# Gravitational focusing effects on streaming dark matter as a new detection concept

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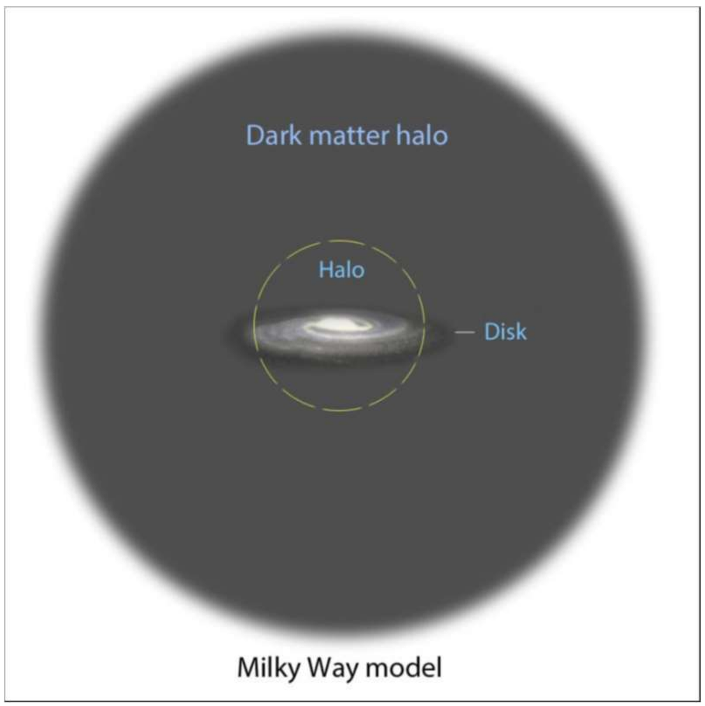
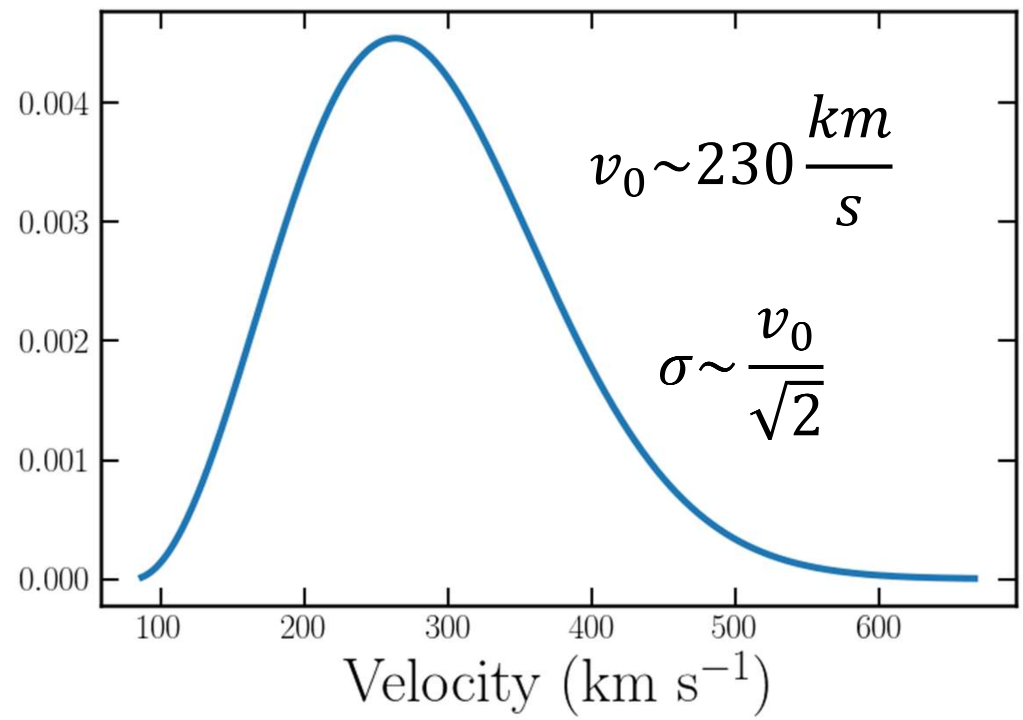
# Standard Halo Model (SHM)

Isothermal sphere with $\rho \sim \frac{1}{r^2}$ and $f(v) \sim e^{-\frac{v^2}{{v_0}^2}}$



WIMPs

Rate on detectors depends on

$$Rate \sim \sigma \cdot \int \rho \cdot \frac{f(v)}{v} dv$$

Cross Section of processes from Particle Physics

Astrophysics & Cosmological Simulations

Axions

Power Spectrum

$$\frac{dP}{d\omega} \sim g_a^2 \, \rho \, \frac{f(v)}{m_a^2}$$

Phase-space distribution impacts rates and power in detectors.

# Fine-Grained Streams and Cosmological Simulations

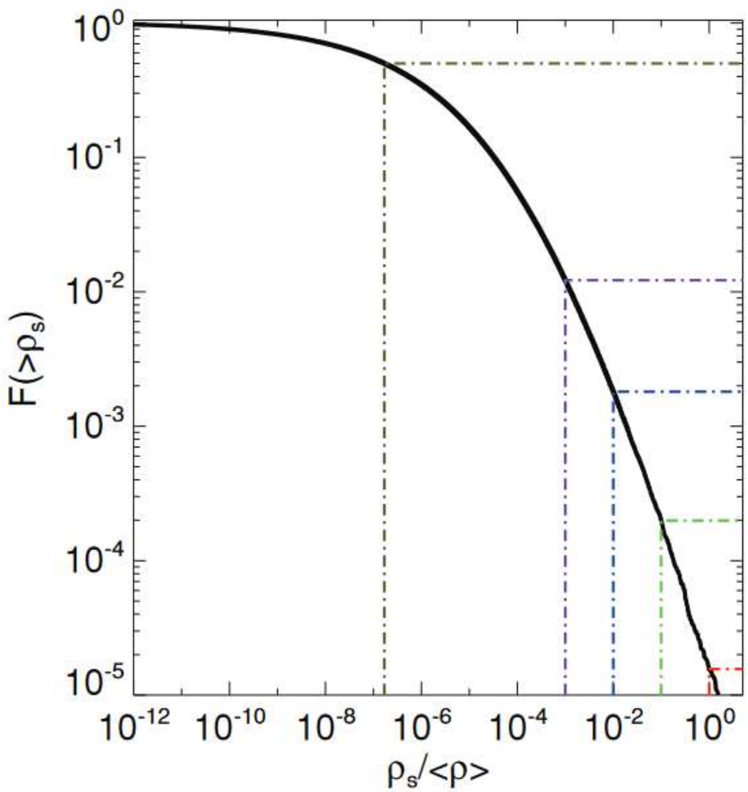
The cold nature of dark matter yields particles with nearly zero dispersions ( ~$10^{-17}$ c for axions and $10^{-10}$ c for WIMPs) at the last scattering

Cosmological simulations show fine-grained nature with very small dispersion. These cosmological streams are different from tidal streams which are caused by sub-halo disruptions.

The DM distribution at a
typical point in the halo is described as a superposition of many fine-grained streams with discrete velocity distributions, each of which has a very small velocity dispersion

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

# Fine-Grained Stream Abundance




Streams with different densities and their probability in solar neighbourhood.

| Density ($\rho_s/\rho_0$) | Number of streams | Probability (%) |
|---|---|---|
| 1 | 1 | 0.002 |
| 0.1 | 1 | 0.2 |
| 0.01 | 1 | 20 |
| $10^{-3}$ | 10 | 100 |
| $10^{-4}$ | 500 | 100 |
| $10^{-5}$ | $2 \cdot 10^4$ | 100 |
| $10^{-6}$ | $4 \cdot 10^5$ | 100 |
| $10^{-7}$ | $2 \cdot 10^6$ | 100 |

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**2 million streams with density> $10^{-7}$ $\rho_0$**

## Fine-Grained 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-grained particles to include:

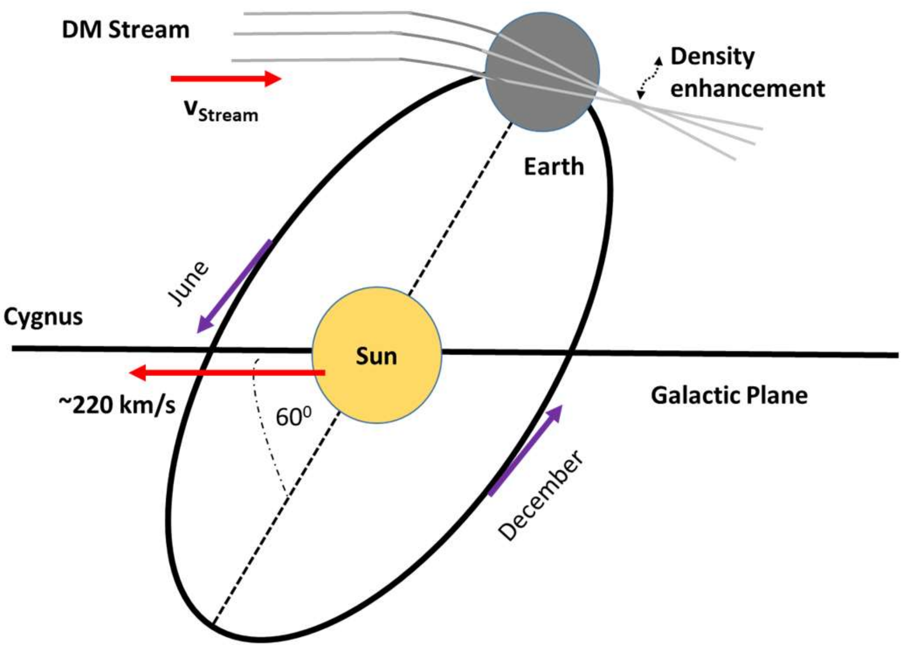
- Dispersion
- Multi-body effects (e.g, Sun, Earth)
- Stand-alone N-body simulation could be adapted by DM groups to calculate the gravitational effects on phase space

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

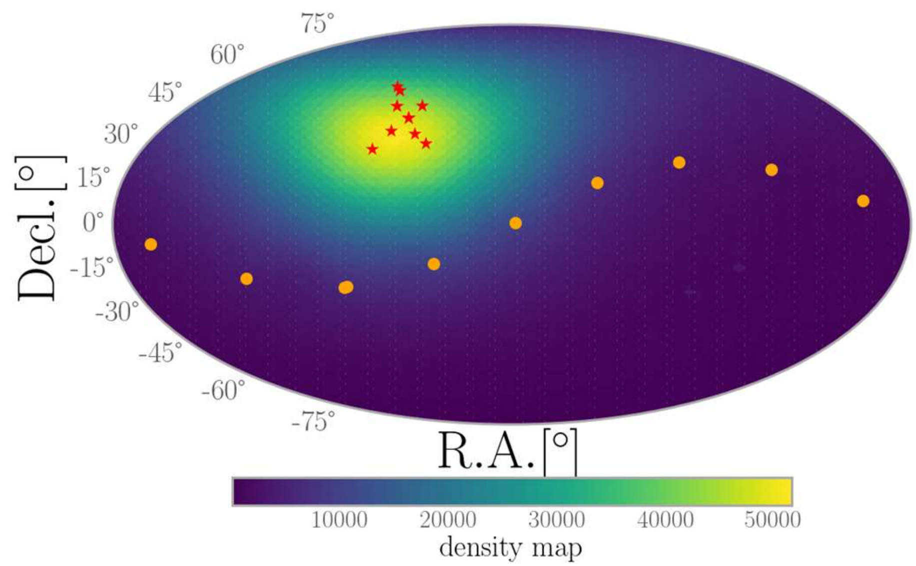
$$m_i \frac{dv_i}{dt} = -\sum_{j=i+1}^{n} \frac{G m_i m_j}{|r_i - r_j|^3}(r_i - r_j)$$ Outside Solar Bodies

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

Schematics of solar system headed towards the Cygnus and illustration of a stream experiencing gravitational effects by the Sun and the Earth

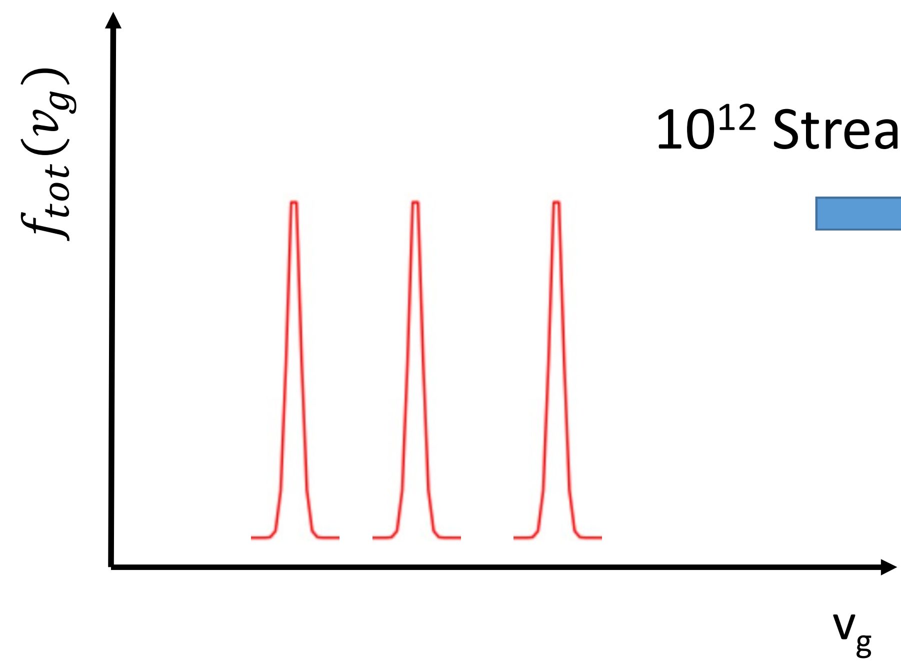



Simulated particles arrive with a peak around Cygnus (Red) as expected from other findings

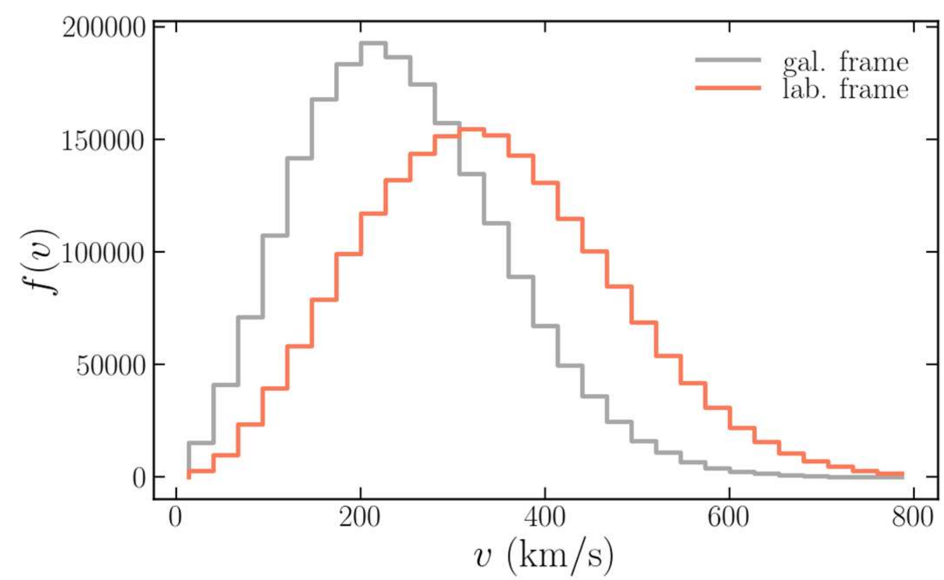


**Superposition of many fine-grained streams appears as the overall Standard Halo Model velocity distributions**

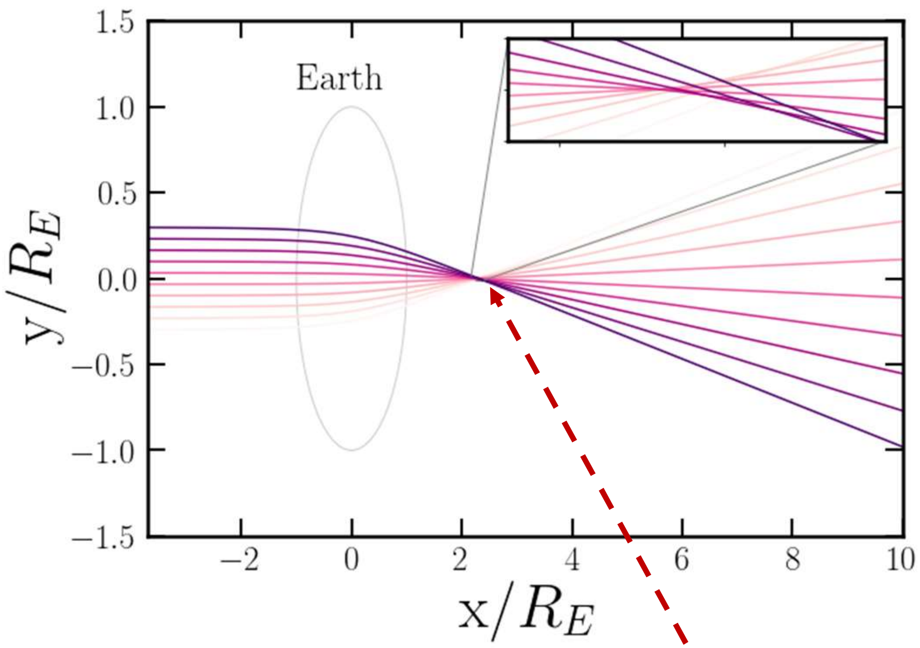
$$f_{\rm tot}(\mathbf{v_g}) = \sum_{\mathbf{i}} \mathbf{N_{si}} \delta^{\mathbf{3}}(\mathbf{v_g} - \mathbf{v_{si}})$$



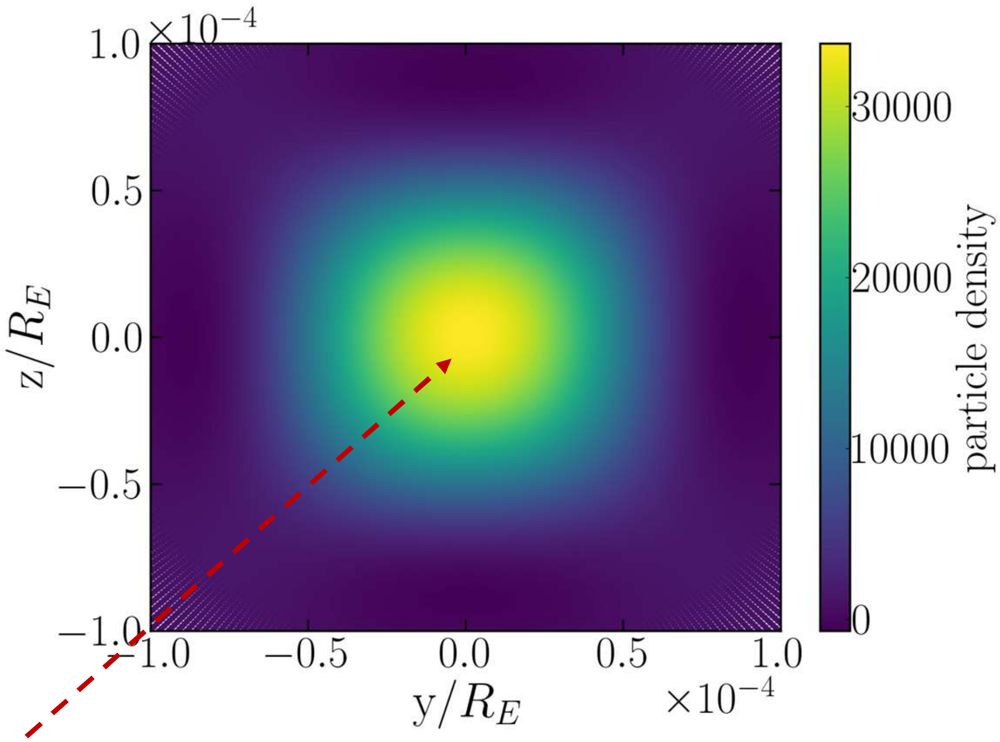

$10^{12}$ Streams



Particles from one stream focus by the inner Earth.

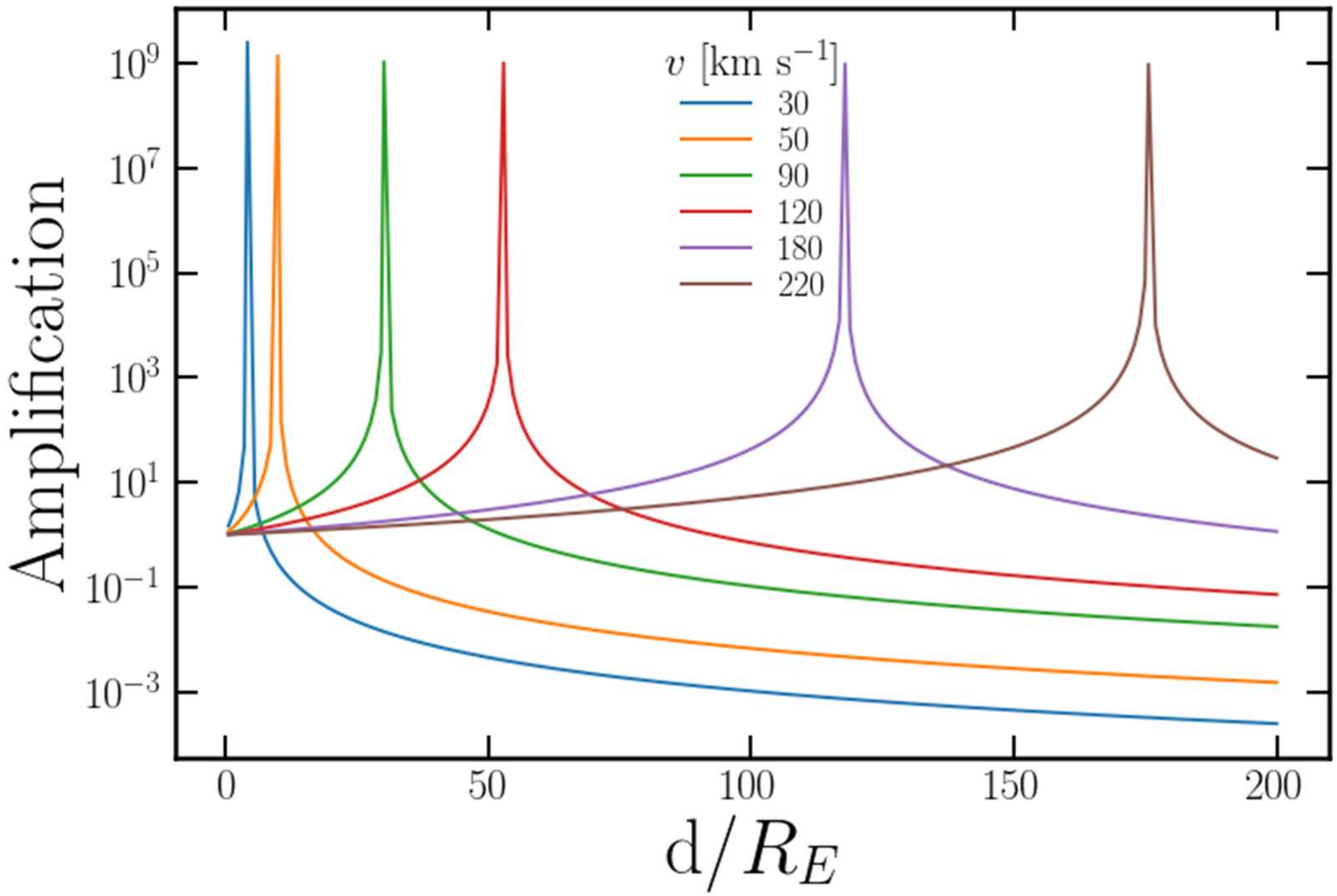



Y-Z projection of simulated particles arriving through the Earth at the focus point.




Gravity Produced Density Enhancement (DE)

Max amplification for dispersion-less streams ~ $10^9$



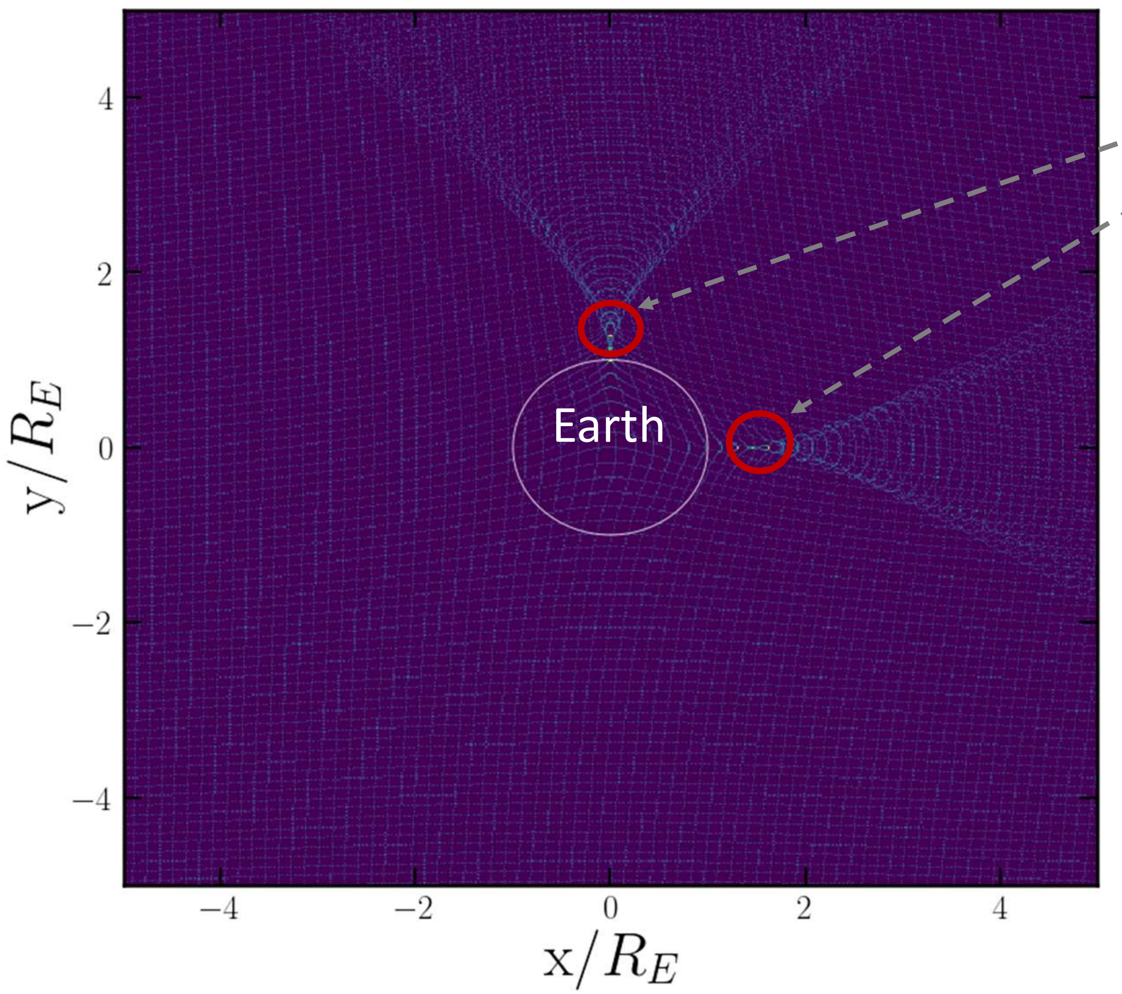

d is the distance from the center of the Earth

Amplification Definition:

$$A \approx \frac{S_0}{S_f} = \frac{\pi r_0^2}{\pi r_{\mathrm{f}}^2};$$

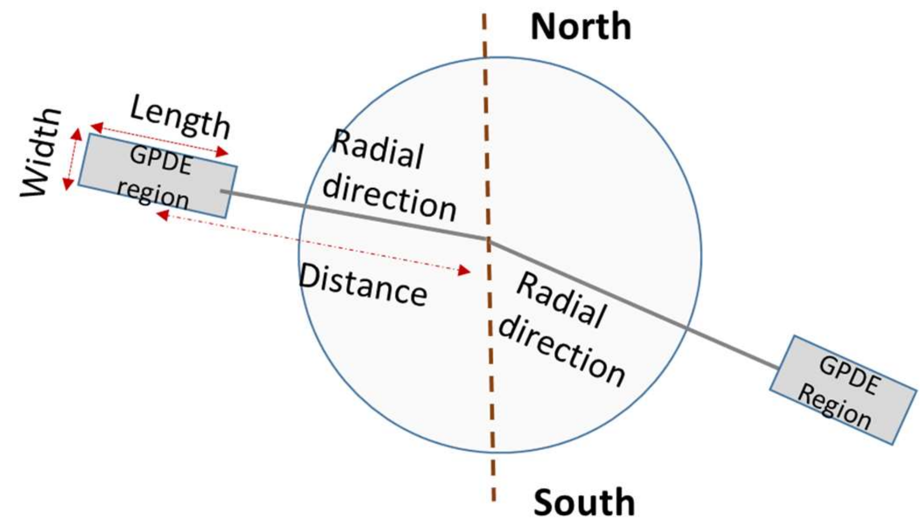
Density After Focusing

$$\rho \sim A_j \rho_{sj}$$

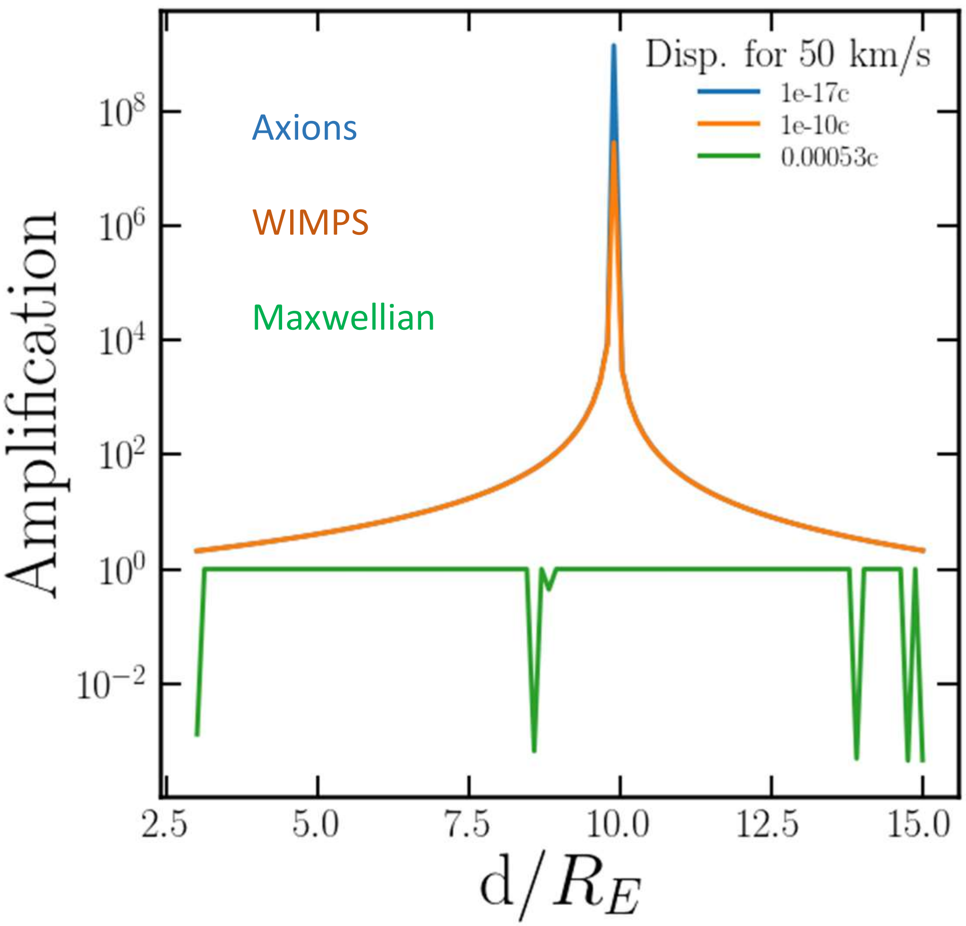



**Density plot showing how two streams form two density enhancement regions**

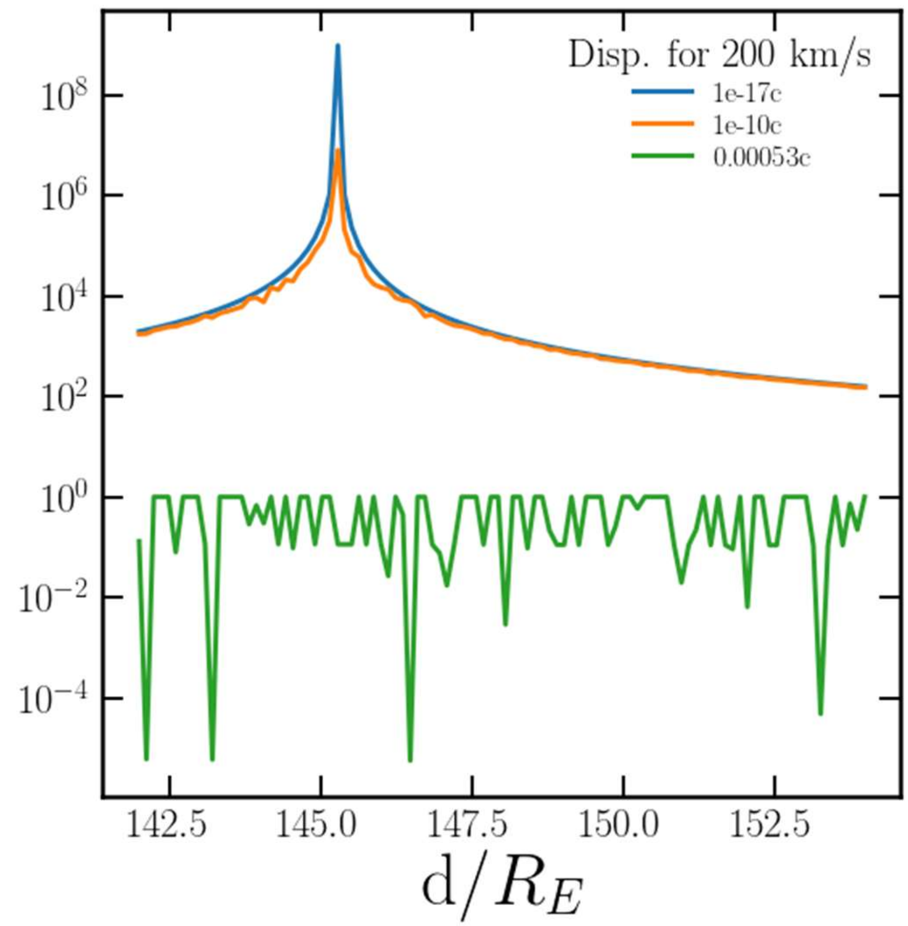
**Note: In a smooth SHM these features will not be there**



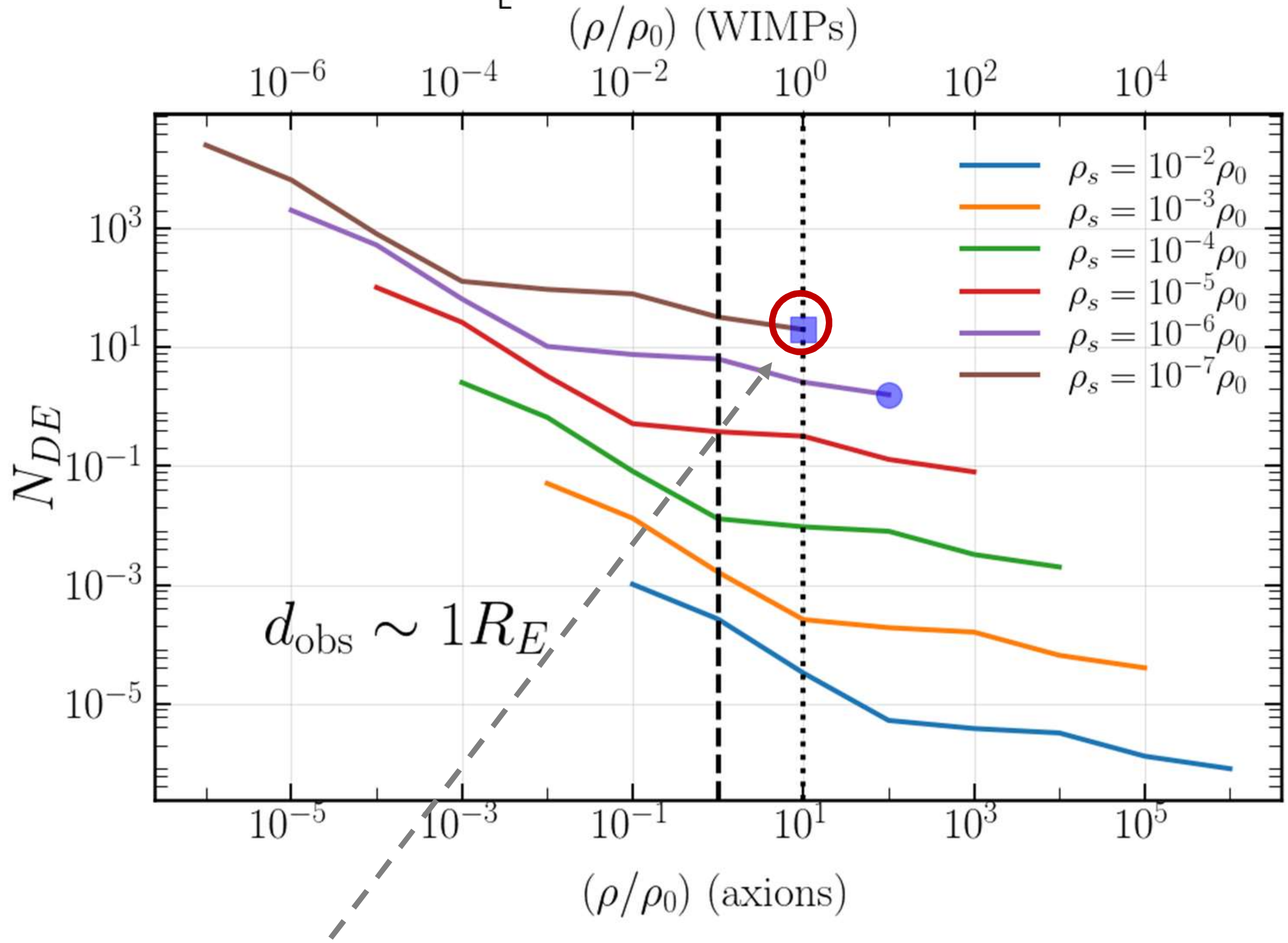
Max amplification axions ~ $10^9$




Max amplification WIMPs ~ $10^8$



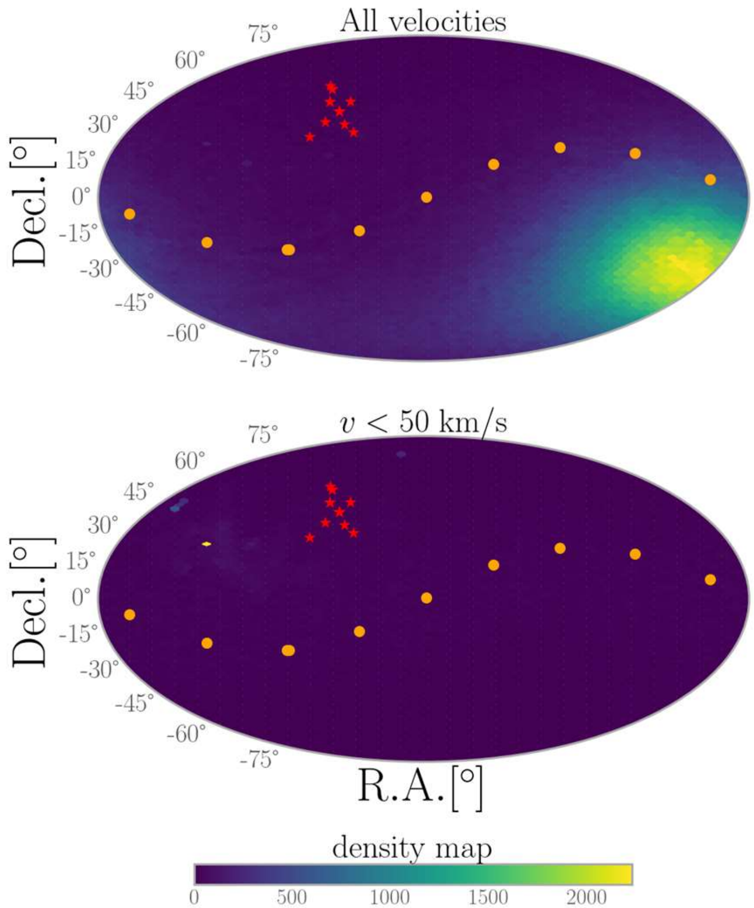
Number of streams with particular density, and amplifications where density enhancements are located at about $1R_E$




Few streams with density (10 $\rho_0$ axions) and (1 $\rho_0$ WIMPs)

# DE regions distribution map for axion and WIMP streams

All streams

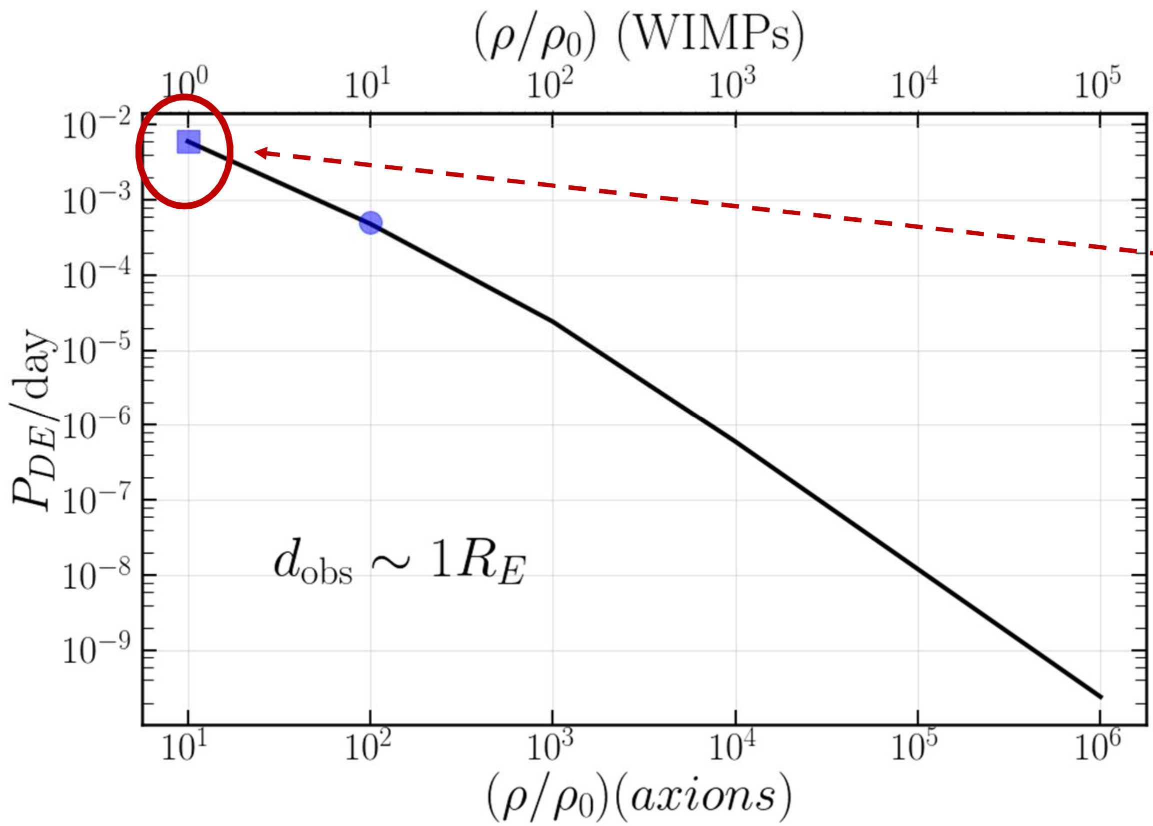



Low speed streams <50 km/s

**Isotropic distribution which means any geographical location is equal probability to detect  DE regions**

$$P_{DE}/\mathrm{day} \sim N_{DE} N_{\mathrm{det}} P_{\mathrm{loc}}$$

$$P_{\mathrm{loc}} \sim \max\left(\frac{2\pi d_{\mathrm{obs}} \cos(\phi)(2r_{\mathrm{ave}})}{4\pi d_{\mathrm{obs}}^2}, \frac{\Delta\Omega}{4\pi}\right)$$




$N_{DE}$/day ~ 0.005 for axions with density of $10\rho_0$

$$t_{\mathrm{enc}} \sim \frac{2\, r_{\mathrm{ave}}}{(d_{\mathrm{obs}}/R_E)\, 0.5 \cos(\phi)}$$

$t_{enc}$ ~ 10 seconds

## Summary & Outlook

- There are enhanced DM fluxes following planetary gravitational lensing effects, resulting to caustics-like configurations in particular when the gravitational self-focusing effects by the inner Earth are at work.

- Likelihood that one terrestrial experiment can encounter an axion density enhancement of $10\rho_0$ per day is about 0.005. In comparison, WIMPs are about a factor of 10 smaller.

- Transient events due to Earth's rotation. The expected signatures last about 10 seconds and it's a unique signature in the search of streaming DM.

- A potential new method to detect and identify DM cosmological streams with Earth bound experiments like the ongoing or future DM searches.

- A network of detectors looking for transient signals (~1-10 s) is the ideal way to utilize the predicted density enhancements.