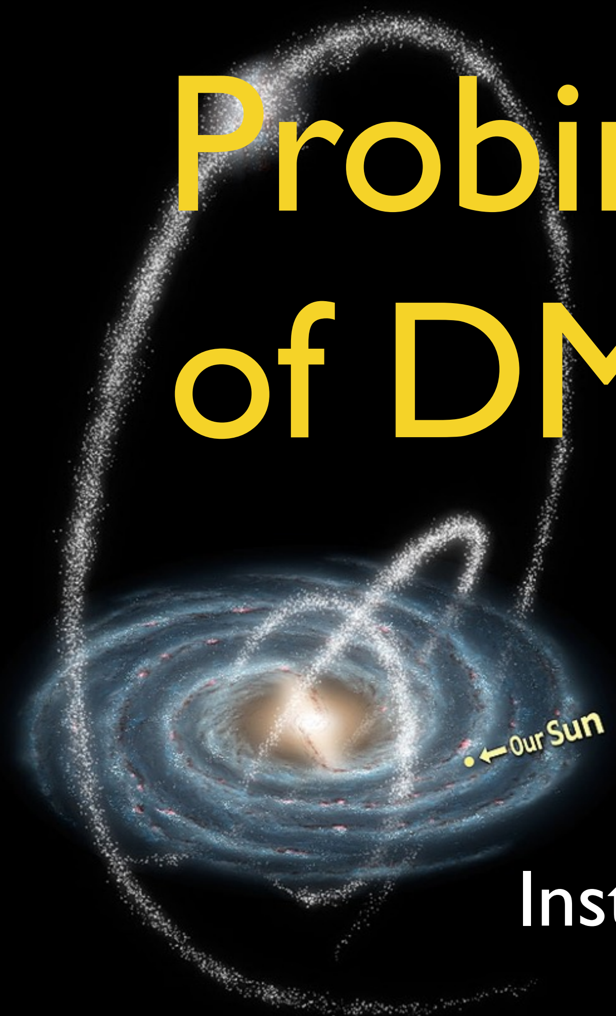
Probing the particle nature of DM with stellar streams



Nassim Bozorgnia

Institute for Particle Physics Phenomenology
Durham University

Based on work done with N. Banik, G. Bertone, J. Bovy
arXiv: 1804.04384

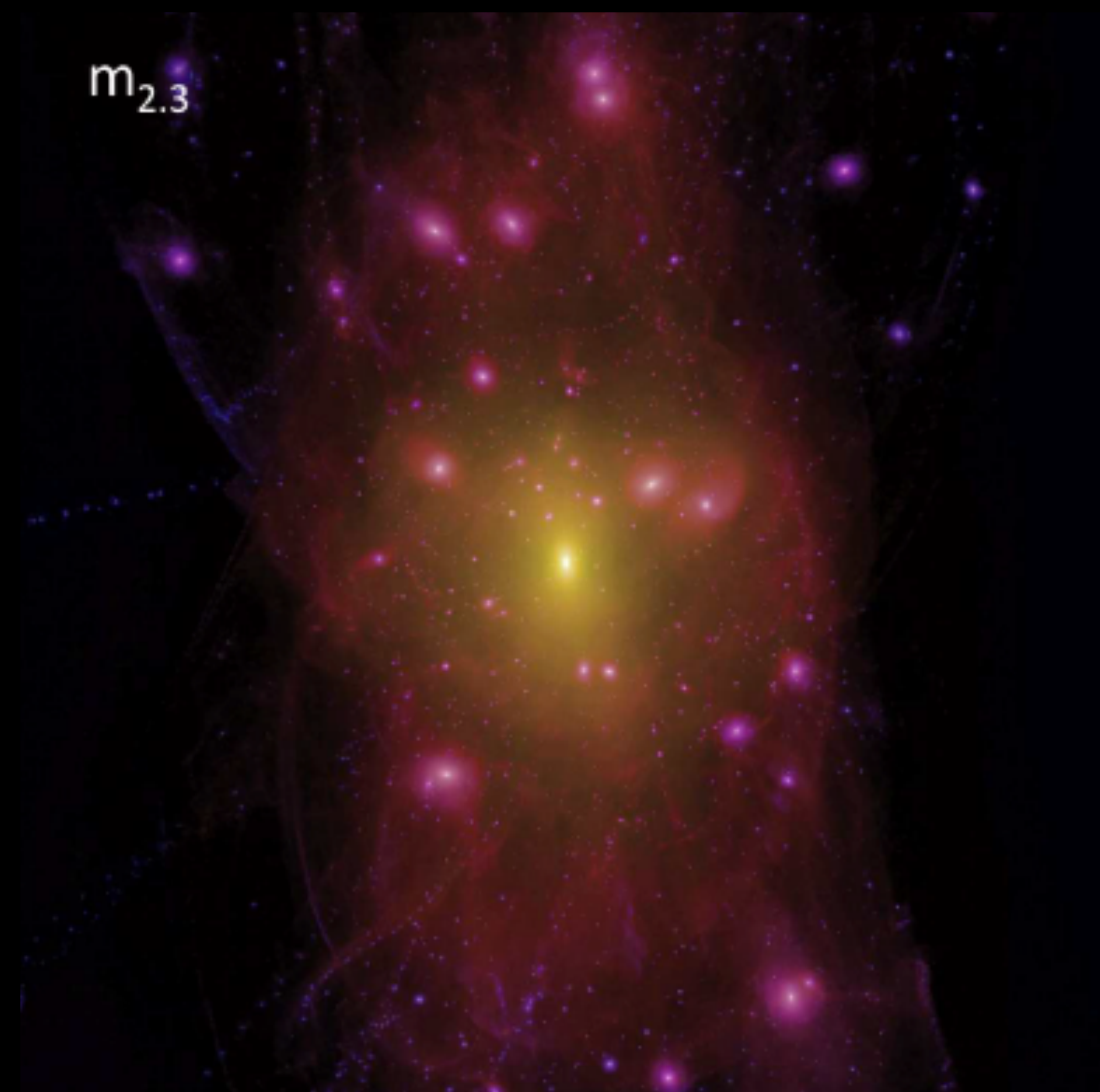
Durham University

IP3

Dark matter subhalos

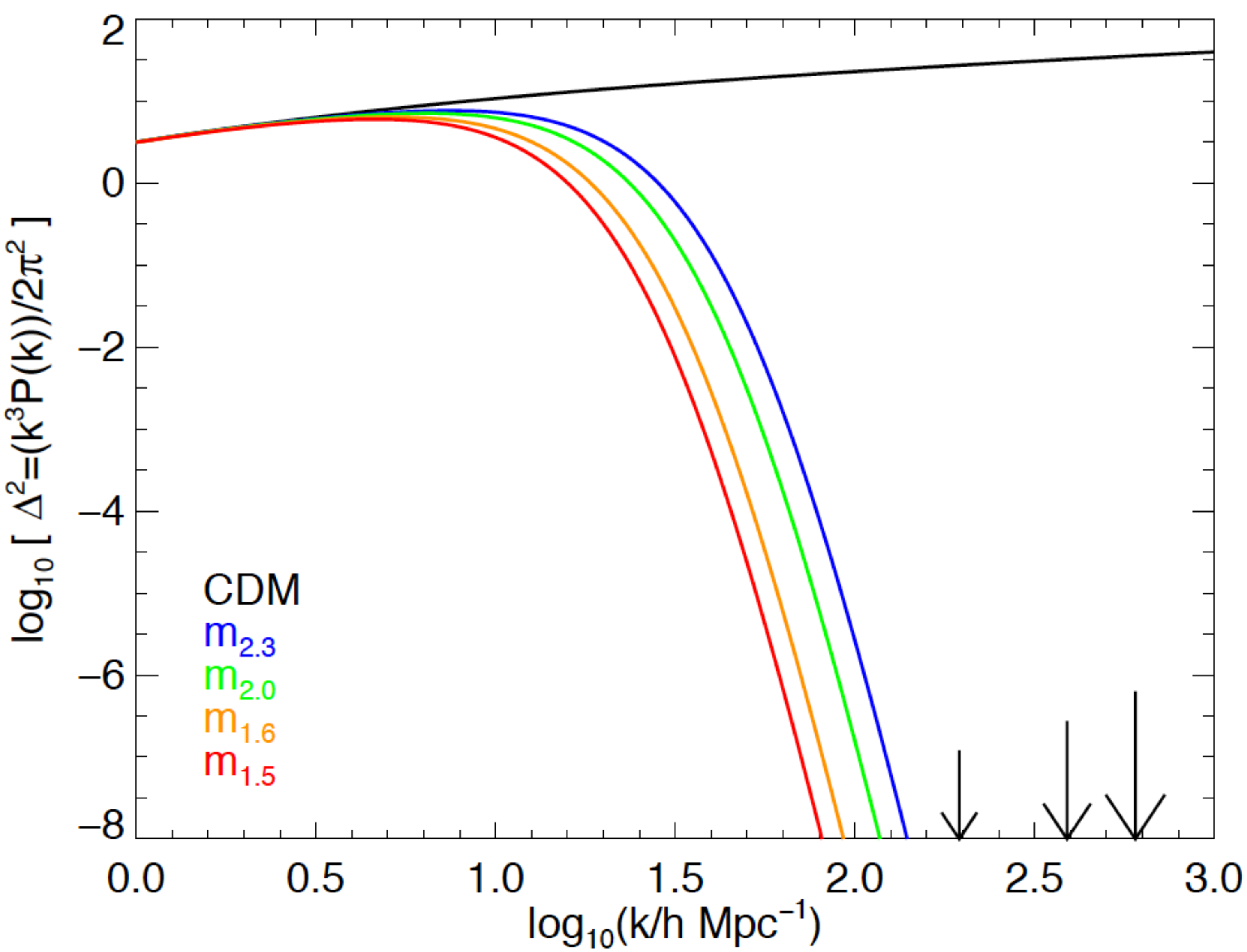
Cold DM

Warm DM



Lovell et al. 1308.1399

Dark matter subhalos



Lovell et al. 1308.1399

Cold DM

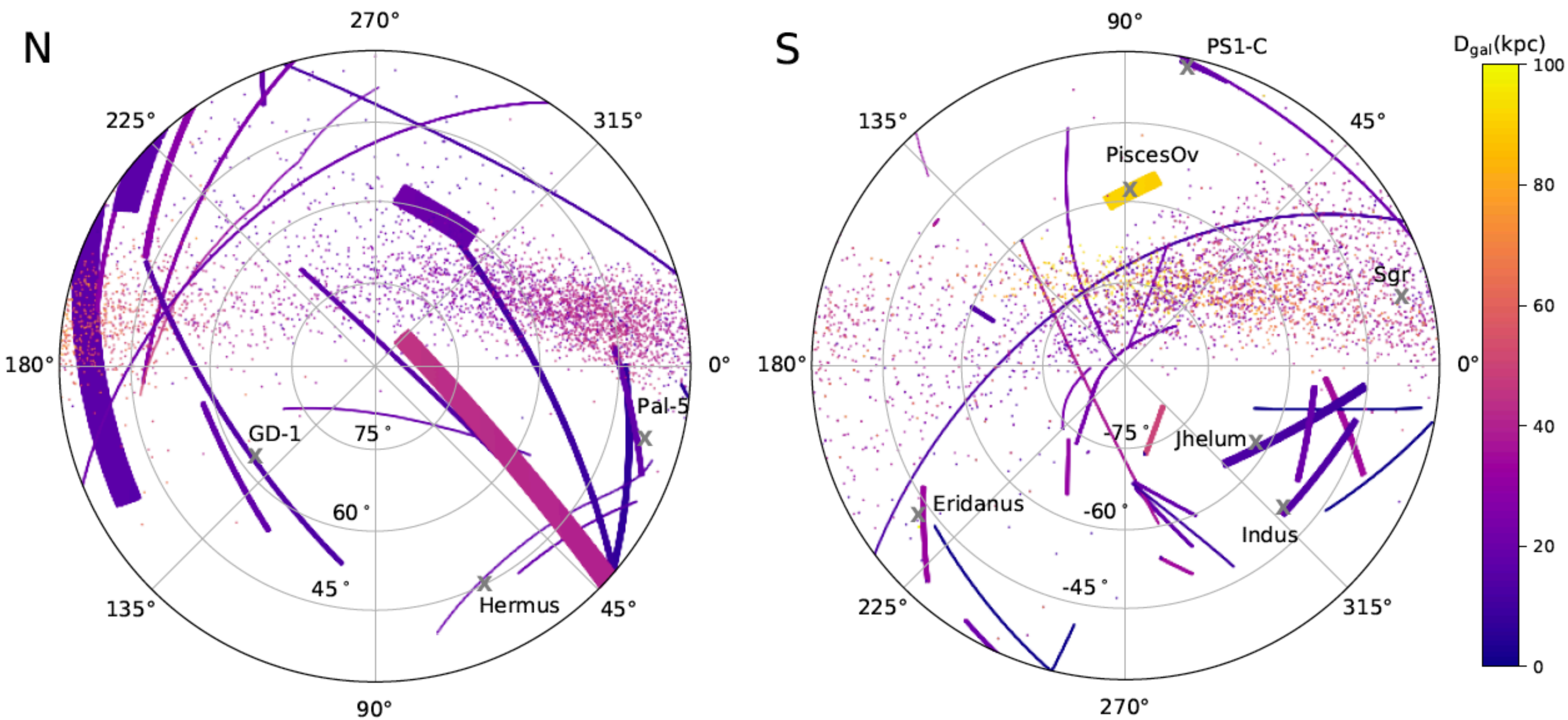
- **Negligible** thermal velocities during structure formation.
- *Small* free-streaming length (~0.1 kpc for m_X=100 GeV).
- *Many substructures at small scales.*

Warm DM

- **Non-negligible** thermal velocities.
- *Large* free-streaming length (~60 kpc for m_X ~ keV).
- *Suppression of small structures below free-streaming scale.*

Milky Way stellar streams

- Stellar streams form when a globular cluster or dwarf galaxy in the halo gets tidally disrupted, and its mass is deposited uniformly into an orbit around the center of the Galaxy.

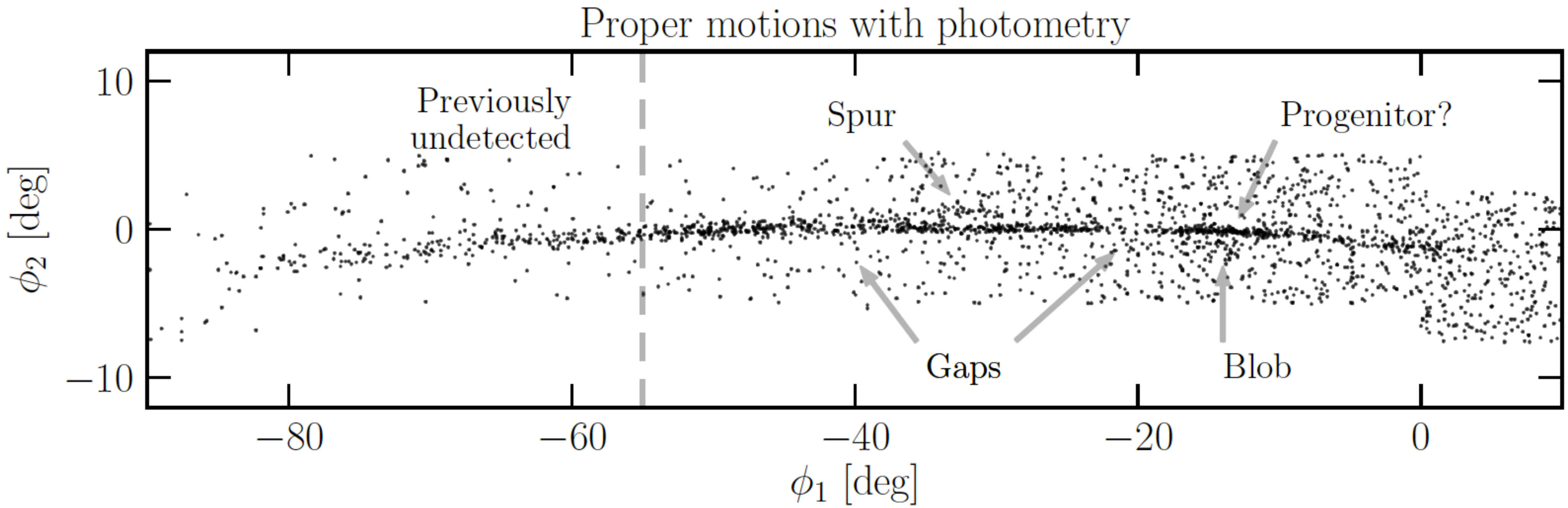


Malhan, Ibata, Martin, 1804.11339, Mateu, Read, Kawata, 1711.03967

Stellar streams & DM subhalos

- A DM subhalo flying by a stream gravitationally perturbs the stars in the stream. ➡ Region of low stellar density (gap) whose size increases with time.

Gaps observed in Gaia DR2 data of GD-1 stream:

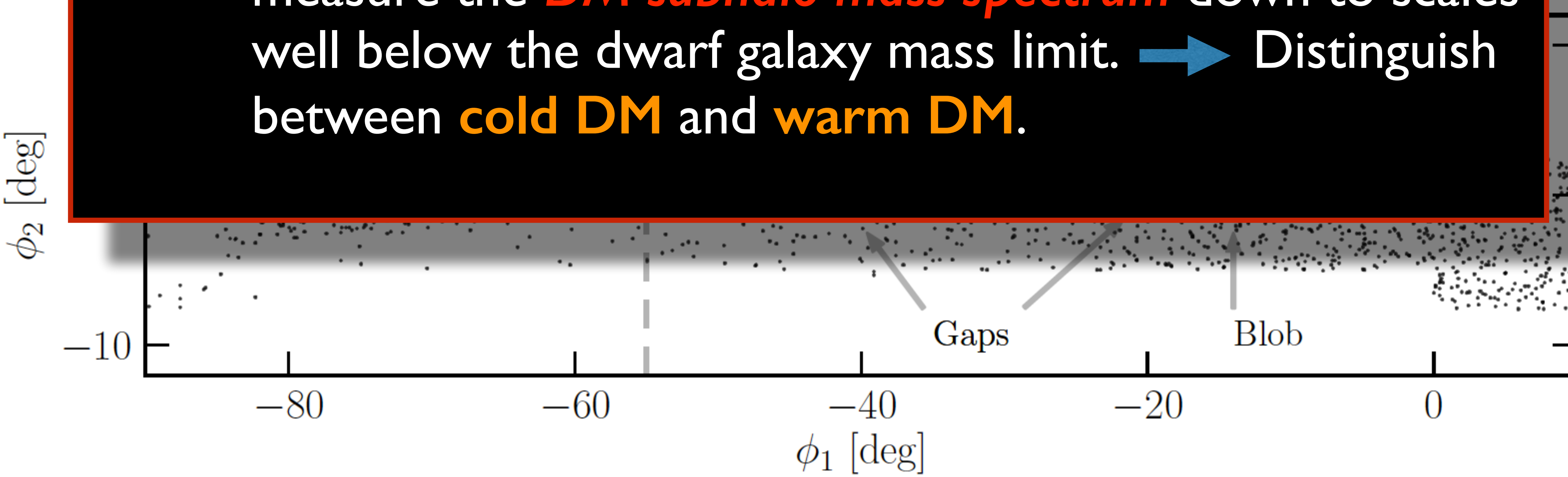


Price-Whelan & Bonaca, 1805.00425

Stellar streams & DM subhalos

- A DM subhalo flying by a stream gravitationally perturbs the stars in the stream. ➔ Region of low stellar density (gap) whose size increases with time.

- Aim of detecting such features in streams is to:
  - measure the *DM subhalo mass spectrum* down to scales well below the dwarf galaxy mass limit. ➔ Distinguish between **cold DM** and **warm DM**.



Price-Whelan & Bonaca, 1805.00425

Stellar streams & DM subhalos

- Many recent works studying gaps in stellar streams as a result of subhalo encounters:
  - Yoon, Johnston, Hogg, 1012.2884
  - Carlberg, 1109.6022, 1307.1929
  - Erkal & Belokurov, 1412.6035, 1507.05625
  - Sanders, Bovy, Erkal, 1510.03426
  - Bovy, Erkal, Sanders, 1606.03470
  - …
- With Gaia and LSST data, possible to measure subhalo impacts with mass as low as 10^7 M_{sun}. Erkal & Belokurov, 1507.05625
- Infer the properties of impacting subhalos by analyzing the power spectrum of density fluctuations of the perturbed stream. Sensitive to 10^5 M_{sun} subhalos with better data. Bovy, Erkal, Sanders, 1606.03470

Stellar streams & DM subhalos

- **Our approach:**
  - Generate mock stream data for upcoming astronomical surveys, and simulate the impacts due to DM subhalos.
  - Analyze the statistical properties of density fluctuations due to subhalo encounters for CDM and WDM scenarios.
  - Reconstruct the mass of the DM particle from the perturbations induced in the stream.

Modeling warm dark matter

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$$P_{\rm WDM}(k) = T^2(k) P_{\rm CDM}(k)$$

Transfer function: $$T(k) = (1 + (\alpha k)^{2\nu})^{-5/\nu}$$

Bode et al., astro-ph/0010389

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Cutoff scale as a result of free streaming:

$$\alpha = 0.047 \left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-1.11} \left(\frac{\Omega_{\rm WDM}}{0.2589}\right)^{0.11} \left(\frac{h}{0.6774}\right)^{1.22} h^{-1}\ {\rm Mpc}$$

Subhalo mass function

- From high resolution N-body simulations of WDM subhalos within a Milky Way-like host halo:

Lovell et al, 1308.1399

$$\left(\frac{dn}{dM}\right)_{\rm WDM} = \left(1 + \gamma \frac{M_{\rm hm}}{M}\right)^{-\beta} \left(\frac{dn}{dM}\right)_{\rm CDM}$$

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$M_{\rm hm}\left(\alpha\left(m_{\rm WDM}\right)\right)$

with γ=2.7 and β=0.99.

M_{hm}: Mean mass enclosed within a sphere of diameter equal to half-mode wavelength, where the transfer function drops by a factor of 2.

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- **CDM subhalo profile** at a given mass and galactocentric radius: Erkal et al, 1606.04946

$$\left(\frac{dn}{dM}\right)_{\mathrm{CDM}} = c_0\left(\frac{M}{m_0}\right)^{-1.9}\exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha}-1\right]\right\}$$

Einasto profile

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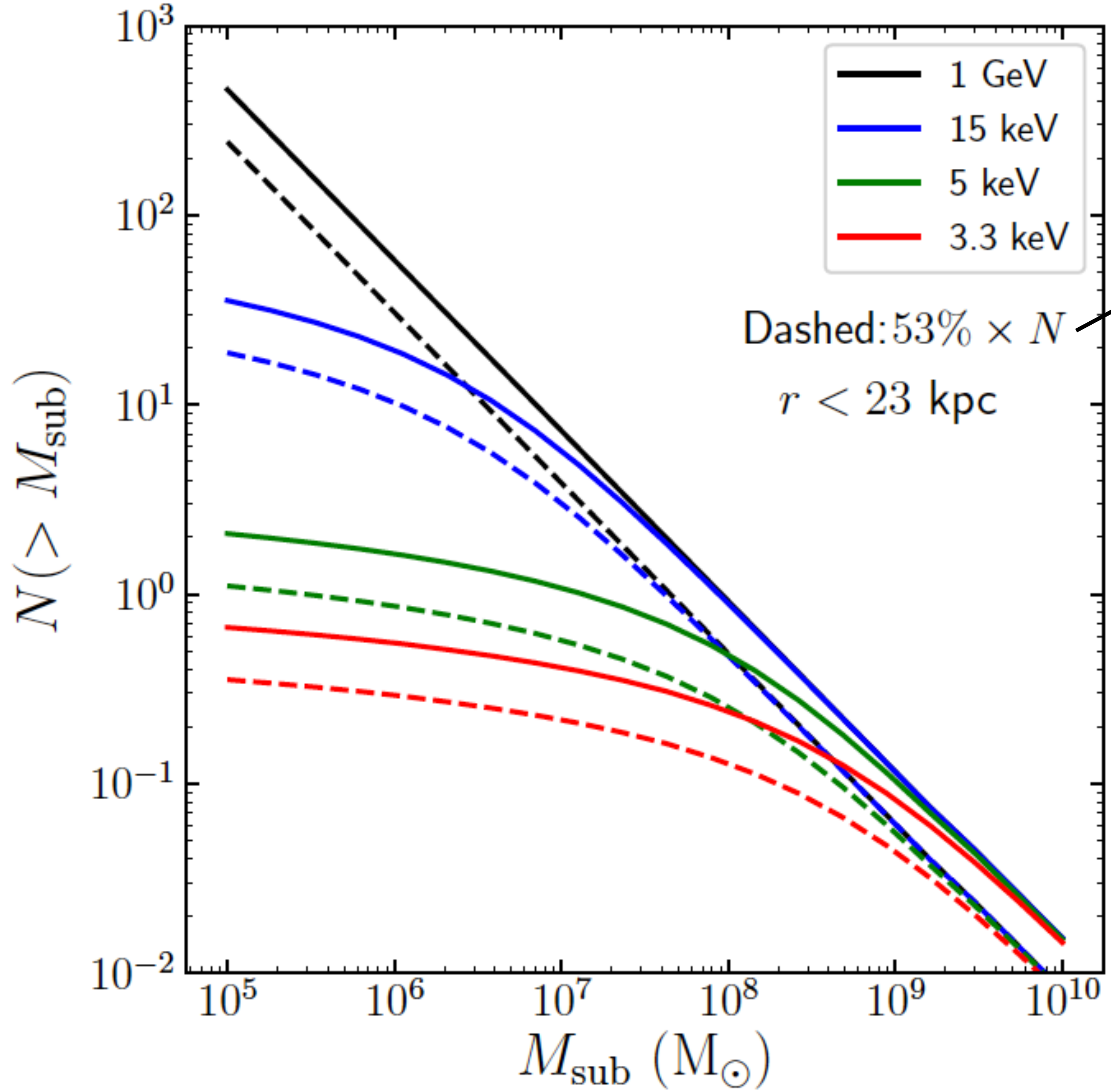
- Ignored evolution of the subhalo number density over the age of the stream. → Not expected to cause significant changes, since gaps fill up over time and very old gaps not visible today.

- *Baryonic effects* will tidally disrupt subhalos, and reduce their abundance by ~45-50% inside the orbit of Pal-5 and GD-1.

Sawala et al., 1609.01718

Cumulative number of subhalos



47% reduction included due to baryonic effects.

Generating a smooth stream

- Need a stream with minimal gap inducing perturbations from baryonic effects, such as the *Milky Way bar* and *giant molecular clouds*.

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- **GD-1** a good candidate:
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Amorisco et al, 1606.02715

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Generate a mock GD-1 stream:

- Tidal stream dynamics most simply described in ***action-angle coordinates***. Once a star is stripped from the progenitor:

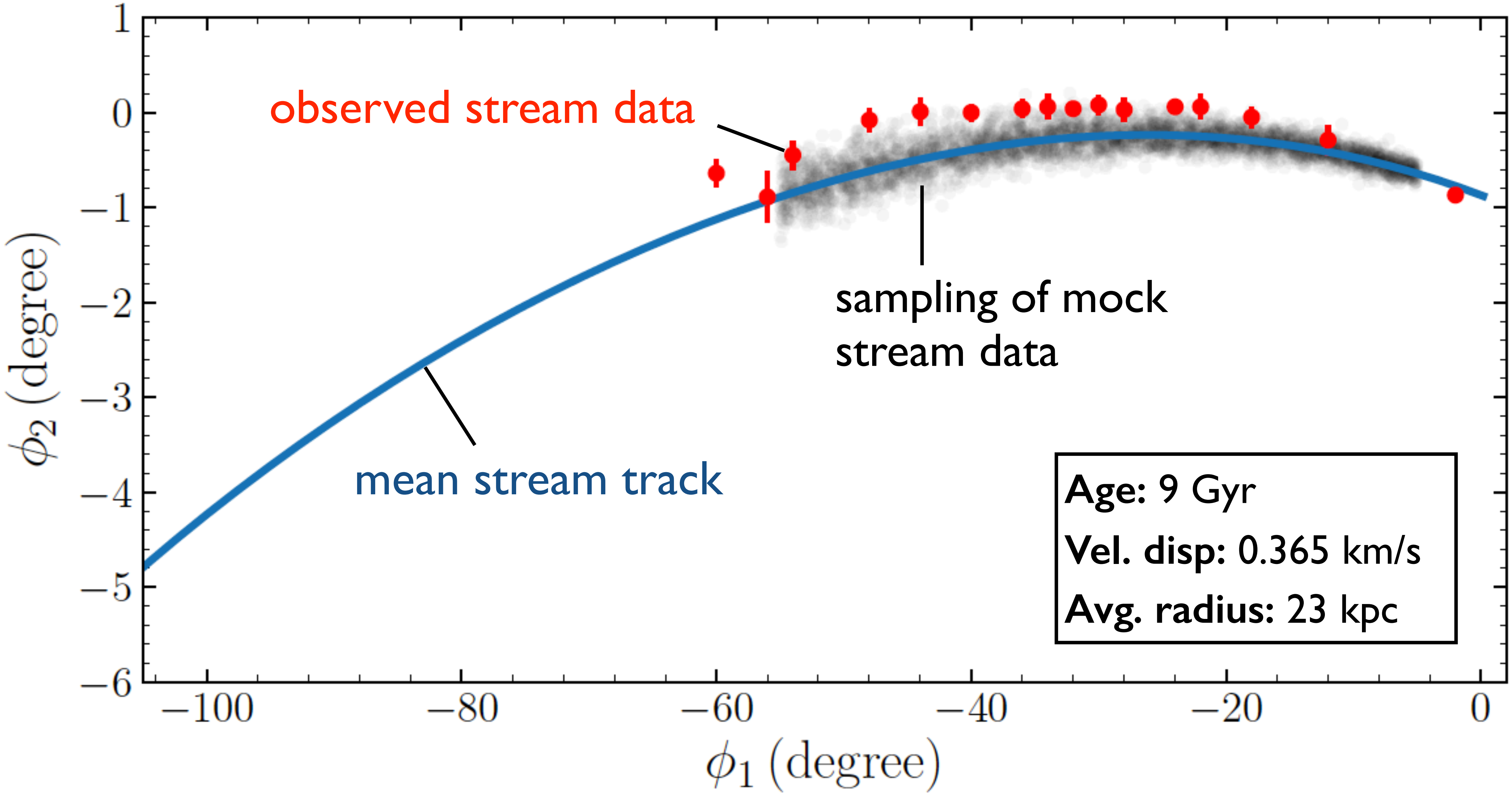
$$\boldsymbol{J} = \text{constant} \qquad \boldsymbol{\theta} = \boldsymbol{\Omega}\, t + \boldsymbol{\theta}(0)$$

↓ ($\boldsymbol{\Omega}$) orbital frequency

Bovy, 1401.2985, 1412.3451 (galpy code)

GD-1 stream model

- GD-1 stream model in sky coordinates:



Modeling stream-subhalo impacts

- **Impulse approximation:** subhalo-stream encounter modeled as an instantaneous velocity kick imparted to the stars in the stream at the point of closest approach. → transform to $(\mathbf{\Omega}, \boldsymbol{\theta})$ space.

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Before impact: $\boldsymbol{\Omega} = \boldsymbol{\Omega}_0 = \text{constant}$ $\quad(\boldsymbol{\Omega}_0, \boldsymbol{\theta}_0)$: at stripping time

$$\boldsymbol{\theta} = \boldsymbol{\Omega}_0 t + \boldsymbol{\theta}_0$$

After impact at t^g:

$$\boldsymbol{\Omega} = \boldsymbol{\Omega}_0 + \delta\boldsymbol{\Omega}^g = \text{constant}$$

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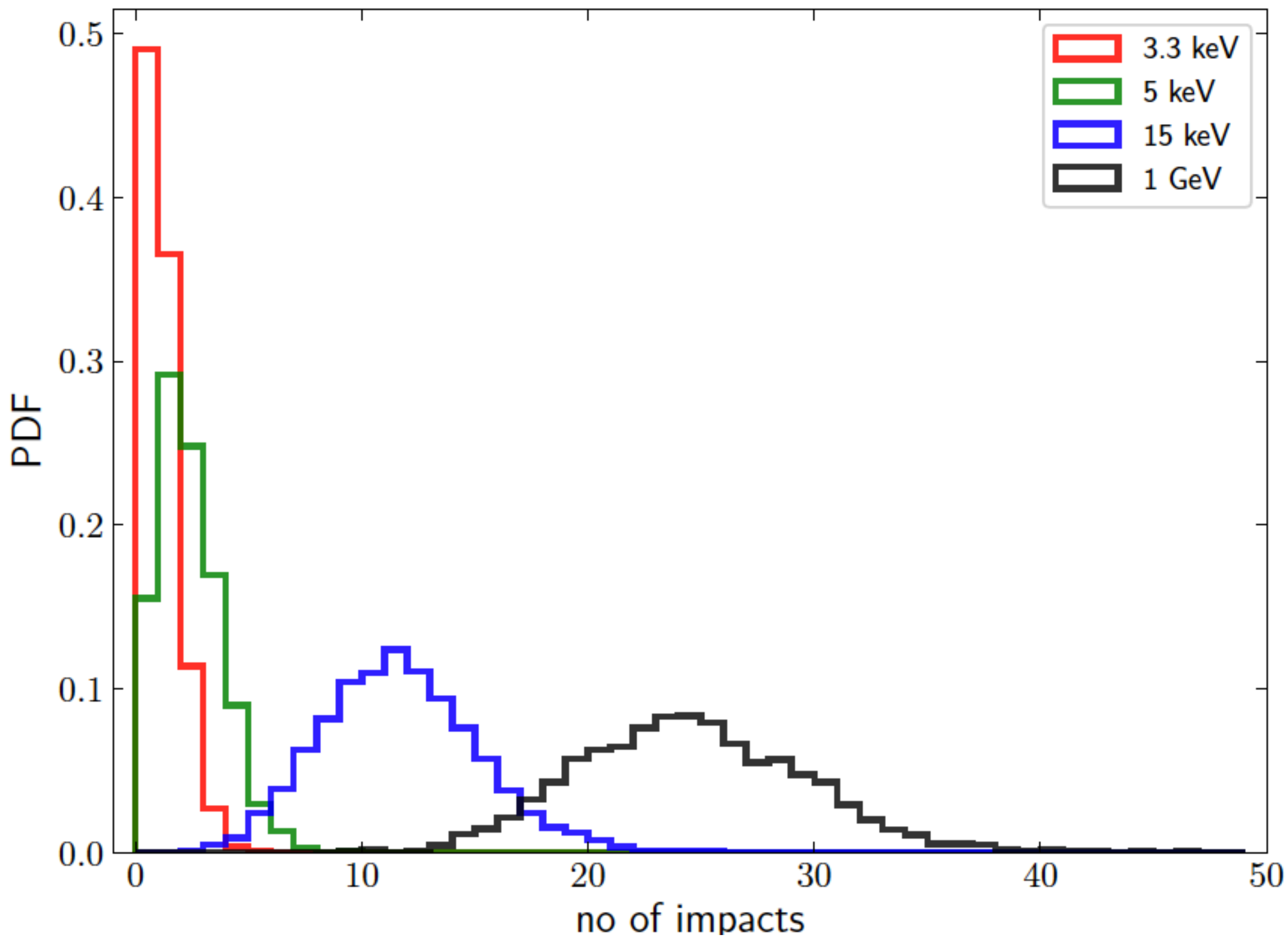
- Simulate the effect of multiple impacts of different masses at different times in the orbit and locations along the stream. → Statistical sampling of multiple impacts.

Bovy, Erkal, Sanders, 1606.03470

Expected number of impacts

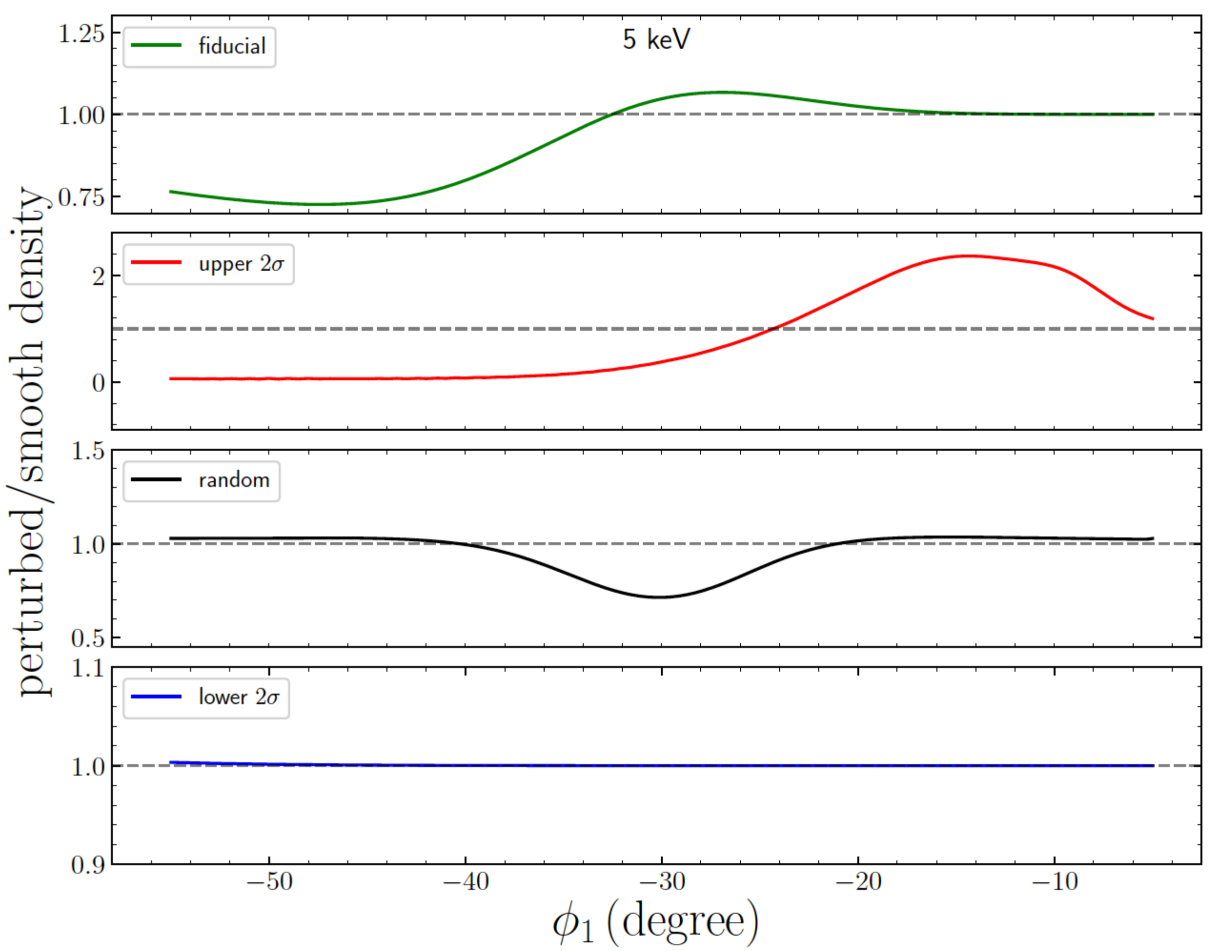
- PDF of the number of impacts that a GD-1 like stream had over 9 Gyr. Each PDF constructed out of 2100 simulations of GD-1.



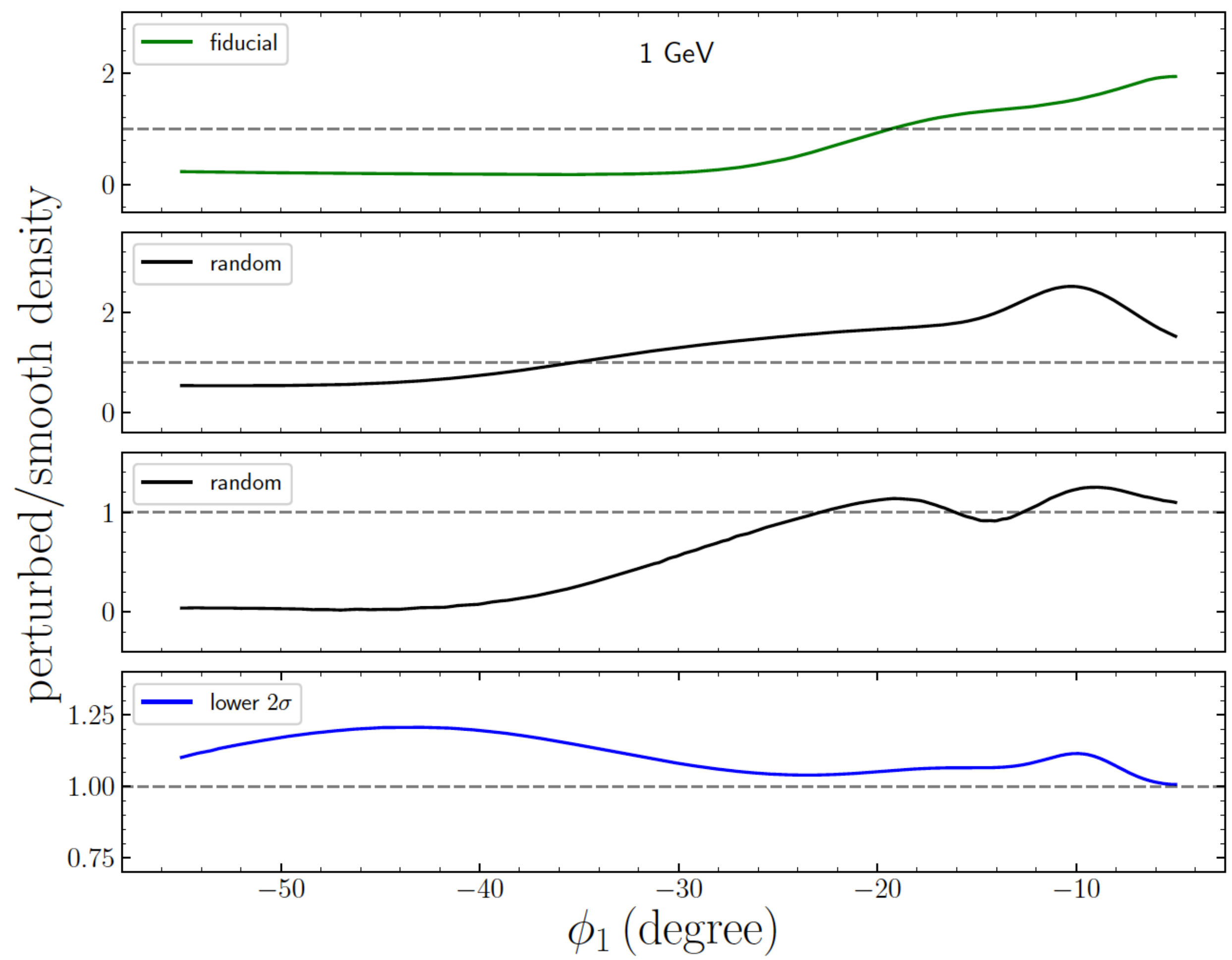
Density contrast

- Run 2100 simulations each for the **3.3 keV, 5 keV**, and **1 GeV** scenarios for a GD-1 like stream, considering subhalo impacts in the mass range of [10^6 - 10^9] M_{sun}.
- Angular extent of the stream along Φ_2 is small. ➡ Analyze the stream as a function of Φ_1.

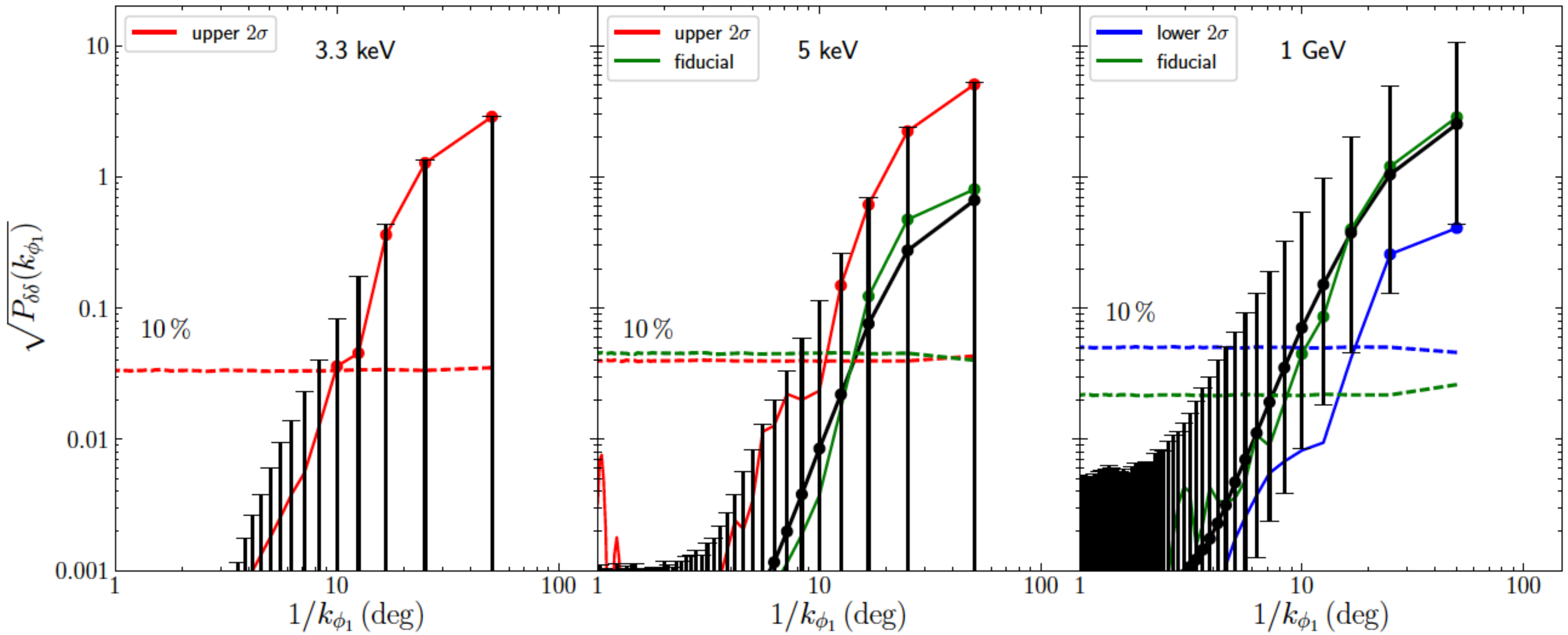
5 keV



1 GeV



Power spectrum of density contrast



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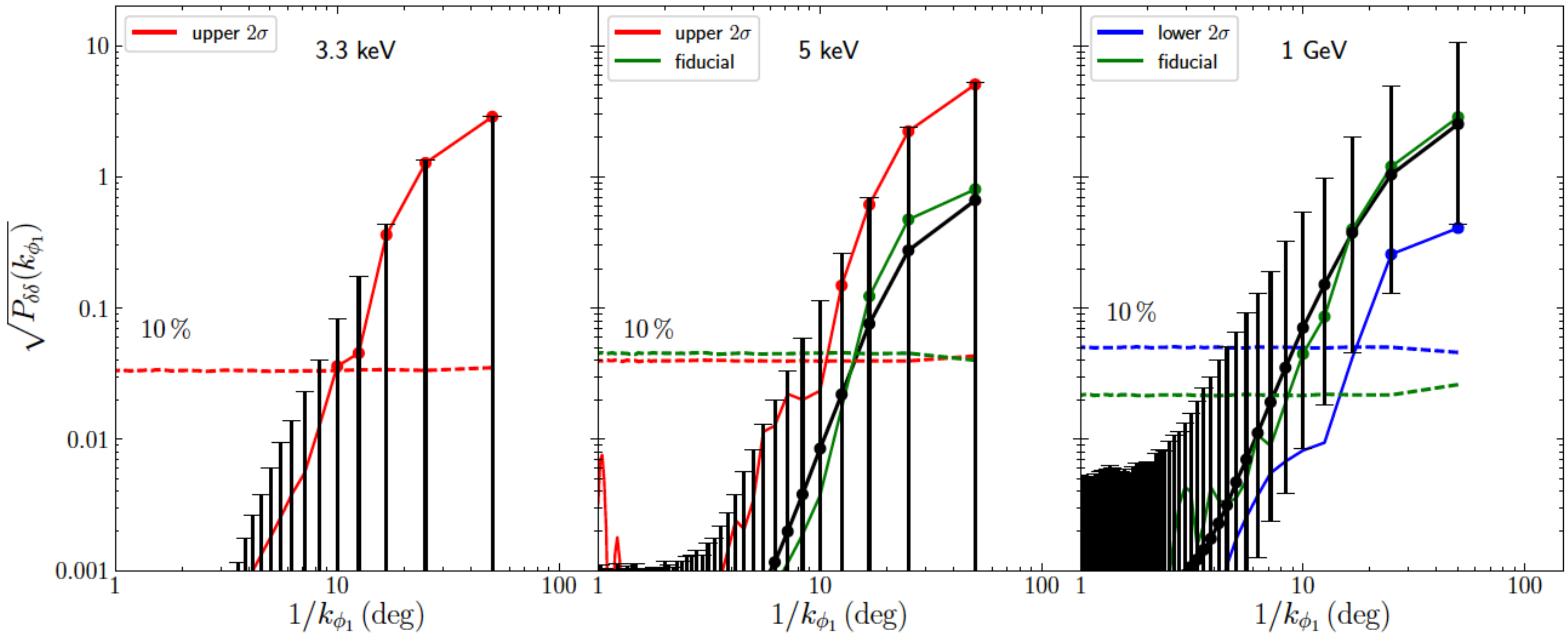
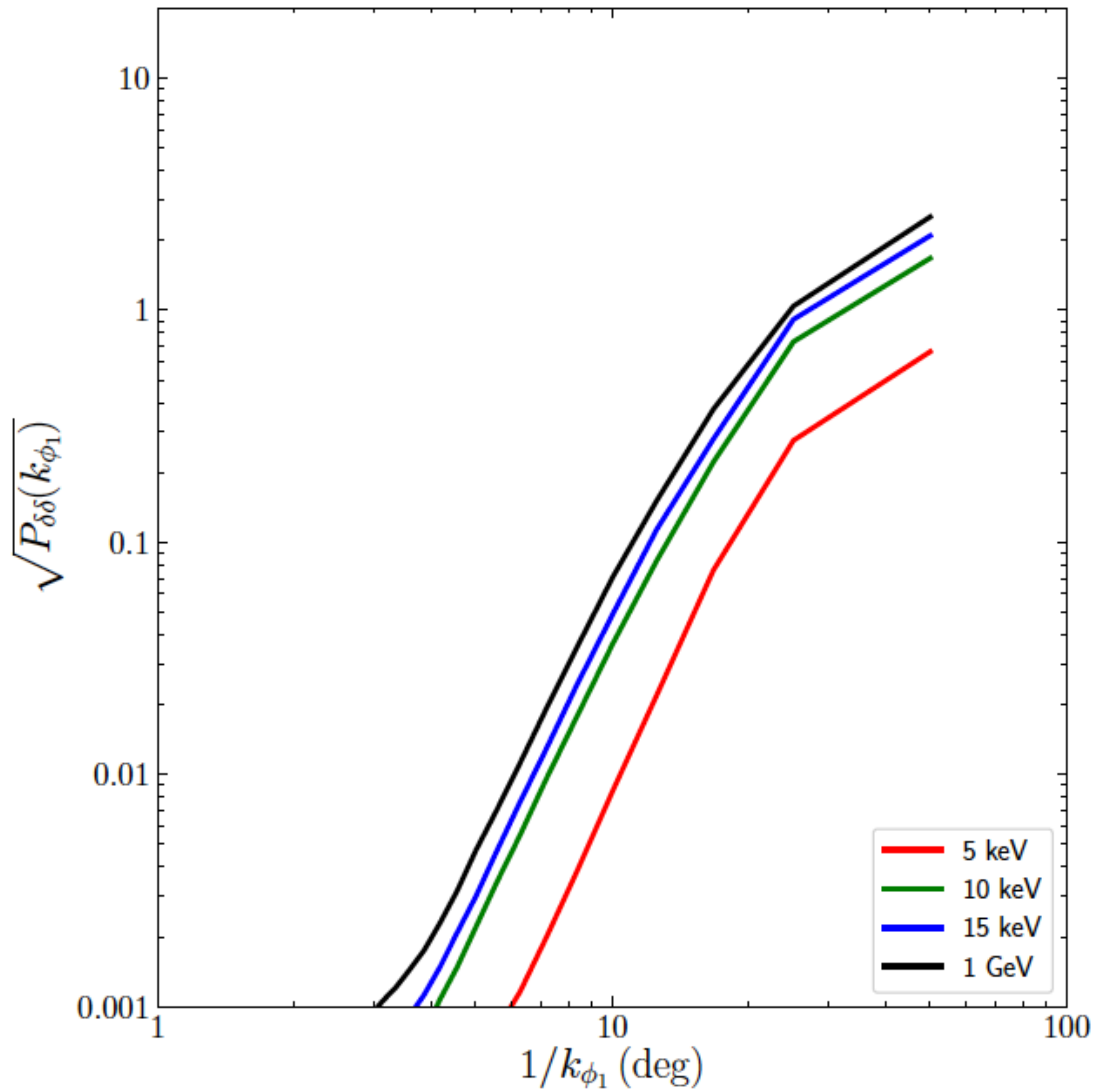


- Large dispersion in the power spectra due to the range of possible ways the impacts can occur.
- Higher rates of impacts in 1 GeV case. → Larger density fluctuations. → More power at the largest scales.
- More low mass subhalos in 1 GeV case. → Density fluctuations on smaller scales. → More power at smaller scales.

Inferring the DM particle mass

- The median power spectrum converges for cases with WDM mass greater than ~15 keV. ➡ Indistinguishable from CDM.



Inferring the DM particle mass

- Construct an approximate posterior PDF of the mass of the DM particle using **Approximate Bayesian Computation (ABC)**.
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Approximate posterior PDF of the parameters in the problem is constructed by comparing the outcome of simulator outputs with observed data.

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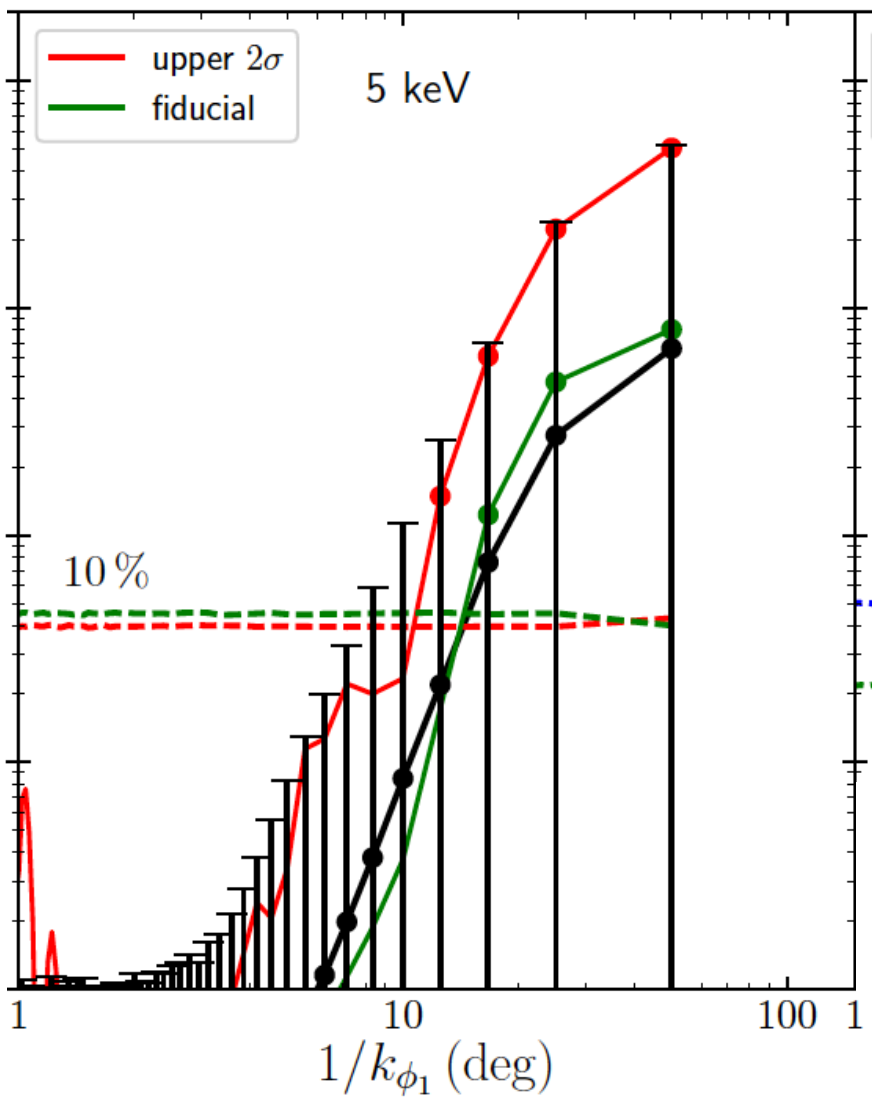
- Fiducial cases as *mock observed data.*
- Randomly draw the DM particle mass from a uniform prior distribution in range [0.1,16] keV.



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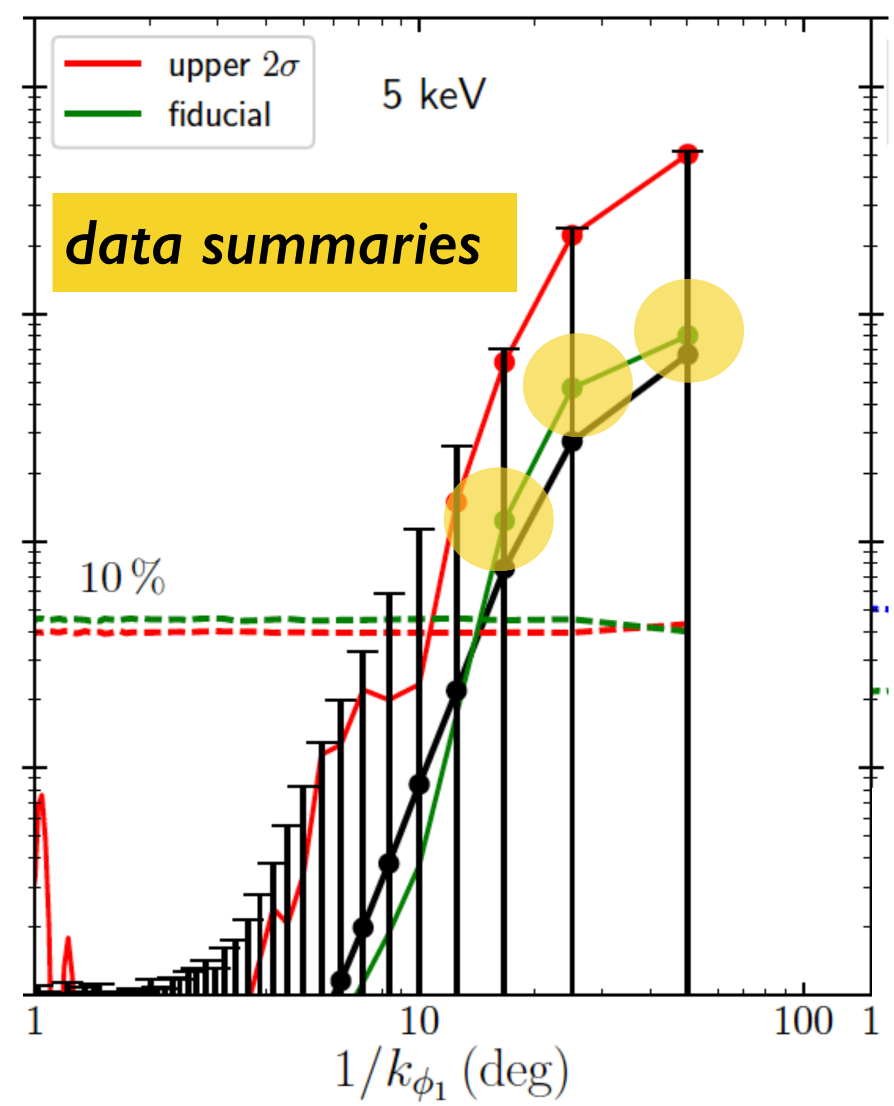
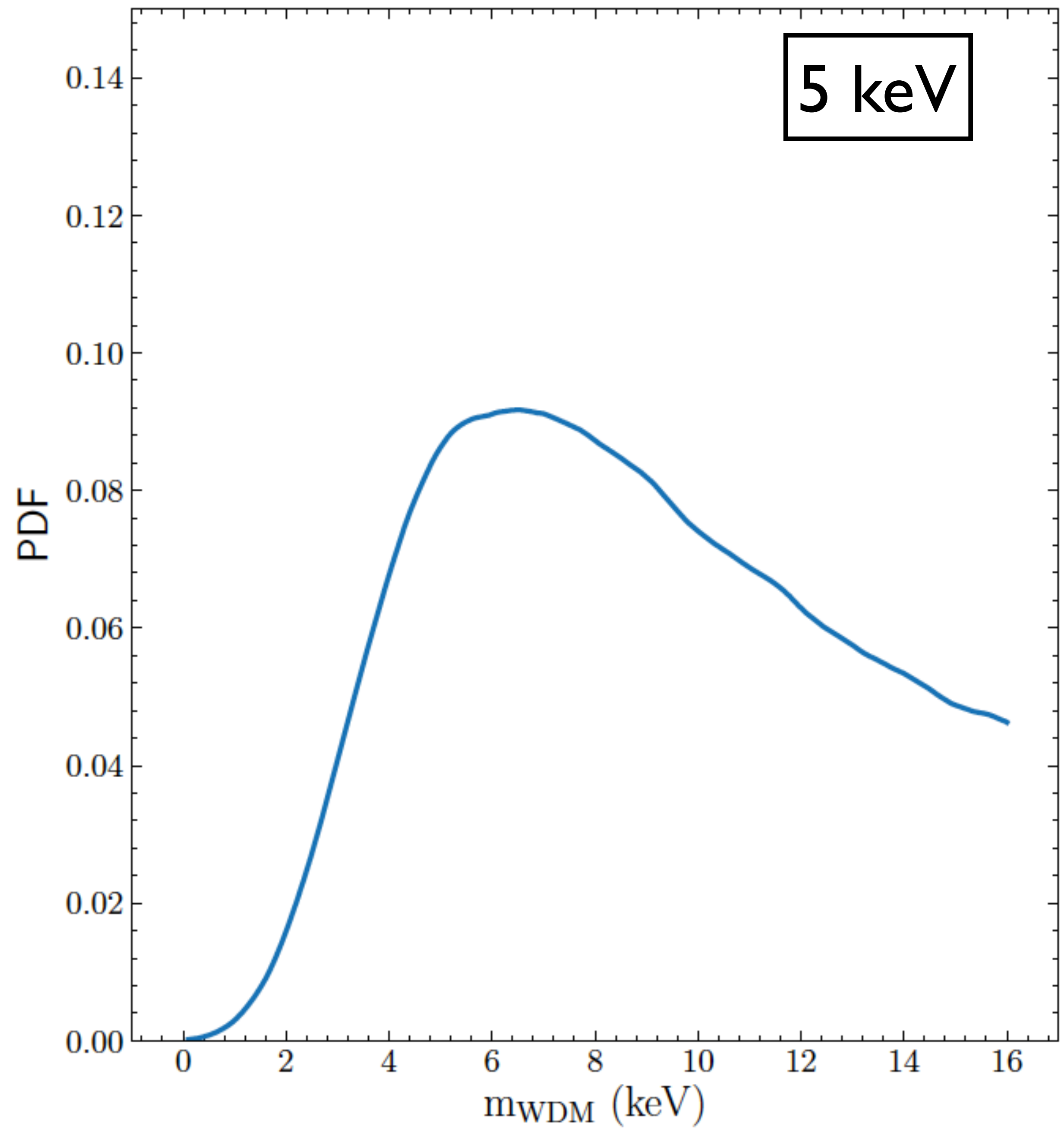
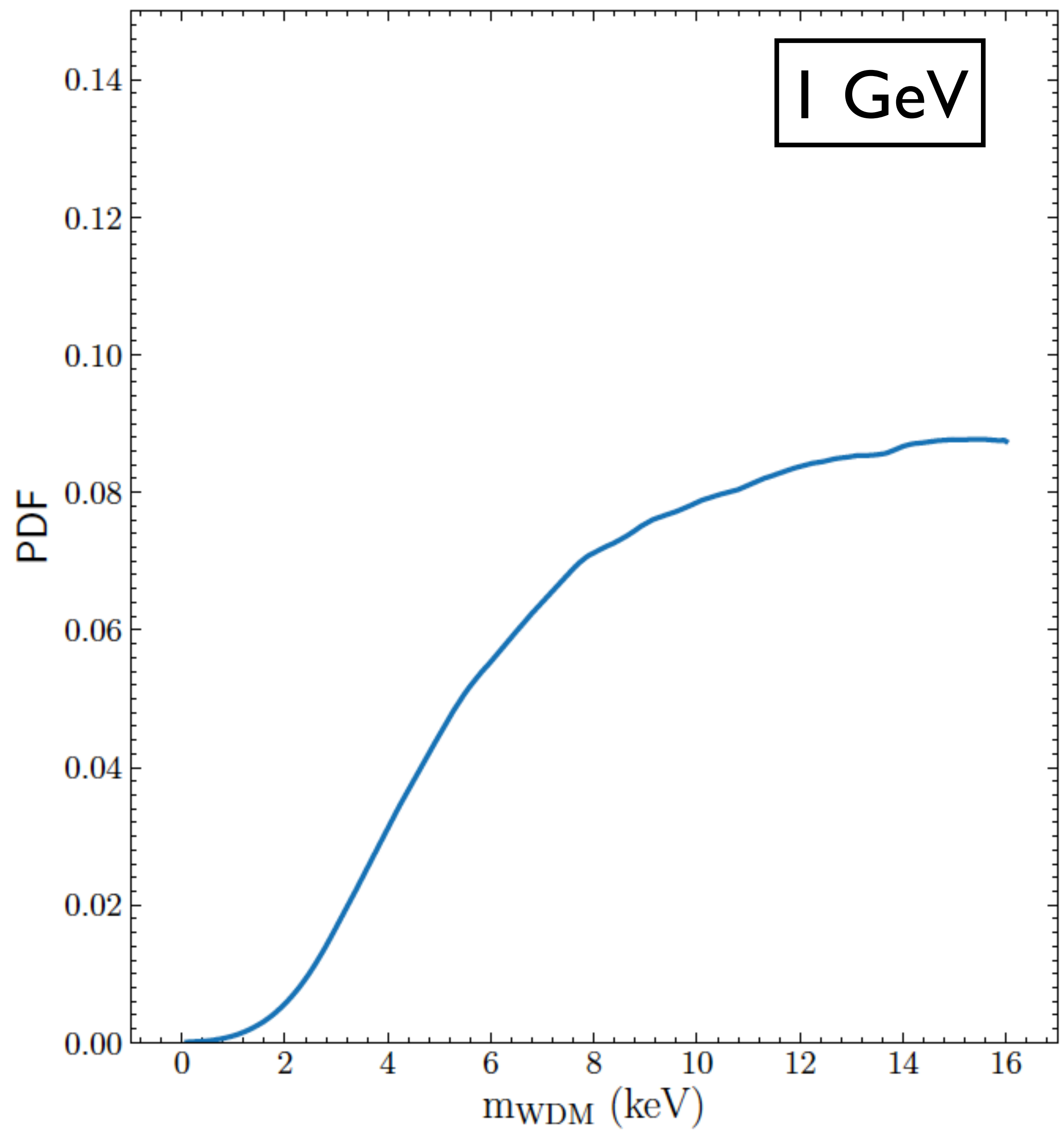


- Fiducial cases as *mock observed data.*
- Randomly draw the DM particle mass from a uniform prior distribution in range [0.1,16] keV.
- ABC accepts those simulations which are within some tolerance of the *data summaries.*

Posterior PDF of DM particle mass



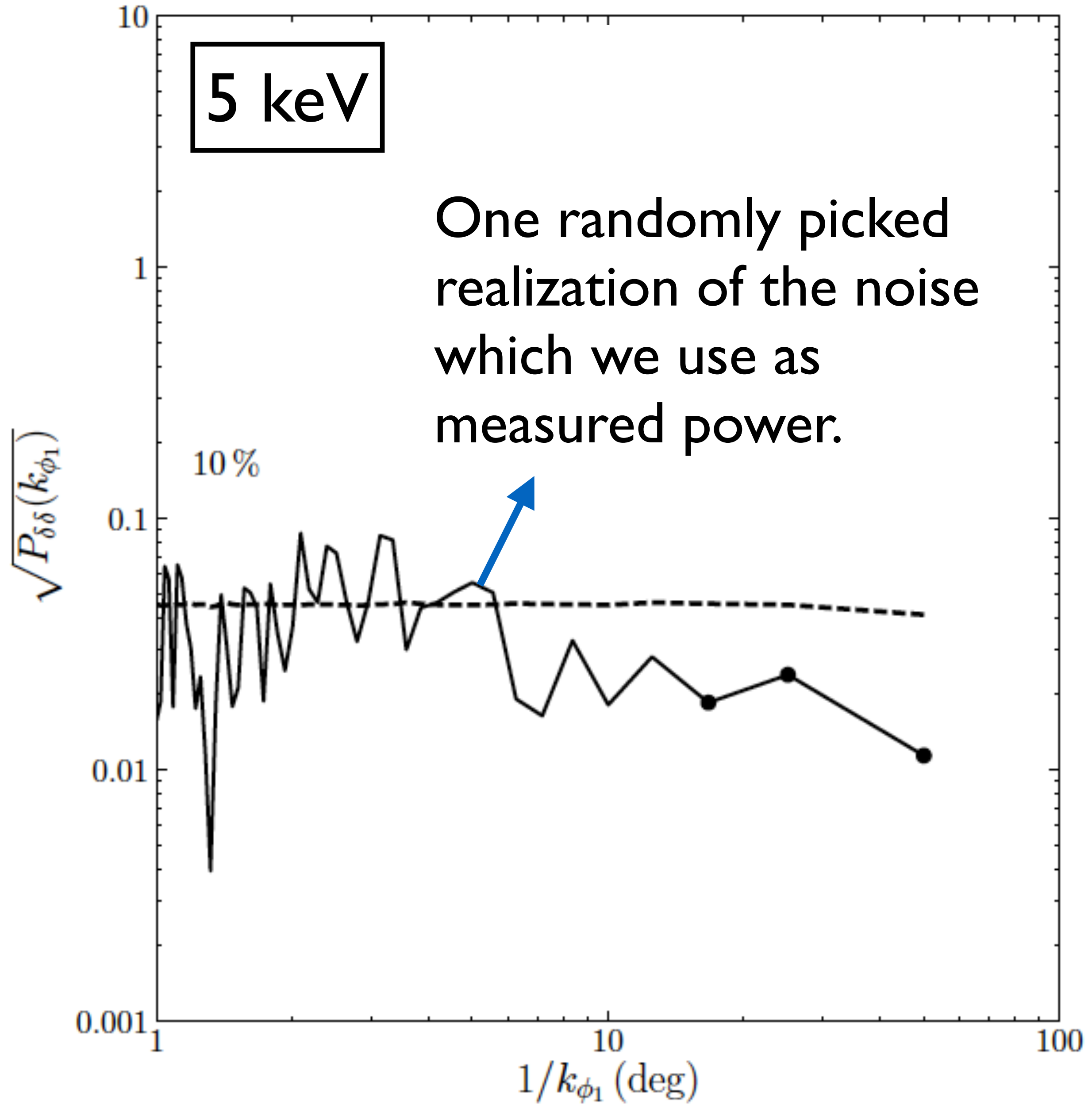


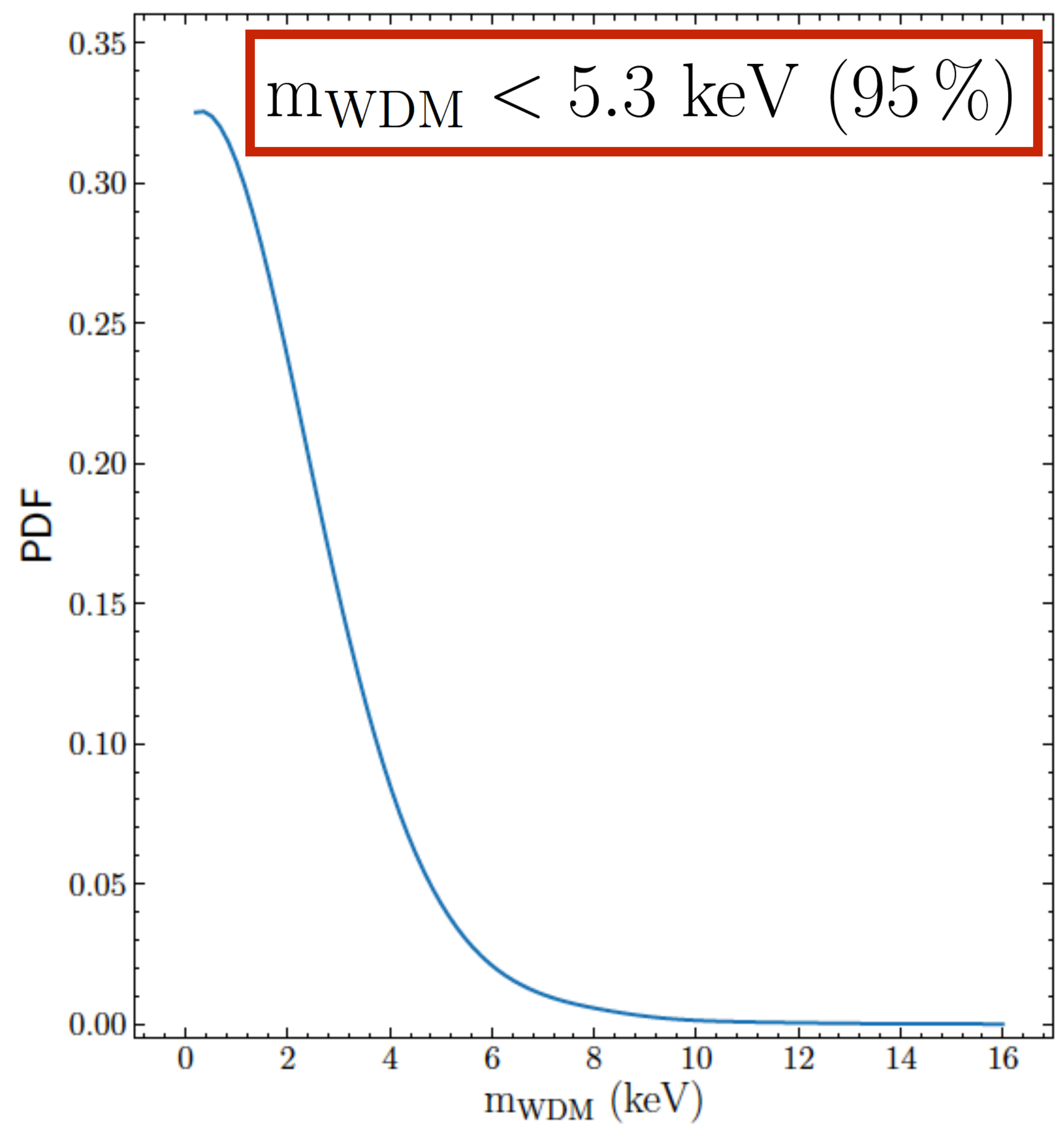
$$m_{\mathrm{WDM}} = 5.9^{+5.9}_{-2.1}\ \mathrm{keV}\ (68\,\%)$$
$$m_{\mathrm{WDM}} < 15.0\ \mathrm{keV}\ (95\,\%)$$

$$m_{\mathrm{WDM}} > 4.3\ \mathrm{keV}\ (95\,\%)$$

Below the noise level (WDM)

The case where the measured power is dominated by noise:





- ABC accepts any simulations whose power is below the noise floor.

Risks of using one stream

Outlier cases: stream-subhalo interactions resulting in a power spectrum very different from the median case. → ***incorrect predictions for the DM mass.***

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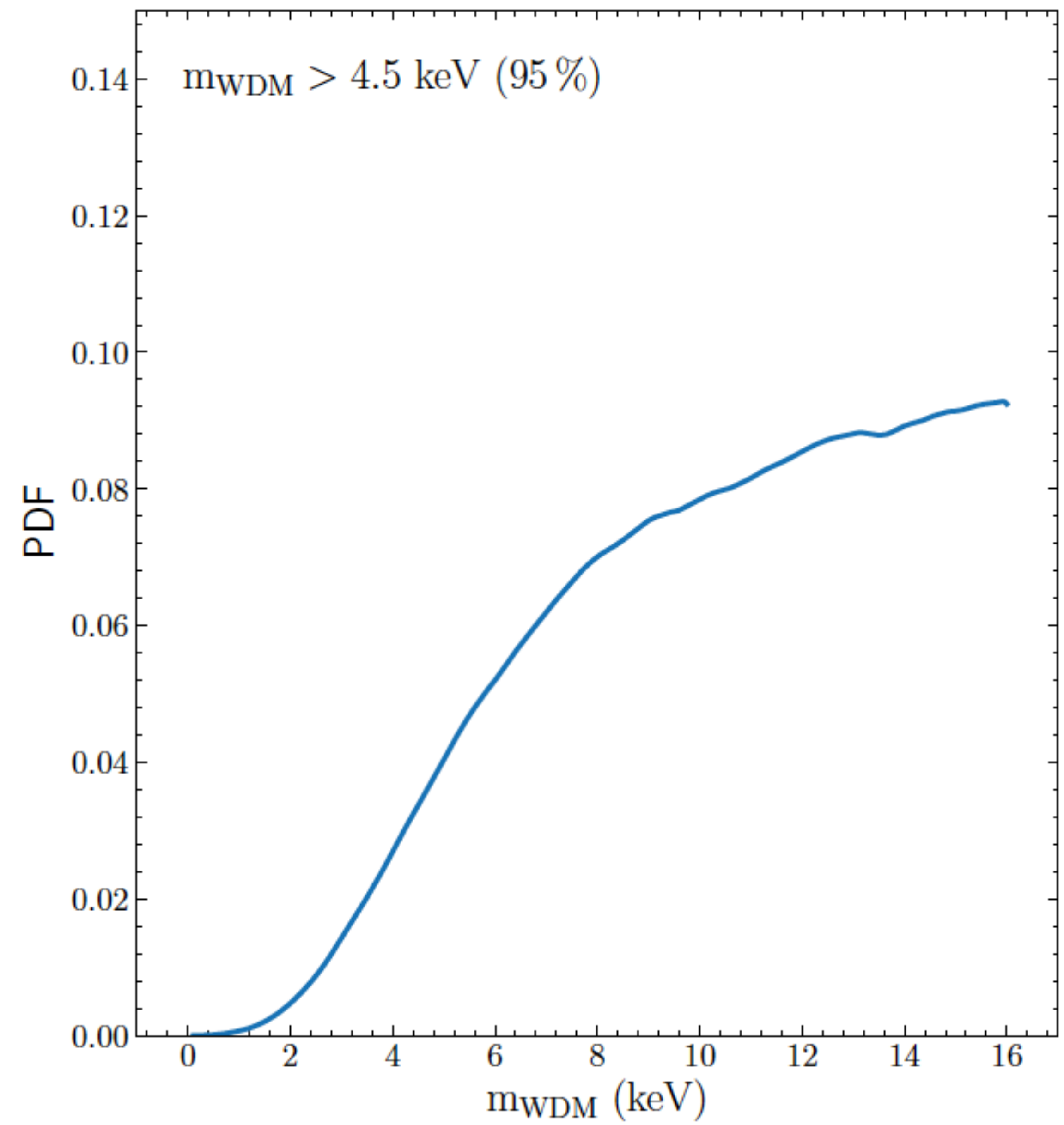
Example 1: 3.3 keV, power spectrum close to the **upper** 2σ bound as mock data.

$$m_{\mathrm{WDM}} > 4.5\ \mathrm{keV}\ (95\,\%)$$



Risks of using one stream

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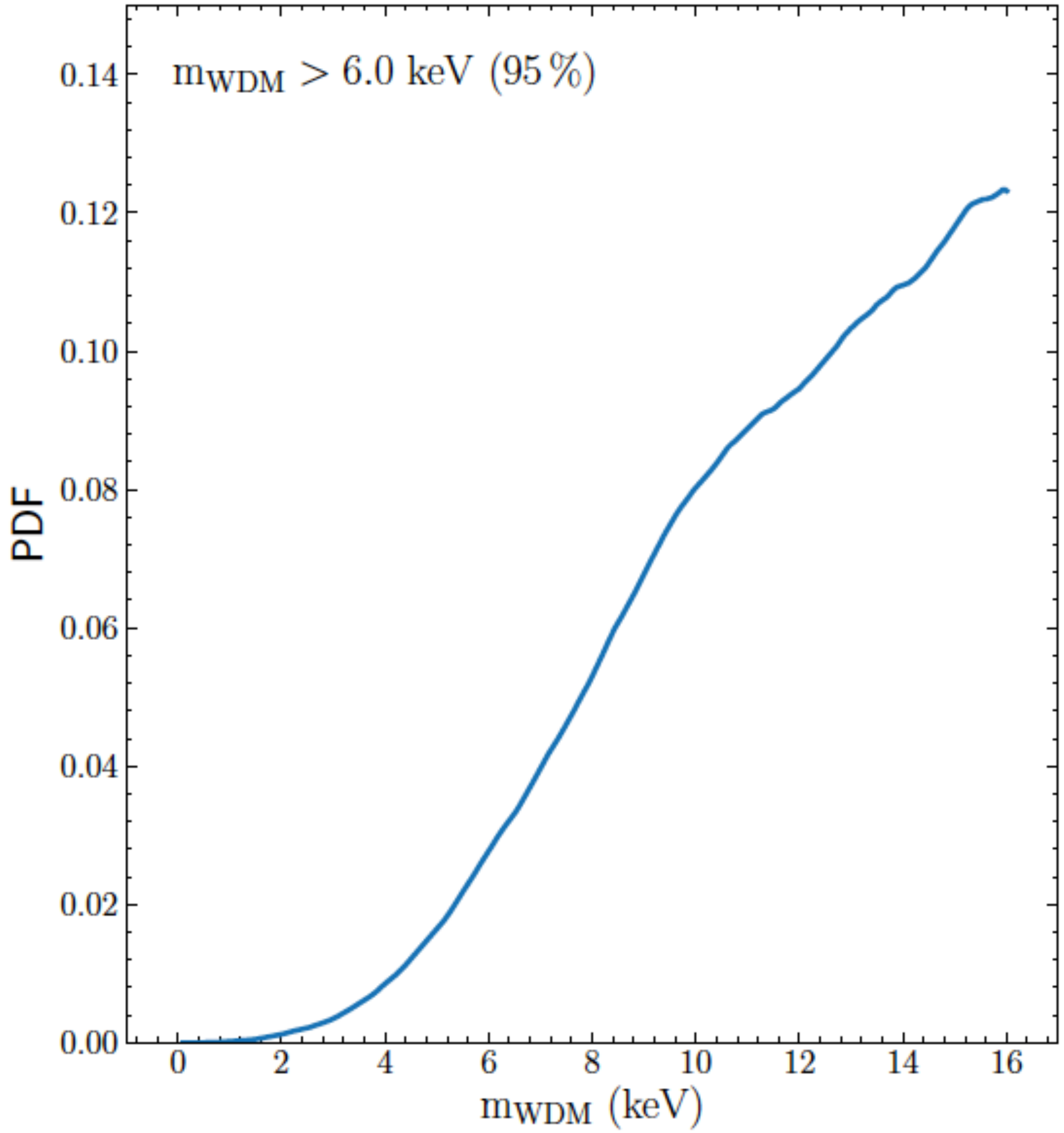
Example 2: 5 keV, power spectrum close to the **upper** 2σ bound as mock data.

$$m_{\rm WDM} > 6.0\ {\rm keV}\ (95\,\%)$$



Risks of using one stream

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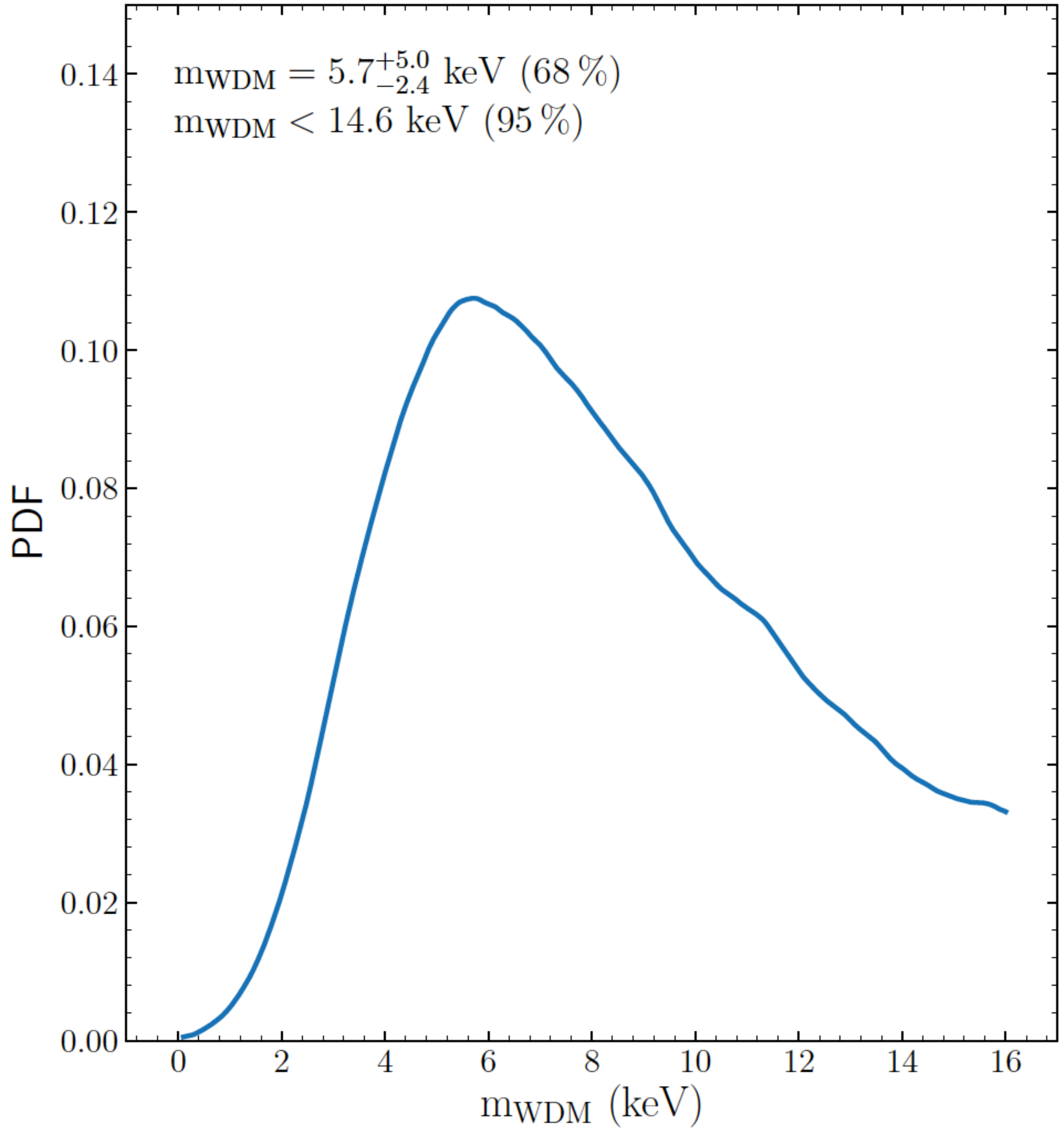
Example 3: 1 GeV, power spectrum close to the **lower** 2σ bound as mock data.

$$m_{\rm WDM} = 5.7^{+5.0}_{-2.4}\ {\rm keV}\ (68\,\%)$$
$$m_{\rm WDM} < 14.6\ {\rm keV}\ (95\,\%)$$



Summary

- Presented a method to probe the particle nature of DM by analyzing the statistical properties of density fluctuations in a stellar stream due to subhalo impacts.

- Used an ABC technique to perform rigorous inference on the dark matter mass using mock streams.

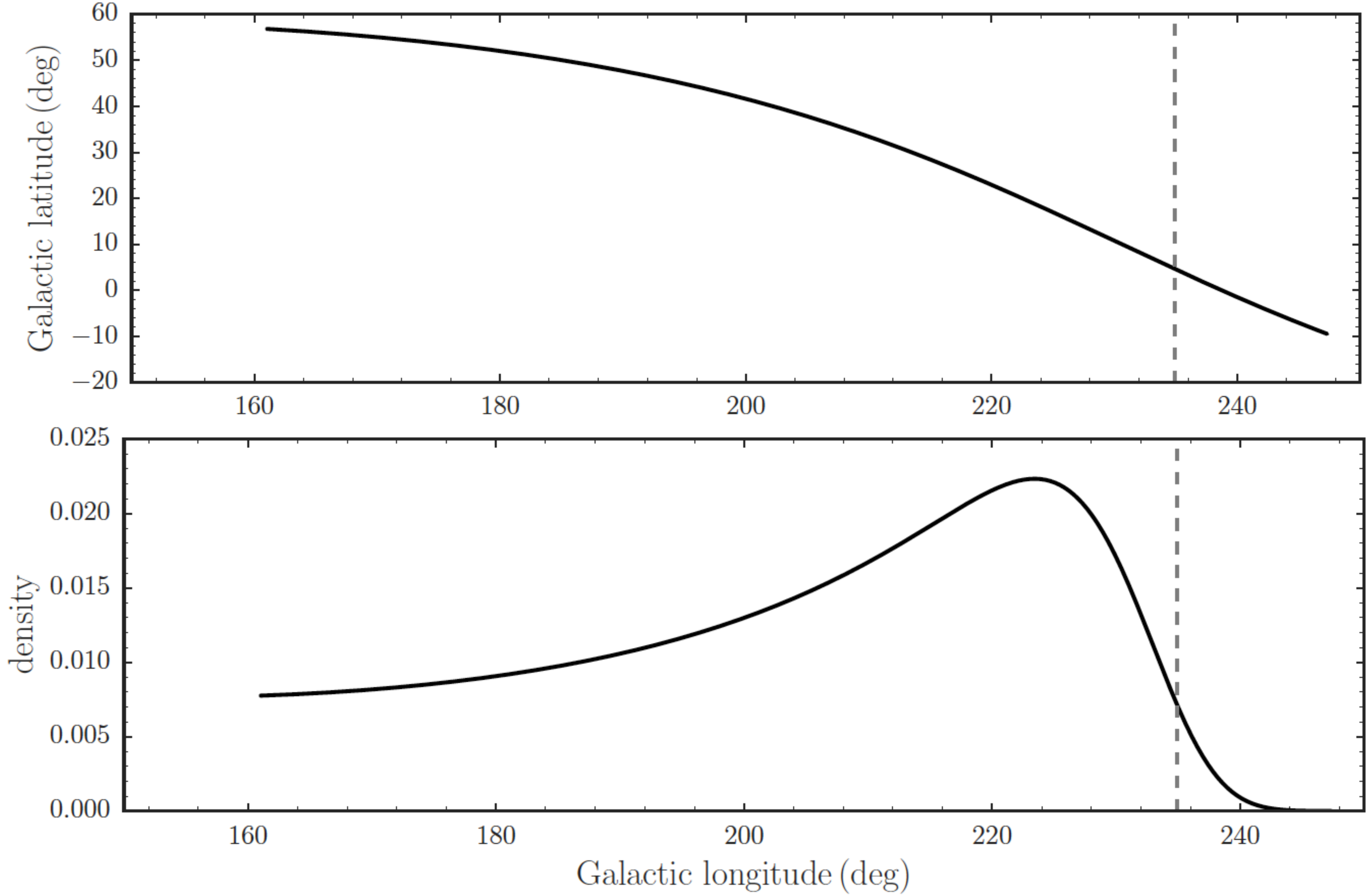
  - If intrinsic power of stream density is *greater* than the noise: can distinguish CDM from WDM, and also constrain the WDM mass if it is a few keV.

  - If intrinsic power of stream density is *less* than the noise: can obtain an upper limit on the mass of WDM.

- Outlier cases can limit our method's ability to distinguish between WDM and CDM. → *Need to use multiple streams.*

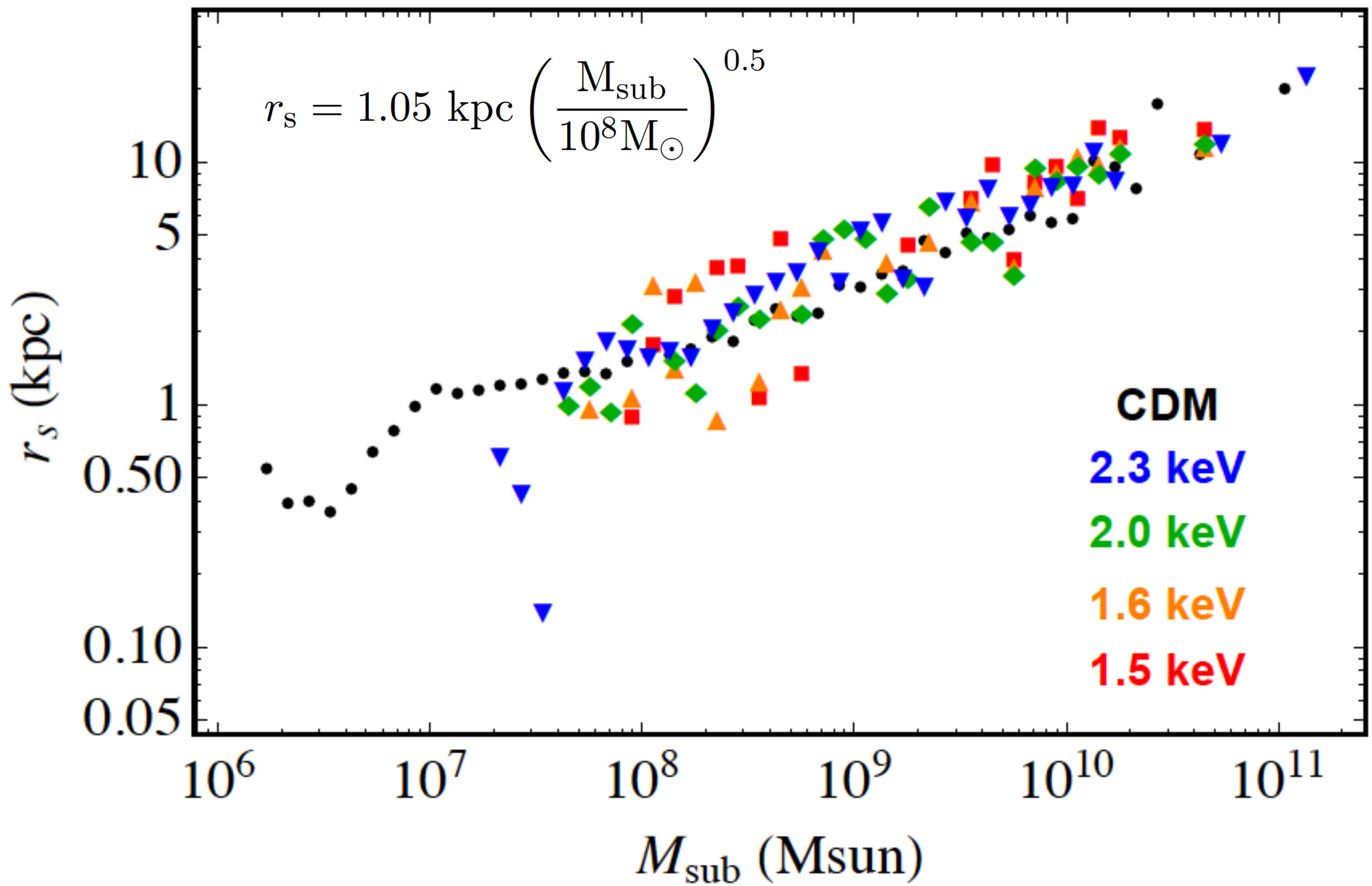
Backup Slides

Mock GD-1 stream



Bovy, Erkal, Sanders, 1606.03470

Scale radius of WDM subhalos



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