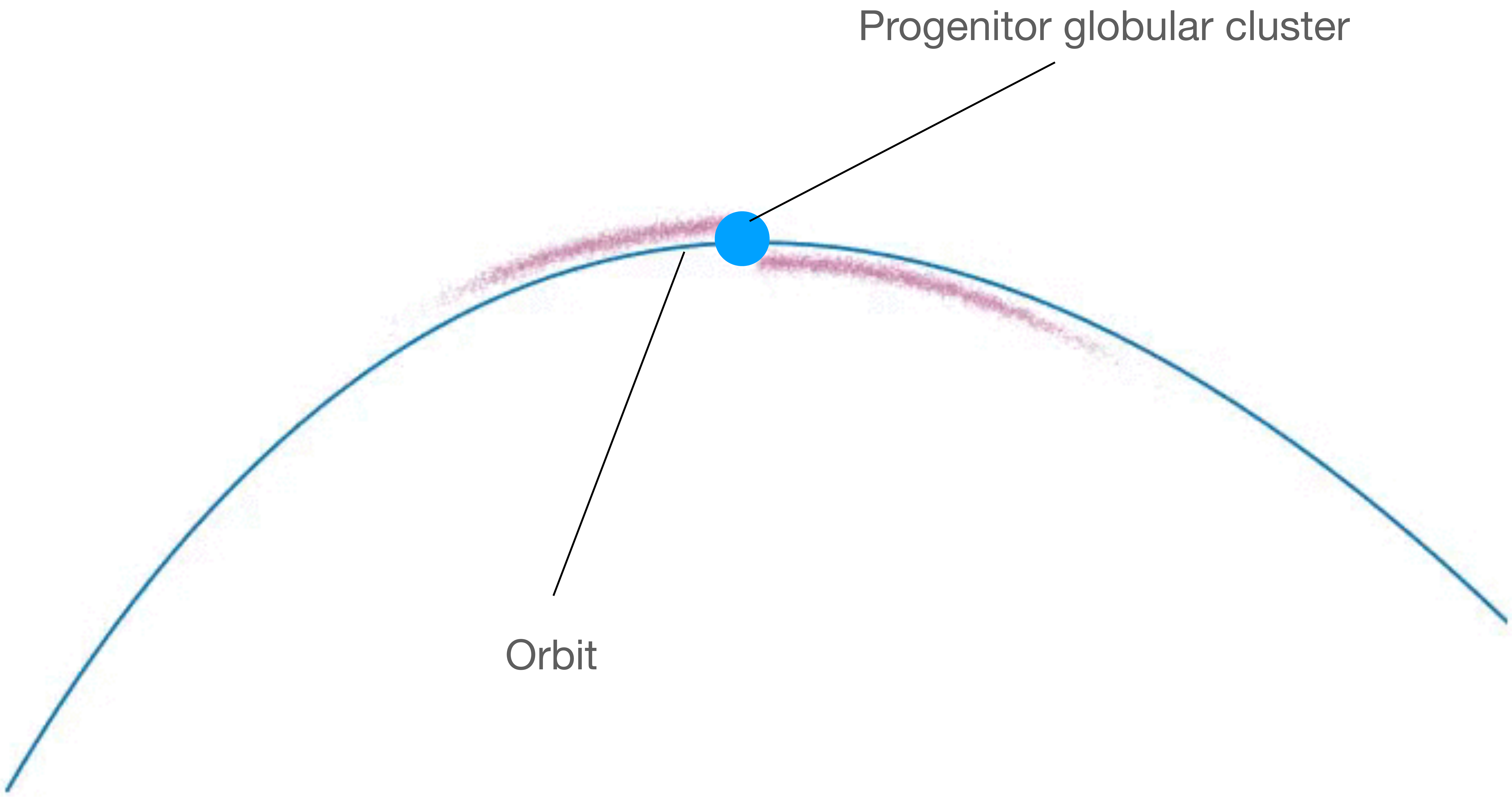
- Current constraints c/a ~ 1.06 +/- 0.06 (Palau & Miralda-Escude 2022)
- Somewhat spherical for standard CDM, but within theoretical uncertainty
- Future:
  - Much better data from, e.g., DESI, LSST, WFIRST
  - Many more streams
- But!
  - Theory prediction not very specific
  - Confounding factors: bar, LMC perturbation, etc.



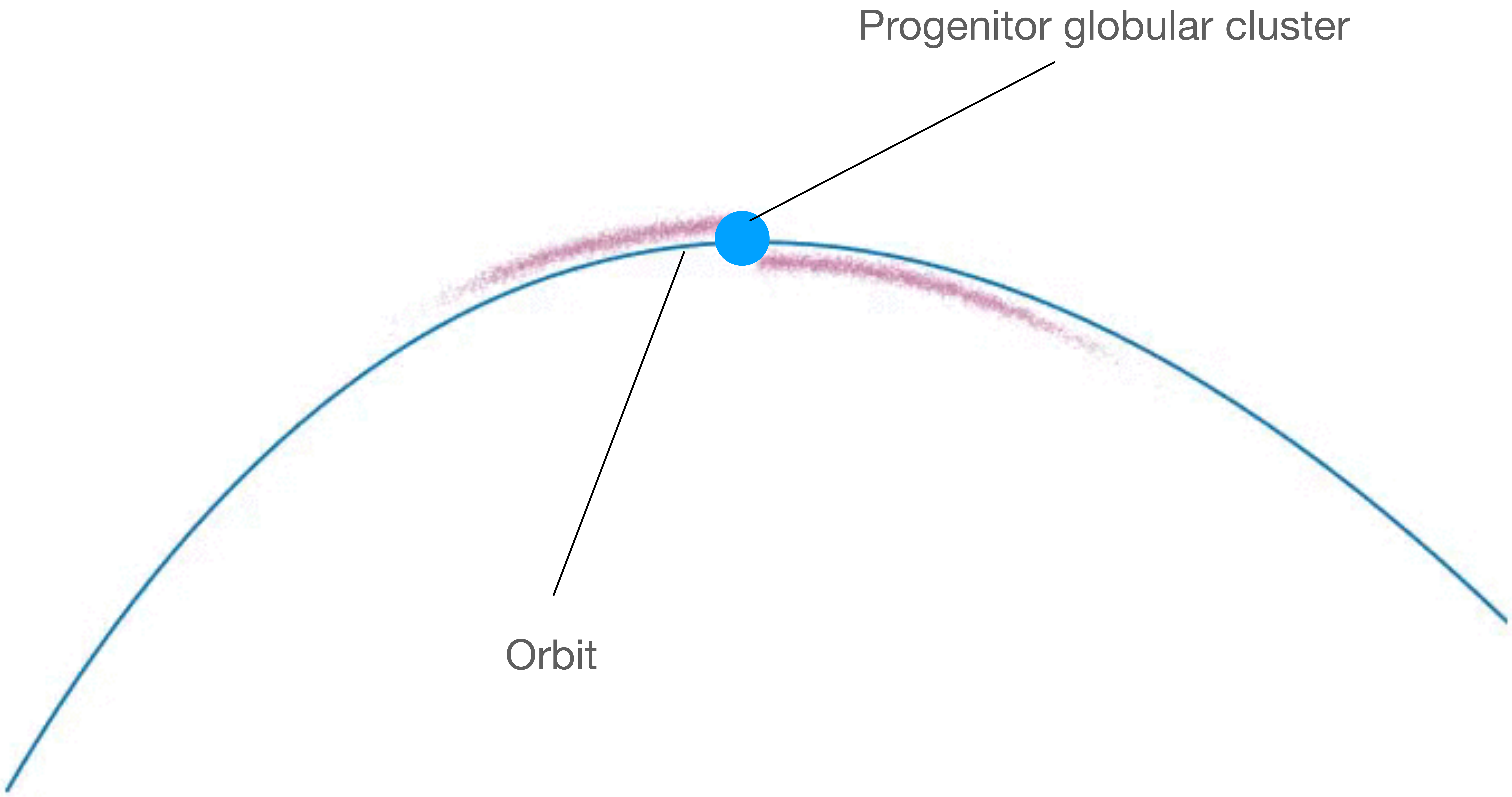
Bovy (2015); Bovy et al. (2016)

Tidal streams and the small-scale dark-matter structure of galactic halos

Aquarius; Volker Springel



Orbital variations caused by eccentric orbit



Orbital variations caused by eccentric orbit

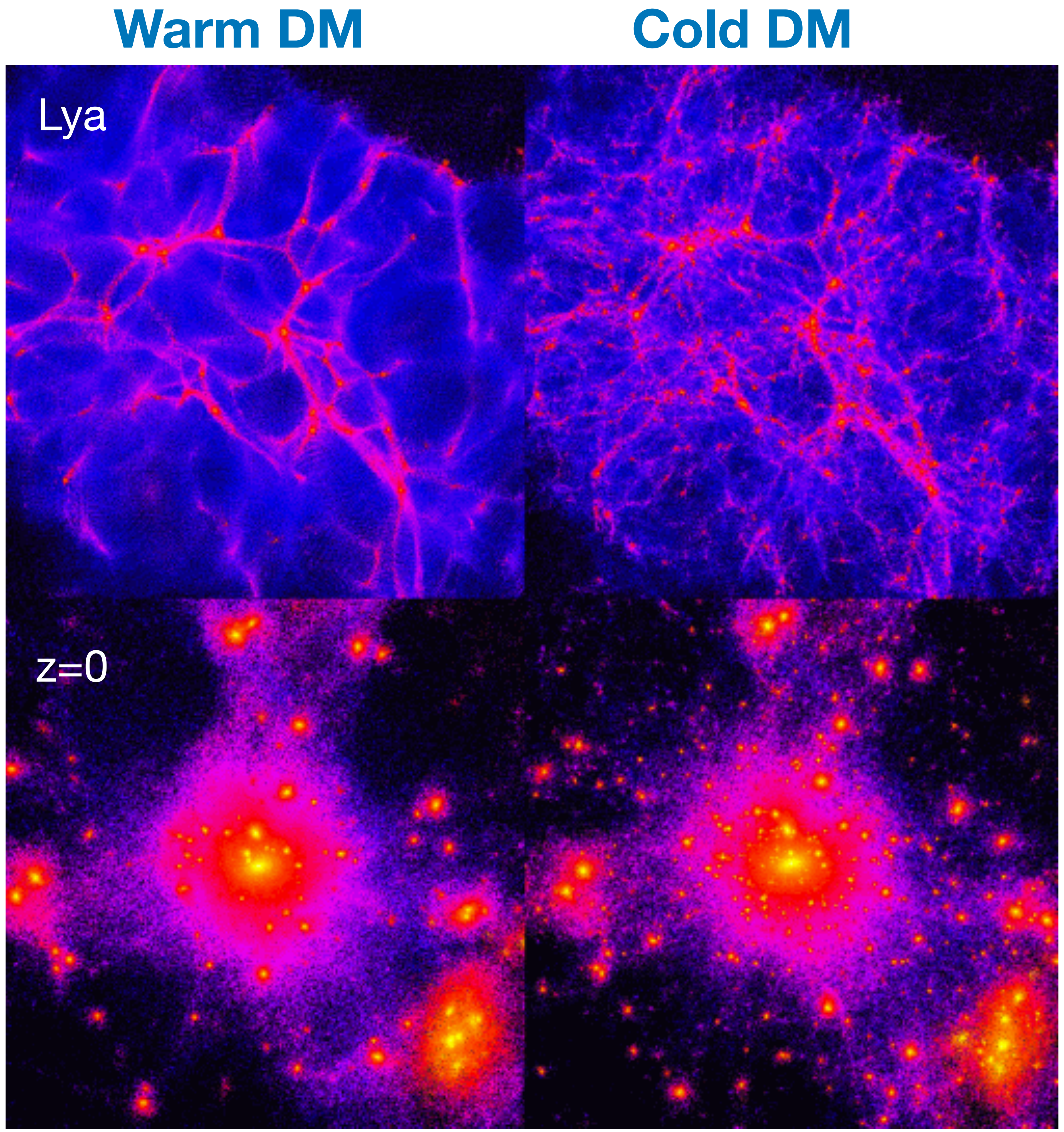
Number of satellites as a probe of dark matter

- Standard cold dark matter has structure ("subhalos") down to solar-to-Earth mass scales, increasing as $dN/dM \sim M^{-2}$

- Amount of small-scale structure can vary significantly in well-motivated models of dark matter, such as

  - Ultra-light axion-like particles: ~1 kpc de Broglie wavelength suppresses bound structures below ~10^{10} Msun or lower

  - Warm dark matter (e.g., sterile neutrino): <~ 0.5 Mpc free-streaming scale suppresses small-scale structure



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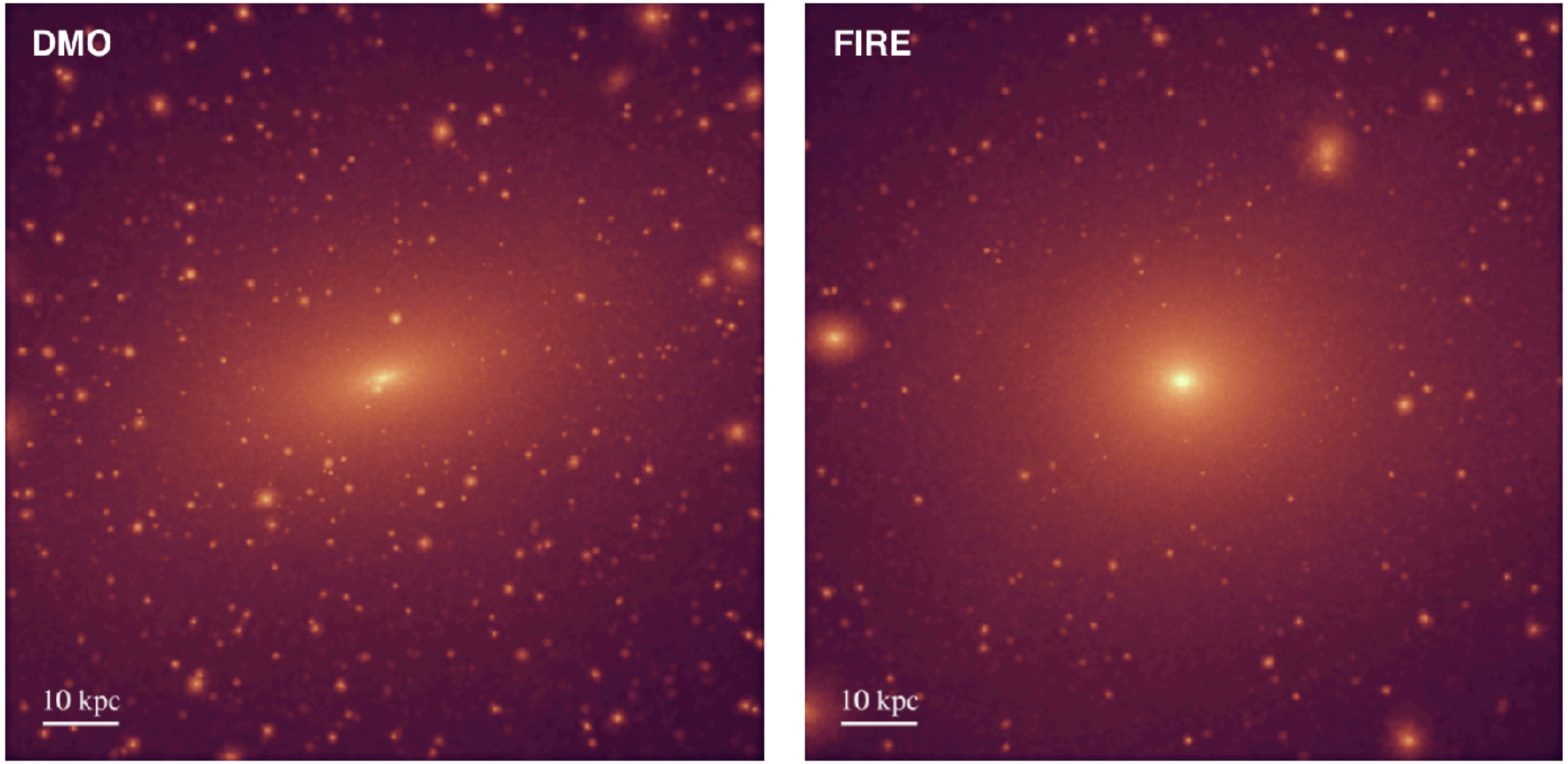
Subhalo mass function from simulations

- **Dark-matter only (DMO)**: Subhalo fraction:
  - ~0.1% of DM near the Sun
  - Increases to tens of % at R_{vir}
- **dN/dM ~ $M^{-1.9}$**



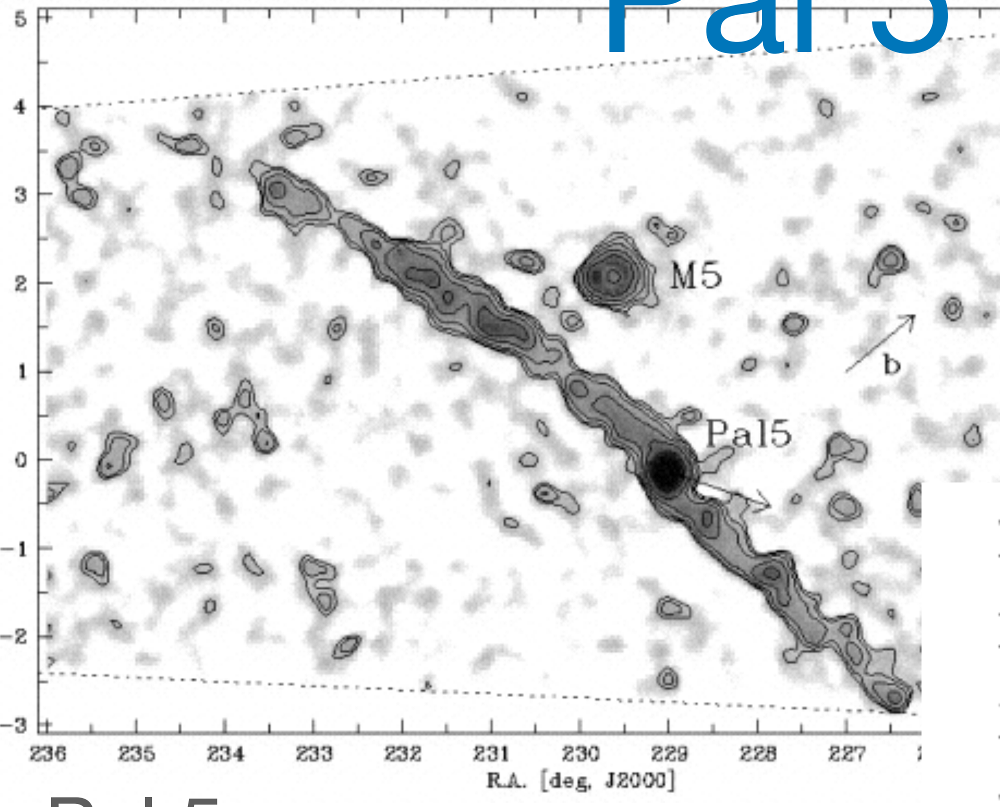
Garrison-Kimmel et al. (2017)

- **DM+baryons**: Subhalo fraction:
  - suppressed near the disk
  - less to almost no suppression at larger radii
- **dN/dM ~ $M^{-1.9}$**

- Resolution effects on sub halo disruption are significant: ultra-high-resolution re-simulations of Via Lactea subhalos in the presence of a disk show **only a ~40% reduction in the sub halo mass function and no change to its shape** (Webb & Bovy 2020)

Example: Pal 5 and GD-1

Pal 5



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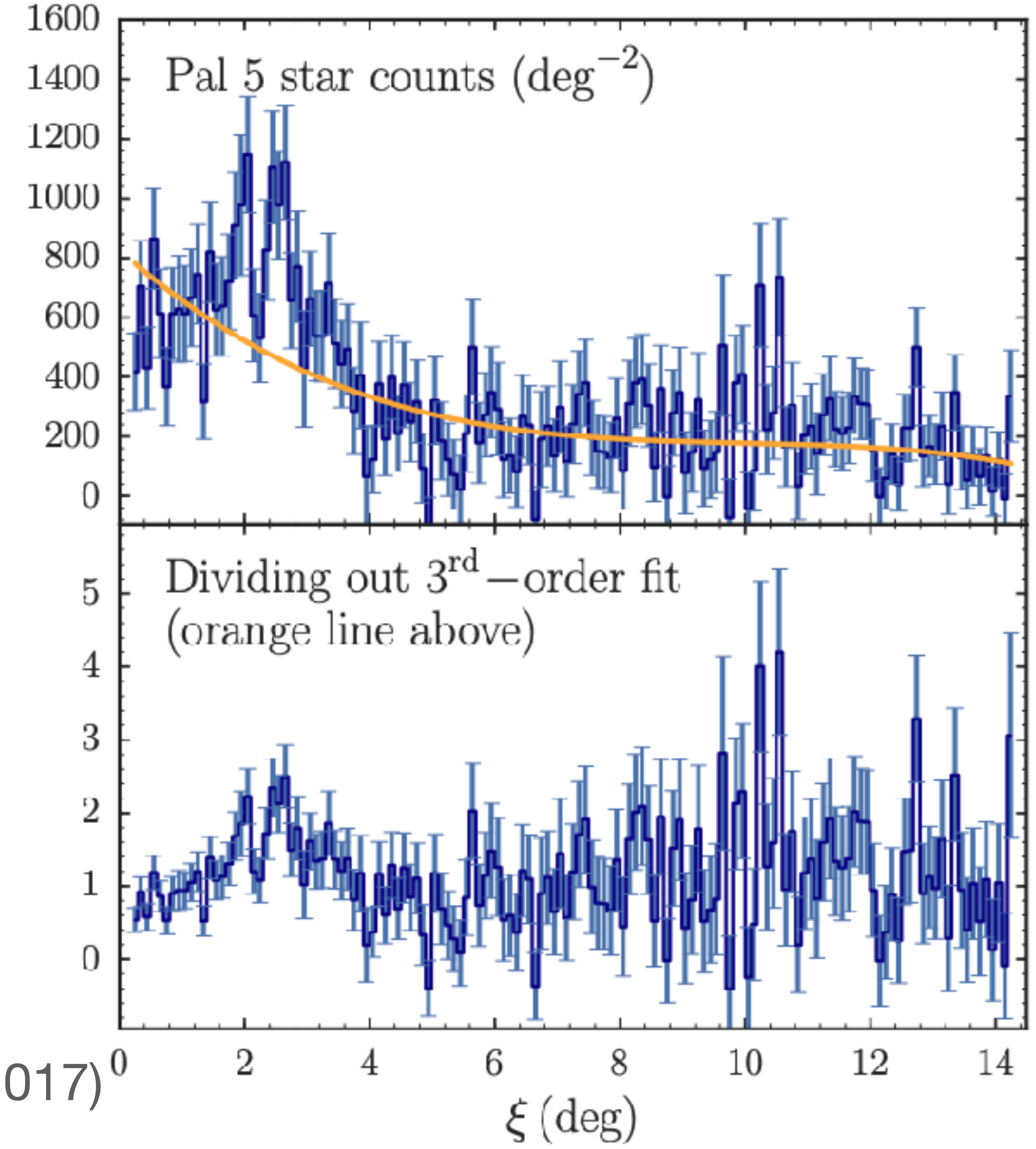

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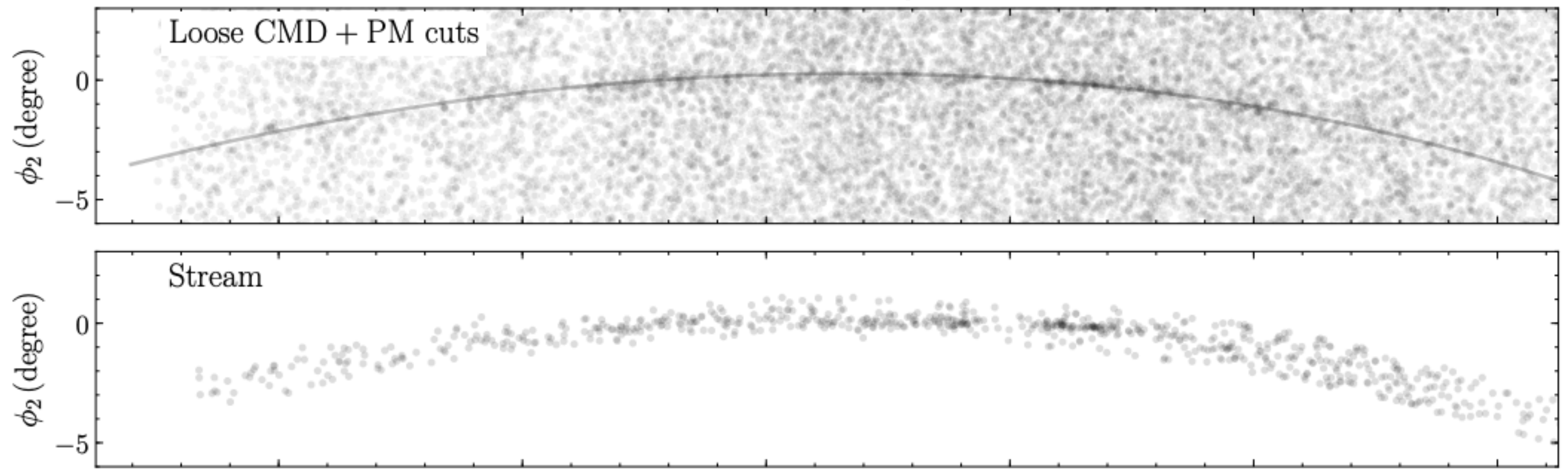

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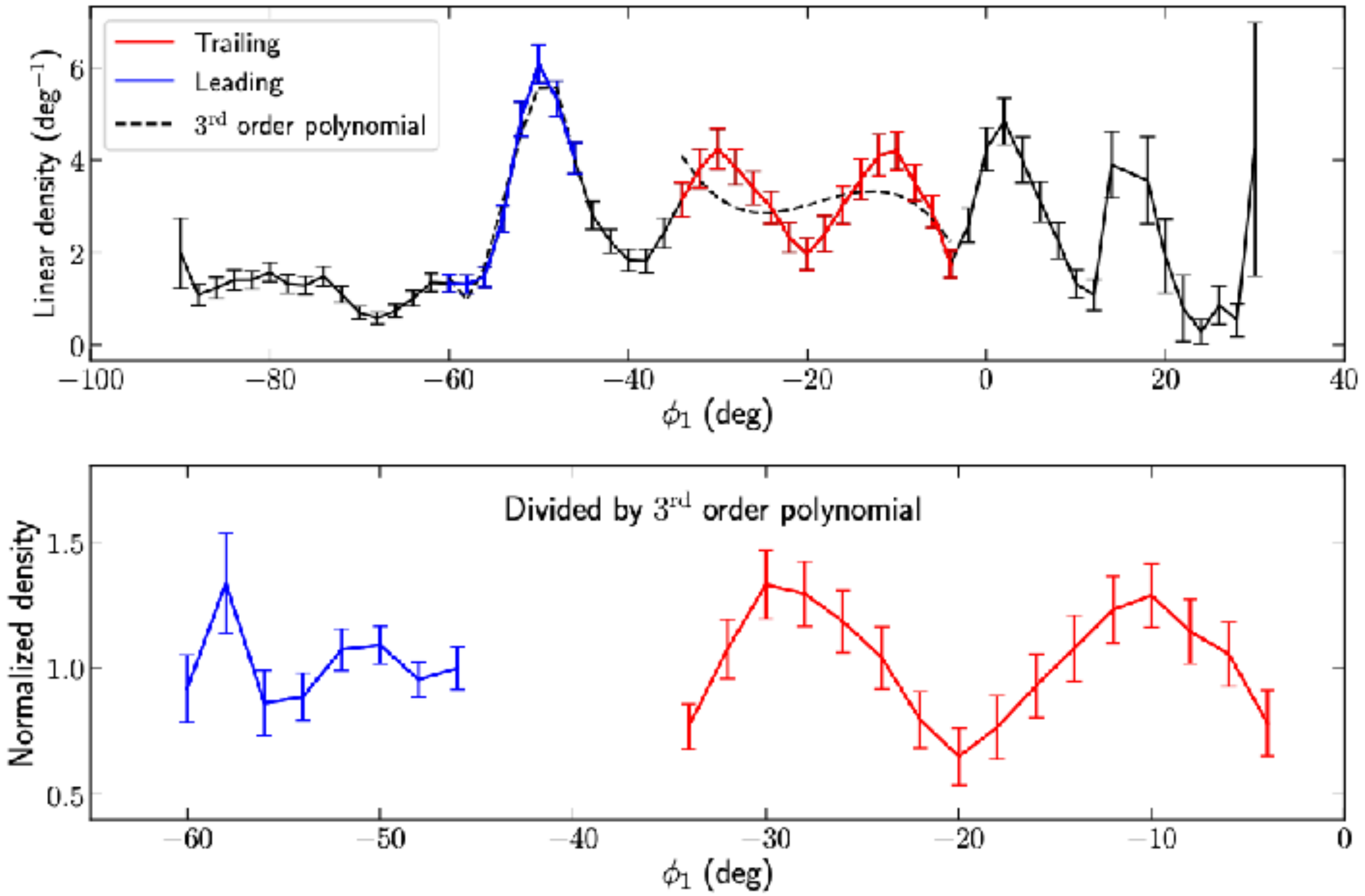

Banik, Bovy, et al. (2021)

Data from Gaia, CFHT, and Pan-STARRS

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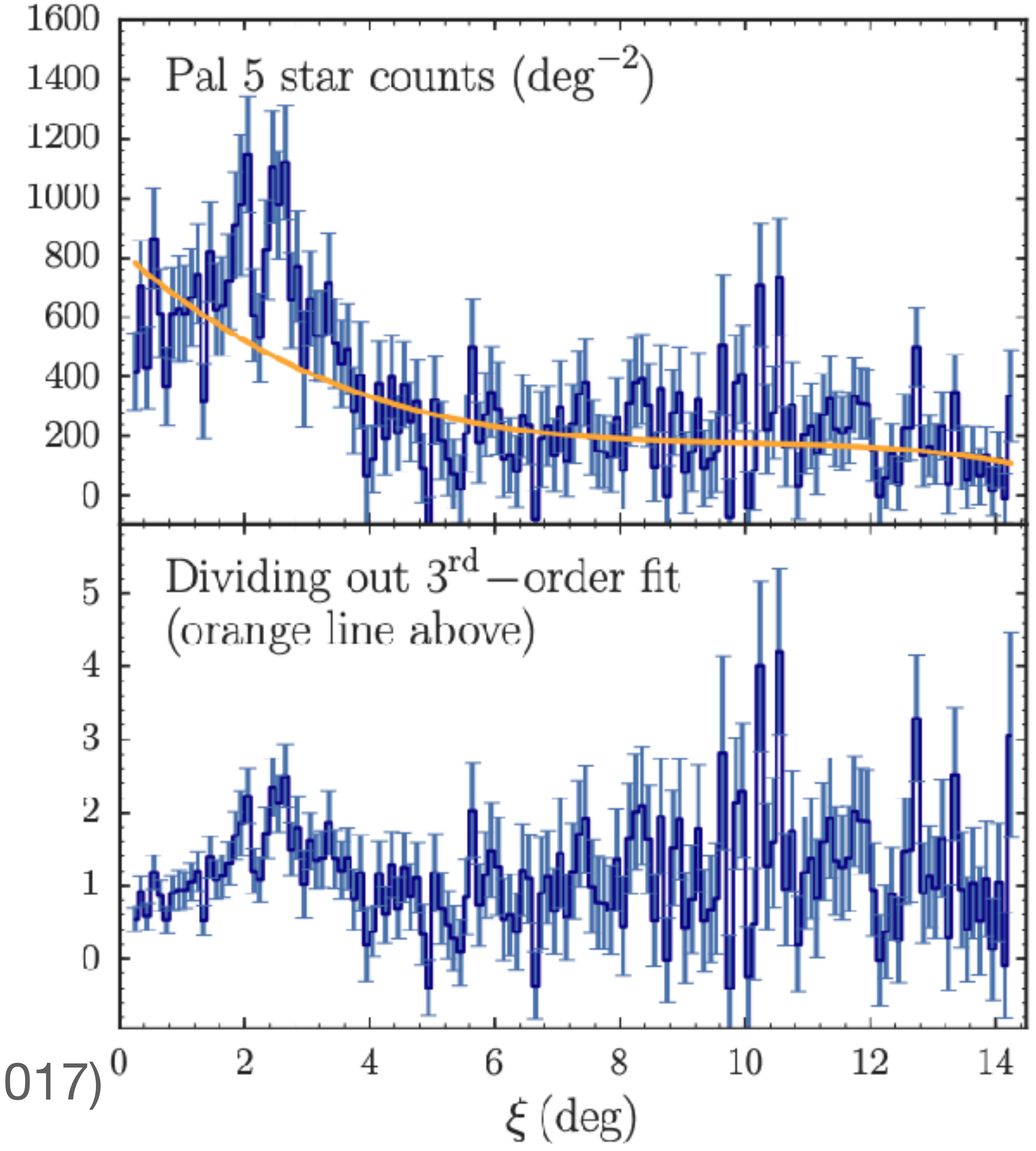

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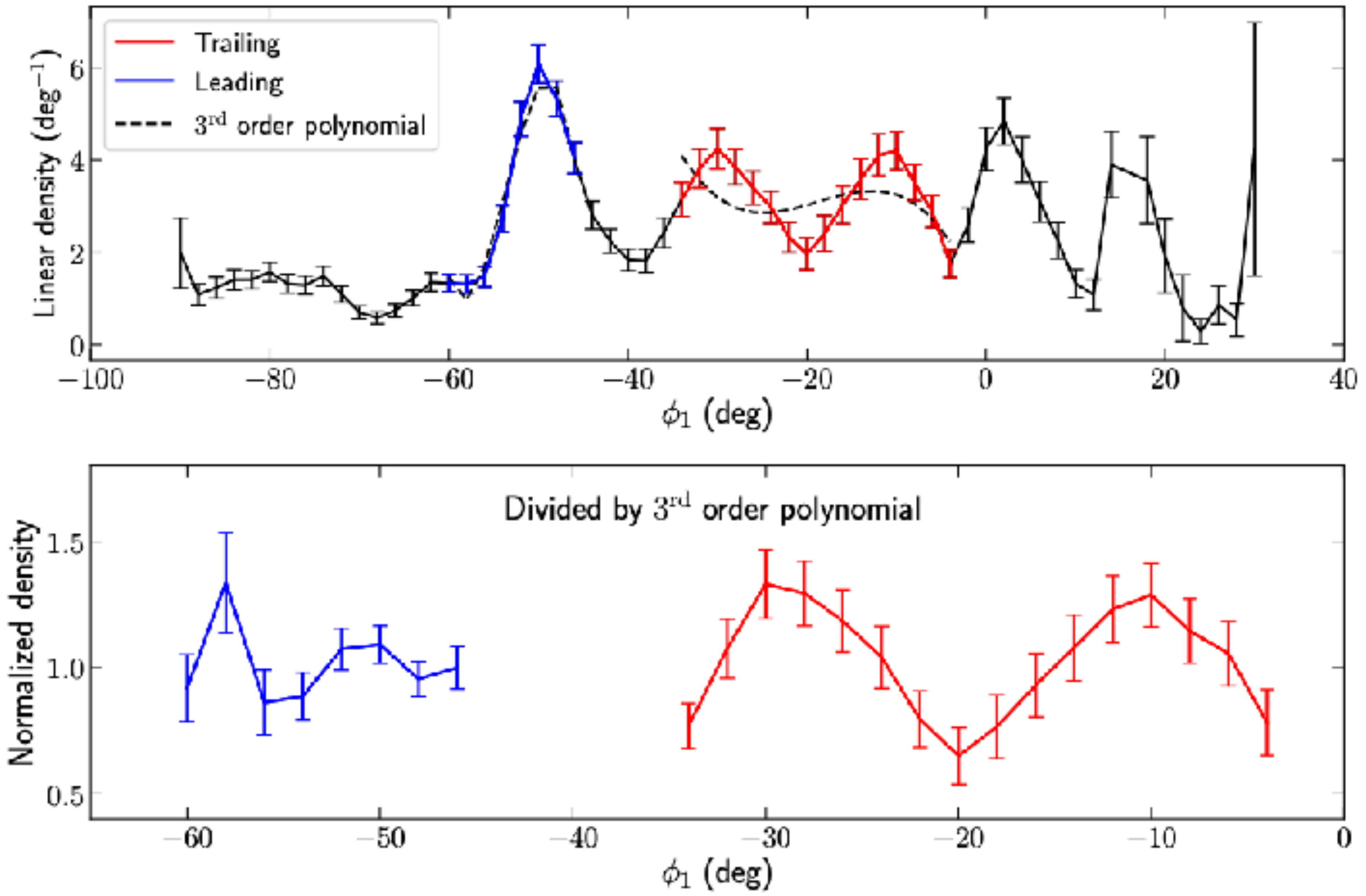

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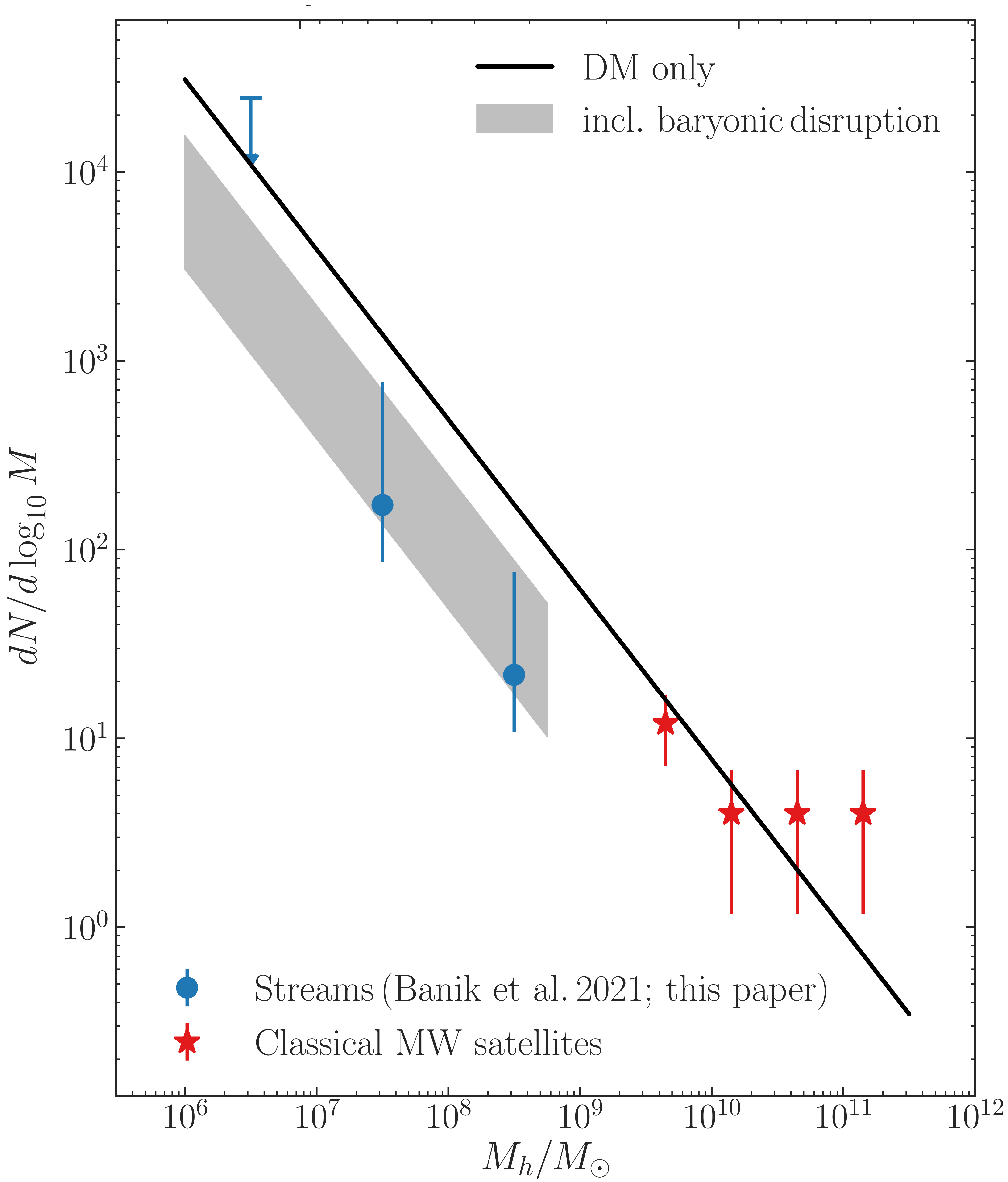
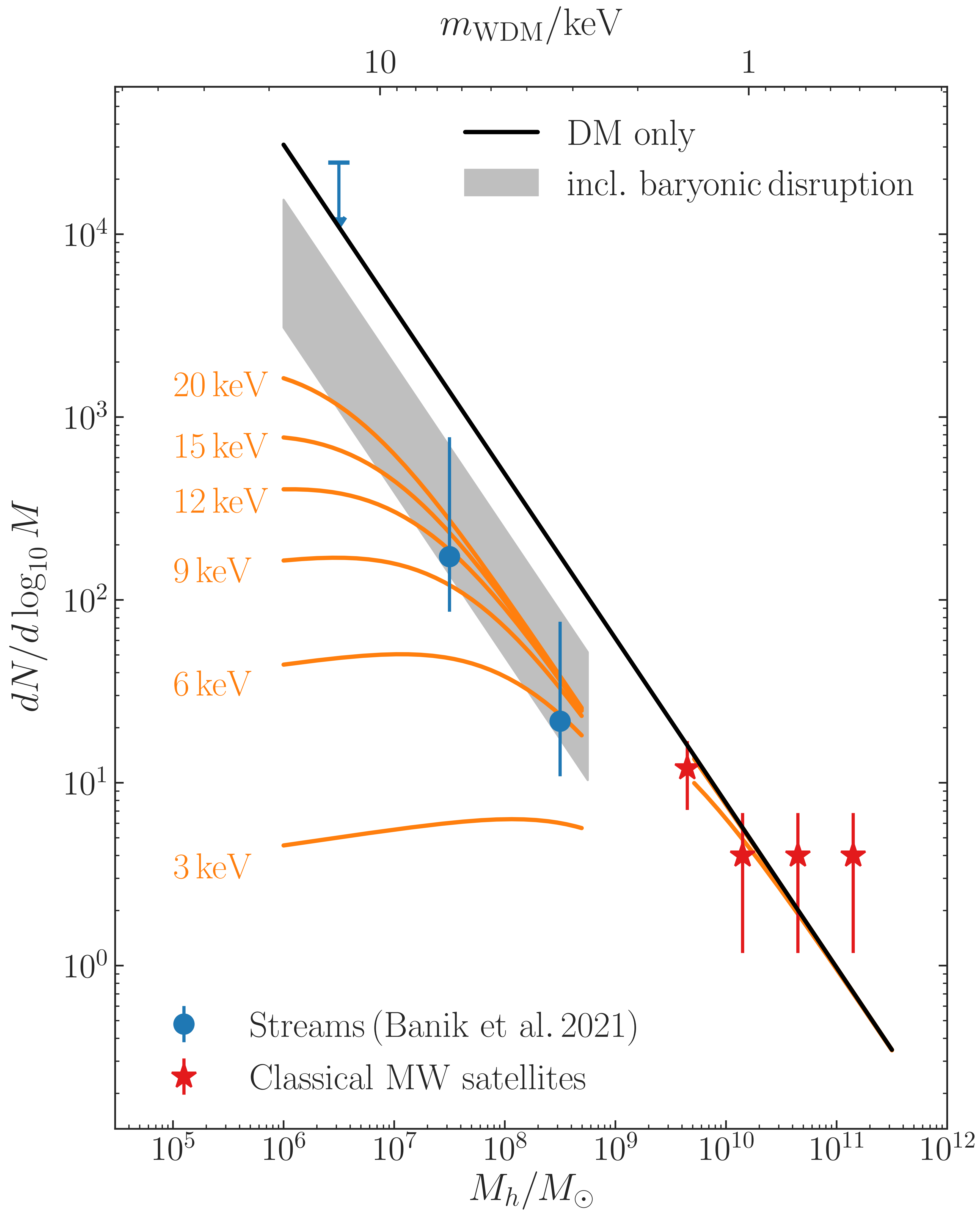


Banik, Bovy, et al. (2021a)

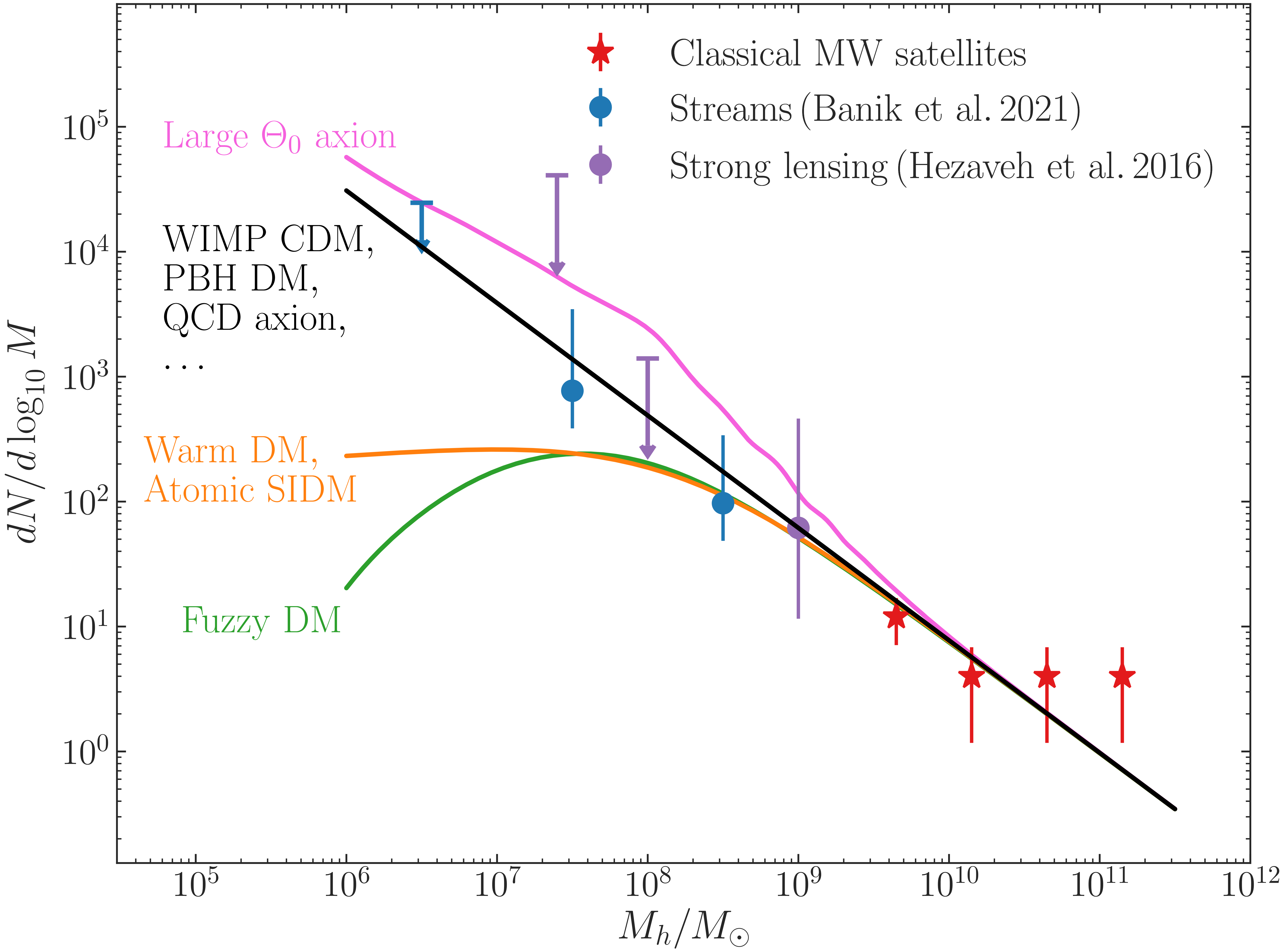
Warm dark matter



- GD-1+Pal 5:
  - $m_{\rm WDM} > 4.6$ keV
- Including classical satellites:
  - $m_{\rm WDM} > 6.3$ keV
- +lensing+other MW dwarfs:
  - $m_{\rm WDM} > 11$ keV
  - (all 95% confidence)

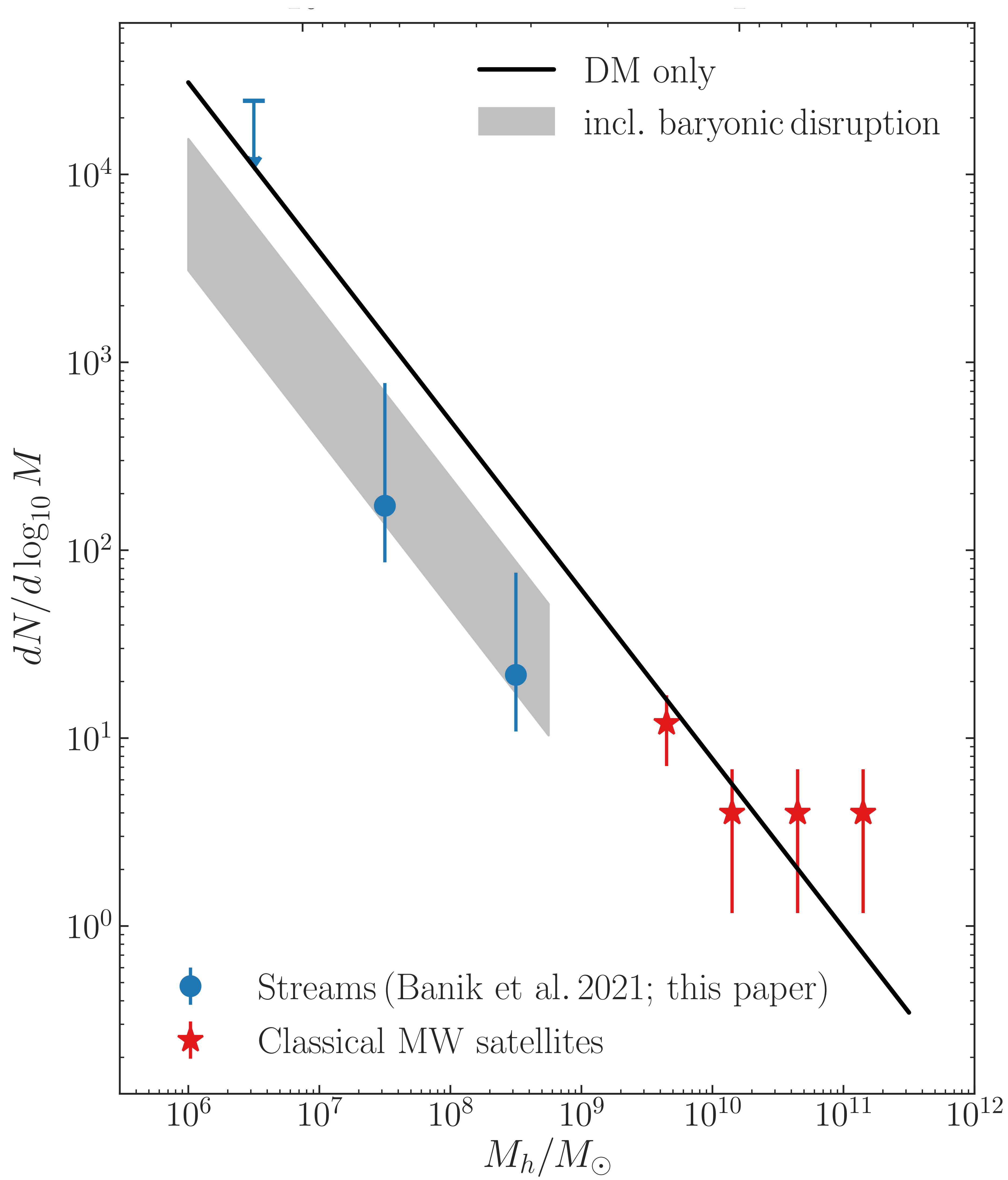
Banik, Bovy, et al. (2021b)

Alternative DM models

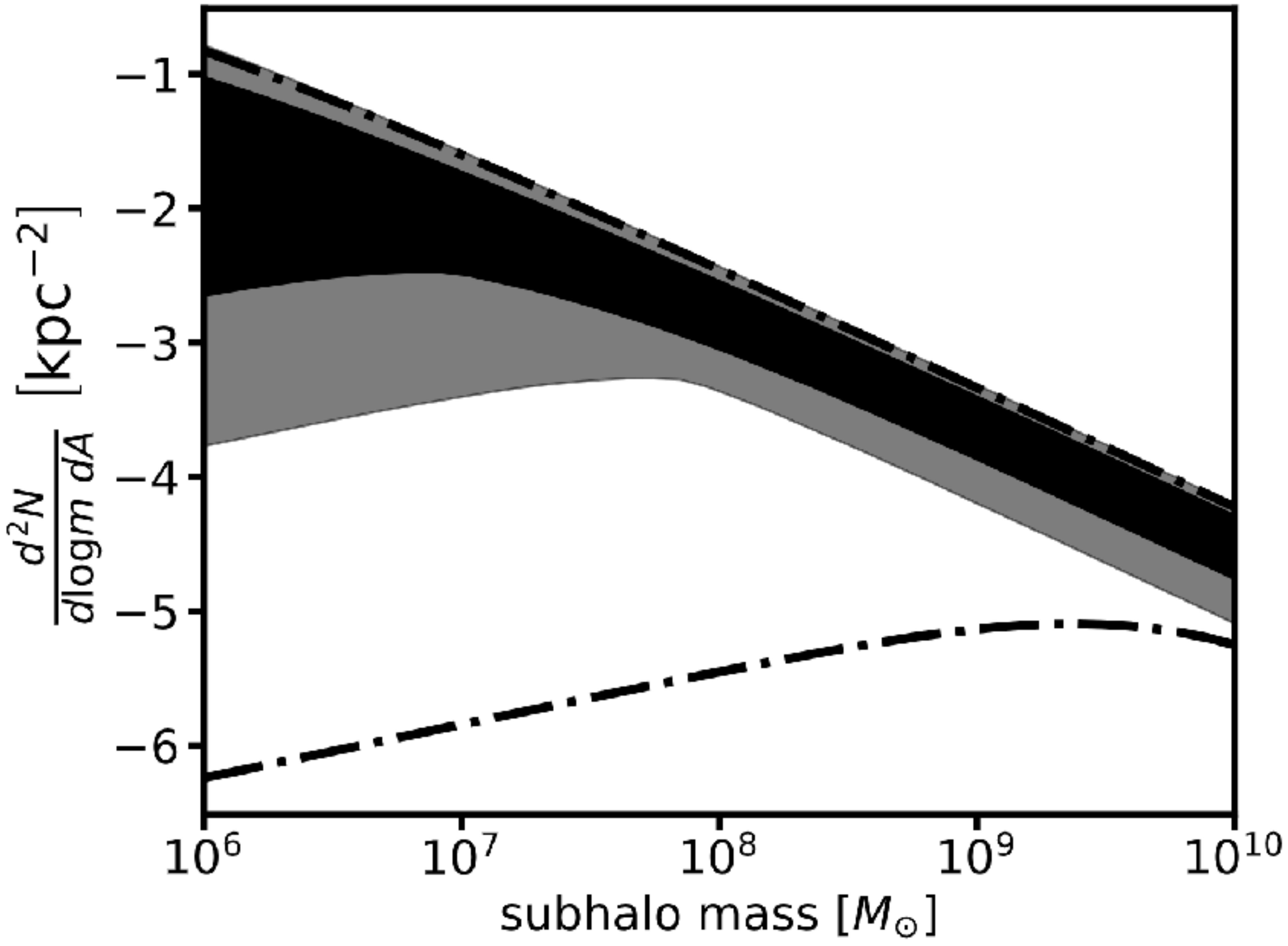


Banik, Bovy, et al. (2021b)

Comparison to strong gravitational lensing



Banik, Bovy, et al. (2021a)



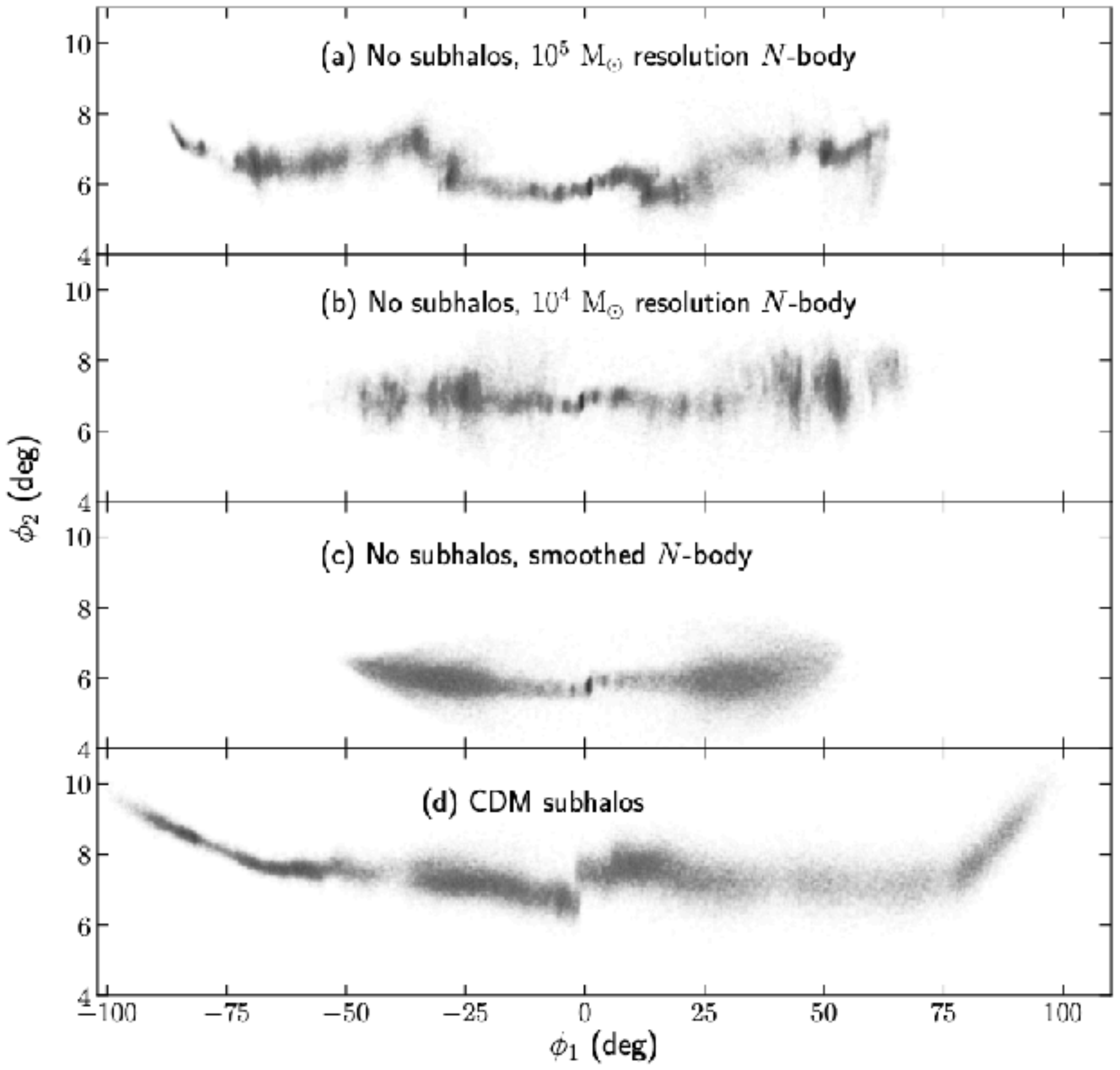
Adapted from Gilman et al. (2019a)

Advantages and disadvantages of streams and lensing

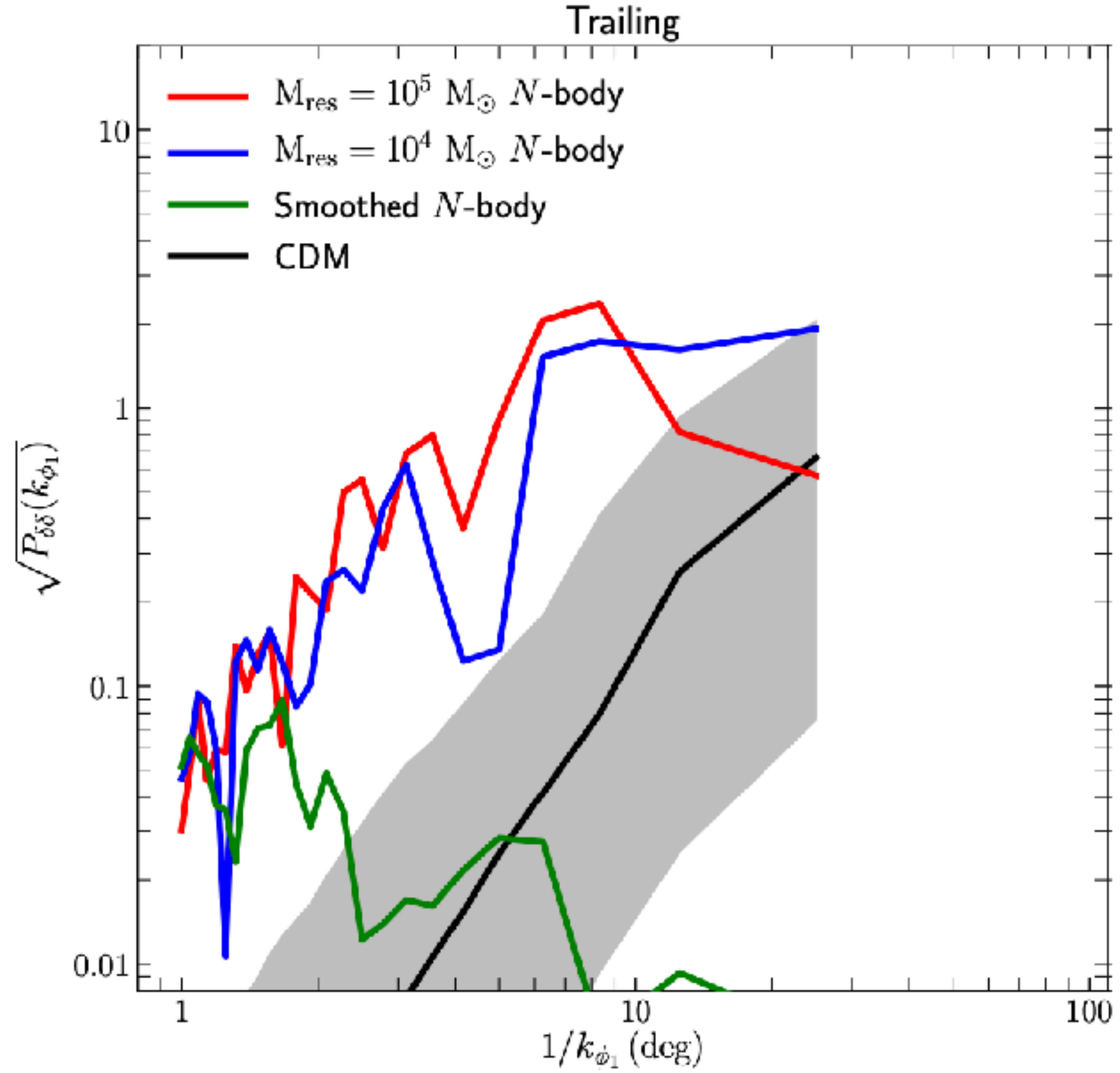
- Streams:
  - Good: local-ish substructure density, possible to do radial variation
  - Bad: somewhat unknown formation process, effect of baryonic substructure (GMCs, bar, …), limited number of galaxies (MW, future: Local Group)
- Lensing:
  - Good: Less baryonic substructure (ellipticals), many galaxies, redshift dependence?
  - Bad: line-of-sight sub-halos, influence of overall mass model
- But complementary:
  - Consistency cross-checks
  - Streams more sensitive to overall number density, lensing to inner structure —> constrain models like self-interacting DM that significantly change inner structure

Streams are so sensitive that they are hard to simulate!

Streams in *N*-body simulations

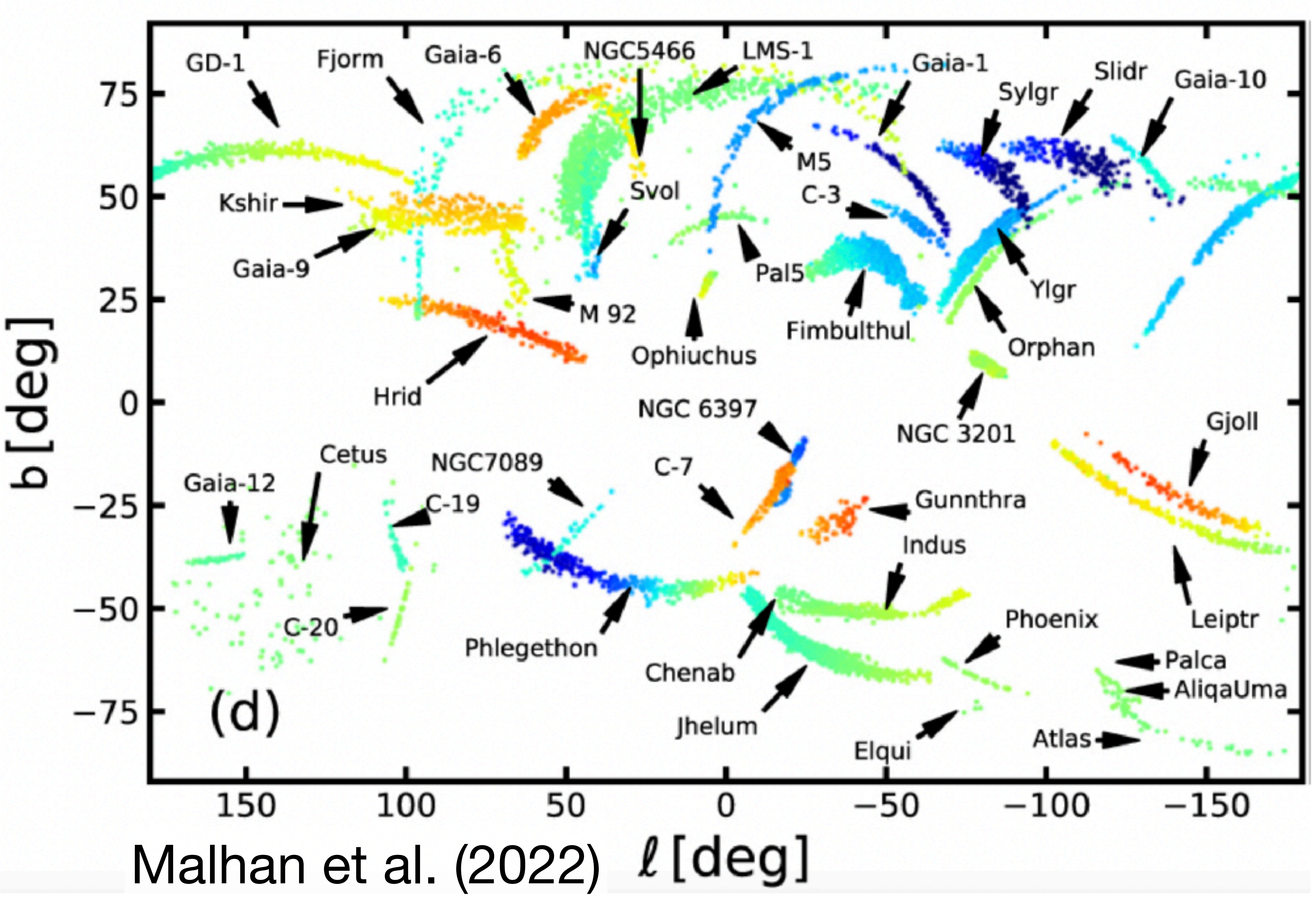


- You may think that the easiest way to predict the structure of tidal streams is by letting them evolve in *N*-body simulations
- But streams are so cold that they are sensitive to the finite-particle DM particle mass used in simulations
- Need DM mass ~1-100 M_{sun} to not have spurious contributions to stream density fluctuations
- Flip side: streams sensitive to compact DM with masses >1 M_{sun}



Banik & Bovy (2021)

Future



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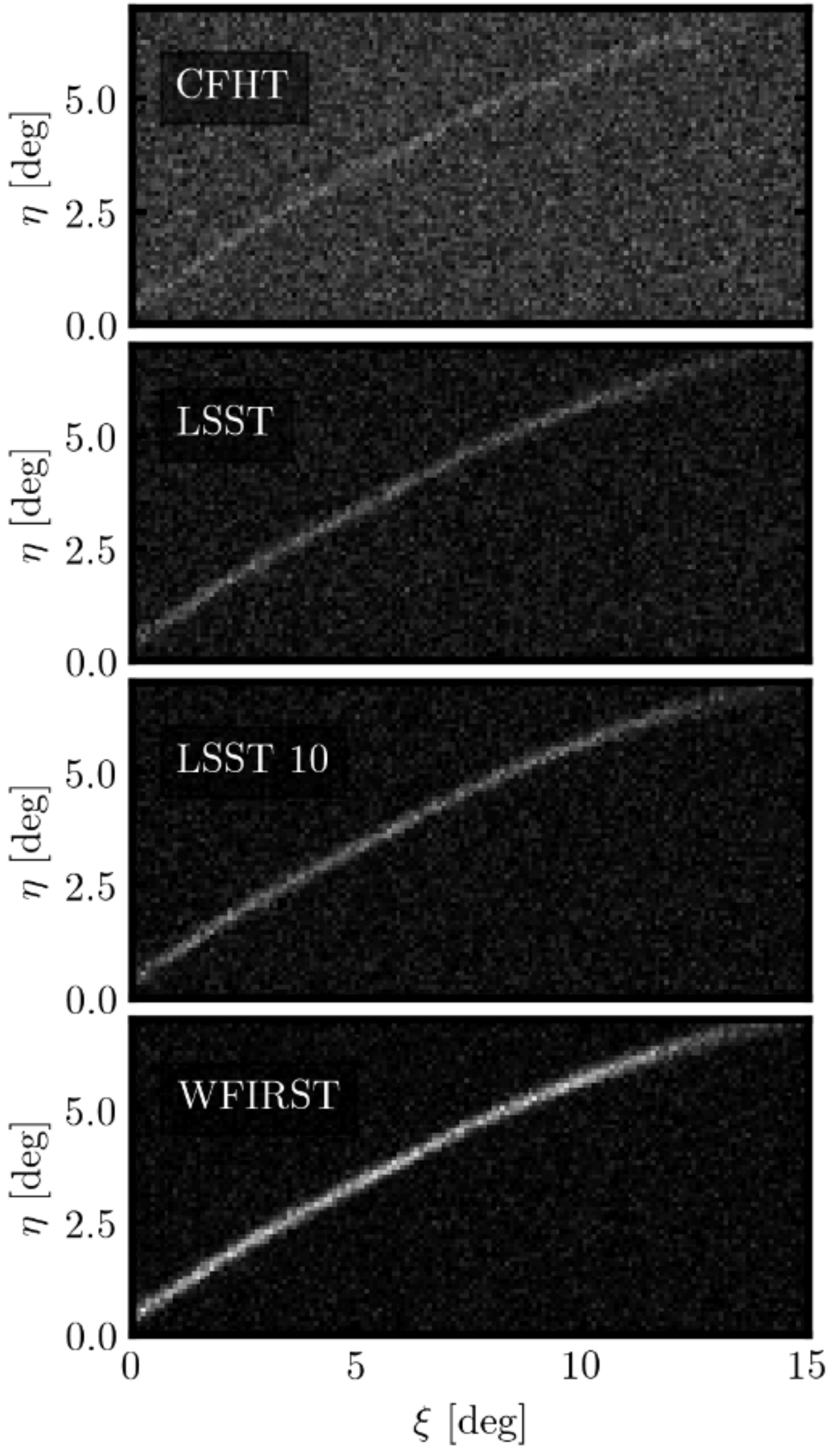
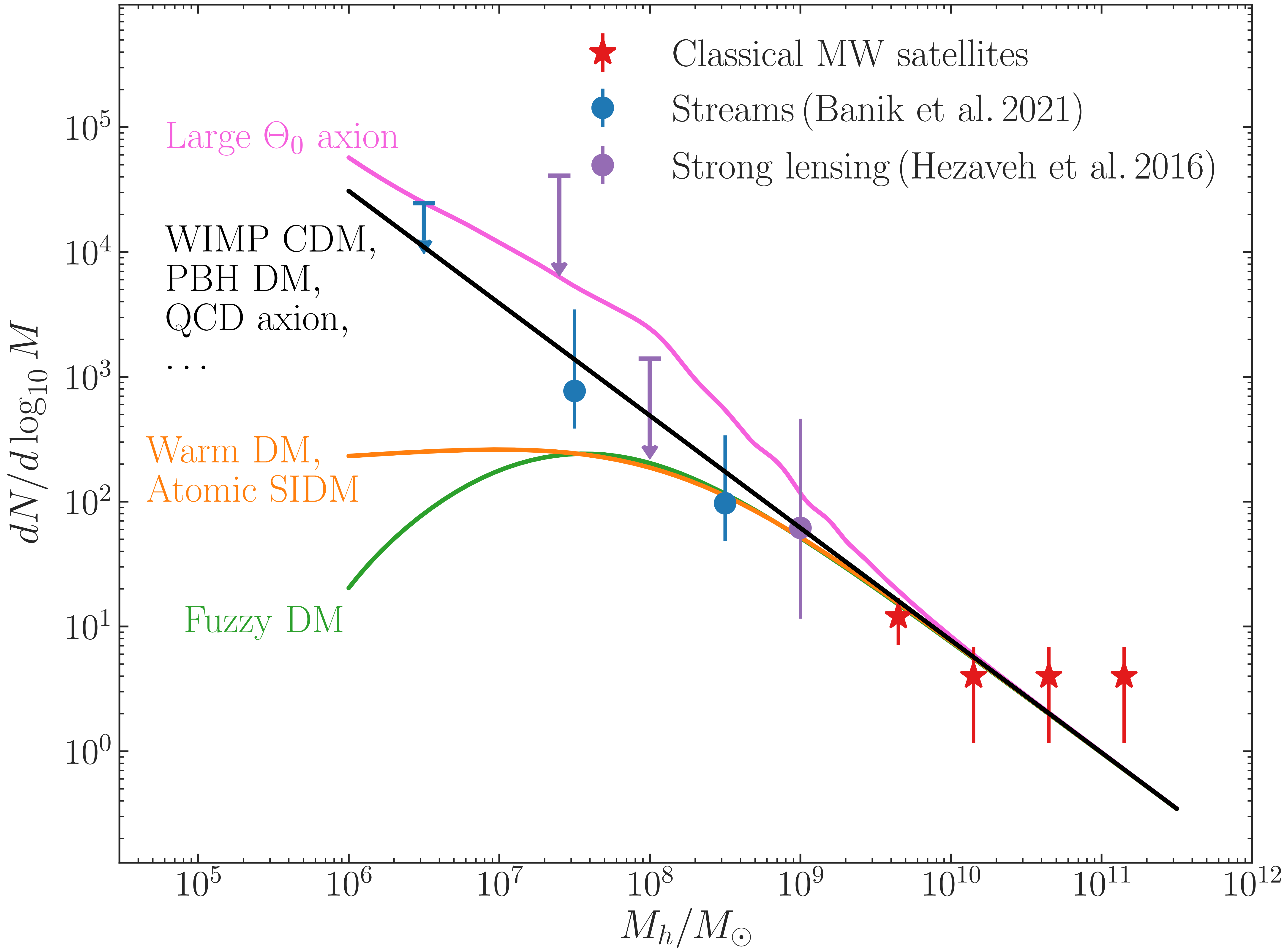


Hendel & Bovy (unpublished)

Conclusion

- Tidal streams uniquely sensitive to large- and small-scale structure of the Milky Way's DM halo
- Inner halo shape ~ spherical, consistent with vanilla CDM observations
- Dark matter acts as cold dark matter on scales down to ~10^7 M_{sun}
- Improvement by factor of 10 in the next few years
- Galaxy formation in the smallest galaxies likely largely unaffected by dark-matter physics



Banik, Bovy, et al. (2021b)