Title: Gravitational fixed points and asymptotic safety from perturbation theory

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Abstract: The fixed point structure of the renormalization flow in Einstein gravity and higher derivative gravity is investigated in terms of the background effective action. Using a covariant operator cutoff that keeps track of powerlike divergences and the transversal-traceless decomposition a construction is proposed that renders the {\it regularized} one-loop effective action gauge independent on-shell. In combination with a `Wilsonian' matching condition nontrivial strictly positive fixed points for the dimensionless Newton constant g and the cosmological constant λ can then be identified already in one loop perturbation theory. The renormalization flow is asymptotically safe with respect to the nontrivial fixed points in both cases. In Einstein gravity a residual gauge dependence of the fixed points is unavoidable while in higher derivative gravity both the fixed point and the flow equations are universal. Along this flow spectral positivity of the Hessians can be satisfied, evading the traditional positivity problems. Dependence on $O(10)$ initial data is erased to accuracy 10^{-5} after $O(10)$ units of the renormalization mass scale and the flow settles on a $\lambda(g)$ orbit.

Gravitational fixed points and asymptotic safety from perturbation theory

Max Niedermaier

CNRS (Centre National de la Recherche Scientifique)

Asymptotic Safety – 30 years later, PI, Nov. 2009

Outline

1. Refi ned PT for gravity theories
2. Results for Einstein-Hilbert gravity
3. Results for Higher Derivative gravity
4. The role of perturbation theory
5. Conclusions

PRL **103** (2009) 101303, and submitted.

Coupling redefinitions for g_N, λ

Dimensionless Newton and cosmological constants:
$g_N := \mu^2\kappa^2 = \mu^2 16\pi G_N$, $\lambda := \mu^{-2}\Lambda$.

Consider fi nite coupling redefi nitions:

$$g_N = g'_N + \frac{\hbar}{(4\pi)^2} {g'_N}^2 C'_1 , \quad \lambda = \lambda' + \frac{\hbar}{(4\pi)^2} g'_N D'_1 .$$

Beta functions transform inhomogeneously!

$$\begin{aligned} \mu\frac{d}{d\mu} g_N &= \beta_g + \frac{\hbar}{(4\pi)^2} {g_N}^2 \left[2C_1 + 2g_N \frac{\partial C_1}{\partial g_N} - 2\lambda \frac{\partial C_1}{\partial \lambda} \right], \\ \mu\frac{d}{d\mu} \lambda &= \beta_\lambda + \frac{\hbar}{(4\pi)^2} g_N \left[4D_1 + 2g_N \frac{\partial D_1}{\partial g_N} - 2\lambda \frac{\partial D_1}{\partial \lambda} \right], \end{aligned}$$

Do they contain intrinsic information?

Refined PT for gravity theories

Proposed answer: Yes, but need:

(a) Regularization that keeps track of powerlike divergences in Λ_{UV}.

(b) Nonminimal subtraction ansatz for κ^2, Λ.

(c) 'Wilsonian' matching condition.

(d) Background effective action Γ_1 that is on-shell gauge independent in regularized form.

Plan: Develop this framework, then apply to Einstein-Hilbert (EH) and Higher Derivative (HD) gravity.

Operator-heat kernel regularization

$\mathbf{A}$ symmetric, covariant differential operator of order $2r$.
$A(x,y;t) = \langle x|\exp(-t\mathbf{A})|y\rangle$ its heat kernel.
$z \mapsto F_{k,\Lambda_{\rm UV}}(z)$ regulator function depending on IR cutoff k and UV cutoff $\Lambda_{\rm UV}$, with $k < \mu \leq \Lambda_{\rm UV}$.
$t \mapsto \widetilde{F}_{k,\Lambda_{\rm UV}}(t)$ its inverse Laplace transform, normalized such that $\widetilde{F}_{0,\infty}(t) = -1/t$. Minus n-th moment $-q_n(\Lambda_{\rm UV}^{2n} - k^{2n})$.

Then: $\ln \mathbf{A}$ is replaced with integral operator

$$\ln \mathbf{A} \mapsto \ln_{k^r,\Lambda_{\rm UV}^r} \mathbf{A} = F_{k^r,\Lambda_{\rm UV}^r}(A)(x,y) := \int_0^\infty dt\, \widetilde{F}_{k^r,\Lambda_{\rm UV}^r}(t) A(x,y;t)$$

Gives unique expressions for regularized:

$\mathbf{A}^{-1}_{k,\Lambda_{\rm UV}}$, $\mathrm{Det}_{k,\Lambda_{\rm UV}}\mathbf{A}$, Gaussian integrals with kernel $\mathbf{A}$.

Divergent part of effective action

Small t expansion of $A(x, y; t)$ gives

$$\mathrm{Tr} F_{k^r, \Lambda^r_{\mathrm{UV}}}(A) = -\frac{\Gamma(2/r)}{r(4\pi)^2} \int d^4x \sqrt{g}$$

$$\times \Big[\Lambda^4_{\mathrm{UV}} q_{2/r}\, E_0(x|A) + \Lambda^2_{\mathrm{UV}} q_{1/r}\, E_2(x|A) + 2r \ln \Lambda_{\mathrm{UV}}\, E_4(x|A) \Big] + O(\Lambda^0_{\mathrm{UV}})$$

with E_0, E_2, E_4 heat kernel coeffi cients of A. Obtain

$$\Gamma_1^{\mathrm{div}} = -\frac{1}{(4\pi)^2} \int d^4x \sqrt{g} \Big\{ \Lambda^4_{\mathrm{UV}} \Upsilon_1 + \Lambda^2_{\mathrm{UV}} [\Upsilon_2 R + \mu^2 \Upsilon_3]$$

$$+ \ln(\Lambda_{\mathrm{UV}}/\mu)[\zeta_1 C^2 + \zeta_2 R^2 + \mu^2 \zeta_4 R + \mu^4 \zeta_5] \Big\}$$

with Υ_i, ζ_i determined by E_n of constituent operators.

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Nonminimal subtraction

Absorb $\Gamma_1^{\rm div}$ by coupling and fi eld renormalizations. For κ^2 and $\tilde{\Lambda} = 2\Lambda/\kappa^2$ use:

$$\tilde{\Lambda}_0 = \mu^4 \frac{2\lambda}{g_N}\left\{1 + \frac{\hbar}{(4\pi)^2}\left[a_0 + a_1 \ln(\Lambda_{\rm UV}/\mu) + a_2\left(\frac{\Lambda_{\rm UV}}{\mu}\right)^2 + a_3\left(\frac{\Lambda_{\rm UV}}{\mu}\right)^4\right]\right\},$$

$$\kappa_0^2 = \mu^{-2} g_N \left\{1 + \frac{\hbar}{(4\pi)^2}\left[b_0 + b_1 \ln(\Lambda_{\rm UV}/\mu) + b_2\left(\frac{\Lambda_{\rm UV}}{\mu}\right)^2\right]\right\},$$

Cancellation condition $\Delta S \stackrel{!}{=} -\Gamma_1^{\rm div}$ fi xes a_i, b_i, $i \neq 0$, in terms of ζ and Υ coeffi cients. Reparameterize a_0, b_0 as

$$a_0 = g_N C_1 - \frac{g_N}{\lambda} D_1 , \quad b_0 = -g_N C_1 .$$

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Matching condition

So far only μ-independence of bare couplings was used.
Impose in addition:

$$\kappa_0^2 \stackrel{!}{=} \Lambda_{\rm UV}^{-2}\, g_N(\mu = \Lambda_{\rm UV}) \qquad \text{iff} \quad b_0 + b_2 = 0\,,$$
$$\tilde{\Lambda}_0 \stackrel{!}{=} \Lambda_{\rm UV}^{4}\left(\frac{2\lambda}{g_N}\right)(\mu = \Lambda_{\rm UV}) \quad \text{iff} \quad a_0 + a_2 + a_3 = 0\,.$$

Shortcuts renormalization conditions for vertex functions.
Fixes uniquely

$$C_1 = \Upsilon_2\,, \quad D_1 = \frac{1}{2}(\Upsilon_1 + \Upsilon_3) + \lambda \Upsilon_2\,.$$

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On-shell independence of gauge condition

Usually only the logarithmically divergent parts of Γ_1 are considered in PT, which are gauge-independent on-shell. Fails for other parts of regularized Γ_1. General theorems inapplicable, Vilkovisky-deWitt action no help, main cuprit

$$\mathrm{Det}\mathbf{AB} \neq \mathrm{Det}\mathbf{A}\mathrm{Det}\mathbf{B}\,,$$

for regularized determinants.

Solution: Use

- transversal-traceless decomposition of metric fluctuations
- geometric measure on space of metrics.
- Hessians relative to (indefi nite) deWitt metric.
- judicious resolution of $\mathrm{Det}\mathbf{AB} \neq \mathrm{Det}\mathbf{A}\mathrm{Det}\mathbf{B}$ ambiguities

to construct regularized Γ_1 exactly gauge-independent on-shell.

Results for Einstein-Hilbert gravity

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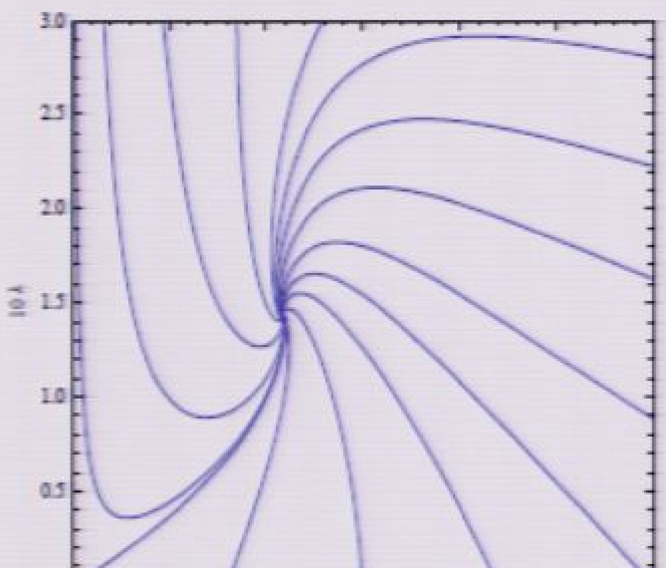
Nontrivial fi xed point:

$$\frac{g_N^*}{(4\pi)^2} = -\frac{2}{\lambda_*(-\frac{2}{3}\zeta_1 + 4\zeta_2 + \zeta_4/\lambda) + 2\Upsilon_2} > 0 \quad \text{robustly}$$

$$\lambda_* = q_1 \frac{40}{87}\left[-1 + \sqrt{1 + \frac{261}{160}\frac{q_2}{q_1^2}}\right] > 0 \quad \text{gauge-independent}$$

Flow equations gauge dependent, stability matrix has complex eigenvalues at g_N^*, λ_*, flow pattern spiralling.



Higher derivative gravity

$$S = \int d^4x \sqrt{g} \left[\Lambda - \frac{1}{\kappa^2} R + \frac{1}{2s} C^2 - \frac{\omega}{3s} R^2 \right]$$

R : Ricci scalar, s, ω, couplings

C^2 : square of Weyl tensor

- Perturbative renormalizability to all loops wrt $1/p^4$ propagator expected [Stelle, 1977].
- 1-loop log-flows known explicitly; s is asymptotically free in PT [Fradkin-Tseytlin 1982; Avramidi-Barvinsky 1985; Berredo-Peixeto 2005].
- $\omega > 0$ classically, $\omega < 0$ near UV fi xed point $\omega_* \approx -0.0228$ [dito].
- Unitarity issue studied in toy models ["Pais-Uhlenbeck", "Lee-Wick"], results encouraging.

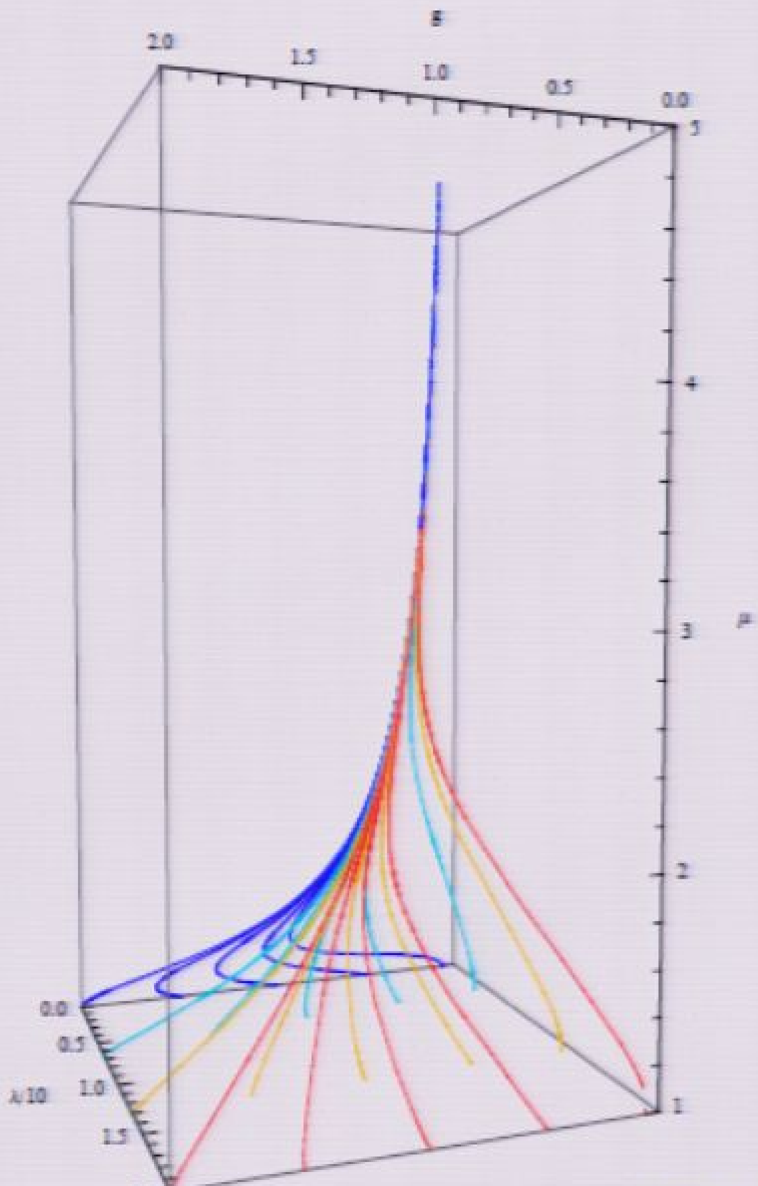
Results for higher derivative gravity

Nontrivial fi xed point [M.N]:

$$\frac{g_N^*}{(4\pi)^2} = \frac{1}{0.9063 q_{1/2} + 2.3224 q_1} > 0\,,$$
$$\lambda_* = \frac{1.25 q_1 + 237.617 q_2}{2(0.9063 q_{1/2} + 2.3224 q_1)} > 0\,.$$

- Stability matrix has eigenvalues $-2, -4$ at nontrivial fi xed point.
- Flow is gauge-independent! Dependence on positive $O(1)$ moments q_n expected, c.f. lattice.
- Memory of $O(10)$ initial data erased to accuracy 10^{-5} after $O(10)$ units in μ and settles on $\lambda(g_N)$ orbit.
- Spectral positivity of Hessian (inverse propagator) satisfi ed for large μ! Traditional problem evaporates.

Gauge-independent fbw



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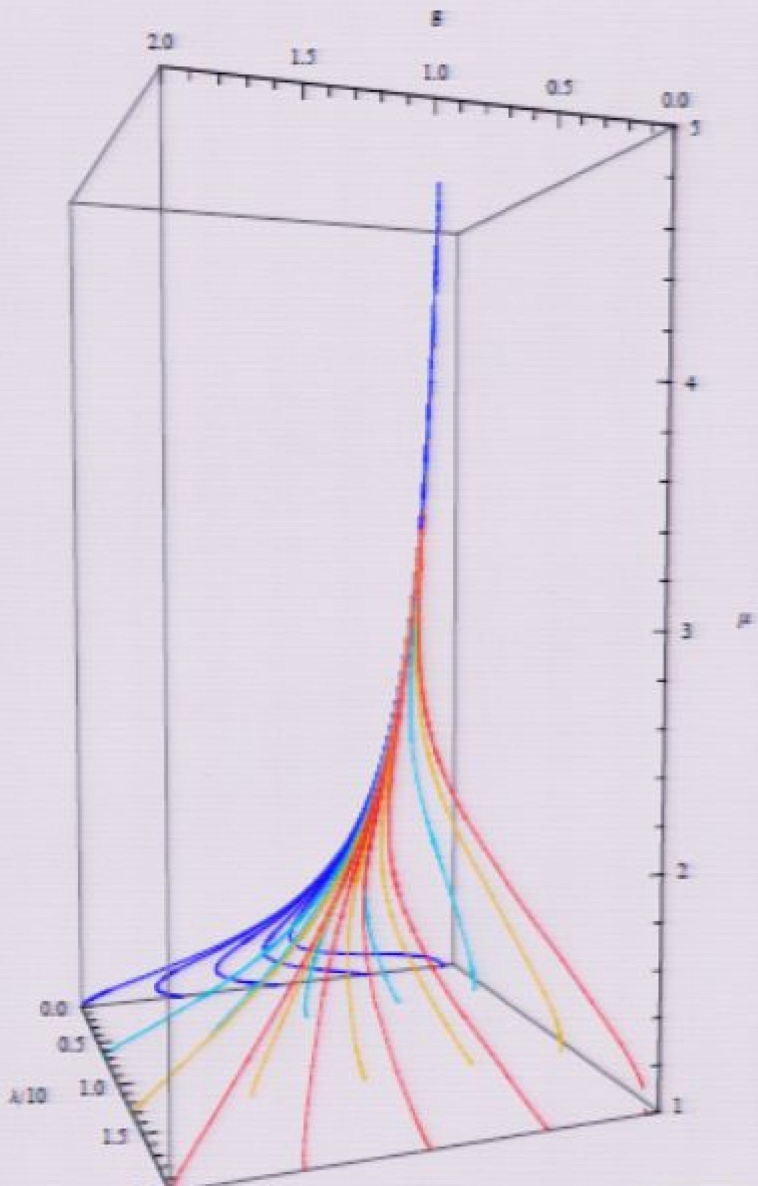


Why perturbation theory, not functional fbw equation?

- Non-perturbative aspects in Γ_k flow equation formalism for gravity are only 'skin-deep': gauge-fi xing, Gribov problem not addressed, naive measure used, structure of Γ_k beyond local terms elusive, etc.
- UV fi nite initial data are postulated to exist but not constructed. Should include a fi ne-tuned dependence on $\Lambda_{\rm UV}$ such that:

$$\lim_{\Lambda_{\rm UV}\to\infty} \Gamma_{k,\Lambda_{\rm UV}} \stackrel{?}{=} S_{\rm ren} \quad \text{for k large,}$$

with $S_{\rm ren}$ determined by dofs aimed at.

- Reconstruction of bare action possible but physicswise and mathematically underdetermined.
- Convergence of (which?) truncations to exact result (in which sense?) elusive.

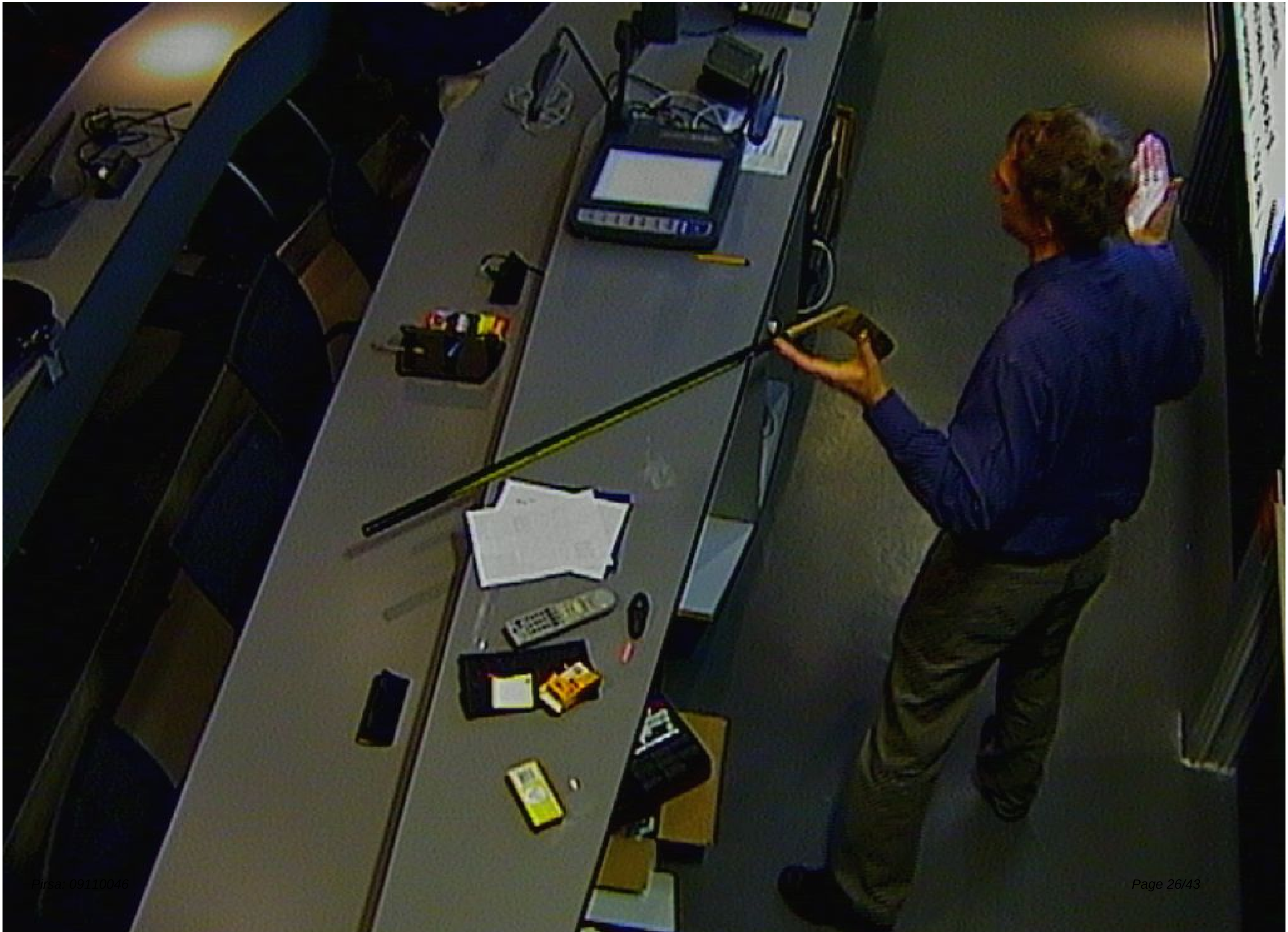
PT addresses the UV problem

- PT produces series in loop counting parameter $\hbar$, UV cutoff can termwise be removed. PT wrt asymptotically free coupling should describe the UV regime correctly.
- Rationale extends to asymptotically safe theories:

(Non-constant essential) coupling g_j is asymptotically safe iff

$$\sup_{\mu_0 \leq \mu \leq \infty} g_j(\mu) < \infty\,, \qquad \lim_{\mu\to\infty} g_j(\mu) = g_j^* < \infty\,,$$

- Define "the coupling constants as coefficients in a power series expansion of the reaction rates themselves around some physical renormalization point" (S. Weinberg, 1979).
- Take one difference $\delta g_1 = g_1 - g_1^*$ of order $\hbar$ at μ_0 to define the expansion via RG improvement.
- 'Gaussianity' refers to preferred basis in space of interaction monomials not necessarily $g_j^* = 0$ for all j



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Conclusions

- Refi ned perturbative framework for gravity allows investigation of asymptotic safety at one loop.
- Attractivity of classical gravity (used in anti-Wick rotation wrt indefi nite deWitt metric) entails anti-screening $\kappa^2 \sim g_N^*/\mu^2$ in UV regime.
- In HD gravity PT expansion is in asymptotically free s not in κ^2. Nontrivial positive gauge independent fi xed point g_N^*, λ_* exists 'beyond reasonable doubt'.
- Traditional positivity problem in HD gravity absent.
- Next step: relate flow to asymptotic expansion of physical quantities.

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$P^{(-1)}$ $\quad \underbrace{Q^{(1)} \quad Q^{(0)}}_{P^{(1)}} \quad P^{(0)}$

$= 0$

$O(s)$

$$H^{-1} = \frac{1}{\lambda_1} P^{(1)} \cdots$$

$$\lambda_1 = p^4 + \frac{s}{k^2}(p^2 - 2\Lambda)$$

$p^2 >$

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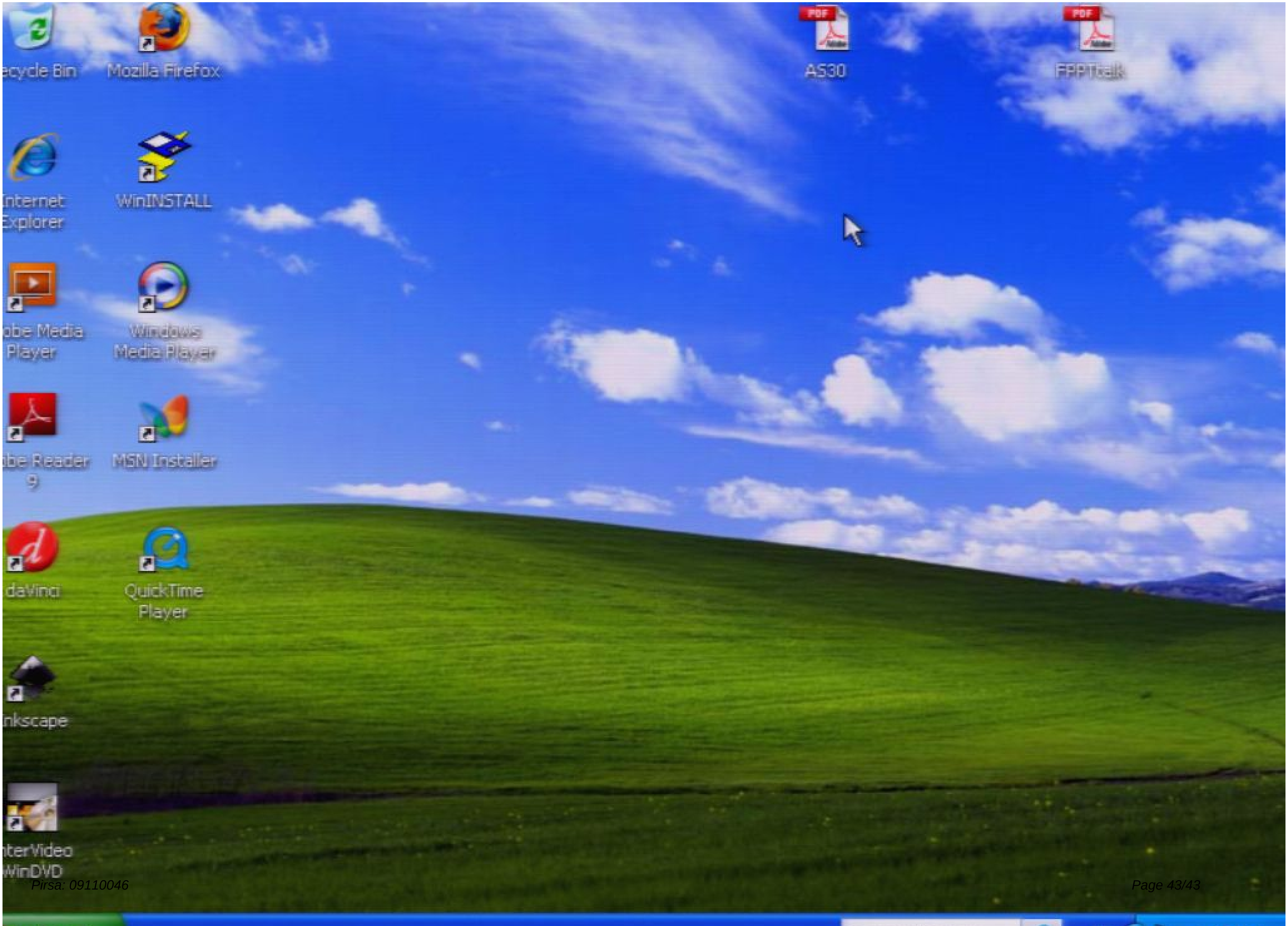
$$\sup_{\mu_0 \leq \mu \leq \infty} g_j(\mu) < \infty \,, \qquad \lim_{\mu \to \infty} g_j(\mu) = g_j^* < \infty \,,$$

- Define "the coupling constants as coefficients in a power series expansion of the reaction rates themselves around some physical renormalization point" (S. Weinberg, 1979).
- Take one difference $\delta g_1 = g_1 - g_1^*$ of order $\hbar$ at μ_0 to define the expansion via RG improvement.
- 'Gaussianity' refers to preferred basis in space of interaction monomials not necessarily $g_j^* = 0$ for all j.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