The Axion Echo Method and the Big Flow

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CERN-Korea TH Institute
Axions in the Laboratory and in the Cosmos
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Collaborators: Ariel Arza, Sankha Chakrabarty,
Anthony Gonzalez, Yaqi Han

Outline

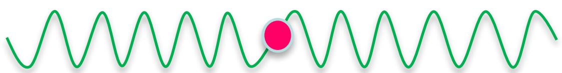
- Production and detection of an axion dark matter echo

  with Ariel Arza, arXiv:1902.00114

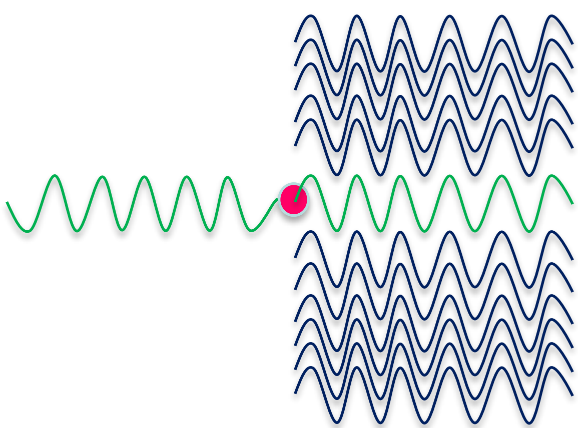
- Constraints on the Big Flow from the GAIA skymap

  with Sankha Chakrabarty, Anthony Gonzalez and Yaqi Han, to appear

Stimulated axion decay



$$\Gamma(a \to 2\gamma) \sim \frac{1}{10^{51}\ \mathrm{sec}}$$



P_1 P_0

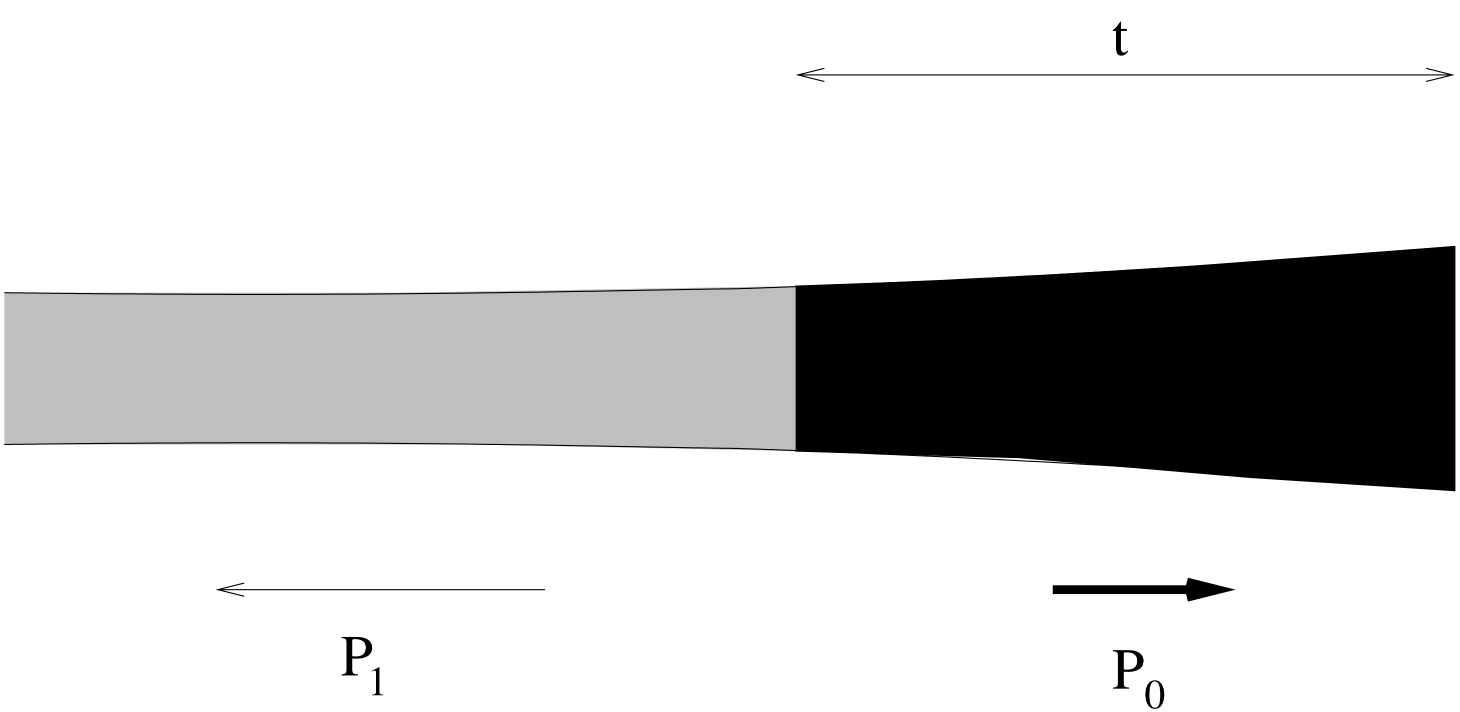
$$\omega = \frac{m_a}{2}$$

$$P_0 = \text{outgoing power}$$

$P_1 = \text{echo power}$

In the rest frame of a perfectly cold axion fluid

the echo traces the outgoing power exactly backward, and lasts forever



$$\mathcal{L}_{a\gamma\gamma} = -g\ \phi(x)\vec{E}(x)\cdot\vec{B}(x)$$

$$g = g_\gamma \frac{\alpha}{\pi}\frac{1}{f_a}$$

$$P_1 = \frac{1}{16} g^2 \rho \frac{dP_0}{d\nu} t$$

$$= 7.8\times 10^{-29}\ P_0\ \left(\frac{10\ \mathrm{kHz}}{\Delta\nu}\right)\left(\frac{g_\gamma}{0.36}\right)^2 \cdot$$

$$\cdot\left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)^2\left(\frac{\rho}{\mathrm{GeV/cm}^3}\right)\left(\frac{t}{1\ \mathrm{sec}}\right)$$

In a perfectly cold axion fluid at rest

$$\phi(t) = \phi_0 \sin(m_a t)$$

axion field

$$\rho = \frac{1}{2} m_a^2 \phi_0^2$$

axion density

$$(\partial_t^2 - \nabla^2)\vec{A}_1 = -g(\vec{\nabla} \times \vec{A}_0)\partial_t \phi$$

echo

outgoing power

$$\vec{A}_0(\vec{x},t) = \Re \int d^3k \; \vec{A}_0(\vec{k}) e^{i(\vec{k}\cdot\vec{x}-\omega t)}$$

$$(\omega = |\vec{k}|)$$

$$\vec{A}_1(\vec{x},t) = \Re \int d^3k \; A_1(\vec{k},t) e^{i\vec{k}\cdot\vec{x}}$$

$$(\partial_t^2 + \omega^2)\vec{A}_1(\vec{k},t) = -gAm_a \cos(m_a t) \; i\vec{k} \times \vec{A}_0(\vec{k}) \; e^{-i\omega t}$$

$\pm\ \omega$ $\qquad\qquad\qquad$ $\pm\ m_a + \ \omega$

proper frequencies $\qquad\qquad\qquad$ driving frequencies

Resonance occurs when

$$-\,\omega \;=\; m_a + \;\omega$$

i.e. $\omega \;=\; +\; m_a/2$

$$\vec{A}_0(\vec{x},t) = \Re\left[e^{-i\frac{m_a}{2}t}\;\vec{e}\int_{|\vec{k}|=m_a/2} d^2k\;A_0(\vec{k})\;e^{i\vec{k}\cdot\vec{x}}\right]$$

produces

$$\vec{A}_1(\vec{x},t) = +\frac{1}{4}gAm_at\;\Re\left[e^{i\frac{m_a}{2}t}\;\vec{e}\times\;\int_{|\vec{k}|=m_a/2} d^2k\;\hat{k}\;A_0(\vec{k})\;e^{i\vec{k}\cdot\vec{x}}\right]$$

Echo power: $$P_1 = \frac{1}{16}g^2\rho\frac{dP_0}{d\nu}t$$

$$\mathcal{L}_{a\gamma\gamma} = -g\ \phi(x)\vec{E}(x)\cdot\vec{B}(x)$$

$$g = g_\gamma \frac{\alpha}{\pi}\frac{1}{f_a}$$

$$P_1 = \frac{1}{16} g^2 \rho \frac{dP_0}{d\nu} t$$

$$= 7.8\times 10^{-29}\ P_0\ \left(\frac{10\ \mathrm{kHz}}{\Delta\nu}\right)\left(\frac{g_\gamma}{0.36}\right)^2\cdot$$

$$\cdot\left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)^2\left(\frac{\rho}{\mathrm{GeV/cm^3}}\right)\left(\frac{t}{1\ \mathrm{sec}}\right)$$

In case of a perfectly cold axion fluid moving with velocity $\vec{v}$ with respect to the observer:

$$\vec{k} = \omega \hat{k}$$ = wavevector of outgoing power

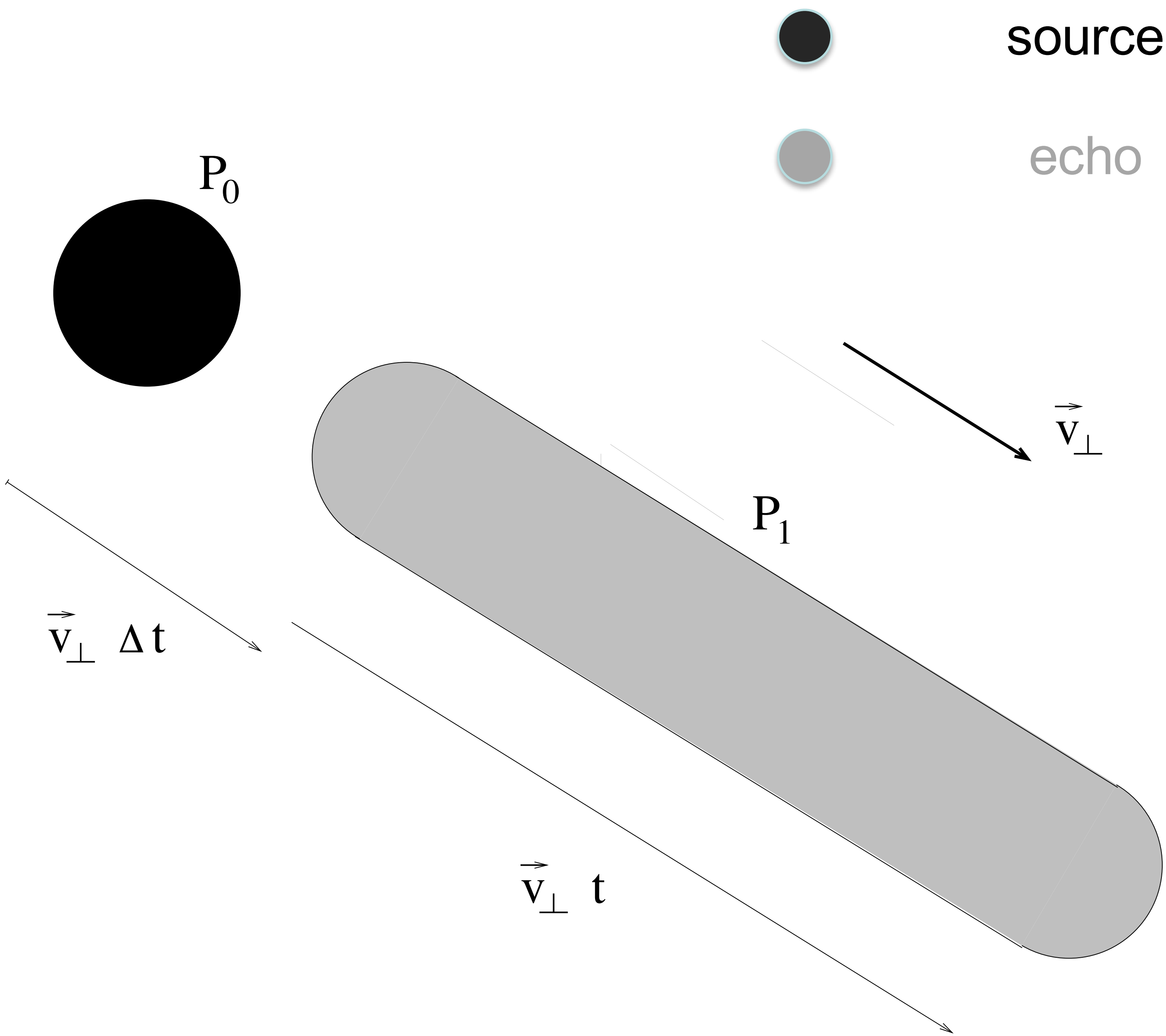
$$\vec{v} = v_{\|} \hat{k} + \vec{v}_{\perp}$$

outgoing resonance frequency

$$\omega_0 = \frac{m_a}{2}(1 + \vec{v} \cdot \hat{k}) + \mathcal{O}(v^2)$$

echo frequency

$$\omega_1 = \frac{m_a}{2}(1 - \vec{v} \cdot \hat{k}) + \mathcal{O}(v^2)$$



source
echo
P_0
P_1
$\vec{v}_\perp$
$\vec{v}_\perp \, \Delta t$
$\vec{v}_\perp \, t$

Collected Echo Power

$$P_c = \frac{1}{16} g^2 \rho \frac{dP_0}{d\nu} t_c$$

$$t_c = C \frac{R}{|\vec{v}_\perp|}$$

$R =$ radius of receiver dish

$$C = \frac{|\vec{v}_\perp|}{2RP_0} \int dt \int_{S_0} d^2x \; I_0(\vec{x}) \Theta_c(\vec{x} + \vec{v}_\perp t)$$

Two contrasting galactic halo models

- the isothermal model

$$\rho = 300 \text{ MeV/cc} \qquad\qquad \delta v = 270 \text{ km/s}$$

$$\vec{v} = -\ 220 \text{ km/s}\ \ \hat{\phi}$$

- the caustic ring model (L. Duffy & PS, 2008)

has a locally prominent cold flow

$$\rho_{\rm BF} \sim (1 \text{ to } 10) \text{ GeV/cc} \qquad\qquad \delta v_{\rm BF} < 70 \text{ m/s}$$

$$\vec{v}_{\rm BF} \simeq (290\ \hat{\phi} - 111\ \hat{r} - 19\ \hat{z}) \text{ km/s}$$

(preliminary)

For a general velocity distribution

$$\rho = \int d^3v \ \frac{d^3\rho}{dv^3}(\vec{v})$$

The echo is spread in frequency

$$\delta\omega_1 = \frac{m_a}{2}\delta v_\parallel$$

and in space

$$\delta\vec{x}_\perp = \delta\vec{v}_\perp t_e$$

Assumptions

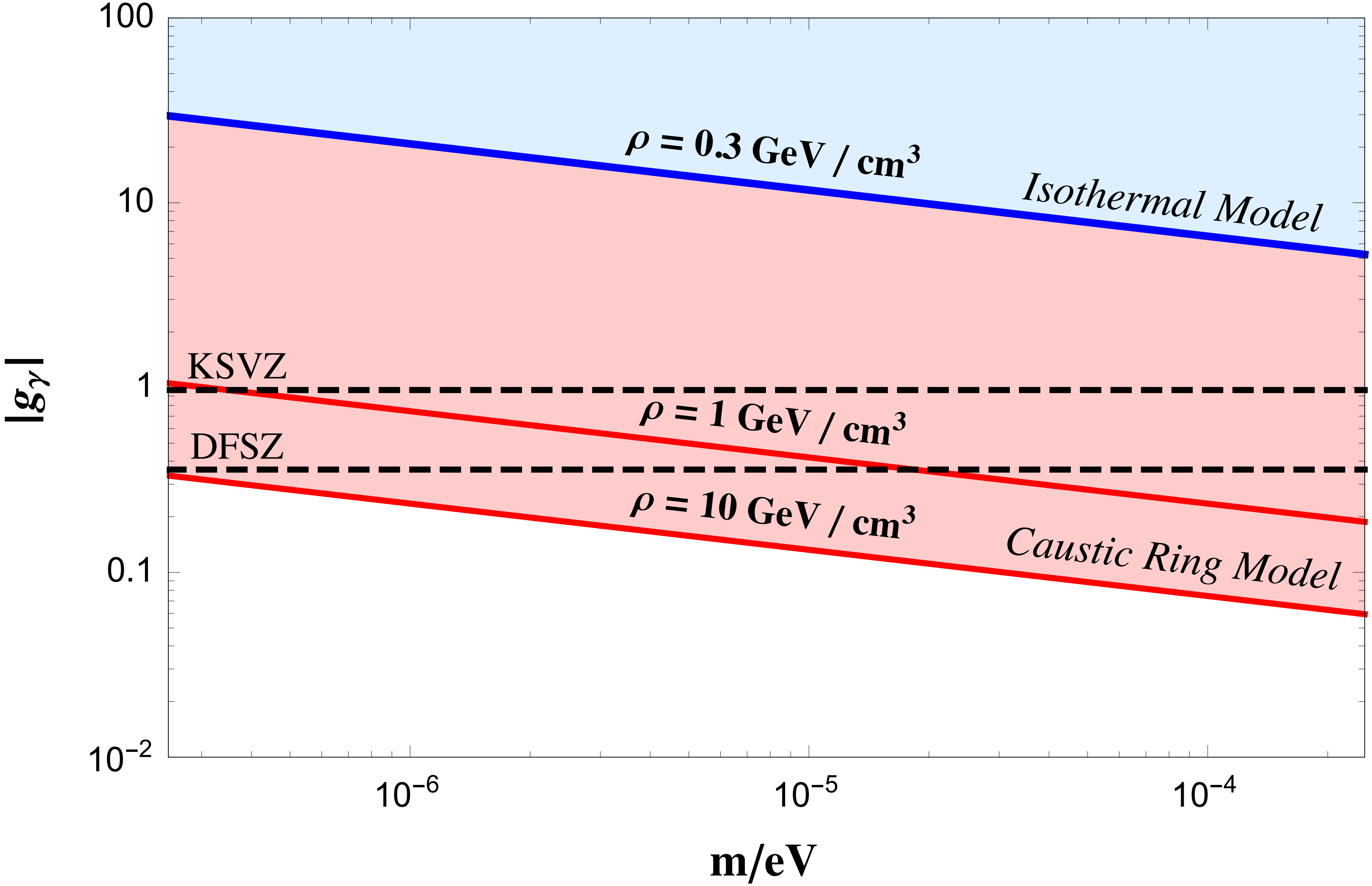
- outgoing energy: 10 MW year per factor of two in frequency covered

- the outgoing power is pulsed (or modulated) on 10 millisec time scale

- 50 meter receiving dish & 20 K system noise temperature

- cold flow with velocity dispersion less than 70 m/s, and known direction

- $|\vec{v}_\perp| < 5\ \mathrm{km/s}$

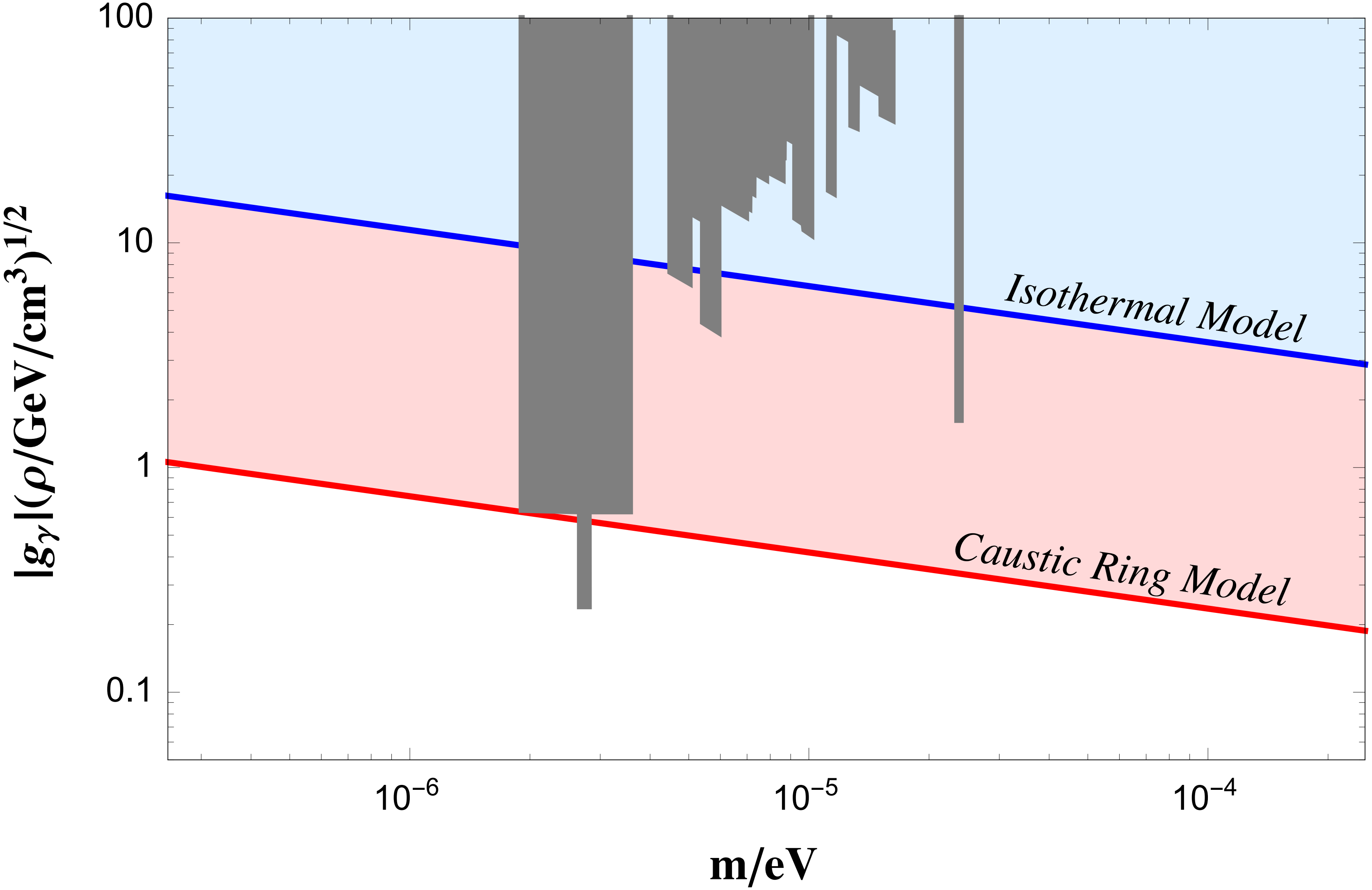


100
10
1
0.1
10^{-2}
10^{-6}
10^{-5}
10^{-4}
$|g_\gamma|$
m/eV
ρ = 0.3 GeV / cm^3
Isothermal Model
KSVZ
ρ = 1 GeV / cm^3
DFSZ
ρ = 10 GeV / cm^3
Caustic Ring Model

The Axion Echo Method works better in the Caustic Ring Model than in the Isothermal Model for three reasons:

1) the axion density is higher
2) the echo has less spread in frequency
3) the echo has less spread in space

Reason 1) helps the cavity method equally.

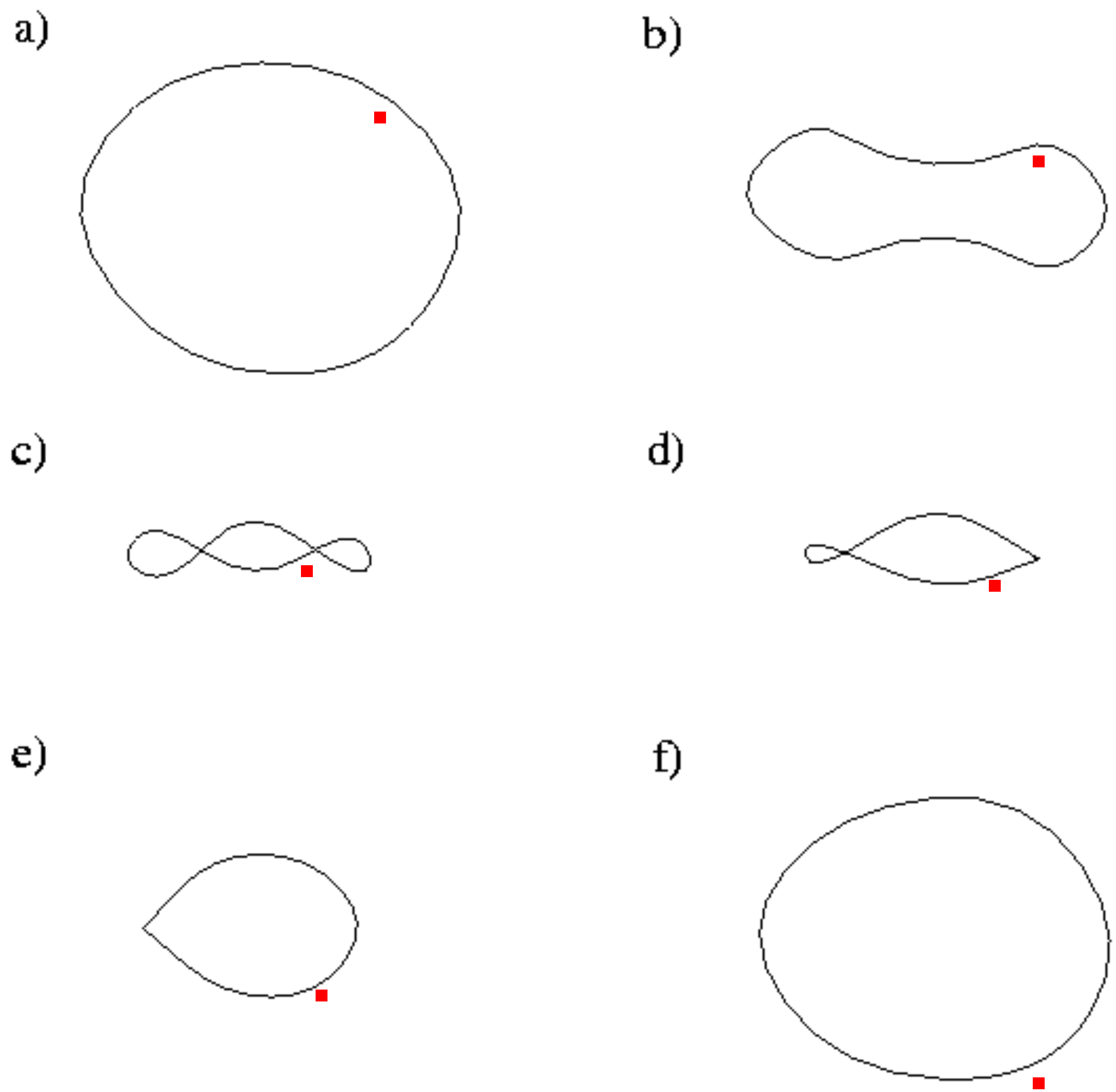


100
10
1
0.1
$|g_\gamma|(\rho/\mathrm{GeV/cm^3})^{1/2}$
10^{-6}
10^{-5}
10^{-4}
m/eV
Isothermal Model
Caustic Ring Model

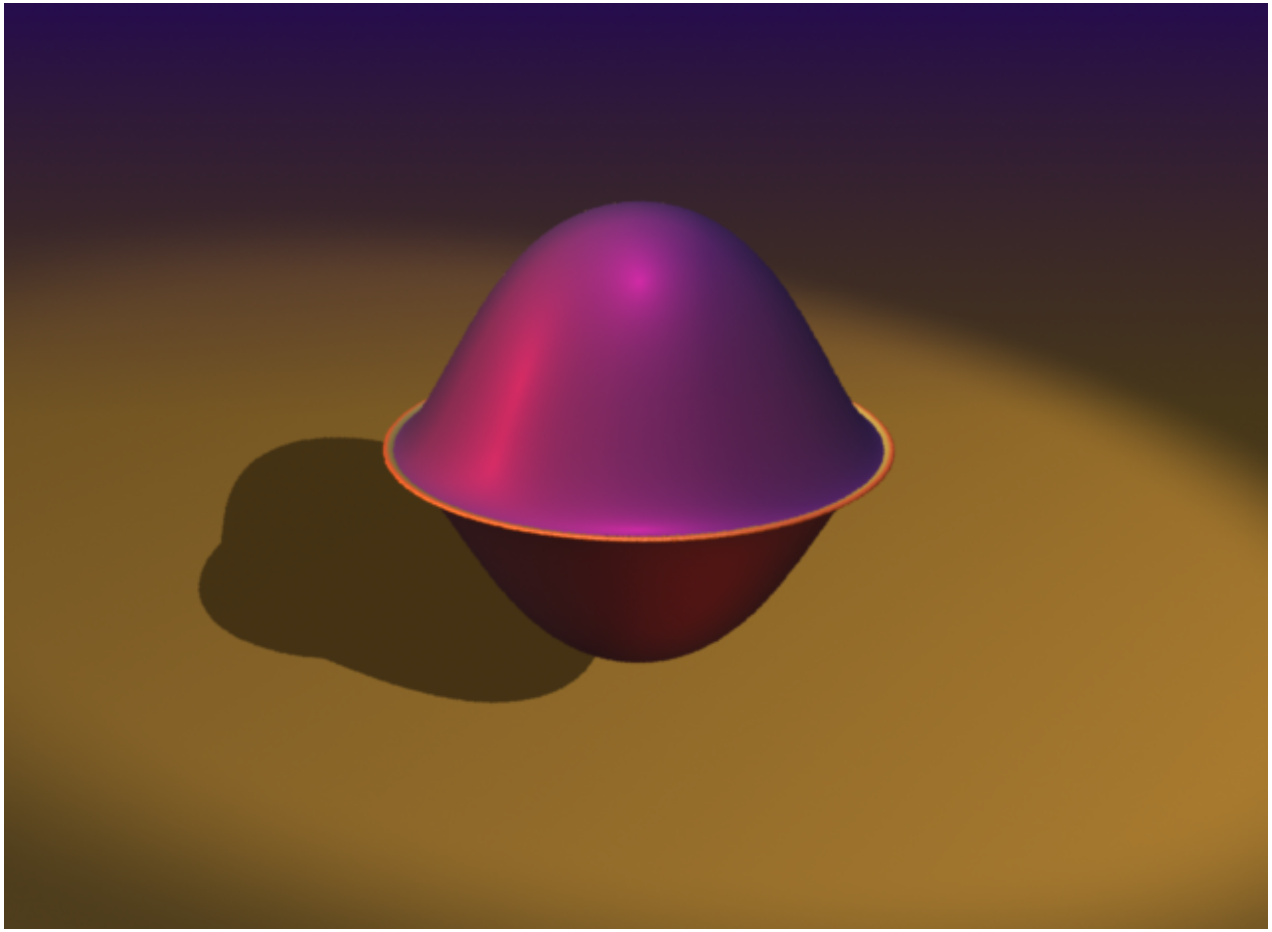
A shell of particles, part of a continuous flow.

The shell has net angular momentum.

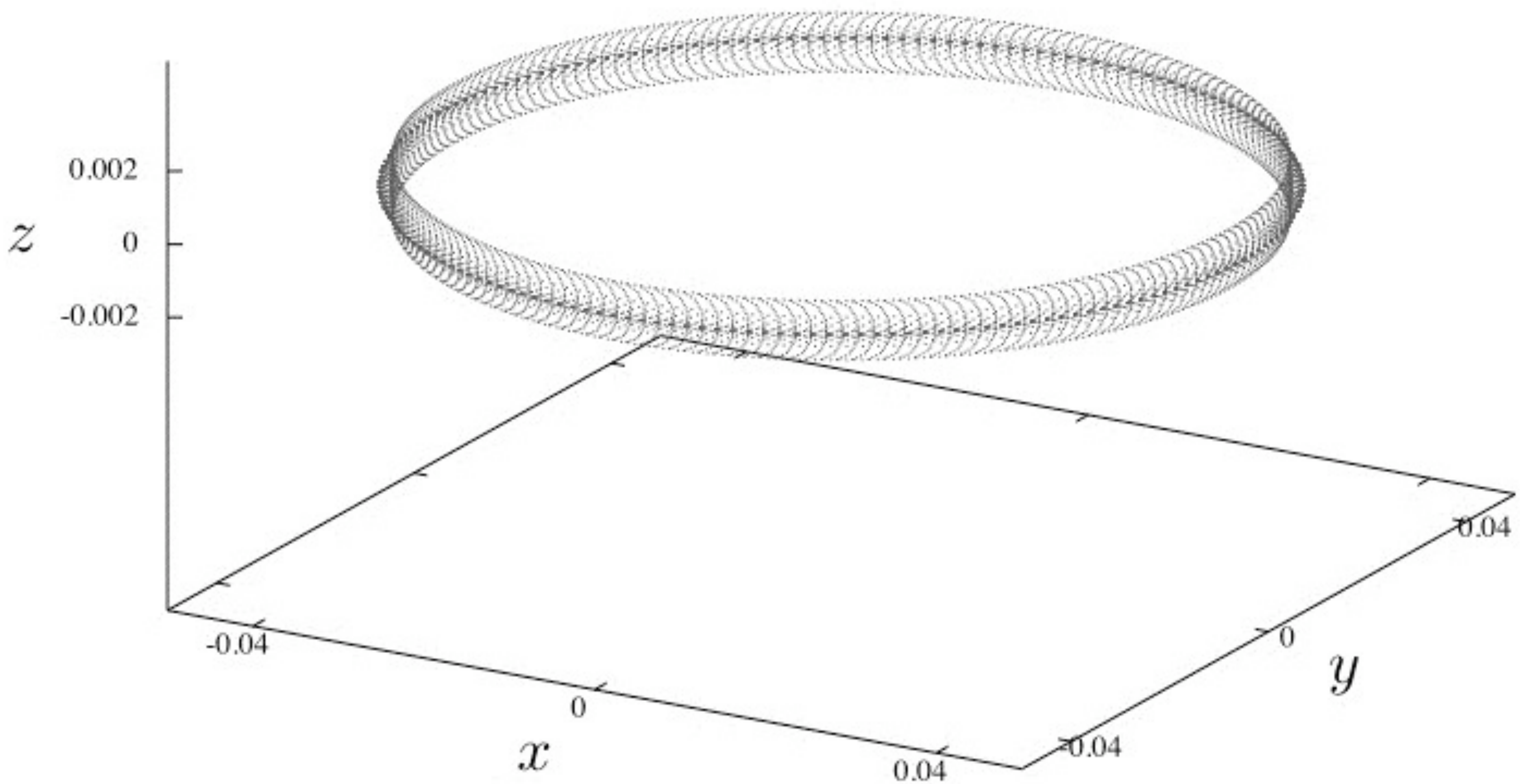
As the shell falls in and out of the galaxy, it turns itself inside out.



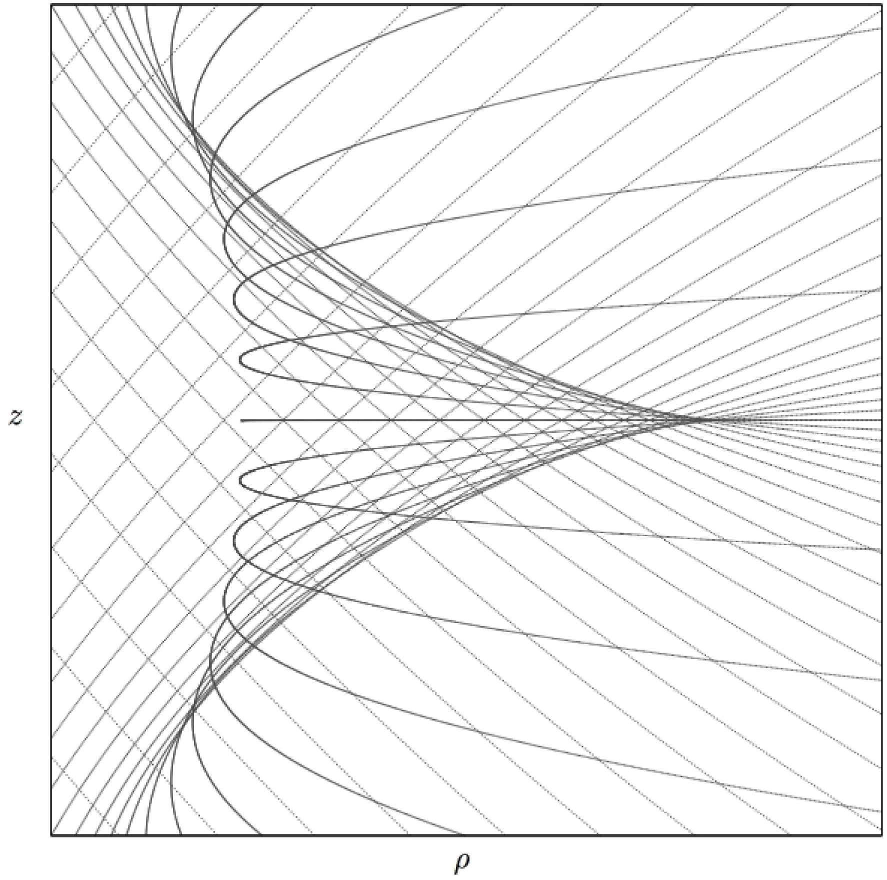
Sphere turning inside out



simulation by Arvind Natarajan

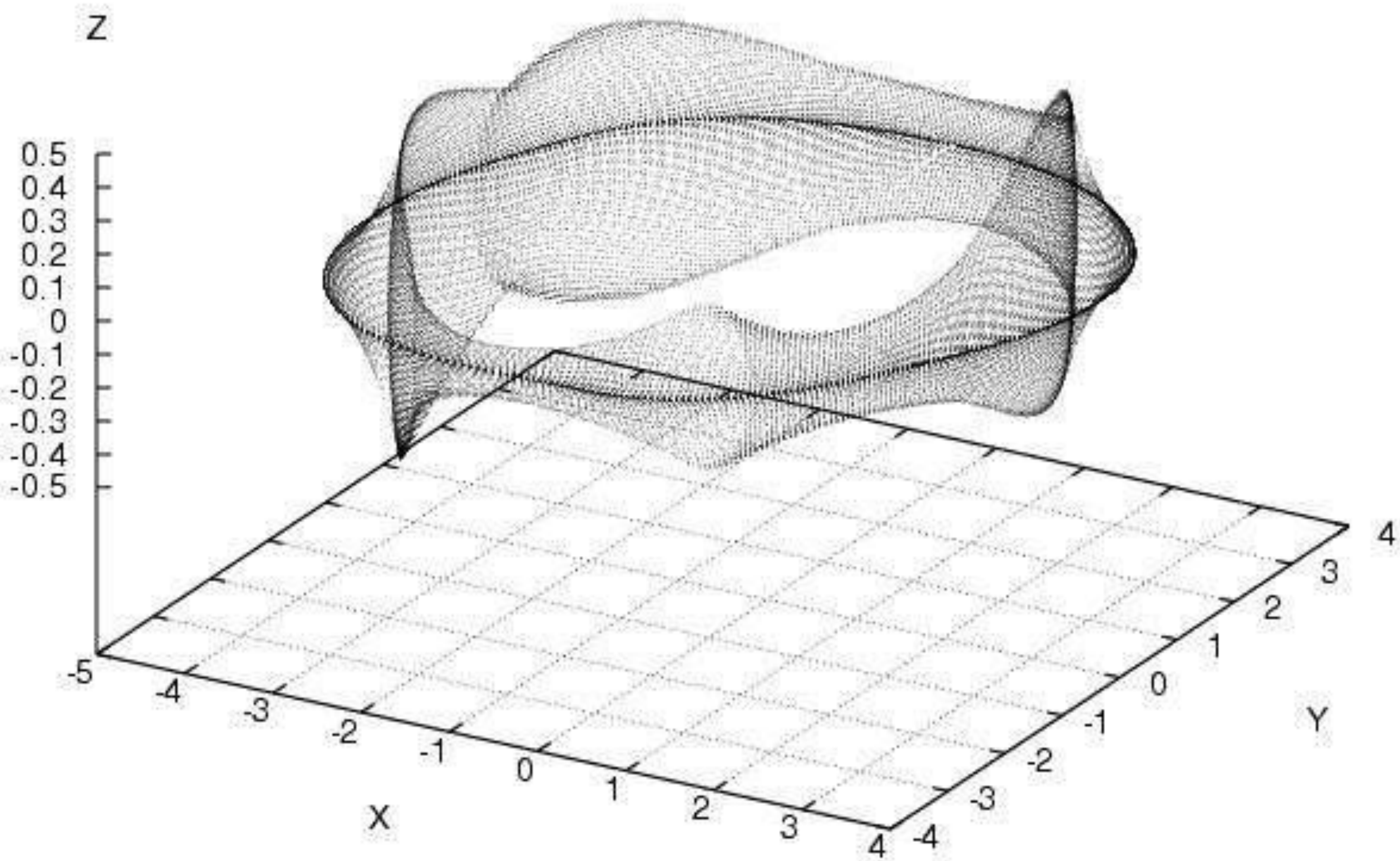


The caustic ring cross-section



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

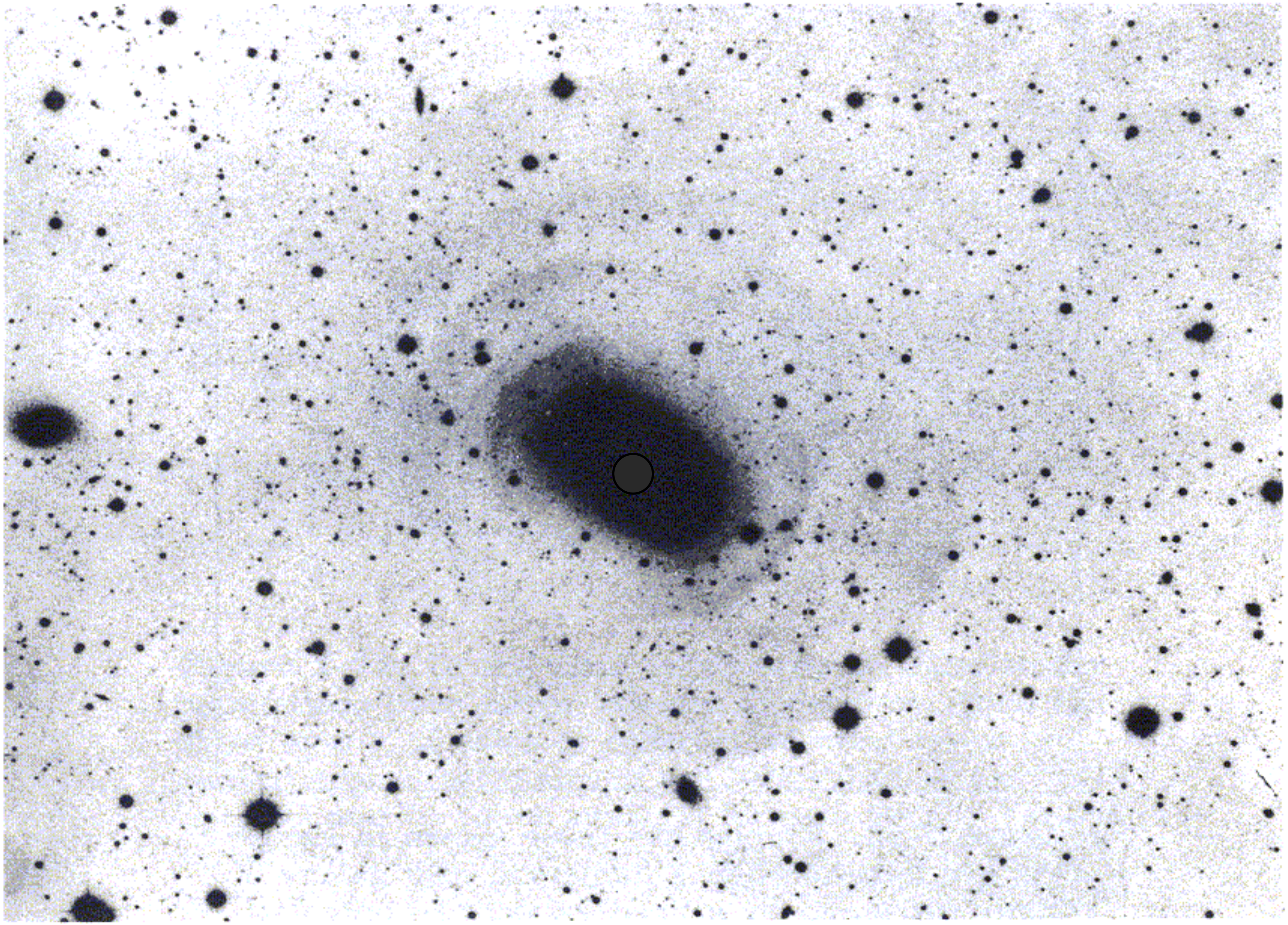


Figure 7-22. The giant elliptical galaxy NGC 3923 is surrounded by faint ripples of brightness. Courtesy of D. F. Malin and the Anglo-Australian Telescope Board.

(from Binney and Tremaine's book)

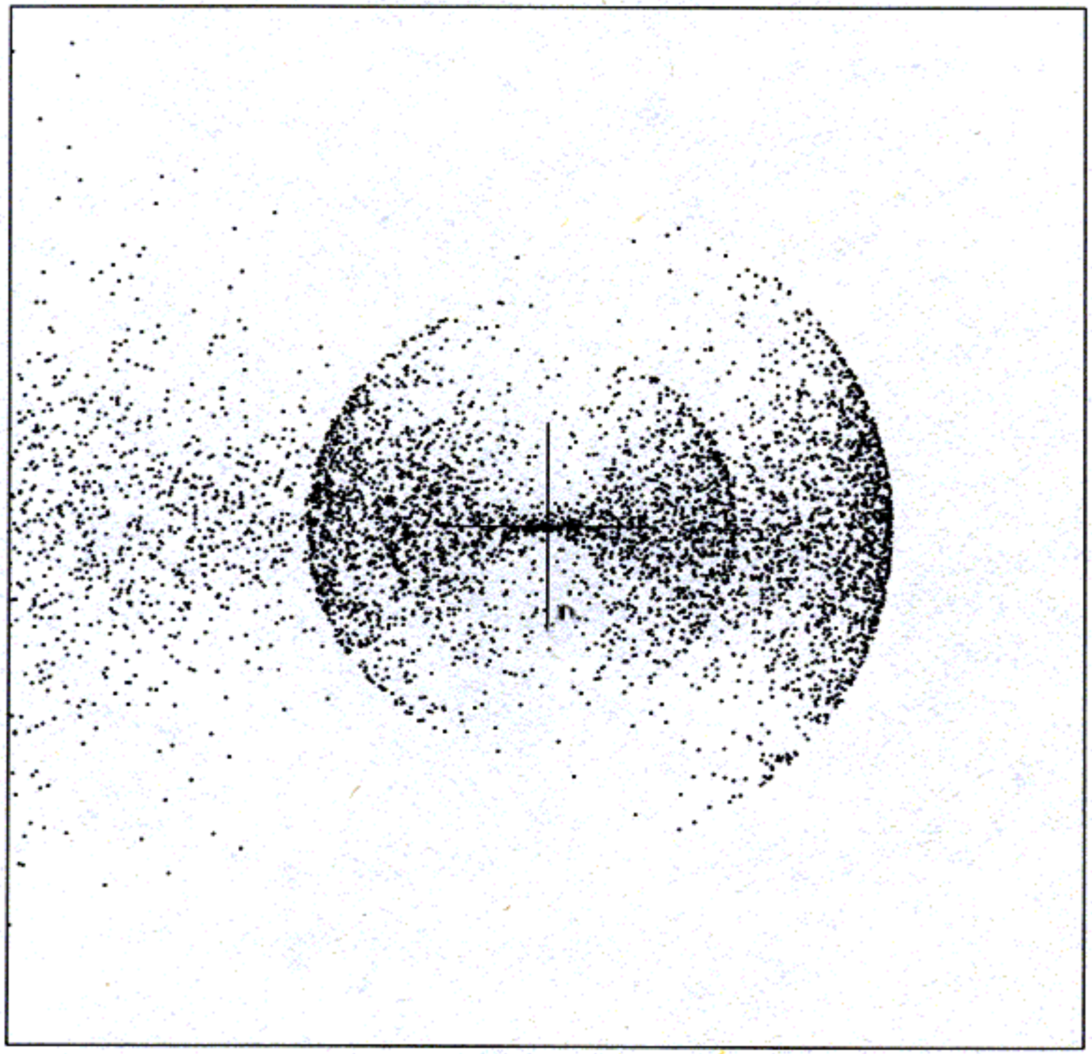


Figure 7-23. Ripples like those shown in Figure 7-22 are formed when a numerical disk galaxy is tidally disrupted by a fixed galaxy-like potential. (See Hernquist & Quinn 1987.)

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

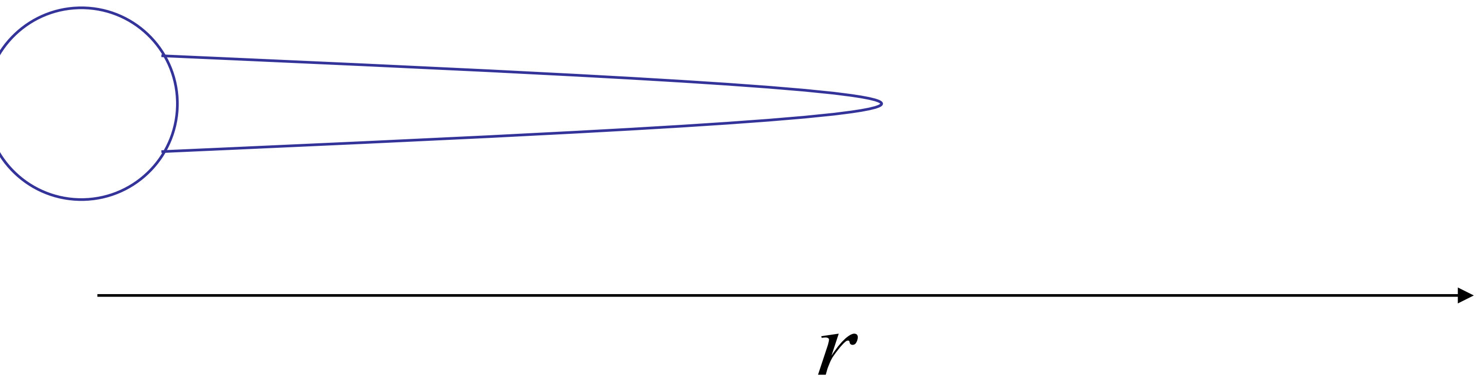
in the galactic plane

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

$$a_n = \frac{40\mathrm{kpc}}{n}\left(\frac{\mathrm{v_{rot}}}{220\mathrm{km/s}}\right)\left(\frac{\mathrm{j_{max}}}{0.18}\right)$$

$\mathrm{j_{max}} \cong 0.18$ was expected for the Milky Way halo from the effect of angular momentum on the inner rotation curve.

Galactic rotation curves

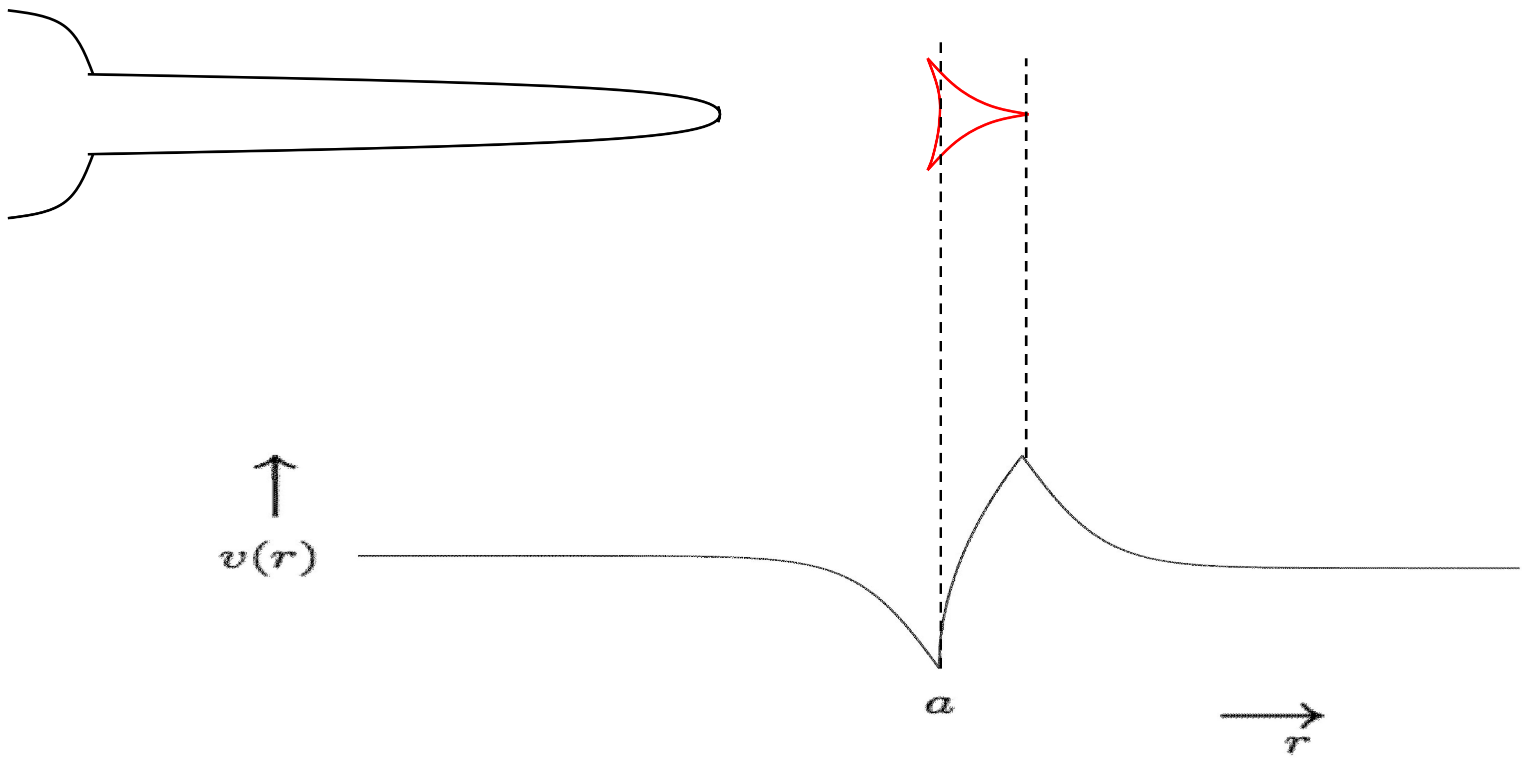


galactic
mass

$$v^2(r) = \frac{G\,M(r)}{r}$$

rotation speed

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



Rotation curve of Andromeda Galaxy

from L. Chemin, C. Carignan & T. Foster, arXiv: 0909.3846

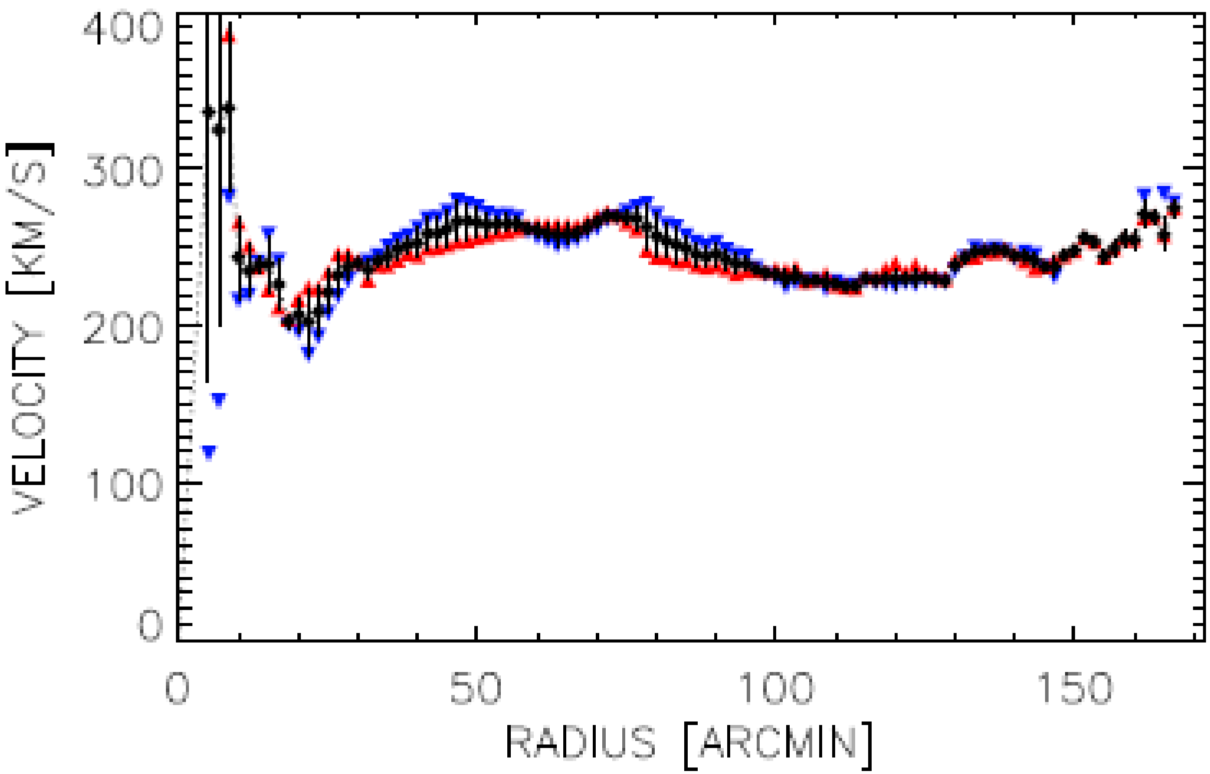
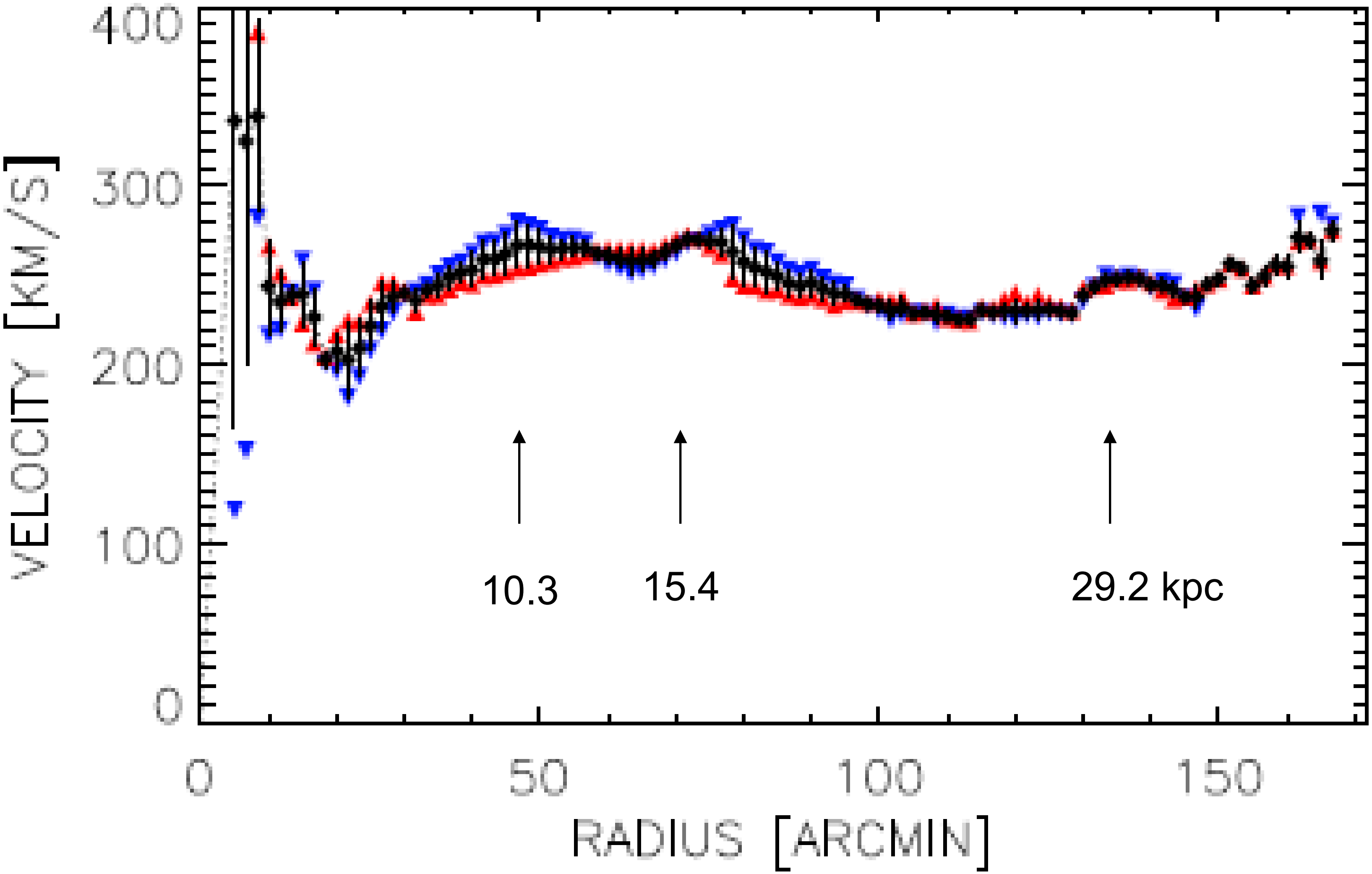


FIG. 10.— HI rotation curve of Messier 31. Filled diamonds are for both halves of the disc fitted simultaneously while blue downward/red upward triangles are for the approaching/receding sides fitted separately (respectively).



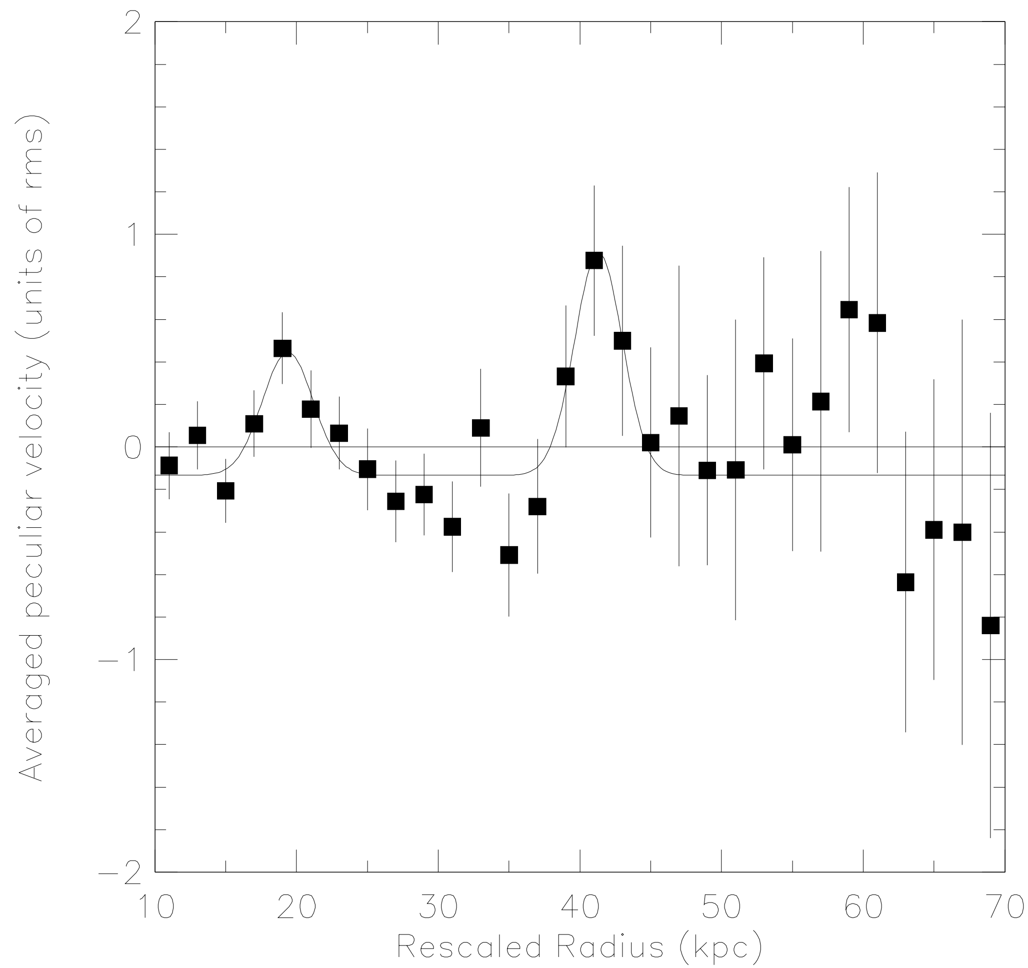
10 arcmin = 2.2 kpc

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



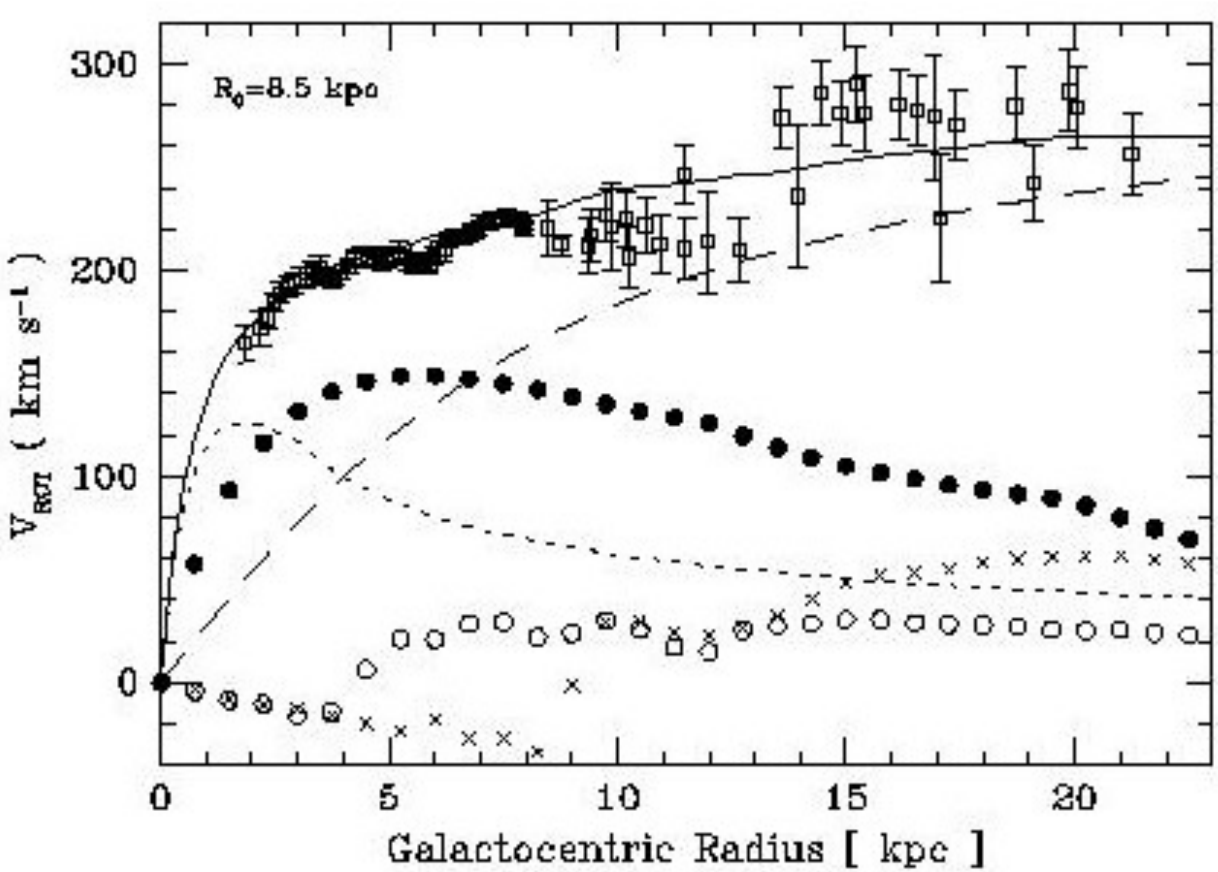
Monoceros Ring of stars

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 $r \sim 20 \text{ kpc}$
appears circular, actually seen for $100^0 < l < 270^0$
scale height of order 1 kpc
velocity dispersion of order 20 km/s

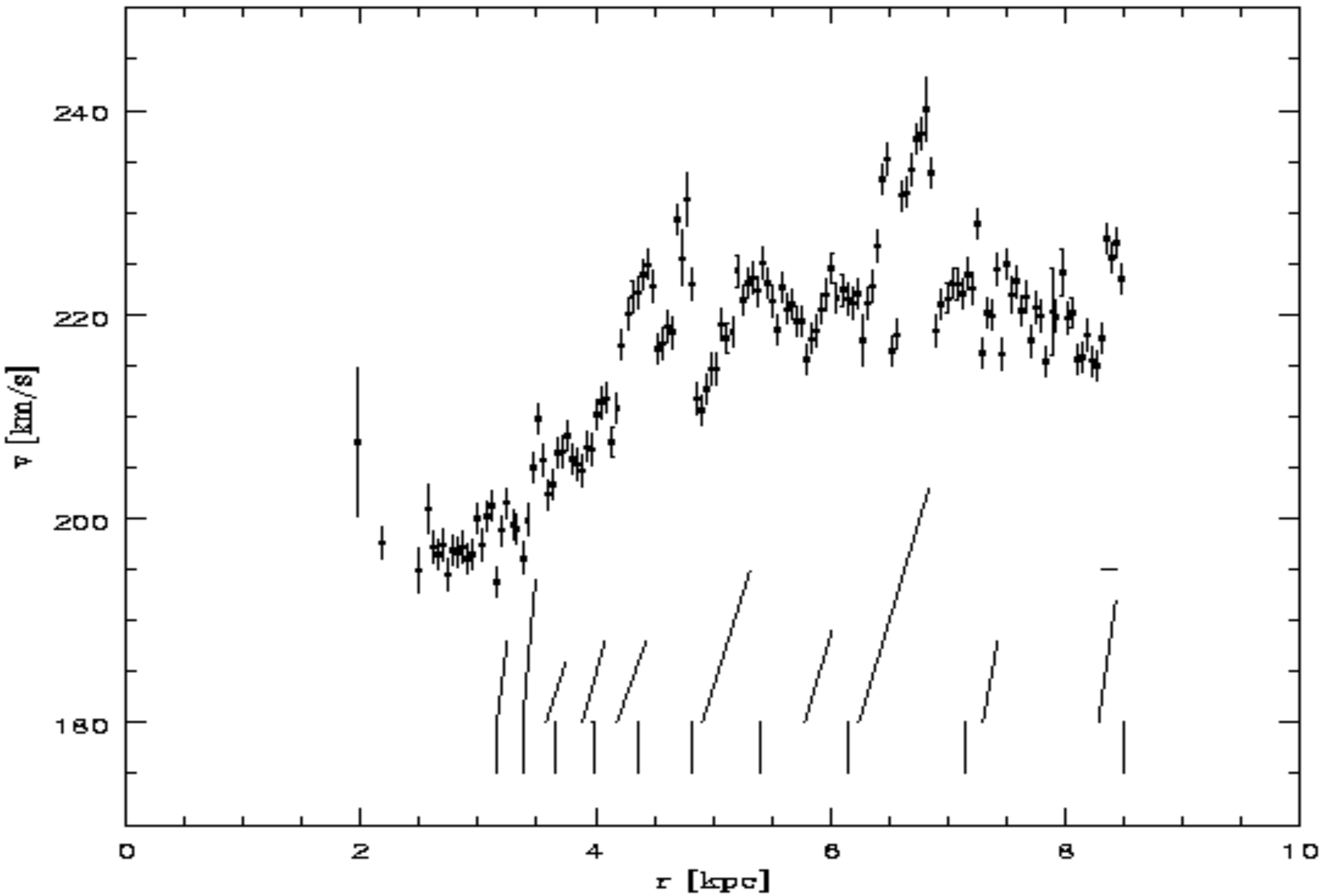
may be caused by the n = 2 caustic ring of dark matter (A. Natarajan & PS, 2007; S. Chakrabarty & PS, 2018)

Outer Galactic rotation curve

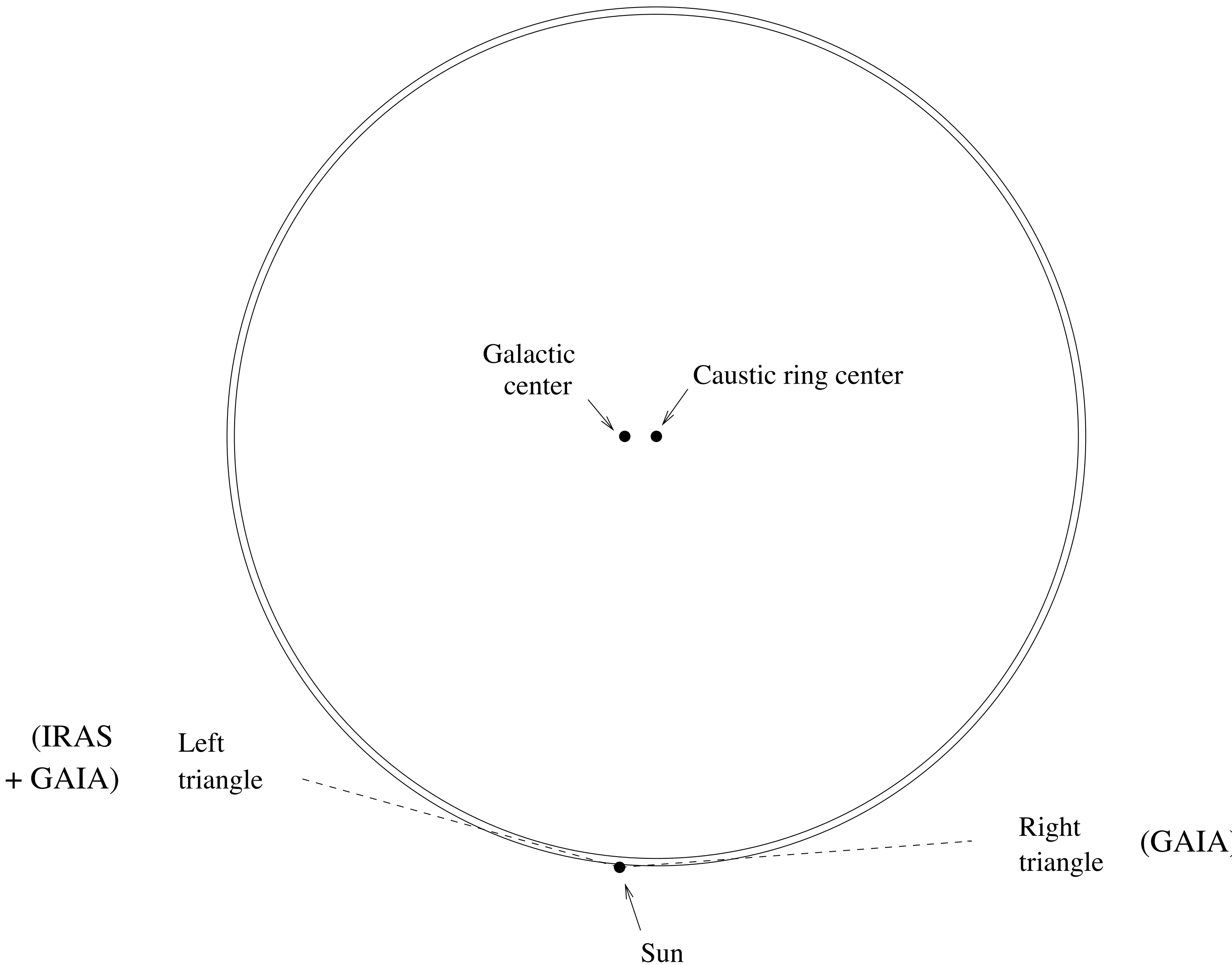


R.P. Olling and M.R. Merrifield, MNRAS 311 (2000) 361

Inner Galactic rotation curve

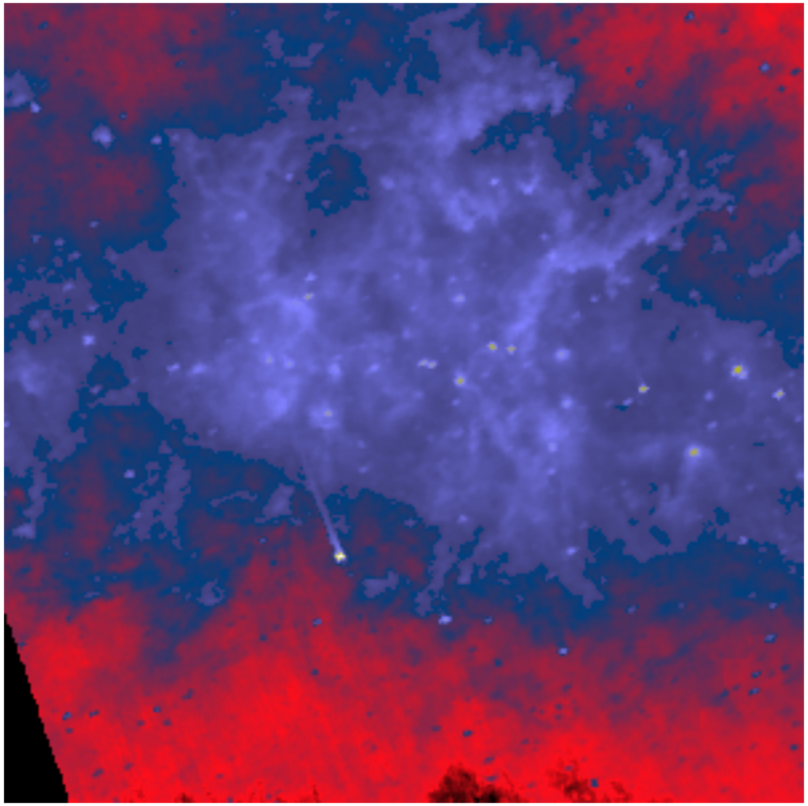


from Massachusetts-Stony Brook North Galactic Pane CO Survey (Clemens, 1985)


Galactic center
Caustic ring center
(IRAS + GAIA)
Left triangle
Right triangle
(GAIA)
Sun

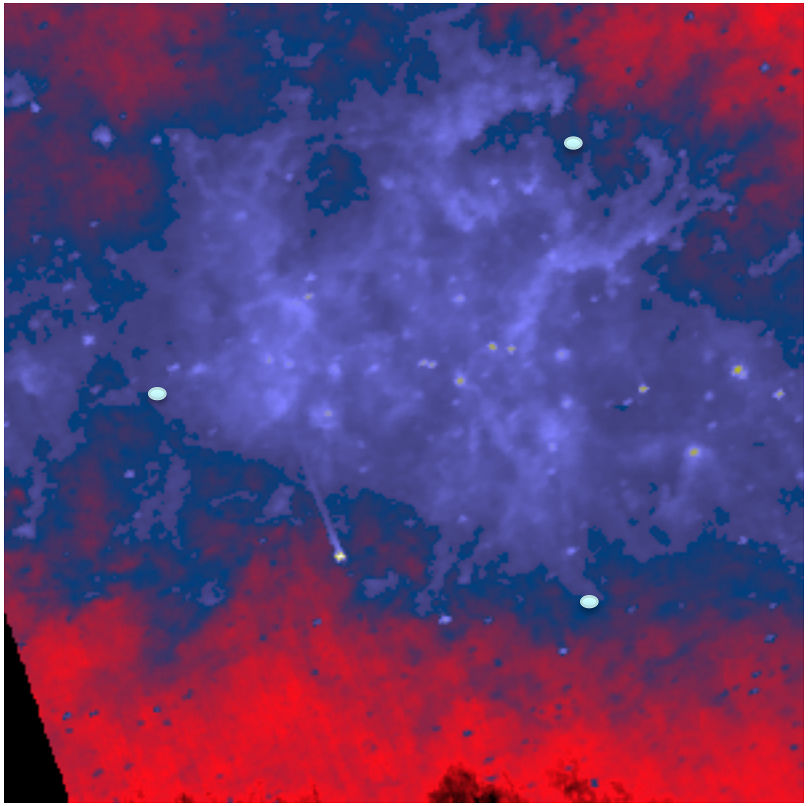
IRAS $\quad$ **12** μm

$(l, b) = (80^{\circ}, 0^{\circ})$ $\quad$ $10^{\circ} \times 10^{\circ}$



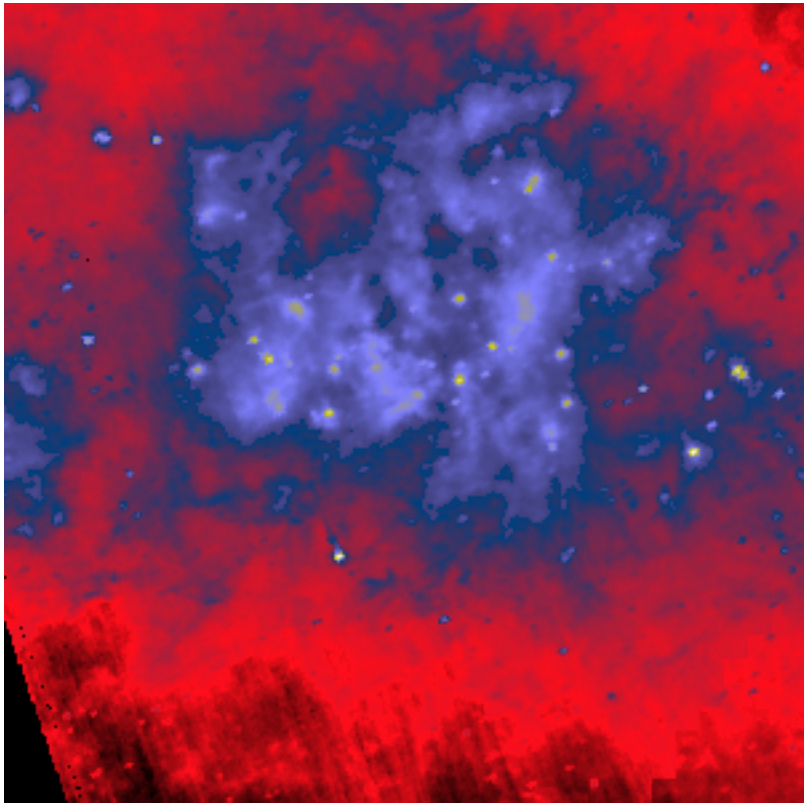
IRAS $\quad$ **12 μm**

$(l\,,\,b) = (80^{o}, 0^{o})$ $\quad$ $10^{o} \times 10^{o}$

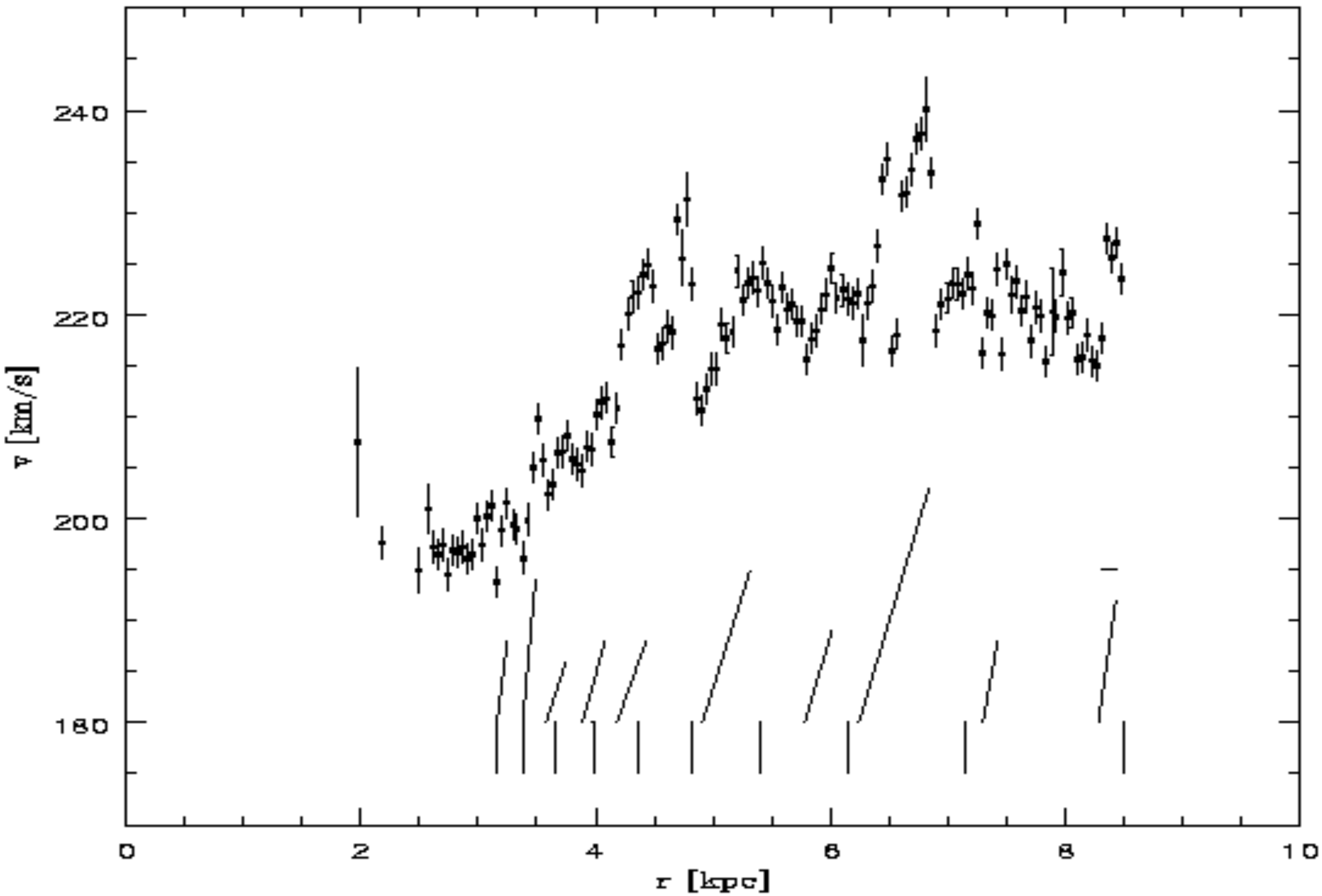


IRAS **25 μm**

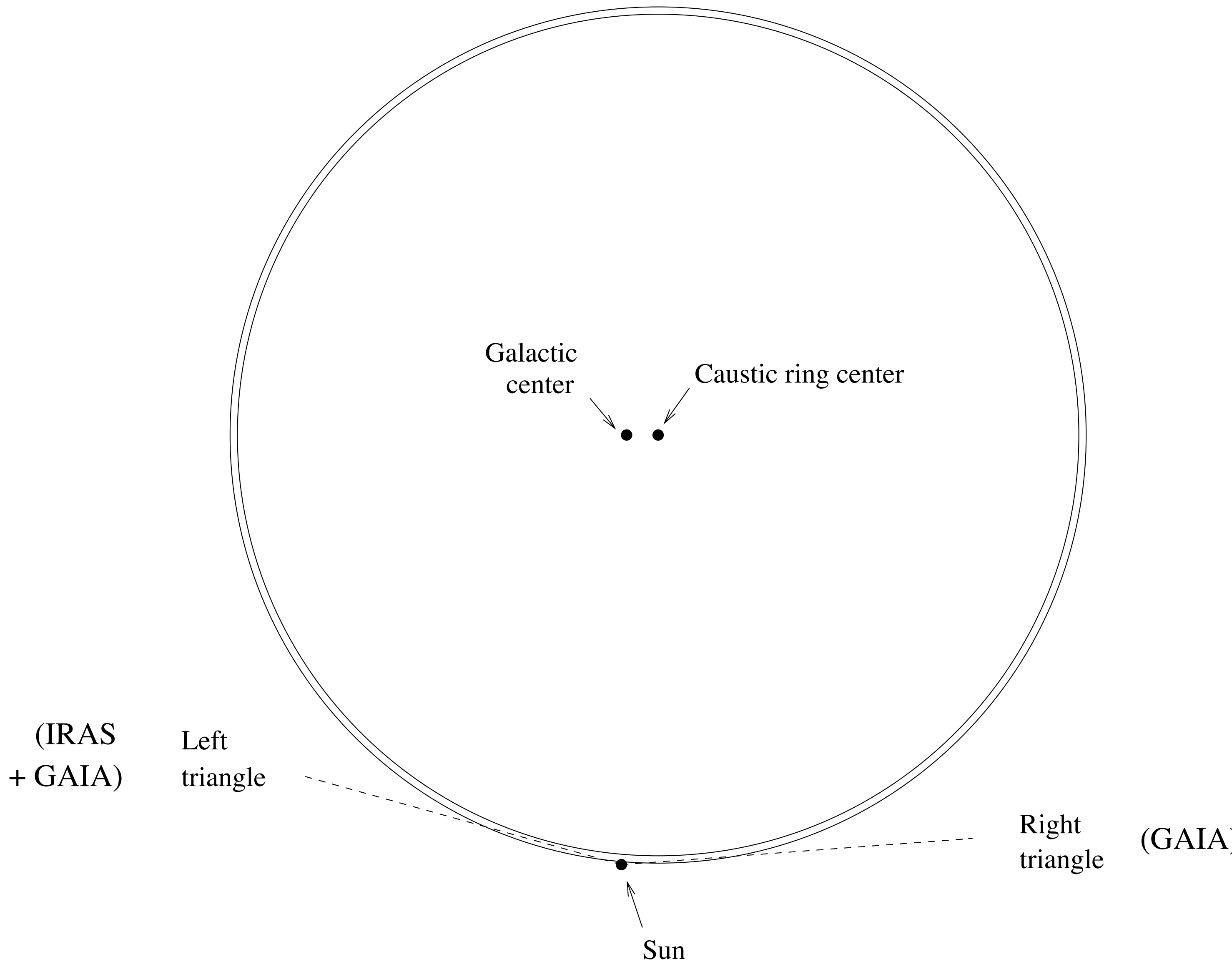
$(l, b) = (80^\circ, 0^\circ)$ $10^\circ \times 10^\circ$



Inner Galactic rotation curve

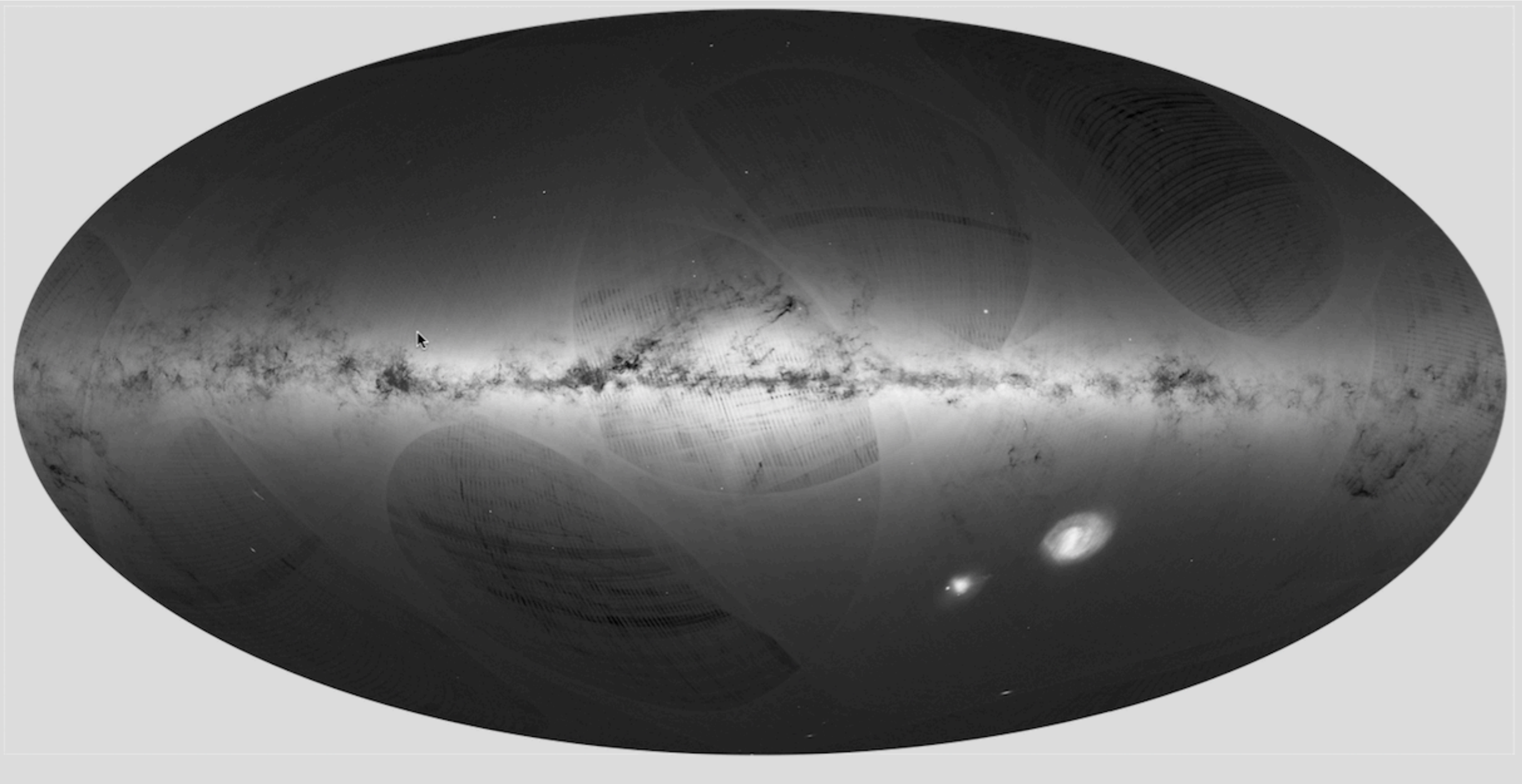


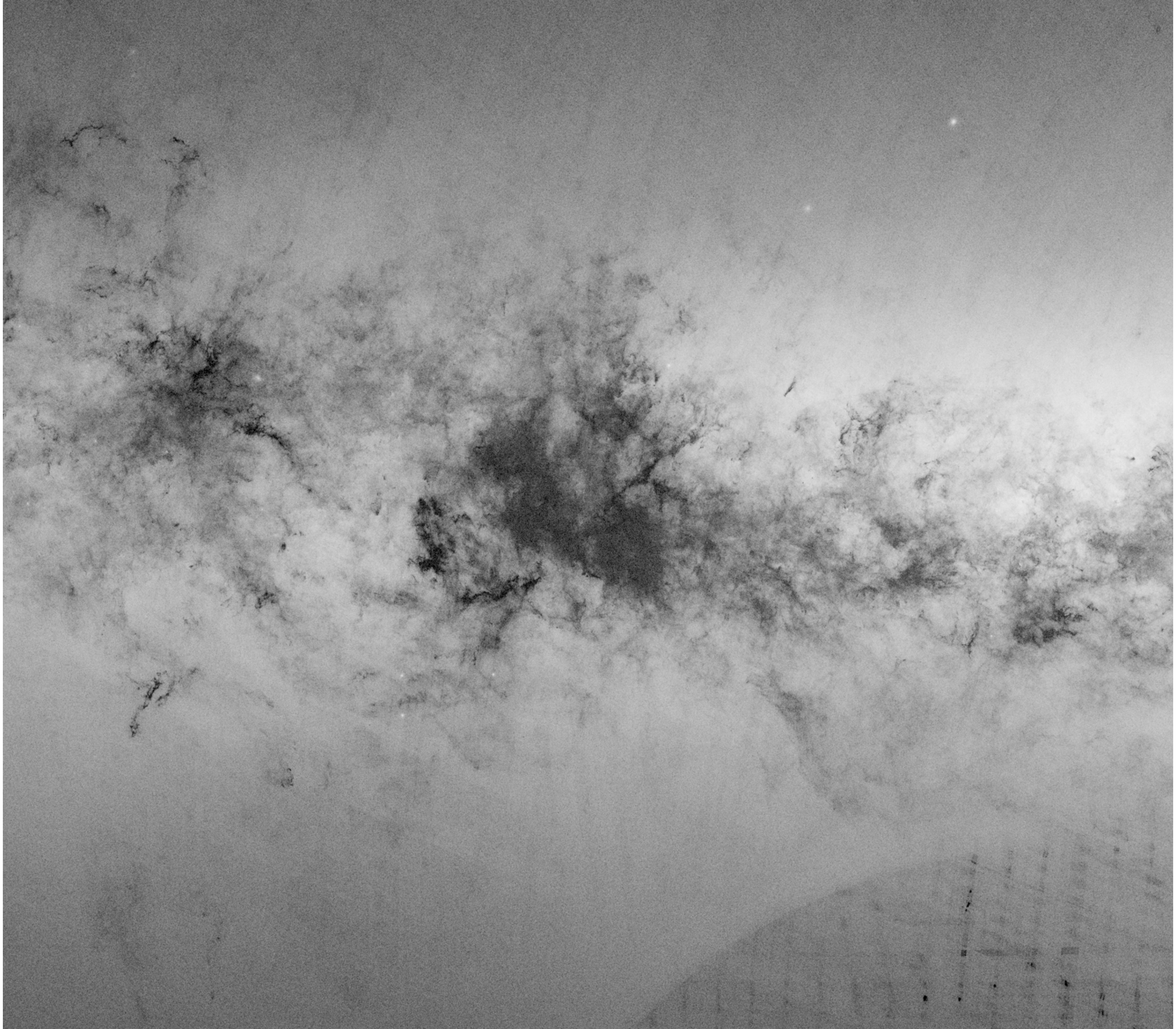
from Massachusetts-Stony Brook North Galactic Pane CO Survey (Clemens, 1985)

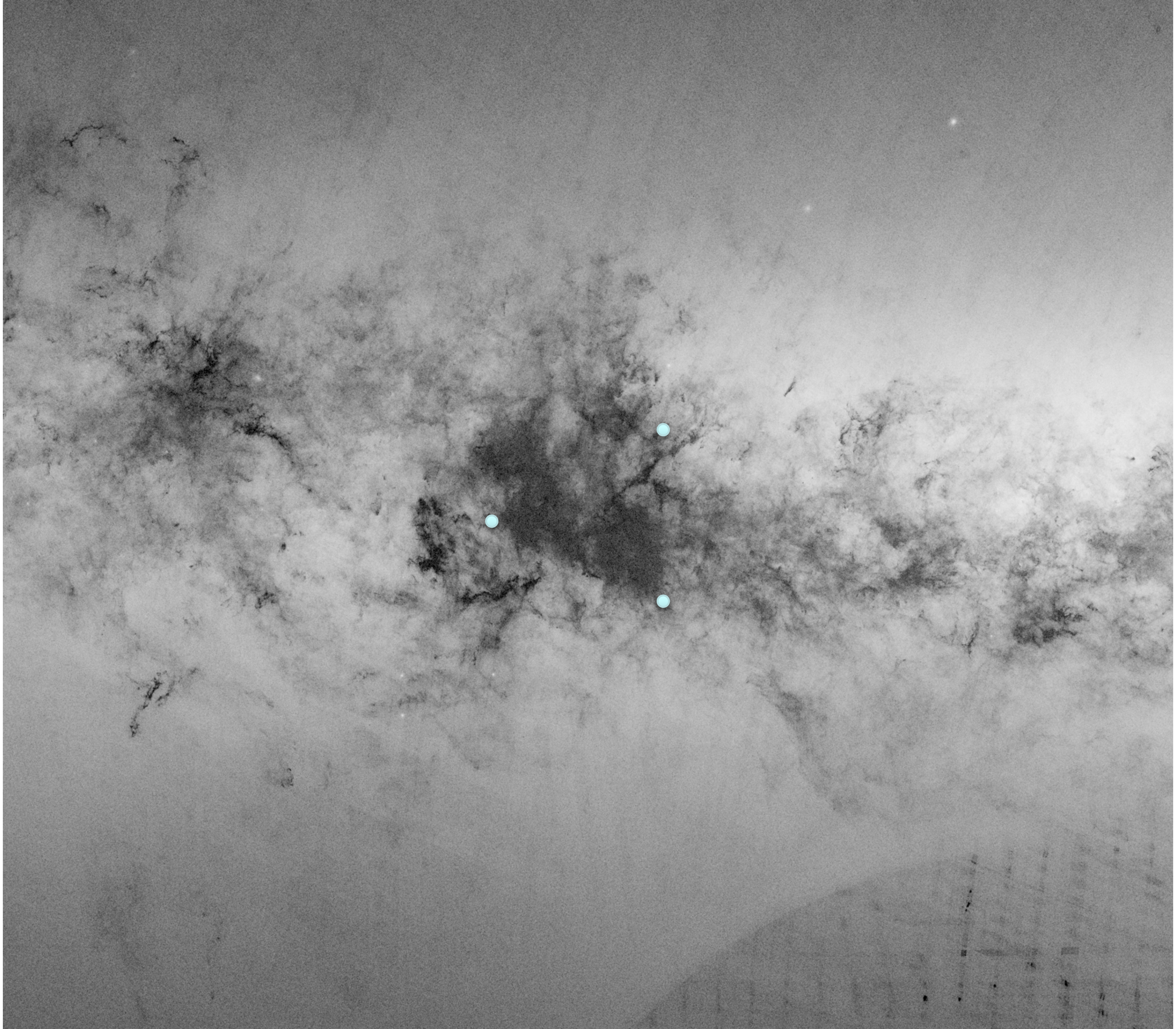


Galactic
center
Caustic ring center
(IRAS
+ GAIA)
Left
triangle
Right
triangle
(GAIA)
Sun

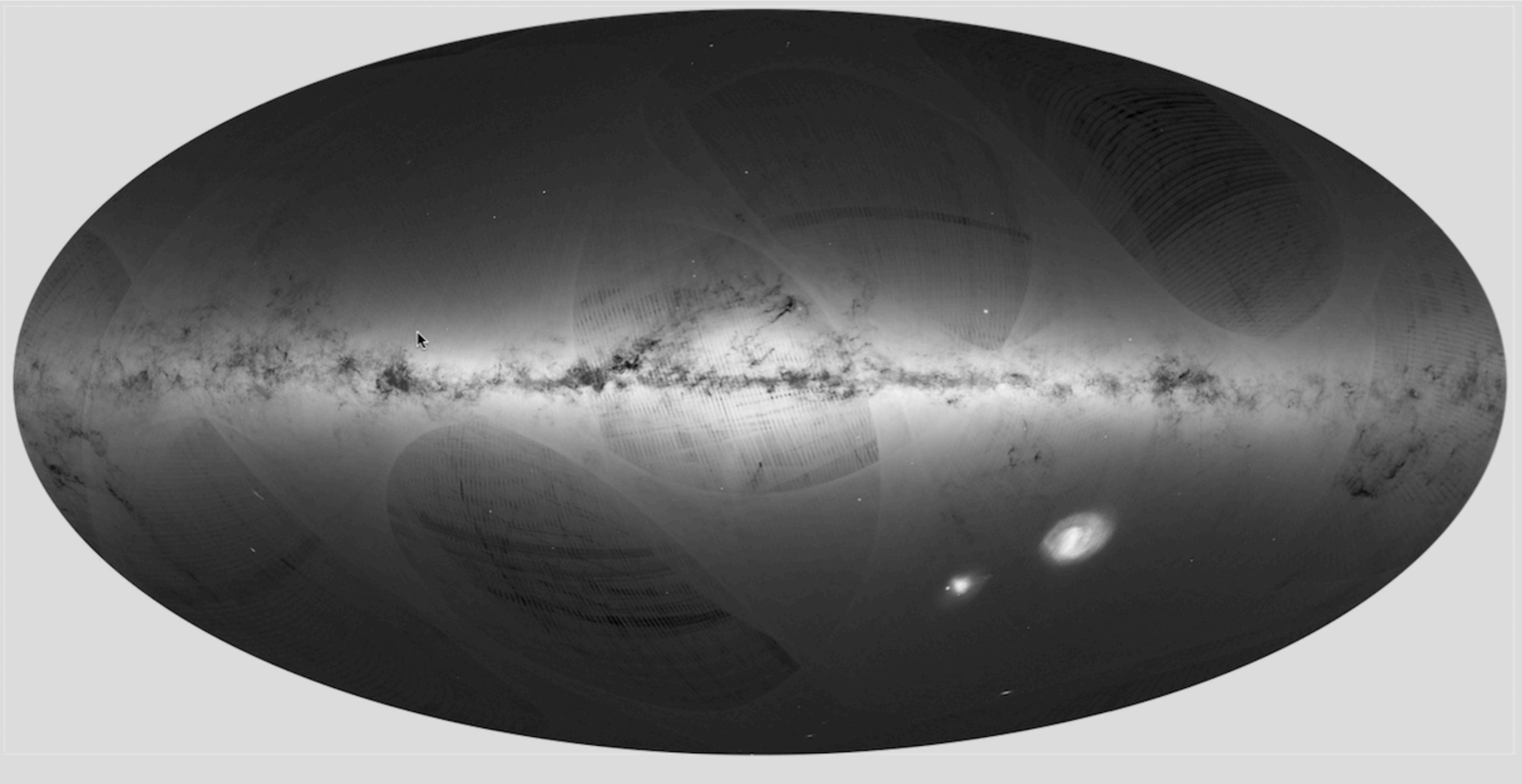
GAIA sky map

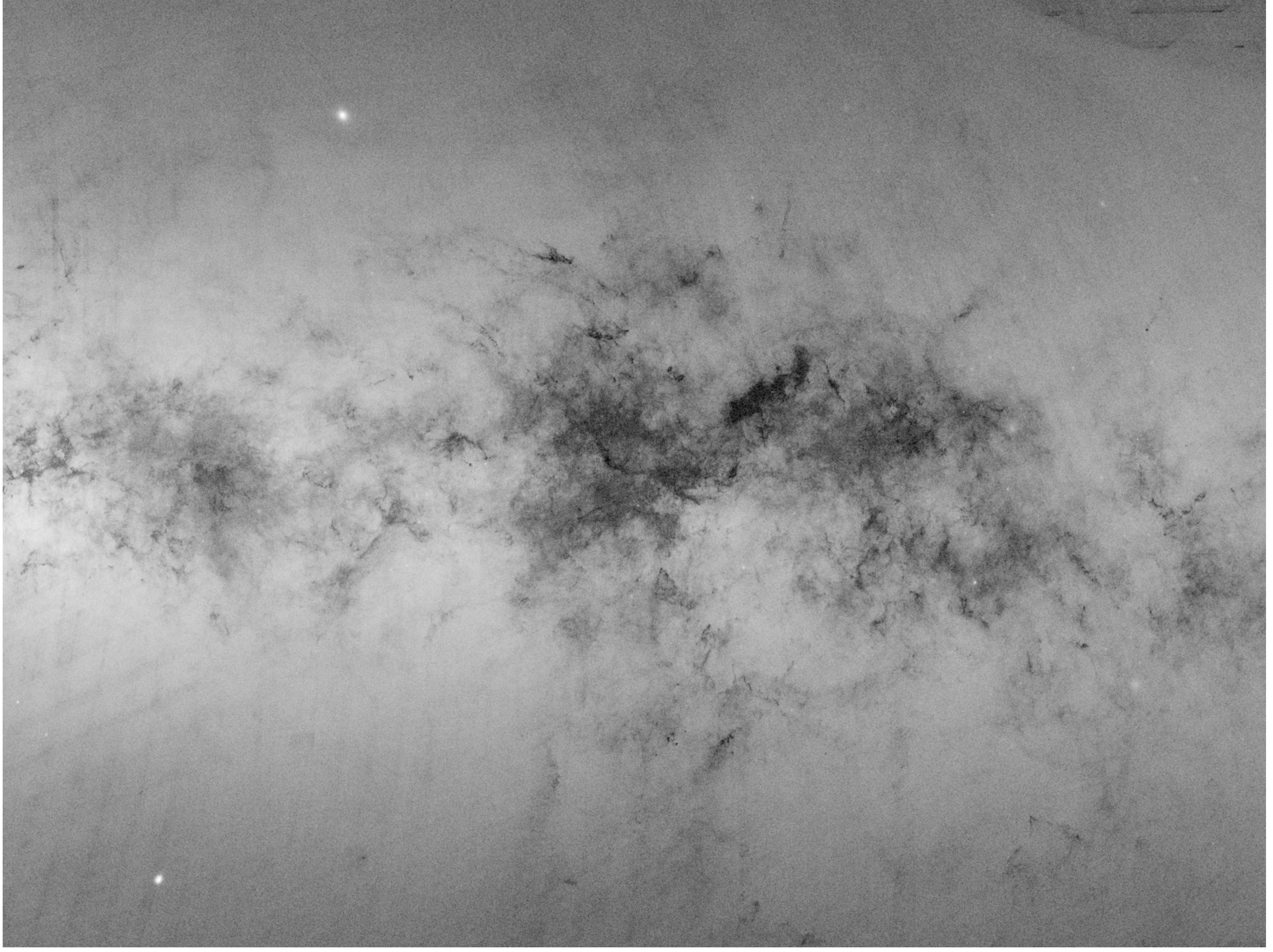


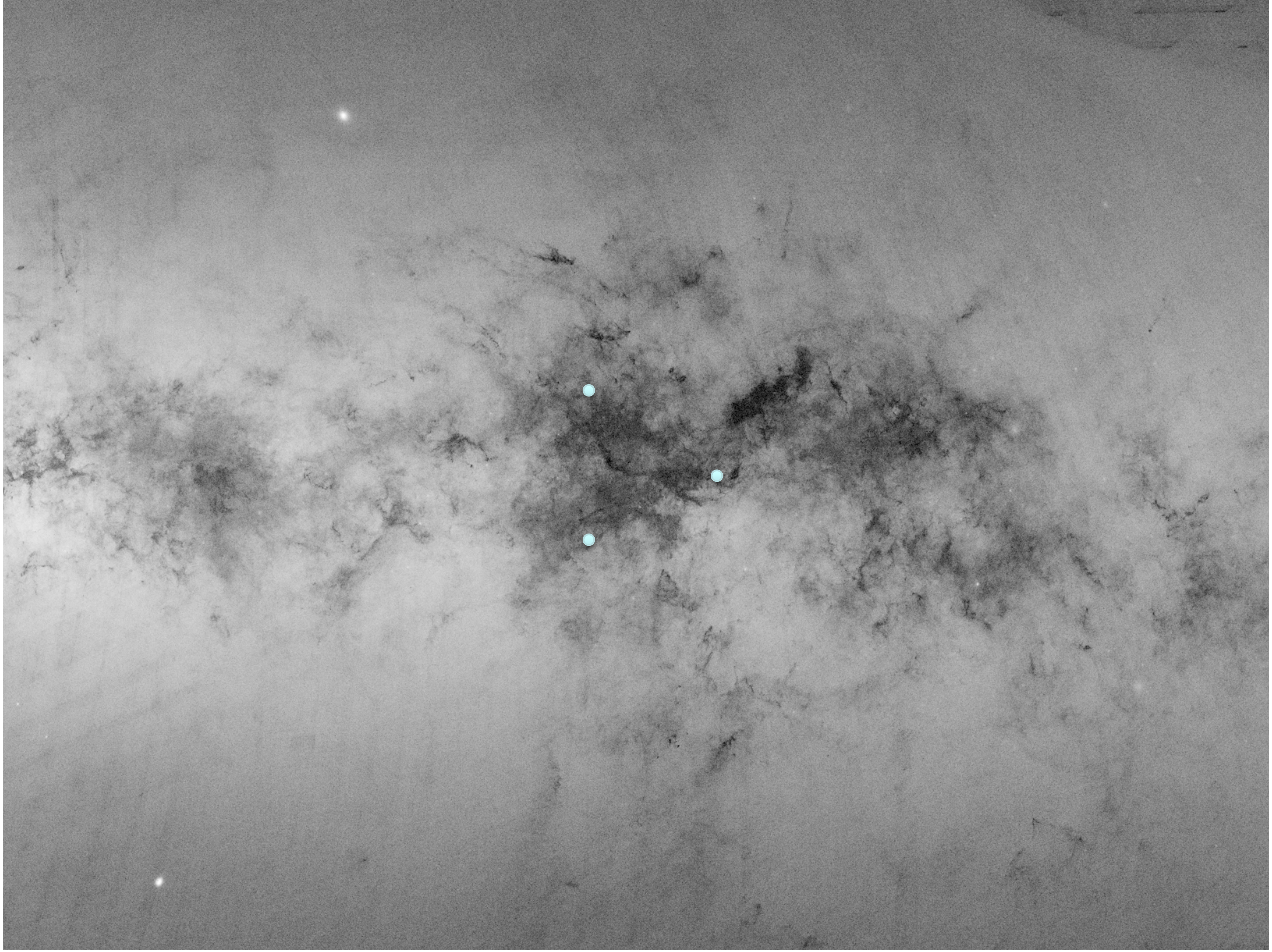


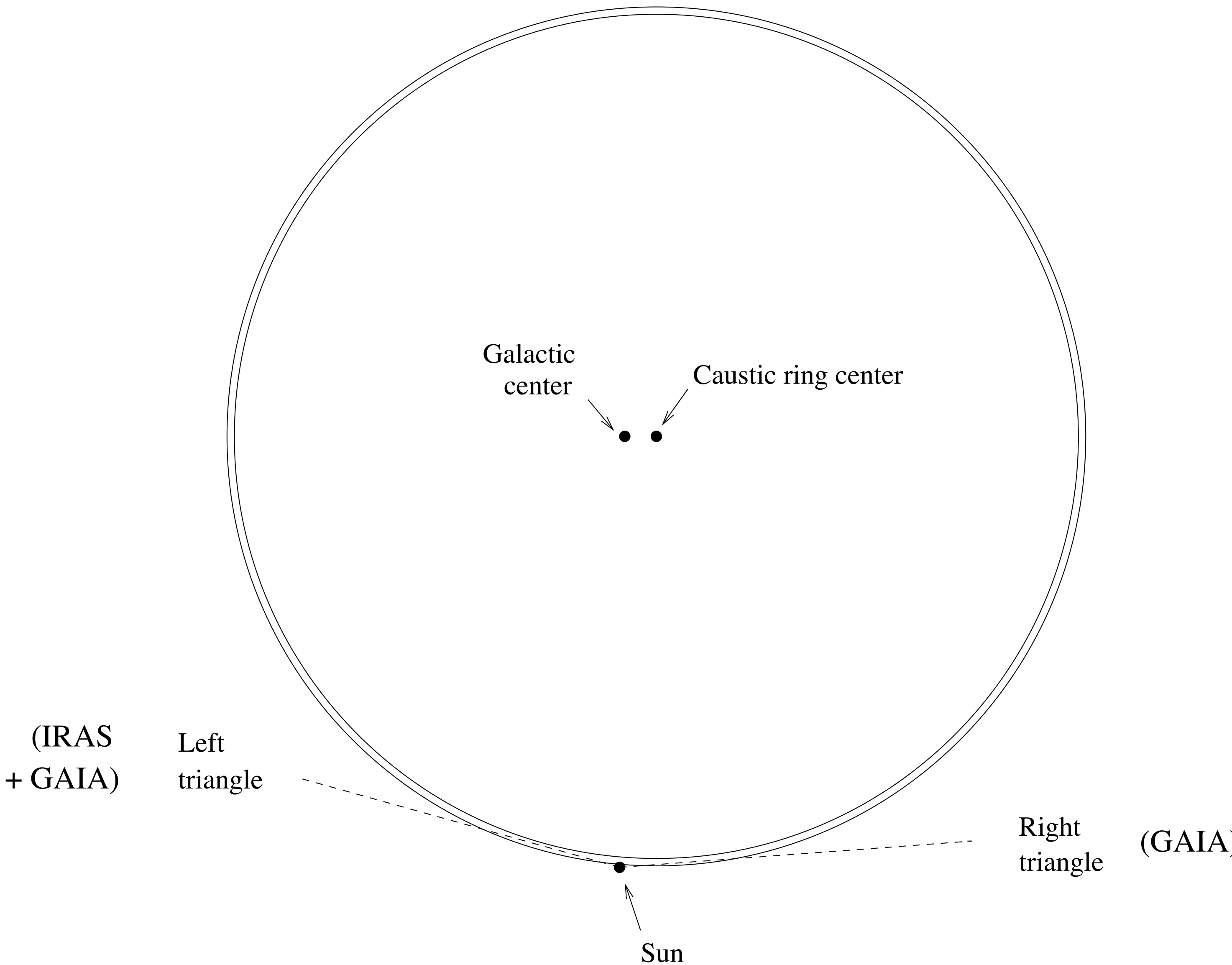


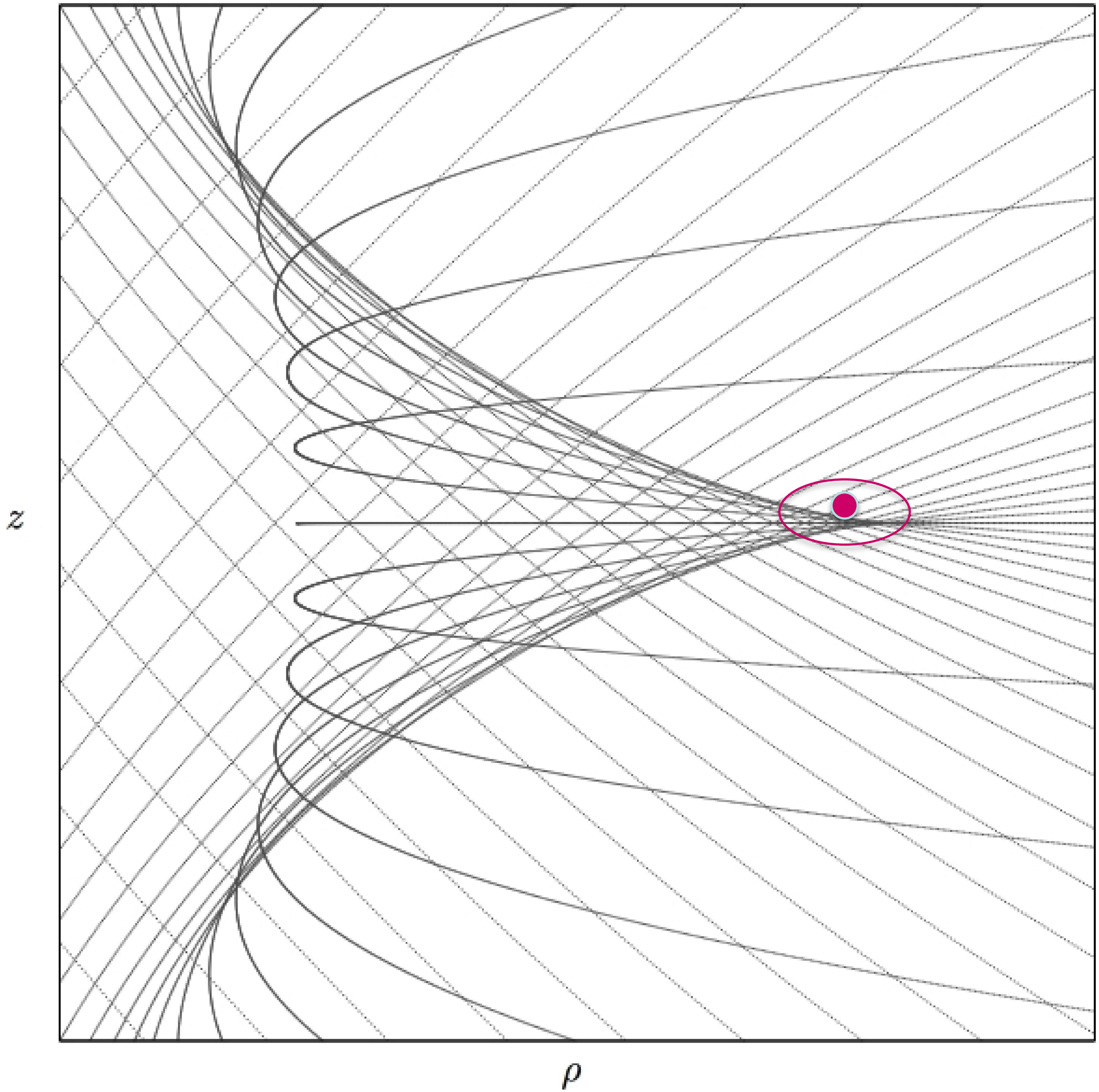
GAIA sky map



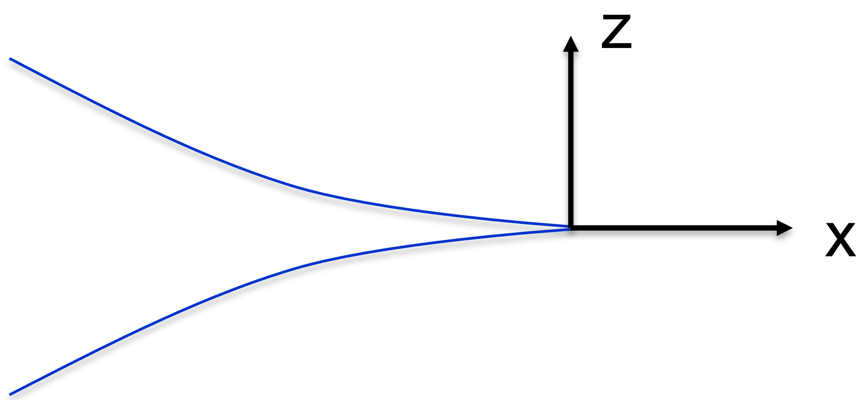





Galactic
center
Caustic ring center
(IRAS
+ GAIA)
Left
triangle
Right
triangle
(GAIA)
Sun



z
ρ



$$x = (-2T - A^2)(61.5\ \mathrm{pc})$$

$$z = -2AT(54.6\ \mathrm{pc})$$

Big Flow density:

$$\rho \simeq 0.96 \cdot 10^{-24}\ \frac{\mathrm{gr}}{\mathrm{cm}^3}\ \frac{1}{|T - A^2|}$$

Big Flow velocity components:

$$v_x = -57\ \frac{\mathrm{km}}{\mathrm{s}}\ (1 - T)$$

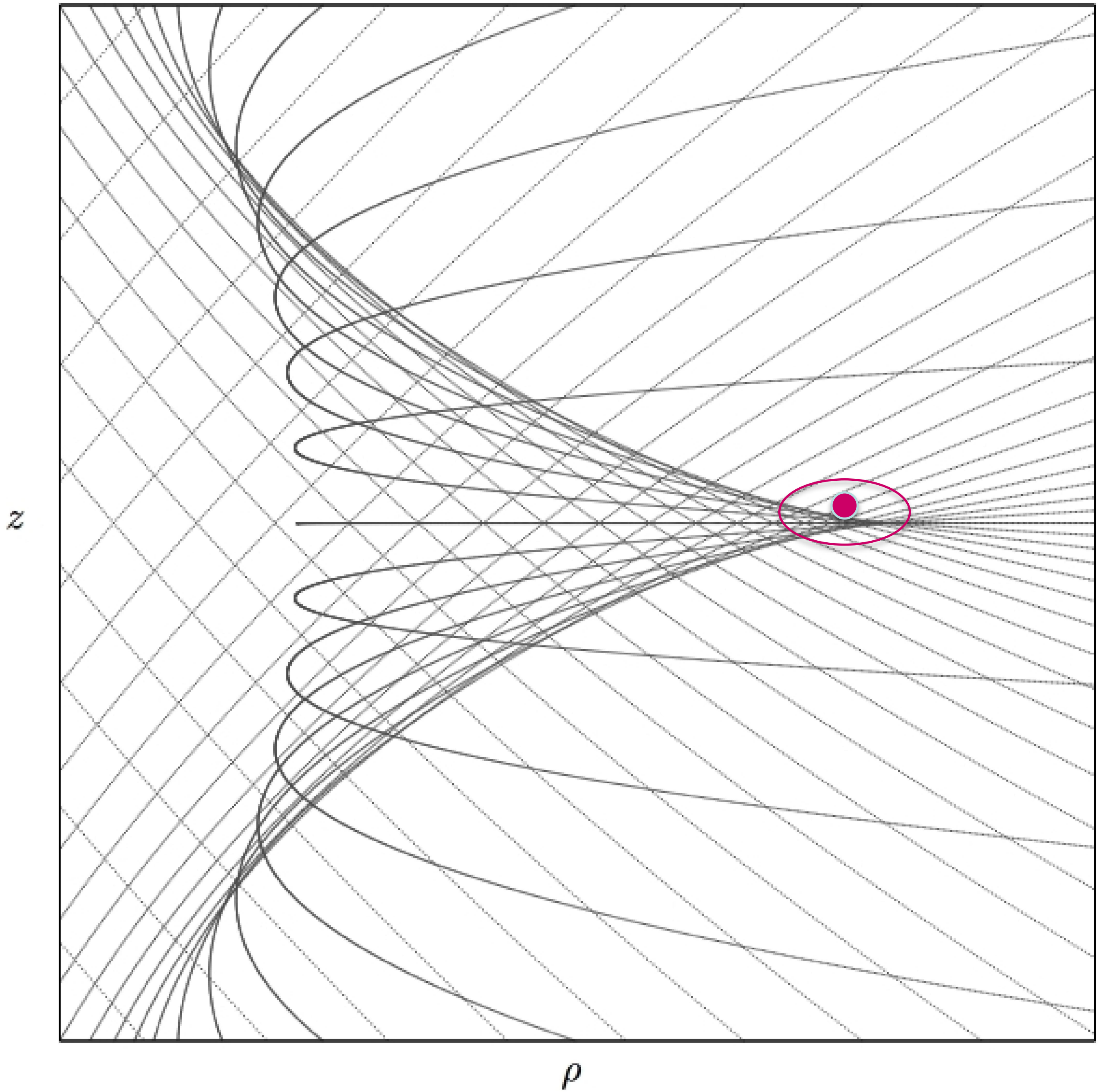
$$v_z = -50.6\ \frac{\mathrm{km}}{\mathrm{s}}\ A$$

Preliminary:

$$x_\odot = -9.2\ \mathrm{pc} \qquad\qquad z_\odot = 1.2\ \mathrm{pc}$$

$$\rho_{\mathrm{BF}} \sim 2.3\ \frac{\mathrm{GeV}}{\mathrm{cm}^3} \times 4$$

$$\vec{v}_{\mathrm{BF}} \simeq (290\ \hat{\phi} - 111\ \hat{r} - 19\ \hat{z})\ \mathrm{km/s}$$



z
ρ

Conclusions

- Dark matter axions can be searched for by sending out a powerful beam of microwave radiation and listening for its echo.
- The GAIA skymap has triangular features which may be interpreted as manifestations of a nearby caustic ring.
- Our proximity to the caustic ring implies the existence on Earth of a Big Flow of dark matter.
- The direction on the Big Flow can be derived from the IRAS and GAIA triangles.