Cosmology of the (QCD) axion coupled with hidden photons

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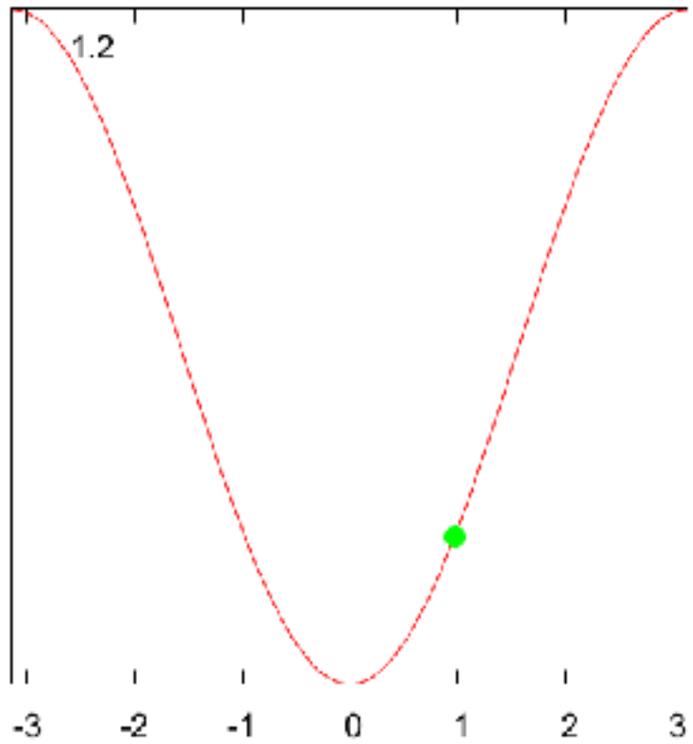
（C研）

素粒子物理学の進展２０１８

アクシオン — 暗黒物質の候補の１つ

$$V = m_a^2 F_a^2 \left[1 - \cos\left(\frac{a}{F_a}\right)\right] \approx \frac{1}{2} m_a^2 a^2$$

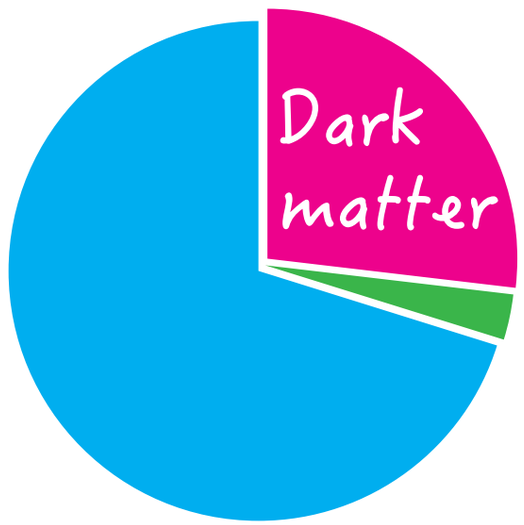


調和振動子 = 冷たい暗黒物質

本当？

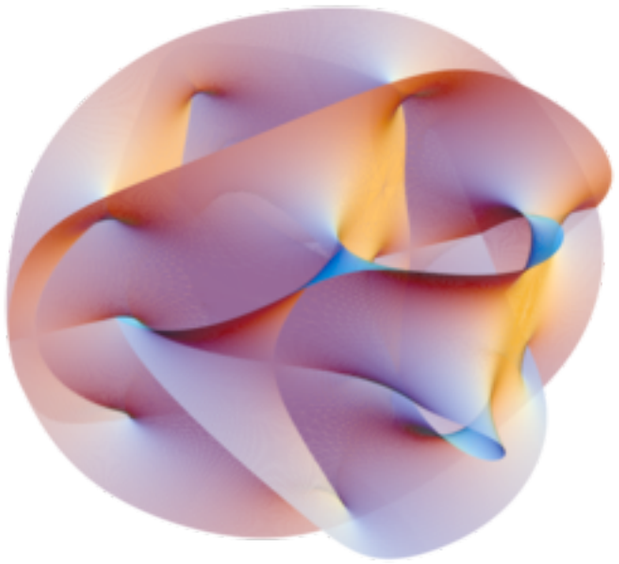
残存量：　$\Omega_a h^2 = 0.18 \theta_i^2 \left(\frac{F_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19}$

質量：　$m_a \simeq 6 \times 10^{-6}\ \mathrm{eV} \left(\frac{10^{12}\ \mathrm{GeV}}{F_a}\right)$

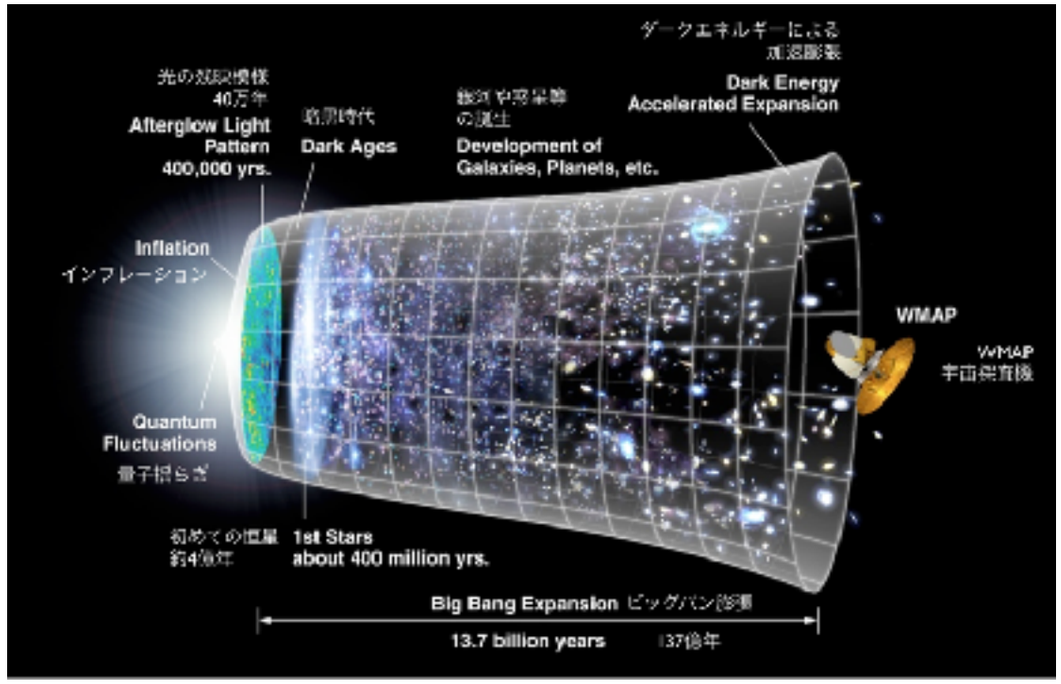


$\Omega_{\mathrm{CDM}} h^2 = 0.12$

ストリングアクシオン



高次元の理論
（超弦理論など）



４次元時空

＋　String axions

どうやって見つける？

“String Axiverse”

Contents

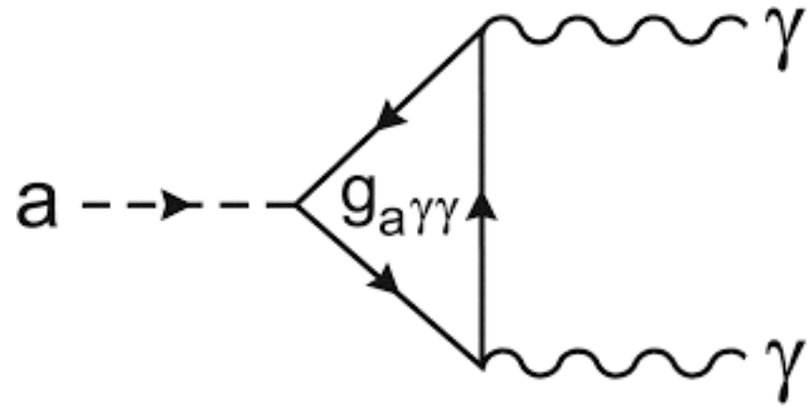
Part 1 - アクシオン暗黒物質の存在量

Part 2 - アクシオンによる重力波生成

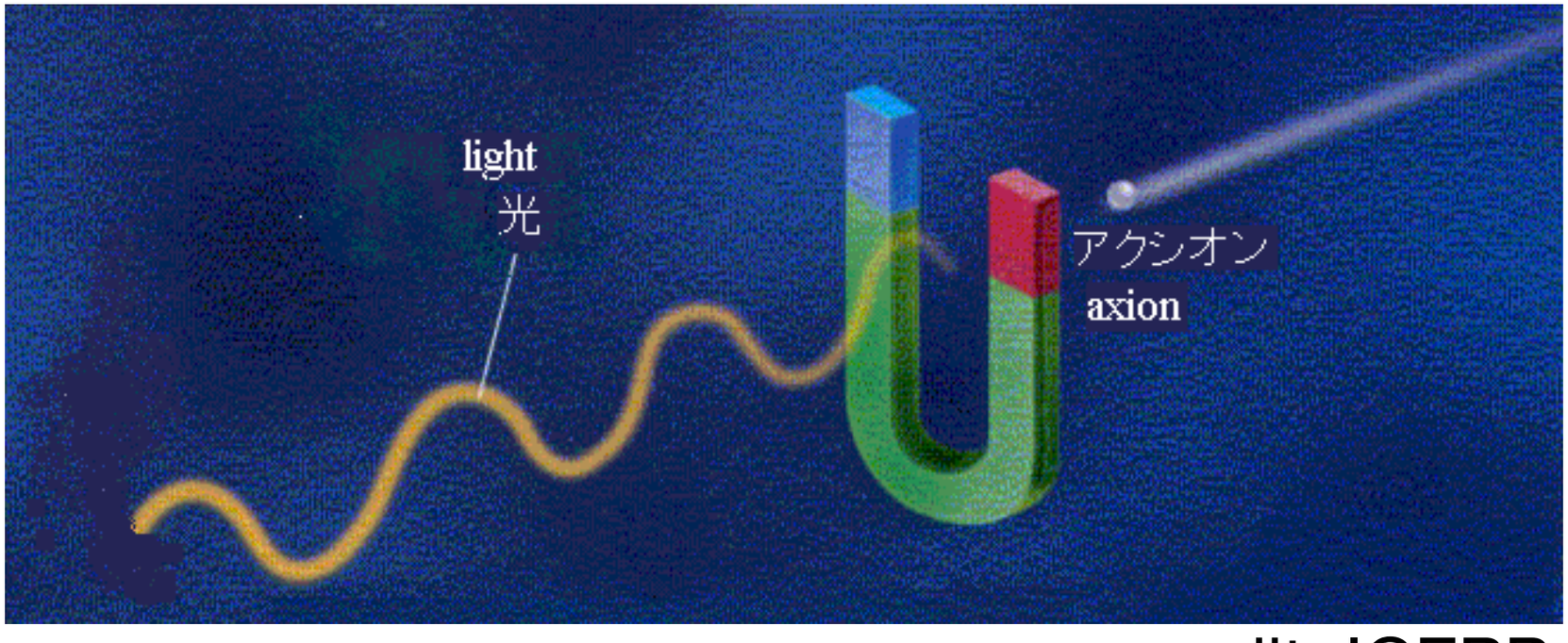
アクシオンと電磁場の相互作用

$$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$= -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$



宇宙初期にどんな影響を及ぼすか？



credit: ICEPP

Axion-Hidden photon coupling and axion abundance

NK, T. Sekiguchi, F. Takahashi, arXiv:1711.06590

Axion-Hidden (dark) photon interaction

$$\Delta\mathcal{L} = -\frac{g_{\phi\gamma'}}{4}\phi F_{\mathrm{H}\mu\nu}\tilde{F}^{\mu\nu}_{\mathrm{H}} \equiv -\frac{\beta_{\mathrm{H}}}{4f_a}\phi F_{\mathrm{H}\mu\nu}\tilde{F}^{\mu\nu}_{\mathrm{H}}$$

$$F_{\mathrm{H}\mu\nu} = \partial_\mu A_{\mathrm{H}\nu} - \partial_\nu A_{\mathrm{H}\mu}, \quad \tilde{F}^{\mu\nu}_{\mathrm{H}} = \epsilon^{\mu\nu\rho\sigma} F_{\mathrm{H}\rho\sigma}/2\sqrt{-g}$$

Hidden U(1) gauge field

axion + hidden U(1) gauge field

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mathrm{H}\mu\nu}F^{\mu\nu}_{\mathrm{H}} - \frac{\beta_{\mathrm{H}}}{4f_a}\phi F_{\mathrm{H}\mu\nu}\tilde{F}^{\mu\nu}_{\mathrm{H}}$$

n.b. $\beta_H >> 1$ is possible in some cases
(e.g. clockwork/aligned axion model)

Evolution equations (in flat-FRW Universe)

- Axion equation of motion

a : scale factor
H : Hubble parameter

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + \frac{\partial V}{\partial \phi} = -\frac{\beta_{\rm H}}{f_a}\boldsymbol{E}_{\rm H}\cdot\boldsymbol{B}_{\rm H}$$

backreaction

$$V(\phi) = m_a^2 f_a^2\left[1-\cos\left(\frac{\phi}{f_a}\right)\right]$$

- Maxwell equations $(F_{{\rm H},0i} = -E_{{\rm H},i},\ F_{{\rm H},ij} = \epsilon_{ijk}B_{{\rm H},k})$

$$\dot{\boldsymbol{B}}_{\rm H} = -\nabla\times\boldsymbol{E}_{\rm H}$$

photon production

$$\dot{\boldsymbol{E}}_{\rm H} + H\boldsymbol{E}_{\rm H} = \frac{1}{a^2}\nabla\times\boldsymbol{B}_{\rm H} - \frac{\beta_{\rm H}}{af_a}(\dot{\phi}\boldsymbol{B}_{\rm H} + \nabla\phi\times\boldsymbol{E}_{\rm H})$$

$$\nabla\cdot\boldsymbol{B}_{\rm H} = 0,\quad \nabla\cdot\boldsymbol{E}_{\rm H} = \frac{\beta_{\rm H}}{af_a}\nabla\phi\cdot\boldsymbol{B}_{\rm H}$$

Tachyonic growth of gauge fields

ゲージ場を円偏光モードで展開

$$\boldsymbol{A}_{\rm H} = \sum_{\lambda=\pm} \int \frac{d^3k}{(2\pi)^3} e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \boldsymbol{\varepsilon}^{\lambda}(\boldsymbol{k}) \left[A^{\lambda}_{\rm H}(\boldsymbol{k}) a_{\lambda}(\boldsymbol{k}) + A^{\lambda *}_{\rm H}(\boldsymbol{k}) a^{\dagger}(-\boldsymbol{k}) \right]$$

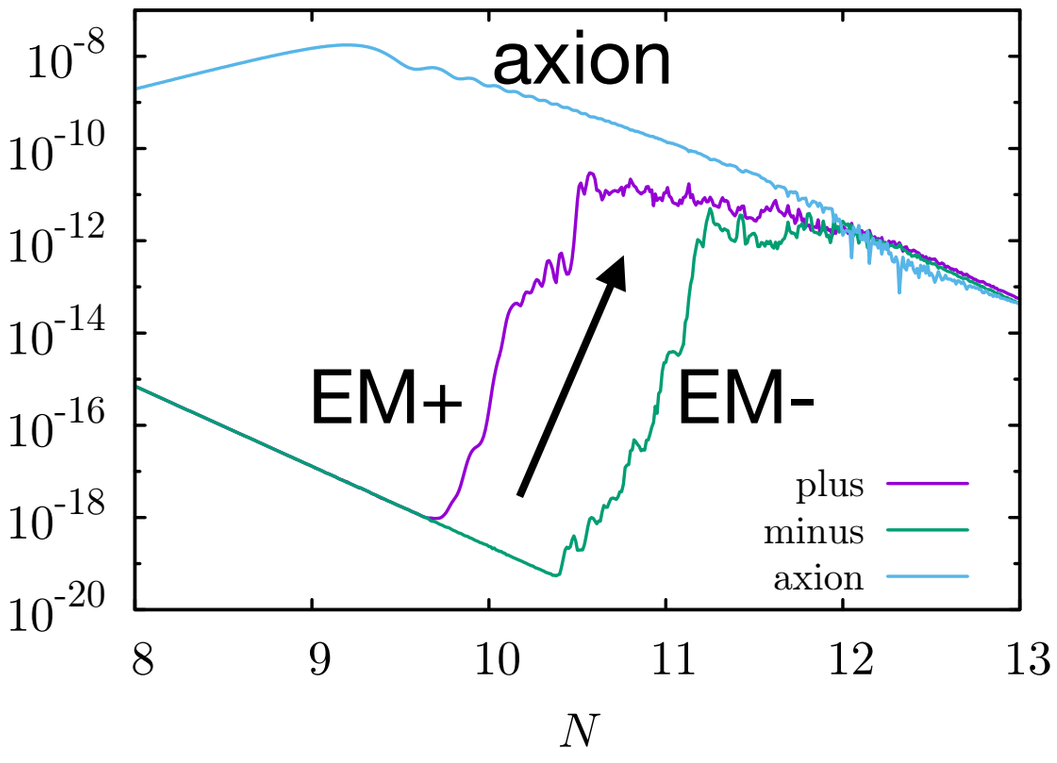
$$\ddot{A}^{(\pm)}_{\rm H}(\boldsymbol{k}) + H \dot{A}^{(\pm)}_{\rm H}(\boldsymbol{k}) + \left(\frac{k^2}{a^2} \mp \frac{k}{a} \frac{\beta_{\rm H} \dot{\phi}}{f_a} \right) A^{(\pm)}_{\rm H}(\boldsymbol{k}) = 0$$

（空間的一様なアクシオン場を仮定）

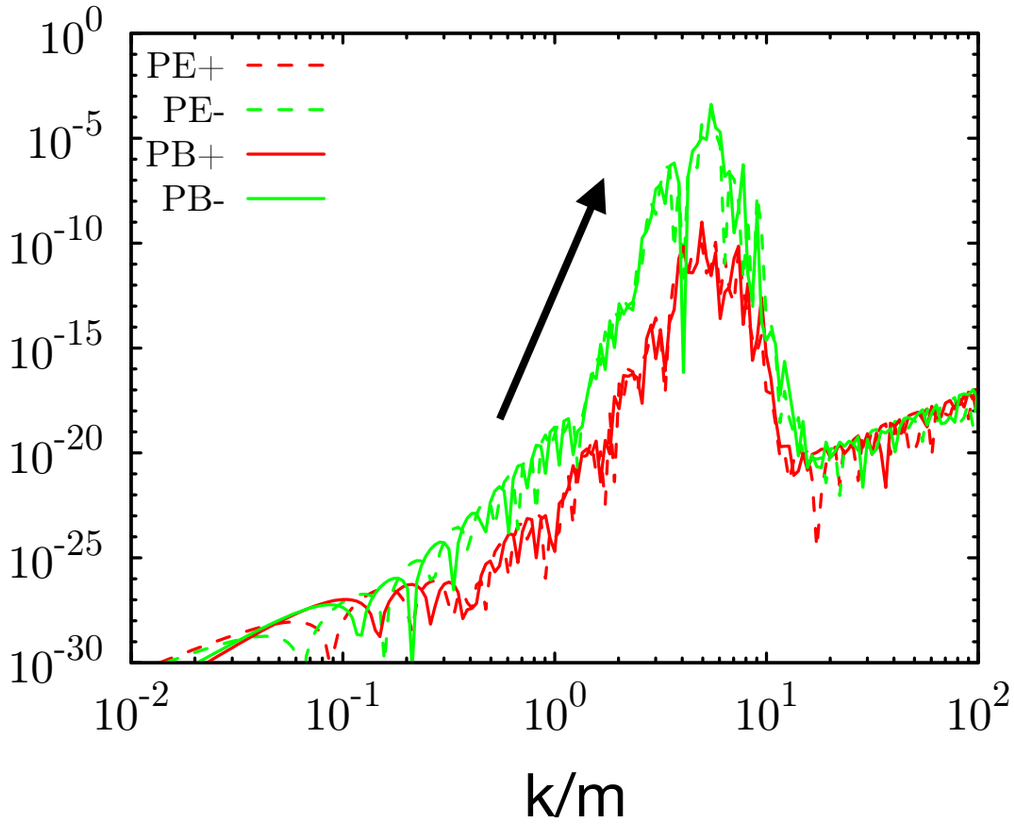
$$\frac{k}{a} < \frac{\beta_{\rm H} \dot{\phi}}{f_a} \quad \Rightarrow \quad A^{\lambda}_{\rm H}(\boldsymbol{k}) \to \frac{1}{\sqrt{2k}} \frac{e^{\pi|\xi|}}{\sqrt{2\pi|\xi|}}, \quad \text{with} \quad \xi \equiv \frac{\beta_{\rm H} \dot{\phi}}{2 f_a H}$$

Tachyonic growth of gauge fields

evolution of energy density



power spectrum



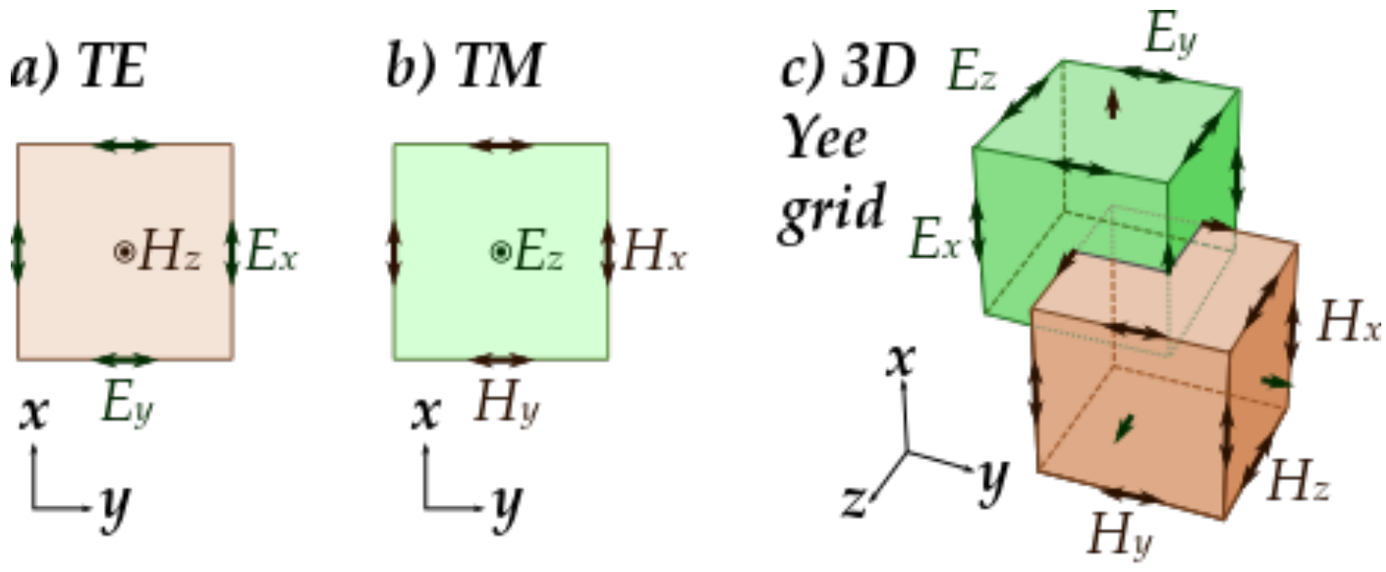
cf. Magnetic field generation in the early universe

Lattice AED (axion electrodynamics)

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + \frac{\partial V}{\partial \phi} = -\frac{\beta_{\rm H}}{f_a}\boldsymbol{E}_{\rm H}\cdot\boldsymbol{B}_{\rm H}$$

$$\dot{\boldsymbol{B}}_{\rm H} = -\nabla\times\boldsymbol{E}_{\rm H}$$

$$\dot{\boldsymbol{E}}_{\rm H} + H\boldsymbol{E}_{\rm H} = \frac{1}{a^2}\nabla\times\boldsymbol{B}_{\rm H} - \frac{\beta_{\rm H}}{af_a}(\dot{\phi}\boldsymbol{B}_{\rm H} + \nabla\phi\times\boldsymbol{E}_{\rm H})$$

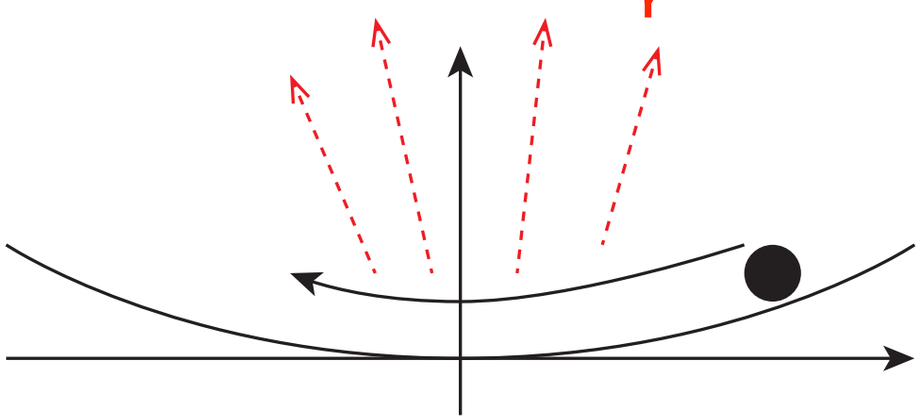


https://en.wikipedia.org/wiki/Finite-difference_time-domain_method

Dissipation or overdamping

1. dissipation

energy dissipation
into hidden photons



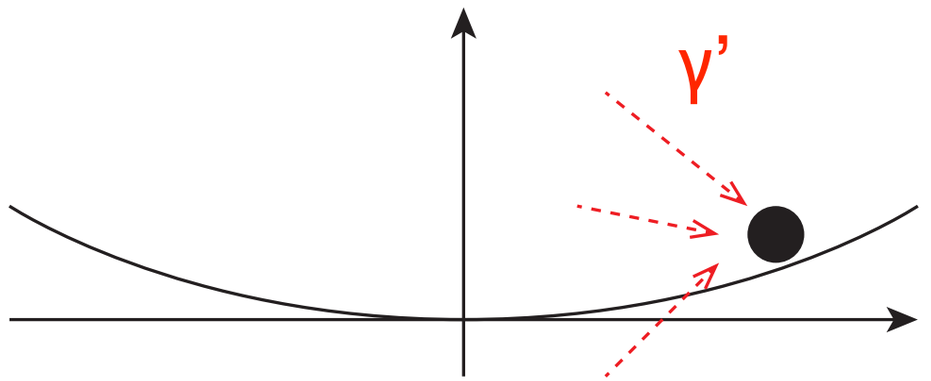
axion energy is dissipated
by gauge field production

↓

axion abundance is suppressed

2. overdamping

large friction
by produced photons

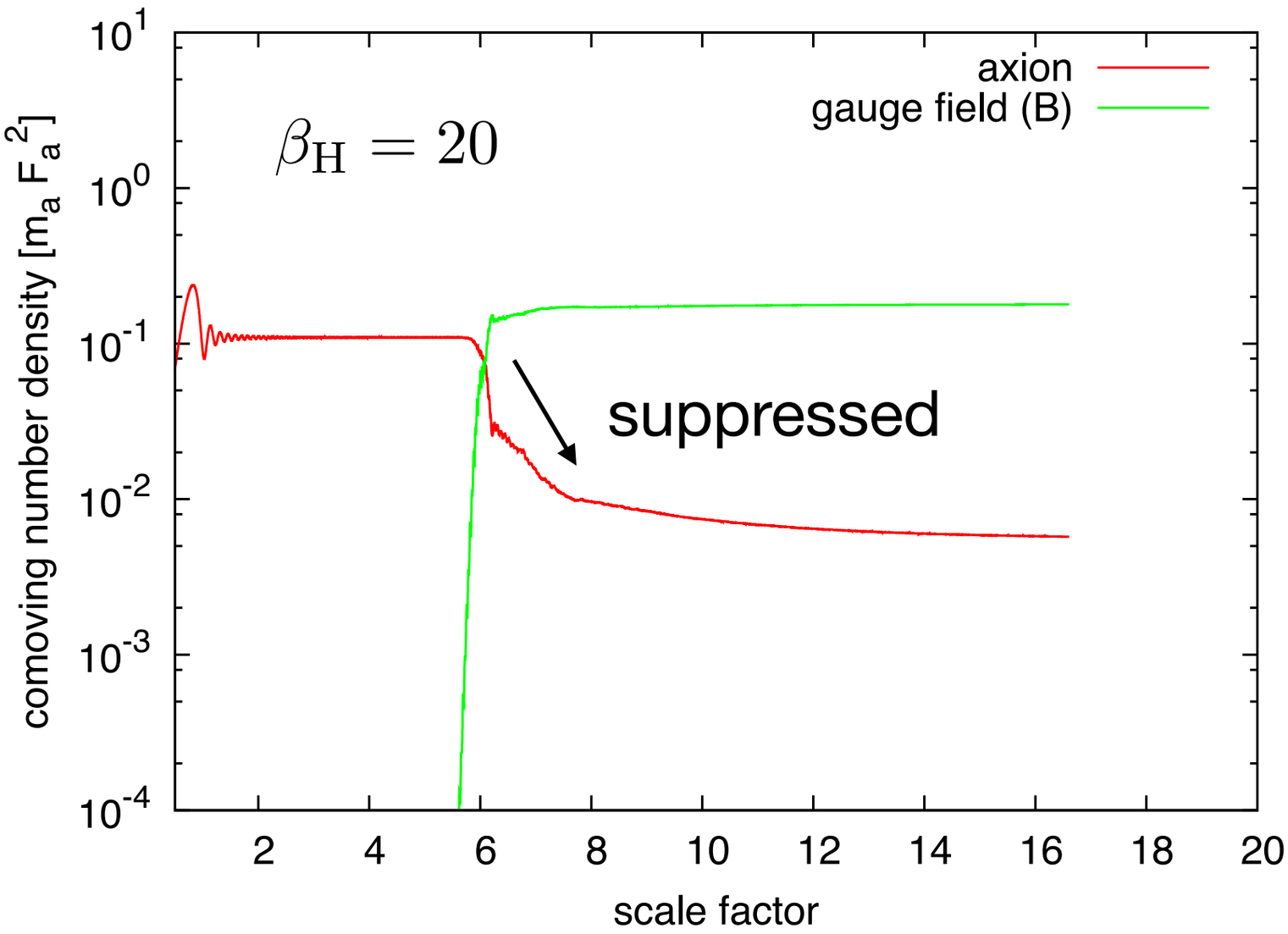


onset of oscillation is delayed
by strong backreaction

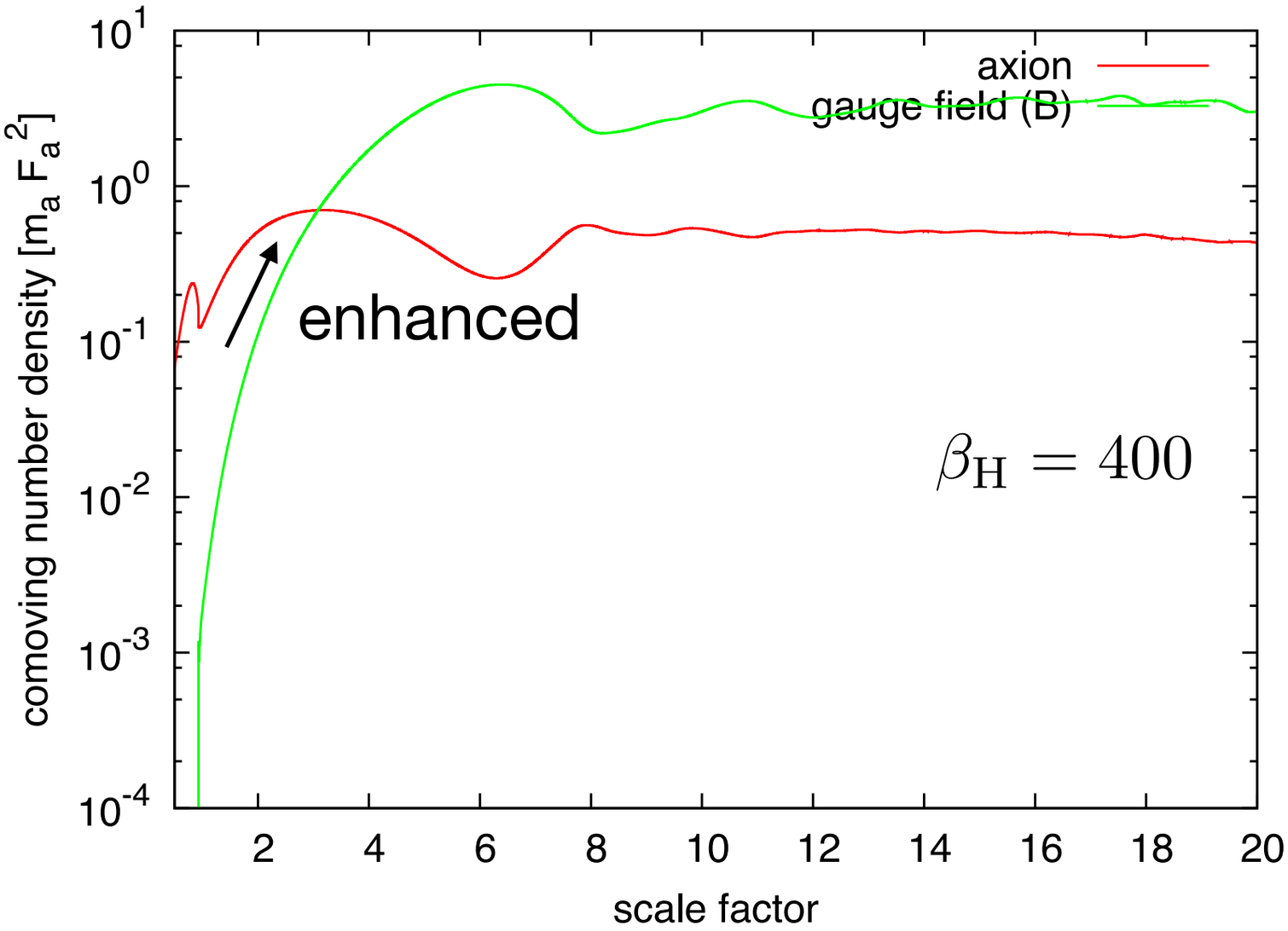
↓

axion abundance is enhanced

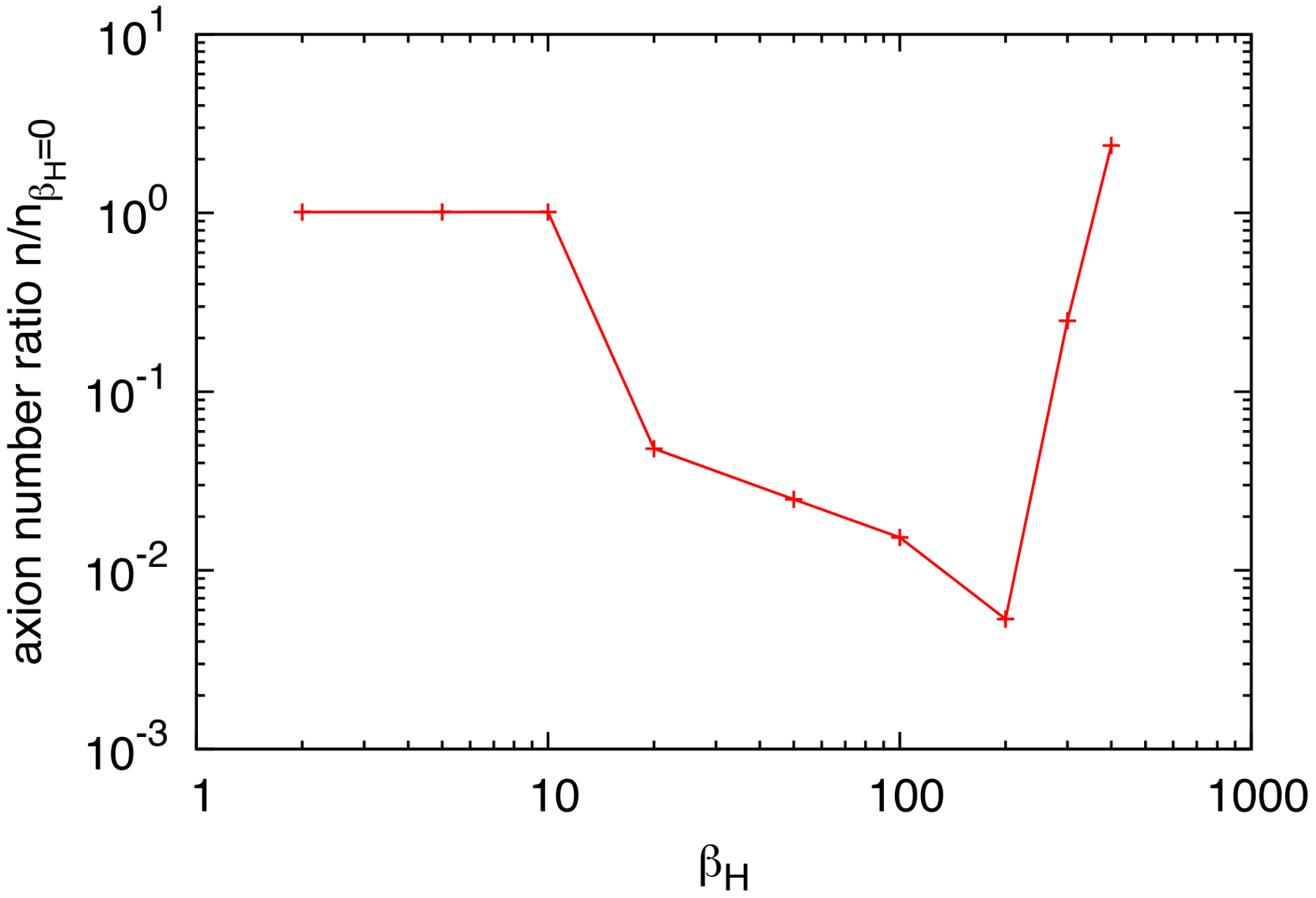
evolution of the comoving number density - dissipation



evolution of the comoving number density - overdamping



suppression/enhancement factor



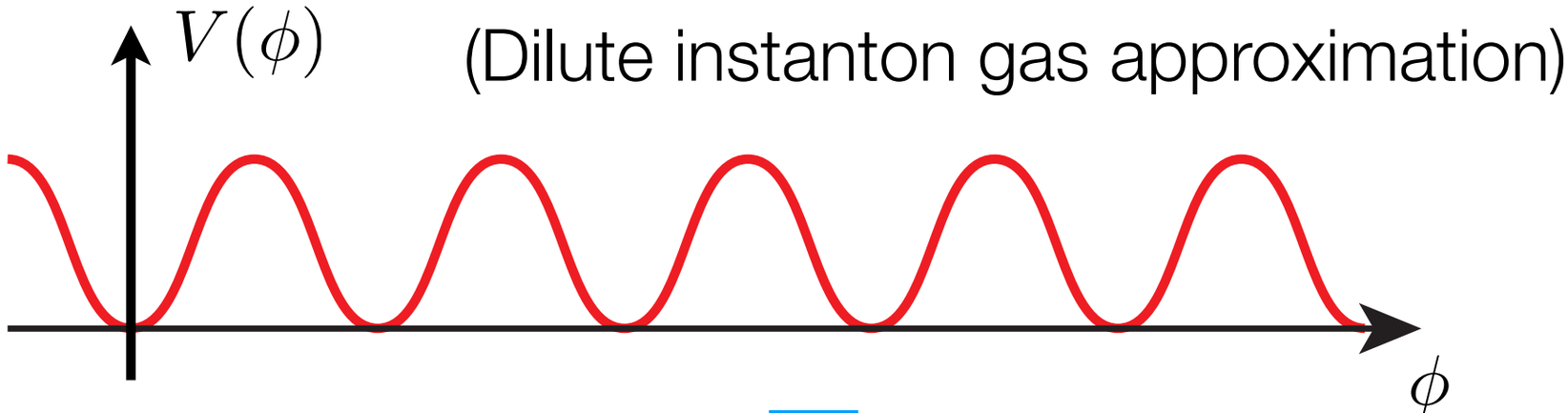
axion abundance can be suppressed ~ 0.01

Gravitational wave forest from axiverse

NK, J. Soda, Y. Urakawa, arXiv:1807.07037

Axion potential (for ALP)

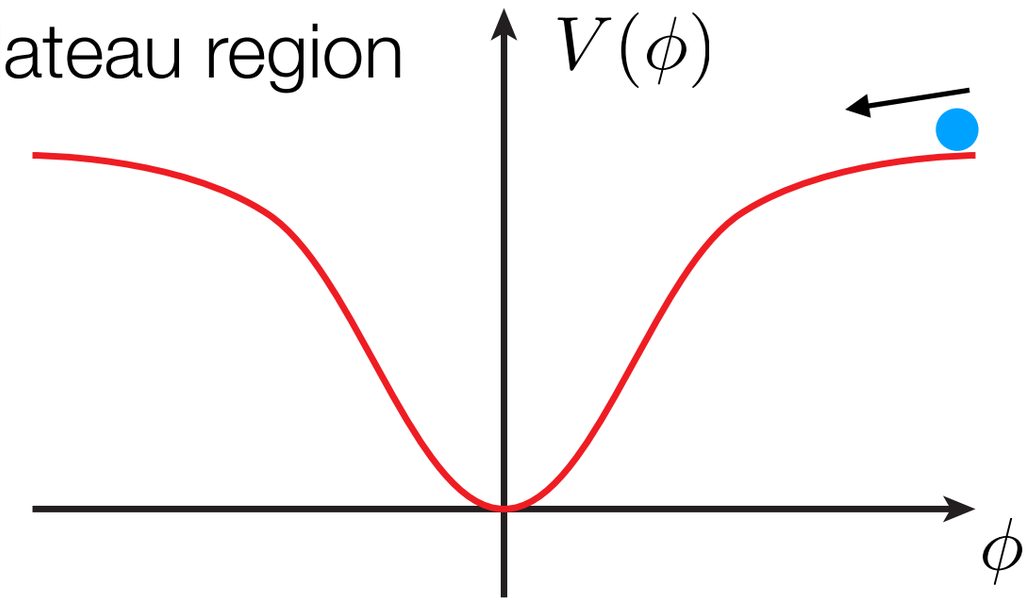
Cosine-type potential : $V(\phi) \simeq \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)$



(Dilute instanton gas approximation)

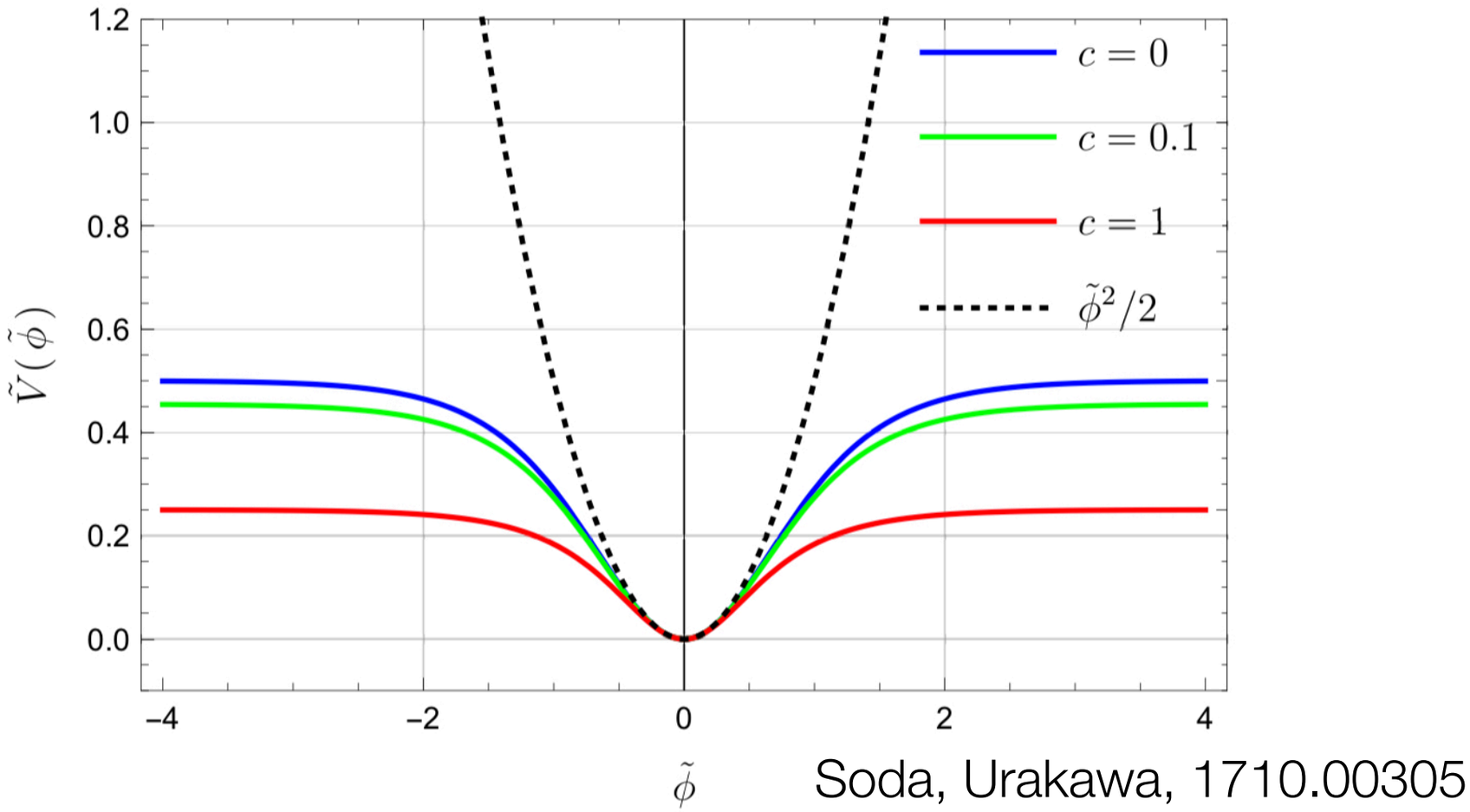
(some classes of) string axion

Potential with plateau region



String axion (with α-attractor type potential)

$$V(\phi) = \frac{m^2 f^2}{2} \frac{\tanh^2(\phi/f)}{1 + c\tanh^2(\phi/f)}$$



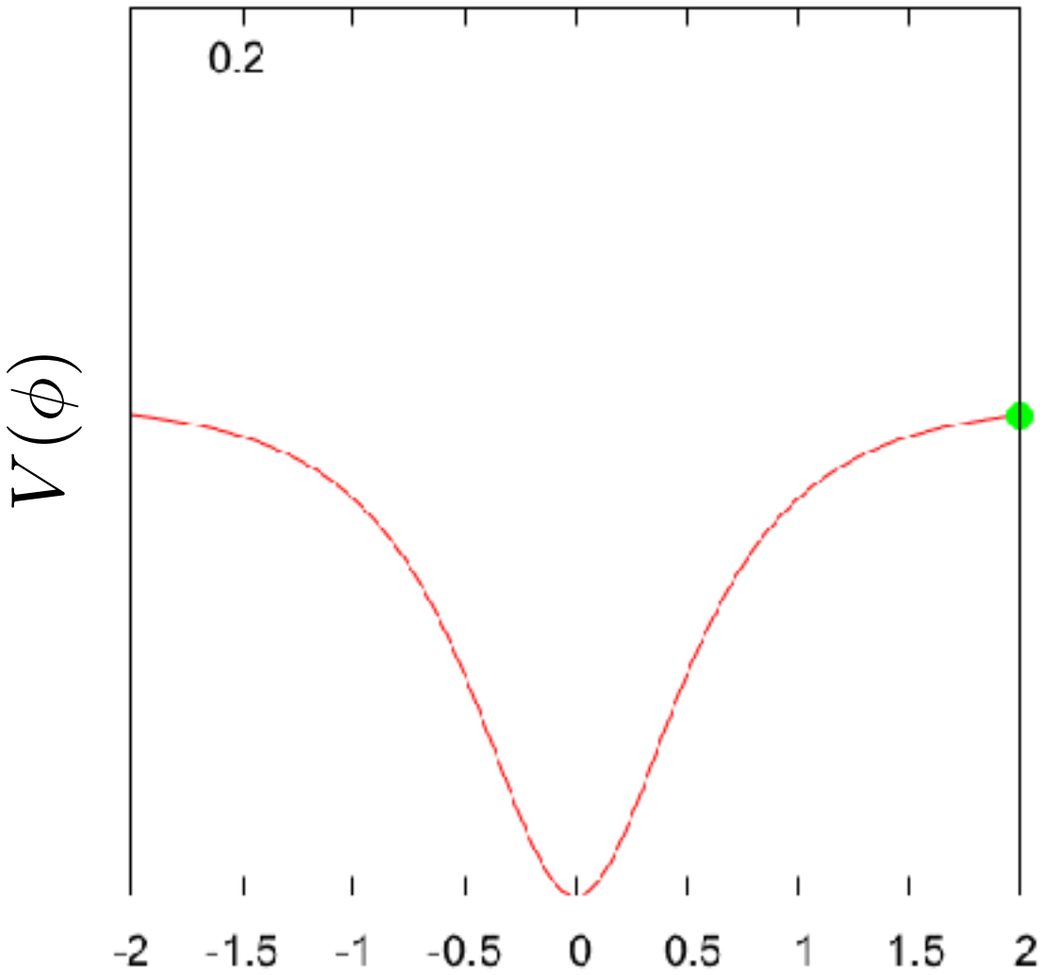
Soda, Urakawa, 1710.00305

自己相互作用 —> パラメター共鳴

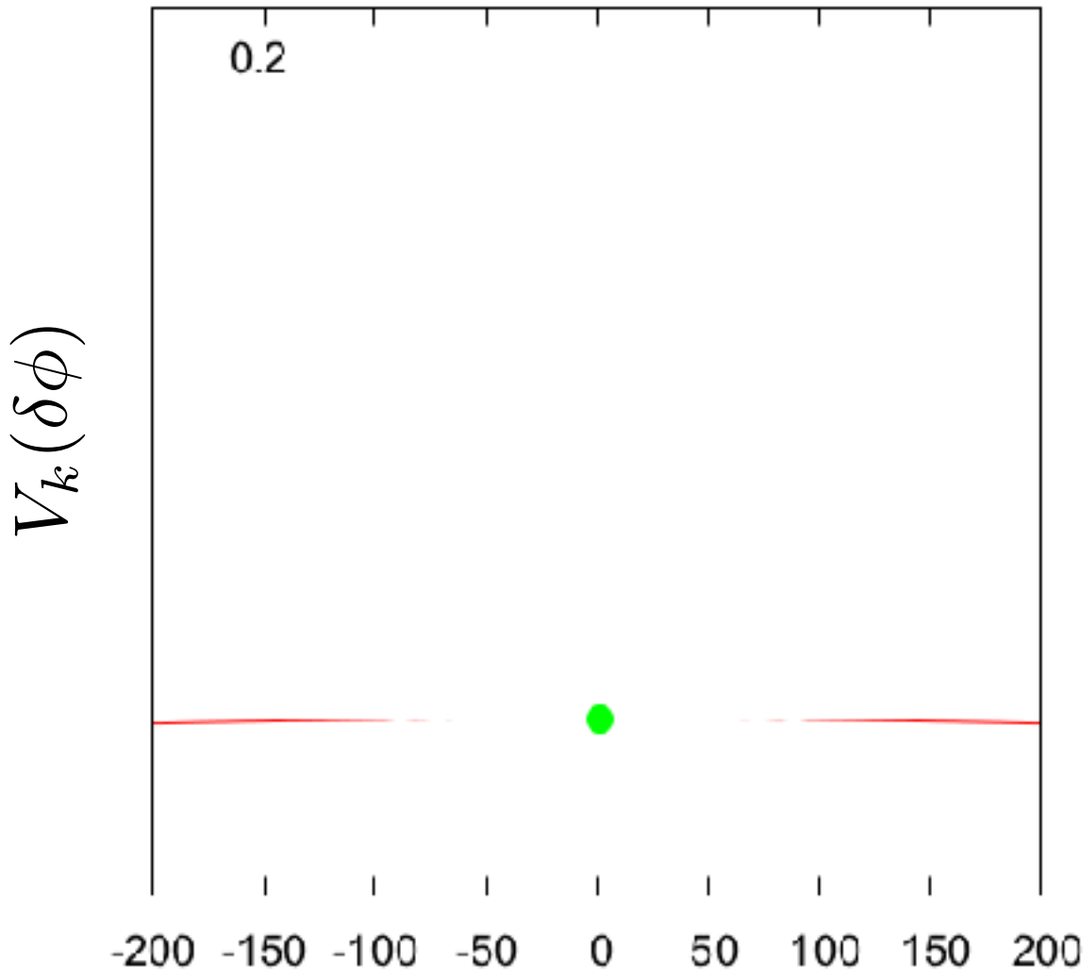
場の揺らぎが指数関数的に成長

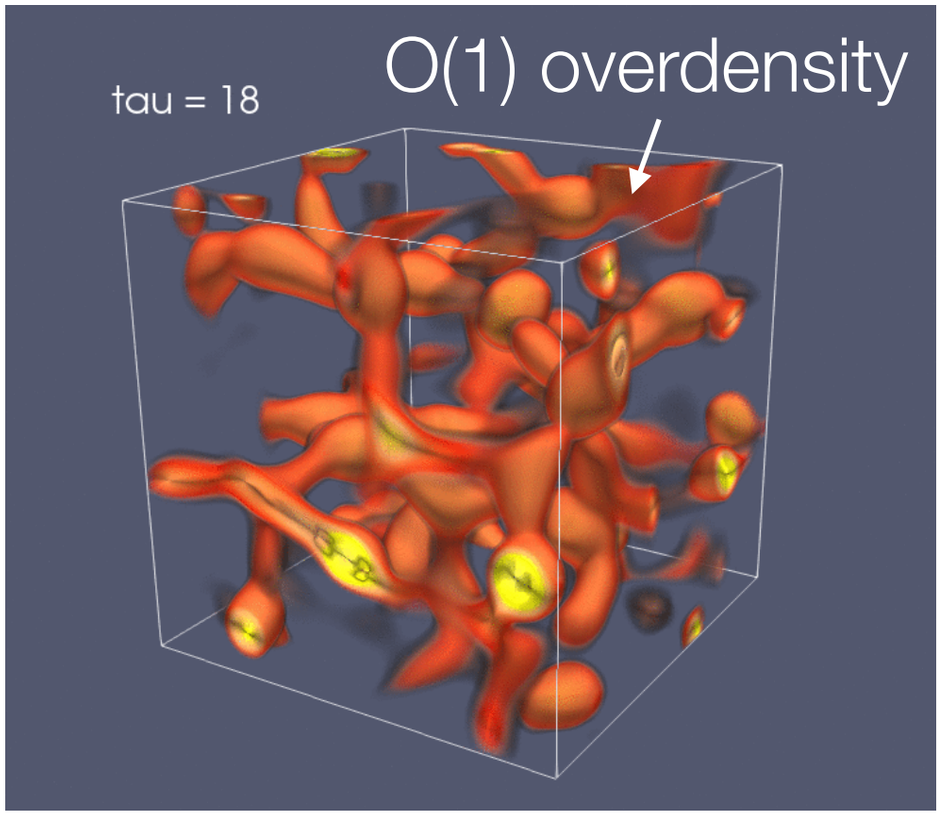
“Frapping” resonance

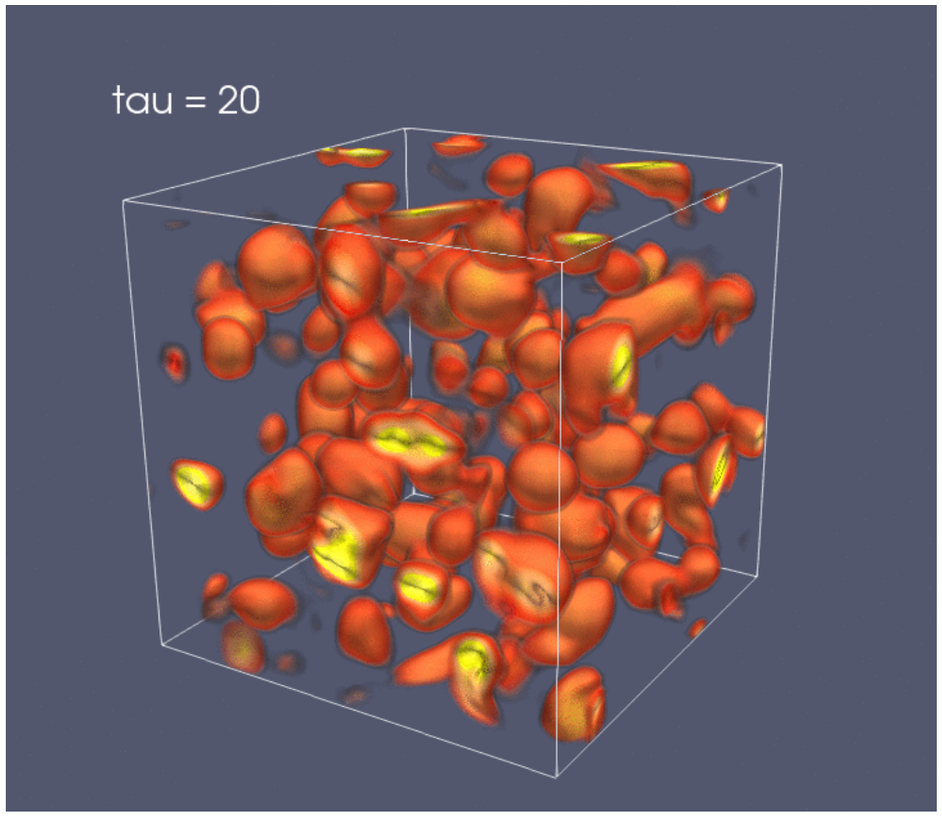
一様モード

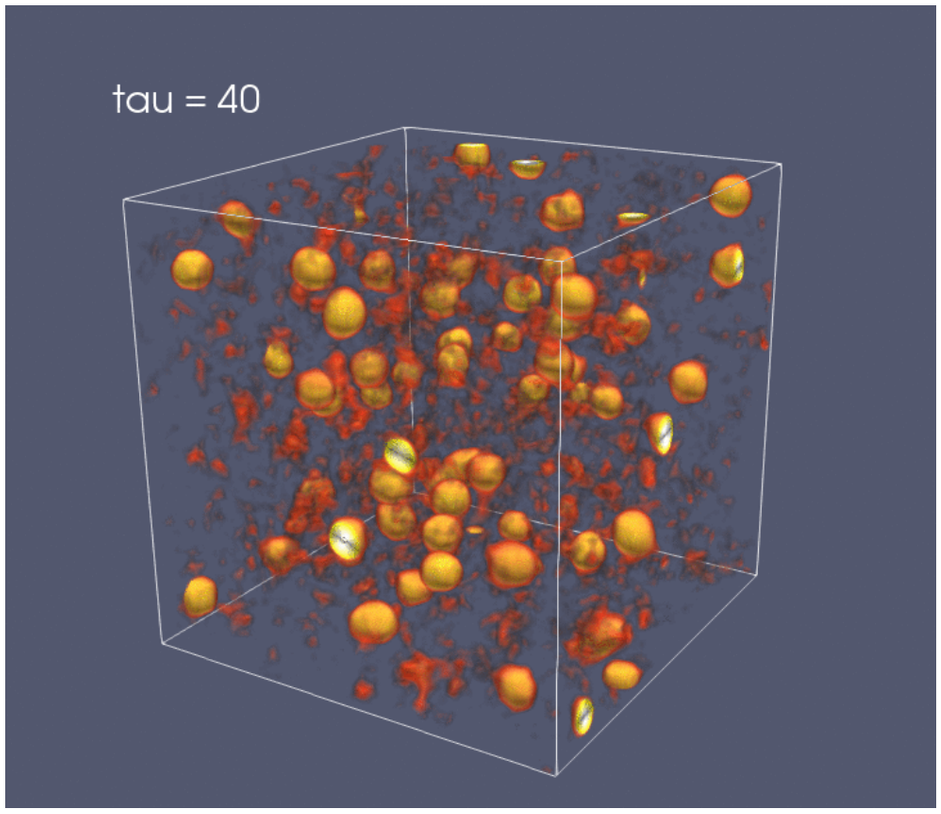


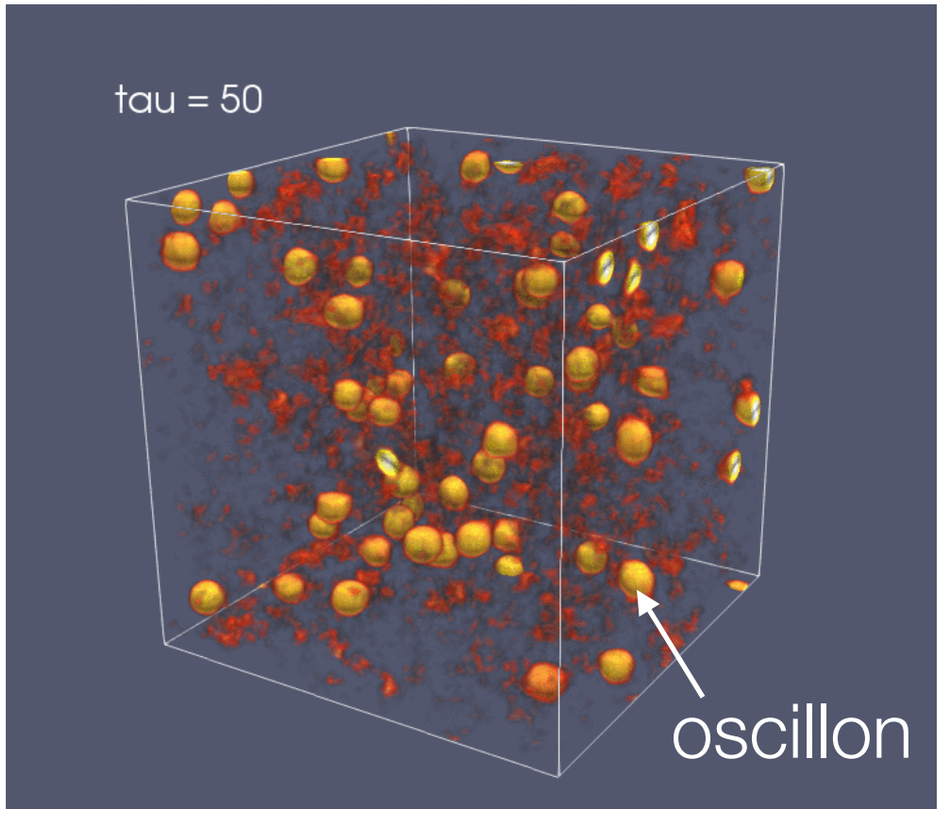
場の揺らぎ (k/m=0.1)

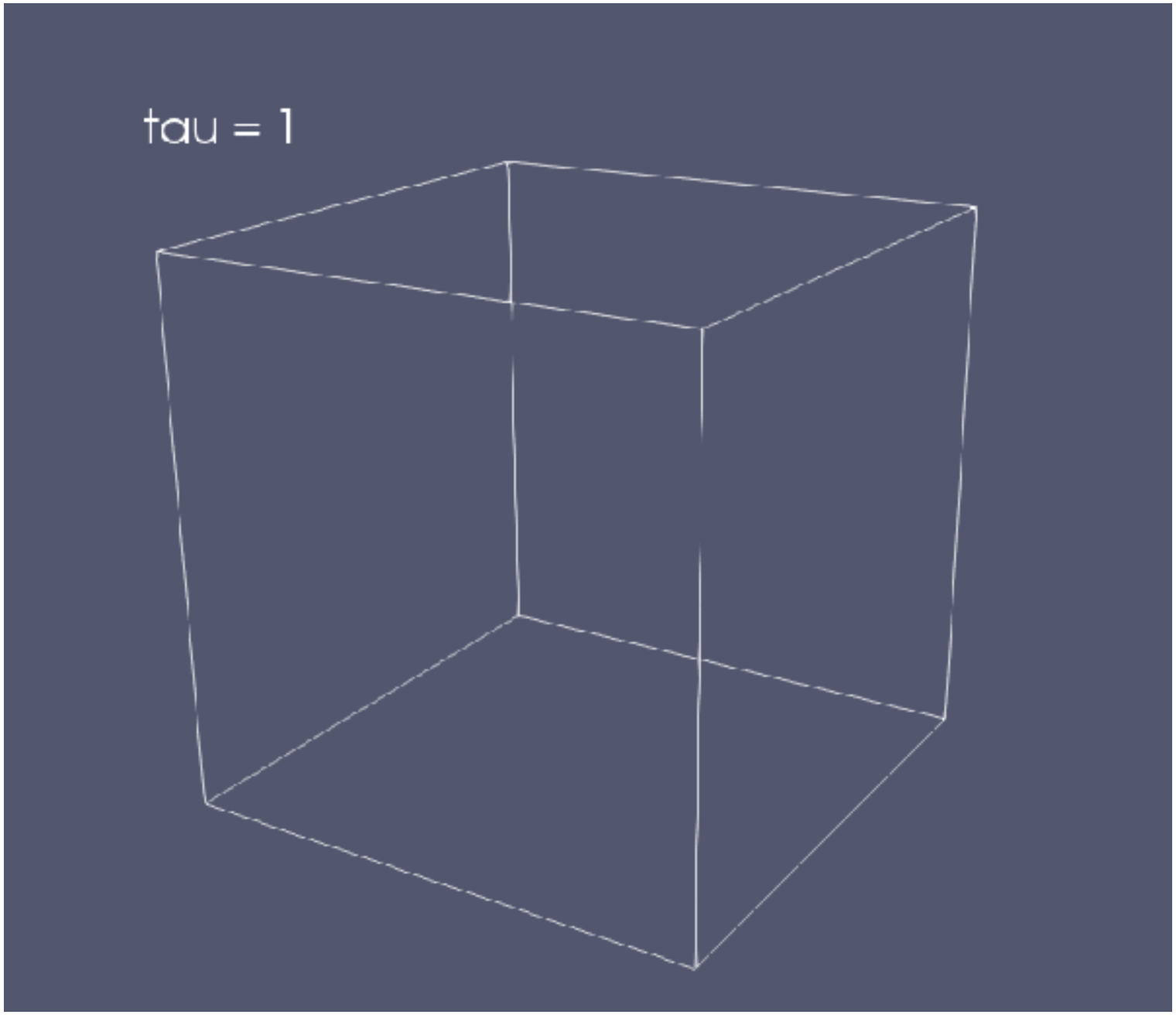



tau = 18
O(1) overdensity


tau = 20


tau = 40


tau = 50
oscillon


tau = 1

Gravitational wave emission

$$ds = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$

tensor metric perturbation (GW)

evolution equation (Einstein equation) for gravitational waves

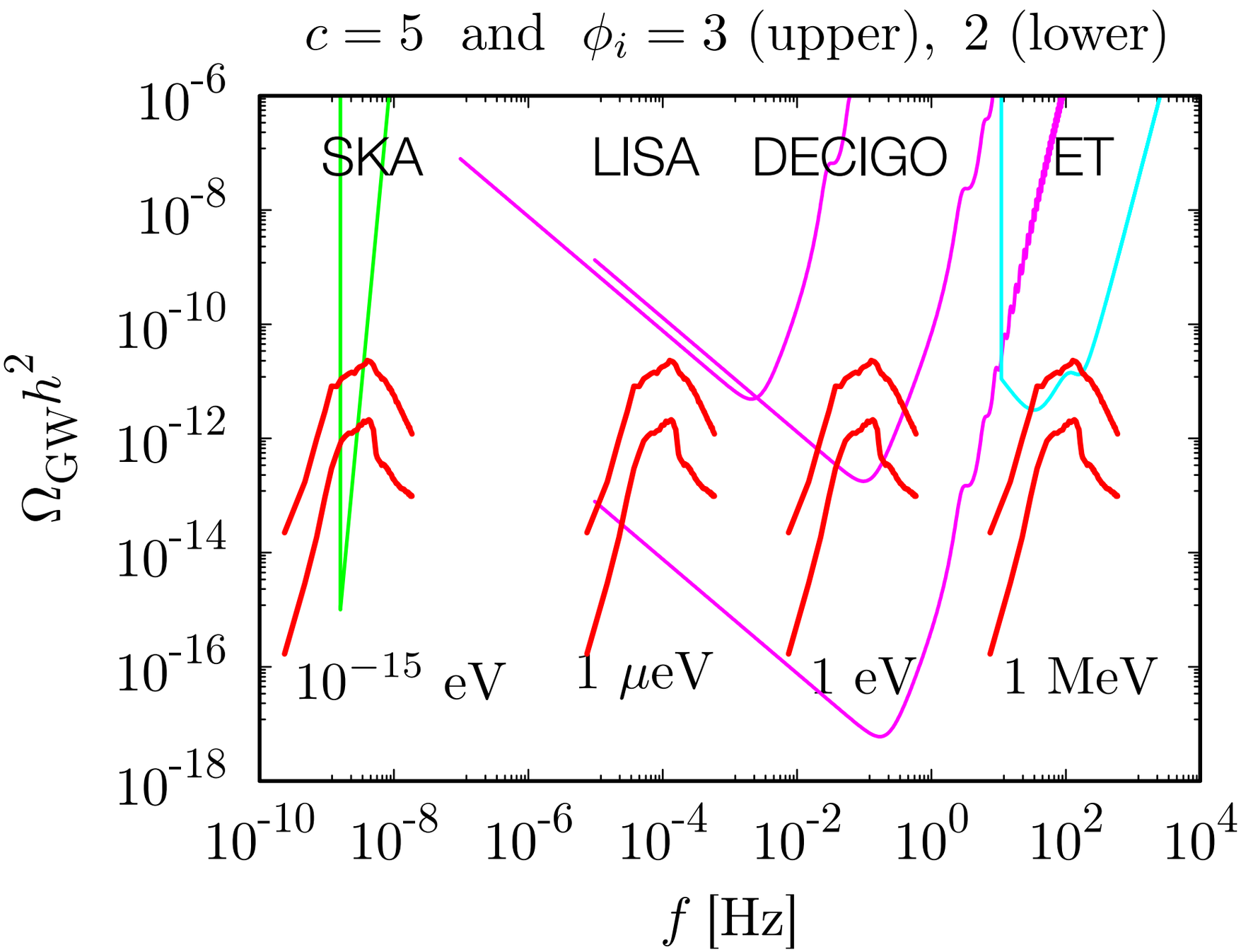
$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{\nabla^2 h_{ij}}{a^2} = 16\pi G \Pi_{ij}^{\mathrm{TT}} \quad \text{with} \quad \Pi_{ij}^{\mathrm{TT}} = -\frac{1}{a^2} P_{ij}^{lm} \partial_i \phi \partial_j \phi$$

TT projection tensor

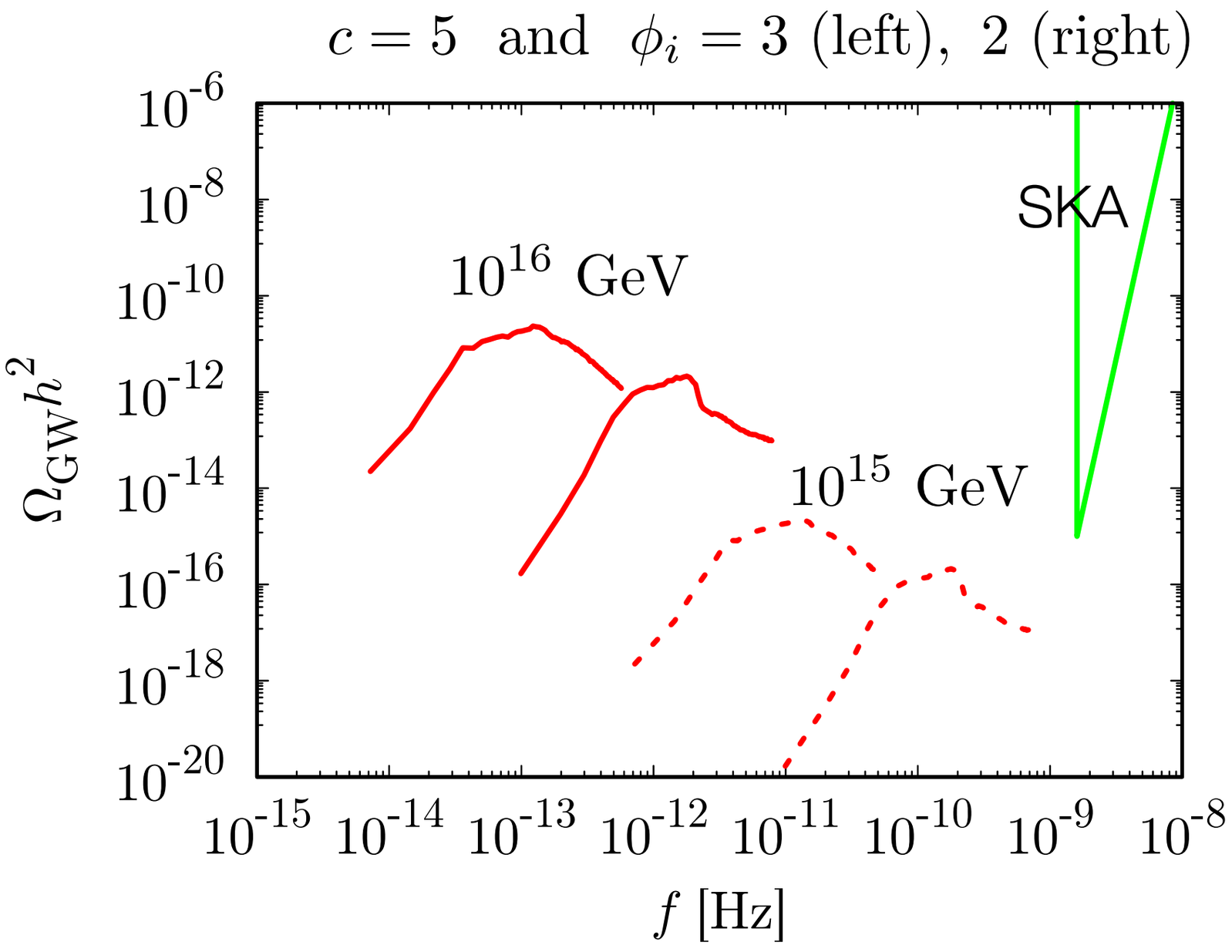
Density spectrum of GW

$$\Omega_{\mathrm{GW}}(k) = \frac{1}{\rho_{\mathrm{cr}}} \frac{d\rho_{\mathrm{GW}}}{d\ln k}, \quad \rho_{\mathrm{GW}} = \frac{1}{32\pi G} \langle \dot{h}_{ij} \dot{h}_{ij} \rangle$$

重力波フォレスト


$c = 5$ and $\phi_i = 3$ (upper), 2 (lower)
SKA
LISA
DECIGO
ET
10^{-15} eV
1 μeV
1 eV
1 MeV
$\Omega_{\rm GW}h^2$
f [Hz]
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4}

Axion = dark matter



axion abundance : $\Omega_\phi h^2 = 1.5 \left(\frac{m}{10^{-14}\,\mathrm{eV}}\right)^{1/2} \left(\frac{m}{H_{\rm osc}}\right)^{3/2} \left(\frac{\phi_{\rm osc}}{10^{16}\,\mathrm{GeV}}\right)^2$

アクシオン-ダークフォトン相互作用を仮定

アクシオンのエネルギーがダークフォトンに散逸

ー> アクシオン存在量は減る

アクシオンの振動がダークフォトンに妨げられる

ー> アクシオン存在量は増える

Plateau typeのポテンシャルをもつアクシオンは重力波を予言

「重力波フォレスト」