Cosmological problems and a possible non-inflationary solution in the framework of de Broglie-Bohm quantum cosmology

TTI, Vallico Sotto, Tuscany - 09/02/10

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Basic cosmology: the standard model and its difficulties

Homogeneous & Isotropic metric (FLRW):

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-\mathcal{K}r^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right]$$

Conformal time $d\eta = \frac{dt}{a(t)} \Longrightarrow$ Conformally flat space

$$ds^2 = a^2(\eta)\left(-d\eta^2 + \gamma_{ij}dx^i dx^j\right)$$

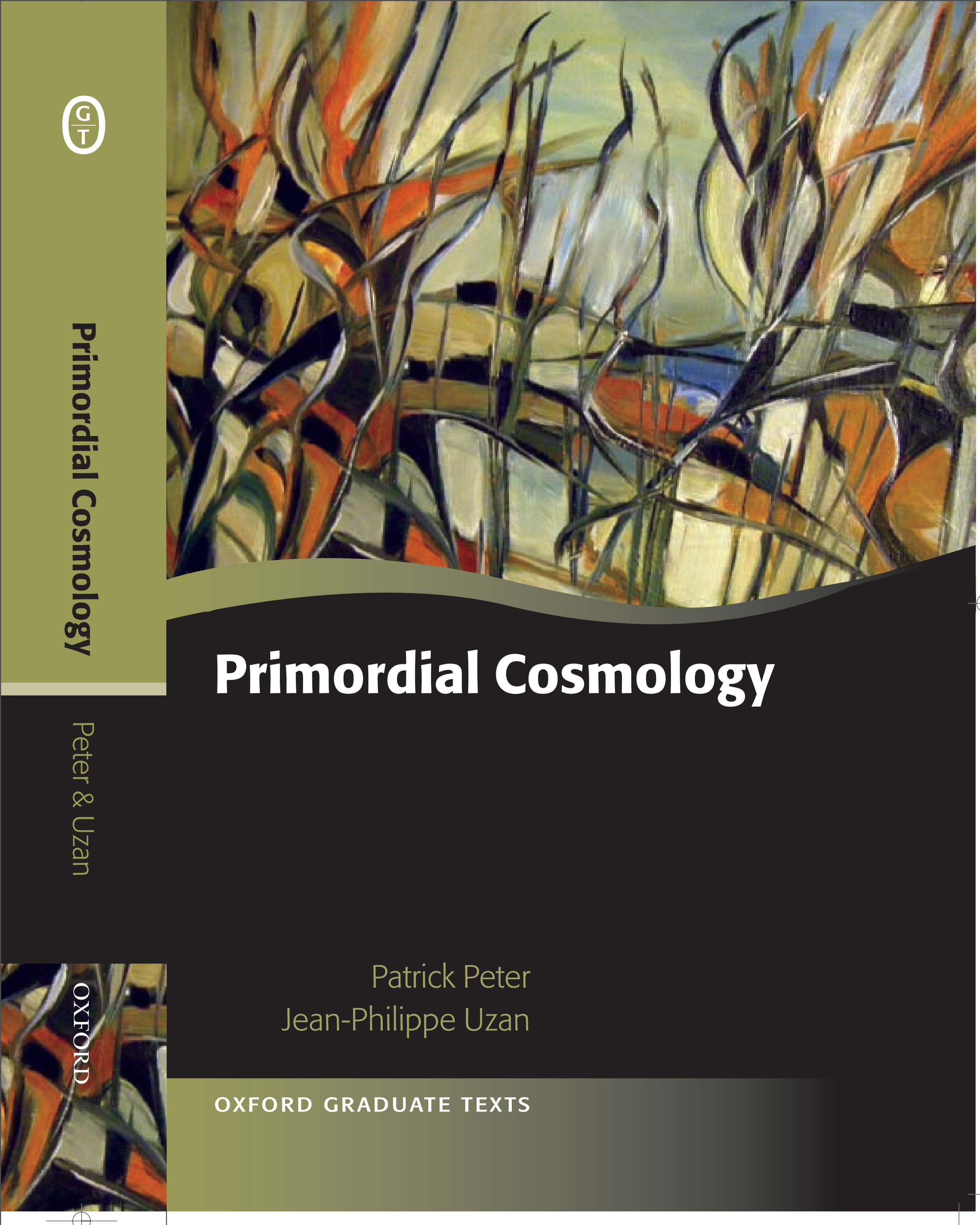
Matter component: perfect fluid: $T_{\mu\nu} = pg_{\mu\nu} + (\rho + p)u_\mu u_\nu$

$$p = \omega\rho \begin{cases} \omega = 0 & \text{dust} \\ \omega = \frac{1}{3} & \text{radiation} \end{cases}$$

+ cosmological constant = Einstein equation:

$$H^2 + \frac{\mathcal{K}}{a^2} = \frac{1}{3}\left(8\pi G_{\text{N}}\rho + \Lambda\right)$$

$$\frac{\ddot{a}}{a} = \frac{1}{3}\left[\Lambda - 4\pi G_{\text{N}}(\rho + p)\right]$$



Problems with standard model:

- *Singularity*
- *Horizon*
- *Flatness*
- *Homogeneity*
- *Perturbations*
- *Dark matter*
- *Dark energy / cosmological constant*
- *Baryogenesis*
- …

Topological defects (monopoles)

Problems:

Singularity $a(t) \to 0$

Horizon

Flatness

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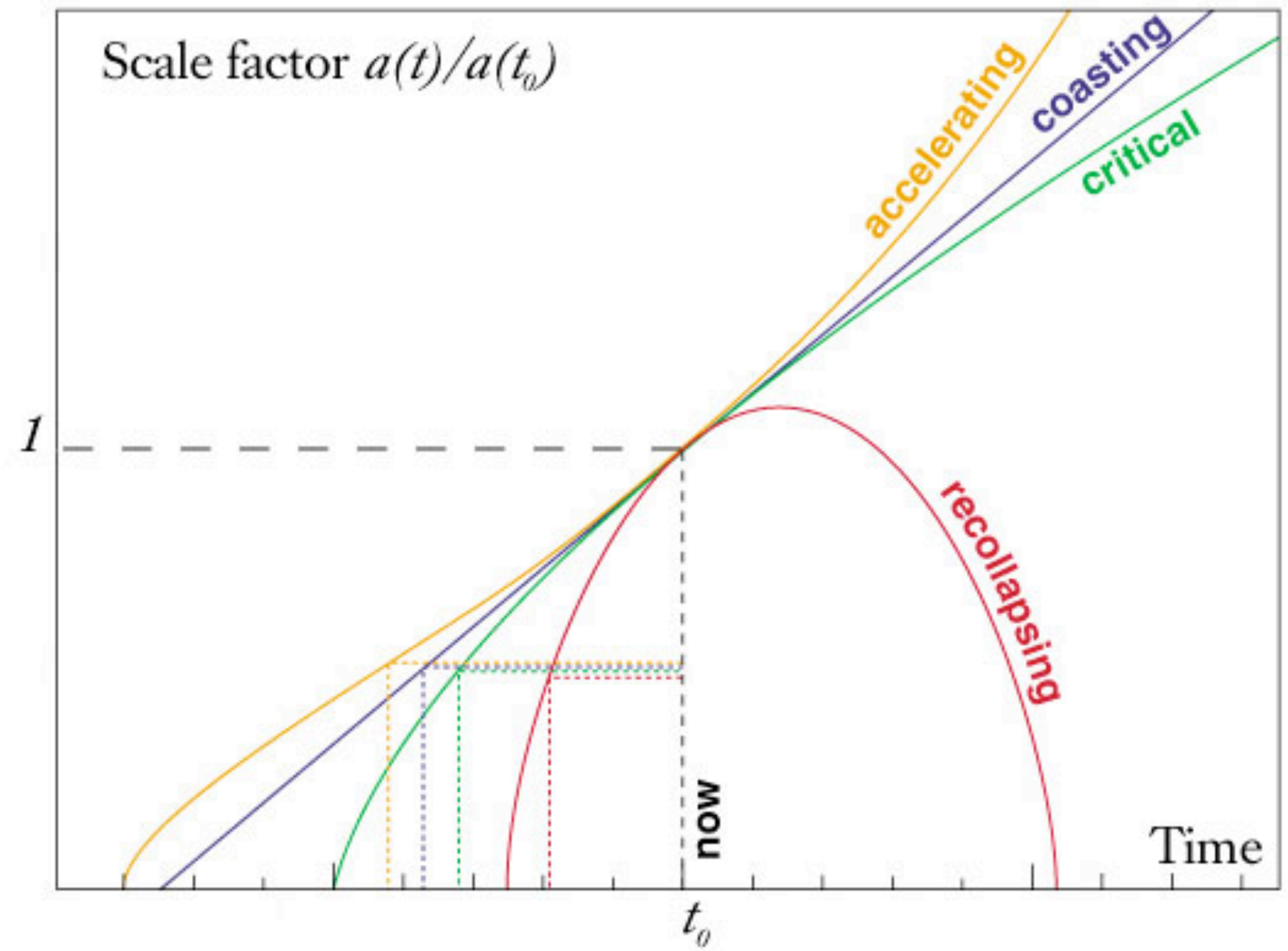

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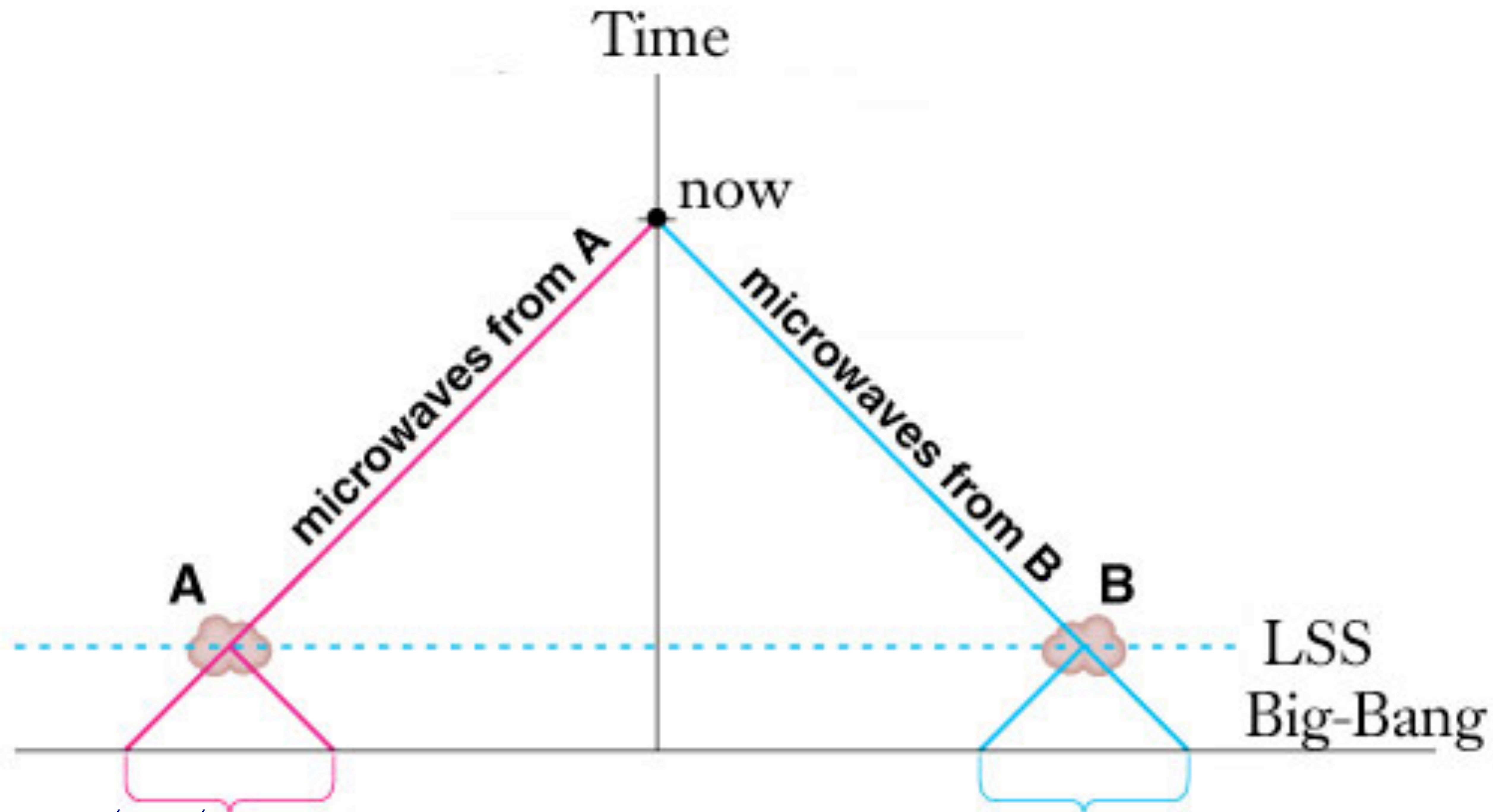

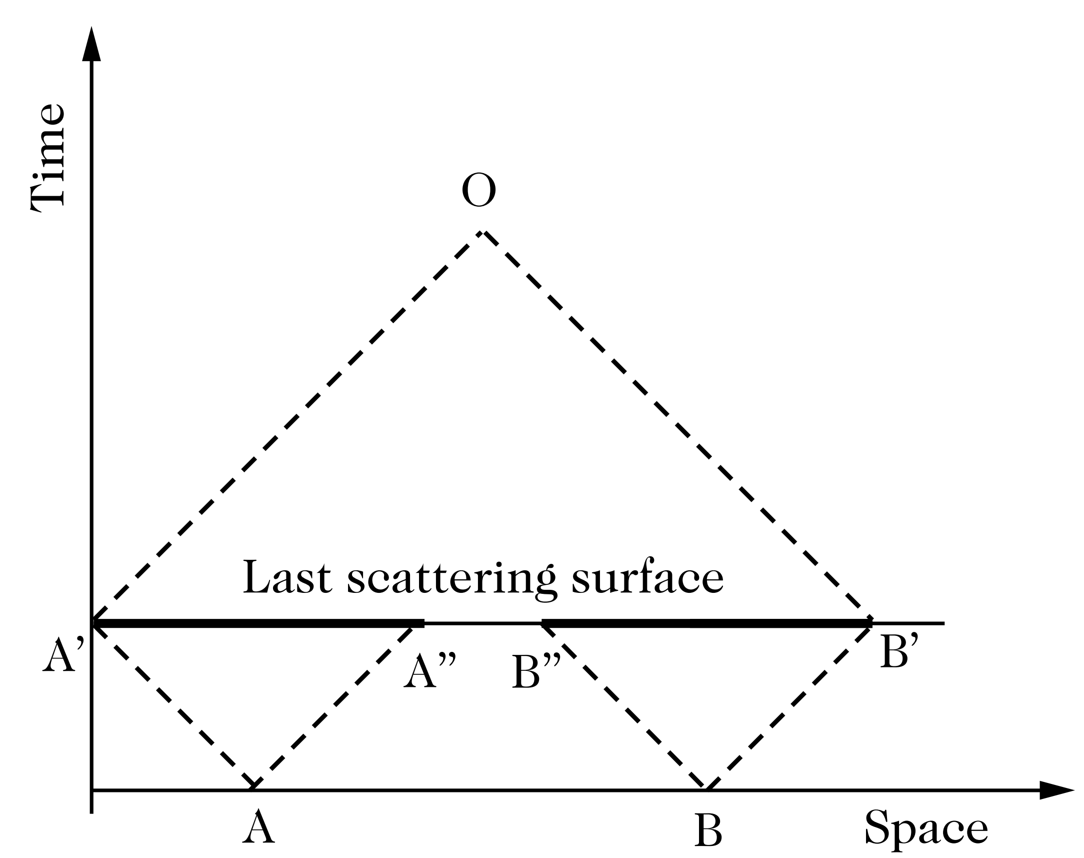

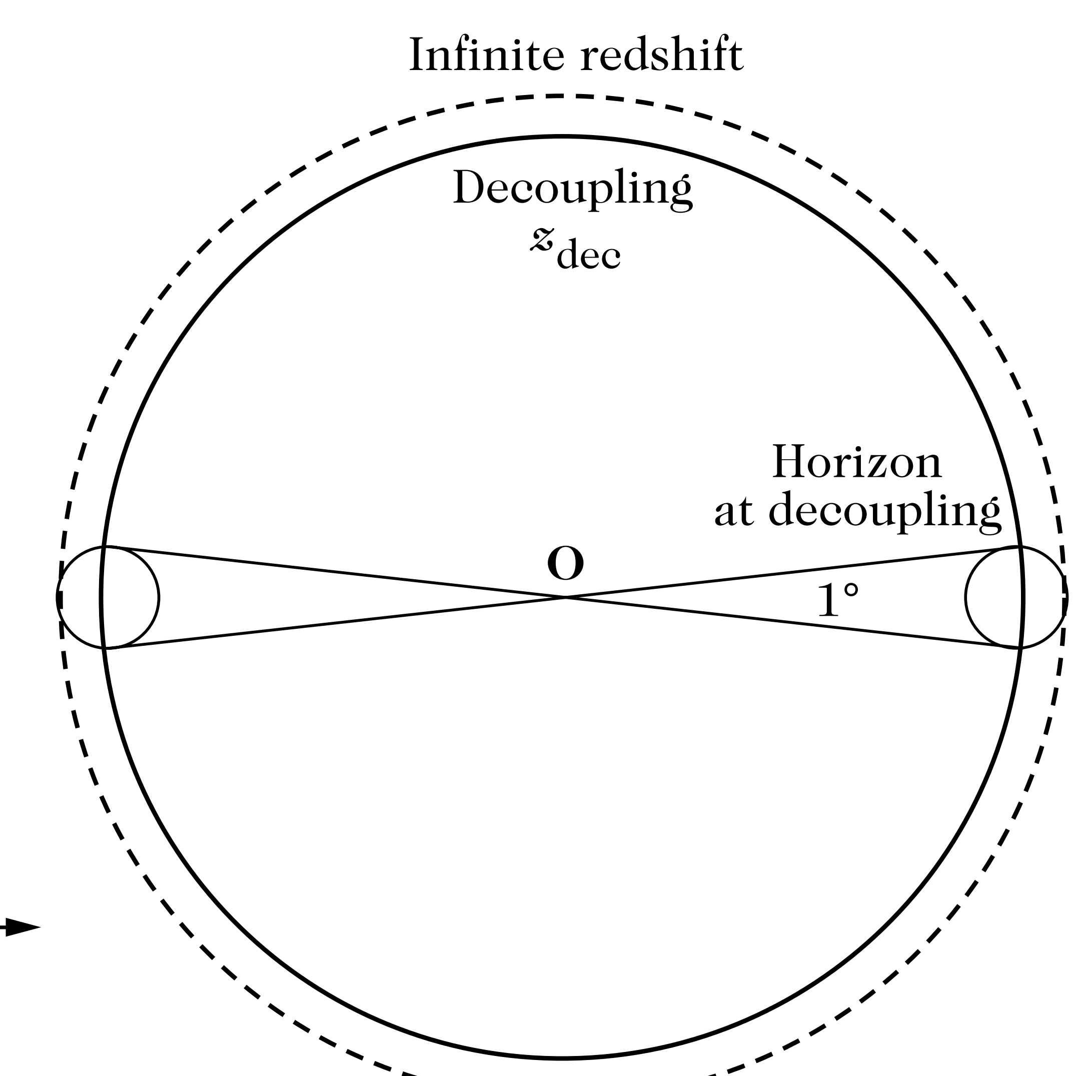

Problems:

Singularity

Horizon

Flatness $\rho_{\mathrm{crit}} \equiv \dfrac{3H^2}{8\pi G_{\mathrm{N}}}$ $\Omega \equiv \dfrac{\rho_{\mathrm{tot}}}{\rho_{\mathrm{crit}}}$ $\Omega = 1 \implies \mathcal{K} = 0$ Flat space

$$\frac{\mathrm{d}}{\mathrm{d}t}|\Omega - 1| = -2\frac{\ddot{a}}{\dot{a}^3}$$ Unstable!

Homogeneity

Perturbations

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Accepted solution = INFLATION

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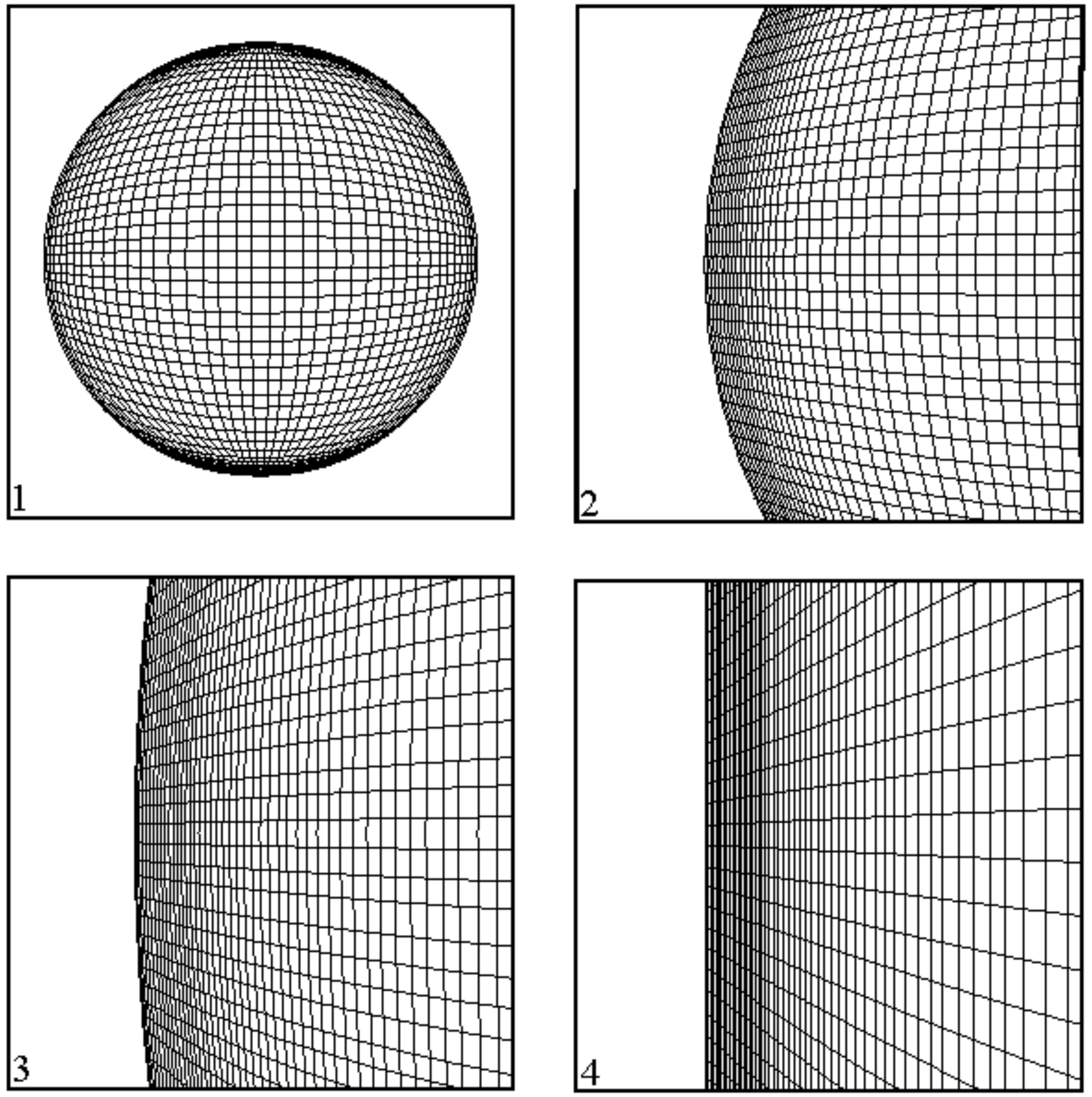
$$\frac{\mathrm{d}}{\mathrm{d}t}|\Omega - 1| = -2\frac{\ddot{a}}{\dot{a}^3}$$

$$\ddot{a} > 0 \;\&\; \dot{a} > 0$$



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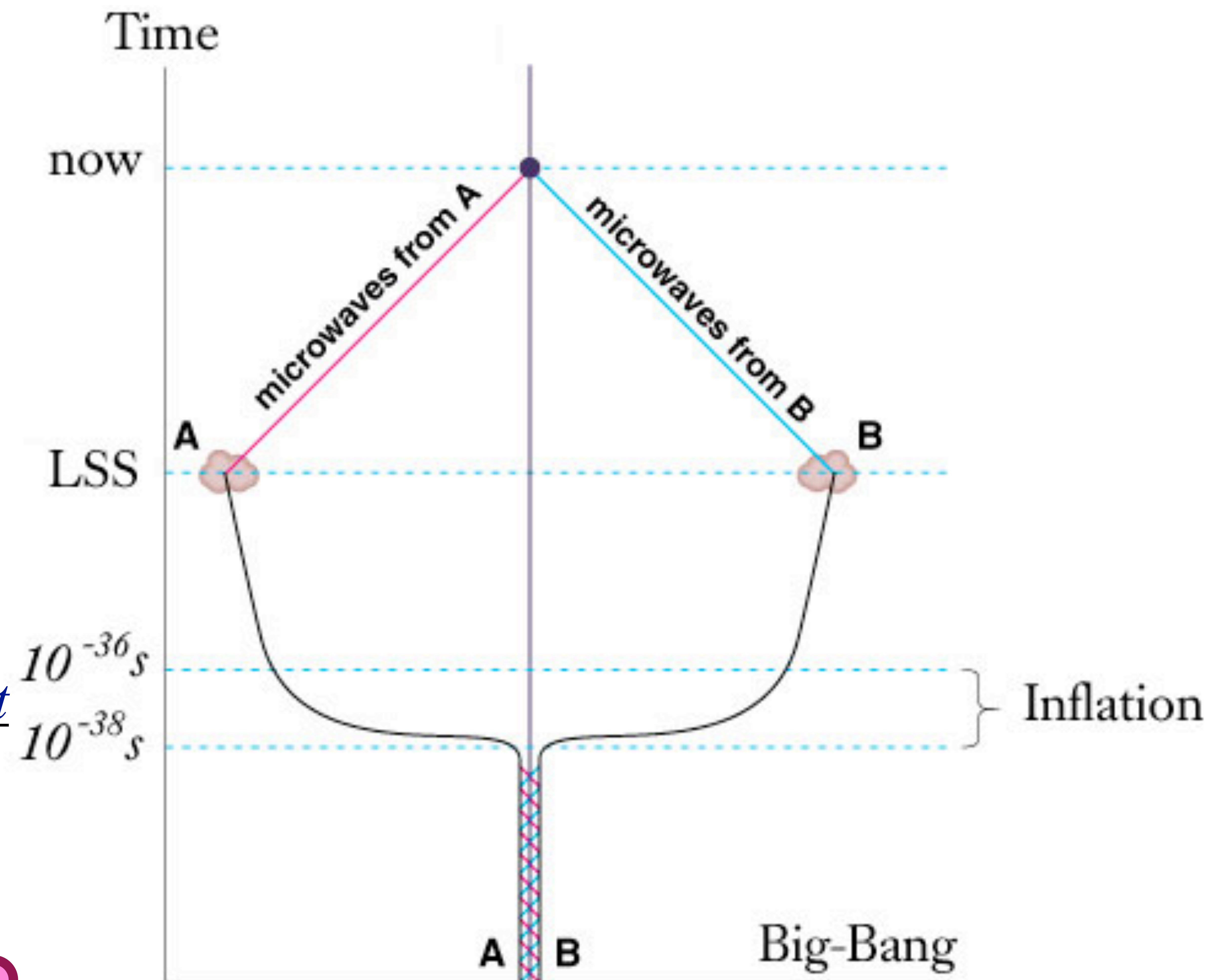

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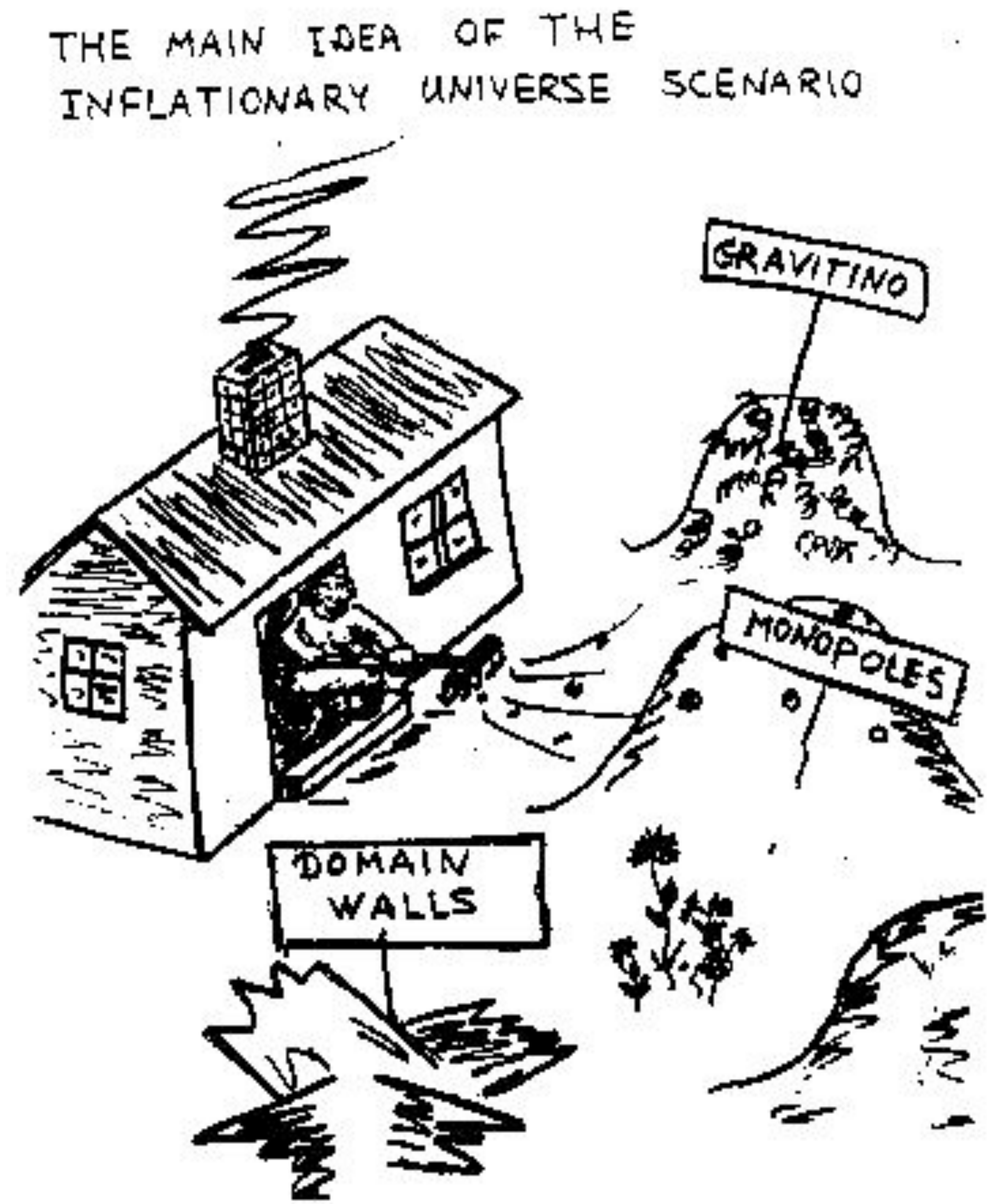
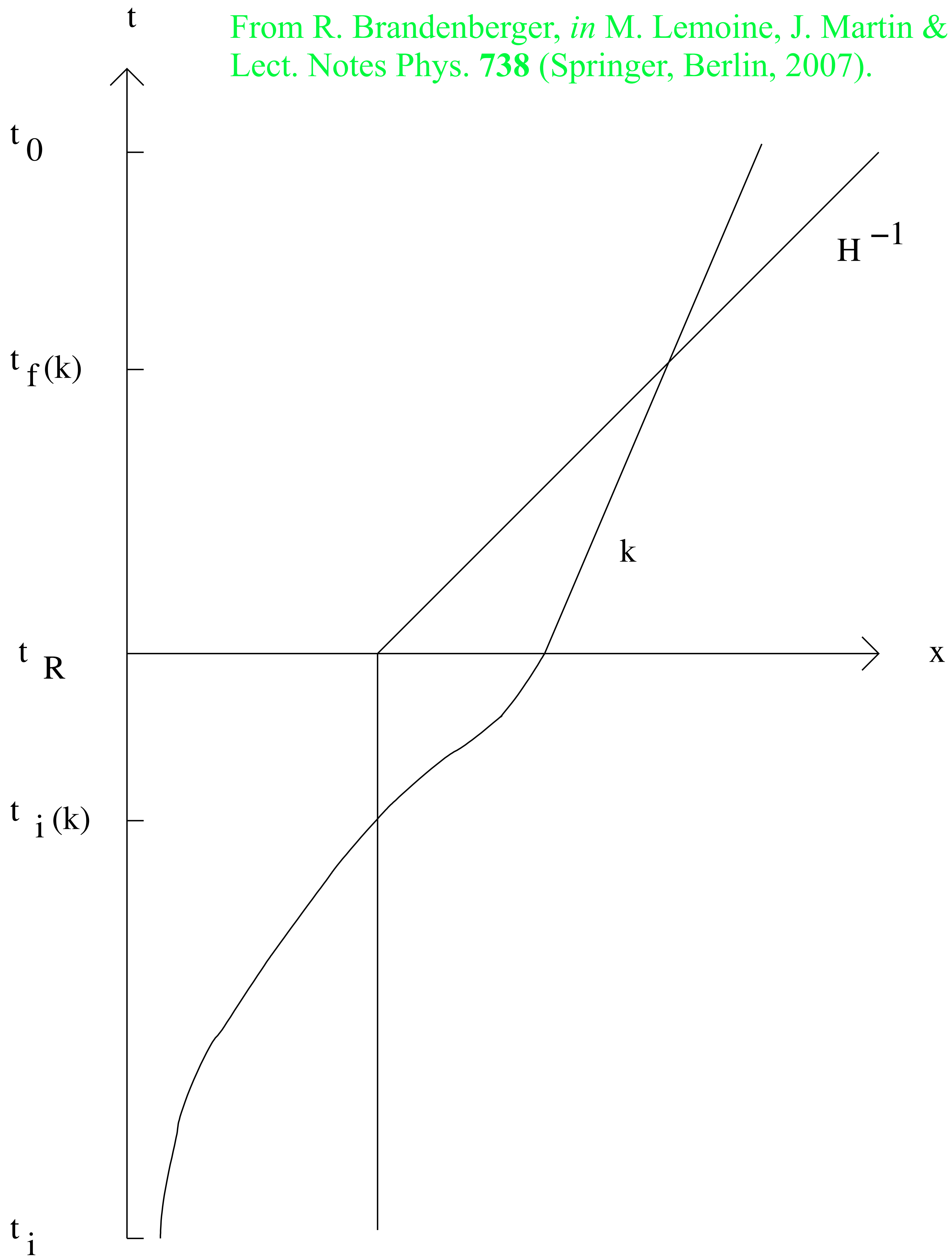


(Linde's book)

From R. Brandenberger, *in* M. Lemoine, J. Martin & P. P. (Eds.), “Inflationary cosmology”, Lect. Notes Phys. **738** (Springer, Berlin, 2007).



- Scalar field origin?
- Trans-Planckian

$$\exists t ; \ell(t) = \ell_0 \frac{a(t)}{a_0} \leq \ell_{\mathrm{Pl}}$$

- Hierarchy (amplitude)

$$\frac{V(\varphi)}{\Delta\varphi^4} \leq 10^{-12}$$

- Singularity

$$\exists t_{(\pm\infty)} ; a(t) \rightarrow 0$$

- **Validity of classical GR?**

$$E_{\mathrm{inf}} \simeq 10^{-3} M_{\mathrm{Pl}}$$

Inflation:

- ☺ **solves cosmological puzzles**
- ☺ **uses GR + scalar fields [(semi-)classical]**
- ☺ **can be implemented in high energy theories**
- ☺ **makes falsifiable predictions ...**
- ☺ **... consistent with all known observations**
- ☺ **string based ideas (brane inflation, ...)**

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- **purely classical theory**
- **Quantum gravity / cosmology**

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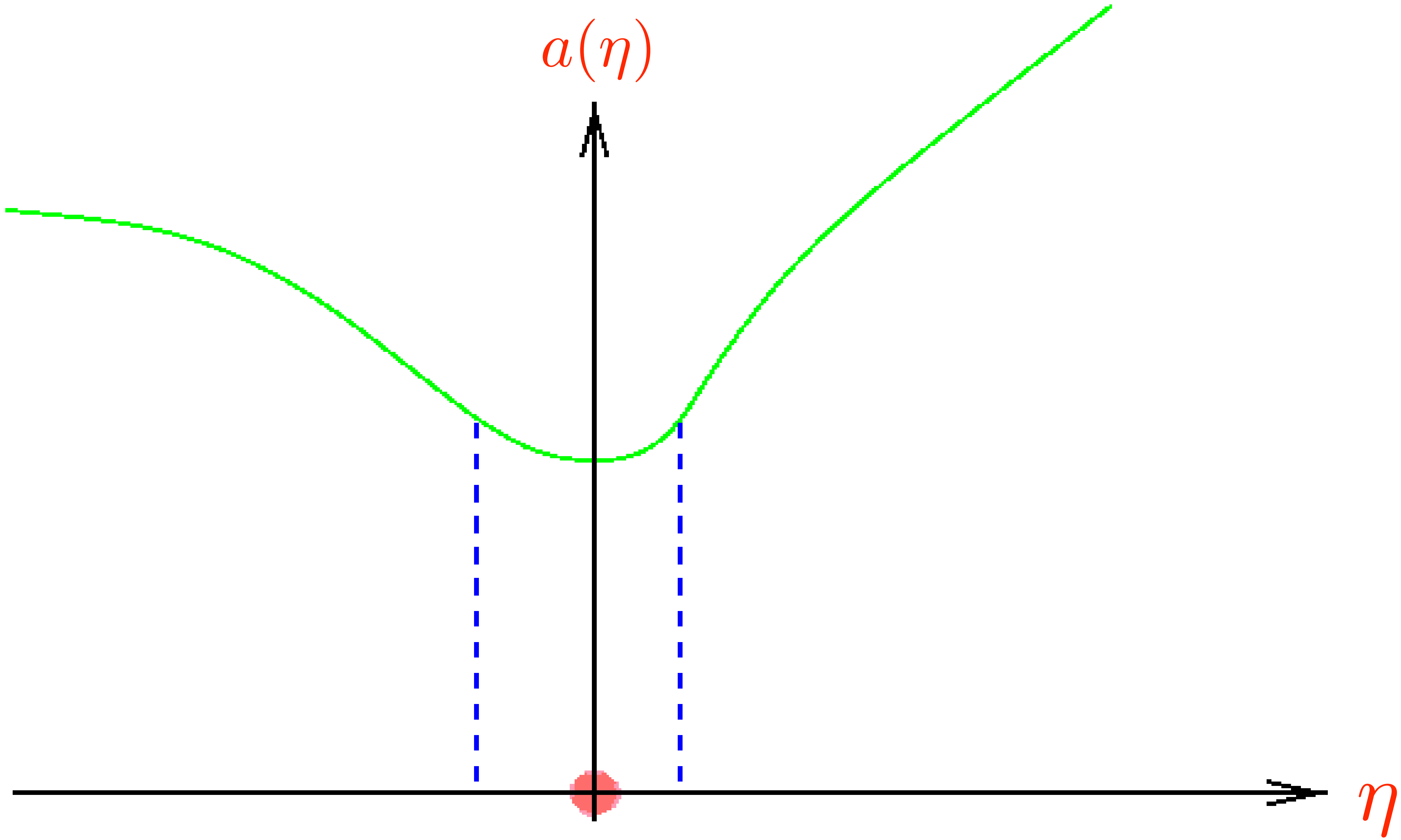
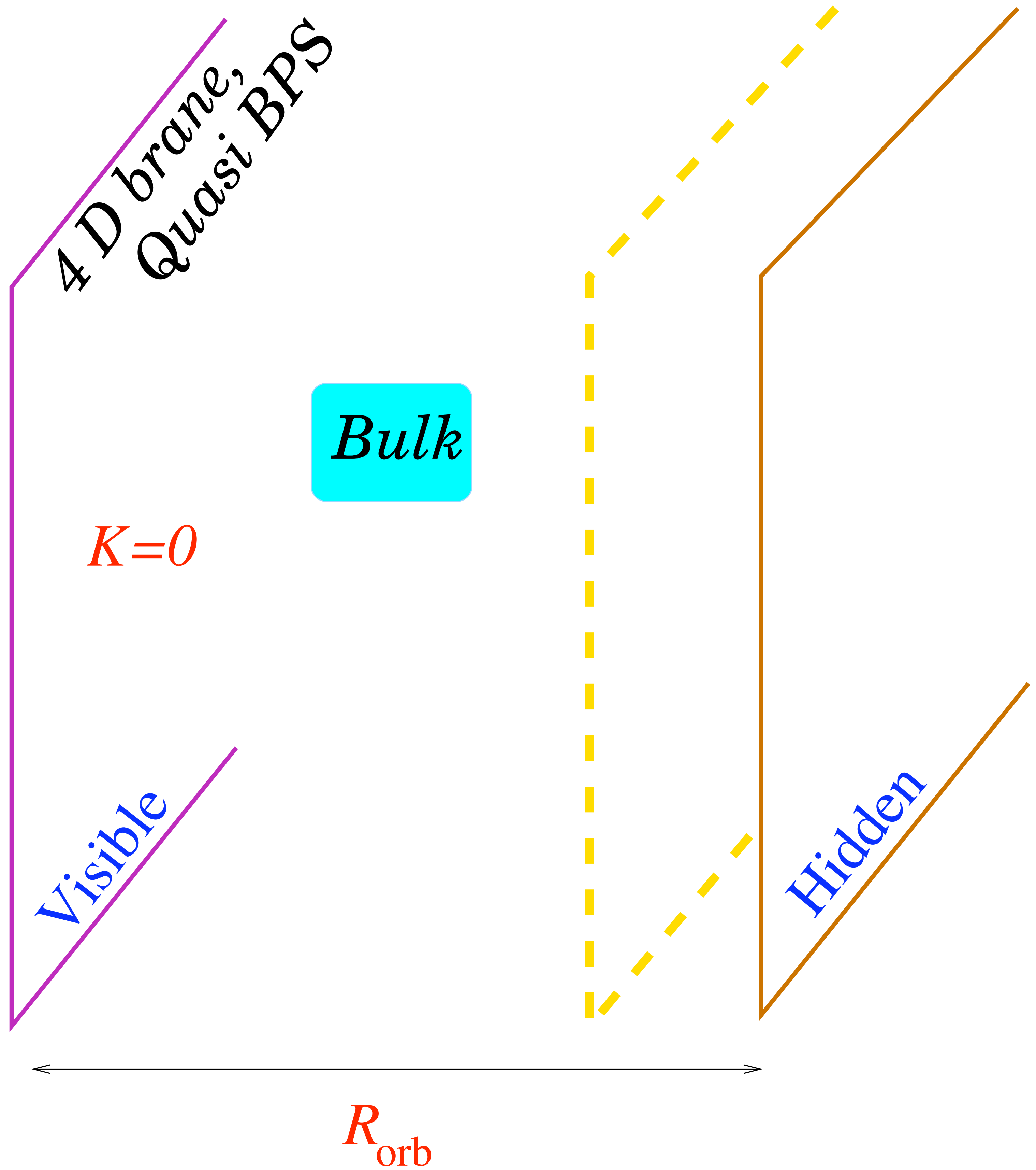
- bounces (always in WdW - recall N. Pinto-Neto's talk)


$a(\eta)$
η

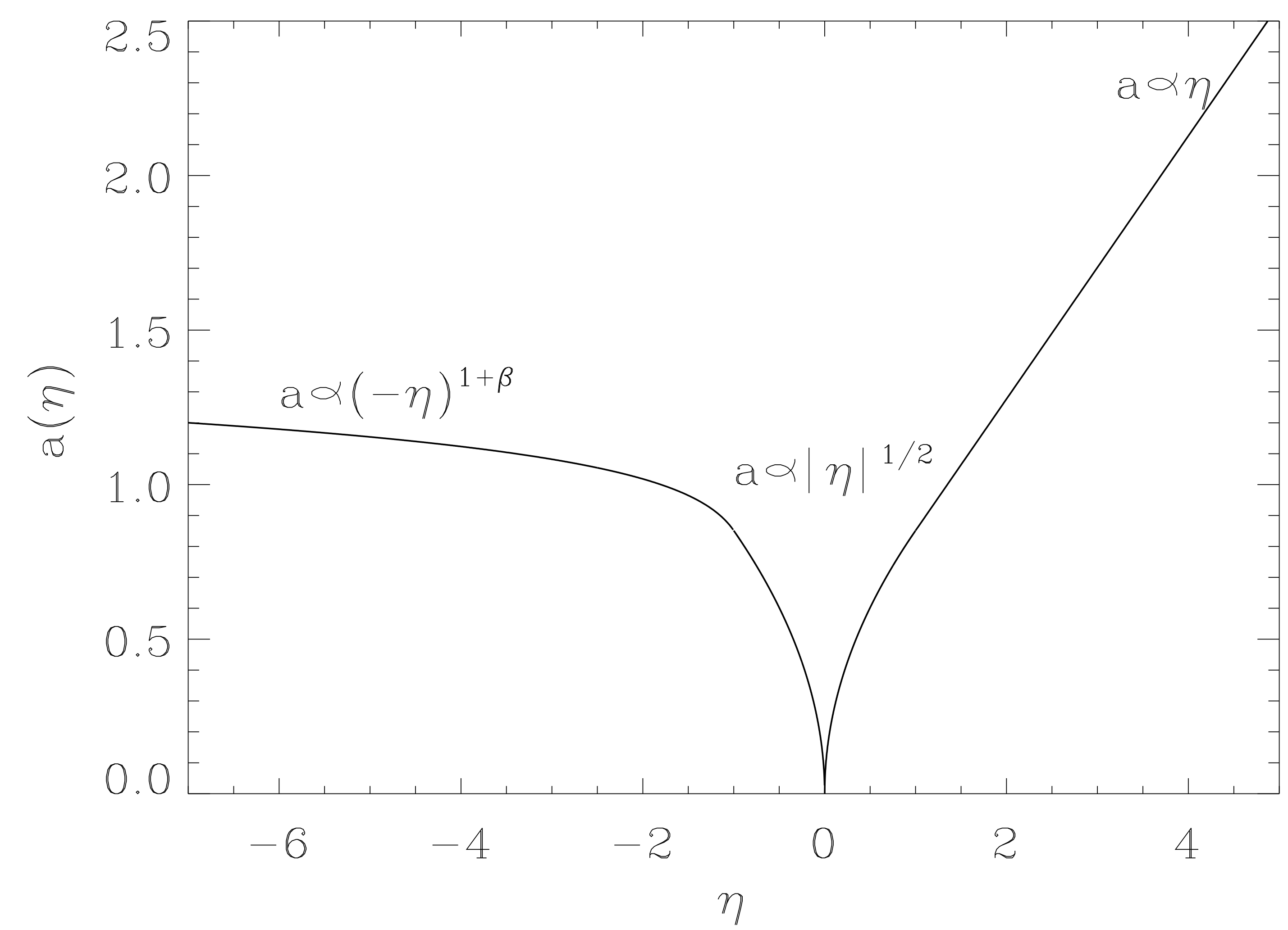
Ekpyrotic scenario:

$$\mathcal{S}_5 \propto \int_{\mathcal{M}_5} \mathrm{d}^5 x \sqrt{-g_5}\left[R_{(5)} - \frac{1}{2}\left(\partial\varphi\right)^2 - \frac{3}{2}\frac{\mathrm{e}^{2\varphi}\mathcal{F}^2}{5\,!}\right],$$



$$\mathcal{S}_4 = \int_{\mathcal{M}_4} \mathrm{d}^4 x \sqrt{-g_4}\left[\frac{R_{(4)}}{2\kappa} - \frac{1}{2}\left(\partial\phi\right)^2 - V(\phi)\right];$$

$$V(\varphi) = -V_{\mathrm{i}} \exp\left[-\frac{4\sqrt{\pi\gamma}}{m_{\mathrm{Pl}}}(\varphi - \varphi_{\mathrm{i}})\right];$$



Standard Failures and some (bouncing) solutions

- Singularity
- Horizon
- Flatness

- Homogeneity

- Perturbations
- Others

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  accelerated expansion (inflation) or decelerated contraction (bounce)
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- **Homogeneity** Large & flat Universe + low initial density + diffusion

  $$\frac{t_\mathrm{dissipation}}{t_\mathrm{Hubble}} \propto \frac{\lambda}{R_\mathrm{H}^{1/3}}\left(1 + \frac{\lambda}{AR_\mathrm{H}^2}\right)$$ enough time to dissipate any wavelength

  $\Longrightarrow$ vacuum state!
- **Perturbations**
- **Others**

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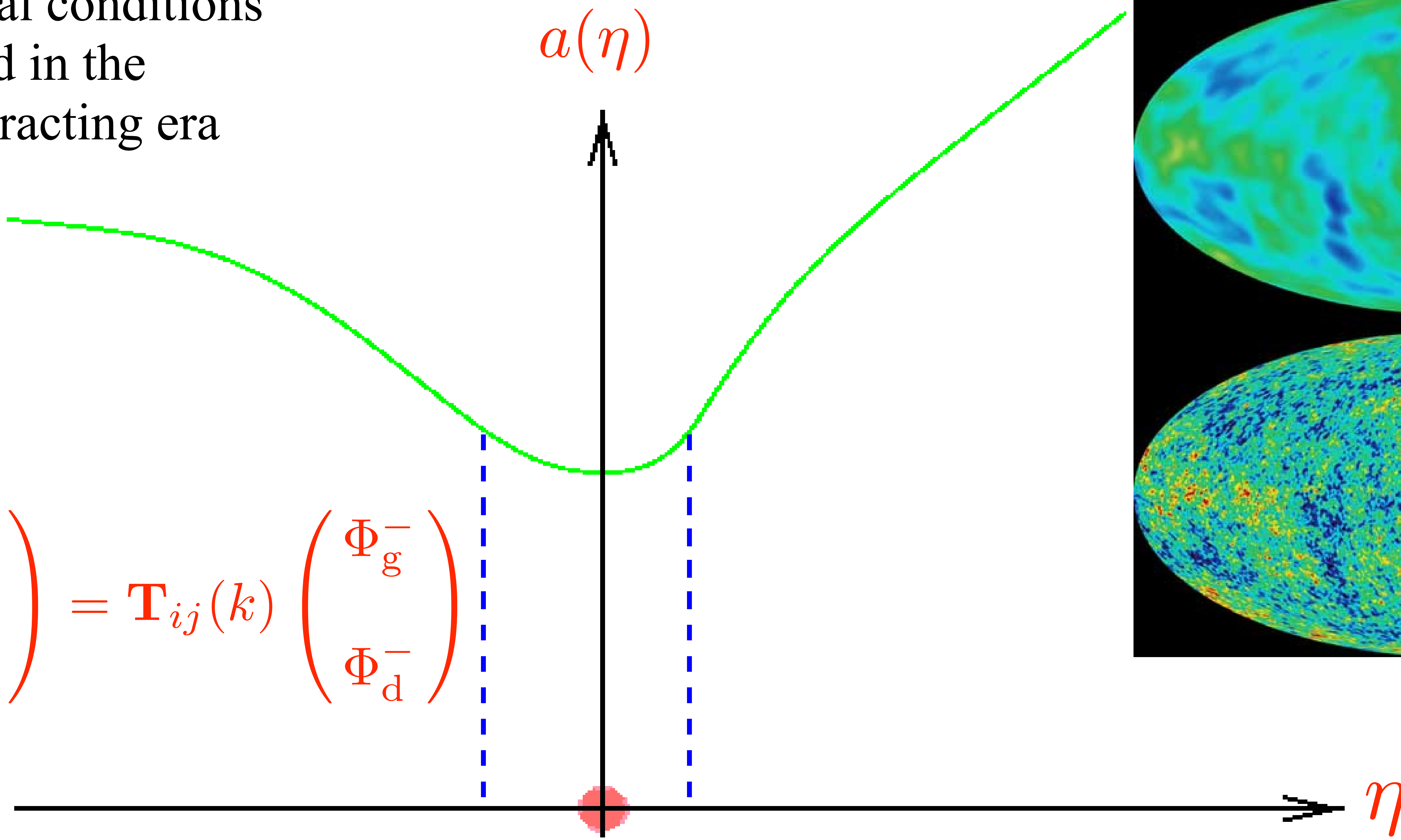
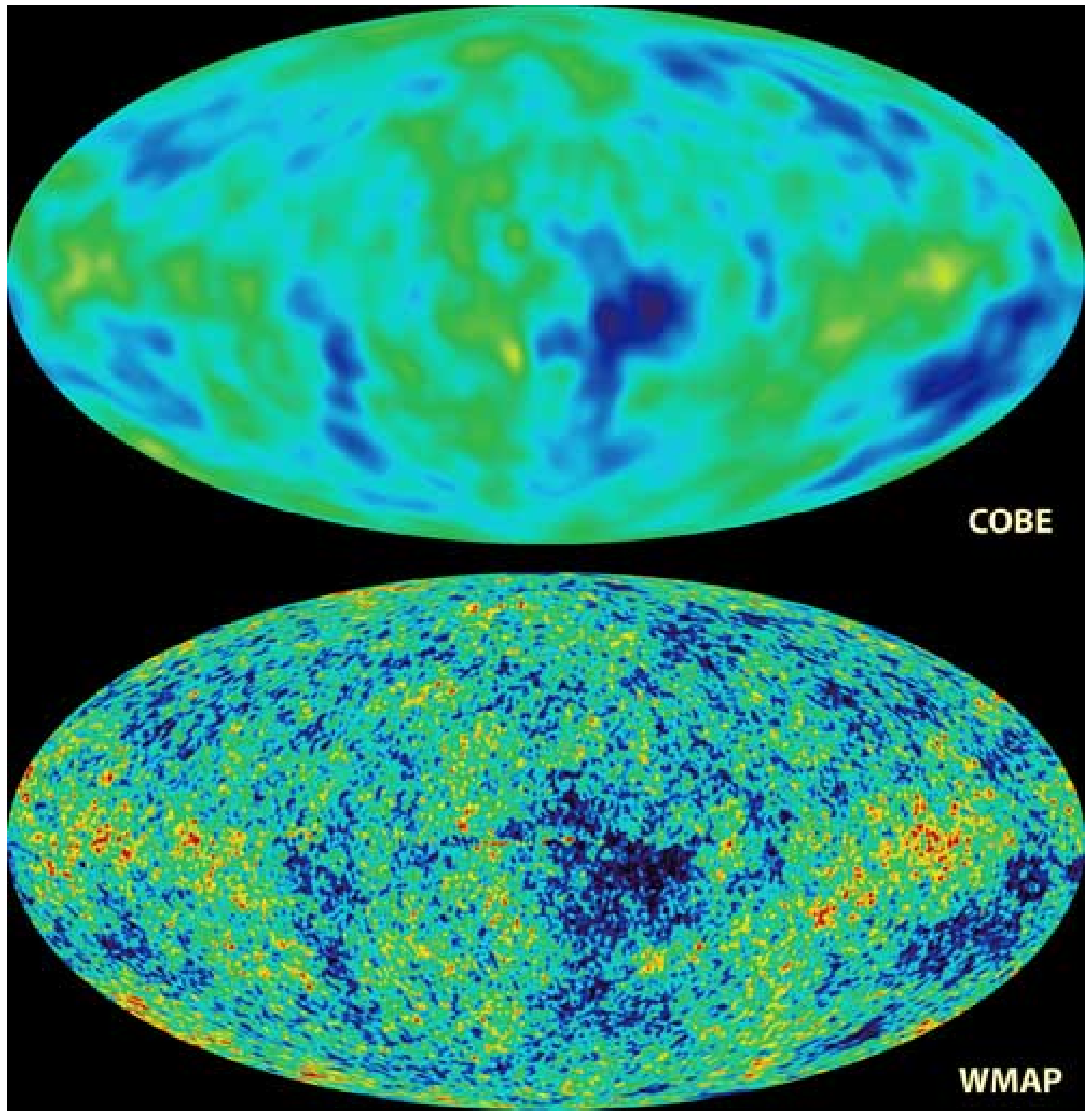
- **Others** dark matter/energy, baryogenesis, ... 

Perturbations: $\mathrm{d}s^2 = a^2(\eta)\left\{(1+2\Phi)\,\mathrm{d}\eta^2 - \left[(1-2\Phi)\,\gamma_{ij} + h_{ij}\right]\mathrm{d}x^i\mathrm{d}x^j\right\}$

Initial conditions fixed in the contracting era



$$\begin{pmatrix} \Phi_{\mathrm{g}}^{+} \\ \\ \Phi_{\mathrm{d}}^{+} \end{pmatrix} = \mathbf{T}_{ij}(k) \begin{pmatrix} \Phi_{\mathrm{g}}^{-} \\ \\ \Phi_{\mathrm{d}}^{-} \end{pmatrix}$$



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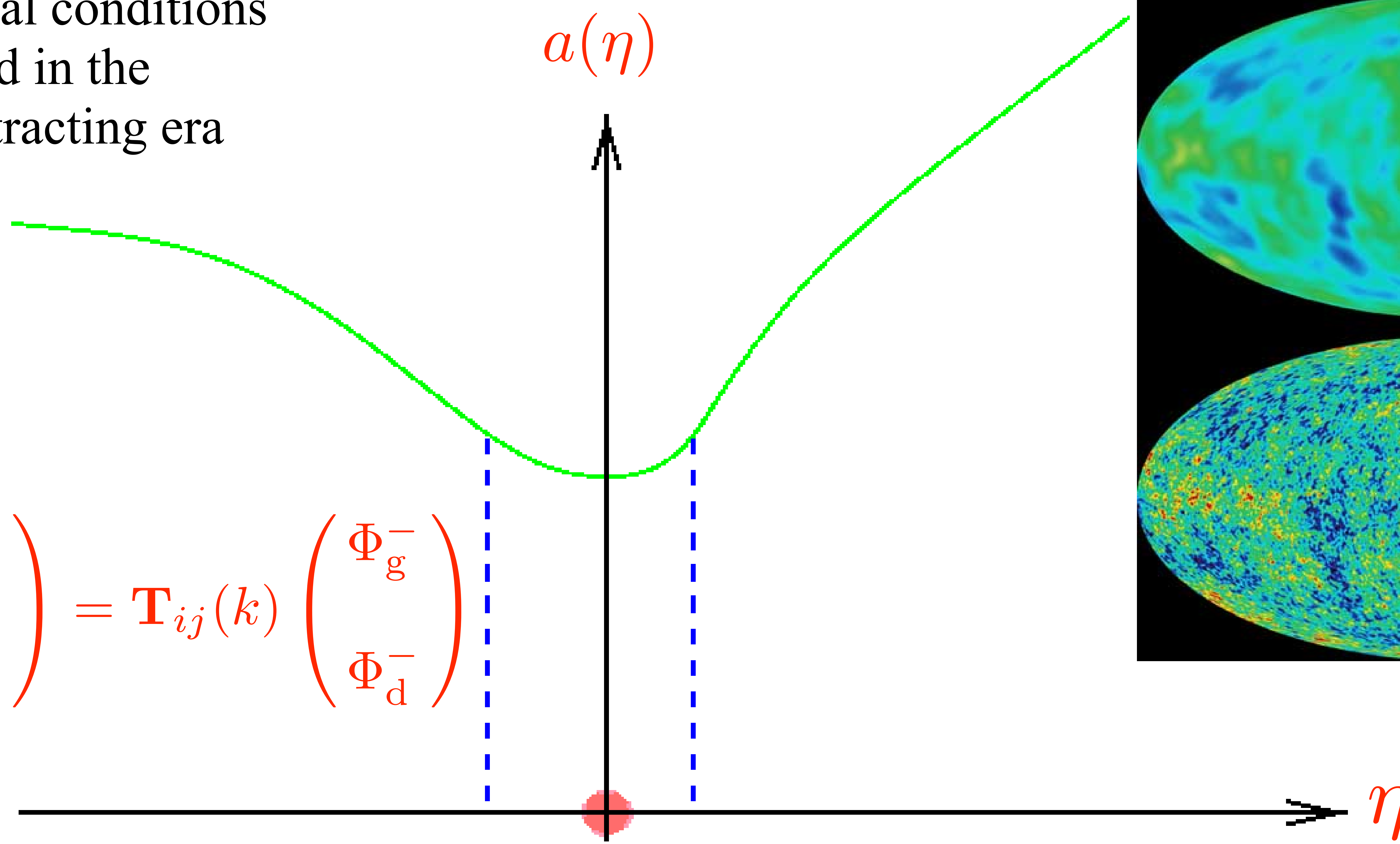

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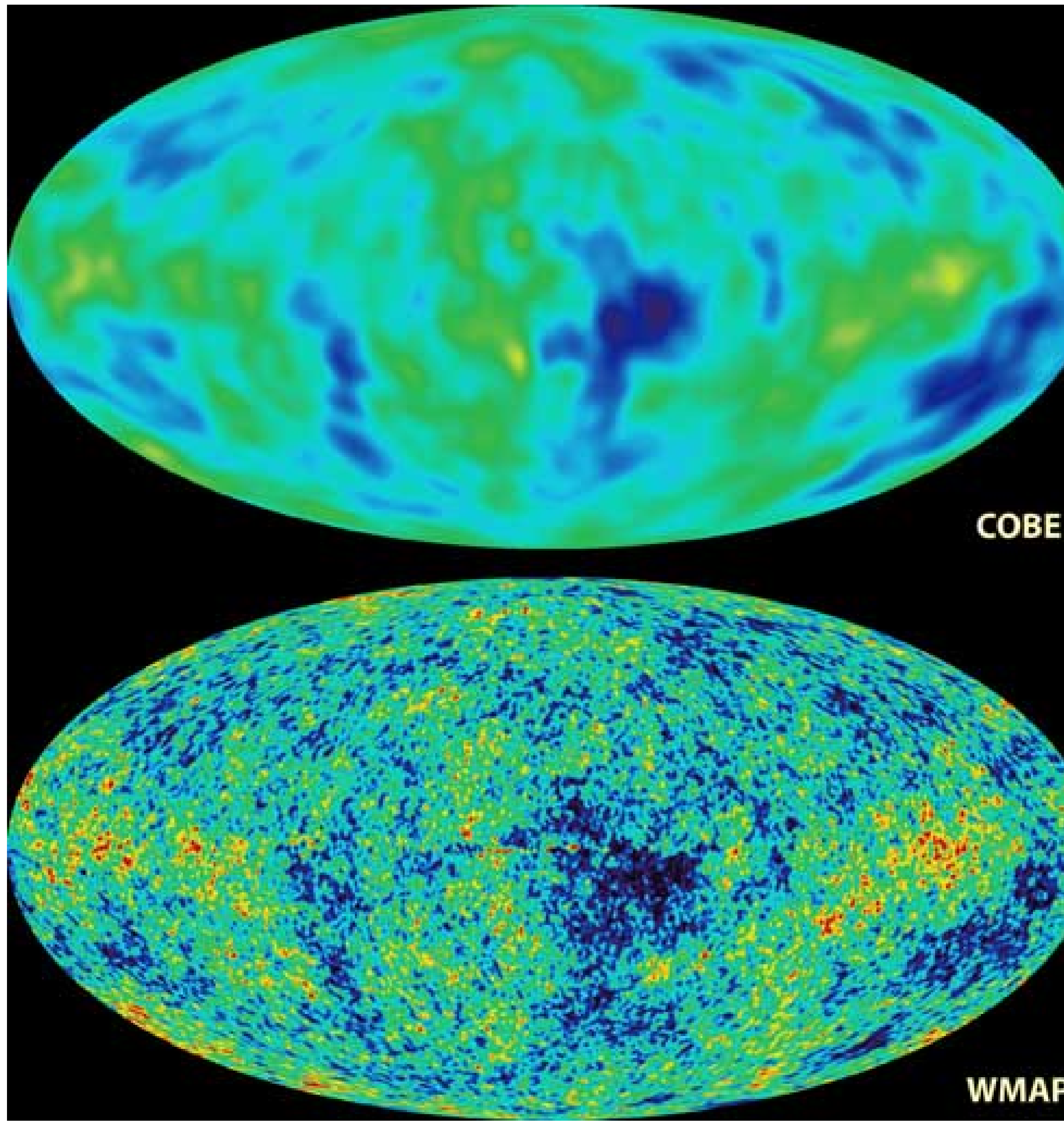

???????

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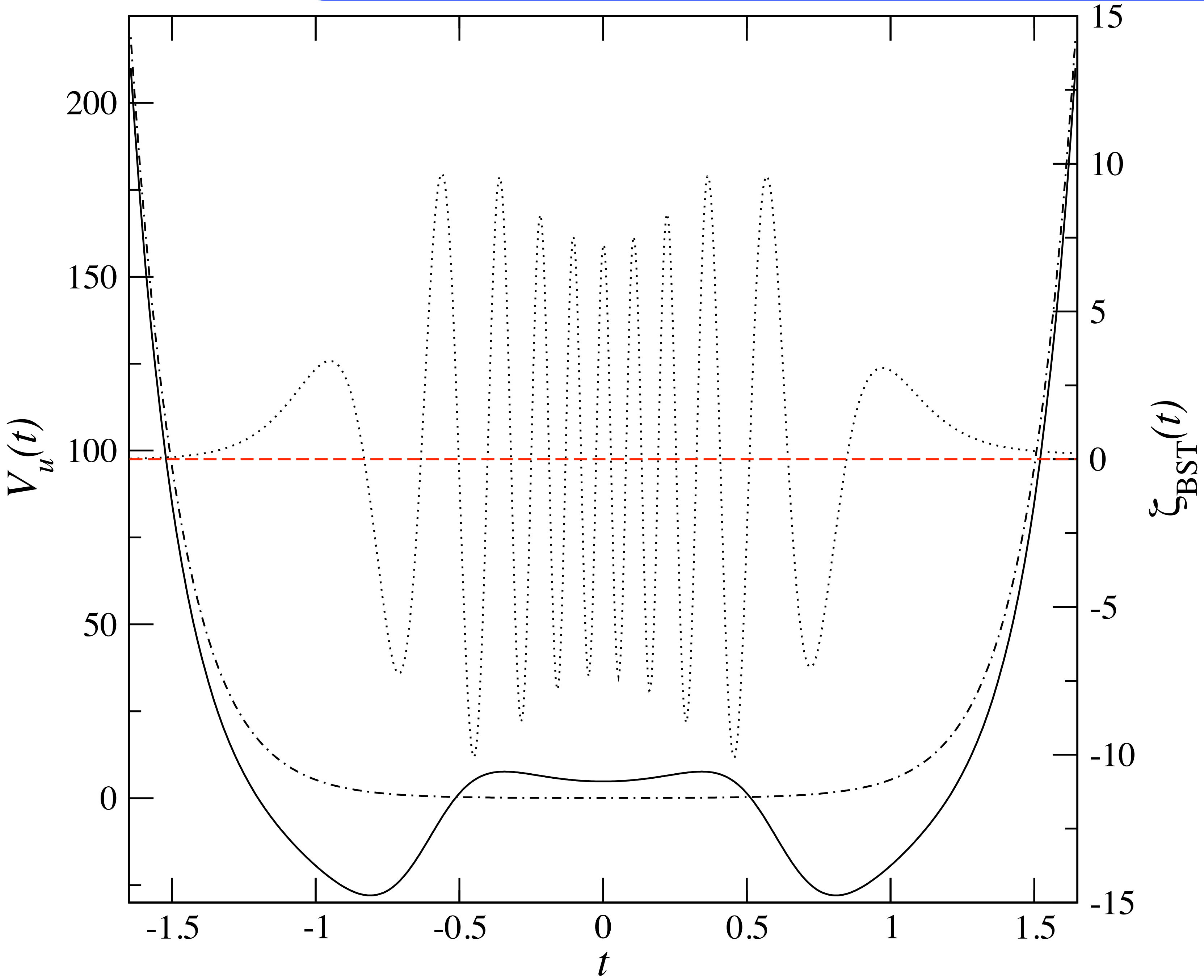
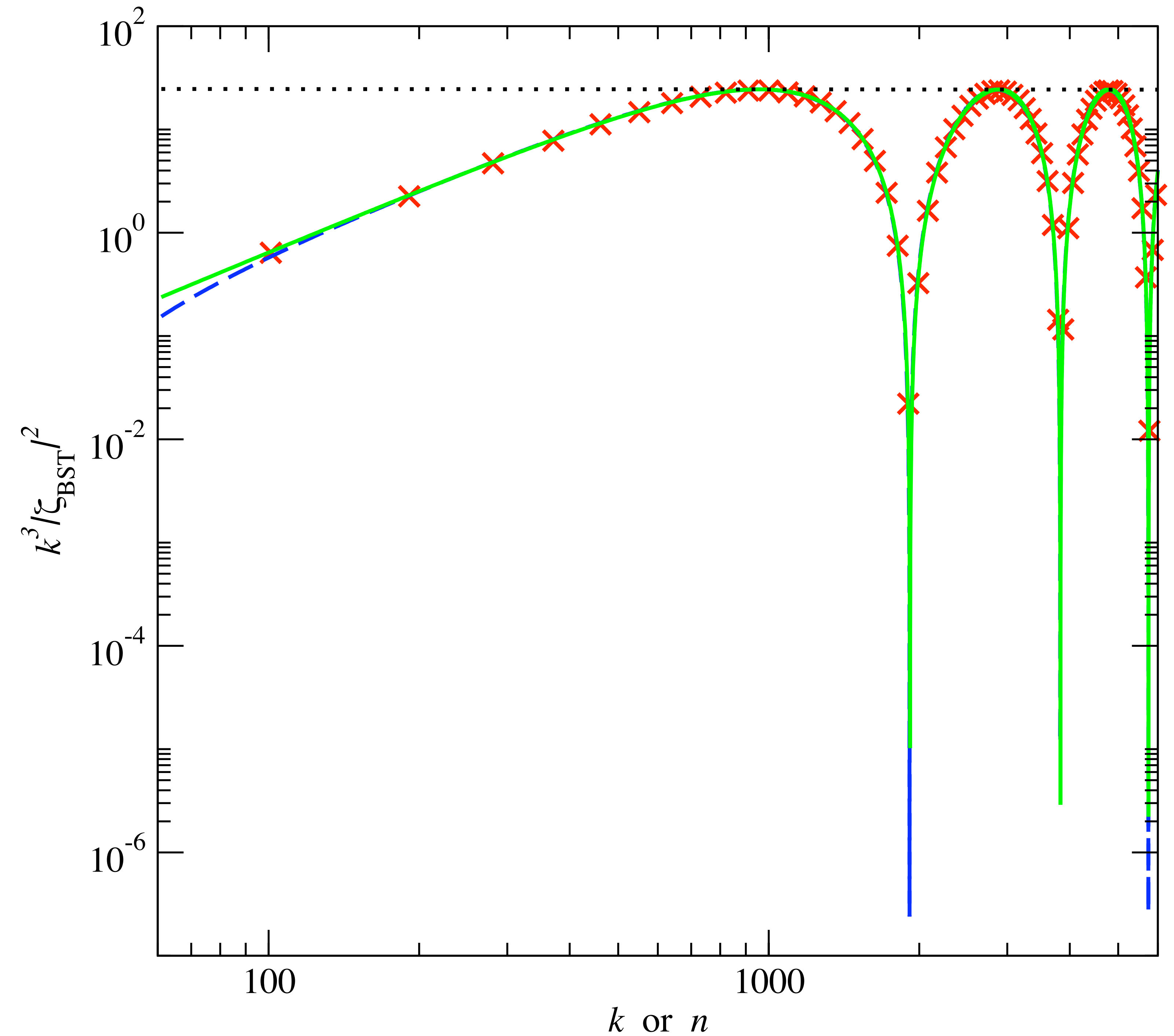
$$\Longleftrightarrow \quad \Phi = \frac{3\mathcal{H}u}{2a^2\theta} \qquad \theta \equiv \frac{1}{a}\sqrt{\frac{\rho_\varphi}{\rho_\varphi + p_\varphi}\left(1 - \frac{3\mathcal{K}}{\rho_\varphi a^2}\right)}$$

$$\boxed{u'' + \left[k^2 - \frac{\theta''}{\theta} - 3\mathcal{K}\left(1 - c_{\mathrm{S}}^2\right)\right]u = 0}$$

$$\mathcal{P}_\zeta = \mathcal{A}k^{n_{\mathrm{S}}-1}\cos^2\left(\omega\frac{k_{\mathrm{ph}}}{k_\star} + \psi\right)$$





Bunch-Davies vacuum initial conditions: quantized perturbations over a classical background!!!

A specific model: 4D Quantum cosmology

$$\mathcal{S} = \int \sqrt{-g}\left(-\frac{R}{6\ell_{\mathrm{P}}^2} + p\right) \mathrm{d}^4x$$

Perfect fluid: $p = \omega\rho$ $\Rightarrow$ **bounce**

no horizon problem if $\omega > -\frac{1}{3}$

Results:

$$n_{\mathrm{T}} = n_{\mathrm{S}} - 1 = \frac{12\omega}{1+3\omega}$$

$$\frac{T}{S} \simeq 4 \times 10^{-2}\sqrt{n_{\mathrm{S}} - 1}$$

Quantum cosmology $\mathrm{d}s^2 = N^2(\tau)\mathrm{d}\tau - a^2(\tau)\gamma_{ij}\mathrm{d}x^i\mathrm{d}x^j$

+ canonical transformation

+ rescaling (volume …) = a simple Hamiltonian:

+ units

$$H = \left(-\frac{p_a^2}{4a} - \mathcal{K}a + \frac{p_T}{a^{3\omega}}\right) N$$

$a^{3\omega}$

Wheeler-De Witt $H\Psi = 0$

+ Technical trick: $\mathcal{K} = 0 \Longrightarrow \chi \equiv \frac{2a^{3(1-\omega)/2}}{3(1-\omega)} \Longrightarrow \boxed{i\frac{\partial\Psi}{\partial T} = \frac{1}{4}\frac{\partial^2\Psi}{\partial\chi^2}}$

constraint $\bar{\Psi}\frac{\partial\Psi}{\partial\chi} = \Psi\frac{\partial\bar{\Psi}}{\partial\chi}$

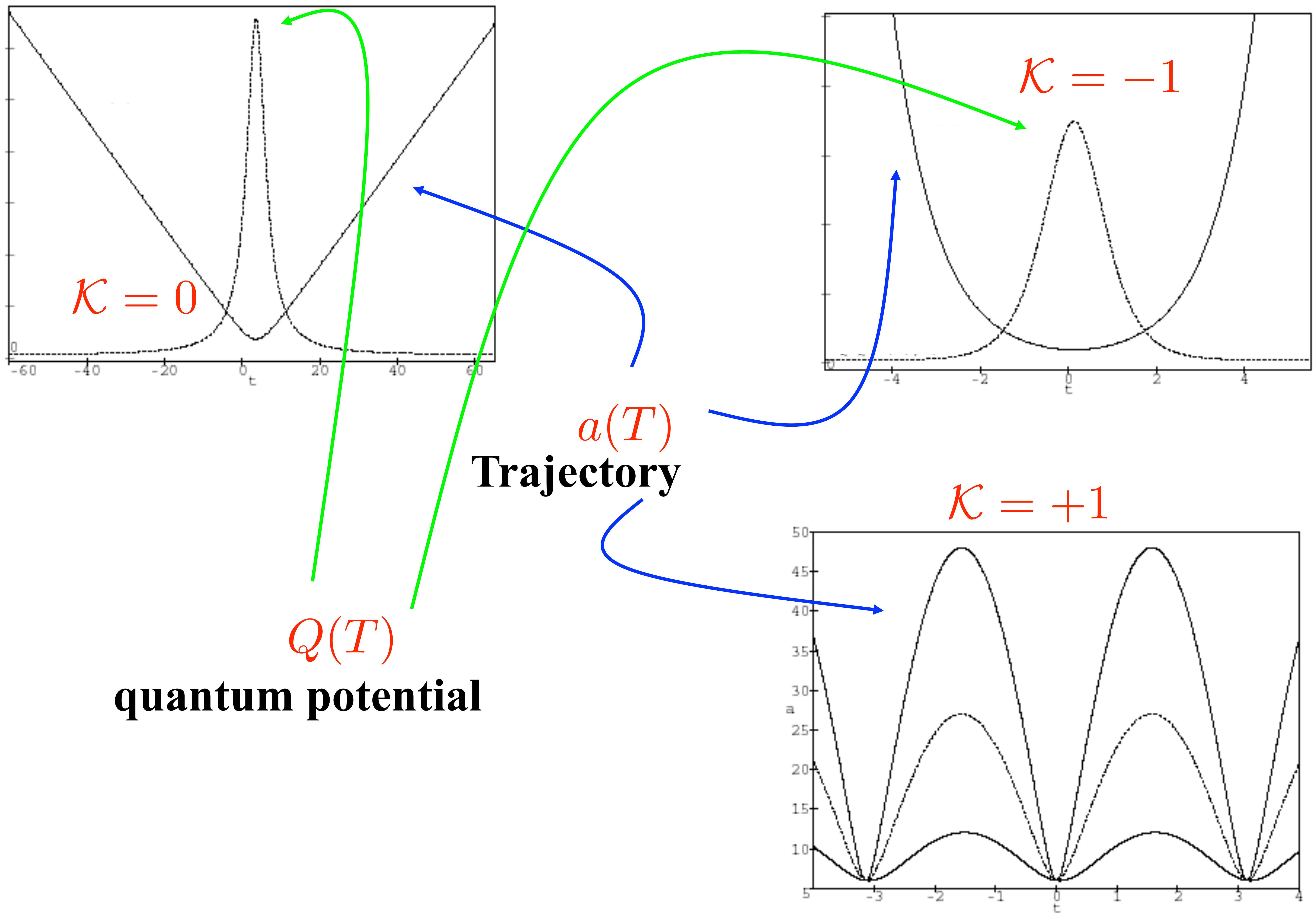
WKB exact superposition: $\Psi = \int \mathrm{e}^{iET}\rho(E)\psi_E(T)\mathrm{d}E$

Gaussian wave packet $\propto \mathrm{e}^{-(ET_0)^2}$

$$\Psi = \left[\frac{8T_0}{\pi\left(T_0^2+T^2\right)^2}\right]^{\frac{1}{4}} \exp\left(-\frac{T_0\chi^2}{T_0^2+T^2}\right)\mathrm{e}^{-iS(\chi,T)}$$

phase $S = \frac{T\chi^2}{T_0^2+T^2} + \frac{1}{2}\arctan\frac{T_0}{T} - \frac{\pi}{4}$

Bohmian trajectory $a = a_0\left[1+\left(\frac{T}{T_0}\right)^2\right]^{\frac{1}{3(1-\omega)}}$



$\mathcal{K} = 0$
$\mathcal{K} = -1$
$\mathcal{K} = +1$
$a(T)$
Trajectory
$Q(T)$
quantum potential

Usual treatment of the perturbations?

Einstein-Hilbert action up to 2nd order $\mathcal{S}_{\mathrm{E-H}} = \int \mathrm{d}^4x \left[R^{(0)} + \delta^{(2)}R\right]$

Bardeen (Newton) gravitational potential

$$\mathrm{d}s^2 = a^2(\eta)\left\{(1+2\Phi)\,\mathrm{d}\eta^2 - \left[(1-2\Phi)\,\gamma_{ij} + h_{ij}\right]\mathrm{d}x^i\mathrm{d}x^j\right\}$$

conformal time $\mathrm{d}\eta = a(t)^{-1}\mathrm{d}t$

$$\Delta\Phi = -\frac{3\ell_{\mathrm{Pl}}^2}{2}\sqrt{\frac{\rho+p}{\omega}}\,a\frac{\mathrm{d}}{\mathrm{d}\eta}\left(\frac{v}{a}\right)$$

Mukhanov-Sasaki variable

$$\int \mathrm{d}^4x\,\delta^{(2)}\mathcal{L} = \frac{1}{2}\int \sqrt{\gamma}\,\mathrm{d}^3\boldsymbol{x}\,\mathrm{d}\eta\left[(\partial_\eta v)^2 - \gamma^{ij}\partial_i v\partial_j v + \frac{z''}{z}v^2\right]$$

Simple scalar field with varying mass in Minkowski space!!! $z = z[a(\eta)]$

Wave function? No question about it ...

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Classical **Quantum**

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Our treatment of the perturbations? Self-consistent ...

Hamiltonian up to 2nd order $H = H_{(0)} + H_{(2)} + \cdots$

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factorization of the wave function

$$\Psi = \Psi_{(0)}\left(a,T\right)\Psi_{(2)}\left[v,T;a\left(T\right)\right]$$

comes from 0th order

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comes from 0th order

Need dBB!!!

+ **canonical transformations:**

$$i\frac{\partial\Psi_{(2)}}{\partial\eta} = \int \mathrm{d}^3x \left(-\frac{1}{2}\frac{\delta^2}{\delta v^2} + \frac{\omega}{2}v_{,i}v^{,i} - \frac{a''}{a}\right)\Psi_{(2)}$$

Fourier mode

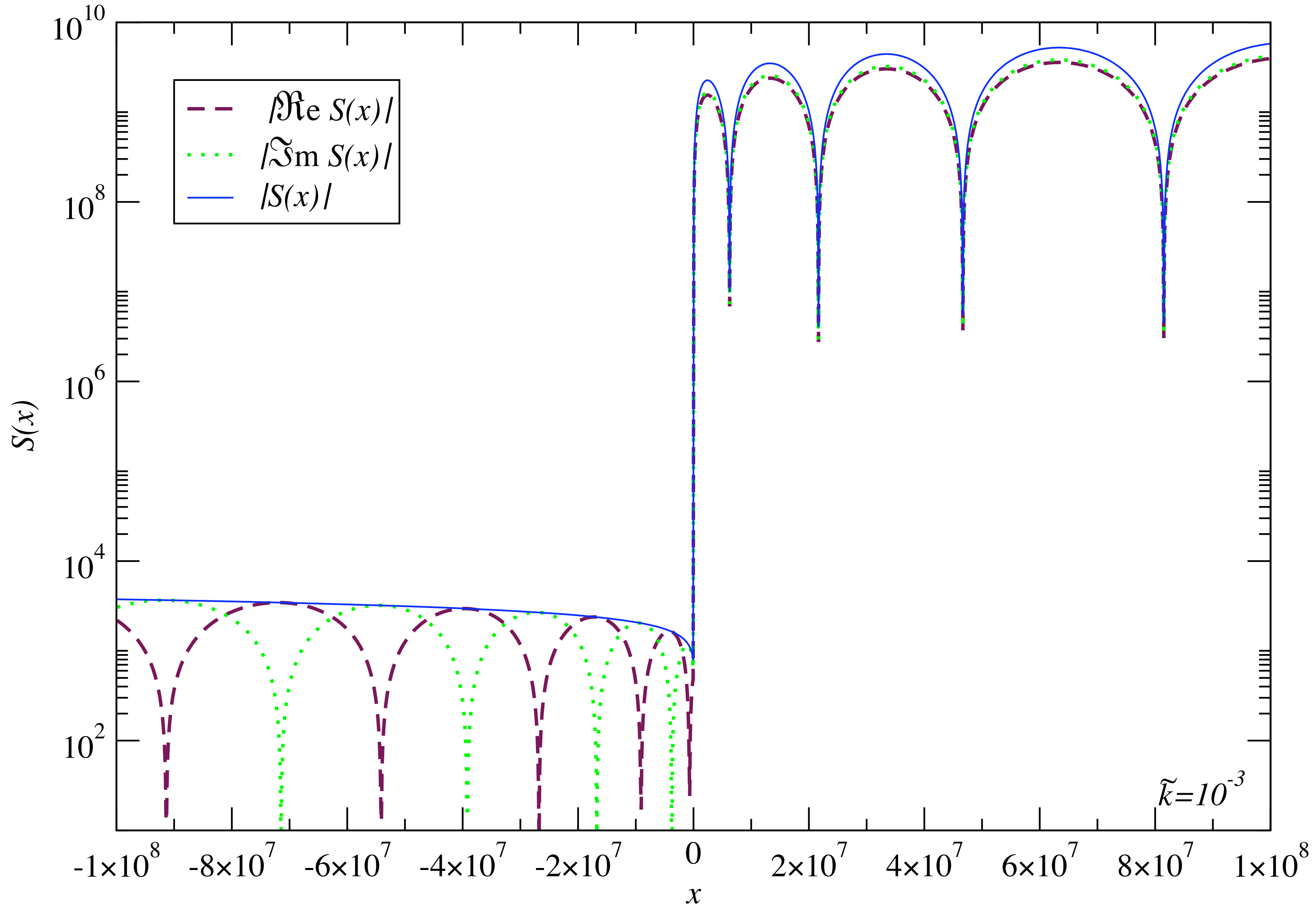
$$\boxed{v_k'' + \left(c_{\mathrm{S}}^2 k^2 - \frac{a''}{a}\right)v_k = 0}$$

$$c_{\mathrm{S}}^2 = \sqrt{\omega} \neq 0$$

Bunch-Davies vacuum initial conditions

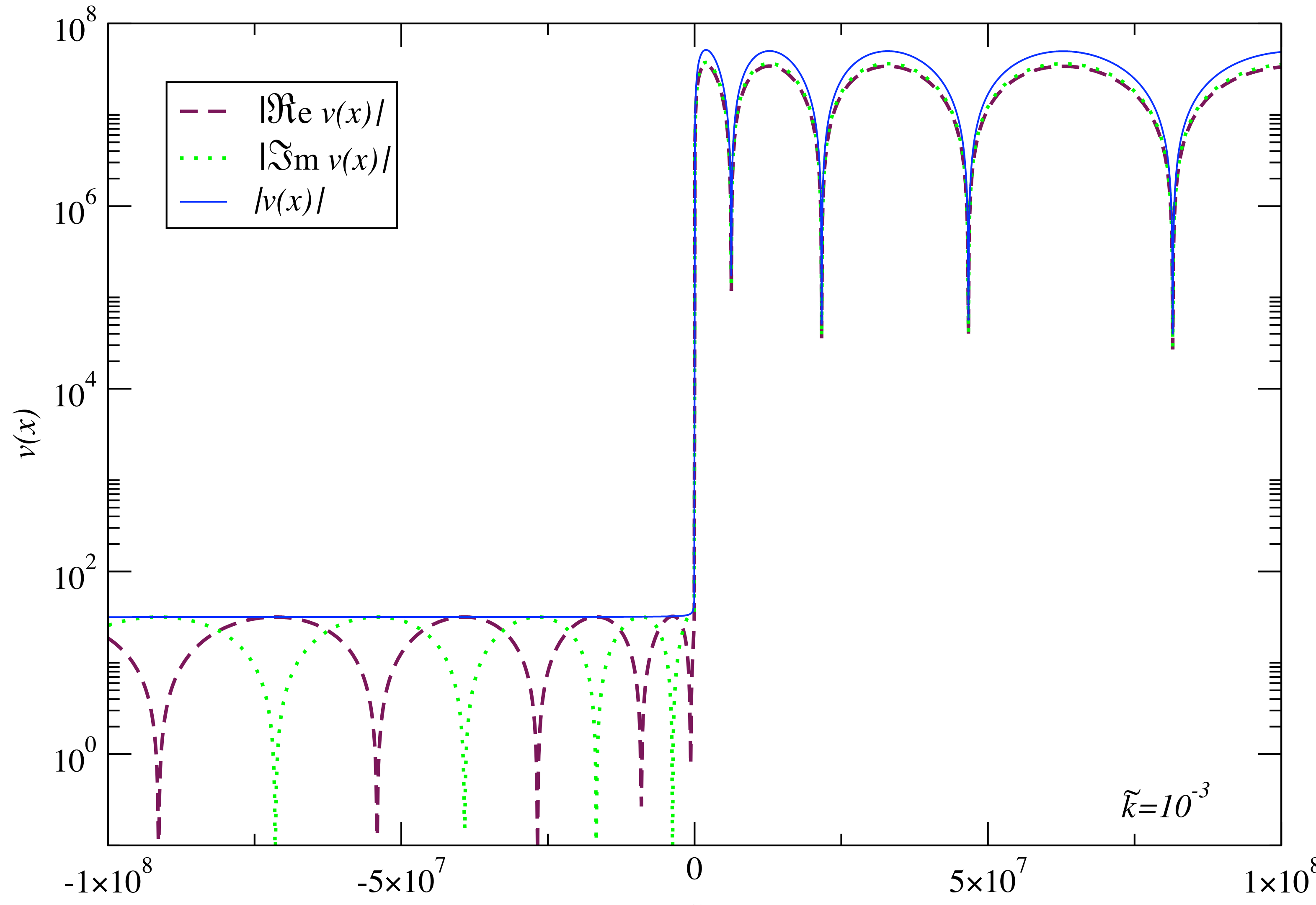
$$v_k \propto \frac{\mathrm{e}^{-ic_{\mathrm{S}}k\eta}}{\sqrt{2c_{\mathrm{S}}k}}$$

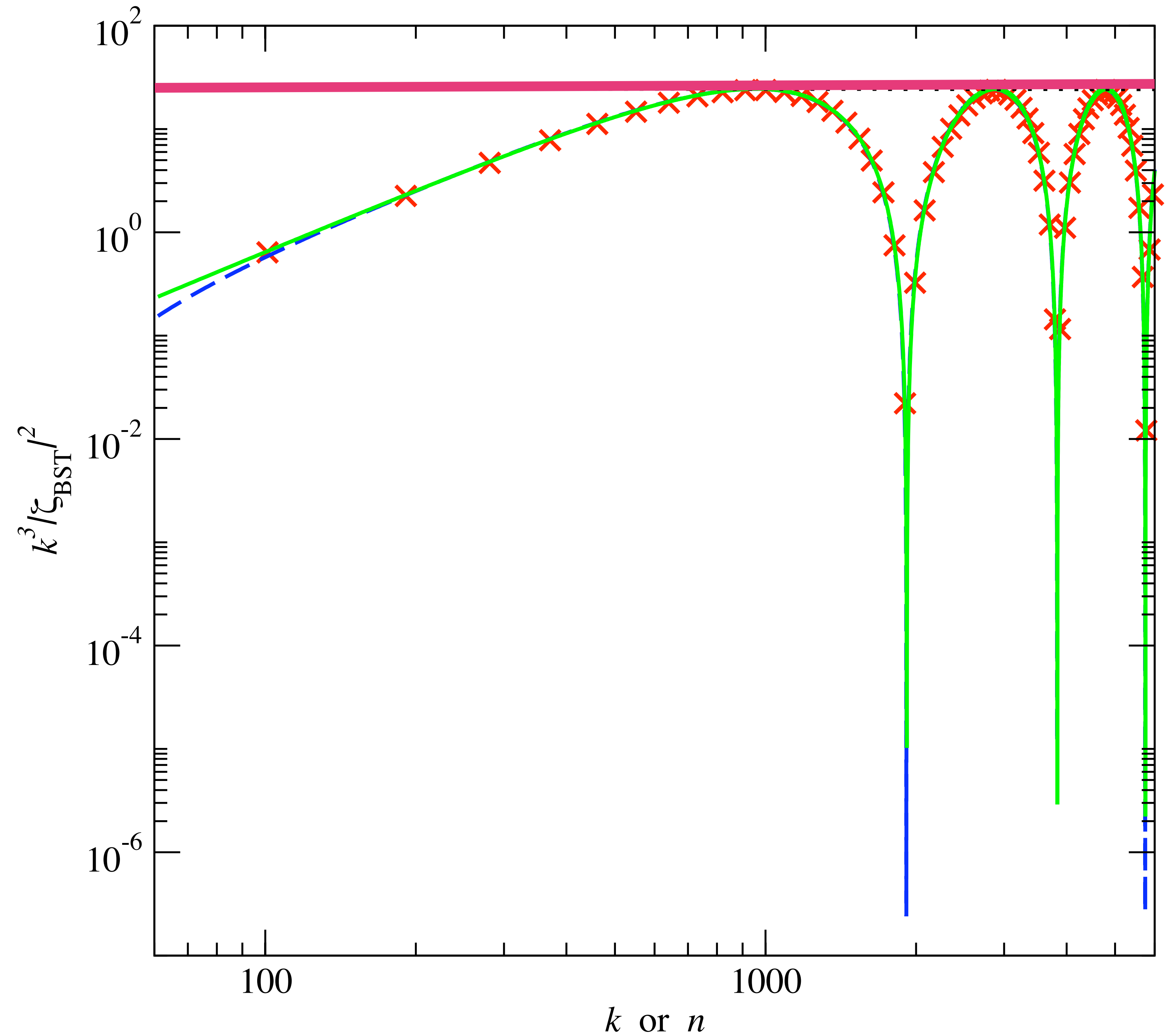
+ **evolution** **(matchings and/or numerics)**

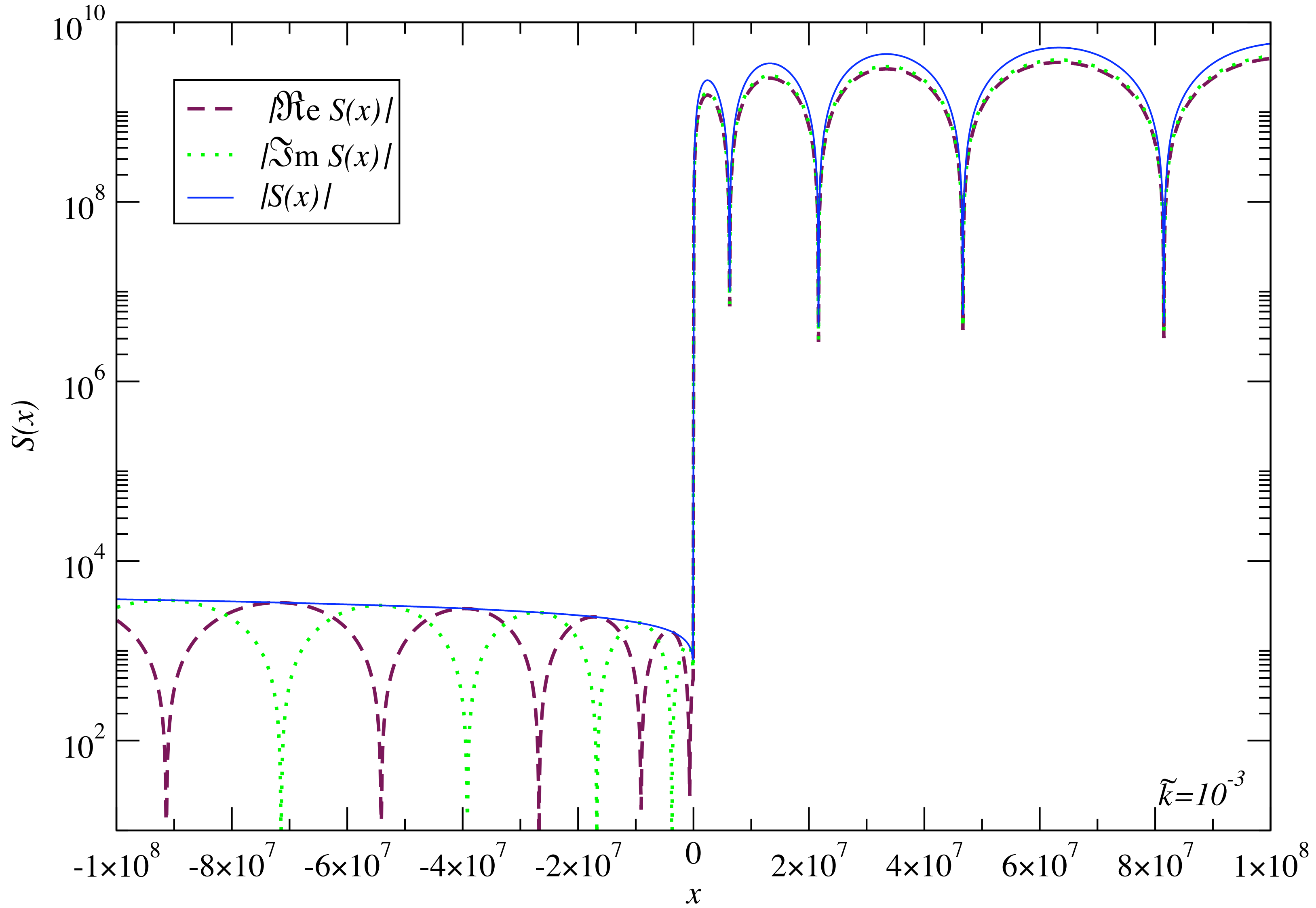


$$s(x) = a^{\frac{1}{2}(1-3\omega)} \frac{v(x)}{\sqrt{T_0}}$$

$$x \equiv \frac{T}{T_0}$$



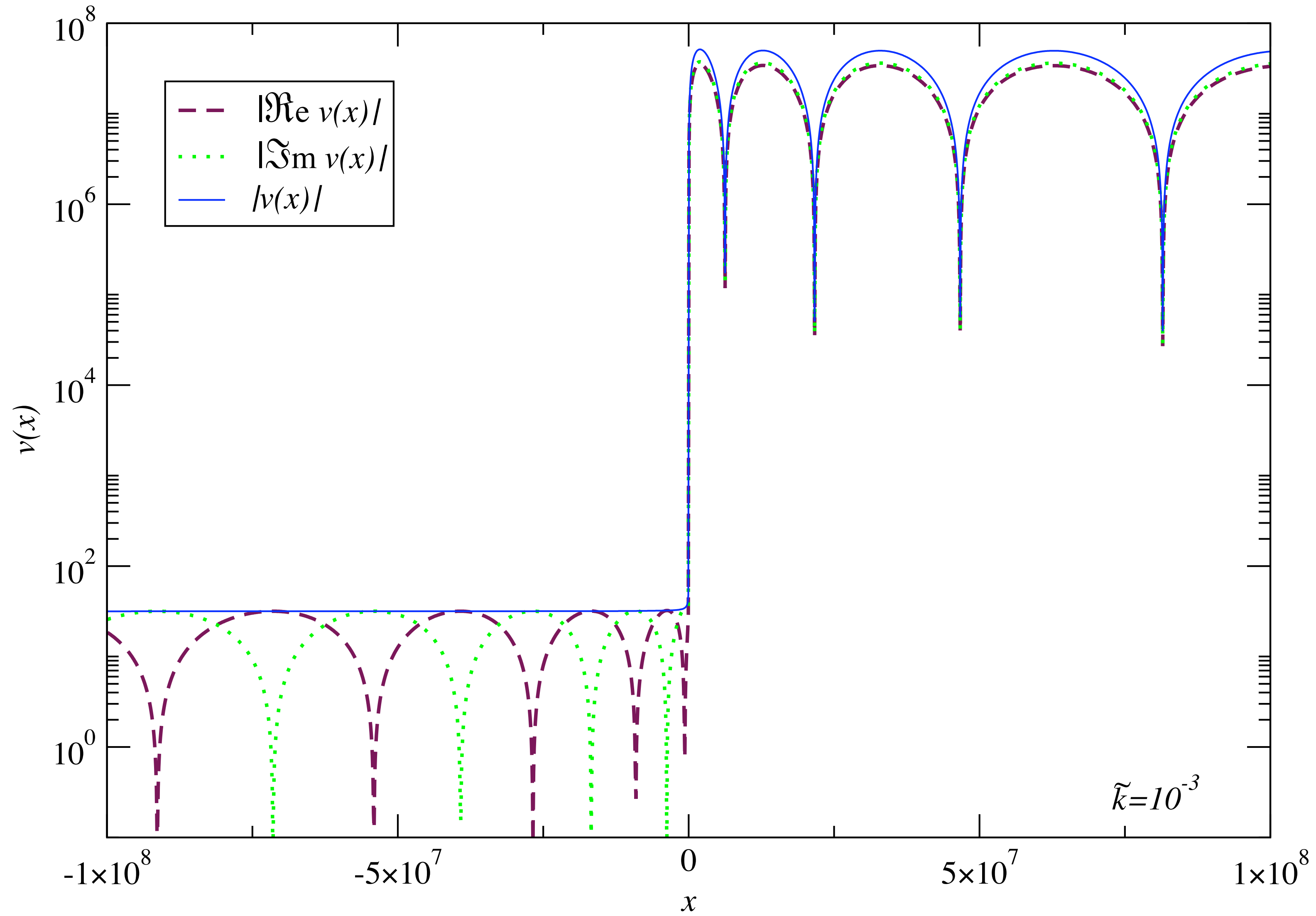


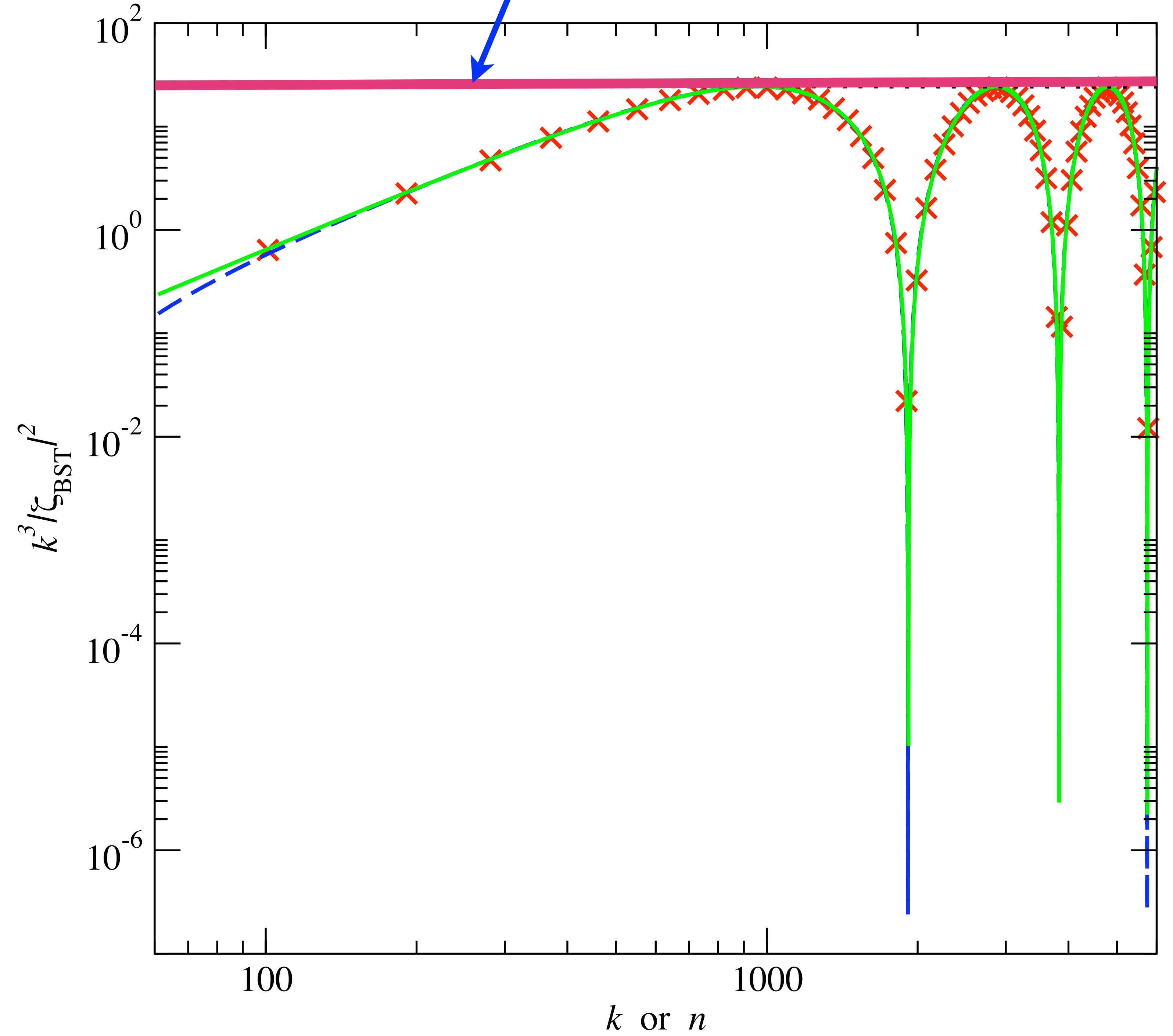


$$s(x) = a^{\frac{1}{2}(1-3\omega)} \frac{v(x)}{\sqrt{T_0}}$$

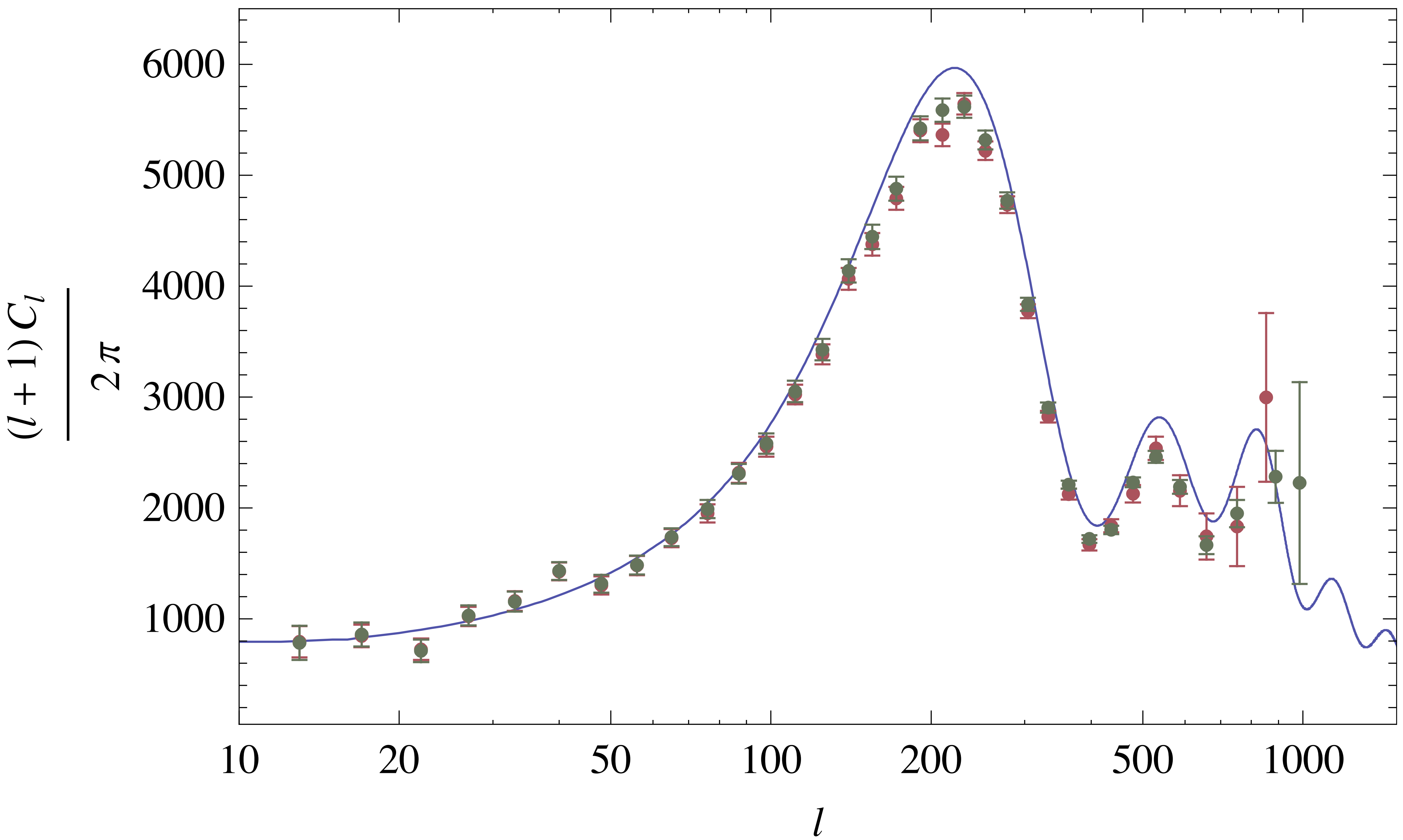
Best fit to the data!!!

$$x \equiv \frac{T}{T_0}$$

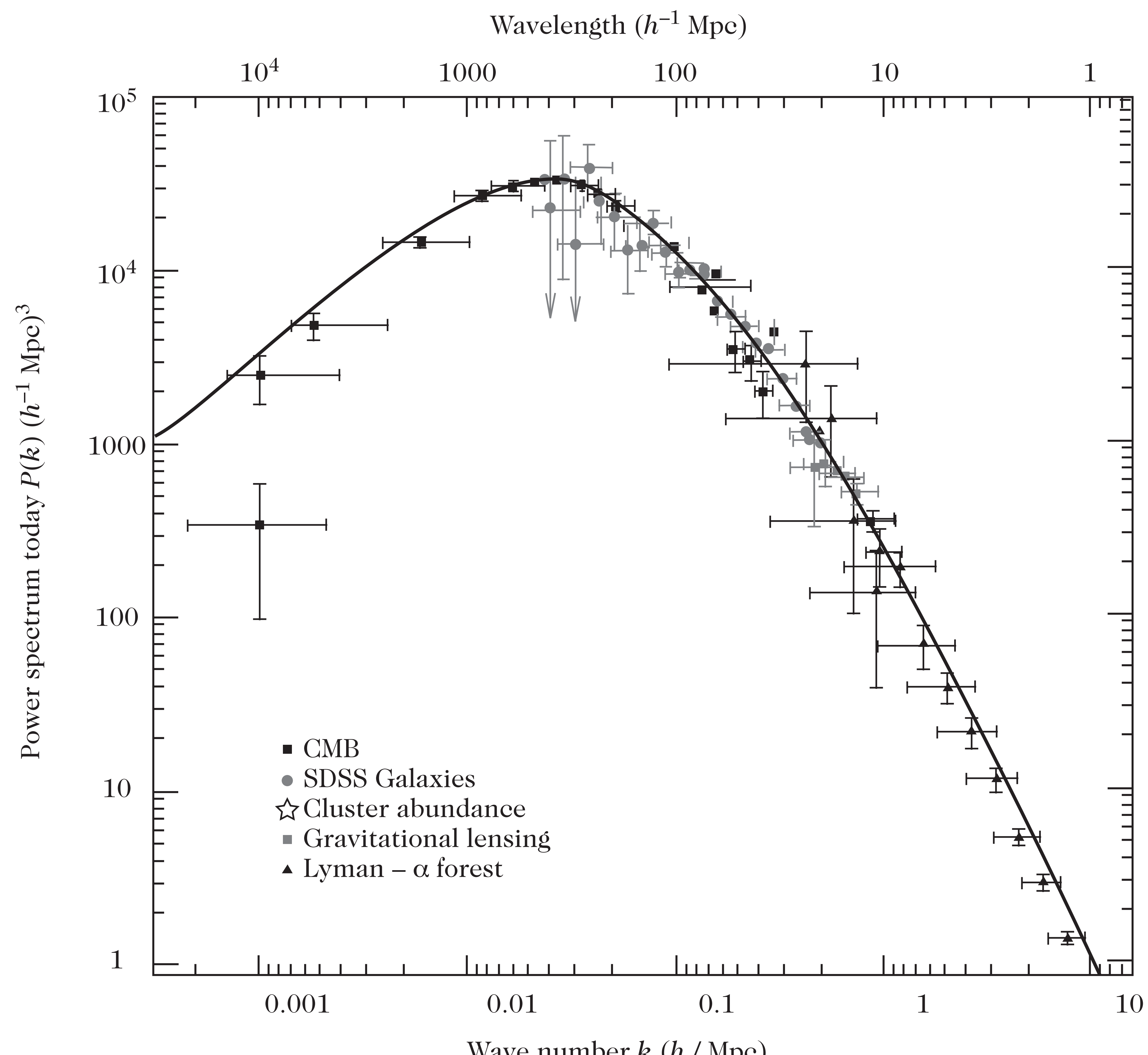


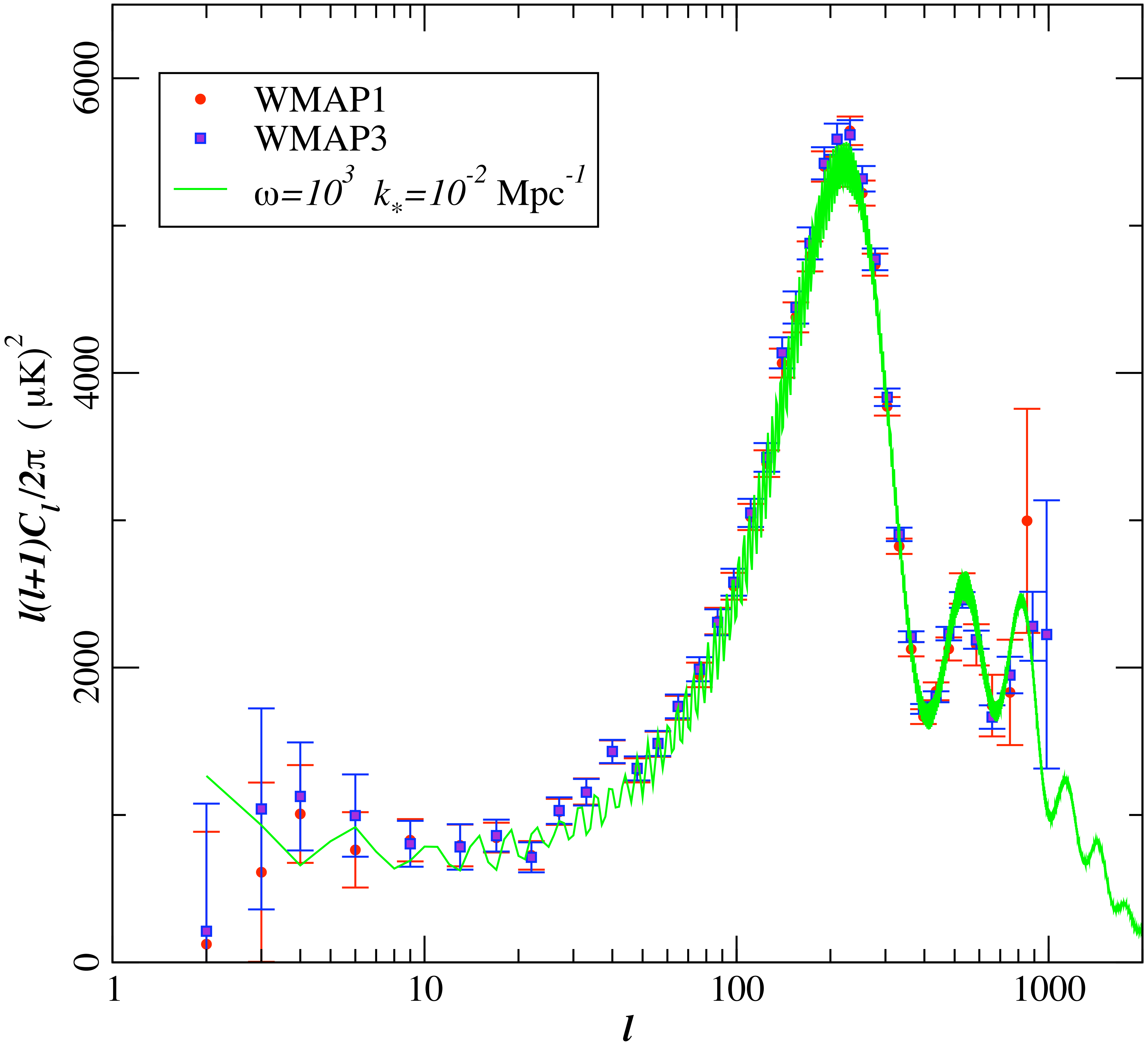


Data!



No obvious oscillations ...




WMAP1
WMAP3
ω=10^3 k_*=10^-2 Mpc^-1
6000
4000
2000
0
l(l+1)C_l/2π (μK)^2
1
10
100
1000
l

spectrum $\mathcal{P}_\Phi \propto k^3 \left|\Phi_k\right|^2 \propto A_{\rm S}^2 k^{n_{\rm S}-1}$

$$\mathrm{d}s^2 = a^2(\eta)\left\{(1+2\Phi)\,\mathrm{d}\eta^2 - \left[(1-2\Phi)\,\gamma_{ij} + h_{ij}\right]\mathrm{d}x^i\mathrm{d}x^j\right\}$$

id. grav. waves: $\mu'' + \left(k^2 - \frac{a''}{a}\right)\mu = 0$ $\mu \equiv \frac{h}{a}$

$\mu_{\rm ini} \propto \frac{\exp(-ik\eta)}{\sqrt{k\eta}}$ $\mathcal{P}_h \propto k^3 \left|h_k\right|^2 \propto A_{\rm T}^2 k^{n_{\rm T}}$

same dynamics + initial conditions ⇨ **same spectrum**

$$\boxed{n_{\rm T} = n_{\rm S} - 1 = \frac{12\omega}{1+3\omega}}$$

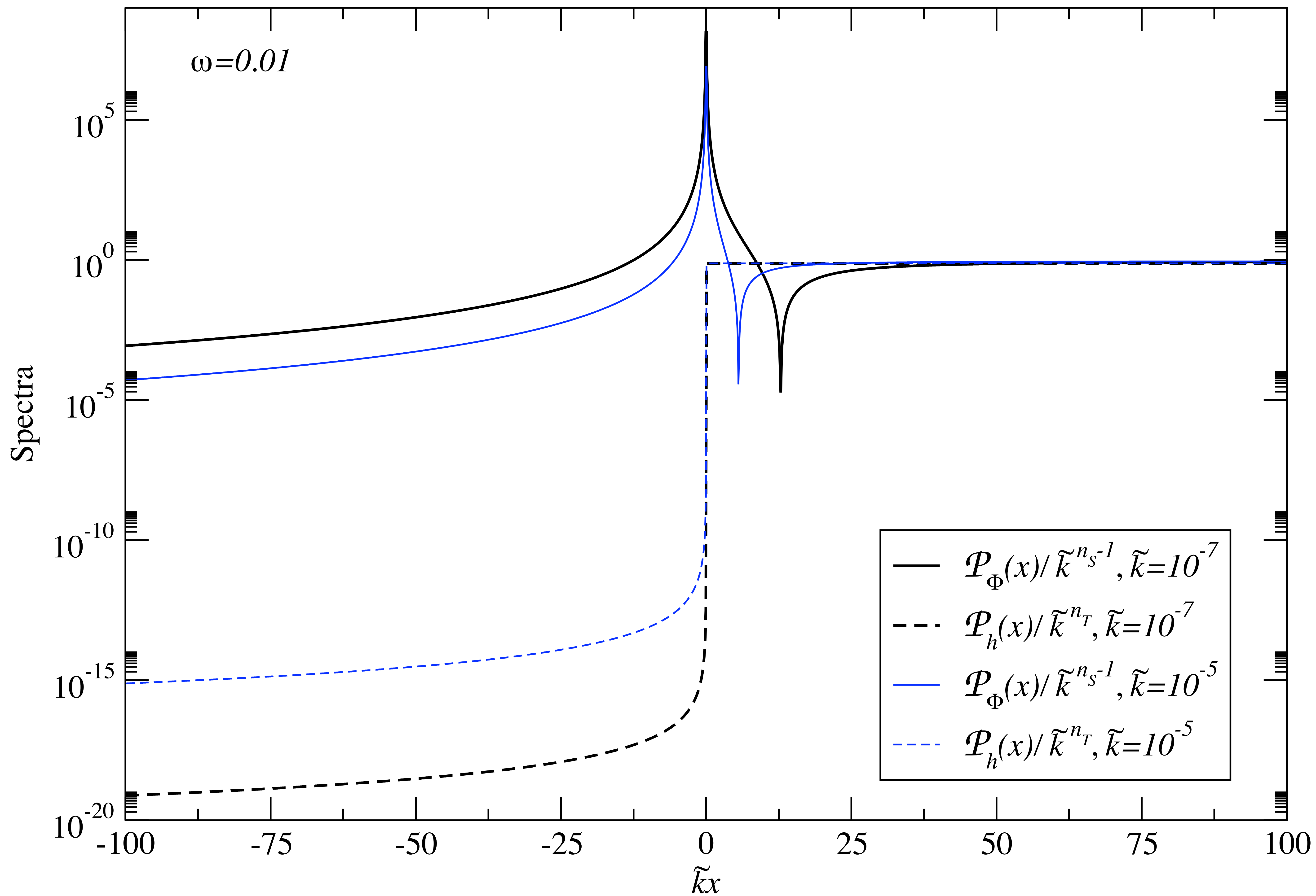
scale invariance + amplification

$\omega \ll 1$ $\omega = \frac{1}{3}$

2 stages are necessary

CMB normalisation $A_{\rm S}^2 = 2.08 \times 10^{-10}$

⇨ **bounce curvature** $T_0 a_0^{3\omega} \simeq 1500\ell_{\rm Pl}$


ω=0.01
Spectra
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
-100
-75
-50
-25
0
25
50
75
100
$\tilde{k}x$
$\mathcal{P}_\Phi(x)/\tilde{k}^{n_S-1}, \tilde{k}=10^{-7}$
$\mathcal{P}_h(x)/\tilde{k}^{n_T}, \tilde{k}=10^{-7}$
$\mathcal{P}_\Phi(x)/\tilde{k}^{n_S-1}, \tilde{k}=10^{-5}$
$\mathcal{P}_h(x)/\tilde{k}^{n_T}, \tilde{k}=10^{-5}$

WMAP constraint

$$n_{\mathrm{S}} = 0.96 \pm 0.02 \Longrightarrow w \lesssim 8 \times 10^{-4}$$

predictions

- **spectrum slightly blue**

power-law + concordance

$$\frac{T}{S} = \frac{C_{10}^{(\mathrm{T})}}{C_{10}^{(\mathrm{S})}} = \underbrace{\mathcal{F}(\Omega, \cdots)}_{\simeq 0.62} \frac{A_{\mathrm{T}}^2}{A_{\mathrm{S}}^2} \propto \sqrt{w}$$

$$\boxed{\frac{T}{S} \simeq 4 \times 10^{-2} \sqrt{n_{\mathrm{S}} - 1}}$$

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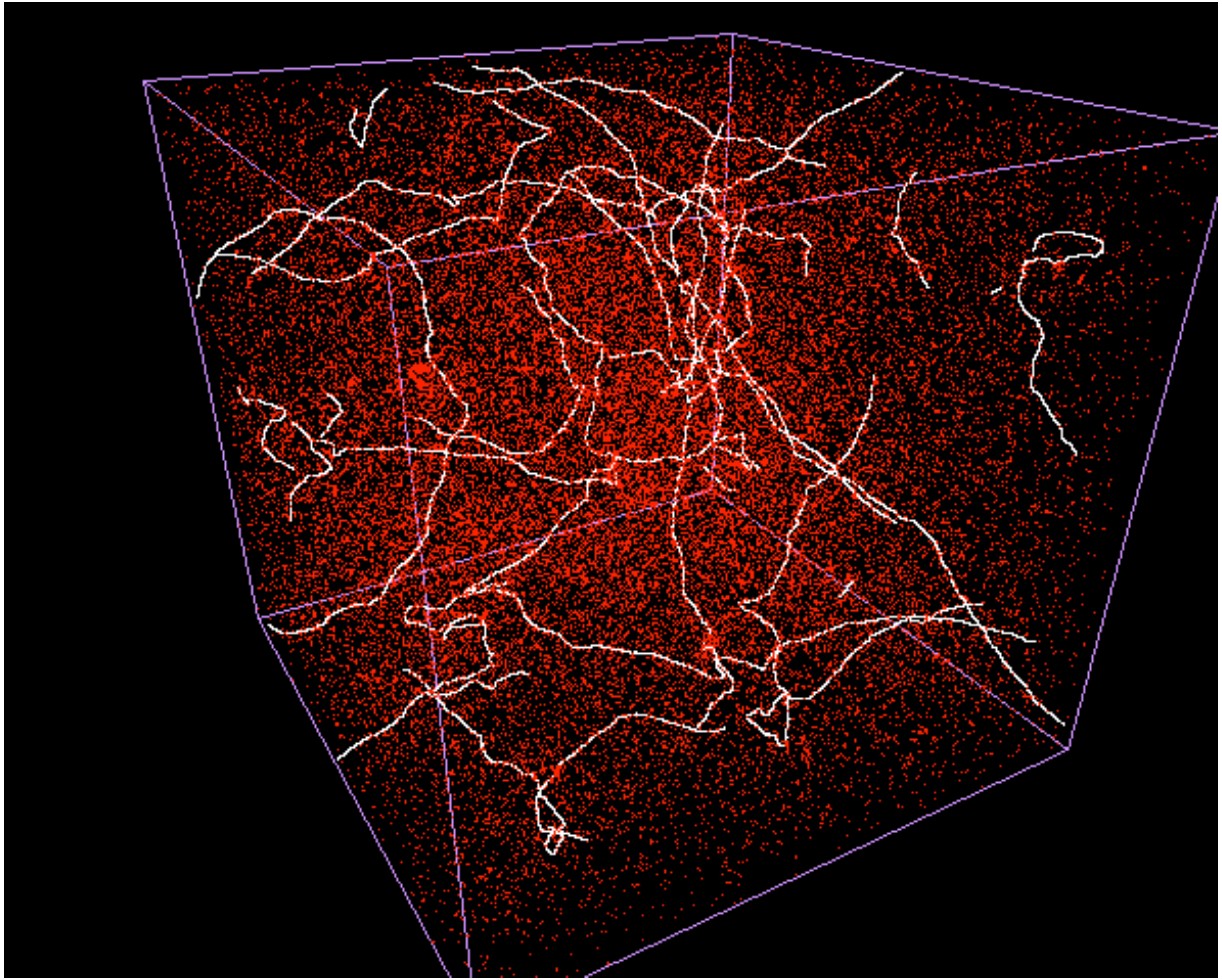
Numerical aside (Mike's talk monday):



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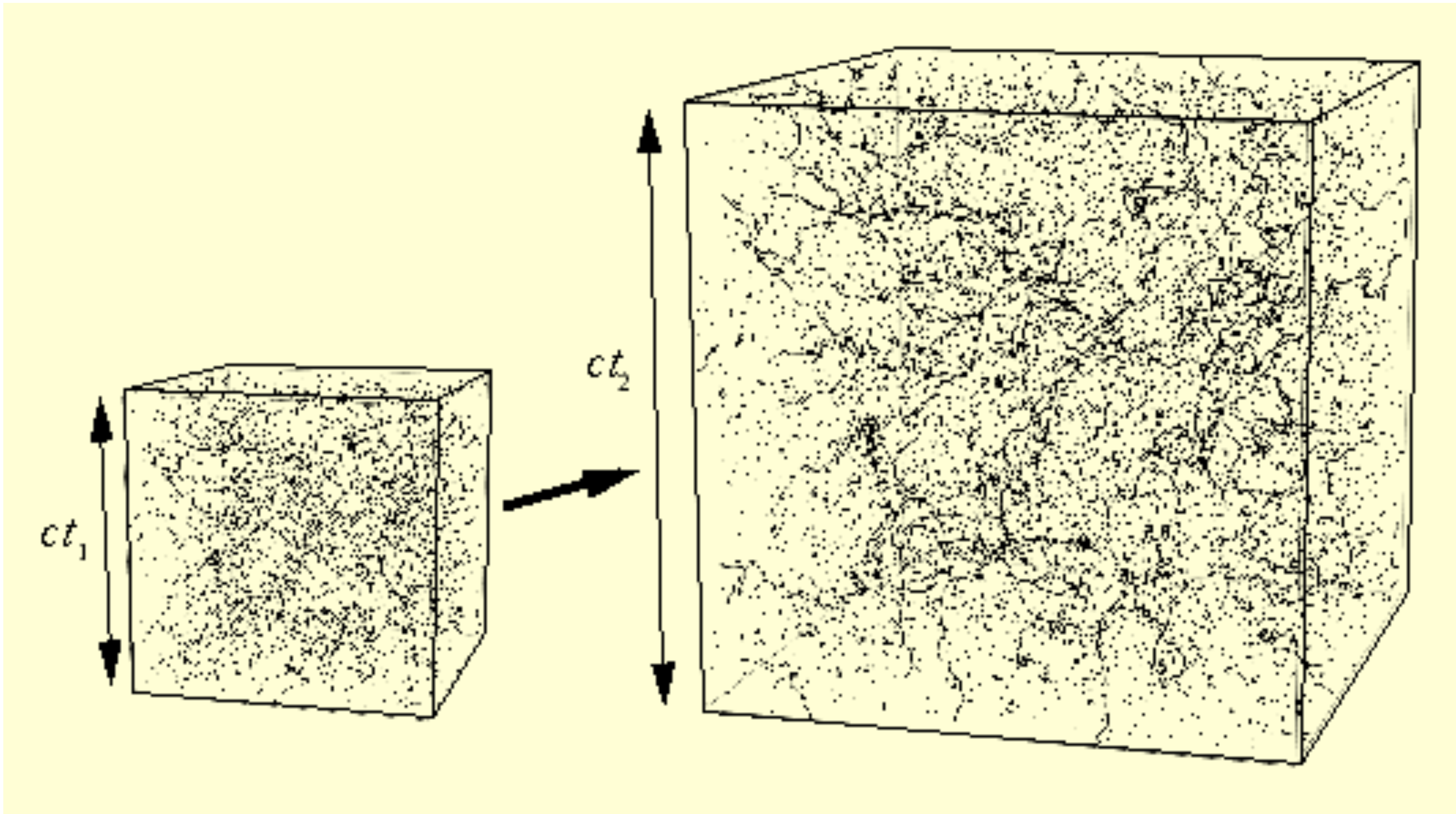

Scaling

dBB Cosmology without inflation? Possible and testable!

- New solutions to old puzzles
- No singularity
- G.R. ...

monopoles = ???

Dark energy ...

Model dependence

New predictions (oscillations, *T/S* ...)

Future

Other models (many fluids, scalar fields, ...)
Non gaussianities
Polarizations

Relaxation?