Pre-inflationary homogenization of the Universe

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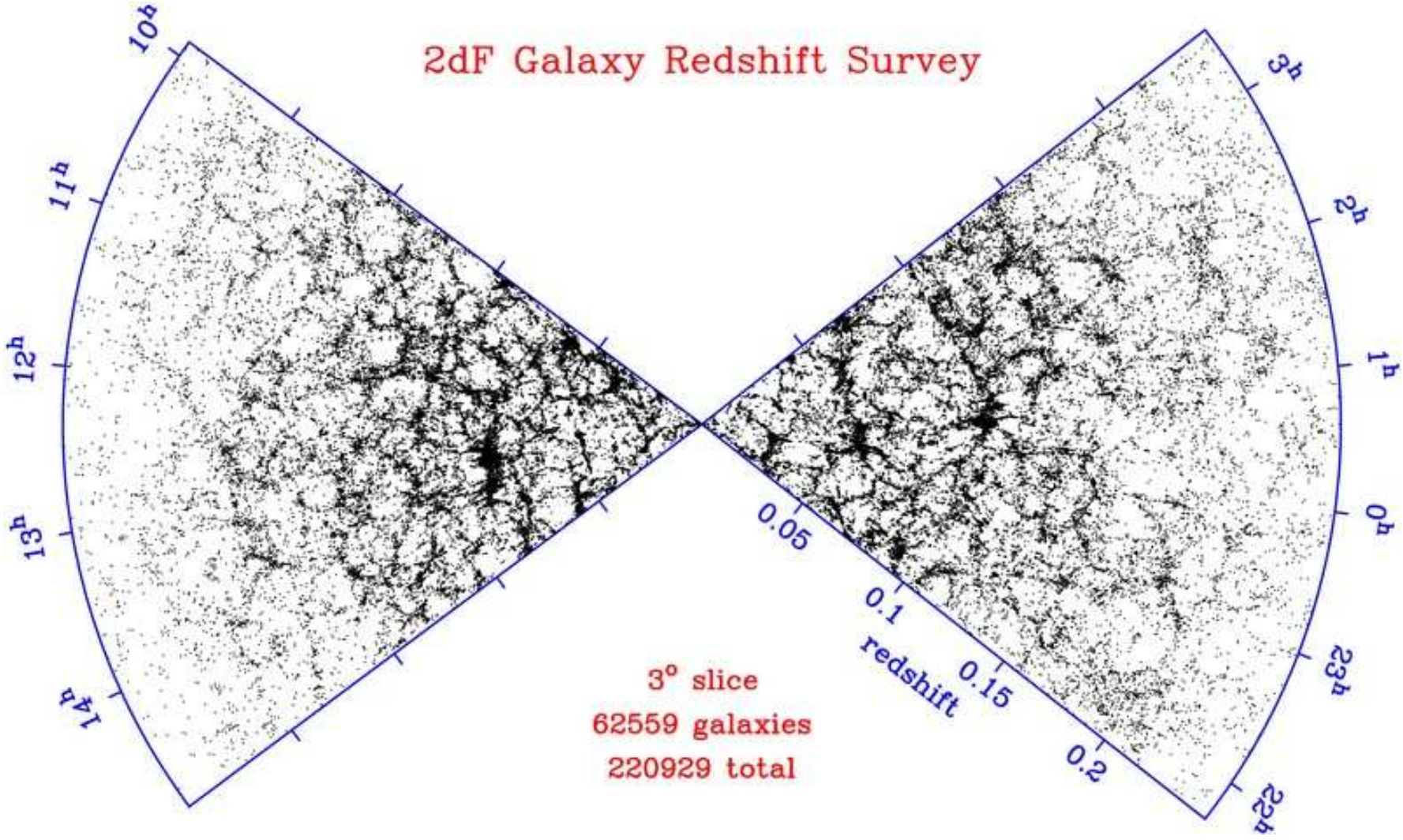
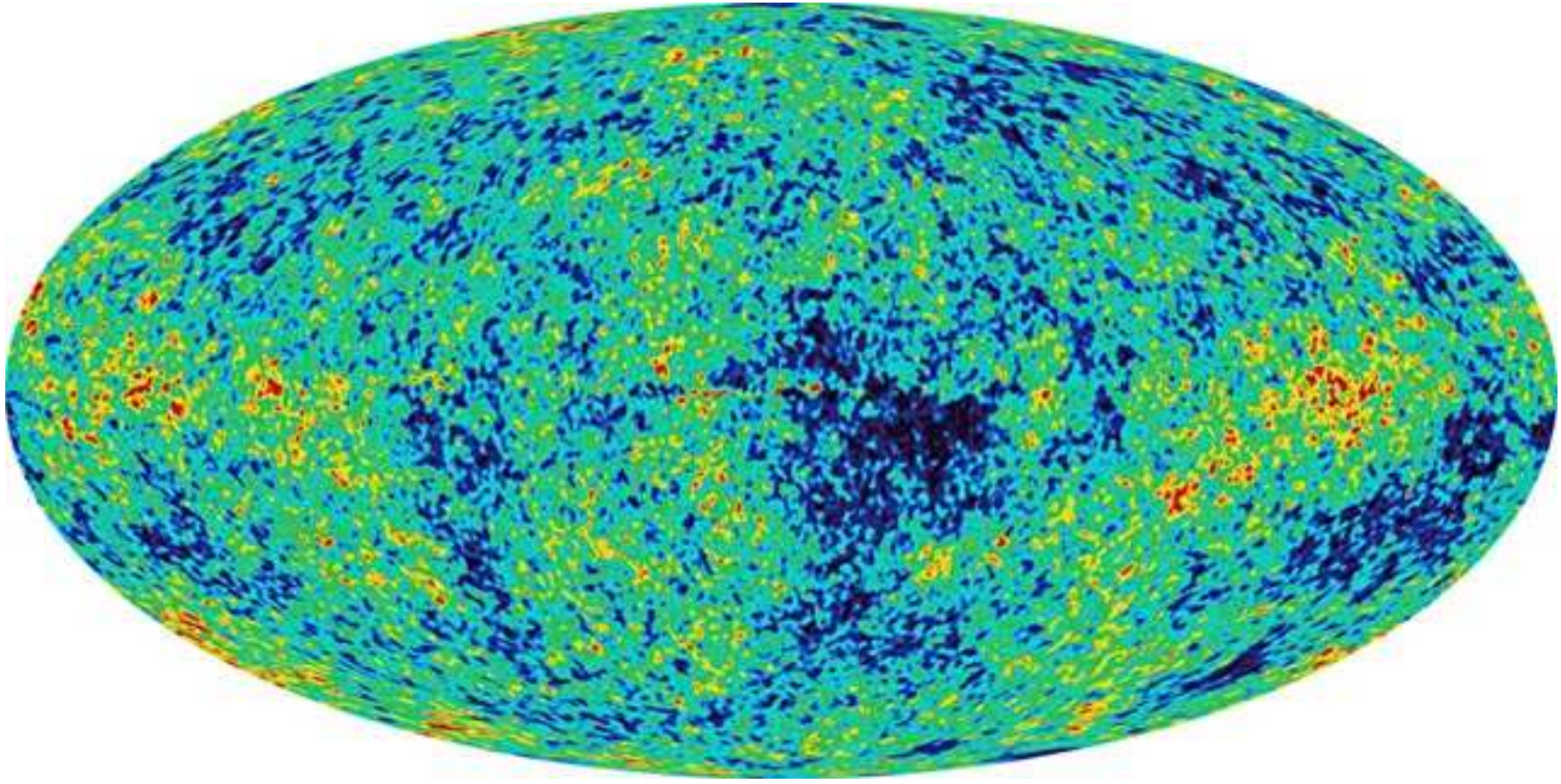
BritGrav2011, Glasgow, 6/4/11

Our Universe



CMB



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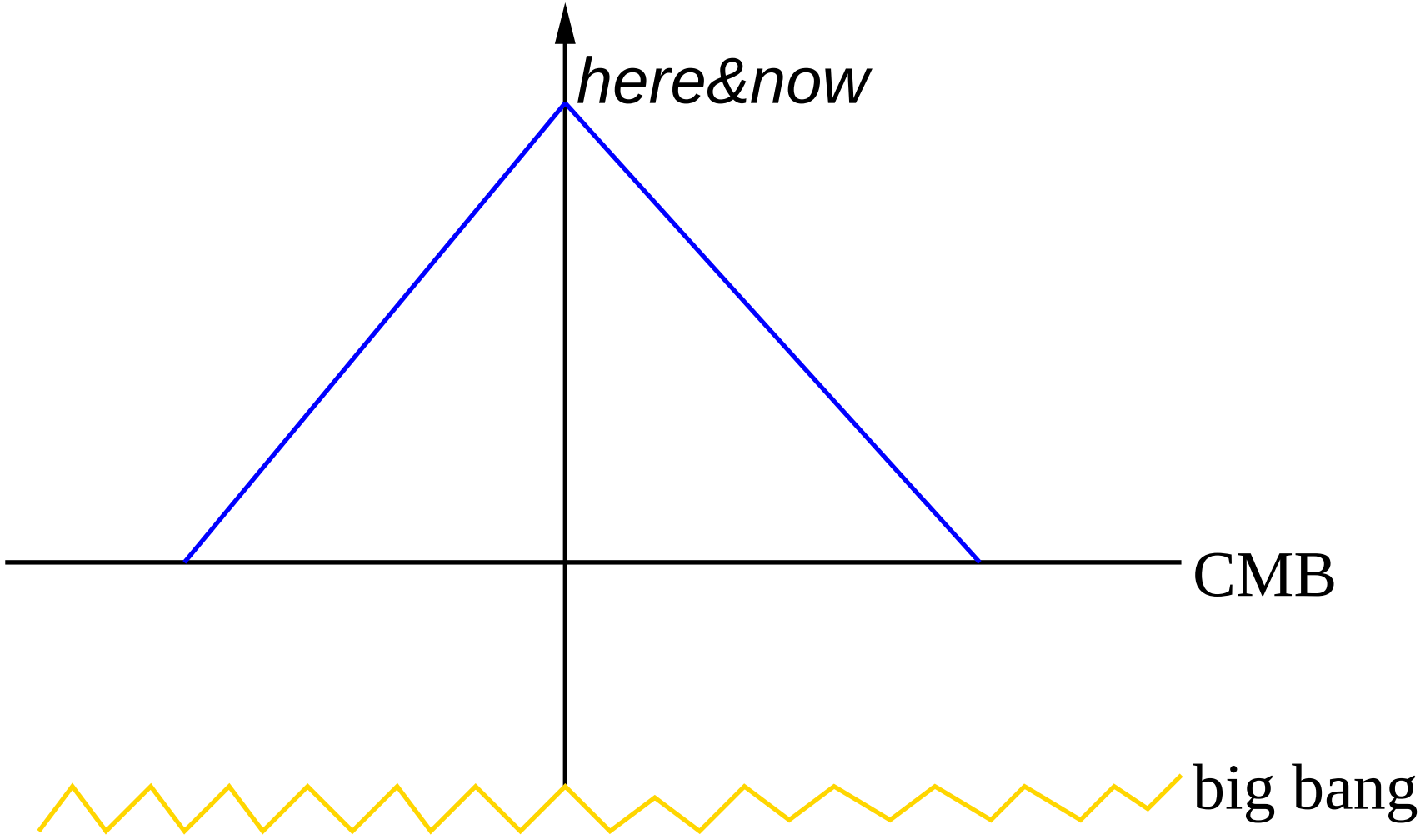

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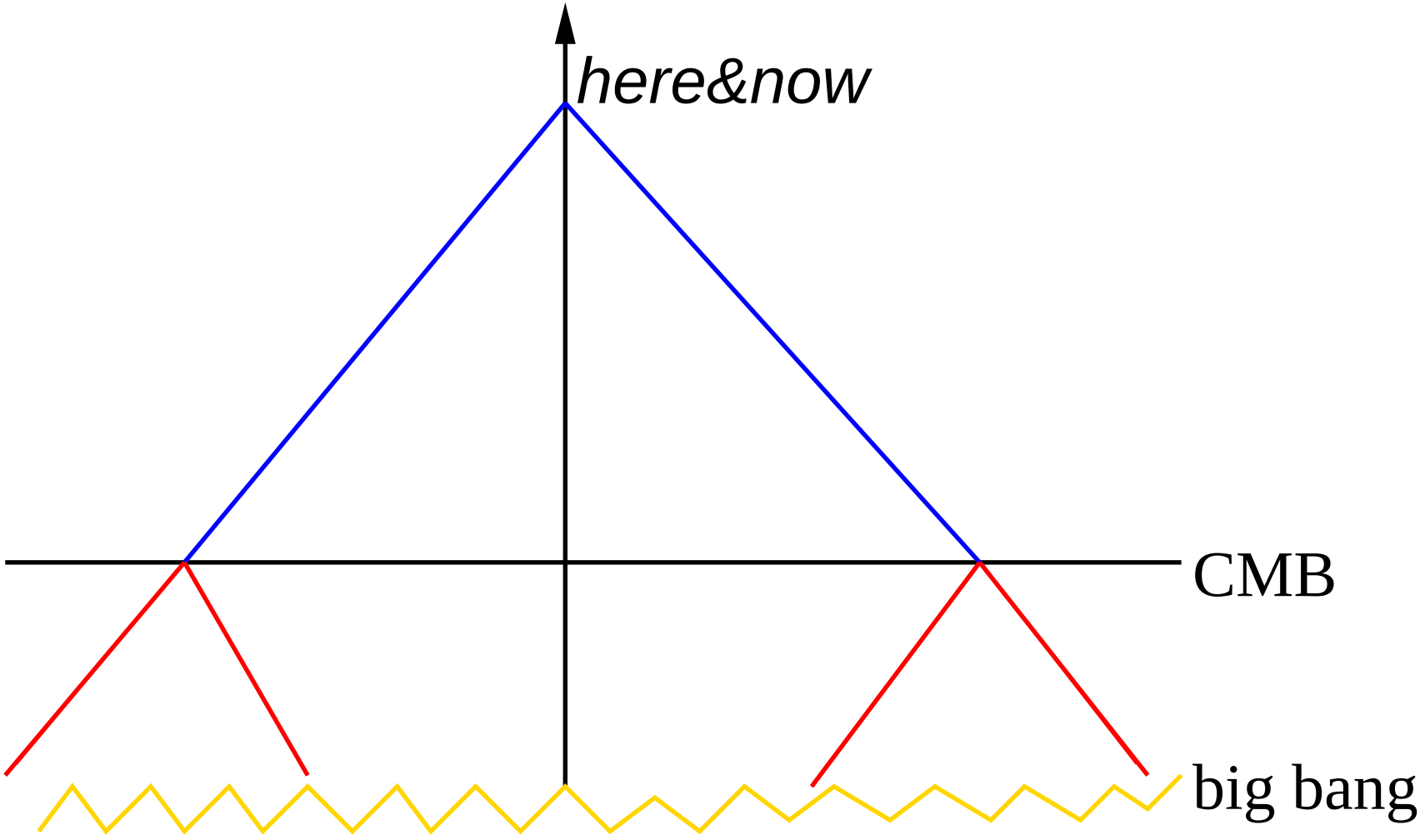
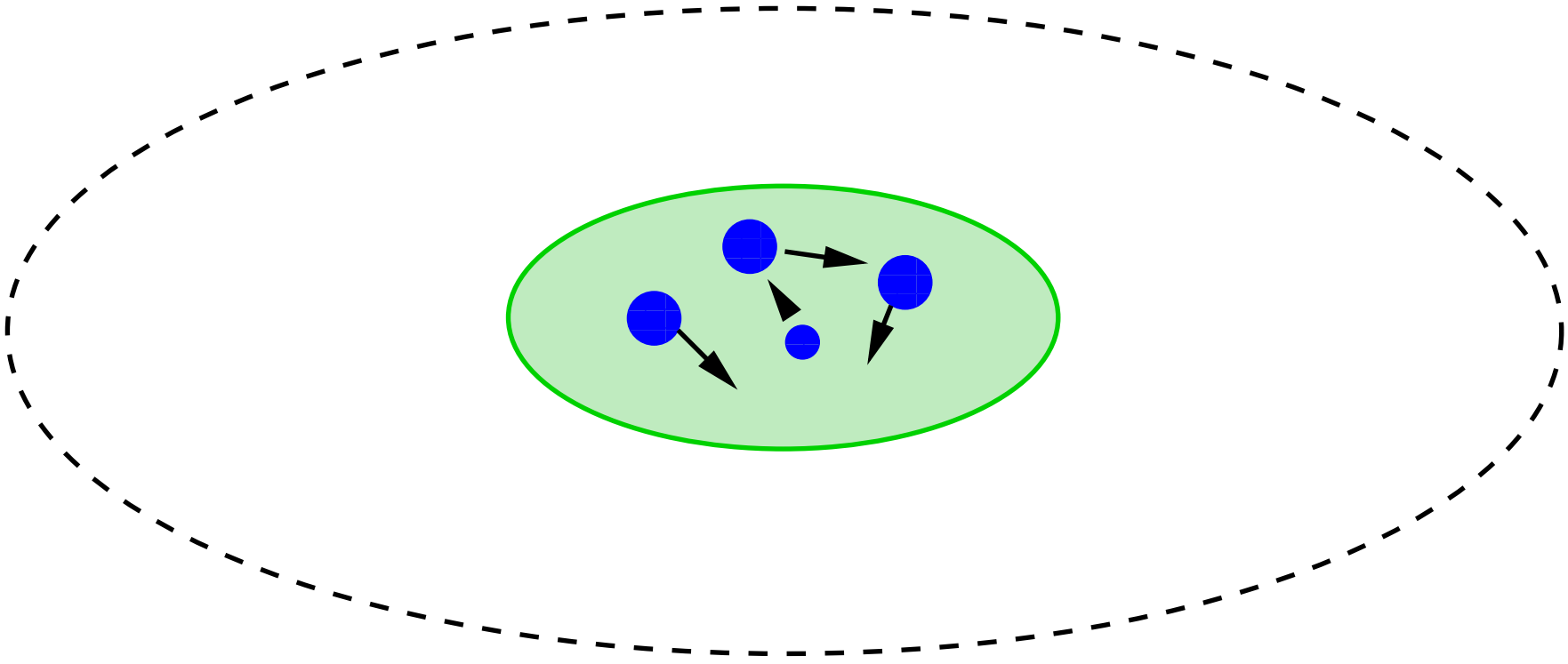
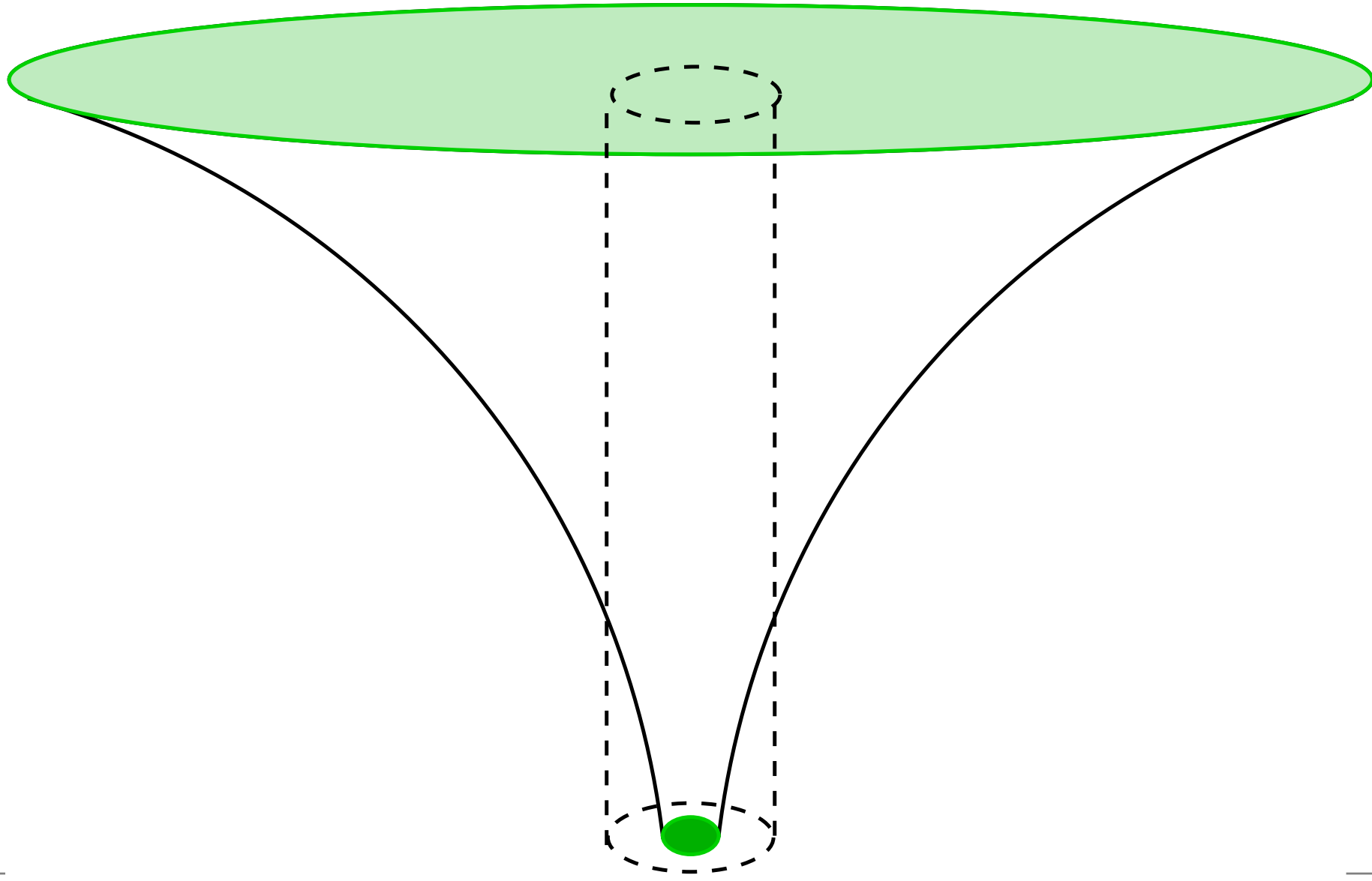


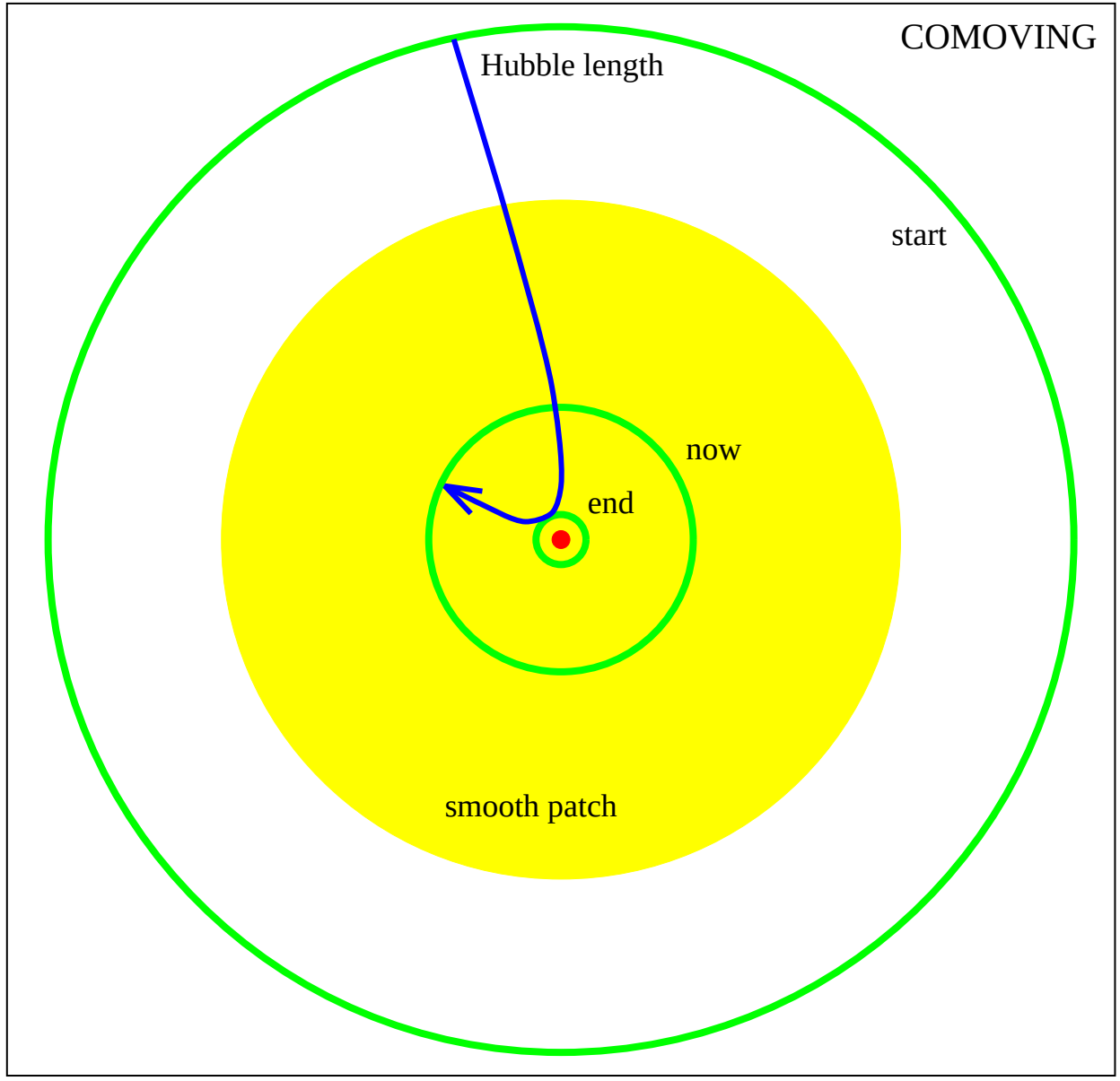
Inflation



Inflation

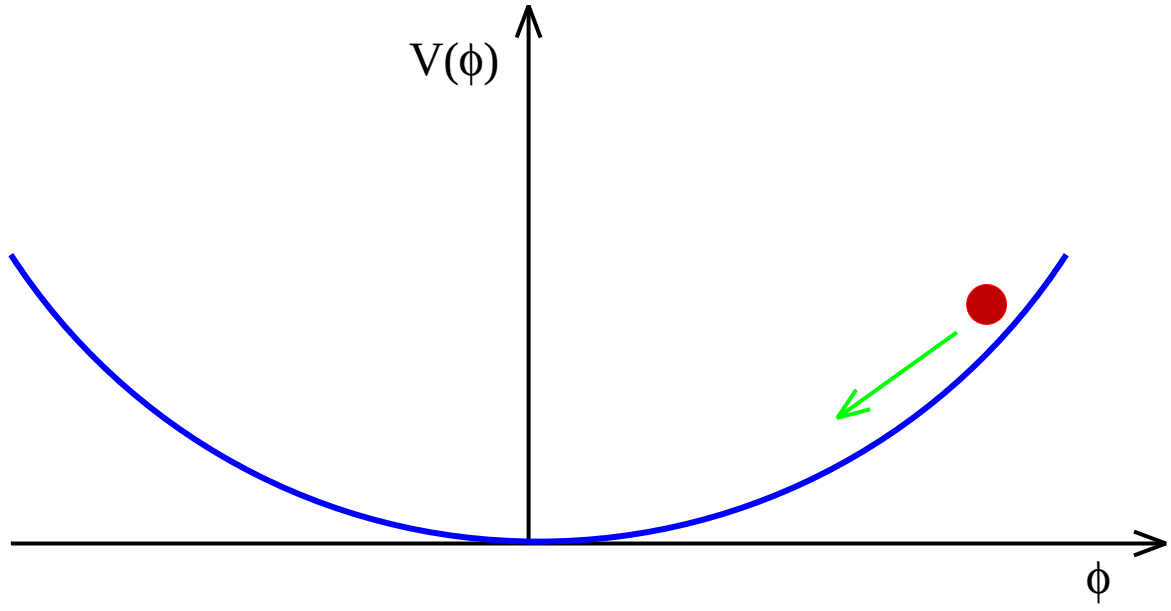


Inflation



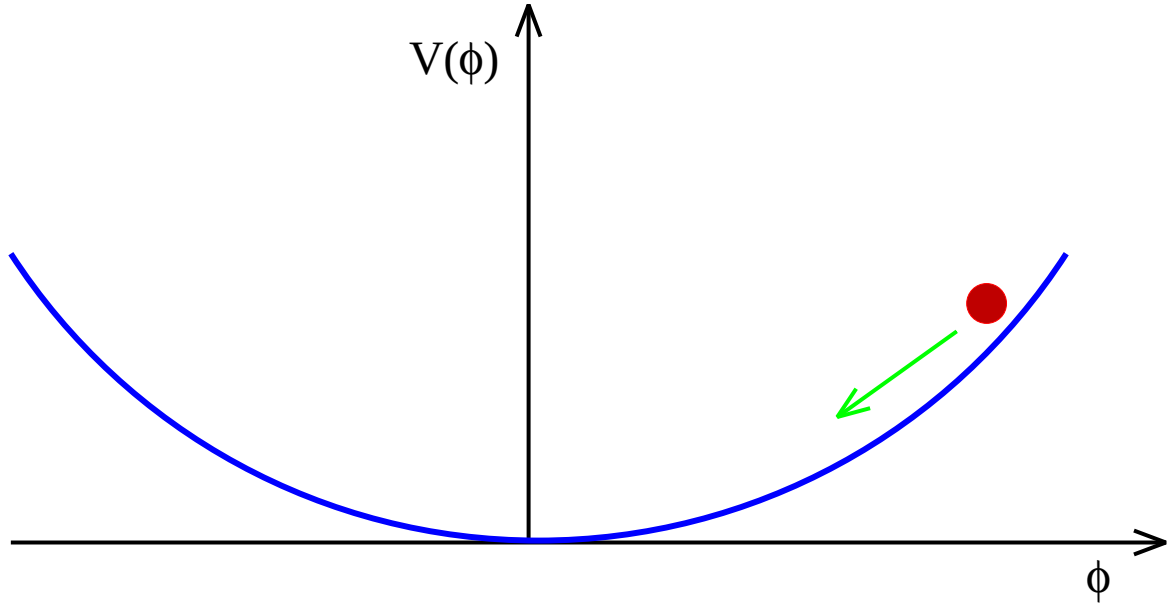
Liddle, arXiv:astro-ph/9901124 (1999)

Scalar field dynamics



$$\text{EFE} \quad \& \quad \phi^{;\alpha}{}_{;\alpha} + \frac{\partial V}{\partial \phi} = 0$$

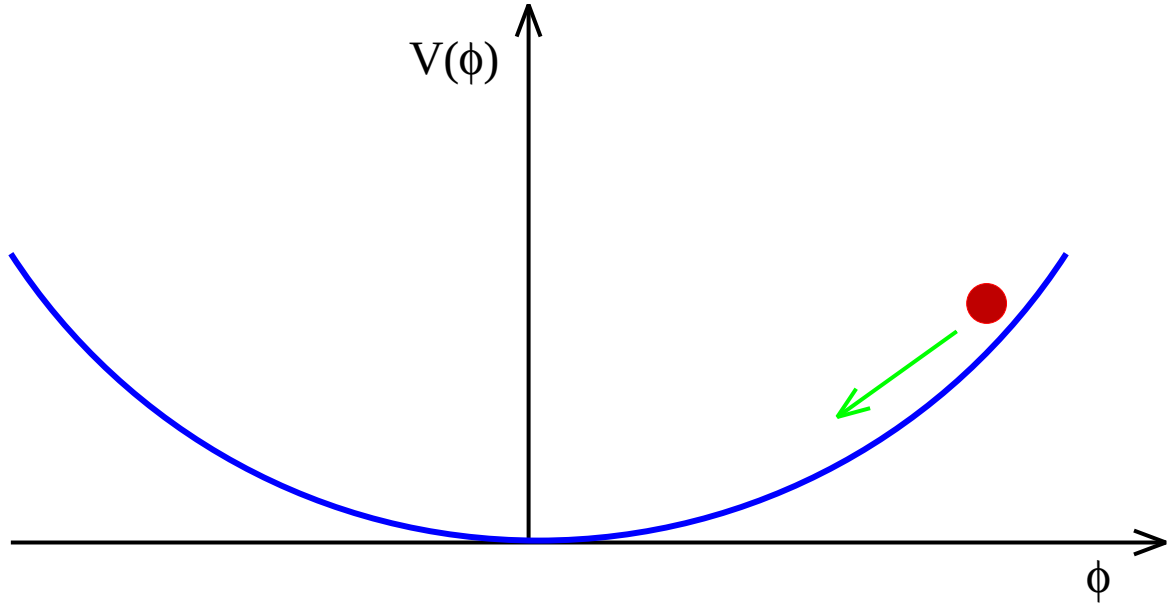
Scalar field dynamics



$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\pi}{3\mathrm{m}_{PL}^2}\left[V(\phi) + \frac{1}{2}\dot{\phi}^2\right]$$

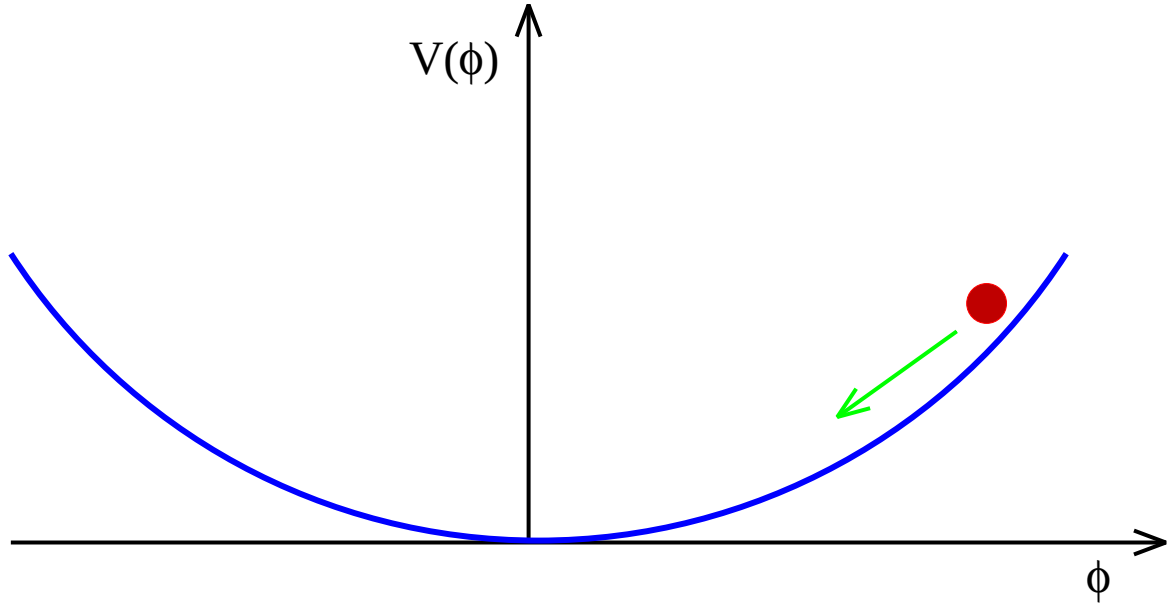
$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi)$$

Scalar field dynamics



$$\frac{\ddot{a}}{a} = \dot{H} + H^2 > 0$$

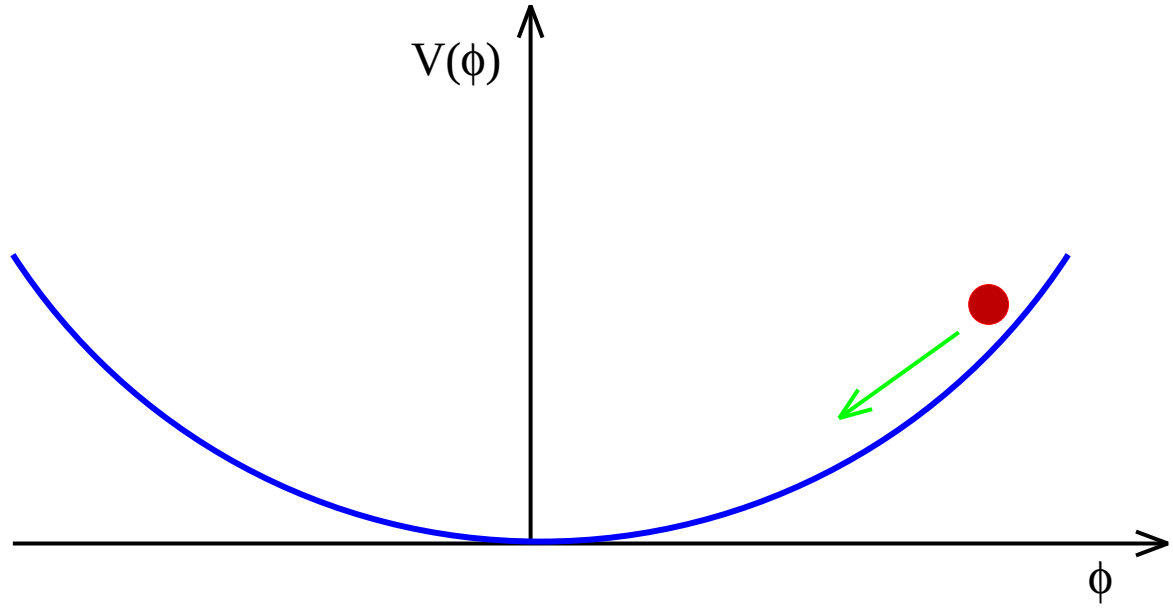
Scalar field dynamics



EFE

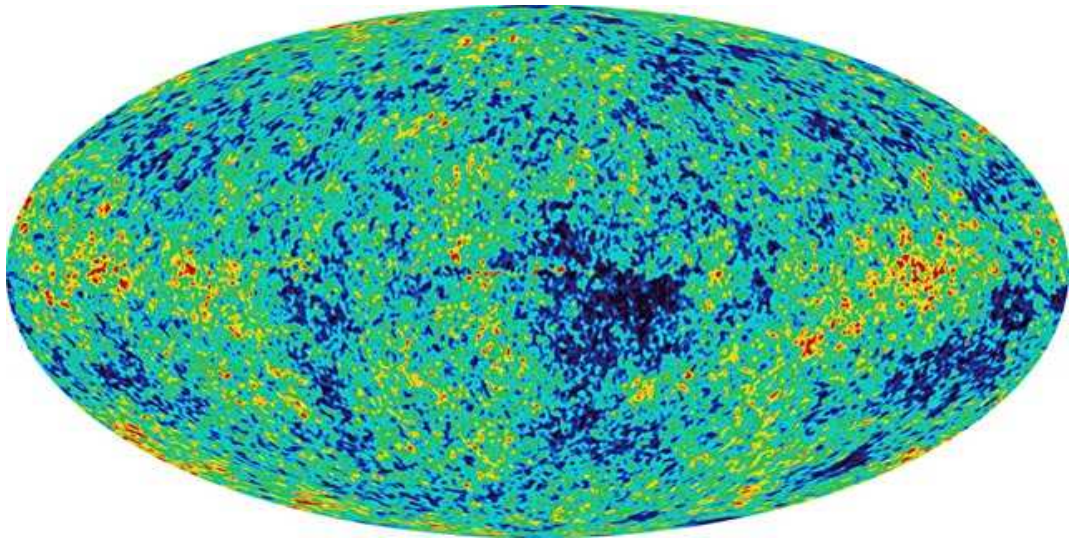
$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi\right)+\frac{\partial V}{\partial\phi}=0$$

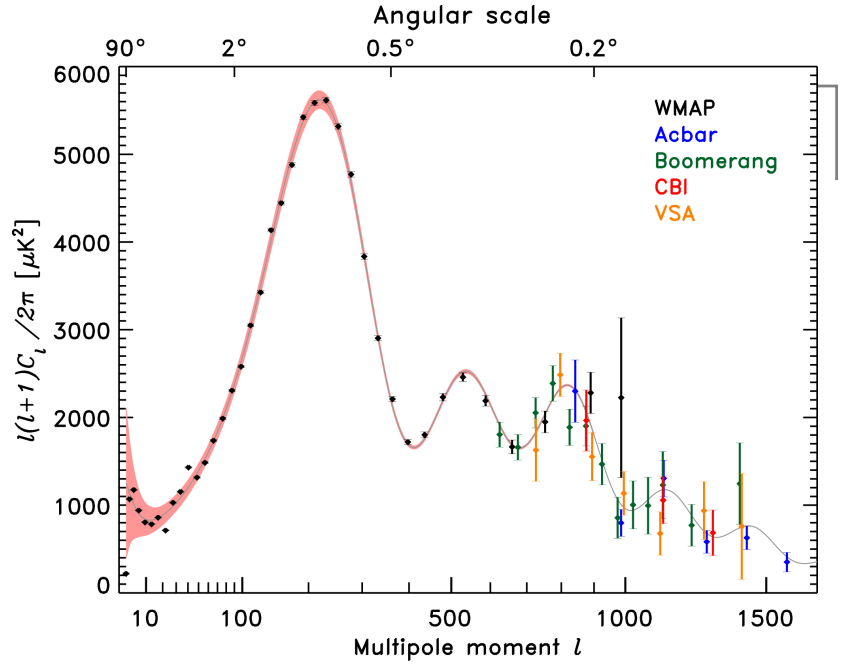
Scalar field dynamics



Stein-Schabes, *Phys. Rev.* **D35**, 2345 (1987)
Goldwirth &Piran, *Phys.Rev.* **D40**, 3263 (1989)
Goldwirth & Piran, *Phys. Rev. Lett.* **64**, 2852 (1990)
Goldwirth & Piran, *Phys.Rept* **214**, 223 (1992)
Calzetta & Sakellariadou, *Phys. Rev.* **D45**, 2802 (1992)

CMB





- does *not* solve the homogenization problem, *but*
- solves the horizon problem
- explains the origin of primordial fluctuations
- solves exotic particle problem
- ...

Evolution

$$
\begin{cases}
\dot{\Theta} = -\frac{1}{3}\,\Theta^2 - \frac{1}{2}\,(\rho + 3p) - 2(\sigma^2 - \omega^2) + \mathrm{D}^a A_a + A_a A^a + \Lambda \\
\dot{\sigma}_{\langle ab\rangle} = -\frac{2}{3}\,\Theta\sigma_{ab} - \sigma_{c\langle a}\sigma^c{}_{b\rangle} - \omega_{\langle a}\omega_{b\rangle} + \mathrm{D}_{\langle a}A_{b\rangle} + A_{\langle a}A_{b\rangle} \\
\qquad\qquad - E_{ab} + \frac{1}{2}\,\pi_{ab} \\
\dot{\omega}_{\langle a\rangle} = -\frac{2}{3}\,\Theta\omega_a - \frac{1}{2}\,\mathrm{curl}A_a + \sigma_{ab}\omega^b
\end{cases}
$$

$$
\begin{cases}
\dot{\rho} = -\Theta(\rho + p) - \sigma^{ab}\pi_{ab} \\
(\rho + p)A_a = -\mathrm{D}_a p - \mathrm{D}^b\pi_{ab} - \pi_{ab}A^b
\end{cases}
$$

$$
\begin{cases}
\dot{E}_{\langle ab\rangle} = -\Theta E_{ab} - \frac{1}{2}\,(\rho + p)\sigma_{ab} + \mathrm{curl}H_{ab} - \frac{1}{2}\,\dot{\pi}_{ab} - \frac{1}{6}\,\Theta\pi_{ab} \\
\qquad\qquad + 3\sigma_{\langle a}{}^c\left(E_{b\rangle c} - \frac{1}{6}\,\pi_{b\rangle c}\right) + \varepsilon_{cd\langle a}\left[2A^c H_{b\rangle}{}^d - \omega^c\left(E_{b\rangle}{}^d + \frac{1}{2}\,\pi_{b\rangle}{}^d\right)\right] \\
\dot{H}_{\langle ab\rangle} = -\Theta H_{ab} - \mathrm{curl}E_{ab} + \frac{1}{2}\,\mathrm{curl}\pi_{ab} + 3\sigma_{\langle a}{}^c H_{b\rangle c} - \\
\qquad\qquad - \varepsilon_{cd\langle a}\left(2A^c E_{b\rangle}{}^d + \omega^c H_{b\rangle}{}^d\right)
\end{cases}
$$

Evolution

$$2\nabla_{[a}\nabla_{b]}u_c = R_{abcd}u^d$$

$$\begin{cases} \dot{\rho} = -\Theta(\rho + p) - \sigma^{ab}\pi_{ab} \\ (\rho + p)A_a = -\mathrm{D}_a p - \mathrm{D}^b\pi_{ab} - \pi_{ab}A^b \end{cases}$$

$$\begin{cases} \dot{E}_{\langle ab\rangle} = -\Theta E_{ab} - \frac{1}{2}(\rho + p)\sigma_{ab} + \mathrm{curl}H_{ab} - \frac{1}{2}\dot{\pi}_{ab} - \frac{1}{6}\Theta\pi_{ab} \\ \qquad + 3\sigma_{\langle a}{}^c\left(E_{b\rangle c} - \frac{1}{6}\pi_{b\rangle c}\right) + \varepsilon_{cd\langle a}\left[2A^c H_{b\rangle}{}^d - \omega^c\left(E_{b\rangle}{}^d + \frac{1}{2}\pi_{b\rangle}{}^d\right)\right] \\ \dot{H}_{\langle ab\rangle} = -\Theta H_{ab} - \mathrm{curl}E_{ab} + \frac{1}{2}\mathrm{curl}\pi_{ab} + 3\sigma_{\langle a}{}^c H_{b\rangle c} - \\ \qquad - \varepsilon_{cd\langle a}\left(2A^c E_{b\rangle}{}^d + \omega^c H_{b\rangle}{}^d\right) \end{cases}$$

Evolution

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\begin{cases}
\dot{\Theta} = -\frac{1}{3}\,\Theta^2 - \frac{1}{2}\,(\rho + 3p) - 2(\sigma^2 - \omega^2) + \mathrm{D}^a A_a + A_a A^a + \Lambda \\
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\qquad\qquad - E_{ab} + \frac{1}{2}\,\pi_{ab} \\
\dot{\omega}_{\langle a\rangle} = -\frac{2}{3}\,\Theta\omega_a - \frac{1}{2}\,\mathrm{curl}A_a + \sigma_{ab}\omega^b
\end{cases}
$$

$$\nabla^b T_{ab} = 0$$

$$
\begin{cases}
\dot{E}_{\langle ab\rangle} = -\Theta E_{ab} - \frac{1}{2}\,(\rho + p)\sigma_{ab} + \mathrm{curl}H_{ab} - \frac{1}{2}\,\dot{\pi}_{ab} - \frac{1}{6}\,\Theta\pi_{ab} \\
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Evolution

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$$\begin{cases} \dot{\rho} = -\Theta(\rho + p) - \sigma^{ab}\pi_{ab} \\ (\rho + p)A_a = -\mathrm{D}_a p - \mathrm{D}^b\pi_{ab} - \pi_{ab}A^b \end{cases}$$

$$\nabla^d C_{abcd} = \nabla_{[b}R_{a]c} + \frac{1}{6}\,g_{c[b}\nabla_{a]}R$$

Evolution

$$\begin{cases} \dot{\Theta} = -\frac{1}{3}\,\Theta^2 - \frac{1}{2}\,(\rho + 3p) - 2(\sigma^2 - \omega^2) + \mathrm{D}^a A_a + A_a A^a + \Lambda \\ \dot{\sigma}_{\langle ab\rangle} = -\frac{2}{3}\,\Theta\sigma_{ab} - \sigma_{c\langle a}\sigma^c{}_{b\rangle} - \omega_{\langle a}\omega_{b\rangle} + \mathrm{D}_{\langle a}A_{b\rangle} + A_{\langle a}A_{b\rangle} \\ \qquad\qquad - E_{ab} + \frac{1}{2}\,\pi_{ab} \\ \dot{\omega}_{\langle a\rangle} = -\frac{2}{3}\,\Theta\omega_a - \frac{1}{2}\,\mathrm{curl}A_a + \sigma_{ab}\omega^b \end{cases}$$

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Evolution

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\begin{cases}
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$$
\begin{cases}
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\qquad\qquad - \varepsilon_{cd\langle a}\left(2A^c E_{b\rangle}{}^{d} + \omega^c H_{b\rangle}{}^{d}\right)
\end{cases}
$$

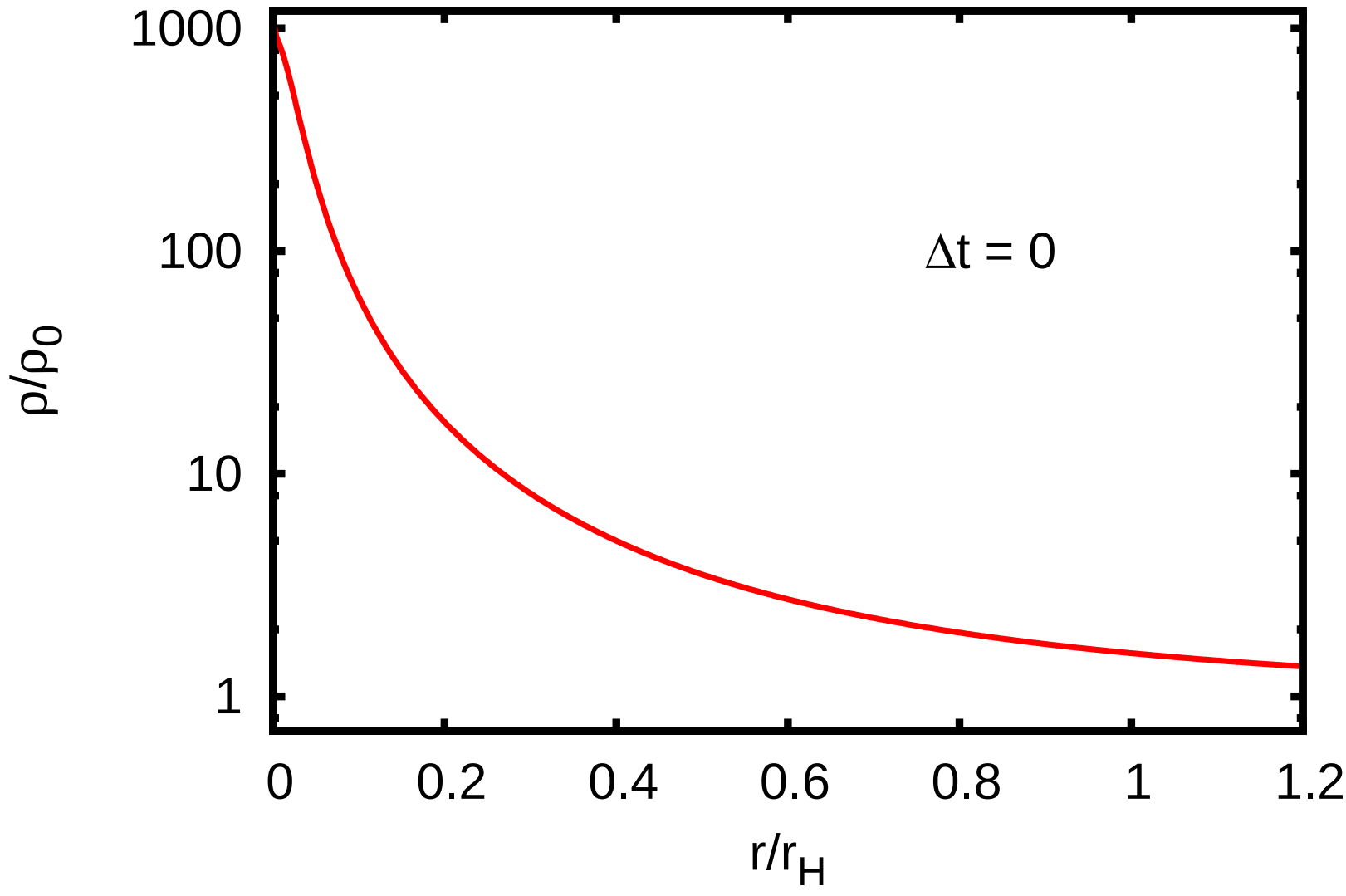
Evolution

$$\begin{cases} \dot{\Theta} = -\frac{1}{3}\,\Theta^2 - \frac{1}{2}\,(\rho + 3p) - 2\sigma^2 + \mathrm{D}^a A_a + A_a A^a \\ \dot{\sigma} = \mathcal{F} - \frac{1}{\sqrt{3}}\sigma^2 - \frac{2}{3}\Theta\sigma - \frac{1}{2\sqrt{3}}(\rho - \overline{\rho}) \end{cases}$$

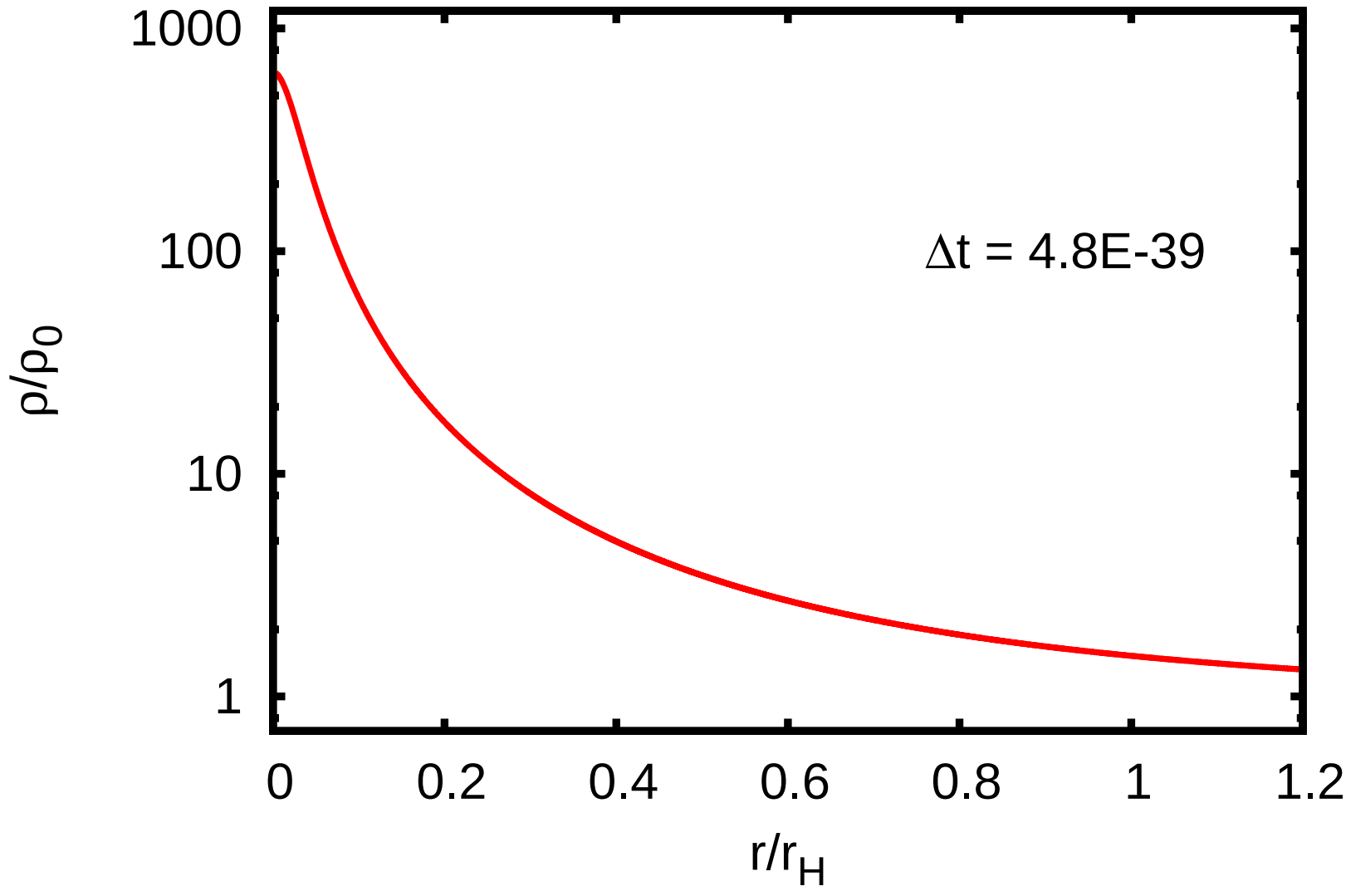
$$\begin{cases} \dot{\rho} = -\Theta(\rho + p) + \lambda\sigma^2 \\ (\rho + p)A = -p' + \frac{2}{\sqrt{3}}(\lambda\sigma)' + 2\sqrt{3}\lambda\sigma R'/R \end{cases}$$

$$\begin{cases} E = \frac{1}{4}(\rho - \overline{\rho}) \\ H = 0 \end{cases}$$

$$t_i = 10^{-34}s \quad T = 10^{14}GeV$$



$$t_i = 10^{-34}s \quad T = 10^{14}GeV$$



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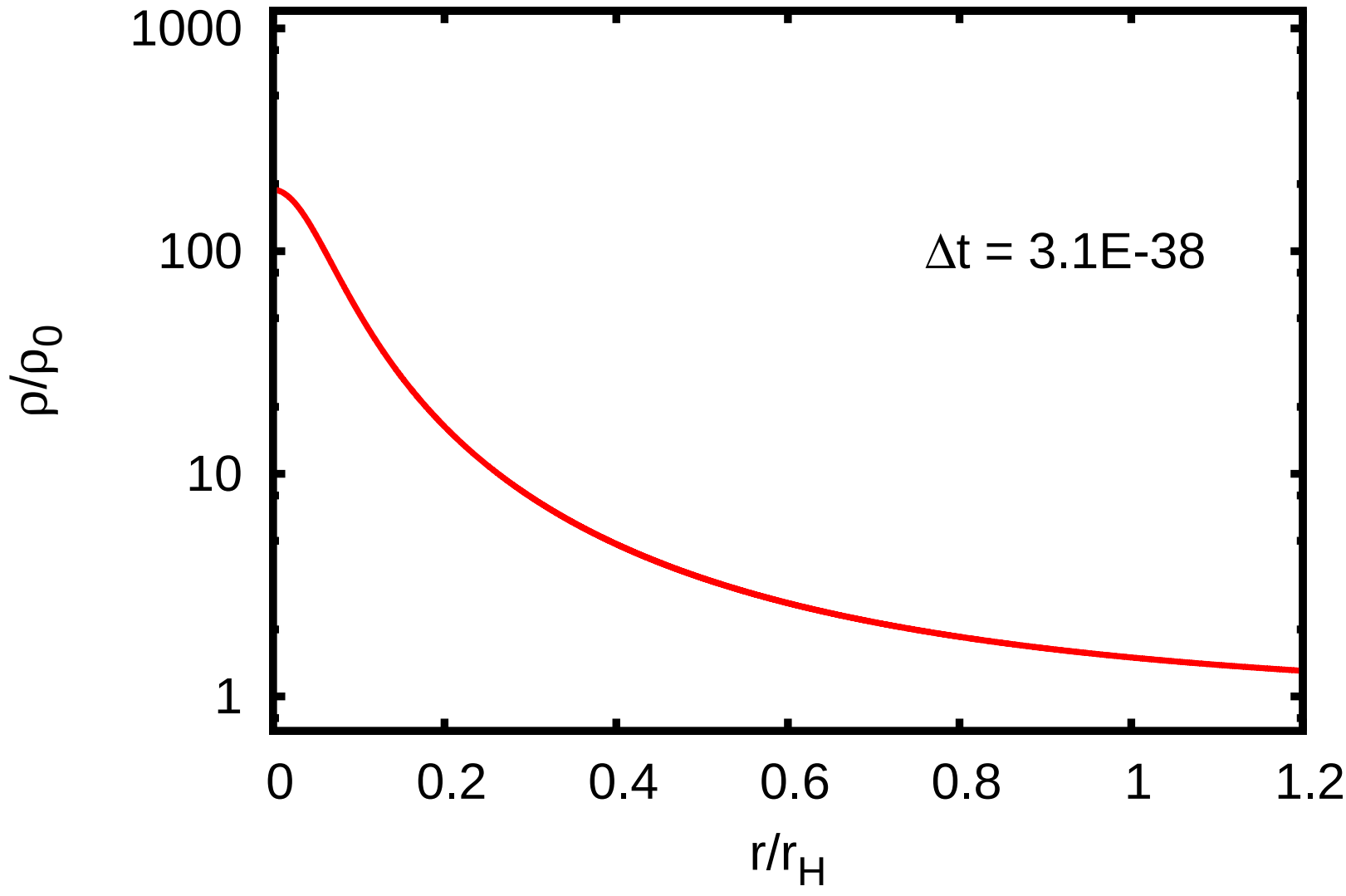

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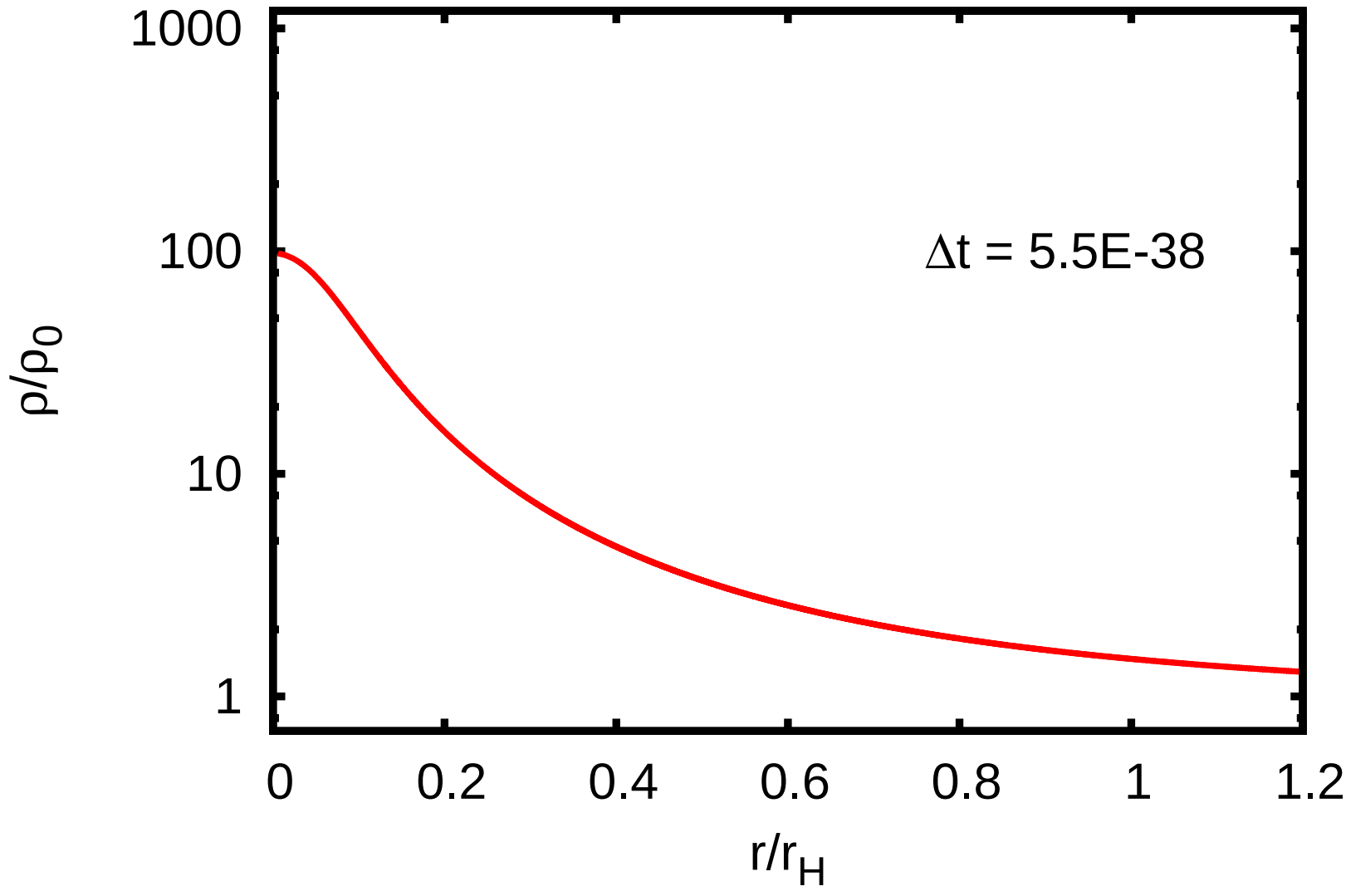

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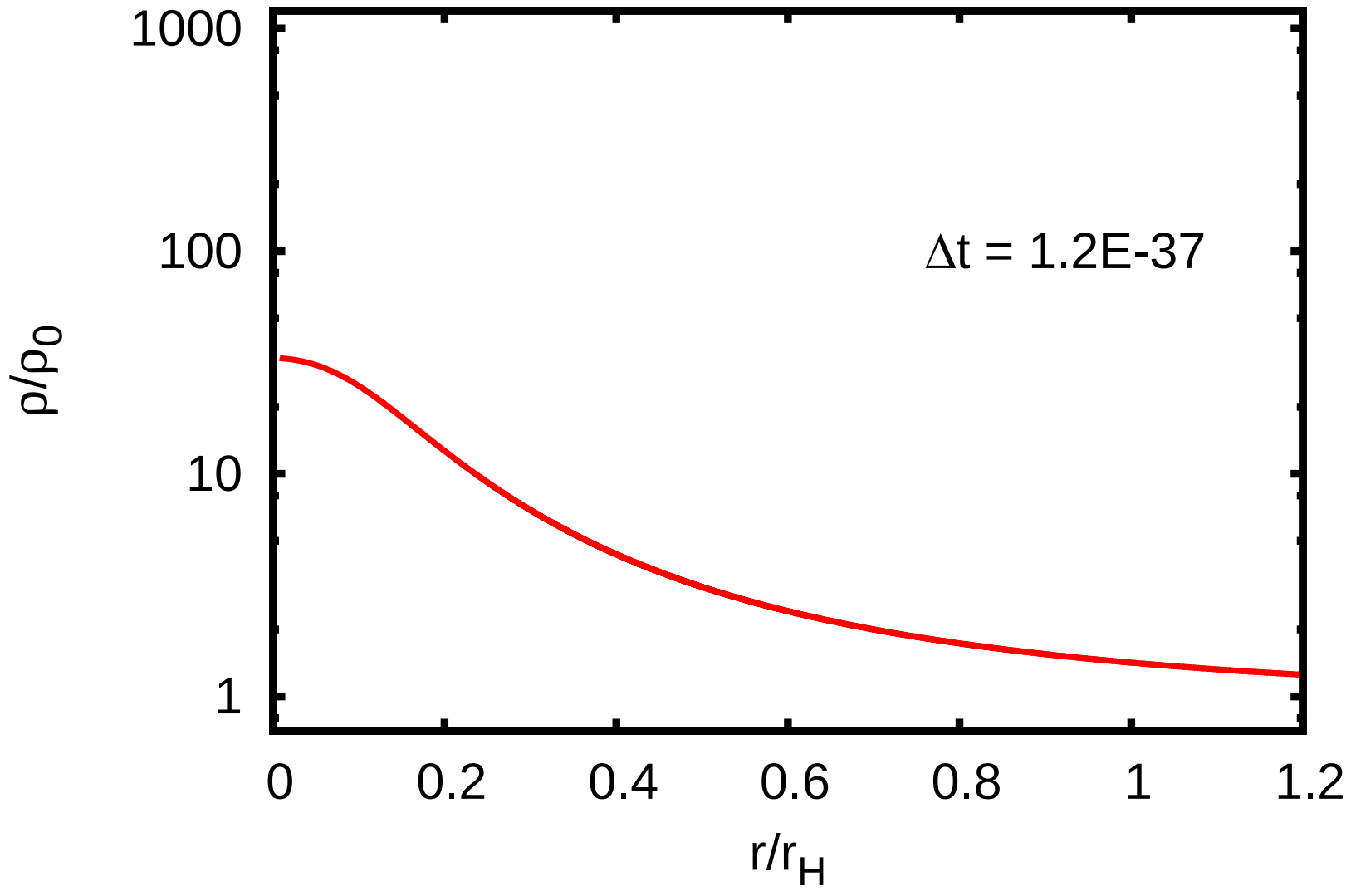

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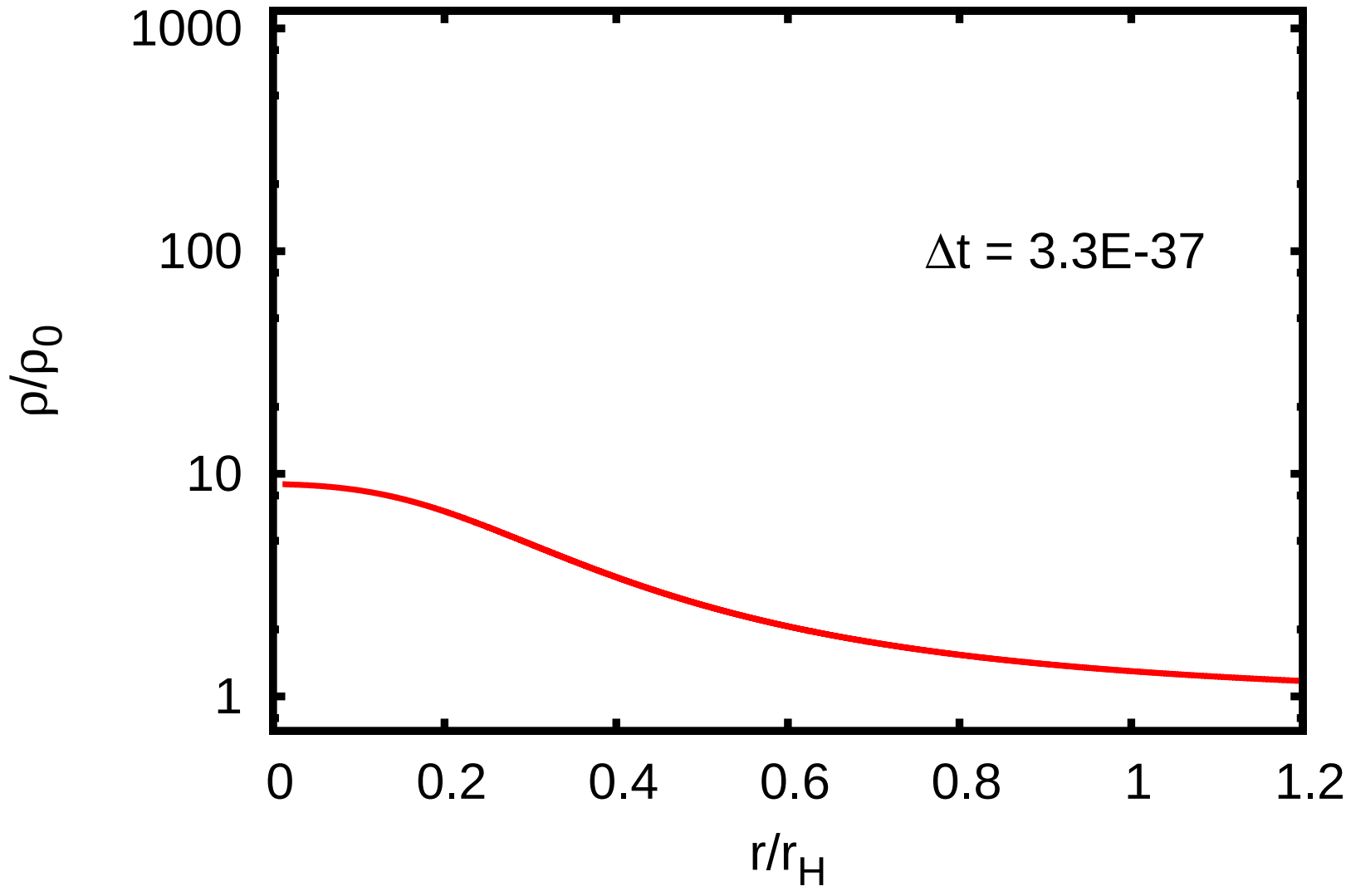
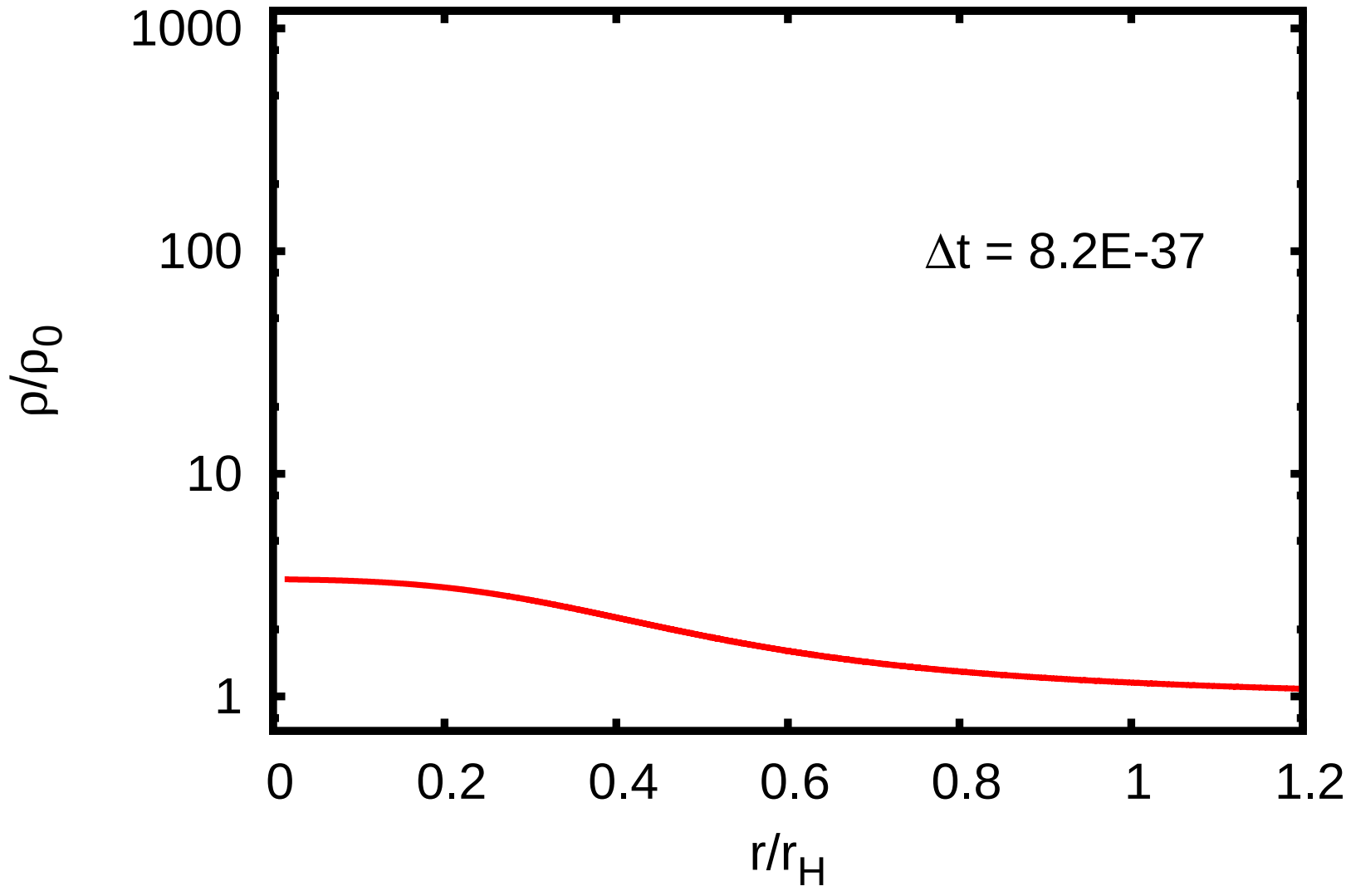
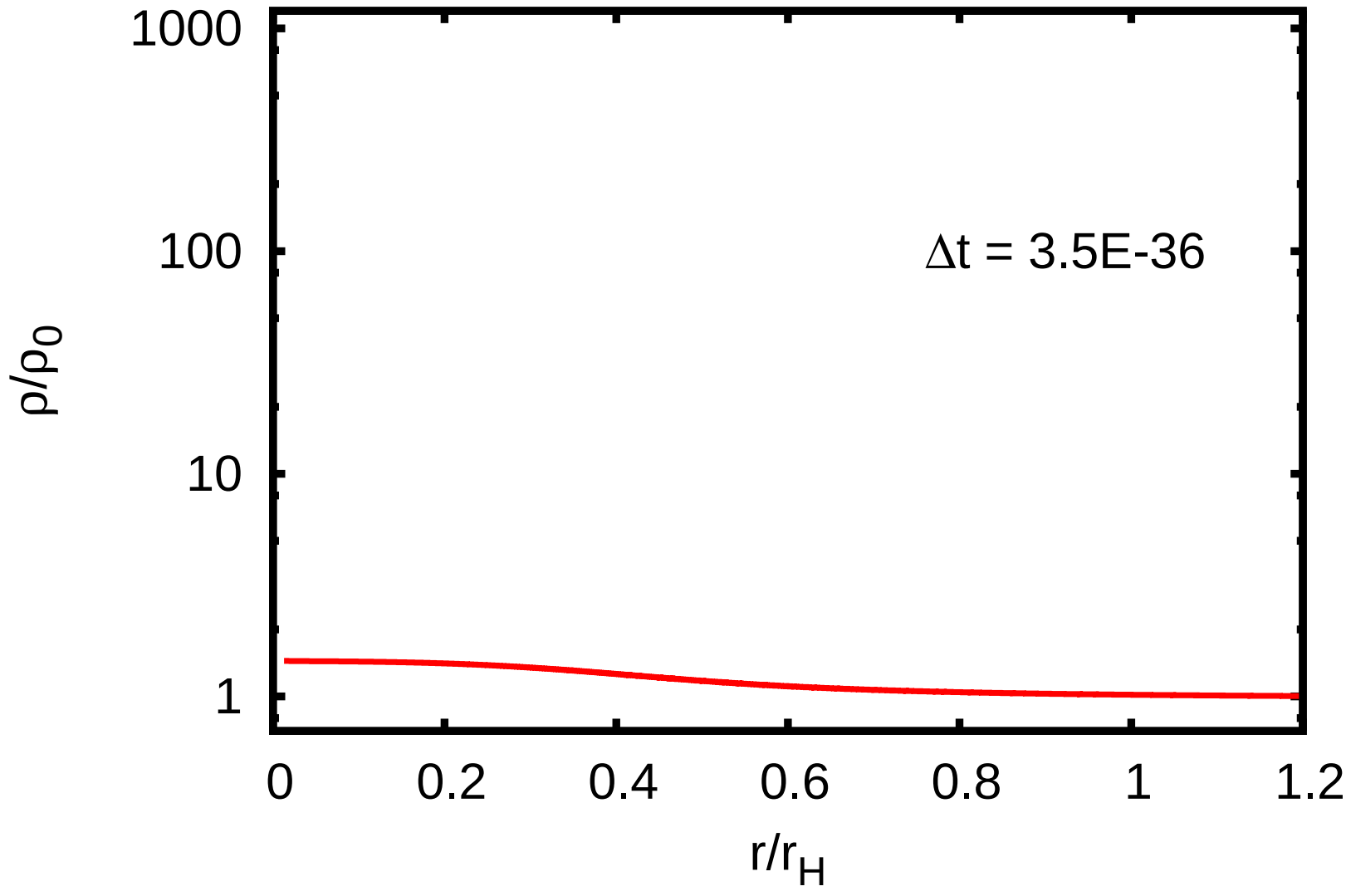


$$t_i = 10^{-34}s \quad T = 10^{14}GeV$$



$t_i = 10^{-34}s \quad T = 10^{14}GeV$



Spontaneous homogenization

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{-k}{R^2} + \frac{2M}{R^3}$$

$$\frac{|k|}{R^2} \ll \frac{2M}{R^3} \qquad \frac{|k'|}{R'R} \ll \frac{2M}{R^3} \qquad \frac{|\dot{k}|}{\dot{R}R} \ll \frac{2M}{R^3}$$

Spontaneous homogenization

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{-k}{R^2} + \frac{2M}{R^3}$$

$$\frac{|k|}{R^2} \ll \frac{2M}{R^3} \qquad \frac{|k'|}{R'R} \ll \frac{2M}{R^3} \qquad \frac{|\dot{k}|}{\dot{R}R} \ll \frac{2M}{R^3}$$

$$K^2 \gg {}^3\mathcal{R} \quad \Leftrightarrow \quad {}^3\mathcal{R} \ll {}^4\mathcal{R}$$

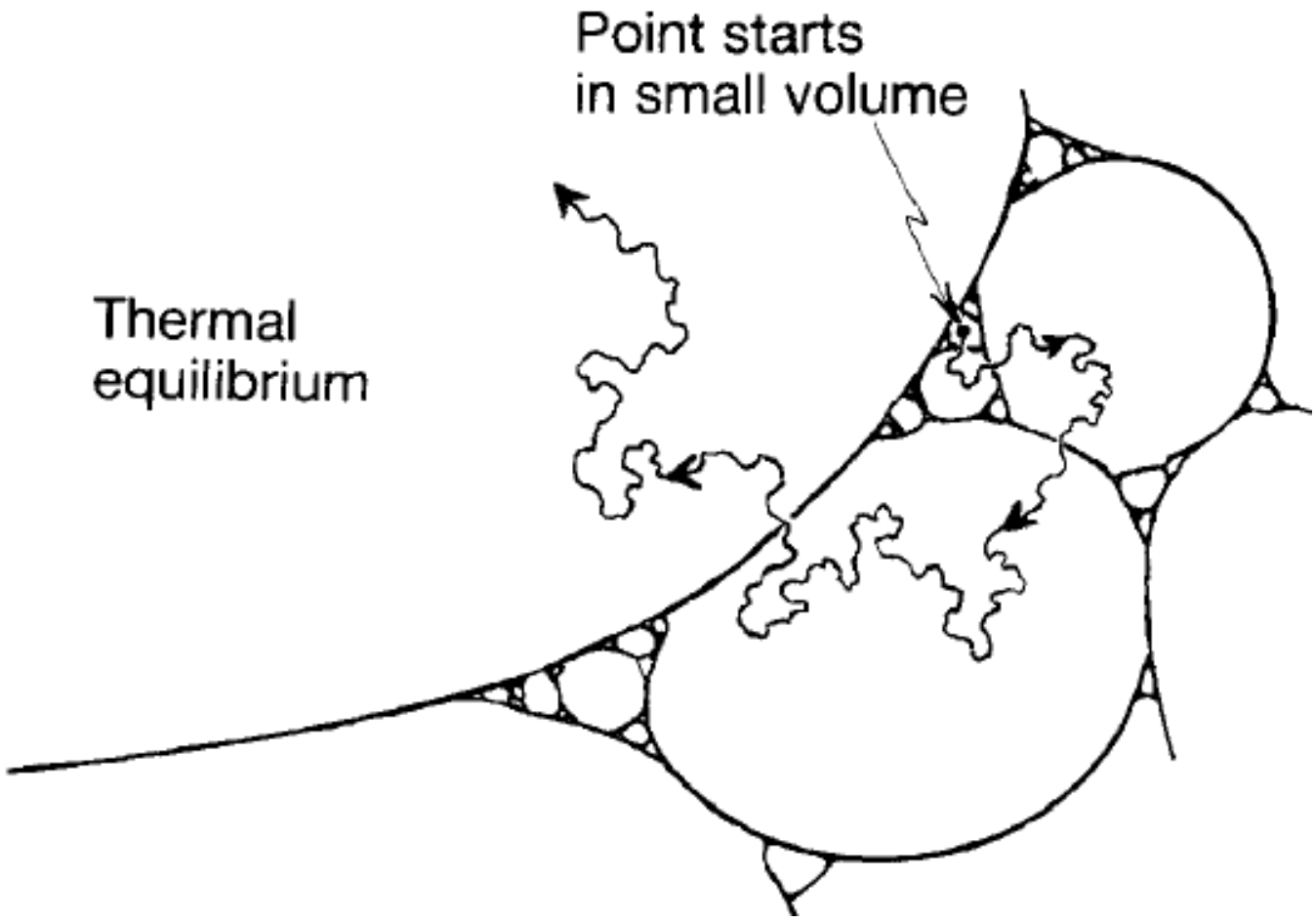
Evolution

$$\begin{cases} \dot{\Theta} = -\frac{1}{3}\,\Theta^2 - \frac{1}{2}\,(\rho + 3p) - 2(\sigma^2 - \omega^2) + \mathrm{D}^a A_a + A_a A^a + \Lambda \\ \dot{\sigma}_{\langle ab\rangle} = -\frac{2}{3}\,\Theta\sigma_{ab} - \sigma_{c\langle a}\sigma^c{}_{b\rangle} - \omega_{\langle a}\omega_{b\rangle} + \mathrm{D}_{\langle a}A_{b\rangle} + A_{\langle a}A_{b\rangle} \\ \qquad\qquad - E_{ab} - \frac{1}{2}\,\lambda\sigma_{ab} \\ \dot{\omega}_{\langle a\rangle} = -\frac{2}{3}\,\Theta\omega_a - \frac{1}{2}\,\mathrm{curl}A_a + \sigma_{ab}\omega^b \end{cases}$$

$$\begin{cases} \dot{\rho} = -\Theta(\rho + p) + \lambda\sigma_{ab}\sigma^{ab} \\ (\rho + p)A_a = -\mathrm{D}_a p + \mathrm{D}^b\lambda\sigma_{ab} + \lambda\sigma_{ab}A^b \end{cases}$$

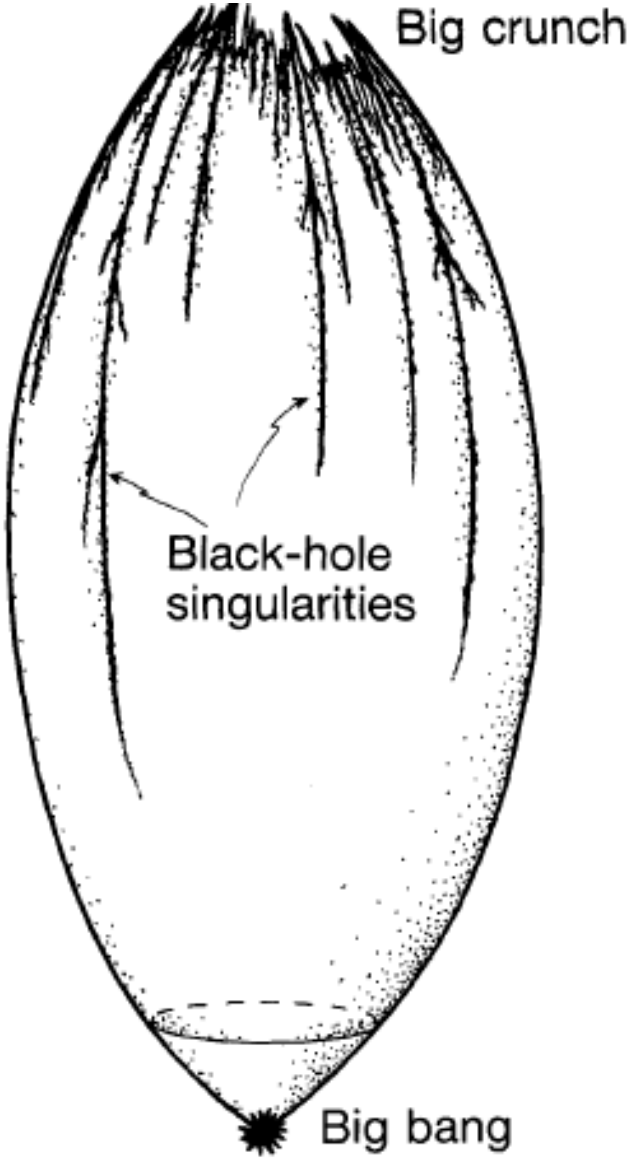
$$\begin{cases} \dot{E}_{\langle ab\rangle} = -\Theta E_{ab} - \frac{1}{2}\,(\rho + p)\sigma_{ab} + \mathrm{curl}H_{ab} + \frac{1}{2}\,\lambda\dot{\sigma}_{ab} + \frac{1}{6}\,\Theta\lambda\sigma_{ab} \\ \qquad\qquad + 3\sigma_{\langle a}{}^c\left(E_{b\rangle c} + \frac{1}{6}\,\lambda\sigma_{b\rangle c}\right) + \varepsilon_{cd\langle a}\left[2A^c H_{b\rangle}{}^d - \omega^c\left(E_{b\rangle}{}^d - \frac{1}{2}\,\lambda\sigma_{b\rangle}{}^c\right.\right. \\ \dot{H}_{\langle ab\rangle} = -\Theta H_{ab} - \mathrm{curl}E_{ab} - \frac{1}{2}\,\lambda\,\mathrm{curl}\sigma_{ab} + 3\sigma_{\langle a}{}^c H_{b\rangle c} - \\ \qquad\qquad - \varepsilon_{cd\langle a}\left(2A^c E_{b\rangle}{}^d + \omega^c H_{b\rangle}{}^d\right) \end{cases}$$

Weyl curvature hypothesis



Penrose, *The Emperor's New Mind*, (Oxford University Press, 1989)

Weyl curvature hypothesis



$$S_g = \frac{C_{abcd}C^{abcd}}{R_{ef}R^{ef}}$$

Penrose, *The Emperor's New Mind*, (Oxford University Press, 1989)

Evolution

$$\begin{cases} \dot{\Theta} = -\frac{1}{3}\,\Theta^2 - \frac{1}{2}\,(\rho + 3p) - 2(\sigma^2 - \omega^2) + \mathrm{D}^a A_a + A_a A^a + \Lambda \\ \dot{\sigma}_{\langle ab\rangle} = -\frac{2}{3}\,\Theta\sigma_{ab} - \sigma_{c\langle a}\sigma^c{}_{b\rangle} - \omega_{\langle a}\omega_{b\rangle} + \mathrm{D}_{\langle a}A_{b\rangle} + A_{\langle a}A_{b\rangle} \\ \qquad\qquad - E_{ab} - \frac{1}{2}\,\lambda\sigma_{ab} \\ \dot{\omega}_{\langle a\rangle} = -\frac{2}{3}\,\Theta\omega_a - \frac{1}{2}\,\mathrm{curl}A_a + \sigma_{ab}\omega^b \end{cases}$$

$$\begin{cases} \dot{\rho} = -\Theta(\rho + p) + \lambda\sigma_{ab}\sigma^{ab} \\ (\rho + p)A_a = -\mathrm{D}_a p + \mathrm{D}^b\lambda\sigma_{ab} + \lambda\sigma_{ab}A^b \end{cases}$$

$$\begin{cases} \dot{E}_{\langle ab\rangle} = -\Theta E_{ab} - \frac{1}{2}\,(\rho + p)\sigma_{ab} + \mathrm{curl}H_{ab} + \frac{1}{2}\,\lambda\dot{\sigma}_{ab} + \frac{1}{6}\,\Theta\lambda\sigma_{ab} \\ \qquad\qquad + 3\sigma_{\langle a}{}^c\left(E_{b\rangle c} + \frac{1}{6}\,\lambda\sigma_{b\rangle c}\right) + \varepsilon_{cd\langle a}\left[2A^c H_{b\rangle}{}^d - \omega^c\left(E_{b\rangle}{}^d - \frac{1}{2}\,\lambda\sigma_{b\rangle}{}^c\right.\right. \\ \dot{H}_{\langle ab\rangle} = -\Theta H_{ab} - \mathrm{curl}E_{ab} - \frac{1}{2}\,\lambda\,\mathrm{curl}\sigma_{ab} + 3\sigma_{\langle a}{}^c H_{b\rangle c} - \\ \qquad\qquad - \varepsilon_{cd\langle a}\left(2A^c E_{b\rangle}{}^d + \omega^c H_{b\rangle}{}^d\right) \end{cases}$$

Evolution

$$\begin{cases} \dot{\Theta} = -\frac{1}{3}\,\Theta^2 - \frac{1}{2}\,(\rho + 3p) - 2(\sigma^2 - \omega^2) + \mathrm{D}^a A_a + A_a A^a + \Lambda \\ \dot{\sigma}_{\langle ab\rangle} = -\frac{2}{3}\,\Theta\sigma_{ab} - \sigma_{c\langle a}\sigma^c{}_{b\rangle} - \omega_{\langle a}\omega_{b\rangle} + \mathrm{D}_{\langle a}A_{b\rangle} + A_{\langle a}A_{b\rangle} \\ \qquad\qquad - E_{ab} - \frac{1}{2}\,\lambda\sigma_{ab} \\ \dot{\omega}_{\langle a\rangle} = -\frac{2}{3}\,\Theta\omega_a - \frac{1}{2}\,\mathrm{curl}A_a + \sigma_{ab}\omega^b \end{cases}$$

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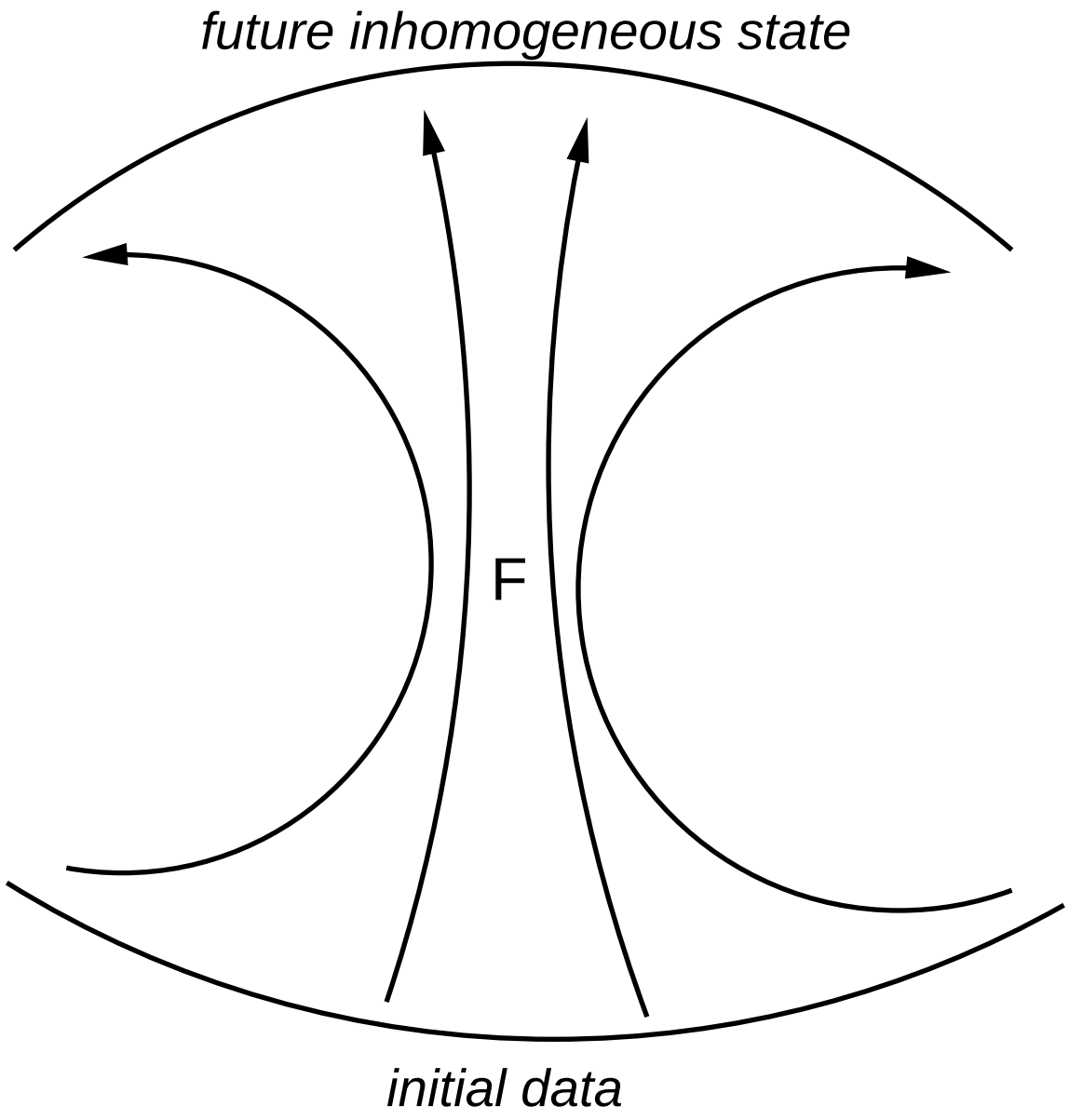
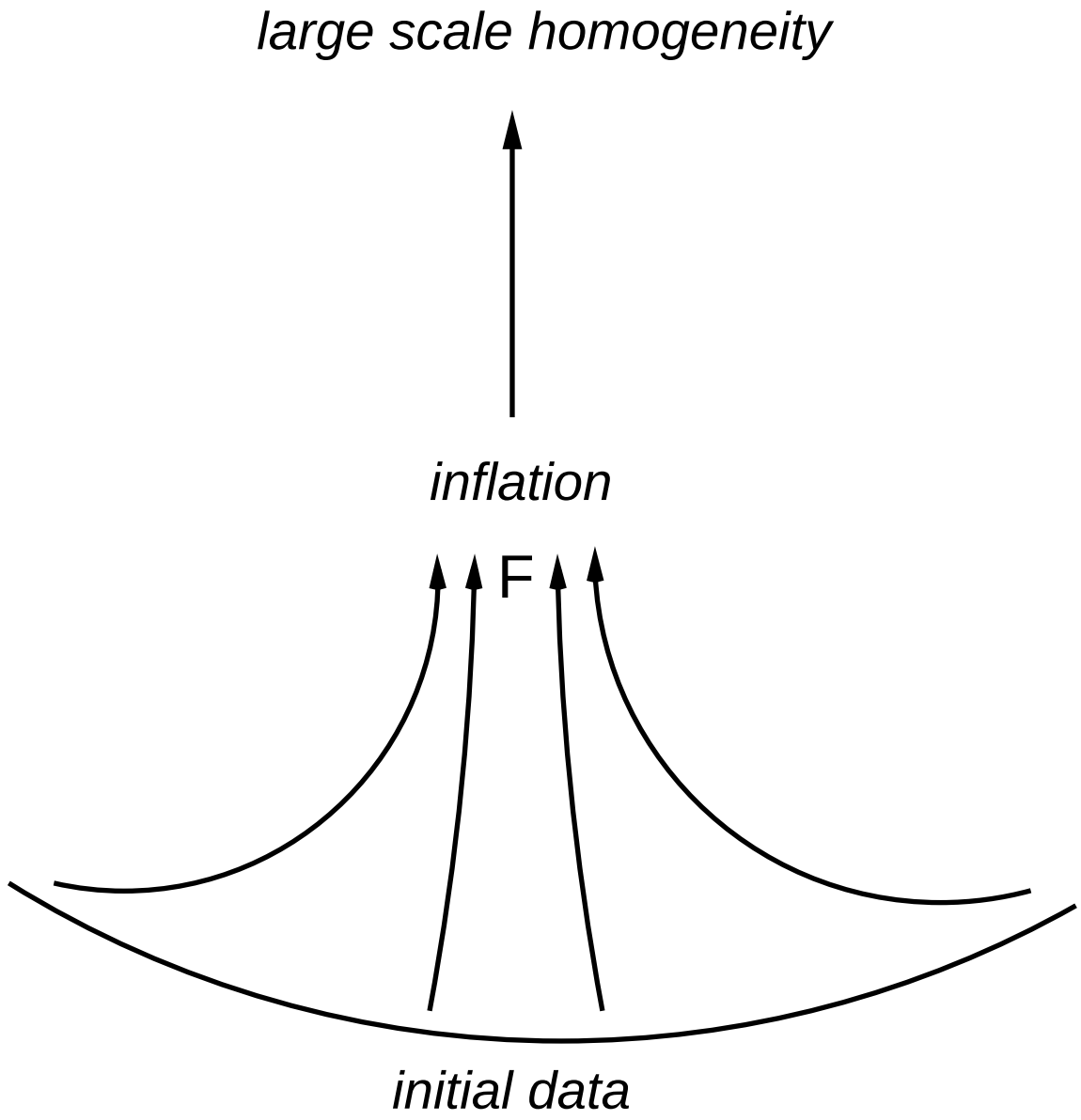
Intermediate homogenization



$$\mathcal{C} \ll \mathcal{R}$$

$$^{3}\mathcal{R} \ll \mathcal{R}$$

Intermediate homogenization



$$C \ll R$$

$${}^3\mathcal{R} \ll \mathcal{R}$$

Summary

AD

$\sim$ eV — matter-radiation equality

50 KeV — nuclear reactions

200 MeV — quark-gluon transition

inflation

.

10^{16} GeV — GUT

10^{19} GeV — Planck era

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