Primordial Spikes from Wrapped Brane Inflation

Takeshi Kobayashi (CITA)

based on arXiv:1210.4427 w/ J. Yokoyama

IPMU, December 11, 2012

Primordial Density Perturbations from Cosmic Inflation

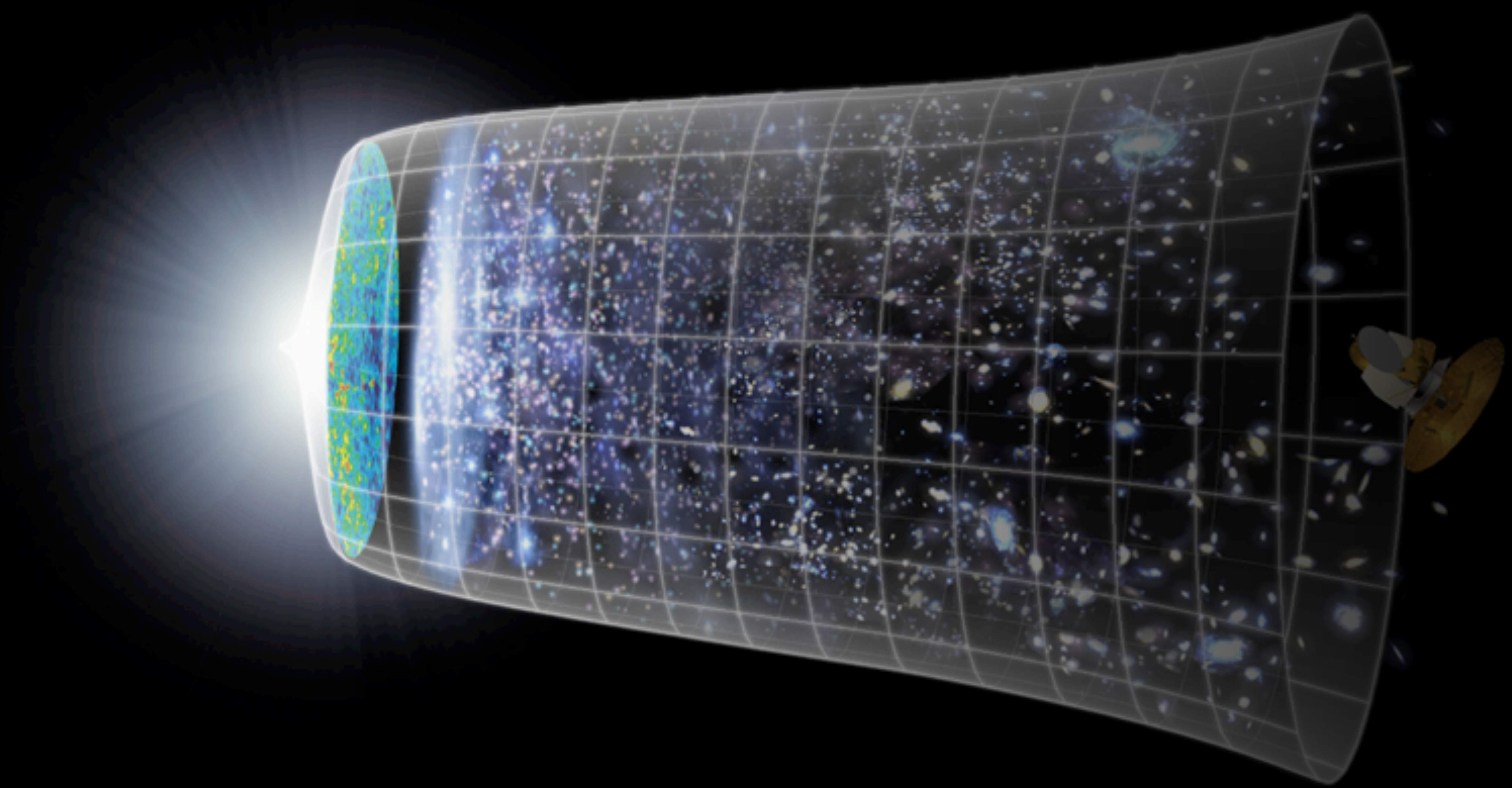
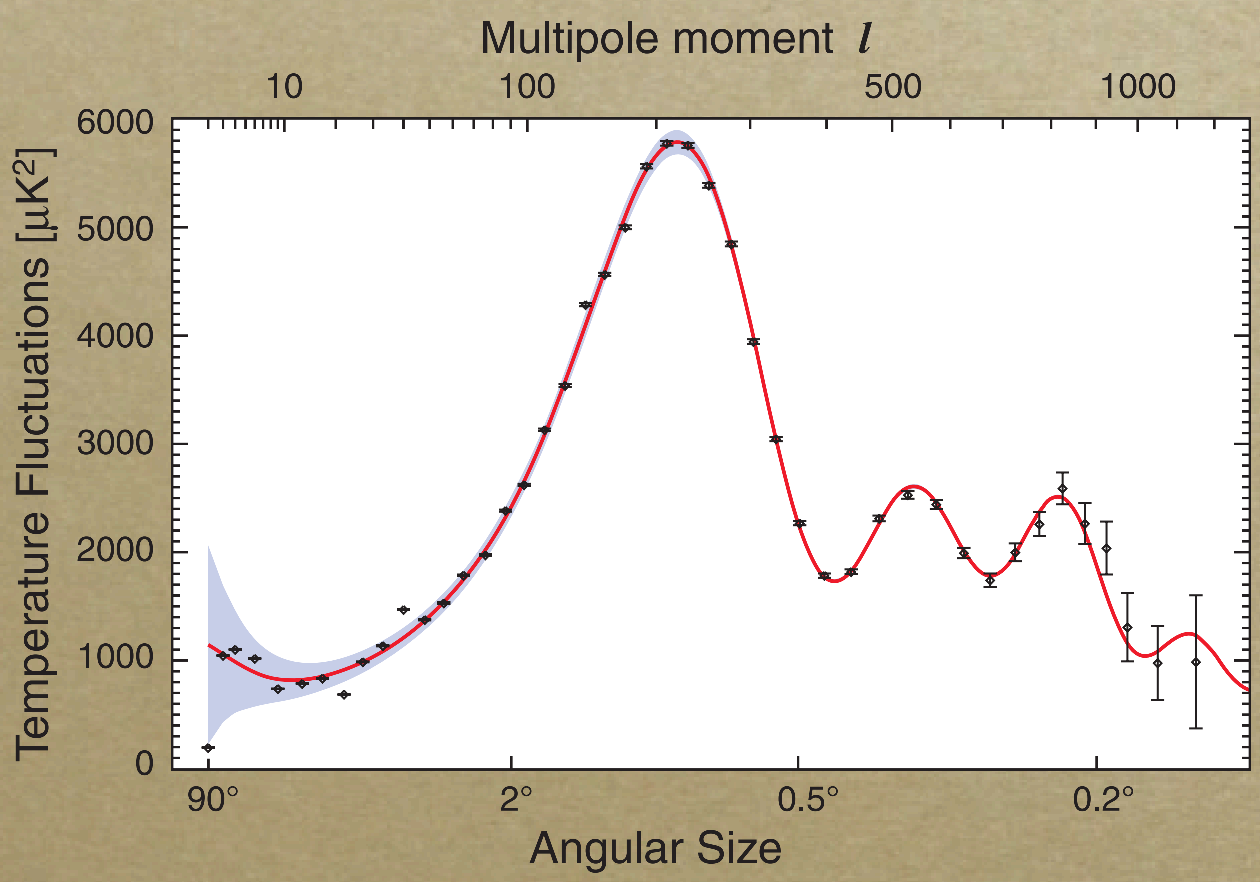


image: NASA/WMAP Science Team

Power Spectrum of Perturbations

almost scale-invariant, with amplitude ~10^{-9}



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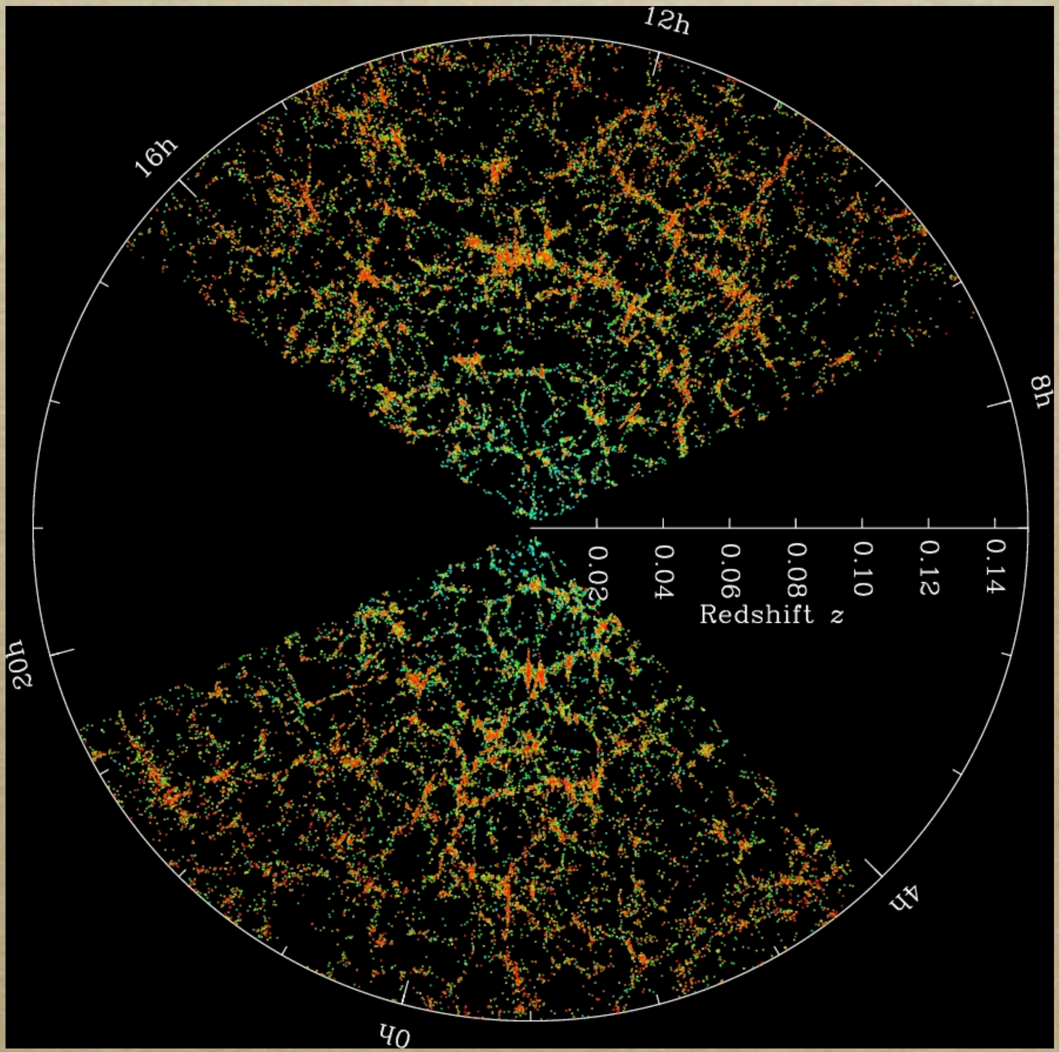
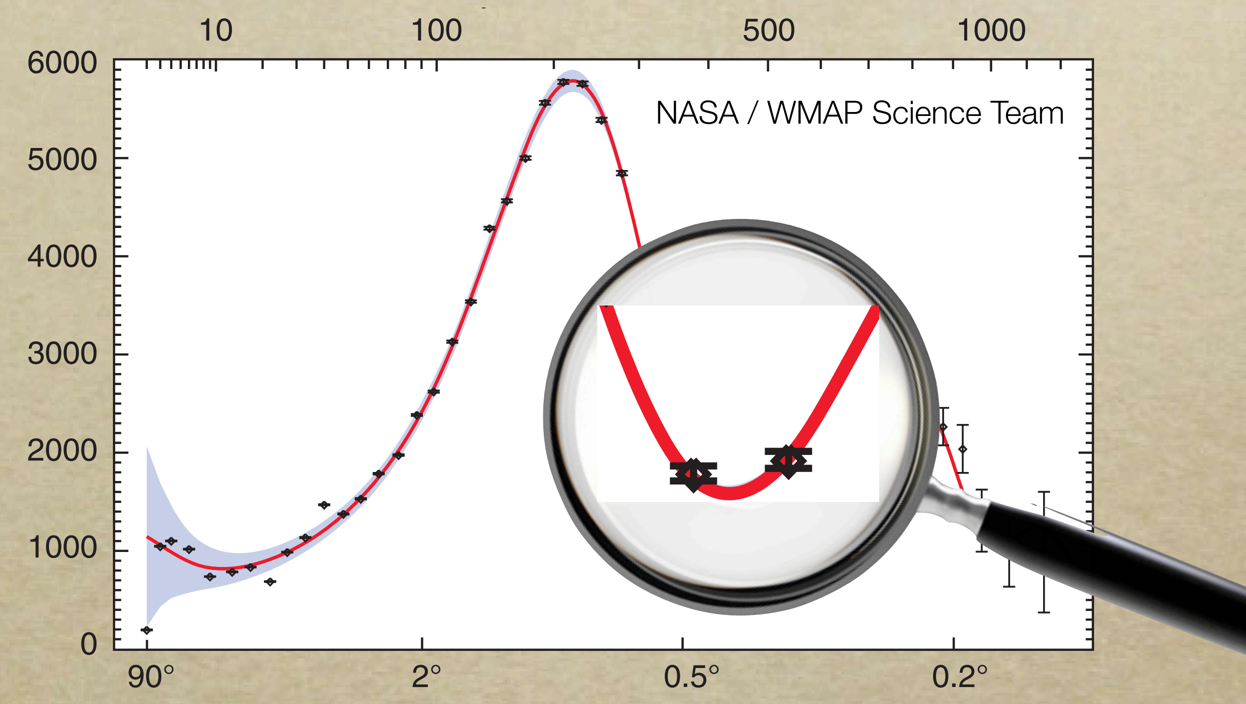


image : M. Blanton and SDSS

A Closer Look at the Primordial Power Spectrum

- fine structures in the power spectrum can tell us much about early universe physics



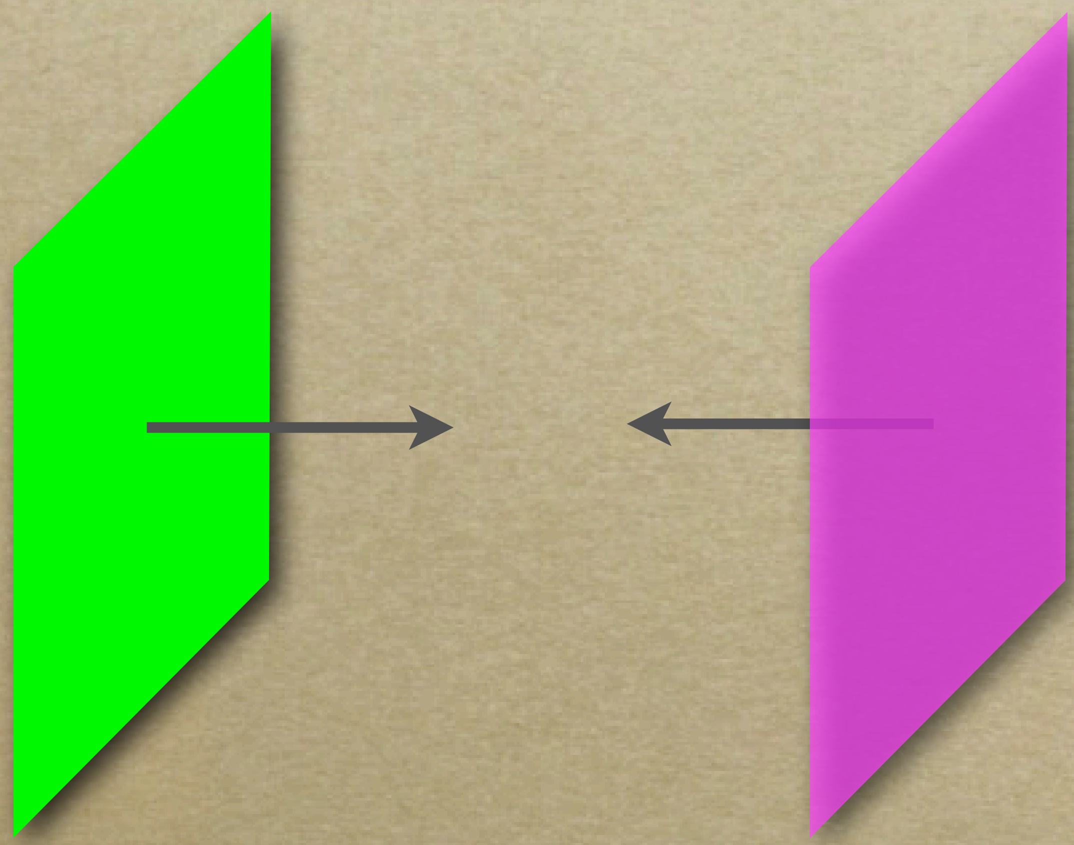
- e.g. oscillations as “standard clocks” Chen ’11

Wrapped brane inflation produces spikes that are tied to properties of the extra dimensional space.

Brane Inflation

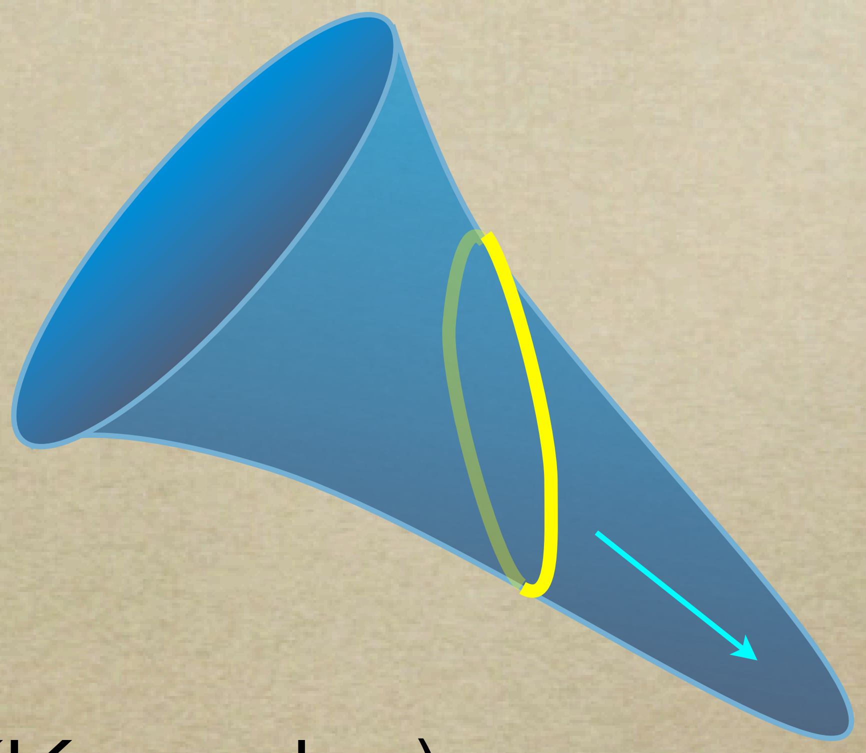
Dvali, Tye '98

Branes moving along the extra dimensions can drive cosmic inflation.



Inflation with Wrapped Branes

TK, Mukohyama, Kinoshita '07   Becker, Leblond, Shandera '07   Silverstein, Westphal '10



- p-branes with p > 3 wrap the internal manifold

- brane's oscillation modes (i.e. KK modes) excited during inflation by localized sources/features

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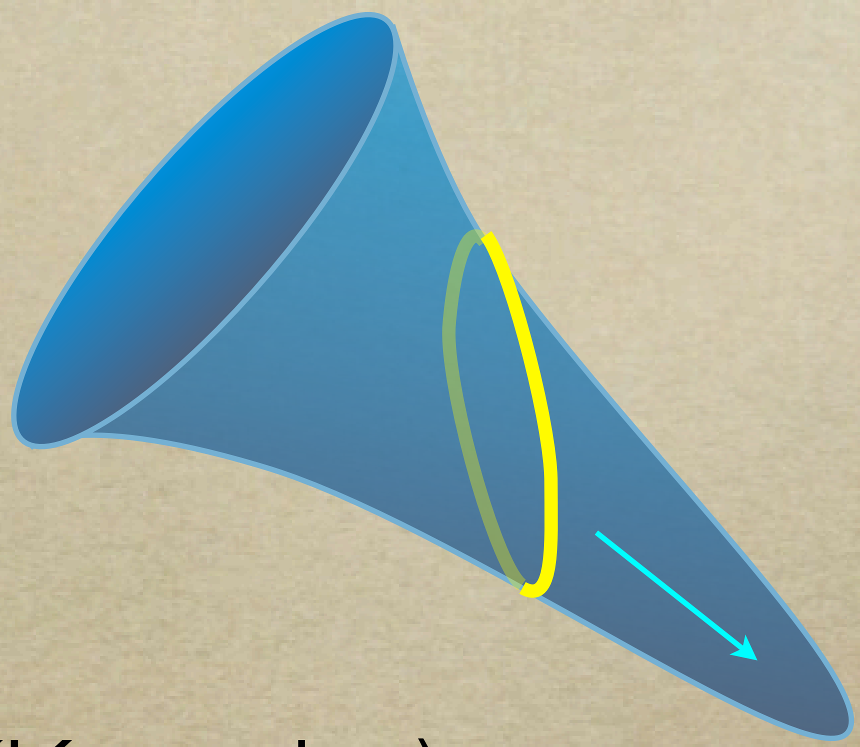


- brane's oscillation modes (i.e. KK modes) excited during inflation by localized sources/features

Excited KK modes produce spikes!

Effective 4-Dim. Theory

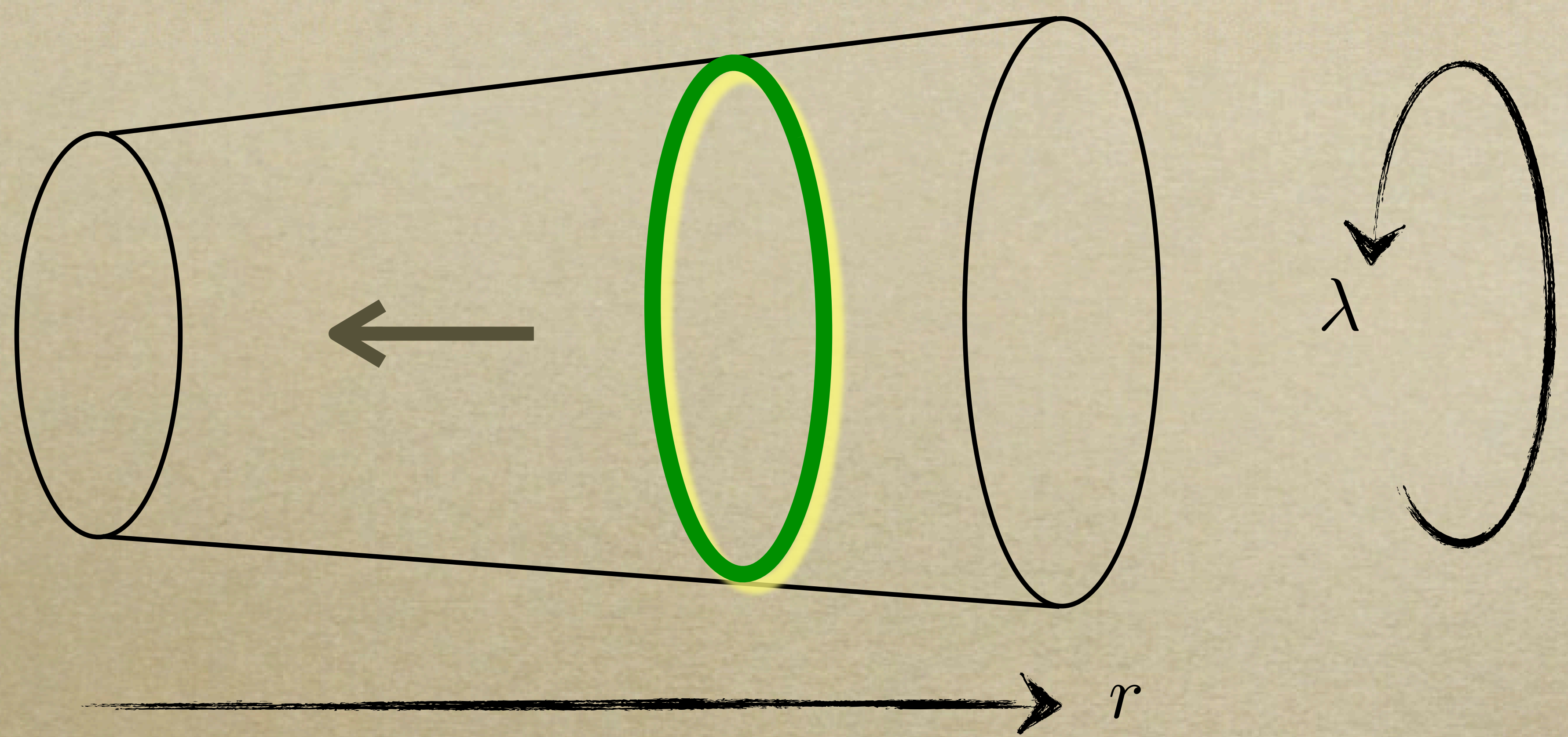
- inflaton (= zero mode position of brane) couples to heavy oscillating fields (= KK modes)
- resonant features in the pert. spectrum are localized to narrow Δk
(in contrast to most previous works)
- brane's Nambu-Goto action sources strong resonance

Outline

- wrapped brane inflation setup
- effects on curv. pert. from oscillating KK modes
  - weak resonance sourcing oscillations
  - strong resonance sourcing spikes

Setup : 4-Brane Inflation

extra dim.
space

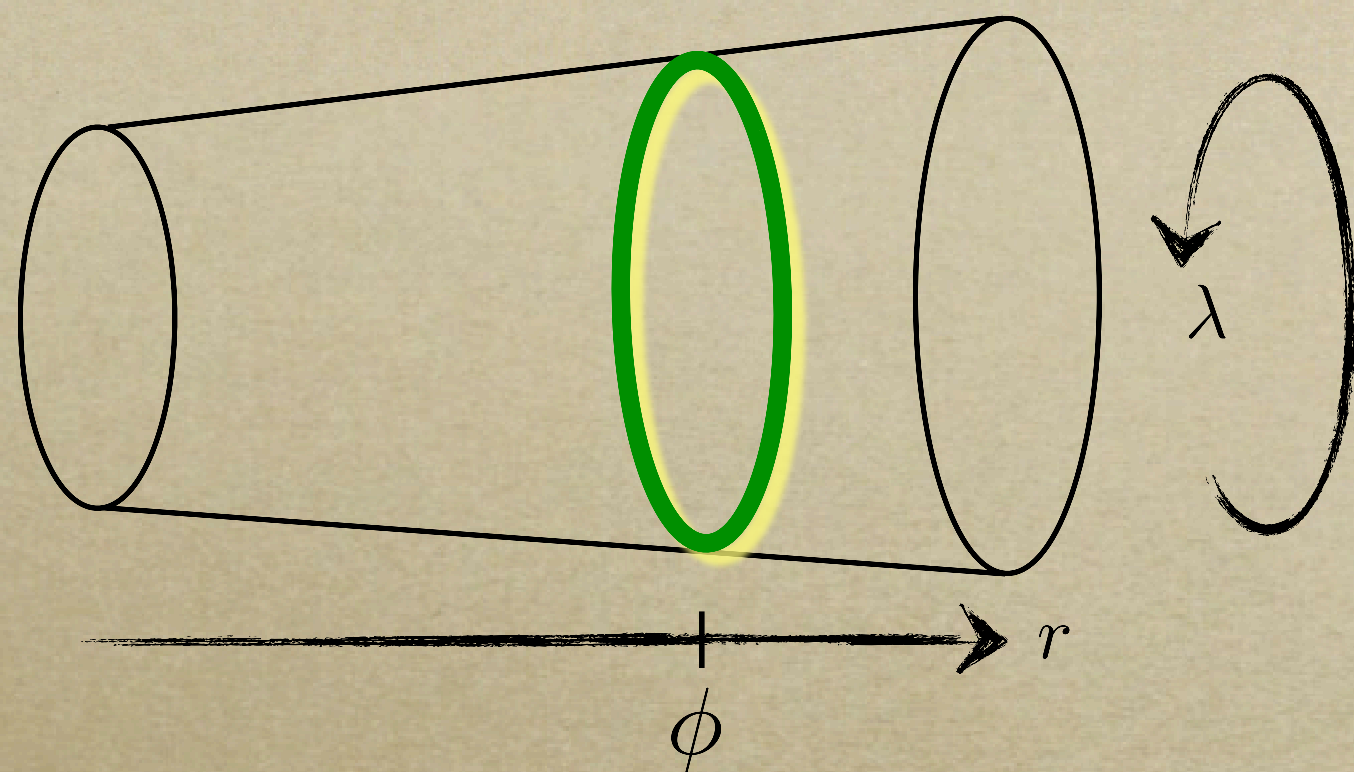


$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu + A^2 dr^2 + B^2 r^2 d\lambda^2$$

Nambu-Goto action $\quad S = -T_4 \int d^5\xi \sqrt{-\det(G_{MN})}$

cf. D-brane monodromy model by Silverstein & Westphal '08

Effective 4-Dim. Theory



$$ds^2_{\rm int} = A^2 dr^2 + B^2 r^2 d\lambda^2$$

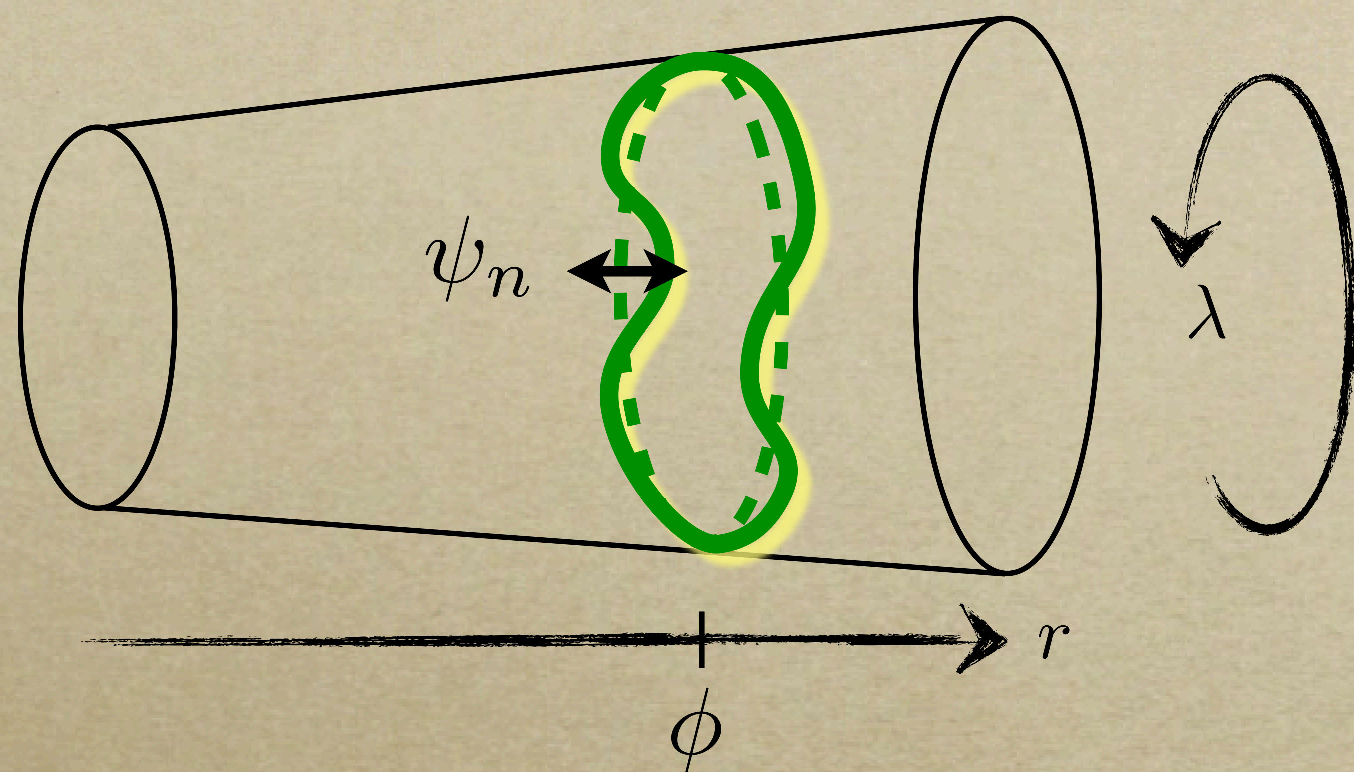
in the absence of KK modes : $\dfrac{\mathcal{L}}{\sqrt{-g}} = -\dfrac{V(\phi)}{\gamma} \simeq -V(\phi) - \dfrac{1}{2}(\partial\phi)^2$

$$V(\phi) = \mu^{10/3}\phi^{2/3} \qquad \mu \equiv \left(\frac{3\pi p T_4 B}{A}\right)^{1/5} \qquad \gamma = \left(1 + \frac{(\partial\phi)^2}{V}\right)^{-1/2}$$

drives large-field inflation

p : winding number

Effective 4-Dim. Theory



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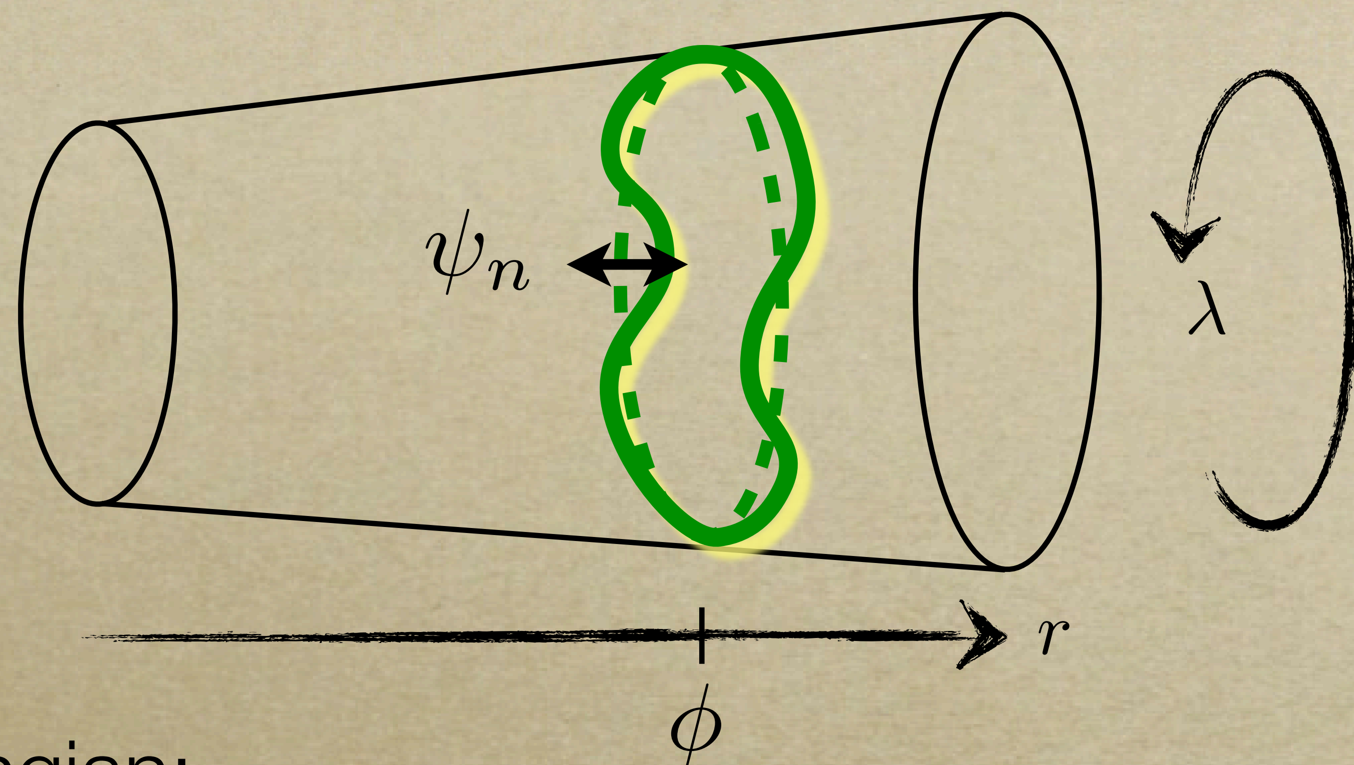

$$ds^2_{\text{int}} = A^2 dr^2 + B^2 r^2 d\lambda^2$$

full Lagrangian:

$$\frac{\mathcal{L}}{\sqrt{-g}} = -V\left(\frac{1}{\gamma} + 2\gamma \sum_{n\neq 0} \alpha_n^2 \frac{\psi_n^2}{\phi^2}\right) - \gamma \sum_{n\neq 0}\left\{\frac{1}{2}(\partial\psi_n)^2 - \frac{1}{6}\frac{\psi_n^2}{\phi^2}(\partial\phi)^2 + \frac{1}{3}\frac{\psi_n}{\phi}(\partial\phi\cdot\partial\psi_n)\right\}$$

$$+\frac{\gamma^3}{2V}\sum_{n\neq 0}\left\{(\partial\phi\cdot\partial\psi_n)^2 + \frac{1}{9}\frac{\psi_n^2}{\phi^2}\left((\partial\phi)^2\right)^2 - \frac{2}{3}\frac{\psi_n}{\phi}(\partial\phi)^2(\partial\phi\cdot\partial\psi_n)\right\} + \mathcal{O}(\psi_n^3)$$

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Field Dynamics

$$\frac{\mathcal{L}}{\sqrt{-g}} = -V\left(\frac{1}{\gamma} + 2\gamma\sum_{n\neq 0}\alpha_n^2\frac{\psi_n^2}{\phi^2}\right) - \gamma\sum_{n\neq 0}\left\{\frac{1}{2}(\partial\psi_n)^2 - \frac{1}{6}\frac{\psi_n^2}{\phi^2}(\partial\phi)^2 + \frac{1}{3}\frac{\psi_n}{\phi}(\partial\phi\cdot\partial\psi_n)\right\}$$

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inflaton ϕ : drives slow-roll inflation while $\phi > M_p$

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effective KK mass

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coupled through potential & kinetic terms

Inhomogeneous Fluctuations

$$\phi \to \phi + Q$$

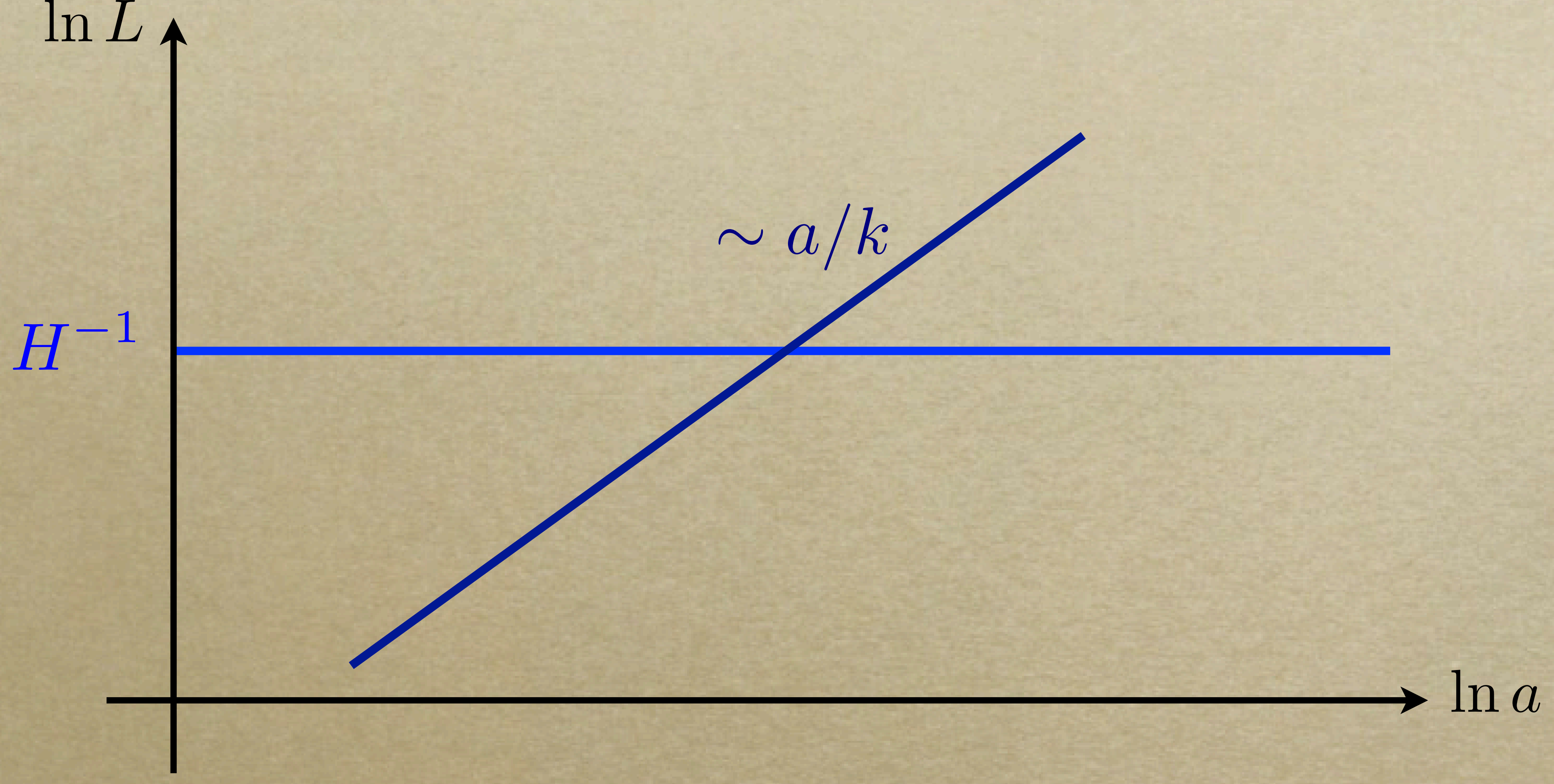
$$S_2 = \int dt d^3x\, a^3 \left[\frac{B}{2}\dot{Q}^2 - \frac{G}{2}\frac{(\partial_i Q)^2}{a^2} + \frac{1}{2}\left\{ M - \frac{(a^3 C)^{\cdot}}{a^3} \right\} Q^2 \right]$$

on flat hypersurfaces

$$\left.\begin{aligned} B &= 1 - 2\sum_{n\neq 0}\alpha_n^2 \frac{\psi_n^2}{\phi^2} + \frac{3}{2}\sum_{n\neq 0}\frac{\dot{\psi}_n^2}{V} + \cdots \\ G &= 1 - 2\sum_{n\neq 0}\alpha_n^2 \frac{\psi_n^2}{\phi^2} + \frac{1}{2}\sum_{n\neq 0}\frac{\dot{\psi}_n^2}{V} + \cdots \\ &\vdots \end{aligned}\right\}$$ oscillating b.g.

$Q_{\boldsymbol{k}} \to \zeta_{\boldsymbol{k}}$ via the δN-formalism

Evolution of Fluctuations



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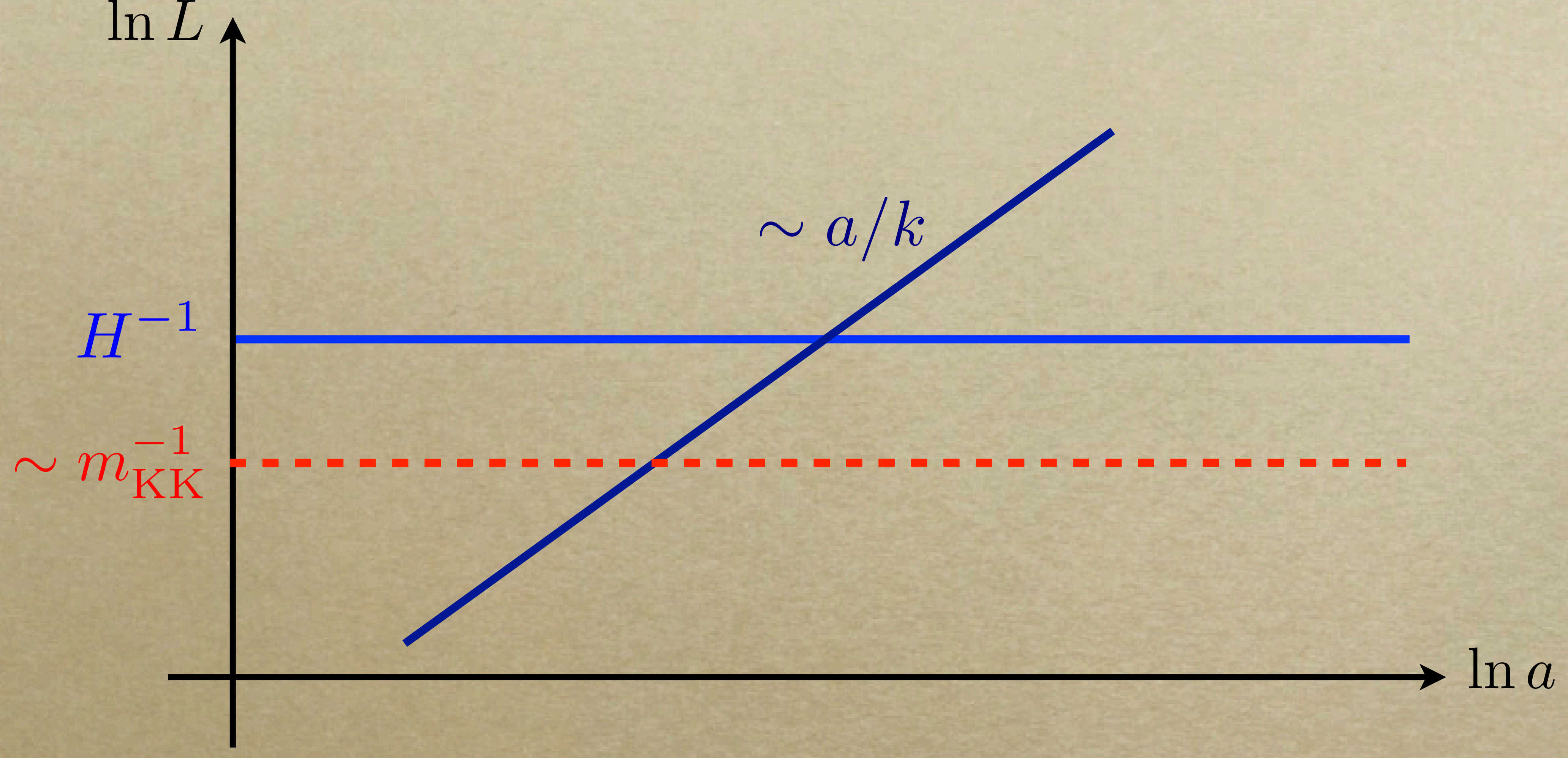

parametric resonance happens when $k/a \sim m_{\rm KK}$

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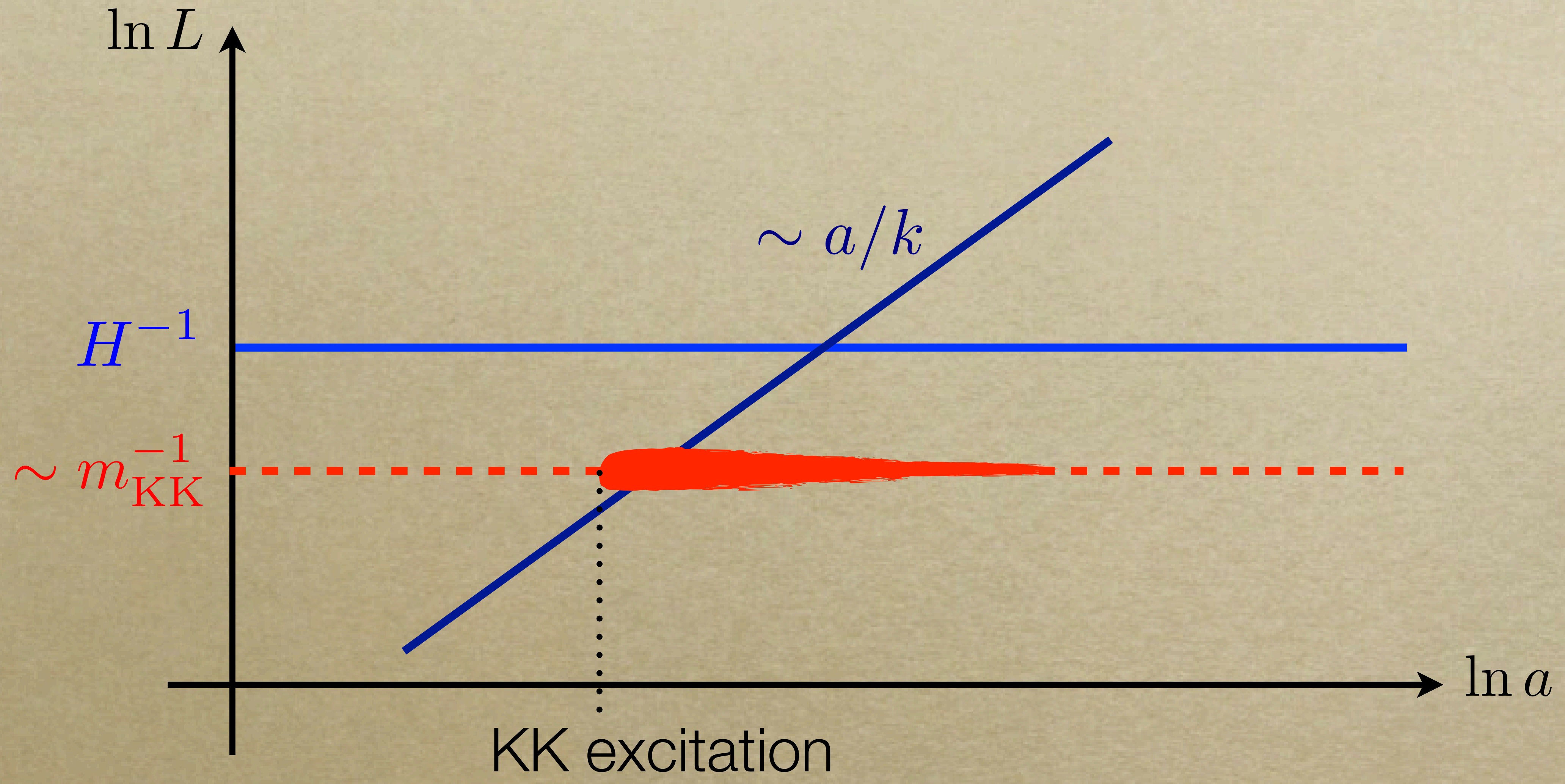

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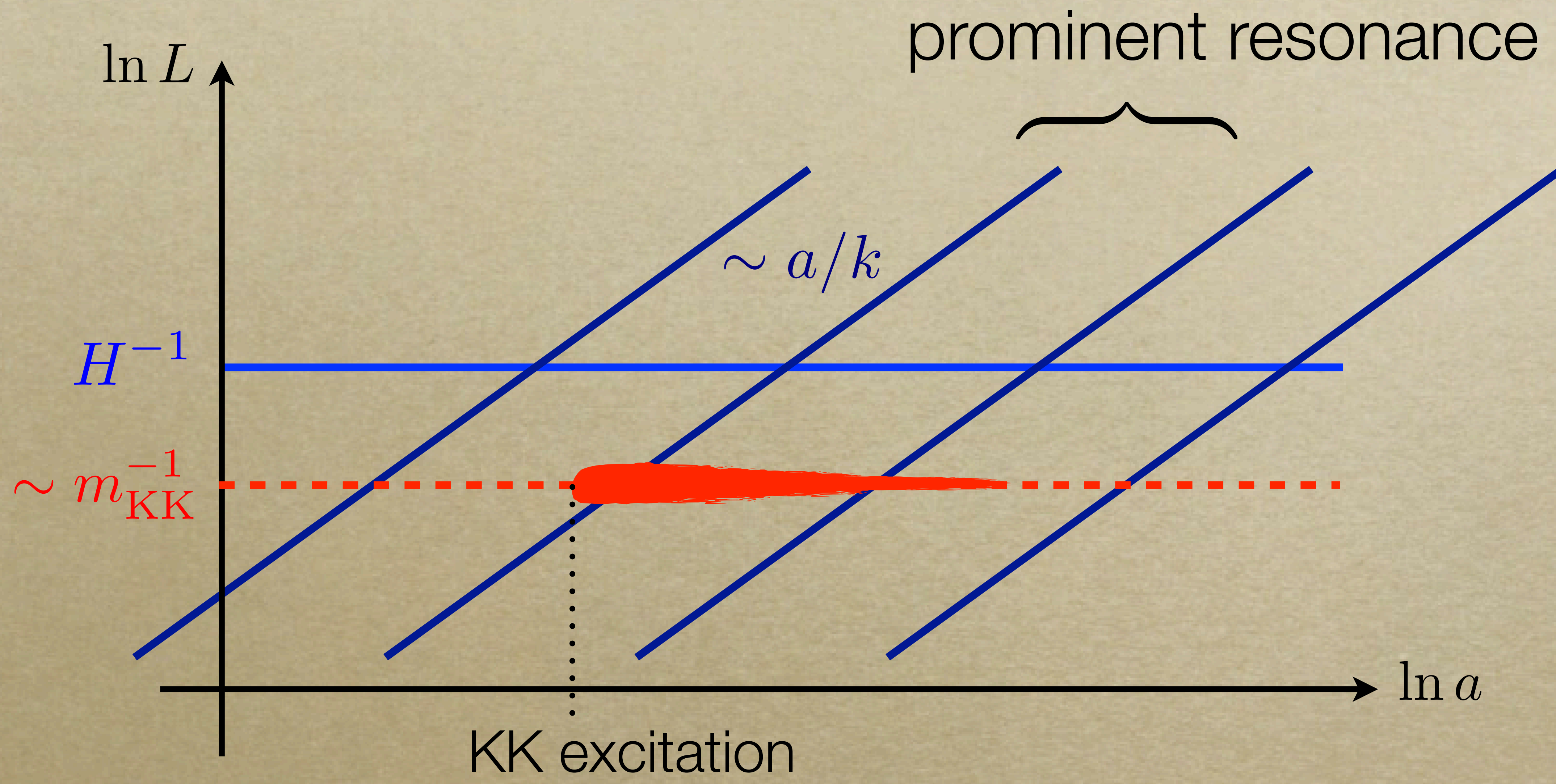

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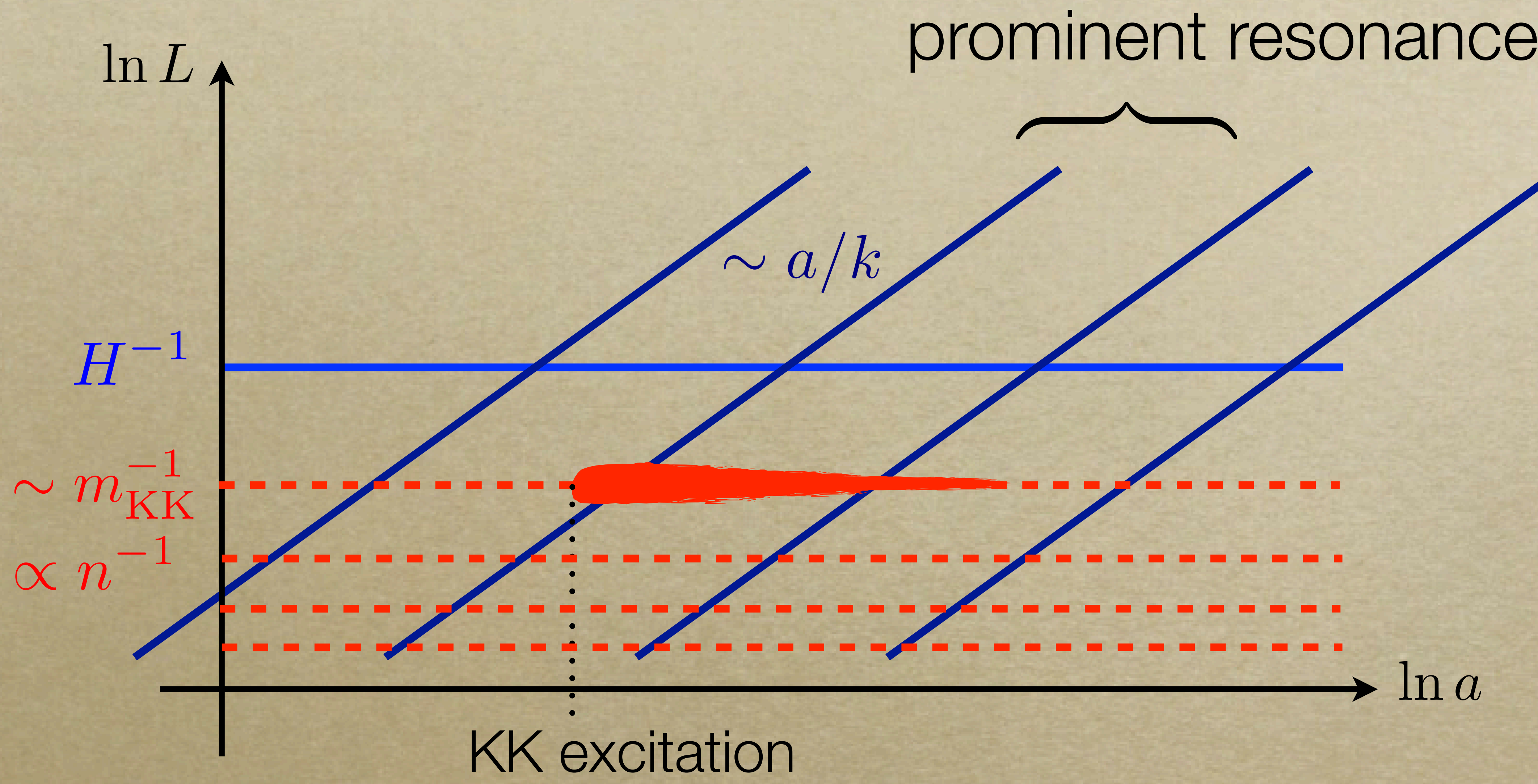


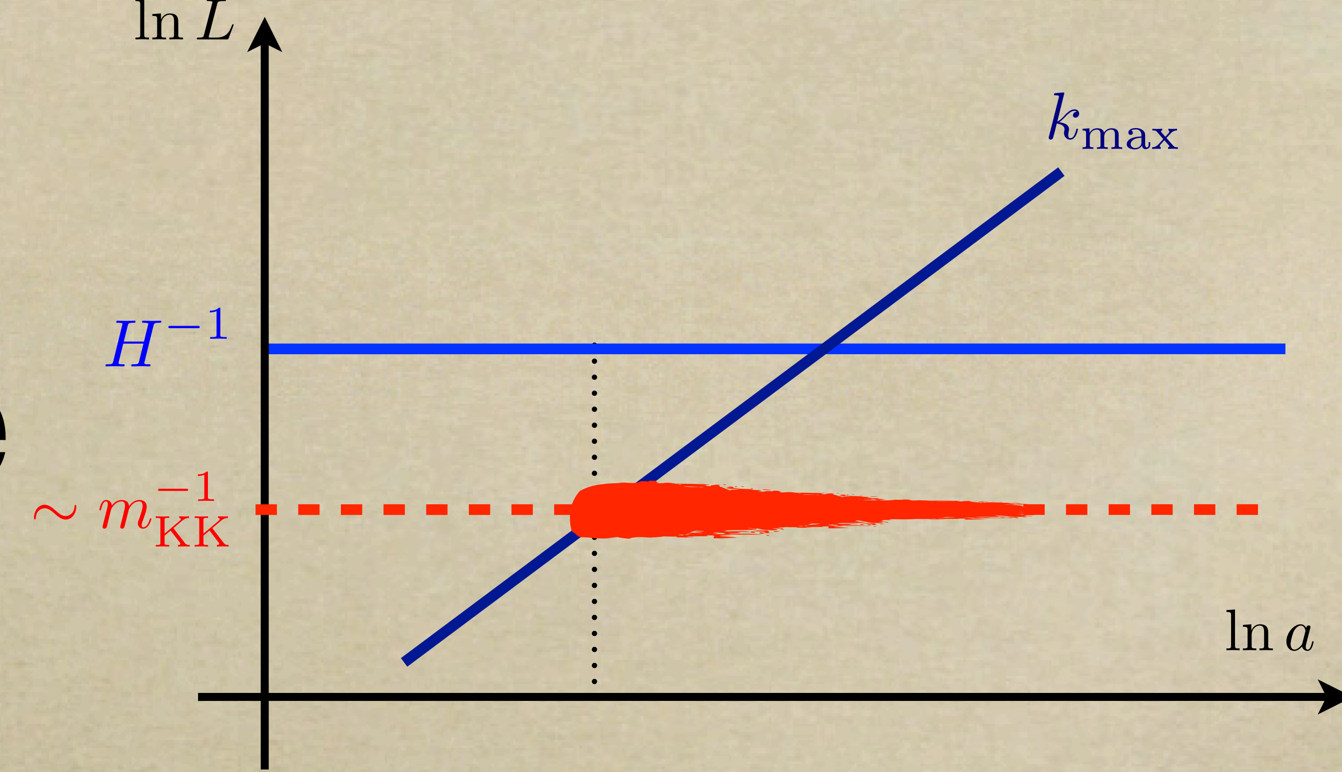
parametric resonance happens when $k/a \sim m_{\mathrm{KK}}$

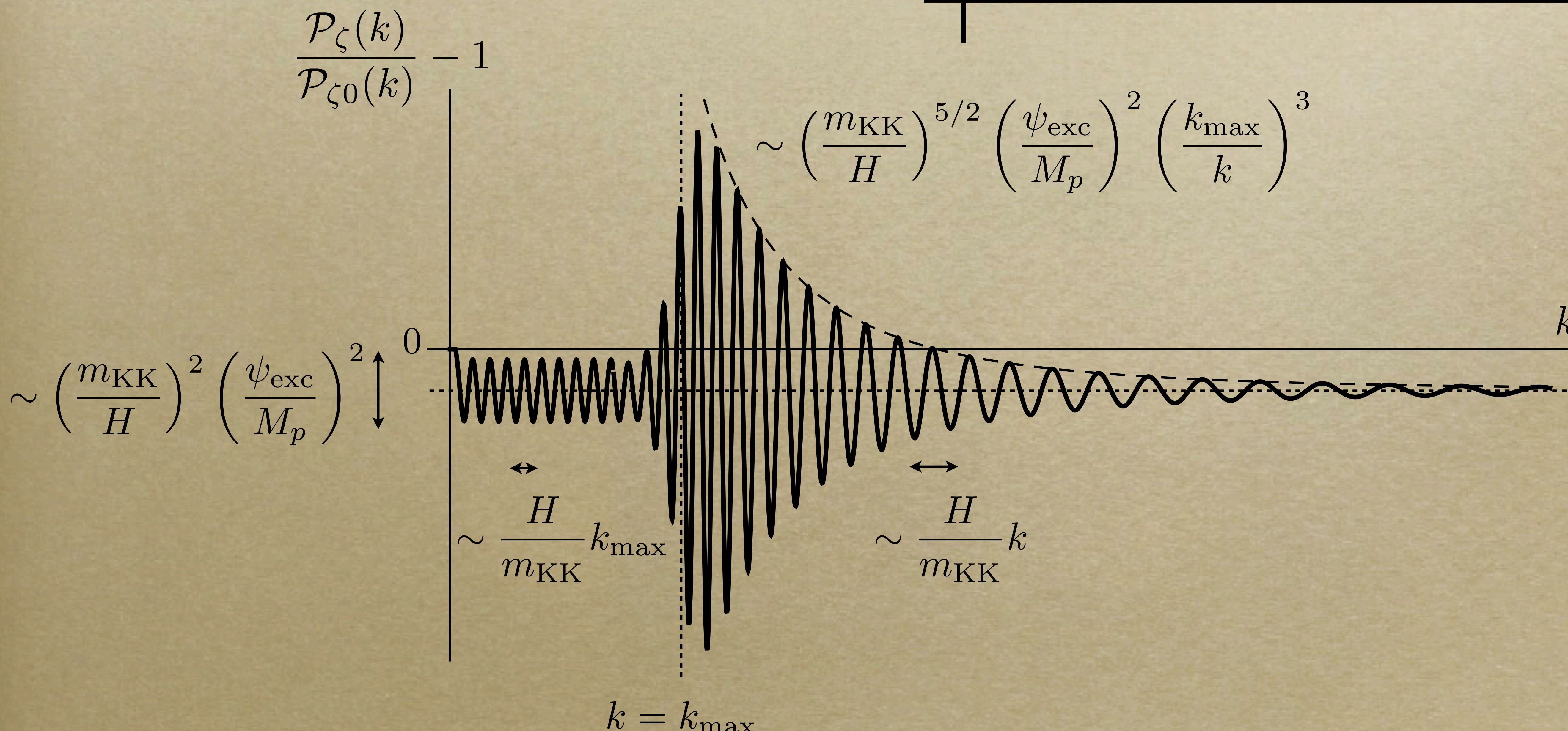
Two Kinds of Parametric Resonance

- Weak Resonance from small KK excitations, sourcing oscillations

- Strong Resonance from large KK excitations, sourcing spikes

Signals from Weak Resonance





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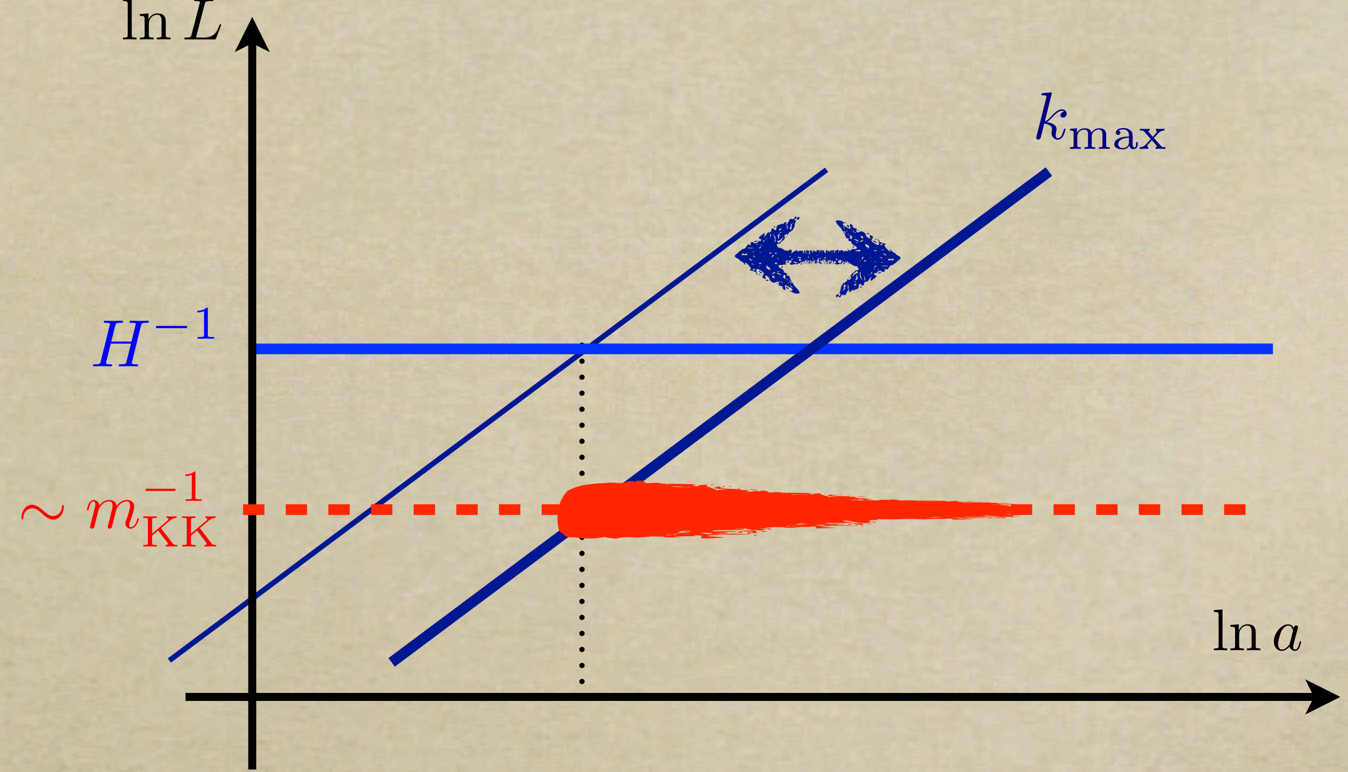

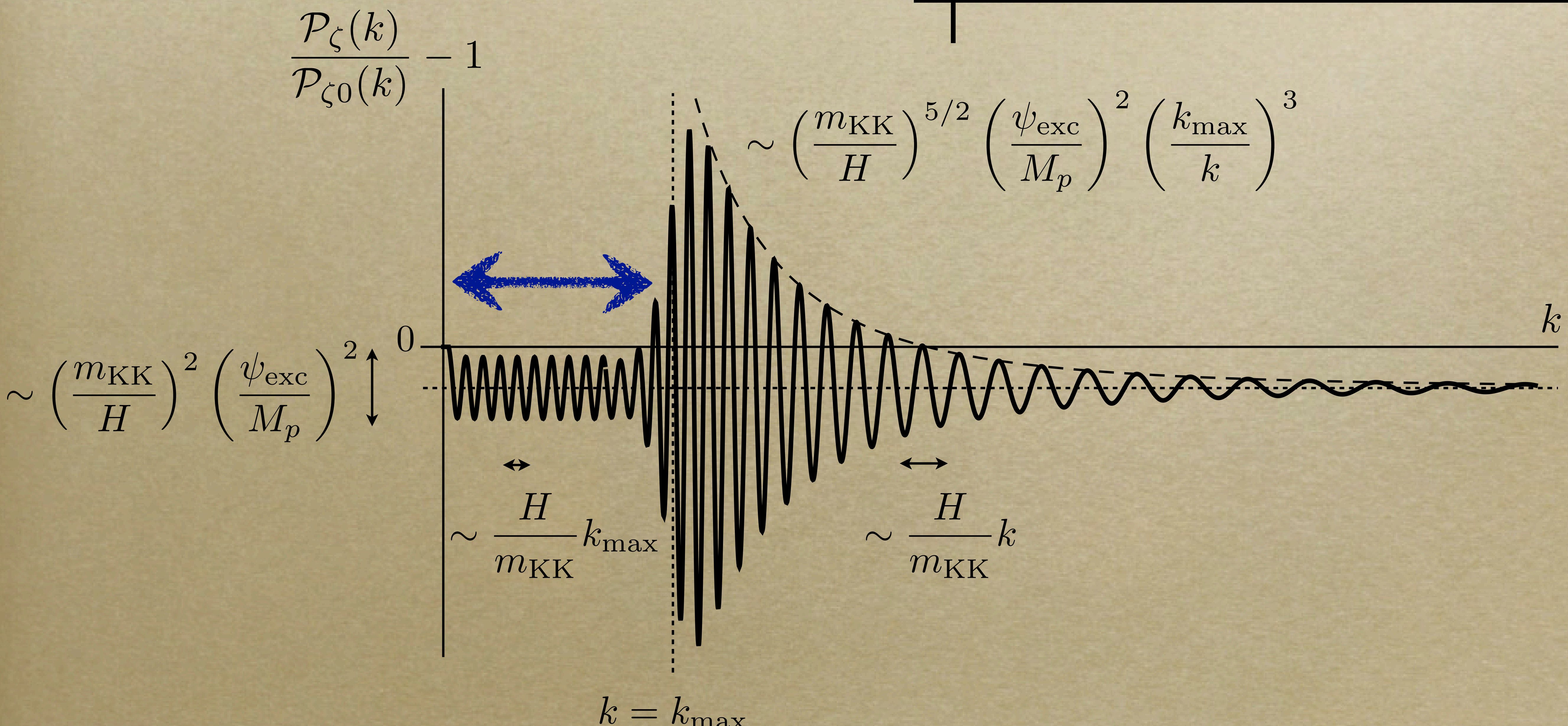

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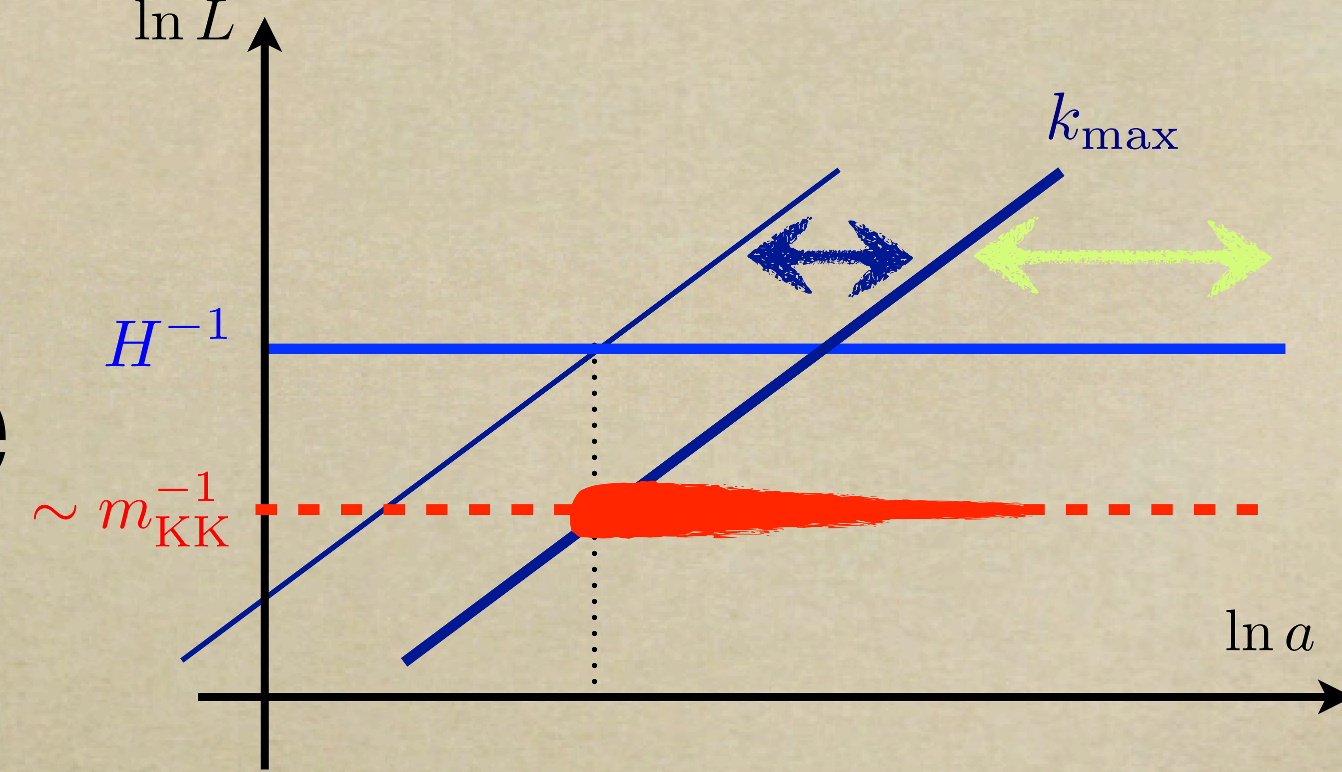
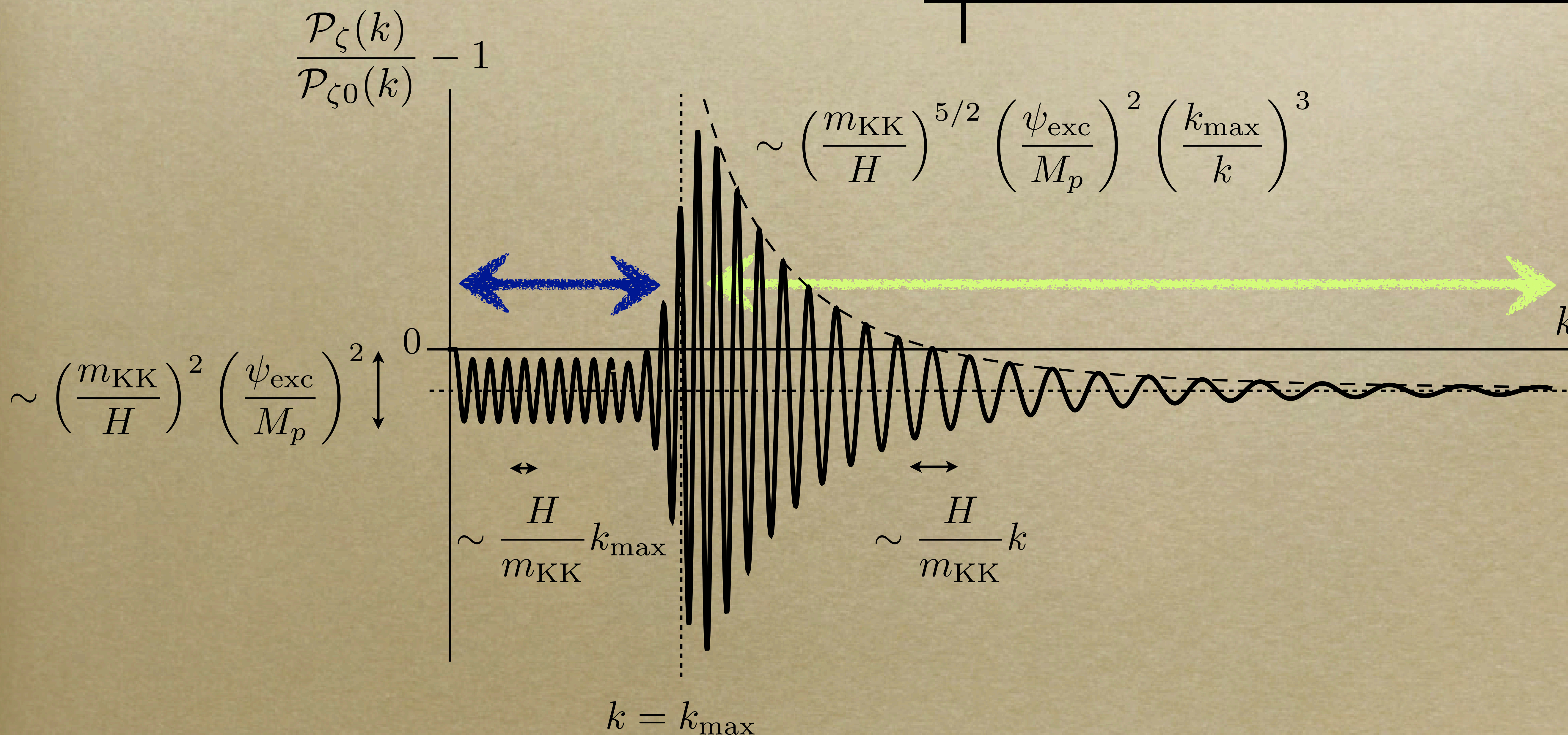


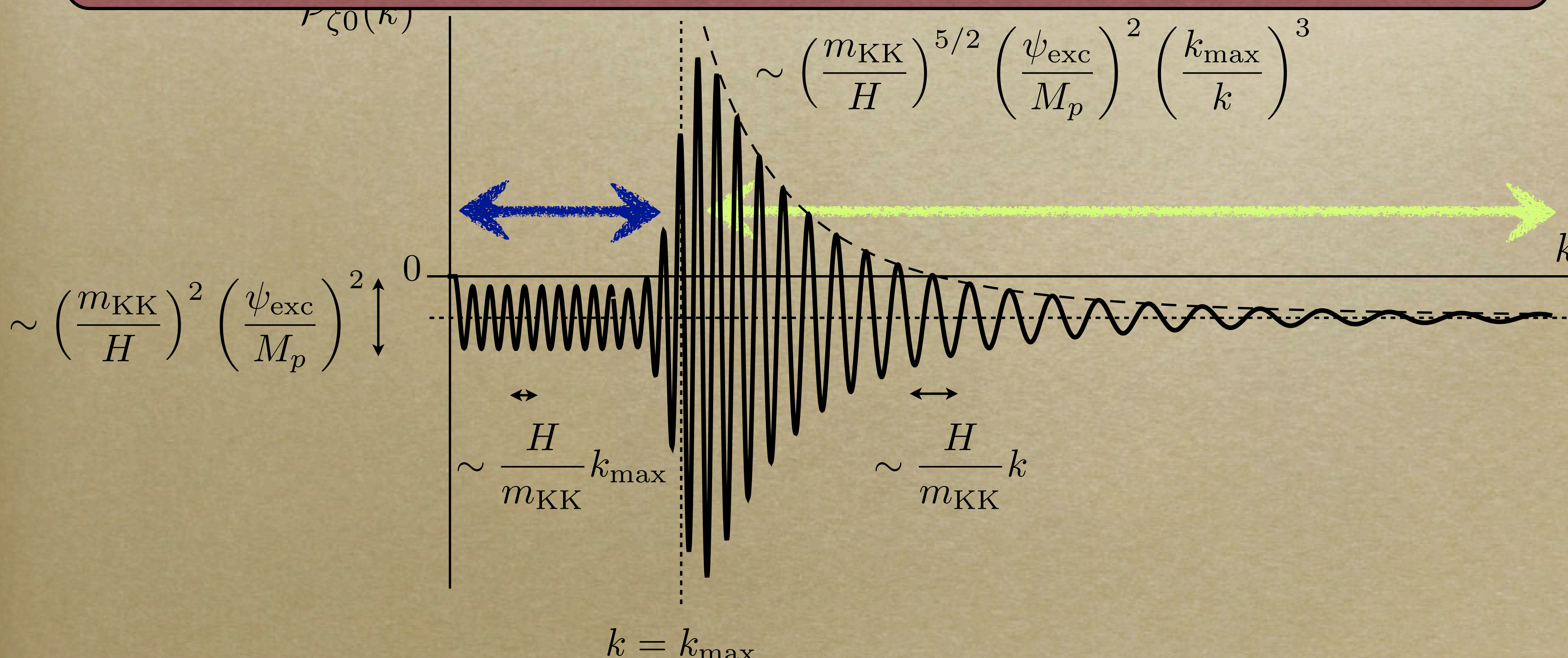


oscillation frequency ⇔ KK mass ⇔ wrapped volume

oscillation amplitude ⇔ excited KK amplitude

position of peak ⇔ when (where) KK are excited

KK tower generates periodic resonant peaks.

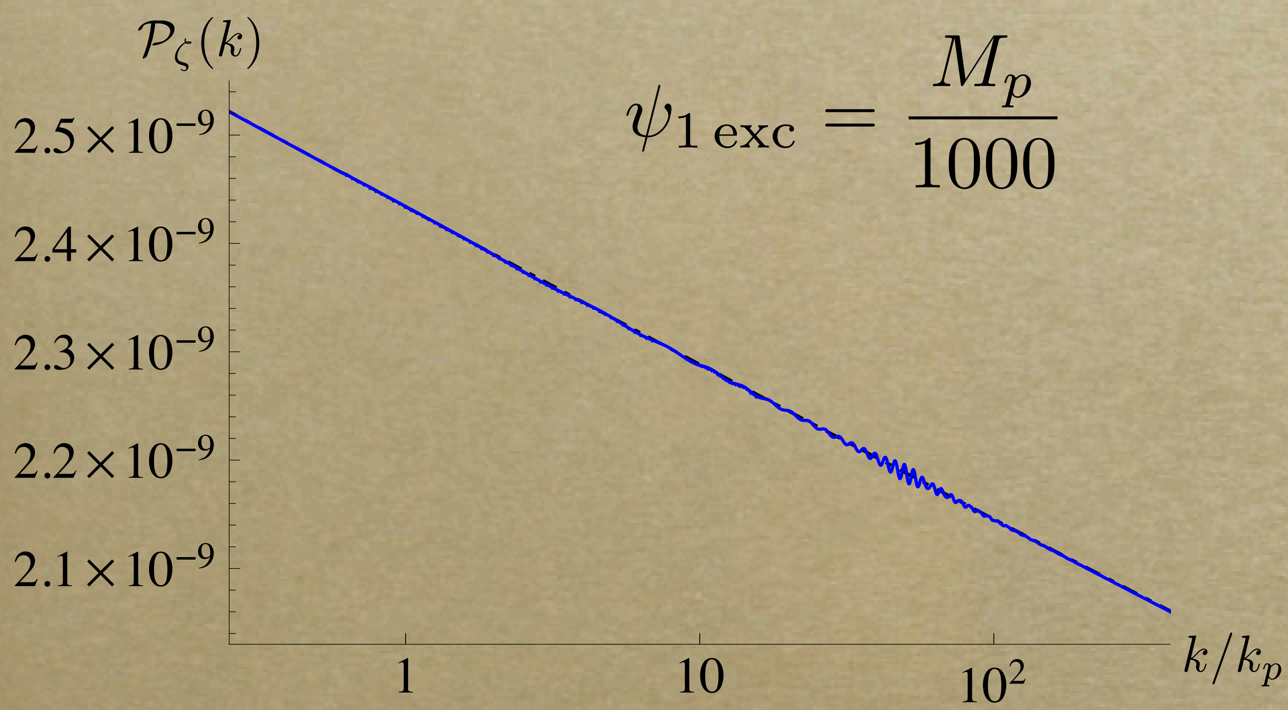


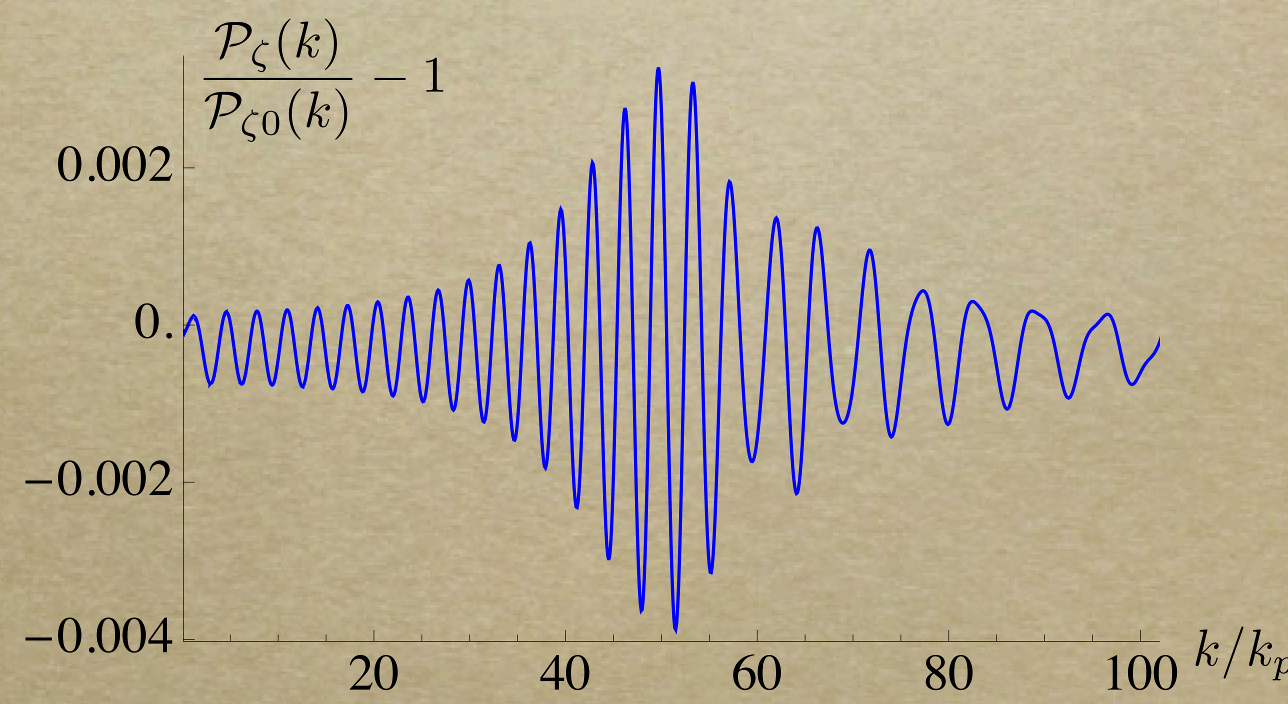
Curvature Pert. Spectrum

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\mu^{10/3}\phi^{2/3}\left(\frac{1}{\gamma} + 2\gamma\alpha_1^2\frac{\psi_1^2}{\phi^2}\right) - \frac{\gamma}{2}(\partial\psi_1)^2 + \cdots$$

one KK mode is excited

$\phi_{\rm exc} \approx 8.2 M_p \qquad \mu \approx 0.0016 M_p \qquad \alpha_1 = 100 \qquad (m_{\rm KK}/H \sim 40)$

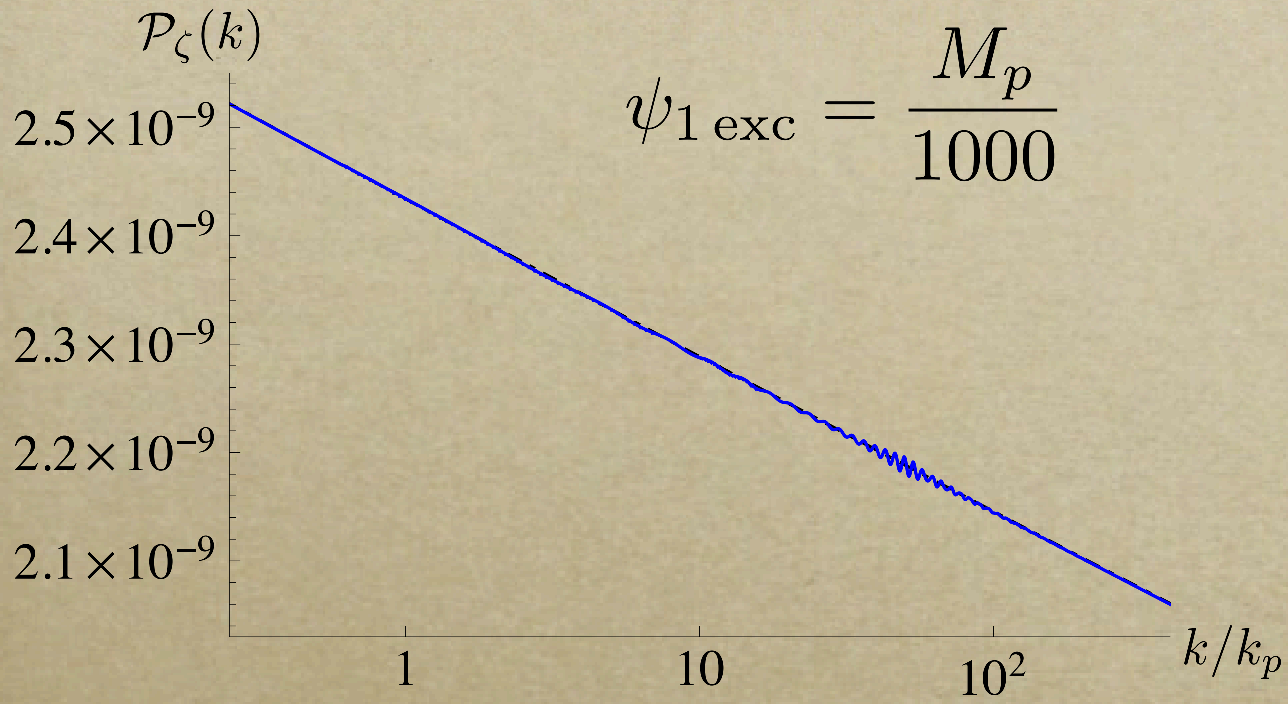


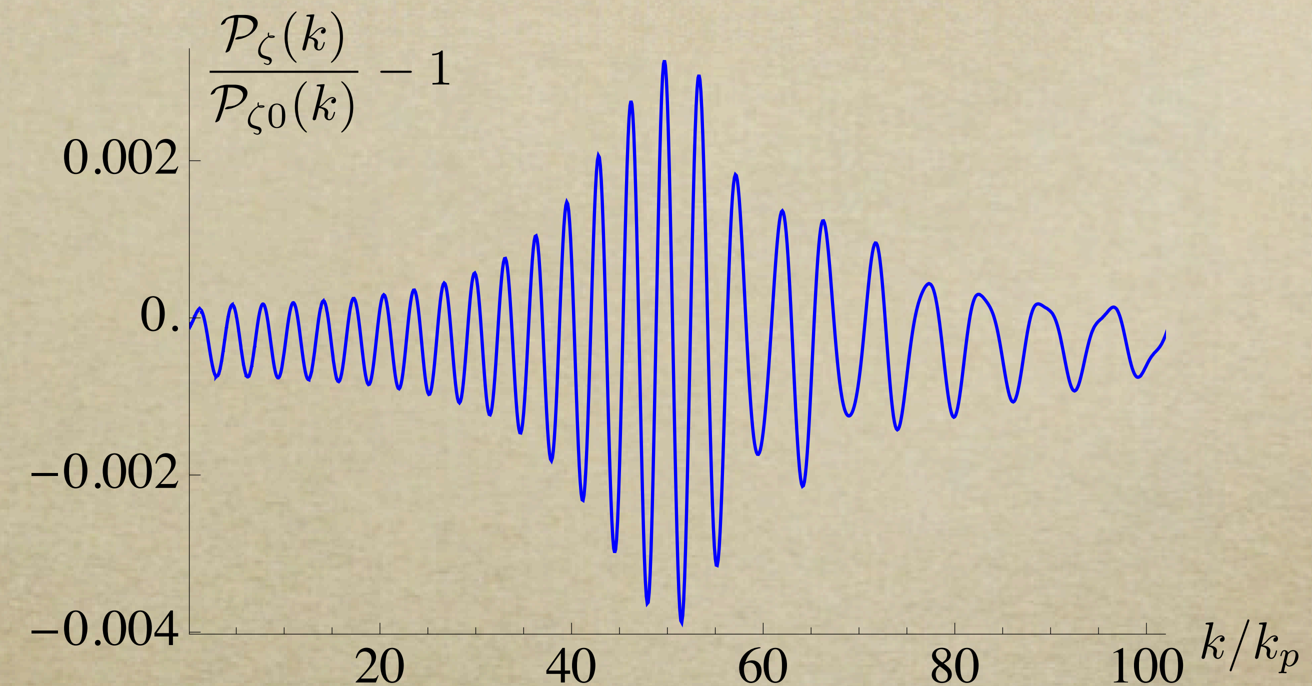


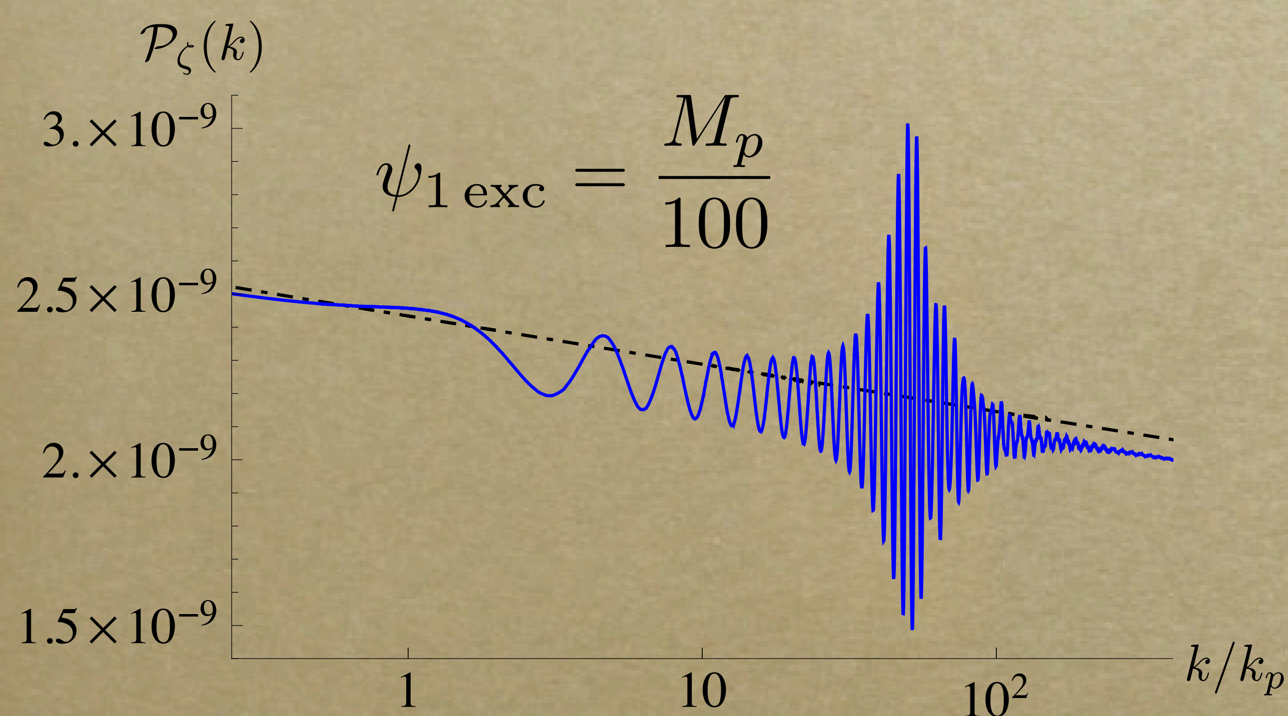
k_p : comoving wave number exiting the horizon at KK excitation

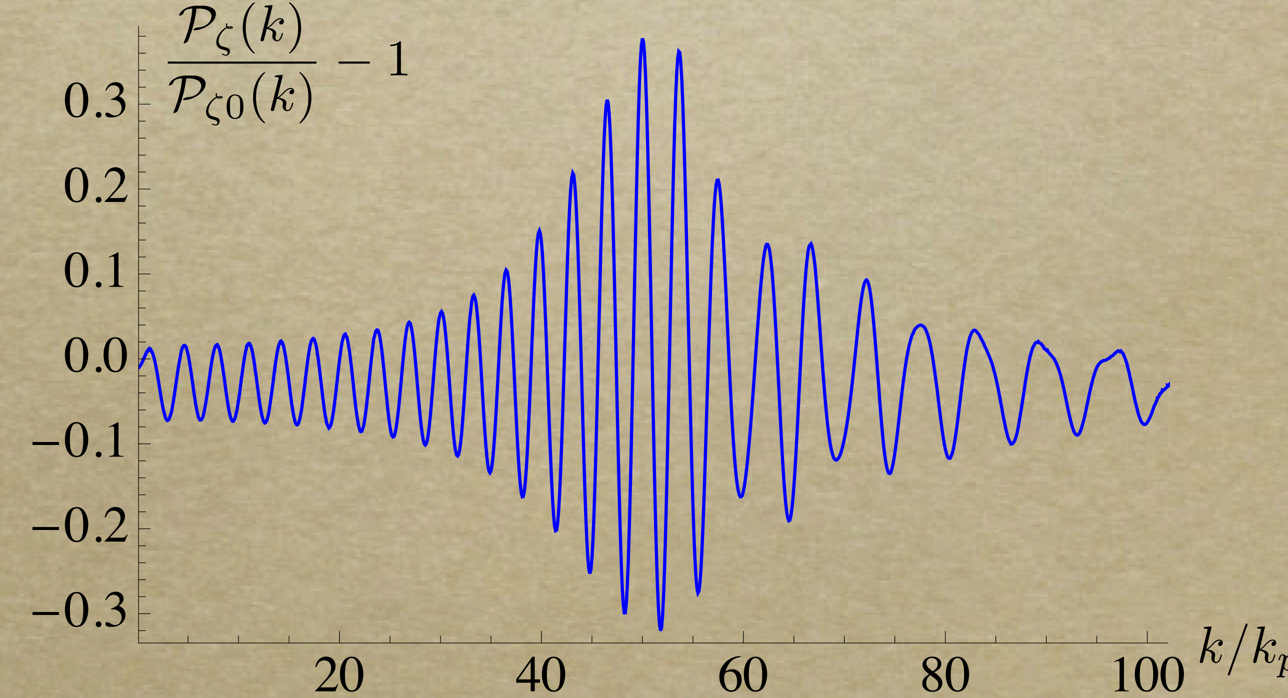
Weak Resonance

resonant signals $\propto \psi_{\mathrm{exc}}^2$



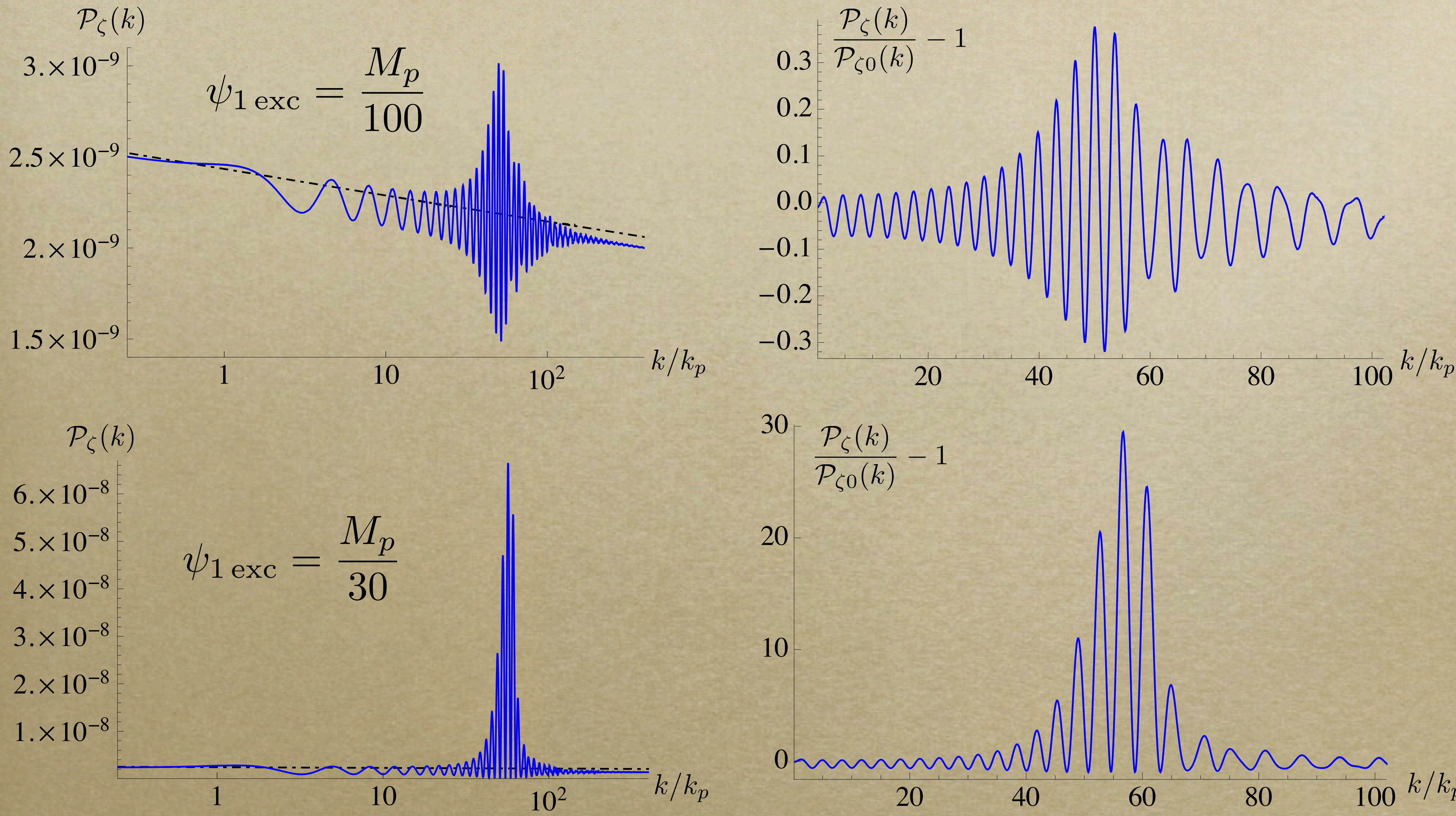






k_p : comoving wave number exiting the horizon at KK excitation

Further Increasing $\psi_{\rm exc}$ ...



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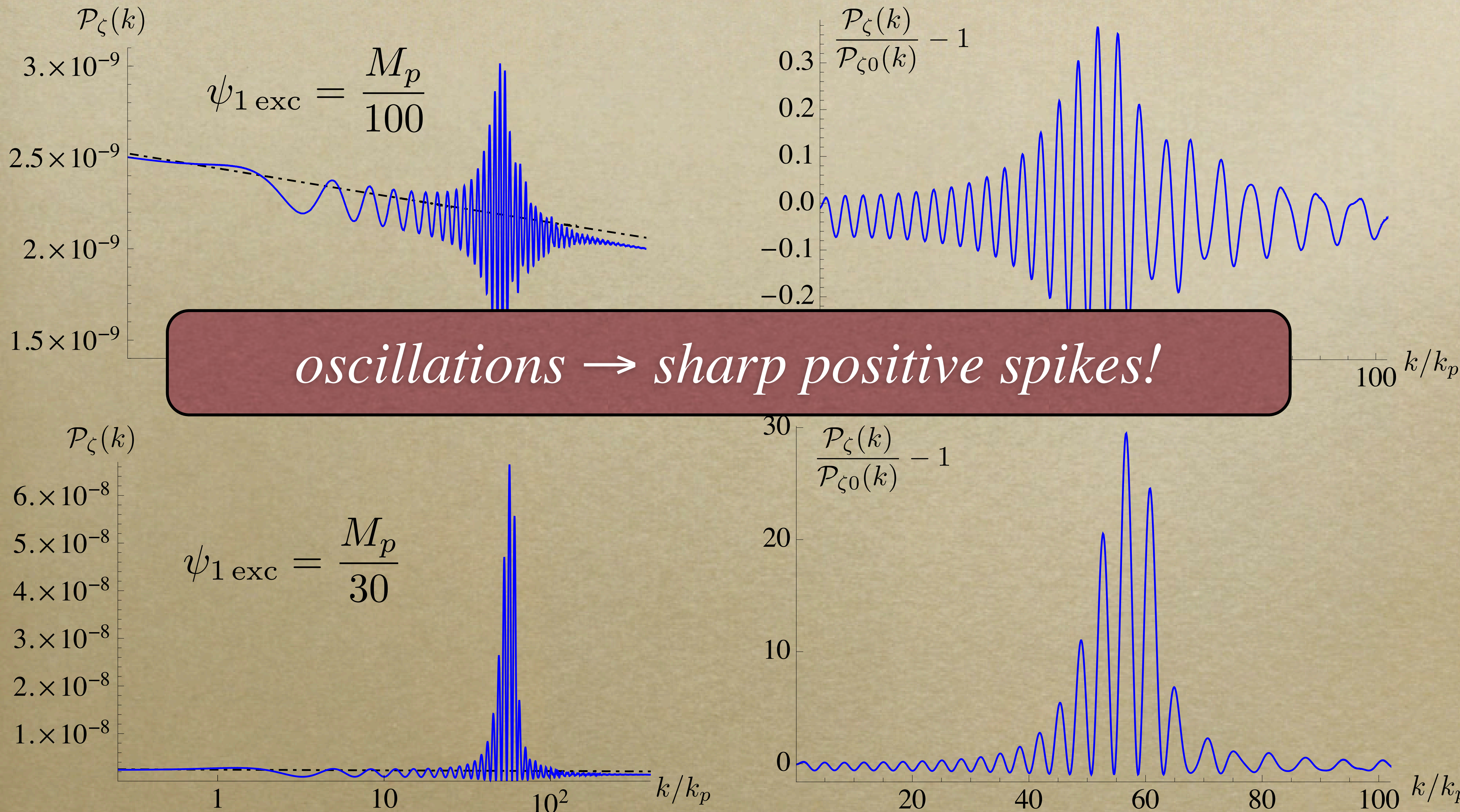
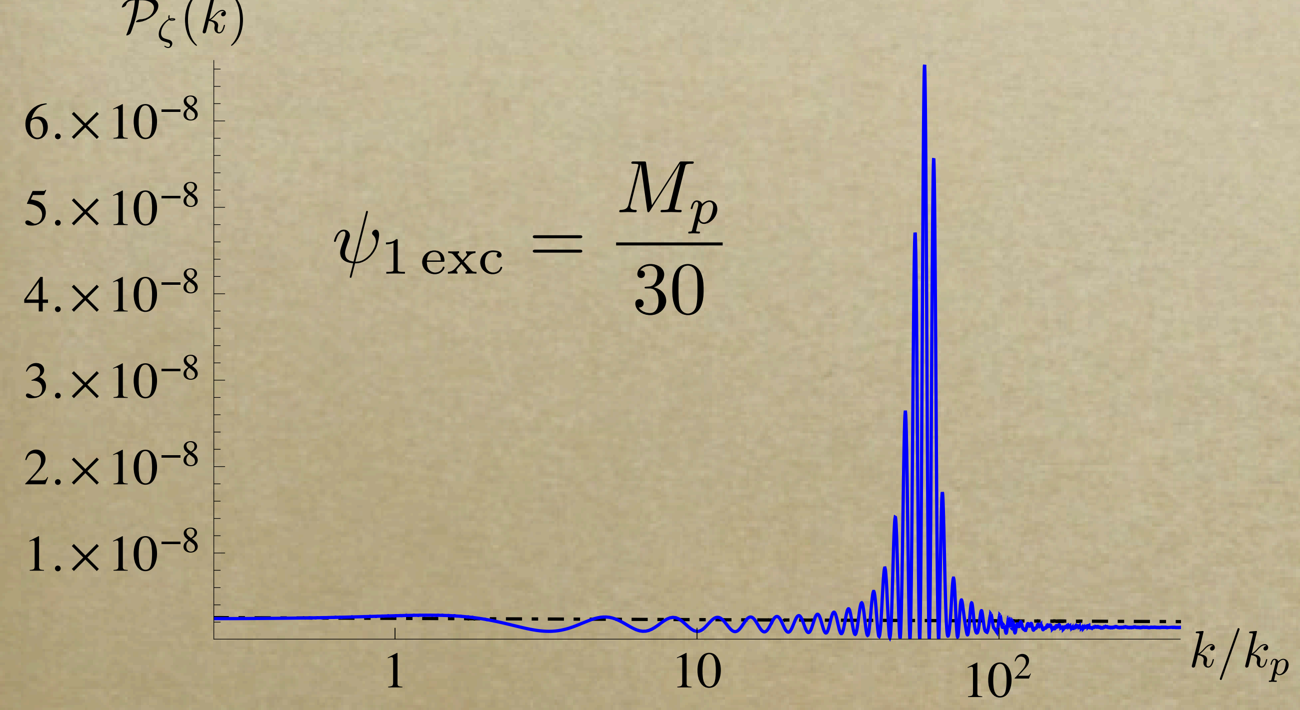
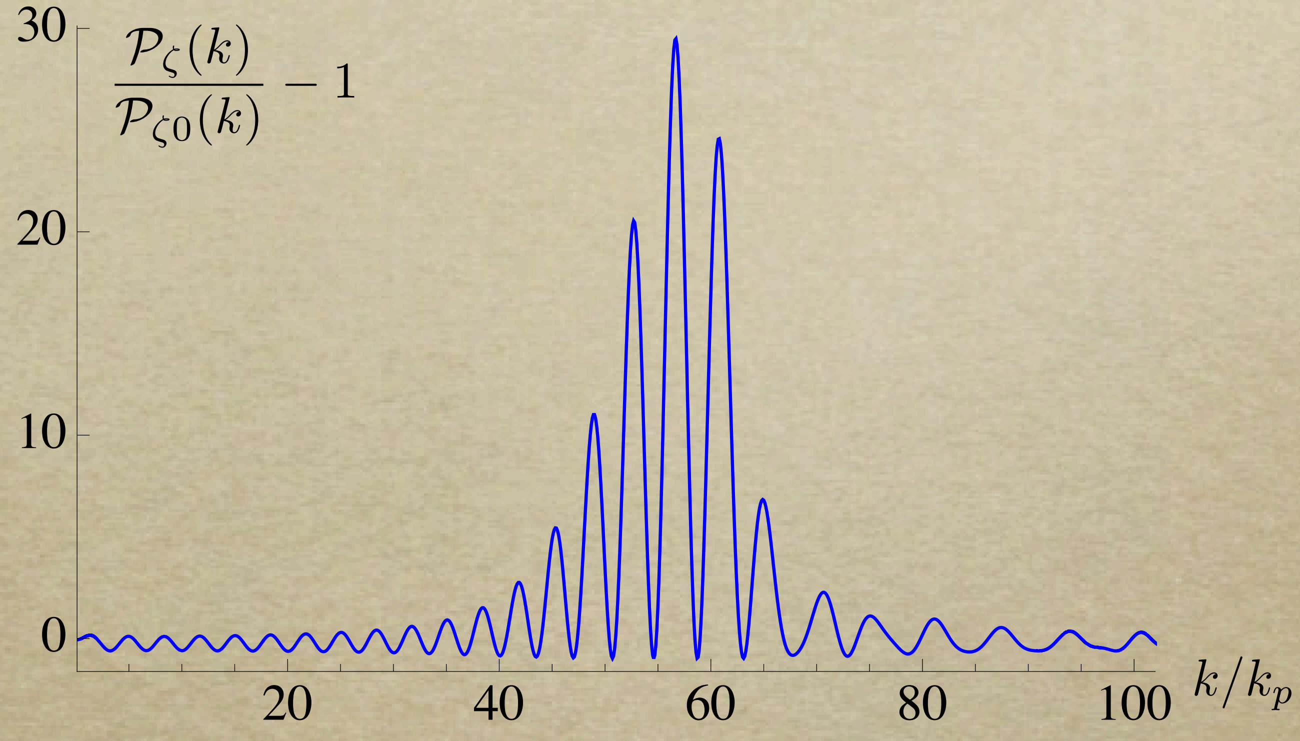


oscillations → sharp positive spikes!

k_p : comoving wave number exiting the horizon at KK excitation

Strong Resonance





Resonant effects depend non-linearly on $\psi_{\rm exc}$.

Strong Resonance

normalized fluctuation : $u_{\boldsymbol{k}} = (a^3 B)^{1/2} Q_{\boldsymbol{k}}$

$$0 = \ddot{u}_{\boldsymbol{k}} + \left\{ \frac{G}{B}\frac{k^2}{a^2} - \frac{M}{B} + \frac{\left(a^3 C\right)^{\cdot}}{a^3 B} - \frac{\left(a^{3/2} B^{1/2}\right)^{\cdot\cdot}}{a^{3/2} B^{1/2}} \right\} u_{\boldsymbol{k}}$$

$$B = 1 - 2\sum_{n\neq 0} \alpha_n^2 \frac{\psi_n^2}{\phi^2} + \frac{3}{2}\sum_{n\neq 0} \frac{\dot{\psi}_n^2}{V} + \cdots$$

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$$= f_{k\,\mathrm{eff}}^2 \left(\simeq \frac{k^2}{a^2} \quad \text{when inside the horizon and little KK modes} \right)$$

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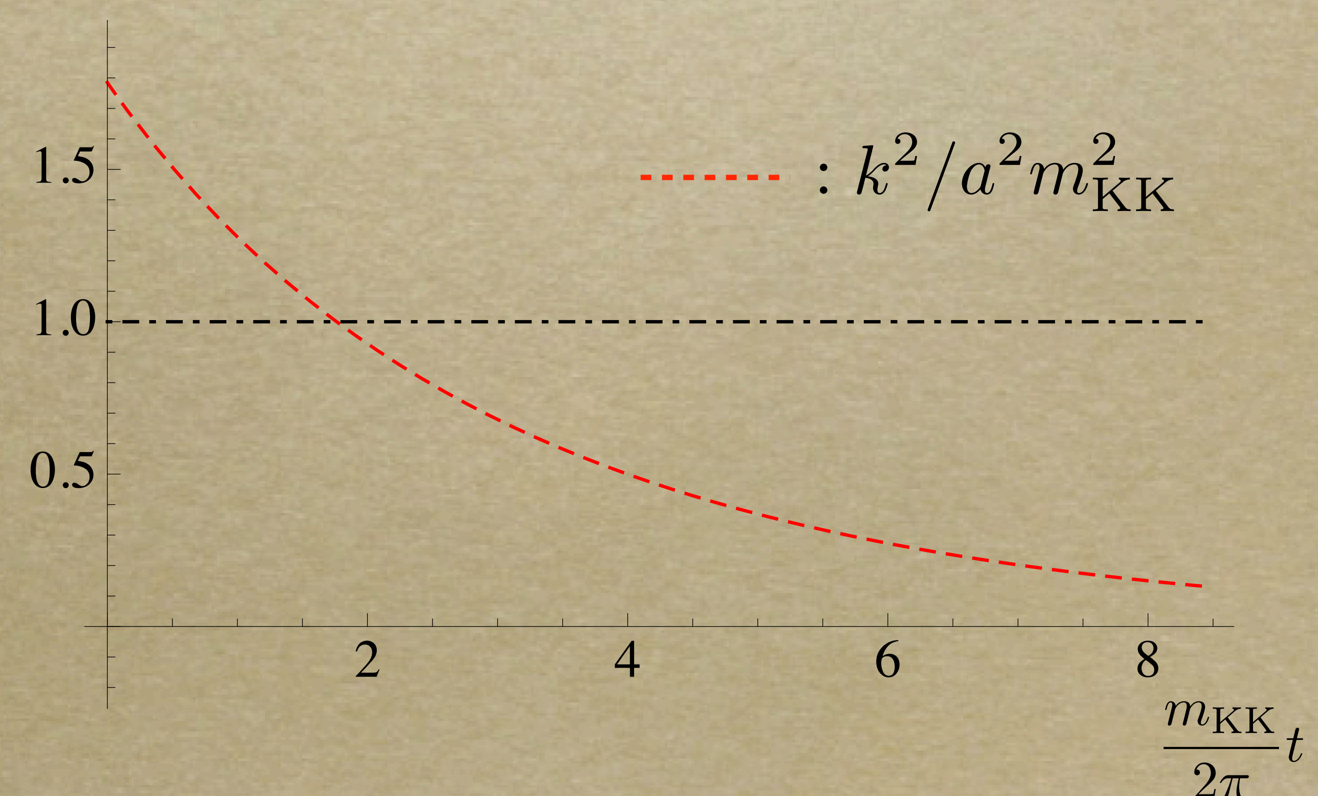
$\vdots$



Strong Resonance

normalized fluctuation : $u_{\boldsymbol{k}} = (a^3 B)^{1/2} Q_{\boldsymbol{k}}$

$$0 = \ddot{u}_{\boldsymbol{k}} + \underline{\left\{ \frac{G}{B}\frac{k^2}{a^2} - \frac{M}{B} + \frac{\left(a^3 C\right)^{\cdot}}{a^3 B} - \frac{\left(a^{3/2} B^{1/2}\right)^{\cdot\cdot}}{a^{3/2} B^{1/2}} \right\}} u_{\boldsymbol{k}}$$

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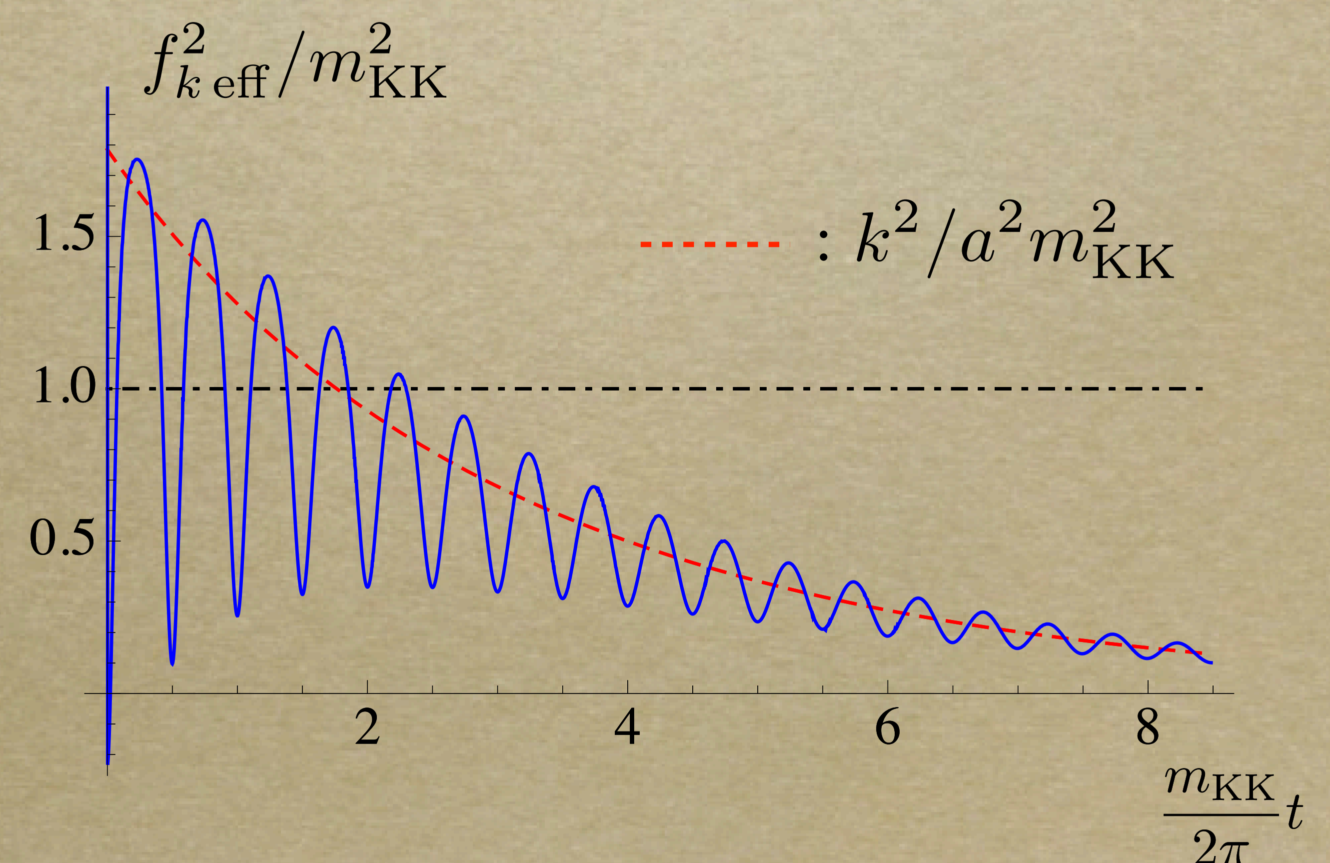

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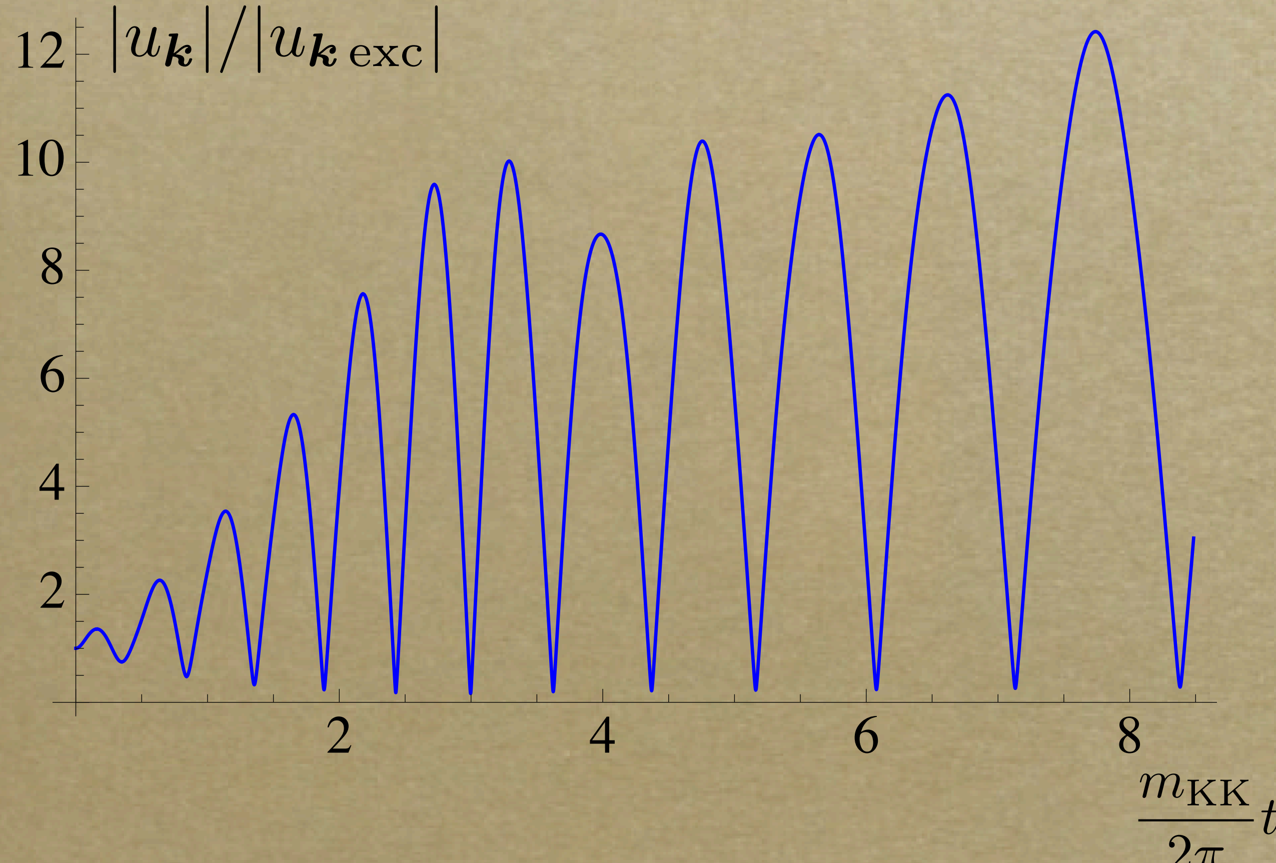

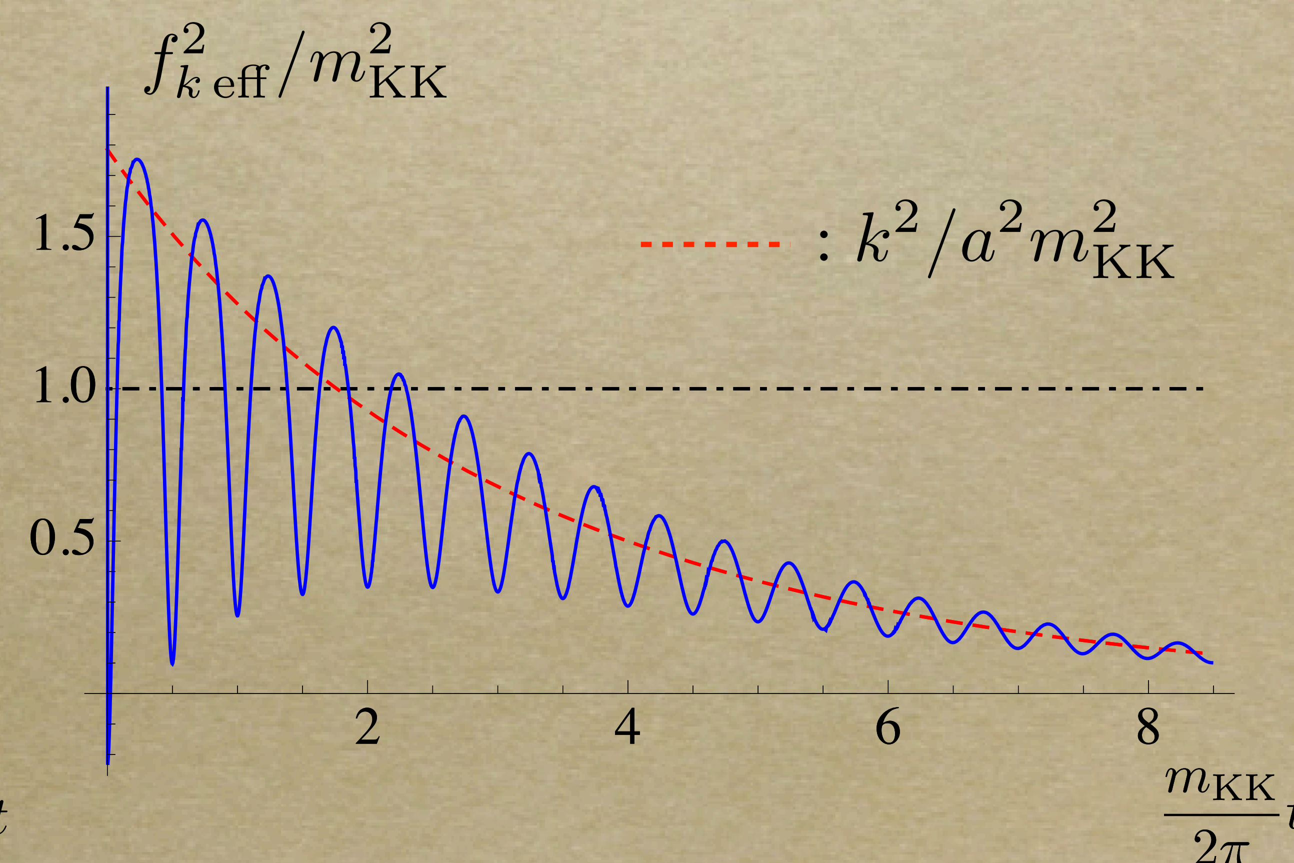

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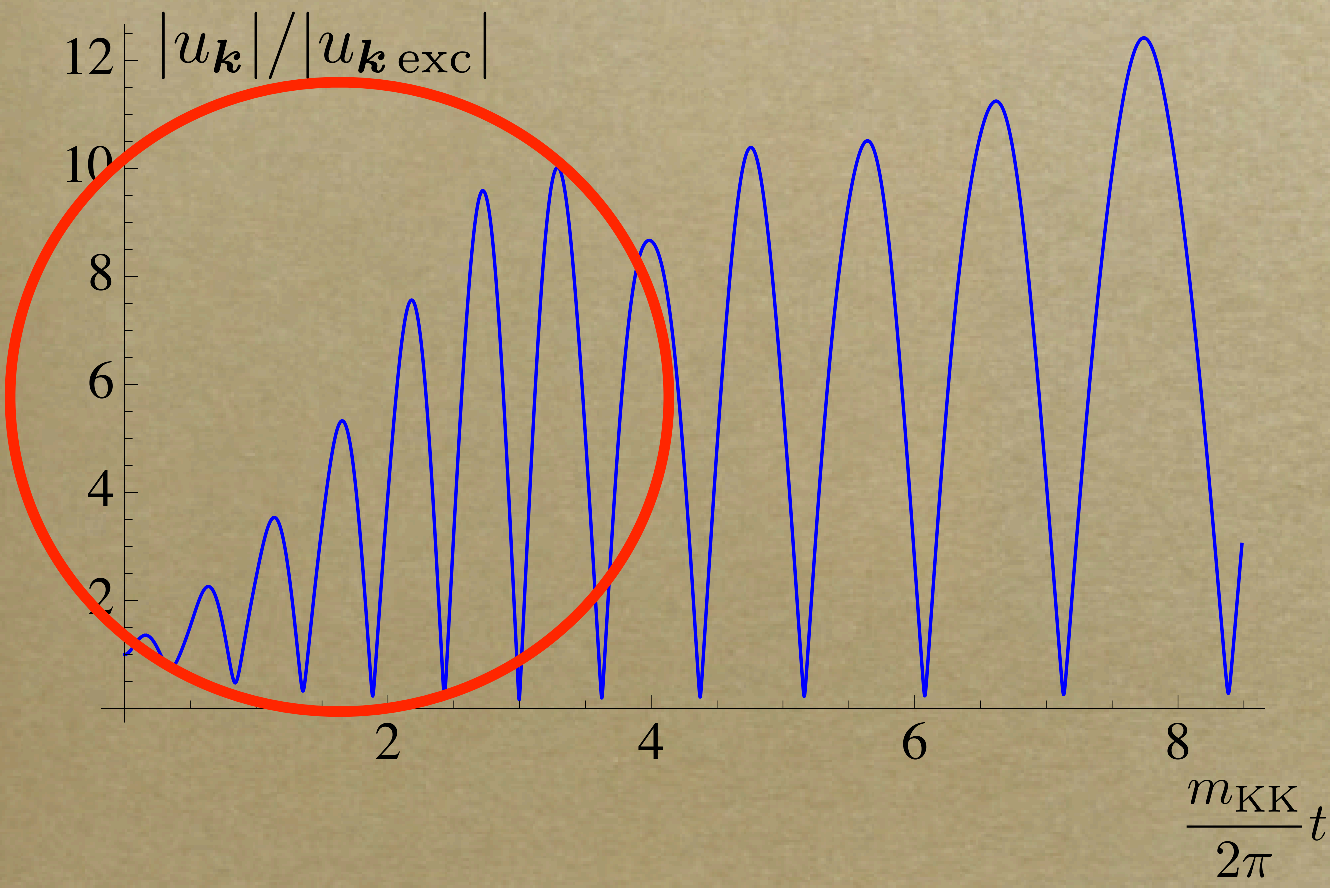
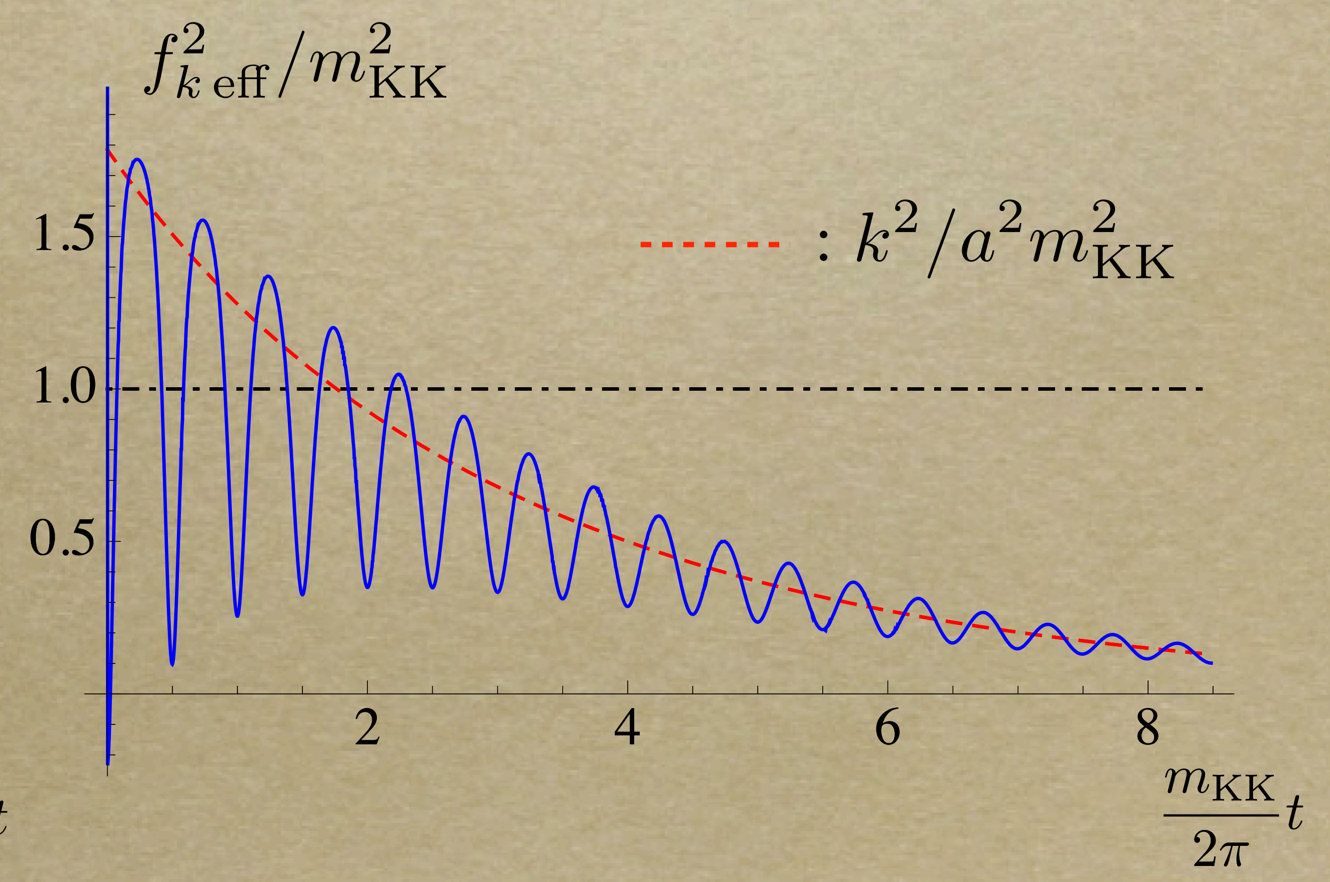
strong resonant amplification

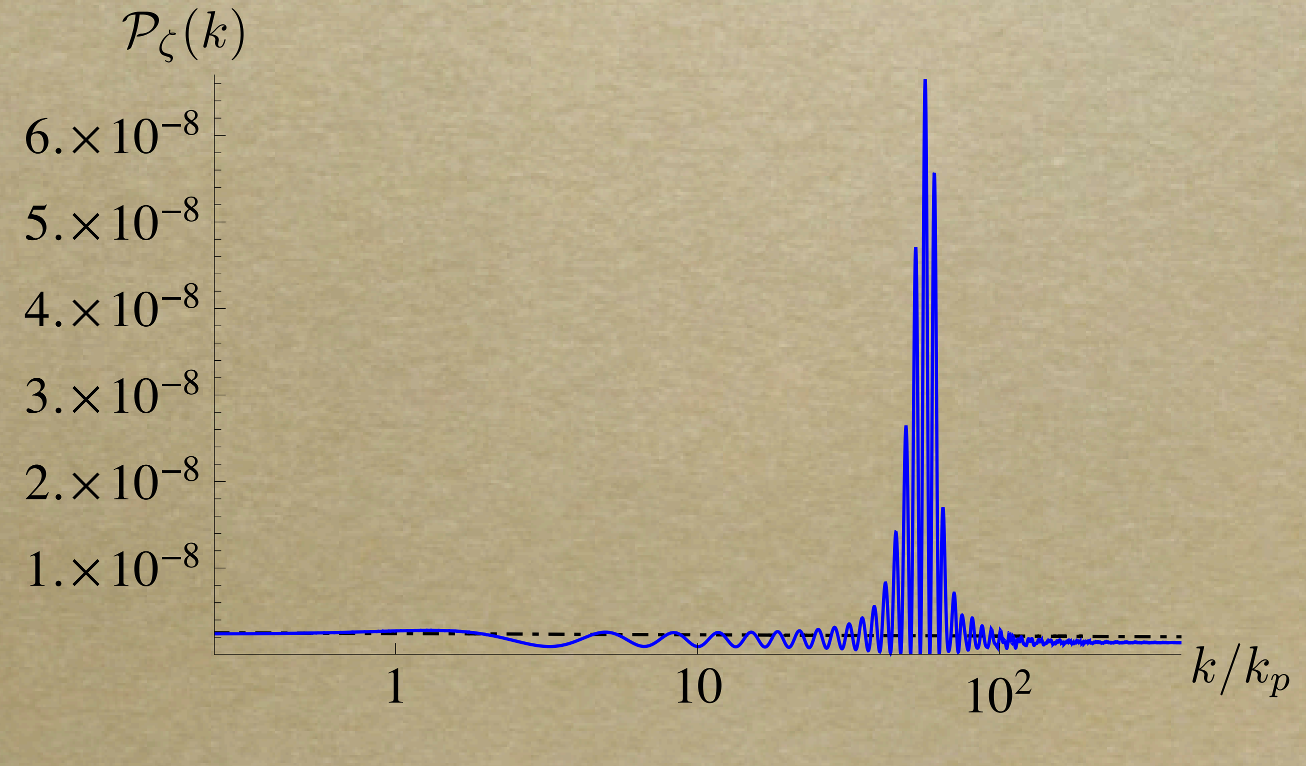
when $f_{k\,\mathrm{eff}}^2$ wildly oscillates around m_{KK}^2





Generation of Spikes

- strong resonant amplification is highly sensitive to the KK amplitude
- expansion of the universe quickly damps away strong resonant effects, leaving spikes in the pert. spectrum



What Causes Resonance?

$$\frac{\mathcal{L}}{\sqrt{-g}} = -V\left(\frac{1}{\gamma} + 2\gamma\sum_{n\neq 0}\alpha_n^2\frac{\psi_n^2}{\phi^2}\right) - \gamma\sum_{n\neq 0}\left\{\frac{1}{2}(\partial\psi_n)^2 - \frac{1}{6}\frac{\psi_n^2}{\phi^2}(\partial\phi)^2 + \frac{1}{3}\frac{\psi_n}{\phi}(\partial\phi\cdot\partial\psi_n)\right\}$$

$$+\frac{\gamma^3}{2V}\sum_{n\neq 0}\left\{(\partial\phi\cdot\partial\psi_n)^2 + \frac{1}{9}\frac{\psi_n^2}{\phi^2}\left((\partial\phi)^2\right)^2 - \frac{2}{3}\frac{\psi_n}{\phi}(\partial\phi)^2(\partial\phi\cdot\partial\psi_n)\right\} + \mathcal{O}(\psi_n^3)$$

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most significantly oscillates $f_{k\,\mathrm{eff}}$

Couplings with $\partial\phi$ source weak/strong resonance.

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Couplings with $\partial\phi$ source weak/strong resonance.

General Lesson : Kinetic couplings efficiently produce sharp resonant features in the perturbation spectrum.

Beyond Strong Resonance

$$\frac{\mathcal{L}}{\sqrt{-g}} = -V\left(\frac{1}{\gamma} + 2\gamma\sum_{n\neq 0}\alpha_n^2\frac{\psi_n^2}{\phi^2}\right) - \gamma\sum_{n\neq 0}\left\{\frac{1}{2}(\partial\psi_n)^2 - \frac{1}{6}\frac{\psi_n^2}{\phi^2}(\partial\phi)^2 + \frac{1}{3}\frac{\psi_n}{\phi}(\partial\phi\cdot\partial\psi_n)\right\}$$

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Cubic and higher order KK interactions become important for very large KK excitations.

Even stronger resonance?

Summary

- Wrapped brane inflation models possess KK degrees of freedom that can be excited during inflation.
- Brane's Nambu-Goto action gives kinetic couplings efficient in producing resonant signals in the perturbation spectrum.
- Weak resonance sources oscillations, and strong resonance sources sharp spikes.
- Resonant signals can be used to probe extra dim.

Future Directions

- observational consequences of resonant signals
- STRONGLY resonant non-Gaussianity Flauger et al. ’09
- explicit example

Thank you