

New Roles of the Axion in Dark Matter, Baryogenesis, and Gravitational Waves

Raymond Co



William I. Fine Theoretical Physics Institute
University of Minnesota



Cambridge High Energy Workshop - Axion Physics July 30th 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: 2004.00629 Lawrence Hall, Keisuke Harigaya, Keith A. Olive, and Sarunas Verner

JCAP 08 (2020) 036

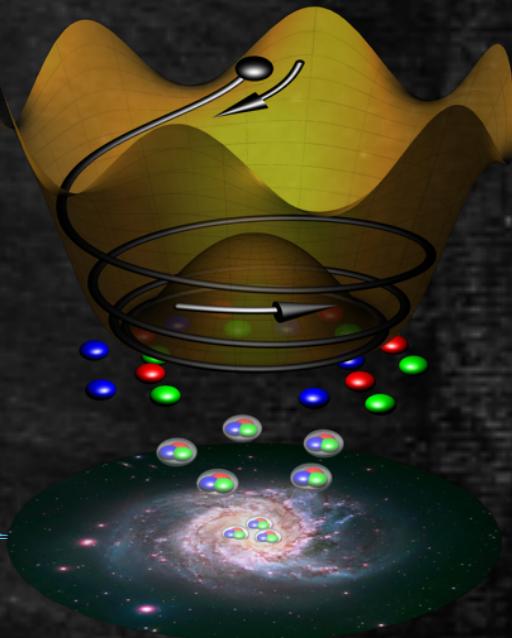
arXiv: 2006.04809 Lawrence Hall, Keisuke Harigaya

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





Today

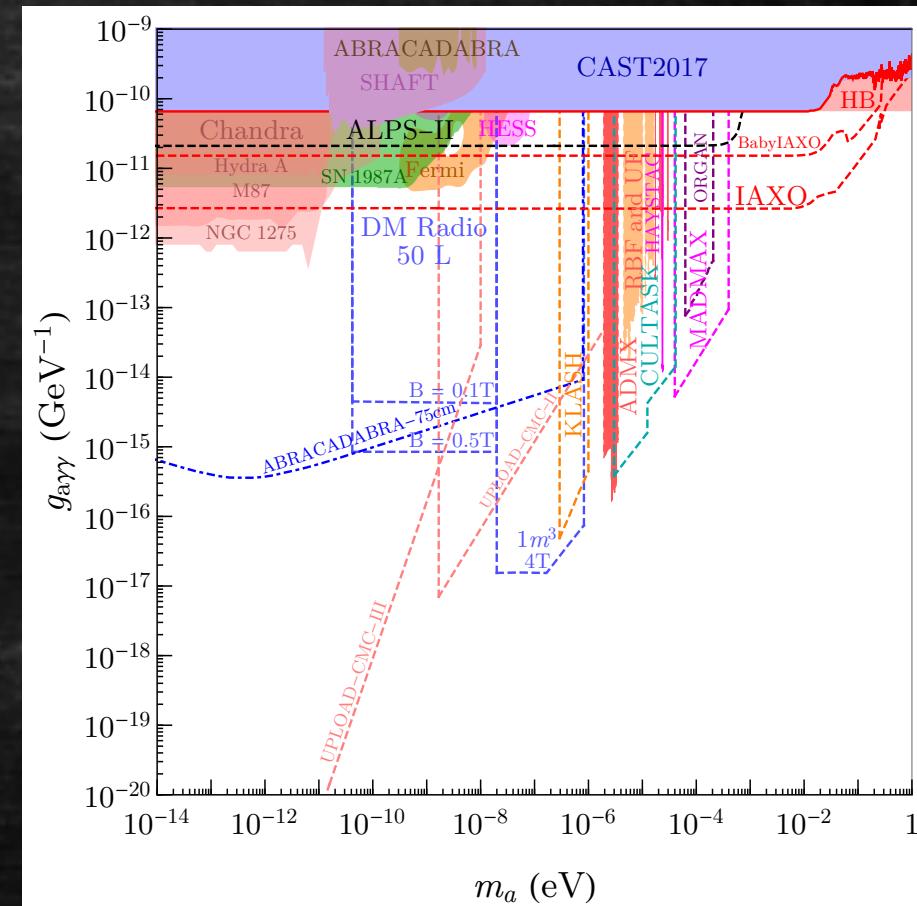
known for the invention of the gravimeter

Felix Andries Vening Meinesz

born on
July 30rd 1887

Axion Parameter Space

Where to look for axions?



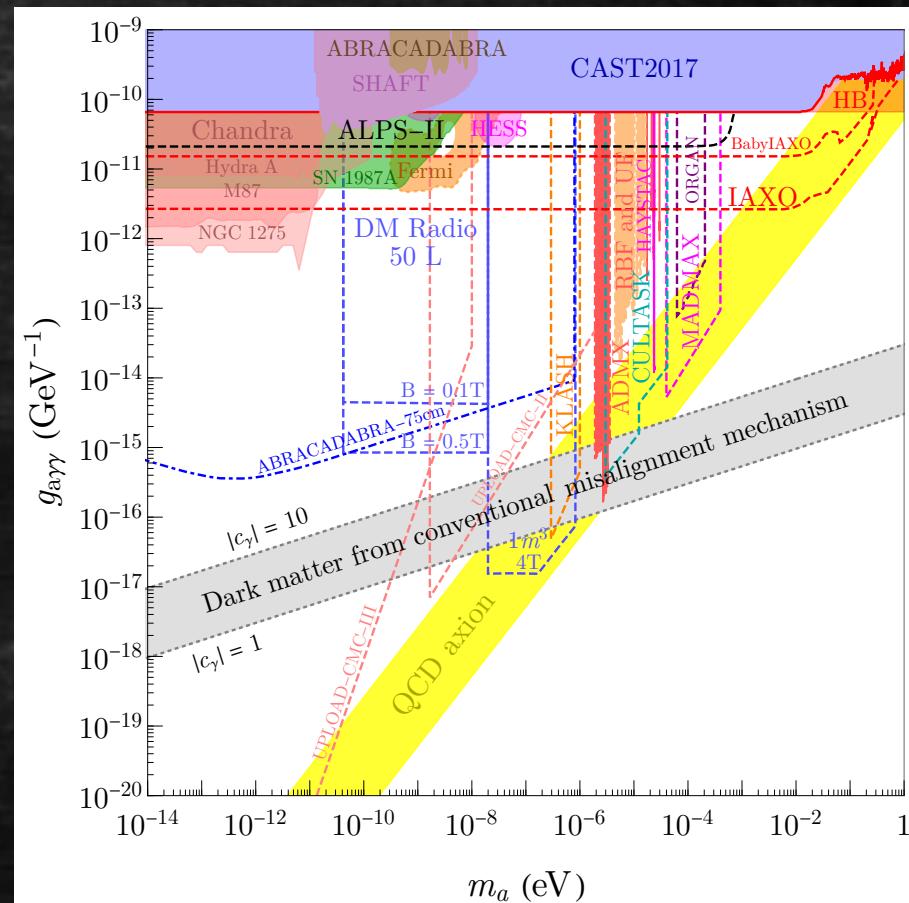
Axion Parameter Space

Where to look for axions?

- Axion: QCD axion and axion-like-particle (ALP)
- Solve the strong CP problem
- Explain dark matter from the misalignment mechanism

 Peccei, Quinn 1977, Weinberg 1978, Wilczek 1978

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



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 + K. Olive, S. Verner 2020

- Axiogenesis

RC, K. Harigaya 2019

- ALP coogenesis

RC, L. Hall, K. Harigaya 2020

- Lepto-Axiogenesis

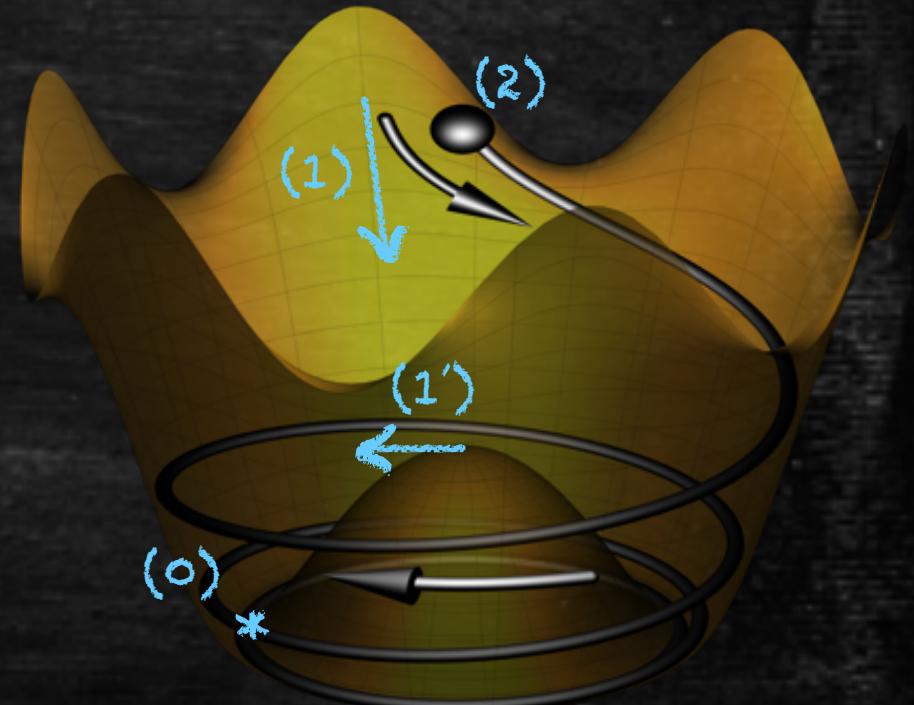
RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya 2020

- Tachyonic instability

RC, K. Harigaya, A. Pierce 2020



Possible initial conditions
Peccei-Quinn symmetry



StoryLine

■ Axion

(o) Misalignment mechanism

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

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K. Harigaya, J. Leedom 2019

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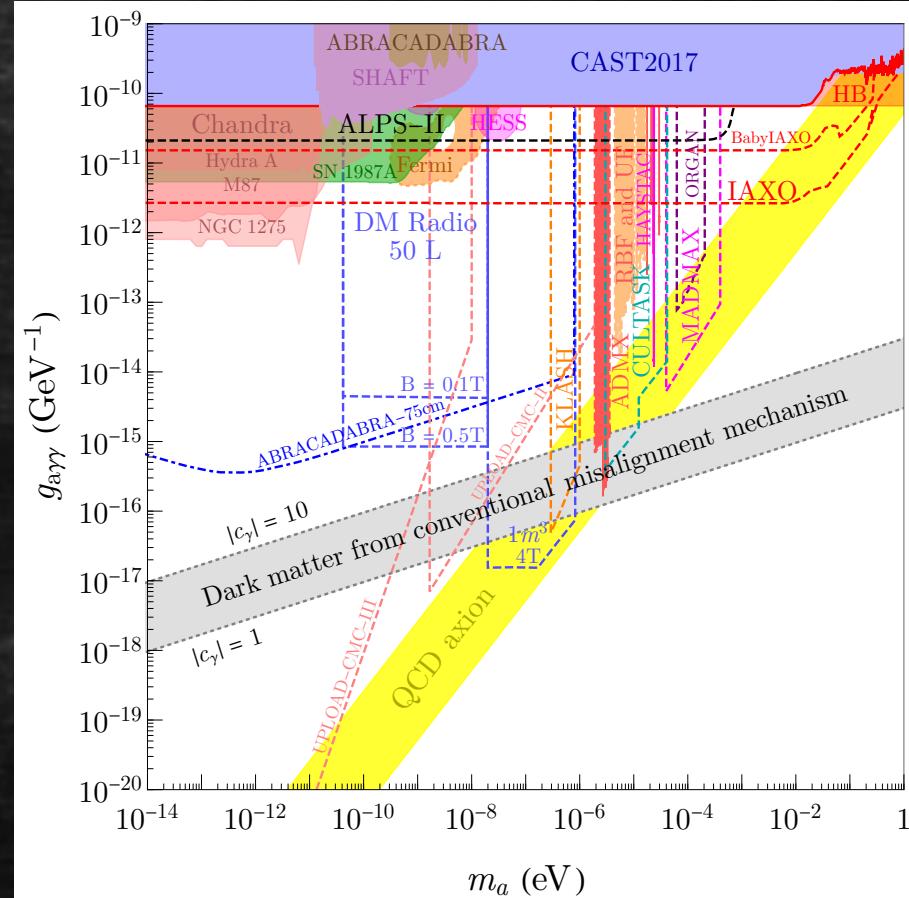
RC, L. Hall, K. Harigaya 2020

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

- Tachyonic instability

RC, K. Harigaya, A. Pierce 2020



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

Storyline

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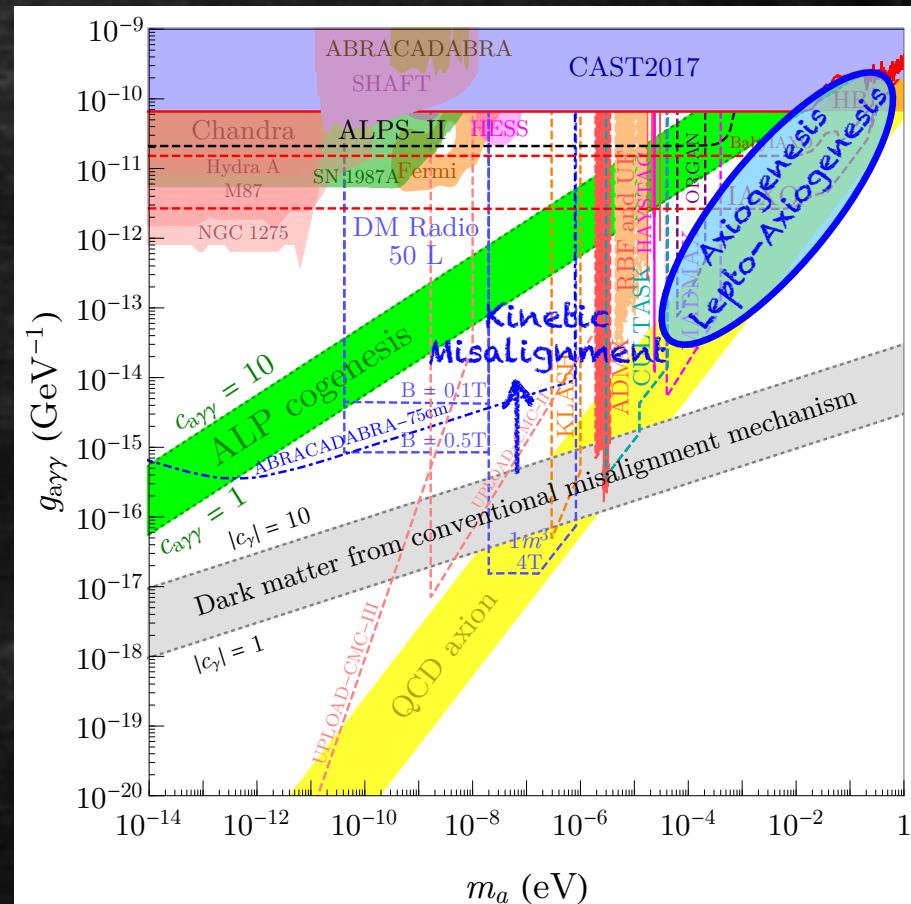
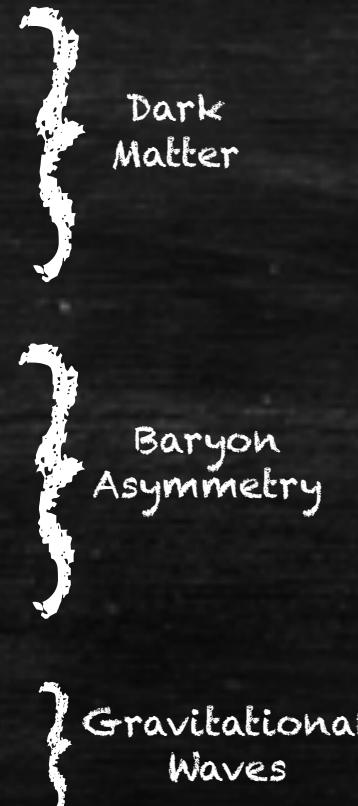
RC, L. Hall, K. Harigaya 2020

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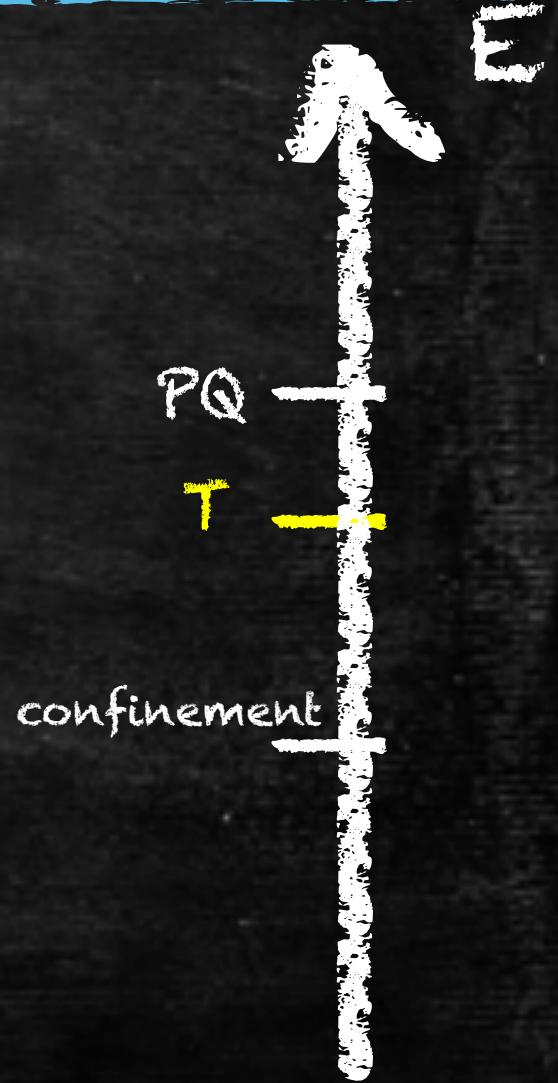
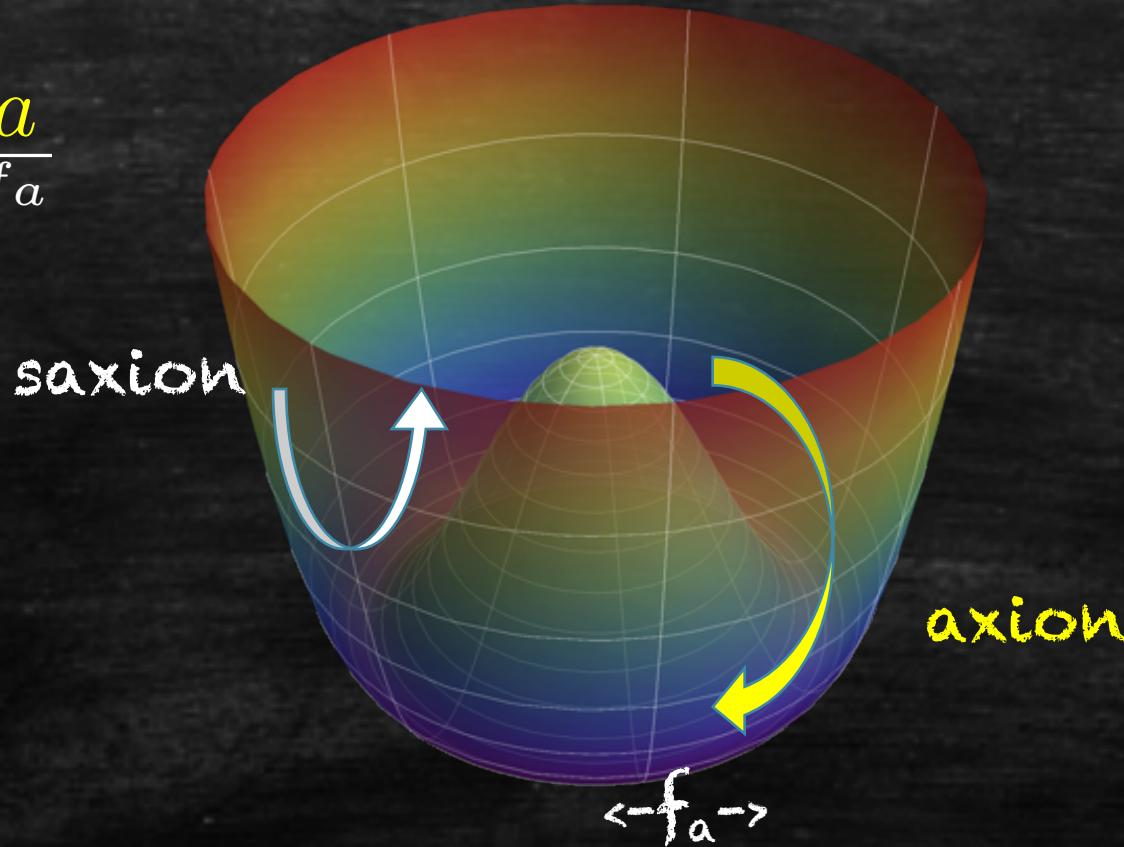
RC, K. Harigaya, A. Pierce 2020



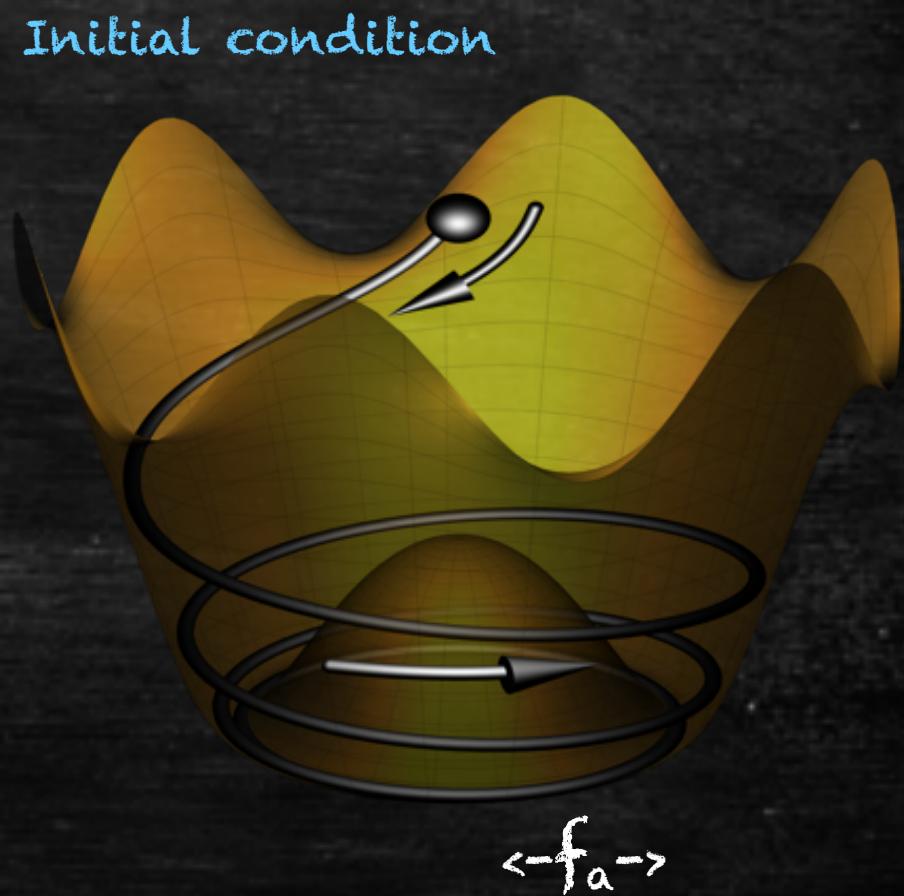
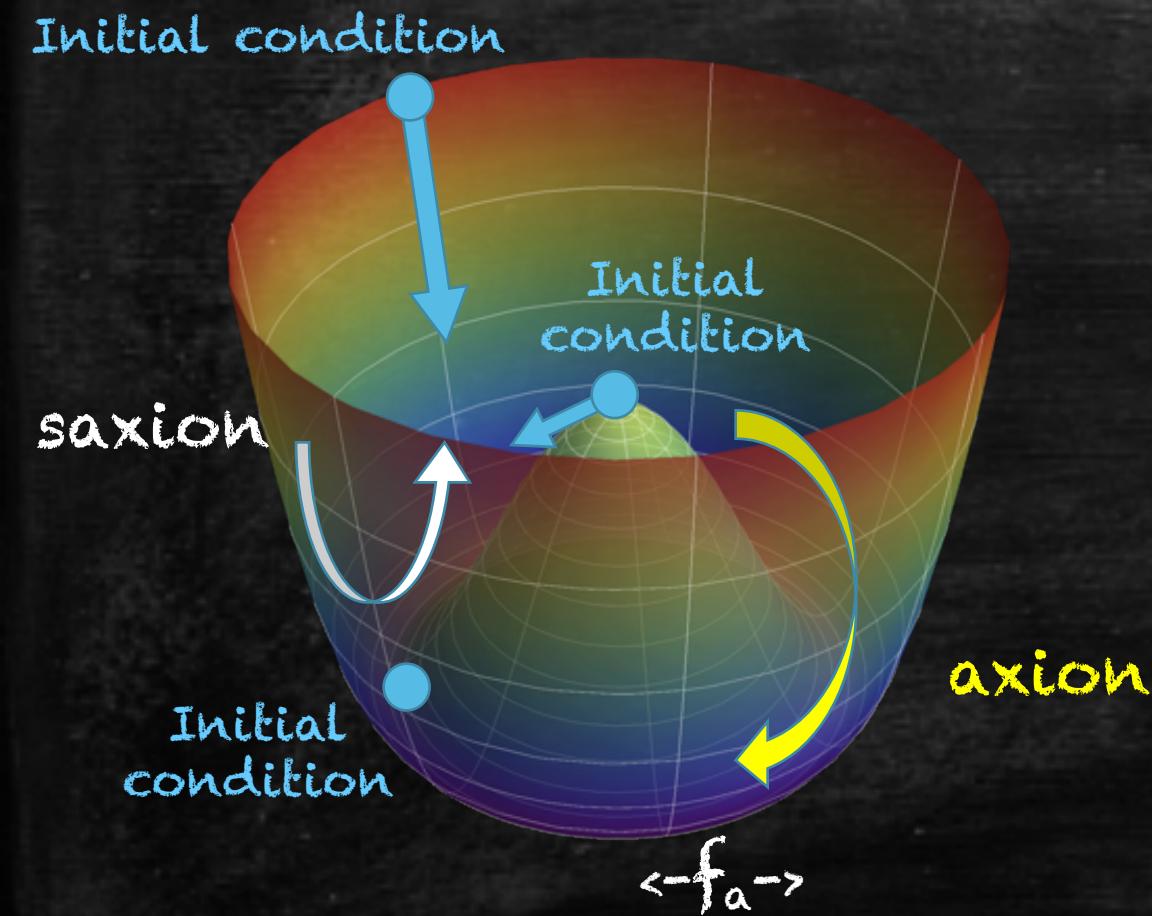
See later slides for axion-electron and axion-nucleon couplings

Axions

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



Rotation



Why Rotation?

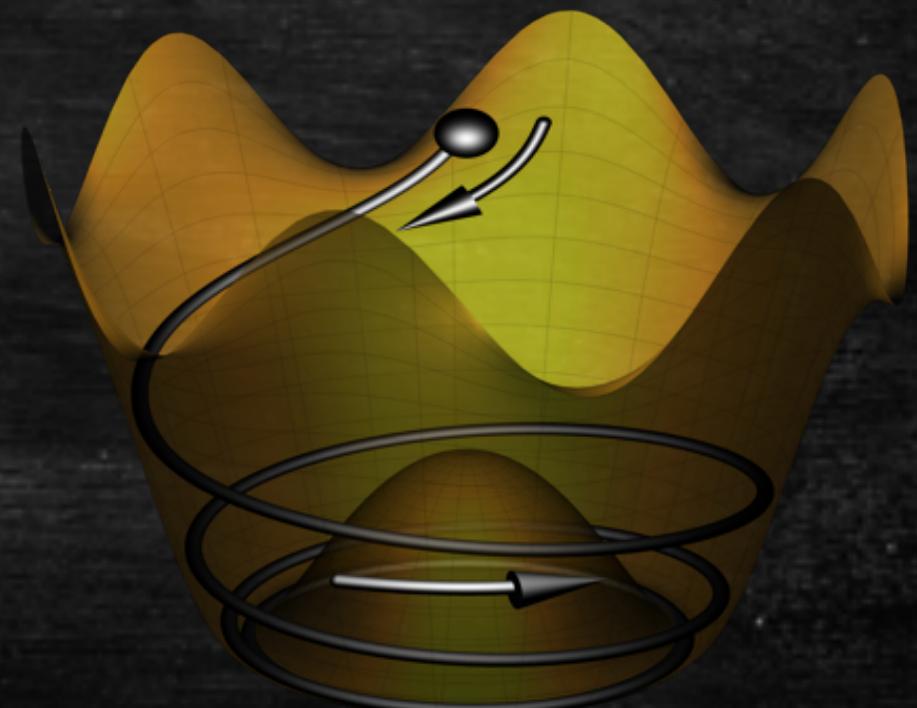
Large field value : Flat potential

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

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



Why Rotation?

Large field value : Flat potential

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

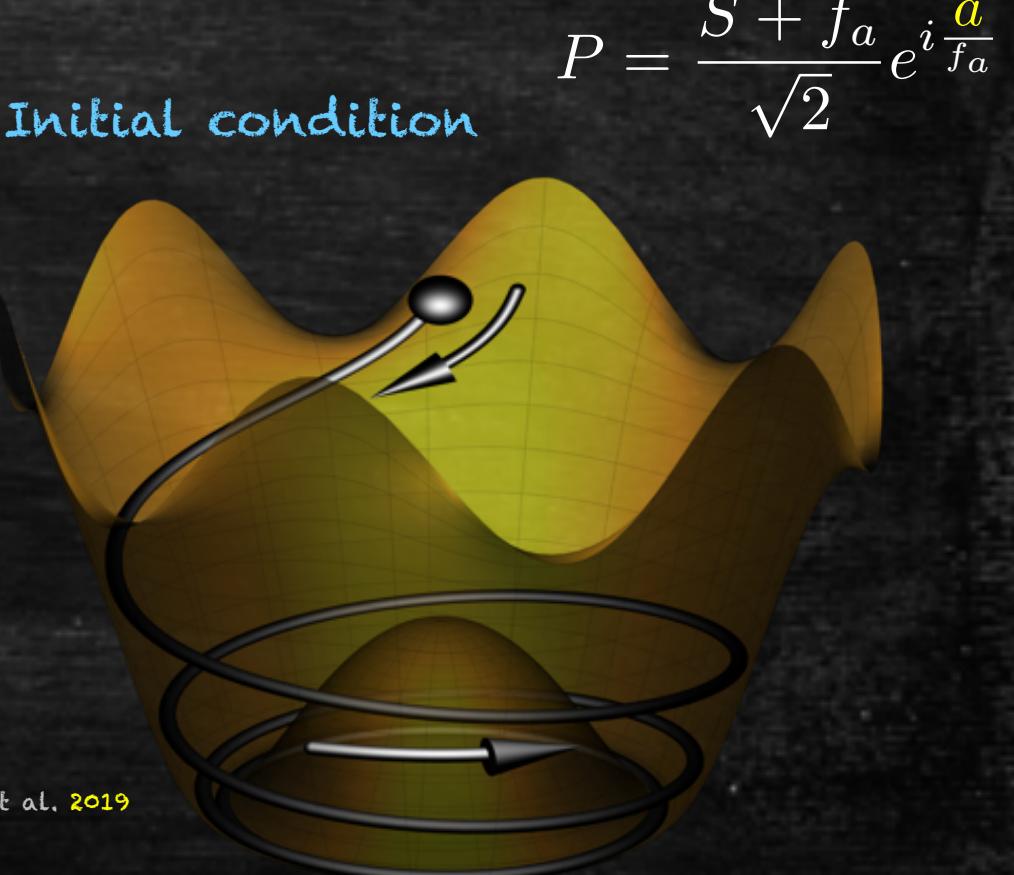
$$V(|P|) \sim -H_I^2 |P|^2 + \frac{|P|^{2d}}{M^{2d-4}}$$

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

Noether charge associated with the shift symmetry

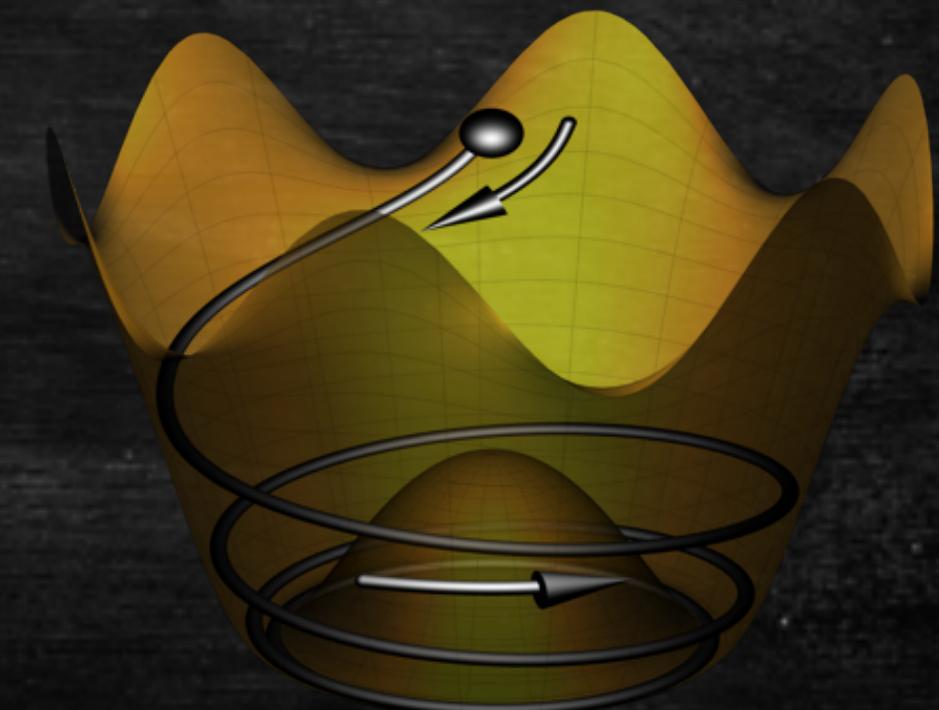
$$P = \frac{S + f_a}{\sqrt{2}} e^{i \frac{a}{f_a}}$$

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

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

PQ asymmetry
PQ charge density = Rotation of PQ field

PQ charge is conserved soon after the onset.



Why a large angular speed?

Reason:

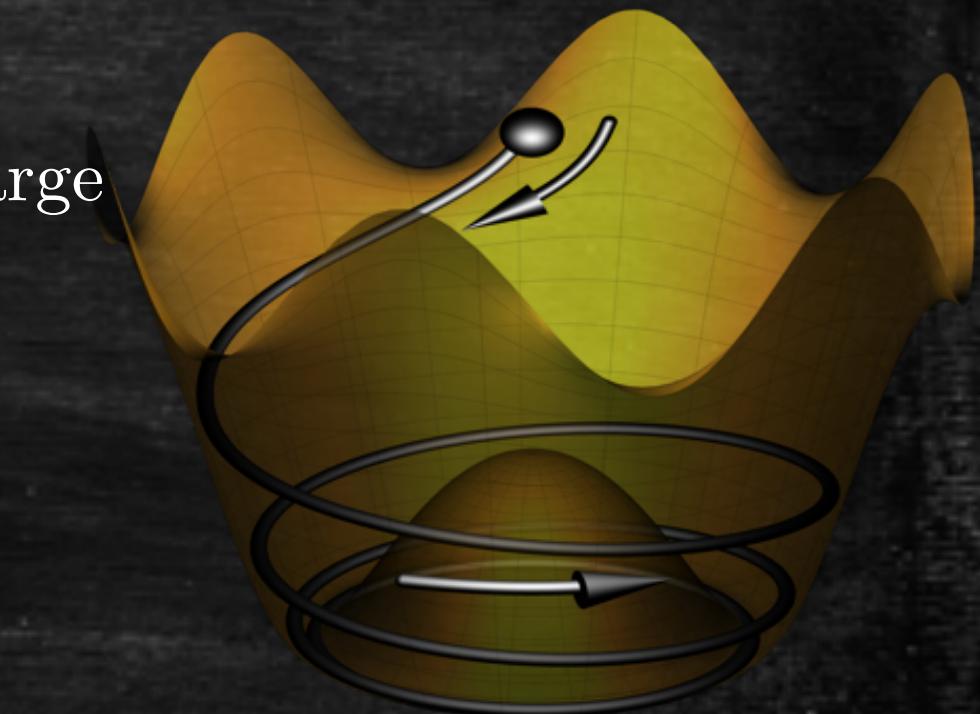
$$n_{PQ} = S^2 \dot{\theta} \quad n_{PQ} R^3 = \text{conserved charge}$$

Conventional:

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

Our scenario ($S \gg f_a$):

$$\left\{ \begin{array}{ll} \text{quartic} & S^2 \propto R^{-2} \quad \dot{\theta} \propto R^{-1} \\ \text{quadratic} & S^2 \propto R^{-3} \quad \dot{\theta} = \text{constant} \end{array} \right\} \text{Slower redshift!}$$



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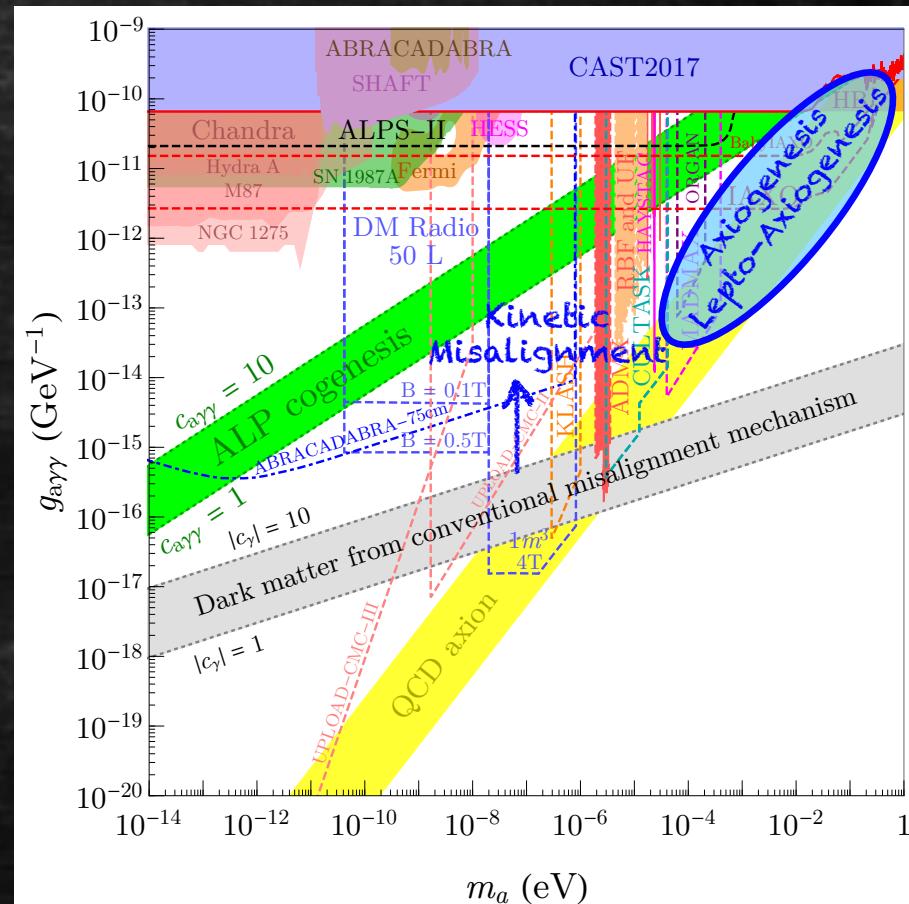
RC, L. Hall, K. Harigaya 2020

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RC, K. Harigaya, A. Pierce 2020

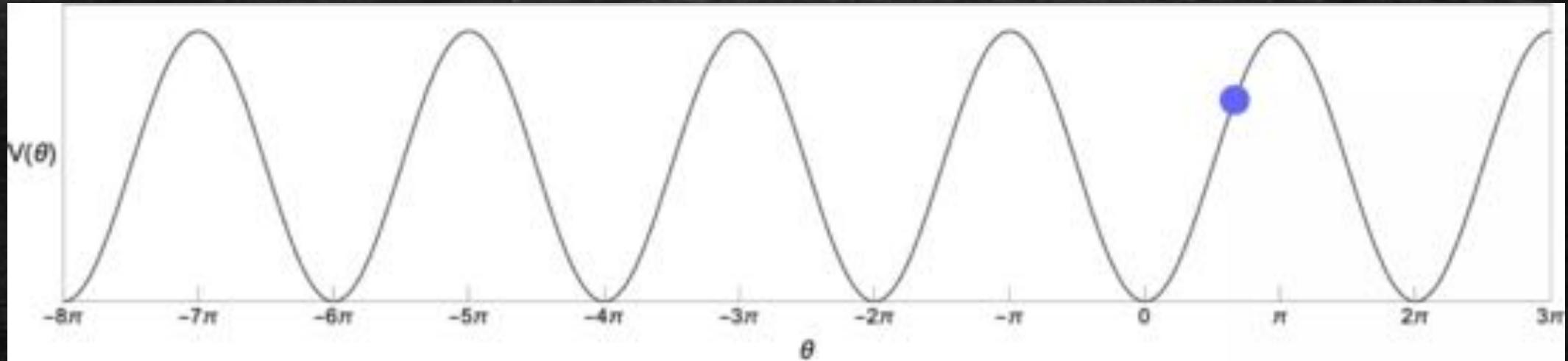


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Kinetic Misalignment Mechanism

(Misalignment + non-zero kinetic energy)

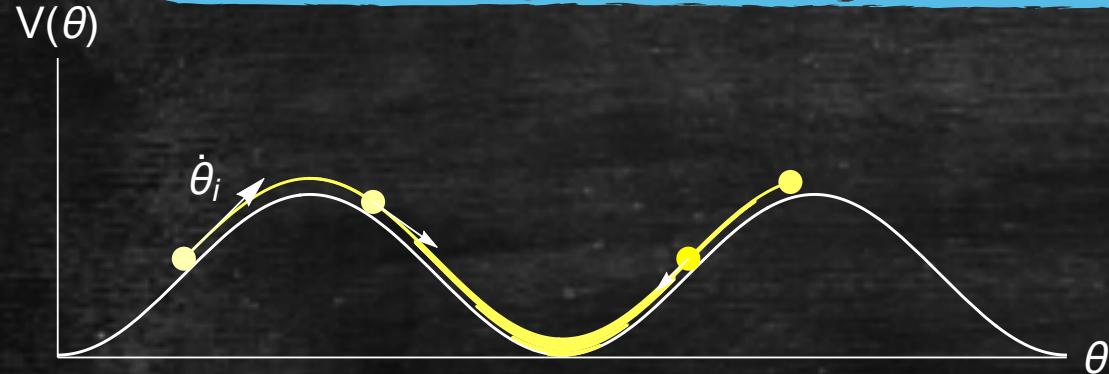


Kinetic Misalignment Mechanism

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

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

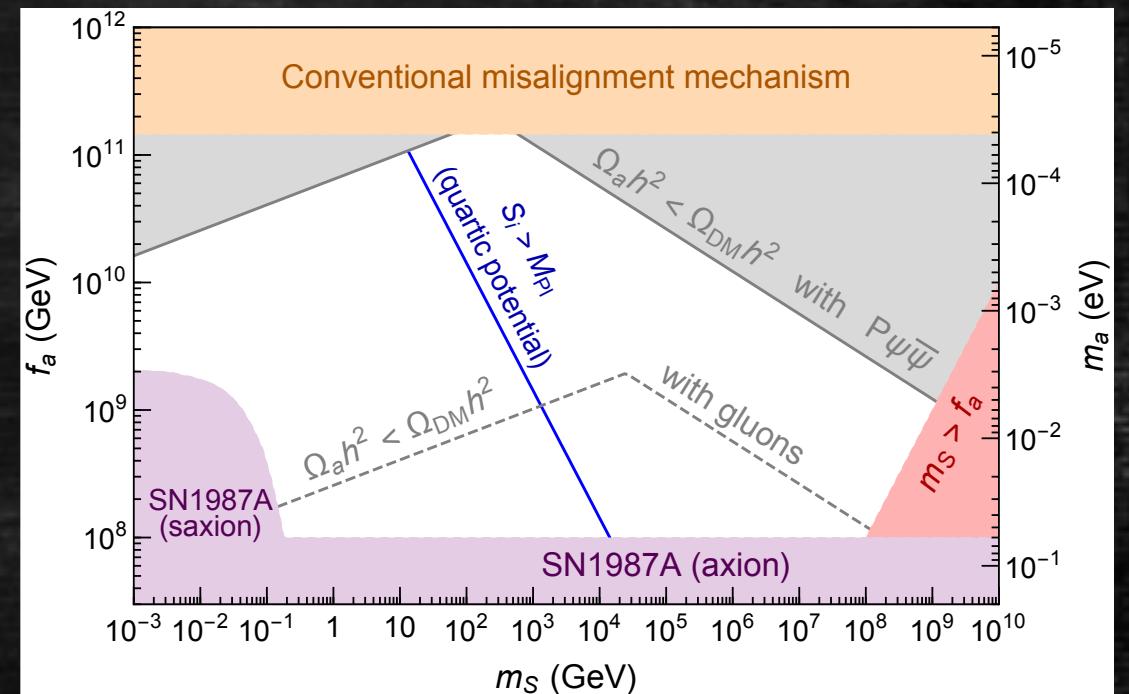
Kinetic Misalignment Mechanism



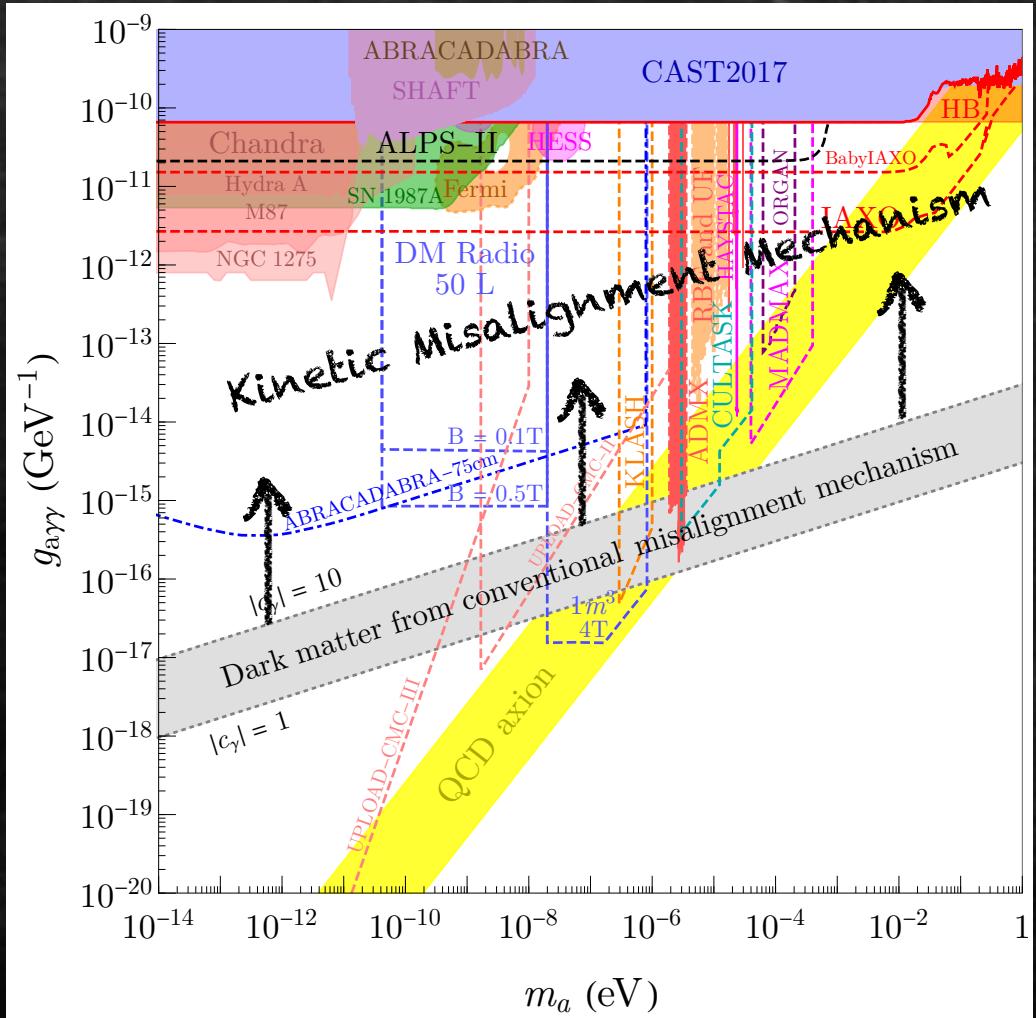
Abundance:

$$\frac{\rho_a}{S} \simeq 2m_a(0)Y_{\text{PQ}}$$

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



Kinetic Misalignment Mechanism



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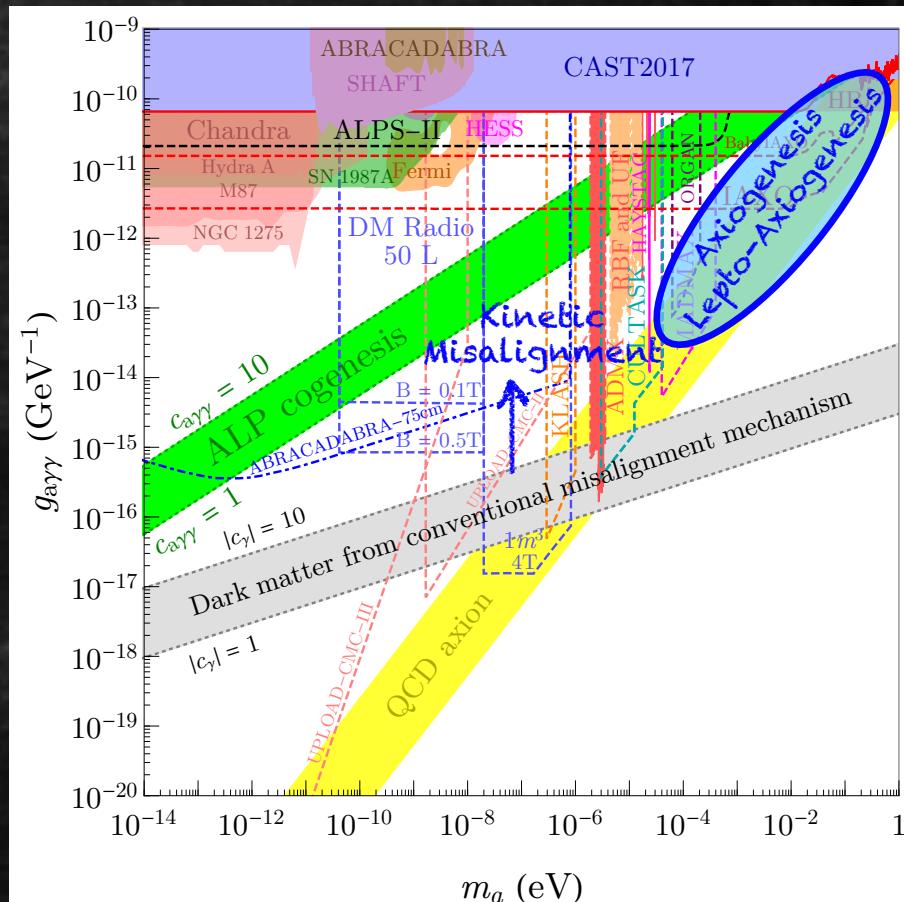
- Tachyonic instability

RC, K. Harigaya, A. Pierce 2020

Dark Matter

Baryon Asymmetry

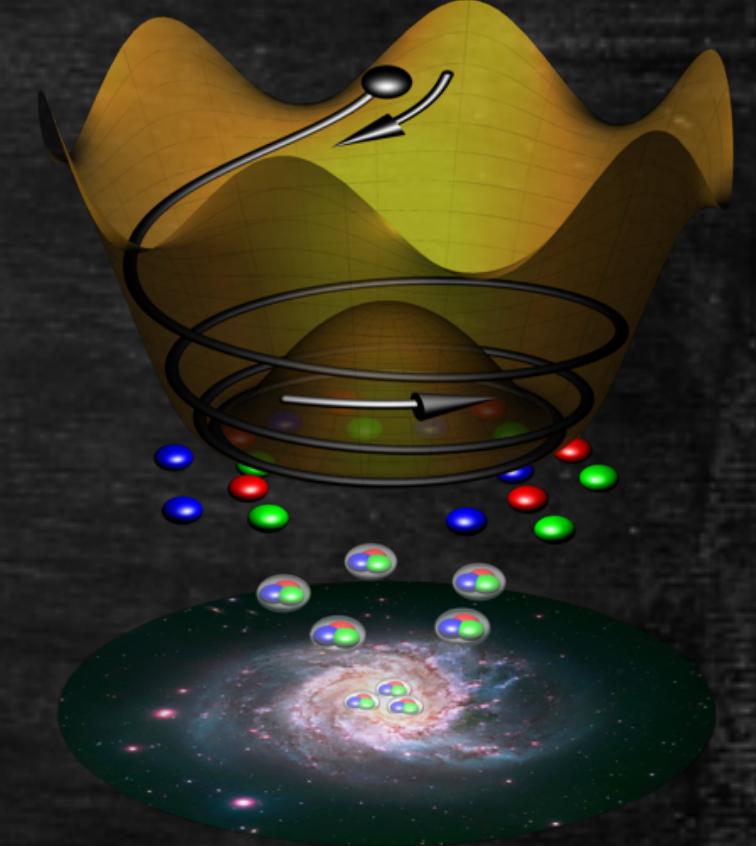
Gravitational Waves



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Axiogenesis

(QCD axion + baryogenesis)

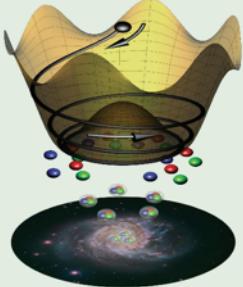


Particles called axions could reveal how matter conquered the universe

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

PHYSICAL
REVIEW
LETTERS

Articles published week ending 20 MARCH 2020



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

PHYSICAL REVIEW LETTERS

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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)

Issue 11 Table of Contents | More Covers

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)

R. Co Minnesota

Physics

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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.

Quanta magazine

Physics Mathematics Biology Computer Science All Article

IAS

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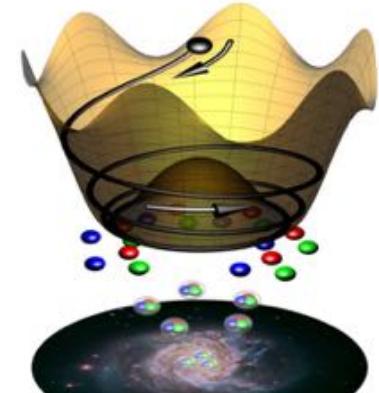
Paper Sheds Light on Infant Universe and Origin of Matter

New Study from Researchers at IAS and University of Michigan

March 19, 2020

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

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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.

EurekAlert! AAAS

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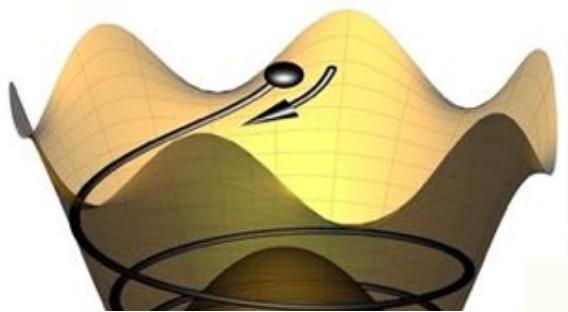
NEWS RELEASE 16-MAR-2020

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

The axion solves three mysteries of the universe



March 10, 2020

研究：假设粒子“轴子”可能帮助解开宇宙三大谜团

2020年03月11日 15:40 937 次阅读 资源: 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。

cnBeta



Gigazine

サイエンス

2020年03月16日 07時00分

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「アキシオン」とは？

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

Главные темы / Космос / Вы тут

Загадки СМ

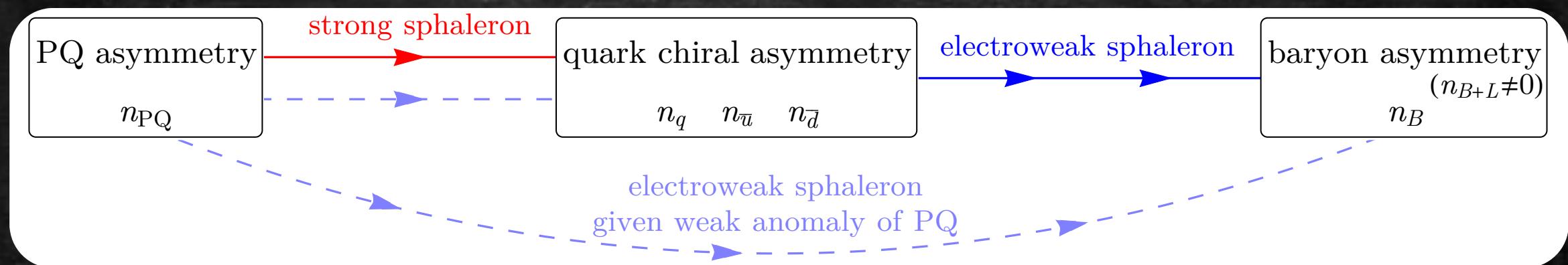
11 марта 2020 15:21

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

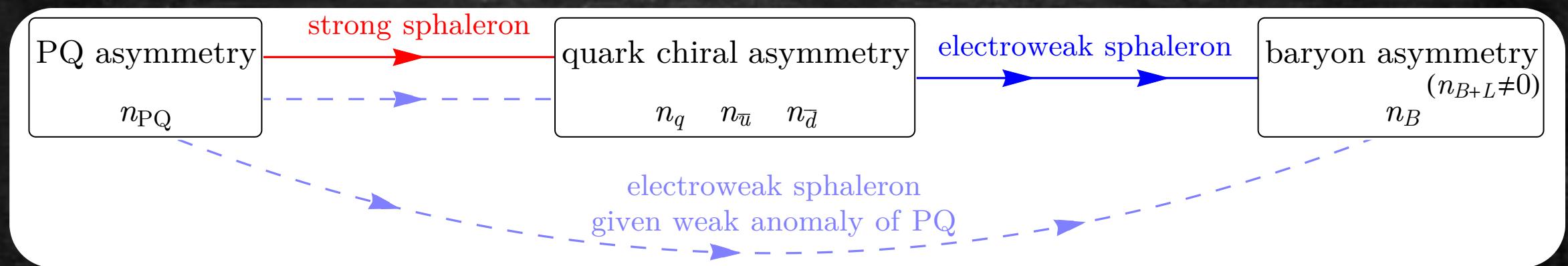
#Космос , #Наука



Axiogenesis



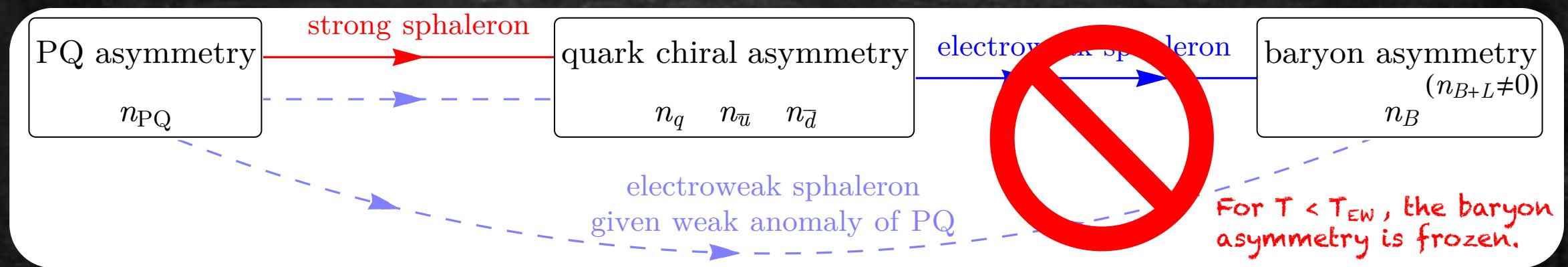
Axiogenesis



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

$$c_B \simeq 0.1 - 0.15 c_W$$

Axiogenesis



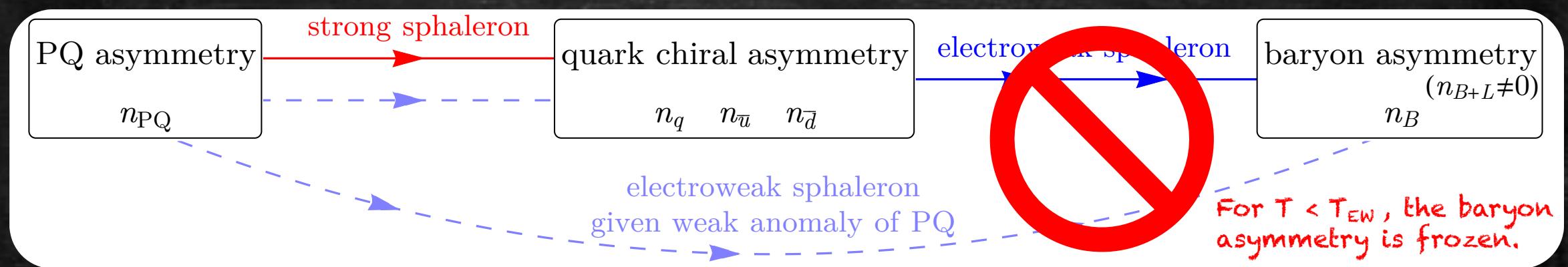
$$n_B = c_B \dot{\theta} T^2$$

$$c_B \simeq 0.1 - 0.15 c_W$$

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

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

Axiogenesis



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

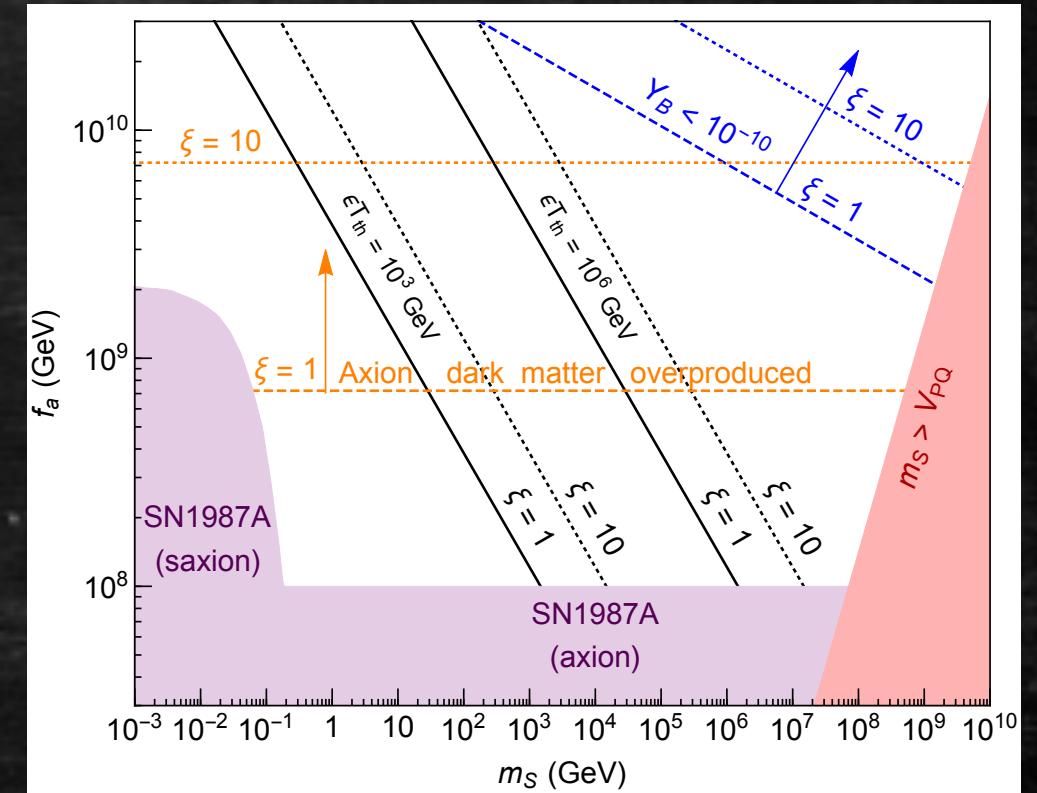
Baryon asymmetry fixes rotational speed, equivalently Y_{PQ} .

Axiogenesis + Kinetic Misalignment

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

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

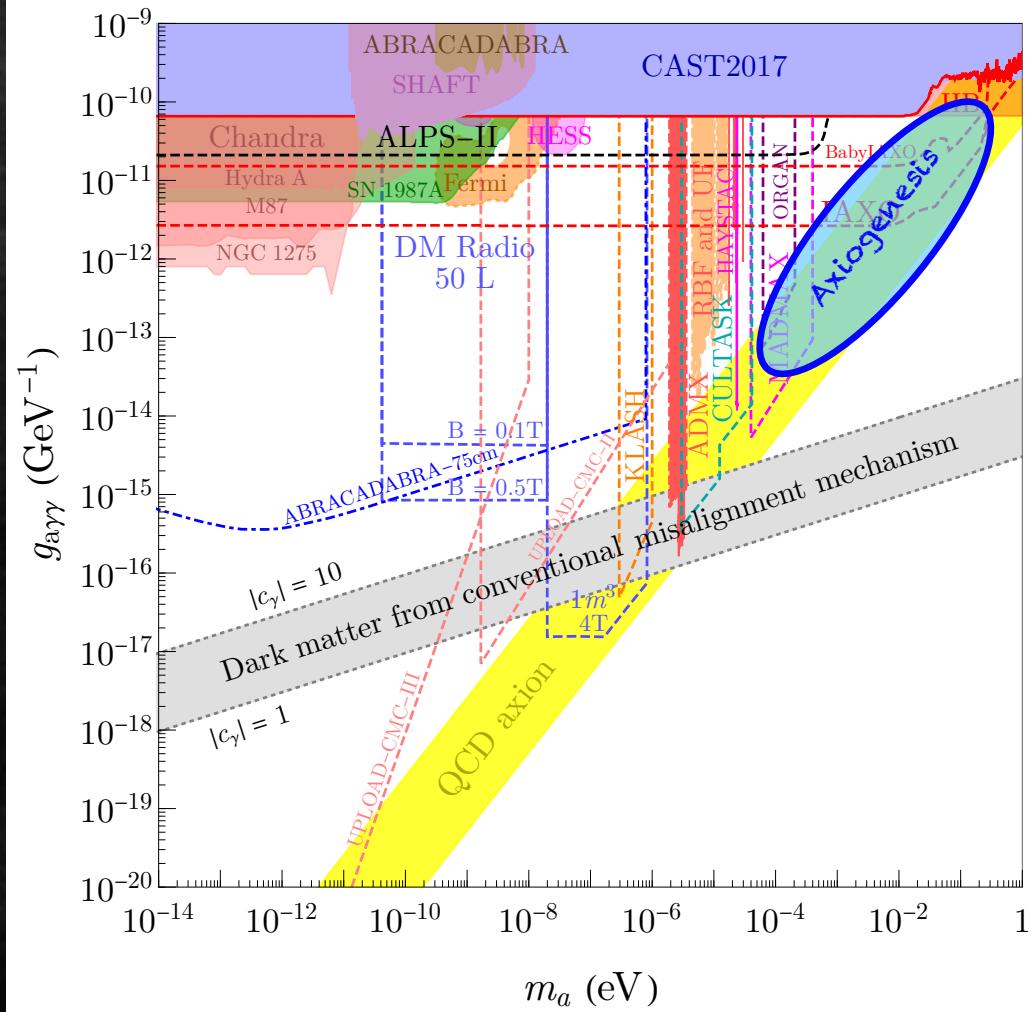
Electroweak physics \longleftrightarrow Axion physics !



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

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

Axion Photon Coupling



Storyline

Axion

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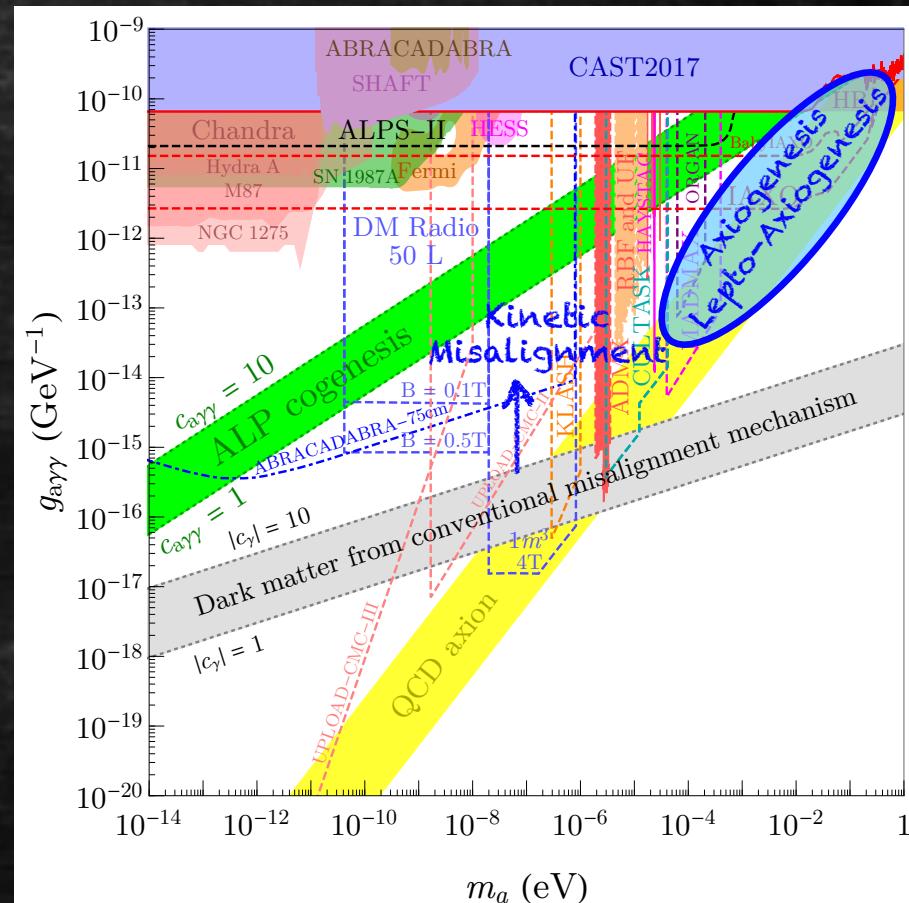
- Tachyonic instability

RC, K. Harigaya, A. Pierce 2020



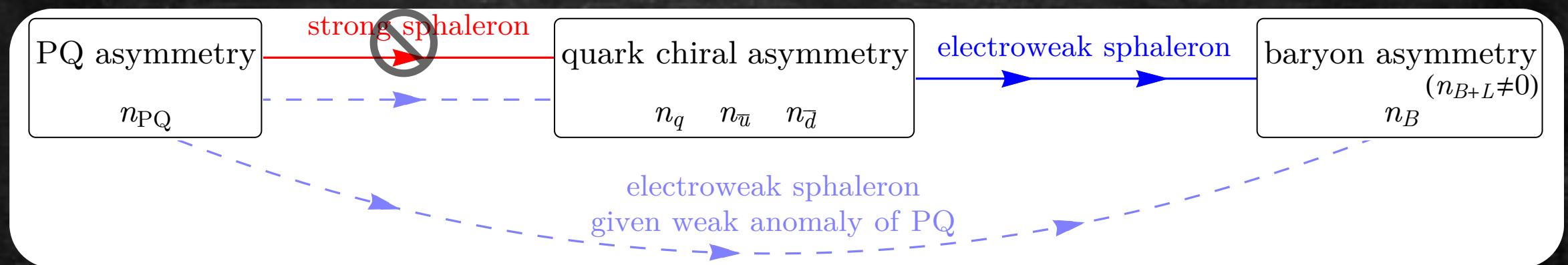
Baryon
Asymmetry

Gravitational
Waves



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ALP-genesis

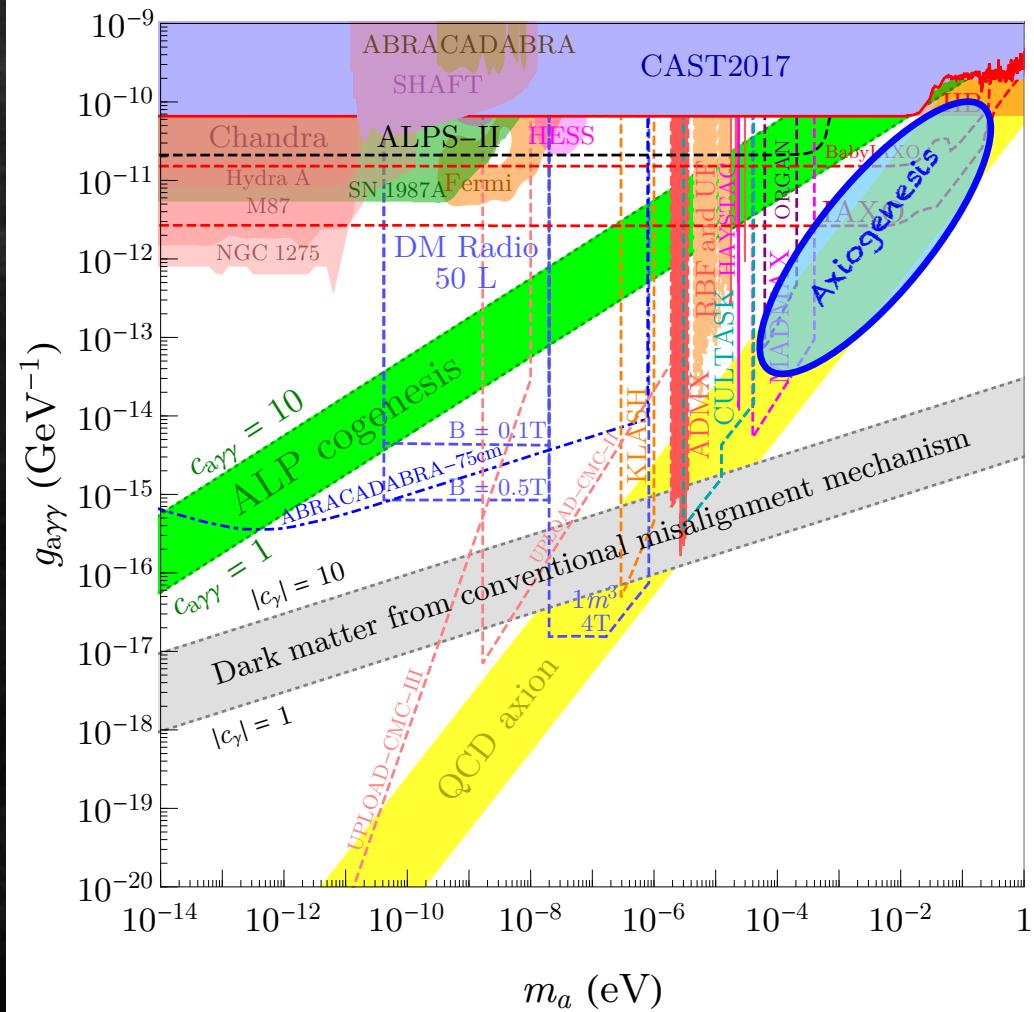


$$Y_B \simeq 10^{-10} \left(\frac{c_B}{0.1} \right) \left(\frac{T_{\text{EW}}}{130 \text{ GeV}} \right)^2 \left(\frac{10^8 \text{ GeV}}{f_a} \right)^2 \left(\frac{Y_{\text{PQ}}}{500} \right)$$

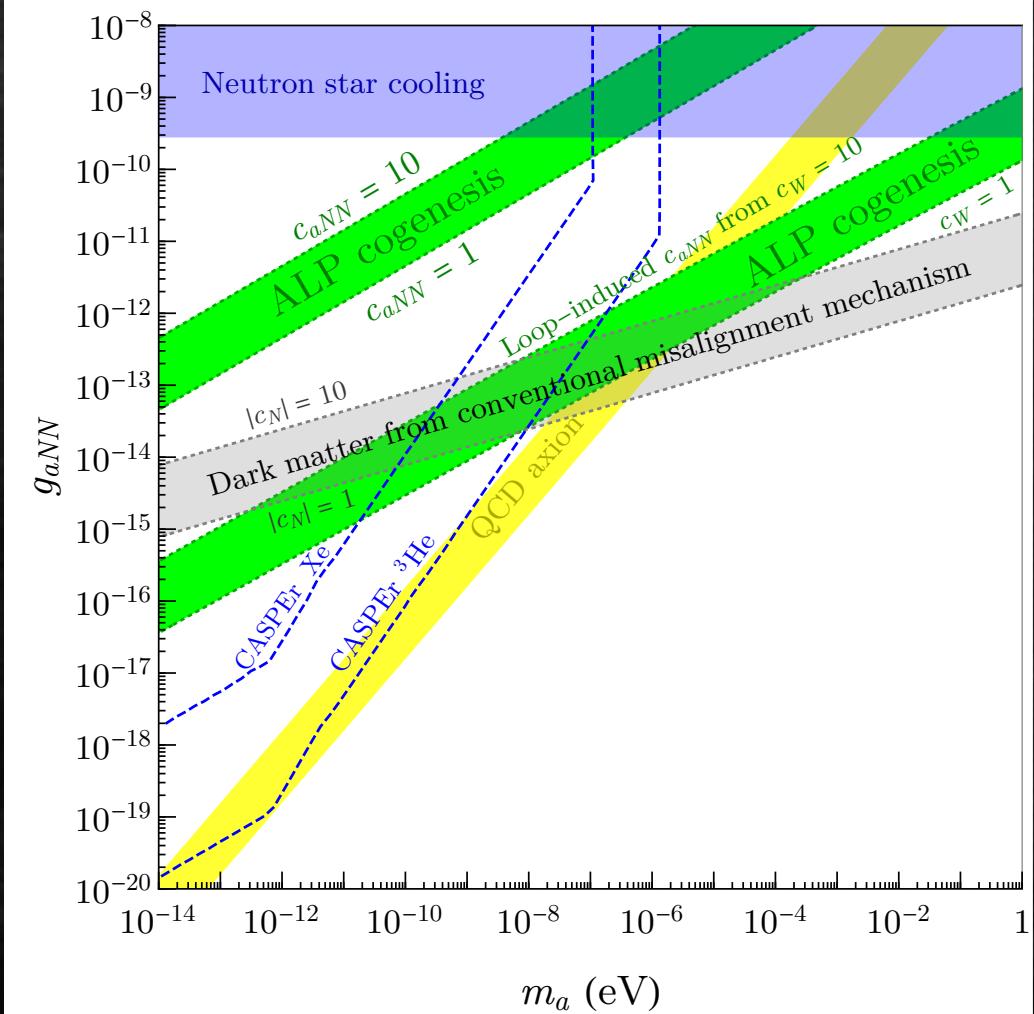
$$c_B = -\frac{12}{79} c_W$$

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

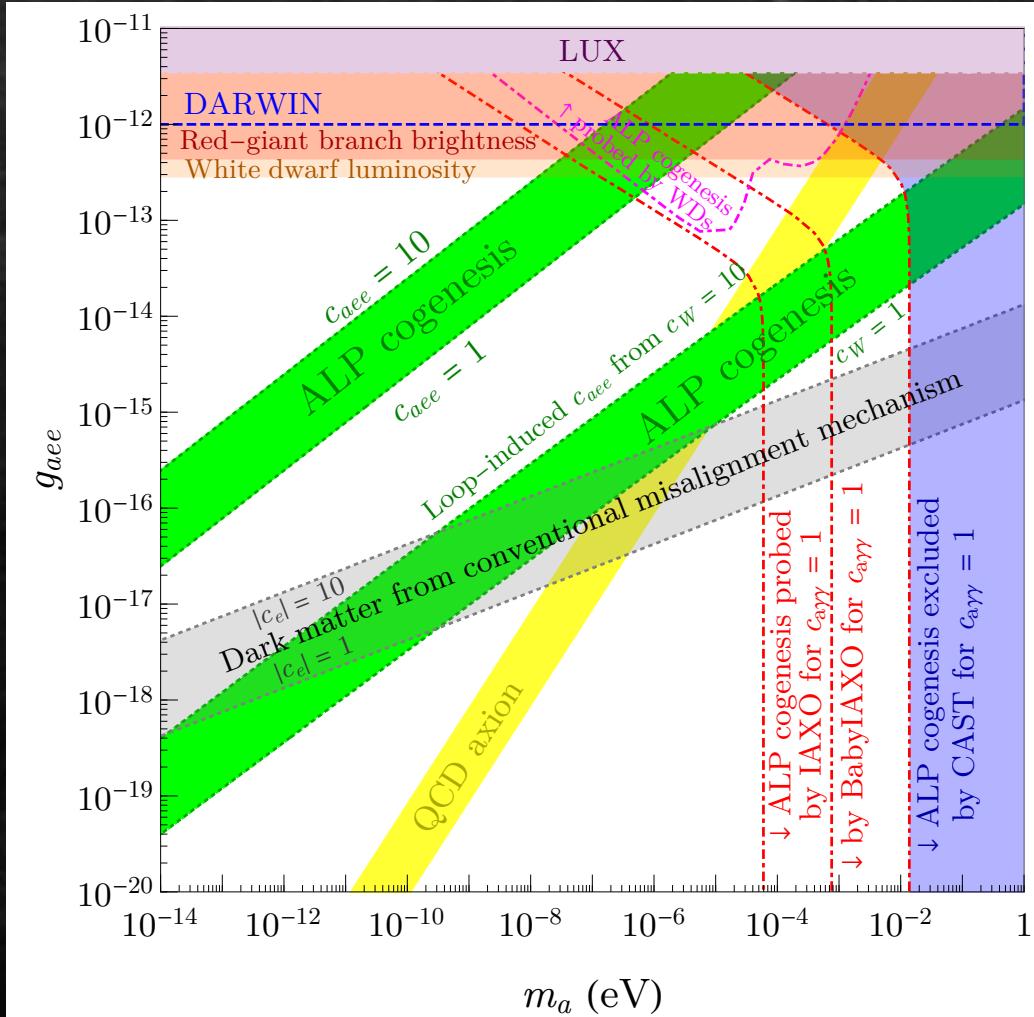
Axion Photon Coupling



Axion Nucleon Coupling



Axion Electron Coupling



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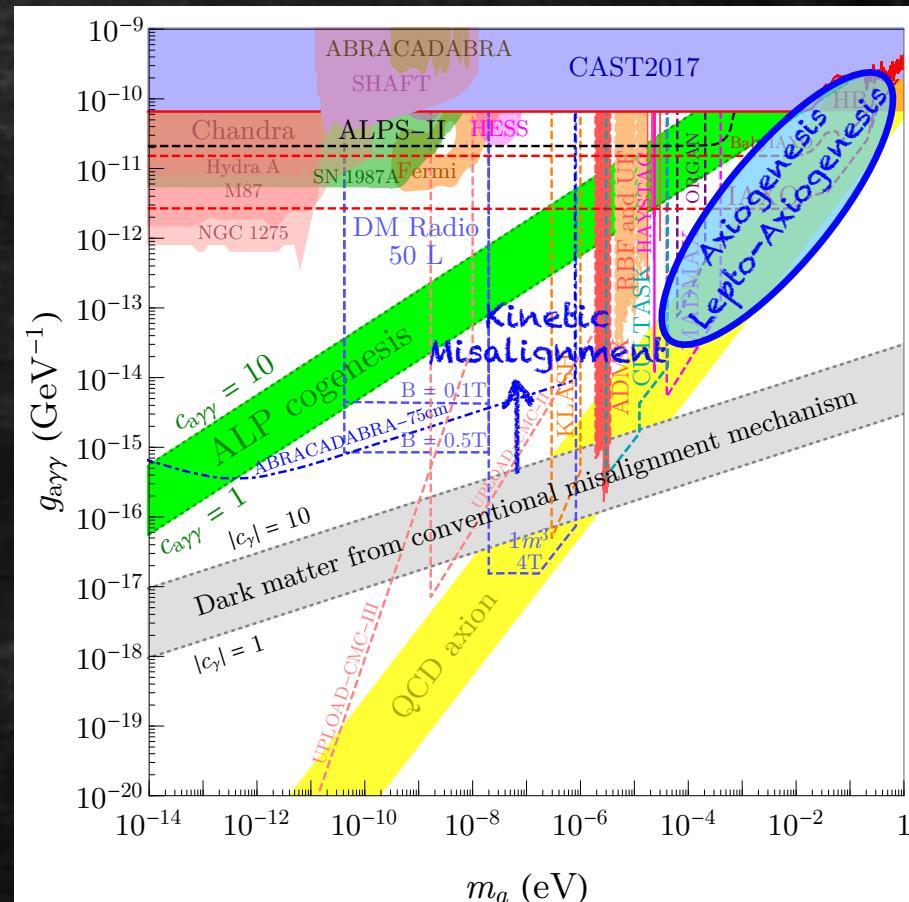
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RC, K. Harigaya, A. Pierce 2020



Baryon
Asymmetry

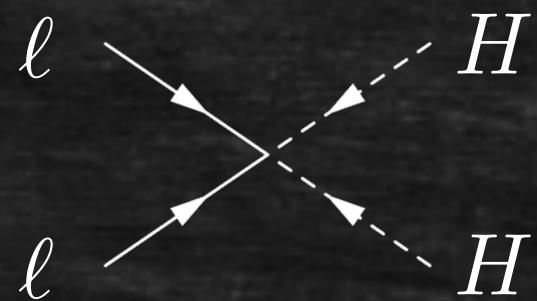
Gravitational
Waves



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Axion with Majorana neutrinos

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



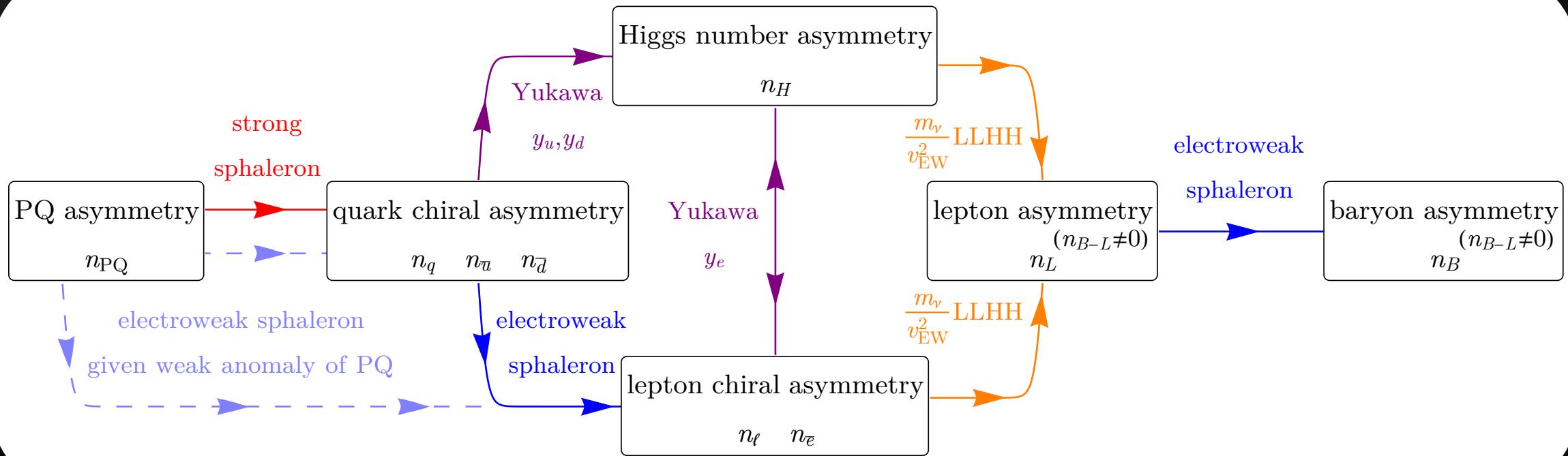
$$n_B \propto \dot{\theta} T^2$$

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

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

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

Lepto-Axiogenesis

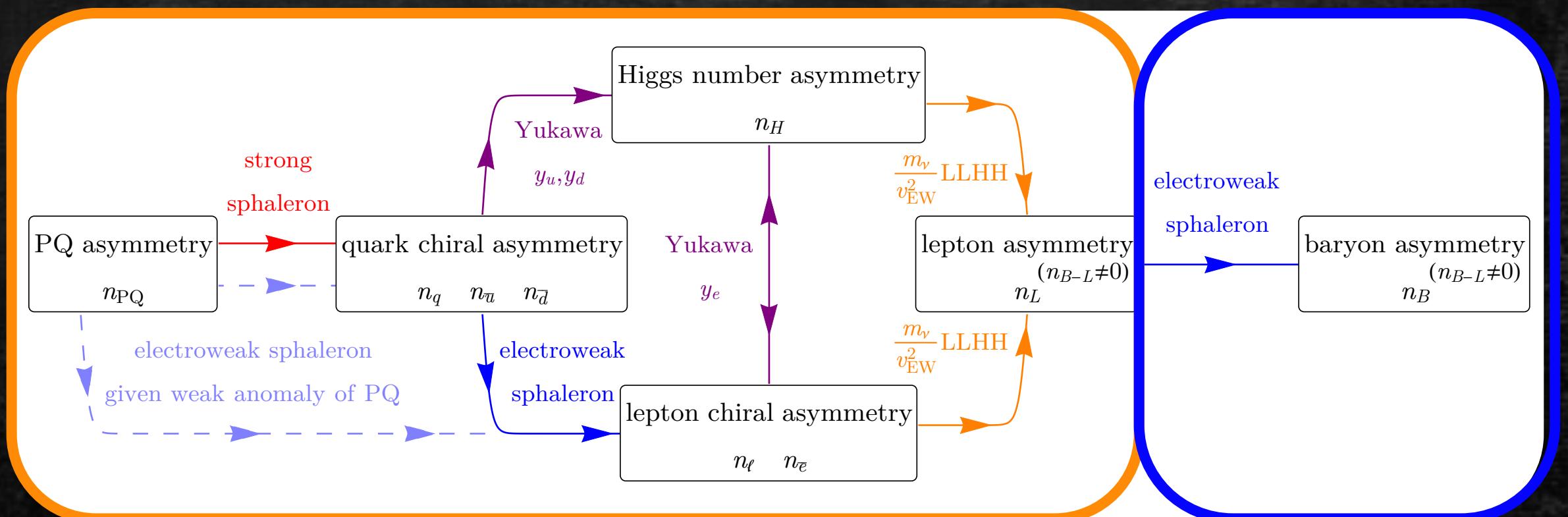


JHEP

Lepto-Axiogenesis

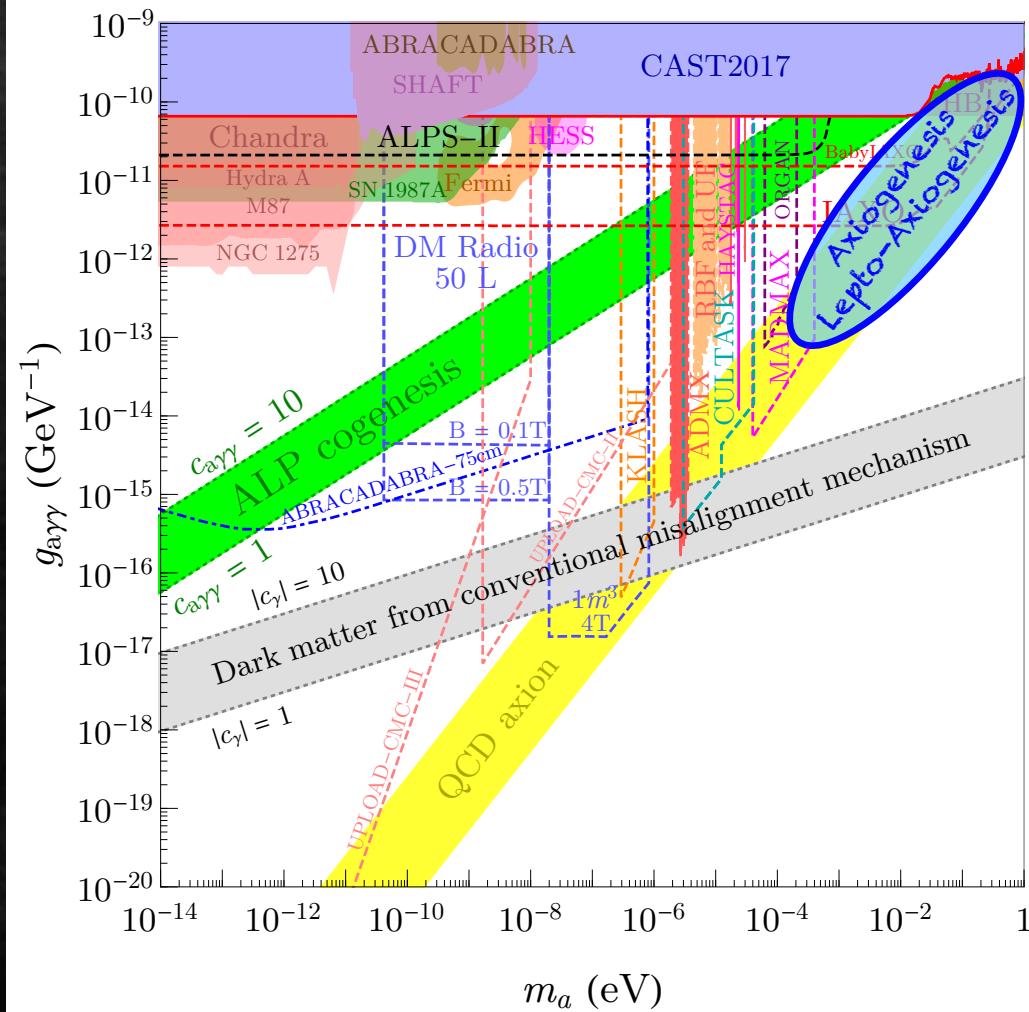
Producing L at high temperatures

Converting to B at TEW



JHEP

Axion Photon Coupling



Kinetic
Misalignment
Mechanism



StoryLine

▪ Axion

(o) Misalignment mechanism

(1) Parametric resonance

(2) - Kinetic misalignment mechanism

- Axiogenesis

RC, K. Harigaya 2019

- ALP cogenesis

RC, L. Hall, K. Harigaya 2020

- Lepto-Axiogenesis

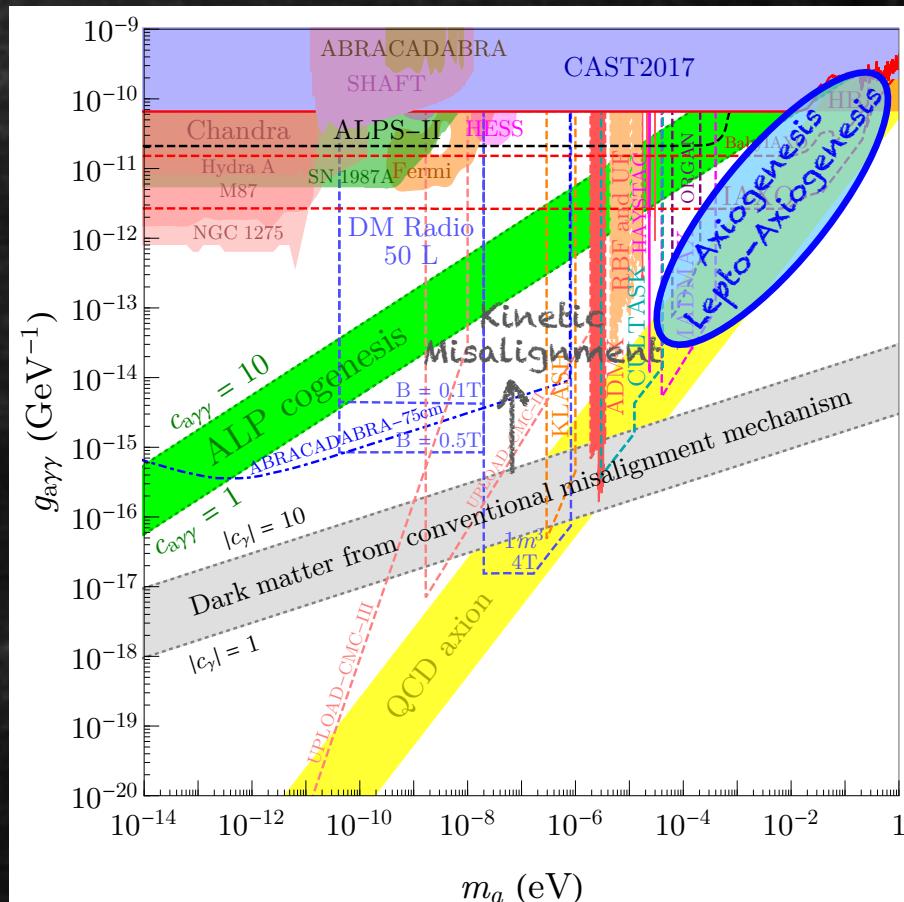
- Tachyonic instability

RC, K. Harigaya, A. Pierce 2020

Dark Matter

Baryon Asymmetry

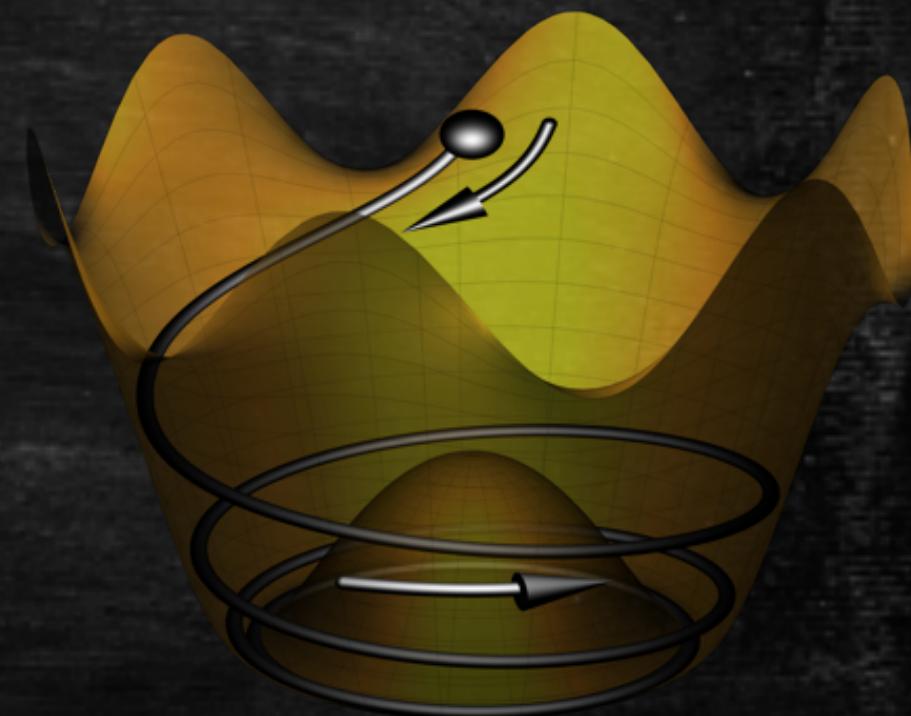
{ Gravitational Waves



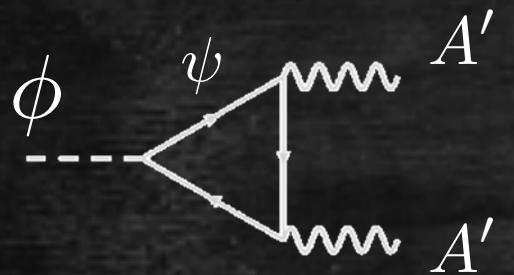
See later slides for axion-electron and axion-nucleon couplings

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'ia-Bellido, Greene, Kofman, Linde, Tkachev 2001

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

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

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$\equiv m_{\text{eff}}^2$

For oscillations:

$$\theta(t) \simeq \theta_i \cos(m_\phi t) (R_i/R)^{3/2}$$

For rotations:

$$\theta(t) \simeq \dot{\theta} t$$

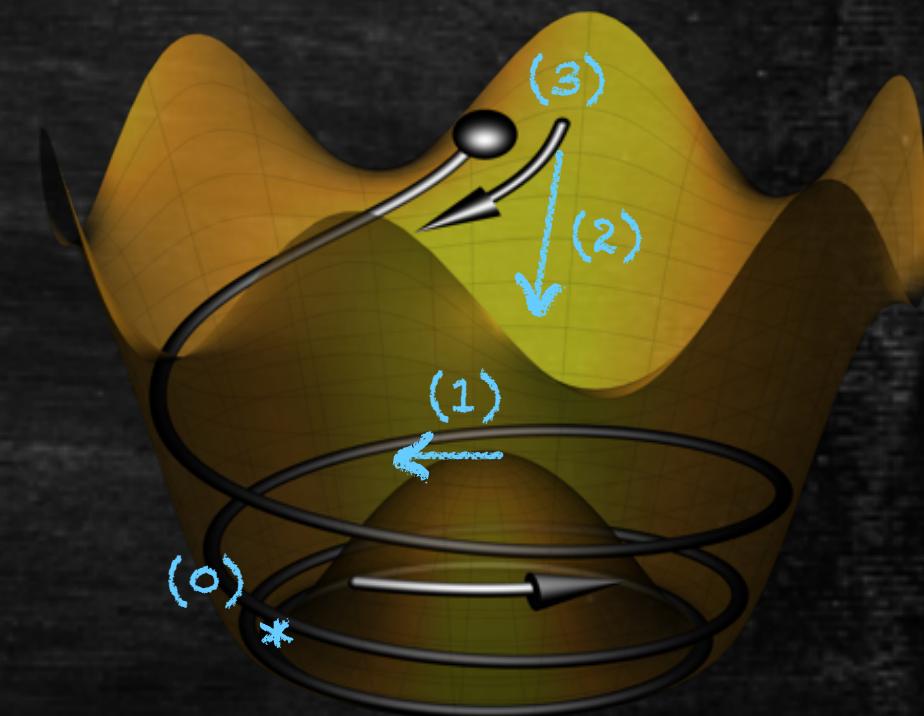
Storyline

□ Axion and dark photon coupling

- Gravitational waves
- Dark photon dark matter

Possible
initial
conditions

Peccei-Quinn
symmetry



Gravitational Waves

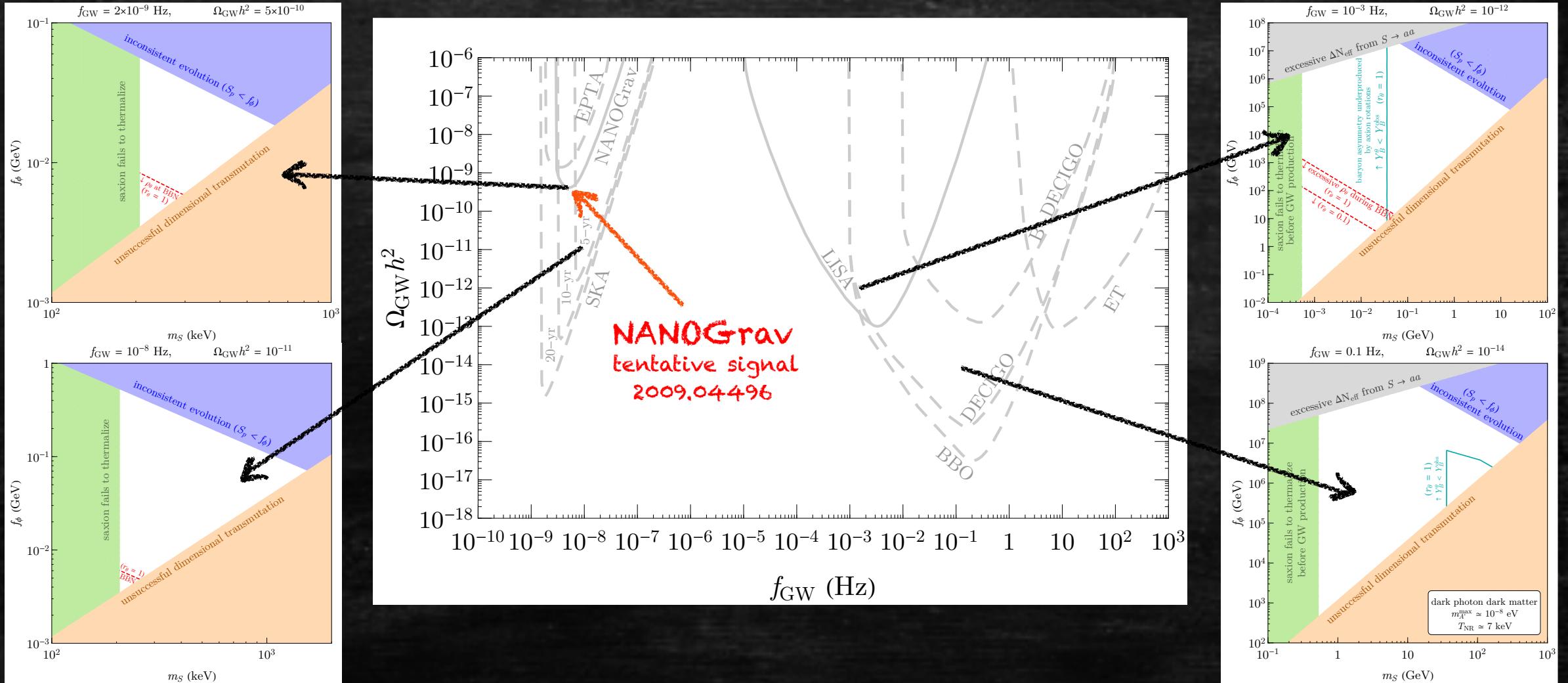
$$ds^2 = R(\tau)^2 \left(d\tau^2 - (\delta_{ij} + h_{ij}) dx^i dx^j \right)$$

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

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

the transverse-traceless
anisotropic stress tensor

Gravitational Waves



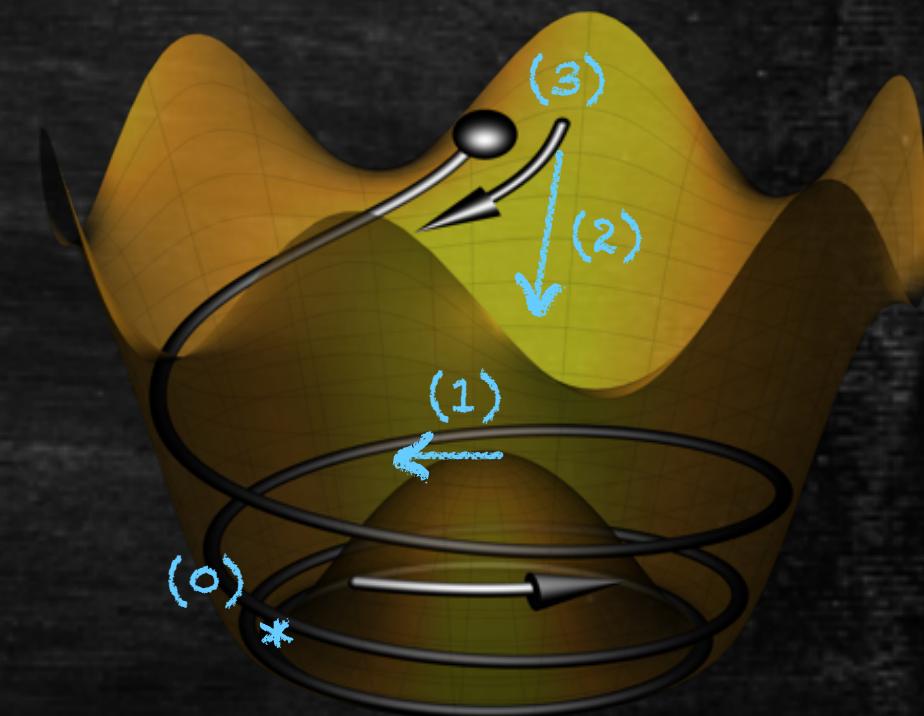
Storyline

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Dark Photon Dark Matter

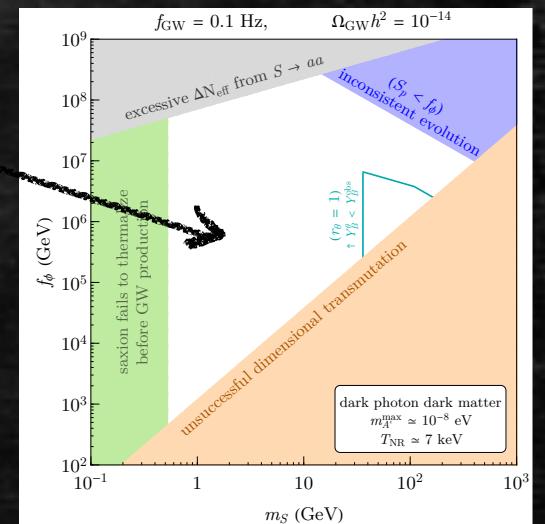
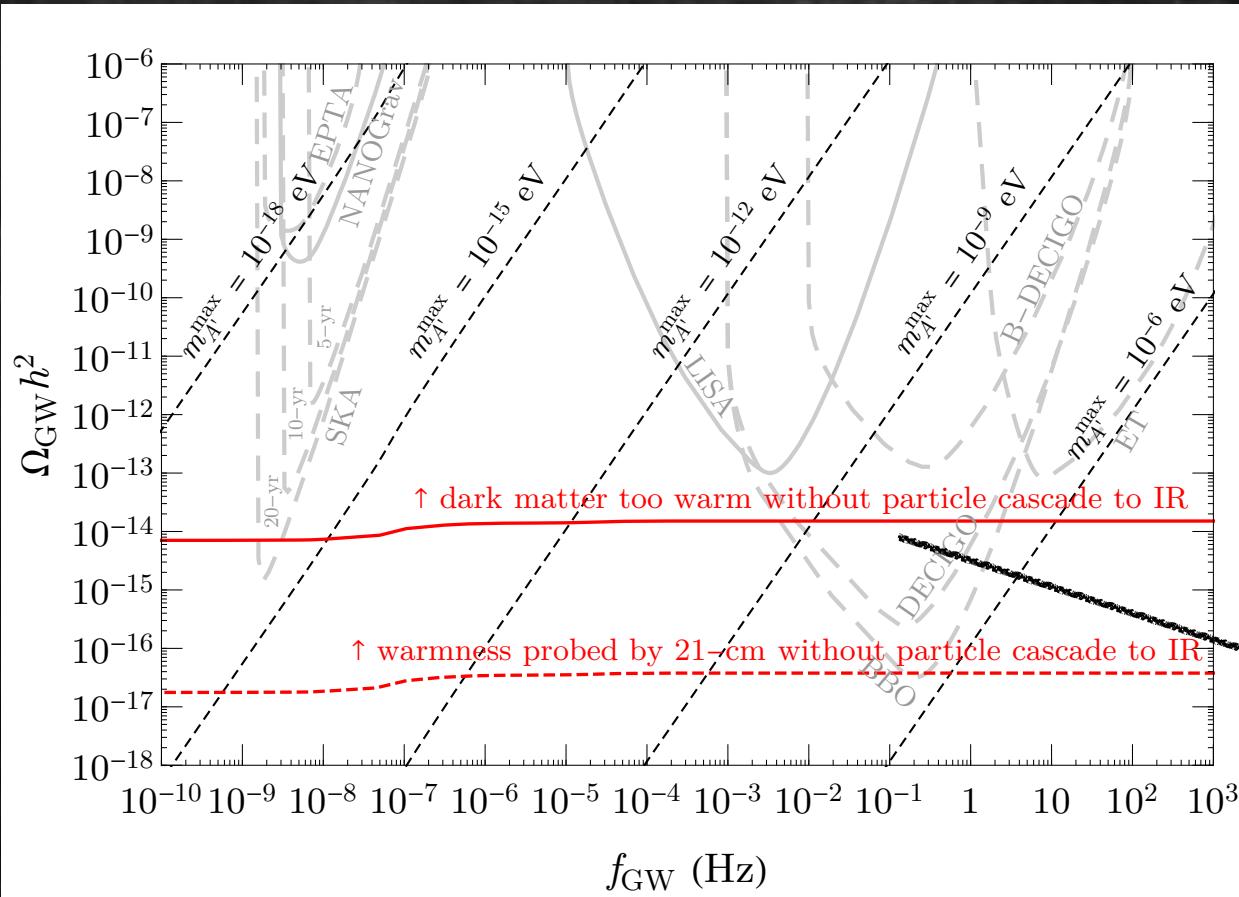
Correlation between
GWs and dark photons

Abundance

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

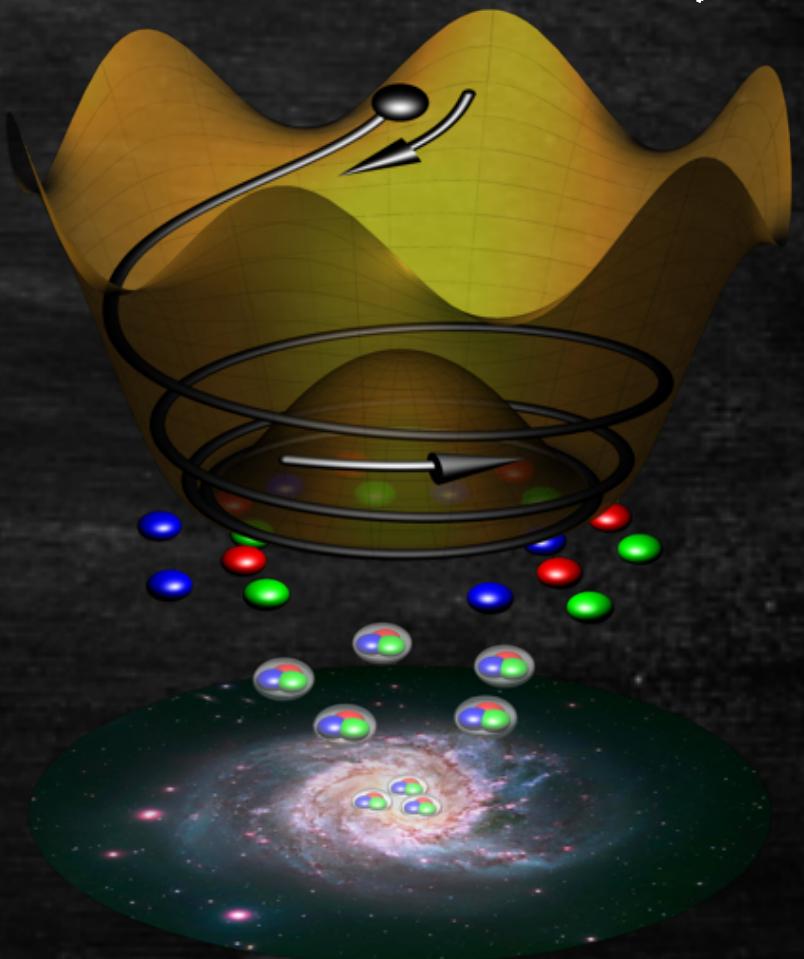
Warmness

$$H_p = \frac{k_{\text{TI}}}{r_p} \begin{cases} \nearrow f_{\text{GW}} \\ \searrow \kappa_{A'} \end{cases}$$



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
 - ✓ Saxon-Higgs mixing
 - ✓ Warm axion dark matter
 - ✓ Gravitational waves
- ✓ New model building opportunities



Thank you!

Happy Birthday to Felix!