Title: IR Renormalizations of G_N, and the Cosmological Constant Problems

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Abstract: We discuss a candidate mechanism through which one might address the various cosmological constant problems. We observe that the renormalization of gravitational couplings manifests non-local modifications to Einstein's equations as quantum corrected equations of motion, and in doing so offers a complimentary realization of the degravitation paradigm-- a realization through which its non-linear completion and the corresponding modified Bianchi identities are readily understood. We proceed to consider theories whose coupling to gravity might a priori induce non-trivial RG flow for gravitational couplings in the IR, and arrive at a class of non-local effective actions which yield a suitably degravitating filter function for Newton's constant upon subsequently being integrated out.

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- The inability to do so underlies much of the motivation to paraphrase the problem away (string landscape).
- 'Degravitation' directly solves the first, implicitly solves the second, and considerably alleviates the third aspect of the C.C. problem.

Filtering gravity at long wavelengths

What if G_N were not a constant, but coupled differently to different sources? In hep-th/0202174 DGS realized what was later elaborated upon and christened in hep-th/0209227 by ADDG as 'Degravitation':

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- How do we actually realize this filtering of gravity?

The filtering effects of extra polarizations

In hep-th/0703027 Dvali, Hofmann and Khoury proposed that one could naturally obtain a one parameter family of suitably degravitating filter functions from models of resonantly massive gravity:

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- In order to be self-consistent, we must address the issue of non-linear completion (so we can do cosmology) as well as better understand the issue of the modified Bianchi identities.

A candidate solution to all aspects of the C.C. problem?

(Based on *arXiv* : 0801.2151 , *arXiv* : 1003.3010) Before we continue our investigation as to how to come up with a concrete implementation of the degravitation scenario, we offer the following interlude to motivate the search. We take the functional form of the filter function corresponding to massive gravity as an example

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- So that its action on any source becomes $\rho_{degrav}(x) = \rho(x) - m^2 \int d^4x' \sqrt{-g(x')} G(x, x') \rho(x')$
- Normalized as $1 = m^2 \int d^4x \sqrt{-g(x)} G(x, y)$, we can rewrite the above as $\rho_{deg}(x) = \rho(x) - \langle \rho \rangle_x$
- $\langle f \rangle_x := \frac{\int d^4x' \sqrt{-g(x')} G(x, x') f(x')}{\int d^4x' \sqrt{-g(x')} G(0, x')}$
- We see immediately how a spatial zero mode (bare c.c.) is degravitated: $\Lambda_{deg} = \Lambda(1 - \langle 1 \rangle) = 0$

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A candidate solution to all aspects of the C.C. problem?

(Based on *arXiv* : 0801.2151 , *arXiv* : 1003.3010) Before we continue our investigation as to how to come up with a concrete implementation of the degravitation scenario, we offer the following interlude to motivate the search. We take the functional form of the filter function corresponding to massive gravity as an example

- $\frac{8\pi G_N}{1+\frac{m^2}{\Box}} = \frac{8\pi G_N \Box}{\Box + m^2} = 8\pi G_N \Box(\Box + m^2)^{-1}$
- So that its action on any source becomes $\rho_{degrav}(x) = \rho(x) - m^2 \int d^4x' \sqrt{-g(x')} G(x,x')\rho(x')$
- Normalized as $1 = m^2 \int d^4x \sqrt{-g(x)} G(x,y)$, we can rewrite the above as $\rho_{deg}(x) = \rho(x) - \langle \rho \rangle_x$
- $\langle f \rangle_x := \frac{\int d^4x' \sqrt{-g(x')} G(x,x') f(x')}{\int d^4x' \sqrt{-g(x')} G(0,x')}$
- We see immediately how a spatial zero mode (bare c.c.) is degravitated: $\Lambda_{deg} = \Lambda(1 - \langle 1 \rangle) = 0$

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Dark energy as a memory

Since we have annihilated the bare C.C., we are now forced to account for what dark energy might be. Consider the effect of the filter function on a given source:

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- Expanding in powers of $m(t - t_i)$, we find $\delta_{degrav}(t - t_i) \sim \theta(t - t_i)m^2\Delta(t)$, with $\Delta(t)$ a decaying function of time.
- Taking the $H \to 0$ limit, we model a universe that goes from a pre-inflationary phase, through a burst of inflation and again onto a radiation dominated phase.

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We see that even though the source is no longer extant, there a memory effect associated with the filter function results in an 'afterglow' energy density, which sources curvature as:

- $\frac{R}{M_{pl}^2} \sim \frac{m^2}{M_{pl}^2} \lesssim \frac{H_0^2}{M_{pl}^2} = 10^{-120}$

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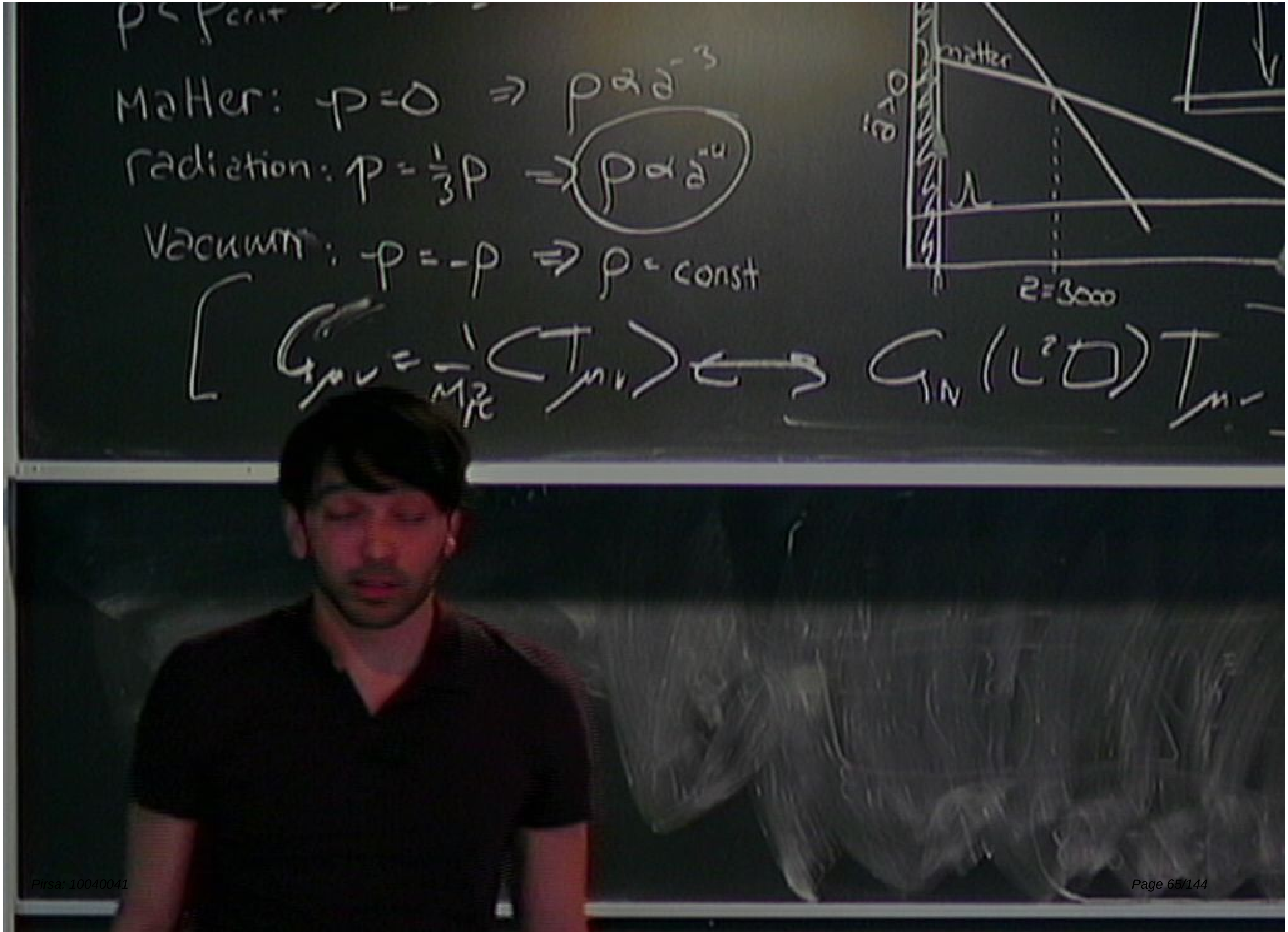
- Working phenomenologically, degravitation appears to solve 2 1/2 of the C.C. problems.
- However if any of these conclusions are to be taken seriously, we need to understand degravitation as a consistent, non-linearly realized modification to Einstein gravity.

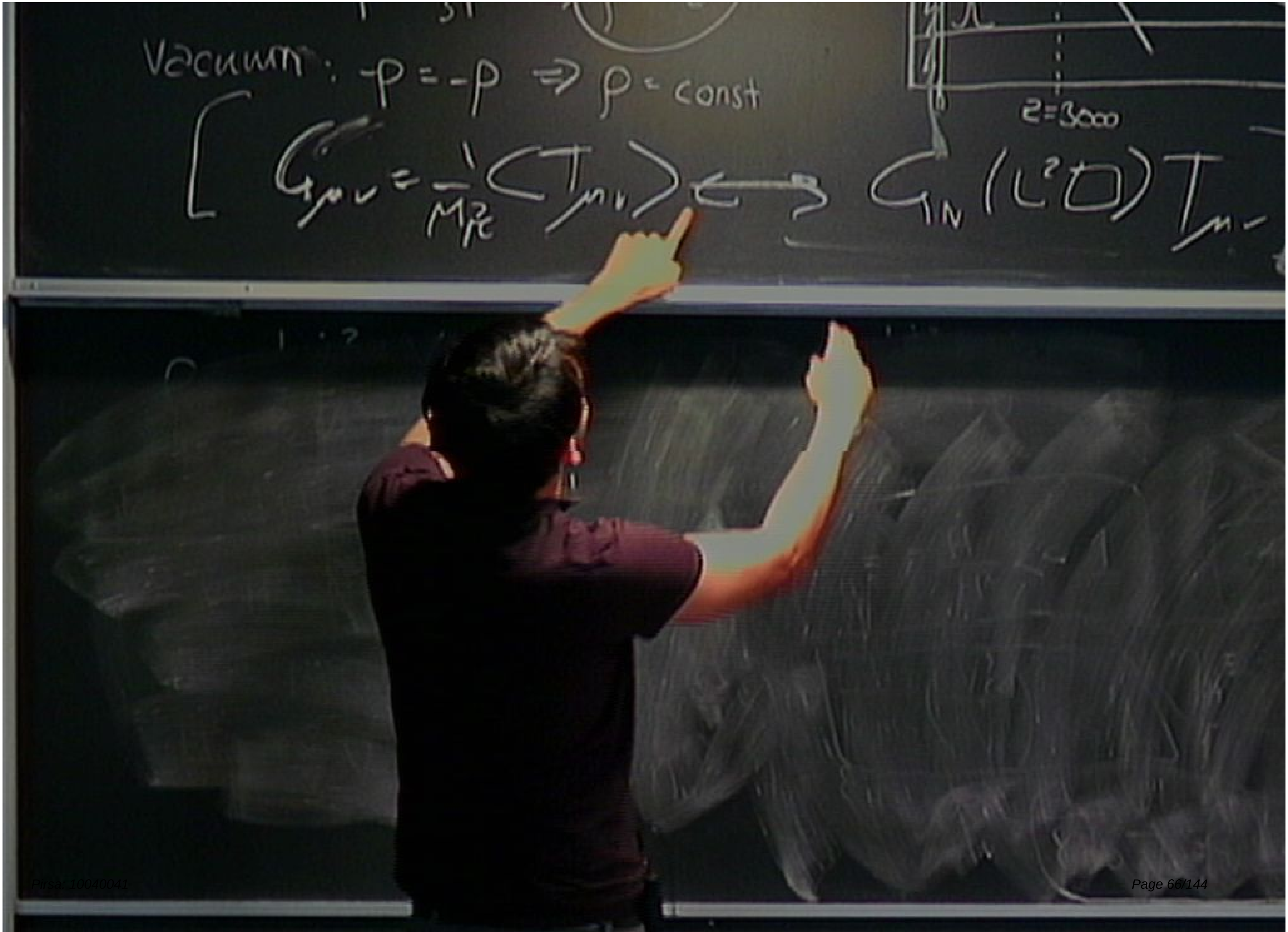
Filtering as a semi-classical effect?

Coupling constants run in interacting QFT's. This running is determined by the renormalization group equations of the theory at hand:

- $\mu \frac{d\alpha}{d\mu} = \beta(\alpha)$



ρ<ρcrit ⇒
Matter: p=0 ⇒ ρ∝a⁻³
radiation: p=⅓ρ ⇒ ρ∝a⁻⁴
Vacuum: p=−ρ ⇒ ρ=const
matter
a→0
z=3000
Gμν = 1/Mpl² ⟨Tμν⟩ ⟷ GN(L²□)Tμν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- 'De-localizes' the vertex, makes the 'equations of motion' non-local

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Running of couplings in gravity?

We now ask, is this possible in gravity? We begin with a suggestive toy example– Quantum gravity in two dimensions, which is a renormalizable theory (G_N in 2-d is dimensionless). Christensen and Duff (1978) working in $d = 2 + \epsilon$ dimensions found:

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We now ask, is this possible in gravity? We begin with a suggestive toy example– Quantum gravity in two dimensions, which is a renormalizable theory (G_N in 2-d is dimensionless). Christensen and Duff (1978) working in $d = 2 + \epsilon$ dimensions found:

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Can this work in 4-d?

We interject an important phenomenological point: gravity is the *only* force whose coupling we directly measure in the UV (via Cavendish type experiments $\sim \mu m$). Clearly, once we go beyond solar system scales, we have to make up sources[1]. Could it be that gravity is IR free and runs towards $1/M_{pl}^2$ at all other cosmologically accessible scales?

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Consider how Newton's constant is renormalized by integrating out matter fields:

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As we have seen, the $g(\tau)$ one obtains from standard matter couplings do not exhibit anything interesting for our purposes. This should be obvious. Why should renormalization of standard matter fields affect anything deep into the IR?

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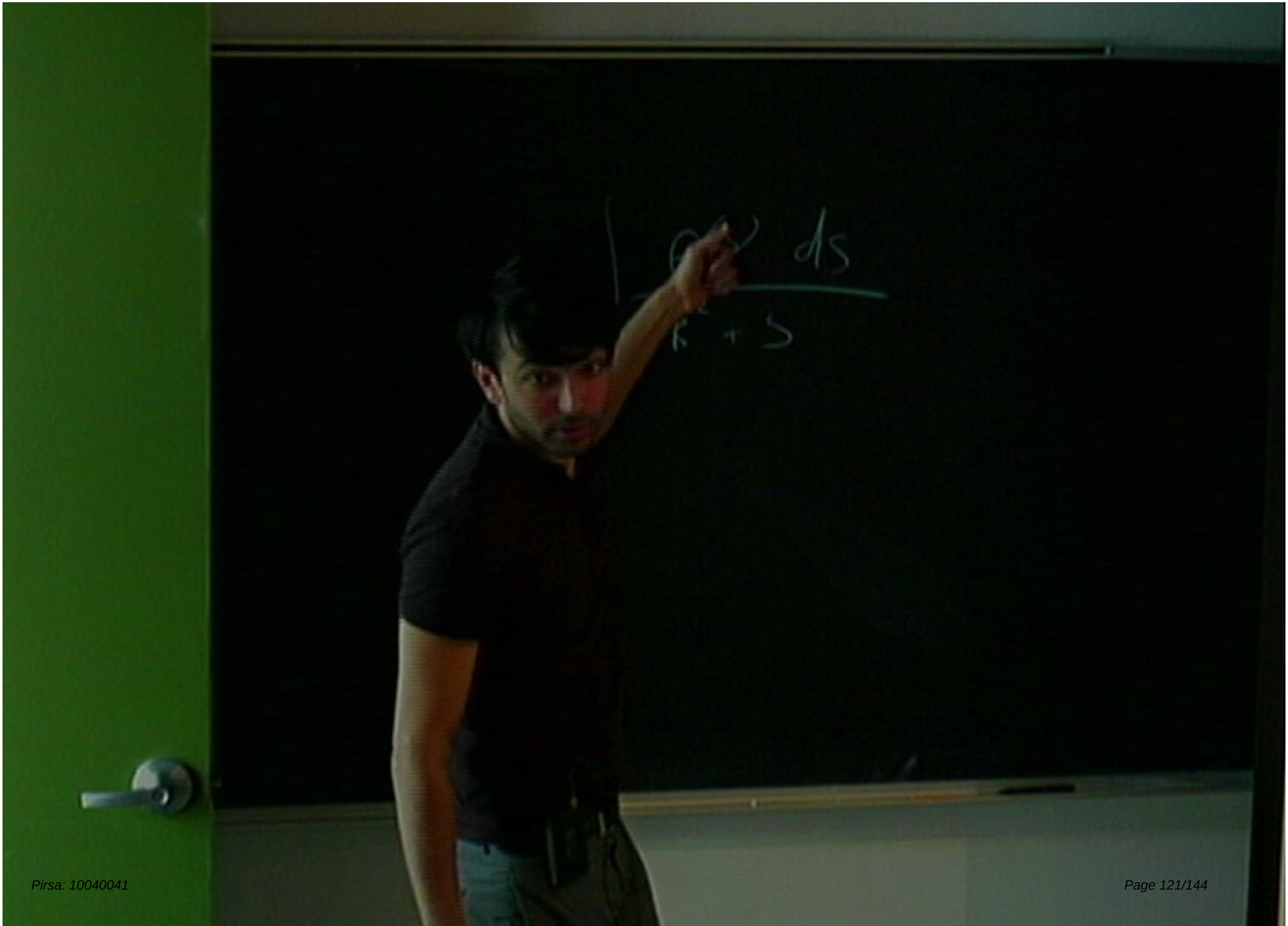

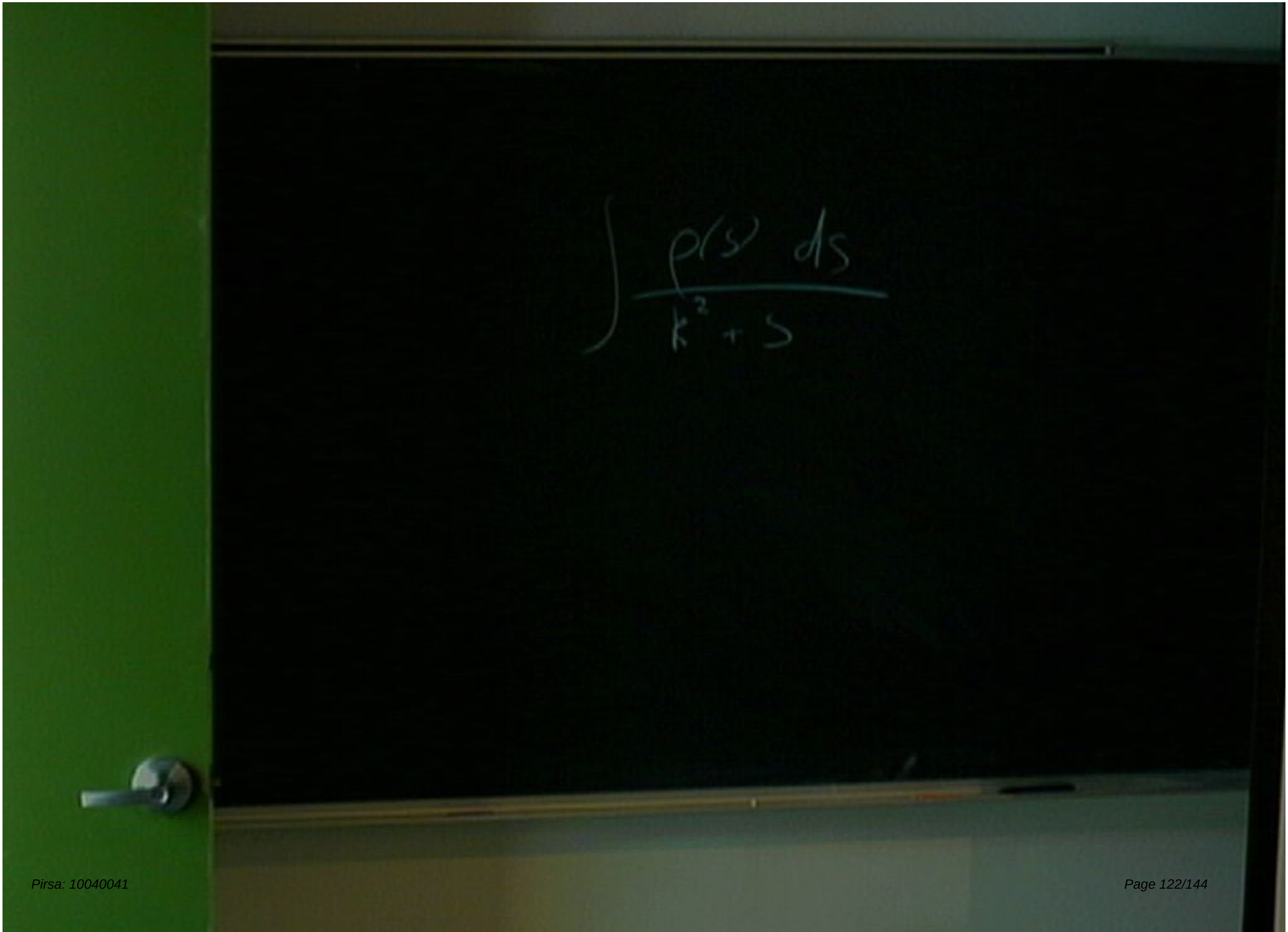
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- Many future directions to explore.

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- Relations to other musings in the literature? (e.g. Polyakov, Antoniadis, Mottola)

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Consider now the following action:

- $S = -\int \sqrt{-g}\mathcal{O}[e^{-m^2/\Box}\Box]\mathcal{O}$
- Results in RG flow $M_{pl}^2 G_N \to 0$, $\Lambda G_N \to 0$ independent of scheme.
- Acting on all other sources, results in the filter function $G_N \to \frac{1}{M_{pl}^2}\frac{1}{1+\frac{m^2}{24\pi M_{pl}^2}\frac{m^2}{\Box}}T^\mu_\nu$ *in a particular scheme*

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