Probing Dark Matter Microphysics Using Stellar Streams

Aditya Parikh
YITP, Stony Brook University

In collaboration with
D. Adams, R. Essig, M. Kaplinghat, A. Price-Whelan, & O. Slone
Based on 2412.13144

Stony Brook University

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CDM: Successes & Shortcomings

- The CDM paradigm has been extremely successful on the largest scales that we have tested it at. Measurements of correlations in the CMB, large scale structure observables, and a litany of other large scale observations support a CDM interpretation.

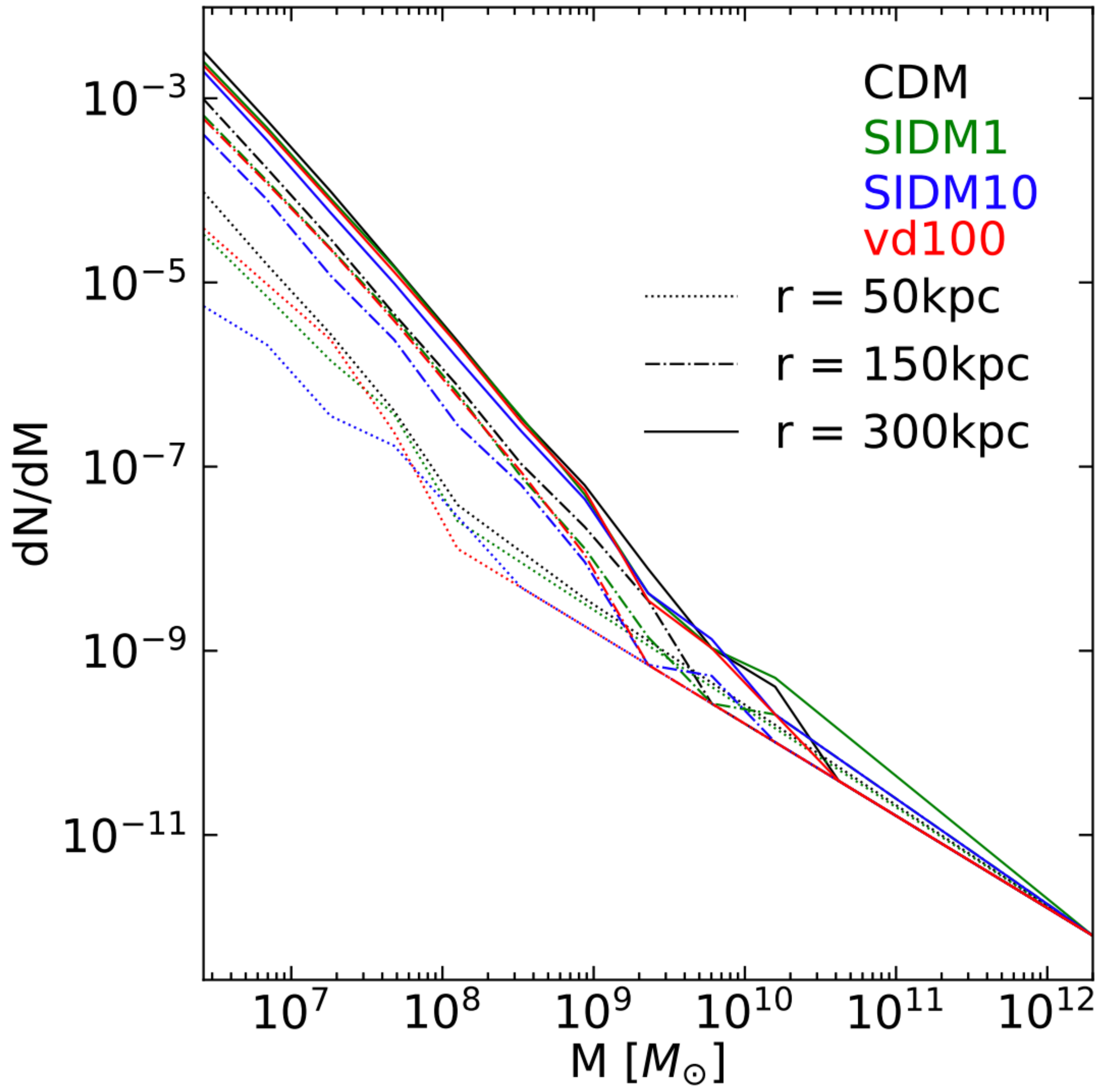
- Discrepancies arise on small scales. DM-only N-body simulations show results which differ from observations. A prime example is the diversity of rotation curves. Baryons are difficult, but necessary! See Andrew's talk from today morning.

- Interactions are well motivated theoretically, specifically from a top down particle physics perspective.

Where can these effects manifest?

Observables of Interest

- Subhalo Mass Function
    - Quantifies the number of subhalos of a particular mass in a galaxy
    - Deviations can be hints of dark matter microphysics
    - Deviations can be large at small mass scales, but subhalos are dark
- Core Collapsed Density Profiles



[2010.02924]

Gravothermal Collapse

- Halo evolution sequence for an initially NFW profile. The same sequence holds for truncated NFW profiles as well as tidally stripped profiles. [1901.00499]

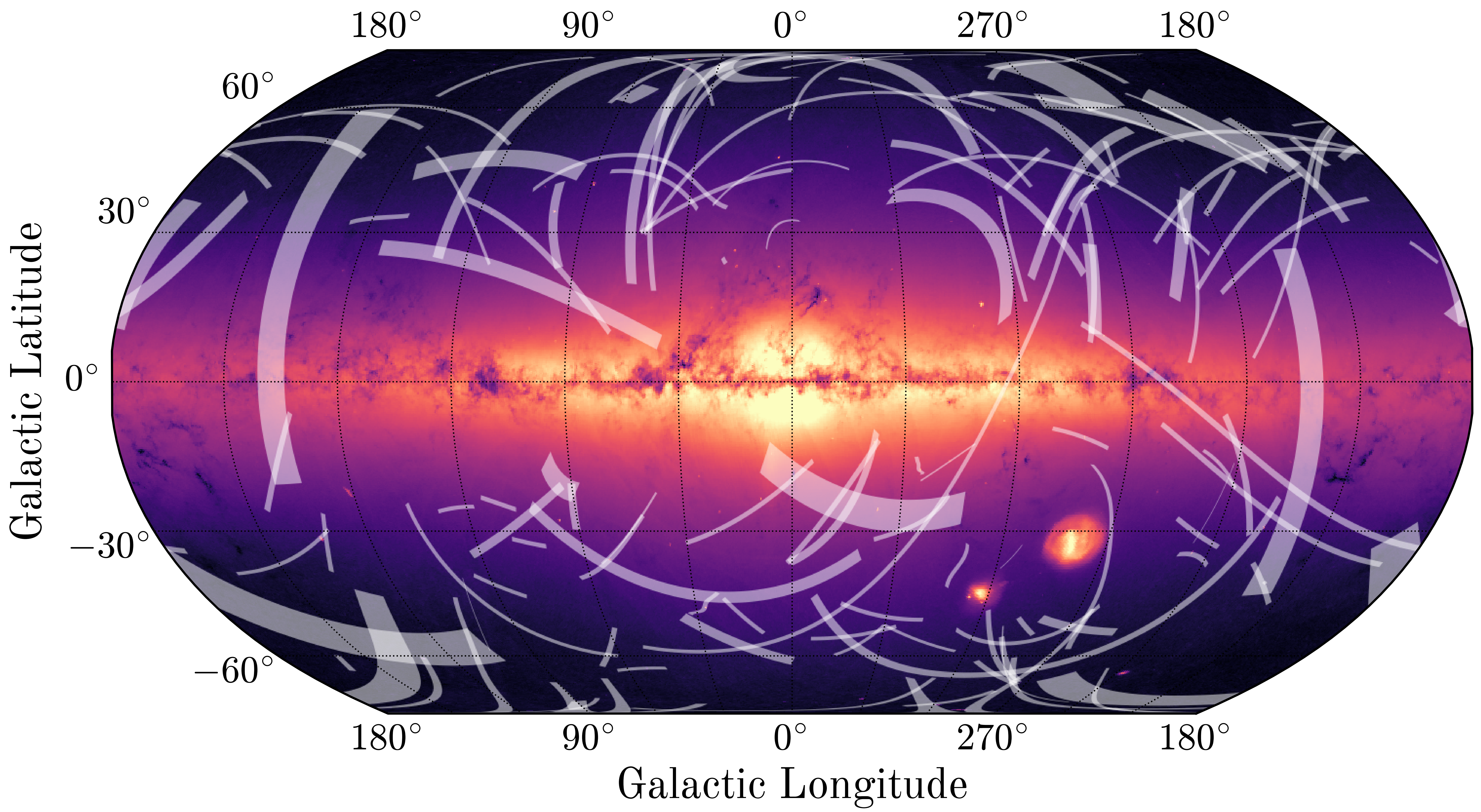
    - Self-interactions begin thermalizing the inner region, increasing the temperature, and forming a gradually expanding core.

    - The expansion halts as an isothermal core is formed. The velocity is roughly constant.

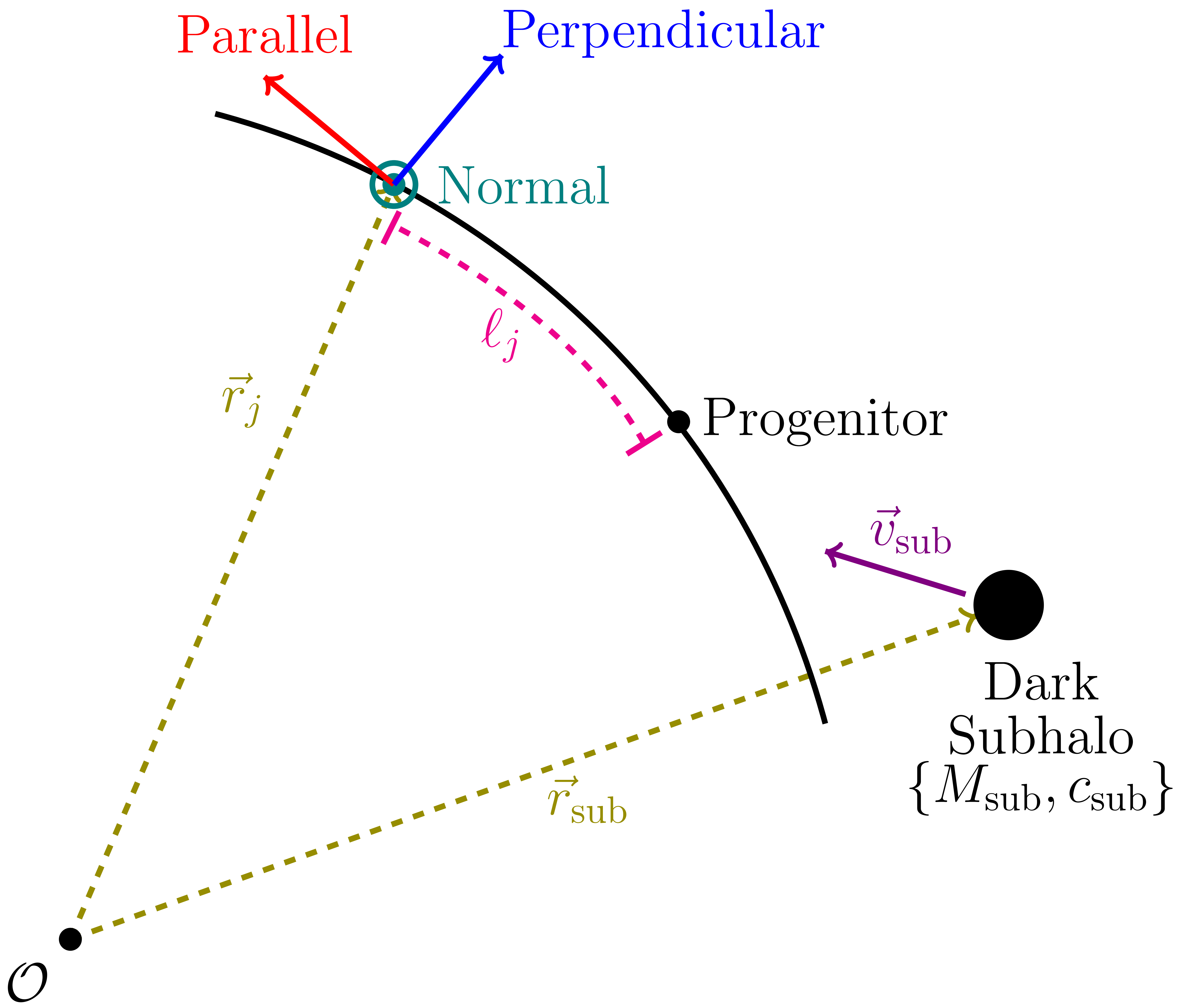
    - Core collapse is initiated. The core becomes denser and hotter as it shrinks in size, but remains isothermal. The evolution is self-similar.

    - Finally, we enter the short mean free path regime and the core becomes optically thick to self-interactions. The core attains its maximum mass, and the density and temperature increase rapidly in this phase.

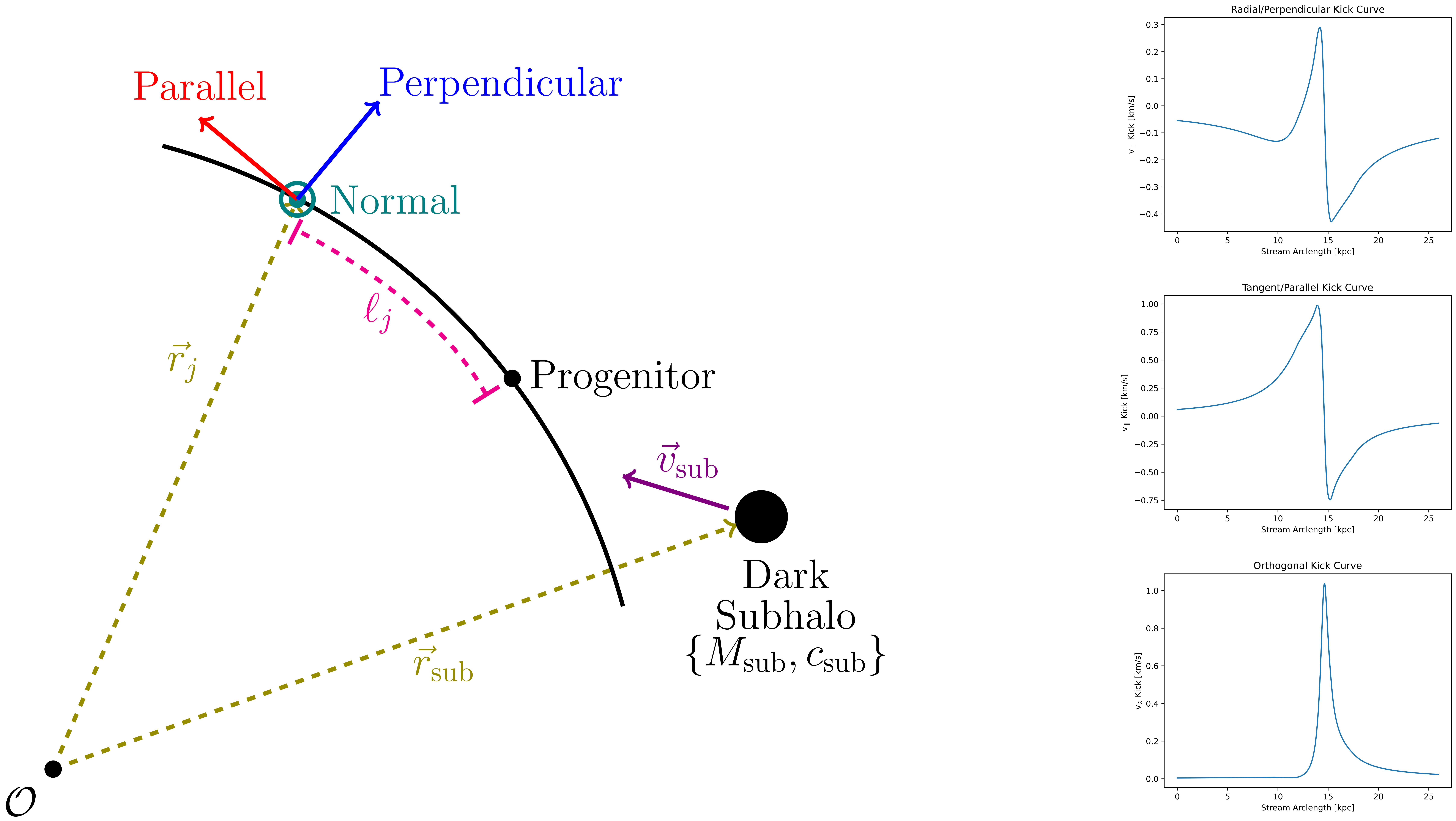
Streams as Detectors?



[2405.19410]



Parallel
Perpendicular
Normal
ℓ_j
$\vec{r}_j$
Progenitor
$\vec{v}_{\text{sub}}$
Dark
Subhalo
$\{M_{\text{sub}}, c_{\text{sub}}\}$
$\vec{r}_{\text{sub}}$
$\mathcal{O}$



Parallel
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Dark Subhalo
$\{M_{\rm sub}, c_{\rm sub}\}$
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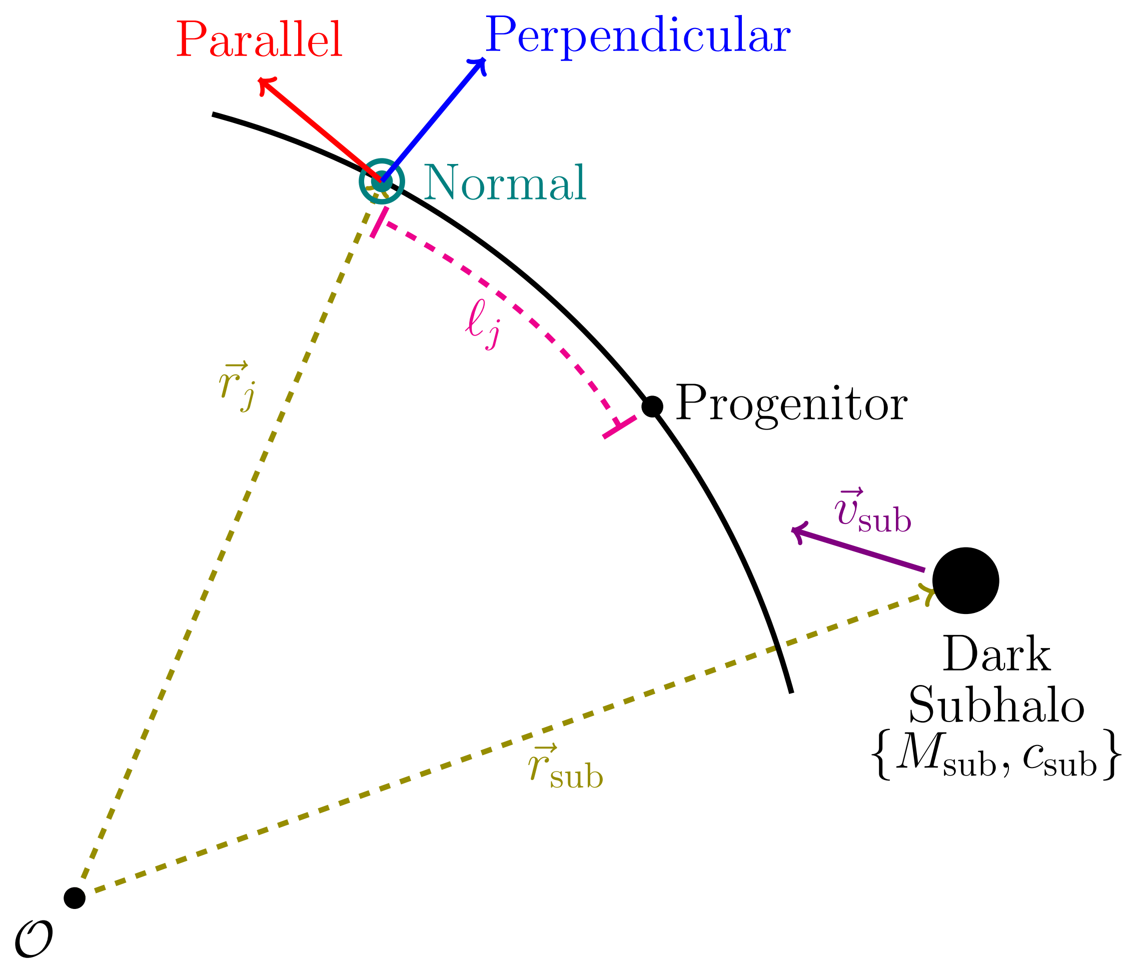
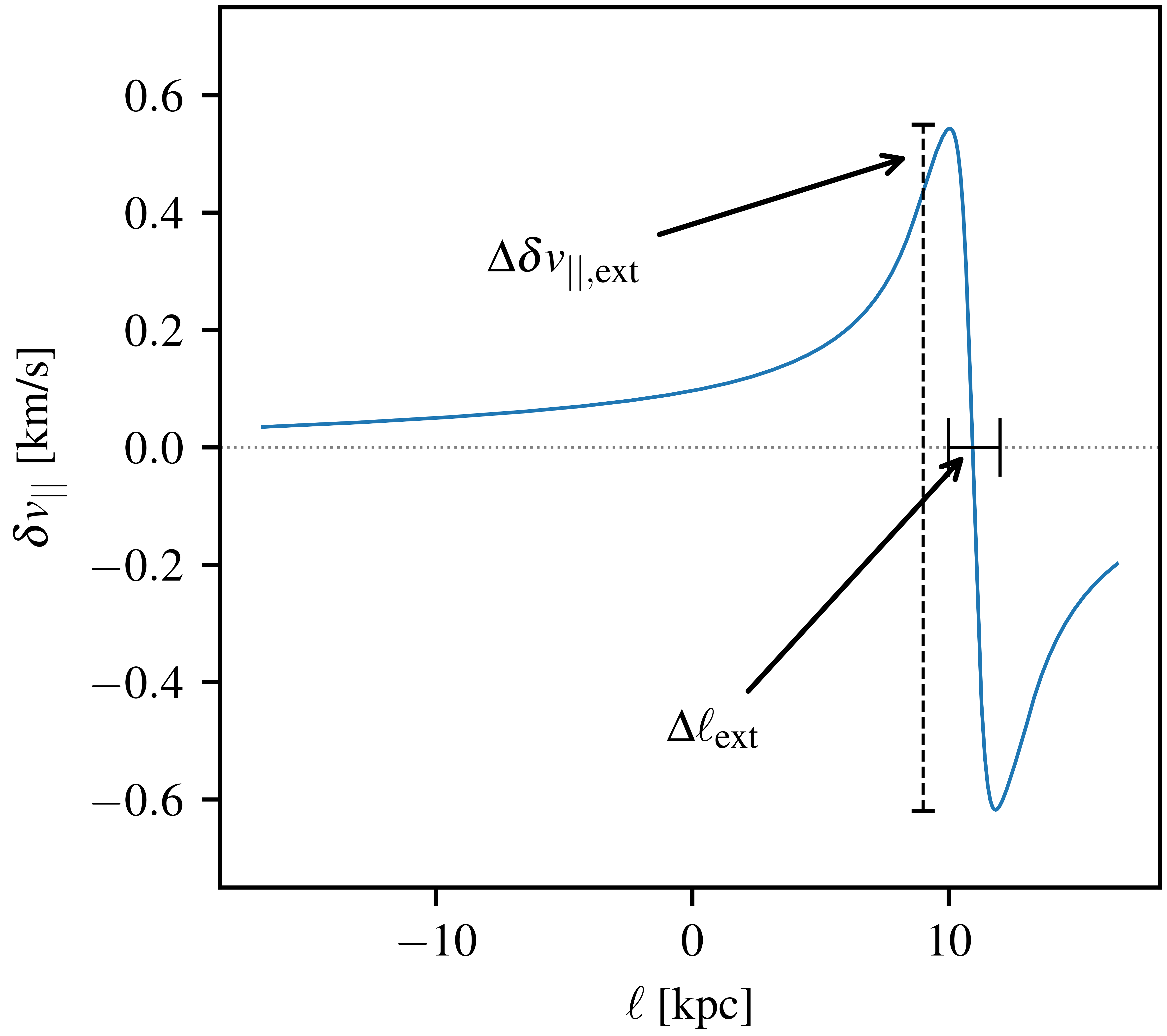
$\mathcal{O}$
Radial/Perpendicular Kick Curve
$v_\perp$ Kick [km/s]
Stream Arclength [kpc]
Tangent/Parallel Kick Curve
$v_\parallel$ Kick [km/s]
Stream Arclength [kpc]
Orthogonal Kick Curve
$v_\odot$ Kick [km/s]
Stream Arclength [kpc]

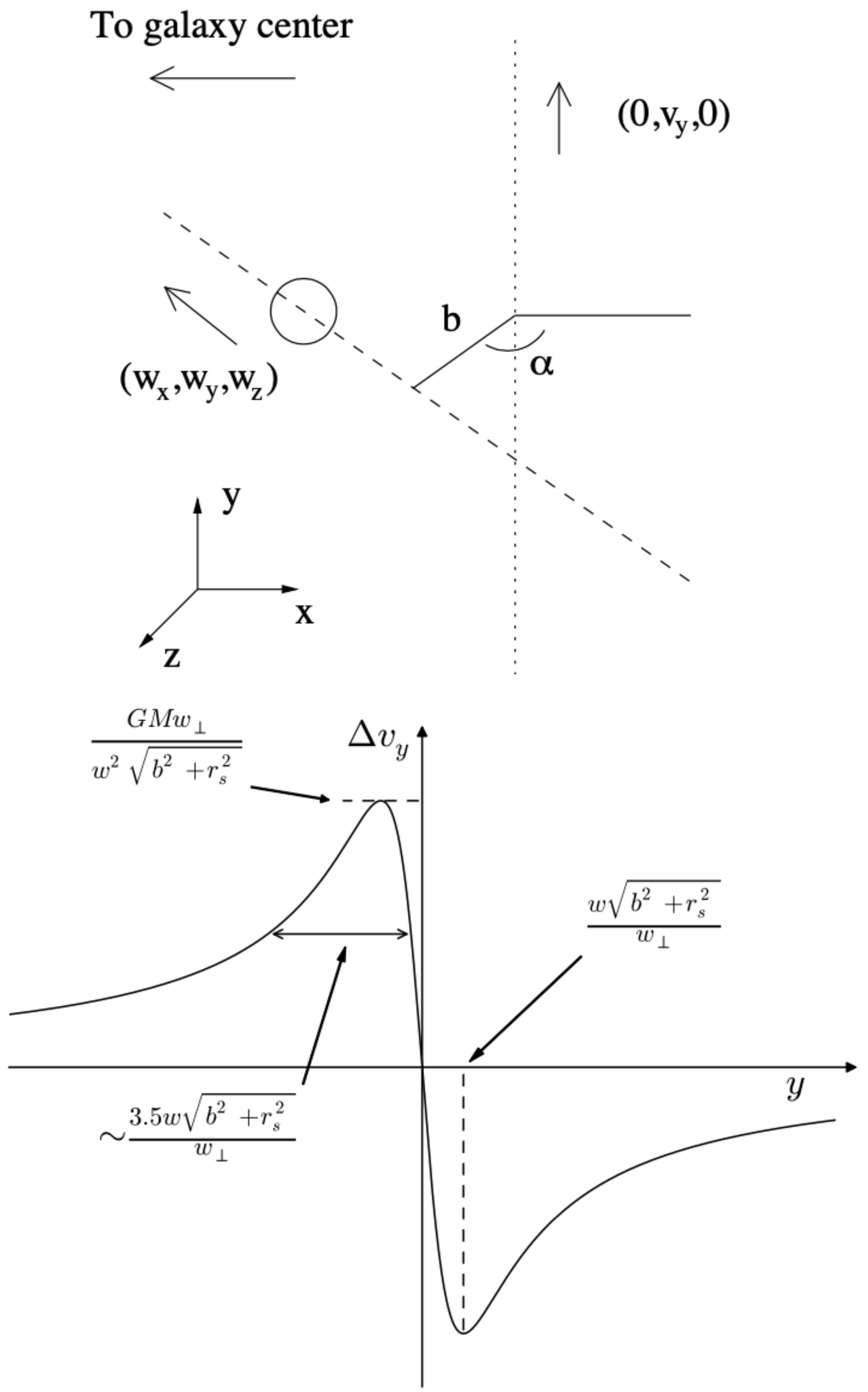
- $\Delta\delta v_{||,\mathrm{ext}}$ and $\Delta\ell_{\mathrm{ext}}$ characterize* the velocity kicks imparted by the perturber.

- What are the distribution of these variables? How many such events do we expect? What can they tell us about subhalo properties?



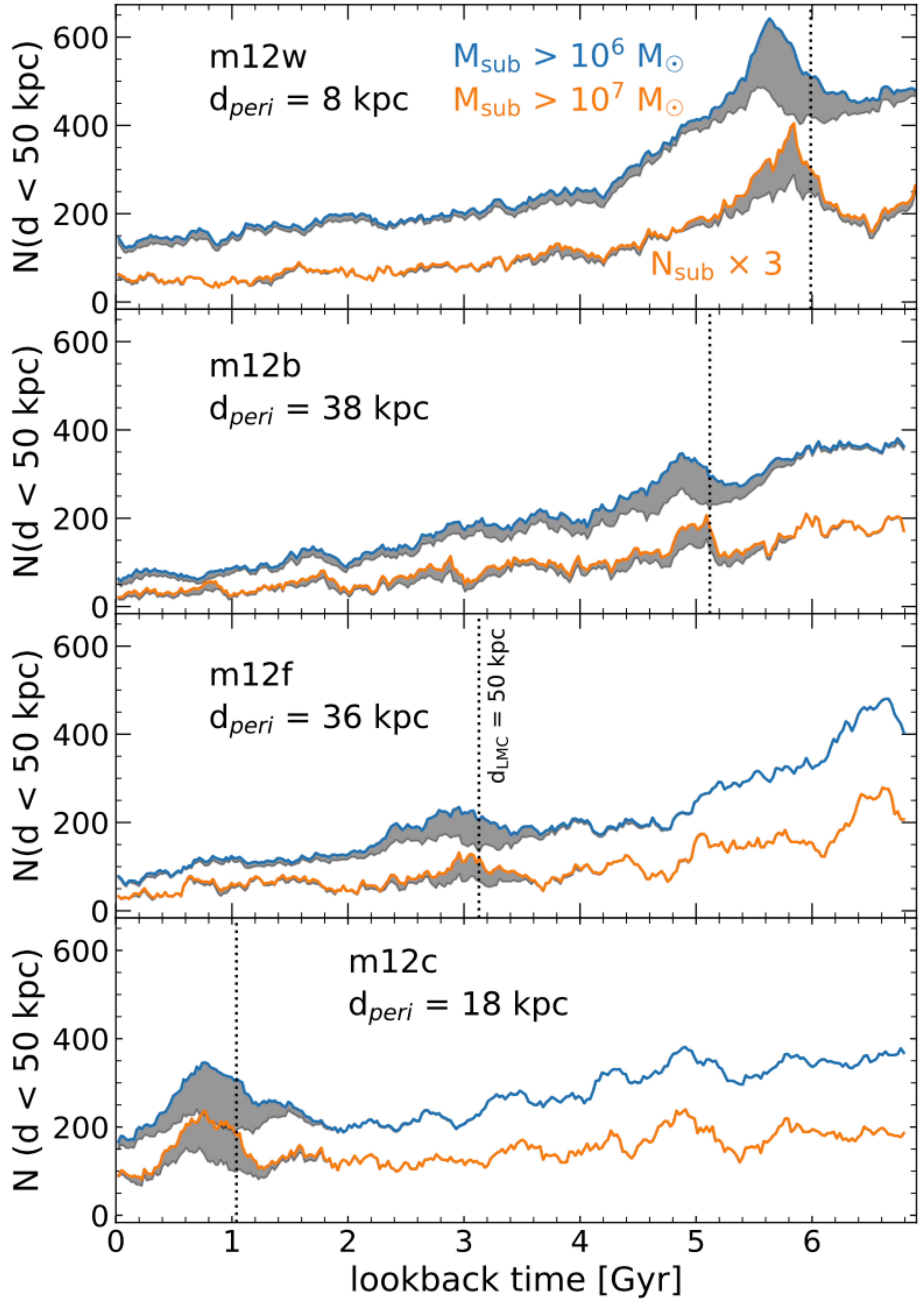


Analytic Approaches
[1412.6035]



- Analytic methods are great for relating subhalo and stream gap properties, but are completely oblivious to subhalo population and phase space distributions.
- N-body simulations can nail down these distributions, but have difficulty producing gaps.
- Can we leverage the power of both approaches?

N-body Simulations
[2303.05527]



The Semi-Analytic Approach

- Semi-analytic tools initialize and generate various Milky Way-like realizations by seeding an initial distribution of subhalos of various masses around the galaxy and then evolving them in the host potential.

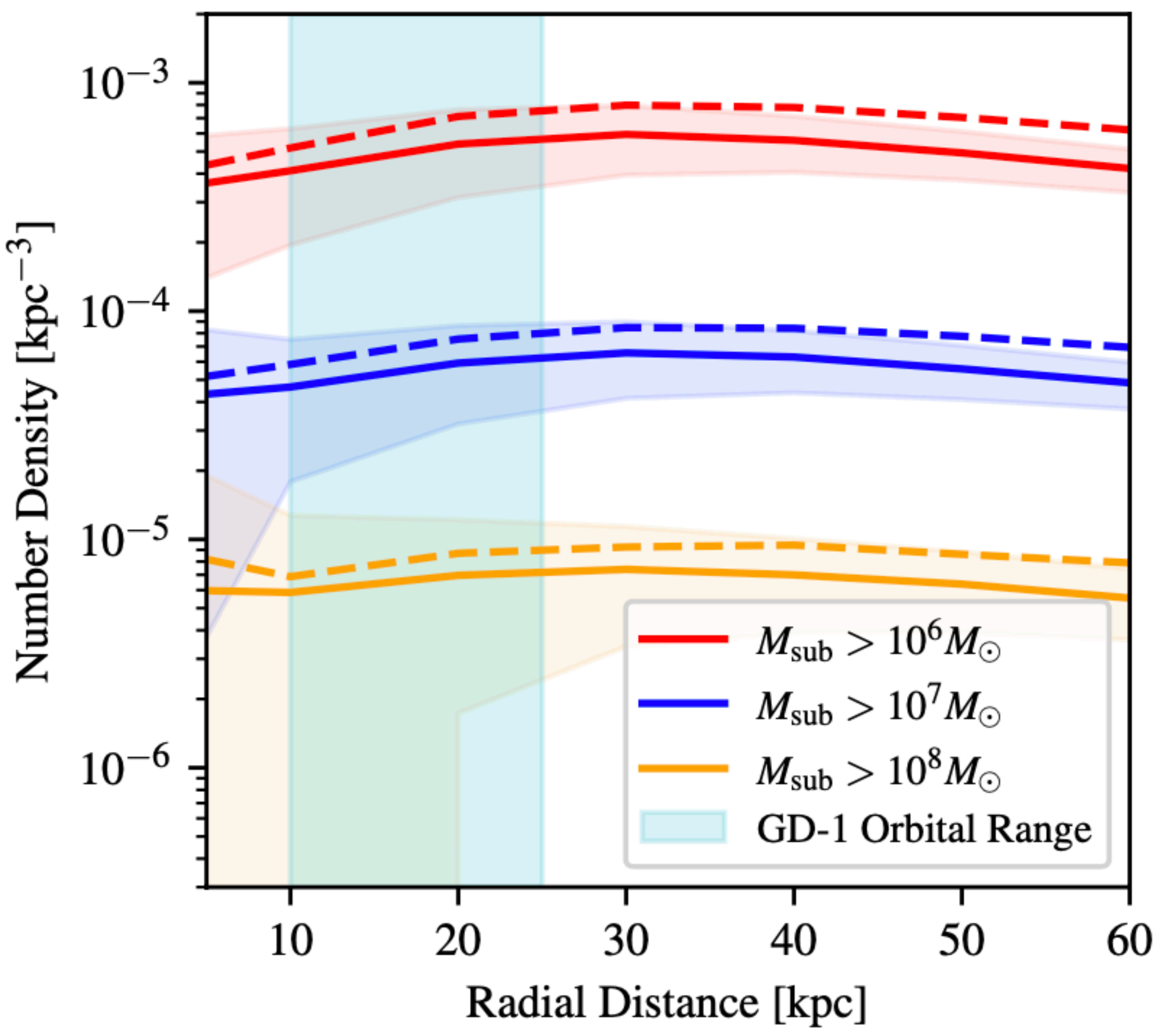
- Semi-analytic approaches allow us to run lots of samples quickly which helps combat effects such as halo-to-halo variance, etc.

- Performing robust population studies is crucial in critically evaluating the extent to which CDM subhalos can create the observed features in streams.


Subhalo Distribution
SatGen
semi-analytic
satellite generator
Simple Stream Modeling
GALPY & StreamDF
1D stream
test particles
Main Event Selection
Impulse Curve
Calculation given
subhalo models
Gap Properties
GALA
N-body simulation
of gap formation

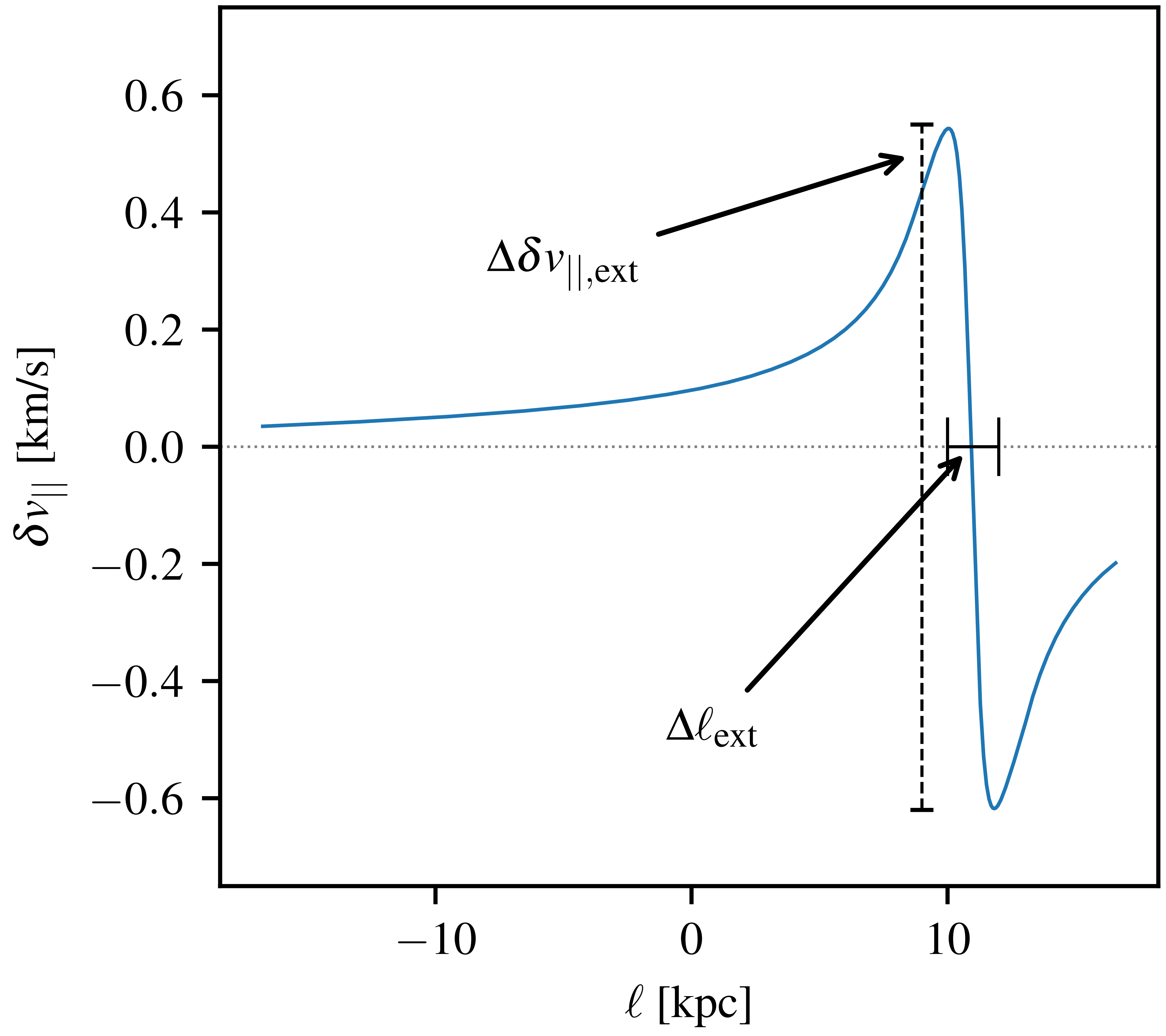
Step 1: Subhalo Distribution & Simple Stream Modeling

- Use SatGen to generate a Milky Way-like system, integrating subhalo orbits within a defined host potential.
- Use GALPY to create a simplified model of a stellar stream's evolution including growth and orbital modulation.
- Output - stream and subhalo phase space information.



Step 2: Main Event Selection

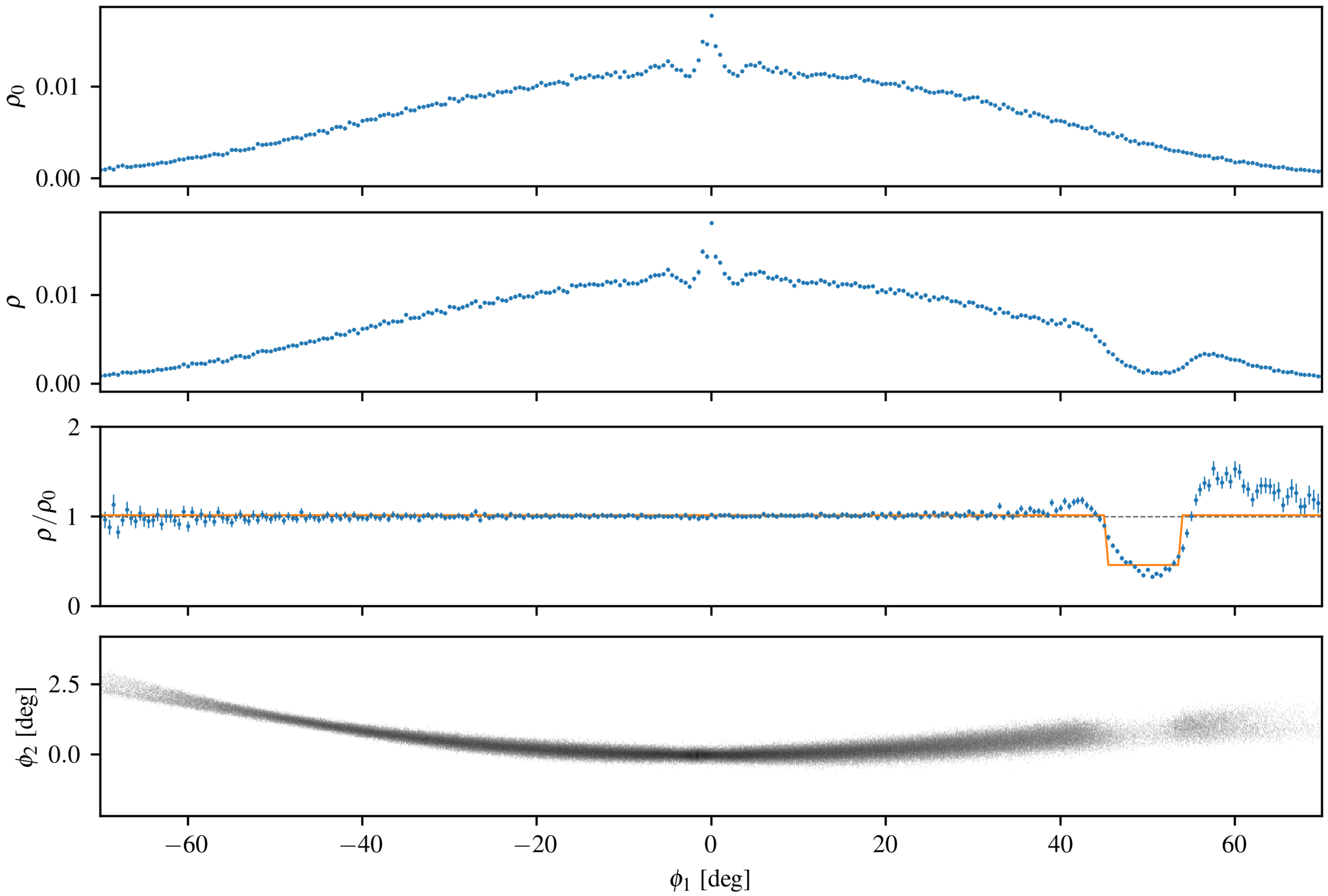
- Select subhalos which have close, impulsive encounters with the stream.
  - Subhalos must pass within 5 times the initial infall scale radius and occur within 250 Myr.
- Compute the impulse imparted along the stream over the course of the interaction.
  - Events must have two extrema, $\Delta\delta v_{||,\mathrm{ext}} \geq 0.1$ km/s and $\Delta\ell_{\mathrm{ext}}/\ell_{\mathrm{stream}} \leq 0.4$.

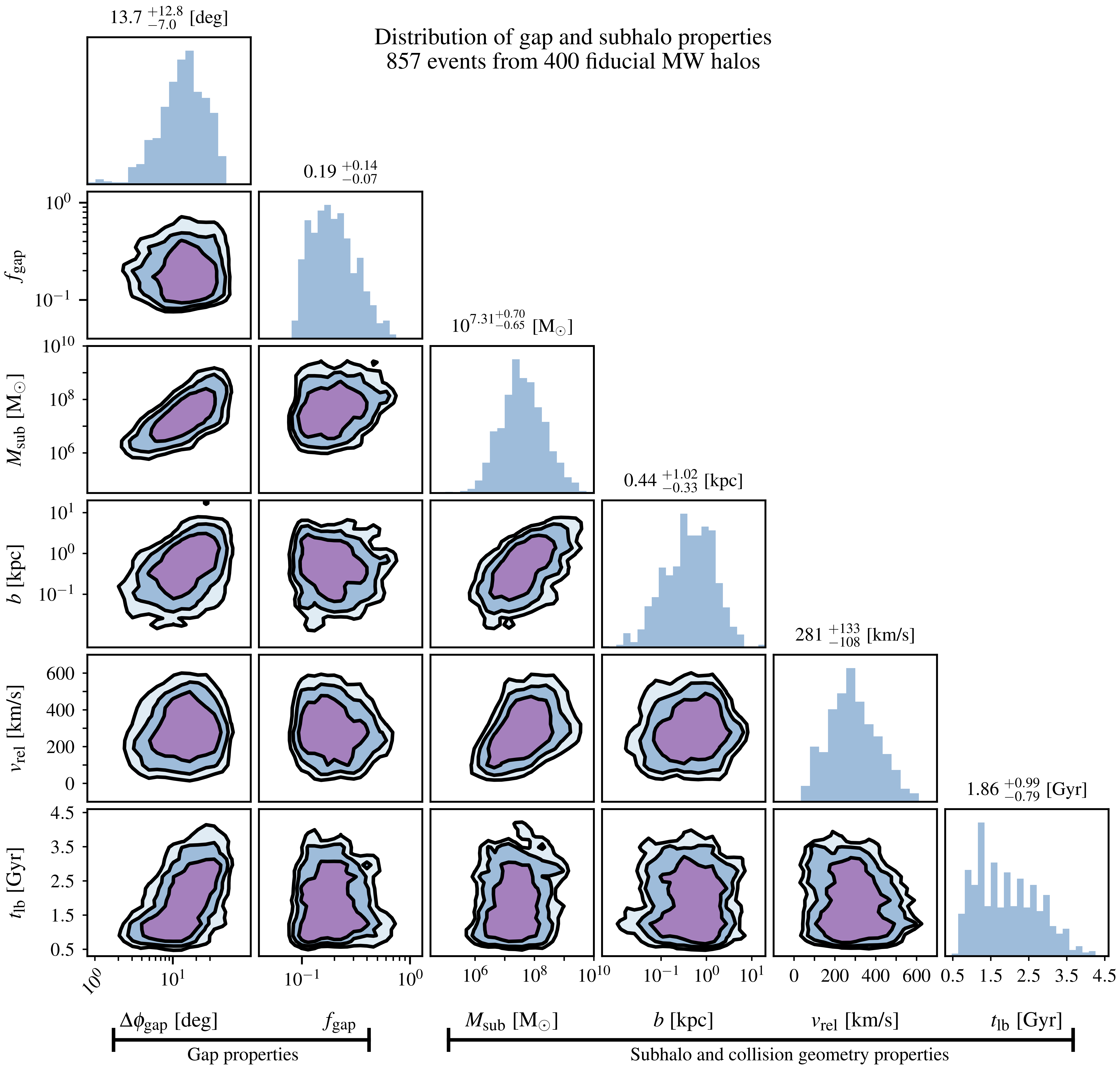


Step 3: Gap Properties & GALA

- Use GALA to more realistically simulate the stream-subhalo encounter.

- Extract gap properties such as width and depth from these results and correlate them with the subhalo and collision geometry properties.





- Joint distributions of gap, subhalo, and collision geometry properties for stream-subhalo encounters that passed the cuts and created gaps.
- $M_{\rm sub}$ correlates positively with b and $v_{\rm rel}$.
  - $\Delta v \sim G\,M_{\rm sub}/(b\,v_{\rm rel})$
- Gap width correlates positively with $M_{\rm sub}$, b, and $t_{\rm lb}$.
  - $\Delta\phi_{\rm gap} \propto (v_{\rm rel}/v_{{\rm rel},\perp})\sqrt{(b^2 + r_s^2)/r_0^2}$

Summary

- This work establishes the CDM baseline expectation for the effects on streams. Further CDM studies still need to be undertaken, such as quantifying the effects of the more frequent, low impulse interactions which increase the inherent velocity dispersion and lead to heating.

- The current MW satellite census is consistent with all subhalos hosting galaxies down to a peak mass of $3 \times 10^8 M_\odot$ [1912.03303]. However, various galaxy formation models predict inefficient galaxy formation at lower masses, such that most halos with peak masses below $\sim 10^7 M_\odot$ remain ``dark'' [2112.04511, 2308.13599]. Thus, gap formation in streams can be caused by both luminous and dark substructures.

- SIDM can alter dark matter density profiles of subhalos, especially for lower mass objects. There are regions of SIDM parameter space where all the subhalos are core collapsed. Stay tuned for results!