Axion Dark Matter

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Rencontres de Moriond
on Electroweak Interactions and Unified Theories

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Outline

- axions in particle physics
- axions in cosmology
- axion dark matter is detectable
- how observation may distinguish between axion and WIMP dark matter

The Strong CP Problem

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

where

$$\begin{aligned}\bar{\theta} &= \theta - \arg\left(m_u\, m_d\ \dots\ m_t\right)\\ &= \theta - \arg\det\left(Y^u\ Y^d\right)\end{aligned}$$

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

$U_{PQ}(1)$

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

Peccei and Quinn, 1977

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

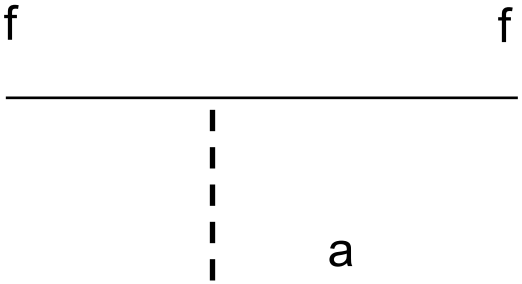
$$\mathcal{L} = \ \ldots \ + \ \frac{a}{f_a}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \ + \ \frac{1}{2}\partial_\mu a \partial^\mu a$$

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

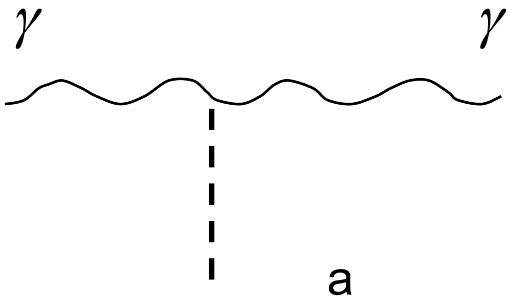
and a light neutral pseudoscalar particle is predicted: the axion.

Weinberg, Wilczek 1978

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



$$\mathcal{L}_{a\bar{f}f} = -\frac{g_f}{2f_a}\partial_\mu a(x)\bar{f}(x)\gamma^\mu\gamma^5 f(x)$$



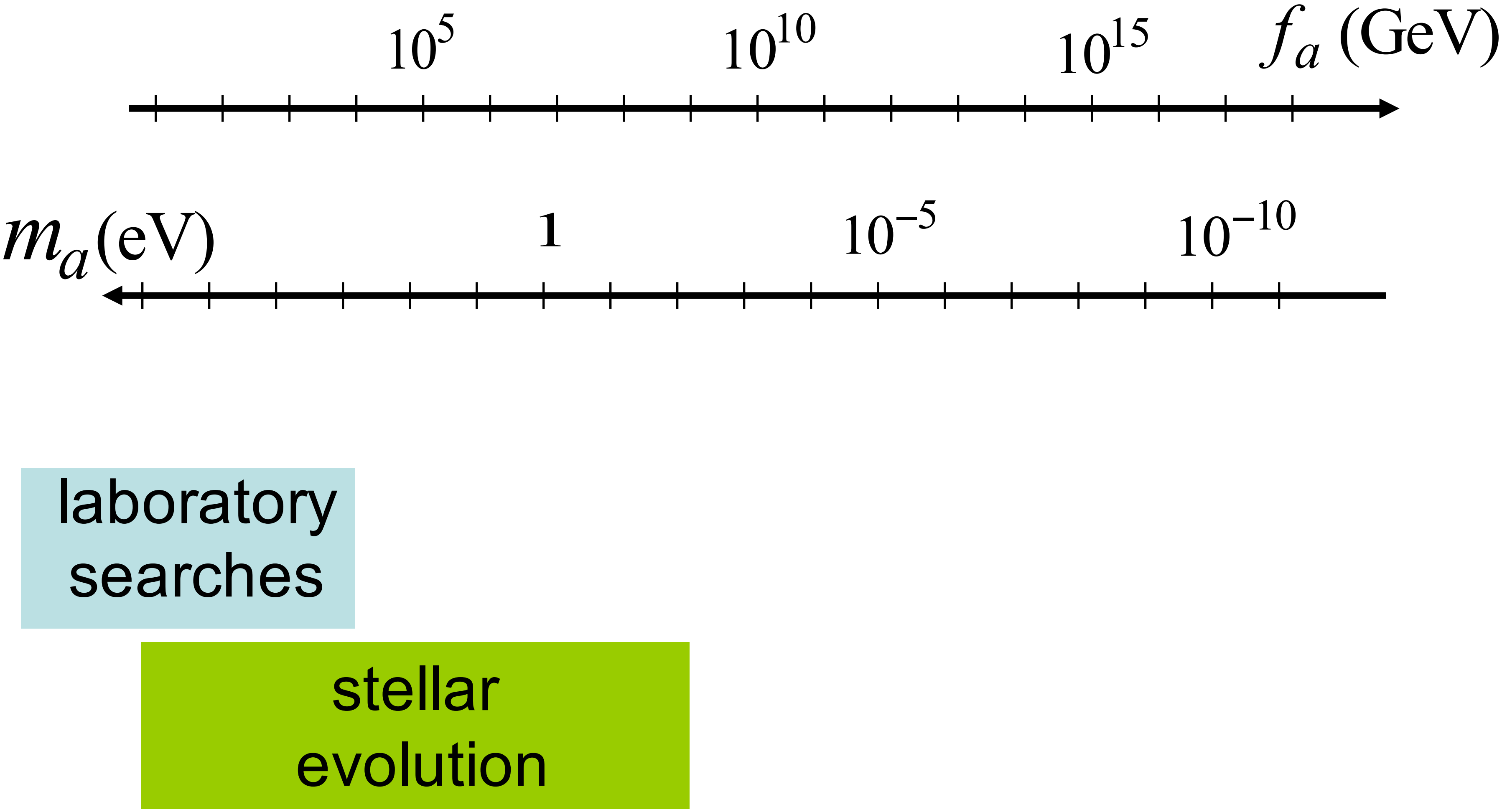
$$\mathcal{L}_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi}\frac{a(x)}{f_a}\vec{E}(x)\cdot\vec{B}(x)$$

g_γ = 0.97 in KSVZ model
0.36 in DFSZ model

Axions are constrained by

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

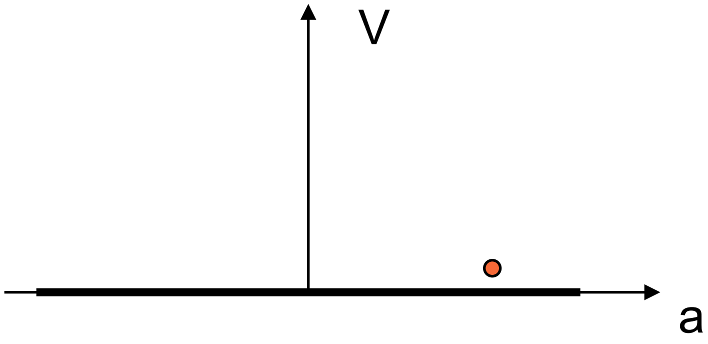
Axion constraints



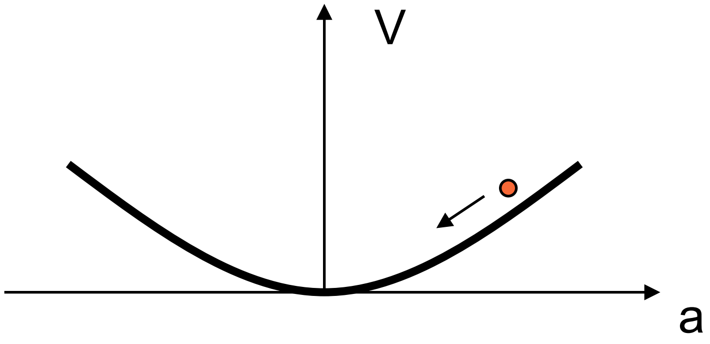
laboratory searches

stellar evolution

Axion production by vacuum realignment



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



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

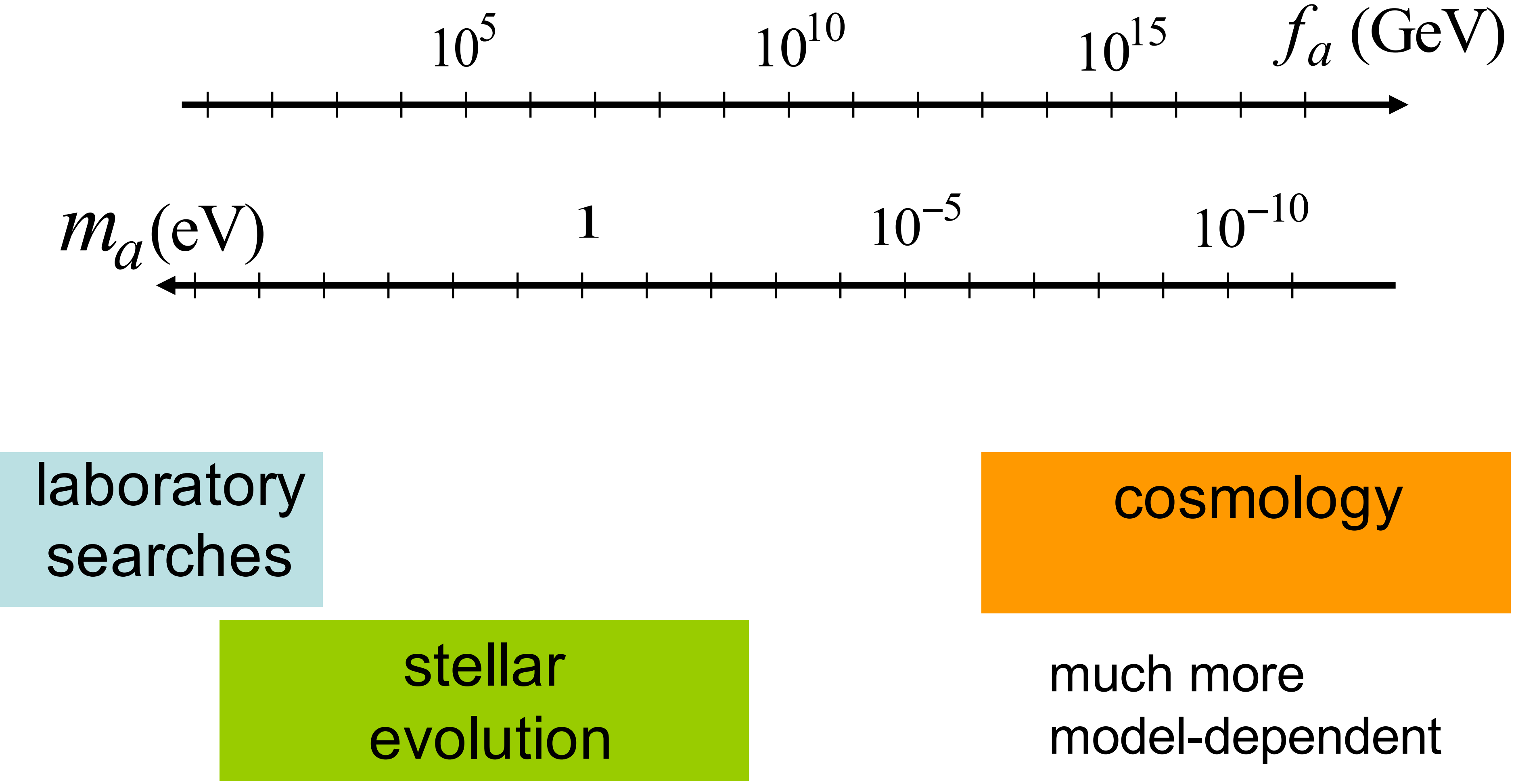
$$n_a(t_1) \simeq \frac{1}{2} m_a(t_1) a(t_1)^2 \simeq \frac{1}{2t_1} f_a^2 \alpha(t_1)^2$$

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

initial misalignment angle

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

Axion constraints



laboratory
searches

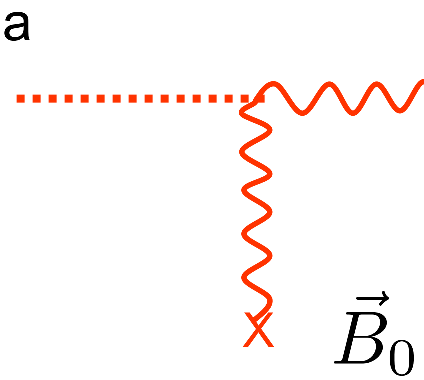
cosmology

stellar
evolution

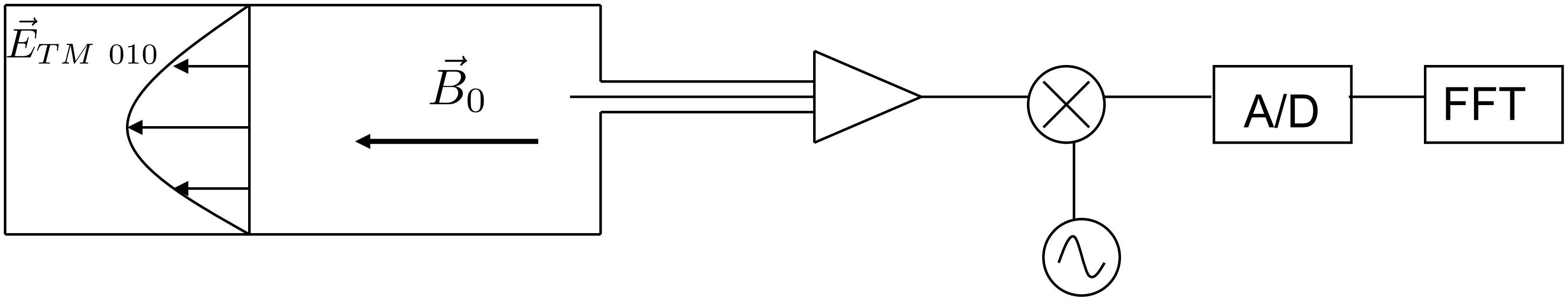
much more
model-dependent

Axion dark matter is detectable

PS, 83



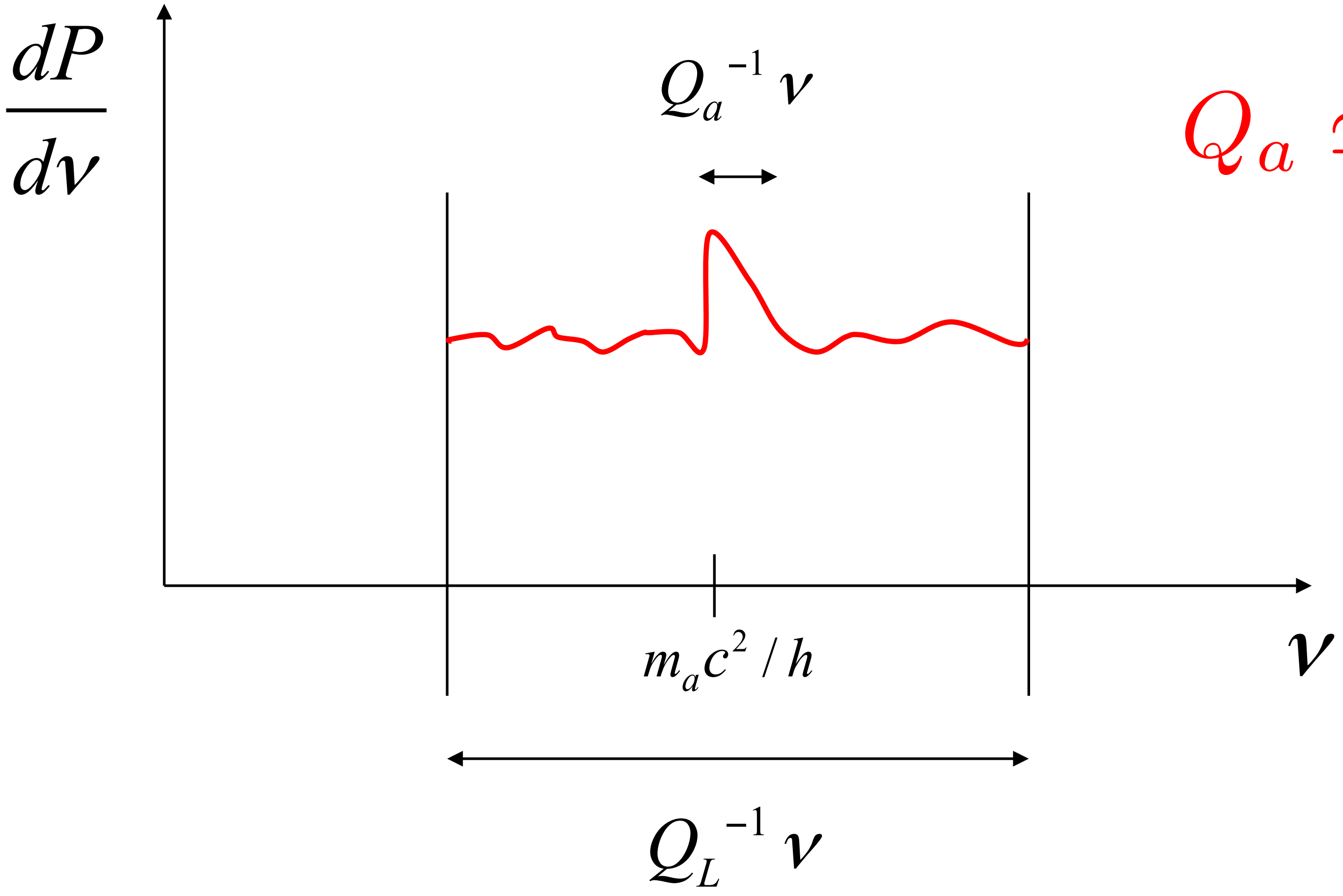
$$\mathcal{L}_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi}\frac{1}{f_a} a(x)\vec{E}(x)\cdot\vec{B}(x)$$



$$h\nu = m_a c^2 (1 + \frac{1}{2}\beta^2)$$

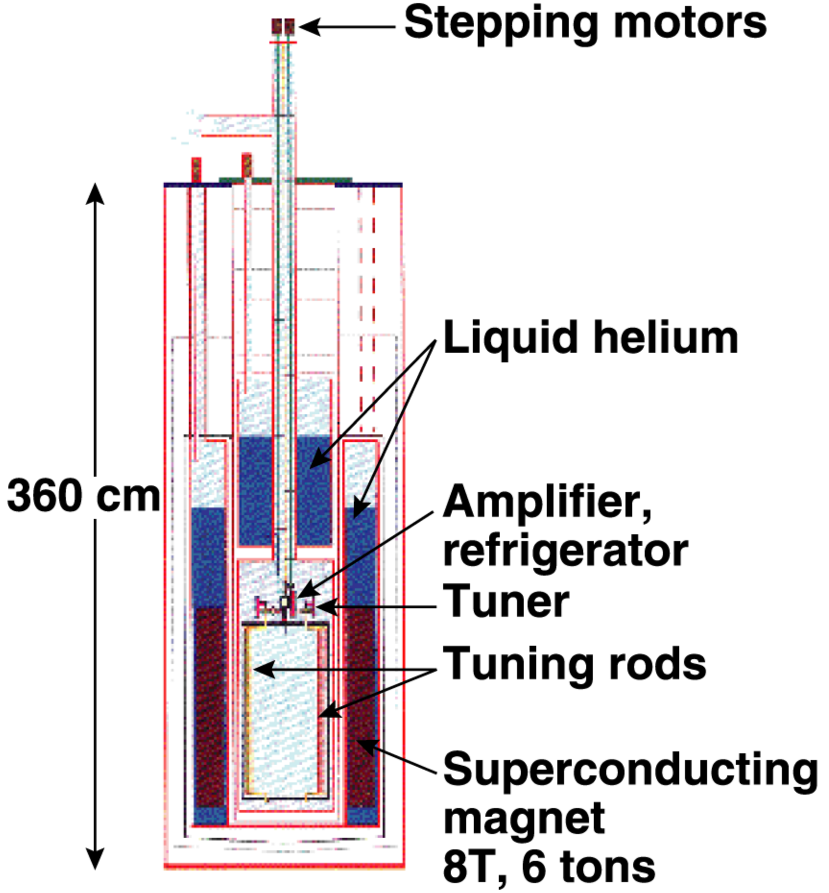
$$\beta = \frac{v}{c} \simeq 10^{-3}$$

$$Q_a \simeq 10^6$$



Axion Dark Matter eXperiment

Magnet with Insert (side view)



Stepping motors

Liquid helium

360 cm

Amplifier, refrigerator

Tuner

Tuning rods

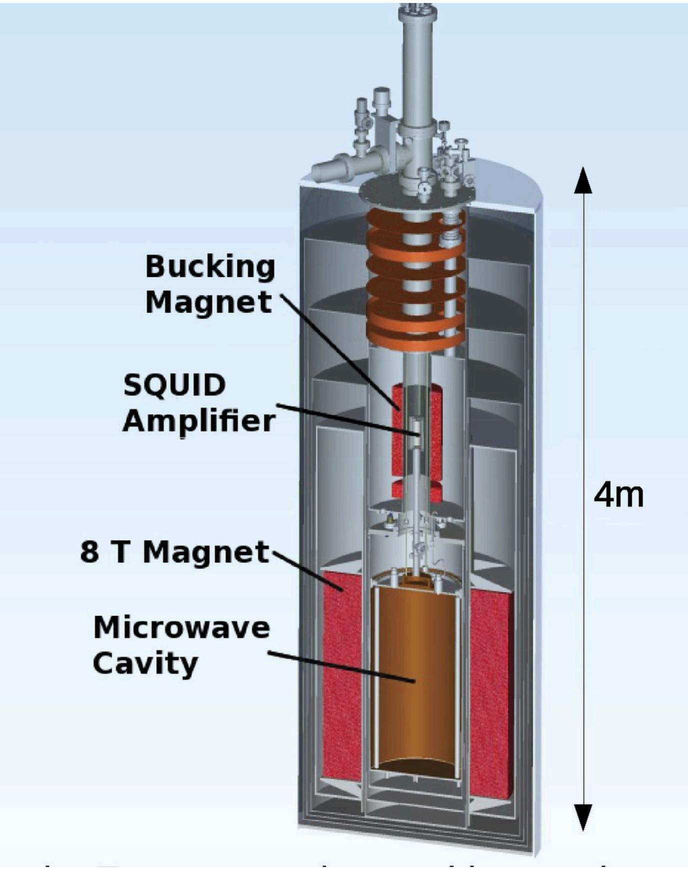
Superconducting magnet
8T, 6 tons

Pumped LHe → T ~ 1.5 k

Magnet

8 T, 1 m × 60 cm ∅

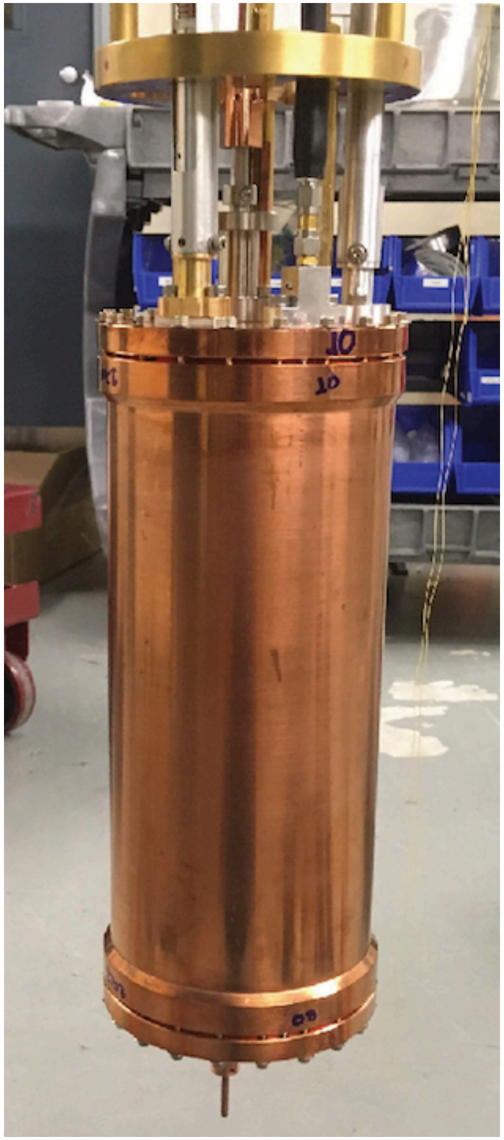
ADMX 2nd generation



SQUIDs from
J. Clarke's group

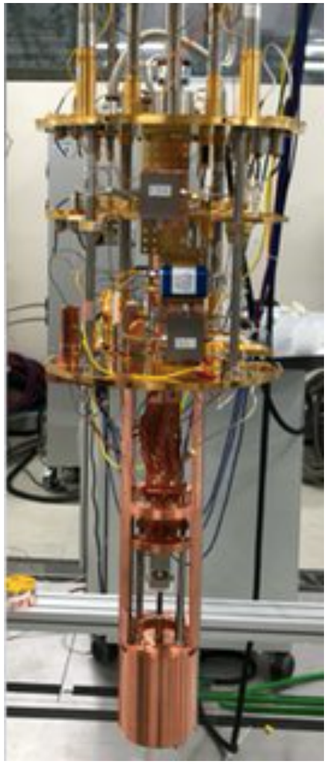
Leslie Rosenberg and
Gray Rybka at U. Wash.

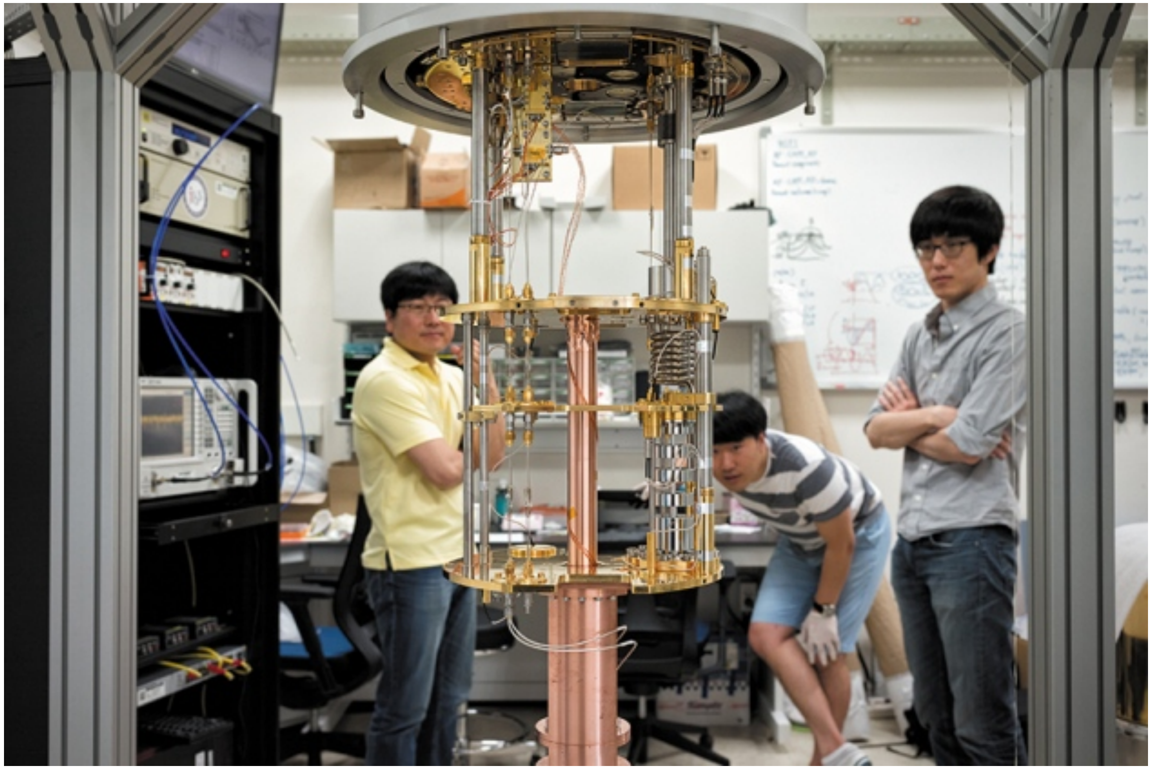
HAYSTAC at Yale



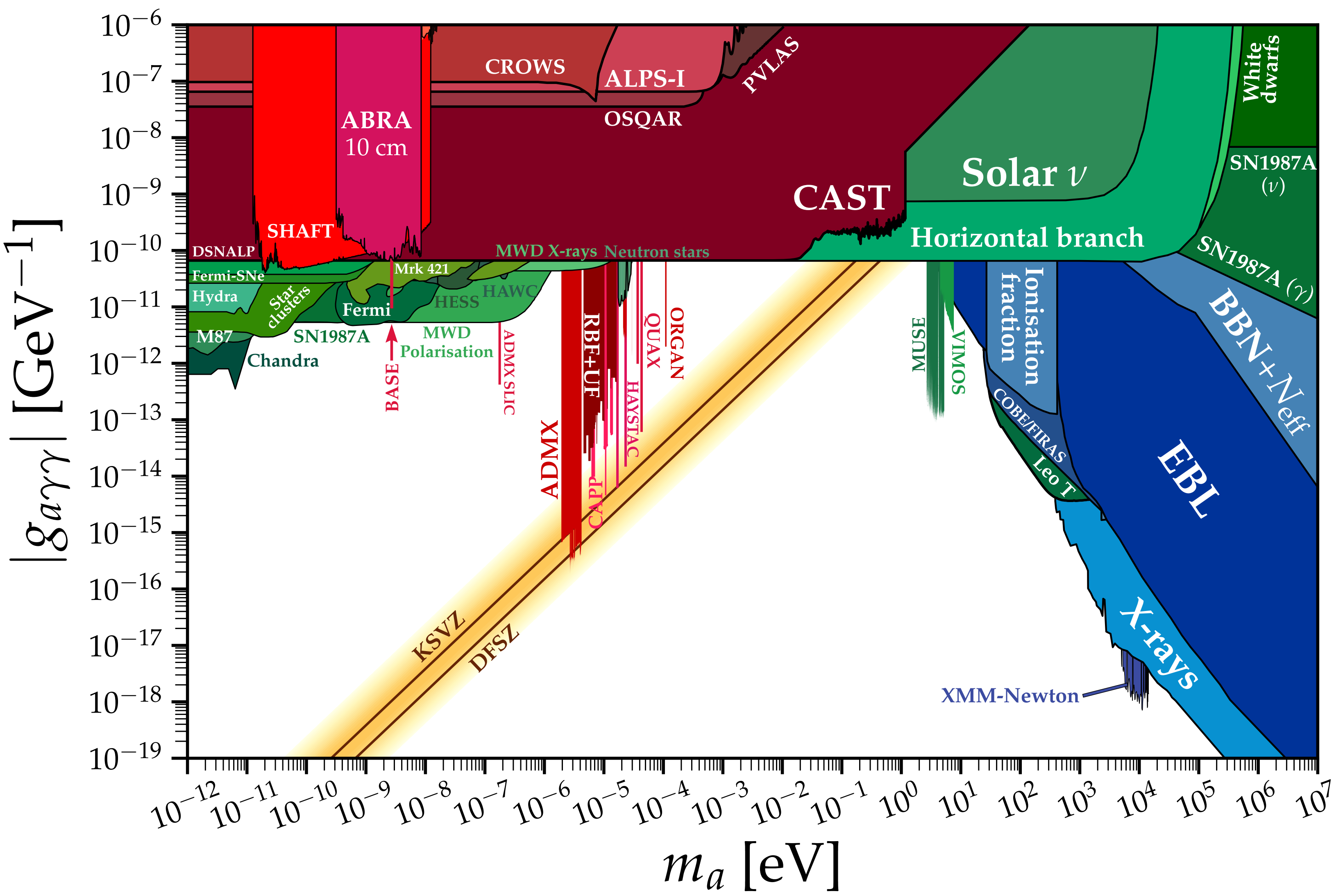
CAPP

Center for
Axion and Precision
Physics Research



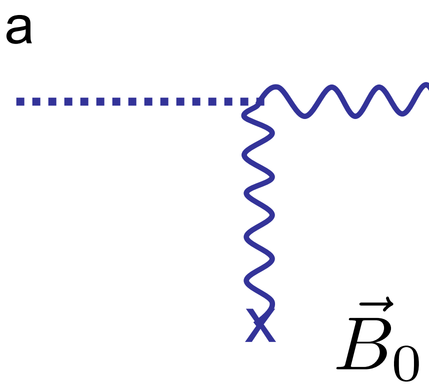


Axion photon constraints



from https://cajohare.github.io/AxionLimits/ by Ciaran O'Hare

Axion to photon conversion in a magnetic field



conversion probability

$$p(a \longleftrightarrow \gamma) = \left(\frac{\alpha\, g_\gamma}{\pi\, f_a}\right)^2 \mathrm{B}_0{}^2 \left(\frac{\sin \frac{q_z L}{2}}{q_z}\right)^2$$

with $q_z = \dfrac{m_a{}^2 - \omega_{\mathrm{pl}}{}^2}{2E_a}$

Theory

- P. S. ’83
- L. Maiani, R. Petronzio and E. Zavattini ’86
- K. van Bibber et al. ’87
- G. Raffelt and L. Stodolsky, ‘88
- K. van Bibber et al. ’89

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Experiment

- D. Lazarus et al. ’92
- R. Cameron et al. ‘93
- S. Moriyama et al. ’98, Y. Inoue et al. ’02
- K. Zioutas et al. 04
- E. Zavattini et al. 05

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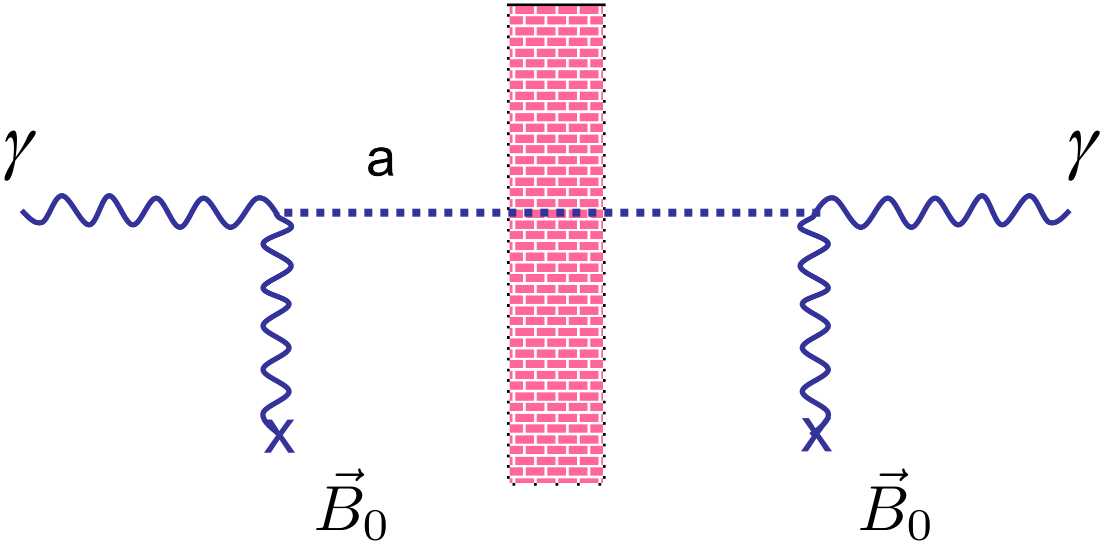
DIPOLE PROTOTYPE
CAST
ANSALDO GIE
EUROPAMETALLI – LMI
E. ZANON

Shining light through walls



rate $\propto \frac{1}{f_a^{\,4}}$

K. van Bibber et al. ‘87

A. Ringwald ‘03

R. Rabadan,
A. Ringwald and
C. Sigurdson ‘05

P. Pugnat et al. '05

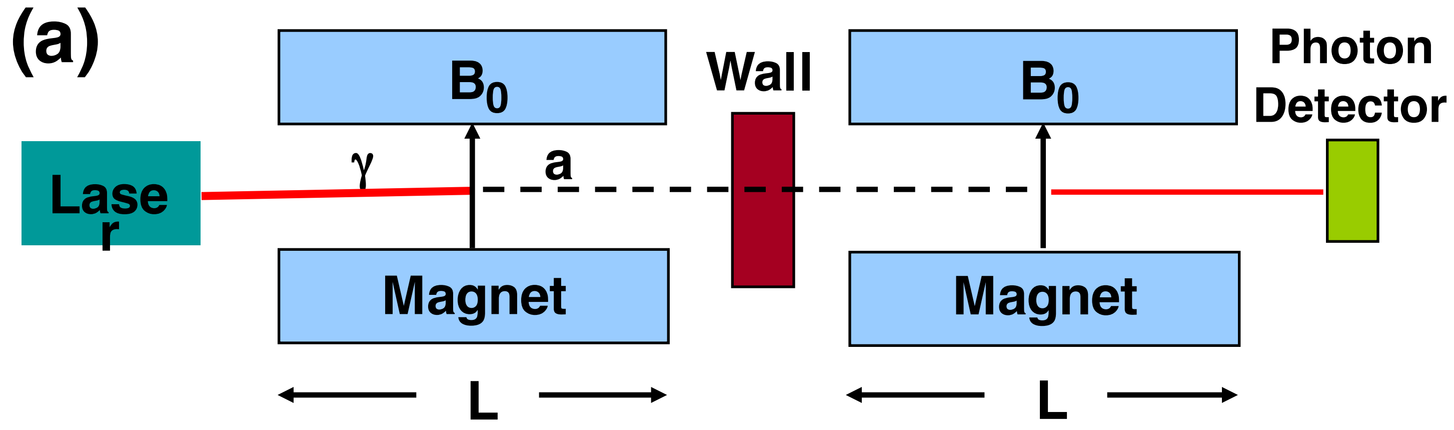
C. Robilliard et al. '07

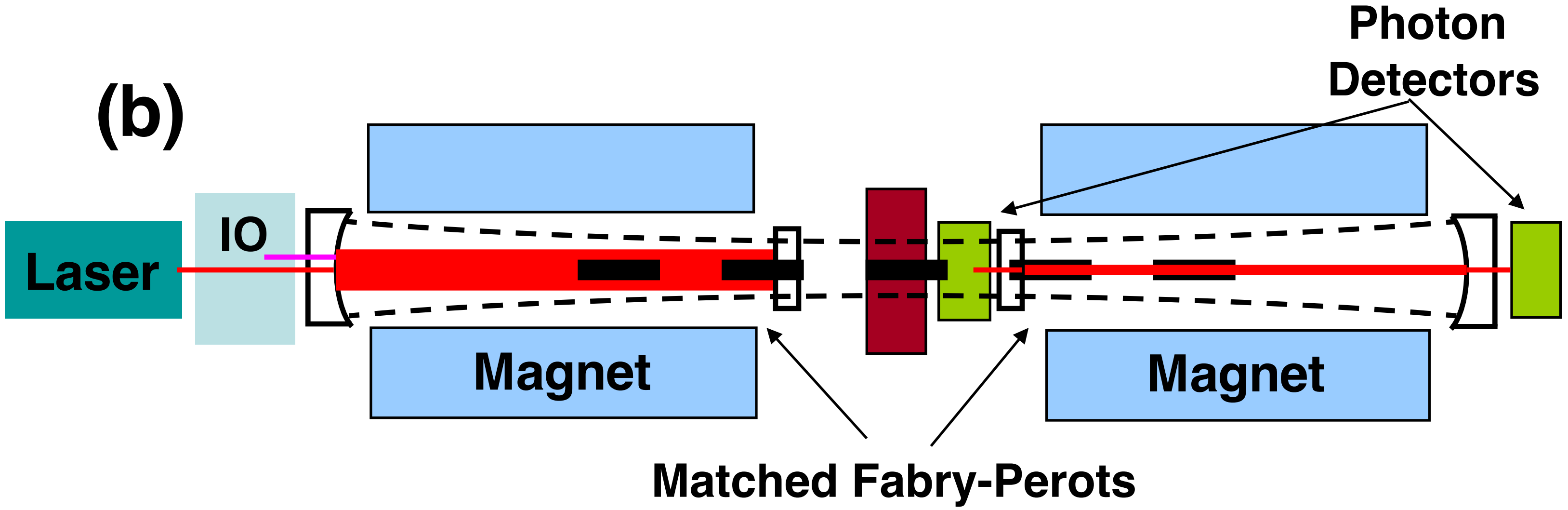
A. Afanasev et al. '08

A. Chou et al. '08

K. Ehret et al. '10

Resonantly Enhanced Axion-Photon Regeneration





Hoogeveen (1996); P.S., Tanner and van Bibber (2007) & G. Mueller (2009)

ALPS II at DESY

A. Ringwald, A. Lindner et al.

$B_0 = 5.3\ \mathrm{T}$ $\quad L = 2 \times 120\ m$ in HERA tunnel

``Invisible" axion detection methods

the cavity haloscope
solar axion searches
shining light through walls
dielectric haloscopes
NMR methods
axion mediated long-range forces
LC circuit
axion echo

Outline

- axions in particle physics
- axions in cosmology
- axion dark matter is detectable
- how observation may distinguish between axion and WIMP dark matter

Axions today

$$\rho_{\mathrm{DM}} = \Omega_{\mathrm{DM}}\ \rho_{\mathrm{crit}}$$

$$\Omega_{\mathrm{DM}} \simeq 0.23 \qquad\qquad \rho_{\mathrm{crit}} \simeq 10^{-29}\ \mathrm{gr/cc}$$

$$n_a(t_0) = \frac{\rho_{\mathrm{DM}}(t_0)}{m_a} \sim 1.3 \cdot 10^8 \frac{1}{\mathrm{cm}^3}$$

$$\Delta p_a = m_a \Delta v_a \sim \frac{1}{t_1} \frac{10^{-4}\ \mathrm{eV}}{\mathrm{GeV}}$$

$$\Delta v_a \sim 3 \cdot 10^{-17} \sim 10^{-6}\ \frac{\mathrm{cm}}{\mathrm{sec}} \sim \frac{30\ \mathrm{cm}}{\mathrm{year}}$$

$$\Delta x\ \Delta p \gtrsim \hbar/2$$

$$\Delta x_a \sim \frac{1}{\Delta p_a} \sim 0.7 \cdot 10^{17}\ \mathrm{cm} \simeq 0.02\ \mathrm{pc}$$

(!)

$$\mathcal{N}_a = \frac{(2\pi)^3 n_a}{(\Delta p_a)^3} \sim 10^{61}$$

Axion dark matter is an extremely degenerate Bose gas.

Does it behave the same way as WIMP dark matter in astrophysical contexts?

WIMPs today

$$\rho_{\rm DM} = \Omega_{\rm DM}\ \rho_{\rm crit}$$

$$\Omega_{\rm DM} \simeq 0.23 \qquad\qquad \rho_{\rm crit} \simeq 10^{-29}\ {\rm gr/cc}$$

$$n_W \simeq 0.13\ \frac{1}{\rm m^3}\left(\frac{10\ \rm GeV}{m_W}\right)$$

$$\Delta p_W \equiv m_W \Delta v_W \sim \sqrt{2 m_W T_{W\rm kin}}\ \frac{T_0}{T_{W\rm kin}}$$

temperature at which WIMPs kinetically decouple

$$T_{W\rm kin} \sim \rm MeV$$

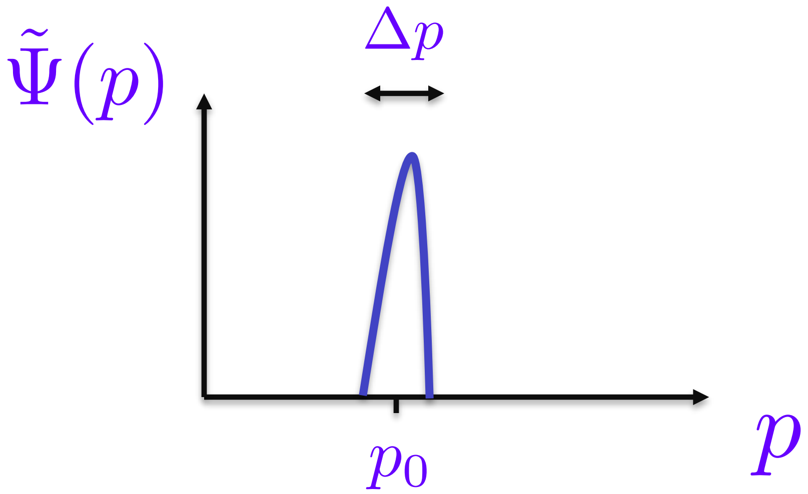
$$\Delta v_W \sim 1.3 \cdot 10^{-12} \sqrt{\frac{10\ \mathrm{GeV}}{m_W}} \qquad (c = 1)$$

$$\Delta x_W \sim \frac{1}{\Delta p_W} \sim 15\mu\mathrm{m} \ \sqrt{\frac{10\ \mathrm{GeV}}{m_W}} \qquad (\hbar = 1)$$

$$\mathcal{N}_W = \frac{(2\pi)^3 n_W}{(\Delta p_W)^3} \sim 10^{-13} \left(\frac{10\ \mathrm{GeV}}{m_W}\right)^{\frac{5}{2}}$$

In the axion case, fluctuations in density are generically large on the length scale $\frac{1}{\Delta p_a}$

$$\ell \equiv \frac{1}{\Delta p_a}$$ = correlation length



$$\Psi(\vec{x}) = \sum_{\vec{p}} \Psi_{\vec{p}}\, e^{i\vec{p}\cdot\vec{x}}$$

$$\rho(\vec{x}) = m_a \, |\Psi(\vec{x})|^2$$

$$= m_a \sum_{\vec{p}} \sum_{\vec{p}'} \Psi_{\vec{p}} \Psi_{\vec{p}'}{}^{*} \, e^{i(\vec{p}-\vec{p}')\cdot\vec{x}}$$

cannot change much over a distance $\ell = \dfrac{1}{\Delta p}$

With random phases

$$\langle \rho(\vec{x}) \rangle = m_a \sum_{\vec{p}} |\Psi_{\vec{p}|}|^2$$

$$\langle \rho(\vec{x}) \rho(\vec{y}) \rangle = m_a^2 \sum_{\vec{p}} \sum_{\vec{p}'} |\Psi_{\vec{p}|}|^2 |\Psi_{\vec{p}'}|^2 \, [1 + \cos((\vec{p} - \vec{p}') \cdot (\vec{x} - \vec{y}))]$$

$$\langle (\rho(\vec{x}))^2 \rangle = 2\langle \rho(x) \rangle^2$$

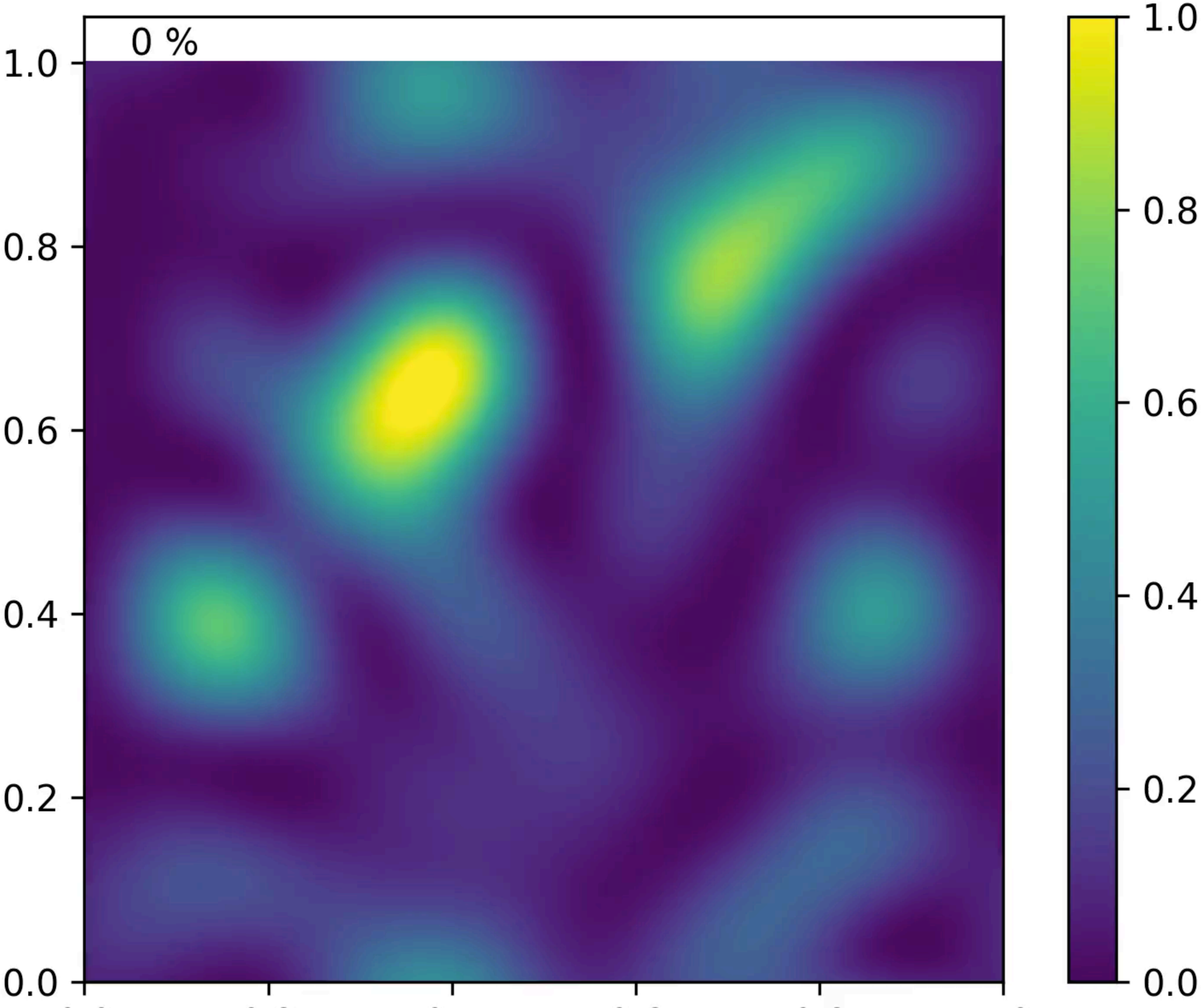
$$\langle (\delta\rho(\vec{x}))^2 \rangle \equiv \langle (\rho(x) - \langle \rho(x) \rangle)^2 \rangle = \langle \rho(x) \rangle^2$$

$$\delta\rho = \rho$$

emphasized by
Hyungjin Kim
yesterday

Generically the fluctuations in the density are of order the density, and the fluctuations are correlated over distances $\ell = \frac{1}{\Delta p}$

simulation by Yuxin Zhao



In the axion case, the fluctuations in the gravitational fields are necessarily large

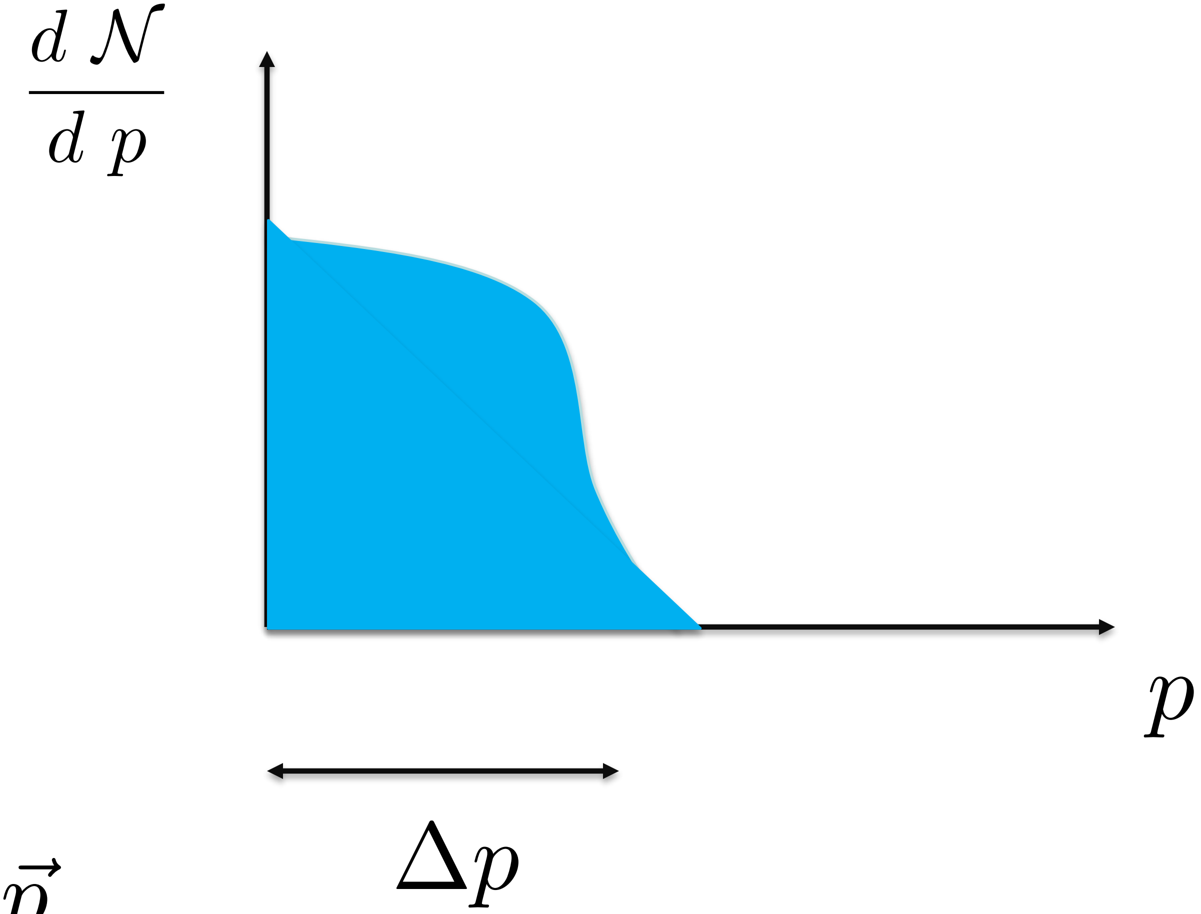
$$\delta g \sim 4\pi G\rho\,\ell$$

regardless of their average value.

For example in a homogeneous universe

$\vec{g} = 0$ in the WIMP case

$\bar{\vec{g}} = 0$ in the axion case, but the typical gravitational field is δg



$$\vec{F} = \frac{d\vec{p}}{dt}$$

$$\tau \sim \frac{\Delta p}{m \delta g} \sim 24 \text{ sec}$$

Thermalization occurs due to gravitational interactions

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

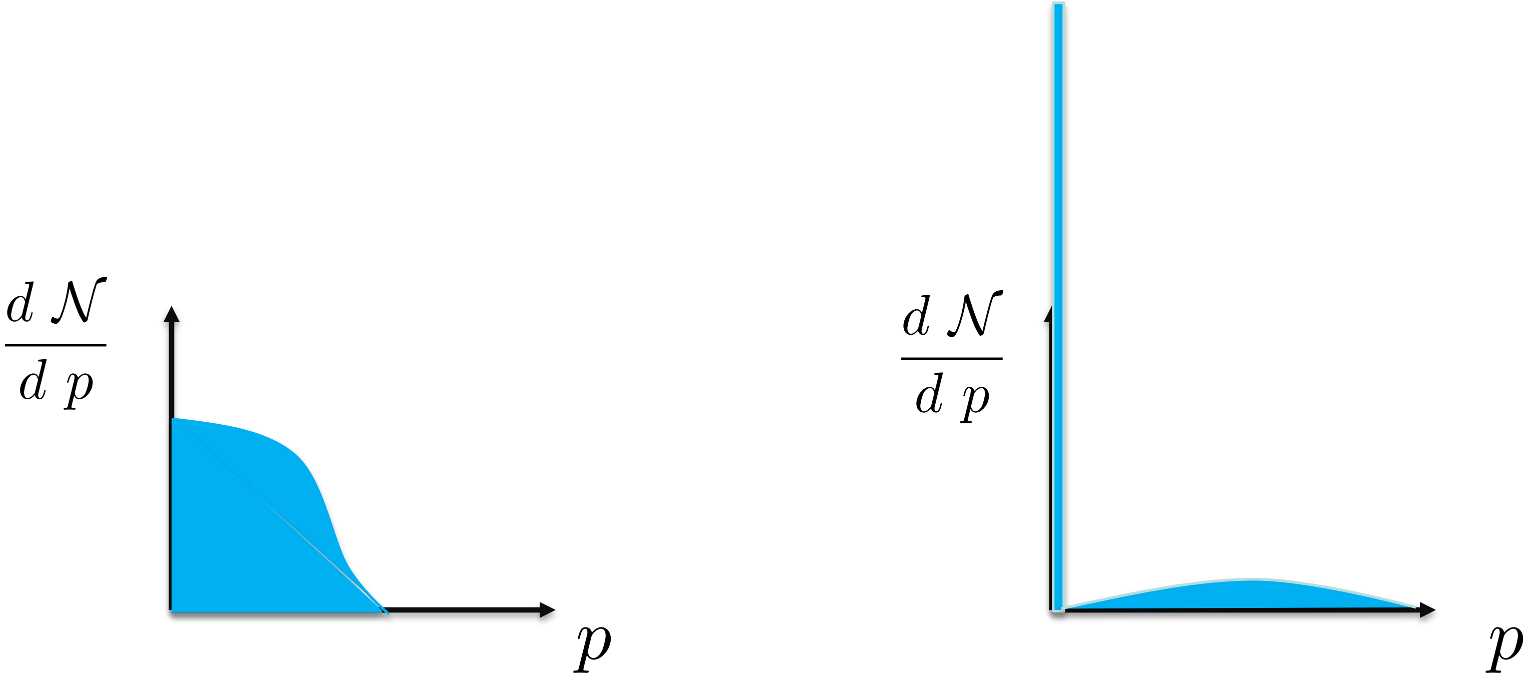
$$\Gamma_g \equiv \frac{1}{\tau} \sim 4\pi G\rho\ell\ m\ \frac{1}{\Delta p} = 4\pi G\rho m\ell^2$$

compare with

$$H(t) = \frac{1}{2t}$$

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

$$T_\gamma \sim 400 \text{ eV} \left(\frac{10^{-5} \text{ eV}}{m_a} \right)^{\frac{1}{2}}$$



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

Generation of vorticity is expected in the axion fluid

N. Banik & PS, 2013

because the axions can move between states of different vorticity

$$|l_z = 3\hbar\rangle + |l_z = 5\hbar\rangle \quad \to \quad |l_z = 2\hbar\rangle + |l_z = 6\hbar\rangle$$

and the state of lowest energy for given total angular momentum (the state the axions condense into when they thermalize and rethermalize) is one of rigid rotation

Generation of vorticity is impossible in the case of WIMP dark matter.

(A. Natarajan + PS, 2006)

For WIMP dark matter

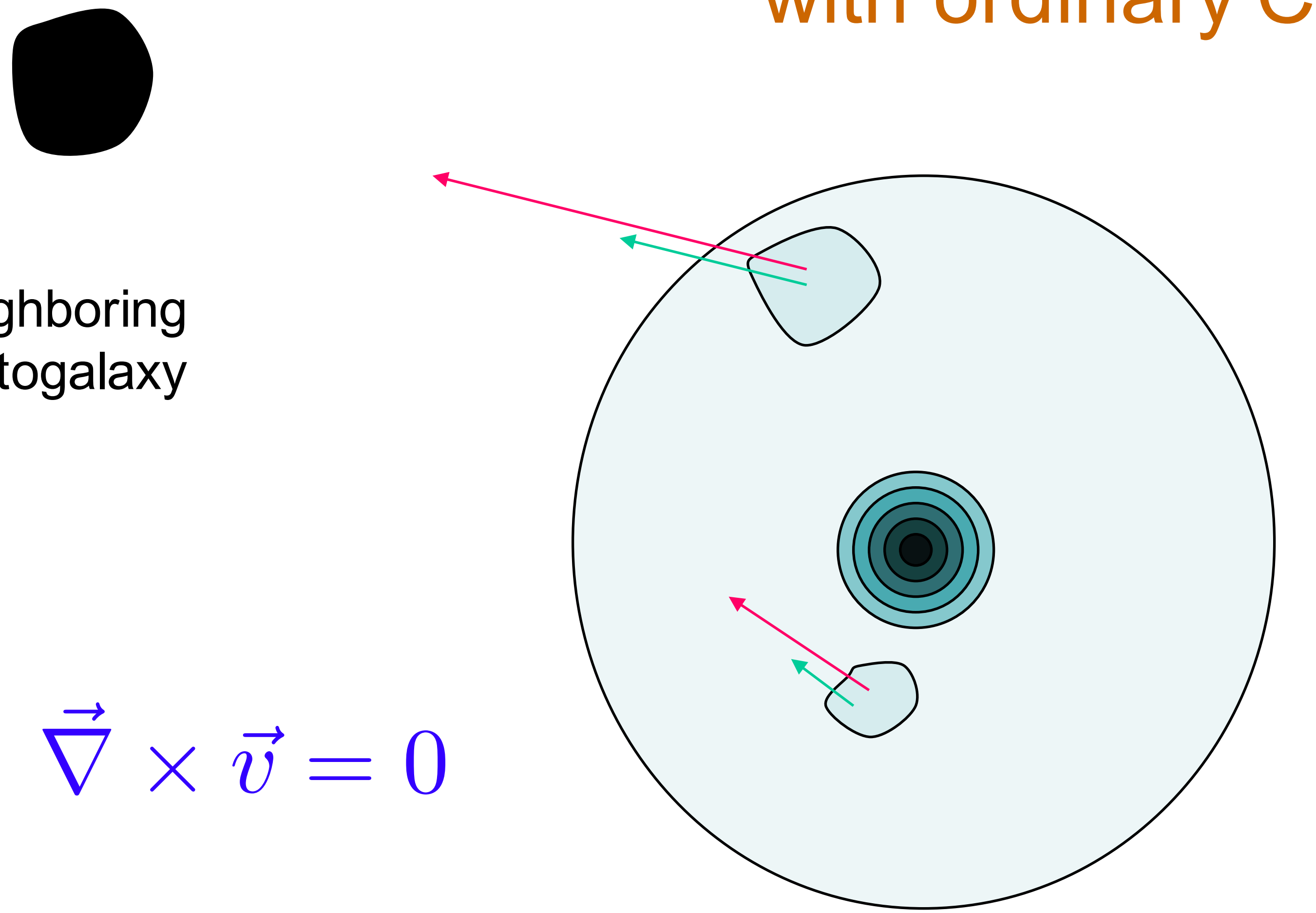
$$\partial_t \vec{v} + \vec{v} \cdot \vec{\nabla} \vec{v} = -\vec{\nabla} \Phi(\vec{x}, t)$$

Newtonian gravitational potential

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

then $\vec{\nabla} \times \vec{v} = 0$ for ever after

Tidal torque theory with ordinary CDM

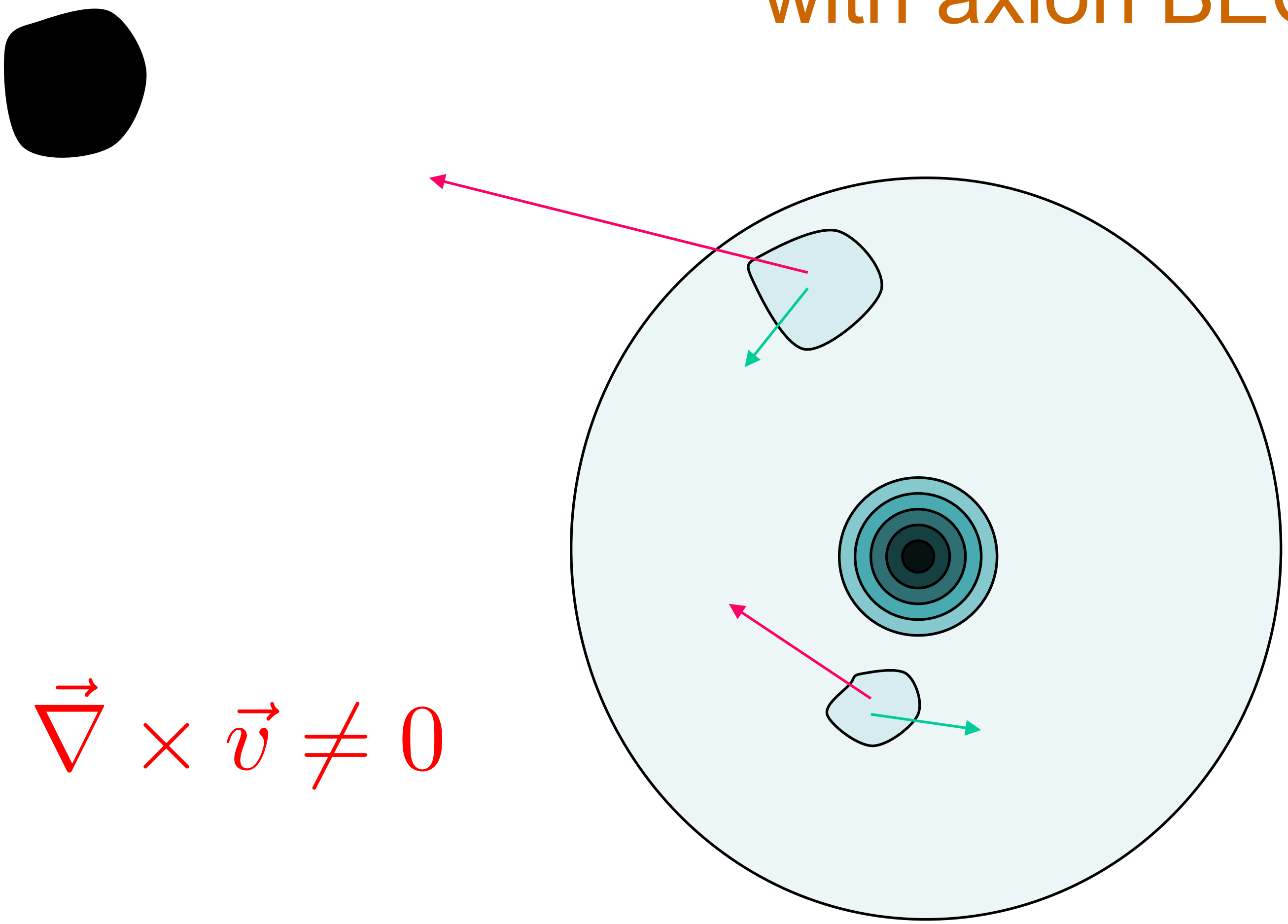


neighboring protogalaxy

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

the velocity field remains irrotational

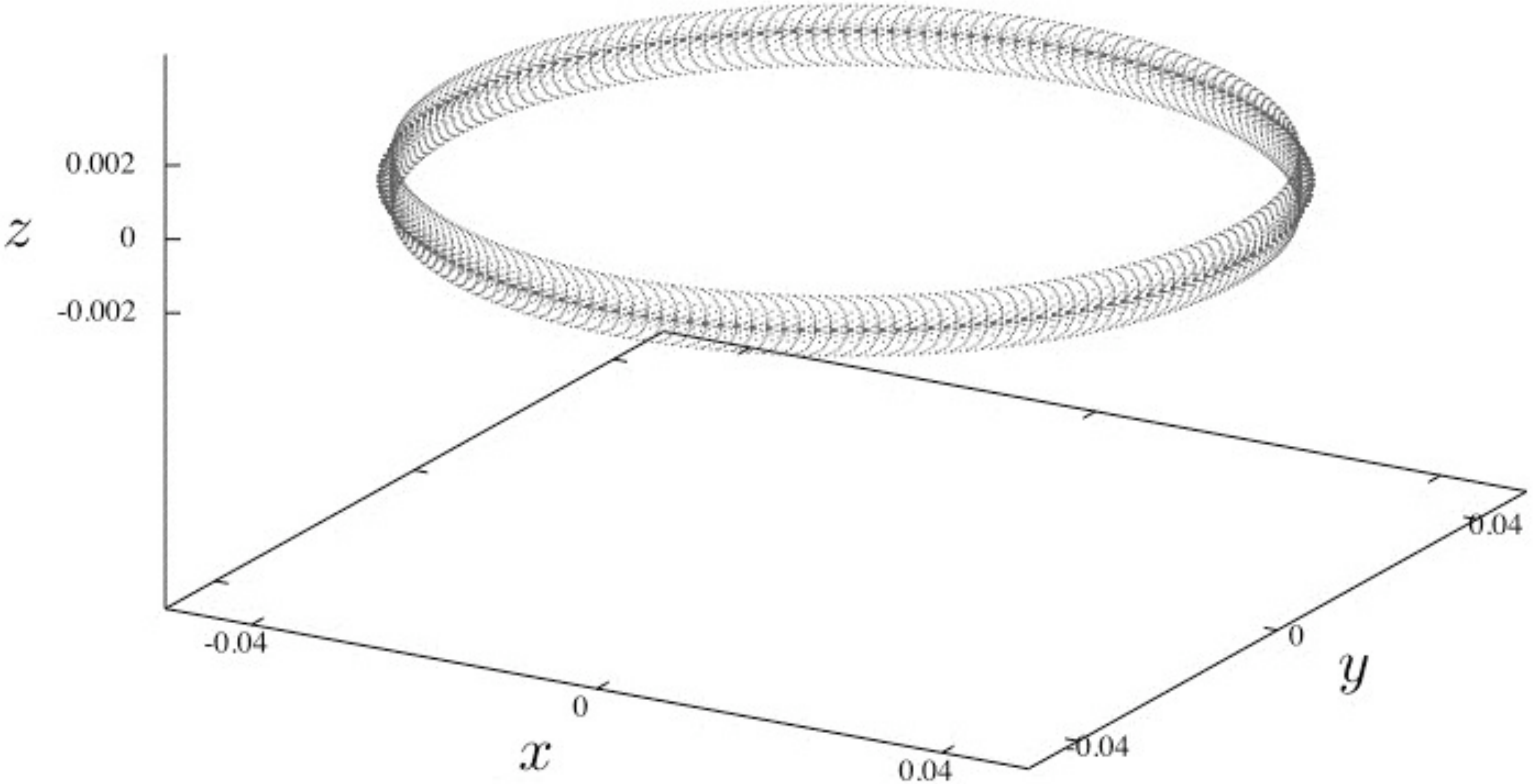
Tidal torque theory with axion BEC



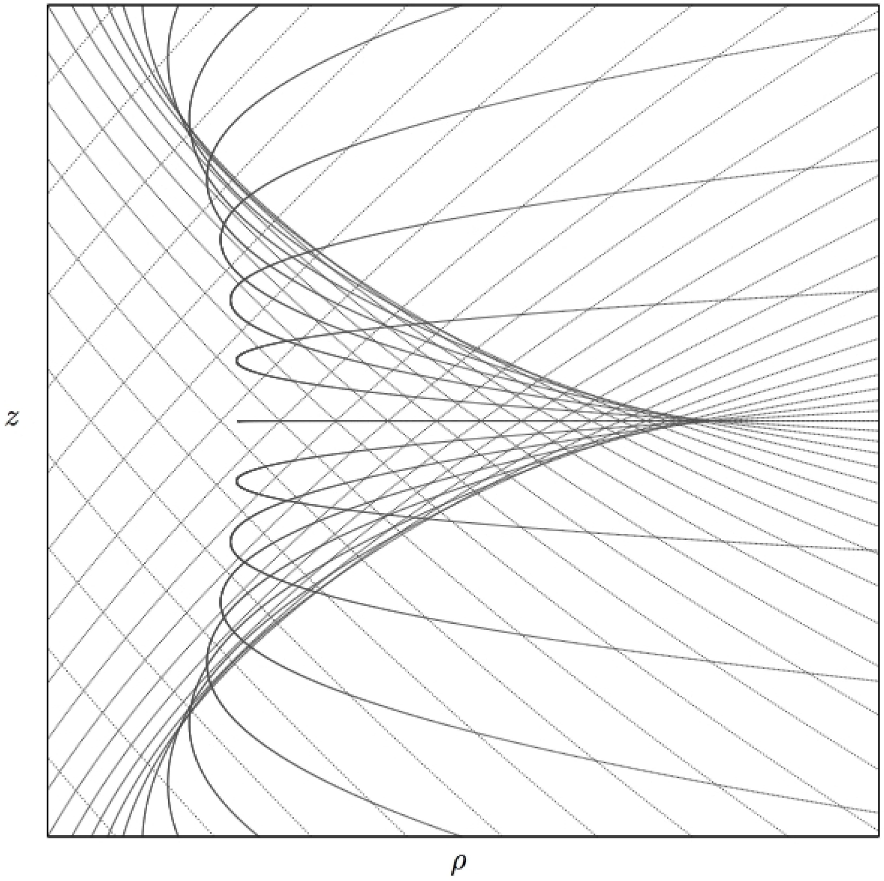
$$\vec{\nabla} \times \vec{v} \neq 0$$

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

in case of net overall rotation

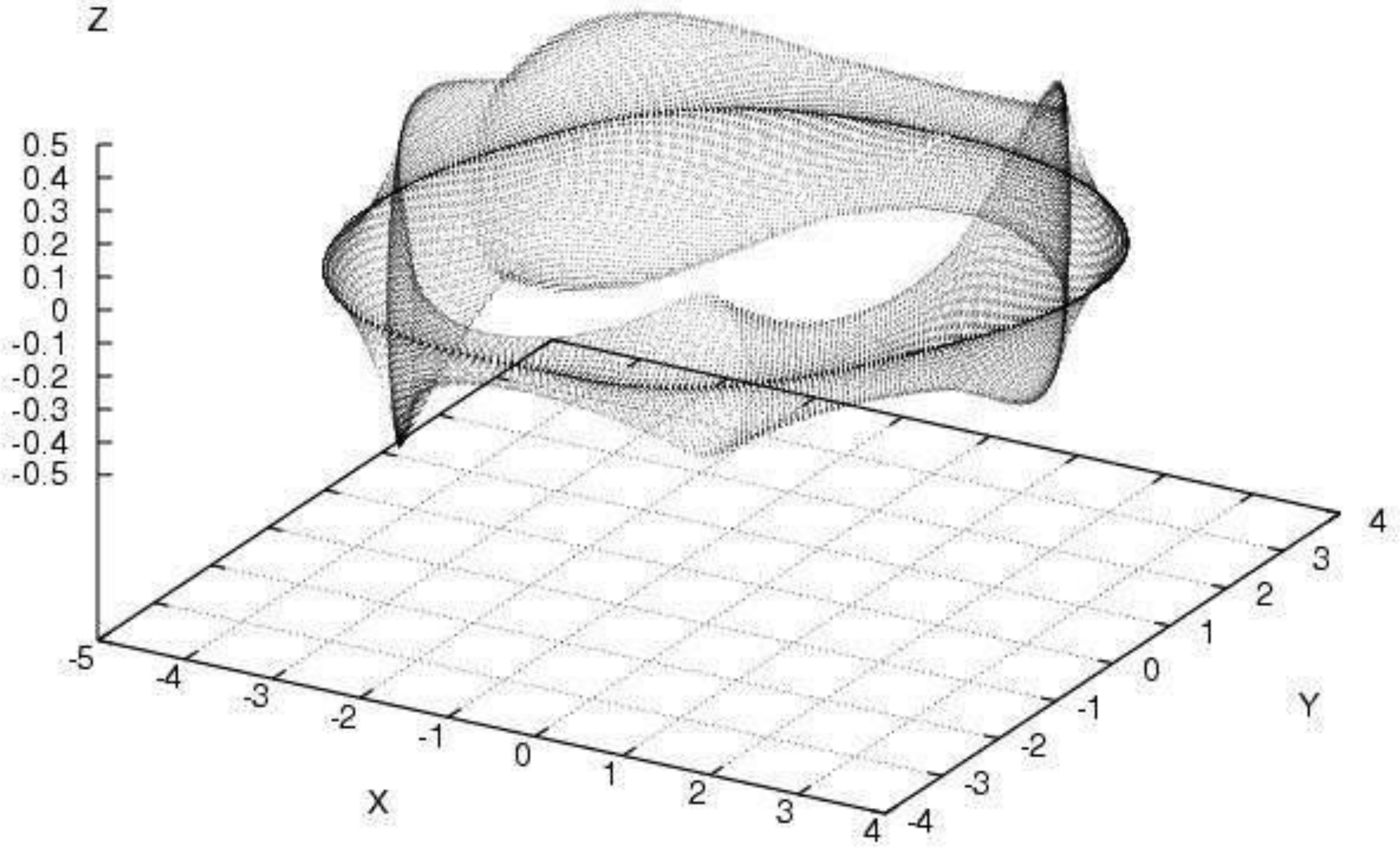


The caustic ring cross-section



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

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
- Axion dark matter has distinctive properties in large scale structure formation