Title: Inflation after WMAP

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Abstract:

Inflation after WMAP

V. Mukhanov

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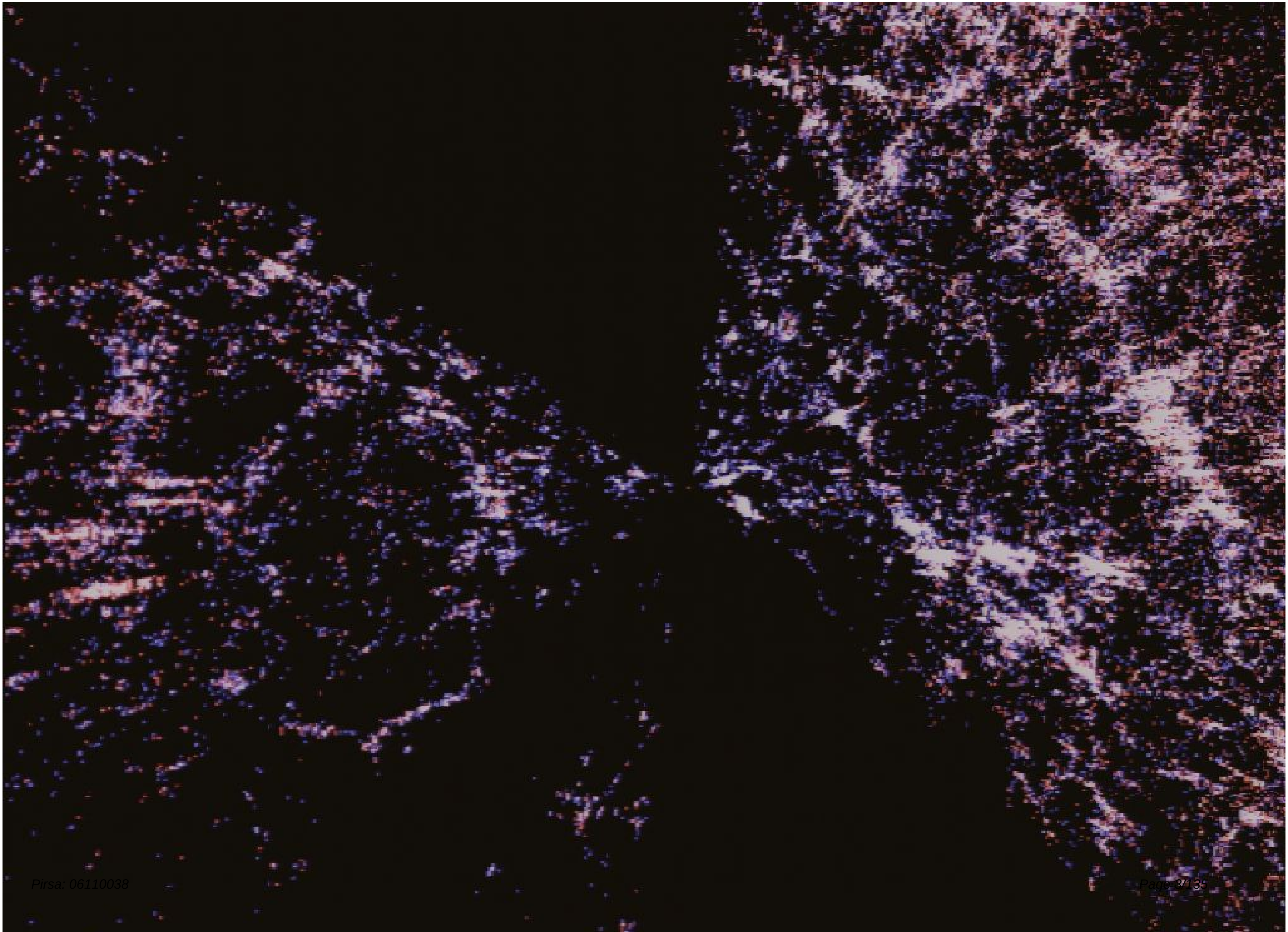
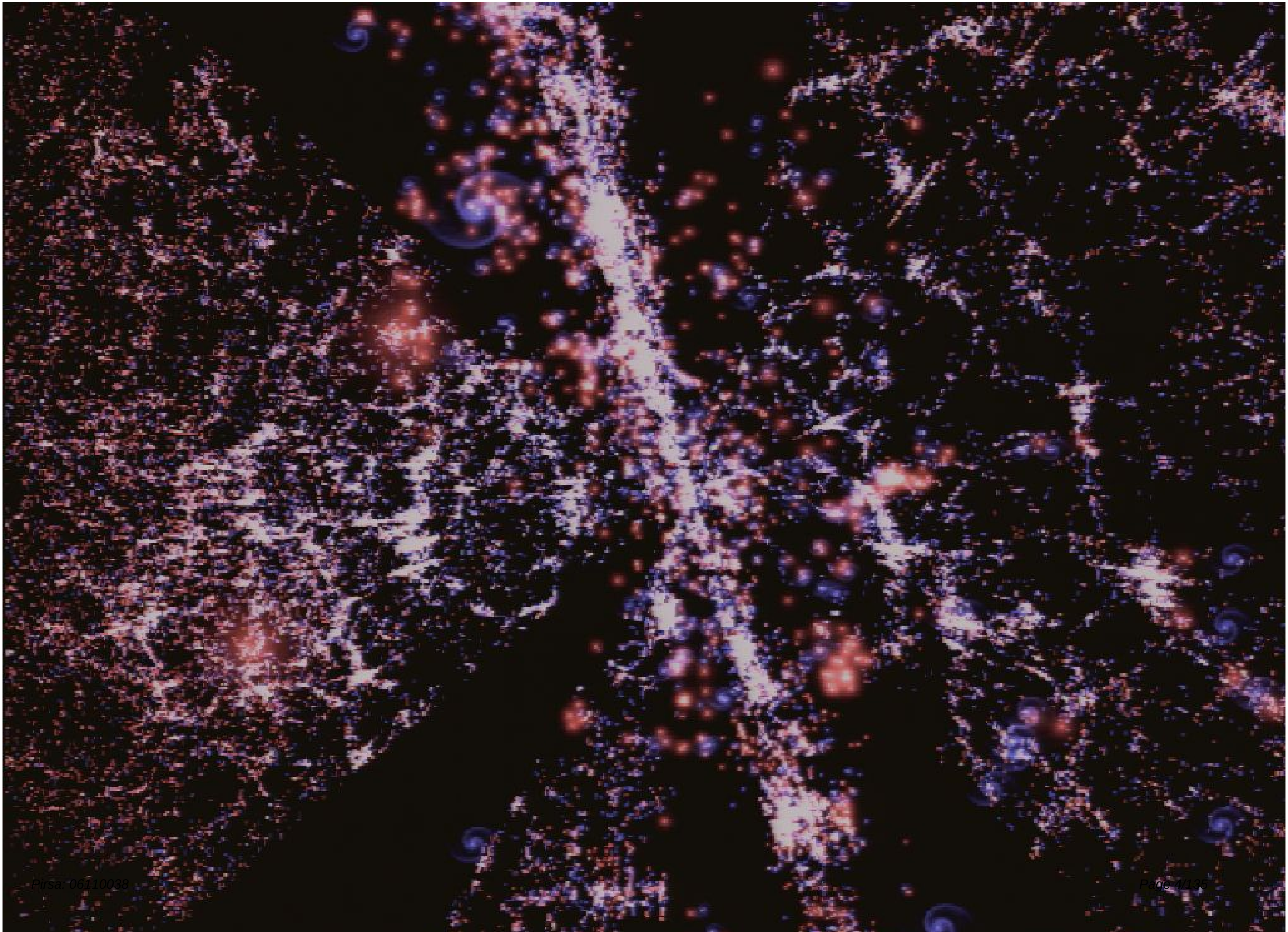
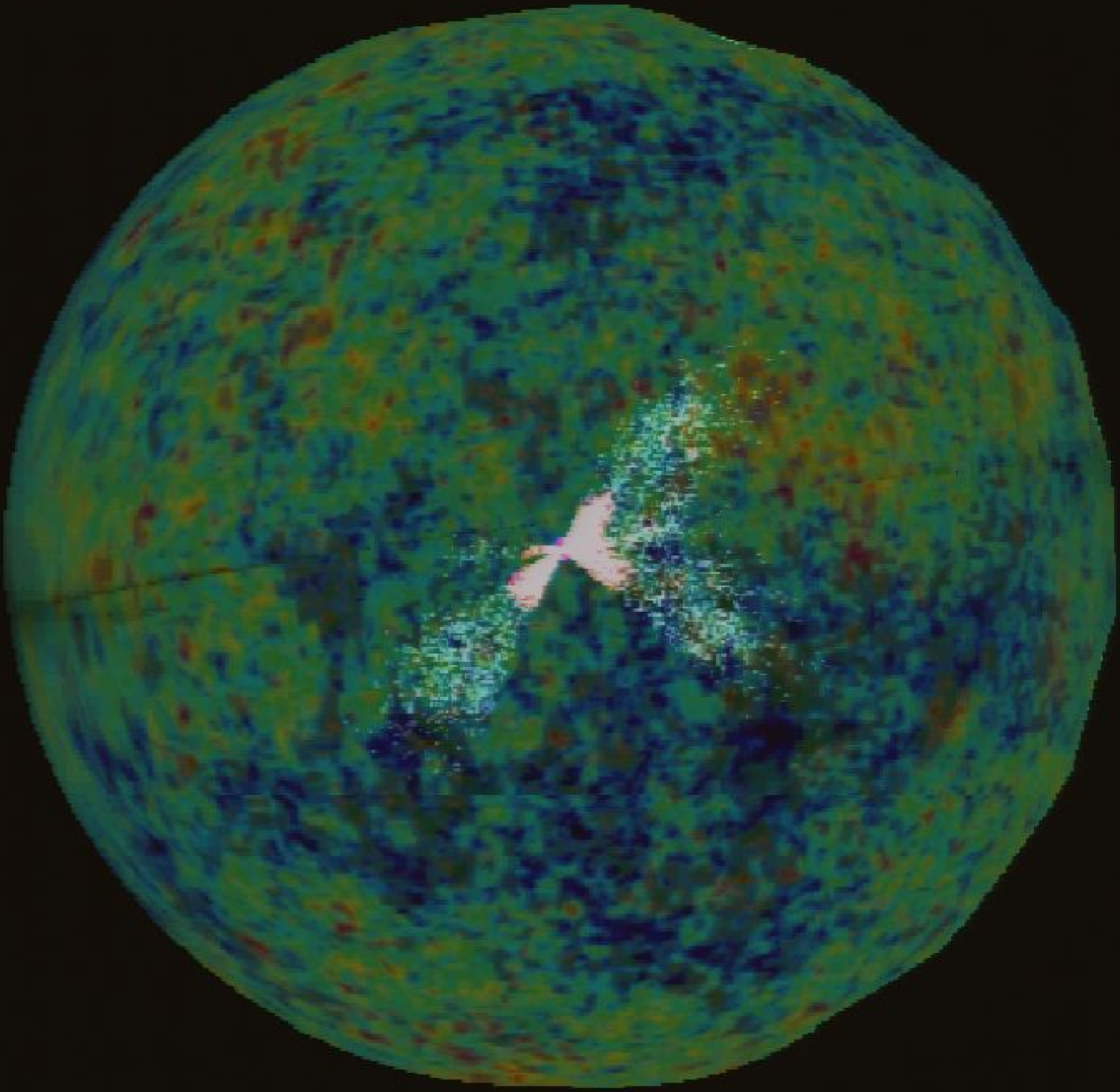


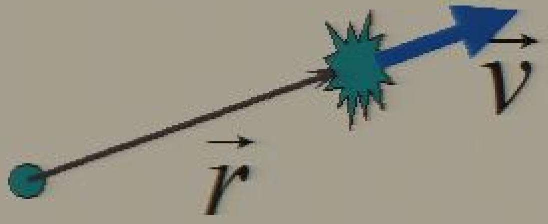




"...our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realize that these numbers and equations we play with at our desks have something to do with the real world..."

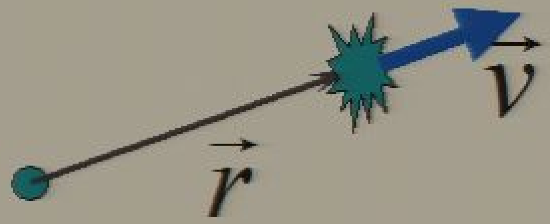
S. Weinberg, "The first three minutes

- Hubble law



- Hubble law

$$\vec{r} = a(t)\vec{\chi}_{com}$$



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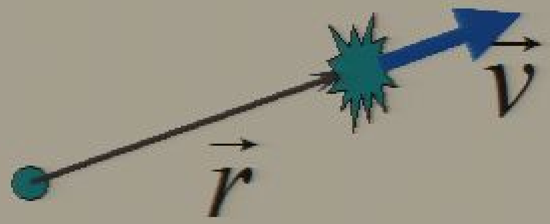

$$\vec{r} = a(t)\vec{\chi}_{com}$$

$$\vec{v} = \dot{a}\vec{\chi}_{com}$$

Matter Distribution

Matter Distribution

Matter Distribution

$t_0 \sim 10^{17}$ sec

Matter Distribution

"Initial" moment of time $t_i = 10^{-43}$ sec

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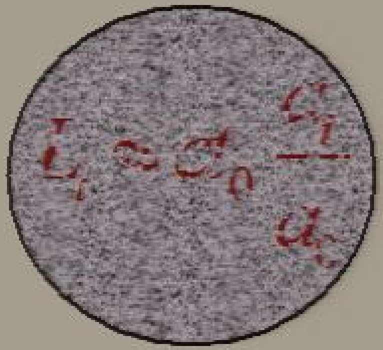

Matter Distribution

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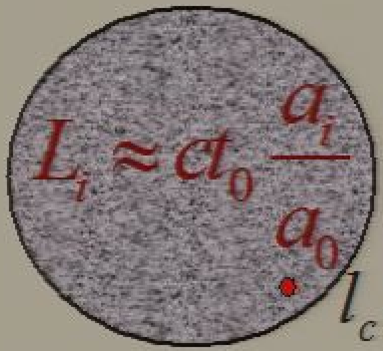

$$L_i \approx ct_0 \frac{a_i}{a_0}$$

$$l_c = ct_i \sim 10^{-33} \text{ cm}$$

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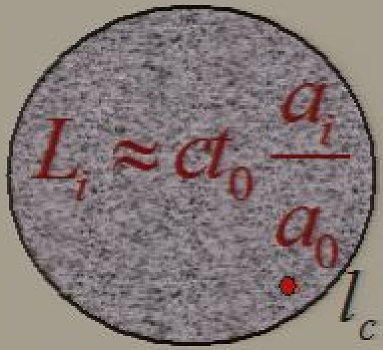

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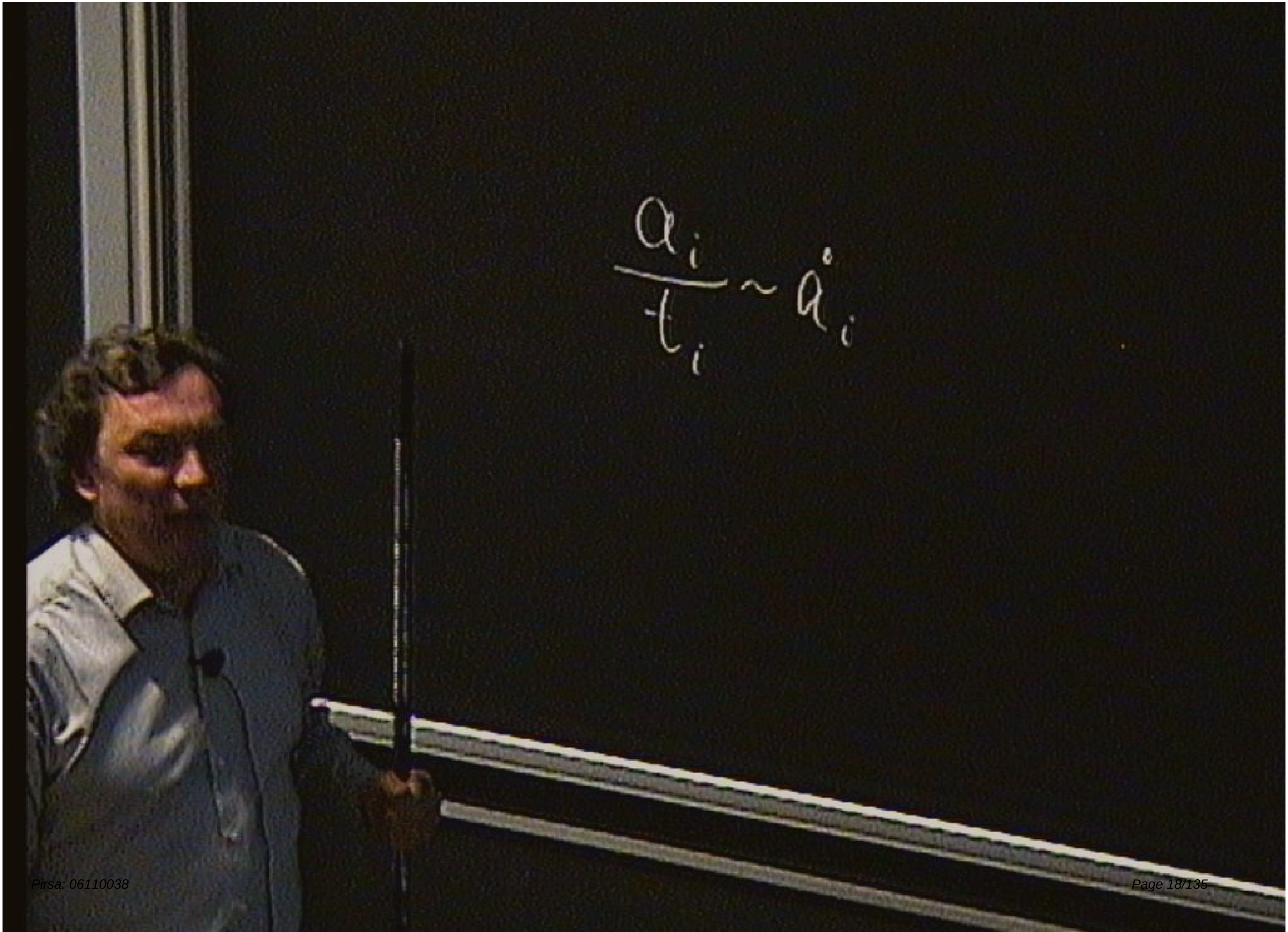
initial rate of expansion

$$\frac{L_i}{ct_i} \approx \frac{\dot{a}_i}{\dot{a}_0}$$

current rate of expansion



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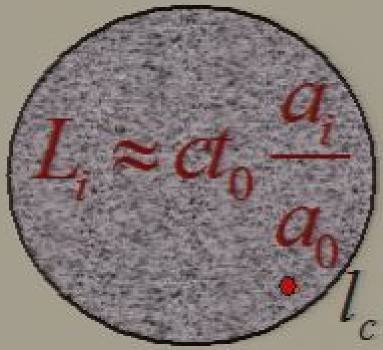

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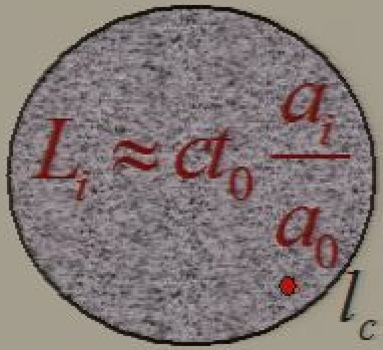

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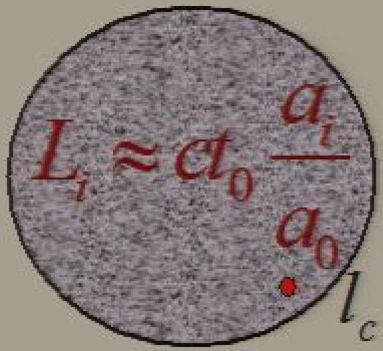

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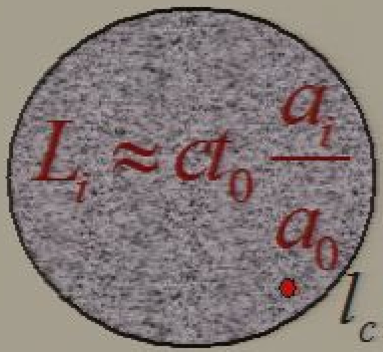

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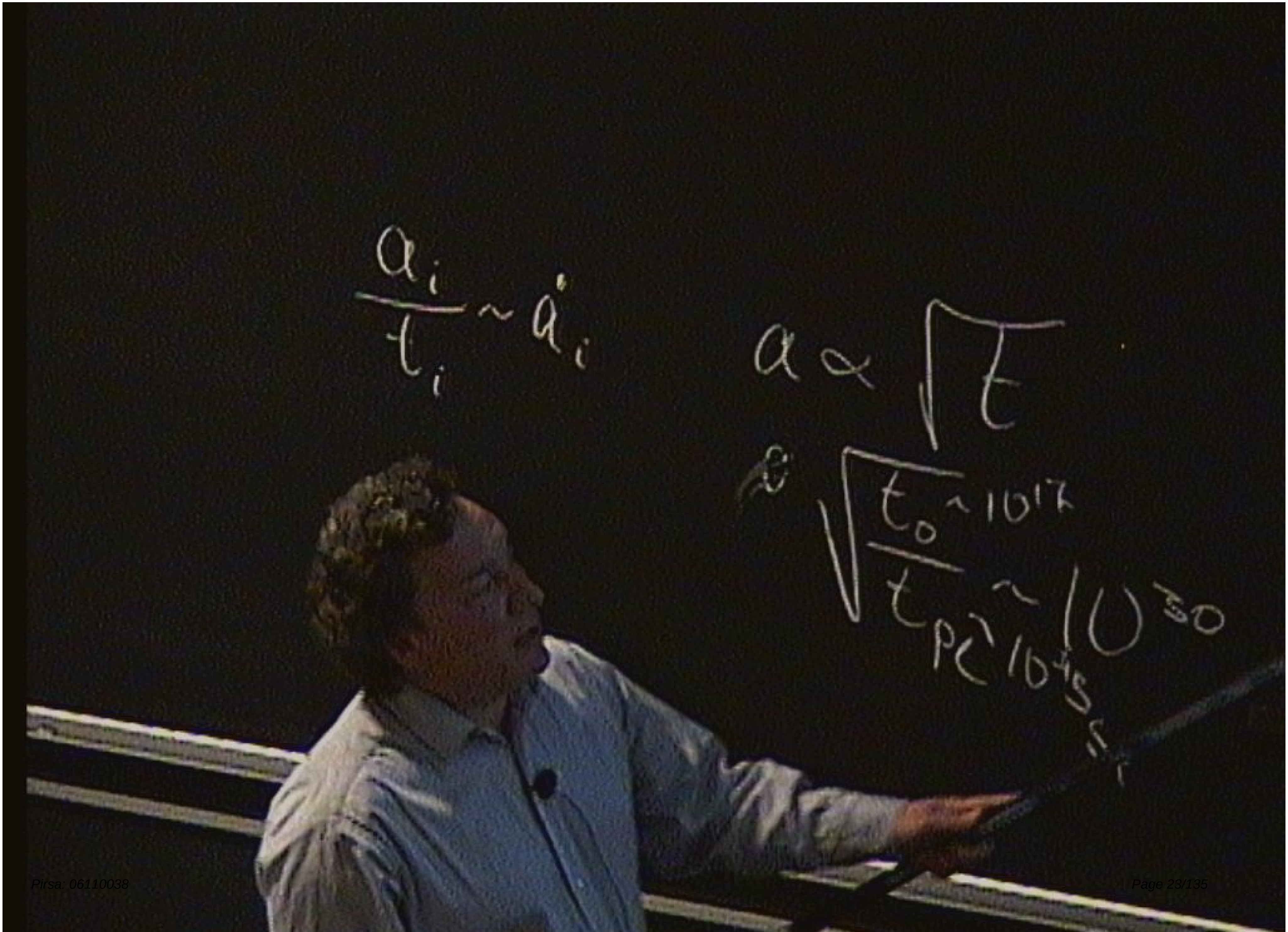

$$\frac{a_i}{t_i} \sim \dot{a}_i$$

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$$\sqrt{\frac{t_0 \sim 10^{17}}{t_{pc} \sim 10^{45}\,s}} \sim 10^{30}$$

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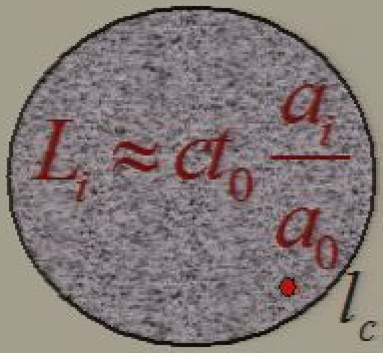

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[illegible]

[illegible]

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- At "initial moment" ($t_i \approx 10^{-43}$ sec)

$$\frac{\left|E_i^{kin} + E_i^{pot}\right|}{E_i^{kin}} \leq \ldots \left(\frac{\dot{a}_0}{\dot{a}_i}\right)^2 \leq \ldots 10^{-60}$$

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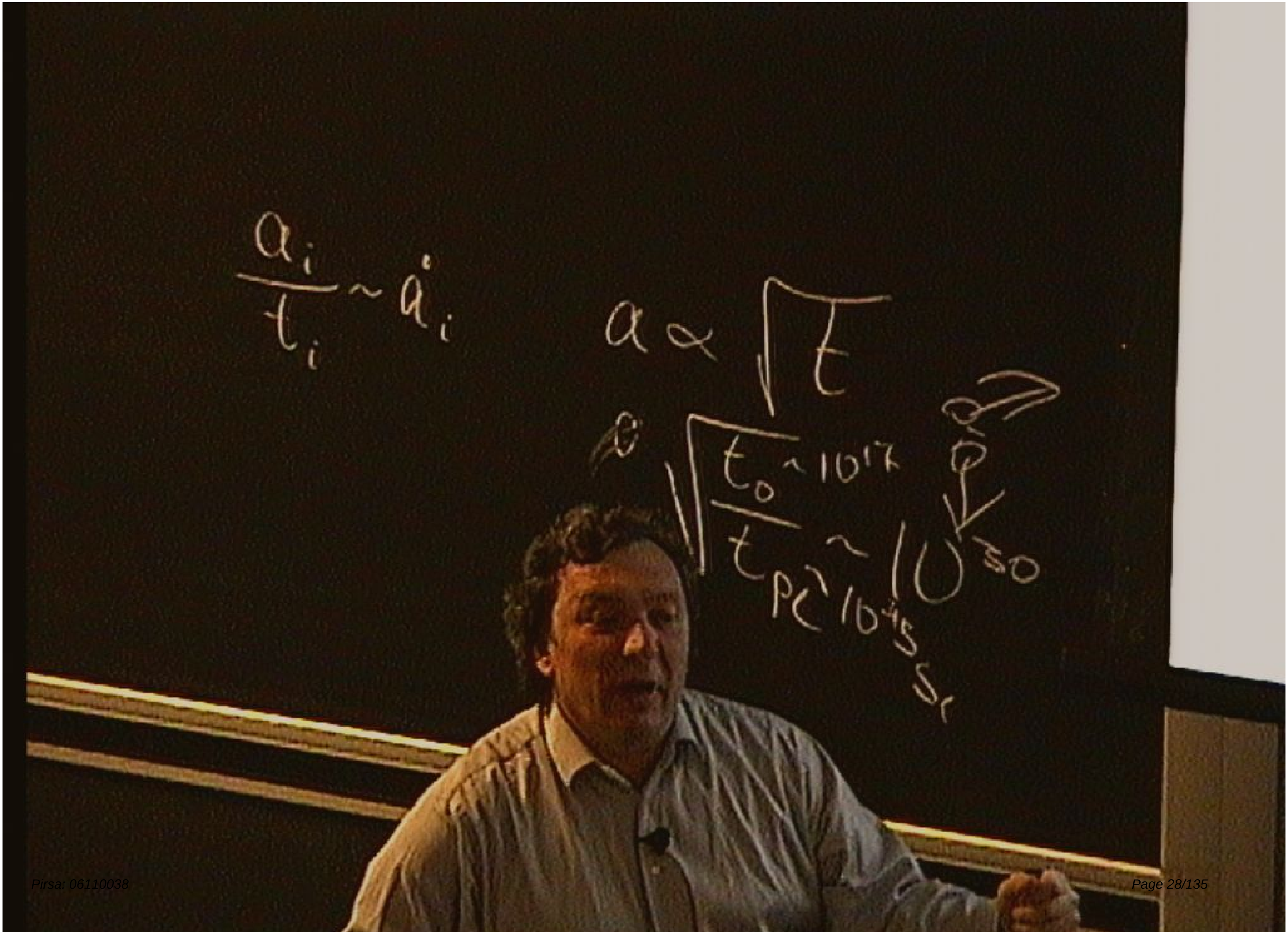
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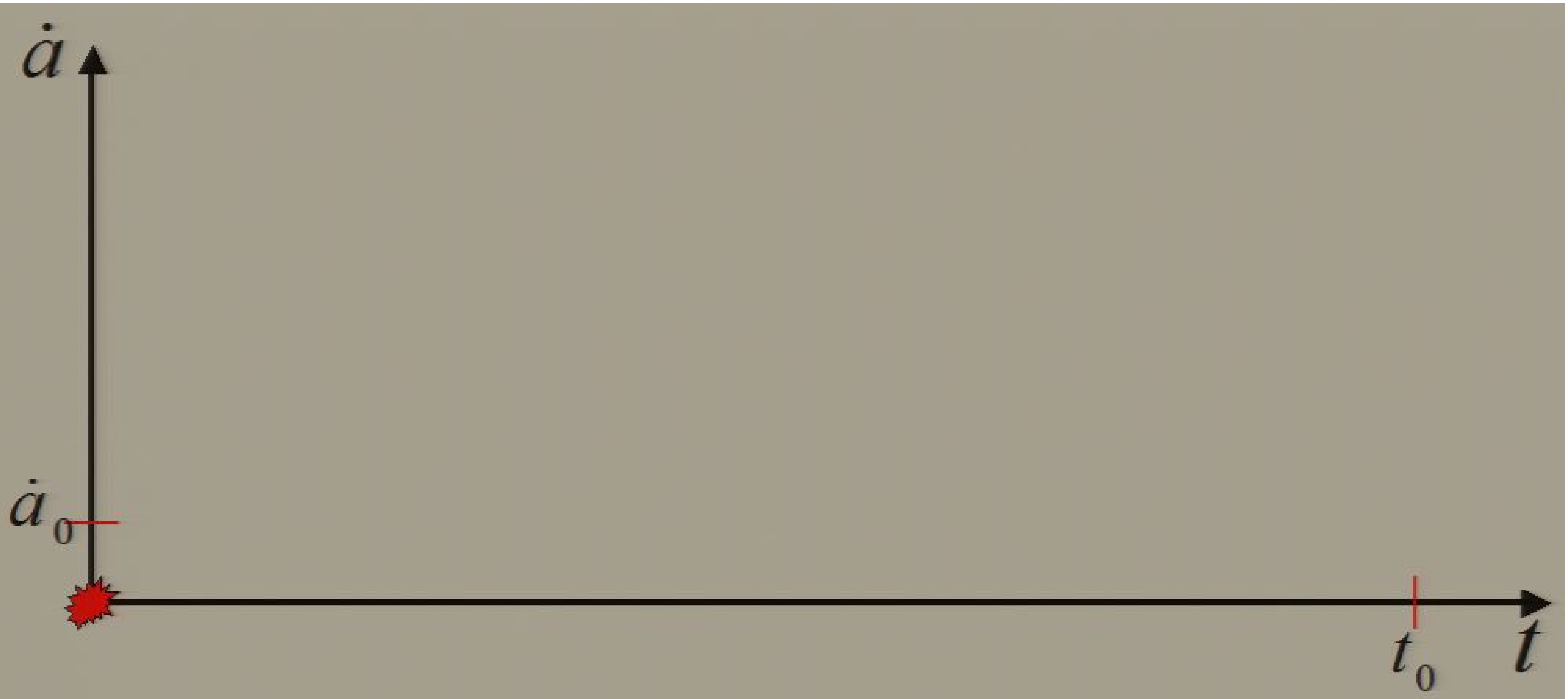
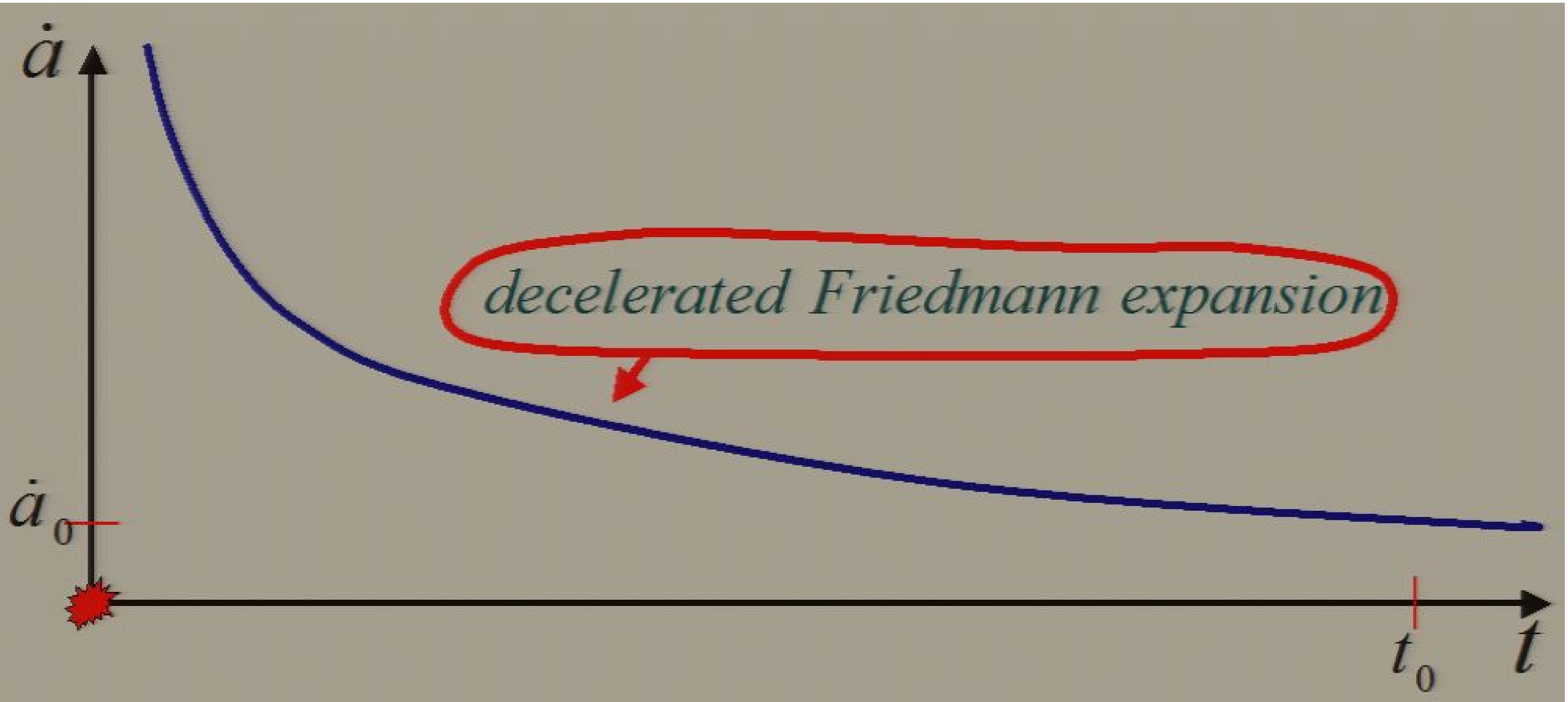
Flatness ($\equiv$ initial velocities) problem

Initial conditions were VERY SPECIAL (nongeneric)!


$\dot{a}$
$\dot{a}_0$
t_0
t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decelerated Friedmann expansion
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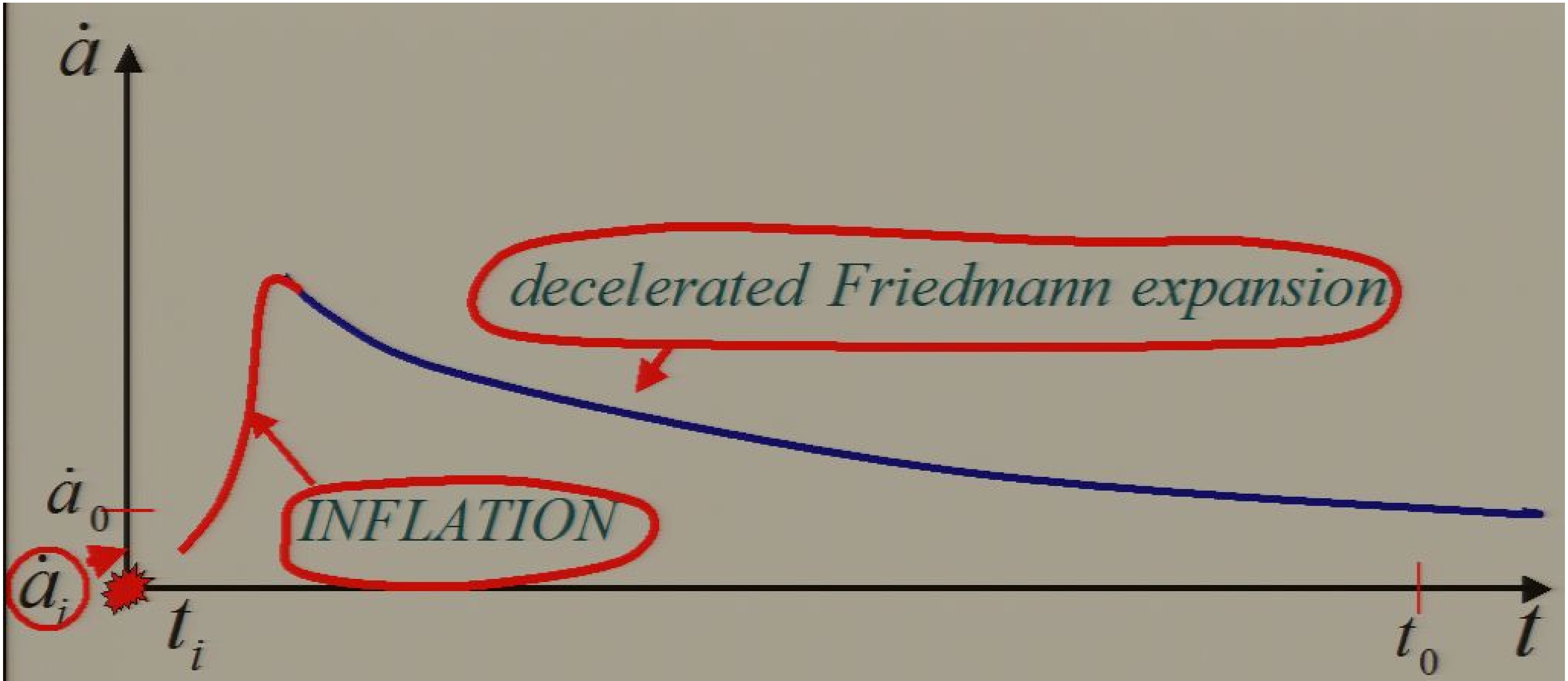
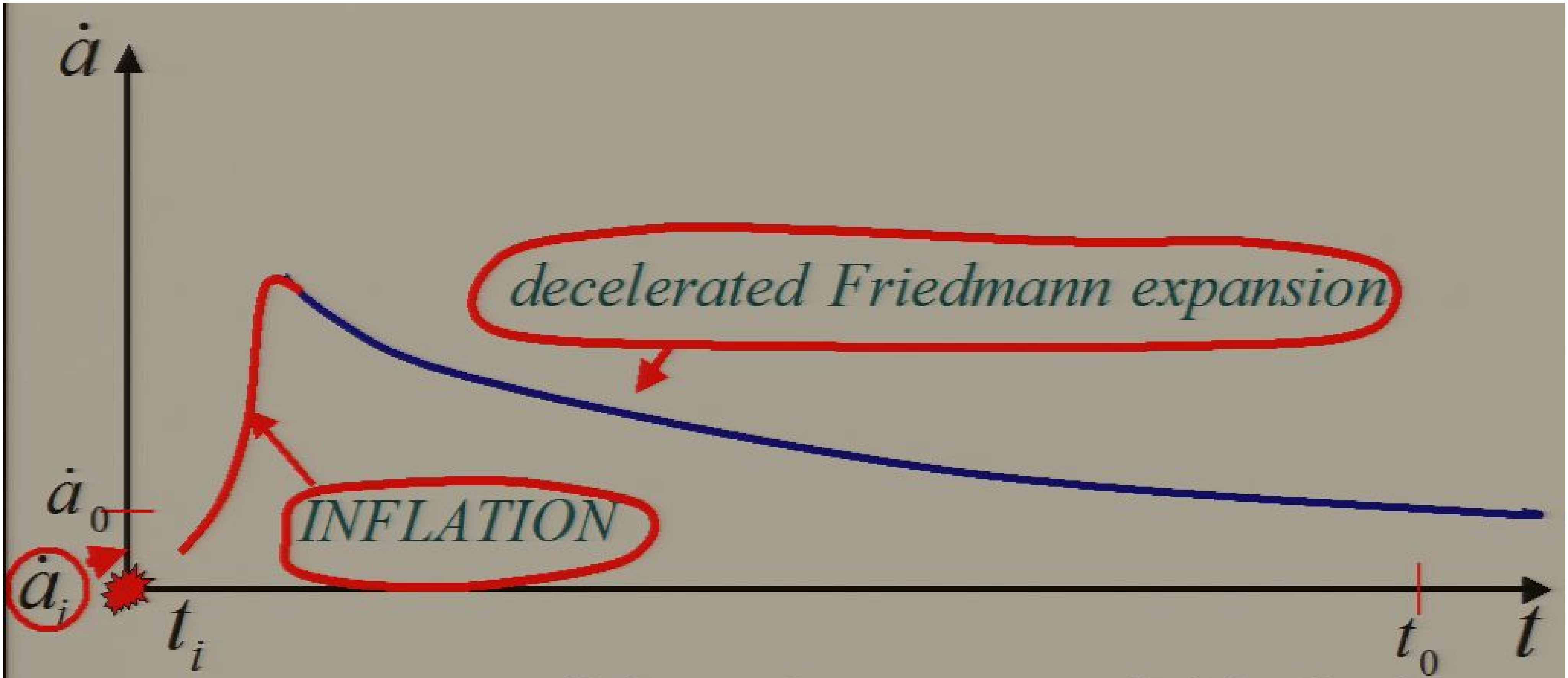
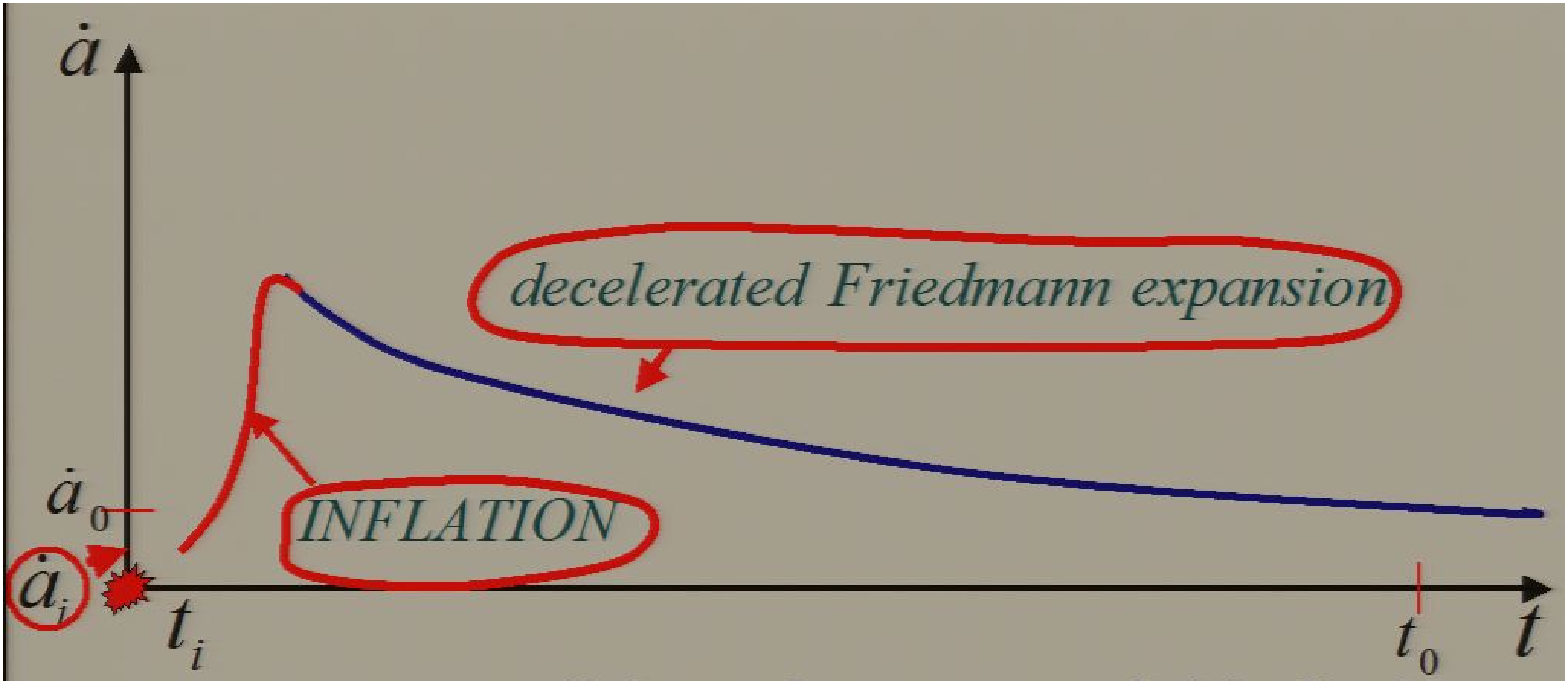

$\dot{a}$
decelerated Friedmann expansion
$\dot{a}_0$
INFLATION
$\dot{a}_i$
t_i
t_0
t



Necessary conditions for successful inflation:



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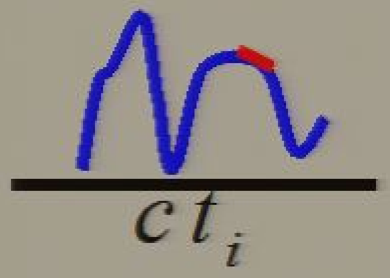
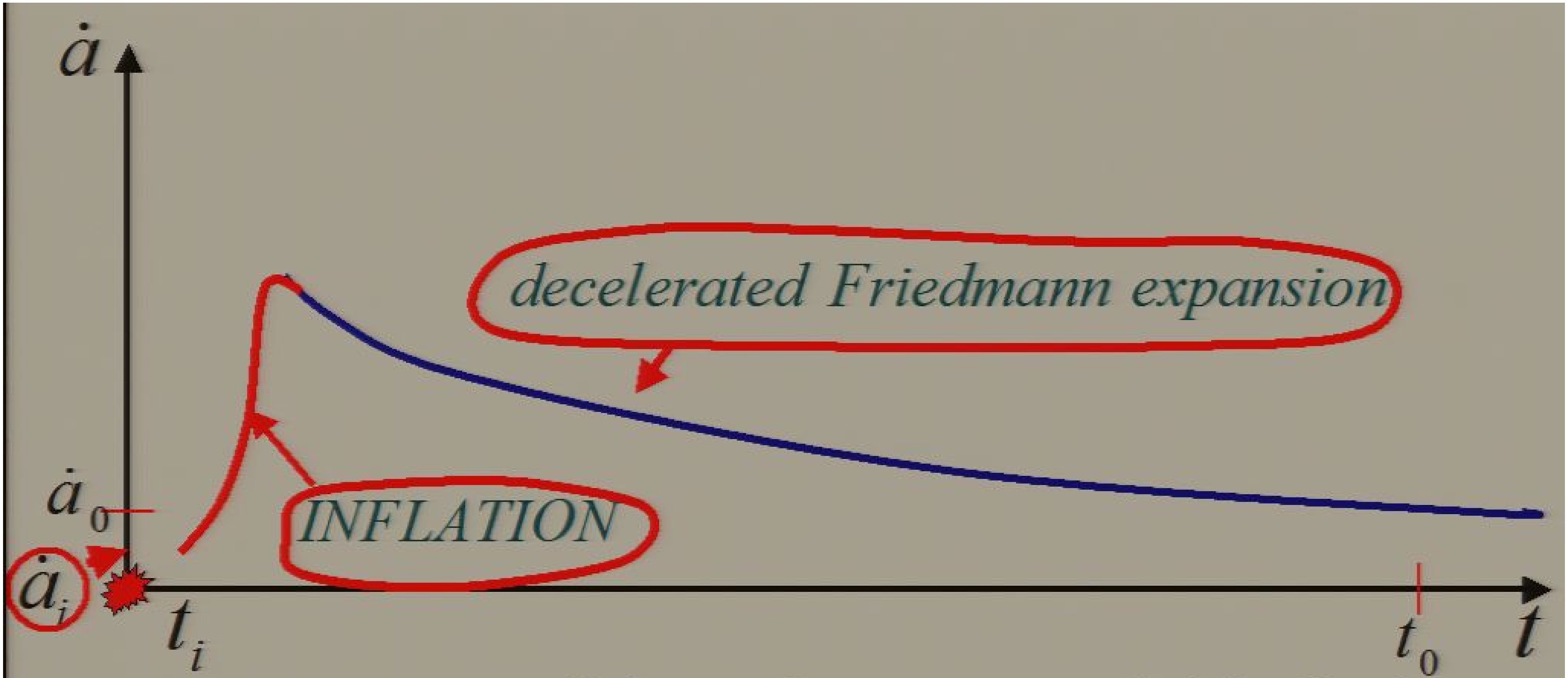
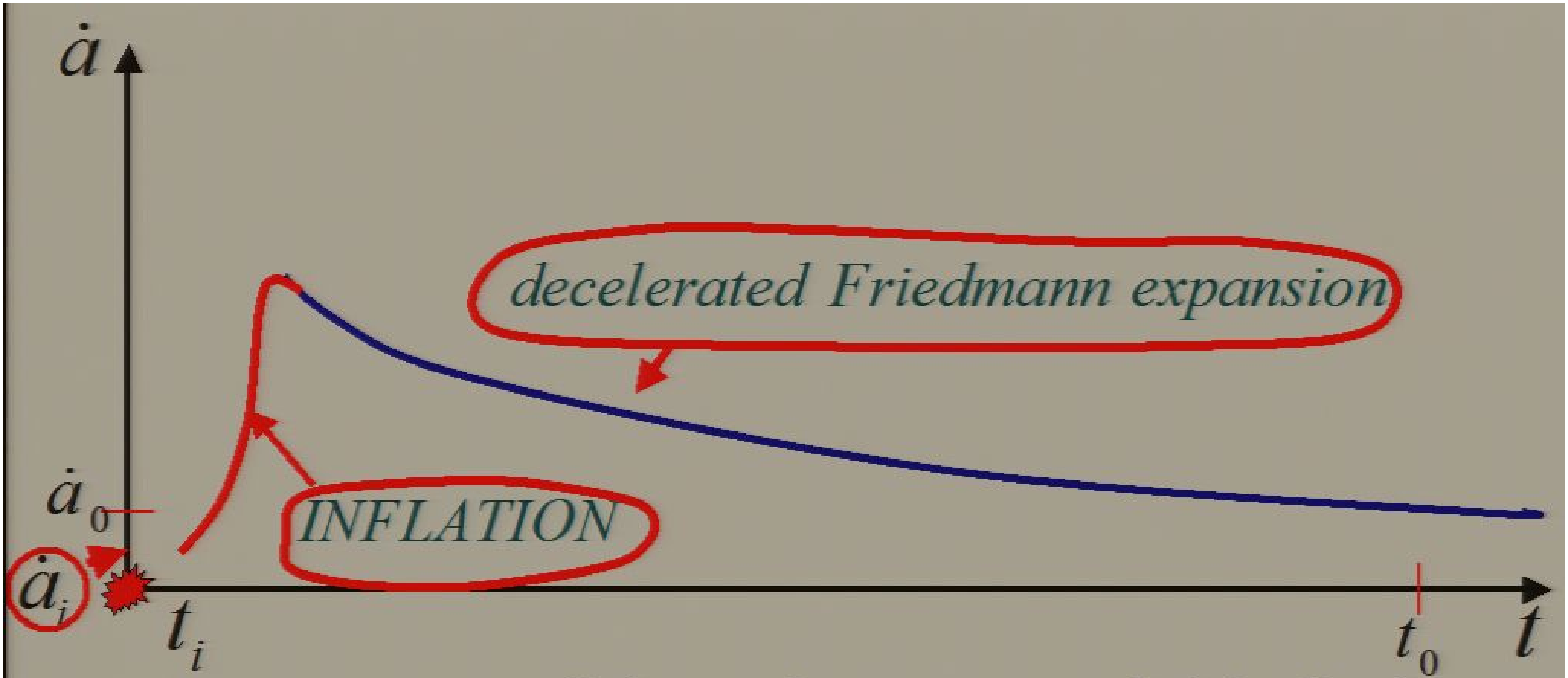
- 



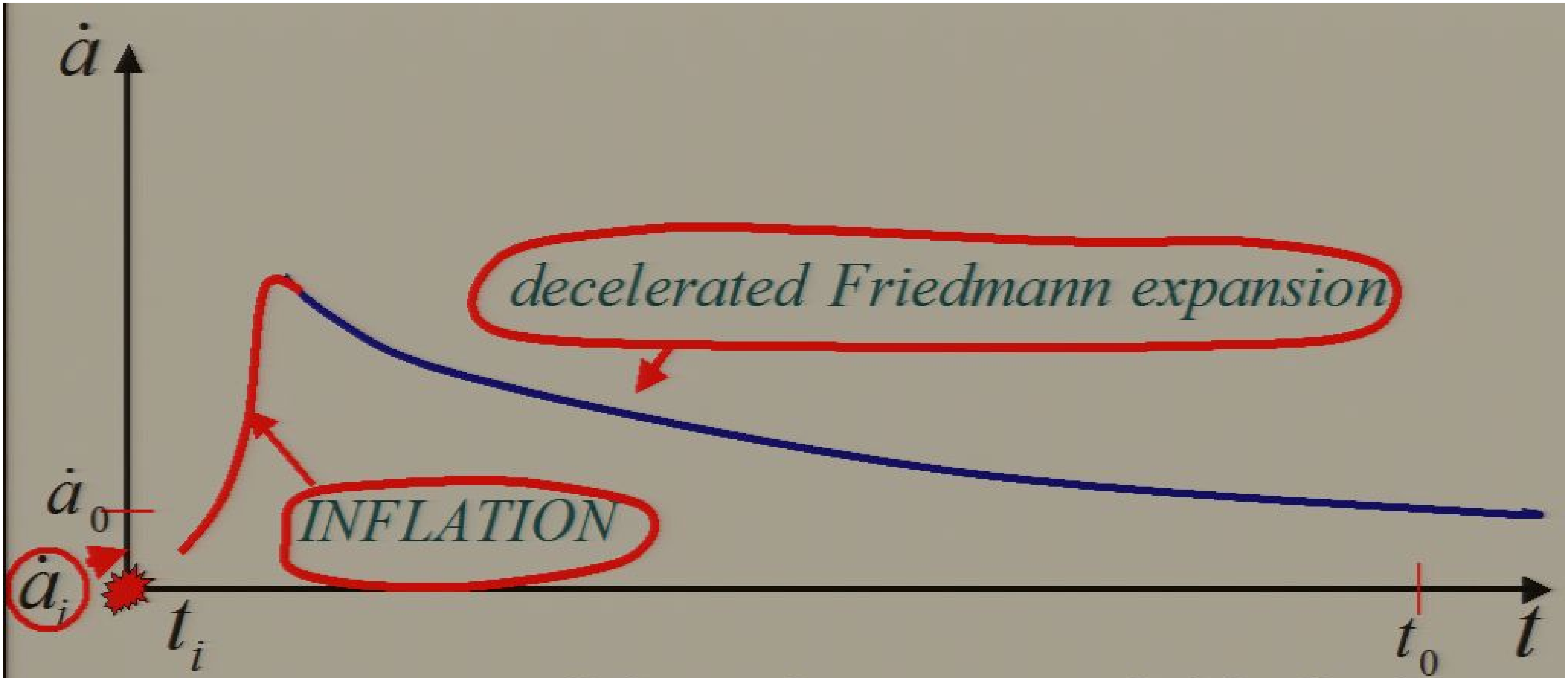
Necessary conditions for successful inflation:

- ${}_i$



Necessary conditions for successful inflation:

- $\dot{a}_i <$



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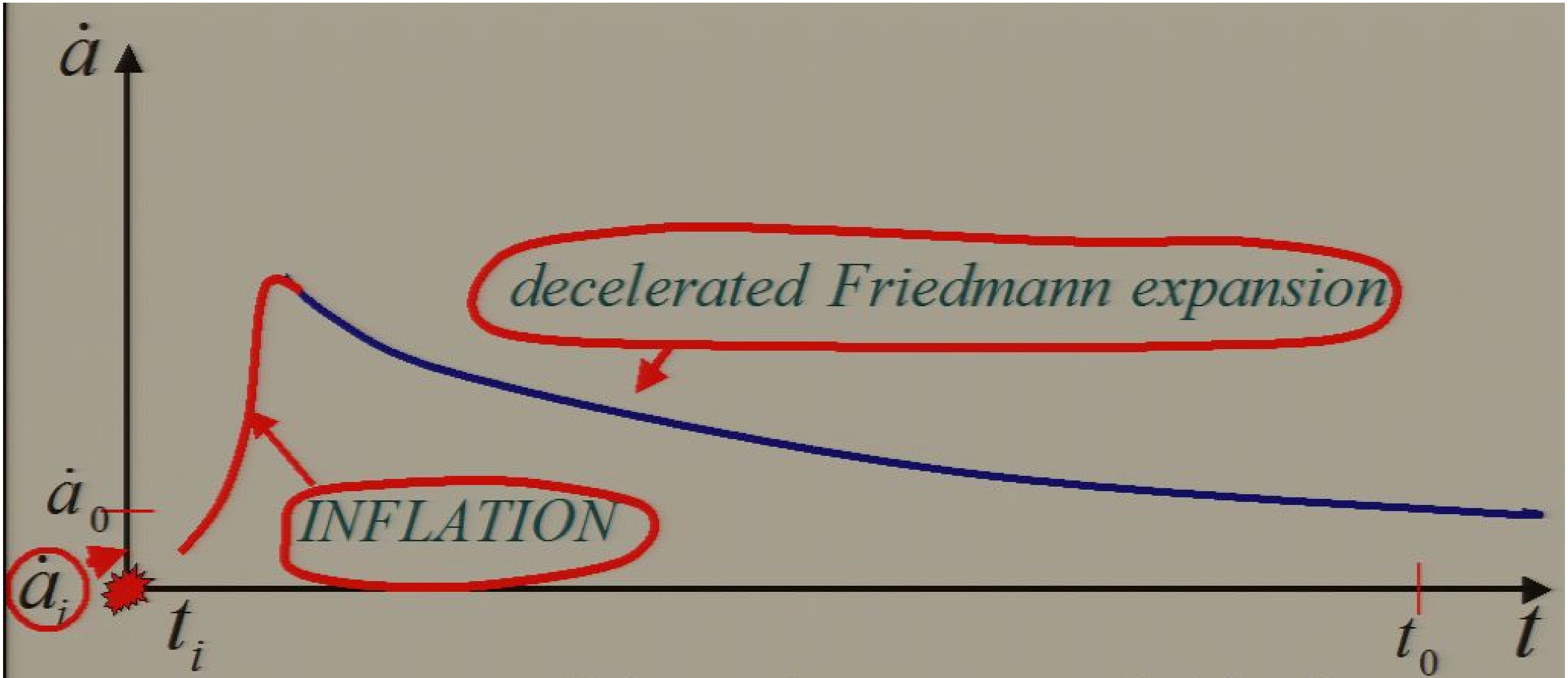

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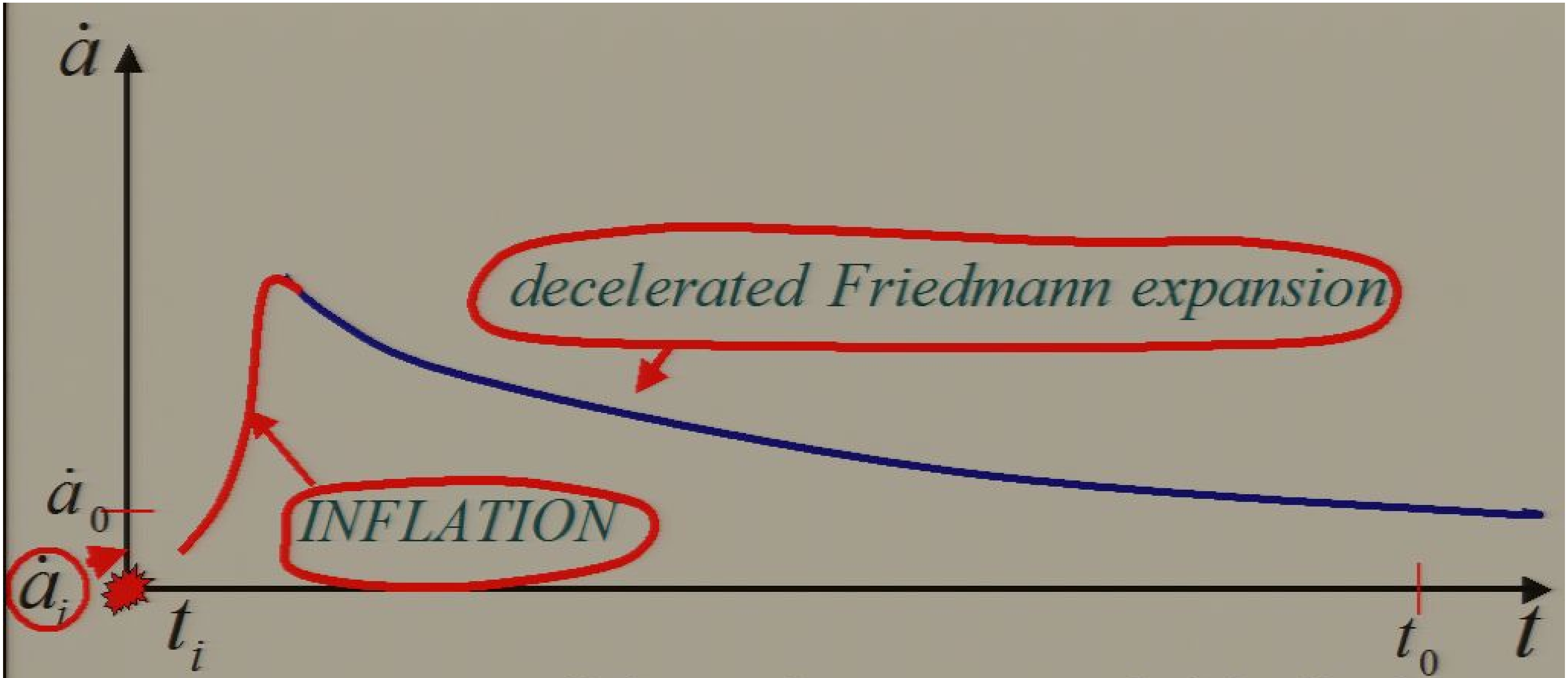
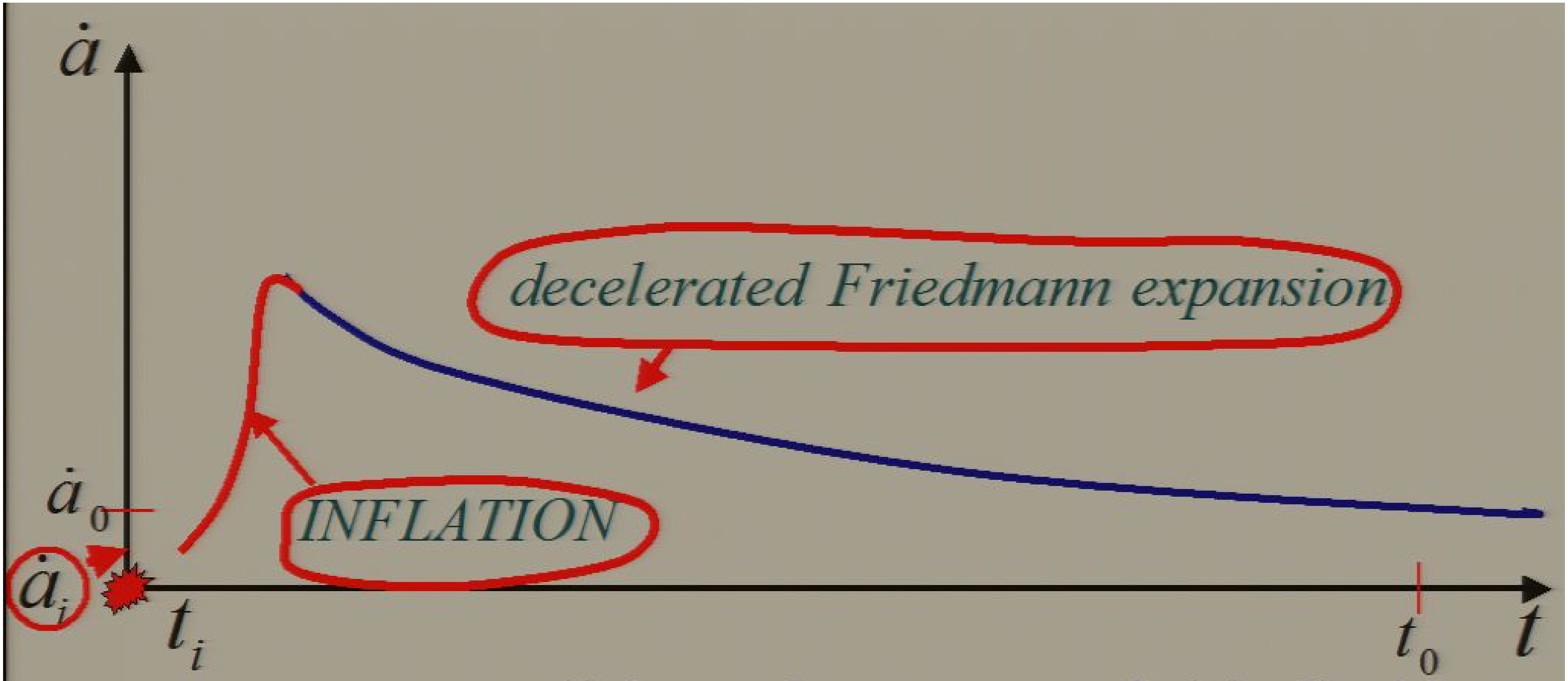
- $\dot{a}_i << \dot{a}_0 \Longrightarrow \Omega_0 \equiv \frac{\left|E_0^{pot}\right|}{E_0^{kin}}$



Necessary conditions for successful inflation:

- $\dot a_i << \dot a_0$ $\Rightarrow$ $\Omega_0 \equiv \frac{\left|E_0^{pot}\right|}{E_0^{kin}} = 1 + O(1)\left(\frac{\dot a_i}{\dot a_0}\right)^2$



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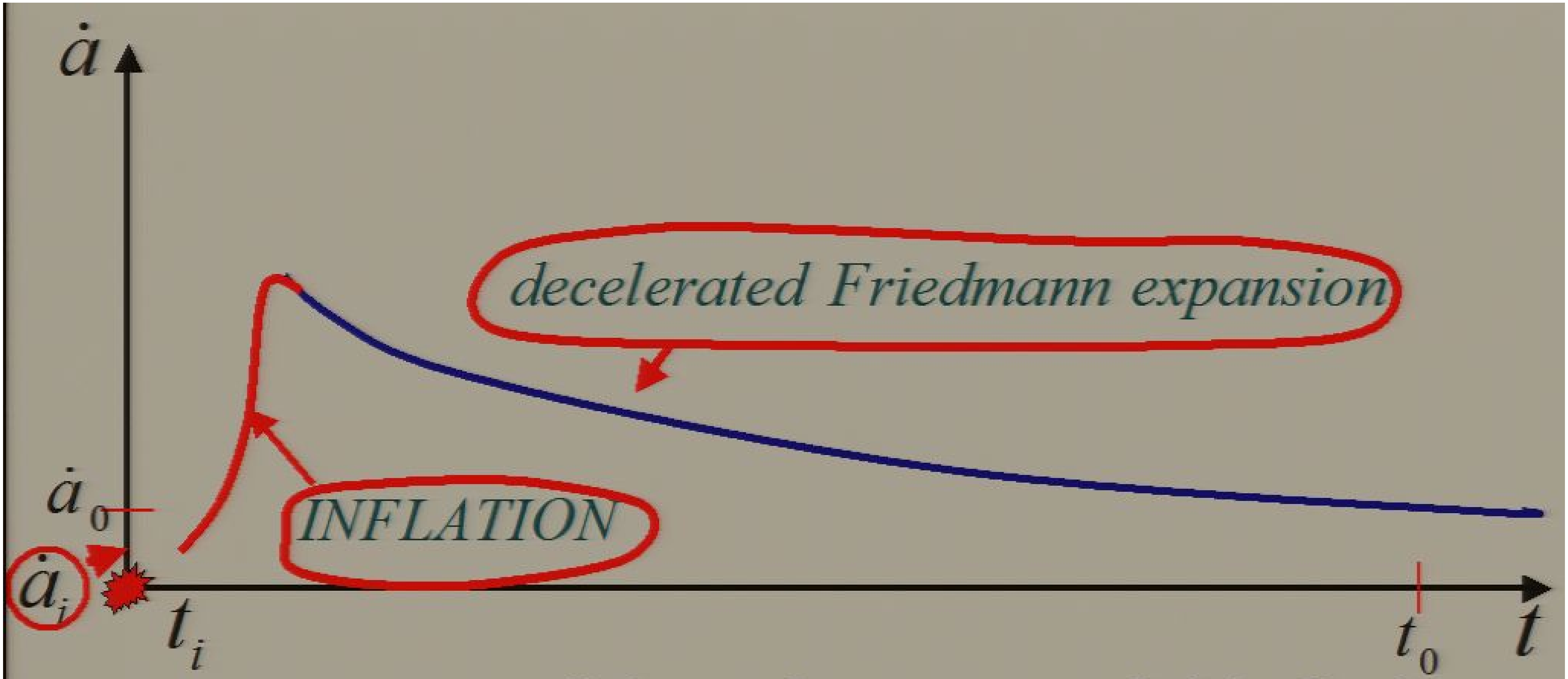
- $\dot{a}_i << \dot{a}_0 \Rightarrow \Omega_0 \equiv \frac{\left|E_0^{pot}\right|}{E_0^{kin}} = 1$



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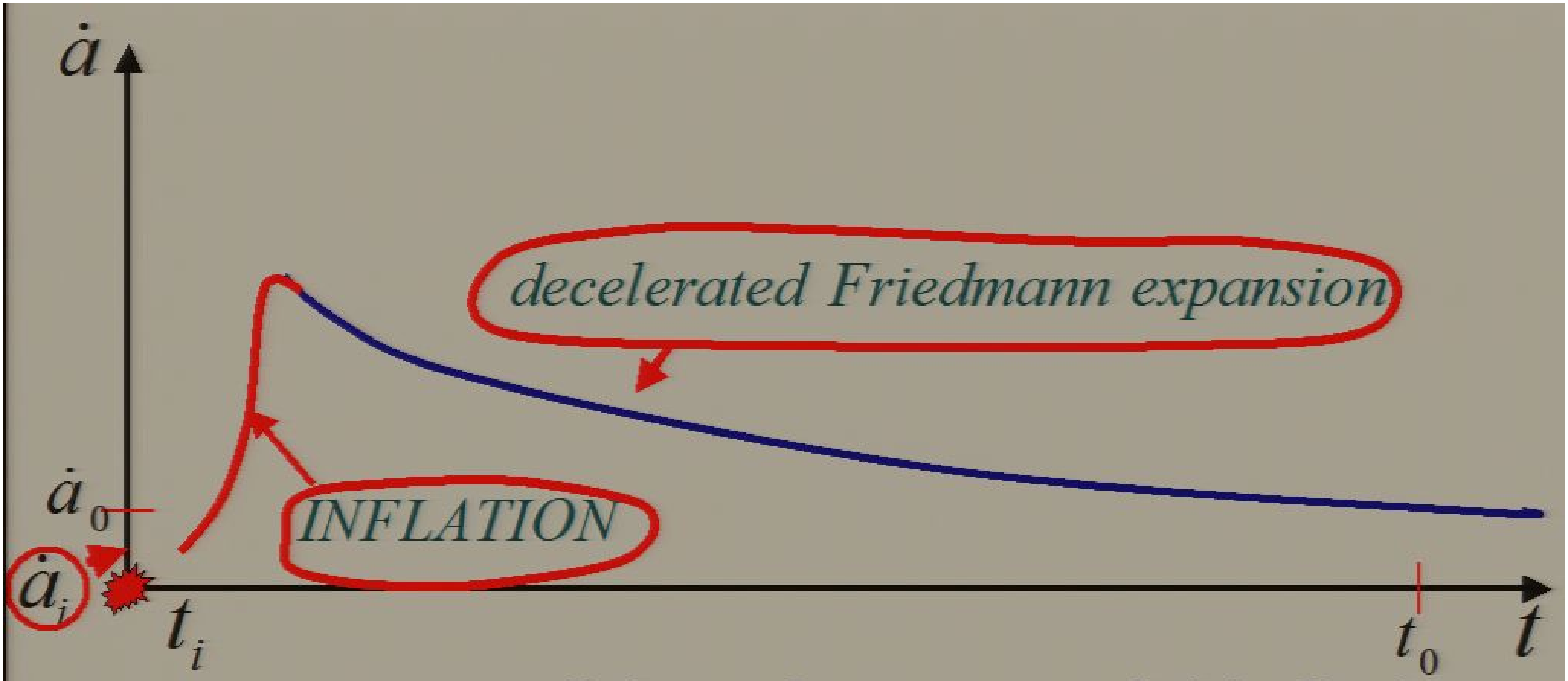

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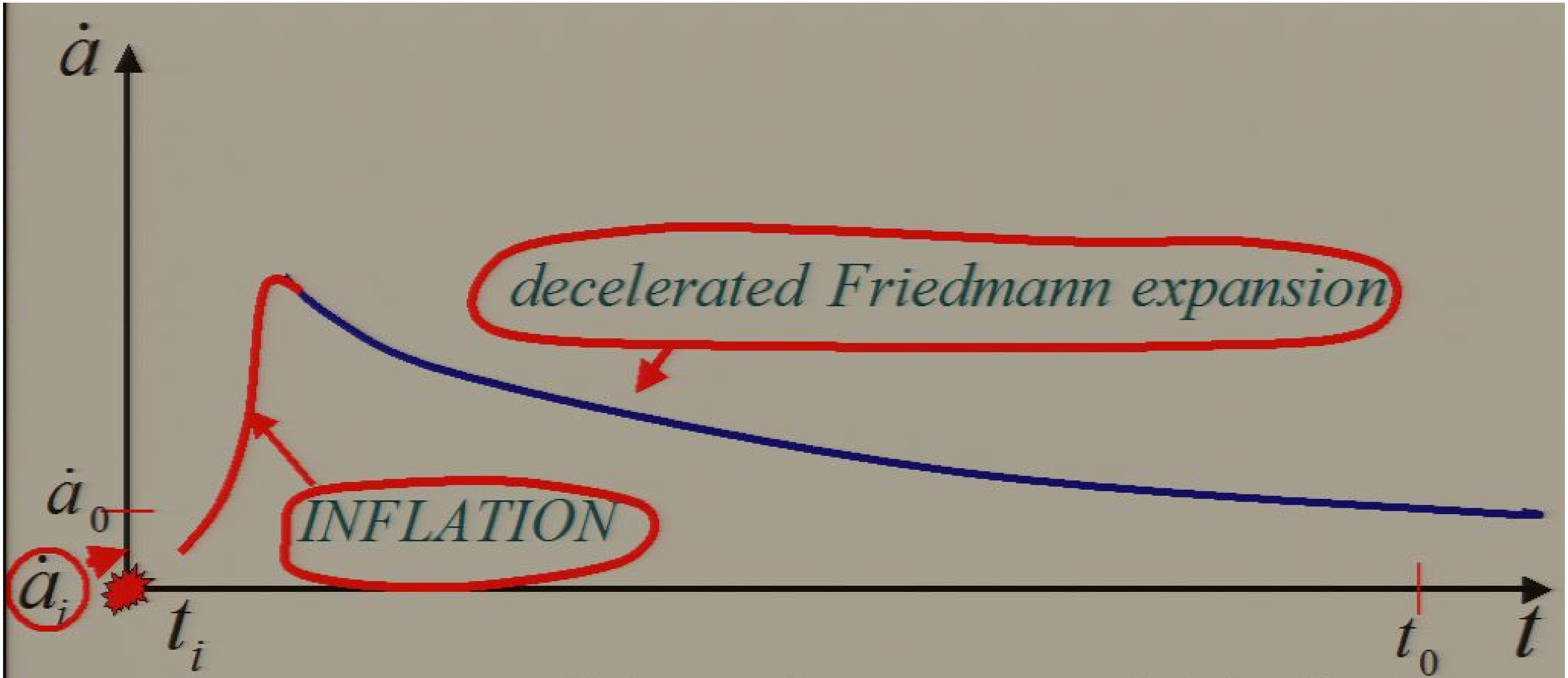
Prediction
of inflation!



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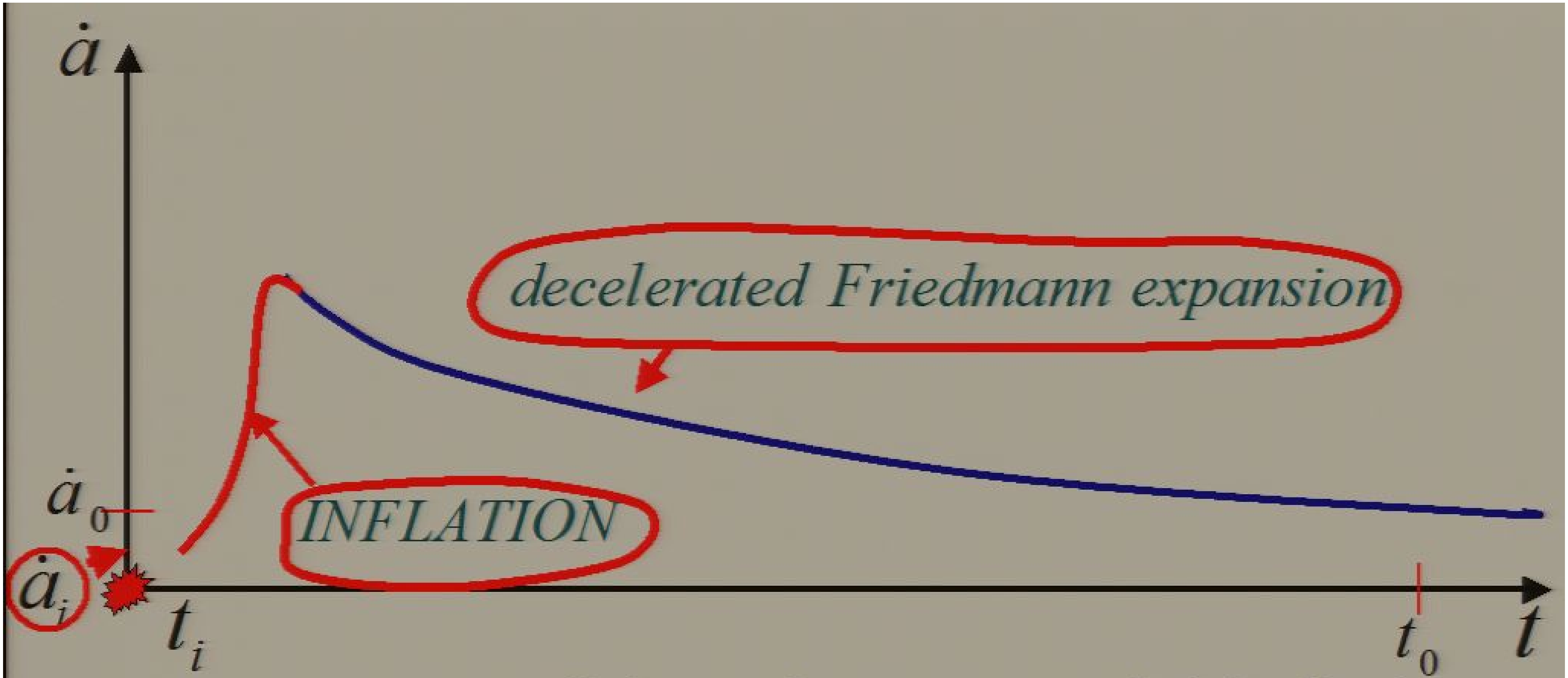

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- Transition from inflation to Friedmann era should be "smoot

- How gravity can become "repulsive"?

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$$\ddot{a} = -\frac{4\pi G}{3}\varepsilon a$$

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acceleration

energy density

pressure

Only if $\varepsilon + 3p < 0 \Rightarrow \ddot{a} > 0 \equiv$ "antigravity"

Scenarios

Scenarios

???

Scenarios

??

Energy density ε, pressure p

Scenarios

???

Energy density ε, pressure p

$p(\varepsilon)-$ equation of state

Scenarios

???

Energy density ε, pressure p

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$p+\varepsilon \ll \varepsilon$ for inflation

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Energy density ε, pressure p

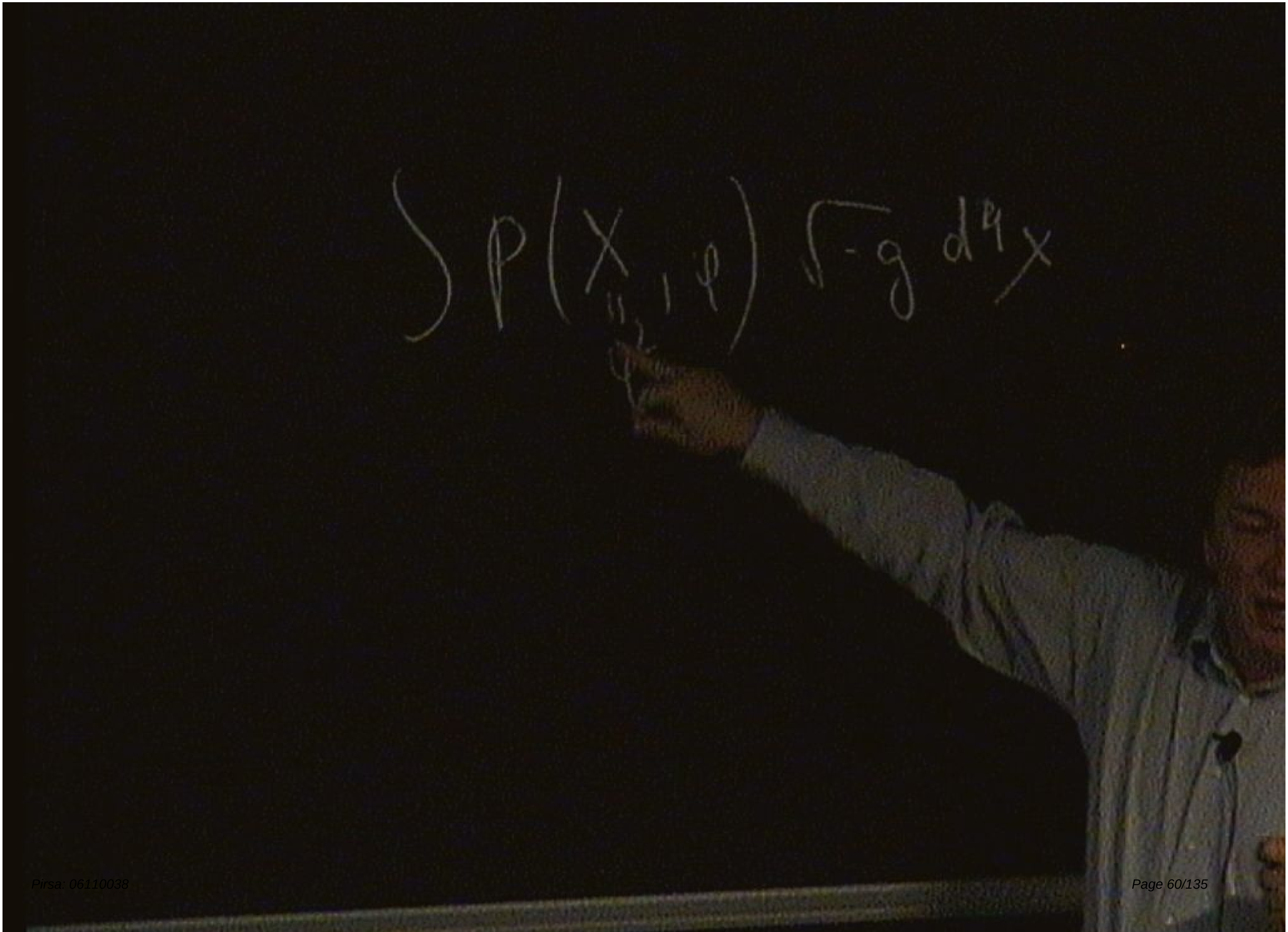
$p(\varepsilon) -$ equation of state

$p + \varepsilon \ll \varepsilon$ for inflation

⬇

$$p \approx -\varepsilon$$

Which concrete scenario was realized ???



$$\int p(X_{\mu}, \ell) \sqrt{-g}\, d^4x$$

$$\int p(\underset{\overset{\shortparallel}{\dot{\varphi}^2}}{X}, \varphi)\sqrt{-g}\, d^4x$$

$$\varepsilon = 2X p_{,X}$$

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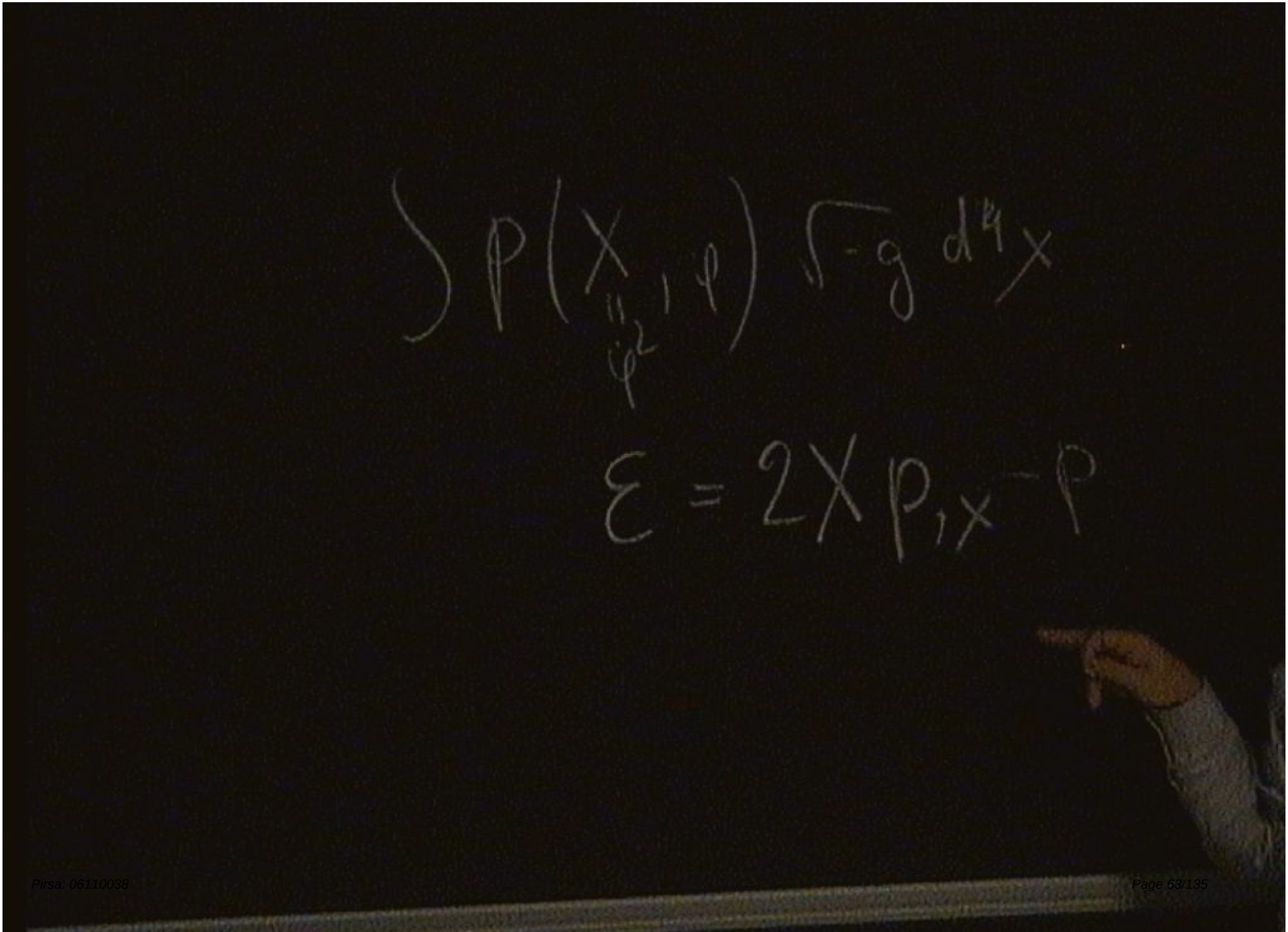

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$$\int p(\underset{\overset{\|}{\dot{\varphi}^2}}{X}, \varphi)\sqrt{-g}\, d^4x$$

$$\swarrow \quad \dot{\varphi} \quad \Downarrow$$

$$\mathcal{E} = 2Xp_{,X} - p$$

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Can quantum fluctuations be amplified up to "needed" value 10^{-5} in expandng Universe???

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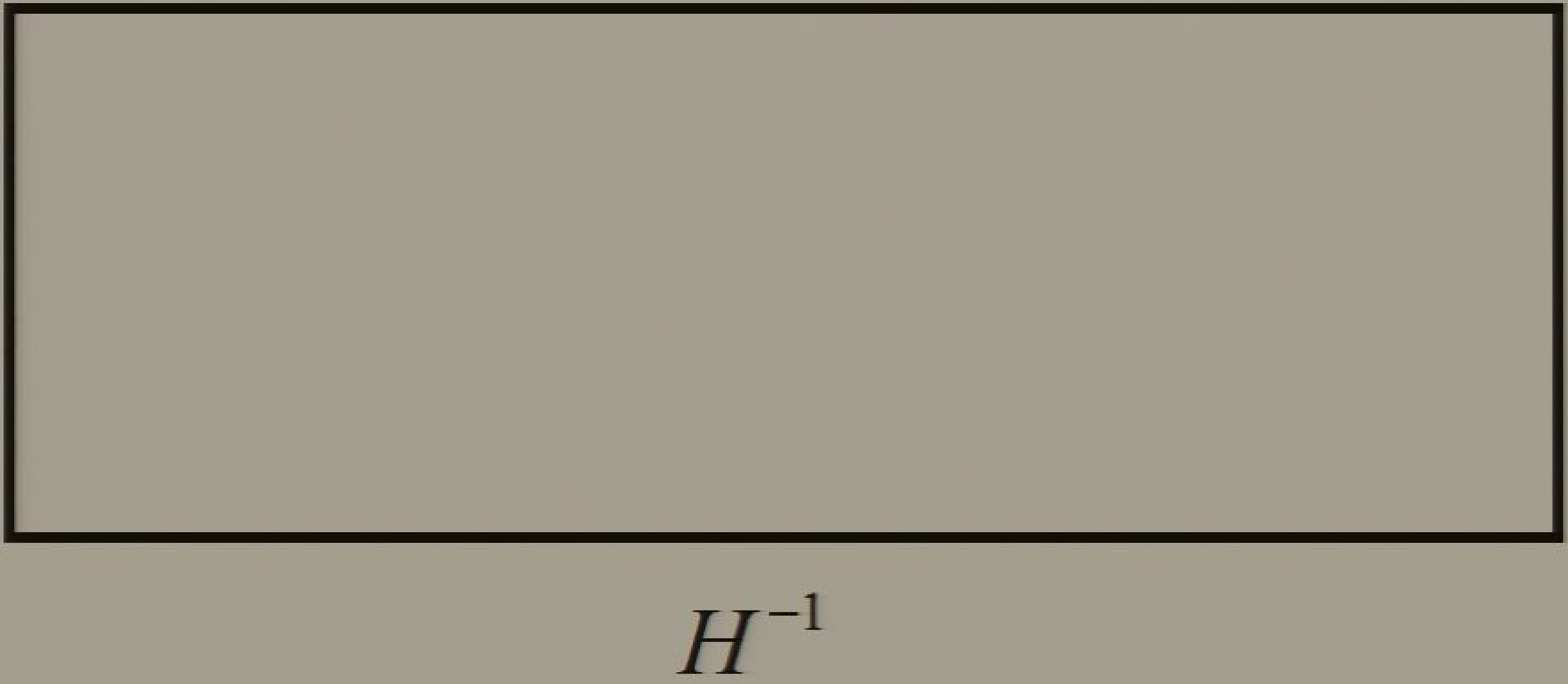
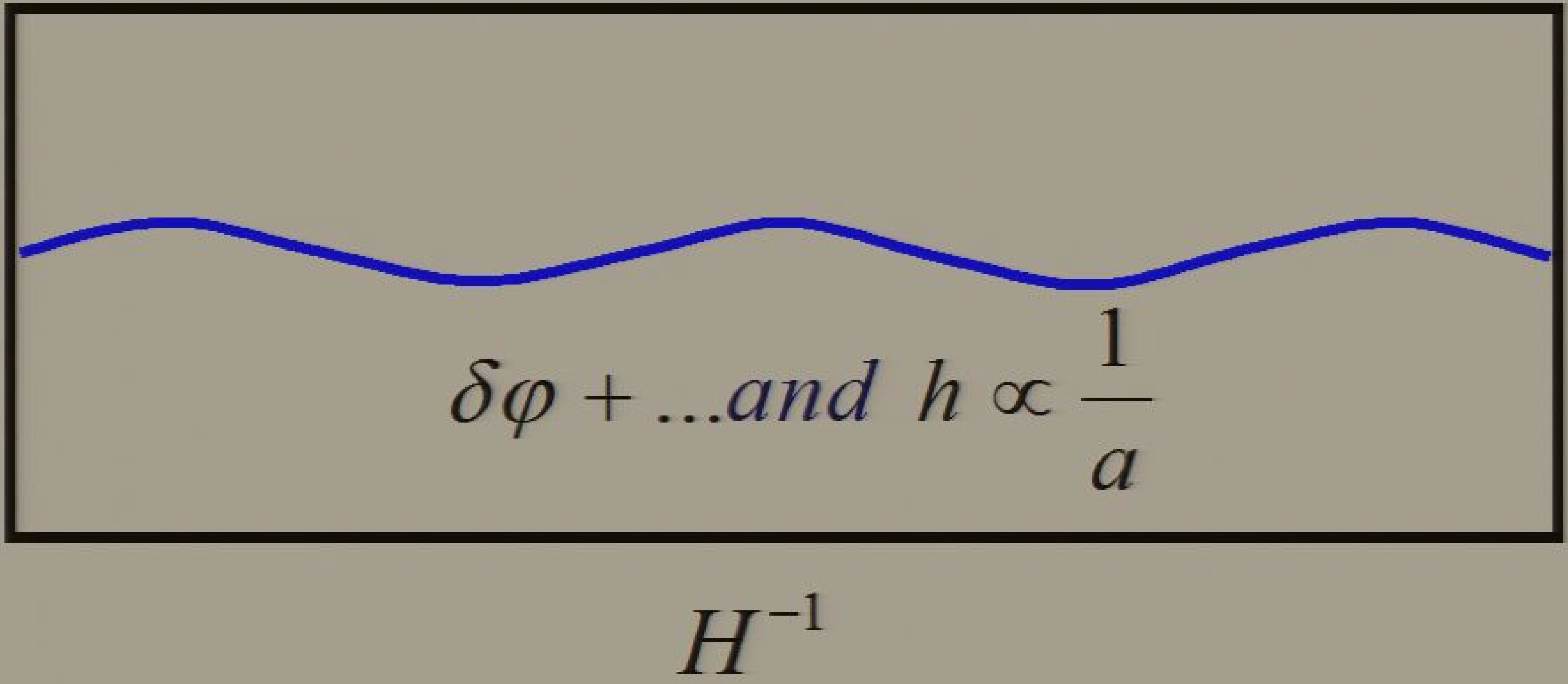
- Consider plane wave perturbation: $\delta\varphi, \Phi \propto \exp\left(i\vec{k}_{com}\vec{x}\right)$

For given k_{com}, $\lambda_{ph}(cm) \propto a / k_{com} \propto a(t)$ and the change of the amplitude with time depends on how big is λ_{phys} compared to the curvature scale (size of Einstein lift) $H^{-1} = a / \dot{a}$

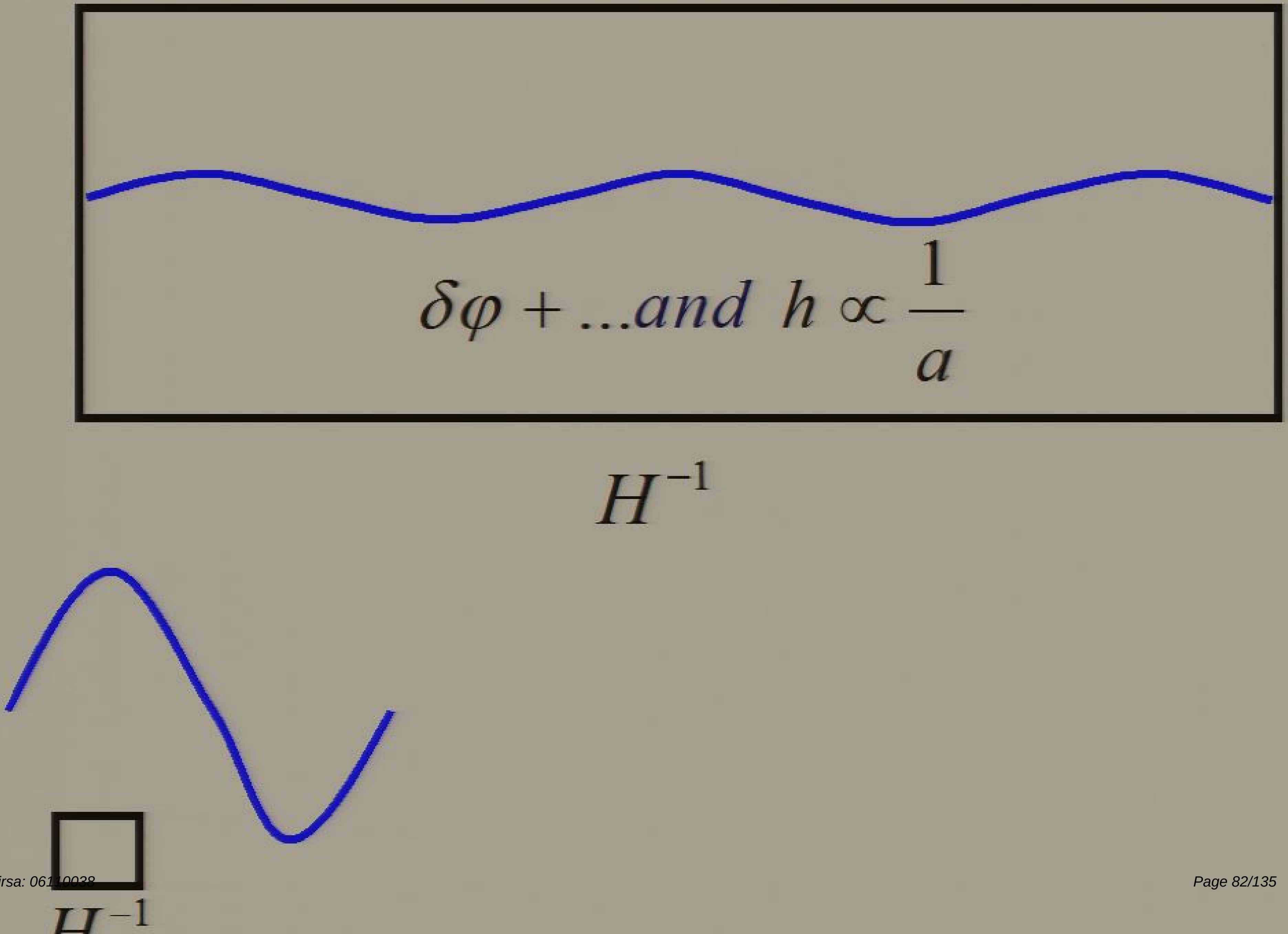

H^{-1}

$$H^{-1}$$



$$\delta\varphi + \ldots and \;\; h \propto \frac{1}{a}$$

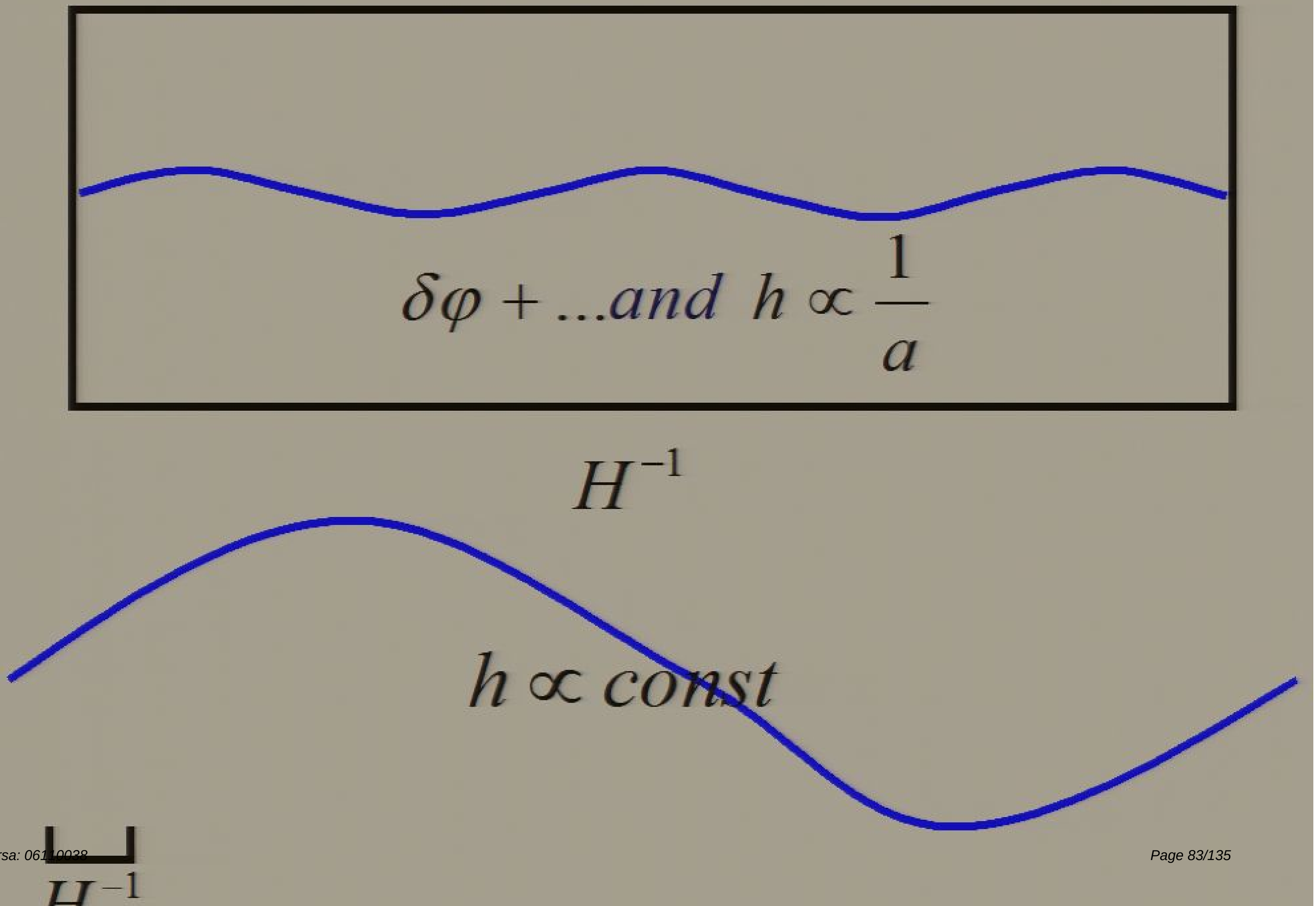
$$H^{-1}$$



$$\delta\varphi + \ldots and\ \ h \propto \frac{1}{a}$$

H^{-1}

H^{-1}

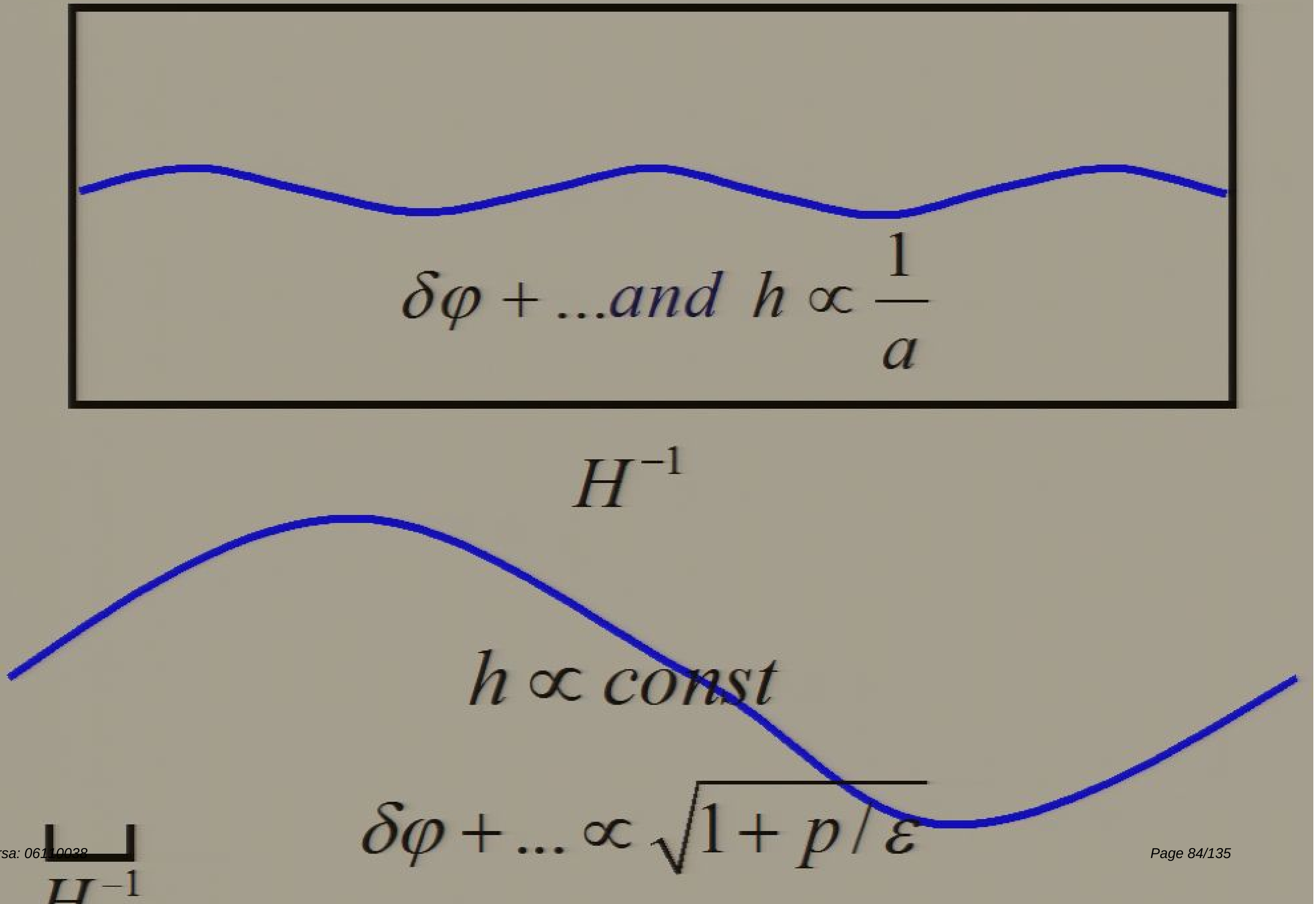


$\delta\varphi + \ldots and\ \ h \propto \frac{1}{a}$

H^{-1}

$h \propto const$

H^{-1}



$$\delta\varphi + \ldots and\ \ h \propto \frac{1}{a}$$

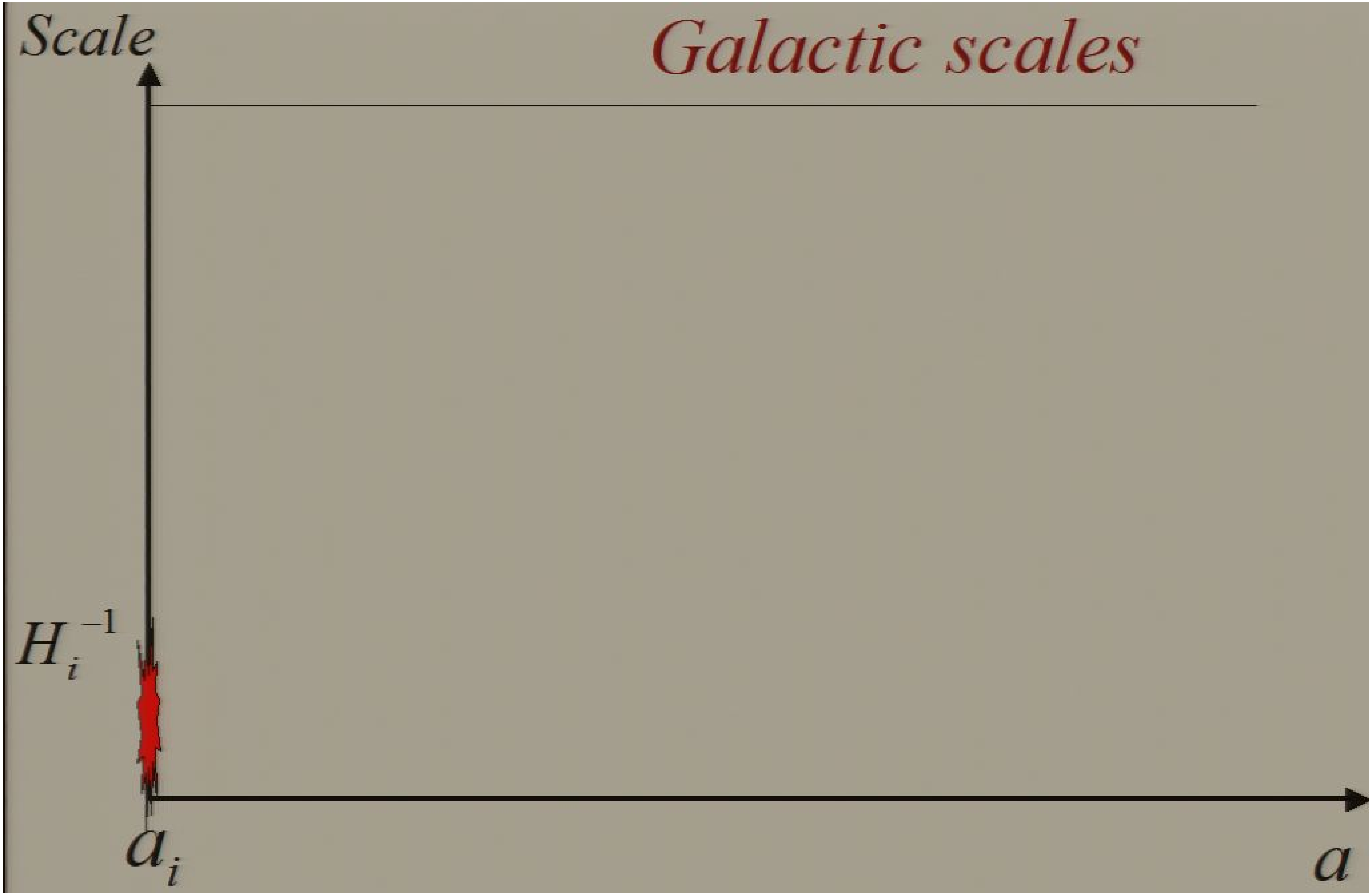
$$H^{-1}$$

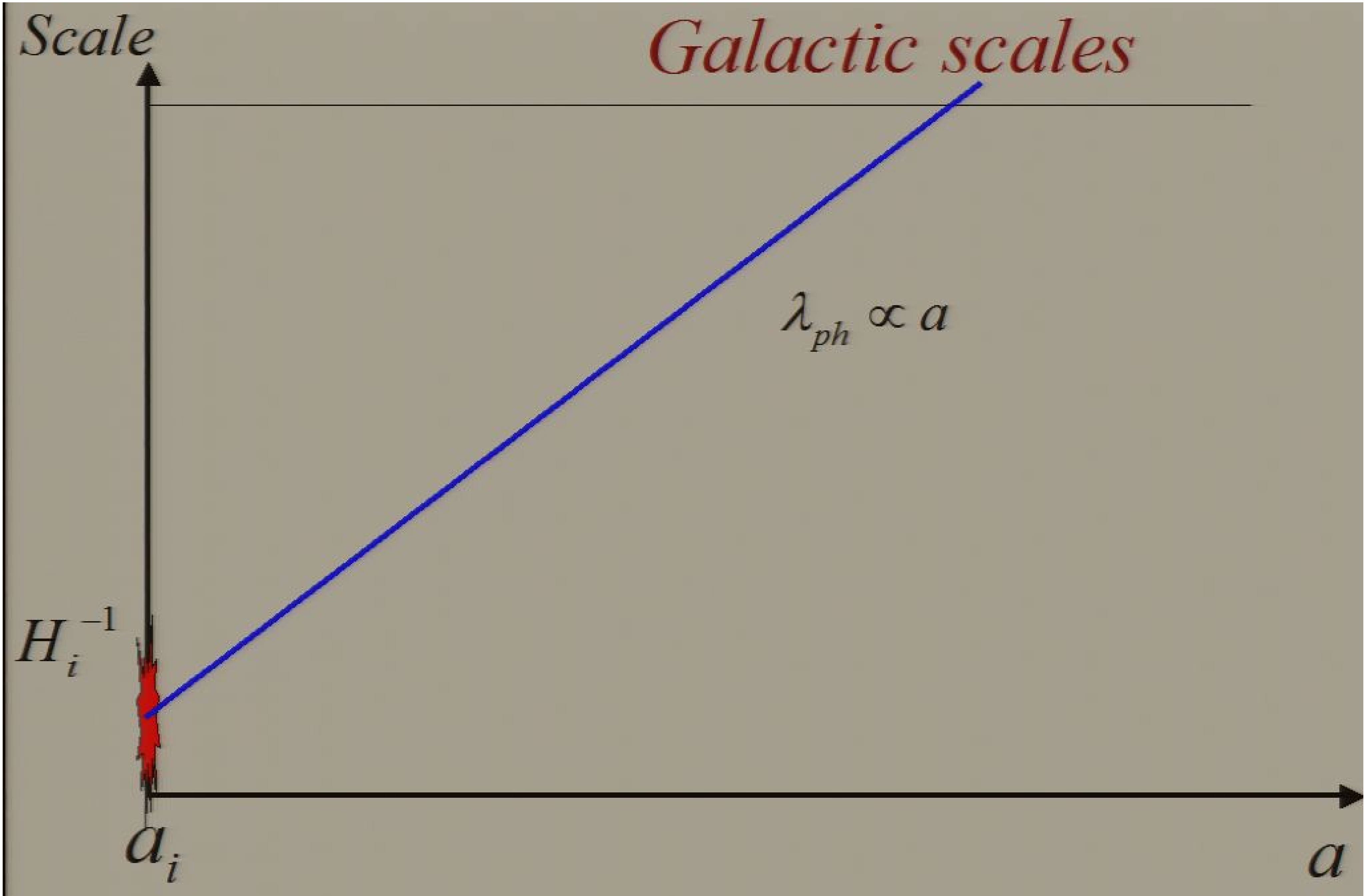
$$h \propto const$$

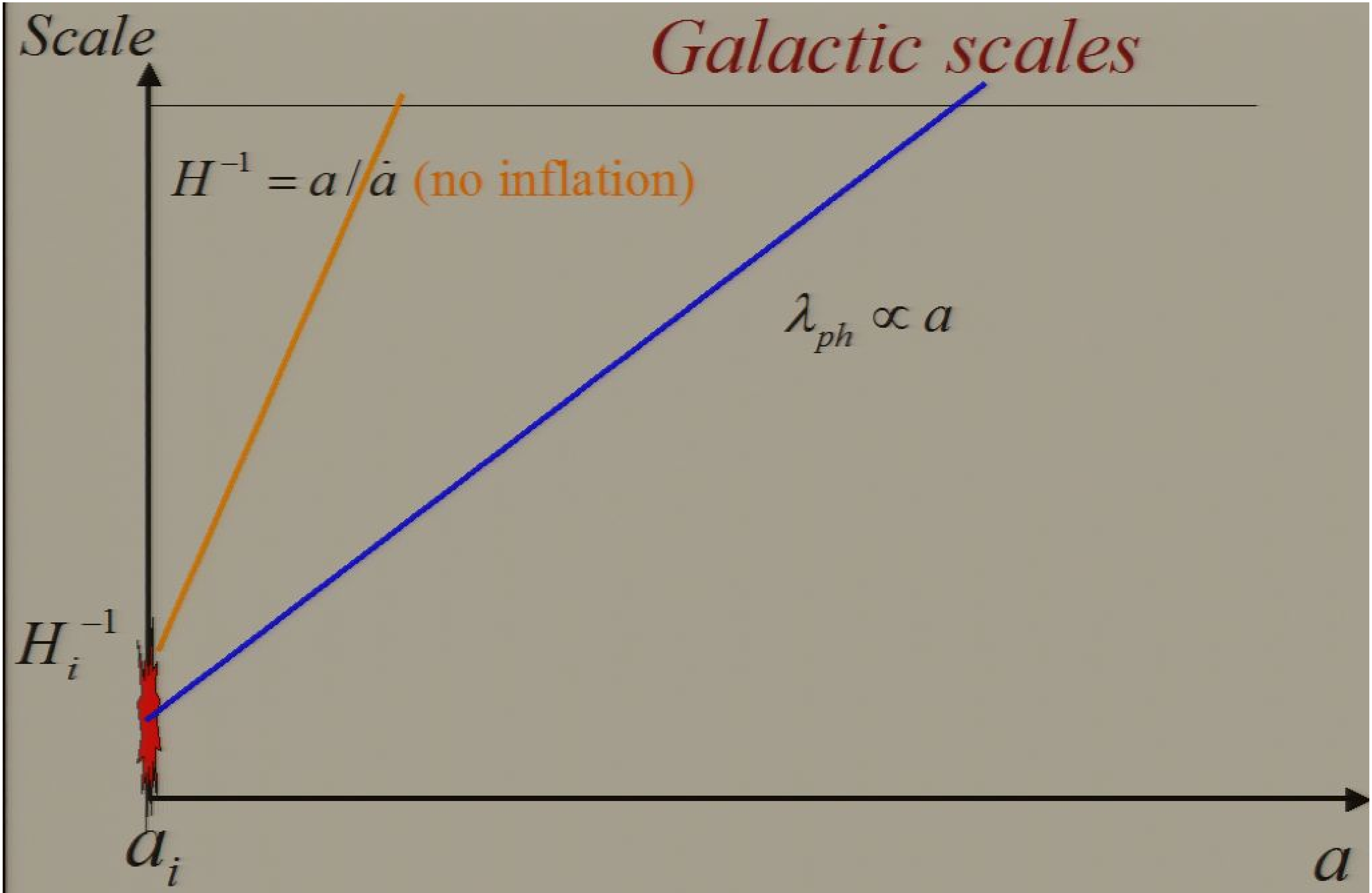
$$\delta\varphi + \ldots \propto \sqrt{1 + p / \varepsilon}$$

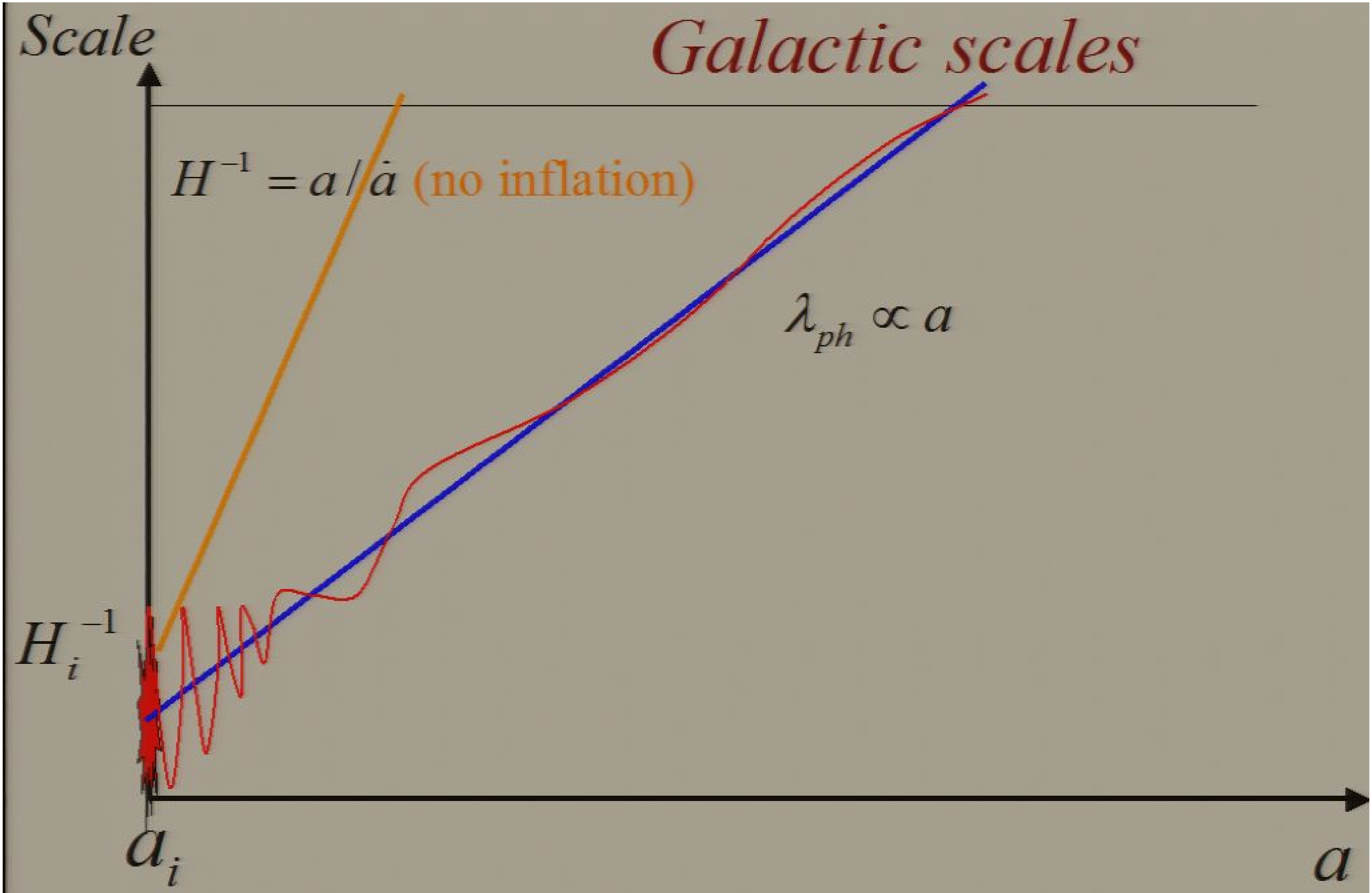
$$H^{-1}$$

Galactic scales




Scale
Galactic scales
$\lambda_{ph} \propto a$
H_i^{-1}
a_i
a


Scale
Galactic scales
$H^{-1} = a/\dot{a}$ (no inflation)
$\lambda_{ph} \propto a$
H_i^{-1}
a_i
a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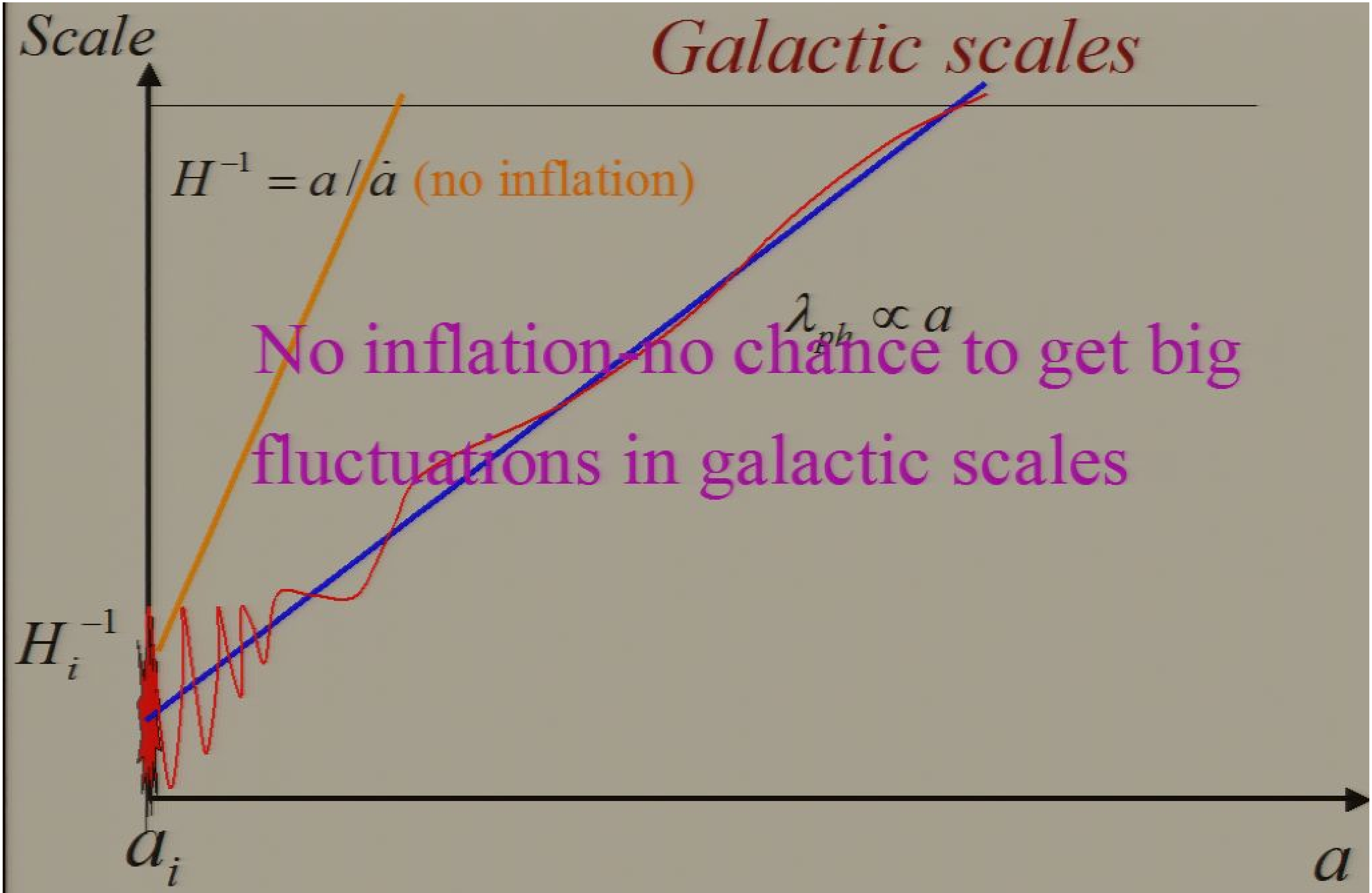
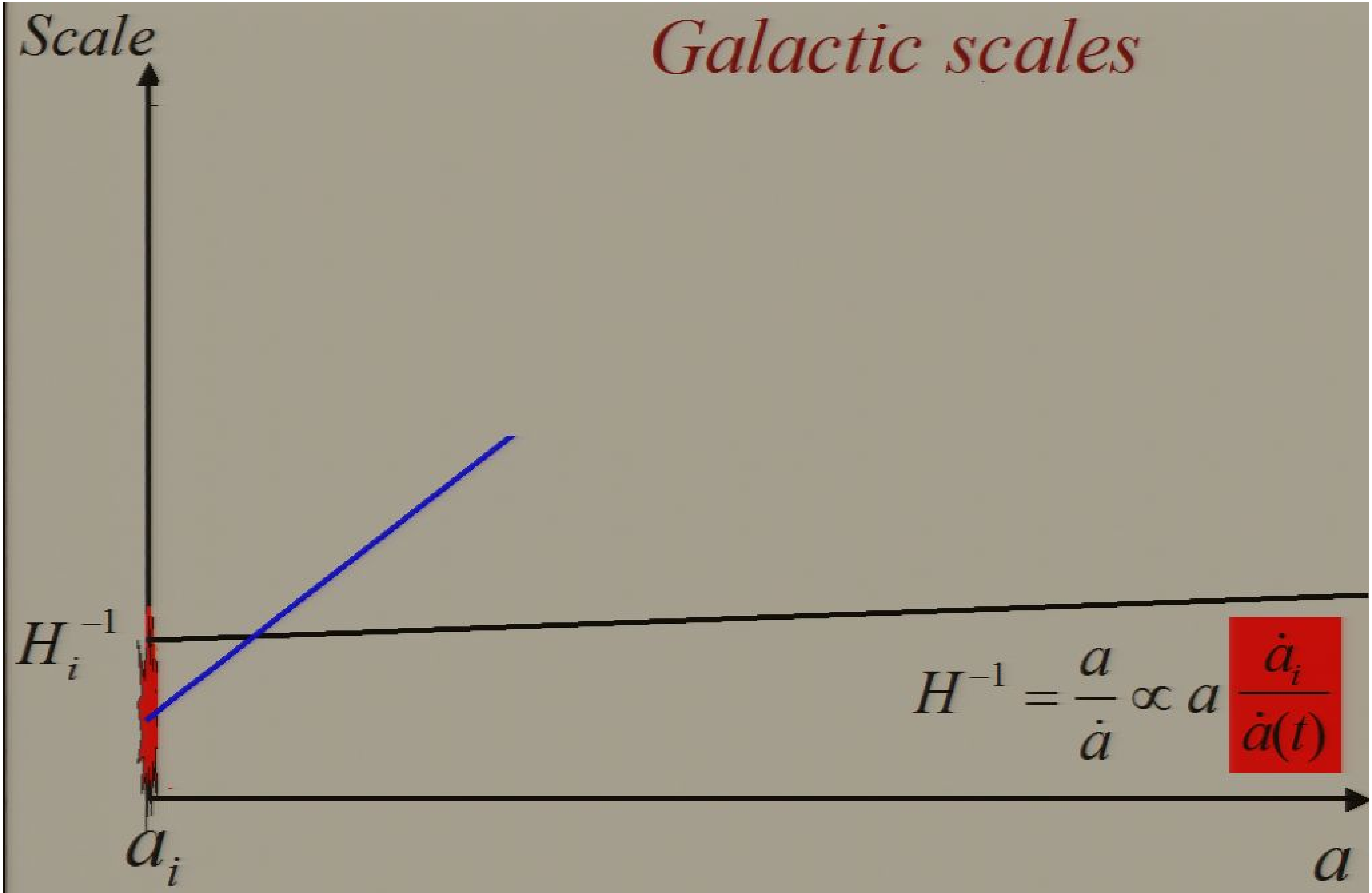


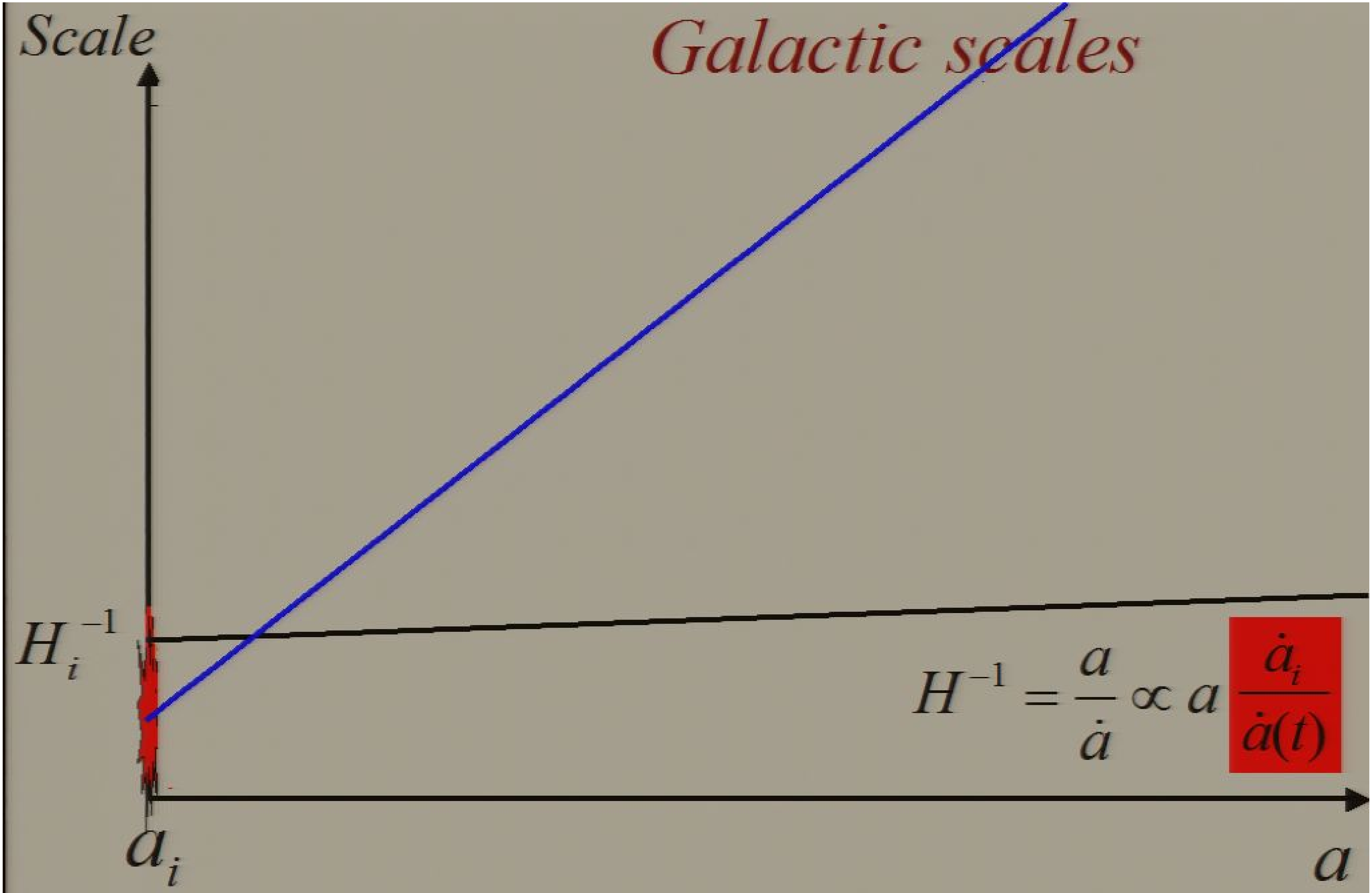
No inflation-no chance to get big fluctuations in galactic scales

Galactic scales



$$H^{-1} = \frac{a}{\dot{a}} \propto a \boxed{\frac{\dot{a}_i}{\dot{a}(t)}}$$

Galactic scales



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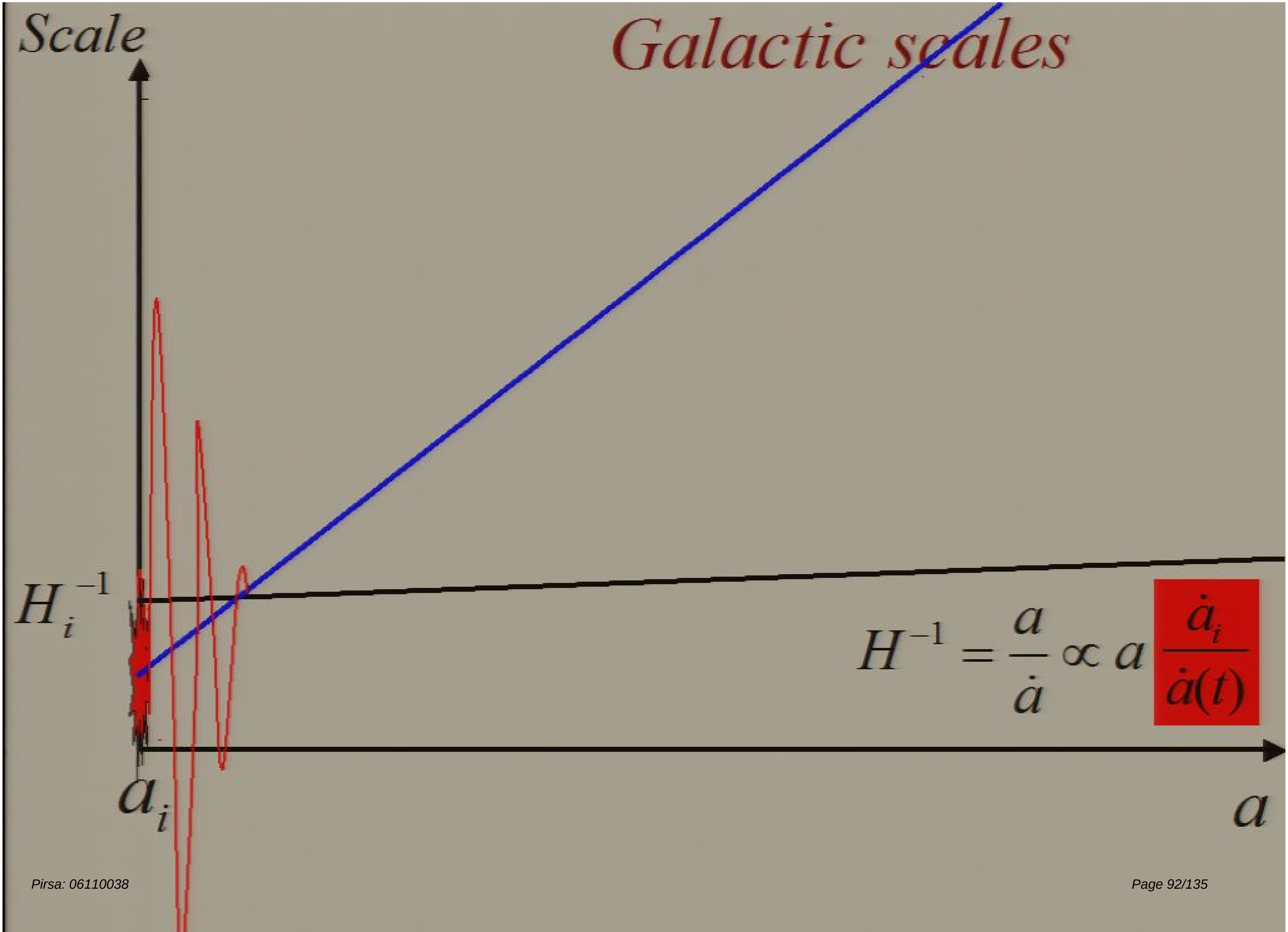

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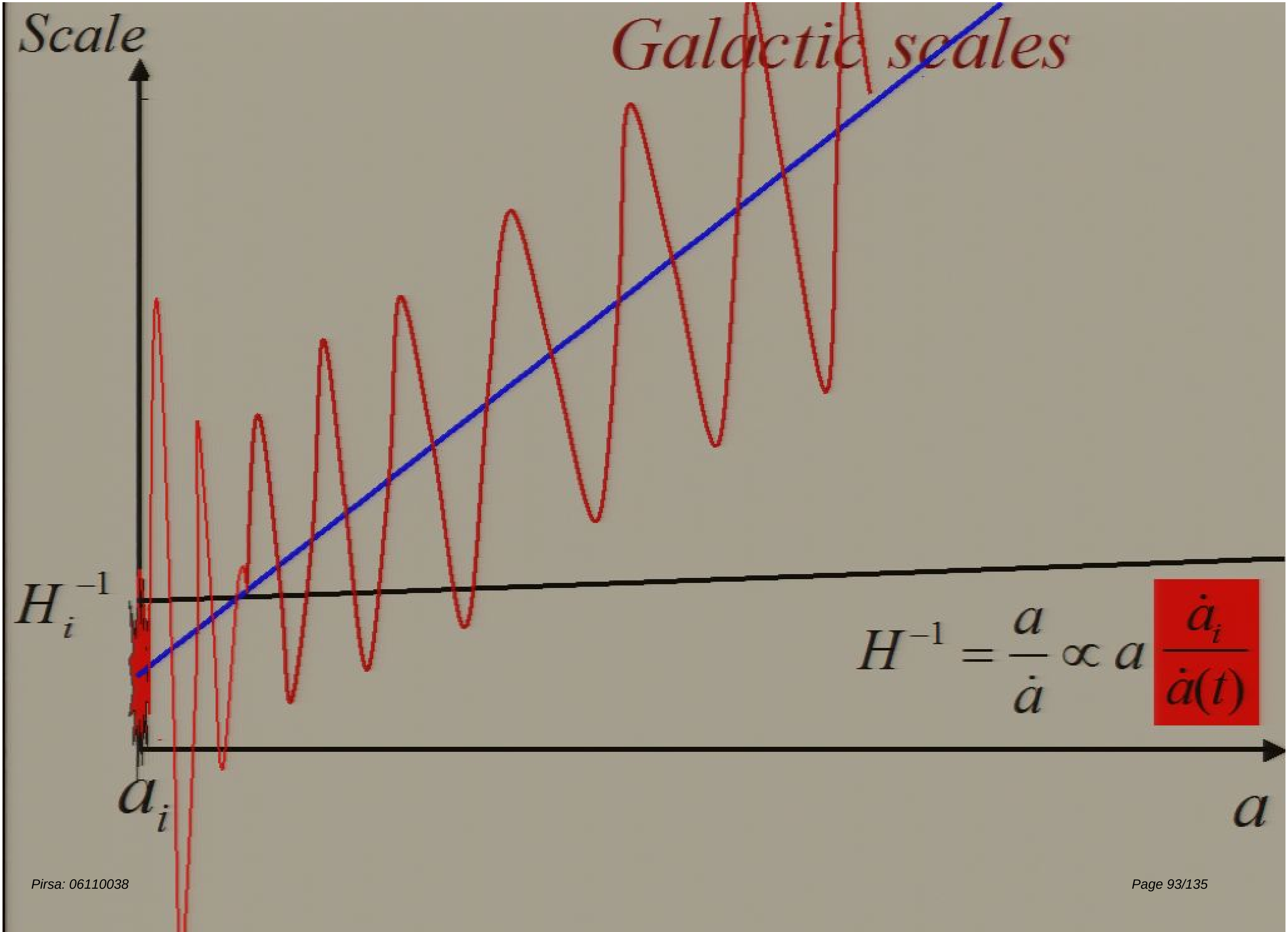

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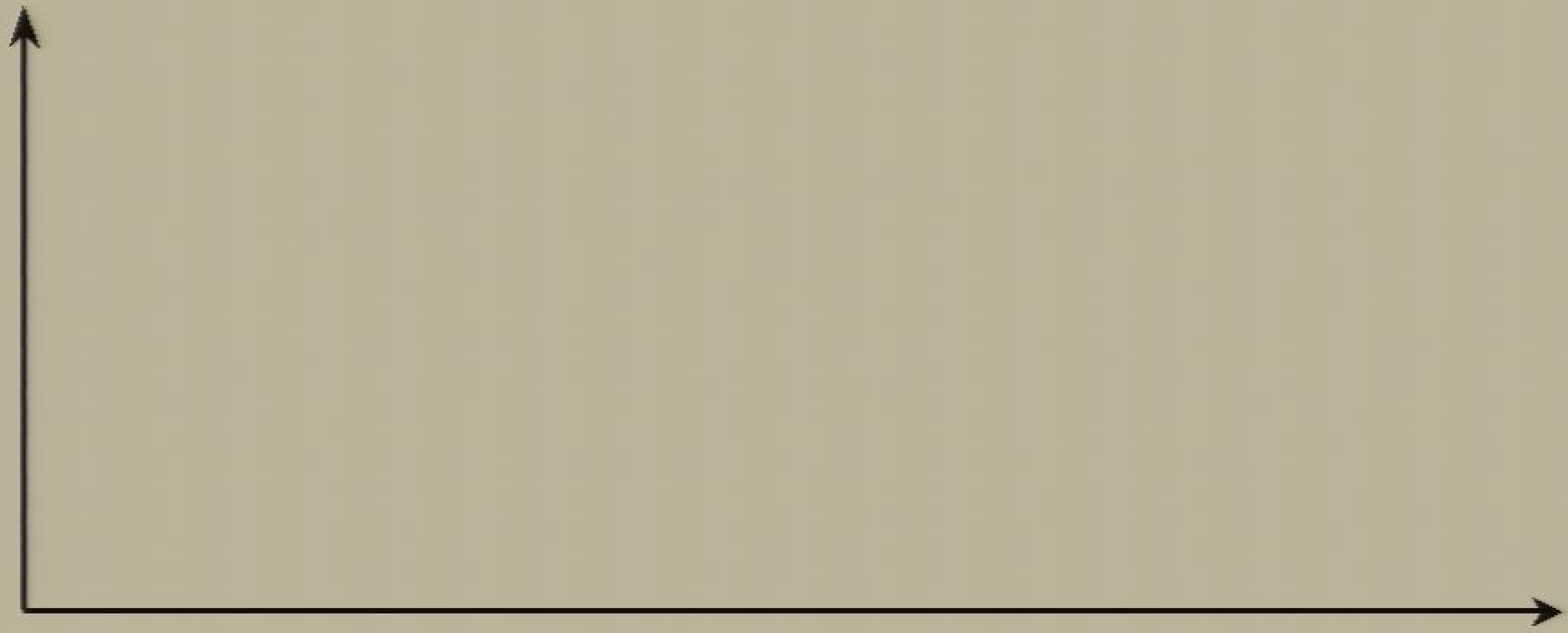
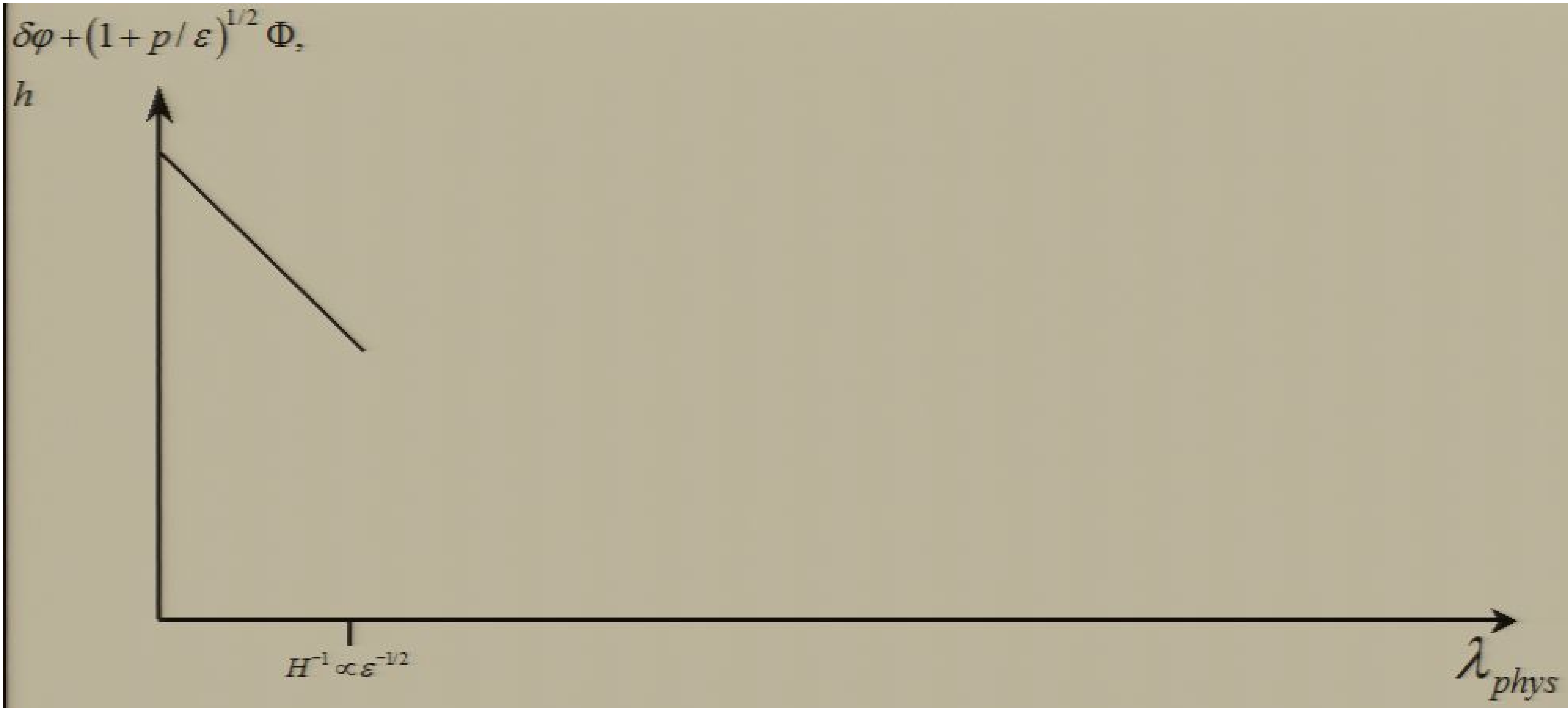
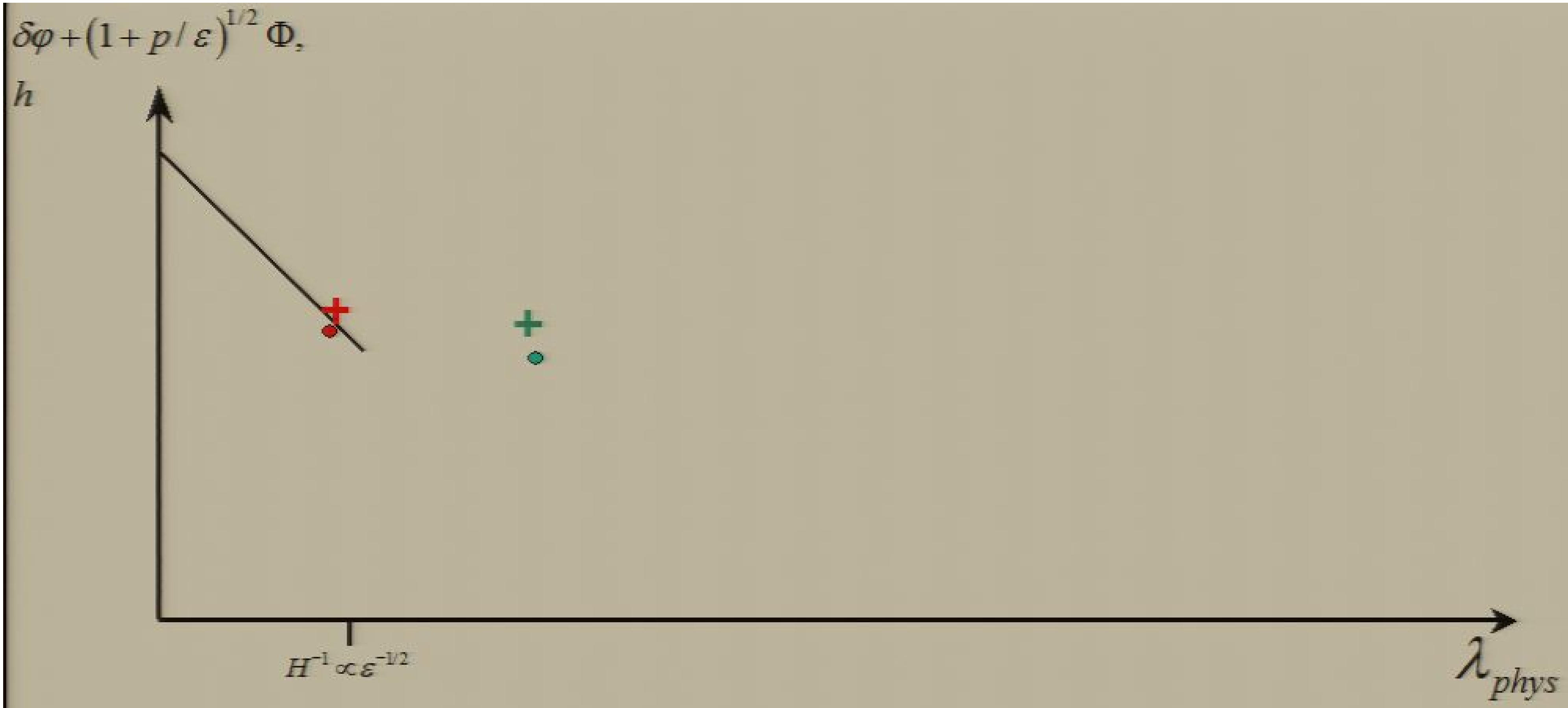



$\delta\varphi + (1 + p/\varepsilon)^{1/2}\,\Phi,$
h
$H^{-1} \propto \varepsilon^{-1/2}$
λ_{phys}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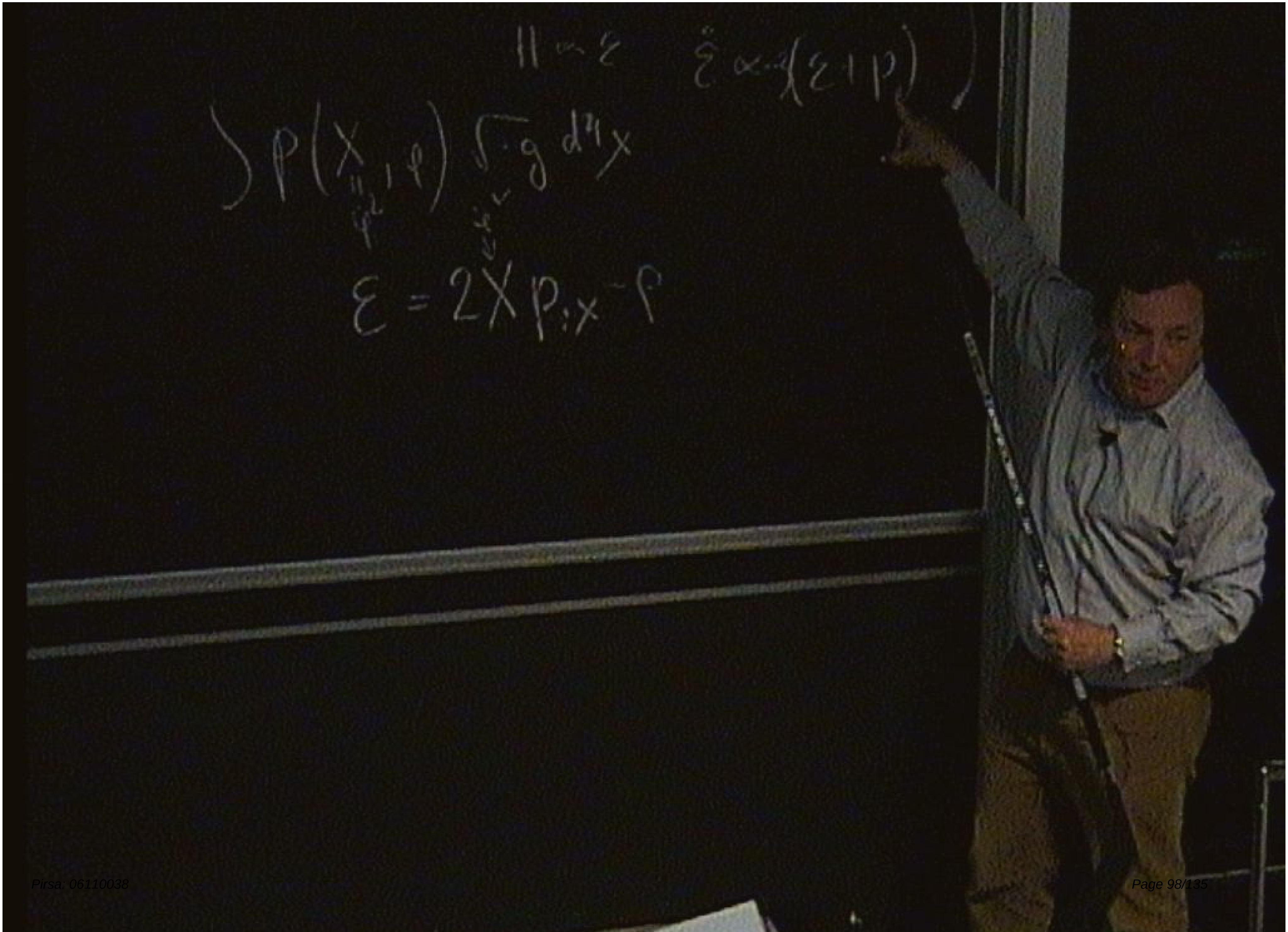
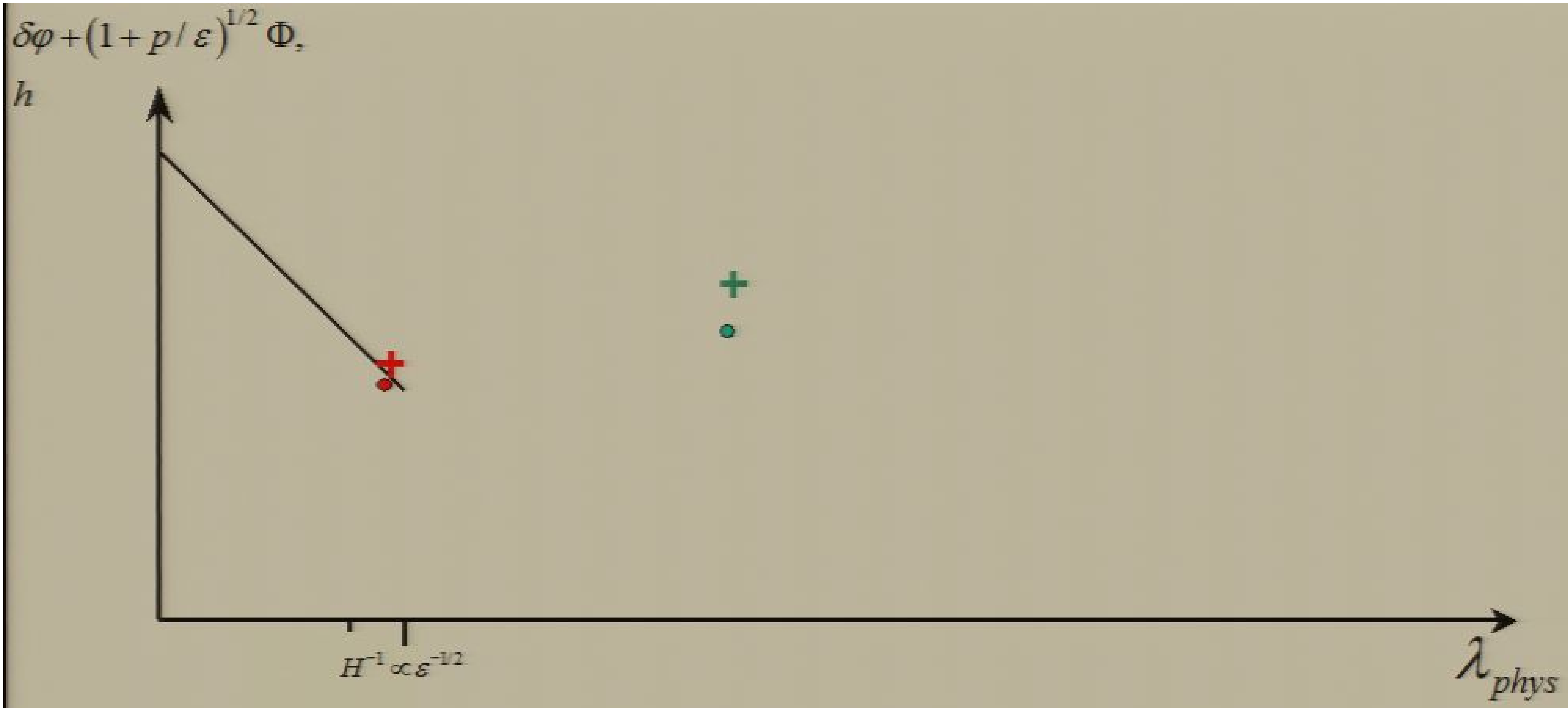


$H \sim \varepsilon \qquad \ddot{\varepsilon} \propto -\lambda(\varepsilon + p)$

$$\int p(\underset{\dot{\varphi}^2}{X}, \varphi)\, \underset{a^3}{\sqrt{-g}}\, d^4x$$

$$\varepsilon = 2X p_{,X} - p$$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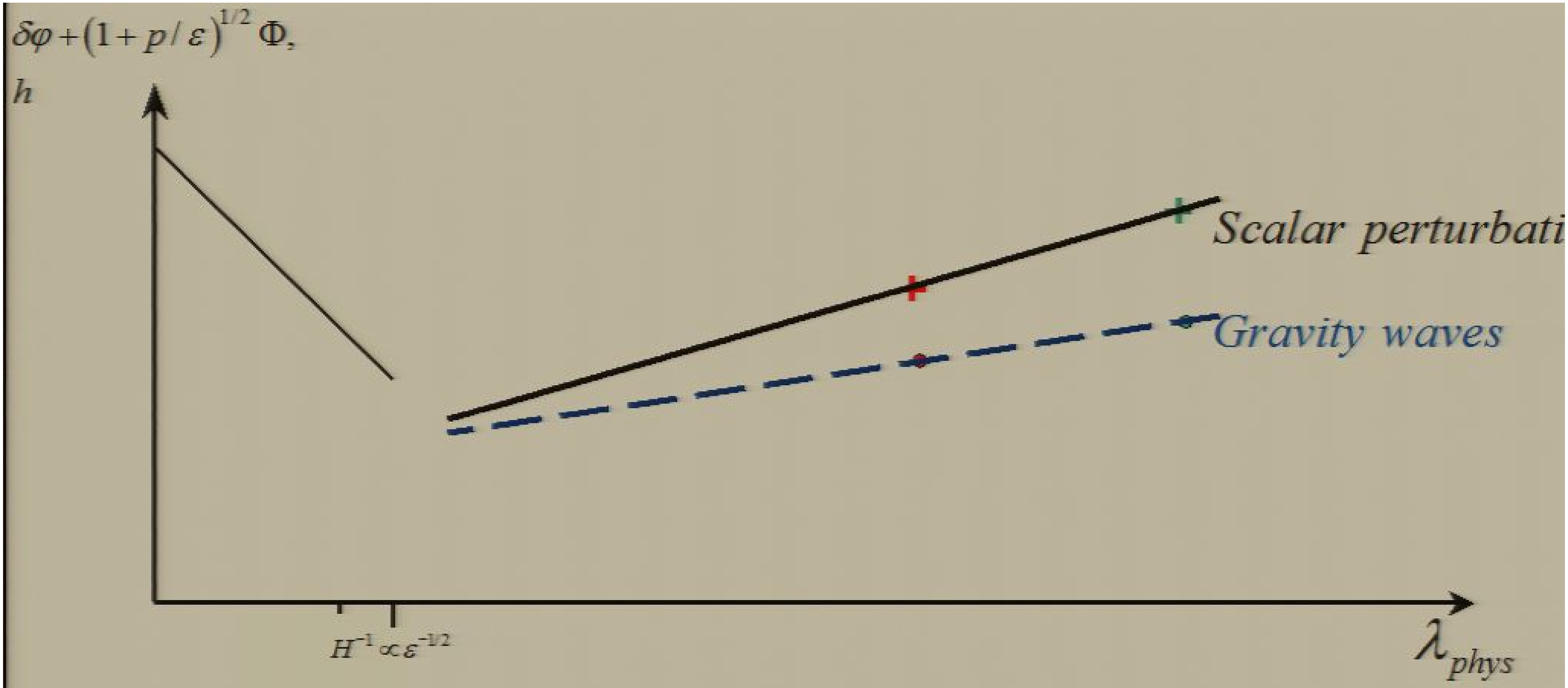
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h
Scalar perturbati
Gravity waves
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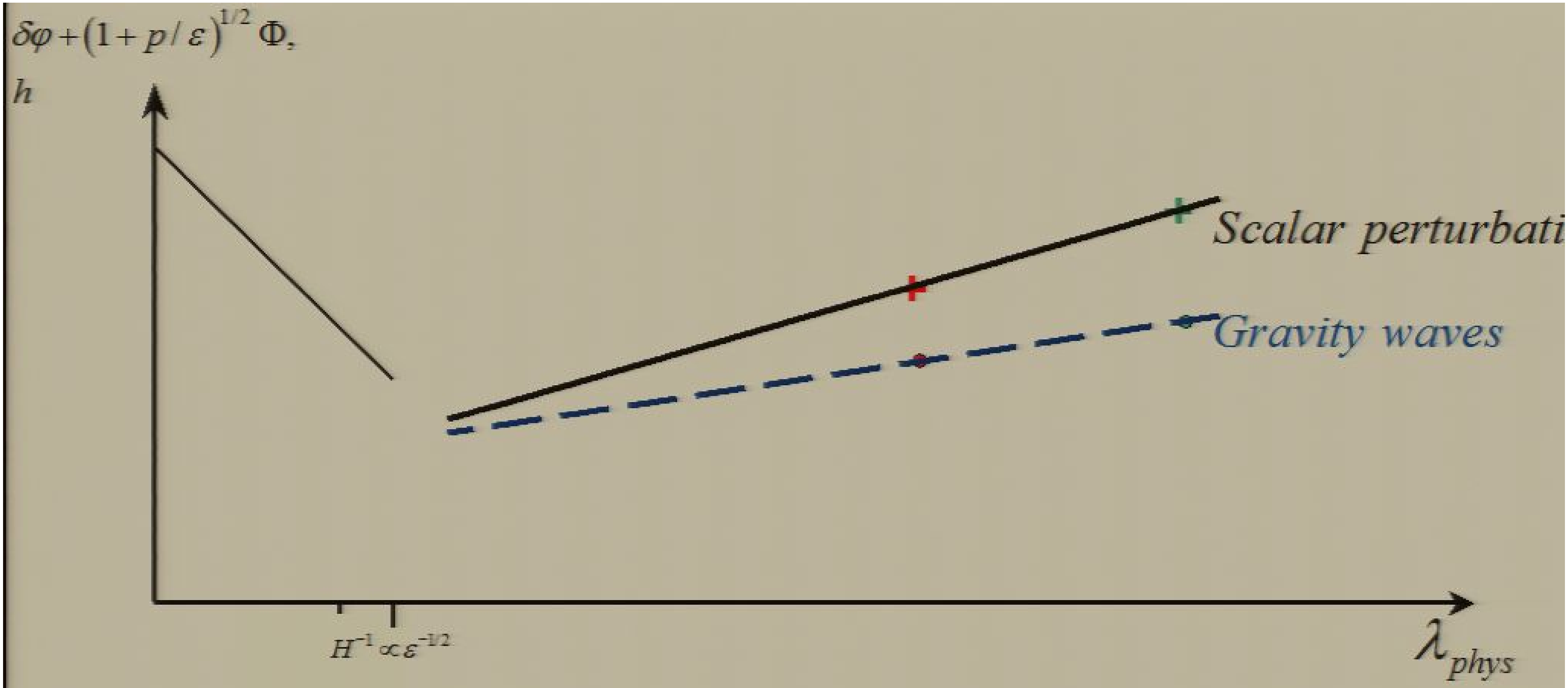
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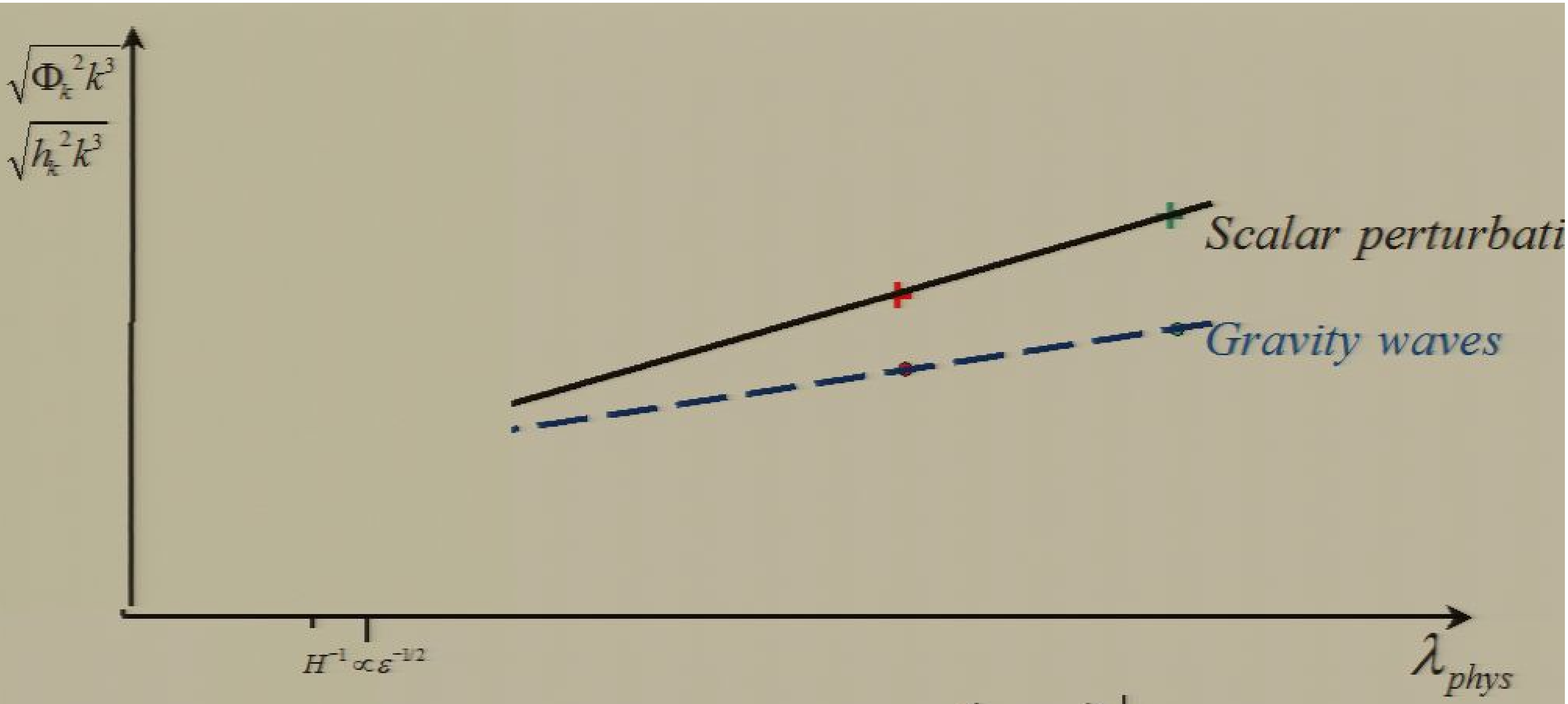
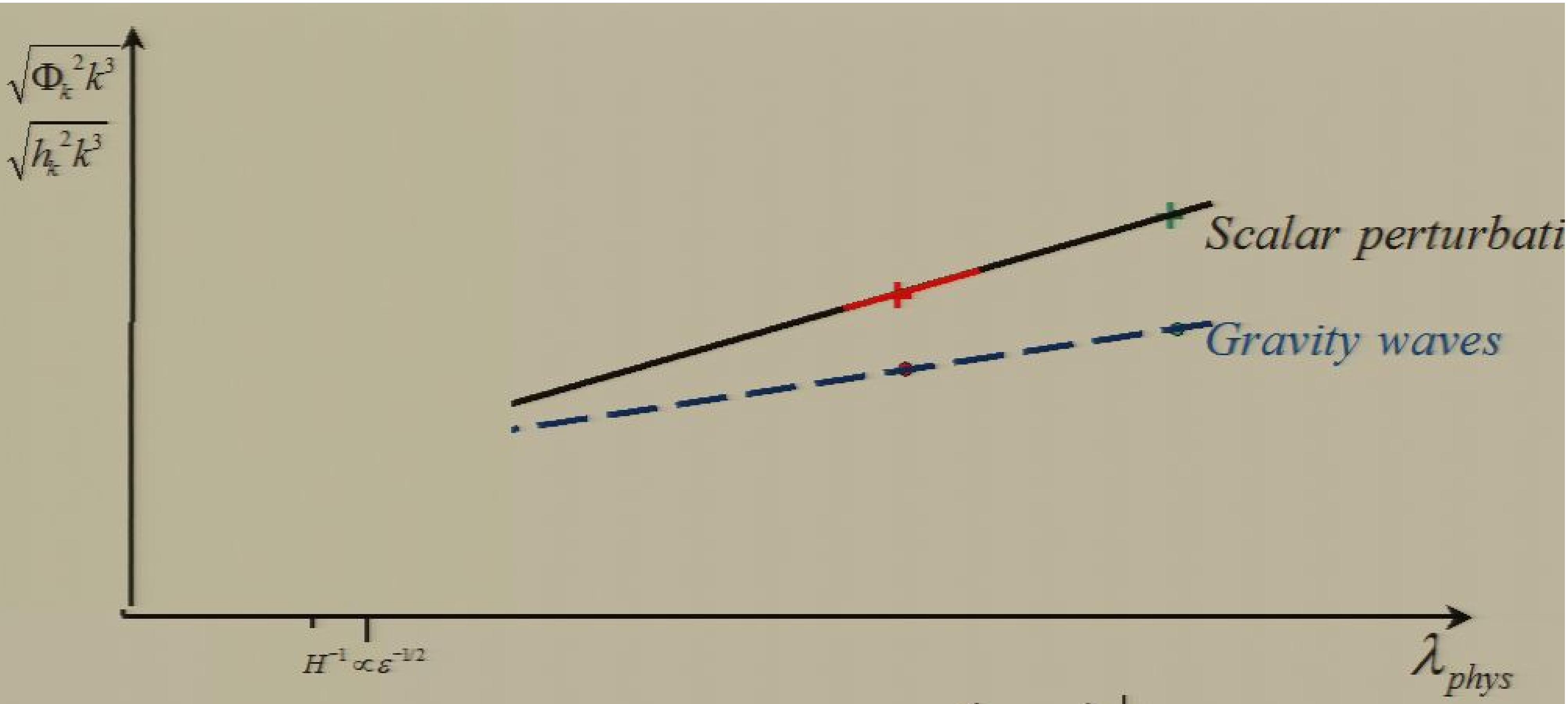


$$\Phi_k{}^2 k^3 = O(1)\frac{1}{1+p/\varepsilon}\left(\frac{\varepsilon}{\varepsilon_{Pl}}\right)\Bigg|_{k\approx Ha}$$



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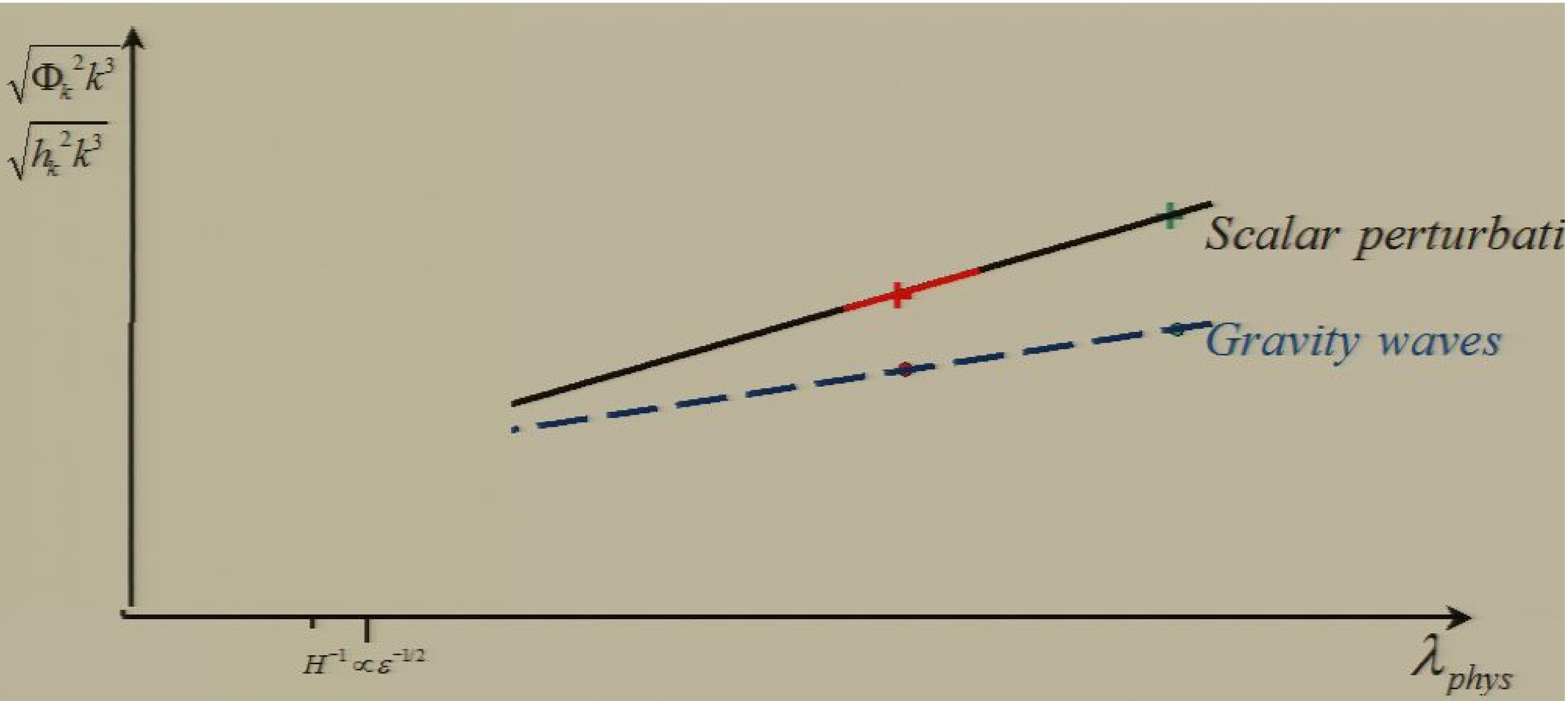
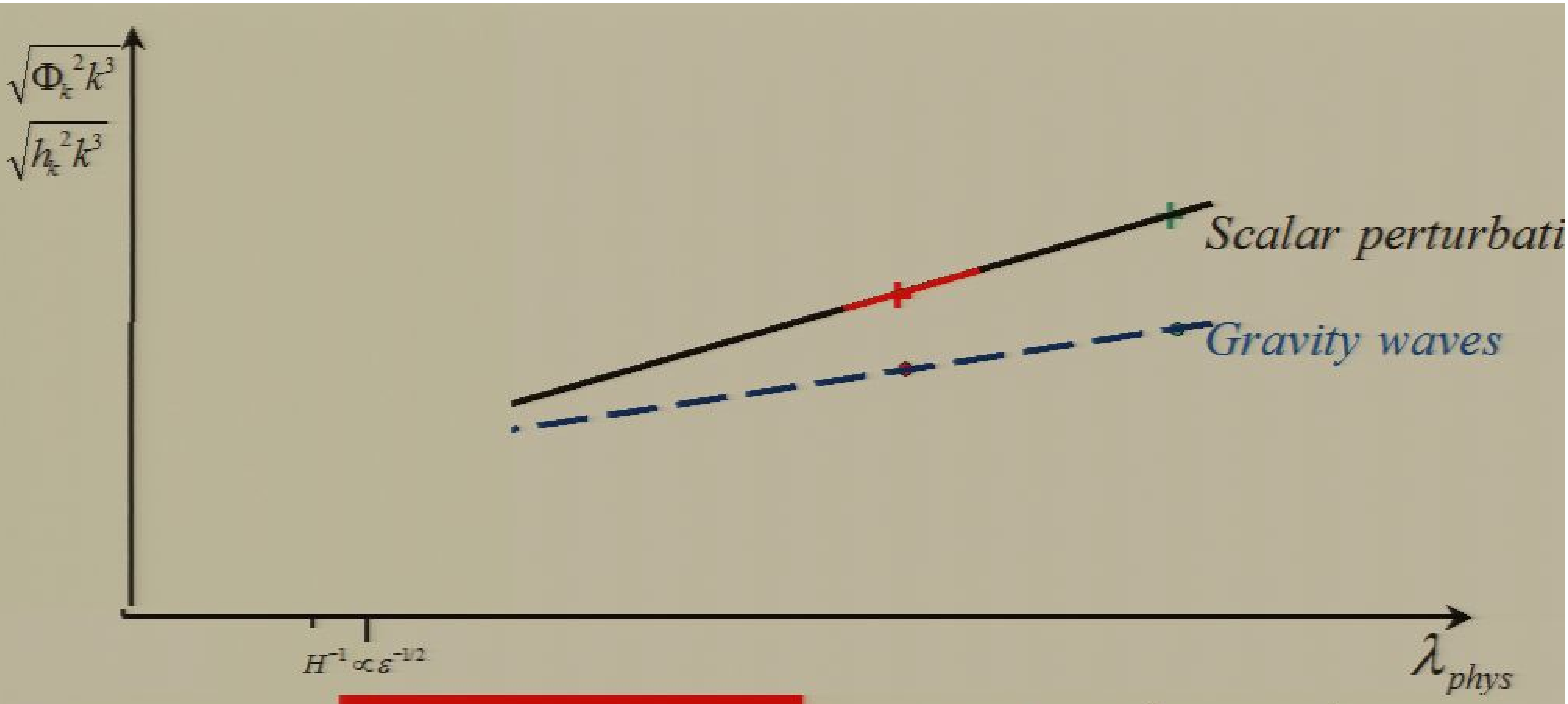
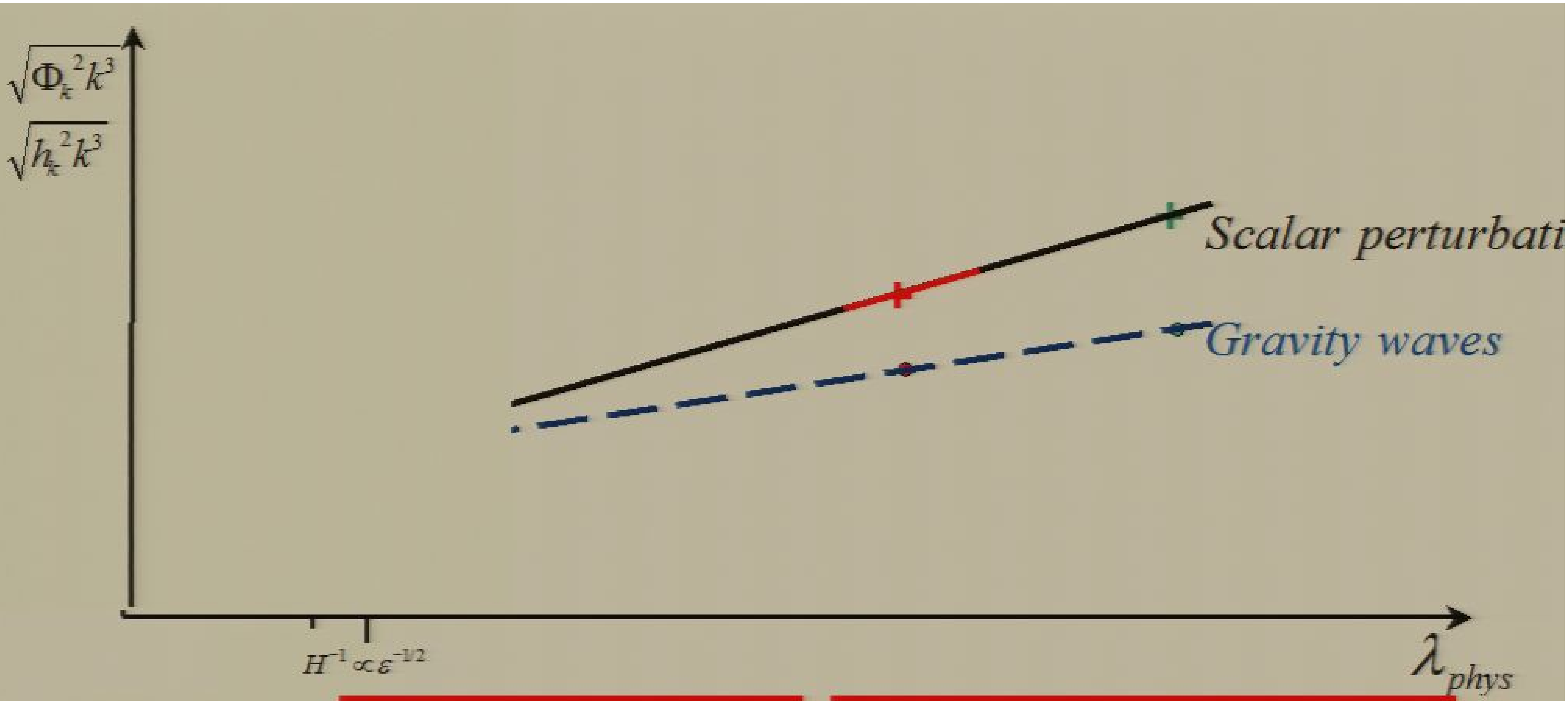


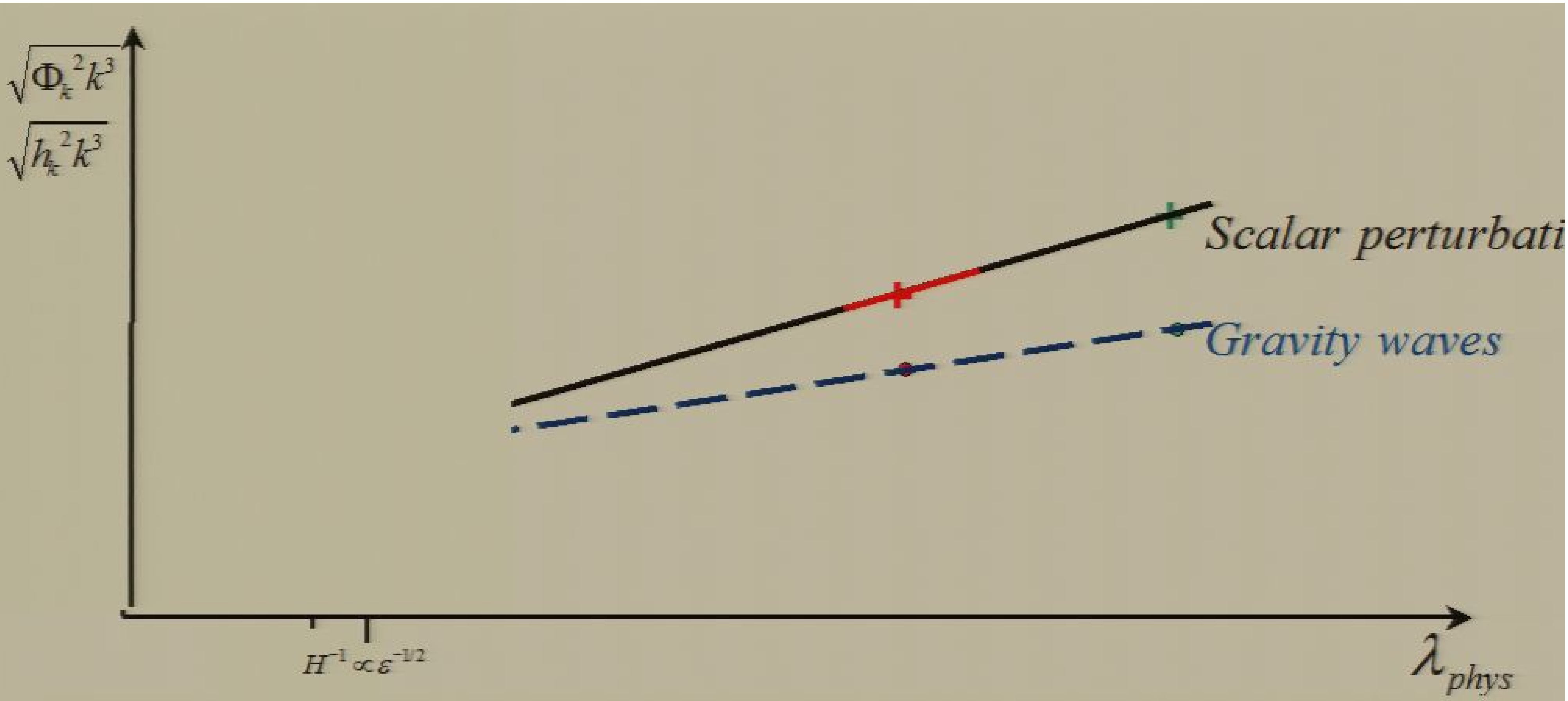
$$n_S - 1 = -3\left(1+\frac{p}{\varepsilon}\right)_{k\approx Ha} + 3\frac{d}{d\ln\varepsilon}\left(1+\frac{p}{\varepsilon}\right)_{k\approx Ha}$$



$$n_S - 1 = \boxed{< \quad 0} + 3\frac{d}{d\ln\varepsilon}\left(1 + \frac{p}{\varepsilon}\right)_{k\approx Ha}$$



$$n_S - 1 = \boxed{<\quad 0} - \boxed{<\quad 0}$$

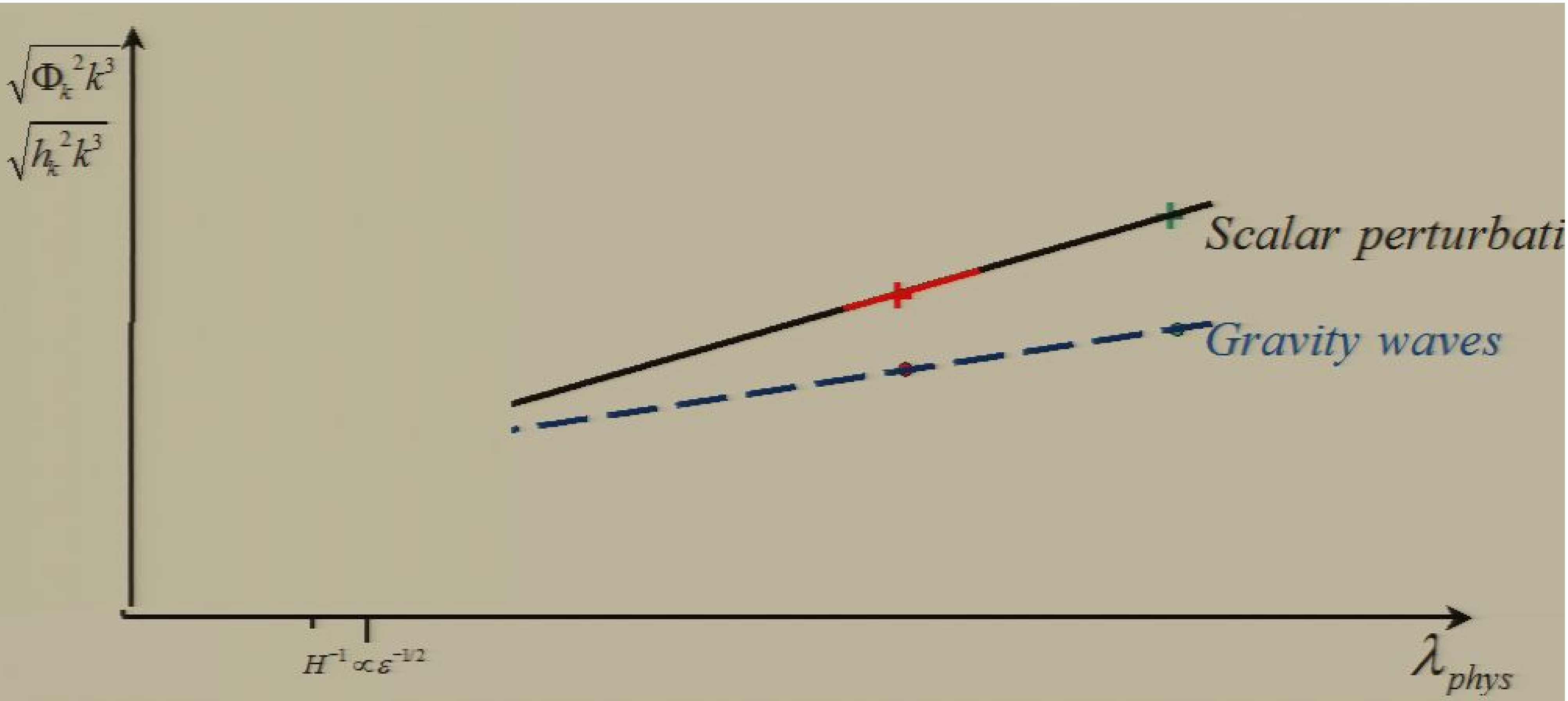

$\sqrt{\Phi_k^2 k^3}$
$\sqrt{h_k^2 k^3}$
Scalar perturbati
Gravity waves
$H^{-1} \propto \varepsilon^{-1/2}$
λ_{phys}

$$0.92 < n_S < 0.97$$

$$\| \sim \varepsilon \qquad \dot{\varepsilon} \propto -3(\varepsilon + p)$$

$$\int p(\underset{\dot{\varphi}^2}{X}, \varphi)\sqrt{-g}\, d^4x$$

$$c_s^2 = \frac{p_{,X}}{\partial \varepsilon} \qquad \varepsilon = 2X p_{,X} - p$$


$\sqrt{\Phi_k^2 k^3}$
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Scalar perturbati
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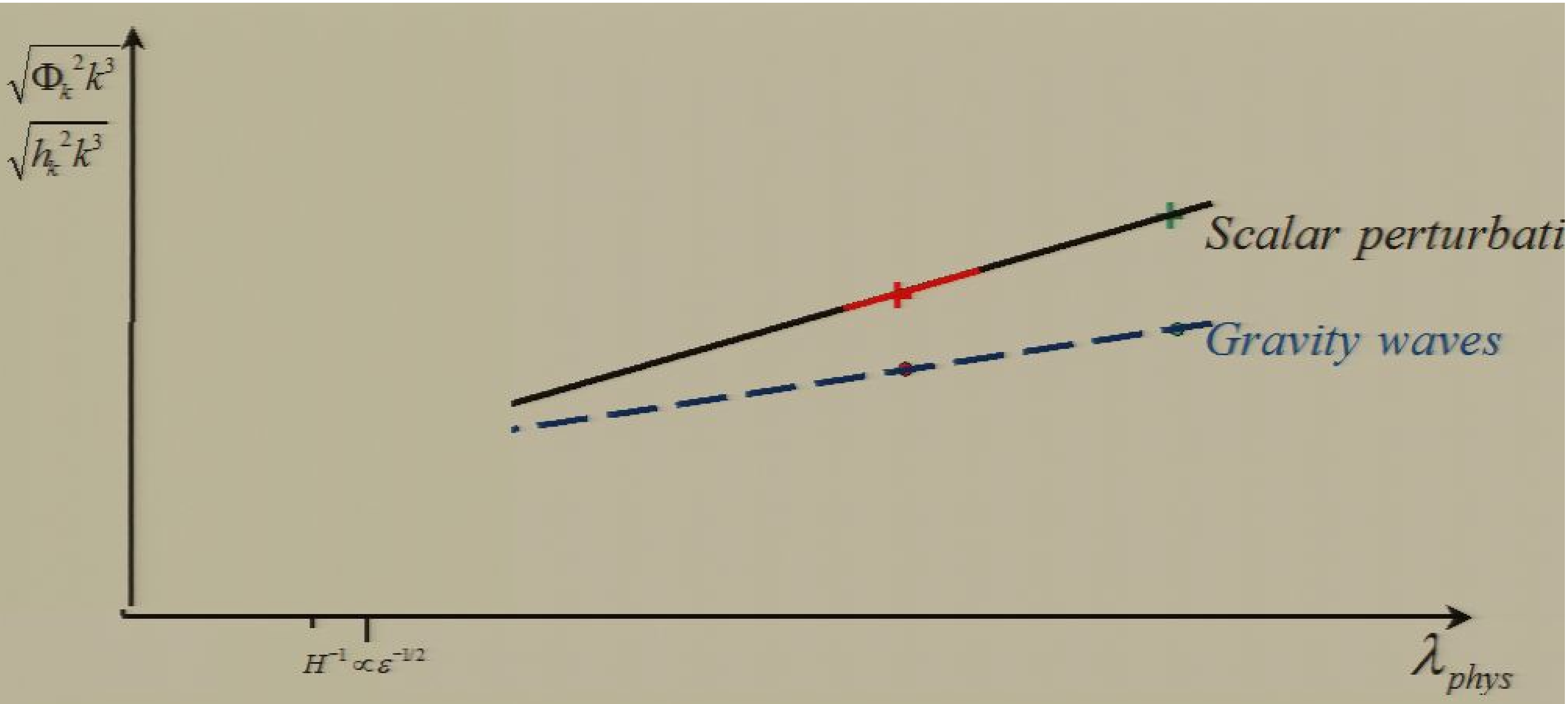

$$0.92 < n_S < 0.97$$

$$\frac{T}{S} = O(1)\left(1 + \frac{p}{\varepsilon}\right)^{1/2}_{k \approx Ha}$$

Summary

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Idea and basic properties of inflation are established:

Inflation is the stage of accelerated expansion of the universe with graceful exit to Friedmann stage

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SCENARIO

???

- Robust predictions:

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–Sligtly red-tilted spectrum of scalar perturbations $(0,92 < n_S < 0,97)$

–Perturbations are Gaussian

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S
C
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R
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Comparison with observations: Present

$$\left\langle \frac{\delta T}{T}(\varphi)\frac{\delta T}{T}(\varphi+\theta)\right\rangle_{\varphi} = \frac{1}{4\pi}\sum(2l+1)C_l P_l(\cos\theta)$$

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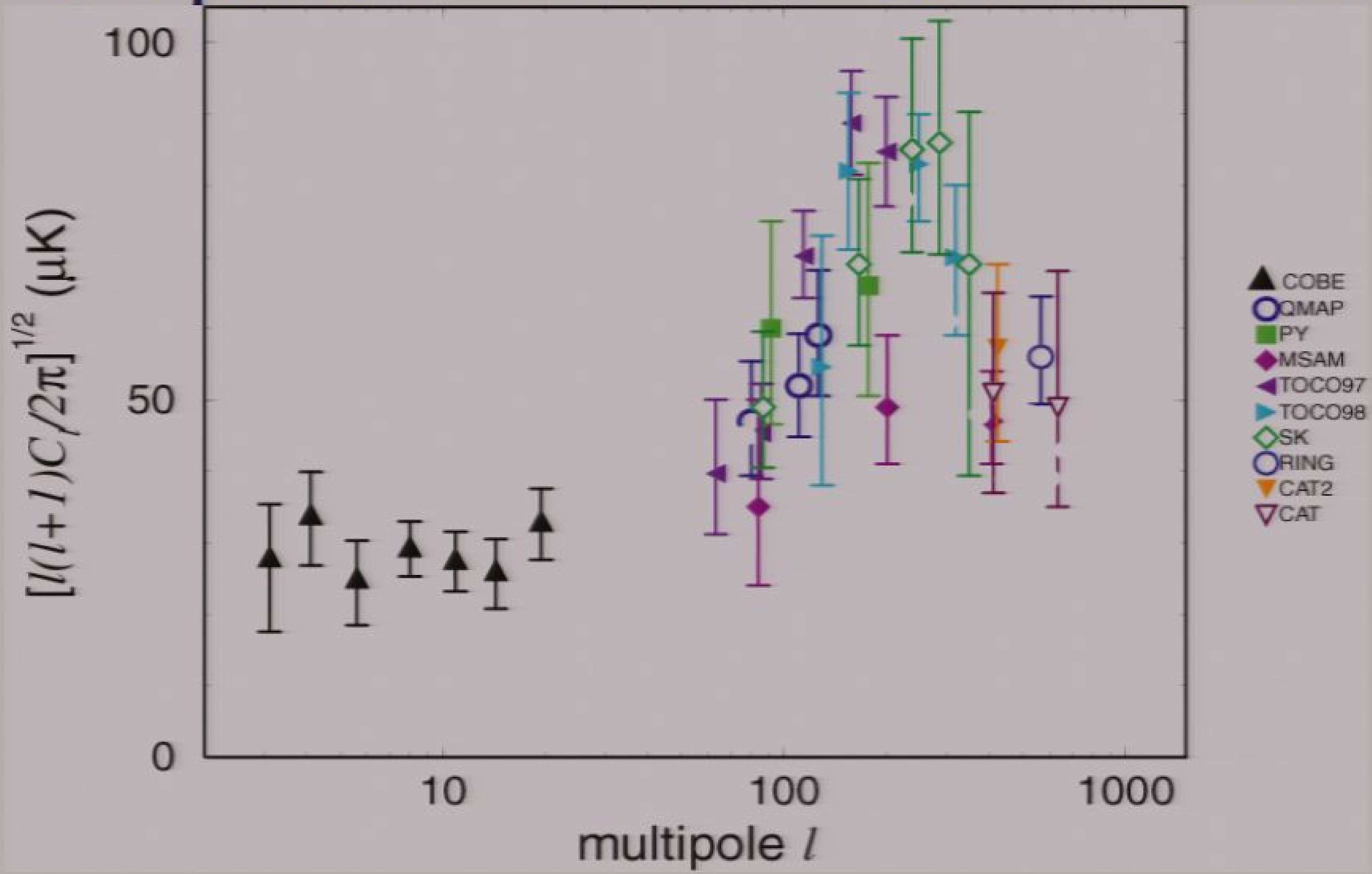

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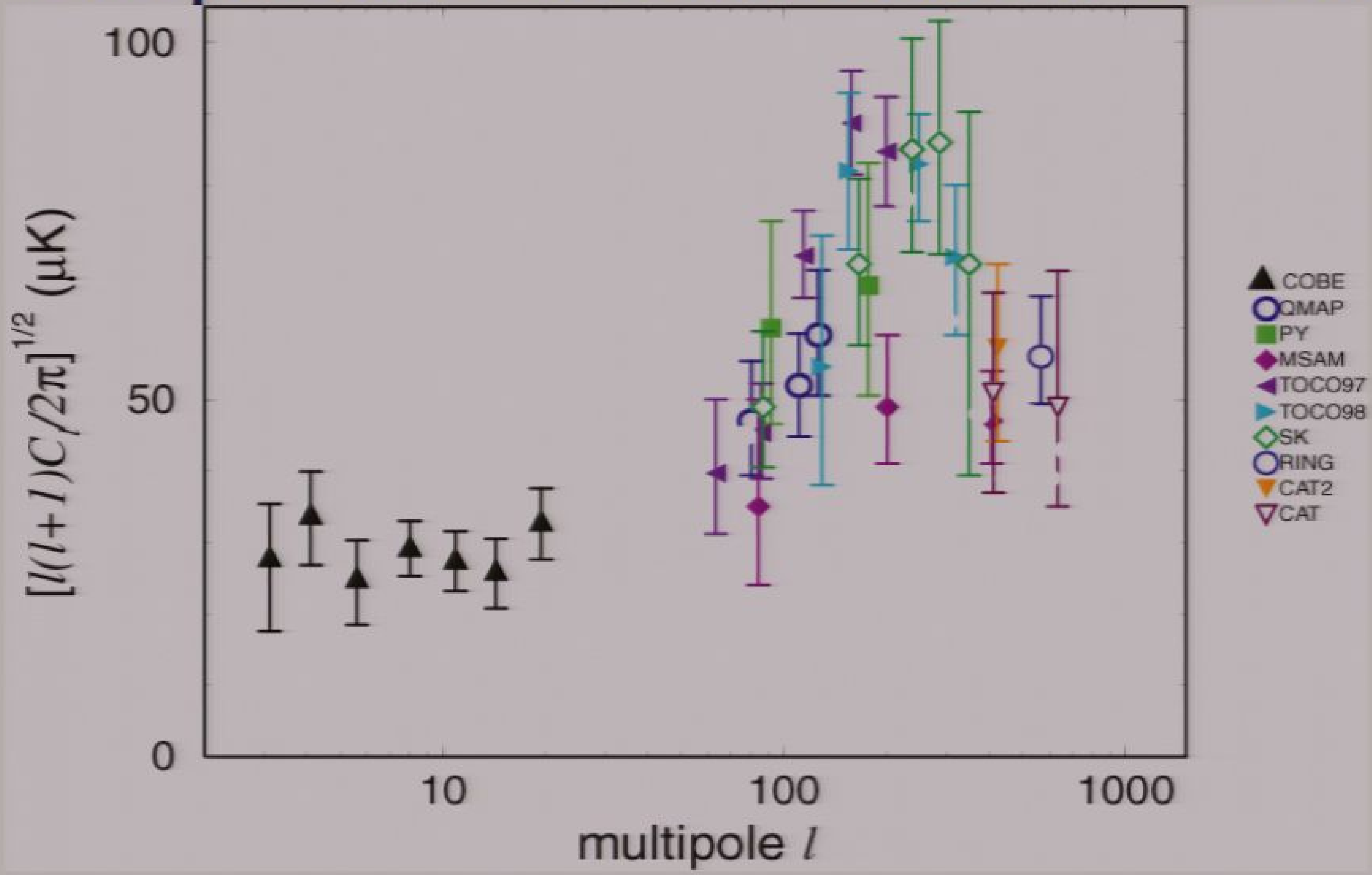
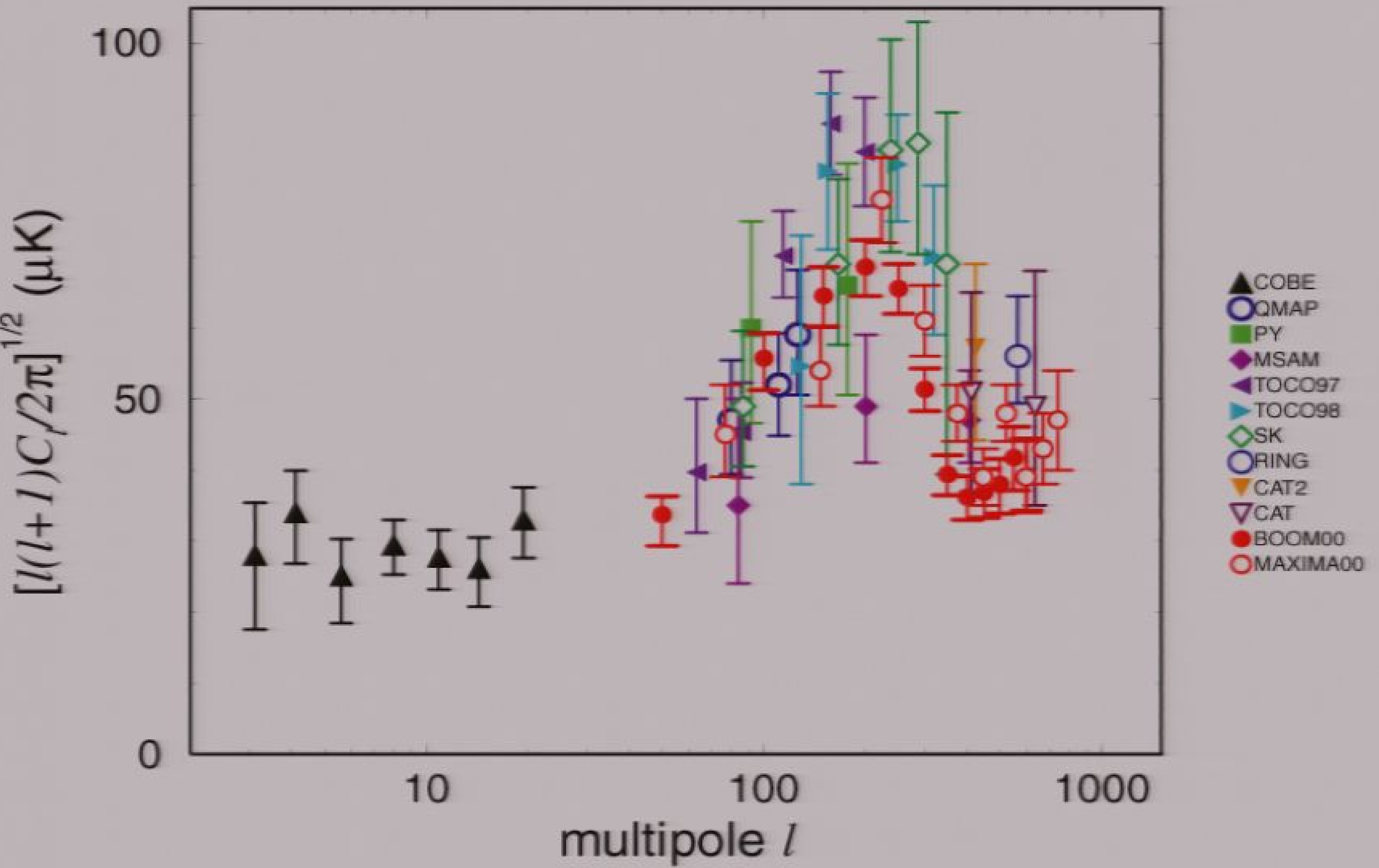
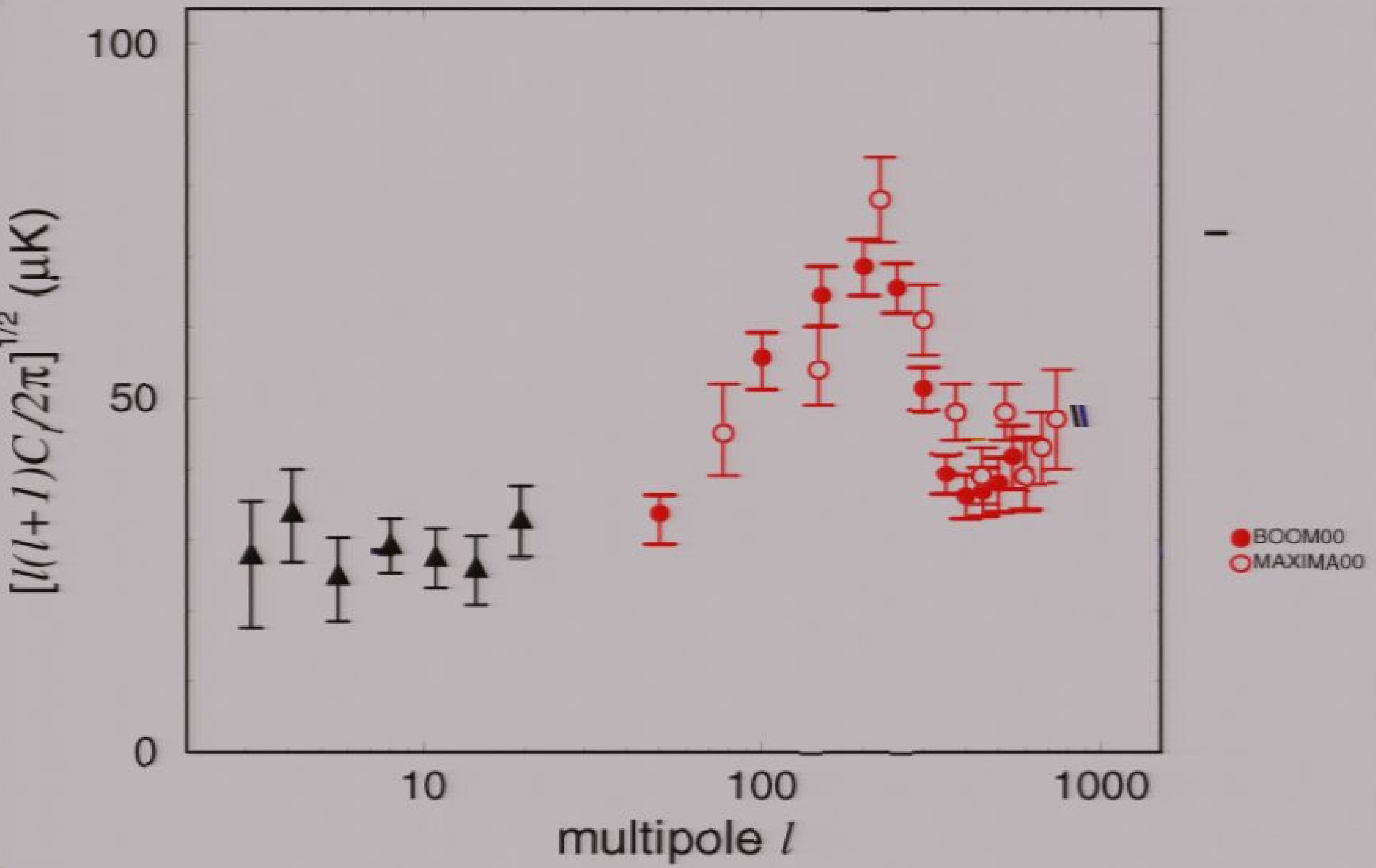
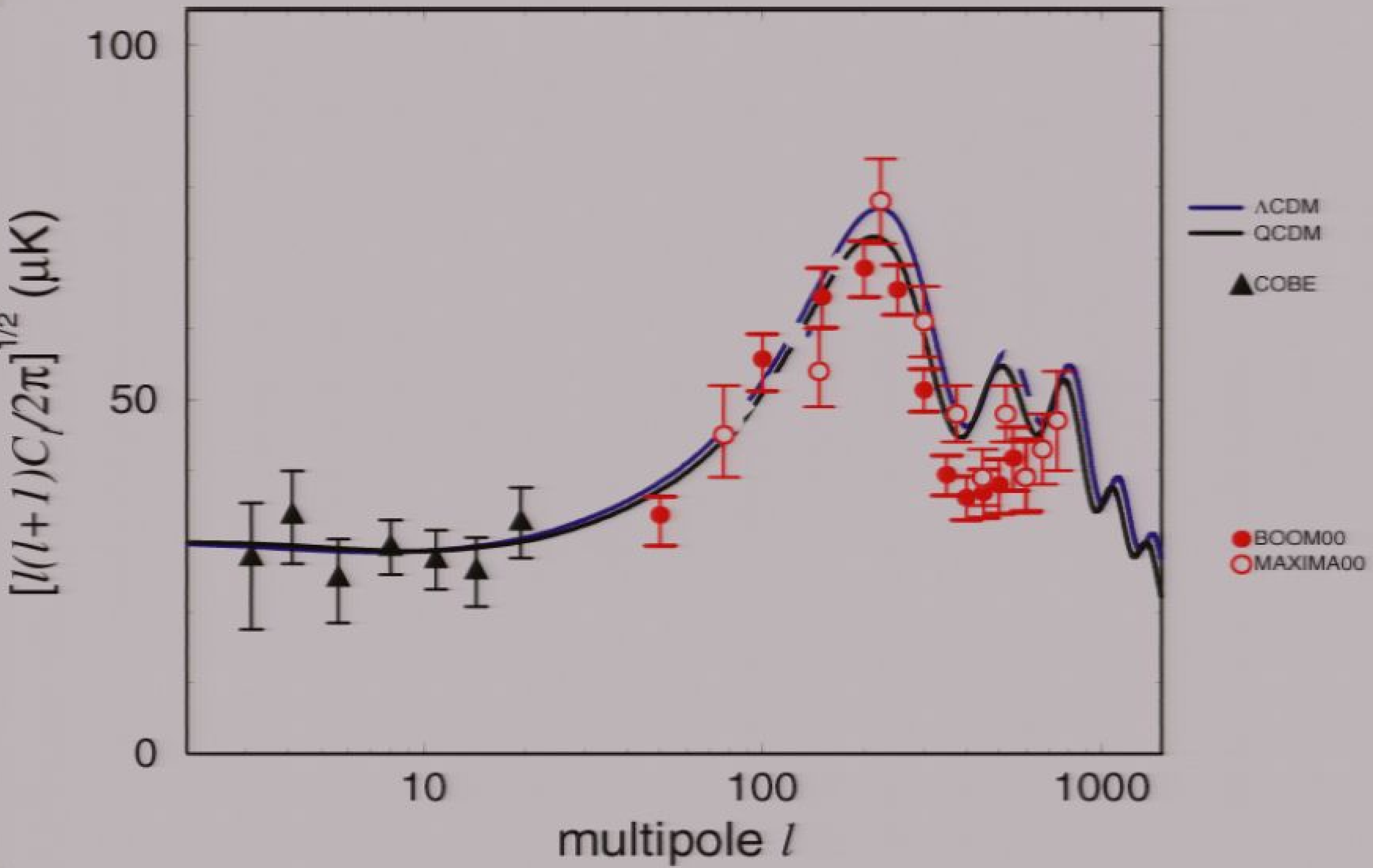
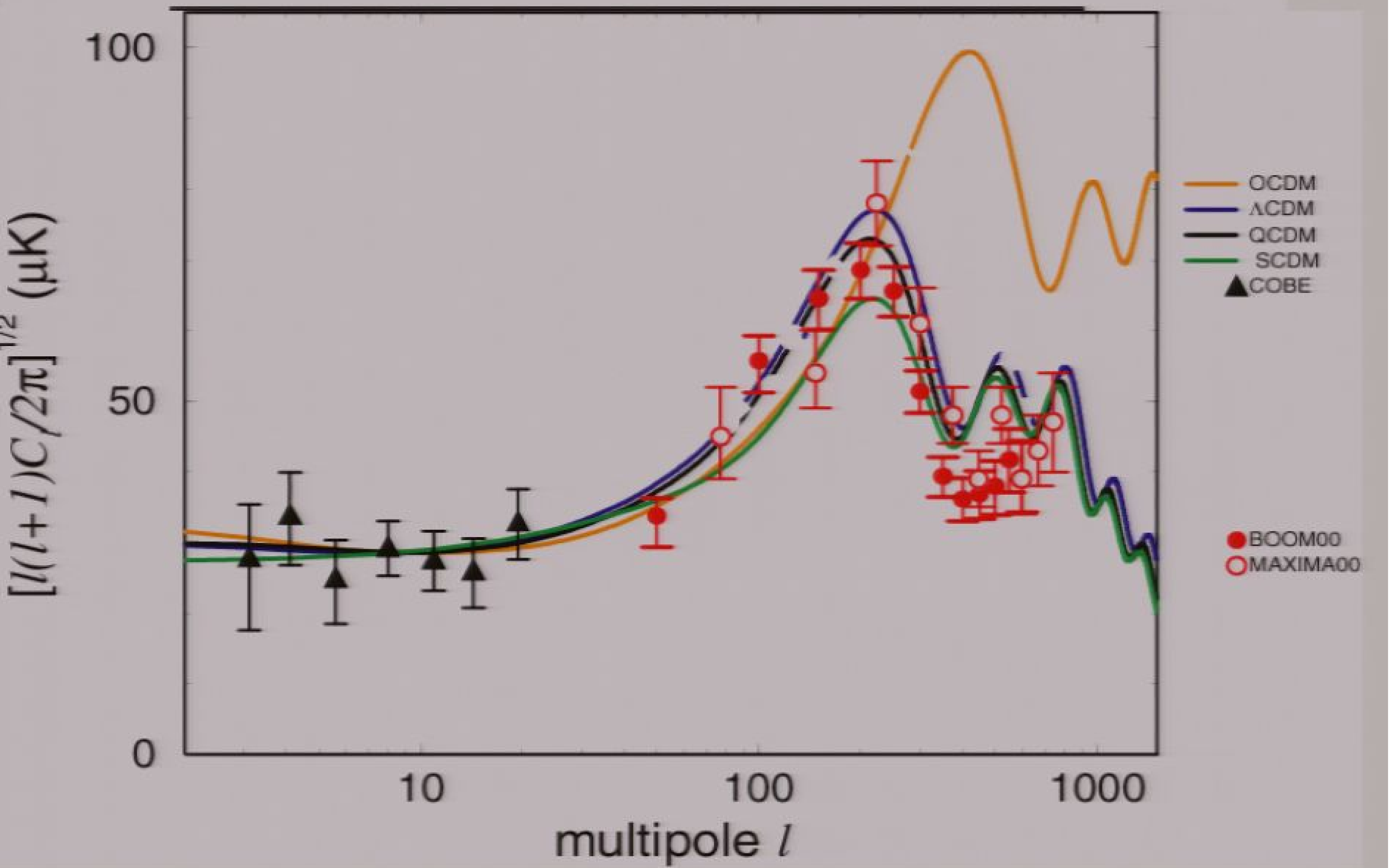
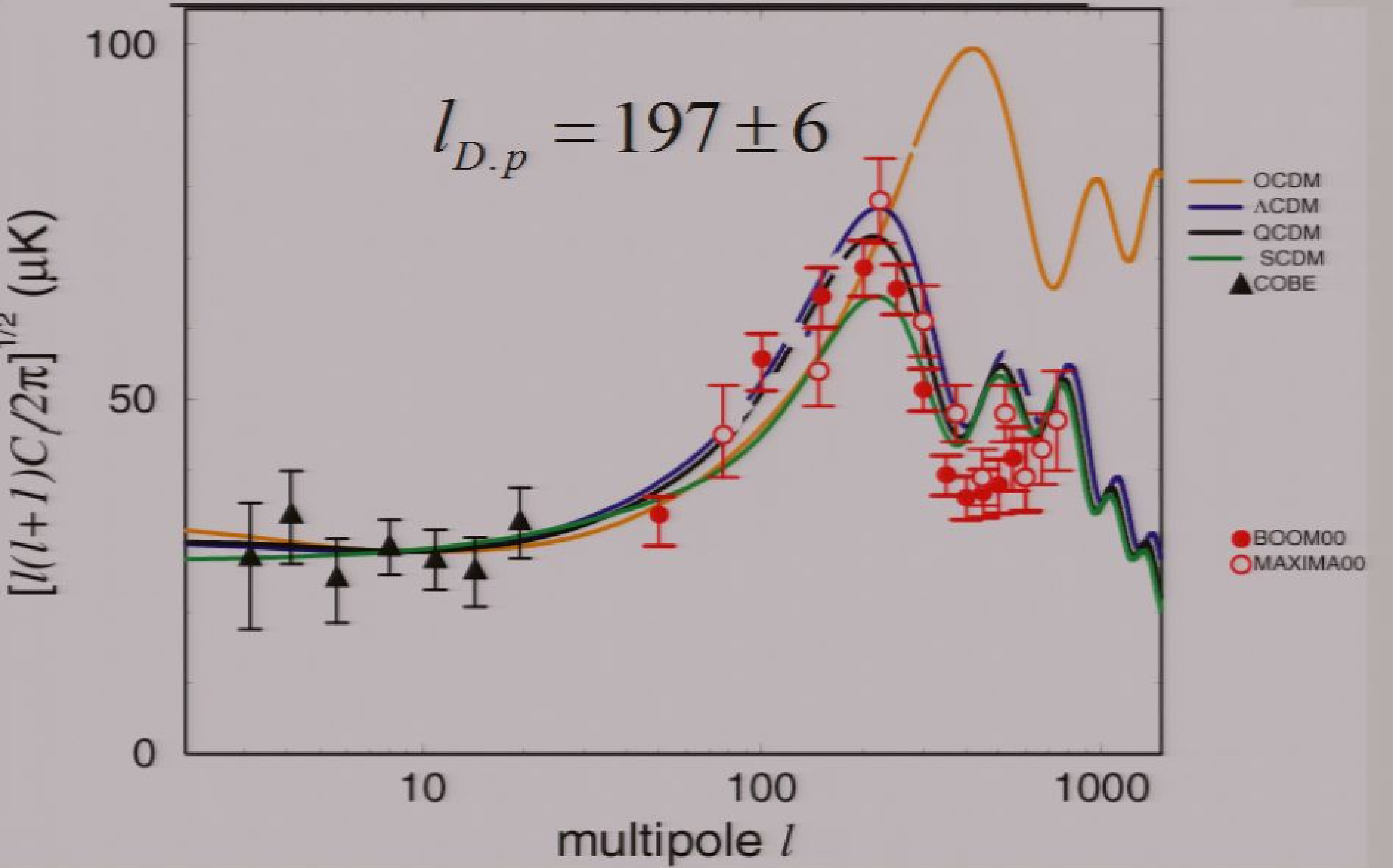


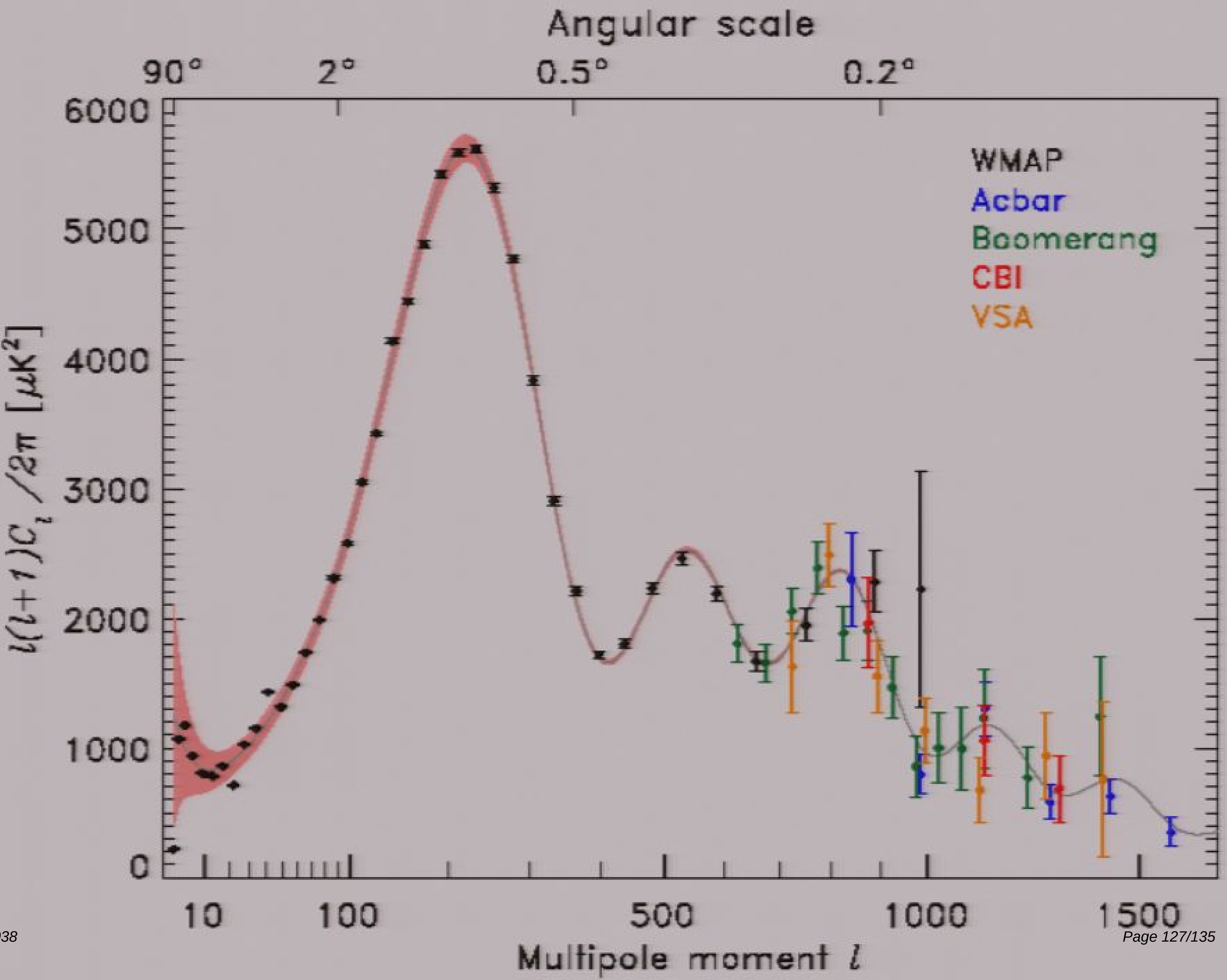

100
50
0
$[l(l+1)C_l/2\pi]^{1/2}$ (μK)
10
100
1000
multipole l
▲COBE
○QMAP
■PY
◆MSAM
◀TOCO97
▶TOCO98
◇SK
○RING
▼CAT2
▽CAT
●BOOM00
○MAXIMA00

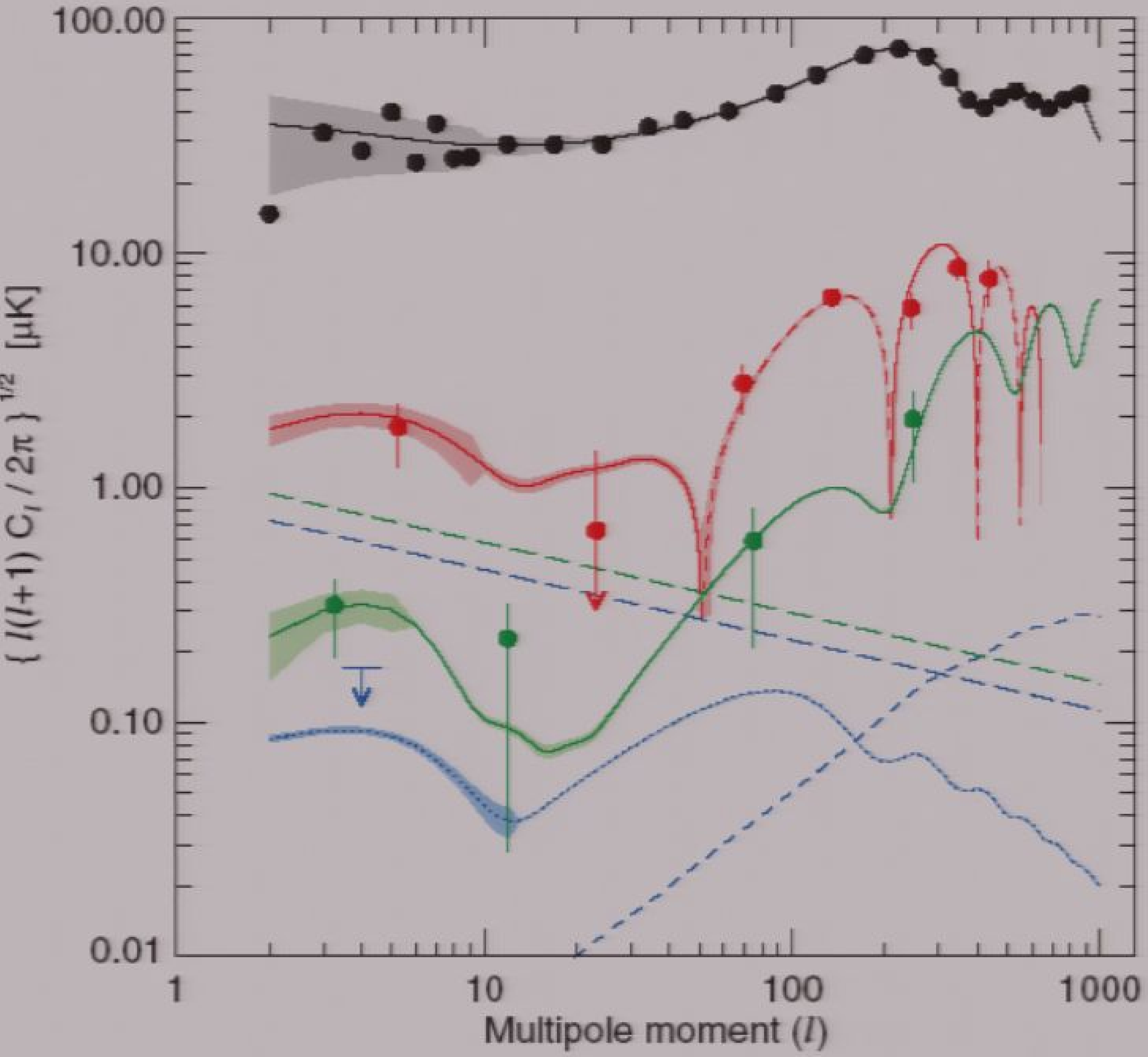

100
50
0
10
100
1000
multipole l
$[l(l+1)C/2\pi]^{1/2}$ (μK)
● BOOM00
○ MAXIMA00

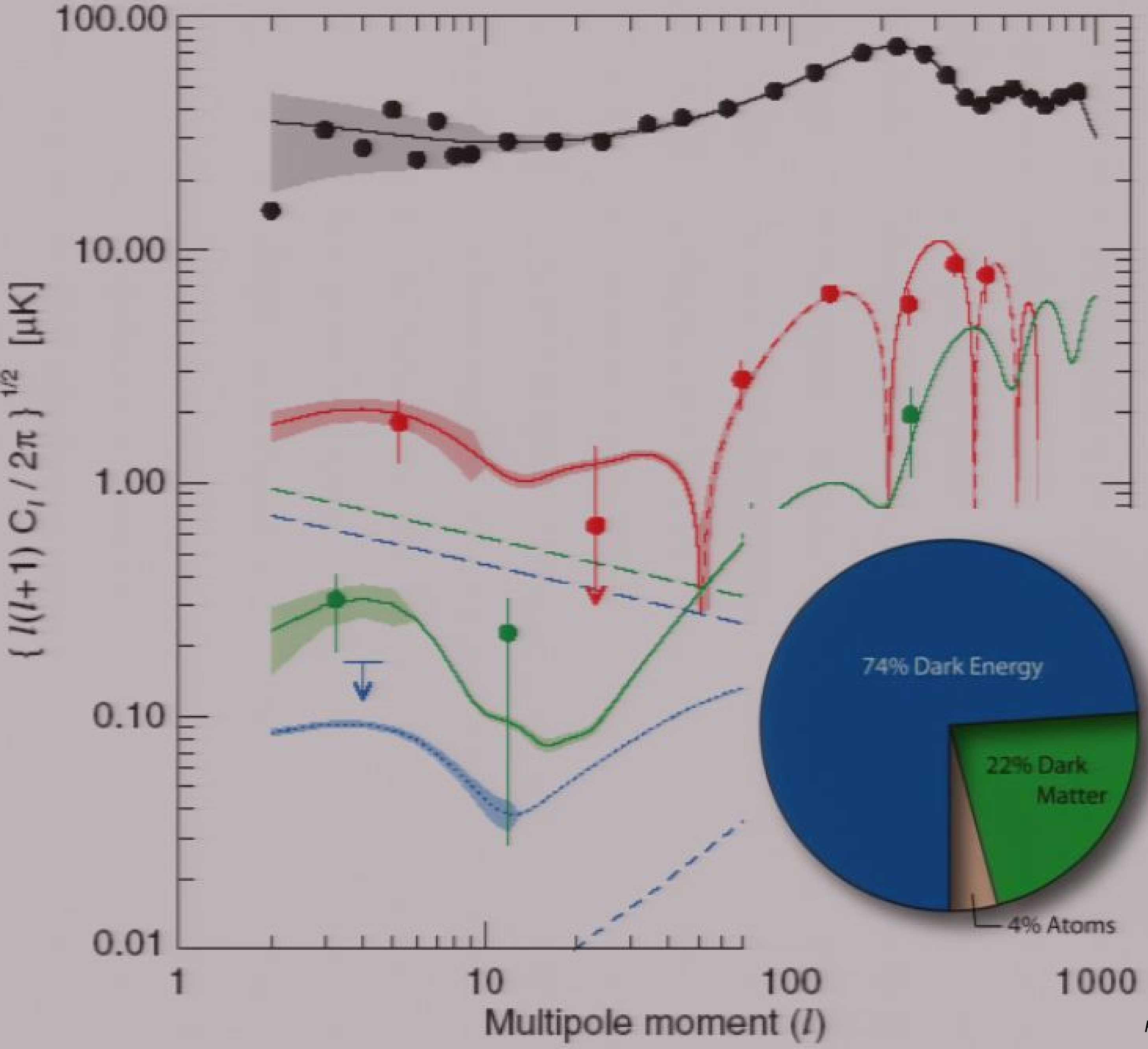

100
50
0
10
100
1000
multipole l
$[l(l+1)C_l/2\pi]^{1/2}$ (μK)
ΛCDM
QCDM
▲COBE
●BOOM00
○MAXIMA00


100
50
0
10
100
1000
multipole l
$[l(l+1)C_l/2\pi]^{1/2}$ (μK)
OCDM
ΛCDM
QCDM
SCDM
▲COBE
●BOOM00
○MAXIMA00


$l_{D.p} = 197 \pm 6$
100
50
0
10
100
1000
multipole l
$[l(l+1)C_l/2\pi]^{1/2}$ (μK)
OCDM
ΛCDM
QCDM
SCDM
▲COBE
●BOOM00
○MAXIMA00


Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
WMAP
Acbar
Boomerang
CBI
VSA
10
100
500
1000
1500
Multipole moment l


100.00
10.00
1.00
0.10
0.01
1
10
100
1000
Multipole moment (l)
$\{ l(l+1)\, C_l / 2\pi \}^{1/2}$ [μK]


100.00
10.00
1.00
0.10
0.01
{ $l(l+1)$ C_l / 2π } $^{1/2}$ [μK]
1
10
100
1000
Multipole moment (l)
74% Dark Energy
22% Dark Matter
4% Atoms

"A finite duration of the de Sitter stage does not by itself rule out the possibility that this stage may exist as an intermediate stage in the evolution of the universe. An interesting question arises here: Might not perturbations of the metric , which would be sufficient for the formation o galaxies and galactic clusters, arise in this stage?..........

$$Q(k) \approx 3lM\left(1+\frac{1}{2}\ln\frac{H}{k}\right)$$

The fluctuation spectrum is... nearly flat...."

(Mukhanov, Chibiov,1981)

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In terms of my own money, I'd bet a lot (many thousands)