Resonant Magnetic Field Generation from axions

with

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Cosmological Magnetic Fields

- Galaxies

Bernet et al 2008

- Galaxy Clusters

Ferreti et al 2012

Radio Faraday Rotation Measurements

$$\mu\text{Gauss}$$

- Cosmic voids

Vovk et al 2012

Primordial?

TeV γ- Ray Blazar Observation

$$10^{-15}\text{G}\begin{cases}\times 1 & \lambda > 1\text{Mpc}\\ \times\sqrt{\dfrac{1\text{Mpc}}{\lambda}} & \lambda < 1\text{Mpc}\end{cases}$$

Various Magnetogenesis Models

- **Primordial Magnetic Fields**
  - Inflationary — B. Ratra 1992, Martin & Yokoyama 2008, Durrer+ 2011, ...
  - Phase transition — Vachaspati 1992, Durrer and Nerenov+2013, ..
- **Post Inflationary**
  - Onset of LSS formation — Galactic winds : Bertone et al 2006, .. Relativistic outflows from AGNs : Rees 1987, ..
  - Biermann batteries — Subramaniam 2018

Setups

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{4}\frac{\phi}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Chern-Simons Coupling

- Inflationary (Monodromy)
- Reheating

Dominant

Subdominant

- Spectator
- Post Inflationary

General equations

Klein-Gordon EOM

$$\phi'' + 2\mathcal{H}\phi' + a^2 V_{,\phi} = a^2 \frac{\alpha}{f} \langle \mathbf{E} \cdot \mathbf{B} \rangle$$

Gauge field EOM

$$\mathcal{A}''_{\pm}(\eta,\ k) + \left(k^2 \mp \frac{\alpha}{f} \frac{\phi'}{\mathcal{H}} k\mathcal{H} \right) \mathcal{A}_{\pm}(\eta,\ k) = 0$$

Fourier expansion in the helicity basis

'+' '-'

Backreaction

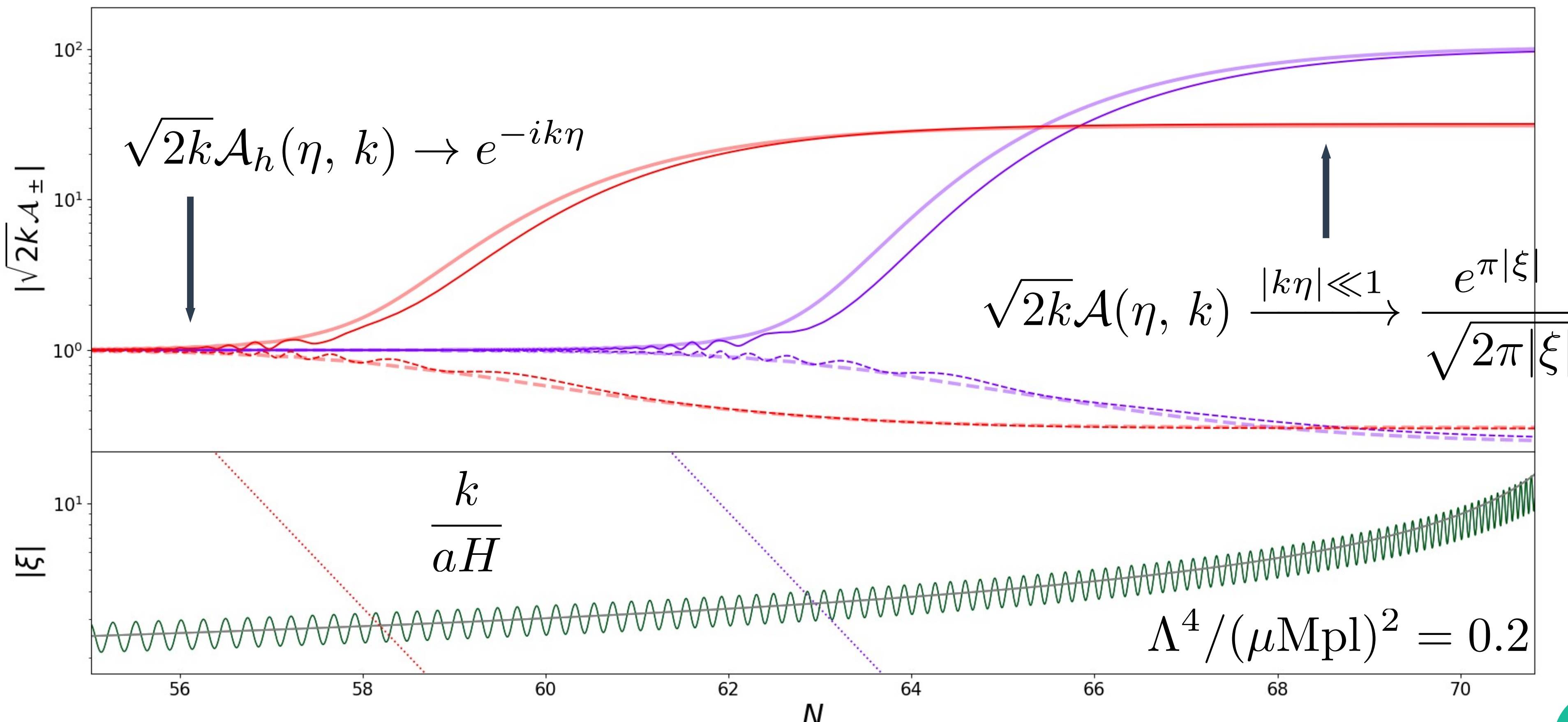
$$\langle \mathbf{E} \cdot \mathbf{B} \rangle = -\frac{1}{8\pi^2} \int \mathrm{d} \ln k \left(\frac{k}{a} \right)^4 \left[\frac{1}{k} \frac{\mathrm{d}}{\mathrm{d}\eta} \left(|\sqrt{2k}\mathcal{A}_+|^2 \right) - \frac{1}{k} \frac{\mathrm{d}}{\mathrm{d}\eta} \left(|\sqrt{2k}\mathcal{A}_+|^2 \right) \right]$$

Monodromy

$$V(\phi) = \mu^2\phi^2 + \Lambda^4 \cos\frac{\phi}{f}$$

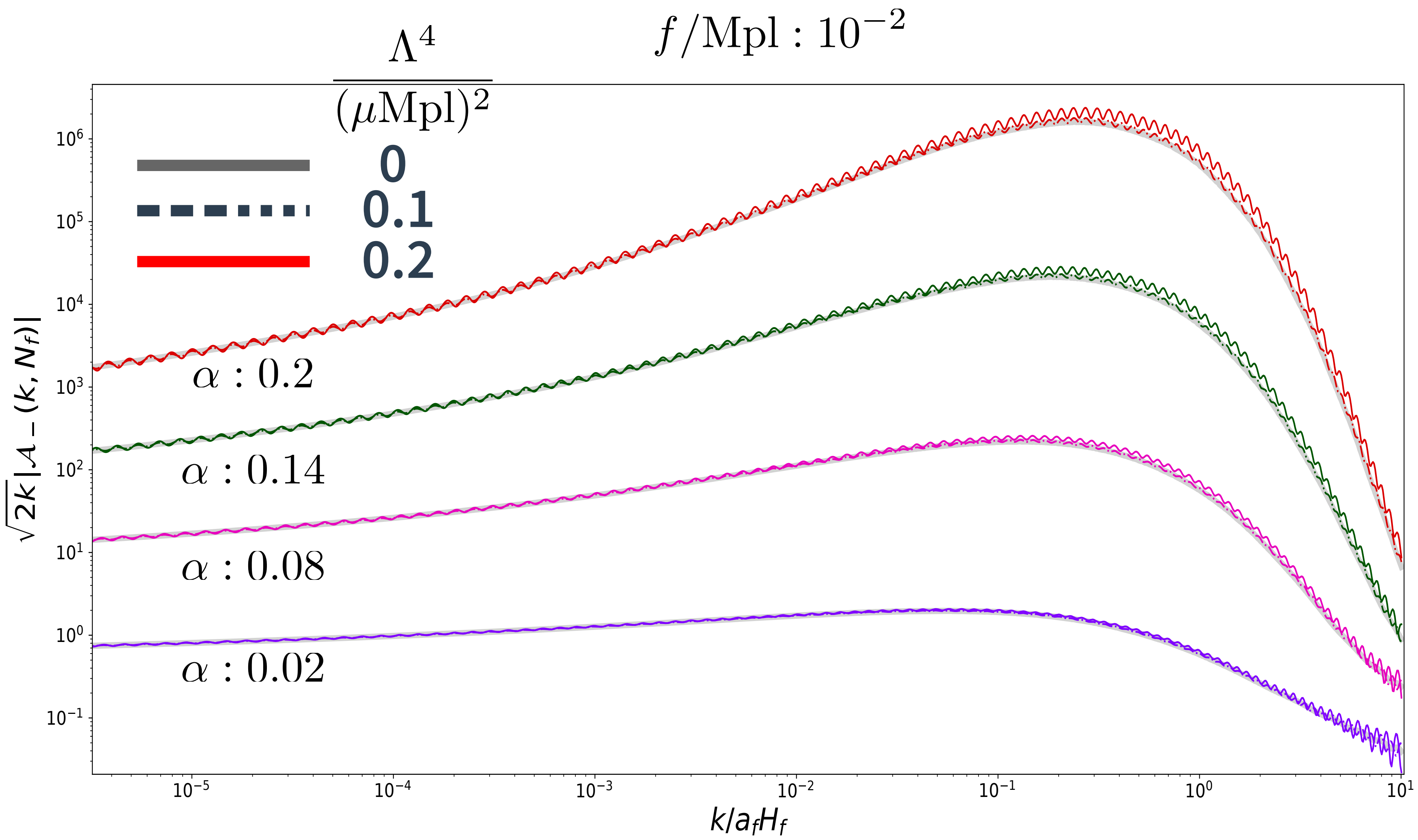
$$\varepsilon \equiv \frac{1}{2\mathrm{Mpl}^2}\left(\frac{\phi'}{\mathcal{H}}\right)^2 \qquad |\xi| = \sqrt{2\varepsilon}\alpha\frac{\mathrm{Mpl}}{f}$$

$\alpha\,(f/\mathrm{Mpl}) : 10$



Monodromy

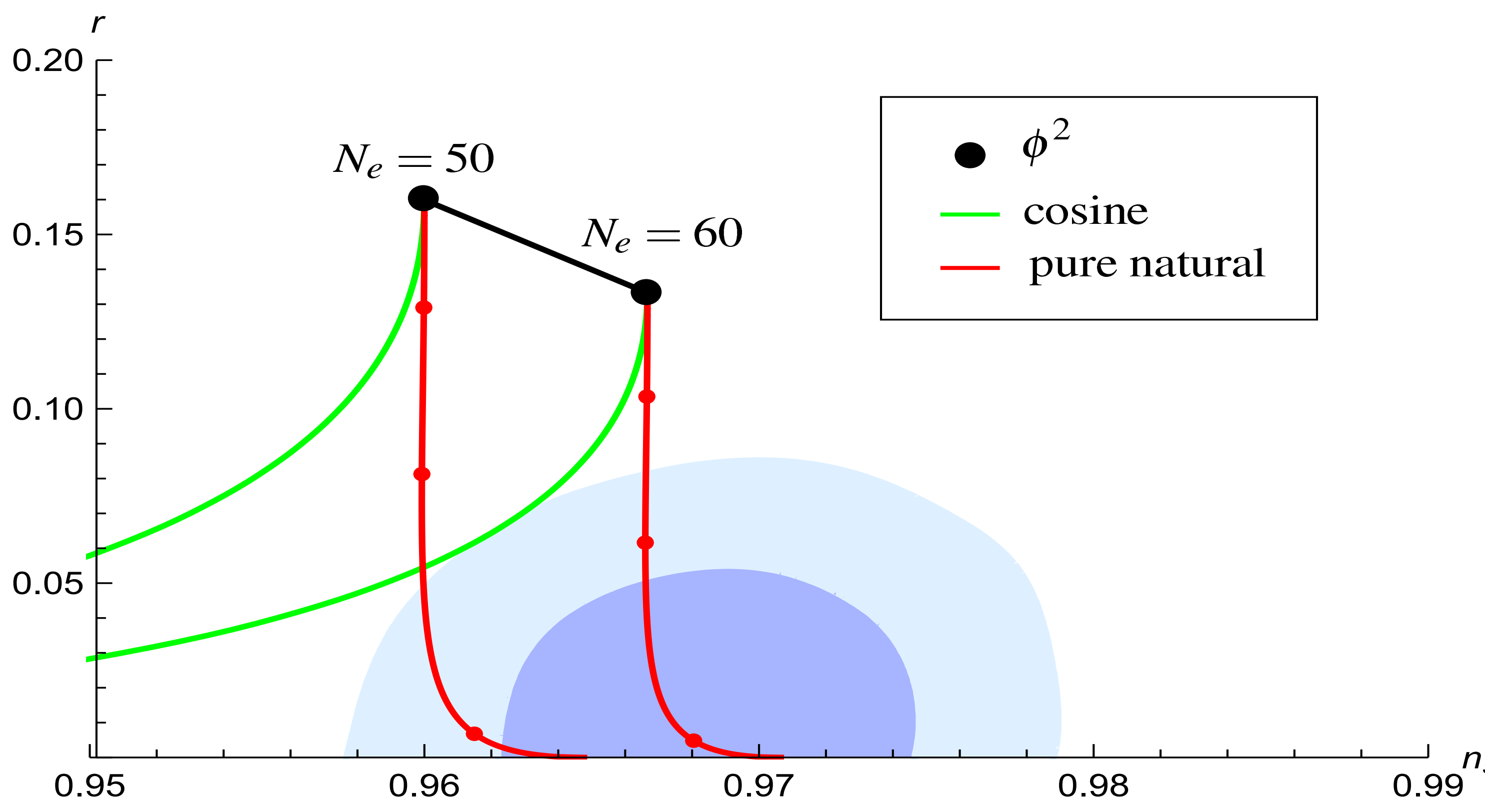
Spectra



Reheating

$$V(\phi) = \frac{(mf)^2}{2}\left[1 - \frac{1}{(1+\tilde{\phi}^2/p)^p}\right] \equiv (mf)^2 \tilde{V}(\tilde{\phi})$$

Pure Natural Potential



Nomura, Watari & Yamazaki 2017

arxiv:1706.08522

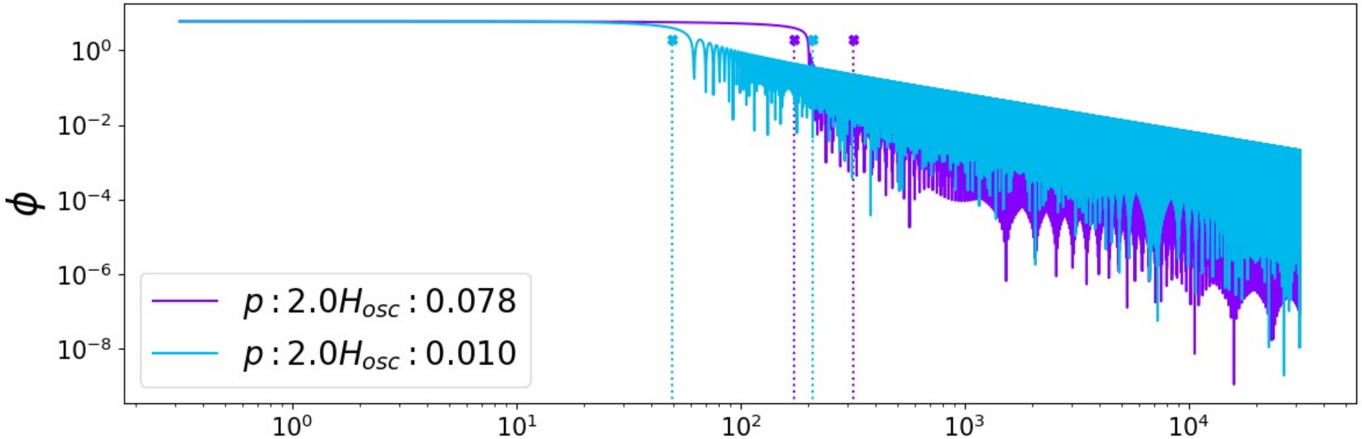
Reheating

Background

$$V(\phi) = \frac{(mf)^2}{2}\left[1 - \frac{1}{(1+\tilde{\phi}^2/p)^p}\right] \equiv (mf)^2\tilde{V}(\tilde{\phi})$$

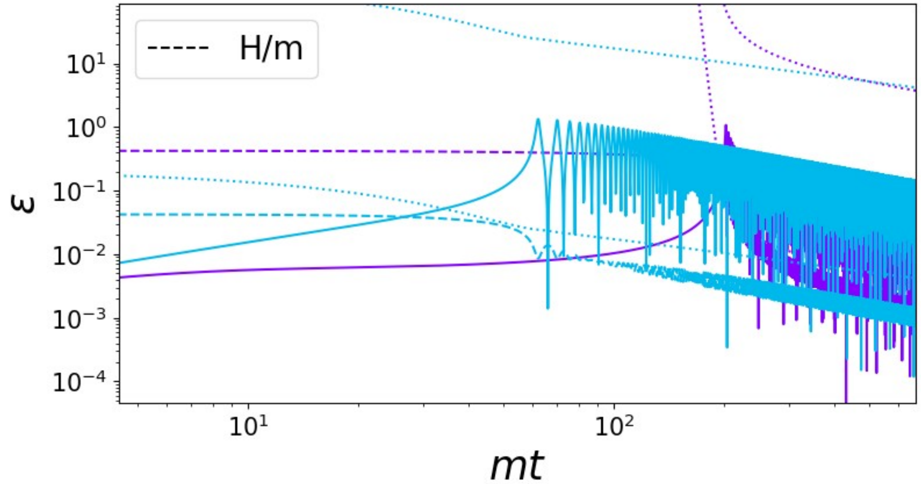
$$\frac{\mathrm{d}^2\tilde{\phi}}{\mathrm{d}\tilde{t}^2} + 3\frac{H}{m}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}\tilde{t}} + \tilde{V}_{,\tilde{\phi}} = 0$$

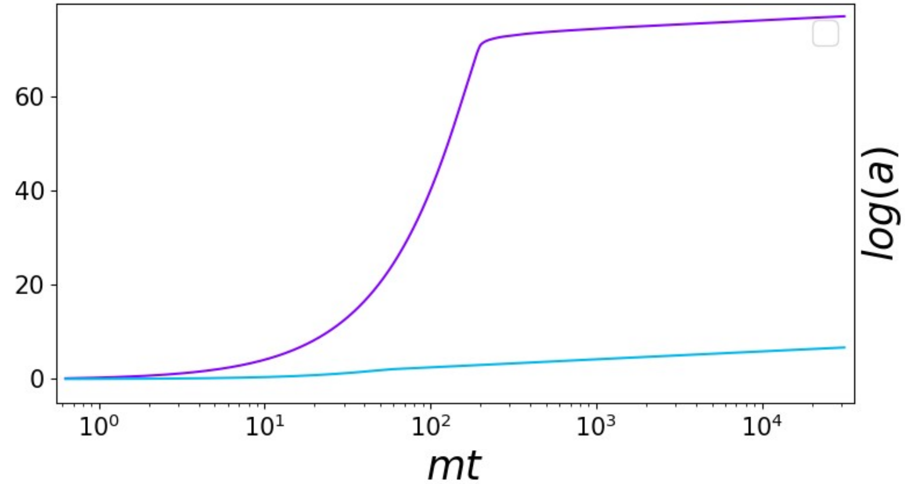
$$\left(\frac{H}{m}\right)^2 = \frac{1}{6}\left(\frac{f}{\mathrm{Mpl}}\right)^2\left[\left(\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}\tilde{t}}\right)^2 + 2\tilde{V}\right]$$



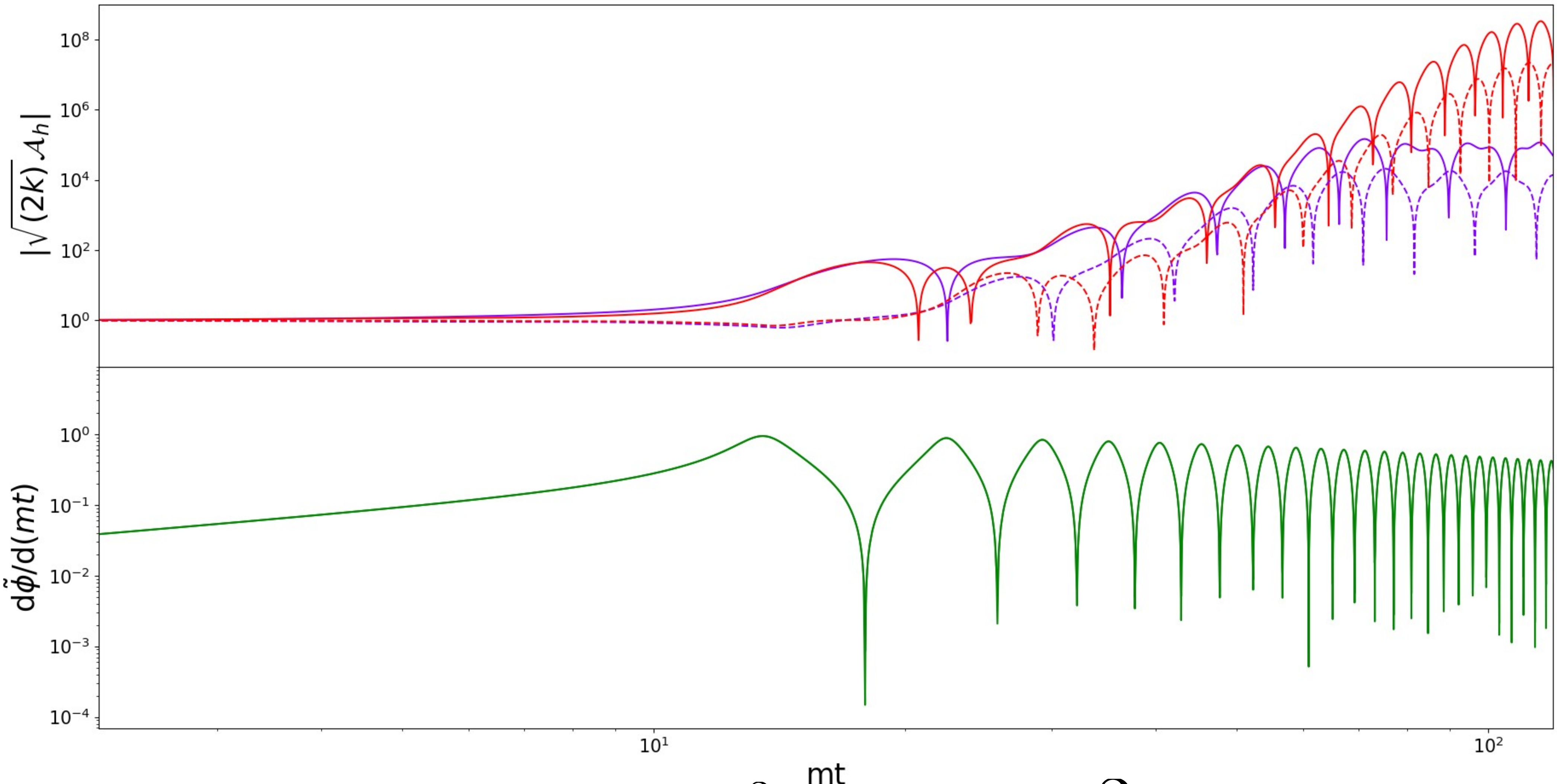
$f/\mathrm{Mpl} : 0.1$

$f/\mathrm{Mpl} : 0.01$





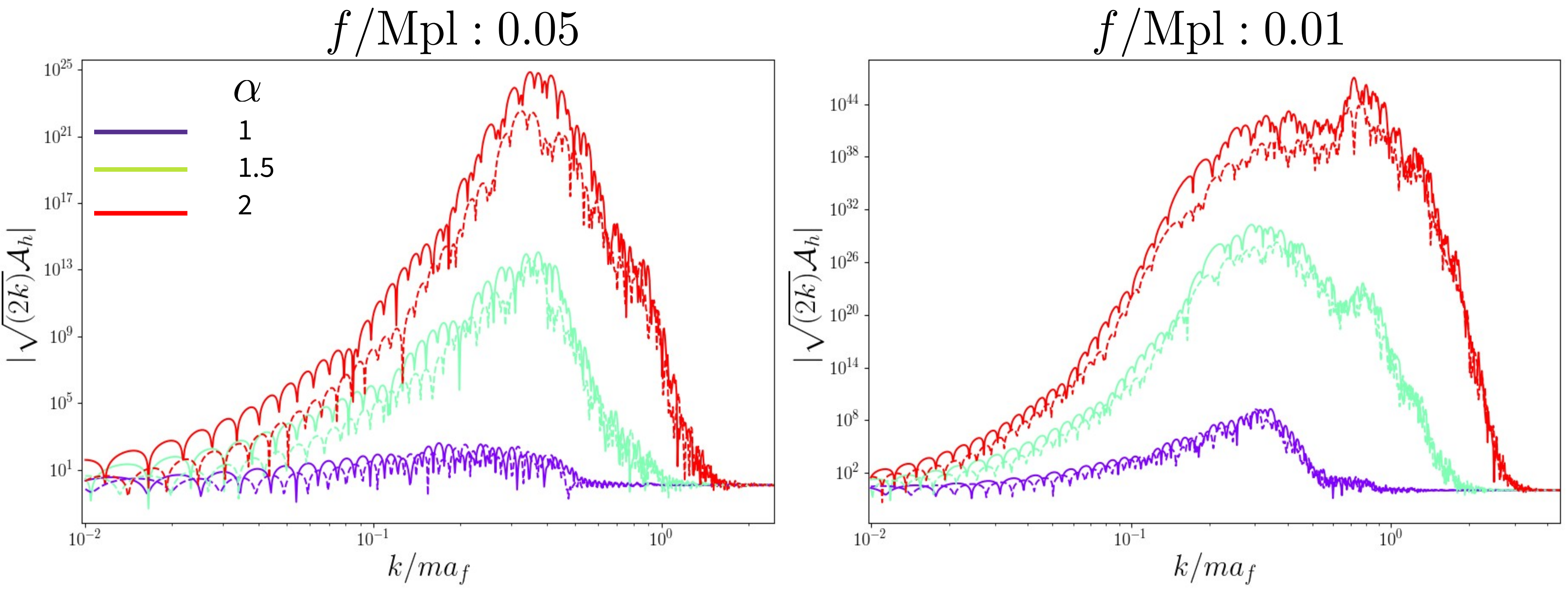
$$\frac{\mathrm{d}\mathcal{A}_h}{\mathrm{d}\tilde{t}^2} + \frac{H}{m}\frac{\mathrm{d}\mathcal{A}_h}{\mathrm{d}\tilde{t}} + \omega_h^2 \mathcal{A}_h = 0 \qquad \omega_h^2 \equiv \frac{k^2}{a^2 m^2} - h\alpha \frac{k}{ma}\left(\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}\tilde{t}}\right)$$



$\alpha : 2$ $\quad f/\mathrm{Mpl} : 10^{-2}$ $\quad p : 2$

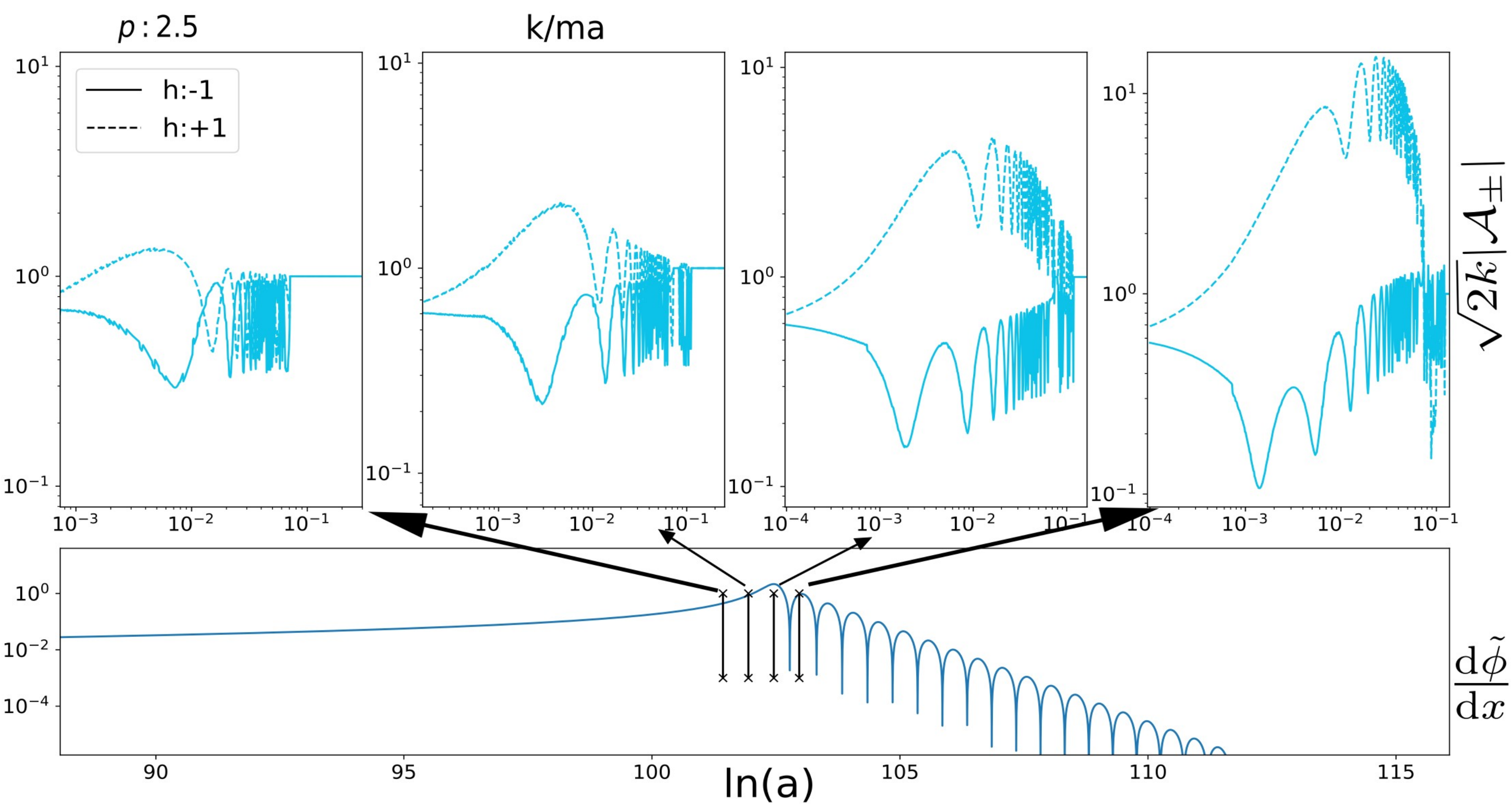
Reheating

Generated Spectra



Tachyonic → Resonance

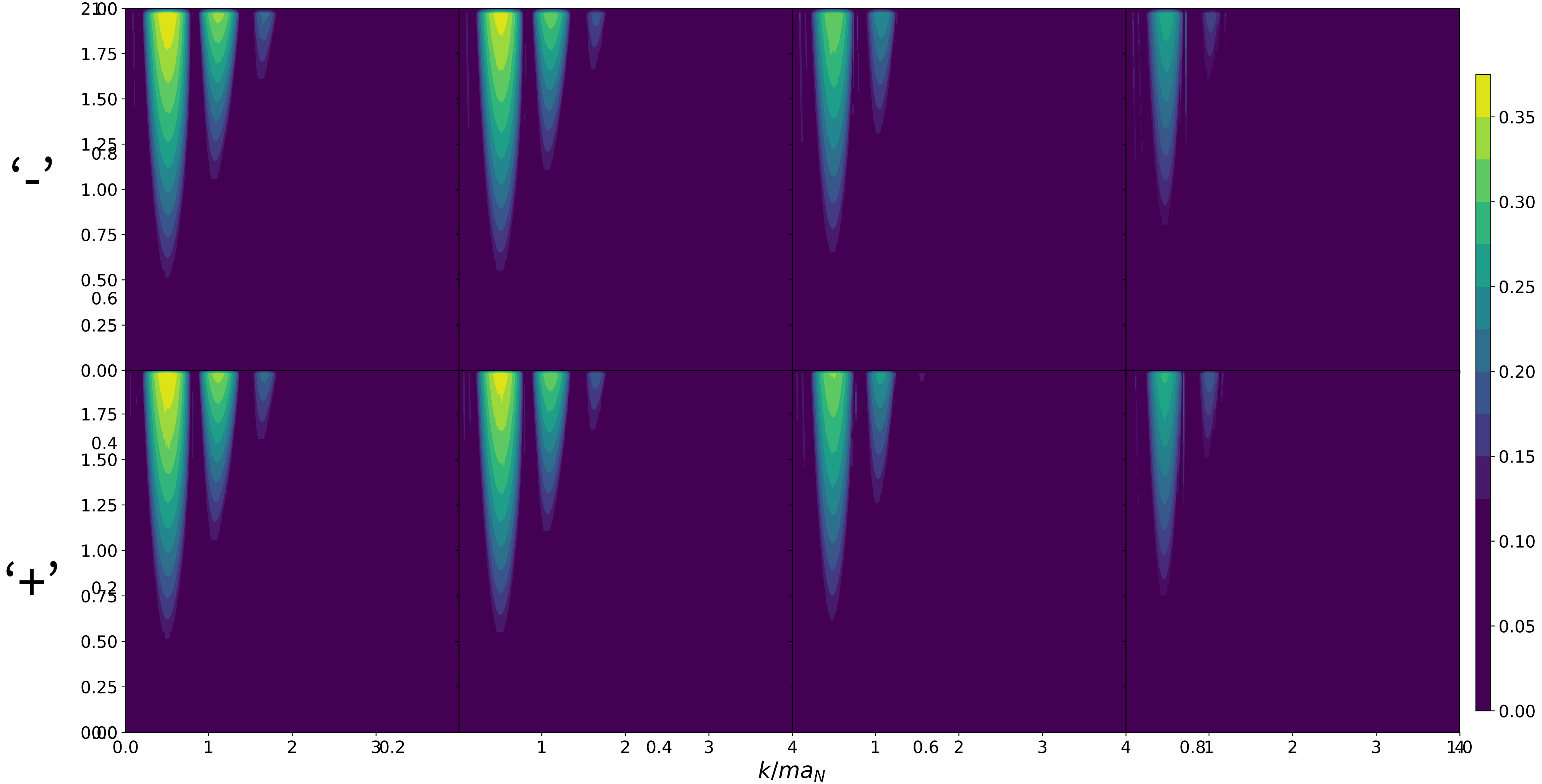
Evolution of spectrum generated by a spectator (Next section)



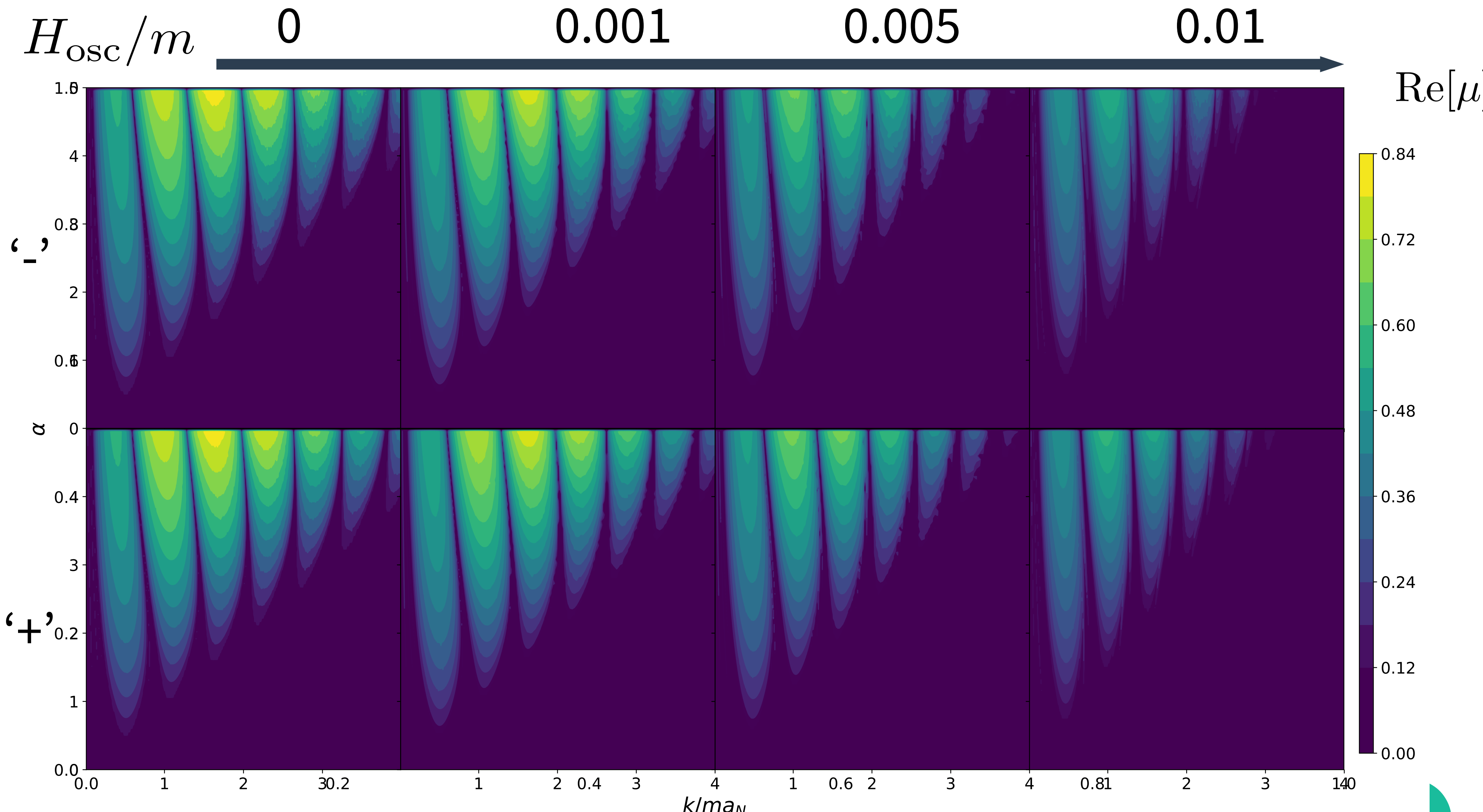
Growth Rate

$$y(z) \propto e^{\mu z}\Phi(z) \qquad \Phi(z+T)$$

$H_{\rm osc}/m$ 0 0.001 0.005 0.01



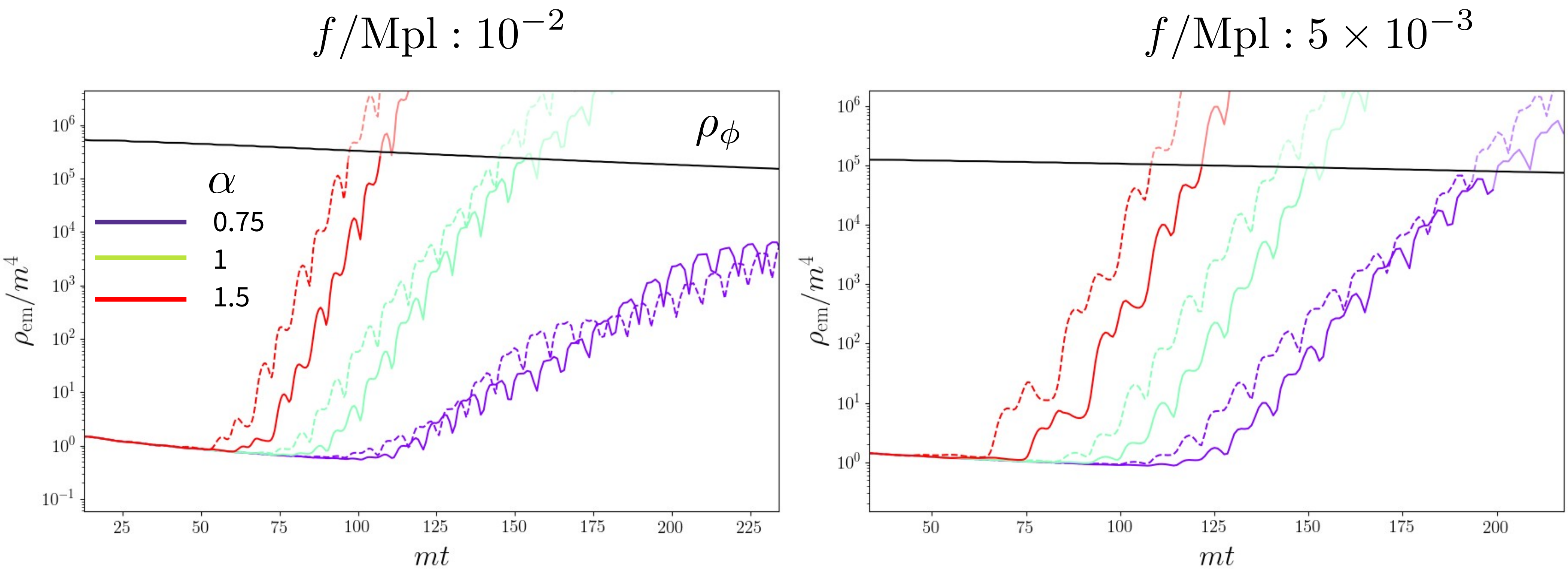
Growth rate



$H_{\rm osc}/m$
0
0.001
0.005
0.01
$\mathrm{Re}[\mu]$
'-'
'+'
α
k/ma_N
0.84
0.72
0.60
0.48
0.36
0.24
0.12
0.00

Reheating

Energy Density



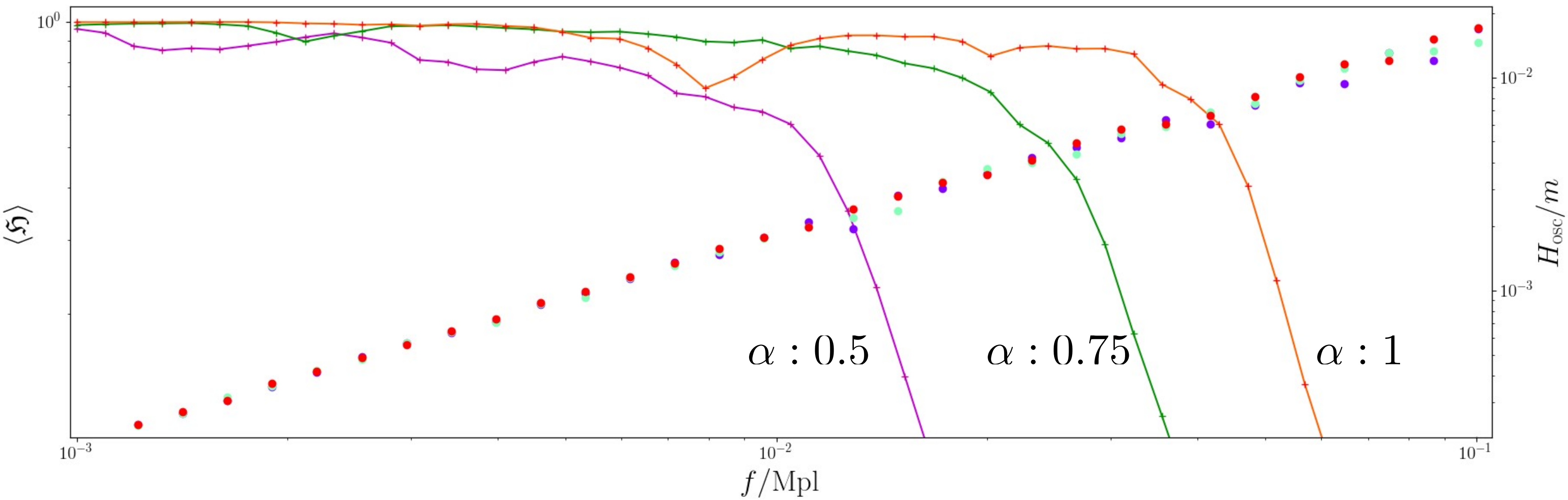
Helicity

Cosine Potential

$$\frac{H_{\rm osc}}{m} \simeq 1$$

Pure Natural Inflation

$$\frac{H_{\rm osc}}{m} \simeq \frac{f}{\rm Mpl}$$



Spectator

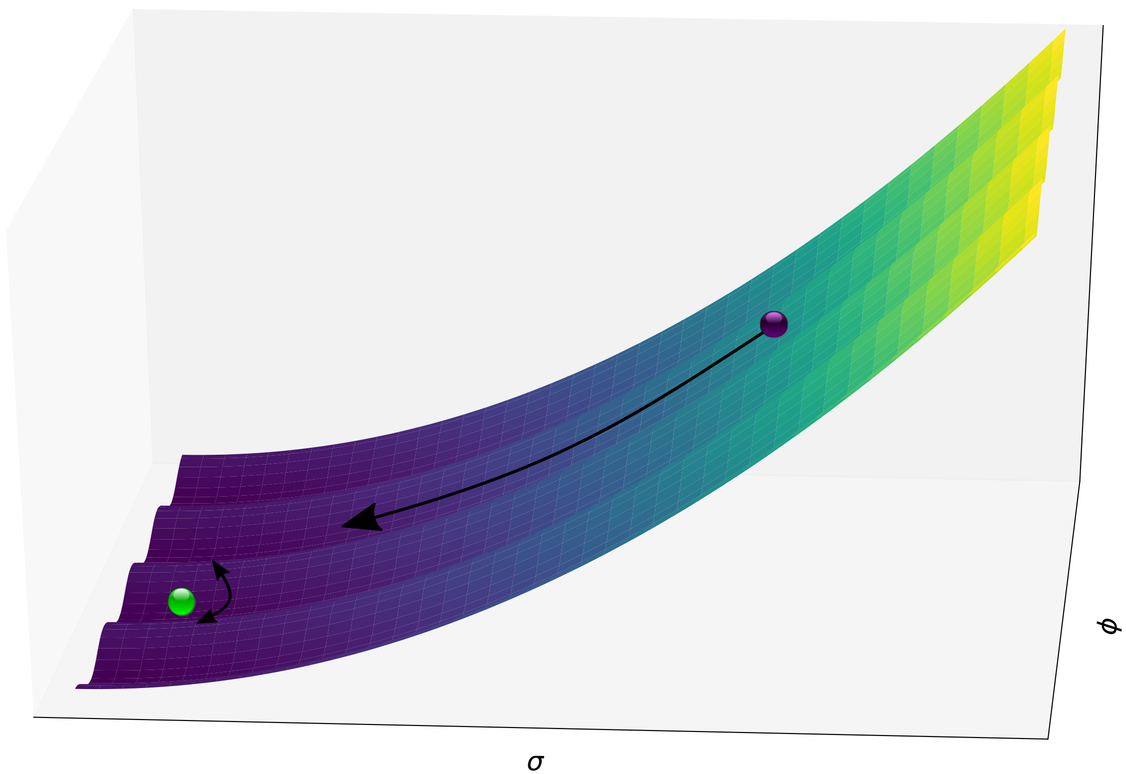
Kitajima, Soda and Yuko, 2018

GW emission in R.D Universe

Setup

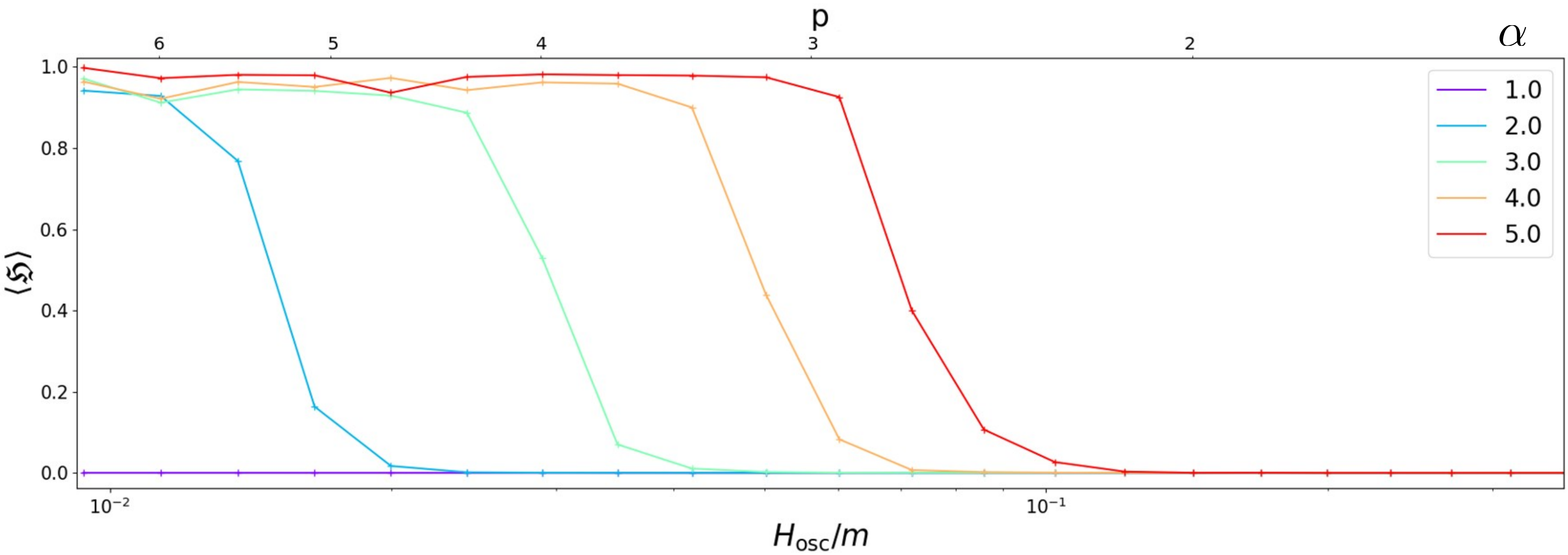
$$H/m = (a/a_{H=m})^{-\epsilon}$$

$$V(\phi) = \frac{(mf)^2}{2}\left[1 - \frac{1}{(1+\tilde{\phi}^2/p)^p}\right] \equiv (mf)^2\tilde{V}(\tilde{\phi})$$

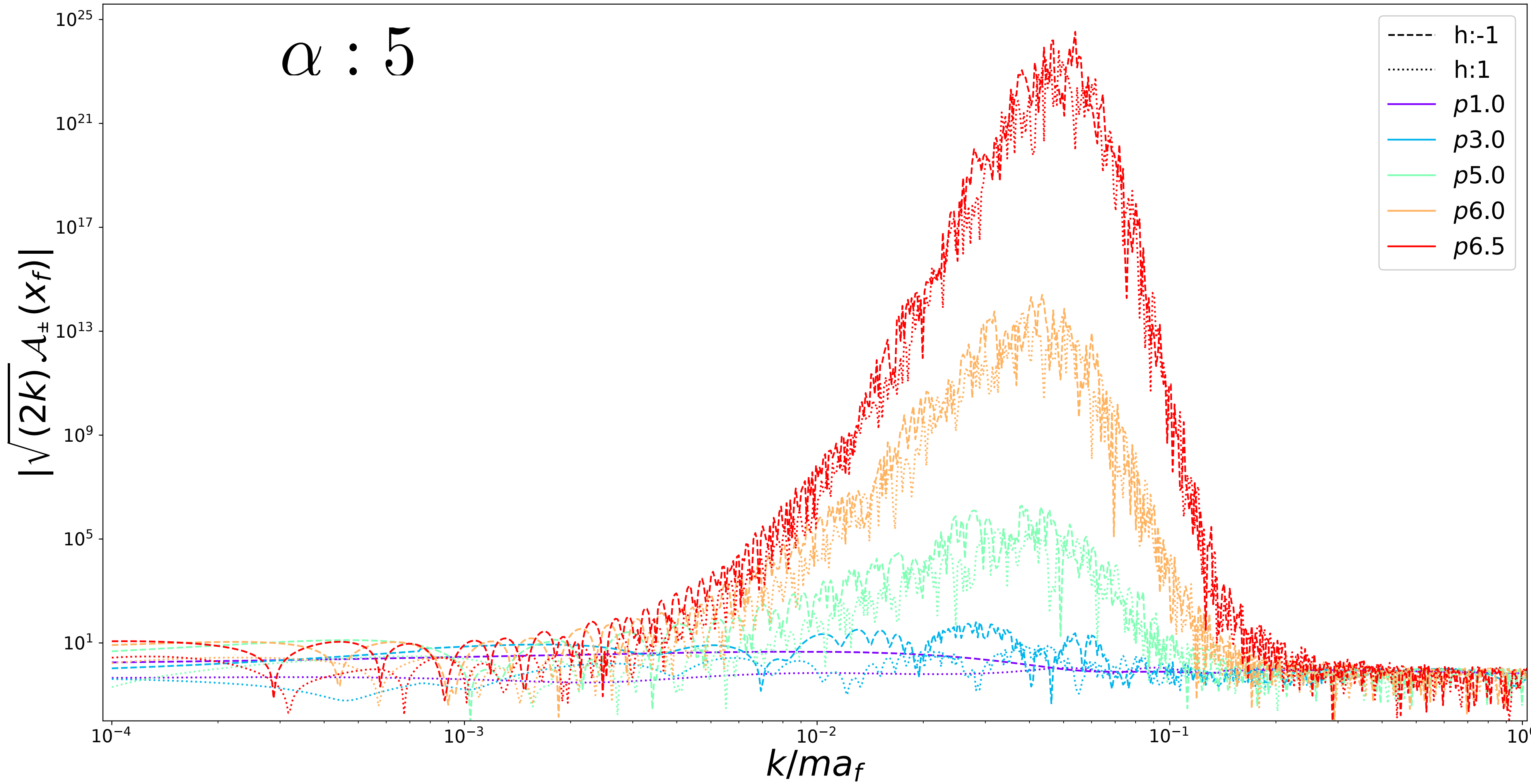


Spectator

Helicity



Spectator



$\alpha : 5$
h:-1
h:1
p1.0
p3.0
p5.0
p6.0
p6.5
$|\sqrt{(2k)}\,\mathcal{A}_\pm(x_f)|$
10^{25}
10^{21}
10^{17}
10^{13}
10^{9}
10^{5}
10^{1}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
k/ma_f

Post Reheating generation

Subdominant axion field oscillating during Radiation Dominated

$$\frac{\mathrm{d}^2\mathcal{A}_h}{\mathrm{d}\tilde{t}^2} + \left(\frac{H}{m} + \frac{4\pi\sigma}{m}\right)\frac{\mathrm{d}\mathcal{A}_h}{\mathrm{d}\tilde{t}} + \omega_h^2\mathcal{A}_h = 0 \qquad \frac{H}{m} = \frac{1}{2mt}$$

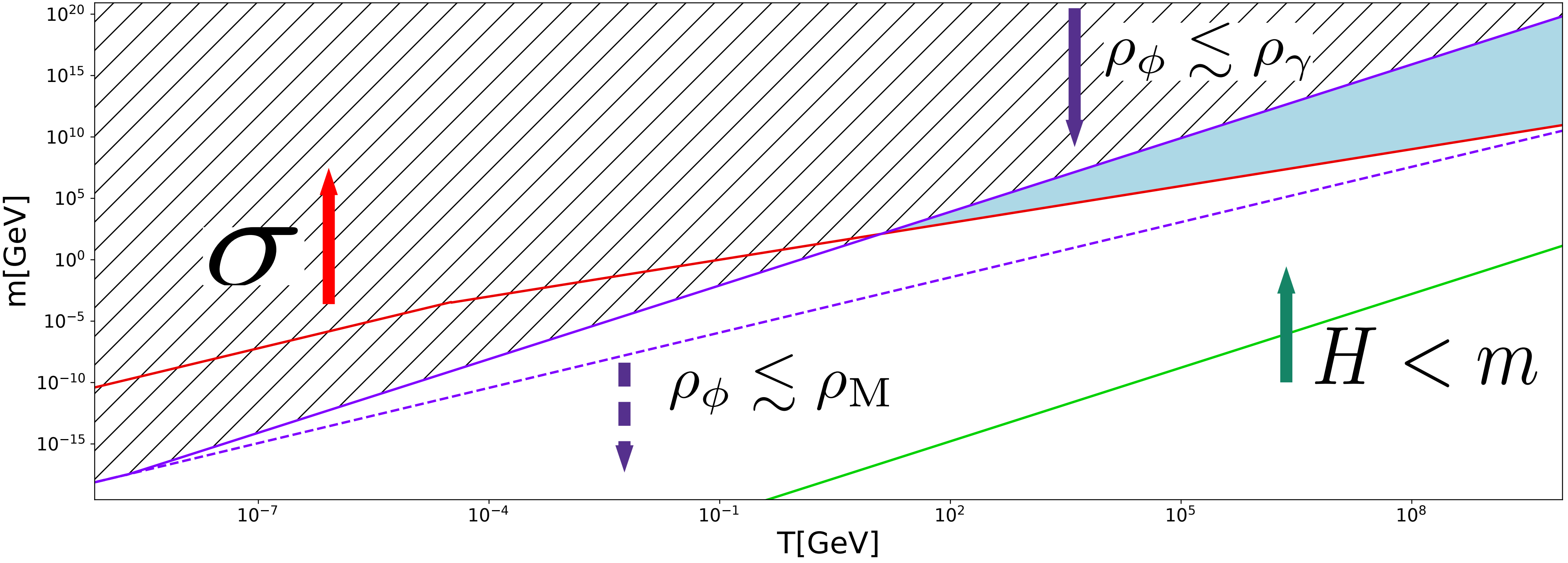
$$\sigma \begin{cases} 10\left(\frac{T}{1\mathrm{GeV}}\right)\mathrm{GeV} \quad T \gg m_e = 0.511\mathrm{MeV} \\ 3.2\times 10^4\mathrm{GeV}\left(\frac{T}{\mathrm{GeV}}\right)^{\frac{3}{2}} \quad T \ll m_e \end{cases}$$

Baym and Heiselberg, 1997

Spitzer, 1953

Criteria

$$\frac{\sigma}{m} \lesssim \mu$$



Post Inflationary Evolution

- **Non-Helical**

$$B \propto \frac{1}{a^2} \qquad \lambda \propto a$$

- **Helical**

Inverse cascade

Helicity conservation → Adiabatic Evolution

$$\langle \mathfrak{H} \rangle \propto \Delta(\ln k) a_{\rm gen}^3 \frac{a_{\rm gen}}{k_{\rm gen}} B_{k_{m,\rm gen}}^2$$

$$\frac{a_{\rm rec}}{k_{m,\rm rec}} \simeq \frac{B_{k_{m,rec}}}{\rho_{rec}/M_{\rm pl}}$$

$$B_{km,0} \simeq 10^{-8}{\rm G} \times \left(\frac{\lambda_{\rm m,0}}{1{\rm Mpc}}\right)$$

Order Estimations

★ Generation

- **Axion Monodromy**

$$\lambda_{m,0} \ll 10^2\mathrm{Mpc}\left(\frac{a_\star}{a_\mathrm{R}}\right)\left(\frac{10^5\mathrm{GeV}}{T_{\gamma,\mathrm{R}}}\right)\left(\frac{f}{10^{-3}\mathrm{Mpl}}\right)^{\frac{2}{3}}\left(\frac{1}{\Delta\ln k_\mathrm{rec}}\right)^{\frac{1}{3}}\cdots.$$

- **Axion Spectator**

$$\lambda_{m,0} \ll 4\mathrm{Mpc}\left(\frac{a_\star}{a_R}\right)\left(\frac{10^6\mathrm{GeV}}{T_{\gamma,\mathrm{R}}}\right)\left(\frac{1}{\alpha}\right)^{\frac{1}{3}}\left(\frac{\rho_\phi}{\rho_\mathrm{inf}}\right)^{\frac{1}{3}}\cdots$$

- **Reheating**

$$\lambda_{m,0} \ll 10^3\mathrm{Mpc}\left(\frac{10^5\mathrm{GeV}}{T_{\gamma,\mathrm{R}}}\right)\left(\frac{f}{10^{-3}\mathrm{Mpl}}\right)^{1/3}\left(\frac{1}{\Delta(\ln k)_\mathrm{rec}}\right)^{\frac{1}{3}}\cdots.$$

Summary

- Resonant production of ‘helical’ magnetic field from axions is efficient
- Generation in the plasma-filled Universe is limited
- These processes can saturate the energy density(without taking non-linear processes into account), and can be promising candidates for origin of cosmic magnetic fields