Evidence of caustic rings and their implications on axion searches

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Axions 2024

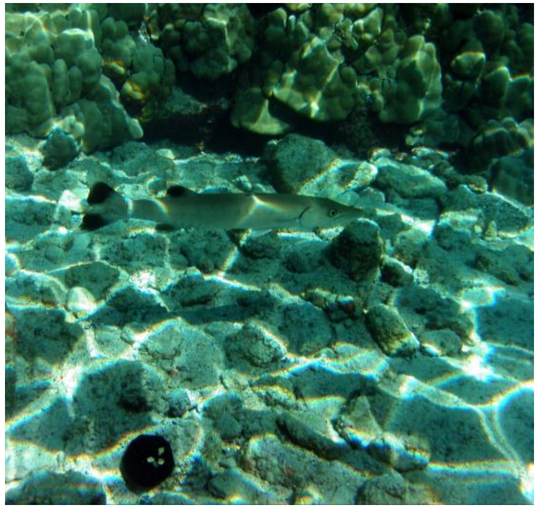
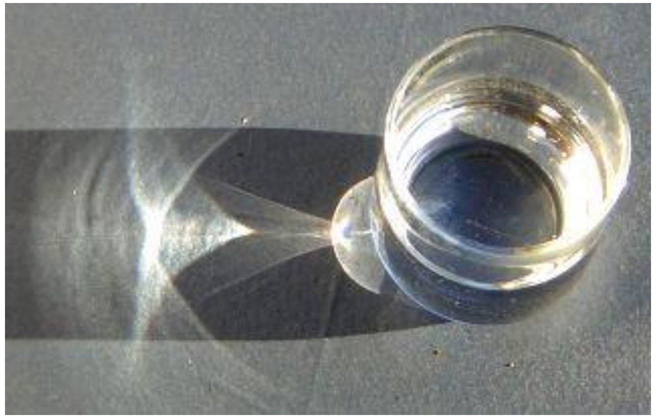
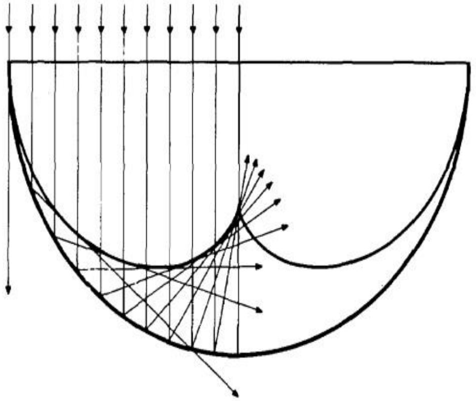
Outline of the talk

- What is a caustic?
- How does a caustic ring form?
- Effects of a caustic ring on the stars and interstellar gas
- Evidence of the caustic rings
- Relevance in axion searches

What is a caustic?

- Derived from the *Greek word for ‘burning’*
- Caustics are regions of physical space where number density is infinite in the limit of zero velocity dispersion.
- Commonly seen in the propagation of light
- Caustic occurs in a flow of radiation or matter under two conditions.

1) The flow must be *collisionless*
2) The flow must have *small initial velocity dispersion*

Credit: Heiner Otterstedt, James Gurney, Brocken Inaglory, The Optical Society of America

Caustics in cold and collisionless dark matter

- **Cold:** *very small primordial velocity dispersion* (δv)

$$\delta v \approx 10^{-12}\, c \left(\frac{GeV}{m_W}\right)^{1/2} \quad \text{(WIMPs)}$$

$$\approx 10^{-17}\, c \left(\frac{\mu eV}{m_a}\right) \quad \text{(decoupled QCD axions)}$$

$$\approx 10^{-4}\, c \left(\frac{eV}{m_\nu}\right) \quad \text{(sterile neutrinos)}$$

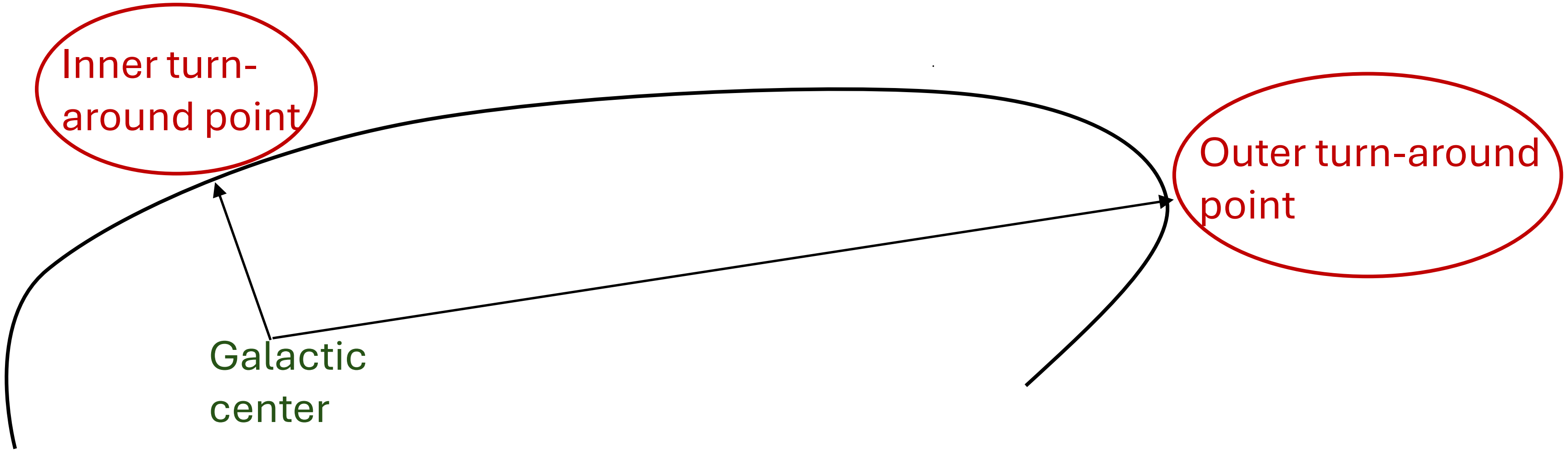
- **Collisionless:** *interact only via gravitational force*.

As the cold dark matter (CDM) particles ***satisfy the two conditions***, caustics are expected in the distribution of dark matter in galactic halo.

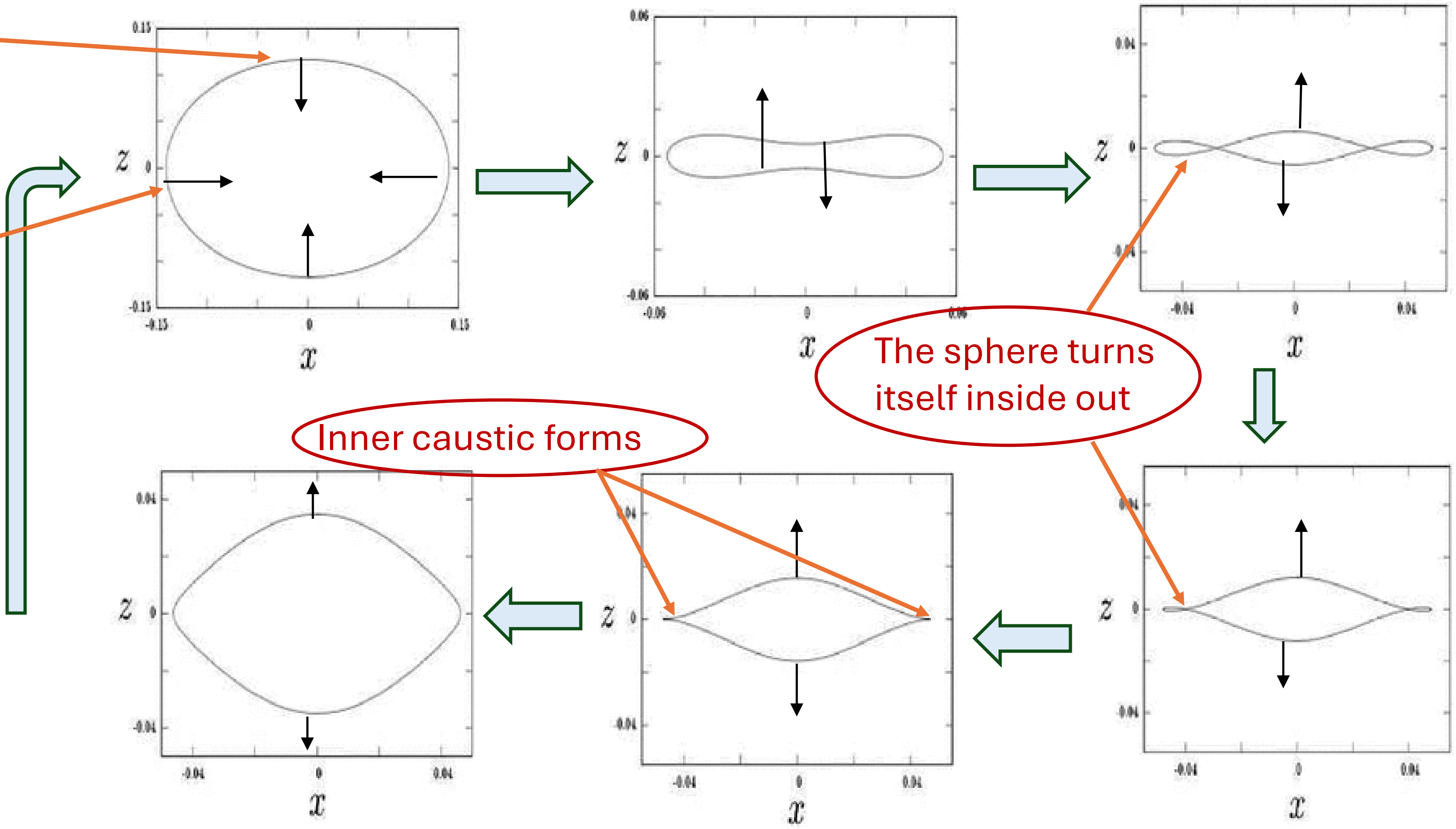
Sikivie, Phys. Rev. D60 (1999), astro-ph/9902210

How does a caustic ring form?

- In a flow of dark matter, there is an outer turn around point and an inner turn around point.
- Inner caustic occurs when particles with maximum angular momentum are closest to the galactic center.
- *n*th inner caustic appears in the flow of particles experiencing *n*th inner turn-around in their history.
- Outer caustic occurs when the particles turn around before falling back in. We do not consider the effects of outer caustics while studying the stars and gas in the disk.



Infall of a turnaround sphere with rigid rotation about the vertical axis:



Lower angular momentum

Higher angular momentum

The sphere turns itself inside out

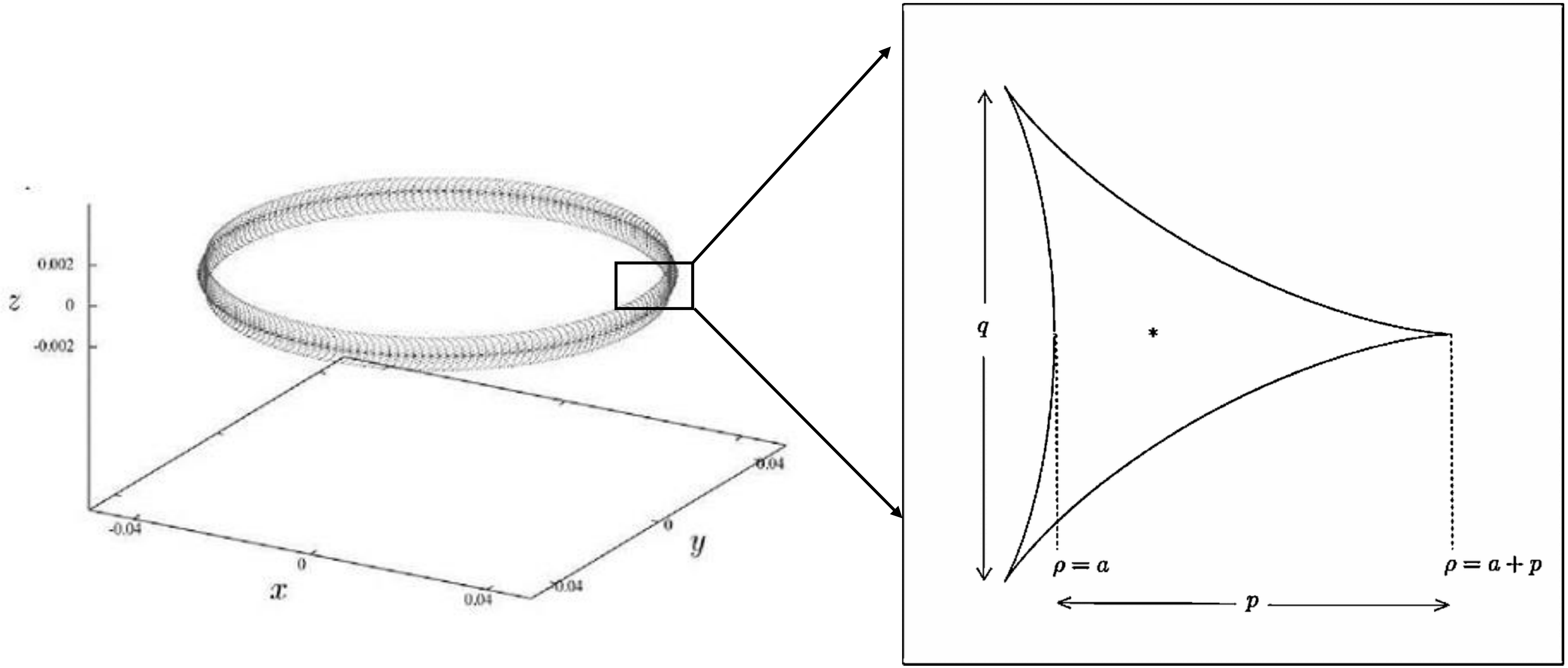
Inner caustic forms

There is a continuous flow of spheres falling in and out. Inner caustic ring is persistent.

Natarajan and Sikivie, Phys. Rev. D73 (2006), astro-ph/0510743

Caustic ring : Closed tube with *tricusp* cross section

$(\boldsymbol{\nabla} \times \boldsymbol{v} \neq \mathbf{0})$



Natarajan and Sikivie: Phys.Rev.D73(2006) astro-ph/0510743 and Duffy and Sikivie, Phys.Rev.D78(2008) arXiv:0805.4556

Self-similarity

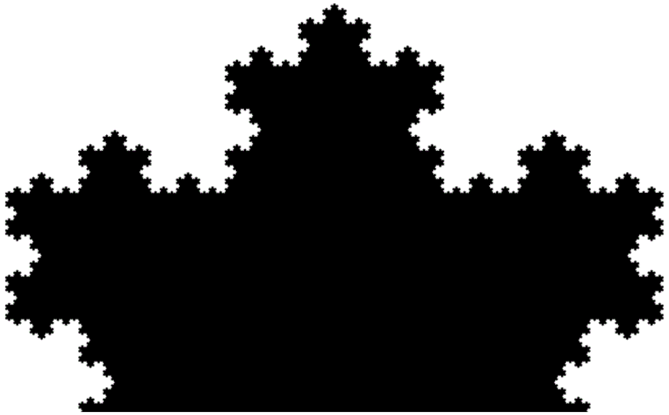
- Evolution of a flow is self-similar if the flow remains identical to itself except for an overall rescaling of its density, size and velocity.

- Evolution of dark matter halo is self-similar because there is no special time in the history of a galactic halo.
- In self-similar model, radii *a(t)* of inner caustic rings increase on cosmological time scale.

$$a(t) \propto t^{4/3} \quad (t = \text{age of the universe})$$

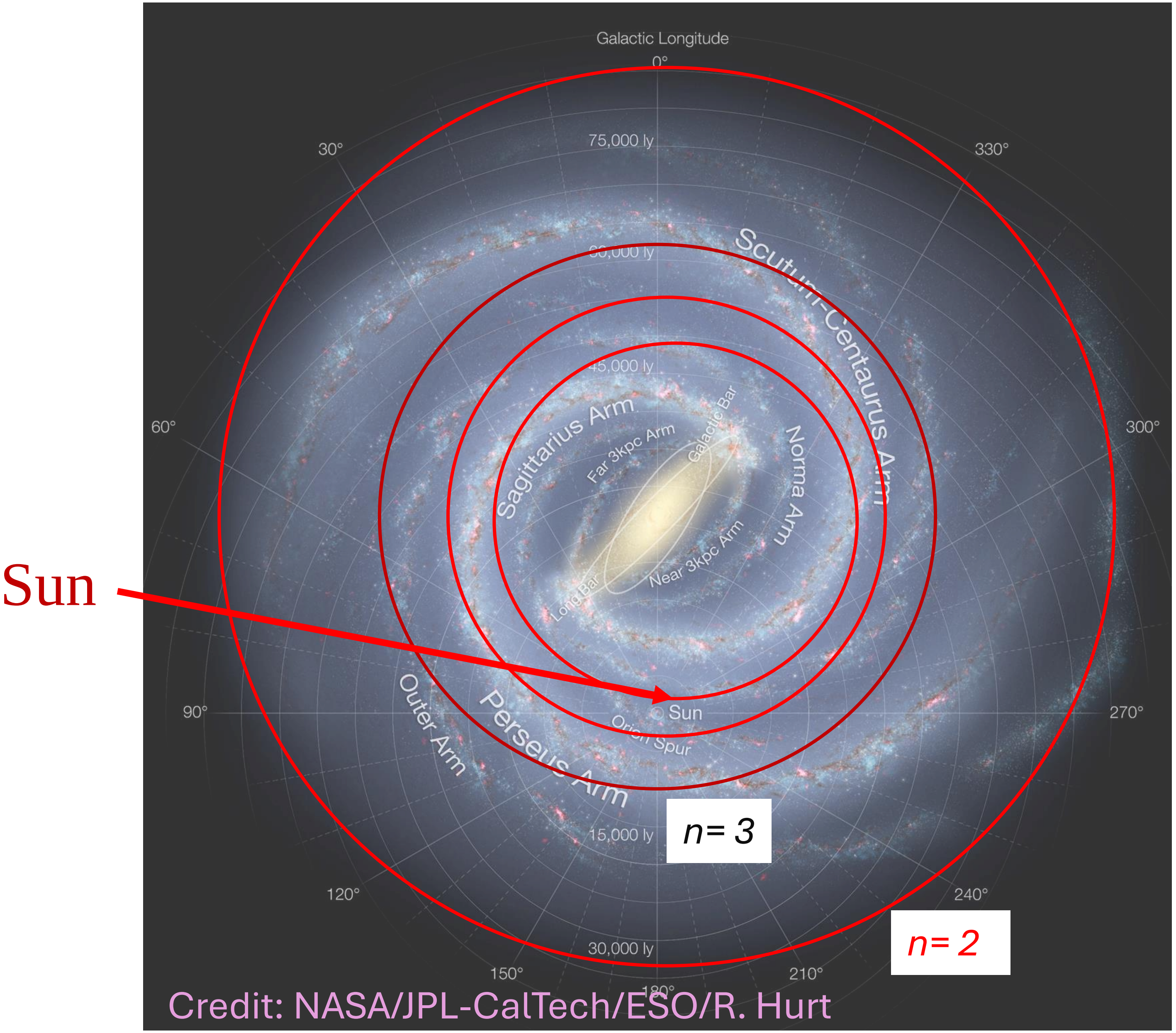
- Current radii of the rings:

$$a_n \approx \frac{40\ kpc}{n}\ , n = 1, 2, 3, \dots$$



Self-similarity of Koch curve.
Courtesy: Wikipedia

Fillmore and Goldreich (1984), Sikivie (1999), Duffy and Sikivie (2008)



Credit: NASA/JPL-CalTech/ESO/R. Hurt

Current radii of the rings:

$$a_n \approx \frac{40\ kpc}{n} \quad ,$$

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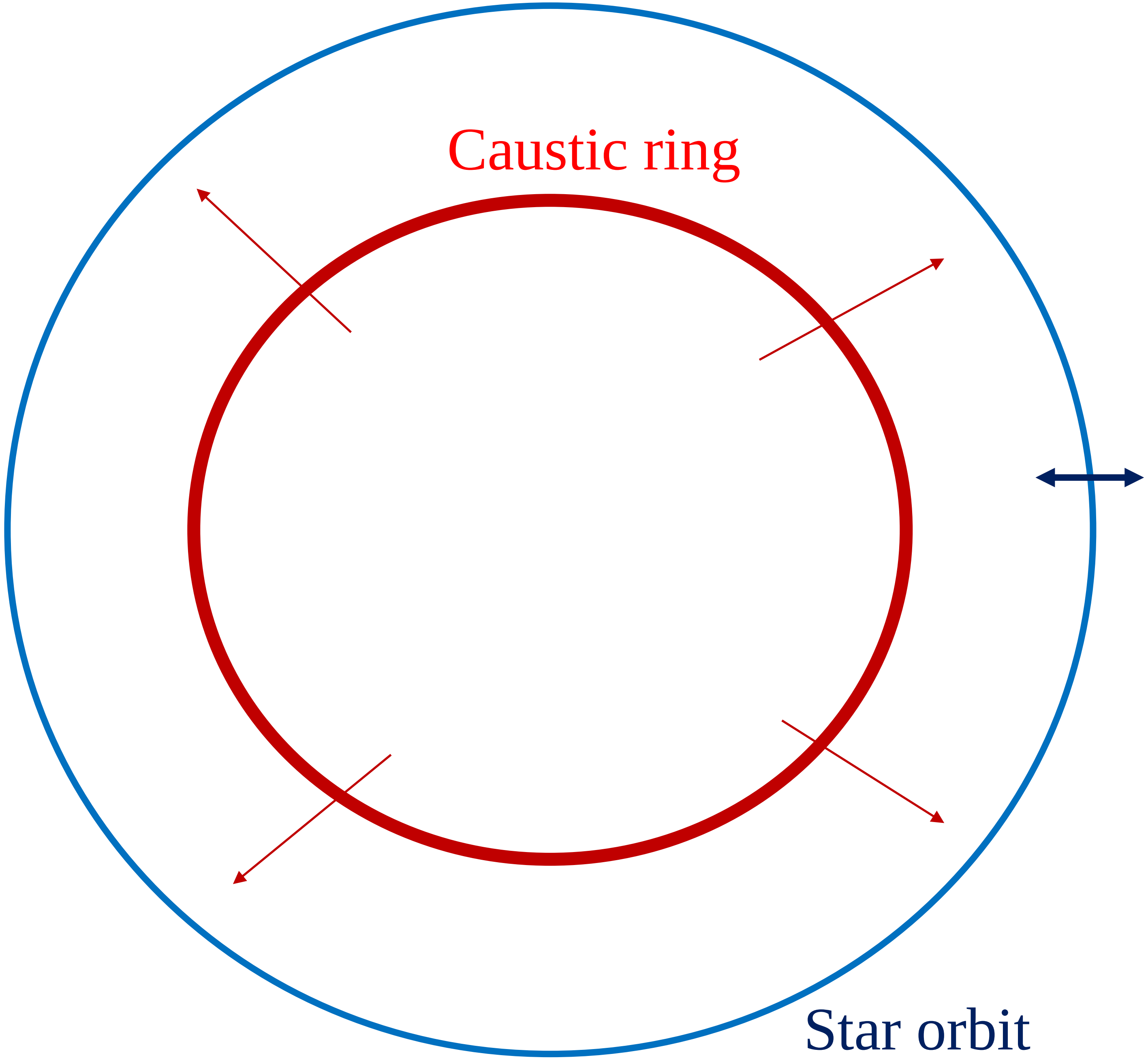
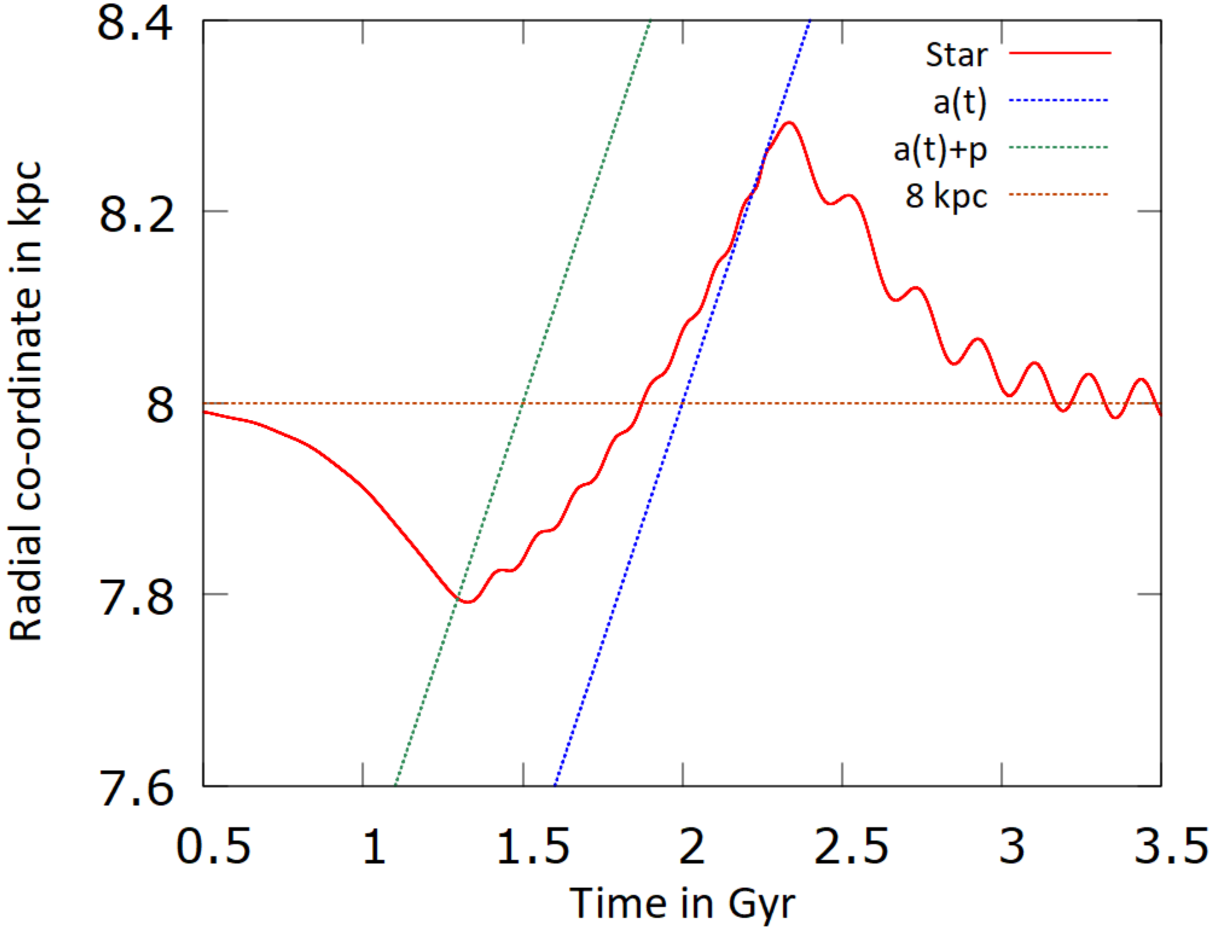
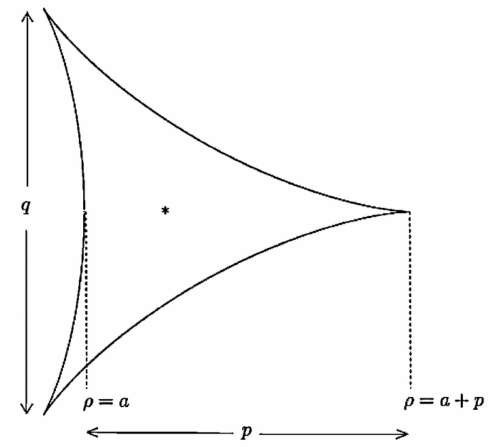

Caustic ring
Star orbit

Exact circular : $\rho_0 = 8 \text{ kpc}$

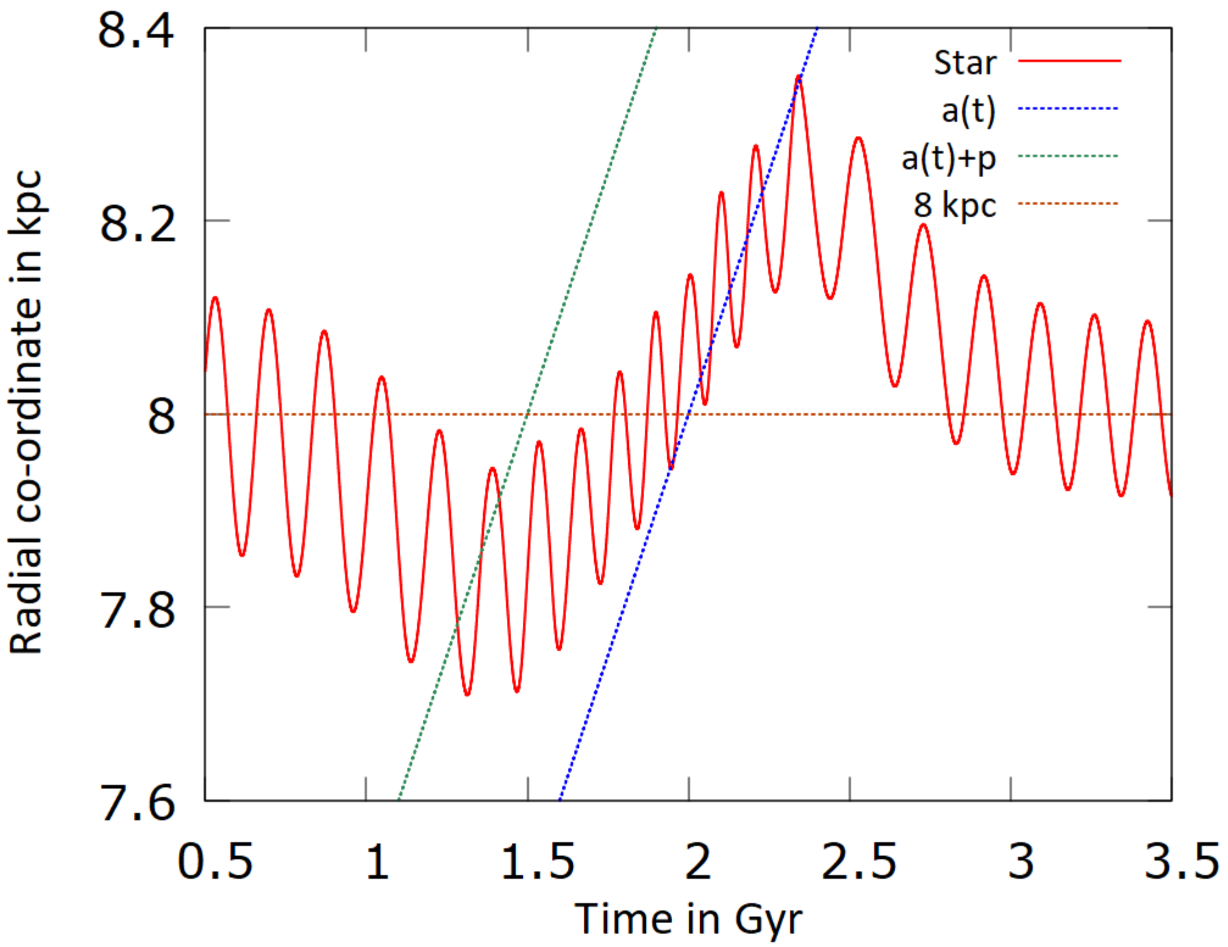


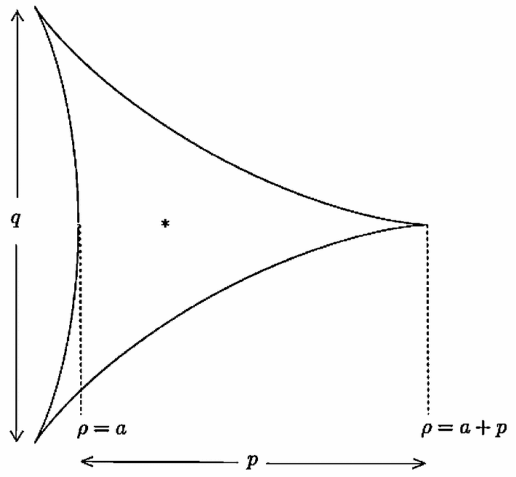


The star is initially attracted to the *tricusp* then moves with and oscillates about it for approximately 1 Gyr before coming back to its initial orbit.

Chakrabarty and Sikivie, Phys. Rev. D98 (2018) arXiv:1808:00027

Perturbed circular : $v_\rho^{max} = v_z^{max} = 5 \text{ km/s}$





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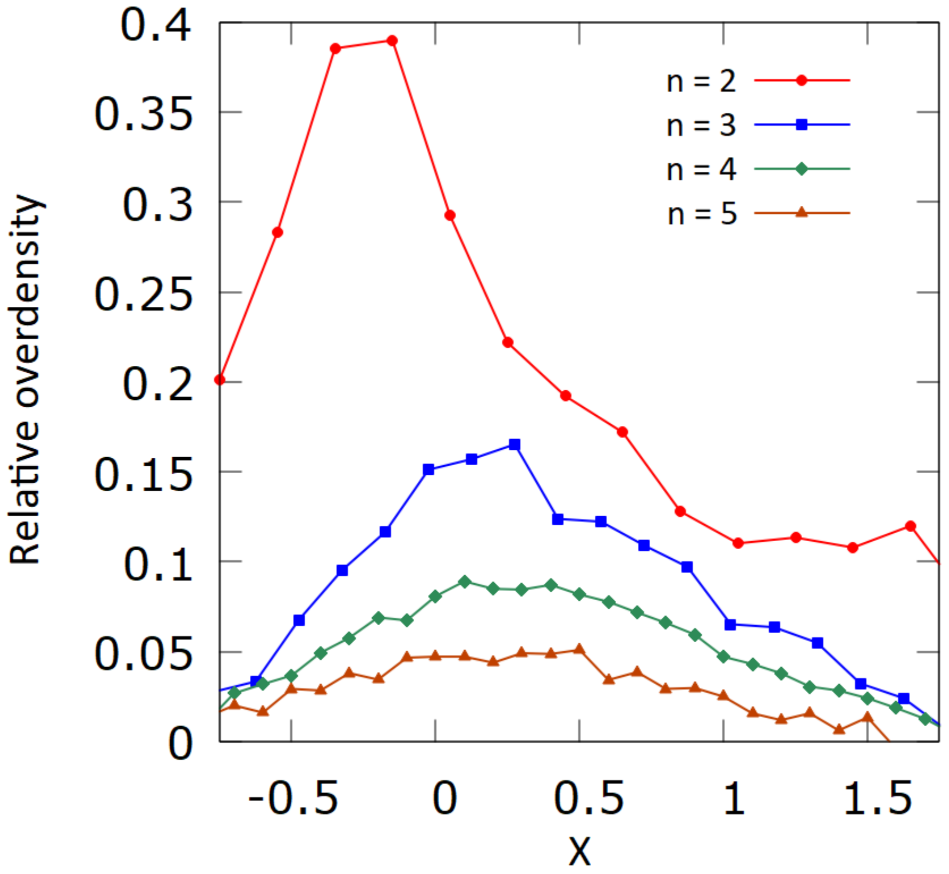
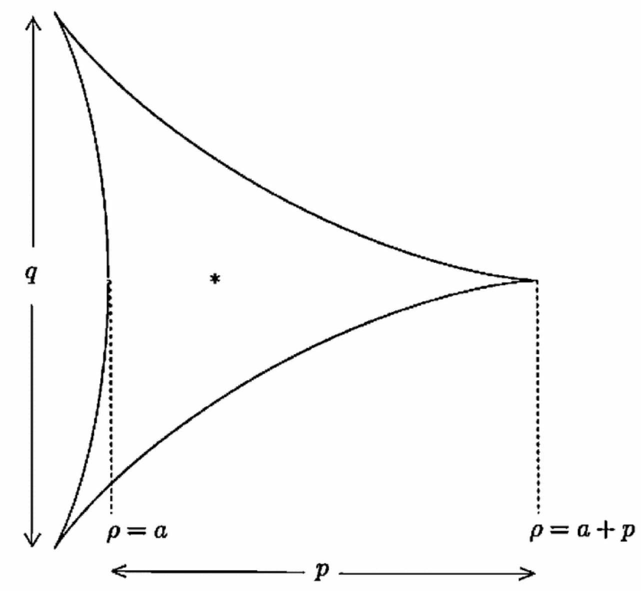
Relative overdensity due to radial motion $(Z = 0)$

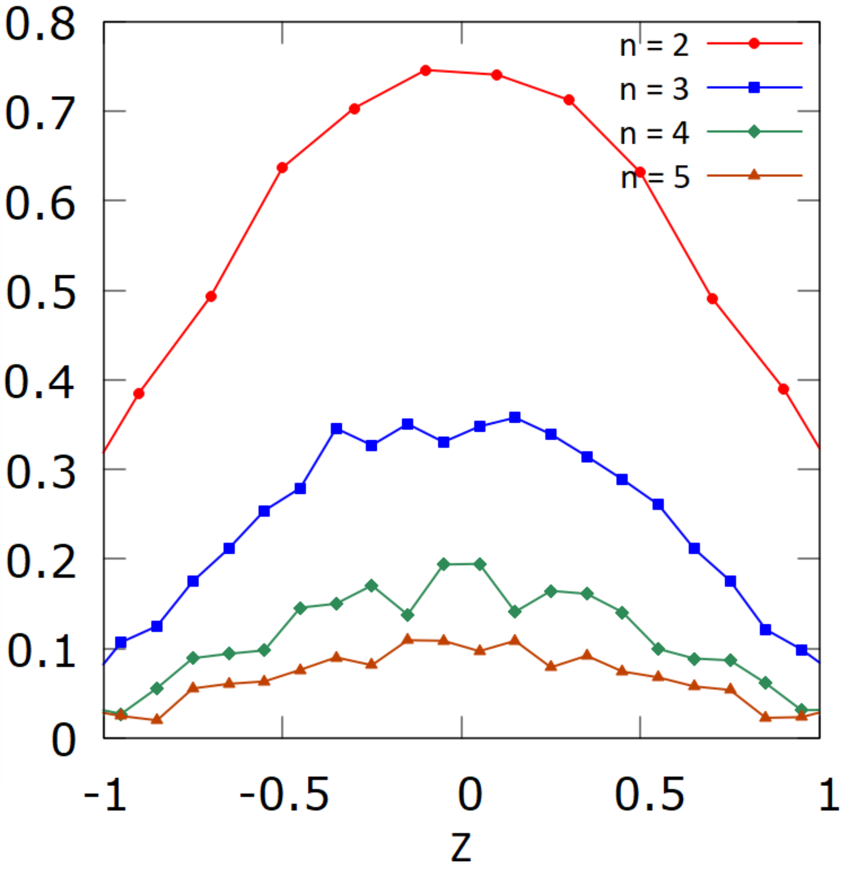


$$\frac{\Delta d}{d} = \frac{d - d_{eq}}{d_{eq}}$$



$X = \frac{\rho - a}{p}$ and $Z = \frac{z}{p}$

Relative overdensity due to vertical motion $(X = 0.25)$



Chakrabarty and Sikivie, Phys. Rev. D98 (2018) arXiv:1808:00027

- In the first approximation, the total relative over-density is the sum of relative overdensities from radial and vertical dynamics.

- Relative overdensities of 120, 45, 30 and 15% near the 2nd, 3rd, 4th and 5th caustic rings.

- Monoceros ring of stars at 20 kpc (Newberg et al 2002, Yanny et al 2003, Ibata et al 2003)

- Ring of stars at 13.6 kpc reported by Binney and Dehnen 1997

- Relative overdensities near 4th and 5th caustic rings may be observable in GAIA.

Chakrabarty and Sikivie, Phys. Rev. D98 (2018) arXiv:1808:00027

Effects on interstellar gas

- Isothermal distribution:

Potential: $$\Phi_g(\rho, z) = \sigma_g^2 \ln\left[\cosh^2\left(\frac{z}{2z_g}\right)\right]$$

Density: $$d_g(\rho, z) = d_g^0 \operatorname{sech}^2\left(\frac{z}{2z_g}\right)$$

- In the solar neighborhood: $\sigma_g \approx$ 5 km/s , $z_g =$ 65 pc , $d_g^0 \approx 0.05\ \mathrm{M}_\odot/\mathrm{pc}^3$

- In the presence of a caustic:

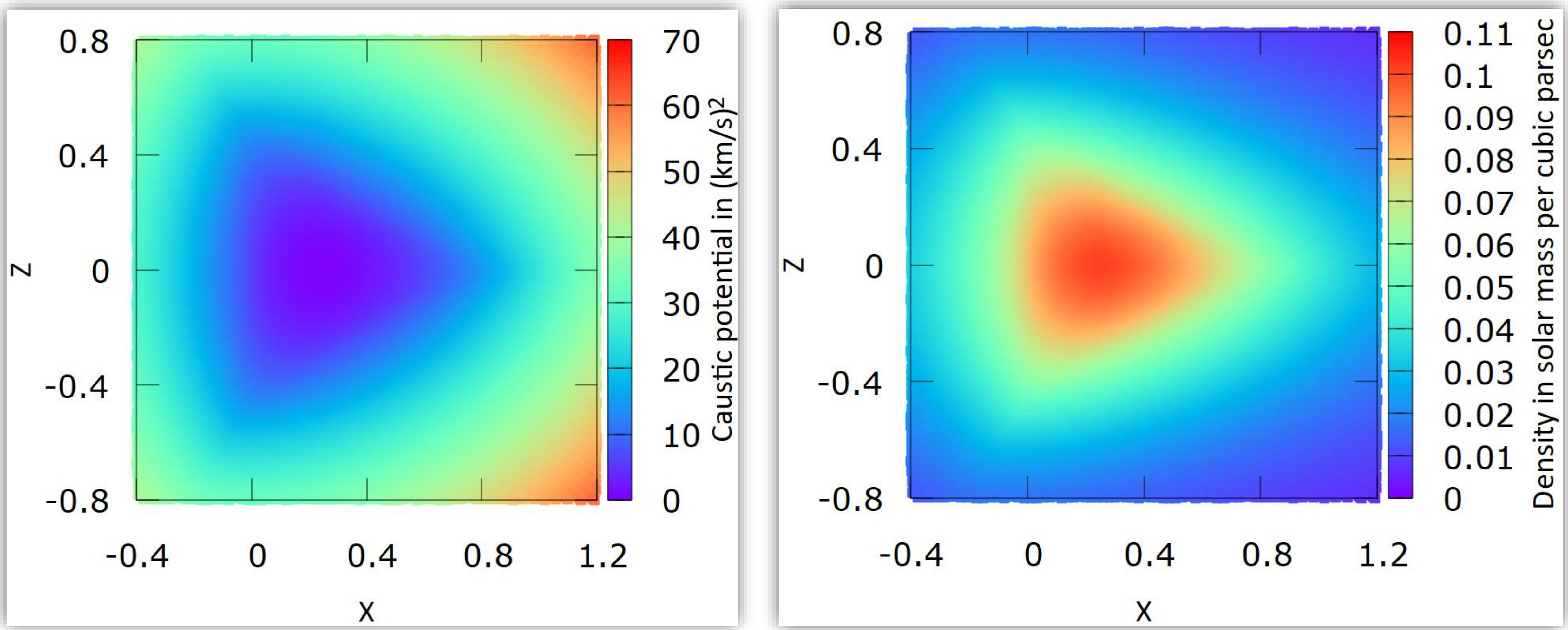
$$\nabla^2\Phi(X, Z) = 4\pi G d_g(X, Z)$$

$$d_g(X, Z) = d_g(X_0, Z_0)\exp\left(-\frac{\Phi(X, Z) + \Phi_c(X, Z)}{\sigma_g^2}\right)$$

(Assuming thermal equilibrium)

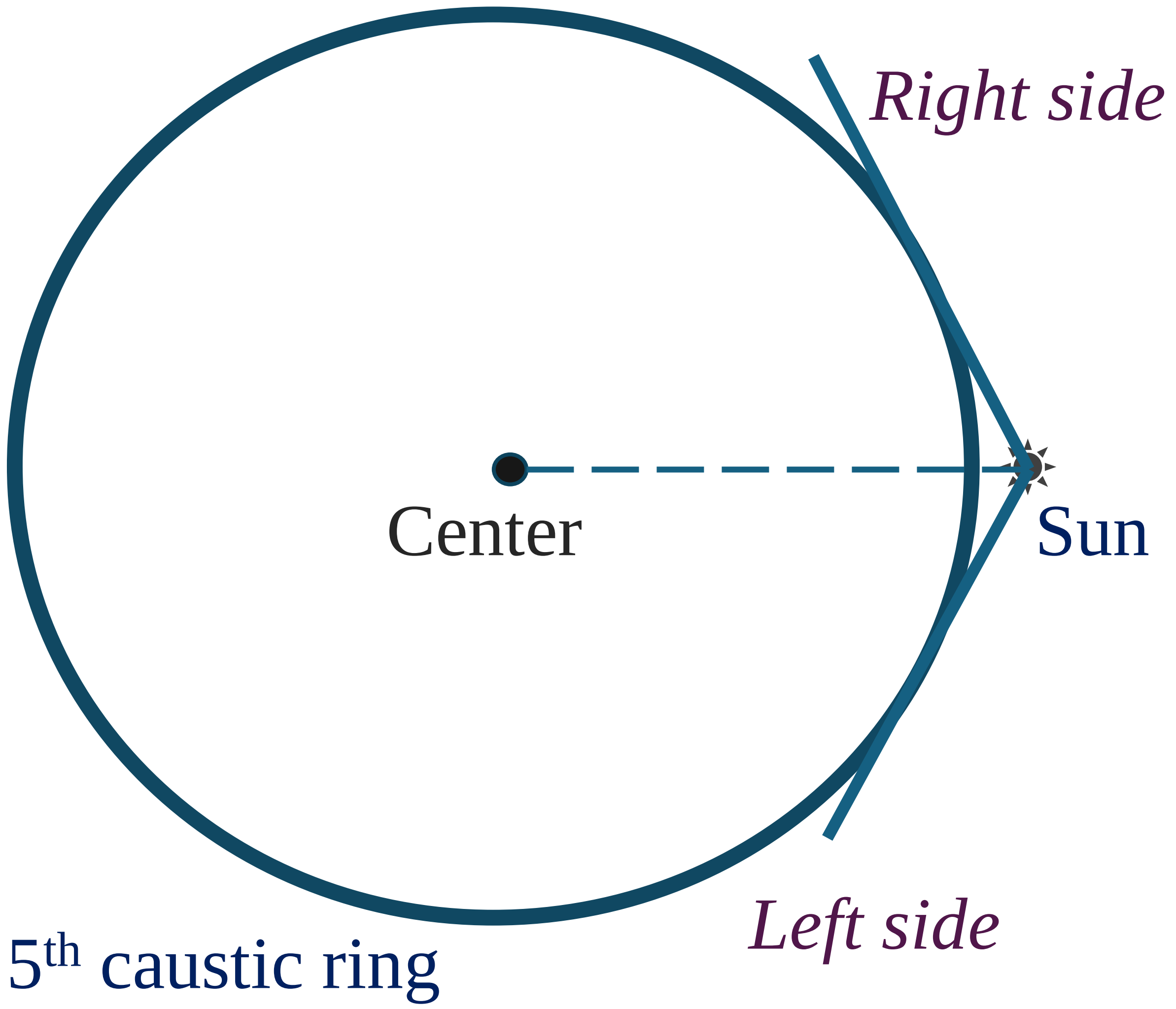
Chakrabarty and Sikivie, Phys. Rev. D98 (2018) arXiv:1808:00027

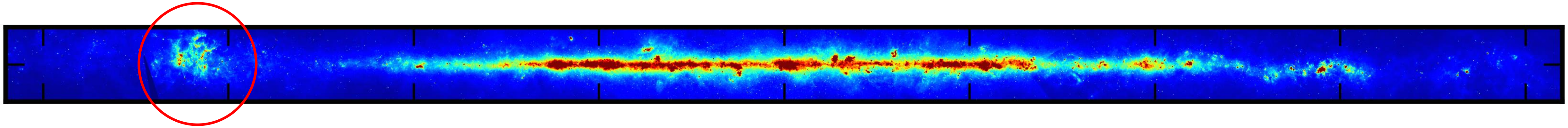
Gravitational potential and density of interstellar gas near the 5th caustic ring



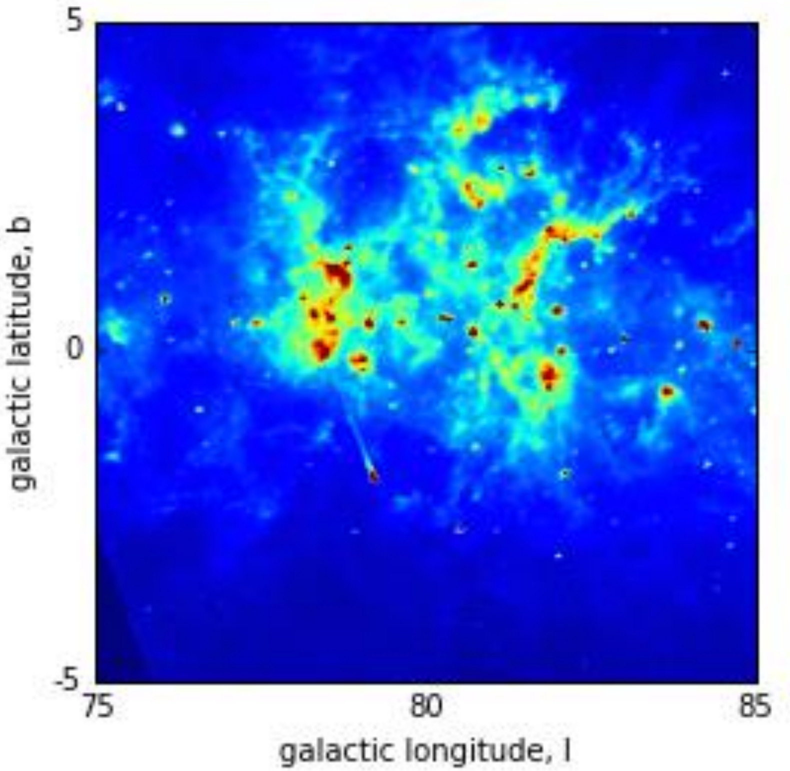
Chakrabarty and Sikivie, Phys. Rev. D98 (2018) arXiv:1808:00027

Evidence of caustic rings in IRAS and GAIA sky maps





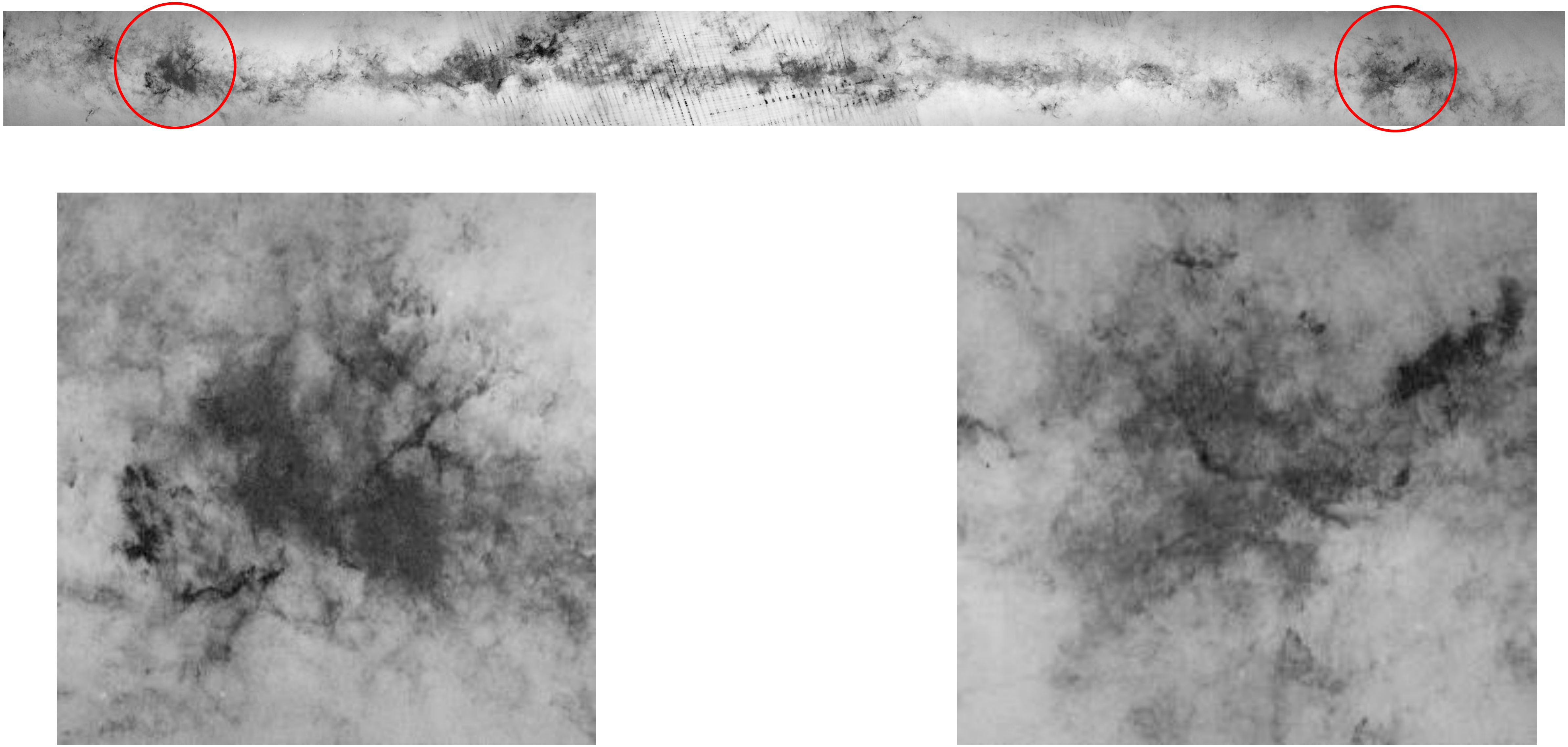
The Milky Way galactic plane from IRAS at 12 μm wavelength.



IRAS 12 μm

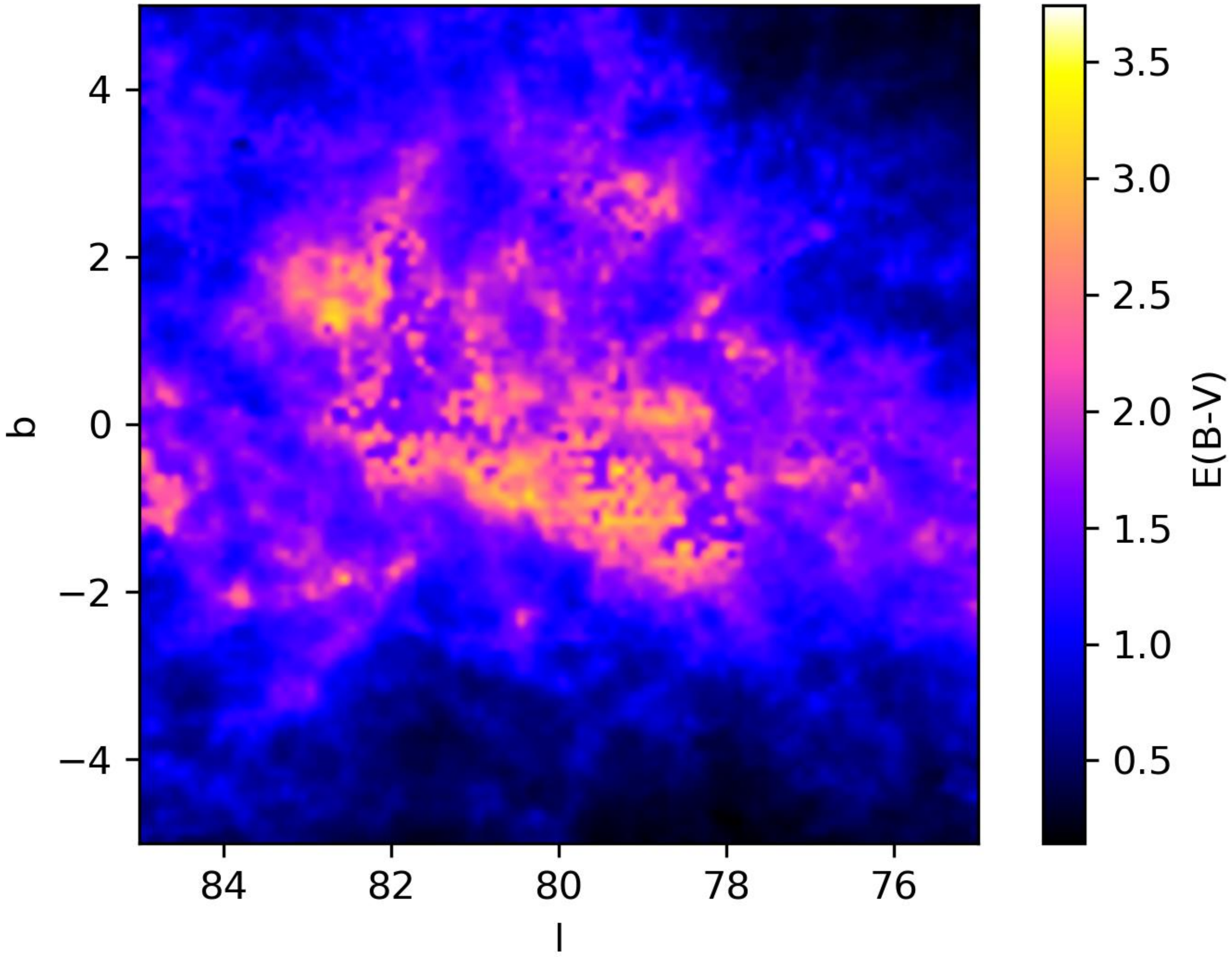
Sikivie, Phys.Lett.B567 (2003) astro-ph/0109296 , Banik et al 2017 arXiv:1701.04573

The Milky Way galactic plane from GAIA skymap



Chakrabarty, Han, Gonzalez, Sikivie, Phys. Dark Univ. 33 (2021), arXiv:2007.10509

Similar triangular features in the dust map



Green, Schlafly, Zucker, Speagle, Finkbeiner: arXiv:1905.02734

Chakrabarty, Han, Gonzalez, Sikivie, Phys. Dark Univ. 33 (2021), arXiv:2007.10509

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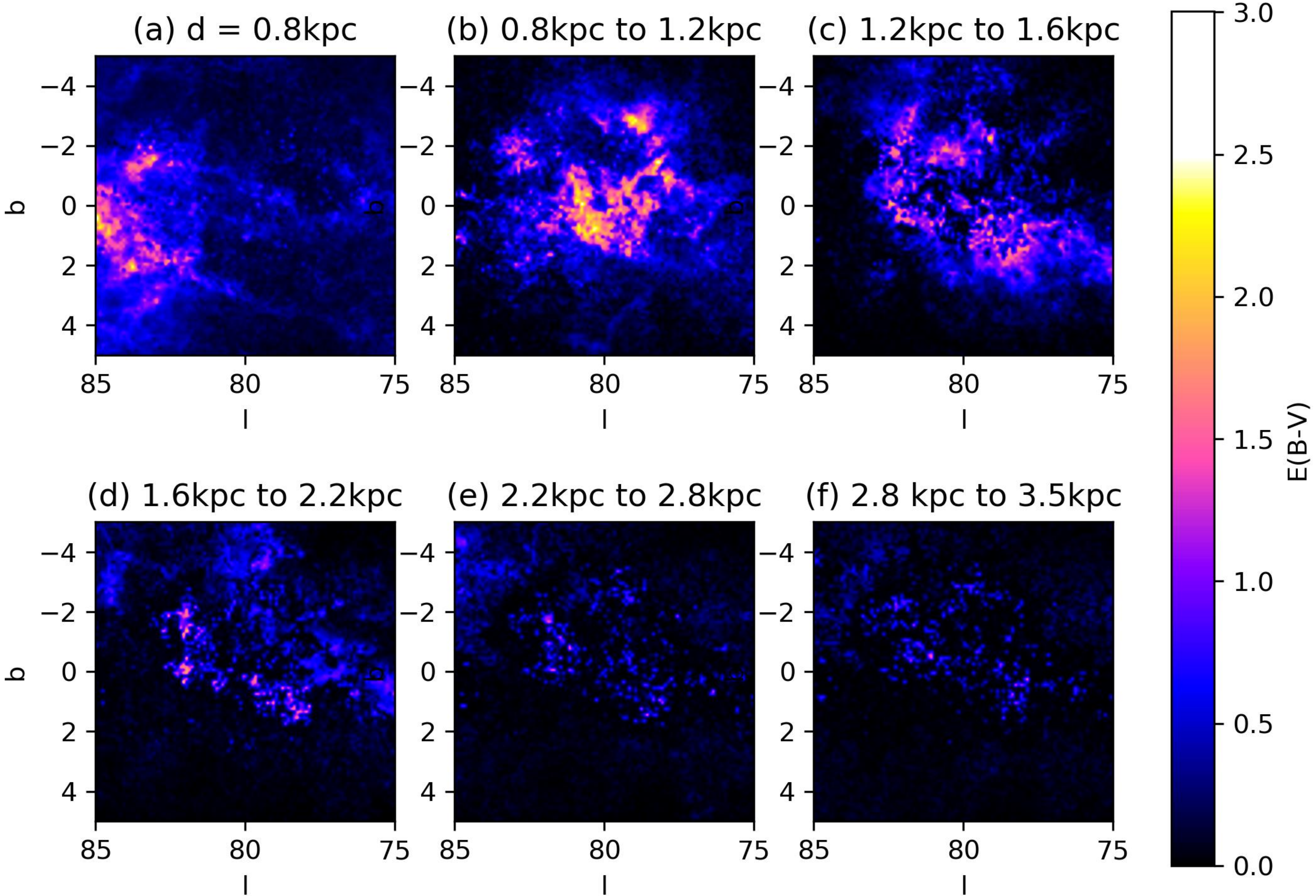
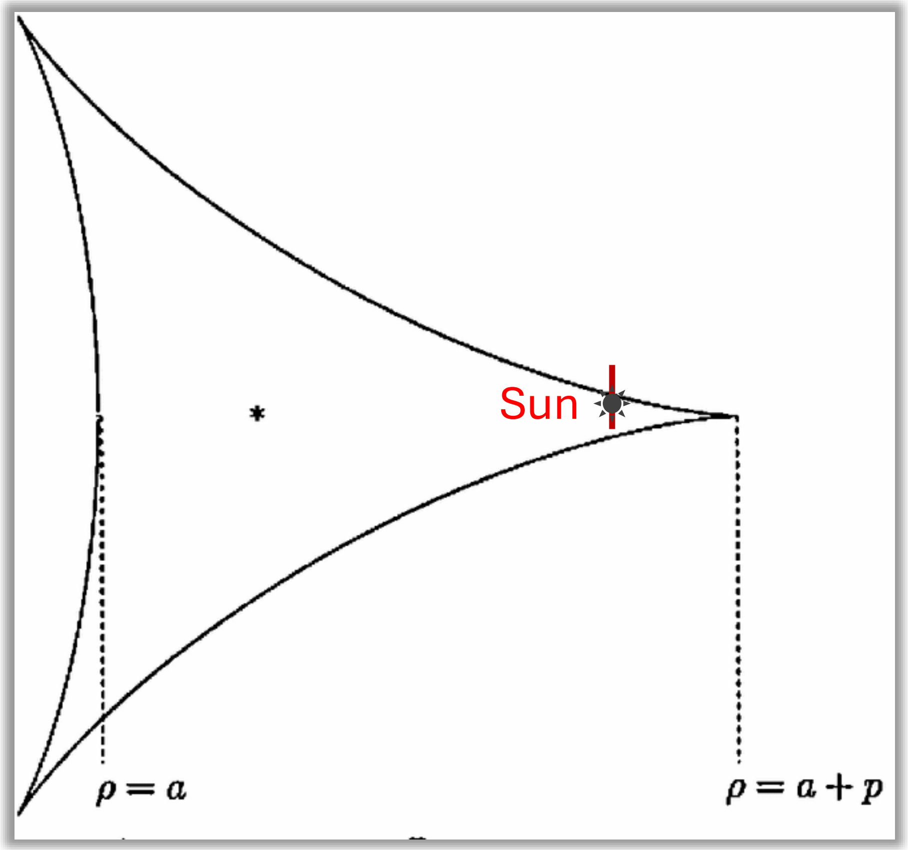
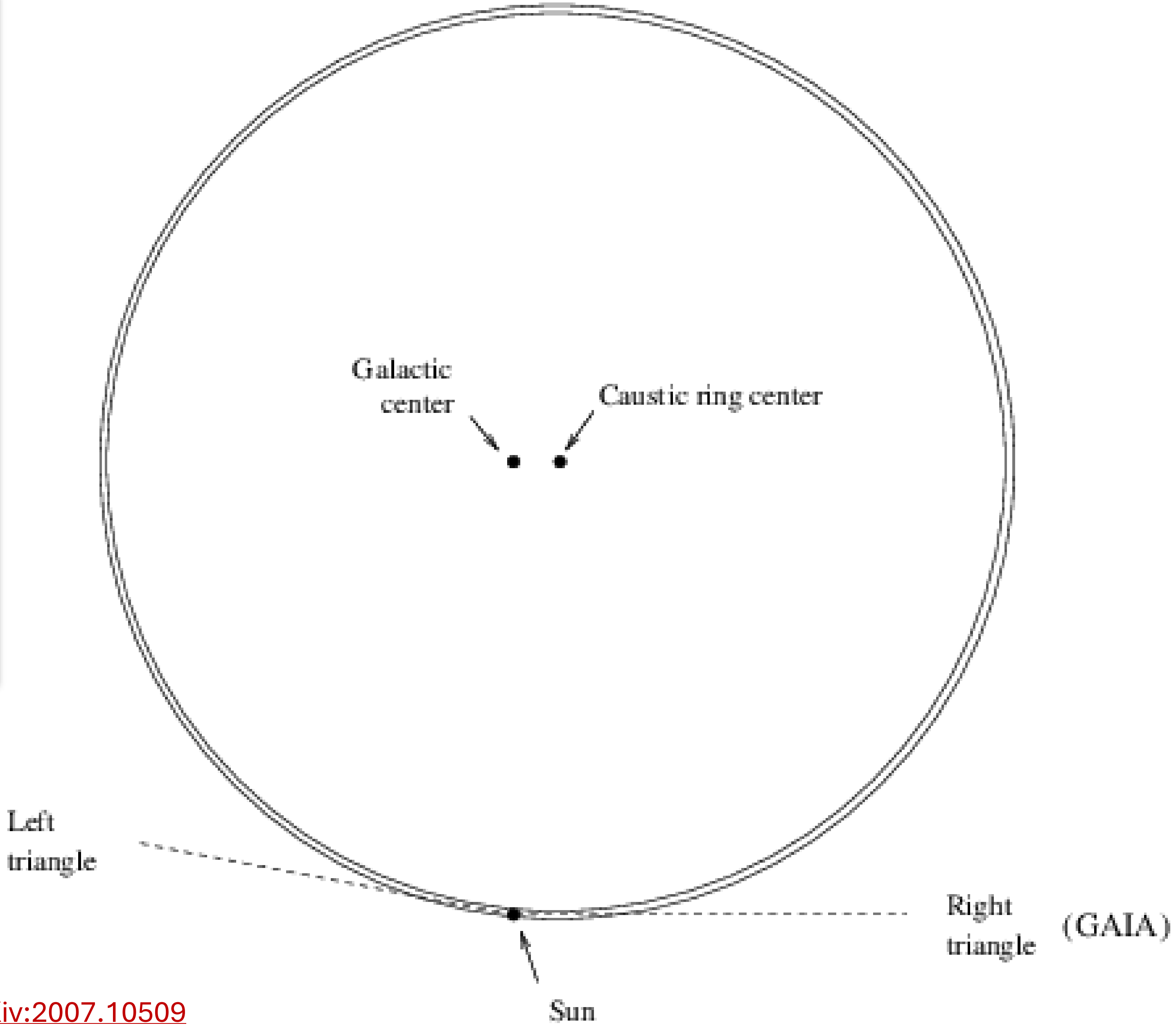


Green, Schlafly, Zucker, Speagle, Finkbeiner: arXiv:1905.02734

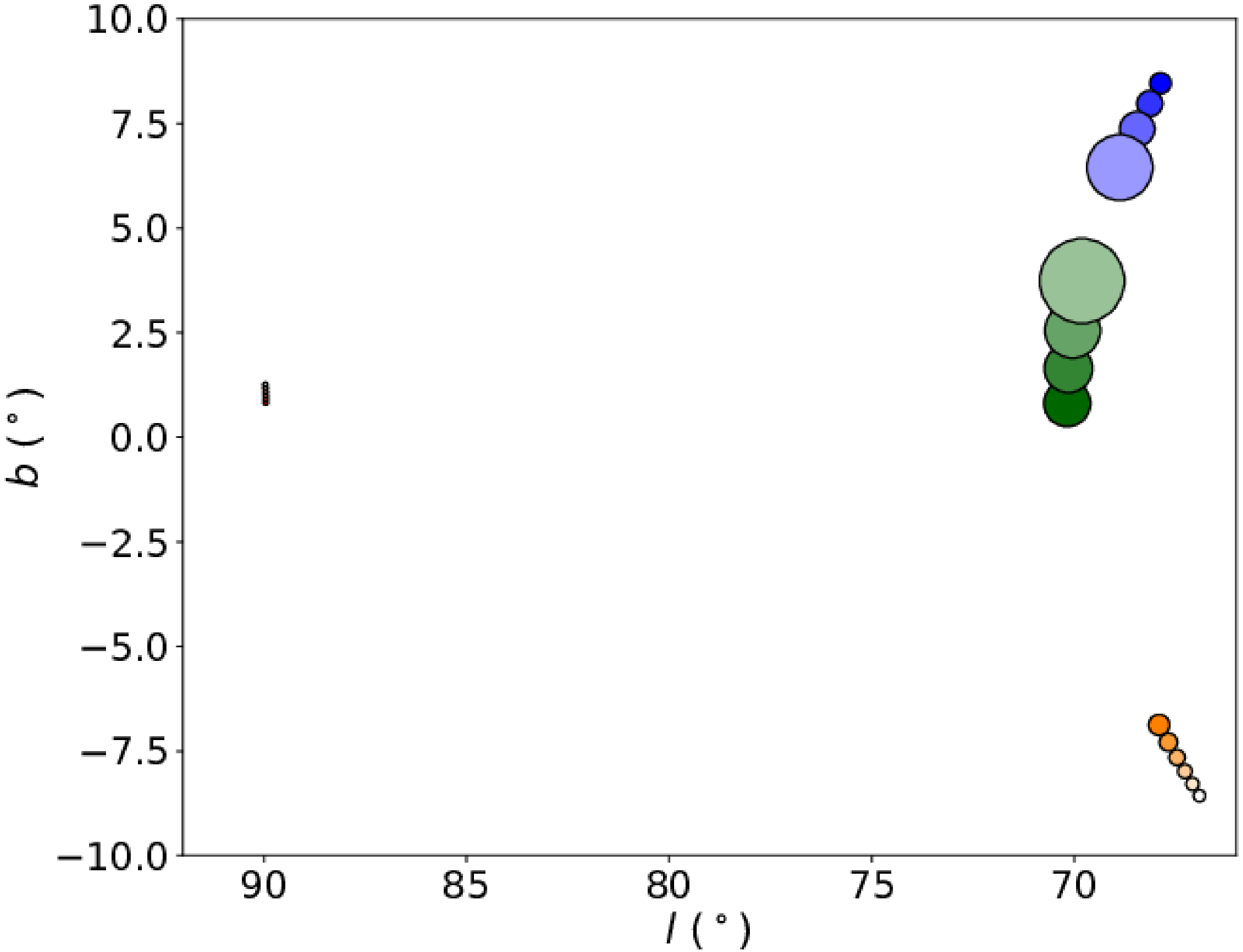
Chakrabarty, Han, Gonzalez, Sikivie, Phys. Dark Univ. 33 (2021), arXiv:2007.10509

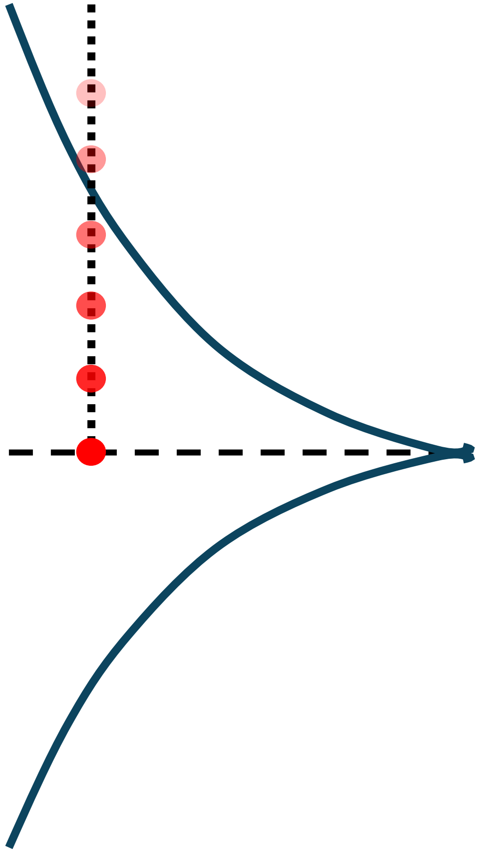
Four Cold Flows of Axions





Chakrabarty, Han, Gonzalez, Sikivie, Phys. Dark Univ. 33 (2021), arXiv:2007.10509



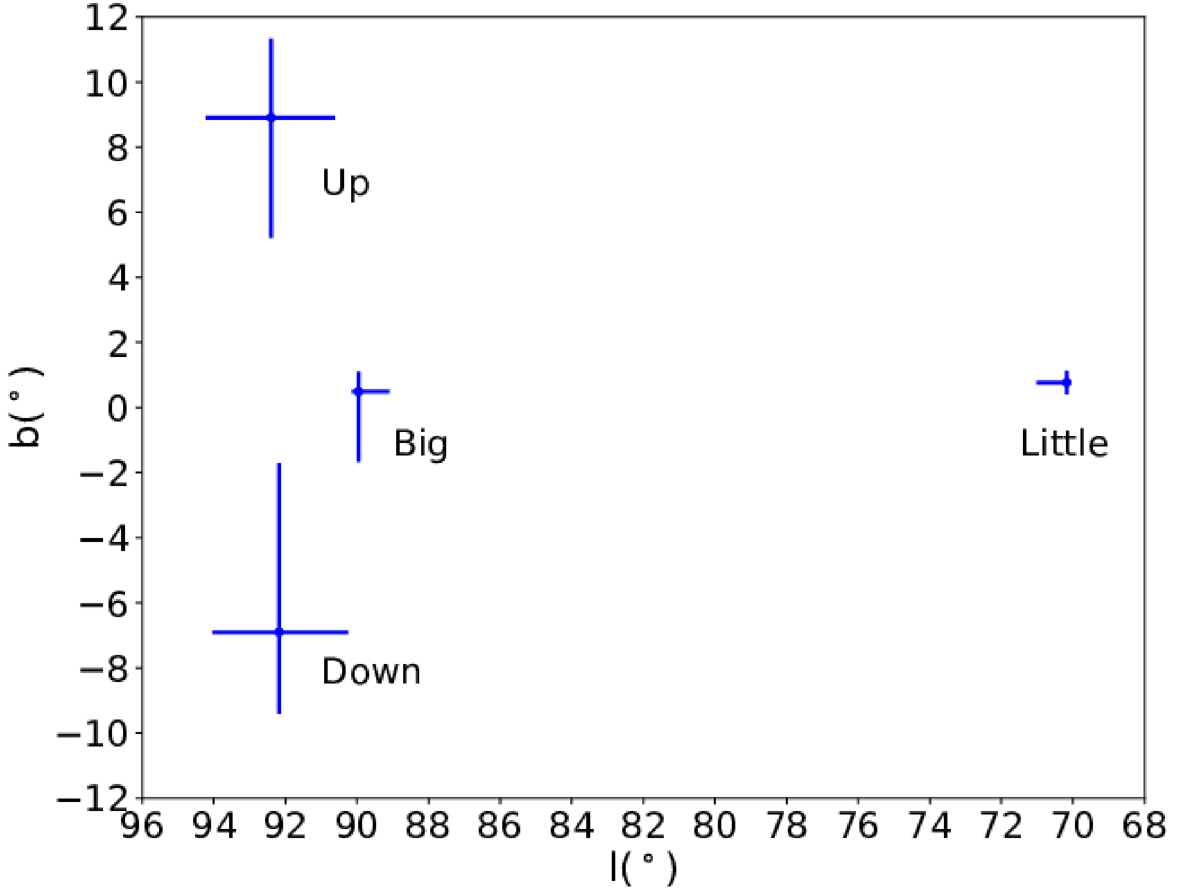


Directions of the four flows are correlated.

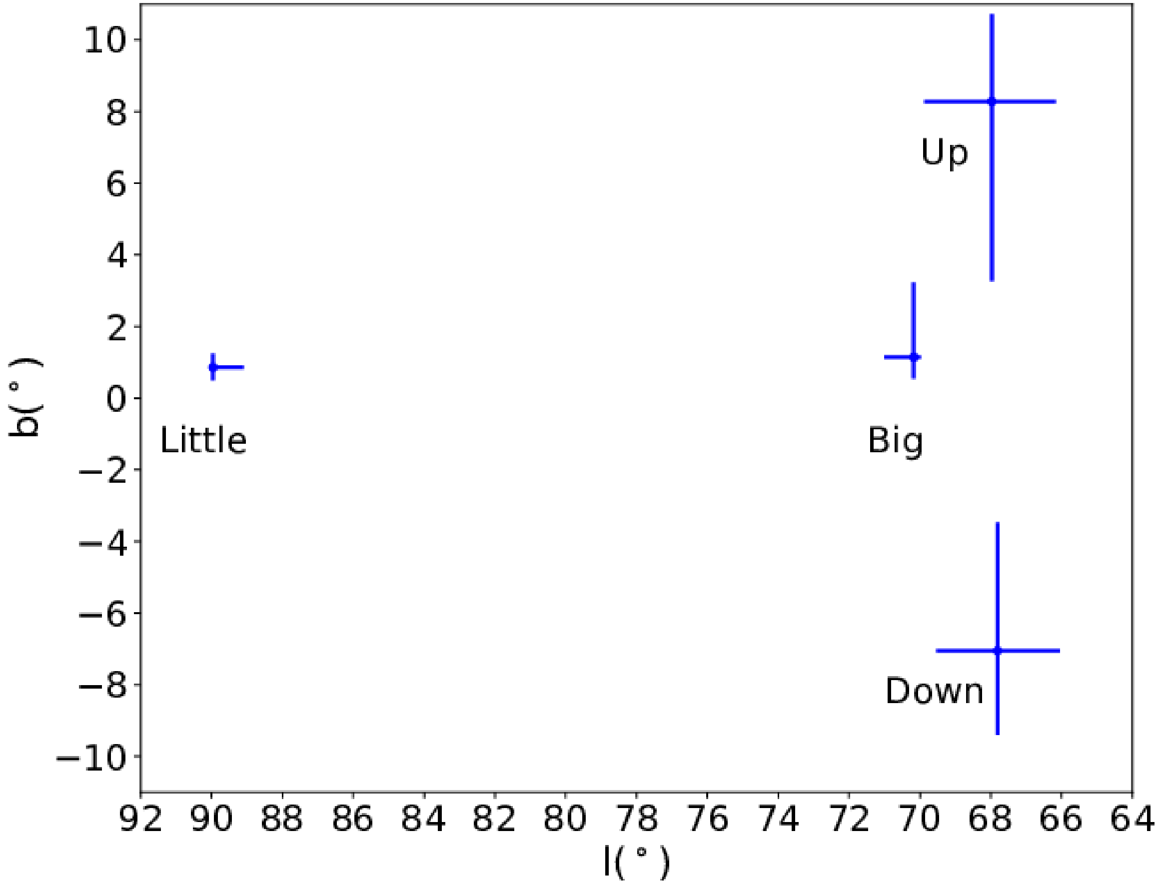
Size of the circles are proportional to flow densities.

Chakrabarty, Han, Gonzalez, Sikivie, Phys. Dark Univ. 33 (2021), arXiv:2007.10509

$\eta_0 > 0$



$\eta_0 < 0$



Chakrabarty, Han, Gonzalez, Sikivie, Phys. Dark Univ. 33 (2021), arXiv:2007.10509

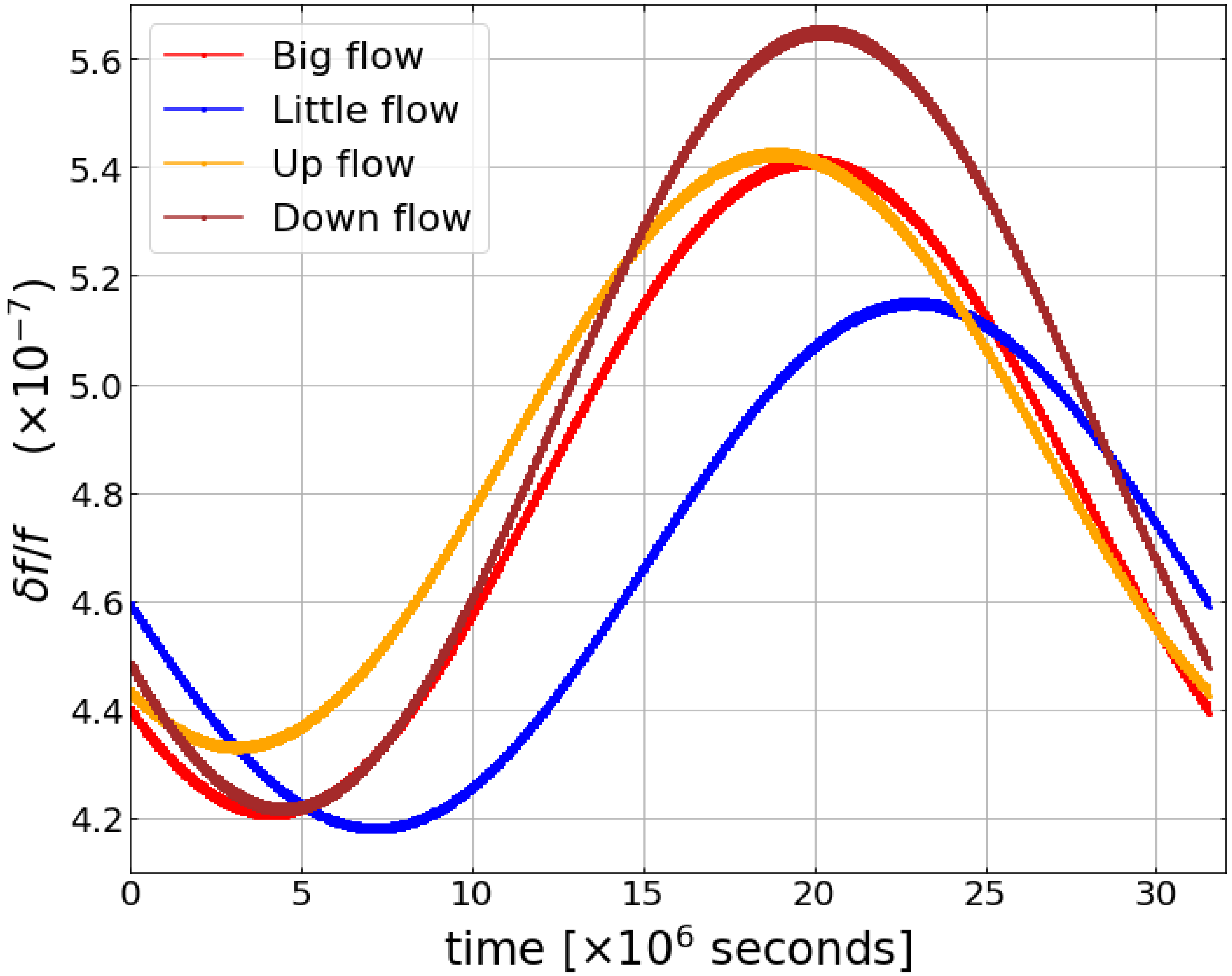
Frequency modulation

$$hf = mc^2 + \frac{1}{2}m\left(\vec{v}_{\text{flow}} - \vec{v}_{\text{detector}}(\vec{\lambda}, t)\right)^2$$

Flow and detector velocitie
in the Galactic rest frame.

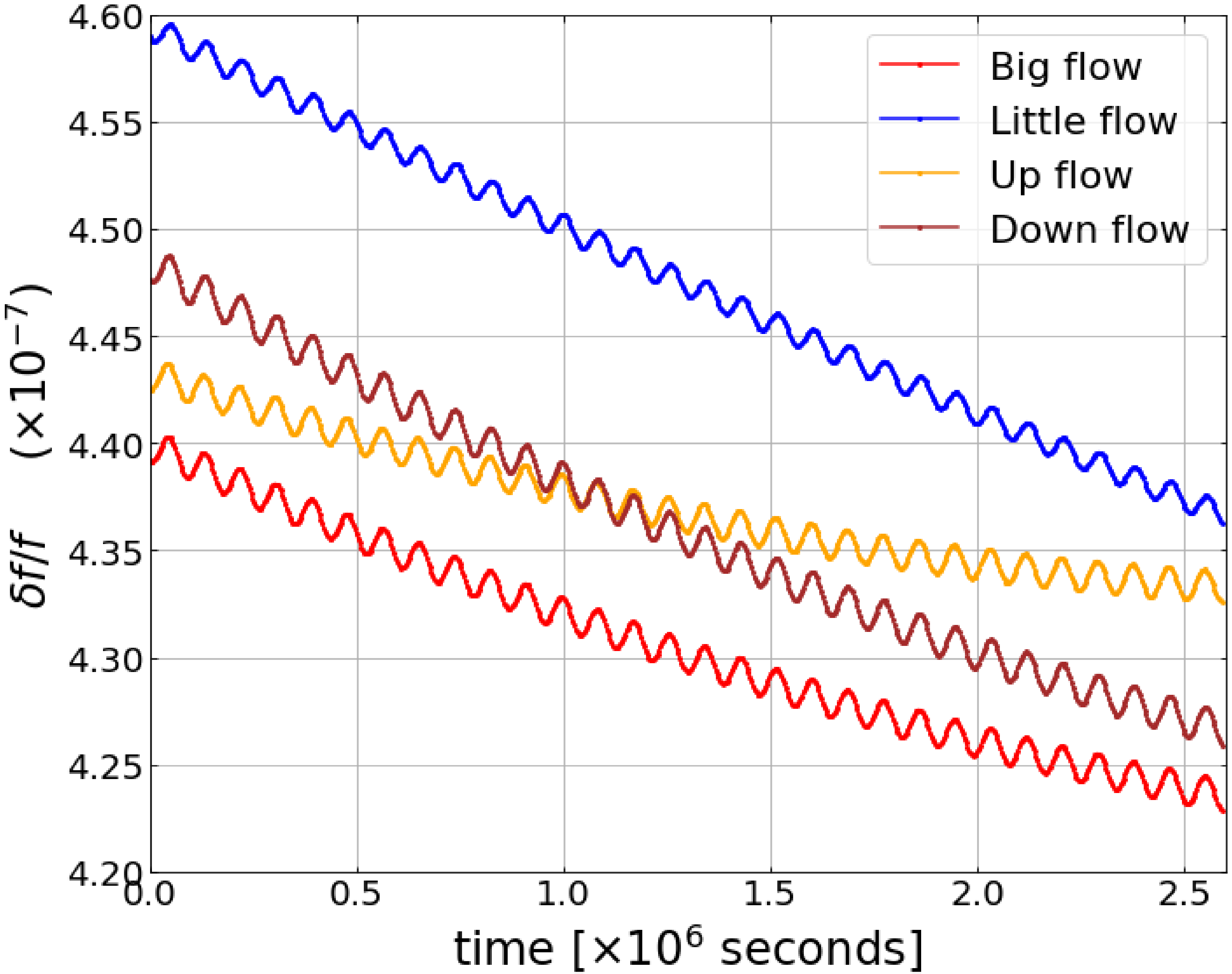
$$\frac{hf}{mc^2} = 1 + \boxed{\frac{1}{2c^2}\left(\vec{v}_{\text{flow}} - \vec{v}_{\text{detector}}(\vec{\lambda}, t)\right)^2} \longrightarrow \frac{\delta f}{f}$$

$$\vec{v}_{\text{detector}}(t) = \vec{v}_{\text{LSR}} + \vec{v}_{\odot,\text{LSR}} + \vec{v}_{\oplus,\odot}(t) + \vec{v}_{\oplus\text{rot}}(\vec{\lambda}, t)$$



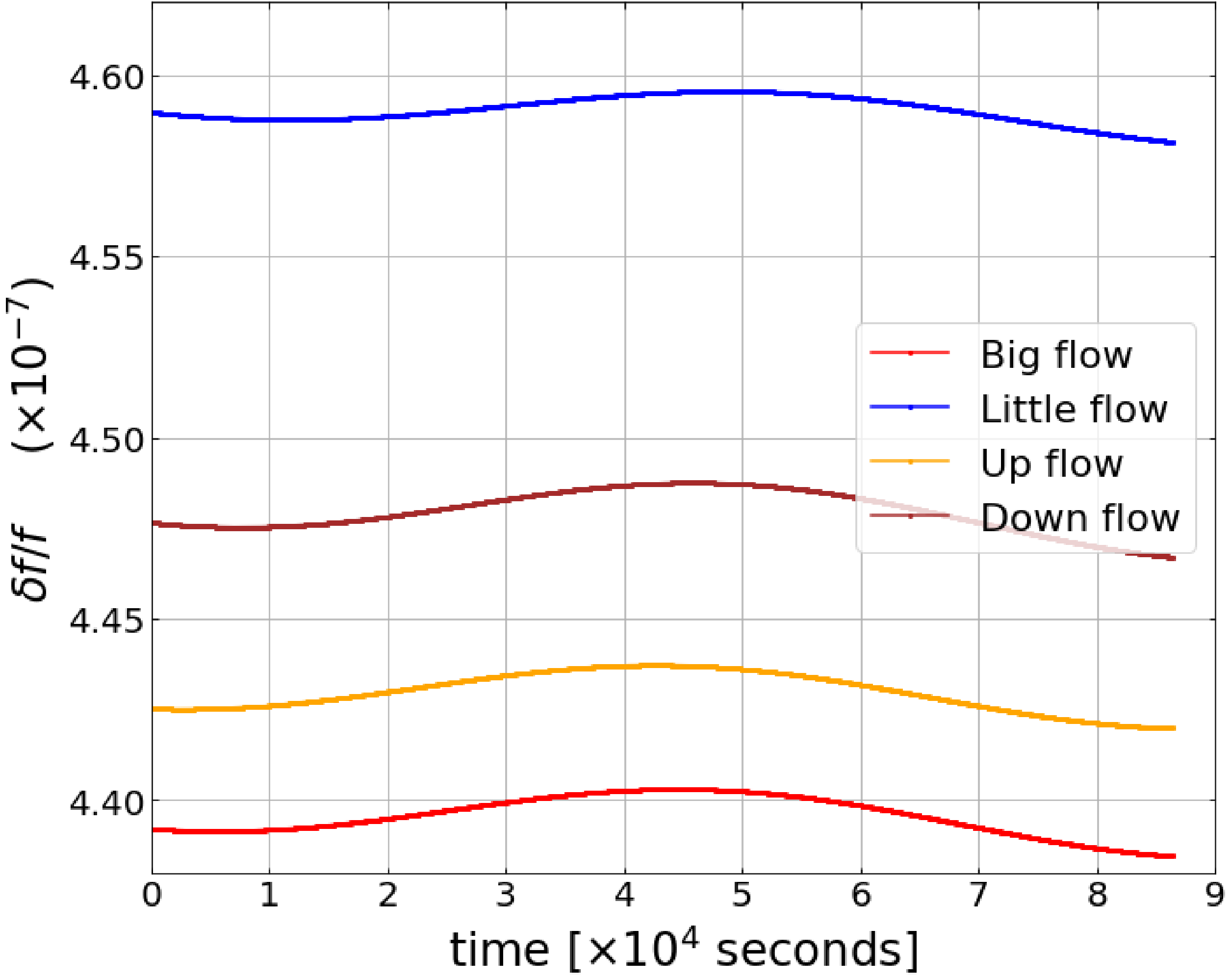
Annual modulation (for the central values of the Caustic Ring Model parameters)

$$\left(\frac{\delta f}{f}\right)_{\max} \sim 10^{-7}$$



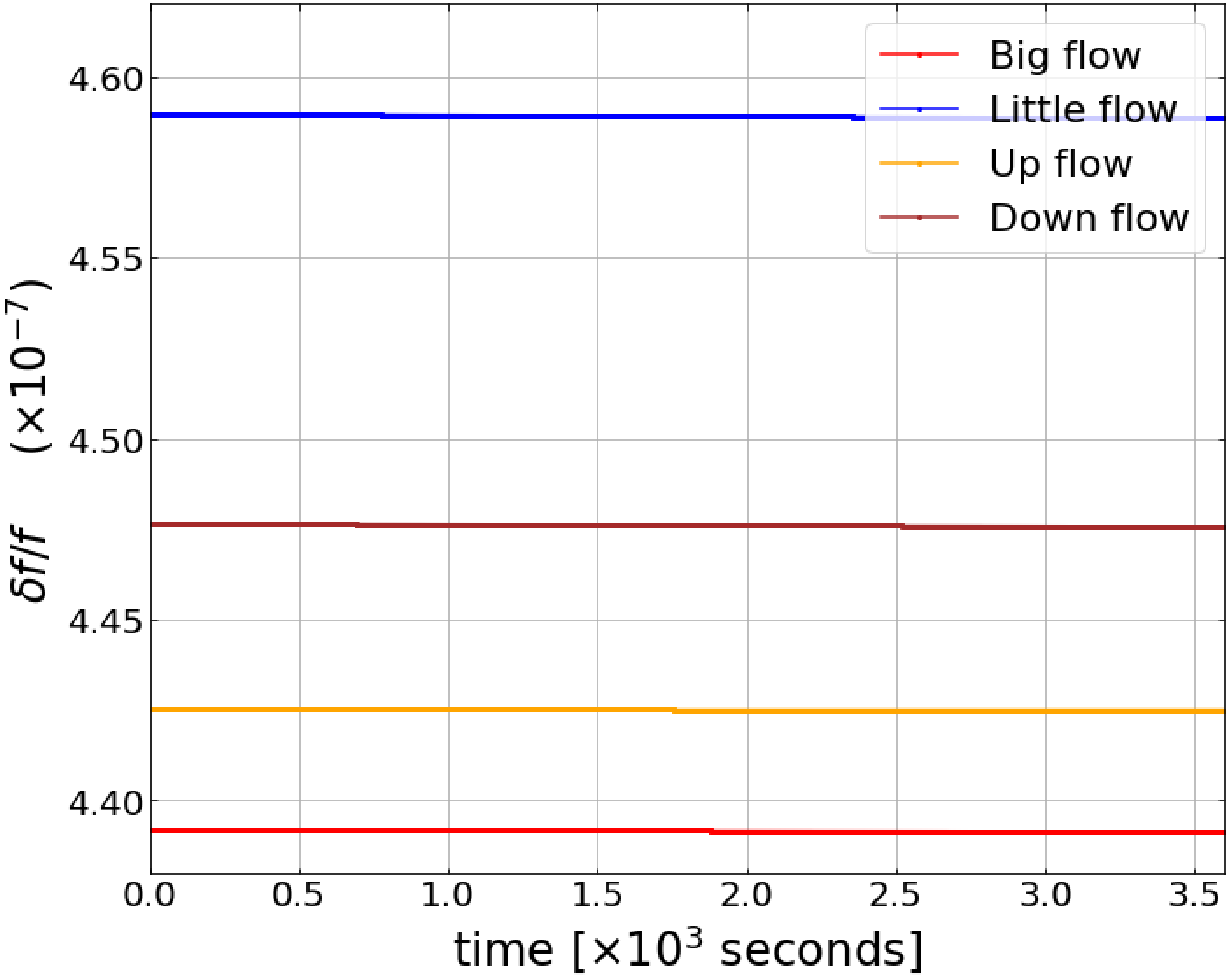
Monthly modulation

$$\left(\frac{\delta f}{f}\right)_{\max} \sim 10^{-8}$$



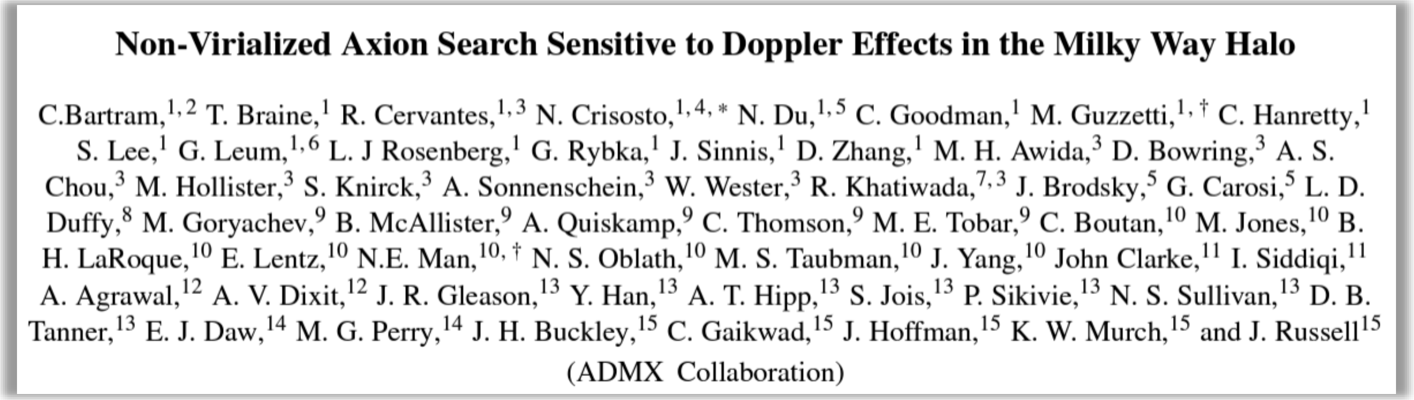
Daily modulation

$$\left(\frac{\delta f}{f}\right)_{\max} \sim 1.2 \times 10^{-9}$$



Hourly modulation

$$\frac{\delta f}{f} \sim 1.5 \times 10^{-10} \left(\frac{\Delta t}{3600\ s}\right)$$



Non-Virialized Axion Search Sensitive to Doppler Effects in the Milky Way Halo

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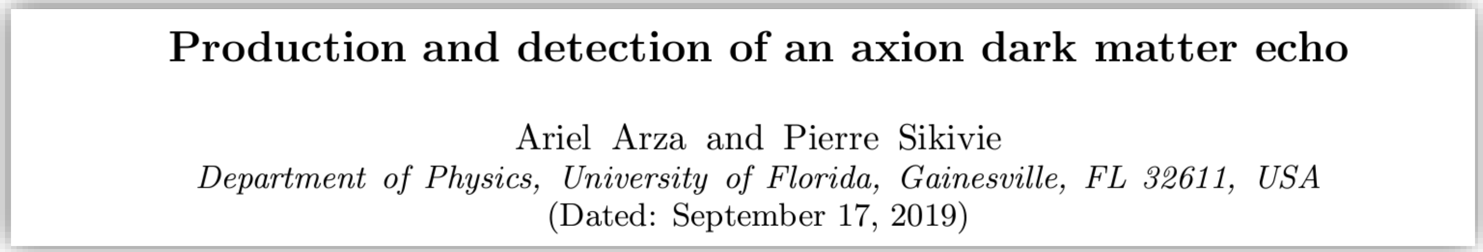
(ADMX Collaboration)

arXiv:2311.07748

Doppler shift in radio frequency: may be detected in hi-res search

arXiv:1902.00114

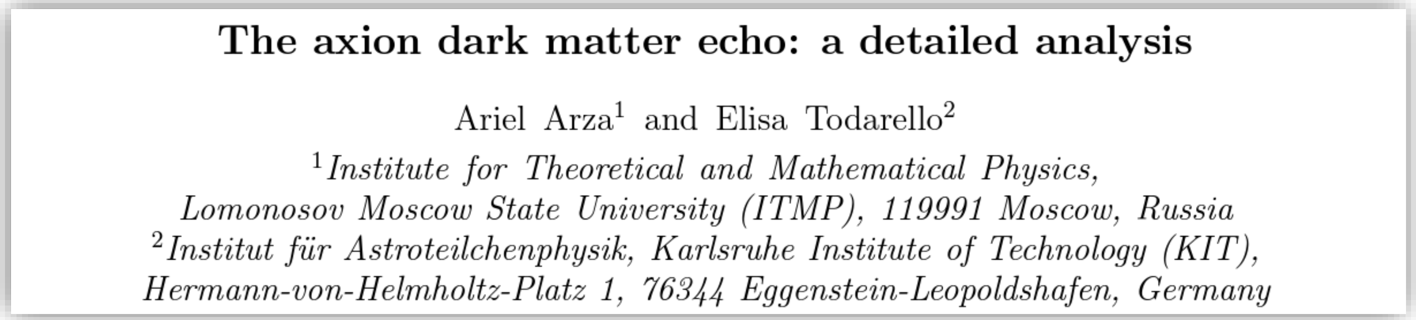


Production and detection of an axion dark matter echo

Ariel Arza and Pierre Sikivie
Department of Physics, University of Florida, Gainesville, FL 32611, USA
(Dated: September 17, 2019)

Axion echo: Microwave beam in the direction of axion flow

arXiv:2108.00195



The axion dark matter echo: a detailed analysis

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