Title: Taming Gravity at Short Distances

Date: Oct 04, 2005 11:00 AM

URL: http://pirsa.org/05100007

Abstract: TBA

Taming Gravity at Short Distances

Anupam Mazumdar

with Tirthabir Biswas & Warren Siegel

hep-th/0508194

NORDITA
Nordic Institute
for Theoretical Physics

Well known problems of GR

$$S = \int d^4x \sqrt{-g} F(R), \qquad F(R) = R + \ldots$$

* GR is an effective description
* An incomplete description
* Space like singularities

Black hole &
Cosmological singularities

Well known problems of GR

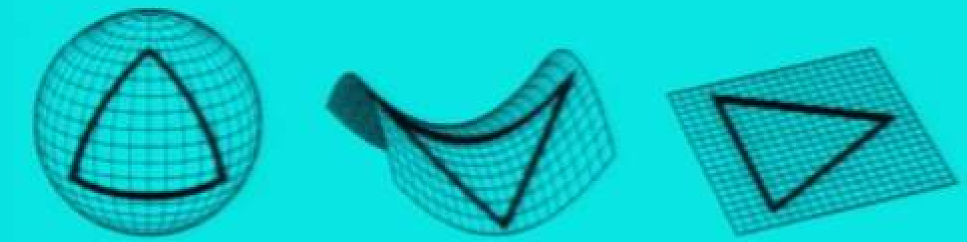
$$S = \int d^4x\sqrt{-g}F(R), \qquad F(R) = R + \ldots$$

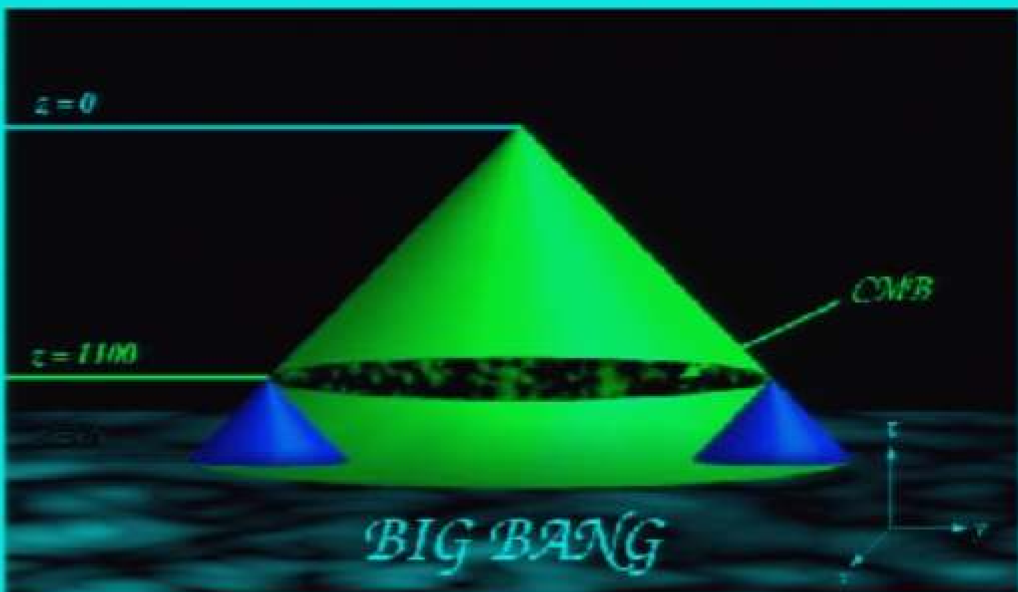
* GR is an effective description
* An incomplete description
* Space like singularities

Black hole &
Cosmological singularities

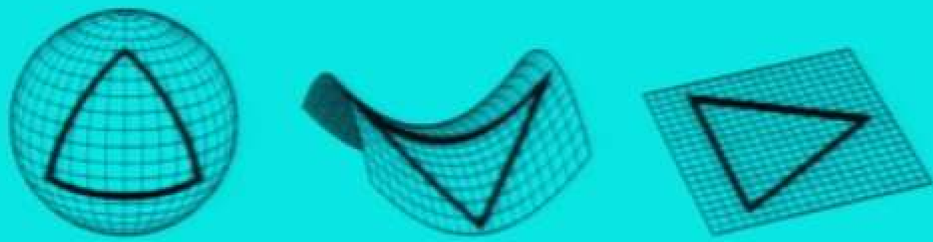
Aim

What becomes Singular





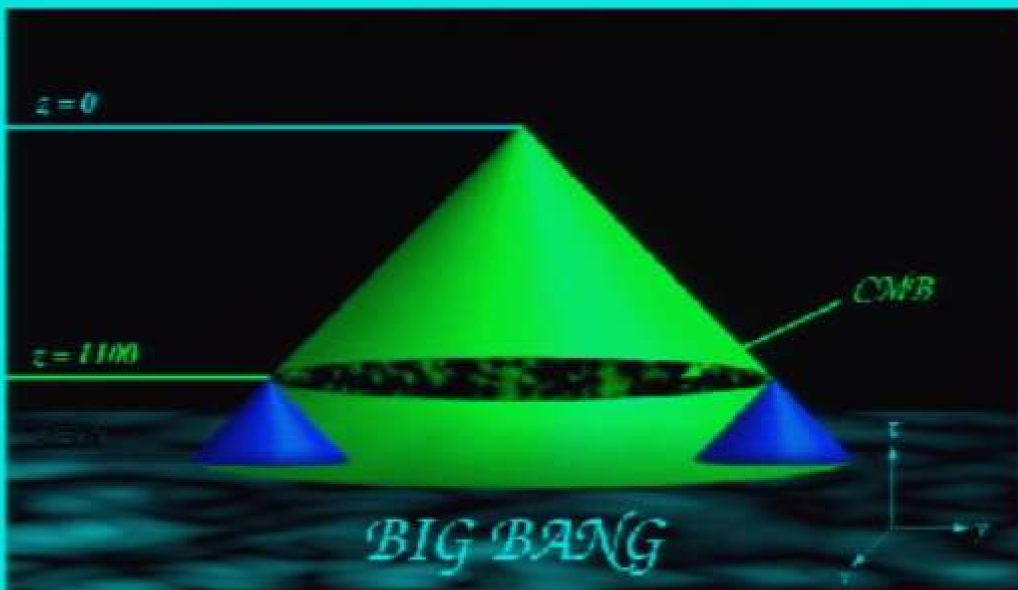
What becomes Singular



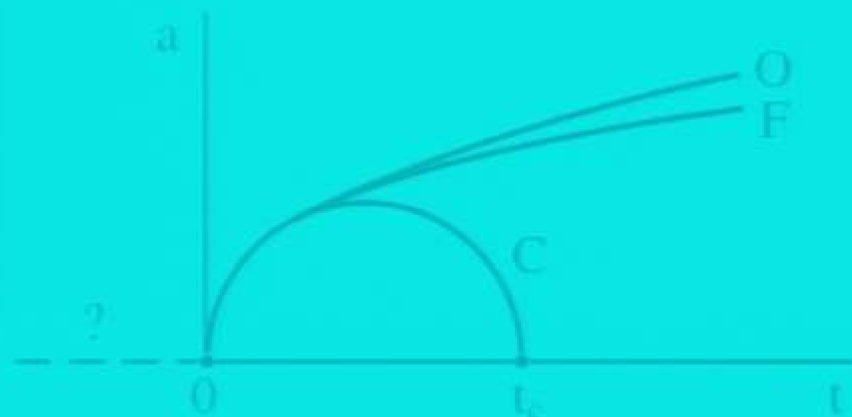
Closed Geometry Open Geometry Flat Geometry

$$H^2 + \frac{k}{a^2} = \frac{8\pi G_4}{3}\rho$$

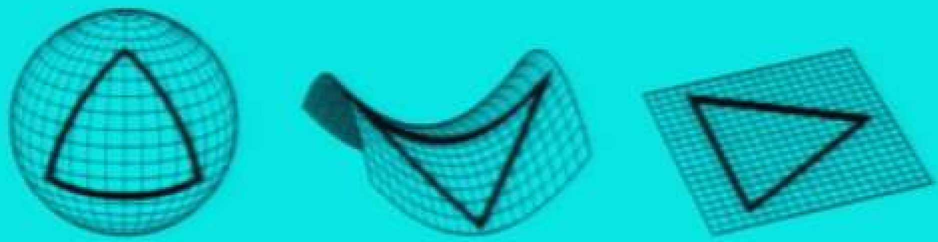
$$\dot{\rho} + 3\,H\,(\rho + p) \,=\, 0$$



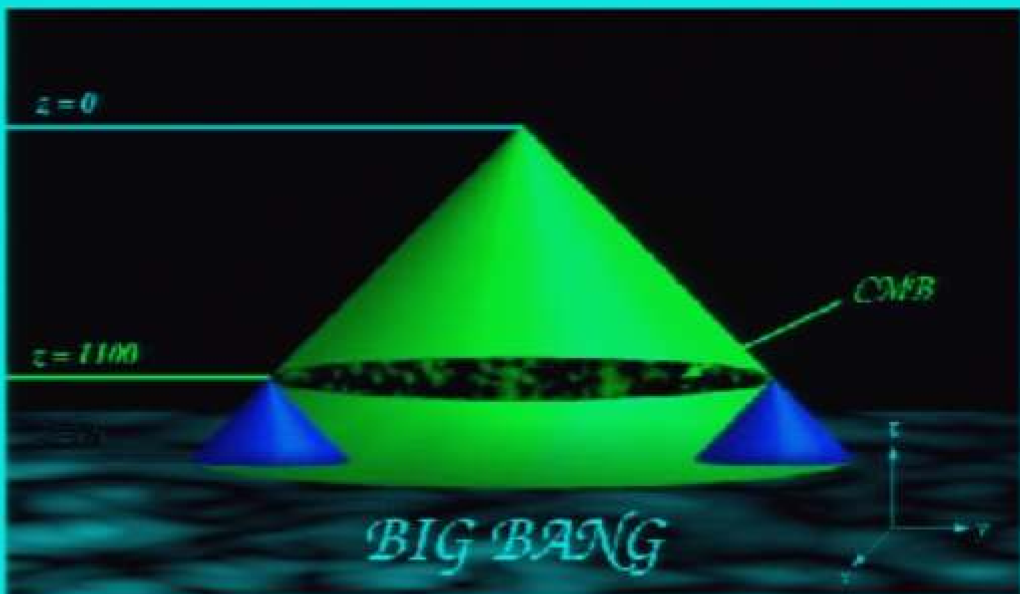
$$\rho \sim a^{-3(1+w)} \qquad p = w\rho$$



What becomes Singular



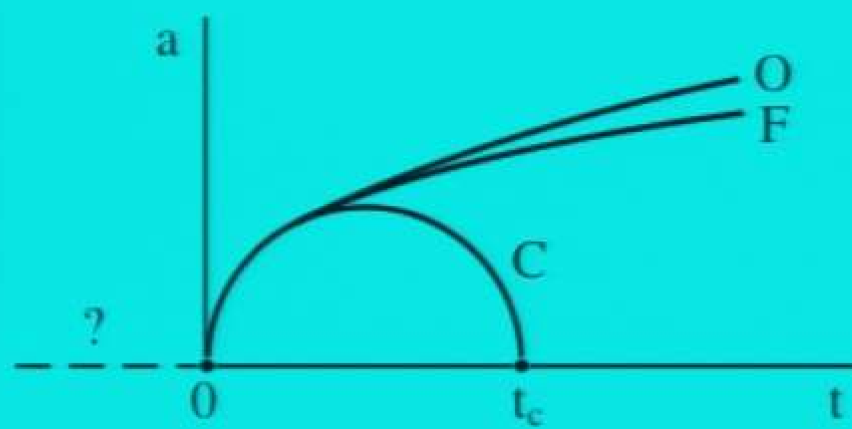
Closed Geometry Open Geometry Flat Geometry



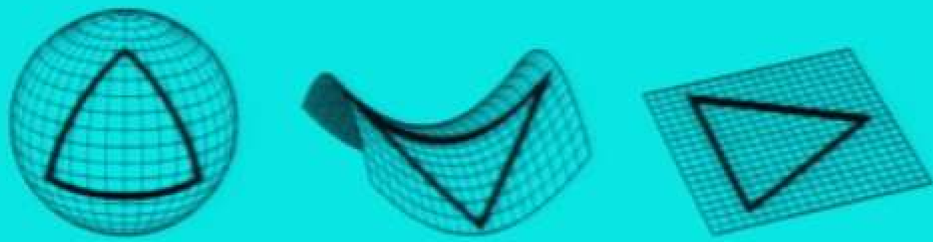
$$H^2 + \frac{k}{a^2} = \frac{8\pi G_4}{3}\rho$$

$$\dot{\rho} + 3\,H\,(\rho + p)\; = \;0$$

$$\rho \sim a^{-3(1+w)} \qquad p = w\rho$$



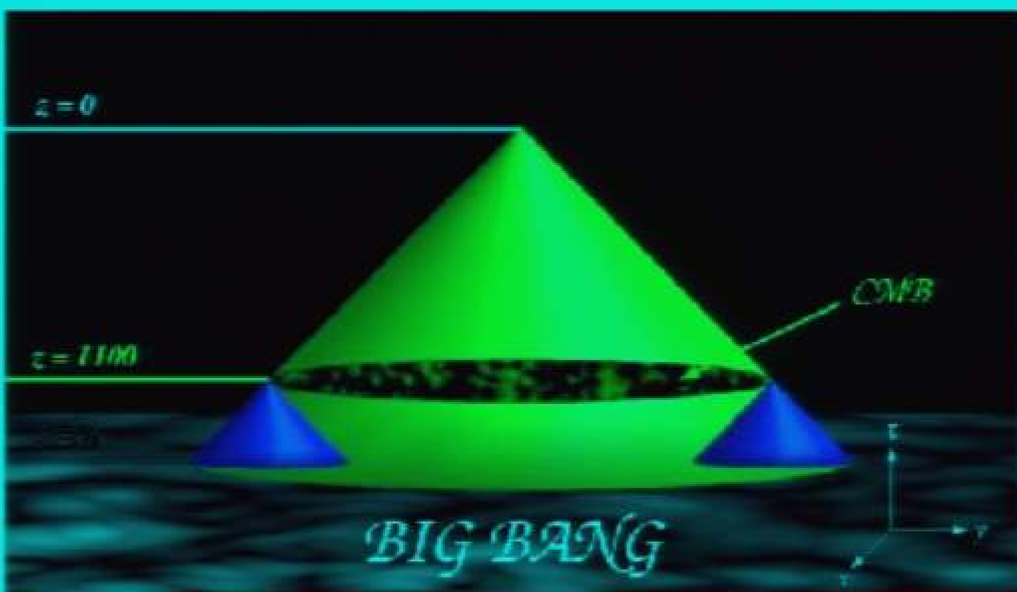
What becomes Singular



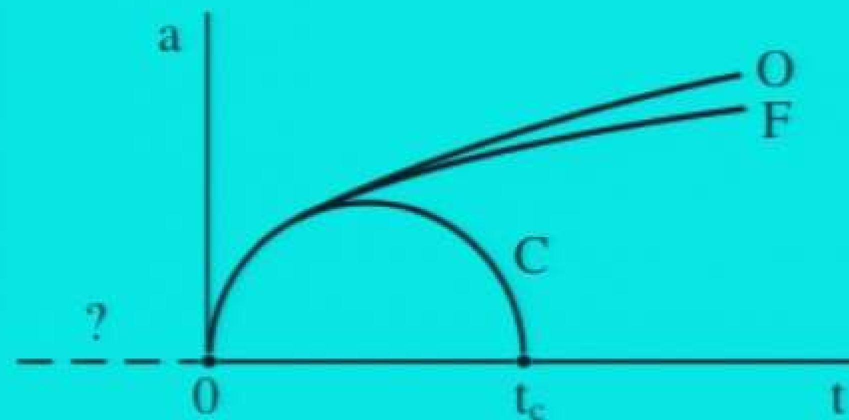
Closed Geometry Open Geometry Flat Geometry

$$H^2 + \frac{k}{a^2} = \frac{8\pi G_4}{3}\rho$$

$$\dot{\rho} + 3\,H\,(\rho + p)\; = \;0$$



$$\rho \sim a^{-3(1+w)} \qquad p = w\rho$$



$$R^{\mu\nu\alpha\beta}R_{\mu\nu\alpha\beta} \rightarrow \infty$$

Various Alternatives

Steady State Universe (V1): Cosmological Constant (1917)

$$R^{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = -8\pi G_4 T_{\mu\nu}$$

432 DOC. 43 COSMOLOGICAL CONSIDERATIONS

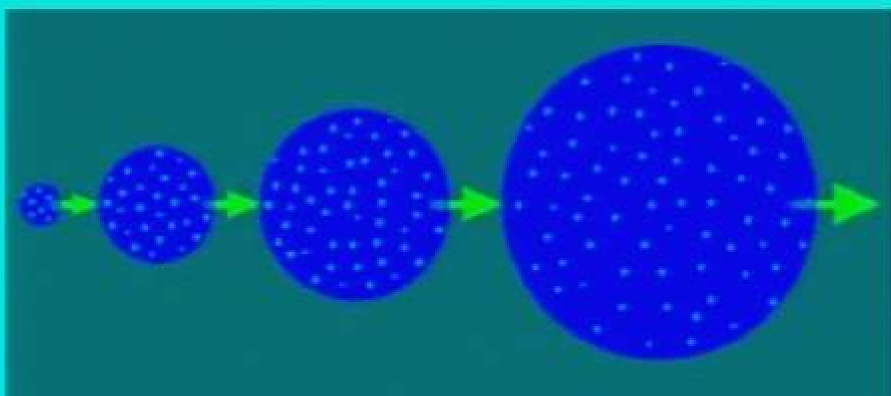
curvature of space is variable in time and place, according to the distribution of matter, but we may roughly approximate to it by means of a spherical space. At any rate, this view is logically consistent, and from the standpoint of the general theory of relativity lies nearest at hand; whether, from the standpoint of present astronomical knowledge, it is tenable, will not here be discussed. In order to arrive at this con-
[16] sistent view, we admittedly had to introduce an extension of the field equations of gravitation which is not justified by our actual knowledge of gravitation. It is to be emphasized, however, that a positive curvature of space is given by our results, even if the supplementary term is not introduced. That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars.

"Universe" = Milky Way

Various Alternatives

Steady State Universe (V2) (1948)

Bondi, Gold, Hoyle



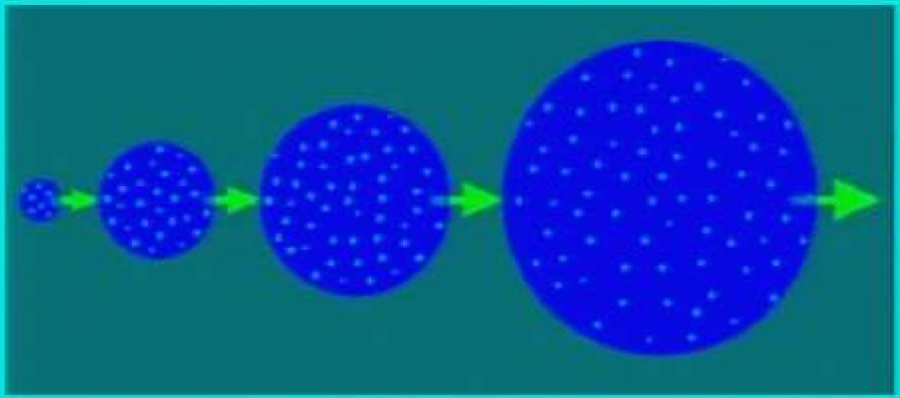
Perfect Cosmological Principle

Matter is constantly created from vacuum

Various Alternatives

Steady State Universe (V2) (1948)

Bondi, Gold, Hoyle



Perfect Cosmological Principle

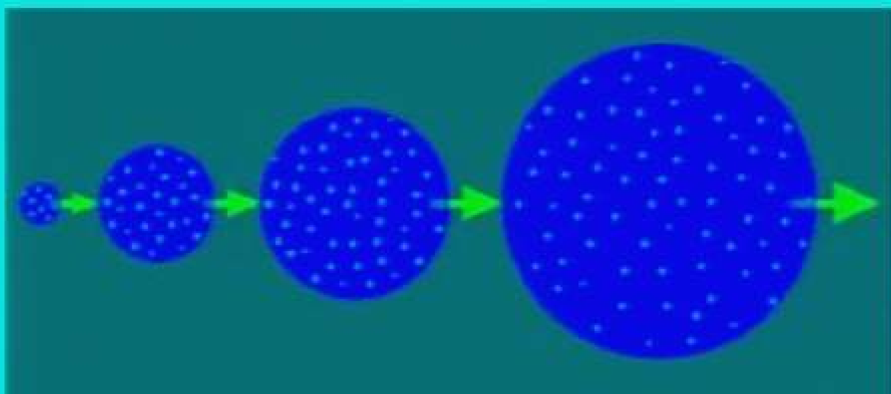
Matter is constantly created from vacuum

$G_4 \propto t^n$ **Milne (1935): 2 times** $\mathrm{M}_h \propto c^3 G^{-1} t$

Various Alternatives

Steady State Universe (V2) (1948)

Bondi, Gold, Hoyle



Perfect Cosmological Principle

Matter is constantly created from vacuum

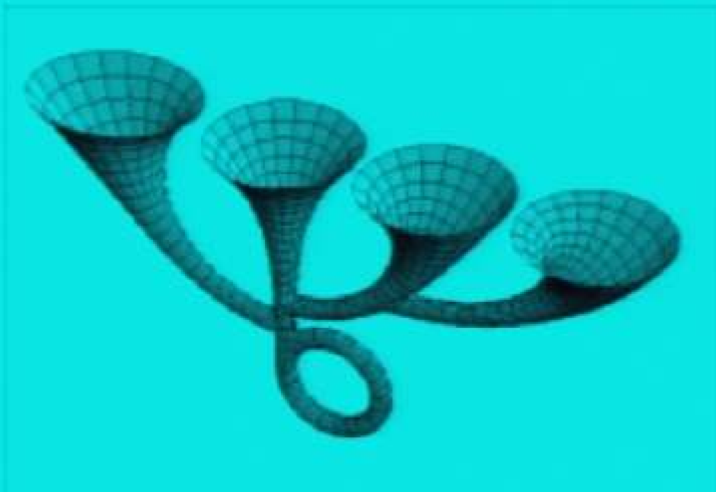
$G_4 \propto t^n$ **Milne (1935): 2 times** $M_h \propto c^3 G^{-1} t$

Dirac (1937) $e^2 G^{-1} m_N$ $G \propto t^{-1}$

Jordan (1938), Brans Dicke (1961) $\left|t^2 G(t)\right| \to \infty$ as $t \to \infty$

Various Alternatives

Quantum Cosmology Wheeler DeWitt (1960-70)

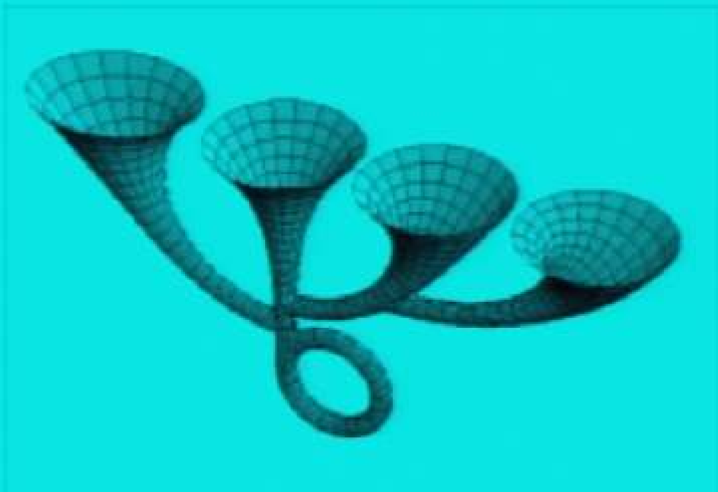


Minisuperspace

$$i\,\frac{\partial\Psi(a,\varphi)}{\partial t} = \mathcal{H}\,\Psi = 0\ .$$

Various Alternatives

Quantum Cosmology Wheeler DeWitt (1960-70)

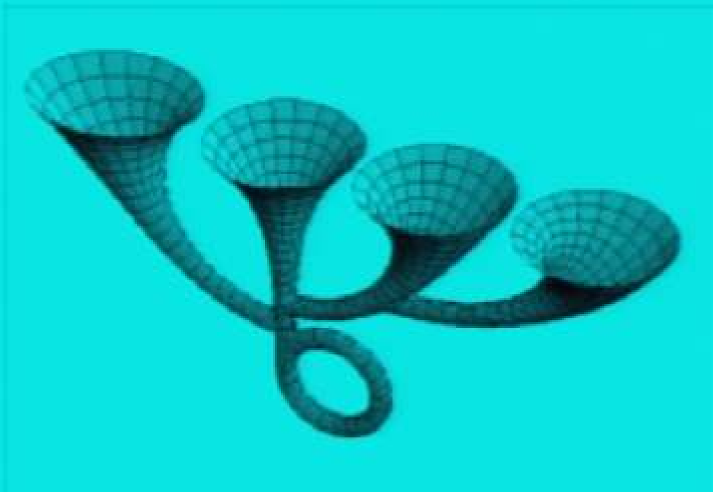


Minisuperspace

$$i\,\frac{\partial\Psi(a,\varphi)}{\partial t} = \mathcal{H}\,\Psi = 0\ .$$

Various Alternatives

Quantum Cosmology Wheeler DeWitt (1960-70)



Minisuperspace

$$i\,\frac{\partial \Psi(a,\varphi)}{\partial t} = \mathcal{H}\,\Psi = 0\ .$$

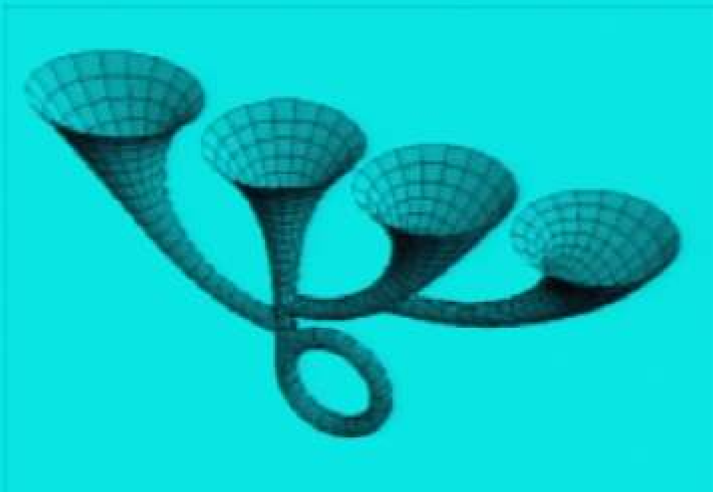
Hartle Hawking (1983)

Let laws of Physics = Define their own Initial conditions

$$\Psi(g^3,\phi) = \int^{\phi,g^3} \mathcal{D}\phi \mathcal{D}g^3 e^{iS}$$

Various Alternatives

Quantum Cosmology Wheeler DeWitt (1960-70)



Minisuperspace

$$i\,\frac{\partial \Psi(a,\varphi)}{\partial t} = \mathcal{H}\,\Psi = 0\ .$$

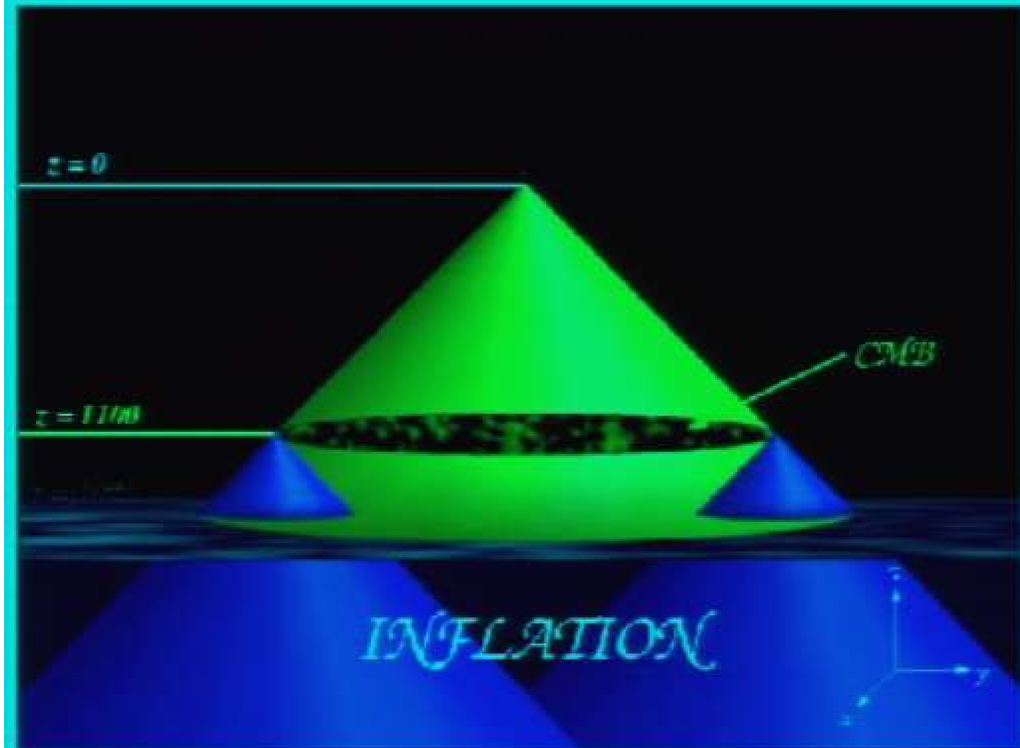
Hartle Hawking (1983)

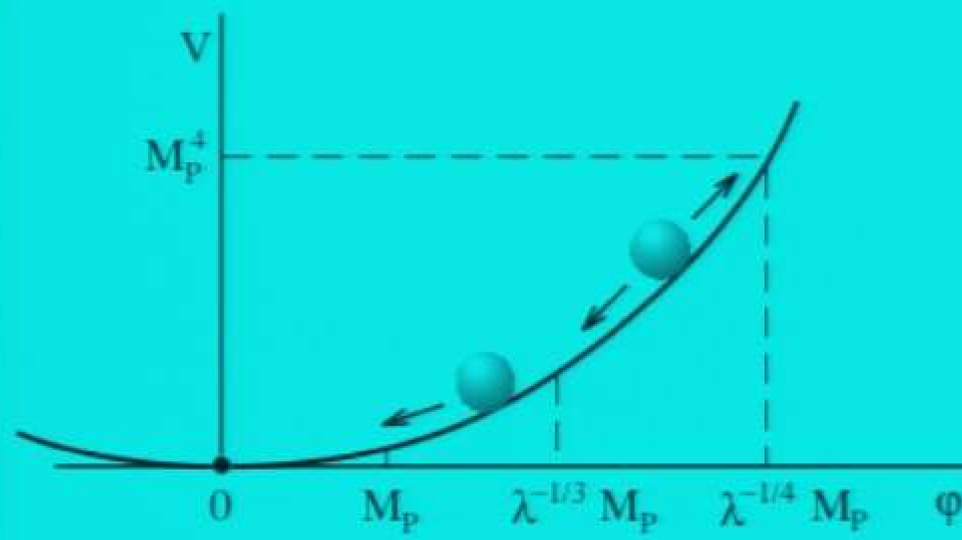
Let laws of Physics = Define their own Initial conditions

$$\Psi(g^3,\phi) = \int^{\phi,g^3} \mathcal{D}\phi\mathcal{D}g^3 e^{iS}$$

Inflation

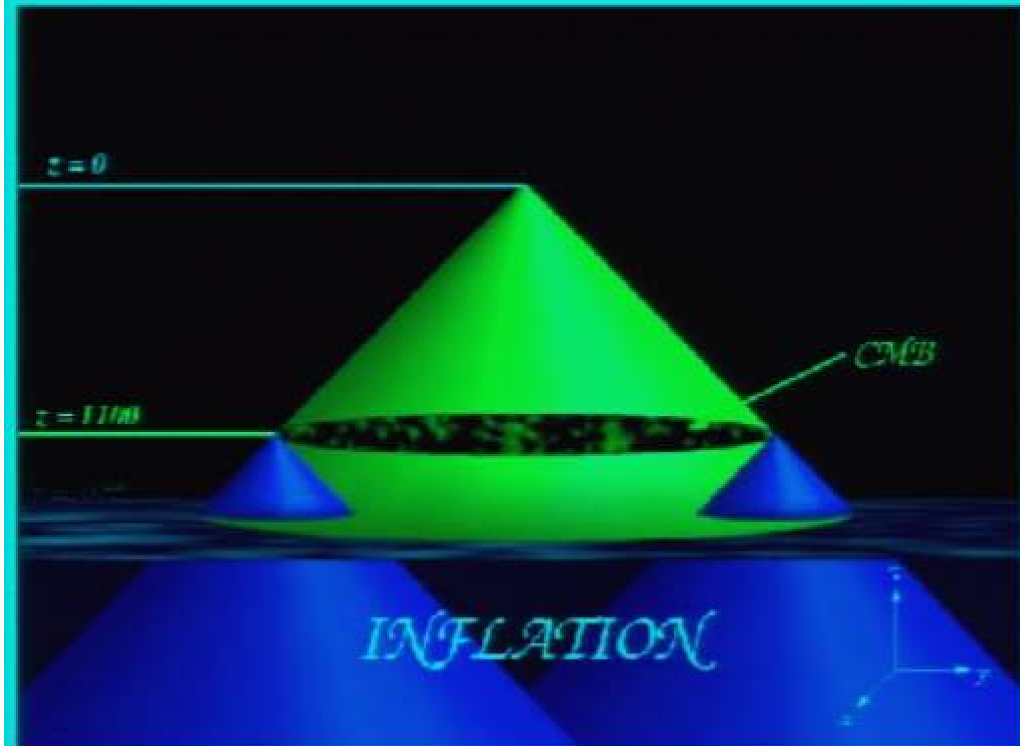
Starobinsky, Guth Linde, Starobinsky, Vilenkin

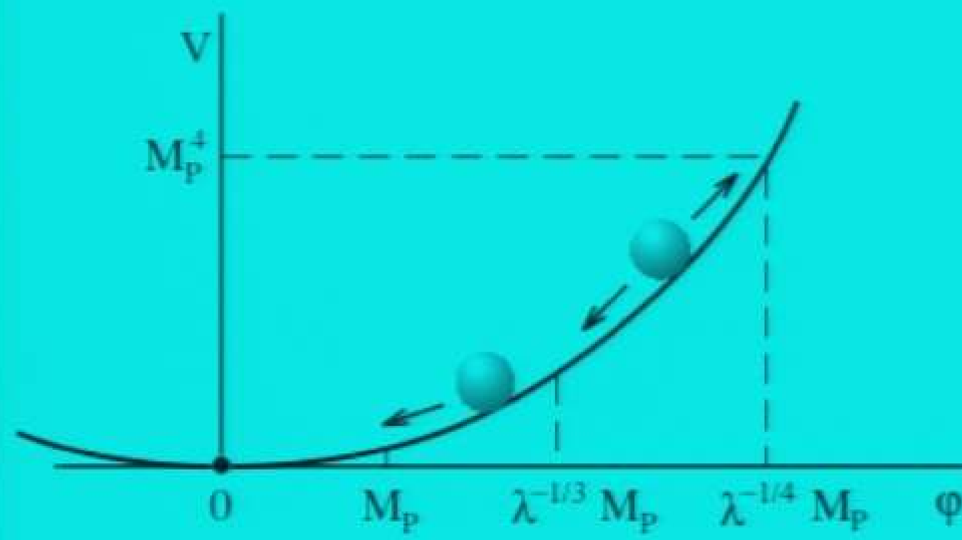


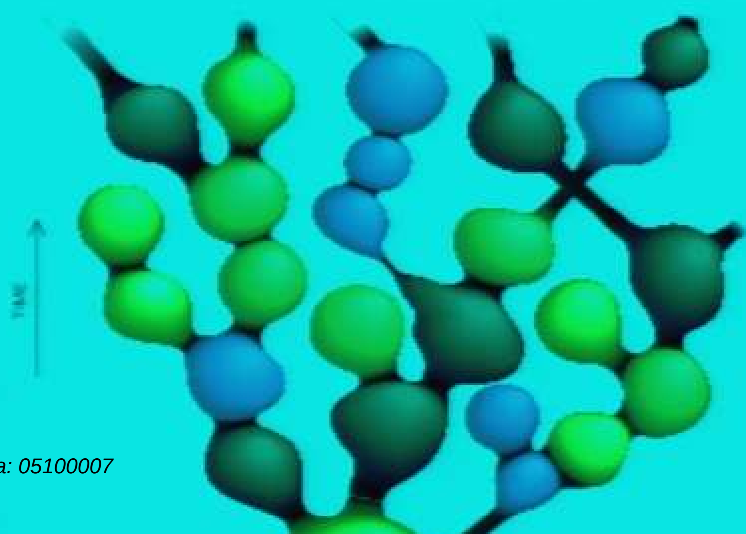


Inflation

Starobinsky, Guth Linde, Starobinsky, Vilenkin

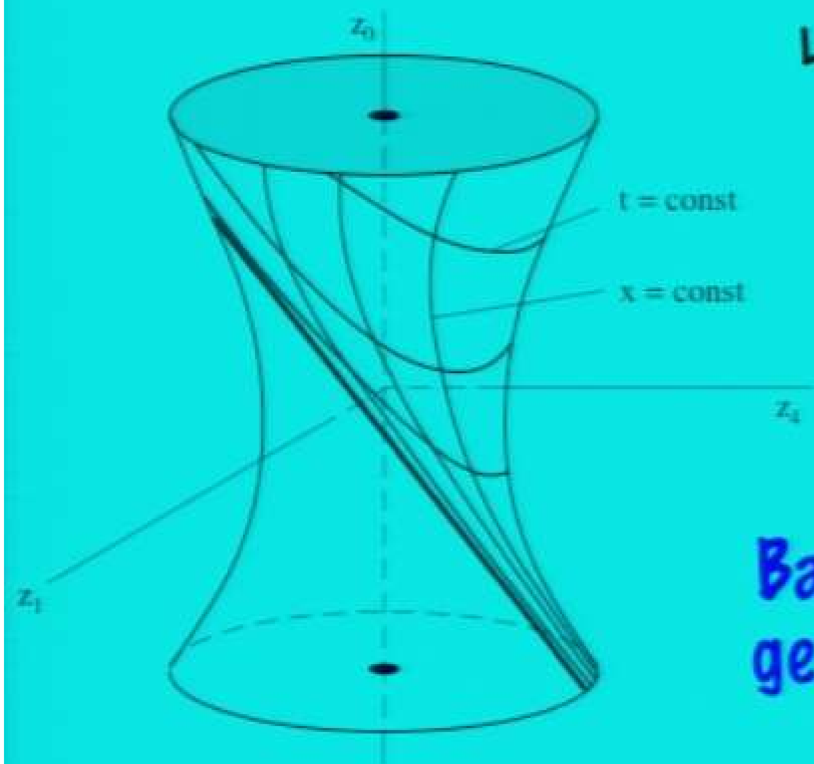






Absence of general cosmological singularity in future

Is inflation past eternal ?



Linde, Borde+Vilenkin, Borde + Guth + Vilenkin

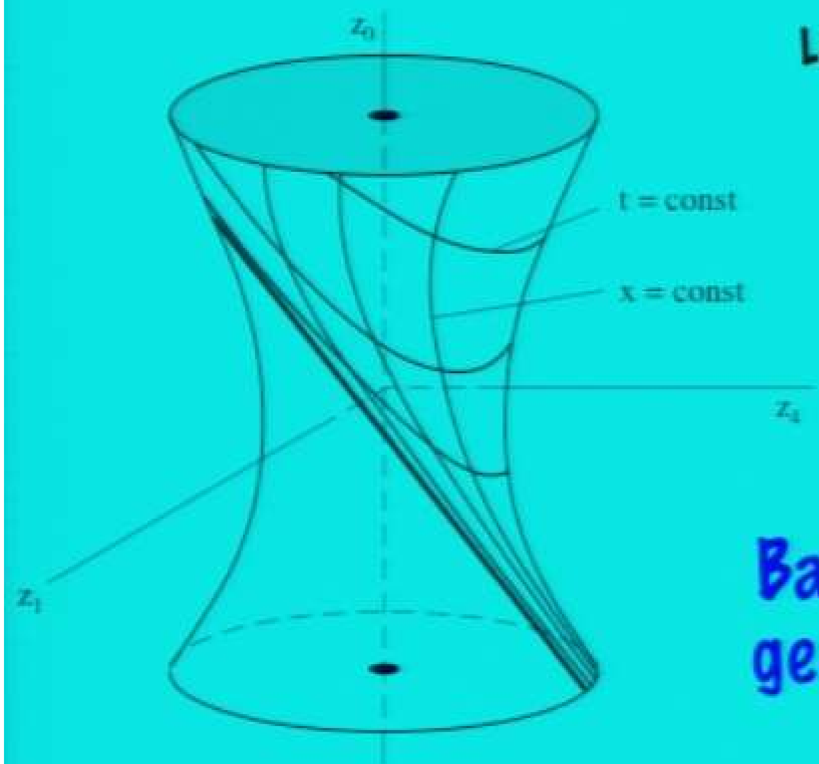
3 dimensional flat Universe

$$z_0^2 - z_1^2 - z_2^2 - z_3^2 - z_4^2 = -\mathrm{H}^{-2}$$

$$ds^2 = dt^2 - e^{2\mathrm{H}t}\, d\mathbf{x}^2$$

Backward going null and time like geodesics have a finite affine length

Is inflation past eternal ?



Linde, Borde+Vilenkin, Borde + Guth + Vilenkin

3 dimensional flat Universe

$$z_0^2 - z_1^2 - z_2^2 - z_3^2 - z_4^2 = -\mathrm{H}^{-2}$$

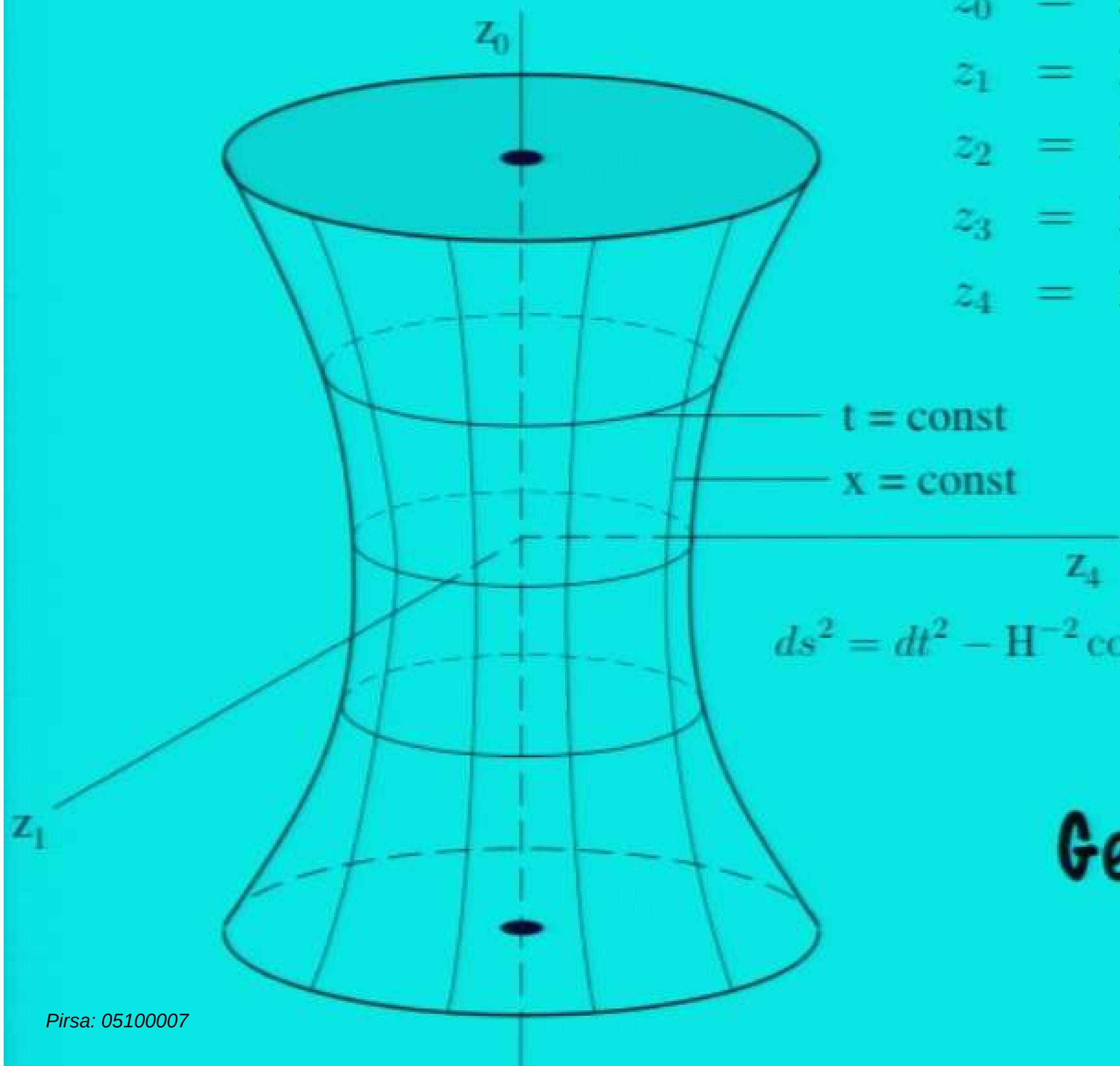
$$ds^2 = dt^2 - e^{2\mathrm{H}\,t}\, d\mathbf{x}^2$$

Backward going null and time like geodesics have a finite affine length

Exponentially expanding (flat) de Sitter is only a part of the closed de Sitter space

Closed deSitter

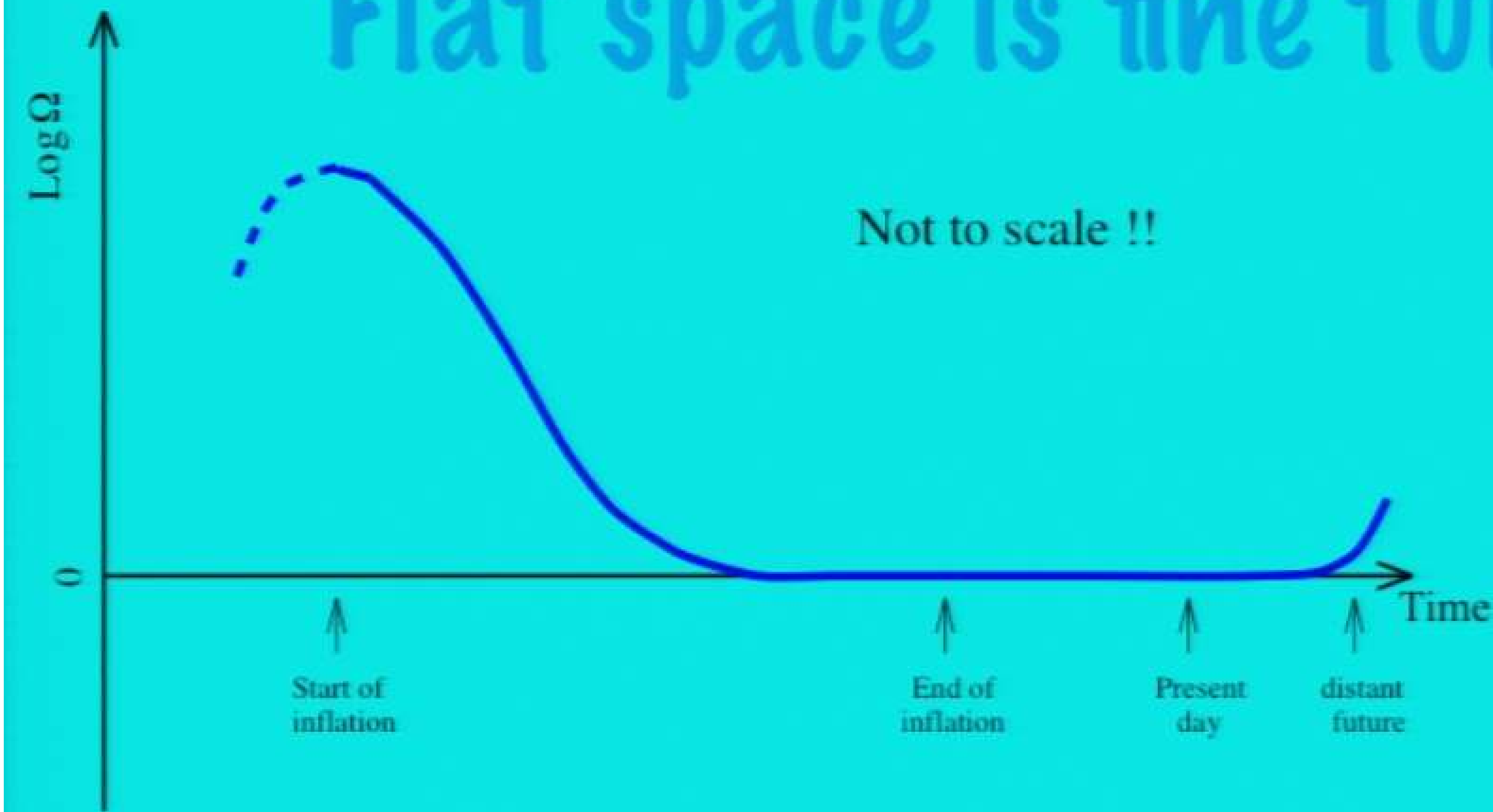
$$\begin{aligned} z_0 &= \mathrm{H}^{-1}\sinh \mathrm{H}\,t \\ z_1 &= \mathrm{H}^{-1}\cosh \mathrm{H}\,t\,\cos\chi\ , \\ z_2 &= \mathrm{H}^{-1}\cosh \mathrm{H}\,t\,\sin\chi\,\cos\theta\ , \\ z_3 &= \mathrm{H}^{-1}\cosh \mathrm{H}\,t\,\sin\chi\,\sin\theta\,\cos\varphi\ , \\ z_4 &= \mathrm{H}^{-1}\cosh \mathrm{H}\,t\,\sin\chi\,\sin\theta\,\sin\varphi\ . \end{aligned}$$



$$ds^2 = dt^2 - \mathrm{H}^{-2}\cosh^2 \mathrm{H}\,t\,[d\chi^2 + \sin^2\chi\,(d\theta^2 + \sin^2\theta\,d\varphi^2)]$$

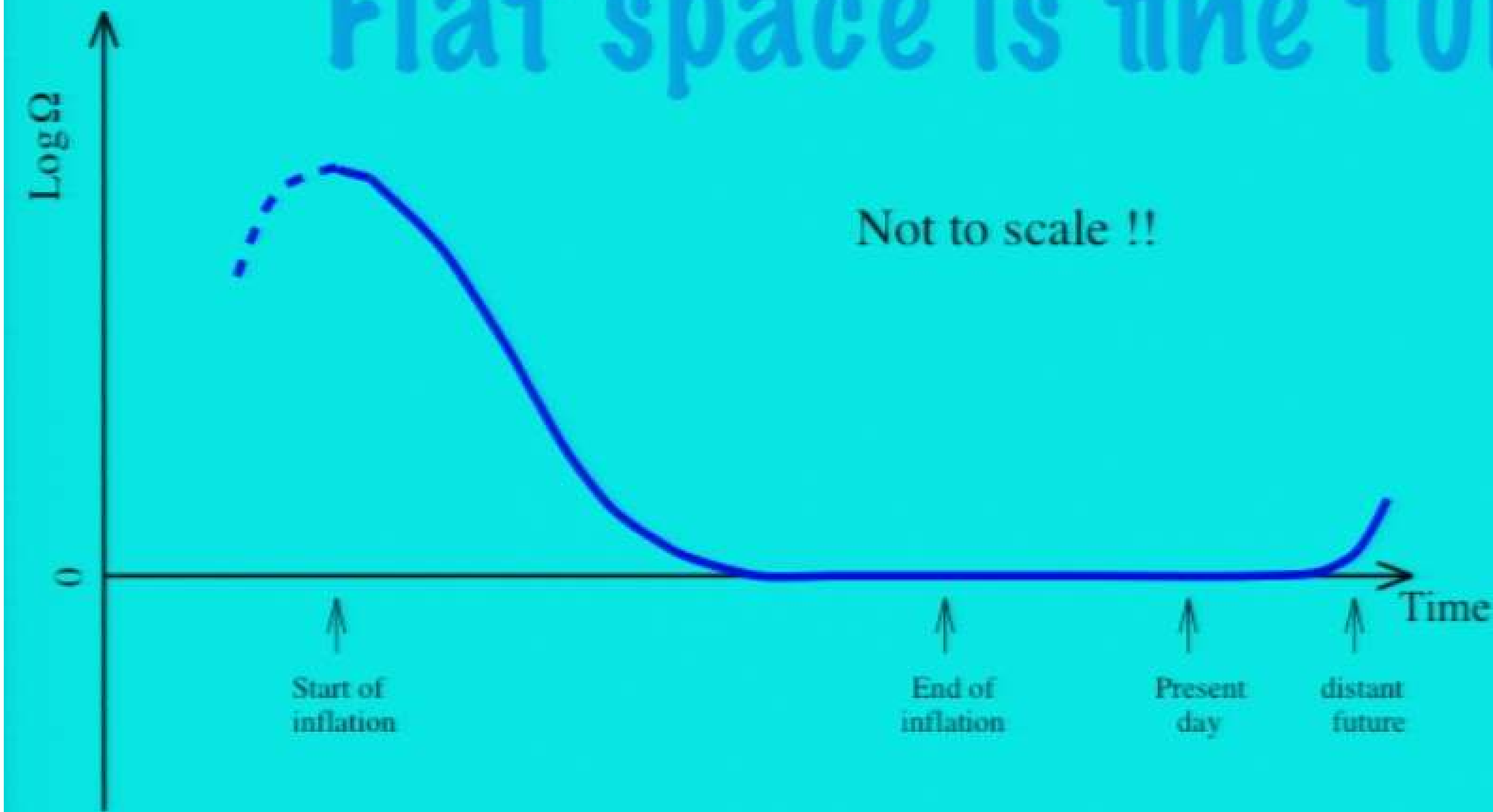
Geodesically Complete

Flat space is fine tuned



$$|\Omega - 1| = \frac{|k|}{a^2 H^2} \, .$$

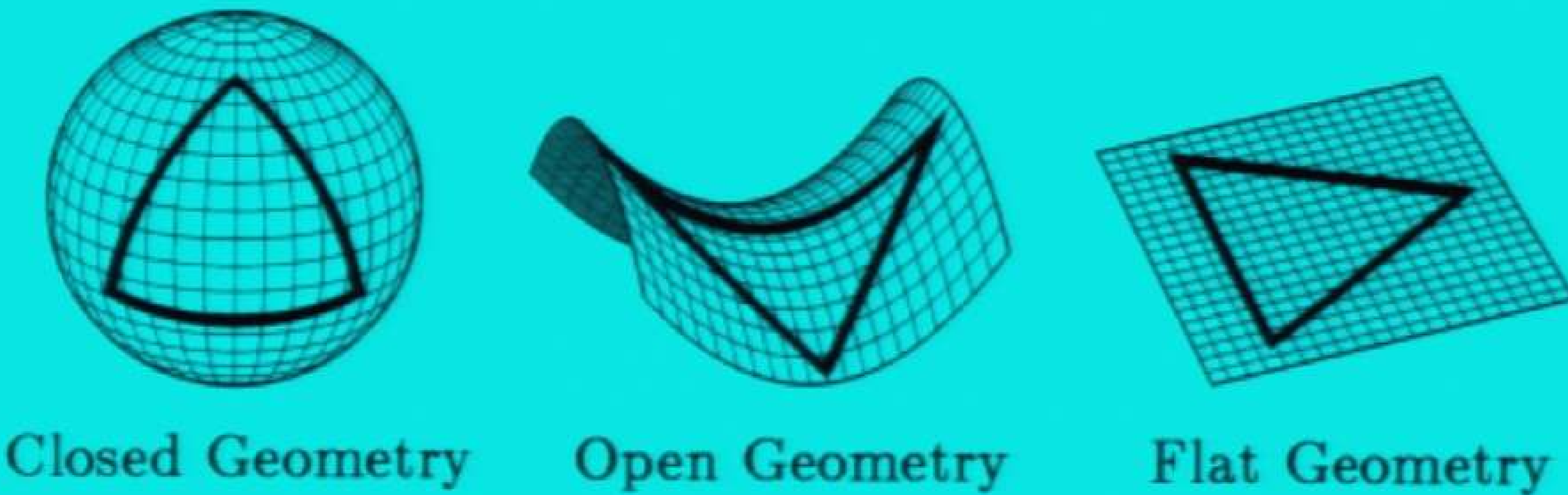
Flat space is fine tuned



$$|\Omega - 1| = \frac{|k|}{a^2 H^2}\,.$$

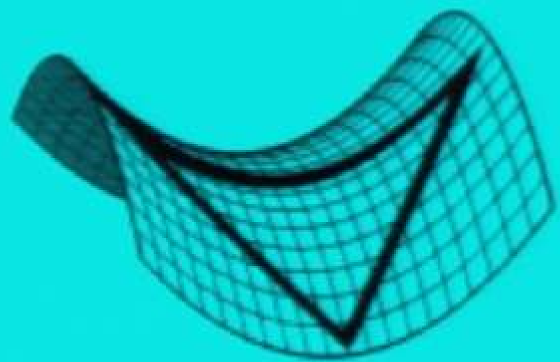
Flat deSitter is boring

Status of the Problem

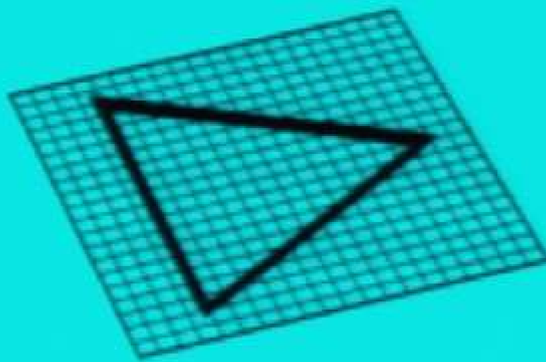


Status of the Problem

Closed Geometry



Open Geometry



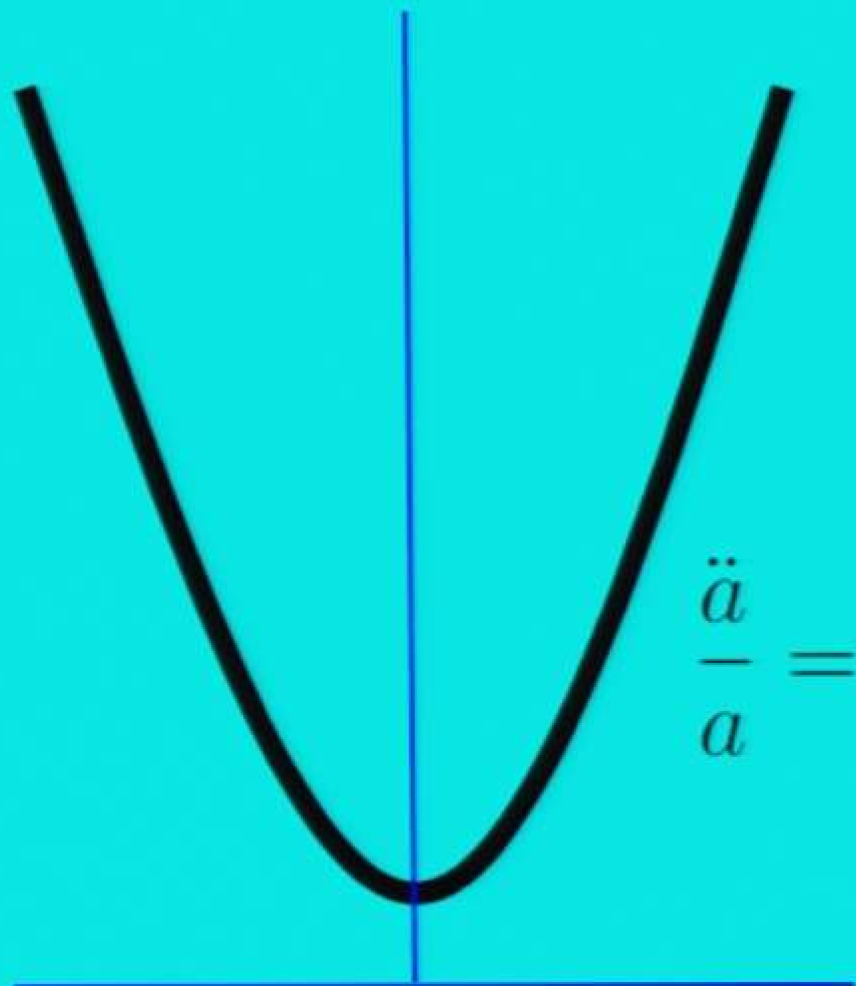
Flat Geometry

Well Behaved

Least understood

Bouncing Universe

$$H \to 0 \quad \ddot{a} > 0 \quad \text{and} \quad a > 0 \quad \to p < -\rho/3$$



$$\frac{\ddot{a}}{a} = -\frac{4\pi G_4}{3}(\rho + 3p)$$

What gives a bounce ?

WEC:	$\rho \geq 0 \quad \text{and } \rho + p \geq 0.$
DEC:	$\rho \geq \lvert p\rvert$ or $1 \geq \omega.$
SEC:	$\rho + p \geq 0$ and $\rho + 3p \geq 0.$

What gives a bounce ?

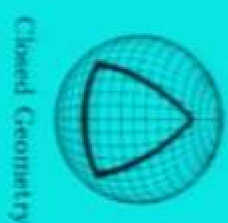
WEC:	$\rho \geq 0 \quad$ and $\rho + p \geq 0.$
DEC:	$\rho \geq \lvert p \rvert$ or $1 \geq \omega.$
SEC:	$\rho + p \geq 0$ and $\rho + 3p \geq 0.$

$$H^2 + \frac{1}{a^2} = \frac{8\pi G_4}{3}\rho$$

~~SEC~~ $p < -\rho/3 \quad \to \omega < -1/3$

What gives a bounce ?

WEC:	$\rho \geq 0$ and $\rho + p \geq 0.$
DEC:	$\rho \geq \lvert p \rvert$ or $1 \geq \omega.$
SEC:	$\rho + p \geq 0$ and $\rho + 3p \geq 0.$



$$H^2 + \frac{1}{a^2} = \frac{8\pi G_4}{3}\rho$$

~~SEC~~ $p < -\rho/3 \quad \rightarrow \omega < -1/3$

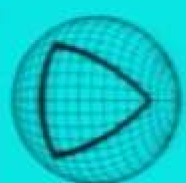
$$H^2 - \frac{1}{a^2} = \frac{8\pi G_4}{3}\rho$$

$\rho < 0$

What gives a bounce ?

WEC:	$\rho \geq 0 \quad$ and $\rho + p \geq 0.$
DEC:	$\rho \geq \lvert p \rvert$ or $1 \geq \omega.$
SEC:	$\rho + p \geq 0$ and $\rho + 3p \geq 0.$

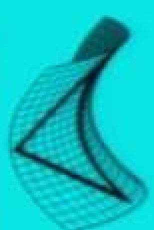
Closed Geometry



$$H^2 + \frac{1}{a^2} = \frac{8\pi G_4}{3}\rho$$

~~SEC~~ $p < -\rho/3 \quad \rightarrow \omega < -1/3$

Open Geometry



$$H^2 - \frac{1}{a^2} = \frac{8\pi G_4}{3}\rho$$

$\rho < 0$

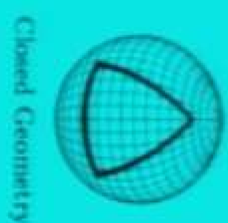
Flat Geometry

$$H^2 = \frac{8\pi G_4}{3}\rho$$

$\rho = 0$

What gives a bounce ?

WEC:	$\rho \geq 0 \quad \text{and } \rho + p \geq 0.$
DEC:	$\rho \geq \lvert p \rvert$ or $1 \geq \omega.$
SEC:	$\rho + p \geq 0$ and $\rho + 3p \geq 0.$



$$H^2 + \frac{1}{a^2} = \frac{8\pi G_4}{3}\rho$$

~~SEC~~ $p < -\rho/3 \quad \rightarrow \omega < -1/3$

$$H^2 - \frac{1}{a^2} = \frac{8\pi G_4}{3}\rho$$

~~SEC~~
~~WEC~~
~~DEC~~

$\rho < 0$

$$H^2 = \frac{8\pi G_4}{3}\rho$$

$\rho = 0$

A Newtonian cure to Gravity

without violating the energy conditions

No $\frac{1}{r}$ fall in the gravitational potential

Newtonian gravity

$$\frac{1}{2}m\dot{r}^2 + G_N\frac{4\pi}{3}r^3\rho V(r) = E\,.$$

$$H^2 \equiv \frac{\dot{r}^2}{r^2} = \frac{M_p^2}{3}\left(\rho + \frac{6E}{M_p^2 m r^2}\right),$$

$$H^2 \equiv \frac{\dot{r}^2}{r^2} = -\frac{M_p^2}{3}\rho r V(r)\,.$$

At short distances the potential tends to a constant

→ **(Asymptotic freedom)**

$H \to 0$ **Bouncing Cosmology**

Asymptotically Safe

A subset of trajectories (characterized by a few renormalized coupling constants) for which all but a few of the couplings vanish as

$$\Lambda \to \infty$$

Weinberg

Asymptotically Safe

A subset of trajectories (characterized by a few renormalized coupling constants) for which all but a few of the couplings vanish as

$$\Lambda \to \infty$$

$$\Lambda \frac{dg(\Lambda)}{d\Lambda} = ag(\Lambda)^2 \quad (a > 0) \longrightarrow \quad g(\kappa\Lambda) = \frac{g(\Lambda)}{1 - ag(\Lambda)\ln\kappa}$$

Weinberg

Asymptotically Safe

A subset of trajectories (characterized by a few renormalized coupling constants) for which all but a few of the couplings vanish as

$$\Lambda \to \infty$$

$$\Lambda \frac{dg(\Lambda)}{d\Lambda} = ag(\Lambda)^2 \quad (a > 0) \longrightarrow \quad g(\kappa\Lambda) = \frac{g(\Lambda)}{1 - ag(\Lambda)\ln\kappa}$$

Weinberg

Asymptotically Safe

A subset of trajectories (characterized by a few renormalized coupling constants) for which all but a few of the couplings vanish as

$$\Lambda \to \infty$$

$$\Lambda \frac{dg(\Lambda)}{d\Lambda} = ag(\Lambda)^2 \quad (a > 0) \longrightarrow \quad g(\kappa\Lambda) = \frac{g(\Lambda)}{1 - ag(\Lambda)\ln\kappa}$$

$g(\Lambda) > 0$ Trajectories become singular

$g(\Lambda) < 0$ Trajectories hit a fixed point for $\Lambda \to \infty$

Green's fn. does not have an unphsyical singularity

Weinberg

Question

* Can we make gravity weak at short distances/high energies ?

Question

* **Can we make gravity weak at short distances/high energies ?**

Improved UV behaviour: 4th Order Gravity

$$S = \int d^4x \, \sqrt{-g}(R + c_0 R^2 + b_0 C^2)$$

even Renormalizable [Stelle, 1978]

Question

* **Can we make gravity weak at short distances/high energies ?**

Improved UV behaviour: 4th Order Gravity

$S = \int d^4x \sqrt{-g}(R + c_0 R^2 + b_0 C^2)$

even Renormalizable [Stelle, 1978]

Not simultaneously Ghost & Asymptotically free

Question

- Can we make gravity weak at short distances/high energies ?

Improved UV behaviour: 4th Order Gravity

$S = \int d^4x \sqrt{-g}(R + c_0 R^2 + b_0 C^2)$

even Renormalizable [Stelle, 1978]

Not simultaneously Ghost & Asymptotically free

Question

* **Can we make gravity weak at short distances/high energies ?**

Improved UV behaviour: 4th Order Gravity

$S = \int d^4x \, \sqrt{-g}(R + c_0 R^2 + b_0 C^2)$

even Renormalizable [Stelle, 1978]

Not simultaneously Ghost & Asymptotically free

$$S \to \int d^4x \, \sqrt{-g} \, e^{(\Box + \frac{1}{6}R)} \frac{1}{6} R,$$

Siegel

Question

- Can we make gravity weak at short distances/high energies ?

Improved UV behaviour: 4th Order Gravity

$S = \int d^4x \sqrt{-g}(R + c_0 R^2 + b_0 C^2)$

even Renormalizable [Stelle, 1978]

Not simultaneously Ghost & Asymptotically free

$$S \to \int d^4x \, \sqrt{-g} \, e^{(\Box + \frac{1}{6}R)} \frac{1}{6} R,$$

Siegel

$$F(R) = R + \sum_{0}^{\infty} c_n R^{n+2}$$

Question

* **Can we make gravity weak at short distances/high energies ?**

Improved UV behaviour: 4th Order Gravity

$S = \int d^4x \sqrt{-g}(R + c_0 R^2 + b_0 C^2)$

even Renormalizable [Stelle, 1978]

Not simultaneously Ghost & Asymptotically free

$$S \to \int d^4x \sqrt{-g}\, e^{(\Box + \frac{1}{6}R)} \frac{1}{6} R,$$

Siegel

$$F(R) = R + \sum_{0}^{\infty} c_n R^{n+2}$$

$$F(R) = R + \sum_{n=0}^{\infty} c_n R \Box^n R$$

Question

* **Can we make gravity weak at short distances/high energies ?**

Improved UV behaviour: 4th Order Gravity

$S = \int d^4x \, \sqrt{-g}(R + c_0 R^2 + b_0 C^2)$

even Renormalizable [Stelle, 1978]

Not simultaneously Ghost & Asymptotically free

$$S \to \int d^4x \, \sqrt{-g} \, e^{(\Box + \frac{1}{6}R)} \frac{1}{6} R,$$

Siegel

~~$F(R) = R + \sum_{n=0}^{\infty} c_n R^{n+2}$~~

$$F(R) = R + \sum_{n=0}^{\infty} c_n R \Box^n R$$

Question

* Can we make gravity weak at short distances/high energies ?

Improved UV behaviour: 4th Order Gravity

$S = \int d^4x \sqrt{-g}(R + c_0 R^2 + b_0 C^2)$

even Renormalizable [Stelle, 1978]

Not simultaneously Ghost & Asymptotically free

$$S \to \int d^4x \sqrt{-g}\, e^{(\Box + \frac{1}{6}R)} \frac{1}{6} R,$$

Siegel

~~$F(R) = R + \sum_{n=0}^{\infty} c_n R^{n+2}$~~

$$F(R) = R + \sum_{n=0}^{\infty} c_n R \Box^n R$$

Question

* **Can we make gravity weak at short distances/high energies ?**

Improved UV behaviour: 4th Order Gravity

$S = \int d^4x \, \sqrt{-g}(R + c_0 R^2 + b_0 C^2)$

even Renormalizable [Stelle, 1978]

Not simultaneously Ghost & Asymptotically free

$$S \to \int d^4x \, \sqrt{-g} \, e^{(\Box + \frac{1}{6}R)} \frac{1}{6} R,$$

Siegel

~~$F(R) = R + \sum_{n=0}^{\infty} c_n R^{n+2}$~~

$$F(R) = R + \sum_{n=0}^{\infty} c_n R \Box^n R$$

Question

* Can we make gravity weak at short distances/high energies ?

Improved UV behaviour: 4th Order Gravity

$S = \int d^4x \sqrt{-g}(R + c_0 R^2 + b_0 C^2)$

even Renormalizable [Stelle, 1978]

Not simultaneously Ghost & Asymptotically free

$$S \to \int d^4x \sqrt{-g}\, e^{(\Box + \frac{1}{6}R)} \frac{1}{6} R,$$

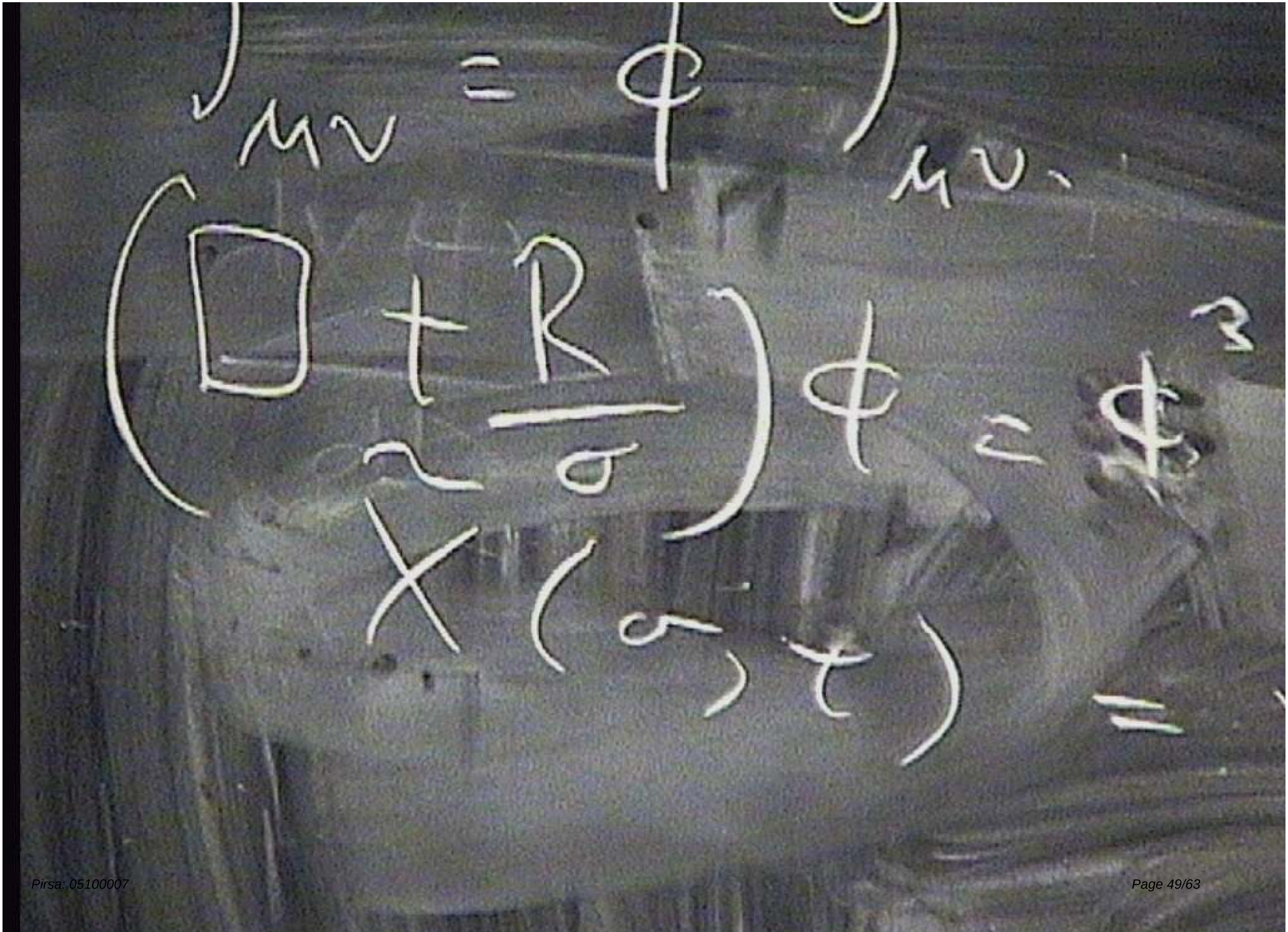
Siegel

$$F(R) = R + \sum_{n=0}^{\infty} c_n R^{n+2}$$

$$F(R) = R + \sum_{n=0}^{\infty} c_n R \Box^n R$$

Lean have

$$\tilde{g}_{\mu\nu} = \phi\, g_{\mu\nu}.$$


g_μν = φ g_μν
(□ + R/σ) φ = φ³
X(σ, t) =

$$\tilde{g}_{\mu\nu} = \phi\, g_{\mu\nu}.$$

$$\left(\Box + \frac{R}{\sigma}\right)\phi = \phi^3$$

$$X(\sigma, t) = X_L(\ldots$$

$$= \tilde{X}\ldots$$

X_R

X_L

Problems & Challenges

* Higher order corrections/derivative theory generically carry ghosts (unitarity / negative energy states)

$$S = \int d^4x \; \phi \Box (\Box + m^2) \phi \Rightarrow \Box (\Box + m^2) \phi = 0$$

$$\Delta(p^2) = \frac{1}{p^2(p^2+m^2)} \sim \frac{1}{p^2} - \frac{1}{(p^2+m^2)}$$

Problems & Challenges

* Higher order corrections/derivative theory generically carry ghosts (unitarity / negative energy states)

$$S = \int d^4x \ \phi\Box(\Box + m^2)\phi \Rightarrow \Box(\Box + m^2)\phi = 0$$

$$\Delta(p^2) = \frac{1}{p^2(p^2+m^2)} \sim \frac{1}{p^2} - \frac{1}{(p^2+m^2)}$$

Problems & Challenges

* Higher order corrections/derivative theory generically carry ghosts (unitarity / negative energy states)

$$S = \int d^4x \ \phi\Box(\Box + m^2)\phi \Rightarrow \Box(\Box + m^2)\phi = 0$$

$$\Delta(p^2) = \frac{1}{p^2(p^2+m^2)} \sim \frac{1}{p^2} - \frac{1}{(p^2+m^2)}$$

No extra states, i.e., non-perturbative

$$\Box e^{-\Box}\phi = 0$$

Novelties of $F(R) = R + \sum_{n=0}^{\infty} c_n R \Box^n R$

E.o.m. $\widetilde{G}_{\mu\nu} \equiv G_{\mu\nu} + \sum_{n=0}^{\infty} G^n_{\mu\nu} = T_{\mu\nu}$ $\nabla^\mu \widetilde{G}_{\mu\nu} = 0$

$G^n_{\mu\nu} \sim c_n(\Box^{n+1} R + \Box^p R \Box^m R)$

Schmidt

$$\widetilde{G} = -\tfrac{1}{2}\Box(1 - 6\textstyle\sum_0^\infty c_i \Box^{i+1})h = -\tfrac{1}{2}\Box\Gamma(\Box)h$$

$$\Delta(p^2) = \frac{1}{p^2\Gamma(-p^2)}$$

$$\Gamma(-p^2) = e^{\gamma(-p^2)}\,.$$

Gaussian Propagator has no Ghost

$$\tilde{G} \sim -m\delta(\vec{r}) \Rightarrow h(r) \sim \frac{1}{r}\int_{-\infty}^{\infty} dp \frac{p}{p^2\Gamma(-p^2)} e^{ipr}$$

Asymptotic Freedom: integrand falls faster than 1/p

$$\Rightarrow h(r) \stackrel{r\to 0}{\to} \text{constant}$$

Newtonian Limit: $\Gamma(-p^2) \stackrel{p\to 0}{\to} 1 \Rightarrow h(r) \stackrel{r\to\infty}{\to} \frac{1}{r}$

Example: $\Gamma(\Box) = e^{-\Box} \Rightarrow h(r) \sim \frac{\mathbf{erf}(r)}{r}$

$$\lim_{r\to\infty} \bar{h}(r) \sim -\frac{1}{r}, \qquad \lim_{r\to 0} \bar{h}(r) \sim \frac{1}{r_0} = \text{const.}\,.$$

Bouncing Cosmology

Prescription: Find $a = a(t)$ such that $\Box R(t) \sim R(t)$

$(\ldots)R(t) + (\ldots)R^2(t) \sim$ matter sources

Entails only solving Algebraic Equations

Bouncing Cosmology

Prescription: Find $a = a(t)$ such that $\Box R(t) \sim R(t)$

$(\ldots)R(t) + (\ldots)R^2(t) \sim$ matter sources

Entails only solving Algebraic Equations

$$a(t) = a_0 \cosh\left(\sqrt{\frac{w}{2}}\, t\right)$$

Bouncing Cosmology

Prescription: Find $a = a(t)$ such that $\Box R(t) \sim R(t)$

$(\ldots)R(t) + (\ldots)R^2(t) \sim$ matter sources

Entails only solving Algebraic Equations

$$a(t) = a_0 \cosh\left(\sqrt{\frac{w}{2}}\, t\right)$$

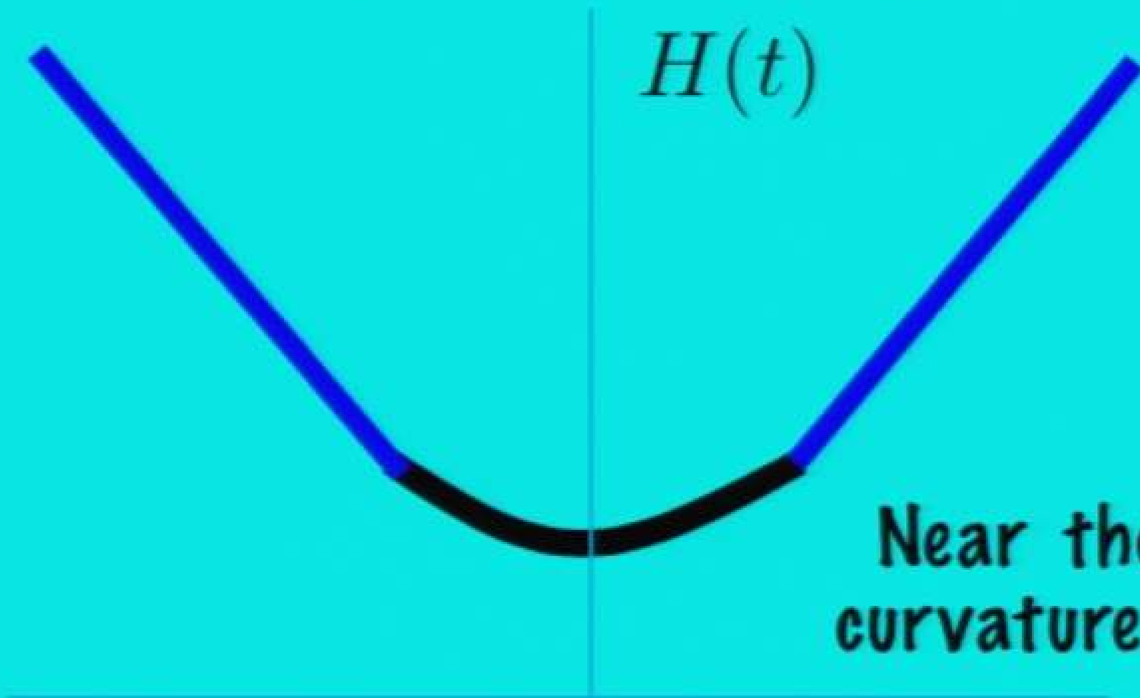
$$H = \sqrt{\frac{w}{2}} \tanh\left(\sqrt{\frac{w}{2}}\, t\right),$$

$$R = 3w\left[2 - \mathrm{sech}^2\left(\sqrt{\frac{w}{2}}\, t\right)\right],$$

$$\Box R = -(\ddot{R} + 3H\dot{R}) = -3w^2\left[\mathrm{sech}^2\left(\sqrt{\frac{w}{2}}\, t\right)\right] = w[R - 6w].$$

$$\Box^n R = w^{n-1}\Box R = -3w^{n+1}\mathrm{sech}^2\left(\sqrt{\frac{w}{2}}\, t\right),\ n \neq 0.$$

Matching Solutions



Einstein Hilbert term dominates

Near the bounce higher curvature terms dominate

$$a(t) \sim t^{1/2}\ ,\ G_{00} \sim \frac{1}{t^2}\ ,\ \widetilde{G}^{n}_{00} \sim \frac{1}{t^{2(n+2)}}$$

$$a(t) = \begin{cases} \cosh\left(\sqrt{\frac{w}{2}}\, t_0\right)\left(\frac{t}{-t_0}\right)^p & \text{for } t < -t_0 \\ \cosh\left(\sqrt{\frac{w}{2}}\, t\right) & \text{for } t_0 > t > -t_0 \\ \cosh\left(\sqrt{\frac{w}{2}}\, t_0\right)\left(\frac{t}{t_0}\right)^p & \text{for } t > t_0 \end{cases}$$

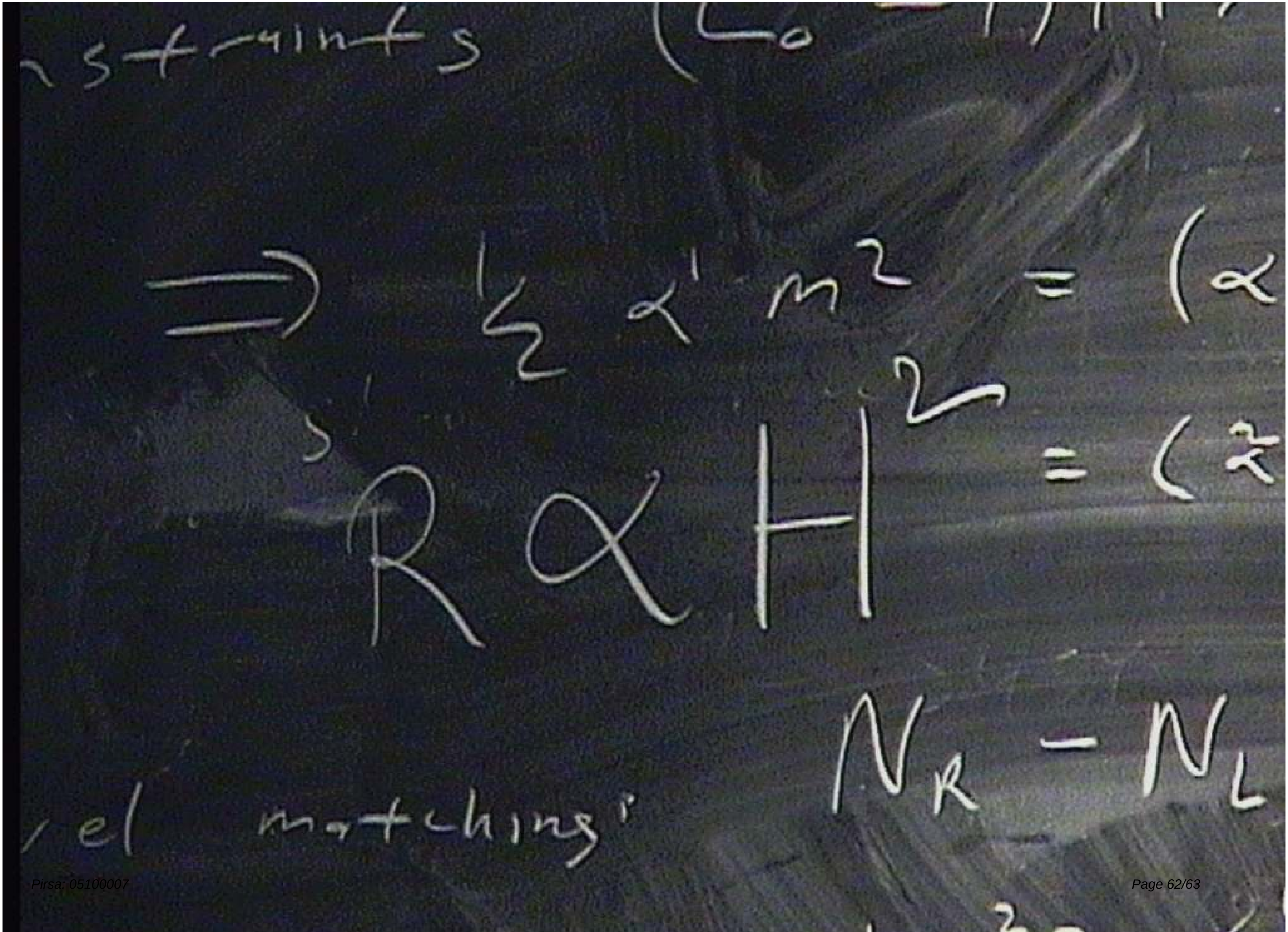
Can Bounce give rise to a Flat Spectrum ?

If the perturbations are generated only by the bounce solution:
NO FLAT SPECTRUM

If the perturbations are generated by the axion like filed:
Possible to get FLAT SPECTRUM

Conclusions & Questions

* It is possible to obtain Ghost and Asymptotic FREE gravity
* Resolving Big Bang Singularity
* Can it also resolve Black Hole Singularity?


nstraints
⇒ ½ α' m² = (α
R α H² = (
N_R − N_L
el matching:

Conclusions & Questions

* It is possible to obtain Ghost and Asymptotic FREE gravity
* Resolving Big Bang Singularity
* Can it also resolve Black Hole Singularity?