Dark Matter Caustics

Dark Side of the Universe 2007

Minneapolis, June 5 -10

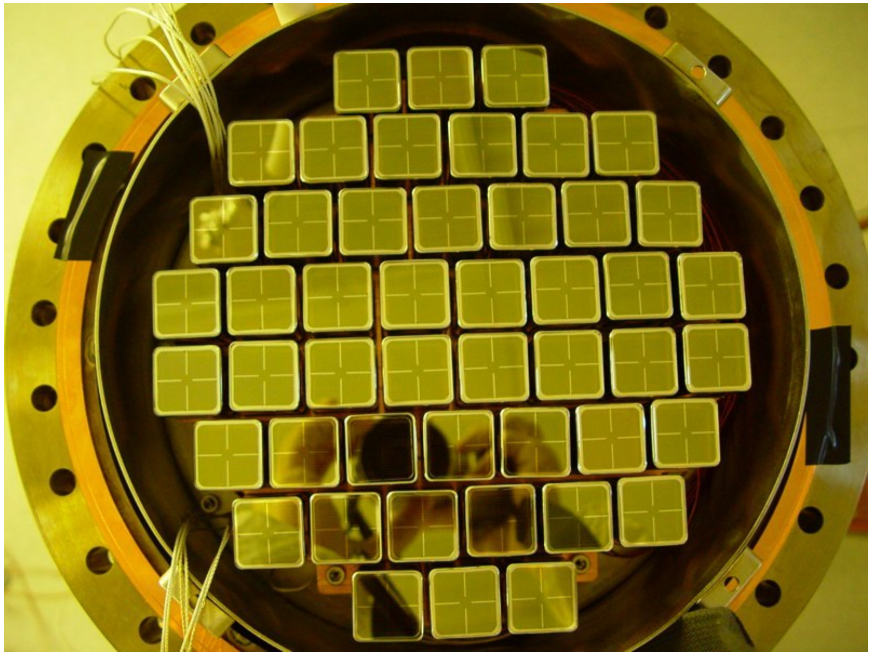
Pierre Sikivie (U of Florida)

Elucidating the structure of galactic halos is important for

- understanding galactic dynamics
- predicting signals for dark matter searches

WIMP detectors

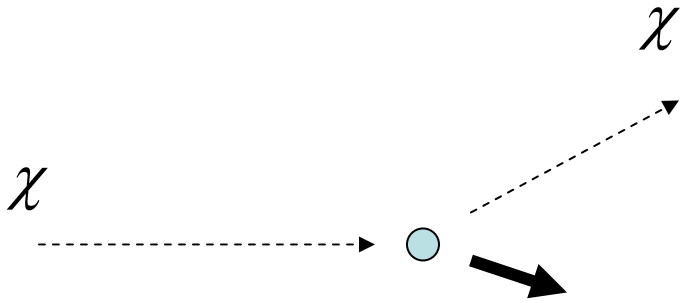
CDMS



Xenon

Also: DAMA, Edelweiss, CRESST, ZEPLIN, …

WIMP – nucleus elastic scattering



ionization, scintillation, phonons …

$$\frac{dR}{dE_r} \propto \sigma_0 \;\; \rho_\chi \;\; F(q) \;\; T(E_r)$$

$$T(E_r) = \frac{\sqrt{\pi}}{2}(220\mathrm{km/s}) \int_{\mathrm{v}_{\min}(E_r)}^{\infty} d\mathrm{v} \frac{f(\mathrm{v})}{\mathrm{v}}$$

Axions

- solve the Strong CP Problem of the Standard Model

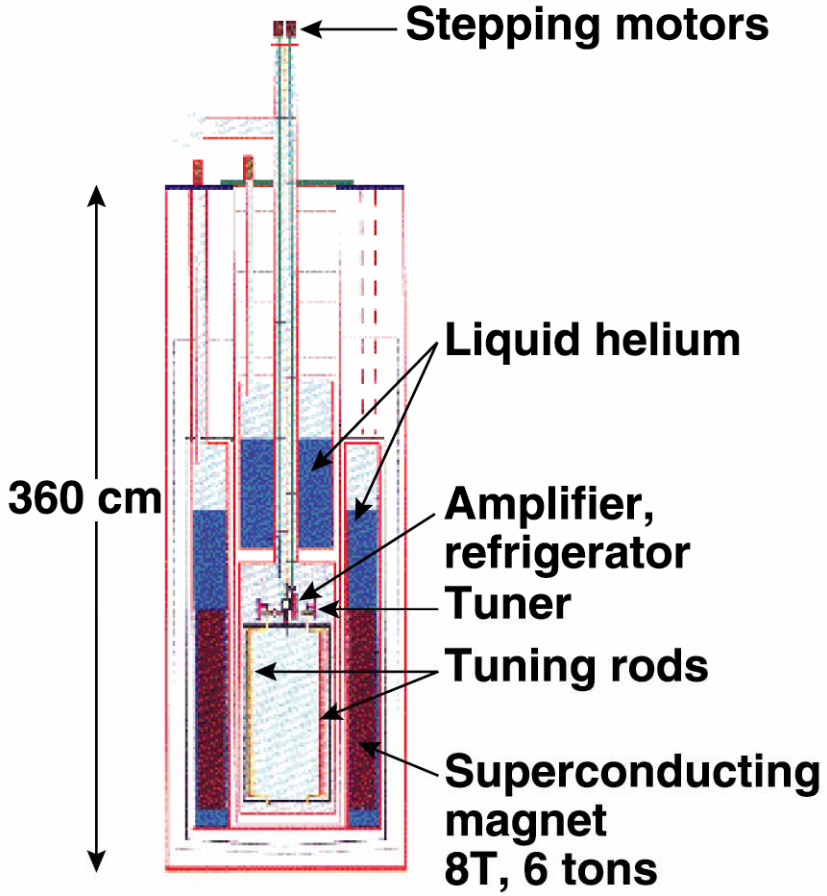
- are a cold dark matter candidate when mass $m_a : 10^{-5}\ \mathrm{eV}$

- require only a gentle modification of the Standard Model

- are detectable by the cavity technique

Axion Dark Matter eXperiment

Magnet with Insert (side view)



Stepping motors

360 cm

Liquid helium

Amplifier, refrigerator

Tuner

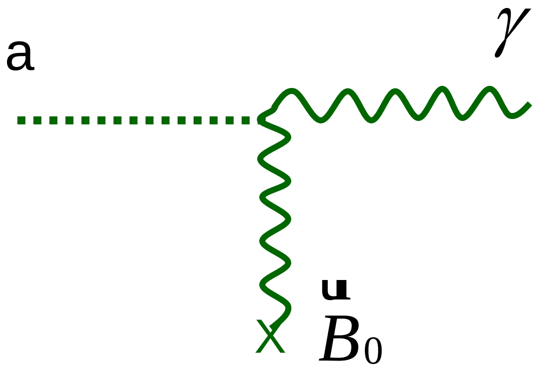
Tuning rods

Superconducting magnet 8T, 6 tons

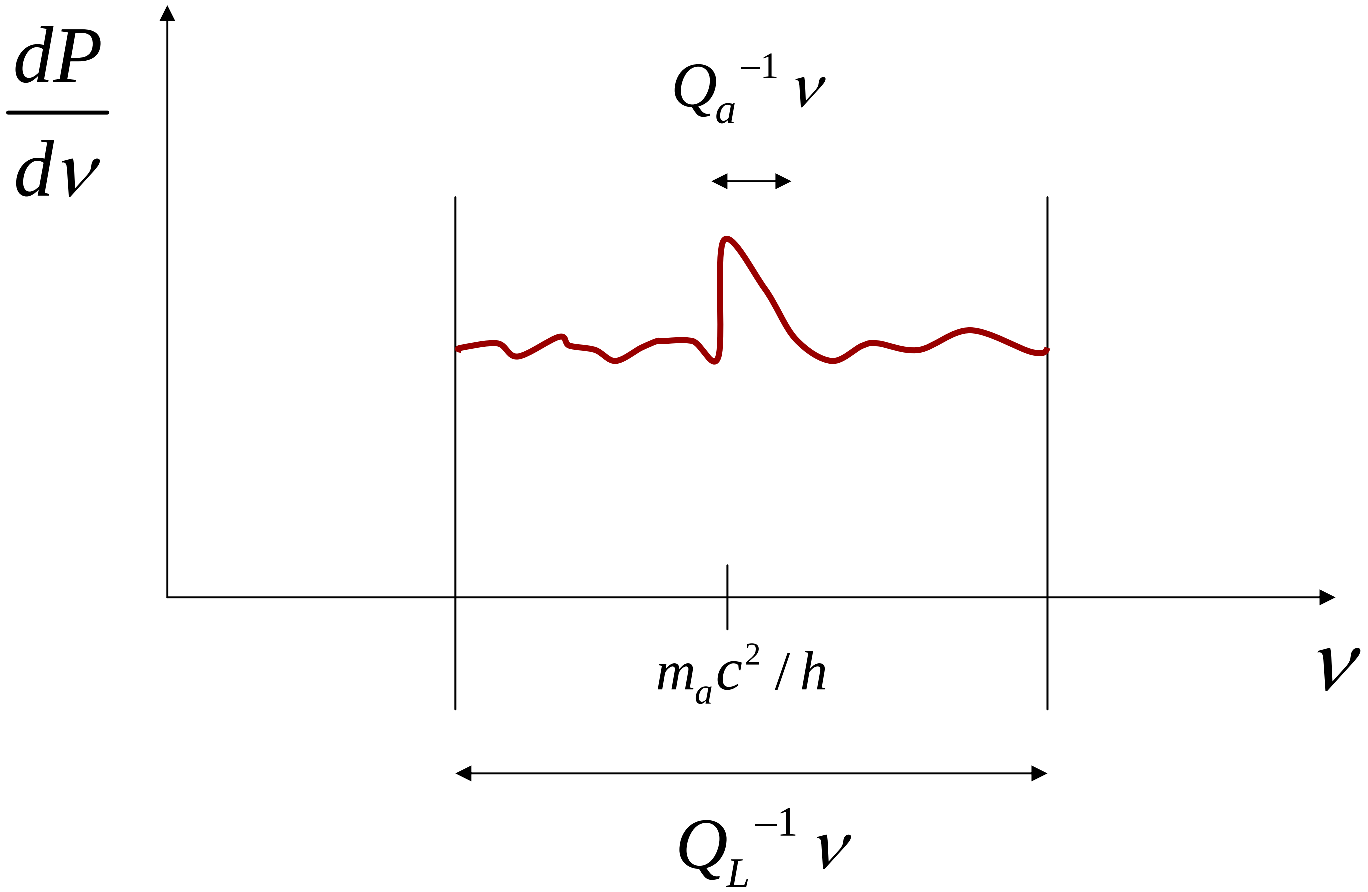
Pumped LHe → T ~ 1.5 k

Magnet

8 T, 1 m × 60 cm ∅



$$h\nu = m_a c^2 \left(1 + \frac{1}{2}\beta^2\right)$$



ADMX

- has reached sufficient sensitivity to detect galactic halo axions in favorable cases (KSVZ coupling)

- is being upgraded with SQUIDs (50 mK noise temperature vs. 2 K with HEMTs)

- when cooled to 50 mK, will have sensitivity to detect dark matter axions at even a fraction of the halo density. The remaining challenge will be to extend the searchable mass range.

- if a signal is found, will be able to measure the local CDM velocity distribution in detail

Galactic halos live in phase space

ordinary fluid

$$d(\vec{r};t) \qquad \vec{v}(\vec{r};t)$$

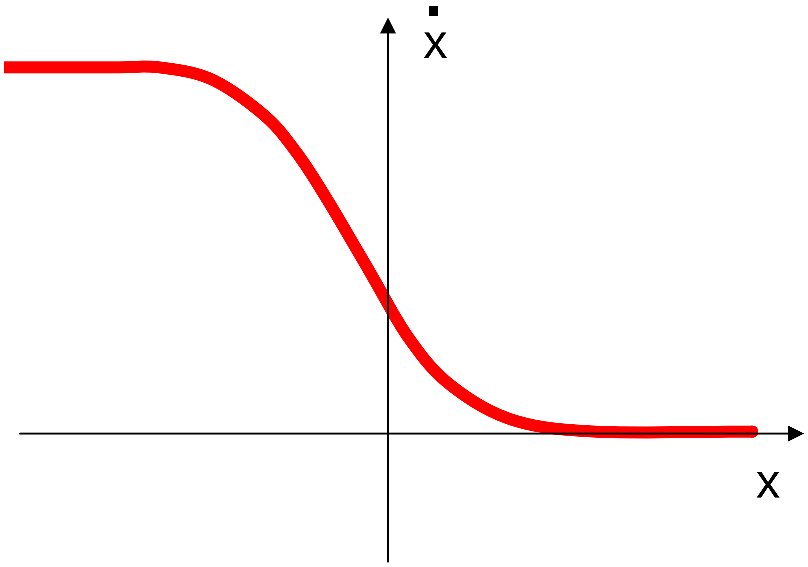
dark matter (collisionless) fluid

$$f(\vec{r},\vec{v};t)$$

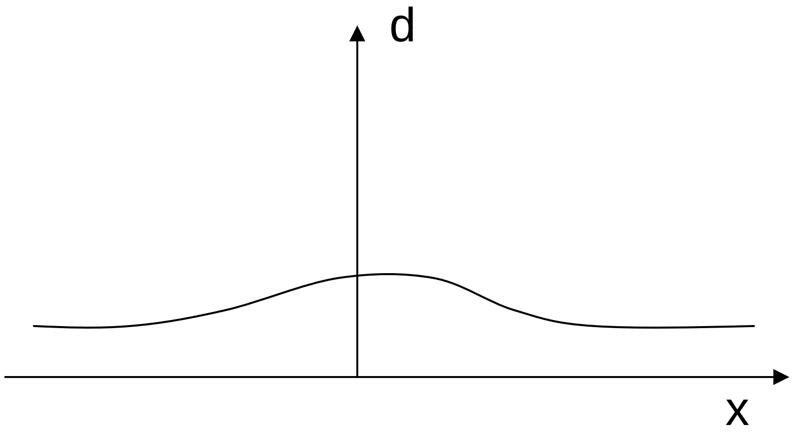
Galactic halo models

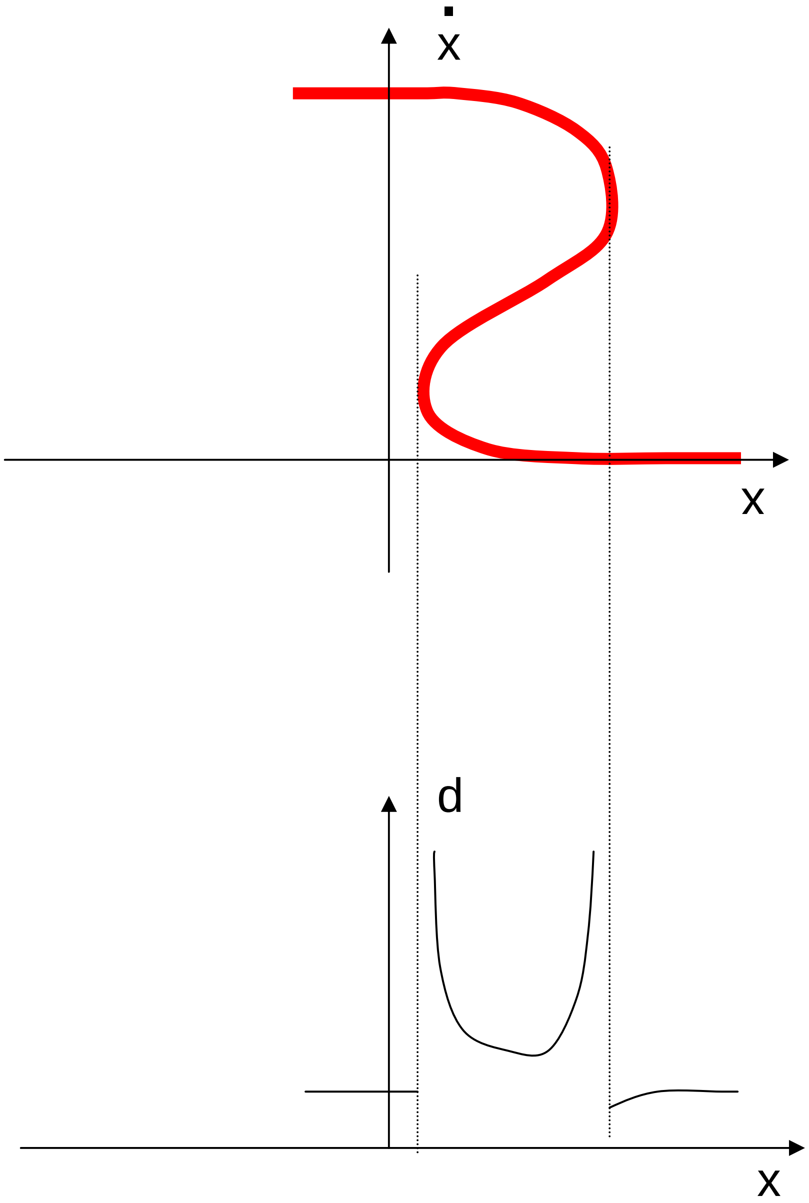
model	complaint
Isothermal sphere	late infalling particles do not thermalize
N-body simulations	present resolution is inadequate
Caustic ring model	

Caustics in cold dark matter



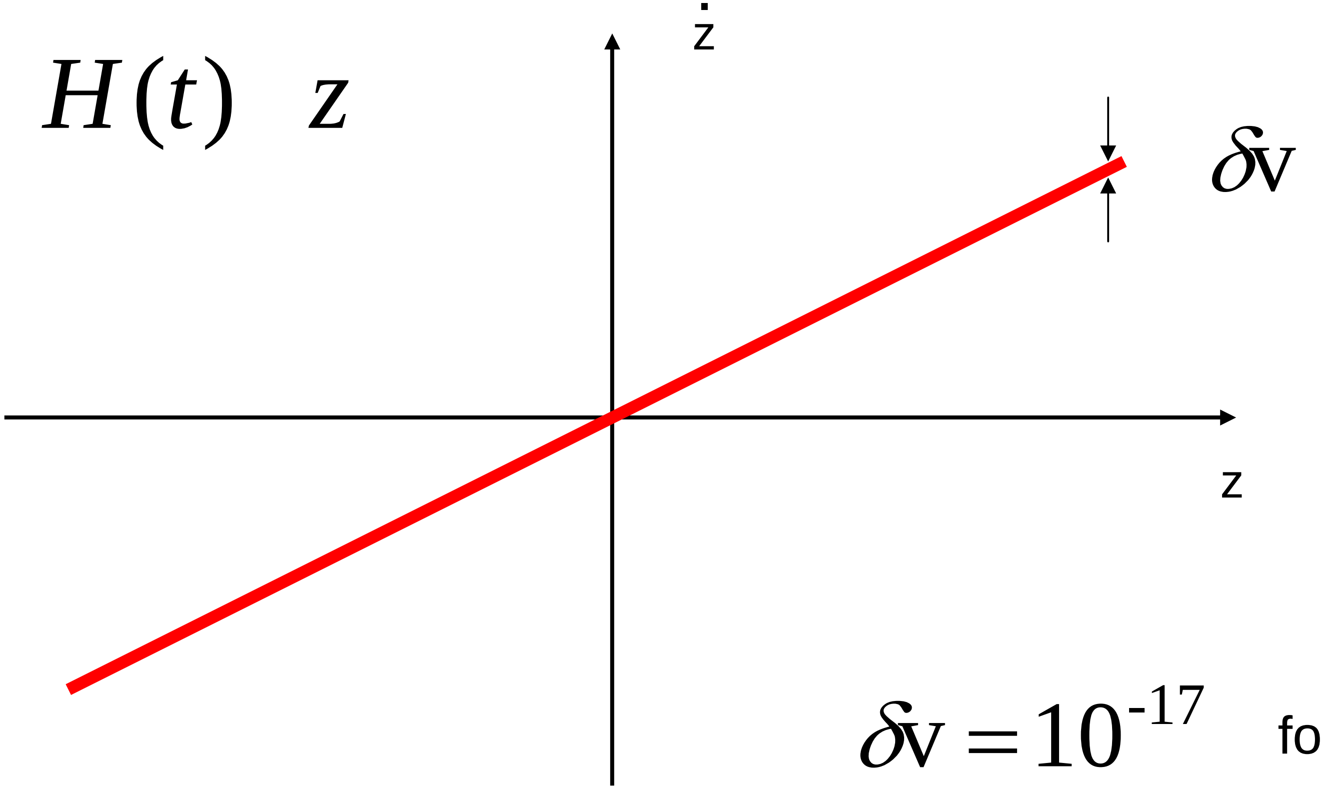
Dark matter particles are red and,
on this page, they are free.





Phase space distribution of CDM in a homogeneous universe

$$\dot{z} = H(t)\, z$$

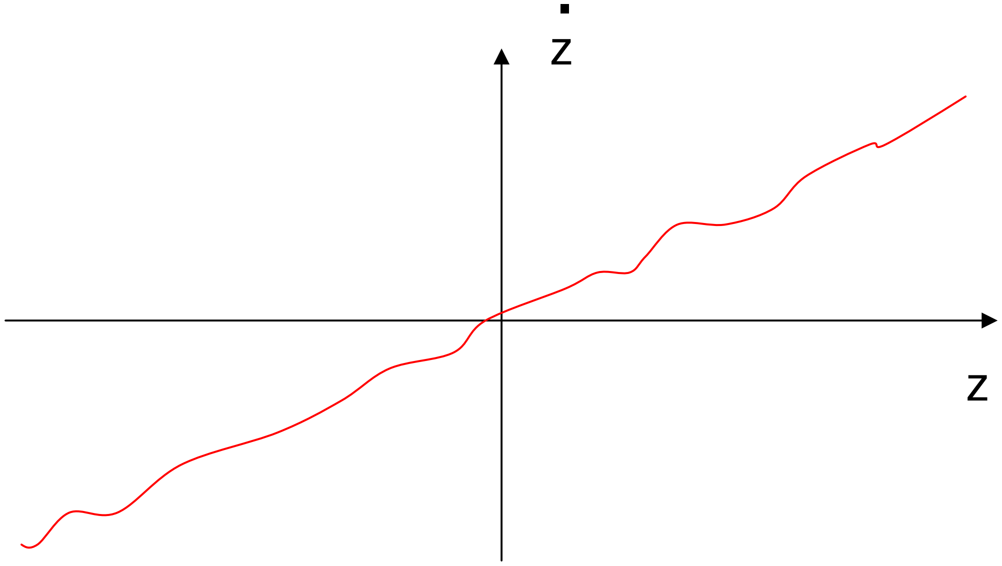


$$\delta v = 10^{-17}$$ for axions

$$\delta v = 10^{-12}$$ for WIMPs

The cold dark matter particles lie on a 3-dimensional sheet in 6-dimensional phase space

the physical density is the projection of the phase space sheet onto position space



$$\vec{v}(\vec{r},t) = H(t)\,\vec{r} + \Delta\vec{v}(\vec{r},t)$$

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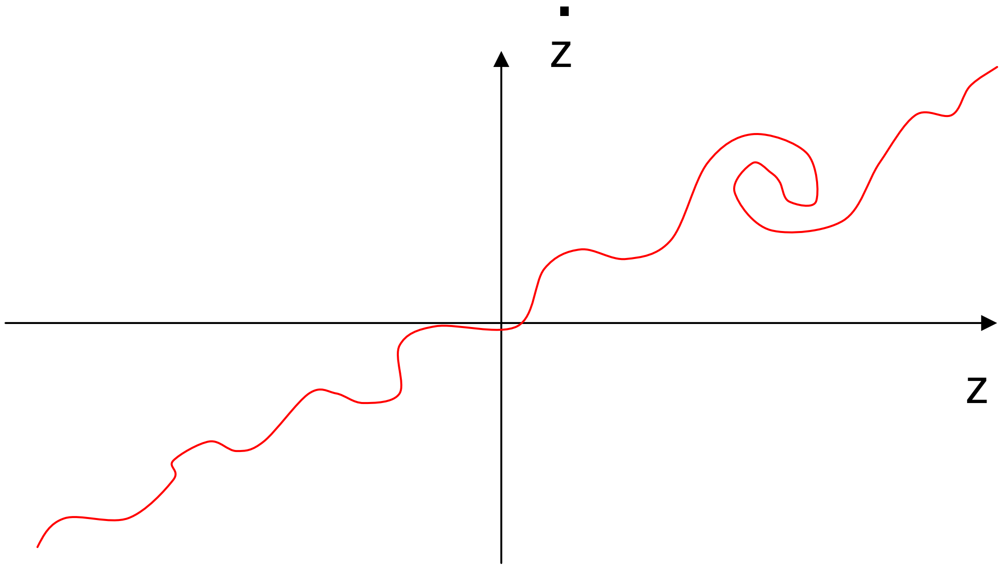
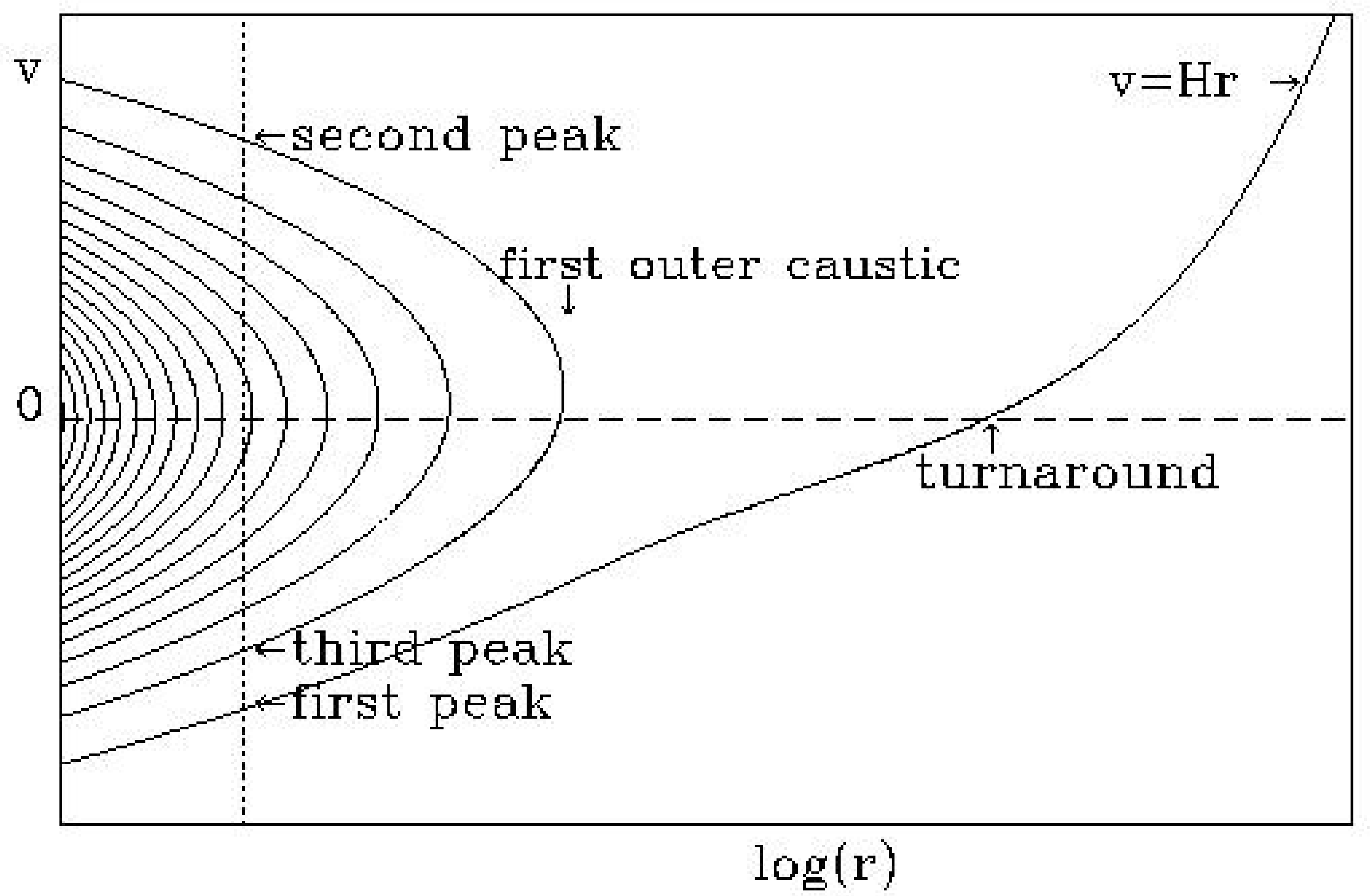


$$\vec{v}(\vec{r},t) = H(t)\,\vec{r} + \Delta\vec{v}(\vec{r},t)$$

Phase space structure of spherically symmetric halos



Implications:

1. At every point in physical space, the distribution of velocities is discrete, each velocity corresponding to a particular flow at that location .

2. At some locations in physical space, where the number of flows changes, there is a caustic, i.e. the density of dark matter is very high there.

- the number of flows at our location in the Milky Way halo is of order 100

- small subhalos from hierarchical structure formation produce an effective velocity dispersion

$$\delta \mathrm{v}_{\mathrm{eff}} \leq 30 \,\mathrm{km/s}$$

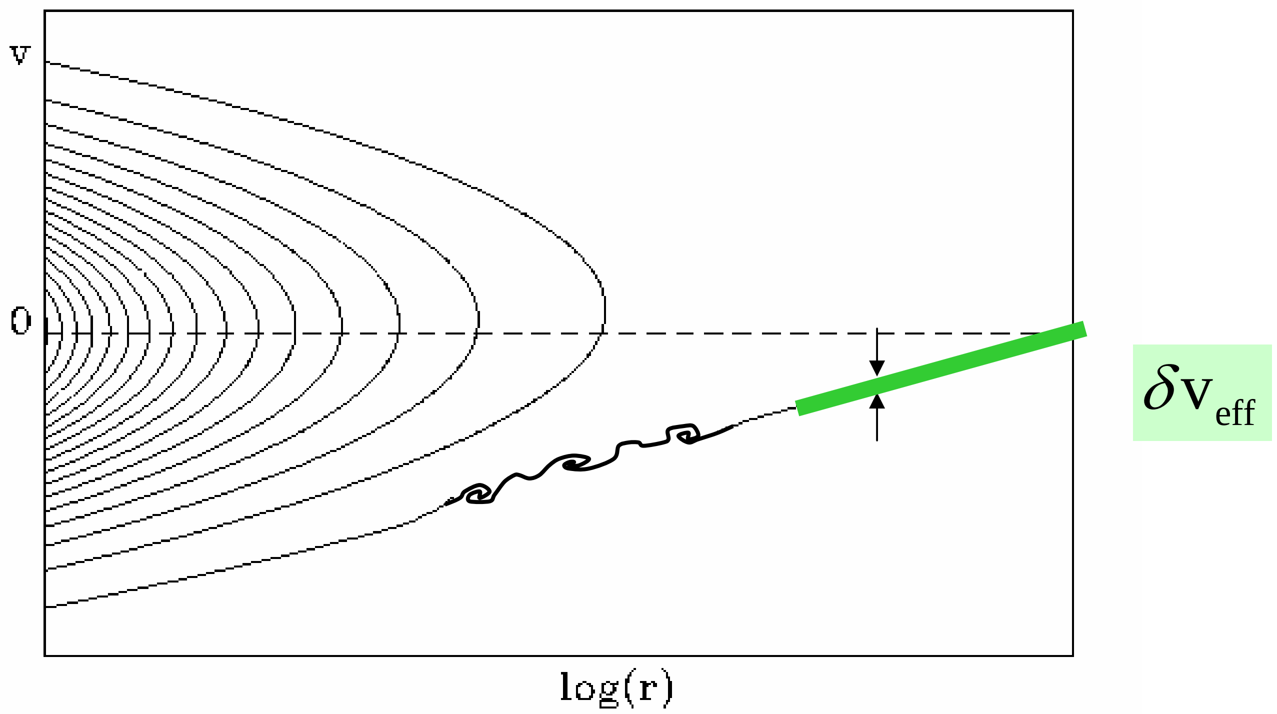
  but do not destroy the sheet structure in phase space

- the known inhomogeneities in the distribution of matter are insufficient to diffuse the flows by gravitational scattering

- present N-body simulations do not have enough particles to resolve all the flows and caustics

  (see however: Melott and Shandarin, Stiff and Widrow, Shirokov and Bertschinger)

Hierarchical clustering introduces effective velocity dispersion



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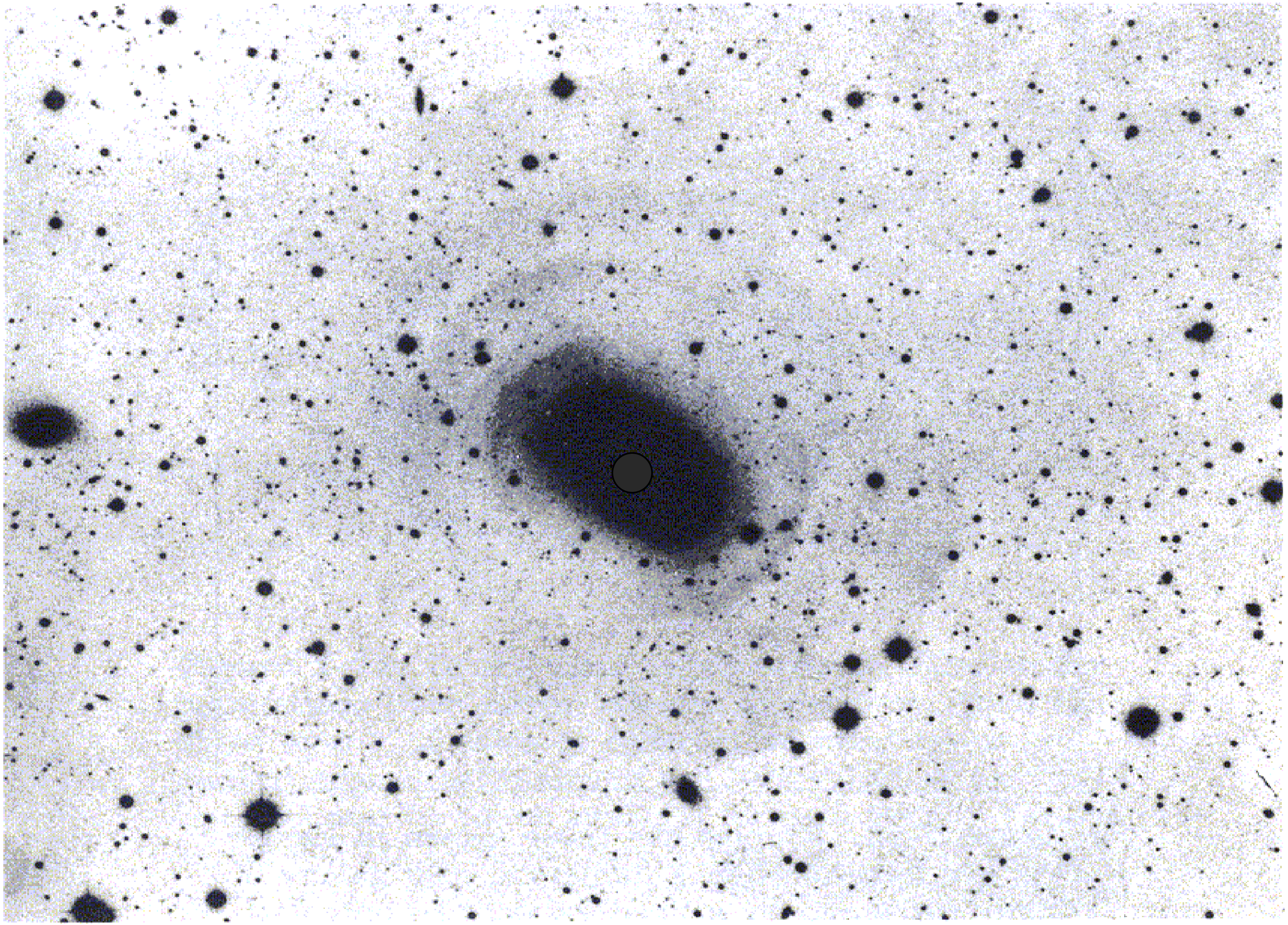


Figure 7-22. The giant elliptical galaxy NGC 3923 is surrounded by faint ripples of brightness. Courtesy of D. F. Malin and the Anglo-Australian Telescope Board.

(from Binney and Tremaine's book)

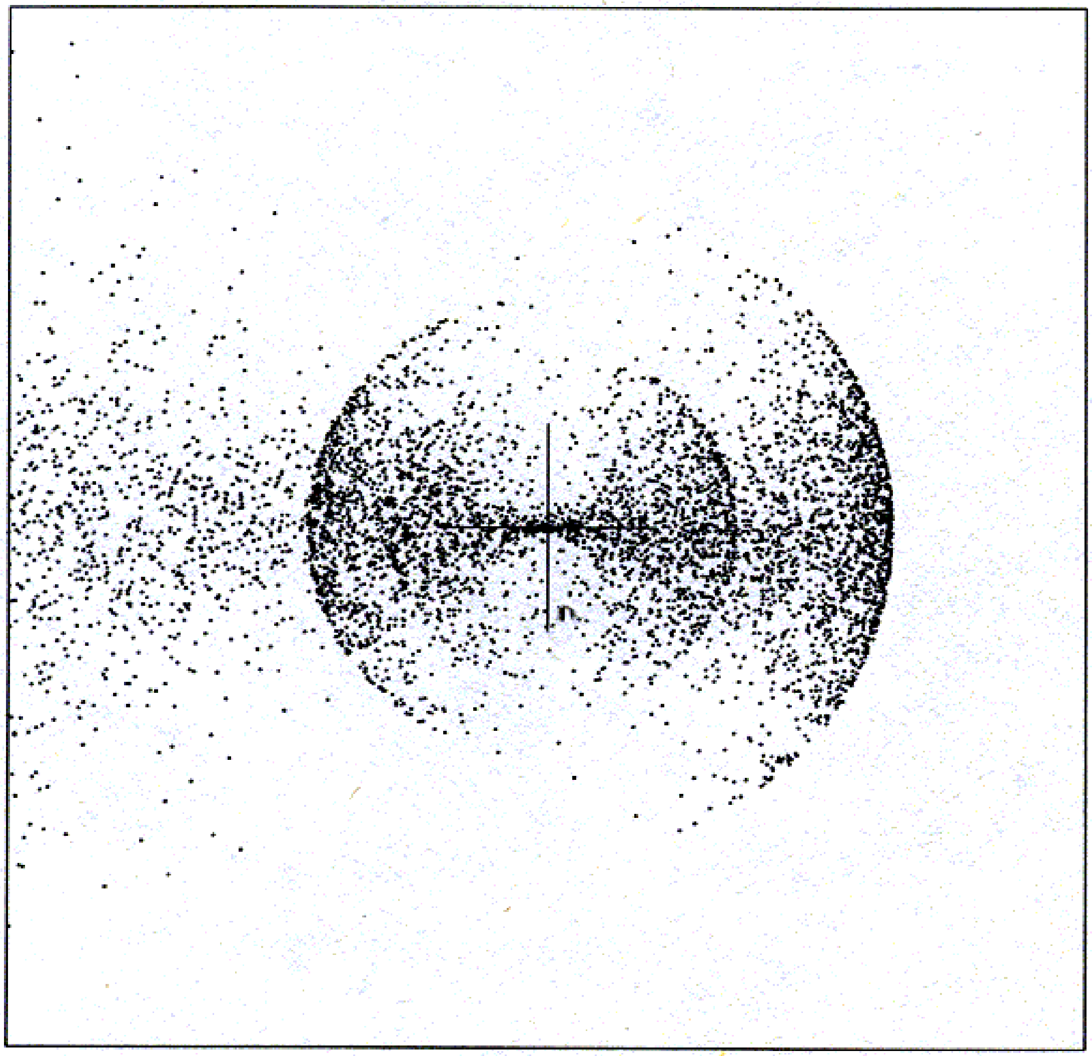
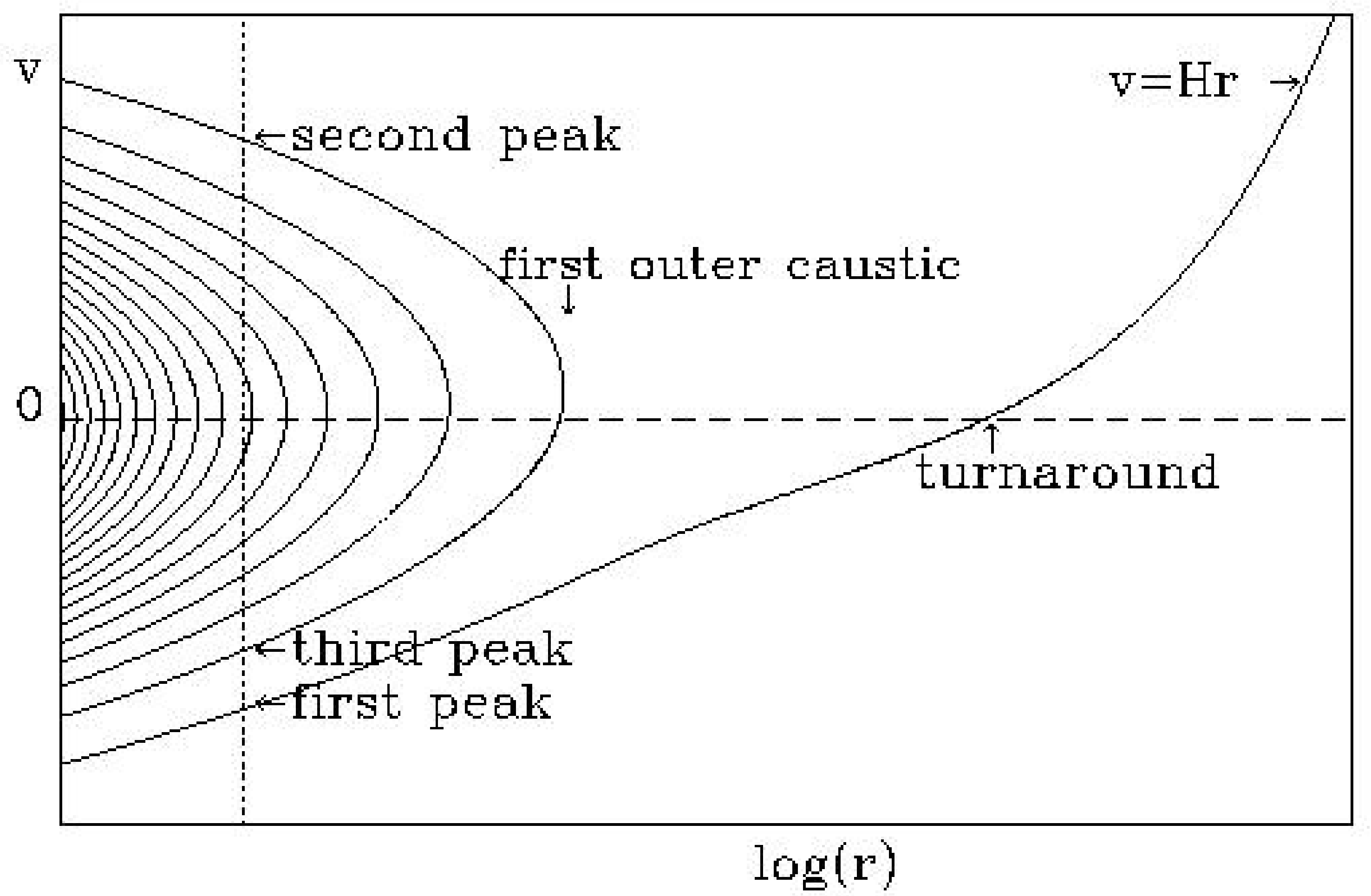


Figure 7-23. Ripples like those shown in Figure 7-22 are formed when a numerical disk galaxy is tidally disrupted by a fixed galaxy-like potential. (See Hernquist & Quinn 1987.)

Phase space structure of spherically symmetric halos



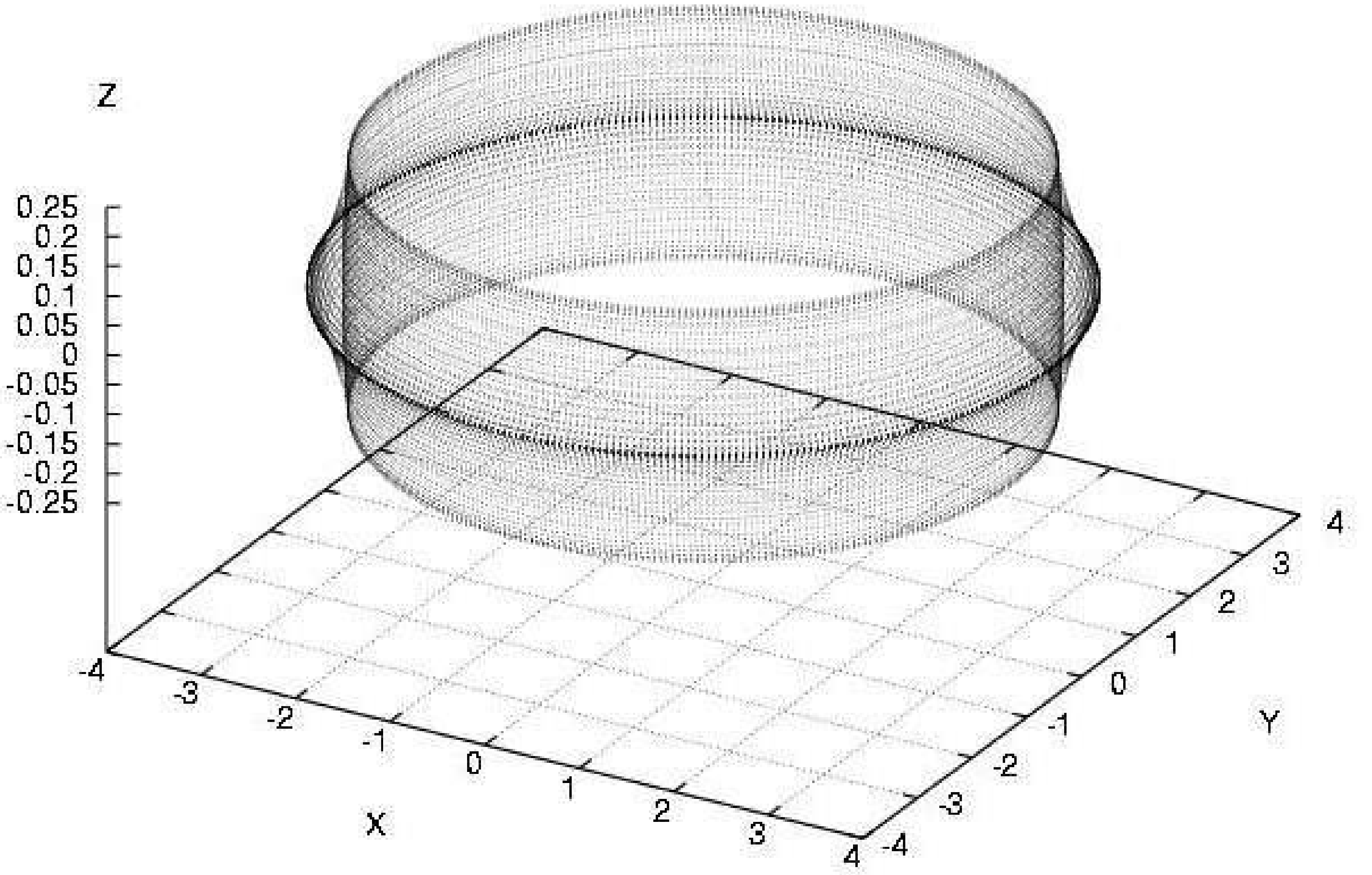
Galactic halos have inner caustics as
well as outer caustics.

If the initial velocity field is dominated by net overall rotation, the inner caustic is a ‘tricusp ring’.

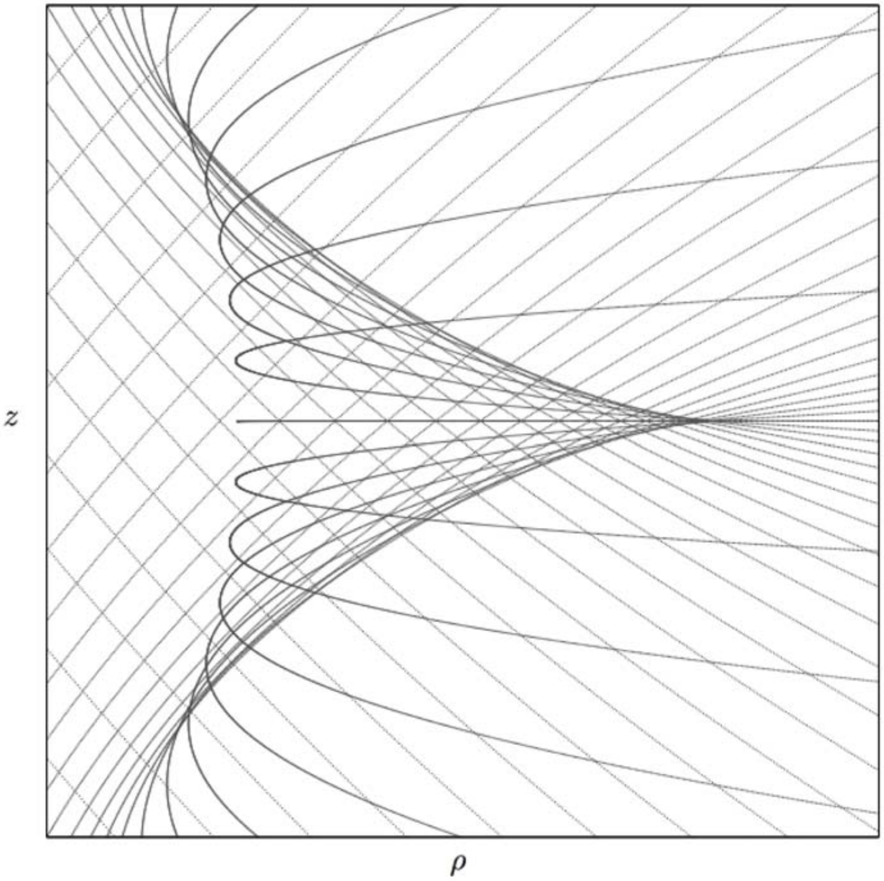
If the initial velocity field is irrotational, the inner caustic has a ‘tent-like’ structure.

(Arvind Natarajan and PS, astro-ph/0510743).

simulations by Arvind Natarajan

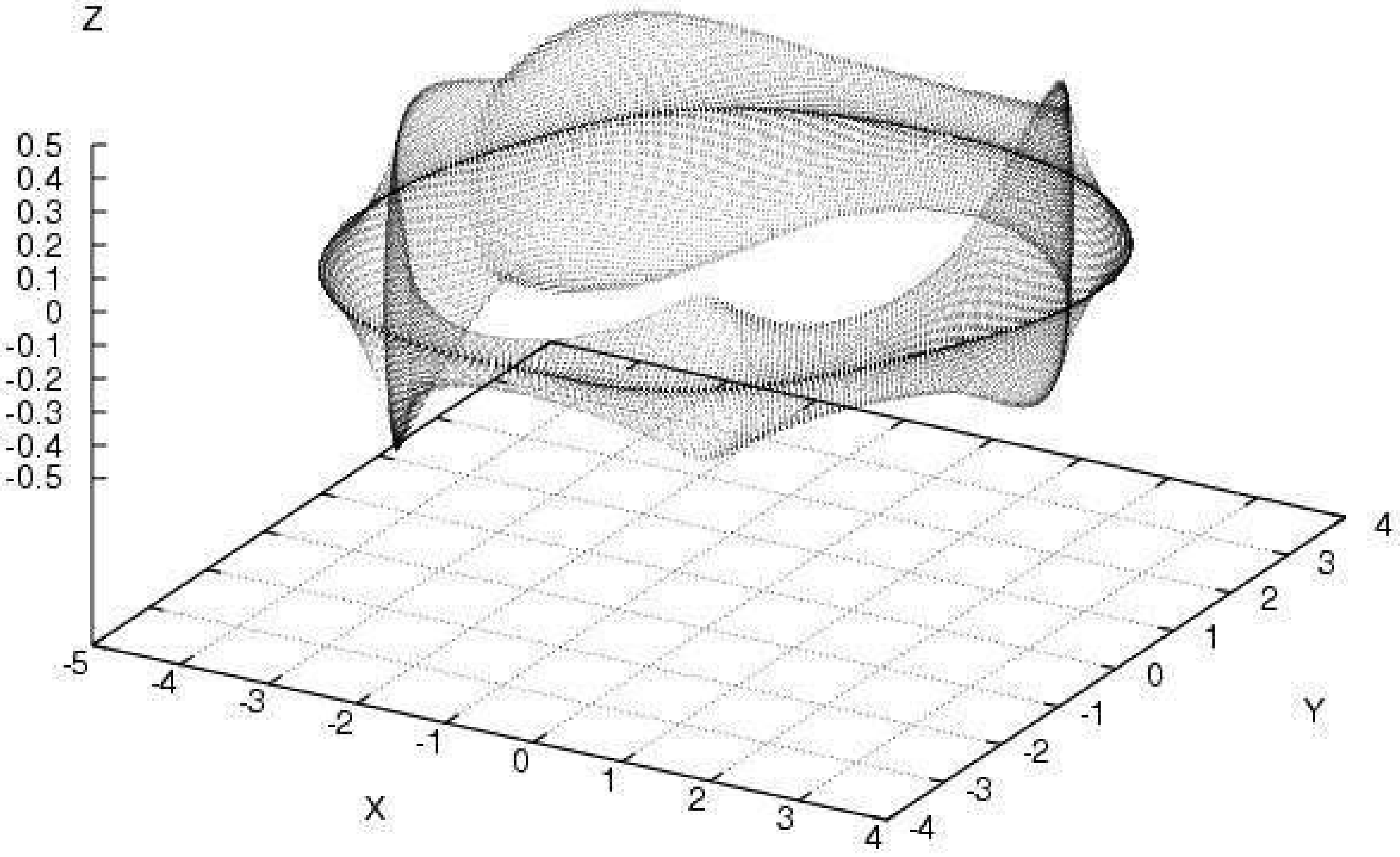


The caustic ring cross-section



D_{-4}

an elliptic umbilic catastrophe


Z
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-5
-4
-3
-2
-1
0
1
2
3
4
X
4
3
2
1
0
-1
-2
-3
-4
Y

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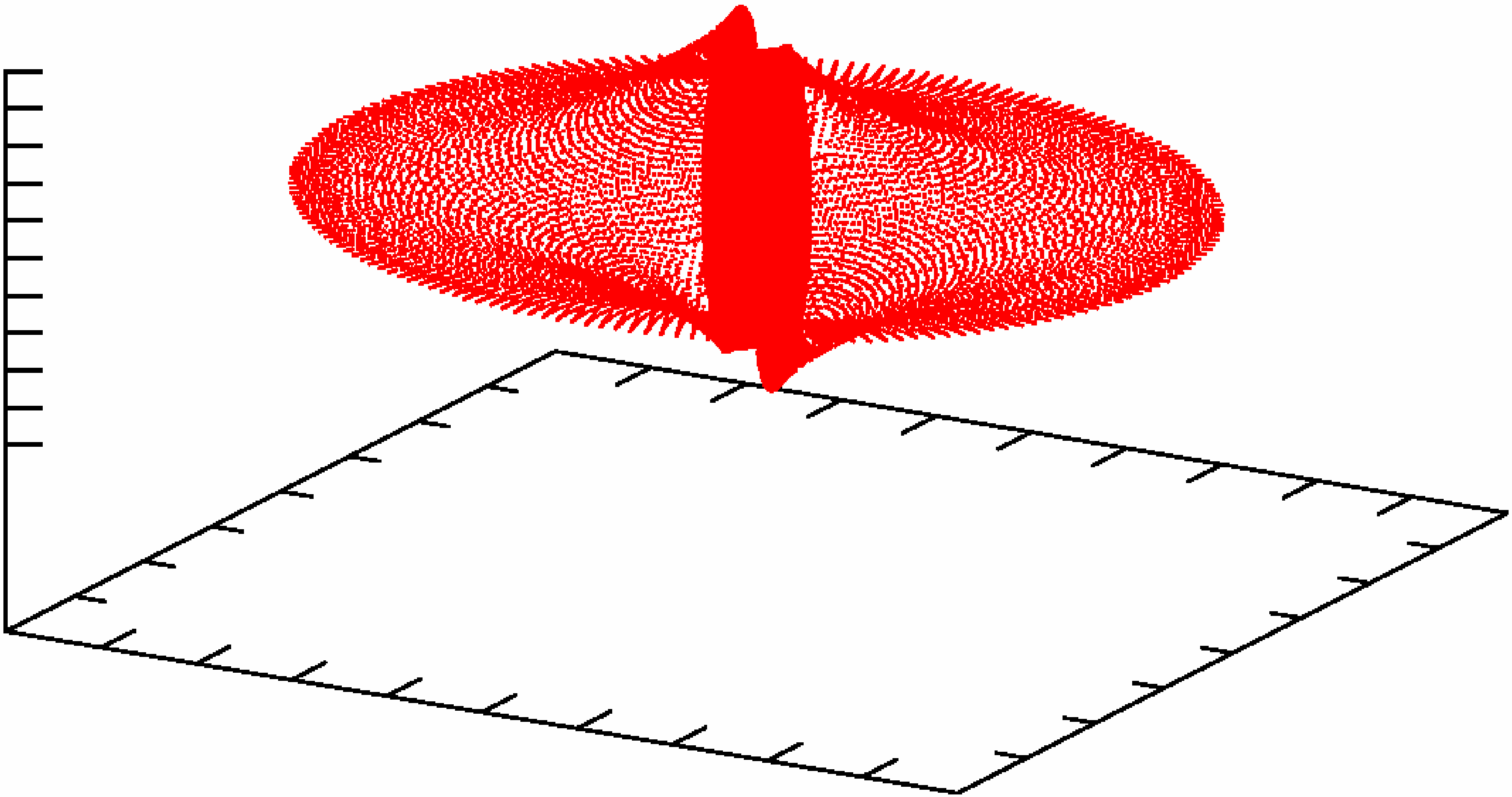
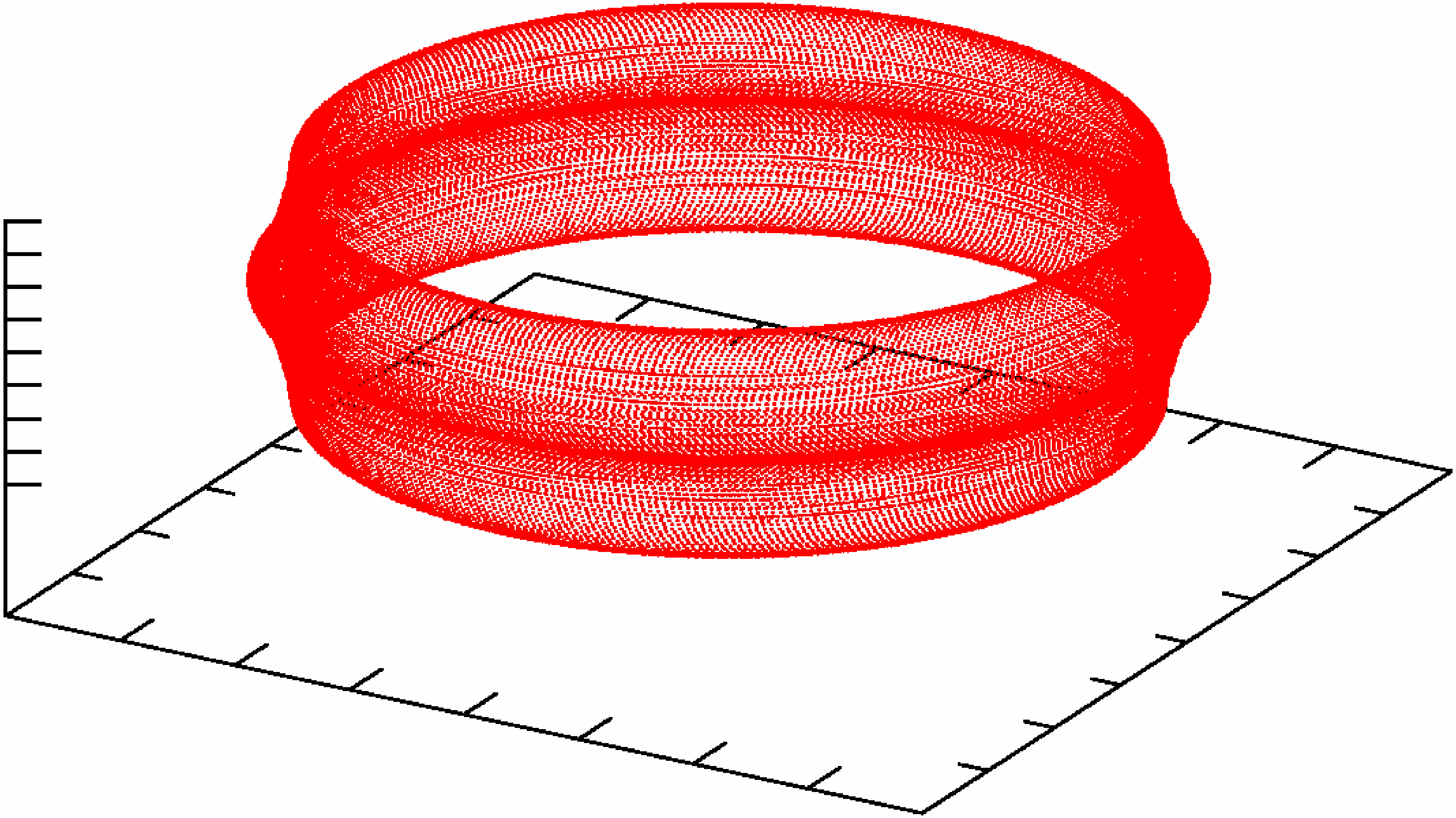
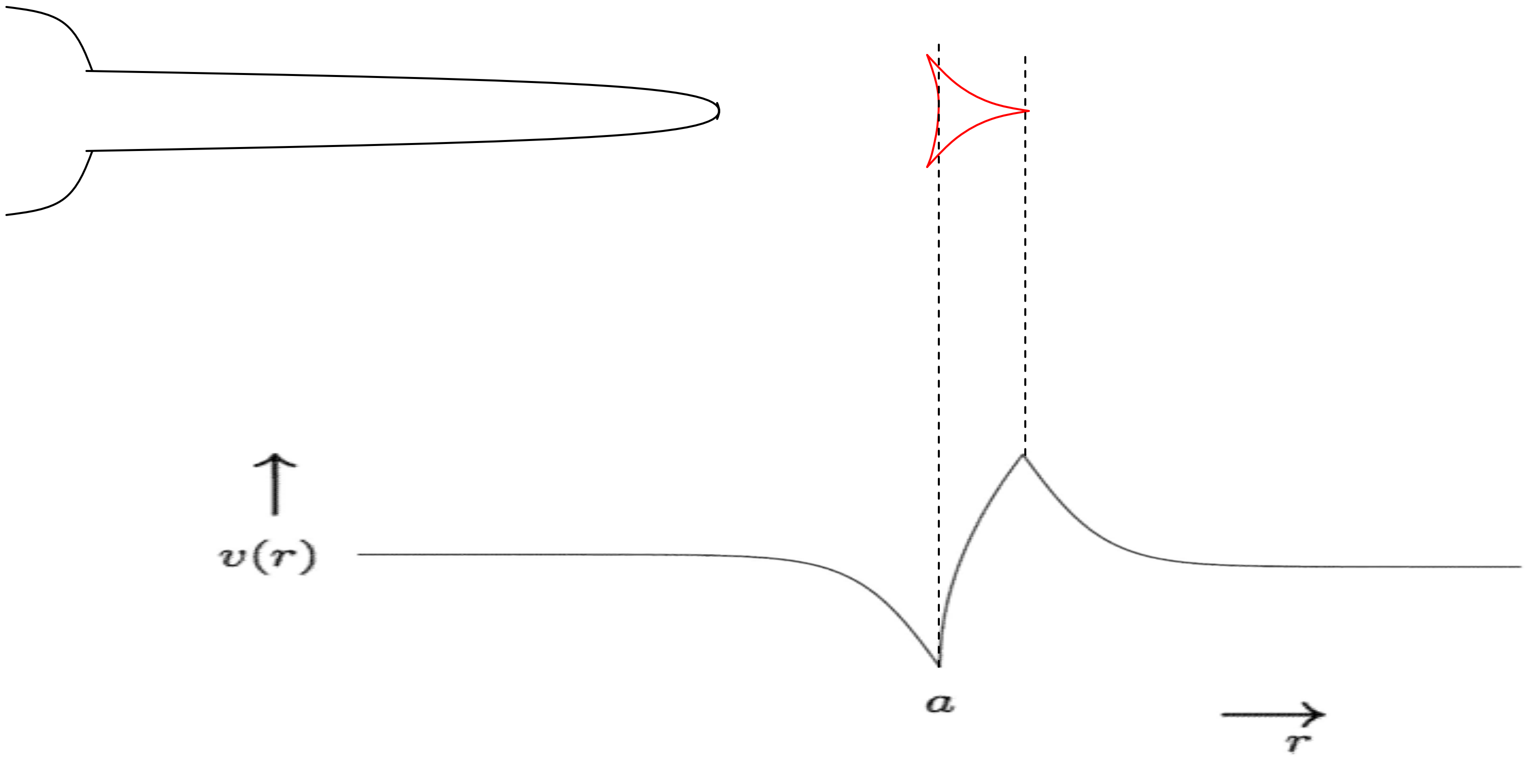




Effect of a caustic ring of dark matter upon the galactic rotation curve



On the basis of the self-similar infall model (Filmore and Goldreich, Bertschinger) with angular momentum (Tkachev, Wang + PS), the caustic rings were predicted to be

in the galactic plane

with radii $(n = 1, 2, 3 \ldots)$

$$a_n = \frac{40\mathrm{kpc}}{n}\left(\frac{\mathrm{v_{rot}}}{220\mathrm{km/s}}\right)\left(\frac{\mathrm{j_{max}}}{0.26}\right)$$

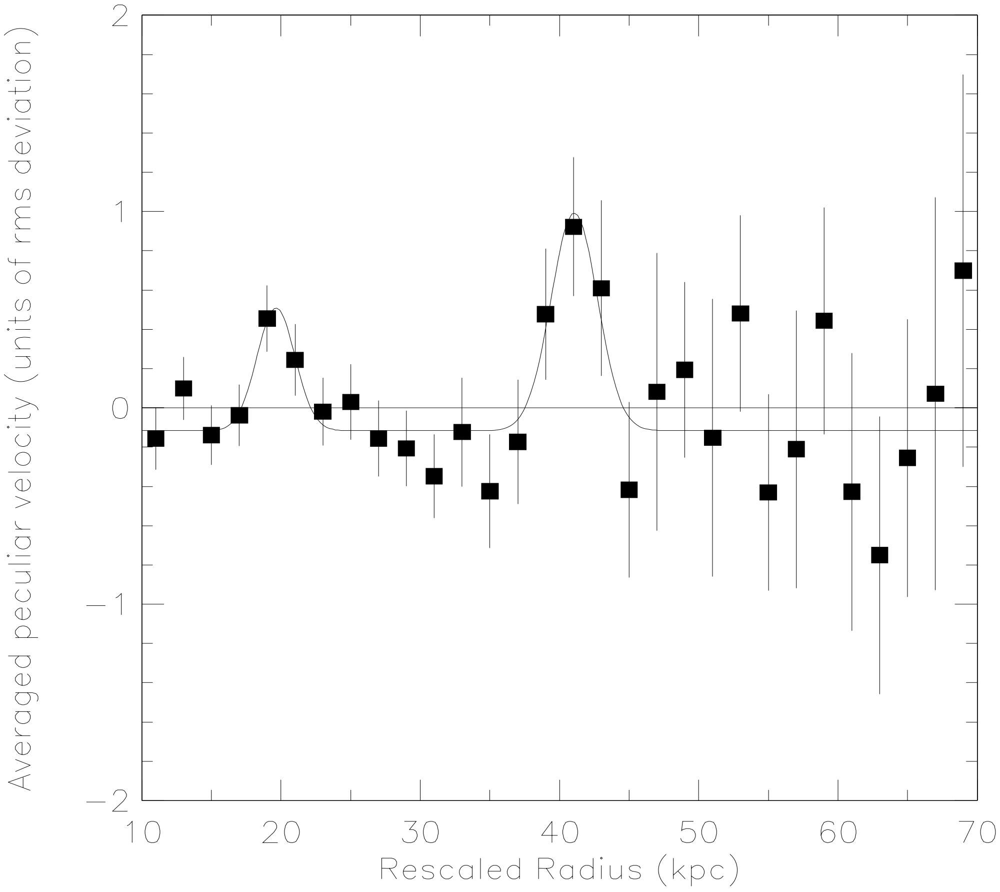
$\mathrm{j_{max}} \cong 0.26$ was expected for the Milky Way halo from the effect of angular momentum on the inner rotation curve.

Composite rotation curve

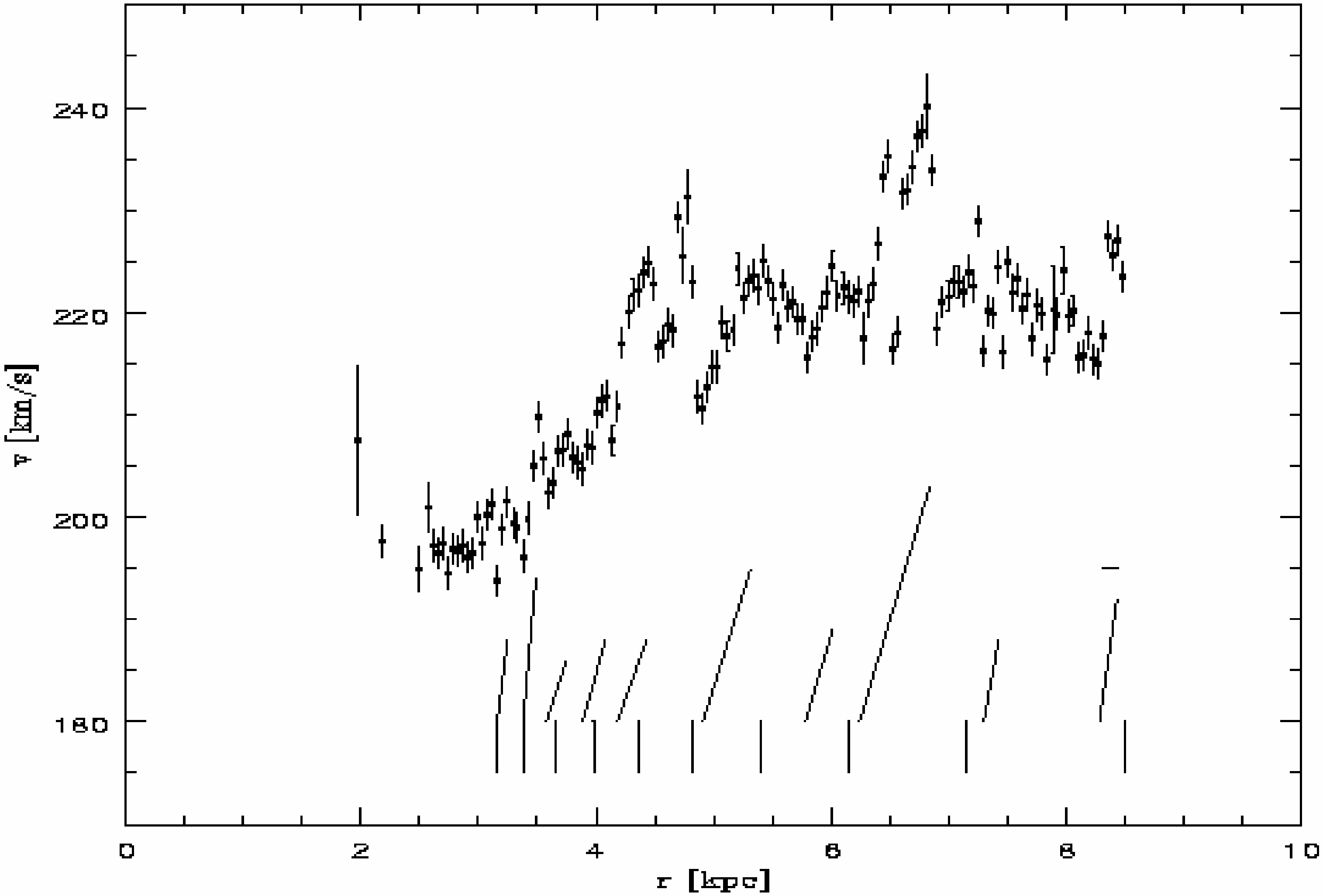
(W. Kinney and PS, astro-ph/9906049)

- combining data on 32 well measured extended external rotation curves

- scaled to our own galaxy

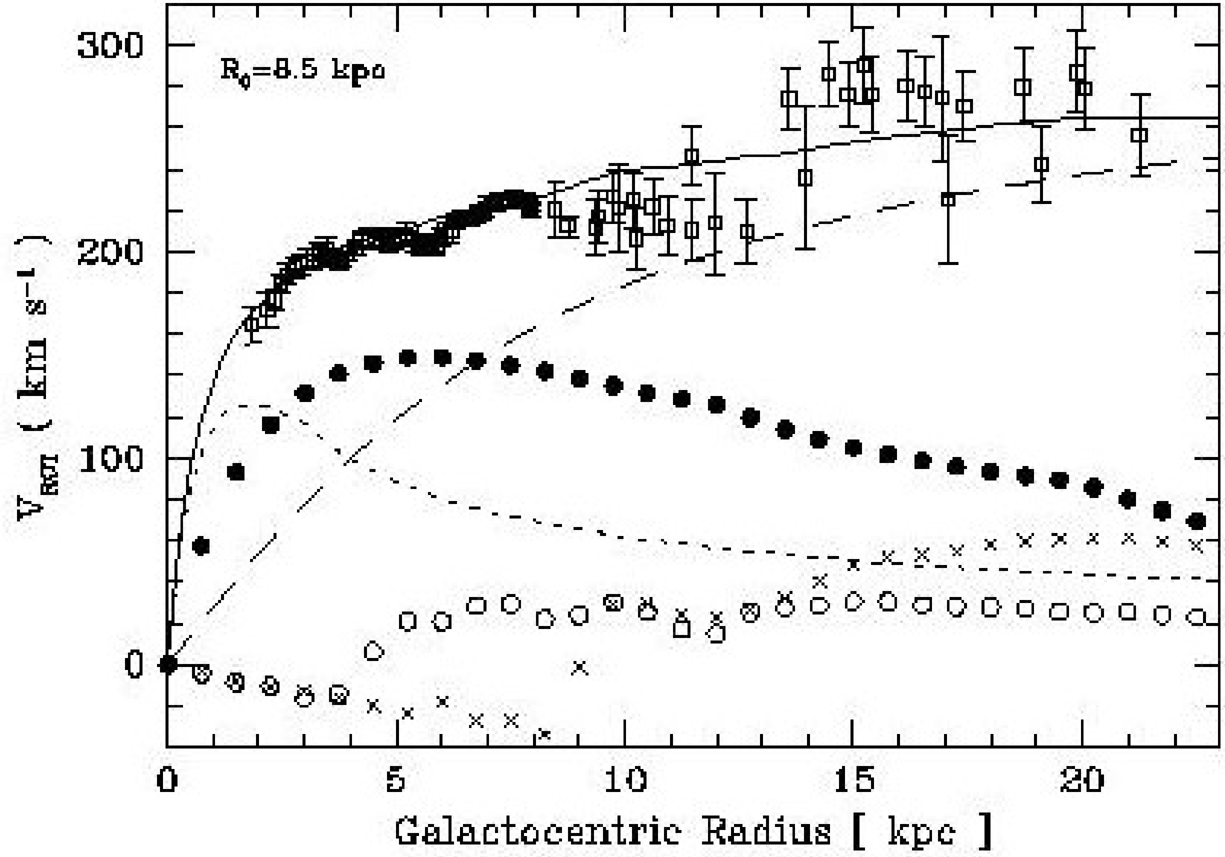


Inner Galactic rotation curve



from Massachusetts-Stony Brook North Galactic Pane CO Survey (Clemens, 1985)

Outer Galactic rotation curve



R.P. Olling and M.R. Merrifield, MNRAS 311 (2000) 361

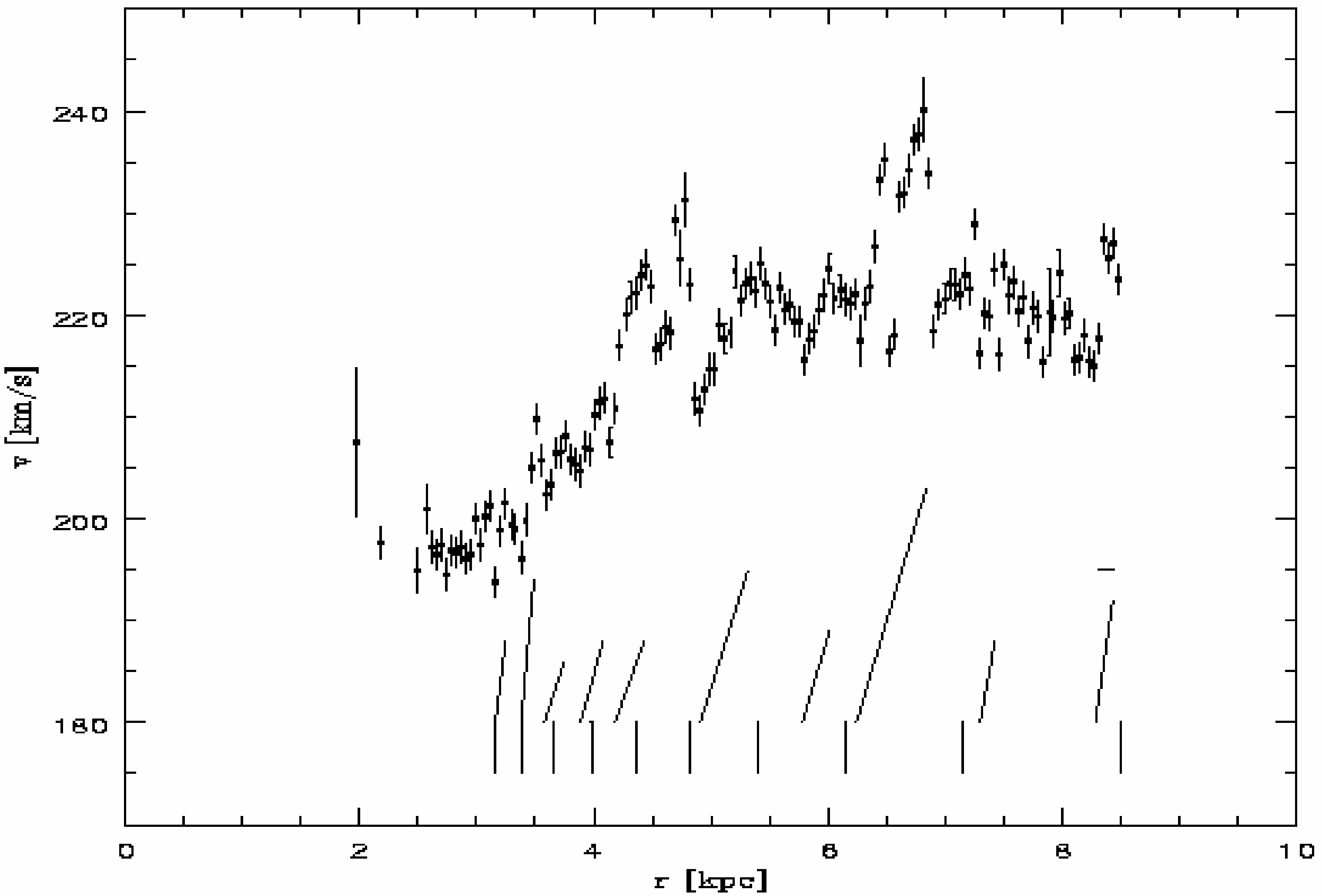
Monoceros Ring of stars

H. Newberg et al. 2002; B. Yanny et al., 2003; R.A. Ibata et al., 2003;
H.J. Rocha-Pinto et al, 2003; J.D. Crane et al., 2003; N.F. Martin et al., 2005

in the Galactic plane
at galactocentric distance $r ; 20\,\text{kpc}$
appears circular, actually seen for $100^0 < l < 270^0$
scale height of order 1 kpc
velocity dispersion of order 20 km/s

may be caused by the n = 2 caustic ring of
dark matter (A. Natarajan and P.S. ’07)

Inner Galactic rotation curve



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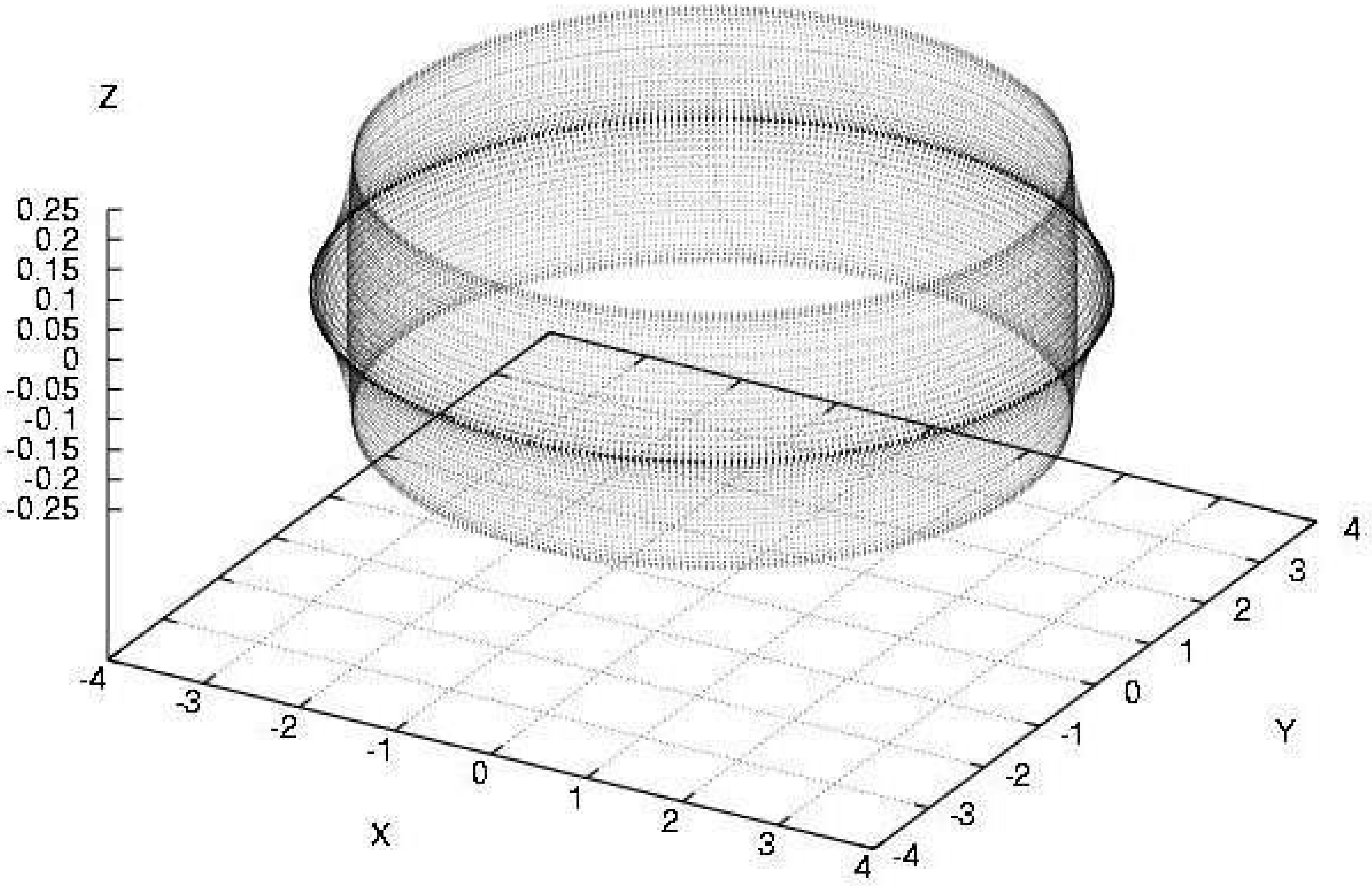


Z
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-4
-3
-2
-1
0
1
2
3
4
X
-4
-3
-2
-1
0
1
2
3
4
Y

The Big Flow

- density $$d_5 \approx 1.7\ 10^{-24}\ \mathrm{gr/cm}^3$$

previous estimates of the total local halo density range from 0.5 to 0.75 10^{-24} gr/cm ^{3}

- velocity $$\vec{v}_5^{\,\pm} \cong (470\ \hat{\phi}\ \pm\ 100\ \hat{r})\ \ \mathrm{km/s}$$

$\hat{\phi}$ in the direction of galactic rotation

$\hat{r}$ in the direction away from the galactic center

- velocity dispersion $$\delta v_5 < 50\ \mathrm{m/s}$$

TABLE I. Velocity vectors $\vec{v}^{n\pm}$ and densities $d_n^{\pm}$ of the first 40 flows in the caustic ring halo model, in galactic coordinates. The flow of velocity vector $\vec{v}^{n\pm}$ has density $d_n^{\pm}$ or $d_n^{\mp}$.

n	$v_G^{n\pm}$ (km/s)	$v_{yG}^{n\pm}$ (km/s)	$v_{zG}^{n\pm}$ (km/s)	$v_{xG}^{n\pm}$ (km/s)	d_n^{+} (10^{-26}gr/cm^3)	d_n^{-} (10^{-26}gr/cm^3)
1	620	130	±605	/	0.3	0.3
2	560	230	±510	/	0.8	0.8
3	530	320	±420	/	1.4	1.4
4	500	405	±300	/	3.4	3.4
5	480	470	0	±100	170.	15.
6	465	400	0	±240	6.5	3.4
7	450	330	0	±305	4.1	1.3
8	430	295	0	±320	2.0	1.1
9	420	240	0	±340	1.5	0.7
10	410	200	0	±355	1.0	1.0
11	395	180	0	±350	0.9	0.9
12	385	160	0	±350	0.8	0.8
13	375	150	0	±345	0.7	0.7
14	365	135	0	±340	0.7	0.7
15	355	120	0	±335	0.6	0.6
16	350	110	0	±330	0.6	0.6
17	340	105	0	±320	0.5	0.5
18	330	95	0	±315	0.5	0.5
19	320	90	0	±310	0.5	0.5
20	310	80	0	±300	0.4	0.4

Experimental implications

- for dark matter axion searches

- peaks in the energy spectrum of microwave photons from $a \to \gamma$ conversion in the cavity detector
- high resolution analysis of the signal yields a more sensitive search (with L. Duffy and ADMX collab.)

- for dark matter WIMP searches

- plateaux in the recoil energy spectrum from elastic WIMP collisions with target nuclei
- the total flux is largest around December

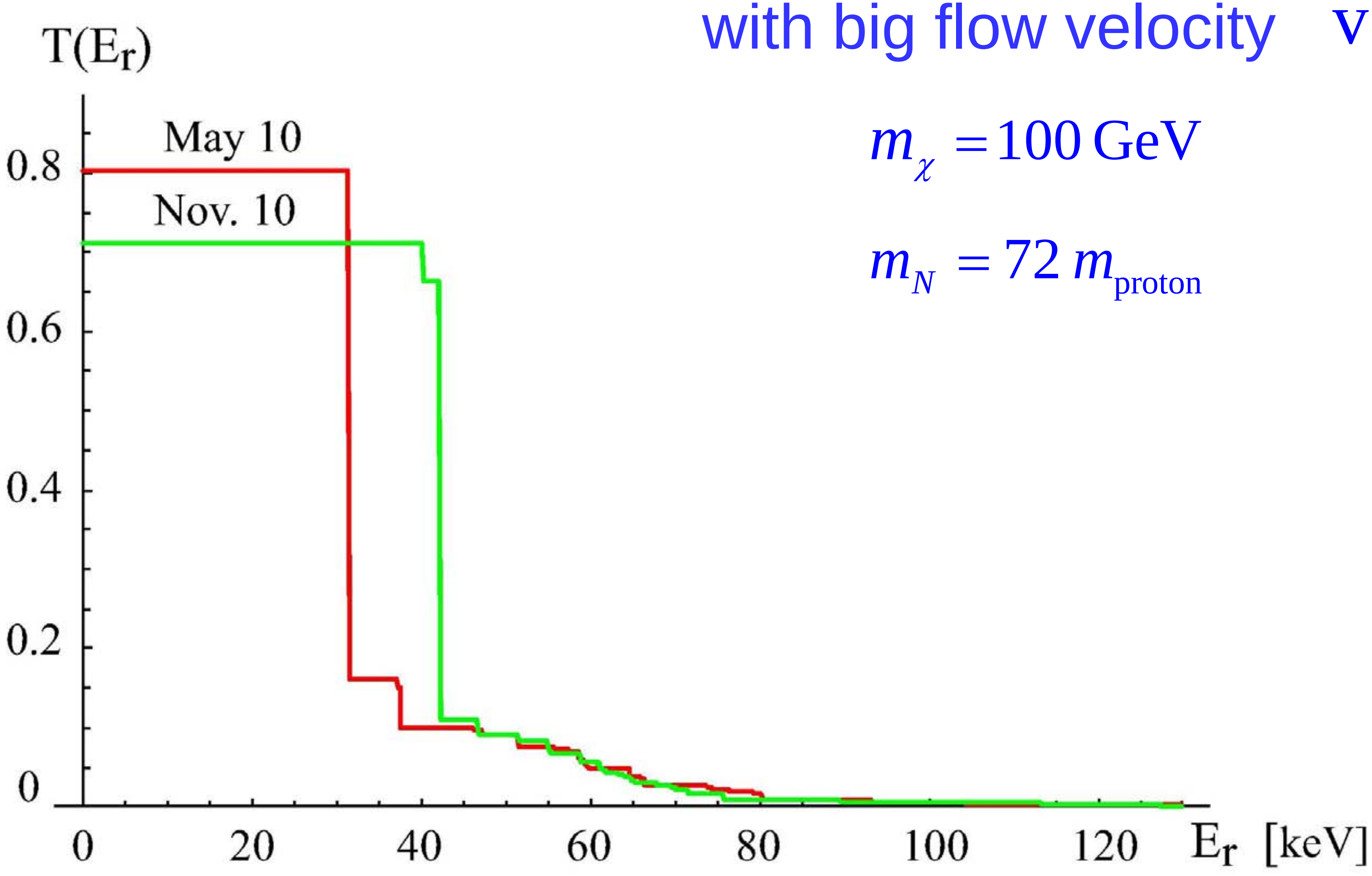
(Vergados; Green; Gelmini and Gondolo; Ling, Wick &PS)

For caustic ring halo model

with big flow velocity $\mathbf{V}^{5-}$

$m_\chi = 100\,\mathrm{GeV}$

$m_N = 72\, m_{\mathrm{proton}}$



Implications for observations

- Gamma rays from WIMP annihilation is logarithmically enhanced at the caustic

  Bergstrom, Edsjo and Gunnarsson, 2000; Hogan '01; Pieri and Branchini '05; Mohayaee and Shandarin '06; Mohayaee, Shandarin and Silk '07, Natarajan '07

- Gravitational lensing by dark matter caustics

  (Hogan '99; Charmousis, Onemli, Qiu and PS '03; Gavazzi, Mohayaee and Fort '06; Onemli '06)

Conclusions

- Cold Dark Matter forms discrete flows and caustics.
- Galactic halos have inner caustics as well as outer caustics.
- There is evidence that the inner caustic ring locations are correctly predicted by the self-similar infall model.
- That evidence implies that the dark matter in our neighborhood is dominated by a Big Flow.