Deep learning approaches to detect dark matter in stellar streams

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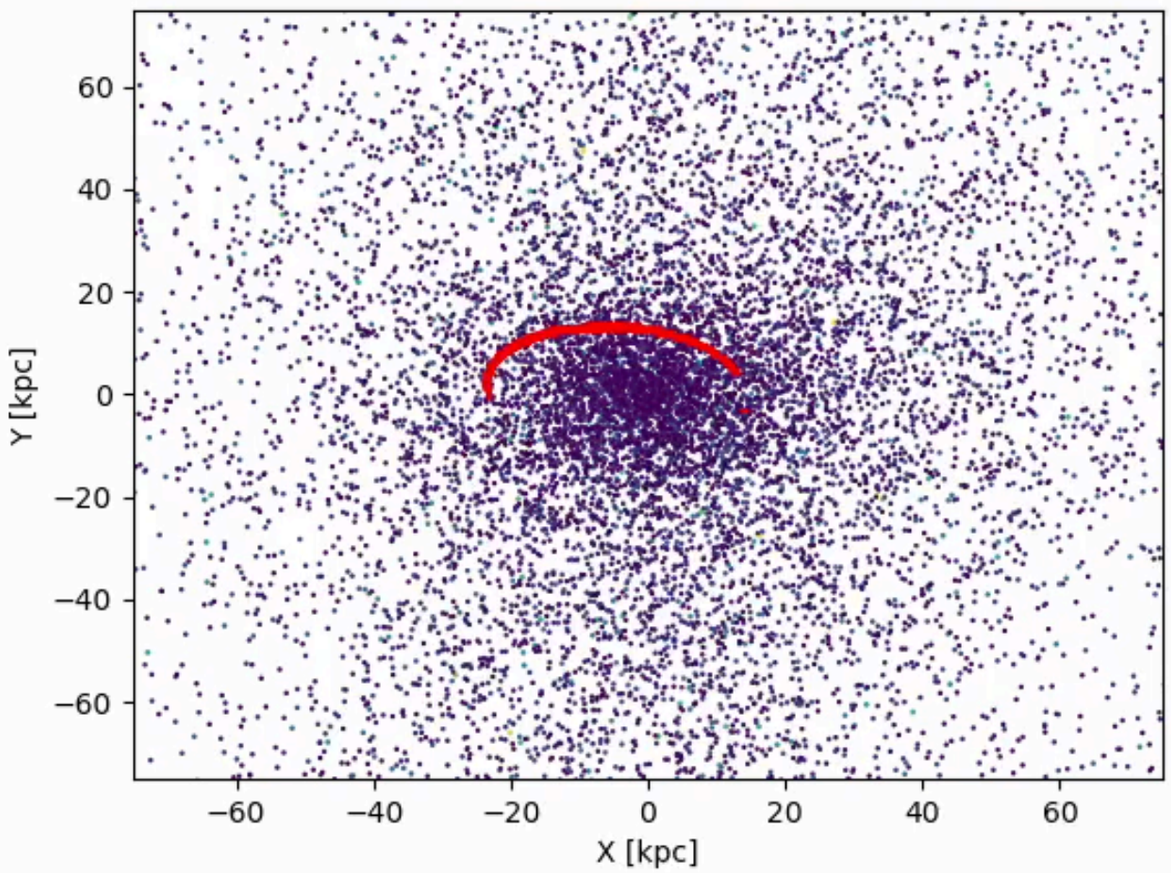
Stellar streams are forecast to probe smallest dark matter structure ever — how achieve this in practice?

- WIMP dark matter increasingly ruled out ⇒ search for astro DM signatures

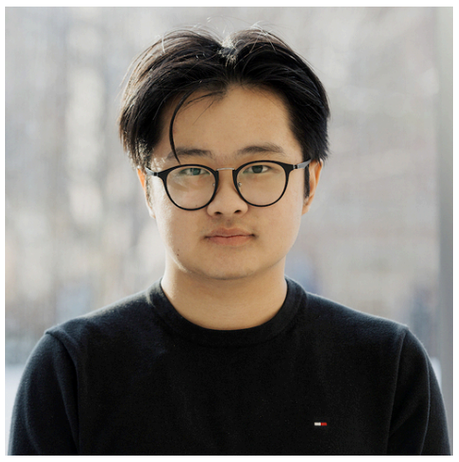
- Dark matter **halos inferred down to ~ 10^7 $M_\odot$** (MW satellites, Ly-α forest)

- Infer **dark structure 100 x below "observable" limit?** (streams, lensing)

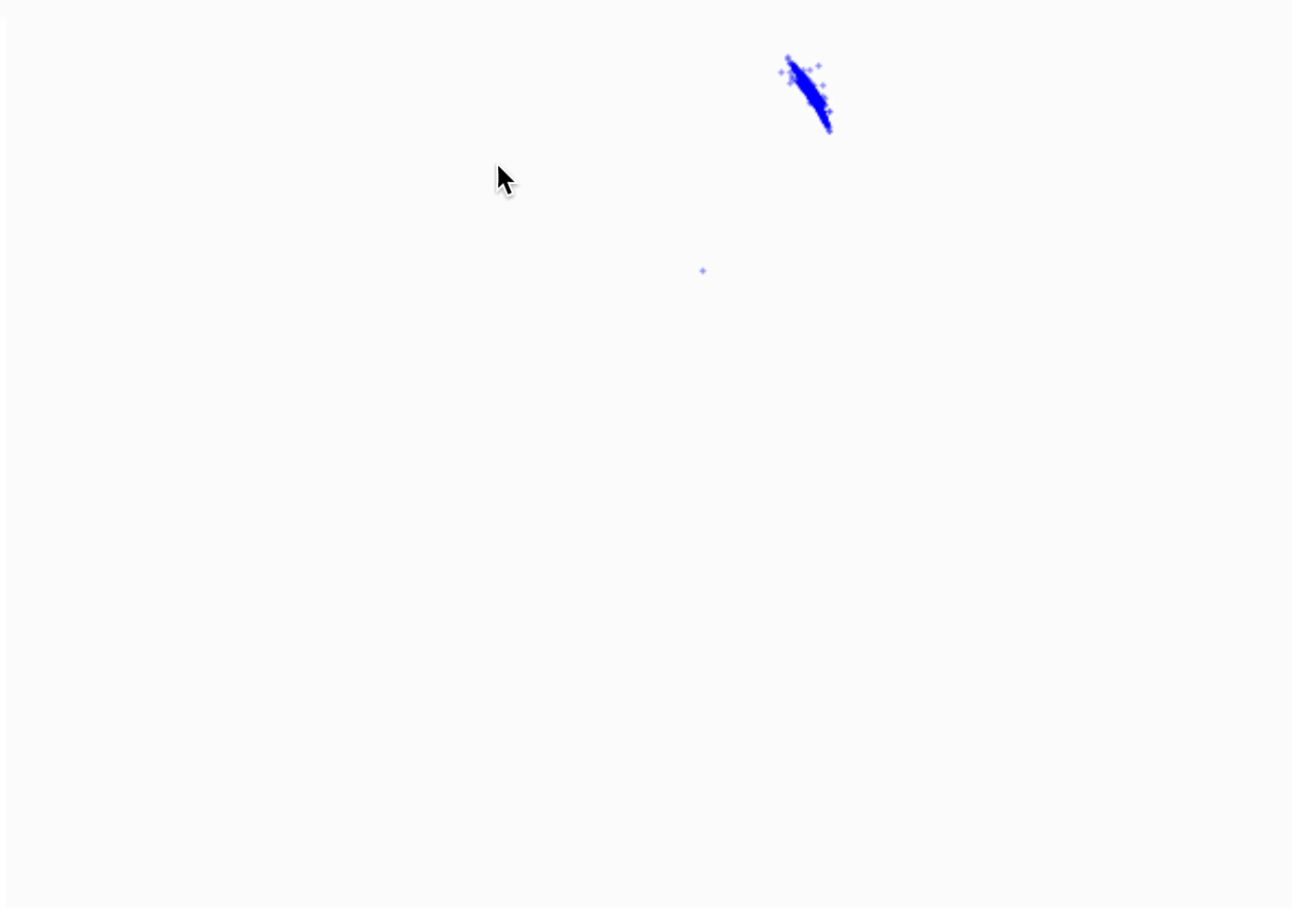
Rogers & Peiris (2021); Nadler et al (2021); Banik et al. (2021); Keeley et al. (2024)



Stellar stream (*red*)
orbiting in cloud of
dark matter
sub-structure (*purple*)

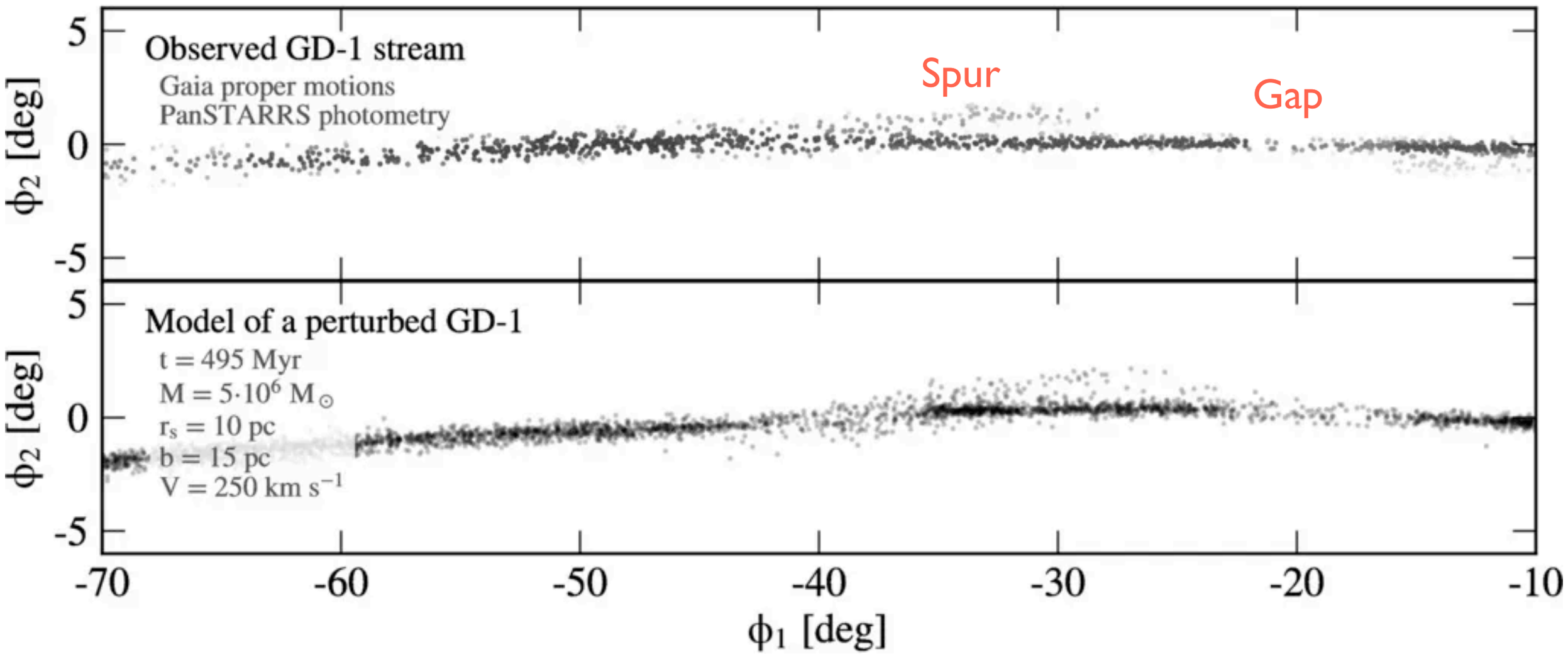


Stream — halo interaction

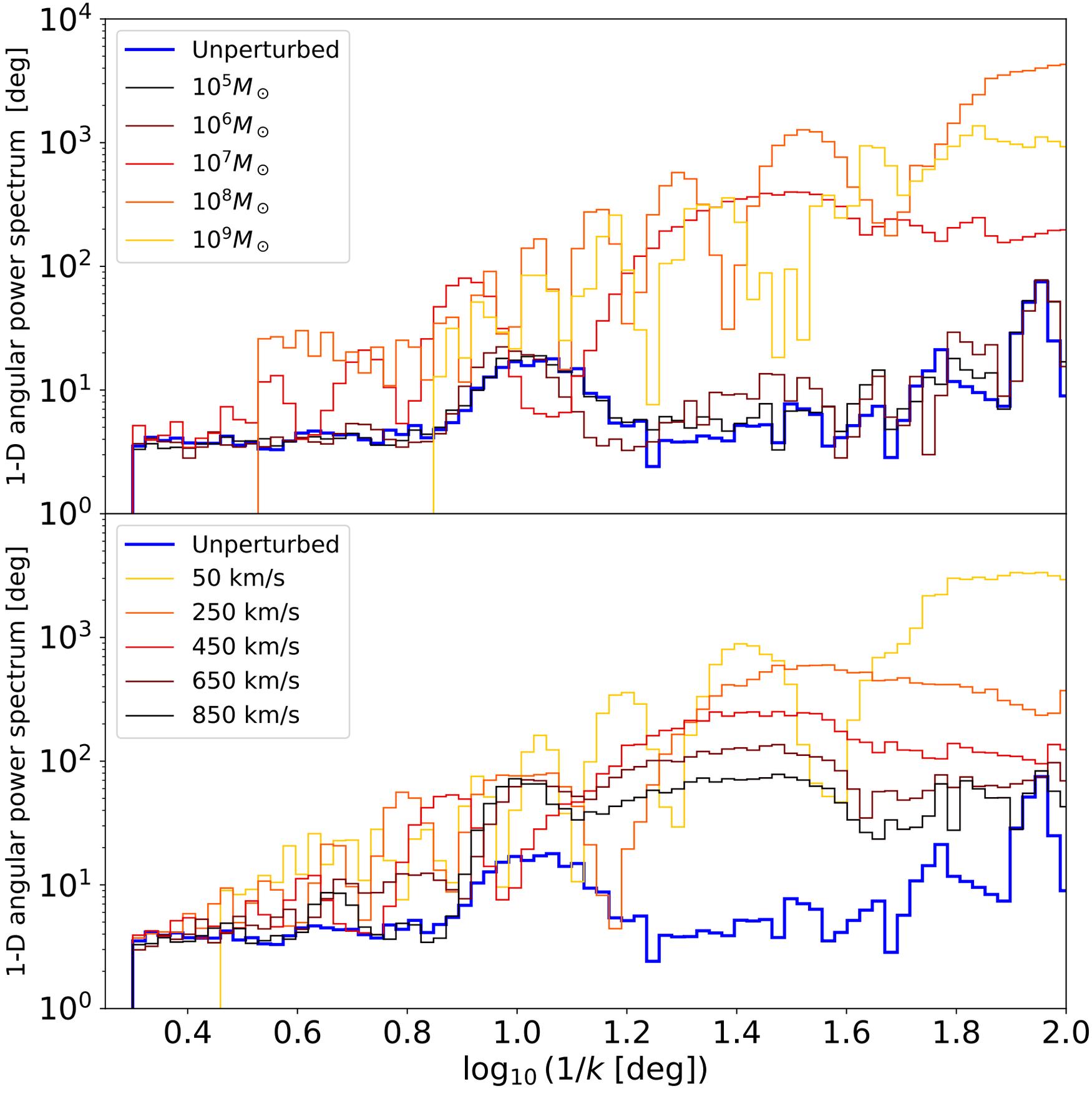


Ma, Rogers, et al. (ApJ, 2025)

Gaps and spurs in Milky Way stellar streams trace dark matter sub-structure

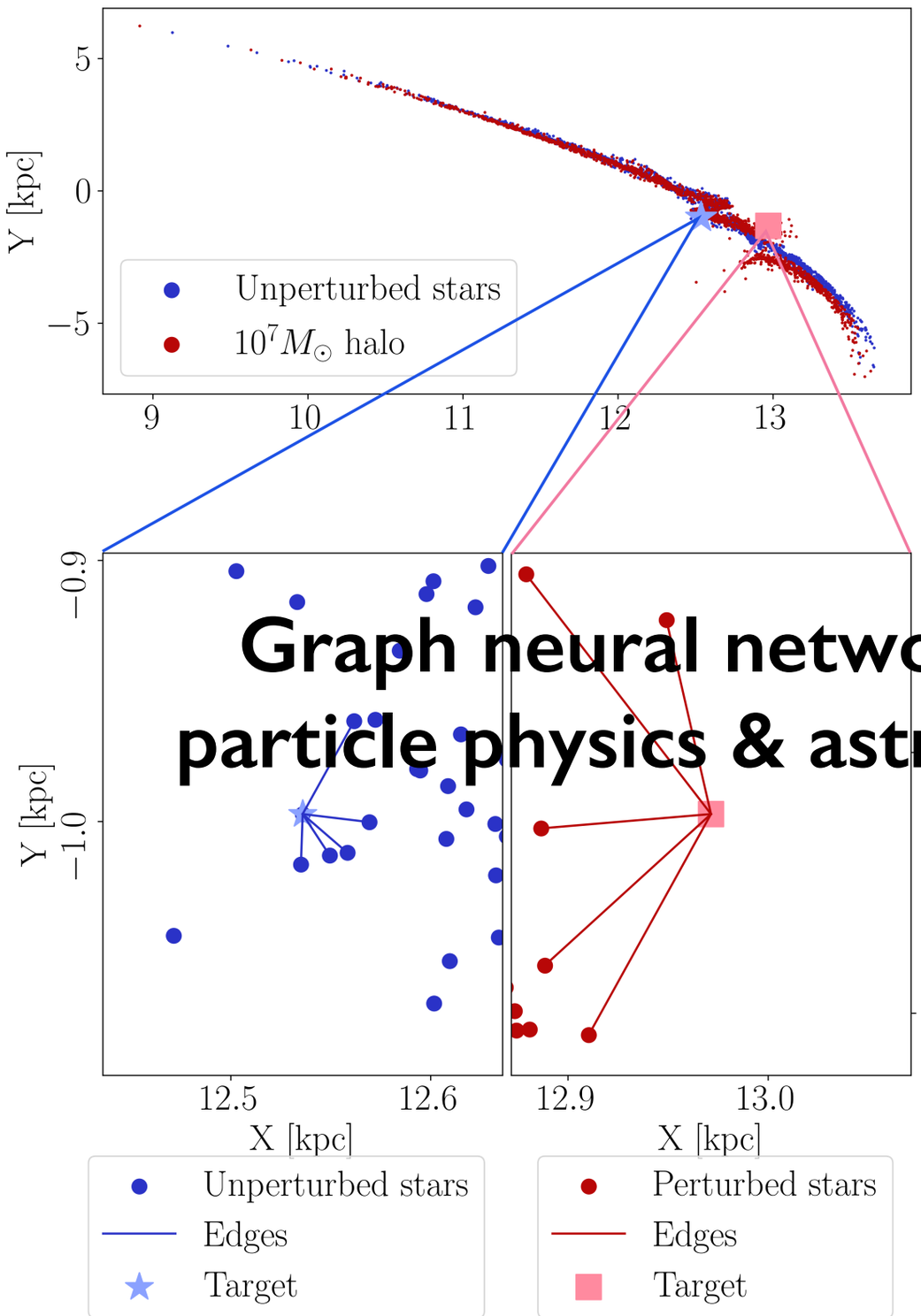


Price-Whelan & Bonaca (2018); Bonaca et al. (2019); Banik et al. (2021)



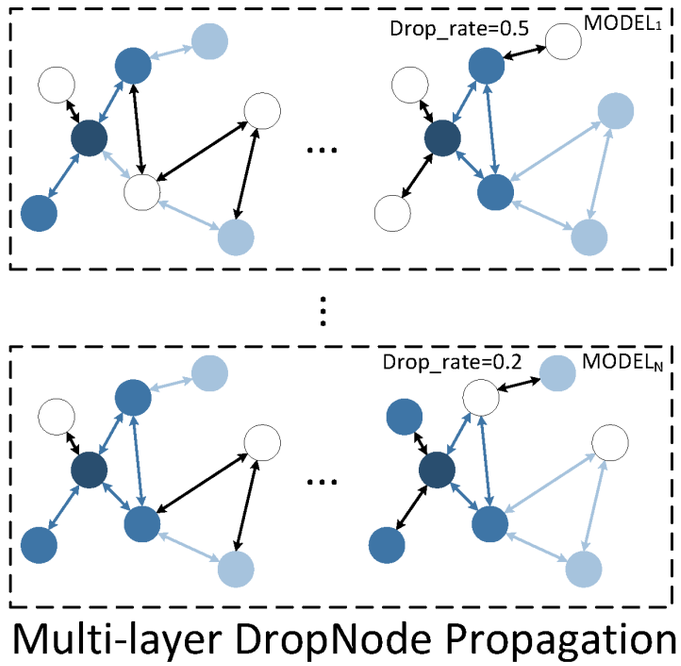
1D power is lossy & degenerate — use 3D/6D?

Bovy et al. (2017); Banik et al. (2021); Ma, Rogers, et al. (ApJ, 2025)



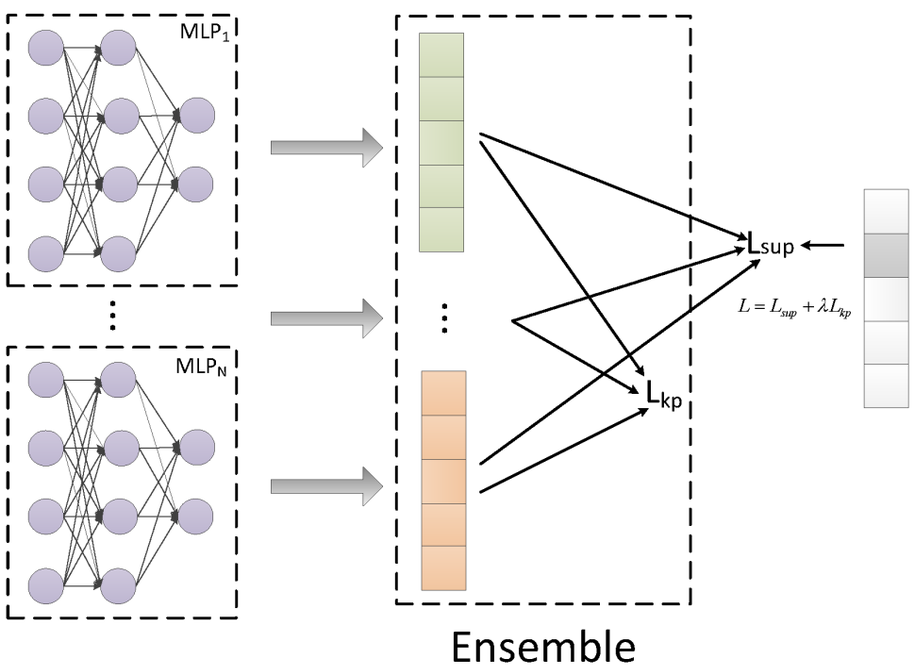
1. Form a graph at each node (star)

2. Graph convolutional layers



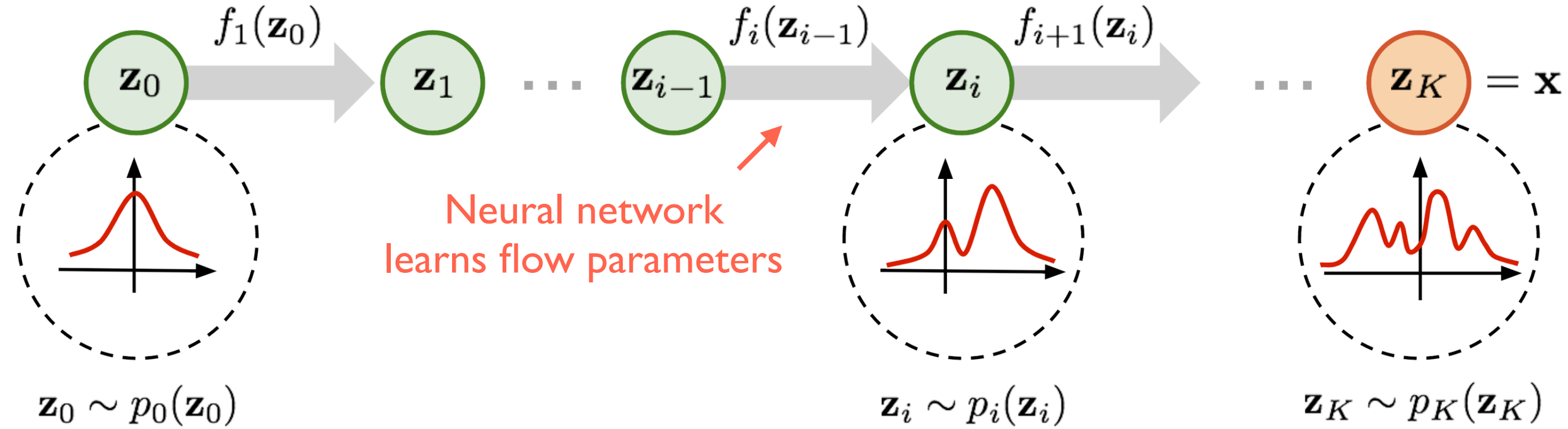
Graph neural networks are a powerful method for particle physics & astronomical event characterisation

3. Pool and standard dense layers



Ma, Rogers, et al. (ApJ, 2025)

Normalising flow model learns series of parameterised transformations from base to posterior



Base distribution
= Normal

Target distribution
= Posterior

Ma, Rogers, et al. (ApJ, 2025)

GCNN data compression leads to stronger constraints

Ma, Rogers+ (2025)

Summary

- Demonstrated proof of concept that **we can detect dark sub-structure**
- **3D phase space for 3000 stars ≈ 6D phase space for 300 stars**
- Now need to **consider incomplete data, more sophisticated simulations**