PHASE-SPACE STRUCTURE OF THE MILKY WAY'S DARK HALO

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Overview

- Dark matter phase-space distribution and detection.
- Evolution and phenomenology of cold dark matter in phase-space.
- Predictions for the Milky Way halo.
- Is this substructure important in our galaxy?

Cold dark matter

- Contributes $\sim 80\%$ of the total matter in the universe (baryons $\sim 20\%$)
- Forms galactic halos - visible galaxies are located at the center of more massive, dark halos
- Non-relativistic, with small velocity dispersion (matter-radiation equality):
  - axions: $\delta v_a \sim 10^{-14} c$ (zero mode)
  - WIMPS: $\delta v_W \sim 10^{-7} c$
- The only significant interactions are gravitational (collisionless)

Dark matter detection

- WIMP direct detection:
  - Measure the number of recoils per energy bin (dN/dE)
  - $E \propto v^2$
  - Rate $\propto$ local density
- Axion direct detection:
  - Look for resonant conversion of axions to photons by measuring power output from a microwave cavity
  - Signal amplitude $\propto$ local density
  - Signal width: $\delta\nu = \nu v \delta v$

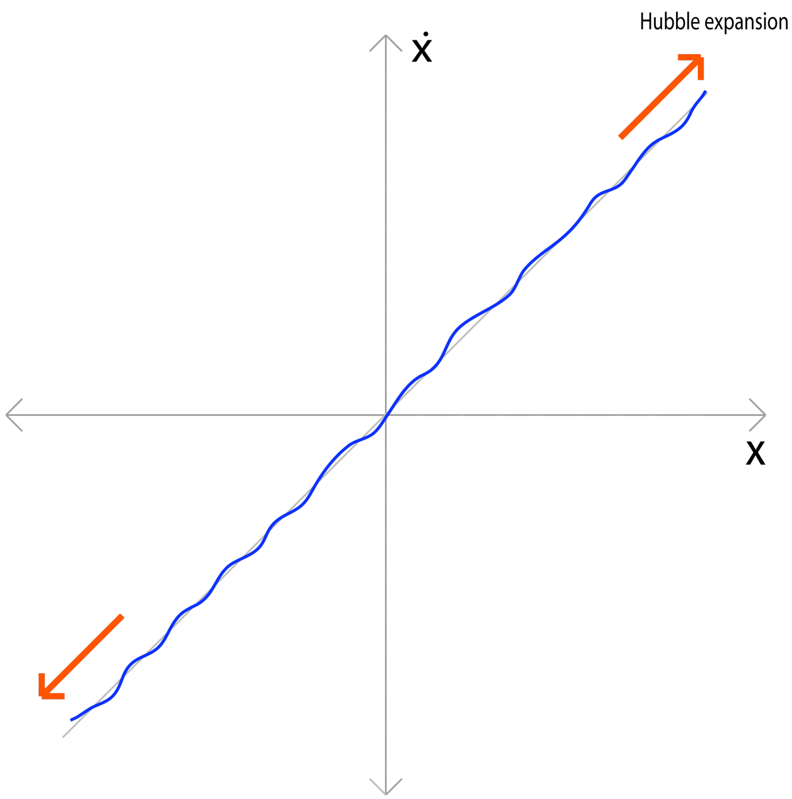
- WIMP indirect detection:
  - Search for decay or annihilation products (e.g. γ, e^-, e^+, $\overline{p}$, νs...)
  - Decay rate $\propto \rho$
  - Annihilation rate $\propto \rho^2$
  - Weak dependence on non-relativistic velocities

Knowing the phase-space distribution, $f(\mathbf{x}, \mathbf{v})$, would aid dark matter detection efforts.

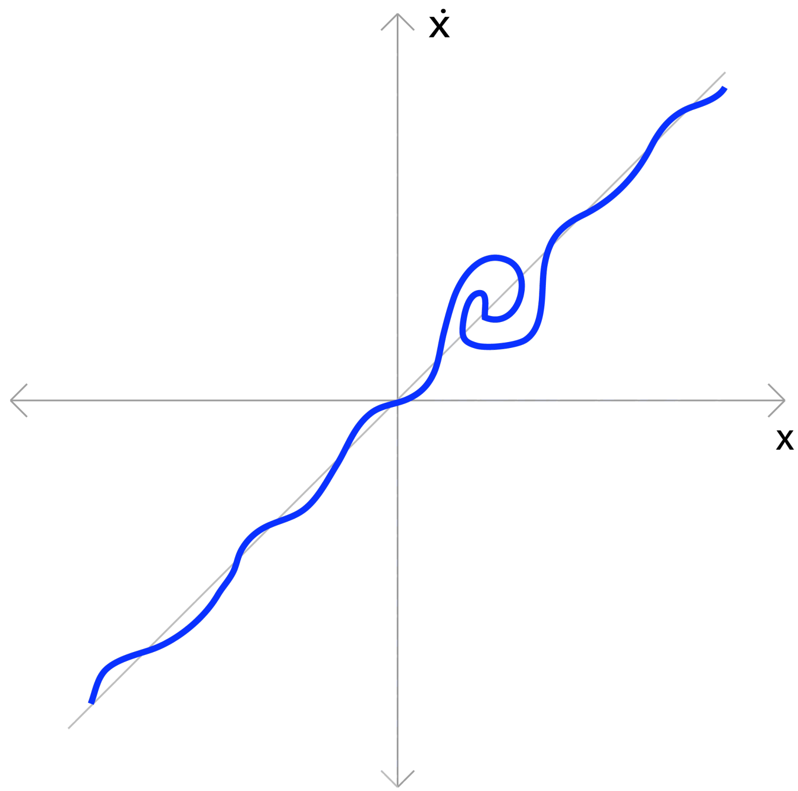
CDM phase-space

- Phase-space is 6-D
- For negligible velocity dispersion, CDM is restricted to lie on a 3-D hypersurface in the 6-D space

Hubble expansion



Gravitational infall



Phenomenology

- An observer in a simple overdensity will see two main features: **flows** and **caustics**.

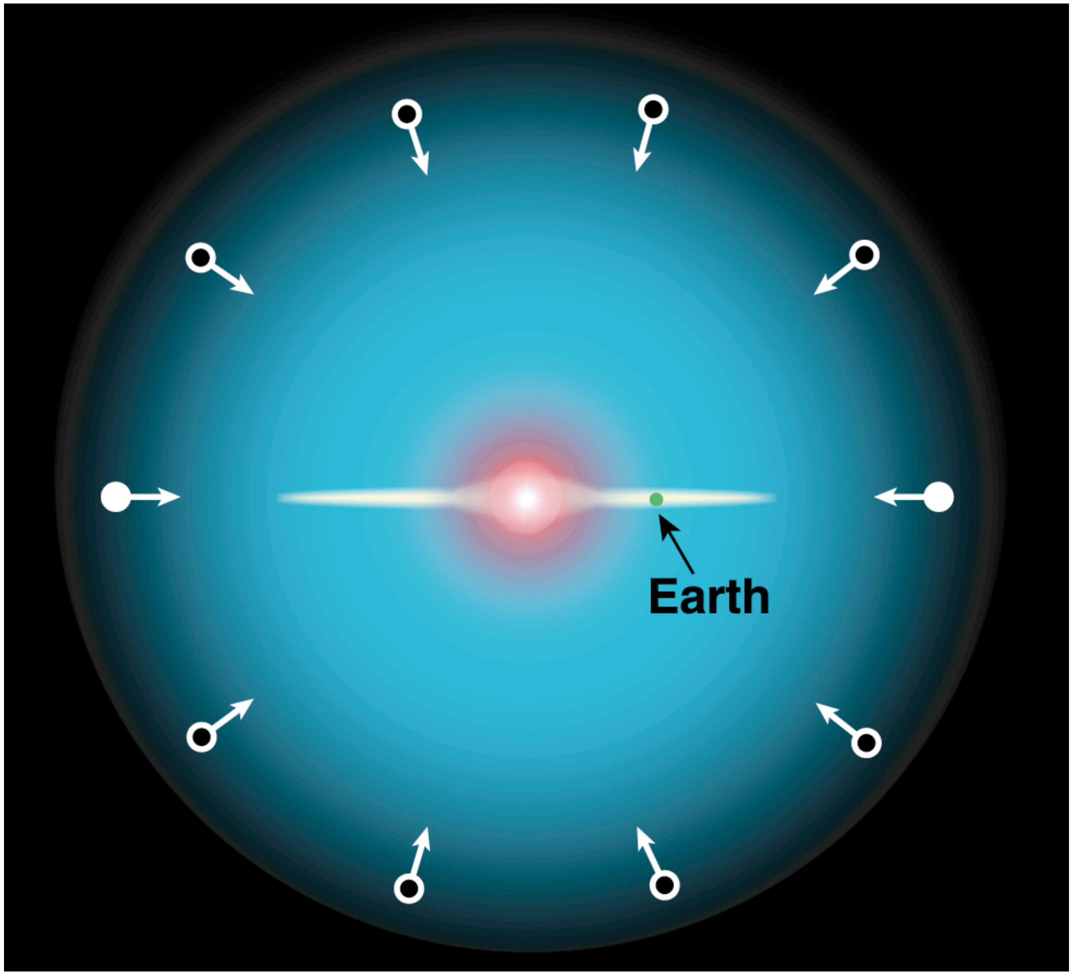
- Caustics form where the mapping from phase space to physical space goes from n-to-one to $(n \pm 2)$-to-one.

- Caustics are regions of high density in physical space.

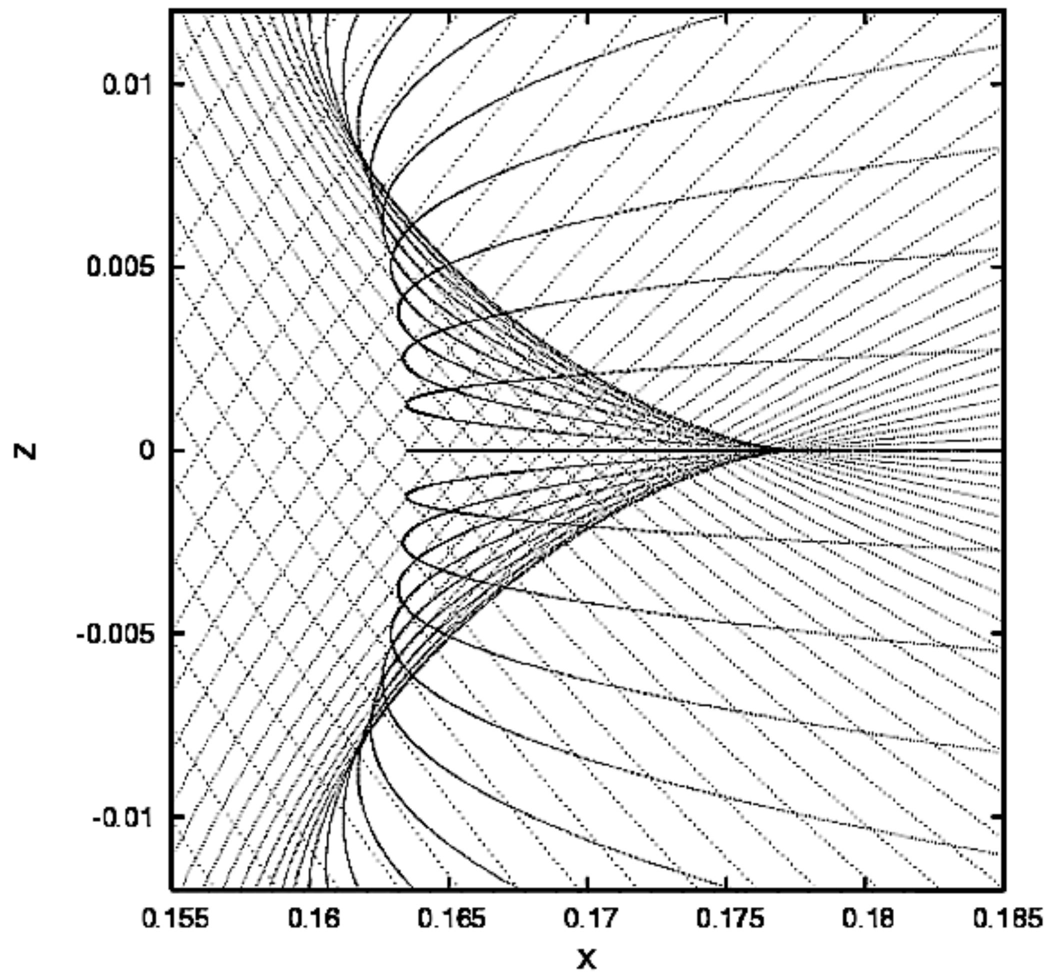
The Caustic Ring Model

- Follows simple evolution of CDM in phase-space
- Model is self-similar, therefore known properties of the Milky Way galaxy today can be used to fit for the phase-space distribution of CDM
- Our recent work characterizes the phase-space distribution of Milky Way halo for current best parameters
- The caustic ring model contains two types of caustics: outer (spheres) and inner (rings).

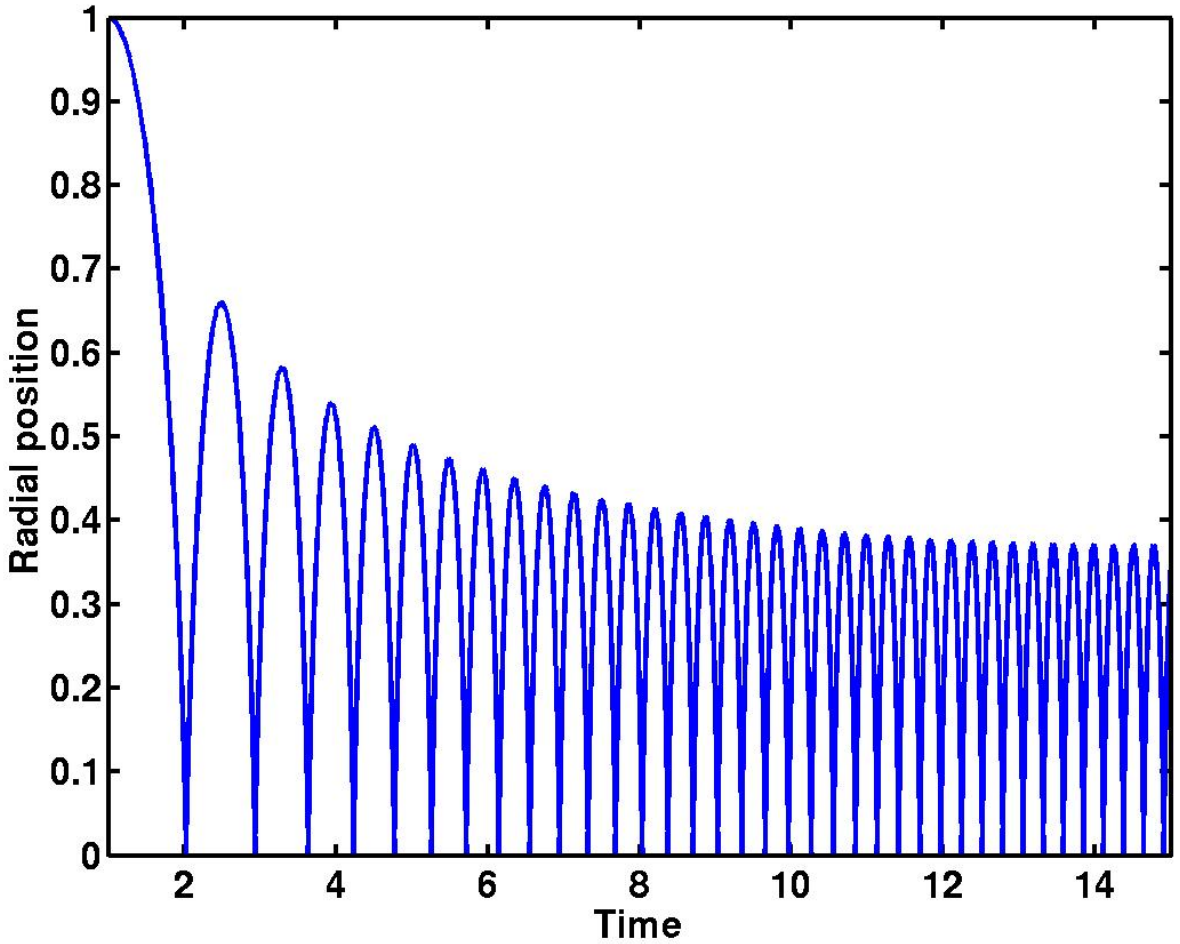
Physical picture



Cross-section of Caustic Ring



Particle Trajectories



Predictions

(See LD & P.Sikivie, PRD **78**, 063508 (2008) for full details)

- Outer caustics: radii and DM densities
- Inner caustics: locations, DM velocities and mass infall rates
- DM flow densities and velocities on Earth
- The “Big Flow”:

$$\rho_{BF} = 1.5 \times 10^{-24} \mathrm{g}/\mathrm{cm}^3 \quad (1)$$

Some caveats

• The late accelerated expansion of the universe introduces a scale – evolution is no longer self-similar.

• Virialization of the inner halo will remove early caustic structure – late infall of cold dark matter can still produce caustics and coherent flows.

• How significant caustic structure is within a galactic halo is still an open question.

• Model assumes a smooth potential. Perturbations to the potential will distort caustic structure (see Natarajan & Sikivie, 2006). Infalling dark matter must have $\delta v << v_{esc}$.

Debate

(1) Simulations:

- Issue with resolution (Diemand et al., 2008; Diemand & Kuhlen, 2008; Vogelsberger et al., 2008).
- New techniques to locate streams, but not their properties (Vogelsberger et al., 2007).

(2) Theory:

- New general framework, which does not require symmetry or smooth accretion (Afshordi, Moyahaee & Bertschinger, 2008).
- Gives predictions for statistical properties.

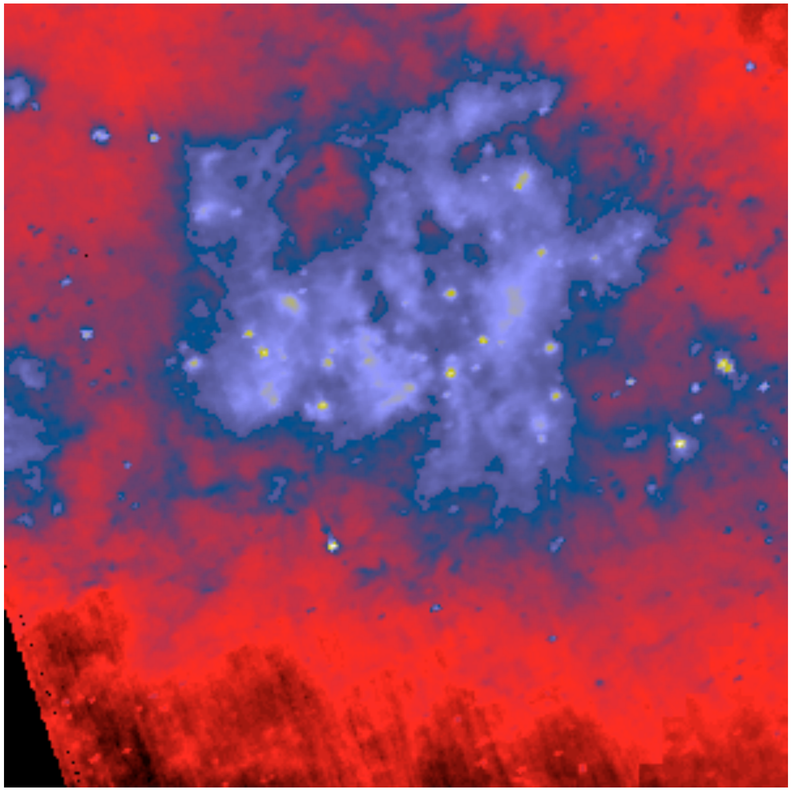
Simulations

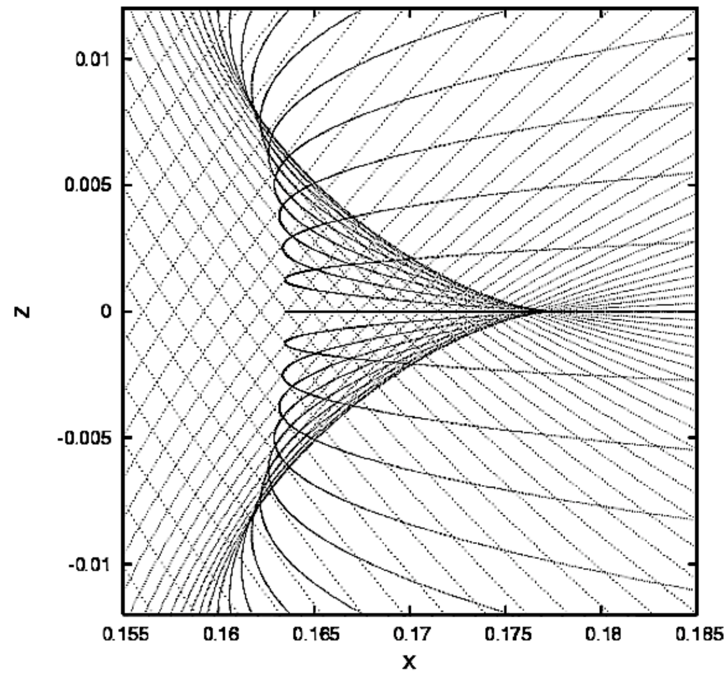
- 10^5 particles in 2 kpc^3 gives 1 particle per 8×10^4 pc^3 (Vogelsberger et al., 2008).
- The scale of a caustic is $\sim$20 pc, so the related volume scale is $\sim8\times10^3$ pc^3.
- We actually need to resolve phase-space, which is 6 dimensional, not 3.

Summary

- Discrete flows and caustics are a consequence of cold dark matter.
- Late infall of dark matter may lead to significant caustic substructure. We have characterized the caustic ring model for our galaxy.
- Such substructure, if significant, will have important consequences for dark matter detection.

Is this a caustic?





See http://www.phys.ufl.edu/∼sikivie/triangle/index.htm for more.