



ACCADEMIA NAZIONALE DEI LINCEI

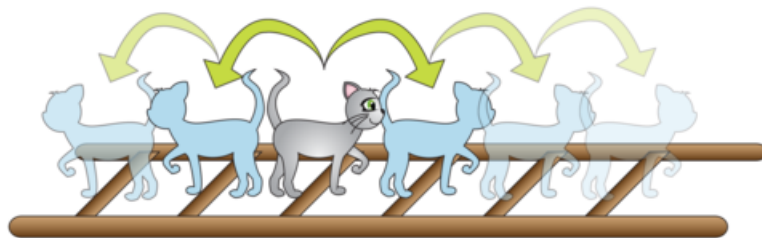
Electroweak, Strong and New Interactions - Symposium

Axion Physics

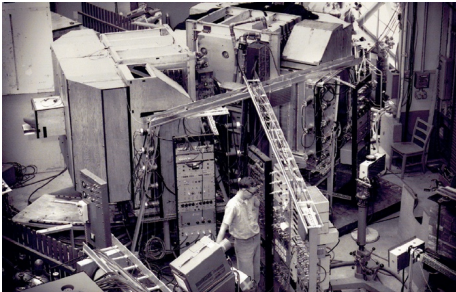
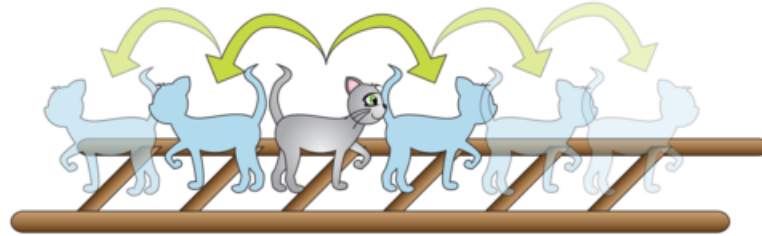
Giovanni Villadoro



Time Reversal



Time Reversal

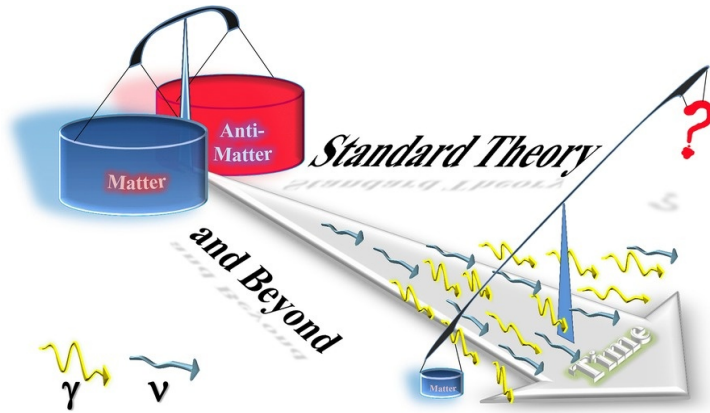
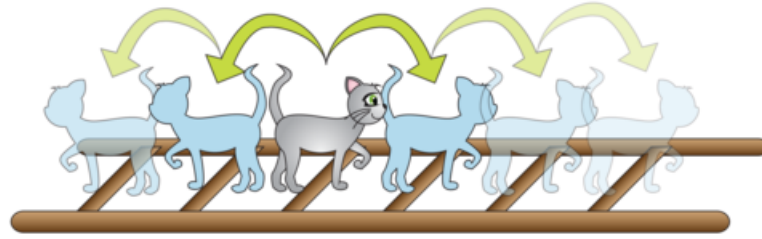


Cronin and Fitch '64

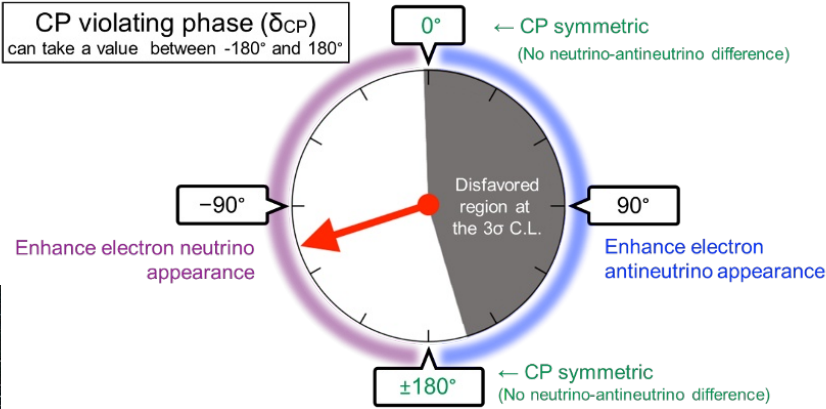
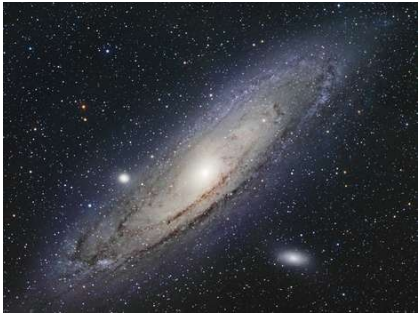
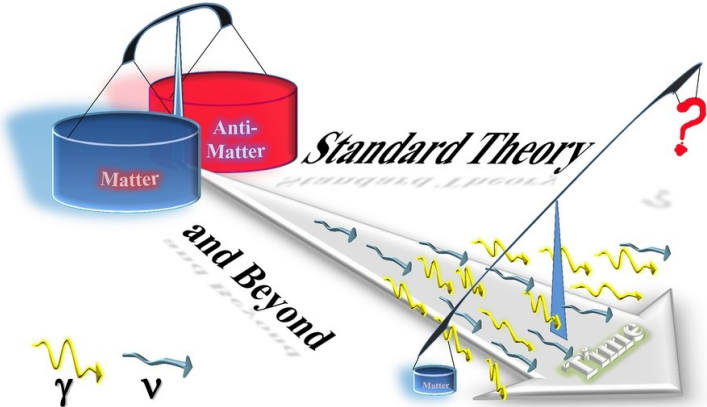
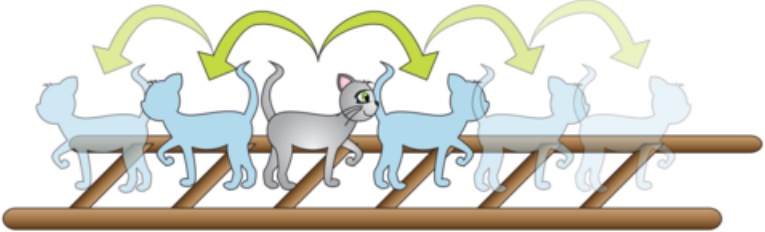
weak nuclear interactions

$$\det [y_u y_u^\dagger, y_d y_d^\dagger] \Rightarrow \delta_{\text{CKM}} \simeq 1.2$$

Time Reversal

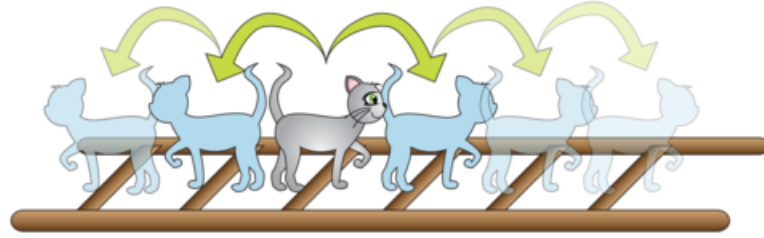


Time Reversal



T2K experiment '19

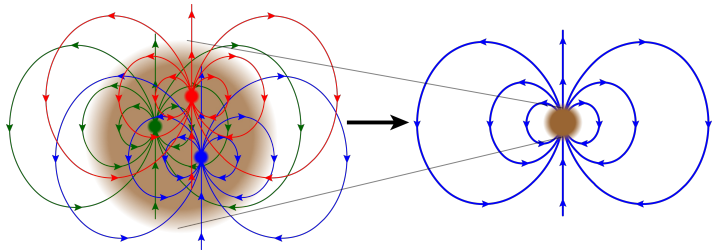
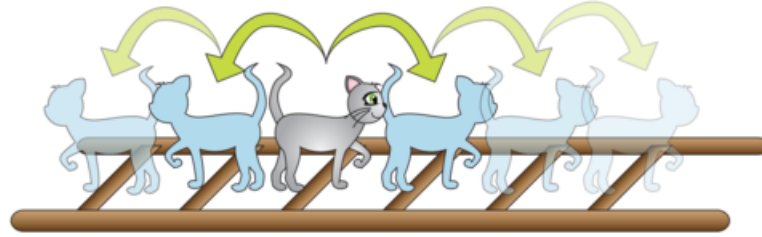
Time Reversal



$$\mathcal{L}_{\text{top}} = \frac{\theta_0}{32\pi^2} G\tilde{G}$$

$$\det(y_u y_d) e^{i\theta_0}$$

Time Reversal



Neutron EDM

$$\mathcal{L}_{\text{top}} = \frac{\theta_0}{32\pi^2} G\tilde{G}$$

$$\det(y_u y_d) e^{i\theta_0} \Rightarrow \theta \lesssim 10^{-10}$$

Strong CP problem!

The QCD Axion Solution

Peccei Quinn '77
Weinberg, Wilczek '78
(KSVZ, DSFZ...)

$U(1)_{PQ}$ with mixed anomaly with $SU(3)_c$ (with SSB)

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$$\mathcal{L}_{SM}^{\theta=0} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a} \frac{\alpha_s}{8\pi} G\tilde{G}$$

$$\theta \rightarrow \frac{a(x)}{f_a}$$

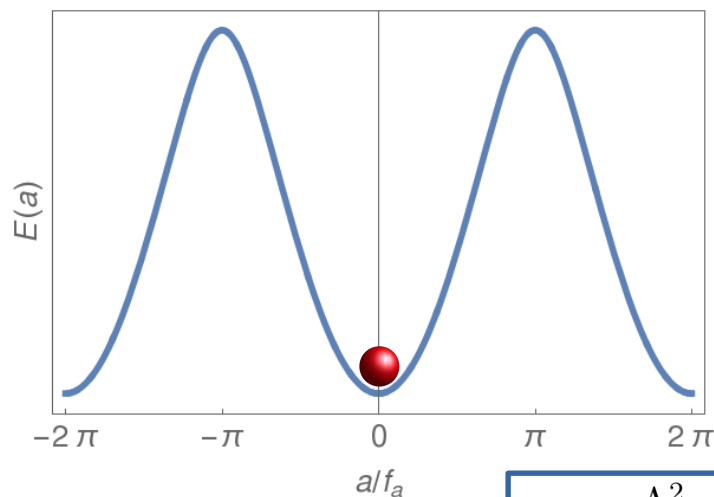
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Vafa Witten '84

$$m_a \approx \frac{\Lambda_{\text{QCD}}^2}{f_a}$$



$$m_a^2 = \frac{\int d^4x \langle G\tilde{G}(x) G\tilde{G}(0) \rangle}{f_a^2} = \frac{\chi_{top}}{f_a^2}$$

From Lattice QCD

Athenodorou et al. '22 $\chi_{top} = (80 \pm 10 \text{ MeV})^4$

Bonati et al. '15 $\chi_{top} = (70 \pm 10 \text{ MeV})^4$

From Chiral Perturbation Theory

$$m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$$

Weinberg '78

the QCD axion: *the mass @NLO*

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Grilli, Hardy, Pardo, GV - 1511.02867

$$m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2} \left[1 + 2 \frac{m_\pi^2}{f_\pi^2} \left(h_1^r - h_3^r - l_4^r + \frac{m_u^2 - 6m_u m_d + m_d^2}{(m_u + m_d)^2} l_7^r \right) \right]$$

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lattice average:

$$z \equiv \frac{m_u^{\overline{\text{MS}}}(2 \text{ GeV})}{m_d^{\overline{\text{MS}}}(2 \text{ GeV})} = 0.48(3)$$

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$$4.8 \pm 1.4 \cdot 10^{-3}$$

$$7(4) \cdot 10^{-3}$$

$$\Delta m_\pi^2|_{(\text{strong})}$$

the QCD axion: *the mass @NLO*

Grilli, Hardy, Pardo, GV - 1511.02867

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$$7(4) \cdot 10^{-3}$$

$$m_a = 5.70(6)(4) \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$$

$$(\chi^{\text{top}})^{1/4} = \sqrt{m_a f_a} = 75.5(5) \text{ MeV}$$

the QCD axion: *the mass beyond NLO*

Gorghetto, GV - 1812.01008

$$m_a = \left[\underbrace{5.815(22)_z(04)_{f_\pi}}_{\text{LO}} \underbrace{-0.121(38)_{\ell_i^r}}_{\text{NLO}} \underbrace{-0.022(07)_{\ell_i^r}(05)_{c_i^r}}_{\text{NNLO}} \underbrace{+0.019(06)_{k_i^r}}_{\text{EM}} \right] \mu\text{eV} \frac{10^{12} \text{ GeV}}{f_a}$$

$$m_a = 5.691(51) \mu\text{eV} \frac{10^{12} \text{ GeV}}{f_a}$$

$$\chi_{\text{top}}^{1/4} = 75.44(34) \text{ MeV}$$

the QCD axion: *the mass beyond NLO*

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QCD Axion Properties

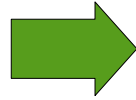
Grilli di Cortona, Hardy, Pardo Vega, Villadoro '15

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} F \tilde{F}$$

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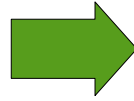


$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a} \left[\frac{E}{N} - 1.92(4) \right] \propto m_a$$

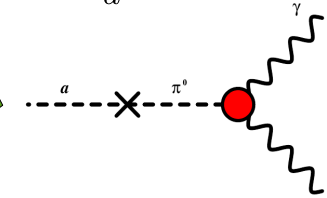
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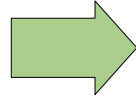
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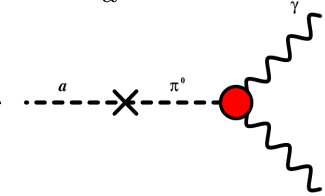
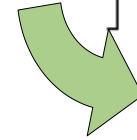
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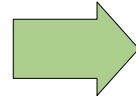
$$\Gamma_{a\gamma\gamma} = \frac{m_a^3}{4\pi} \left(\frac{g_{a\gamma\gamma}}{4} \right)^2$$

$$\tau \approx 10^{18} \tau_U \left(\frac{f_a}{10^9 \text{ GeV}} \right)^5 \approx \tau_U \left(\frac{23 \text{ eV}}{m_a} \right)^5$$

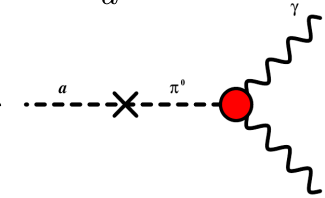
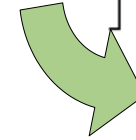
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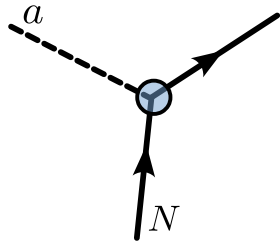


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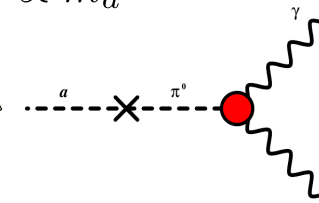
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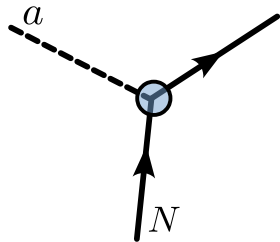
$$\frac{\partial_\mu a}{2f_a} c_N \bar{N} \gamma^\mu \gamma_5 N$$

QCD Axion Properties

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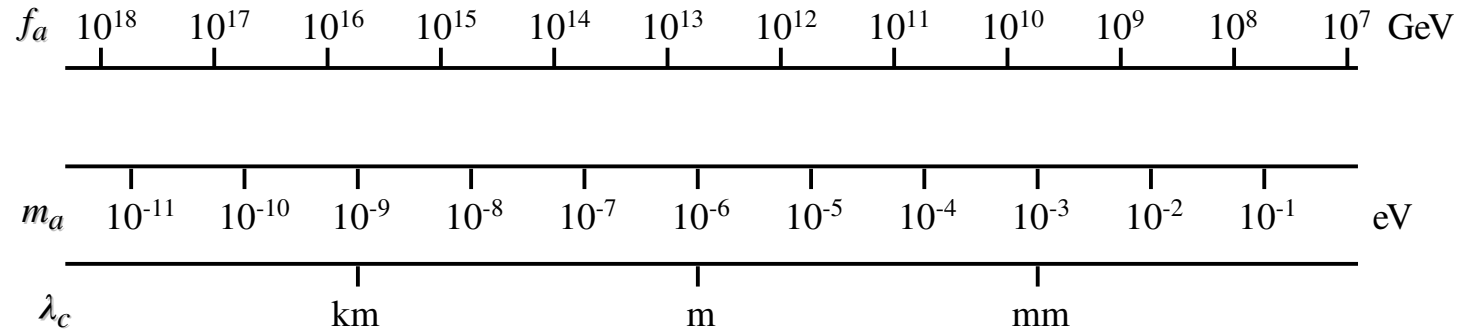
$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} F \tilde{F} \quad \longrightarrow \quad g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a} \left[\frac{E}{N} - 1.92(4) \right] \propto m_a$$


$$\Gamma_{a\gamma\gamma} = \frac{m_a^3}{4\pi} \left(\frac{g_{a\gamma\gamma}}{4} \right)^2 \quad \tau \approx 10^{18} \tau_U \left(\frac{f_a}{10^9 \text{ GeV}} \right)^5 \approx \tau_U \left(\frac{23 \text{ eV}}{m_a} \right)^5$$

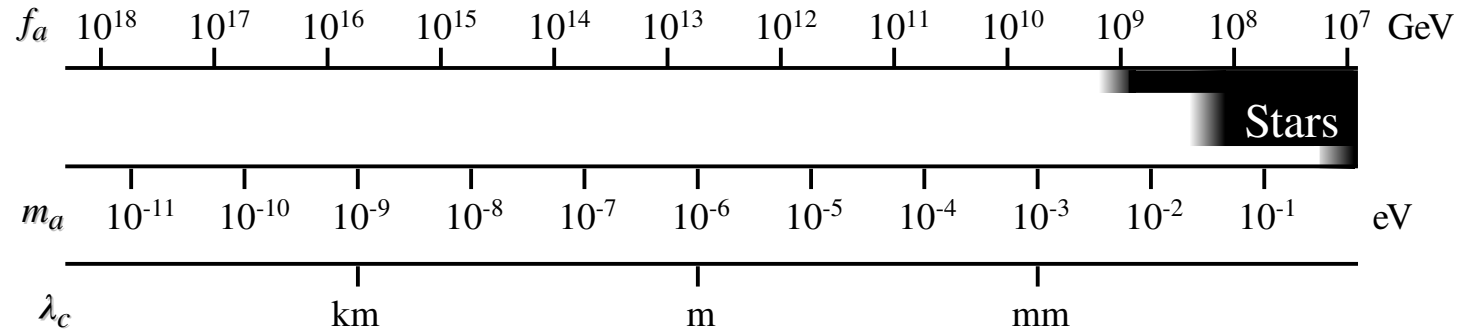


$$\frac{\partial_\mu a}{2f_a} c_N \bar{N} \gamma^\mu \gamma_5 N \quad \left\{ \begin{array}{l} c_p = -0.47(3) + 0.88(3)c_u^0 - 0.39(2)c_d^0 - 0.038(5)c_s^0 \\ \quad \quad \quad - 0.012(5)c_c^0 - 0.009(2)c_b^0 - 0.0035(4)c_t^0, \\ c_n = -0.02(3) + 0.88(3)c_d^0 - 0.39(2)c_u^0 - 0.038(5)c_s^0 \\ \quad \quad \quad - 0.012(5)c_c^0 - 0.009(2)c_b^0 - 0.0035(4)c_t^0, \end{array} \right.$$

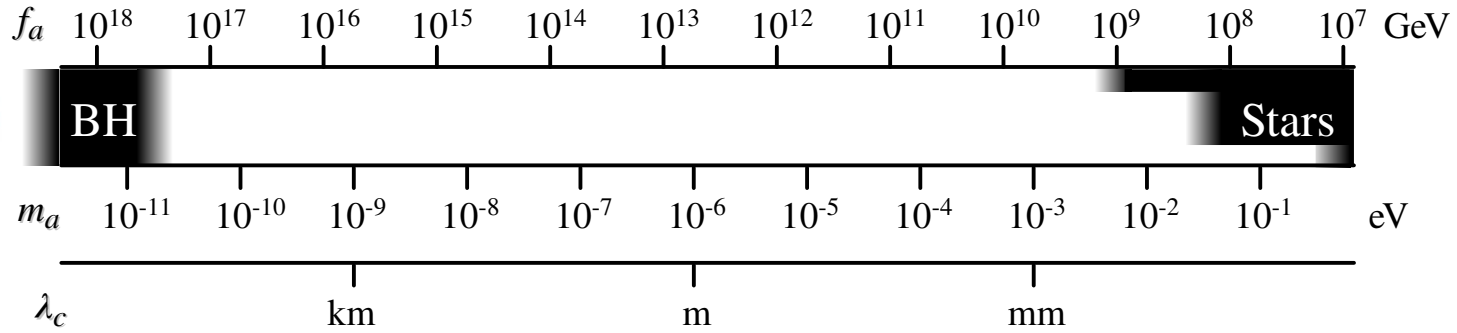
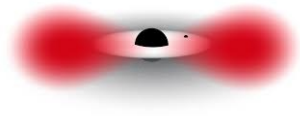
Axion Parameter Space



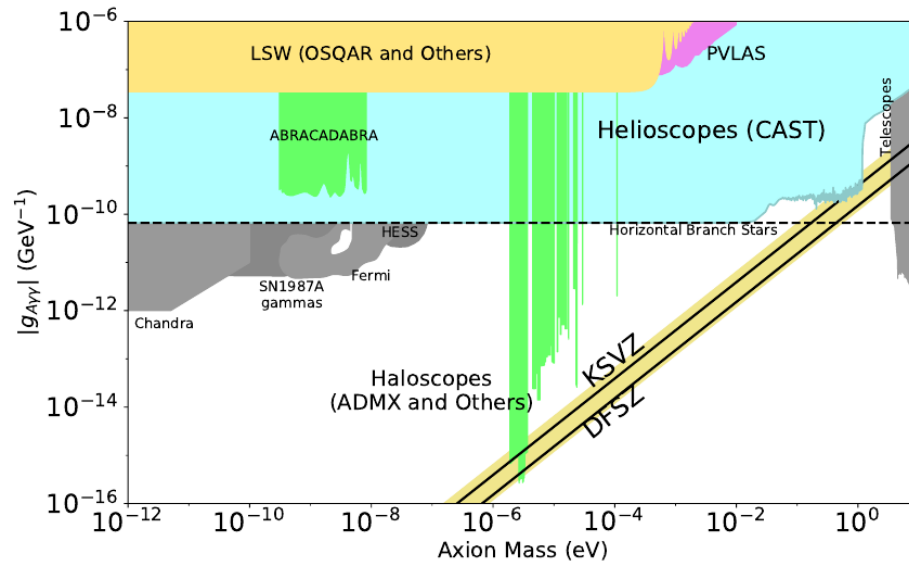
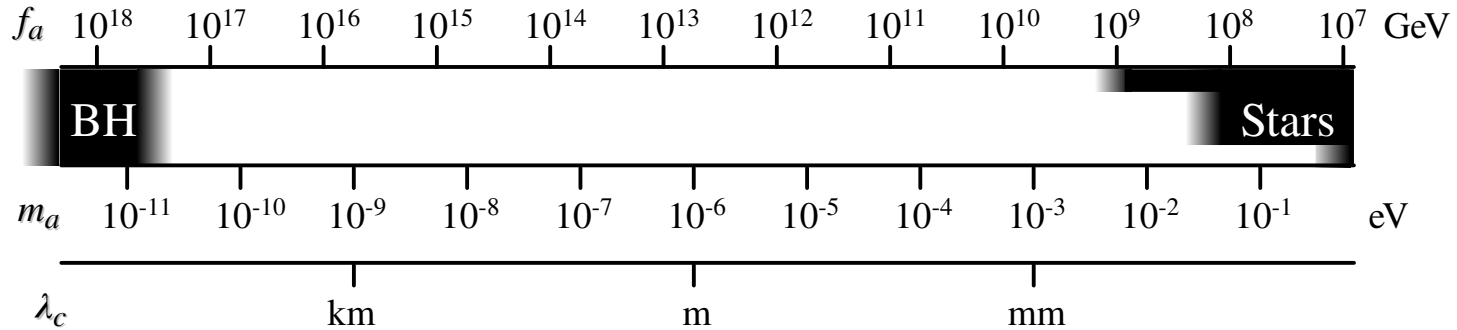
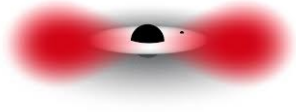
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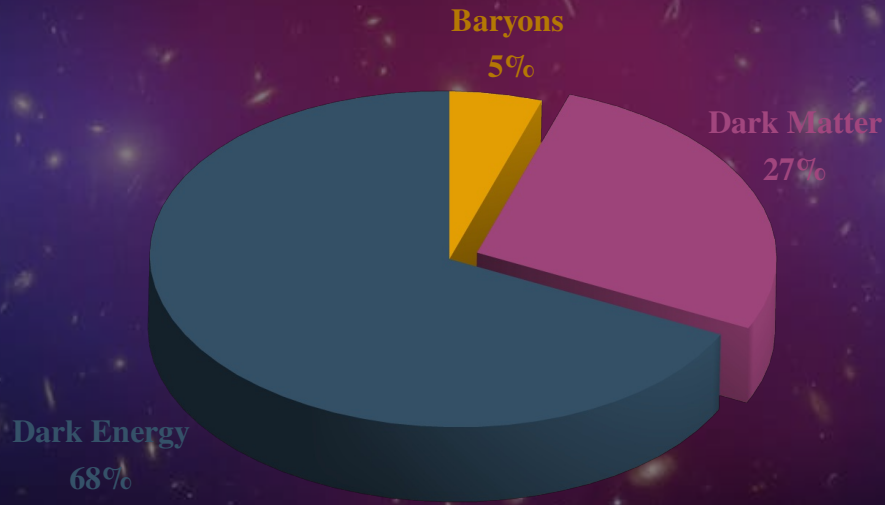
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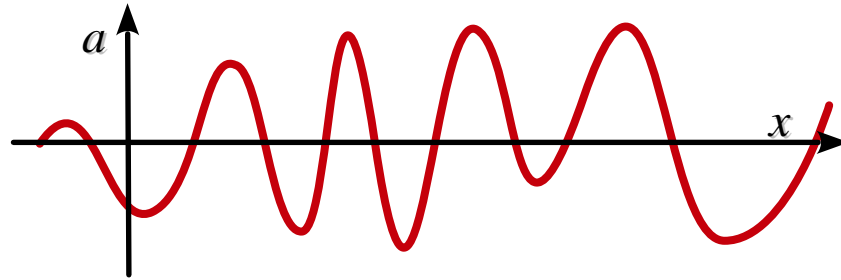
Dark Matter



Preskill, Wise, Wilczek
Abbott, Sikivie
Dine, Fischler, '83

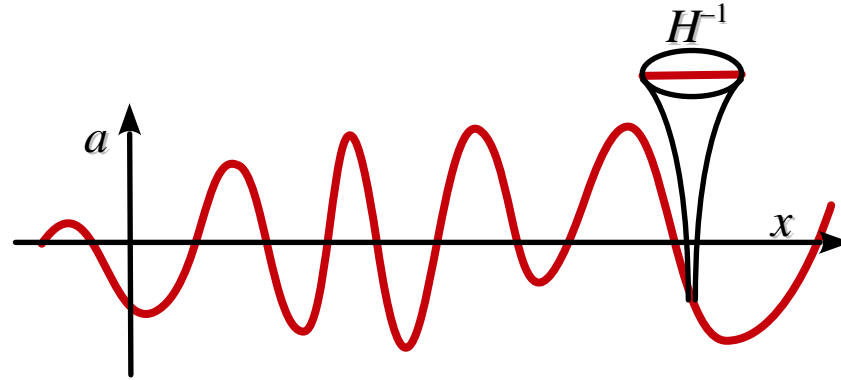
Scenario I: no PQ restoration after inflation

$$f_a > \max\{H_I, T_R\}$$



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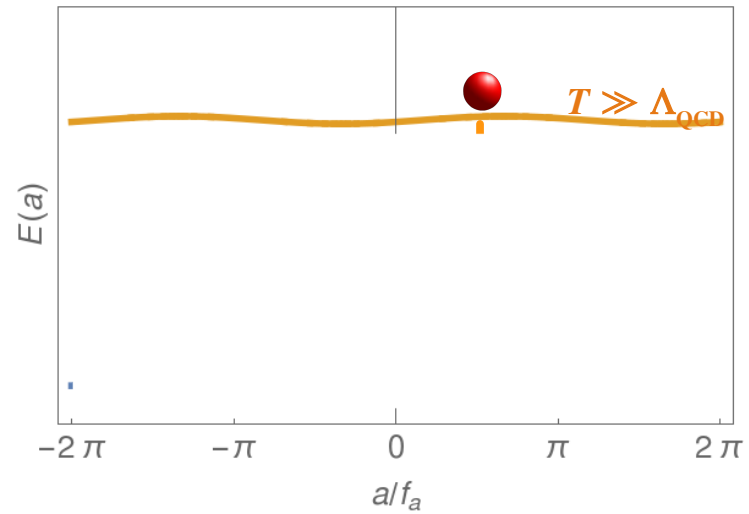


$a(t_0) = \text{const}$ (within Hubble)
after inflation

Scenario I:

$$a(t_0) = \text{const} \equiv \theta_0 f_a$$

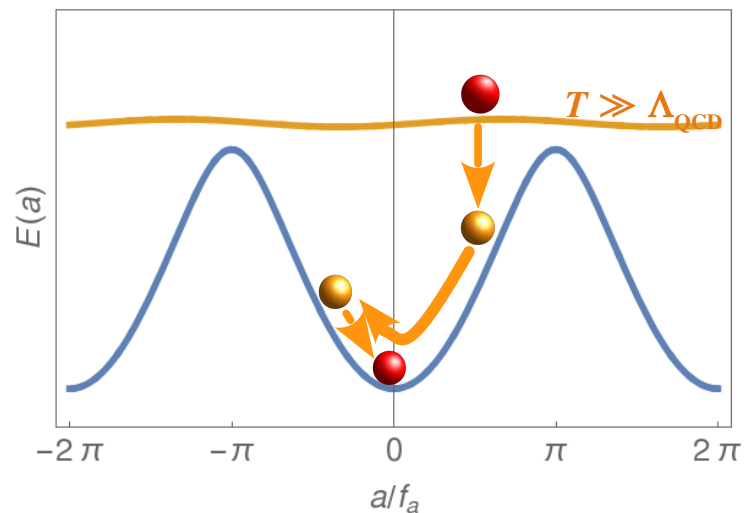
$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$



Scenario I:

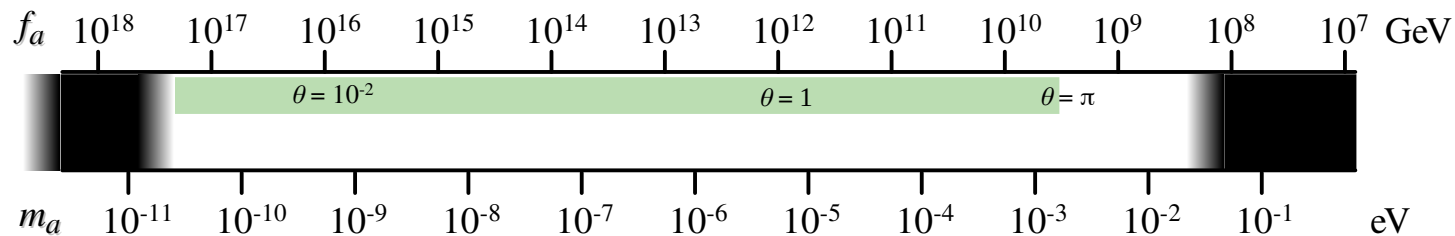
$$a(t_0) = \text{const} \equiv \theta_0 f_a$$

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$



$$\rho_a = m_a^2 a^2$$

$$\Omega_a \simeq \Omega_{DM} \theta_0^2 \left[\frac{f_a}{10^{12} \text{ GeV}} \right]^{\frac{7}{6}}$$



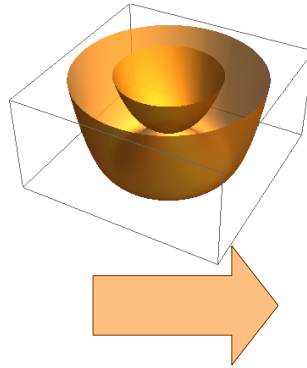
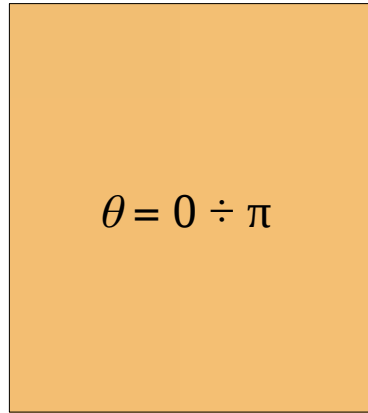
Post-Inflationary Scenario

$$f_a < \max\{H_I, T_{\max}\}$$

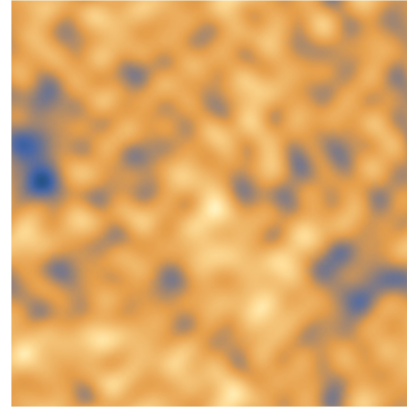

$$\theta = 0 \div \pi$$

Post-Inflationary Scenario

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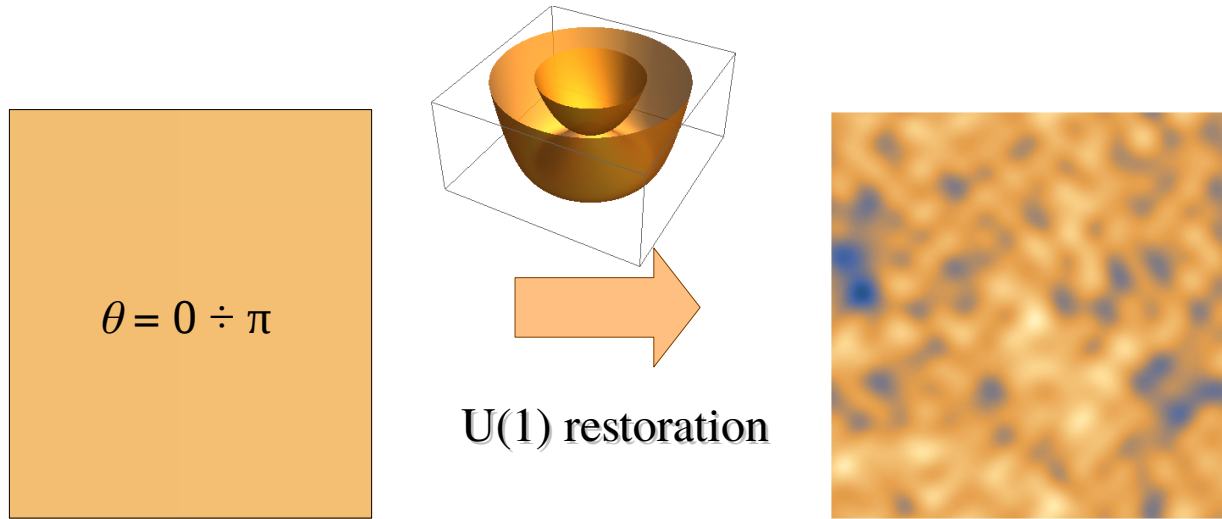


U(1) restoration



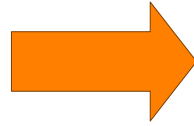
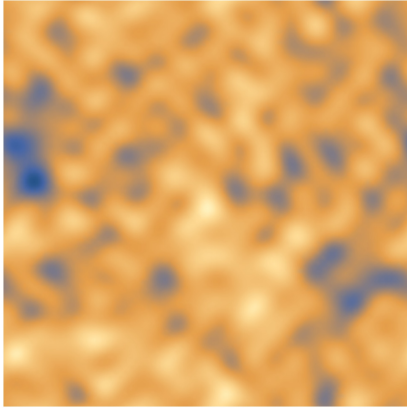
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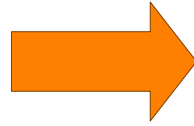
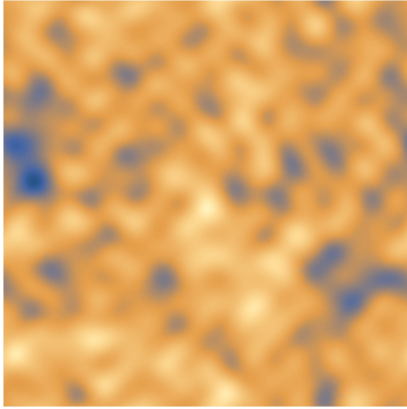


No initial θ dependence

$$\Omega_a = \Omega_{DM} \quad \longrightarrow \quad \text{Prediction for } m_a !$$

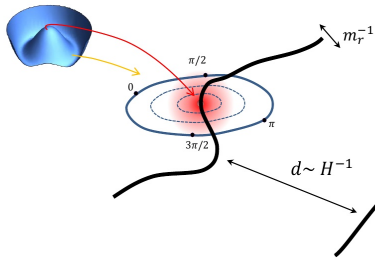


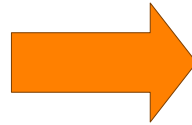
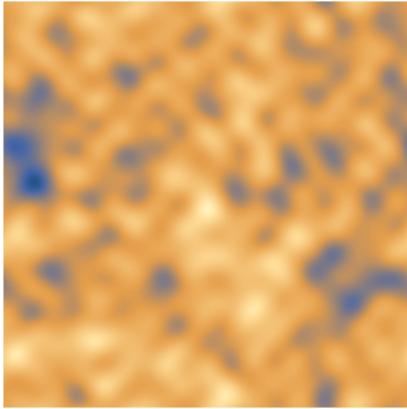
Complex non-linear evolution



Complex non-linear evolution

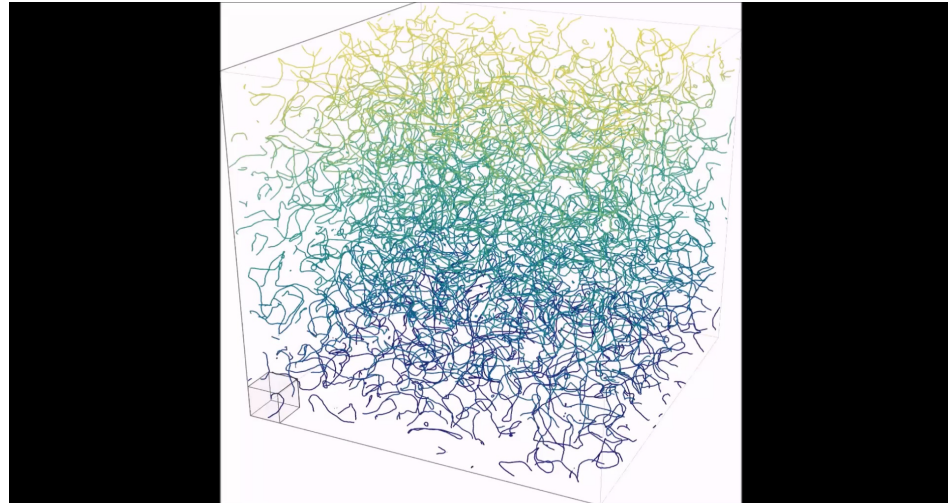
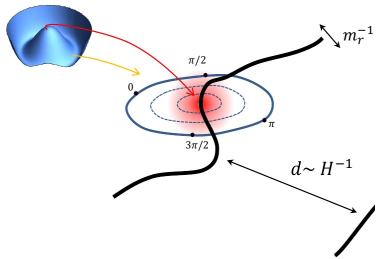
Strings

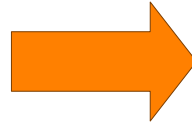
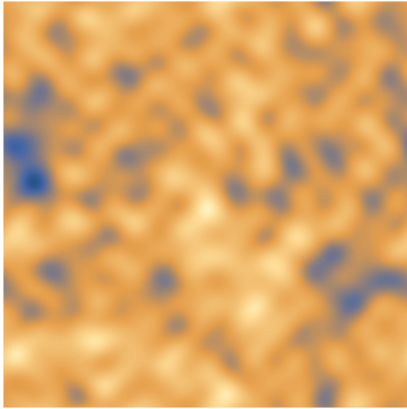




Complex non-linear evolution

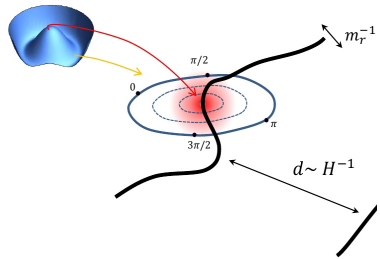
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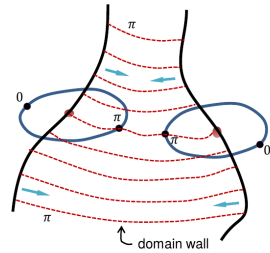


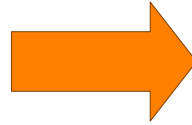
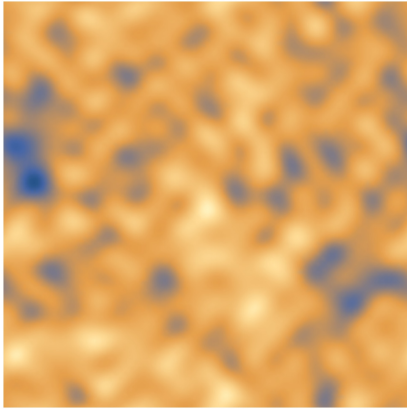
Complex non-linear evolution

Strings



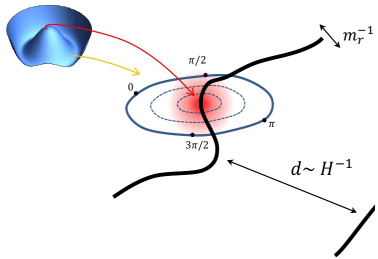
Domain Walls



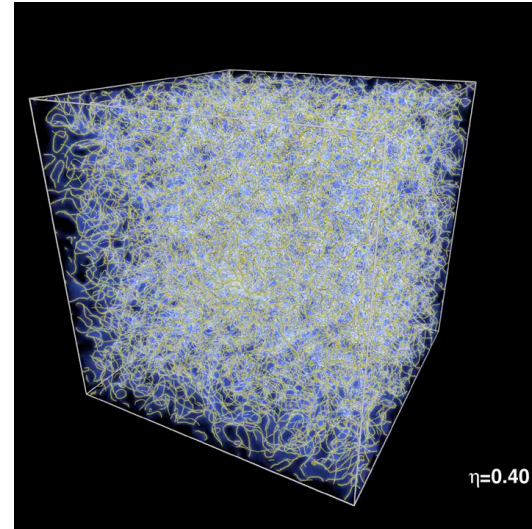
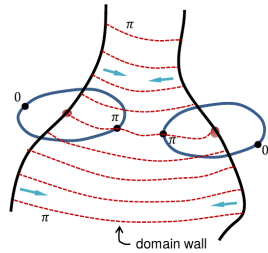


Complex non-linear evolution

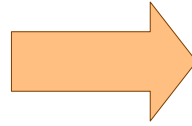
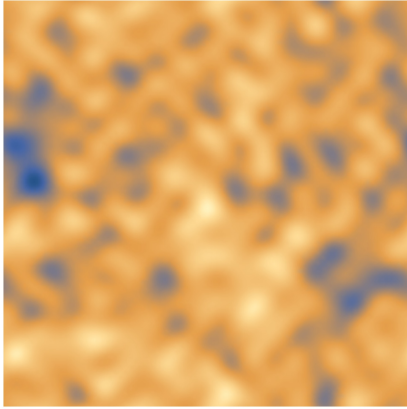
Strings



Domain Walls

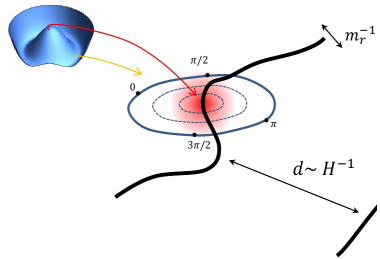


from 1906.00967

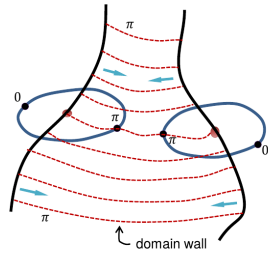


Complex non-linear evolution

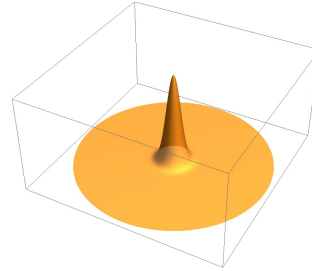
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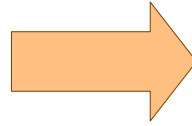
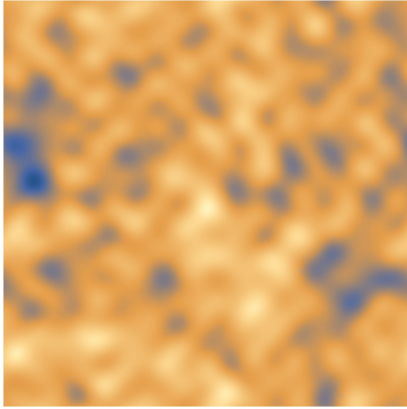


Domain Walls



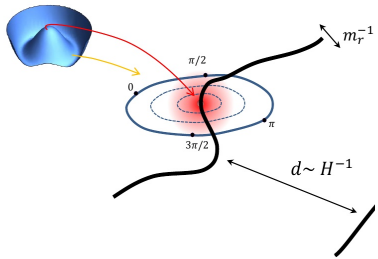
Oscillons



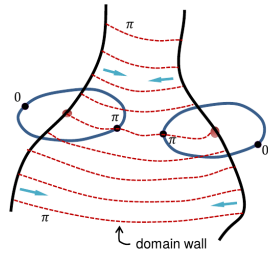


Complex non-linear evolution

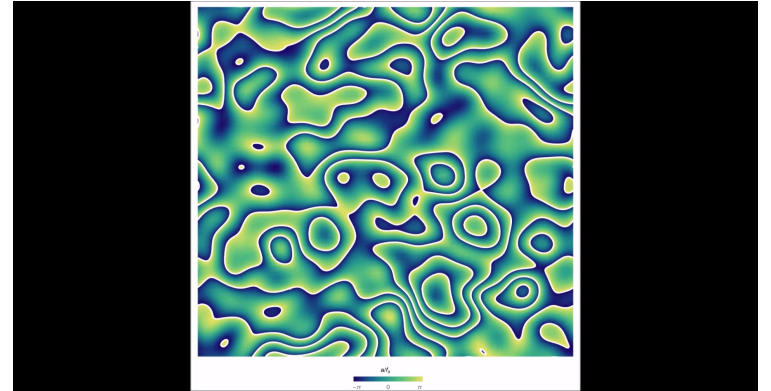
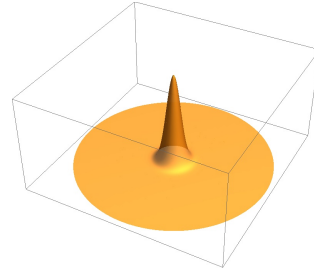
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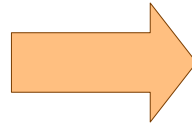
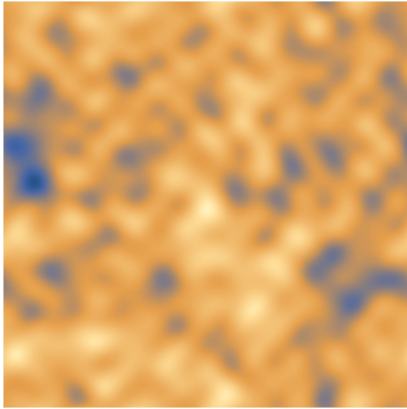


Domain Walls



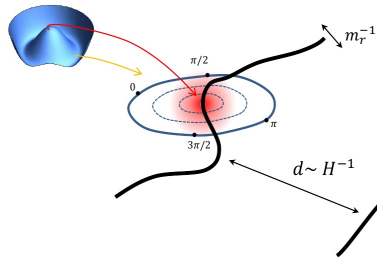
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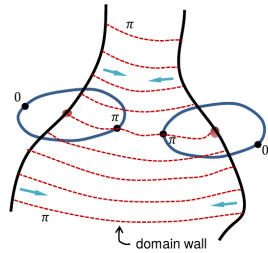


Complex non-linear evolution

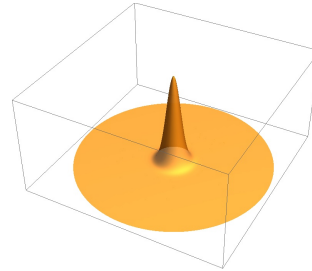
Strings



Domain Walls



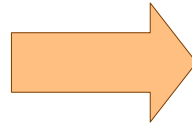
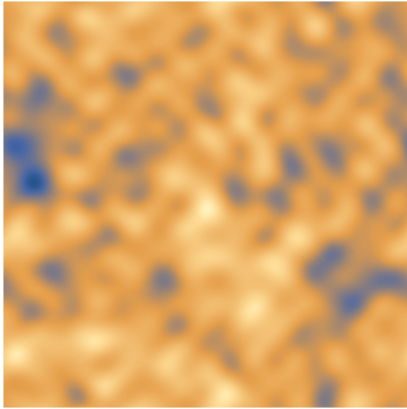
Oscillons



Mini-Clusters

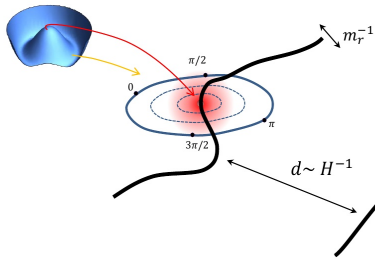


from 1804.05857

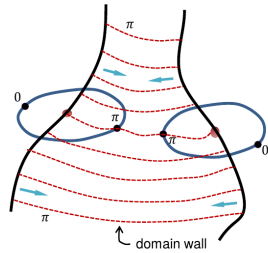


Complex non-linear evolution

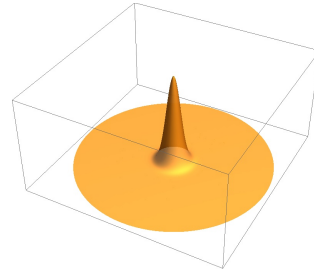
Strings



Domain Walls



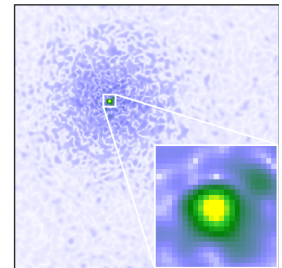
Oscillons



Mini-Clusters

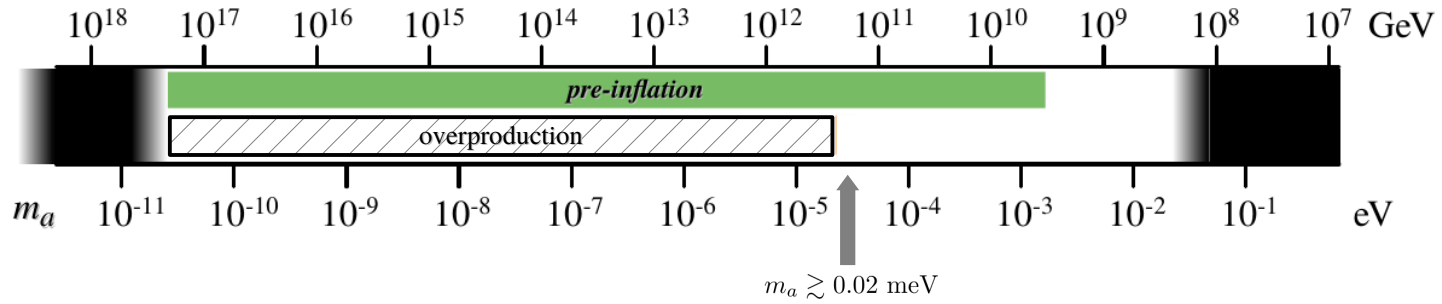


Axion-Stars

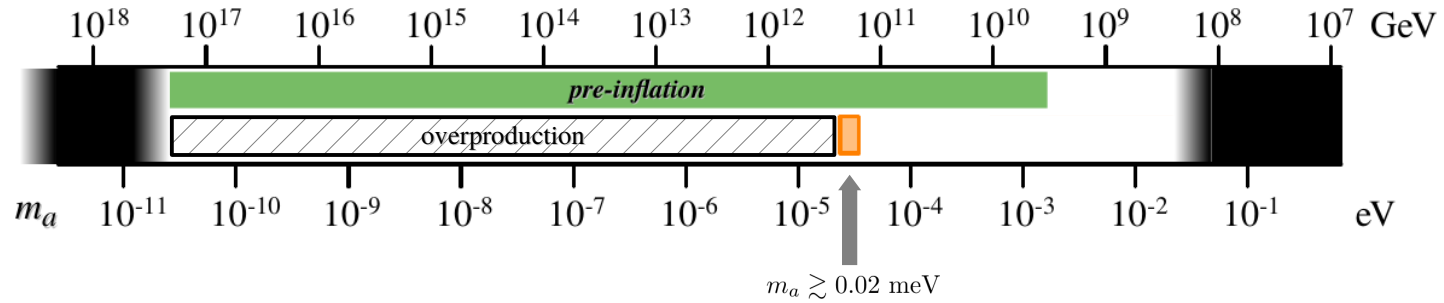


from 1804.05857

QCD Axion Dark Matter

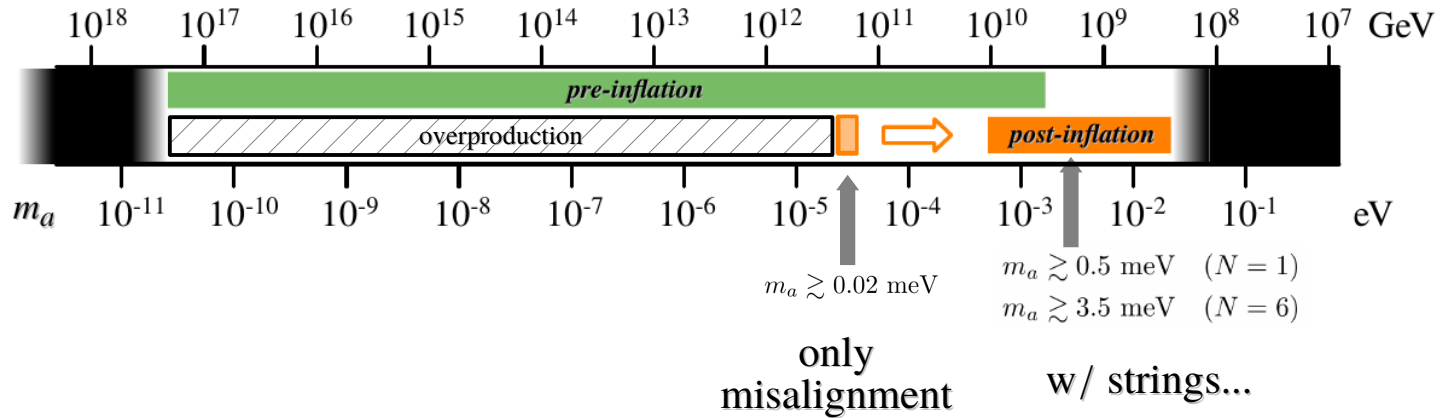


QCD Axion Dark Matter



only
misalignment

QCD Axion Dark Matter



Gorghetto Hardy Villadoro '18 - '20

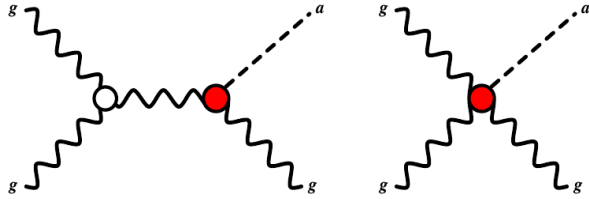
Klaer Moore '17

Kawasaki, Sekiguchi, Yamaguchi, Yokohama '18

Buschmann, Foster, Safdi '19 - '21

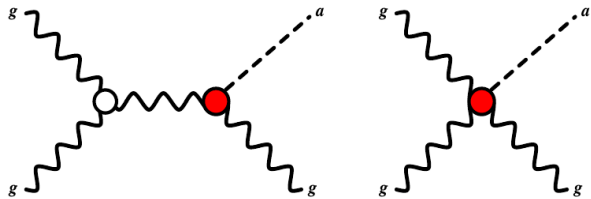
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QCD Axion Cosmology: Thermal Production



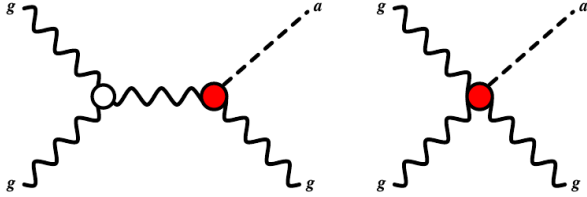
$$H \lesssim \Gamma$$

QCD Axion Cosmology: Thermal Production



$$\xi \frac{T^2}{M_p} = H \lesssim \Gamma = \langle \sigma n v \rangle \approx 10^{-5} \frac{T^3}{f_a^2}$$

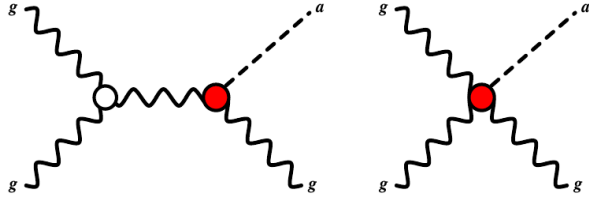
QCD Axion Cosmology: Thermal Production



$$\xi \frac{T^2}{M_p} = H \lesssim \Gamma = \langle \sigma n v \rangle \approx 10^{-5} \frac{T^3}{f_a^2}$$

$$T \gtrsim f_a \left(\frac{f_a}{10^{13} \text{ GeV}} \right)$$

QCD Axion Cosmology: Thermal Production

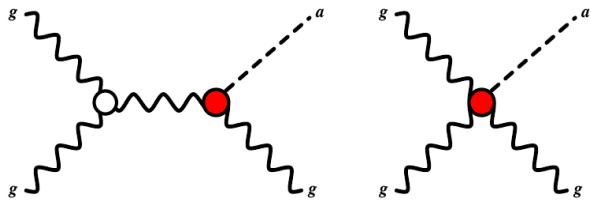


$$\xi \frac{T^2}{M_p} = H \lesssim \Gamma = \langle \sigma n v \rangle \approx 10^{-5} \frac{T^3}{f_a^2}$$

$$T \gtrsim f_a \left(\frac{f_a}{10^{13} \text{ GeV}} \right)$$

$$\Delta N_\nu = \frac{\rho_a}{\rho_\nu} = \frac{4}{7} \left(\frac{g_\nu}{g_{eq}} \right)^{4/3} = 0.0264 \left(\frac{107.75}{g_{eq}} \right)^{4/3}$$

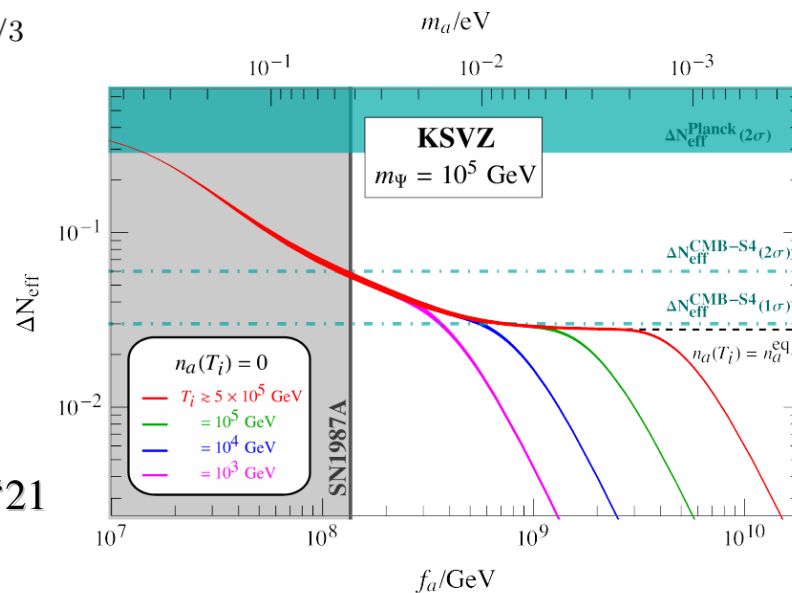
QCD Axion Cosmology: Thermal Production



$$\xi \frac{T^2}{M_p} = H \lesssim \Gamma = \langle \sigma n v \rangle \approx 10^{-5} \frac{T^3}{f_a^2}$$

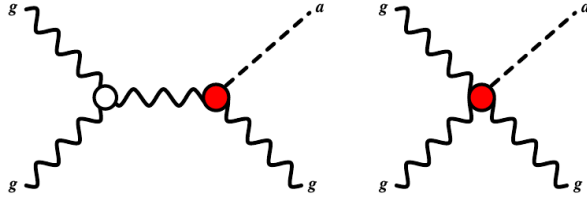
$$T \gtrsim f_a \left(\frac{f_a}{10^{13} \text{ GeV}} \right)$$

$$\Delta N_\nu = \frac{\rho_a}{\rho_\nu} = \frac{4}{7} \left(\frac{g_\nu}{g_{eq}} \right)^{4/3} = 0.0264 \left(\frac{107.75}{g_{eq}} \right)^{4/3}$$



from d'Eramo, Hajkarim, Yun '21

QCD Axion Cosmology: Thermal Production



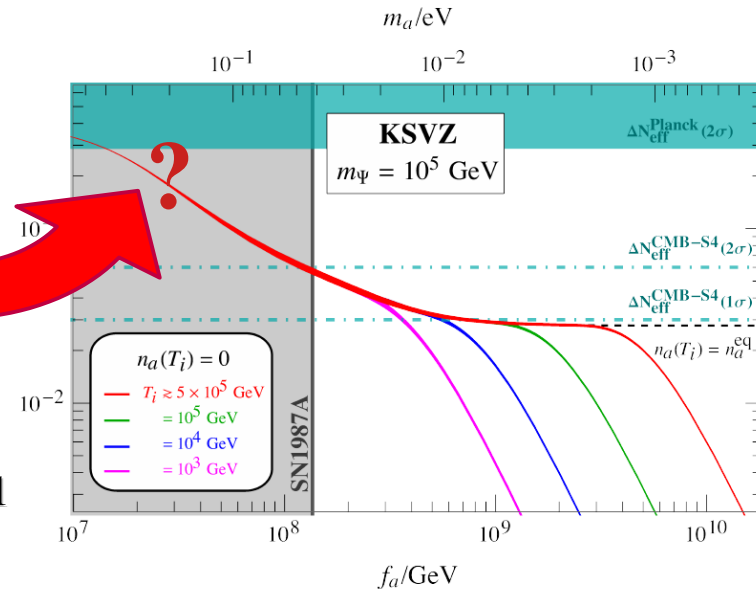
$$\xi \frac{T^2}{M_p} = H \lesssim \Gamma = \langle \sigma n v \rangle \approx 10^{-5} \frac{T^3}{f_a^2}$$

$$T \gtrsim f_a \left(\frac{f_a}{10^{13} \text{ GeV}} \right)$$

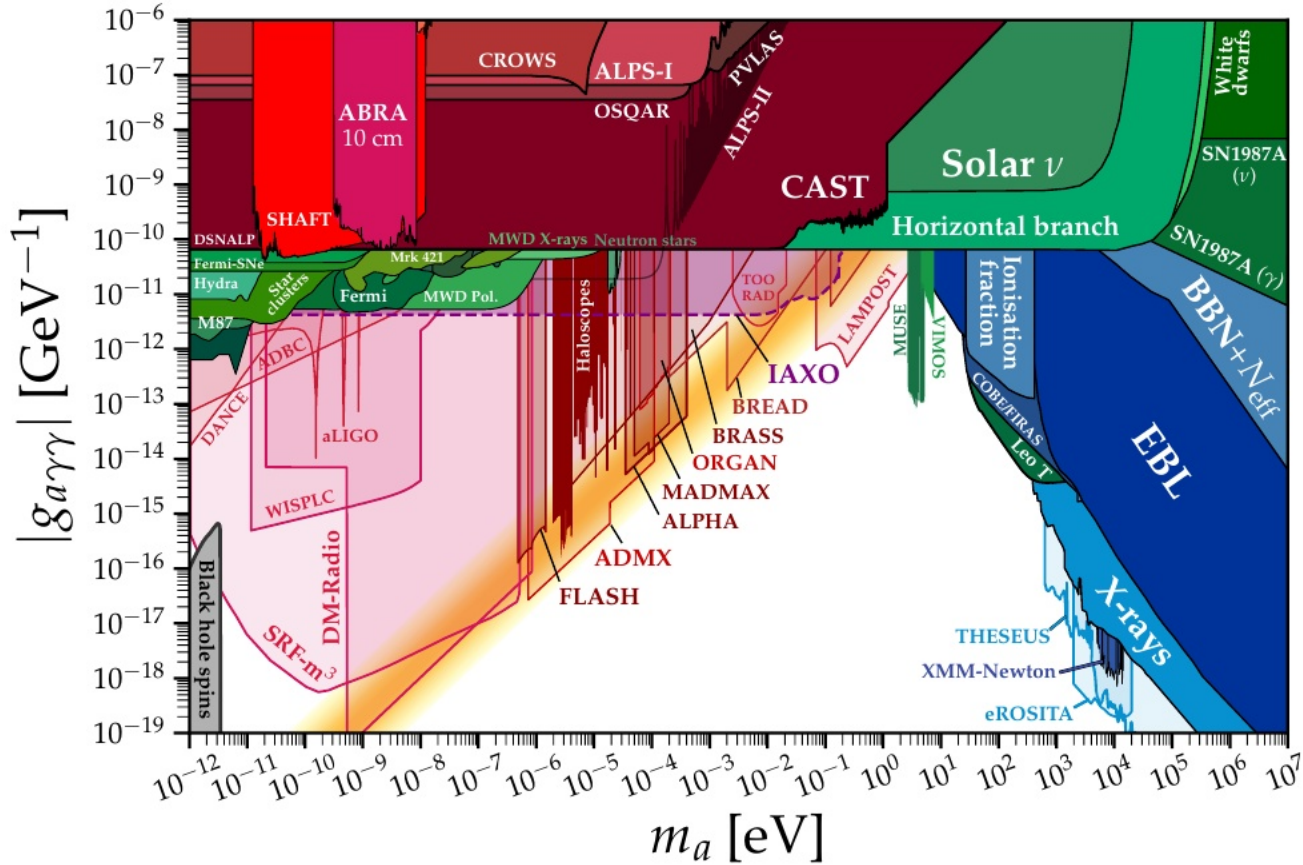
$$\Delta N_\nu = \frac{\rho_a}{\rho_\nu} = \frac{4}{7} \left(\frac{g_\nu}{g_{eq}} \right)^{4/3} = 0.0264 \left(\frac{107.75}{g_{eq}} \right)^{4/3}$$

di Luzio, Martinelli, Piazza '21

from d'Eramo, Hajkarim, Yun '21



Axion Future Present and Future Searches



2203.14923

