Global flows in quantum gravity

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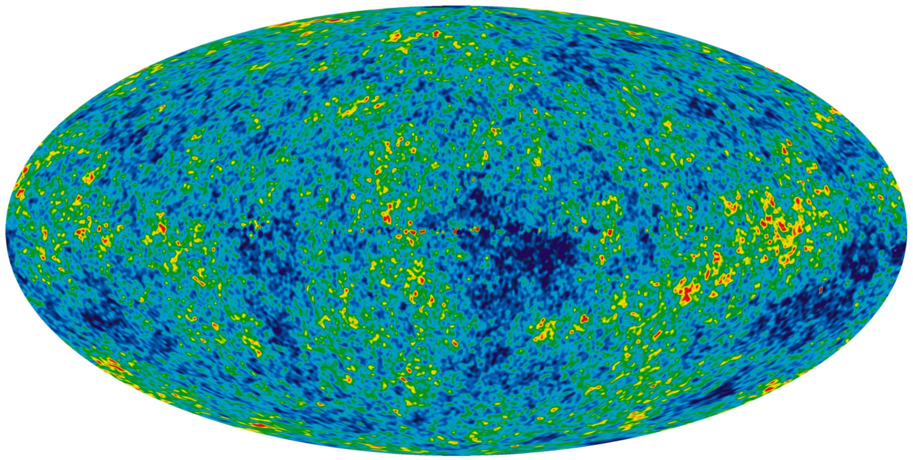
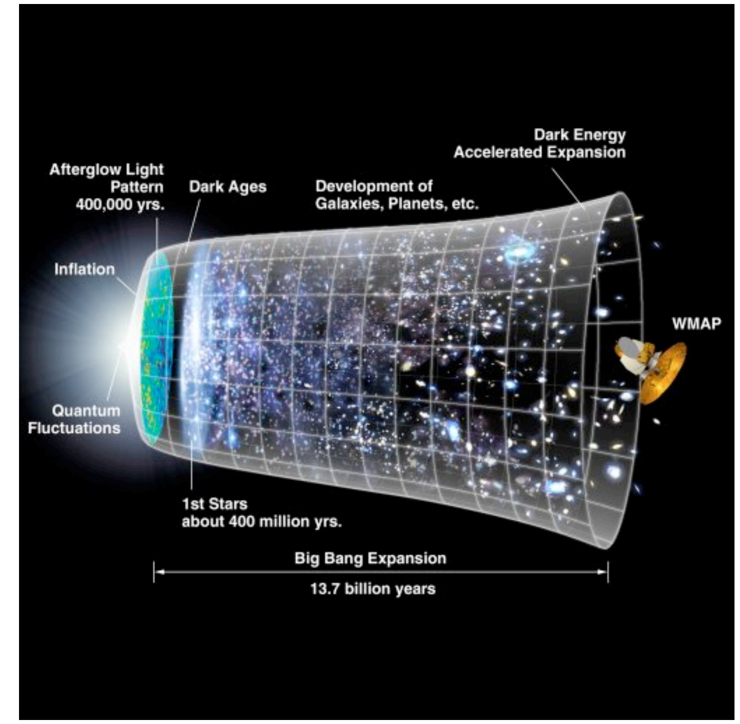
Universität Heidelberg & ExtreMe Matter Institute

Perimeter Institute, April 24th 2014

Phase diagram of quantum gravity

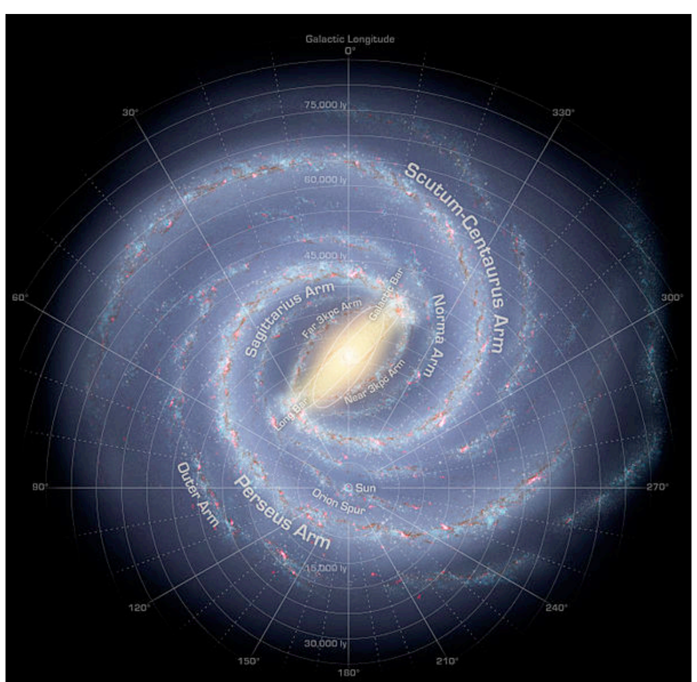


early universe

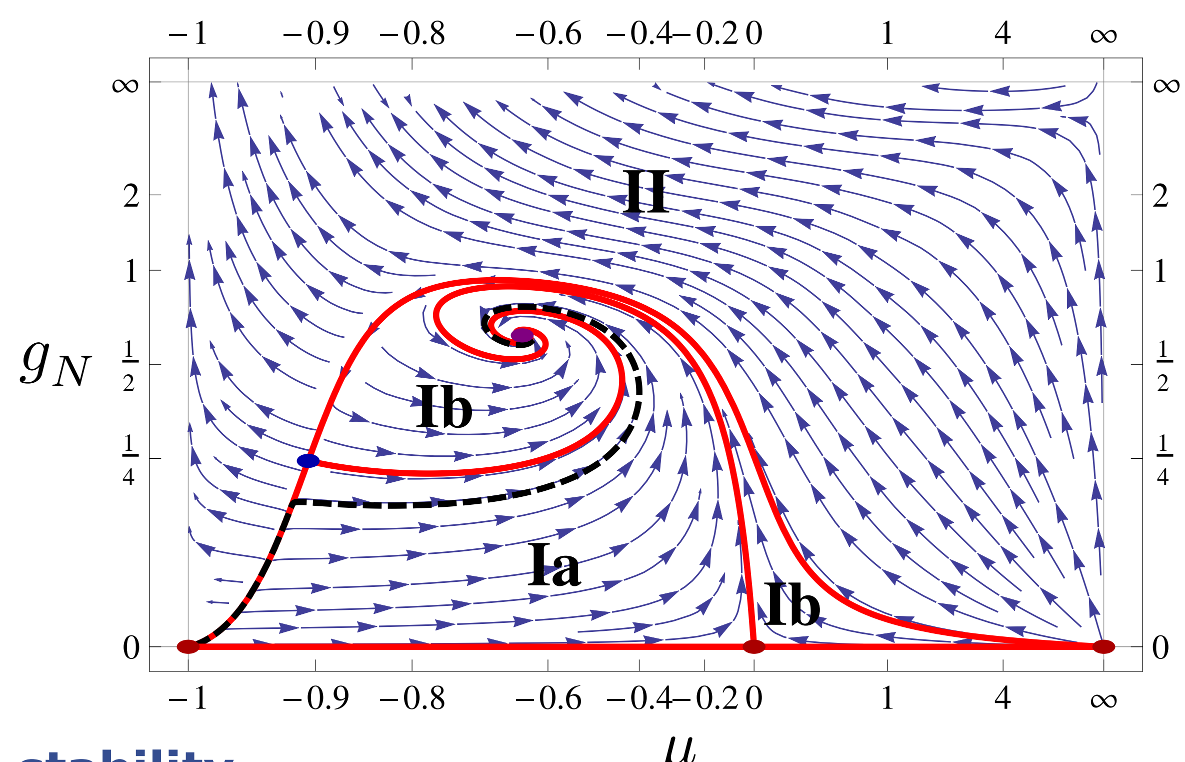


$$g_N(E) \qquad \lambda(E)$$

rotation curves



UV stability



IR stability

Functional approach to quantum gravity
and
diffeomorphism invariance

Functional approach to quantum gravity

Einstein-Hilbert action

Metric g **Cosmological constant** Λ

$$S[g] = \frac{1}{16\pi G_N} \int d^4x \sqrt{g} \left(-R(g) + 2\Lambda \right)$$

Newton constant G_N **Ricci scalar** $R(g)$

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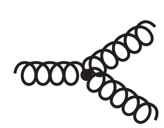
Momentum dimension of couplings

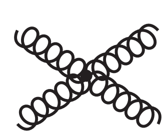
$$\dim G_N = -2$$

$$\dim \Lambda = 2$$

perturbatively non-renormalisable

graviton propagator :  $\propto \frac{1}{p^2}$

3 – grav. vertex :  $\propto \sqrt{G}\, p^2$

4 – grav. vertex :  $\propto G\, p^2$

$\vdots$

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Correlation functions

diffeomorphism invariant

$$\langle R(g(x_1)) \cdots R(g(x_n)) \rangle$$

Ricci scalar correlations

not diffeomorphism invariant

$$\langle g(x_1) \cdots g(x_n) \rangle$$

metric correlations

Functional approach to quantum gravity

reparameterisation invariance

path integral

$$\int dg\, e^{-S[g]+\int_x J\cdot g}$$

$\bar{g}$ **average of metrics?**

$$\bar{g}(x) = \langle g(x) \rangle$$

Functional approach to quantum gravity

reparameterisation invariance

reparameterisation invariant path integral

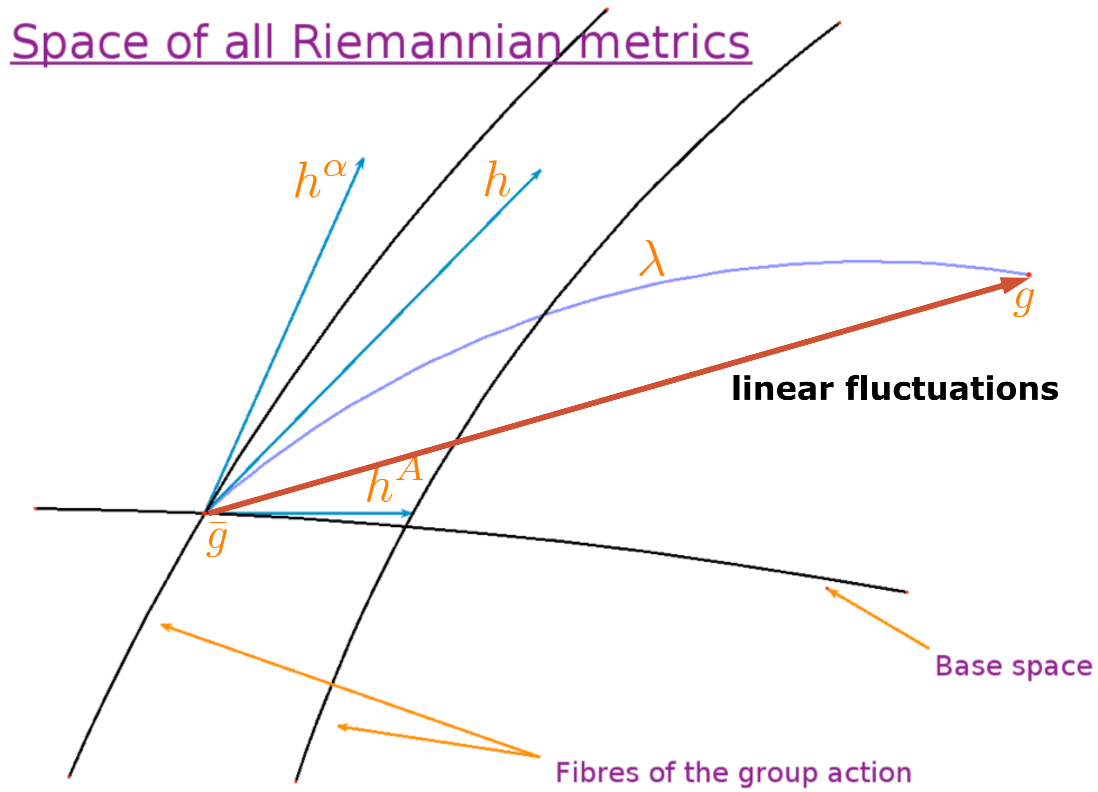
$$\int d\mu(\bar{g}, h)\, e^{-S[\bar{g},h]+\int_x J_h \cdot h}$$

linear split (reminder)

$$g = \bar{g} + h$$

$\bar{h}$ **average of tangent vectors**

$$\bar{h}(x) = \langle h(x) \rangle$$



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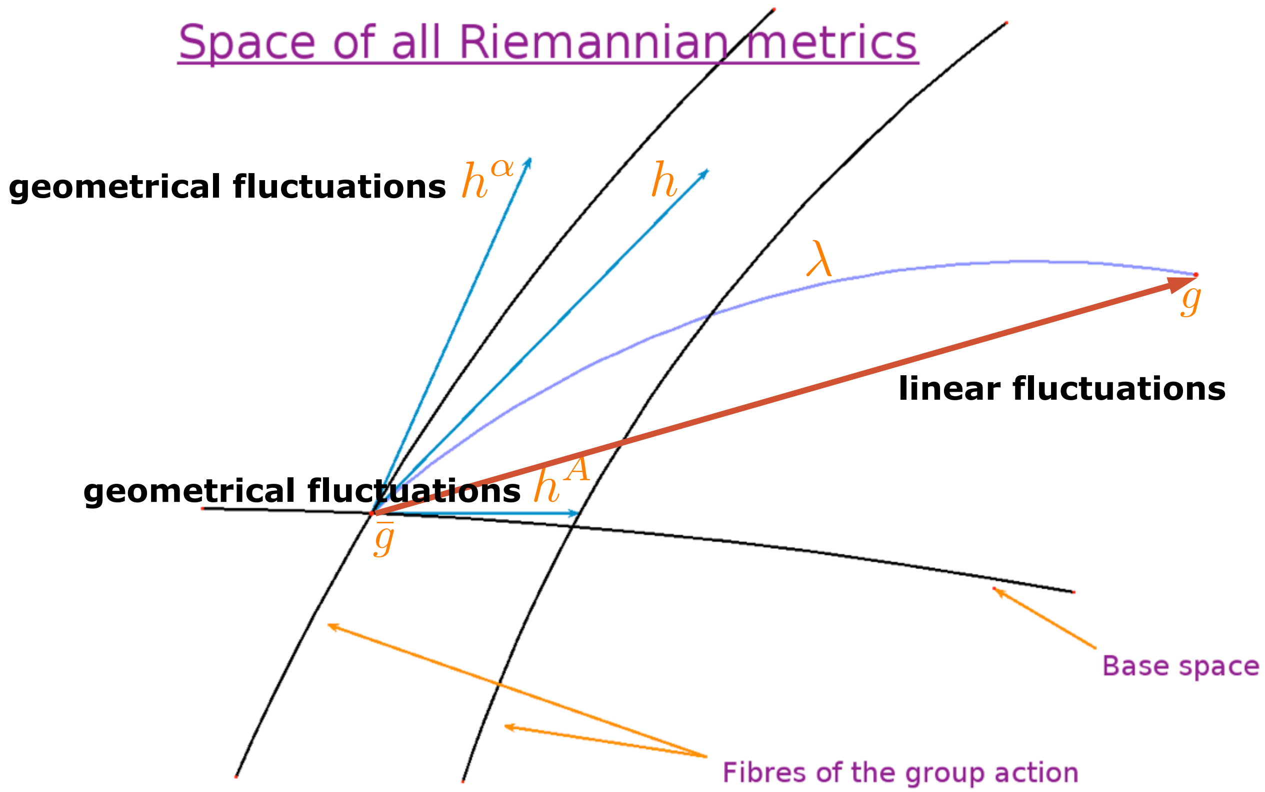
Geodesic normal fields

$$g = \bar{g} + h + \Delta g(\bar{g}, h)$$

$$\Delta g(h) = -\frac{1}{2}\Gamma_V * h^2 + O(h^3)$$

$$Dh = 1\!\!1 + O(h^2)$$

Γ_V**-covariant derivative**



Vilkovisky connection

$$\Gamma_V{}^A{}_{\beta C} = \Gamma_V{}^A{}_{B\gamma} = \Gamma_V{}^A{}_{\beta C} = 0$$

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geometrical effective action

$$\Gamma = \Gamma[\bar g, \bar h^A]$$

$$Dh = \mathbb{1} + O(h^2)$$

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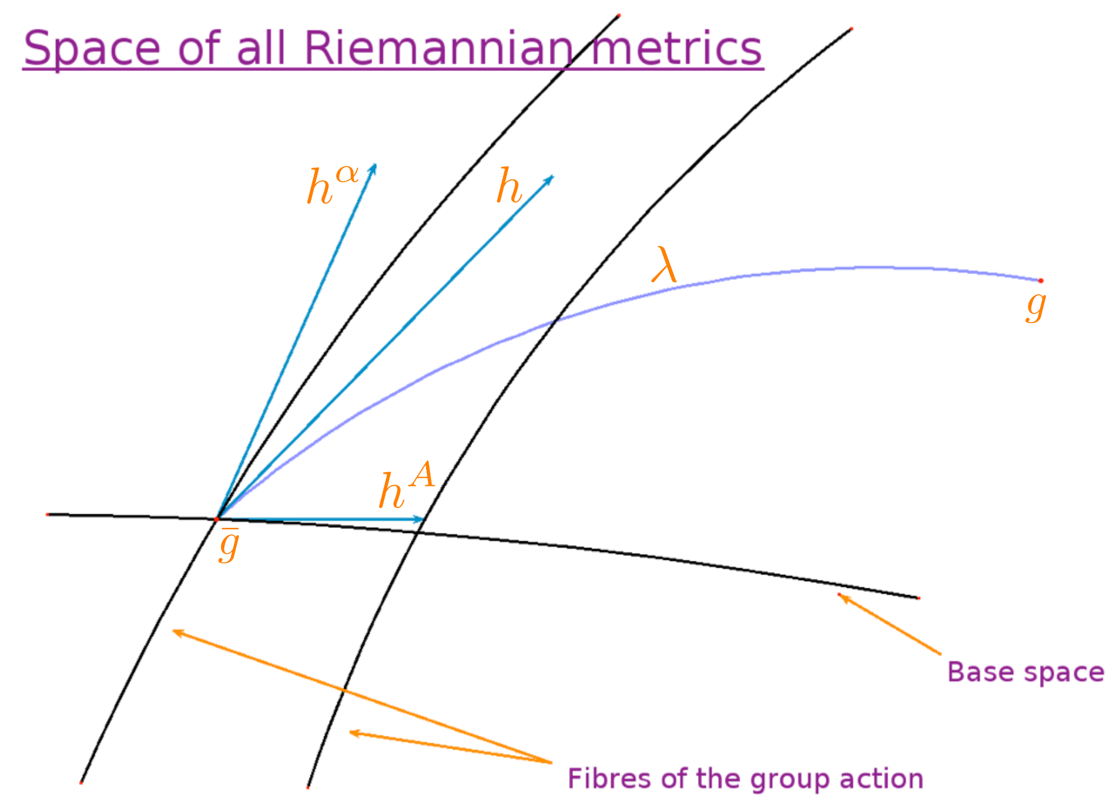

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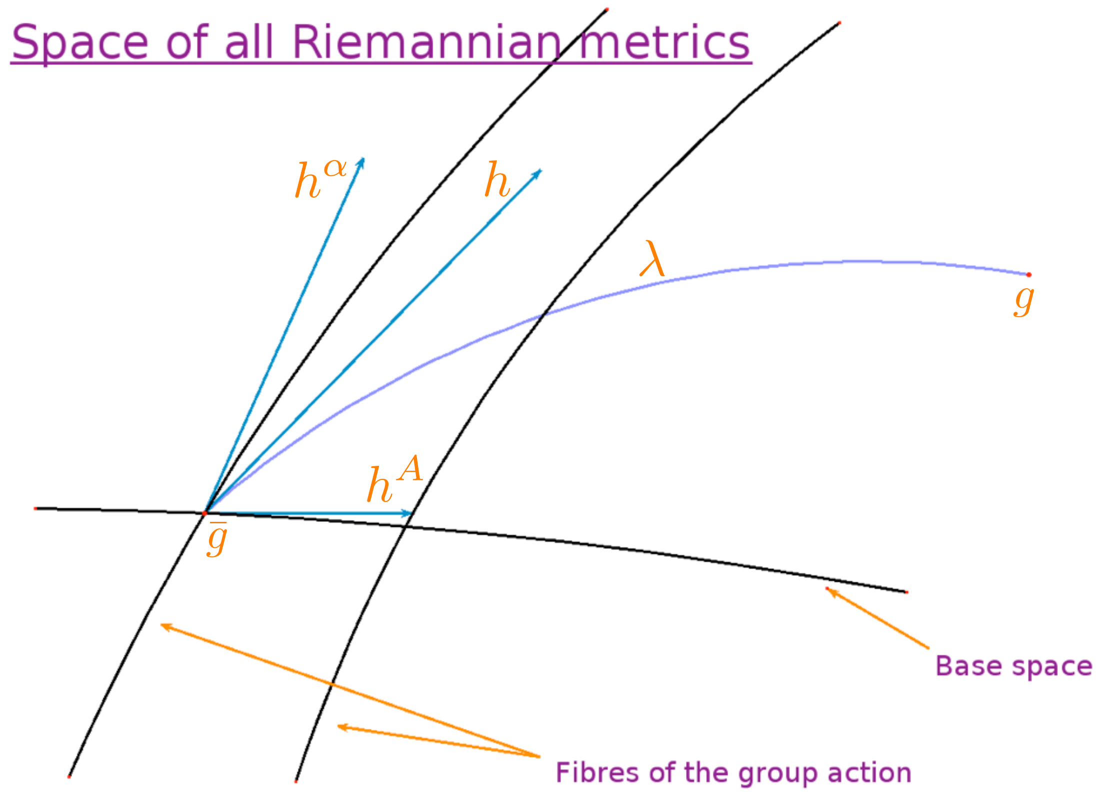

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background independence

$$\frac{\delta \Gamma}{\delta \bar g} = \langle Dh \rangle * \frac{\delta \Gamma}{\delta \bar h}$$

Nielsen identity

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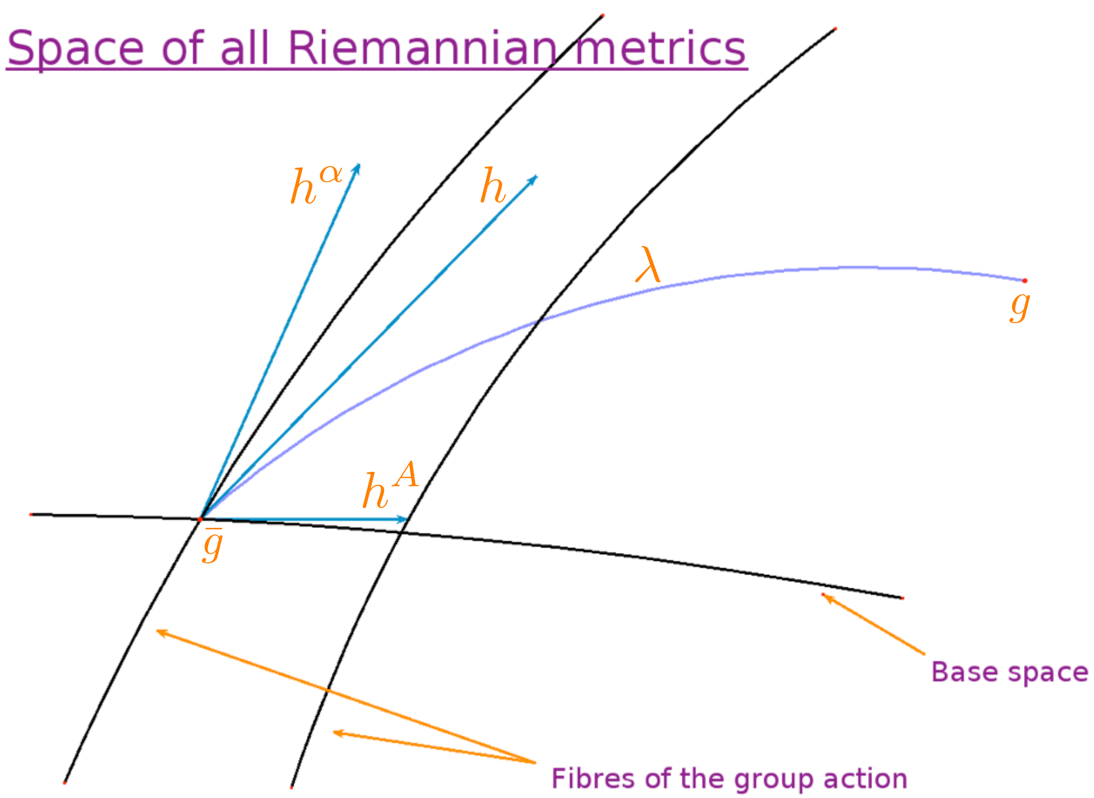
$$\Gamma_k = \Gamma_k[\bar g, \bar h^A]$$

Branchina, Meissner, Veneziano '03
JMP '03



background independence

$$\frac{\delta\Gamma_k}{\delta\bar g} = \langle Dh\rangle * \frac{\delta\Gamma_k}{\delta\bar h} + R_k - \text{terms}$$

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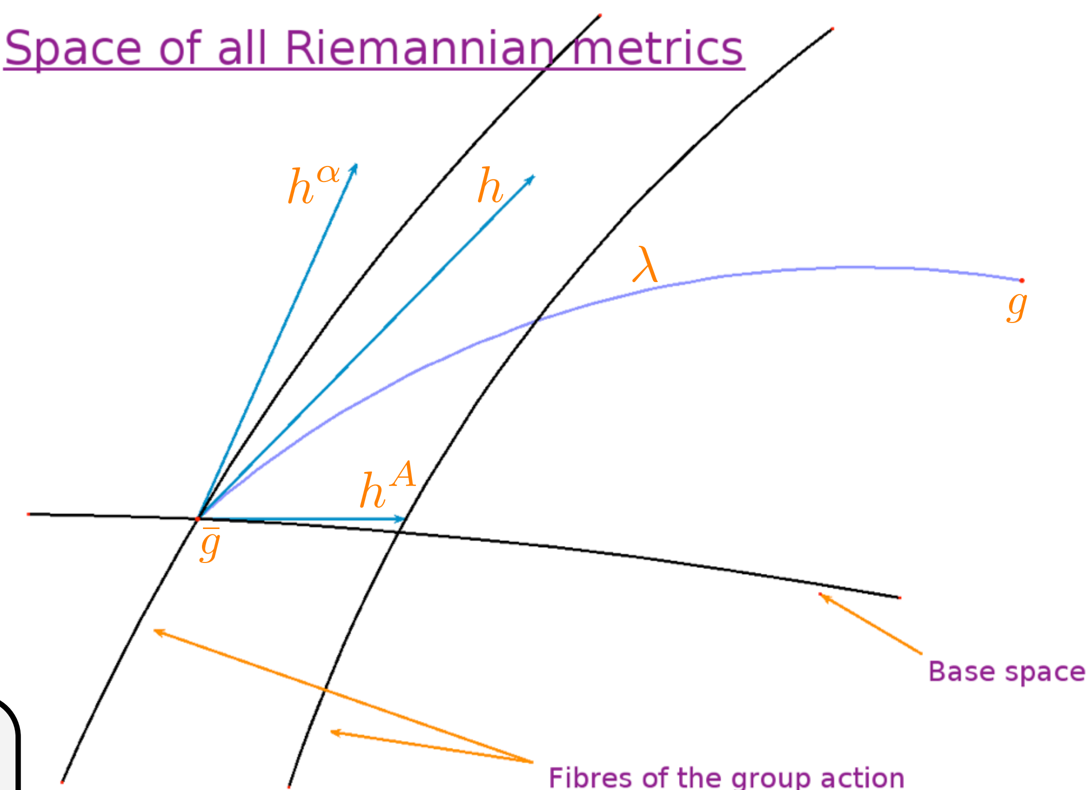

background independence

$$\frac{\delta\Gamma_k}{\delta\bar{g}} = \frac{\delta\Gamma_k}{\delta\bar{h}} + \left\langle \left.\frac{\delta(S_{\rm gf}+S_{\rm ghost})}{\delta\bar{g}}\right|_g \right\rangle_{\rm 1PI} + R_k - {\rm terms}$$

linear split (reminder)

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see talk of T. Morris

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symmetries and all that in the Wetterich RG

Wetterich '93
Ellwanger '94
Morris '94

QED/QCD:
Reuter, Wetterich '94
Ellwanger '94
D'Attanasio, Morris '96
Reuter, Wetterich '97
Litim, JMP '98
Igarashi, Itoh, So '99
Freire, Litim, JMP '00
JMP '02, '03
Litim, JMP '02
Braun, Gies, JMP '07
Lavrov, Shapiro '12
Fister, JMP '13

Gravity:
Reuter '96
JMP '03
Folkerts, Litim, JMP '11

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Used in non-perturbative QCD since '96
Ellwanger, Hirsch, Weber

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Gravity:
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Used in non-perturbative QG since '12 Donkin, JMP

Functional approach to quantum gravity

What is at stake?

background approximation

$$\frac{\delta^2\Gamma}{\delta\bar{g}^2} \simeq \frac{\delta^2\Gamma}{\delta\bar{h}^2}$$

aka split symmetry in the linear approx.

$$\Gamma[\bar{g},h] = \Gamma[g] + S_{\text{gf}} + S_{\text{ghost}} + \Delta\Gamma_{\text{gauge}}[\bar{g},h]$$

dropped as irrelevant

background independence

$$\frac{\delta\Gamma_k}{\delta\bar{g}} = \langle Dh \rangle * \frac{\delta\Gamma_k}{\delta\bar{h}} + R_k - \text{terms}$$

Nielsen identity

aka split symmetry

aka mSTI

JMP '03

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scalar theories

Litim, JMP '02

Bridle, Dietz, Morris '13

at finite cutoff: change of universal quantities in the FRG even at one loop

e.g. $\beta_{\rm 1loop,YM}$ **Litim, JMP '02**

JMP '02

cured by use of Nielsen identity

e.g. $\mathrm{sign}(\Delta\beta_{\rm gravity,YM})$ **Folkerts, Litim, JMP '11**

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JMP '02

cured by use of Nielsen identity

e.g. $\text{sign}(\Delta\beta_{\text{gravity},\text{YM}})$ **Folkerts, Litim, JMP '11**

at vanishing cutoff: loss of the confining property of the order parameter potential

$$\frac{\delta^2\Gamma}{\delta\bar{A}^2}(p\to 0) \propto p^2 \qquad \frac{\delta^2\Gamma}{\delta\bar{a}^2}(p\to 0) \propto \text{mass gap}$$

Braun, Gies, JMP '07

Braun, Eichhorn, Gies, JMP '10

Fister, JMP '13

Functional approach to quantum gravity

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relevance for gravity

Folkerts, Litim, JMP '11
Donkin, JMP '12
Christiansen, Litim, JMP, Rodigast '12
Christiansen, Knorr, JMP, Rodigast '14

the simpler **the** **merrier**

$$\Gamma[\bar{g},h] = \Gamma[g] + S_{\rm gf} + S_{\rm ghost} + \Delta\Gamma_{\rm gauge}[\bar{g},h]$$

dropped as irrelevant

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power counting

the more relevant **the un-merrier**

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qualitative difference

semi-qualitative/quantitative difference

cosmological constant $\neq$ graviton mass parameter

Newton constant ren. $\neq$ graviton wave function

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qualitative difference

cosmological constant $\neq$ **graviton mass parameter**

$\neq$ **const. part of vertex** $\Gamma^{(3)}$

⋮

semi-qualitative/quantitative difference

Newton constant ren. $\neq$ **graviton wave function**

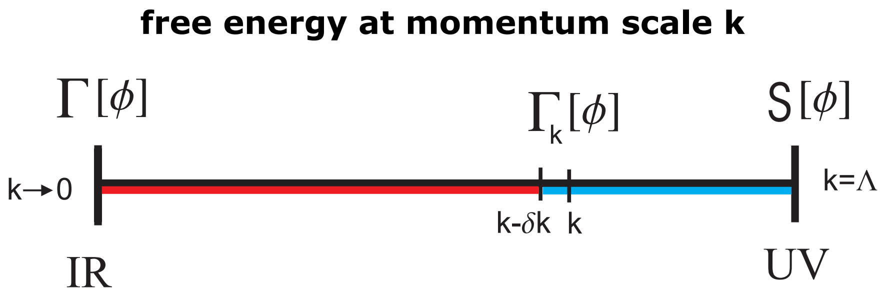
⋮

Global phase structure of quantum gravity

Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232

Functional approach to quantum gravity

Functional RG

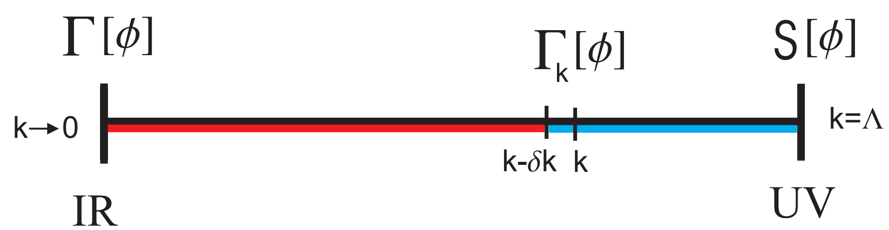


RG-scale k: $t = \ln k$

Functional approach to quantum gravity

Functional RG

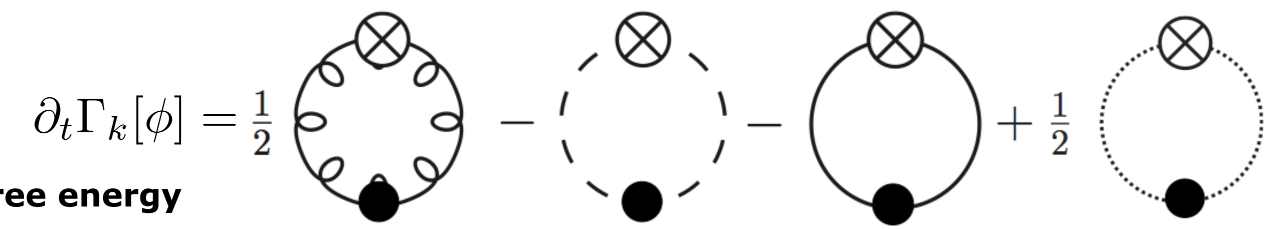
free energy at momentum scale k



RG-scale k: $t = \ln k$

gravity
quantum fluctuations

bosonic
quantum fluctuations



free energy

fermionic
quantum fluctuations

Geometrical approach: fully diffeomorphism invariant

1st global (UV-IR) phase structure: Donkin, JMP '12

$g = \bar{g} + h + O(h^2)$

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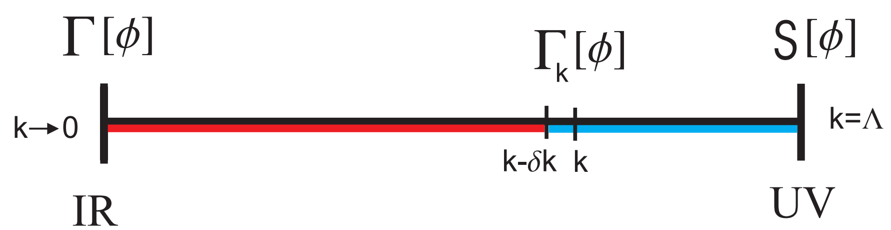

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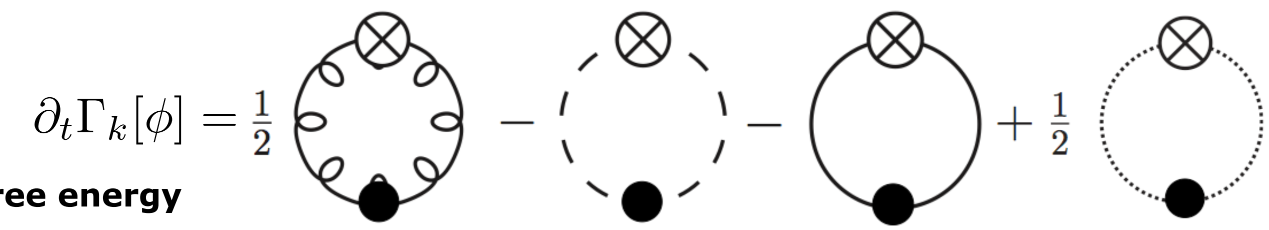

Geometrical approach: fully diffeomorphism invariant

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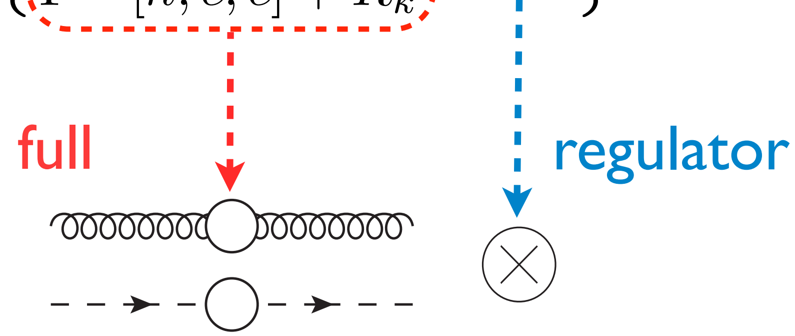
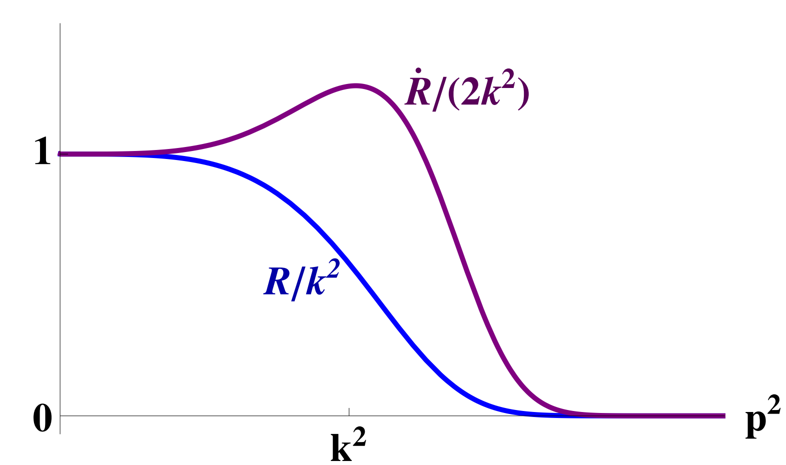
pure gravity

$$\partial_t \Gamma_k[\bar{g}; h, \bar{c}, c] = \frac{1}{2} \mathrm{Tr} \left\{ \frac{1}{\Gamma^{(2)}[\bar{h}, \bar{c}, c] + R_k} \partial_t R_k \right\} - \partial_t C_k[\bar{g}]$$

$\partial_t = k\, \partial_k$



fluctuation propagators



Functional approach to quantum gravity

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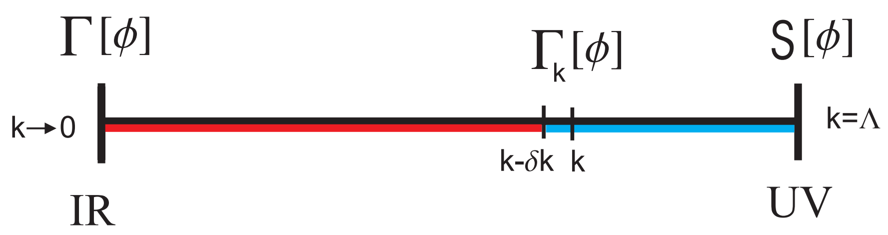
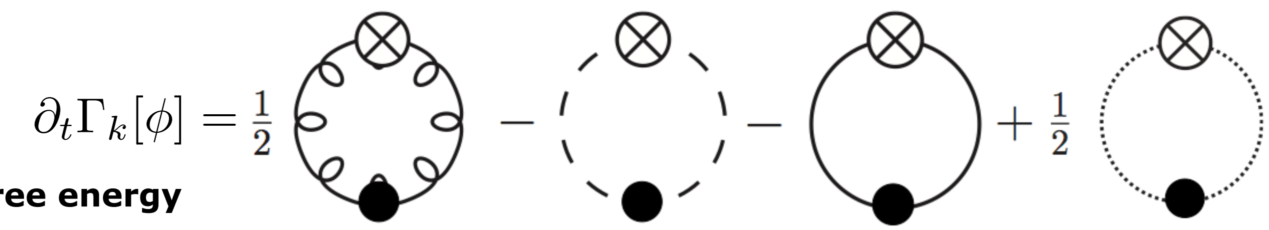


RG-scale k: $t = \ln k$

gravity quantum fluctuations **bosonic quantum fluctuations**



fermionic quantum fluctuations

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Flat expansion about Minkowski background

1st smooth global phase structure

Christiansen, Litim, JMP, Rodigast '12

Functional approach to quantum gravity

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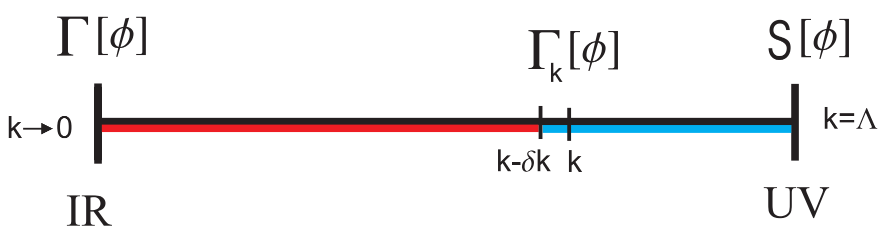

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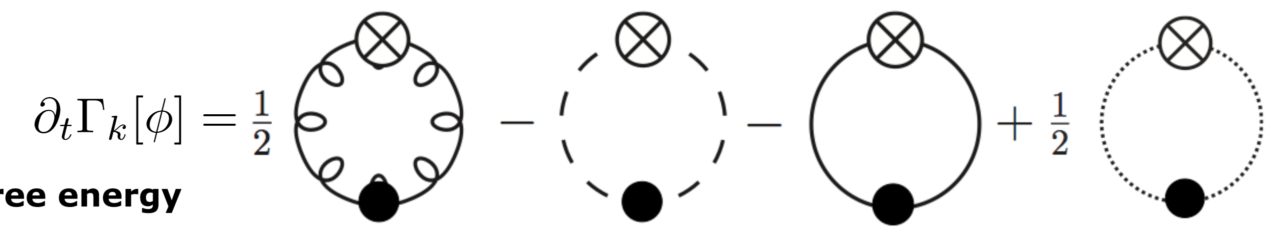

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Flows

$$\partial_t g_{i,\mathrm{fluc}} = \mathrm{Flow}_{g_{i,\mathrm{fluc}}}(\vec{g}_{\mathrm{fluc}})$$

$$\partial_t g_{i,\mathrm{back}} = \mathrm{Flow}_{g_{i,\mathrm{back}}}(\vec{g}_{\mathrm{fluc}}, \vec{g}_{\mathrm{back}})$$

dynamical flow

Nielsen ID

background flow

Donkin, JMP '12

Functional approach to quantum gravity

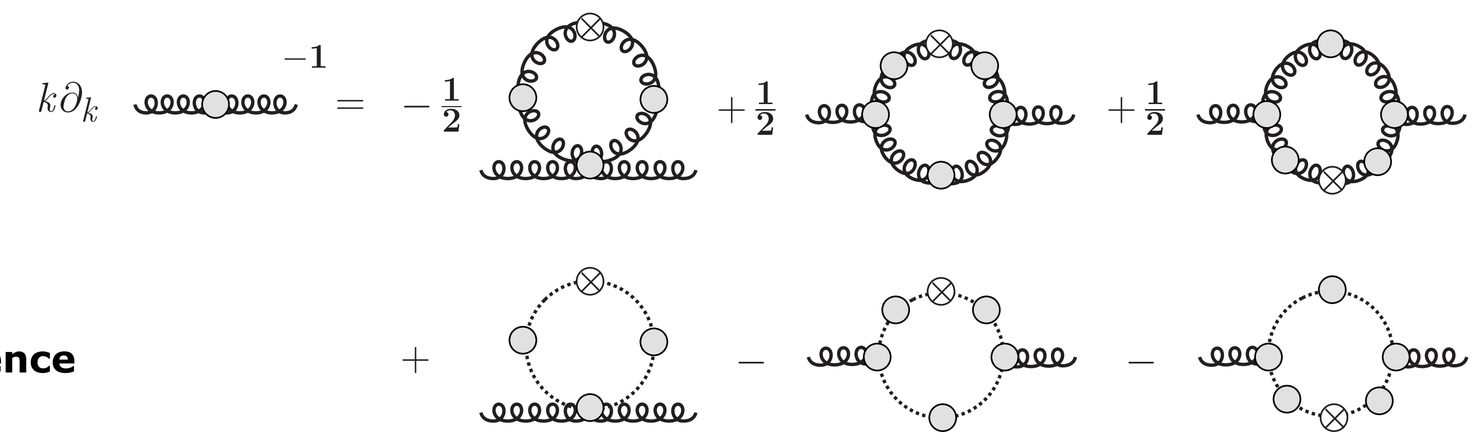
approximation scheme

Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232

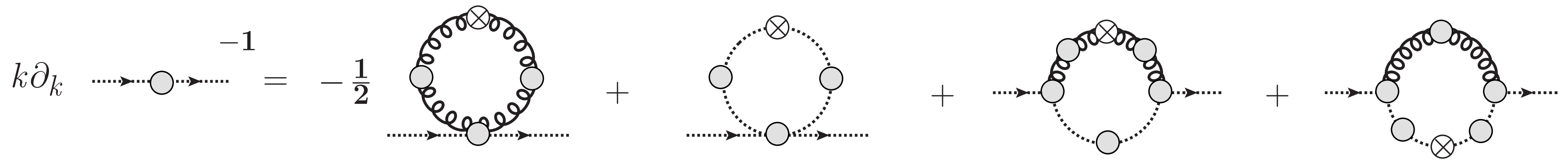
Propagators

graviton

full momentum dependence

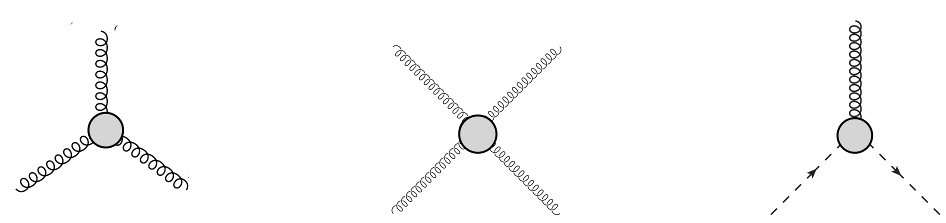


ghost



Vertices

consistent momentum-dependent RG-dressing



a la Fischer, JMP '09

Donkin, JMP '12

similar: Codello, D'Odorico, Pagani '13

$$Z_{\text{graviton}} \neq Z_{g_N}$$

$$M^2_{\text{graviton}} \neq -2\Lambda$$

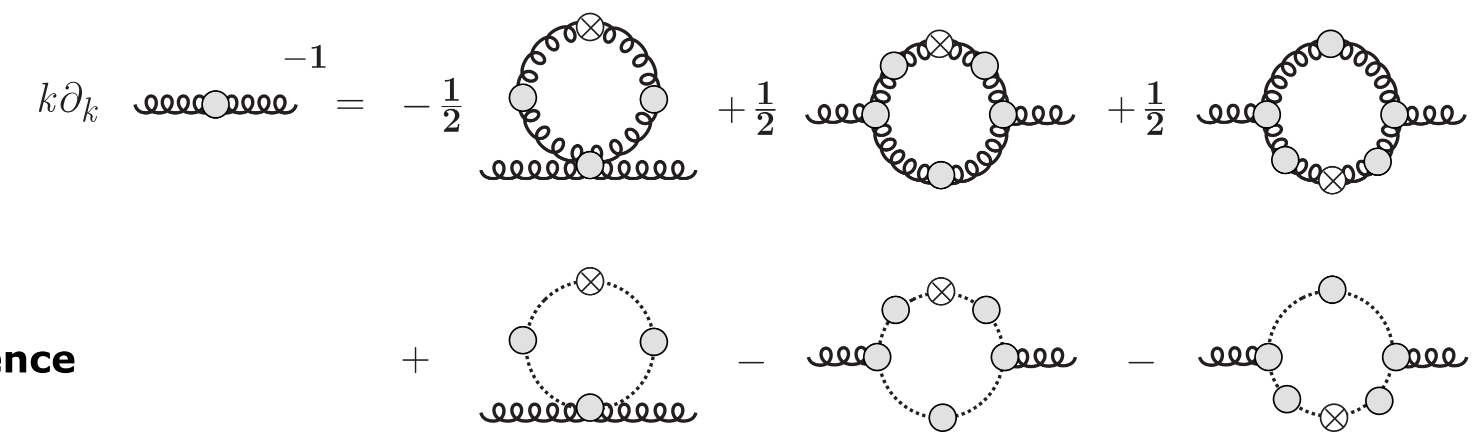
Functional approach to quantum gravity

approximation scheme

Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232

Propagators

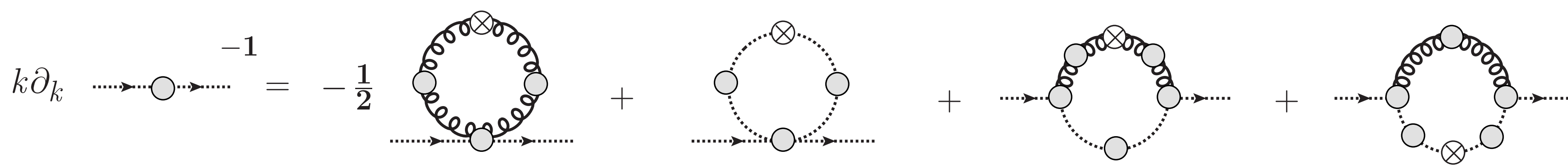
graviton



full momentum dependence

New

ghost



Vertices

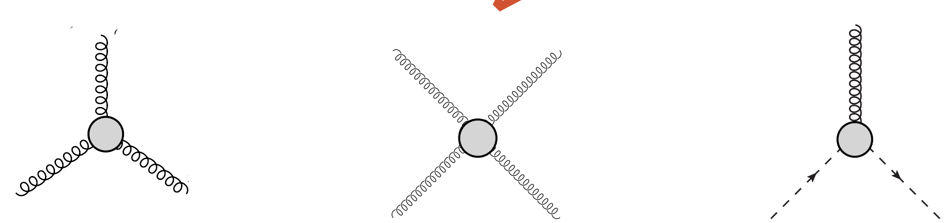
$$Z_{\text{graviton}} \neq Z_{g_N}$$

$$M^2_{\text{graviton}} \neq -2\Lambda$$

New

consistent momentum-dependent RG-dressing

New



a la Fischer, JMP '09

Donkin, JMP '12

similar: Codello, D'Odorico, Pagani '13

Functional approach to quantum gravity

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Propagators

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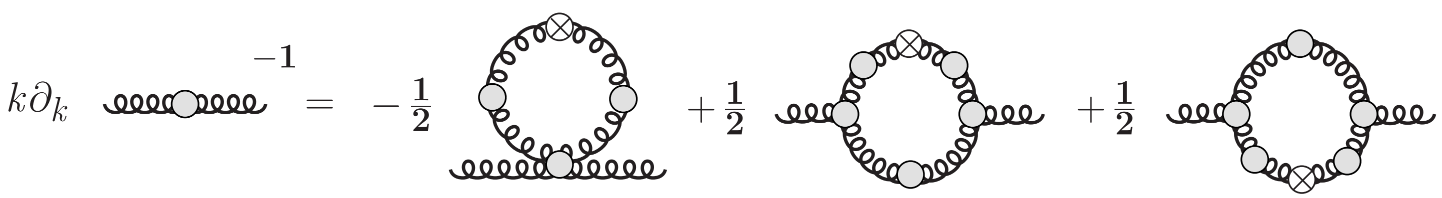
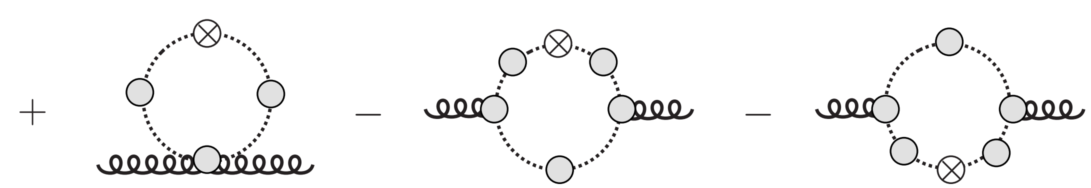
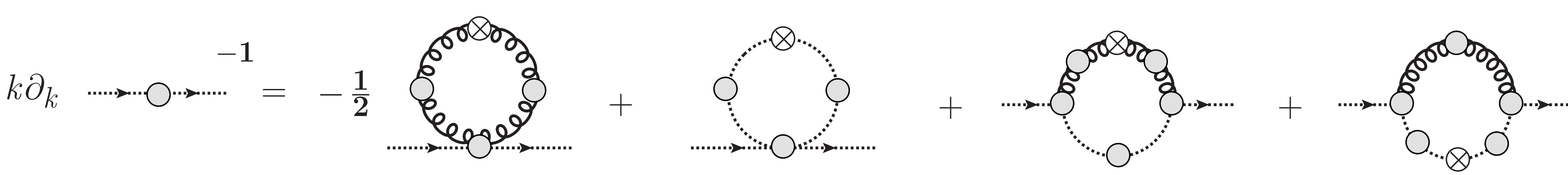


full momentum dependence



ghost



Flows & scalings

propagators

$Z_{\text{graviton}}(p^2)$ M^2_{graviton} $Z_{\text{ghost}}(p^2)$

vertices

G_N $\Lambda^{(3)}$ $\Lambda^{(4)}$

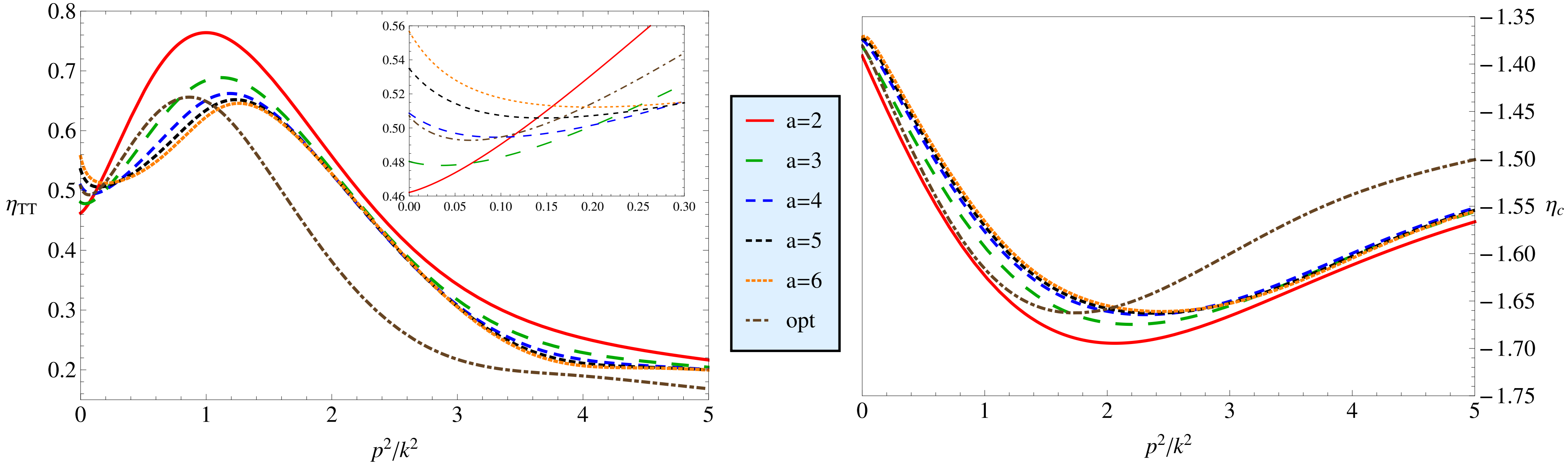
background observables

Λ $\bar{G}_N$

cosmological constant **Newton constant**

Phase diagram of quantum gravity

Propagators



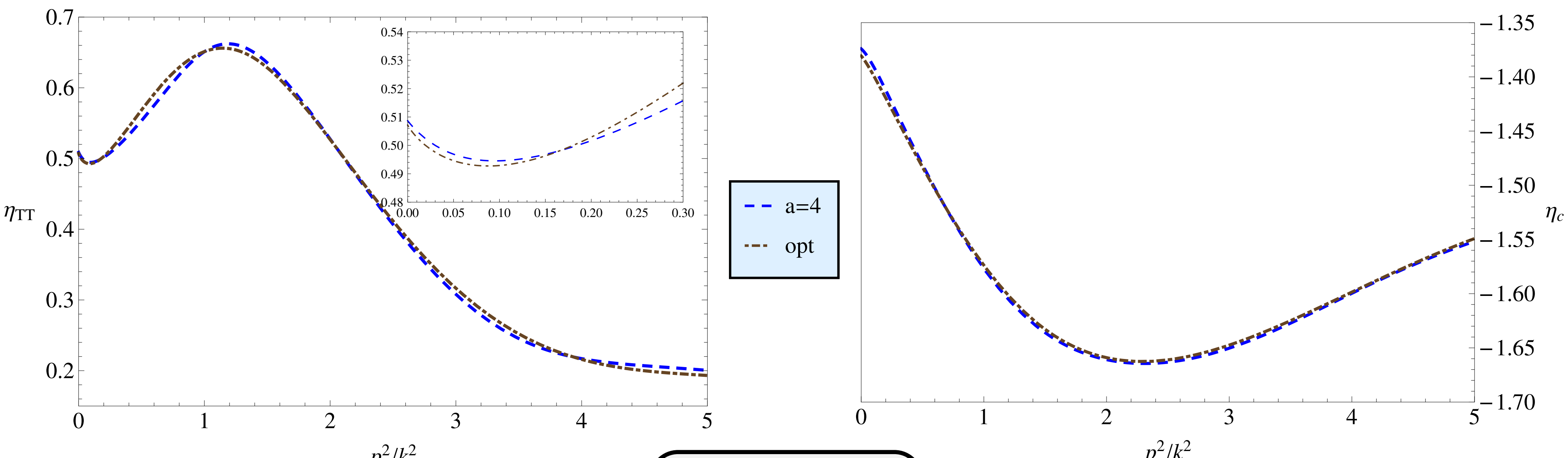
graviton **anomalous dimensions** **ghost**

regulators

$$R_{k,a}(p^2) = p^2\, r_a(x)$$

$$x = \frac{p^2}{k^2}$$

$$r_a(x) = \frac{1}{x(2e^{x^a} - 1)}$$

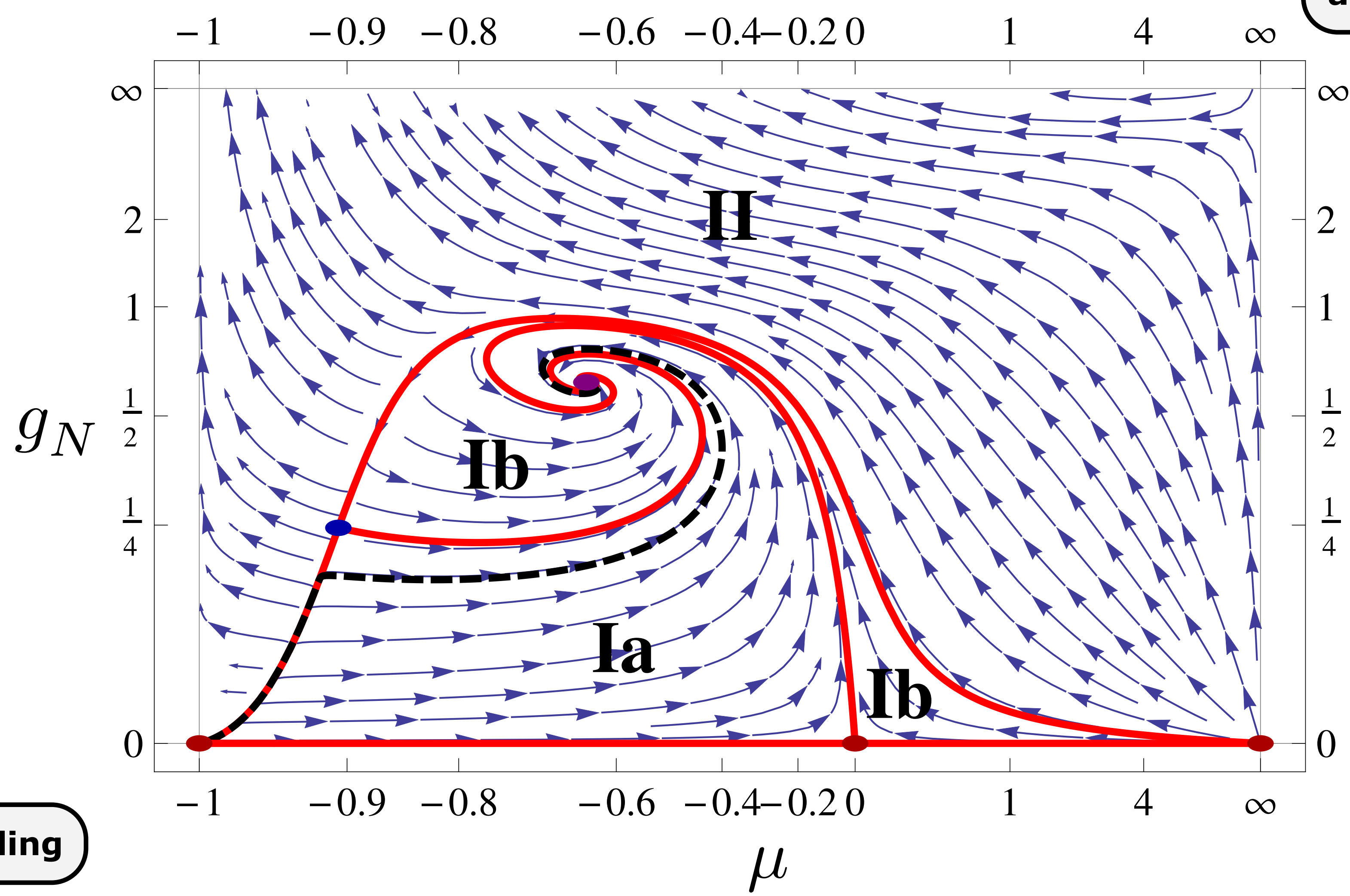


$$k_{\rm opt} = 1.15\, k_4$$

Phase diagram of quantum gravity

global phase diagram

asymptotically safe UV scaling



$a = 4$

classical IR scaling

$g_N = G_N k^2$

$\mu = \frac{M^2_{\text{graviton}}}{k^2}$

Phase diagram of quantum gravity

global phase diagram

UV-fixed point

regulator-dependence

a	2	3	4	5	6	opt
μ_*	-0.637	-0.641	-0.645	-0.649	-0.651	-0.489
g_*	0.621	0.622	0.614	0.606	0.600	0.831
$\overline{g}_*$	0.574	0.573	0.567	0.559	0.553	0.763
λ_*	0.319	0.316	0.316	0.318	0.319	0.248
EVs	-1.284 $\pm$3.247**i**	-1.284 $\pm$3.076**i**	-1.268 $\pm$3.009**i**	-1.255 $\pm$2.986**i**	-1.244 $\pm$2.974**i**	-1.876 $\pm$2.971**i**
	-2	-2	-2	-2	-2	-2
	-1.358	-1.360	-1.360	-1.358	-1.356	-1.370

regulators

$$R_{k,a}(p^2) = p^2\, r_a(x)$$

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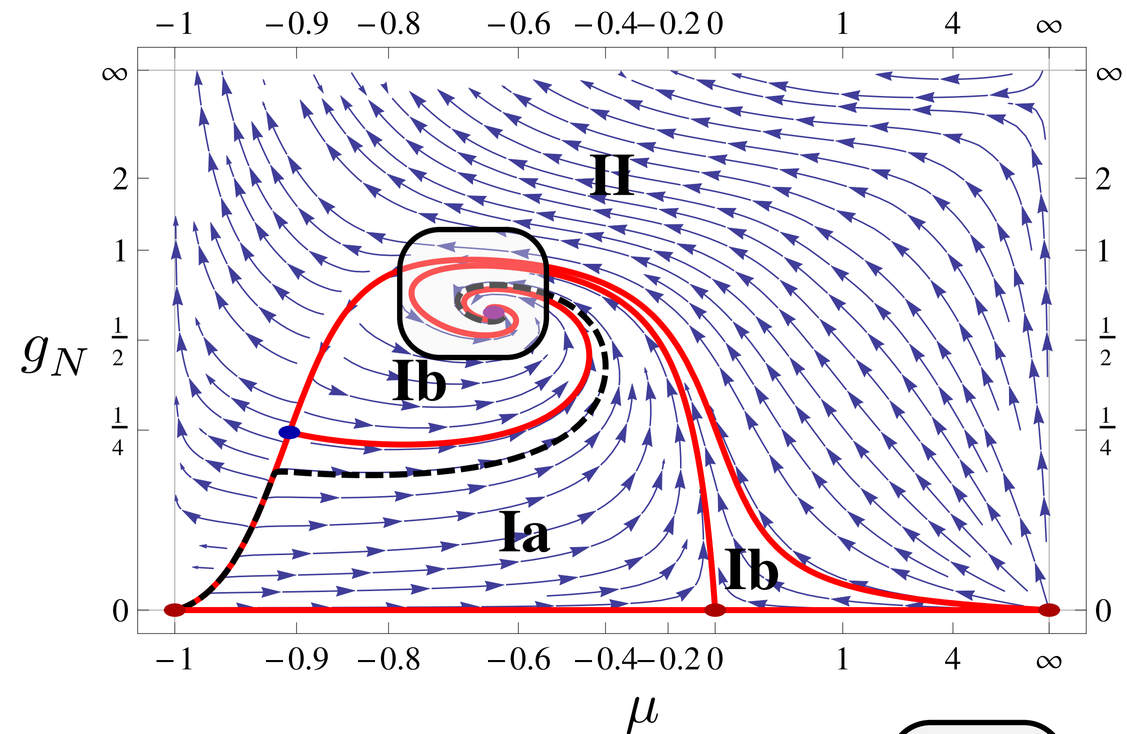

$a = 4$

Phase diagram of quantum gravity

global phase diagram

UV-fixed point

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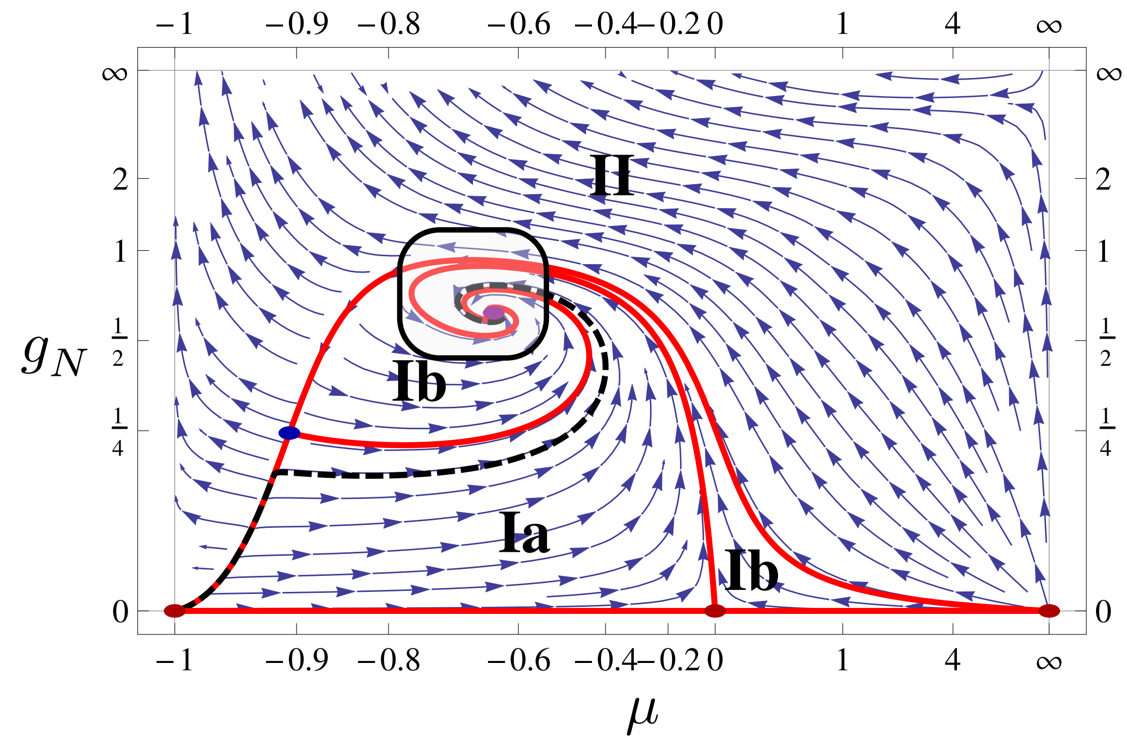

comparison with other results

	here	Litim03	Christiansen12	Donkin12	Manrique10	Becker14	Codello13	here mixed
$\bar{g}_*$	0.763	1.178	2.03	0.966	1.055	0.703	1.617	1.684
λ_*	0.248	0.250	0.22	0.132	0.222	0.207	-0.062	-0.035
$\bar{g}_*\lambda_*$	0.189	0.295	0.45	0.128	0.234	0.146	-0.100	-0.059

Litim ’03 — background approximation

Christiansen, Litim, JMP, Rodigast ’12 — flat expansion, bi-local

Donkin, JMP ’12 — geometrical

Manrique, Reuter, Saueressig ’10 — bi-metric

Becker, Reuter ’14 — bi-metric

Codello, D’Odorico, Pagani ’13 — flat expansion, mixed approach

mixed approach: $\mu = -2\lambda$

bi-metric: see talk of M. Reuter

Phase diagram of quantum gravity

global phase diagram

UV-fixed point

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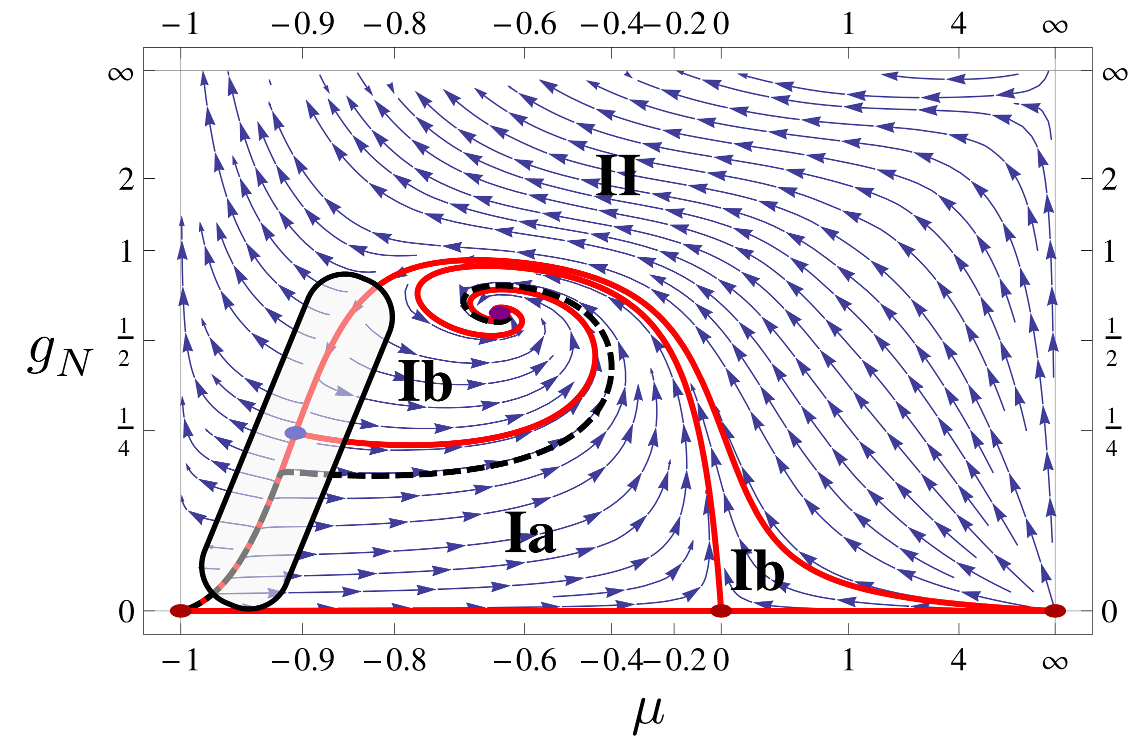
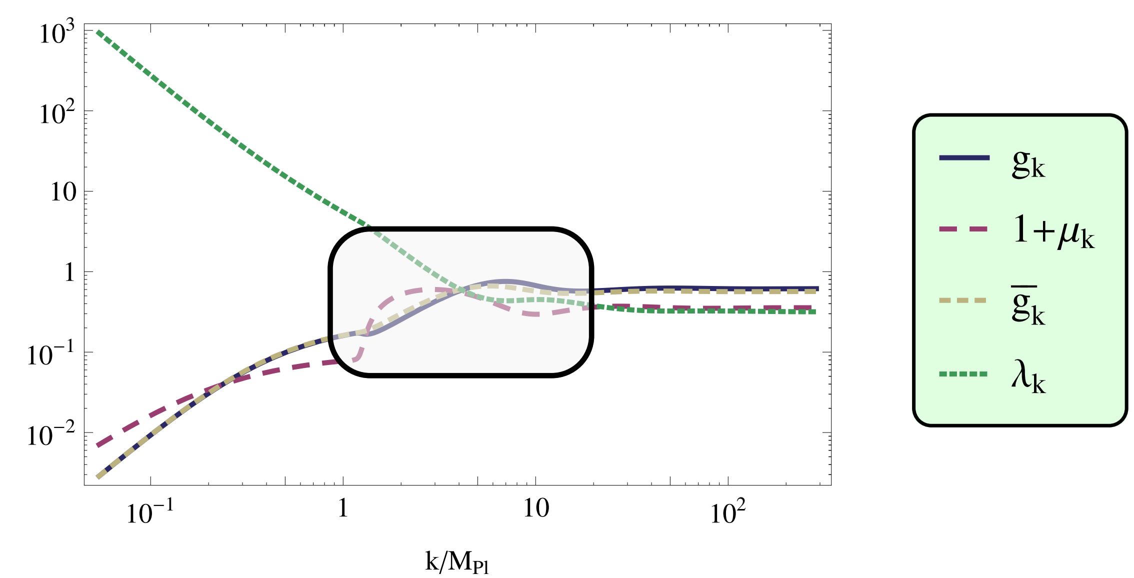


UV-IR transition

dominance of constant parts $\lambda^{(3)}, \lambda^{(4)}$ **of** $\Gamma^{(3)}, \Gamma^{(4)}$



Phase diagram of quantum gravity

global phase diagram

UV-fixed point

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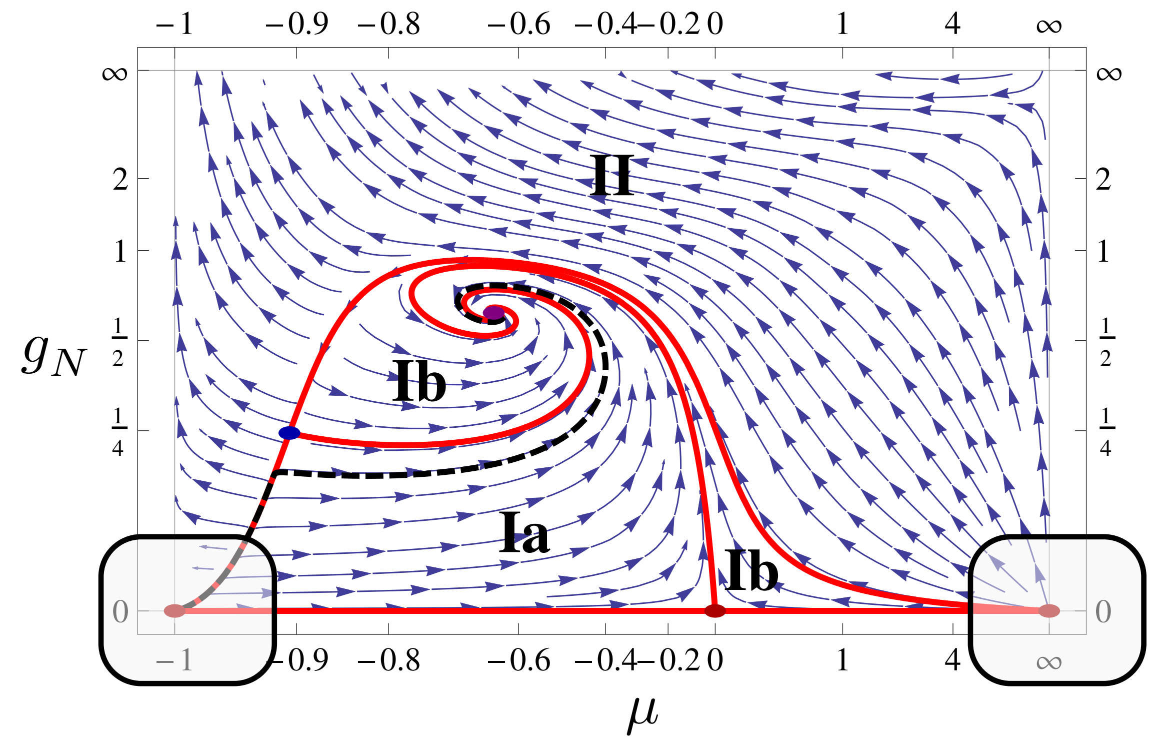


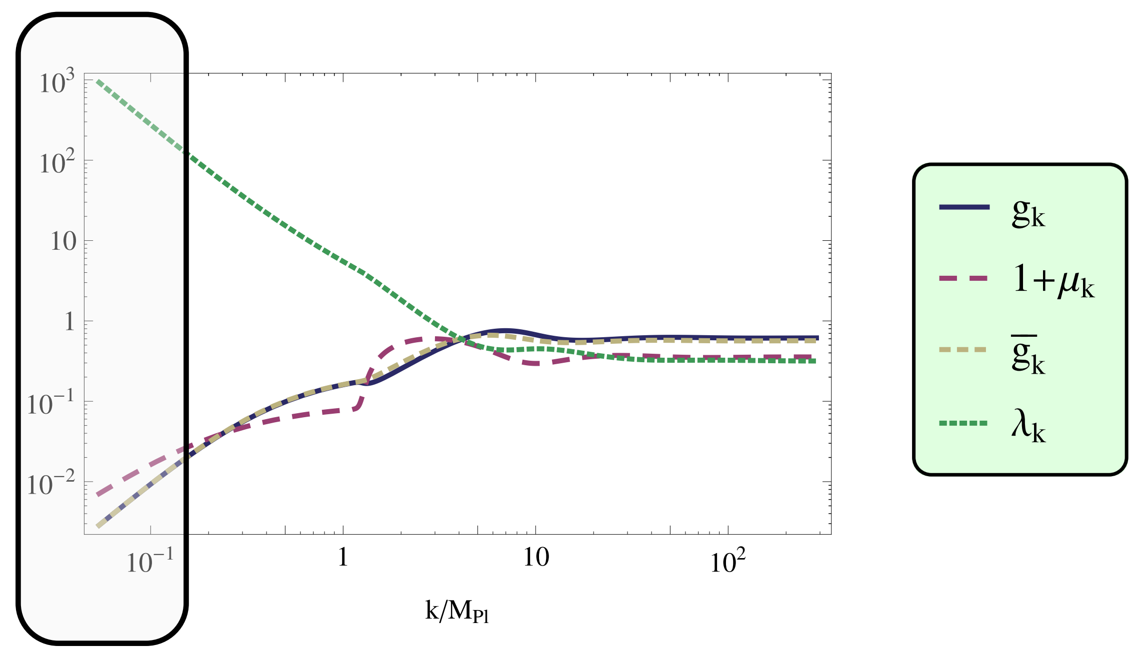
IR-fixed points

$$g, \bar{g} \sim k^2$$

$$\lambda \sim \frac{1}{k^2}$$

$$\eta_h \to 0$$

$$\eta_c \to 0$$



Coupling to gauge fields

see also talk of A. Eichhorn

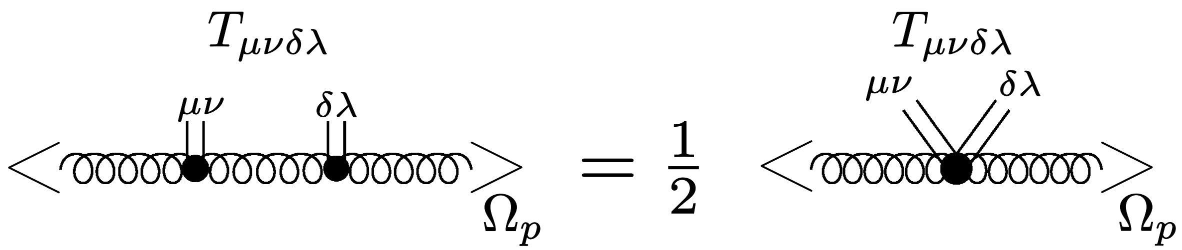
Phase diagram of quantum gravity

UV stability of the gauge-gravity system

Gravity contribution to Yang-Mills beta-function supports asymptotic freedom

Size depends on gauge and regulator, the sign does not

Folkerts, Litim, JMP '11

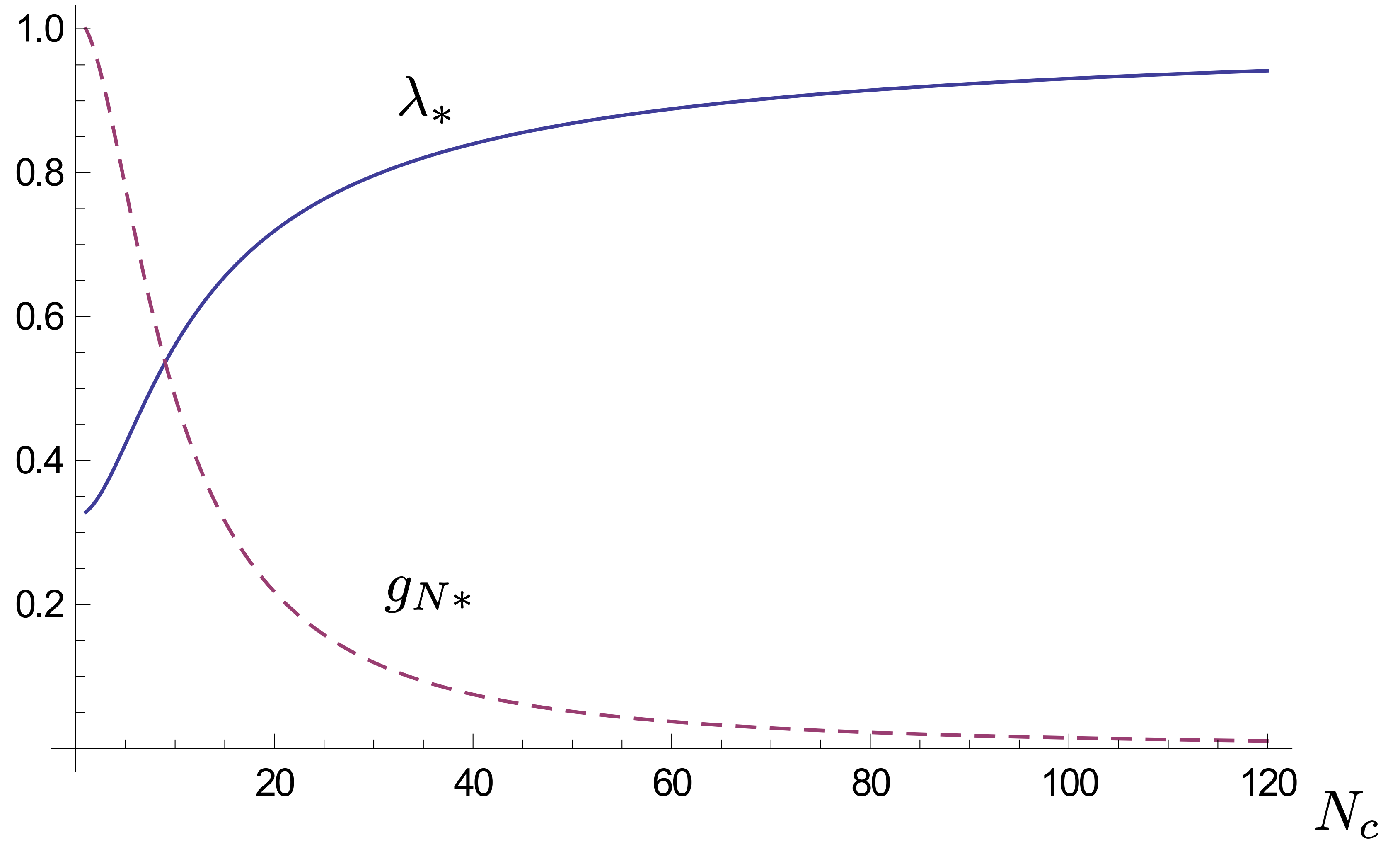


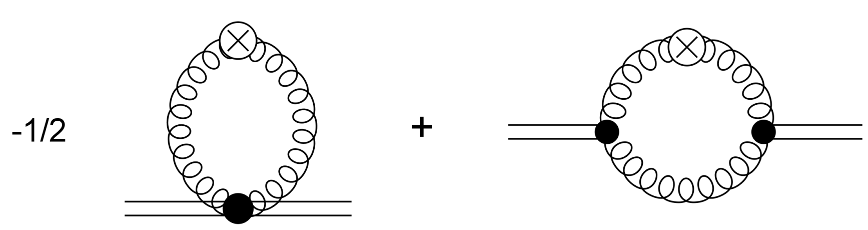
kinematic identity

Phase diagram of quantum gravity

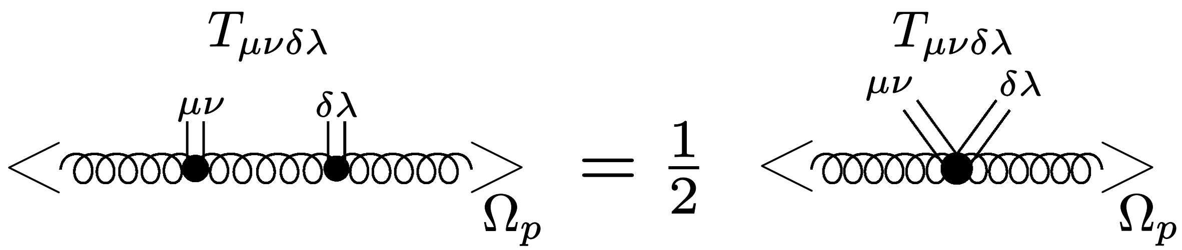
UV stability of the gauge-gravity system

Folkerts, Litim, JMP ’11 & unpublished
Christiansen, Diploma thesis ´11
work in progress





gauge contribution to gravity



kinematic identity

Summary & outlook

- **Phase diagram of quantum gravity**
  - **first smooth global flow diagram with classical IR regime**

    in agreement with experimental observations
  - **IR-stability of quantum gravity**
  - **UV-stability of the gauge-gravity system**
- **Outlook**
  - **fully-coupled matter-gauge-gravity systems in the UV**

    see talk of A. Eichhorn
  - **long & short distance physics**