Axions in Particle Physics and Cosmology

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Chiral symmetry breaking

in the two flavor quark model (u,d)

$$SU_L(2) \otimes SU_R(2) \otimes U_A(1) \otimes U_V(1)$$

$$\downarrow$$

$$SU_V(2) \otimes U_V(1)$$

4 Nambu-Goldstone bosons $\pi^+ \; \pi^0 \; \pi^- \; \eta$

$$m_\eta < \sqrt{3}\, m_\pi$$

S. Weinberg

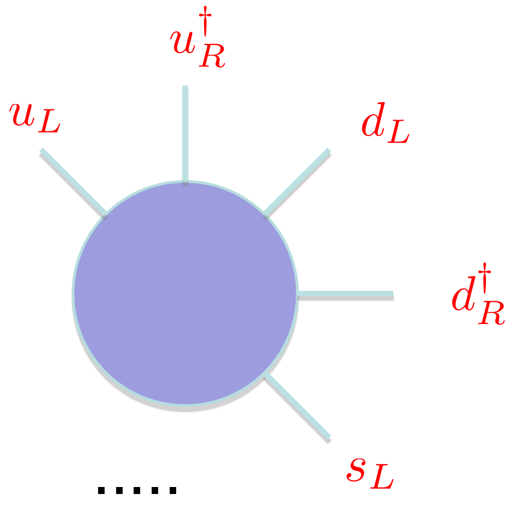
The $U_A(1)$ Problem

In Quantum Chromodynamics (QCD)

$U_A(1)$ has a Adler-Bell-Jackiw anomaly, and is therefore explicitly broken.

Quantum tunneling events, called instantons, produce axial charge for each flavor

't Hooft, 1976



$$\mathcal{L}_{\rm QCD} = \ ... \ + \ \bar{\theta}\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \theta - \arg(m_u \ m_d \ \ldots \ m_t)$$

The Strong CP Problem

$$\bar{\theta} = \theta - \arg(m_u\, m_d\, \ldots\, m_t)$$
$$= \theta - \arg\det(Y^u\, Y^d)$$

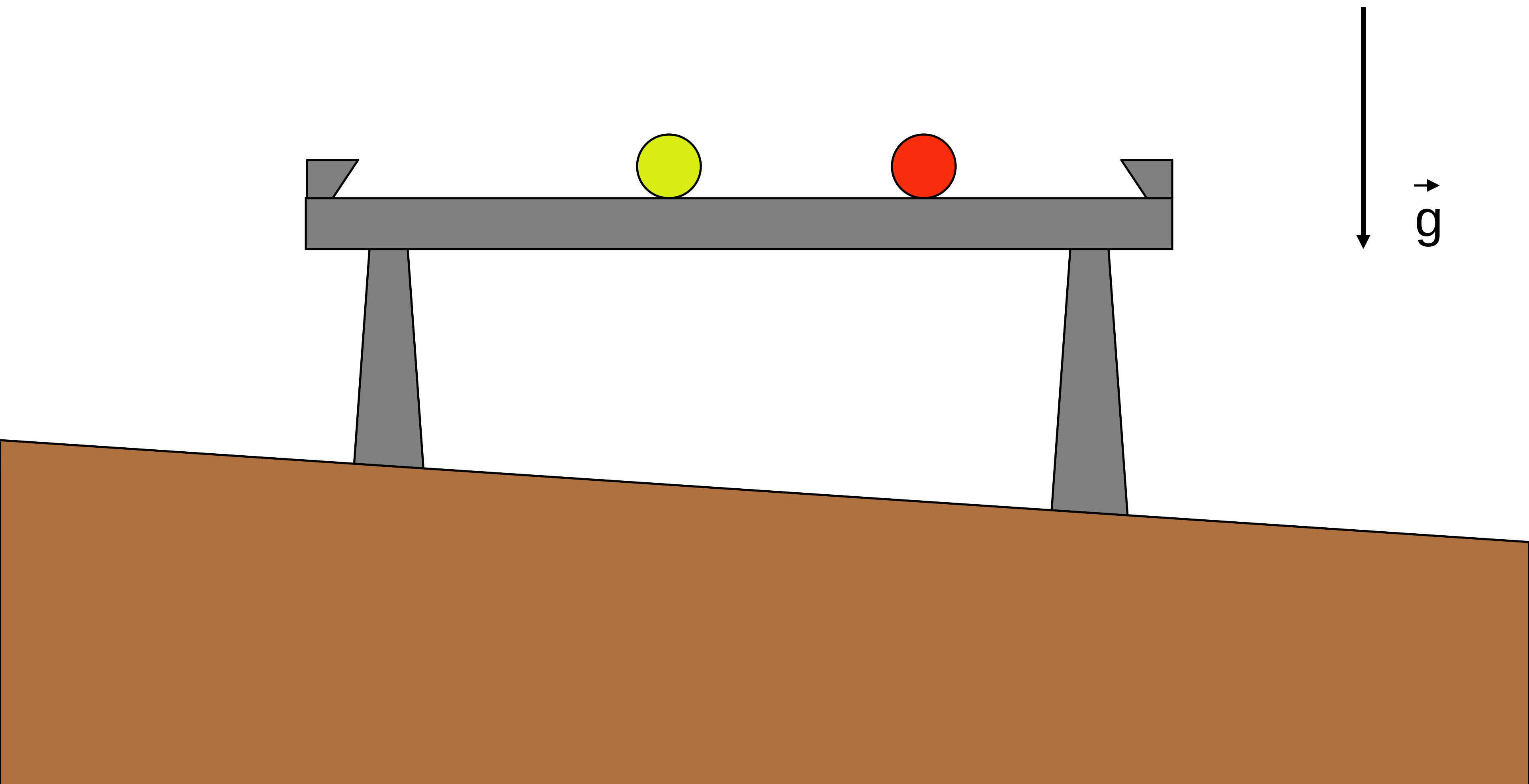
is expected to be of order one

The absence of P and CP violation in the strong interactions requires

$$\bar{\theta} \leq 10^{-10}$$

from upper limit on the neutron electric dipole moment

A level pooltable on an inclined floor



$$U_{PQ}(1)$$

- is a symmetry of the classical action
- is spontaneously broken
- has a color anomaly

Peccei and Quinn, 1977

If a $U_{PQ}(1)$ symmetry is assumed,

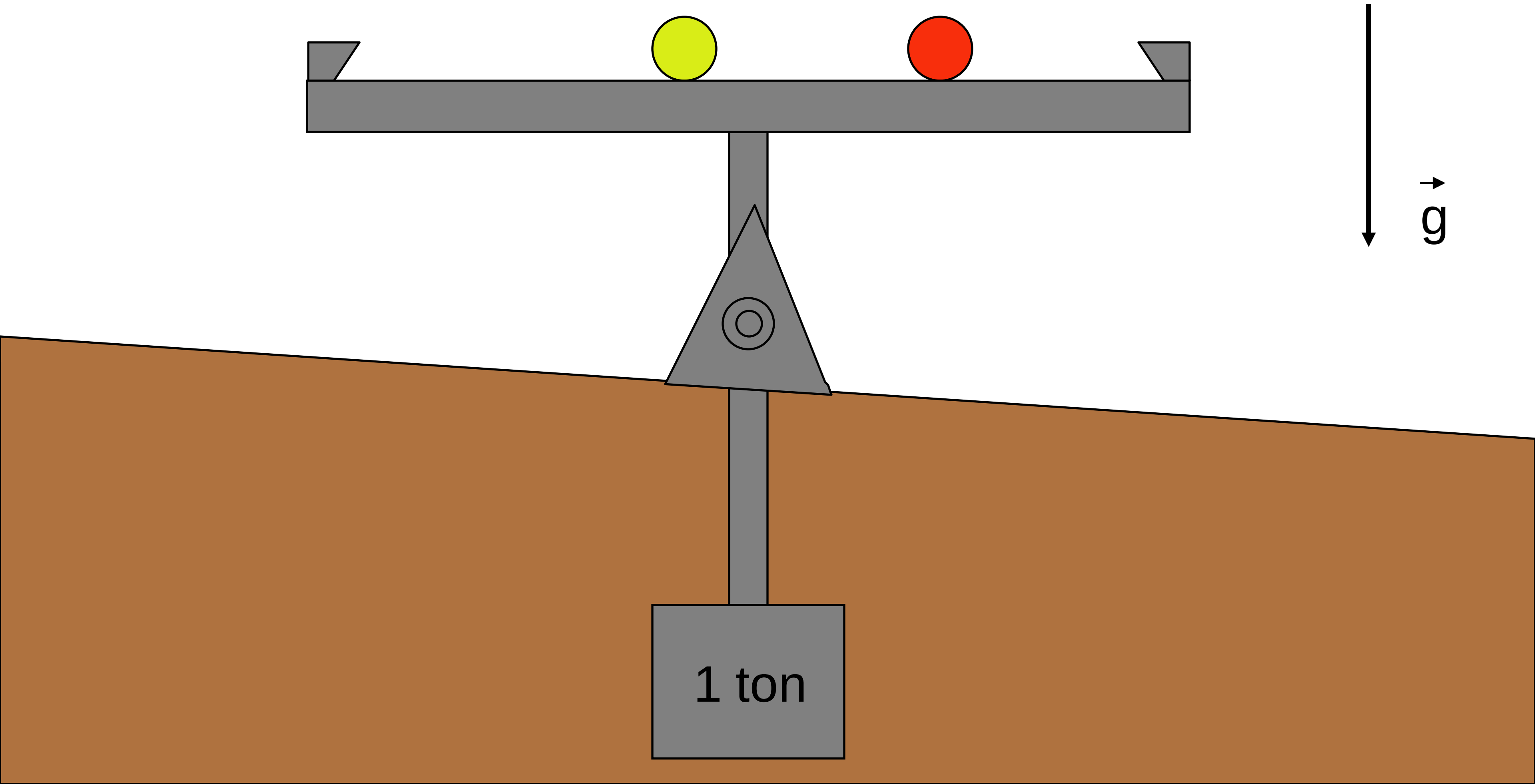
$$\mathcal{L} = \ ... \ + \ \frac{a}{f_a}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \ + \ \frac{1}{2}\partial_\mu a \partial^\mu a$$

$\bar{\theta} = \frac{a}{f_a}$ relaxes to zero,

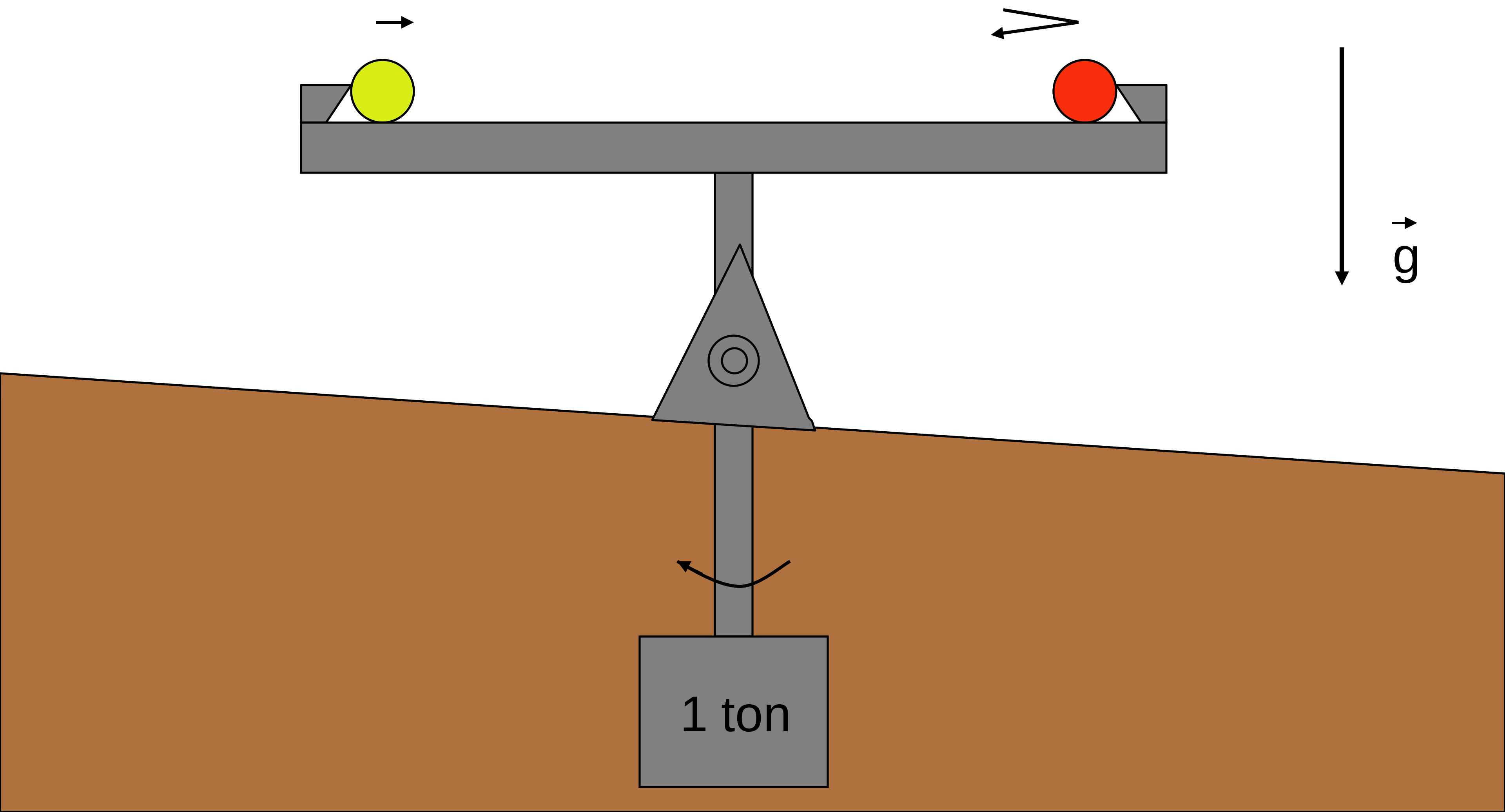
and a light neutral pseudoscalar particle is predicted: the axion.

Weinberg, Wilczek 1978

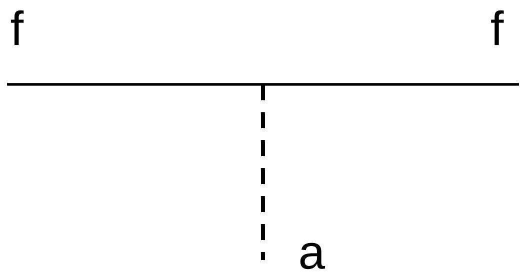
A self adjusting pooltable



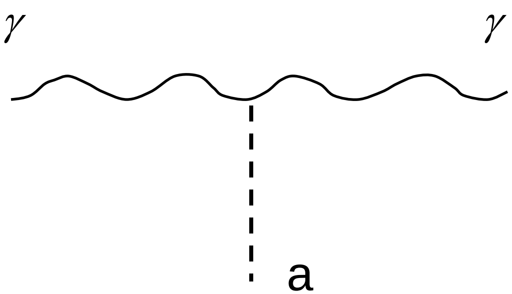
Searching for the pooltable oscillation quantum



$$m_a \simeq 6 \text{ eV} \, \frac{10^6 \text{ GeV}}{f_a}$$



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



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

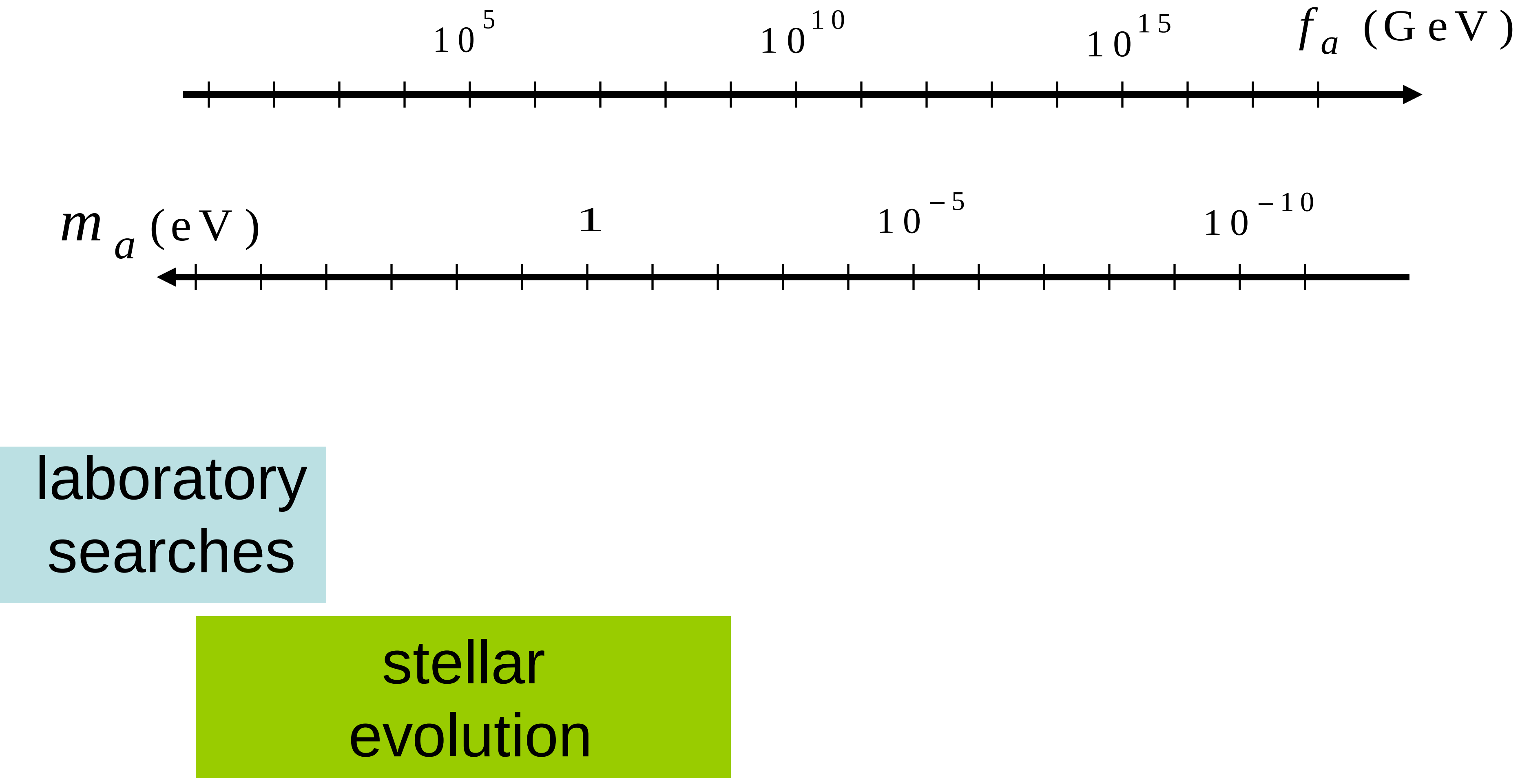
g_γ = 0.97 in KSVZ model

0.36 in DFSZ model

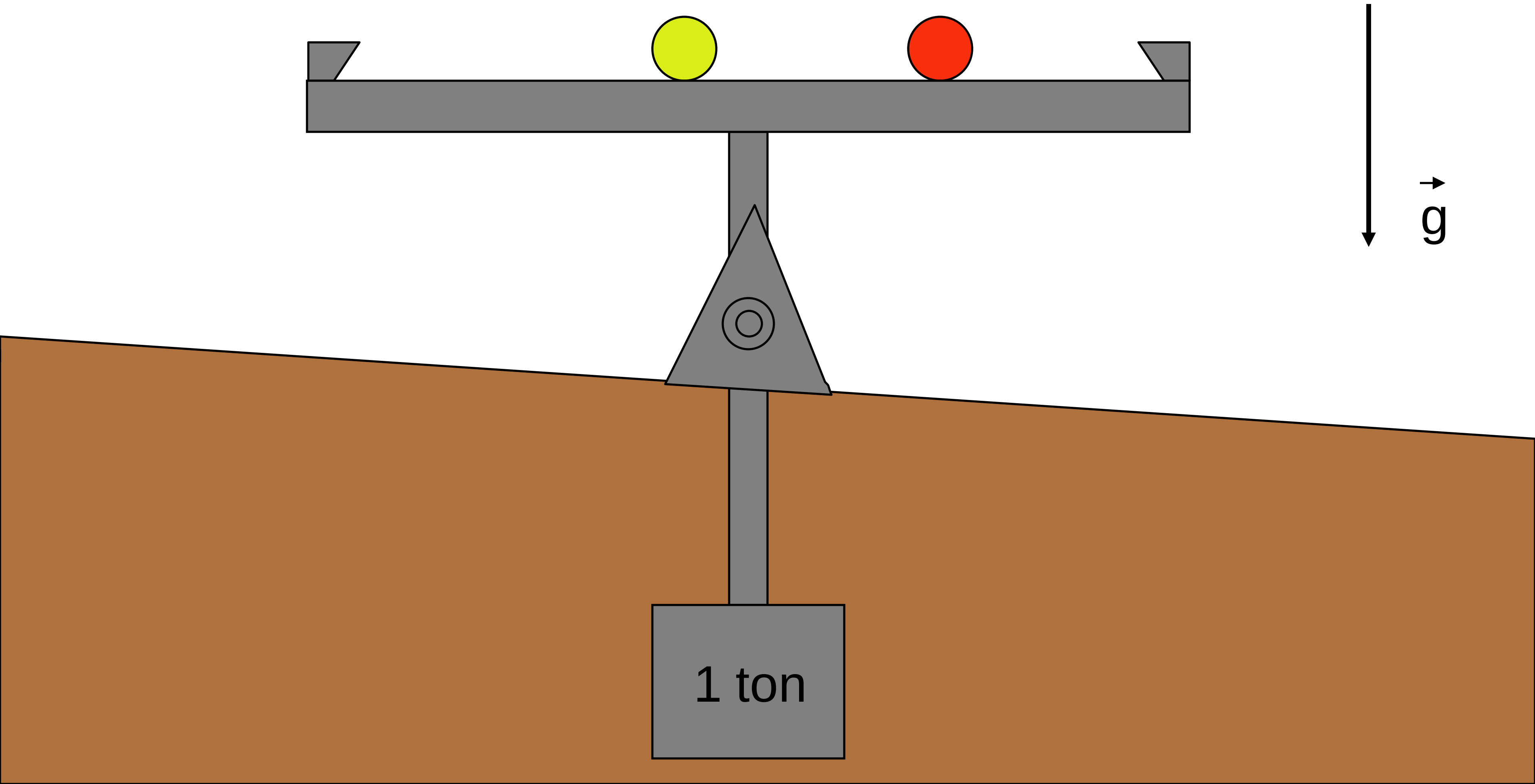
Axions are constrained by

- beam dump experiments
- rare particle decays $(e.g.\ \ K^+ \rightarrow \pi^+\, a)$
- radiative corrections
  $(e.g.\ \ \text{the } \mu^- \text{ anomalous magnetic moment})$
- the evolution of stars

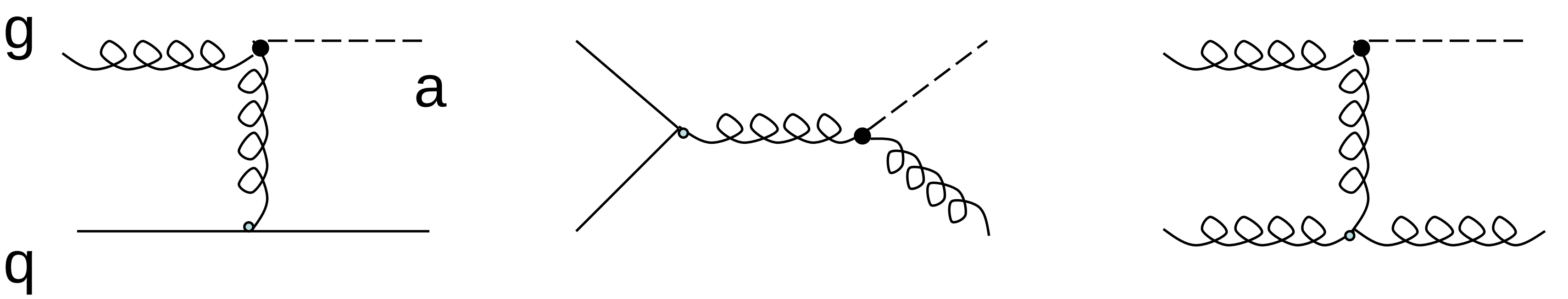
Axion constraints



A self adjusting pooltable



Thermal axions



these processes imply an axion decoupling temperature

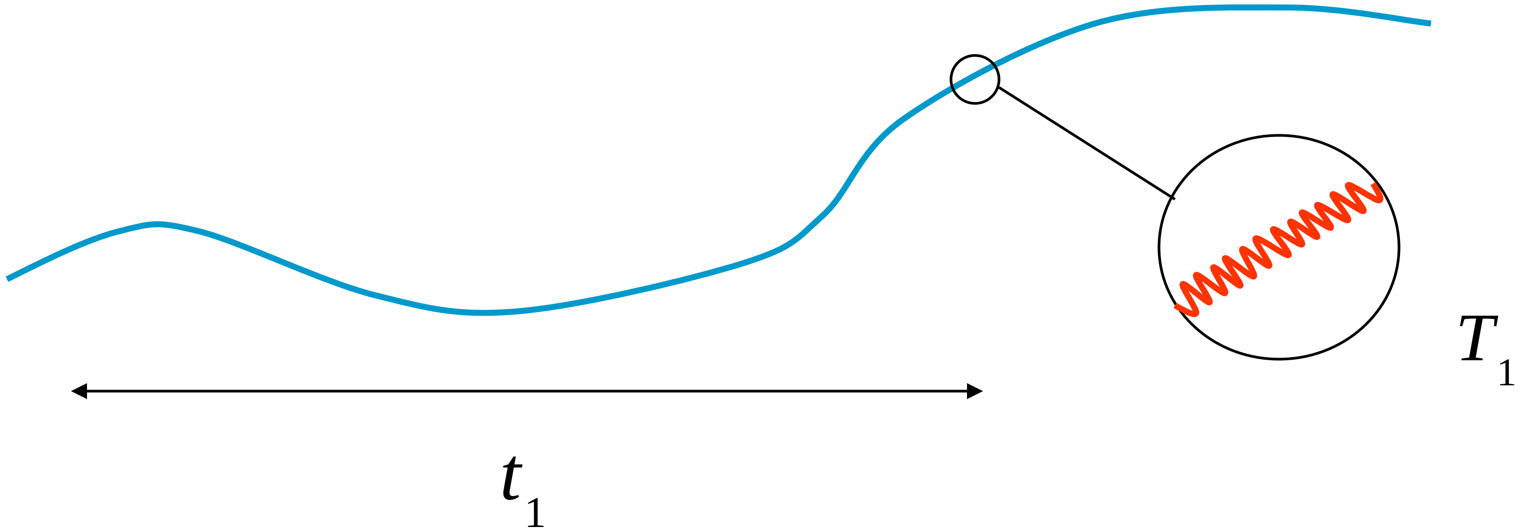
$$T_D \simeq 3 \times 10^{11}\ \text{GeV} \left(\frac{f_a}{10^{12}\ \text{GeV}} \right)^2$$

thermal axion temperature today:

$$T_a(t_0) = 0.908\ \text{K} \left(\frac{106.75}{N_D} \right)^{\frac{1}{3}}$$

N_D = effective number of thermal degrees of freedom at axion decoupling

There are two cosmic axion populations: hot and cold.



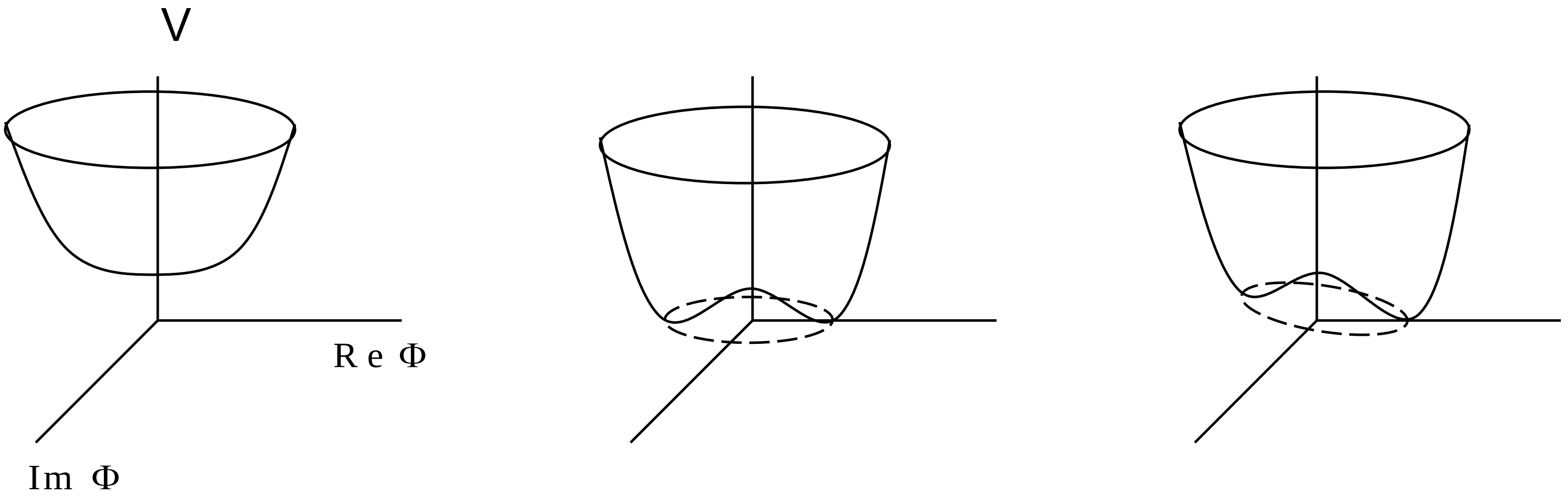
When the axion mass turns on, at QCD time,

$$T_1 \simeq 1 \text{ GeV}$$

$$t_1 \simeq 2 \times 10^{-7} \text{ sec}$$

$$p_a(t_1) \simeq \frac{1}{t_1} \simeq 3 \times 10^{-9} \text{ eV}$$

Effective potential $V(T, \Phi)$

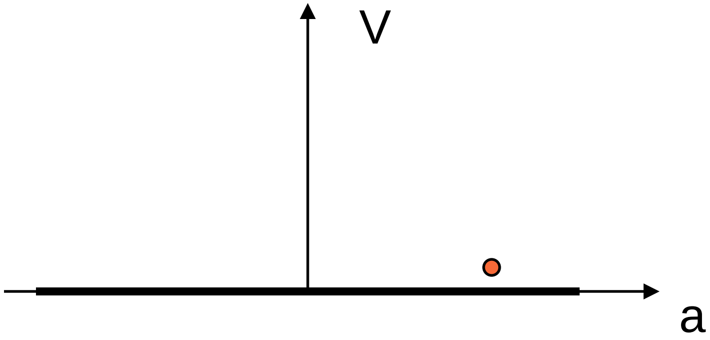


$T > f_a$

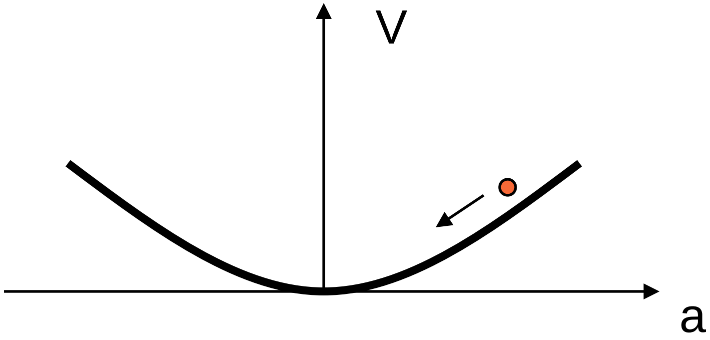
$f_a > T > 1\,\mathrm{GeV}$ → axion strings

$1\,\mathrm{GeV} > T$ → axion domain walls

Axion production by vacuum realignment



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



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

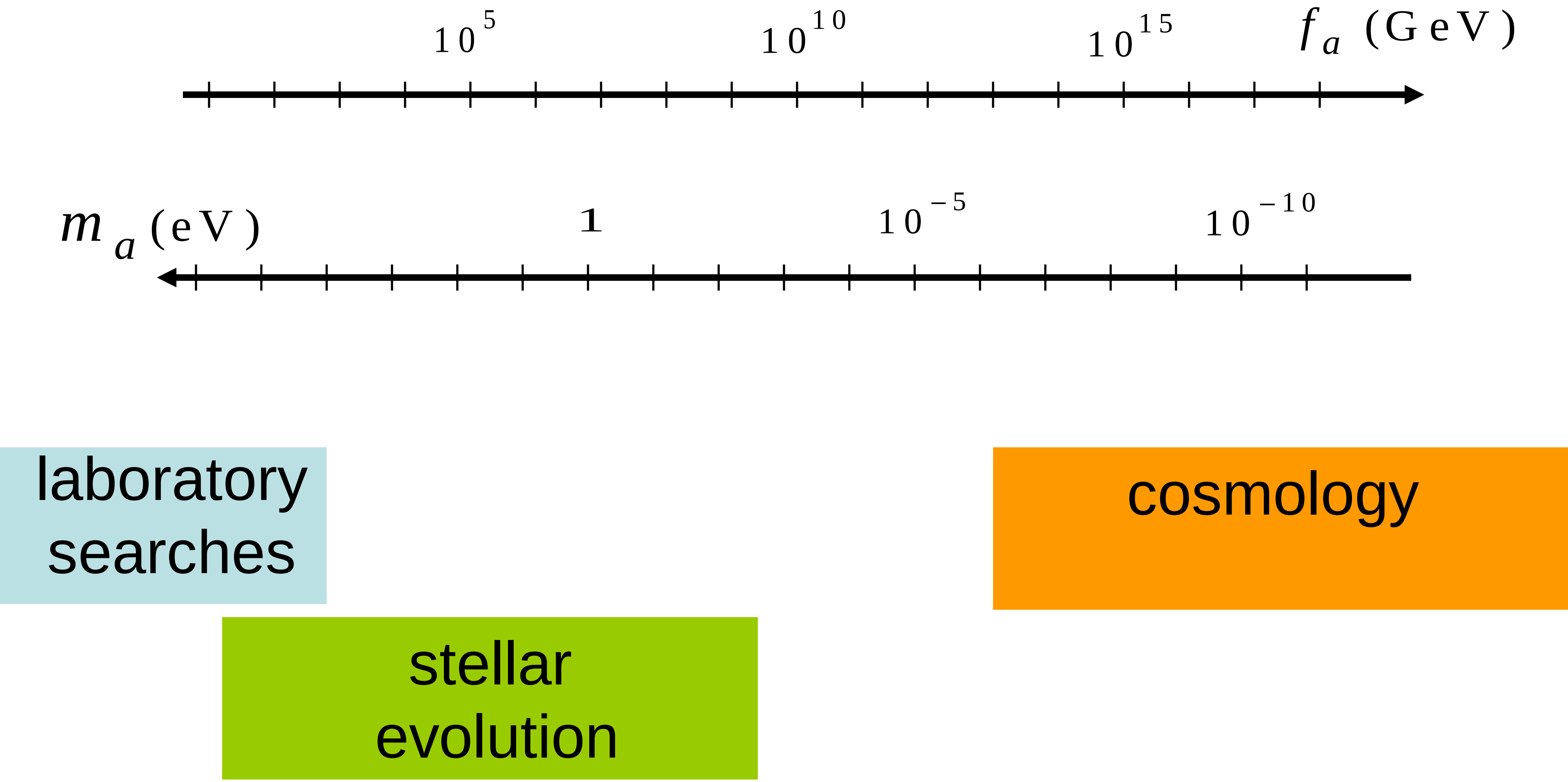
$$n_a(t_1) \simeq \frac{1}{2} m_a(t_1) a(t_1)^2 \simeq \frac{1}{2t_1} f_a^2 \alpha(t_1)^2$$

$$\rho_a(t_0) \simeq m_a n_a(t_1) \left(\frac{R_1}{R_0}\right)^3 \propto m_a^{-\frac{7}{6}}$$

initial misalignment angle

J. Preskill, M. Wise & F. Wilczek, L. Abbott & PS, M. Dine & W. Fischler, 1983

Axion constraints



If inflation after the PQ phase transition

- $$\Omega_a \simeq 0.25 \left(\frac{10^{-5}\ \mathrm{eV}}{m_a} \right)^{\frac{7}{6}} \alpha(t_1)^2$$ may be accidentally suppressed

- $$\sqrt{< (\delta a(x))^2 >} \simeq \frac{H_I}{2\pi}$$ produces isocurvature density perturbations

M. Axenides, R.H. Brandenberger and M.S. Turner, 1983;
P.J. Stein-hardt and M.S. Turner, 1983; A.D. Linde, 1985;
D. Seckel and M.S. Turner, 1985; D.H. Lyth,1990;
M.S. Turner and F. Wilczek,1991.

Axion isocurvature constraint

$$H_I \lesssim 10^{-5} f_a$$

in case inflation occurs after the PQ phase transition

$$H_I = \sqrt{\frac{8\pi}{3} G \, \rho_I} \sim \frac{\Lambda_I^2}{M_{\mathrm{Pl}}}$$

$$\text{e.g.} \quad f_a = 10^{13}\ \mathrm{GeV} \quad , \quad H_I = 10^{5}\ \mathrm{GeV} \quad , \quad \Lambda_I = 10^{12}\ \mathrm{GeV}$$

If no inflation after the PQ phase transition

- cold axions are produced by vacuum realignment, string decay and wall decay

$$\Omega_a = 0.3\ X \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{\frac{7}{6}} \qquad 2 \lesssim X \lesssim 10$$

- axion miniclusters appear

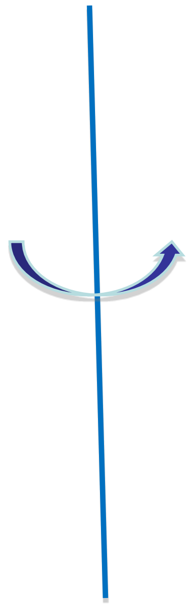
E. Kolb & I. Tkachev
1993, 1996

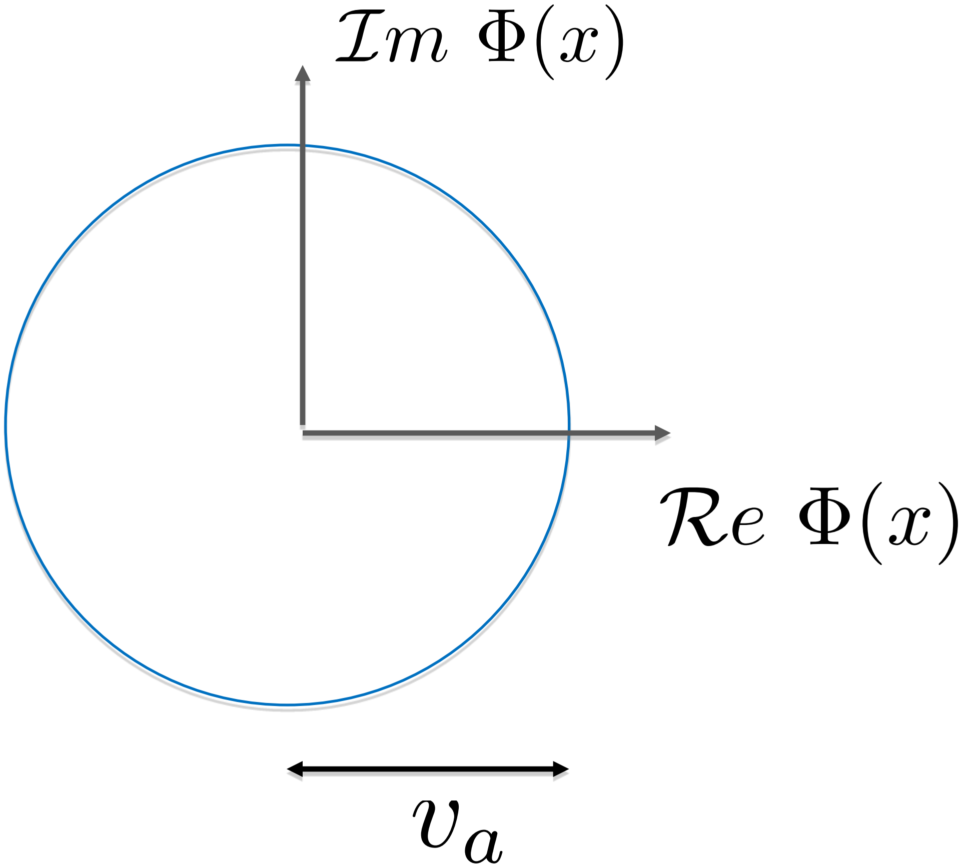
$$M_{mc} \sim 10^{-12}\ M_\odot \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{\frac{5}{3}}$$

$$l_{mc} \sim 2 \cdot 10^{13}\ \mathrm{cm} \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{\frac{1}{6}}$$

Axion string

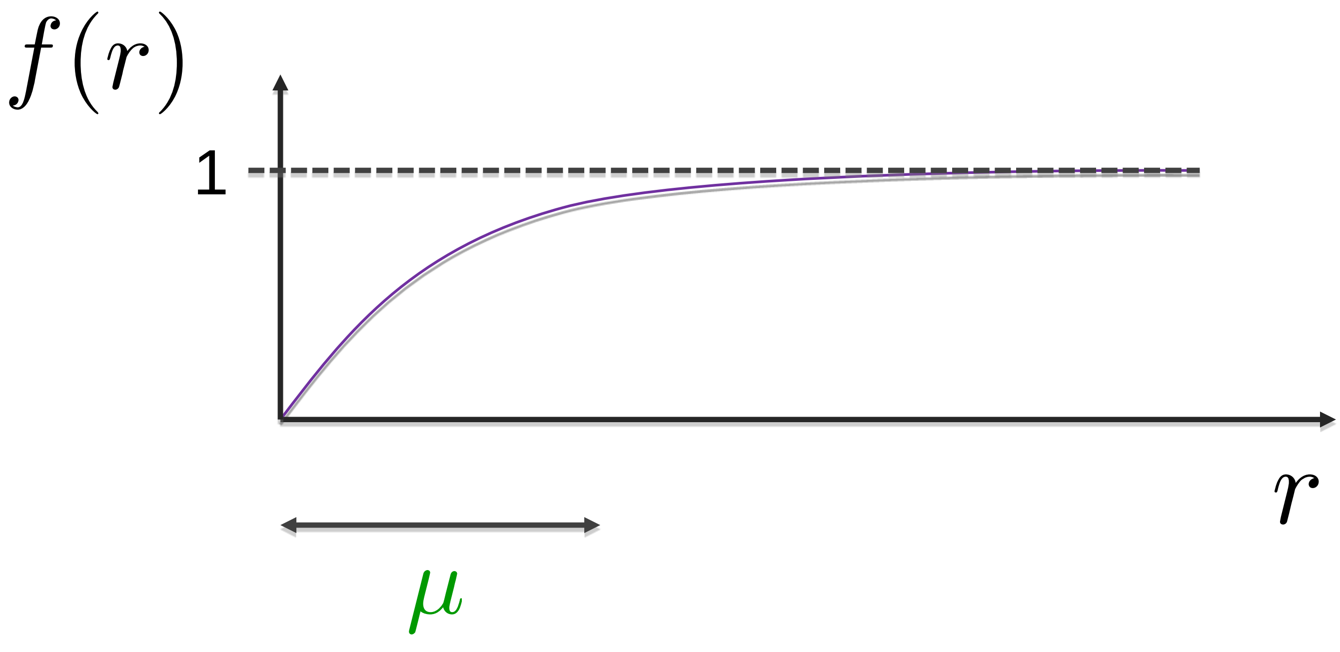
$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi(x)^\dagger \partial^\mu \Phi(x) - \frac{\lambda}{4}(\Phi(x)^\dagger \Phi(x) - v_a^2)^2$$





Axion string configuration

$$\Phi(r,\theta) = v_a \ f(r) \ e^{i\theta}$$



$$\mu = \sqrt{\lambda} v_a$$

Axion string energy per unit length

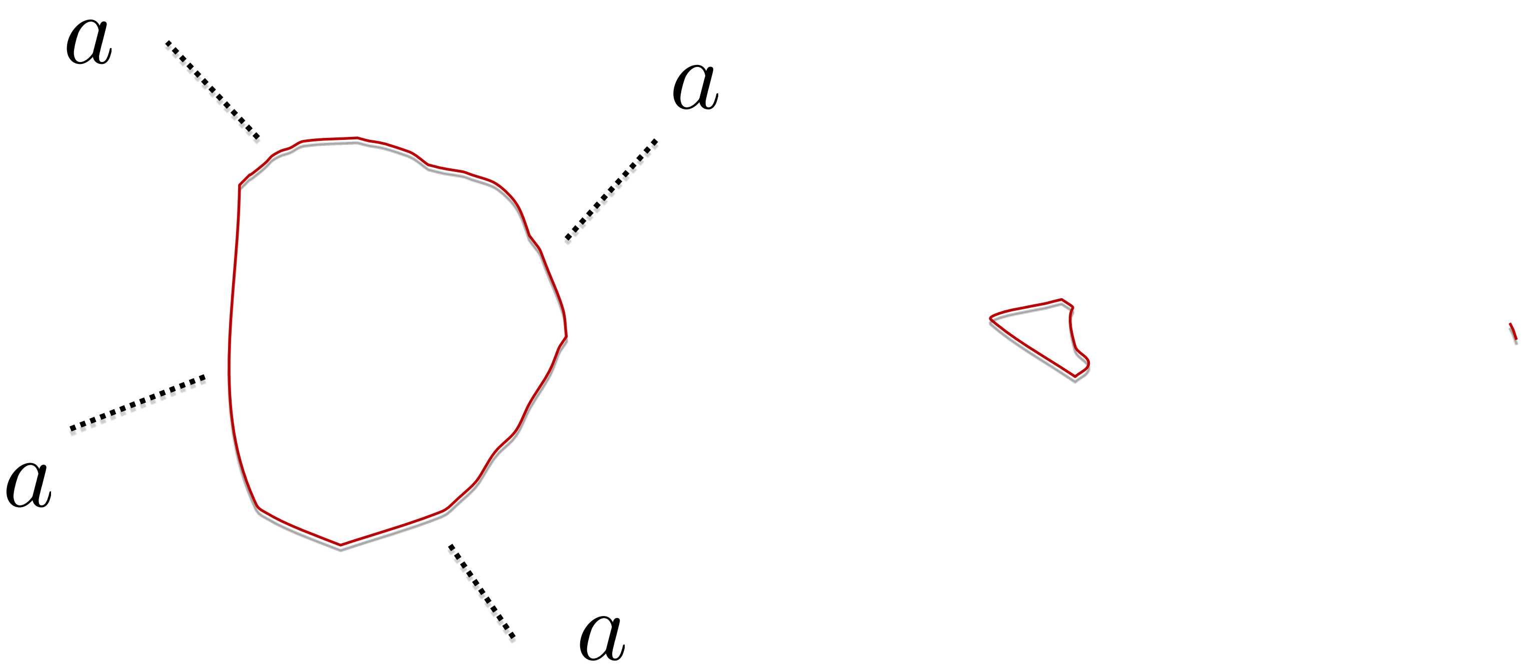
$$\lambda \simeq \int d^2x \frac{1}{2} \vec{\nabla}\Phi(x)^\dagger \cdot \vec{\nabla}\Phi(x)$$

$$\simeq \pi v_a^2 \int_{\mu^{-1}}^{L} r\ dr\ (\frac{1}{r}\hat{\theta})^2$$

$$\simeq \pi\ v_a^2\ ln(L v_a)$$

$$\simeq \pi\ v_a\ \int_{v_a}^{L^{-1}}\ \frac{dk}{k}$$

$\frac{d\lambda}{d\ ln(k)}$
L^{-1}
v_a
$ln(k)$



a
a
a
a

$$\frac{dn_a^{\text{str rad}}}{dk} \propto \frac{1}{k^q}$$

$$\rho_a^{\text{str rad}}(t_0) = m_a \; n_a^{\text{str rad}}(t_1) \left(\frac{a(t_1)}{a(t_0)} \right)^3$$

$$n_a^{\text{str rad}}(t_1) = \frac{v_a^2}{t_1} \; \alpha$$

two scenarios

$q > 1$

$$\alpha = ln(Lv_a) \simeq 100$$

$$\alpha \simeq 10$$

$$\alpha \simeq 3$$

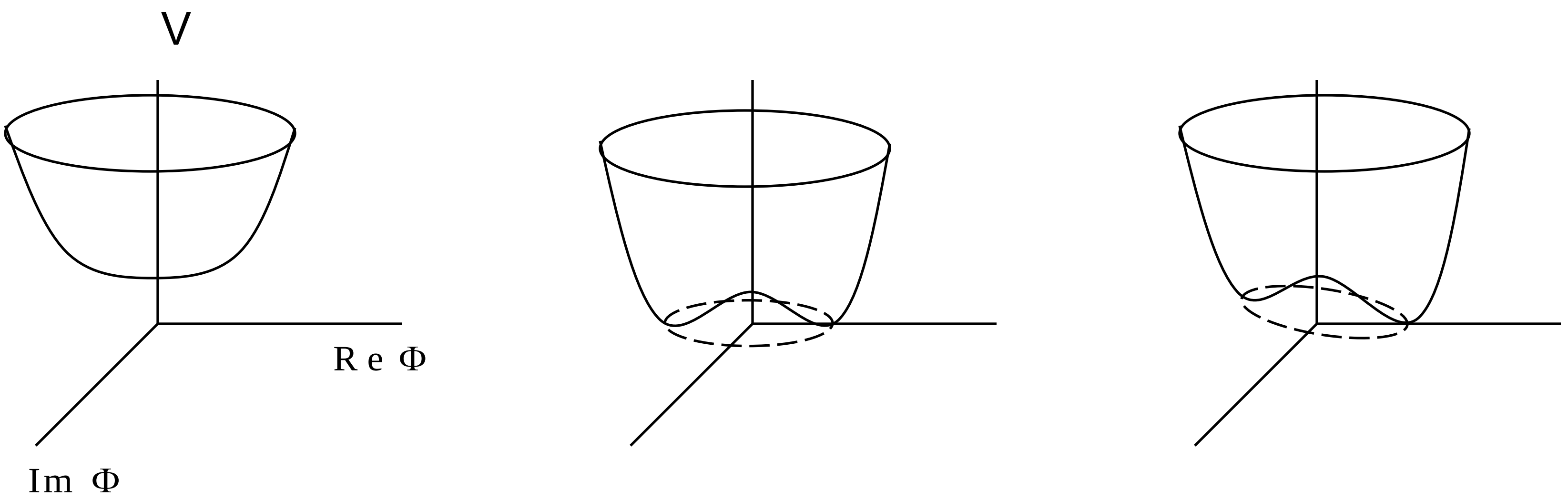
R. Davis
A. Vilenkin
P. Shellard & R. Battye
.....
Matsuki et al.
....

$q = 1$

$$\alpha \simeq 1$$

D. Harari & PS
C. Hagmann,
S. Chang & PS
....
T. Vachaspati et al.
B. Safdi et al.

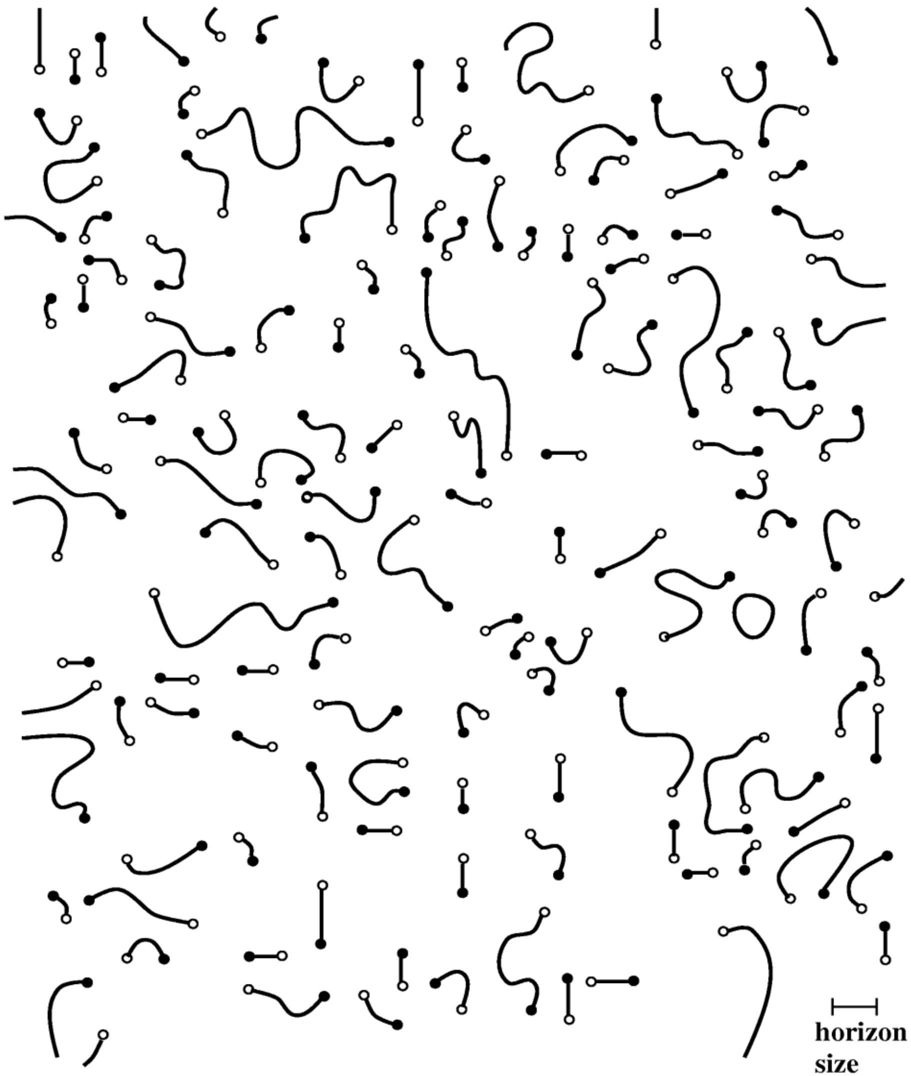
Effective potential V(T,Φ)



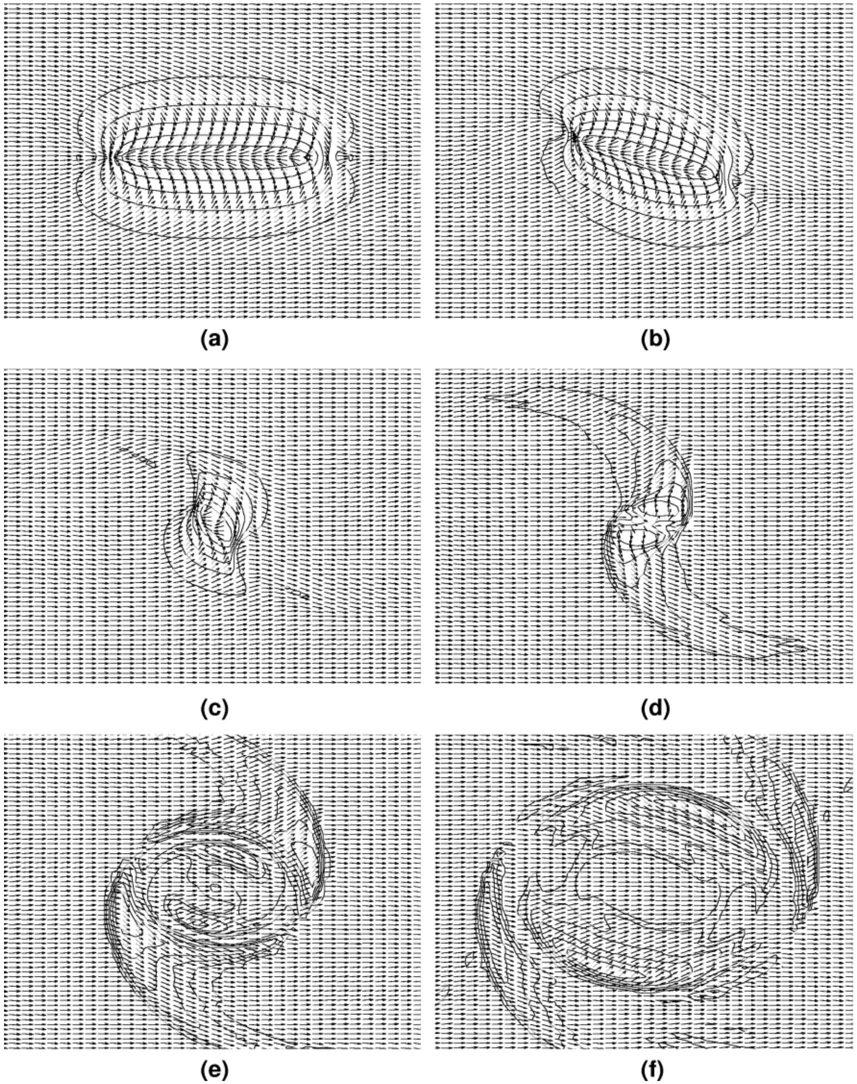
$T > f_a$ $\quad$ $f_a > T > 1\,\text{GeV}$ $\quad$ $1\,\text{GeV} > T$

$f_a > T > 1\,\text{GeV}$ → axion strings

$1\,\text{GeV} > T$ → axion domain walls



Axion
domain walls
bounded
by string
during the
QCD phase
transition



Domain wall bounded by string decaying into axion radiation

Cold axion properties

- number density

$$n(t) \simeq \frac{4\cdot 10^{47}}{\text{cm}^3}\left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{\frac{5}{3}}\left(\frac{R(t_1)}{R(t)}\right)^3$$

- velocity dispersion

$$\delta v(t) \simeq \frac{1}{m_a t_1}\frac{R(t_1)}{R(t)}$$

if decoupled

- phase space density

$$\mathcal{N} = \frac{(2\pi)^3 n(t)}{\frac{4\pi}{3}(m_a \delta v)^3} \simeq 10^{61}\left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{\frac{8}{3}}$$

Bose-Einstein Condensation

if identical bosonic particles
are highly condensed in phase space
and their total number is conserved
and they thermalize

then most of them go to the lowest energy
state available by the thermalizing
interactions

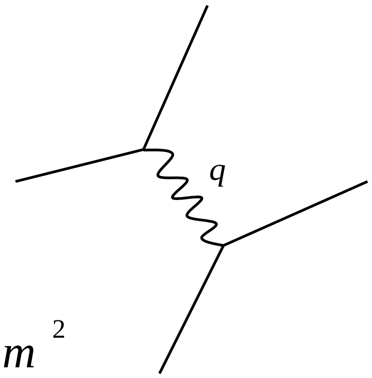
why do they do that?

by yielding their energy to the non-condensed particles, the total entropy is increased.

preBEC BEC

Thermalization occurs due to gravitational interactions

PS + Q. Yang, PRL 103 (2009) 111301



$$\frac{G m^2}{q^2}$$

$$\Gamma_g \sim 4\pi G n m^2 l^2 \quad \text{with } l = (m\,\delta v)^{-1}$$

$$\sim 5 \cdot 10^{-7} H(t_1) \left(\frac{f}{10^{12}\ \mathrm{GeV}} \right)^{\frac{2}{3}}$$

at time t_1

$$\Gamma_g(t)/H(t) \propto t\,a(t)^{-1} \propto a(t)$$

Gravitational interactions thermalize the axions and cause them to form a BEC when the photon temperature

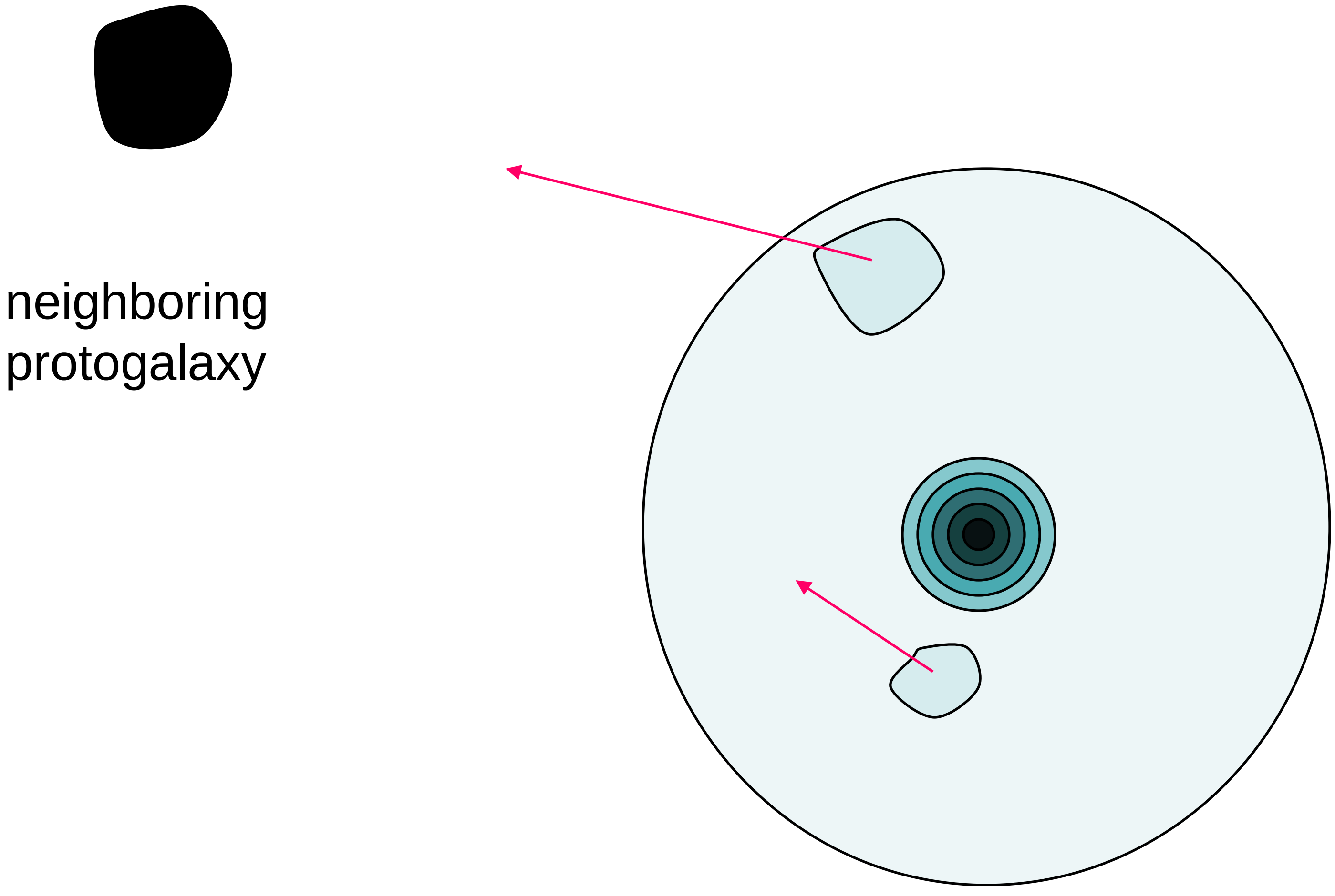
$$T_\gamma \sim 500 \text{ eV} \left(\frac{f}{10^{12} \text{ GeV}} \right)^{\frac{1}{2}}$$

After that

$$\delta v \sim \frac{1}{mt}$$

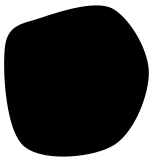
$$\Gamma_g(t) / H(t) \propto t^3 a(t)^{-3}$$

Tidal torque theory

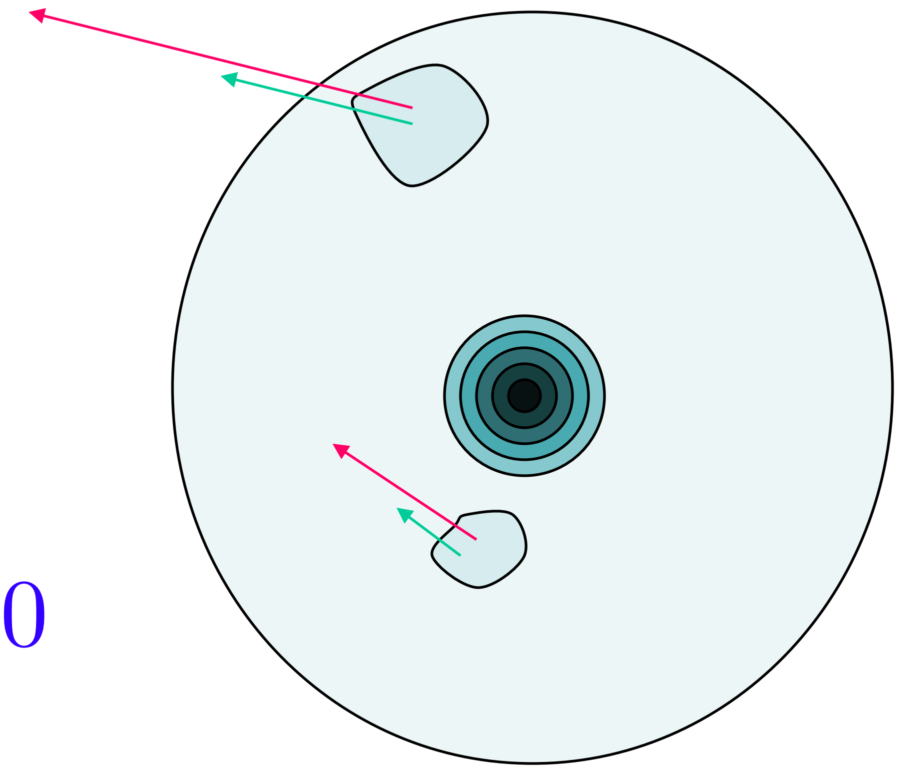


Stromberg 1934; Hoyle 1947; Peebles 1969, 1971

Tidal torque theory with ordinary CDM



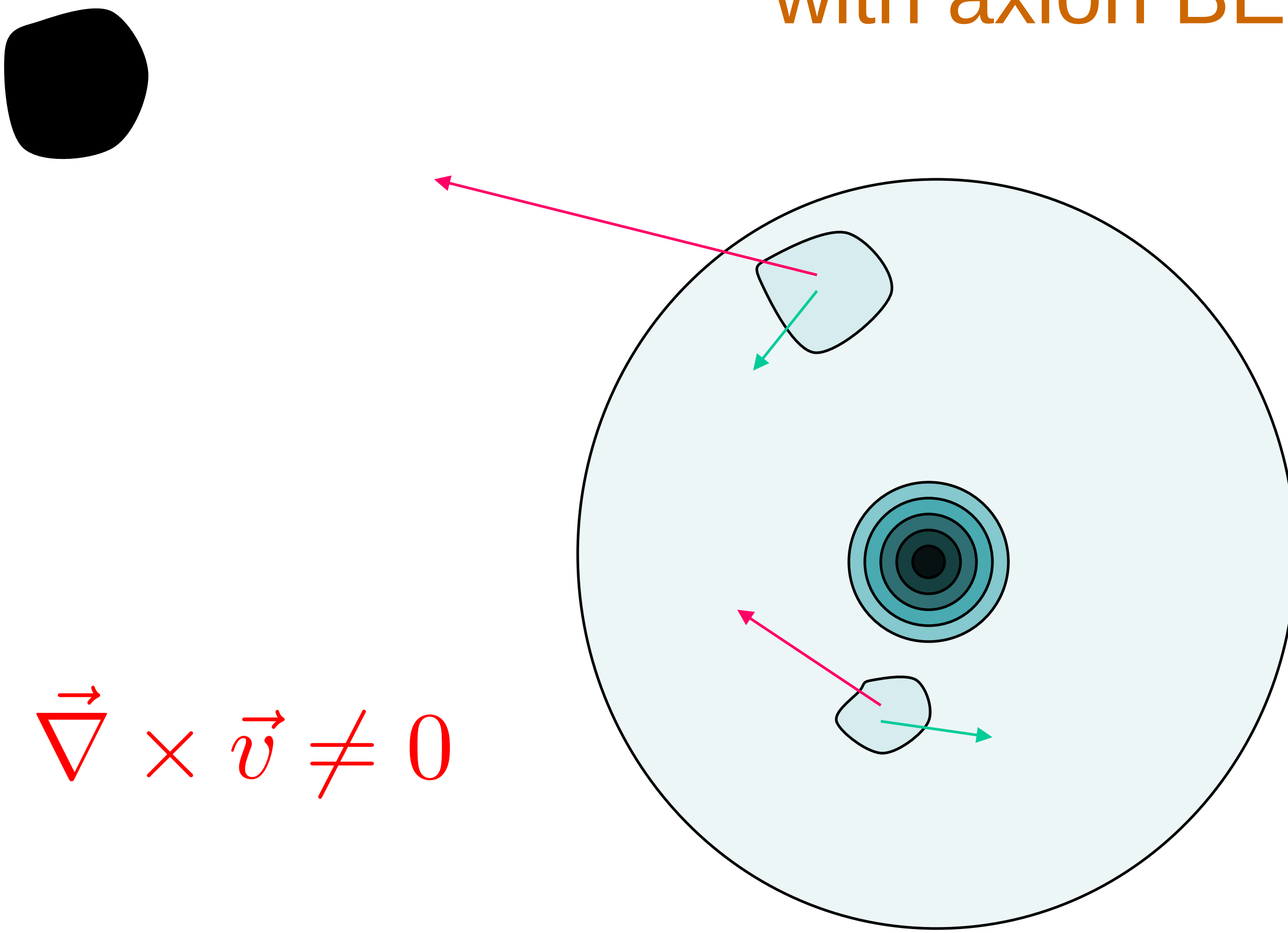
neighboring protogalaxy



$$\vec{\nabla} \times \vec{v} = 0$$

the velocity field remains irrotational

Tidal torque theory with axion BEC



$$\vec{\nabla} \times \vec{v} \neq 0$$

net overall rotation is obtained because, in the lowest energy state, all axions fall with the same angular momentum

Galactic halos live in phase space

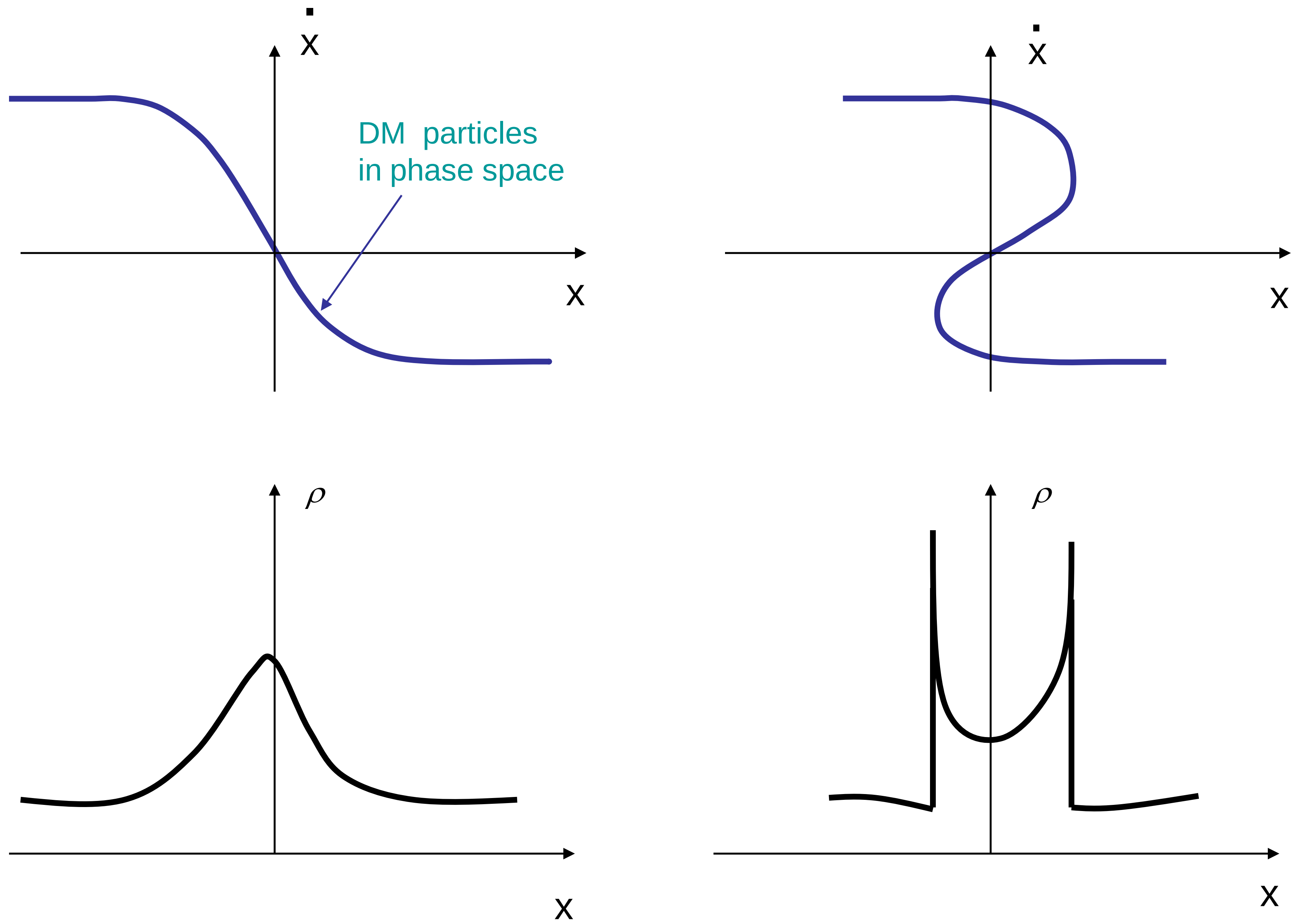
ordinary fluid

$$d(\vec{r};t) \qquad \vec{\mathrm{v}}(\vec{r};t)$$

dark matter (collisionless) fluid

$$f(\vec{r},\vec{\mathrm{v}};t)$$

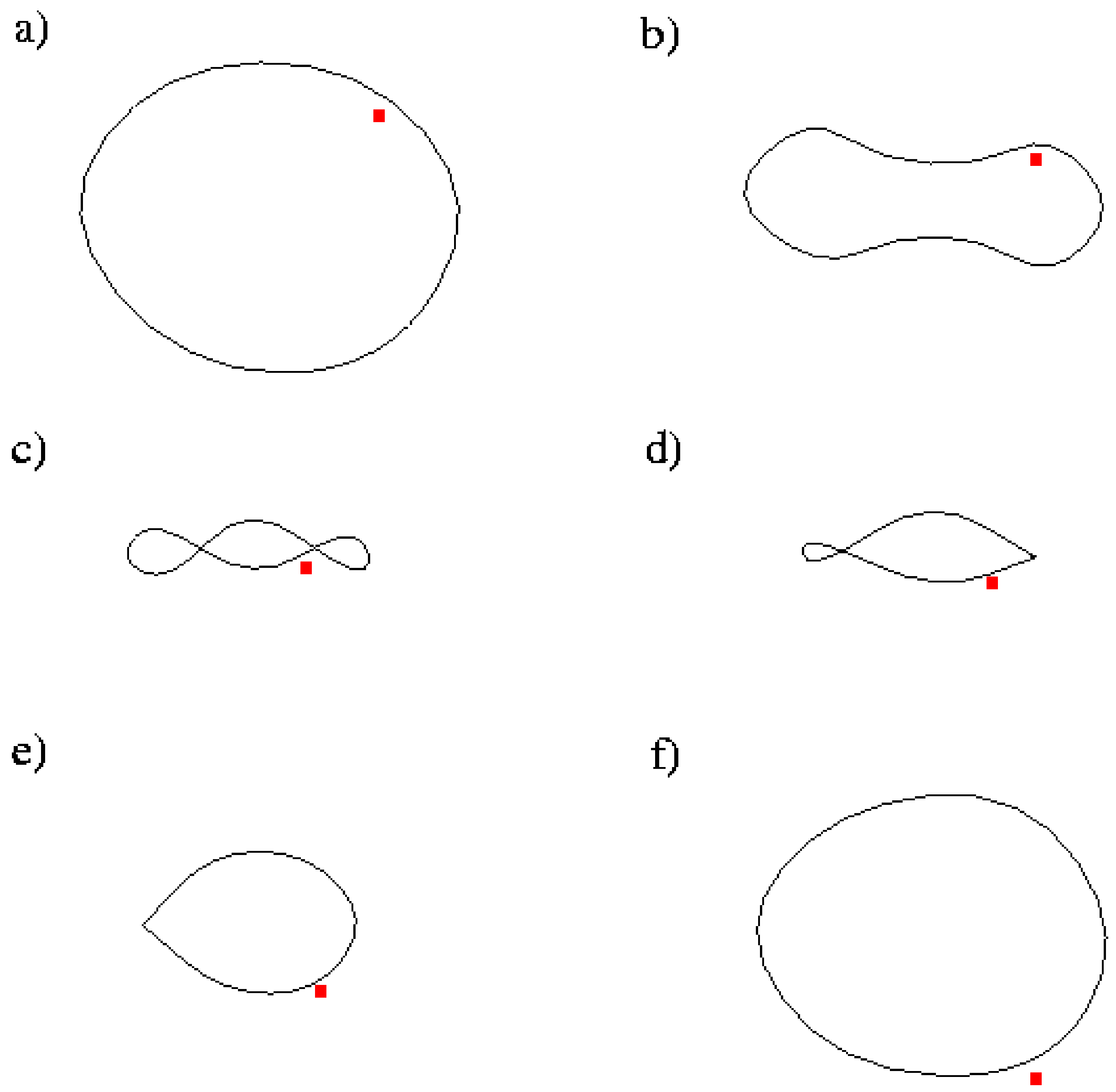
DM forms caustics in the non-linear regime



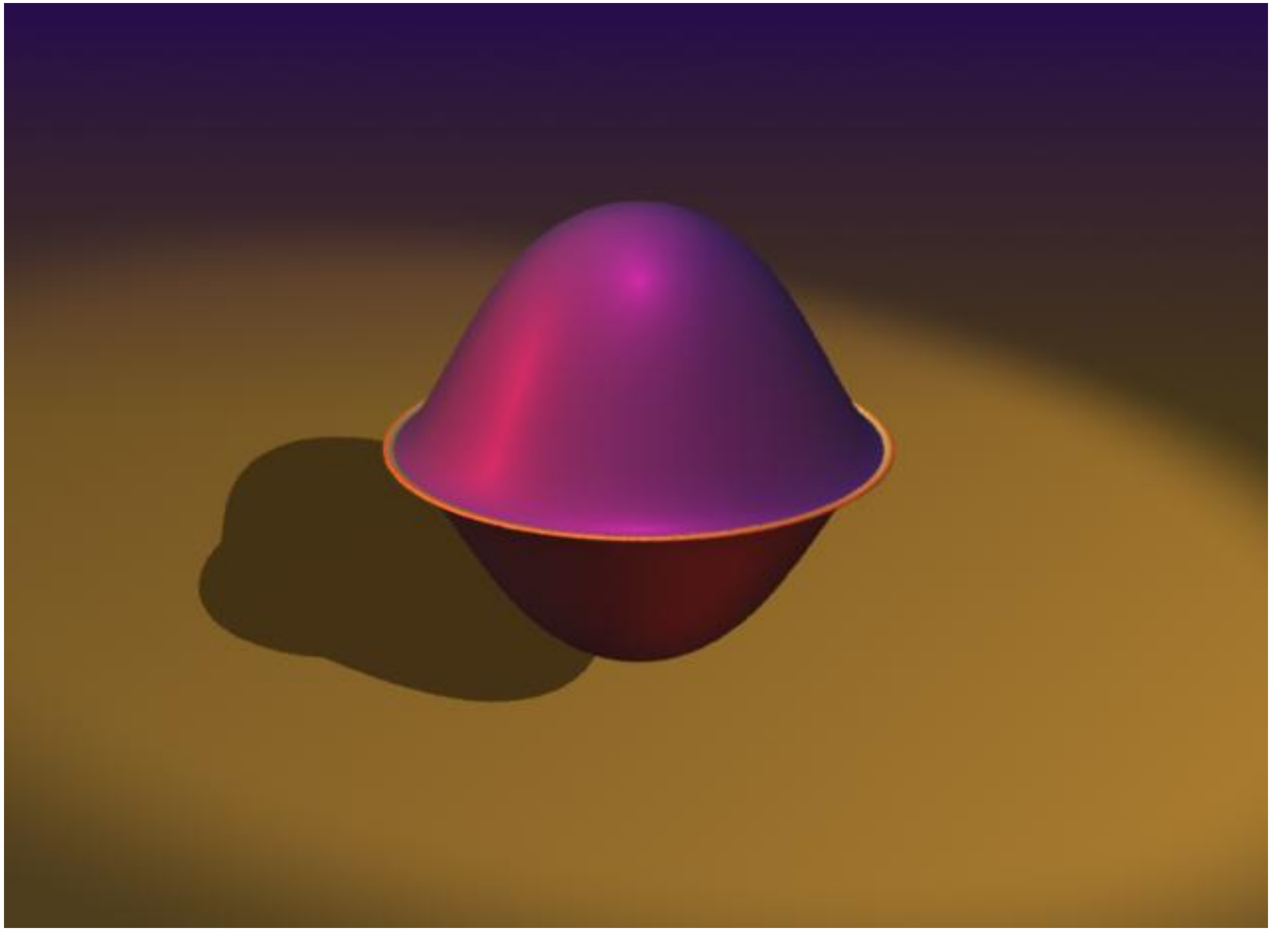
A shell of particles, part of a continuous flow.

The shell has net oreall rotation.

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

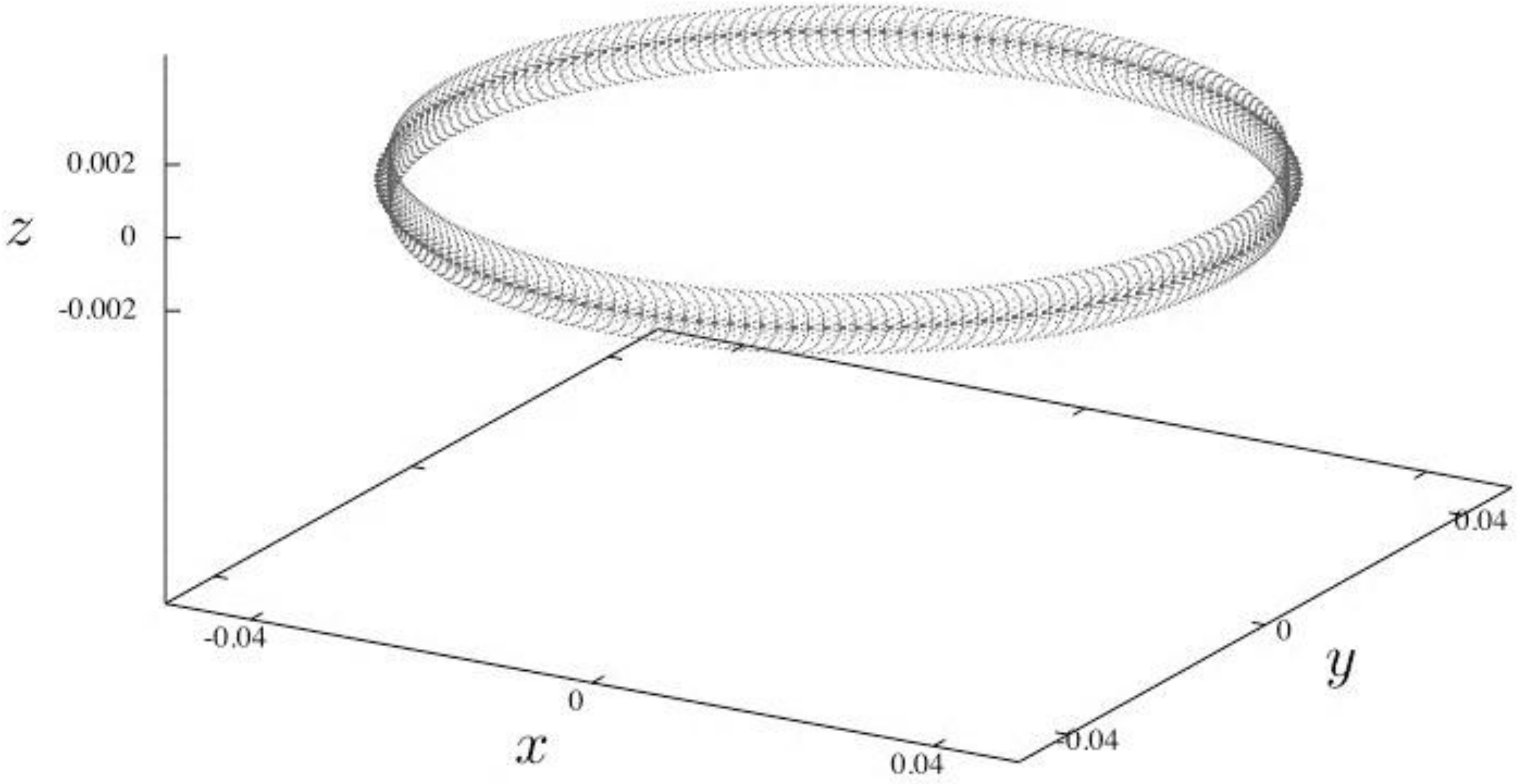


Sphere turning inside out

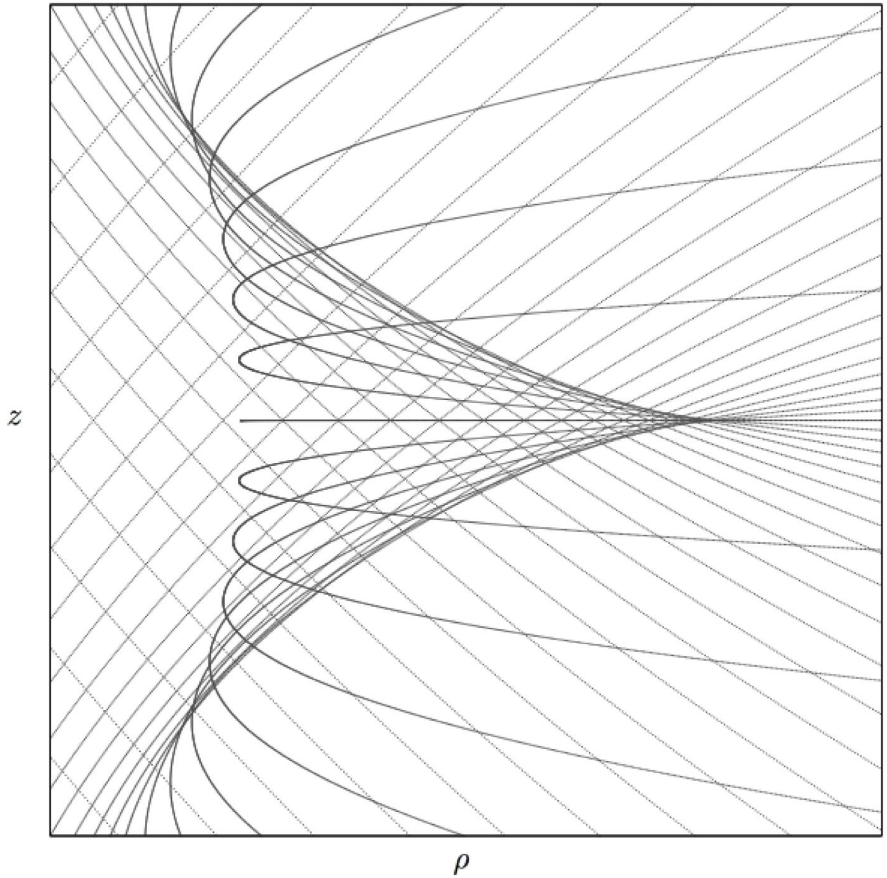


simulations by Arvind Natarajan

in case of net overall rotation

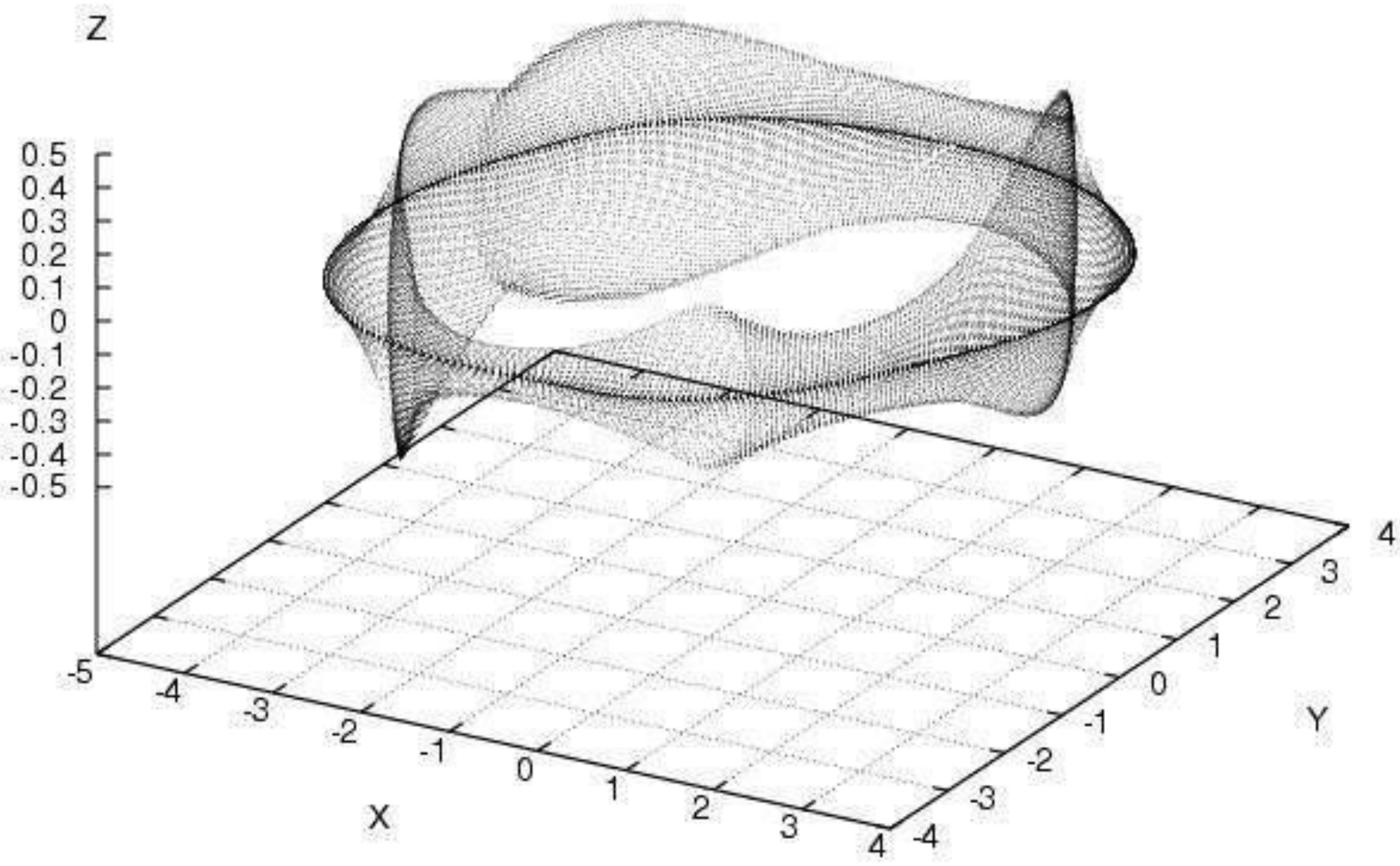


The caustic ring cross-section

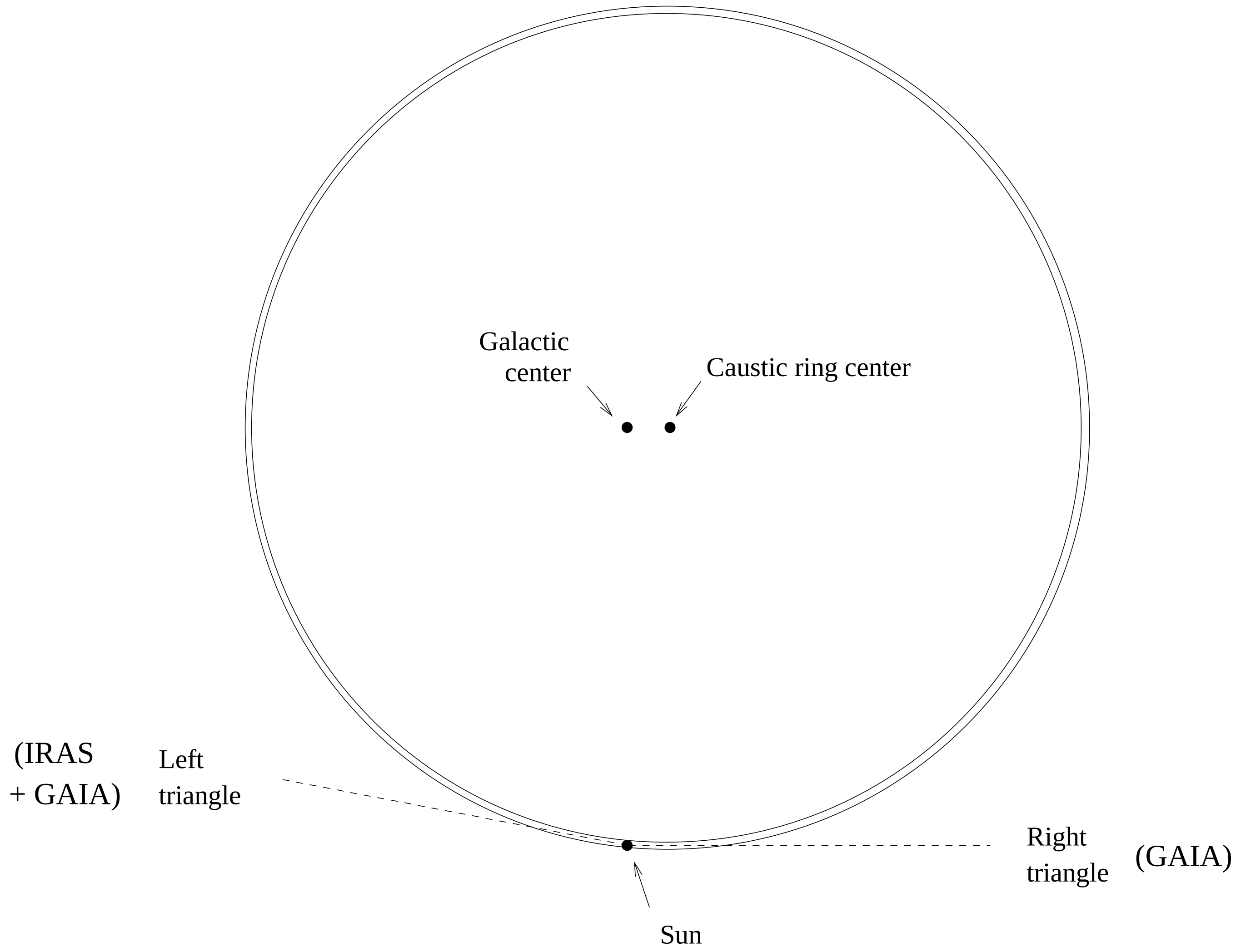


D_{-4}

an elliptic umbilic catastrophe

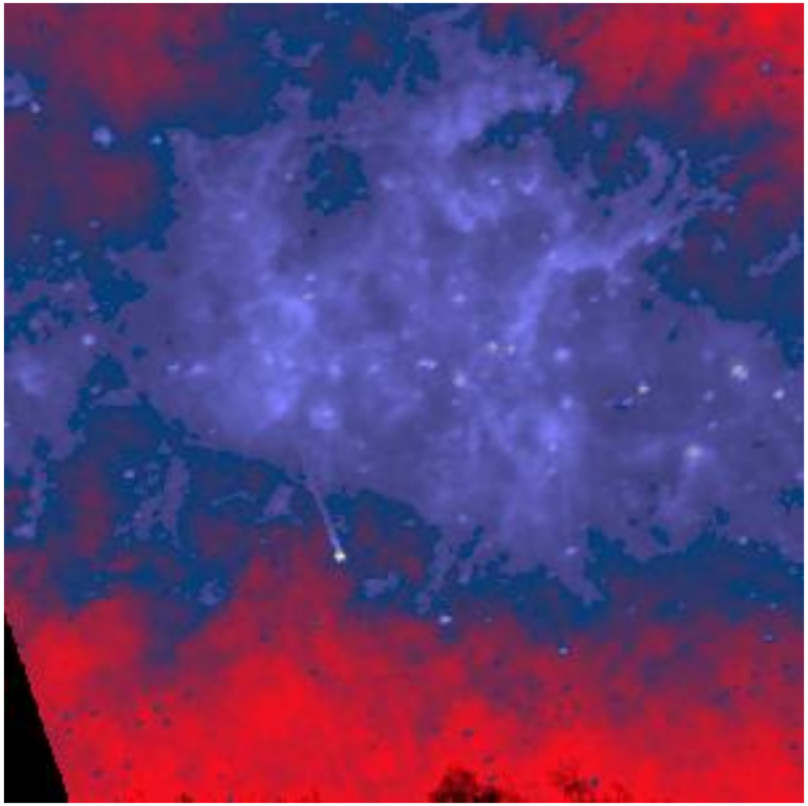

Z
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-5
-4
-3
-2
-1
0
1
2
3
4
X
4
3
2
1
0
-1
-2
-3
-4
Y

S. Chakrabarty, Y. Han, A. Gonzalez & PS, 2007.10509



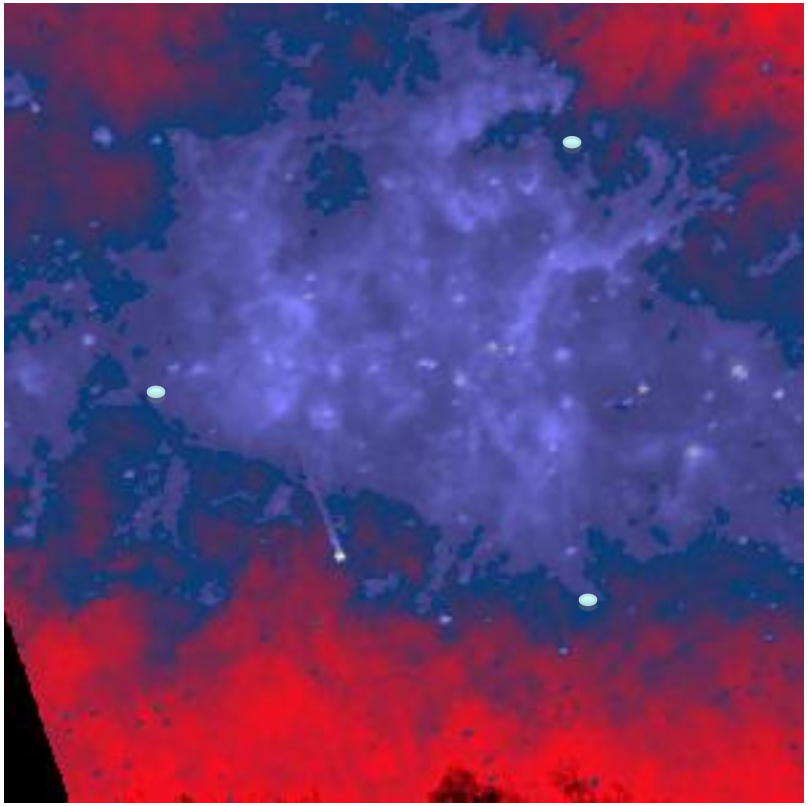
IRAS $12\ \mu m$

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



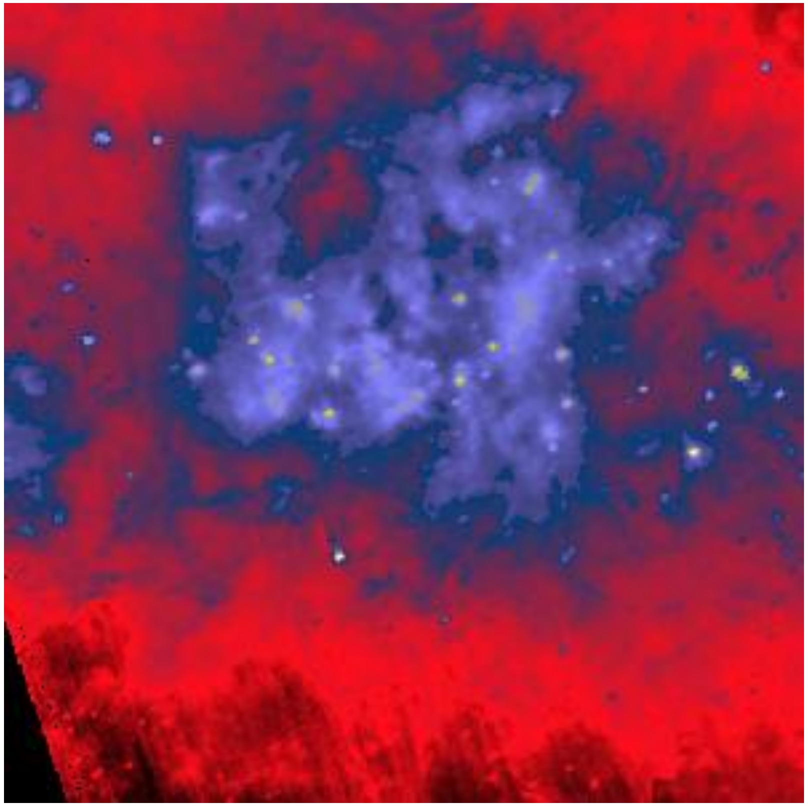
IRAS $12\ \mu m$

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

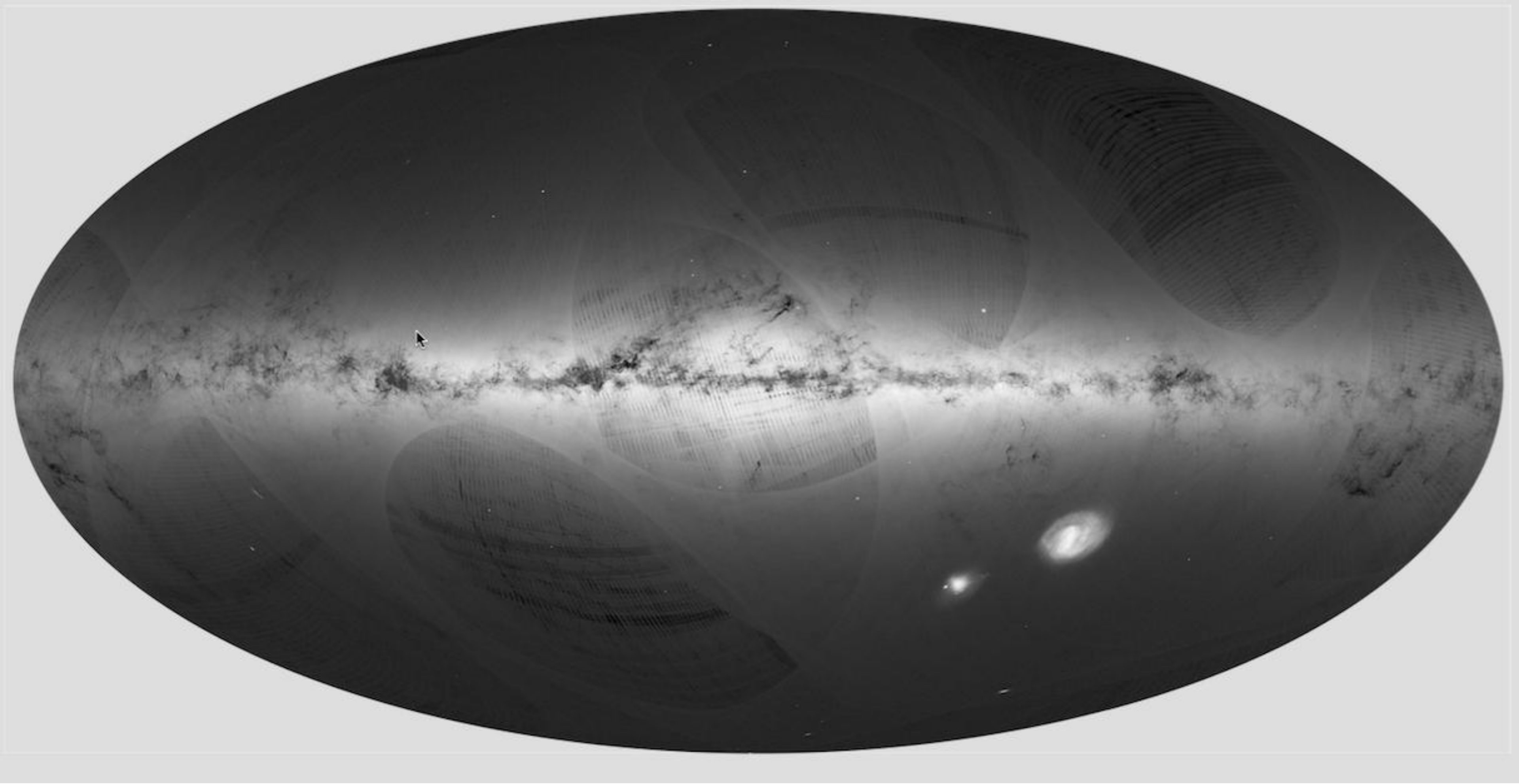


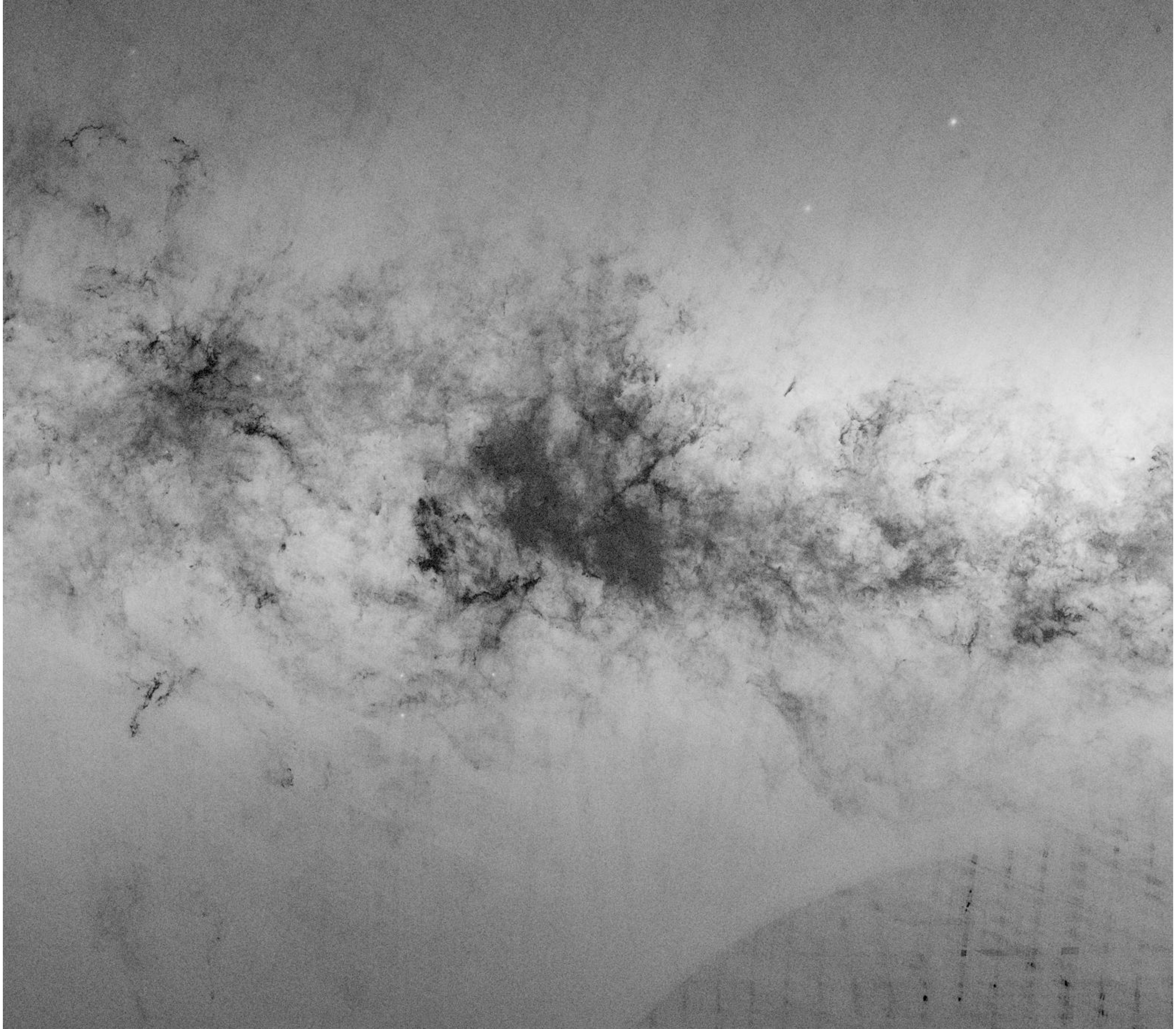
IRAS $25\ \mu m$

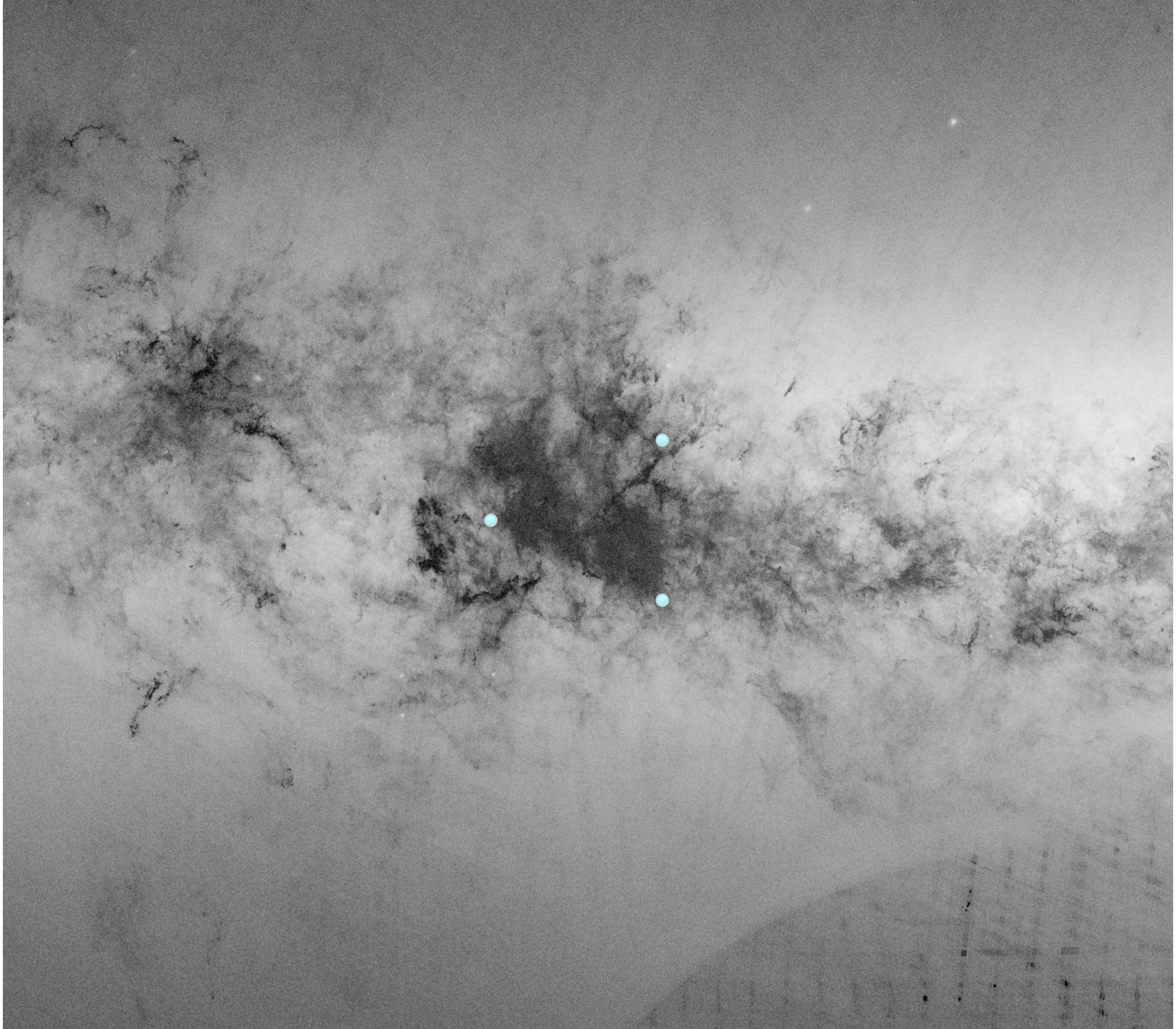
$(l, b) = (80^{o}, 0^{o})$ $10^{o} \times 10^{o}$

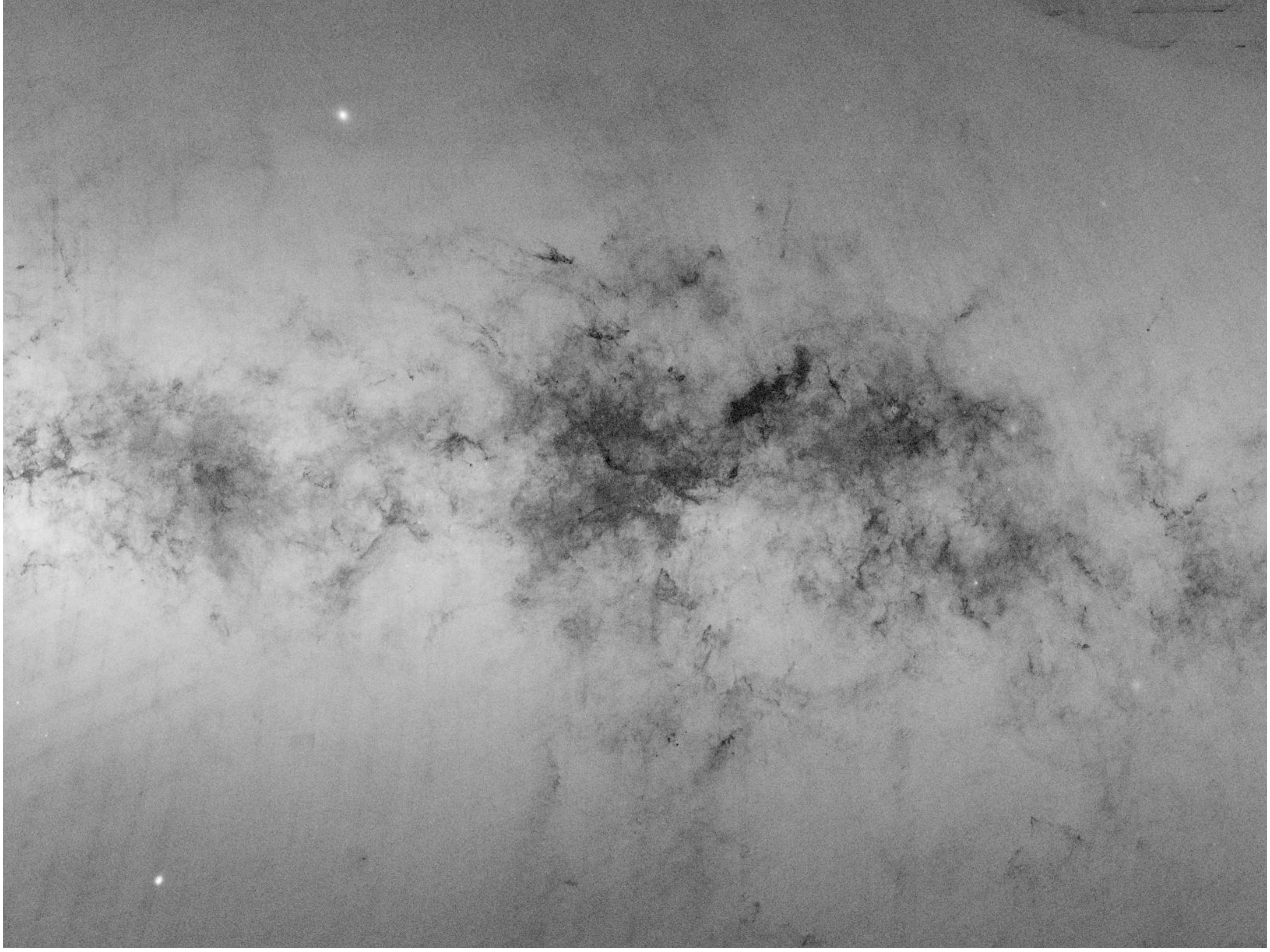


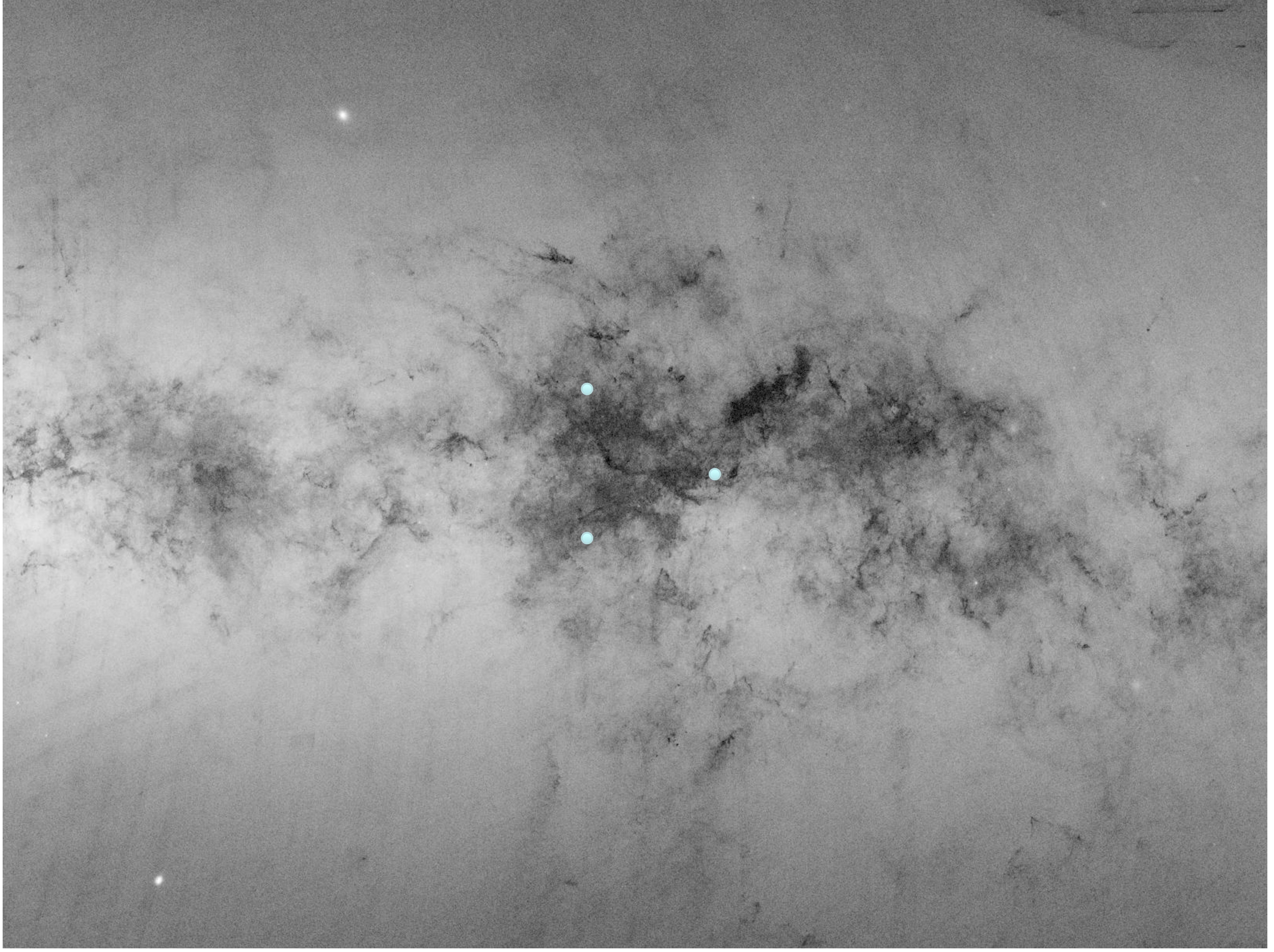
GAIA sky map (2016)



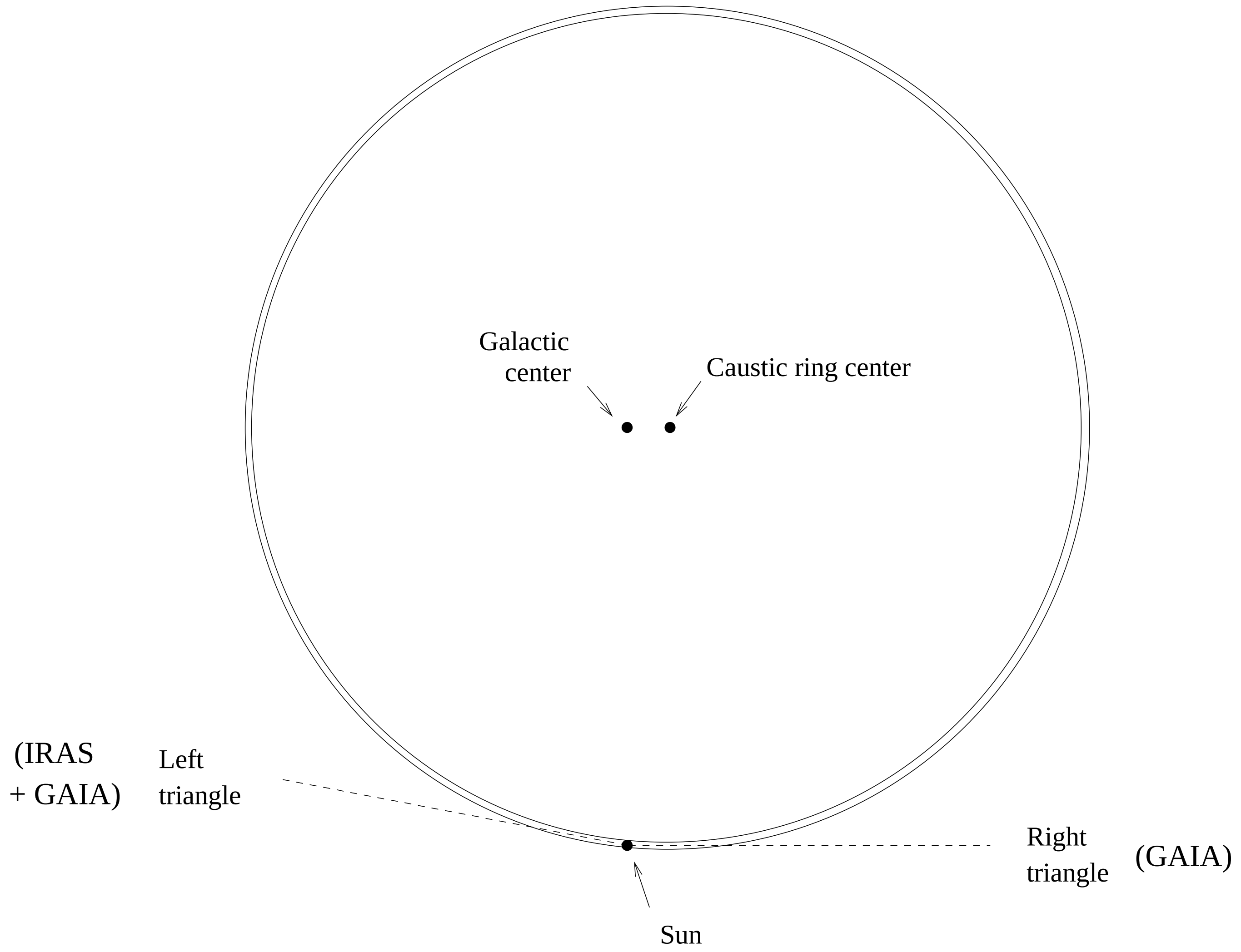


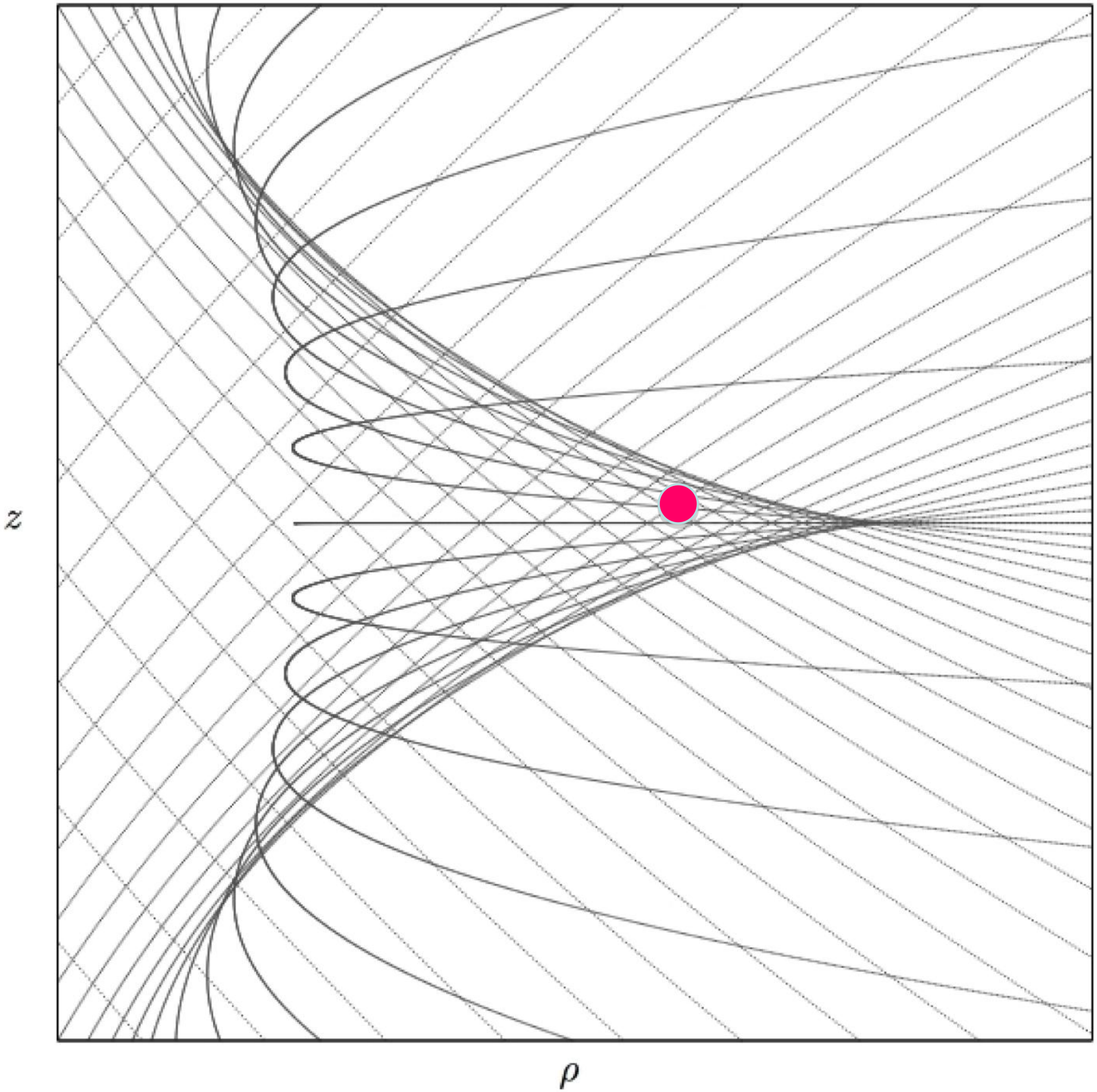




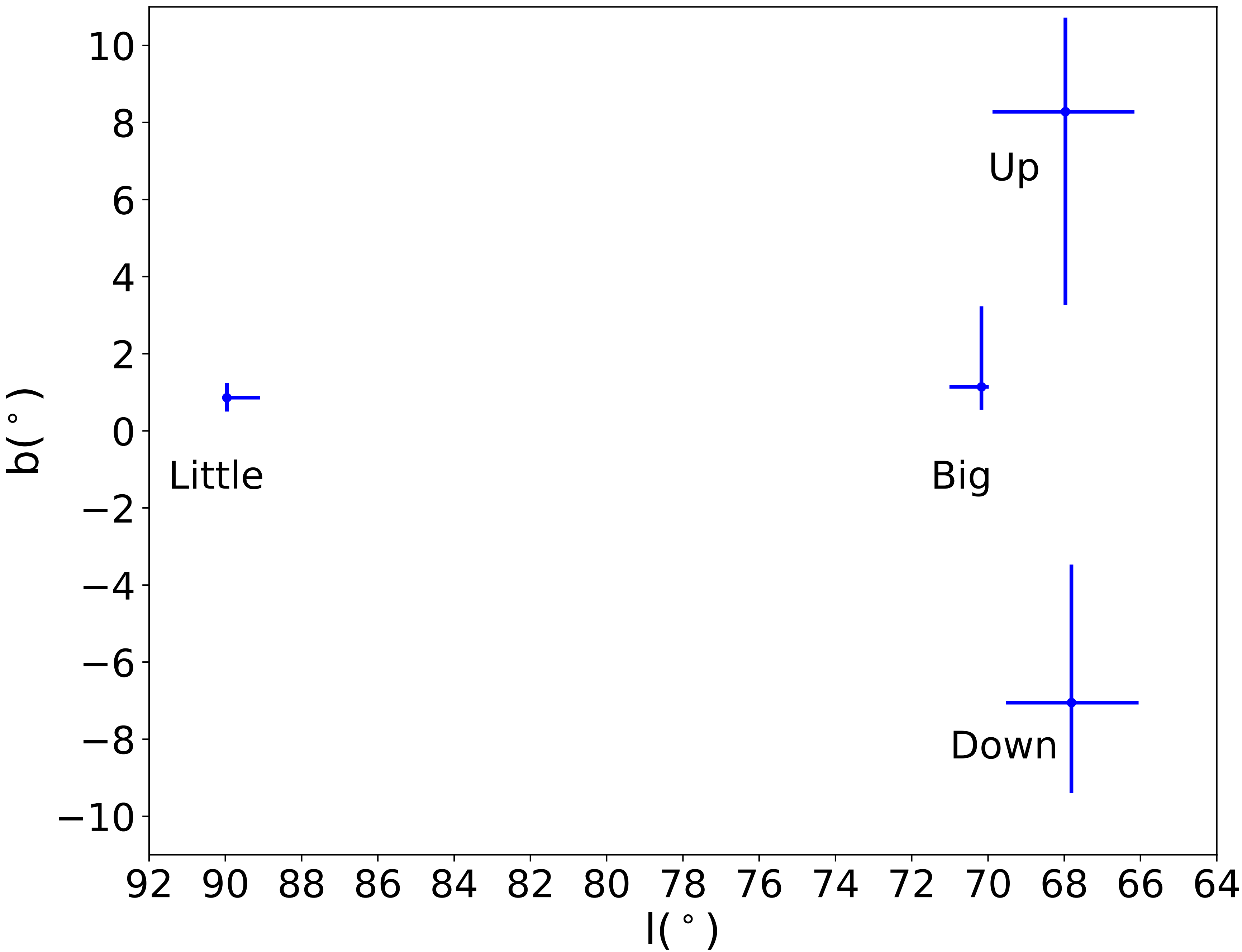


S. Chakrabarty, Y. Han, A. Gonzalez & PS, 2007.10509





z
ρ



10
8
6
4
2
0
−2
−4
−6
−8
−10
b(∘)
Up
Big
Little
Down
92
90
88
86
84
82
80
78
76
74
72
70
68
66
64
l(∘)

Conclusions

- Axions solve the strong CP problem
- A population of cold axions is naturally produced in the early universe which may be the dark matter today
- Axion dark matter has distinctive properties in large scale structure formation