Distinguishing between WDM and CDM by studying the gap power spectrum of stellar streams

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NFC with the DES's DR1 and beyond

Dark matter subhalos : from “light” to dark

- In the ΛCDM framework, hierarchical structure formation predicts a dark matter halo containing a Milky way sized galaxy should have hundreds of thousands of DM subhalos, some as massive as 10^9 Msun.

- Subhalos more massive than 10^9 Msun are able to initiate star formation, and manifest themselves as dwarf galaxies.

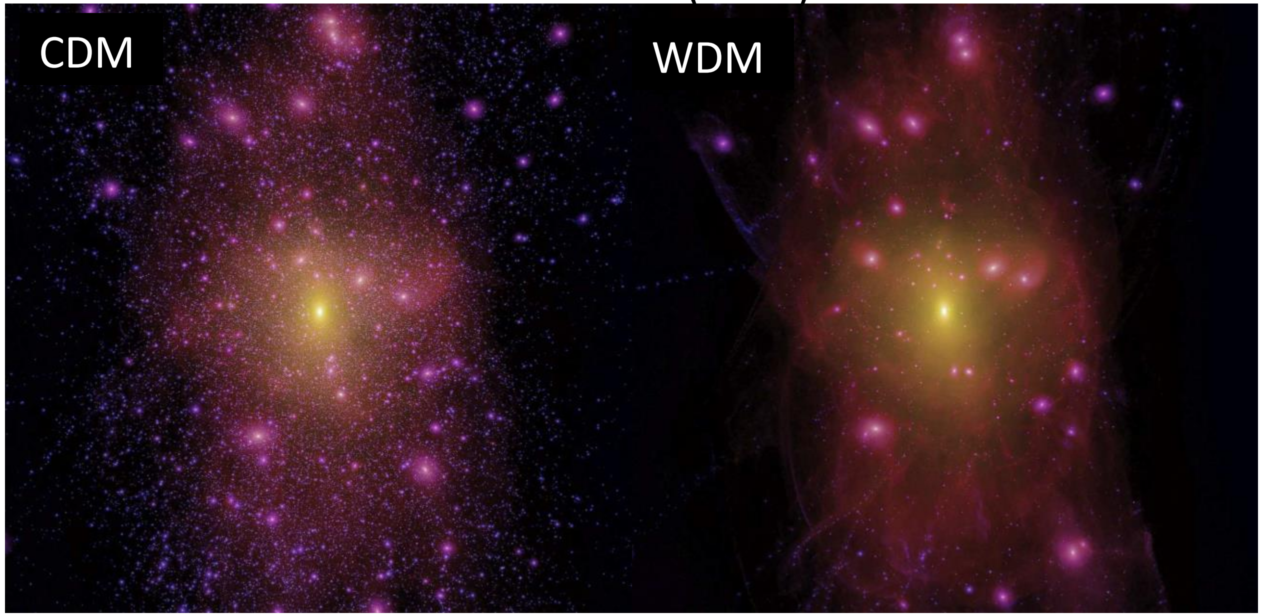
- Subhalos less massive remain devoid of stars and therefore are undetected.

- Detecting these low mass subhalos will give crucial insight on the particle nature of dark matter.

CDM vs. WDM

- WDM have higher velocity dispersion compared to CDM which prevents structure formation below a certain scale.
- From combined Ly-α power spectrum (BOSS-SDSS-III + VLT/XSHOOTER + HIRES/MIKE) $\boldsymbol{m_\chi \gtrsim 4.65}$ **keV** at 2σ (Yeche et al (2017))

Lovell et al (2014)



Modeling thermal WDM

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

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

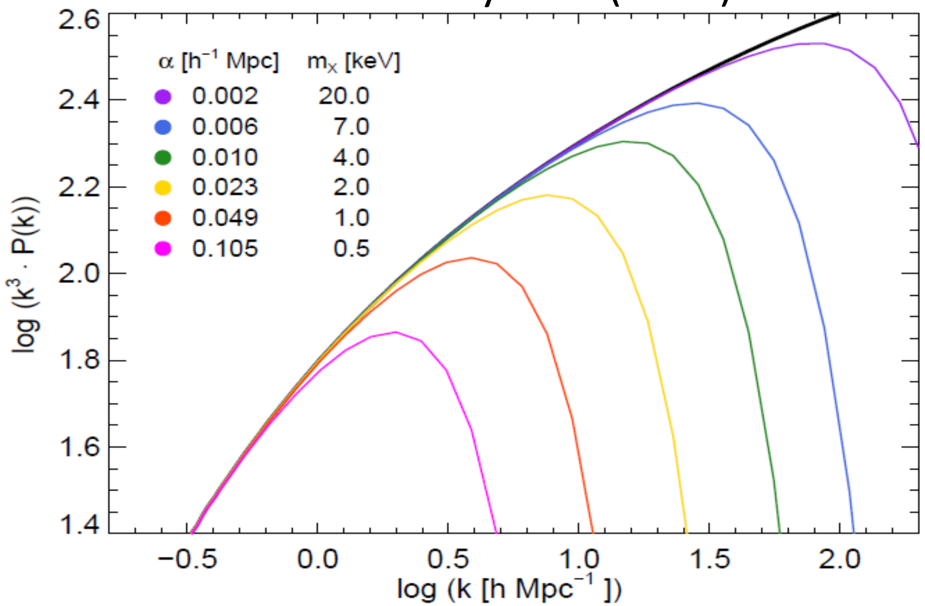
Bode et al (2001), using P3M code, υ =1.12 (fitting parameter)

The cutoff scale α depends only on the mass of the WDM particle

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

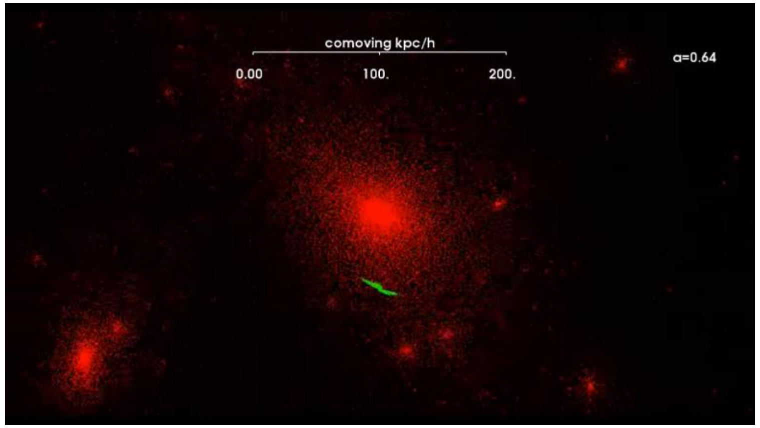
This can be generalized to sterile neutrinos by including the lepton asymmetry parameter.

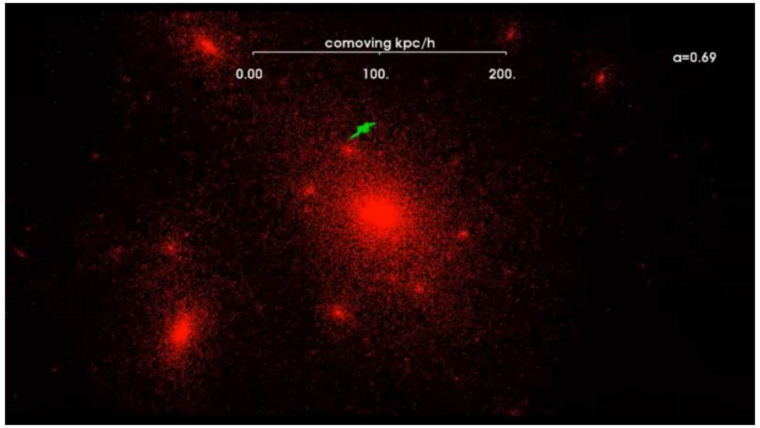
Kennedy et al (2014)

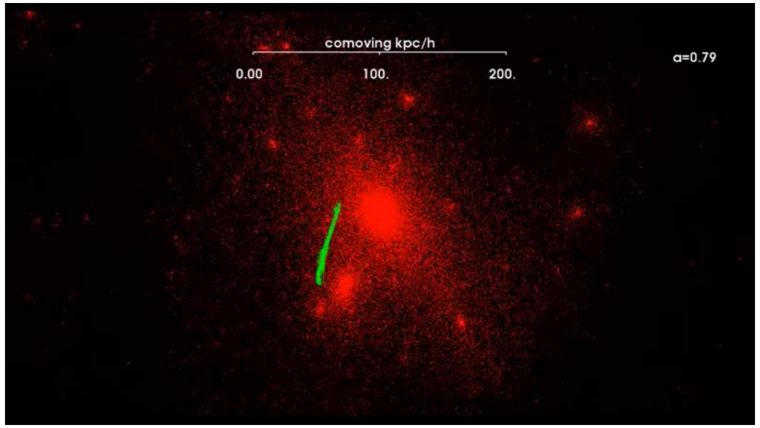


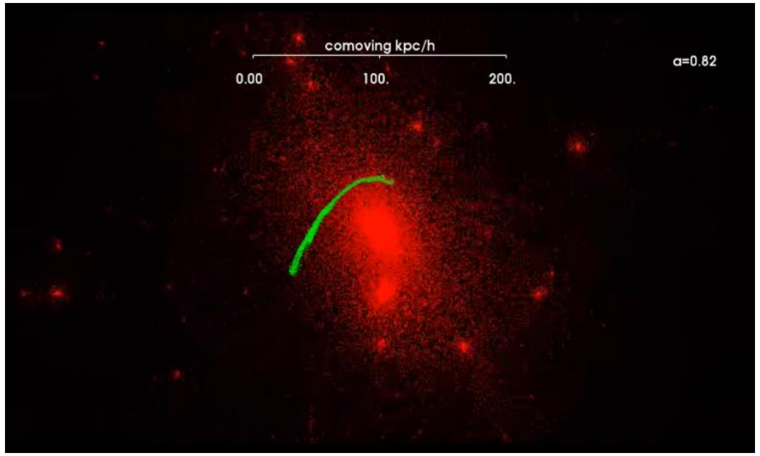
Stellar streams

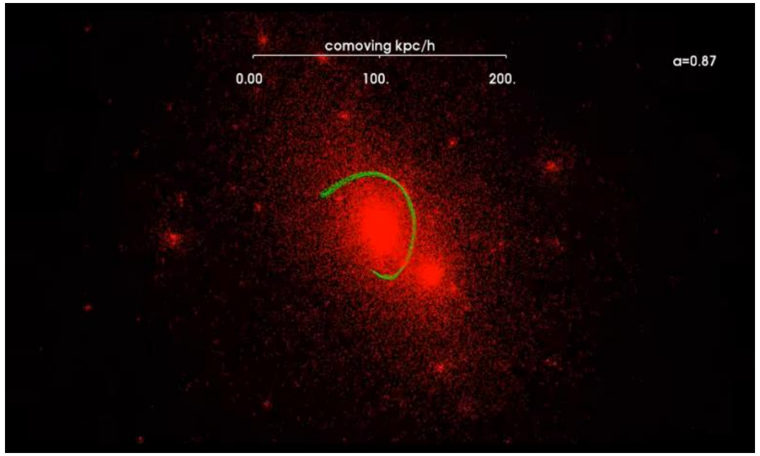
- Gravitational potential of the Milky way galaxy can tidally disrupt near by globular clusters and dwarf galaxies stretching them along their orbit, resulting in a stream of stars – stellar streams.









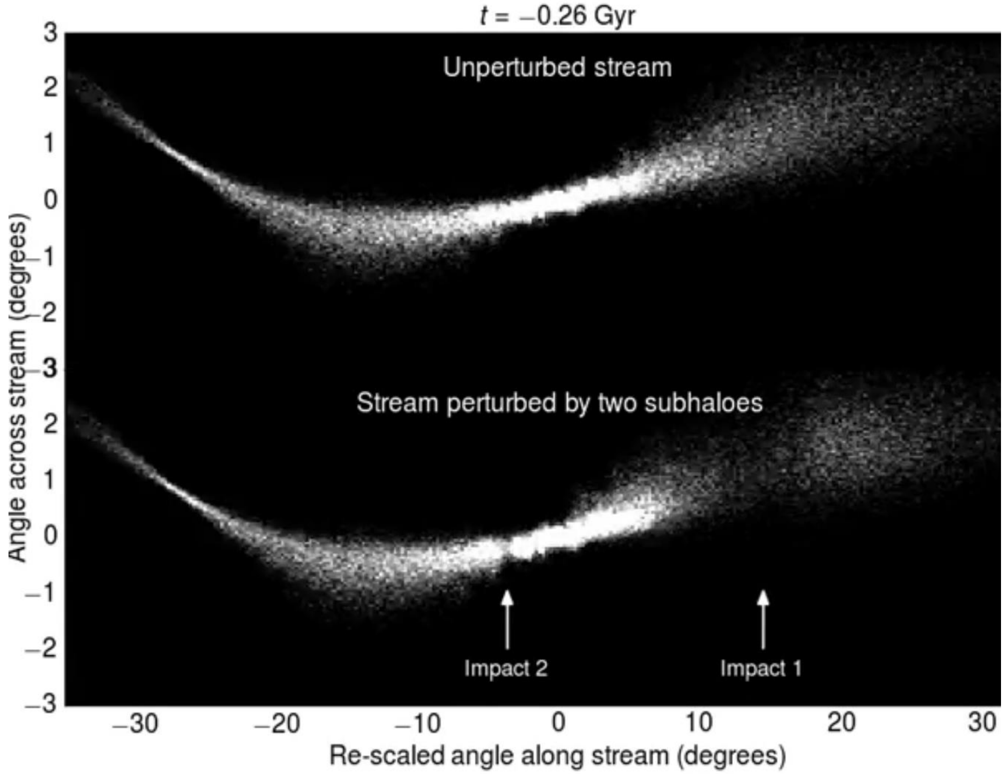


Snapshots from animation done by Denis Erkal

Probing DM substructures using stellar streams

- A stellar stream will encounter several DM subhalos during its dynamical age.
- A cold stellar stream has largely a uniform stellar density along its length. A flyby subhalo will impart velocity kicks to the stars near the point of closest approach. This will change their orbital period. This results in a "gap" in the stellar stream- a region of low stellar density.
- The gap structure depends mainly on :

    1. $M_{subhalo}$
    2. α (angle of impact)
    3. r_s (scale radius of the subhalo)
    4. v (velocity of flyby)
    5. b (impact parameter)
    6. t (time of impact).



Snapshots from animation done by Denis Erkal

Simulating cold stellar streams and DM subhalo encounters

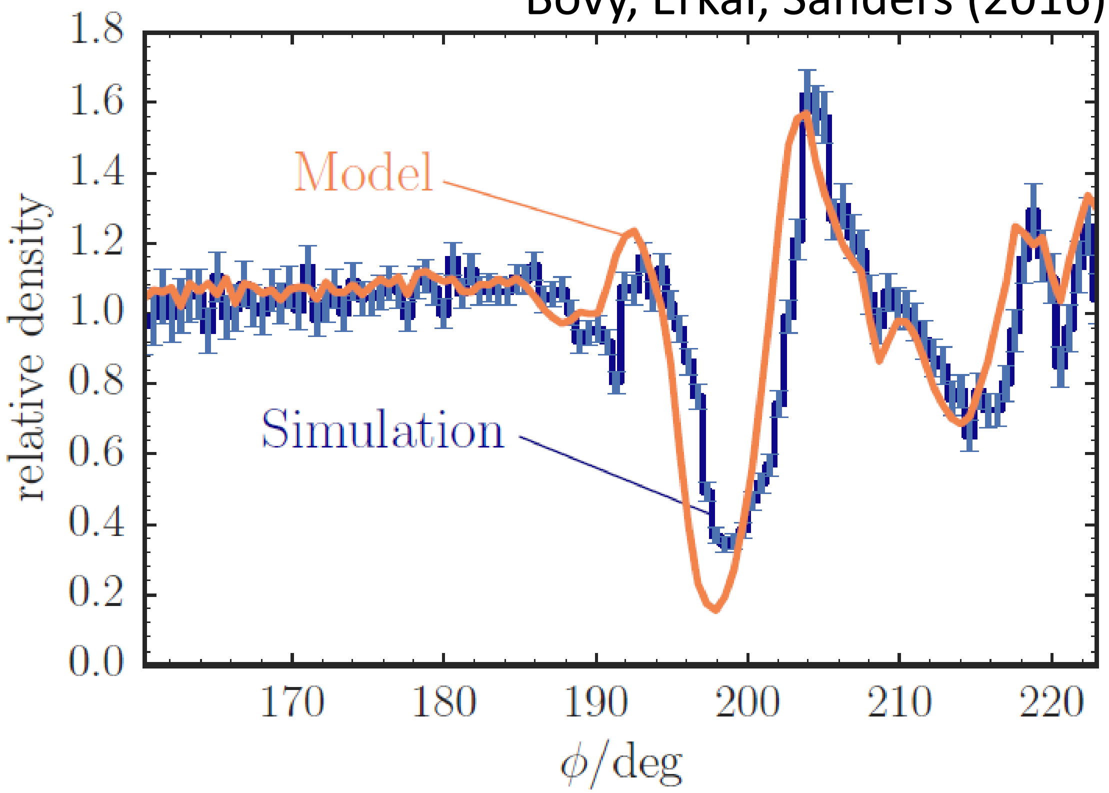
- The action-angle coordinates provide the simplest description of the evolution and dynamics of a stellar stream (Helmi & White 1999; Tremaine 1999).
- Recent advances by Bovy 2014; Sanders & Binney 2014; Binney & McMillan 2016 in computing the transformation between configuration space and action-angle space for realistic potentials have made action-angle modeling of tidal streams practical.
- Bovy (2014) and Sanders (2014) have showed that the structure of an unperturbed stellar stream as well as the effects of subhalo encounters can be accurately and efficiently modeled in the space of **orbital frequencies** ($\Omega = \partial H/\partial J$) and angles space.

Stream simulations in (Ω, θ) vs. N-body

- Density perturbation due to 24 subhalo impacts with masses between $10^6\, M_\odot$ and $10^8\, M_\odot$ create 5 visible gaps.

- They agree pretty well.

Bovy, Erkal, Sanders (2016)



Sampling dark matter subhalos in the simulations

CDM : use $dn/dM \propto M^{-1.9}$ from Aquarius simulations (Springel et al (2008)) .

- The radial distribution of subhalos in the range $10^5\,M_\odot$ - $10^9\,M_\odot$ follows an Einasto profile.

WDM :

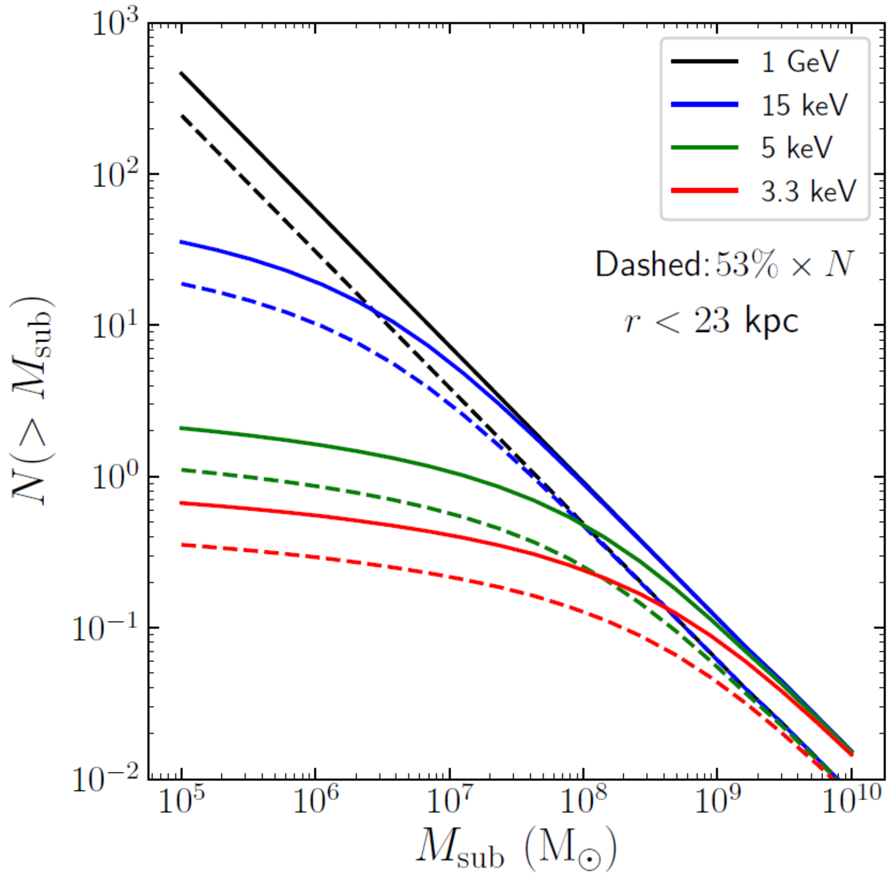
Lovell et al (2013) improved Schneider et al (2012) analytic fit:

$$\left(\frac{dn}{dM}\right)_{\mathrm{WDM}} = \left(1 + \gamma\frac{M_{\mathrm{hm}}}{M}\right)^{-\beta} \left(\frac{dn}{dM}\right)_{\mathrm{CDM}} \qquad \gamma = 2.7, \beta = 0.99$$

Assume radial distribution also follows Einasto profile.

Subhalo mass function

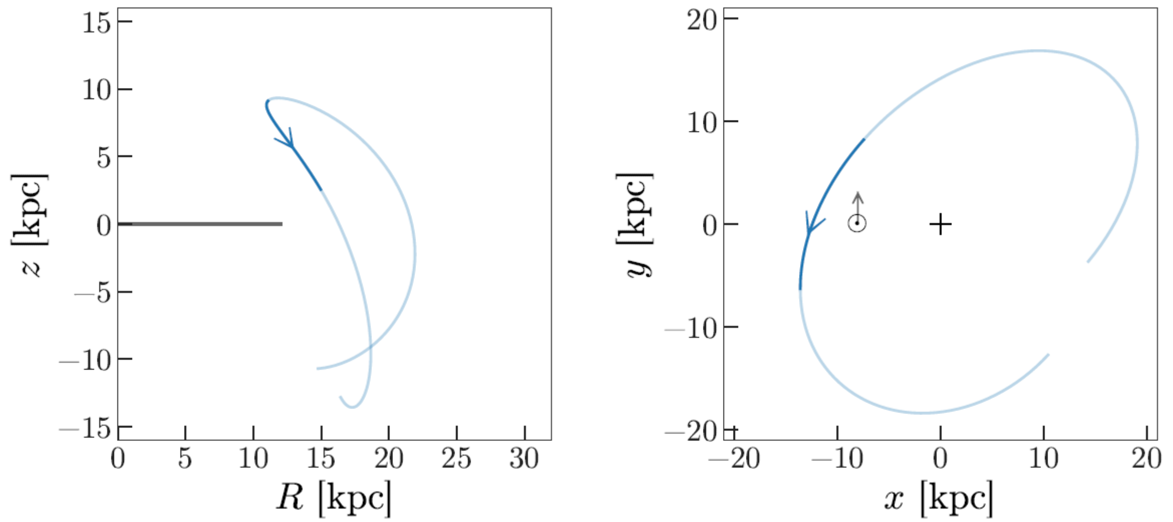
- Using APOSTLE simulations, Sawala et al (2016) found that baryonic effects such as interaction with the disk, can disrupt $\sim 45 - 50$ % of the dark matter subhalos.



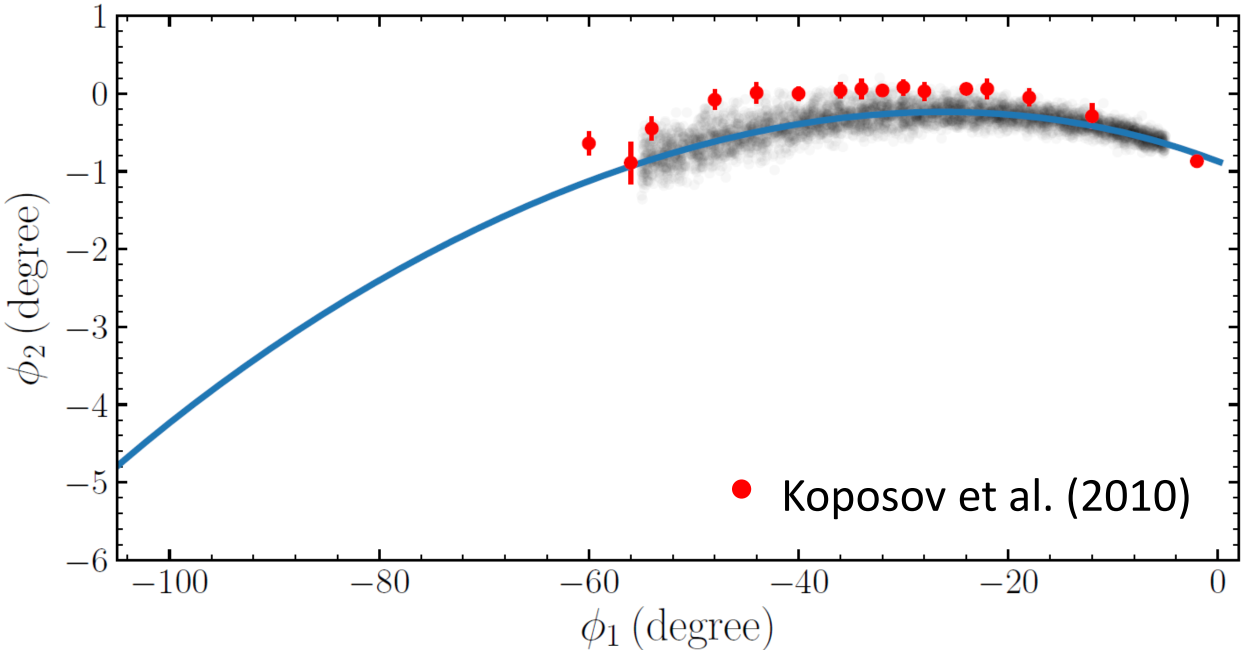
Everyone's favorite stream: the GD-1!

- Gaps in stellar streams can be caused by the gravitational torqueing by the galactic bar (Pearson et al (2016)), the sweeping spiral arms and impacts from molecular clouds.
- The GD-1 stream which in a retrograde orbit and far away from the bulk of the baryonic disk in our galaxy is the perfect candidate.

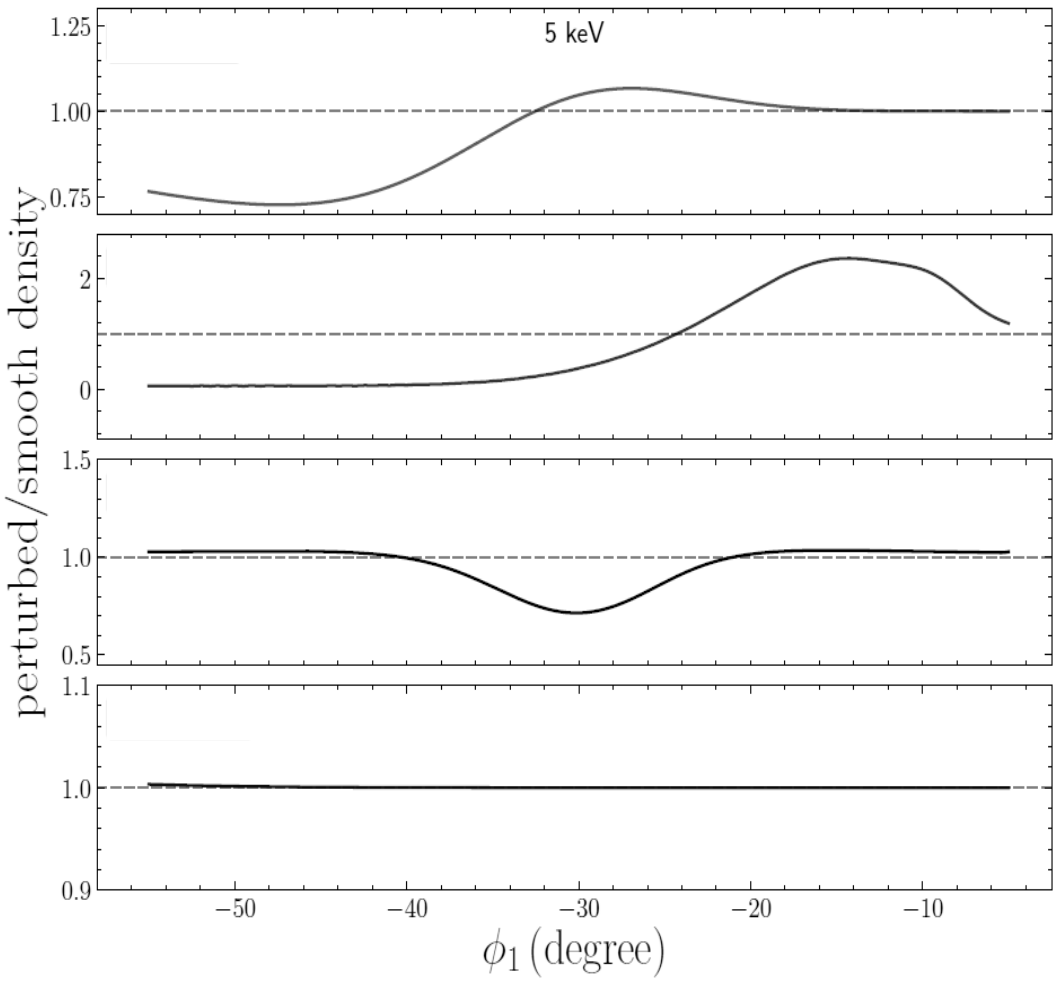
Price-Whelan & Bonaca (2018)

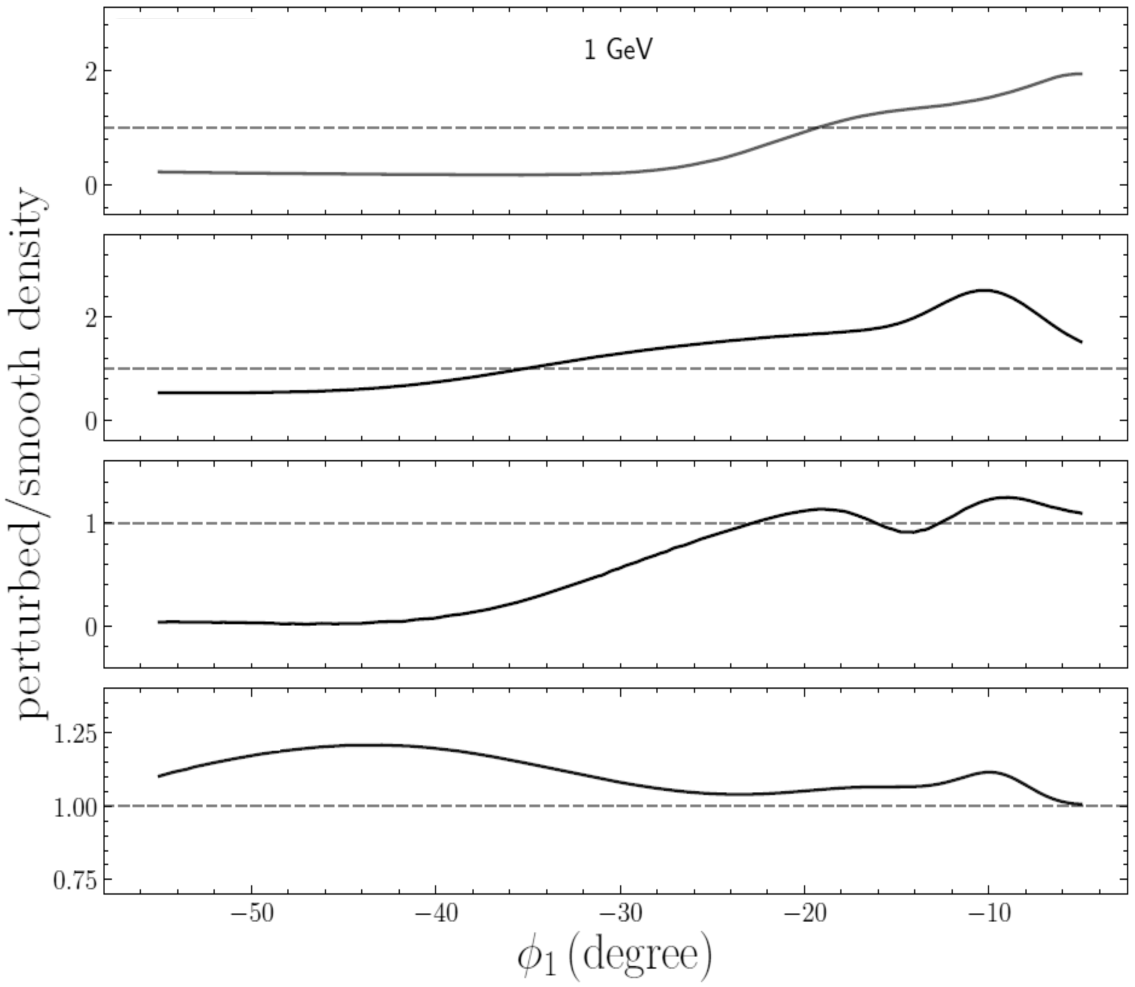


Banik et al (2018)



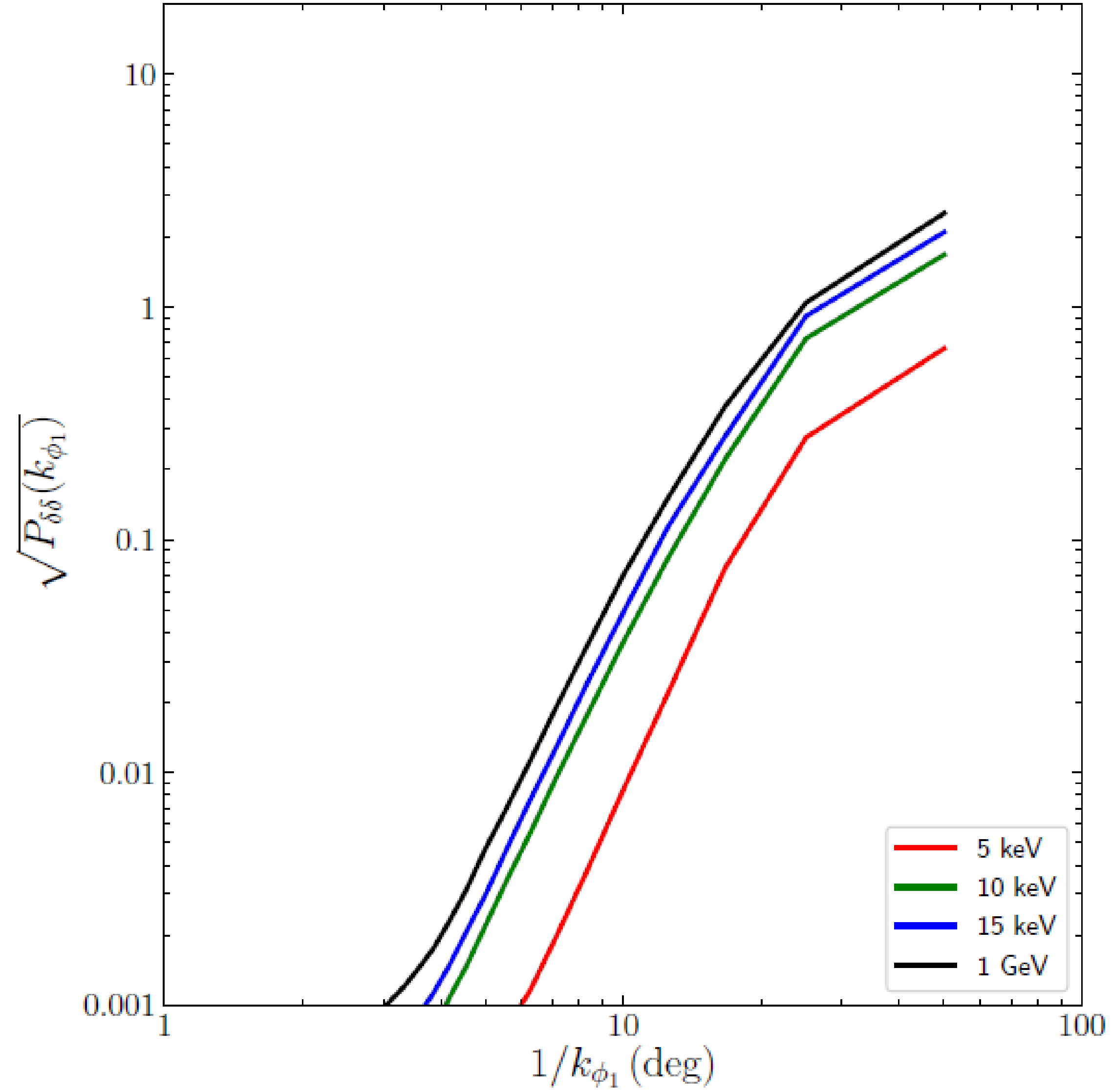
Density contrast





Power spectrum

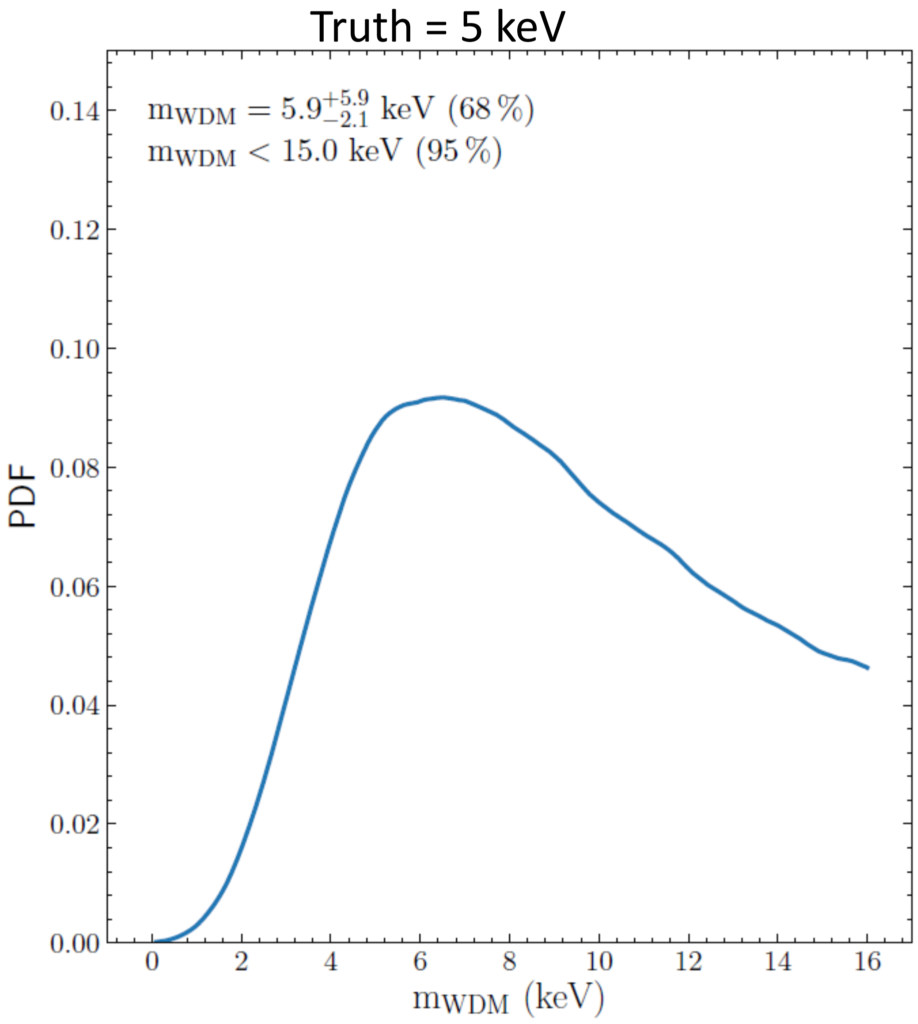
- We compute the power of the density contrast along the stream.
- Median power of 2100 simulations

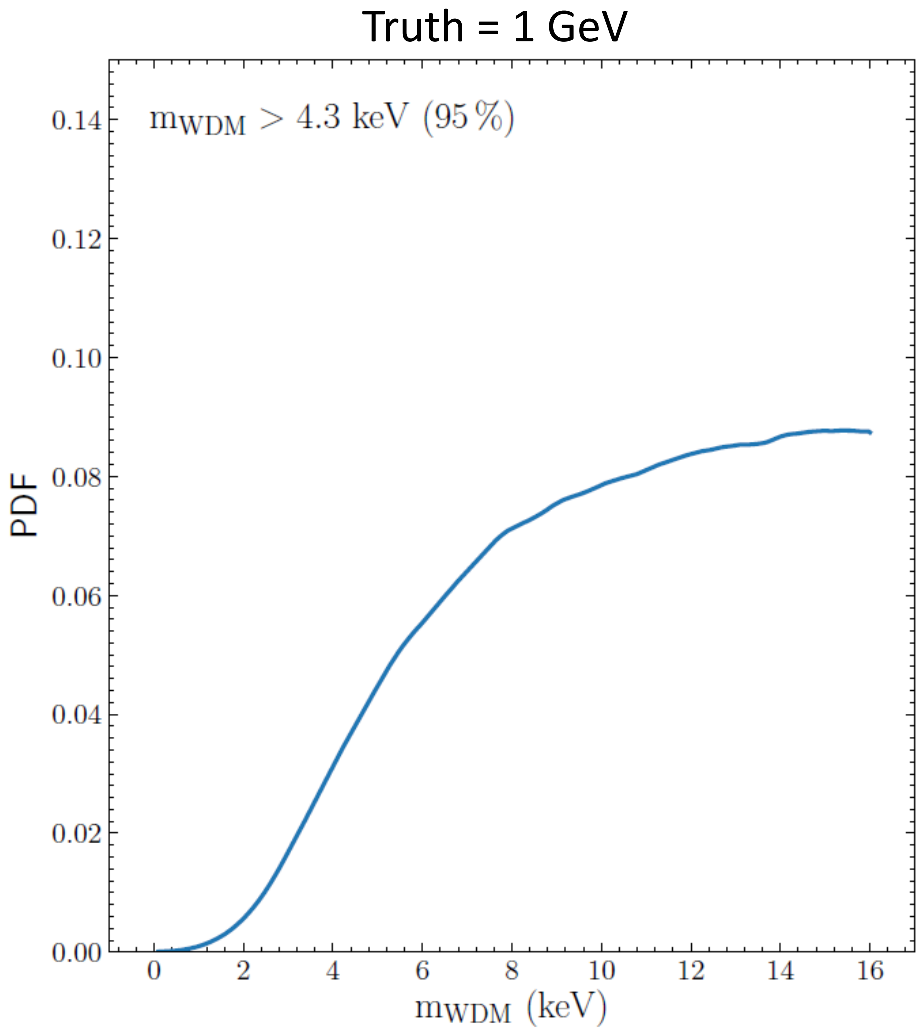


We use the ABC (Approximate Bayesian Computation) method for parameter inference

- Likelihood free method.
- For a given set of data, which in our case is the computed power spectrum of a particular stream, we generated many simulations over a uniform prior [0.1-17] keV on the mass of WDM and accept only those that are within certain defined tolerance around the data summaries.
- From the accepted simulations, we construct the posterior.

Posterior PDFs





Conclusions

- Stellar streams can not only allow us to study the MW potential but provide an avenue for exploring the dark substructures in our galaxy.
- We presented a statistical method of constraining the mass of dark matter by comparing the power of the density contrast of a stellar stream.
- A very appropriate time to push this effort forward : DES discovered 11 new streams in our galaxy and we expect to discover many new stellar streams with Gaia and future LSST.
- By combining high quality data on several streams we will be able to put a more robust constraint on the mass of dark matter as well as be sensitive to subhalos with mass as low as 10^5Msun.
- Detecting these subhalos will strongly suggest the existence of dark matter as well as give us valuable information on its particle nature.

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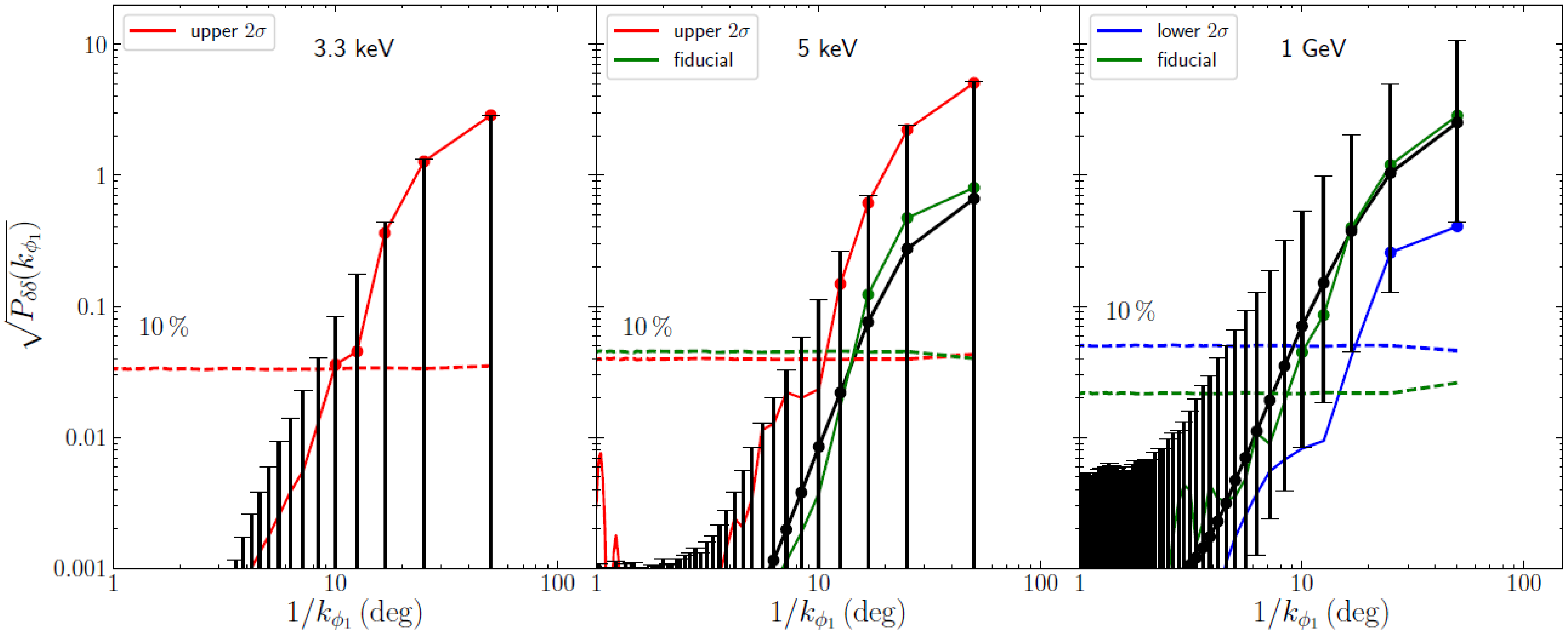
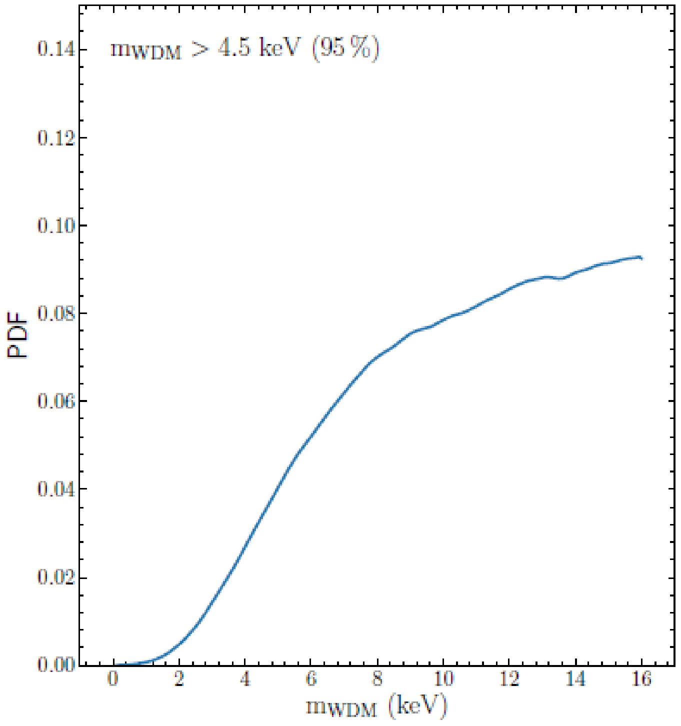
Backup slides

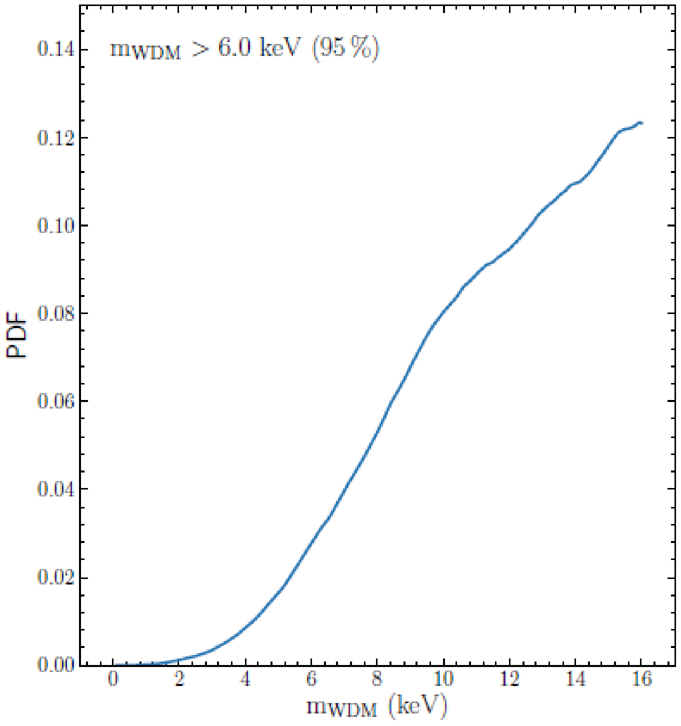


Extreme cases

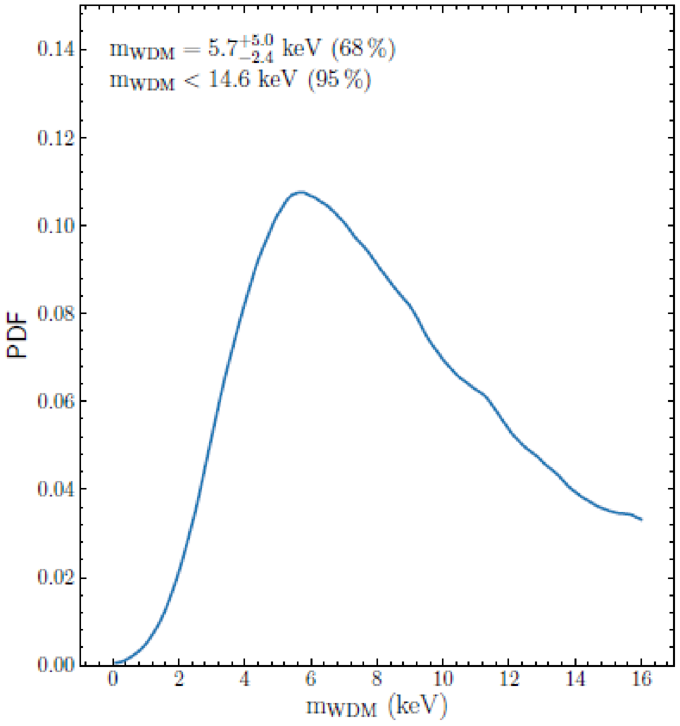
Upper 2σ 3.3 keV



Upper 2σ 5 keV



Lower 2σ 1 GeV



No subhalo impacts