Gravitational Focusing of Dark Matter Streams in Solar Neighborhood and Implications for Detection

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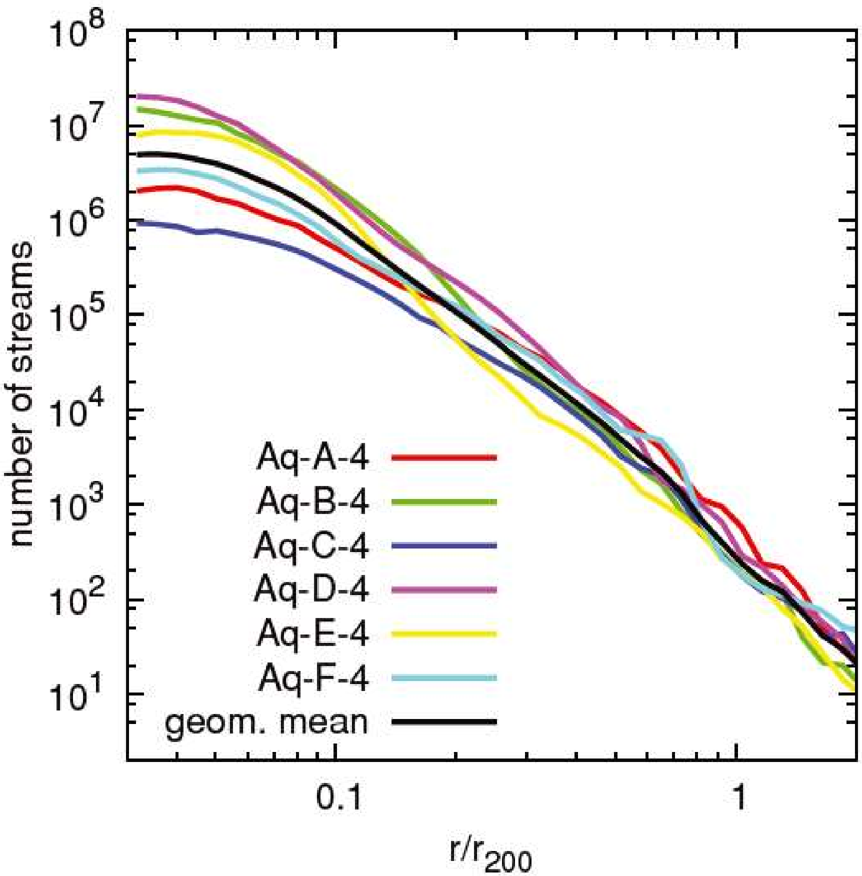
Fine-Grain Streams and Cosmological Simulations

The cold nature of dark matter yields particles with nearly zero dispersions
($\sim 10^{-10}$ c for WIMPs and 10^{-17} c for Axions)

Analytical work on these dispersionless streams was studied early on by Sikivie et al

N-Body Cosmological simulations reveal substructure more complex than a standard smooth Halo, Fine-Grain Streams of very small dispersion are part of the substructure

Fine-Grain Stream Abundance



Number of fine-grained streams at solar position could be as high as ~10^{14} where most massive streams that 50% of local dark matter density are 10^6 and the single most massive stream **contributed 0.1% of local dark matter density**

Mark Vogelsberger and Simon D. M. White, Mon. Not. R. Astron. Soc. **413,** 1419–1438 (2011)

Fine-Grain streams at Solar Position

Analytical calculations of zero dispersion streams by Sun or other planets have been done before, however realistic streams would have some dispersion and are affected by gravity of more than one solar body

We focused on simulating the fine-grain particles to include

- Dispersion
- Multi-body effects (Sun, Moon, Earth)
- Stand-alone N-body simulation could be adapted by DM groups to calculate the Gravitational effects on DM rates

Python
Numpy, Scipy
Scipy.integrate.odeint package as equation solver

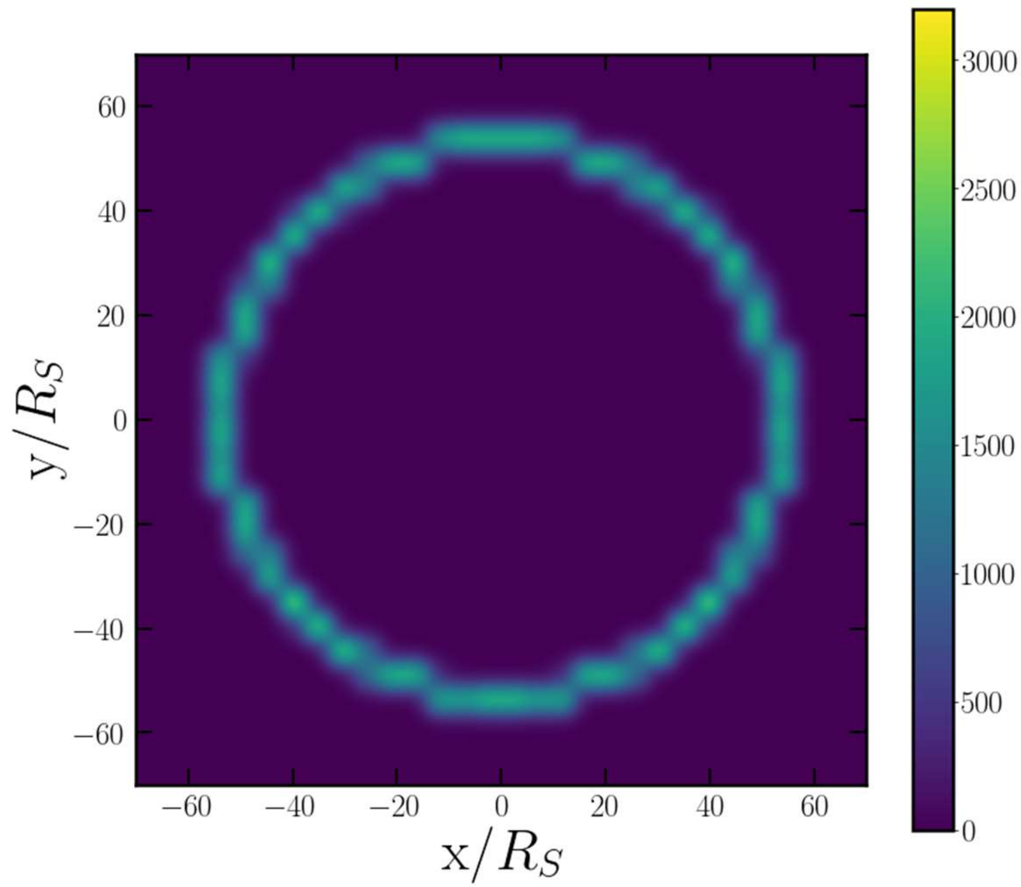
$$m_i \frac{dr_i}{dt} = \sum_{j=i+1}^{n} \frac{G m_i m_j}{|r_i - r_j|^3}(r_i - r_j)$$

Outside Solar Bodies

$$m_i \frac{dr_i}{dt} = \sum_{j=i+1}^{n} \frac{4}{3}\pi G \rho (r_i - r_j)$$

Inside Solar Bodies

Gravitational effects by the Sun only on a zero dispersion stream



Example of a spatially uniform stream of velocity 220 km/s with impact parameters around 50 R_S will focus on Earth

An Observer on Earth will see the typical Einstein ring at position of the Sun

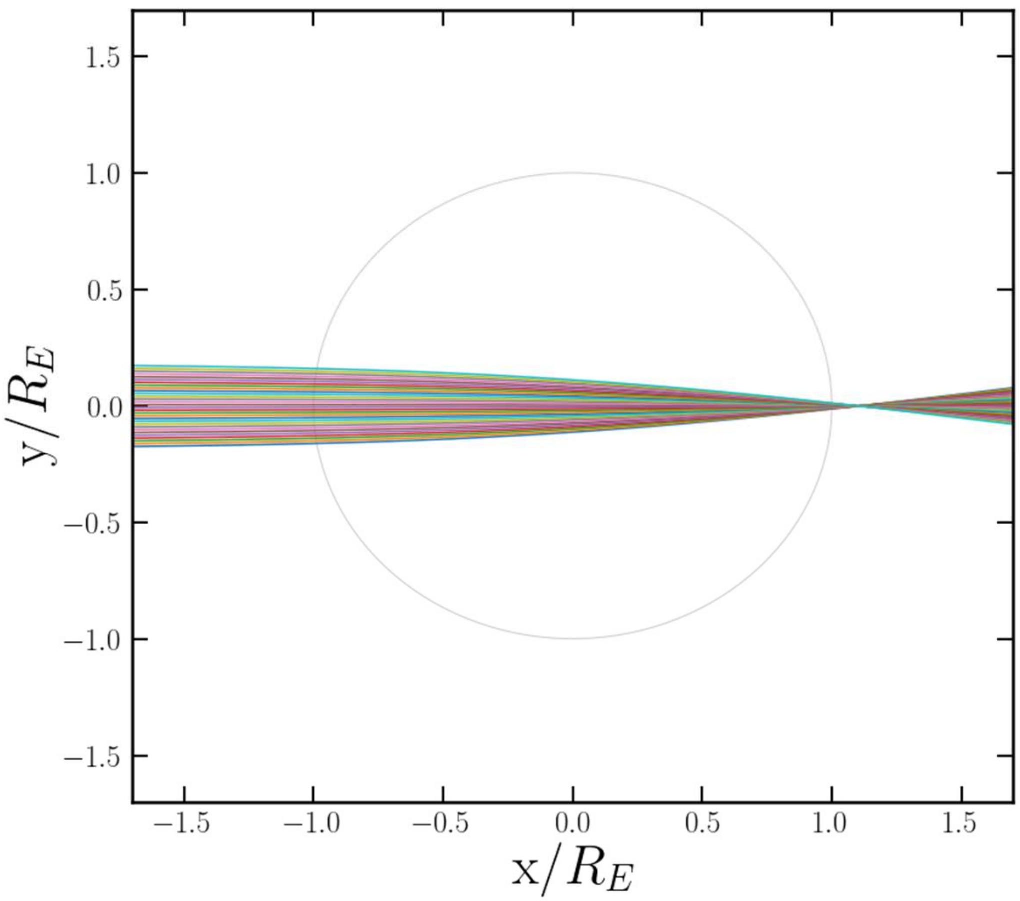
The density enhancement over nominal is about 3000

Result consistent with work from:

- **Y. Sofue,** arXiv:2005.08252 (2020)
- **M. S. Alenazi and P. Gondolo**
Phys. Rev. D 74, 083518 – (2006)

Deflection of particles by the Sun goes as $1/v^2$

Gravitational effects by the Earth itself only on a zero dispersion stream



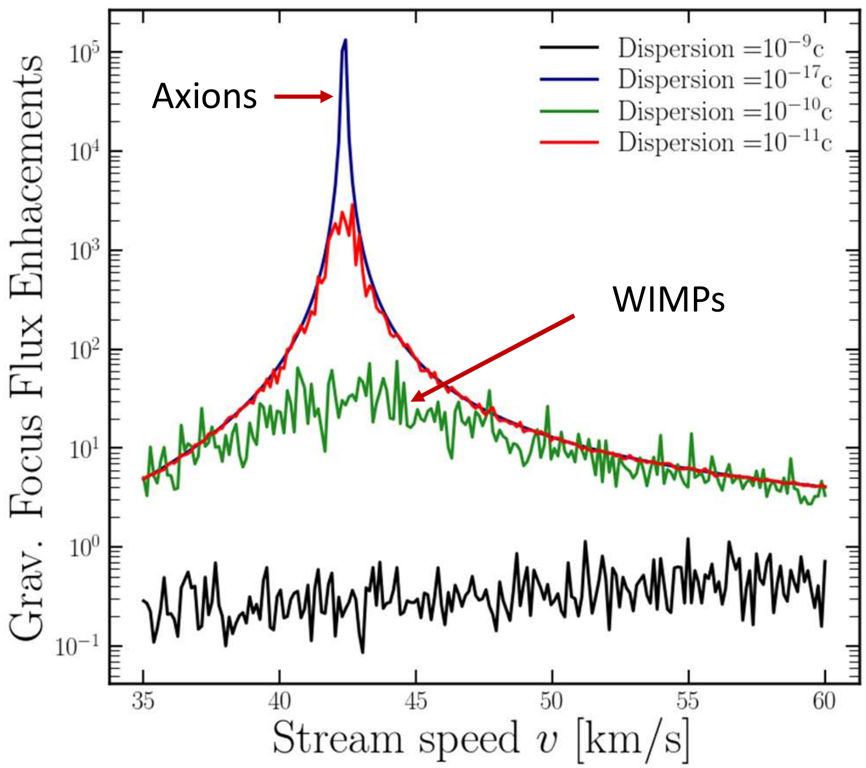
An example of zero dispersion stream with low speed of ~13 km/s with respect to the geo-center experiences gravitational focusing on the other side at the surface

Density enhancement are of the order ~10^6

Result consistent with:

- **Y. Sofue,** arXiv:2005.08252 (2020)
- G. Prézeau 2015 *ApJ* **814** 122

Gravitational effects by the Moon only on a fine-grained stream including dispersion

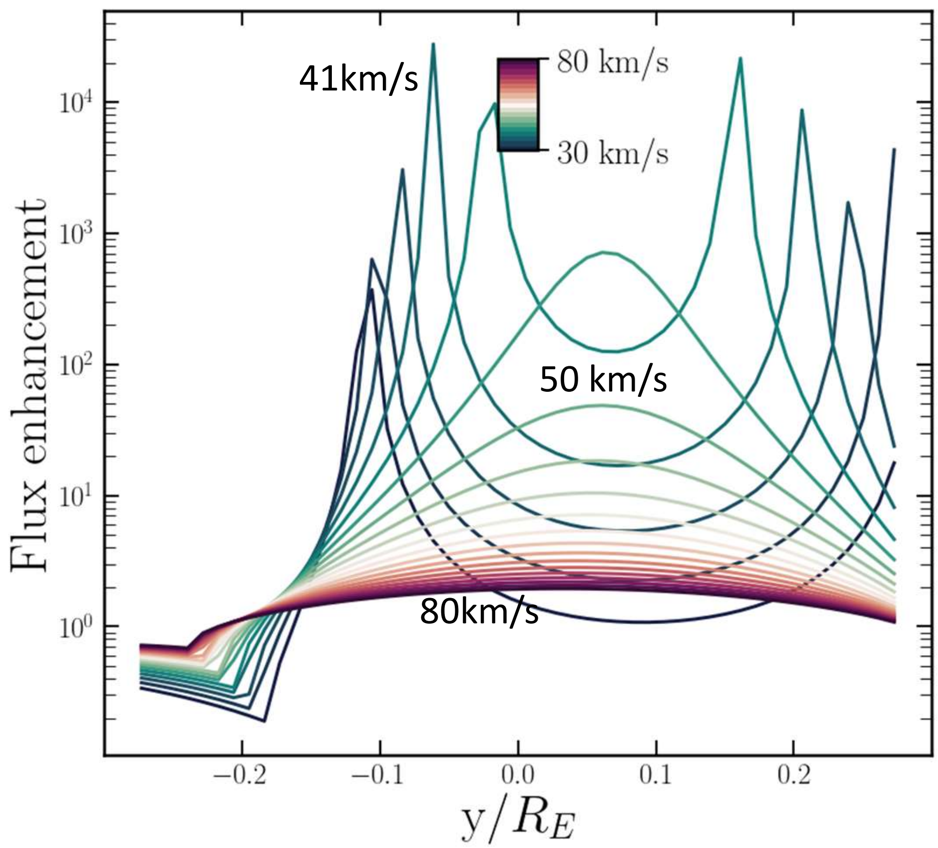


Sofue (2020) described the Moon as gravitational focusing candidate with large density enhancements.

To simulate the velocity dispersion we inject particles from “infinity” with a Gaussian velocity distribution with widths defining the dispersion value.

The stream speed is wrt geo-center
The density enhancements could be as high as 10^5 for Axions and 100 for WIMPs.

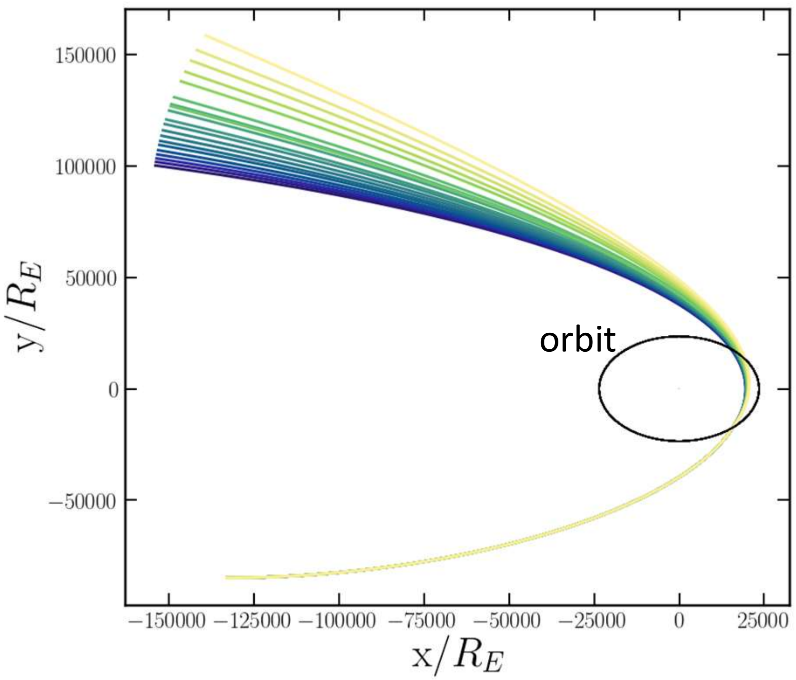
Gravitational effects by the Moon only on a fine-grained stream

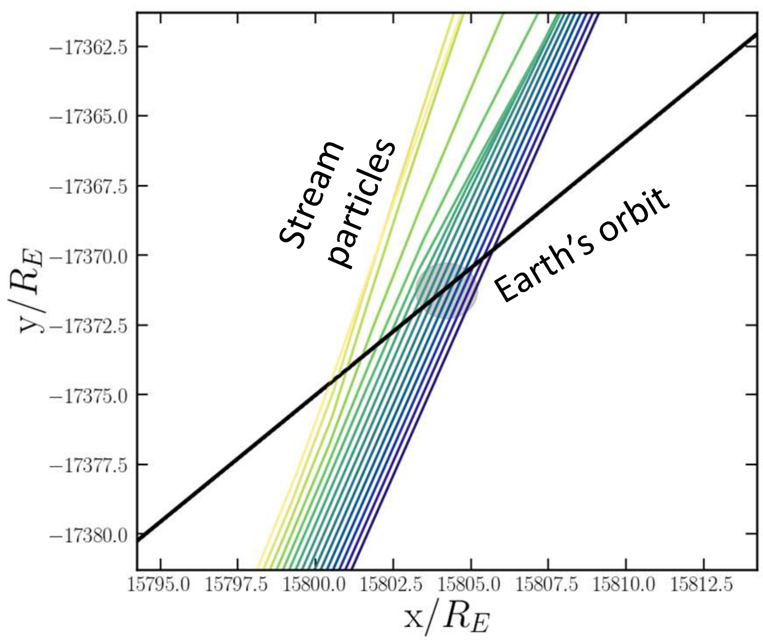


The Moon has a small aperture as manifested by the y-span, also the enhancements are more pronounced at particular speed streams wrt Earth's center.

Gravitational effects by the Sun and Earth together on a fine-grained stream

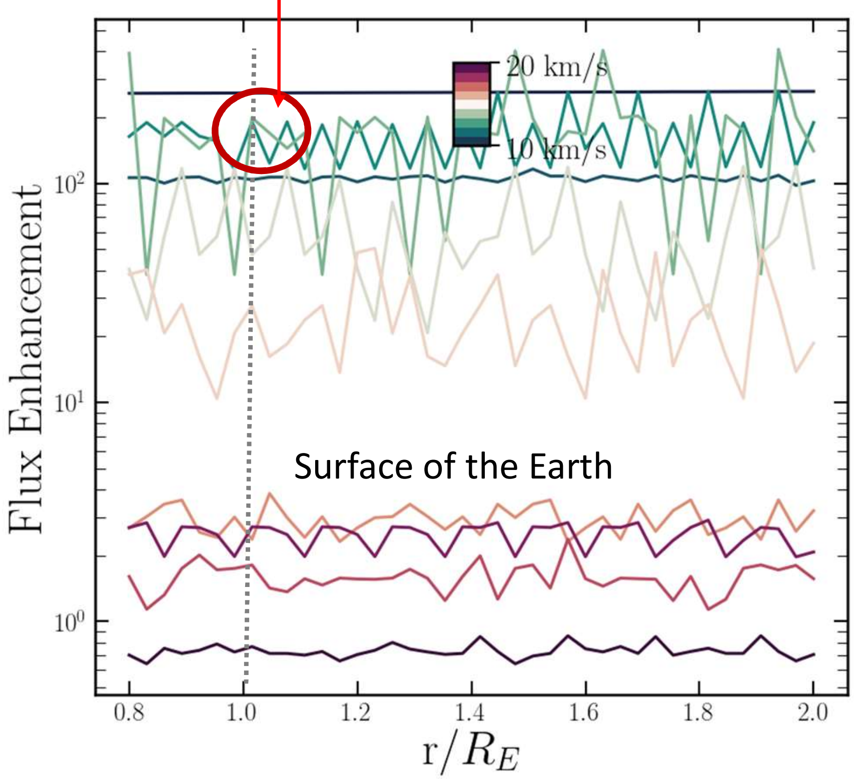
An example of a 10 km/s speed stream at infinity with respect to the Sun experiences deflection from the Sun and Earth.





The lab velocity of the stream in this case is about 20 km/s

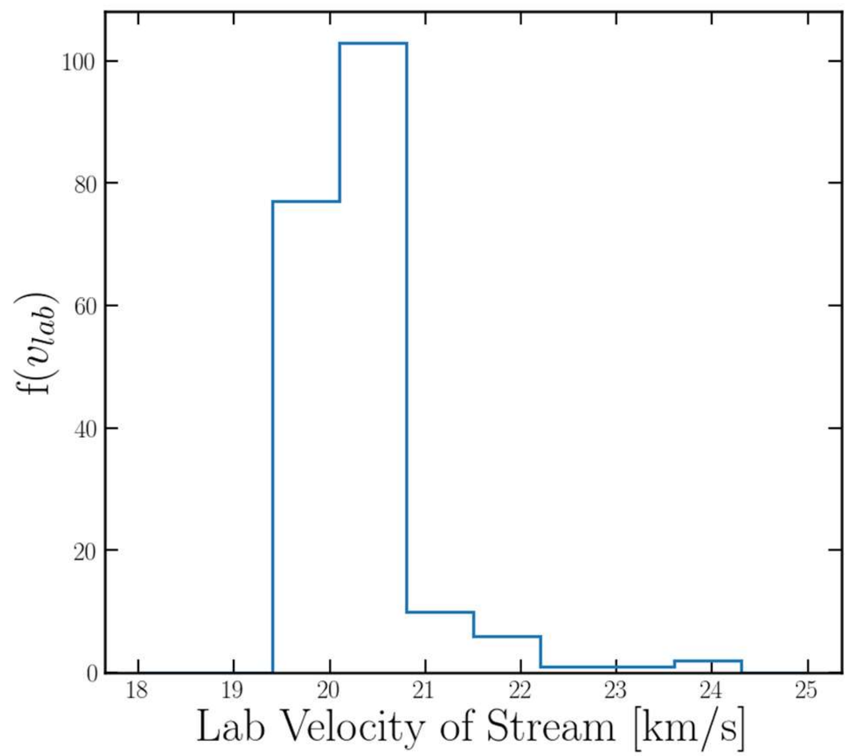
Flux enhancements by the Sun and Earth on the direction of incoming stream



Streams with lower speed are more enhanced. The effects of both Sun and Earth up to the surface of the Earth for a 10 km/s stream (wrt Sun) yield a flux enhancement of about 200. The stream continues through the Earth under self-focusing and this will yield further amplification.

As Earth is orbiting it encounters particles in the stream and focuses them. There would be a modulation due to velocity of the stream wrt orbital speed of the Earth.

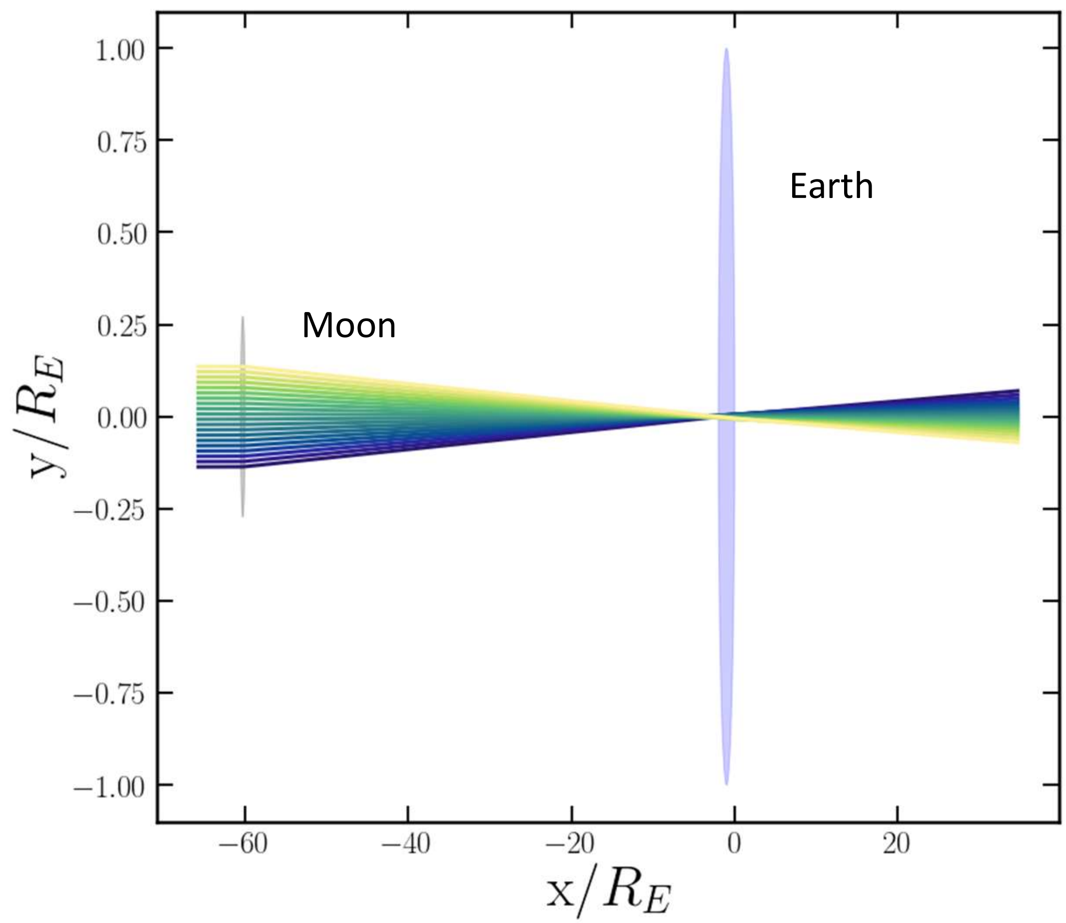
Effects on Stream velocity due to tidal differential force of the Sun



In this example a stream of velocity 10 km/s wrt Sun with zero dispersion experiences a broadening in lab velocity due to differential gravitational force on DM particles closer vs further away from the Sun.

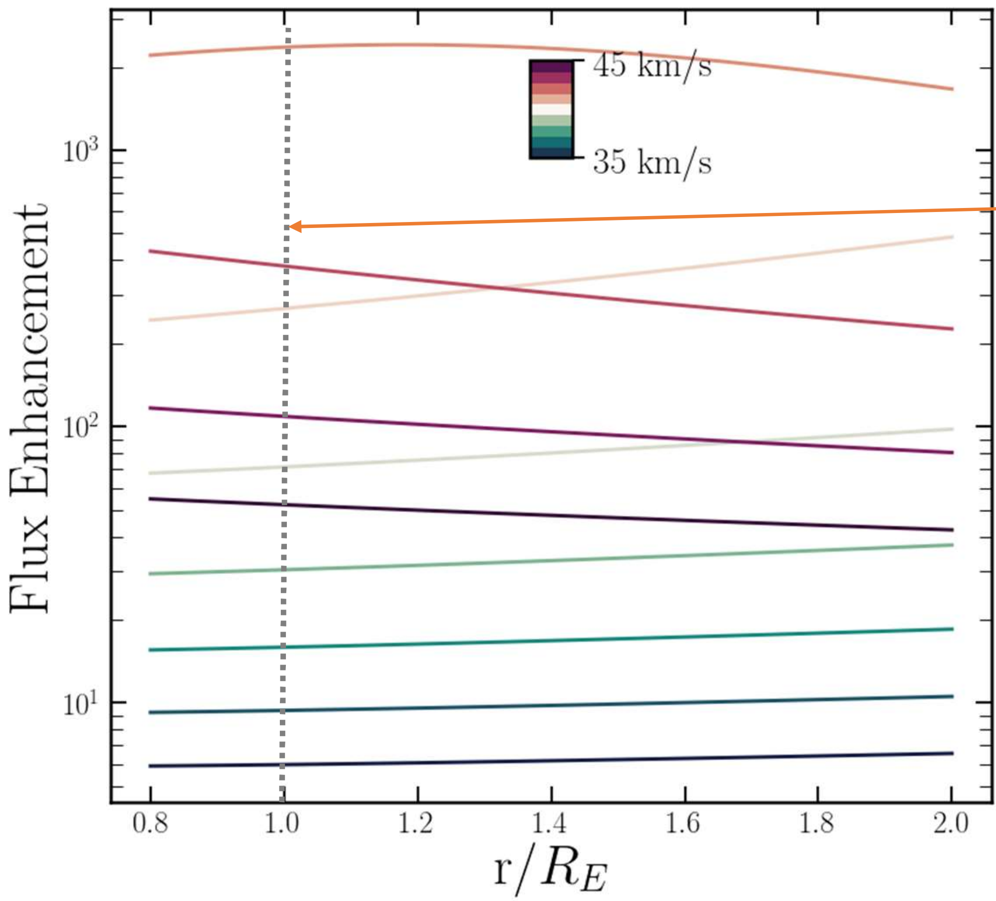
Dispersion and modulation effects reduce the amplification however for Axions detectors that can tune to particular band even a conservative amplification of 100 with a diurnal signature would be of interest for DM stream studies

Gravitational effects by the Moon and Earth together on a fine-grained stream



Example of a stream of 41 km/s wrt geo-center experiences gravitational focusing from the Moon and Earth

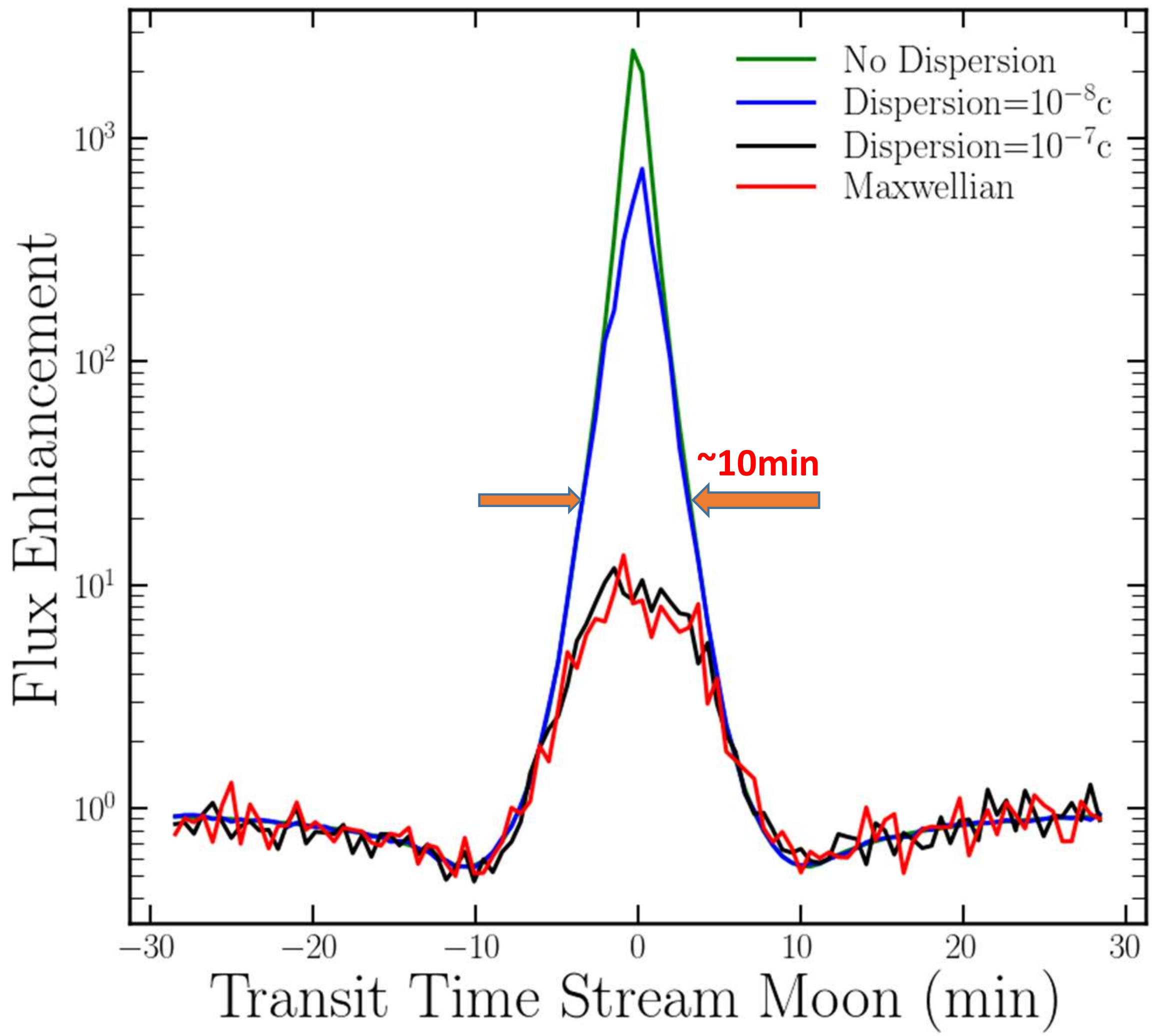
Enhancements by the Moon-Earth for different velocities



Flux Enhancement for different heights from center of the Earth

The dashed line shows enhancements at the surface of the Earth

Enhancements of ~2000 achieved on surface on the Earth for 41 km/s streams wrt Earth



The Enhancements for different dispersion values and for a stream of velocity 41 km/s.

The transit time represents how long this enhancement lasts as the moon moves around the Earth

This could manifest itself as a 20 minute transient in an Axion detector

Preliminary Summary & Outlook

- **Sun, Moon, and Earth individually can focus dark matter at Earth's position with density enhancement examples**
  - **~3000 (220 km/s wrt Sun),**
  - **10^6 (13 km/s wrt Earth)**
  - **and ~10^5 (~40 km/s wrt Earth)**
- **The larger the dispersion the smaller the density enhancements**
- **Overall these preliminary studies show that density enhancements from 100-10^6 could be achieved for individual streams which would be beneficial for axion searches since they can be tuned to narrow-bands and especially when correlated with diurnal time.**
- **The dynamics of slow moving streams on moving Earth needs to be understood better**
- **The overall density of dark matter depends on weight contribution of each stream and is subject of further investigation. Multi-stream effects will continue to be investigated.**

Back Up Slides

Sofue (2020)

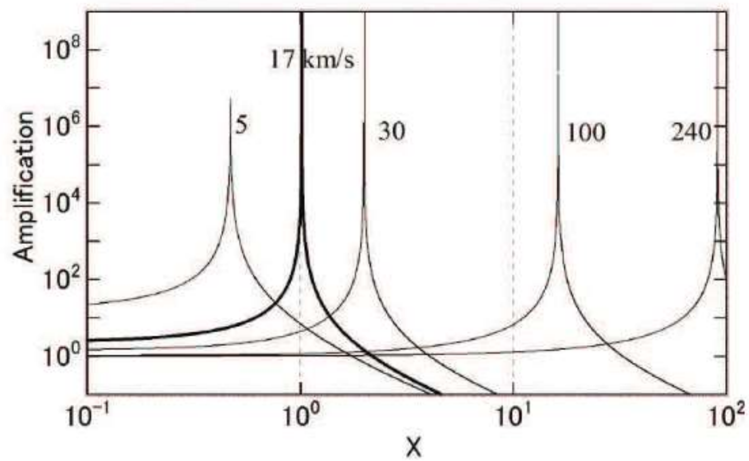


Figure 5: DM flux amplification by the Earth for injection velocities 5, 17, 30, 100, and 240 km s^{-1} . DM flow with $v_{\rm inj}$ = 17 km s^{-1} focuses on the Earth's surface with the focal length equal to $R_{\rm E}$ at high amplification. Lower/higher velocity flows focus inside/outside the Earth with shorter/longer focal length than $R_{\rm E}$.