Cosmological abundance of axion coupled to hidden photons

Toyokazu Sekiguchi
(RESCEU, U of Tokyo)

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Outline

- Introduction: axions and their large coupling to U(1) gauge field
- Axion electrodynamics & suppression of axion abundance
- Summary

References:

Naoya Kitajima, TS & Fuminobu Takahashi, arXiv:1711.06590

Axion

- Strong CP problem in QCD

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi}\theta G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \longrightarrow \text{CP violation}$$

experimental bound: $\theta_0 = \theta + \mathrm{Arg}[\mathrm{Det}\ m_q] \lesssim 10^{-10}$; new physics?

- Solution: Peccei-Quinn mechanism Peccei & Quinn '77

Anomalous global $U(1)_{PQ}$ broken spontaneously at ~ F_a

$$\theta \to \phi(x)/F_a$$

QCD instanton induces axion potential: dynamical cancelation of θ_0

$$m_a \simeq \frac{m_\pi F_\pi}{F_a} \simeq 6\mu\mathrm{eV}\left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{-1}$$

Pseudo-NG boson $\phi(x)$: axion → candidate of CDM

Weinberg '78; Wilczek '78

Anomalous coupling to gauge field

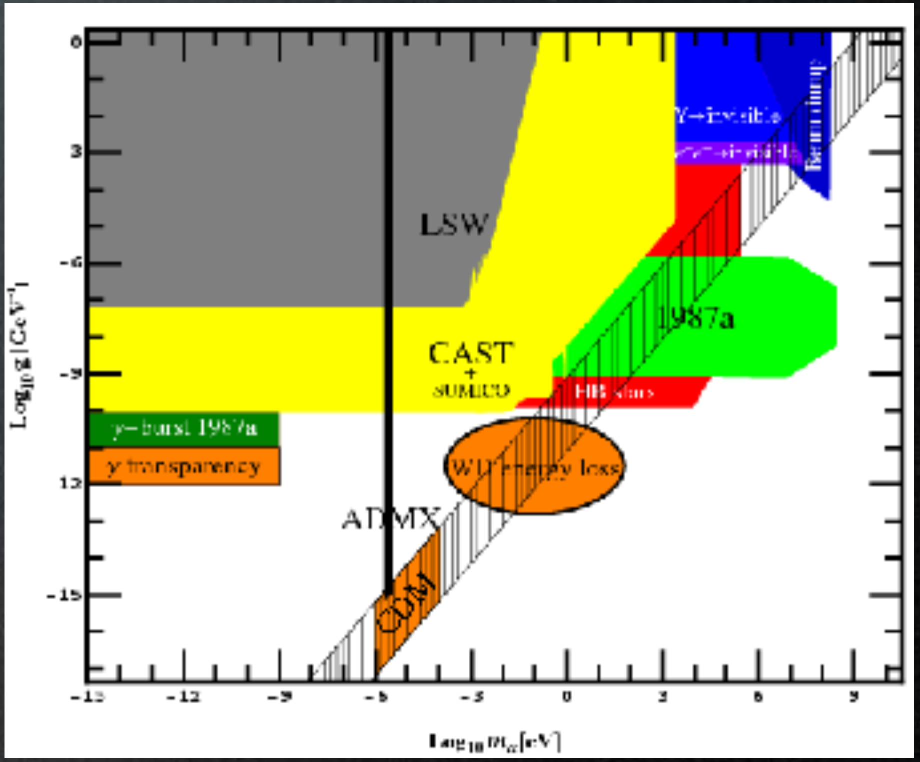
$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi F_a} C_s \phi G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{\alpha_{EM}}{8\pi F_a} C_{\rm EM}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$

C_i : coupling dependent on the $U(1)_{PQ}$ charge assignment

Subject to variety of constraints

- Astrophysics: stellar evolution
  Dicus, Kolb, Teplitz '87; Sato '87; Vysotsskii+ '87
  - SN1987A
  - lifetime of red giants
  - white dwarf cooling

→ lower bound: $F_a > 10^9$GeV



Jackel+ '10

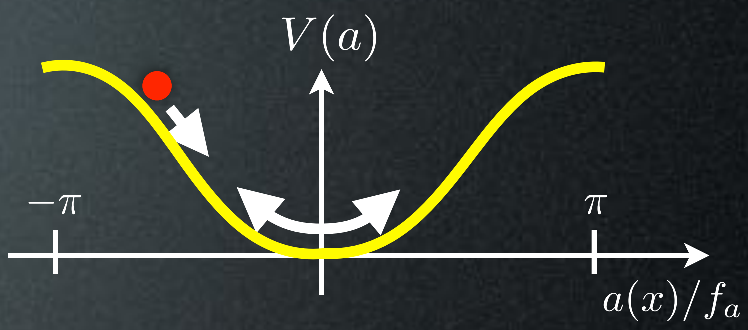
- Terrestrial experiments Sikivie '85
  - microwave cavity (ADMX, CAPP, …)
  - axion helioscope (SUMICO, CAST, IAXO, …)

Production of axions in cosmology

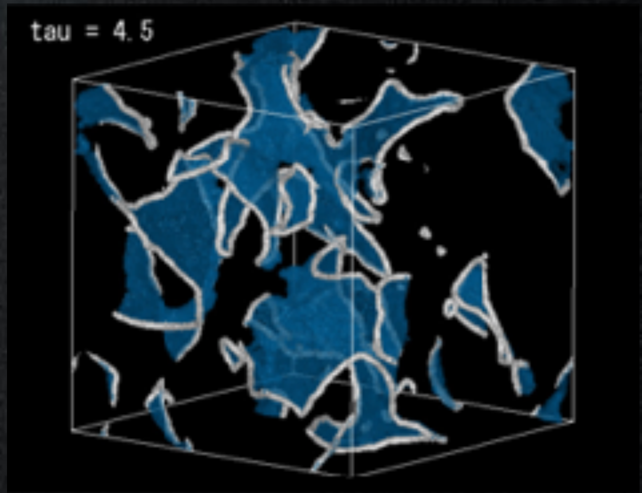
- Coherent oscillation
  - Misalignment mechanism: $a_{\rm ini} \sim F_a$
  - The larger F_a becomes, the later the oscillation starts

    → upper bound: $F_a < 10^{12}$GeV

  - CDM isocurvature perturbations can be generated in inflation→ bound on H_{inf}



- Topological defects
  - Iff the PQ phase transition occurs after inflation
  - Strings/domain-walls form at PQ/QCD PT
  - CDM axions are radiated from network of these defects
  - Tighter upper bound on F_a



Hiramatsu, Kawasaki, Saikawa, TS ’12

A theoretical puzzle in the QCD axion

Kamionkowski & March-Russell '92

Explicit breaking of $U(1)_{PQ}$ needs to be highly suppressed

- Naive expectation: $F_a = \langle \Phi_{PQ} \rangle$ (breaking scale of PQ symmetry)

- Quantum gravity effects

$$V \supset \frac{\Phi^{4+n}}{M_{\rm Pl}^n} + {\rm h.\,c.} \quad ➡ \quad \Delta V \sim \frac{F_a^{4+n}}{M_{\rm Pl}^n} \cos\left[c\frac{\phi}{F_a} + \Delta\theta_0\right]$$

- Terms all up to n~10 should be absent for the PQ mechanism to work

Origin of the PQ "symmetry"?

Axions in string theory

- Axiverse:
  - Plentitude (~10^4) of "axions" exist

    ex) anti-symetric tensor from compactifications of heterotic string

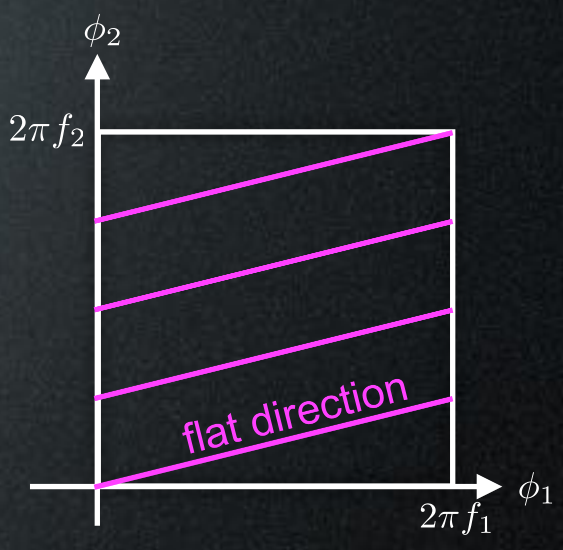
  - $U(1)_{PQ}$ symmetries survive accidentally from discrete gauge symmetries
  - Low-scale SUSY may suppress non-QCD instanton effects

- Harmful axions Choi & Kim '85
  - Decay constant is genrally large: $M_{Pl} \geq F_a \geq M_{GUT}$
  - Those axions are incompatible with the QCD axion window ($F_a < 10^{12}$GeV)

$$\Omega_{\rm axion} h^2 \simeq 1.1 \times \theta_{\rm ini}^2 \left(\frac{F_a}{10^{12}{\rm GeV}} \right)^{1.2}$$

Alignment/clockwork mechanism

Kim, Nilles, Peloso '04; Choi, Kim, Yun '14; Choi, Im '15; Kaplan, Rattazzi '15

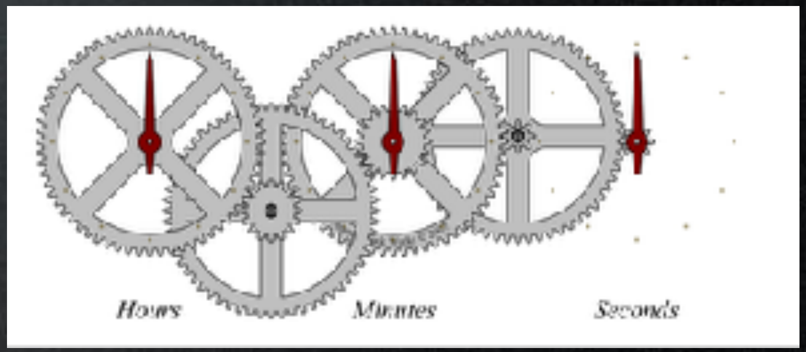


Natural inflation from two axions with F_1, $F_2 \leq M_{Pl}$

$$V \approx M^4 \cos\left(\frac{\phi_1}{F_1} + n\frac{\phi_2}{F_2}\right)$$

Flat direction with large periodicity

$$F_{\rm eff} = \sqrt{n^2 F_1^2 + F_2^2}$$



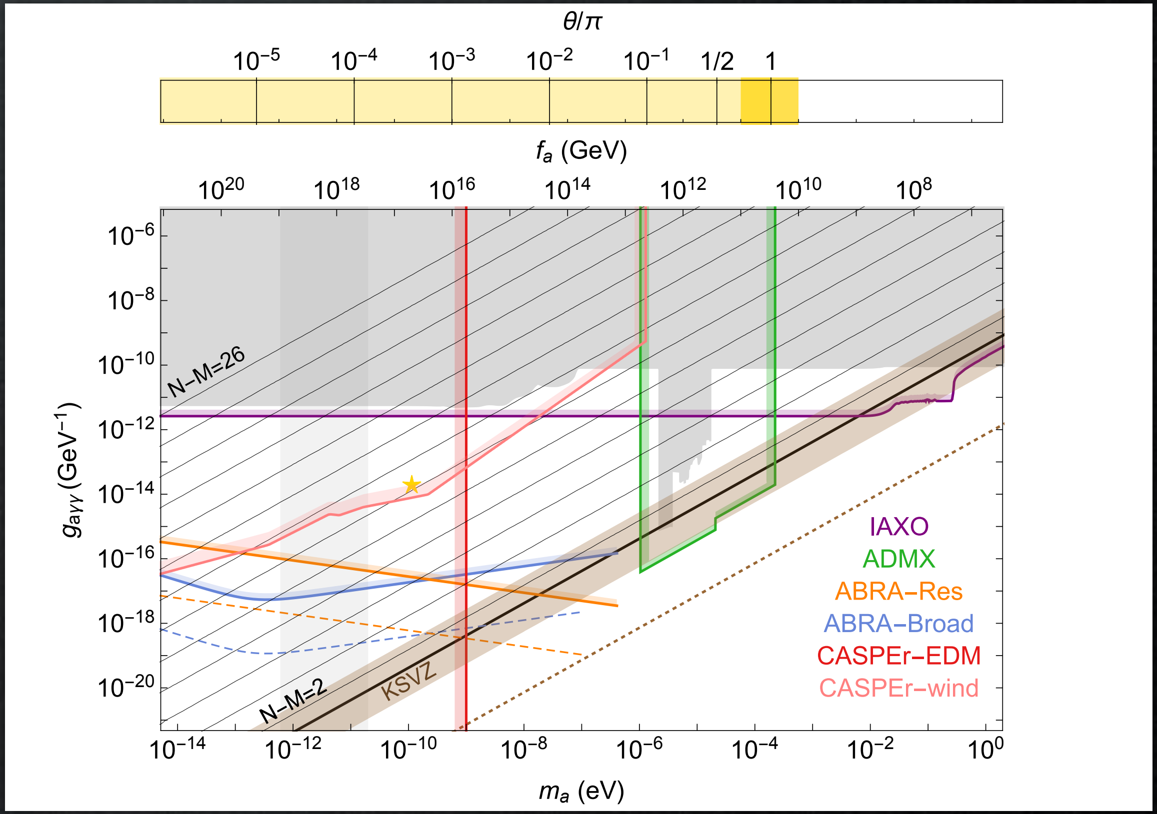
Large hierarchy $F_{\rm eff} \gg F_i$ is realized without introducing tiny parameters.

Photophilic axions:

$$L \supset -\frac{\alpha_{\rm eff}}{8\pi F_{\rm eff}}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \text{with} \quad \alpha_{\rm eff} \sim \alpha\frac{F_{\rm eff}}{F_i} \gg \alpha$$

Summary so far

- Plentitude of axions exist in string theory
- Some of those “axions” can be the QCD axion, but the decay constant is in general harmfully large $F_a \geq M_{GUT}$ unless initial misalignment is finely tuned.
- (Hidden) photophilic “axions” can be realized in the alignment/ clockwork mechanism



Farina+ 2017

Dissipation via production of tachyonic hidden photons

Agrawal+ 1708.05008

- Coupling to hidden U(1) gauge field

$$-\frac{\alpha_X}{4F_a}\phi X_{\mu\nu}\tilde{X}^{\mu\nu}$$ with α_X~O(10) *a la* e.g. clockwork

- Tachyonic instability in gauge field induced by moving ϕ

$$\ddot{X}_{\boldsymbol{k},\pm} - k(k \mp \frac{\alpha_X \dot{\phi}}{F_a})X_{\boldsymbol{k},\pm} = 0$$ with $\dot{\phi} \simeq m_a \bar{\phi}(t)\cos(m_a t)$

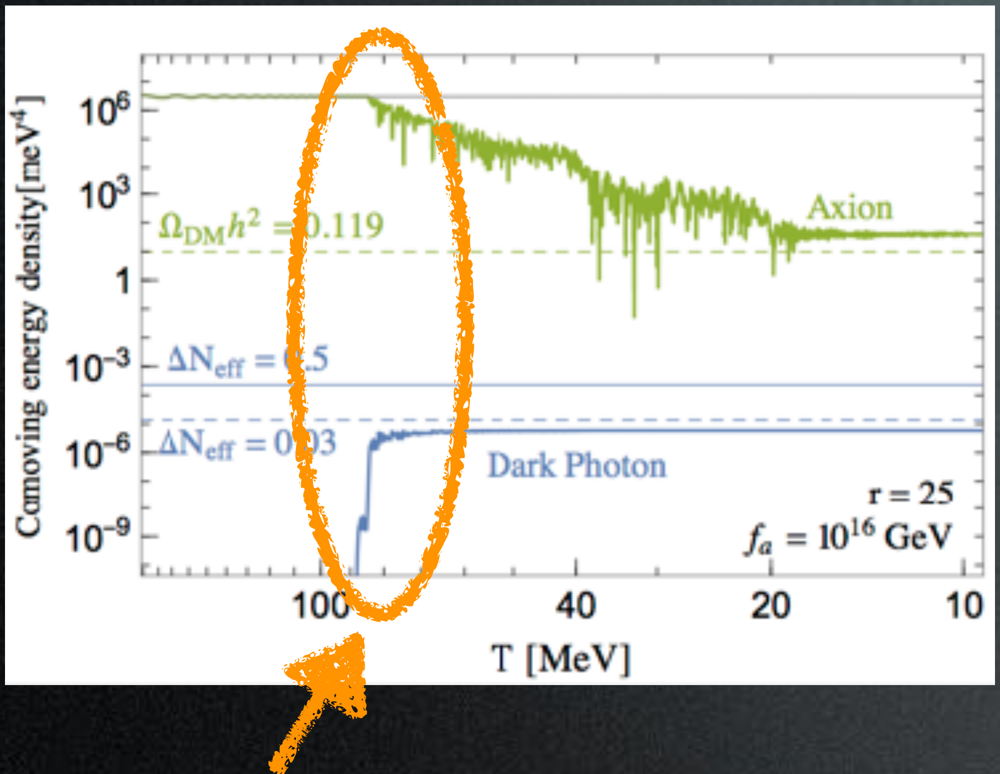
Instability at $k \lesssim \frac{\alpha_X m_a}{F_a}\bar{\phi}(t)$ (broad resonance)

→ exponential production of gauge field at large scales

- Backreaction: axion coherent energy is dissipated into hidden photon

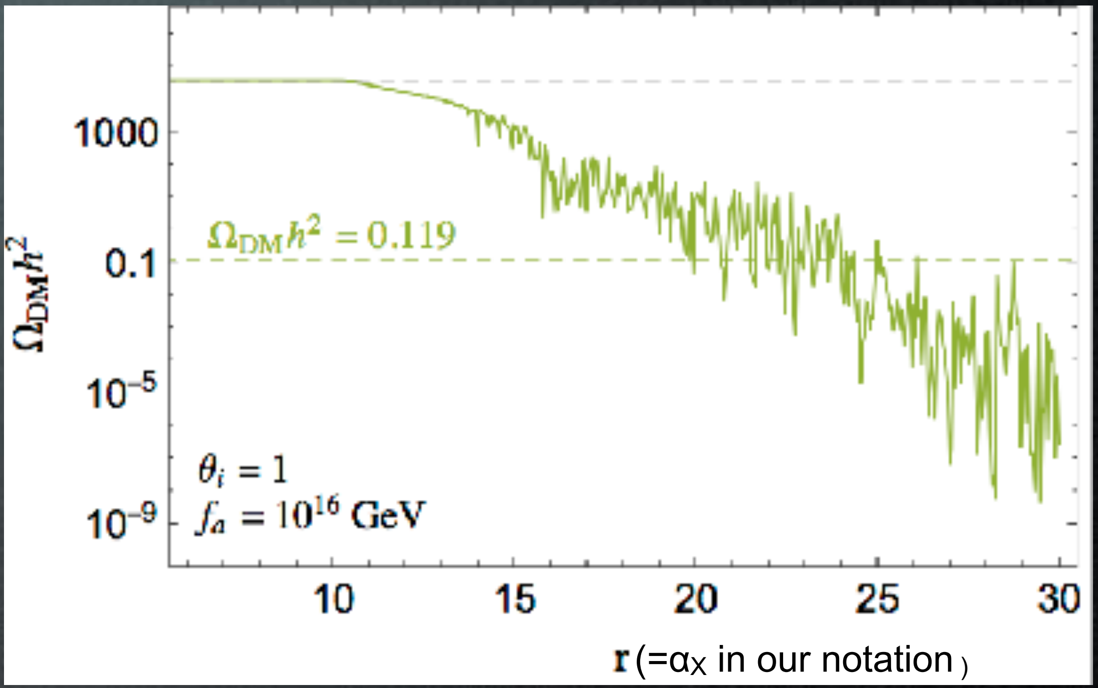
Suppressing the axion abundance Agrawal+ 1708.05008

- Evolution of number density



Saturation:
entire conversion of axion energy into gauge field

- Suppression as function of coupling



Suppression is largely increasing function of the coupling, possibly being as large as 10^{-13}

If true, the axion window would be opened up to M_{GUT}

Issue of axion nonzero modes

- After saturation, gauge field dominates over the axion zero modes
- Gauge field can source axion nonzero modes via mode-mode coupling

$$\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + \left[-\nabla^2 + a^2 m^2(\bar{\phi}(t))\right]\delta\phi = \frac{\alpha_X}{F_a a^2}\boldsymbol{E}_X \cdot \boldsymbol{B}_X$$

- This coupling is also strong; gauge field and axion nonzero modes coevolve
- Alters the previous conclusion?

Axion electrodynamics

Lagrangian

$$\mathcal{L} = \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \chi(T)\left[1-\cos\left(\frac{\phi}{F_a}\right)\right] \quad -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_X}{4F_a}\phi X_{\mu\nu}\tilde{X}^{\mu\nu}$$

χ(T): topological susceptibility in QCD (lattice QCD calc.)

Axion-Maxwell equation

$$\ddot{\phi} + 2\mathcal{H}\dot{\phi} - \nabla^2\phi + a^2\frac{\partial V}{\partial\phi} = \frac{\alpha_X}{F_a a^2}\dot{\boldsymbol{E}}_X\cdot\boldsymbol{B}_X$$

$$\nabla\cdot\boldsymbol{B}_X = 0,$$

$$\nabla\cdot\boldsymbol{D}_X = 0,$$

$$\dot{\boldsymbol{B}}_X = -\nabla\times\boldsymbol{E}_X,$$

$$\dot{\boldsymbol{D}}_X = \nabla\times\boldsymbol{H}_X$$

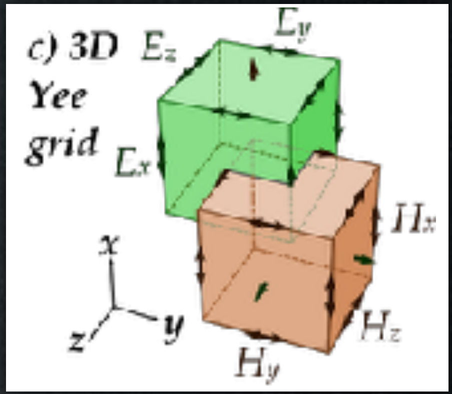
with

$$\boldsymbol{D}_X = \boldsymbol{E}_X + \frac{\alpha_X}{F_a}\phi\boldsymbol{B}_X,$$

$$\boldsymbol{H}_X = \boldsymbol{B}_X - \frac{\alpha_X}{F_a}\phi\boldsymbol{E}_X$$

Nonlinearity → Lattice simulation

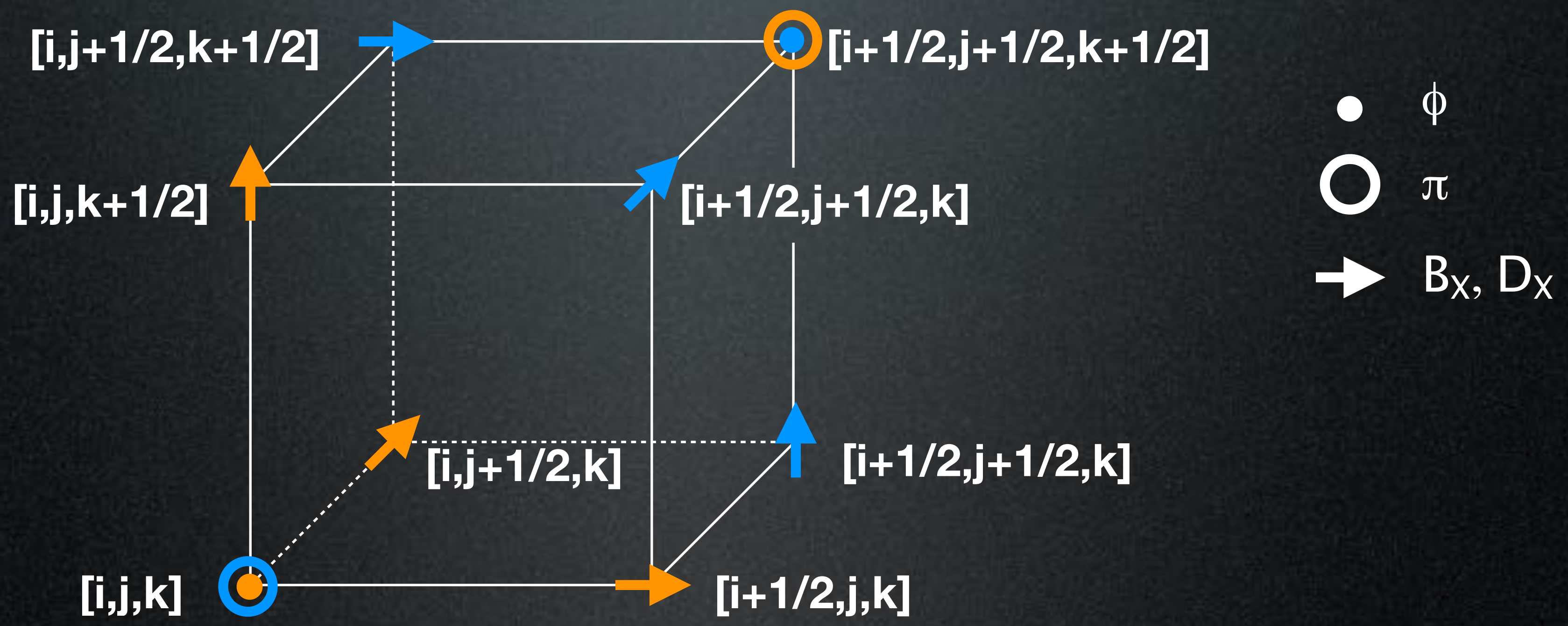
3D lattice simulation of axion electrodynamics



Kitajima, TS & Takahashi, arXiv:1711.06590

Extension of staggered grid method (*Yee's algorithm*) K. Yee '66

★ Dynamical variables: $\phi,\ \pi = \dot{\phi}/a^2,\ \boldsymbol{B}_X = \nabla \times \boldsymbol{X},\ \boldsymbol{D}_X = -\dot{\boldsymbol{X}} + \frac{\alpha_X}{F_a}\phi \boldsymbol{B}_X$



★ Time integration: leapfrog (explicit symplectic) method

➡ staggered grids both in space and time

Advantages of our implementation

✓ Simple implementation of second order (both in time and space) method

✓ Symmetric and symplectic method, conserving energy etc.

✓ Efficient mixing of both axion and gauge fields

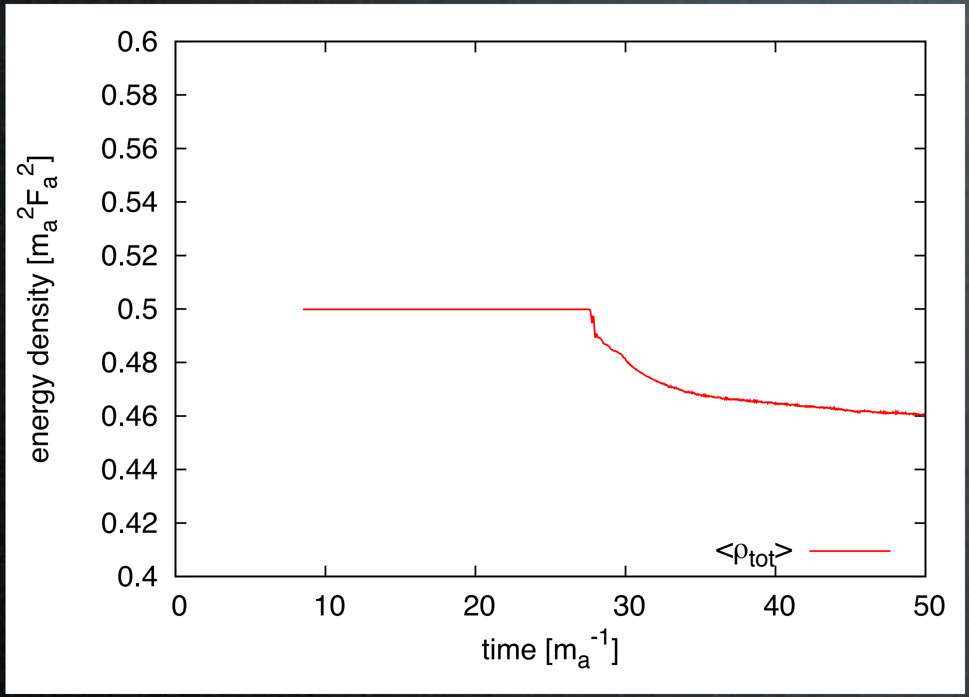
Original Yee's staggered grids boosts E and B mixing
→ extended to accommodate axion

✓ Discretized constraint eqs. are satisfied automatically (barring round-off error)

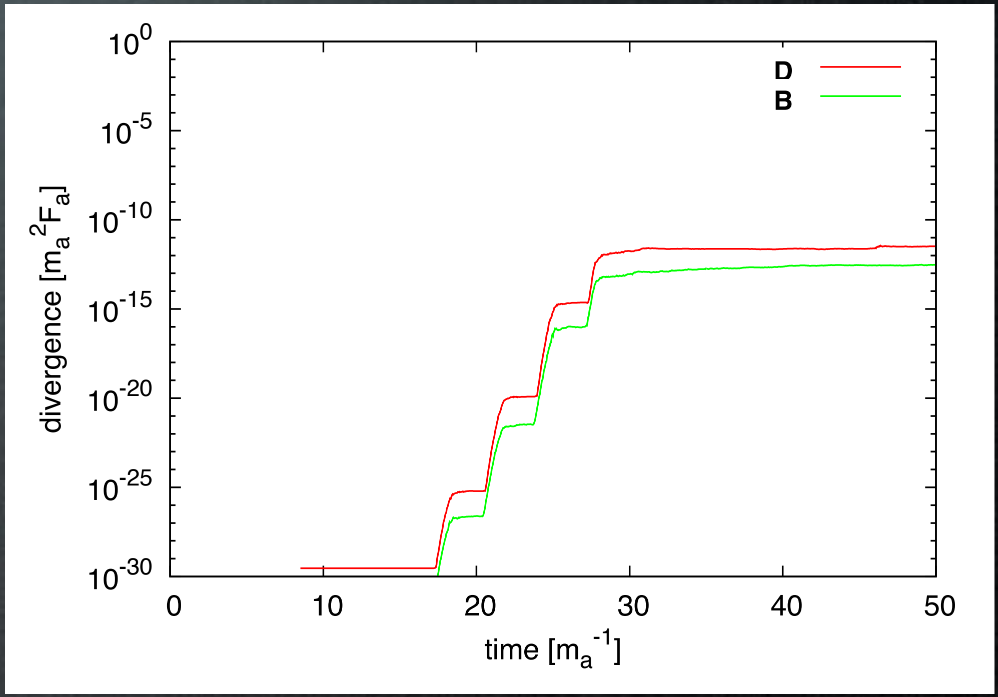
$$\begin{aligned}
\nabla \cdot \boldsymbol{B}_X =& 0, \\
\nabla \cdot \boldsymbol{D}_X =& 0, \\
\dot{\boldsymbol{B}}_X =& -\nabla \times \boldsymbol{E}_X, \\
\dot{\boldsymbol{D}}_X =& \nabla \times \boldsymbol{H}_X
\end{aligned}$$

Validation check in Minkowski

- Energy conservation



- Constraint equations



Underdamping regime (α_X=50)

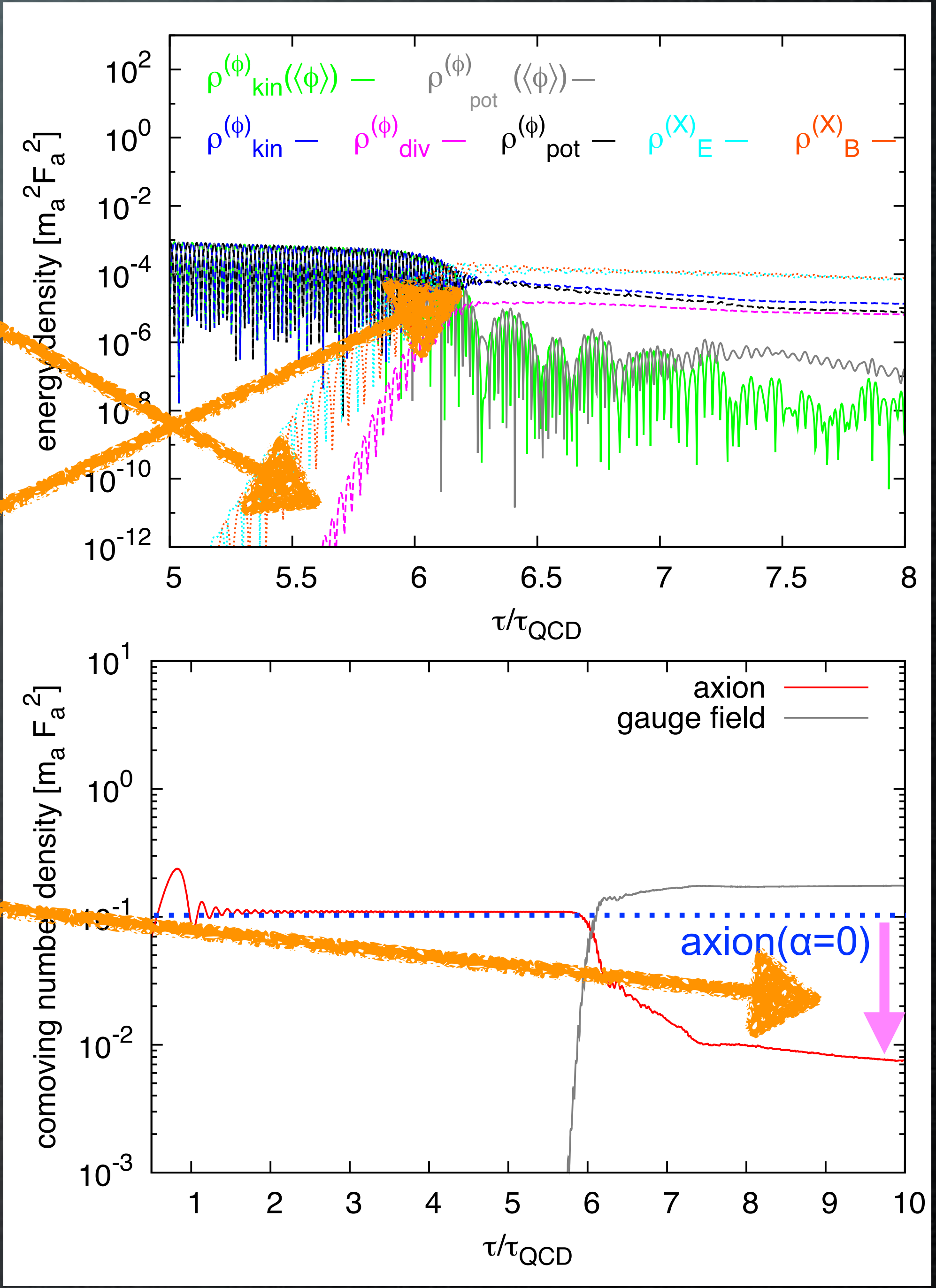
F_a=10^{16}GeV, θ_{ini}=1

Gauge field production is accompanied by the production of axion nonzero modes

After saturation, gauge field dominates but axion nonzero modes partition O(0.1) of the initial oscillation energy of axion zero modes

Suppression of axion abundance is moderated significantly by axion nonzero modes

cf. 10^{-13} (α_X~30) in Agrawal+ 1708.05008



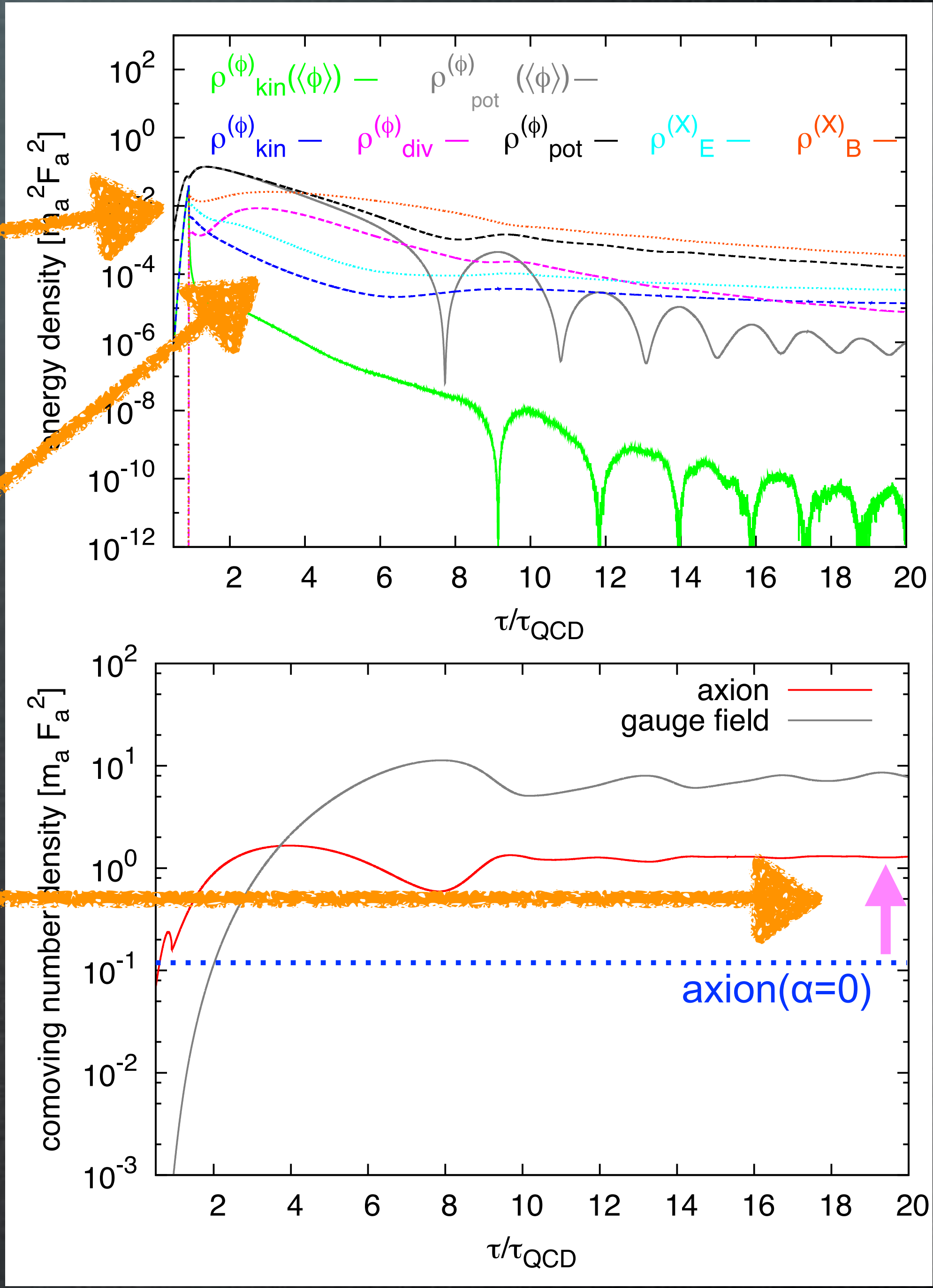
Overdamping regime (α_X=500)

$F_a=10^{16}$GeV, $\theta_{ini}=1$

Significant amount of gauge field is produced before axion zero modes oscillate a single time

Too large friction exhausts the kinetic energy of axion zero modes; axion moves only at the Hubble rate (<mass)

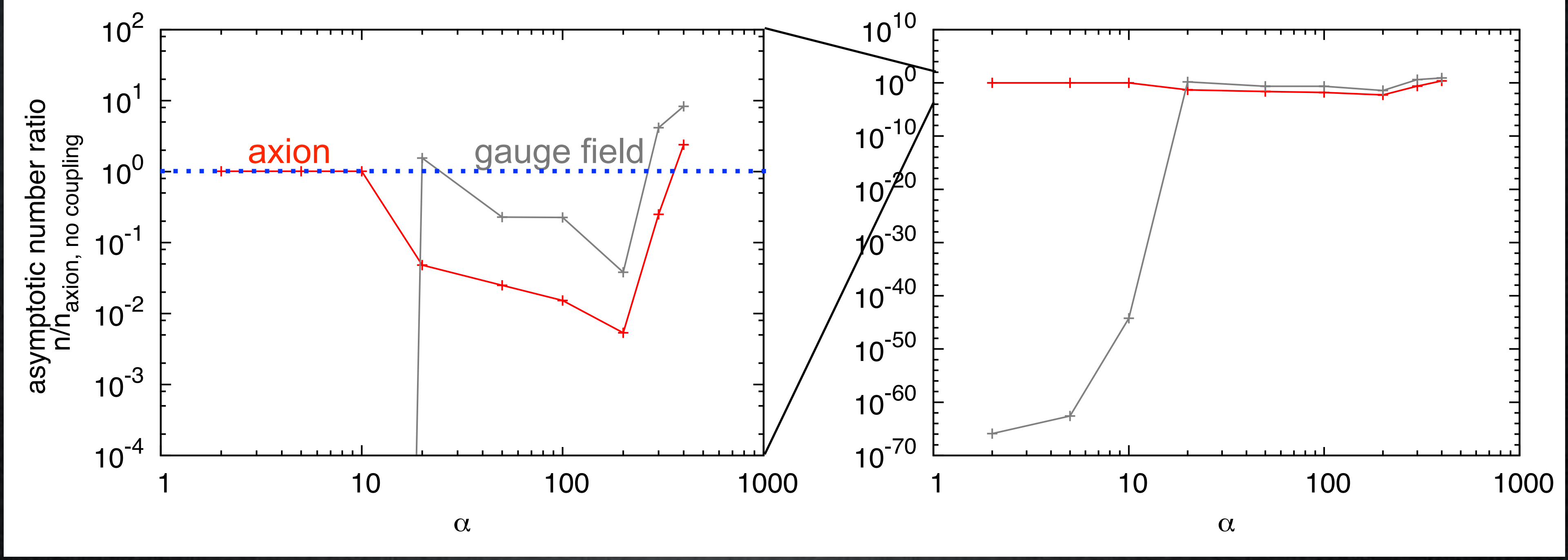
Onset of axion oscillation is delayed; axion abundance is enhanced compared to α=0



Suppression of axion abundance

- Ratio of $n_{axion}/n_{gauge\ field}$ to n_{axion} w/o coupling

$F_a=10^{16}$GeV, $\theta_{ini}=1$



- The suppression cannot be arbitrarily large:

$$n_{\rm axion}/n_{\rm axion,\ no\ coupling} \gtrsim 10^{-3}$$

- Critical damping occurs around α~200

Summary

We studied cosmological abundance of axions coupled to hidden photons.

The previous study claims that axion abundance can be suppressed by $>10^{10}$ with moderately large coupling. However, production of axion nonzero modes is omitted in their analysis.

We implemented the lattice simulation of the coupled axion-gauge field system. Our results show axion nonzero modes play a crucial role in the estimation of the axion abundance. The suppression is significantly moderated and reaches only $\sim 10^3$ at best.

Our implementation of axion electrodynamics can be applied to variety of cosmological and terrestrial environments.