Non-Thermal Production of Bosonic Dark Matter

Raymond Co

Winter Aspen March 28th 2019

Leinweber Center for Theoretical Physics
at the University of Michigan

LEINWEBER CENTER
FOR THEORETICAL PHYSICS
UNIVERSITY OF MICHIGAN

Collaborators:

arXiv:1711.10486 Lawrence Hall, Keisuke Harigaya

arXiv:1810.07196 Aaron Pierce, Zhengkang Zhang, Yue Zhao

arXiv:1812.11186 Eric Gonzalez, Keisuke Harigaya
1812.11192

Today

Jerome Isaac Friedman

1990 Nobel Prize in Physics

for showing an internal structure for protons

born on

March 28th 1930

R. Co Michigan

https://en.wikipedia.org/wiki/Jerome_Isaac_Friedman

Dark Matter Production Mechanism

- Thermal production

- Non-thermal production

Dark Matter Abundance

Observed dark matter abundance:

$$\frac{\rho_{\rm DM}}{s} \equiv m_{\rm DM} \frac{n_{\rm DM}}{s} \simeq 0.44 \text{ eV}$$

Full thermal equilibrium abundance:

$$Y_{\rm eq} \equiv \frac{n_{\rm eq}}{s} \simeq 0.3 \frac{g}{g_*}$$

Non-thermal production is needed when:

$$m_{\rm DM} < \mathcal{O}(100 \text{ eV})$$

Dark Matter Production Mechanism

- Thermal production
  - Freeze-out, freeze-in, …

    J. McDonald 1991   L. Hall, K. Jedamzik, J. March-Russell, S. West 2009
- Non-thermal production
  - Misalignment mechanism

    Preskill, Wise, Wilczek 1983, Abbott, Sikivie 1983, Dine, Fischler 1983
  - Phase transition: topological defects

    R. L. Davis 1986

Experimental Searches of Bosonic Dark Matter

QCD Axion

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	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

Dark Photon

Dish antenna	10^{-6} - 3 eV	D. Horns et al. 1212.2970 S. Knirck et al. 1806.05120
DM radio	10^{-12} - 0.003 eV	S. Chaudhuri et al. 1411.7382 M. Silva-Feaver et al. 1610.09344

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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    R. L. Davis 1986, A. Long, L.T. Wang 2019
  - Inflationary quantum fluctuations

    P. Graham, J. Mardon, S. Rajendran 2016
  - Anything else?

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  - Anything else?
    - Parametric resonance RC, L. Hall, K. Harigaya 2017
    - Tachyonic instability RC, A. Pierce, Z. Zhang, Y. Zhao 2018

P. Agrawal, N. Kitajima, M. Reece, T. Sekiguchi, F. Takahashi 2018

J. A. Dror, K. Harigaya and V. Narayan, 2018

M. Bastero-Gil, J. Santiago, L. Ubaldi and R. VegaMorales 2018

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P. Graham et al. 2018
F. Takahashi et al. 2018
RC, E. Gonzalez, K. Harigaya 2018

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This talk

  - Anything else?
    - Parametric resonance
    - Tachyonic instability

RC, L. Hall, K. Harigaya 2017

RC, A. Pierce, Z. Zhang, Y. Zhao 2018
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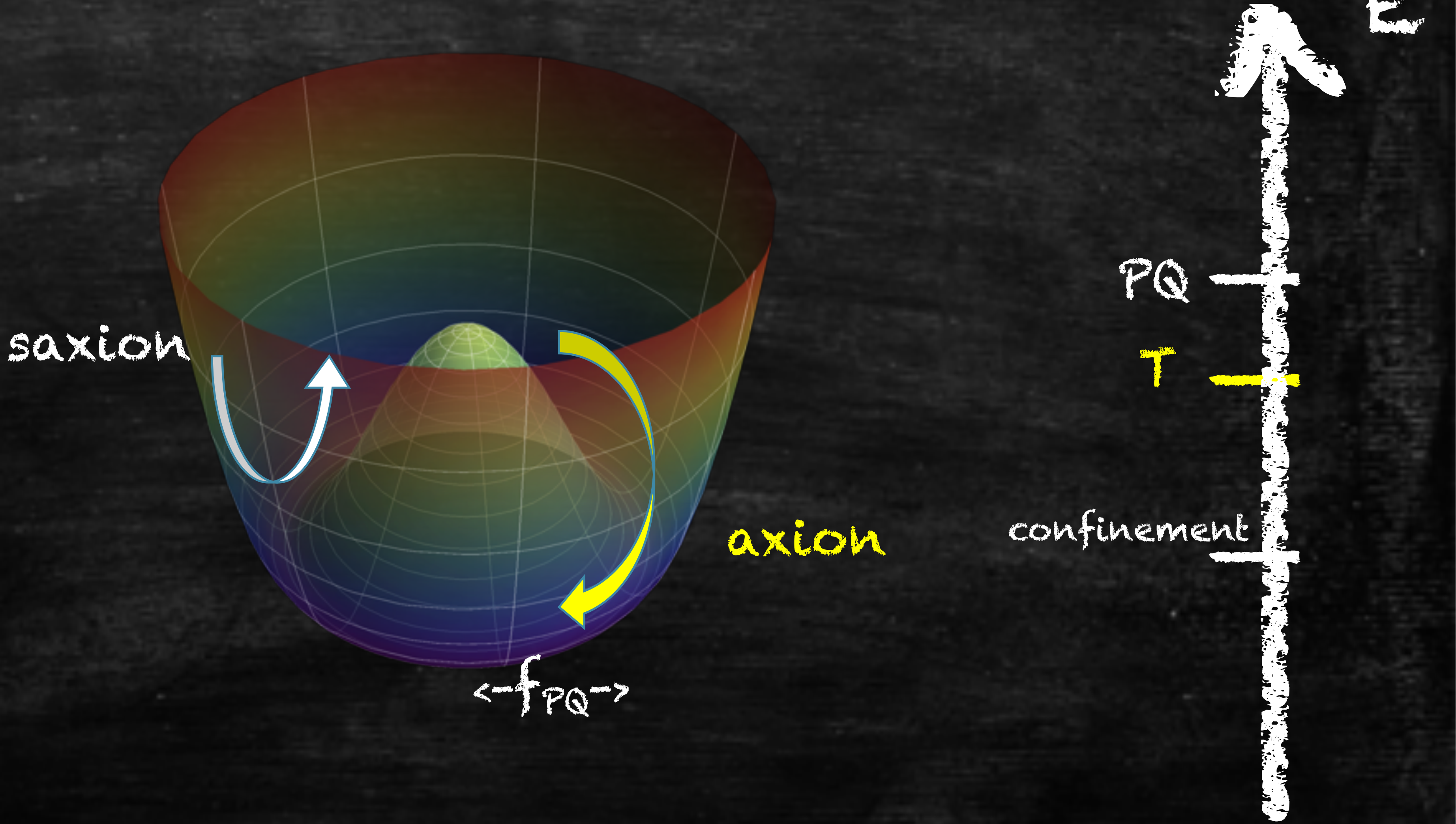
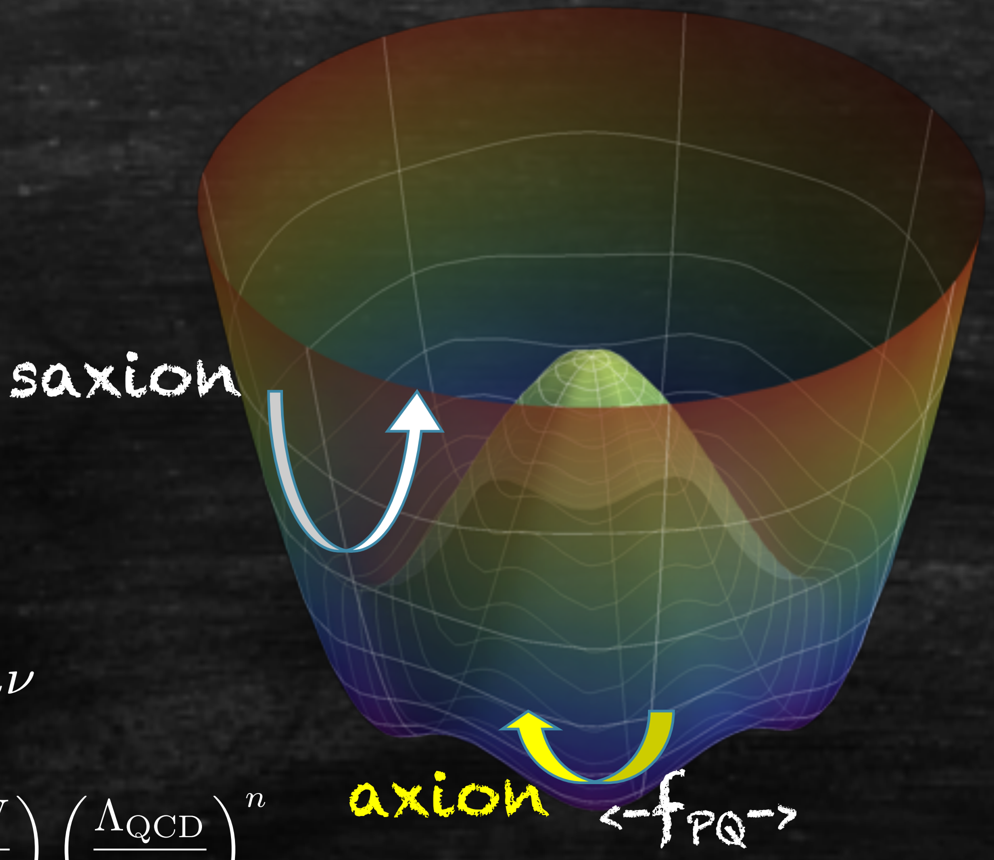
New Production Mechanisms

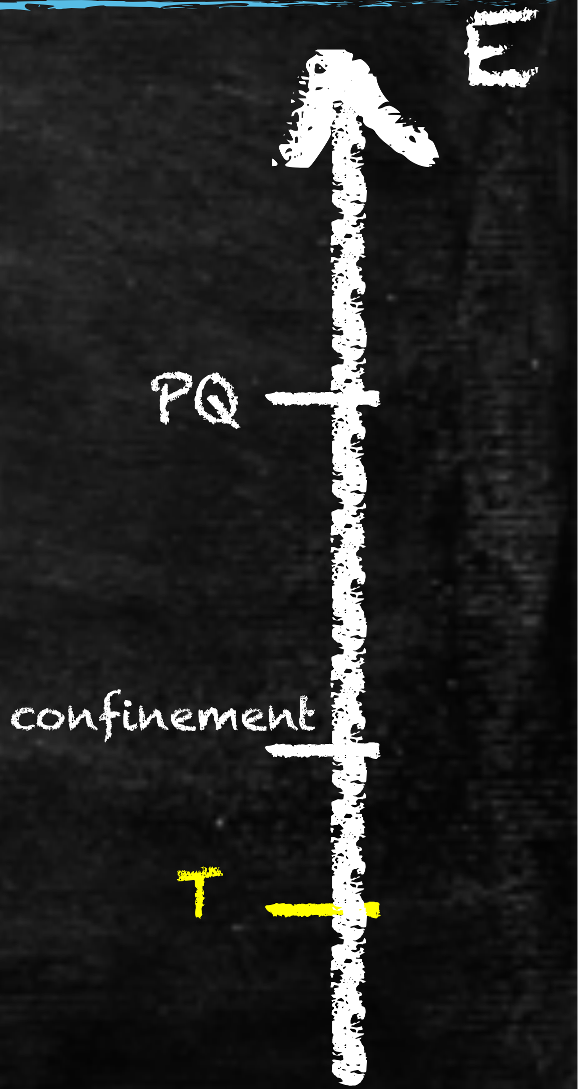
- Misalignment Mechanism
  - QCD axions: misalignment driven to the hilltop/bottom
- Exponential Particle Production
  - QCD axions: parametric resonance
  - Dark photons: tachyonic instability

Axions



Axions





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

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

Misalignment Mechanism

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

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

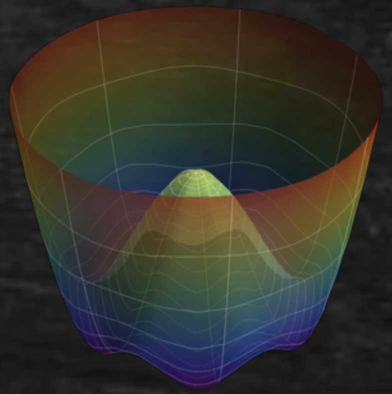
scales like matter

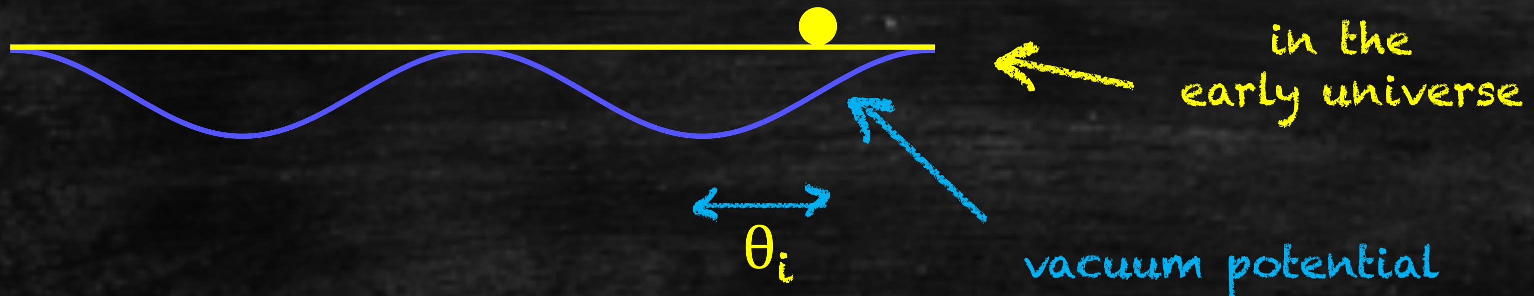
Except for long inflation:
P. Graham et al. 1805.07362
F. Takahashi et al. 1805.08763

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

Misalignment Mechanism: Axions

$m_a \ll H$ $T \gg \Lambda_{QCD}$



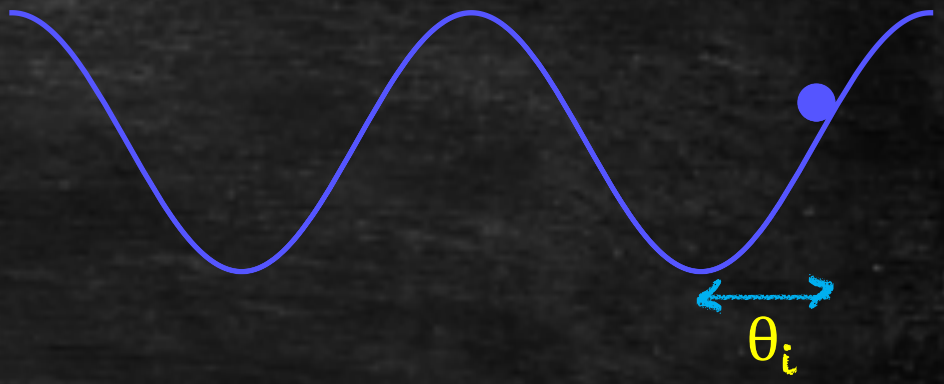


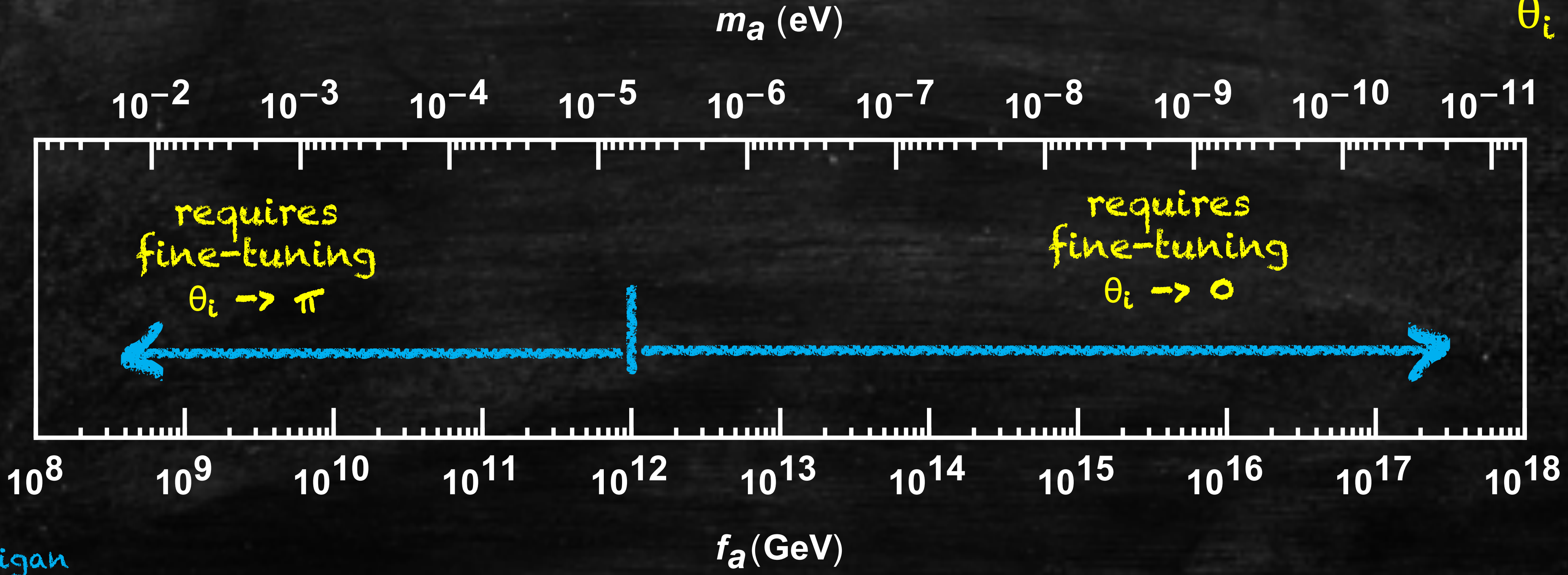
in the early universe

vacuum potential

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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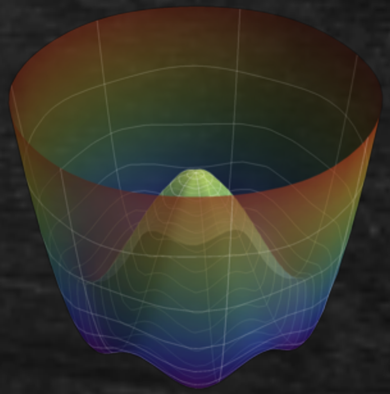
Dynamical Axion Misalignment Production

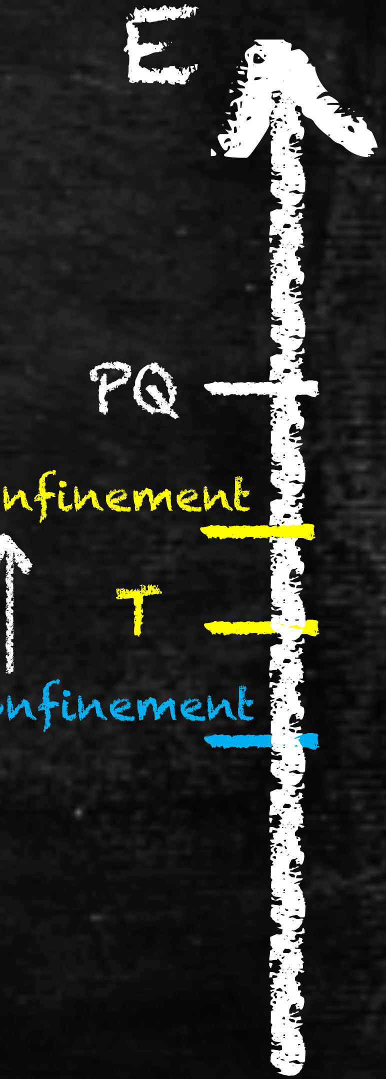
(DAMP)

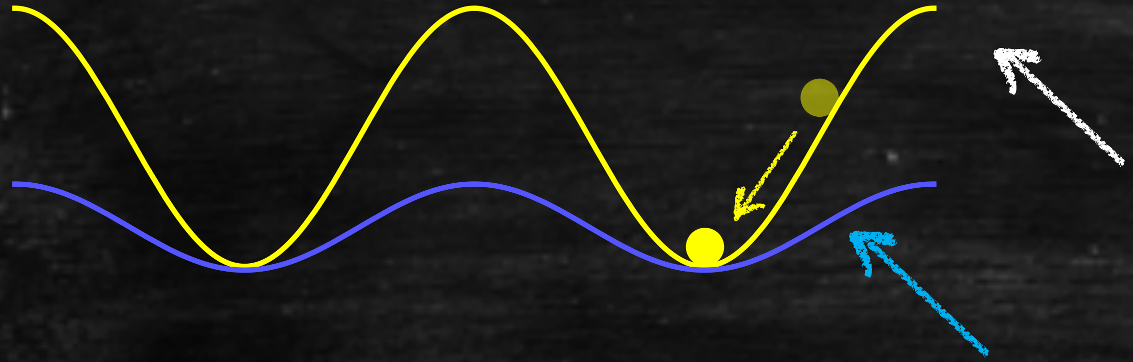
Dynamical Axion Misalignment Production

(DAMP)

$m_a \propto \Lambda^2_{QCD}$







raised in the early universe

vacuum potential

θ_i driven to zero

G. Dvali 1995
T. Banks and M. Dine 1997
K. Choi, H. B. Kim, J. E. Kim 1997

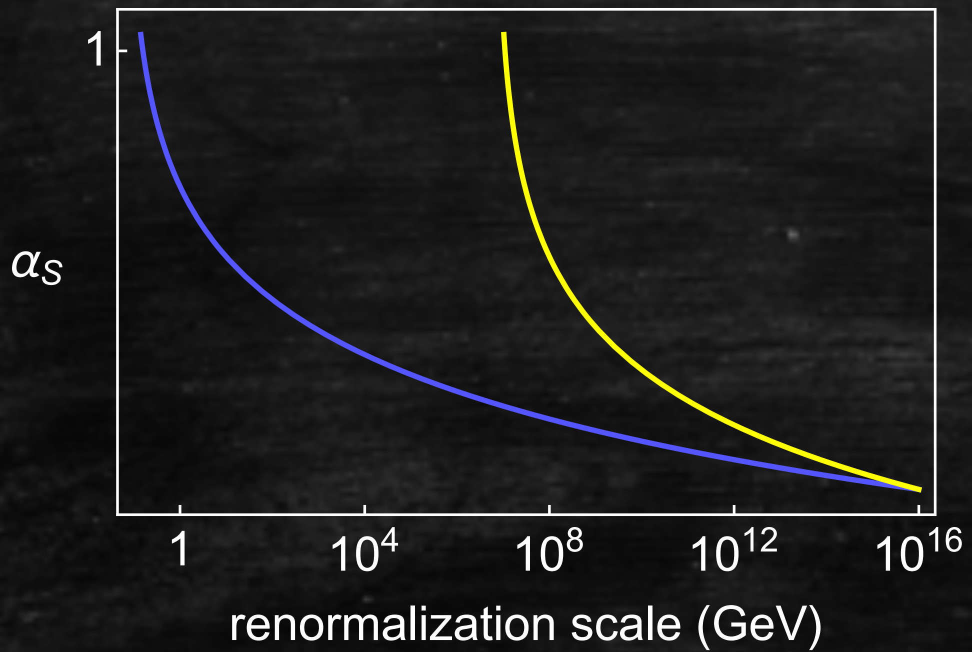
Large f_a is *predicted* !

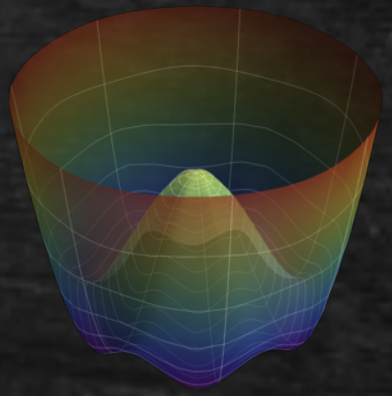
arXiv:1812.11186, 1812.11192 RC, E. Gonzalez, K. Harigaya

Large Λ_{QCD} in the early Universe

$m_a \propto \Lambda^2_{QCD}$

$\Lambda_{QCD} \propto (\text{Higgs vev})^{2/3}$



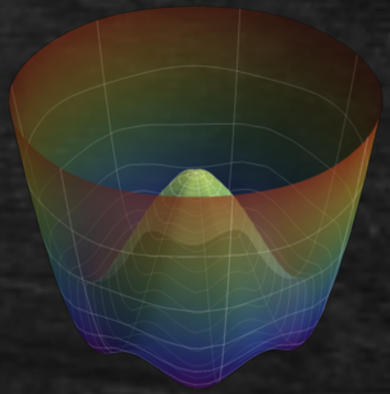


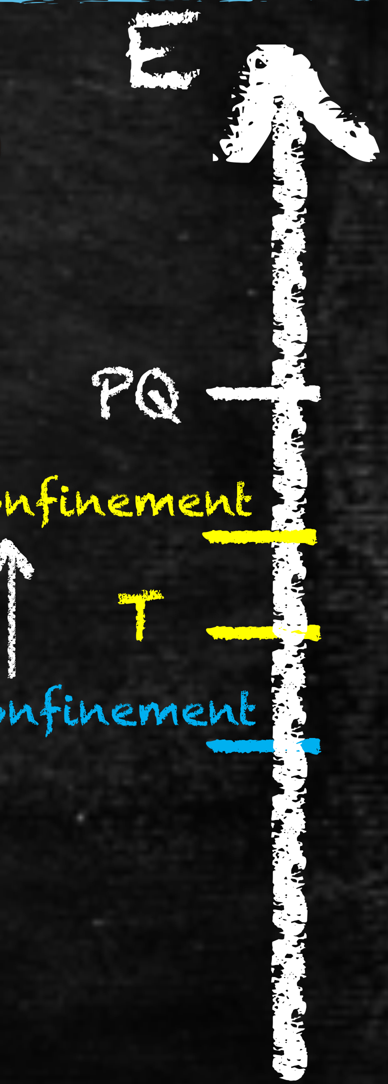
arXiv:1812.11186, 1812.11192 RC, E. Gonzalez, K. Harigaya

Large Higgs vev in the early Universe

$m_a \propto \Lambda^2_{QCD}$

$\Lambda_{QCD} \propto (\text{Higgs vev})^{2/3}$





Higgs couplings with the inflaton

$$\Delta K = \frac{|X|^2}{M^2}\left(|H_u|^2 + |H_d|^2 + (H_u H_d + c.c.) - \frac{|H_u|^2|H_d|^2}{M^2} - \frac{|H_u|^4}{M^2} - \frac{|H_d|^4}{M^2}\right)$$

$$\Delta V = cH_I^2\left(-|H_u|^2 - |H_d|^2 - (H_u H_d + c.c.) + \frac{|H_u|^2|H_d|^2}{M^2} + \frac{|H_u|^4}{M^2} + \frac{|H_d|^4}{M^2}\right)$$

The Hubble induced mass induces a negative mass, driving Higgs to a large field value.

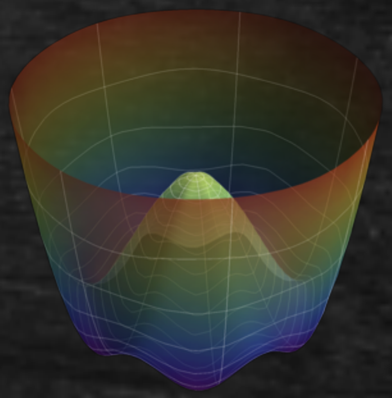
arXiv:1812.11186, 1812.11192 RC, E. Gonzalez, K. Harigaya

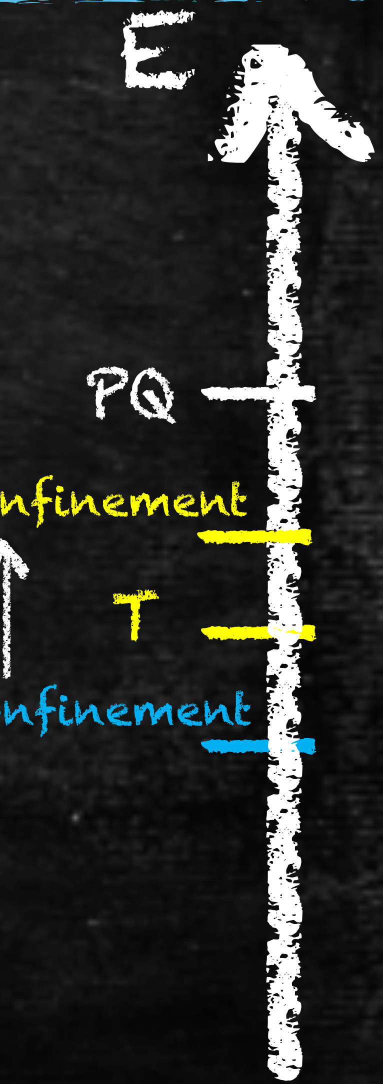
Dynamical Axion Misalignment Production

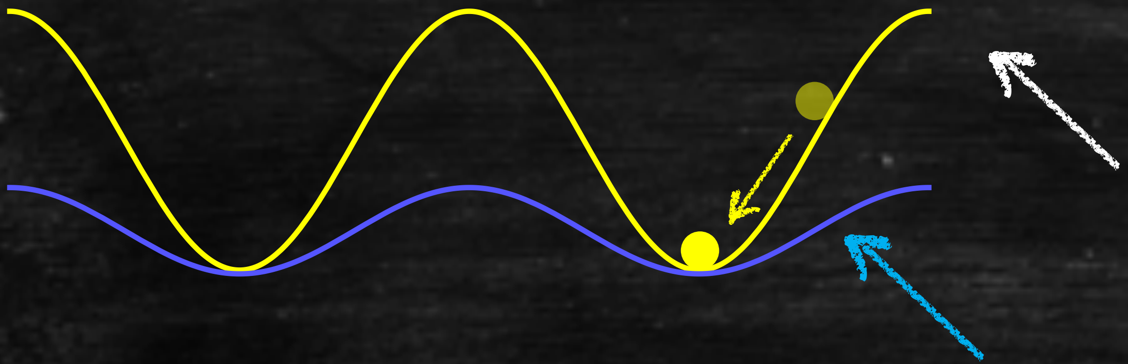
(DAMP)

$m_a \propto \Lambda^2_{QCD}$

$\Lambda_{QCD} \propto (\text{Higgs vev})^{2/3}$







raised in the early universe

vacuum potential

θ_i driven to zero

Large f_a is *predicted* !

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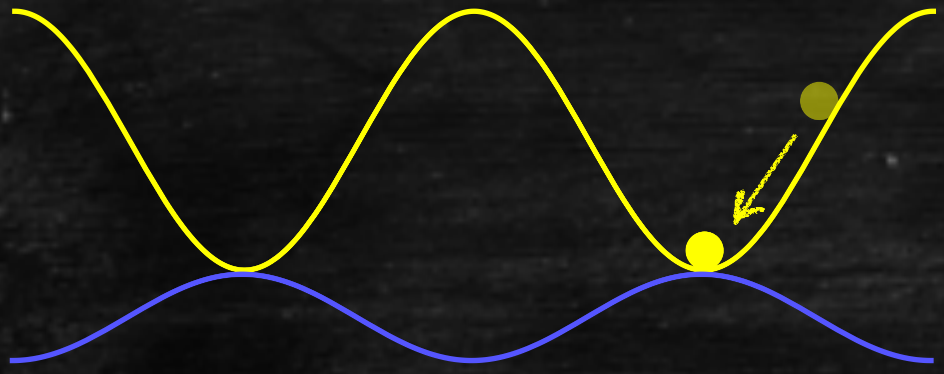
Phase Shift of the Axion Potential

(DAMP)

$\theta_{eff} = a + \theta_{QCD} + \arg(\det(m_u m_d))$ ← π shifted

$V = -B\mu H_u H_d + cH_I^2 H_u H_d$ → sign flipped ↑

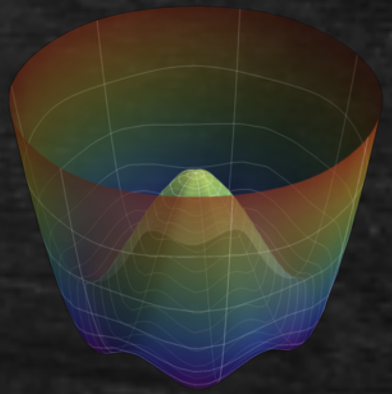


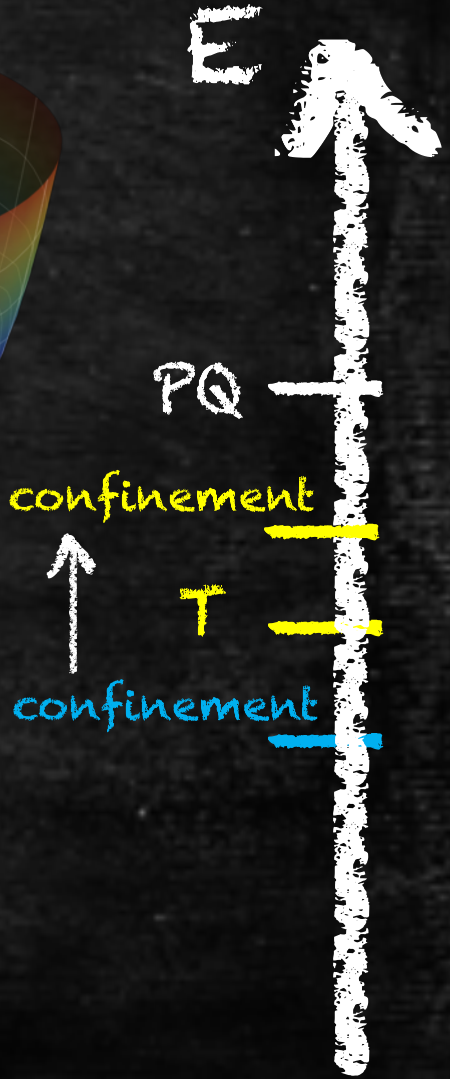
raised in the early universe

vacuum potential

θ_i driven to hilltop!

Small f_a is *predicted* !





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arXiv:1812.11186, 1812.11192 RC, E. Gonzalez, K. Harigaya

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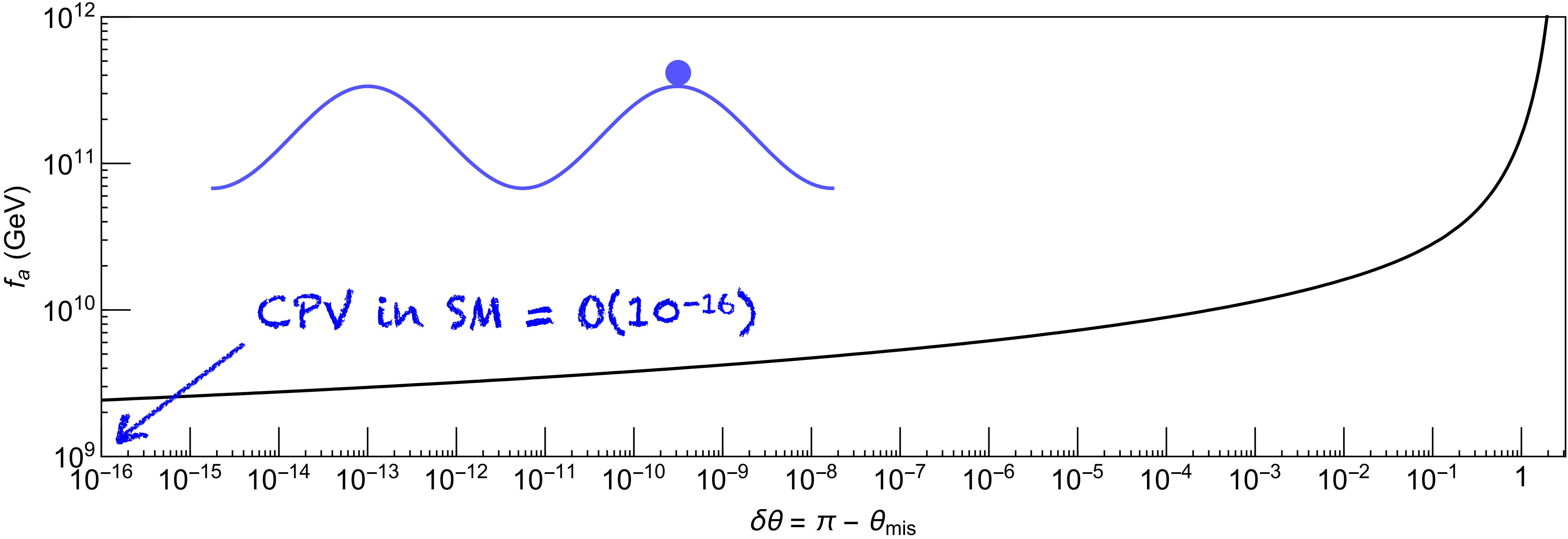

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Exponential Production

Parametric Resonance
Tachyonic Instability

J. H. Traschen and R. H. Brandenberger 1990
L. Kofman, A. D. Linde and A. A. Starobinsky 1994, 1997

Parametric Resonance

Pedagogical example: (Non-expanding Universe)

Quartic potential:

$$V = \lambda^2 |P|^4 \qquad P = \frac{\overset{\text{saxion}}{S} + i\overset{\text{“axion”}}{\chi}}{\sqrt{2}}$$

$$= \frac{\lambda^2}{4}\left(S^2 + \chi^2\right)^2$$

PHYSICAL REVIEW LETTERS

EDITORS' SUGGESTION

QCD Axion Dark Matter with a Small Decay Constant

A proposed new cosmological production mechanism for QCD axion dark matter that involves parametric resonance in field oscillation predicts larger axion masses than the conventional misalignment mechanism.

Raymond T. Co, Lawrence J. Hall, and Keisuke Harigaya

Phys. Rev. Lett. **120**, 211602 (2018)

Equation of motions:

$$\ddot{\chi} - \nabla^2 \chi + V''(\chi)\ \chi = 0 \qquad V''(\chi) = \lambda^2 S^2 = \lambda^2 S_0^2 \cos^2(\lambda S_0 t)$$

$$S \sim S_0 \cos(\lambda S_0 t)$$

arXiv:1711.10486 RC, L. Hall, and K. Harigaya

Parametric Resonance

$$\frac{d^2}{dz^2}\widetilde{\chi}+\underline{\left(\left(\frac{k}{\lambda S_0}\right)^2+\frac{1}{2}\right)}\,\widetilde{\chi}+\frac{1}{2}\cos\left(\underline{2z}\right)\widetilde{\chi}=0$$

Oscillation frequency
of the field
in absence of
the driving force

Oscillation
frequency of the
driving force

Fourier transform:

$$\chi(x,t)=\int\frac{d^3k}{(2\pi)^3}e^{ikx}\widetilde{\chi}(k,t)$$

Change of variables:

$$z=\lambda S_0 t$$

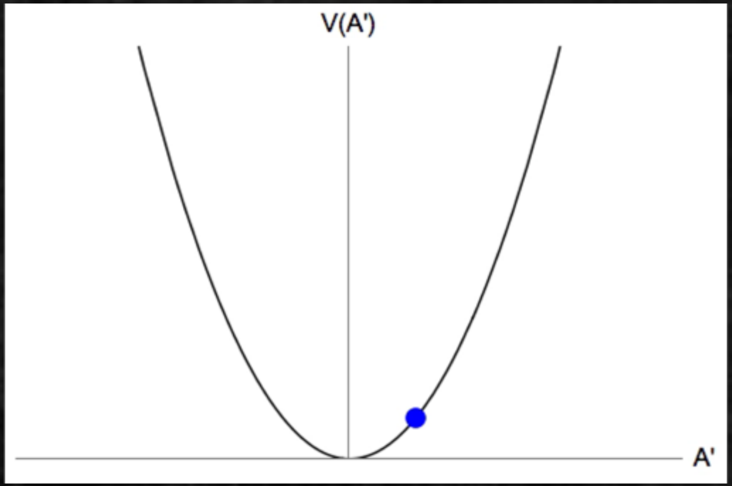
Resonance occurs for some specific frequencies.

arXiv:1711.10486 RC, L. Hall, and K. Harigaya

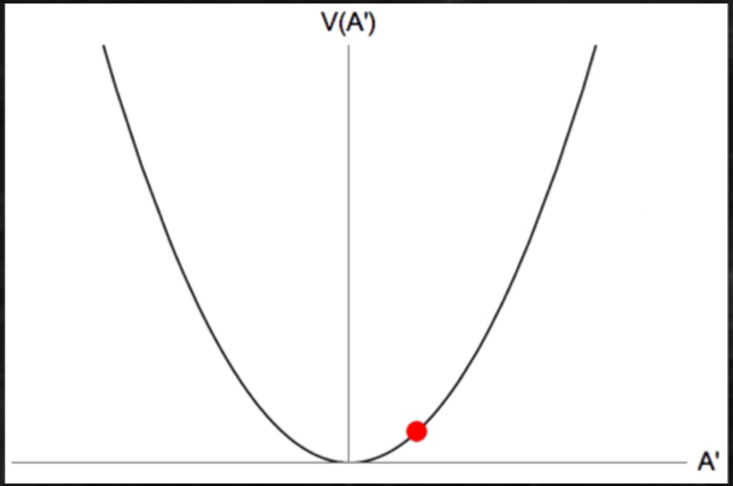
Parametric Resonance

Graphical understanding

No Enhancement



Parametric Resonance



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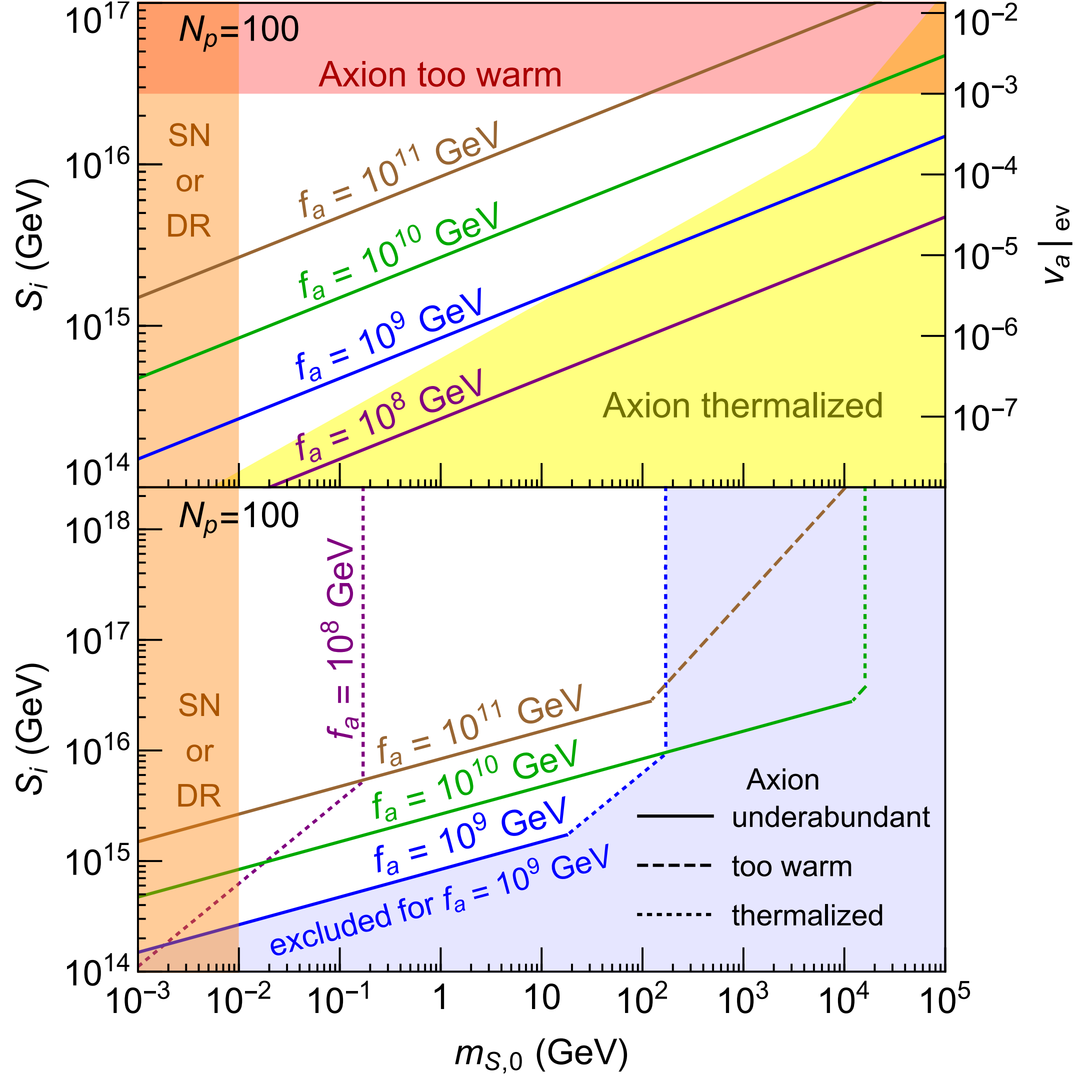
Parameter Space for Quadratic Potential

Radiation Domination

Matter Domination



arXiv:1711.10486

RC, L. Hall, and K. Harigaya

Dark Photon Dark Matter

- An abelian gauge symmetry $U(1)_D$ in the dark sector

$$\mathcal{L}_{U(1)_D} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$$

  - Dark photon mass
    - Higgs mechanism
    - Stückelberg mechanism
  - Interactions with the Standard Model
    - Kinetic mixing with the photons

$$\mathcal{L}_{U(1)_D} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$$

Misalignment Mechanism: Vectors

$$\left(\partial_t^2 + \frac{3k^2 + a^2 m_{A'}^2}{k^2 + a^2 m_{A'}^2} H \partial_t + \frac{k^2}{a^2} + m_{A'}^2\right) A' = 0$$

Early time

$$H \gg m_{A'} \gg \frac{k}{a}$$

Hubble friction dominates

$$\left(\partial_t^2 + H\partial_t\right) A' = 0$$

$$A' = \text{constant}$$

Field value is "stuck"

$$\rho_{A'} = m_{A'}^2 A' A'$$

Energy density

$$g^{\mu\nu} A'_\mu A'_\nu \propto a^{-2}$$

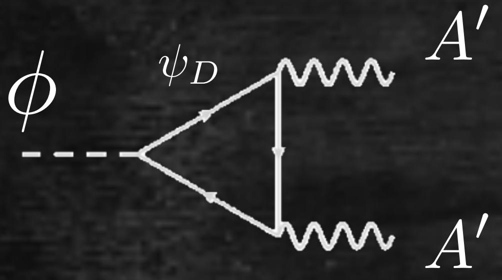
Non-trivial mass term

$$\rho_{A'} \propto a^{-2}$$

scales differently

A. Nelson and J. Scholtz arXiv:1105.2812
P. Aria et al. arXiv:1201.5902
P. Graham, J. Mardon, S. Rajendran arXiv:1504.02102

Tachyonic Instability



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

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

Tachyonic Instability

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

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

$$\phi(t) \simeq \phi_i \cos(m_\phi t)\,(a_i/a)^{3/2}$$

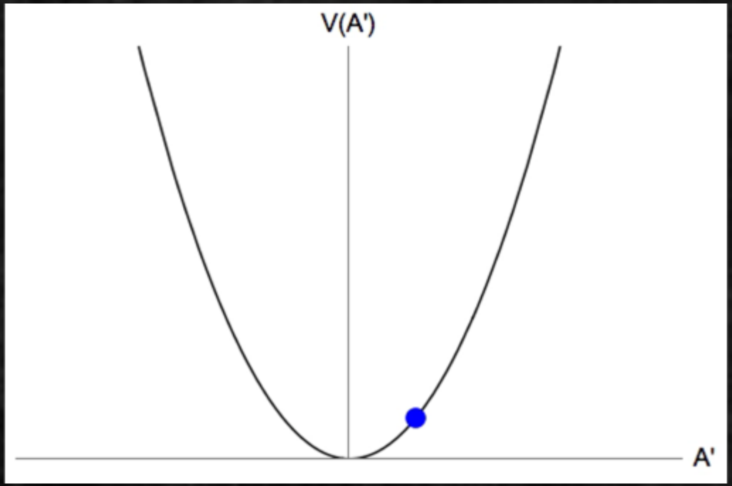
$$\frac{\partial^2 \vec{A}'_\pm}{\partial\eta^2} + \underline{\left(m_{A'}^2 + k_{A'}^2 \mp \frac{\alpha_D k_{A'}}{2\pi f_D}\frac{\partial\phi}{\partial\eta}\right)}\,\vec{A}'_\pm = 0$$

If $m^2_{\rm eff} \equiv \left(m_{A'}^2 + k_{A'}^2 \mp m_\phi \frac{\alpha_D \phi}{2\pi f_D} k_{A'} \cos(m_\phi t)\right) < 0$, then the solution of A′ is exponential.

"tachyonic" = "$m^2_{\rm eff} < 0$"
"instability" = "exponential/unstable solution"

Tachyonic Instability

Graphical understanding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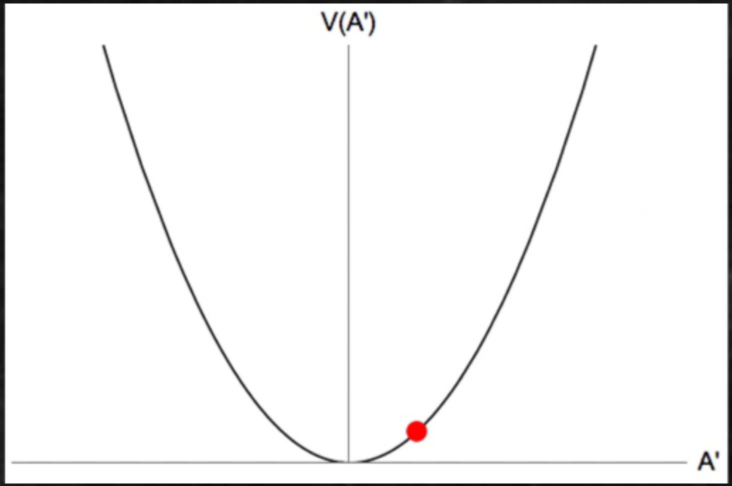
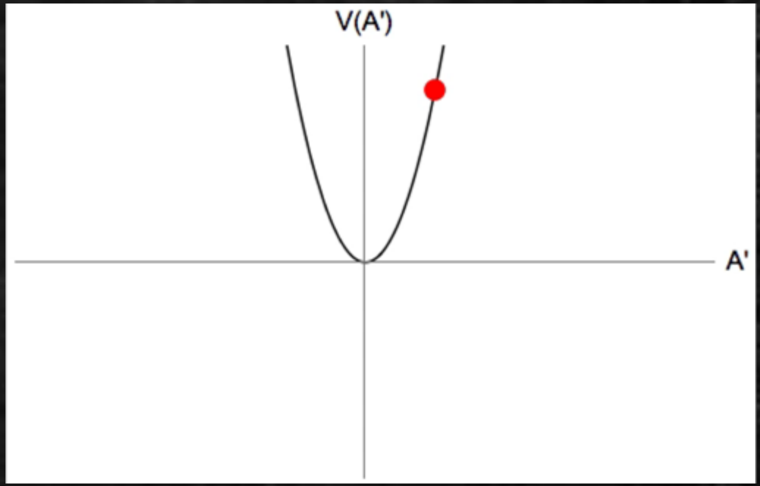
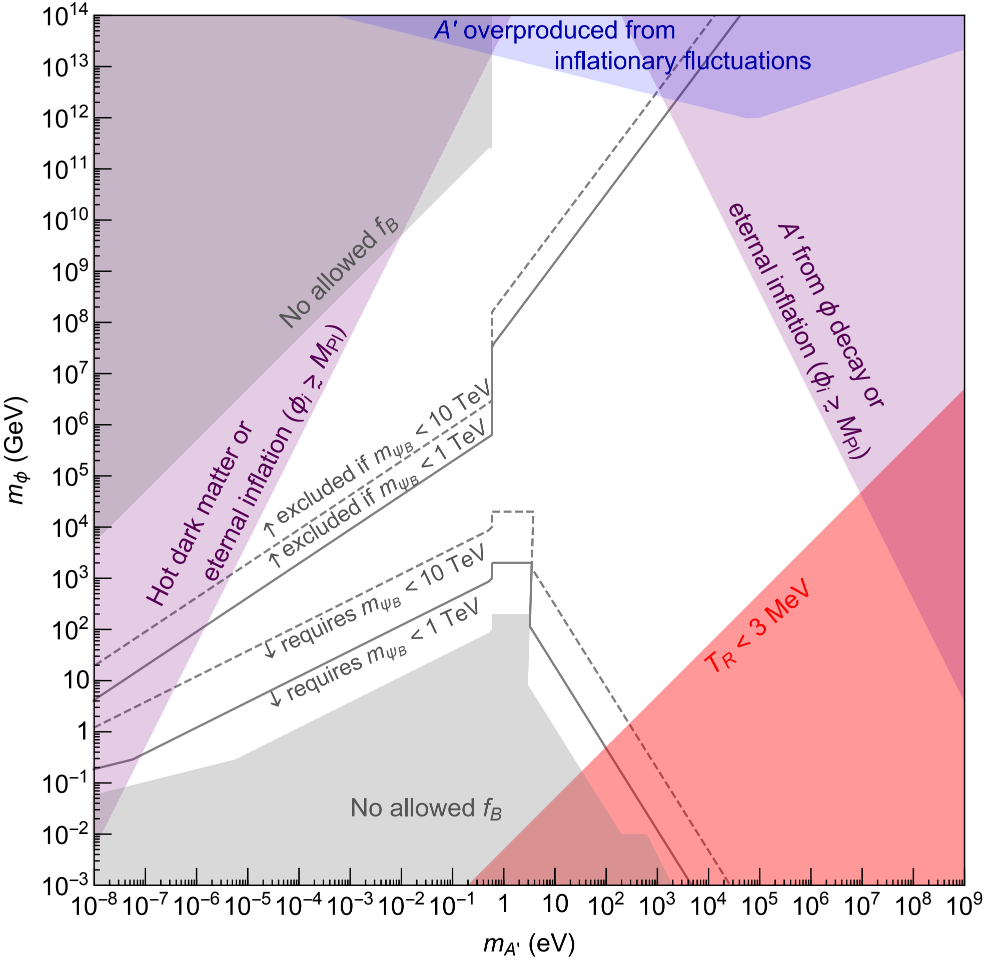

Parametric Resonance

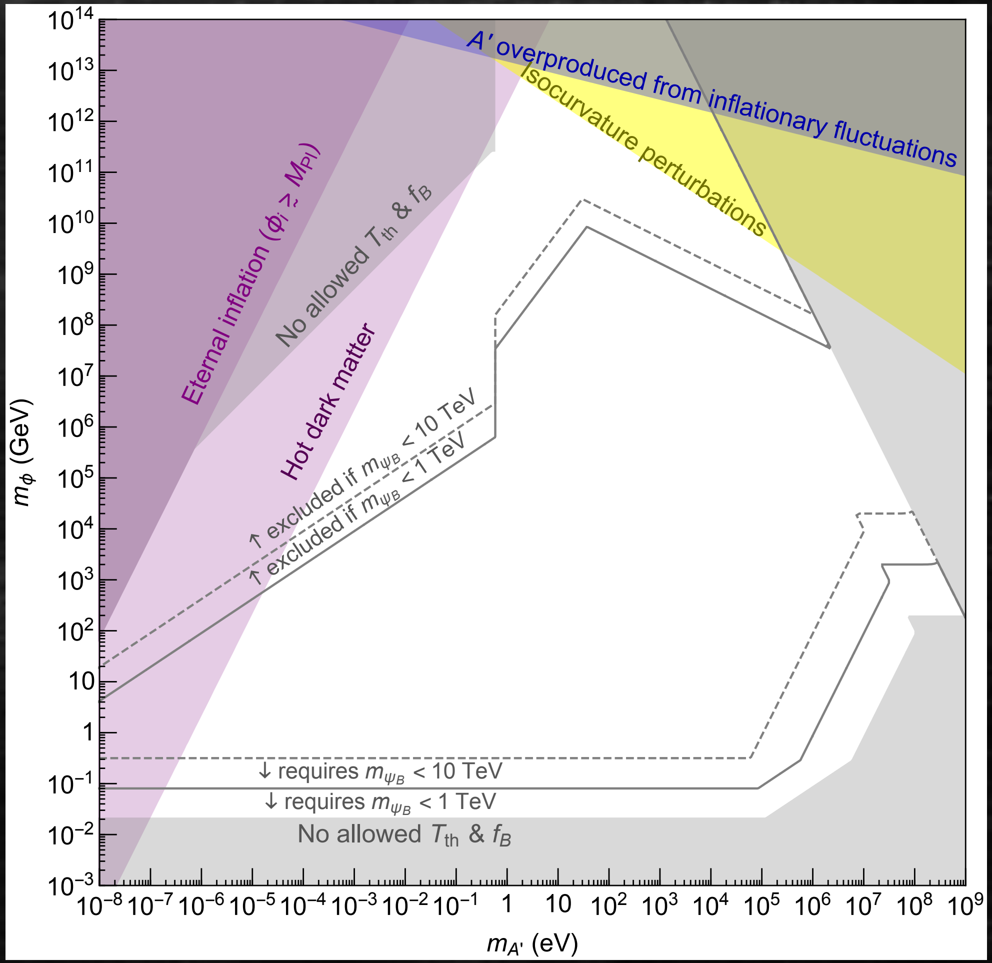

Tachyonic Instability

Dark Photon Dark Matter

Matter Domination



Radiation Domination



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

Exponential Production

- Candidates
  - Axions: parametric resonance
  - Dark photons: tachyonic instability
- Properties
  - Momentum: of order the parent particle mass
  - Production: when the parent particle oscillates

Conclusions

- ✓ Axion's initial misalignment can be dynamically driven to the hilltop or the bottom of the potential.
  - ✓ prediction rather than fine-tuning.
- ✓ Exponential production mechanisms open up explored parameter space of axions and dark photons.
- ✓ Possible signatures:
  - ✓ dark matter searches
  - ✓ dark matter structure formation
  - ✓ warm dark matter
  - ✓ gravitational waves from the non-linear effects