Cosmological collider vs particle scanner:

primordial features as early universe scenario discriminator and signs of new particles

PERIMETER INSTITUTE

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CAP Meeting

May 29, 2024

Mostly based on joint work with

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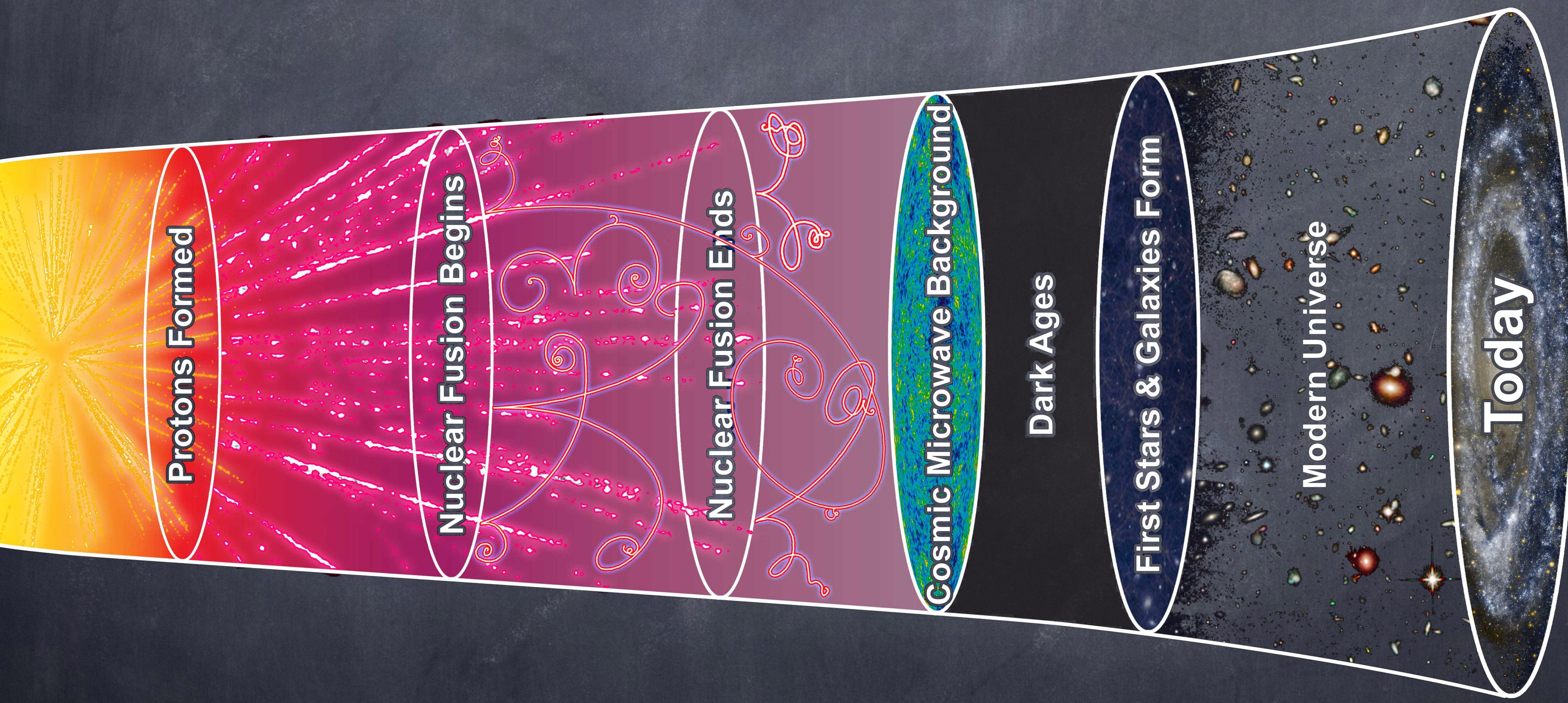
and

Reza Ebadi (Maryland)

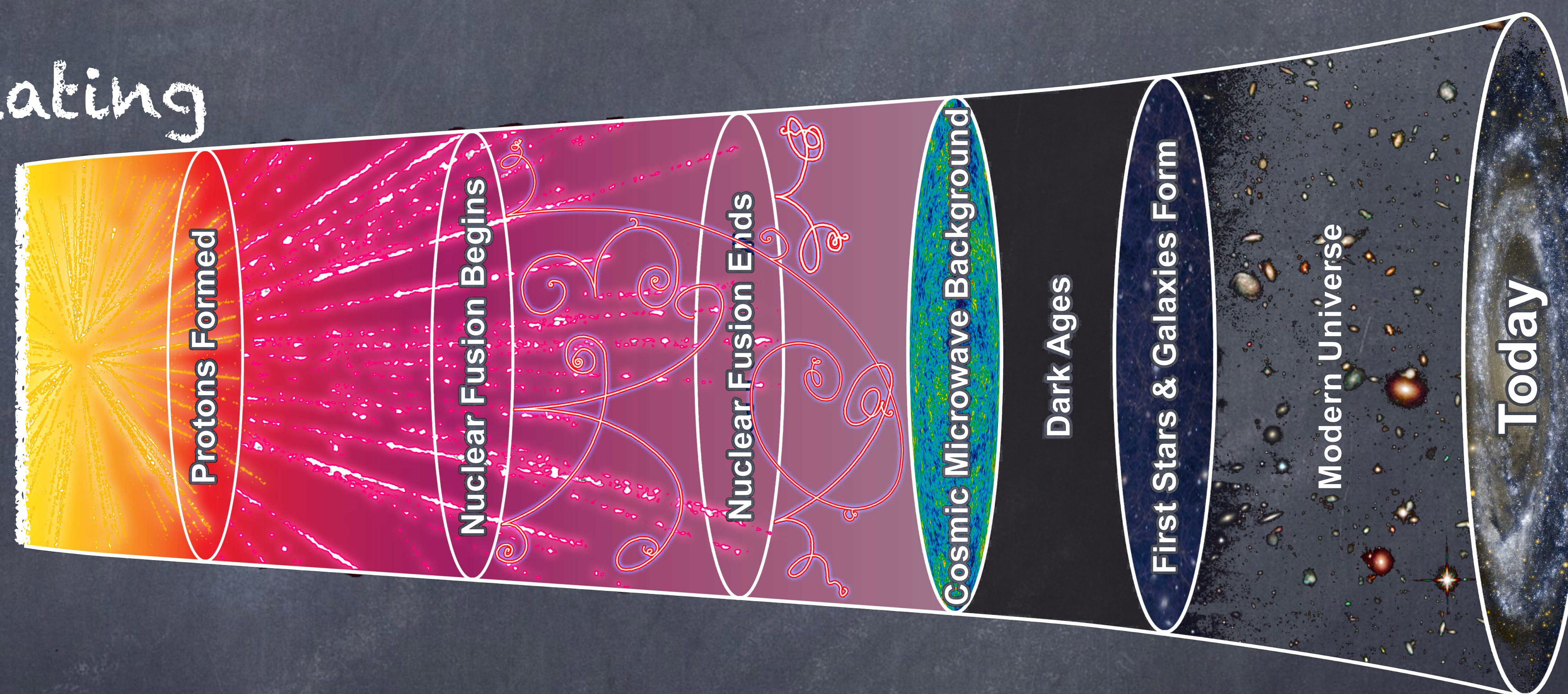
arXiv:2405.11016



Credit: BICEP2/CERN/NASA

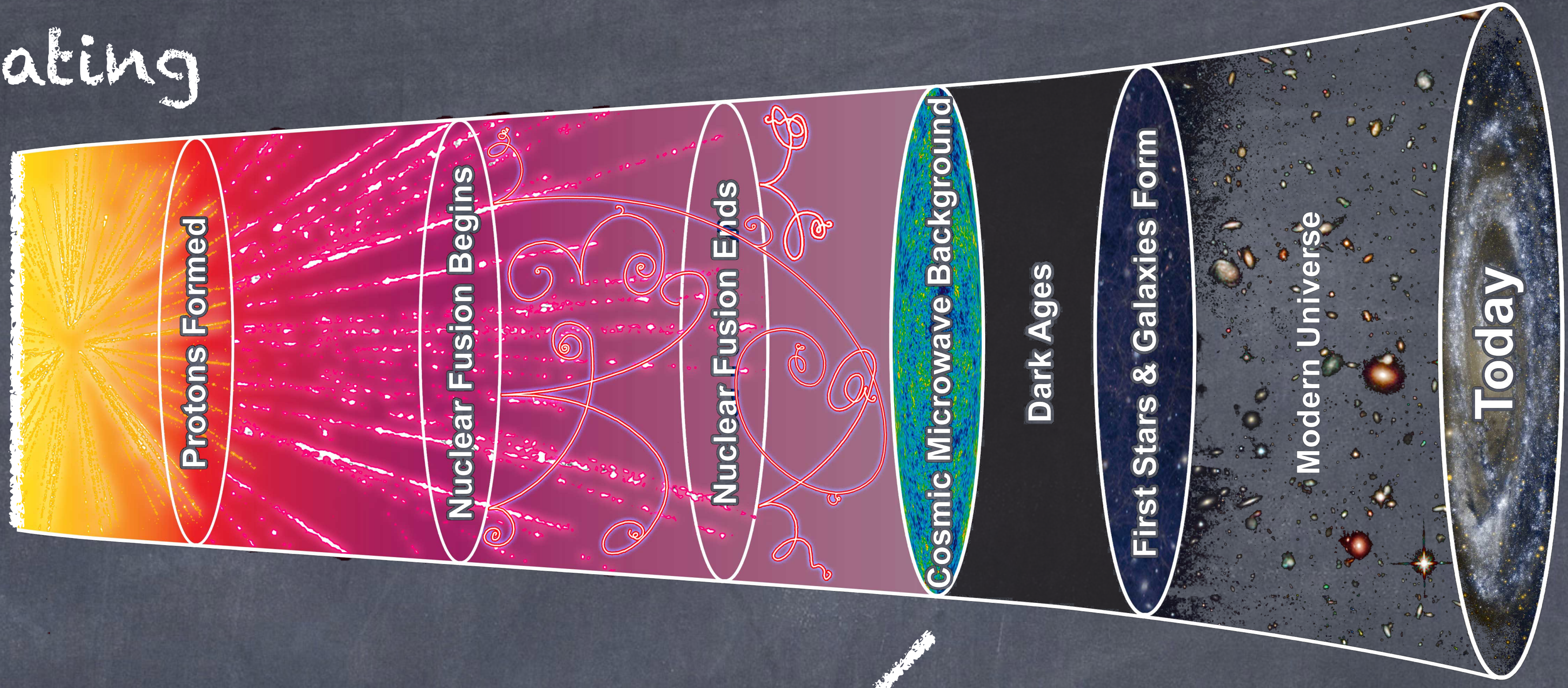
reheating

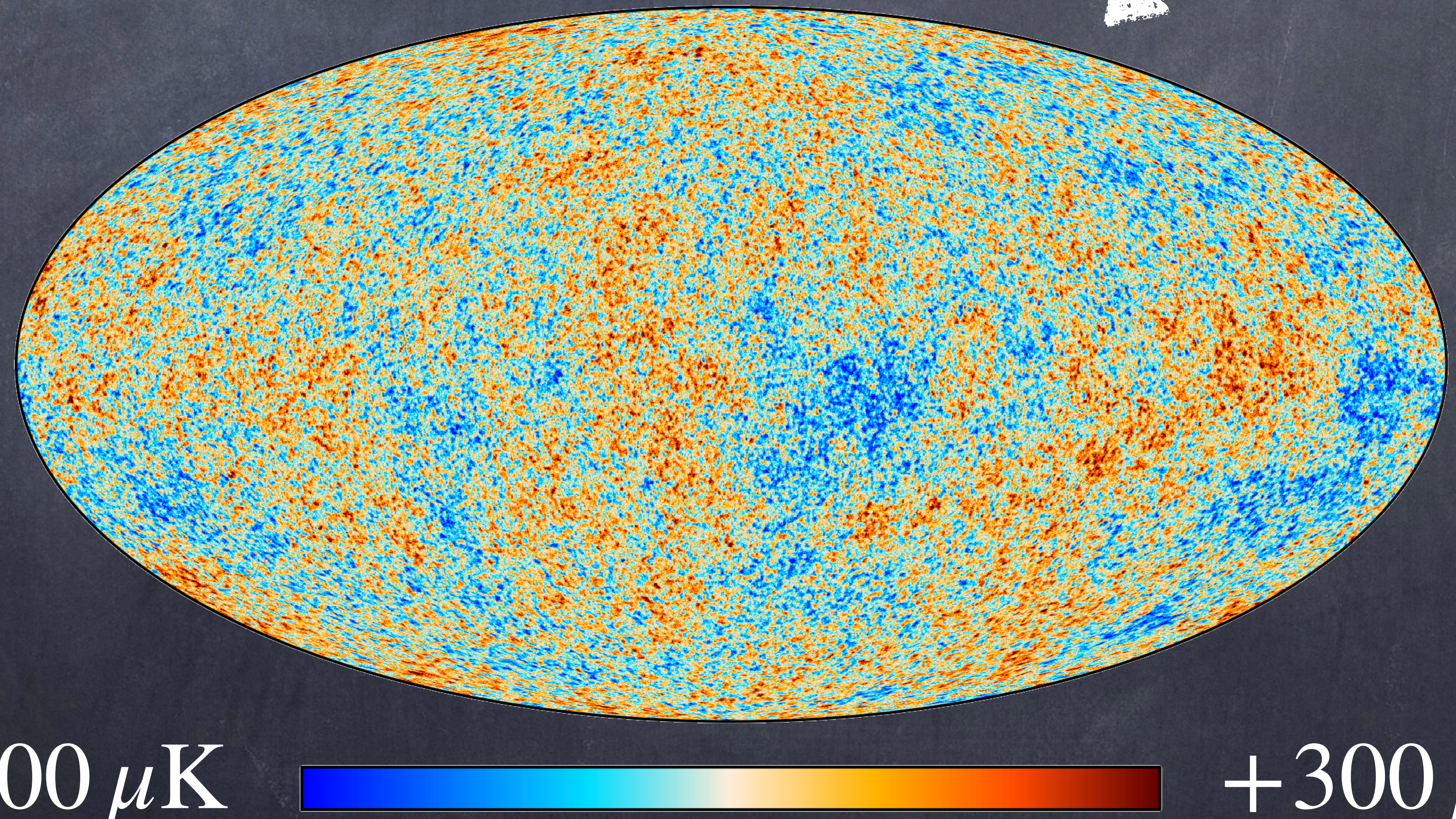
?


Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today

reheating

?





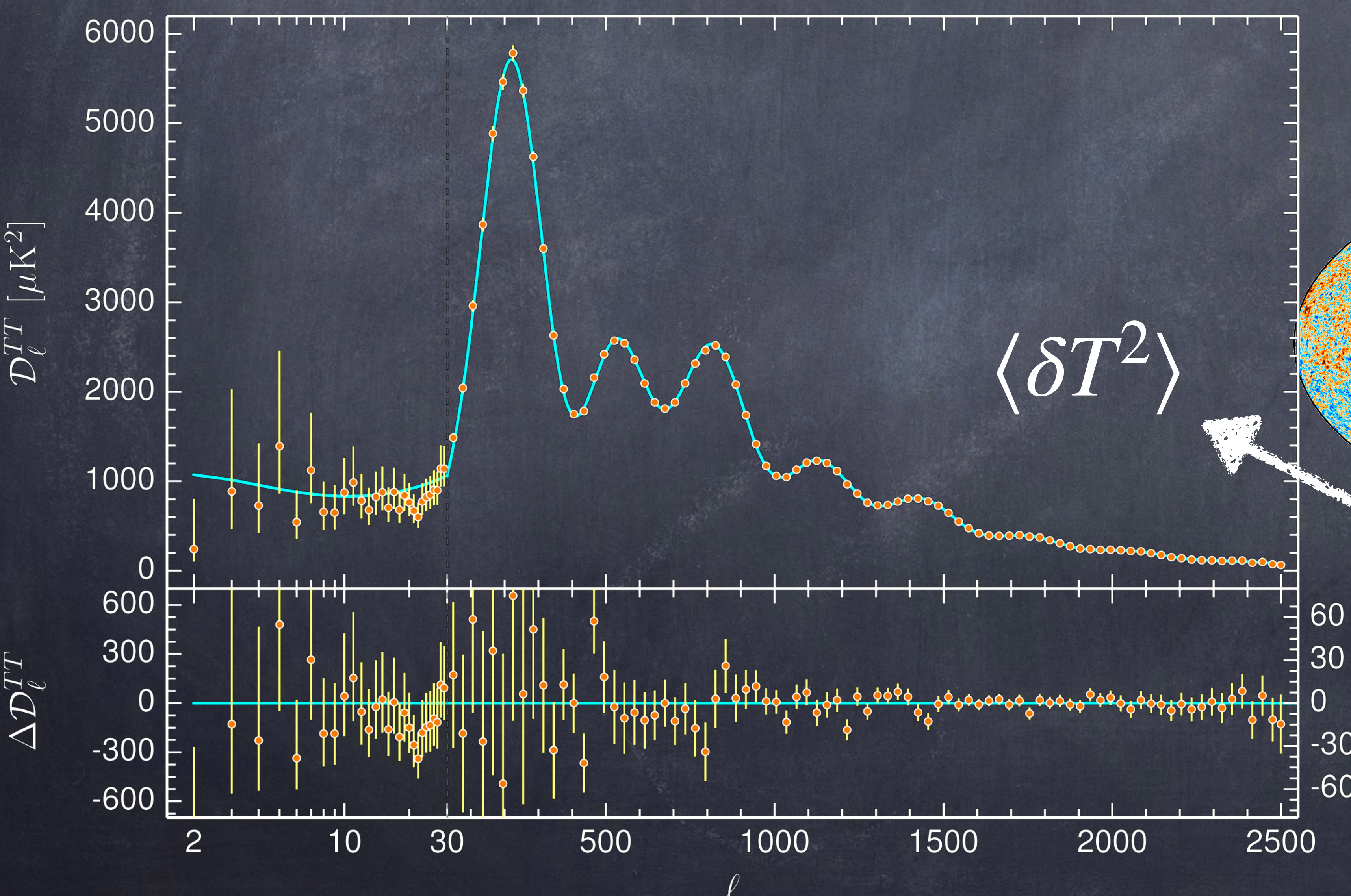
$-300\,\mu K$ $+300\,\mu K$

δT

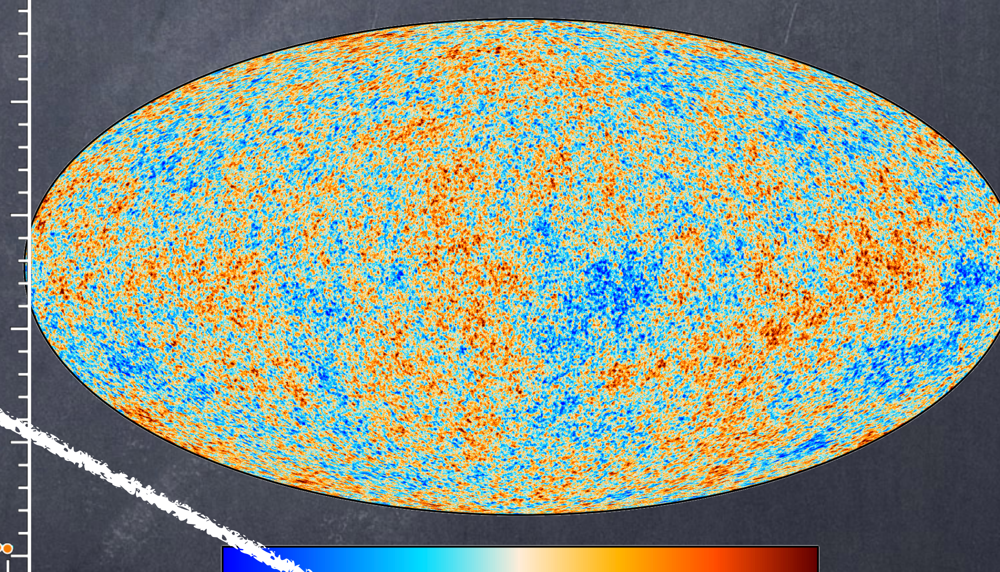
PLANCK (2018)

reheating

?



$\langle \delta T^2 \rangle$

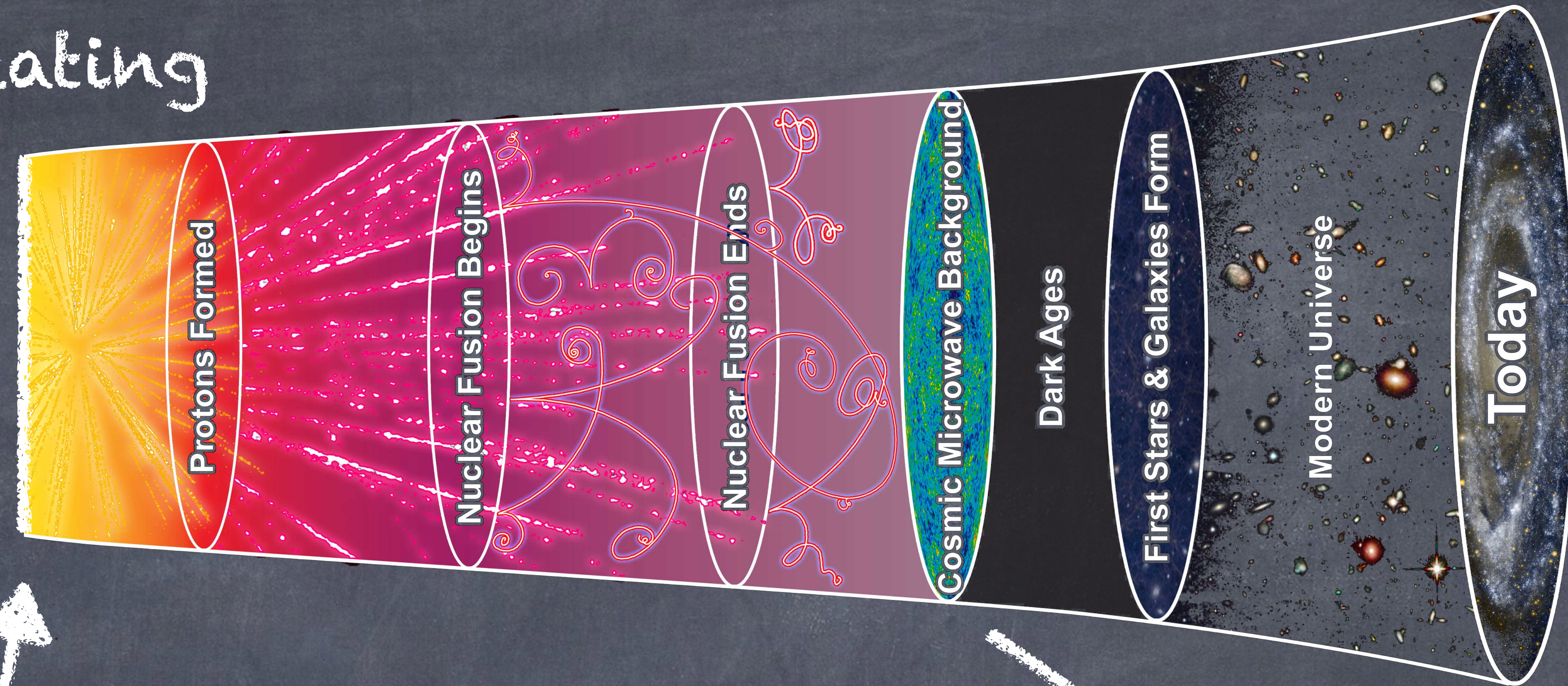


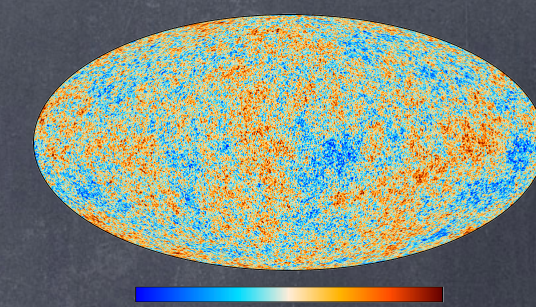
δT

PLANCK (2018)

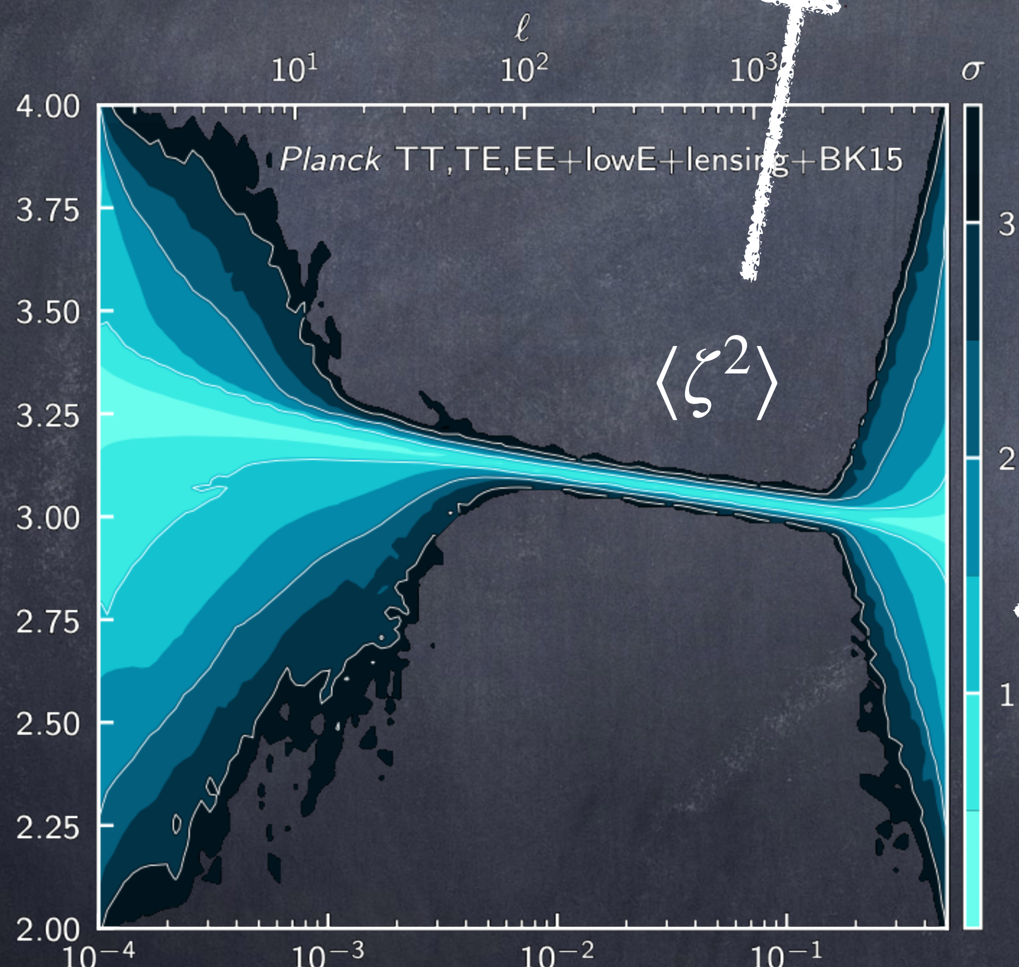
reheating

?



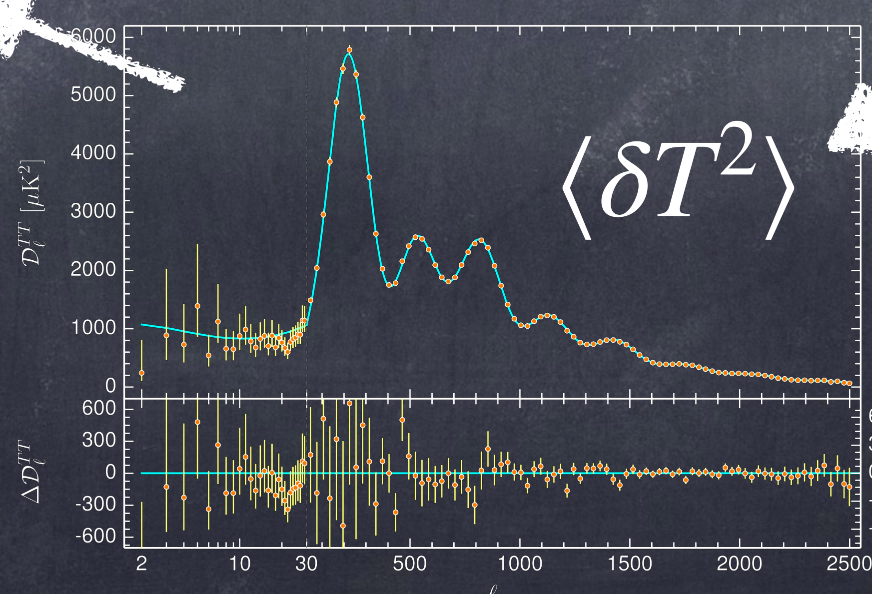


δT



$\langle \zeta^2 \rangle$

k [Mpc^{-1}]

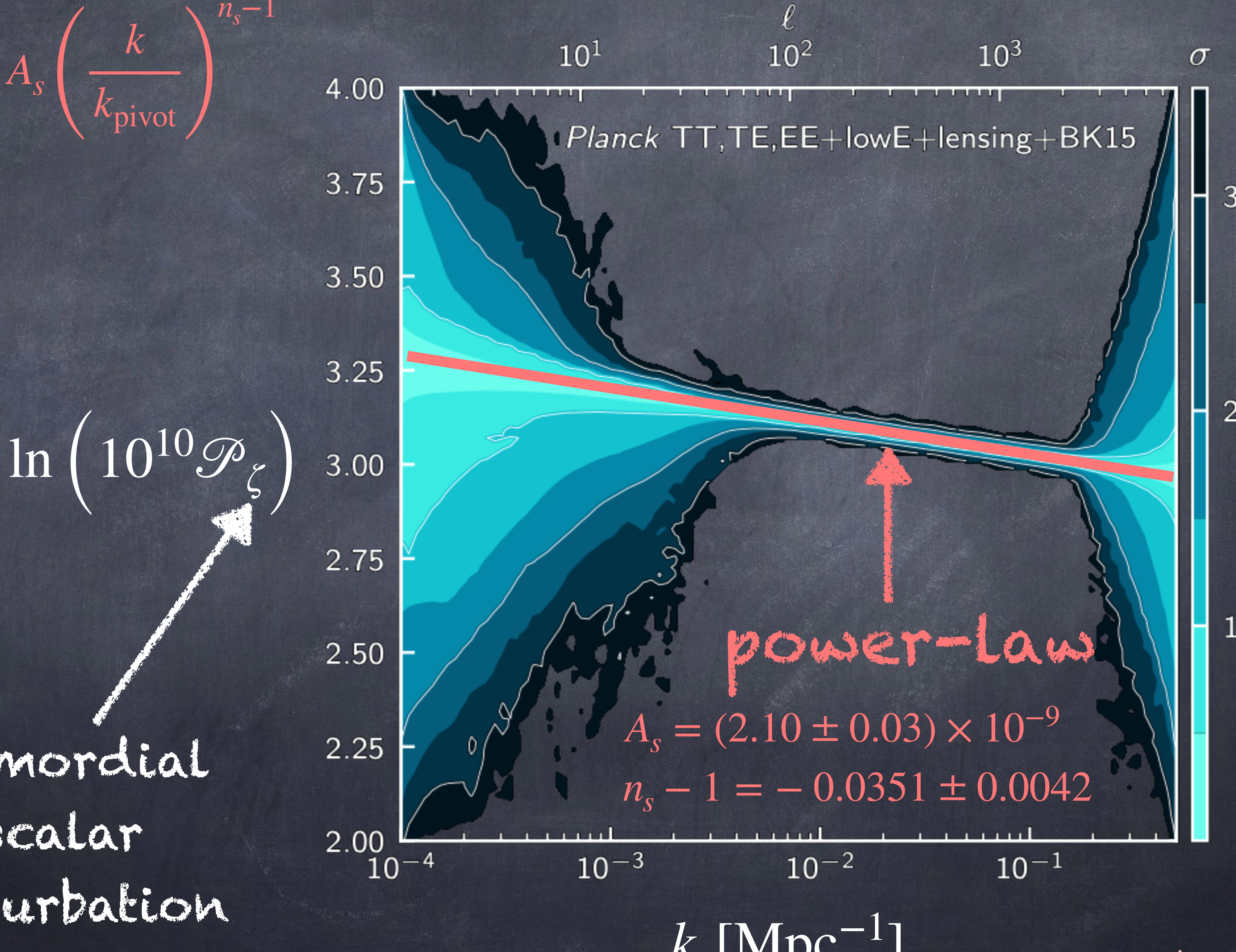


$\langle \delta T^2 \rangle$

PLANCK (2018)

$$\langle \zeta_{\vec{k}} \zeta_{\vec{k}'} \rangle = (2\pi)^3 \delta^{(3)}(\vec{k} + \vec{k}') \frac{2\pi^2}{k^3} \mathcal{P}_\zeta(k)$$

$$\bar{\mathcal{P}}_\zeta(k) = A_s \left(\frac{k}{k_{\text{pivot}}} \right)^{n_s - 1}$$



primordial scalar perturbation

PLANCK (2018)

quantum vacuum
+ evolution

many ways
of "evolving"

scale-invariant
power spectrum

$$\bar{\mathcal{P}}_\zeta(k) \sim k^0$$

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

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

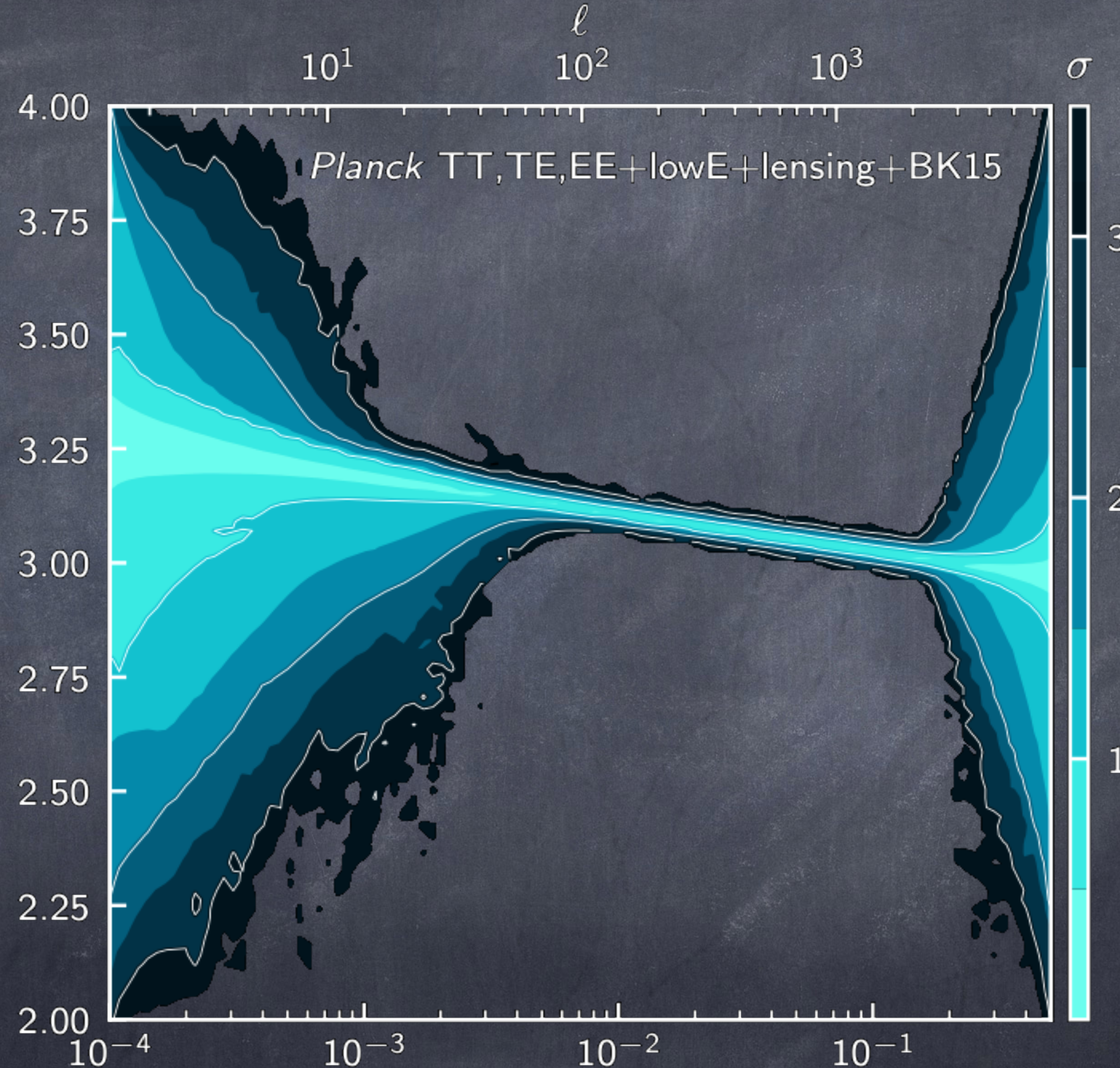
$$\langle\zeta^3\rangle \begin{cases} f_{\rm NL}^{\rm local} = -0.9 \pm 5.1 \\ f_{\rm NL}^{\rm equil} = -26 \pm 47 \\ f_{\rm NL}^{\rm ortho} = -38 \pm 24 \end{cases}$$

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

$$\ldots$$

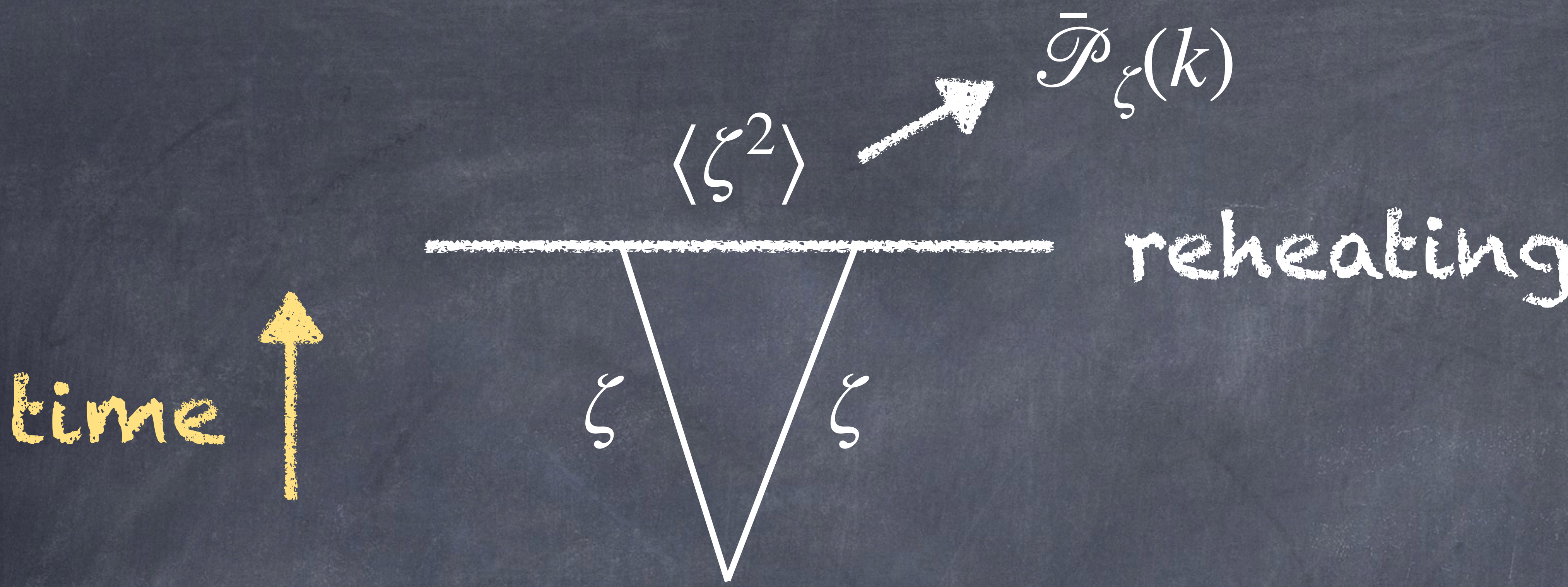
all consistent with zero

PLANCK (2018)

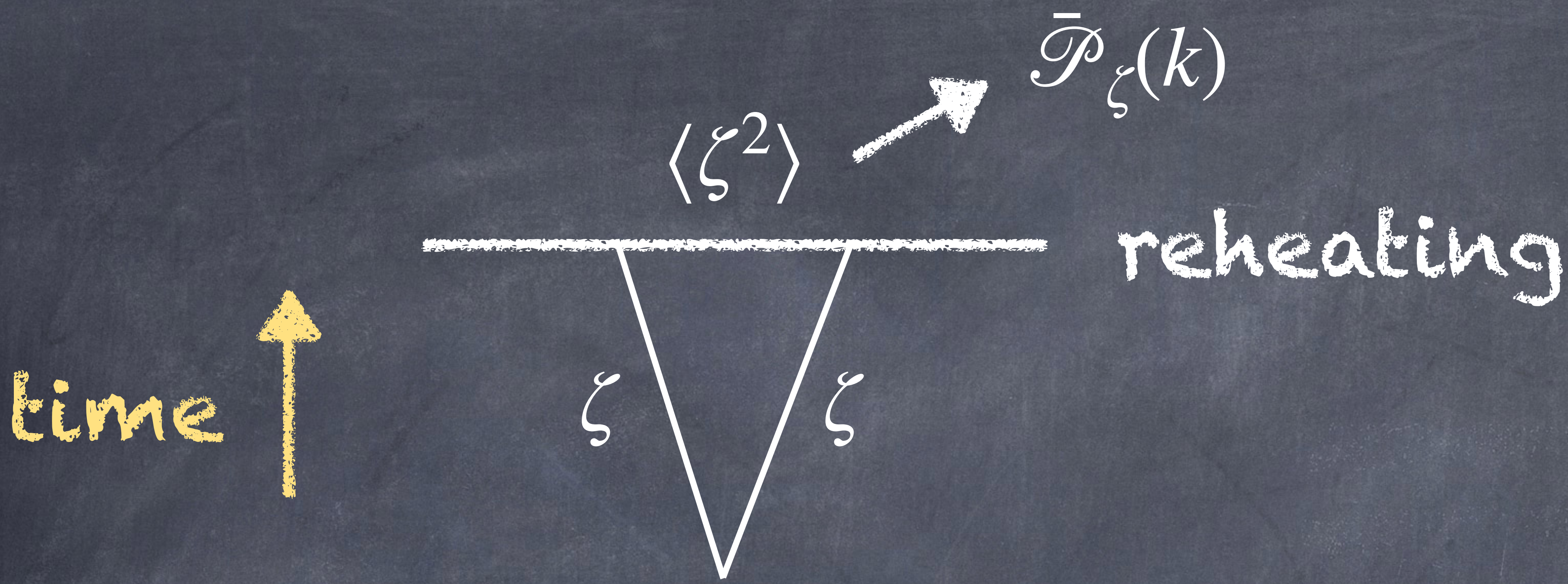


$\ln\left(10^{10}\mathscr{P}_\zeta\right)$

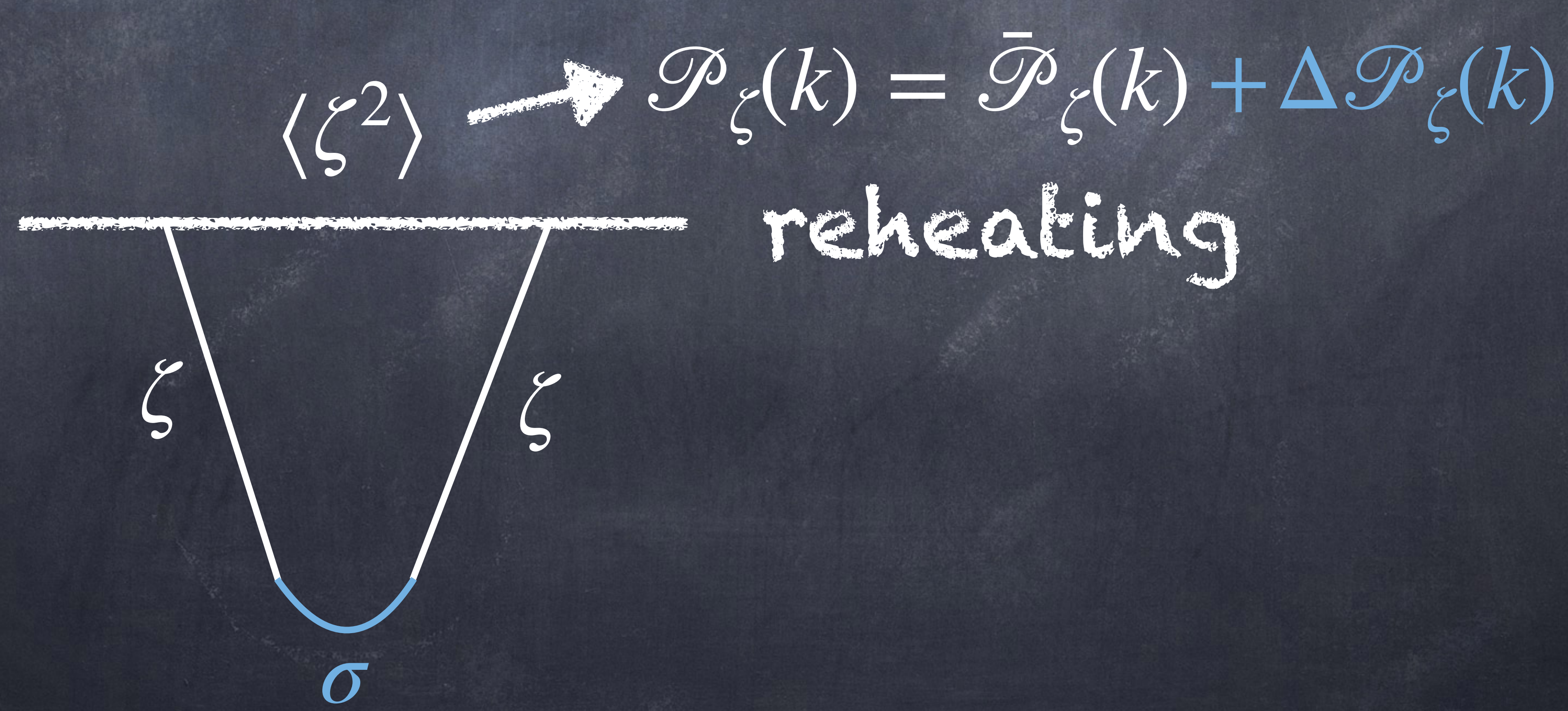
k [Mpc^{-1}]



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



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

Massive spectator fields:

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

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

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

in-in:

free theory vacuum

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

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

interaction vacuum

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

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

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

⟶ heavy fields can usually be integrated out in low-energy effective field theories

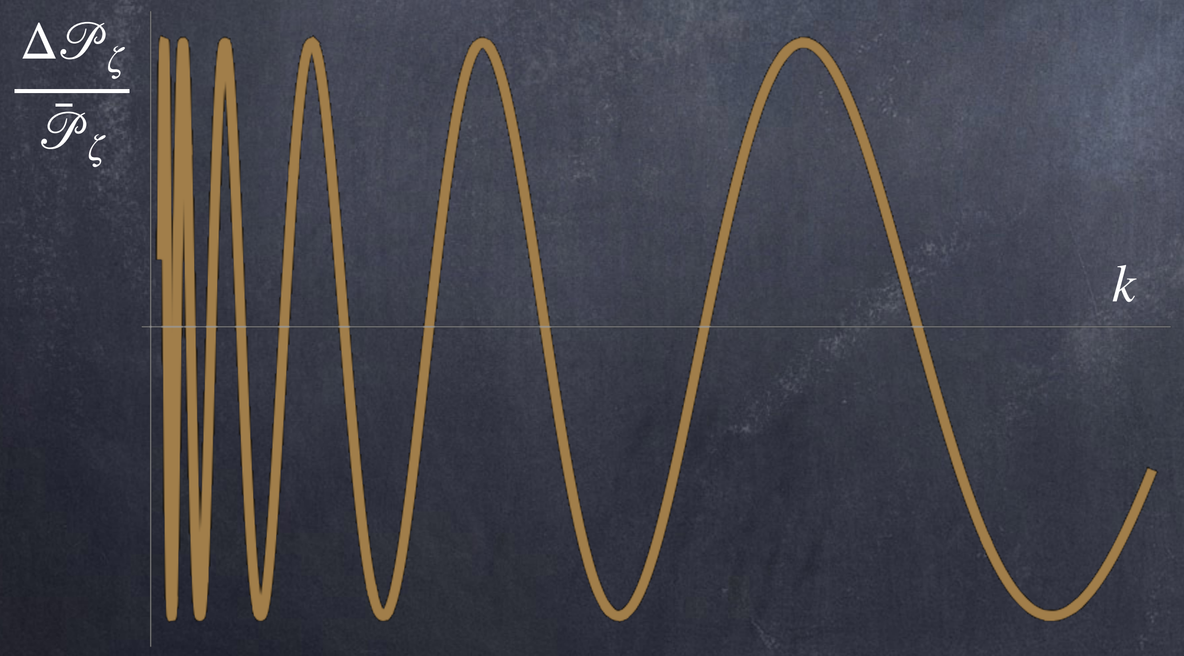
Except for resonance (saddle point) when

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

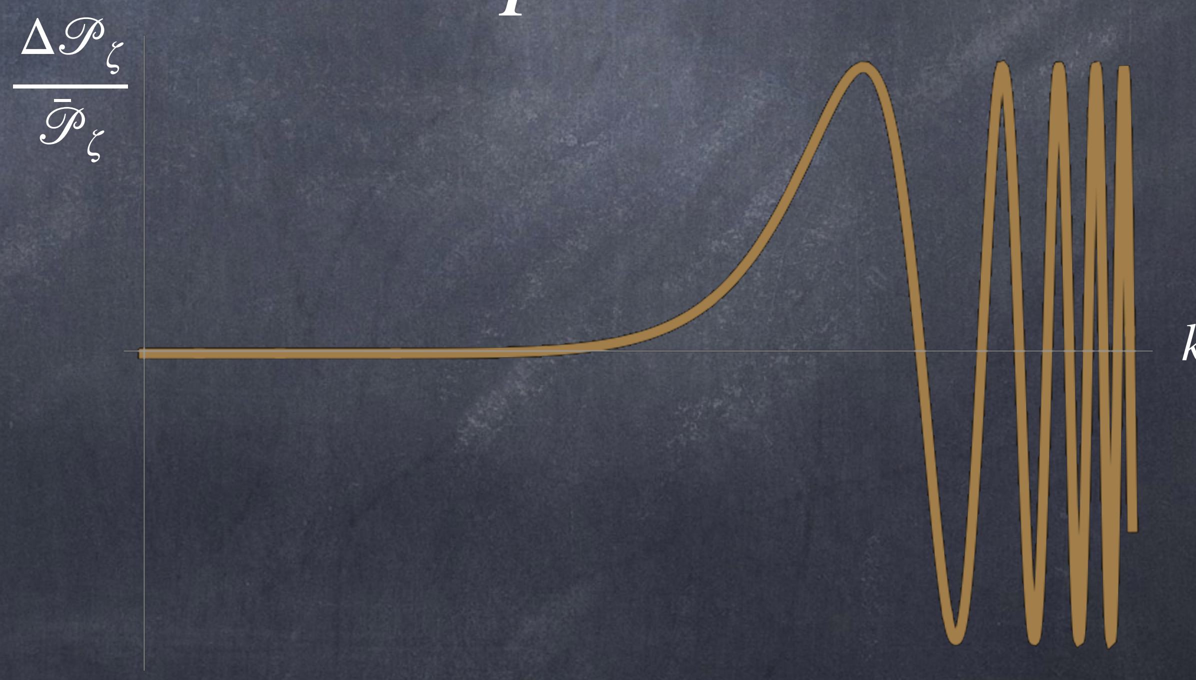
$$a(t) \propto |t|^p$$

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

$p \gg 1$

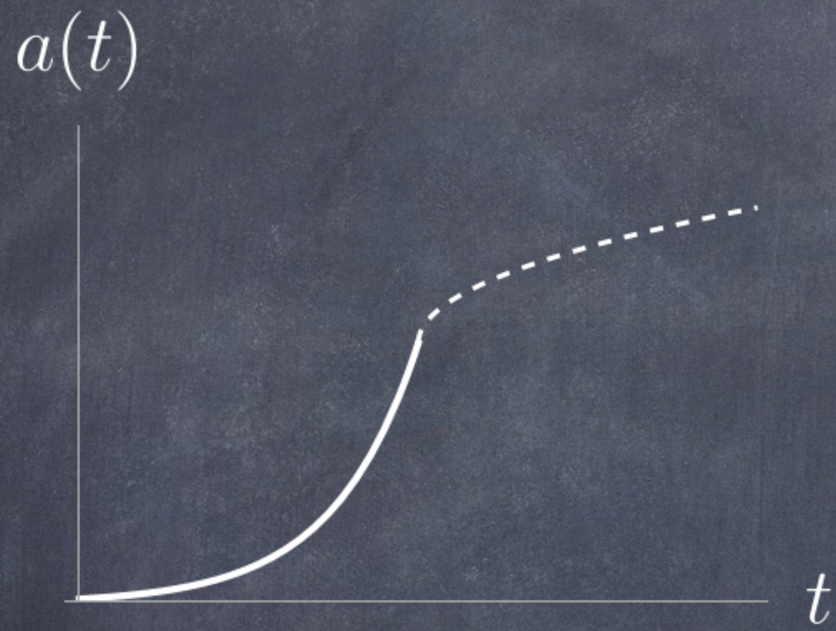


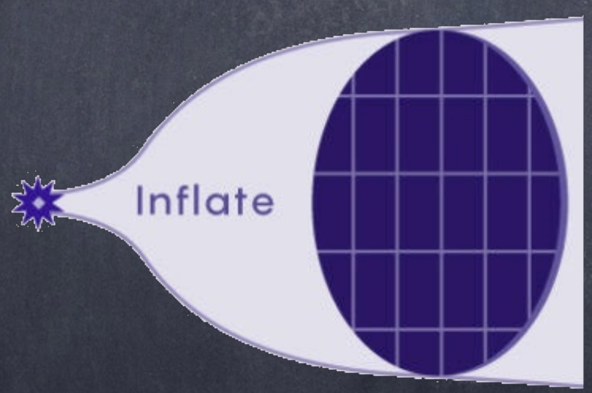
$p \ll 1$



Chen (2011, 2012)

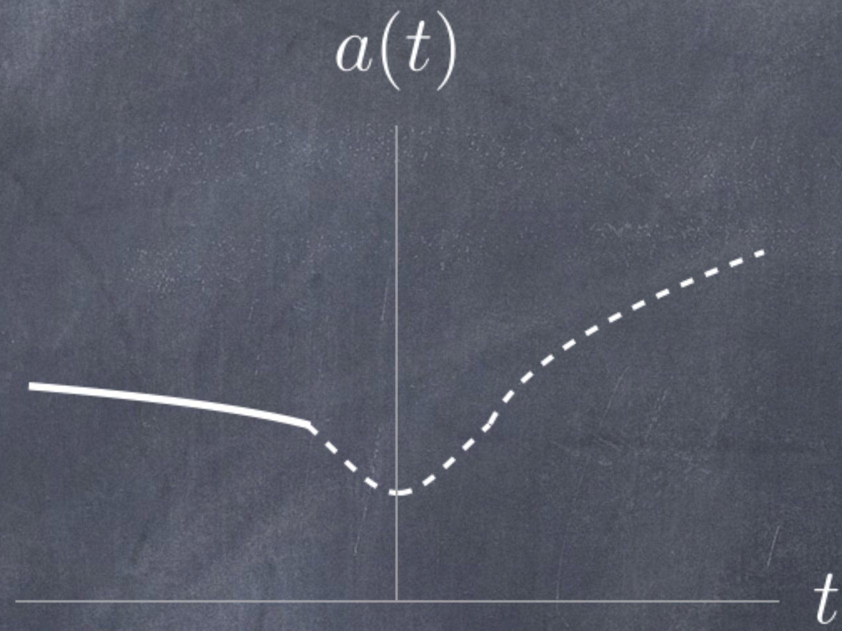
inflationary cosmology





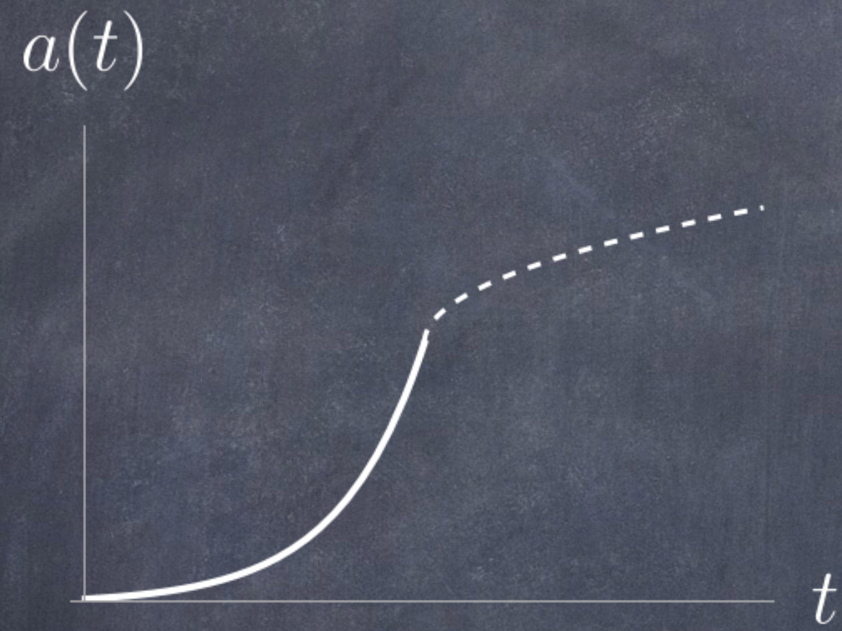
Guth (1980),
...

contracting cosmology (before a bounce)

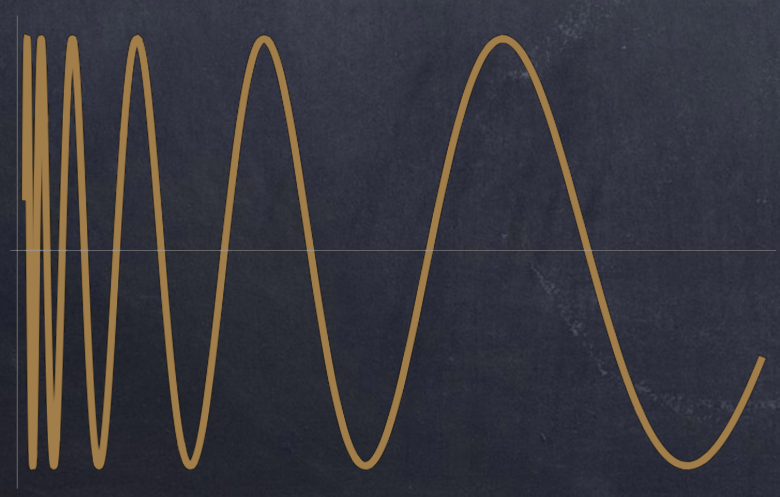


Gasperini-Veneziano (1993),
Khoury-Ovrut-Steinhardt-Turok (2001),
JQ+ (2014, ...),
...

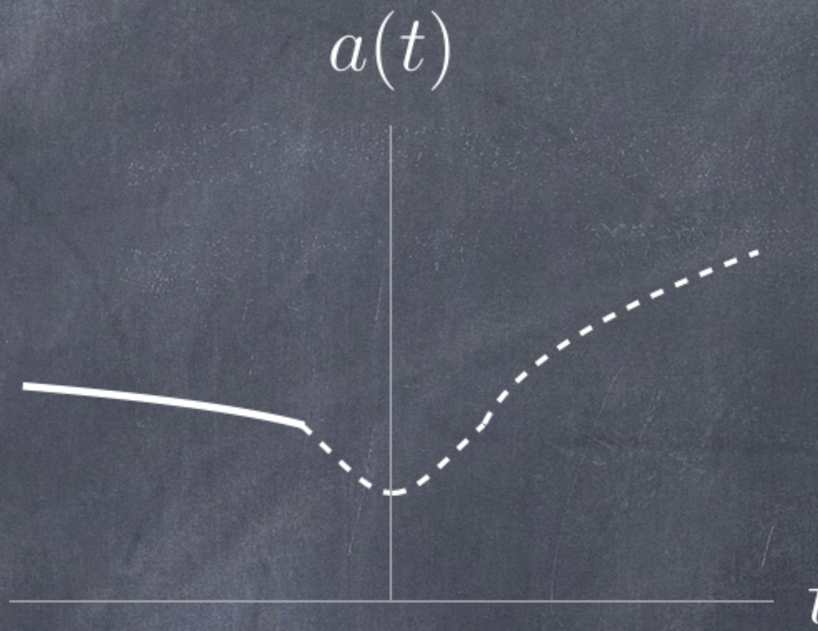
inflationary cosmology



$$a(t) \sim t^p\,, \quad t > 0\,, \quad p \gg 1$$



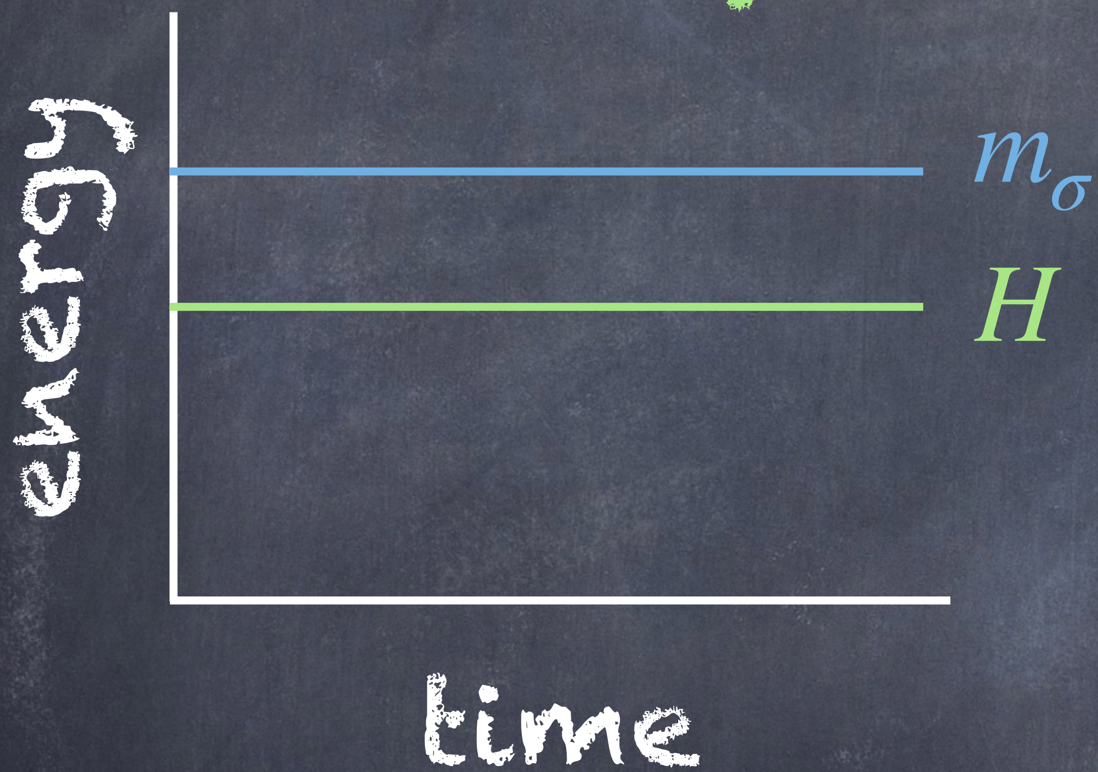
contracting cosmology (before a bounce)



$$a(t) \sim (-t)^p\,, \quad t < 0\,, \quad p \ll 1$$

$$H \equiv \frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t}$$

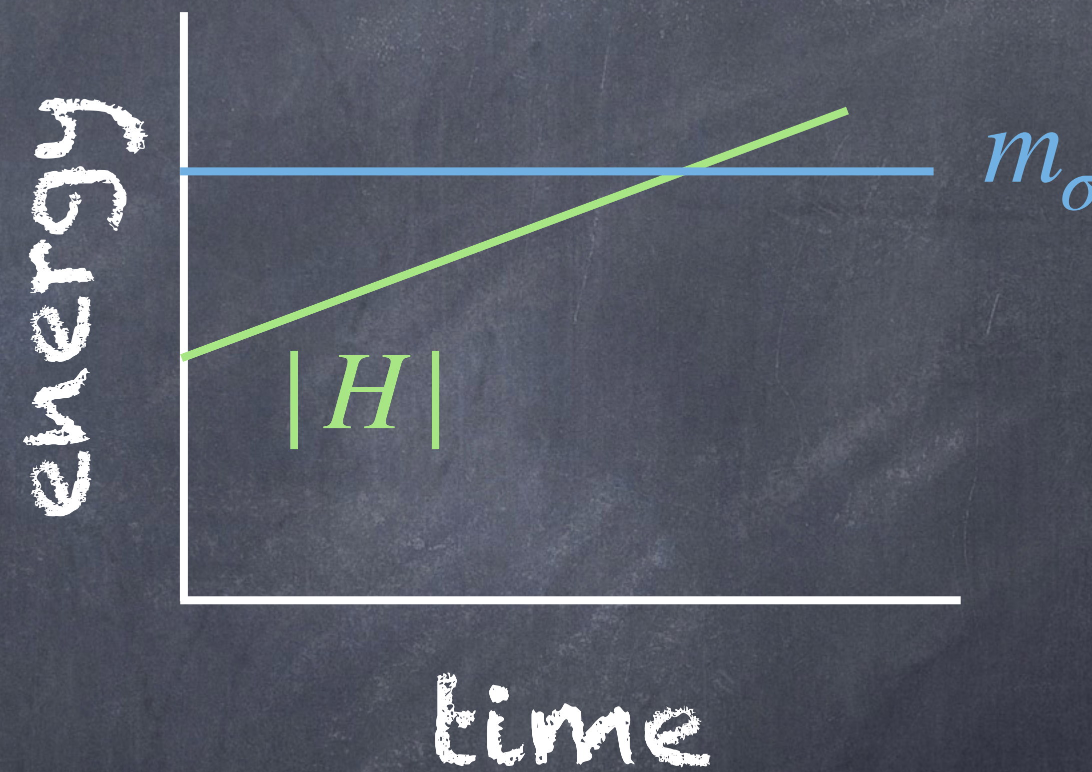
inflationary cosmology



cosmological collider

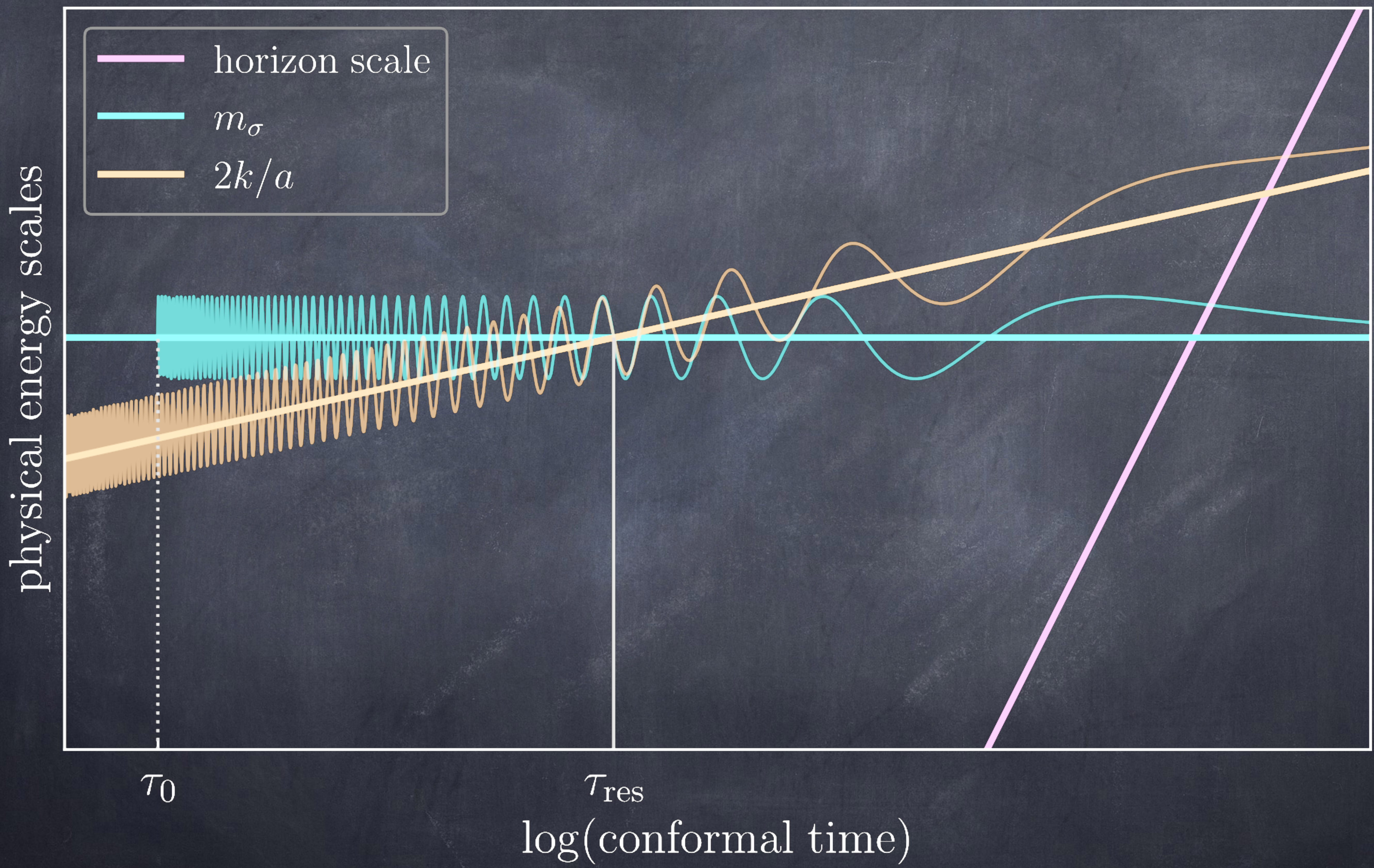
Chen–Wang (2009), Arkani-Hamed–Maldacena (2015)

contracting cosmology (before a bounce)



particle scanner

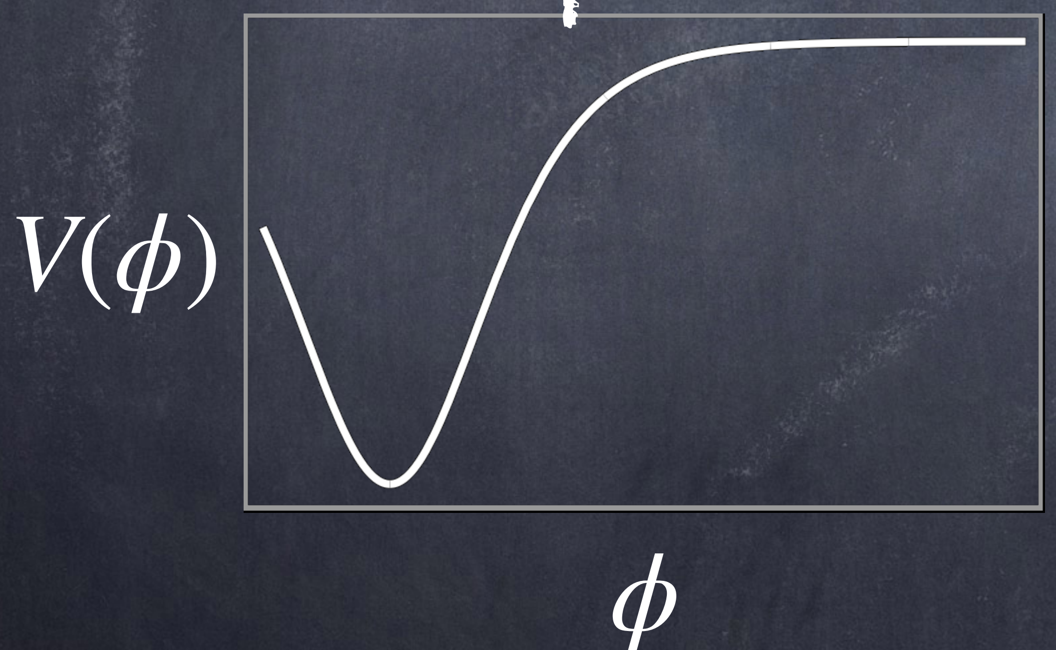
Chen–Loeb–Xianyu (2019)



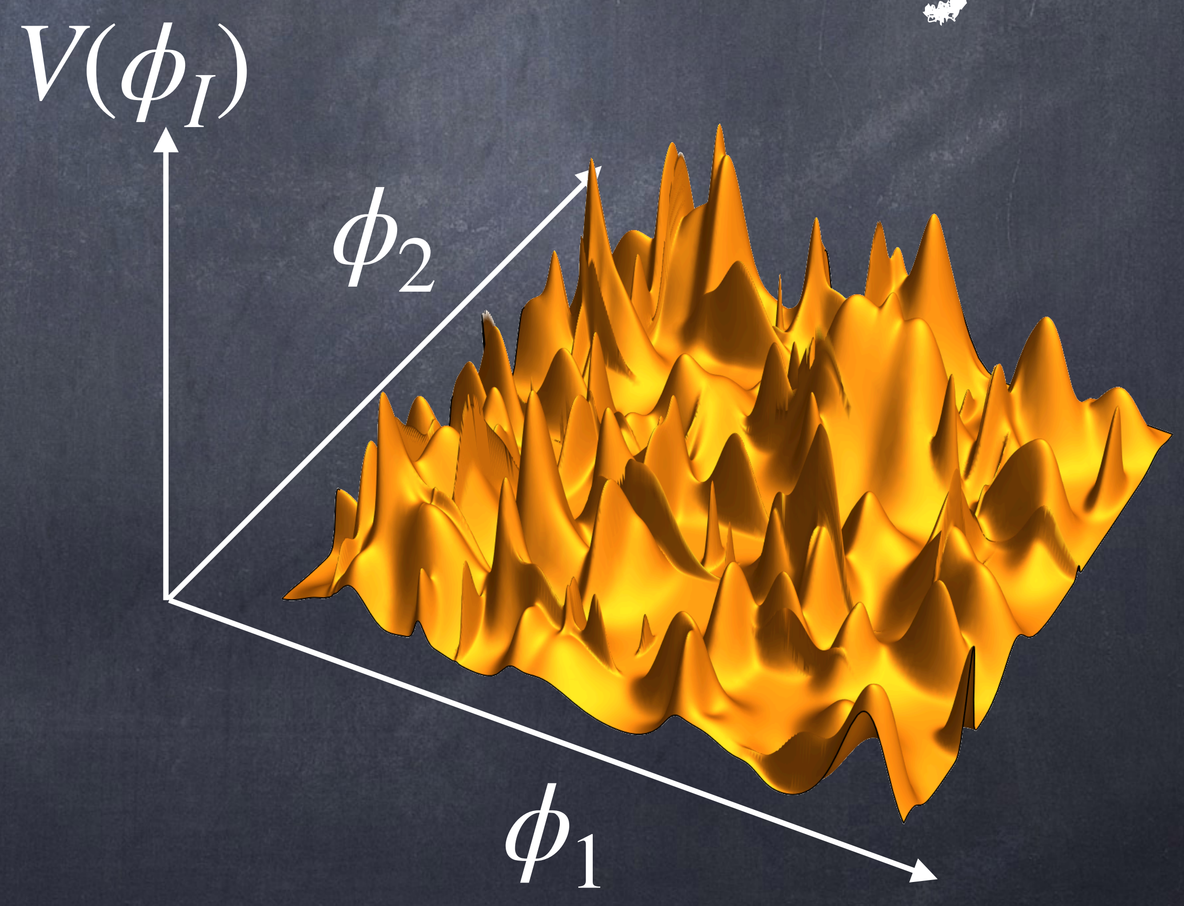
JQ-Chen-Ebadi (2024)

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

We hope for...



But the reality...



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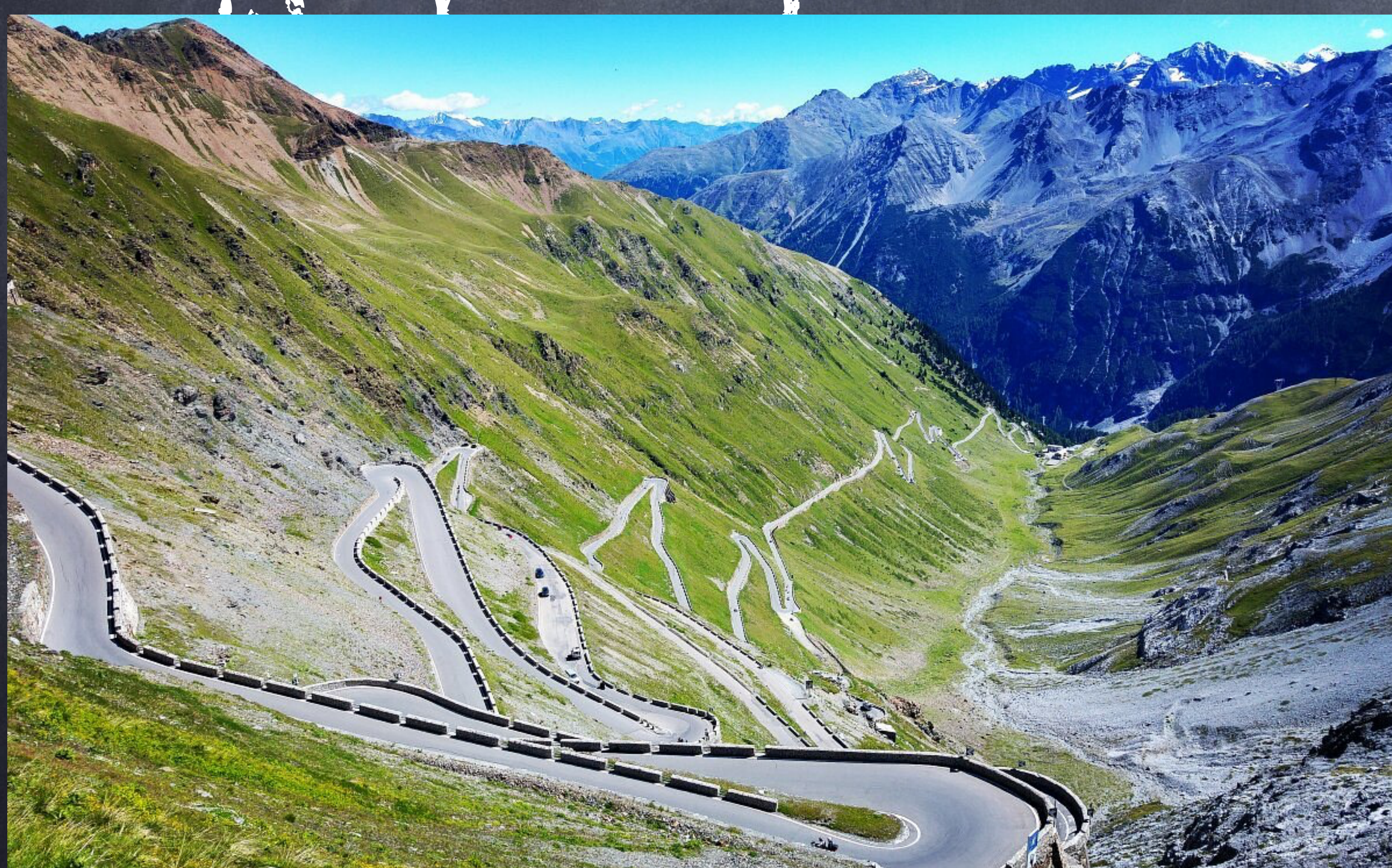
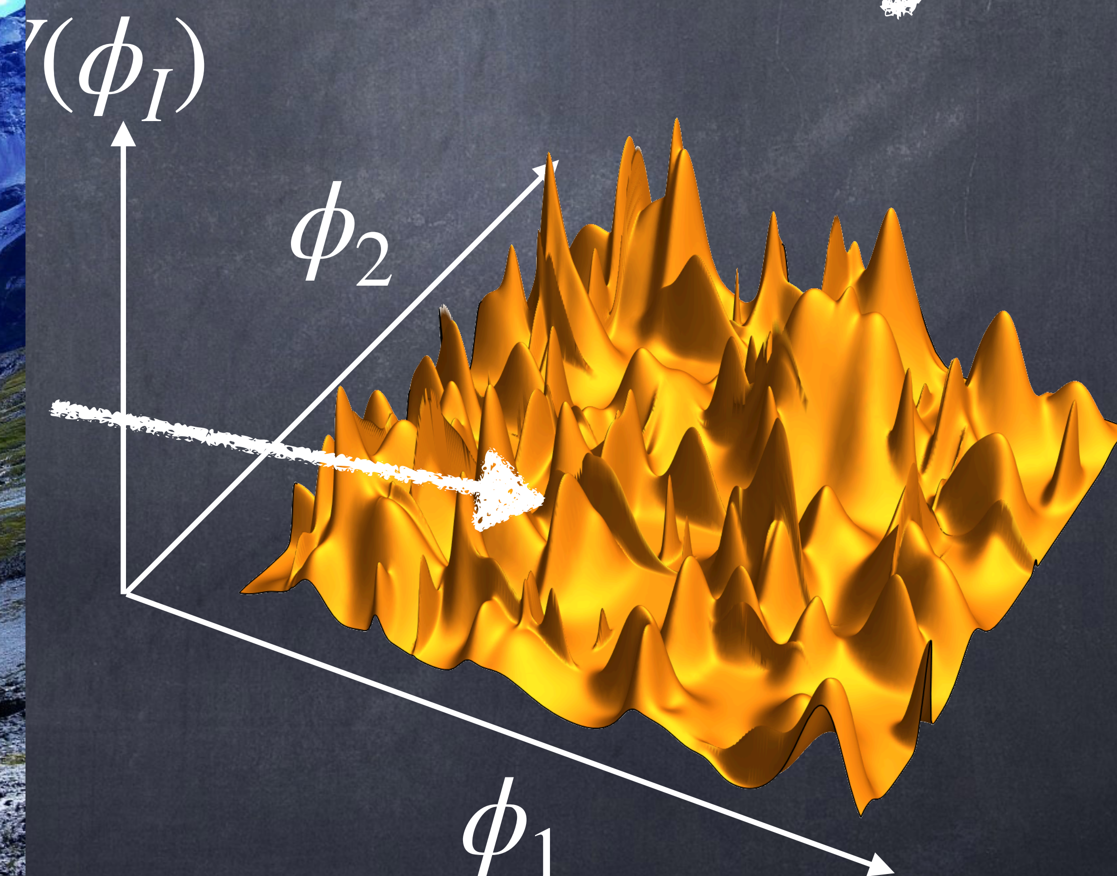
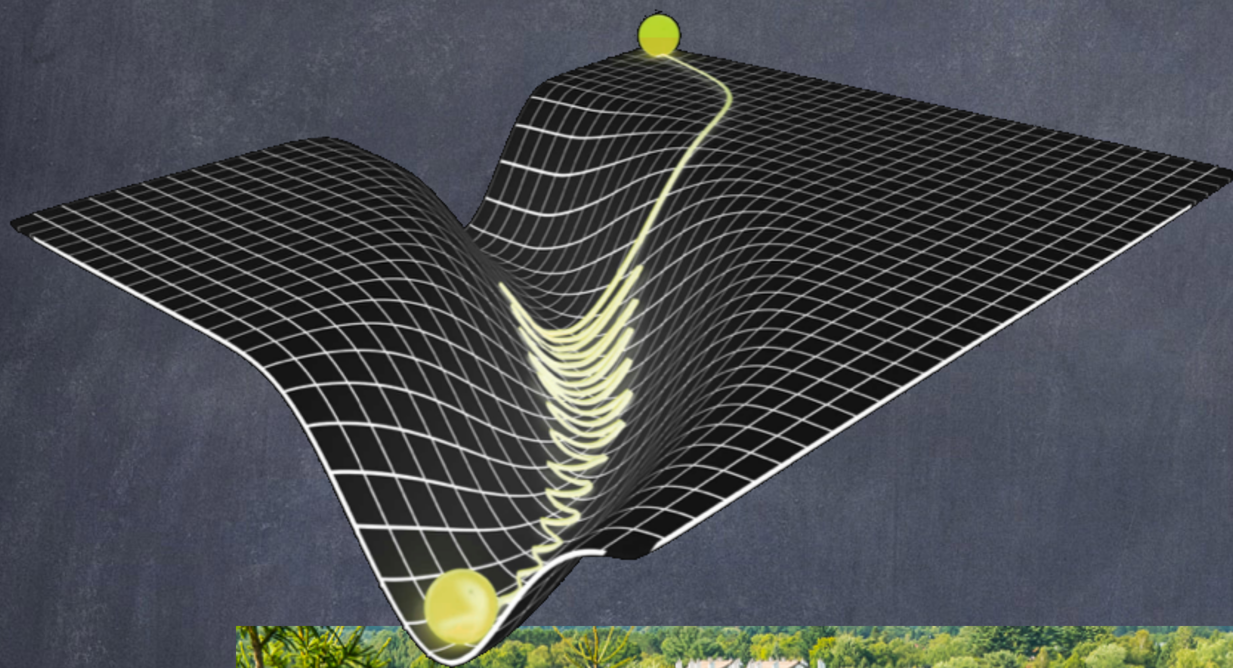
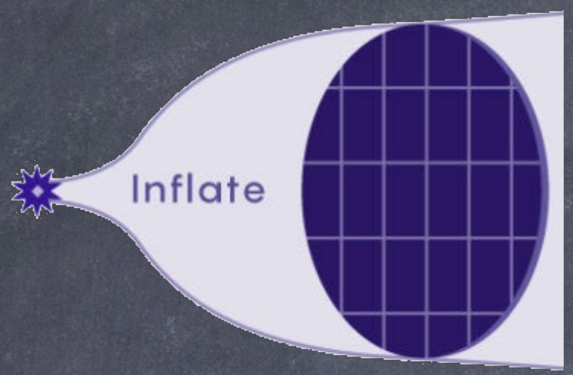


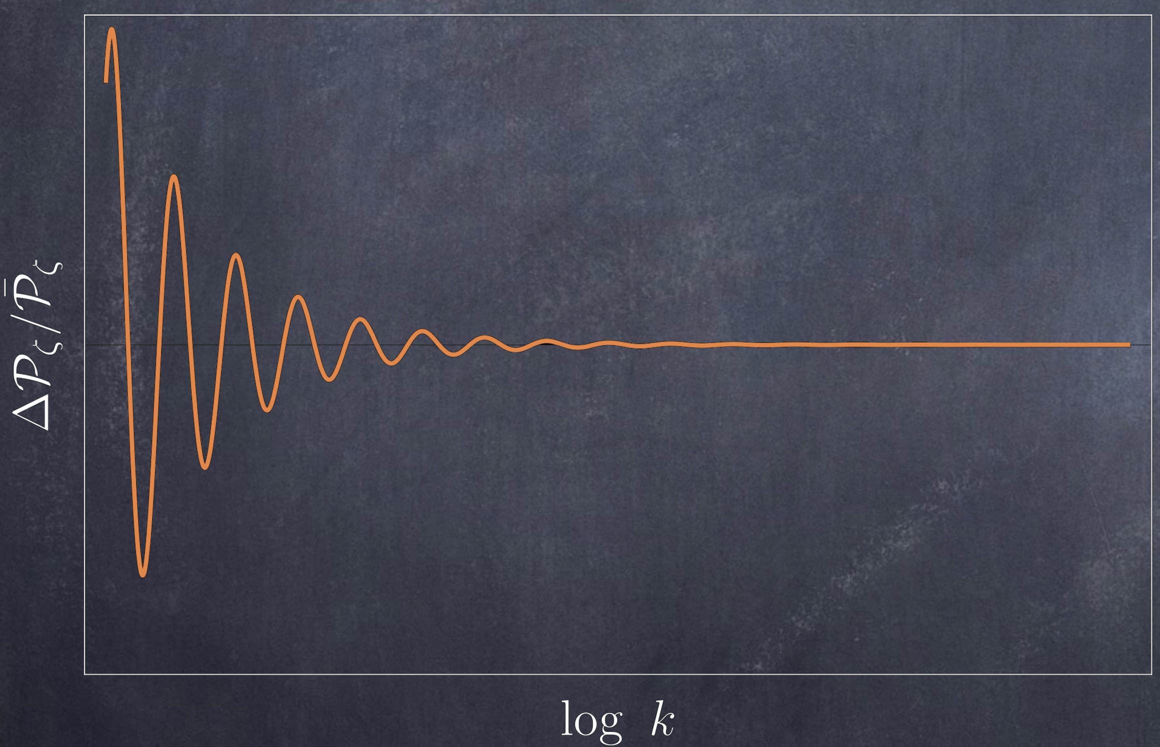


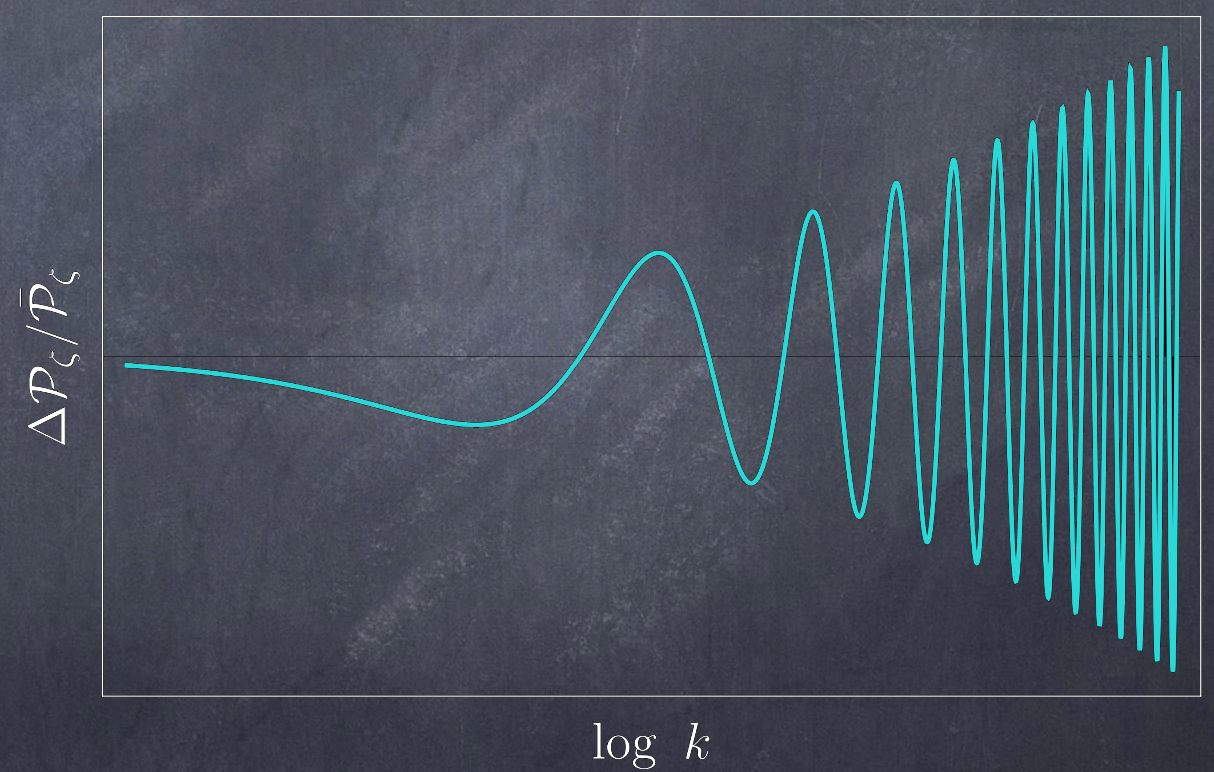
Modelling




Inflate

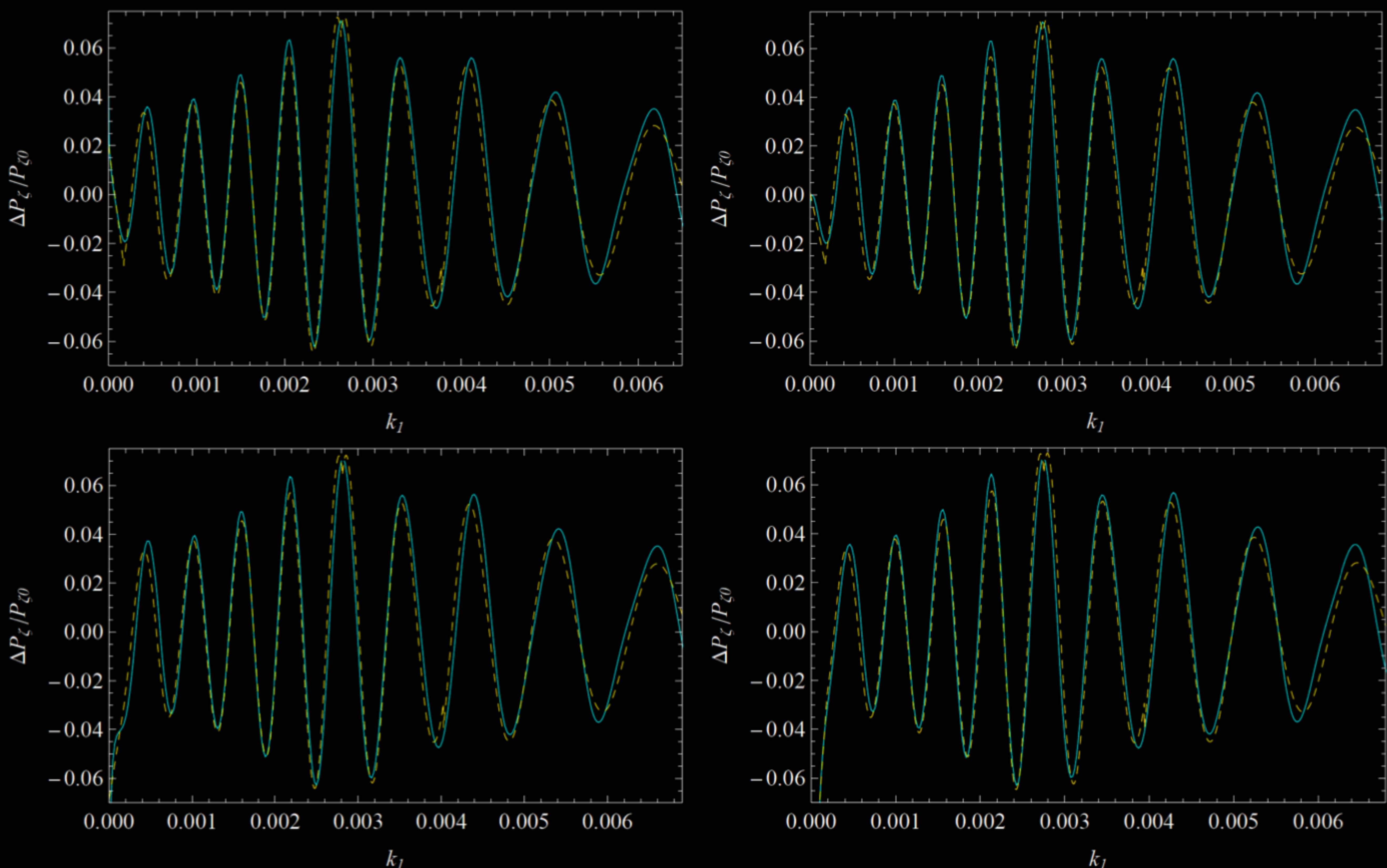

Contract


$\Delta\mathcal{P}_\zeta/\bar{\mathcal{P}}_\zeta$
$\log\ k$


$\Delta\mathcal{P}_\zeta/\bar{\mathcal{P}}_\zeta$
$\log\ k$

Chen-Namjoo-Wang (2015)

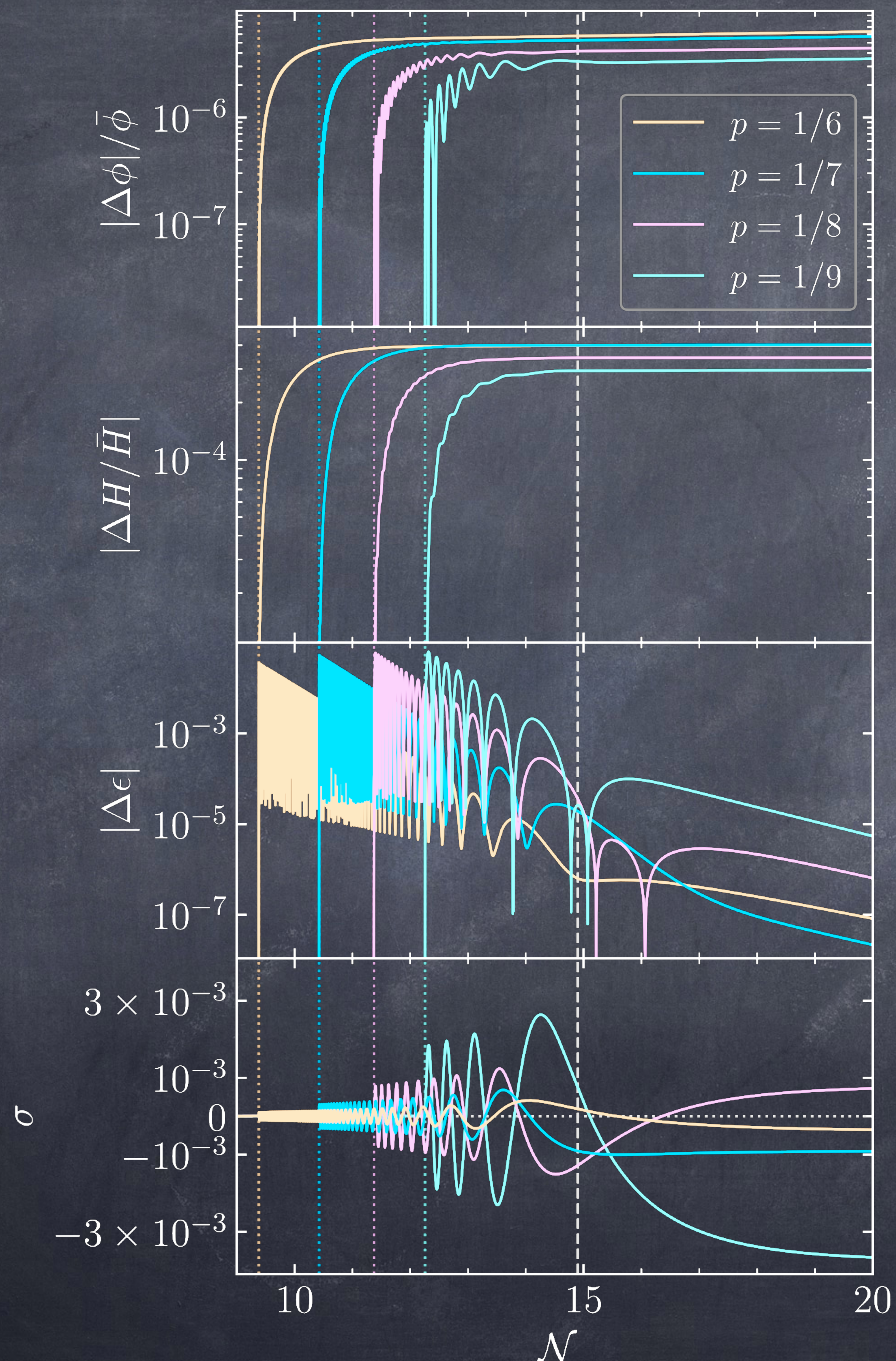
In inflation...



JQ-Chen-Ebadi (2024)

$$a(t) \propto (-t)^p\,, \quad t < 0$$

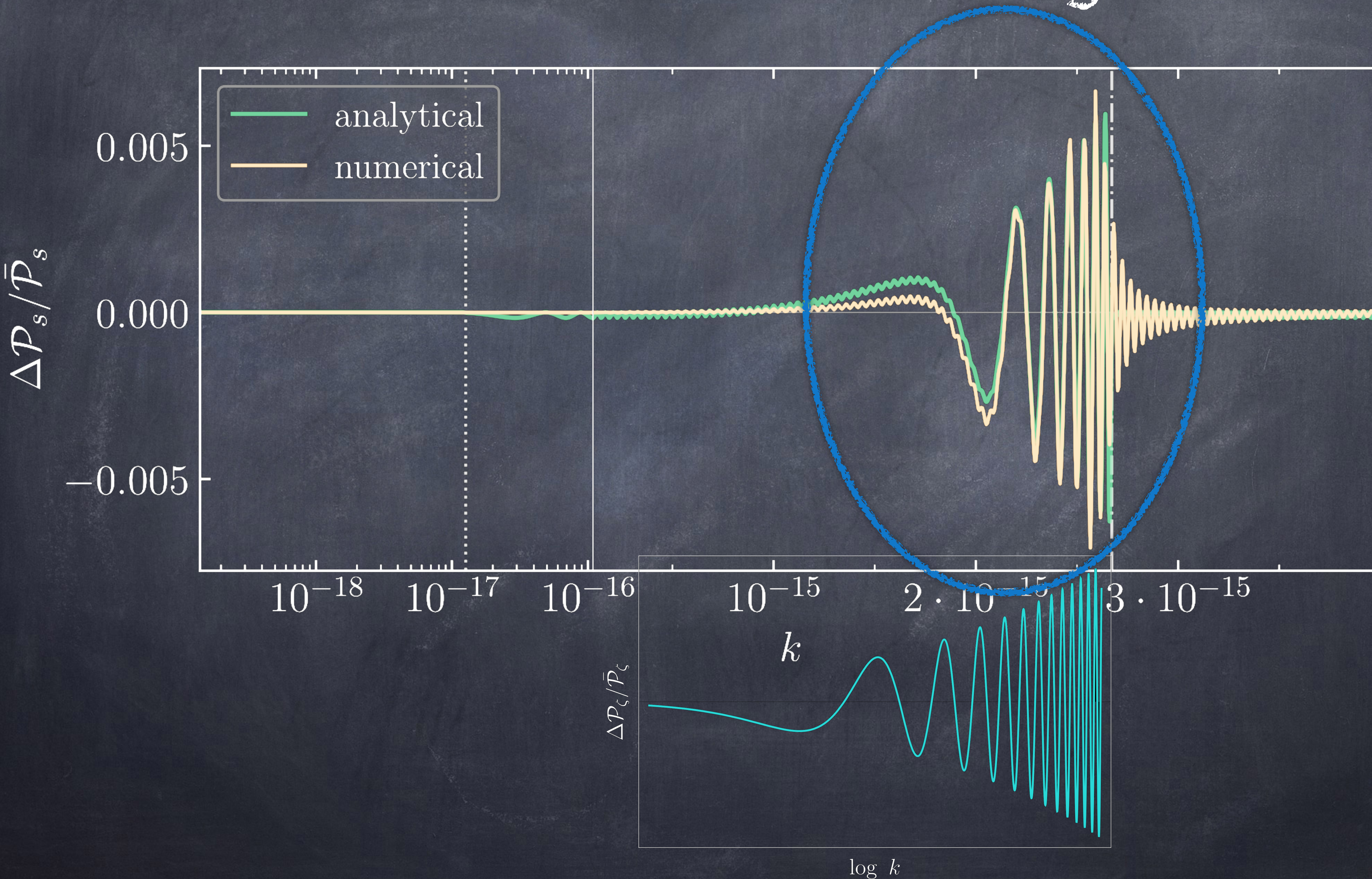
$$\epsilon \equiv -\frac{\dot{H}}{H^2}$$



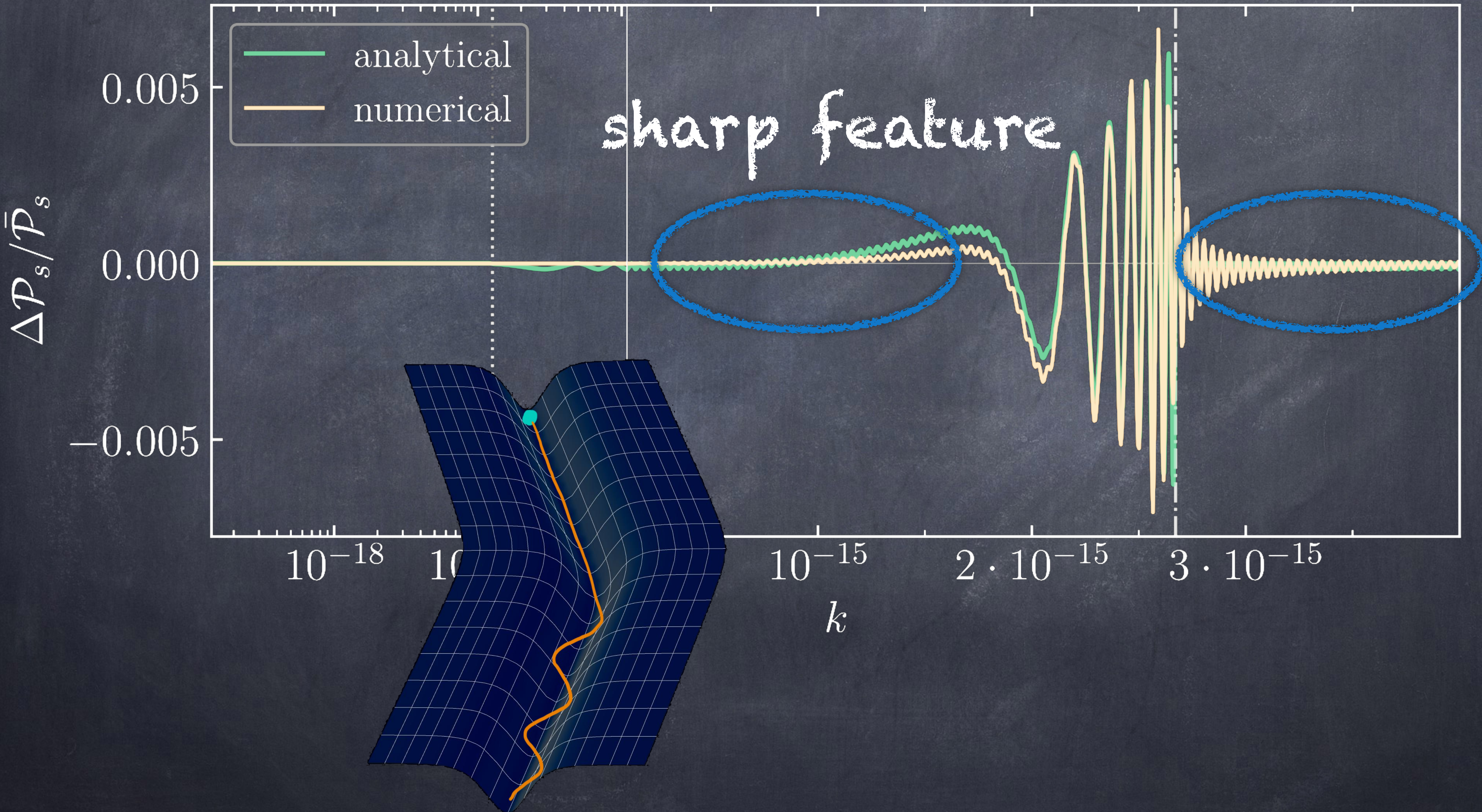
$$\mathrm{d}\mathcal{N} \equiv \mathrm{d}\ln(a\,|H|)$$

JQ-Chen-Ebadi (2024)

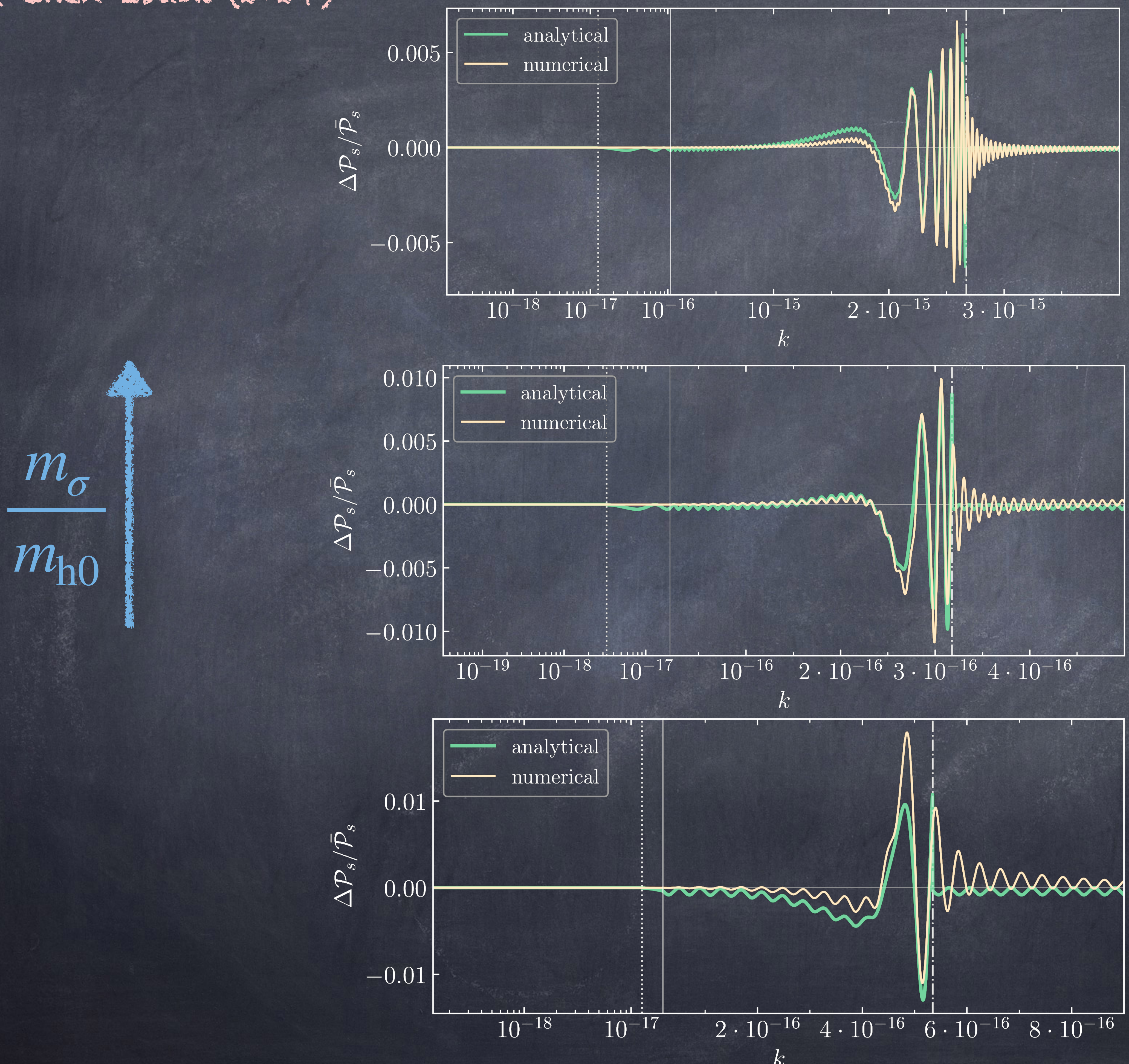
clock signal

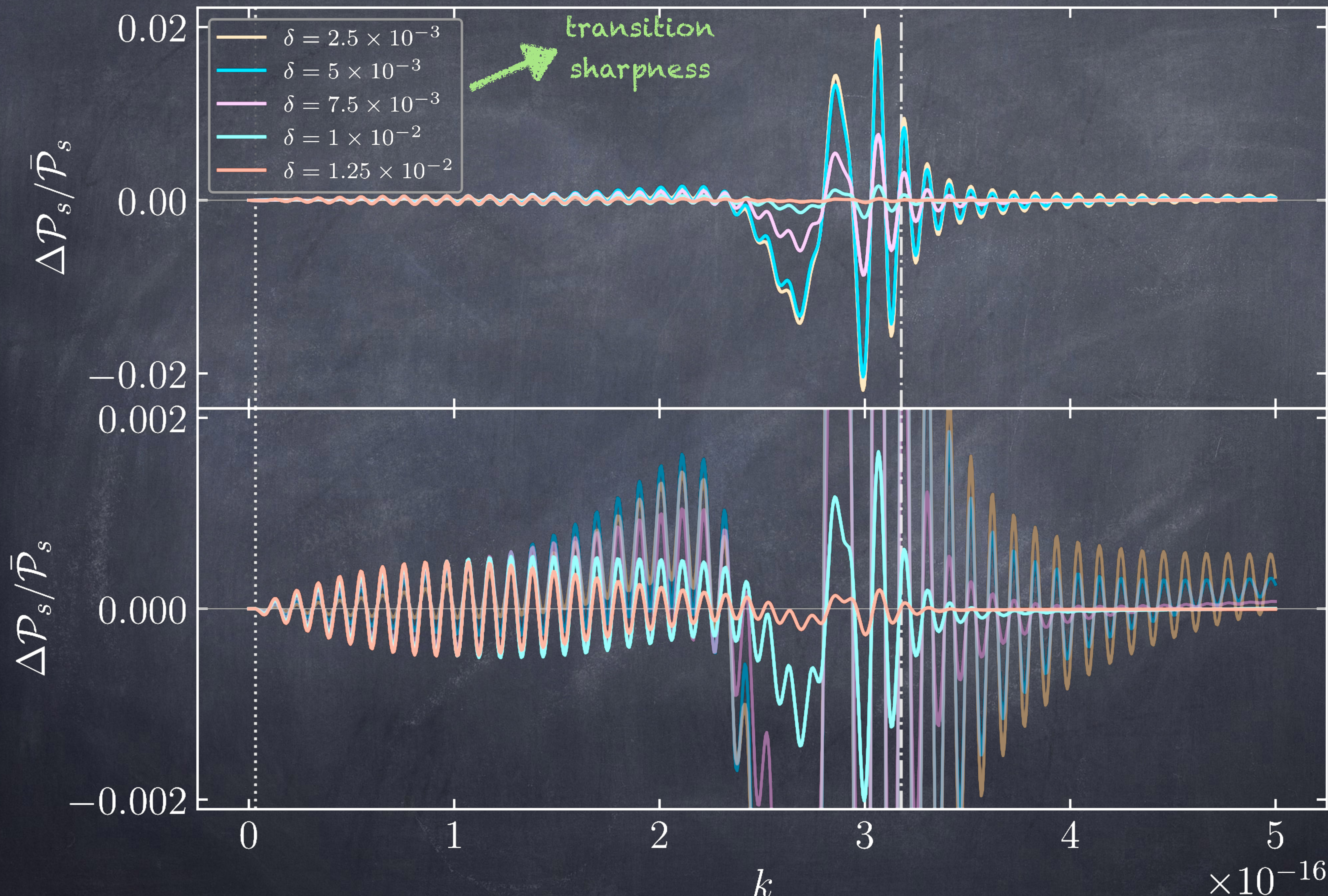


JQ-Chen-Ebadi (2024)



JQ-Chen-Ebadi (2024)



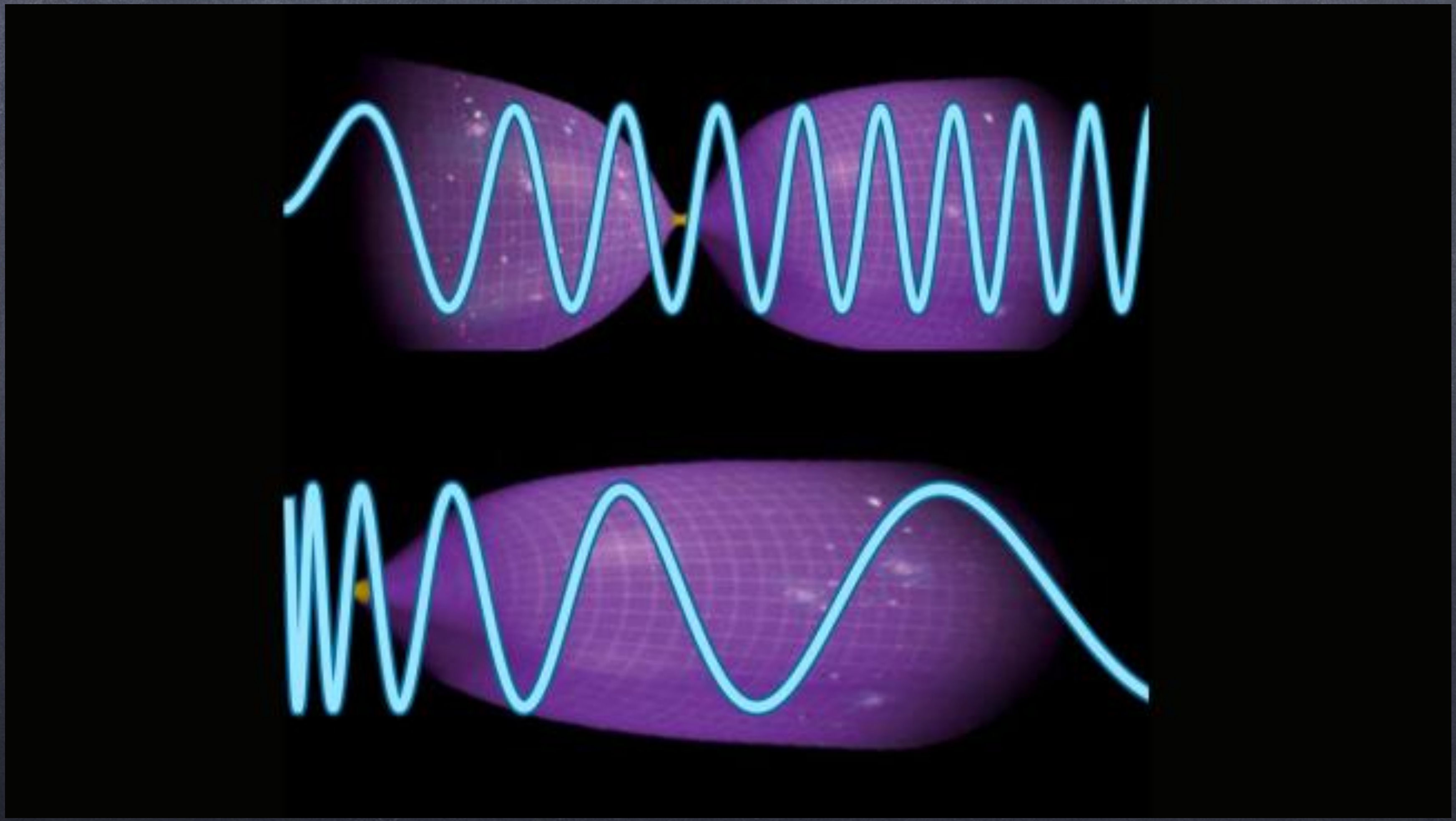


JQ-Chen-Ebadi (2024)

Cosmological collider

vs particle scanner:

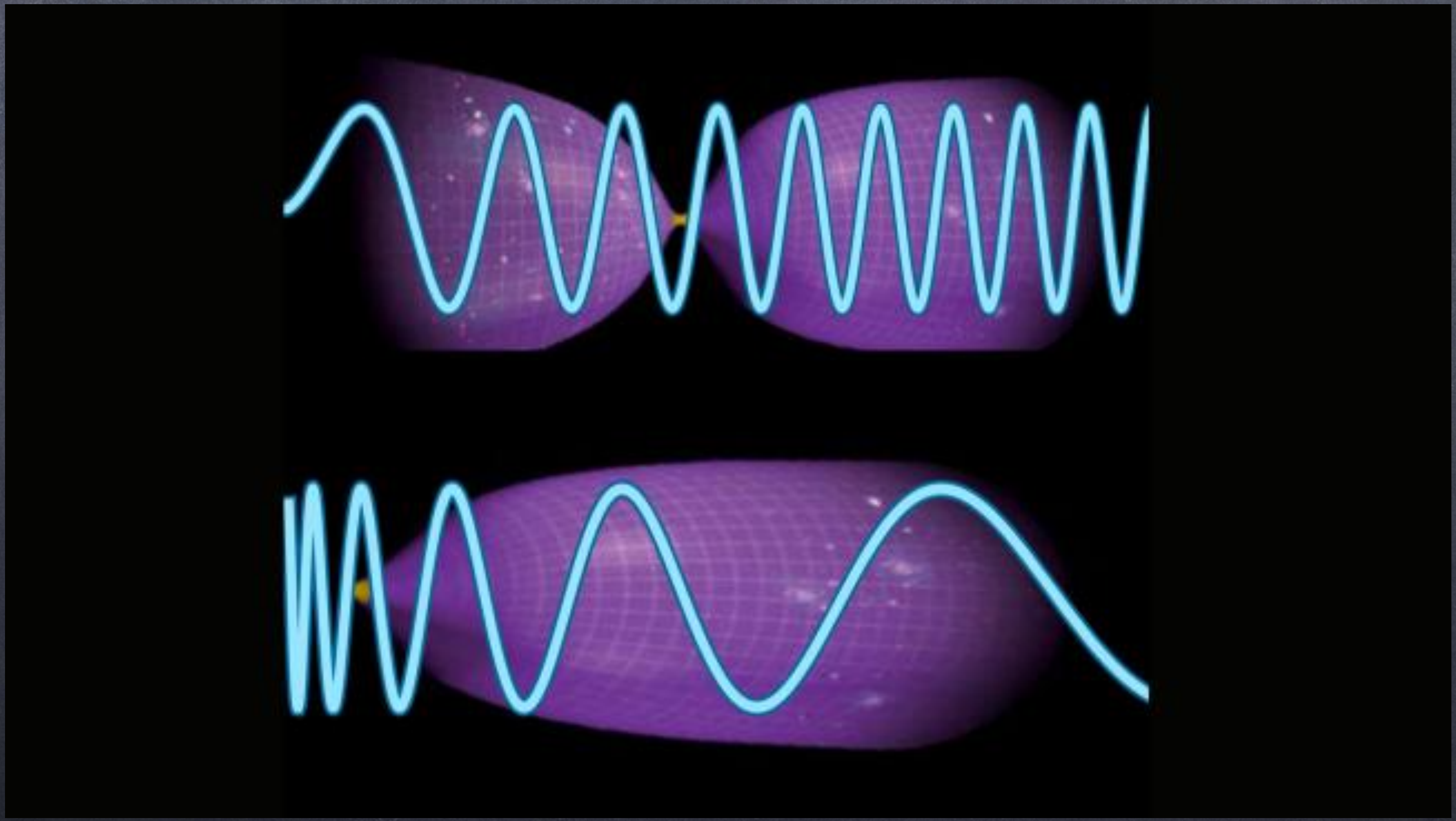
primordial features as early universe scenario discriminator and signs of new particles



Credit: Harvard

Cosmological collider vs particle scanner:

primordial features as early universe scenario discriminator and signs of new particles



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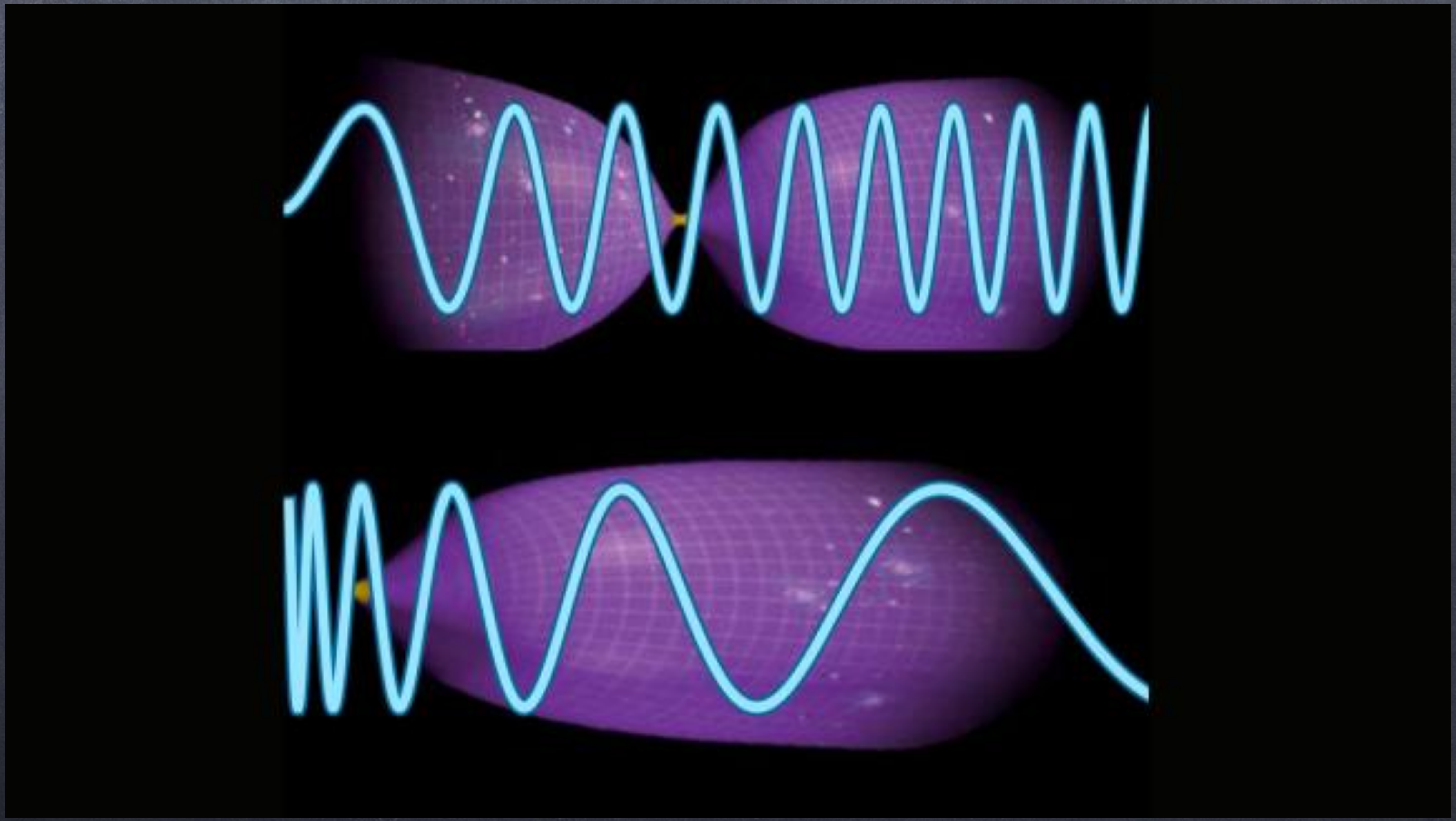

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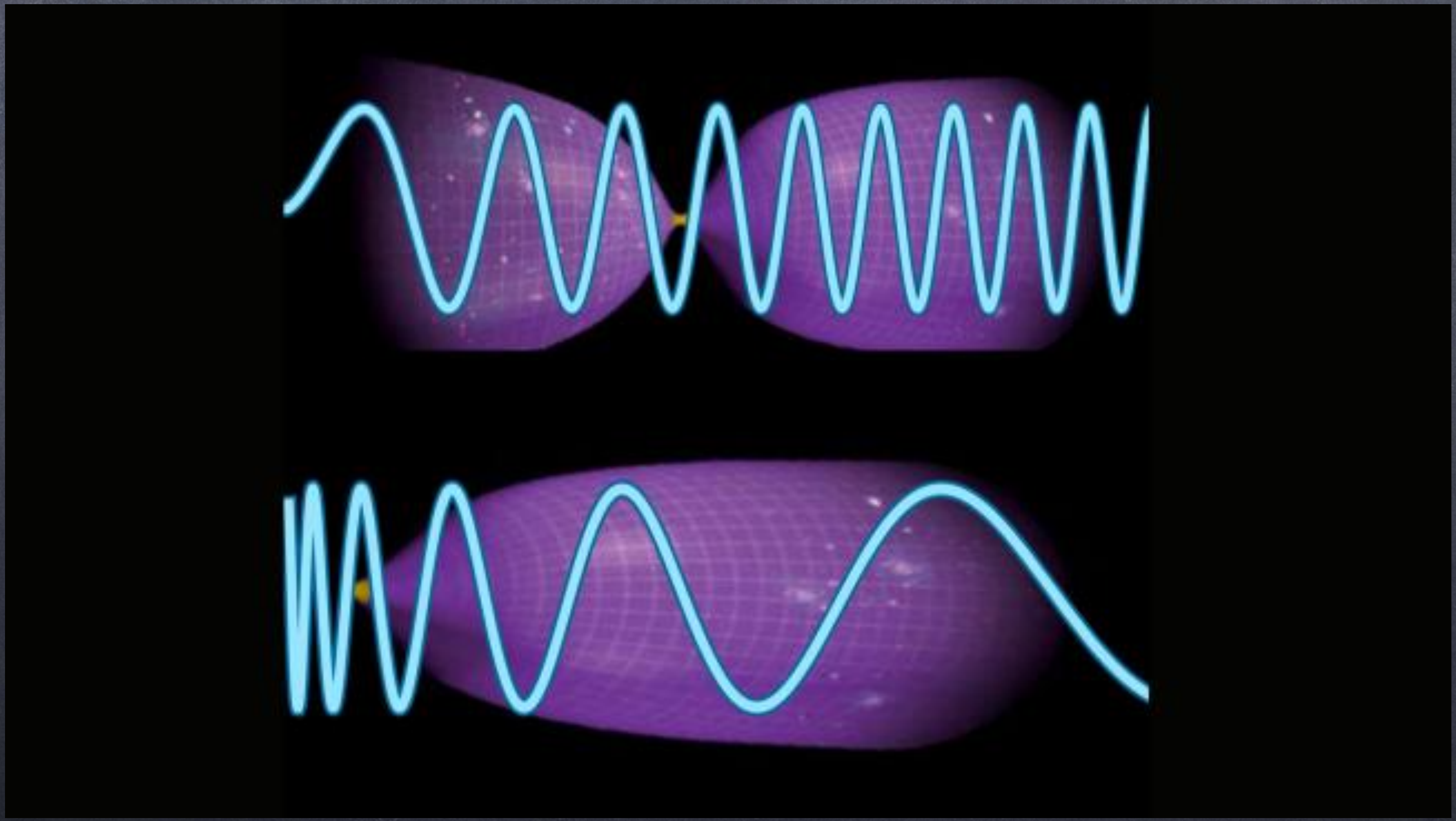
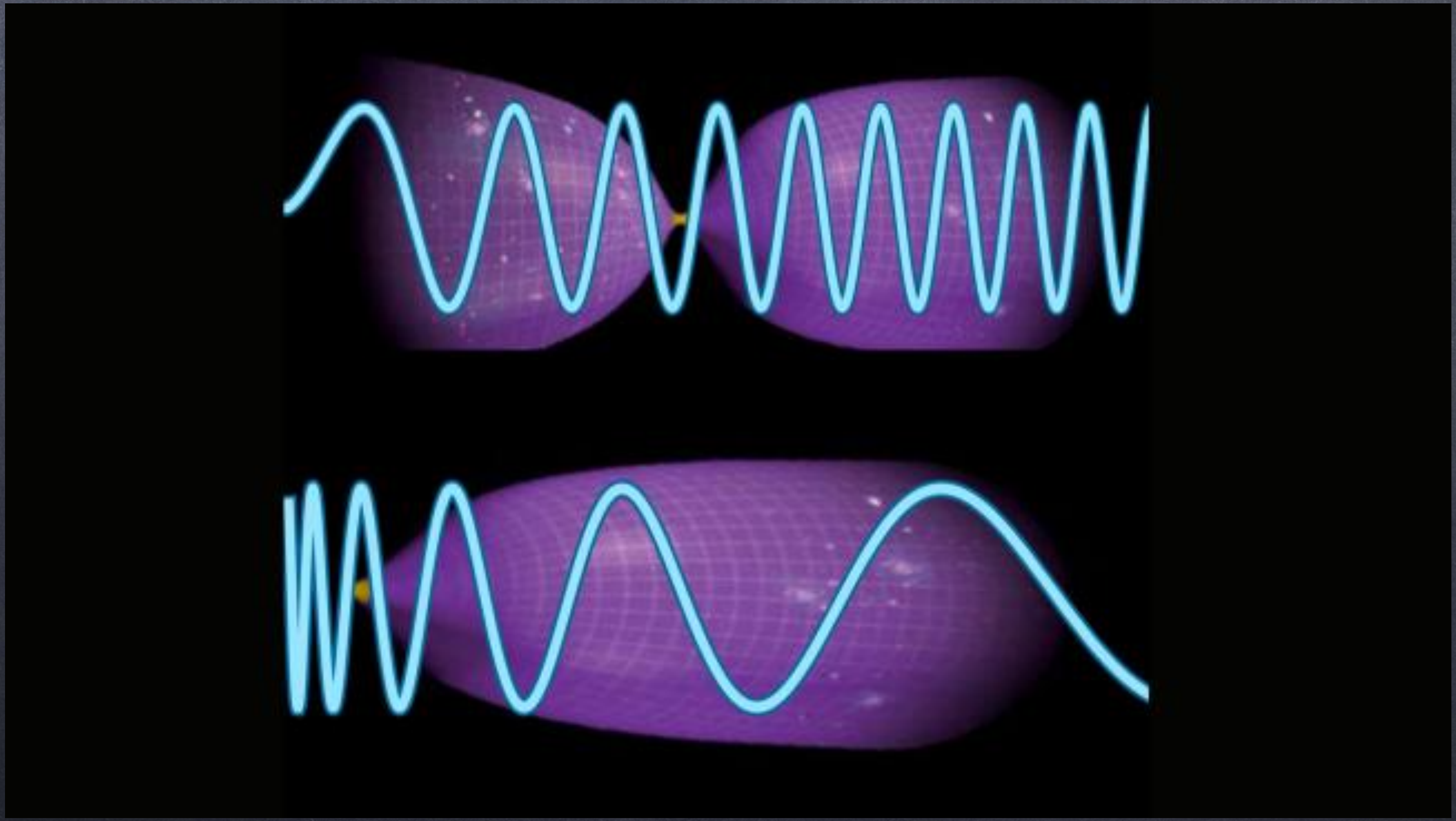


Ongoing/ next

- connecting with data
- quantum clock
- non-Gaussianities
- (Beyond) Standard Model massive fields
- ...



More in arXiv:2405.11016

Thank you for your attention!

Questions?