Axiogenesis

Raymond Co

Leinweber Center for Theoretical Physics
University of Michigan

↓

William I. Fine Theoretical Physics Institute
University of Minnesota

Online "Newton 1665" Seminars April 6th 2020

Collaborators:

arXiv: 1910.02080 Keisuke Harigaya Phys. Rev. Lett. 124, 111602 (2020)

arXiv: 1910.14152 Lawrence Hall, Keisuke Harigaya

Today

Horst Ludwig Störmer

1998 Nobel Prize in Physics

"for their discovery of a new form of quantum fluid with fractionally charged excitations".

born on

April 6th 1949

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https://en.wikipedia.org/wiki/Horst_Ludwig_St%C3%B6rmer

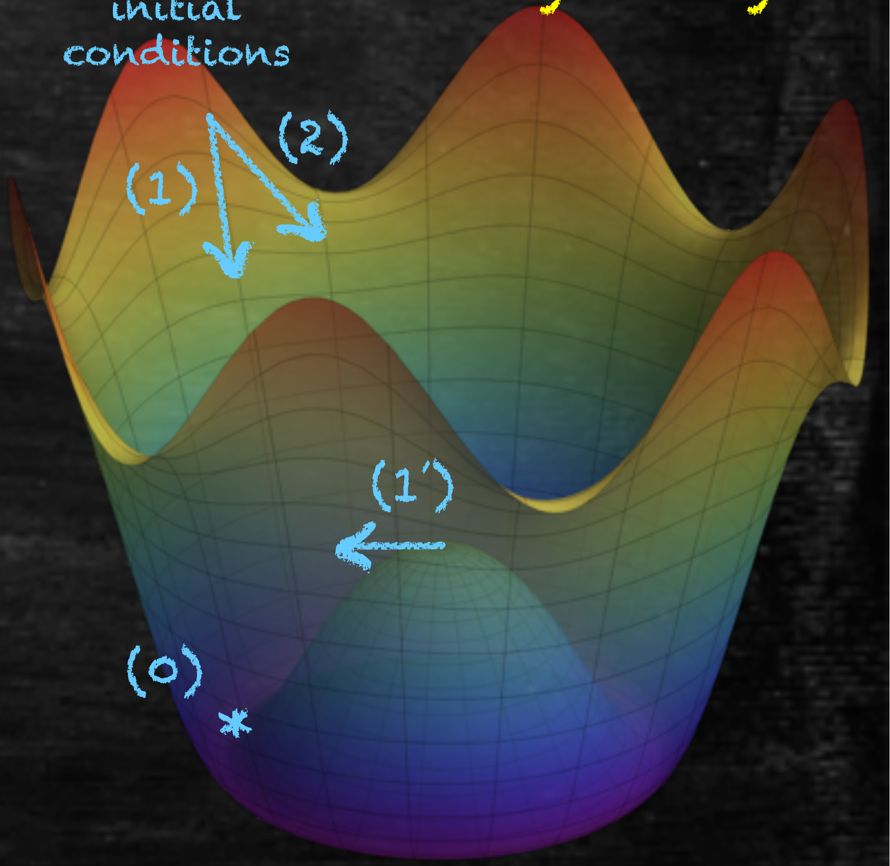
Storyline

- QCD axion

(0) Misalignment mechanism
Preskill, Wise, Wilczek 1983, Abbott, Sikivie 1983, Dine, Fischler 1983

(1)

(2)



Storyline

- **QCD axion**

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RC, L. Hall, K. Harigaya 2017 K. Harigaya, J. Leedom 2019

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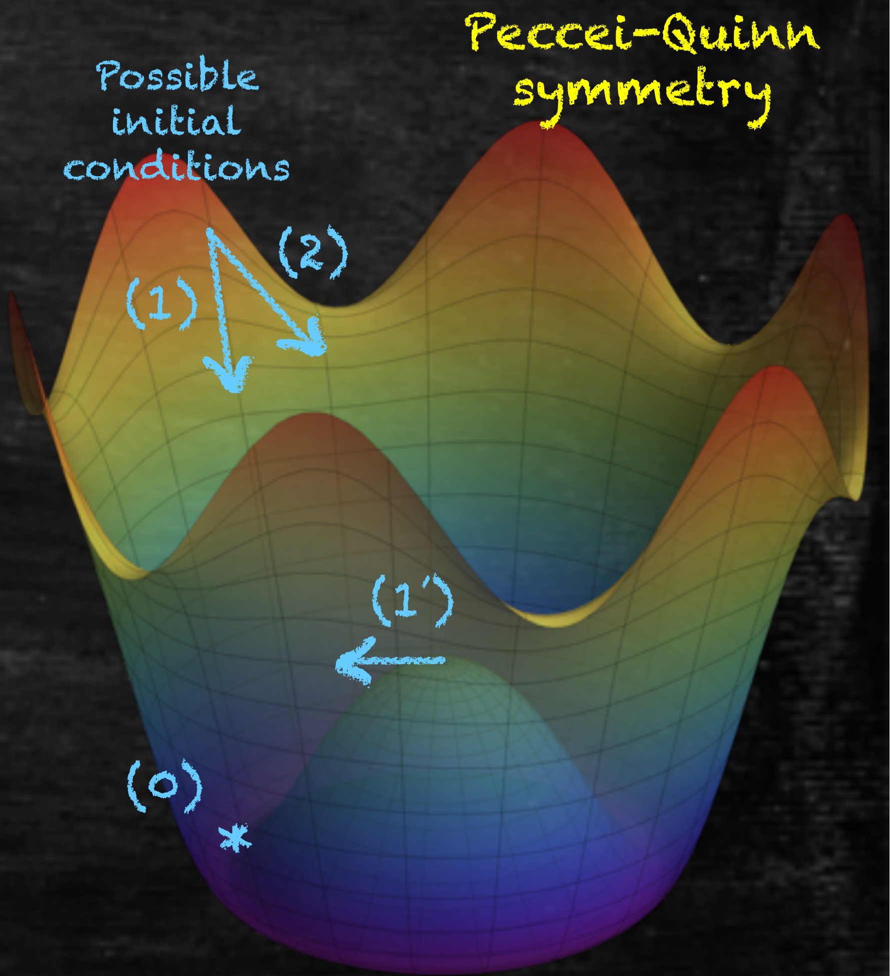
RC, L. Hall, K. Harigaya 2019

} Dark Matter

- Axiogenesis
RC, K. Harigaya 2019

} Baryon Asymmetry



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This talk

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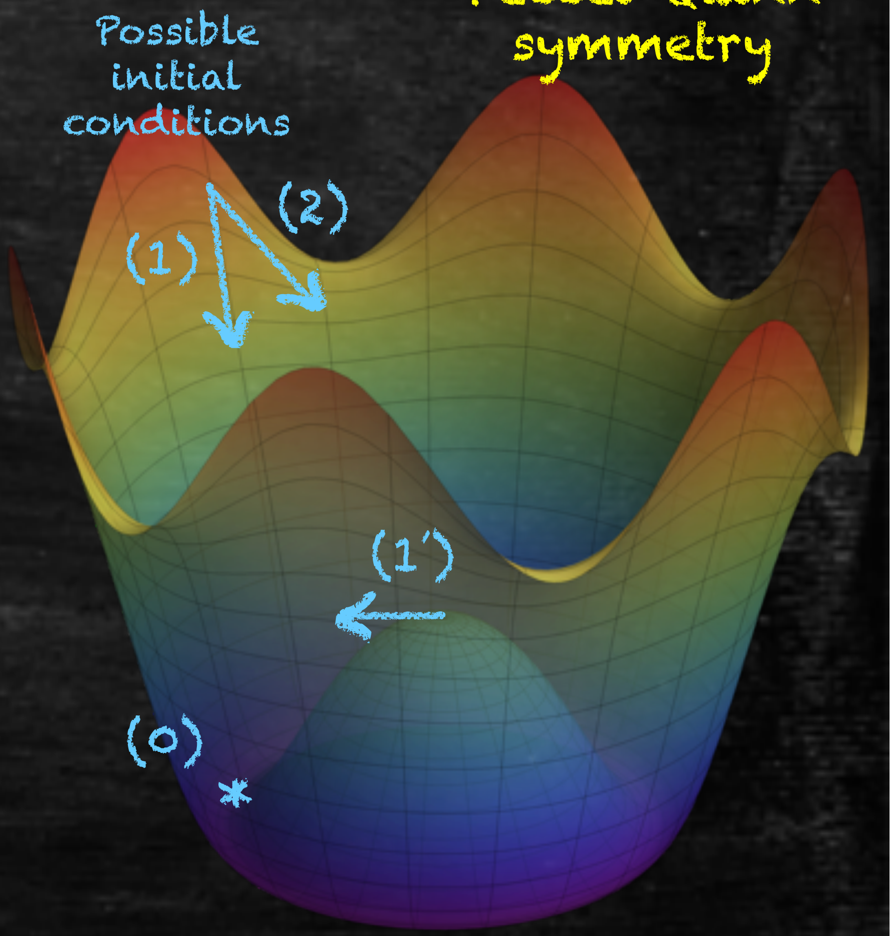
Peccei-Quinn symmetry



Experimental Searches of QCD Axions

CASPEr	$0 - 10^{-9}$ eV	D. Budker et al. 1306.6089
ABRACADABRA	$10^{-9} - 10^{-6}$ eV	Y. Kahn et al. 1602.01086
ADMX	$10^{-6} - 10^{-3}$ eV	P. Sikivie 1983 N. Du et al. 1804.05750
IAXO	$10^{-3} - 1$ eV	J. K. Vogel et al. 1302.3273 E. Armengaud et al. 1401.3233
ARIANDE	$10^{-6} - 10^{-2}$ eV	A. Arvanitaki et al. 1403.1290 A. A. Geraci et al. 1401.3233
Orpheus	$10^{-5} - 10^{-3}$ eV	G. Rybka et al. 1403.3121
MADMAX	$10^{-5} - 10^{-4}$ eV	A. Caldwell et al. 1611.05865
TASTE	$10^{-3} - 1$ eV	V. Anastassopoulos et al. 1706.09378
Multilayer optical haloscopes	0.1 - 10 eV	M. Baryakhtar, J. Huang, R. Lasenby 1803.11455
Resonant absorption in molecules	0.2 - 20 eV	A. Arvanitaki, S. Dimopoulos, K. Van Tilburg 1709.05354

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Axiogenesis favors
$10^{-3} - 1$ eV

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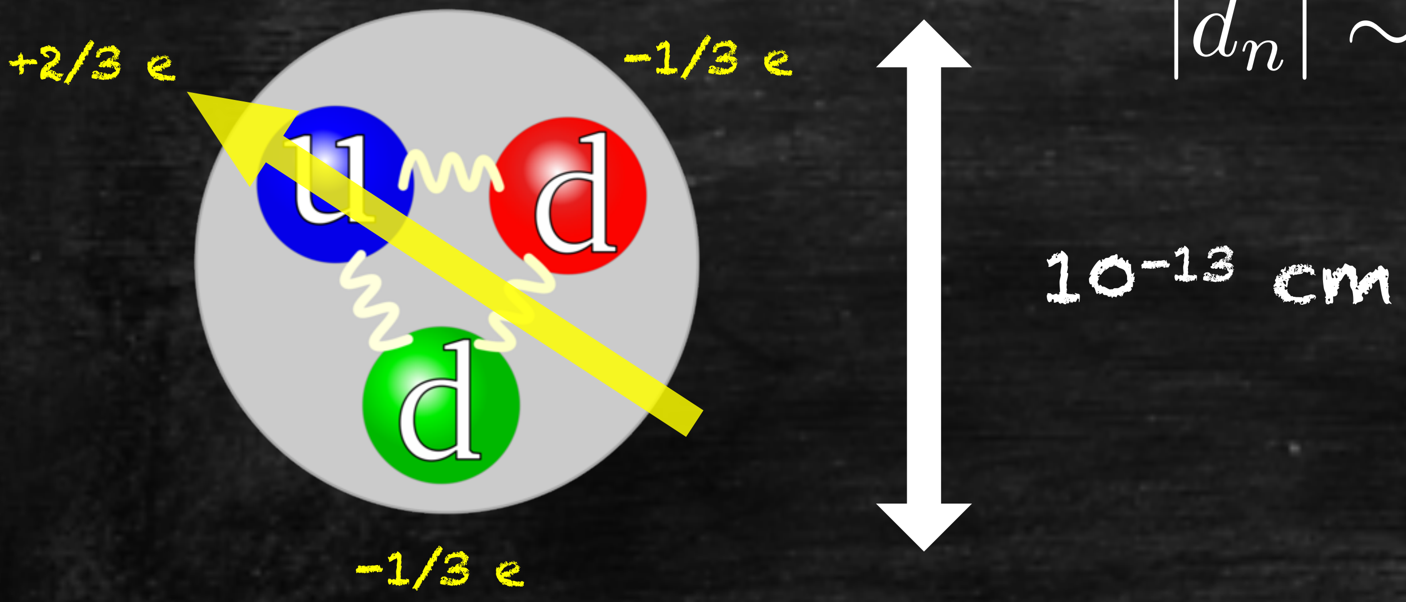
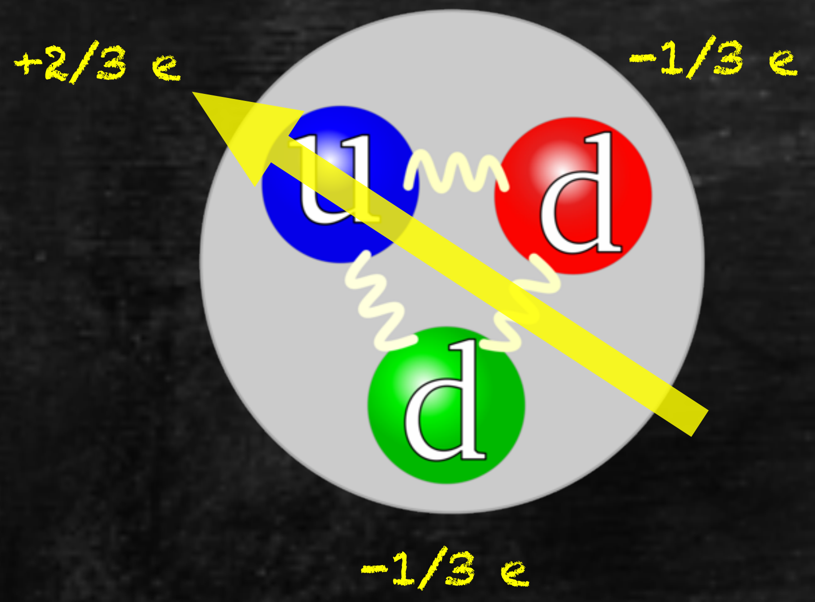
QCD axion

Neutron EDM

$$|d_n| \sim e \times d \sim 10^{-13}\ \mathrm{e \cdot cm}$$



Strong CP Problem



$$|d_n| \sim e \times d \sim 10^{-13}\ \mathrm{e \cdot cm}$$

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \widetilde{G}_{b\mu\nu}$$

$$|d_n| \simeq 3 \times 10^{-16} \bar{\theta}\ \mathrm{e \cdot cm}$$

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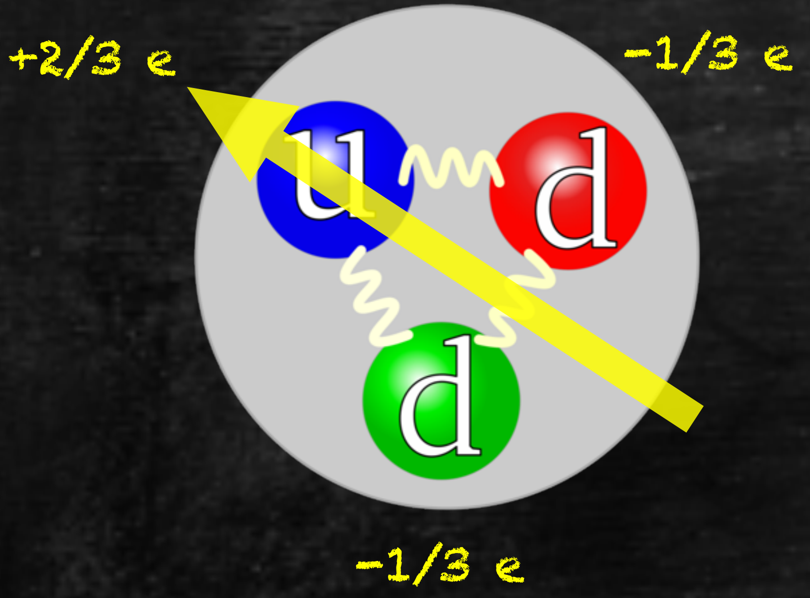

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$$|d_n| \simeq 3 \times 10^{-16} \bar{\theta}\ \mathrm{e \cdot cm}$$

Experiments: $|d_n| \lesssim 3 \times 10^{-26}\ \mathrm{e \cdot cm}$

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

Pendlebury et al. 2015, Bake et al. 2016, Abel et al. 2020

Strong CP Problem

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \widetilde{G}_{b\mu\nu}$$

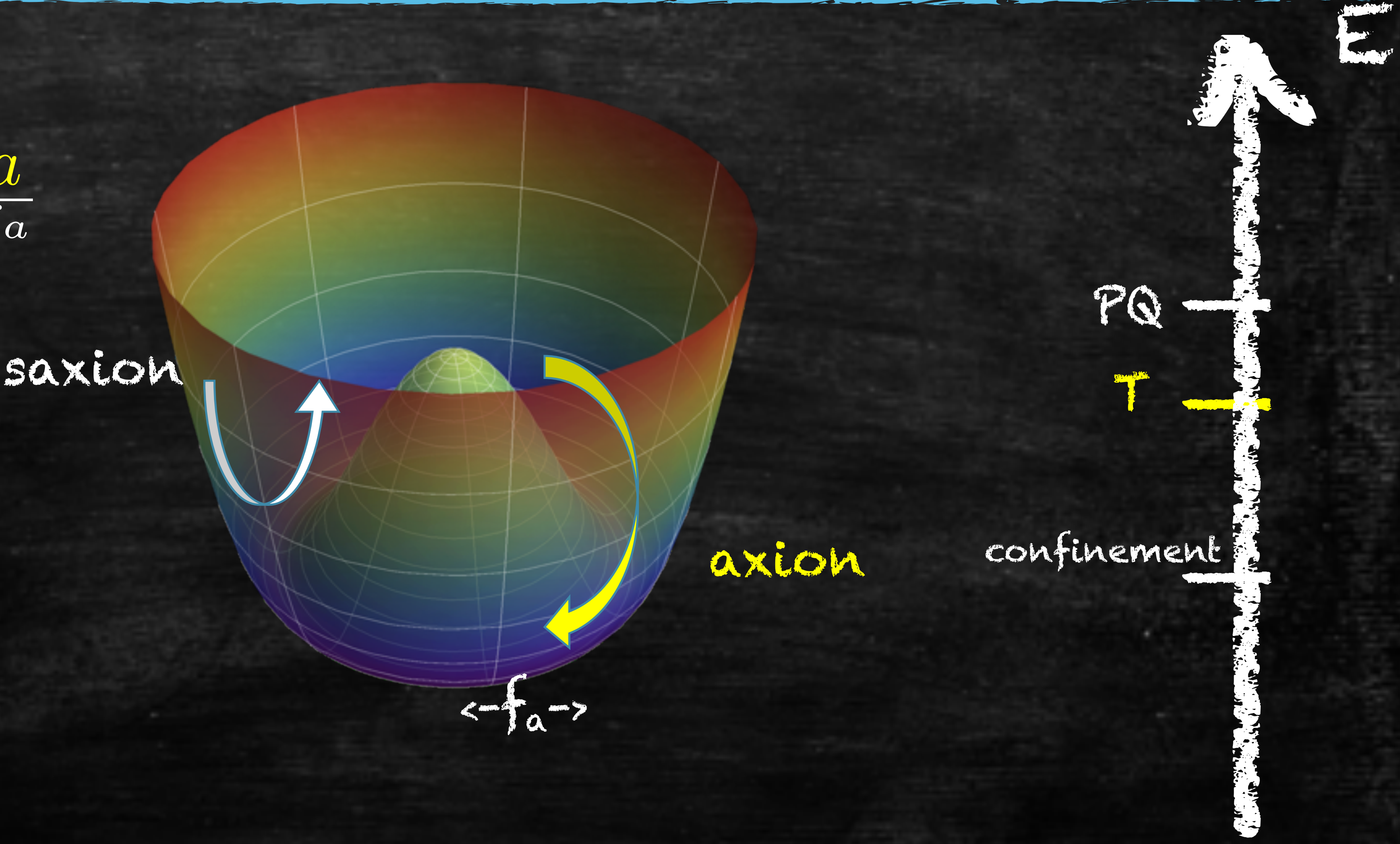
$$\downarrow$$

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \widetilde{G}_{b\mu\nu} + \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \widetilde{G}_{b\mu\nu}$$

Peccei-Quinn 1977

Axions

$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$



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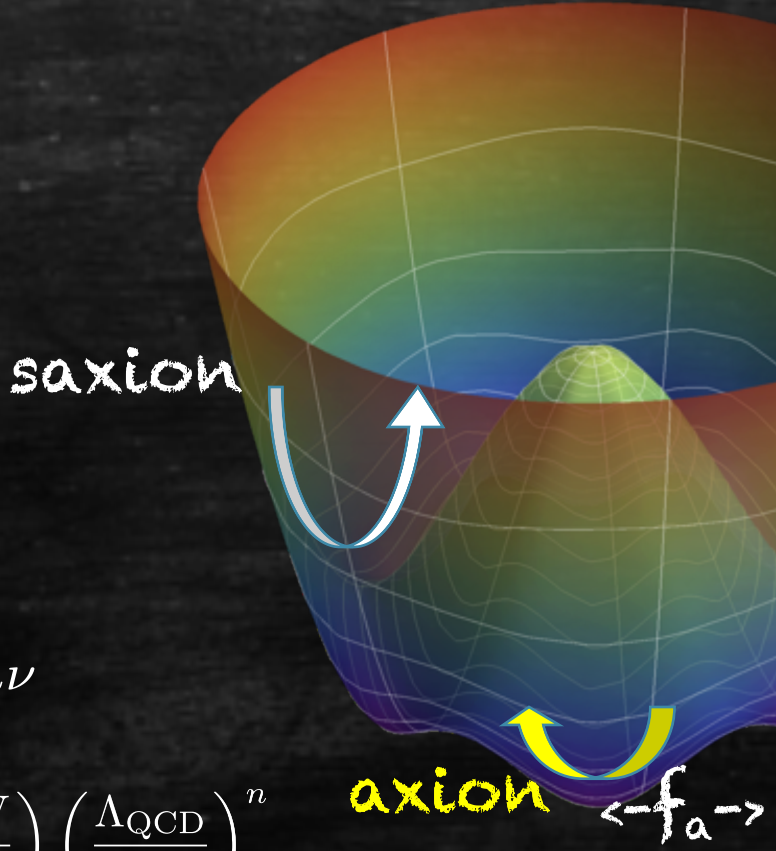
Axions



$$\mathcal{L} \supset \frac{\alpha}{8\pi}\frac{a}{f_a}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

$$m_a(T \geq \Lambda_{\rm QCD}) = 6\,{\rm eV}\left(\frac{10^6\ {\rm GeV}}{f_a}\right)\left(\frac{\Lambda_{\rm QCD}}{T}\right)^n$$

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RC, K. Harigaya 2019

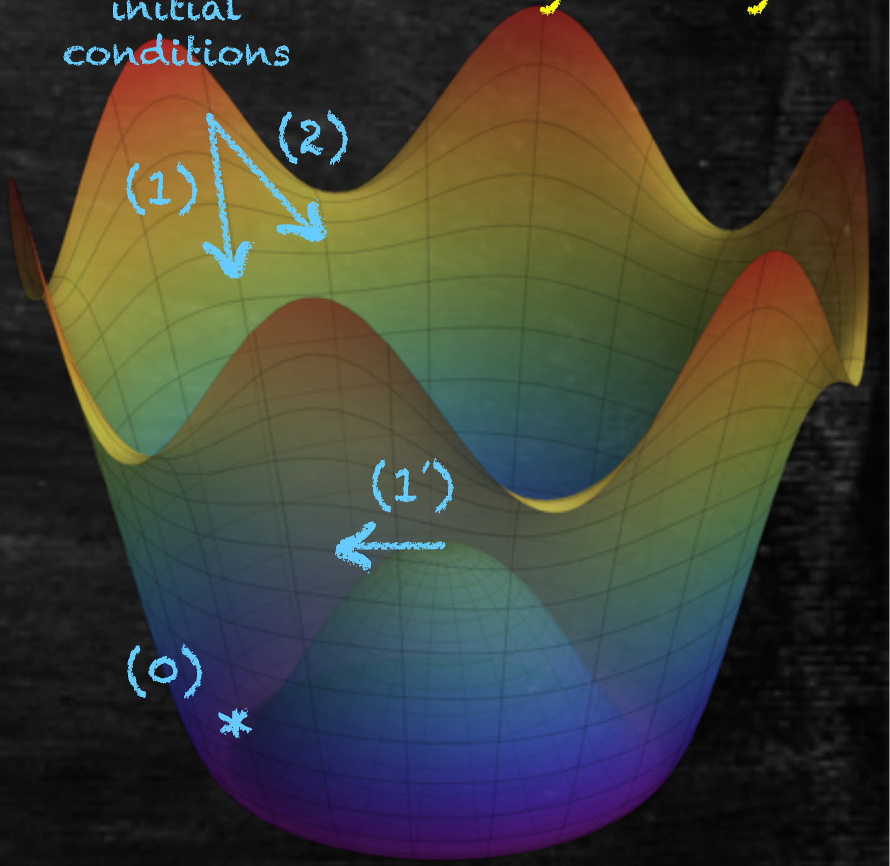
This talk

} Dark Matter

} Baryon Asymmetry

Possible initial conditions

Peccei-Quinn symmetry



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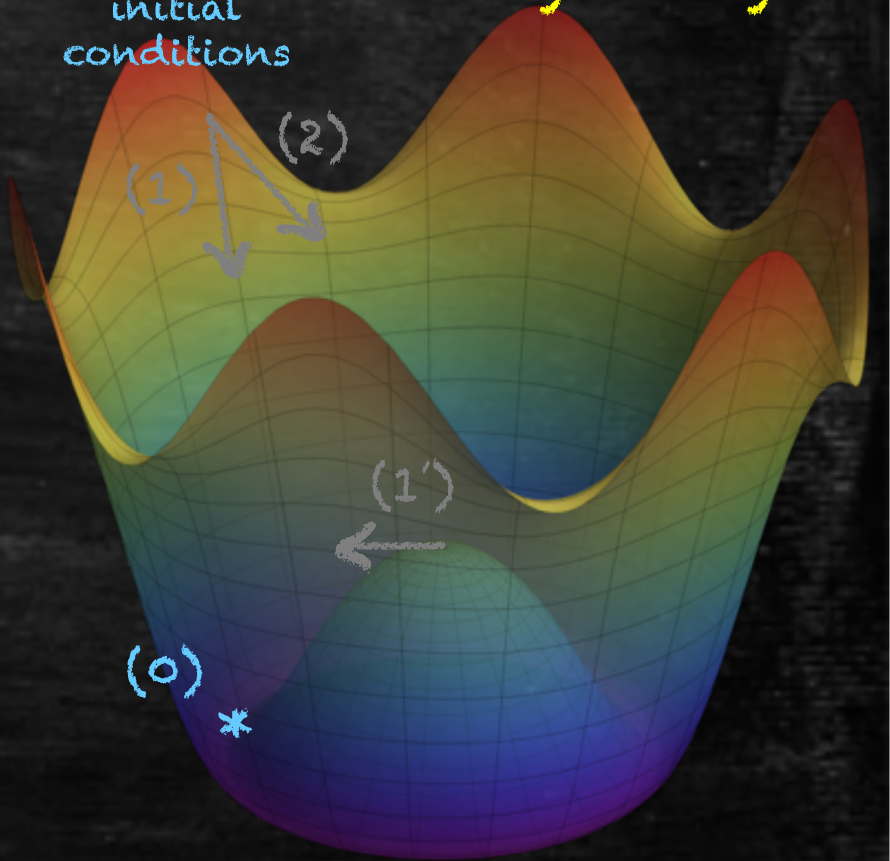


Misalignment Mechanism: Scalars

$$\left(\partial_t^2 + 3H\partial_t + m_\phi^2\right)\phi = 0$$

Early time

$$H \gg m_\phi$$

Hubble friction dominates

$$\phi = \text{constant}$$

Field value is "stuck"

$$\rho_\phi = m_\phi^2 \phi^2$$

Energy density

$$\rho_\phi = \text{constant}$$

is also "stuck"

Late time

$$m_\phi \gg H$$

Oscillations begin

$$\phi \propto a^{-\frac{3}{2}}$$

Field value redshifts

$$\rho_\phi = m_\phi^2 \phi^2$$

Energy density

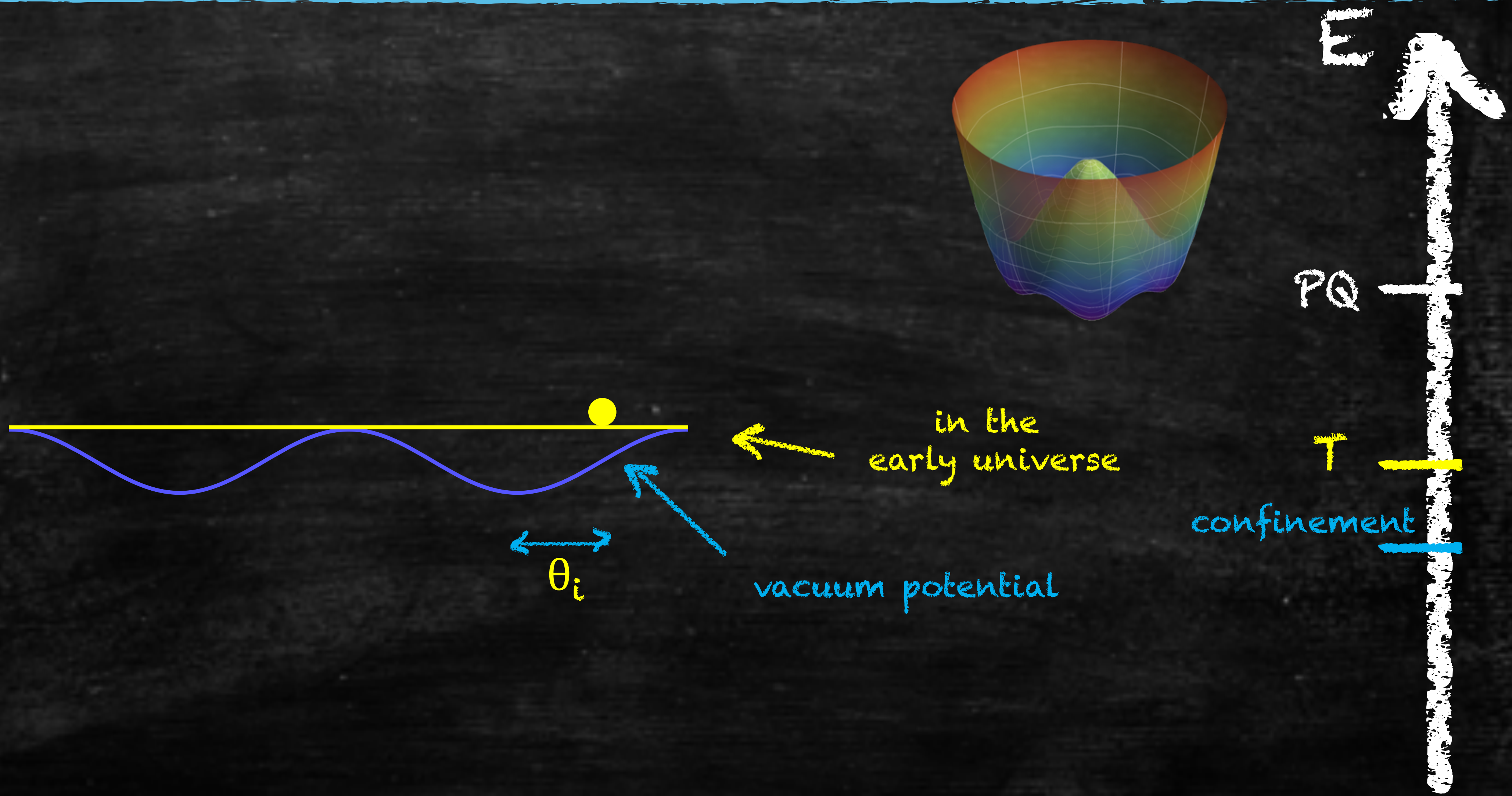
$$\rho_\phi \propto a^{-3}$$

scales like matter

Except for long inflation:
P. Graham et al. 1805.07362
F. Takahashi et al. 1805.08763

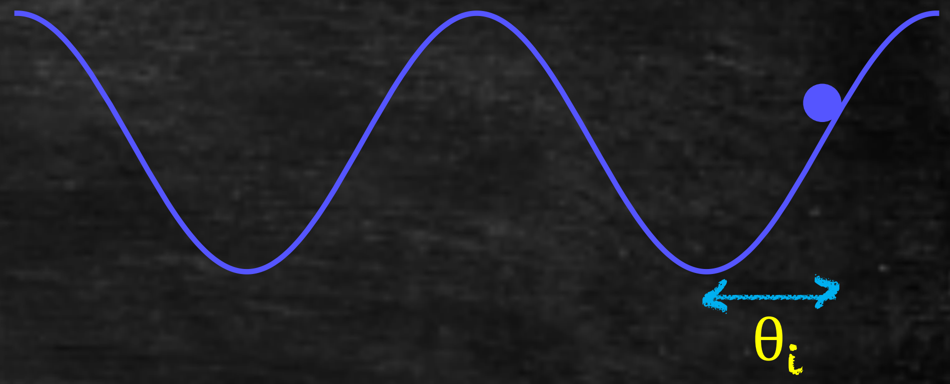
Preskill, Wise, Wilczek 1983
Abbott, Sikivie 1983
Dine, Fischler 1983

Misalignment Mechanism: Axions



Axion Misalignment Mechanism

$$\Omega_a h^2 \approx 0.11 \left(\frac{f_a}{5 \times 10^{11} \mathrm{GeV}} \right)^{1.184} F \bar{\Theta}_i^2$$



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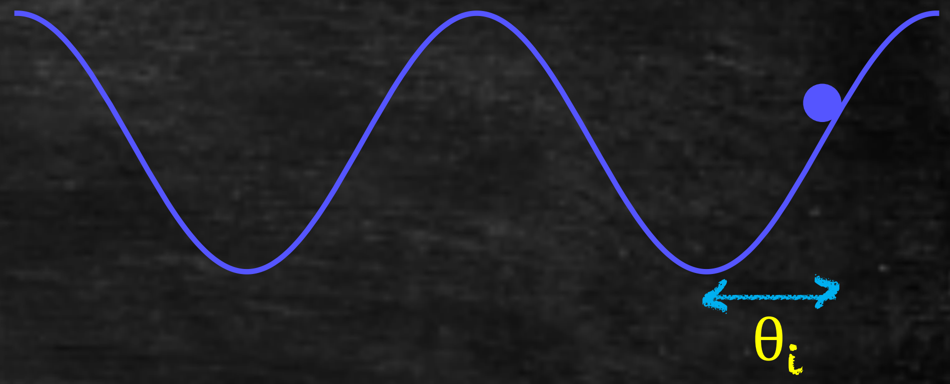

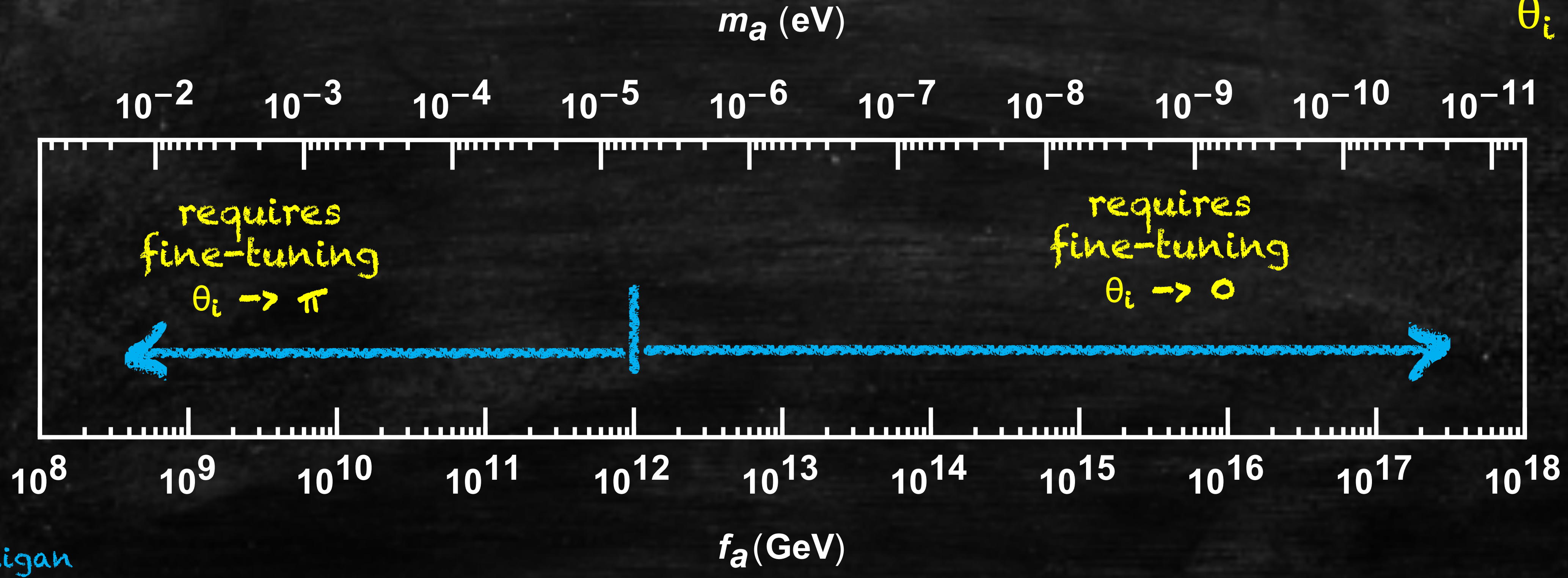

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New Production Mechanisms

- Misalignment Mechanism
  - QCD axions: misalignment driven to the hilltop/bottom

    arXiv:1812.11186, 1812.11192 RC, E. Gonzalez, K. Harigaya
  - QCD axions: kinetic misalignment mechanism

    arXiv:1910.14152 RC, L. Hall, K. Harigaya
    arXiv:2004.00629 RC, L. Hall, K. Harigaya, K. Olive, S. Verner
- Exponential Particle Production
  - QCD axions: parametric resonance

    arXiv:1711.10486 RC, L. Hall, K. Harigaya
  - Dark photons: tachyonic instability

    arXiv:1810.07196 RC, A. Pierce, Z. Zhang, Y. Zhao

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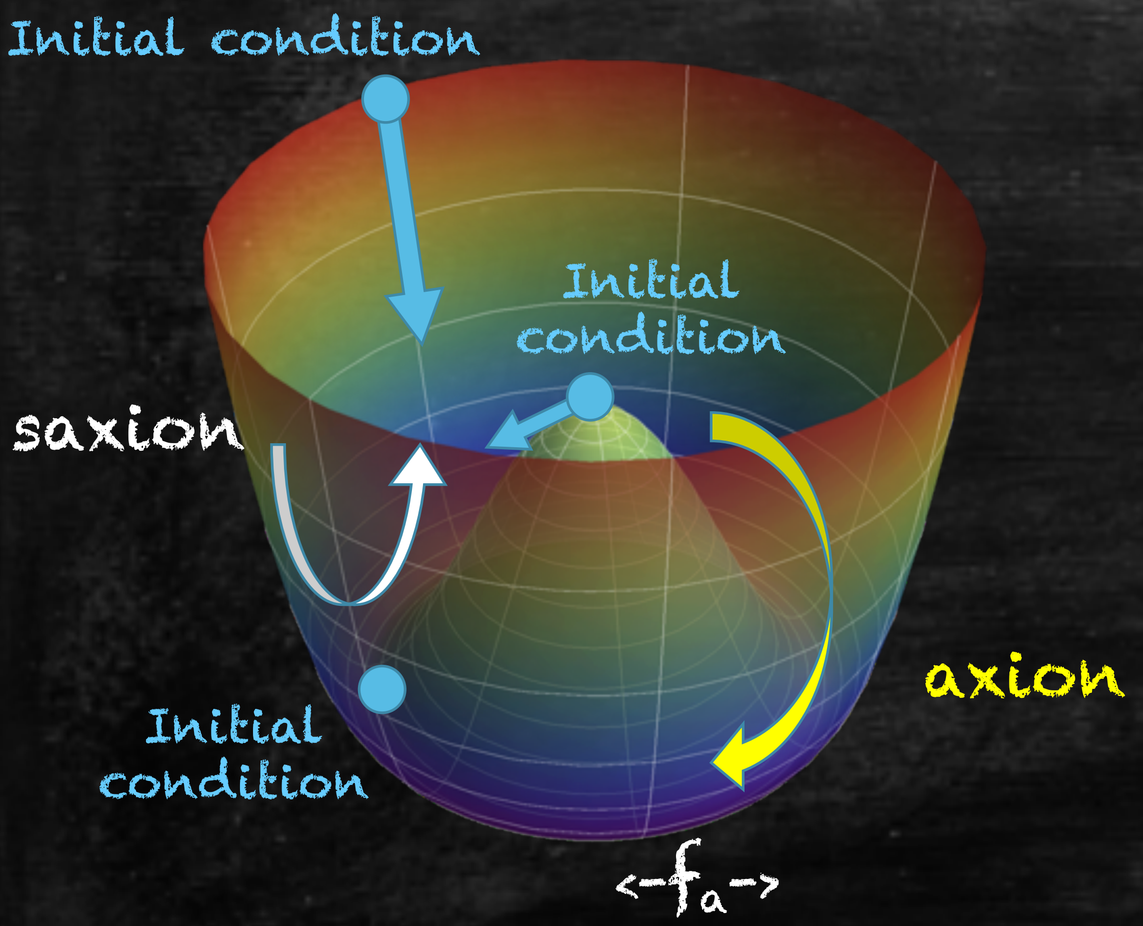
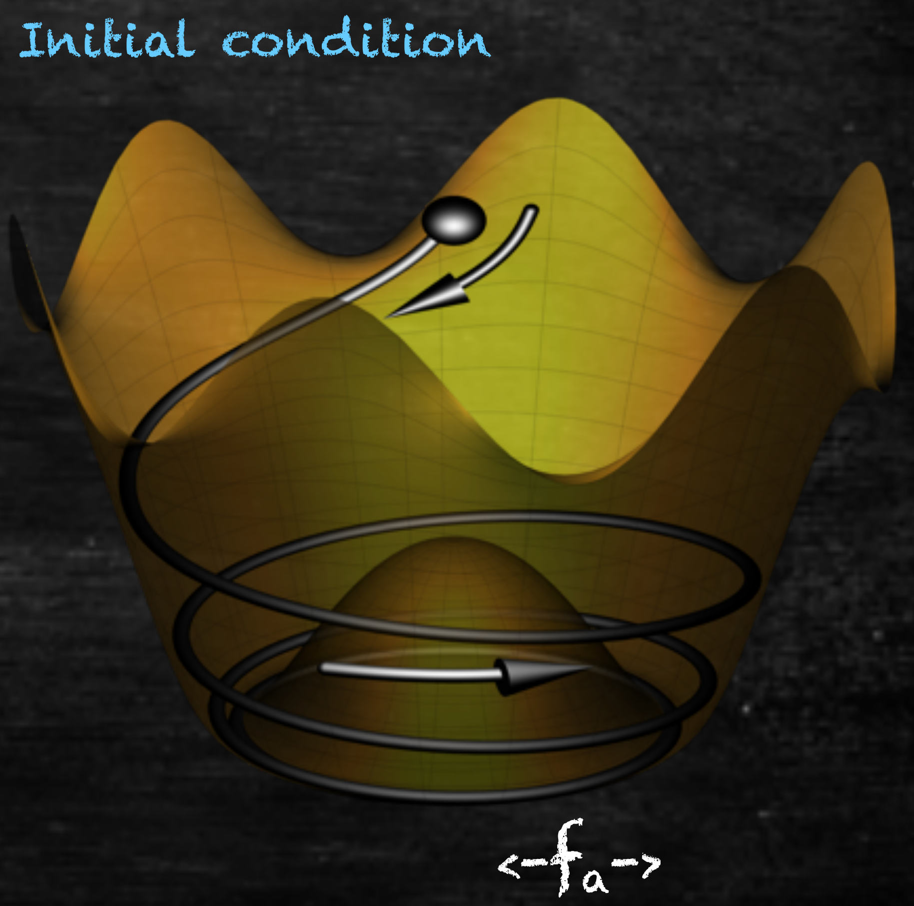
This talk

Rotation





PRL 124, 111602 (2020) RC and K. Harigaya

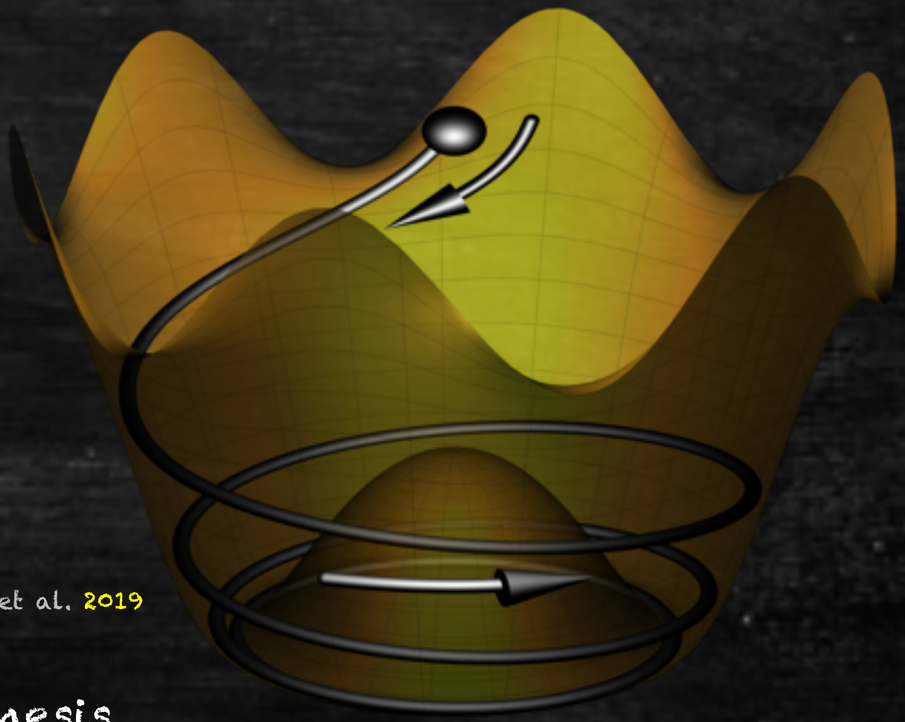
Why Rotation?

$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

Large field value : Inflaton coupling

Initial condition

$$V(|P|) \sim -H_I^2 |P|^2 + \frac{|P|^{2d}}{M^{2d-4}}$$



Angular motion : Explicit PQ breaking

$$V(P) \sim \frac{P^n}{M^{n-4}} + \text{h.c.}$$

expected from quantum gravity
or PQ as an accidental symmetry

S. Giddings et al. 1988, S. Coleman 1988, G. Gilbert 1988, D. Harlow et al. 2019
R. Holman 1992, S. Barr 1992, M. Kamiokowski 1992, D. Dine 1992

Dynamics analogous to that in Affleck-Dine baryogenesis

I. Affleck and M. Dine 1991

PRL 124, 111602 (2020) RC and K. Harigaya

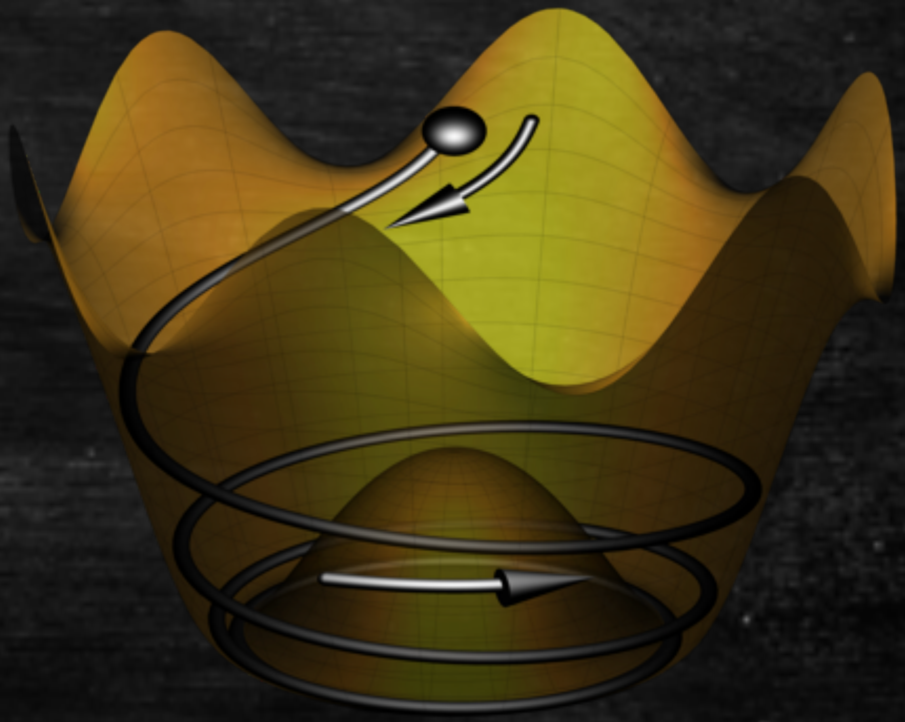
Asymmetry of PQ Charge

$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

Noether charge associated with the shift symmetry

$$n_{PQ} = iP\dot{P}^* - iP^*\dot{P}$$

$$n_{PQ} = S^2\dot{\theta}$$



PQ asymmetry
PQ charge density = Rotation of PQ field

PQ charge is conserved soon after the onset.

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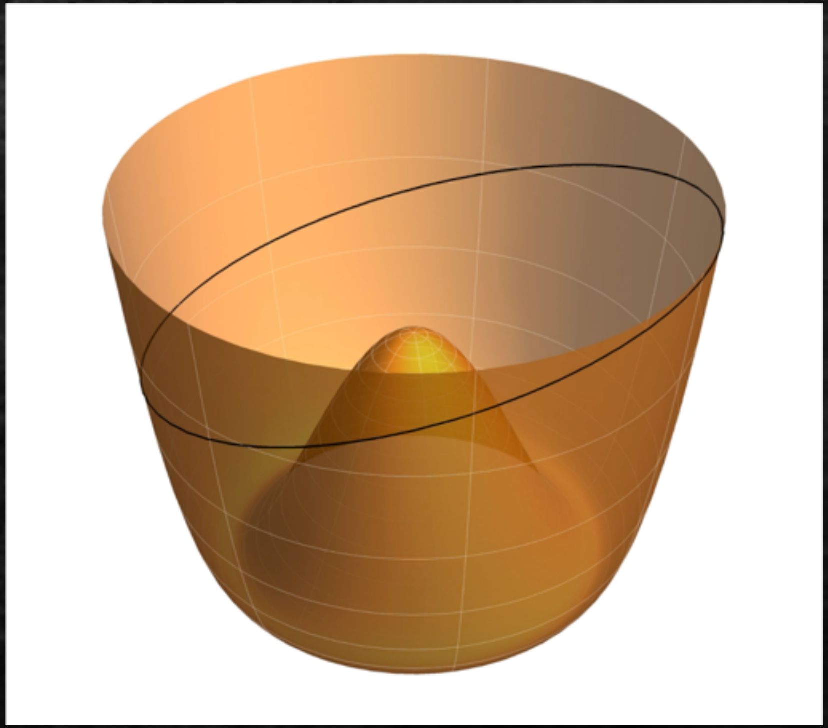
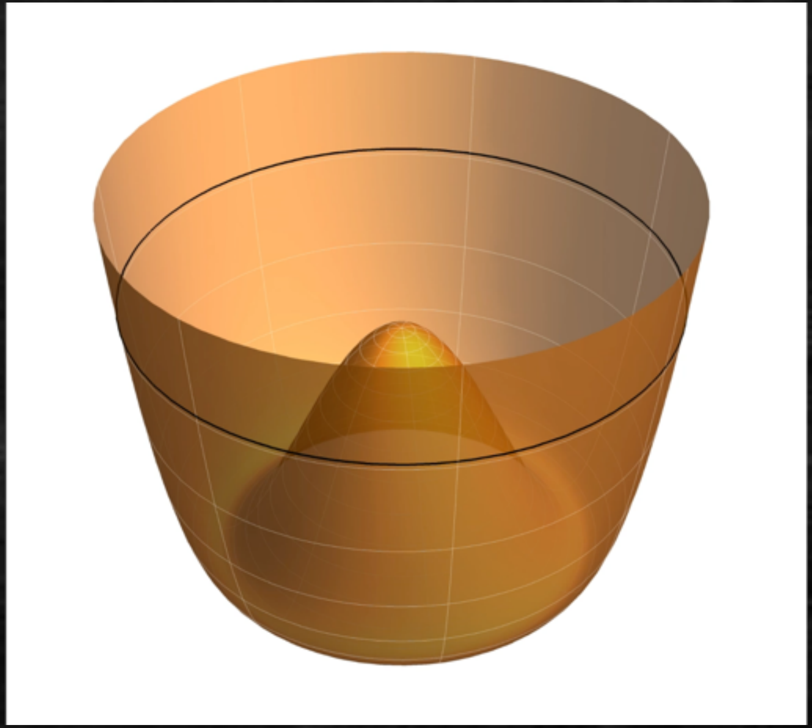
PQ Field Evolution

Thermalization

$$n_{\mathrm{PQ}} = S^2\dot{\theta}$$

Redshift





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This talk

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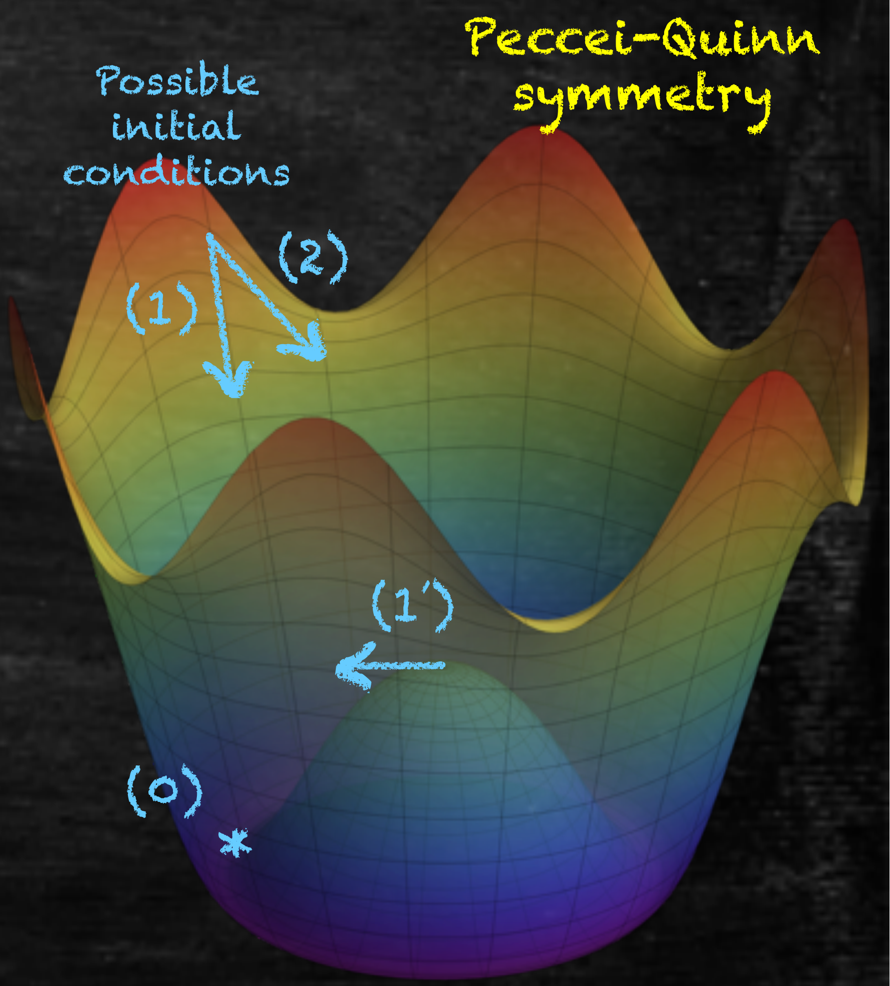
} Baryon Asymmetry



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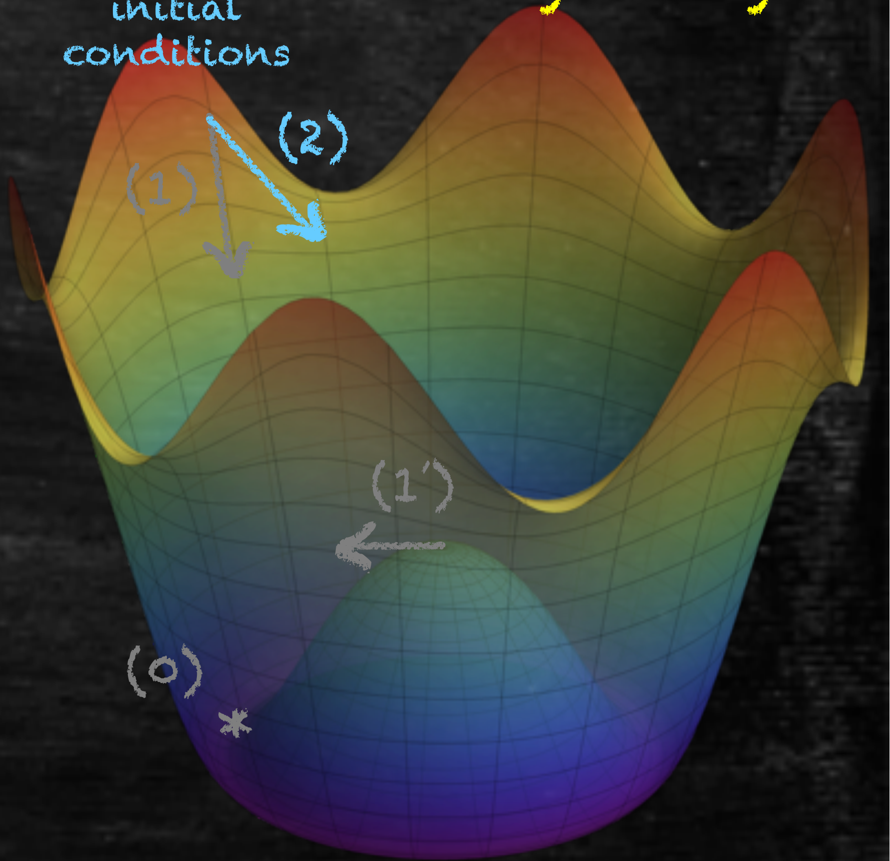
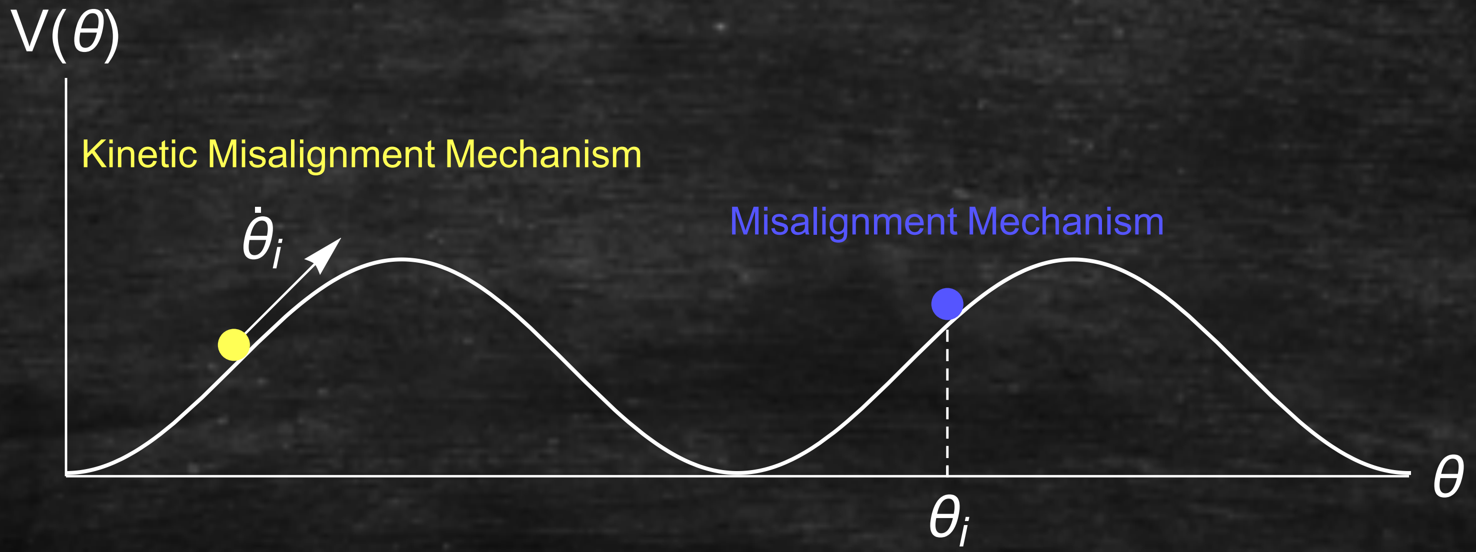
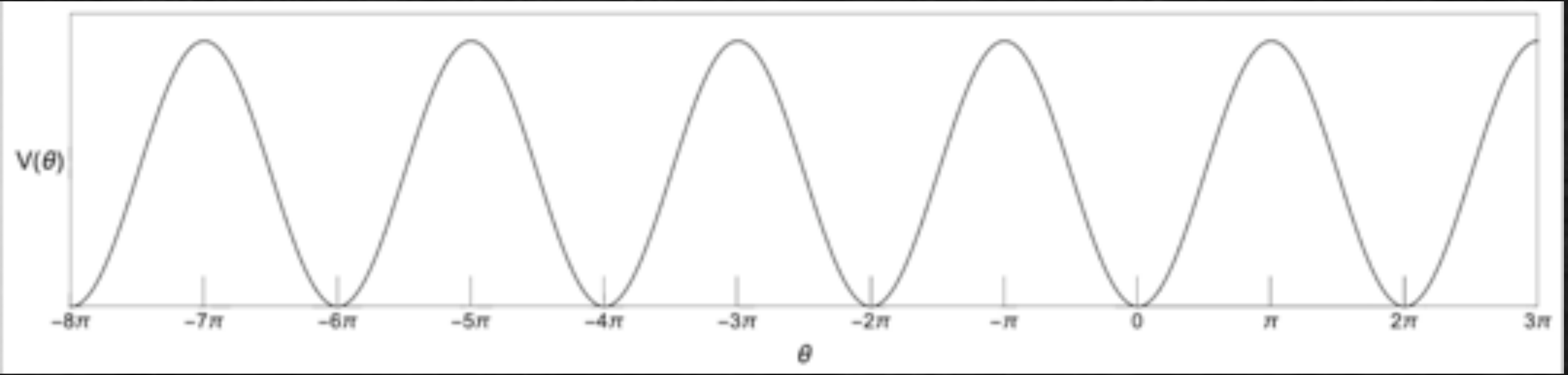




Kinetic Misalignment Mechanism

(Misalignment + non-zero kinetic energy)

arXiv:1910.14152 RC, L. Hall, and K. Harigaya



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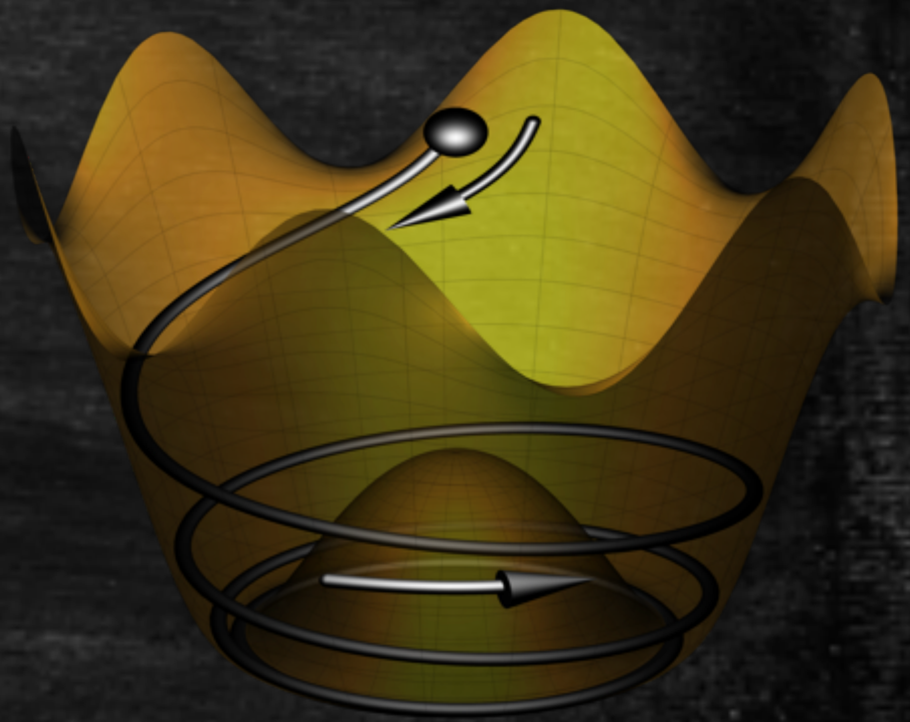
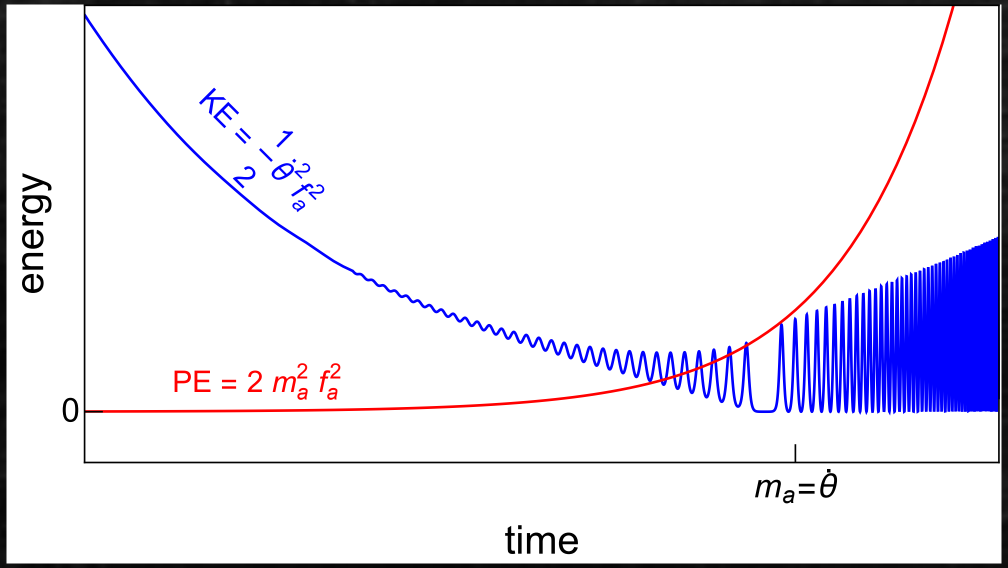


Consequence: delaying usual T_{osc} until KE = PE



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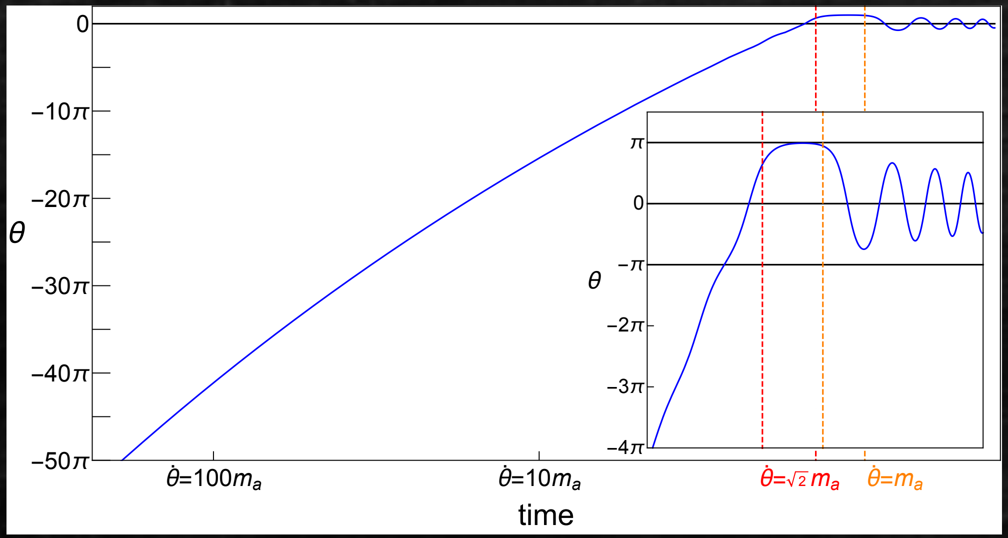

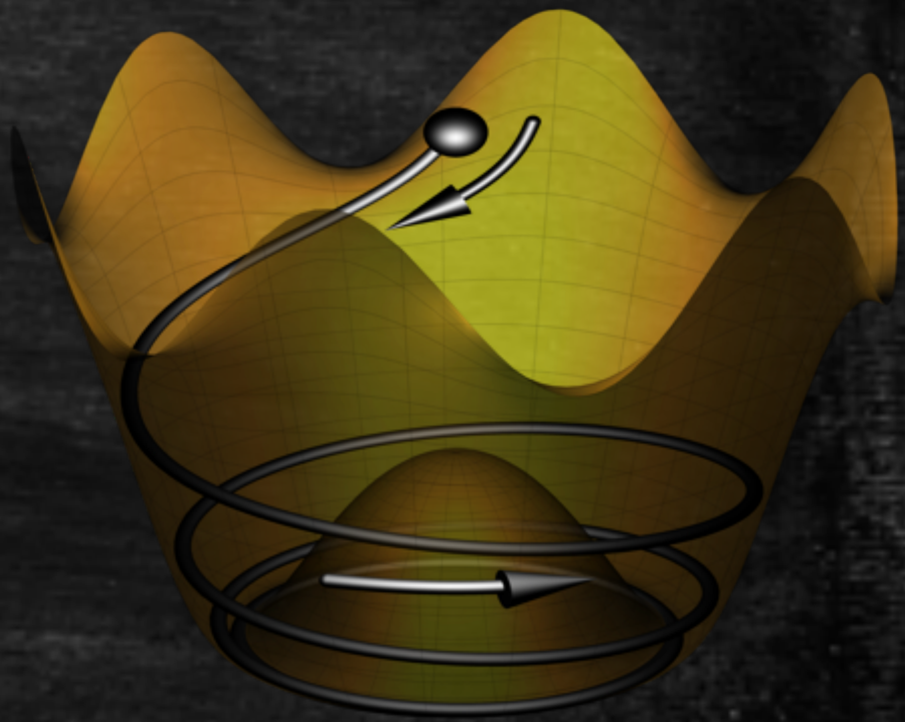

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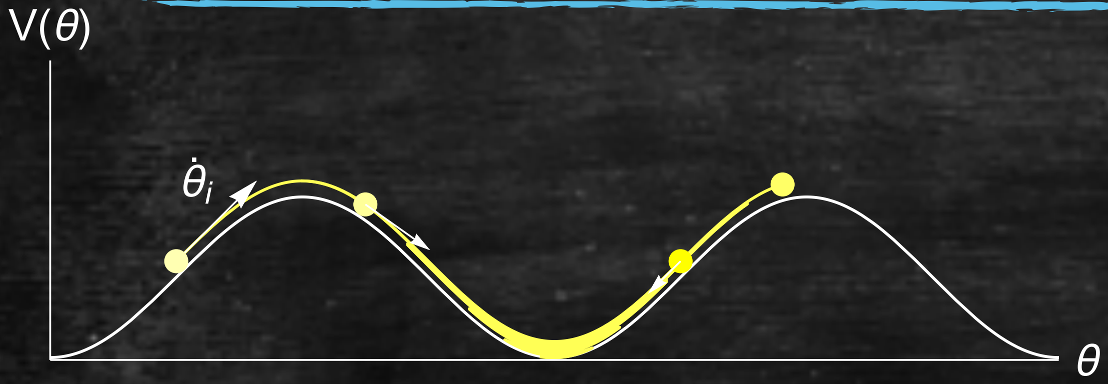
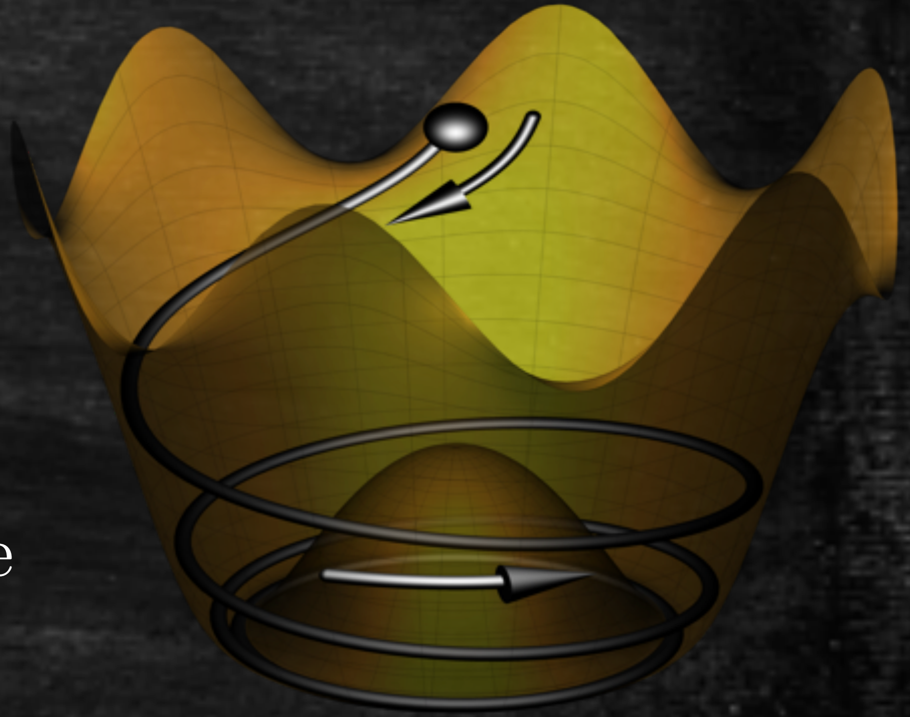




Reason: Why such a large angular speed?

$$n_{\rm PQ} = S^2 \dot{\theta} \qquad n_{\rm PQ} R^3 = \text{conserved charge}$$

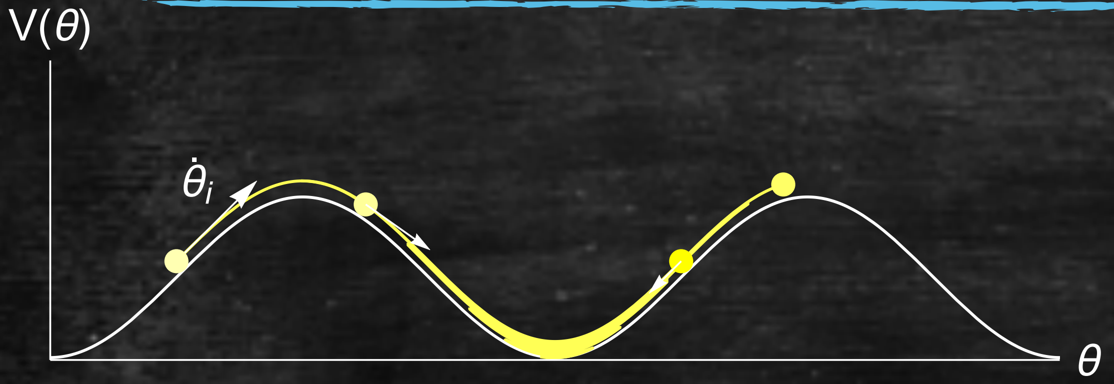
Conventional: $S^2 = f_a^2$ $\qquad \dot{\theta} \propto R^{-3}$

S >> f_a:
- quadratic: $S^2 \propto R^{-3}$ $\qquad \dot{\theta} = \text{constant}$
- quartic: $S^2 \propto R^{-2}$ $\qquad \dot{\theta} \propto R^{-1}$

} Slower redshift!

arXiv:1910.14152 RC, L. Hall, and K. Harigaya

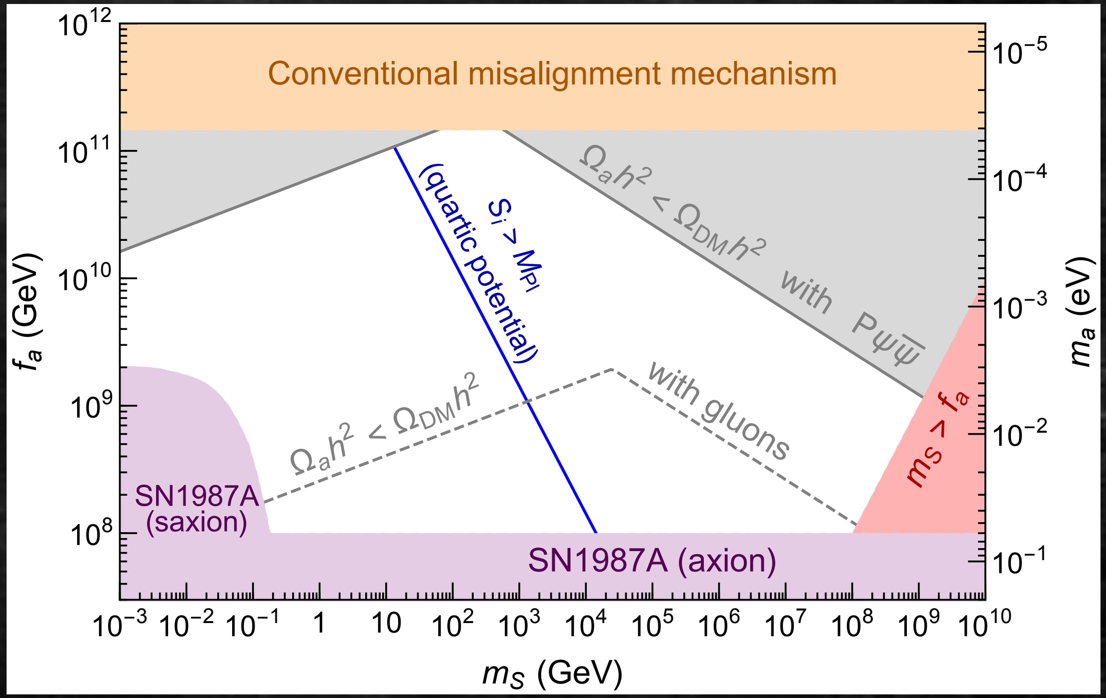
Kinetic Misalignment Mechanism



Abundance:

$$\frac{\rho_a}{s} \simeq 2 m_a(0) Y_{\rm PQ}$$

$$\Omega_a h^2 \simeq \Omega_{\rm DM} h^2 \left(\frac{10^9 \rm GeV}{f_a} \right) \left(\frac{Y_{\rm PQ}}{40} \right)$$



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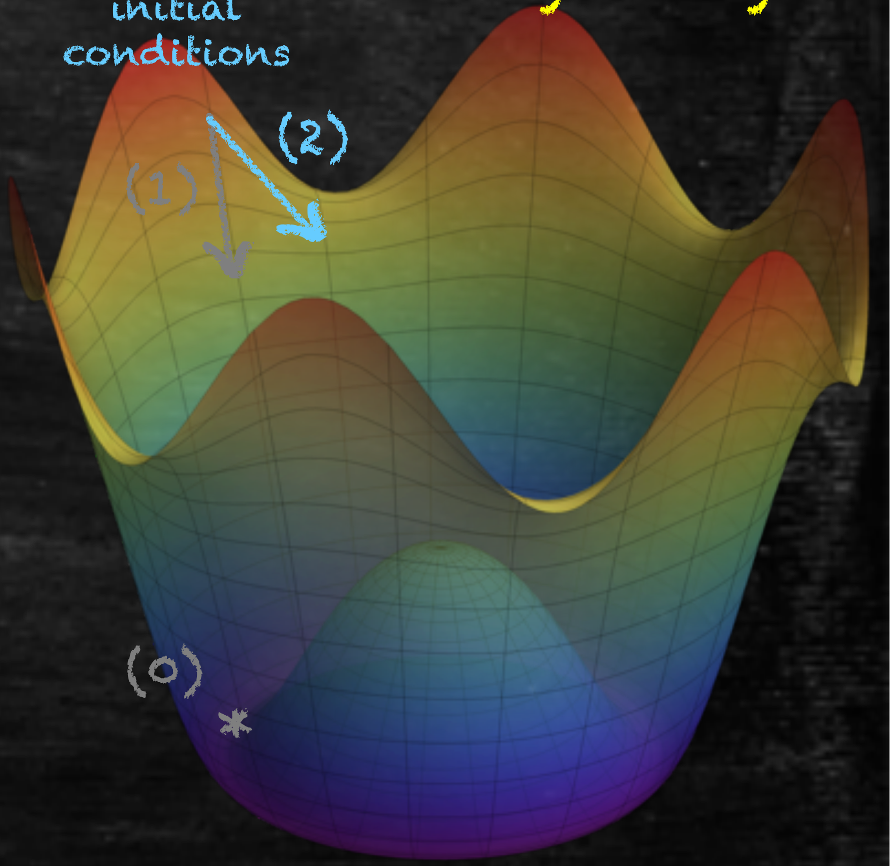
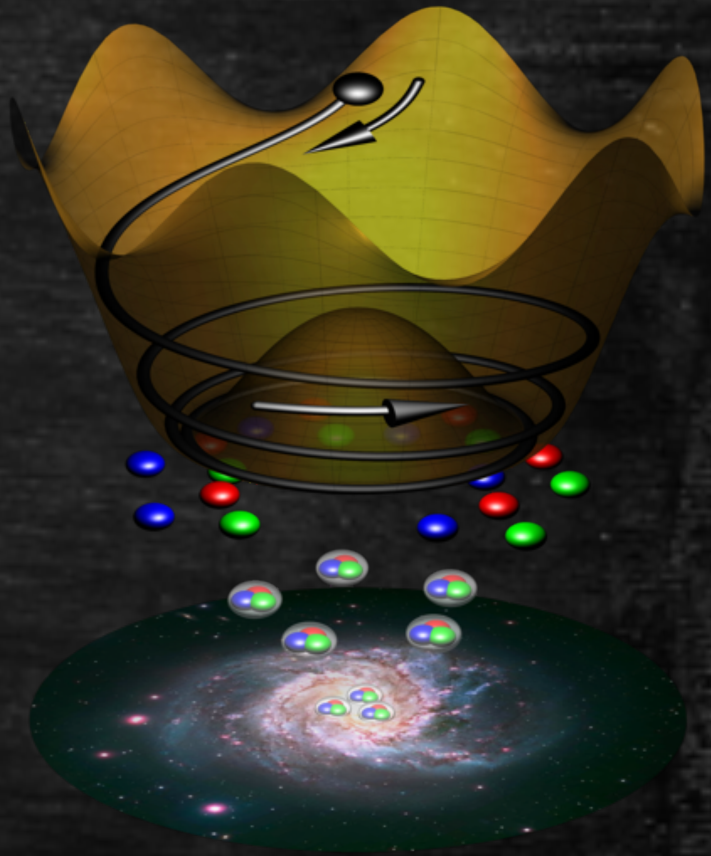


Axiogenesis



(QCD axion + baryogenesis)

PRL 124, 111602 (2020) RC and K. Harigaya

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NEWS PARTICLE PHYSICS

Particles called axions could reveal how matter conquered the universe

The subatomic particles may already solve two important puzzles of particle physics

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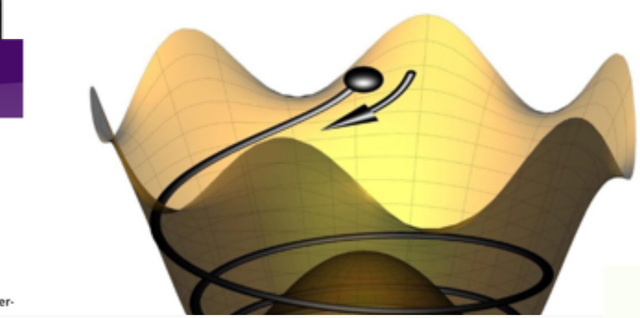
The axion solves three mysteries of the universe



March 10, 2020

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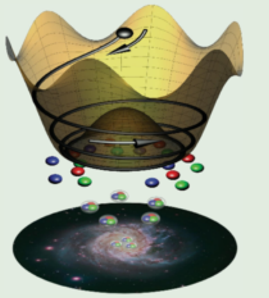
Articles published week ending 20 MARCH 2020



Published by American Physical Society
APS physics
Volume 124, Number 11

Physics ABOUT BROWSE PRESS COLLECTIONS

Synopsis: Axions Could Explain Baryon Asymmetry

March 19, 2020 • *Physics* 13, s38

A new theory proposes that a rotation of the axion field early in the Universe's life could have generated matter-antimatter asymmetry.

研究：假设粒子“轴子”可能帮助解开宇宙三大谜团

cnBeta

2020年03月11日 15:40 937 次阅读 稿源：cnBeta.COM 0 条评论

据外媒报道，粒子物理学的标准模型(Standard Model)在解释宇宙方面做得相当不错，但它仍有一些漏洞。现在，一项新的研究提出了一个假想的粒子--轴子--将可能帮助解开宇宙中三个独立的、巨大的谜团--包括我们人类为什么会在这里。

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Paper Sheds Light on Infant Universe and Origin of Matter

New Study from Researchers at IAS and University of Michigan

March 10, 2020

Press Contact | Lee Sandberg | lsandberg@ias.edu | 609-455-4398

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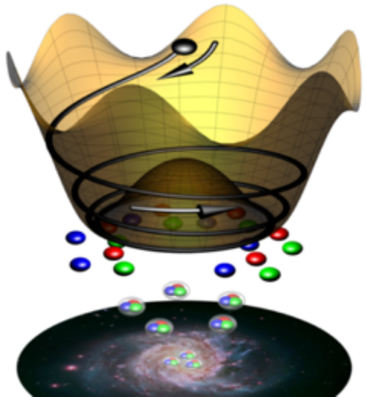

ABSTRACTIONS BLOG

Axions Would Solve Another Major Problem in Physics

In a new paper, physicists argue that hypothetical particles called axions could explain why the universe isn't empty.

2020年03月16日 07時00分 サイエンス

ダークマターの正体や人類が存在する理由など宇宙の3つの謎に迫る粒子「アクシオン」とは？

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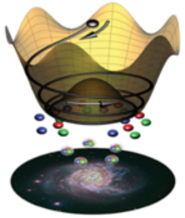

ON THE COVER

Axiogenesis

March 19, 2020

The rotation of the QCD axion field (black marble) around its potential (yellow surface) during the earliest moments of the Universe could generate the excess of matter (colored marbles) over antimatter, allowing galaxies to exist (galaxy photo credit: NASA). Selected for a Synopsis in *Physics* and an Editors' Suggestion.

Raymond T. Co and Keisuke Harigaya
Phys. Rev. Lett. 124, 111602 (2020)

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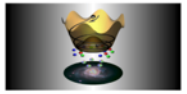

Physics NEWS AND COMMENTARY

Axions Could Explain Baryon Asymmetry

March 19, 2020

A new theory proposes that a rotation of the axion field early in the Universe's life could have generated matter-antimatter asymmetry.

Synopsis on:
Raymond T. Co and Keisuke Harigaya
Phys. Rev. Lett. 124, 111602 (2020)

MEDIA INAF
Il notiziario online dell'Istituto nazionale di astrofisica
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CON UN COMMENTO DI FABRIZIO TAVECCHIO DELL'INAF DI BRERA

Assiogenesi primordiale e origine della materia

Un nuovo studio condotto da due ricercatori dell'Institute for Advanced Study e dell'Università del Michigan riporta che la rotazione dell'assione della cromodinamica quantistica potrebbe essere in grado di spiegare l'eccesso di materia presente nell'universo. Il meccanismo è stato chiamato 'assiogenesi' e viene descritto dagli autori in un articolo che verrà presto pubblicato su Prl

EurekAlert! AAAS
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NEWS RELEASE 16-MAR-2020

APS tip sheet: Origins of matter and antimatter

Study suggests an 'axiogenesis' mechanism for the explanation of the matter to antimatter ratio in the Universe

AMERICAN PHYSICAL SOCIETY

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Главная / Темы / Космос / Вы тут

Западные СМИ

11 марта 2020 15:21

Учёные обнаружили ответ на одну из главных загадок физики. В схватке двух сил Вселенной нашли третьего игрока

#Космос , #Наука

R. Co Michigan

Baryon Asymmetry

For $T > T_{EW}$,

Sphaleron processes

$$n_{PQ} \xrightarrow{\text{QCD}} n_q \xrightarrow{\text{EW}} n_B$$

PQ asymmetry — chiral asymmetry — baryon asymmetry

$$\mathcal{L} = \frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\widetilde{G}$$

PRL 124, 111602 (2020) RC and K. Harigaya

Baryon Asymmetry

For $T > T_{EW}$,

Sphaleron processes

Weak anomaly: $n_{PQ} \longrightarrow n_B$

$$n_{PQ} \xrightarrow{\text{QCD}} n_q \xrightarrow{\text{EW}} n_B$$

PQ asymmetry — chiral asymmetry — baryon asymmetry

$$\mathcal{L} = \frac{a}{f_a}\frac{g_s^2}{32\pi^2} G\widetilde{G} + c_W \frac{a}{f_a}\frac{g_w^2}{32\pi^2} W\widetilde{W}$$

PRL 124, 111602 (2020) RC and K. Harigaya

Baryon Asymmetry

For $T > T_{EW}$,

Sphaleron processes

Weak anomaly: $n_{PQ} \longrightarrow n_B$

QCD: $n_{PQ} \longrightarrow n_q$; EW: $n_q \longrightarrow n_B$

n_{PQ} — PQ asymmetry

n_q — chiral asymmetry

n_B — baryon asymmetry

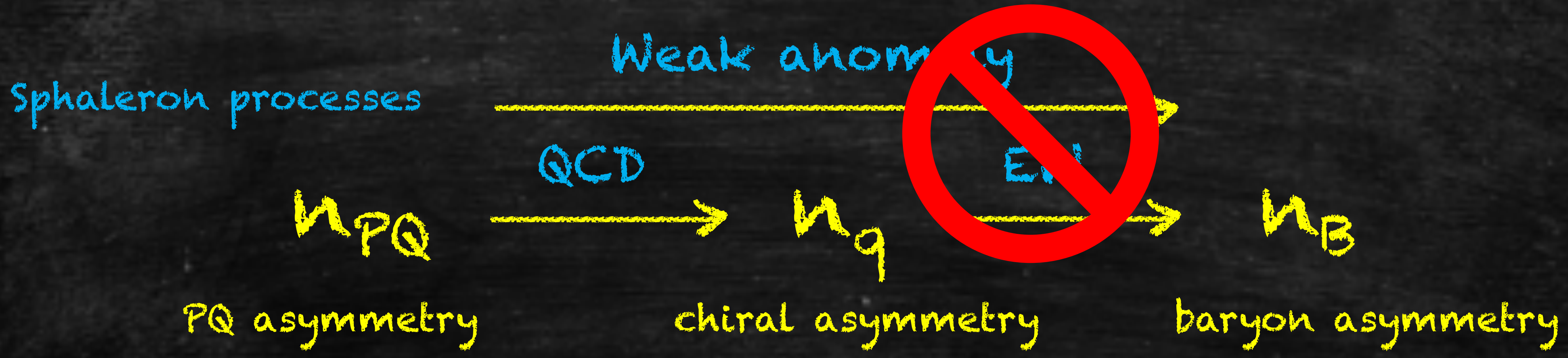
$$n_B = c_B \dot{\theta} T^2$$

$$c_B \simeq 0.1 - 0.15\, c_W$$

PRL 124, 111602 (2020) RC and K. Harigaya

Baryon Asymmetry

For $T < T_{EW}$, the baryon asymmetry is frozen



$$n_B = c_B \dot{\theta} T^2$$

$$c_B \simeq 0.1 - 0.15\, c_W$$

PRL 124, 111602 (2020) RC and K. Harigaya

Baryon Asymmetry

At $T < T_{EW}$, the baryon asymmetry is frozen

$$Y_B \equiv \frac{n_B}{s} \simeq 2 \times 10^{-3} \left(\frac{c_B}{0.1}\right) \frac{\dot{\theta}(T_{\rm EW})}{T_{\rm EW}}$$

Baryon asymmetry fixes rotational speed

PRL 124, 111602 (2020) RC and K. Harigaya

Storyline

- QCD axion

Review

(0) Misalignment mechanism
Preskill, Wise, Wilczek 1983, Abbott, Sikivie 1983, Dine, Fischler 1983

(1) Parametric resonance
RC, L. Hall, K. Harigaya 2017 K. Harigaya, J. Leedom 2019

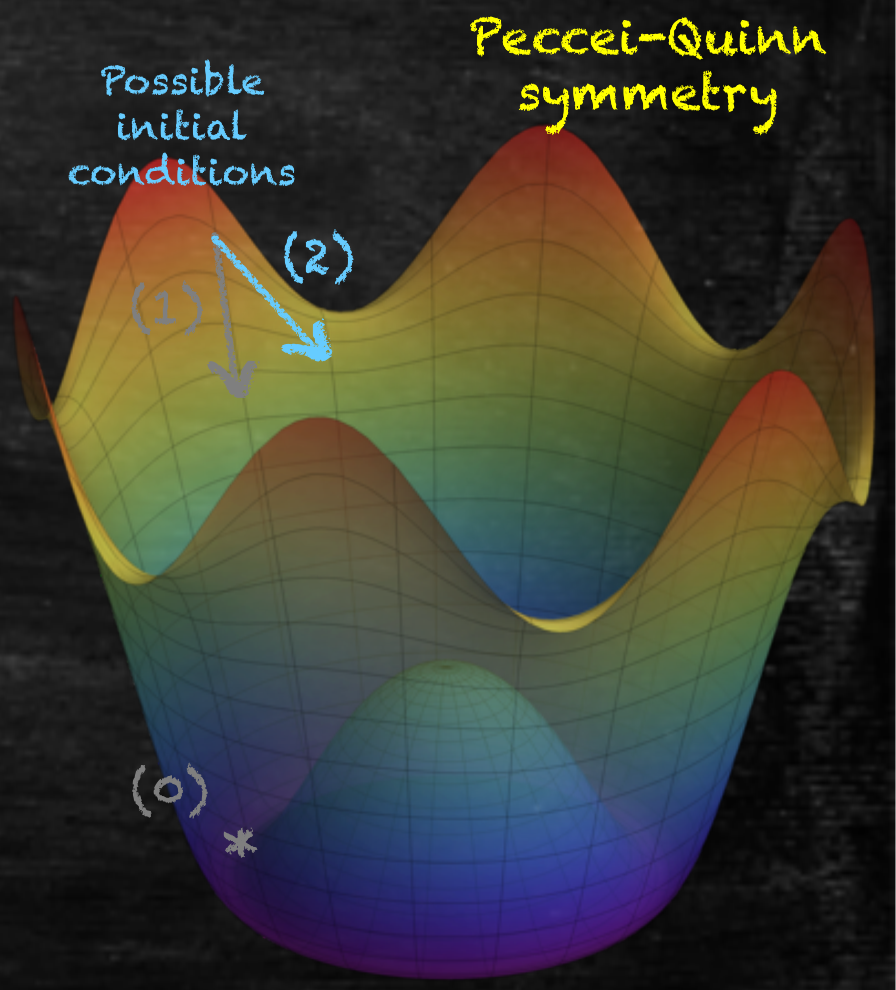
(2) - Kinetic misalignment mechanism
RC, L. Hall, K. Harigaya 2019

} Dark Matter

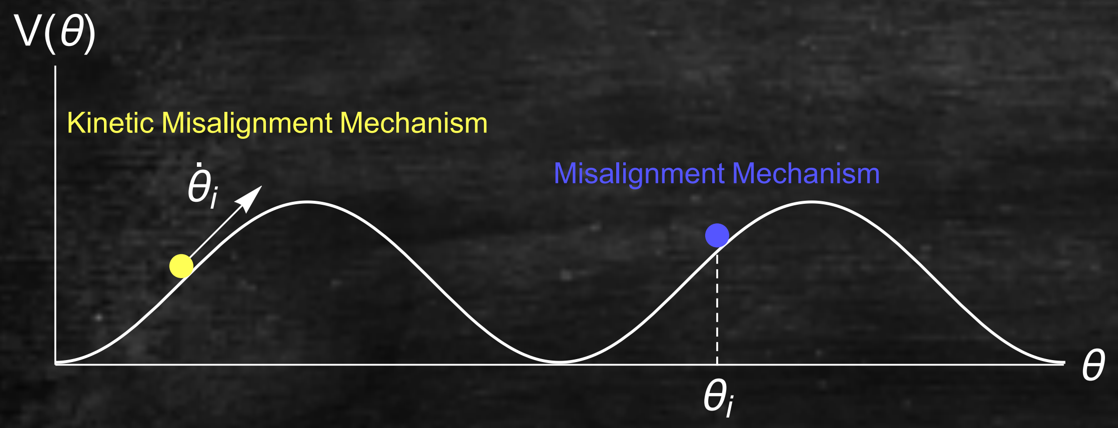
- Axiogenesis
RC, K. Harigaya 2019

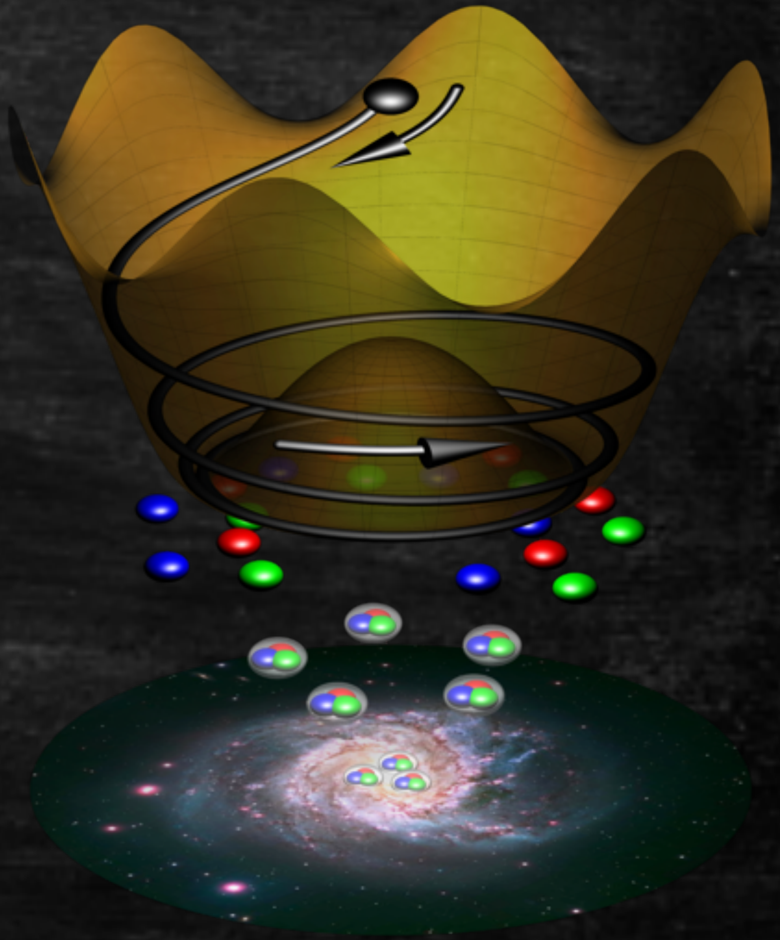
} Baryon Asymmetry

This talk



Axiogenesis + Kinetic Misalignment



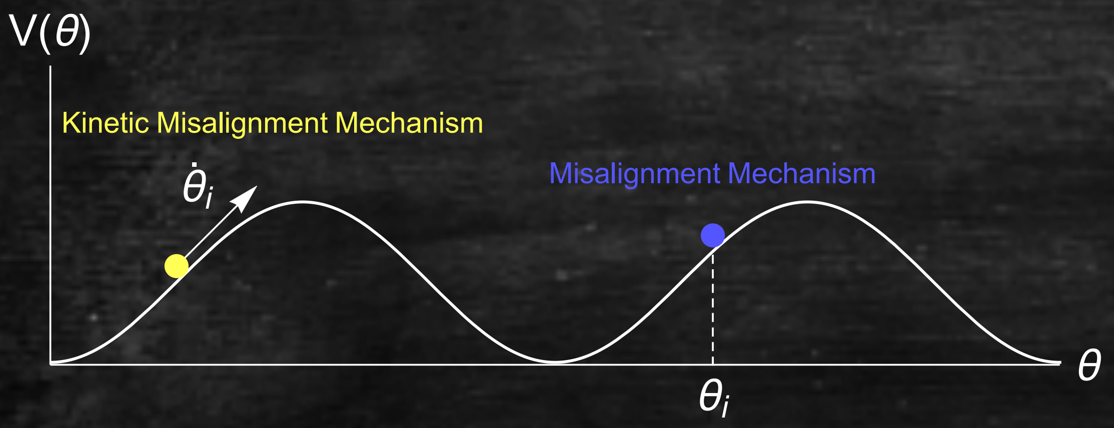


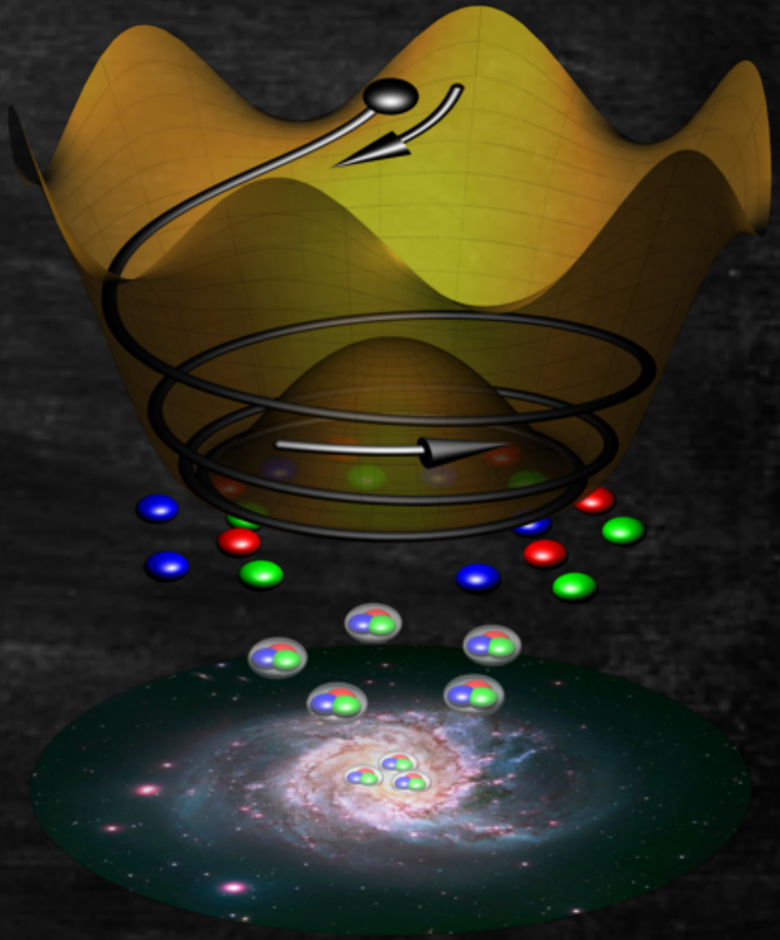
$$\frac{\rho_a}{s} = m_a Y_B \left(\frac{2 f_a^2}{c_B T_{\rm EW}^2} \right)$$

$$\frac{\Omega_a h^2}{\Omega_{\rm DM} h^2} \simeq ? \left(\frac{f_a}{10^8 \ {\rm GeV}} \right) \left(\frac{130 \ {\rm GeV}}{T_{\rm EW}} \right)^2 \left(\frac{0.1}{c_B} \right)$$

arXiv:1910.02080 RC and K. Harigaya
arXiv:1910.14152 RC, L. Hall, and K. Harigaya

Axiogenesis + Kinetic Misalignment





$$\frac{\rho_a}{s} = m_a Y_B \left(\frac{2 f_a^2}{c_B T_{\rm EW}^2} \right)$$

$$\frac{\Omega_a h^2}{\Omega_{\rm DM} h^2} \simeq \text{[see talk]} \left(\frac{f_a}{10^8\ \mathrm{GeV}} \right) \left(\frac{130\ \mathrm{GeV}}{T_{\rm EW}} \right)^2 \left(\frac{0.1}{c_B} \right)$$

arXiv:1910.02080 RC and K. Harigaya
arXiv:1910.14152 RC, L. Hall, and K. Harigaya

Axiogenesis + Kinetic Misalignment

$$\frac{\Omega_a h^2}{\Omega_{\rm DM} h^2} \simeq \text{see talk} \left(\frac{f_a}{10^8\ \text{GeV}}\right)\left(\frac{130\ \text{GeV}}{T_{\rm EW}}\right)^2\left(\frac{0.1}{c_B}\right)$$

f_a ~

see talk

PRL 124, 111602 (2020) RC and K. Harigaya

Axiogenesis + Kinetic Misalignment

$$\frac{\Omega_a h^2}{\Omega_{\rm DM} h^2} \simeq \text{[see talk]} \left(\frac{f_a}{10^8 \ \mathrm{GeV}} \right) \left(\frac{130 \ \mathrm{GeV}}{T_{\rm EW}} \right)^2 \left(\frac{0.1}{c_B} \right)$$

T_{EW} ~ see talk ?

see talk

PRL 124, 111602 (2020) RC and K. Harigaya

Axiogenesis + Kinetic Misalignment

$$\frac{\Omega_a h^2}{\Omega_{\rm DM} h^2} \simeq \text{see talk} \left(\frac{f_a}{10^8\ \text{GeV}}\right)\left(\frac{130\ \text{GeV}}{T_{\rm EW}}\right)^2\left(\frac{0.1}{c_B}\right)$$

c_B ~ see talk so c_W ~ see talk ?

$$c_B \simeq 0.1 - 0.15\, c_W$$

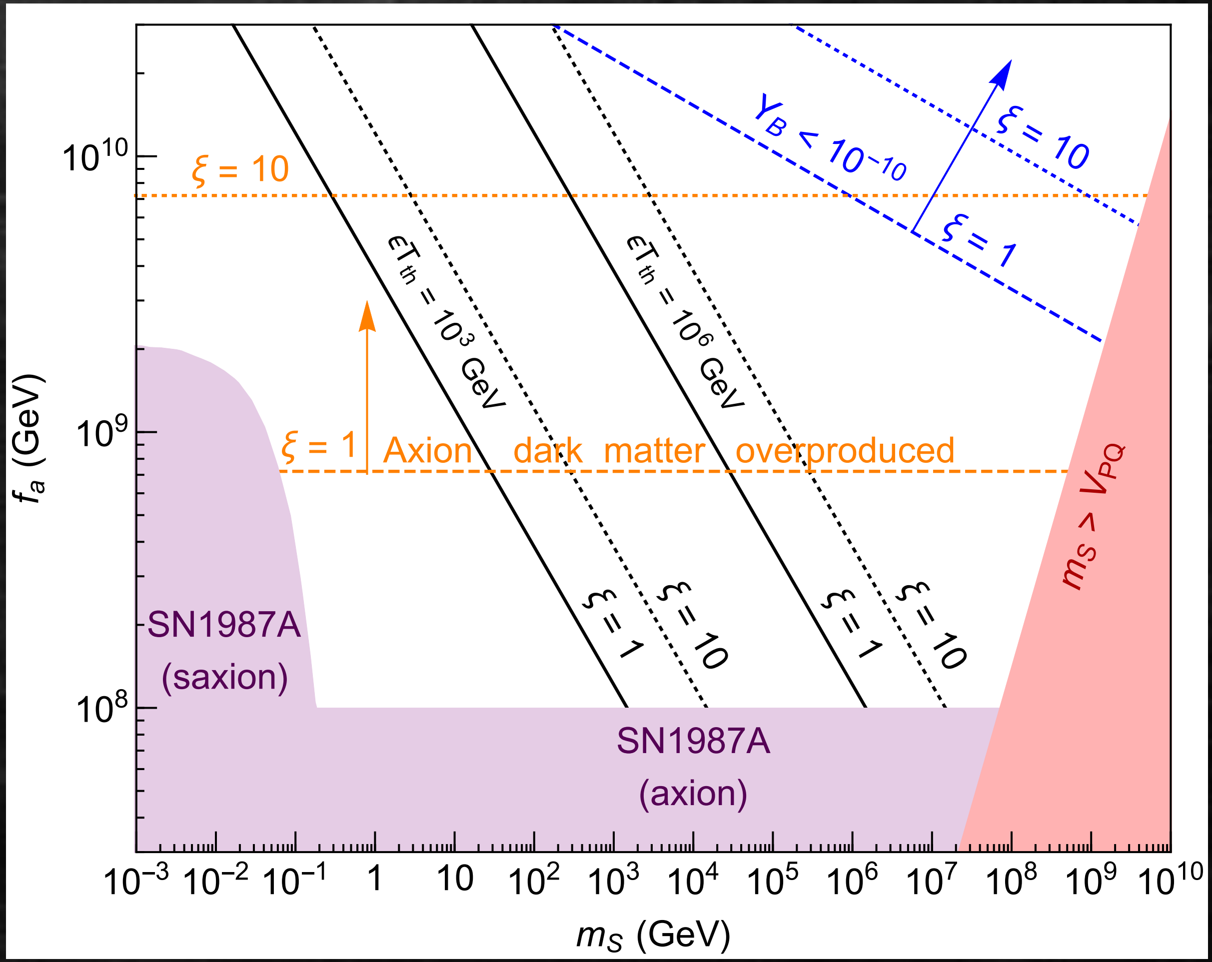
see talk

PRL 124, 111602 (2020) RC and K. Harigaya

Axiogenesis + Kinetic Misalignment

$$\frac{\Omega_a h^2}{\Omega_{\rm DM} h^2} \simeq \text{see talk} \left(\frac{f_a}{10^8\ \text{GeV}}\right)\left(\frac{130\ \text{GeV}}{T_{\rm EW}}\right)^2\left(\frac{0.1}{c_B}\right)$$

$$\xi \equiv \text{see talk} \times \left(\frac{T_{\rm EW}}{130\text{GeV}}\right)^2\left(\frac{c_B}{0.1}\right)$$

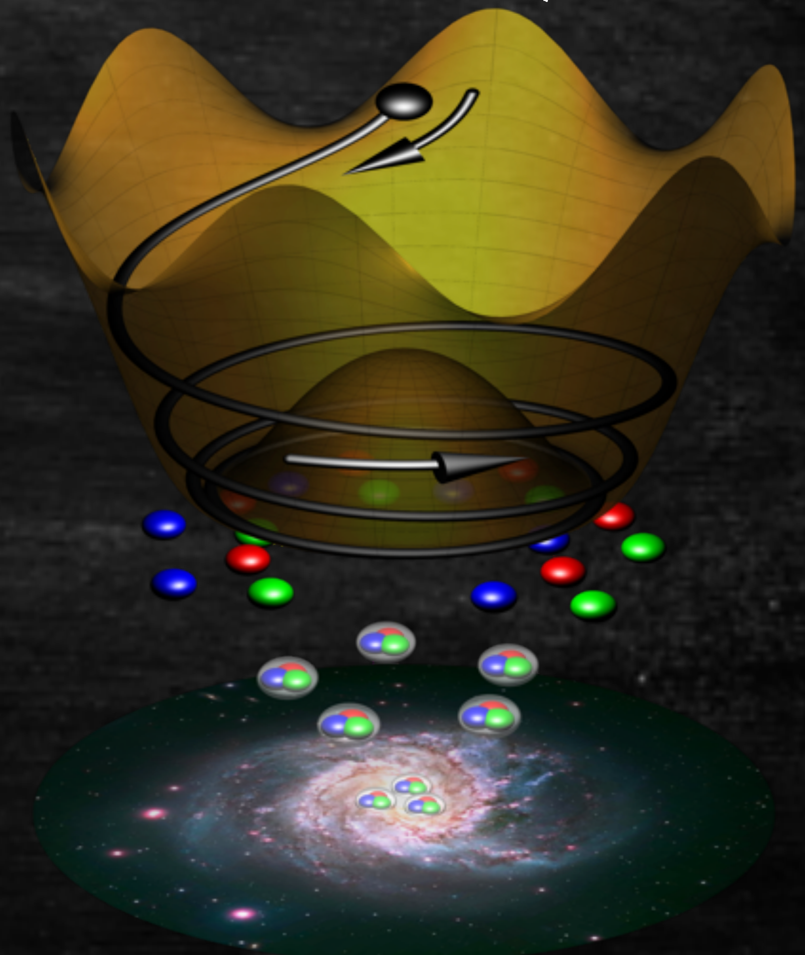


T_{th} = thermalization temperature of saxions

PRL 124, 111602 (2020) RC and K. Harigaya

Conclusions

- ✓ Axiogenesis allows the QCD axion to simultaneously explain
  - ✓ the Strong CP problem
  - ✓ the dark matter abundance
  - ✓ the baryon asymmetry
- ✓ Possible signatures:
  - ✓ QCD axion searches
  - ✓ TeV-scale new particles
  - ✓ dark matter ultracompact minihalos
- ✓ New model building opportunities



Thank you!

Happy birthday to Horst Störmer!