Dark Matter Caustics

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Z. Qiu
S. Wick
...

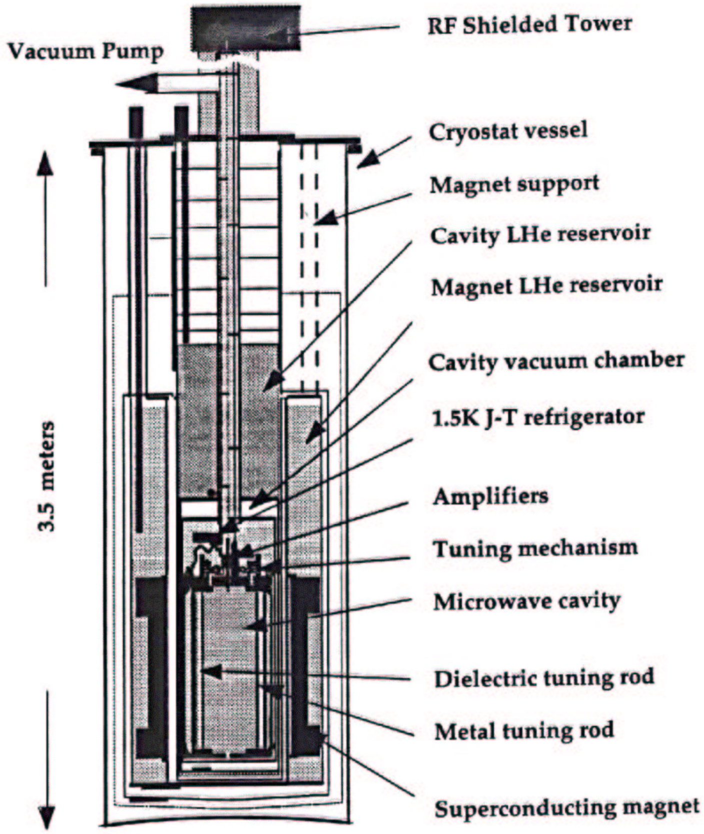
see also: S. Tremaine, C. Hogan, ...

Motivation

Elucidating the structure of galactic halos is centrally important for

- understanding galactic dynamics
- predicting signals for dark matter searches

The US large scale axion dark matter search.



ADMX cfr. D. Kinion
M. Mueck

Galactic halo models

Model	Complaint
1. Isothermal model	Infalling particles do not thermalize
2. N body simulations (NFW, Moore, ...)	With 10^7 particles the resolution is inadequate
3. Caustic ring model	

Outline

- Topology → dark matter caustics

  outer caustic spheres

  inner caustic rings

- Self-similar infall

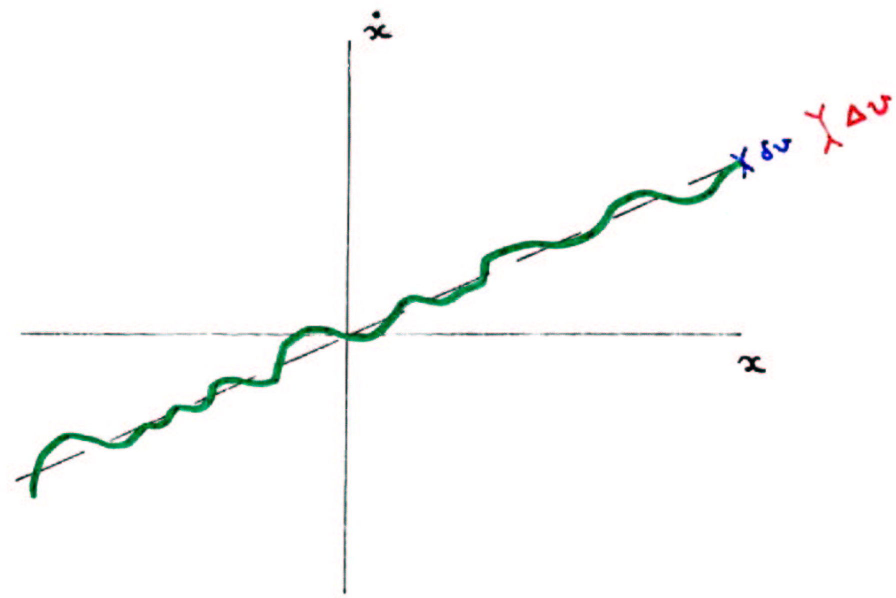
  → caustic ring radii

$$a_n \simeq \frac{1}{n}\, 40\,\text{kpc} \cdot \frac{v_{rot}}{220\ \text{km/s}} \cdot \frac{j_{max}}{0.27}$$

- Observational evidence

The initial phase space distribution of CDM at time t_i

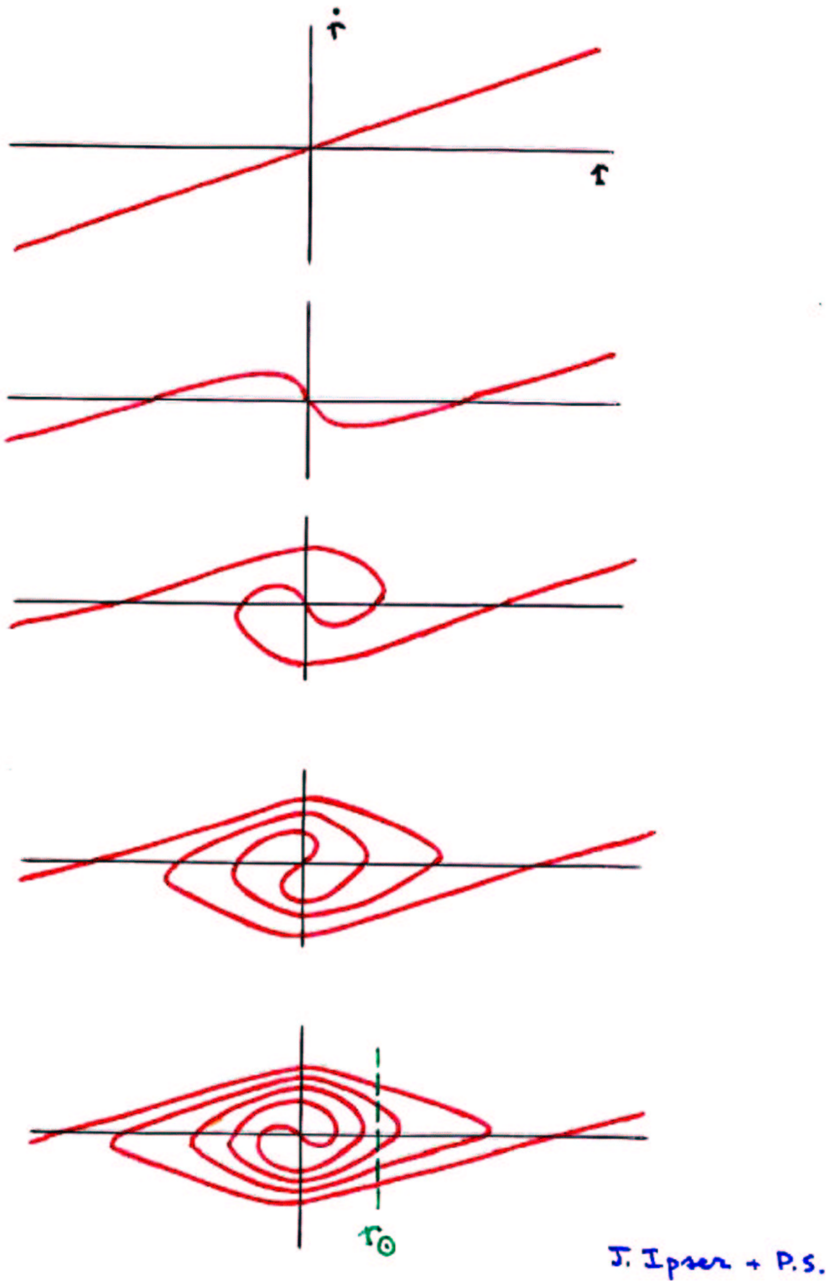
$t_{eq} < t_i \ll t_0$

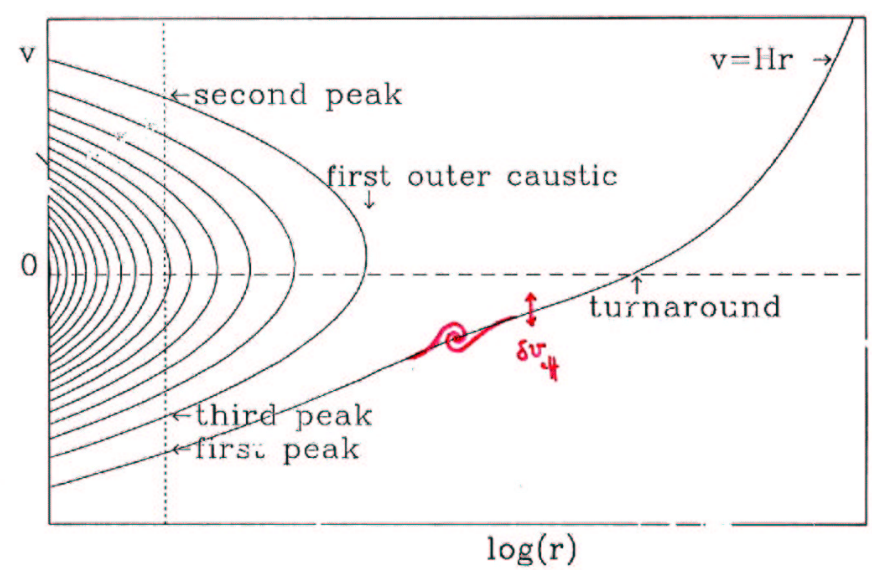


$$\delta v \simeq 10^{-17} \left(\frac{t_0}{t}\right)^{2/3} \quad \text{for axions}$$

$$\simeq 10^{-12} \left(\frac{t_0}{t}\right)^{2/3} \quad \text{for WIMPs}$$

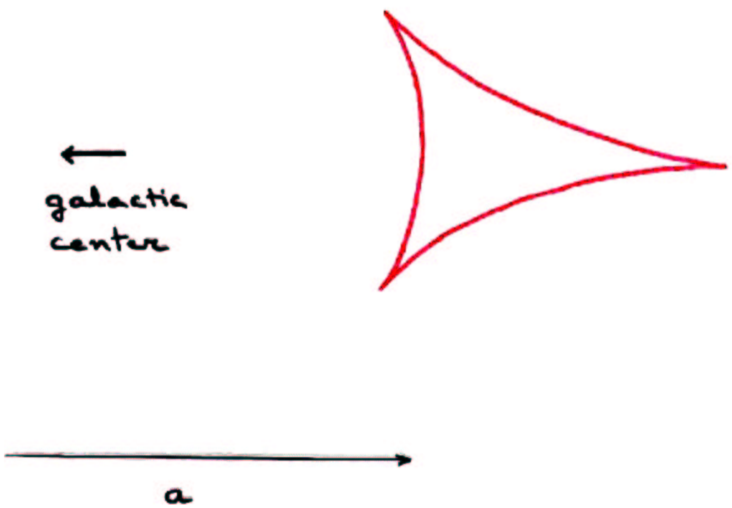
$$\Delta v \sim \frac{\delta \rho}{\rho} \sim t^{2/3}$$


ṙ
r
r⊙
J. Ipser + P.S.


v
0
←second peak
v=Hr →
first outer caustic
turnaround
δv
←third peak
←first peak
log(r)

The outer caustics are topological spheres (A_2 catastrophe)

The inner caustics are closed tubes (rings) whose cross-section is a D_{-4} catastrophe)



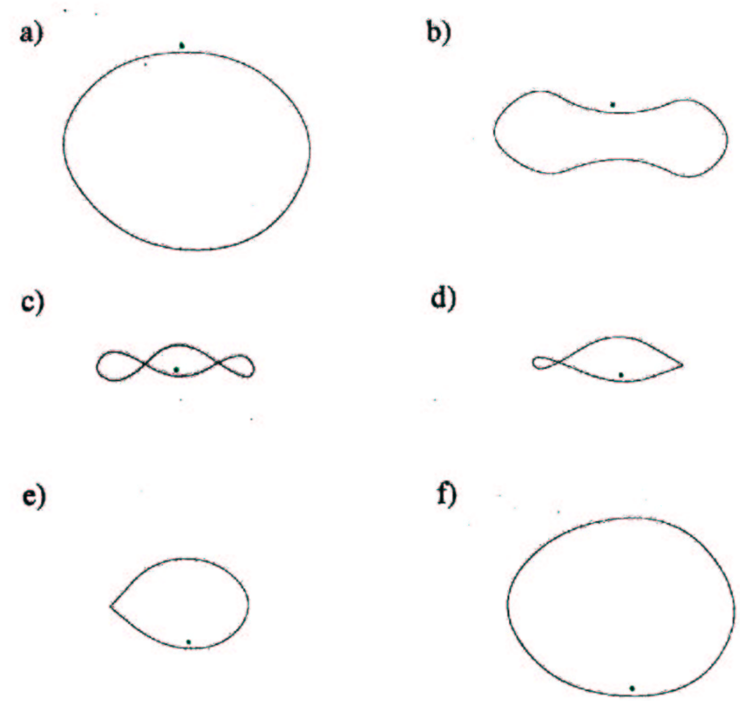
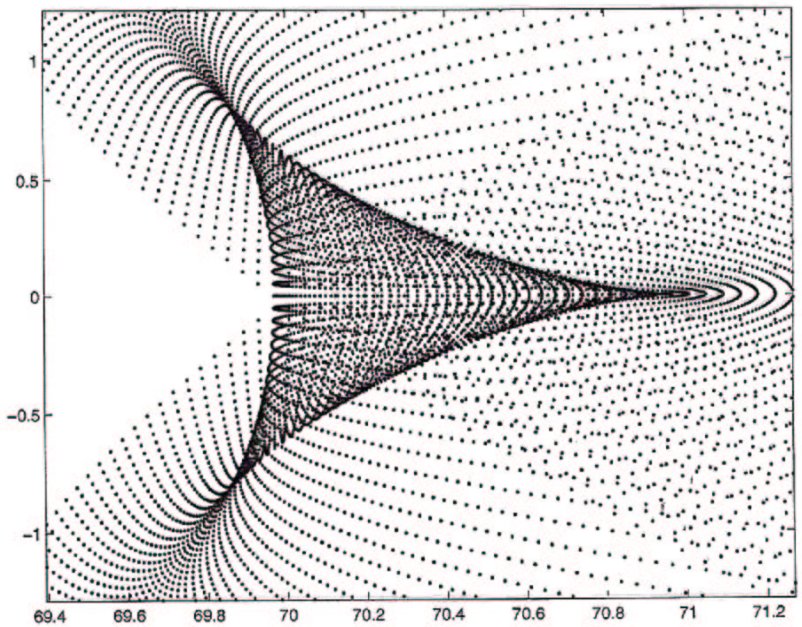


FIG. 1. Infall of all particles on a given initial turnaround sphere. The sphere crosses itself between frames b) and c). The cusps in frames d) and e) are at the intersection of the ring caustic with the plane of the figure.



Charmousis, Onemli,
Qiu + P.S.

Caustic rings of dark matter form around isolated galaxies

if

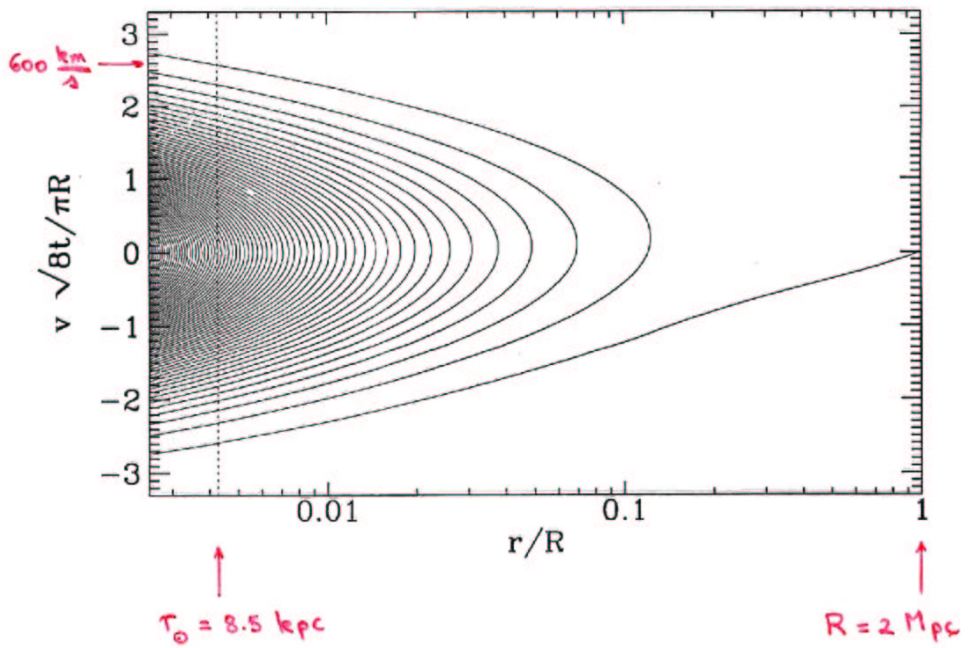
1) collisionless dark matter exists
(axions, WIMPs, neutrinos)

2) the velocity dispersion of infalling dark matter is less than 30 km/s

3) the angular momentum distribution of infalling dark matter is dominated by a smooth component which carries net angular momentum

The minimum number of flows on Earth is of order 100.

Of order $(100)^6 = 10^{12}$ particles are needed to resolve this structure



for $\epsilon = 0.2$, $h = 0.7$

Galactic halo formation by CDM infall is self-similar, in the zero angular momentum case, if

$$\frac{\delta M_i}{M_i} = \left(\frac{M_0}{M_i}\right)^{\epsilon}$$

Fillmore + Goldreich

Bertschinger

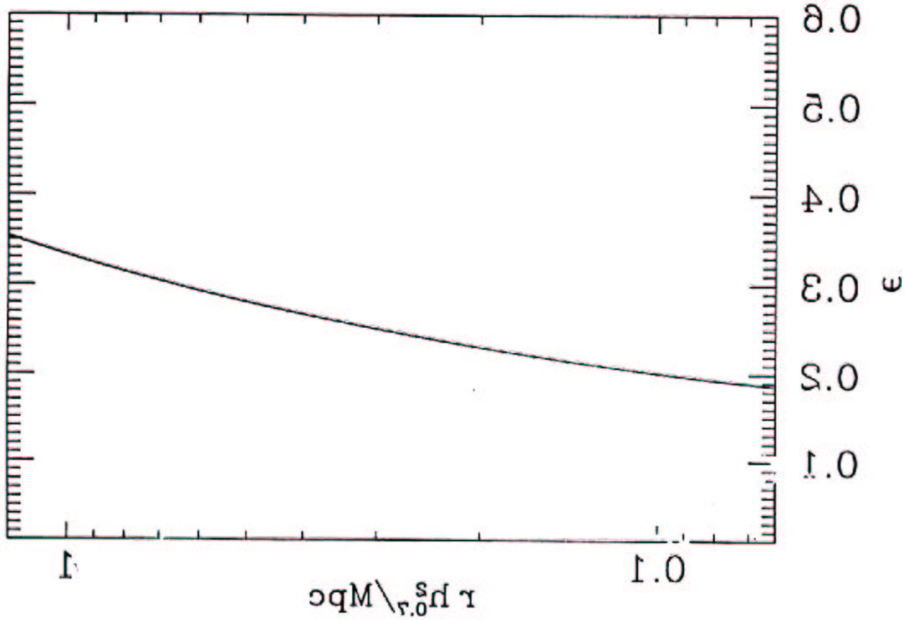
$(0 \leq \epsilon \leq 1)$

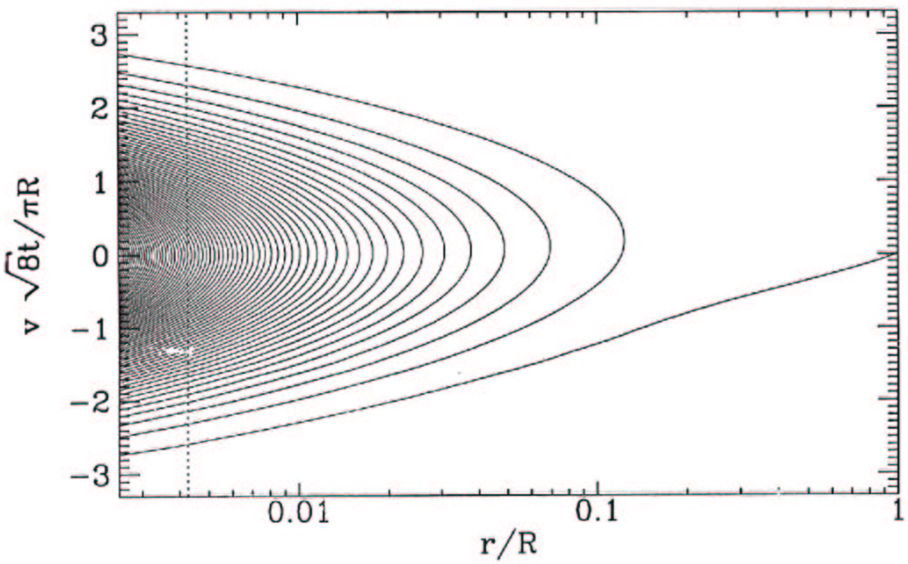
It produces flat rotation curves if

$$0 \leq \epsilon \leq 2/3$$

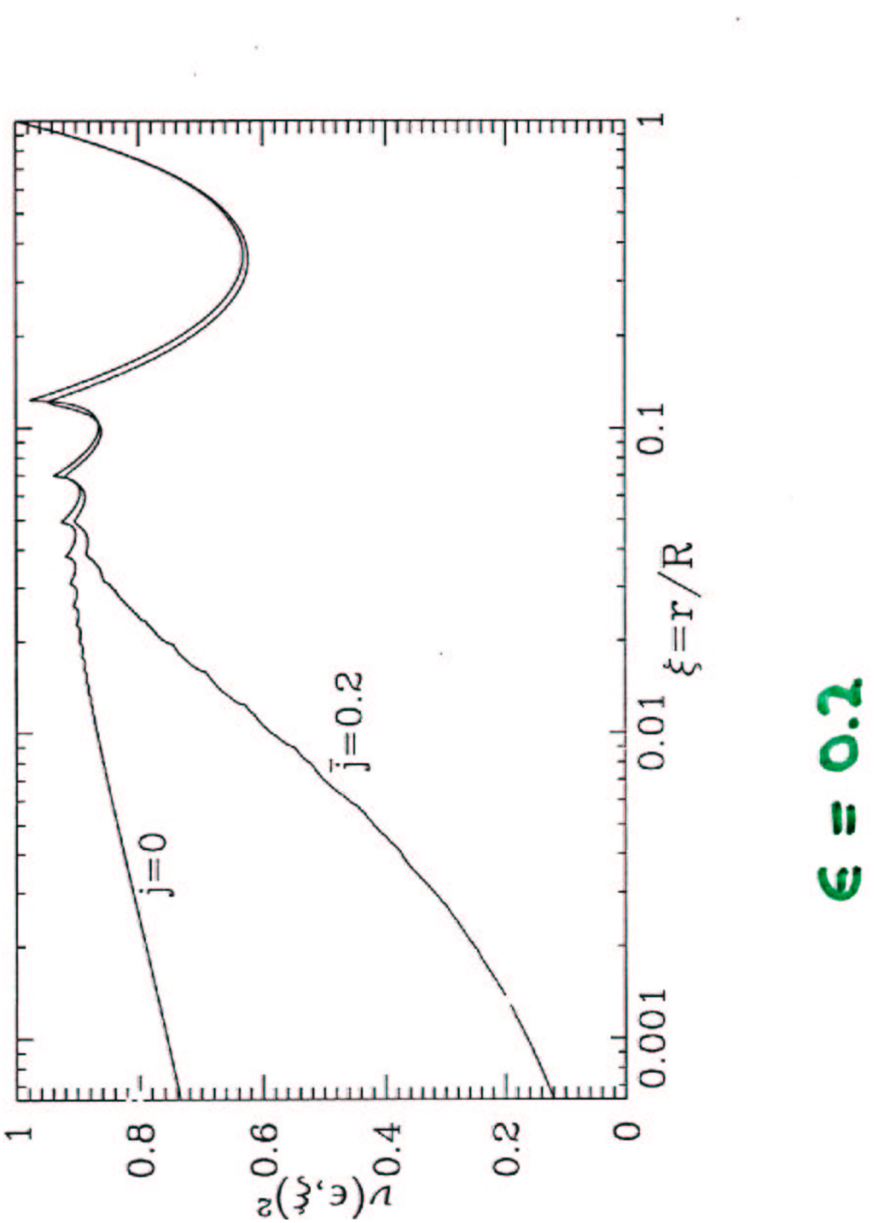
In standard (n=1) CDM models of structure formation

$$\epsilon \simeq 0.2 - 0.35$$





$\epsilon = 0.2$, $j = 0$, $h = 0.7$



Galactic halo formation by CDM infall, with angular momentum, is self-similar if in addition

$$\ell(\hat{r},t) = j(\hat{r})\,\frac{R^2(t)}{t}$$

P.S.
Tkachev
Wang

↑ ang. mom. per unit mass distribution

↑ dimensionless time-independent distribution

Angular momentum has the effect of producing an effective core radius b

For the Milky Way galaxy

$b \simeq 12$ kpc $\leftrightarrow$ $\bar{j} \simeq 0.2$

$R \simeq 2$ Mpc

In the self-similar infall model

Fillmore + Goldreich

Bertschinger

with angular momentum

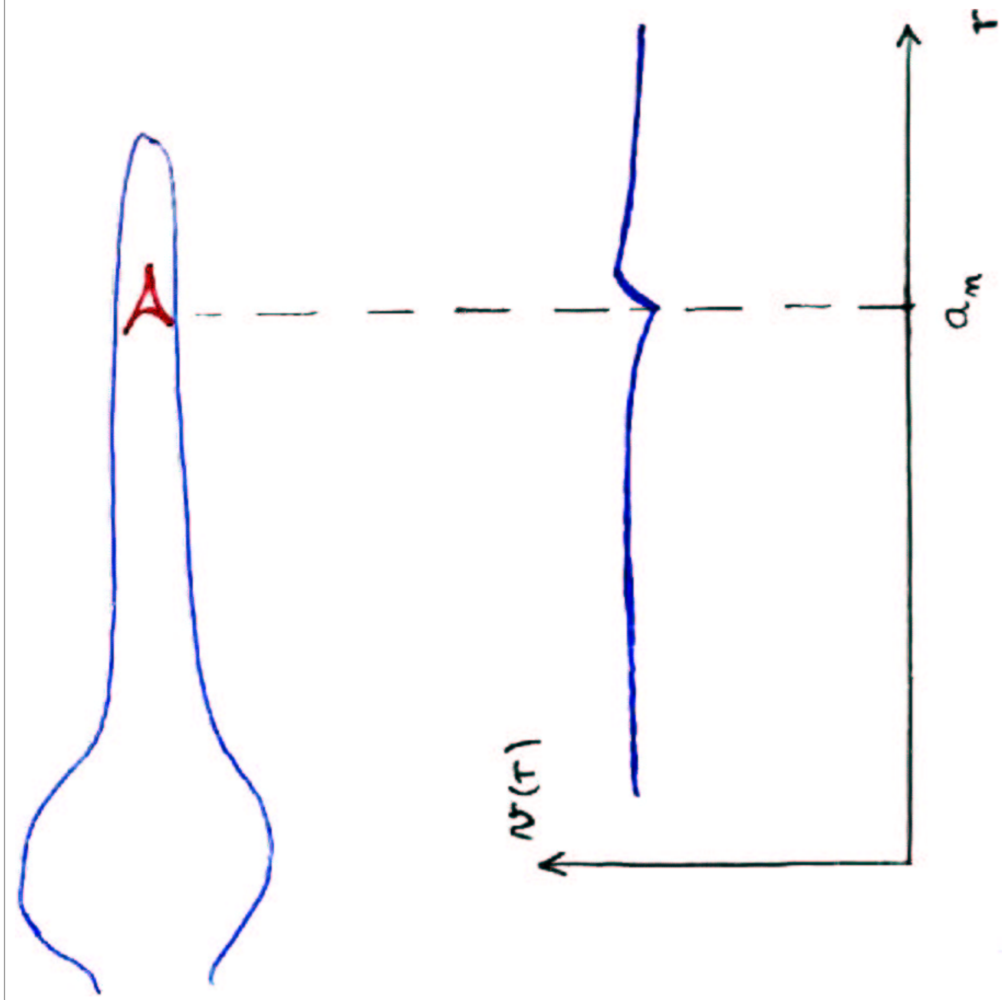
PS, Thacker + Wang

the caustic ring radii are predicted:

$$a_n \simeq 40 \text{ kpc} \cdot \frac{1}{n} \cdot \left(\frac{v_{rot}}{220 \text{ km/s}} \right) \cdot \left(\frac{j_{max}}{0.27} \right) \cdot \left(\frac{0.7}{h} \right)$$

$n = 1, 2, 3 \ldots$

$$\ell_n = j_{max} \, v_{rot} \, R_n$$



With Will Kinney (astro-ph/9906049), we looked at 32 well-measured extended rotation curves selected by R.H. Sanders and K.G. Begeman et al.

$$a_n = (41\,, 20\,, 13.3\,, 10\,, \ldots)\ \text{kpc} \times \left(\frac{v_{rot}}{220\ \text{km/s}}\right)\left(\frac{j_{max}}{0.27}\right)\left(\frac{0.7}{h}\right)$$

For each rotation curve

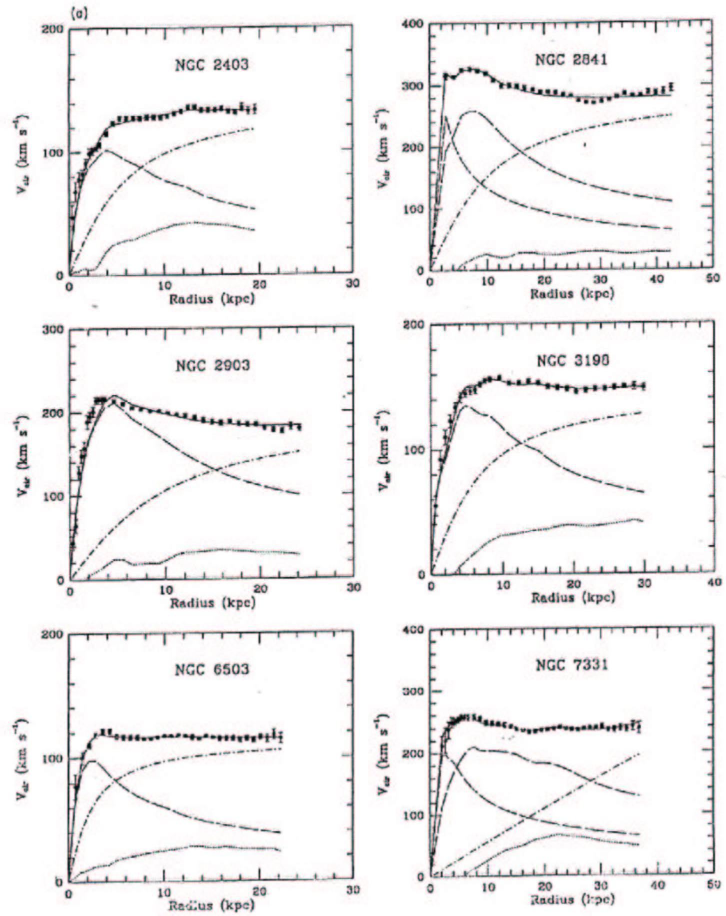
1) rescale

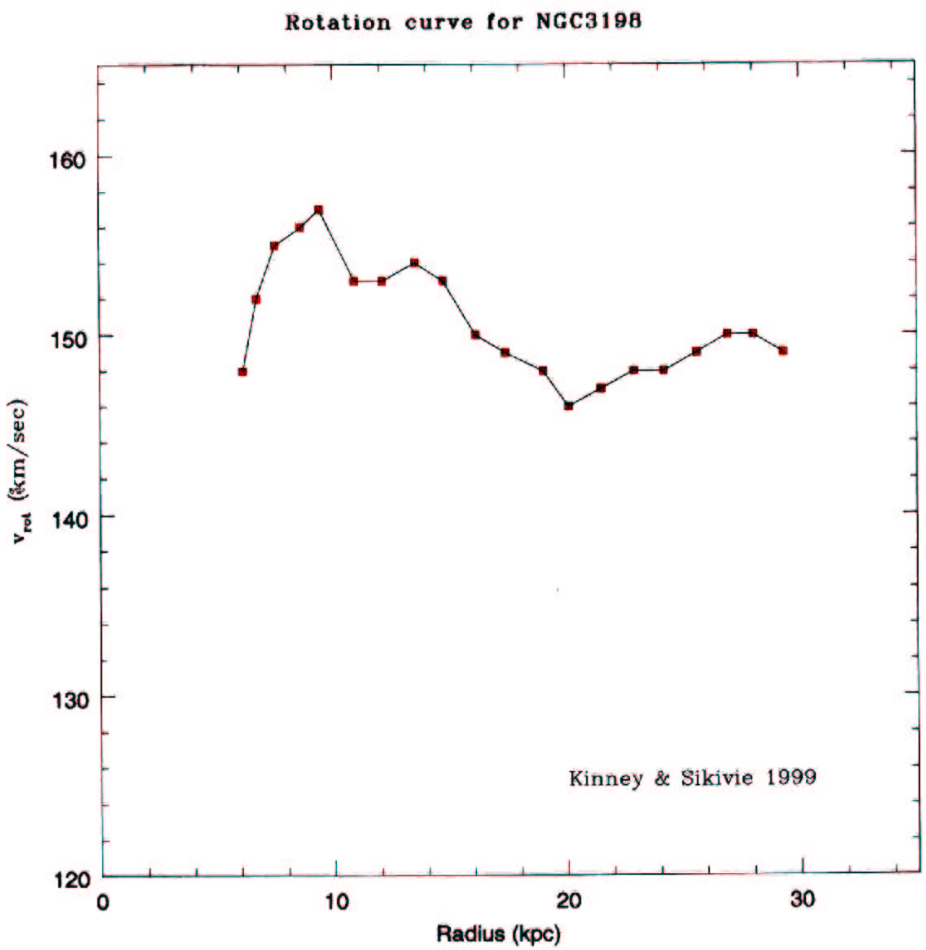
$$r \to \tilde{r} = r\left(\frac{220\ \text{km/s}}{v_{rot}}\right)$$

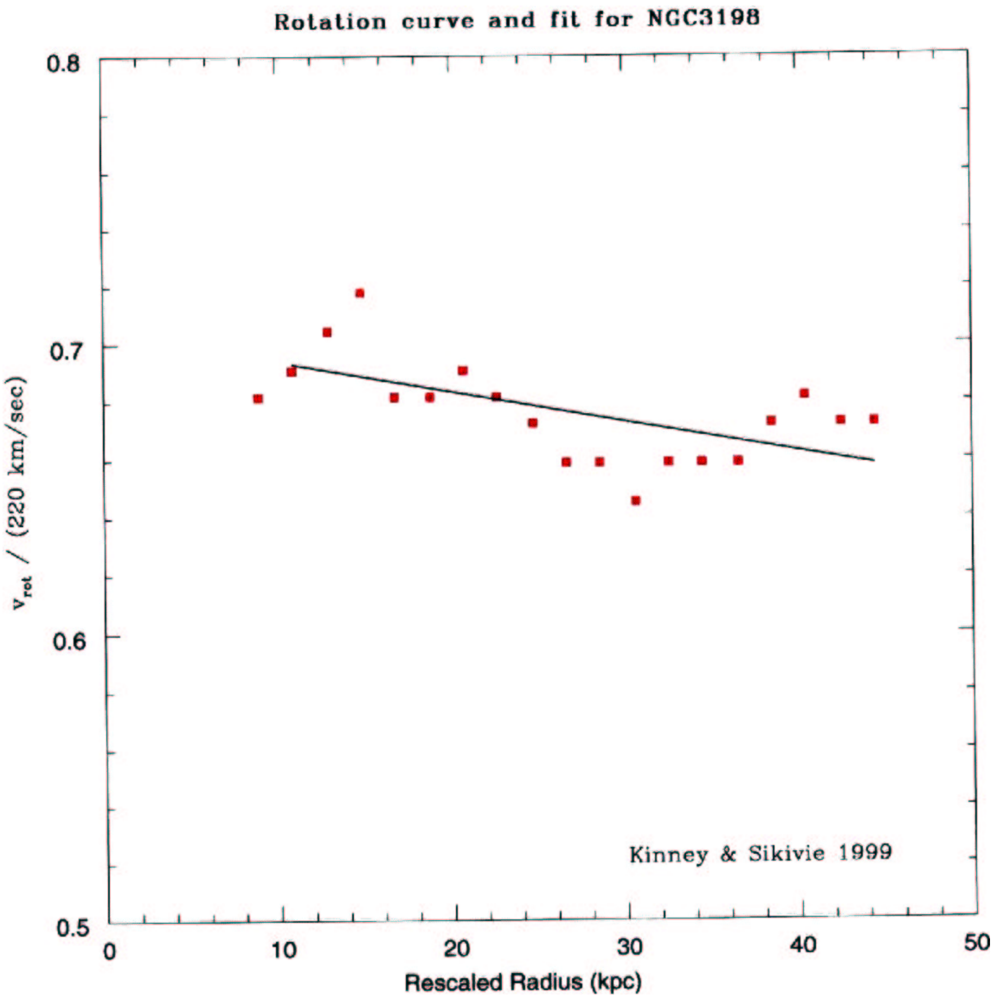
2) cut-off

$$\tilde{r} > 10\ \text{kpc}$$

From Begeman, Broeils and Sanders MNRAS 249 (1991) 523




Rotation curve for NGC3198
160
150
140
130
120
0
10
20
30
Radius (kpc)
Kinney & Sikivie 1999


Rotation curve and fit for NGC3198
0.8
0.7
0.6
0.5
0
10
20
30
40
50
Rescaled Radius (kpc)
v_rot / (220 km/sec)
Kinney & Sikivie 1999

3) fit to line or quadratic polynomials

$\therefore$ δv_j residuals

$\therefore$ $\langle \delta v^2 \rangle^{1/2}$

$\therefore$ $\delta \tilde{v}_j = \frac{\delta v_j}{\langle \delta v^2 \rangle^{1/2}}$

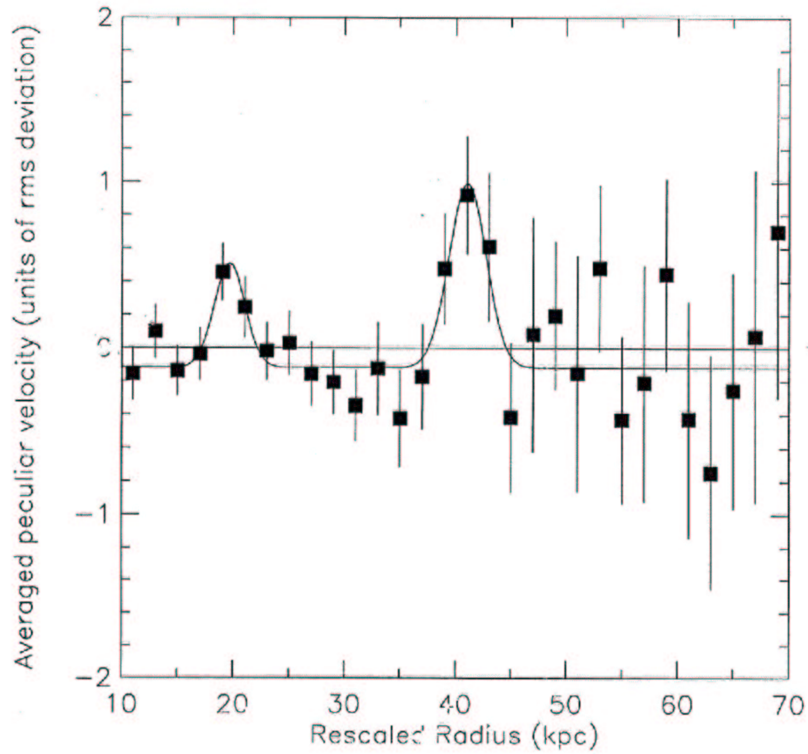
Average over the sample of 32 galaxies

$$b_i \equiv \frac{1}{N_i} \sum_{j=1}^{N_i} \delta \tilde{v}_j$$

(where N_i is the # data points in i^{th} bin)

with assigned error

$$\Delta b_i = \frac{1}{\sqrt{N_i}}$$

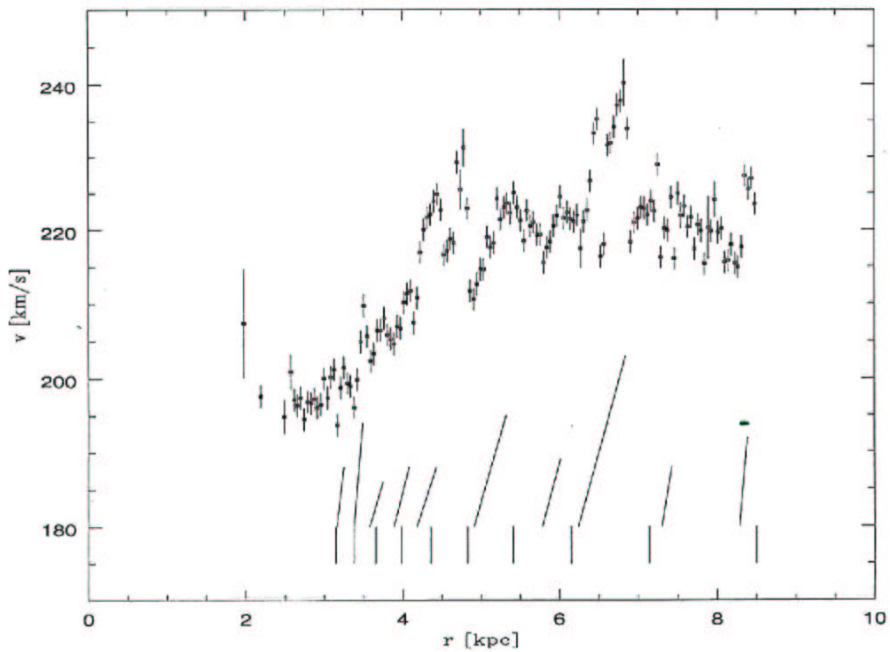


W. Kinney + PS

North Galactic Rotation Curve

D. P. Clements (1985)

derived from the Massachusetts - Stony Brook Galactic plane CO survey



Rises in galactic rotation curves have been interpreted in the past as due to the presence of spiral arms.

If so,

- why are there eight rises between 3 and 7 kpc?
- why are the rises so sharp?

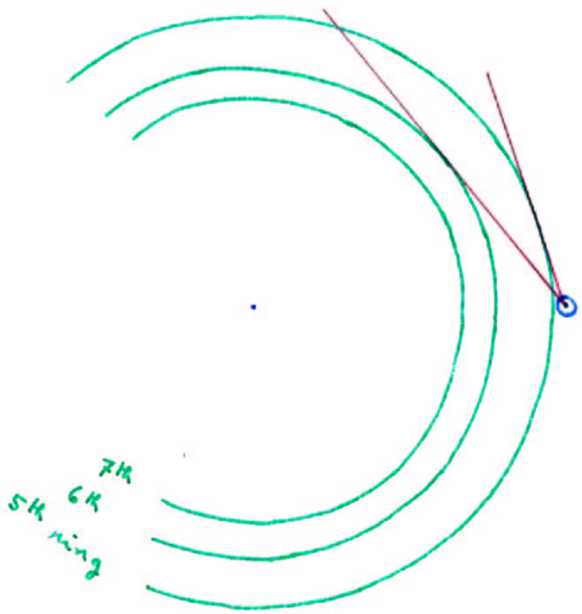
$\epsilon = 0.3$

$j_{max} = 0.263$

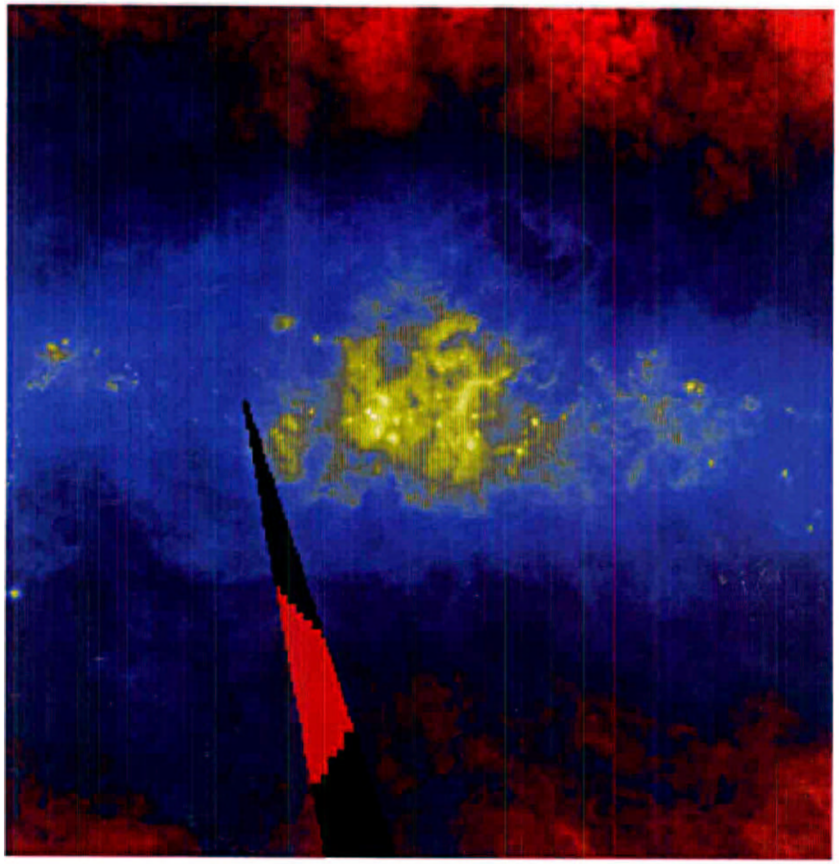
↓

n	a_n^{obs} (kpc)	a_n^{theor} (kpc)	
1		41.2	
2		20.5	
3		13.9	
4		10.5	
5	8.28	8.50	+ 2.6 %
6	7.30	7.14	− 2.2 %
7	6.24	6.15	− 1.5 %
8	5.78	5.41	− 6.4 %
9	4.91	4.83	− 1.6 %
10	4.18	4.36	+ 4.3 %
11	3.89	3.98	+ 2.3 %
12	3.58	3.66	+ 2.2 %
13	3.38	3.38	0.0 %
14	3.16	3.15	− 0.3 %
			rmsd = 3.1 %

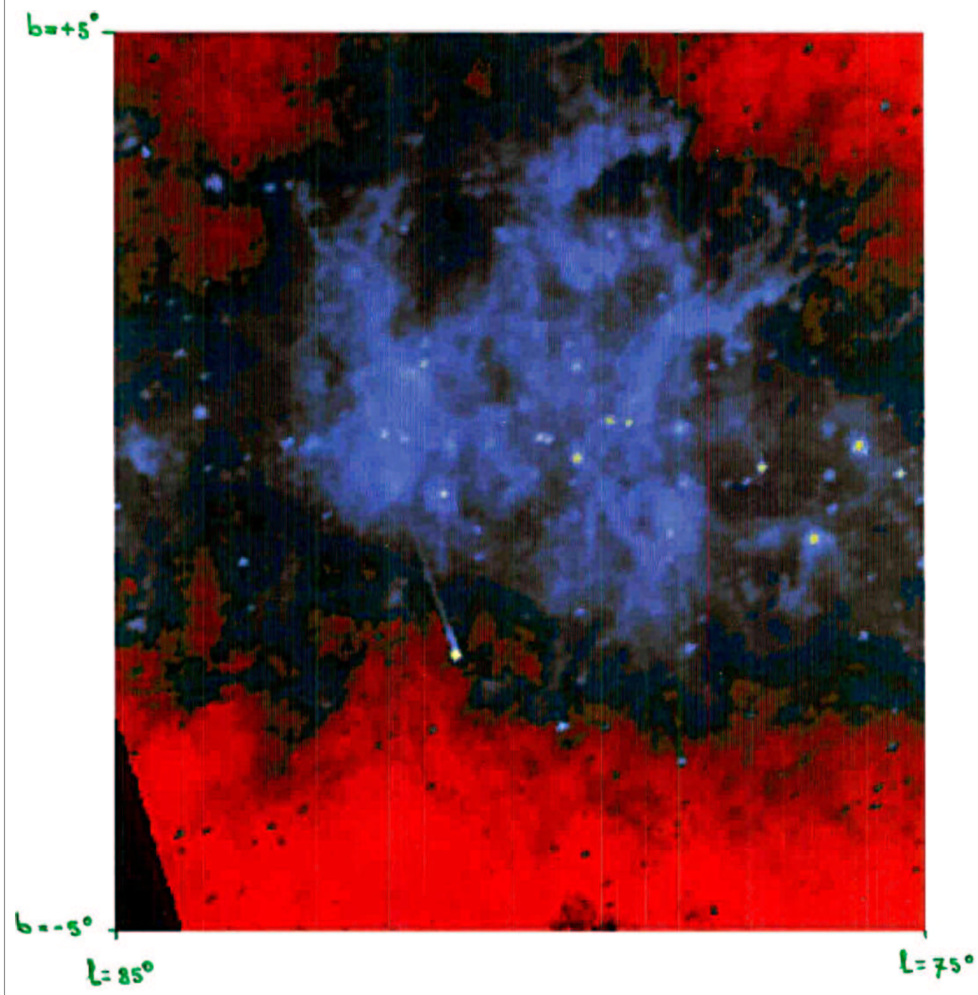
Caustic in the Sky?



Look in the direction tangent to the ring to search for its imprint on the distribution of gas in the galactic disk



IRAS100.30.gif

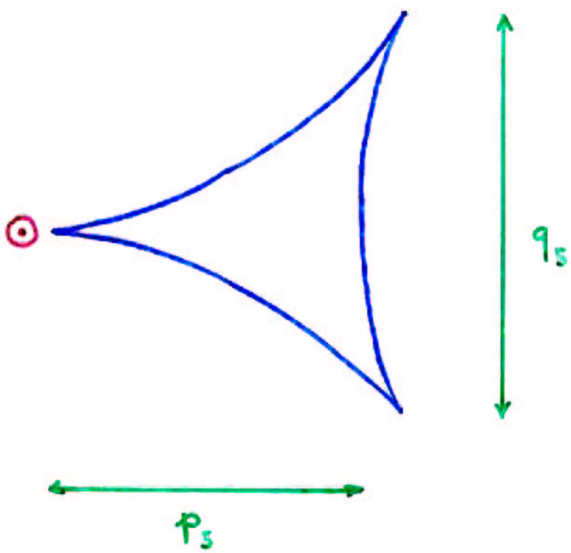


from http://skyview.gsfc.nasa.gov/

IRAS12.mod.gif

5^{th} Caustic parameters

(assuming $R_\odot = 8.5$ kpc)



$$a_5 = 8.31 \pm 0.01 \text{ kpc}$$

$$a_5 + p_5 = 8.45 \pm 0.01 \text{ kpc}$$

$$p_5 = 134 \pm 10 \text{ pc}$$

$$q_5 = 199 \pm 14 \text{ pc}$$

Local densities and velocities of the $n=5$ flows

$$d^+ = 1.7\ 10^{-24}\ \text{gr/cm}^3$$

3X previous estimates of the total local DM density !

$$d^- = 0.15\ 10^{-24}\ \text{gr/cm}^3$$

$$\vec{v}^{\,\pm} = (470\ \hat{\varphi} \pm 100\ \hat{r})\ \text{km/s}$$

(z, φ, r) are galactocentric cylindrical coordinates

The caustics are smoothed by the velocity dispersion δv_{DM} of infalling dark matter over distances of order

$$\delta a \simeq R \frac{\delta v_{DM}}{v}$$

R = turnaround radius

v = flow velocity

From the sharpness of the edges of the triangular feature of the IRAS map:

$$\delta a \lesssim 20 \text{ pc}$$

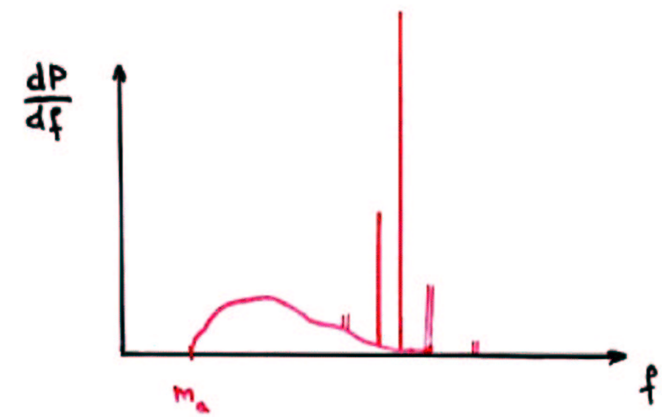
$$\therefore \quad \delta v_{DM} \lesssim 50 \text{ m/s}$$

Signal to noise ratio in axion dark matter search

$$\frac{s}{n} = \frac{P_{signal}}{T_{noise}} \sqrt{\frac{t}{B}}$$

t = measurement integration time

B = bandwidth



Full signal $B \sim 10^{-6} m_a$

Narrow peak $B \sim 10^{-10} m_a$

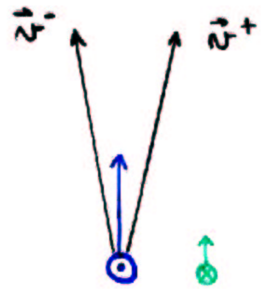
$\frac{P_{signal}}{\sqrt{B}}$ is increased by the factor

$$\frac{3}{\sqrt{10^{-4}}} = 300$$

$\therefore \frac{s}{n}$ increased by a factor ~ 100

Also T_{noise} is decreased by a factor $\frac{1}{100}$ by using SQUIDs instead of HEMTs

J. Clarke et al.



The annual modulation in WIMP searches is the reverse of what is usually thought, i.e. the flux is

lowest in June

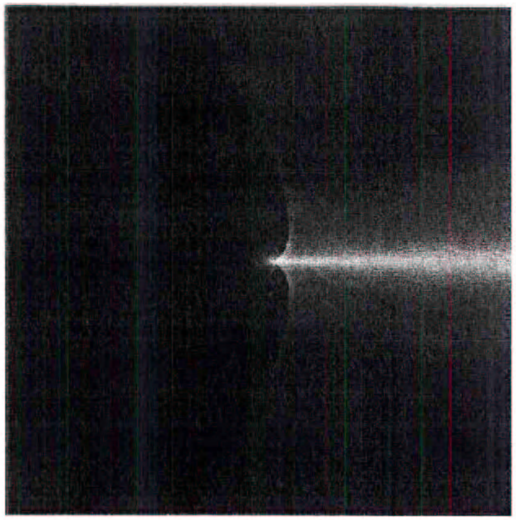
highest in December

J. Vergados

A. Green

G. Gelmini + P. Gondolo

M. Kamionkowski + P. Ullio



picture by Ben Bromley

Solar wakes of dark matter flows

S. Wick + P.S. astro-ph/02...

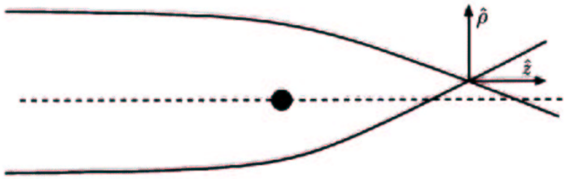
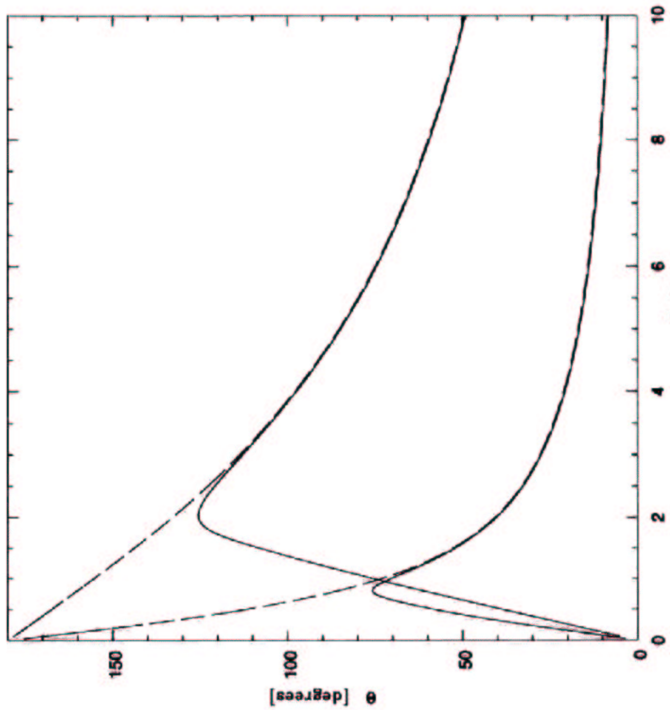


FIG. 1. Two trajectories past a spherically symmetric mass distribution. The incident flow is assumed to be uniform and to have vanishing velocity dispersion. If the scatterer is a point mass, the particles with small impact parameter are scattered by an angle close to 180°, and hence the number of flows $n = 2$ everywhere. If the scatterer is distributed over a finite radius, there is a maximum scattering angle $\Theta_{max} < 180°$. In that case, $n = 1$ upstream of the scatterer, and $n = 3$ downstream.

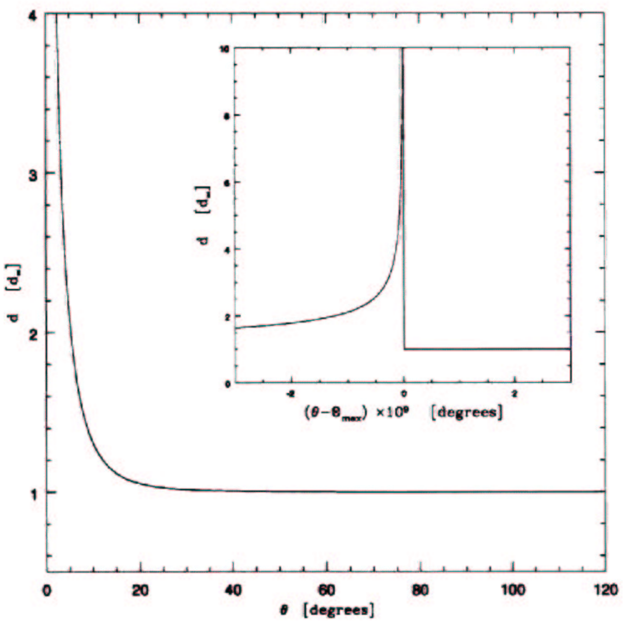
Scattering Angle

Initial velocities: 200 km/sec and 500 km/sec
dashed line: 1/r potential



Density Wake vs θ

v_∞ = 255 km/sec
inset: skirt caustic at $\theta = 115°$



Summary of Evidence for Dark Matter Caustics

- Why does the 32 galaxy composite rotation curve fluctuate upwards at 40 kpc (3.1σ) and 20 kpc (2.6σ)?

  [probability ~ $3 \cdot 10^{-4}$]

- Why eight rises in the Milky Way rotation curve between 3 and 7 kpc?

- Why are the rises sharp?

- Why is there a triangular feature in the IRAS map of the galactic plane near 80° longitude?

- Why is the triangle equilateral, with axis parallel to the galactic plane, and pointing away from the galactic center?

- Why does the triangle (8.31 to 8.44 kpc) coincide with a rise in the rotation curve (8.28 to 8.43 kpc)?

  [probability ~ 10^{-3}]

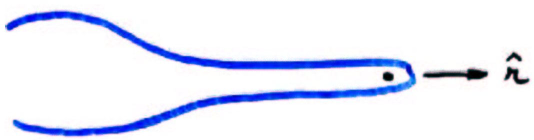
↓

The Big Flow:

$d = 1.7 \; 10^{-24} \; \mathrm{gr}/\mathrm{cm}^3$

3X previous estimates of the <u>total</u> local DM density

$\vec{v} = (470 \, \hat{\varphi} \pm 100 \, \hat{r}) \; \frac{\mathrm{km}}{\mathrm{s}}$



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

$\vec{v}_\odot = 220 \; \mathrm{km/s} \; \hat{\varphi}$