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

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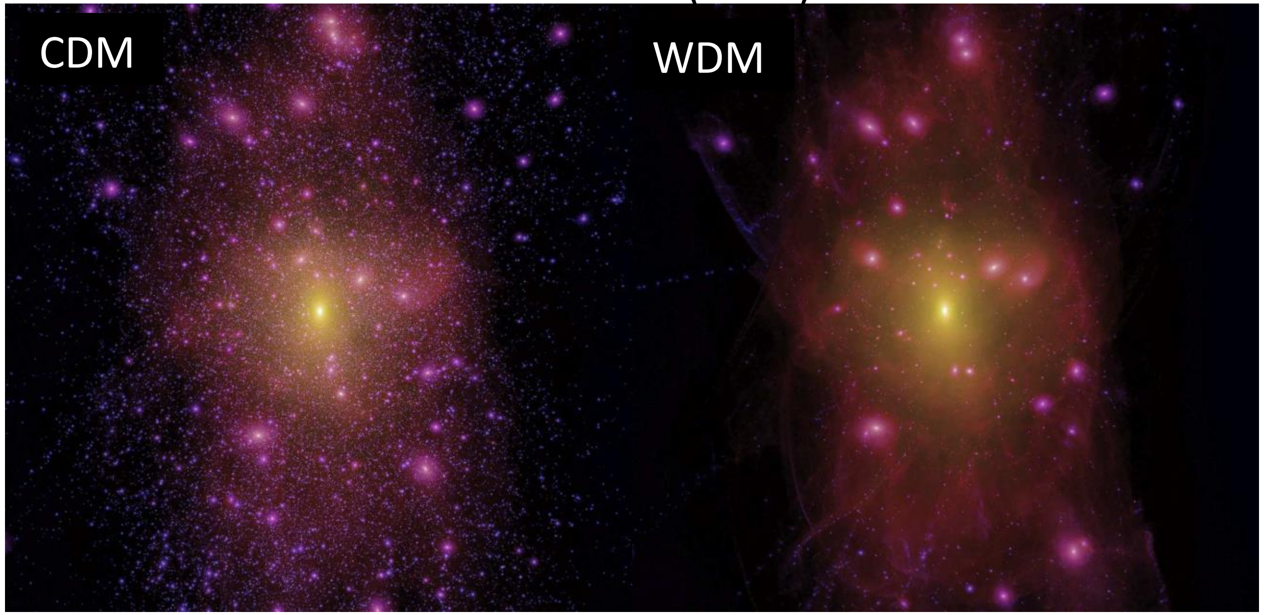
ΛCDM predicts many dark matter subhalos

- 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.
- Subhalos less massive than 10^9 Msun are devoid of stars and therefore remain undetected. Detecting these low mass subhalos will give crucial insight on the particle nature of dark matter.

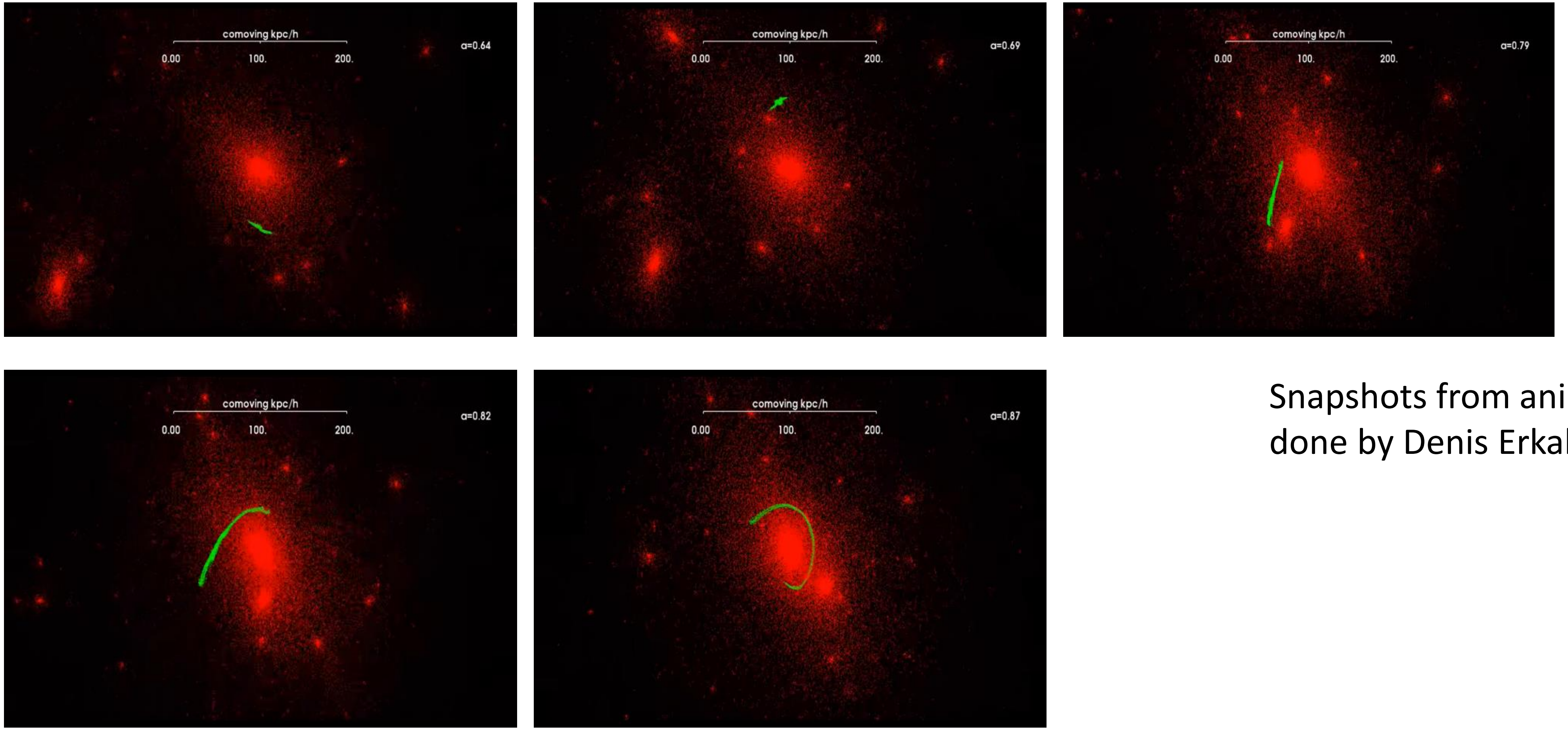
Lovell et al (2014)



- Dark matter can be broadly classified as cold and warm.
- WDM have higher velocity dispersion compared to CDM which prevents structure formation below a certain scale.

What are stellar streams?

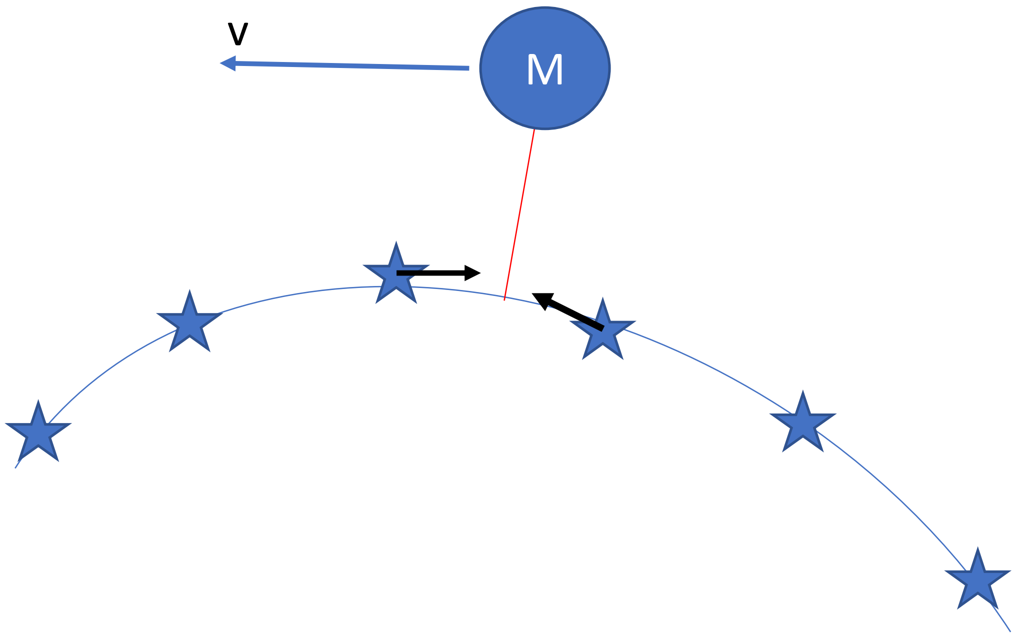
- Gravitational potential of the Milky way galaxy can tidally disrupt near by globular clusters and dwarf galaxies stretching them along their orbit, resulting in a stream of stars – stellar streams.

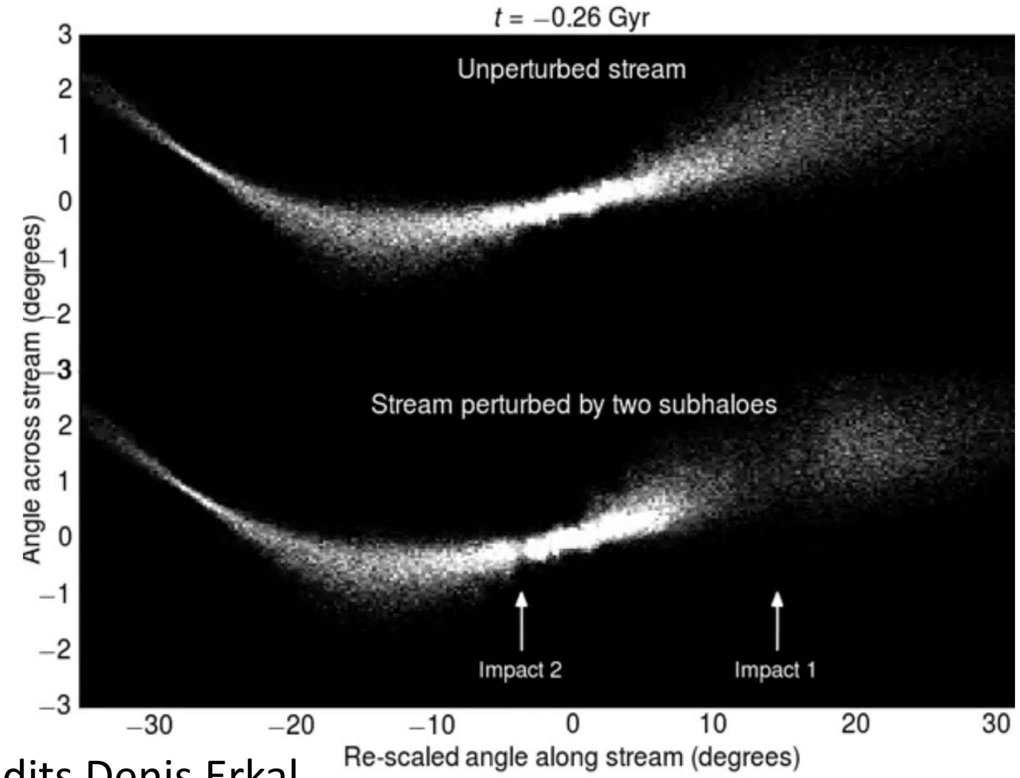


Snapshots from animation done by Denis Erkal

Probing DM subhalos using stellar streams

- A cold stellar stream has largely a uniform stellar density along its length.
- A flyby DM subhalo will impart velocity kicks to the stars near the point of closest approach. This will put them in different orbits. This results in a region of low stellar density in the stellar stream or a “gap”.

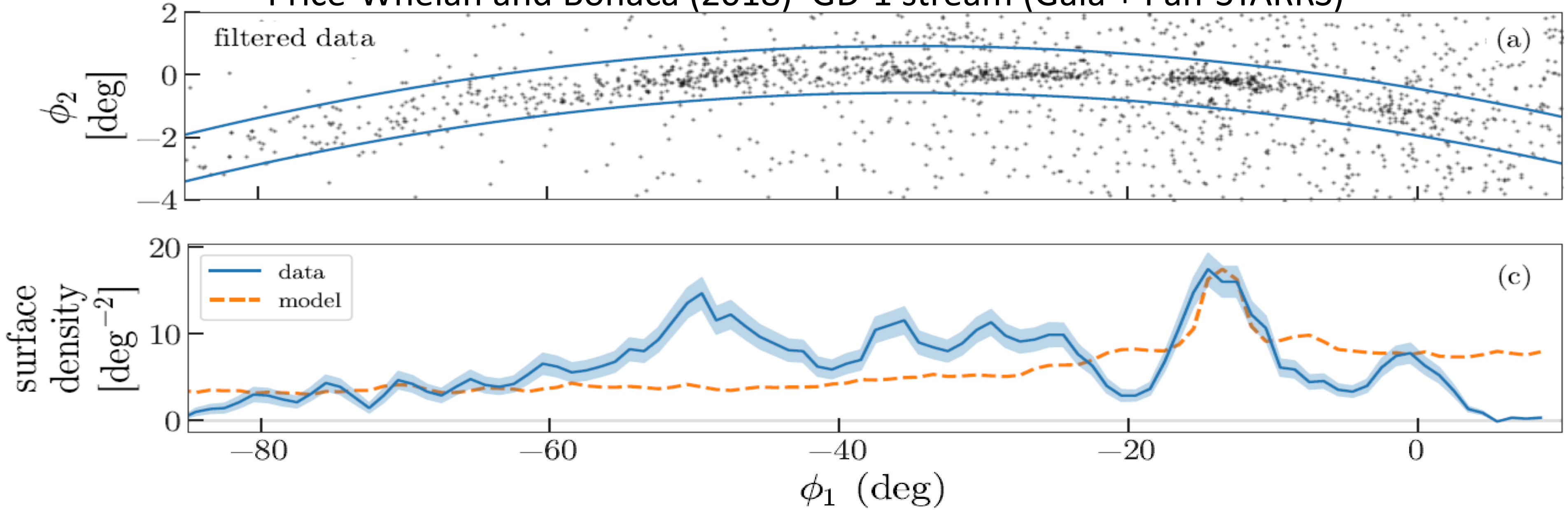




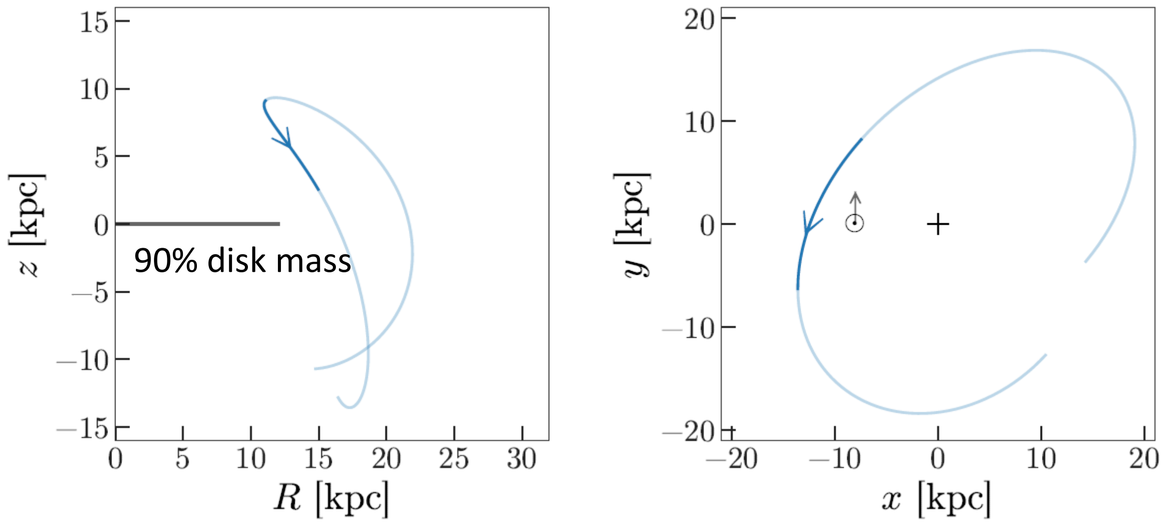
Credits Denis Erkal

We do see gaps in stellar streams!

Price-Whelan and Bonaca (2018) GD-1 stream (Gaia + Pan-STARRS)



And they are most probably caused by DM subhalo impacts



The main idea

- CDM: many subhalos therefore more density perturbations (gaps)
- WDM: fewer subhalos therefore less density perturbations.

Statistically, a stellar stream evolved in a WDM Universe should have less density perturbations than a one evolved in a CDM Universe.

Subhalo mass function of CDM and thermal WDM

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:

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

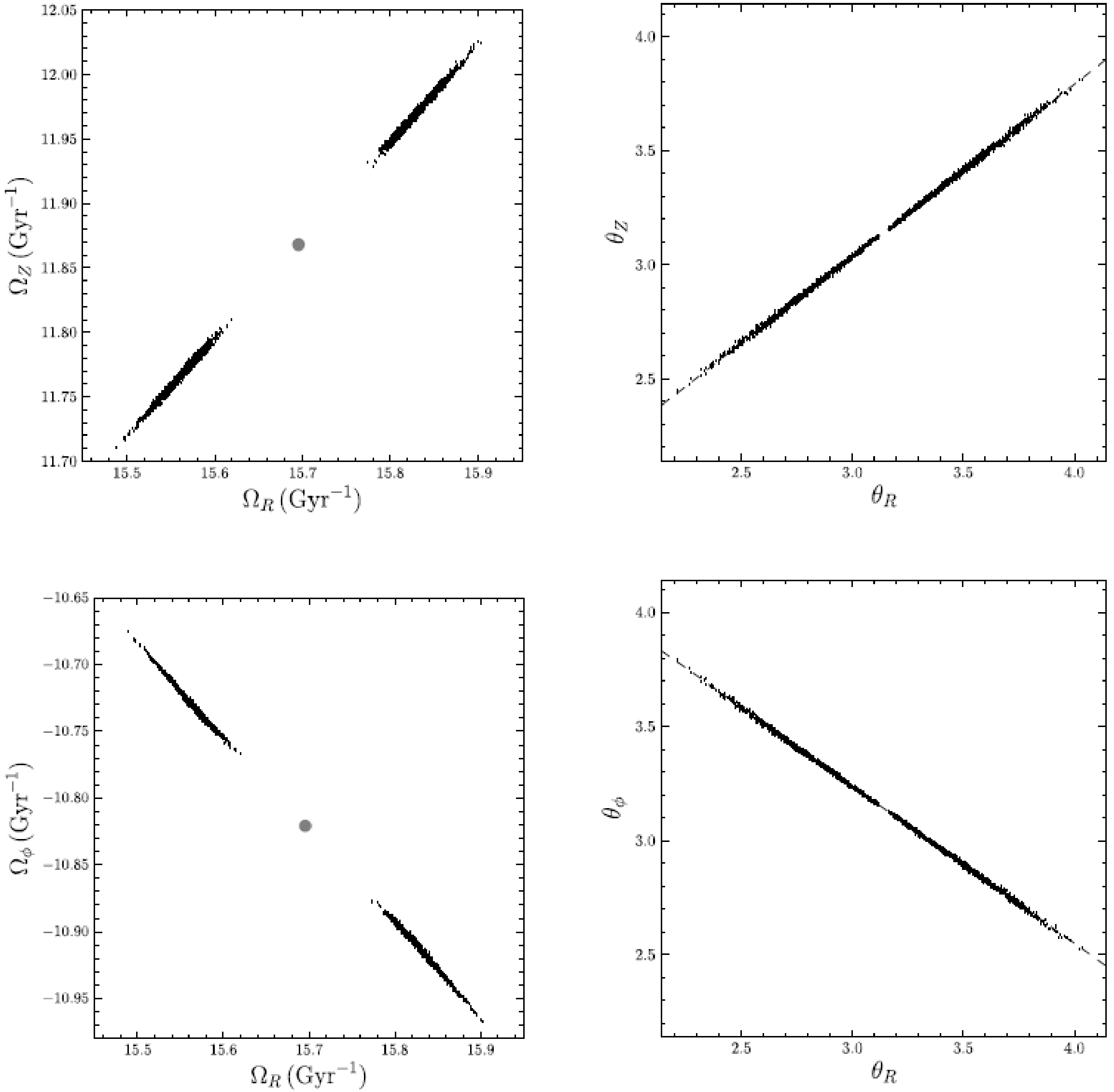
Assume radial distribution also follows Einasto profile. M_{hm} - half mode mass.

Simulating cold stellar streams

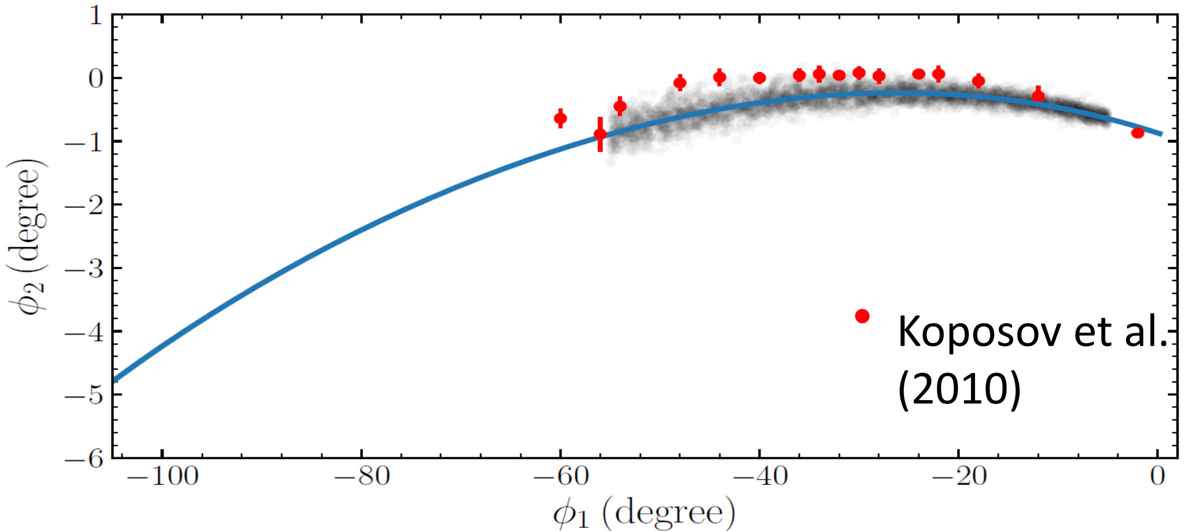
- Generation and evolution of a cold stellar stream is most easily described in frequency-angle space, where the stream is practically one dimensional.
- Their evolution is governed by these linear equations :

$$\boldsymbol{\Omega} = \boldsymbol{\Omega}_0 = \text{constant}$$
$$\boldsymbol{\theta} = \boldsymbol{\Omega}_0\, t + \boldsymbol{\theta}_0$$

Bovy (2014)



Banik et al (2018)



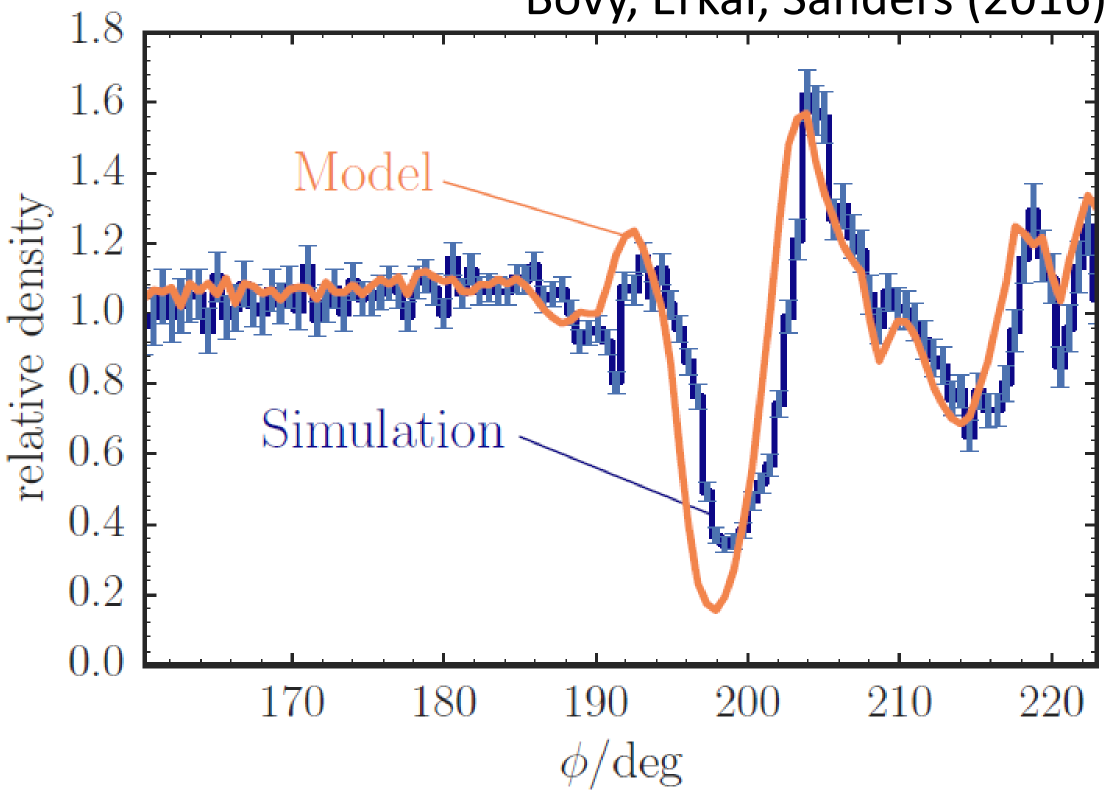
Modelling subhalo impacts in (Ω, θ) vs. N-body

- We model the stream-subhalo encounters by the impulse kick approximation.
- In (Ω, θ) space this translates to

$$\boldsymbol{\Omega} = \boldsymbol{\Omega}_0 + \delta\boldsymbol{\Omega}^g = \text{constant}$$
$$\boldsymbol{\theta} = \boldsymbol{\Omega}_0\, t + \delta\boldsymbol{\Omega}^g\,(t - t^g) + \delta\boldsymbol{\theta}^g + \boldsymbol{\theta}_0$$

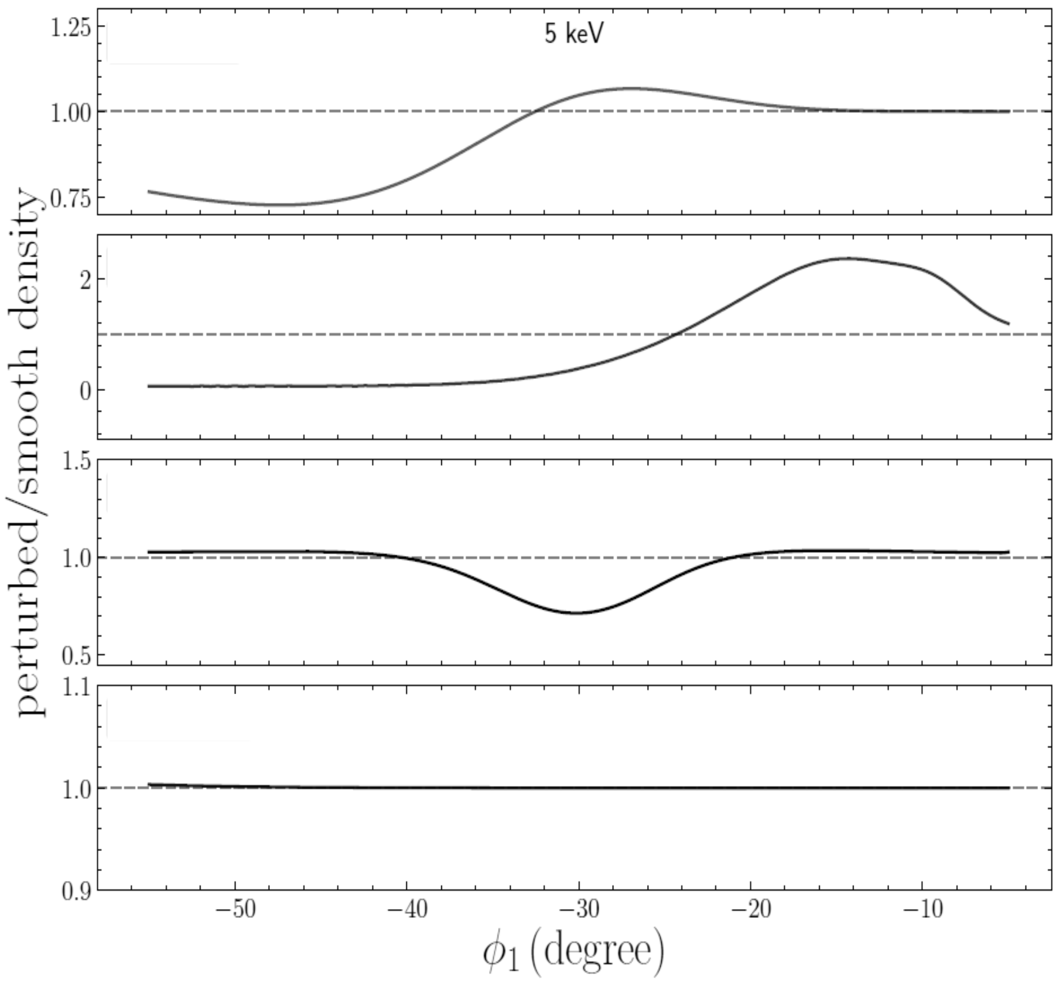
- The stream simulations in the (Ω, θ) framework are orders of magnitude faster than in an N-body simulation, enabling us to run thousands of different subhalo realizations within a few hours.

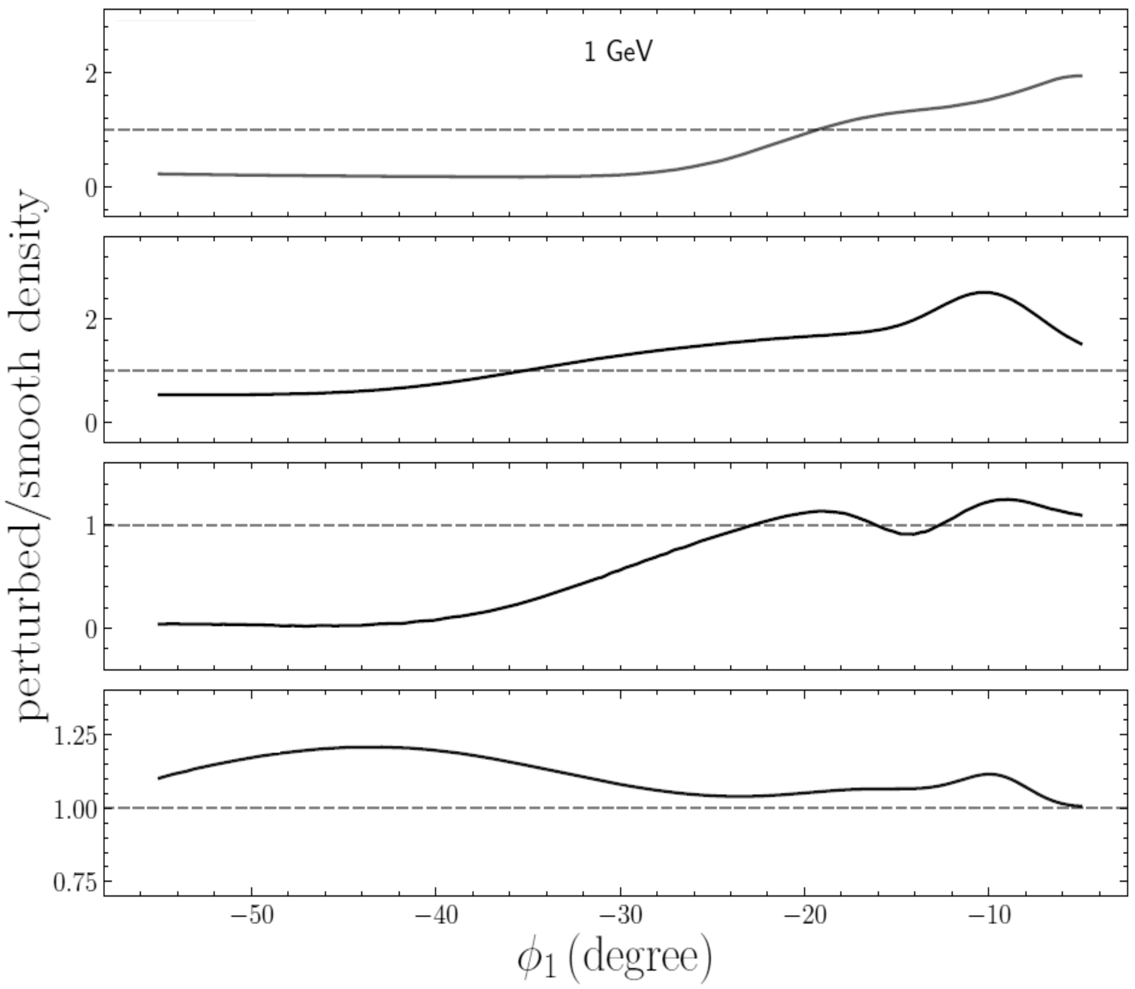
Bovy, Erkal, Sanders (2016)



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

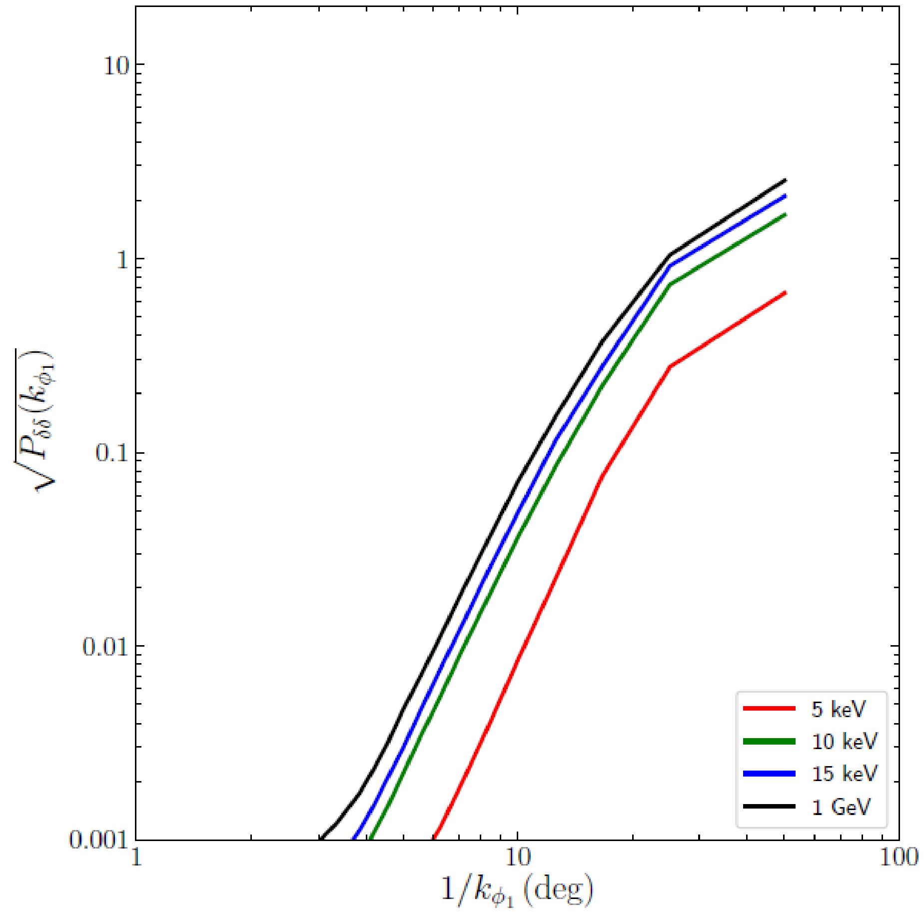
Density contrast





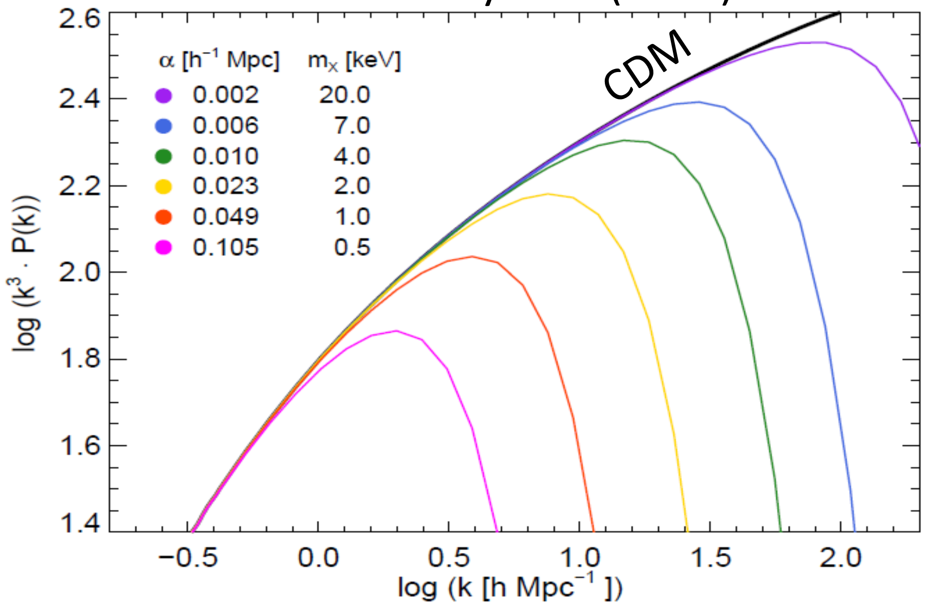
Power spectrum

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



This makes sense since higher the mass of thermal DM particle, closer it gets to CDM.

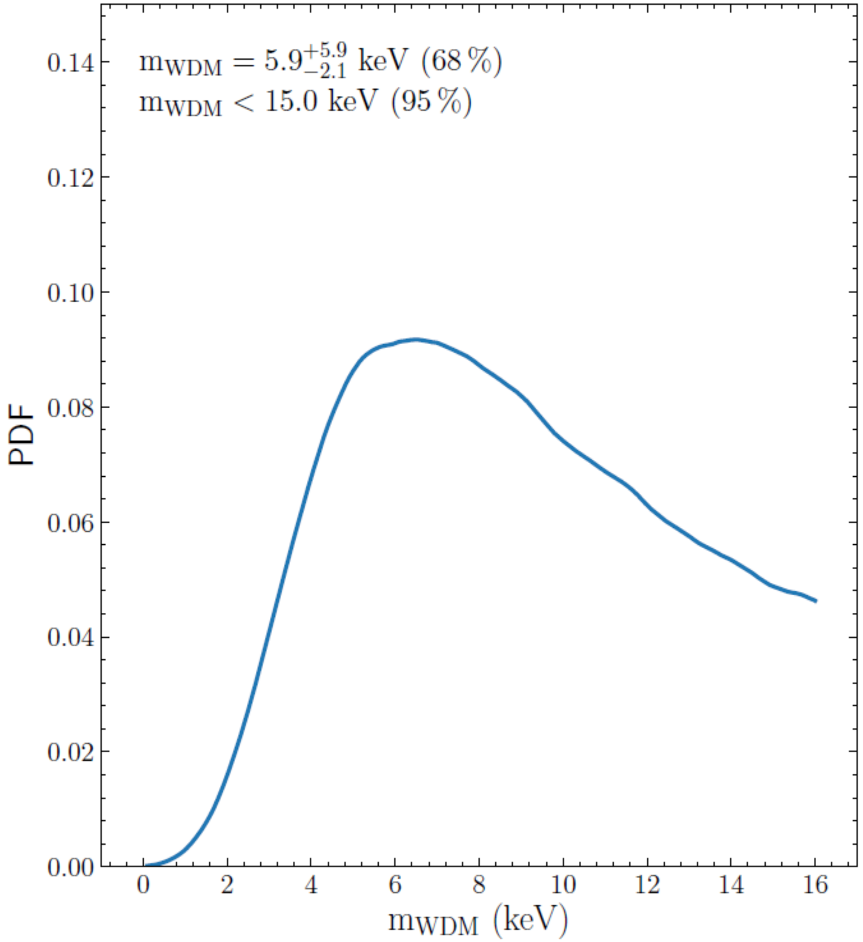
Kennedy et al (2014)



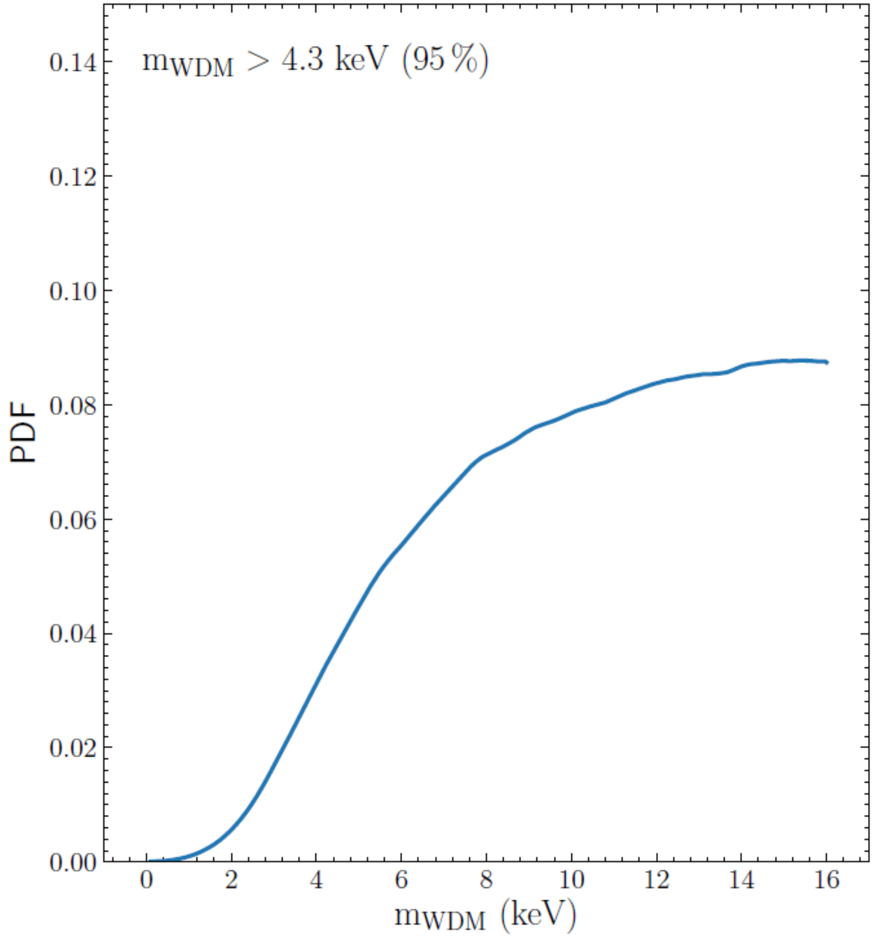
Posterior PDFs

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

Truth = 5 keV



Truth = 1 GeV



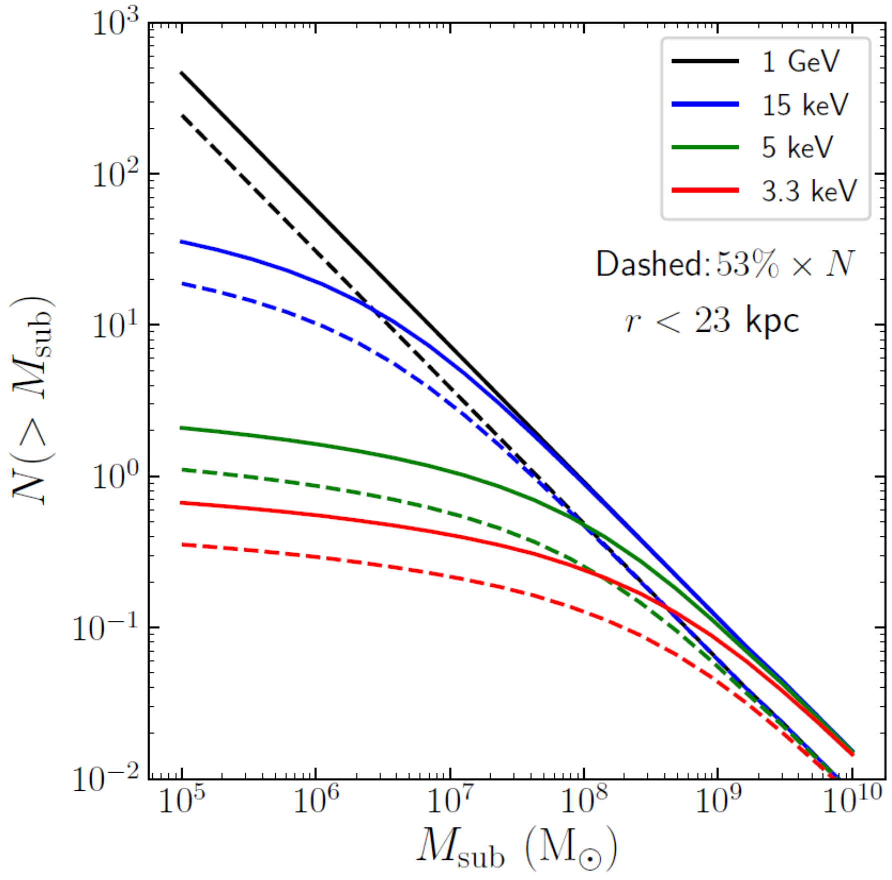
Conclusions

- Stellar streams provide a novel method of detecting dark matter subhalos in our galaxy.
- We presented a statistical method of distinguishing between CDM and WDM by comparing the power of the density contrast of a stellar stream.
- 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.

END OF SLIDES

Reduction of subhalos

- 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.



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.

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

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

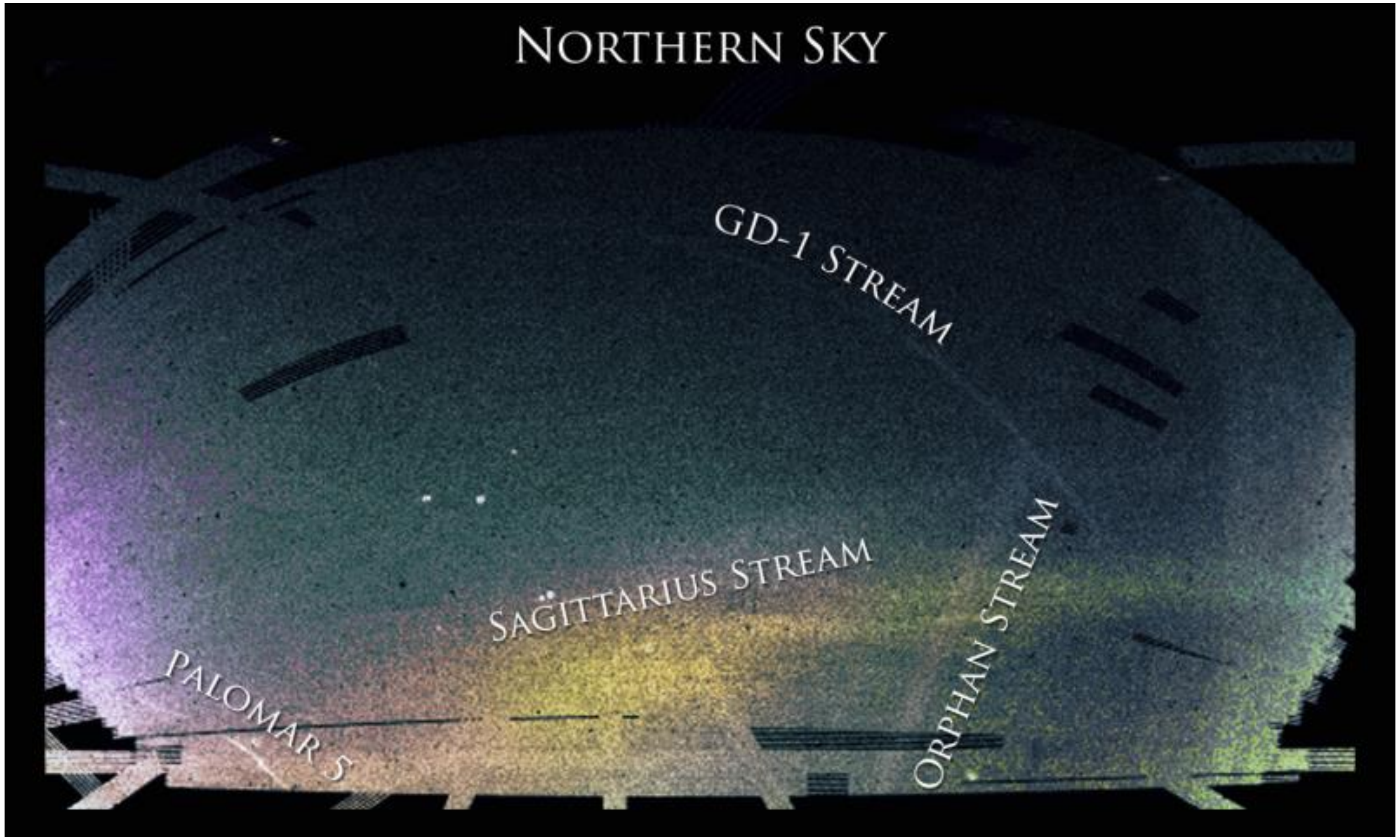
Bode et al (2001), using P3M code, υ =1.12 (fitting parameter)

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

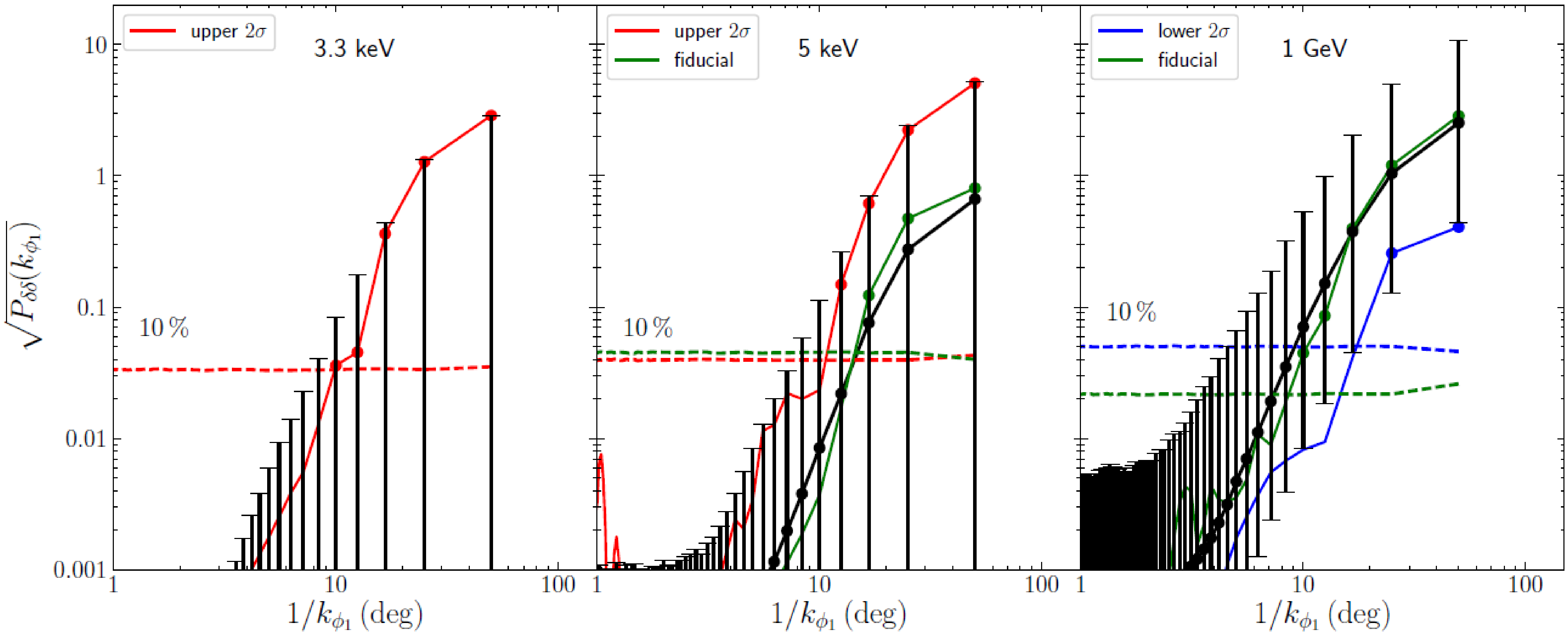
$$\alpha = 0.047 \left(\frac{m_{\mathrm{WDM}}}{\mathrm{keV}}\right)^{-1.11} \left(\frac{\Omega_{\mathrm{WDM}}}{0.2589}\right)^{0.11} \left(\frac{h}{0.6774}\right)^{1.22} h^{-1}\mathrm{Mpc}$$

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

There is a bunch of stellar streams to that we know till date. GD-1 and Pal 5 are two of the most well studied globular cluster streams.

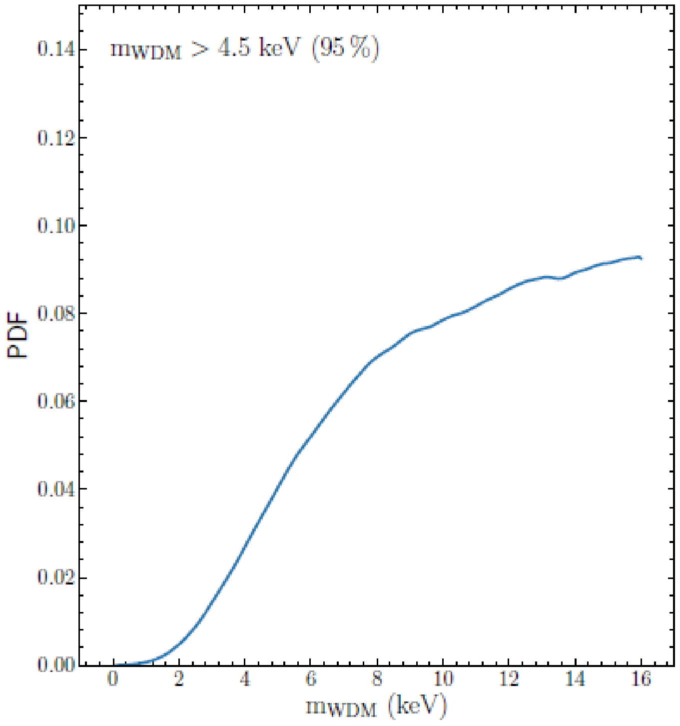


Backup slides

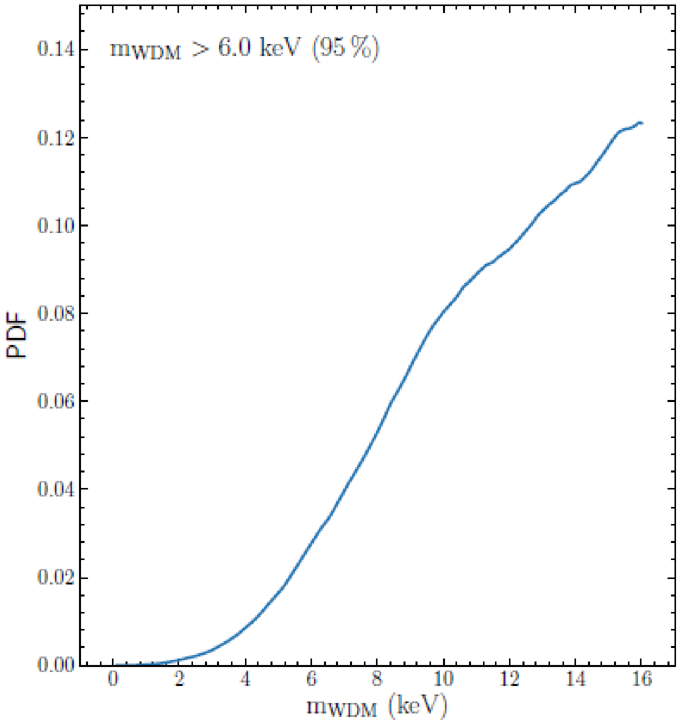


Extreme cases

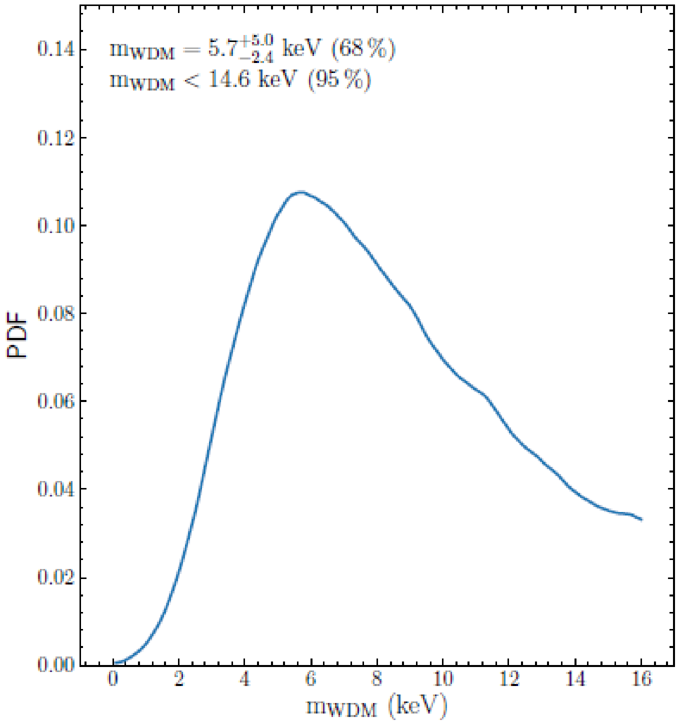
Upper 2σ 3.3 keV



Upper 2σ 5 keV



Lower 2σ 1 GeV



No subhalo impacts