Gravitational wave emission and oscillon formation in string axiverse

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in collaboration with
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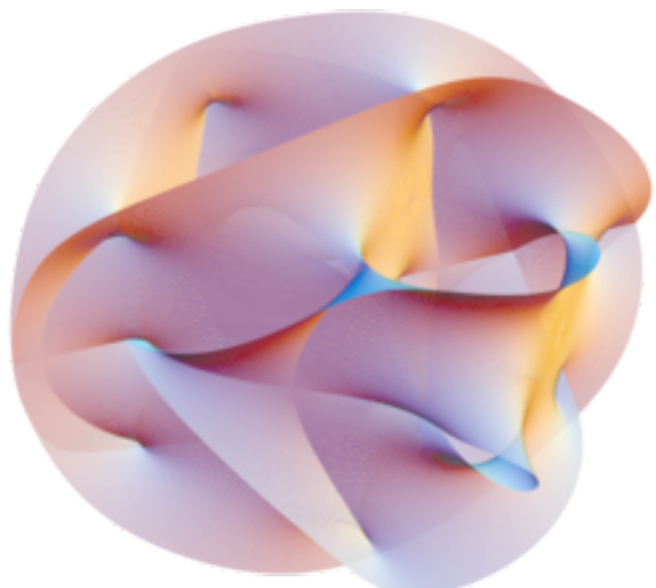
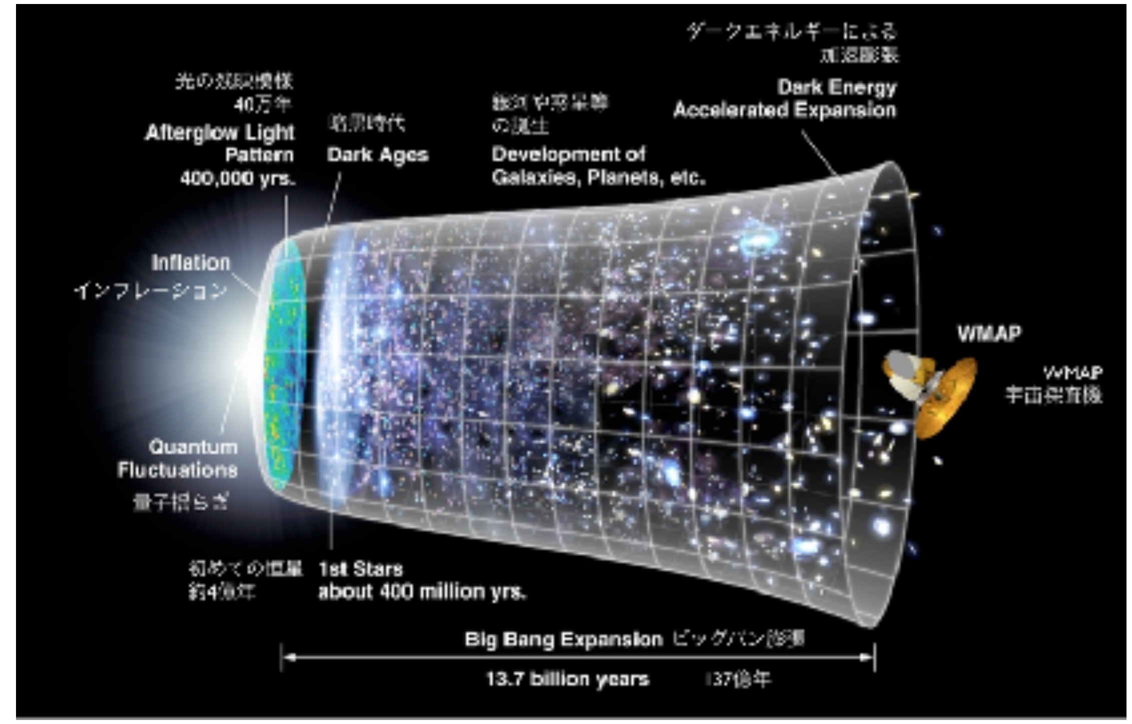
KEK-PH 2018, 2/13-16

Axiverse



10D string / supergravity theory



4D spacetime

+

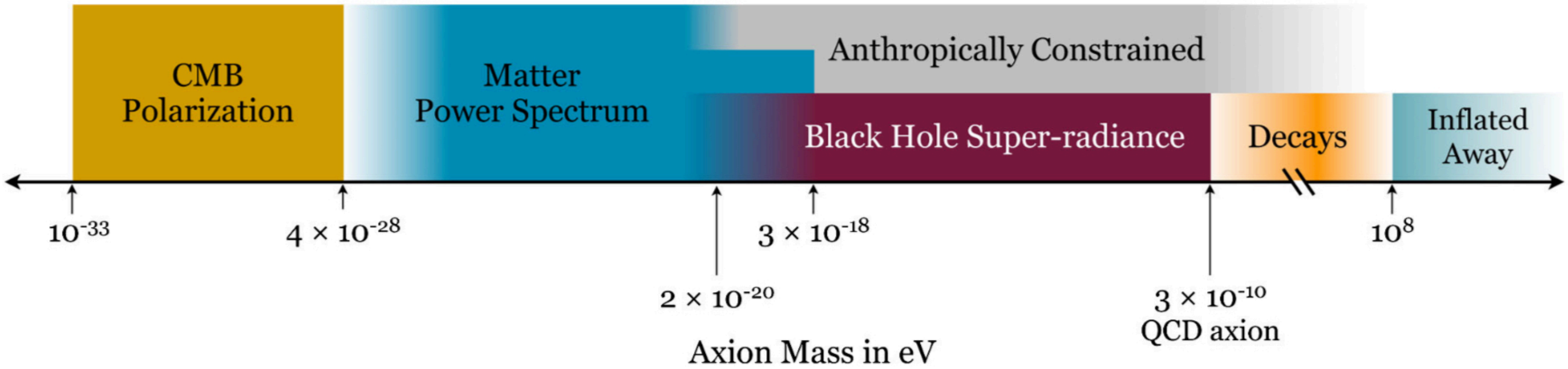
String axion

Strong CP problem

—> QCD axion

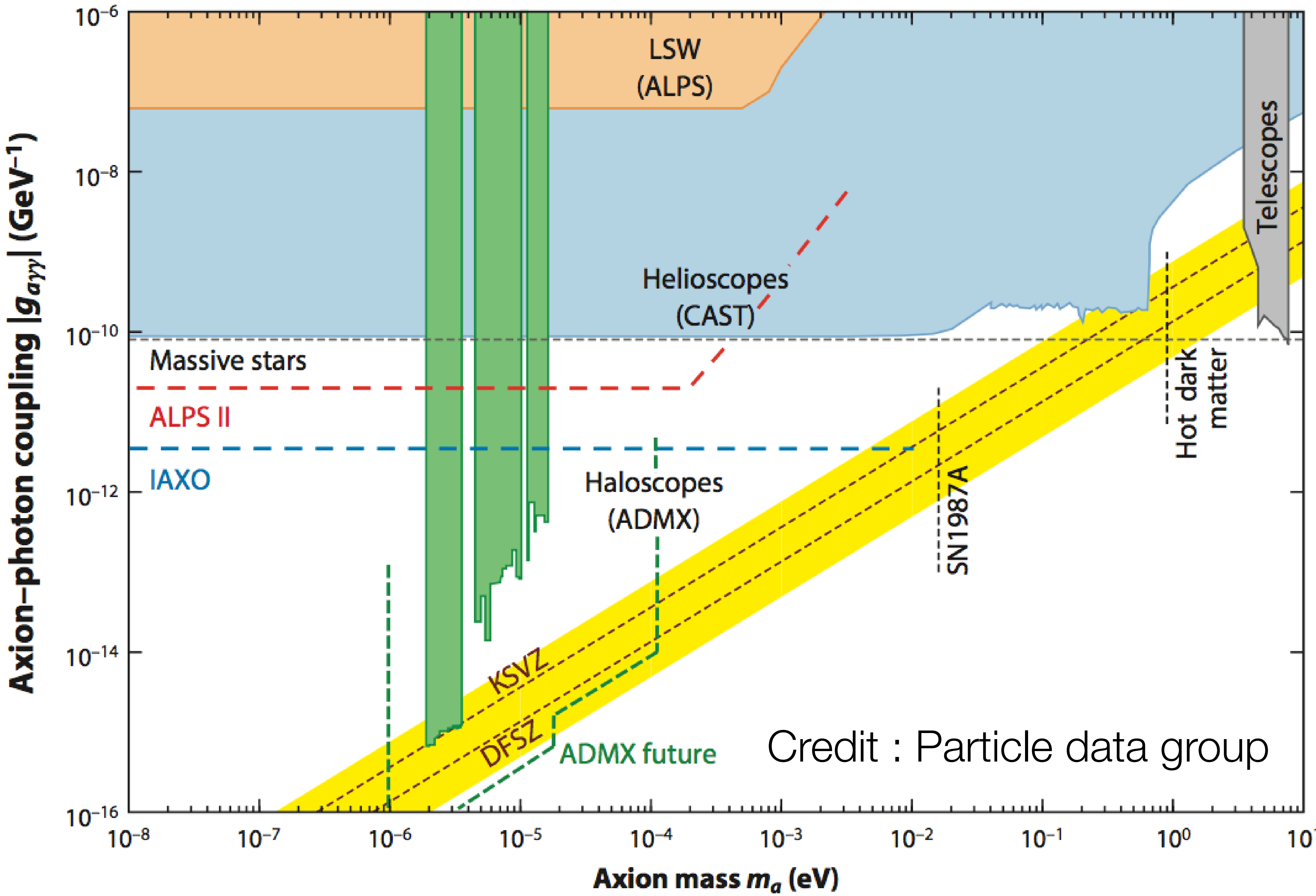
Axiverse

Arvanitaki et al. (2010)



String theory predicts many axions with broad mass range with typical decay constant f~10^{15-16} GeV

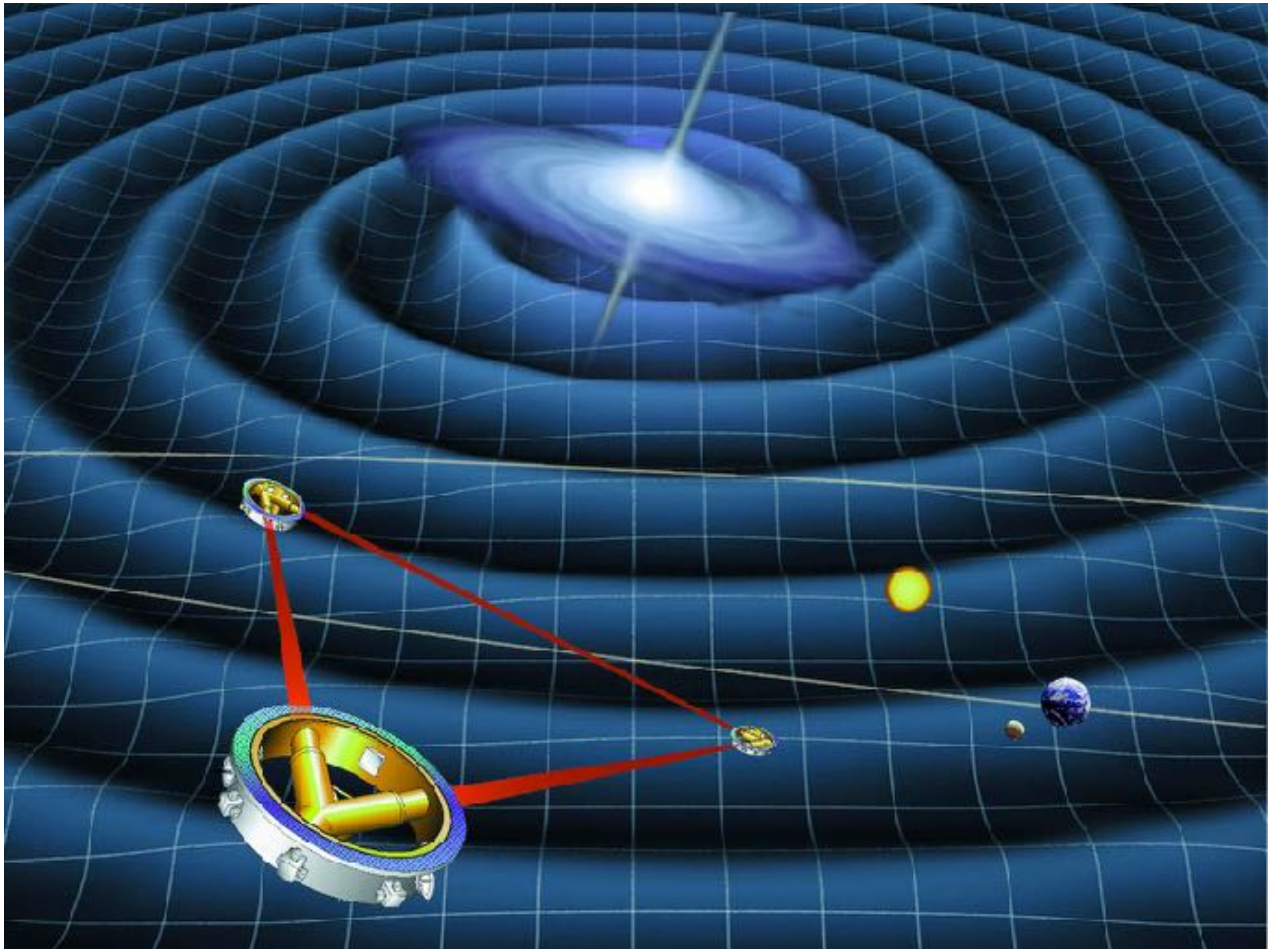
Axion detection



Axion-photon interaction is suppressed by f~10^{16} GeV

—> it is difficult to search string axions by direct detection experiments

String axion —> Gravitational wave

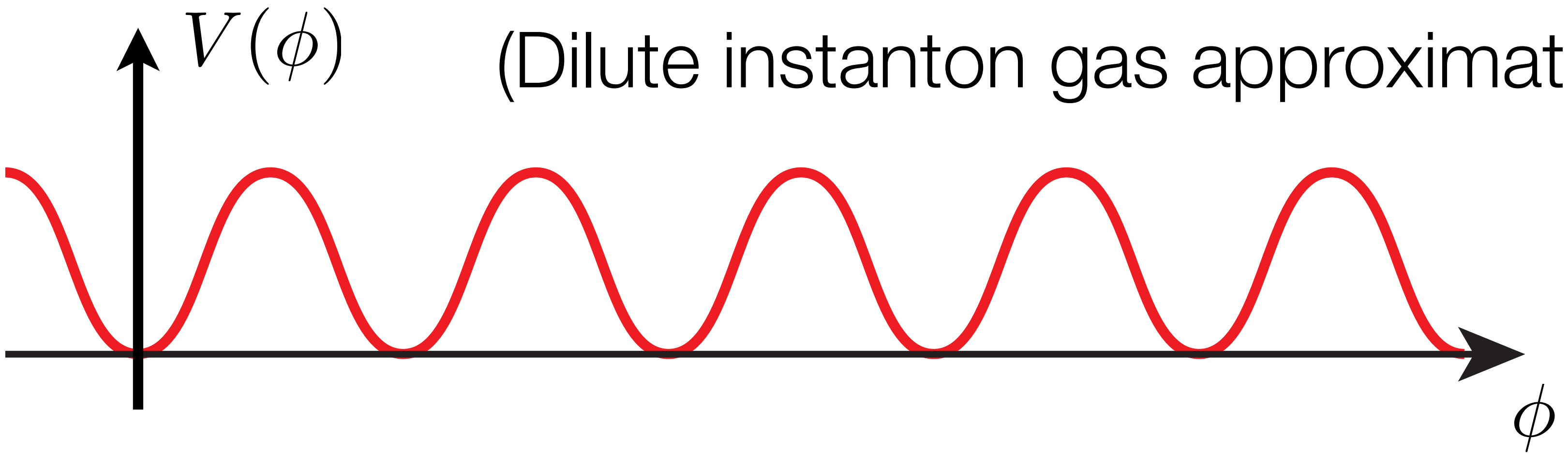


GW signal becomes strong for larger decay constants

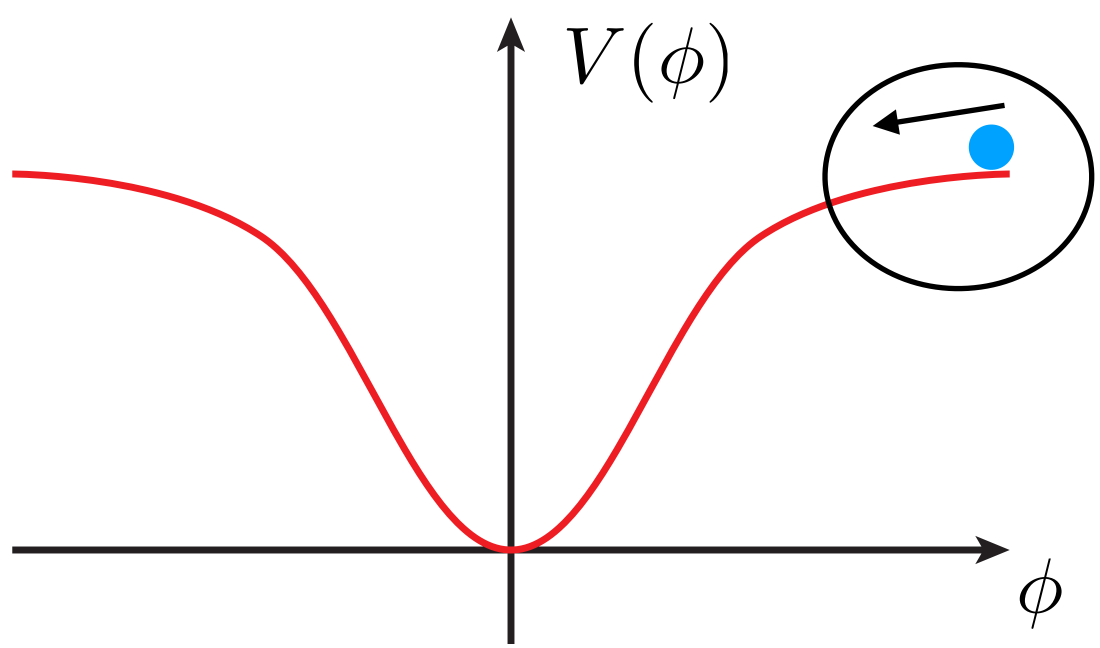
Axion potential

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

(Dilute instanton gas approximation)

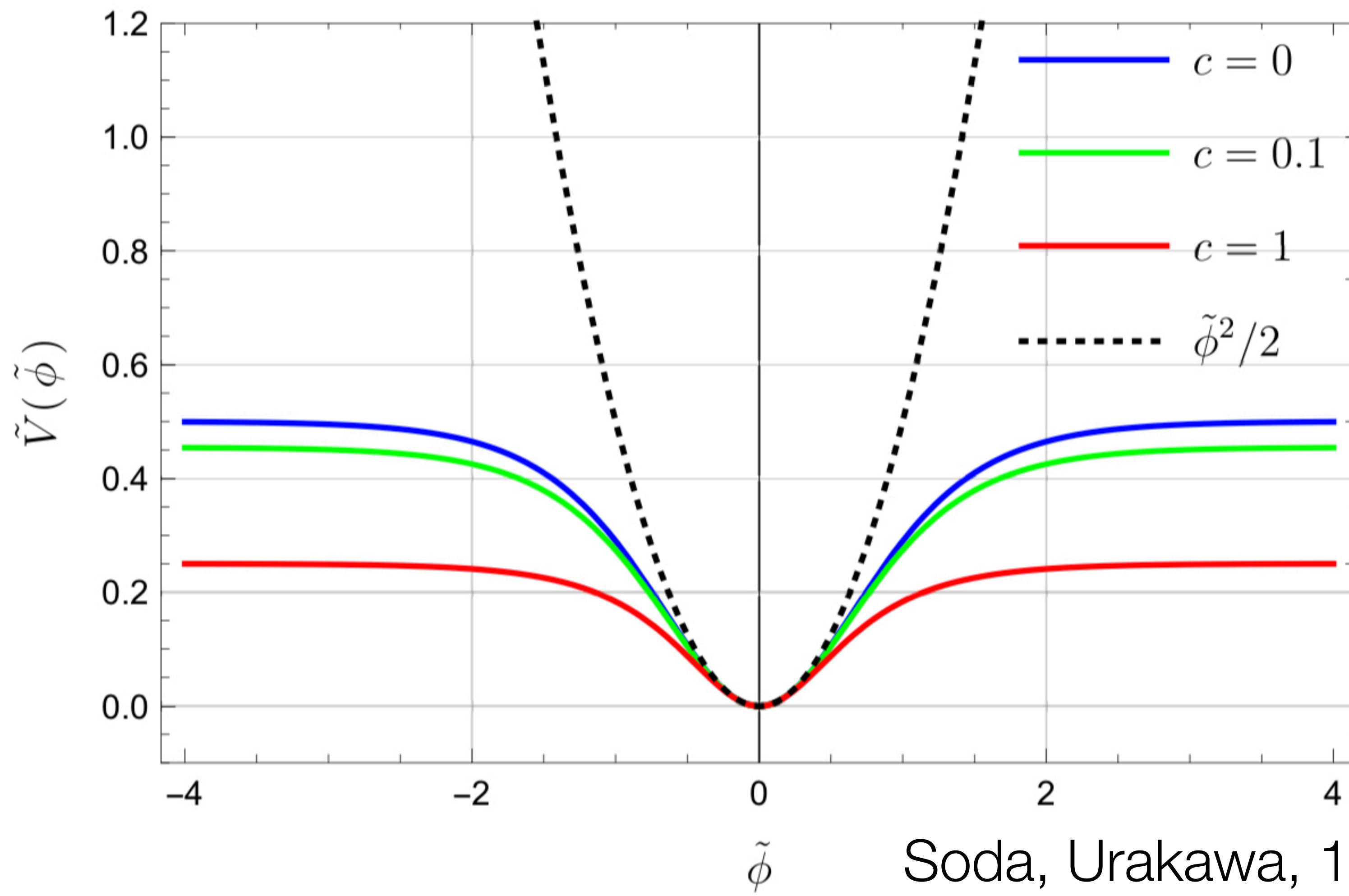


Potential with plateau region



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

Self interaction —> parametric resonance

field fluctuations (with mode k~m) is amplified exponentially

Kofman, Linde, Starobinsky, 1997

resonance instability

Soda, Urakawa, 1710.00305

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

evolution of nonzero modes

$$\frac{d^2\varphi_k}{dx^2} + (A - 2q\cos 2x)\varphi_k = 0$$

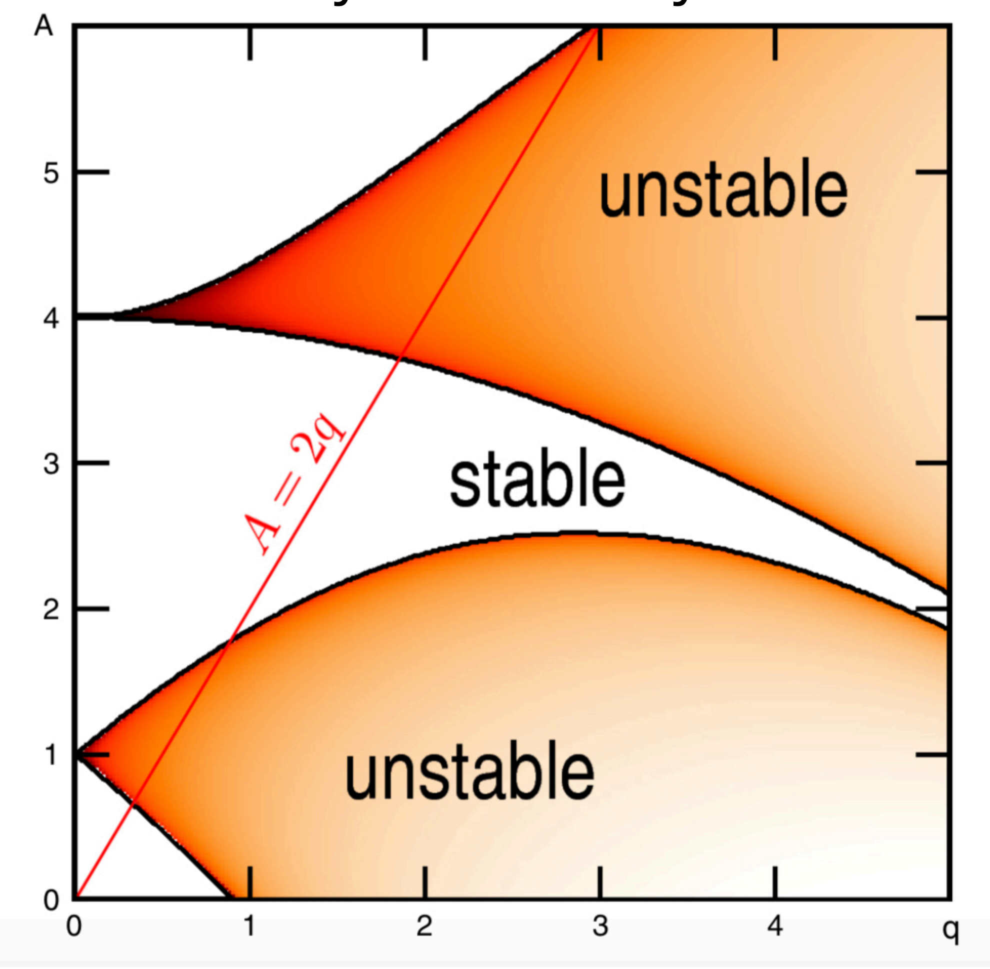
(Mathieu equation)

$$A = \frac{1}{4}\left[\left(\frac{k}{m a_{\rm osc}}\right)^2 + 1 - (2+3c)\varphi_*^2\right]$$

$$q = \frac{2+3c}{8}\varphi_*^2 \quad , x = m/H$$

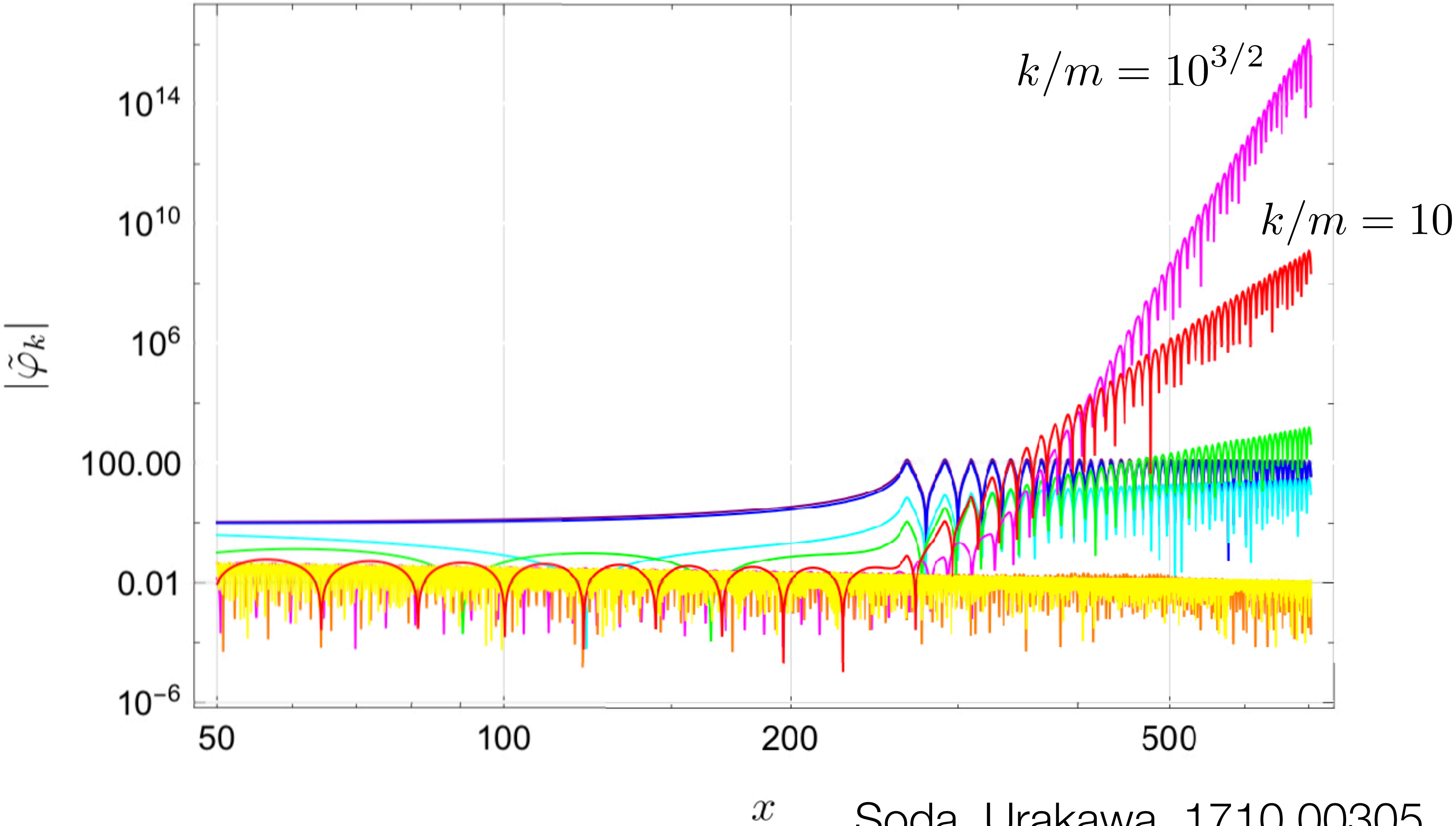
amplitude of the zero mode

stability/instability chart



for k in an instability band —> $\varphi_k \propto e^{qx/2}$

resonance instability



Soda, Urakawa, 1710.00305

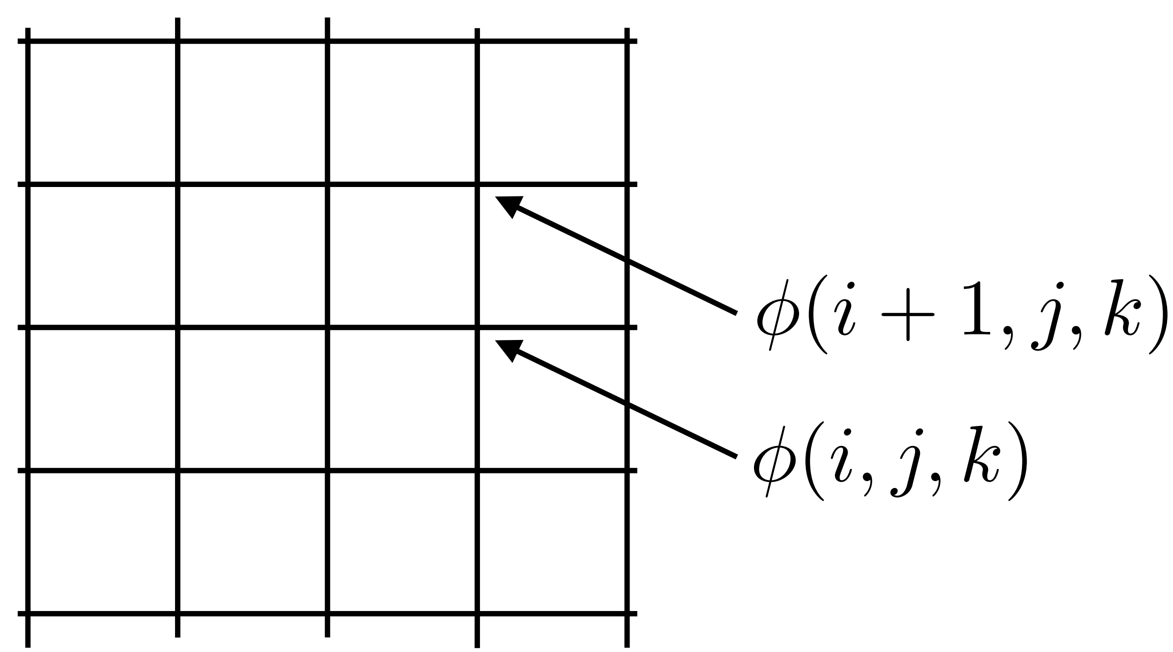
Fluctuations go into the non-linear regime
—> lattice similation is requred

Lattice simulation

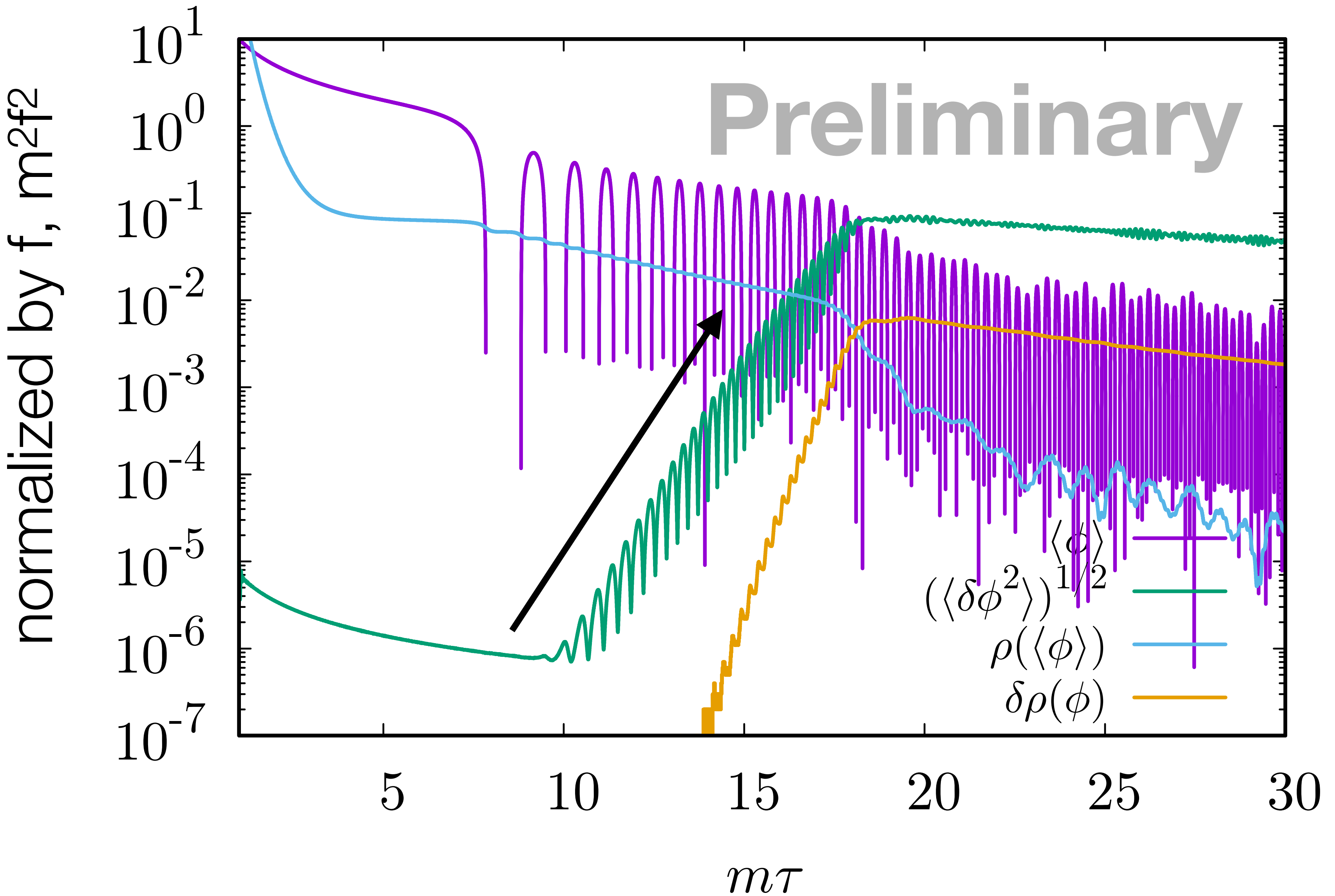
$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + \frac{\partial V}{\partial \phi} = 0 \quad \text{with} \quad V(\phi) = \frac{m^2 f^2}{2}\frac{\tanh^2(\phi/f)}{1 + c\tanh^2(\phi/f)}$$

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

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

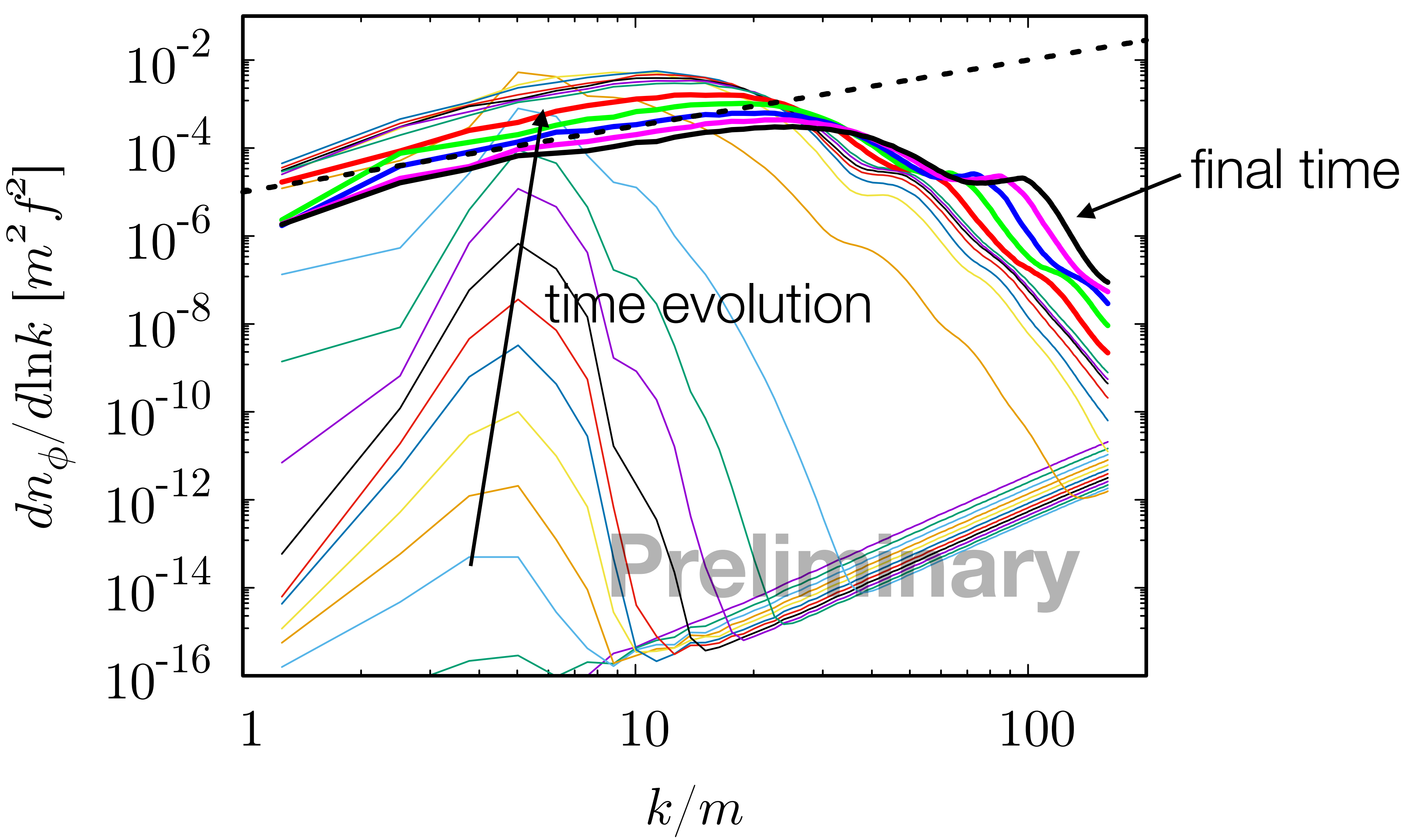


Evolution of the field & the energy density



$$c = 5,\ \phi_i/f = 10$$

Evolution of the number density spectrum



$$a/a_i = 1 - 50 \quad \text{with} \quad H_i = m$$

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

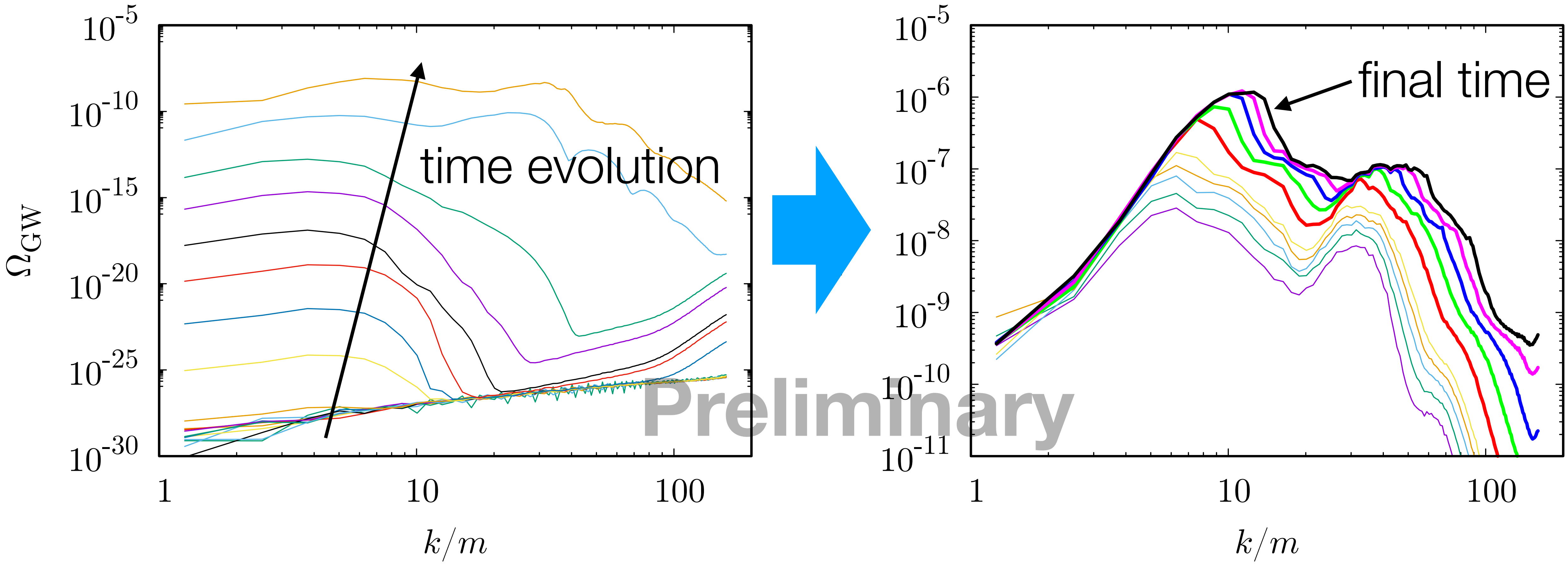
$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{\nabla^2 h_{ij}}{a^2} = 16\pi G \Pi_{ij}^{\mathrm{TT}} \quad \text{with} \quad \Pi_{ij}^{\mathrm{TT}} = \frac{1}{a^2} P_{ij}^{lm} \partial_l \phi \partial_m \phi$$

TT projection tensor

Density spectrum of GW

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

GW density spectrum

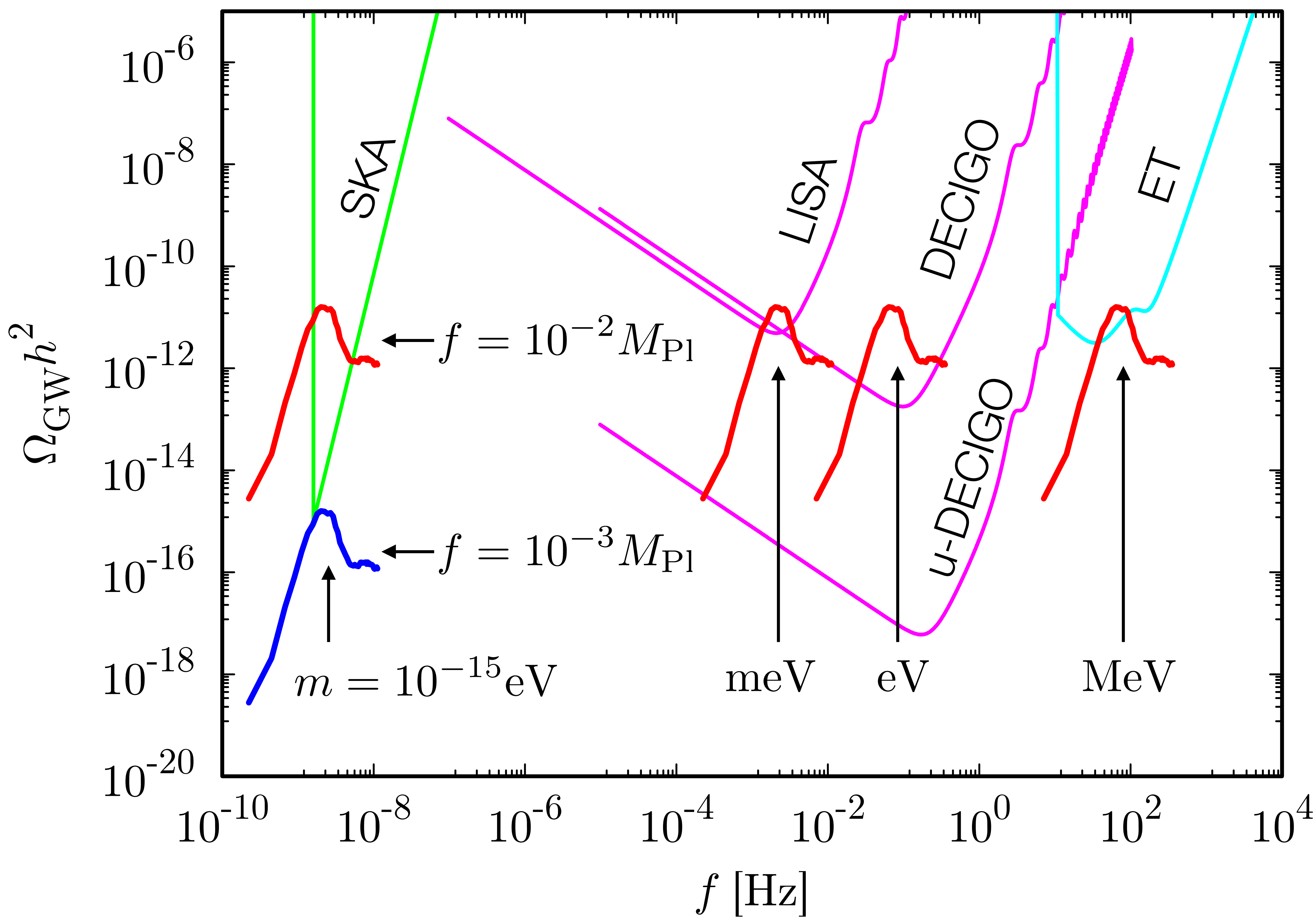


$$c = 5,\ \ \phi_i/f = 10,\ \ f = 0.01 M_P$$

$$h_{ij} \sim \left(\frac{\phi_{\rm em}}{M_{\rm Pl}}\right)^2 \sim \left(\frac{0.1 f}{M_{\rm Pl}}\right)^2 \quad \& \quad \Omega_{\rm GW} \sim \left(\frac{k}{H_{\rm em}}\right)^2 h_{ij}^2 \sim 10^2 \left(\frac{f}{M_{\rm Pl}}\right)^4$$

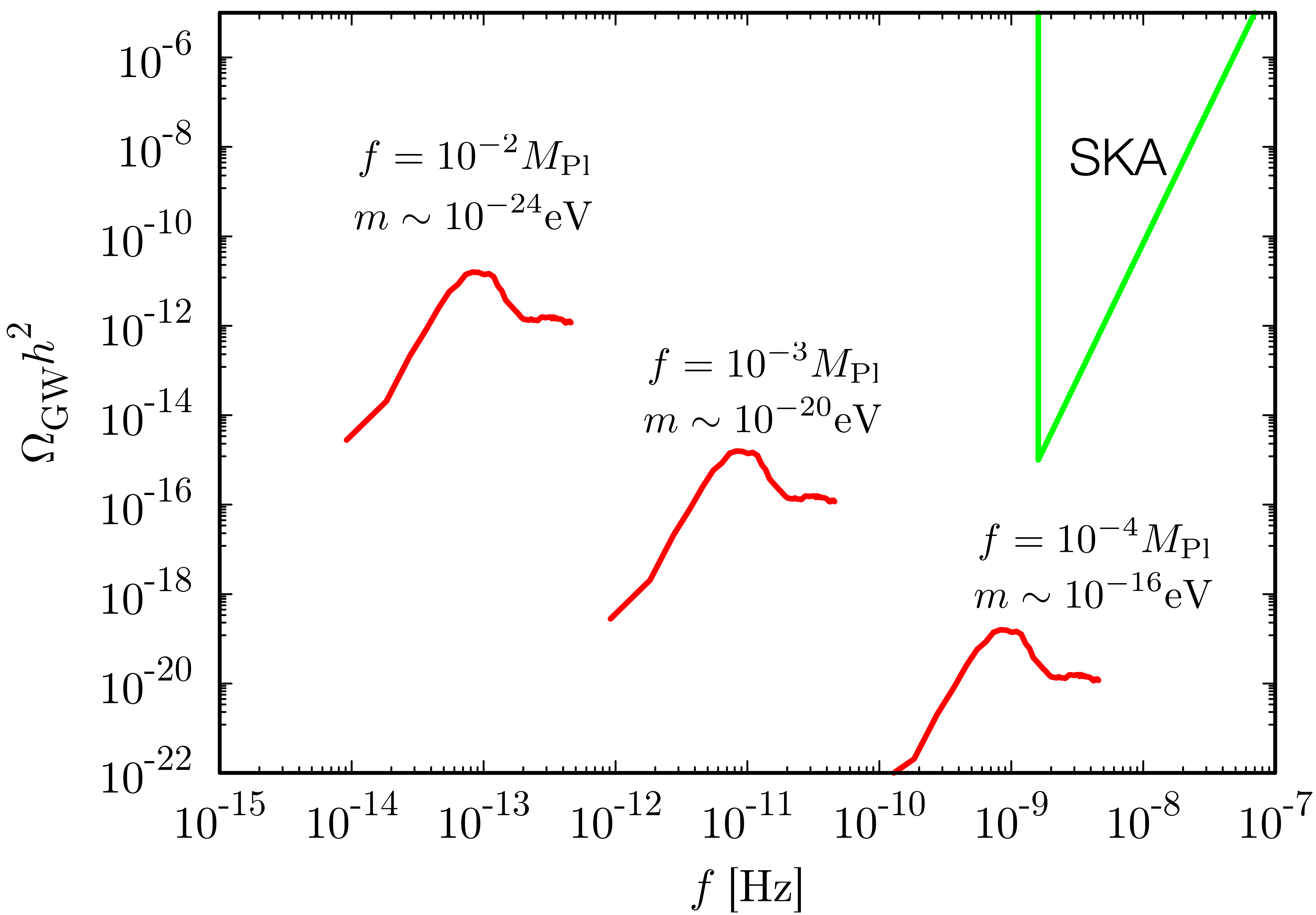
with $\phi_{\rm em} = 0.1 f,\ \ H_{\rm em} = 0.01 m$

Detectability

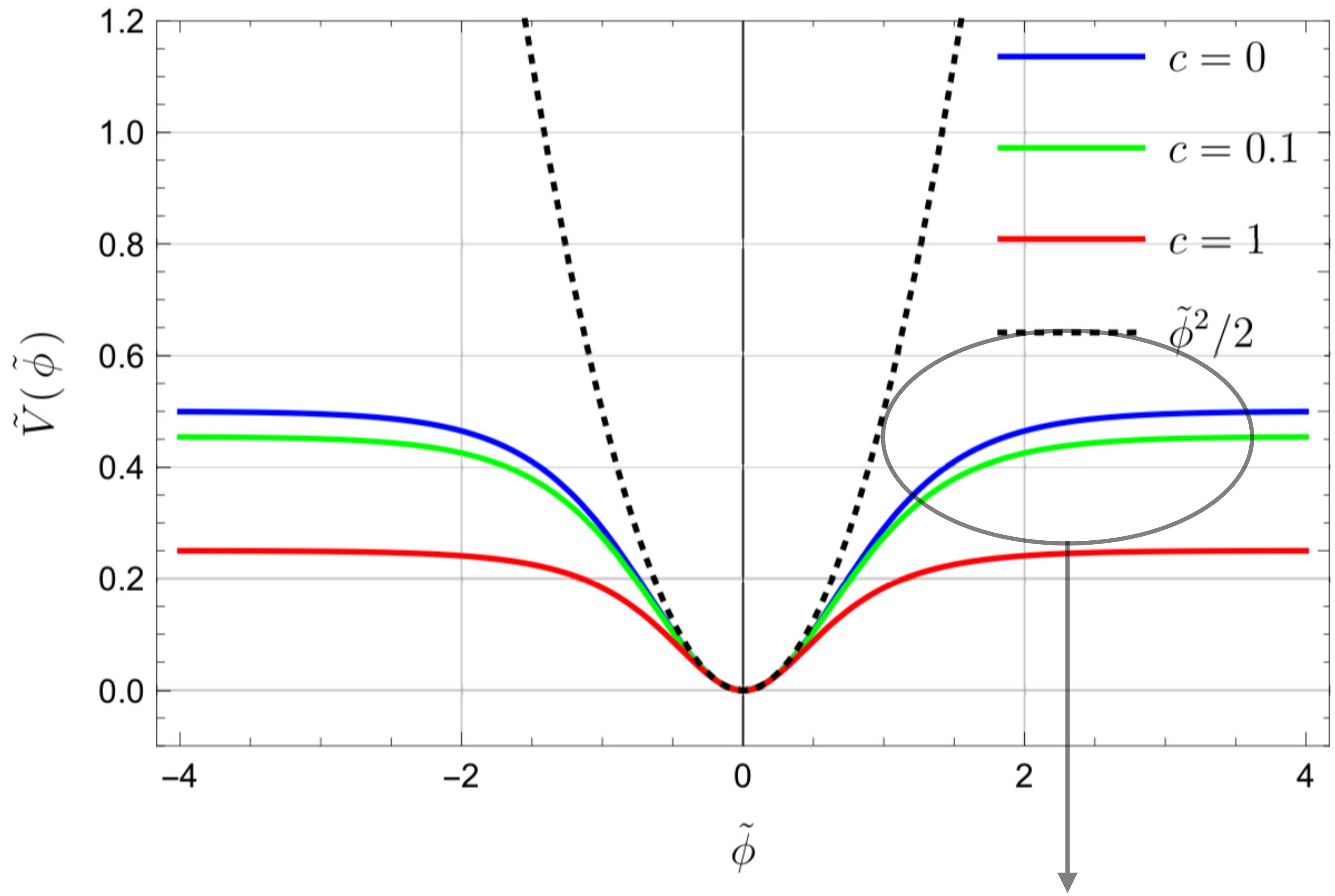


Axion as the present dark matter

$$\Omega_\phi h^2 \sim \left(\frac{g_{*\mathrm{osc}}}{100}\right)^{-1/4} \left(\frac{m}{10^{-24}\mathrm{eV}}\right)^{1/2} \left(\frac{m}{H_{\mathrm{osc}}}\right)^{3/2} \left(\frac{f}{M_{\mathrm{Pl}}}\right)^2$$



Oscillon / I-ball formation

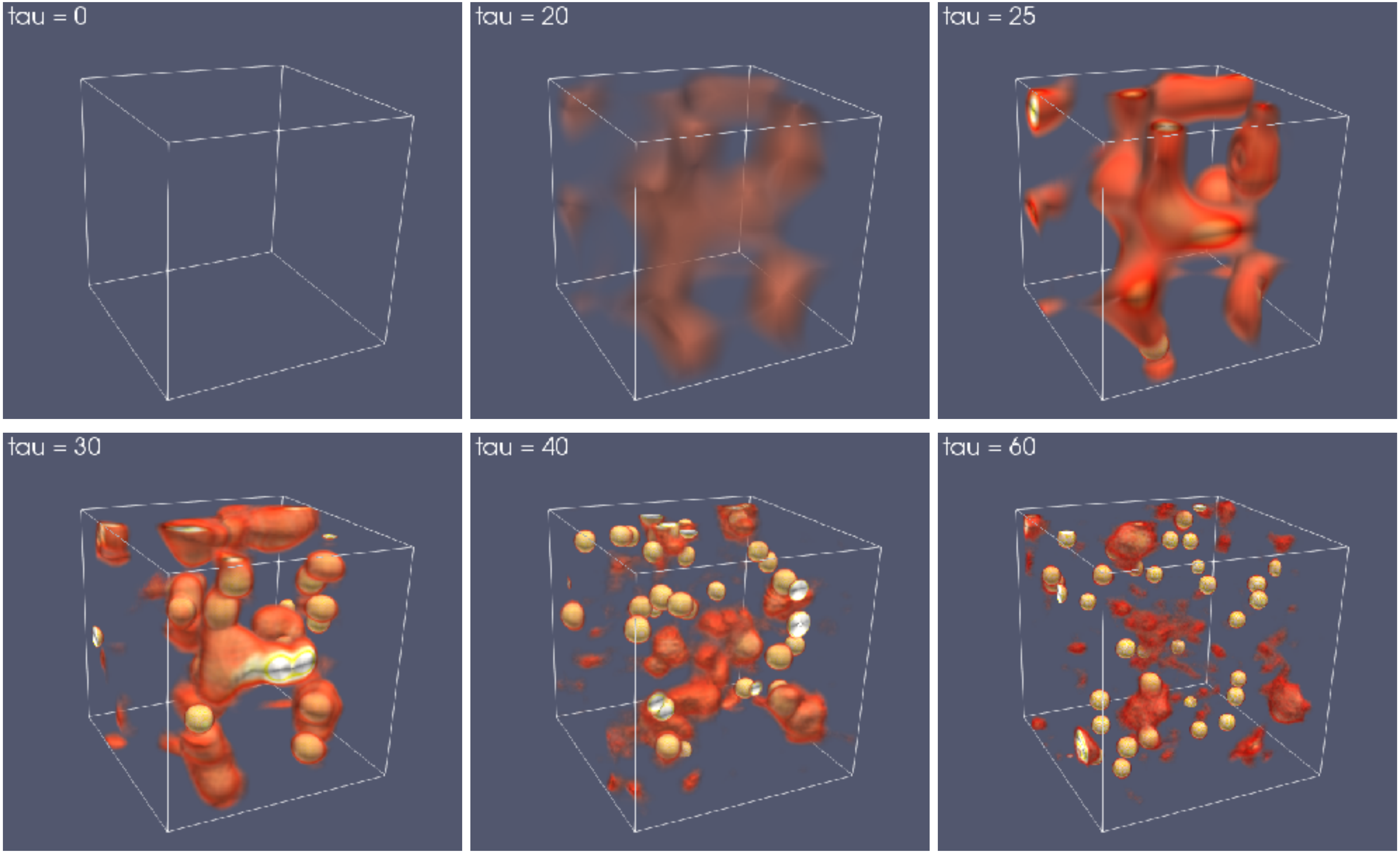


potential becomes flat at large field value
—> oscillon formation

Oscillon : quasi-stable, non-topological soliton

Gleiser (1994), Copeland+ (1995), Amin+ (2012) and…

Oscillon / I-ball formation



$$c = 5,\ \ \phi_i/f = 10,\ \ \rho/\langle\rho\rangle > 2 \ \ \text{(red)},\ \ 10 \ \ \text{(yellow)}$$

Summary

- String theory predicts many axions (string axions) with wide mass spectrum

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

- Oscillon formation is followed by the prametric instability.

multi-band GW observation can be a probe of string axions with wide mass range