Resonant conversion of QCD axions into hidden axions and suppressed isocurvature perturbations

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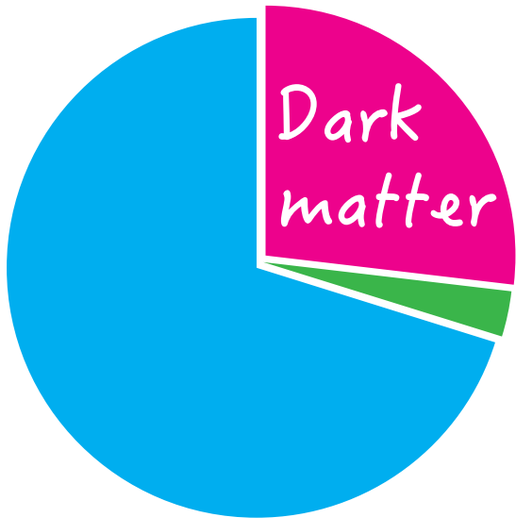
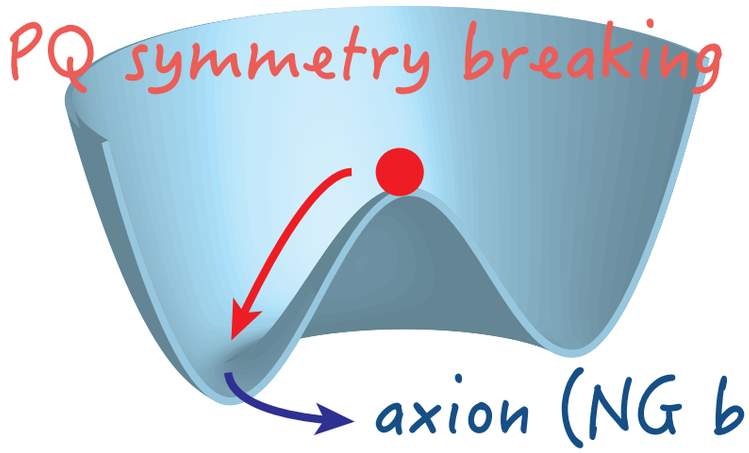
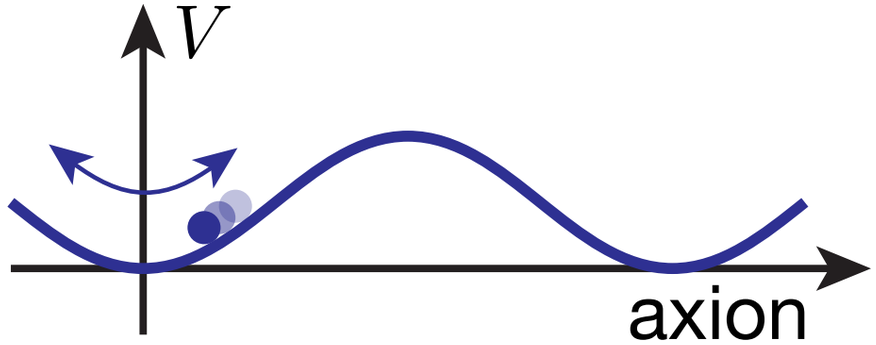
1. Introduction



- Our Universe is filled with the Dark matter

- Axion may exist <= strong CP problem

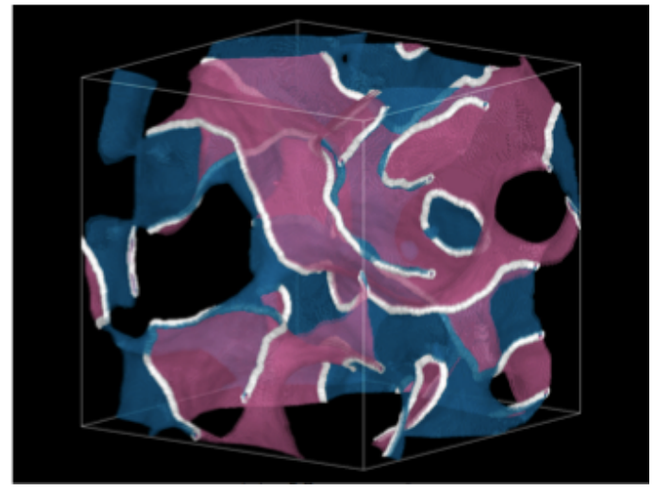




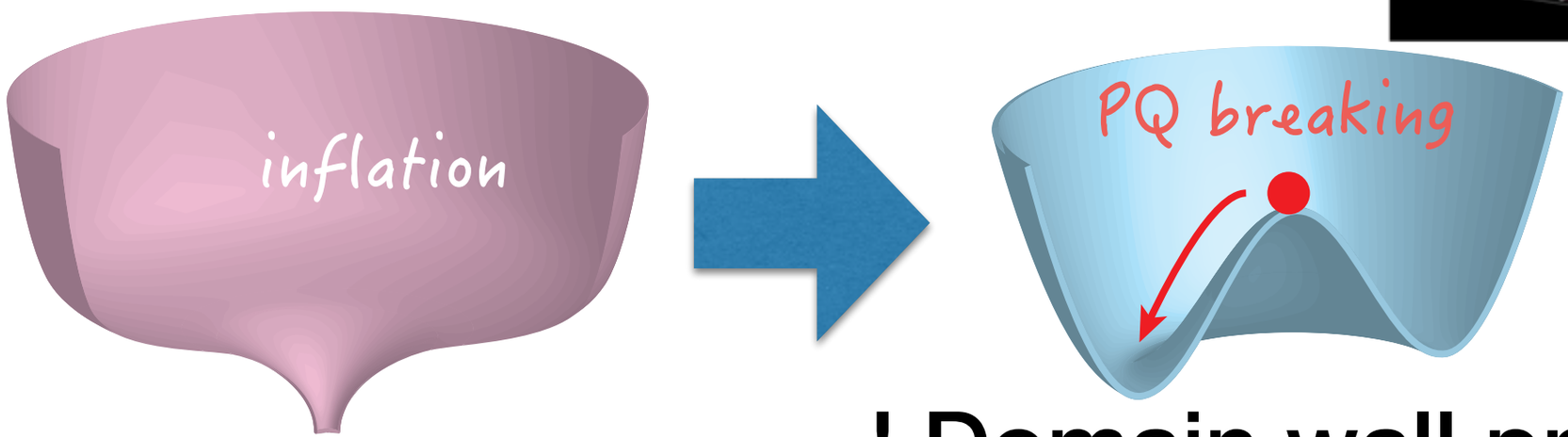
$$\Omega_a h^2 \simeq 0.195 \theta_i^2 f(\theta_i) \left(\frac{F_a}{10^{12}\ \mathrm{GeV}} \right)^{1.184}$$

Axion = Dark matter

Two scenarios :

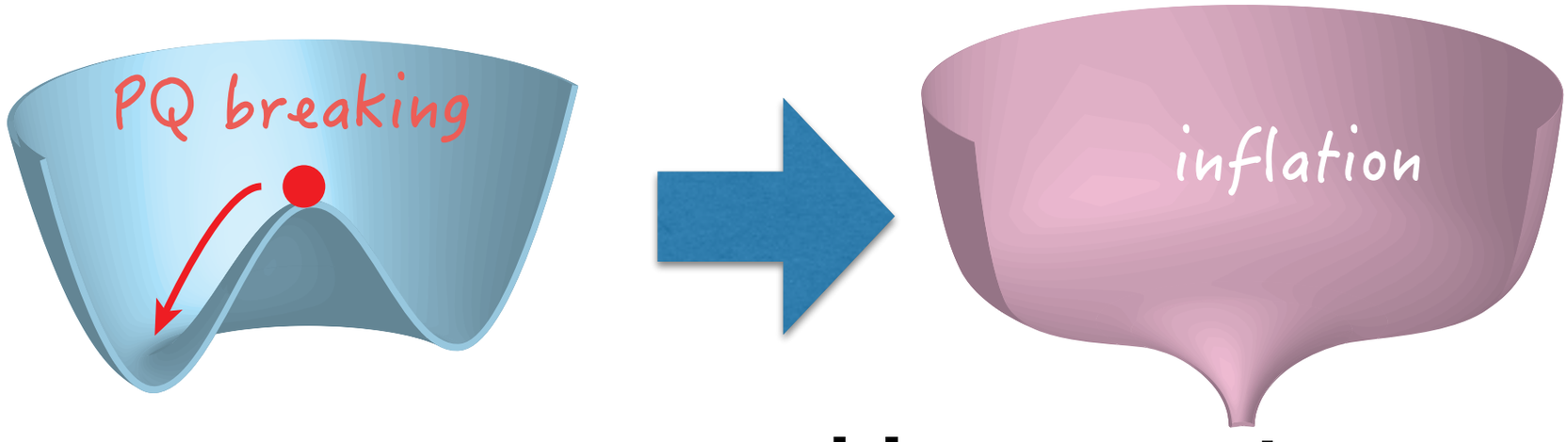


(a) inflation => PQ breaking



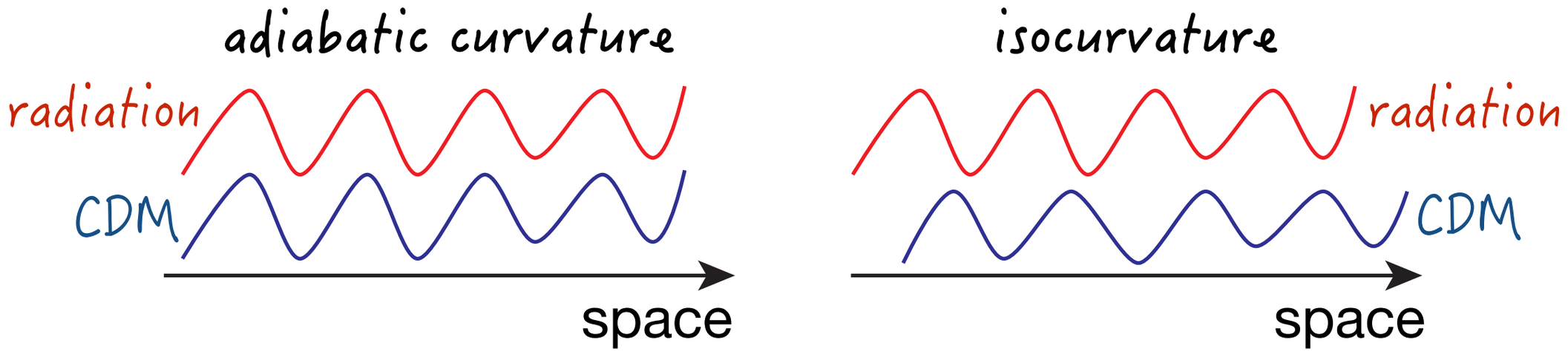
! Domain wall problem

(b) PQ breaking => inflation



! Isocurvature problem

Isocurvature problem



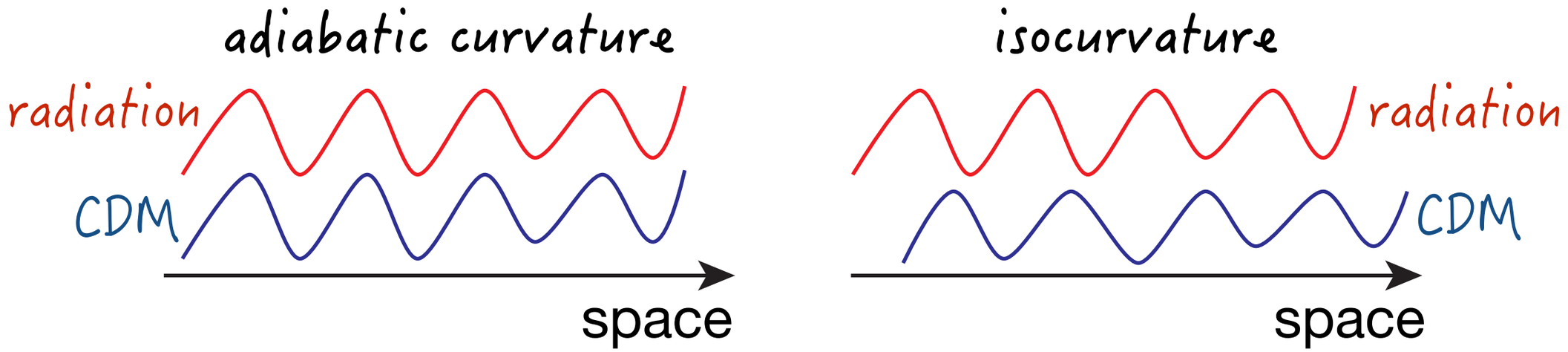
Axion CDM isocurvature perturbation

$$\Delta_{\mathcal{S},\mathrm{CDM}} = \left(\frac{\Omega_a}{\Omega_{\mathrm{CDM}}}\right)\Delta_{\mathcal{S},a} \quad \text{and} \quad \Delta_{\mathcal{S},a} = \frac{\partial \ln \Omega_a}{\partial \theta_i}\frac{H_{\mathrm{inf}}}{2\pi F_a} \sim \frac{\delta\Omega_a}{\Omega_a}$$

Current constraint : $\Delta^2_{\mathcal{S},\mathrm{CDM}} < \dfrac{\beta}{1-\beta}\Delta^2_{\mathcal{R}}$ with $\beta = 0.039$

Planck collaboration:1303.5076,1303.5082

Isocurvature problem



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Tightly constrained

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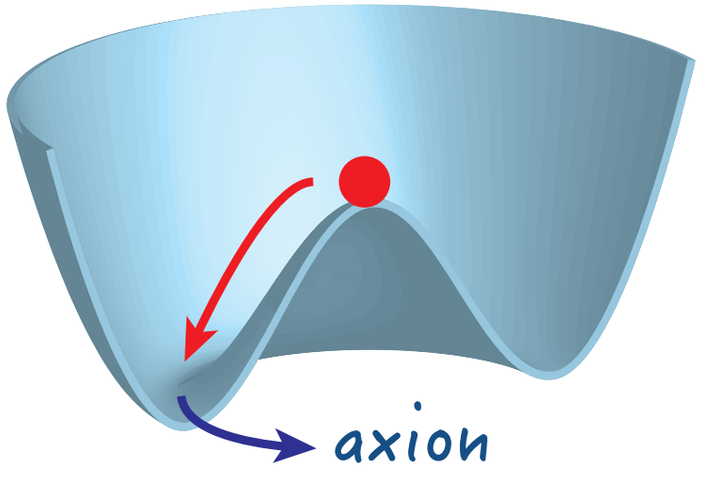
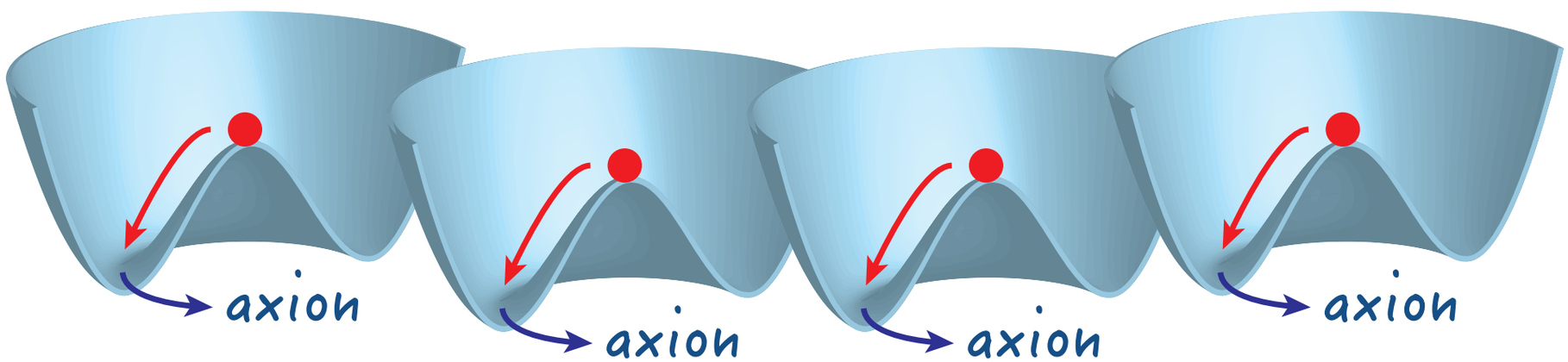


Single axion?

or

Multi-axion?



QCD axion + Hidden axion

with mass mixing

MSW-like resonance

Abundance is suppressed

Hill and Ross, Nucl.Phys.(1988)

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Our work

- Precise numerical calculations
- Implication for isocurvature perturbations

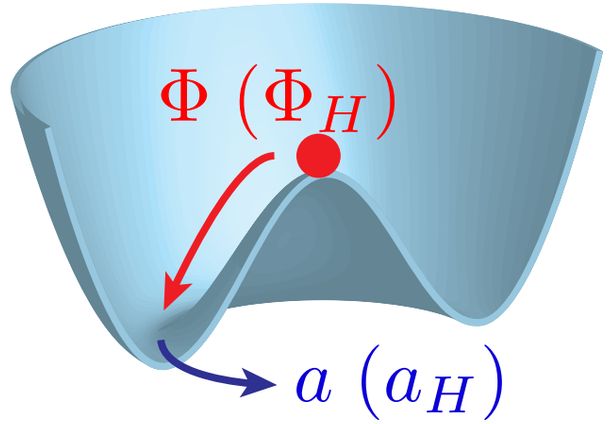
New suppression mechanism for isocurvature perturbations

2. Model

PQ field & hidden PQ field with heavy quarks

$$\mathcal{L} = \kappa \Phi Q \bar{Q} + \frac{\lambda}{M_P} \Phi \Phi_H Q_H \bar{Q}_H$$

$\mathrm{U(1)_{PQ}}$ & $\mathrm{U(1)_H}$



Potential for QCD and hidden axions

$$V(a, a_H) = m_a^2(T) F_a^2 \left[1 - \cos\left(\frac{a}{F_a}\right)\right] + m_H^2 F_H^2 \left[1 - \cos\left(\frac{a_H}{F_H} + \frac{a}{F_a}\right)\right]$$

m_a, m_H : masses

F_a, F_H : decay constants

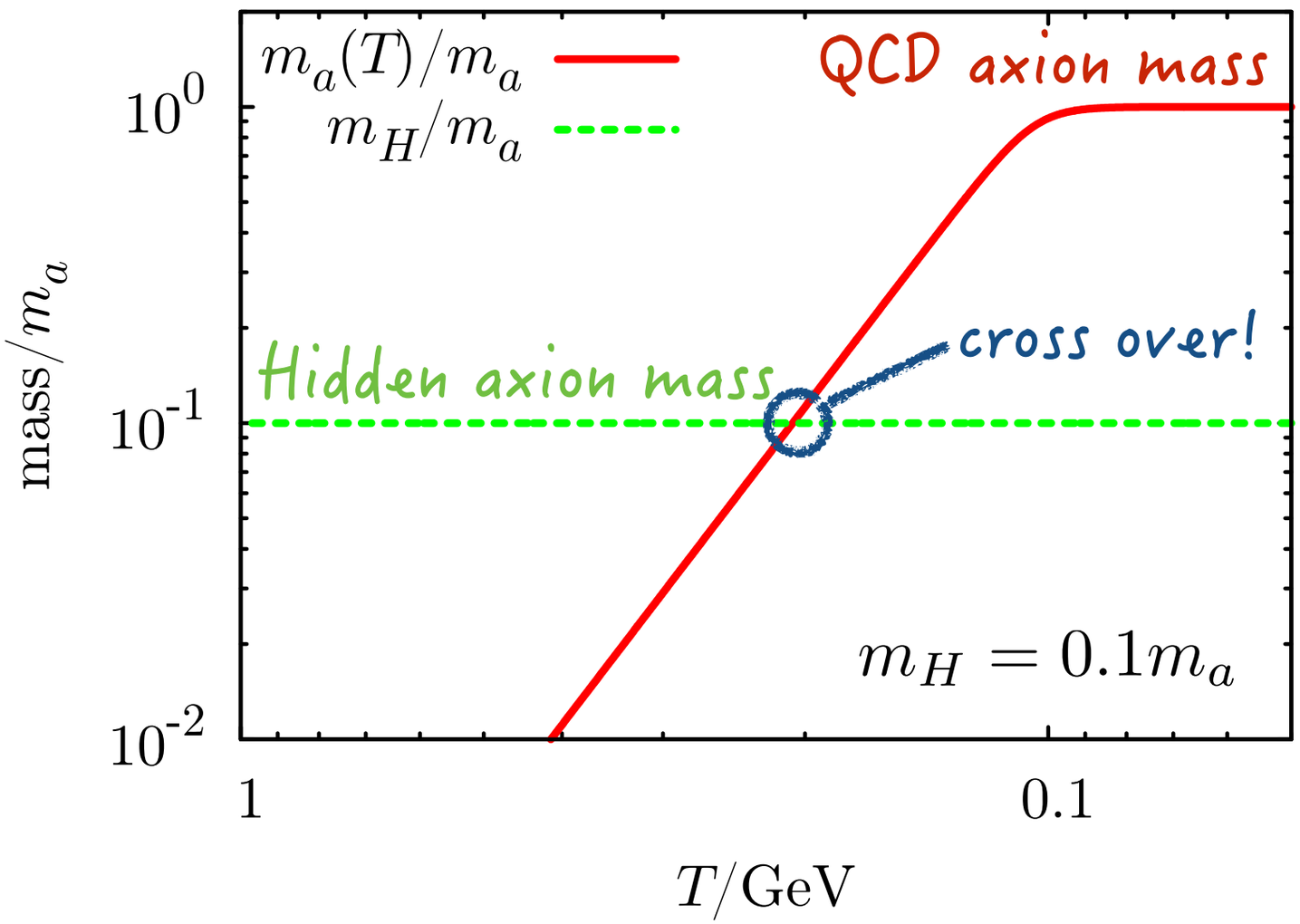
Charge assignments

	Φ	Φ_H	Q	$\bar{Q}$	Q_H	$\bar{Q}_H$
$\mathrm{U(1)_{PQ}}$	1	0	1/2	−1/2	1/2	−1/2
$\mathrm{U(1)_H}$	0	1	0	0	1/2	−1/2

Temperature dependent QCD axion mass

$$m_a(T) = \begin{cases} 4.05 \times 10^{-4} \dfrac{\Lambda_{\rm QCD}^2}{F_a} \left(\dfrac{T}{\Lambda_{\rm QCD}} \right)^{-3.34} & \text{for } T > 0.26\Lambda \\ 3.82 \times 10^{-2} \dfrac{\Lambda_{\rm QCD}^2}{F_a} & \text{for } T < 0.26\Lambda_{\rm QCD}, \end{cases}$$

If zero temp. QCD axion mass >> hidden axion mass…



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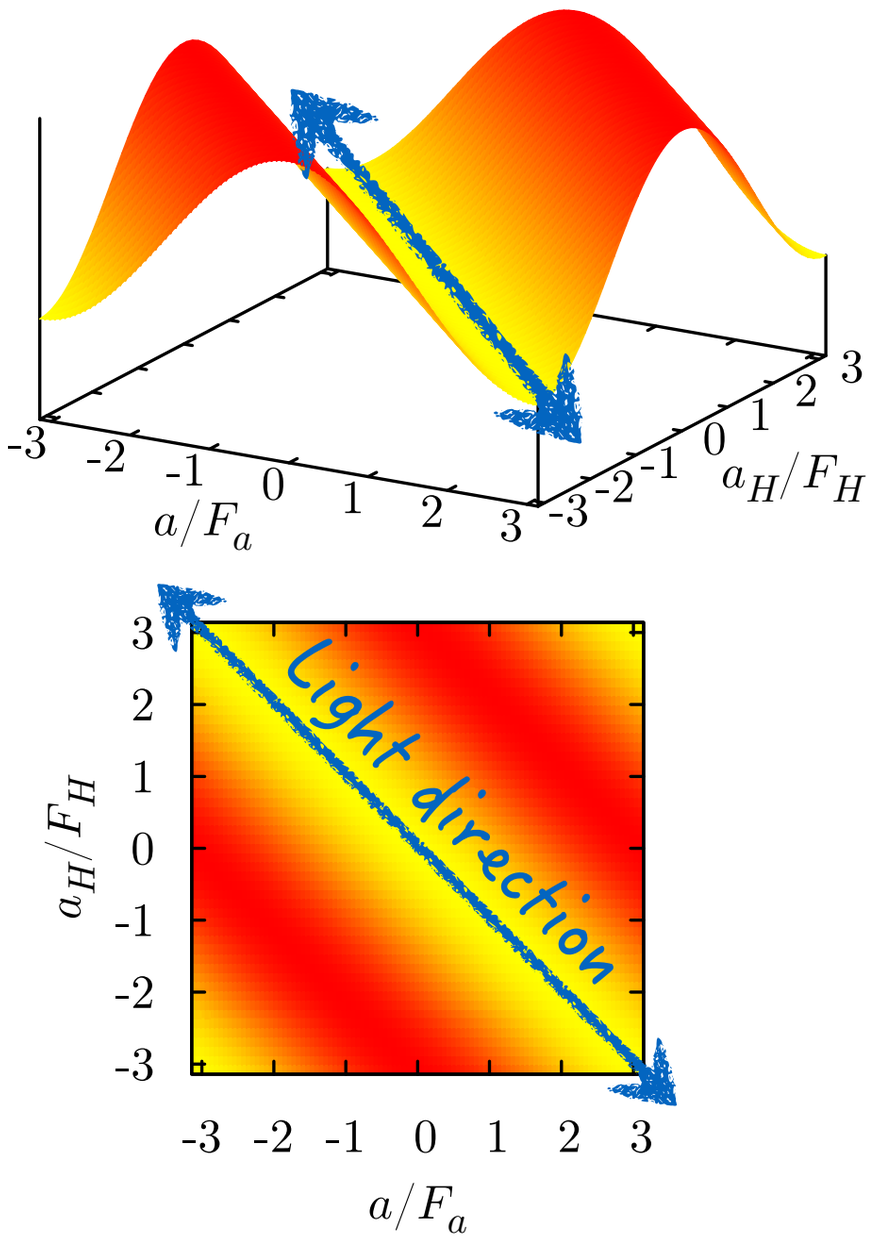
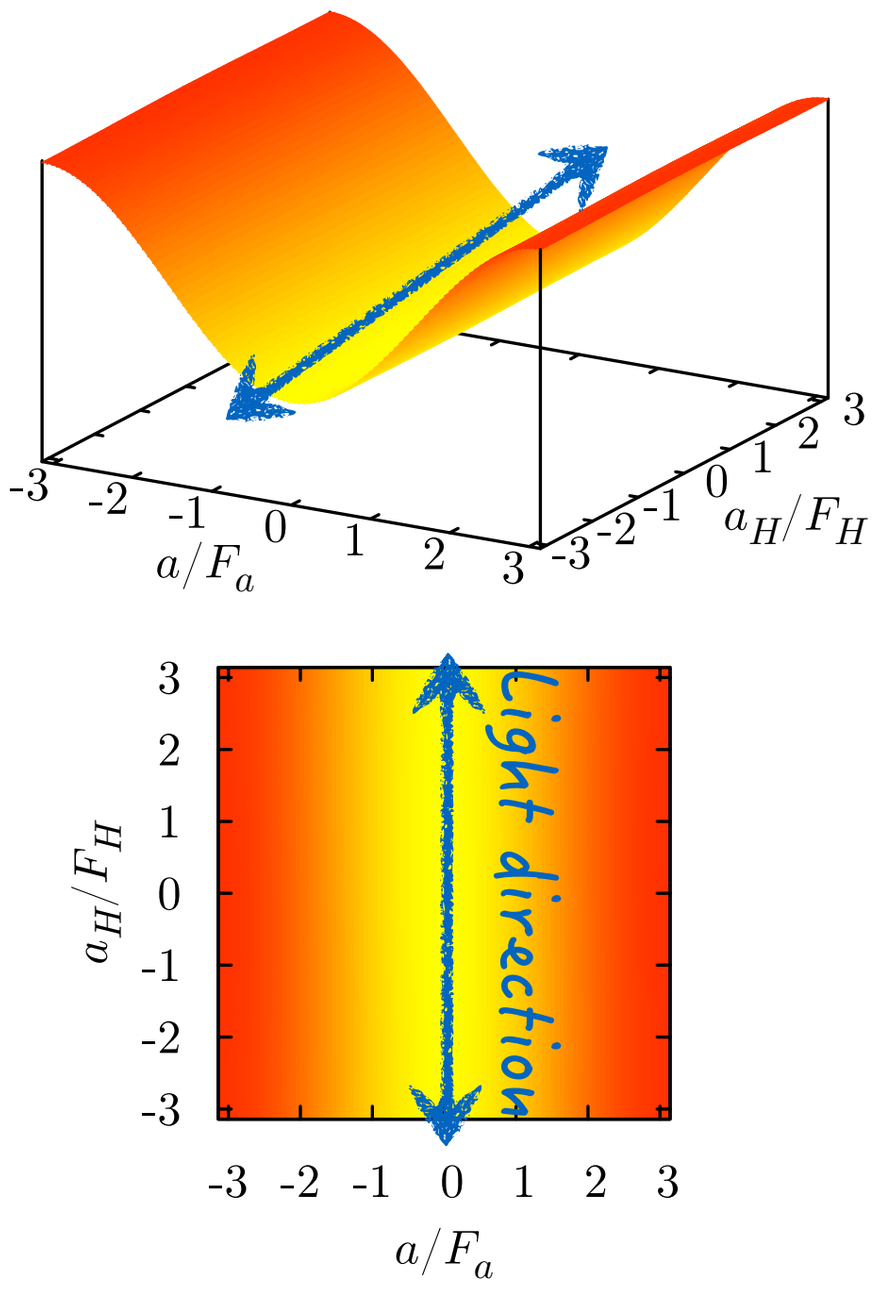
$T \gg \Lambda_{\rm CDM}$



$T \ll \Lambda_{\rm CDM}$



Linearized equation of motion

$$\ddot{A} + 3H\dot{A} + M^2 A = 0$$

with

$$A = \begin{pmatrix} a \\ a_H \end{pmatrix} \quad \text{and} \quad M^2 = \begin{pmatrix} m_a^2(T) + (F_a/F_H)^2 m_H^2 & (F_H/F_a)m_H^2 \\ (F_H/F_a)m_H^2 & m_H^2 \end{pmatrix}$$

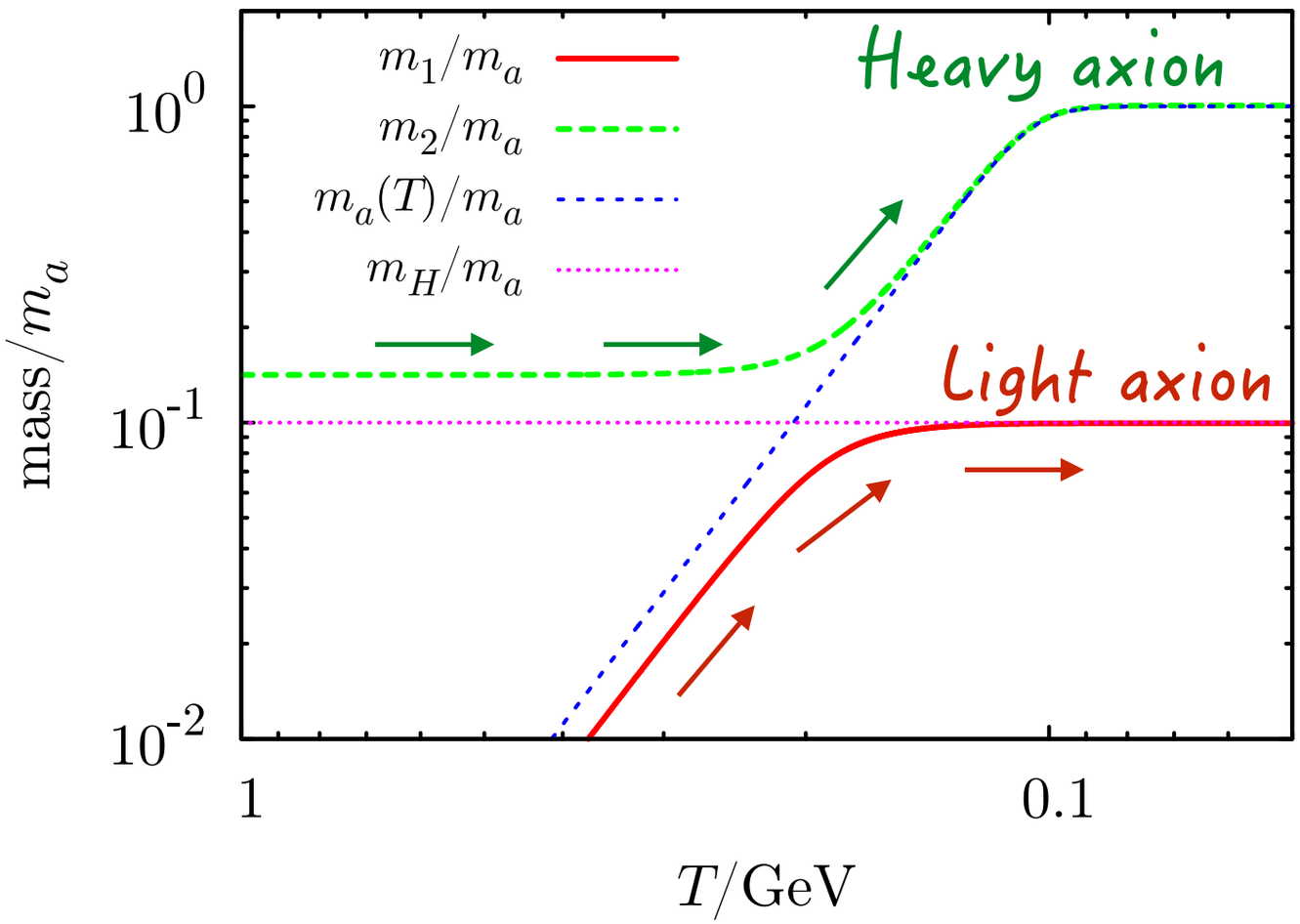
Mass eigenstates

$$\begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} = O^T M^2 O \quad \text{and} \quad \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = O^T A$$

a_1 : Light axion

a_2 : Heavy axion

Evolution of mass eigenvalues



Initial condition

$$V(a, a_H) = m_a^2(T) F_a^2 \left[1 - \cos\left(\frac{a}{F_a}\right)\right] + m_H^2 F_H^2 \left[1 - \cos\left(\frac{a_H}{F_H} + \frac{a}{F_a}\right)\right] \equiv \delta = 0$$

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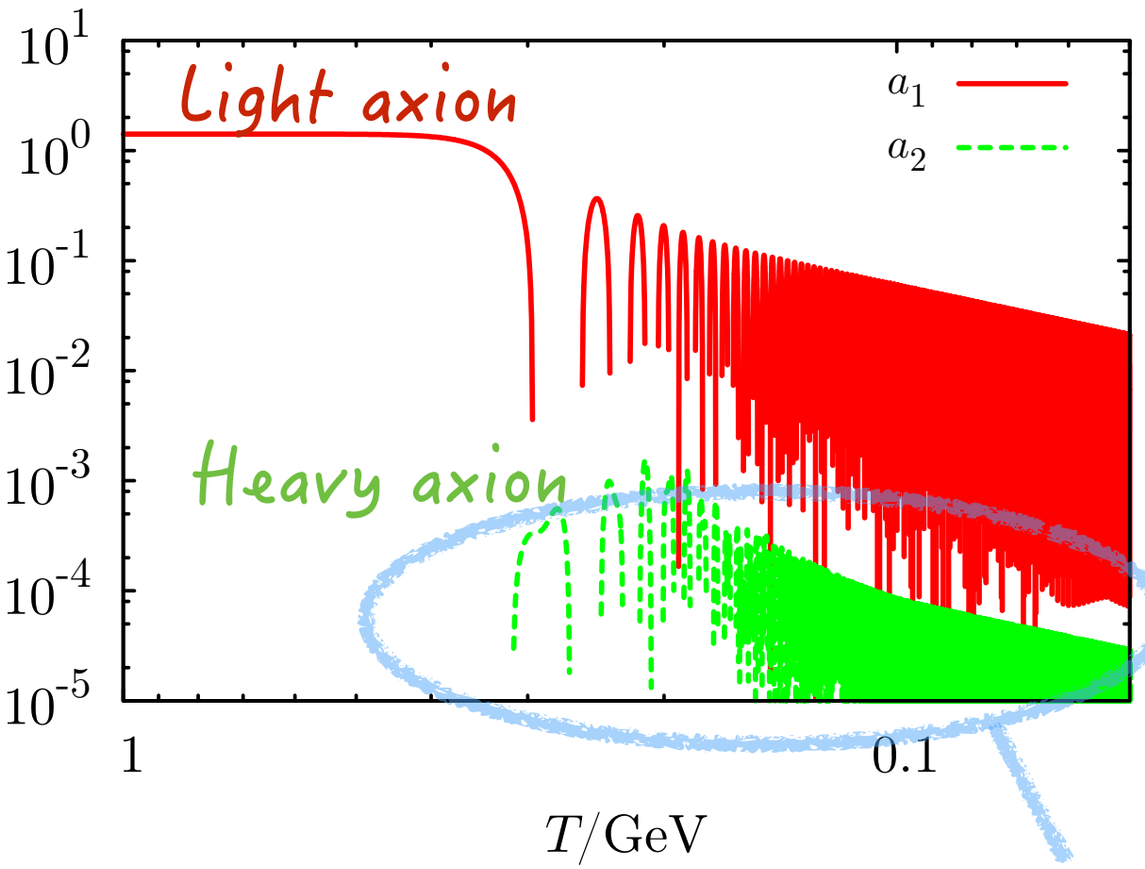
$$\equiv \delta = 0$$

Heavy axion is suppressed, but…

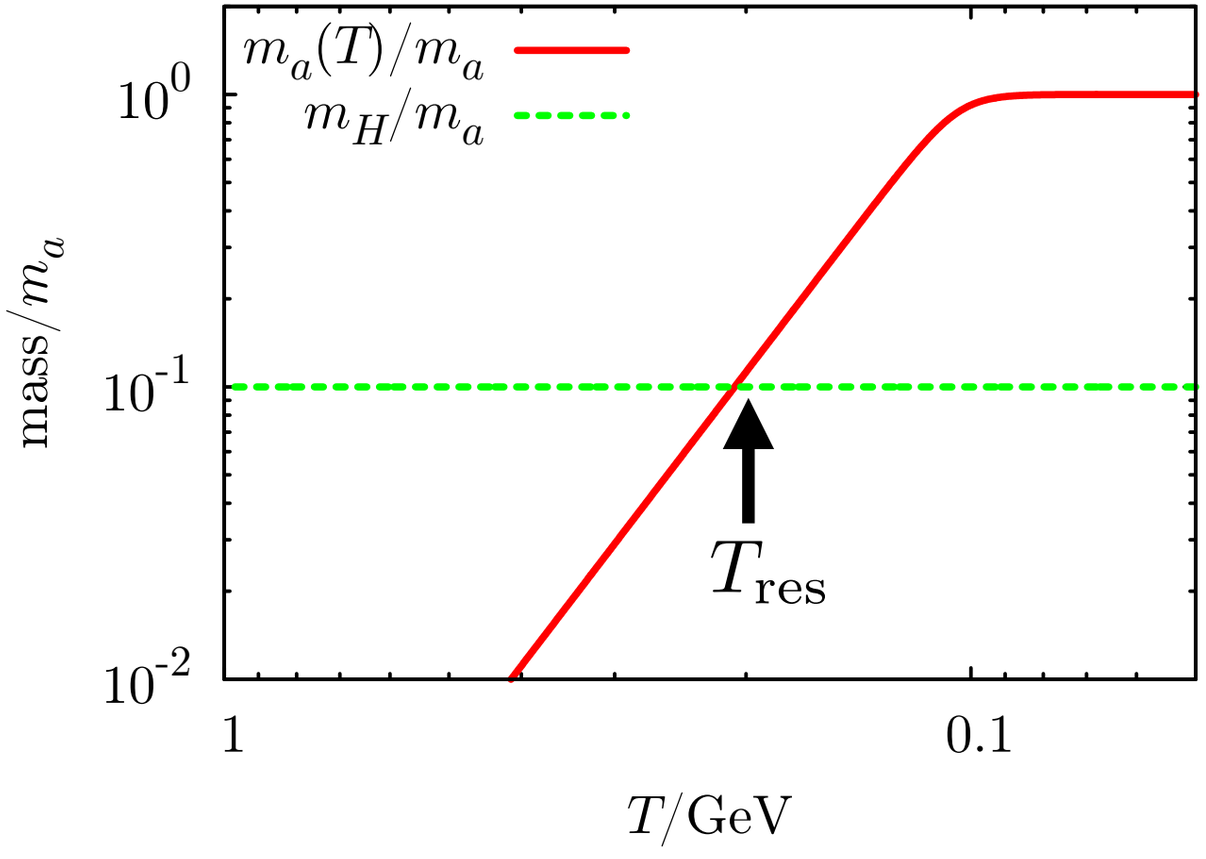


Heavy axion is suppressed

Adiabaticity, Anharmonicity

$$\xi = \frac{H(T_{\rm res})}{m_H} \simeq 4.4 \left(\frac{m_H}{m_a}\right)^{-1.6} \frac{F_a}{M_P}$$

$$T_{\rm res} \simeq 0.1 \left(\frac{\Lambda_{\rm QCD}^2}{F_a m_H}\right)^{0.3}$$



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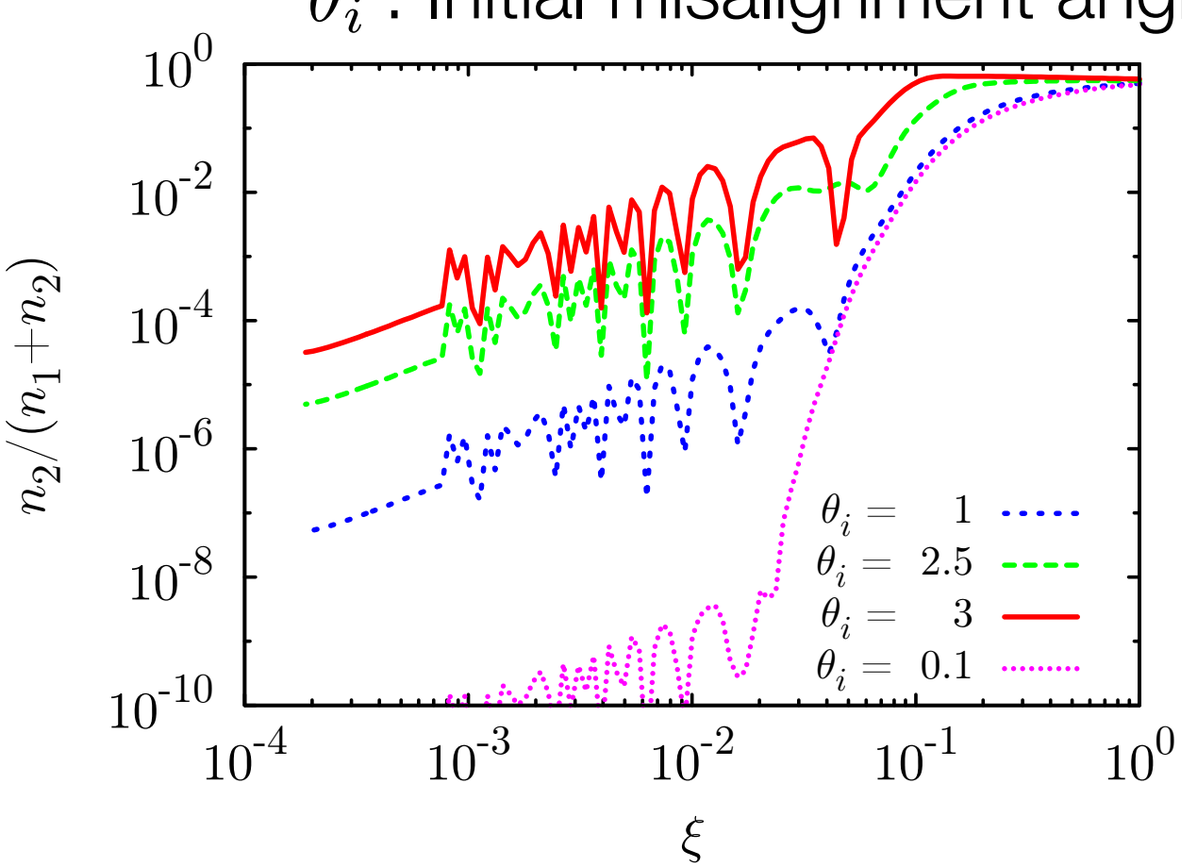
θ_i : Initial misalignment angle for QCD axion

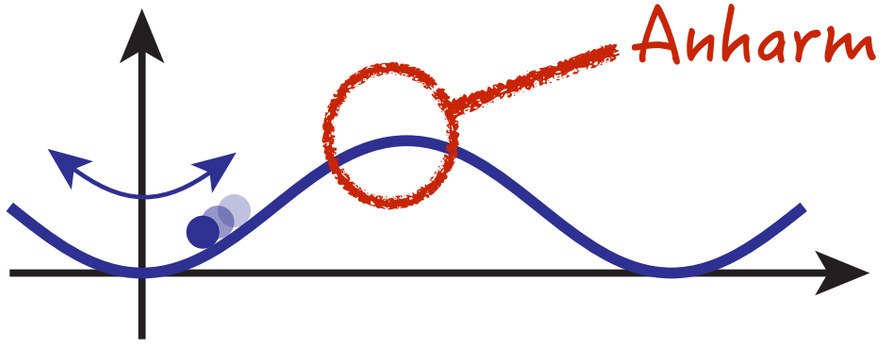


n_1 : # of light axion

n_2 : # of heavy axion

Adiabaticity, Anharmonicity

Anharmonicity = departure from the quadratic potential



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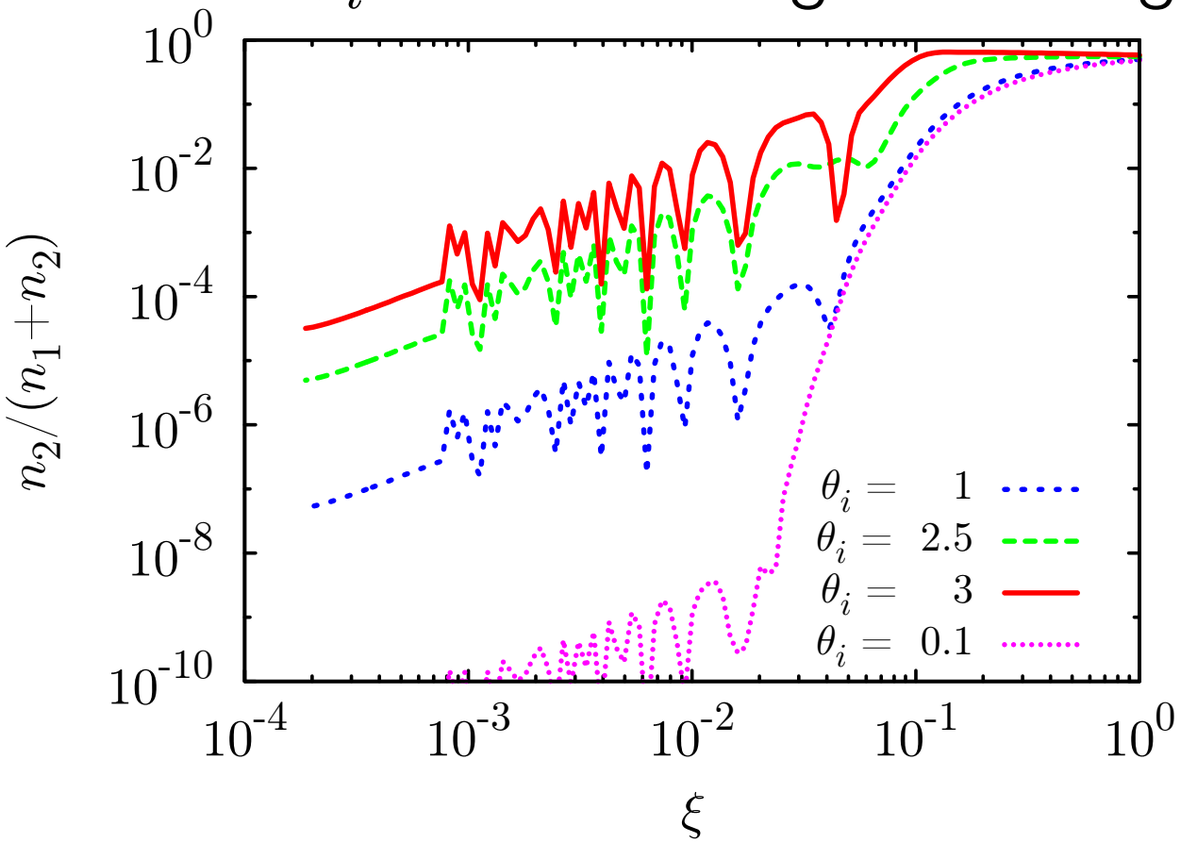

n_1 : # of light axion

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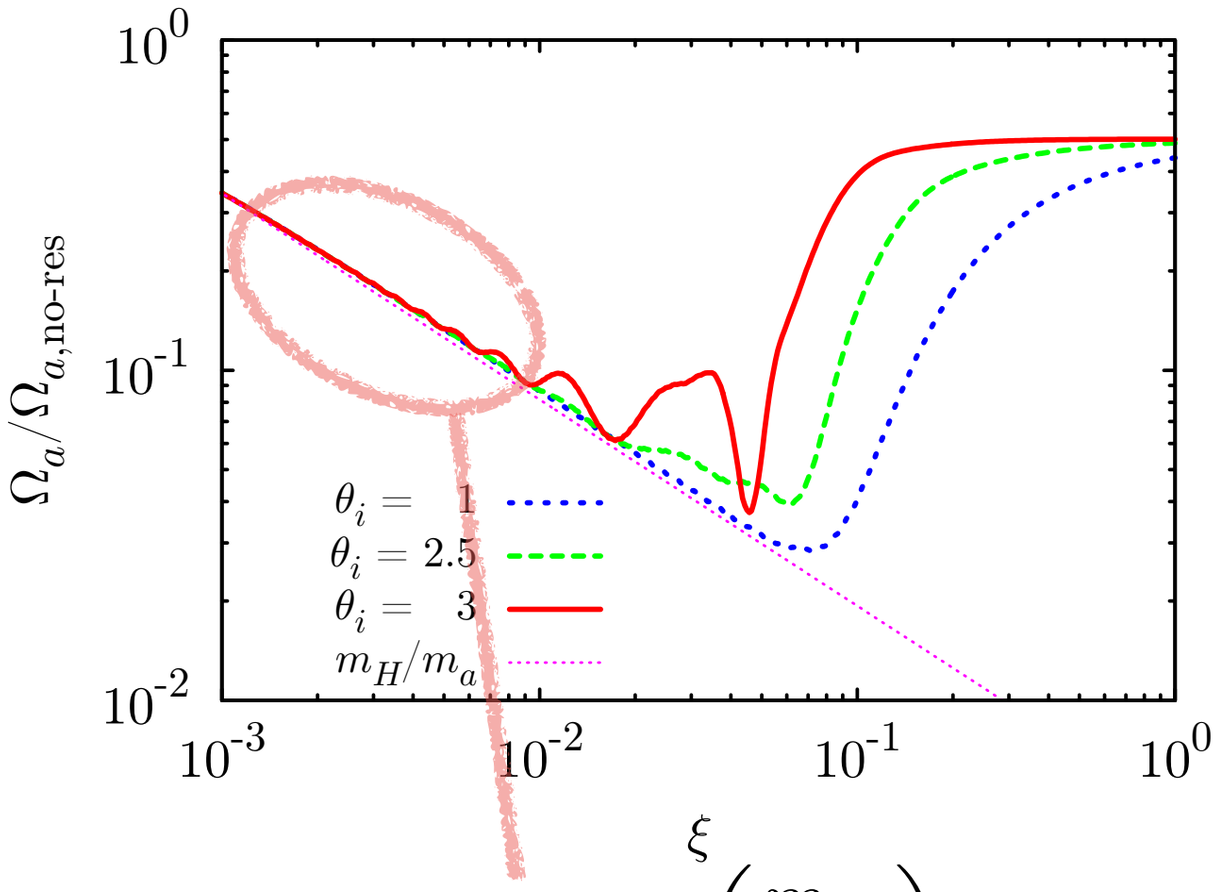
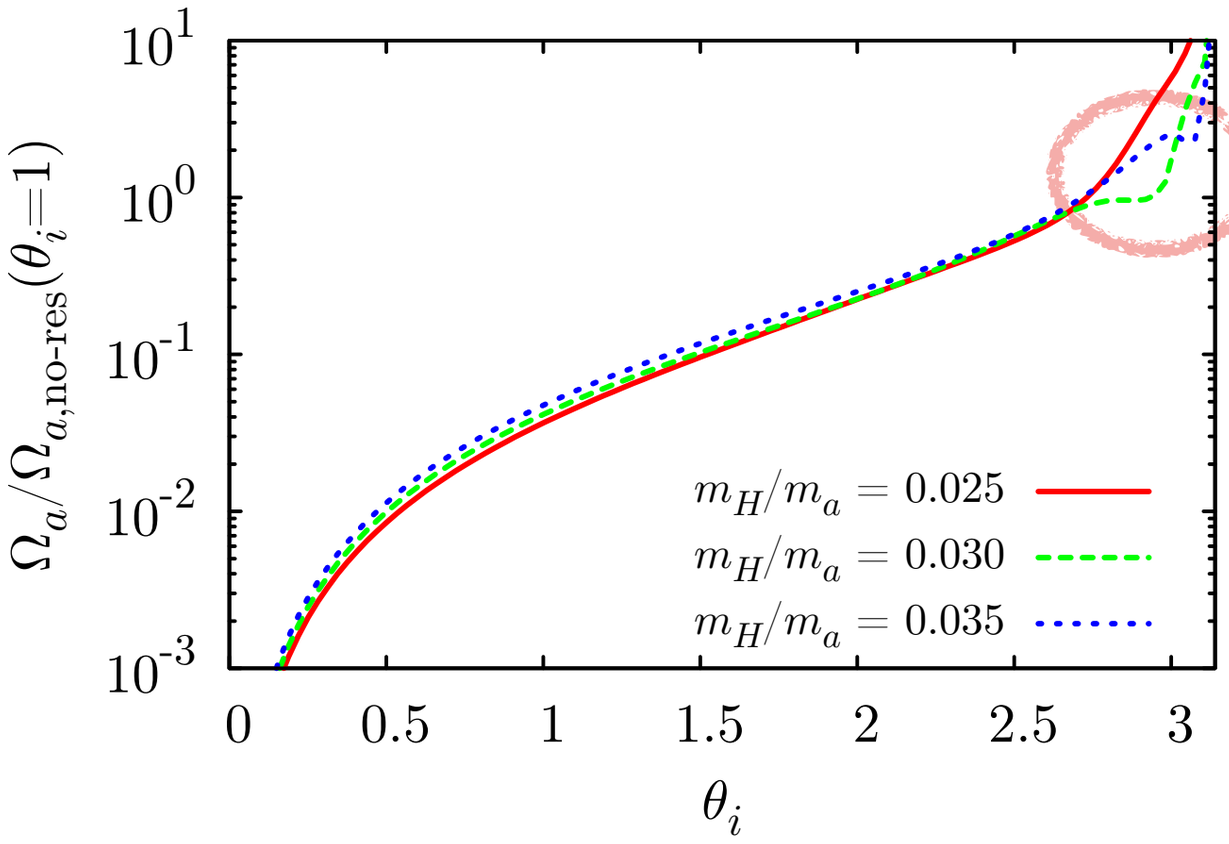
3. Cosmological implications

(i) Abundance

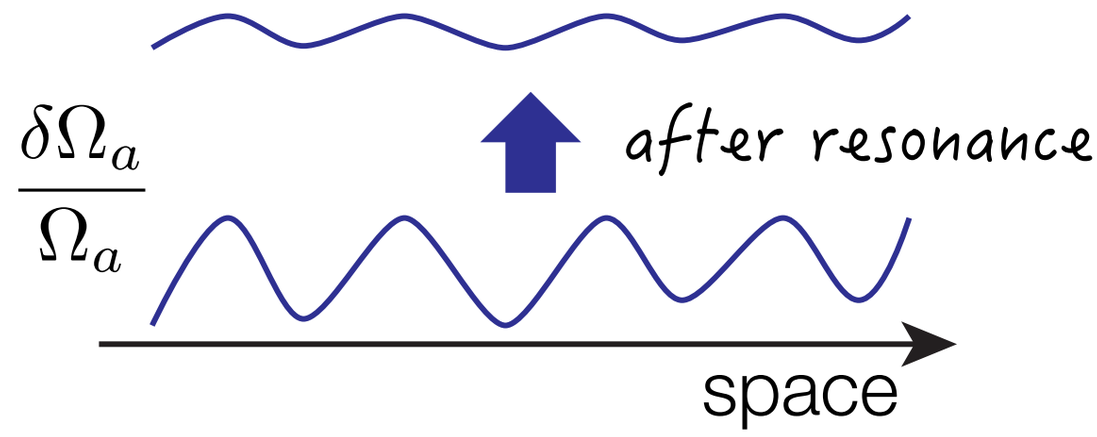


$$\Omega_a \to \left(\frac{m_H}{m_a}\right)^{\xi} \Omega_a$$

(ii) Isocurvature perturbations



θ_i -dependence vanishes!



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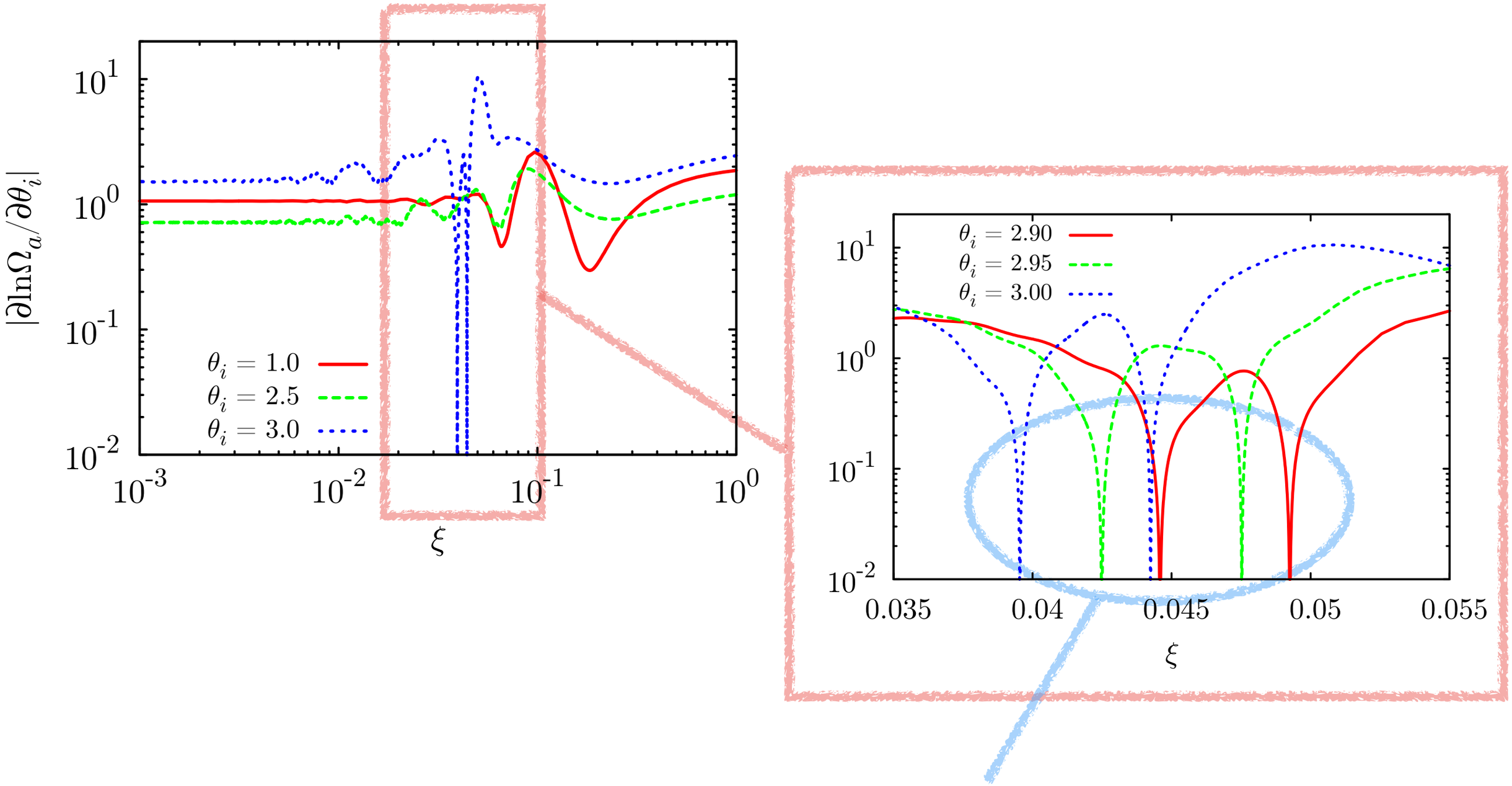


Isocurvature perturbation can be suppressed!

4. Conclusions

- We considered QCD axion & hidden axion with mass mixing

- MSW-like resonance takes place
  and QCD axion is converted into hidden axions

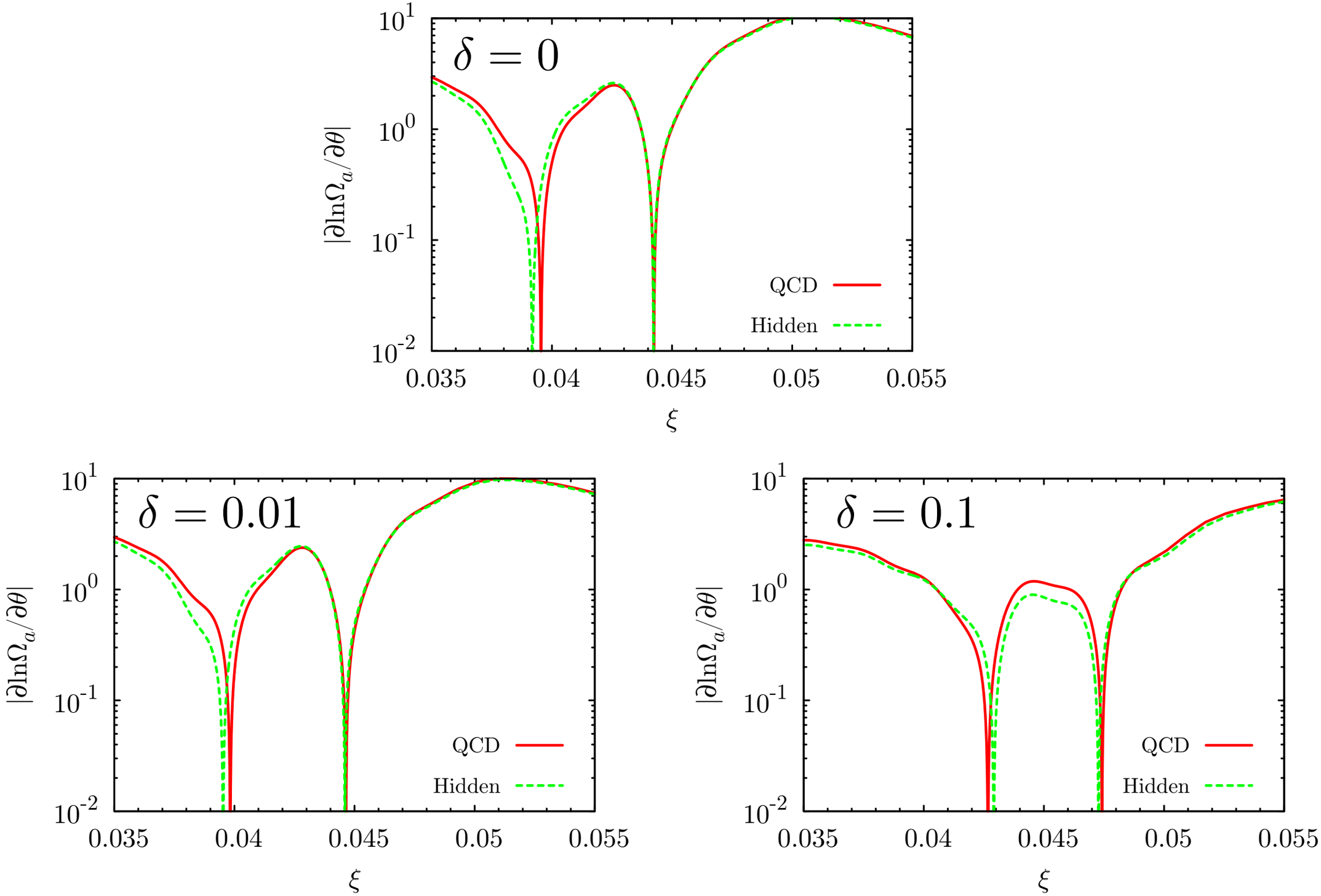
- Abundance can be suppressed

- Isocurvature perturbation can also be suppressed!

We proposed a completely new mechanism to suppress isocurvature perturbations

Thank you!

Isocurvature perturbation from QCD + hidden axion



Non-Gaussianity from isocurvature perturbation

$$f_{\rm NL}^{\rm (iso)} = -1 + \frac{1}{r}\left(1 + \left(\frac{\partial^2 \ln \Omega_a}{\partial \theta_i^2}\right)\left(\frac{\partial \ln \Omega_a}{\partial \theta_a}\right)^{-2}\right)$$

$$\left(\frac{\beta}{1-\beta}\right)^2 f_{\rm NL}^{\rm (iso)} = 40 \pm 66$$

Hikage,Kawasaki,Sekiguchi & Takahashi:1211.1095