Fingerprints of a Non-Inflationary Universe from Massive Fields

PERIMETER INSTITUTE

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Mostly based on joint work with

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and

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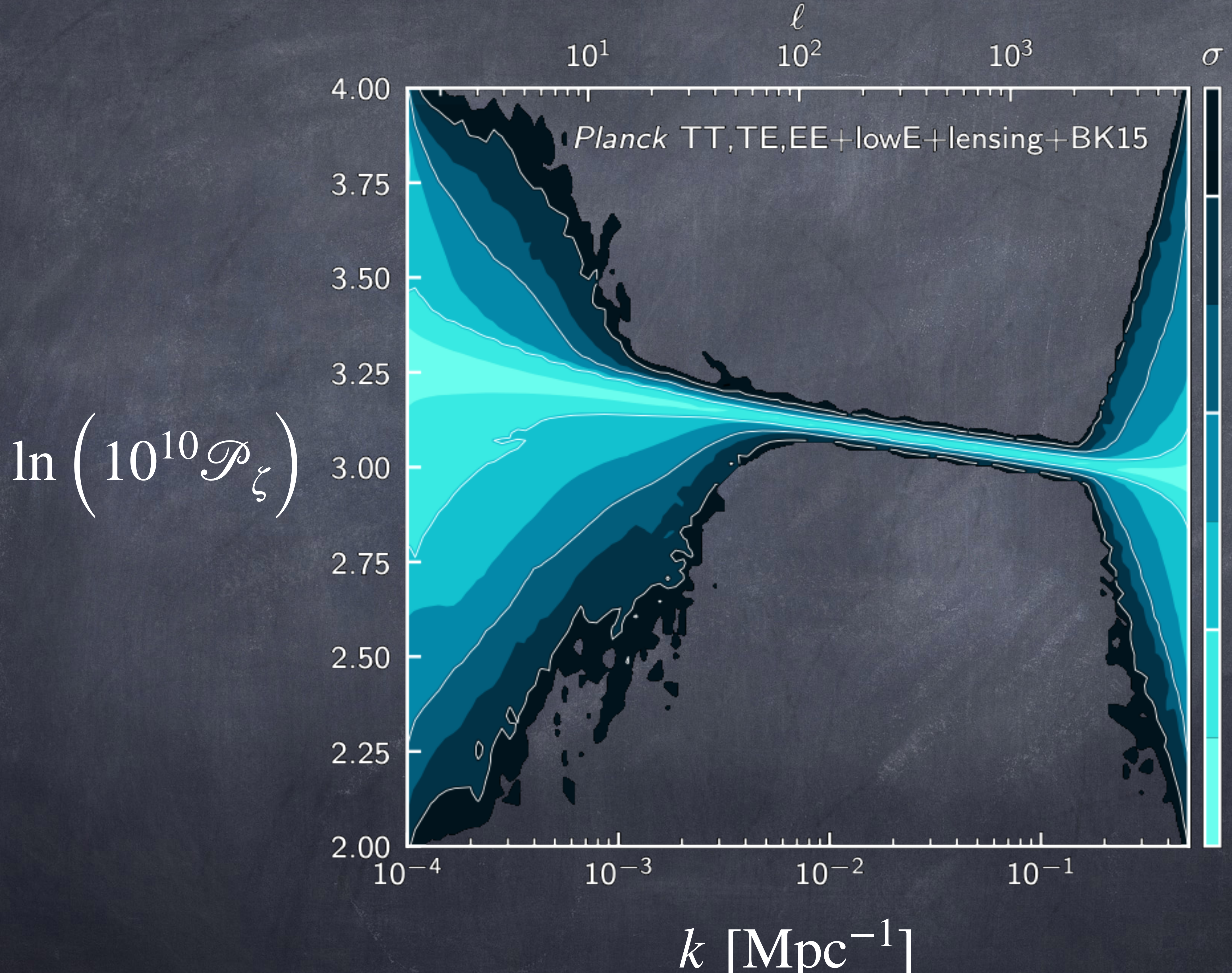
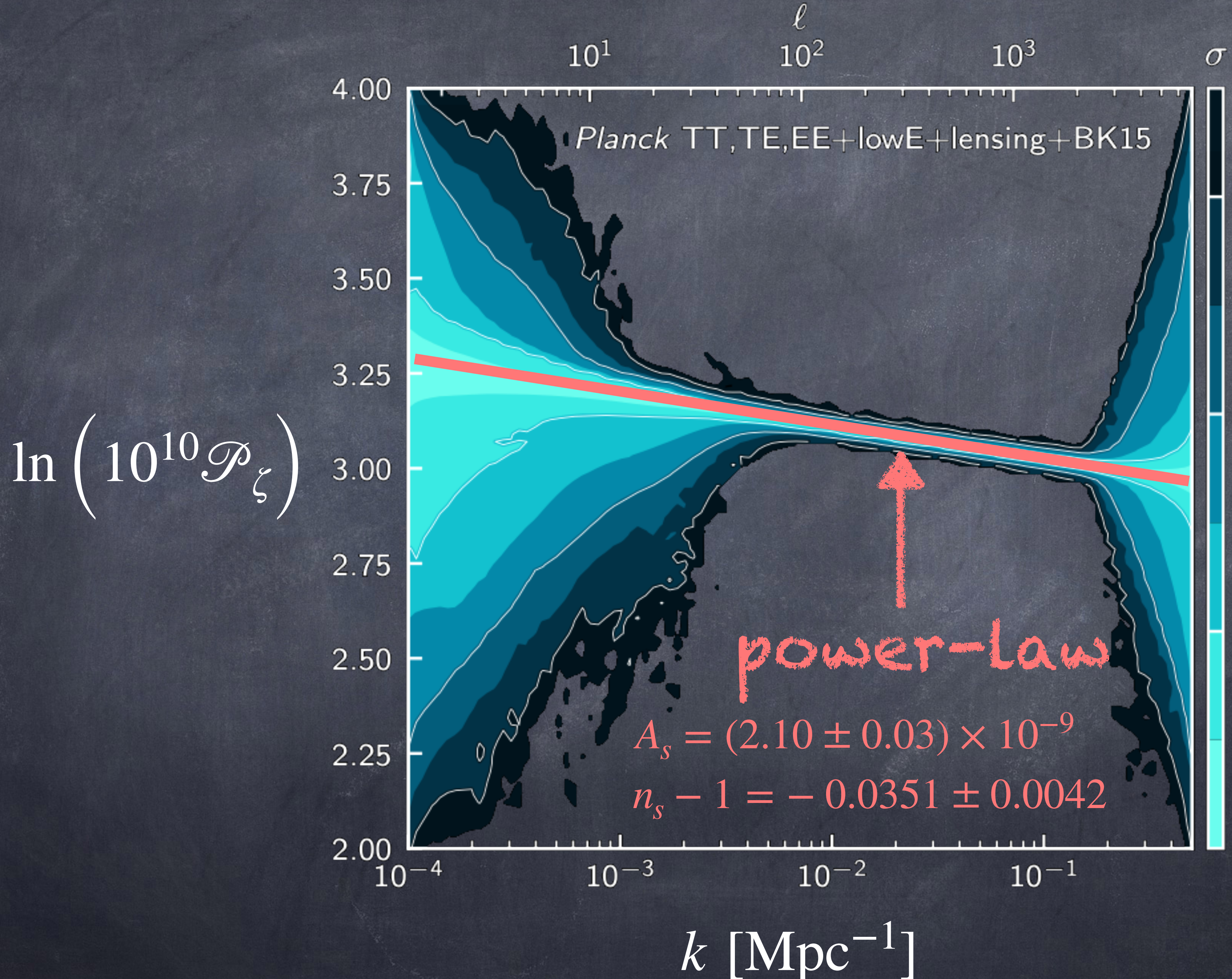
JCAP09(2024)026, arXiv:2405.11016

Part 1
What we know of the very early universe


Planck TT,TE,EE+lowE+lensing+BK15
ℓ
10^1
10^2
10^3
σ
3
2
1
4.00
3.75
3.50
3.25
3.00
2.75
2.50
2.25
2.00
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\ln\left(10^{10}\mathscr{P}_\zeta\right)$
k [Mpc^{-1}]

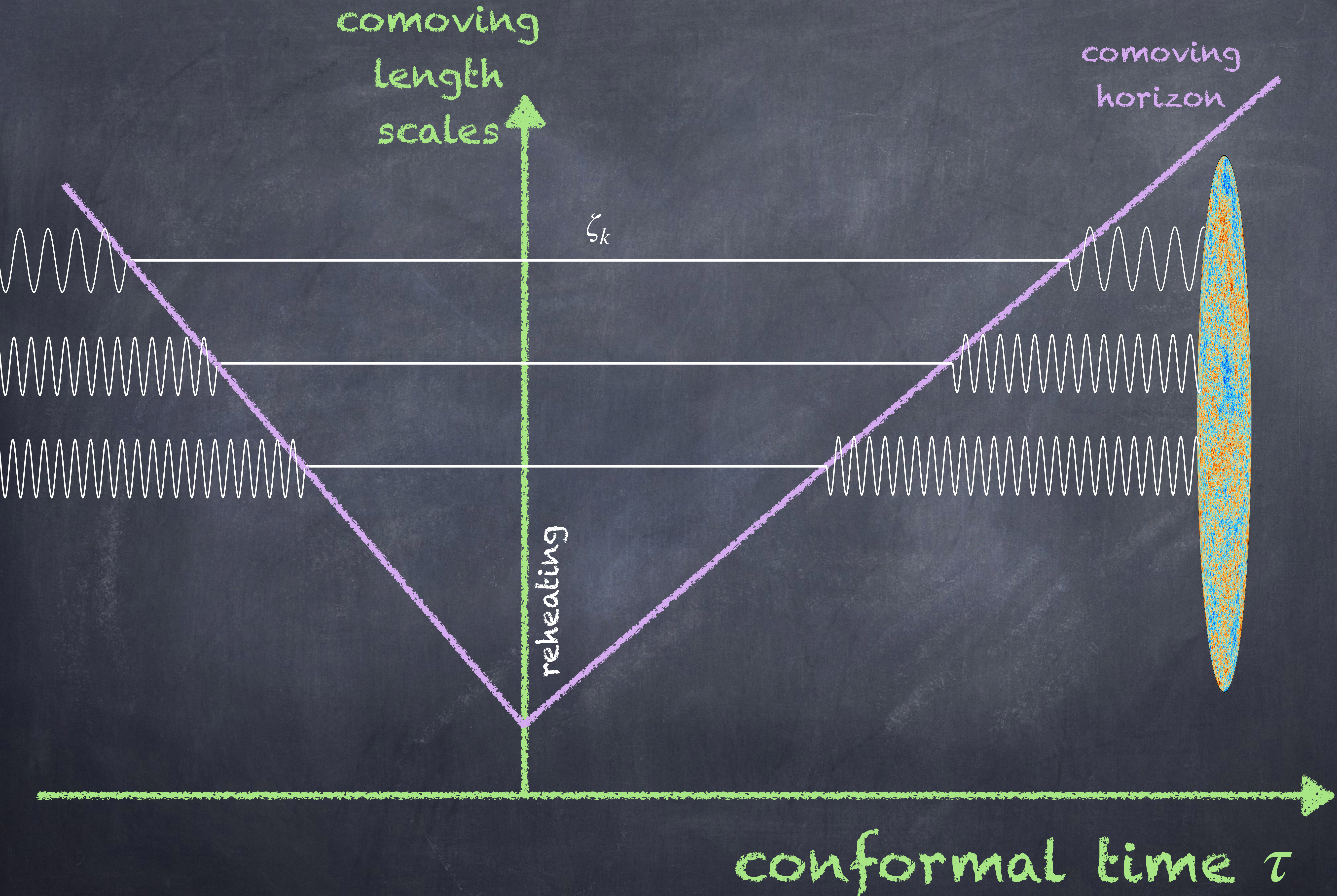
PLANCK (2018)



ℓ
10^1 10^2 10^3
σ
Planck TT,TE,EE+lowE+lensing+BK15
4.00 3.75 3.50 3.25 3.00 2.75 2.50 2.25 2.00
3 2 1
power-law
$A_s = (2.10 \pm 0.03) \times 10^{-9}$
$n_s - 1 = -0.0351 \pm 0.0042$
10^{-4} 10^{-3} 10^{-2} 10^{-1}
$\ln\left(10^{10}\mathscr{P}_\zeta\right)$
k [Mpc^{-1}]

PLANCK (2018)

Part 2a
How do we explain this?
(scenarios for the very early universe)



comoving length scales
comoving horizon
ζ_k
reheating
conformal time τ

Comoving horizon $= \dfrac{1}{a|H|}$, $\quad H \equiv \dfrac{\dot{a}}{a}$

Shrinking comoving horizon: $\dfrac{\mathrm{d}}{\mathrm{d}\tau}\left(\dfrac{1}{a|H|}\right) < 0$

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\left(\frac{1}{a|H|}\right) = \begin{cases} -(1-\epsilon) & (\text{if } H > 0) \\ 1-\epsilon & (\text{if } H < 0) \end{cases} \overset{!}{<} 0 \iff \begin{cases} w < -\frac{1}{3} & \text{and } H > 0 \\ w > -\frac{1}{3} & \text{and } H < 0 \end{cases}$$

$$1 - \epsilon = 1 + \frac{\dot{H}}{H^2} \overset{\text{Friedmann}}{=} -\frac{1}{2}(1+3w), \quad w \equiv \frac{P}{\rho}$$

Comoving horizon = $\dfrac{1}{a|H|}$, $\quad H \equiv \dfrac{\dot{a}}{a}$

Shrinking comoving horizon: $\dfrac{\mathrm{d}}{\mathrm{d}\tau}\left(\dfrac{1}{a|H|}\right) < 0$

$$\Longleftrightarrow \begin{cases} w < -\frac{1}{3} & \text{and } H > 0 \\ w > -\frac{1}{3} & \text{and } H < 0 \end{cases} \quad \Longleftrightarrow \begin{cases} \ddot{a} > 0 & \text{and } \dot{a} > 0 \\ \ddot{a} < 0 & \text{and } \dot{a} < 0 \end{cases}$$

$$\Longleftrightarrow \begin{cases} \text{expanding and inflating} \\ \text{contracting and decelerating} \end{cases}$$

Comoving horizon = $\dfrac{1}{a|H|}, \quad H \equiv \dfrac{\dot{a}}{a}$

Shrinking comoving horizon: $\dfrac{\mathrm{d}}{\mathrm{d}\tau}\left(\dfrac{1}{a|H|}\right) < 0$

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$$\Longleftrightarrow \begin{cases} \text{expanding and inflating} \\ \text{contracting and decelerating} \end{cases}$$

inflationary cosmology

Comoving horizon = $\dfrac{1}{a|H|}$, $\quad H \equiv \dfrac{\dot{a}}{a}$

Shrinking comoving horizon: $\dfrac{\mathrm{d}}{\mathrm{d}\tau}\left(\dfrac{1}{a|H|}\right) < 0$

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$$\Longleftrightarrow \begin{cases} \text{expanding and inflating} \\ \text{contracting and decelerating} \end{cases}$$

expanding and inflating → inflationary cosmology

contracting and decelerating → bouncing cosmology

Comoving horizon $= \dfrac{1}{a|H|}, \quad H \equiv \dfrac{\dot{a}}{a}$

Shrinking comoving horizon: $\dfrac{\mathrm{d}}{\mathrm{d}\tau}\left(\dfrac{1}{a|H|}\right) < 0$

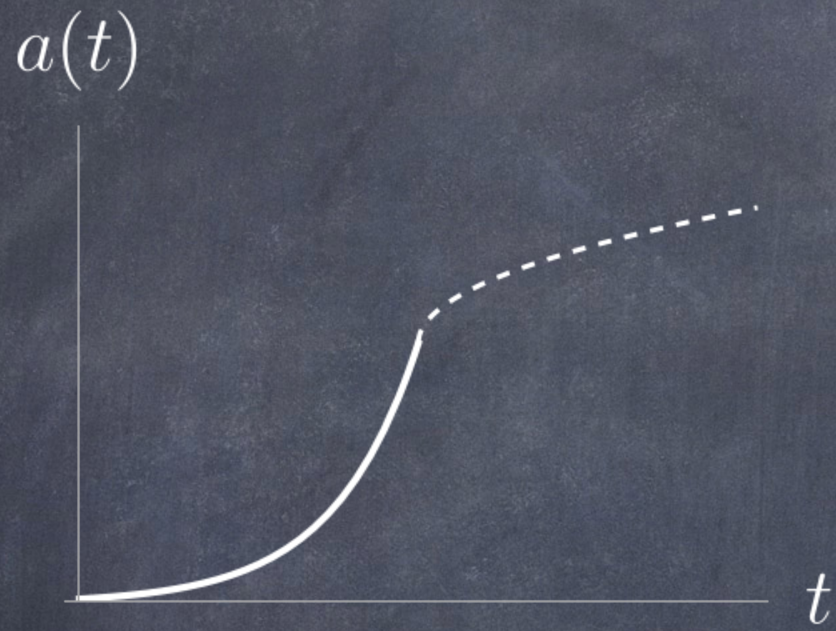
$$\Longleftrightarrow \begin{cases} w < -\frac{1}{3} & \text{and } H > 0 \\ w > -\frac{1}{3} & \text{and } H < 0 \end{cases} \qquad \Longleftrightarrow \begin{cases} \ddot{a} > 0 & \text{and } \dot{a} > 0 \\ \ddot{a} < 0 & \text{and } \dot{a} < 0 \end{cases}$$

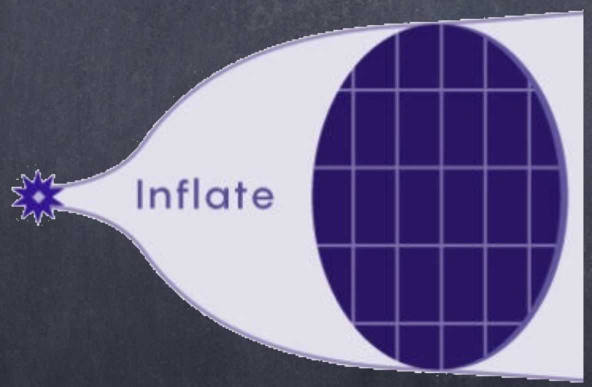
$\Longleftrightarrow$ { expanding and inflating → inflationary cosmology

contracting and decelerating → bouncing cosmology }

(typically the same requirement for the flatness problem)

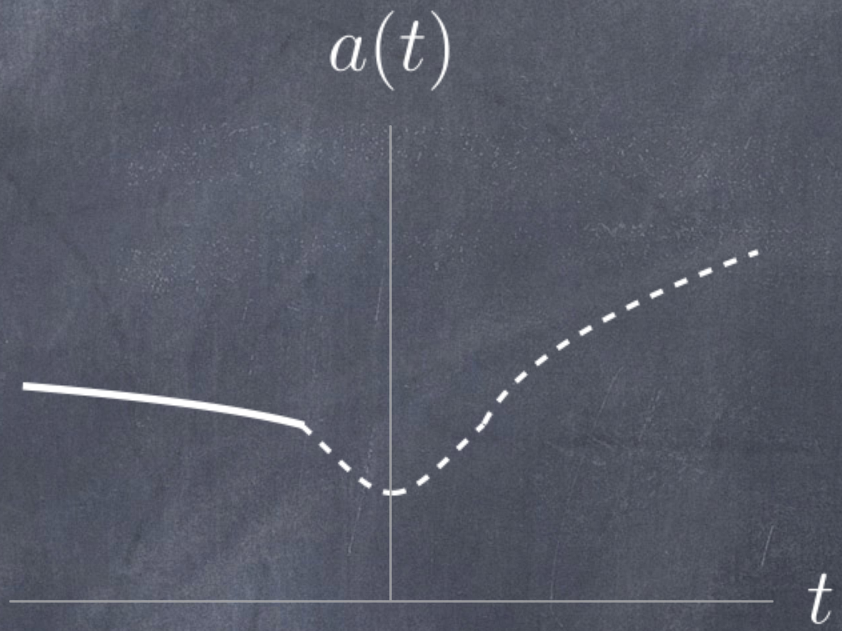
inflationary cosmology





Guth (1980),
...

contracting cosmology (before a bounce)



Gasperini-Veneziano (1993),
Khoury-Ovrut-Steinhardt-Turok (2001),
JQ+ (2014, ...),
...

Part 2b
What about the perturbations?

GR/modified gravity + single/multifield

canonical scalar/k-essence/Horndeski

$$\Longrightarrow \qquad S_s^{(2)} = \frac{1}{2}\int \mathrm{d}^3x\mathrm{d}\tau \left((v_s')^2 + \frac{z''}{z}v_s^2 - (\partial_i v_s)^2 \right)$$

$$\frac{z''}{z} = \frac{\nu^2 - 1/4}{\tau^2}, \qquad \nu \approx \frac{3}{2}$$

$$v_s = -\frac{\sqrt{-\pi\tau}}{2} H_\nu^{(1)}(-k\tau) \overset{-k\tau \gg 1}{\simeq} \frac{e^{-ik\tau}}{\sqrt{2k}}$$

$$\mathscr{P}_s(k) = \frac{k^3}{2\pi^2}\frac{|v_s|^2}{z^2} \overset{-k\tau \ll 1}{\sim} k^{3-2\nu}$$

Couple examples

(GR + BD + single minimally coupled scalar field of constant ϵ and constant c_s)

$$\frac{z''}{z} = \frac{a''}{a} \overset{!}{\approx} \frac{2}{\tau^2} \qquad \Leftrightarrow \qquad a(\tau) \sim \tau^{-1} \quad \text{or} \quad \tau^2$$

Couple examples

(GR + BD + single minimally coupled scalar field of constant ϵ and constant c_s)

de Sitter exponential expansion
(fast expansion)

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Couple examples

(GR + BD + single minimally coupled scalar field of constant ϵ and constant c_s)

de Sitter exponential expansion
(fast expansion)

$$\frac{z''}{z} = \frac{a''}{a} \overset{!}{\approx} \frac{2}{\tau^2} \qquad \Leftrightarrow \qquad a(\tau) \sim \tau^{-1} \quad \text{or} \quad \tau^2$$

matter-dominated contraction
(fast contraction)

Wands (1999)

Part 2c
What scenarios are consistent?

	inflation	matter bounce	genesis	ekpyrosis
scale factor	expands	contracts	expands	contracts
"speed"	fast	fast	slow	slow

More in the supplementary material

$$\langle\zeta^2\rangle \begin{cases} A_s = (2.10 \pm 0.03) \times 10^{-9} \\ n_s - 1 = -\,0.0351 \pm 0.0042 \end{cases}$$

$$\langle h_{ij}^2\rangle \qquad r = \frac{A_t}{A_s} < 0.036 \;(95\,\%\ \mathrm{CL})$$

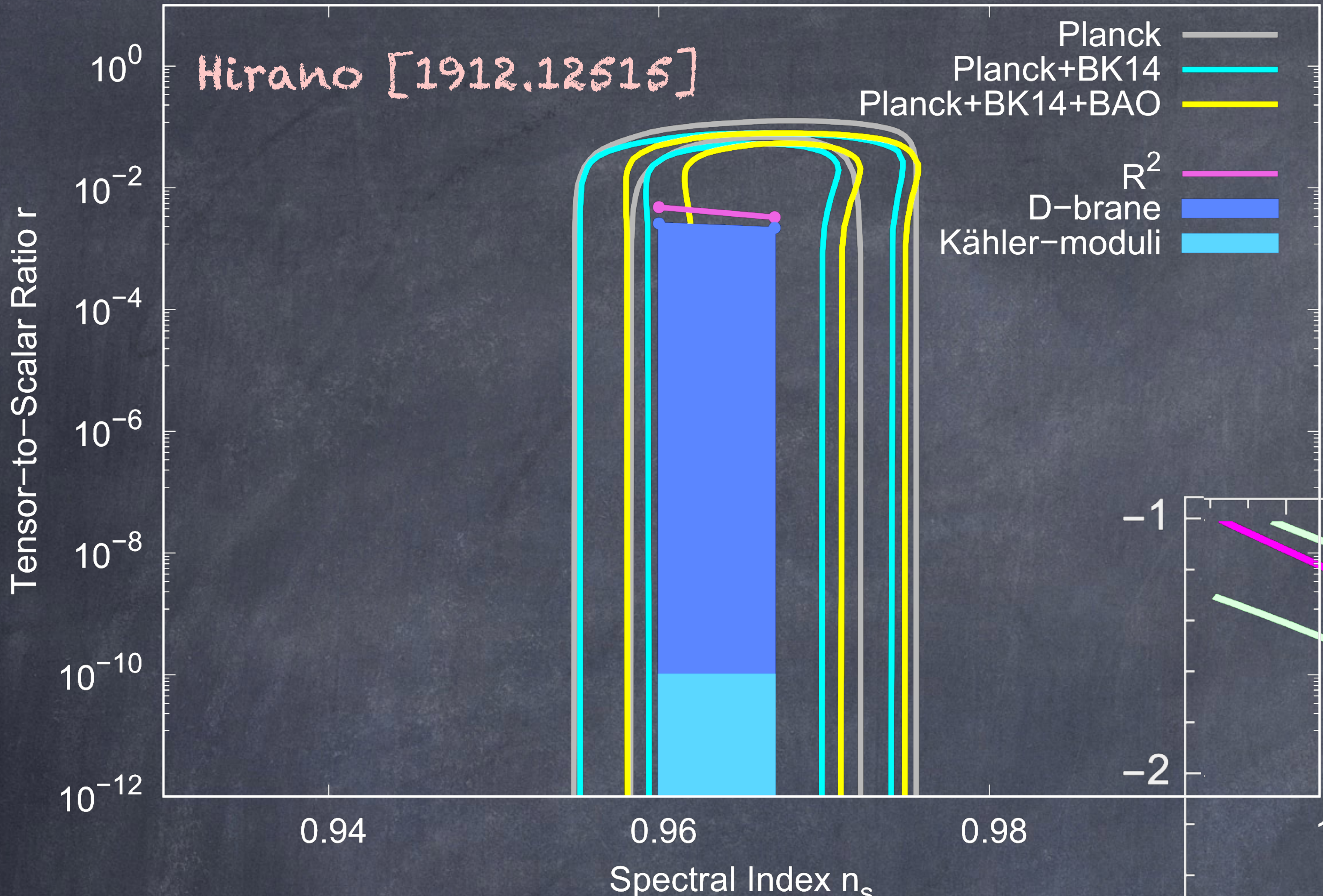
$$\langle\zeta^3\rangle \begin{cases} f_{\mathrm{NL}}^{\mathrm{local}} = -\,0.9 \pm 5.1 \\ f_{\mathrm{NL}}^{\mathrm{equil}} = -\,26 \pm 47 \\ f_{\mathrm{NL}}^{\mathrm{ortho}} = -\,38 \pm 24 \end{cases}$$

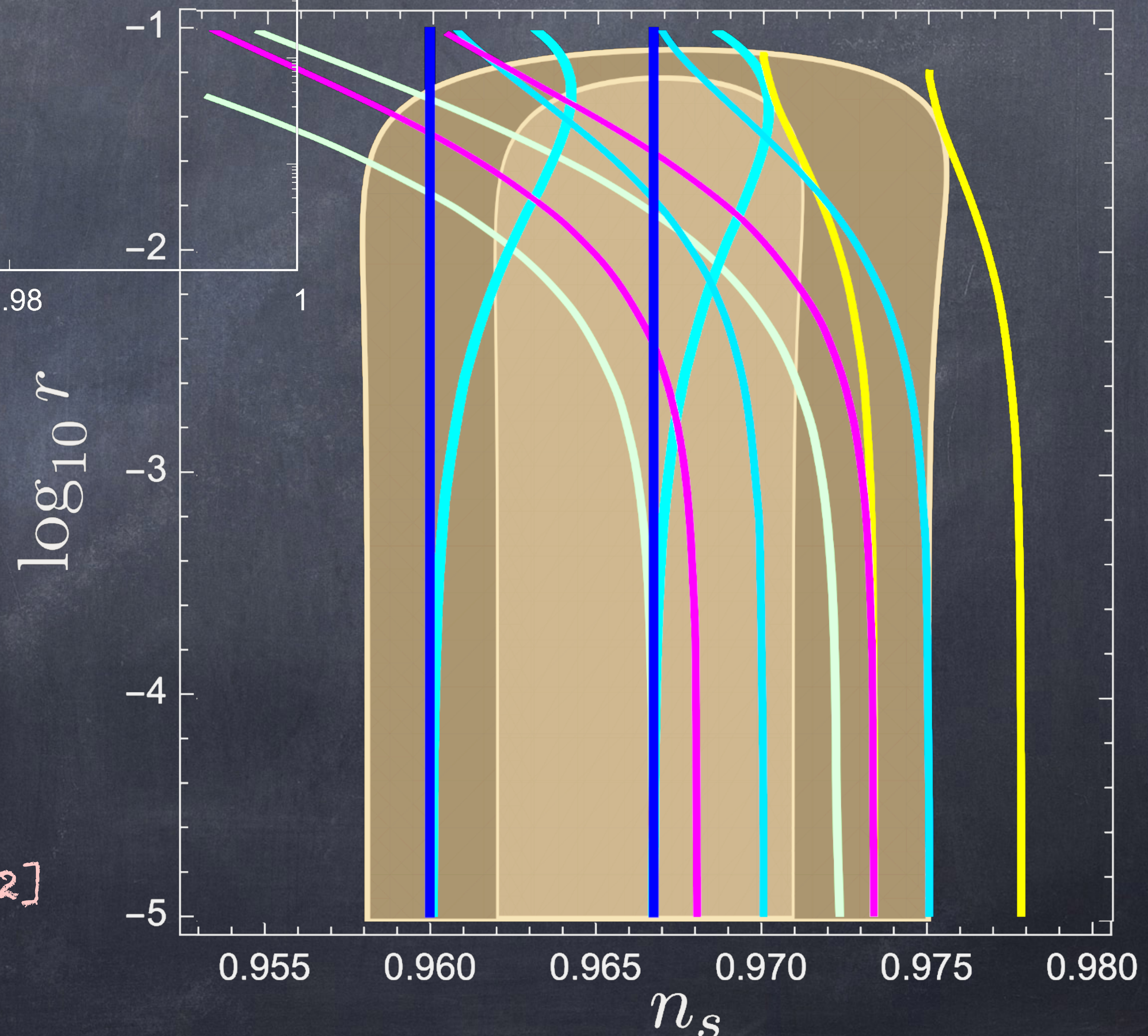
$$\langle\zeta^4\rangle \qquad g_{\mathrm{NL}}^{\mathrm{local}} = (-5.8 \pm 6.5) \times 10^4$$

$$\ldots$$

all consistent with zero

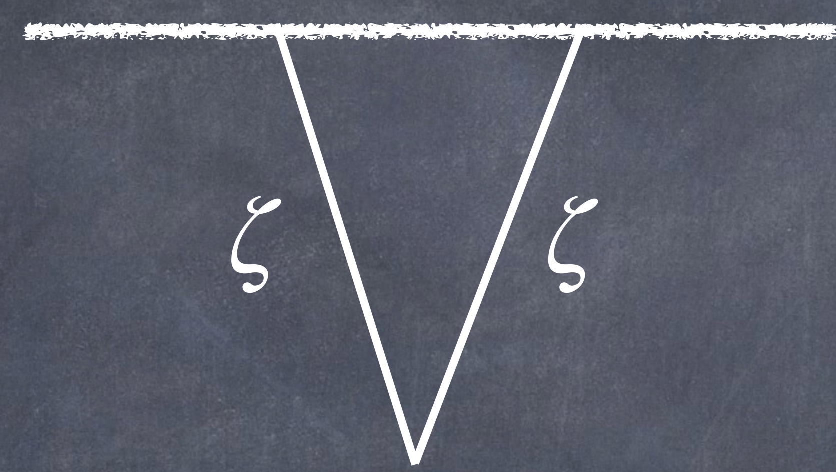
PLANCK (2018)


Hirano [1912.12515]
Planck
Planck+BK14
Planck+BK14+BAO
R2
D−brane
Kähler−moduli
Tensor−to−Scalar Ratio r
Spectral Index n_s
0.94
0.96
0.98
1


Kallosh-Linde [2110.10902]
log10 r
n_s
0.955
0.960
0.965
0.970
0.975
0.980
−1
−2
−3
−4
−5

Part 3
We want to do better and
have more to look after!
(add massive fields)

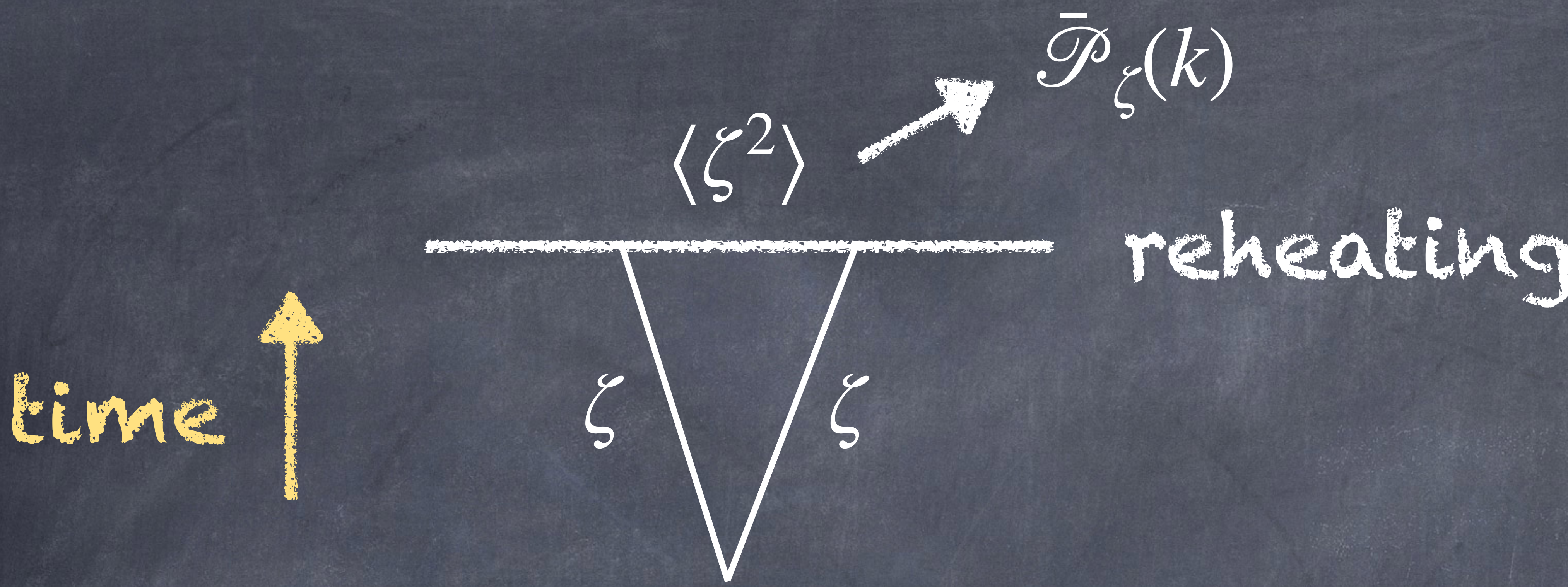
$\langle \zeta^2 \rangle \rightarrow \bar{\mathcal{P}}_\zeta(k)$

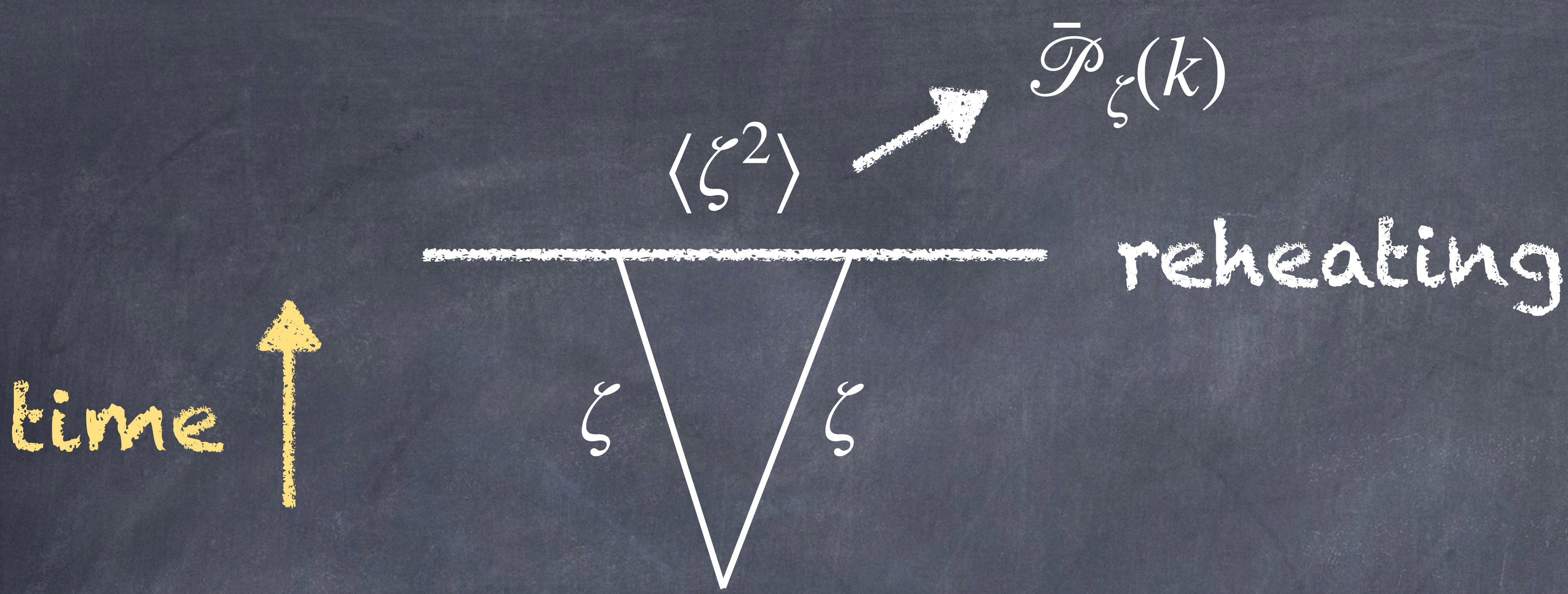


reheating

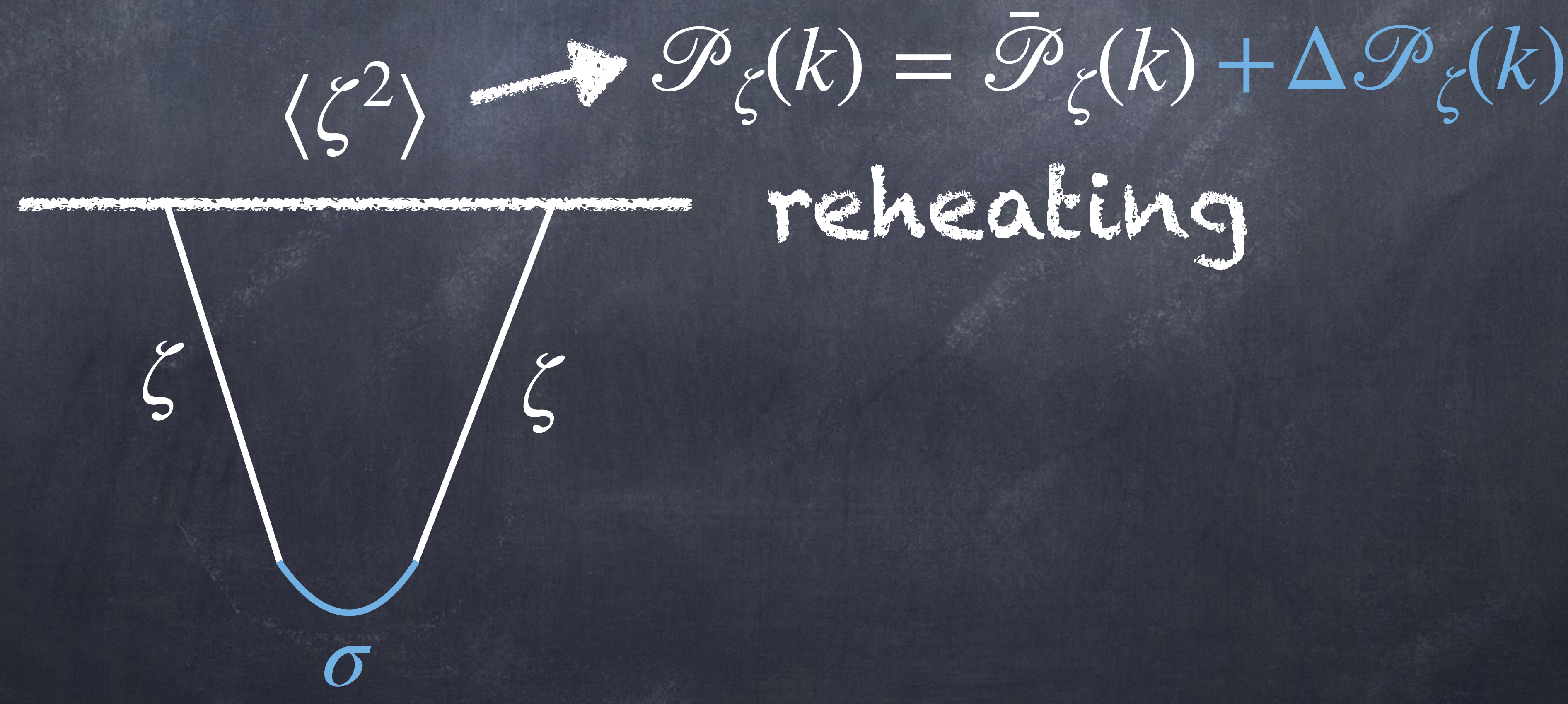
time

$\langle \zeta\zeta \rangle \longrightarrow \langle \mathrm{in} | \mathrm{in} \rangle$


$\bar{\mathcal{P}}_\zeta(k)$
$\langle \zeta^2 \rangle$
reheating
time
ζ
ζ



Add interaction with massive field σ



Quantum vacuum:

$$\mathrm{d}s^2 = a(\tau)^2(-\mathrm{d}\tau^2 + \mathrm{d}\vec{x}^2)$$

large k
early time $\Rightarrow \quad \partial_\tau^2 \zeta_k + k^2 \zeta_k = 0 \quad \Rightarrow \quad \zeta_k(\tau) \sim e^{-ik\tau}$

Massive spectator fields:

$$\mathrm{d}s^2 = -\,\mathrm{d}t^2 + a(t)^2 \mathrm{d}\vec{x}^2$$

large m_σ
early time $\Rightarrow \quad \partial_t^2 \sigma + m_\sigma^2 \sigma = 0 \quad \Rightarrow \quad \sigma(t) \sim e^{\pm i m_\sigma t}$

$$a\,\mathrm{d}\tau = \mathrm{d}t$$

in-in:

free theory vacuum

$$\langle\Omega|\,\hat{\zeta}^2\,|\Omega\rangle = \langle 0|\left(\bar{T}e^{i\int \mathrm{d}\tau\,\mathscr{H}_{\rm int}}\right)\hat{\zeta}^2\left(Te^{-i\int \mathrm{d}\tau\,\mathscr{H}_{\rm int}}\right)|0\rangle$$

$$= \underbrace{\langle 0|\,\hat{\zeta}^2\,|0\rangle}_{\bar{\mathscr{P}}_\zeta(k)} + \underbrace{2\mathrm{Im}\langle 0|\,\hat{\zeta}^2\int \mathrm{d}\tau\,\mathscr{H}_{\rm int}\,|0\rangle}_{\Delta\mathscr{P}_\zeta(k)} + \ldots$$

interaction vacuum

$$\Rightarrow \quad \frac{\Delta\mathscr{P}_\zeta}{\bar{\mathscr{P}}_\zeta} \sim 2\mathrm{Im}\int \mathrm{d}\tau\,\sigma(\partial\zeta)^2$$

$$\int \mathrm{d}\tau\, e^{\pm i m_\sigma t} e^{-2ik\tau}$$

$$\int \mathrm{d}\tau\, e^{\pm i m_\sigma t} e^{-2ik\tau}$$ $\longrightarrow$ highly oscillatory integrals average to zero

$\longrightarrow$ heavy fields can usually be integrated out in low-energy effective field theories

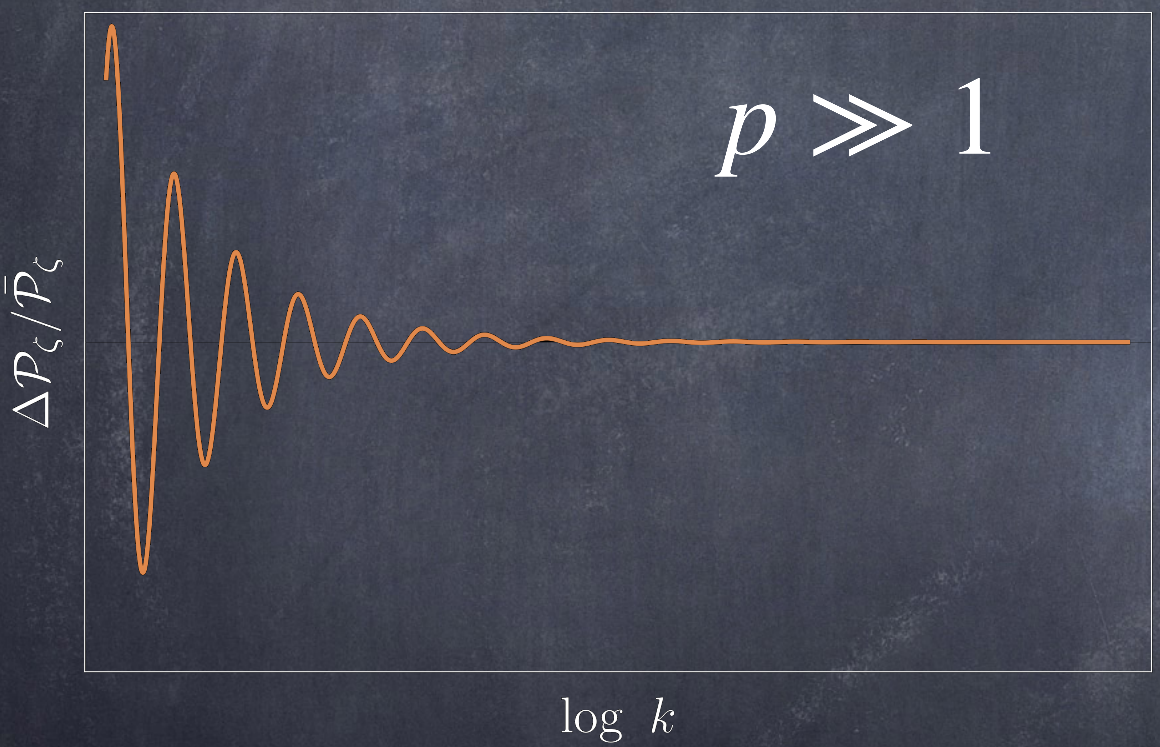
Except for resonance (saddle point) when

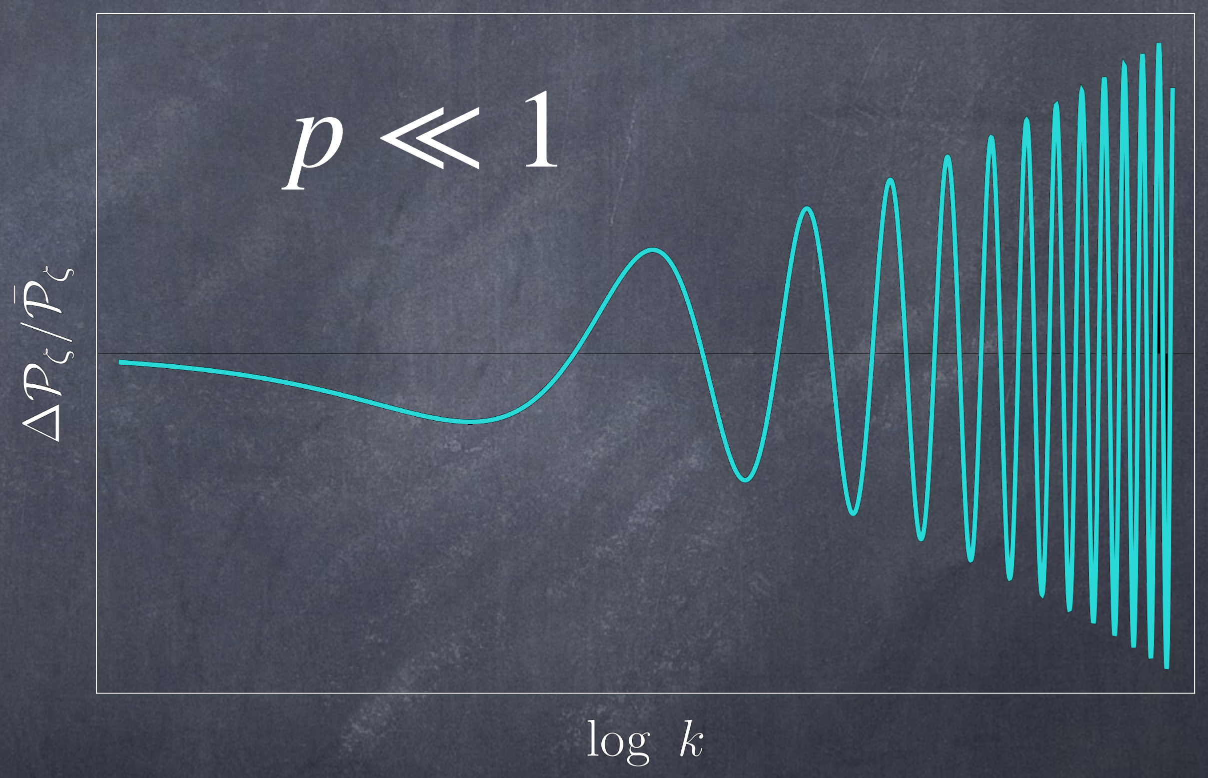
$$\frac{\mathrm{d}}{\mathrm{d}\tau}\left(\pm i m_\sigma t - 2ik\tau\right)\Big|_{\tau=\tau_{\rm res}} = 0 \quad \Rightarrow \quad m_\sigma = \frac{2k}{a(\tau_{\rm res})}$$

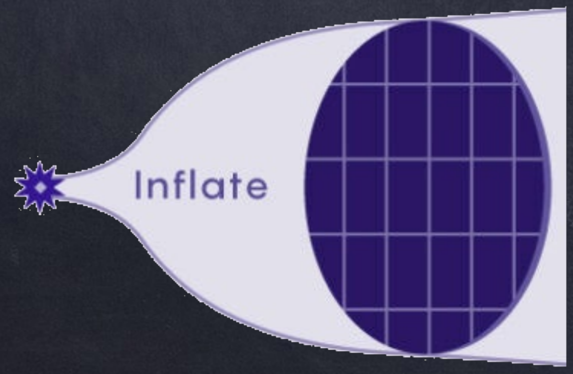
Chen (2011, 2012), ...

$$a(t) \propto |t|^p$$

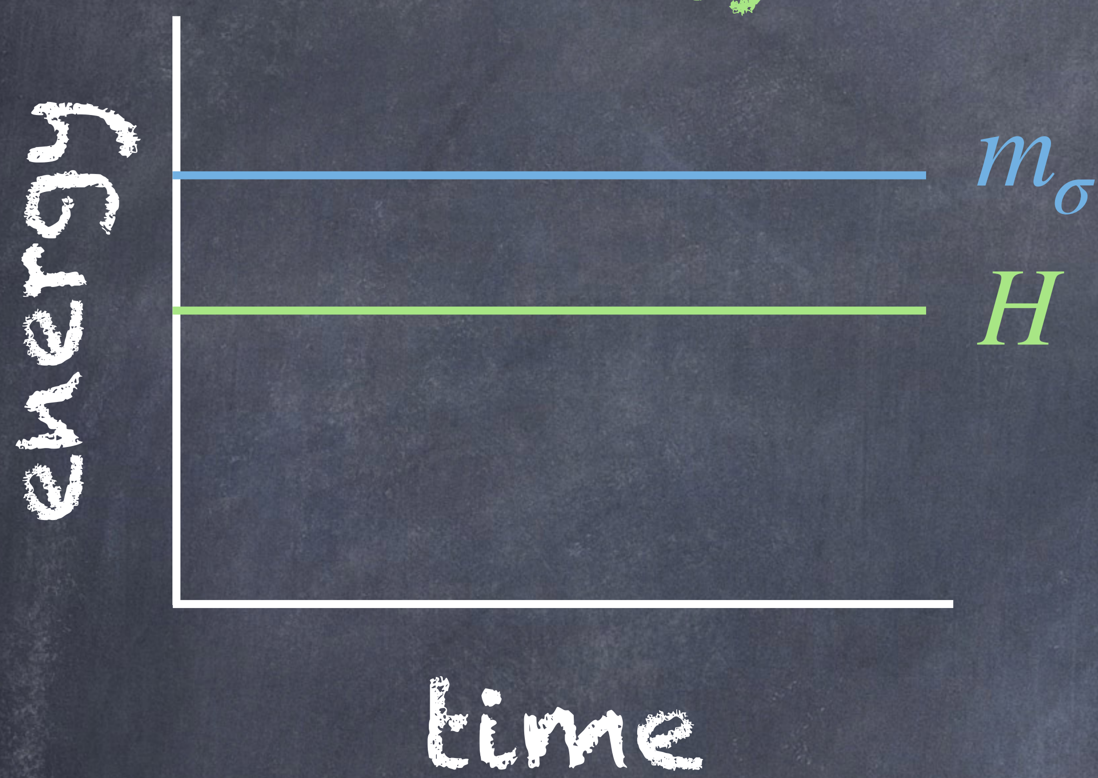
$$\frac{\Delta\mathscr{P}_\zeta}{\bar{\mathscr{P}}_\zeta} \sim \mathrm{Im}\int \mathrm{d}\tau\, e^{\pm i m_\sigma t} e^{-2ik\tau} \sim k^{-\frac{3}{2}+\frac{1}{2p}} \sin\left(k^{1/p}\right)$$







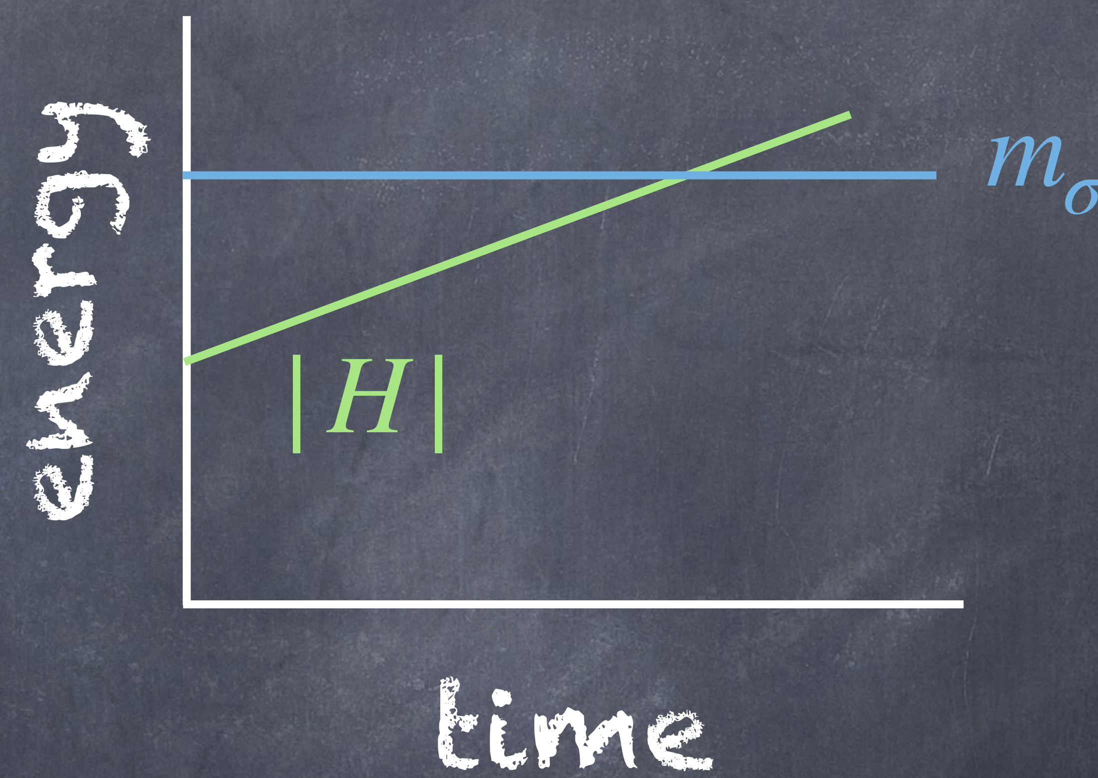
inflationary cosmology



cosmological collider

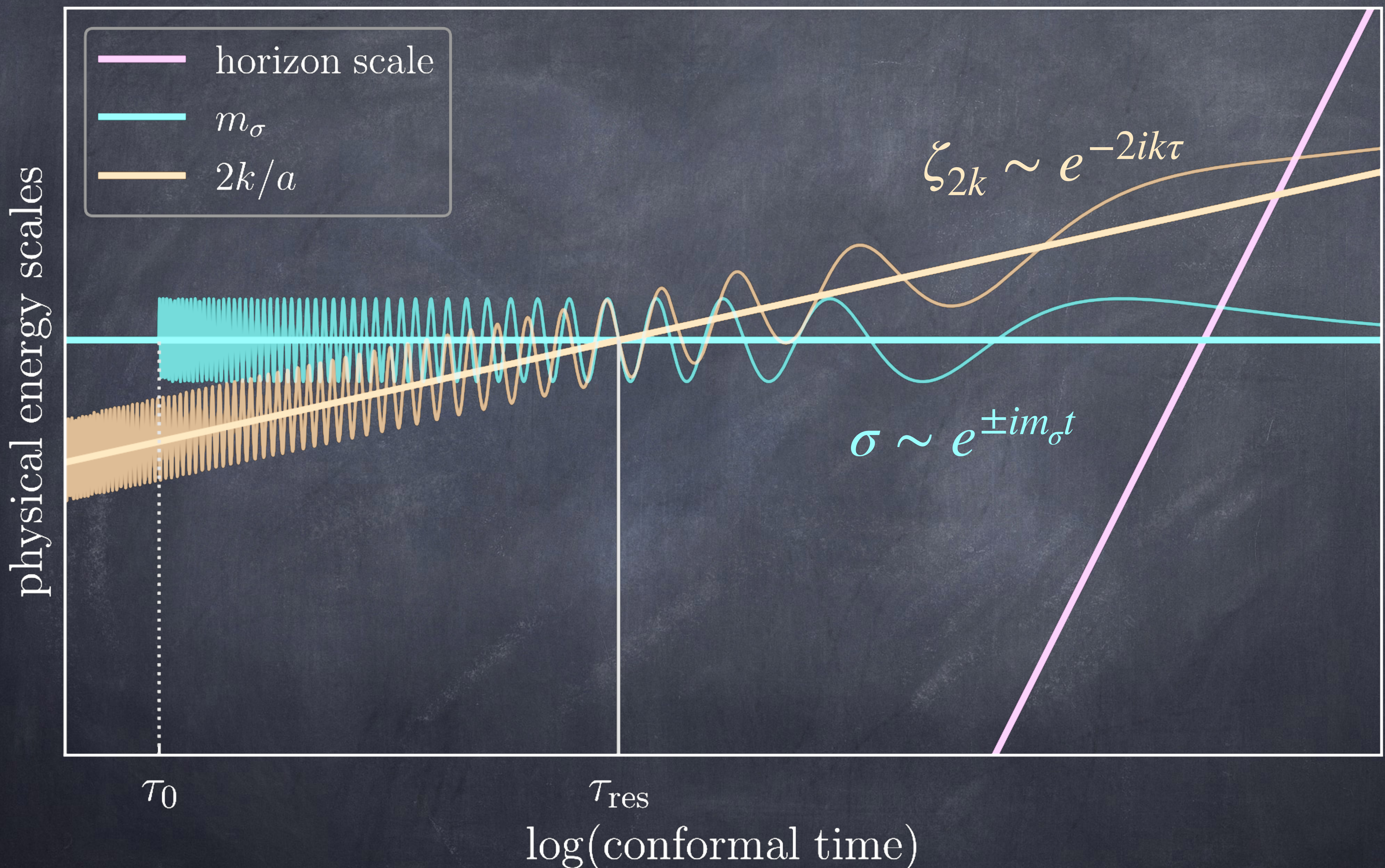
Chen and Wang (2009),
Arkani-Hamed and Maldacena (2015),
...

contracting cosmology (before a bounce)



particle scanner

Chen–Loeb–Xianyu (2019)



JQ-Chen-Ebadi (2024)

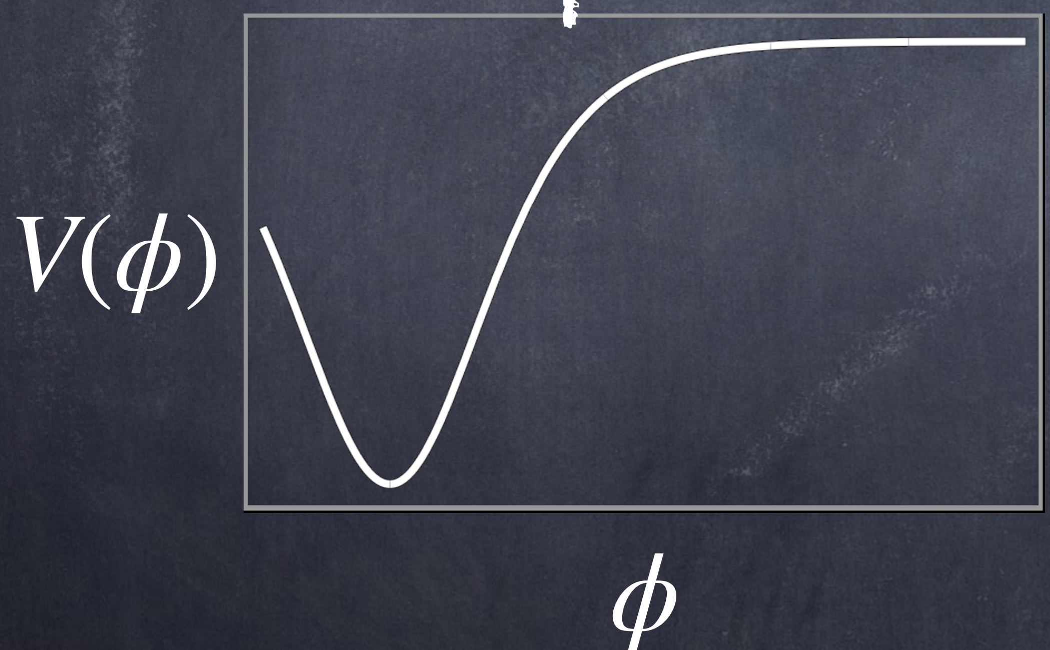
Part 4a

Modelling massive fields

We do not know what degrees of freedom there are at high energies…

We do not know what degrees of freedom there are at high energies...

We hope for...



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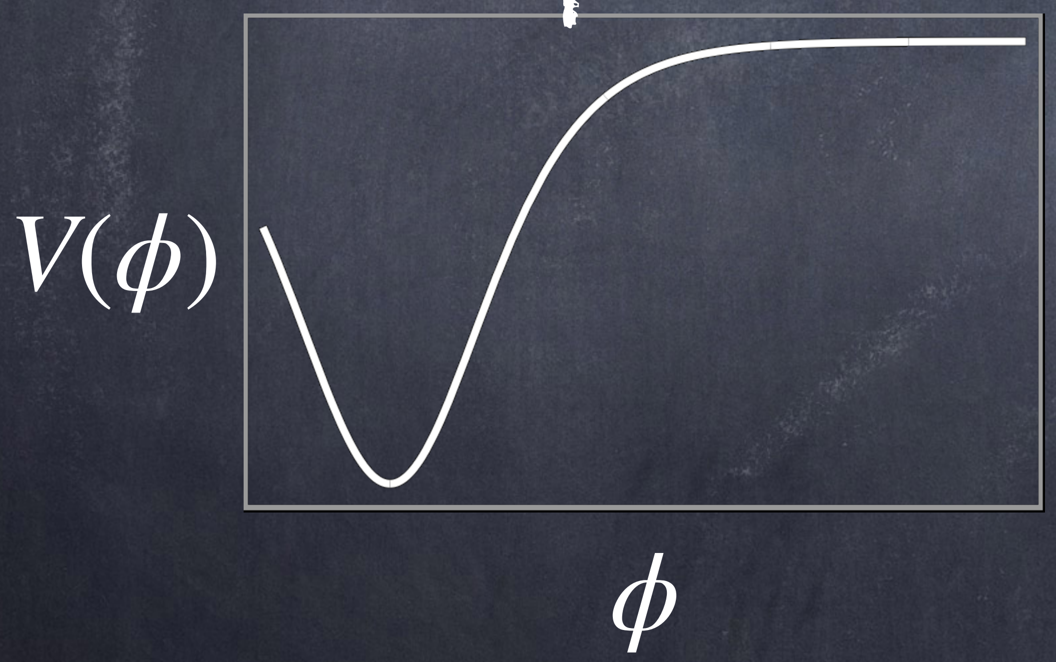
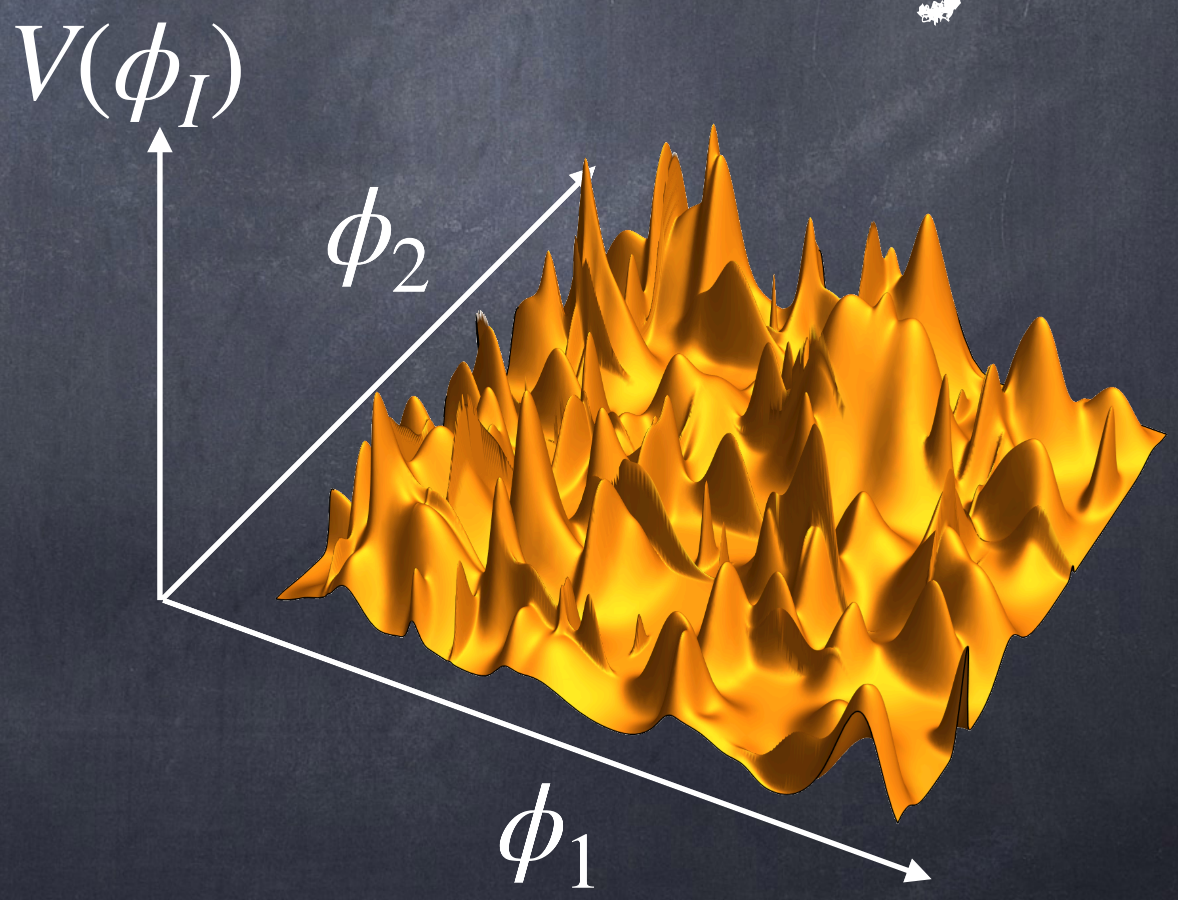


But the reality...



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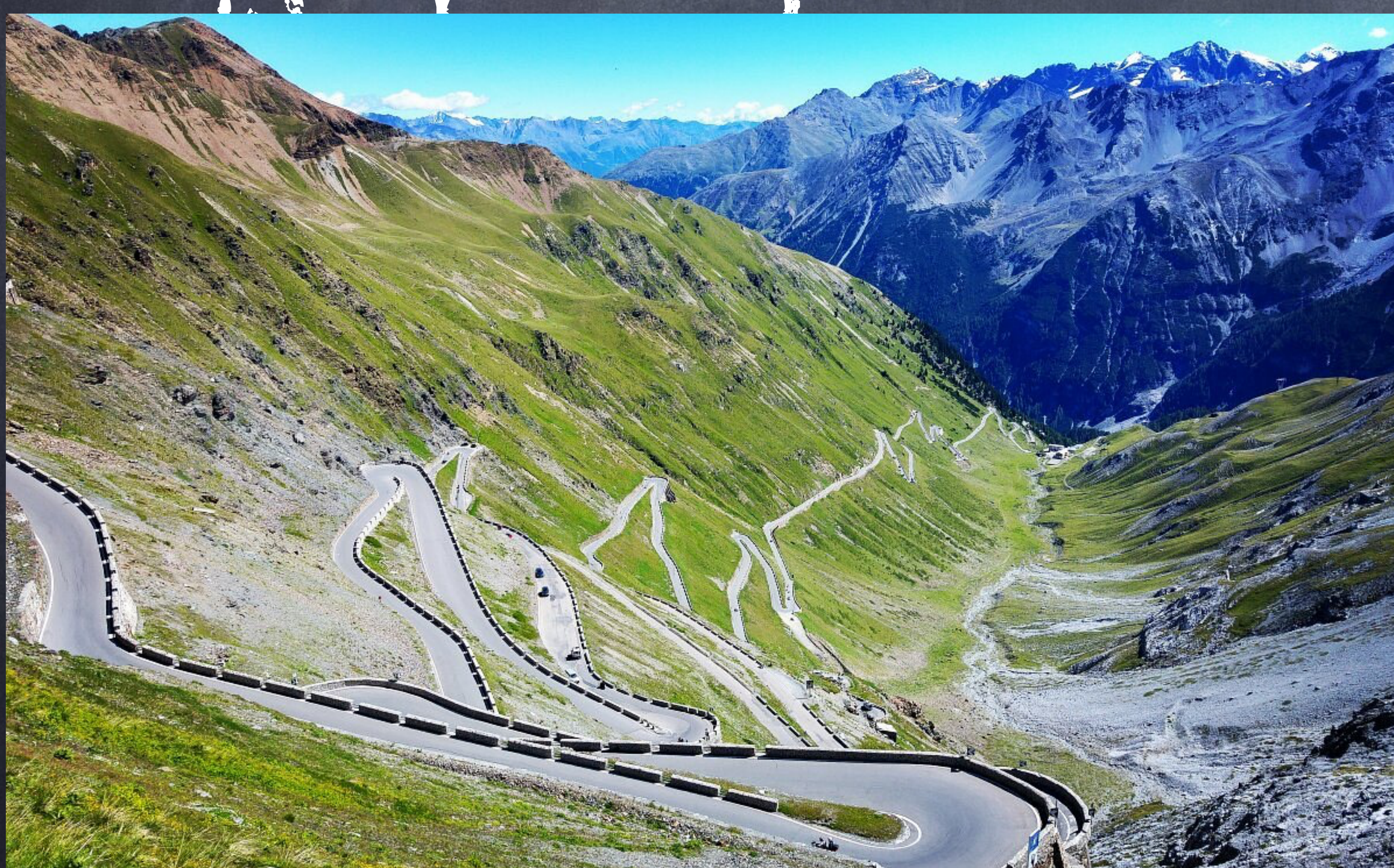
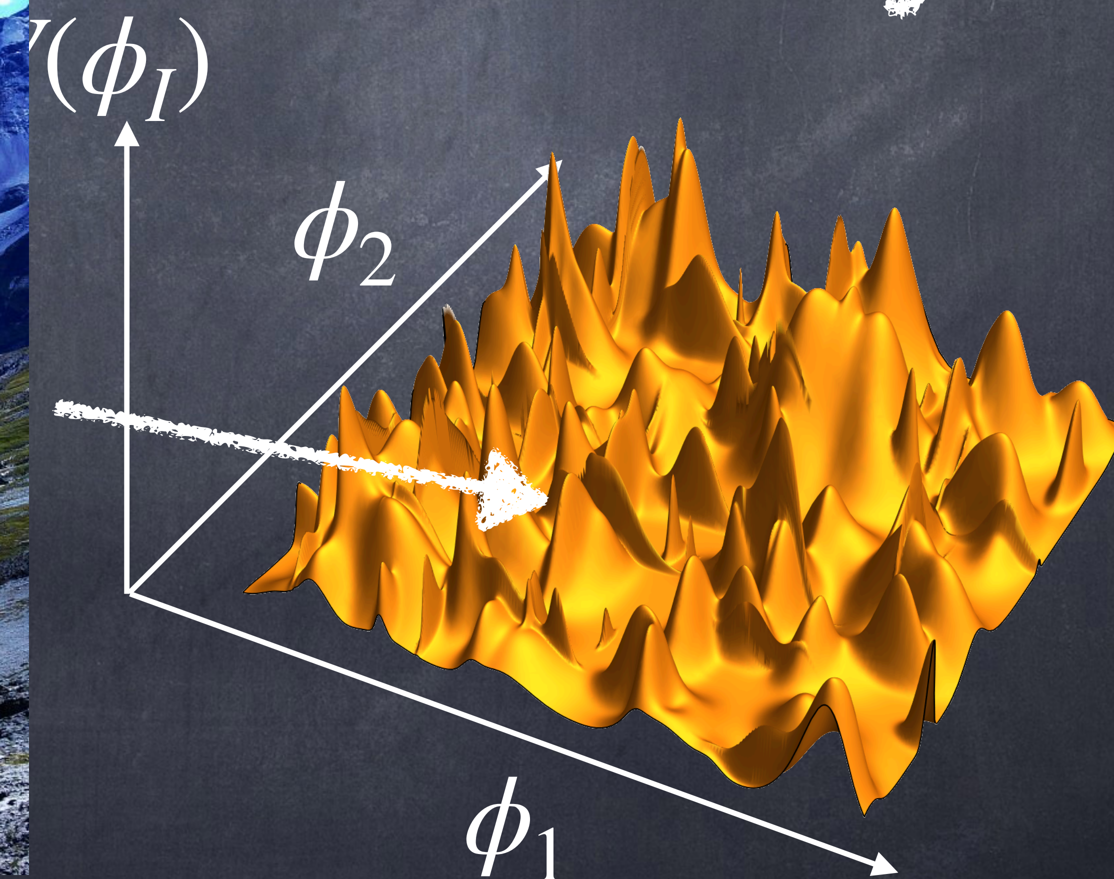
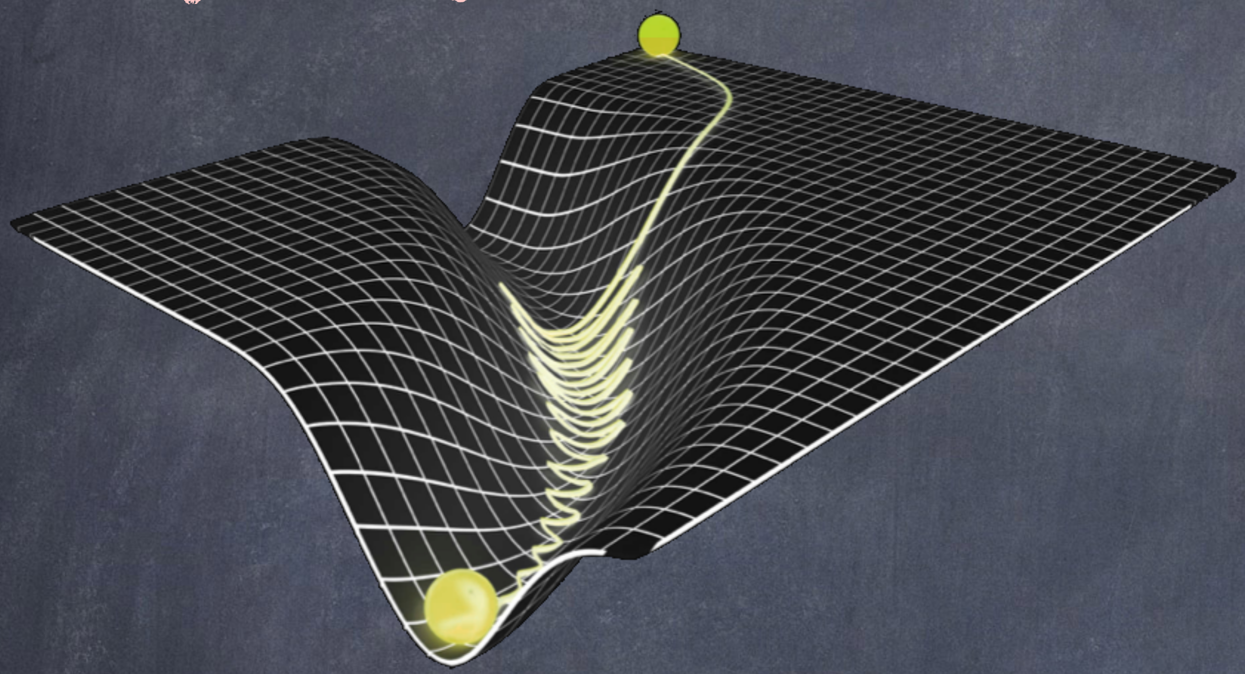
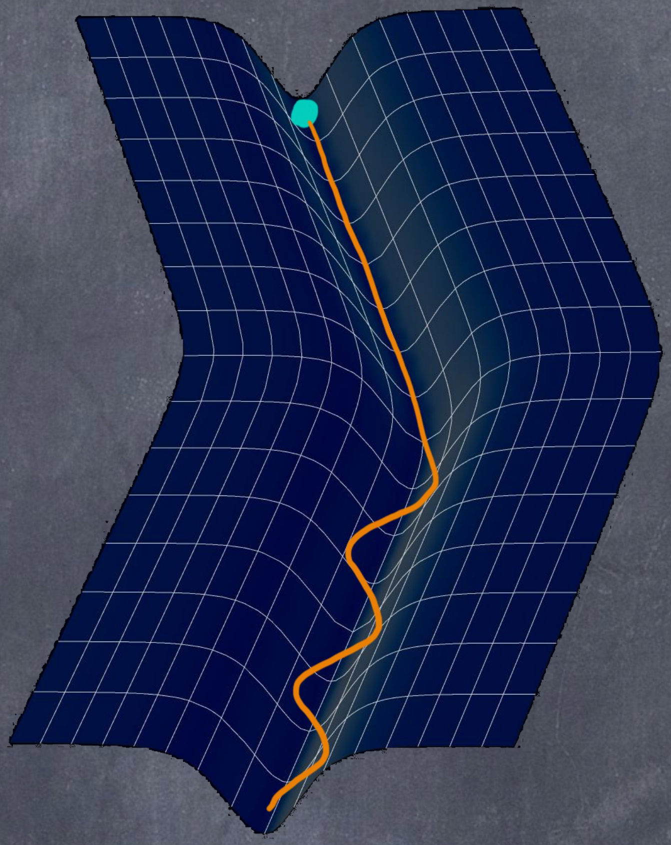




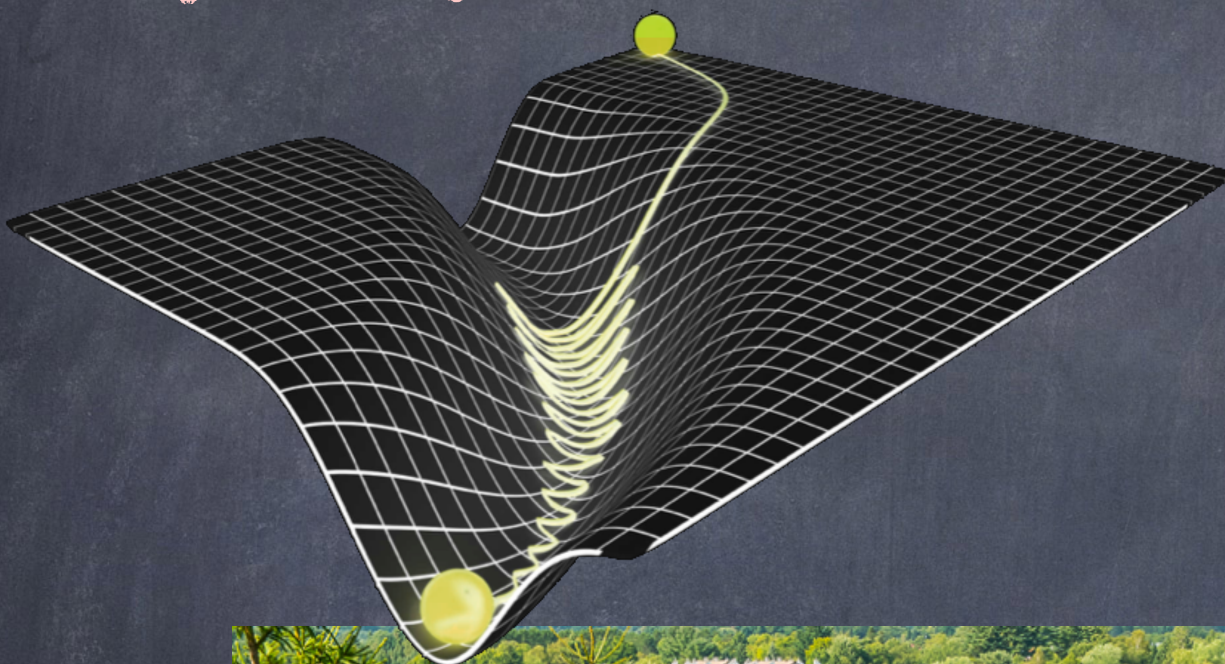
Chen-Namjoo-Wang (2015)



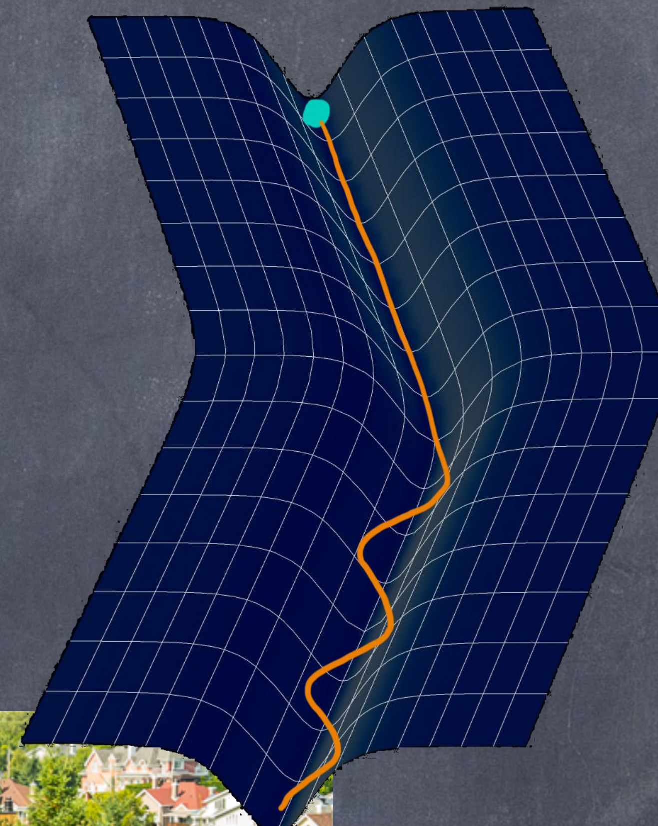
JQ-Chen-Ebadi (2024)



Chen-Namjoo-Wang (2015)

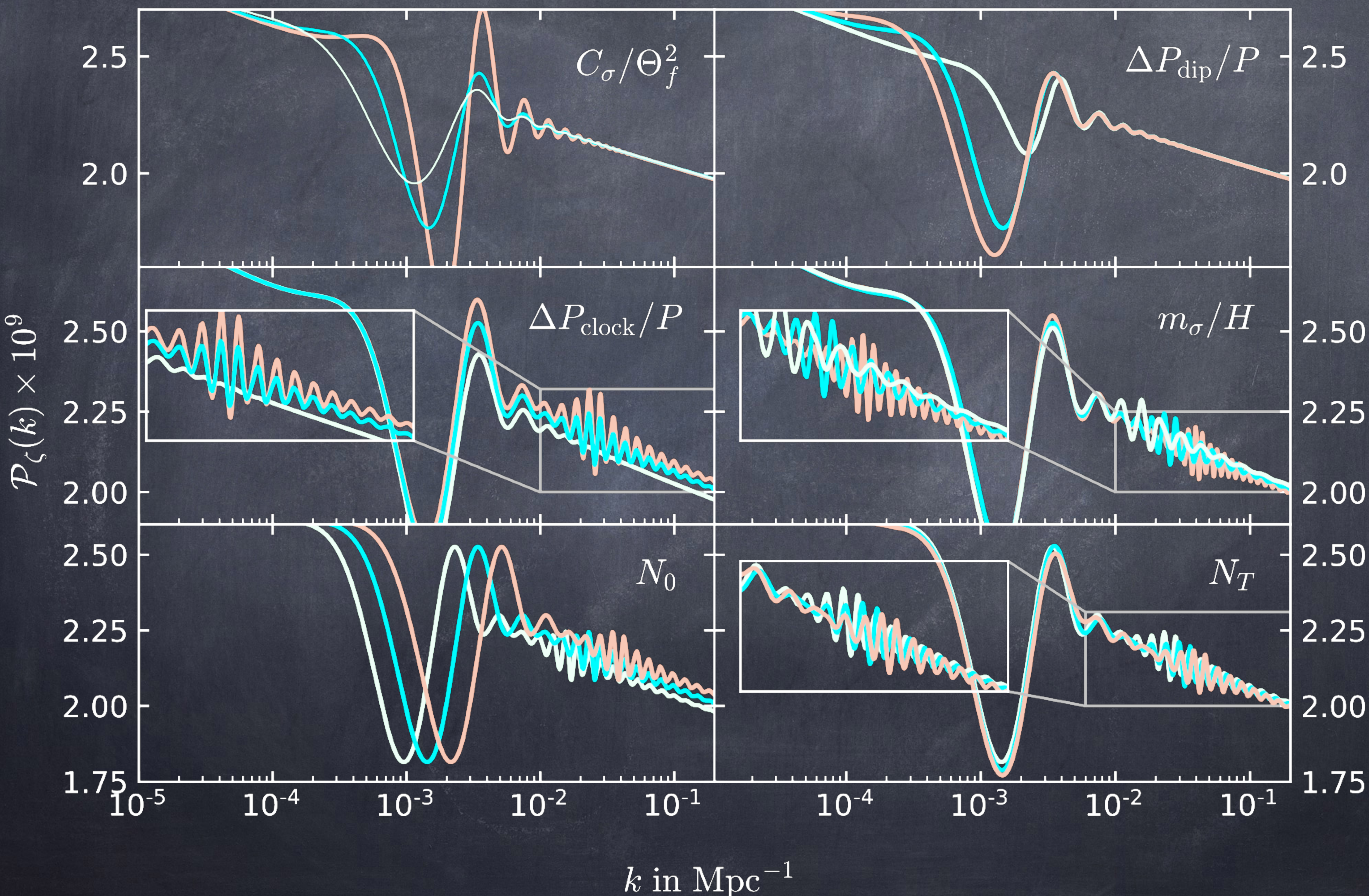


JQ-Chen-Ebadi (2024)



Braglia-Chen-Hazra (2022)

In inflation...



Part 4b
First realization in a non-inflationary alternative: ekpyrotic scenario (slow contraction)

first 2 slides can be skipped in the interest of time

Vanilla ekpyrosis

$$\mathcal{L} = \frac{R}{2} - \frac{1}{2}(\partial\phi)^2 + V_0 e^{-\sqrt{2/p}\phi} - \frac{1}{2} e^{-\sqrt{2/b}\phi}(\partial\chi)^2$$

$$(V_0 > 0, \quad 0 < p < 1/3, \quad b \approx p)$$

$$\delta_\phi \mathcal{L} = 0 \qquad \Rightarrow \qquad a(t) \propto (-t)^p \quad (t < 0)$$

$$\delta_\chi \mathcal{L} = 0 \qquad \Rightarrow \qquad n_s - 1 \approx 2\left(1 - \sqrt{\frac{p}{b}}\right)$$

isocurvature to curvature perturbation conversion

$$\mathscr{P}_\chi(k) \xrightarrow[\text{bounce}]{} \mathscr{P}_\zeta(k)$$

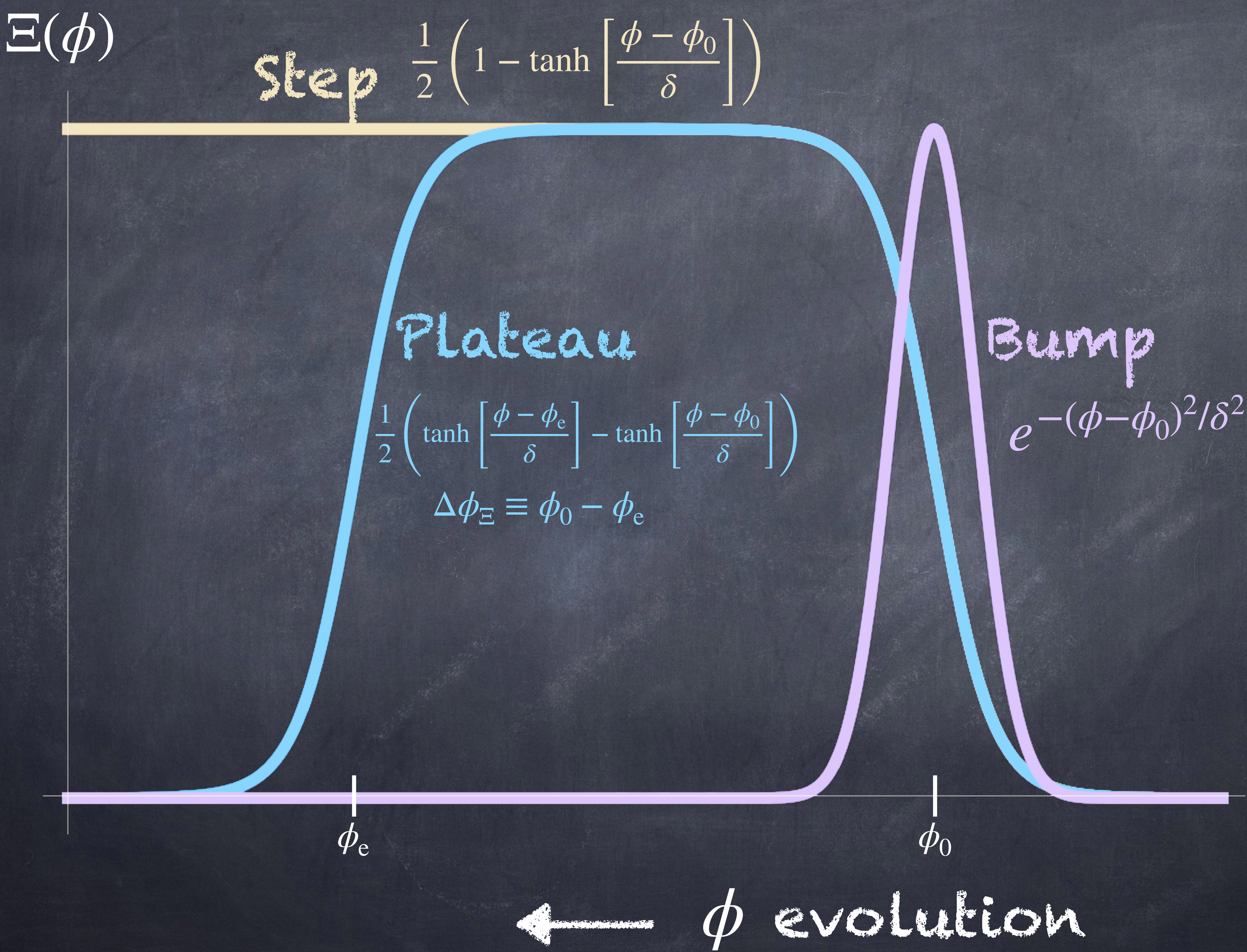
Battarra+ (2014)
Fertig+ (2016)
...

Implementing a classically excited massive scalar field

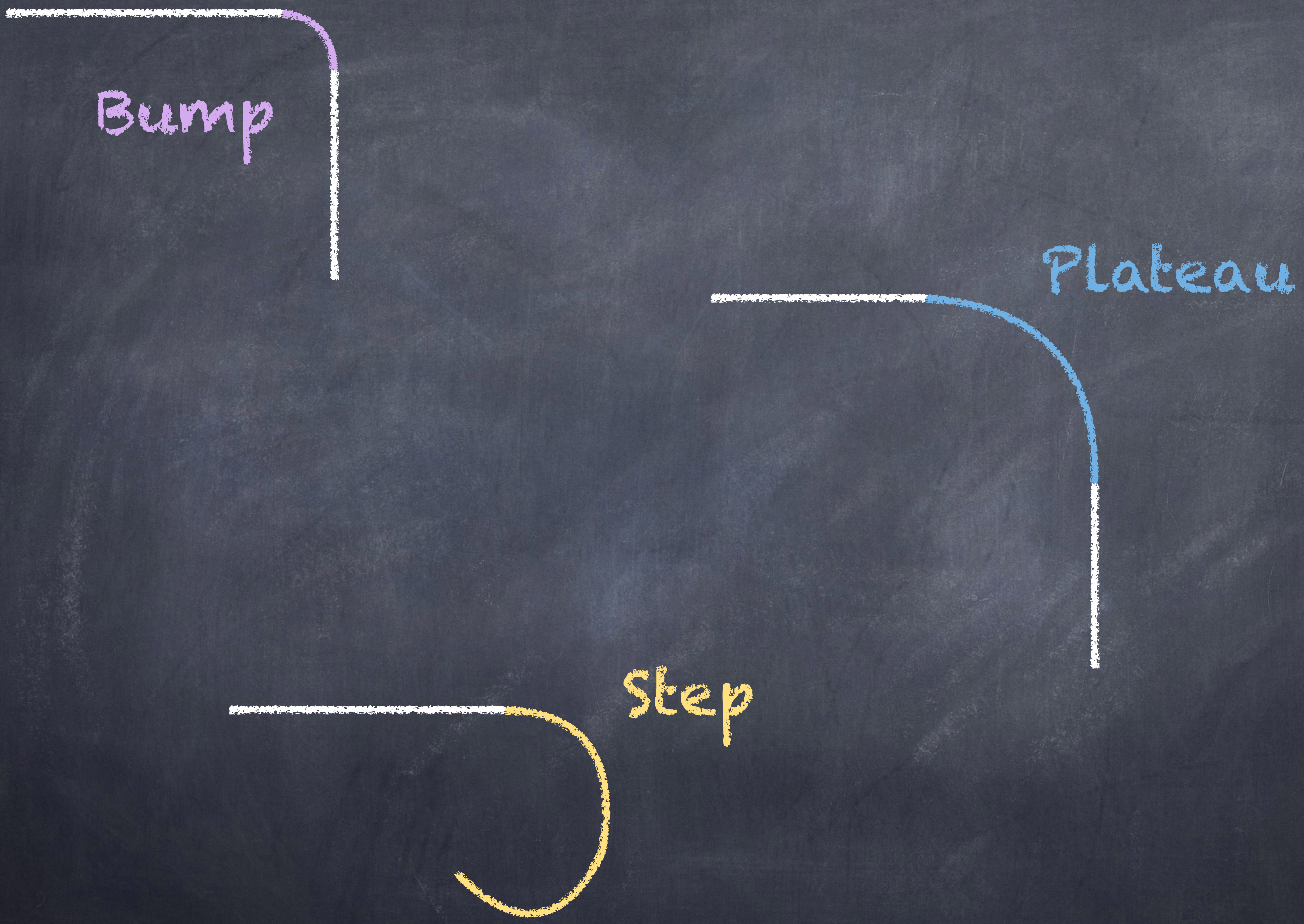
Add to $\mathscr{L}$: $$-\frac{1}{2}(\partial\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2$$

And change: $$(\partial\phi)^2 \longrightarrow \left(1 + \Xi(\phi)\frac{\sigma}{\varrho}\right)(\partial\phi)^2$$

$$(\partial\chi)^2 \longrightarrow \left(1 + \frac{\sigma}{\Lambda}\right)(\partial\chi)^2$$



$\Xi(\phi)$
Step $\frac{1}{2}\left(1 - \tanh\left[\frac{\phi-\phi_0}{\delta}\right]\right)$
Plateau
$\frac{1}{2}\left(\tanh\left[\frac{\phi-\phi_e}{\delta}\right] - \tanh\left[\frac{\phi-\phi_0}{\delta}\right]\right)$
$\Delta\phi_\Xi \equiv \phi_0 - \phi_e$
Bump
$e^{-(\phi-\phi_0)^2/\delta^2}$
ϕ_e
ϕ_0
ϕ evolution


Bump
Plateau
Step

Part 5
Results (background)

Focus on bump. Other couplings in the extra material.

Bump

$$\ddot{\sigma} + 3\bar{H}\dot{\sigma} + m_\sigma^2\sigma = 0$$

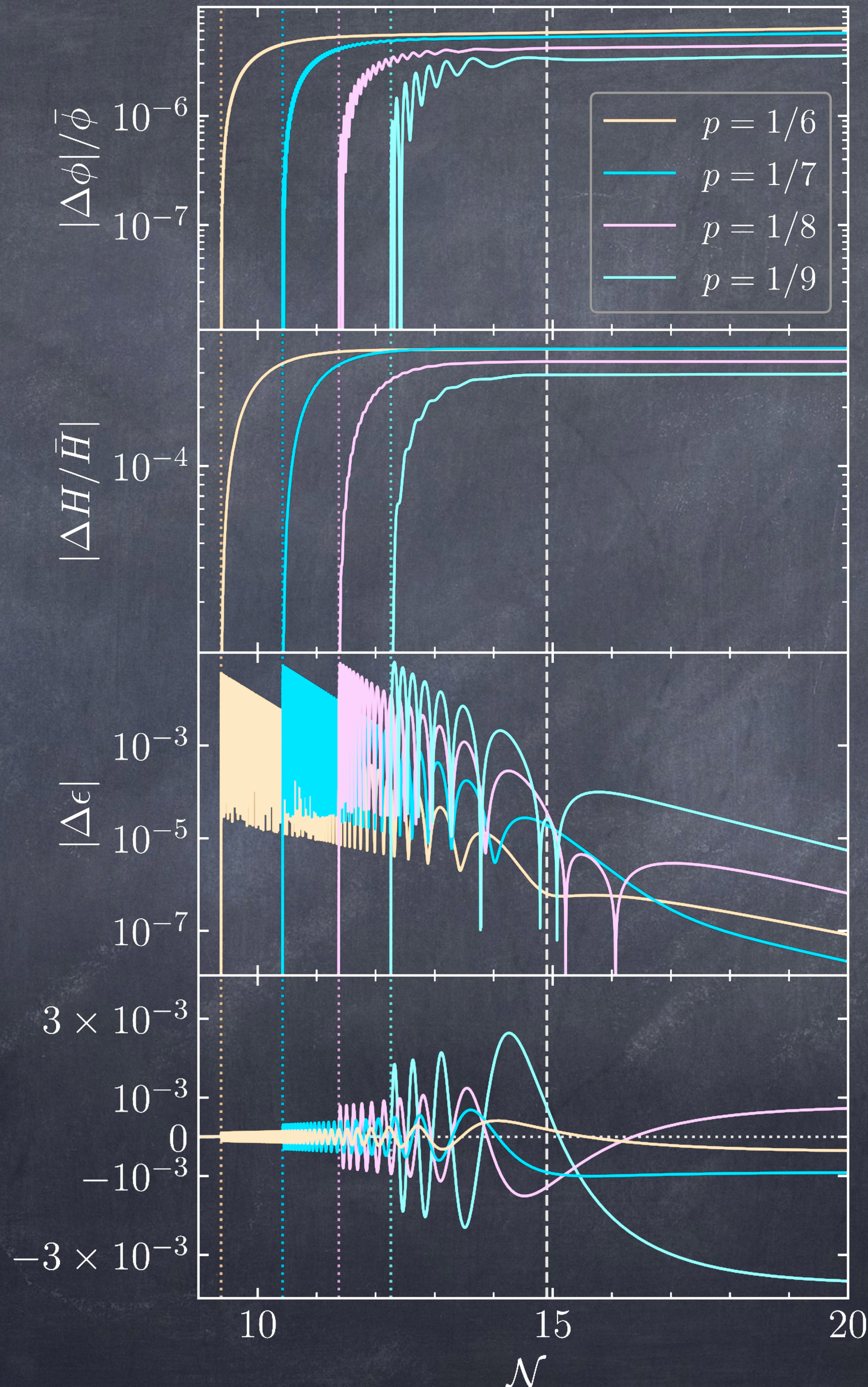
$$\ddot{\sigma} + \frac{3p}{t}\dot{\sigma} + m_\sigma^2\sigma = 0$$

$$\sigma(t) = (-t)^\alpha(c_1 J_\alpha(-m_\sigma t) + c_2 Y_\alpha(-m_\sigma t))$$

$$\alpha = \frac{1-3p}{2}$$

$$\sigma(t) \sim \frac{\sin(-m_\sigma t)}{(-m_\sigma t)^{3p/2}}$$

$$(-m_\sigma t \gg 1)$$



$$\epsilon \equiv -\frac{\dot{H}}{H^2}$$

$$\mathrm{d}\mathcal{N} \equiv \mathrm{d}\ln(a|H|)$$

Part 6a
Revisiting perturbations Analytically

can be skipped in the interest of time

Perturbations

$$S \supset -\frac{1}{2}\int \mathrm{d}^4x\,\sqrt{-g}\,\left(1+\frac{\sigma}{\Lambda}\right)\Omega^2(\phi)(\partial\chi)^2\,, \qquad \Omega^2(\phi) = e^{-\sqrt{2/b}\phi}$$

$$= \frac{1}{2}\int \mathrm{d}^3x\mathrm{d}\tau\,\tilde{z}^2\left((\chi')^2-(\partial_i\chi)^2\right)\,, \qquad \tilde{z}^2 = \left(1+\frac{\sigma}{\Lambda}\right)z^2\,, \qquad z^2 = a^2\Omega^2(\phi)$$

$$\Rightarrow \qquad \chi_k'' + \left(\frac{(\bar{z}^2)'}{\bar{z}^2} + \underbrace{2\Delta\left(\frac{a'}{a}\right) - \sqrt{\frac{2}{b}}\Delta\phi'}_{} + \frac{\sigma'/\Lambda}{1+\sigma/\Lambda}\right)\chi_k' + k^2\chi_k = 0$$

$\bar{\mathcal{P}}_s(k)$

massive field
induced oscillations

direct
coupling
to massive
field

Perturbations (interaction picture)

$$\mathscr{L}_0 = \frac{1}{2} z^2 \left((\chi')^2 - (\partial_i \chi)^2 \right) \,, \qquad \delta\mathscr{L} = \frac{\sigma}{\Lambda} \mathscr{L}_0$$

$$\mathscr{H}_0 = \frac{1}{2} z^2 \left((\chi_{\rm int}')^2 + (\partial_i \chi_{\rm int})^2 \right) \,, \qquad \mathscr{H}_{\rm int} = -\frac{1}{2} \frac{\sigma}{\Lambda} z^2 \left((\chi_{\rm int}')^2 - (\partial_i \chi_{\rm int})^2 \right)$$

$$\frac{\Delta \mathscr{P}_s}{\bar{\mathscr{P}}_s} = \mathrm{Im} \int_{-\infty}^{\tau_{\rm end}} \mathrm{d}\tau \, \frac{\sigma}{\Lambda} \underbrace{\bar{z}^2 \left((\bar{\chi}_k')^2 - k^2 \bar{\chi}_k^2 \right)^*}_{}$$

$$= \frac{\pi}{4} k^2 \tau \left(H_\nu^{(1)}(-k\tau)^2 - H_{\nu-1}^{(1)}(-k\tau)^2 \right)^*$$

Sharp feature signal

$$\sigma(t) = \sigma_0 \Theta(\tau - \tau_0)$$

$$\frac{\Delta \mathscr{P}_s}{\bar{\mathscr{P}}_s} = -\frac{\pi \sigma_0}{4\Lambda} \mathrm{Im} \left[i k \tau \left[(\cot(\pi\nu) - i) J_{\nu-1}(-k\tau) + \csc(\pi\nu) J_{1-\nu}(-k\tau) \right] H_\nu^{(1)}(-k\tau) \right]_{\tau_0}^{\tau_{\mathrm{end}}}$$

$$\Rightarrow \qquad \frac{\Delta \mathscr{P}_s}{\bar{\mathscr{P}}_s} \simeq -\frac{\sigma_0}{2\Lambda} \left(1 + \cos(-2k\tau_0)\right) = -\frac{\sigma_0}{2\Lambda} \left(1 + \cos\left(\frac{2k}{k_0} \right) \right)$$

$$(\nu \approx 3/2\,, \qquad -k\tau_0 \gg 1\,, \qquad -k\tau_{\mathrm{end}} \ll 1\,, \qquad k_0 \equiv -1/\tau_0)$$

Clock signal

$$\sigma(t) = \Theta(t - t_0)\sigma_0 \left(\frac{t_0}{t}\right)^{3p/2} \sin[-m_\sigma(t - t_0)]$$

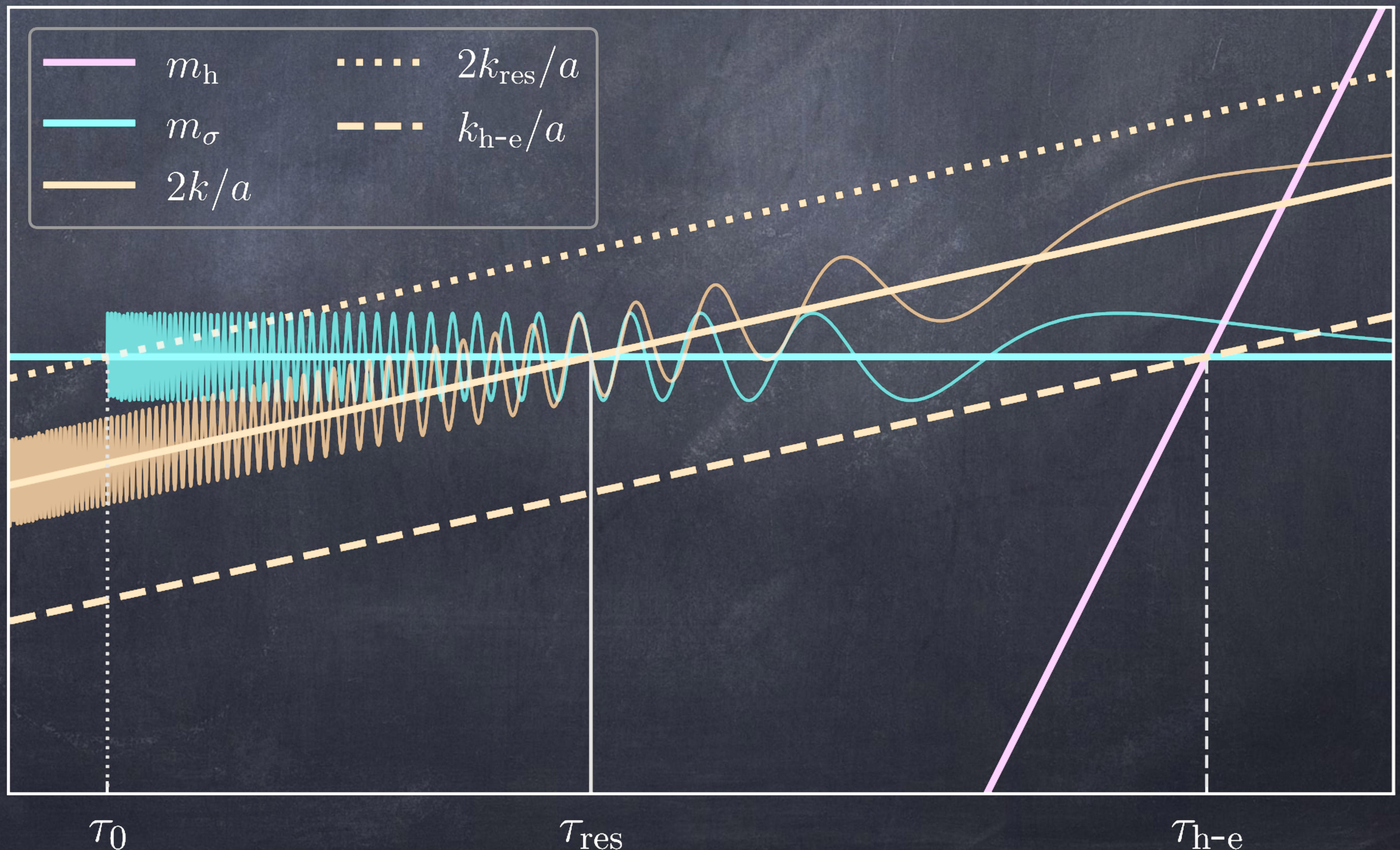
$$(-m_\sigma t \gg 1)$$

$$\frac{\Delta\mathscr{P}_s}{\bar{\mathscr{P}}_s} \simeq \Theta\left(k_{\rm res} - k\right)\Theta\left(k - k_{\rm h-e}\right)\frac{\sigma_0}{2\Lambda}\sqrt{\frac{\pi m_\sigma}{2|H_0|}}\left(\frac{k}{k_{\rm res}}\right)^{\frac{1-3p}{2p}} \sin\left(p\frac{m_\sigma}{m_{\rm h0}}\left(\frac{k}{k_{\rm res}}\right)^{1/p} + \varphi\right)$$

$$k_{\rm res} = \frac{m_\sigma}{m_{\rm h0}}k_0$$

$$m_{\rm h0} = \frac{1-p}{p}|H_0|$$

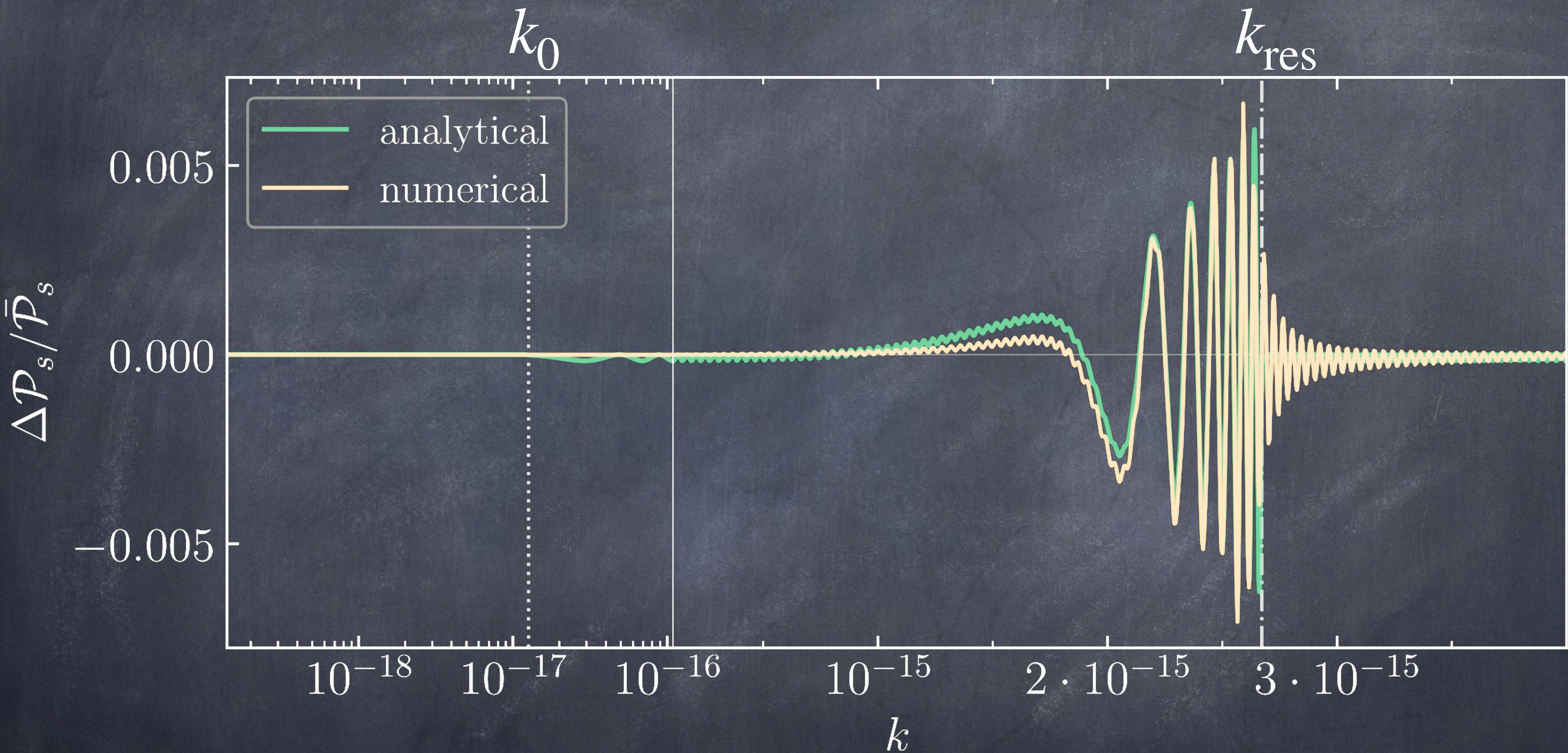
$$k_{\rm h-e} = \left(\frac{m_\sigma}{m_{\rm h0}}\right)^{1-p} k_0$$



Part 6b
Revisiting perturbations
Numerically

JQ-Chen-Ebadi (2024)

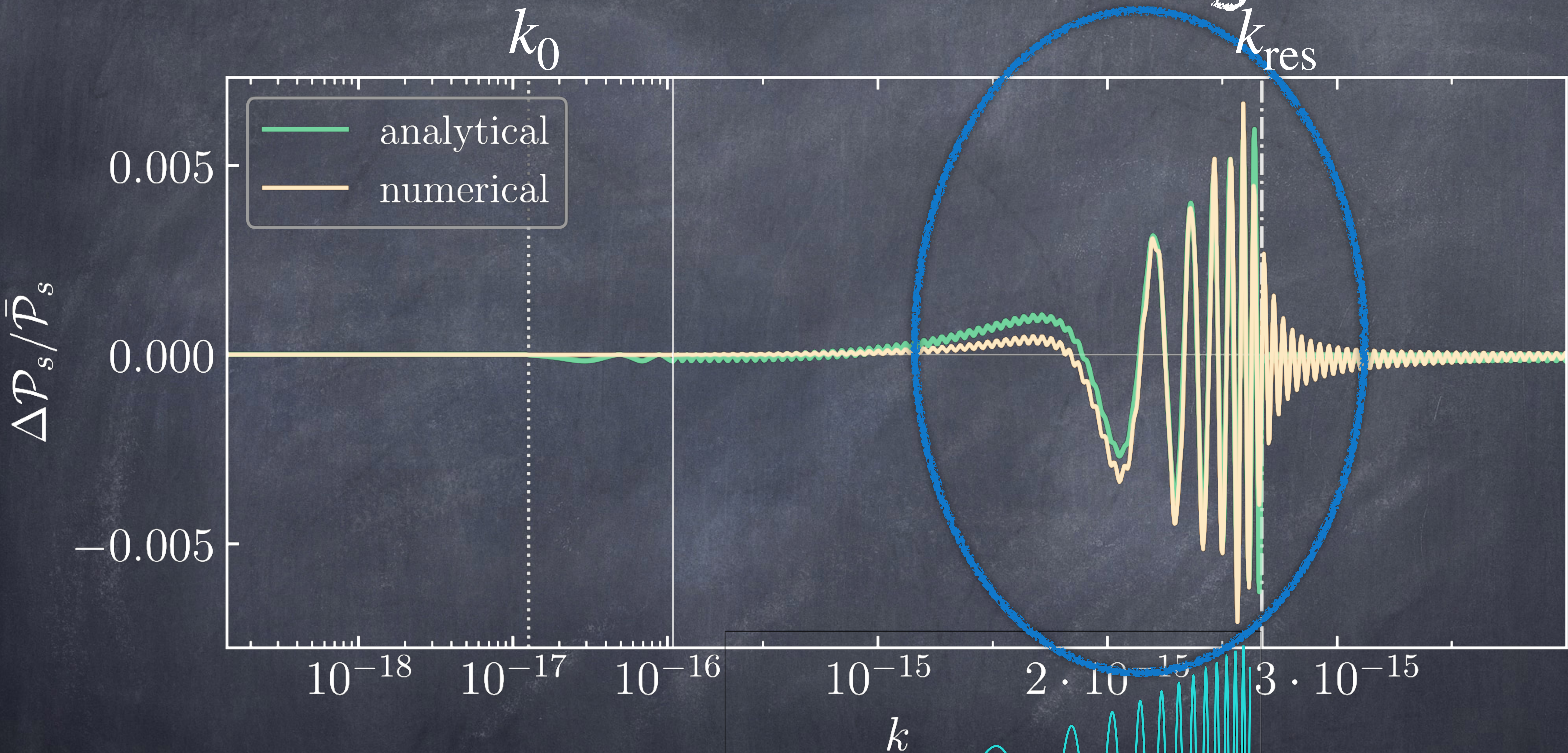
Bump

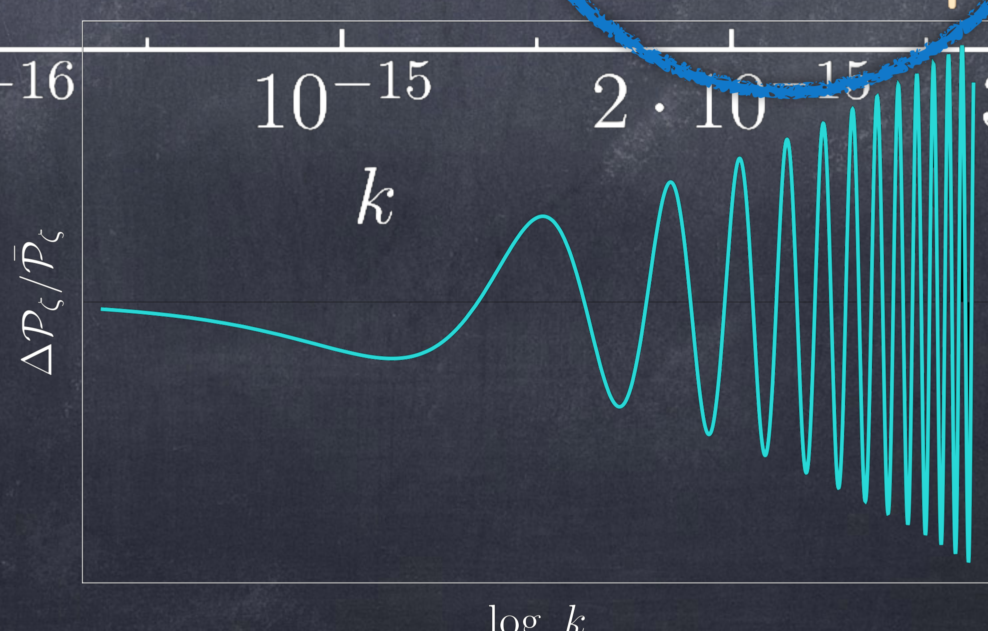


JQ-Chen-Ebadi (2024)

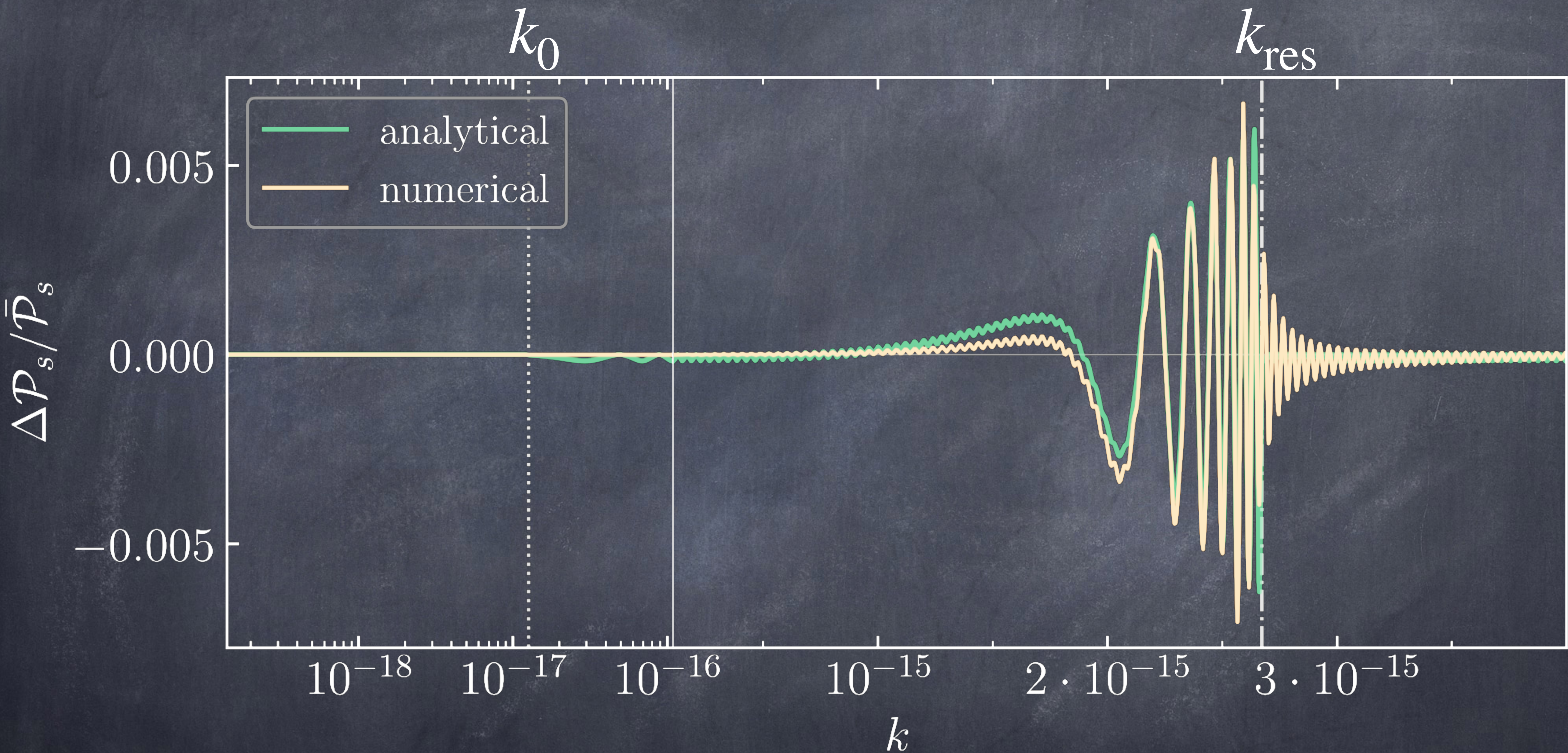
Bump

clock signal

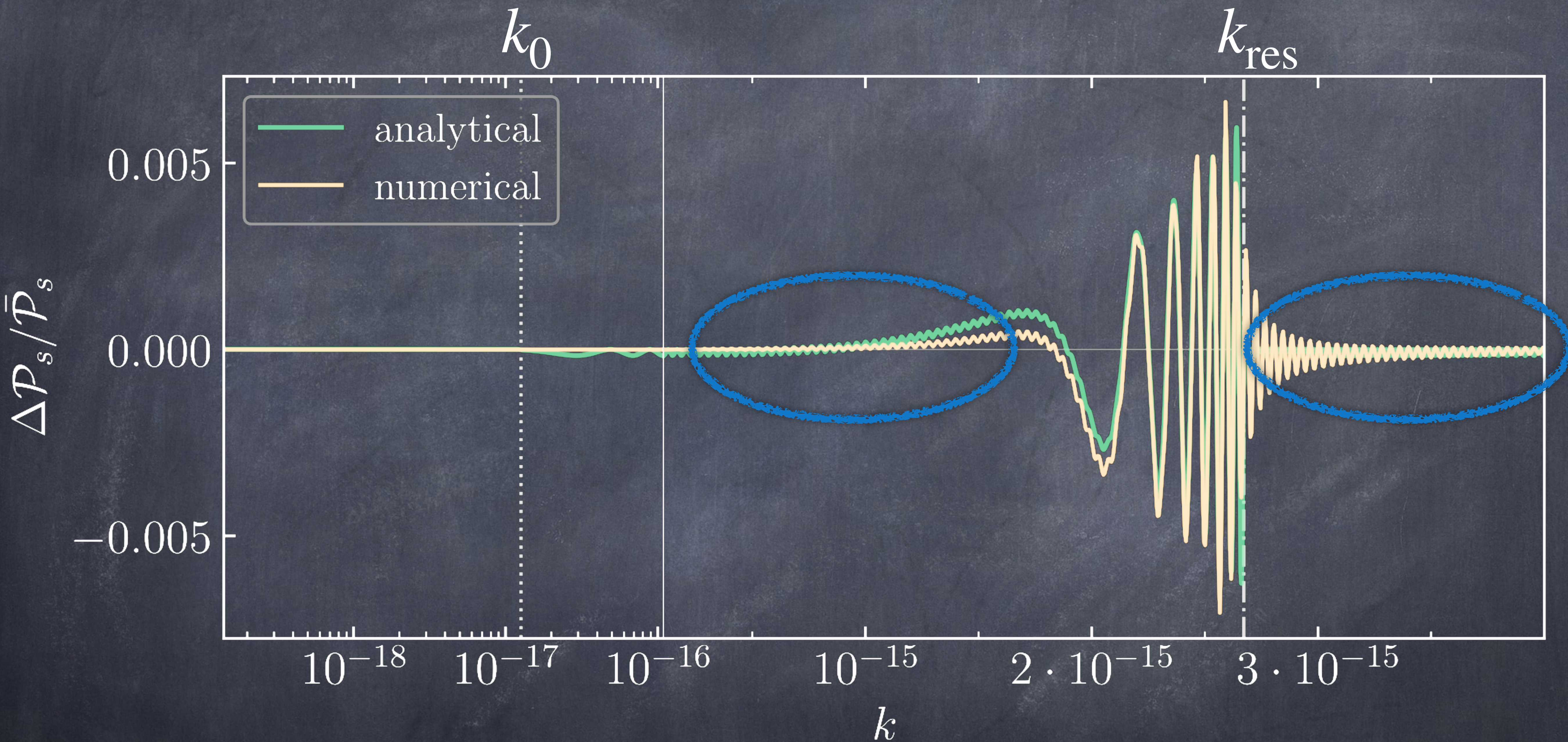




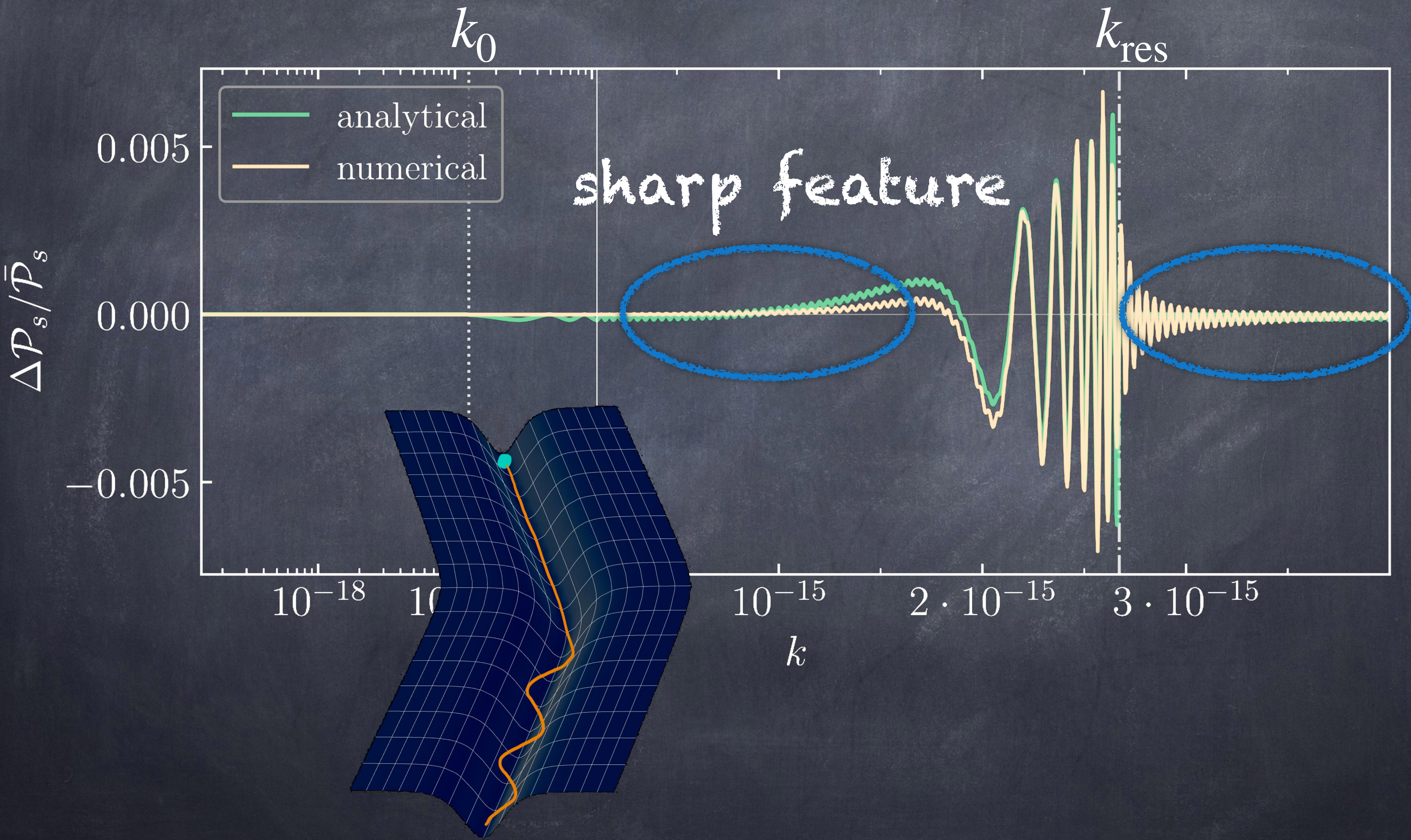
JQ-Chen-Ebadi (2024)



JQ-Chen-Ebadi (2024)

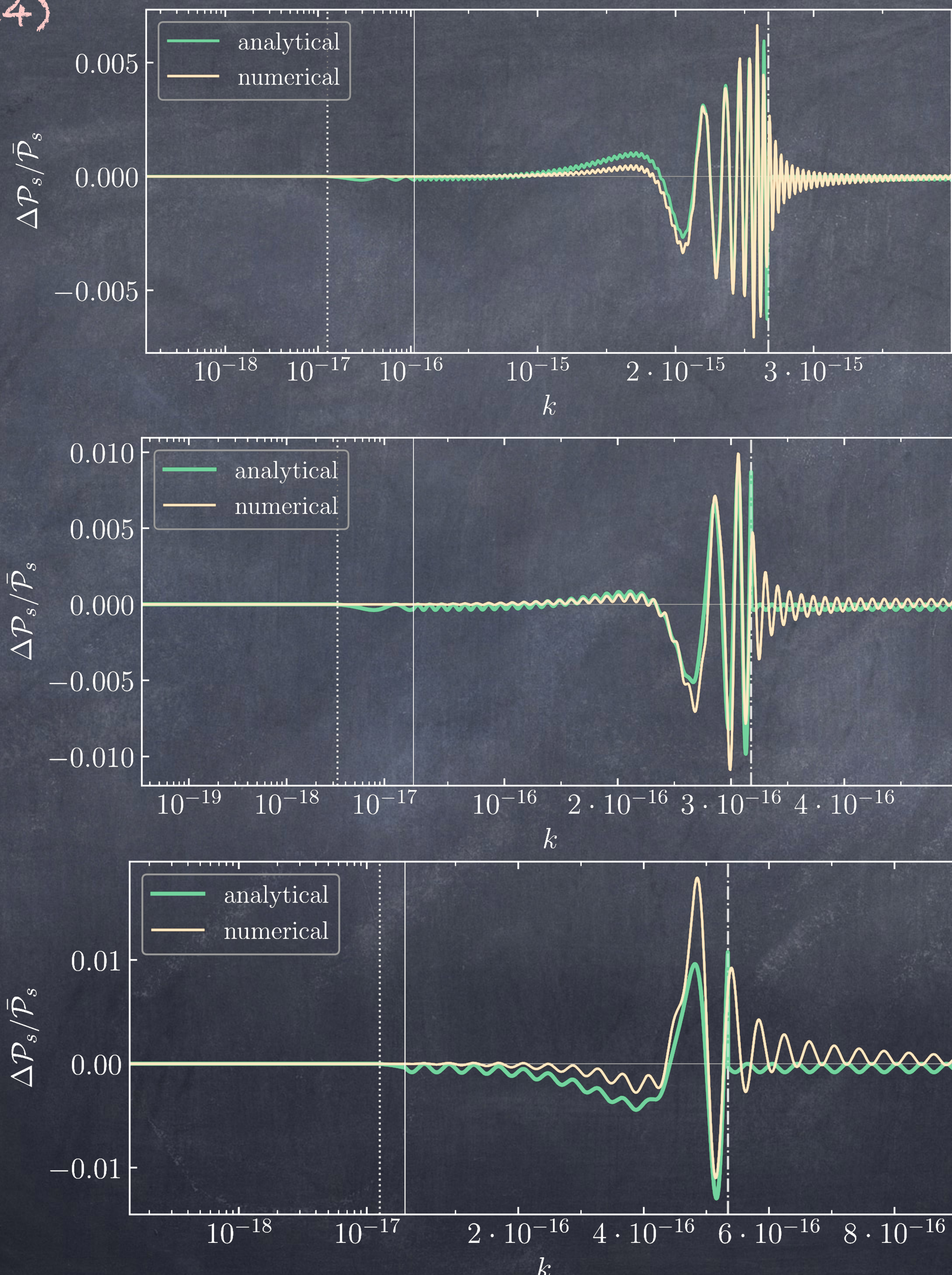


JQ-Chen-Ebadi (2024)

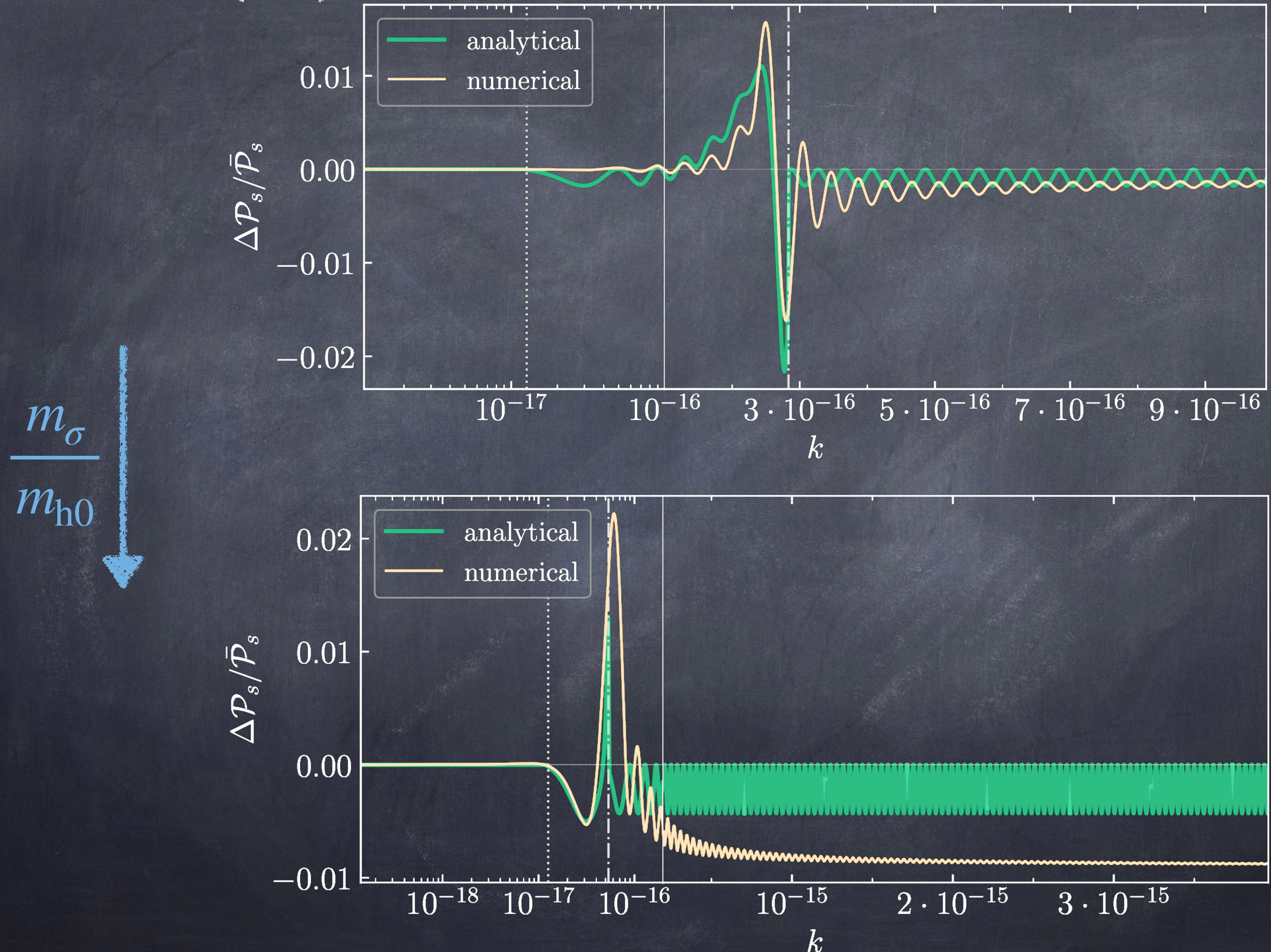


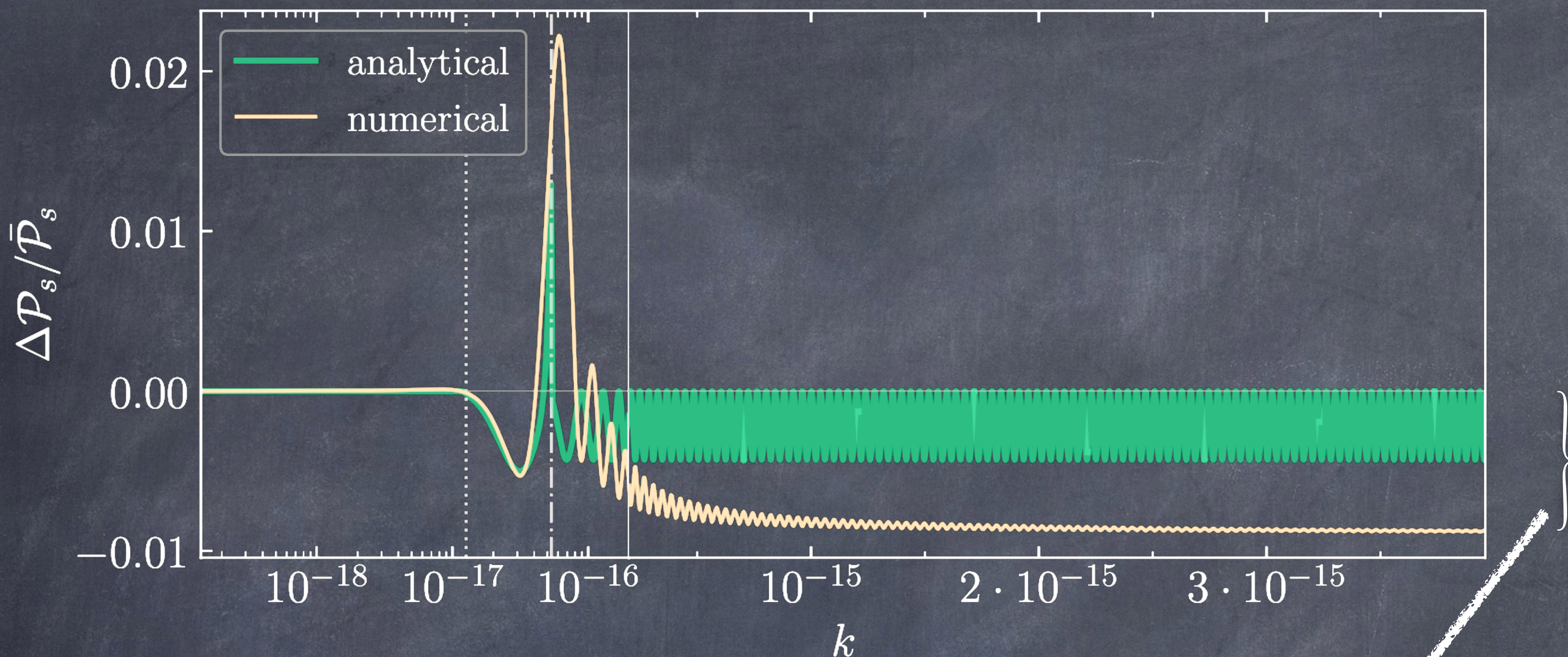
JQ-Chen-Ebadi (2024)

$$\frac{m_\sigma}{m_{\mathrm{h0}}}$$



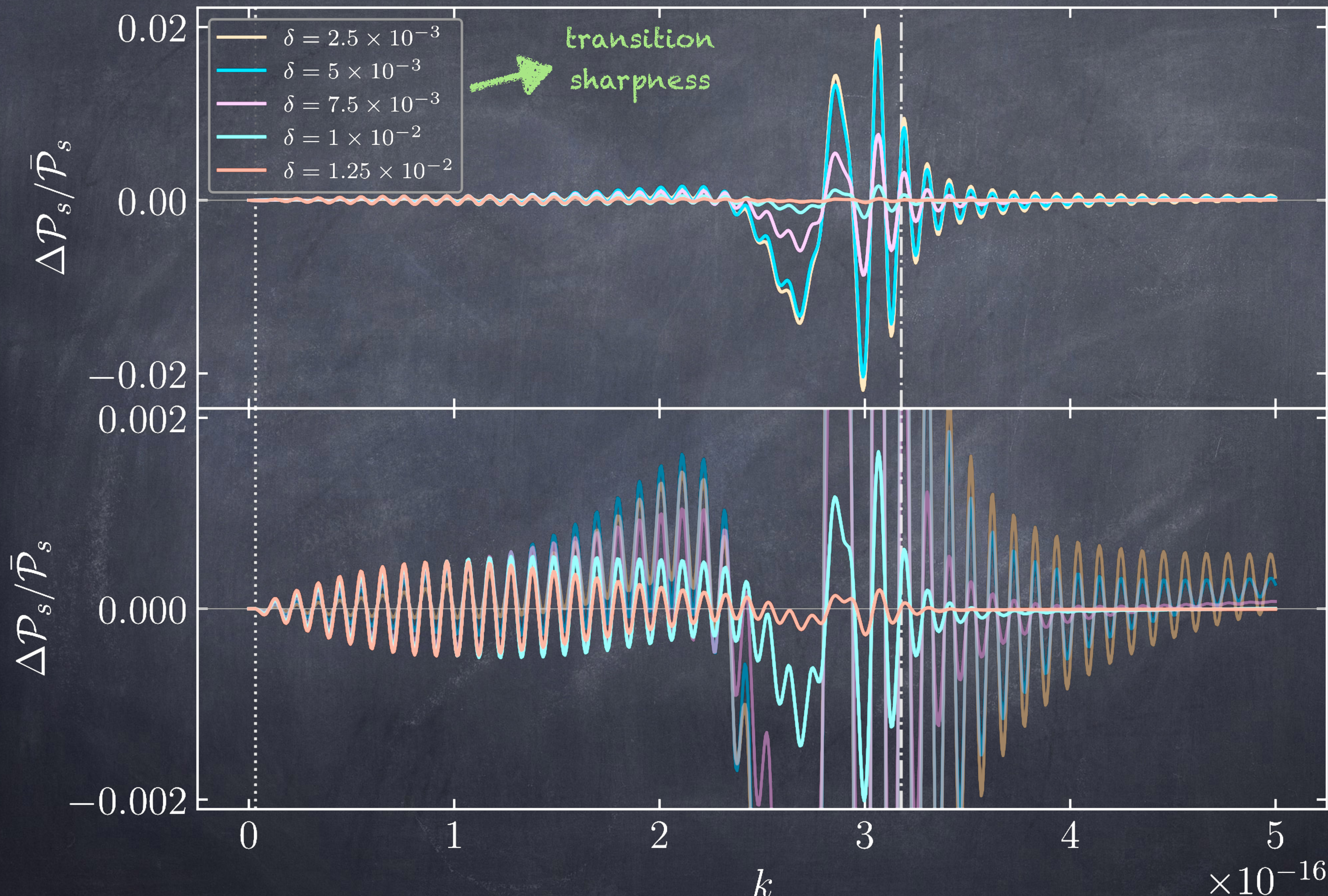
JQ-Chen-Ebadi (2024)



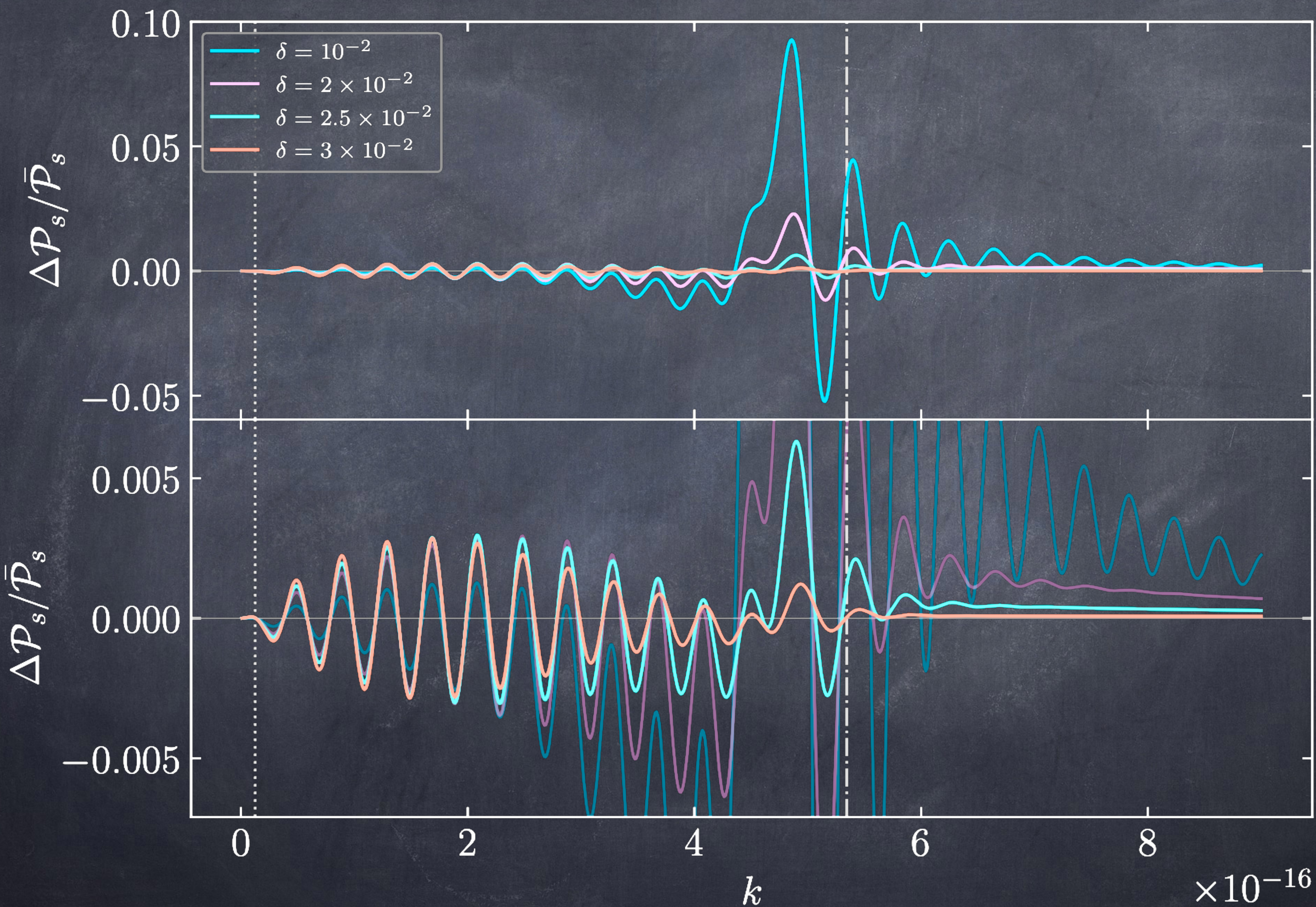


$$\frac{\Delta\mathscr{P}_s}{\bar{\mathscr{P}}_s} \xrightarrow{k \gg k_{\rm res}} -\frac{\sigma_{\rm late}}{\Lambda}$$

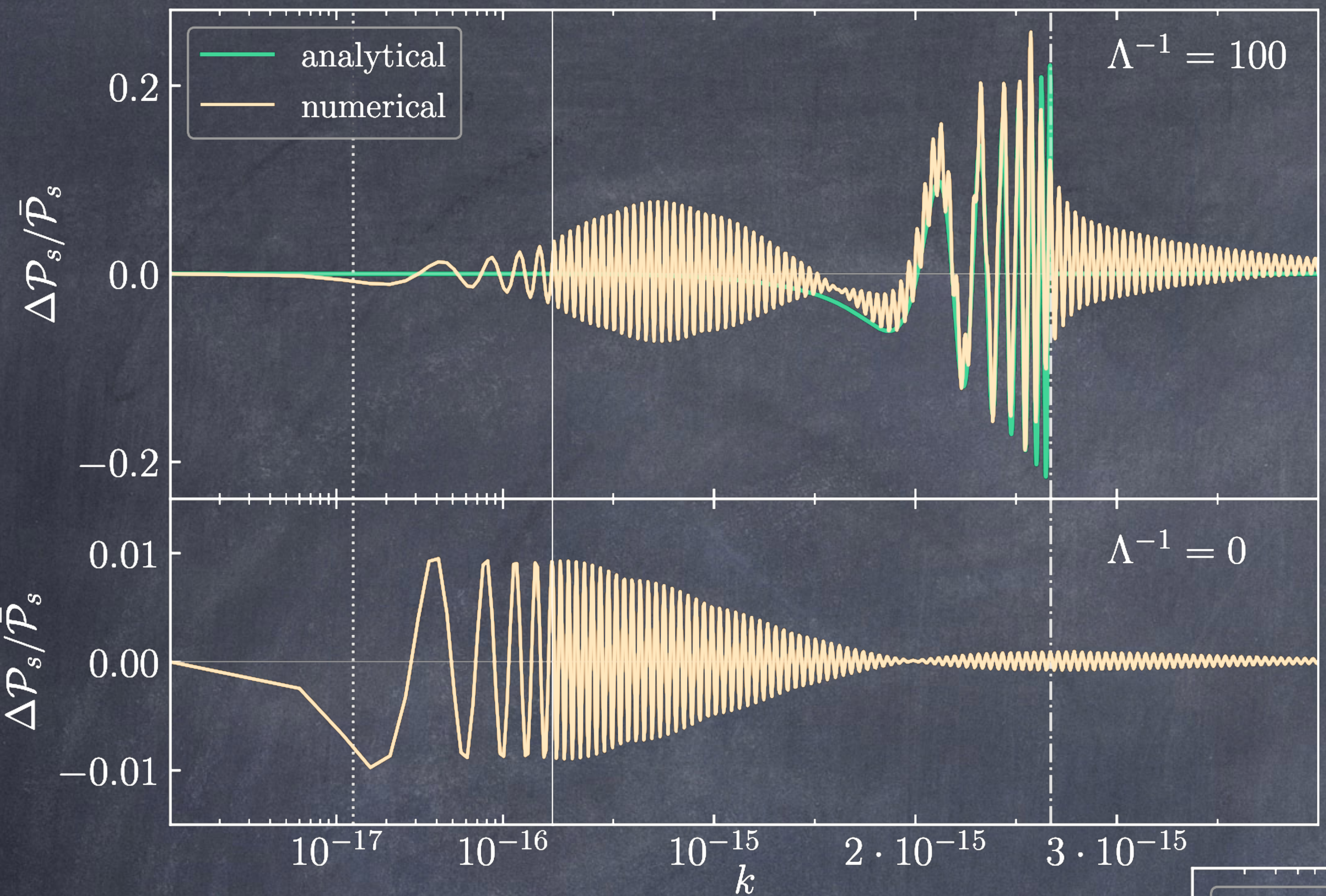
Late-time freezing
of massive field
as it becomes light
after horizon crossing



$\delta = 2.5 \times 10^{-3}$
$\delta = 5 \times 10^{-3}$
$\delta = 7.5 \times 10^{-3}$
$\delta = 1 \times 10^{-2}$
$\delta = 1.25 \times 10^{-2}$
transition sharpness
$\Delta\mathcal{P}_s/\bar{\mathcal{P}}_s$
0.02
0.00
−0.02
0.002
0.000
−0.002
0
1
2
3
4
5
k
$\times 10^{-16}$

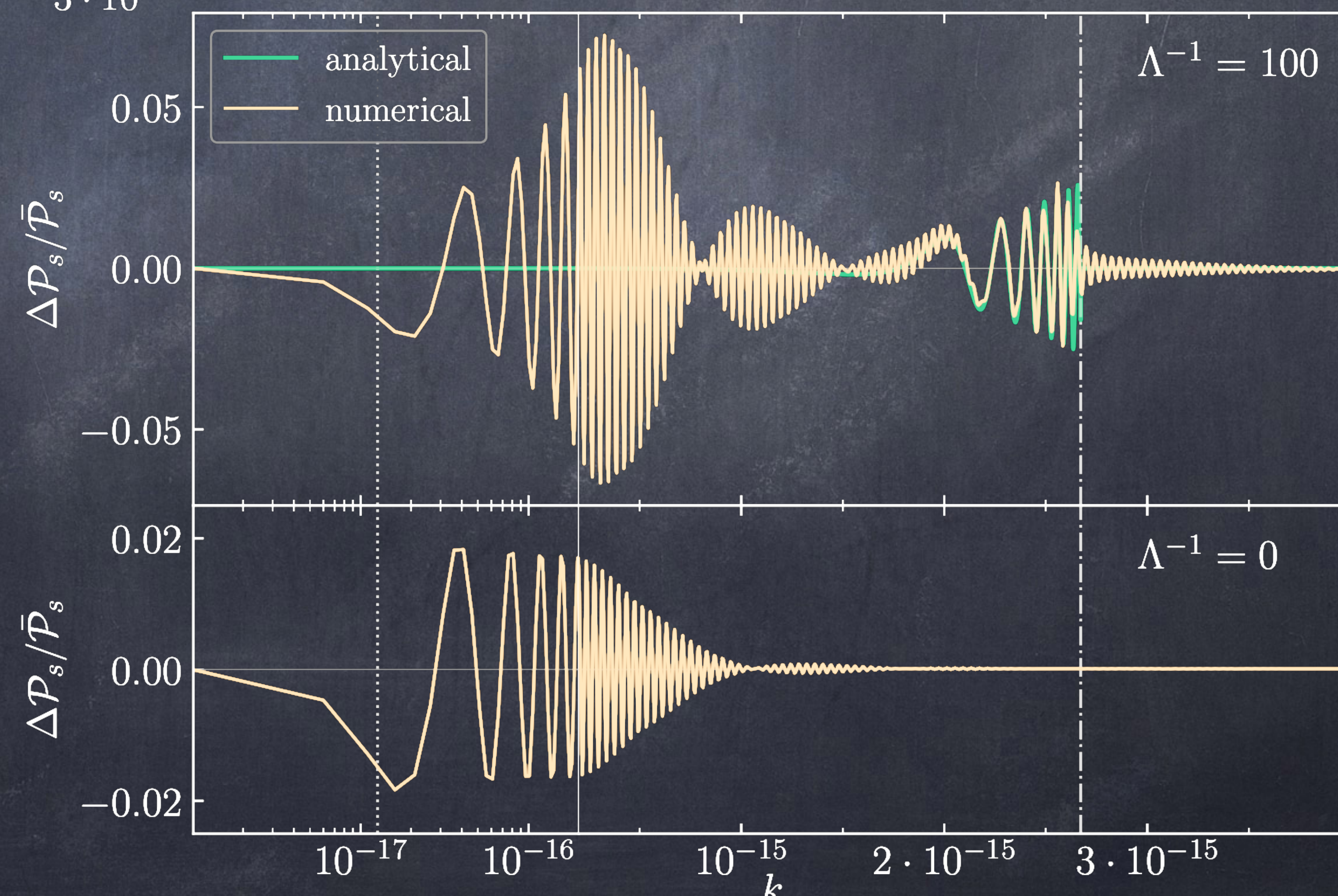


$\delta = 10^{-2}$
$\delta = 2 \times 10^{-2}$
$\delta = 2.5 \times 10^{-2}$
$\delta = 3 \times 10^{-2}$
$\Delta \mathcal{P}_s / \bar{\mathcal{P}}_s$
0.10
0.05
0.00
−0.05
0.005
0.000
−0.005
0
2
4
6
8
k
$\times 10^{-16}$



$$\mathscr{L}^{(2)} \supset -\frac{1}{2}\left(1+\frac{\sigma}{\Lambda}\right)(\bar{z}+\Delta z)^2(\partial\chi)^2$$

$$\mathscr{L}^{(2)} \supset -\frac{1}{2}(\bar{z}+\Delta z)^2(\partial\chi)^2$$



Part 7
Summary and outlook

What we achieved

- Slow contraction (a.k.a. ekpyrotic cosmology) can support spectator massive fields
- Better if $\sigma(\partial\phi)^2$ coupling goes to zero
- Confirmed clock signal and how it connects to sharp feature signal

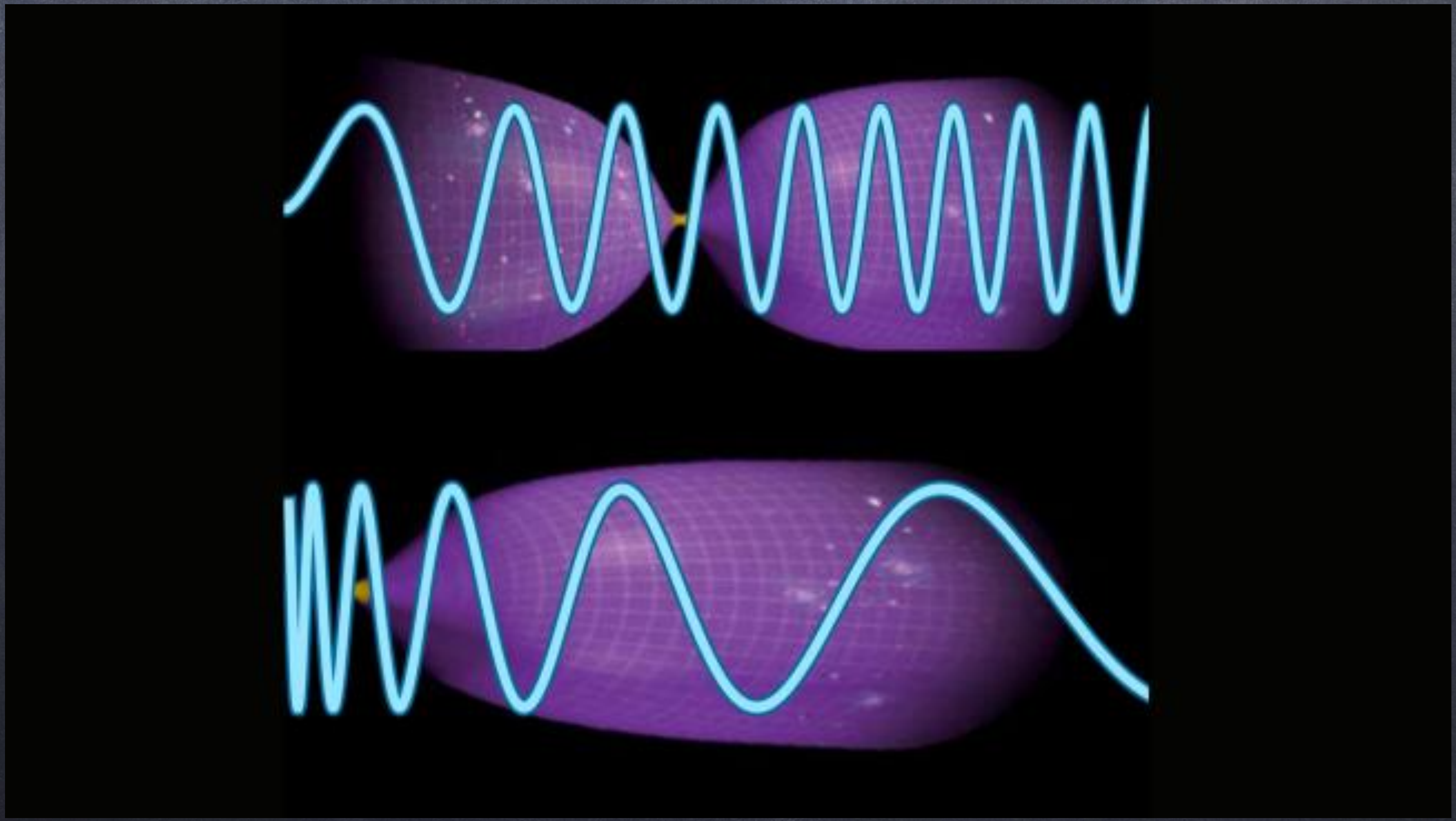
→ Signal could really tell apart inflationary cosmology from ekpyrotic cosmology

Still many things to explore!

- Further implementations
- Fit to data
- Full bispectrum calculation
- Full quantum standard clocks models and more cosmological collider business
- Non-standard clocks (time-dependent masses)
- Other alternatives
- ...

Thank you for your attention!

Questions?



Extra

	inflation	matter bounce	genesis	ekpyrosis
scale factor	expands	contracts	expands	contracts
"speed"	fast	fast	slow	slow
number of fields	1 or more	1 or more	2 or more	2 or more
content	positive, flat potential	pressureless matter	CFT	negative, steep potential
property	dS SO(4,1) -> ISO(3)	needs to be stabilized	Mink SO(4,2) -> SO(4,1)	smoothing attractor

inflation

$$n_s - 1 = -2\epsilon - \eta$$

$$\alpha_s = 2\epsilon_{,\mathcal{N}} - \frac{\epsilon_{,\mathcal{N}\mathcal{N}}}{\epsilon} + \left(\frac{\epsilon_{,\mathcal{N}}}{\epsilon}\right)^2$$

$$r = 16\epsilon$$

$$f_{\mathrm{NL}} \sim \mathcal{O}(\epsilon, \eta, c_s^{-2})$$

matter bounce

$$n_s - 1 = 12w - 9w_{,\mathcal{N}}$$

$$\alpha_s = -12w_{,\mathcal{N}}$$

$$r = 24c_s$$

$$f_{\mathrm{NL}} \sim \mathcal{O}(1, c_s^{-2})$$

ekpyrosis

$$n_s - 1 = 2\left(1 - \sqrt{\frac{p}{b}}\right) - \frac{7\epsilon_{,\mathcal{N}}}{3\epsilon}$$

$$\alpha_s = -\sqrt{\frac{p}{b}}\frac{\epsilon_{,\mathcal{N}}}{\epsilon} + \frac{7\epsilon_{,\mathcal{N}\mathcal{N}}}{3\epsilon} - \frac{7}{3}\left(\frac{\epsilon_{,\mathcal{N}}}{\epsilon}\right)^2$$

$$r \lll 1 \qquad (n_t = 2)$$

$$f_{\mathrm{NL}} \sim \mathcal{O}(1)$$

inflation

$$n_s - 1 = -2\epsilon - \eta$$

$$\alpha_s = 2\epsilon_{,\mathcal{N}} - \frac{\epsilon_{,\mathcal{N}\mathcal{N}}}{\epsilon} + \left(\frac{\epsilon_{,\mathcal{N}}}{\epsilon}\right)^2$$

$$r = 16\epsilon$$

$$f_{\rm NL} \sim \mathcal{O}(\epsilon, \eta, c_s^{-2})$$

Lehners and Wilson-Ewing (2015)
Li-JQ-Wang-Cai (2017)
Akama-Hirano-Kobayashi (2020)
...

matter bounce

$$n_s - 1 = 12w - 9w_{,\mathcal{N}}$$

$$\alpha_s = -12w_{,\mathcal{N}}$$

$$r = 24c_s$$

$$f_{\rm NL} \sim \mathcal{O}(1, c_s^{-2})$$

ekpyrosis

$$n_s - 1 = 2\left(1 - \sqrt{\frac{p}{b}}\right) - \frac{7\epsilon_{,\mathcal{N}}}{3\epsilon}$$

$$\alpha_s = -\sqrt{\frac{p}{b}}\frac{\epsilon_{,\mathcal{N}}}{\epsilon} + \frac{7\epsilon_{,\mathcal{N}\mathcal{N}}}{3\epsilon} - \frac{7}{3}\left(\frac{\epsilon_{,\mathcal{N}}}{\epsilon}\right)^2$$

$$r \lll 1 \qquad (n_t = 2)$$

$$f_{\rm NL} \sim \mathcal{O}(1)$$

Fertig-Lehners-Mallwitz (2014)
Lehners and Wilson-Ewing (2015)
...

Plateau

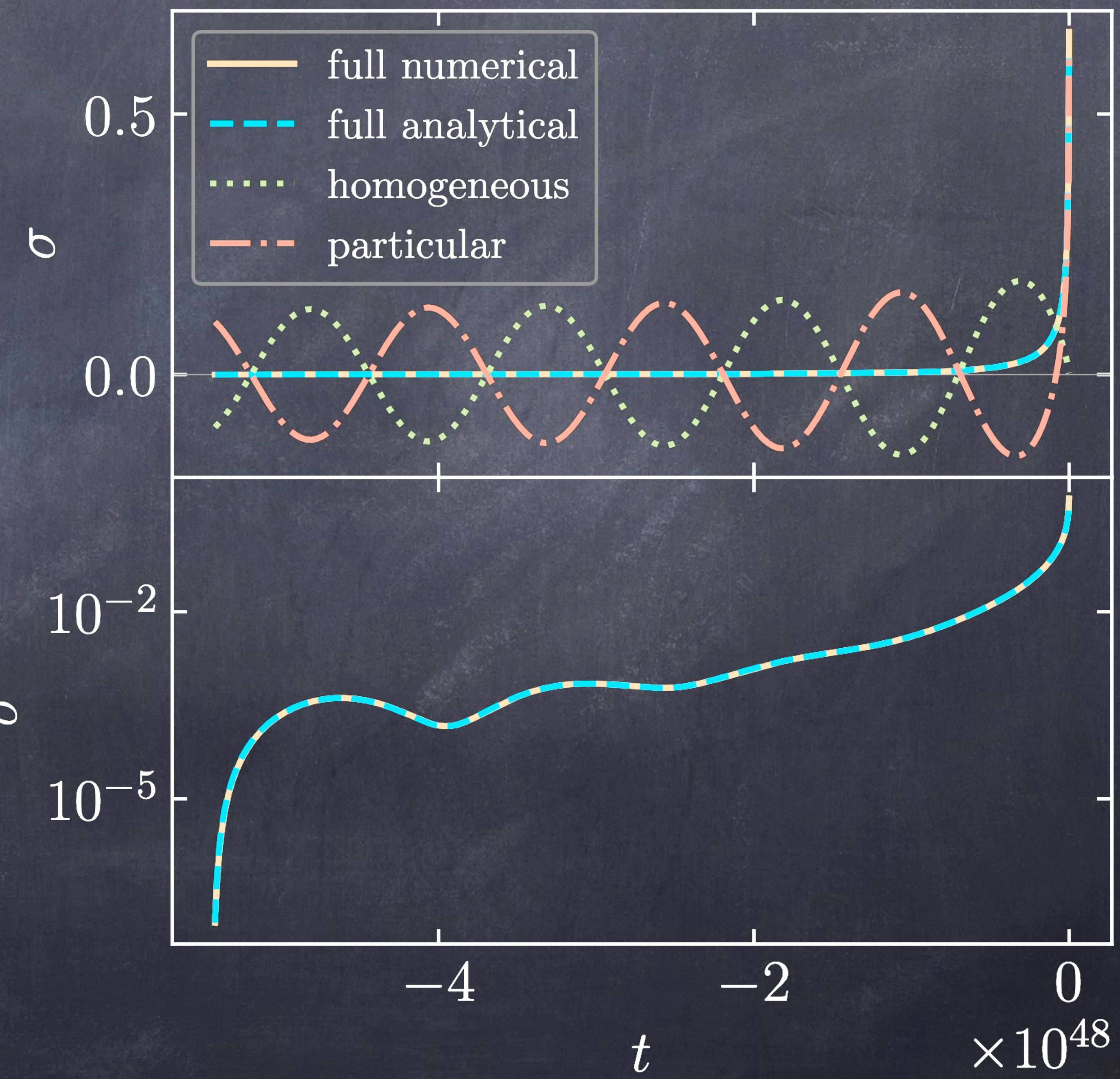
Step

$$\ddot{\sigma} + 3\bar{H}\dot{\sigma} + m_\sigma^2\sigma = \frac{\dot{\bar{\phi}}^2}{2\varrho} \;\Rightarrow\; \ddot{\sigma} + \frac{3p}{t}\dot{\sigma} + m_\sigma^2\sigma = \frac{p}{\varrho t^2}$$

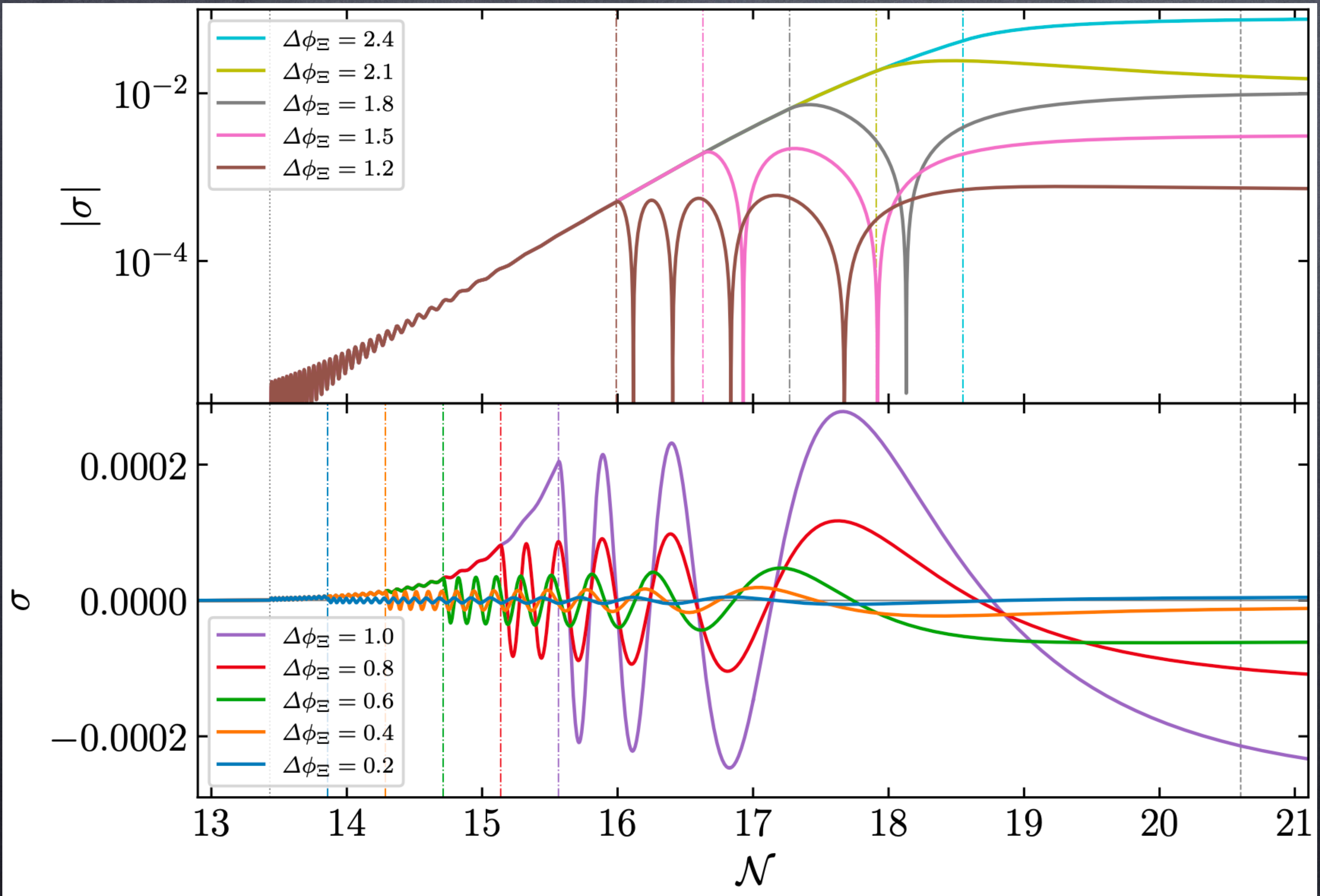
$$\Rightarrow \sigma_{\rm p}(t) = \frac{\pi p}{4\varrho \sin(\pi\alpha)}\left(\frac{J_\alpha(-m_\sigma t)\,{}_1F_2(-\alpha; 1-\alpha, 1-\alpha; -y^2)}{\alpha^2\Gamma(-\alpha)y^\alpha} + e^{-i\pi\alpha}y^\alpha J_{-\alpha}(m_\sigma t)G_{1,3}^{2,0}\left(y^2\,\middle|\,{1 \atop 0,0,-\alpha}\right)\right)$$

$$\Rightarrow \sigma_{\rm p} \sim \frac{\sin(-m_\sigma t)}{(-m_\sigma t)^{3p/2}},$$

$$(-m_\sigma t \gg 1)$$

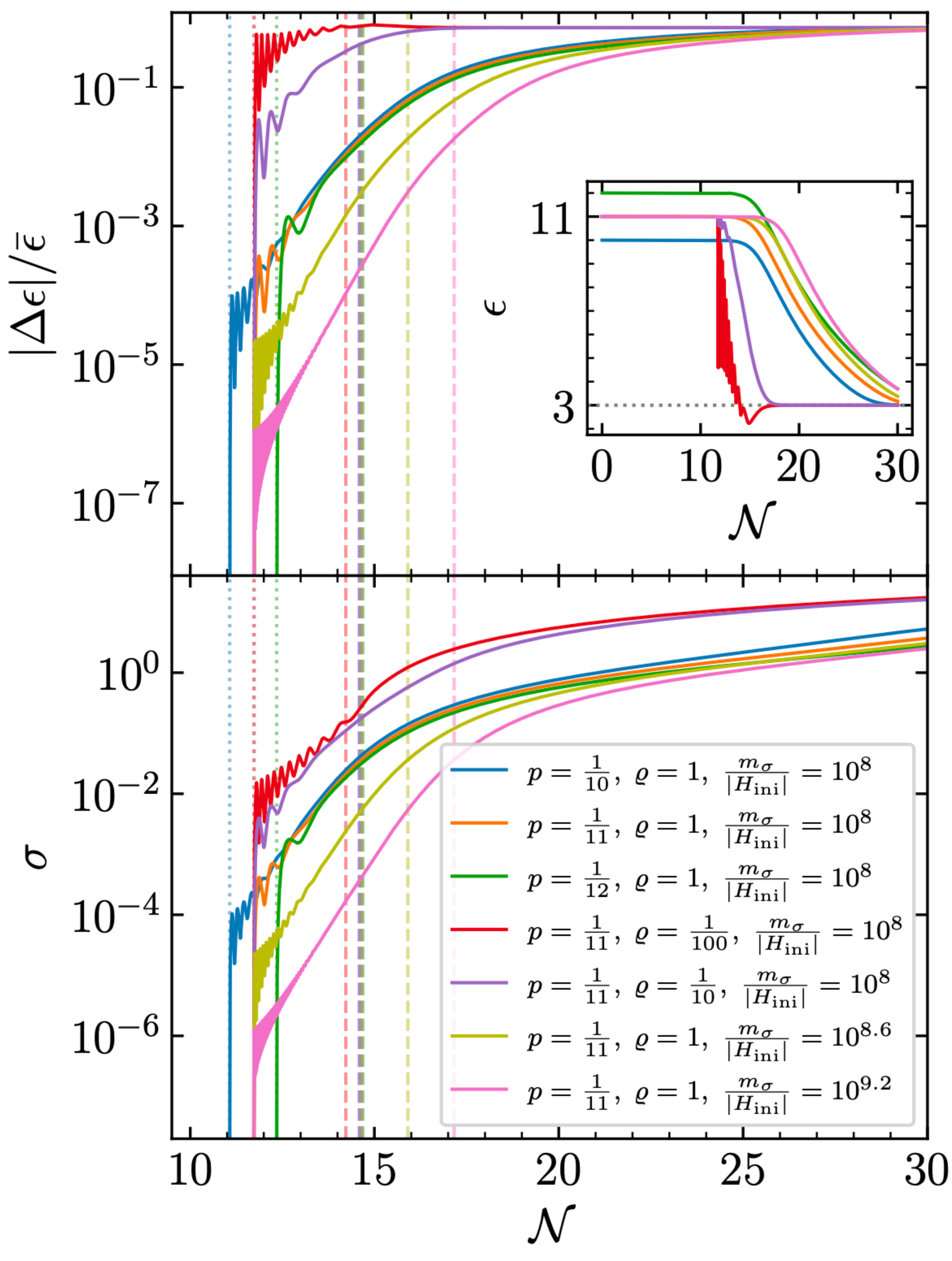


Plateau

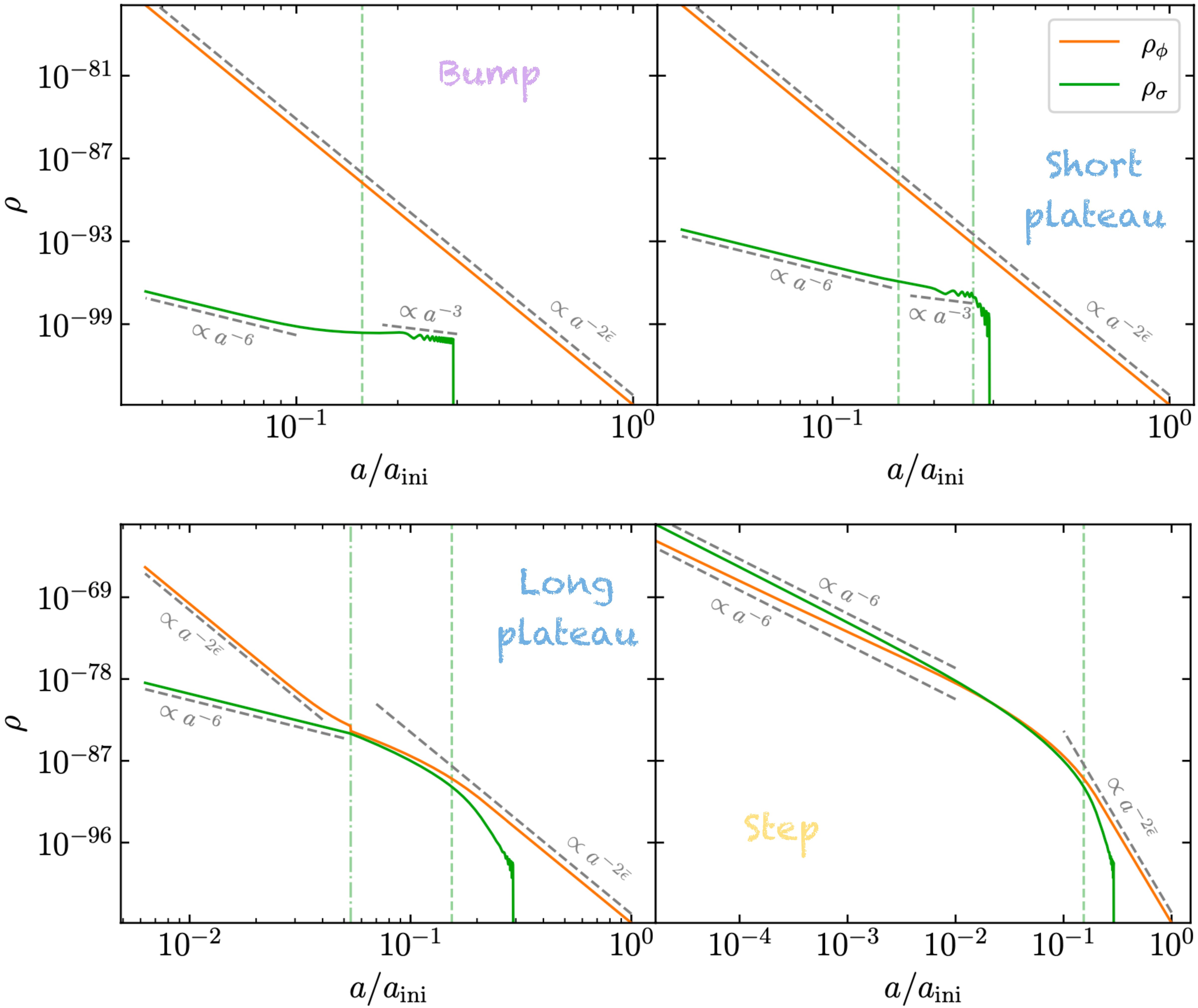


$\Delta\phi_\Xi = 2.4$
$\Delta\phi_\Xi = 2.1$
$\Delta\phi_\Xi = 1.8$
$\Delta\phi_\Xi = 1.5$
$\Delta\phi_\Xi = 1.2$
10^{-2}
10^{-4}
$|\sigma|$
0.0002
0.0000
-0.0002
σ
$\Delta\phi_\Xi = 1.0$
$\Delta\phi_\Xi = 0.8$
$\Delta\phi_\Xi = 0.6$
$\Delta\phi_\Xi = 0.4$
$\Delta\phi_\Xi = 0.2$
13
14
15
16
17
18
19
20
21
$\mathcal{N}$

Step

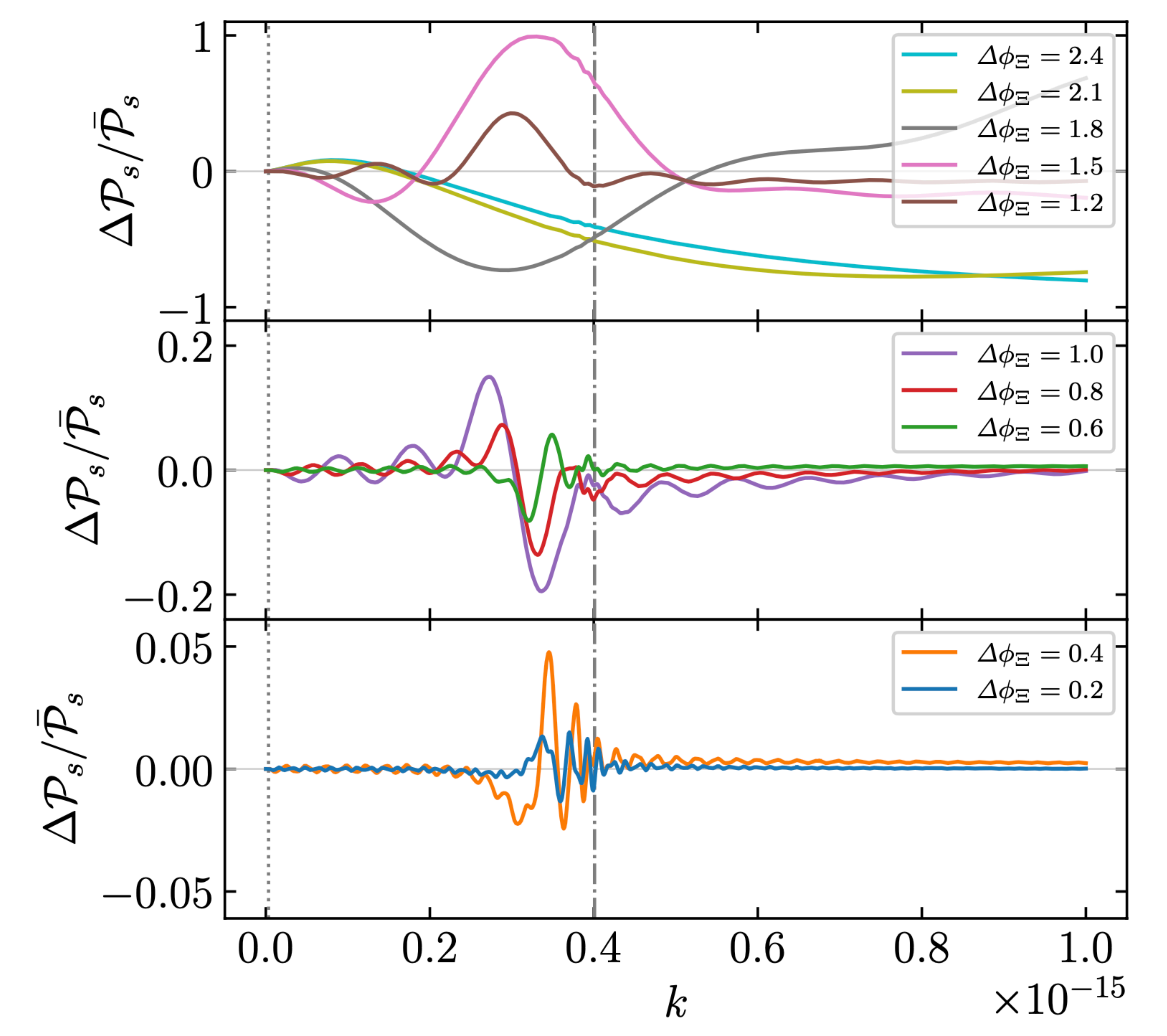


$|\Delta\epsilon|/\bar{\epsilon}$
10^{-1}
10^{-3}
10^{-5}
10^{-7}
ϵ
11
3
0
10
20
30
$\mathcal{N}$
σ
10^{0}
10^{-2}
10^{-4}
10^{-6}
$p = \frac{1}{10},\ \varrho = 1,\ \frac{m_\sigma}{|H_{\rm ini}|} = 10^8$
$p = \frac{1}{11},\ \varrho = 1,\ \frac{m_\sigma}{|H_{\rm ini}|} = 10^8$
$p = \frac{1}{12},\ \varrho = 1,\ \frac{m_\sigma}{|H_{\rm ini}|} = 10^8$
$p = \frac{1}{11},\ \varrho = \frac{1}{100},\ \frac{m_\sigma}{|H_{\rm ini}|} = 10^8$
$p = \frac{1}{11},\ \varrho = \frac{1}{10},\ \frac{m_\sigma}{|H_{\rm ini}|} = 10^8$
$p = \frac{1}{11},\ \varrho = 1,\ \frac{m_\sigma}{|H_{\rm ini}|} = 10^{8.6}$
$p = \frac{1}{11},\ \varrho = 1,\ \frac{m_\sigma}{|H_{\rm ini}|} = 10^{9.2}$
10
15
20
25
30
$\mathcal{N}$



Bump
Short plateau
Long plateau
Step
ρ_ϕ
ρ_σ
$\propto a^{-6}$
$\propto a^{-3}$
$\propto a^{-2\bar{\epsilon}}$
ρ
$a/a_{\rm ini}$
10^{-81}
10^{-87}
10^{-93}
10^{-99}
10^{-69}
10^{-78}
10^{-96}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

Plateau



$\Delta\phi_\Xi = 2.4$
$\Delta\phi_\Xi = 2.1$
$\Delta\phi_\Xi = 1.8$
$\Delta\phi_\Xi = 1.5$
$\Delta\phi_\Xi = 1.2$
$\Delta\phi_\Xi = 1.0$
$\Delta\phi_\Xi = 0.8$
$\Delta\phi_\Xi = 0.6$
$\Delta\phi_\Xi = 0.4$
$\Delta\phi_\Xi = 0.2$
$\Delta\mathcal{P}_s/\bar{\mathcal{P}}_s$
1
0
−1
0.2
0.0
−0.2
0.05
0.00
−0.05
0.0
0.2
0.4
0.6
0.8
1.0
k
$\times 10^{-15}$