Dark Matter, Baryogenesis, and Gravitational Waves from Axion Rotations

Raymond Co

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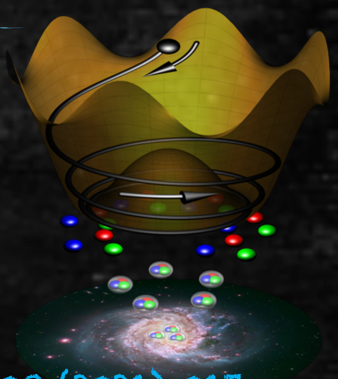
WIN2021 May 20th 2021



Collaborators:

arXiv: 1910.02080 Keisuke Harigaya Phys. Rev. Lett. 124, 111602 (2020)
arXiv: 1910.14152 Lawrence Hall, Keisuke Harigaya Phys. Rev. Lett. 124, 251802 (2020)
arXiv: 2006.04809 Lawrence Hall, Keisuke Harigaya JHEP 01 (2021) 172
arXiv: 2006.05687 Nicolas Fernandez, Akshay Ghalsasi, Lawrence Hall, Keisuke Harigaya JHEP 03 (2021) 017
arXiv: 2104.02077 Keisuke Harigaya and Aaron Pierce

Storyline

- Axion

(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

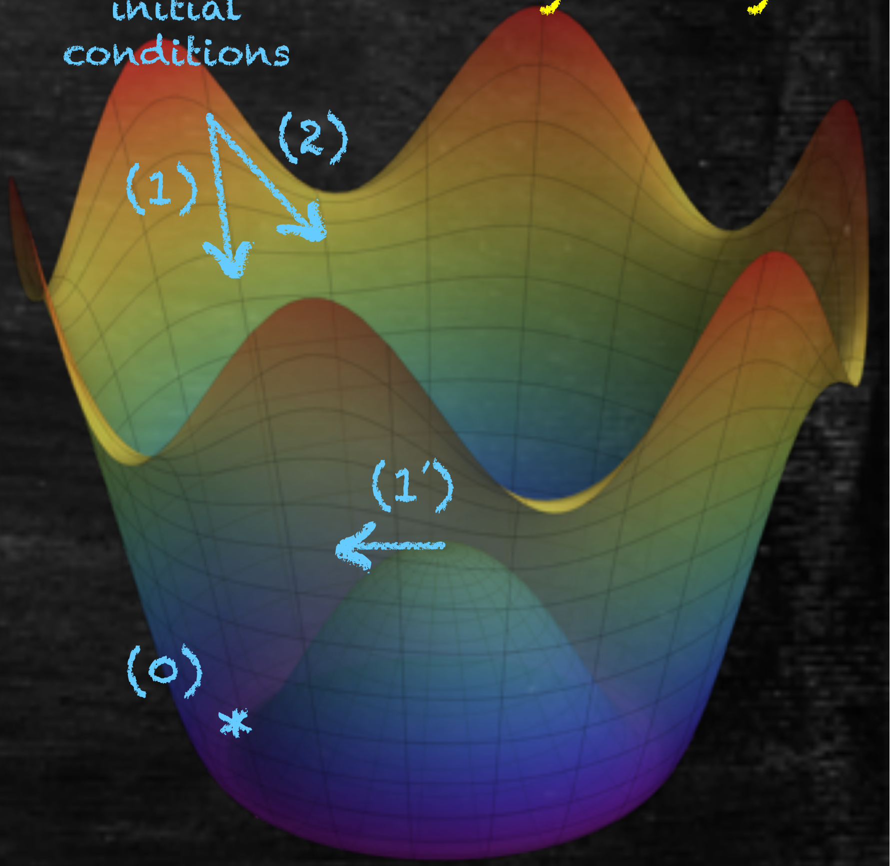
} Dark Matter

- Axiogenesis
RC, K. Harigaya 2019

- ALP cogenesis
RC, L. Hall, K. Harigaya 2020

- Lepto-Axiogenesis
RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya 2020

} Baryon Asymmetry



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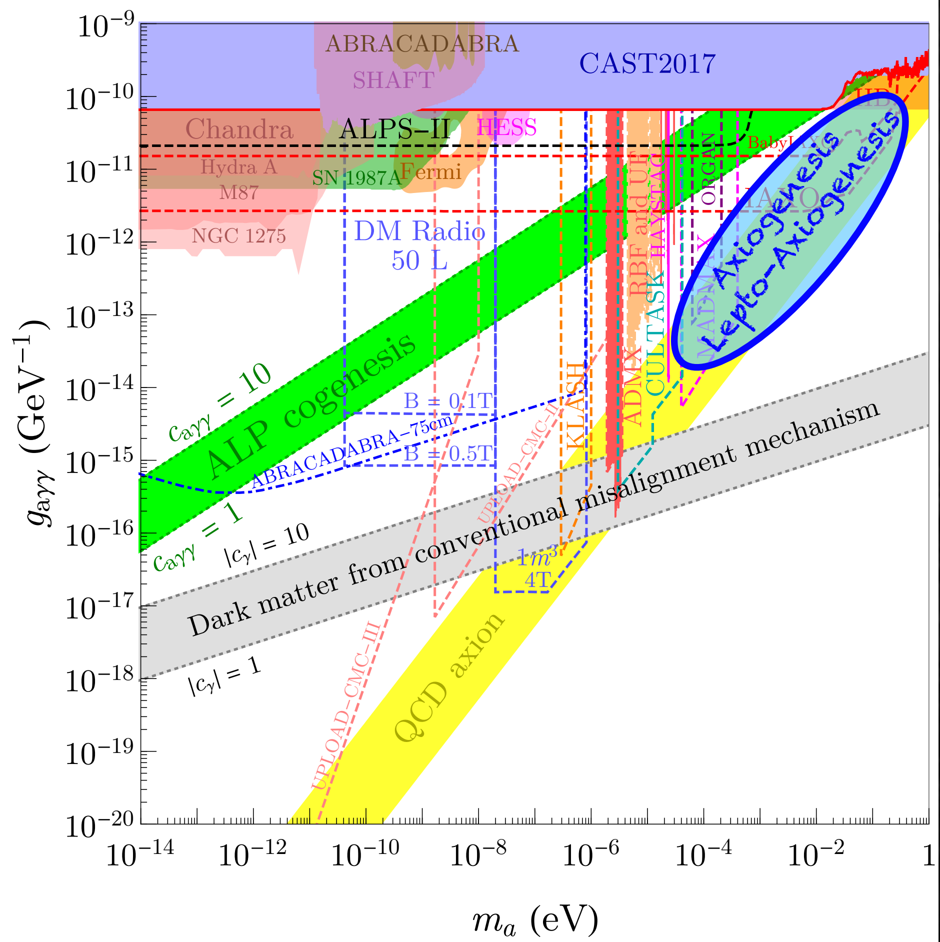
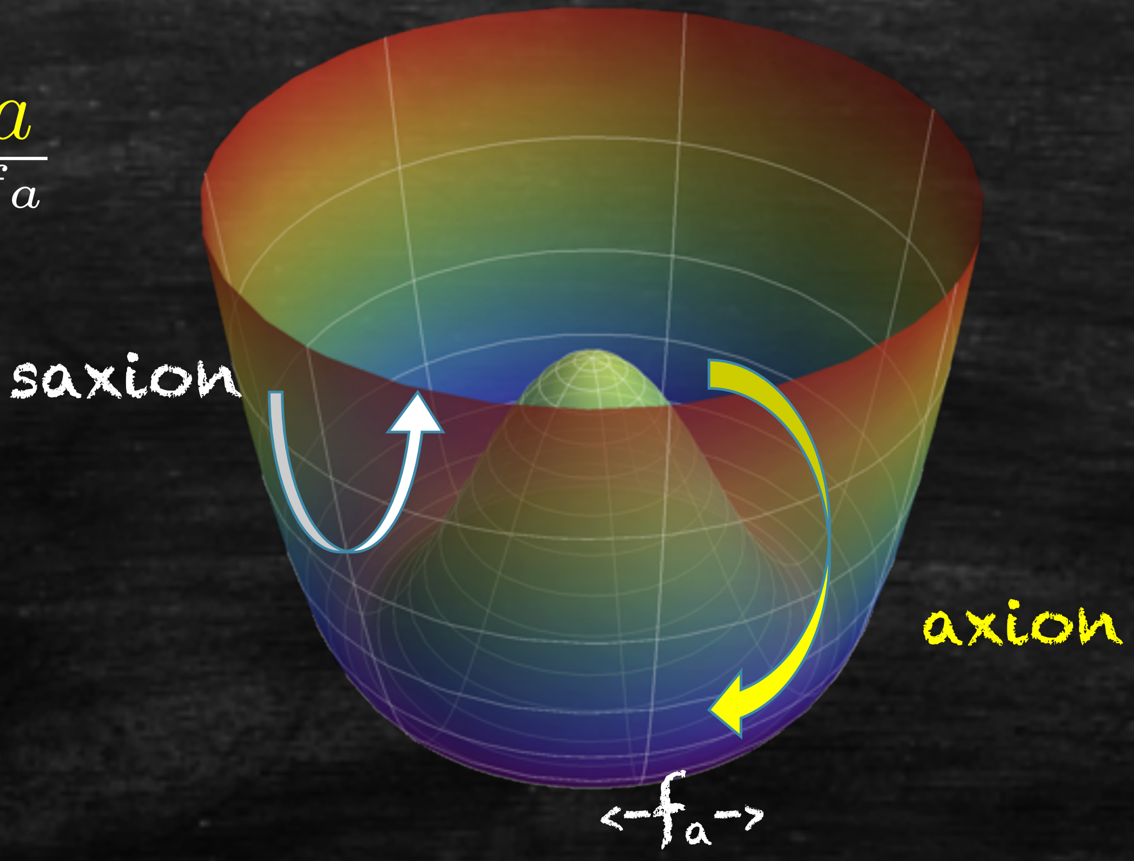


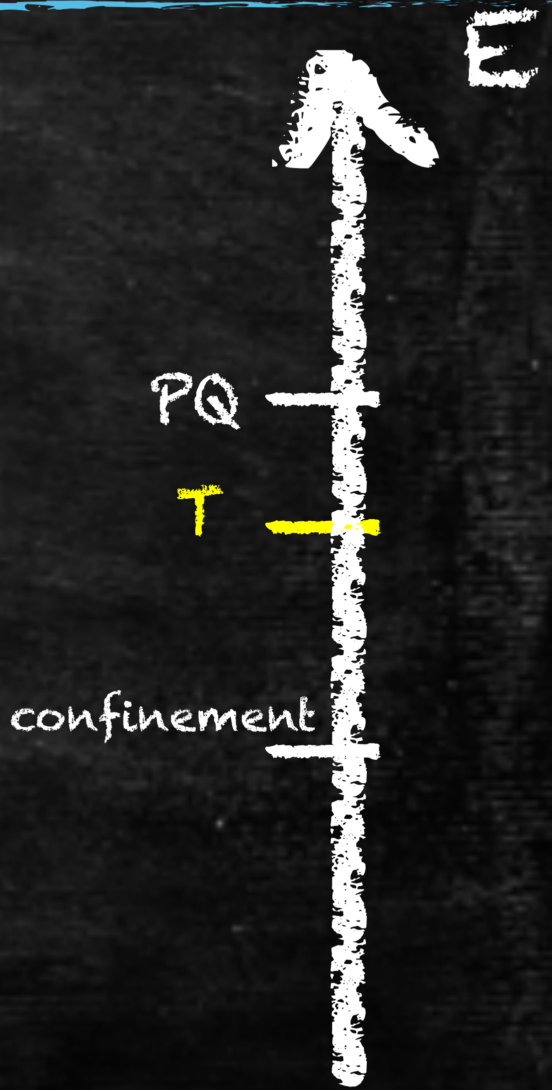
Kinetic Misalignment Mechanism ↑

See later slides for axion-electron and axion-nucleon couplings

Axions

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





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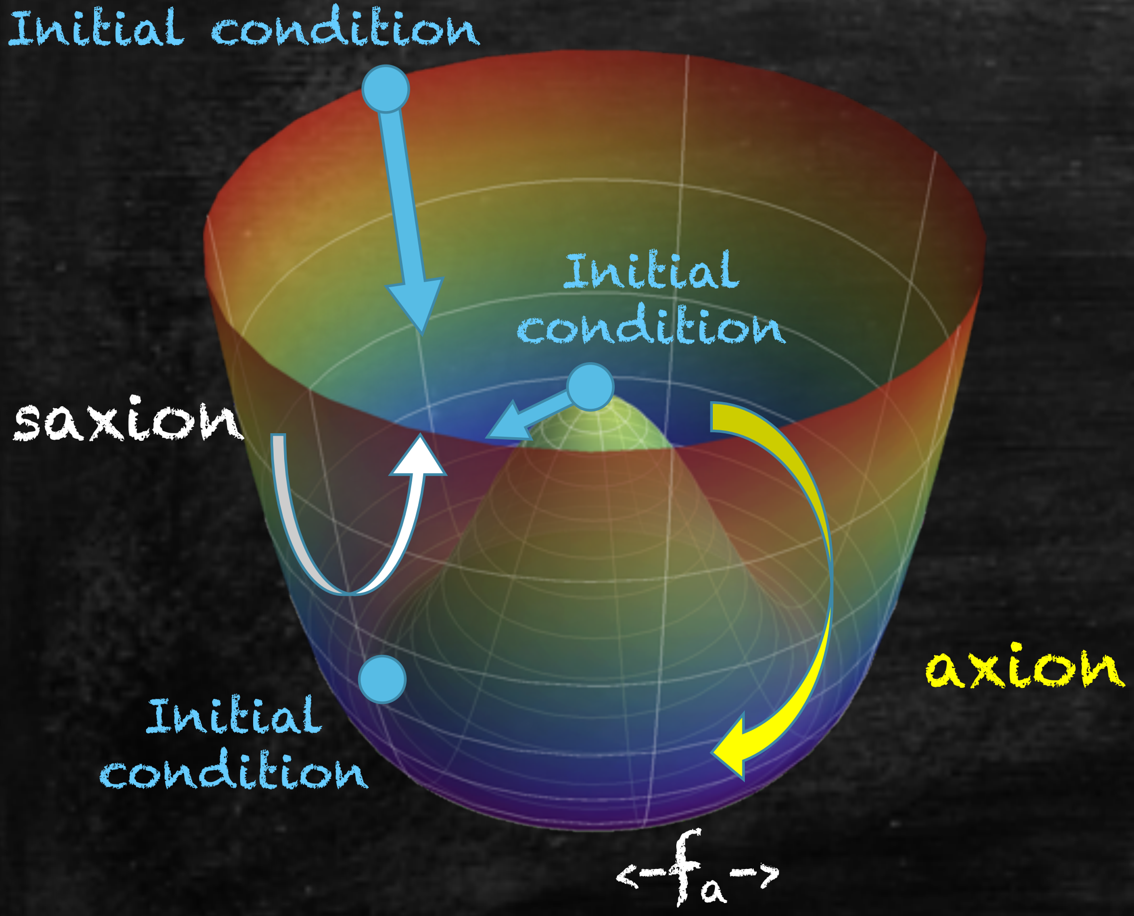
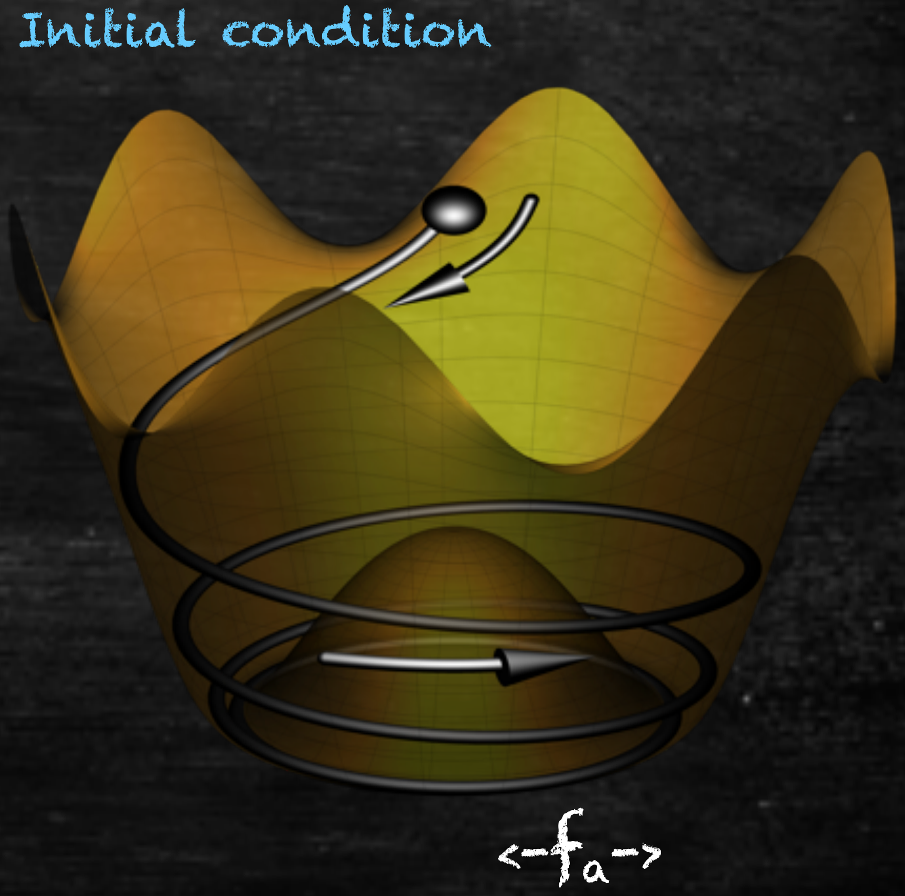
Rotation





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

Why Rotation?

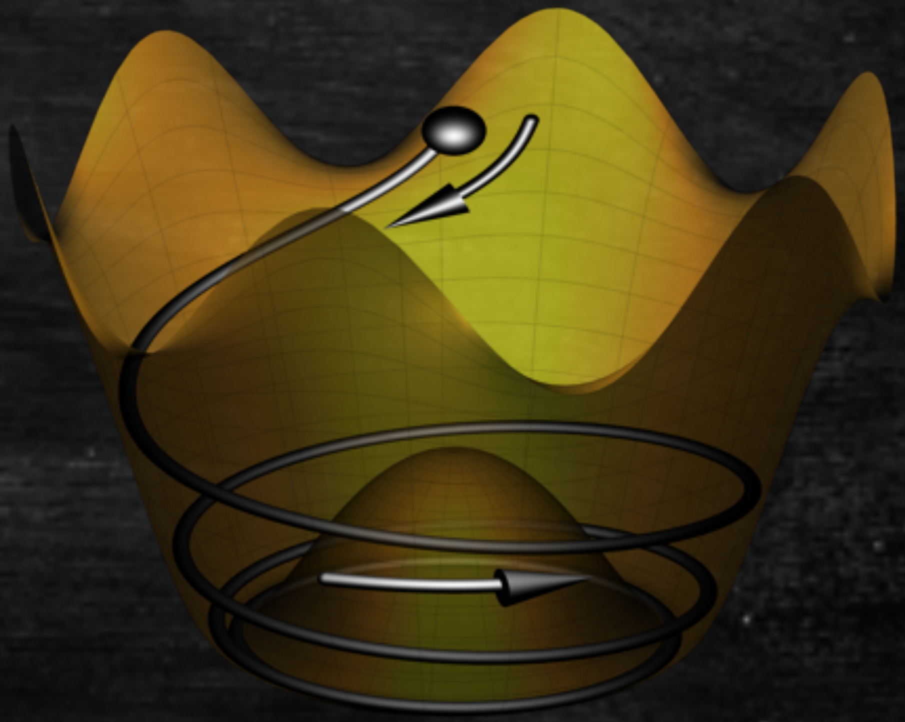
$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

Large field value : Flat potential

For example, as an initial condition or
set dynamically by the Hubble-induced mass

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

Initial condition



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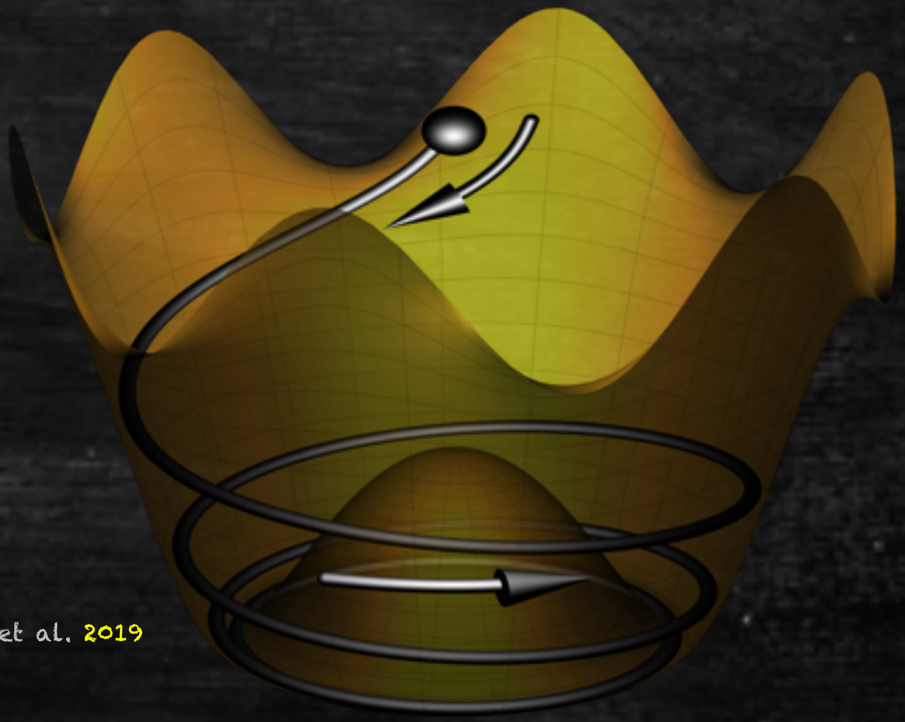


Angular motion : Explicit PQ breaking

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

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

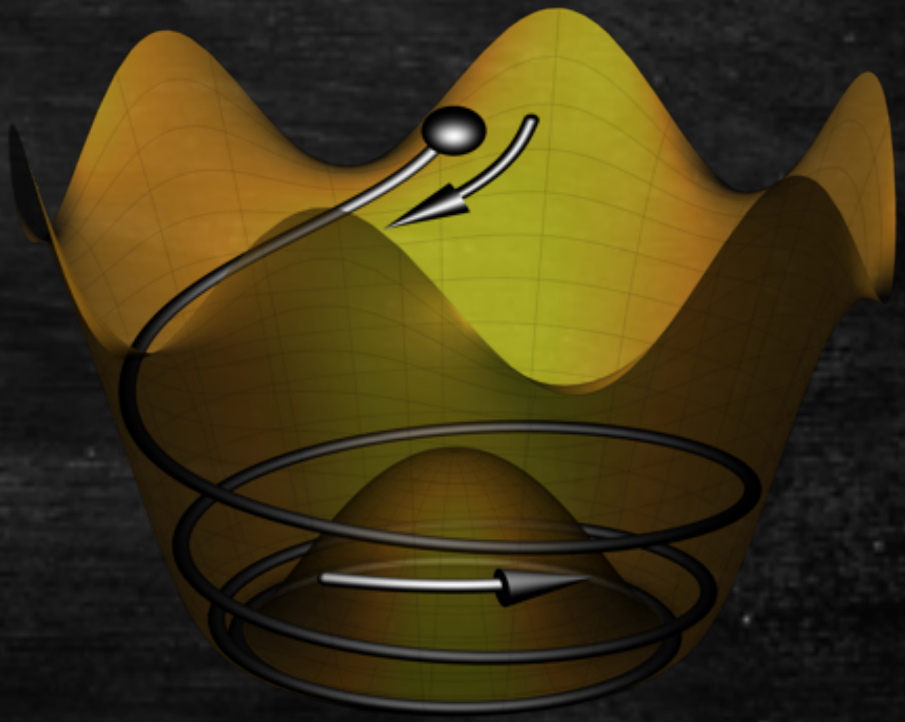
$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

Noether charge associated with the shift symmetry

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

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

PQ asymmetry
PQ charge density = Rotation of PQ field



PQ charge is conserved soon after the onset.

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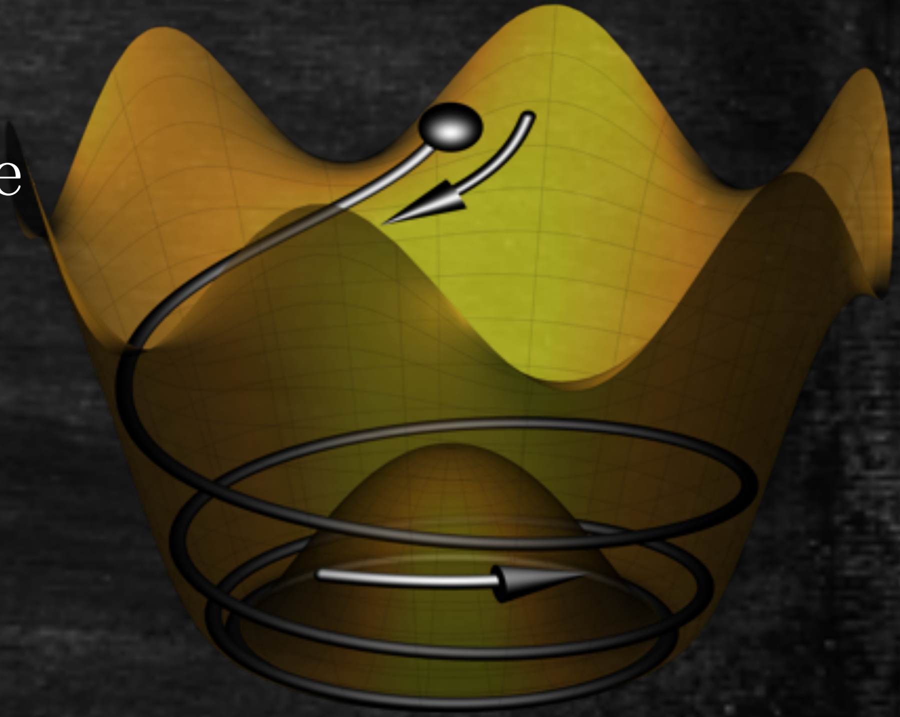
Why a large angular speed?

Reason:

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



Conventional:

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

Our scenario ($S \gg f_a$):

quartic	$S^2 \propto R^{-2}$	$\dot\theta \propto R^{-1}$	Slower redshift!
quadratic	$S^2 \propto R^{-3}$	$\dot\theta = \text{constant}$	

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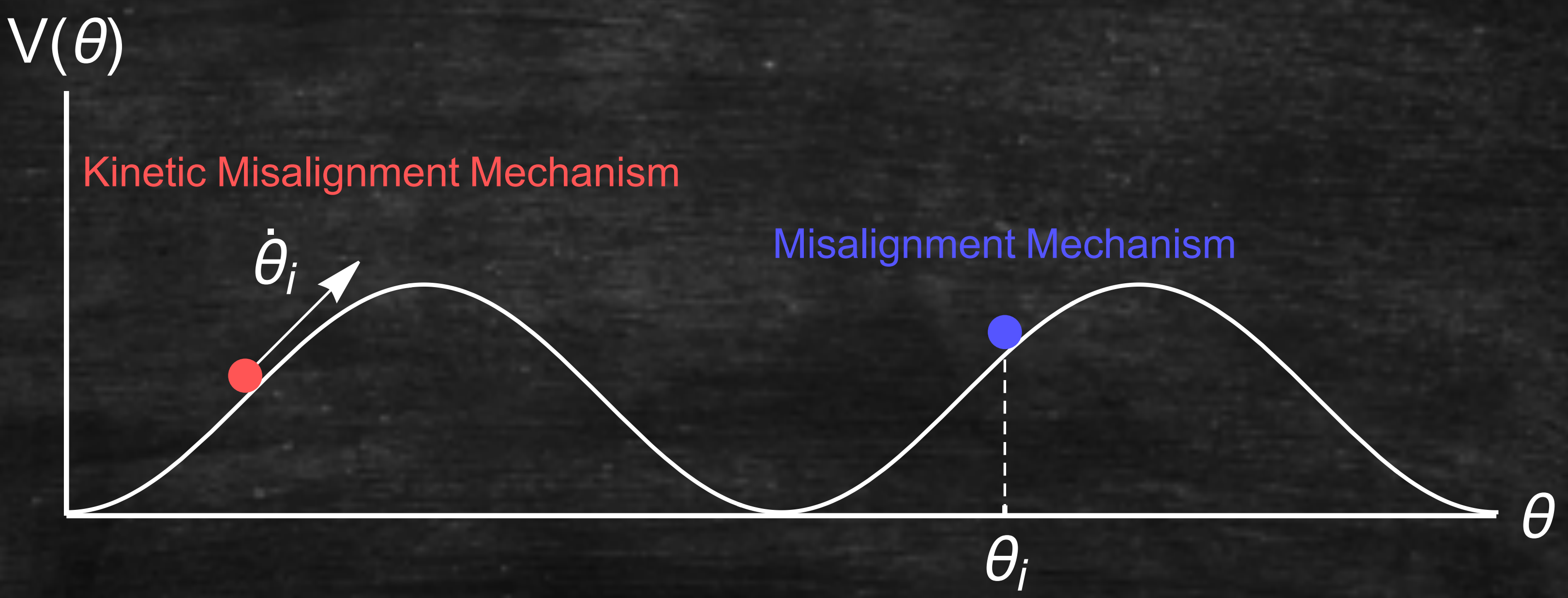
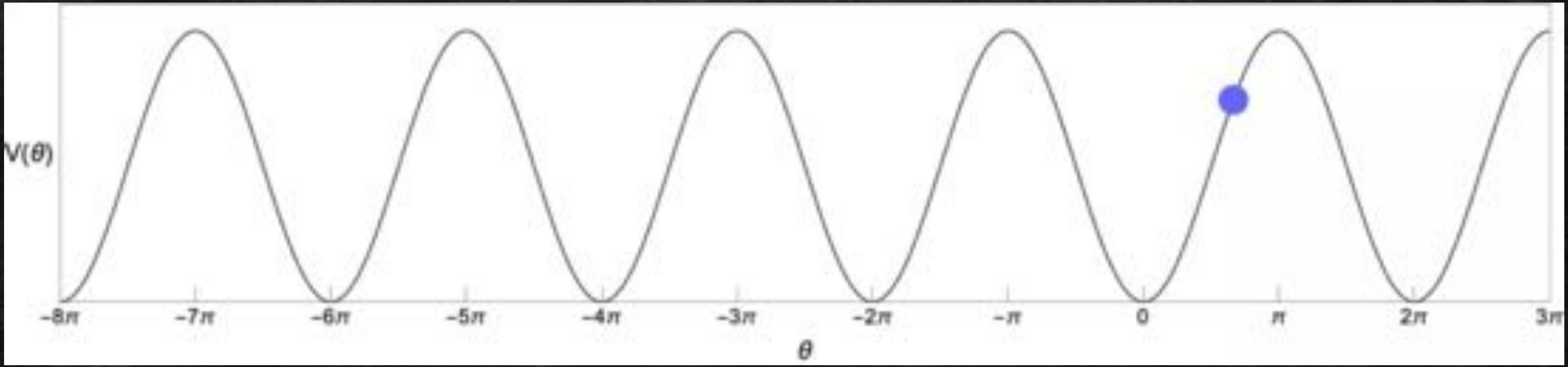


Kinetic Misalignment Mechanism

(Misalignment + non-zero kinetic energy)

PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya



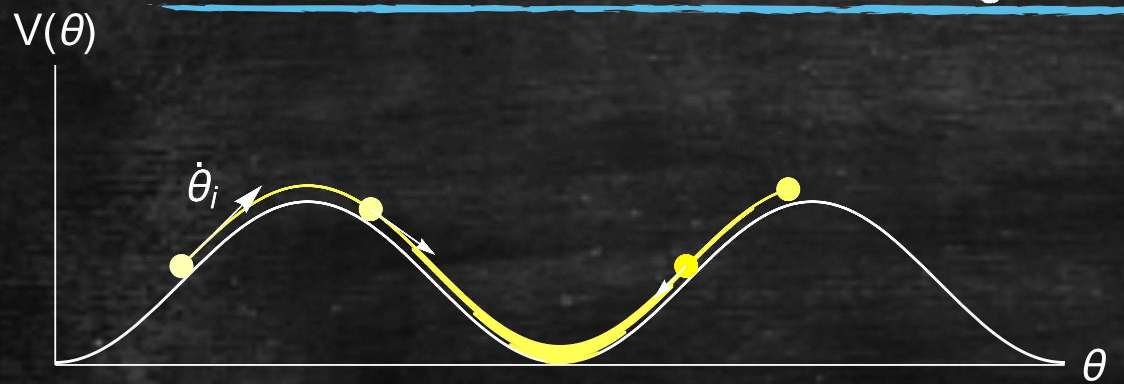
Kinetic Misalignment Mechanism

Consequence: delaying usual T_{osc} until KE = PE, enhancing the dark matter abundance

Abundance: $\Omega_a h^2 \propto \dot{\theta}$

PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

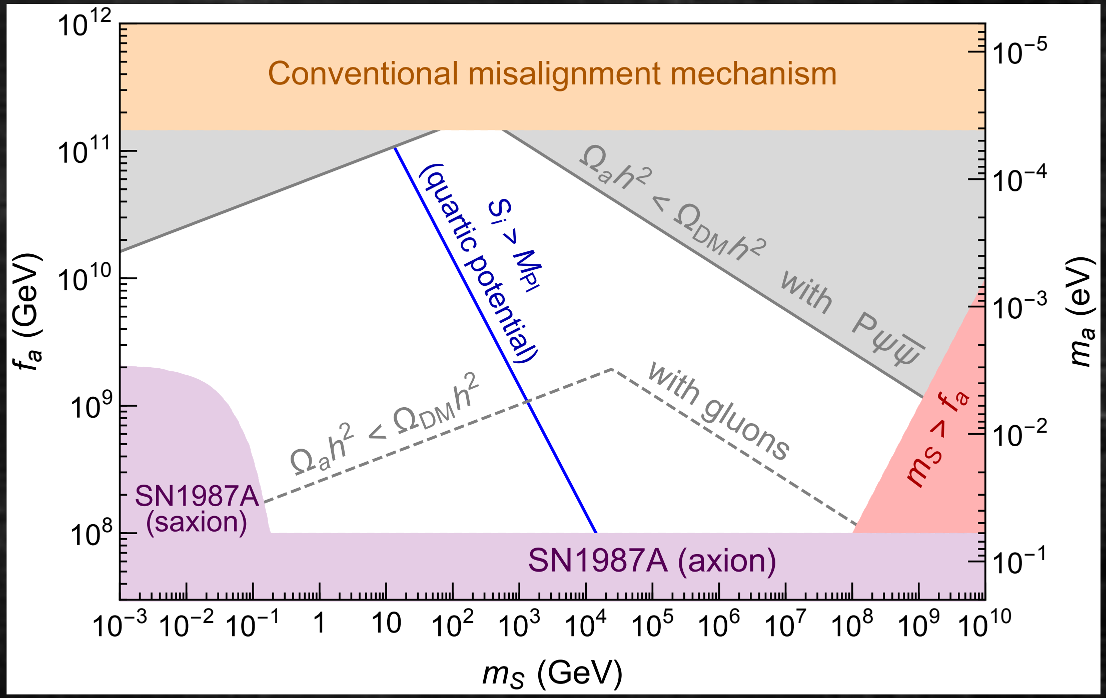
Kinetic Misalignment Mechanism



Abundance:

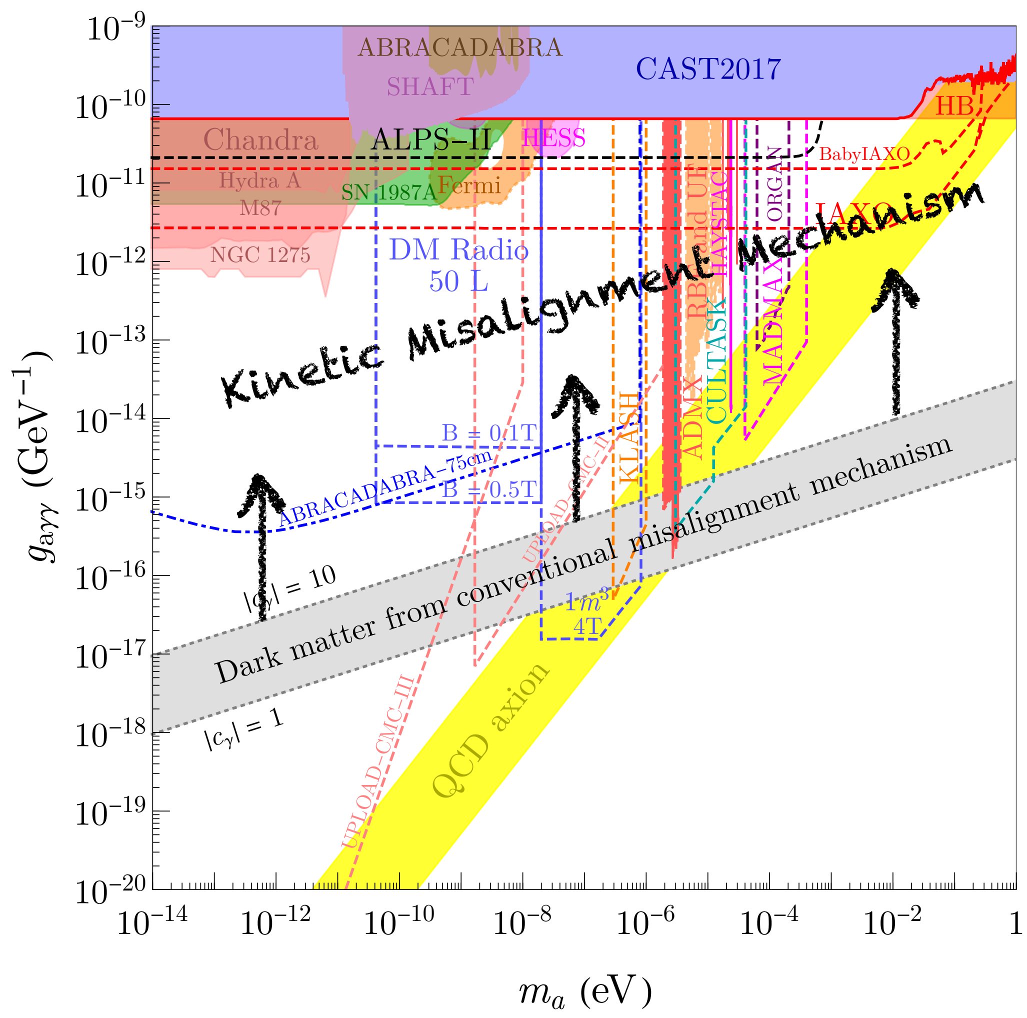
$$\frac{\rho_a}{s} \simeq 2m_a(0)Y_{\rm PQ}$$

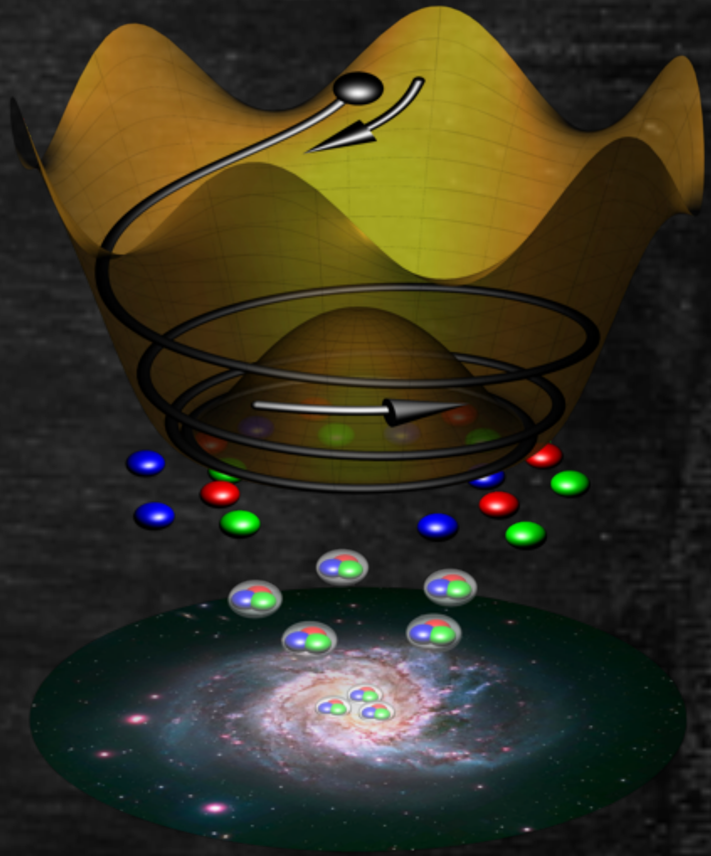
$$\Omega_a h^2 \simeq \Omega_{\rm DM} h^2 \left(\frac{10^9\,{\rm GeV}}{f_a}\right)\left(\frac{Y_{\rm PQ}}{40}\right)$$



PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

Kinetic Misalignment Mechanism

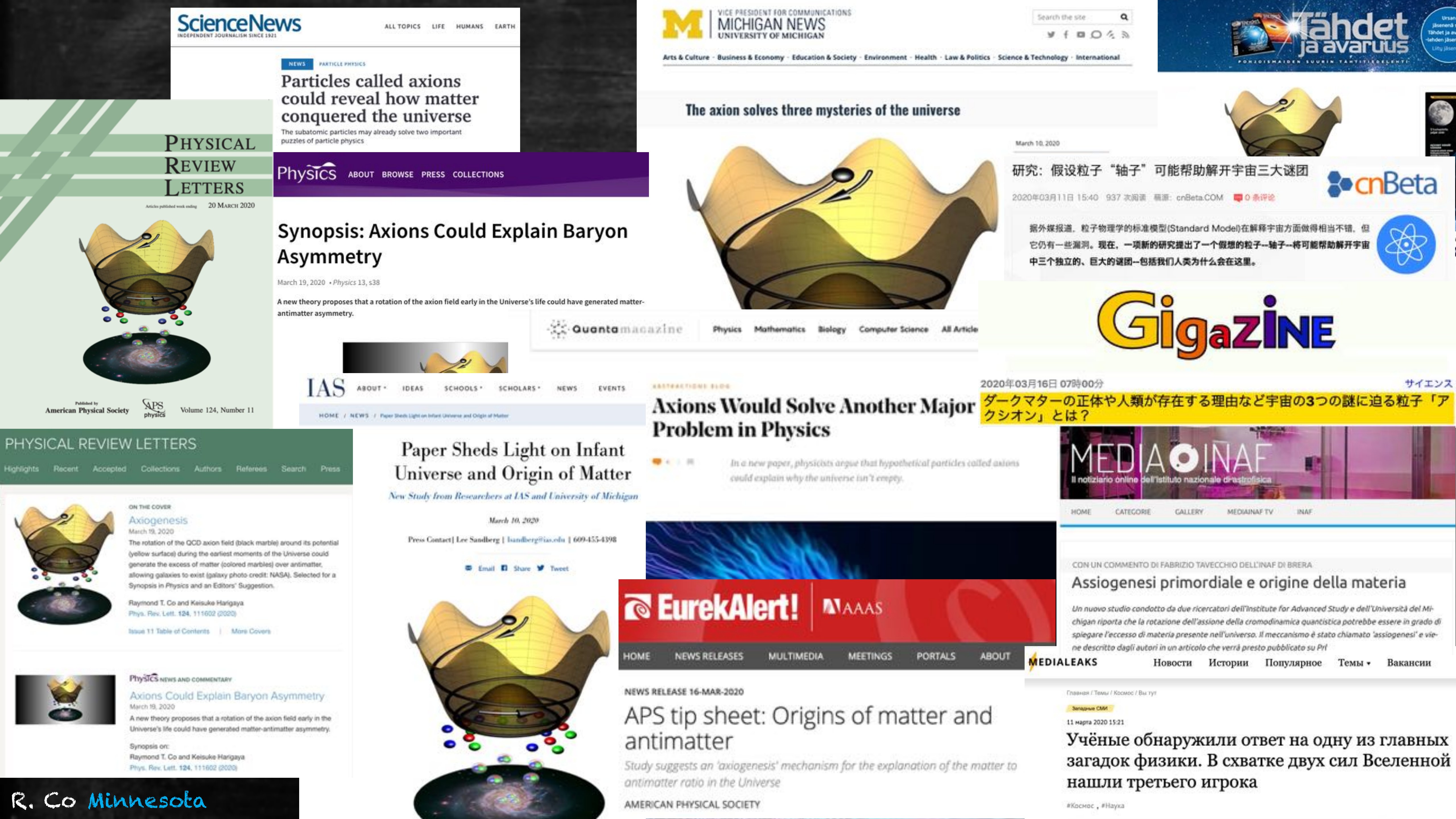




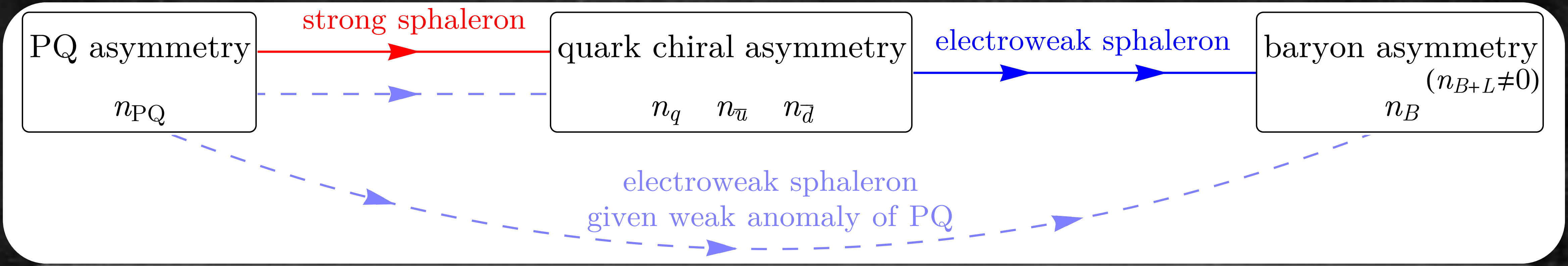
Axiogenesis

(QCD axion + baryogenesis)

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

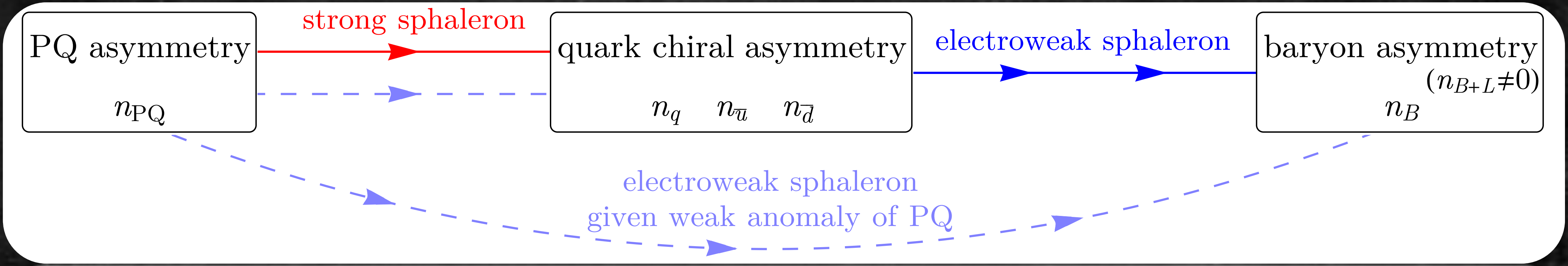

ScienceNews
INDEPENDENT JOURNALISM SINCE 1921
ALL TOPICS LIFE HUMANS EARTH
NEWS PARTICLE PHYSICS
Particles called axions could reveal how matter conquered the universe
The subatomic particles may already solve two important puzzles of particle physics
PHYSICAL REVIEW LETTERS
20 March 2020
Published by American Physical Society
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.
MICHIGAN NEWS
UNIVERSITY OF MICHIGAN
Arts & Culture · Business & Economy · Education & Society · Environment · Health · Law & Politics · Science & Technology · International
The axion solves three mysteries of the universe
March 10, 2020
Tähdet ja avaruus
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。
Quanta magazine
Physics Mathematics Biology Computer Science All Articles
GIGAZINE
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？
IAS
ABOUT IDEAS SCHOOLS SCHOLARS NEWS EVENTS
Paper Sheds Light on Infant Universe and Origin of Matter
New Study from Researchers at IAS and University of Michigan
March 10, 2020
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.
PHYSICAL REVIEW LETTERS
Highlights Recent Accepted Collections Authors Referees Search Press
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)
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)
EurekAlert! AAAS
HOME NEWS RELEASES MULTIMEDIA MEETINGS PORTALS ABOUT
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
MEDIA INAF
Il notiziario online dell'Istituto nazionale di astrofisica
HOME CATEGORIE GALLERY MEDIAINAF TV INAF
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
MEDIALEAKS
Новости Истории Популярное Темы Вакансии
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 Minnesota

Axiogenesis



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

Axiogenesis

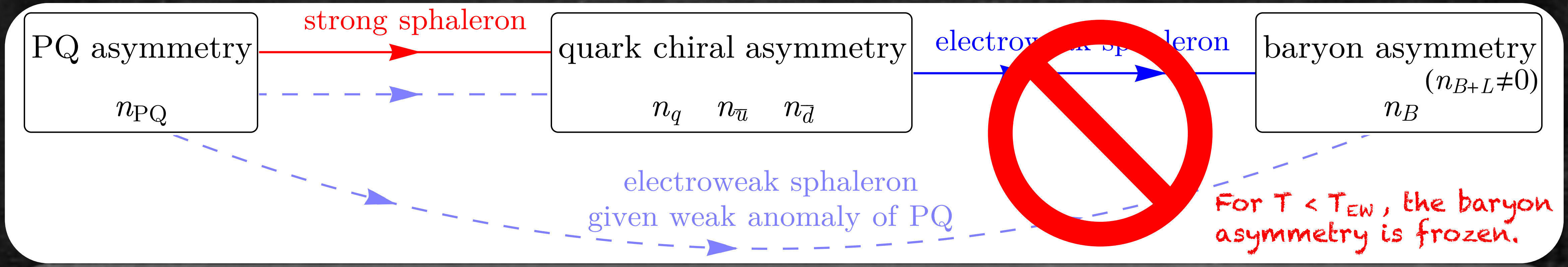


$$n_B = c_B \dot{\theta} T^2$$

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

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

Axiogenesis



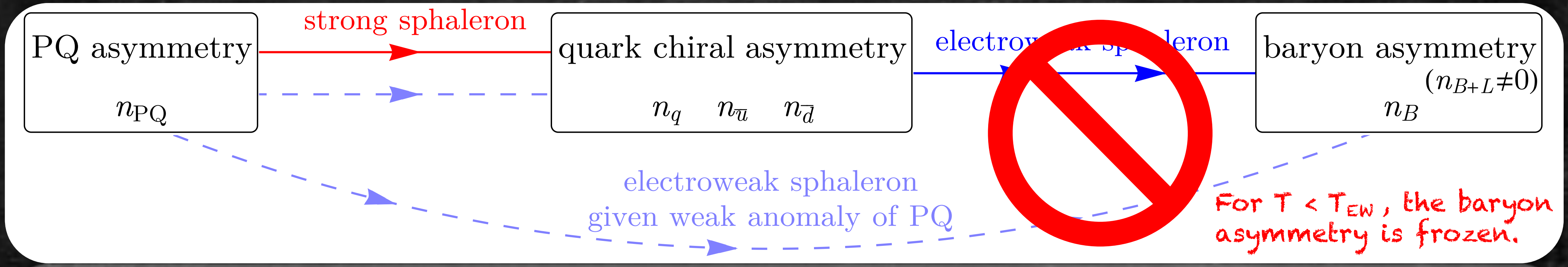
$$n_B = c_B \dot{\theta} T^2$$
$$c_B \simeq 0.1 - 0.15\, c_W$$

$$Y_B \equiv \frac{n_B}{s} = \left.\frac{c_B \dot{\theta} T^2}{s}\right|_{T=T_{\rm EW}} = c_B Y_{\rm PQ} \left(\frac{T_{\rm EW}}{f_a}\right)^2$$

Baryon asymmetry fixes rotational speed, equivalently $Y_{\rm PQ}$.

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

Axiogenesis



$$Y_B \simeq 10^{-10} \left(\frac{c_B}{0.1}\right) \left(\frac{T_{\mathrm{EW}}}{130\ \mathrm{GeV}}\right)^2 \left(\frac{10^8\ \mathrm{GeV}}{f_a}\right)^2 \left(\frac{Y_{\mathrm{PQ}}}{500}\right)$$

Baryon asymmetry fixes rotational speed, equivalently Y_{PQ}.

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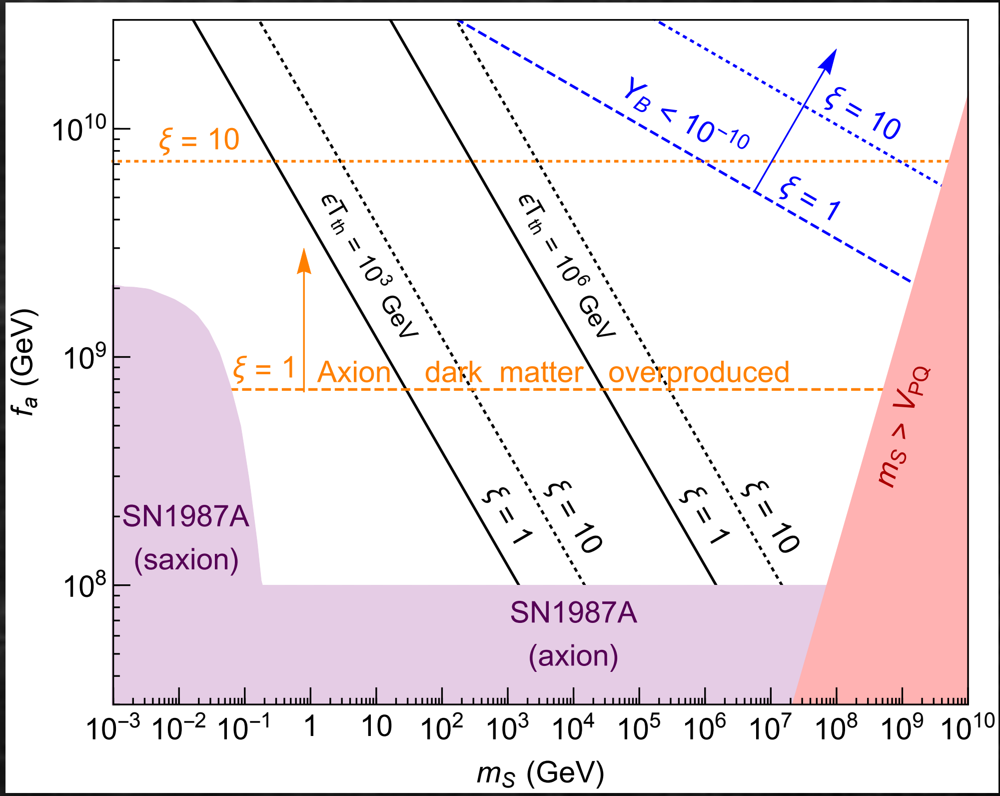
Axiogenesis + Kinetic Misalignment

$$\frac{\Omega_a h^2}{\Omega_{\rm DM} h^2} \simeq 70 \left(\frac{f_a}{10^8\ \mathrm{GeV}}\right)\left(\frac{130\ \mathrm{GeV}}{T_{\rm EW}}\right)^2\left(\frac{0.1}{c_B}\right)$$

$$T_{\rm EW} = 1\ \mathrm{TeV}\left(\frac{f_a}{10^8\ \mathrm{GeV}}\right)^{\frac{1}{2}}$$

Electroweak physics ⟷ Axion physics !



$T_{\rm th}$ = thermalization temperature of saxions

$$\xi \equiv 10^{-2} \times \left(\frac{T_{\rm EW}}{130\mathrm{GeV}}\right)^2\left(\frac{c_B}{0.1}\right)$$

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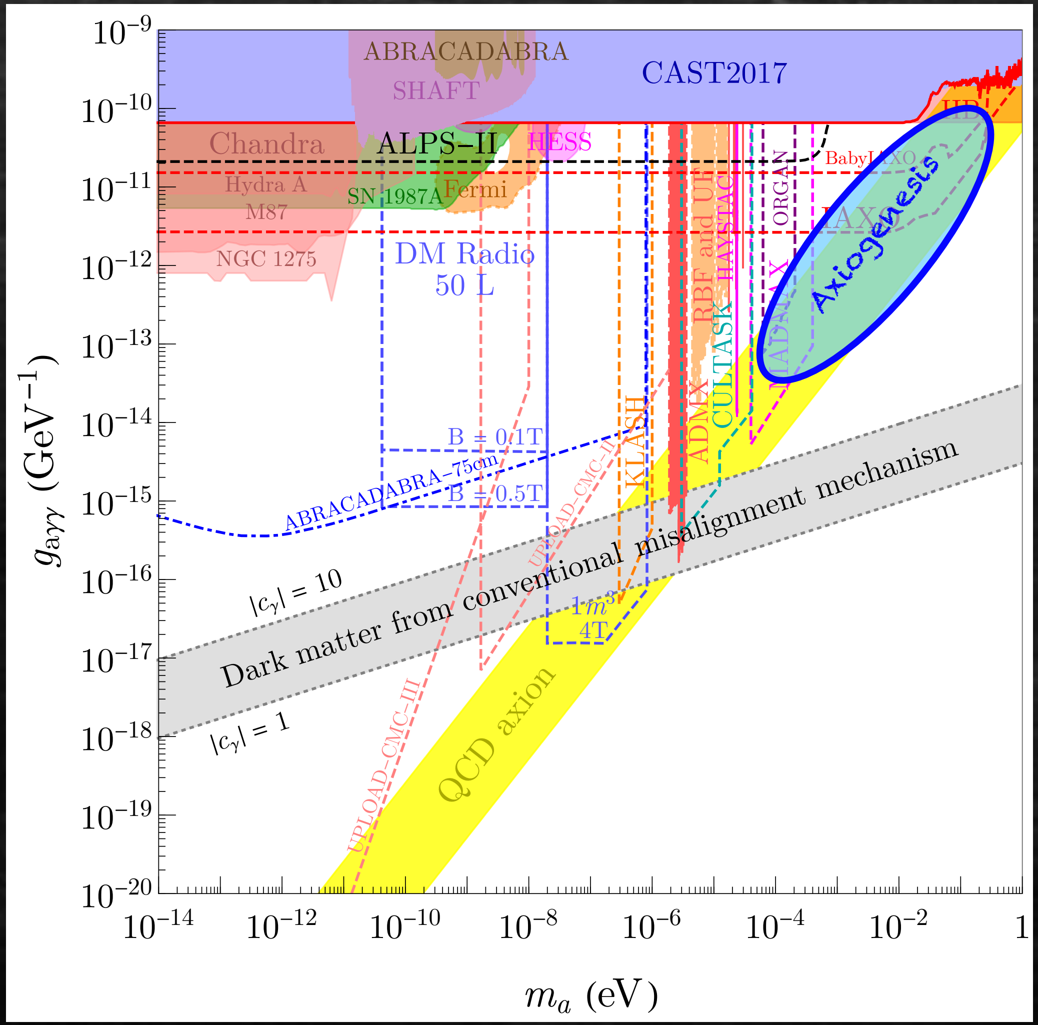
Axion Photon Coupling



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2006.04809 RC, L. Hall, K. Harigaya

Storyline

- **QCD axion**

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

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

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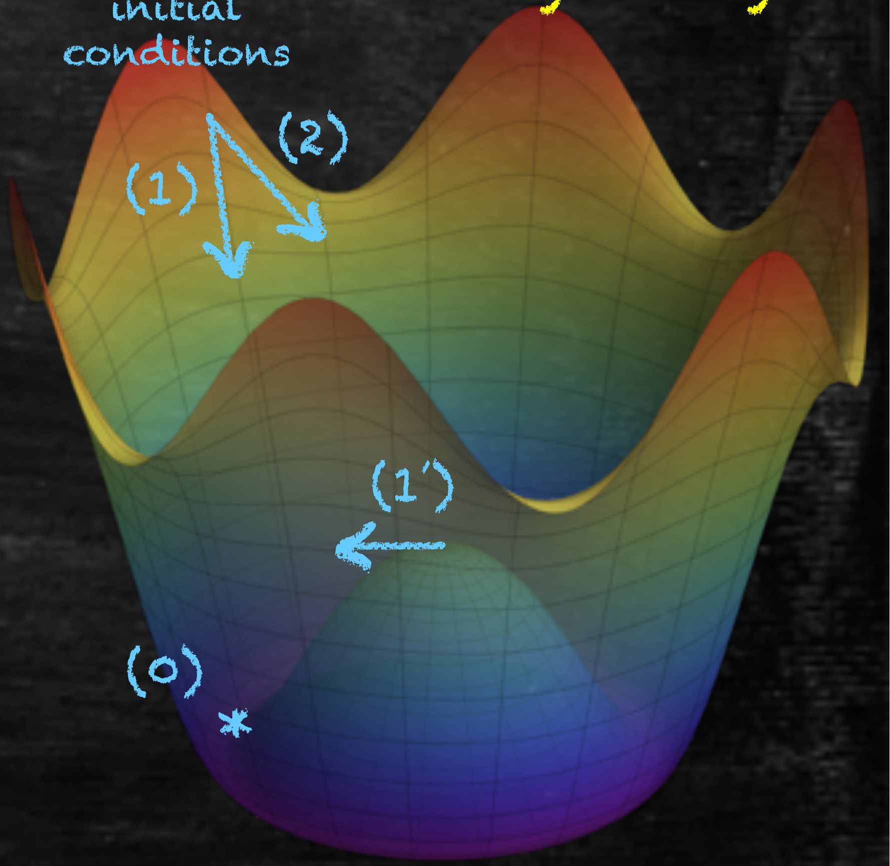
} Dark Matter

- Axiogenesis
RC, K. Harigaya 2019

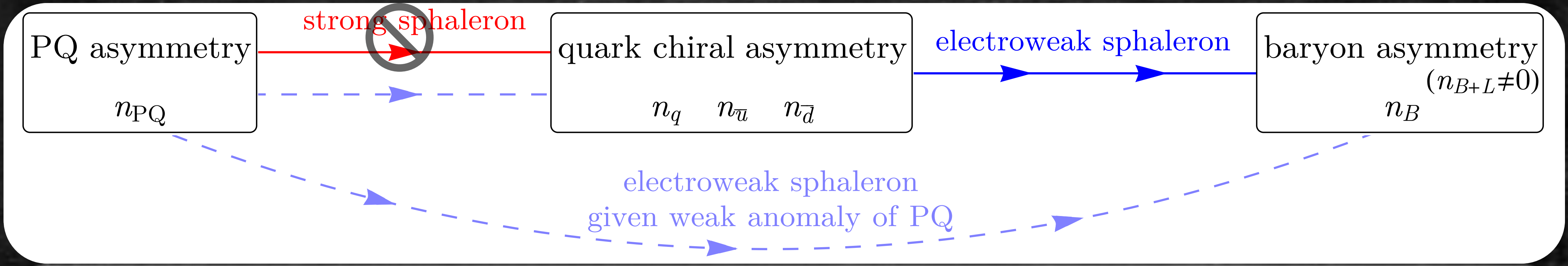
- ALP cogenesis
RC, L. Hall, K. Harigaya 2020

- Lepto-Axiogenesis
RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya 2020

} Baryon Asymmetry



ALP-genesis



$$Y_B \simeq 10^{-10} \left(\frac{c_B}{0.1}\right) \left(\frac{T_{\rm EW}}{130 \text{ GeV}}\right)^2 \left(\frac{10^8 \text{ GeV}}{f_a}\right)^2 \left(\frac{Y_{\rm PQ}}{500}\right)$$

$$c_B = -\frac{12}{79} c_W$$

Baryon asymmetry fixes rotational speed, equivalently $Y_{\rm PQ}$.

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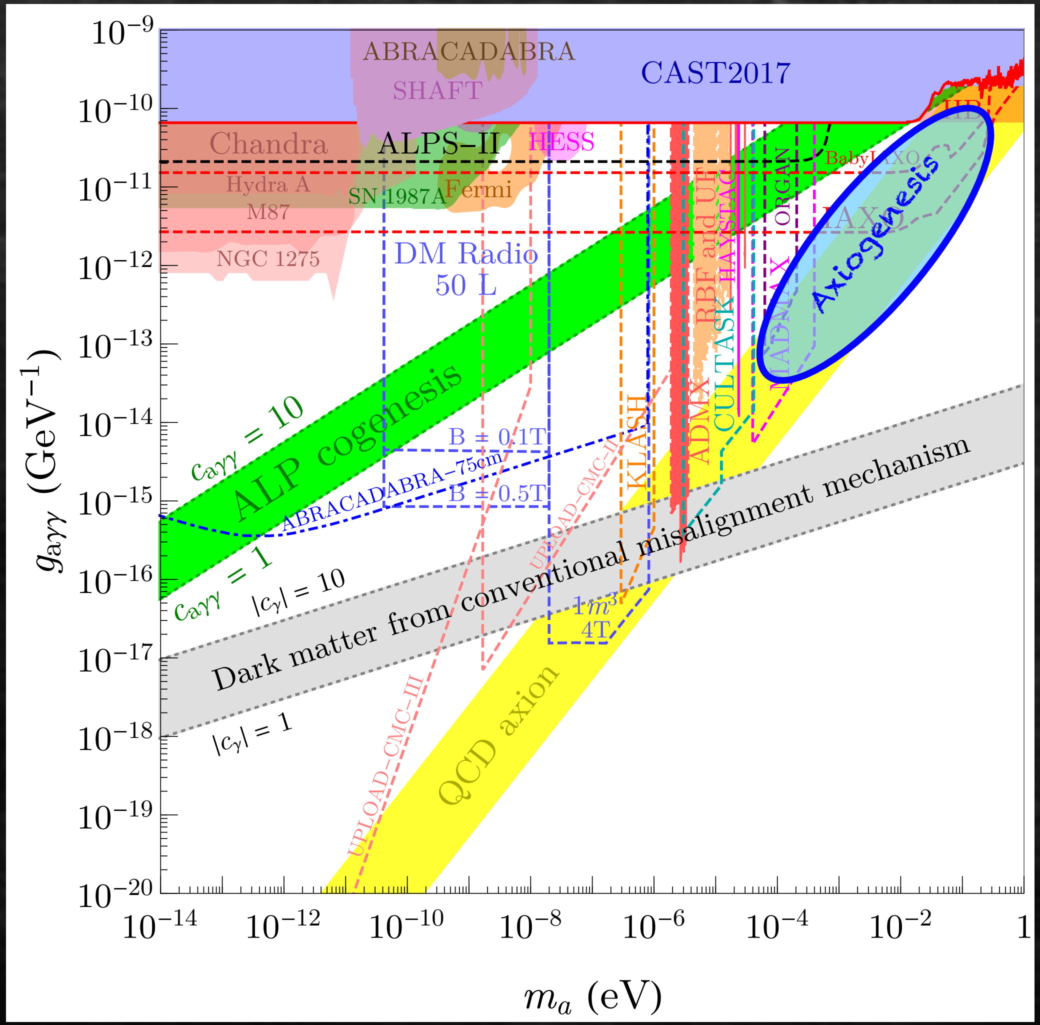
Axion Photon Coupling



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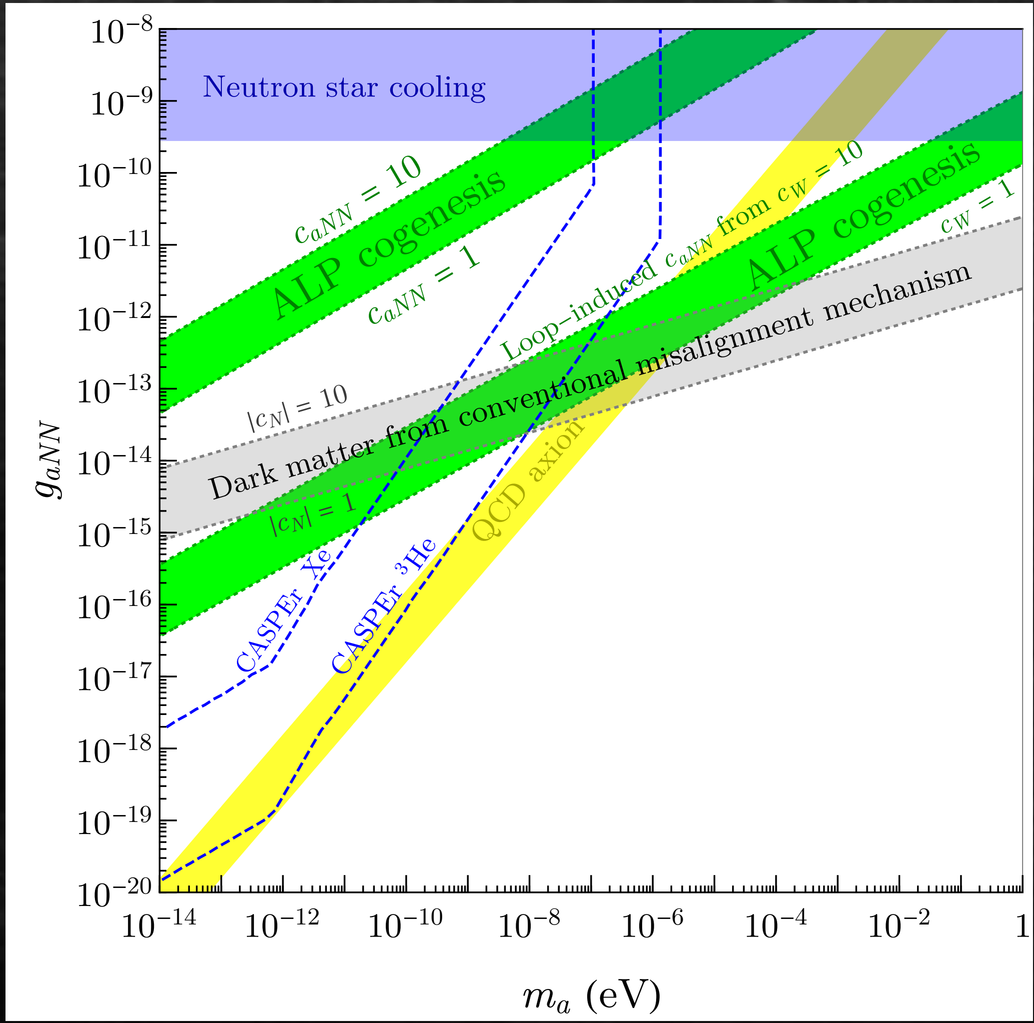
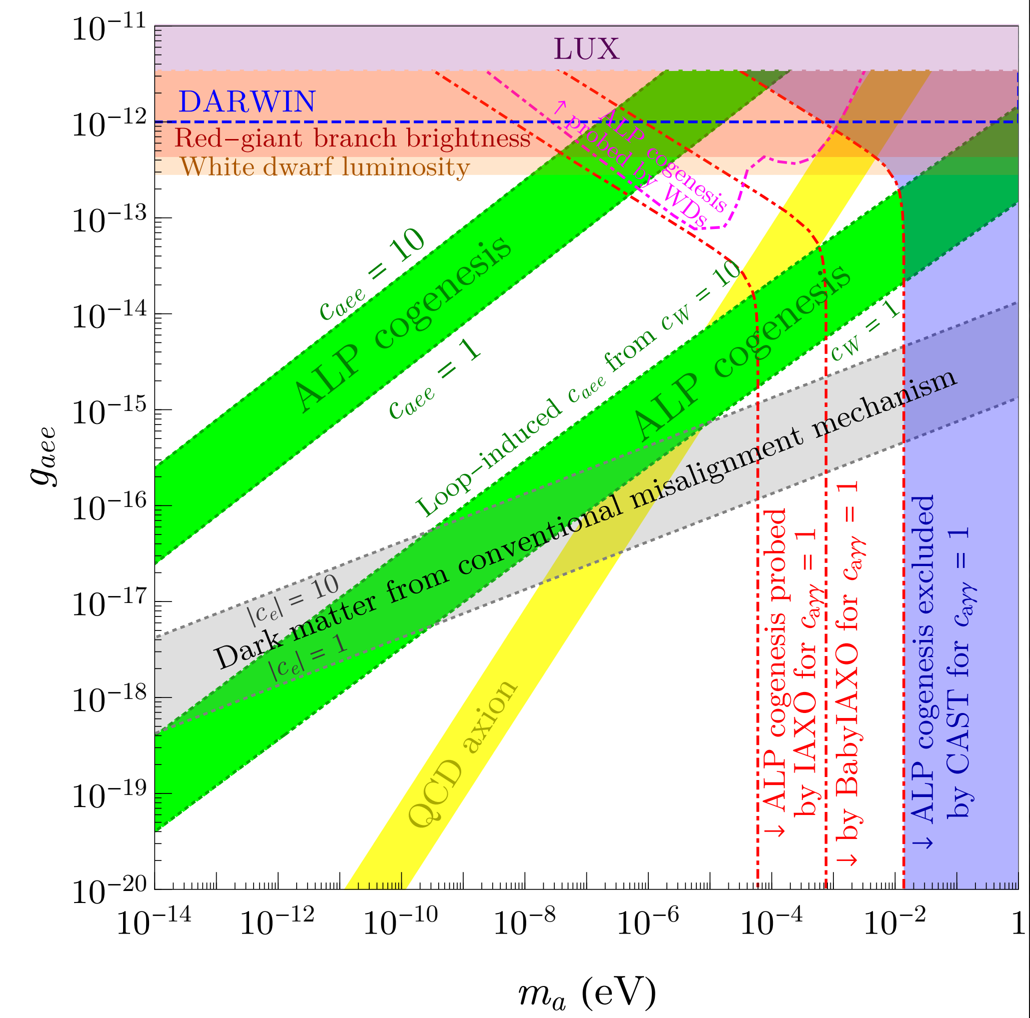
Axion Nucleon Coupling



2006.04809 RC, L. Hall, K. Harigaya

Axion Electron Coupling



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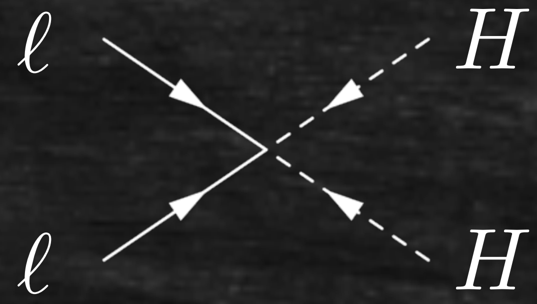
2006.04809 RC, L. Hall, K. Harigaya

Axion with Majorana neutrinos

$$\dot{\theta} \neq 0$$



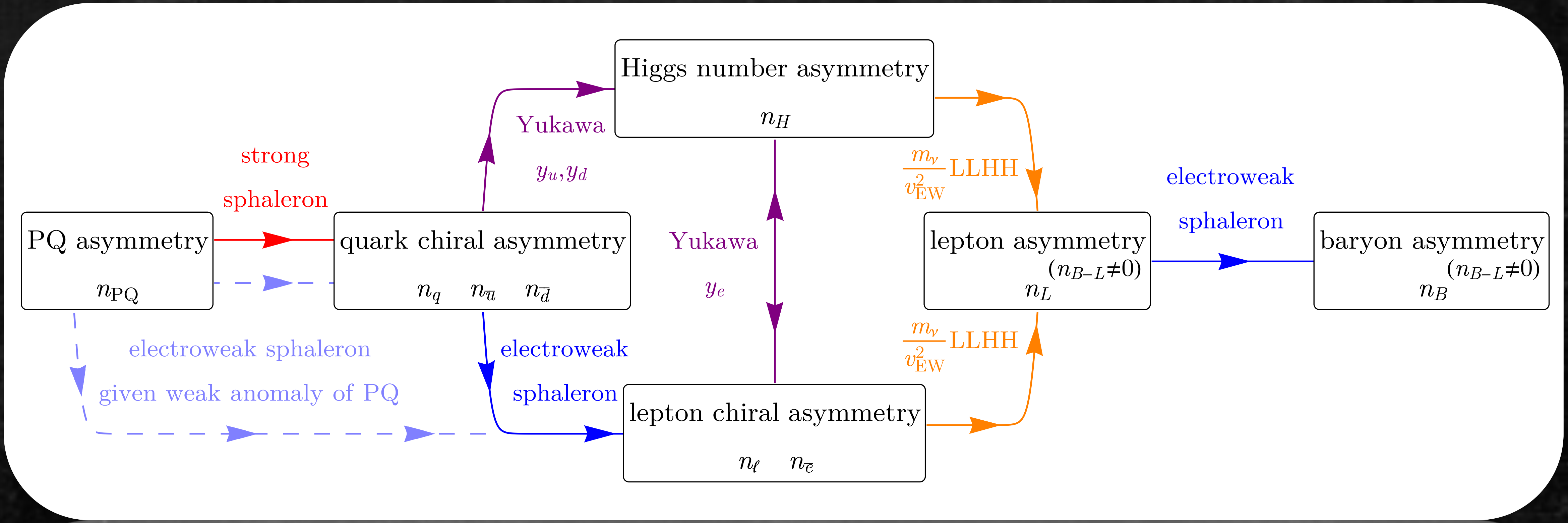
$$n_B \propto \dot{\theta} T^2$$

$$\mathcal{L} = \frac{m_\nu}{2 v_{\rm EW}^2} \ell\ell H^\dagger H^\dagger$$

2006.03148 V. Domcke, Y. Ema, K. Mukaida, M. Yamada

2006.05687 RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya

Lepto-Axiogenesis



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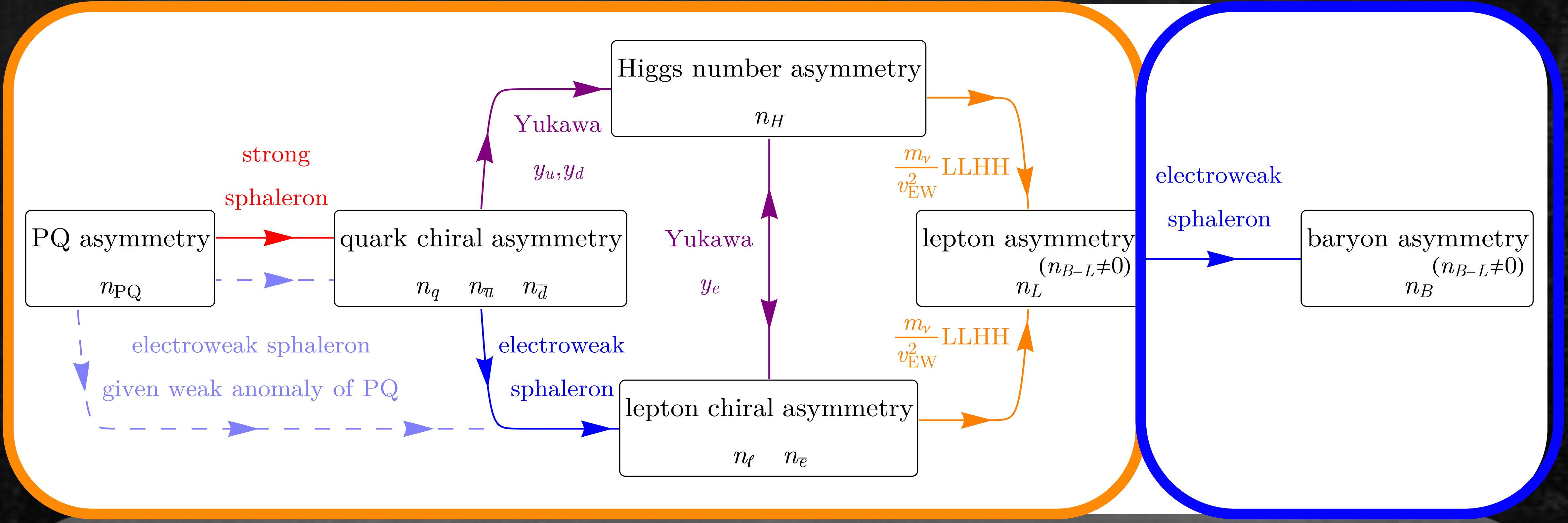
2006.05687 RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya

Lepto-Axiogenesis

Producing L at high temperatures

Converting to B at T_{EW}



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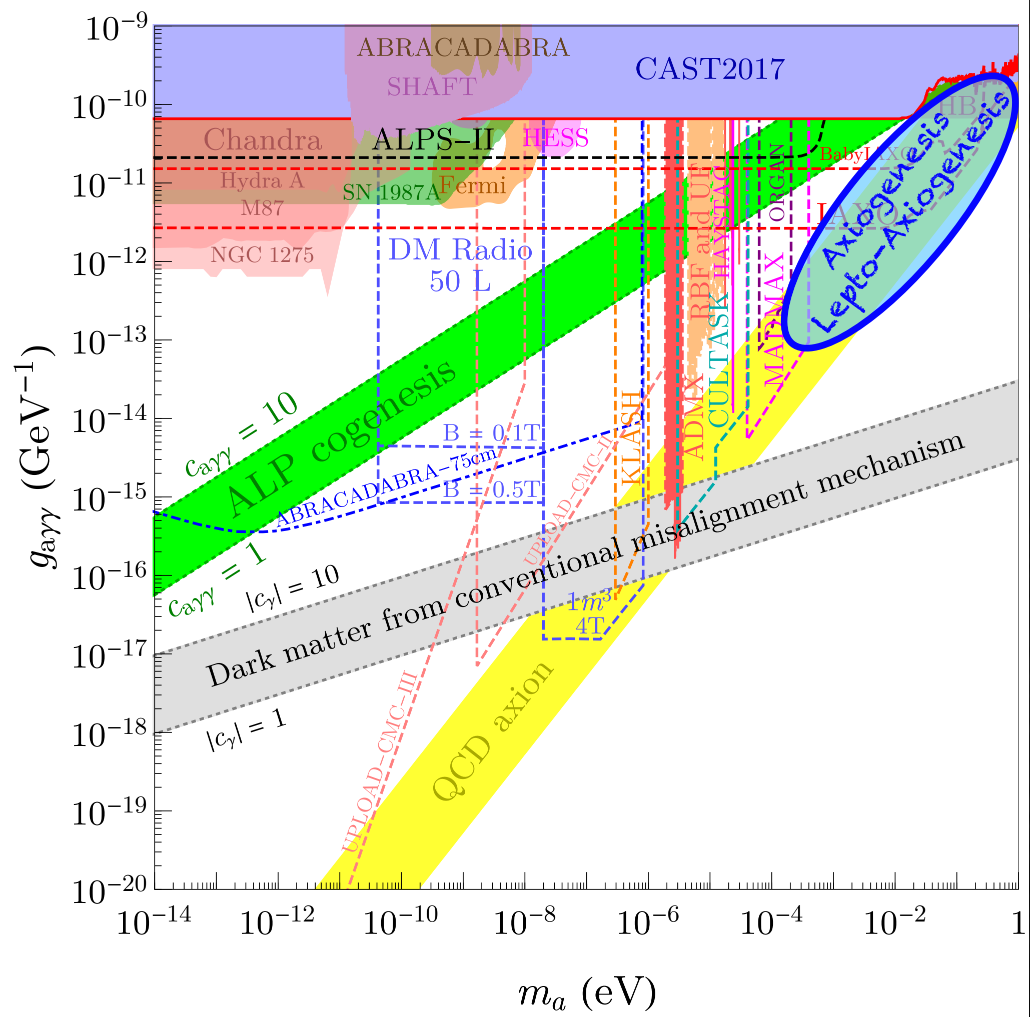
Axion Photon Coupling



Kinetic Misalignment Mechanism

↑

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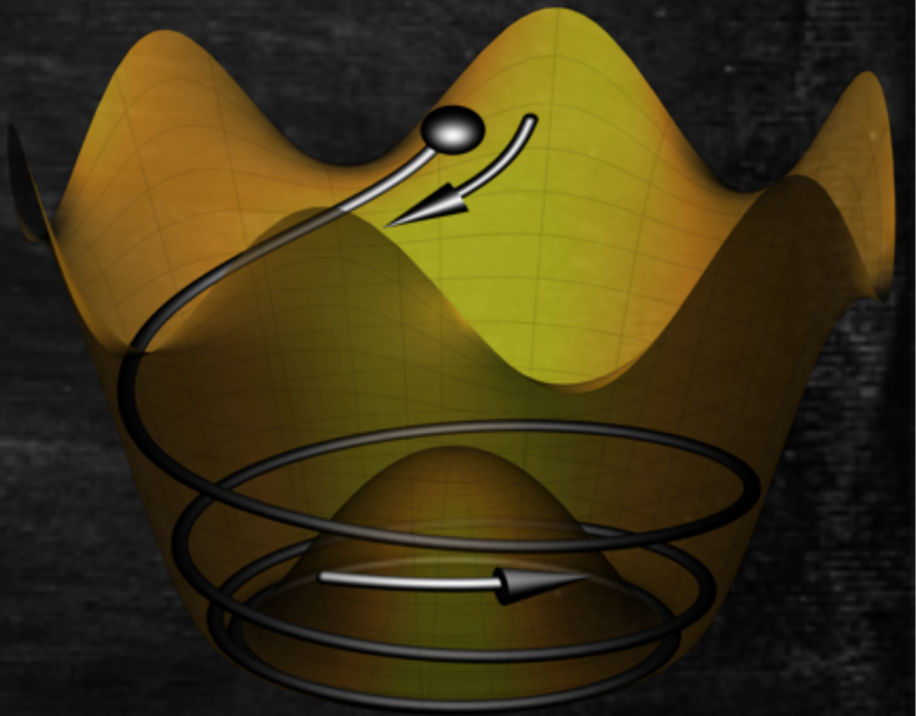
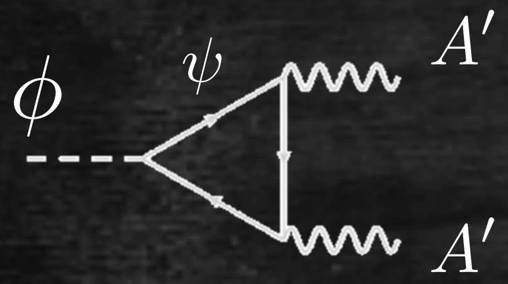
Storyline

- Axion and dark photon coupling
  - Gravitational waves
  - Dark photon dark matter



Tachyonic Instability



$$\mathcal{L}_{\text{dark}} = \frac{\alpha_D}{8\pi}\frac{\phi}{f_\phi}F'_{\mu\nu}\tilde{F}'^{\mu\nu}$$

$$F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$$
$$\tilde{F}'^{\mu\nu} = \epsilon^{\alpha\beta\mu\nu}F'_{\alpha\beta}/2$$

Tachyonic Instability

Carroll and Field 1991 + Garretson 1992, Ratra 1992
Felder, Garc´ıa-Bellido, Greene, Kofman, Linde, Tkachev 2001

$$\mathcal{L}_{\rm dark} = \frac{\alpha_D}{8\pi}\frac{\phi}{f_\phi} F'_{\mu\nu}\tilde{F}'^{\mu\nu}$$

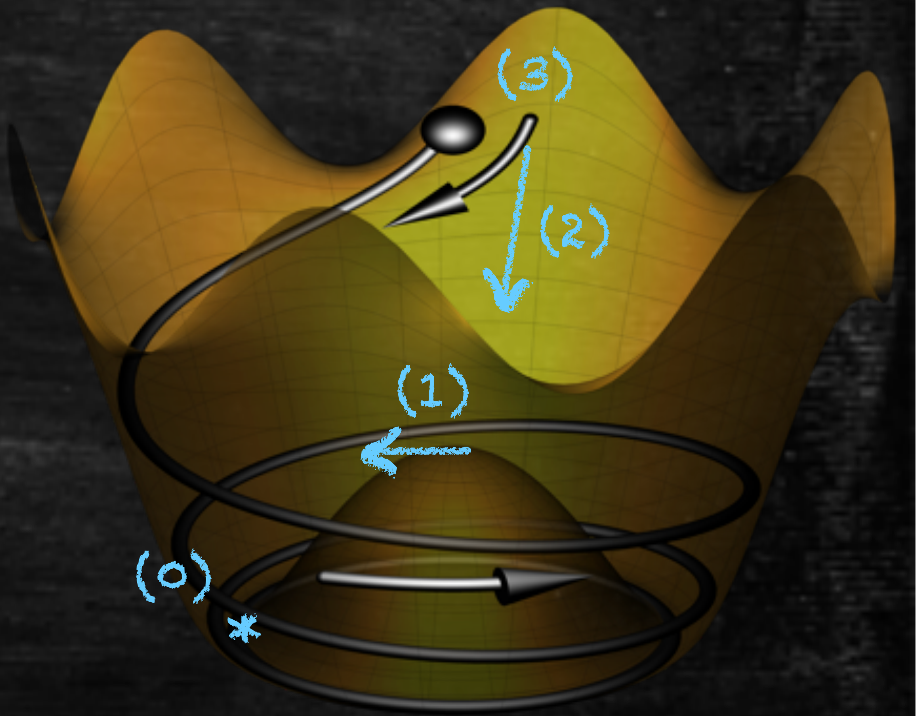
$$\frac{\partial^2 A'_\pm}{\partial t^2} + H\frac{\partial A'_\pm}{\partial t} + \left(m_{A'}^2 + \frac{k^2}{R^2} \pm \frac{e_D^2}{8\pi^2}\frac{k}{R}\dot{\theta} \right) A'_\pm = 0$$

Storyline

- ❑ Axion and dark photon coupling
  - ➢ Gravitational waves
  - ➢ Dark photon dark matter

Possible initial conditions

Peccei-Quinn symmetry



Gravitational Waves

$$ds^2 = R(\tau)^2 \left(d\tau^2 - (\delta_{ij} + h_{ij})\, dx^i dx^j\right)$$

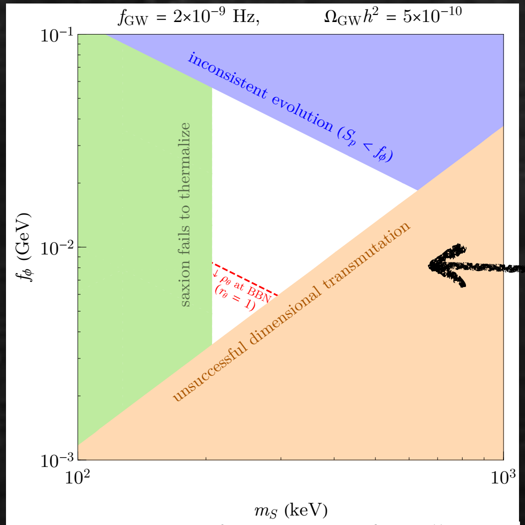
$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{R^2}\nabla^2 h_{ij} = \frac{2}{M_{\rm Pl}^2}\Pi_{ij}^{TT}$$

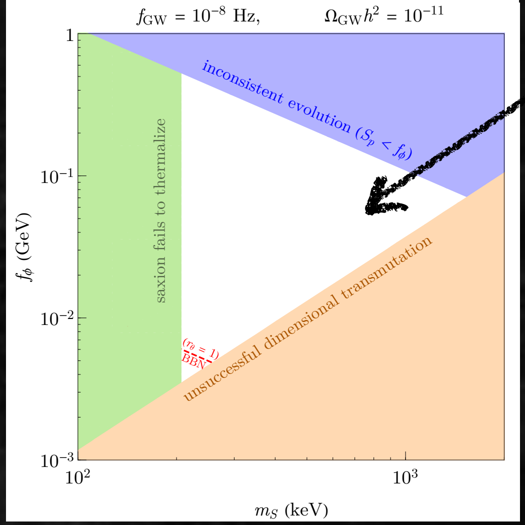
the transverse-traceless anisotropic stress tensor

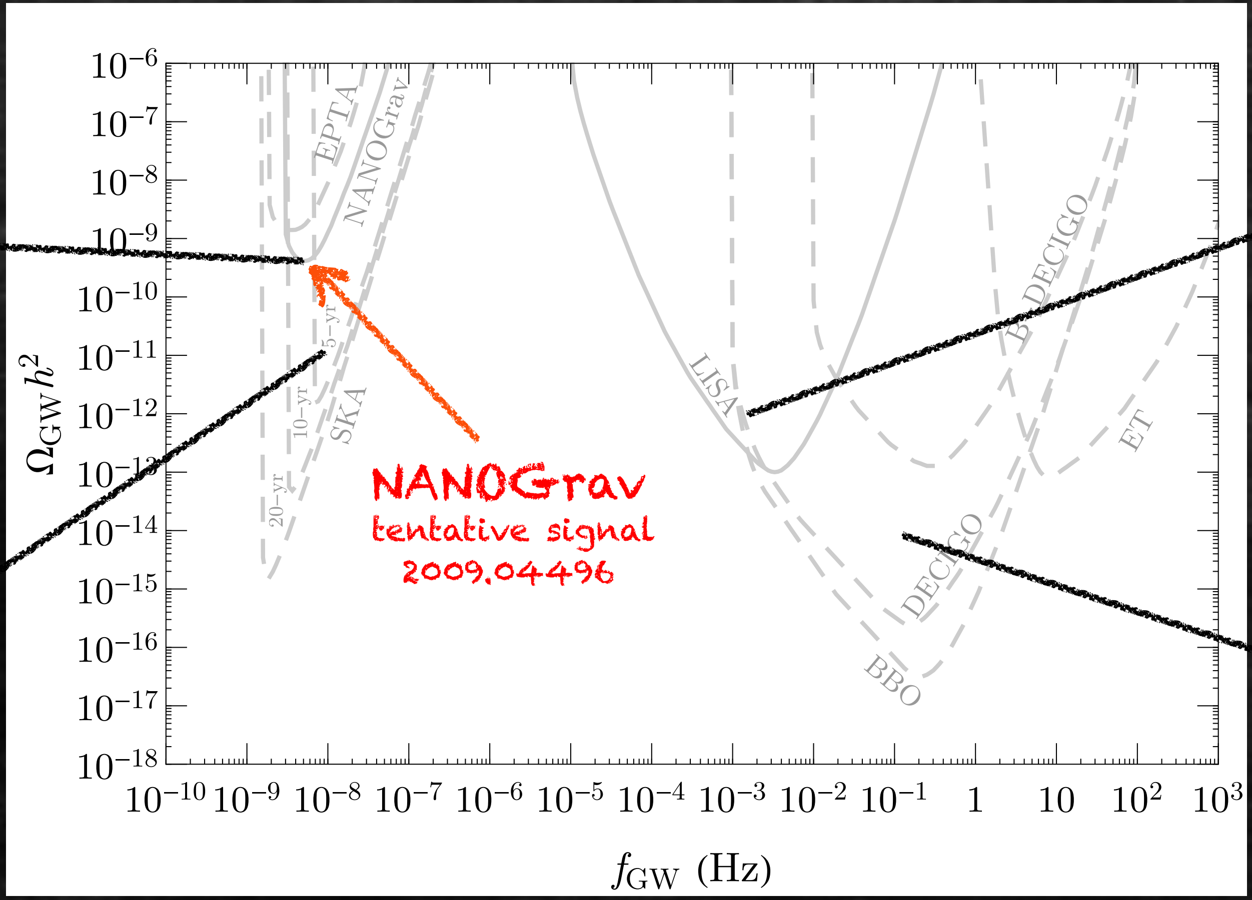
$$\frac{\rho_{\rm GW}}{\rho_R} = \frac{r_p^2 \rho_{A'}^2}{3k_{\rm TI}^4 M_{\rm Pl}^4}$$

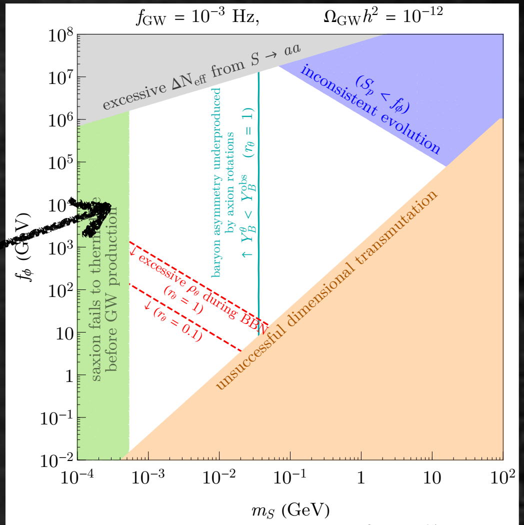
C. Machado, W. Ratzinger, P. Schwaller, and B. Stefanek arXiv:1811.01950

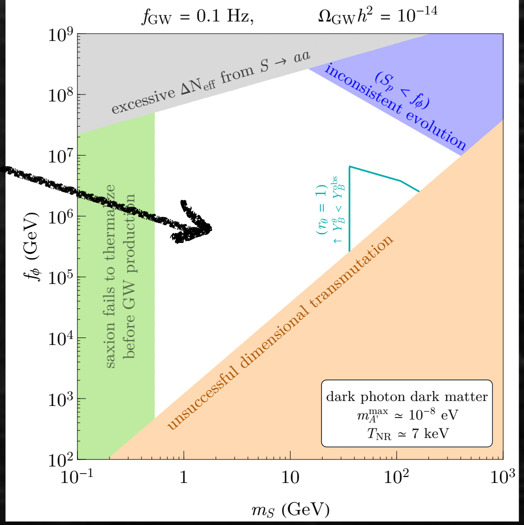
Gravitational Waves







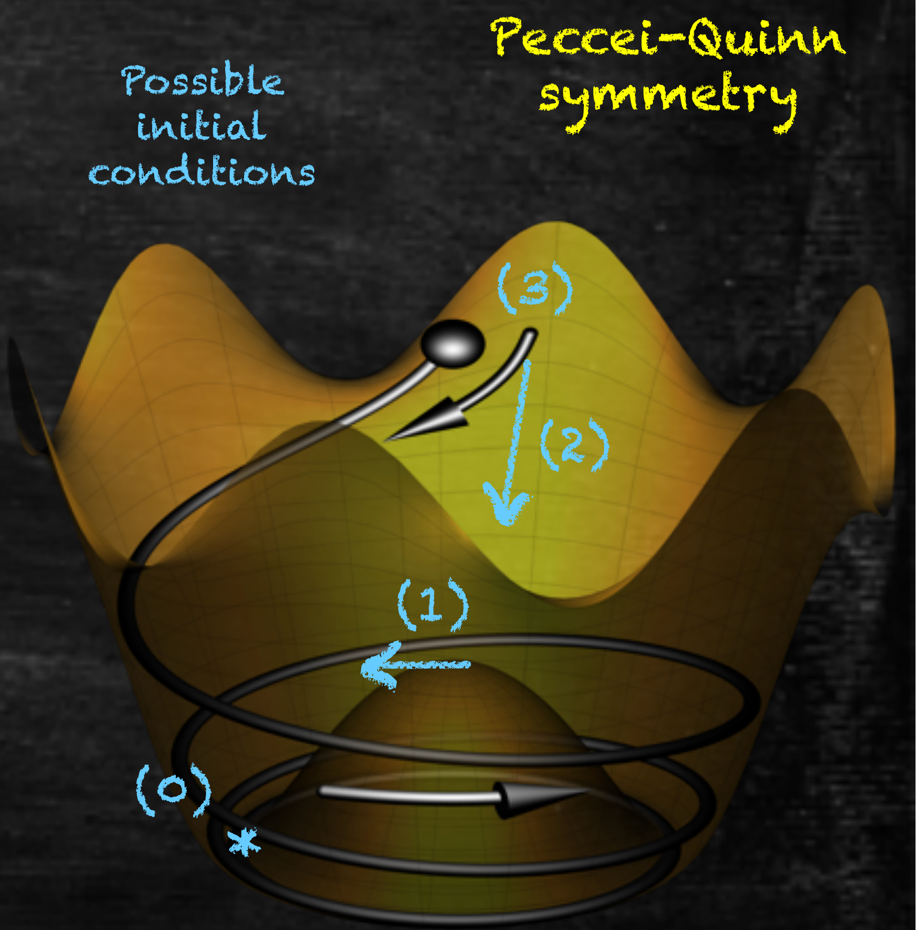




arXiv:2104.02077 RC, K. Harigaya, A. Pierce,

Storyline

- Axion and dark photon coupling
  - Gravitational waves
  - Dark photon dark matter



Dark Photon Dark Matter

Correlation between GWs and dark photons

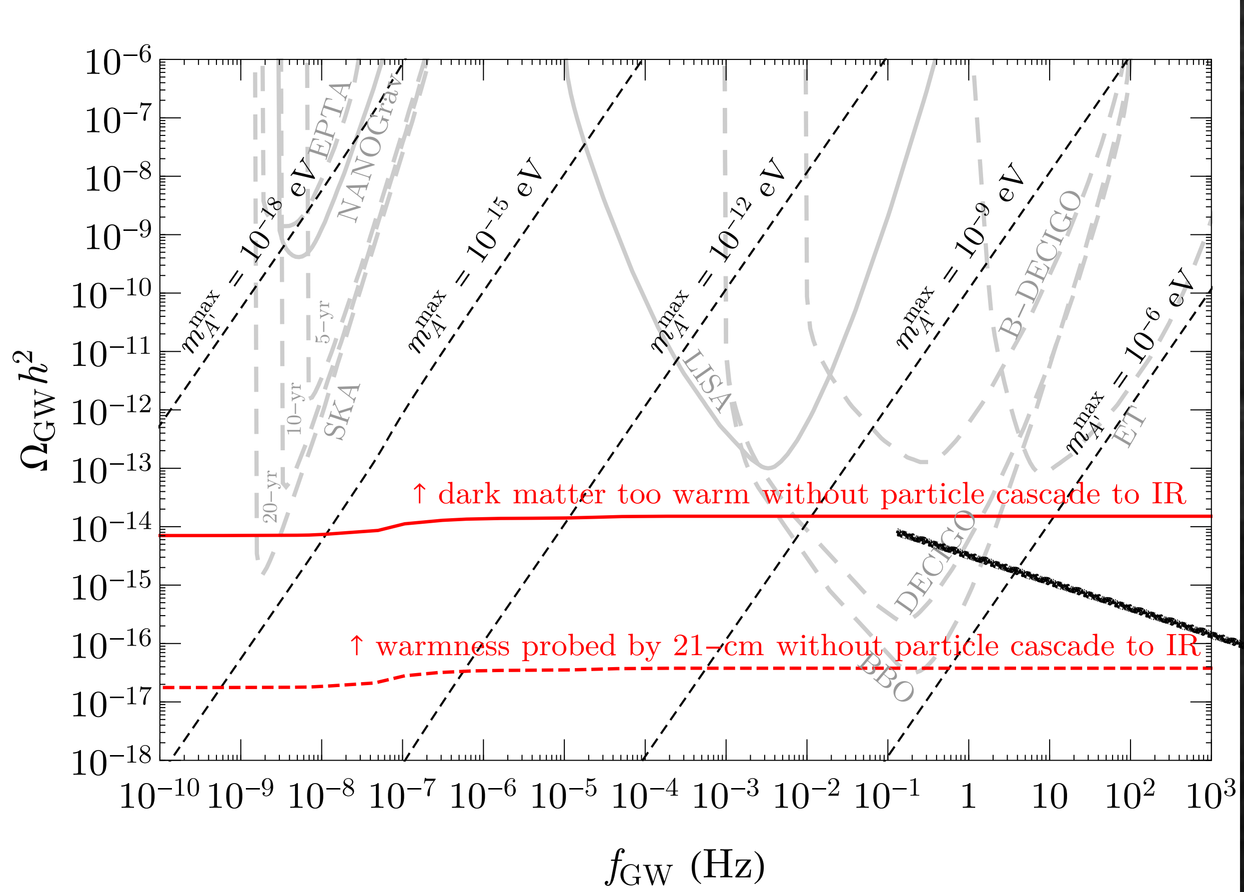
Abundance

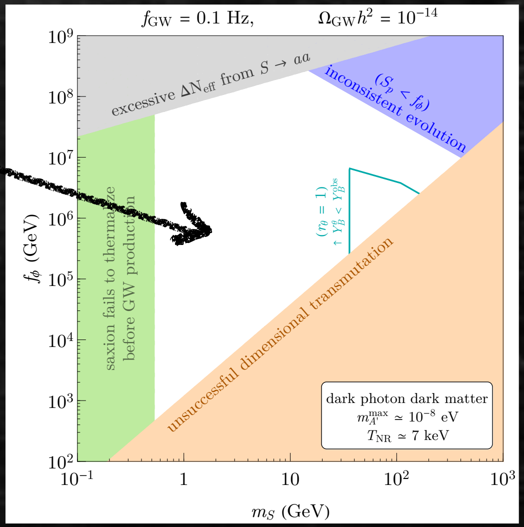
$$\frac{\rho_{\rm GW}}{\rho_R} = \frac{r_p^2 \rho_{A'}^2}{3k_{\rm TI}^4 M_{\rm Pl}^4}$$

Warmness

$$H_p = \frac{k_{\rm TI}}{r_p}$$

$k_{\rm TI}$ → $f_{\rm GW}$, $k_{A'}$

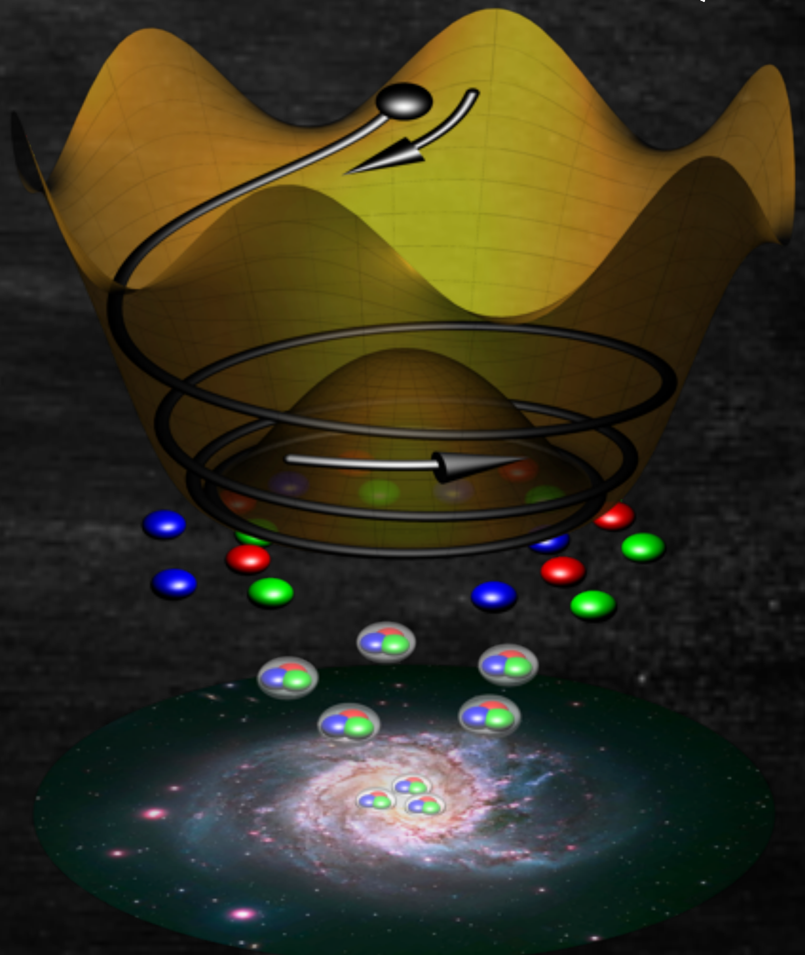




arXiv:2104.02077 RC, K. Harigaya, A. Pierce,

Conclusions

- ✓ New axion dynamics allows the QCD axion to simultaneously explain
  - ✓ the Strong CP problem
  - ✓ the dark matter abundance
  - ✓ the baryon asymmetry



- ✓ Possible signatures:
  - ✓ (QCD) axion searches
  - ✓ Saxion-Higgs mixing
  - ✓ Warm axion dark matter
  - ✓ Gravitational waves
- ✓ New model building opportunities