Gravitational wave forest from axions

Naoya Kitajima

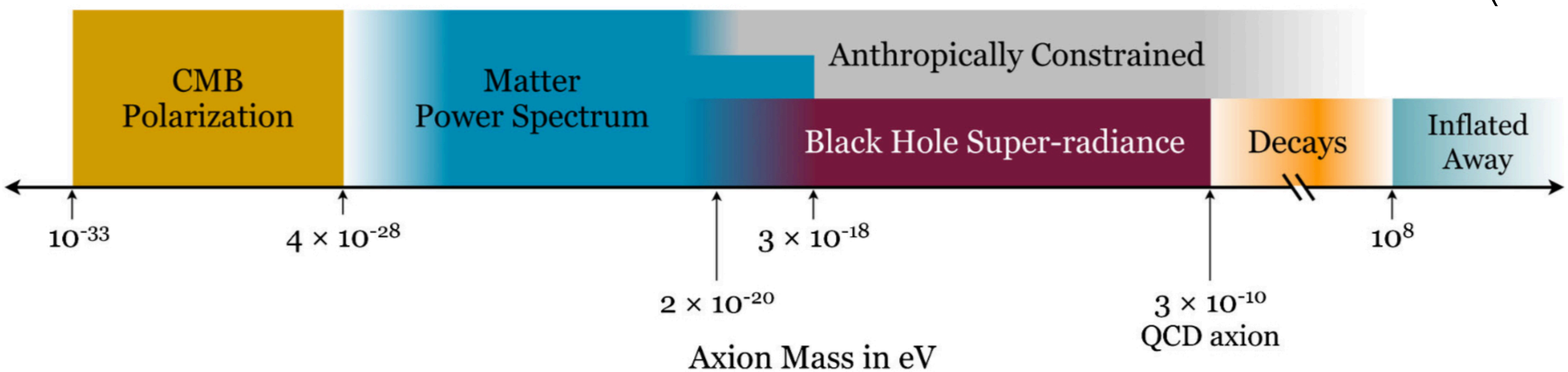
FRIS, Tohoku U.

Collaboration with Y. Urakawa, J. Soda,
P. Agrawal, M. Reece, T. Sekiguchi, F. Takahashi

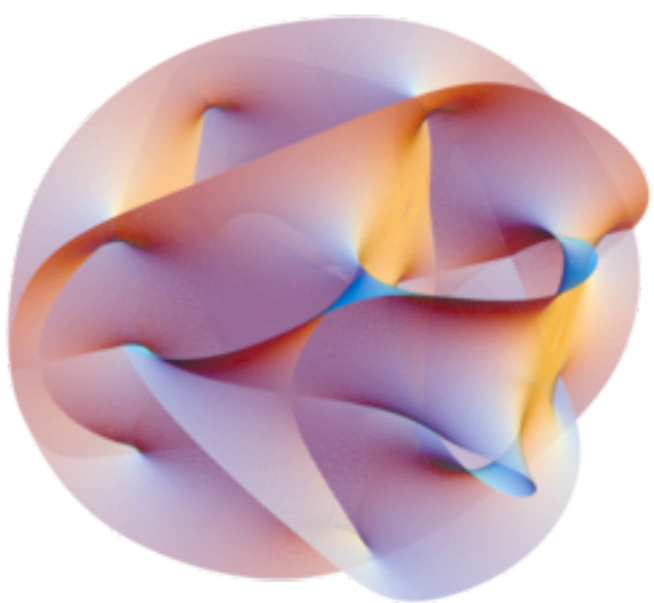
Axion Cosmology 2019/5/14 in YITP

Axiverse

Arvanitaki et al. (2010)

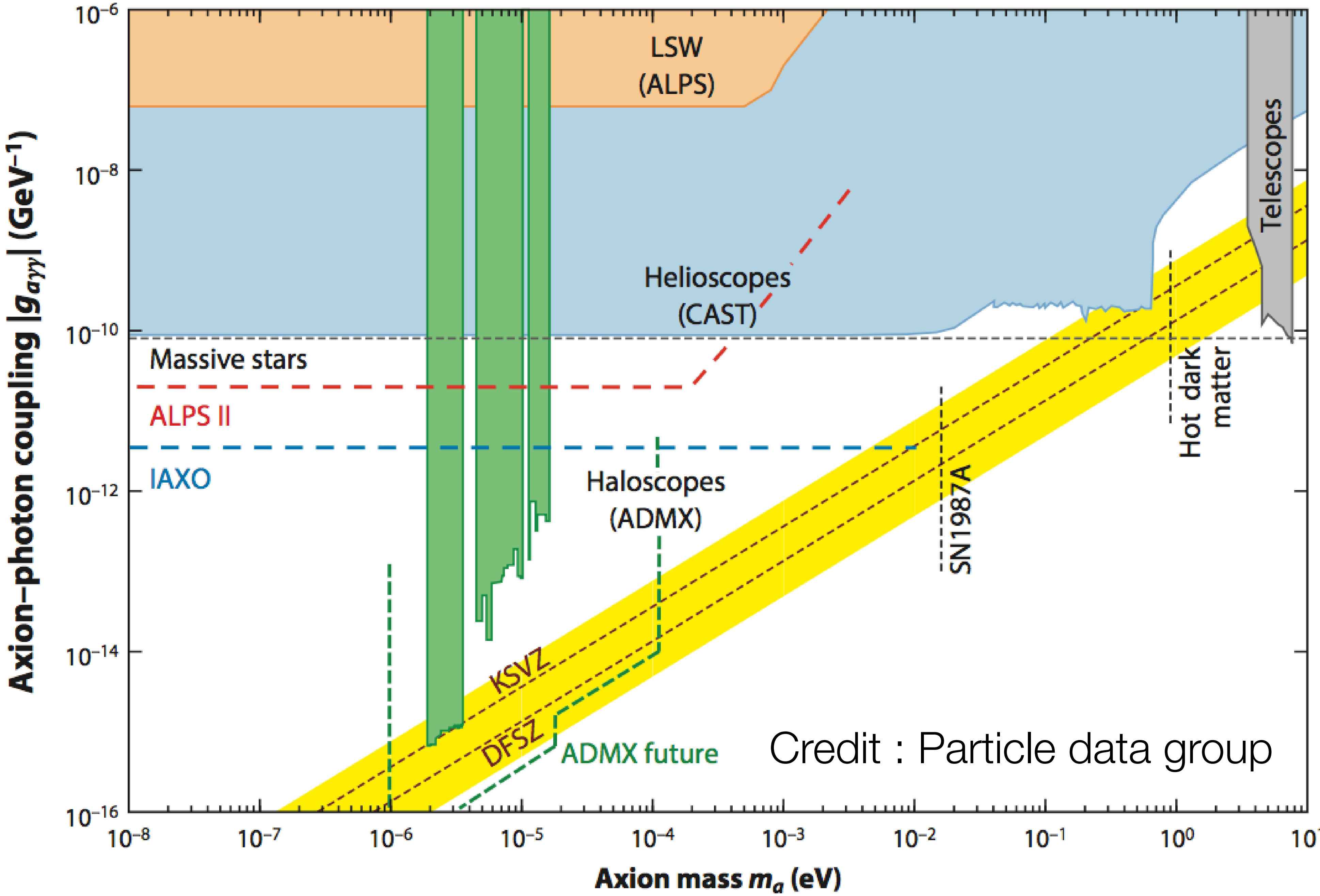


String theory predicts many axions with broad mass range



Constraints on axion/ALPs

(see also Obata, Ito, Kato, Chiueh, Hayashi's talks)

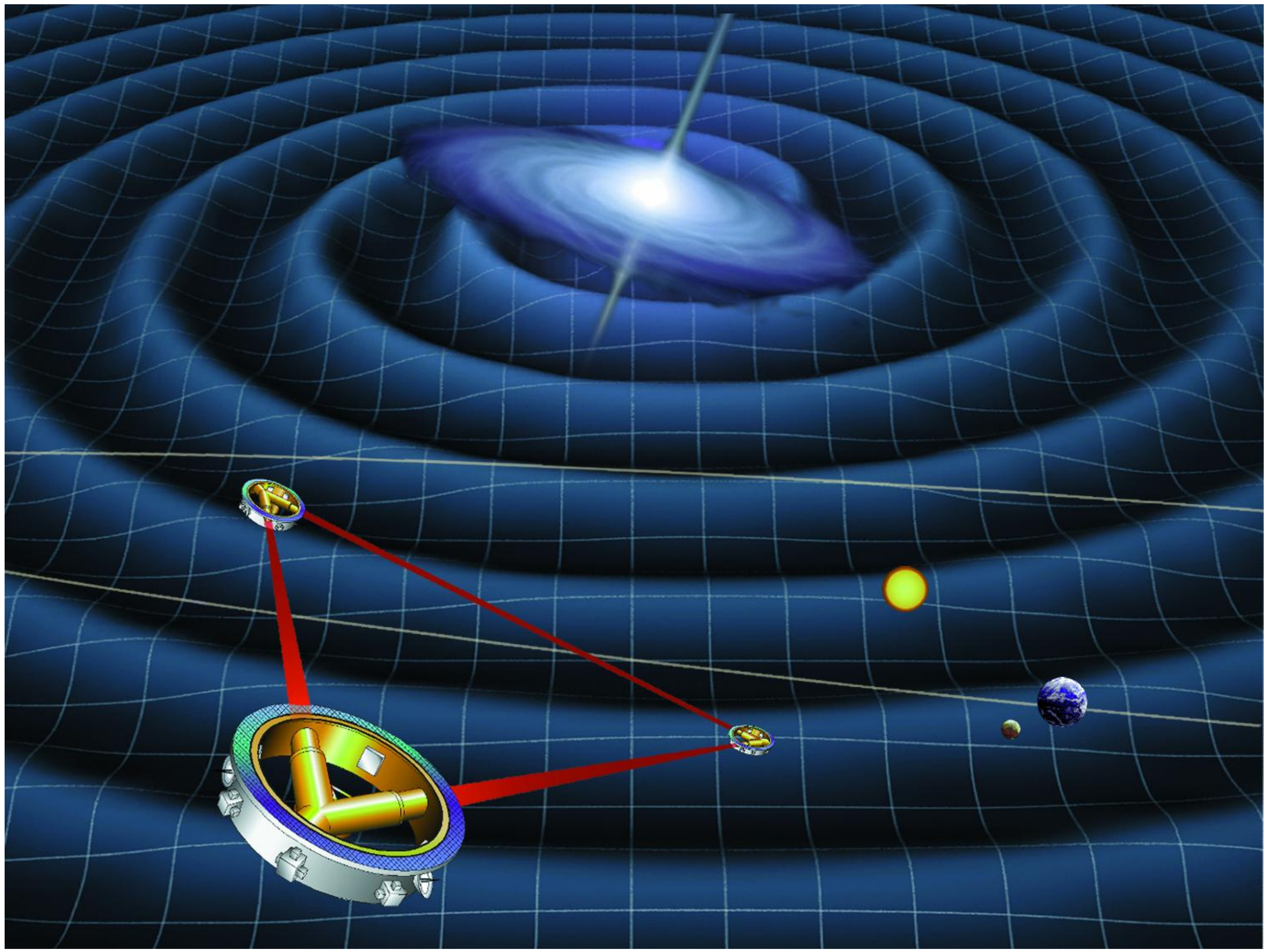


String axions with large decay constant ~10^{16} GeV or small $g_{a\gamma\gamma}$

—> it is difficult to search them by direct detection experiments

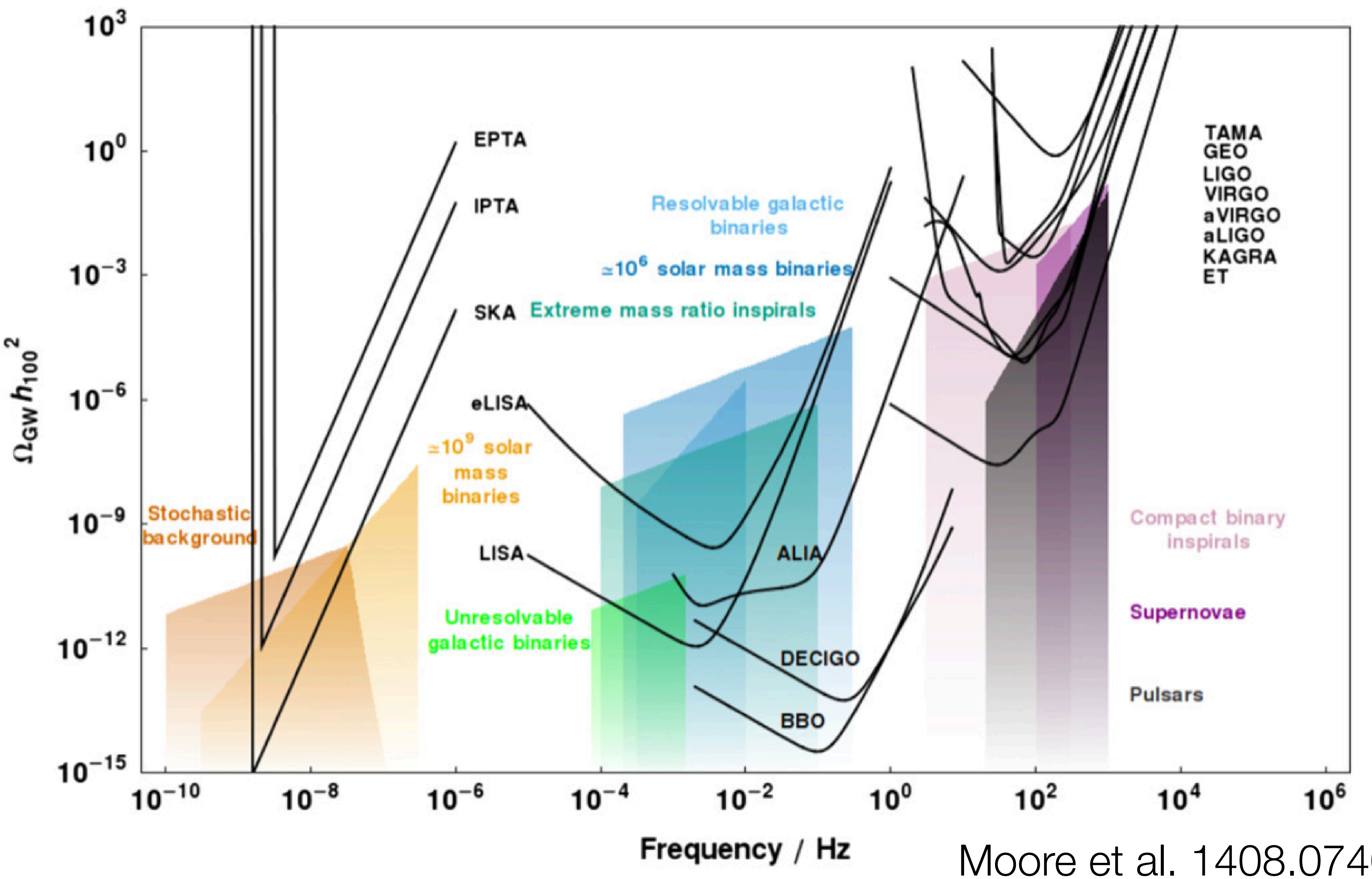
String axion search via Gravitational wave (GW)

GW can be sourced by scalar field fluctuations



GW signal becomes strong for larger decay constants $\sim 10^{16}\ \mathrm{GeV}$

Future GW observation with multi-frequency bands



Moore et al. 1408.0740

Axion mass (m) <—> frequency

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1. GW production from axion self-resonance

- Flapping resonance
- Oscillon formation
- GW forest

2. Tachyonic gauge field production from axion

- Dark photon dark matter production
- Helical GW production

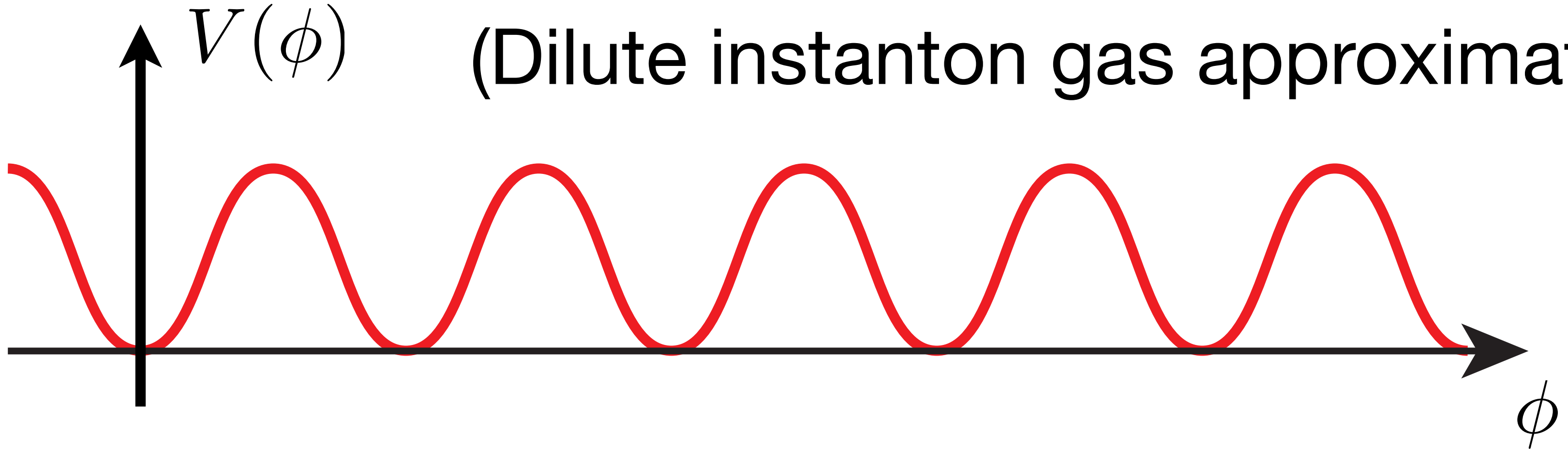
Axion as DM in radiation dominated Universe

GW production from axion self-resonance

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

Axion potential

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

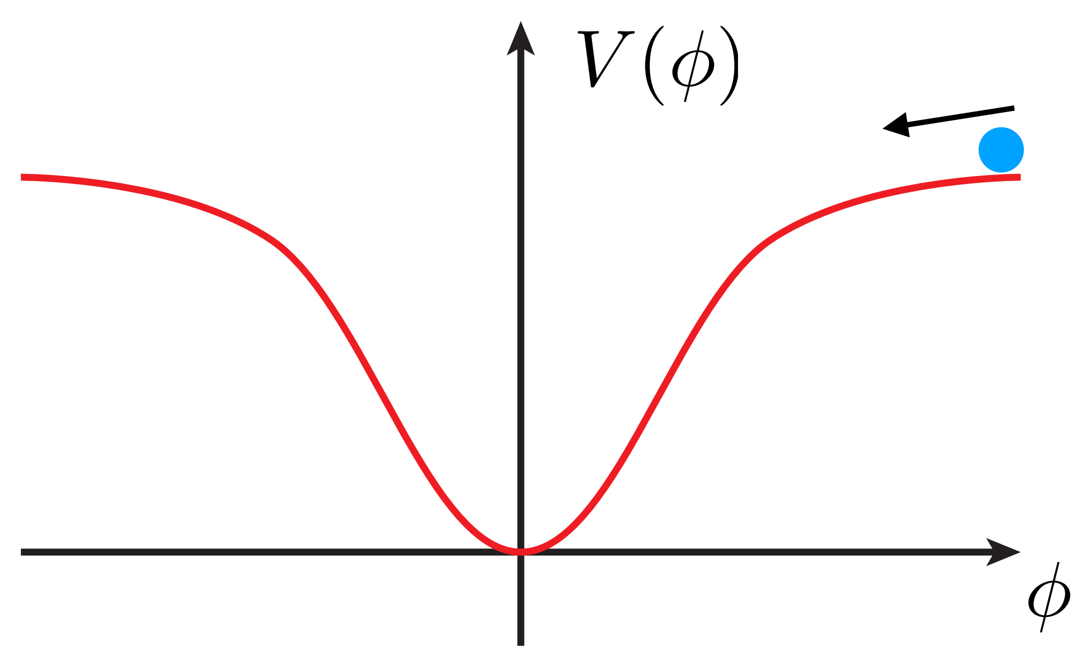


(Dilute instanton gas approximation)

(some classes of) string axion

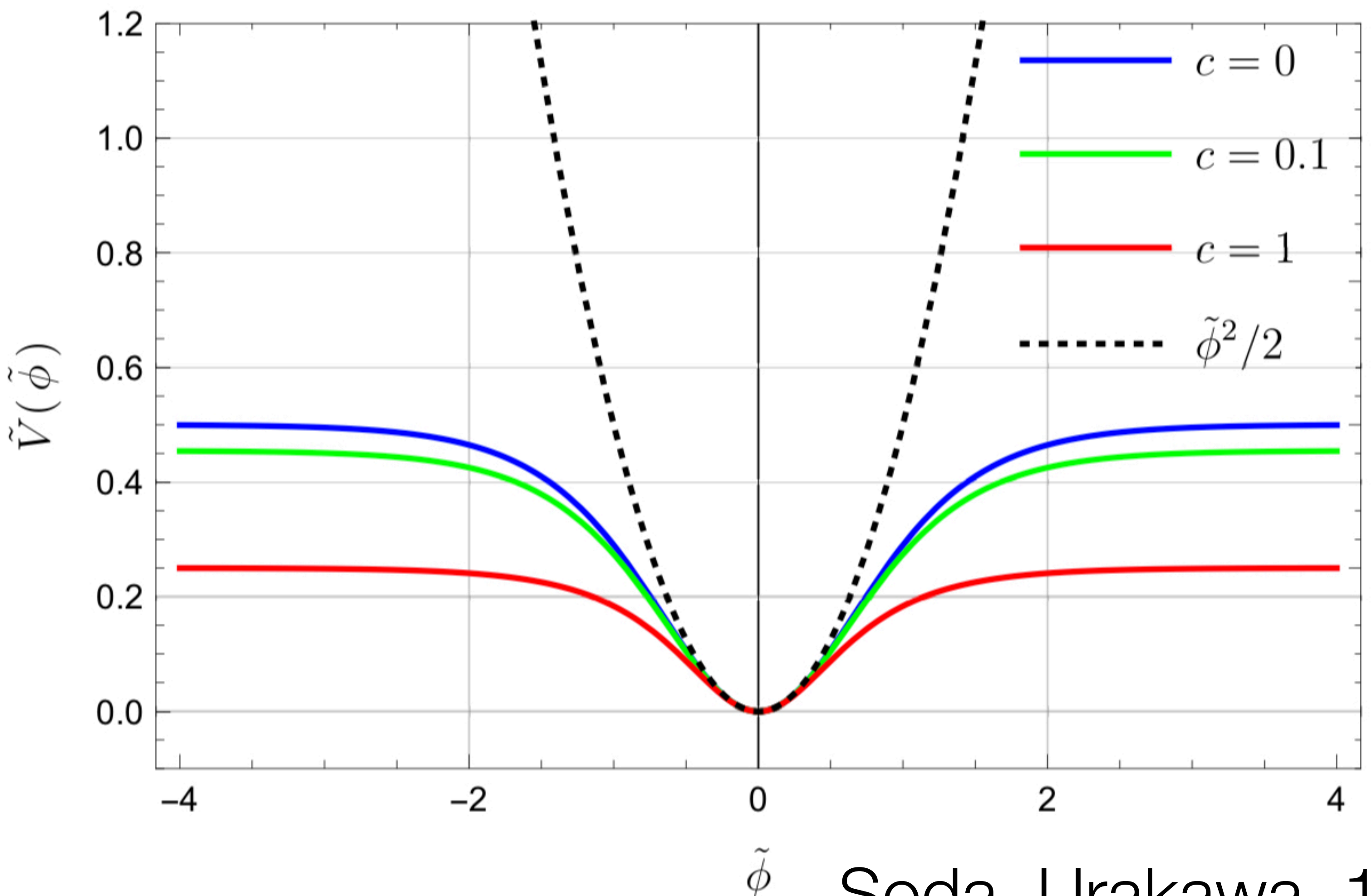
Potential with plateau region

e.g. pure-natural potential
Nomura, Watari, Yamazaki (2017)



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

- Delay of the oscillation onset
- Tachyonic instability (at V” < 0)

→ strong instability

Evolution equations (Minkowski background)

Zero-mode : $$\ddot{\phi} + \frac{dV}{d\phi} = 0$$

Fluctuation (nonzero mode) : $$\ddot{\delta\phi}_{\mathbf{k}} + \left(k^2 + \frac{d^2V}{d\phi^2} \right) \delta\phi_{\mathbf{k}} = 0$$

tachyonic

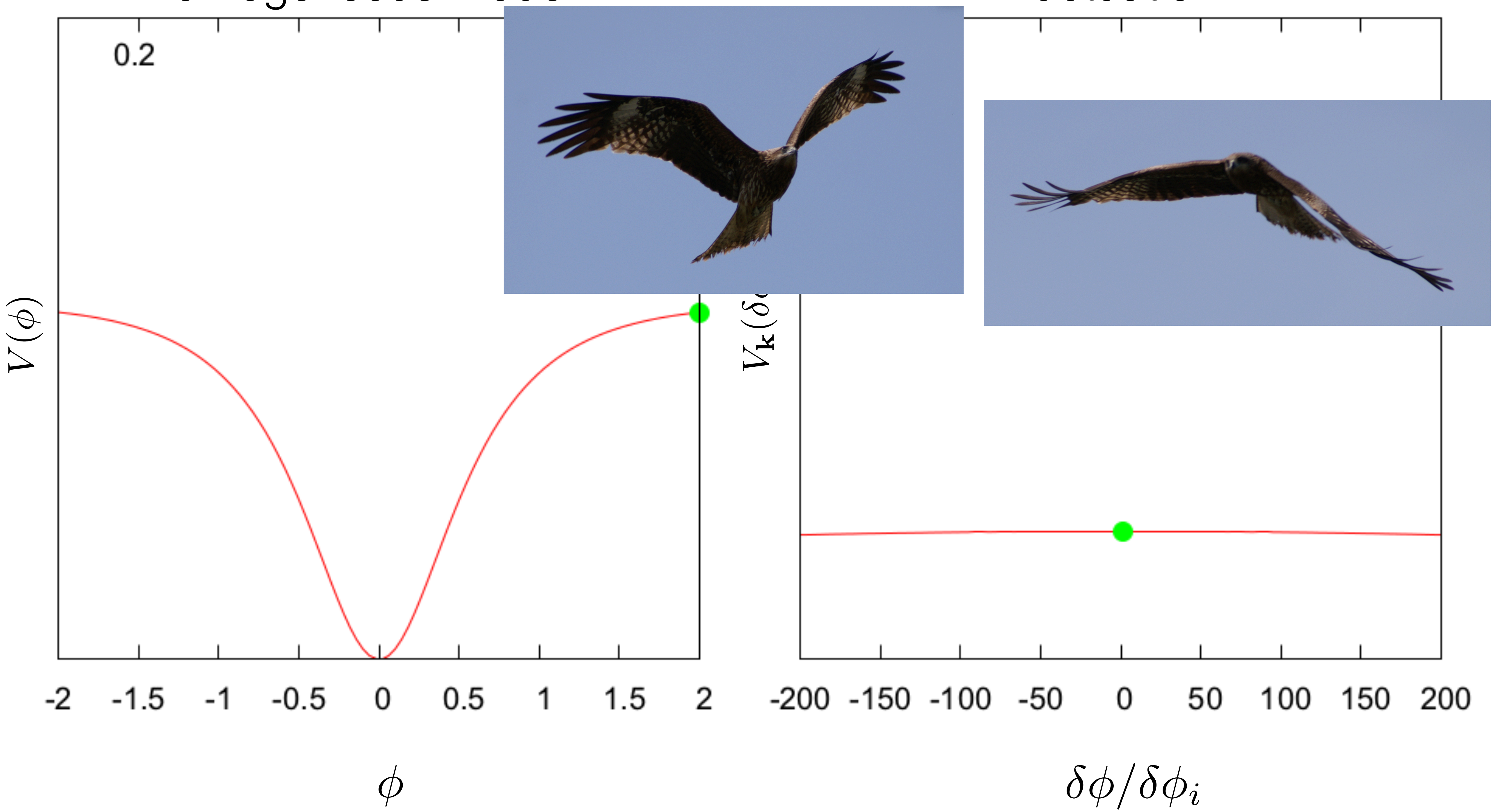
potential

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

$$V_{\mathbf{k}}(\delta\phi_{\mathbf{k}}) = \frac{1}{2} \left(k^2 + \frac{d^2V}{d\phi^2} \right) \delta\phi_{\mathbf{k}}^2$$

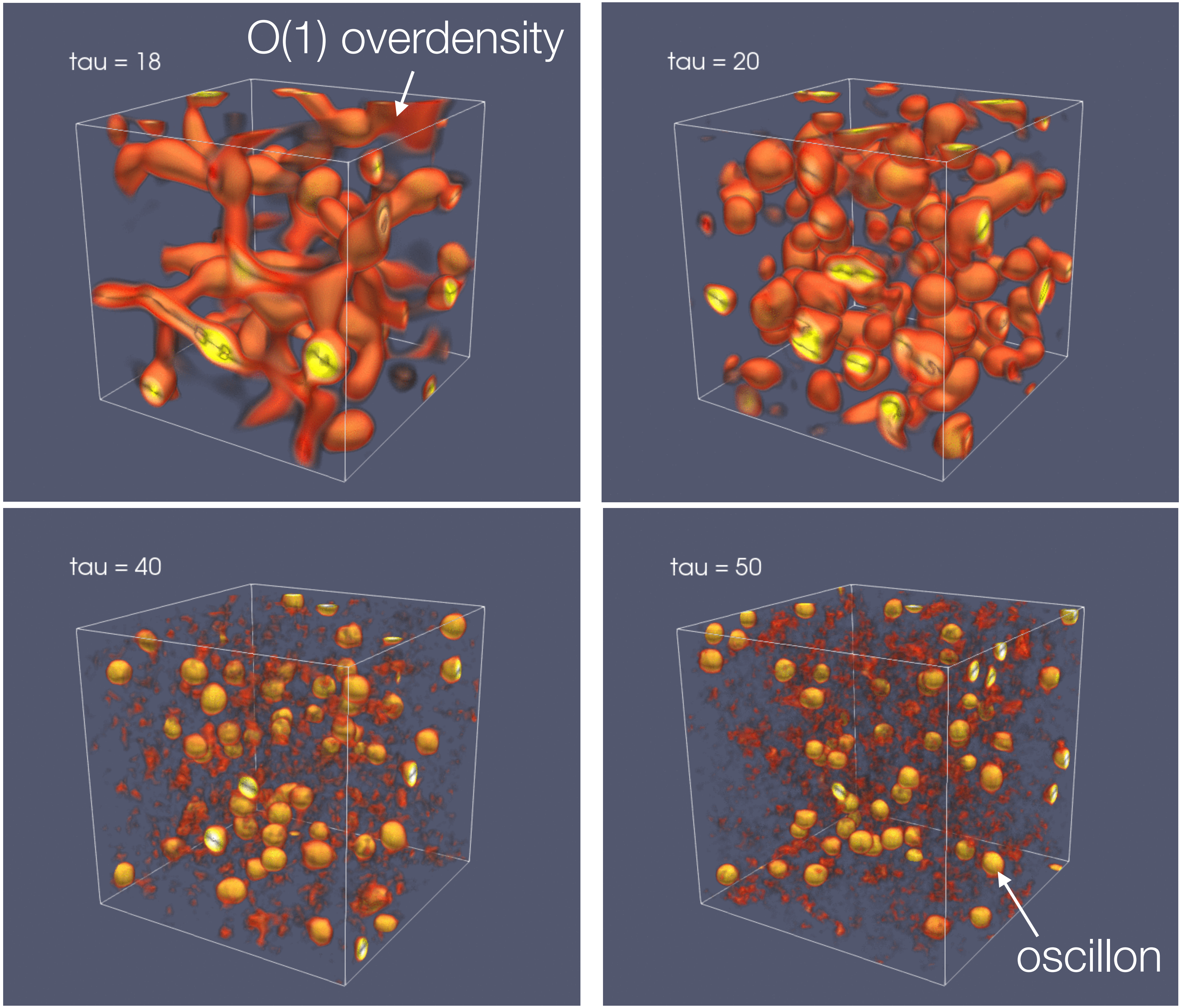
Flapping resonance

homogeneous mode | fluctuation



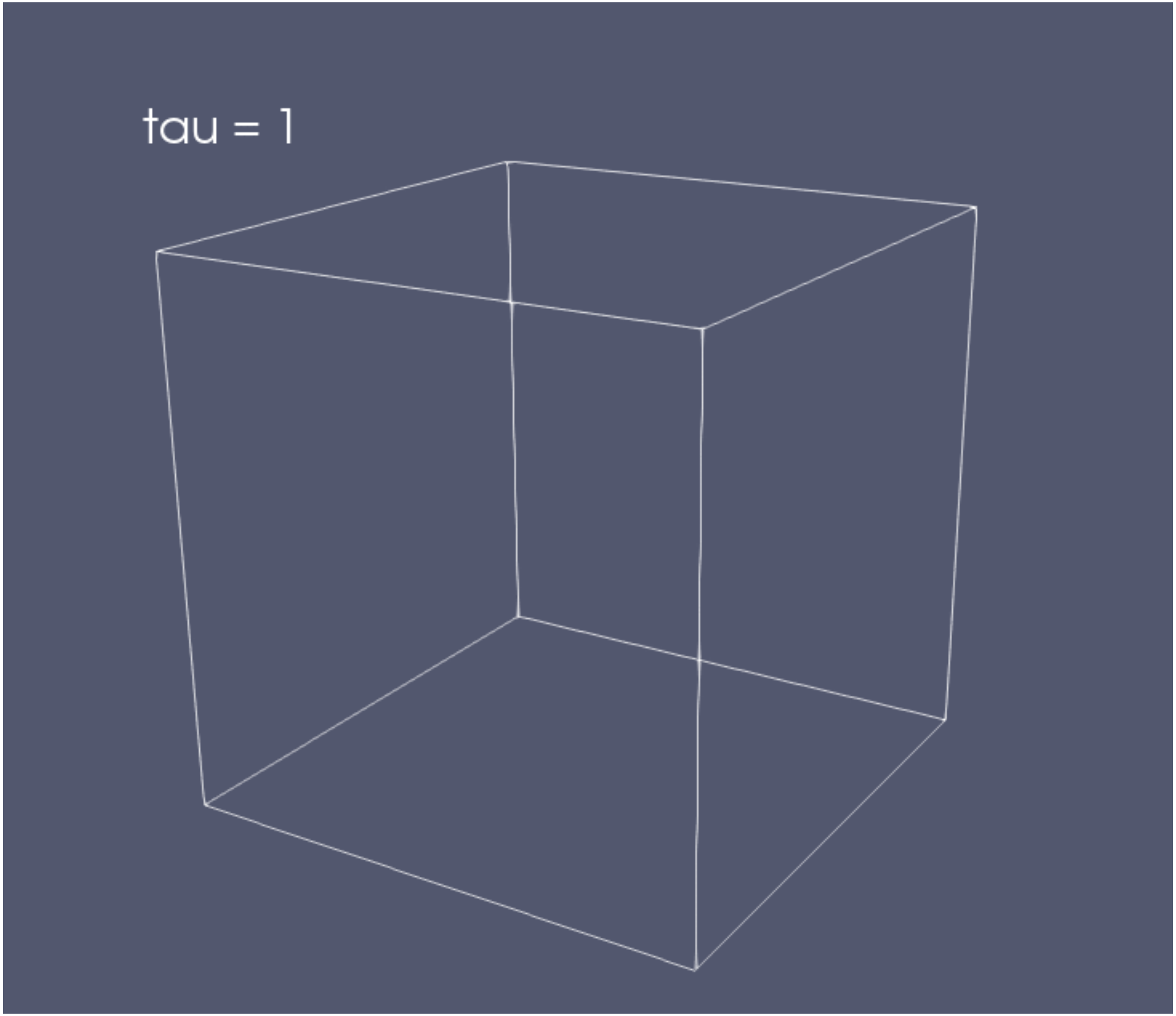
Fukunaga, NK, Urakawa 1903.02119 —> Fukunaga's talk

Lattice simulation



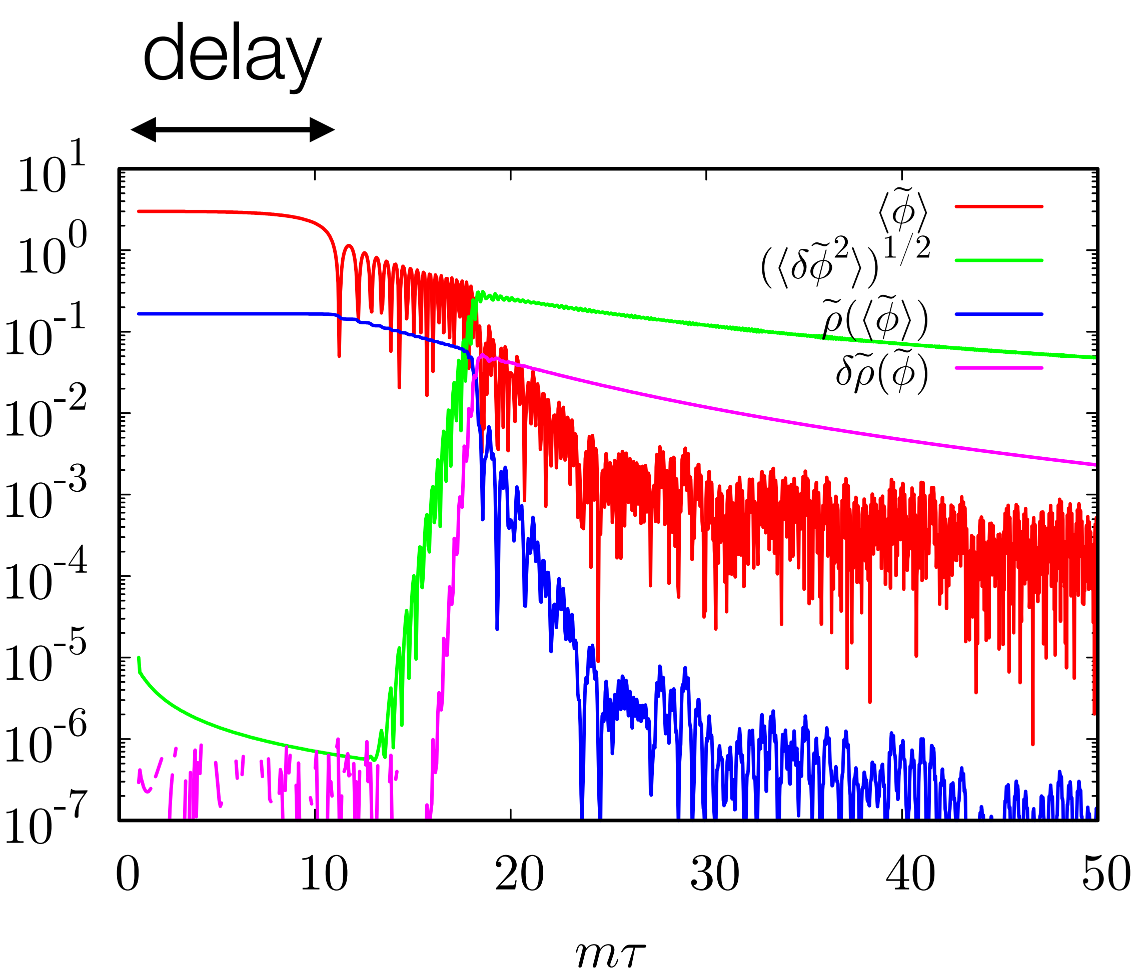
(see also next Takashi's talk for oscillon formation after inflation)

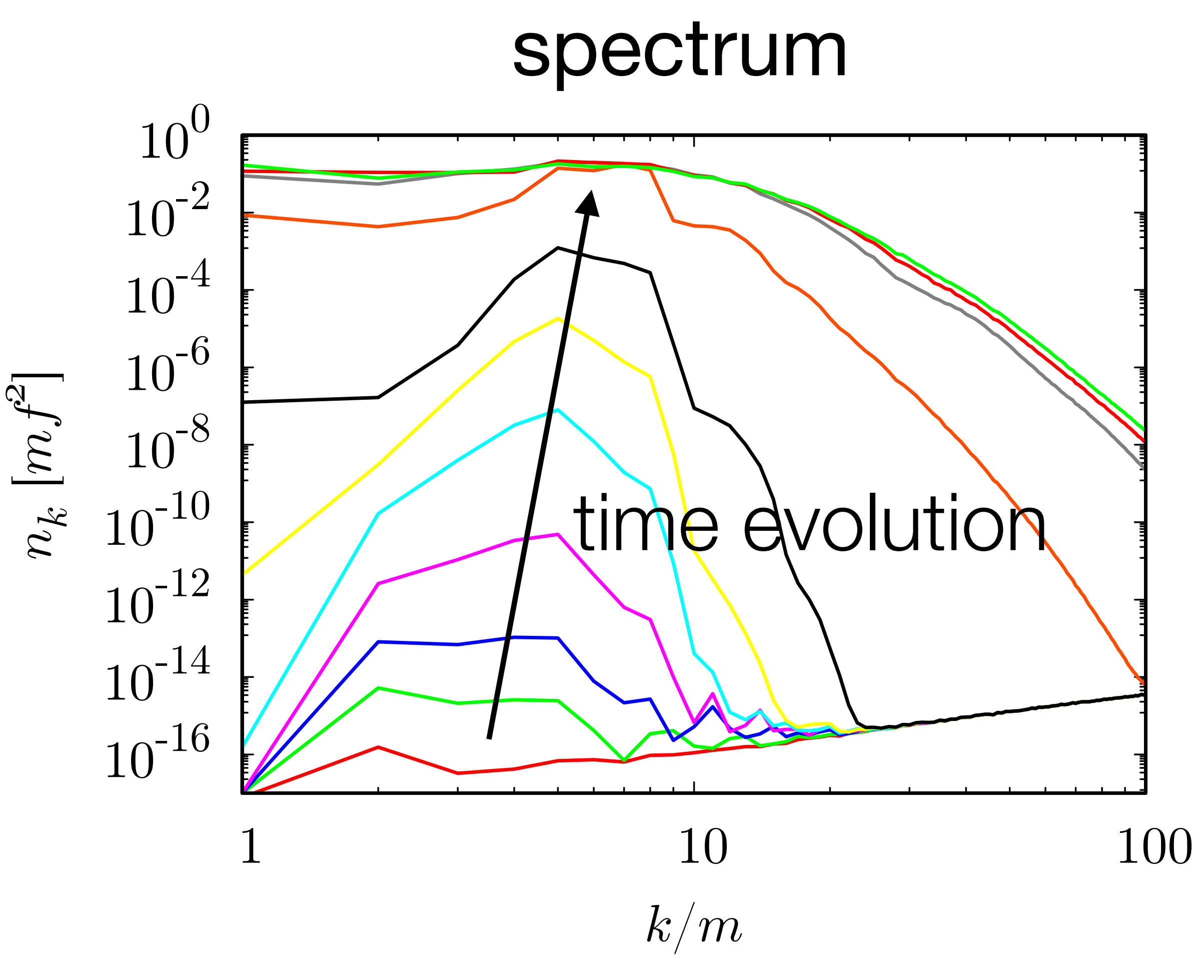
Lattice simulation



128^3 grids

Axion evolution and spectrum





$$c = 2,\ \ \phi_i = 3f$$

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

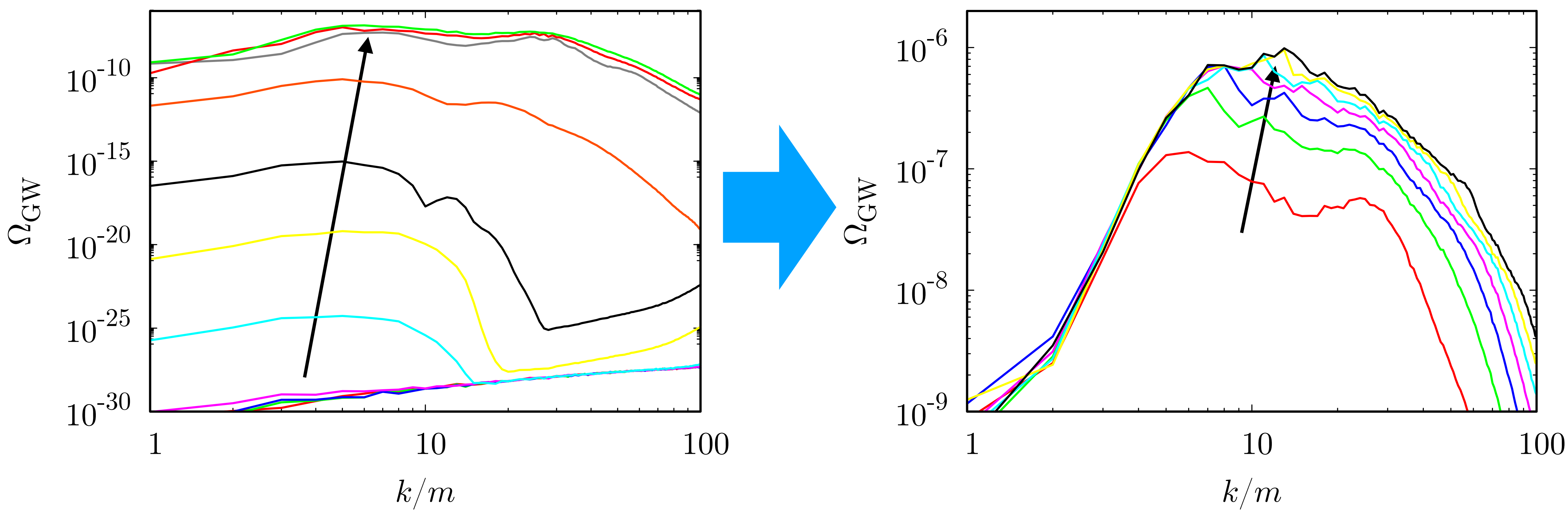
$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{\nabla^2 h_{ij}}{a^2} = 16\pi G \Pi_{ij}^{\mathrm{TT}} \quad \text{with} \quad \Pi_{ij}^{\mathrm{TT}} = -\frac{1}{a^2} P_{ij}^{lm} \partial_i \phi \partial_j \phi$$

TT projection tensor

Density spectrum of GW

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

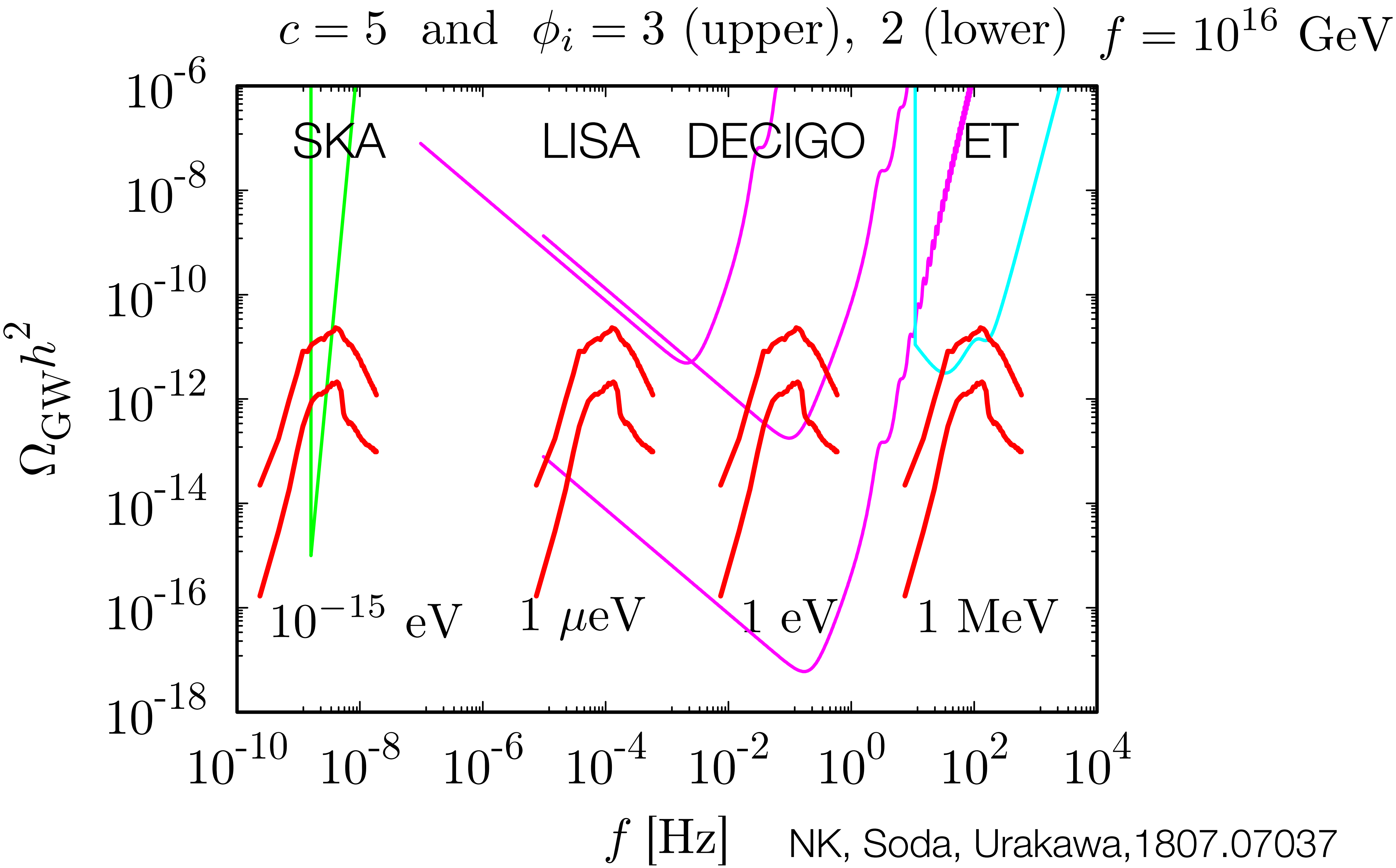
Evolution of GW spectrum



$c = 2,\ \phi_i = 3f \qquad f = 10^{16}\ \mathrm{GeV}$

GW frequency : $f_0 = 0.7\ \mathrm{nHz}\ \dfrac{k}{m}\left(\dfrac{m}{10^{-12}\ \mathrm{eV}}\right)^{1/2}\left(\dfrac{m}{H_{\mathrm{em}}}\right)^{1/2}$

Gravitational Wave forest

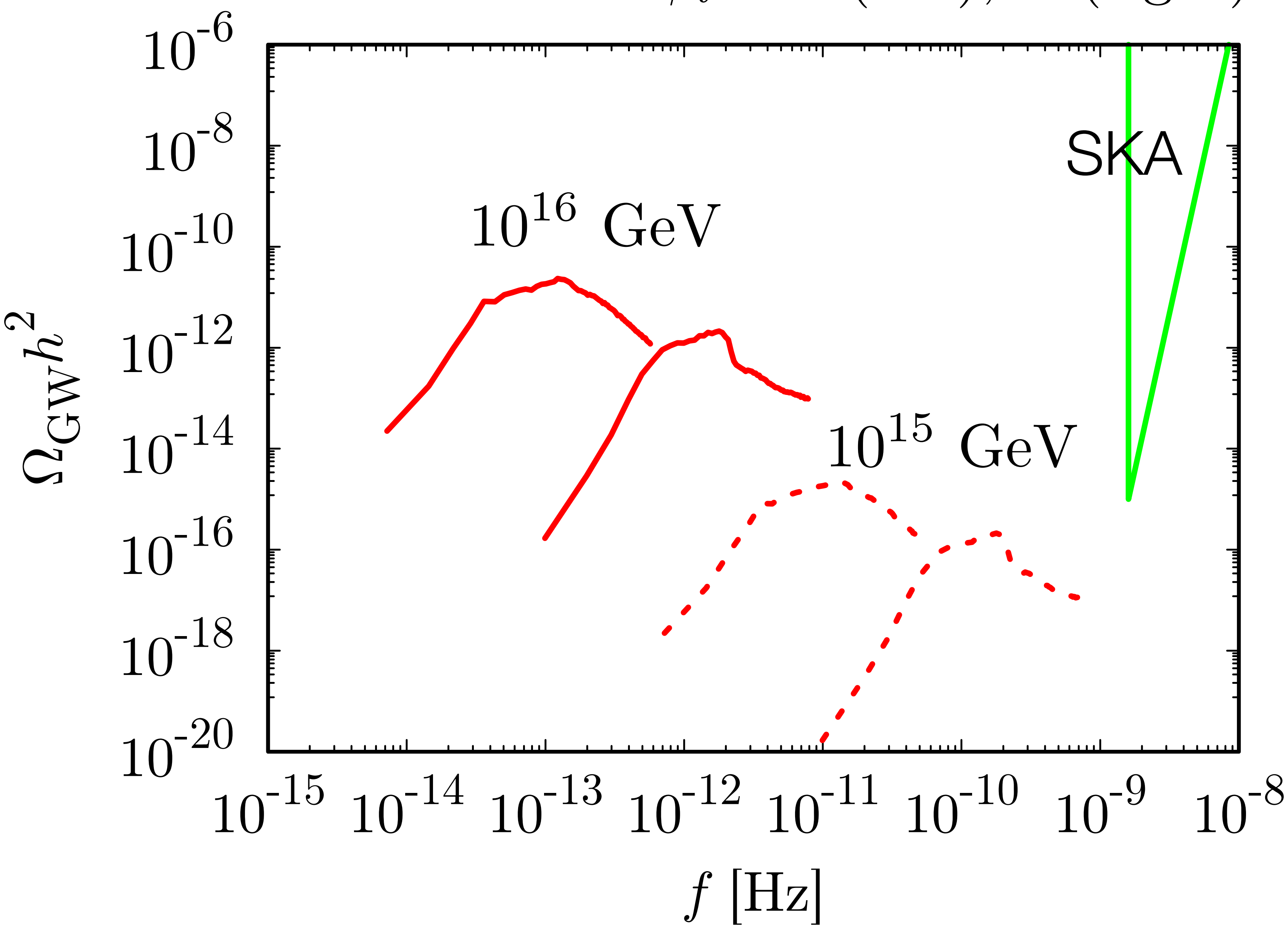


NK, Soda, Urakawa,1807.07037

! axions are easily overproduced

Axion = dark matter

$c = 5$ and $\phi_i = 3$ (left), 2 (right)



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

Tachyonic U(1) gauge field production from axion

Agrawal, NK, Reece, Sekiguchi, Takahashi, 1810.07188

NK, J. Soda, Y. Urakawa, in prep.

Non-Abelian case —> Peter's talk

magnetogenesis —> Kamada & Teerthal's talk

1. Dark photon DM production from axion

Agrawal, NK, Reece, Sekiguchi, Takahashi, 1810.07188

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_{\gamma'}^2 A_\mu A^\mu - \frac{\beta}{4f_a}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

dark photon mass

Equations of motion

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + \frac{\partial V}{\partial\phi} + \frac{\beta}{4f_a}F_{\mu\nu}\widetilde{F}^{\mu\nu} = 0,$$

$$\ddot{\mathbf{A}} + H\dot{\mathbf{A}} - \frac{\nabla^2\mathbf{A}}{a^2} + m_{\gamma'}^2\mathbf{A} - \frac{\beta}{f_a a}\left(\dot{\phi}\nabla\times\mathbf{A} - \nabla\phi\times\left(\dot{\mathbf{A}} - \nabla A_0\right)\right) = 0$$

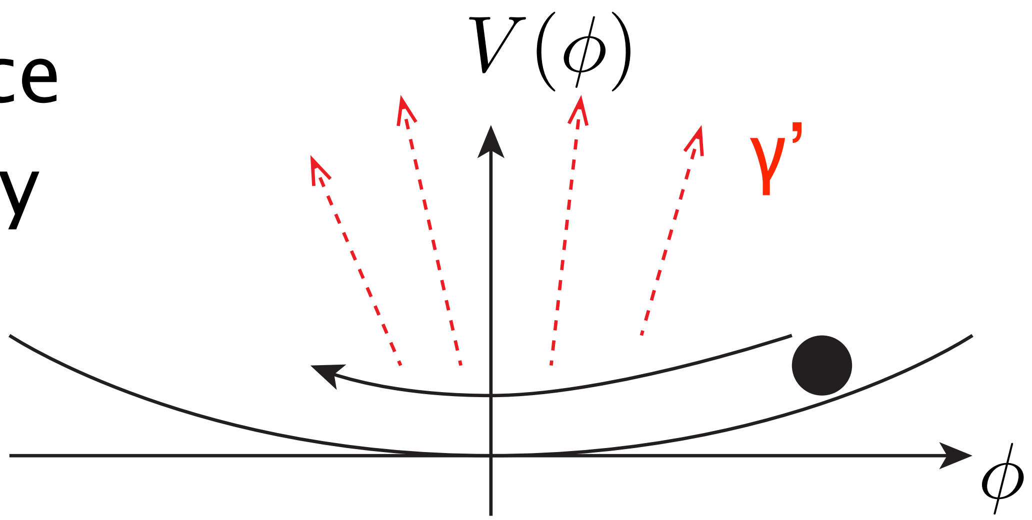
with $\partial_\mu(\sqrt{-g}A^\mu) = 0$: Lorentz gauge condition

Decomposing gauge field into circular polarization modes :

$$\ddot{\mathbf{A}}_{\mathbf{k},\pm} + H\dot{\mathbf{A}}_{\mathbf{k},\pm} + \left(m_{\gamma'}^2 + \frac{k^2}{a^2} \mp \frac{k}{a}\frac{\beta\dot{\phi}}{f_a} \right)\mathbf{A}_{\mathbf{k},\pm} = 0$$

tachyonic

Initially misaligned axion can produce dark photons via tachyonic instability



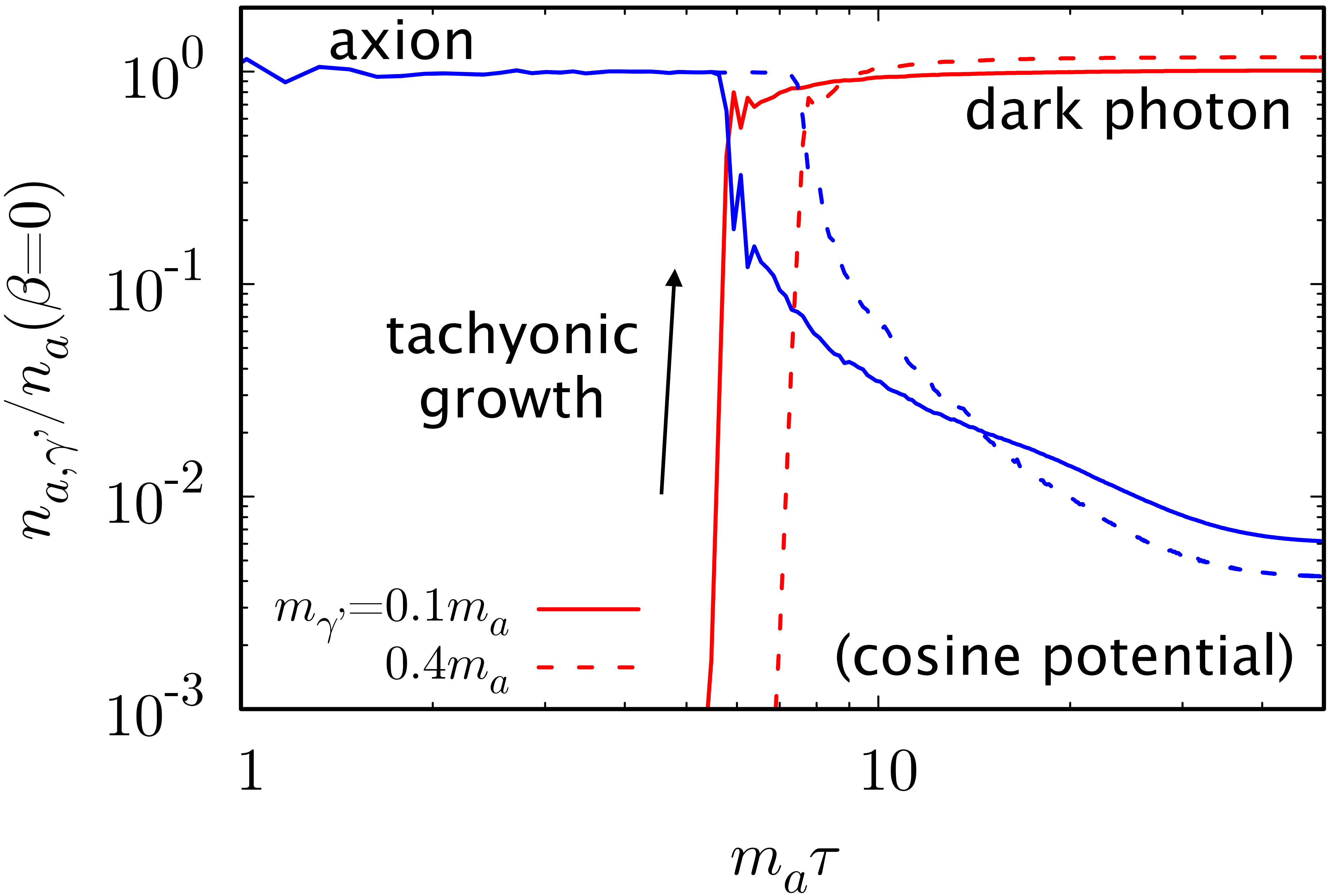
<u>New production mechanism of dark photon DM</u>

See also, Co, Pierce, Zhang, Zhao, 1810.07196
Bastero-Gil, Santiago, Ubaldi, Vega-Morales, 1810.07208

Numerical results : time evolution

(comoving number density)

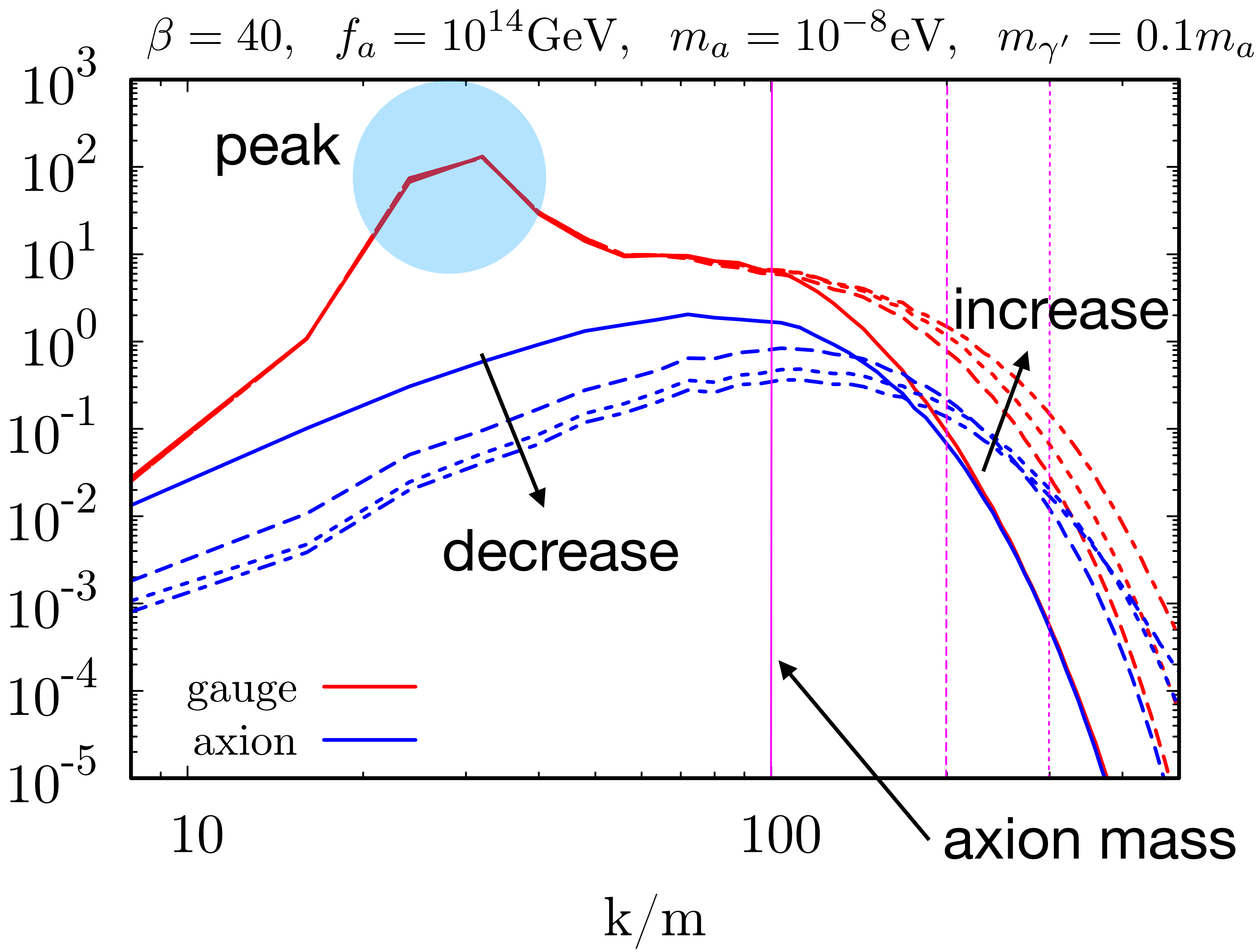
$\beta = 40, \quad f_a = 10^{14}\text{GeV}, \quad m_a = 10^{-8}\text{eV}, \quad m_{\gamma'} = 0.1 m_a$



axion abundance is suppressed & dark photon becomes dominant

Numerical results : power spectrum

(comoving number density)

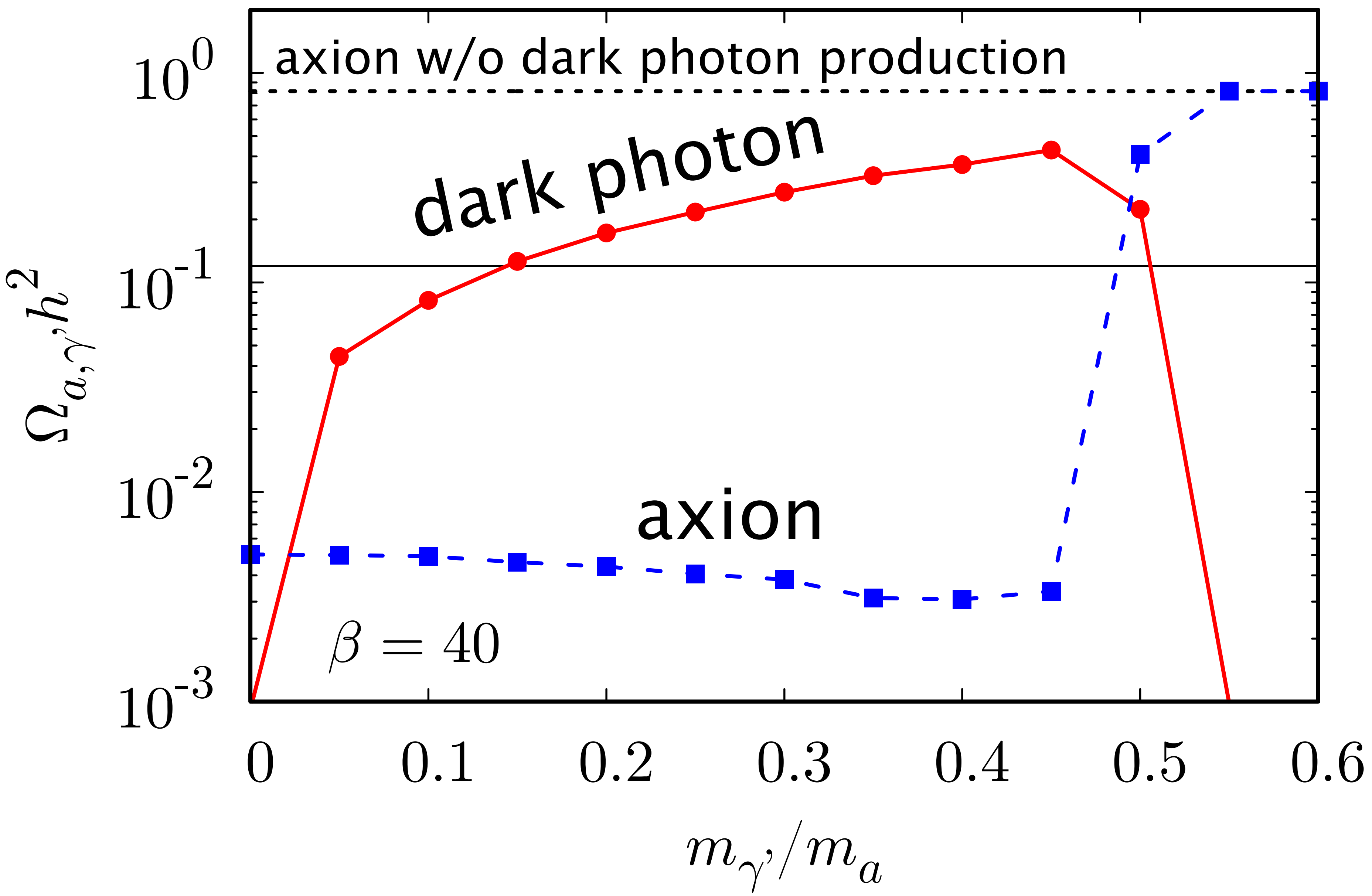


Dark photon spectrum has a peak at low momentum

(determined by the coupling)

Numerical results : relic abundance

Agrawal, NK, Reece, Sekiguchi, Takahashi, 1810.07188



Dark photon can be the dominant component of DM

2. GW emission with circular polarization

NK, J. Soda, Y. Urakawa, in prep.

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla h_{ij} = -16\pi G a^{-2}\Pi_{ij}^{\mathrm{TT}}$$

$$\Pi_{ij} = -\partial_i\phi\partial_j\phi + E_iE_j + \frac{1}{a^2}B_iB_j$$

electric & magnetic field contributions

circular polarization of GW

$$h_{ij}(\mathbf{k}) = h_{\mathbf{k}}^{+}e_{ij}^{+}(\mathbf{k}) + h_{\mathbf{k}}^{-}e_{ij}^{-}(\mathbf{k}) \quad \text{(Fourier mode)}$$

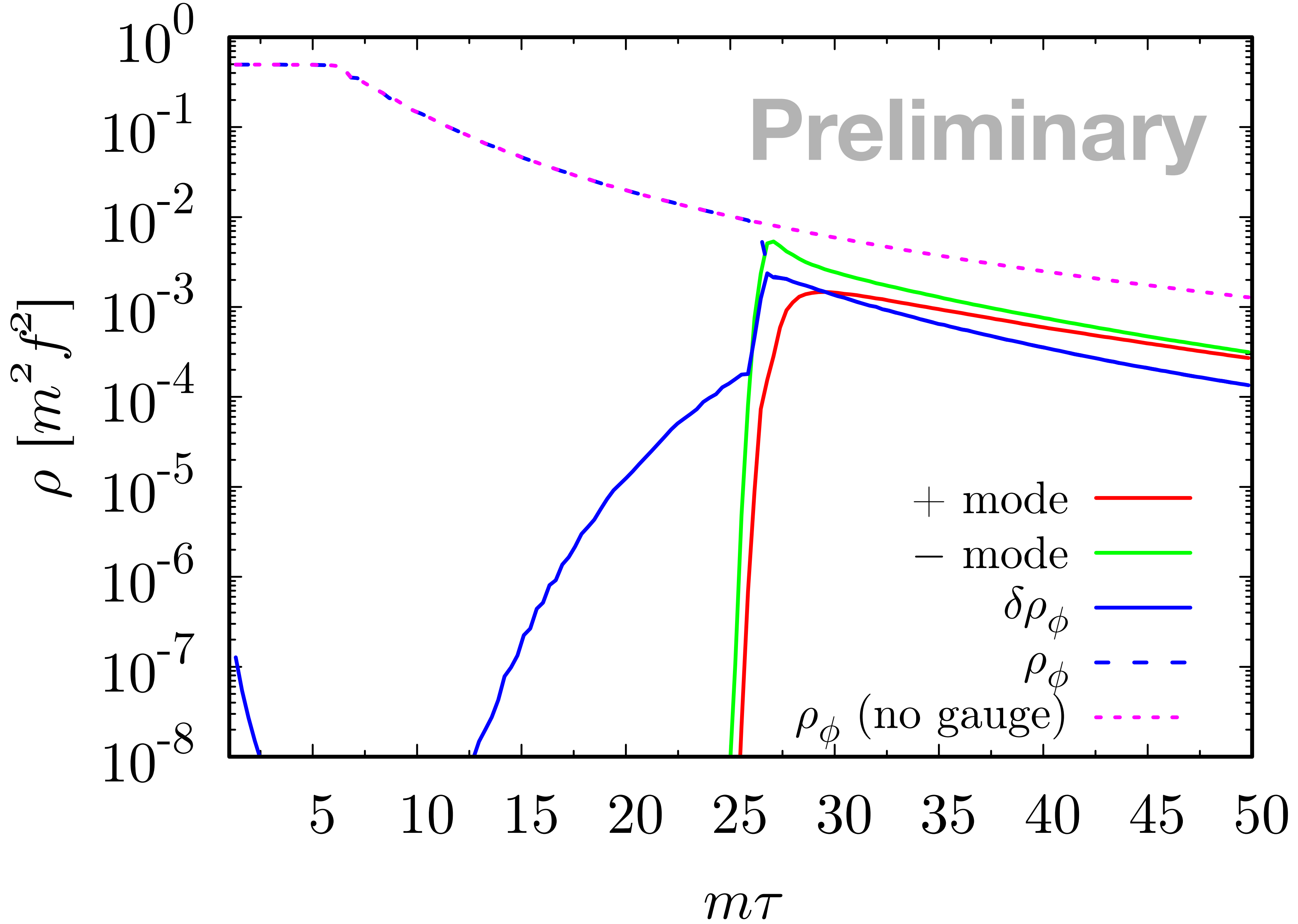
Circular polarization tensor : $e_{ij}^{\pm}(\mathbf{k}) = e_i^{\pm}(\mathbf{k})e_j^{\pm}(\mathbf{k})$

↑

Circular polarization vector

$$\mathbf{k}\times\mathbf{e}^{\pm}(\mathbf{k}) = \mp i\mathbf{e}^{\pm}(\mathbf{k})$$

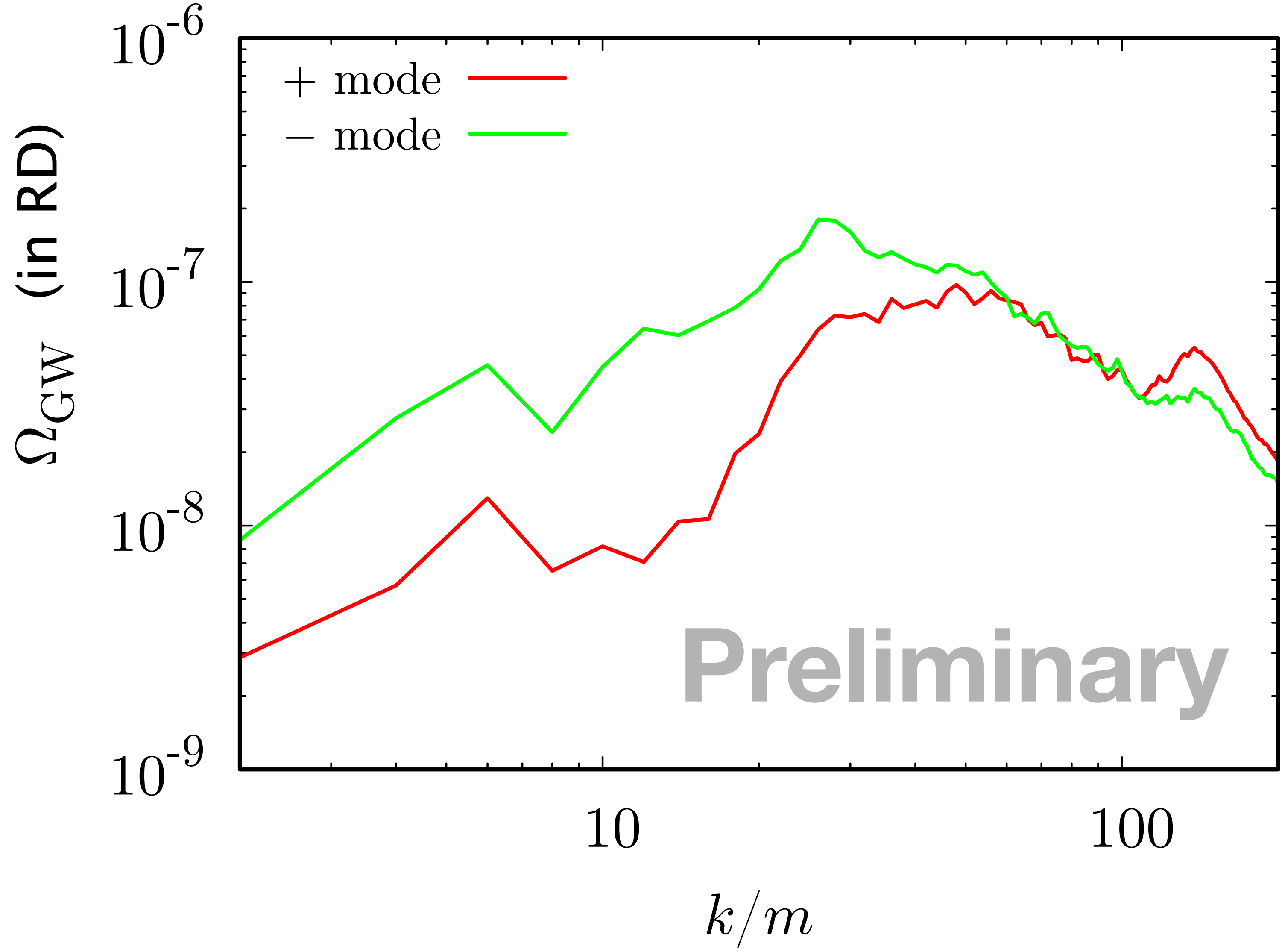
Numerical results : Time evolution of gauge/axion (circular polarization modes)



tanh-type axion potential, c=0 & β=5
& dark photon is massless

Numerical results : GW spectrum (circular polarization modes)

NK, Soda, Urakawa in prep



Circular polarization asymmetry

see also Adshead+ 1805.04550, Machado+ 1811.01950, Peter's talk

Summary

- String axion whose potential has a plateau region (e.g. alpha-attractor model) can show resonance instabilities, leading to GW emission.

—> Multi-band GW observation can be a powerfull probe of string axions with wide mass range

- Axion-photon interaction in the early Universe can produce correct relic abundance of dark photon dark matter and suppress axion abundance

—> It can predict circular polarization of GW

Lattice simulation

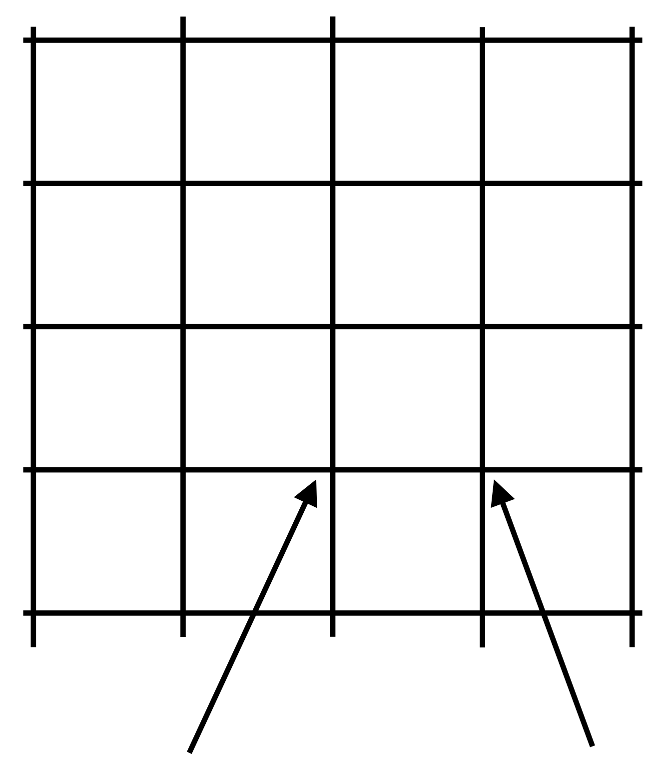
$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + \frac{\partial V}{\partial \phi} = 0 \quad \text{with} \quad V(\phi) = \frac{m^2 f^2}{2} \frac{\tanh^2(\phi/f)}{1 + c\tanh^2(\phi/f)}$$

$$\varphi'' - \nabla^2\varphi - \frac{a''}{a}\varphi + a^3\frac{\partial V}{\partial \phi} = 0 \quad \text{with} \quad dt = a d\tau, \ \phi = \frac{\varphi}{a}$$

RD flat-FRW universe : $a \propto \tau, \ a'' = 0$

$$\phi(t, \boldsymbol{x}) \rightarrow \phi(n, i, j, k)$$

$$(t, x, y, z) = \left(t_0 + n\delta t, \frac{iL}{N_{\text{grid}}}, \frac{jL}{N_{\text{grid}}}, \frac{kL}{N_{\text{grid}}}\right)$$



EoM in flat-FRW spacetime & temporal gauge

$$(ds^2 = dt^2 - a^2\delta_{ij}dx^i dx^j \quad \& \quad A_0 = 0)$$

— Equation of motion for axion —

$$\boxed{\ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2}\nabla^2\phi + \frac{\partial V}{\partial \phi} + \frac{\alpha}{4f}F_{\mu\nu}\tilde{F}^{\mu\nu} = 0}$$

$H = \dot{a}/a$ $\cdots$ Hubble parameter

— Equation of motion for gauge field —

$$\boxed{\ddot{A}_i + H\dot{A}_i - \frac{1}{a^2}\nabla^2 A_i + \frac{1}{a^2}\partial_i\partial_j A_j - \frac{\alpha}{fa}\epsilon_{ijk}(\dot{\phi}\partial_j A_k - \partial_j\phi\dot{A}_k) = 0}$$

$$\partial_i\dot{A}_i - \frac{\alpha}{fa}\epsilon_{ijk}\partial_i\phi\partial_j A_k = 0$$ (modified Gauss's law)

! longitudinal mode can be excited