The Strong CP Problem

↓

Axions

P. Sikivie
(U. of Florida)

Blois, June 2002

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Cold Dark Matter

↓

Caustics

↓

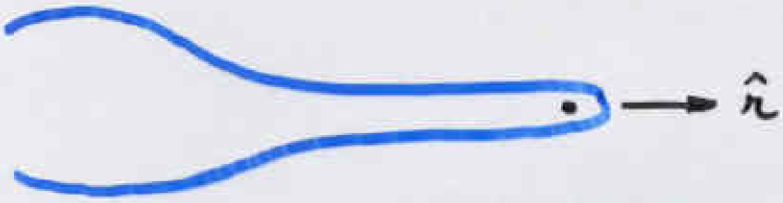
↓

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

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

The strong CP problem

- QCD allows the interaction

$$\mathcal{L}_\theta = \theta \, F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

which violates P and CP

- The absence of P and CP violation in the strong interaction implies

$$\theta < 10^{-9}$$

- But the Standard Model leads one to expect

$$\theta = O(1)$$

The Peccei-Quinn mechanism

makes θ dynamical

$$\mathcal{L}_\theta = \frac{a(x)}{f_a} F^a_{\mu\nu} \tilde{F}^{a\,\mu\nu}$$

In the lowest energy state

$$\theta = \frac{a(x)}{f_a} = 0$$

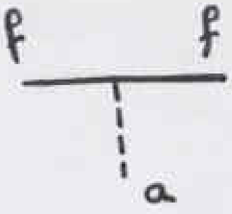
The axion is a light

pseudo-scalar particle of mass

$$m_a = 6\ \mathrm{eV}\ \frac{10^6\ \mathrm{GeV}}{f_a}$$

Weinberg
Wilczek

Couplings

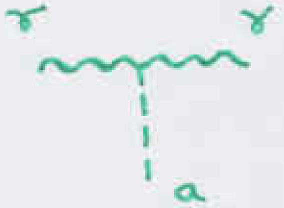


$$\mathcal{L}_{a\bar{f}f} = g_f \frac{m_f}{f_a} \, i \, a \, \bar{f} \gamma_5 f$$

f = fermion

$g_f = O(1)$ generically

$g_{e,\mu \dots} = 0$ in "hadronic" models

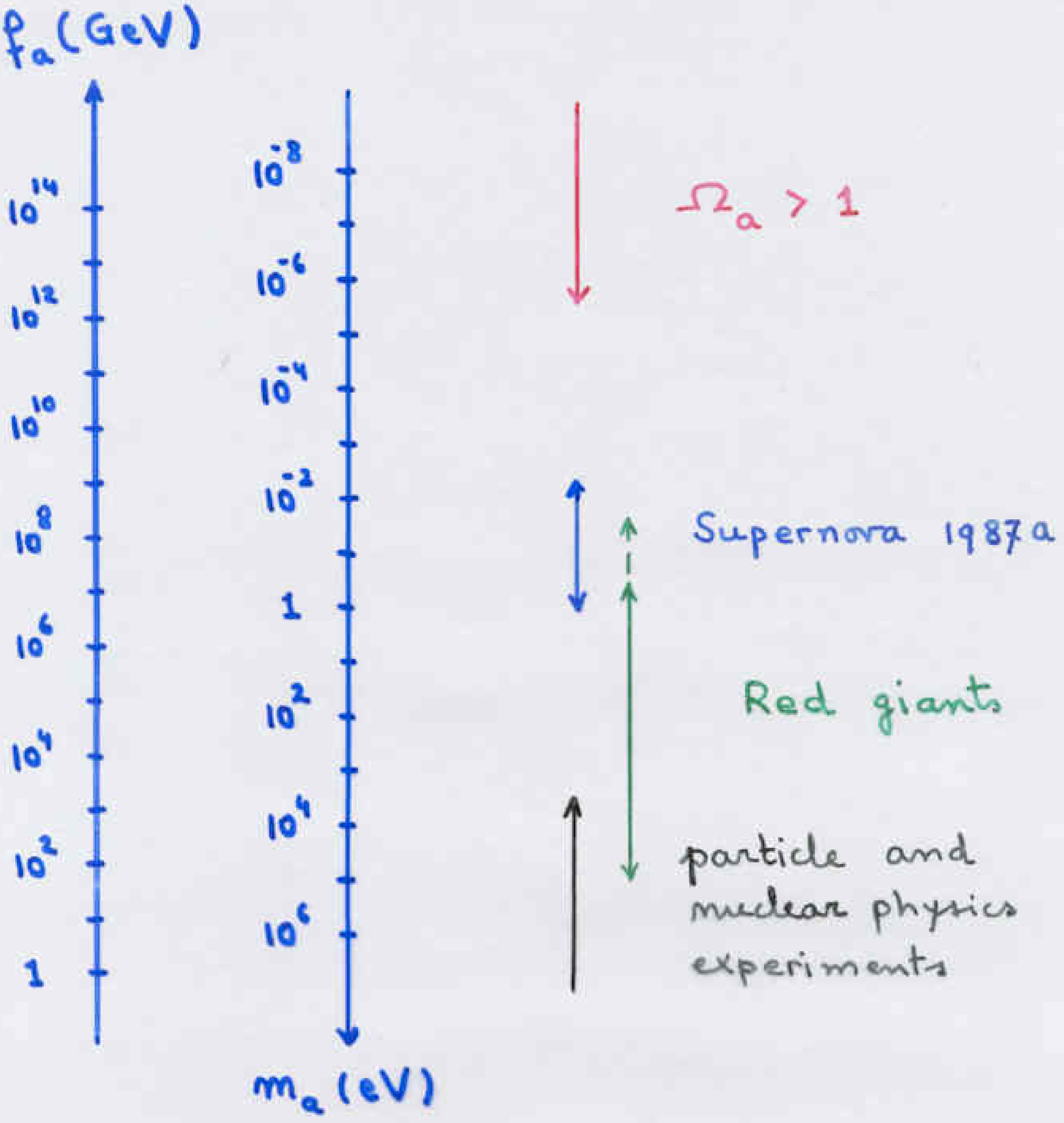


$$\mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a} \, a \, \vec{E} \cdot \vec{B}$$

$g_\gamma \simeq 0.36$ in PQWW and DFSZ models (Bardeen & Tye)

$\simeq -0.97$ in KSVZ model

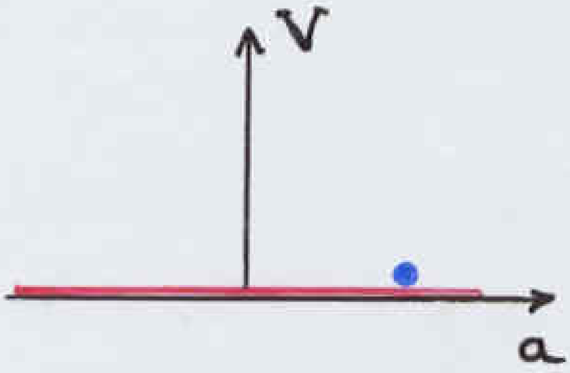
Constraints on the Axion



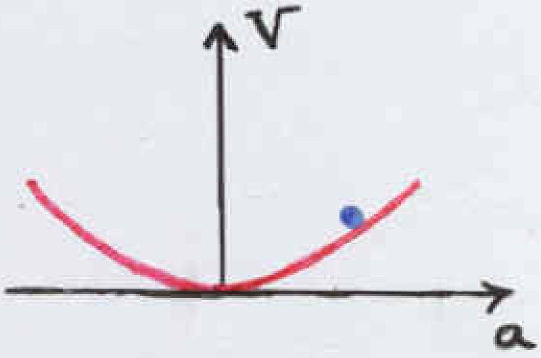
$$m_a = 6\,\mathrm{eV}\left(\frac{10^6\,\mathrm{GeV}}{f_a}\right)$$

Axions from vacuum realignment

The axion mass turns on during the QCD phase transition ..



$T \gg 1\,\mathrm{GeV}$



$T \ll 1\,\mathrm{GeV}$

$$m_a(t) \sim T^{-4} \sim t^2$$

Critical time t_1 : $m_a(t_1) = \frac{1}{t_1}$

$$T(t_1) \simeq 1\,\mathrm{GeV}$$

After t_1, the number of axions is an adiabatic invariant

$$n_a(t_1) = \frac{1}{m_a(t_1)}\,\rho_a(t_1) \simeq f_a^2\, m_a(t_1) \simeq \frac{f_a^2}{t_1}$$

$$n_a(t_1)\, R_1^3 = n_a(t_0)\, R_0^3$$

$$\therefore \quad \Omega_a = \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \left(\frac{200\,\mathrm{MeV}}{\Lambda_{QCD}}\right)^{3/4} \left(\frac{75\,\mathrm{km/sec.Mpc}}{H_0}\right)$$

$$\therefore \quad f_a \lesssim 10^{12}\,\mathrm{GeV}$$

or $\quad m_a \gtrsim 6\,\mu\mathrm{eV}$

Axions are cold dark matter since

$$p_a(t_1) \sim \frac{1}{t_1} \sim \frac{1}{2.10^{-7}\,\mathrm{sec}} \sim 10^{-8}\,\mathrm{eV}$$

Cold dark matter necessarily contributes to galactic halos by falling into the gravitational wells of galaxies.

Axion Populations

- Thermal axions

$$\langle p_a \rangle \sim T_{CMBR} \sim 10^{-4}\,eV$$

$$\Omega_a^{thermal} \sim m_a$$

- Cold axions

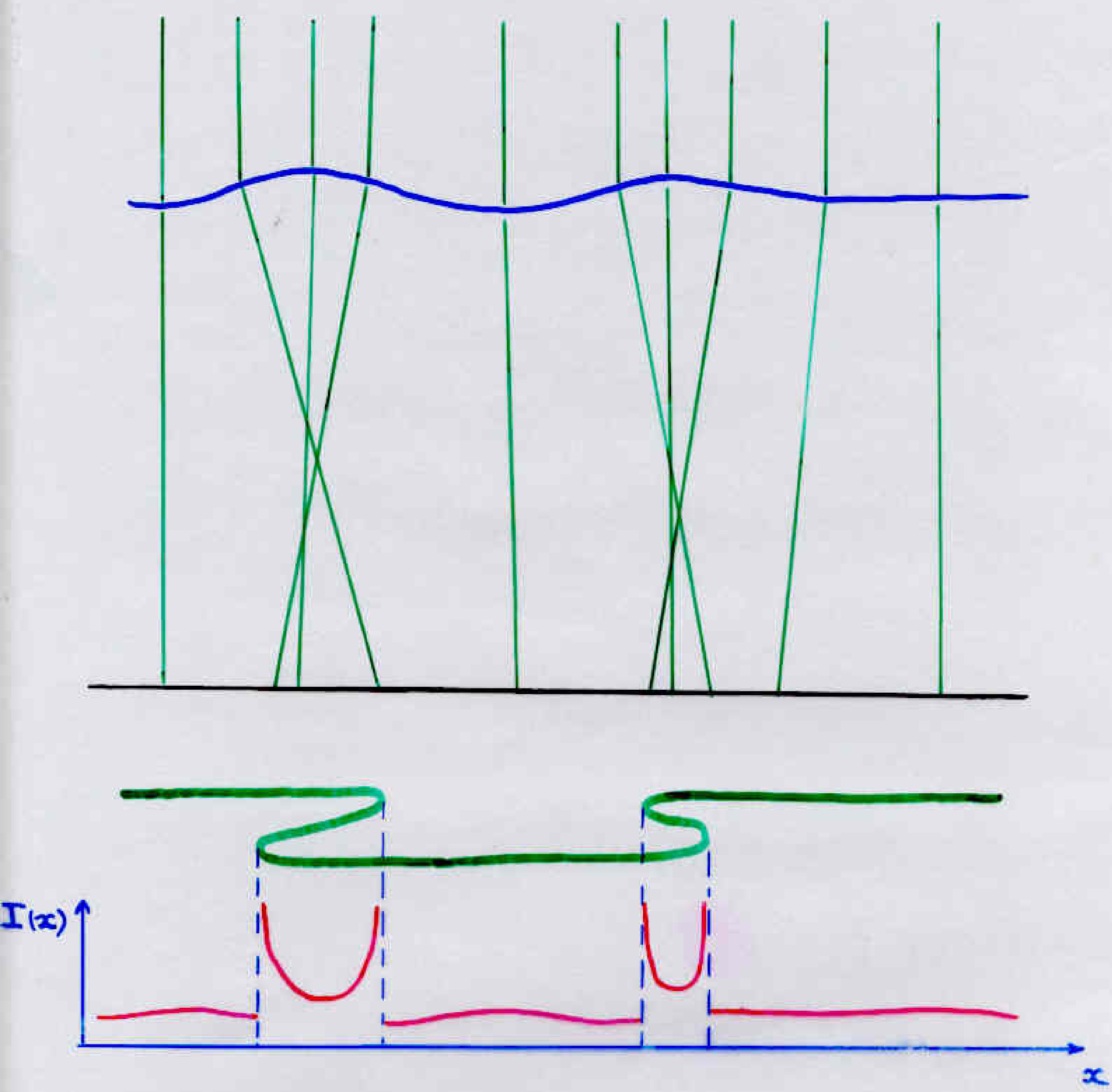
$$\langle p_a \rangle \sim \frac{1}{t_{QCD}} \left(\frac{R_{QCD}}{R_{today}} \right) \sim 10^{-22}\,eV$$

$$(10^{-18}\,K\ !)$$

$$\Omega_a^{cold} \sim m_a^{-7/6}$$

produced by vacuum realignment
string decay
wall decay

Line caustics of light at the bottom of a swimming pool.



Conditions

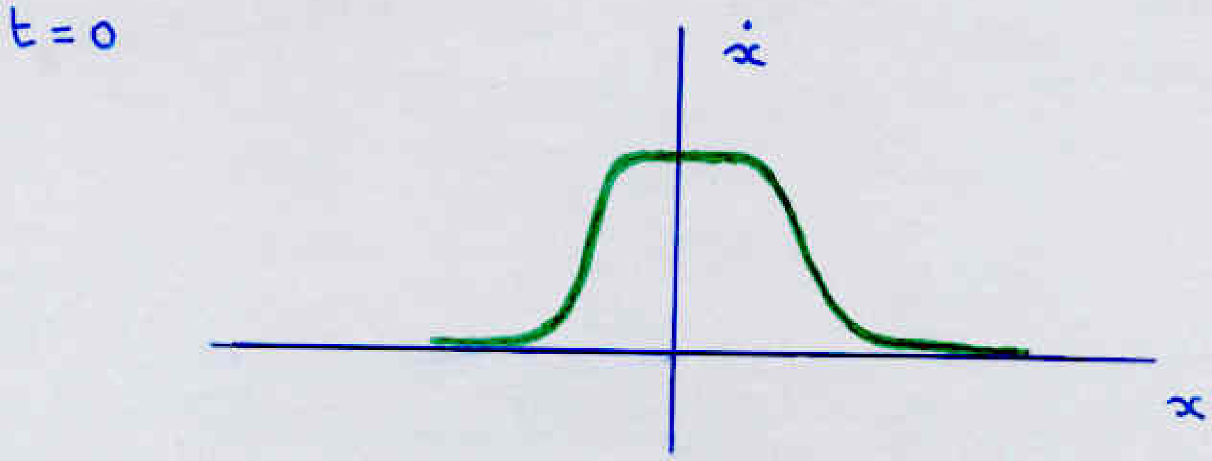
- single velocity (or finite number) at every point
- collisionless particles

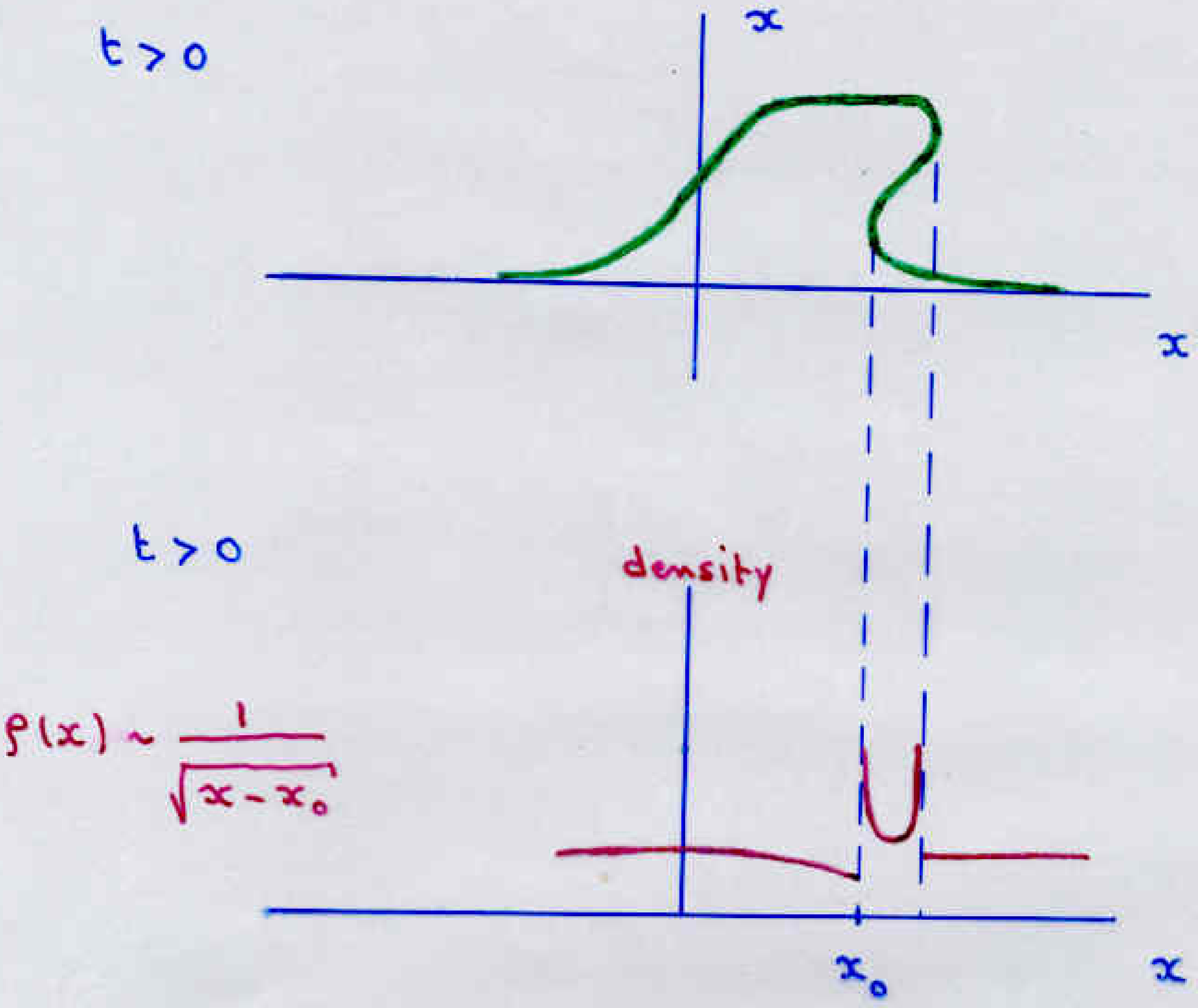
Caustics

are generic

are sharp

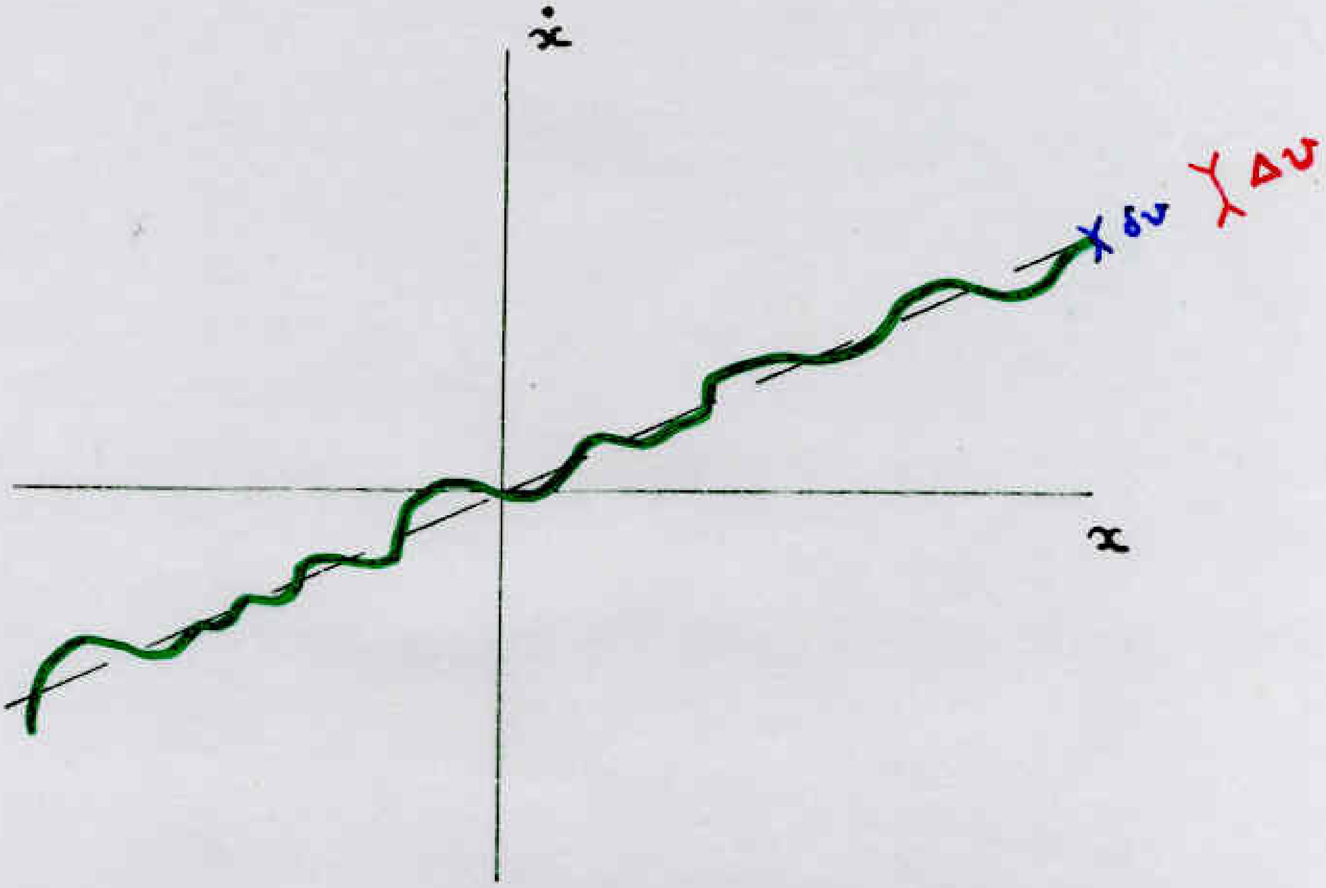
Phase Space





The initial phase space distribution of CDM at time t_i

$$t_{eq} < t_i \ll t_0$$



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

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

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

FIGURES

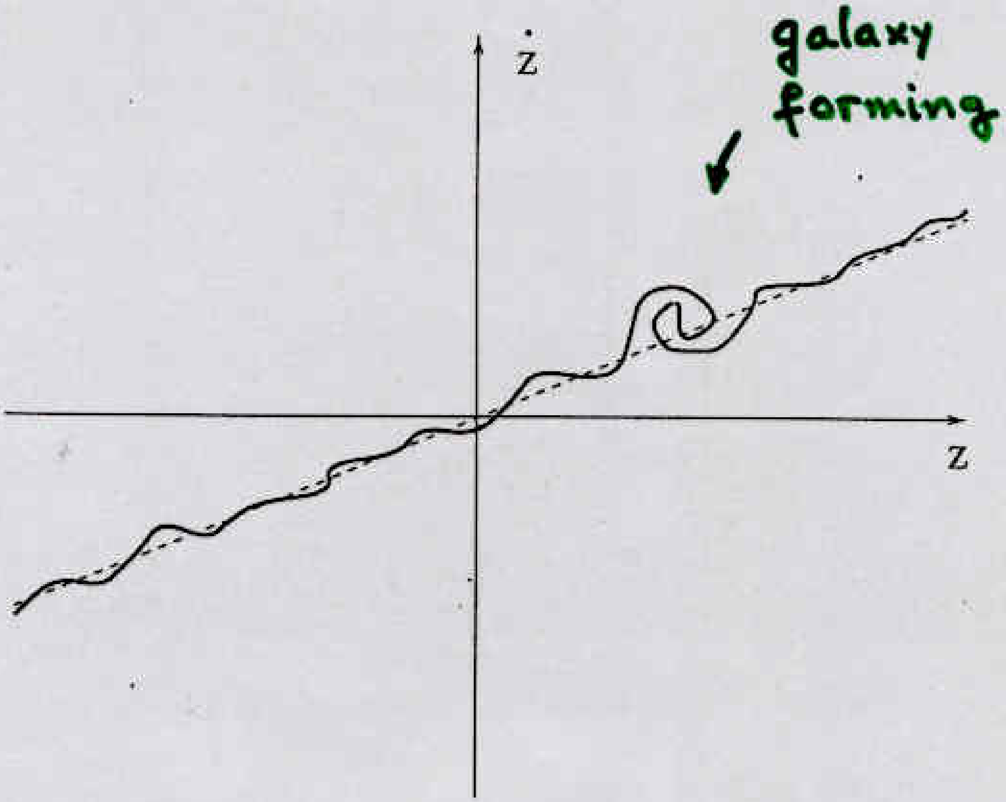
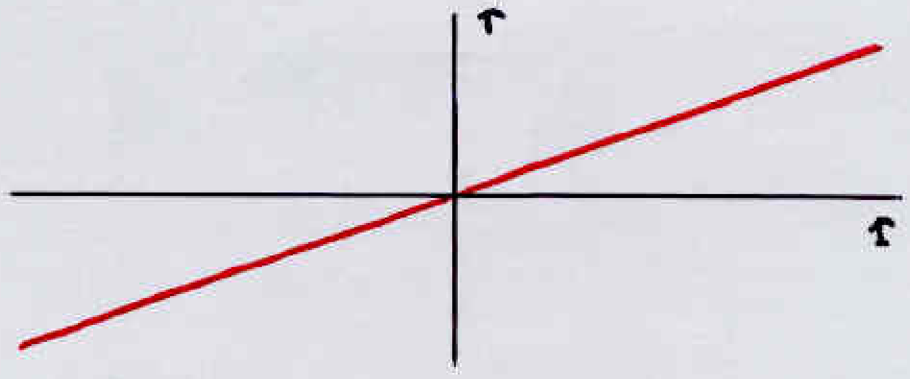
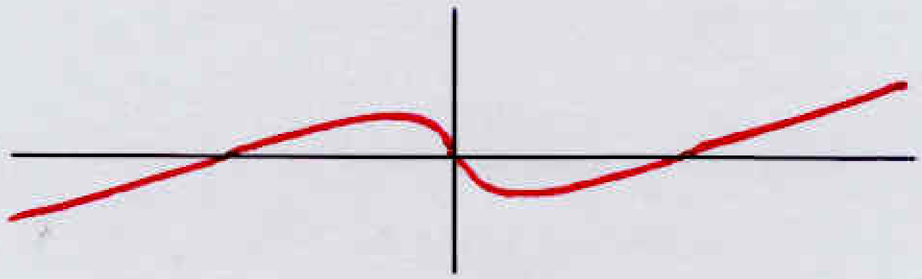
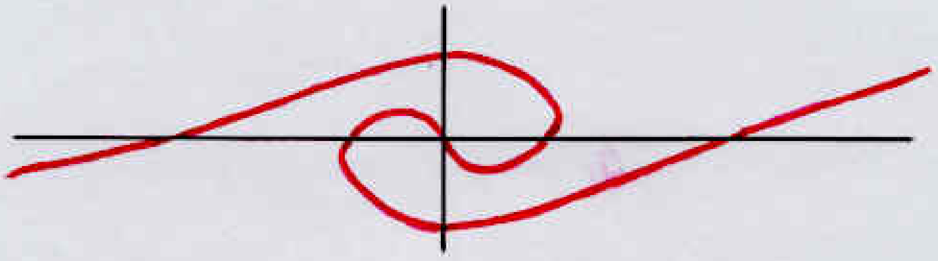
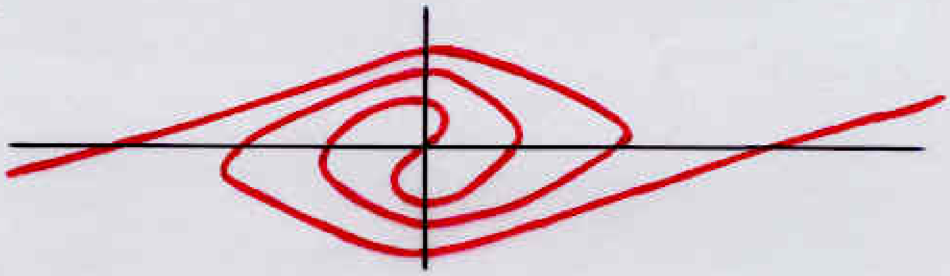


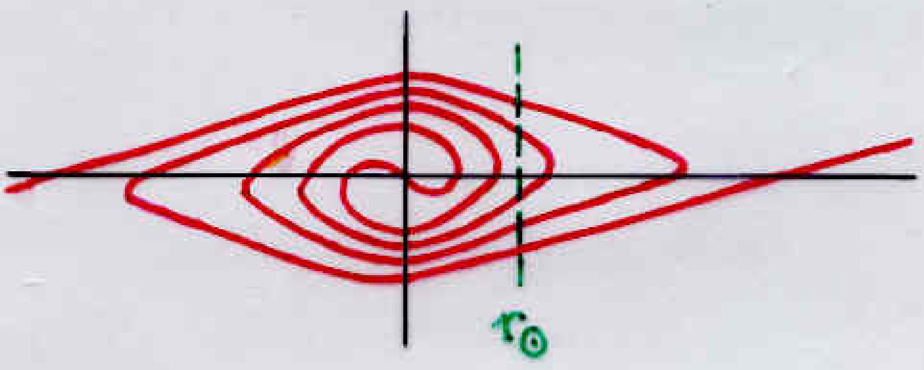
FIG. 1. The wiggly line is the intersection of the $(z, \dot{z})$ plane with the 3D sheet on which the collisionless dark matter particles lie in phase-space. The thickness of the line is the primordial velocity dispersion. The amplitude of the wiggles in the $\dot{z}$ direction is the velocity dispersion associated with density perturbations. Where an overdensity grows in the non-linear regime, the line winds up in clockwise fashion. One such overdensity is shown.

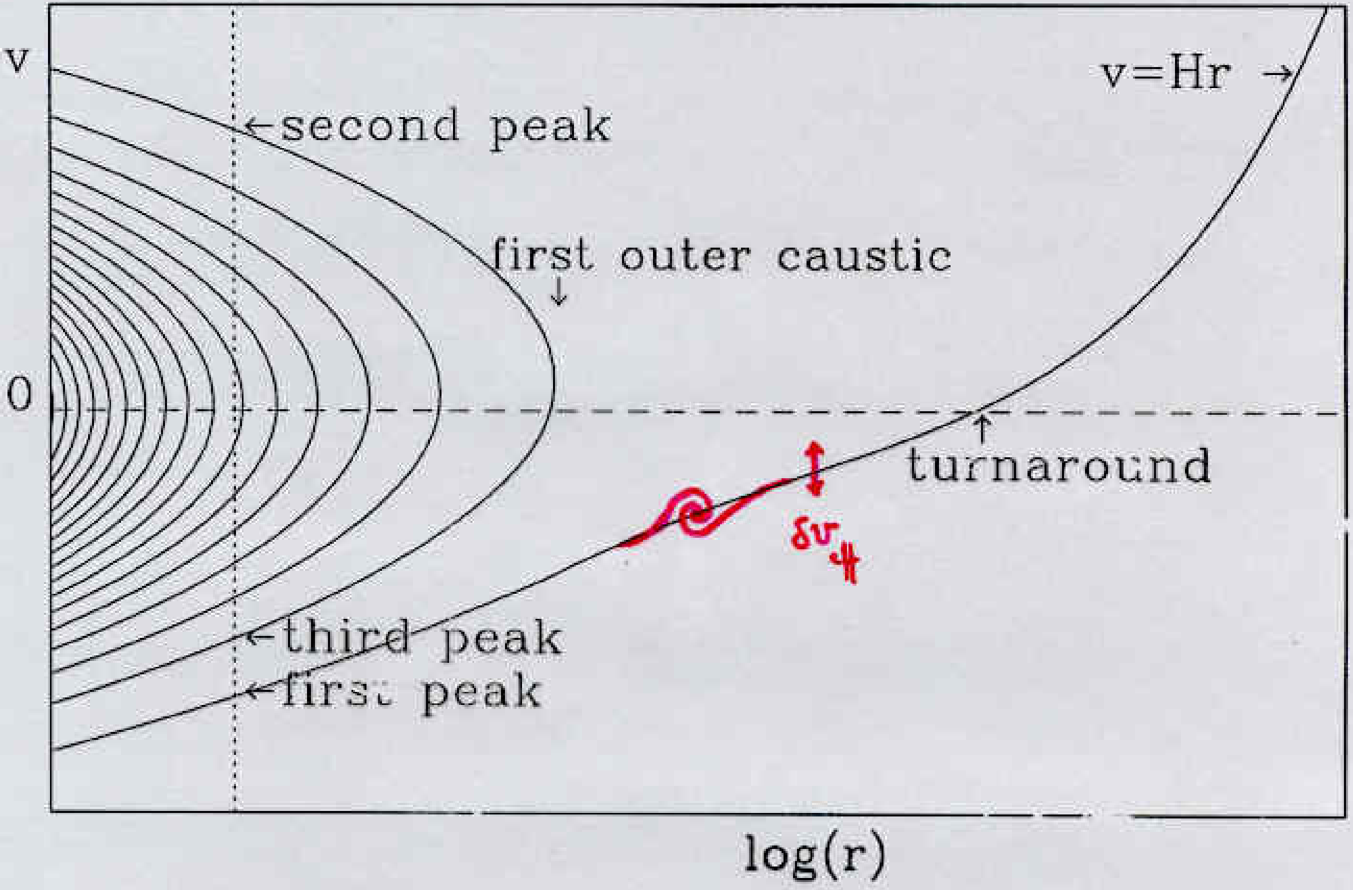

$\dot{r}$
r





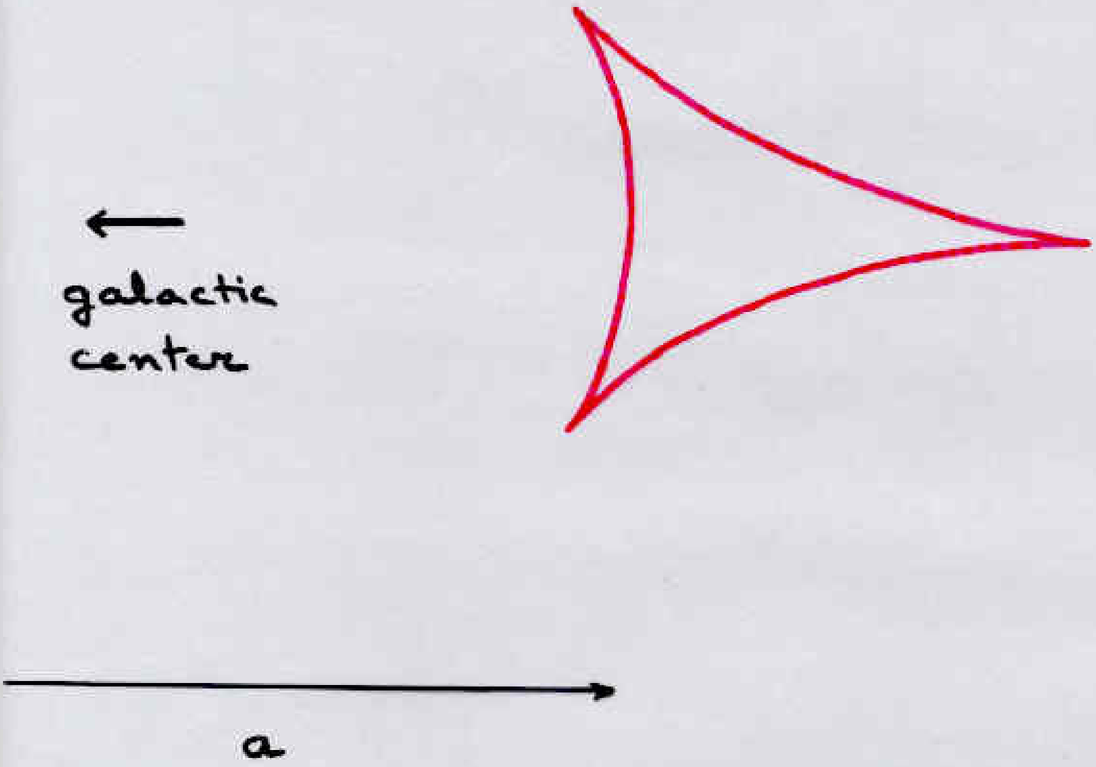


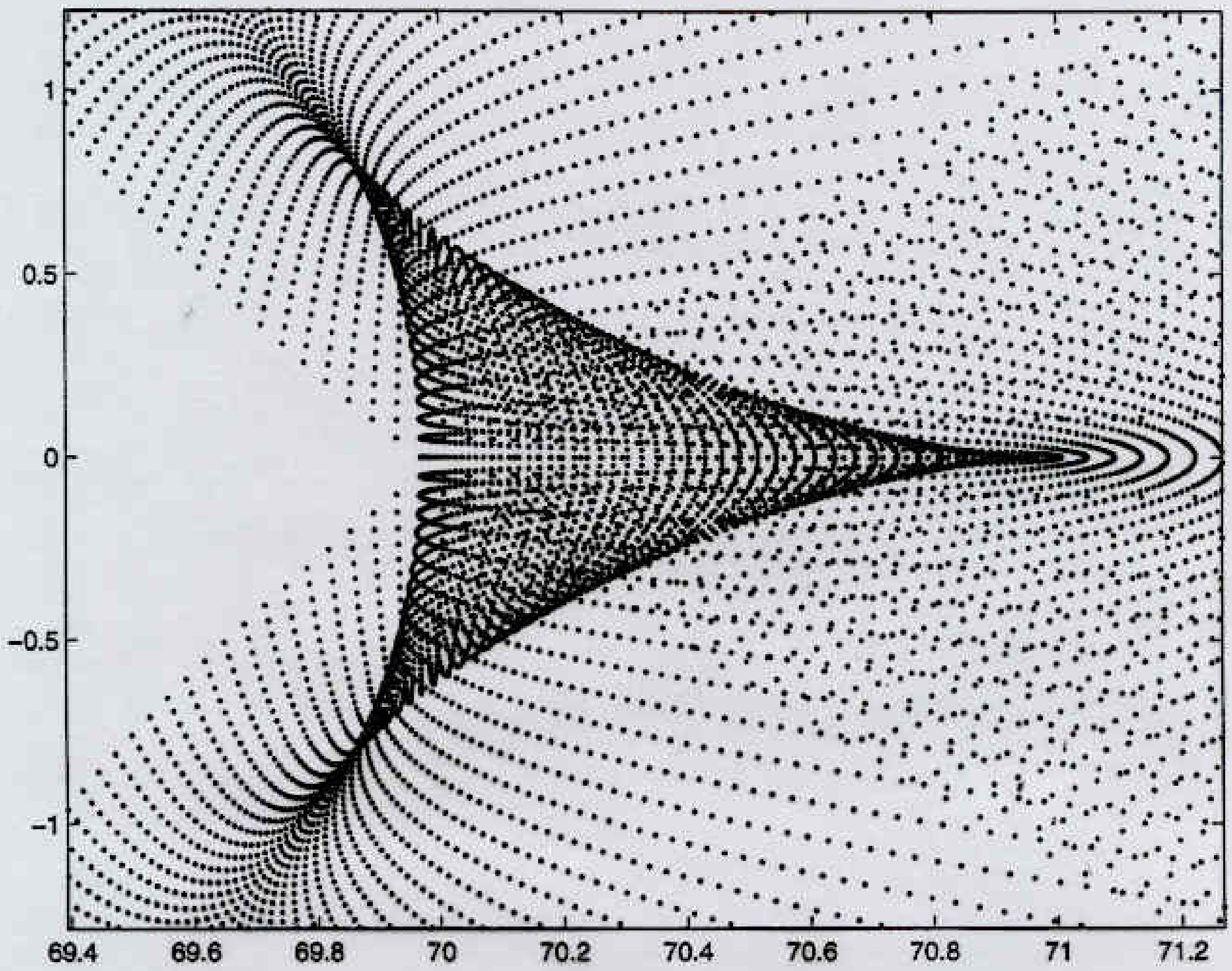

r_0


v
0
←second peak
first outer caustic ↓
v=Hr →
turnaround
δv_{ff}
←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)





Charmousis, Onemli,
Qiu + P.S.

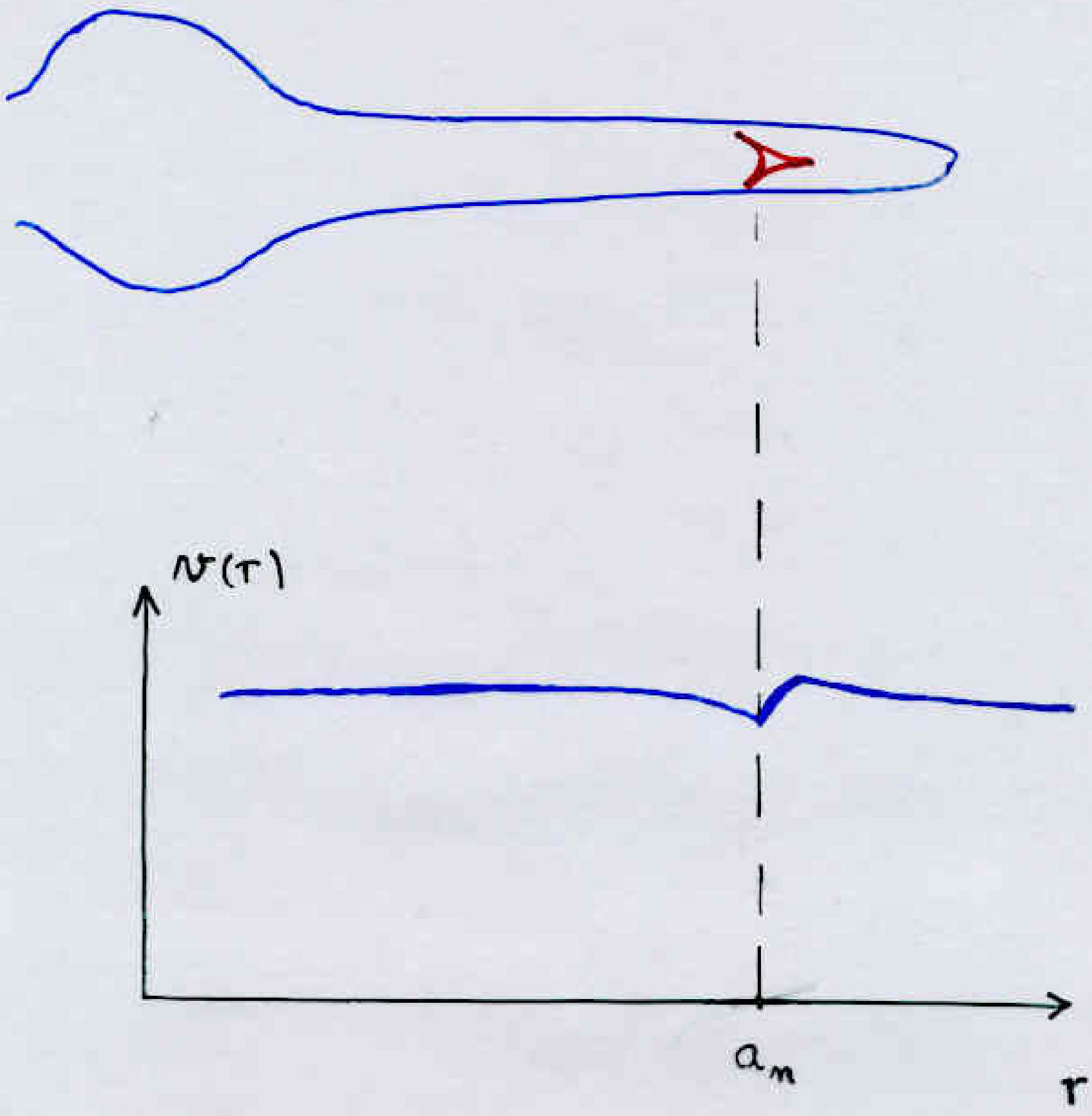
Caustic rings of dark matter form around isolated galaxies

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


$v(r)$
a_n
r

In the self-similar infall model

Fillmore + Goldreich
Bertschinger

with angular momentum

PS, Tkachev + 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.

$$a_m = (41\ ,20\ ,13.3\ ,10\ ,\ldots)\ \mathrm{kpc}\ \times$$

$$\times\left(\frac{v_{rot}}{220\ \mathrm{km/s}}\right)\left(\frac{j_{max}}{0.27}\right)\left(\frac{0.7}{h}\right)$$

For each rotation curve

1) rescale

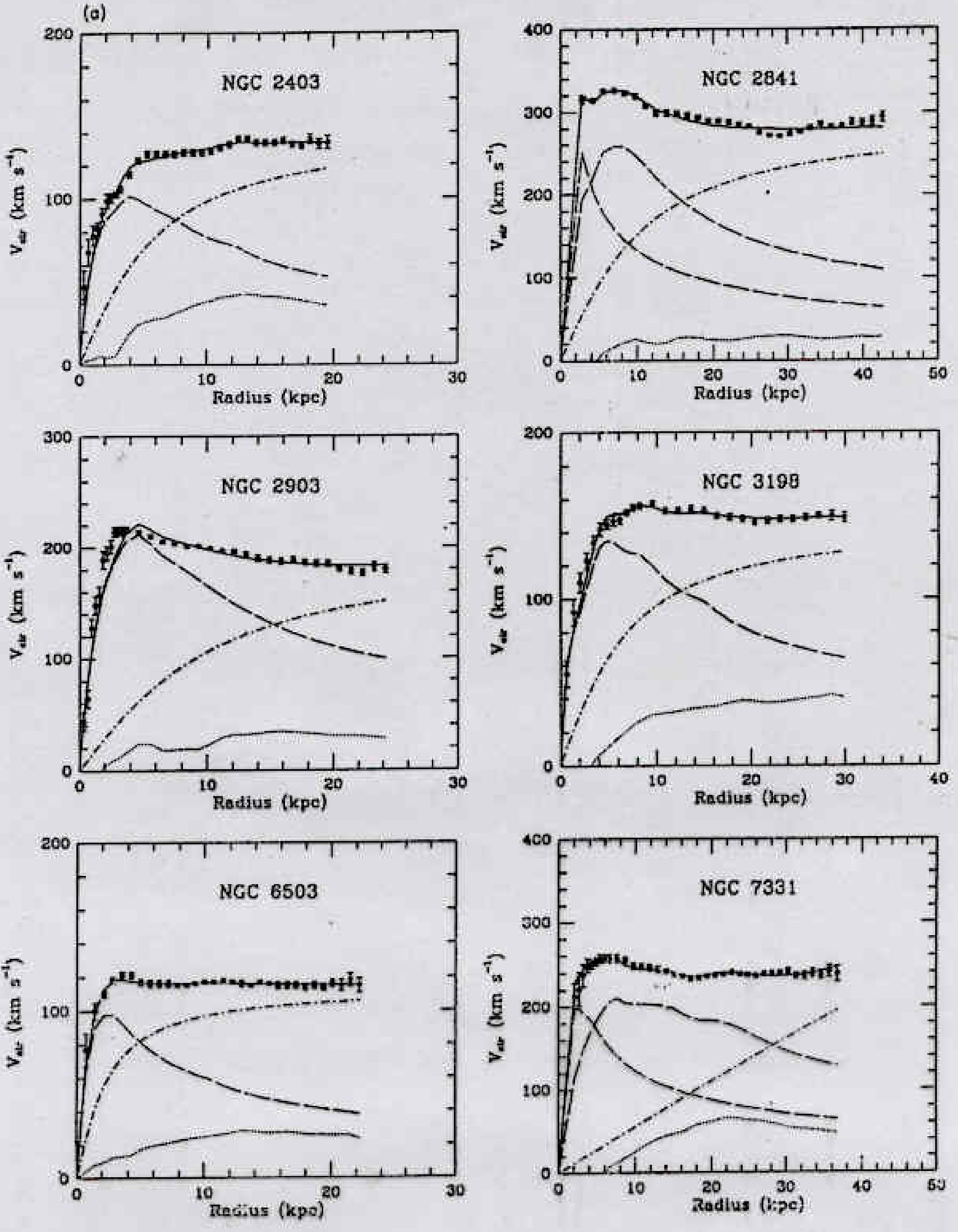
$$r \to \tilde{r} = r\left(\frac{220\ \mathrm{km/s}}{v_{rot}}\right)$$

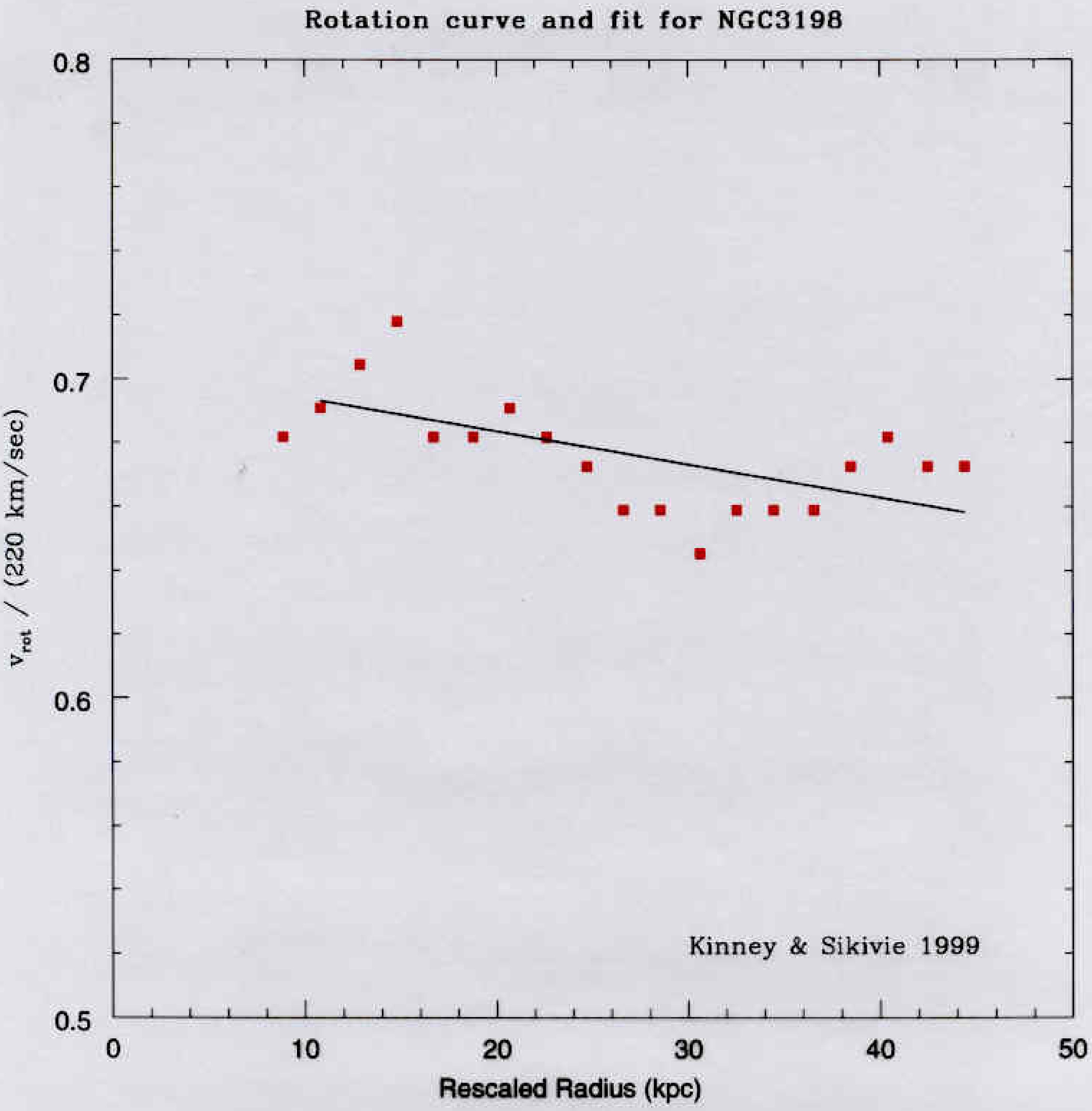
2) cut-off

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

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

(a)




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

3) fit to line or quadratic polynomials

$\therefore$ δv_j residuals

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

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

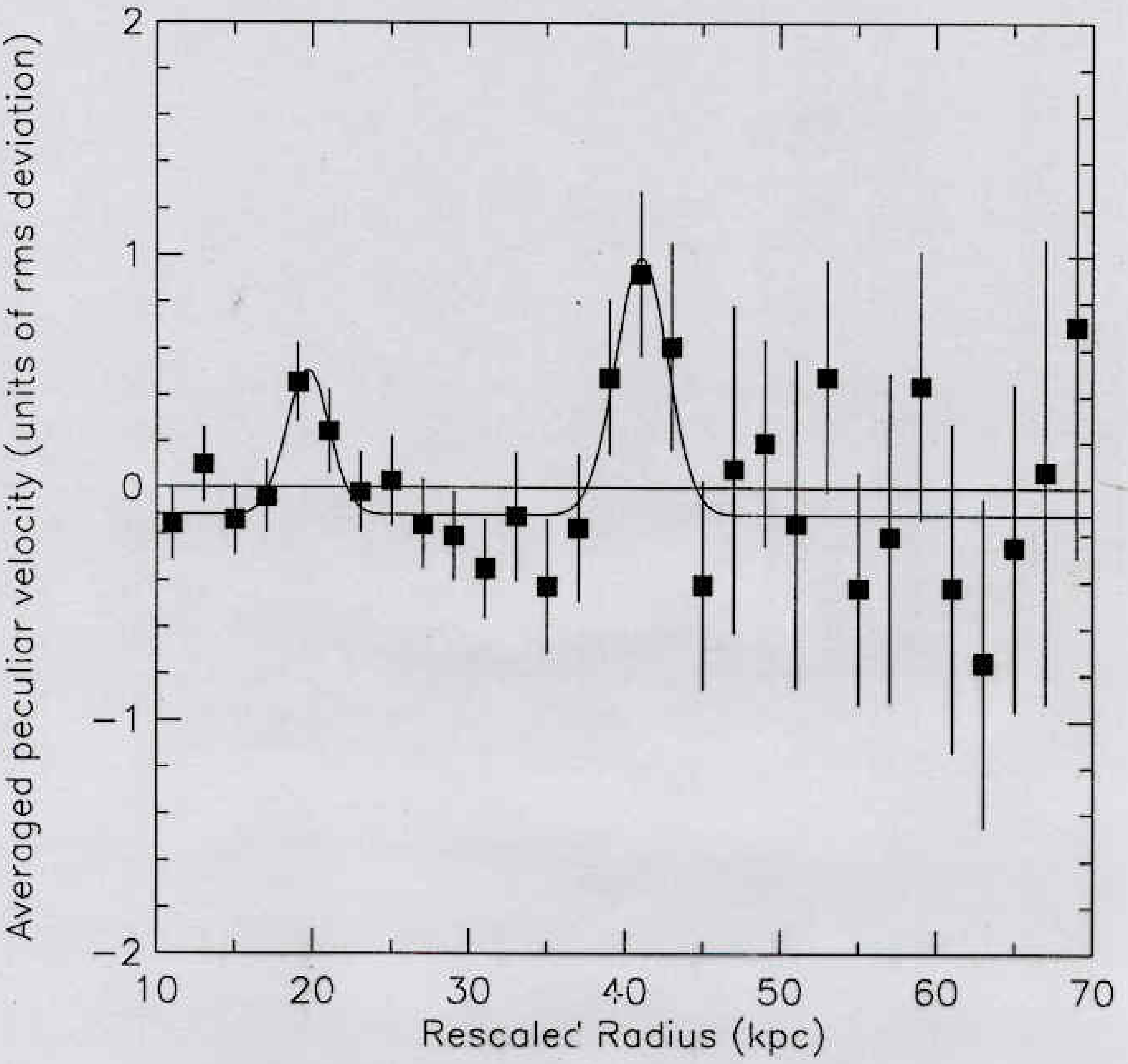
Average over the sample of 32 galaxies

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

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

with assigned error

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


2
1
0
−1
−2
10
20
30
40
50
60
70
Averaged peculiar velocity (units of rms deviation)
Rescaled Radius (kpc)

W. Kinney + PS

From D. P. Clemens, Ap. J. 295 (1985) 422

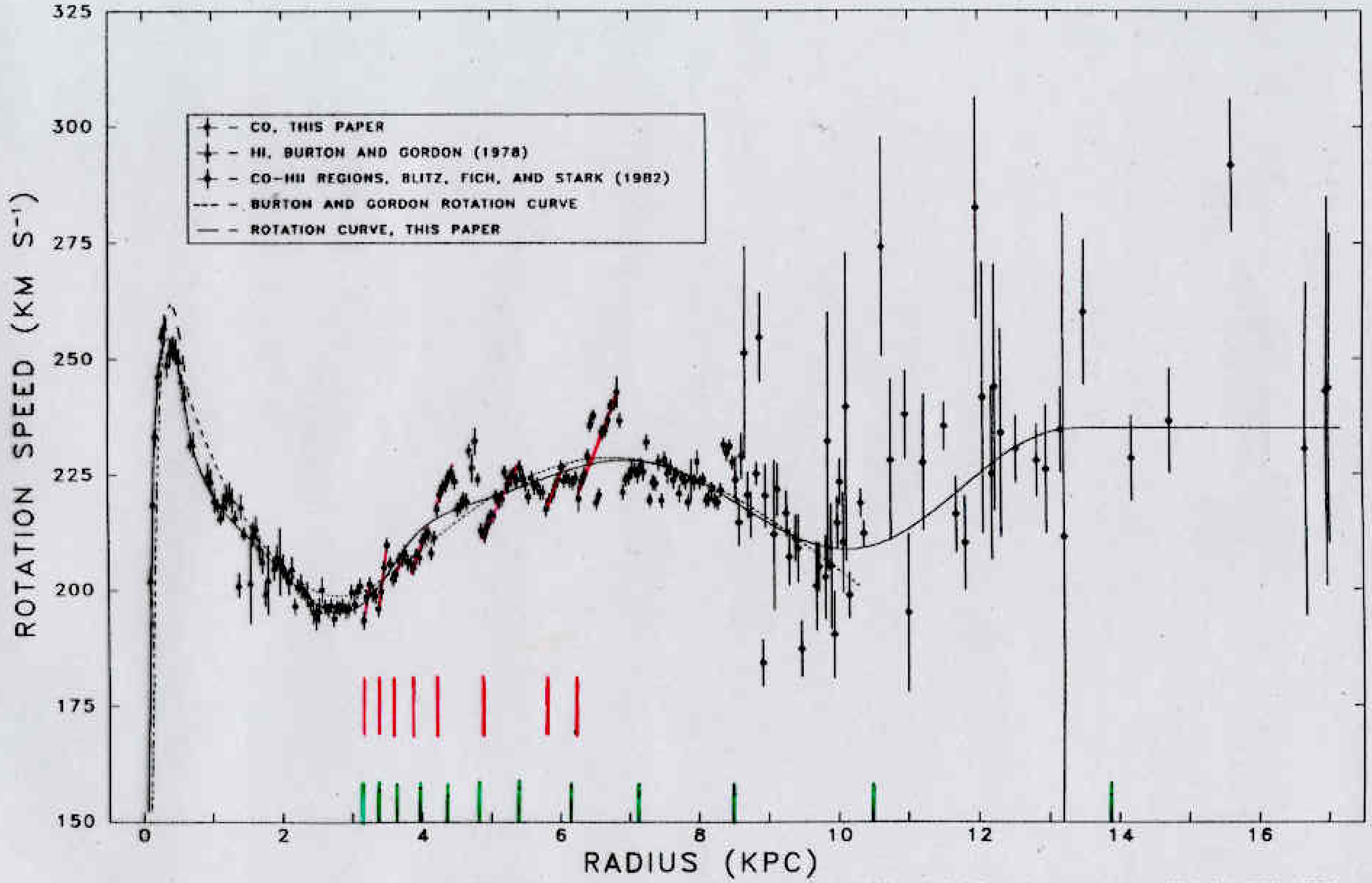


FIG. 3.—Plots of the rotation speed versus galactocentric radius. The solid lines correspond to the polynomials, and the dashed lines are the BG rotation curve. (*upper panel*)((R_0, θ_0) = (10 kpc, 220 km s^{-1}); (*lower panel*) (8.5 kpc, 220 km s^{-1}).

$\epsilon = 0.3$

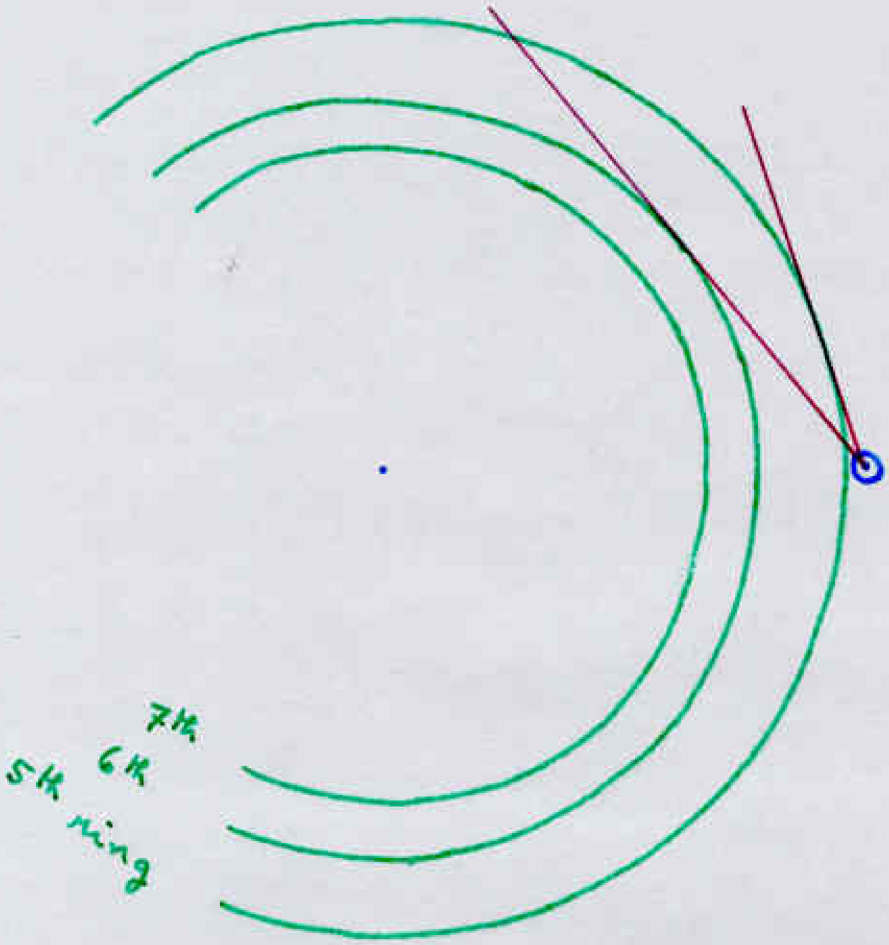
$j_{max} = 0.263$

↓

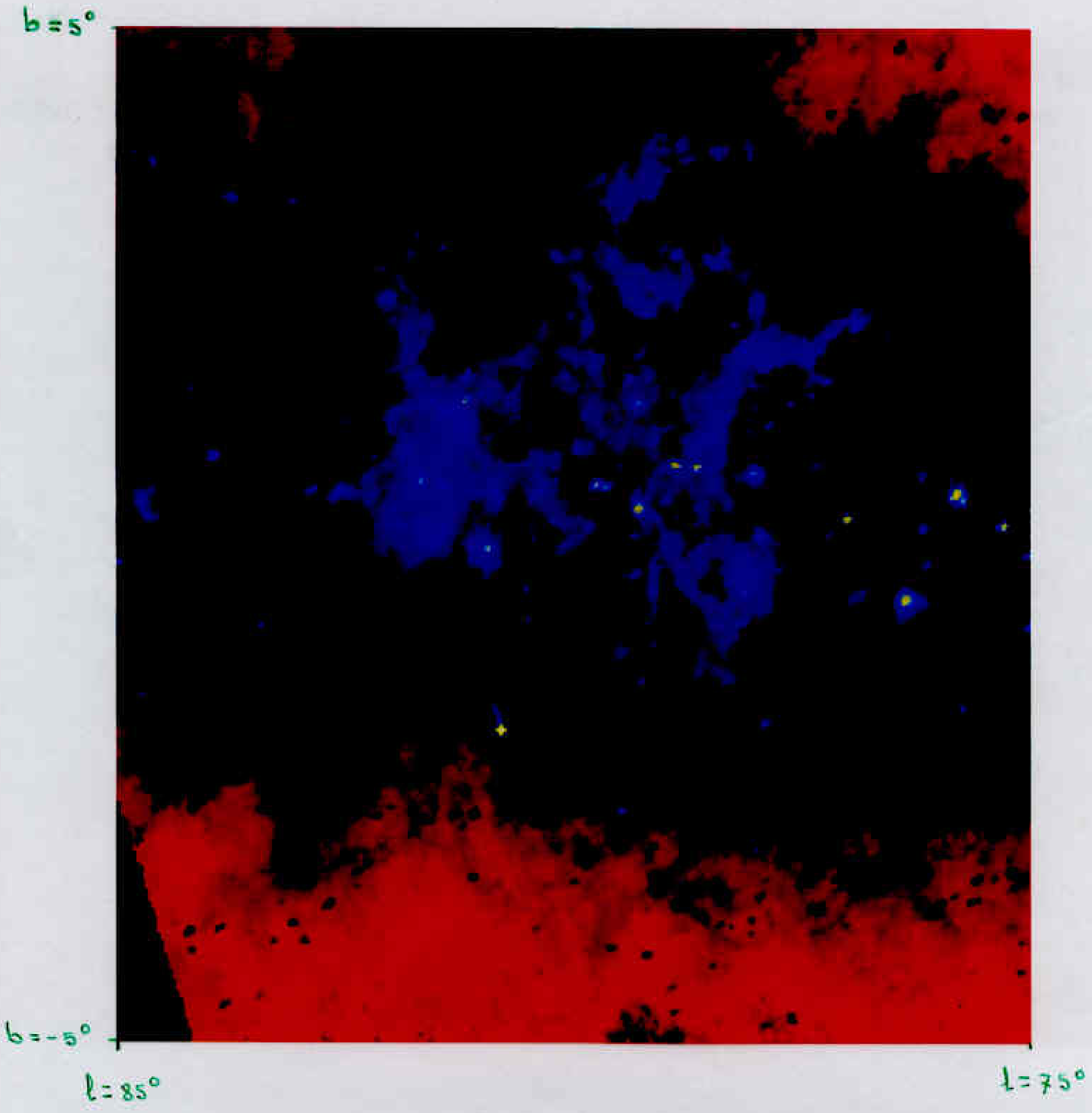
n	a_n^{obs} (kpc)	a_n^{theor} (kpc)	
1		41.2	
2		20.5	
3		13.9	
4		10.5	
5	8.28	8.50	+ 2.6 %
6	7.30	7.14	− 2.2 %
7	6.24	6.15	− 1.5 %
8	5.78	5.41	− 6.4 %
9	4.91	4.83	− 1.6 %
10	4.18	4.36	+ 4.3 %
11	3.89	3.98	+ 2.3 %
12	3.58	3.66	+ 2.2 %
13	3.38	3.38	0.0 %
14	3.16	3.15	− 0.3 %

rmsd = 3.1 %

Caustic in the Sky?

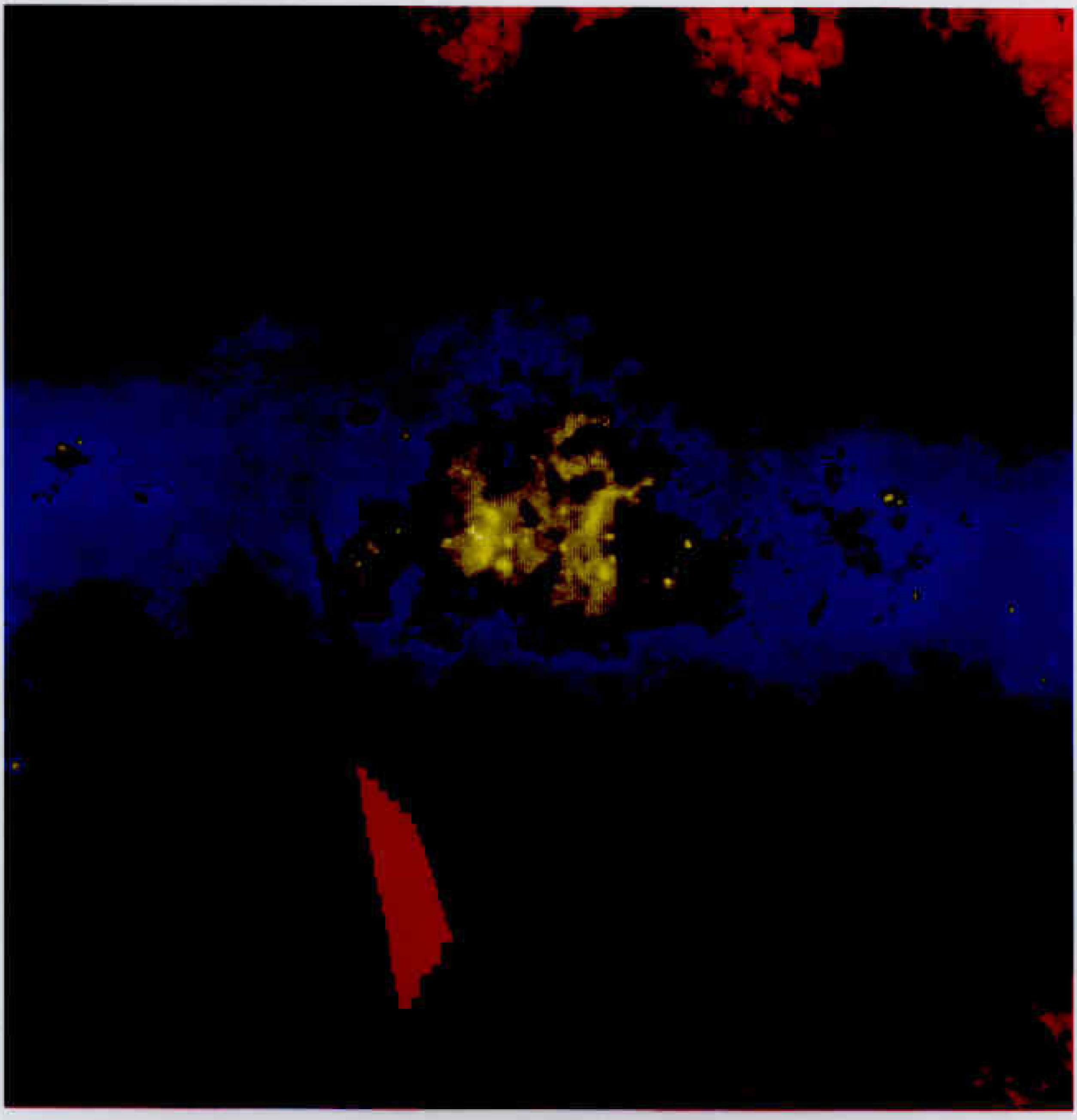


Look in the direction tangent to the ring to search for its imprint on the distribution of gas in the galactic disk



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

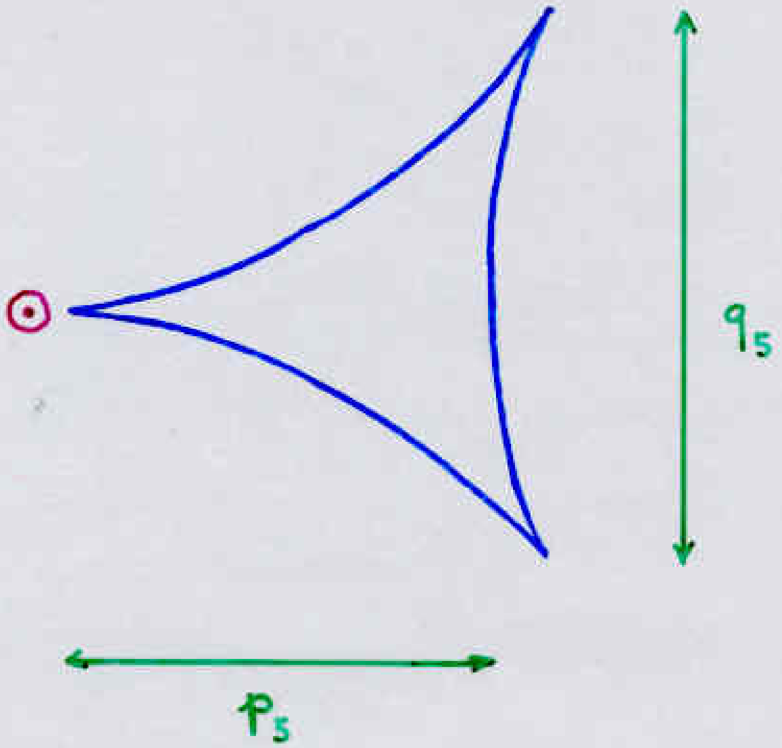
IRAS12.mod.gif



IRAS100.30.gif

5th Caustic parameters

(assuming $R_\odot = 8.5$ kpc)



$a_5 = 8.31 \pm 0.01$ kpc

$a_5 + p_5 = 8.45 \pm 0.01$ kpc

$p_5 = 134 \pm 10$ pc

$q_5 = 199 \pm 14$ pc

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

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

3X previous estimates of the total local DM density !

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

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

(z, φ, r) are galacto centric cylindrical coordinates

The caustics are smoothed

by the velocity dispersion δv_{DM}

of infalling dark matter over

distances of order

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

R = turnaround radius

v = flow velocity

From the sharpness of the edges

of the triangular feature of the IRAS map:

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

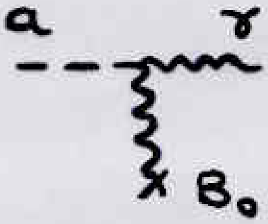
$$\therefore \quad \delta v_{DM} \lesssim 50 \text{ m/s}$$

Conclusions.

- Remaining axion window

  $$3 \cdot 10^{-3}\,\text{eV} > m_a > 10^{-6}\,\text{eV}$$

- In this window, axions are an important contribution to Ω in the form of cold dark matter (CDM)

- Galactic halo axions are susceptible to direct detection through  in a cavity

- The phase-space structure of galactic halos is characterized by
  - discrete dark matter flows
  - outer caustic spheres
  - inner caustic rings

- In the self-similar infall model, the caustic ring radii

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

- There is observational evidence for this pattern in galactic rotation curves

- There is evidence that the caustic rings of NGC 3198 and of the Milky Way follow the self-similar pattern, with $j_{max} = 0.28$ and 0.263 respectively

- In a statistical study of 32 extended well-measured rotation curves, there is evidence
  1) for the self-similar pattern
  2) for a peak in the j_{max} distribution at $j_{max} \simeq 0.27$
     (for $\epsilon = 0.3$)

- The triangular feature in IRAS map is correctly oriented +
  matches a rise in the rotation curve

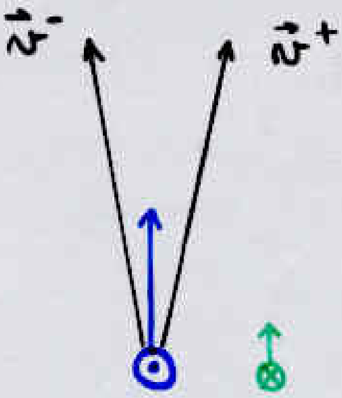
:. the local dark matter density is dominated by a single flow :

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

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

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

- Relevance to dark matter searches
  - narrow peak in axion search
  - reversed annual modulation + increased signal anisotropy in WIMP searches
  - more γ-rays from neutralino annihilation



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

- dark matter caustics may be observable by weak lensing methods

C. Hogan

in particular, the lensing pattern caused by the 5th caustic can be predicted

C. Charmousis, V. Onemli, Z. Qiu + P.S.

- from the sharpness of the 5th caustic, an upper limit on the velocity dispersion of infalling dark matter

$$\Delta v < 0.05 \text{ km/s}$$