Encounters with the Axion

Pierre Sikivie

Physics Department e-Colloquium
University of Florida
January 28, 2021

Supported by US Department of Energy grant DE-SC 00101296

encounters with

encounters with **jesus**
encounters with **the archdruid**
encounters with **angels**
encounters with **god**
encounters with **jesus in the bible**
encounters with **unexpected animals**
encounters with **jesus tim keller**
encounters with **canada**
encounters with **the holy spirit**
encounters with **dolphins**

Google Search | I'm Feeling Lucky

Report inappropriate predictions

Helen Quinn Roberto Peccei

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

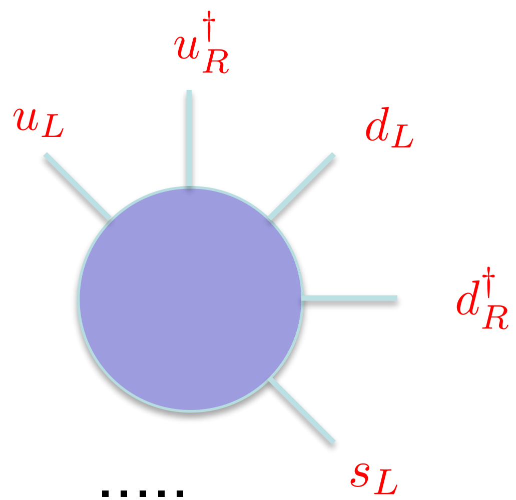
The $U_A(1)$ Problem

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



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

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

The Strong CP Problem

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

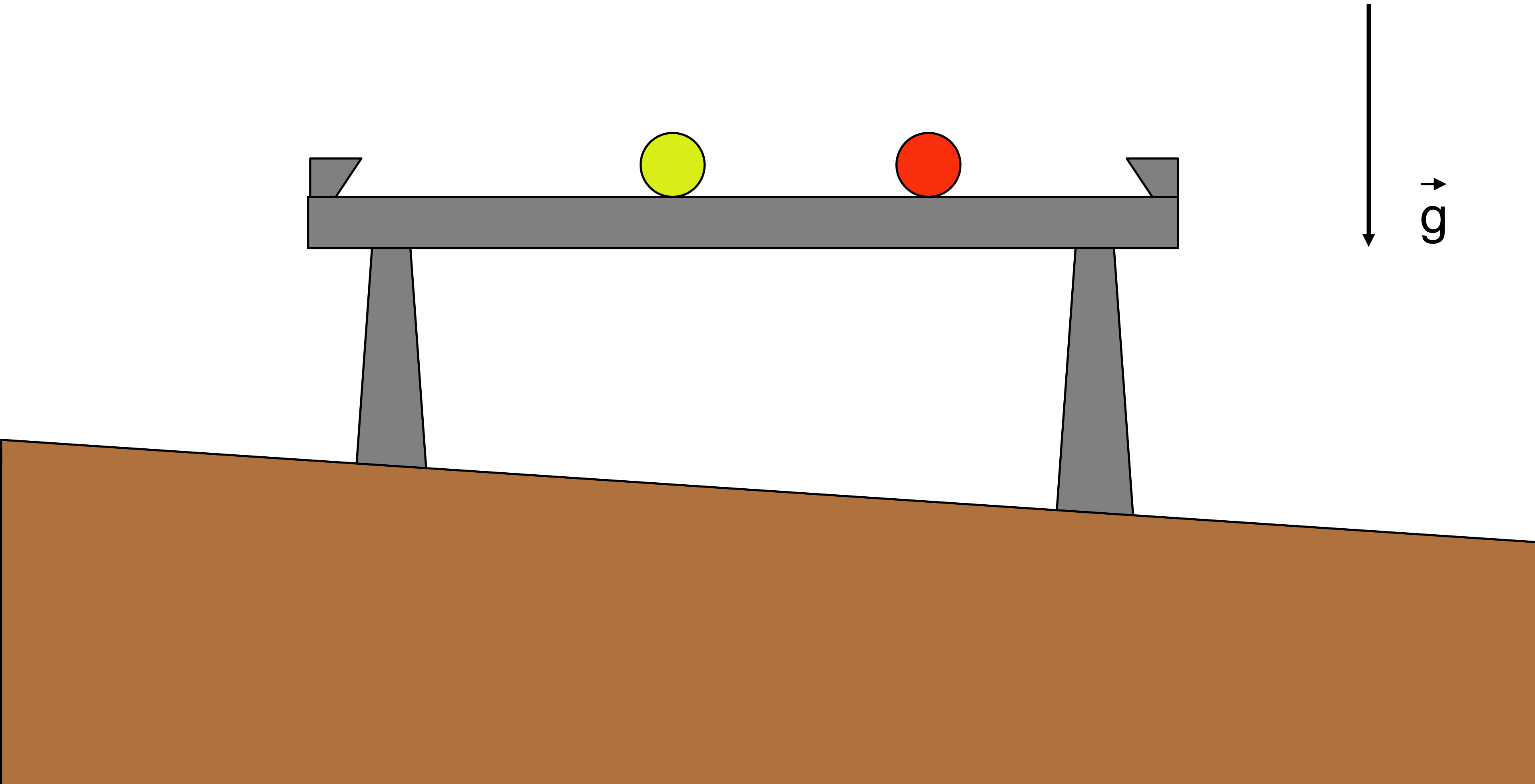
is expected to be of order one

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,

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

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

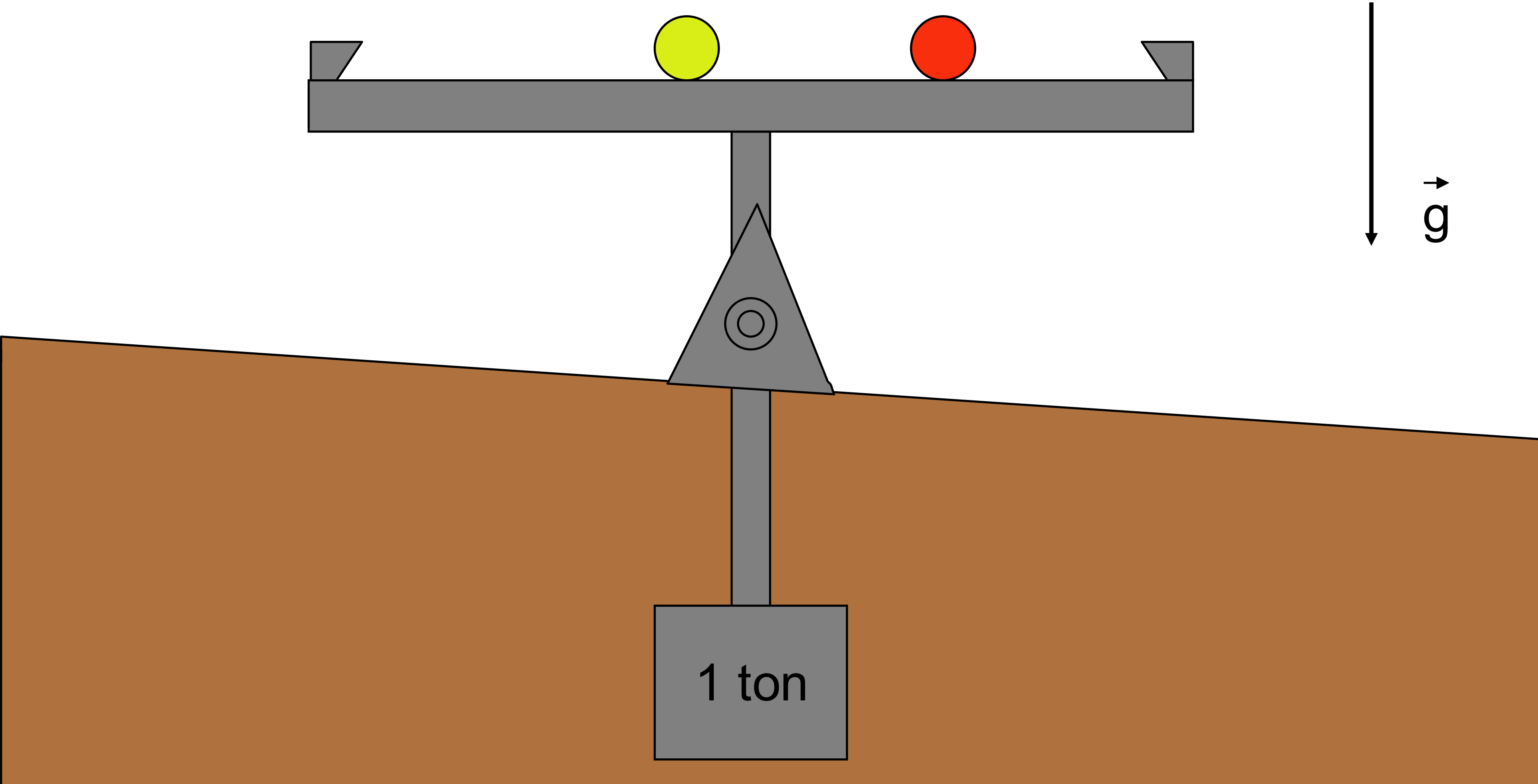
and a light neutral pseudoscalar particle is predicted: the axion.

Weinberg, Wilczek 1978

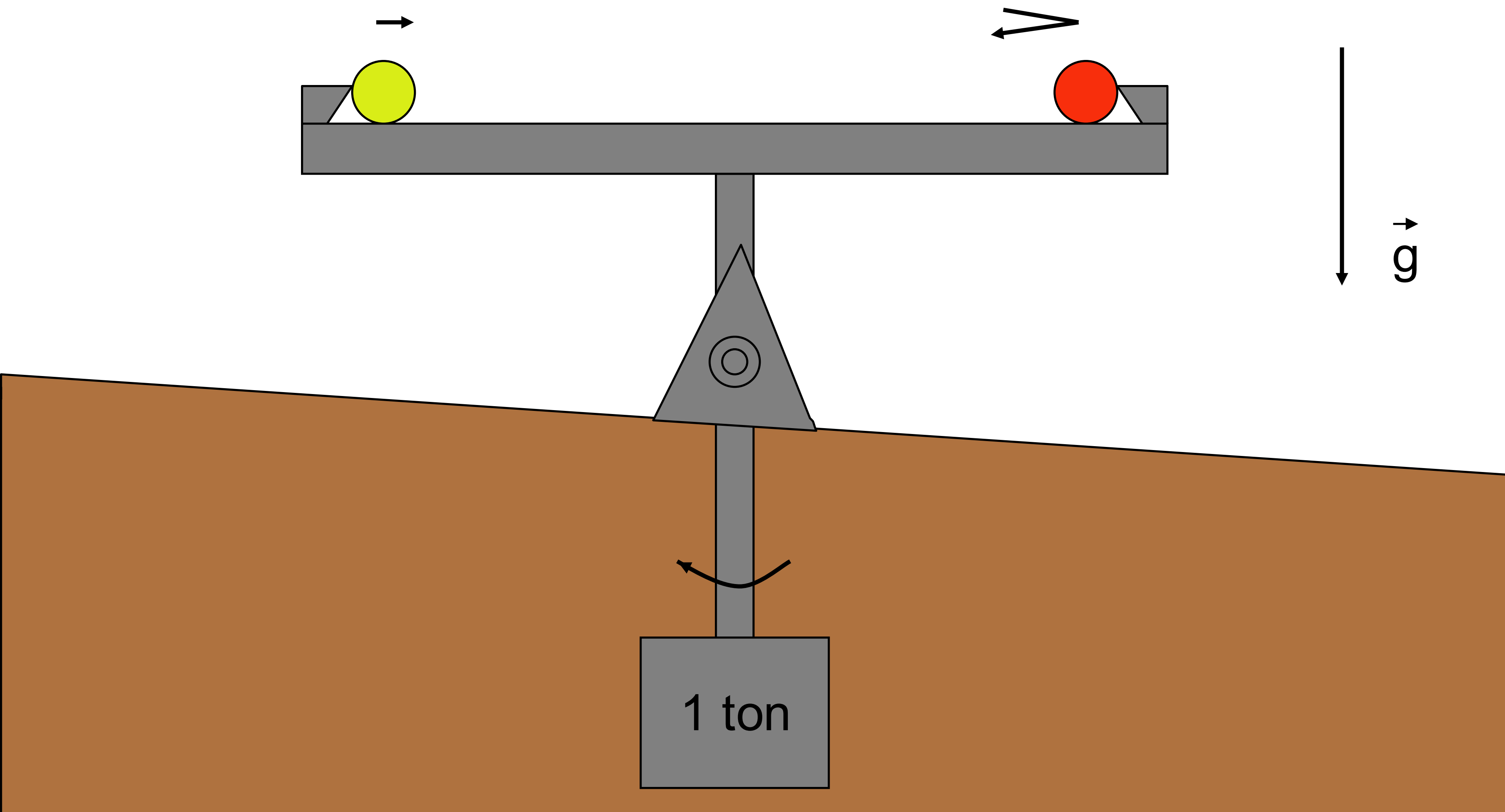
Steven Weinberg

Frank Wilczek

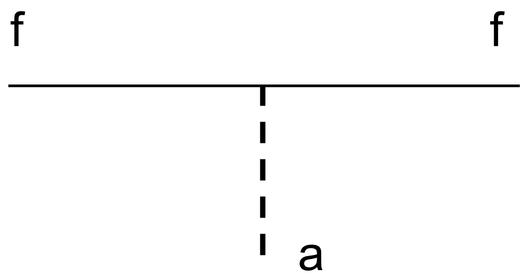
A self adjusting pooltable



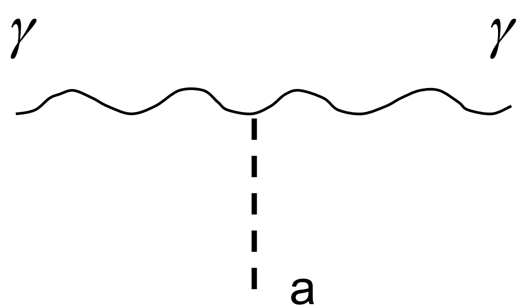
Searching for the pooltable oscillation quantum



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



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

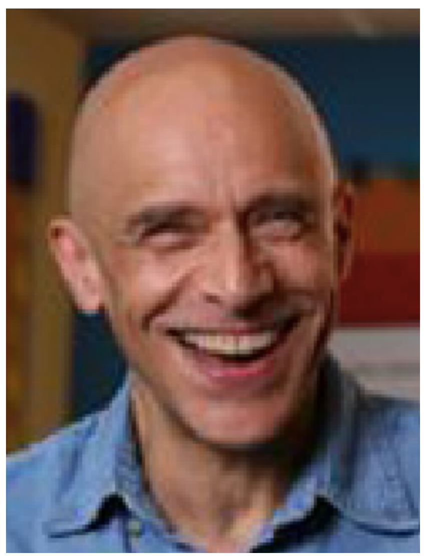


$$\mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

g_γ = 0.97 in KSVZ model
0.36 in DFSZ model




J.E. Kim   M. Shifman   A. Vainshtein   V.I. Zakharov

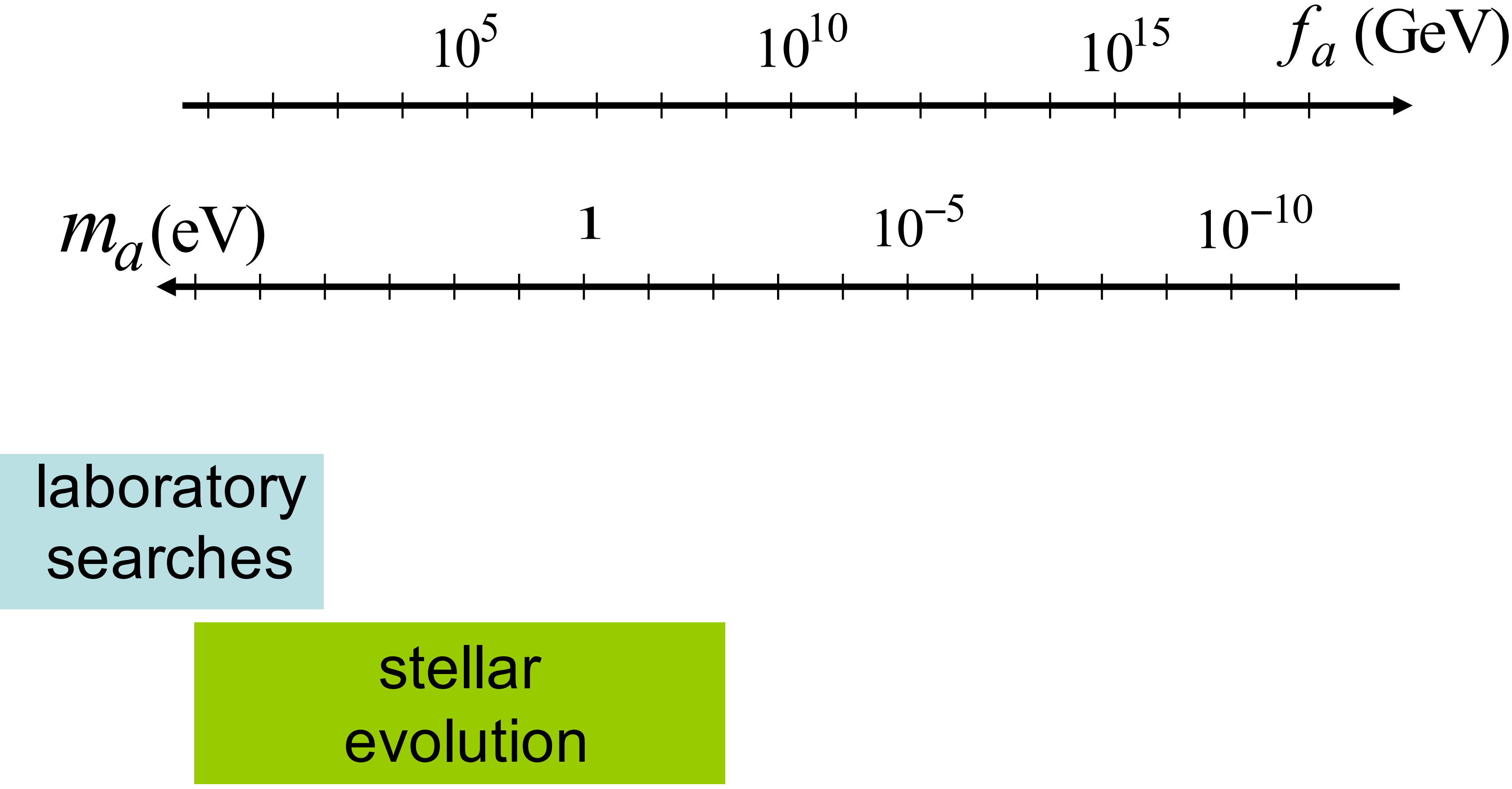



M. Dine   W. Fischler   M. Srednicki   A. Zhitnitsky

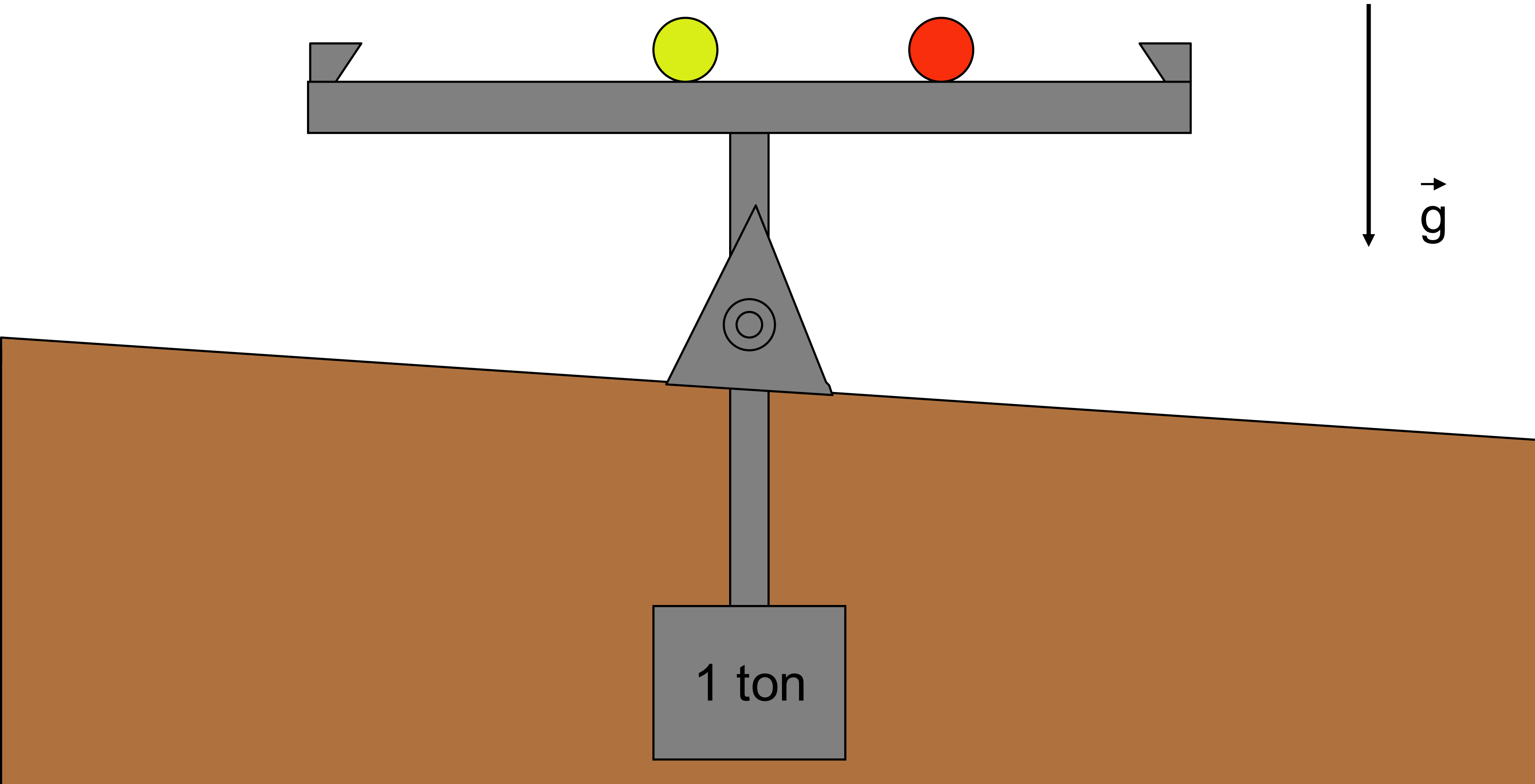
Axions are constrained by

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

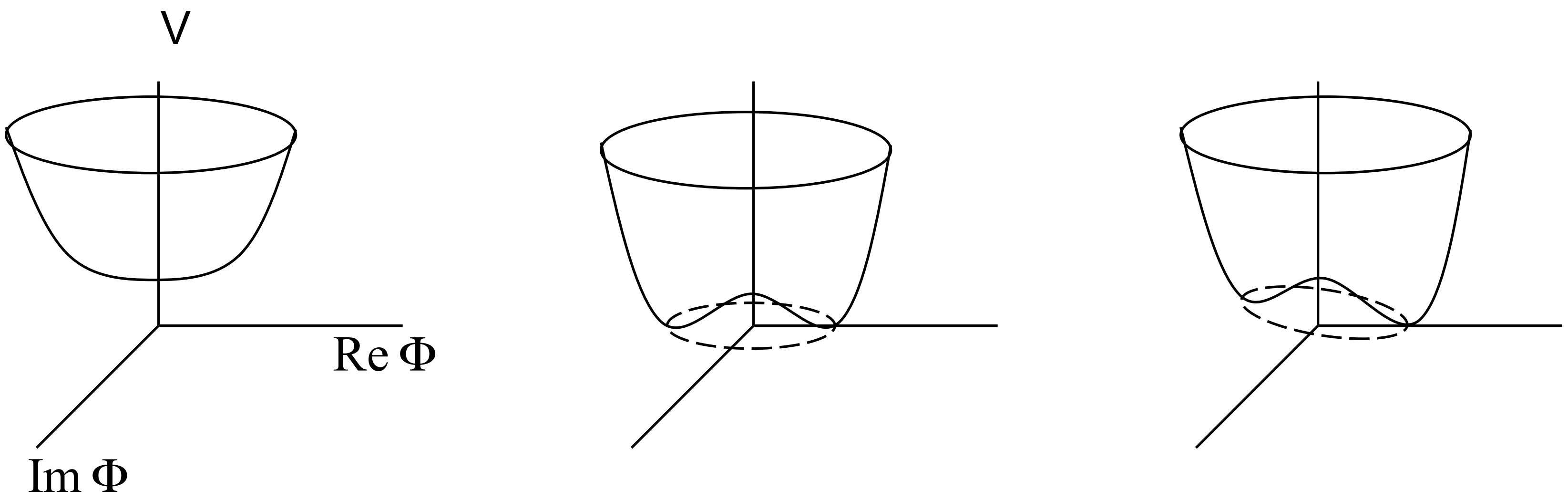
Axion constraints



A self adjusting pooltable



Effective potential V(T, Φ)

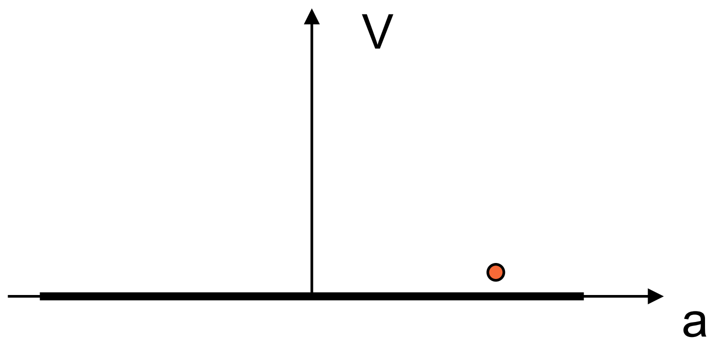


$T > f_a$ $\quad$ $f_a > T > 1\,\mathrm{GeV}$ $\quad$ $1\,\mathrm{GeV} > T$

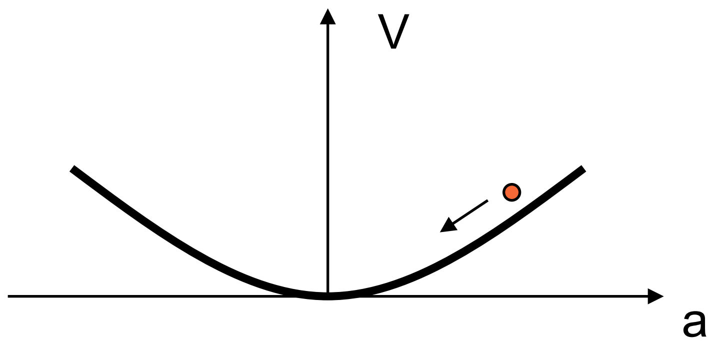
$f_a > T > 1\,\mathrm{GeV}$ → axion strings

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

Axion production by vacuum realignment



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



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

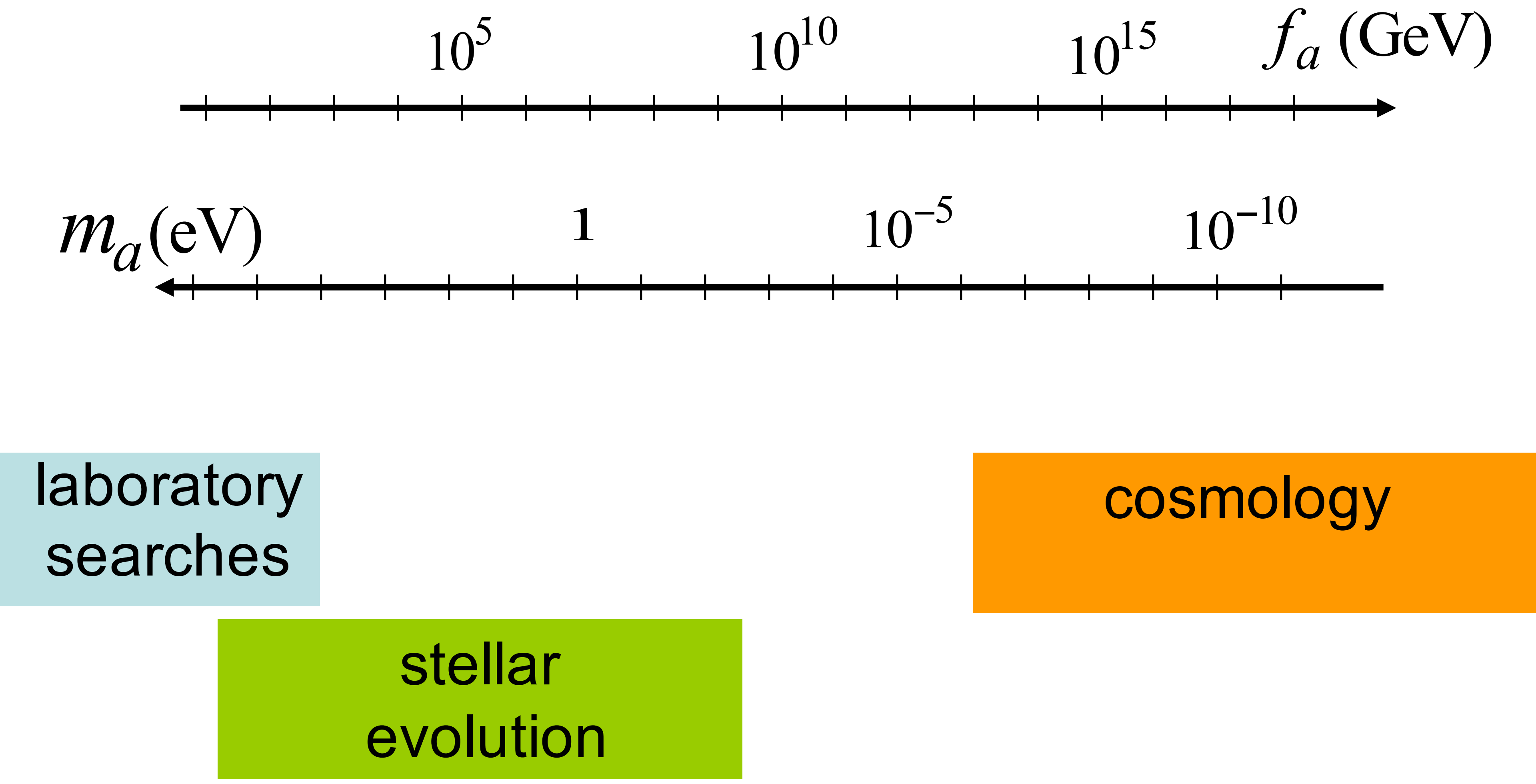
$$n_a(t_1) \simeq \frac{1}{2} m_a(t_1) a(t_1)^2 \simeq \frac{1}{2t_1} f_a^2 \alpha(t_1)^2$$

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

initial misalignment angle

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

Axion constraints



James R. Ipser

Axions produced by vacuum realignment are cold dark matter

The Witten Effect (1979)

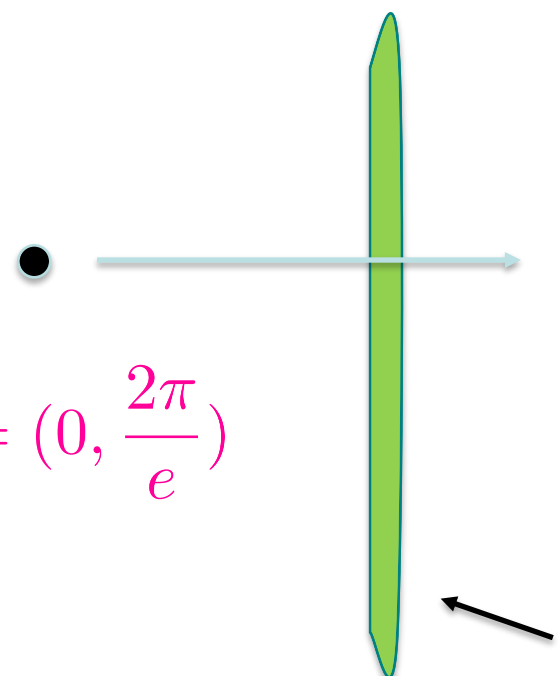
When $\theta \neq 0$ magnetic monopoles acquire electric charge

$$q_e = \frac{\alpha}{\pi}\,\theta\, q_m$$

$$q_e = \frac{\alpha}{\pi}(\theta + \frac{a}{f_a})q_m$$

with axion

$$(q_e, q_m) = (0, \frac{2\pi}{e})$$



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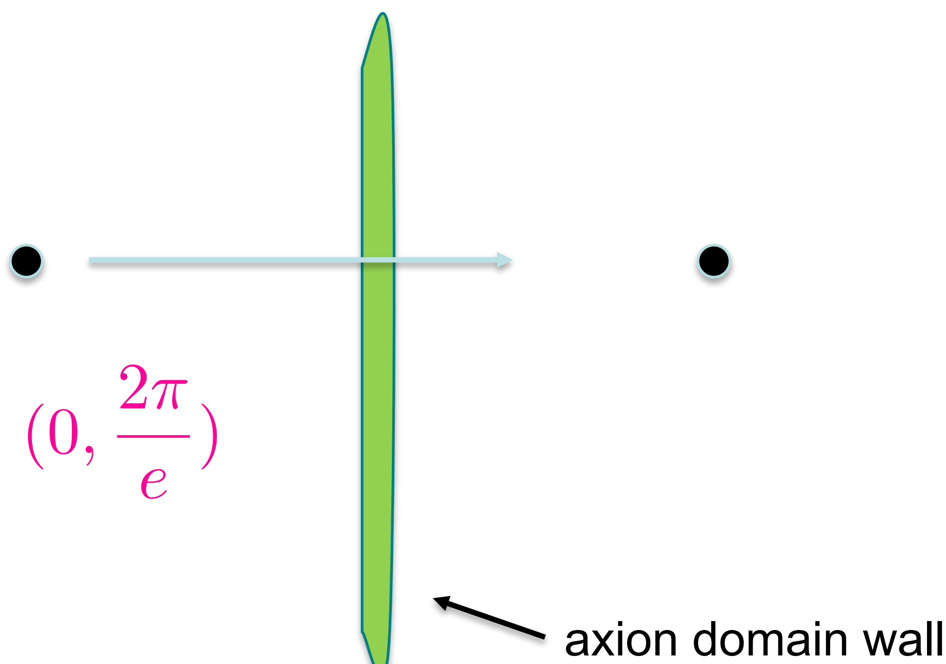

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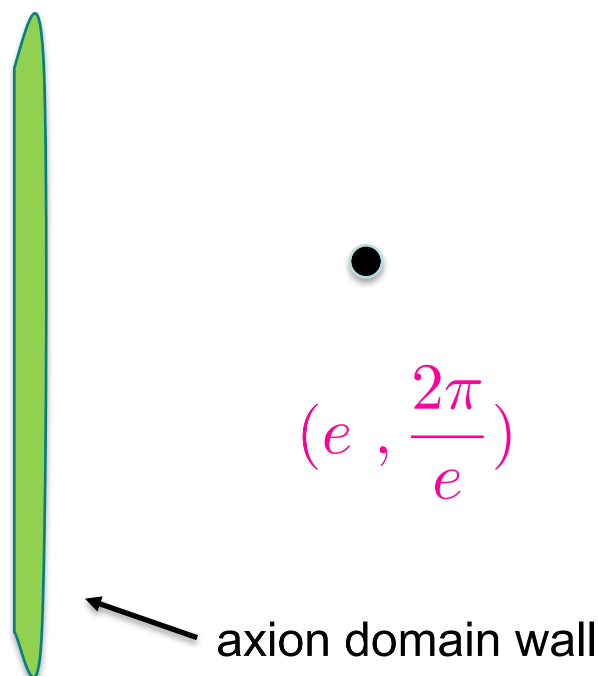


Axion Electrodynamics

$$\vec{\nabla} \cdot (\vec{E} - ga\vec{B}) = \rho_{\rm el}$$

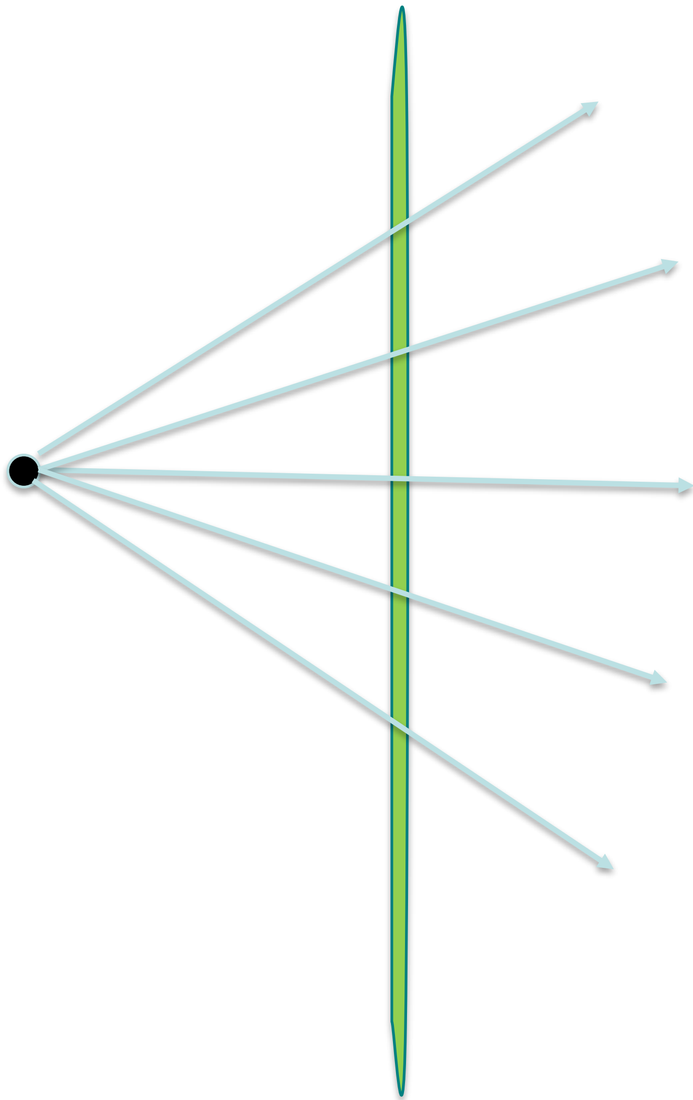
$$\vec{\nabla} \times (\vec{B} + ga\vec{E}) - \partial_t(\vec{E} - ga\vec{B}) = \vec{j}_{\rm el}$$

$$\vec{\nabla} \times \vec{E} + \partial_t \vec{B} = 0$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\partial_t^2 a - \nabla^2 a + m_a^2 a = -g\vec{E} \cdot \vec{B}$$

$$\vec{\nabla} \cdot \vec{E} = g\vec{\nabla} a \cdot \vec{B} + g a \vec{\nabla} \cdot \vec{B}$$



electric charge
surface density

$$\sigma_{\rm el} = g\Delta a B_\perp = 2\alpha B_\perp$$

Axion Electrodynamics

$$\vec{\nabla} \cdot (\vec{E} - ga\vec{B}) = \rho_{\rm el}$$

$$\vec{\nabla} \times (\vec{B} + ga\vec{E}) - \partial_t(\vec{E} - ga\vec{B}) = \vec{j}_{\rm el}$$

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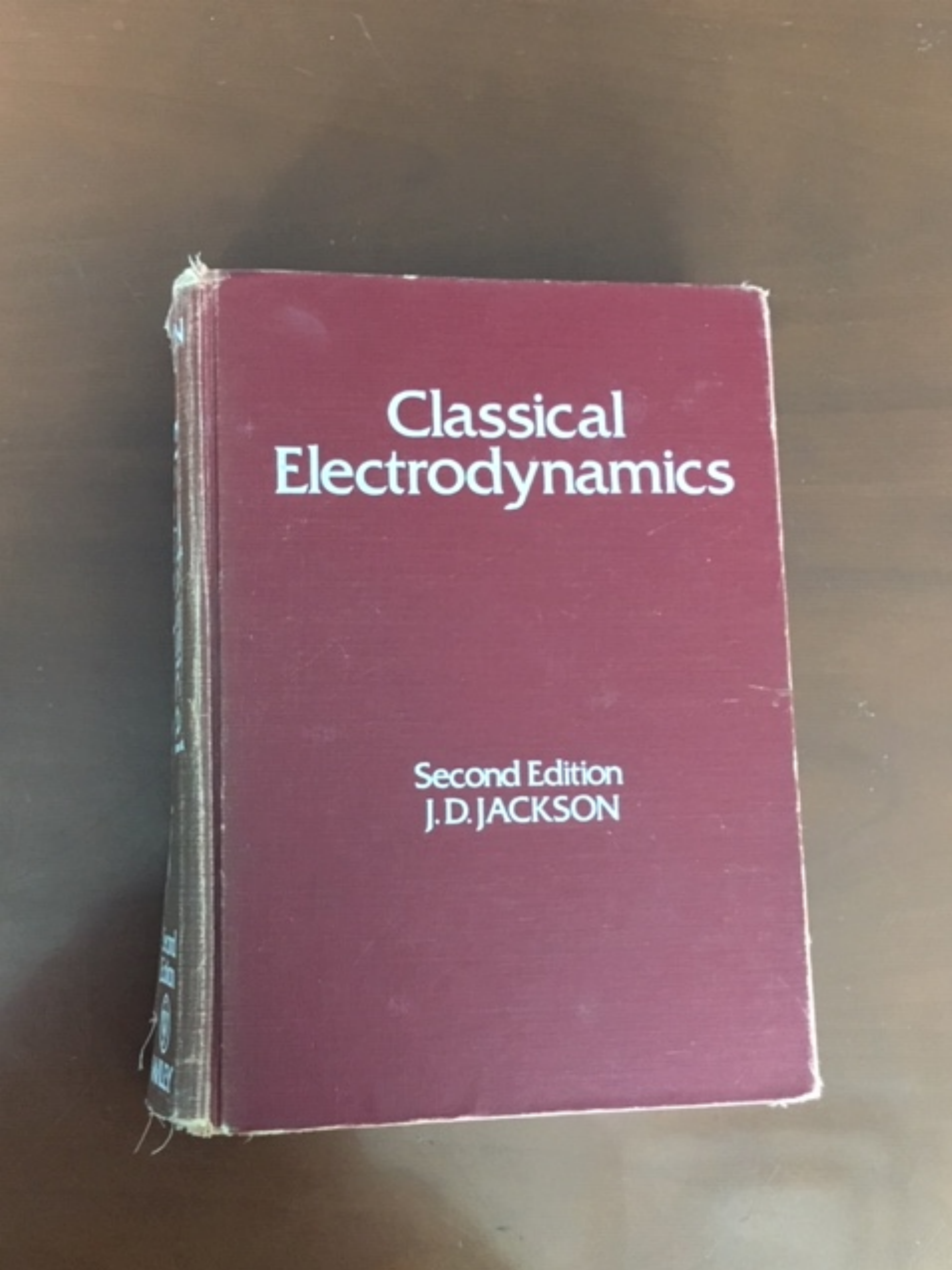
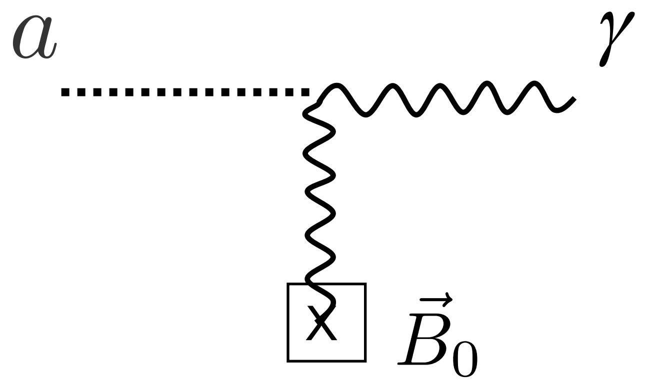

Classical
Electrodynamics
Second Edition
J. D. JACKSON

In background electric and magnetic fields

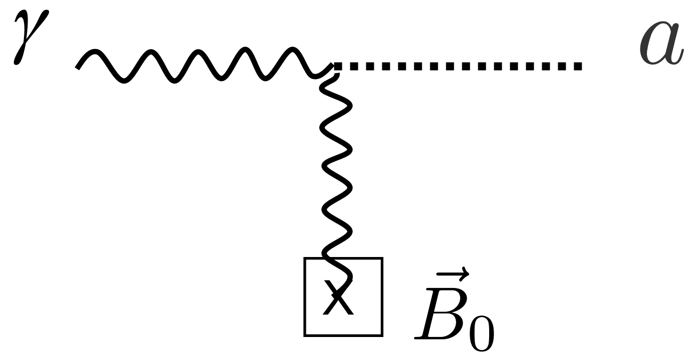
the axion field is a source of electromagnetic radiation

$$\partial_t^2 \vec{A} - \nabla^2 \vec{A} = g(\vec{E}_0 \times \vec{\nabla} a - \vec{B}_0 \partial_t a)$$



Axions convert to photons in a magnetic field and vice-versa

$$\partial_t^2 a - \nabla^2 a = -g\vec{B}_0 \cdot \vec{E}$$



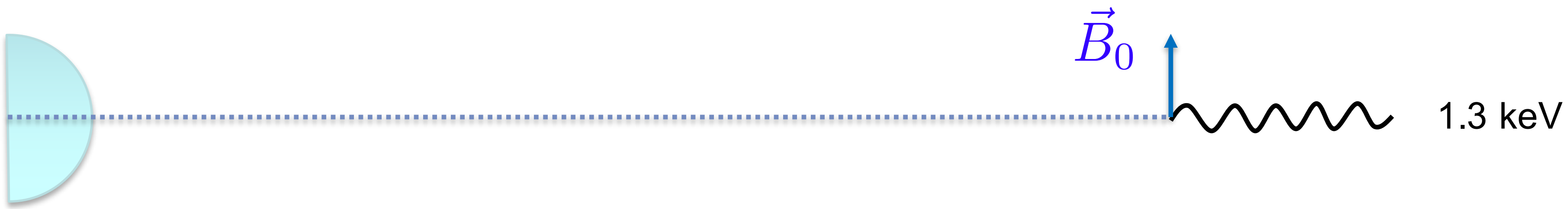
BUT

$$N_{\rm signal} \sim N_\gamma \left(\frac{\alpha}{\pi}\frac{B_0}{f_a}L\right)^2 \left(\frac{\alpha}{\pi}\frac{B_0}{f_a}L\right)^2 \sim 10^{-48} N_\gamma$$

We may search for axions produced in the Sun or present on Earth as dark matter

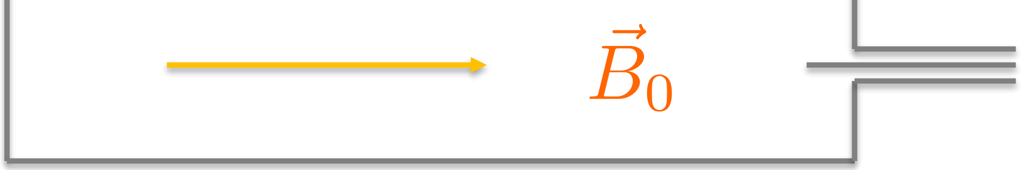
- Axion helioscope

10^{14} axions/cm^{2}sec



- Axion haloscope

10^{14} axions/cm^3



UF Axion Project

David Tanner

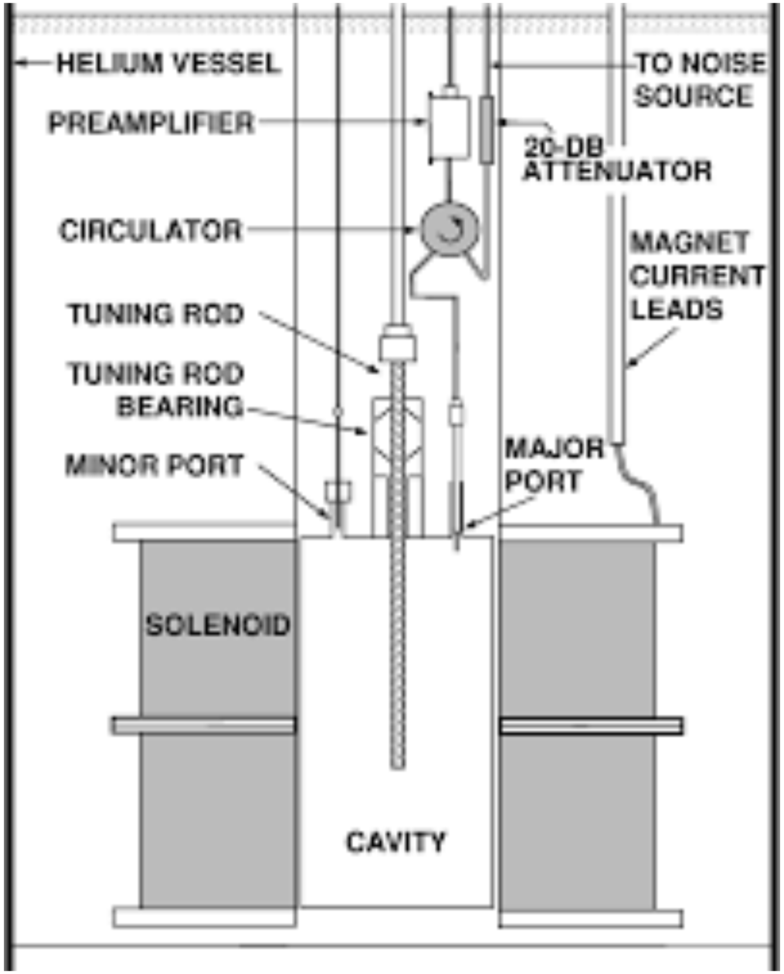
Neil Sulllivan

+ Chris Hagmann (PhD student)

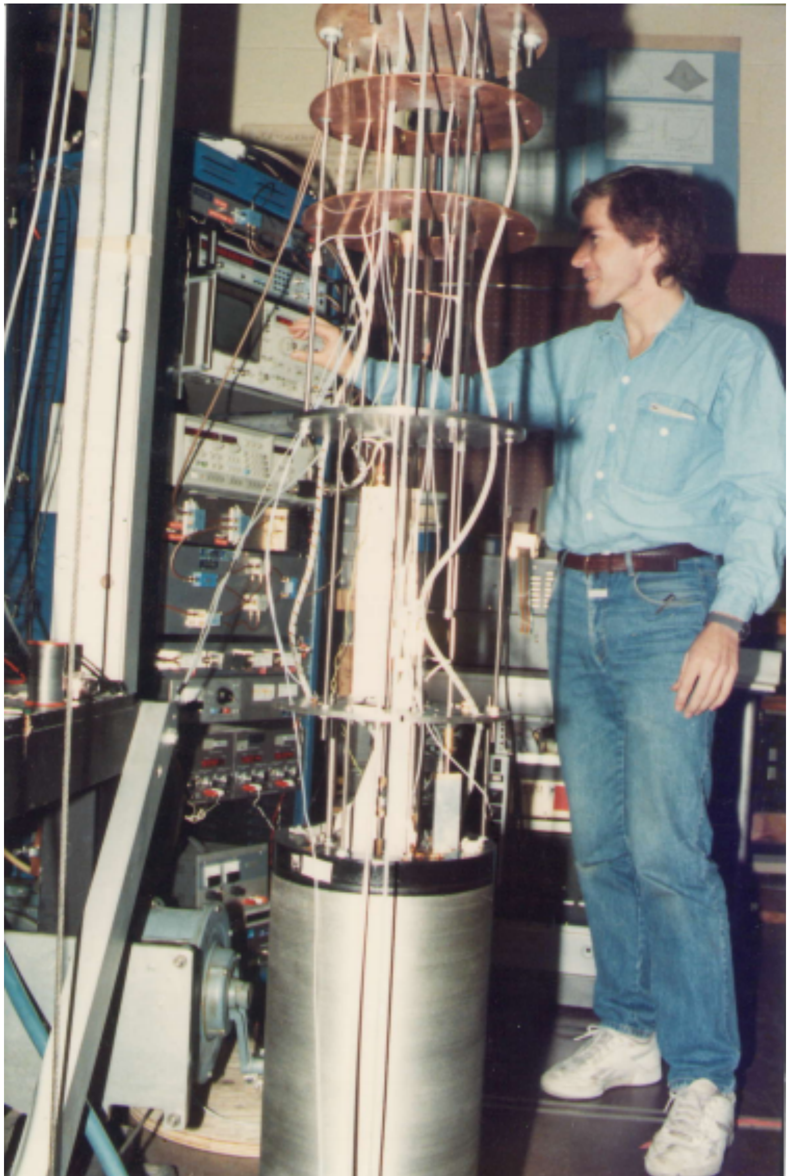
Rochester-Brookhaven-Fermilab Collaboration

Adrian Melissinos
et al.

Yannis Semertzidis (CAPP, Korea)

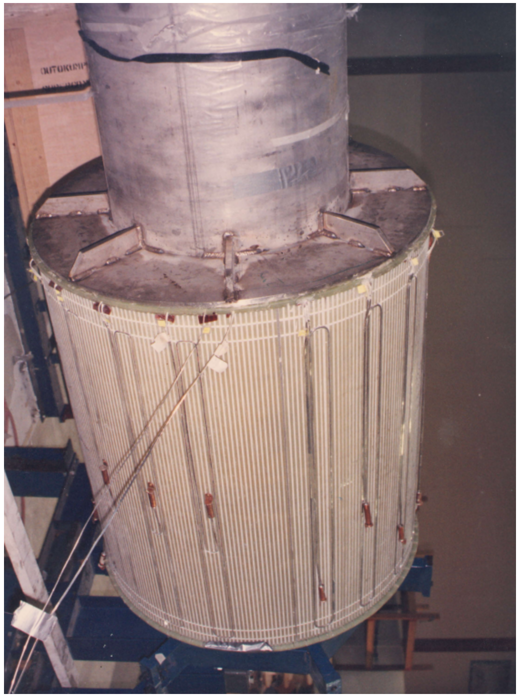


Chris Hagmann and the UF axion detector



A new magnet for the cavity experiment

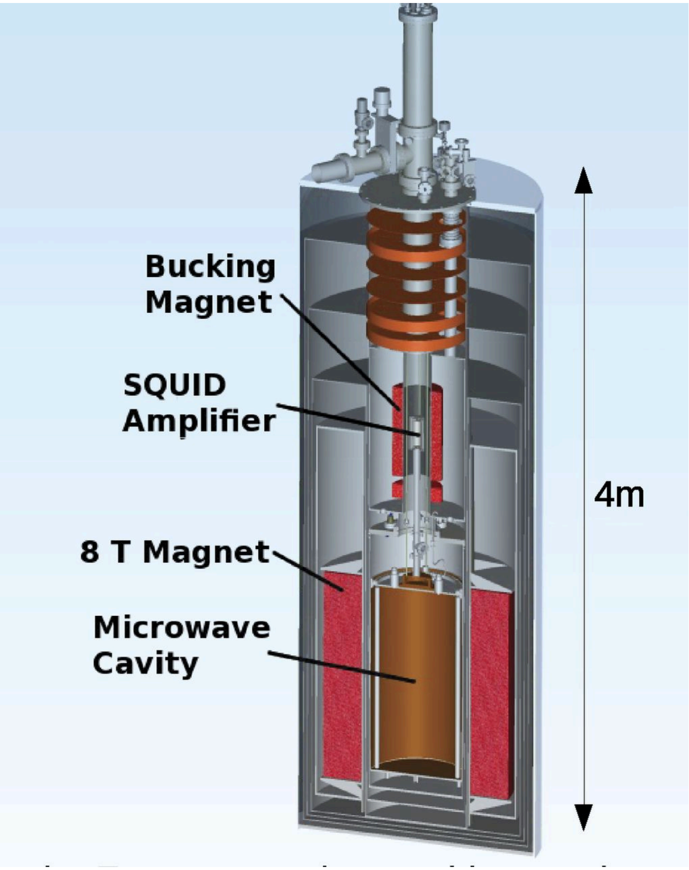
Karl van Bibber



8T magnet from Wang NMR, Inc

Michael Turner

ADMX

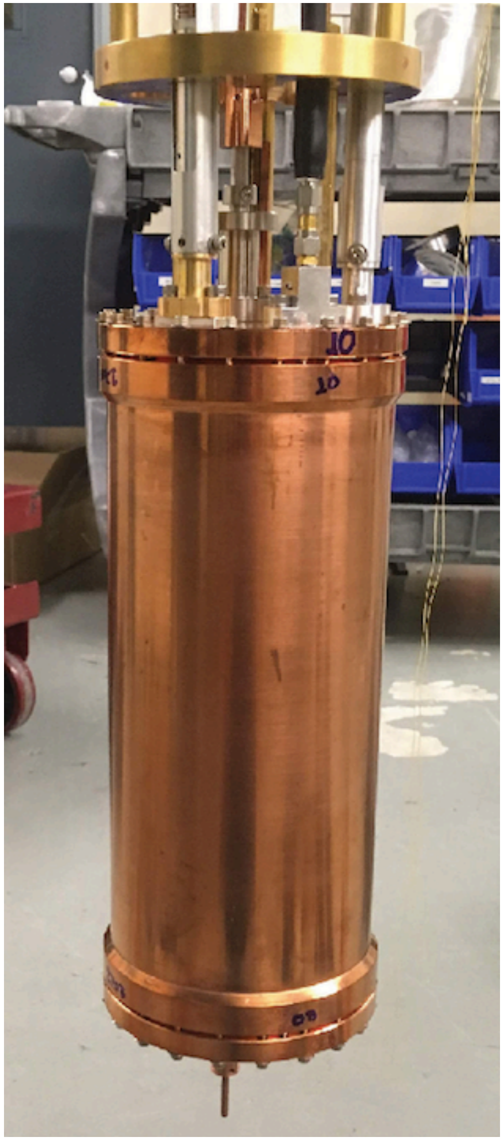


SQUIDs from
J. Clarke's group

Leslie Rosenberg and
Gray Rybka at U. Wash.

ADMX meeting at Fermilab

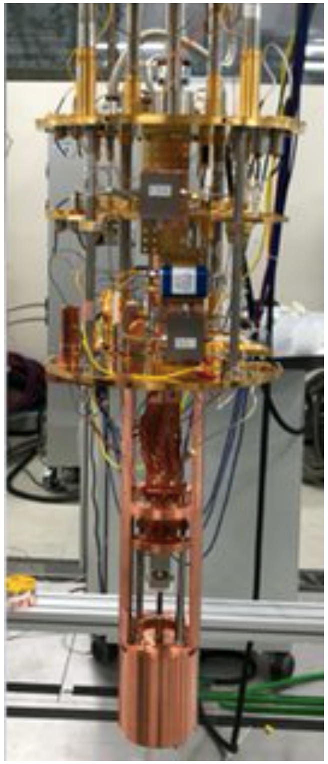
HAYSTAC at Yale

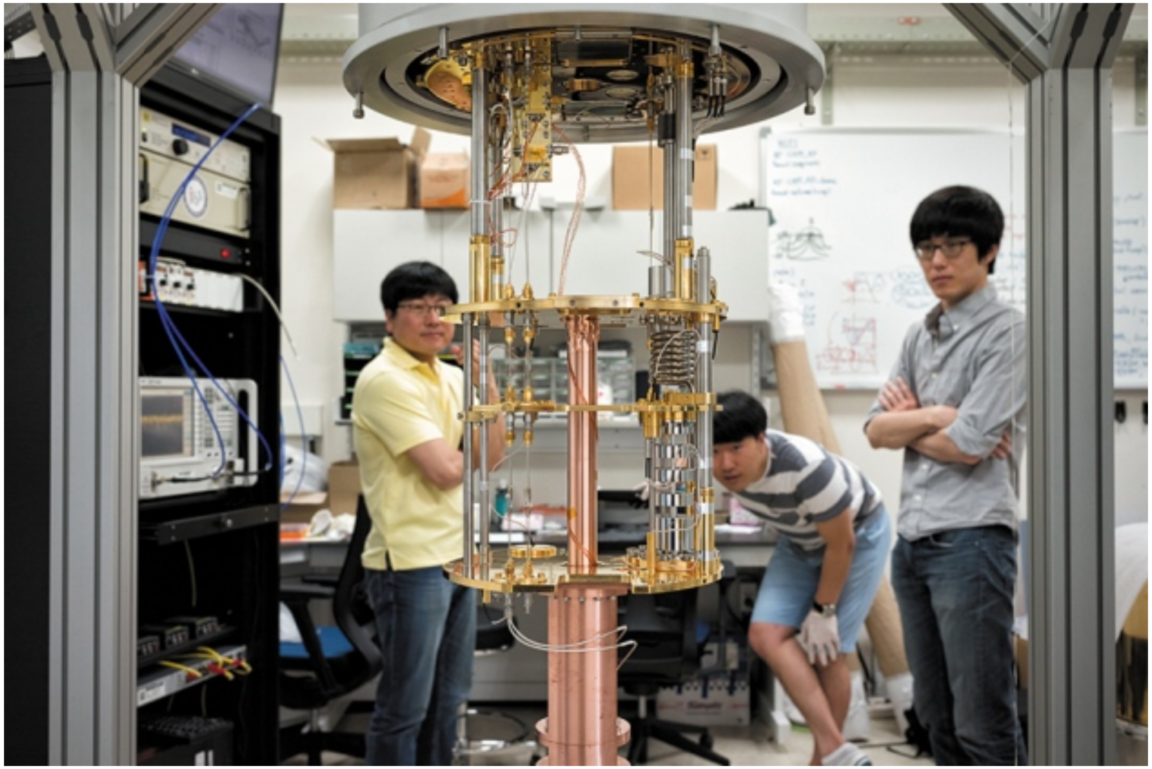


Institute for Basic Science
ibs
기초과학연구원

CAPP

Center for
Axion and Precision
Physics Research





Cavity haloscopes under construction

- at INFN laboratory in Legnaro QUAX
- at University of Western Australia ORGAN
- at CERN RADES
- at INFN laboratory in Frascati KLASH

Cavity haloscopes under construction

- at INFN laboratory in Legnaro QUAX
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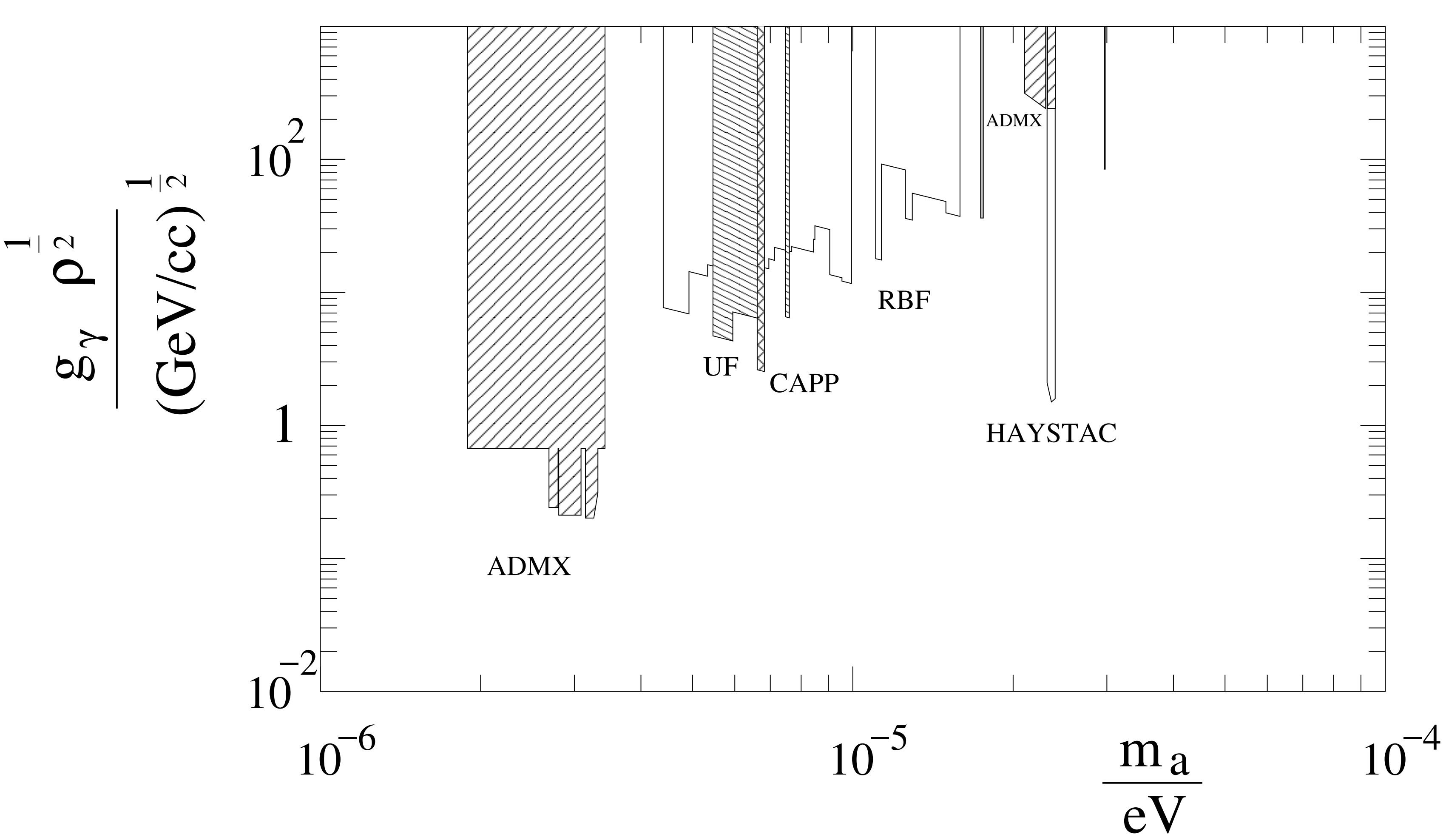
- at CERN RADES

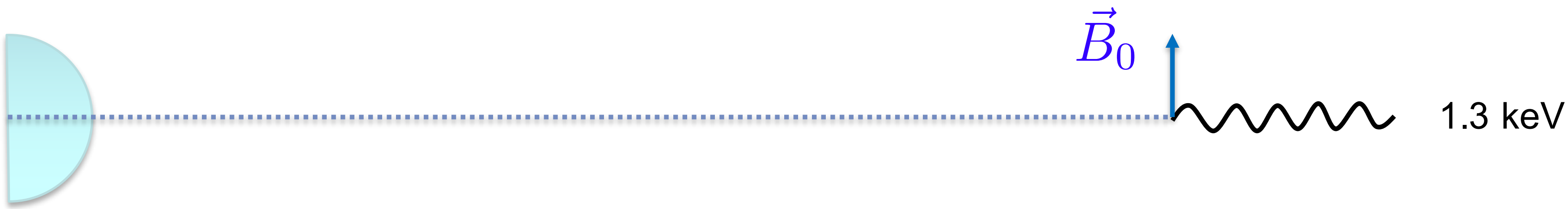
Constraints on dark matter axions from cavity haloscopes



We may search for axions produced in the Sun or present on Earth as dark matter

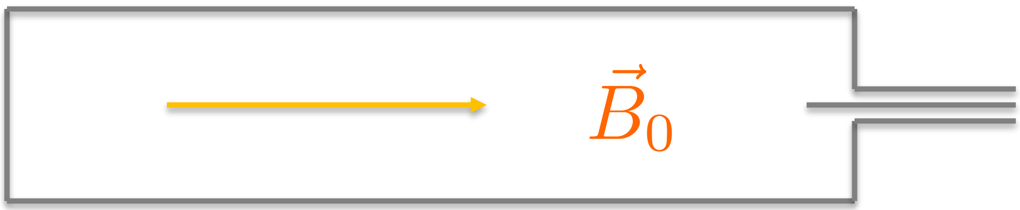
- Axion helioscope

$$10^{14}\ \mathrm{axions/cm^2 sec}$$



- Axion haloscope

$$10^{14}\ \mathrm{axions/cm^3}$$

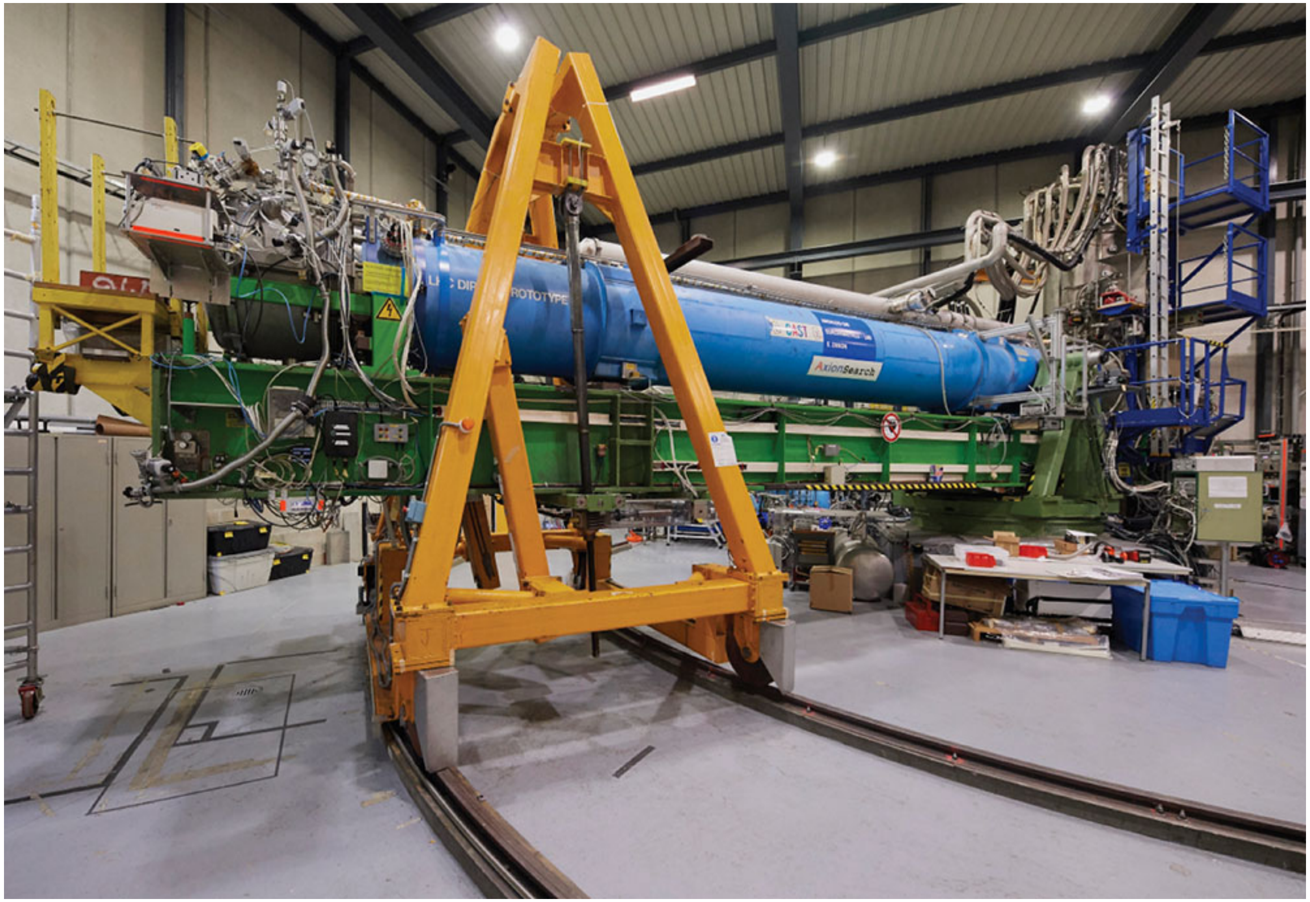


Tokyo Helioscope - Sumico

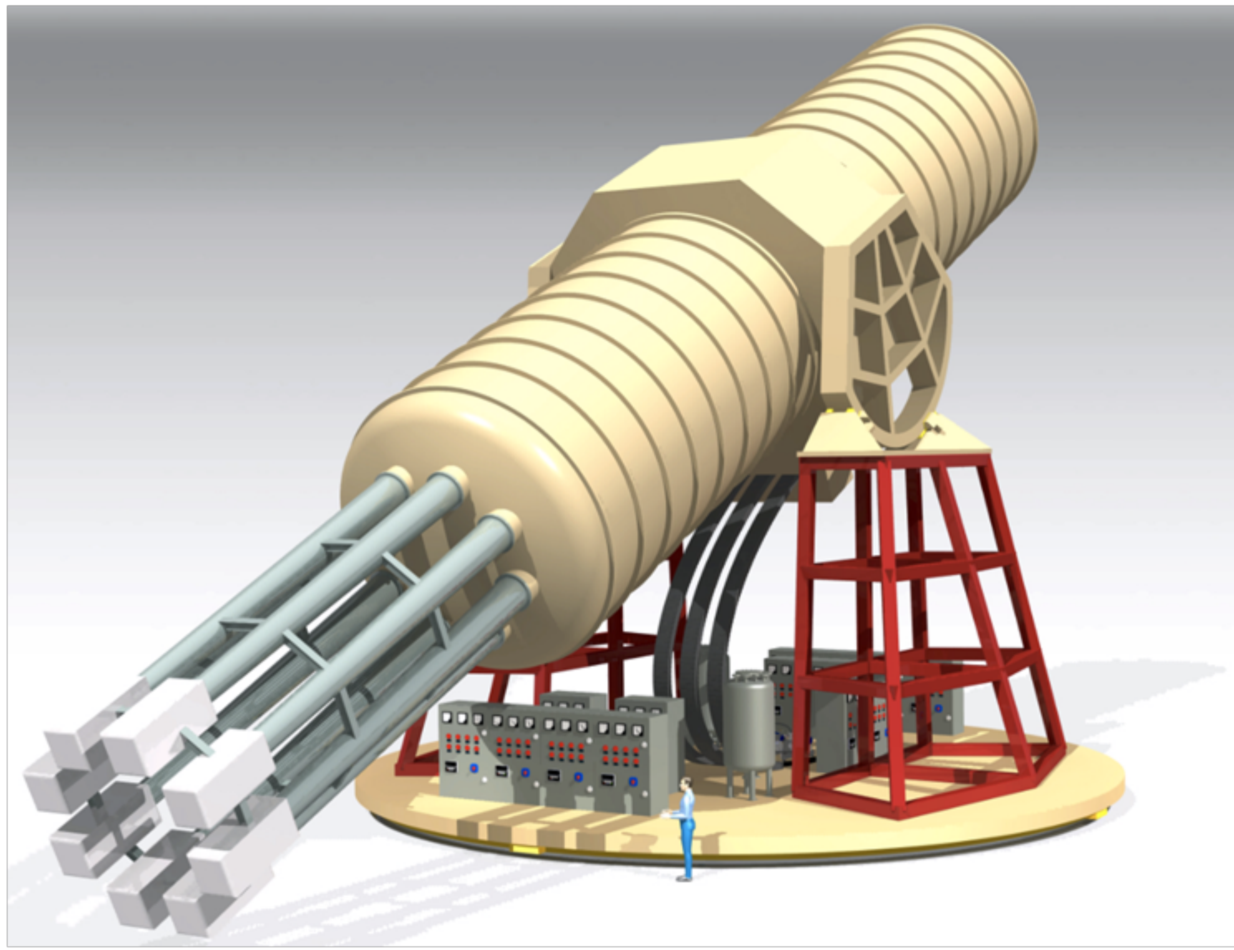
Makoto Minowa
et al.

CERN Axion Solar Telescope

Konstantin Zioutas et al.



International AXion Observatory



Igor Irastorza
et al.

Axio-Electric and Primakoff Effects

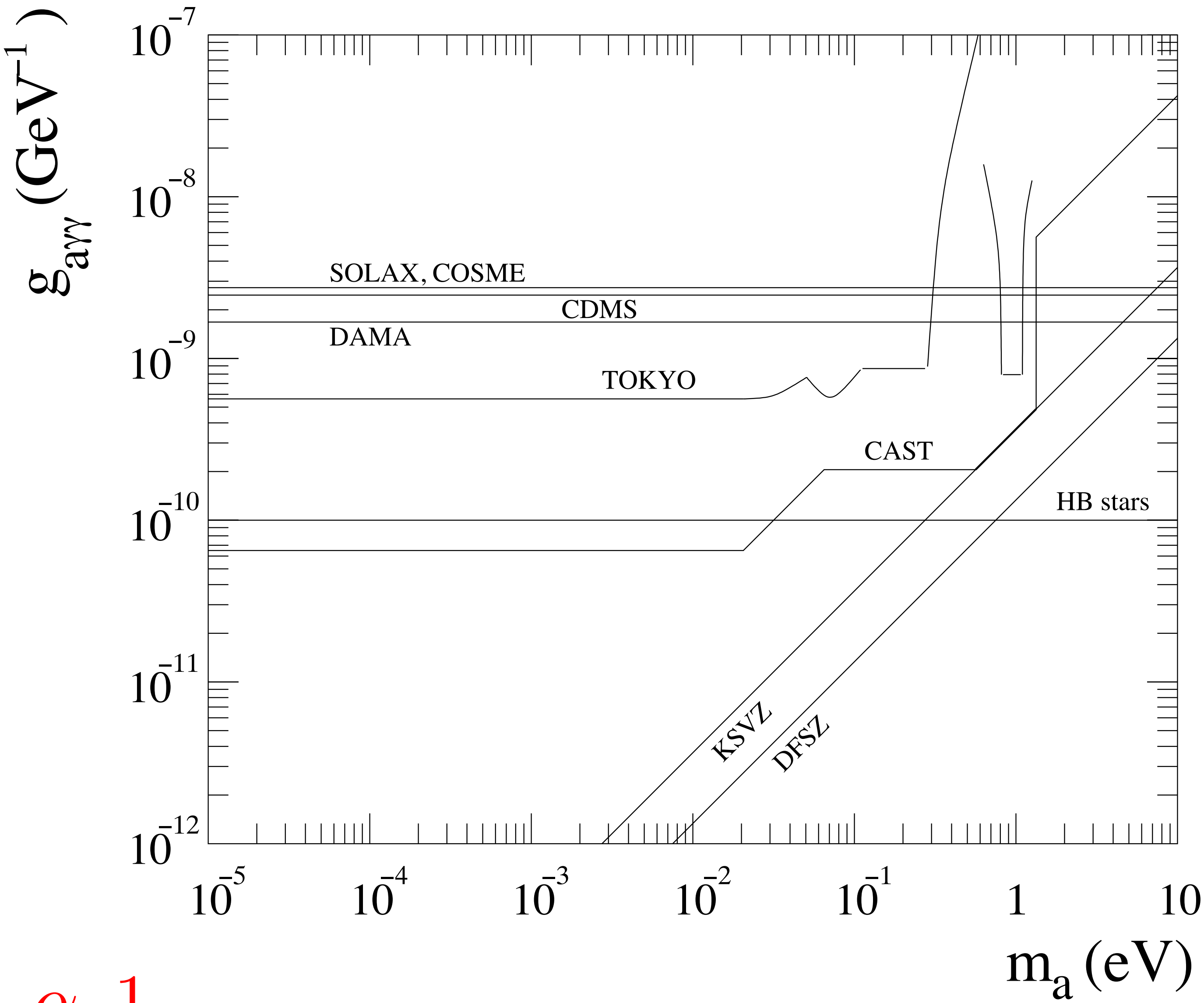
Frank Avignone

e.g. $$a + \mathrm{Ge} \to e + \mathrm{Ge}^+$$

Dimopoulos, Starkman & Lynn, 1986

$$a + (Z, A) \to \gamma + (Z, A)$$

constraints from SOLAX, COSME, DAMA, CDMS, EDELWEISS, XMASS, CUORE, CDEX, Xenon, LUX, PandaX



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

Many approaches to axion detection

Dielectric haloscopes — MADMAX

Nuclear Magnetic Resonance — CASPEr

Axion to magnon conversion — QUAX

LC circuit — ABRACADABRA, SLIC, DMradio

Axion echo

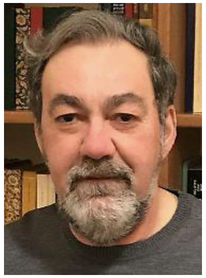
Shining light through walls (SLW) … ALPs, OSQAR

Guido Mueller

Long range forces — ARIADNE

Stellar evolution constraints — white dwarf cooling

SLW in astrophysical magnetic fields

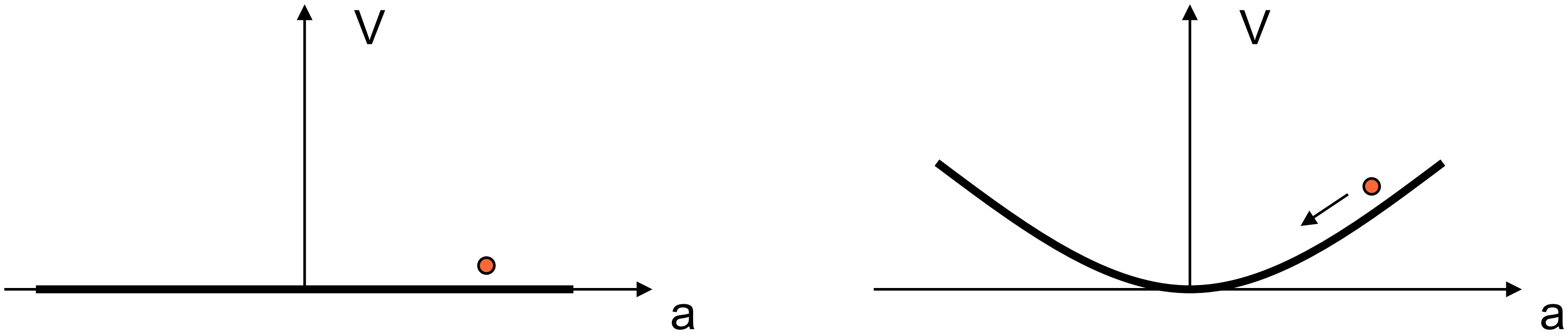


Marco Roncadelli

Axions relate to

- particle physics
- nuclear physics
- astrophysics
- cosmology
- solid state physics (topological insulators)
- atomic physics
- statistical mechanics (Bose-Einstein condensation)
- ...

Axion production by vacuum realignment



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

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

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

initial misalignment angle

Axions produced by vacuum realignment are cold dark matter

Cold axion properties

- number density

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

- velocity dispersion

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

if decoupled

- phase space density

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

Bose-Einstein Condensation

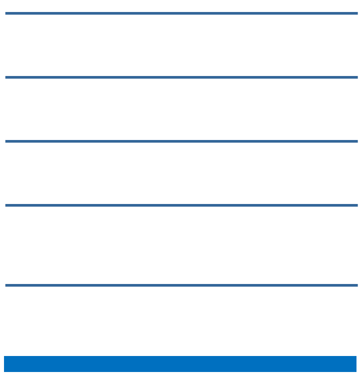
if identical bosonic particles
are highly condensed in phase space
and their total number is conserved
and they thermalize

then most of them go to the lowest energy
available state

why do they do that?

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

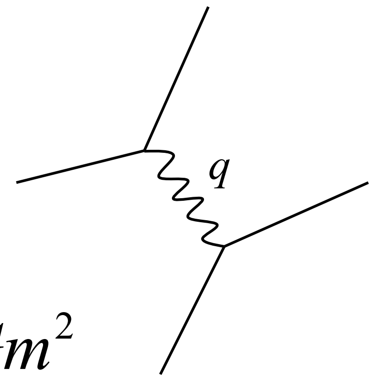
preBEC



BEC

Thermalization occurs due to gravitational interactions

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



$$\frac{Gm^2}{q^2}$$

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

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

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

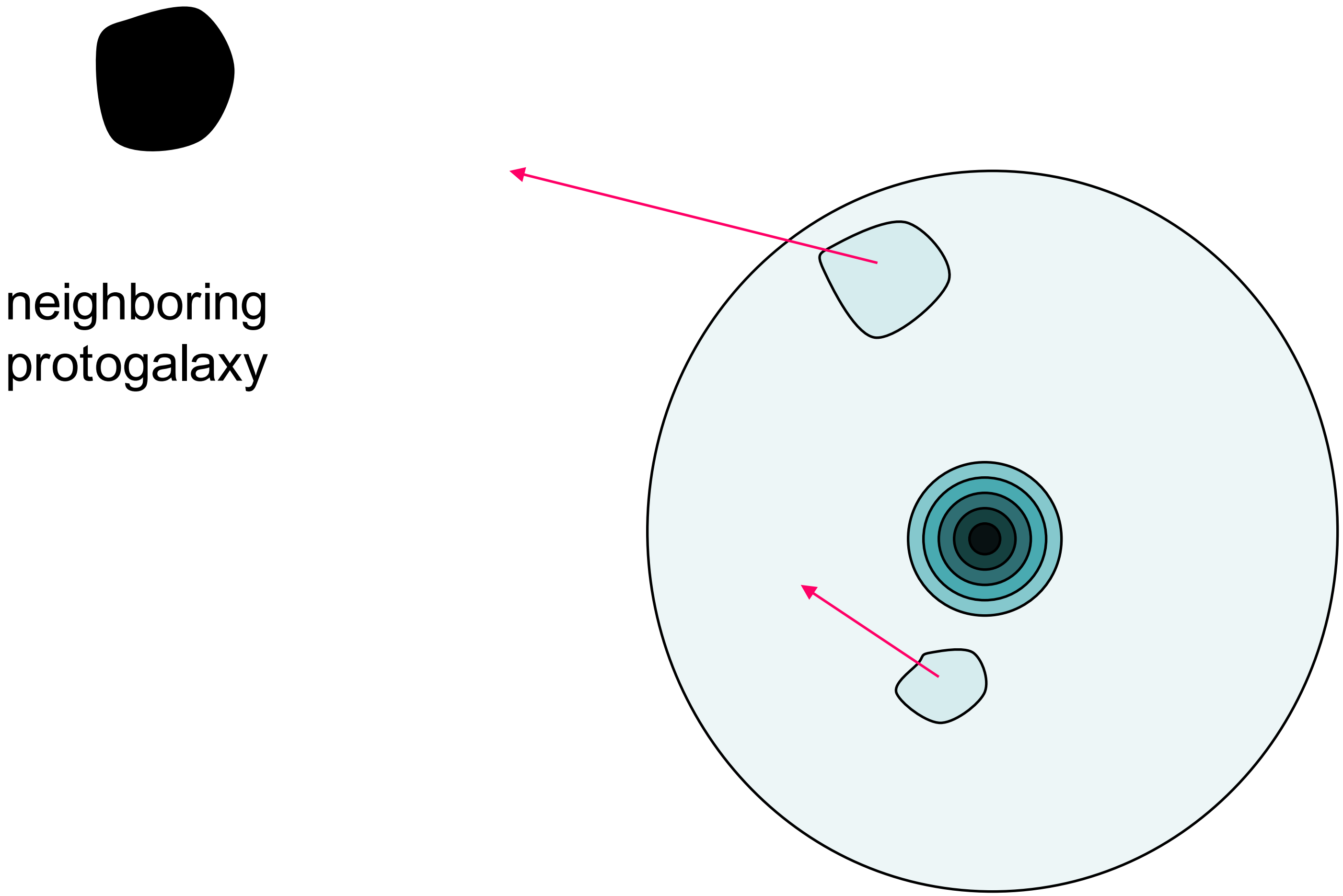
$$T_\gamma \sim 500 \text{ eV} \left(\frac{f}{10^{12} \text{ GeV}} \right)^{\frac{1}{2}}$$

After that

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

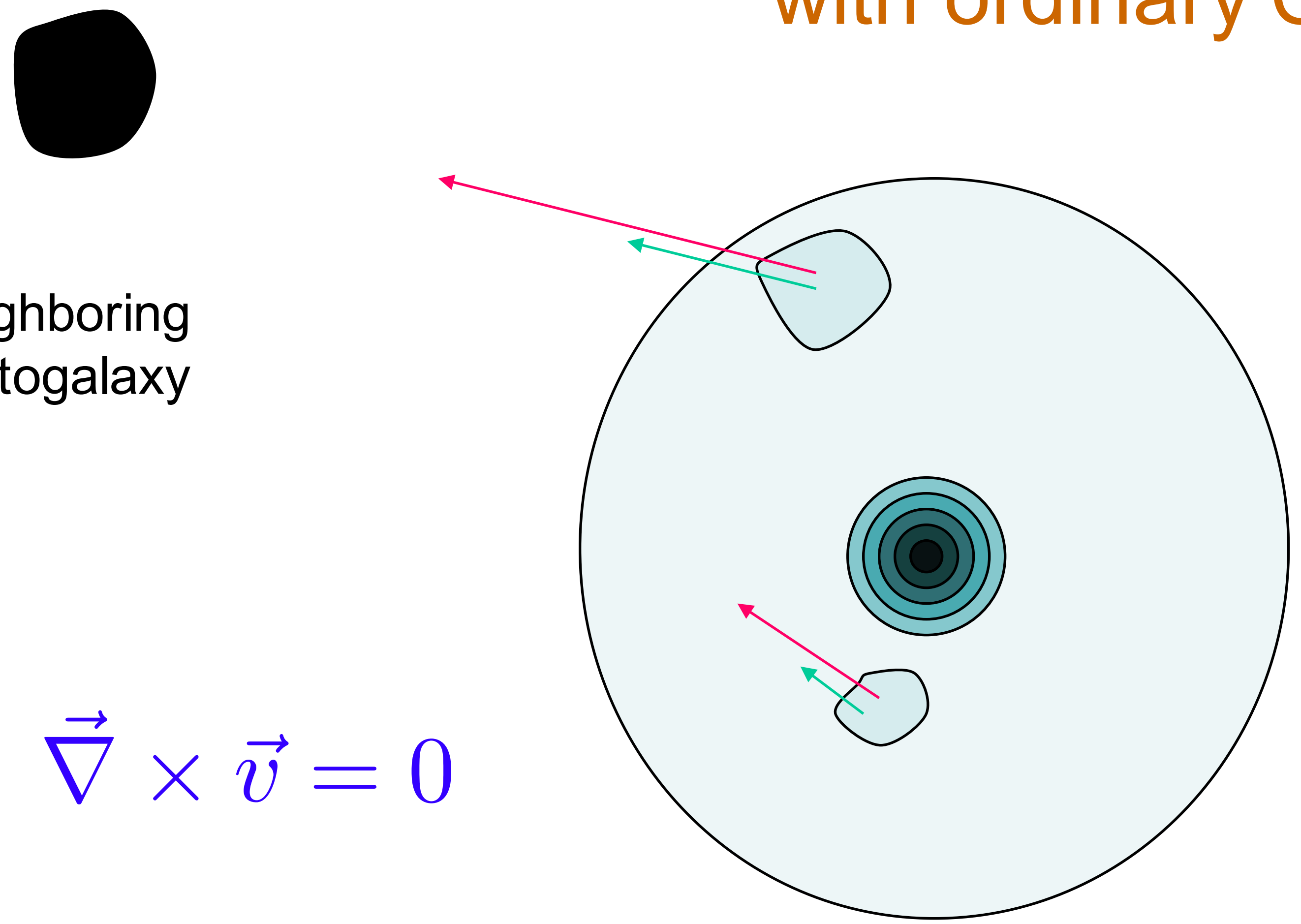
$$\Gamma_g(t) / H(t) \propto t^3 a(t)^{-3}$$

Tidal torque theory



Stromberg 1934; Hoyle 1947; Peebles 1969, 1971

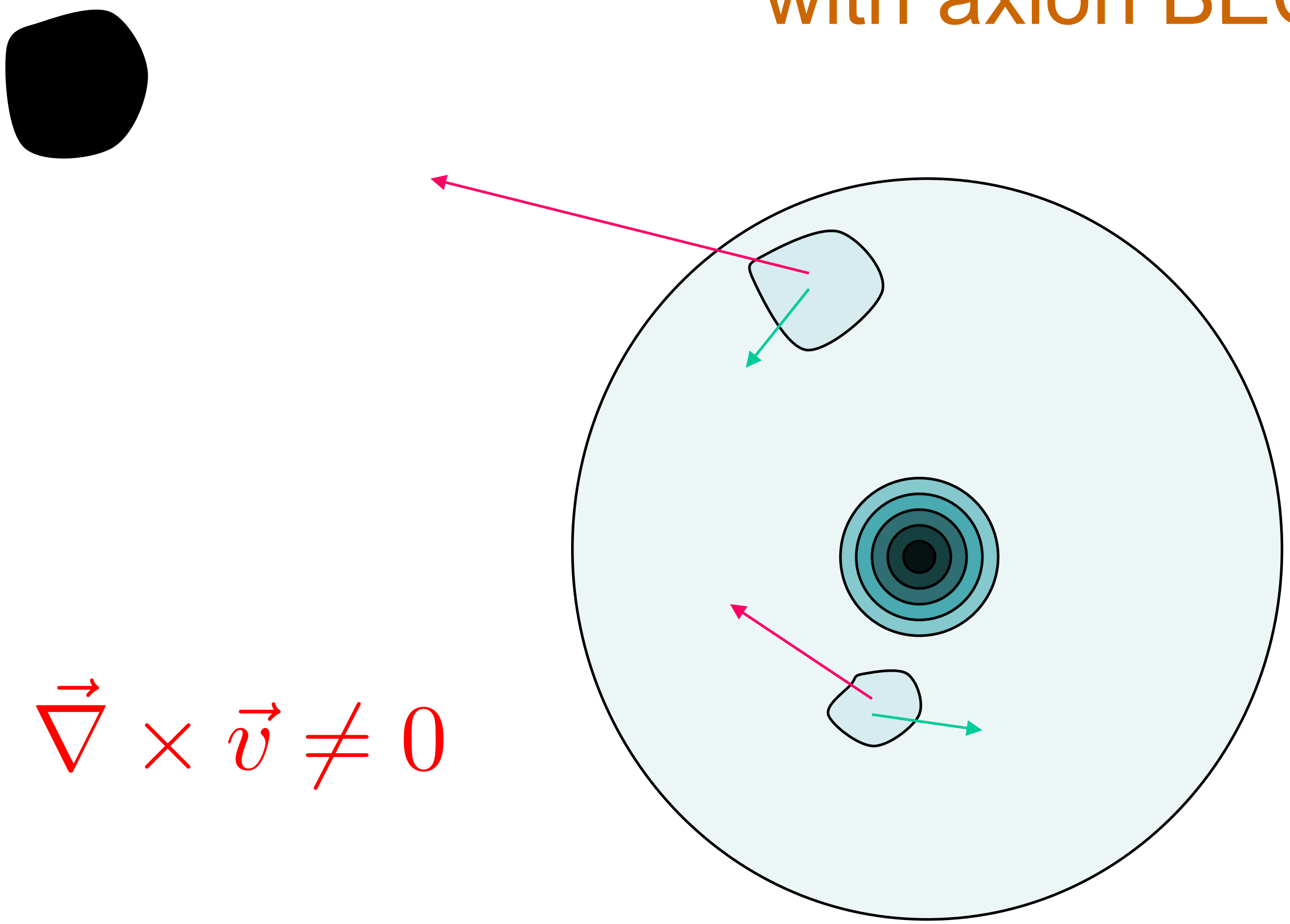
Tidal torque theory with ordinary CDM



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

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

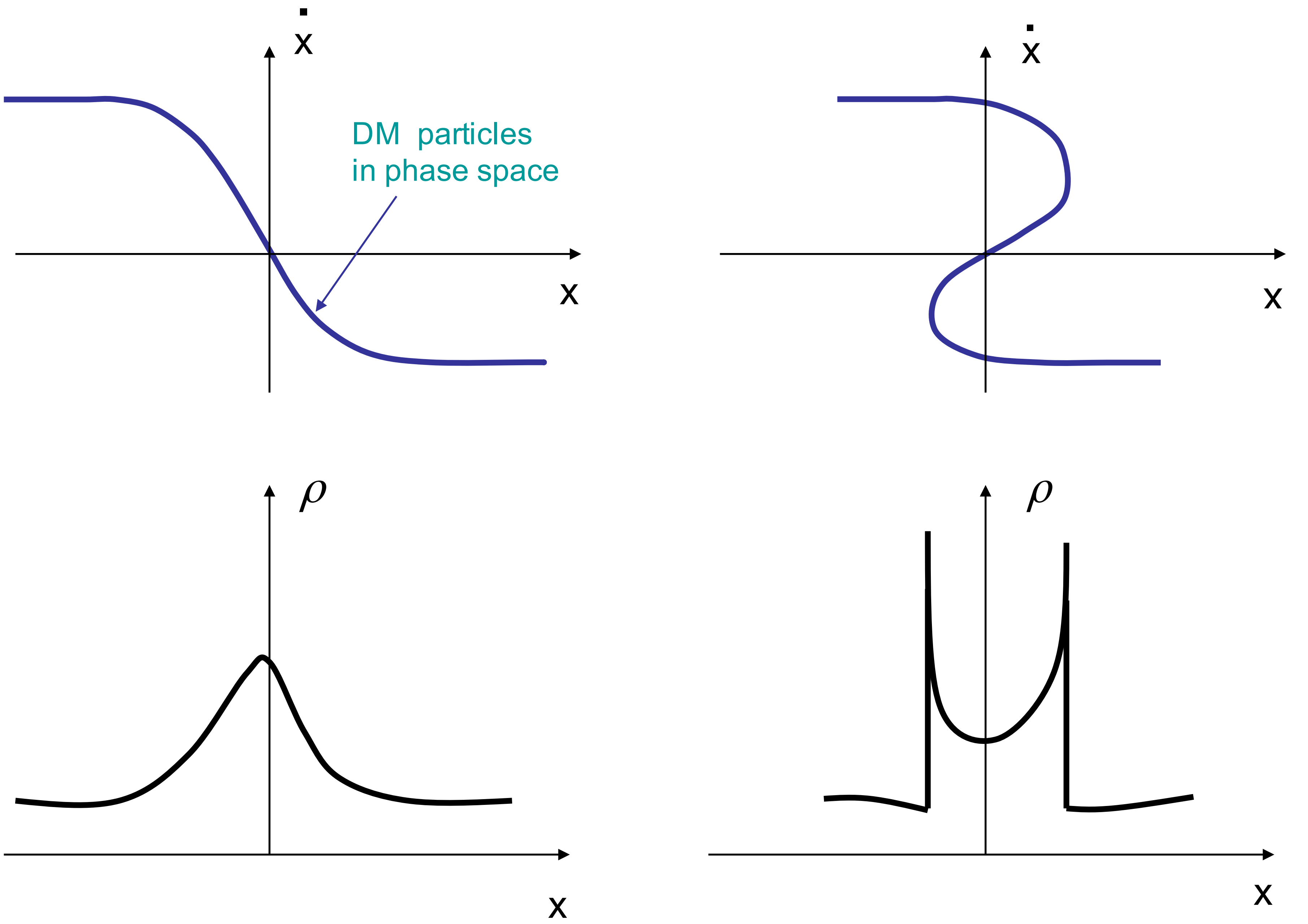
ordinary fluid

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

dark matter (collisionless) fluid

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

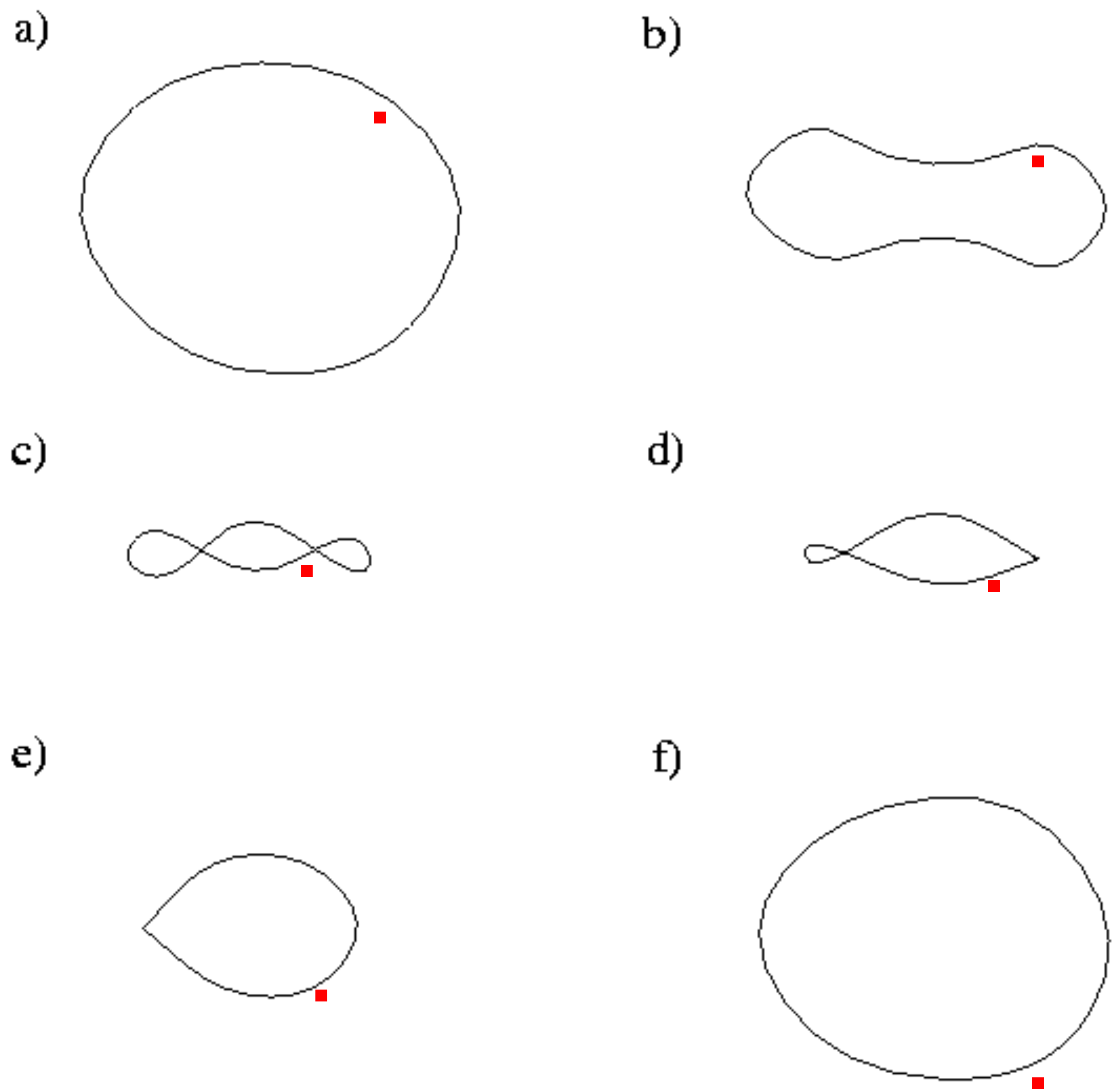
DM forms caustics in the non-linear regime



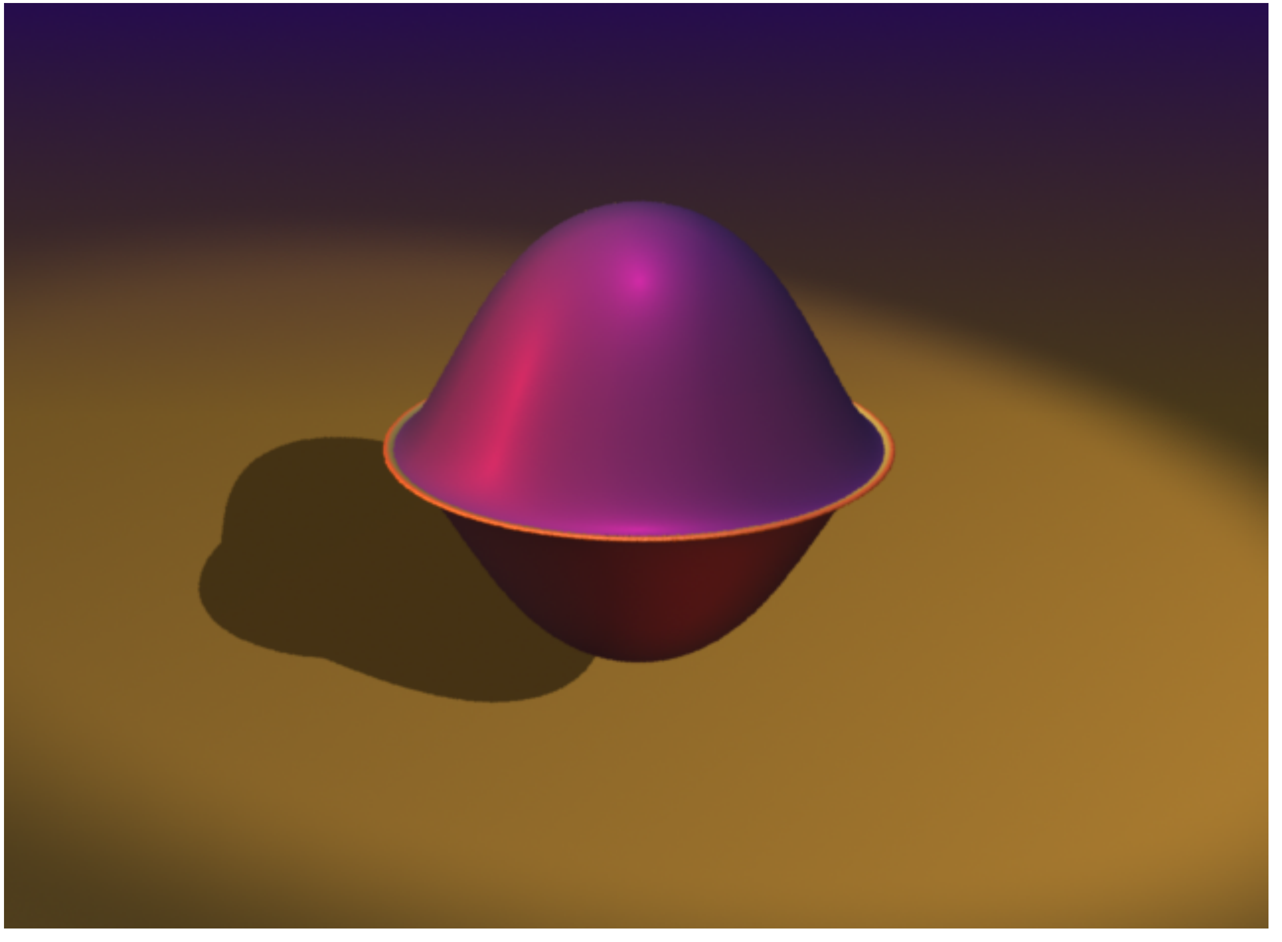
A shell of particles, part of a continuous flow.

The shell has net oreall rotation.

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

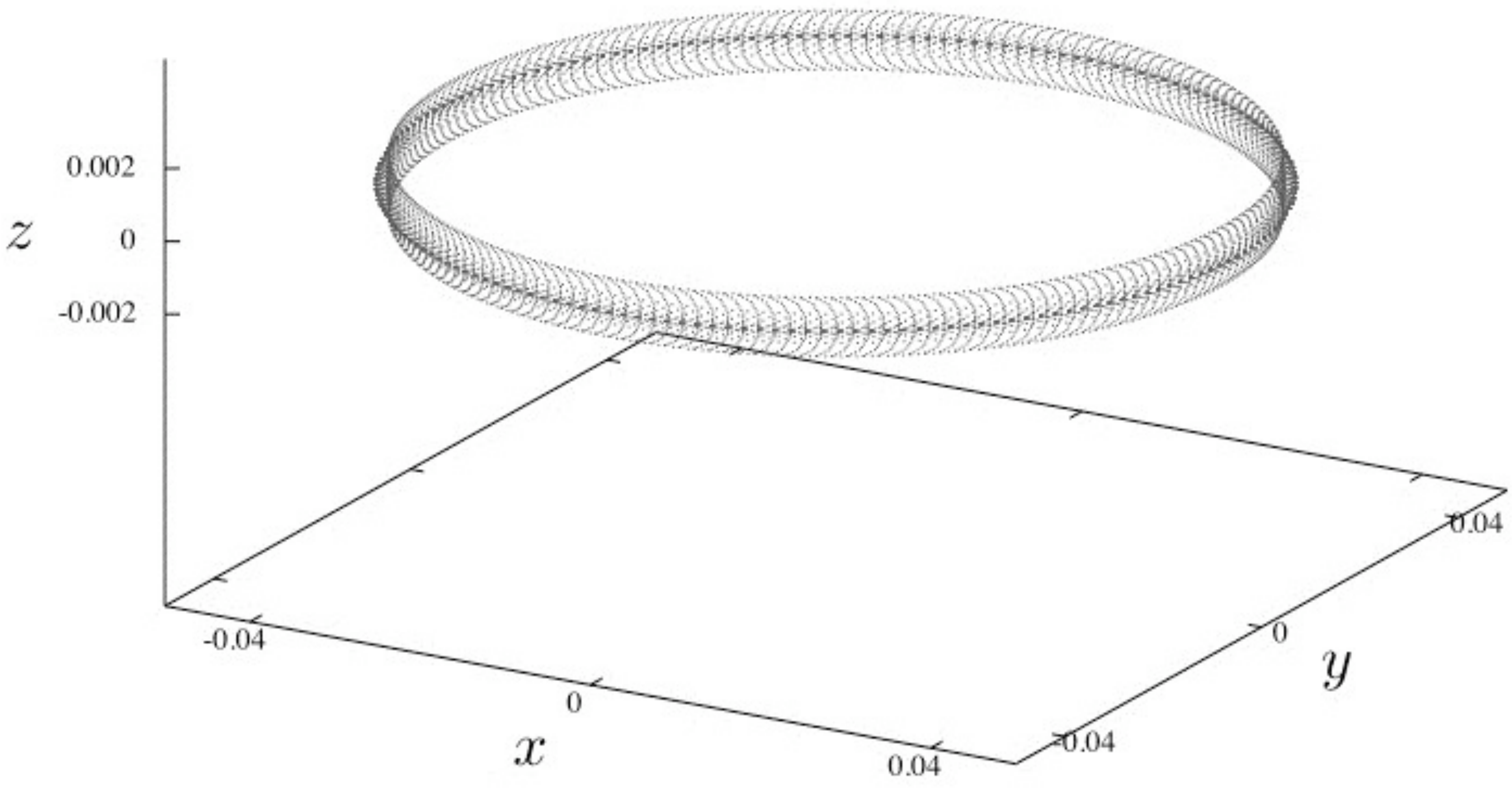


Sphere turning inside out

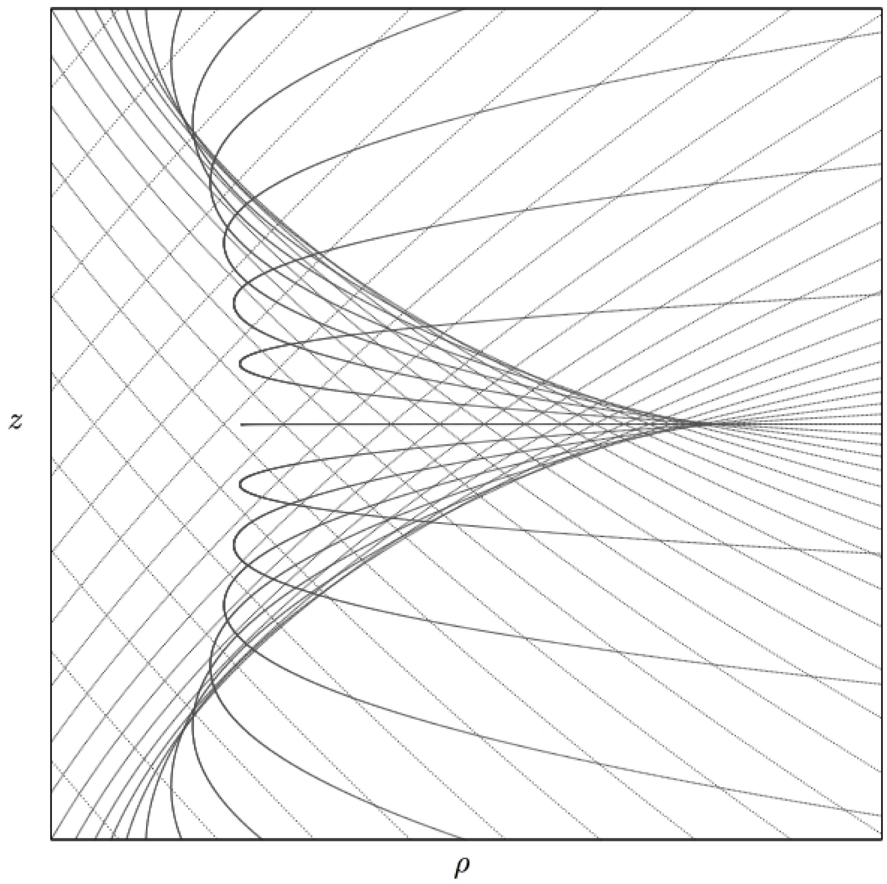


simulations by Arvind Natarajan

in case of net overall rotation

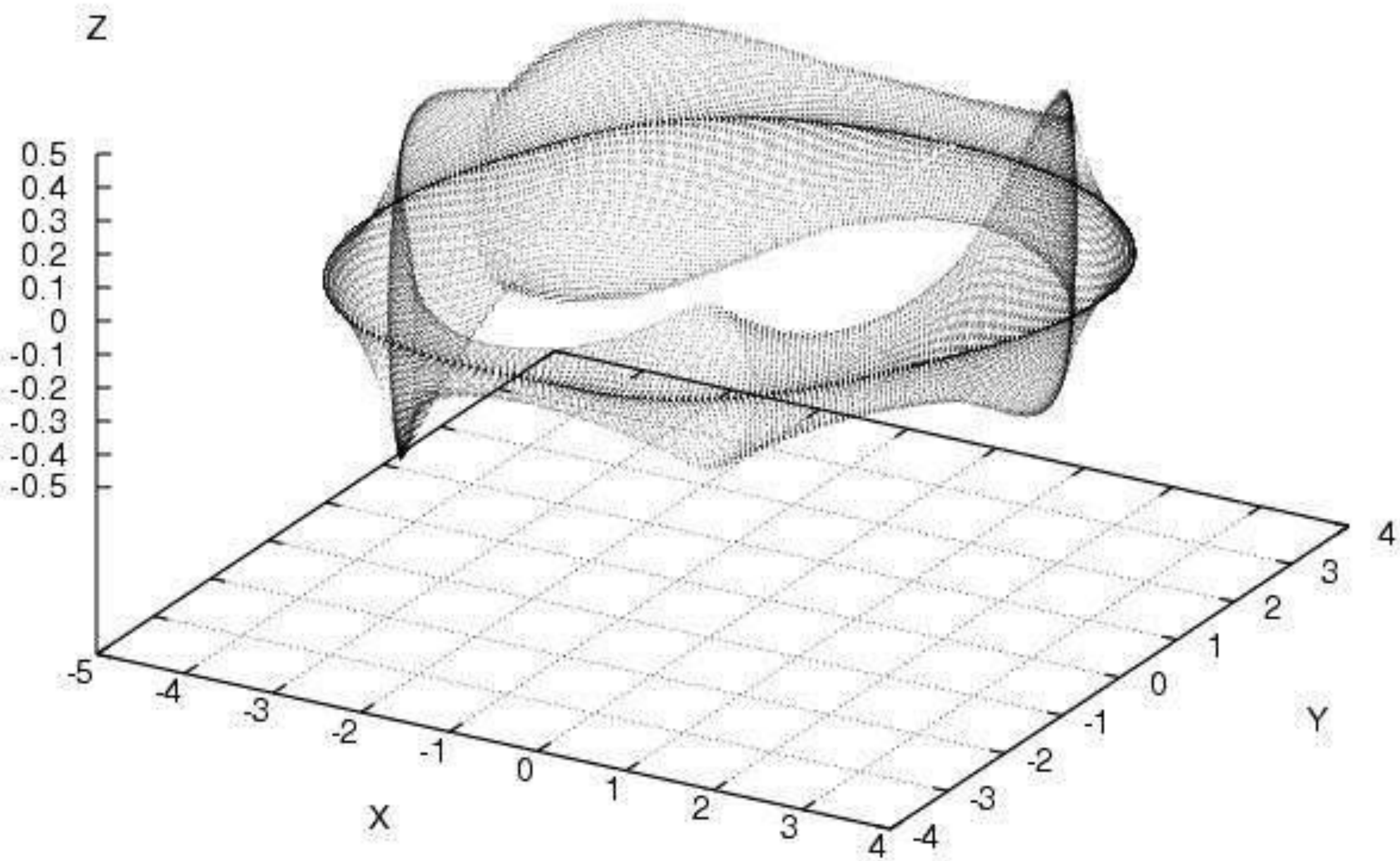


The caustic ring cross-section

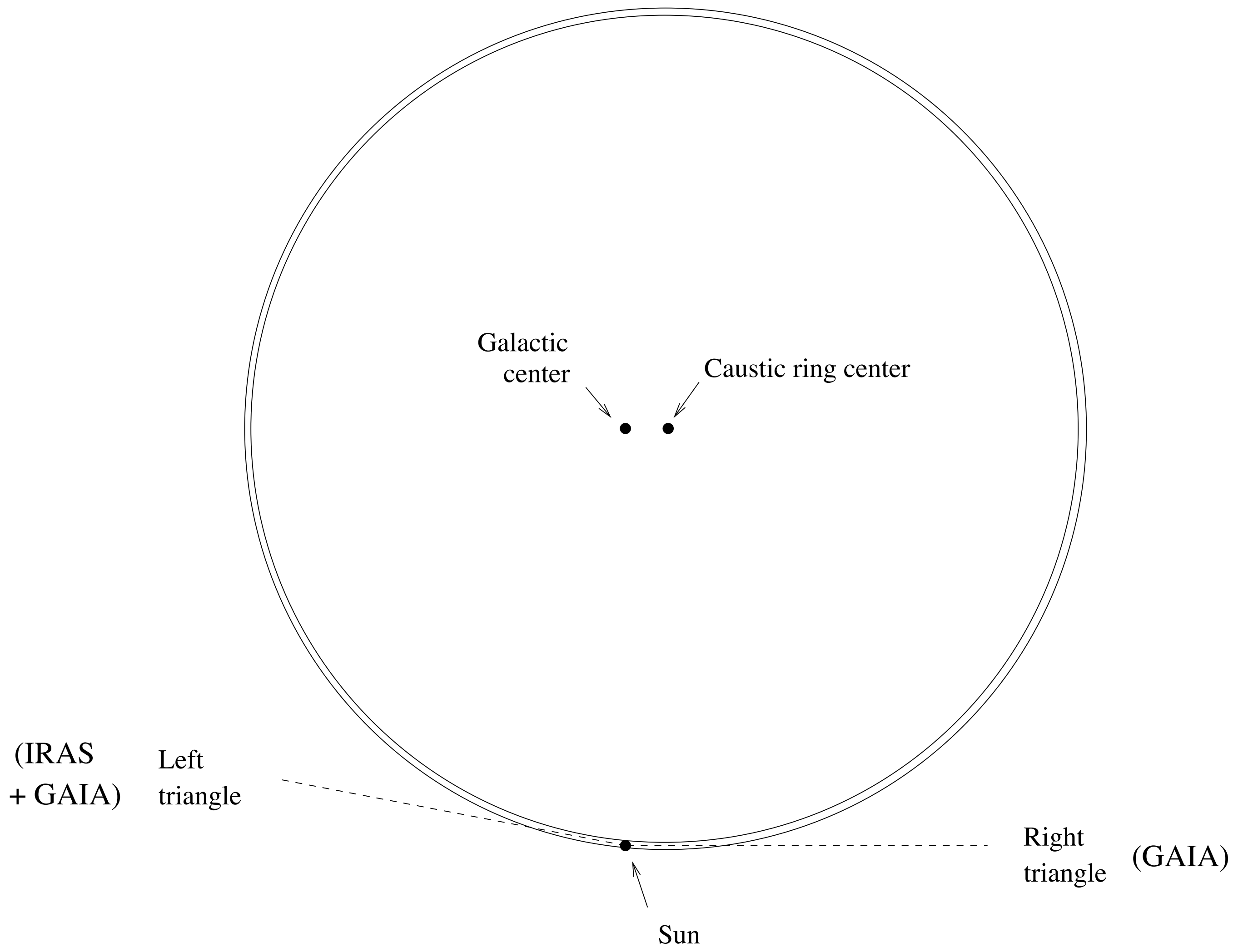


D_{-4}

an elliptic umbilic catastrophe

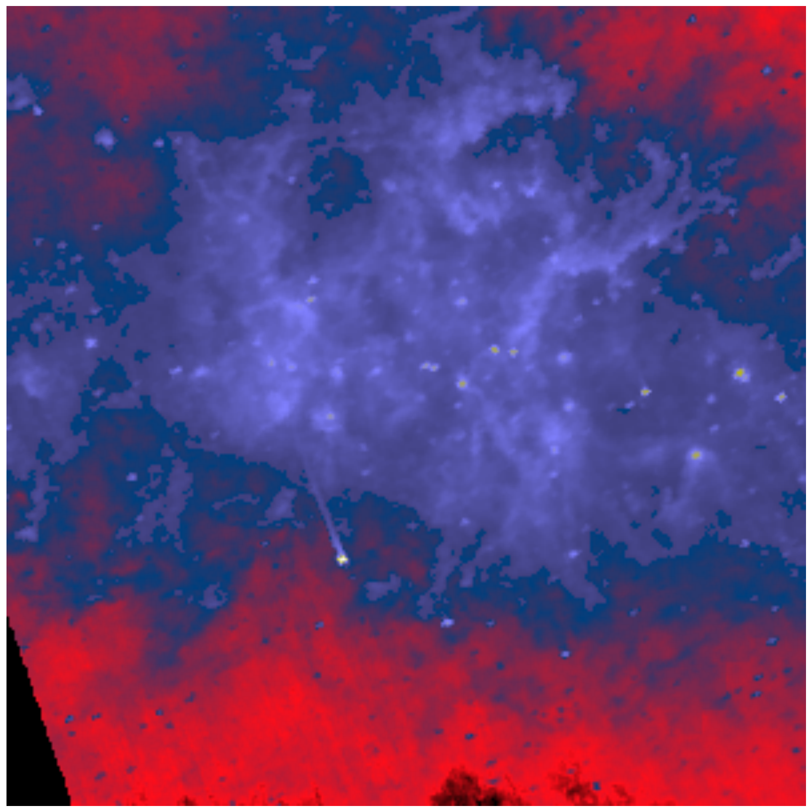

Z
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-5
-4
-3
-2
-1
0
1
2
3
4
X
4
3
2
1
0
-1
-2
-3
-4
Y

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



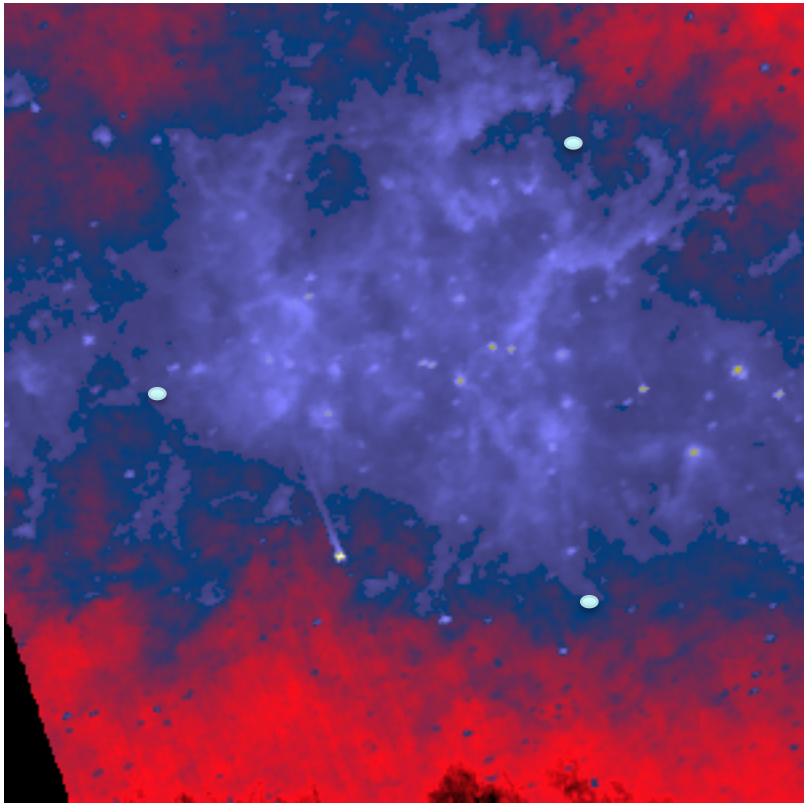
IRAS **12 μm**

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



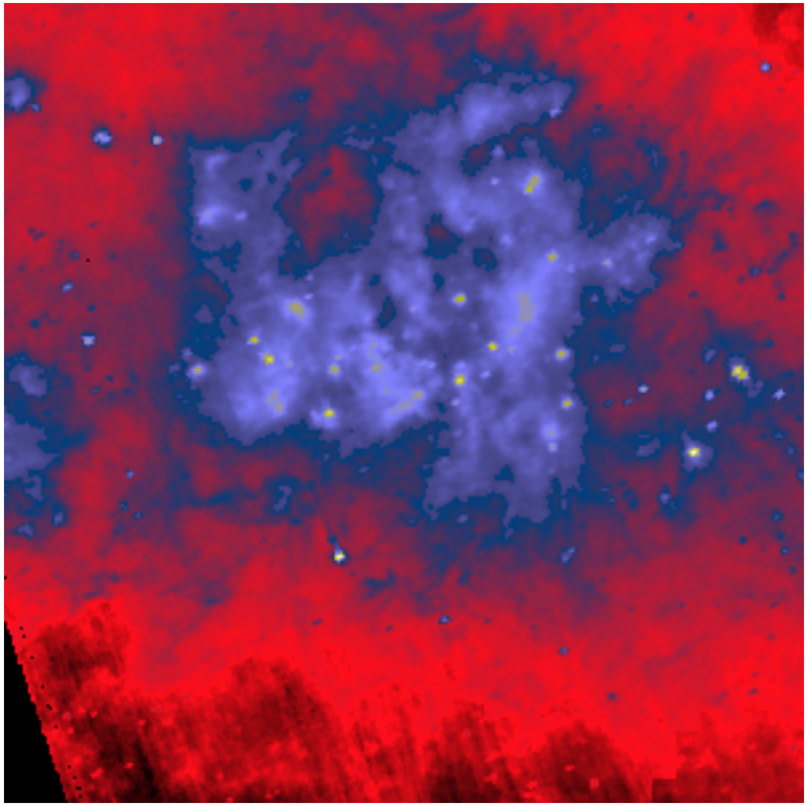
IRAS **12 μm**

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

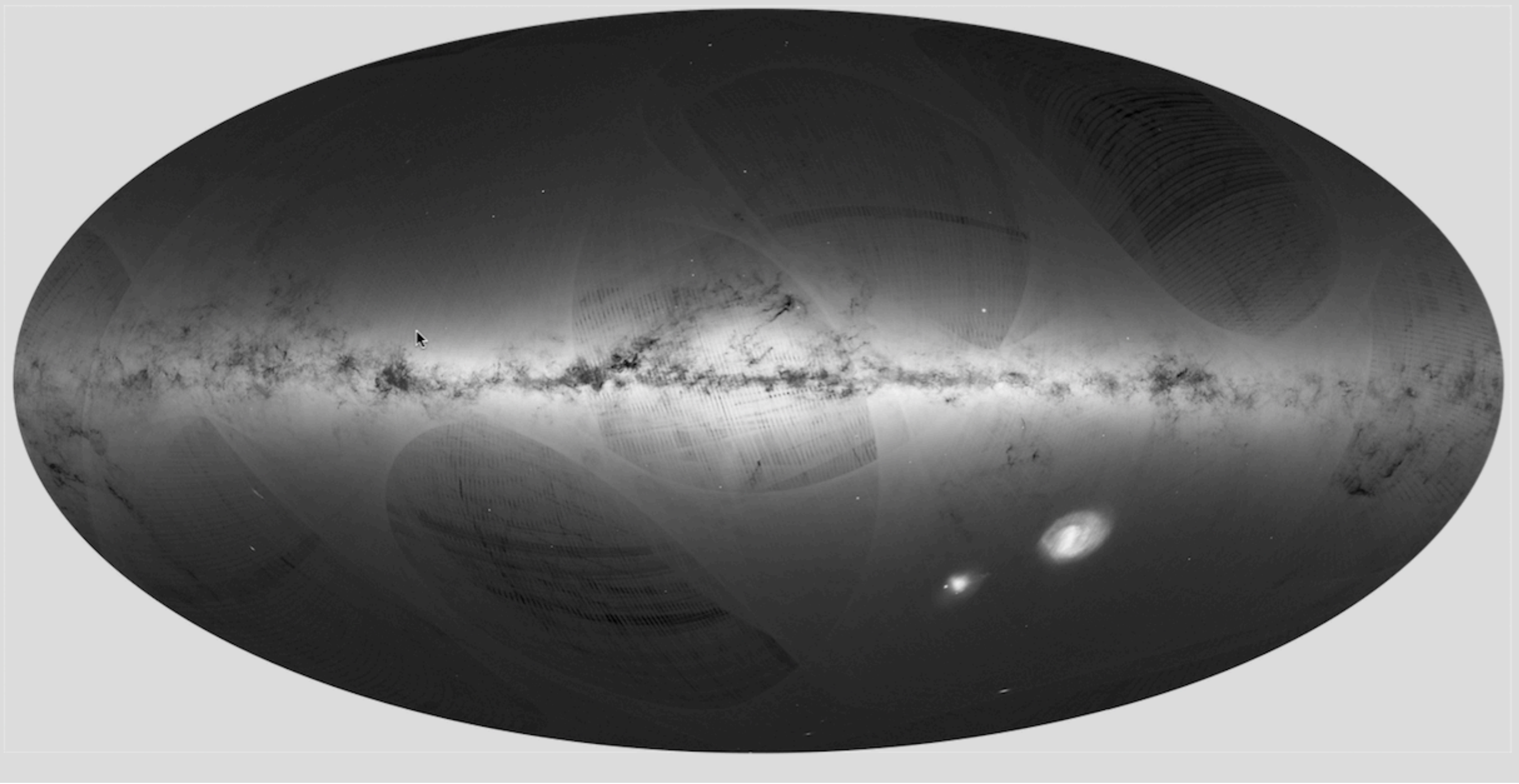


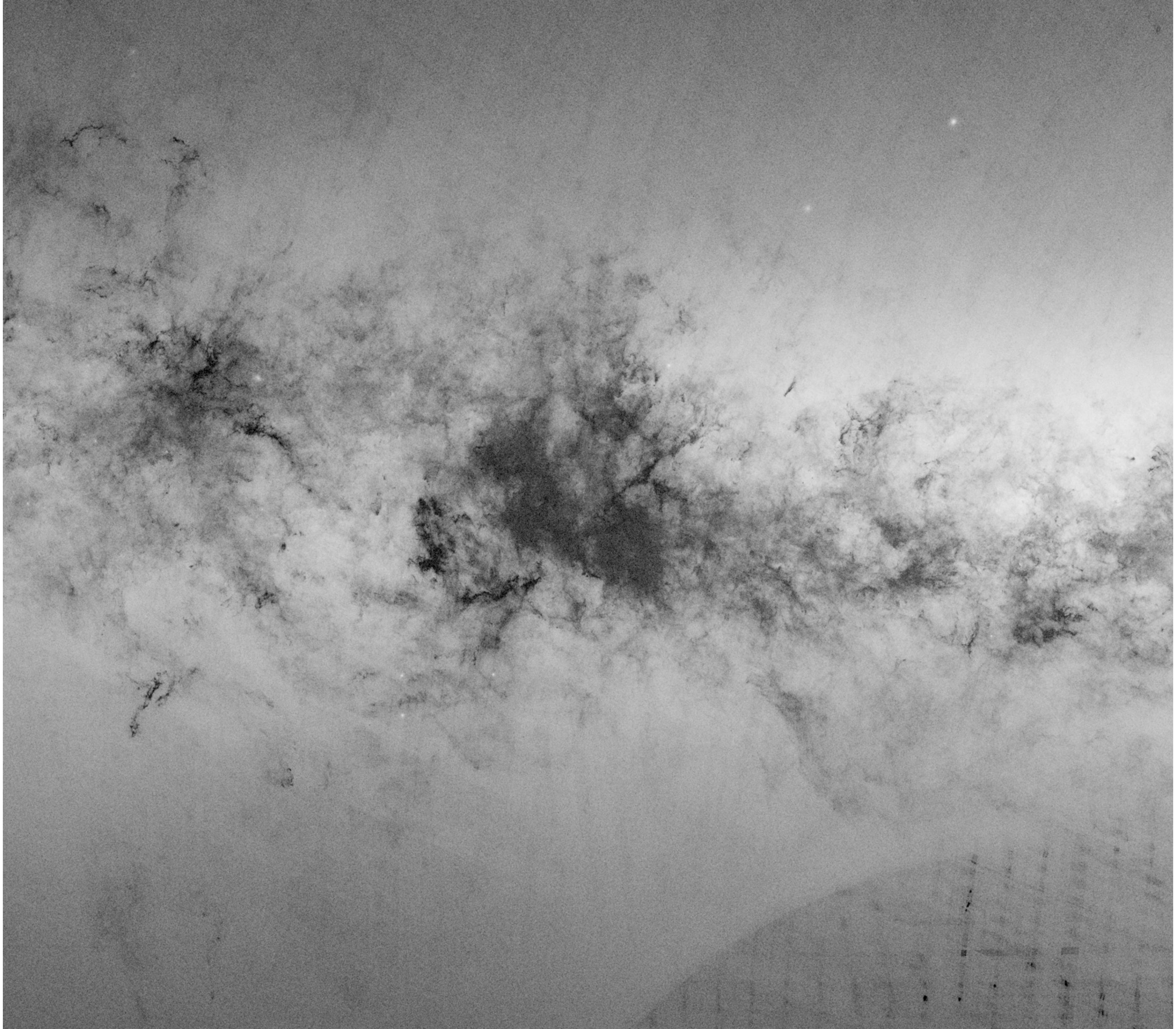
IRAS **25 μm**

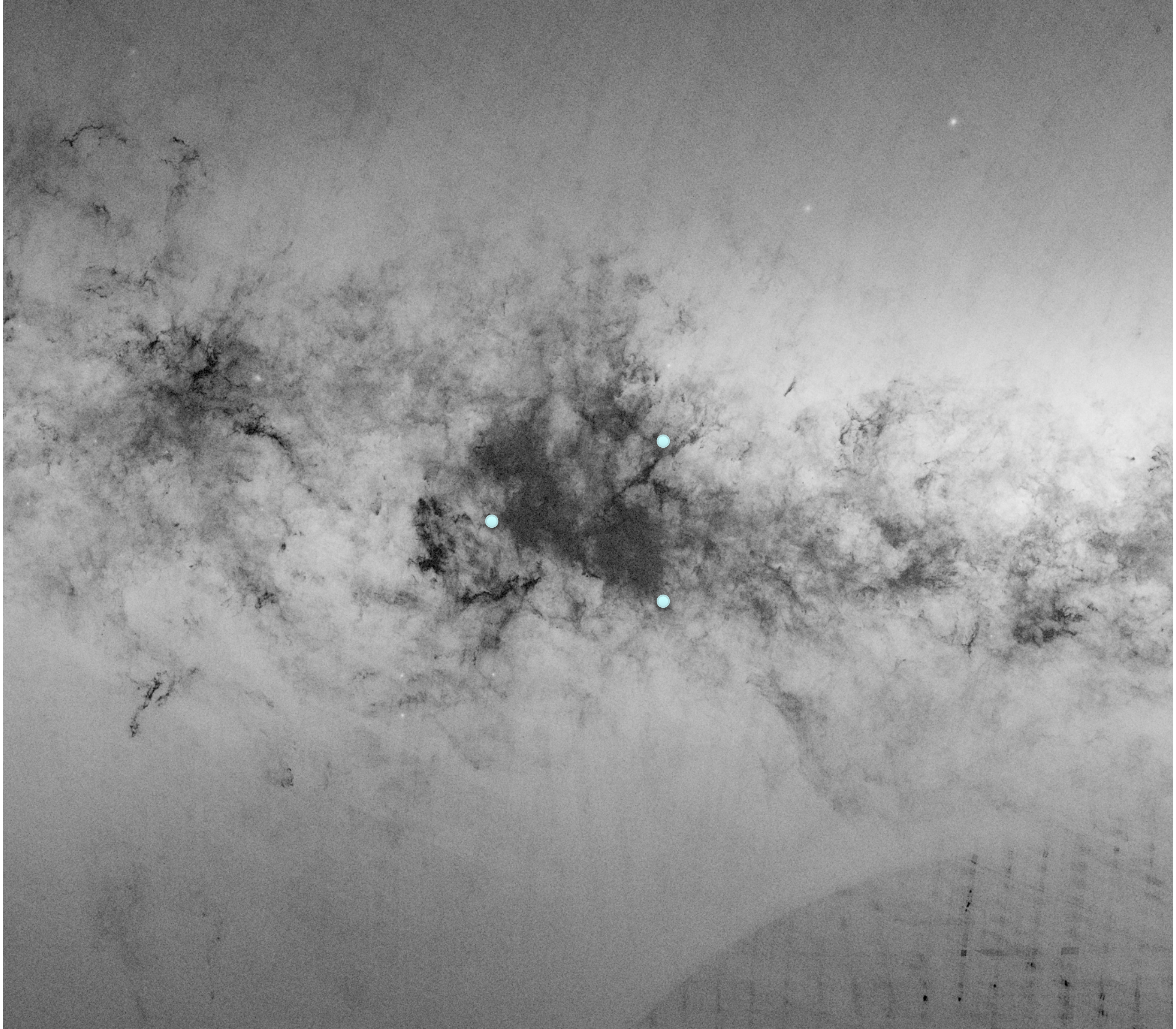
$(l, b) = (80^{o}, 0^{o})$ $10^{o} \times 10^{o}$



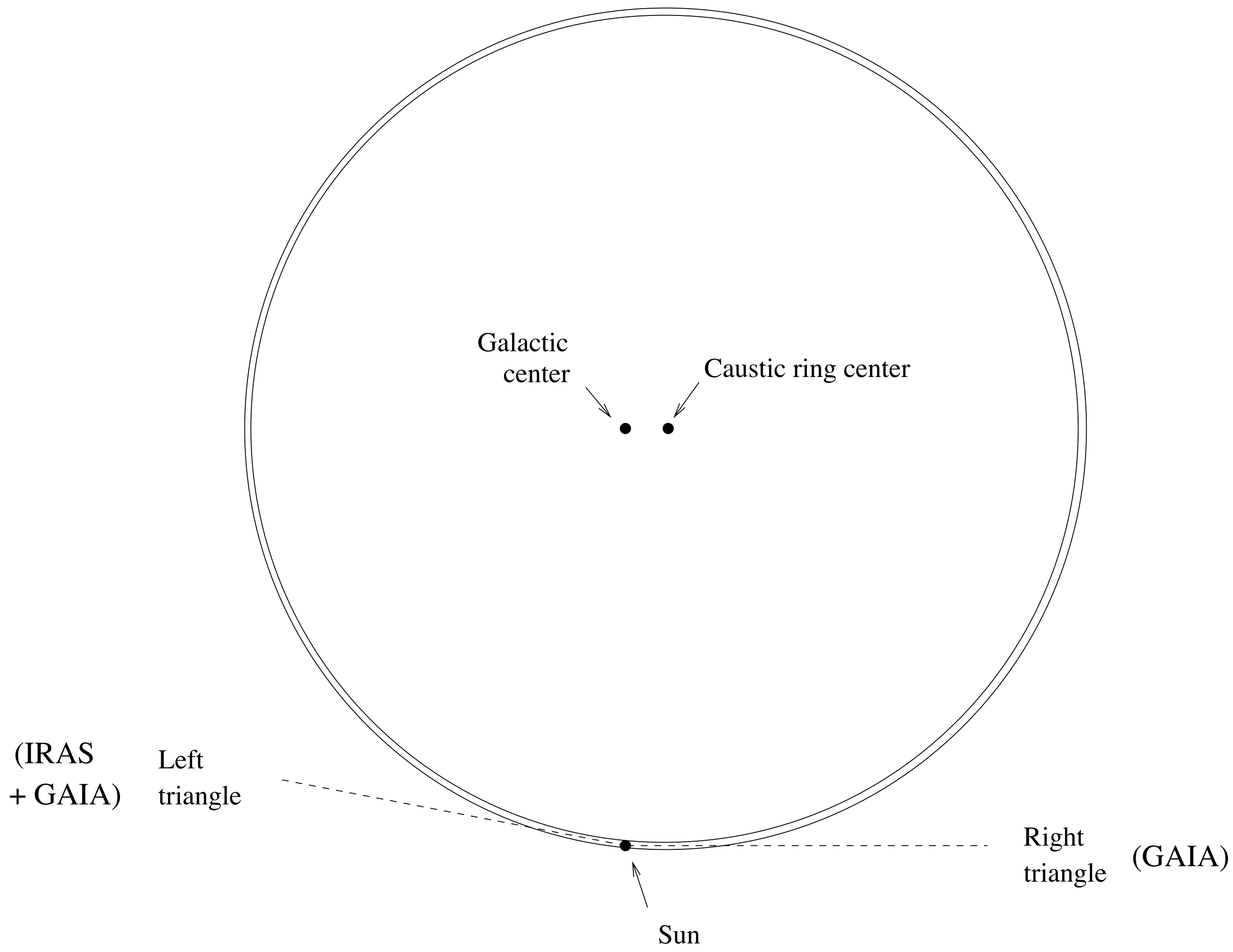
GAIA sky map (2016)

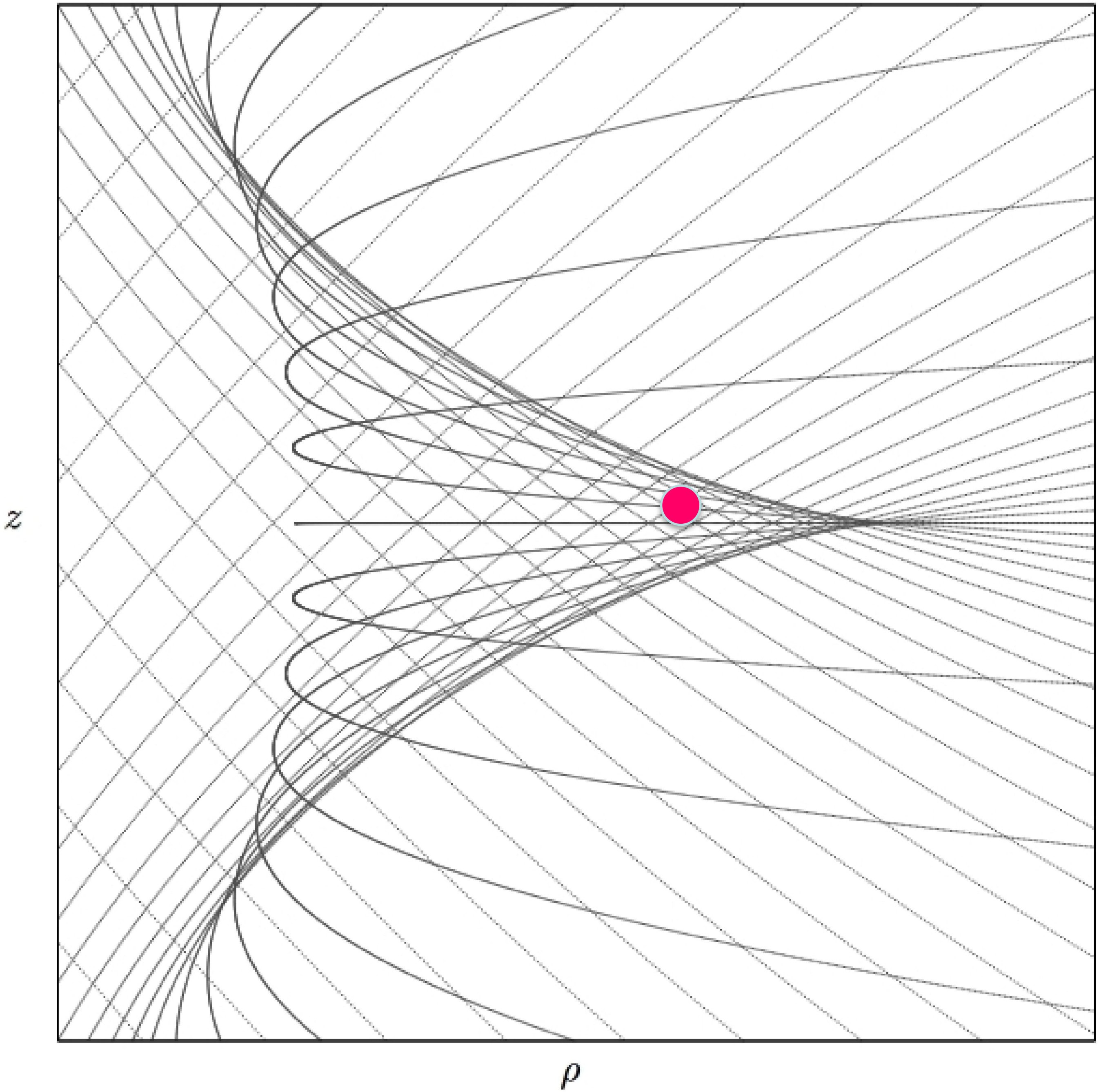


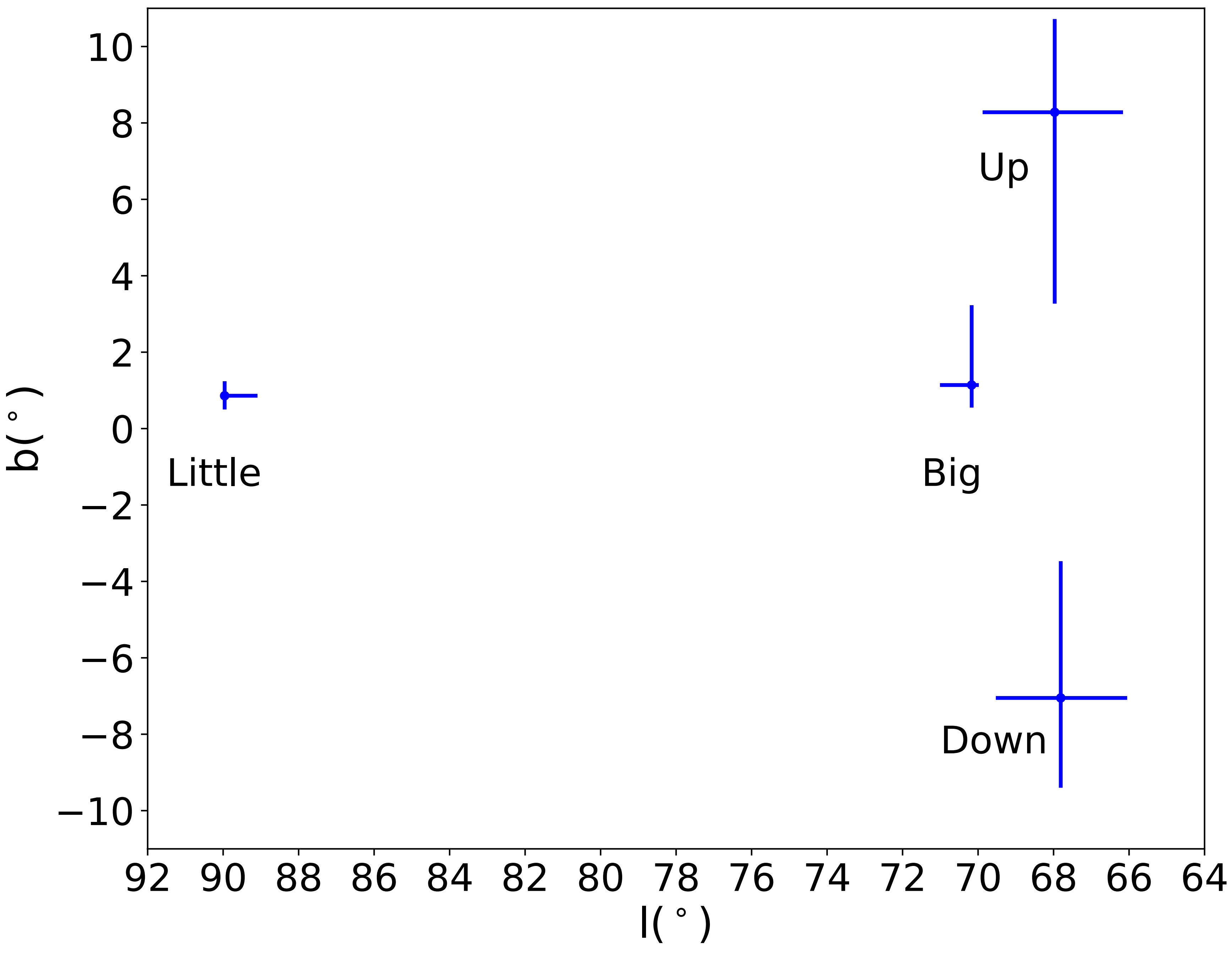




S. Chakrabarty, Y. Han, A. Gonzalez & PS, 2007.10509




z
ρ



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

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 is detectable