Signals of new dynamics during the inflation era

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Work in collaboration
with Zhong-zhi Xianyu 1910.12876, 2004.02887,
with Zhong-zhi Xianyu, Yiming Zhong, 2109.14635
with Haipeng An, KunFeng Lyu, and Siyi Zhou, 2009.12381, 2111.xxxx

UC Davis. Oct. 25, 2021

Inflation:
a stage for new dynamics

- High energy: H can be 10^{13} GeV.
  - Can produce heavy new physics particles.
- Inflaton can travel a large distance in field space.
  - Can trigger dramatic changes in spectator sectors which couple to the inflaton

This talk

* Signal of particle production. “Cosmological collider physics”.
* Drama in the spectator sector, signal of a first order phase transition during the inflation.

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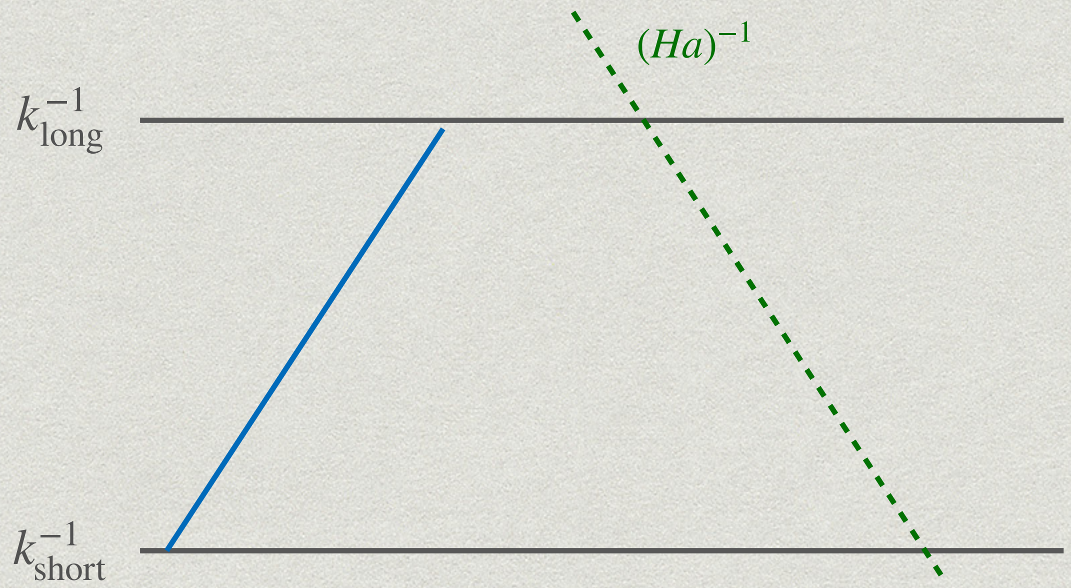
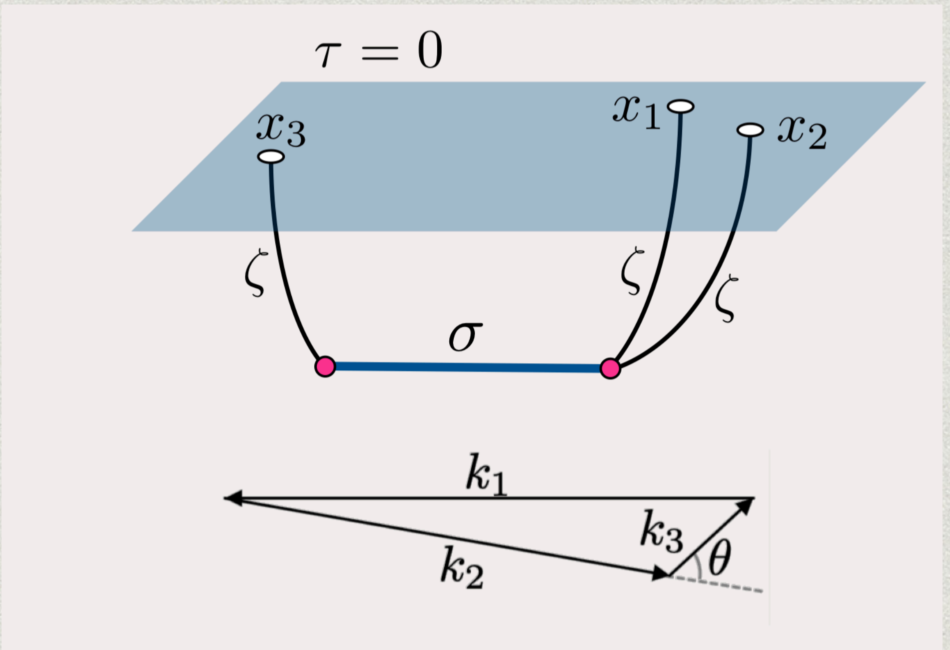
Signal of particle production



Time of propagation:

$$t = \frac{1}{H} \log \frac{k_{\rm short}}{k_{\rm long}}$$



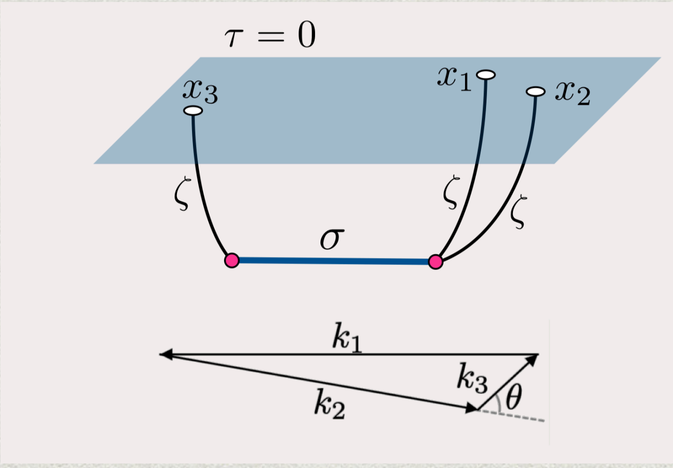
$k_1 \sim k_2 \sim k_{\rm short} \quad k_3 \sim k_{\rm long}$

oscillatory signal

$$\sim \sin(mt) = \sin\left(\frac{m}{H} \log \frac{k_{\rm short}}{k_{\rm long}}\right)$$

"Cosmological collider"
Chen, Wang, 2009, 2012
Arkani-Hamed, Maldacena, 2015

More specifically



$$\frac{\langle \zeta_1 \zeta_2 \zeta_3 \rangle}{\langle \zeta\zeta \rangle_{\text{short}} \langle \zeta\zeta \rangle_{\text{long}}} \sim e^{-\pi\nu} \left[f(\nu) \left(\frac{k_{\text{long}}}{k_{\text{short}}} \right)^{\frac{3}{2}+i\nu} + c.c. \right] P_s(\cos\theta) \qquad \nu = \sqrt{\frac{m_\sigma^2}{H^2} - \frac{9}{4}}$$

$e^{-\pi\nu}$ Boltzmann suppressed if $m_\sigma \gg H$

$\left(\frac{k_{\text{long}}}{k_{\text{short}}} \right)^{\frac{3}{2}+i\nu}$ No oscillation if $m_\sigma < 3/2\ H$

The presence of oscillation signal requires $m_\sigma \approx H$

Example:

Relevant scales for inflation	SUSY	Strong dynamics
$V_{\rm inf}^{1/4} \simeq 10^{16}$ GeV	$\Lambda_{\rm GUT}, \Lambda_{\rm string}, \dots$	$\Lambda_{\rm TC}, \dots$
$(\dot\phi_0)^{1/2} \simeq 10^{14\div15}$ GeV		$m_\rho, \dots$
$H \simeq 10^{13}$ GeV	$m_{3/2}, m_{\tilde q}, \dots$	$m_\pi, \dots$

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Can be probed by cosmological collider

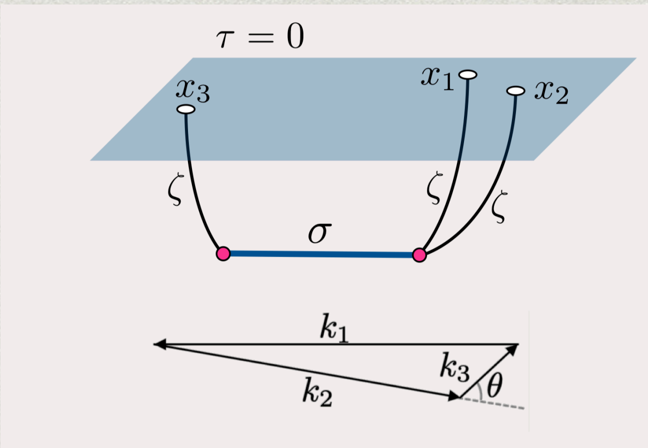
Sensitivity of the cosmological collider

- What kind of inflaton - new physics coupling lead to observable signals.

Many recent works:

X. Chen, Z. Xianyu, Y. Wang, et. al.
H. An, M. McAneny, A. Ridgway, M. Wise
H. Lee, D. Baumann, G. L. Pimentel.
S. Kumar, R. Sundrum
A. Hook, J. Huang, D. Racco

Size of the signal



$$\langle \zeta_1 \zeta_2 \zeta_3 \rangle = (2\pi)^4 P_\zeta^2 \frac{1}{(k_1 k_2 k_3)^2} S(k_1, k_2, k_3)$$

CMB: $$P_\zeta = \frac{H^2}{\dot{\phi}_0^2} \left(\frac{H}{2\pi} \right)^2 \simeq 2 \times 10^{-9} \qquad \dot{\phi}_0^{1/2} \simeq 60H$$

$$S(k_1, k_2, k_3) \sim f_{\rm NL} \sim \frac{1}{2\pi P_\zeta^{1/2}} \times \text{ interactions}$$

interactions = couplings, loops, propagators

For comparison. Planck: $f_{NL} \lesssim$ a few; LSS: $f_{NL} \sim 1$; 21cm: 10^{-2}

1: non-derivative coupling

$$\mathscr{L} \supset \lambda\phi^2\sigma^2 + \mu\phi\sigma^2, \quad \sigma : \text{scalar}$$

None-zero value of the inflaton field will generate a mass for σ.

$$\delta m_\sigma = \lambda\phi_0^2, \quad \phi_0 = \langle\phi\rangle$$

For the mass of σ to be around H, without fine-tuning, we need

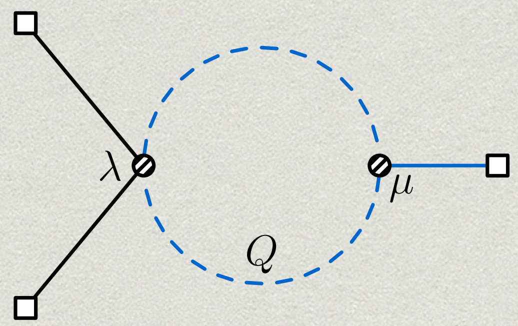
$$\delta m_\sigma^2 < H^2 \rightarrow \lambda < \frac{H^2}{\phi_0^2}$$

For a similar reason, we need $\mu < \frac{H^2}{\phi_0}$

1: non-derivative coupling

$$\delta m_\sigma^2 < H^2 \to \lambda < \frac{H^2}{\phi_0^2}$$

$f_{\rm NL}^{\rm (osc)}$ (



)

$$\sim \frac{1}{2\pi P_\zeta^{1/2}} \cdot \frac{1}{16\pi^2}\lambda\frac{\mu}{H} < \frac{1}{2\pi P_\zeta^{1/2}}\frac{1}{16\pi^2}\left(\frac{H}{\phi_0}\right)^3$$

1: non-derivative coupling

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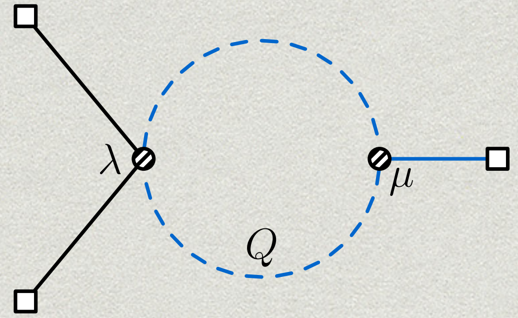
$f_{\mathrm{NL}}^{(\mathrm{osc})}$ (



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Generic size of ϕ_0 :

$$N \simeq \int \mathrm{d}\phi \, \frac{H}{\dot{\phi}_0} \sim \frac{H}{\dot{\phi}_0} \Delta\phi = \mathcal{O}(10)$$

$$\phi_0 \sim \Delta\phi \sim N\dot{\phi}_0/H \;\Rightarrow\; \frac{H}{\phi_0} \sim \frac{2\pi P_\zeta^{1/2}}{N} \sim 10^{-5}$$

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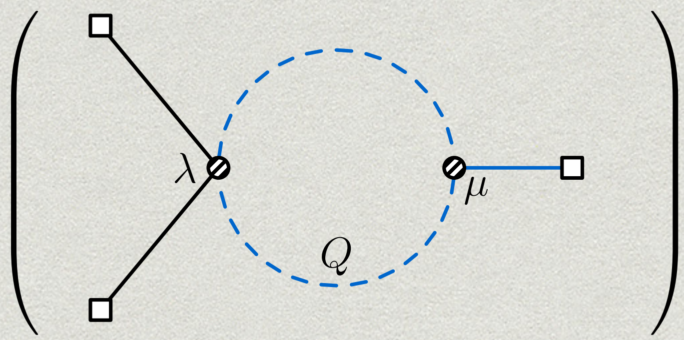
$f_{\rm NL}^{\rm (osc)}$



$$\sim \frac{1}{2\pi P_\zeta^{1/2}} \cdot \frac{1}{16\pi^2} \lambda \frac{\mu}{H} < \frac{1}{2\pi P_\zeta^{1/2}} \frac{1}{16\pi^2} \left(\frac{H}{\phi_0}\right)^3$$

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Hence: $f_{\rm NL}^{\rm (osc)} \sim \dfrac{1}{4N^3} P_\zeta$ tiny!

Lesson learned

- Sizable coupling to the inflaton can generate a mass correction to the matter field σ.
- Requiring this not to make σ too heavy requires small coupling, and small signal.
- Can't avoid by fine-tuning. Inflaton has a sizable excursion, can at most fine tune for a very narrow range.

2. Derivative coupling

- A consequence of an approximate $\phi \rightarrow \phi + c$
- Well motivated from the flatness of inflaton potential.
- It turns out this is also favored for giving a sizable signal.

2. Derivative coupling

Dim 5: $\frac{1}{\Lambda}\partial_\mu \phi J^\mu, \quad \frac{\phi}{\Lambda} F \wedge F$

Naive estimate:

$$f_{\rm NL}^{(\rm osc)} \sim \frac{1}{16\pi^2}\frac{1}{2\pi P_\zeta^{1/2}}\left(\frac{H}{\Lambda}\right)^3 < \frac{1}{16\pi^2}\frac{1}{2\pi P_\zeta^{1/2}}\left(\frac{H}{\dot\phi_0^{1/2}}\right)^3 = \frac{1}{16\pi^2}\cdot\sqrt{2\pi}P_\zeta^{1/4}$$

At the same time, there is a further enhancement.

Modified dispersion relation

Particle production proportional to $\frac{\dot{\omega}}{\omega^2}$

A modified dispersion relation in the inflationary background of the form

$$\omega^2 = k_{\rm phys}^2 + 2\mu k_{\rm phys} + m^2 + \ldots, \quad \text{where } k_{\rm phys} = \frac{k}{a(t)}$$

$$\rightarrow \frac{\dot{\omega}}{\omega^2} \simeq \frac{\mu}{\omega^2}$$

Enhancement possible for sizable **μ**

Coupling:

$$\omega^2 = k_{\rm phys}^2 + 2\mu k_{\rm phys} + m^2 + \ldots, \quad k_{\rm phys} = \frac{k}{a(t)}$$

Comes from $\overrightarrow{k} \cdot \hat{n}, \quad \hat{n} =$ another vector

Without broken rotational invariance, $\hat{n}$ comes from spin.

Possible couplings:

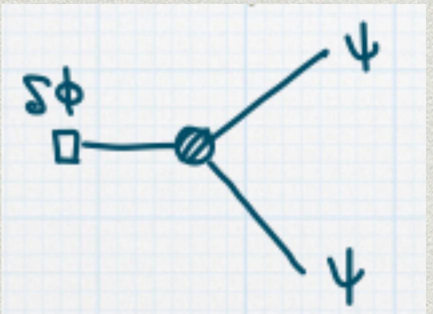
$$\frac{1}{\Lambda}\partial_\mu \phi J^\mu, \qquad J^\mu = \bar{\psi}\gamma_5\gamma^\mu\psi, \quad \epsilon^{\mu\nu\rho\sigma}A_\nu\partial_\rho A_\sigma$$

$$\rightarrow \mu = \frac{\dot{\phi}_0}{\Lambda}$$

An alternative scenario with scalars:
Bodas, Kumar, Sundrum, 2010.04727

Chiral fermion

$$\mathcal{L} = \sqrt{-g}\left[\mathrm{i}\psi^\dagger \bar{\sigma}^\mu \mathrm{D}_\mu \psi - \frac{1}{2}m(\psi\psi + \psi^\dagger\psi^\dagger) + \frac{1}{\Lambda}(\partial_\mu \phi)\psi^\dagger \bar{\sigma}^\mu \psi\right]$$



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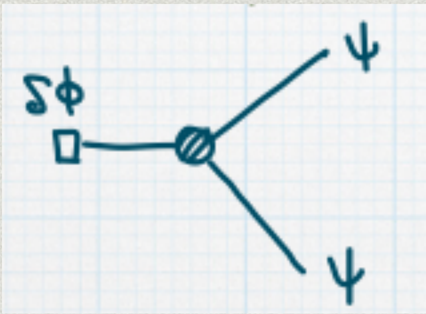

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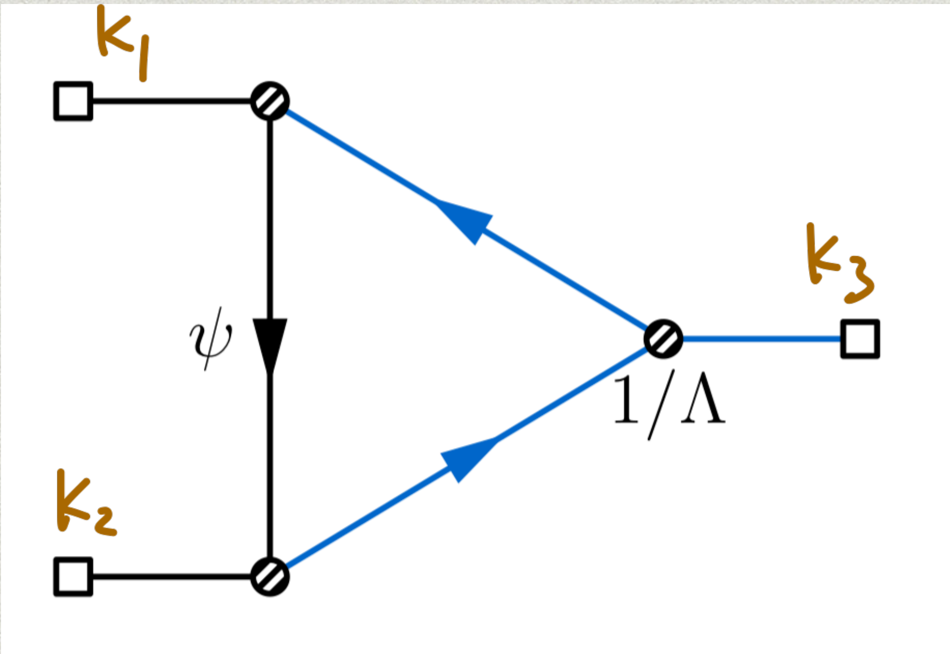
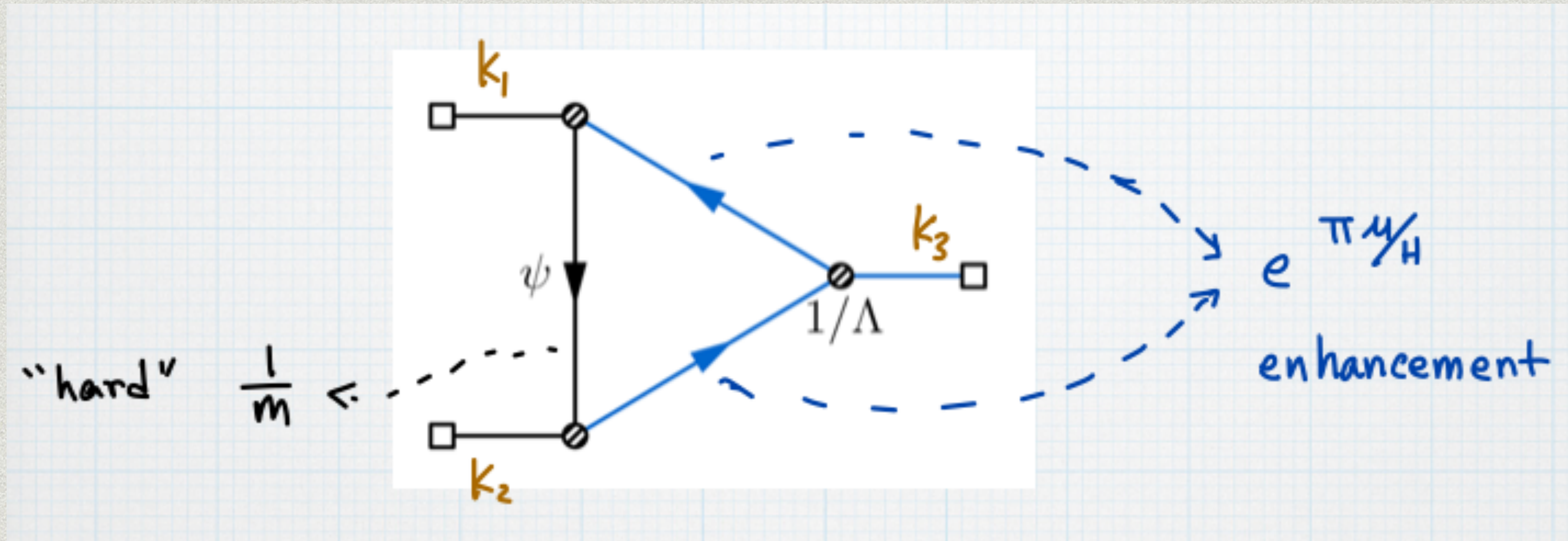




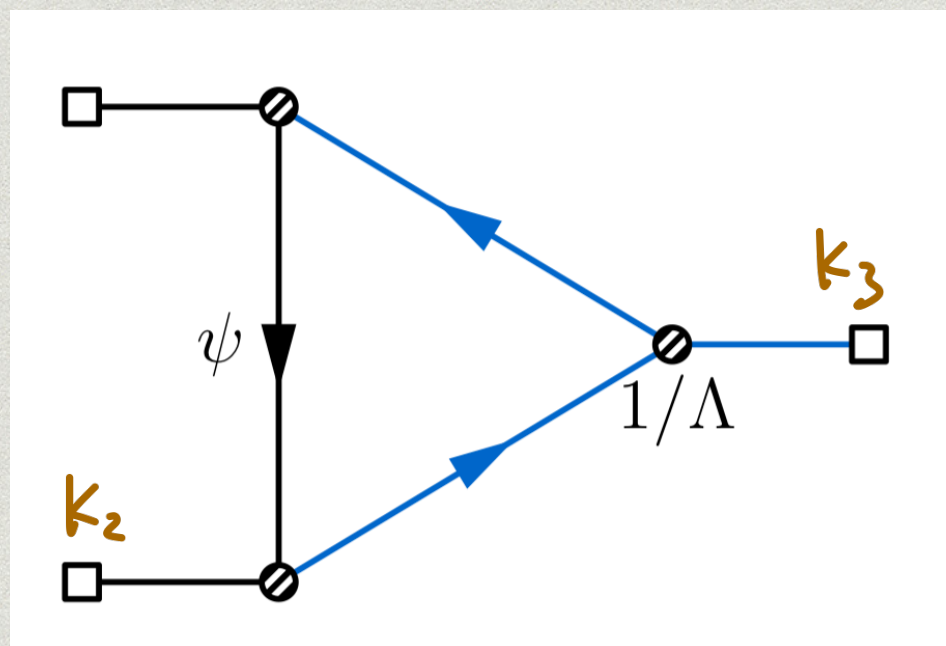
$$\exp(\pi\mu)\exp\left(-\frac{\pi}{H}\sqrt{m^2+\mu^2}\right) \simeq \exp\left(-\frac{\pi m^2}{2H\mu}\right) \sim O(1), \quad \text{for } \mu \gg m \gg H$$

No $e^{-m/H}$-like suppression!

Enhanced mode peaks in a region around $k_{\text{phys}} \sim \mu$, with size $\Delta k_{\text{phys}} \sim m$.

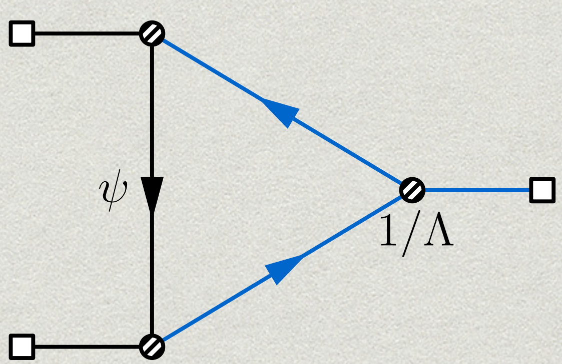
→ phase space = a shell with volume $4\pi\mu^2 m$

Putting it together:



Overall exp factor: $e^{-\pi m^2/\mu H}$

Phase space: $4\pi m\mu^2$

$f_{\rm NL}^{\rm (osc)}\Big($  $\Big) \sim \frac{1}{2\pi P_\zeta^{1/2}}\frac{1}{16\pi^2}\left(\frac{m}{\Lambda}\right)^3\frac{H}{m}\cdot 4\pi m\mu^2\cdot e^{-\pi m^2/(\mu H)}$

Signal can be large for $\mu > m > H$

General form of signal

analytic piece / "background part"

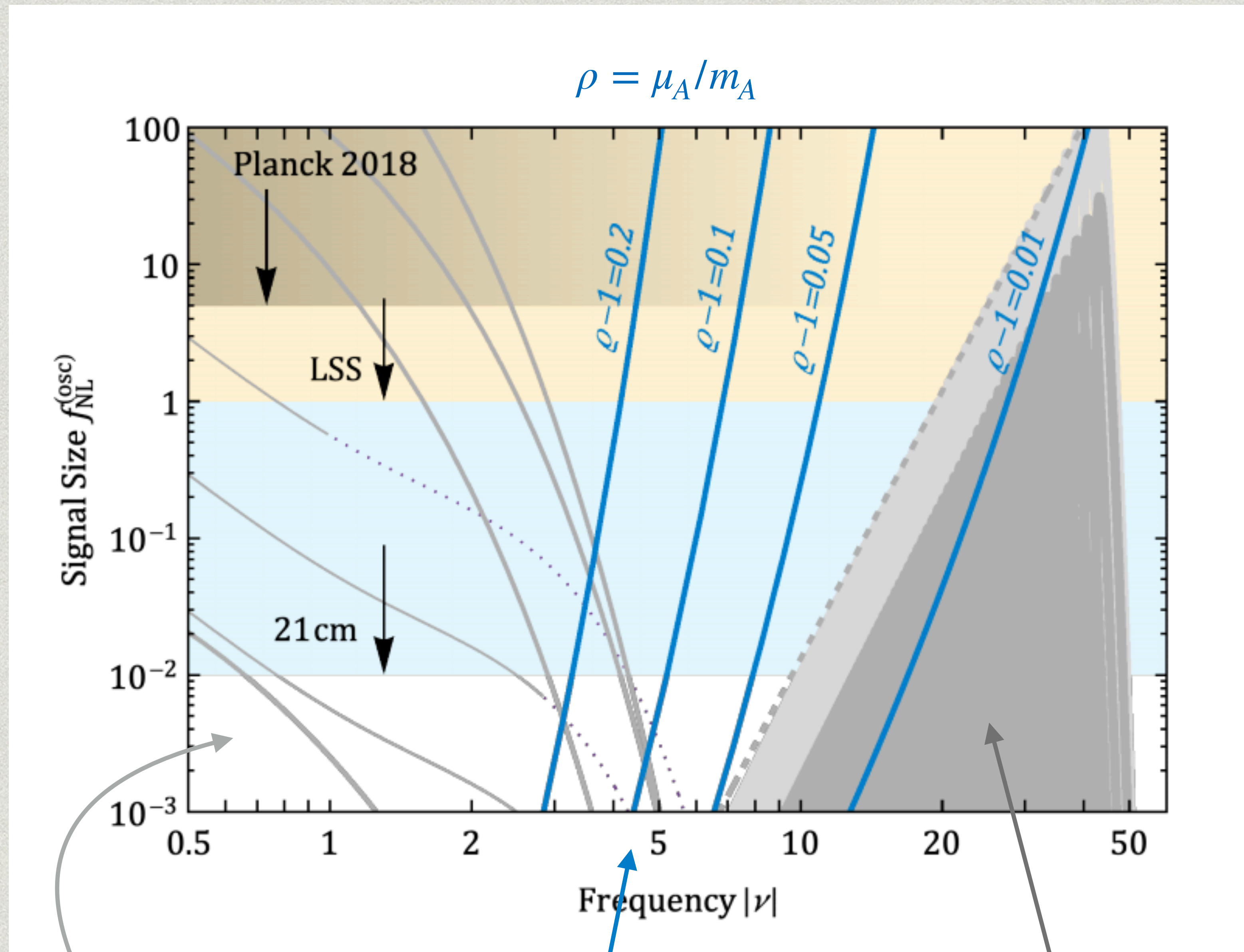
$$\mathcal{S} \approx A\left(\frac{k_1}{k_3}\right)^{-N} + B\left(\frac{k_1}{k_3}\right)^{-L}\sin\left(\omega\log\frac{k_1}{k_3}+\varphi\right)$$

nonanalytic piece / "signal part"

		B	L	ω
$s=0$, $m>\frac{3}{2}$, $\mu=0$ [7]	tree	$e^{-\pi m}$	$\frac{1}{2}$	$\sqrt{m^2-\frac{9}{4}}$
$s=0$, $0<m<\frac{3}{2}$, $\mu=0$ [7]	tree	–	$\frac{1}{2}-\sqrt{\frac{9}{4}-m^2}$	0
$s>0$, $m>s-\frac{1}{2}$, $\mu=0$ [13]	tree	$e^{-\pi m}$	$\frac{1}{2}$	$\sqrt{m^2-(s-\frac{1}{2})^2}$
$s>0$, $0<m<s-\frac{1}{2}$, $\mu=0$ [13]	tree	–	$\frac{1}{2}-\sqrt{(s-\frac{1}{2})^2-m^2}$	0
$s=0$, $m>\frac{3}{2}$, $\mu=0$ [7]	1-loop	$e^{-2\pi m}$	2	$2\sqrt{m^2-\frac{9}{4}}$
Dirac fermion, $m>0$, $\mu=0$ [8]	1-loop	$e^{-2\pi m}$	3	$2m$
Dirac fermion, $m>0$, $\mu>0$ [8]	1-loop	$e^{2\pi\mu-2\pi\sqrt{m^2+\mu^2}}$	2	$2\sqrt{m^2+\mu^2}$
$s=1$, $m>\frac{1}{2}$, $\mu\geq 0$ [10]	1-loop	$e^{2\pi\mu-2\pi m}$	2	$2\sqrt{m^2-\frac{1}{4}}$

With μ enhancement

Zhong-Zhi Xianyu and LTW. 1910.12876, 2004.02887



$$\nu_{\rm scalar} = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

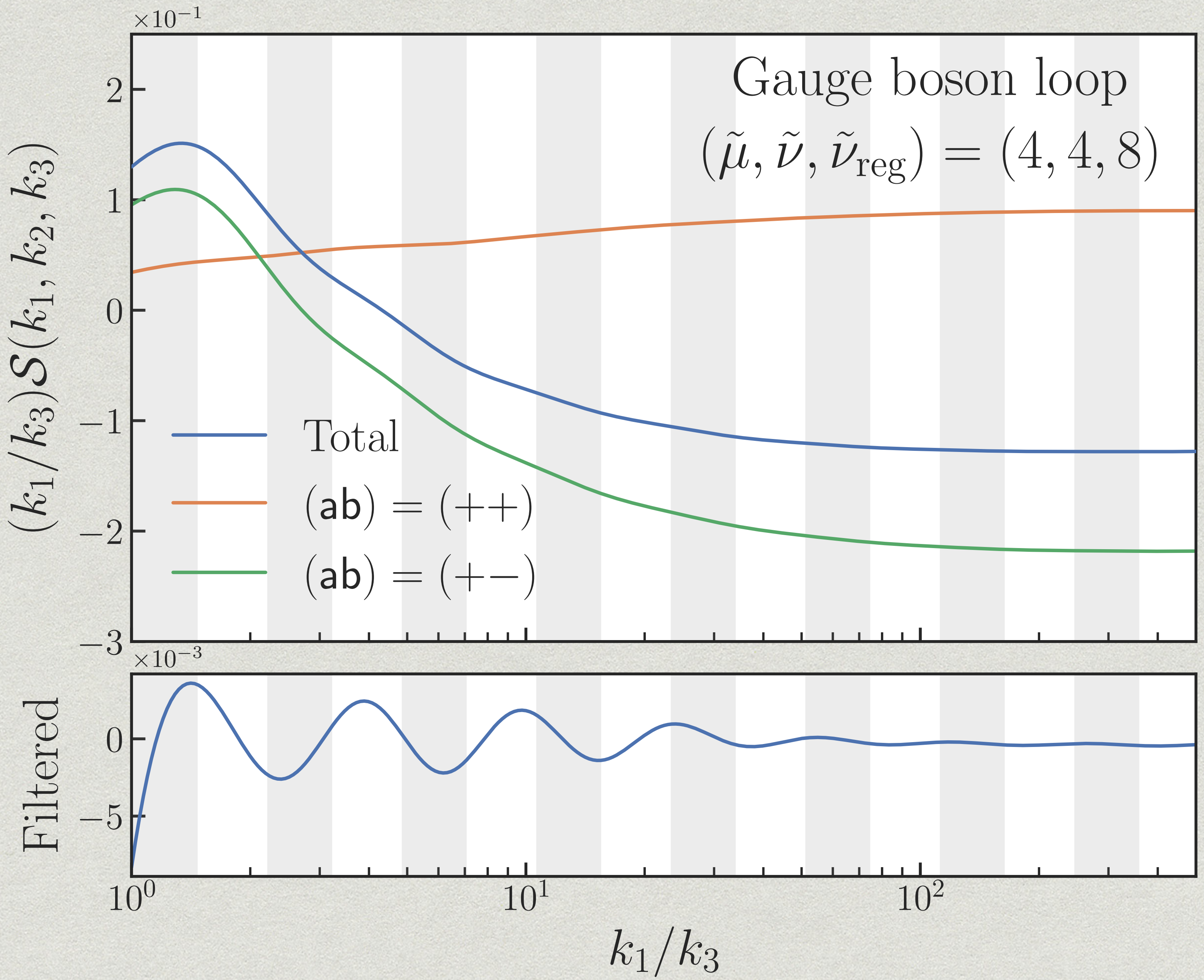
$$\nu_{\rm vector} = \sqrt{\frac{1}{4} - \frac{m^2}{H^2}}$$

$$\nu_{\rm fermion} = \frac{1}{H}\sqrt{m^2 + \mu^2}$$

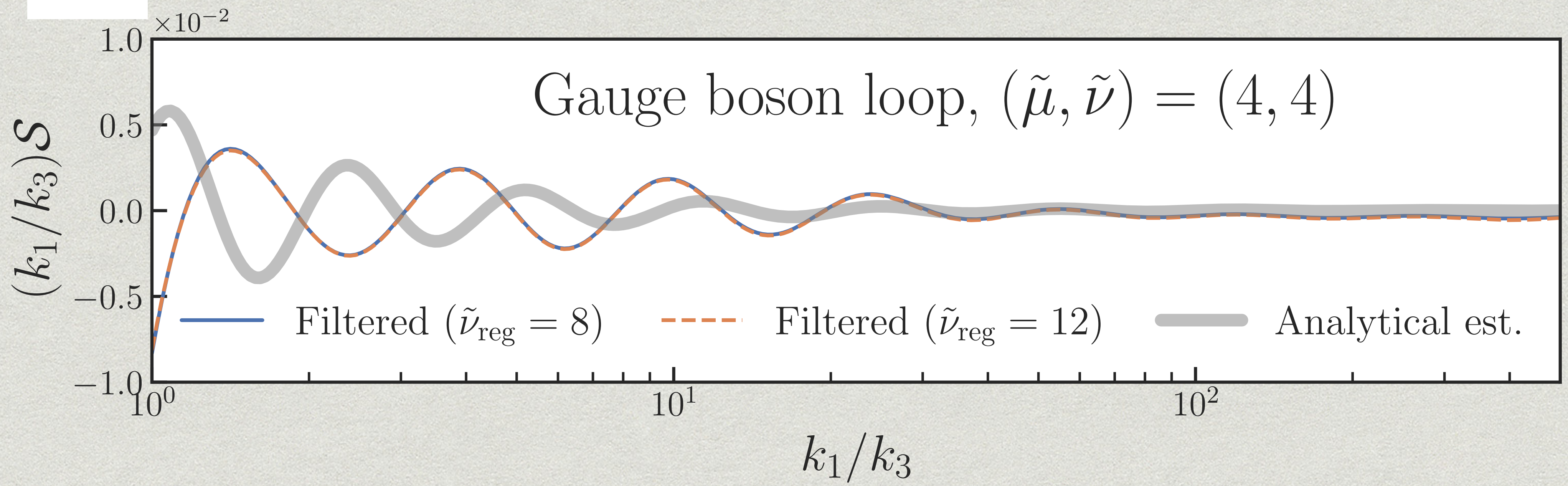
dim-6

Full numerical calculation

Zhong-Zhi Xianyu, Yiming Zhong, and LTW. 2109.14635



Comparing with analytic est.



- Good agreement for $k_1/k_3 > 20$.
- Some shift in frequency for lower k_1/k_3

This talk

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- Drama in the spectator sector, signal of a first order phase transition during the inflation.

The excursion of the inflaton

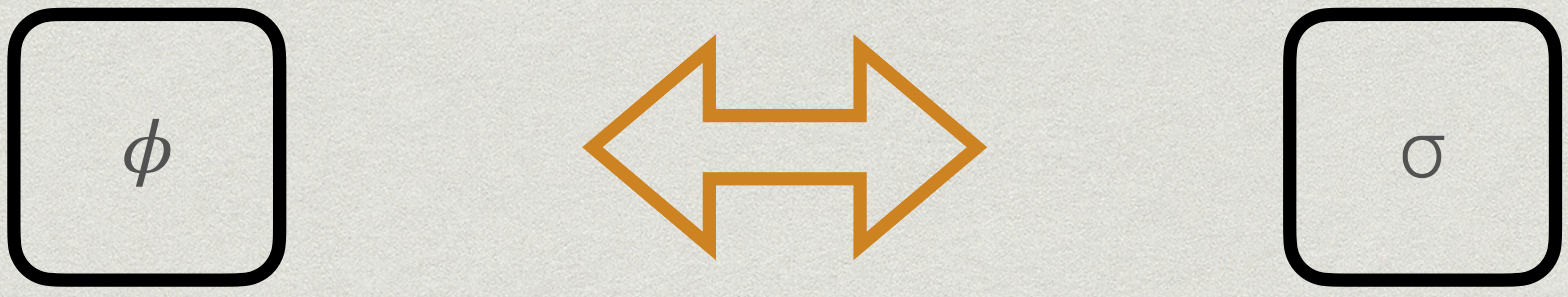
$$\Delta\phi \sim N_{\text{efold}}\sqrt{\epsilon}M_{\text{Planck}}$$

Large excursion of the inflaton field plausible, even if we restrict ourselves to the case where $\Delta\phi < M_{\text{Planck}}$

This is the case even for a small part of inflation with $N_{\text{efold}} \approx O(1)$

Any physics/observable effect?

Example: Inflaton + spectator



Inflation sector
Single field slow roll…

Spectator, less energy,
not driving spacetime evolution

Suppose the coupling is weak, suppressed by some high scale M $\sim \phi \sim \Delta\phi$

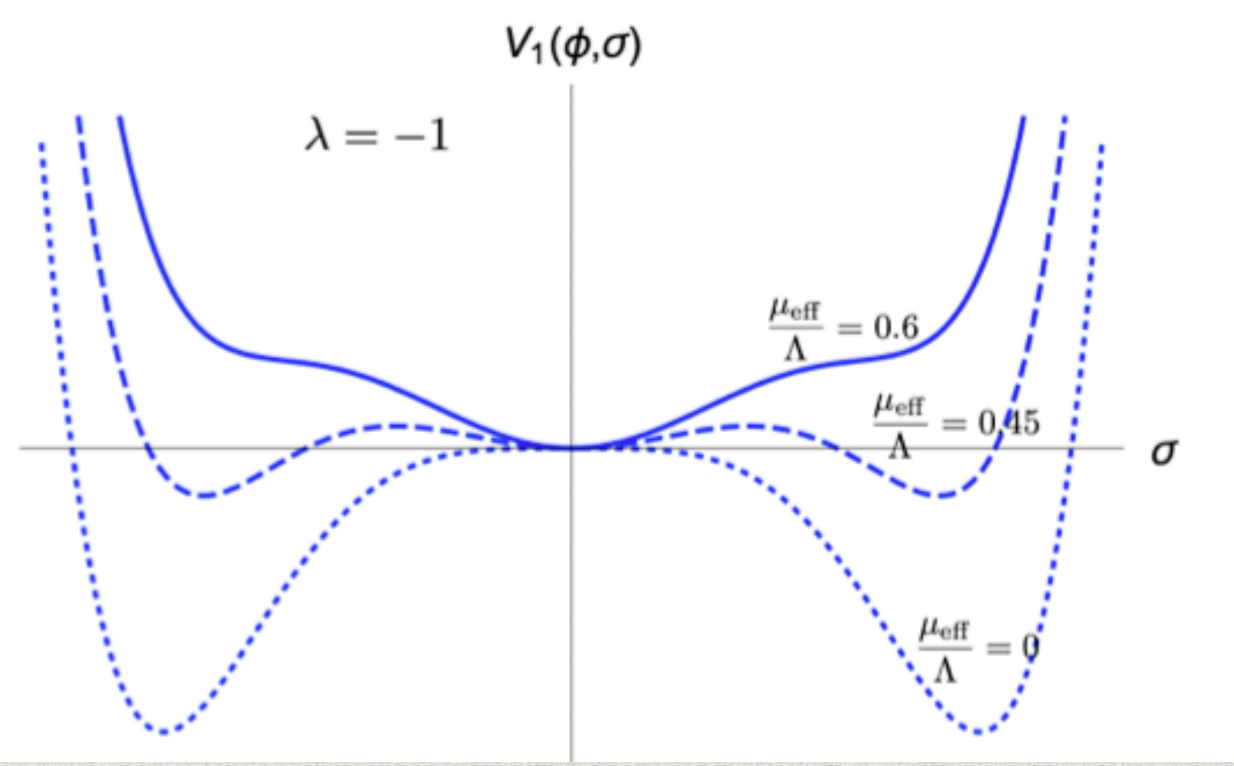
For example: $f\left(\frac{\phi}{M}\right) m_\sigma^2 \sigma^2, \quad g\left(\frac{\phi}{M}\right) b\sigma^4,$ etc.

Field excursion of inflaton can change the mass and couplings in the spectator sector, leading to interesting dynamics.

For example

$$V(\phi,\sigma) = \frac{1}{2}\mu_{\rm eff}^2 + \frac{\lambda}{4}\sigma^4 + \frac{1}{8\Lambda^2}\sigma^6 + V_{\rm inf}(\phi), \quad \mu_{\rm eff}^2 = -\left(m_\sigma^2 - c^2\phi^2\right)$$

$$c^2 \sim \frac{m_\sigma^2}{M^2} \ll 1$$

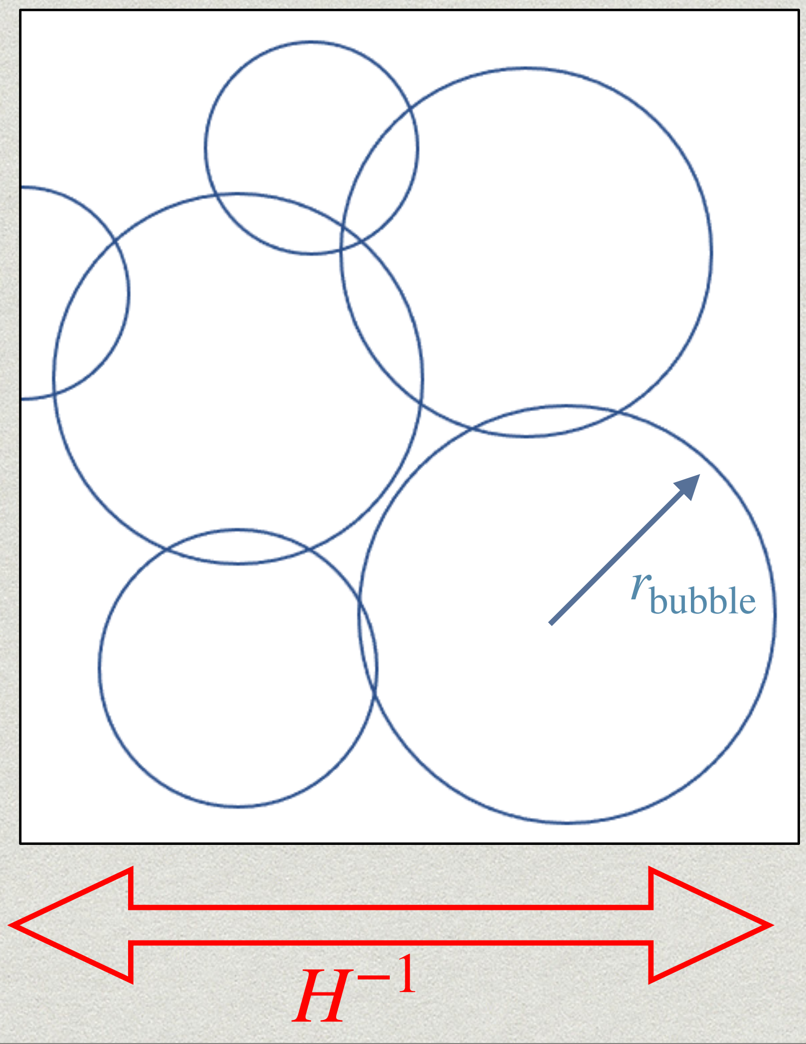


Rolling inflaton → (1st order?) phase transition in the spectator sector

1st order phase transition

Phase transition is 1st order, and spectator sector does not dominate energy density:

$$H^4 \ll m_\sigma^4 \ll 3M_{\rm Pl}^2 H^2$$ This is possible to arrange.

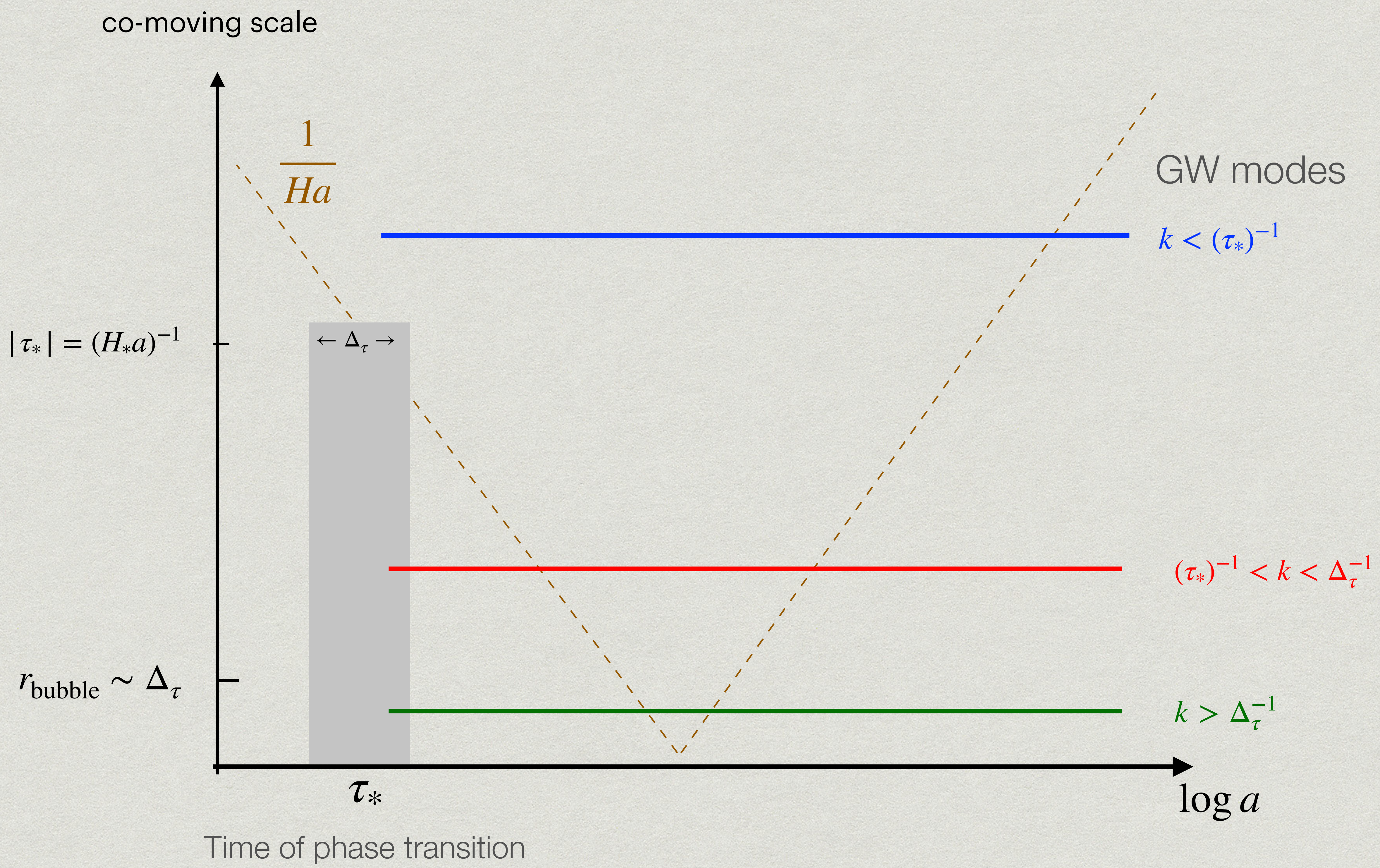


$$r_{\rm bubble} \ll H^{-1}$$

$$t_{\text{bubble collision}} \sim r_{\rm bubble} \ll H^{-1}$$

An instantaneous source of GW.

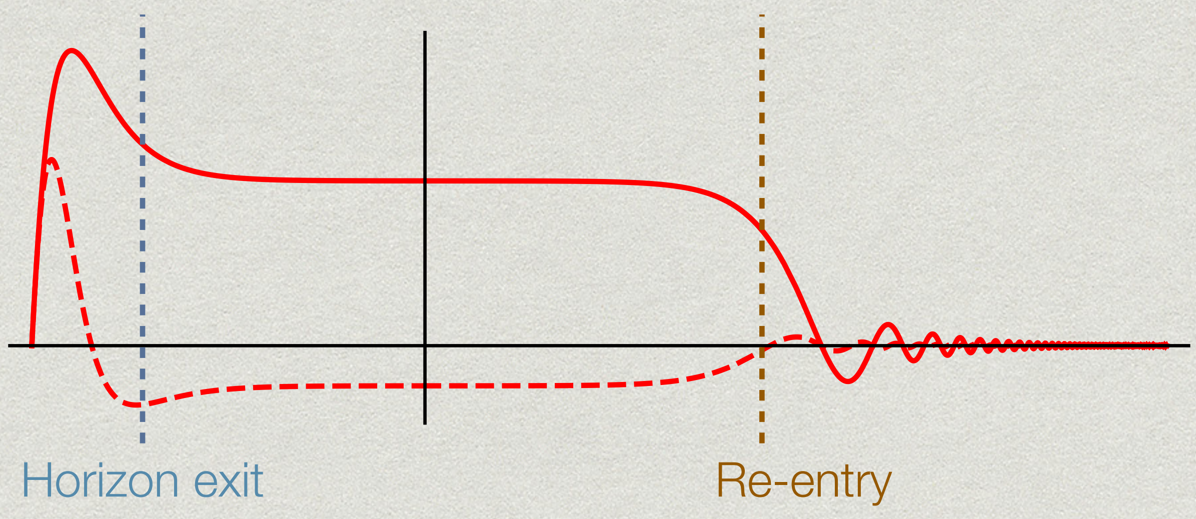
GW in three regimes



GW signal

$$h''_{ij} + \frac{2a'}{a} h'_{ij} - \nabla^2 h_{ij} = 16\pi G_N a^2 \sigma_{ij}$$

$$\tau_*^{-1} < k < \Delta_\tau^{-1}$$



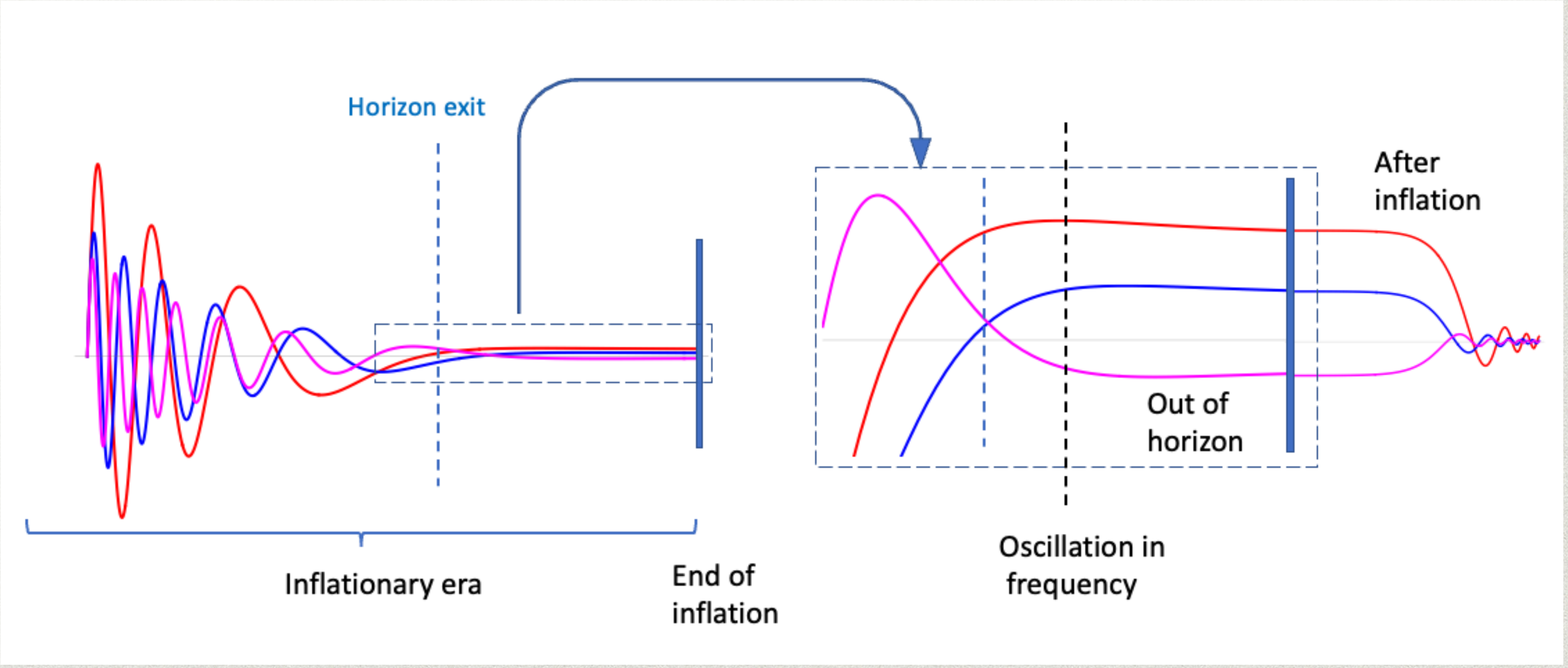
During inflation:

Mode starts inside horizon, oscillates till horizon exit.
➡ Amplitude depends on k.
➡ Leads to oscillatory pattern in frequency.

After reheating, modes re-enter the horizon

Oscillations

$$\tau_*^{-1} < k < \Delta_\tau^{-1}$$



GW signal

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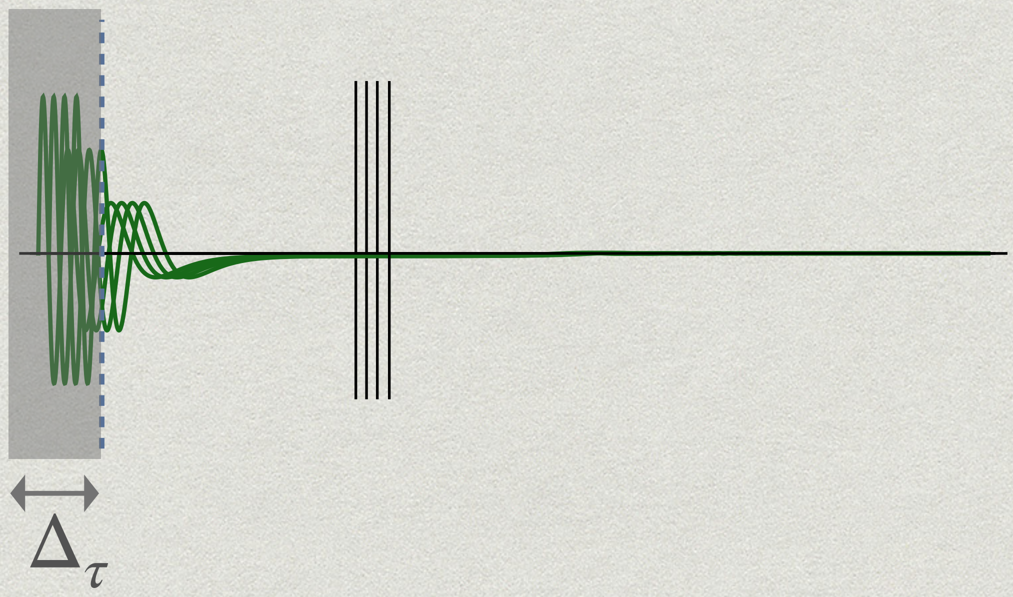
$k > \Delta_\tau^{-1}$



Time scale of bubble collision $\approx \Delta_\tau$.

Oscillation pattern in frequency smeared out in this regime.

GW signal

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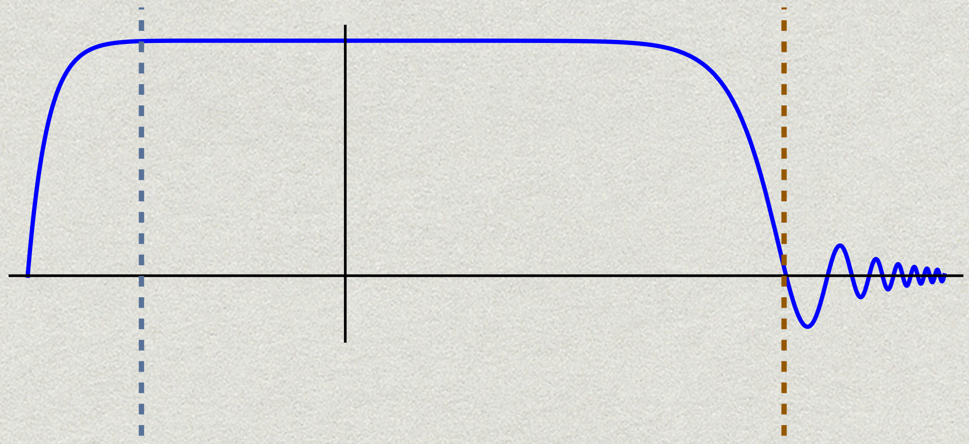
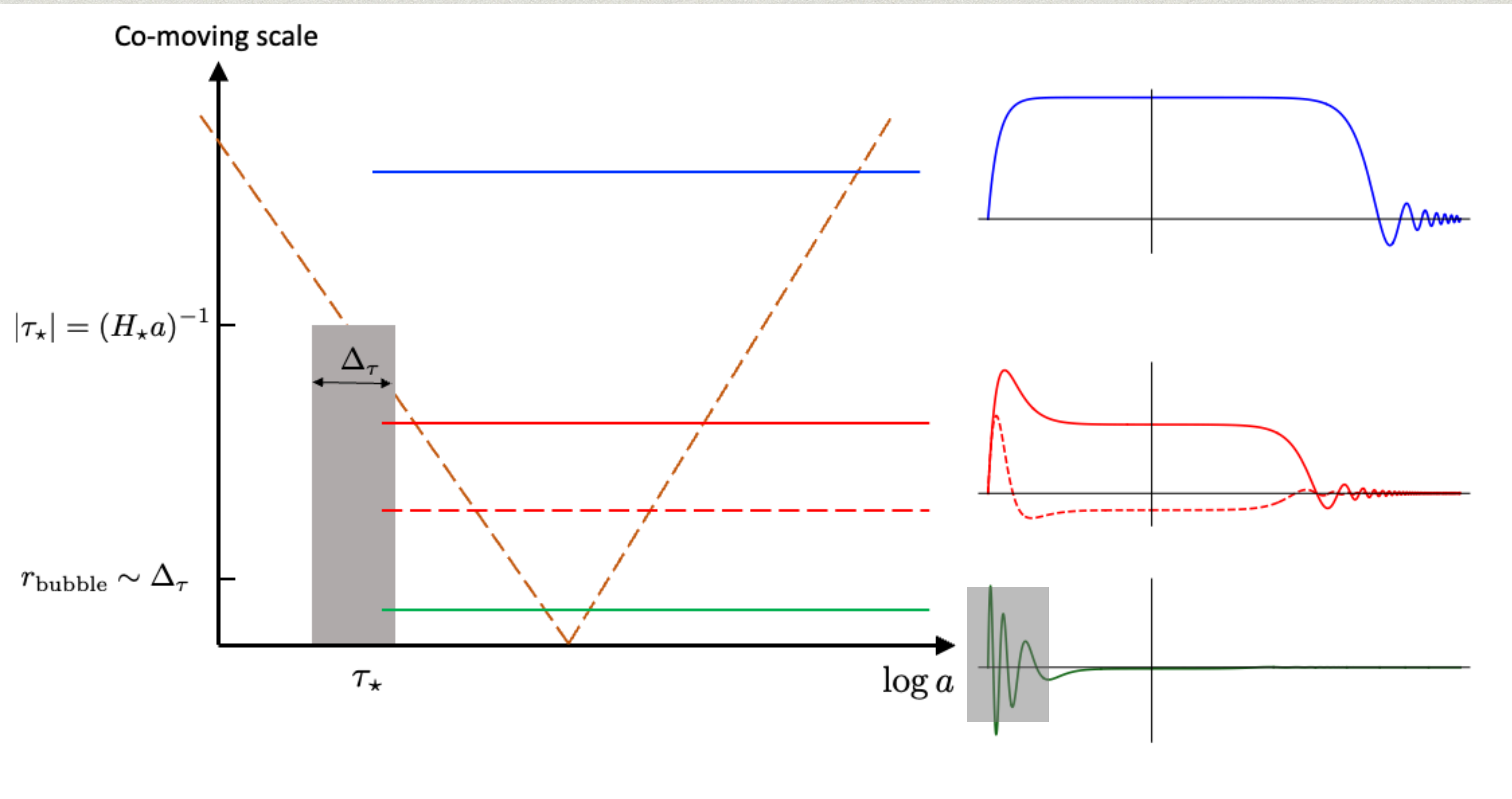
$k < \tau_*$

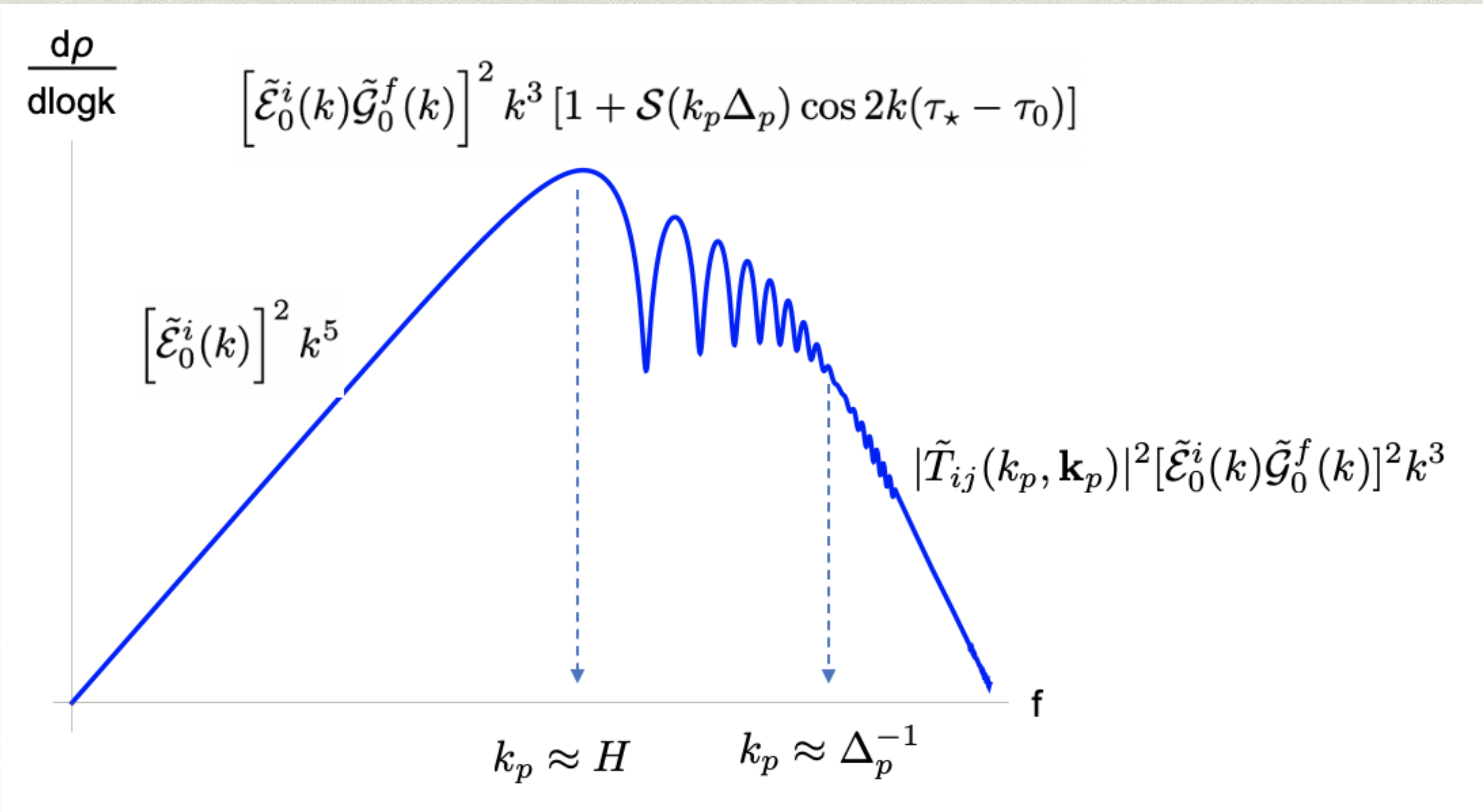


Mode outside horizon at the time of phase transition

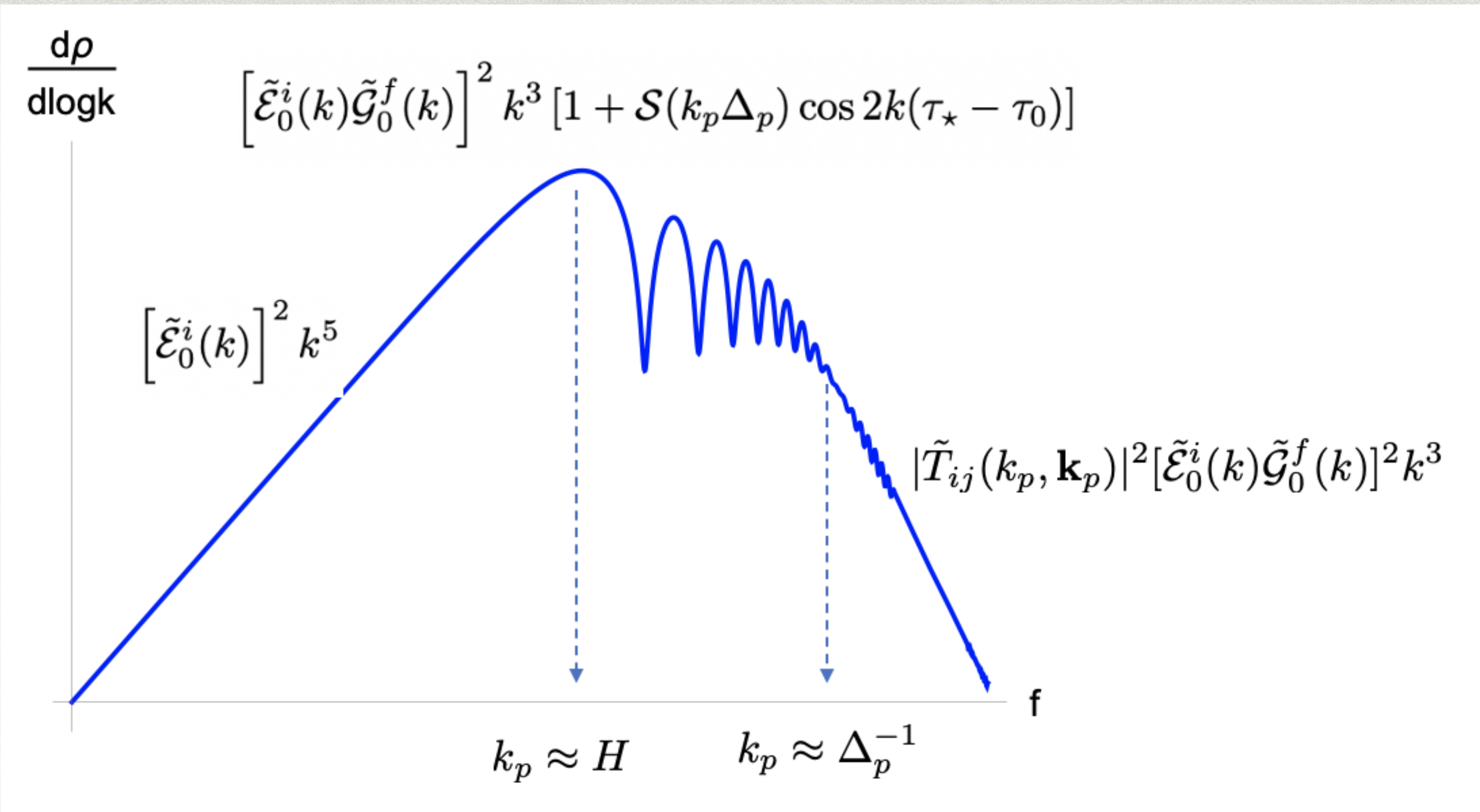
No oscillation. Can treat the GW as if it is from a point source.



Co-moving scale
$|\tau_\star| = (H_\star a)^{-1}$
Δ_τ
$r_{\rm bubble} \sim \Delta_\tau$
$\tau_\star$
$\log a$



$$\frac{d\rho_{\rm GW}^{\rm osc}}{d\log k}=\frac{2G_N|\tilde{T}_{ij}(0,0)|^2}{\pi V a^4(\tau)a^2(\tau_\star)}\left\{\left[\tilde{\mathcal{E}}_0^i(k)\tilde{\mathcal{G}}_0^f(k)\right]^2 k^3\left[1+\mathcal{S}(k\Delta_\tau)\cos 2k(\tau_\star-\tau_0)\right]\right\}$$



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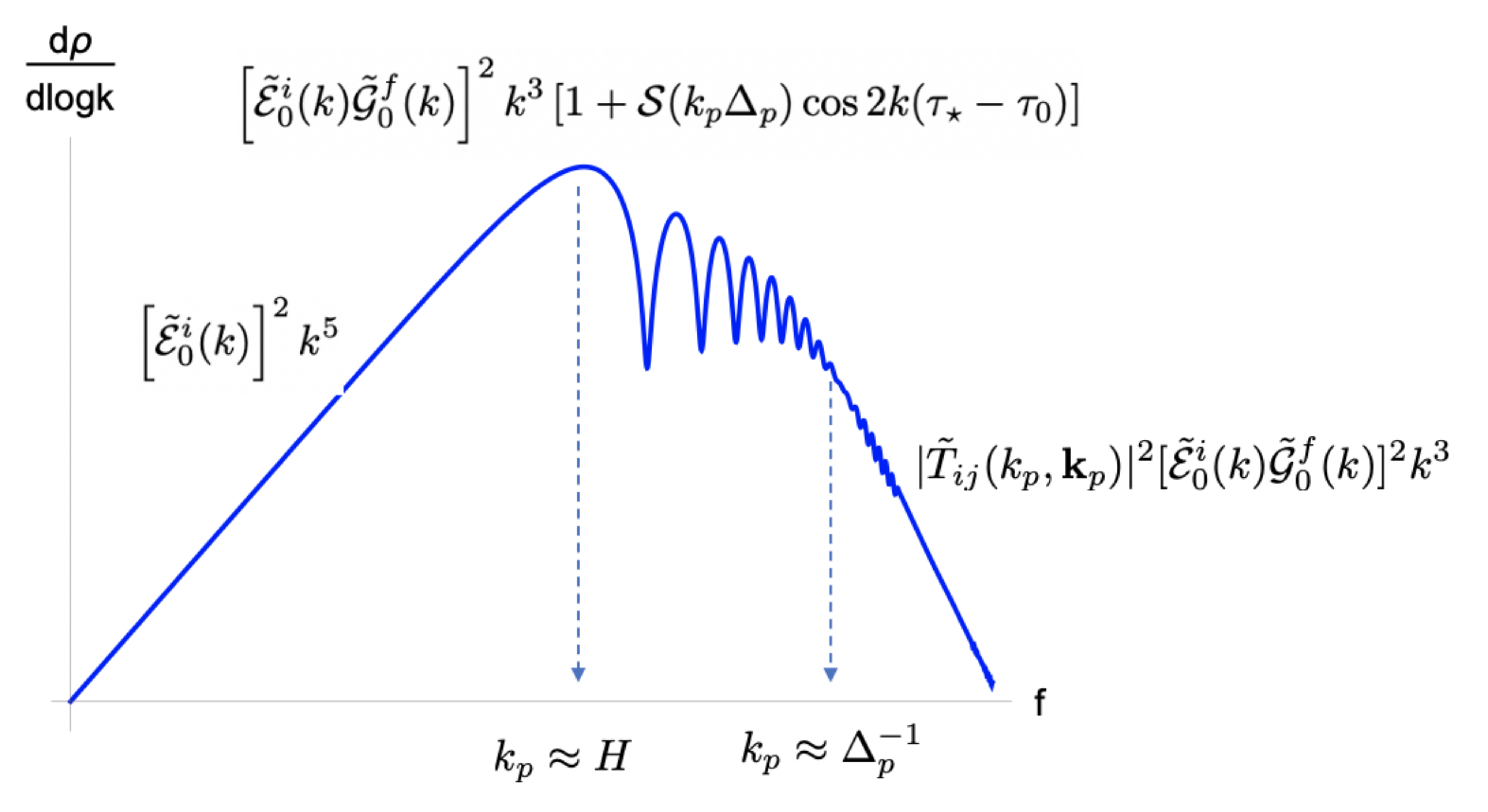
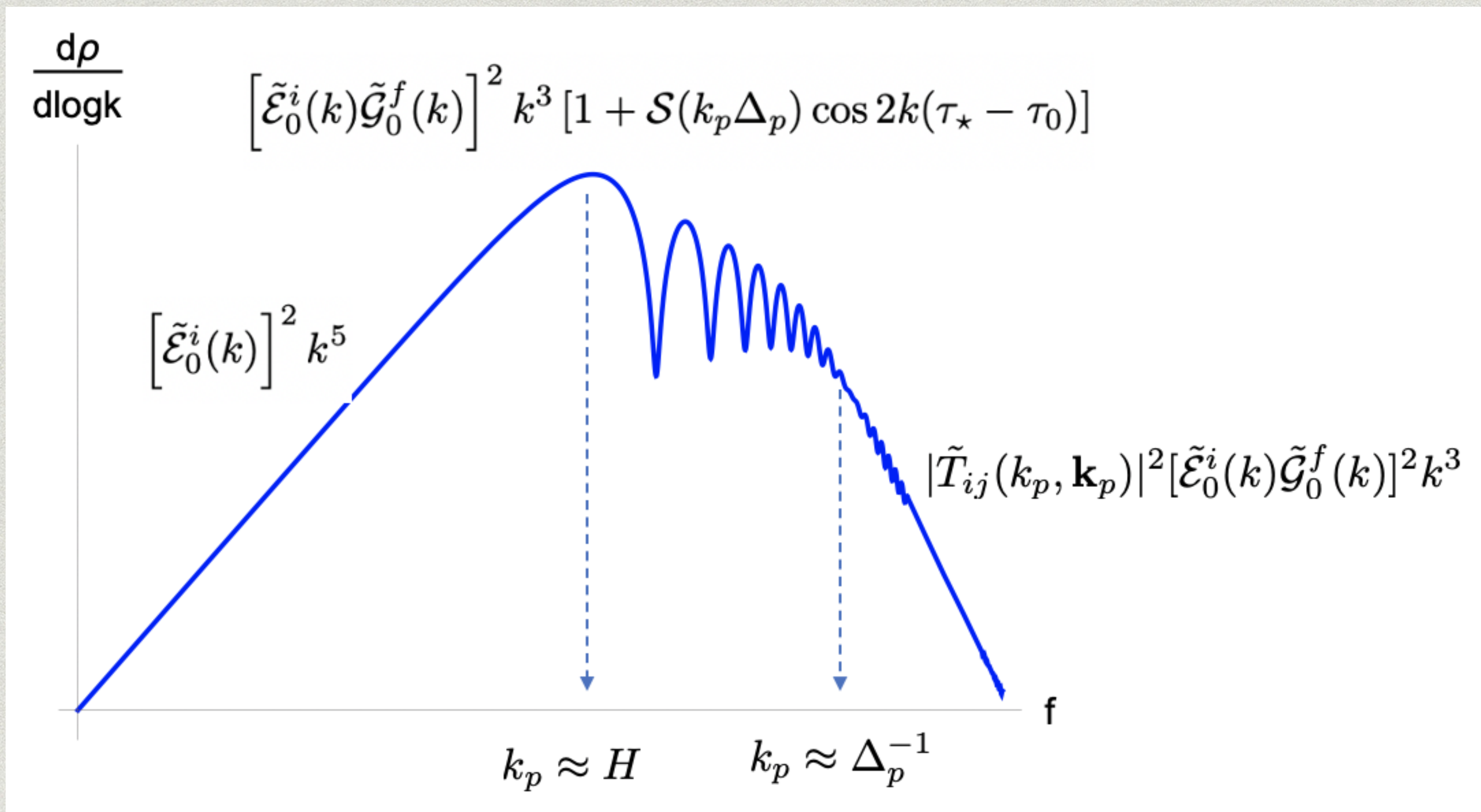
Oscillation



$$\frac{d\rho_{\rm GW}^{\rm osc}}{d\log k}=\frac{2G_N|\tilde{T}_{ij}(0,0)|^2}{\pi V a^4(\tau)a^2(\tau_\star)}\left\{\left[\tilde{\mathcal{E}}_0^i(k)\tilde{\mathcal{G}}_0^f(k)\right]^2 k^3\left[1+\mathcal{S}(k\Delta_\tau)\cos 2k(\tau_\star-\tau_0)\right]\right\}$$

Smearing for $k\boldsymbol{\Delta_\tau} \gg 1$

Oscillation



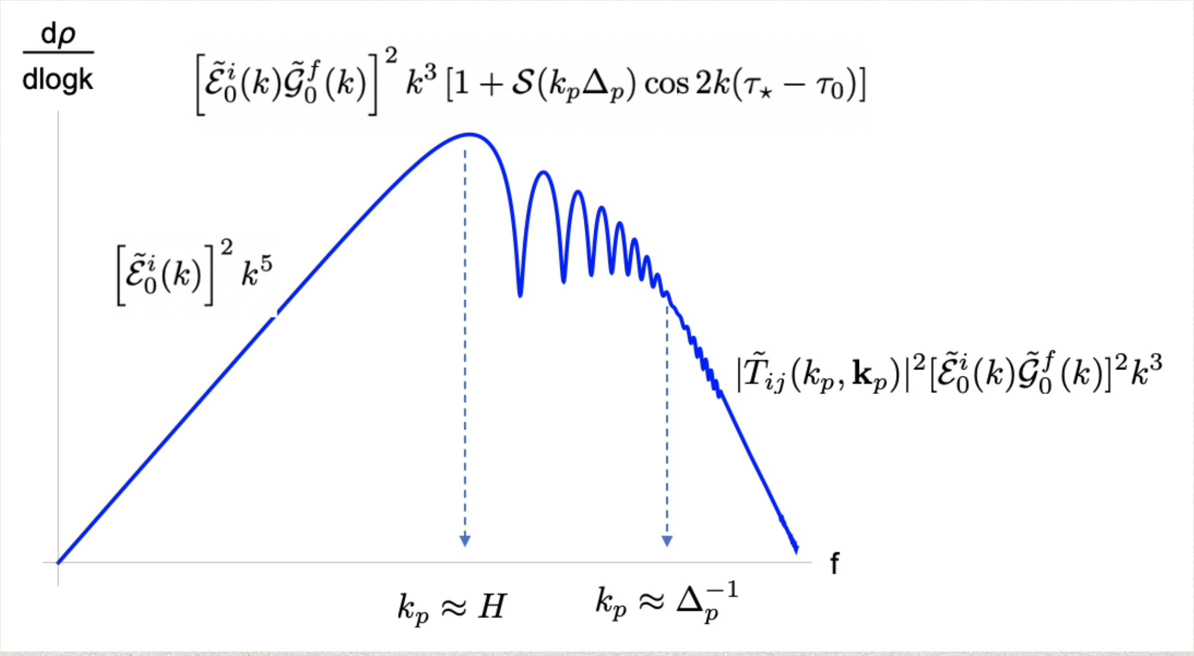
$$\frac{d\rho_{\rm GW}^{\rm osc}}{d\log k} = \frac{2G_N|\tilde{T}_{ij}(0,0)|^2}{\pi V a^4(\tau)a^2(\tau_\star)}\left\{\left[\tilde{\mathcal{E}}_0^i(k)\tilde{\mathcal{G}}_0^f(k)\right]^2 k^3\left[1+\mathcal{S}(k\Delta_\tau)\cos 2k(\tau_\star-\tau_0)\right]\right\}$$

Depending on Time evolution

Smearing for $k\boldsymbol{\Delta}_\tau \gg 1$

Oscillation

Dependence on later evolution



$\tilde{\mathcal{G}}_0^f(k)$ Depends on the evolution of the background spacetime during inflation

$\tilde{\mathcal{E}}_0^i(k)$ Depends on the evolution of the background spacetime after inflation

Alternative scenarios can change the shape of the GW signal!

Scenarios of inflation and its aftermath

Scenarios of inflation

Quasi de Sitter: $a(\tau) = -\frac{1}{H\tau}$

Power law: $a(t) = a_0(t/t_0)^p$

Lucchin and Matarrese, 1985

p→∞, quasi de Sitter

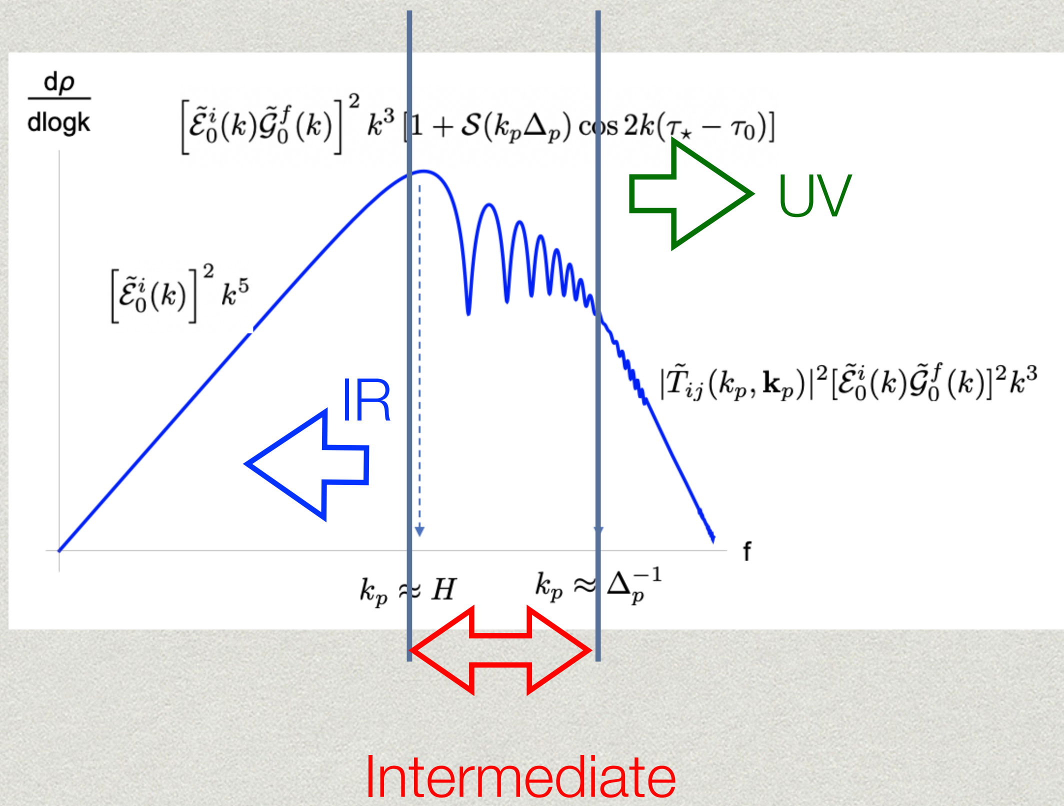
Scenarios after inflation:

Parameterized as

$a(t) \sim t^{\tilde{p}}$

	w	$\rho(a)$	$\tilde{p}$	$\tilde{\alpha}$
MD	0	a^{-3}	2/3	-3/2
RD	1/3	a^{-4}	1/2	-1/2
Λ	-1	a^0	∞	3/2
Cosmic string	-1/3	a^{-2}	1	∞
Domain wall	-2/3	a^{-1}	2	5/2
kination	1	a^{-6}	1/3	0

Impact on spectrum



UV

	RD	MD	$t^{\tilde{p}}$
dS	k^{-5}	k^{-7}	$k^{-3+2\frac{\tilde{p}}{\tilde{p}-1}}$
t^p	$k^{-3+2\frac{p}{1-p}}$	$k^{-5+2\frac{p}{1-p}}$	$k^{-1+2\left(\frac{p}{1-p}+\frac{\tilde{p}}{\tilde{p}-1}\right)}$

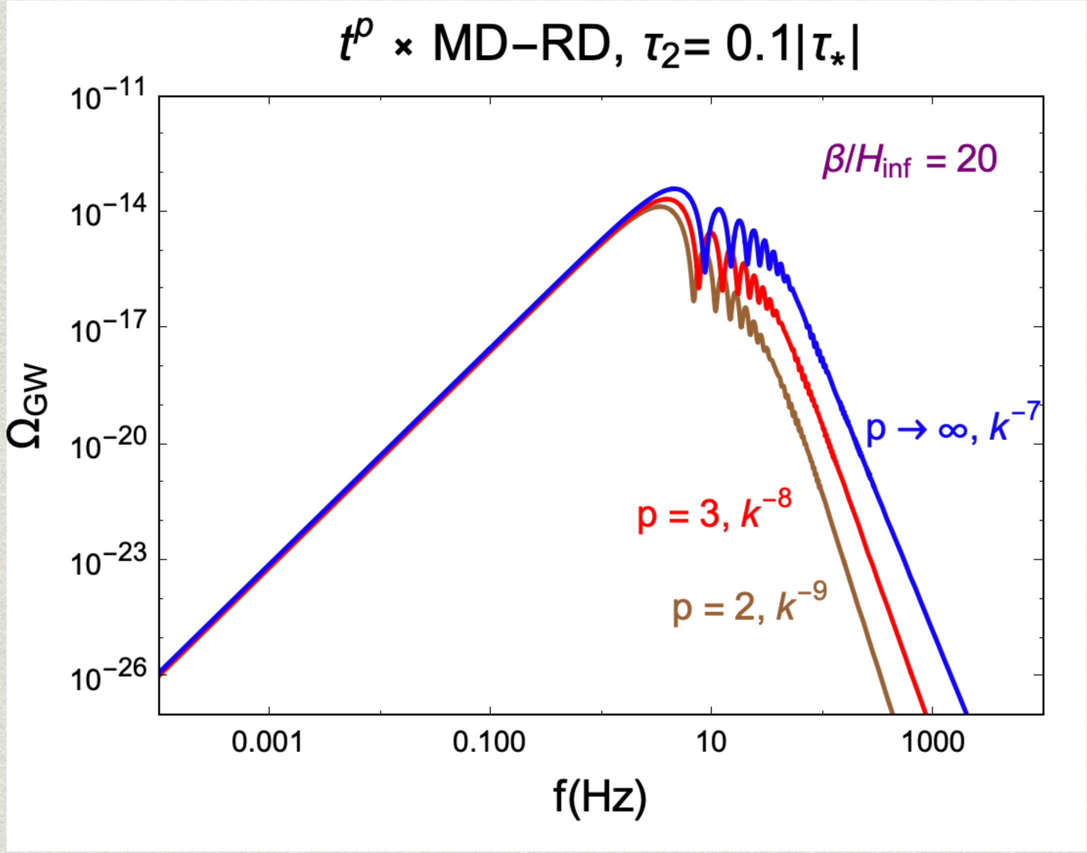
Intermediate

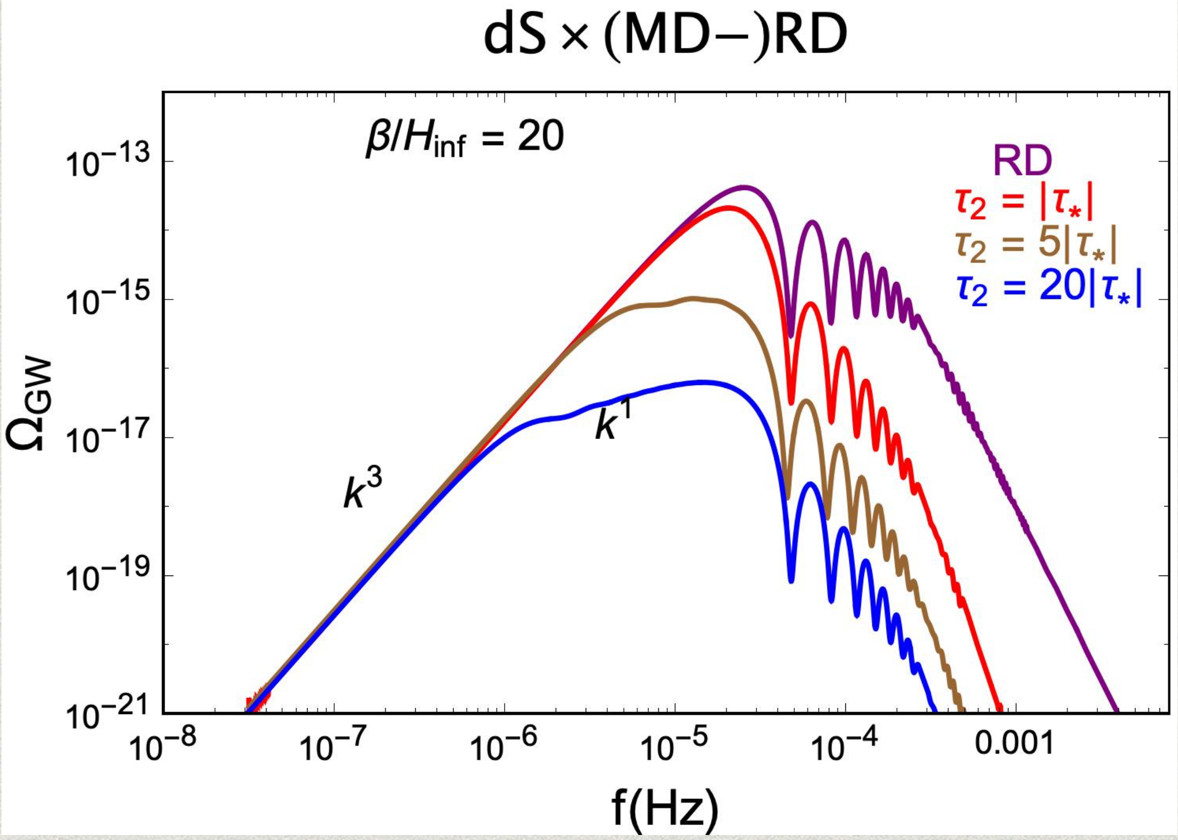
	RD	MD	$t^{\tilde{p}}$
dS	k^{-1}	k^{-3}	$k^{1+2\frac{\tilde{p}}{\tilde{p}-1}}$
t^p	$k^{1+2\frac{p}{1-p}}$	$k^{-1+2\frac{p}{1-p}}$	$k^{3+2\left(\frac{p}{1-p}+\frac{\tilde{p}}{\tilde{p}-1}\right)}$

IR

	RD	MD	$t^{\tilde{p}}$
dS	k^3	k^1	$k^{5+2\frac{\tilde{p}}{\tilde{p}-1}}$
t^p	k^3	k^1	$k^{5+2\frac{\tilde{p}}{\tilde{p}-1}}$

Comparing scenarios





Different inflationary scenarios.
→ different slope in UV part.

Scenarios after reheating.

τ_2 = MD-RD transition

Conclusions

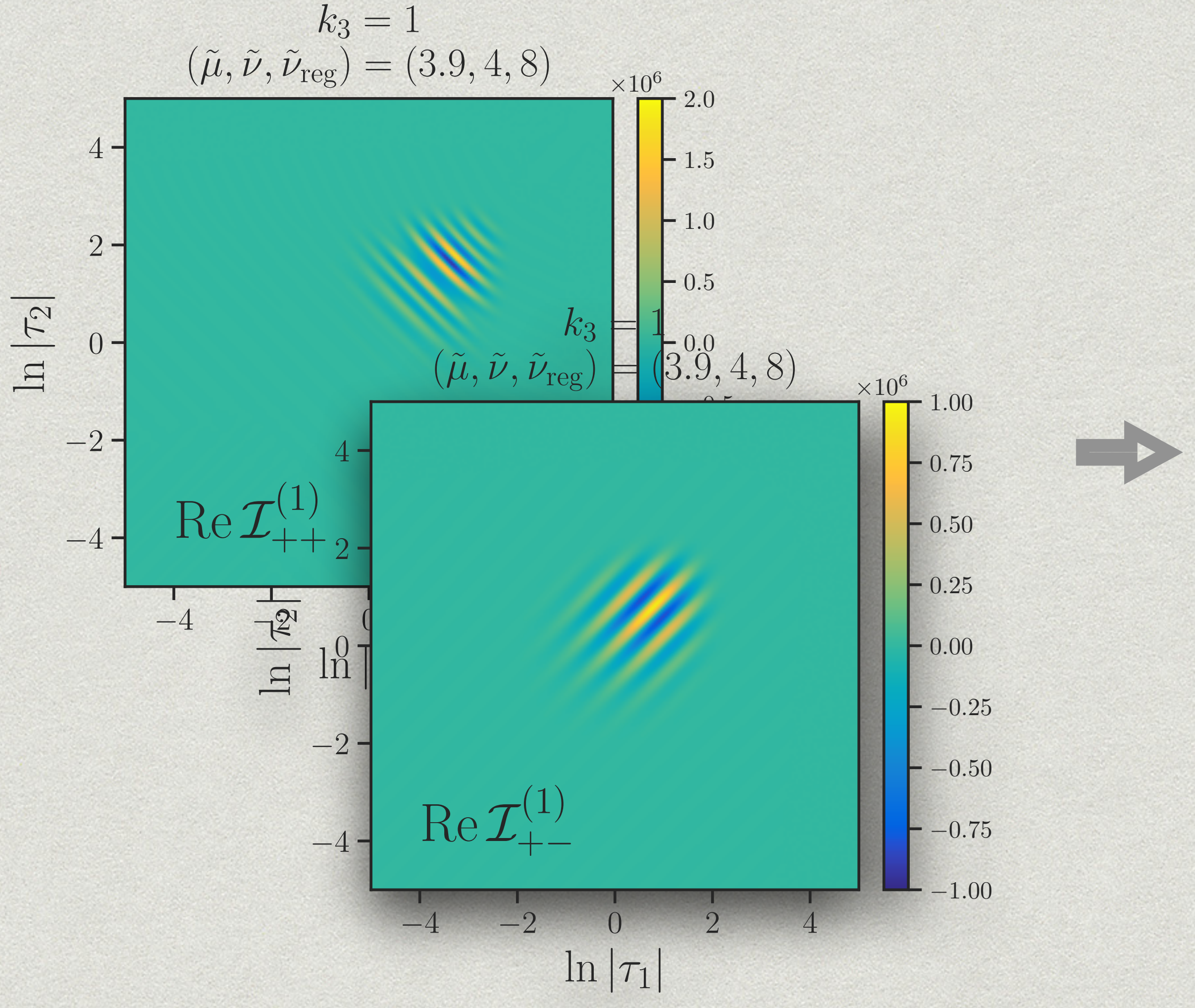
- Cosmological observations can reveal new dynamics in the inflationary era.
- Production of new particles with $m \sim H$ leads to distinct signals.
  - Non-derivative coupling does not lead to large signal due to correction to the mass of new particle
  - Well motivated derivative couplings → observable signals.

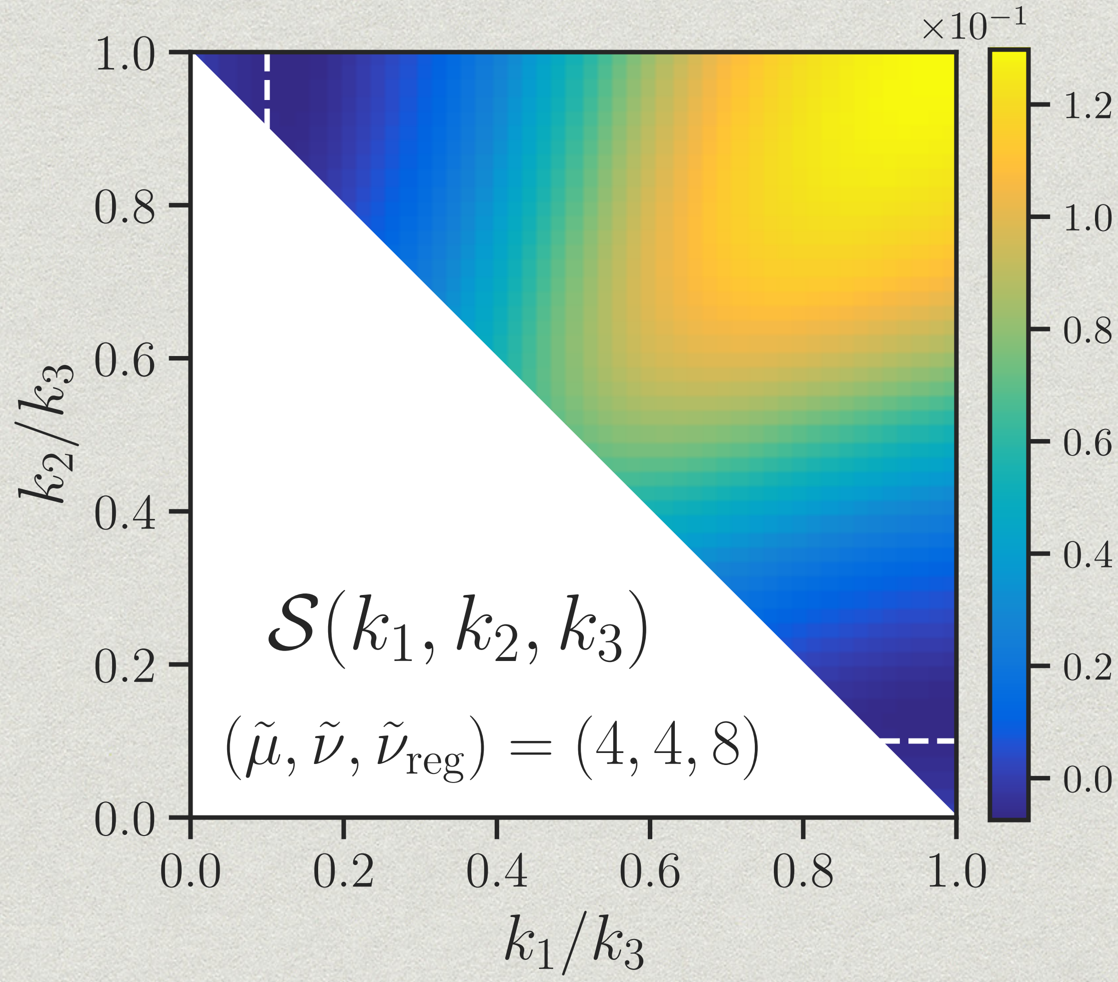
Conclusions

- Cosmological observations can reveal new dynamics in the inflationary era.
- Potentially large inflaton excursion can trigger new dynamics in a spectator sector.
  - Can trigger 1st order phase transition → GW.
  - Can probe an era invisible from CMB/LSS observables.

Extra

More general configuration





2. Derivative coupling

Dim-6 (quasi single field):

$$\mathcal{L} \supset \frac{c_6}{\Lambda^2}(\partial\phi)^2 Q^\dagger Q - m_Q^2 Q^\dagger Q - \lambda_Q |Q|^4$$

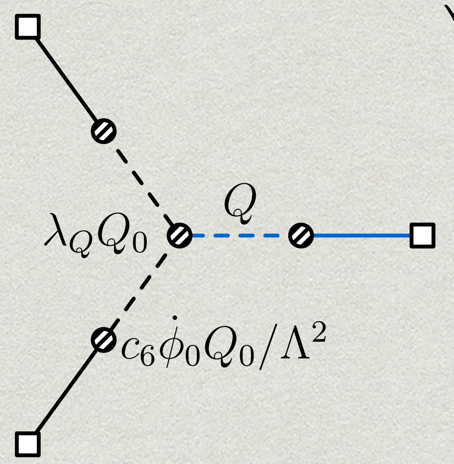
Validity of EFT in inflationary background: $\Lambda^2 > \dot{\phi}_0$

$\dot{\phi}_0 \neq 0$ contributes to the mass of Q. To avoid fine tuning:

$$\mathrm{Max}\left\{ m_Q^2,\ \lambda_Q Q_0^2,\ \delta m_Q^2 = c_6 \left(\frac{\dot{\phi}_0}{\Lambda}\right)^2 \right\} \lesssim H^2 \qquad \frac{c_6}{\Lambda^2} \lesssim \frac{H^2}{\dot{\phi}_0^2} = \frac{(2\pi)^2 P_\zeta}{H^2}$$

2. Derivative coupling

$f_{\rm NL}^{\rm (osc)}$

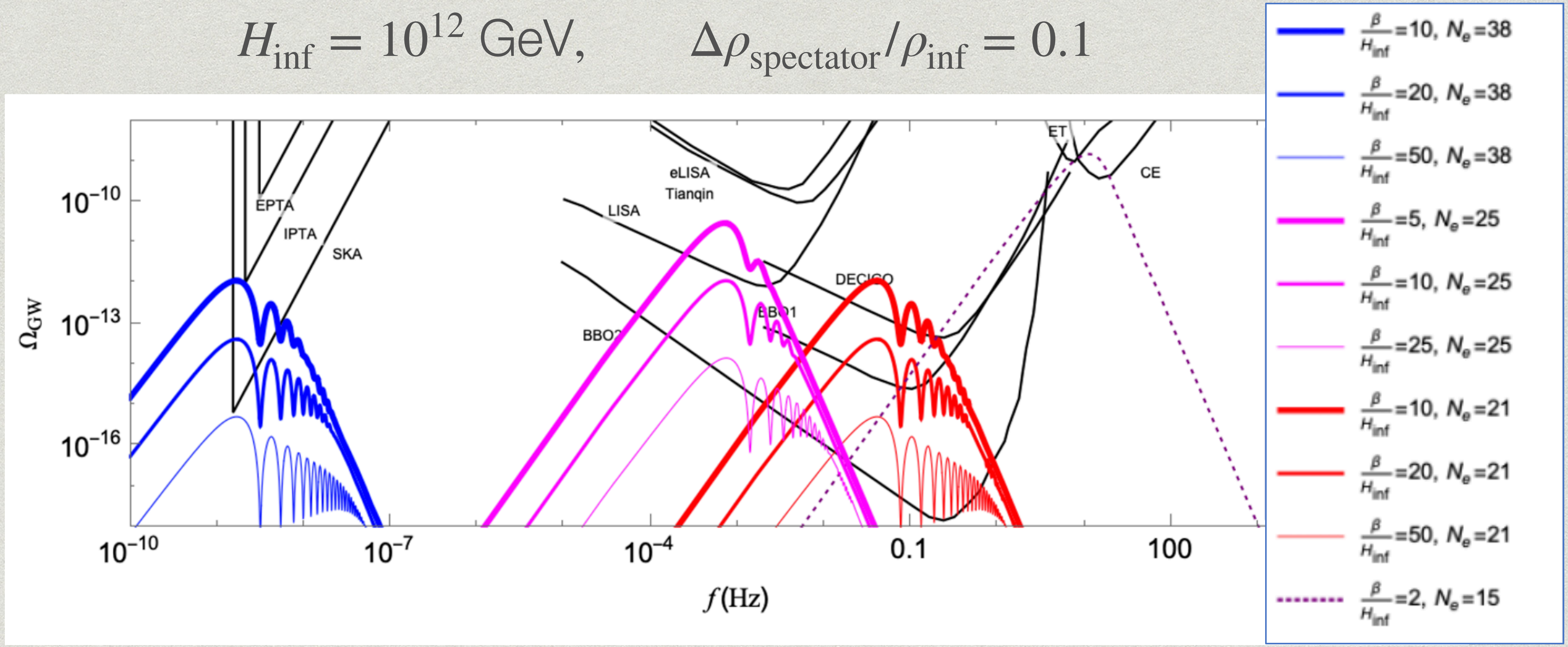


$$\sim \frac{1}{2\pi P_\zeta^{1/2}}\left(\frac{c_6}{\Lambda^2}\dot{\phi}_0 Q_0\right)^3 \lambda_Q Q_0 \frac{1}{H^4} \lesssim \lambda_Q^{-1}(2\pi)^2 P_\zeta$$

Can be sizable (O(1)) if $\lambda_Q \sim (2\pi)^2 P_\zeta \simeq 8\times 10^{-8}$

Observing the signal

$H_{\text{inf}} = 10^{12}$ GeV, $\Delta\rho_{\text{spectator}}/\rho_{\text{inf}} = 0.1$



N_e: efold till the end of inflation = time of the phase transition

1st order phase transition during inflation

Bubble nucleation rate: $\frac{\Gamma}{V} \simeq m_\sigma^4 e^{-S_4}$

Efficient phase transition:

$$\int_{-\infty}^{t} dt' \frac{\Gamma}{V}\frac{1}{H^3} \simeq O(1) \ \rightarrow \ S_4 \sim \log\left(\frac{\phi H}{\dot{\phi}}\frac{m_\sigma^4}{H^4}\right) \sim \log\left(\frac{\phi}{\epsilon^{1/2} M_{\rm Pl}}\frac{m_\sigma^4}{H^4}\right)$$

Phase transition is 1st order ($S_4 \gg 1$), and spectator sector does not dominate energy density:

$$H^4 \ll m_\sigma^4 \ll 3M_{\rm Pl}^2 H^2$$

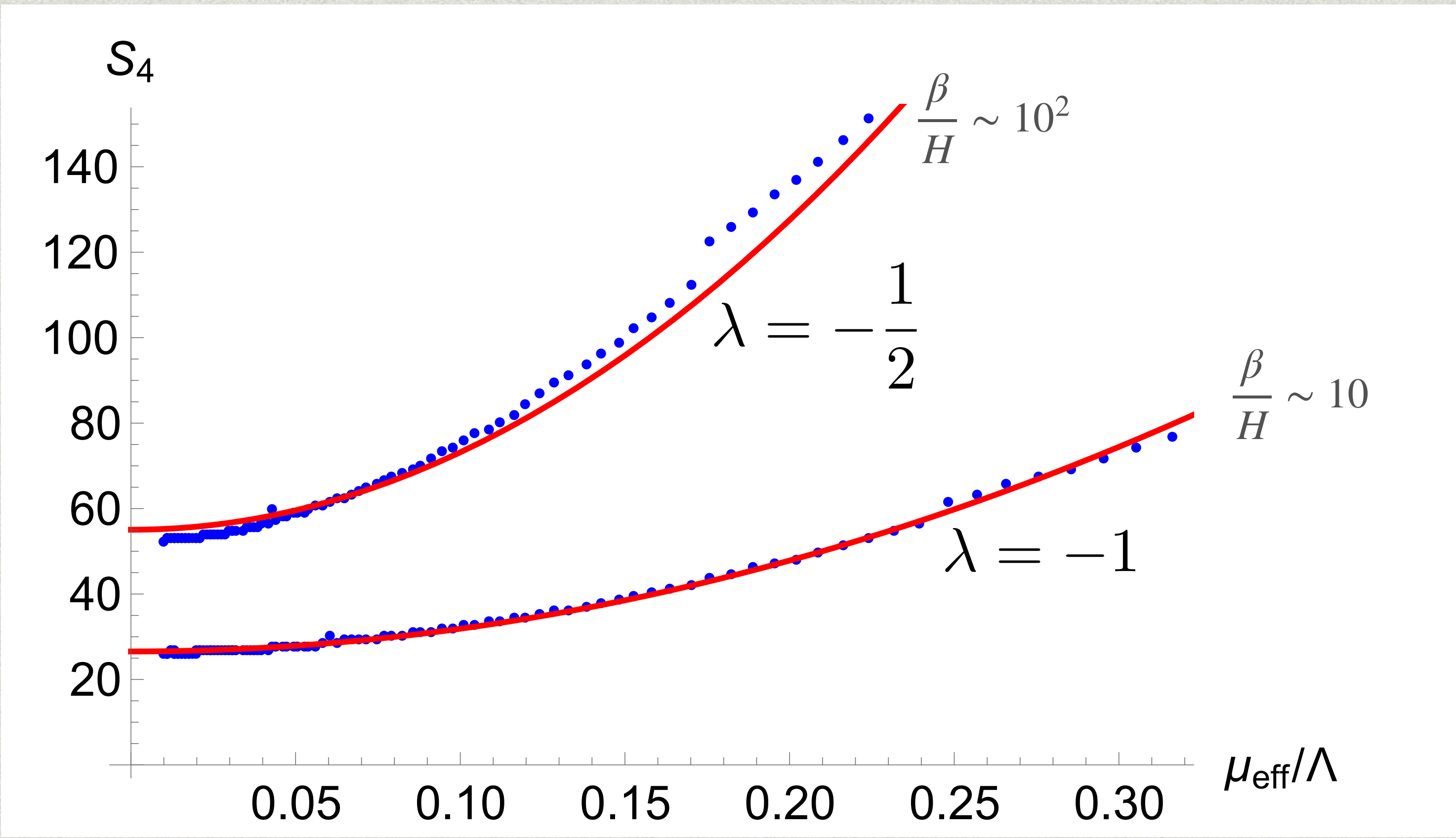
This is possible to arrange.

Typical bubble

$$r_{\rm bubble}^{-1} \simeq \beta = \left| \frac{dS_4}{dt} \right|$$

In our example:

$$\frac{\beta}{H} = \left| \frac{dS_4}{d\log \mu_{\rm eff}^2} \right| (2\epsilon)^{1/2} \times \frac{M_{\rm Pl}}{\phi\left(1 - m_\sigma^2/(c^2\phi^2)\right)} \sim \left| \frac{dS_4}{d\log \mu_{\rm eff}^2} \right| \times \frac{\Lambda^2}{\mu_{\rm eff}^2}$$



CosmoTransitions