Title: The Cosmology of Degravitation

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Abstract:

- Degravitation (hep-th/0209227; ADDG
 - phenomenological proposal to solve cosmological const. problem directly (hep-th/0703027; Dvali, Khoury, Hofmann)

$$G_N \rightsquigarrow G_N(\lambda, L) \to 0 \quad \lambda \gg L$$
$$\to G_N \quad \lambda \ll L$$

- scale dependent coupling
 → IR decoupling
 normal gravity in the 'UV'

c.f. $\nabla \cdot E = \frac{\rho}{4\pi\epsilon_0}$

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$$\to (1 + K)\nabla \cdot E = \frac{\rho}{4\pi\epsilon_0}$$

$$\nabla \cdot E = \frac{\rho}{4\pi\epsilon_0(1+\kappa)}$$

if $\kappa(\omega)$ s.t. $\kappa \nearrow \infty$ $T \ll \omega^{-1}$;
we 'de-electrify' the source.
(high pass filter).

in gravity $\Rightarrow$ $G_N \to G_N(L^2\Box)$ covariant

$L^2 \equiv$ IR cutoff...

• $(f, \Box g) = (\Box f, g)$

$\Rightarrow$ $\Box$ has (,) complete set of mode functions in any spacetime...

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$\exists \{f_\lambda\} : \Box f_\lambda = \lambda^{-2} f_\lambda$

$\Rightarrow \quad G_N \rightarrow G_N (L^2 \lambda^{-2})$

- eg: Minkowski space: $\{f_\lambda\} = \{e^{ik\cdot x}\}$

$\{\lambda^{-2}\} = \{-k^2\}$

$G_N(\alpha) \rightarrow 0 \quad \alpha \ll 1$

$G_N(\alpha) \rightarrow G_N = \frac{M_{pl}^{-2}}{8\pi} \quad \alpha \gg 1$

- c.c. $\Rightarrow \Lambda \delta^\mu{}_\nu = T^\mu{}_\nu$

$\Rightarrow 8\pi G_N (L^2 \Box) \Lambda \delta^\mu{}_\nu = 0$

... in fact, any source in null space of $\Box$ is degravitated, e.g. plane waves; but not radiation gas...

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$$8\pi G_N \to \frac{8\pi G_N}{1+\left(\frac{-m^2}{\Box}\right)^{1-\alpha}} \qquad 0 \le \alpha < 1$$

$\alpha = 0$ Massive $h_{\mu\nu}$

$\alpha = 1/2$ DGP models

Q) Inflation?

Q) Any observational consequences (CMB?)

Q) Any wanted/unwanted extra baggage?

Q) Smallness of C.C.? tuning?

Outline

- Modification to Einstein's eqs & Bianchi Identities
- Inflation (& Quintessence) v.s. Cosmological const.
- Apparent c.c. → Afterglows & hints of nearby vacua
- IR perturbations ($\alpha = 0$)
- Novel solutions

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$$G^\mu{}_\nu = 8\pi G_N (L^2\Box)\, T^\mu{}_\nu$$

$$[\nabla_\mu, \Box] \neq 0$$

... imposes new constraints

N.B. matter sector e.o.m's unaffected except for ↑

e.g: $S = \int \sqrt{-g}\,(\nabla_\mu\phi\nabla^\mu\phi - m^2\phi^2)$

$$\Rightarrow (\Box + m^2)\phi = 0$$

$$\Box[g] \leftrightarrow G^\mu{}_\nu = 8\pi G_N (L^2\Box)\, T^\mu{}_\nu$$

$$\Rightarrow T^\mu{}_\nu = (\rho, -p, -p, -p)$$

$$\nabla^\lambda\nabla_\lambda T^\mu{}_\nu \rightarrow \Box T^0{}_0 = \ddot{\rho} + 3H\dot{\rho} + 6H^2(\rho + p)$$

$$\Box T^i{}_i = \ddot{p} + 3H\dot{p} + 2H^2(\rho + p)$$

$$\Box T^{\mu}{}_{\nu} = (\rho_{\Box}, -P_{\Box}, -P_{\Box}, -P_{\Box})$$

if $P = w\rho$

$$\rho_{\Box} = [\Box + 6H^2(1+w)]\rho$$

$$P_{\Box} = w\left[\Box + \frac{6H^2}{3w}(1+w)\right]\rho$$

$$P_{\Box} = w\rho_{\Box} \Leftrightarrow w = -1, \tfrac{1}{3} ; H^2 = 0$$

$$\rho_{\Box^{n+1}} = \Box\rho_{\Box^n} + 6H^2(1+w)\rho_{\Box^n}$$

$$P_{\Box^{n+1}} = \Box P_{\Box^{n+1}} + 2H^2(\rho_{\Box^n} + P_{\Box^n})$$

... by induction...

(also need $P_{\Box^{n-1}} = w\rho_{\Box^{n-1}}$ .. ..)

$$P_{[8\pi G_N(L^2\Box)]} = w\rho_{[8\pi G_N(L^2\Box)]}$$

$$G^{\mu}{}_{\nu} = 8\pi G_N(L^2\Box)\,T^{\mu}{}_{\nu}$$

$$\dots \quad \nabla_\mu G^{\mu}{}_{\nu} = 0$$

$$\Rightarrow \quad \partial_t\, \rho[8\pi G_N(L^2\Box)] + 3H\left\{\rho[8\pi G_N(L^2\Box)] + P[8\pi G_N(L^2\Box)]\right\} = 0$$

$$= \quad \partial_t \rho[\ ] + 3H(1+w)\rho[\ ] = 0$$

$$\Rightarrow \quad \rho[8\pi G_N] \propto 1/a^{3(1+w)}$$

⇒ we get same scaling of degravitated matter

⇒ functionally similar FRW eq's but scales now depend on degravitated matter

... imposes new constraints

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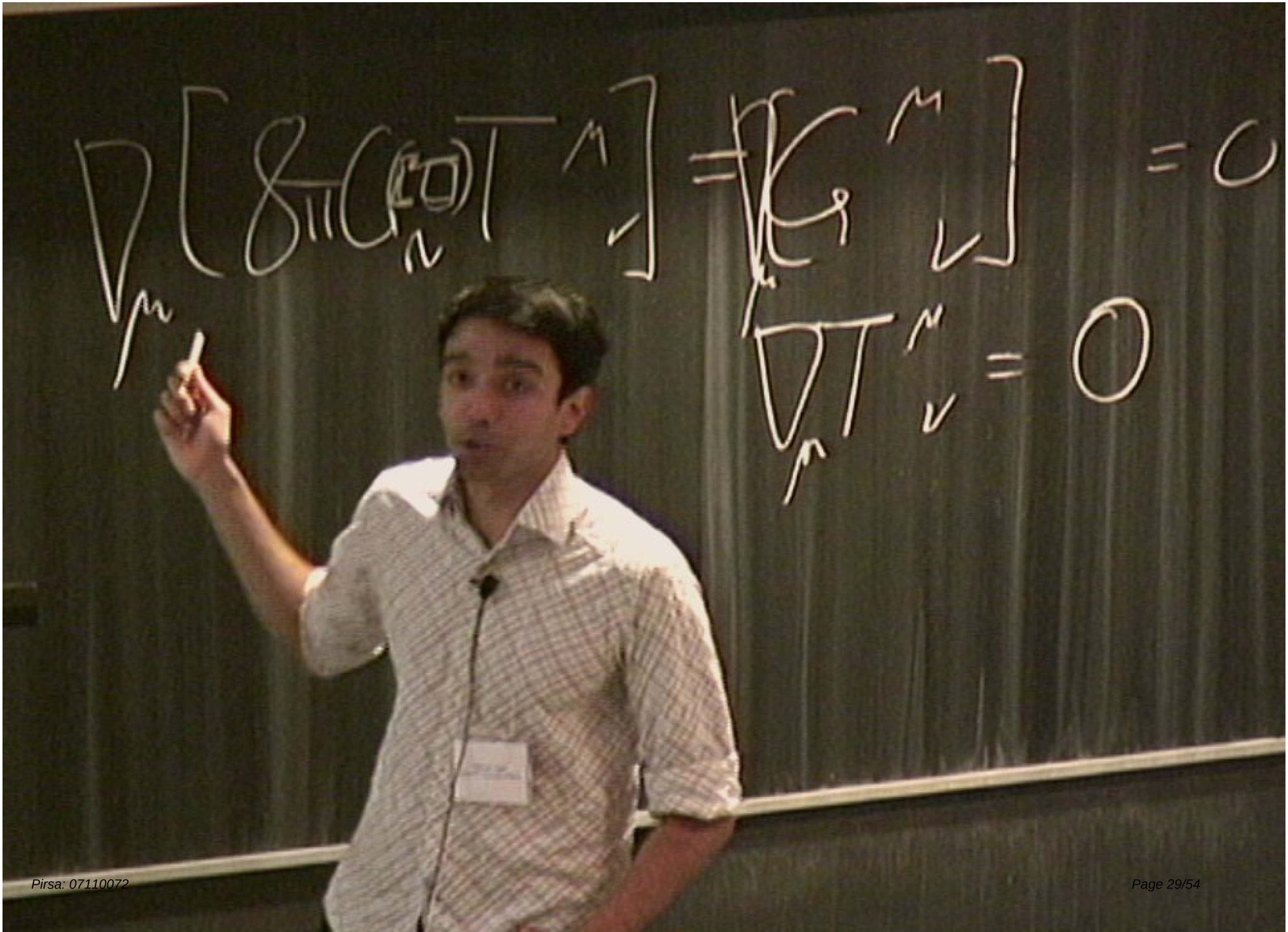
$$8\pi G_N(\square)\, T^{\mu}{}_{\nu} = G^{\mu}{}_{\nu}$$

$$\nabla_{\mu} T^{\mu}{}_{\nu} = 0$$


$\nabla_\mu T^\mu_\nu = 0$

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- Inflation

$w = -1$ only 1 FRW eqn to consider:

$$3H^2 = \frac{8\pi G_N}{1 - \frac{m^2}{\Box}} \rho \quad (= V(\varphi))$$

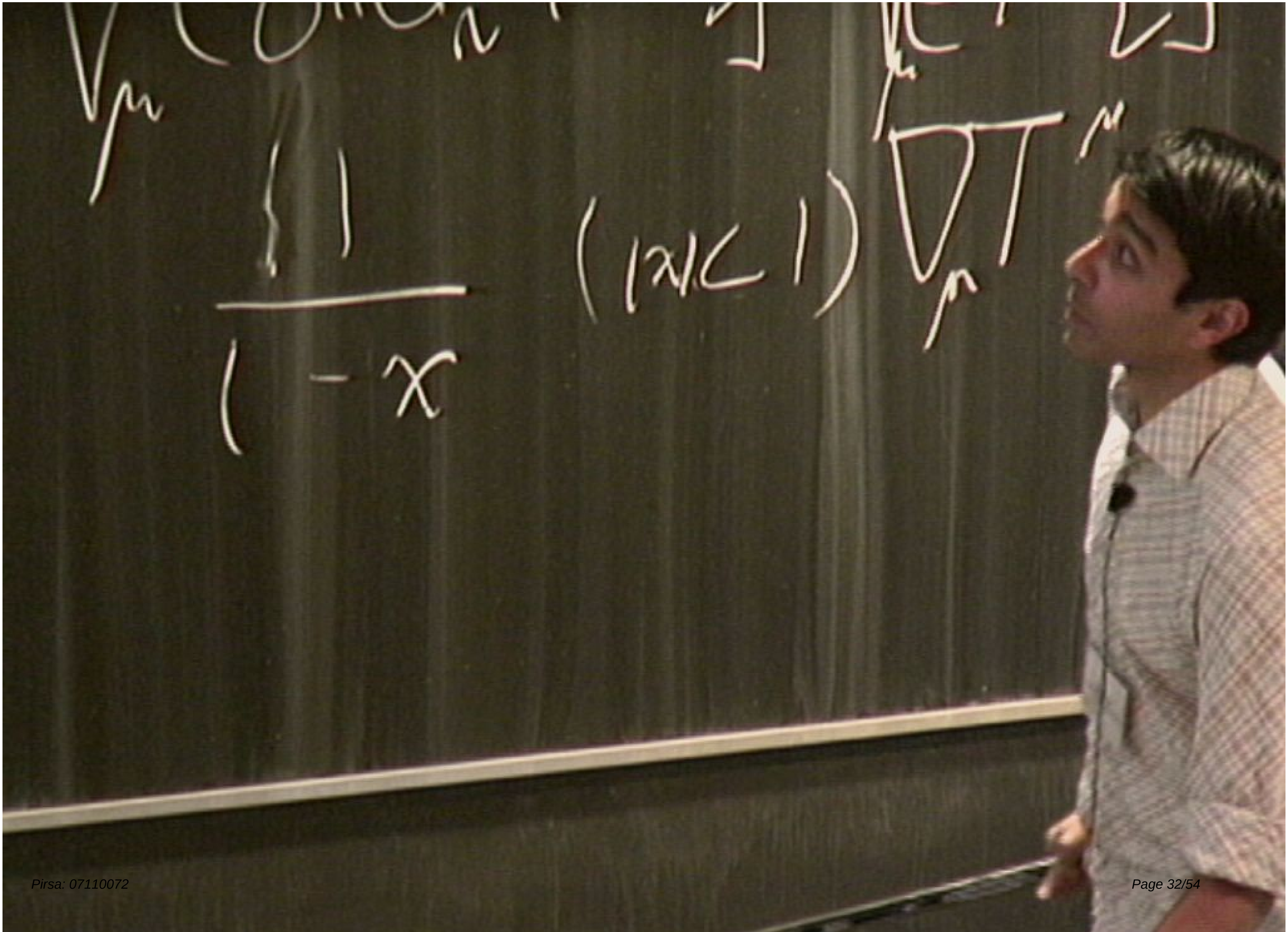
- expansion of degravitation filter depends on wavelength of source:

$\Rightarrow$ mode expand as homogeneous plane waves $\sim e^{i\omega t}$... not eigenfns but $\Box e^{i\omega t} = (-\omega^2 + 3iH\omega) e^{i\omega t}$

$\hookrightarrow$ "eigenvalue"

$$\frac{8\pi G_N}{1 - \frac{m^2}{\Box}} = \sum_{n=0}^{\infty} \left(\frac{m^2}{\Box}\right)^n = \sum_{n=0} \left(\frac{m^2}{k^2}\right)^n ; \; m^2 < k^2$$

$$= \frac{-\Box}{m^2} \frac{8\pi G_N}{1 - \frac{\Box}{m^2}} = -\sum_{n=0}^{\infty} \left(\frac{\Box}{m^2}\right)^n \frac{\Box}{m^2} = -\sum_{n=1}^{\infty} \left(\frac{k^2}{m^2}\right)^n_{k^2 < m^2}$$


$\frac{1}{1-x}$
$(|x|<1)$
$\nabla_\mu T^\mu$

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$\Rightarrow$ sources w/ wavelengths $> \lambda_{th,\circ}$ degravitate

$$G_{eff} = G_N\, O\!\left(k^2/m^2\right) \quad k^2 \ll m^2$$

$$G_{eff} = G_N\left(1 + O\!\left(\frac{m^2}{k^2}\right)\right) \quad m^2 \ll k^2$$

ex: Chaotic inflation (easily generalized to ϕ^n)

$$V(\phi) = \frac{m_\phi^2}{2}\varphi^2 + \Lambda$$

$$\rho = \underbrace{\cancel{\frac{\dot\phi^2}{2}}}_{0} + \frac{m_\phi^2}{2}\varphi^2 + \Lambda$$

expansion of degravitation filter

d[illegible]n wavelength of source:

[illegible] expand as homogeneous

[illegible] $\sim e^{i\omega t}$ ... not eigenfn's

[illegible] $e^{i\omega t} = (-\omega^2 + 3iH\omega)\, e^{i\omega t}$

↳ "eigenvalue"

$$\frac{[illegible]\, G_N}{[illegible] - \frac{m^2}{\Box}} = \sum_{n=0}^{\infty} \left(\frac{m^2}{\Box}\right)^n = \sum_{n=0} \left(\frac{m^2}{k^2}\right)^n ; \; m^2 < k^2$$

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$\Rightarrow$ sources w/ wavelengths $\gtrsim \lambda_{th,0}$ degravitate

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$$\rho = \underset{\to\, 0}{\cancel{\frac{\dot\phi^2}{2}}} + \frac{m_\phi^2}{2}\phi^2 + \Lambda$$

in slowroll approx:

$$(\Box + m_\varphi^2)\varphi = 0$$

$$\Rightarrow \quad \Box\varphi^2 = 2\varphi\Box\varphi + 2\cancel{\dot{\varphi}^2} \approx 0$$

$$\approx -2m_\varphi^2\varphi^2$$

$\Rightarrow$ φ^2 is a mode fn w/ e.val $-2m_\varphi^2$

$$\Rightarrow \quad \frac{8\pi G_N}{1 - \frac{m^2}{\Box}} \frac{m_\varphi^2}{2}\varphi^2 = \frac{8\pi G_N}{1 + \frac{m^2}{2m_\varphi^2}} \frac{m_\varphi^2\varphi^2}{2}$$

if $m_\varphi^2 \gg m^2$

$$= 8\pi G_N \frac{m_\varphi^2\varphi^2}{2} + O(m^2/m_\varphi^2)$$

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$$= 8\pi G_N \frac{m_\varphi^2\varphi^2}{2} + O(m^2/m_\varphi^2)$$

but Λ is also an eigenfn. w/ eigenvalue 0...

$$\frac{8\pi G_N \Lambda}{1 - \frac{m^2}{\Box}} = -\frac{8\pi G_N}{1 - \frac{\Box}{m^2}} \frac{\Box}{m^2} \Lambda$$

$$= 0$$

... zero mode is completely degravitated

... slow roll left almost unaffected

Hybrid inflation is reduced to slow roll inflation:

$$V(\sigma, \phi) = \frac{1}{4\lambda}(M^2 - \lambda\sigma^2)^2 + \frac{m^2\phi^2}{2} + \frac{g^2\phi^2\sigma^2}{2}$$

$\phi > \phi_c = M/g$, $\sigma = 0$ 

... zero mode piece inflates...

$\phi < \phi_c$ 

... inflation ends...

$$V(t) = \int_{-\infty}^{\infty} d\omega \, e^{i\omega t} V(\omega)$$

inverse Laplace x-form

say $V(t) = V_0$ + slowly varying piece

$$\Rightarrow V(\omega) = V_0 \delta(\omega) + V_1 \delta(\omega - \epsilon)$$

$$\frac{8\pi G_N}{1-\frac{m^2}{\Box}}\Lambda = -\frac{8\pi G_N}{1-\frac{\Box}{m^2}}\frac{\Box}{m^2}\Lambda$$

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$$\frac{8\pi G_N}{1-\frac{m^2}{\Box}} V(t) = 8\pi G_N \int_{-\infty}^{\infty} d\omega \frac{V(\omega) e^{i\omega t}}{1 + \frac{m^2}{\omega^2 - 3iH\omega}}$$

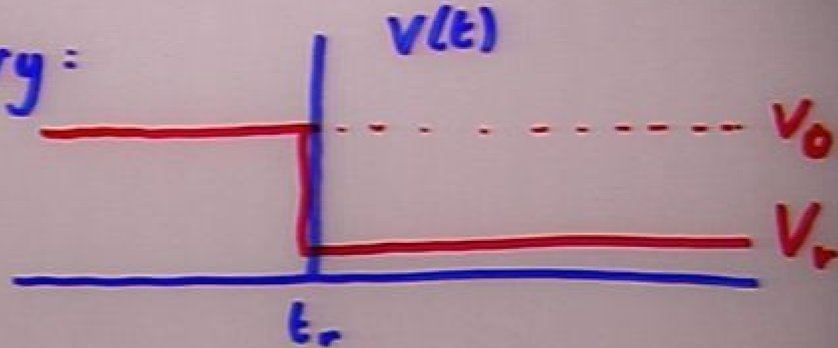
$$= 8\pi G_N \int_{-\infty}^{\infty} \frac{[\omega^2 - 3iH\omega] e^{i\omega t} V(\omega)}{[\omega^2 - 3iH\omega + m^2]}$$

$$m^2 \neq 0 \; ; \; V(\omega) = \delta(\omega) V_0 + V_1 \delta(\omega - \epsilon)$$

$$= 8\pi G_N \left[\delta(m^2) V_0 + \frac{e^{i\epsilon t}}{1 + \frac{m^2}{\epsilon^2 - 3iH\epsilon}} \right]$$

if $\epsilon^2 \gg m^2$, slow rolling/ (quintessent) piece unaffected.

now try:



$$V(t) = V_0 - (V_0 - V_r)\,\theta(t - t_r)$$

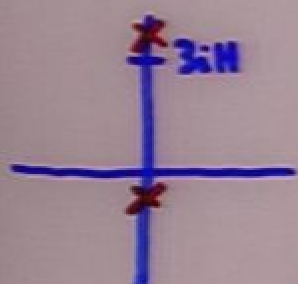
$$\Rightarrow \theta(t - t_r) = \int_{-\infty}^{\infty} d\omega\, e^{i\omega(t-t_r)} \left[\frac{\delta(\omega)}{2} + \frac{1}{2\pi i \omega} \right]$$

$$\begin{pmatrix} t > t_r \\ t < t_r \end{pmatrix}$$

$$\Rightarrow V(t) = \int_{-\infty}^{\infty} d\omega\, e^{i\omega(t-t_r)} \left[\delta(\omega)\frac{(V_r + V_0)}{2} + \frac{(V_r - V_0)}{2\pi i \omega} \right]$$

$$\frac{V(t)}{1-m^2/\Box} = \int_{-\infty}^{\infty} e^{i\omega(t-t_r)} \frac{\left[\frac{\delta(\omega)}{2}(V_r+V_0) + \frac{(V_r-V_0)}{2\pi i\omega}\right]\left[\omega^2-3iH\omega\right]}{\left[\omega^2-3iH\omega+m^2\right]}$$

$$\omega_\pm = \frac{3iH}{2}\left(1 \pm \sqrt{1+\frac{4m^2}{9H^2}}\right)$$



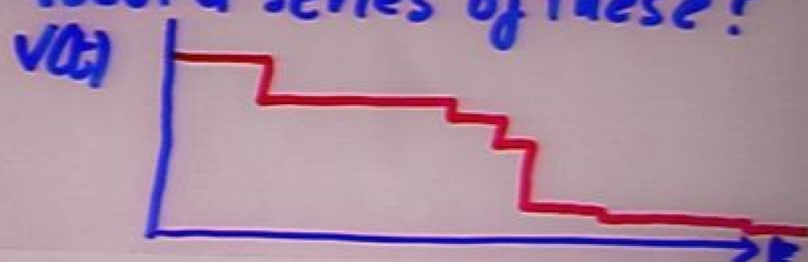
$\Delta V!$

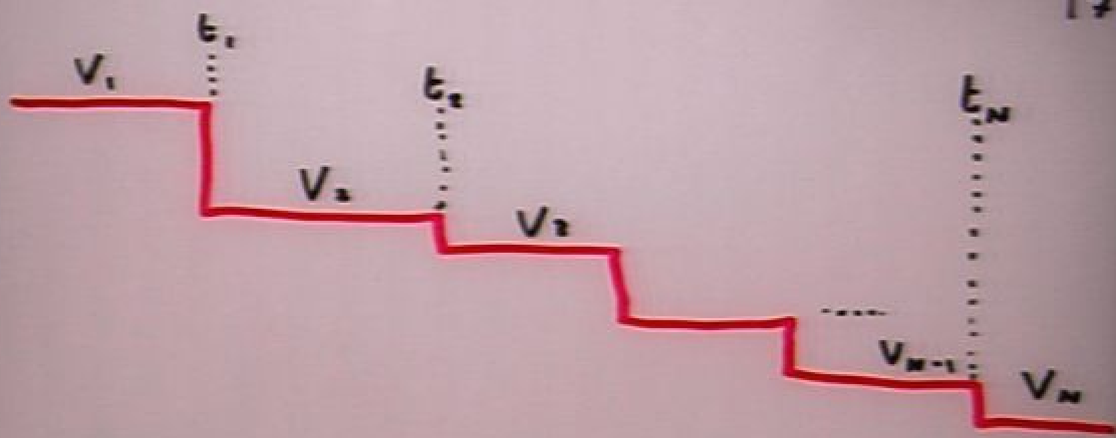
$$t<t_r = V_r\,\delta(m^2) - \frac{(V_r-V_0)}{2}\left(1+\frac{1}{\sqrt{1+\frac{4m^2}{9H^2}}}\right)$$

$$t>t_r = V_r\,\delta(m^2) + \frac{(V_r-V_0)}{2}\left(1-\frac{1}{\sqrt{1+\frac{4m^2}{9H^2}}}\right)$$

$\lim_{m^2\to 0}$ is O.K. (no vDVZ...)

Q) What about a series of these?





$$\frac{8\pi G_N}{1-\frac{m^2}{\Box}} V(t) \quad \text{at } t_k < t < t_{k+1}$$

$$= 8\pi G_N \Big[V_k + \frac{m^2}{9H^2}\sum_{i=k+1}^{N}(V_{i-1}-V_i)$$

$$- \frac{m^2}{9H^2}\sum_{i=1}^{k}(V_{i-1}-V_i)\Big)$$

... at $t > t_N$

$$= \frac{m^2}{9H^2}\Delta V\, 8\pi G_N$$

$$3H^2 = 8\pi G_N \left(\frac{m^2}{9H^2}\right) \Delta V$$

$$\Rightarrow \quad H^4 = \frac{8\pi G_N}{3} m^2 \Delta V$$

$$H^4 = \left(\frac{m}{M_{pl}}\right)^2 \frac{\Delta V}{3}$$

$$\Rightarrow \quad H^2 = \frac{m}{M_{pl}} \left(\frac{\Delta V}{3}\right)^{1/2}$$

$$\sim \Lambda$$

... observed as c.c... still too large ($m/M_{pl} \sim 10^{-60}$)

"afterglow" of other vacua?
need to improve calculation
to include nucleation ...

Other observational consequences?

$$\frac{\delta\rho}{\rho} = \frac{V^{3/2}}{V' M_{Pl}^3} \leftarrow \text{changes here}$$

$\sim$

$$G^\mu{}_\nu = 8\pi G_N (L^2\Box) T^\mu{}_\nu$$

$$\delta G^\mu{}_\nu = 8\pi G(L^2\Box)\delta T^\mu{}_\nu \quad ?$$
$$+ 8\pi G'(L^2\Box) T^\mu{}_\nu \,\delta\Box L^2$$

N.B. if $L^2 \approx H^{-2}$ then
possible suppression of low multipoles?

need to improve calculation
to include nucleation ...

Other observational consequences?

$$\frac{\delta\rho}{\rho} = \frac{V^{3/2}}{V' M_{pc}^3} \leftarrow \text{changes here}$$

$$\sim \quad G^\mu{}_\nu = 8\pi G_N (L^2\Box) T^\mu{}_\nu$$

$$\delta G^\mu{}_\nu = 8\pi G (L^2\Box) \delta T^\mu{}_\nu \quad ?$$
$$+ 8\pi G' (L^2\Box) T^\mu{}_\nu \, \delta\Box L^2$$

N.B. if $L^2 \approx H^{-2}$ then
possible suppression of low multiples?

$$G_N = \frac{8\pi G_N}{1+\left(\frac{m^2}{-\Box}\right)^{1-\alpha}} = \frac{8\pi G_N}{1+\left(\frac{1}{x}\right)^{1-\alpha}}$$

$$G_N' = \frac{8\pi G_N(\alpha-1)\delta x}{(-x)^{\alpha}\left[(-x)^{1-\alpha}+1\right]}$$

$x \to 0 \quad G_N' \nearrow \infty$!

... but $\exists\, k_{IR} = H$

& if $H_0^{-1} \ll 1/m$

almost no effect on pert. calculations...

Novel soln's?

if $H = 0 \Rightarrow \left(8\pi G_N(\Box)\, T^{\mu}{}_{\nu}\right)^{0}_{;0} = 8\pi G(\Box)\rho$

$\therefore$ if $8\pi G_N(L^2\Box)\,\rho = 0$

... we can obtain new loitering soln's ...

$\rho = E^2 + B^2$; plane wave

$\vec{E} = \vec{\epsilon}\, e^{ik\cdot x}$

$\vec{B} = \hat{k}\times\vec{\epsilon}\; e^{ik\cdot x}$

$\rho = \lambda e^{2ik\cdot x}$

$\Rightarrow \Box\rho = 0$ .... so a plane wave in Minkowski sp. is a soln. to Einstein's eq's... decoherent superposition is as usual...

Conclusions

- Degravitation kills all zero modes completely ($c.c. = \Lambda\delta^{\mu}{}_{\nu}$)
- Slow roll inflation, Old inflation O.K. Hybrid inflation nullified
- non-locality of degravitation → observed c.c is a memory of previous energy densities (vacua?) → Afterglow c.c? = Λ_{obs}
- not just c.c. degravitates... anything interesting for cosmology? Loitering?