Tom Kephart & Tom Weiler

Nashville,
March 15, 2018

The Axion Echo Method and the Big Flow

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August 14, 2019

Collaborators: Ariel Arza, Sankha Chakrabarty, Anthony Gonzalez, Yaqi Han


Happy
Birthday,
Tom

Outline

- Production and detection of an axion dark matter echo

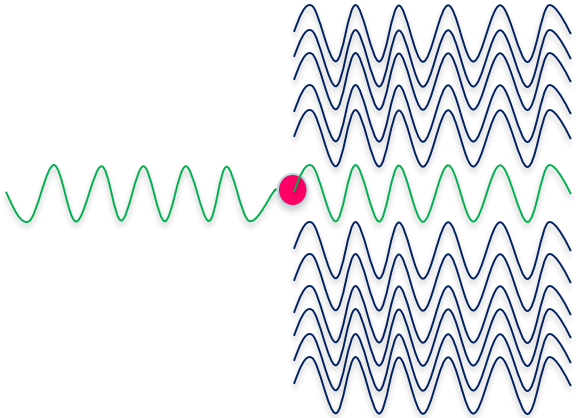
  with Ariel Arza, arXiv:1902.00114

- Constraints on the Big Flow from the GAIA skymap

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

Stimulated axion decay

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



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

P_1 P_0

$P_0 = \text{outgoing power}$

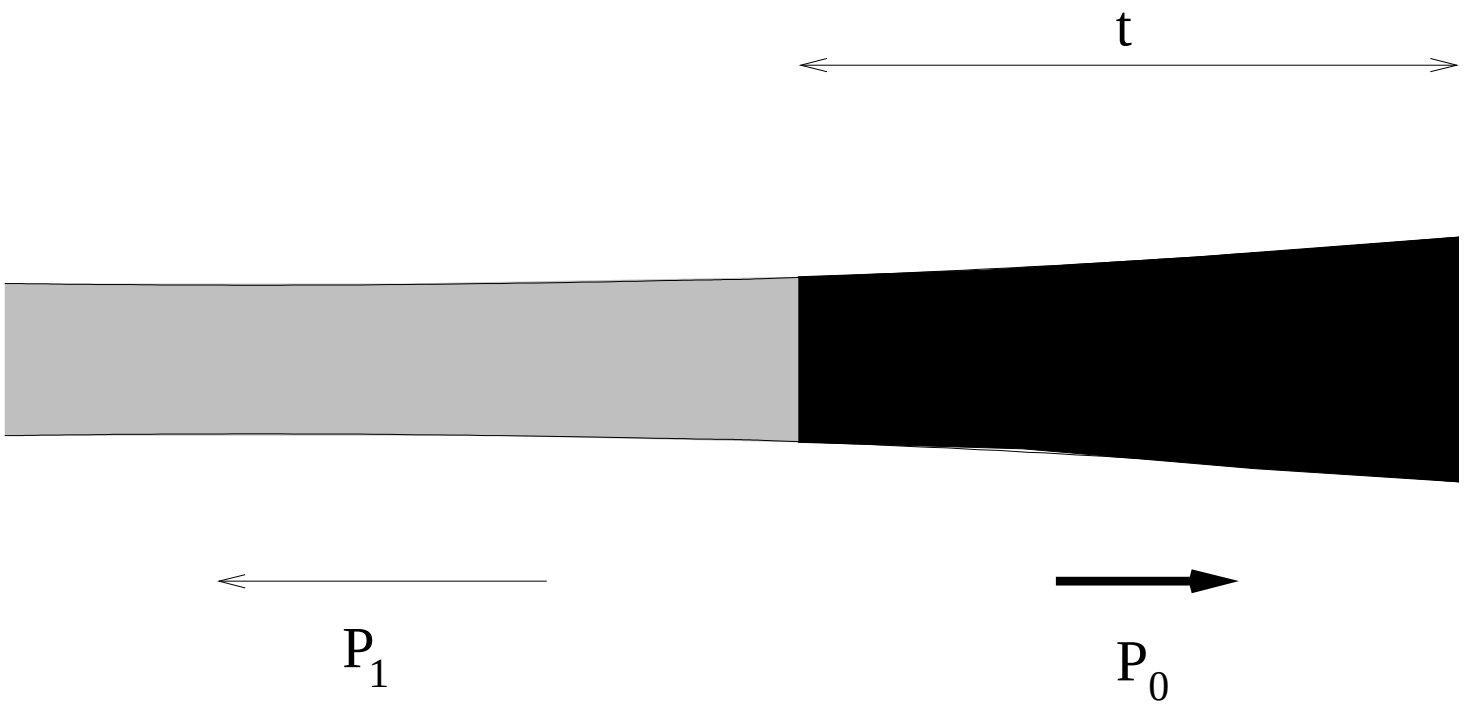
$P_1 = \text{echo power}$

Within the framework of standard big-bang cosmology and the standard electroweak model, it is shown that $\nu\ \bar{\nu}$ annihilation on the Z resonance is the only cosmic-ray process sensitive to relic neutrinos. For massive (m $\gtrsim 10^{-3}$ eV) neutrinos originating from a z~3 red-shifted source, a 15% to 50% absorption dip is predicted at
GeV.

Tom Weiler, 1998

In the rest frame of a perfectly cold axion fluid

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



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

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

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

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

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

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

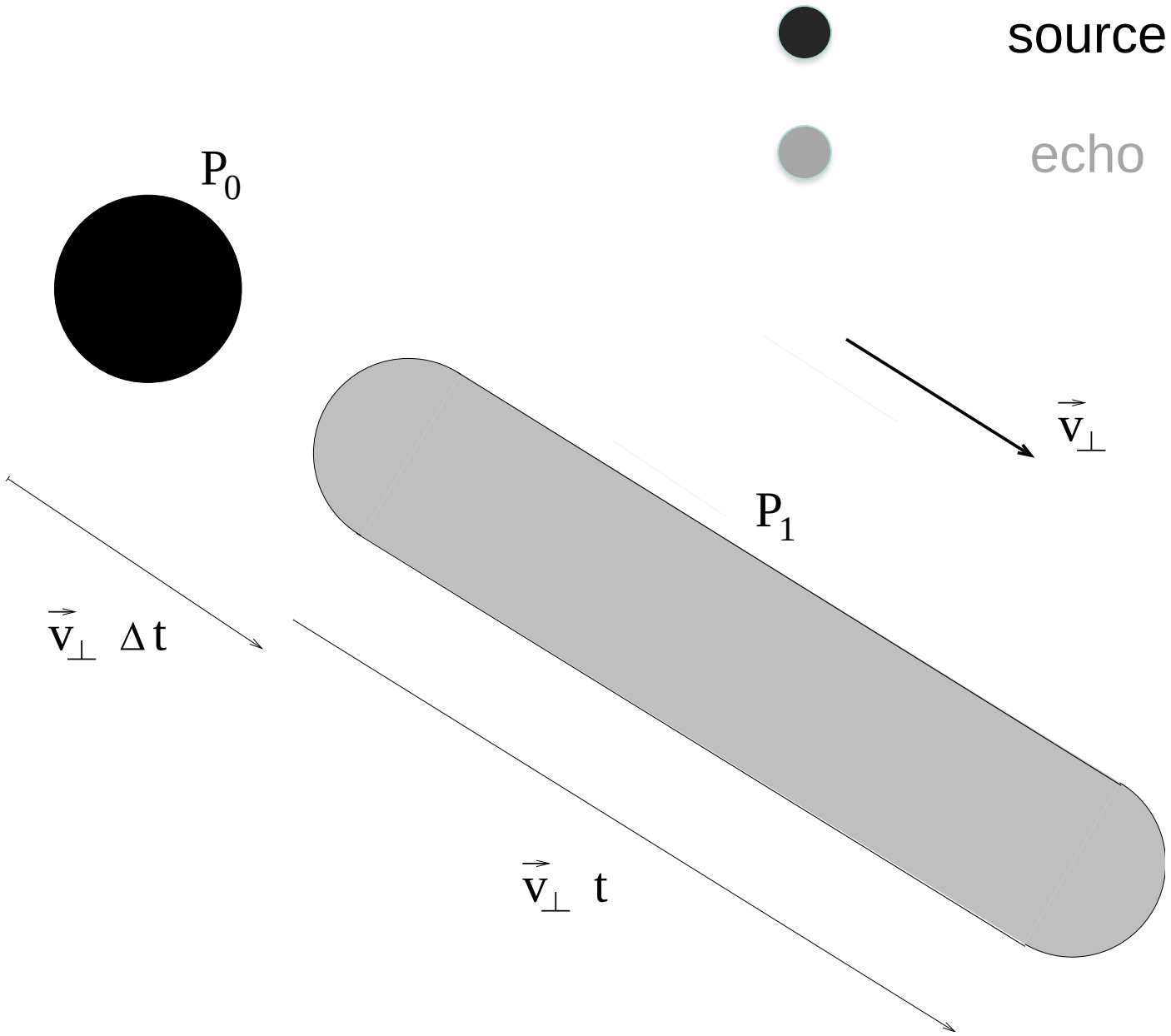
$$\vec{v} = v_{||} \hat{k} + \vec{v}_{\perp}$$

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

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

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

- the caustic ring model (L. Duffy & PS, 2008) has a locally prominent cold flow

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

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

(preliminary)

For a general velocity distribution

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

The echo is spread in frequency

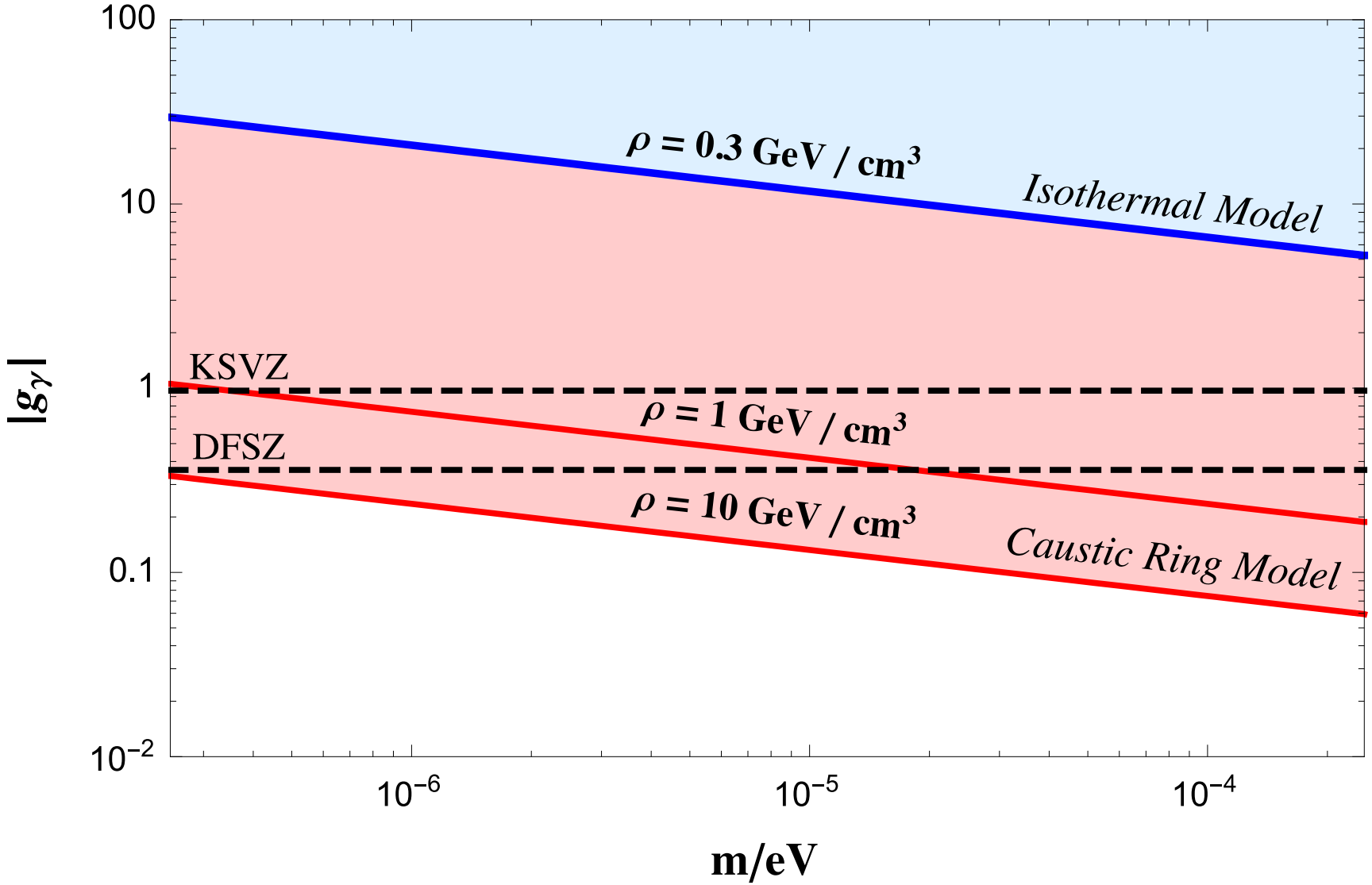
$$\delta\omega_1 = \frac{m_a}{2}\delta v_{\parallel}$$

and in space

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

Assumptions

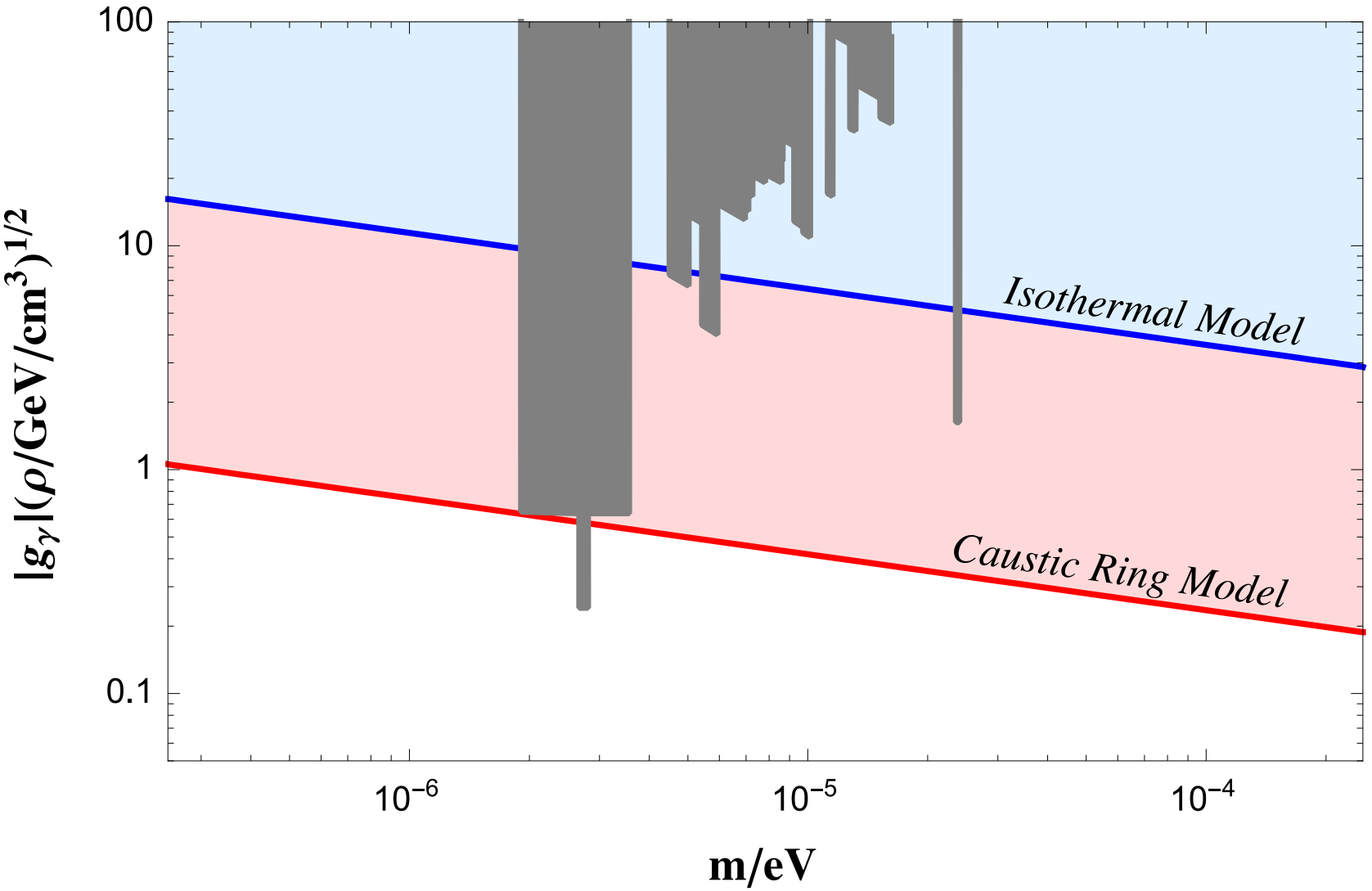
- outgoing energy: 10 MW year per factor of two in frequency covered
- the outgoing power is pulsed (or modulated) on 10 millisec time scale
- 50 meter receiving dish & 20 K system noise temperature
- cold flow with velocity dispersion less than 70 m/s, and known direction
- $|\vec{v}_\perp| < 5 \text{ km/s}$


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

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

Outline

- Production and detection of an axion dark matter echo

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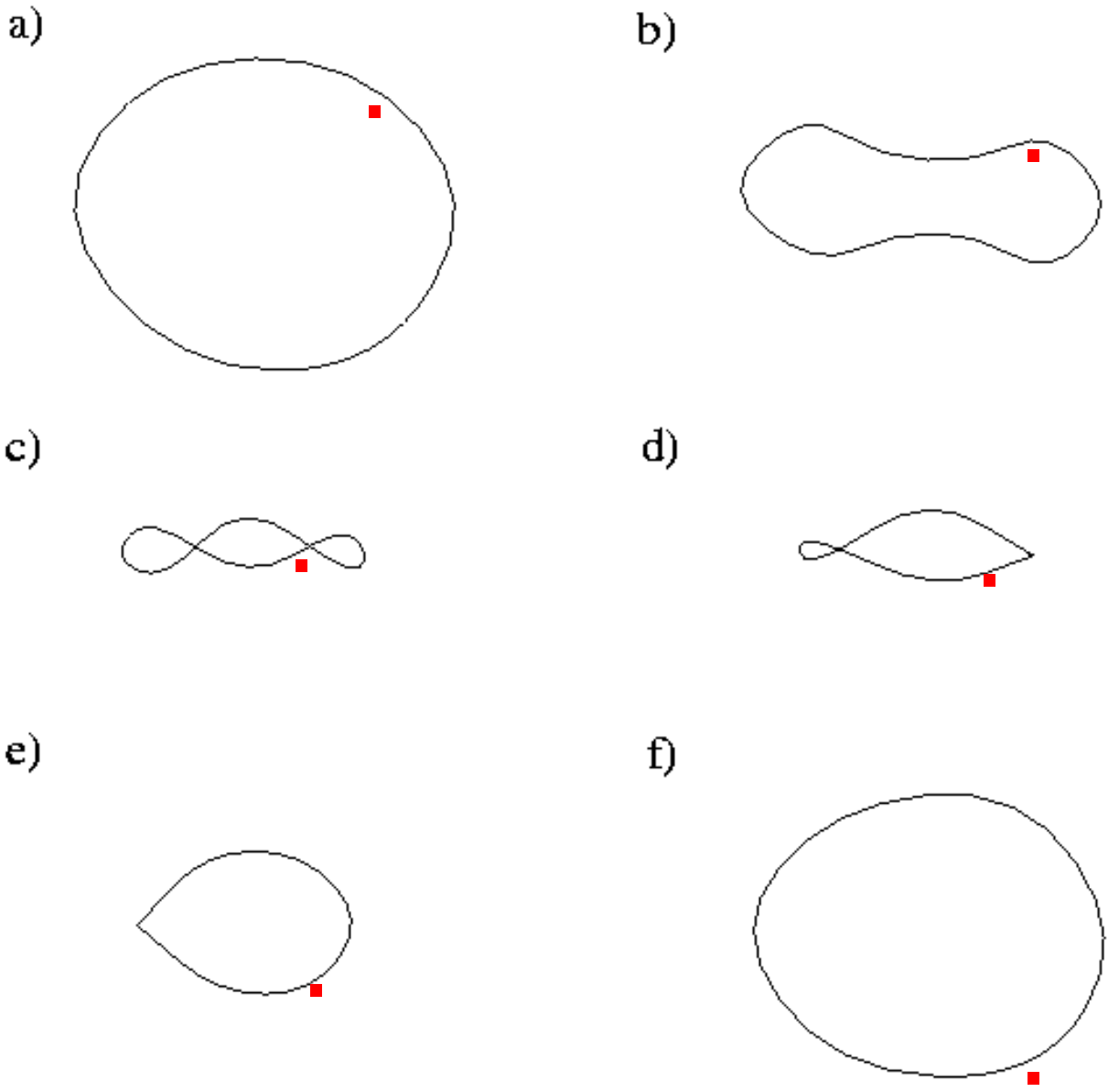
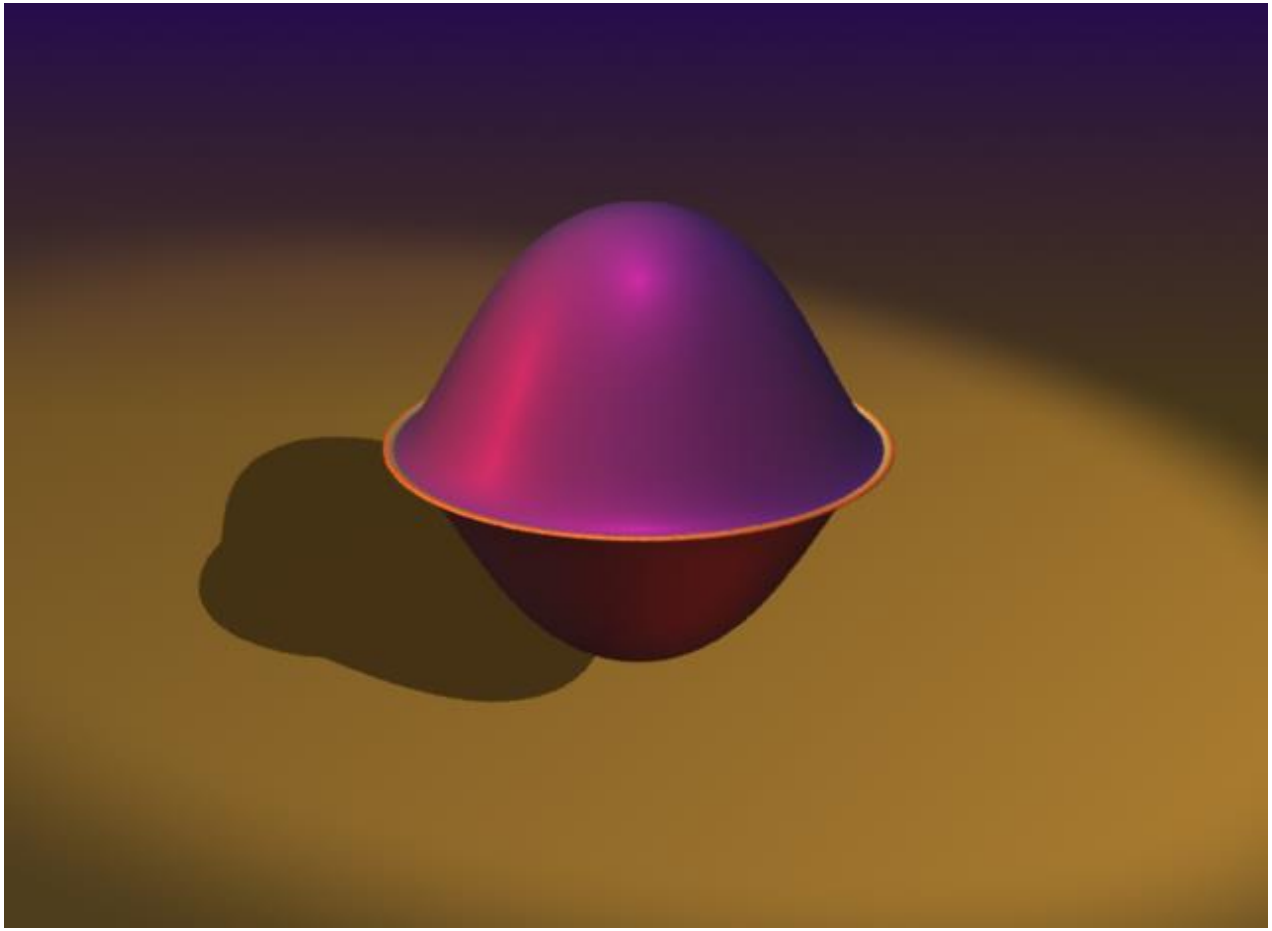
A shell of particles, part of a continuous flow.

The shell has net angular momentum.

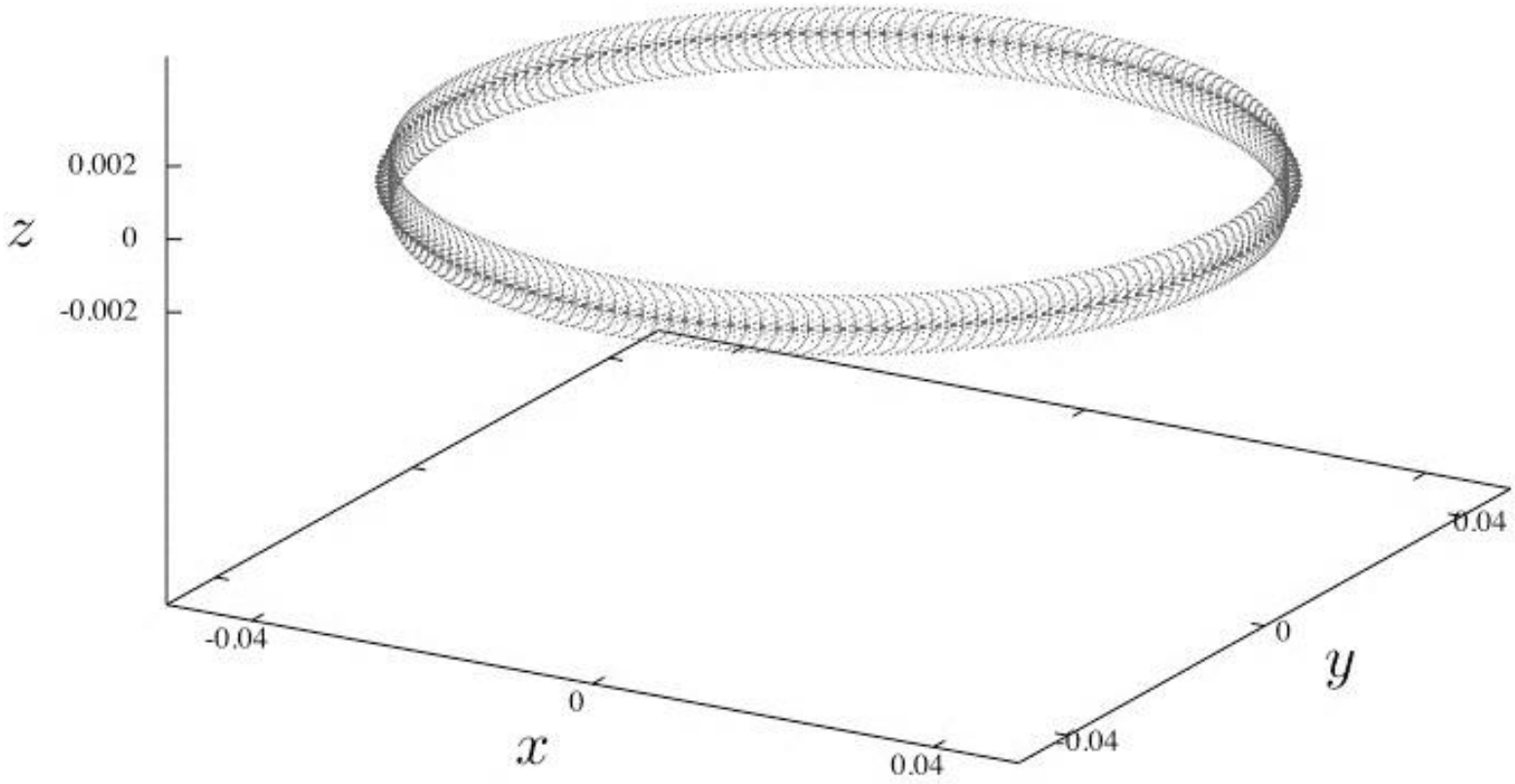
As the shell falls in and out of the galaxy, it turns itself inside out.



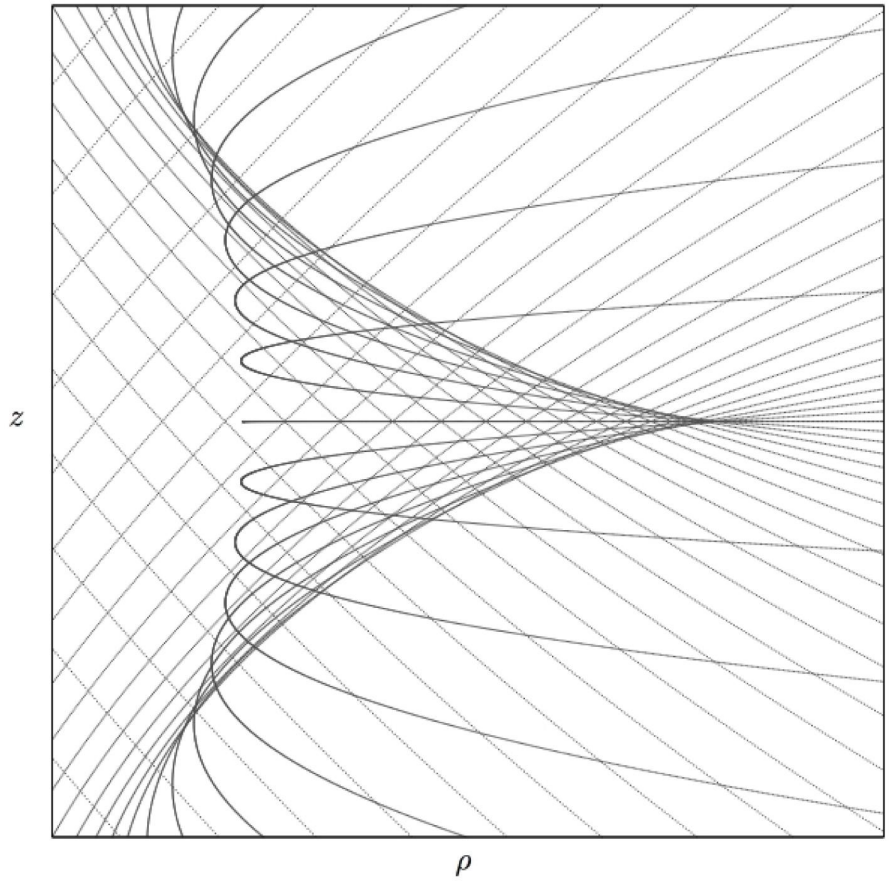
Sphere turning inside out



simulation by Arvind Natarajan



The caustic ring cross-section



D_{-4}

an elliptic umbilic catastrophe

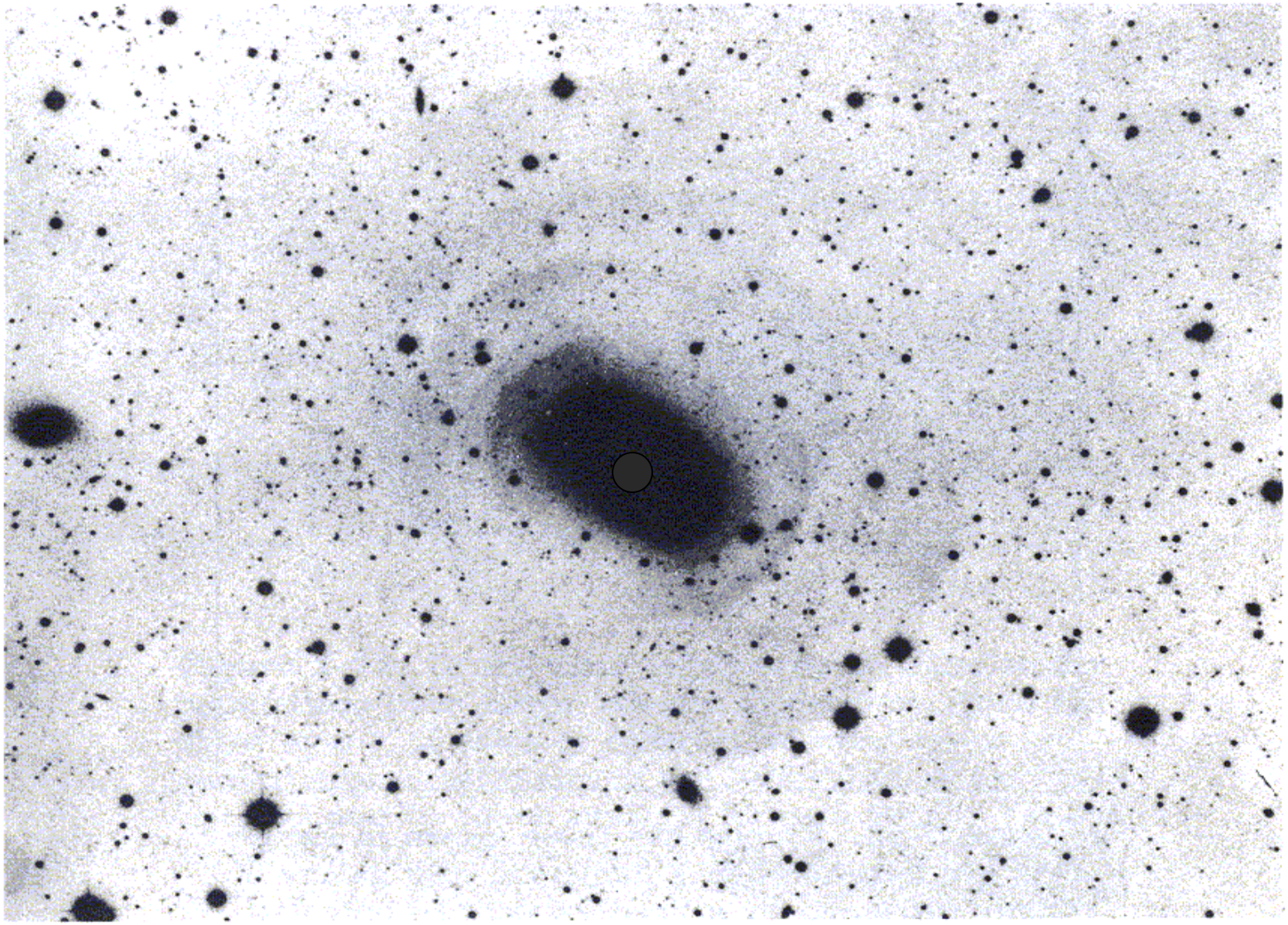


Figure 7-22. The giant elliptical galaxy NGC 3923 is surrounded by faint ripples of brightness. Courtesy of D. F. Malin and the Anglo-Australian Telescope Board.

(from Binney and Tremaine's book)

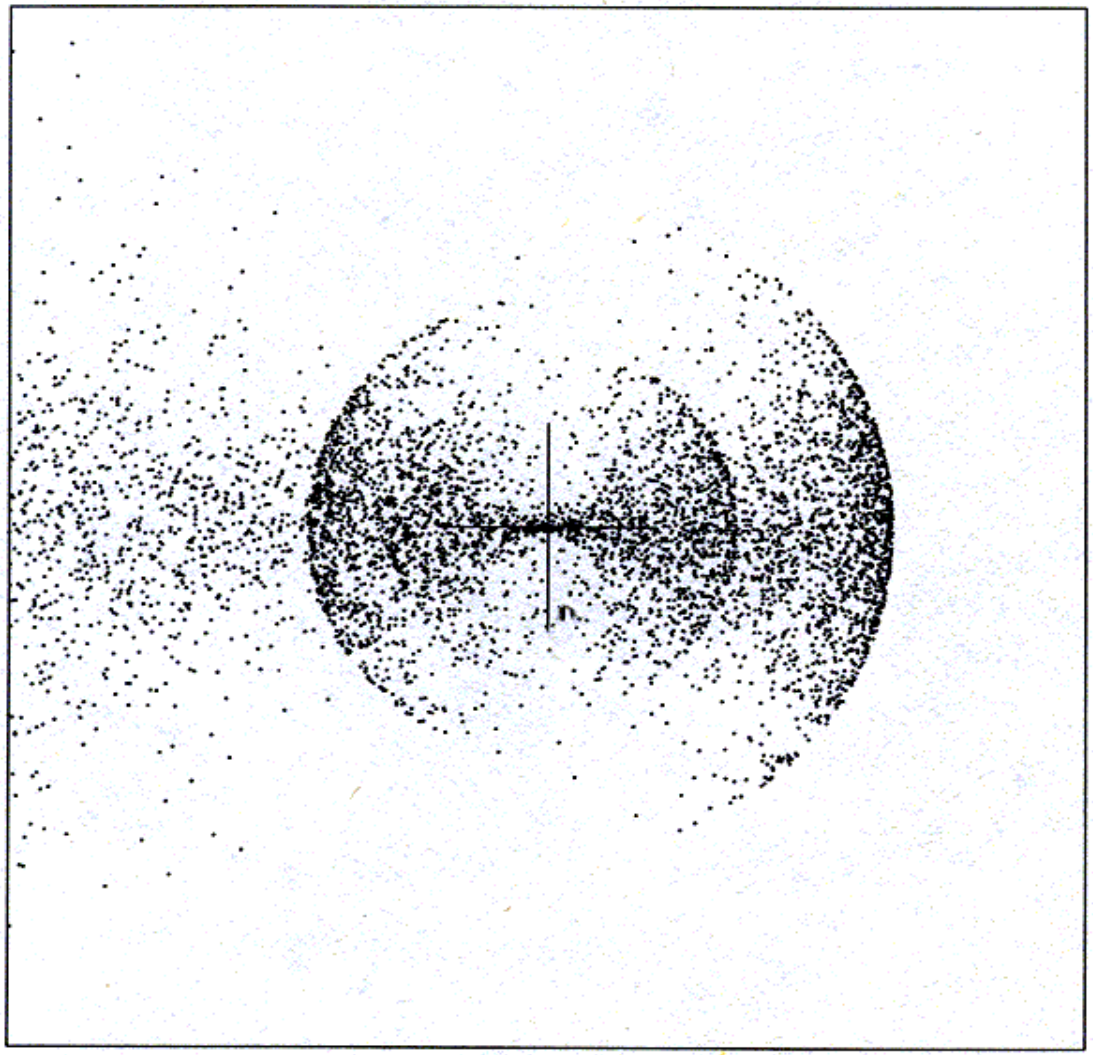


Figure 7-23. Ripples like those shown in Figure 7-22 are formed when a numerical disk galaxy is tidally disrupted by a fixed galaxy-like potential. (See Hernquist & Quinn 1987.)

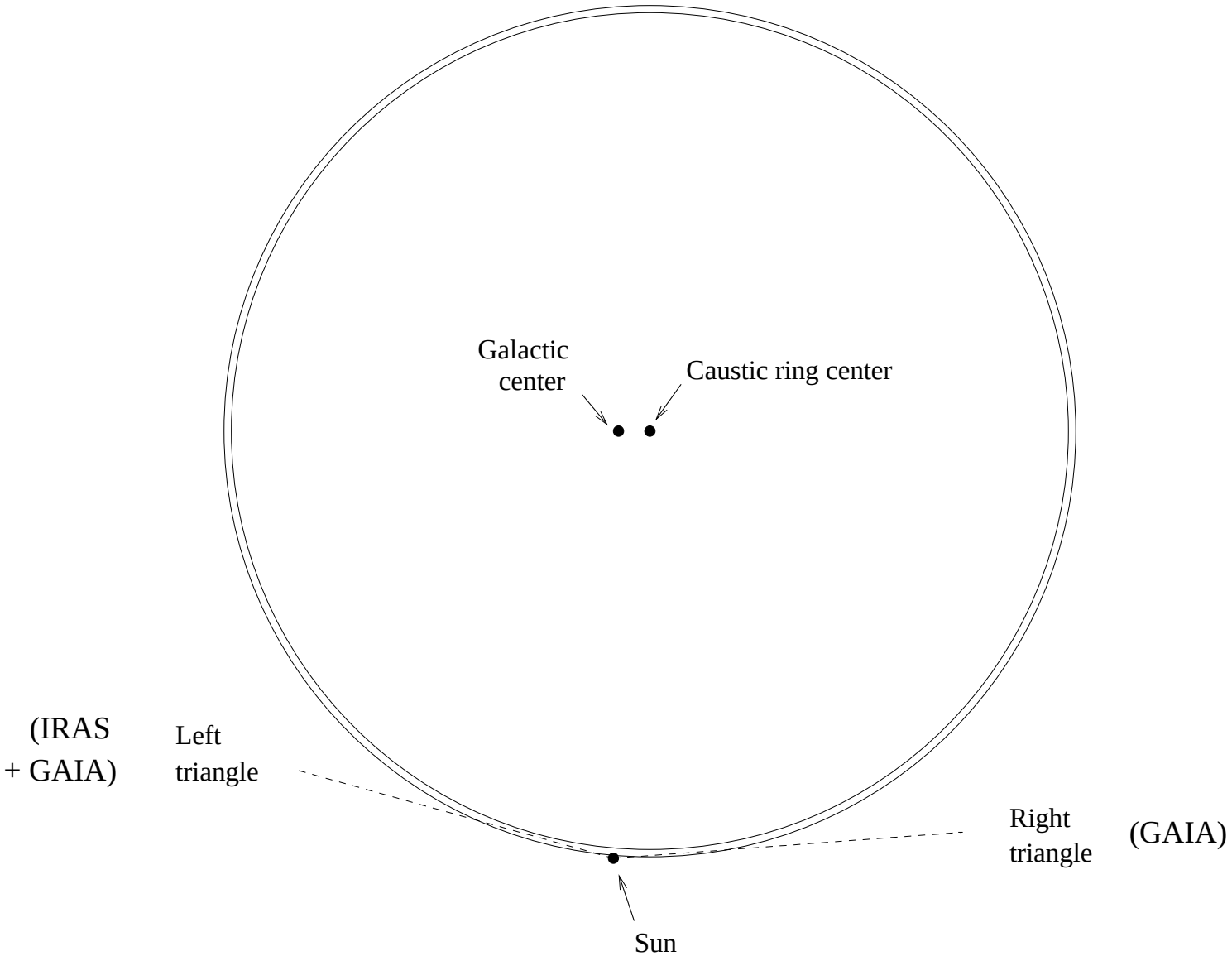
On the basis of the self-similar infall model (Filmore and Goldreich, Bertschinger) with angular momentum (Tkachev, Wang + PS), the caustic rings were predicted to be

in the galactic plane

with radii $(n = 1, 2, 3...)$

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

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

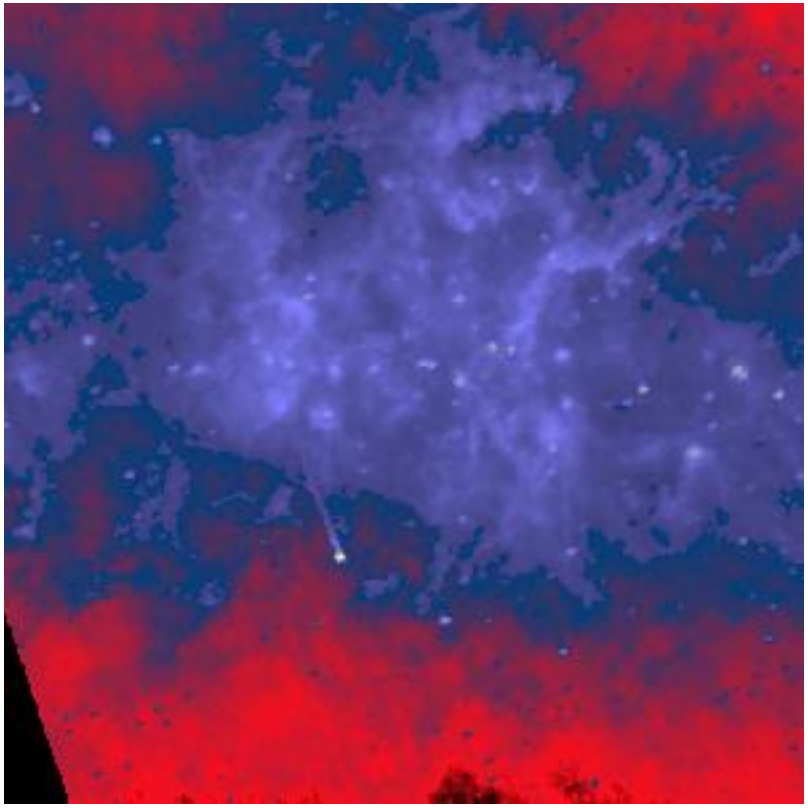

Galactic
center
Caustic ring center
(IRAS
+ GAIA)
Left
triangle
Right
triangle
(GAIA)
Sun

IRAS

12 μm

$(l, b) = (80^o, 0^o)$

$10^o \times 10^o$



IRAS

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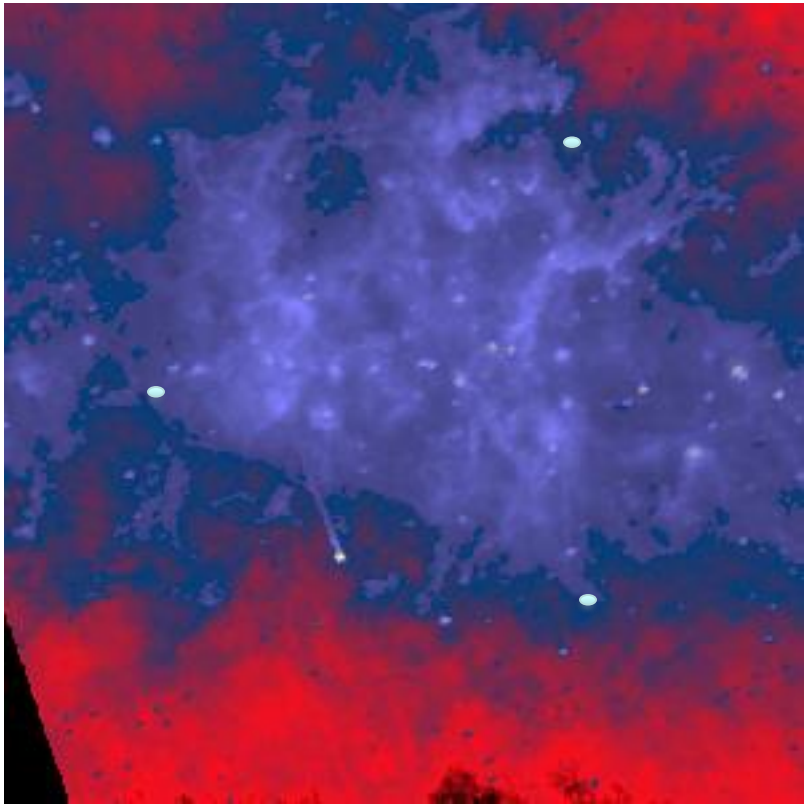
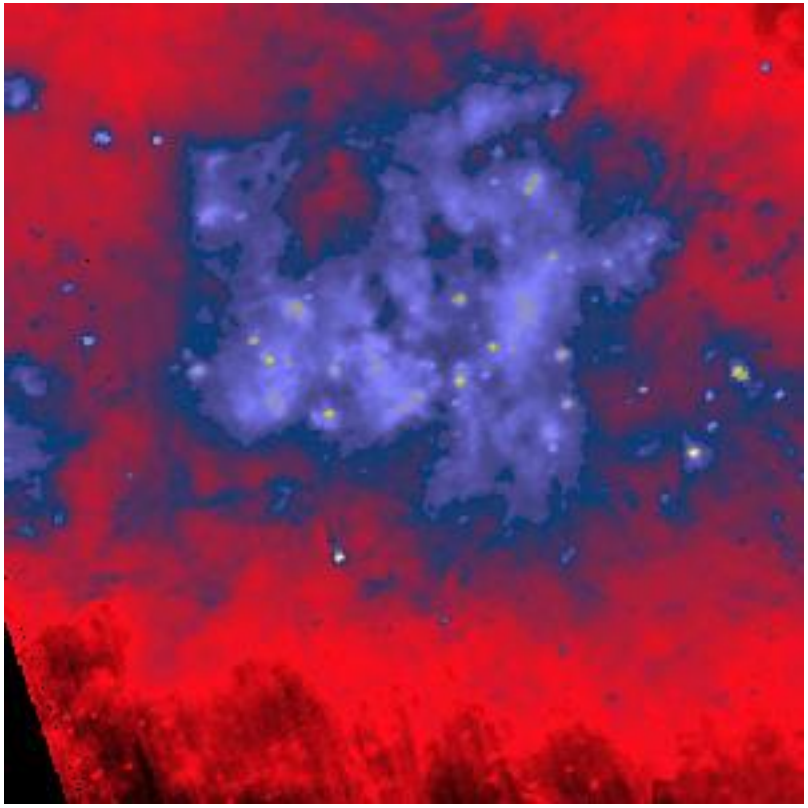


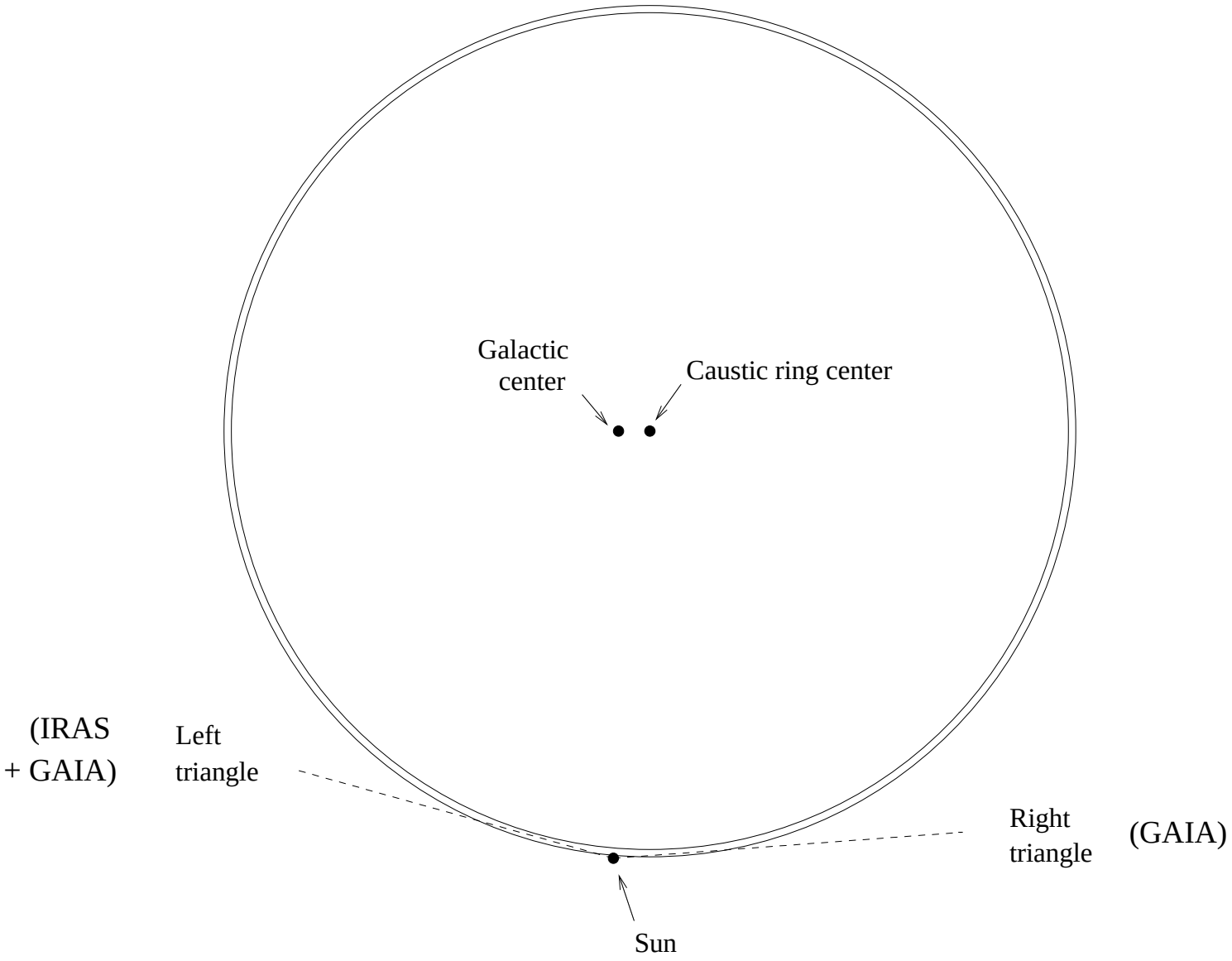
IRAS

$25\ \mu\mathrm{m}$

$(\mathrm{l}, \mathrm{b}) = (80^{\mathrm{o}}, 0^{\mathrm{o}})$

$10^{\mathrm{o}} \times 10^{\mathrm{o}}$

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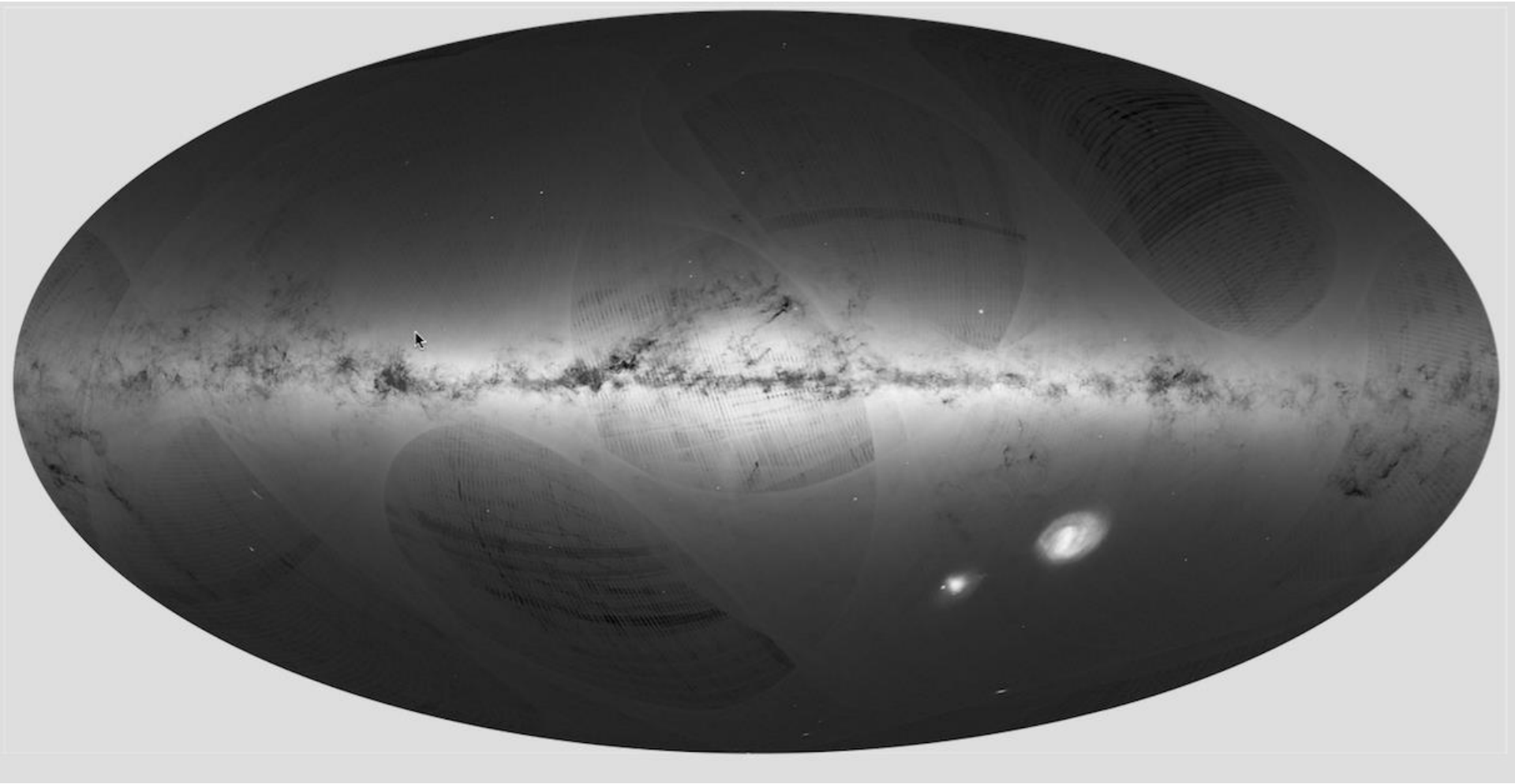
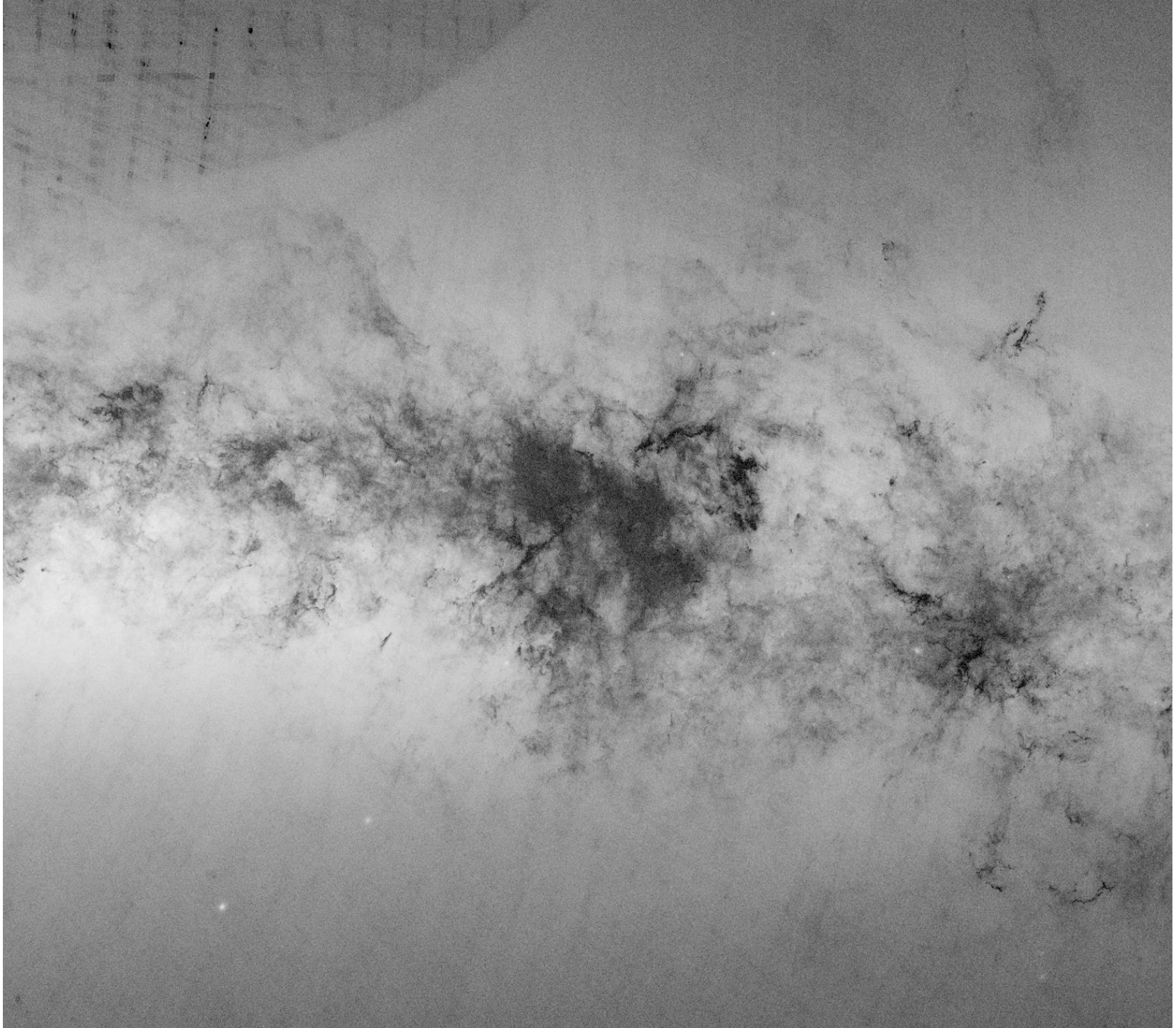
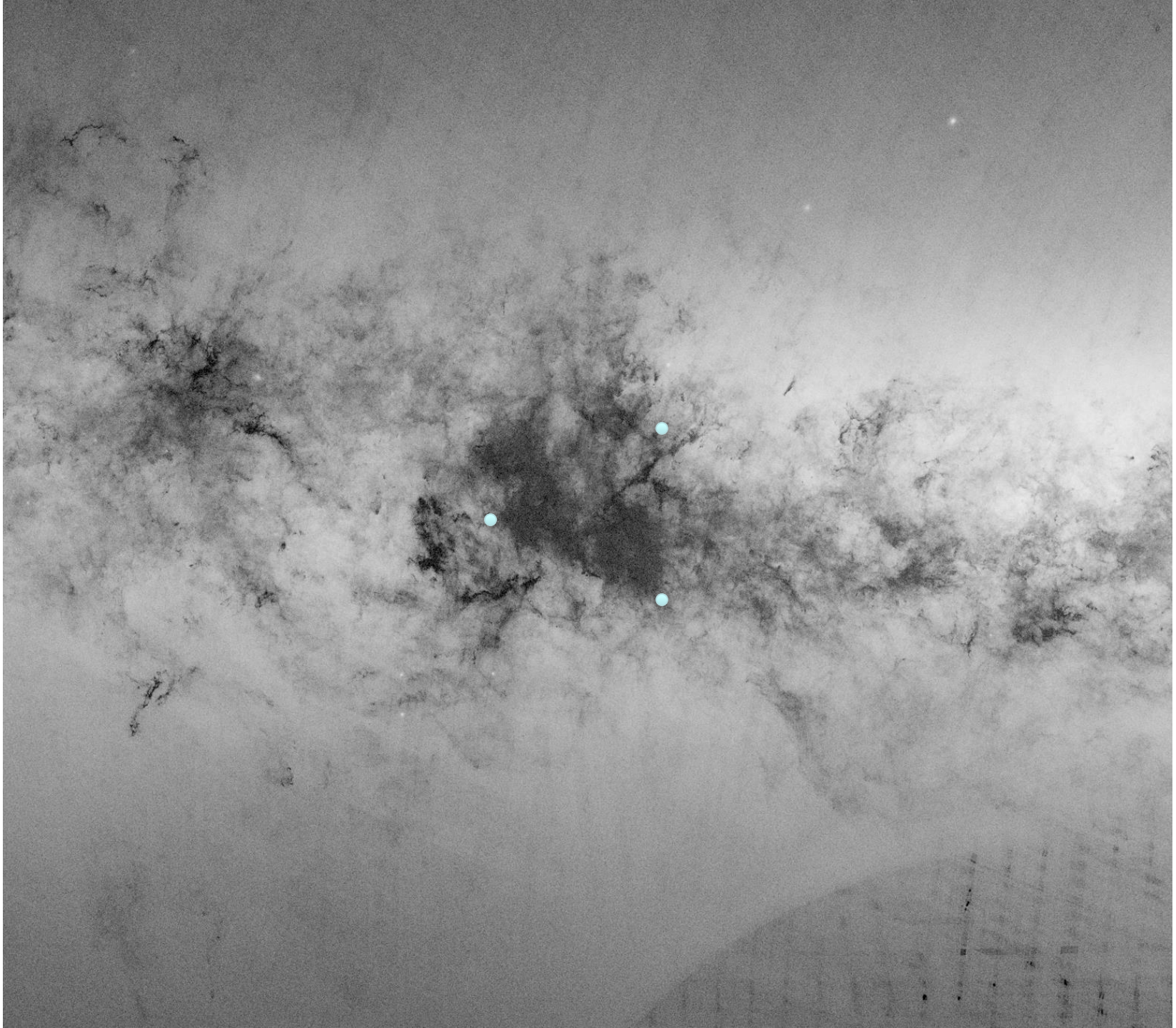
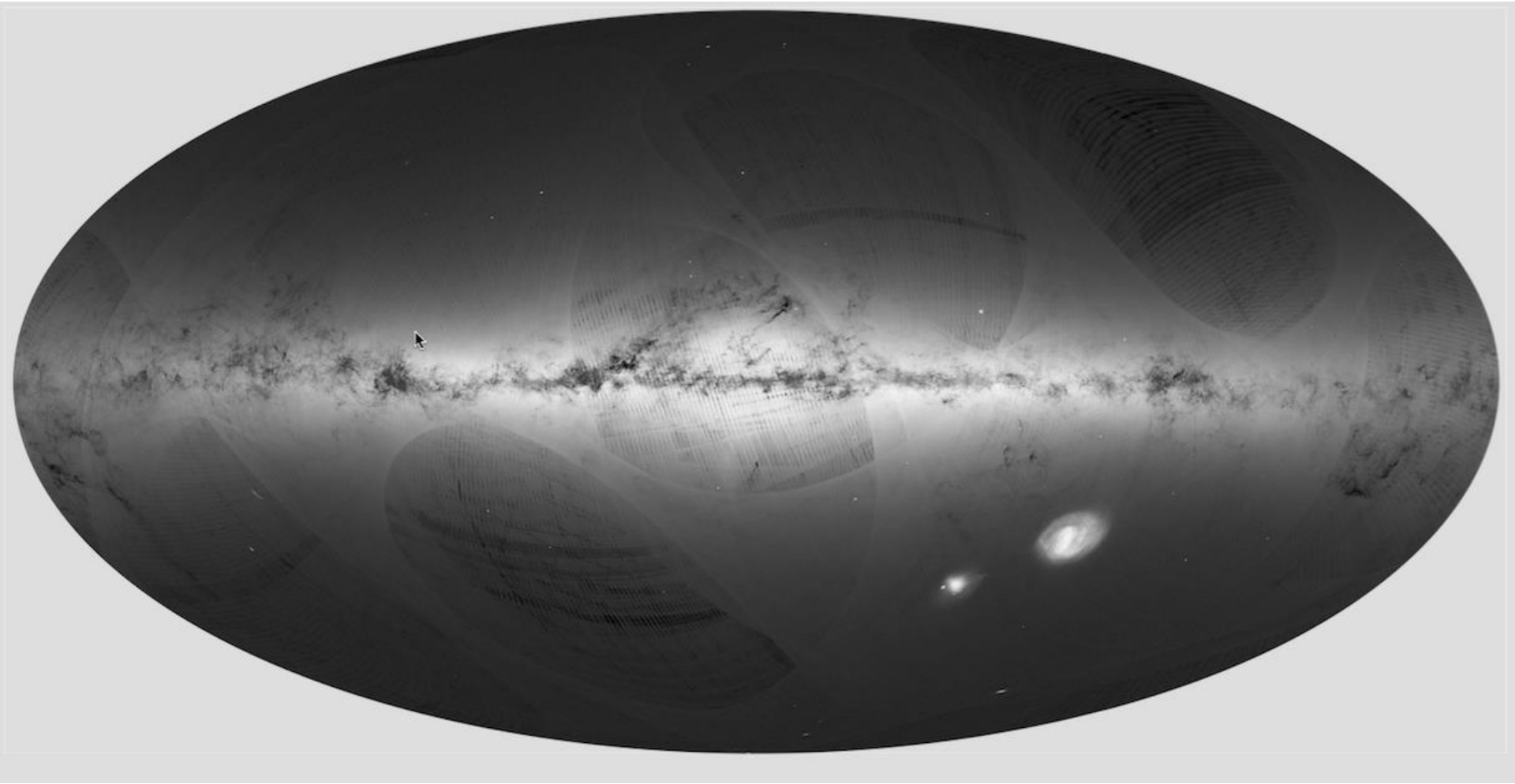
GAIA sky map

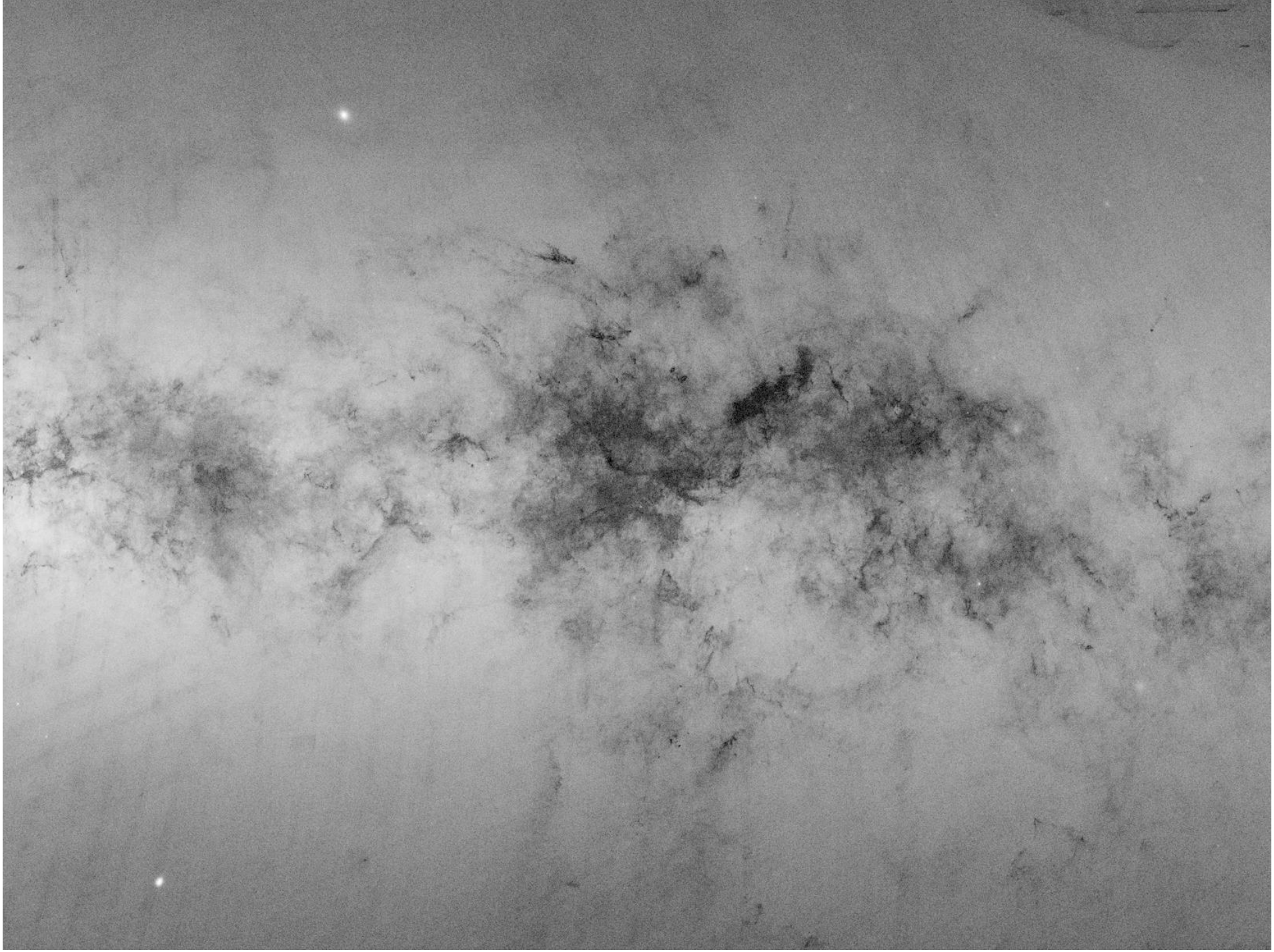


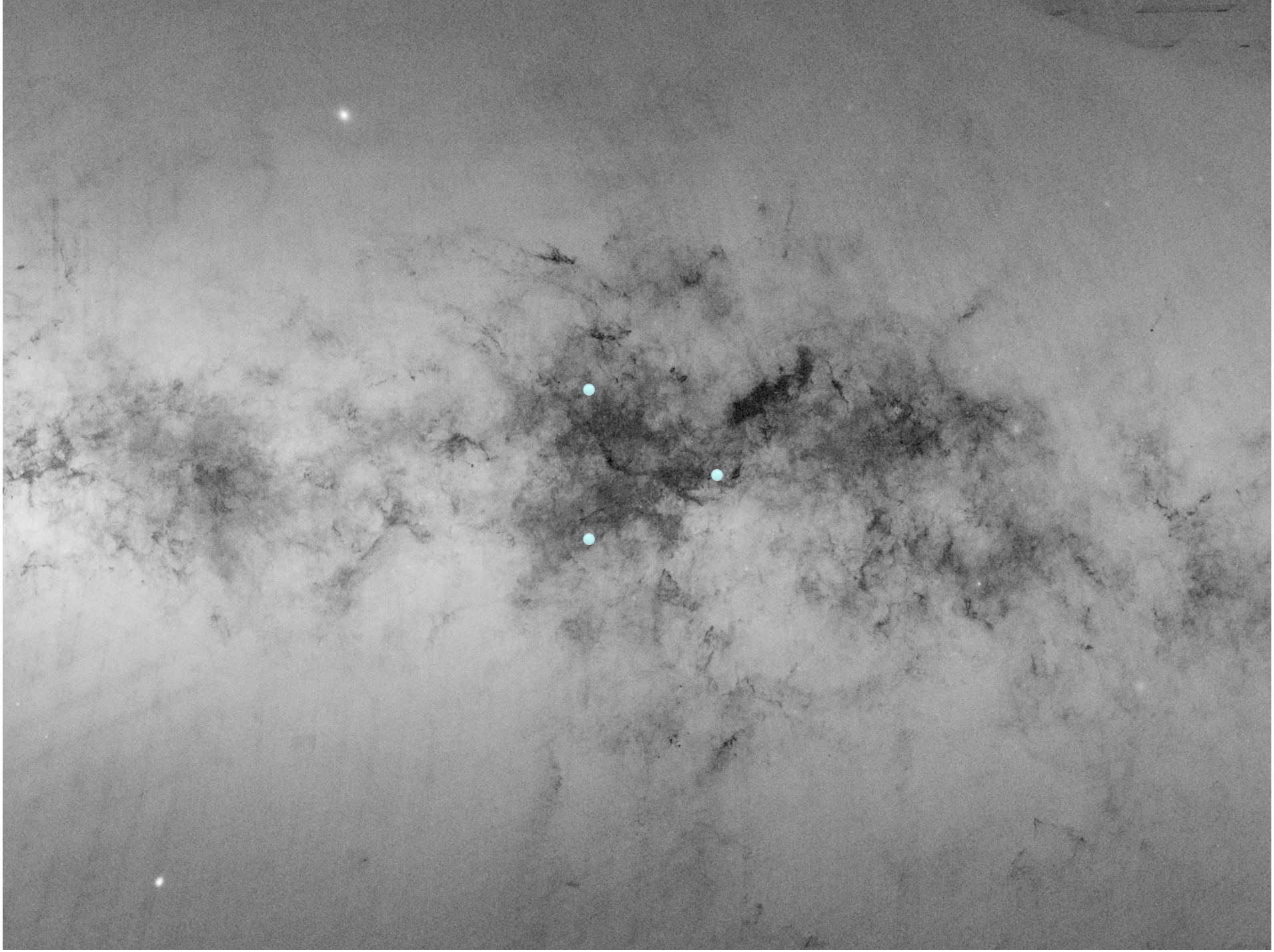


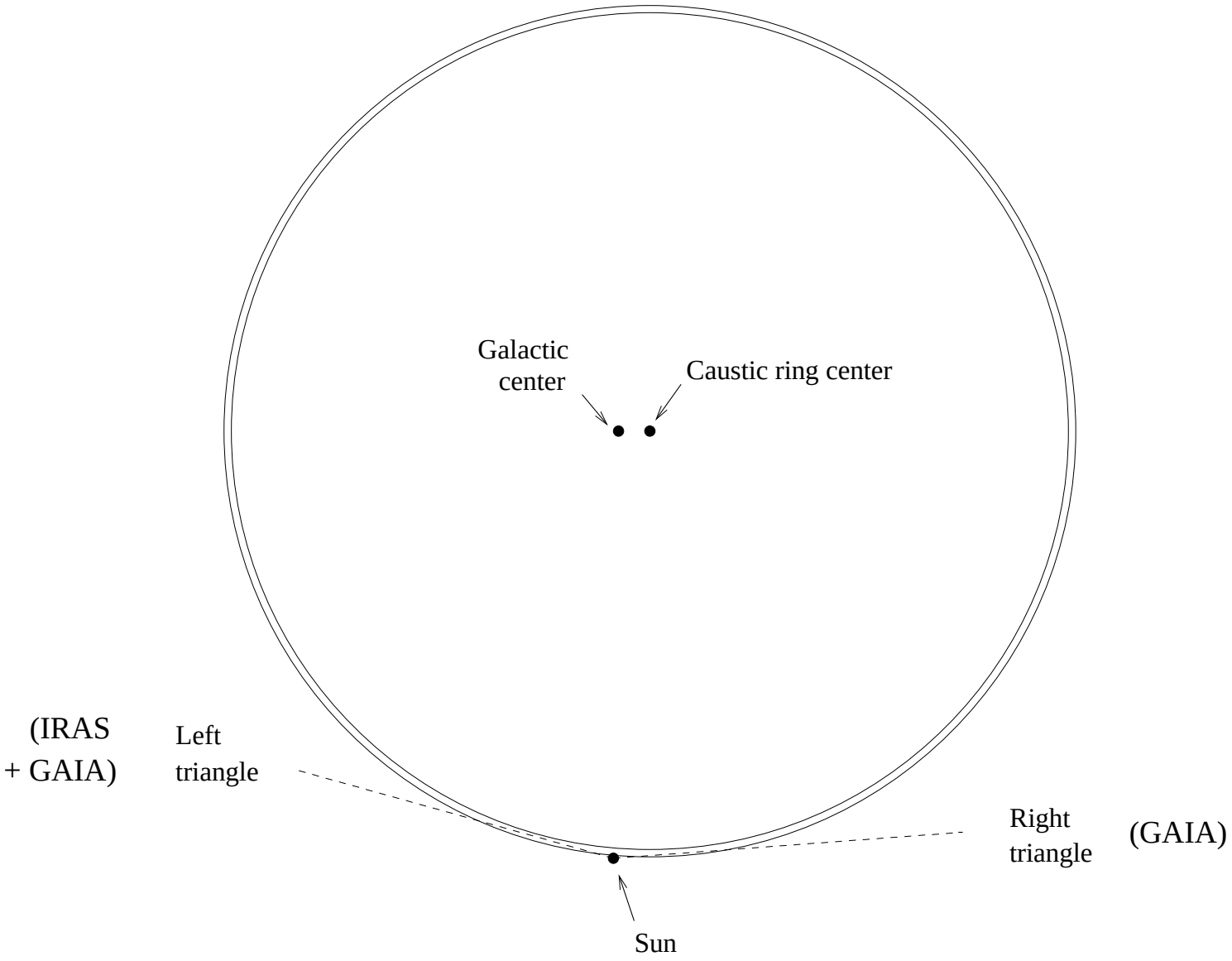


GAIA sky map





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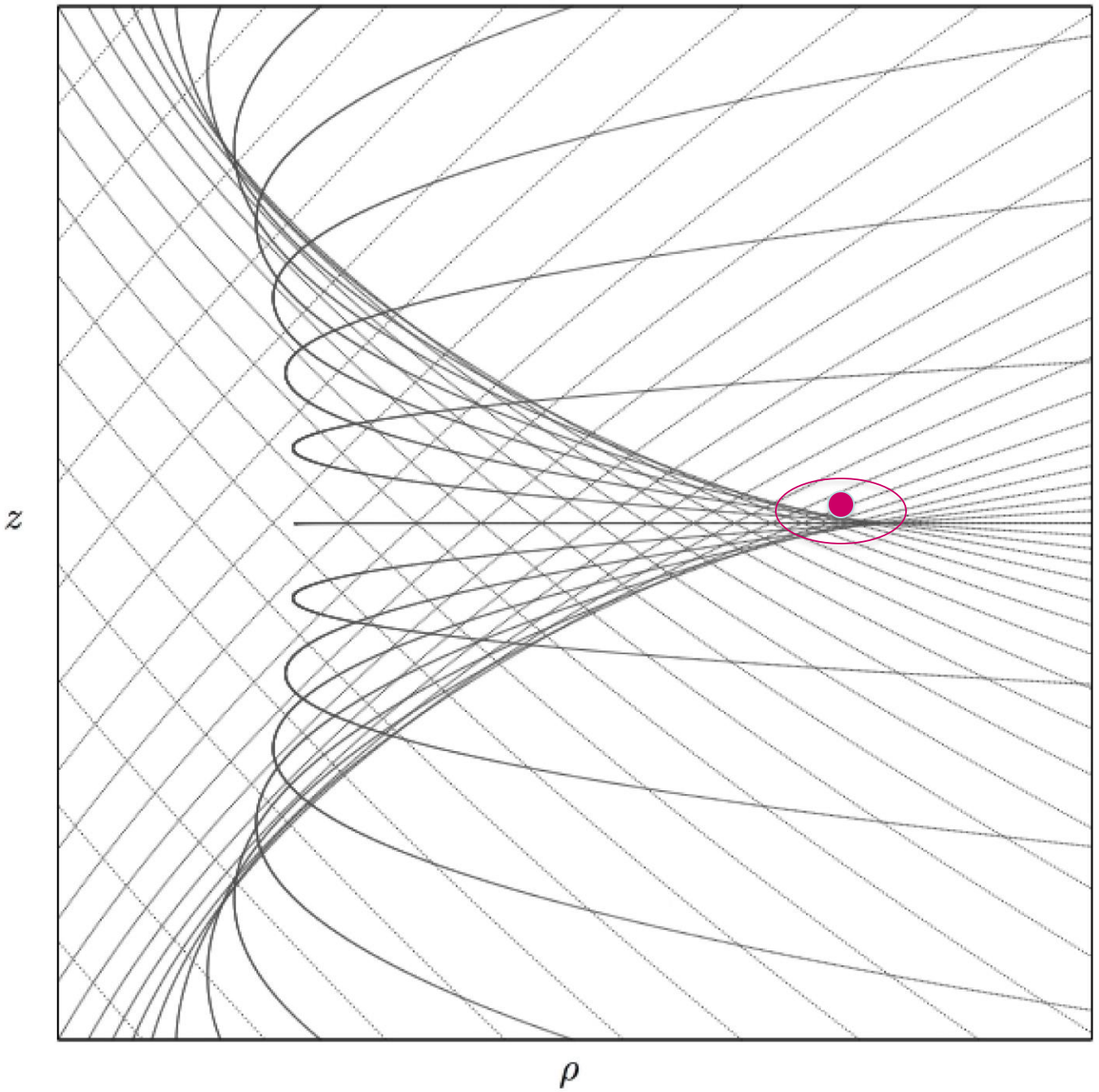
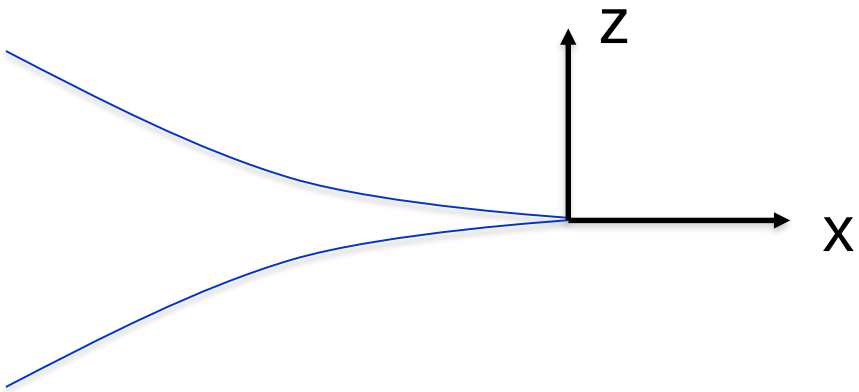

z
ρ



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

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

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:

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

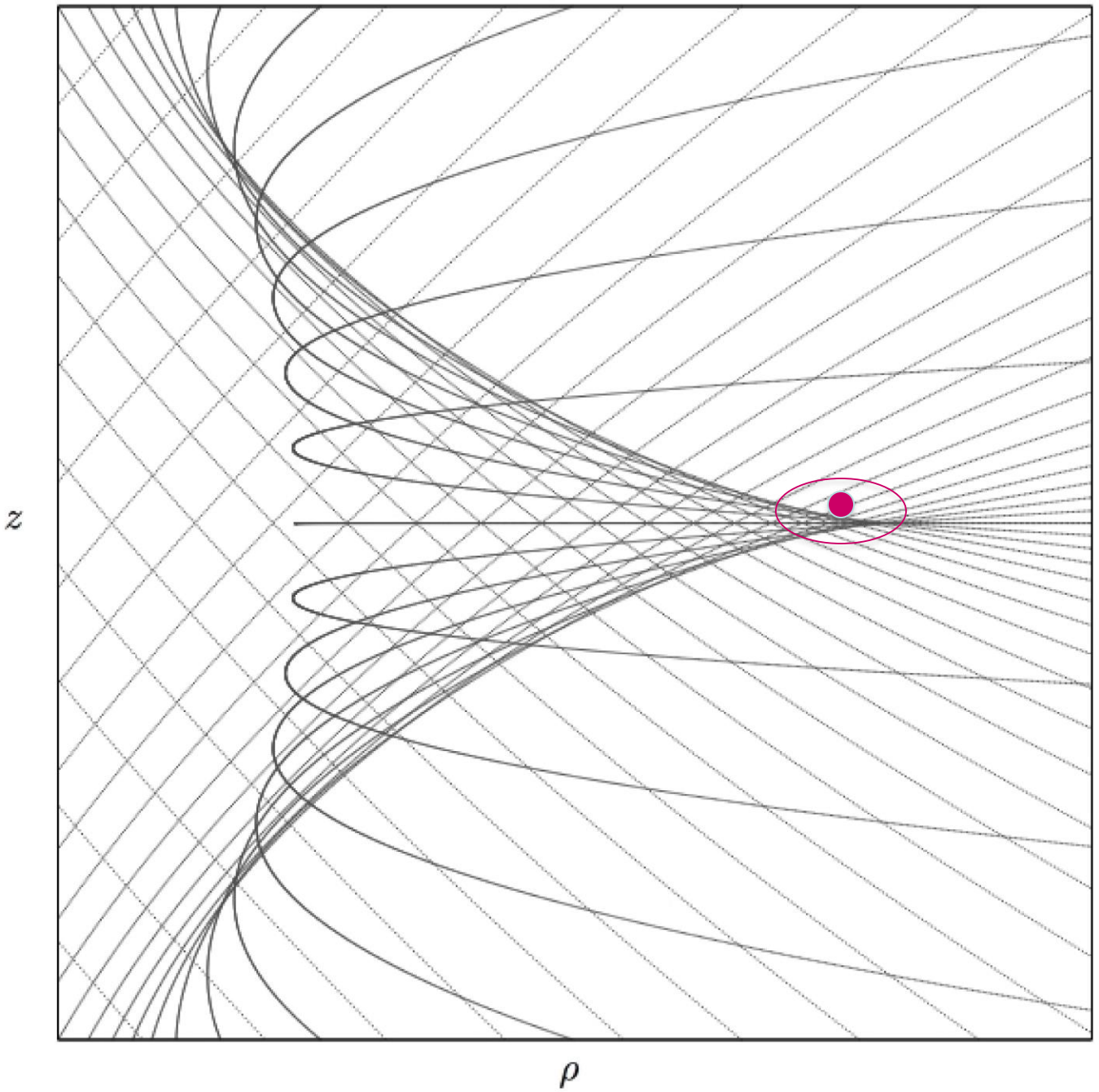
$$v_z = -50.6 \ \frac{\mathrm{km}}{\mathrm{s}} \ A$$

Preliminary:

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

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

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


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.