Background independence, gauge/diffeomorphism invariance & locality

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Universität Heidelberg & ExtreMe Matter Institute

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GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

ISOQUANT SFB1225

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Related talks & posters

talks

Astrid Eichhorn (Thursday) *'Quantum effects on a Higgs-Yukawa model'*

Nicolai Christiansen (Thursday) *'Vertex functions in quantum gravity'*

posters

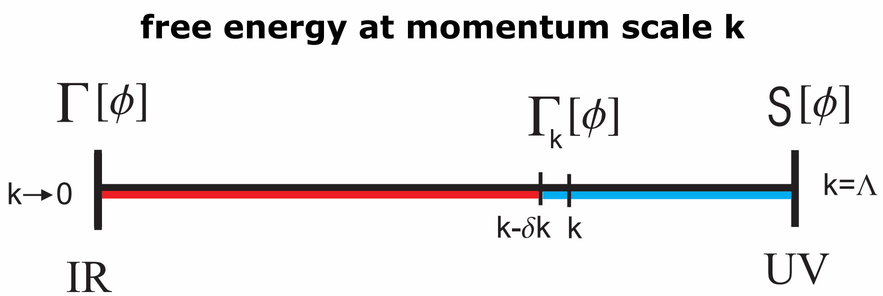
Tobias Denz *'Towards apparent convergence in asymptotically safe QG*
'

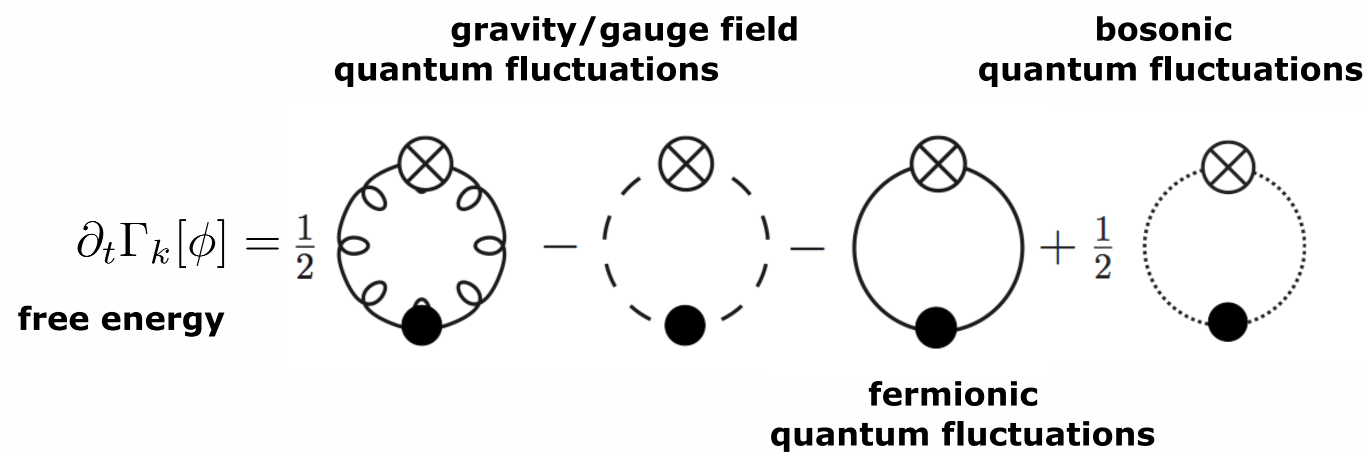
Aaron Held *'QG-effects on a Higgs-Yukawa model'*

Manuel Reichert *'QG with a vertex expansion on curved backgrounds'*

Background independence in the FRG

Background (in)dependence in the FRG



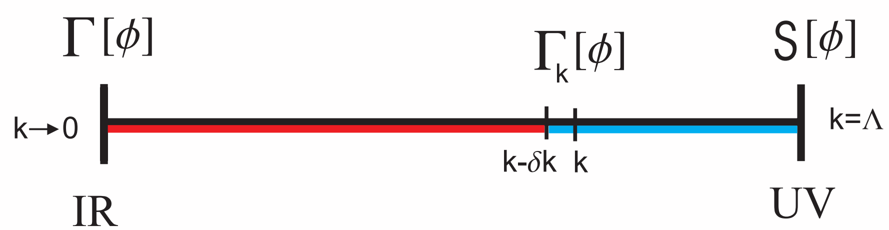


RG-scale k: $t = \ln k$

$\phi = \bar{\phi} + \varphi$

Background (in)dependence in the FRG

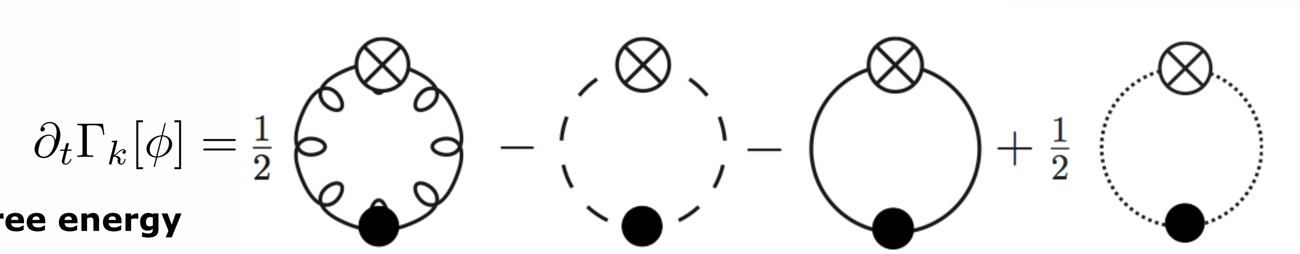
free energy at momentum scale k



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

gravity/gauge field quantum fluctuations

bosonic quantum fluctuations



free energy

fermionic quantum fluctuations

$\phi = \bar{\phi} + \varphi$

Expansion of the effective action

$$\Gamma_k[\bar{\phi} + \varphi] = \Gamma_k[\bar{\phi}] + \Gamma_k^{(0,1)}[\bar{\phi}] * \varphi + \frac{1}{2}\Gamma_k^{(0,2)}[\bar{\phi}] * \varphi^2 + \frac{1}{6}\Gamma_k^{(0,3)}[\bar{\phi}] * \varphi^3 + \cdots$$

Appropriately chosen backgrounds may facilitate convergence

$$\Gamma_k^{(n,m)} = \frac{\delta^{n+m}\Gamma_k}{\delta\bar{\phi}^n\,\delta\varphi^m}$$

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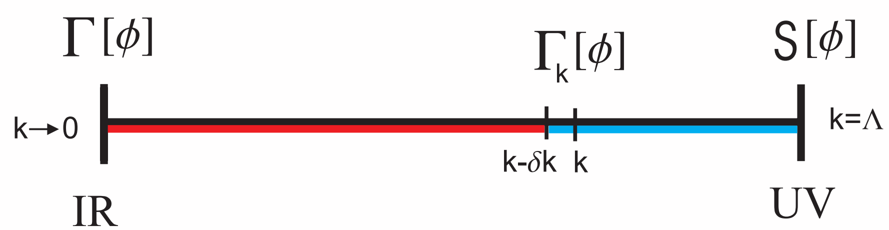

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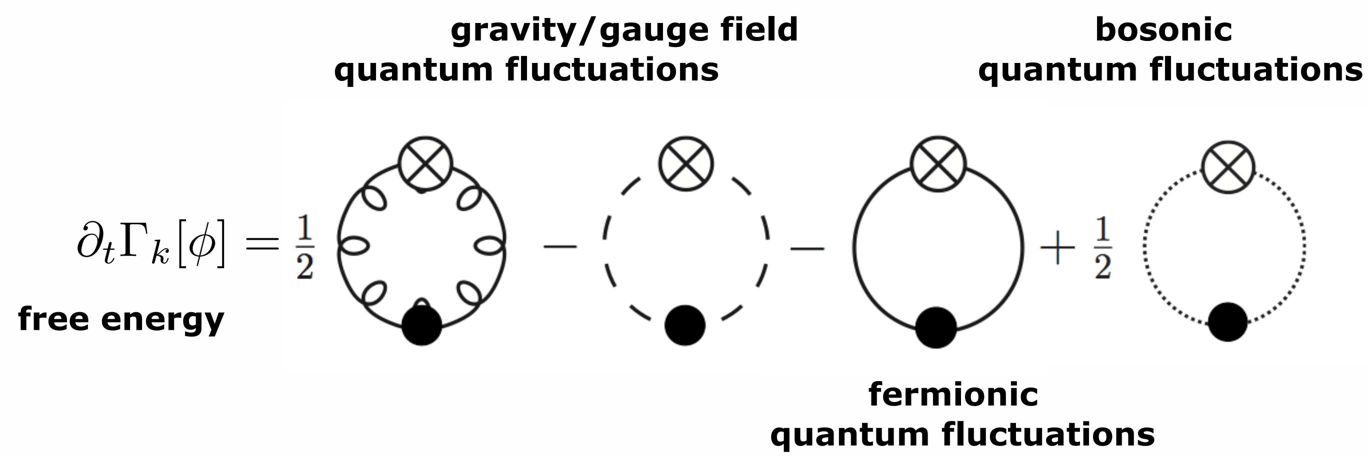

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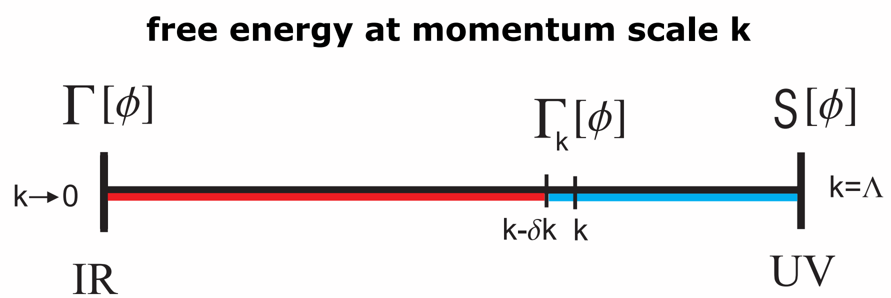
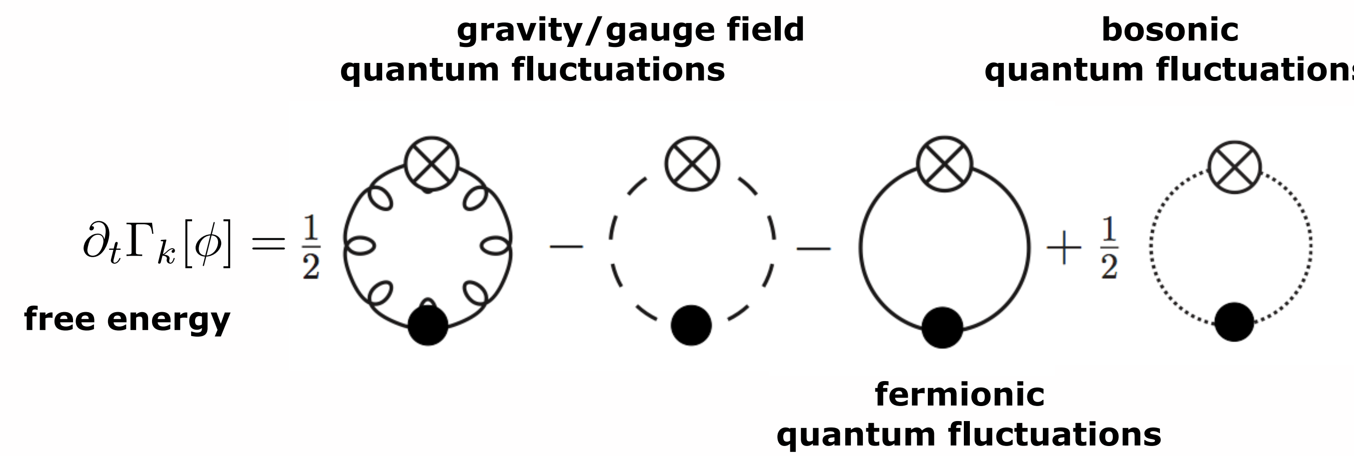
Examples:

- **solution of the equation of motion**
- **topological configuration or defect**
- **simplification of numerics**

Background (in)dependence in the FRG





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Translation invariance

$$\frac{\delta\Gamma_k}{\delta\bar{\phi}} = \frac{\delta\Gamma_k}{\delta\varphi}$$

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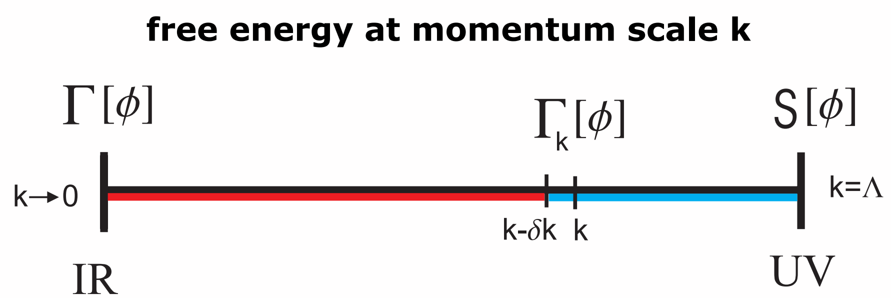

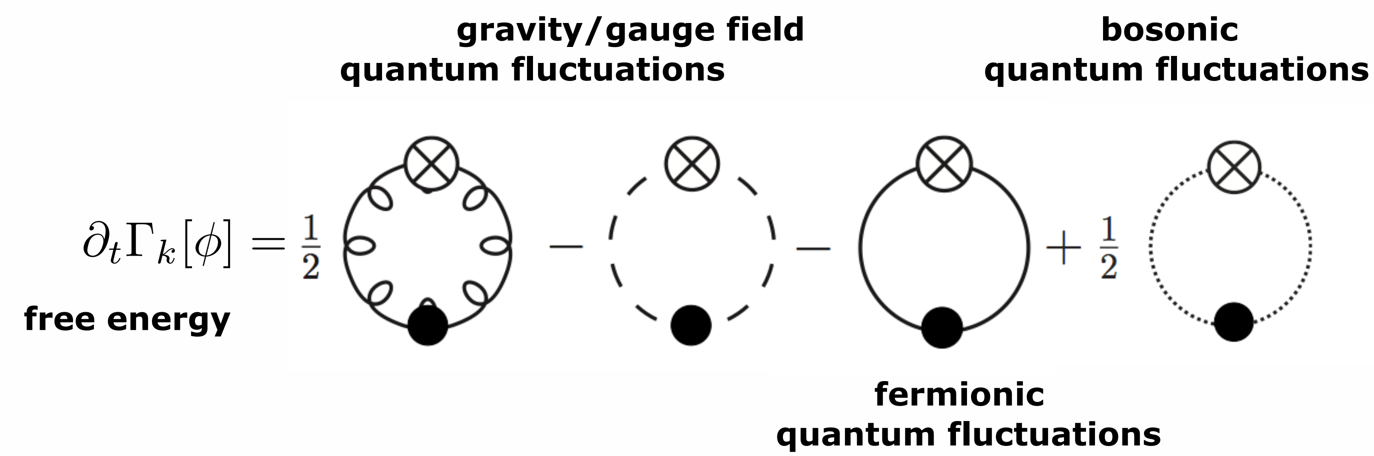

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$$\frac{\delta \Gamma_k}{\delta \bar{\phi}} = \frac{\delta \Gamma_k}{\delta \varphi} \quad \longrightarrow \quad \frac{\delta \Gamma_k^{(0,n)}}{\delta \bar{\phi}} = \Gamma_k^{(0,n+1)}$$

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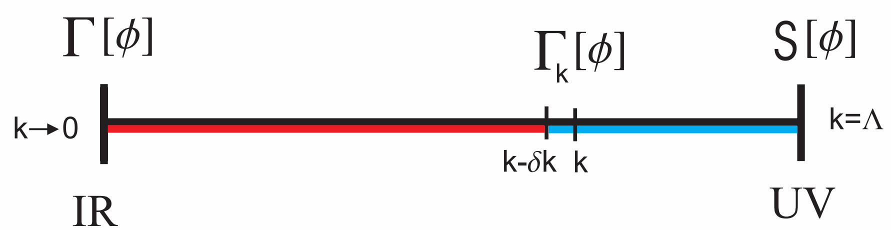

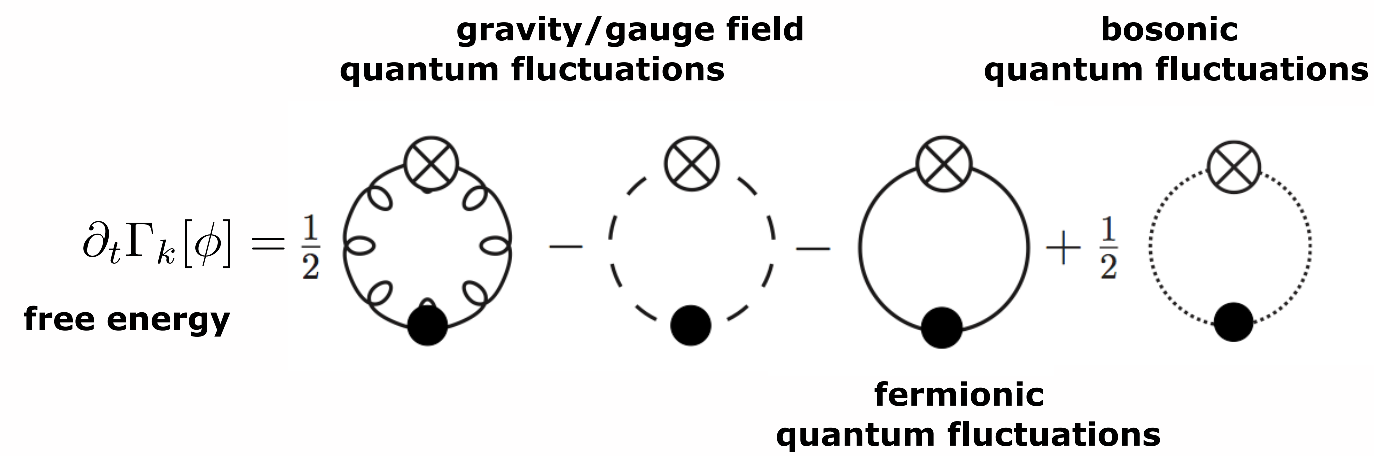

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Translation invariance

'Split WI/Nielsen ID'

$$\frac{\delta \Gamma_k}{\delta \bar{\phi}} = \frac{\delta \Gamma_k}{\delta \varphi} \quad \longrightarrow \quad \frac{\delta \Gamma_k^{(0,n)}}{\delta \bar{\phi}} = \Gamma_k^{(0,n+1)}$$

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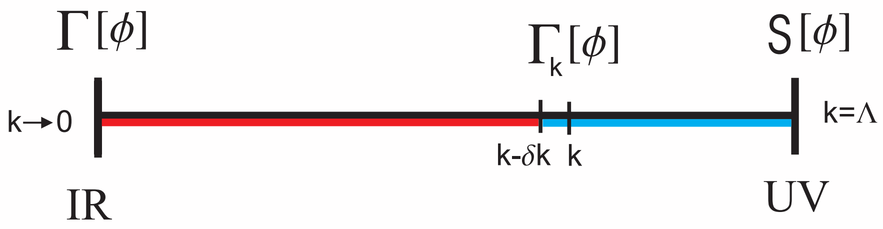

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gravity/gauge field quantum fluctuations

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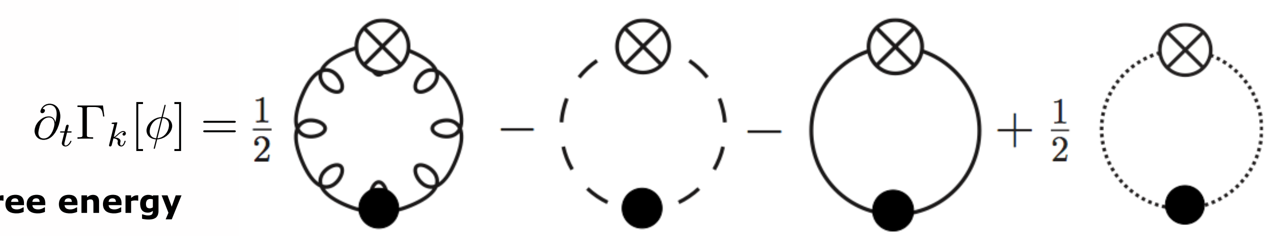

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Translation invariance

broken by regulators $R_k[\bar{\phi}]$

$$\frac{\delta \Gamma_k}{\delta \bar{\phi}} = \frac{\delta \Gamma_k}{\delta \varphi}$$

→

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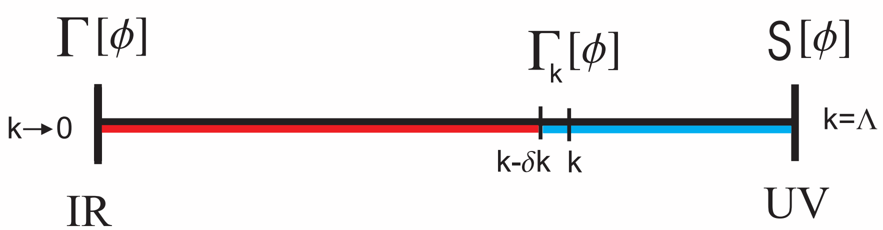
$$\frac{\delta \Gamma_k^{(0,n)}}{\delta \bar{\phi}} = \Gamma_k^{(0,n+1)}$$

Background dependence in gravity

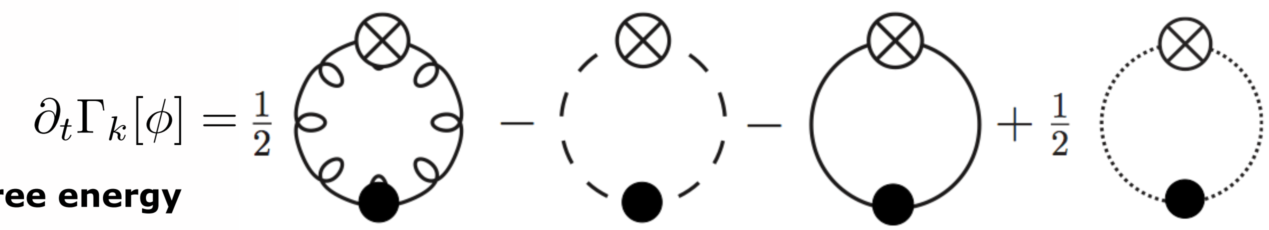
free energy at momentum scale k



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

gravity
quantum fluctuations

bosonic
quantum fluctuations

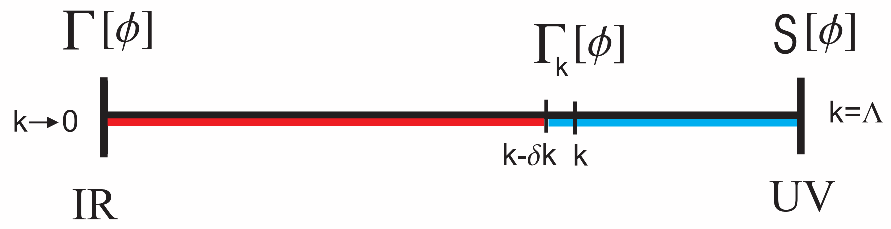


fermionic
quantum fluctuations

$\phi = (g, \ldots)$

Background dependence in gravity

free energy at momentum scale k



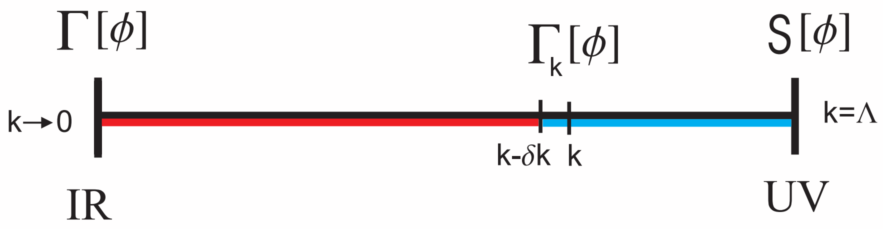
RG-scale k: $t = \ln k$

Wetterich equation (pure gravity)

$$\partial_t \Gamma_k[g] = \frac{1}{2} \mathrm{Tr} \, \frac{1}{\Gamma_k^{(2)}[g] + R_k} \partial_t R_k$$

Background dependence in gravity

free energy at momentum scale k



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Gauge fixing

$$S_{\mathrm{gf}}[\bar{g}, g] = \frac{1}{2\alpha} \int d^4x \sqrt{\bar{g}} \, (L[\bar{g}] * g)^2$$

e.g.: $(L[\bar{g}] * g)_\mu = \bar{\nabla}^\nu g_{\mu\nu} - \frac{1}{2} \nabla^\mu g^\nu{}_\nu$

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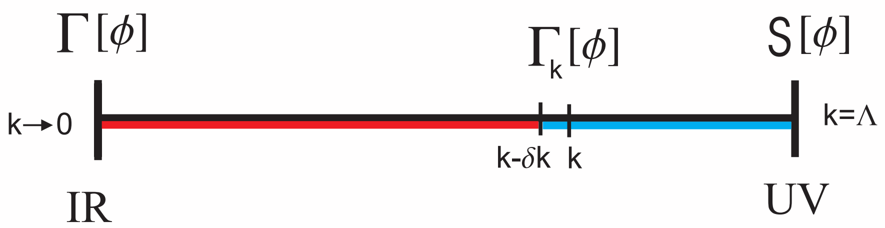
free energy at momentum scale k



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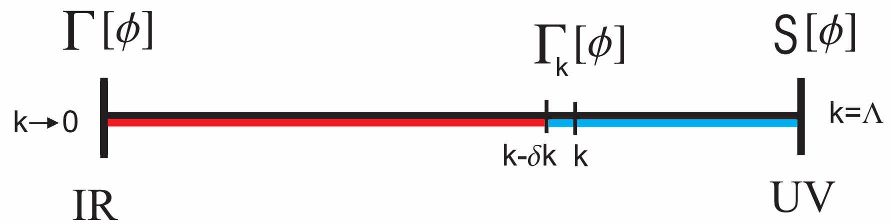
$$\partial_t \Gamma_k[\bar{g}, h] = \frac{1}{2} \mathrm{Tr}\, \frac{1}{\frac{\delta^2 \Gamma_k}{\delta h^2} + R_k} \partial_t R_k \; + \; \text{ghosts}$$

linear split

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

Background dependence in gravity

free energy at momentum scale k



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Gauge/diffeomorphism invariance
mSTIs/Nielsen IDs (split mWI)

$$\frac{\delta\Gamma_k}{\delta h} = \frac{\delta\Gamma_k}{\delta\bar g} + L\,\&R_k\; - \text{terms}$$

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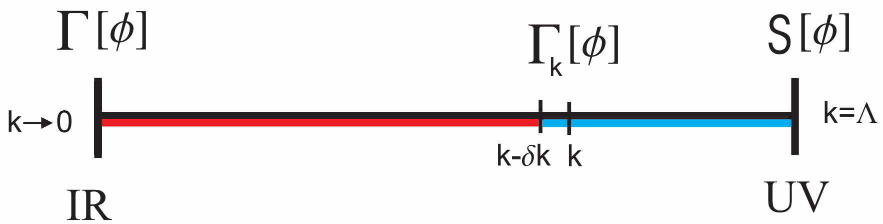

Only one field!

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Background approximation I

mSTIs/Nielsen IDs (split mWI)

$$\frac{\delta\Gamma_k}{\delta h} \approx \frac{\delta\Gamma_k}{\delta\bar{g}}$$

Litim, JMP, PLB 546 (2002) 279, PRD 66 (2002) 025030

Gravity **Folkerts,Litim, JMP, PLB 709 (2012) 234**

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Wetterich equation in background approximation

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Regulator bootstrap I

$$R_k[\bar\phi] = \Gamma_k^{(2)}[\bar\phi]\, r$$

$$\partial_t\Gamma_k[\bar\phi] = \frac{1}{2}\mathrm{Tr}\,\frac{1}{1+r}\,\partial_t r + \frac{1}{2}\mathrm{Tr}\,\partial_t\Gamma_k^{(2)}\frac{1}{\Gamma_k^{(2)}}\frac{r}{1+r}$$

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Regulator bootstrap II

Given $F[\bar\phi]$

Welches Schweinderl hätten's denn gerne?

Solve

$$F[\bar\phi] = \frac{1}{2}\mathrm{Tr}\,\frac{1}{\Gamma_k^{(2)} + R_k[\bar\phi]}\partial_t R_k[\bar\phi]$$

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Testing universal beta-functions: A simple one loop example in Yang-Mills theory

Litim, JMP, JHEP 0209 (2002) 049

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$$\frac{\delta \Gamma_k}{\delta a} \approx \frac{\delta \Gamma_k}{\delta \bar{A}}$$

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Regulators

$$R_k(\bar\Delta) = \bar\Delta\, r(\bar\Delta/k^2)$$

IR-behaviour: $r(x\to 0) \propto \frac{1}{x^n}$

$$\bar\Delta = -\bar D^2 + \mathrm{spin-contr.}$$

Background approximation II

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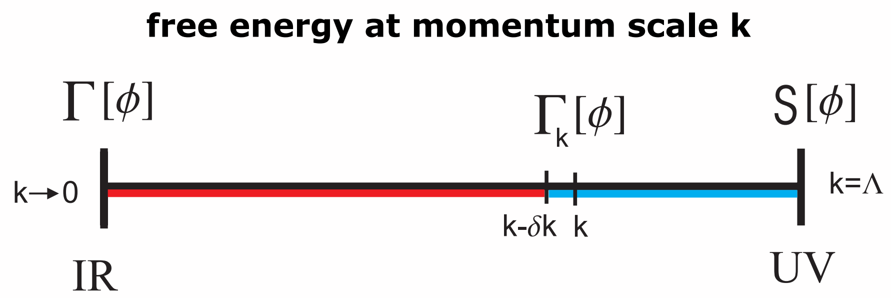
1-loop beta-function

$$\beta_{\mathrm{background-approx}} = \frac{1}{11}\left[10 n_a + n_c\right]\beta_{1-\mathrm{loop}}$$

Background (in)dependence in gravity



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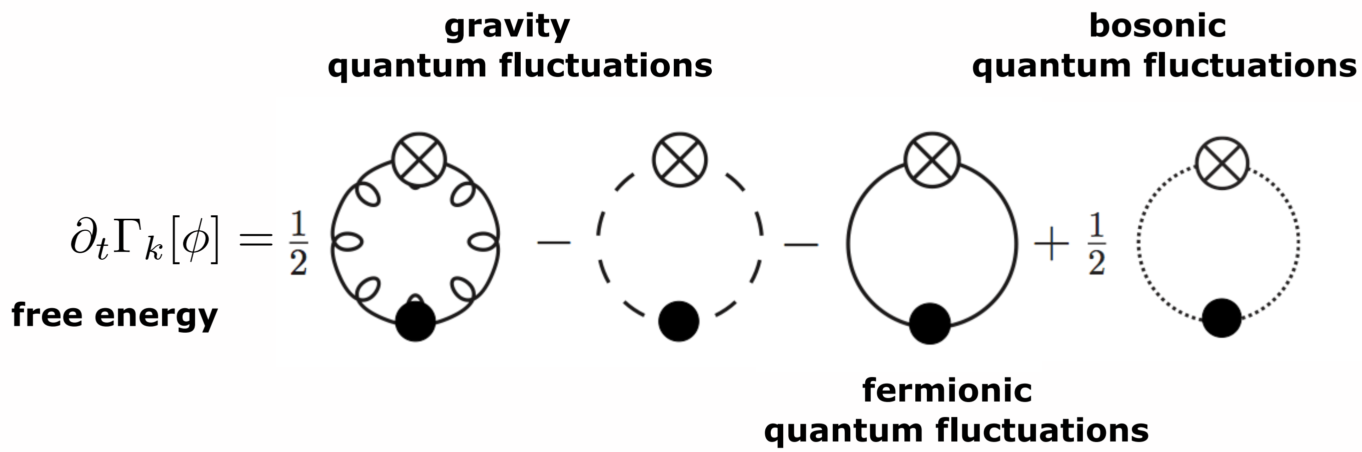

Geometrical approach: fully diffeomorphism invariant

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

Effective action

$$\Gamma_k[\bar{g}, \bar{h}] = \Gamma_k[\bar{g}] + \Gamma_k^{(0,1)}[\bar{g}] * \bar{h} + \frac{1}{2}\Gamma_k^{(0,2)}[\bar{g}] * \bar{h}^2 + \frac{1}{6}\Gamma_k^{(0,3)}[\bar{g}] * \bar{h}^3 + \cdots$$

$$\bar{h} = \langle h \rangle$$

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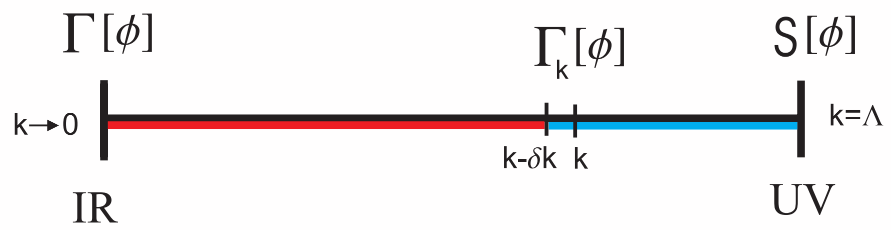

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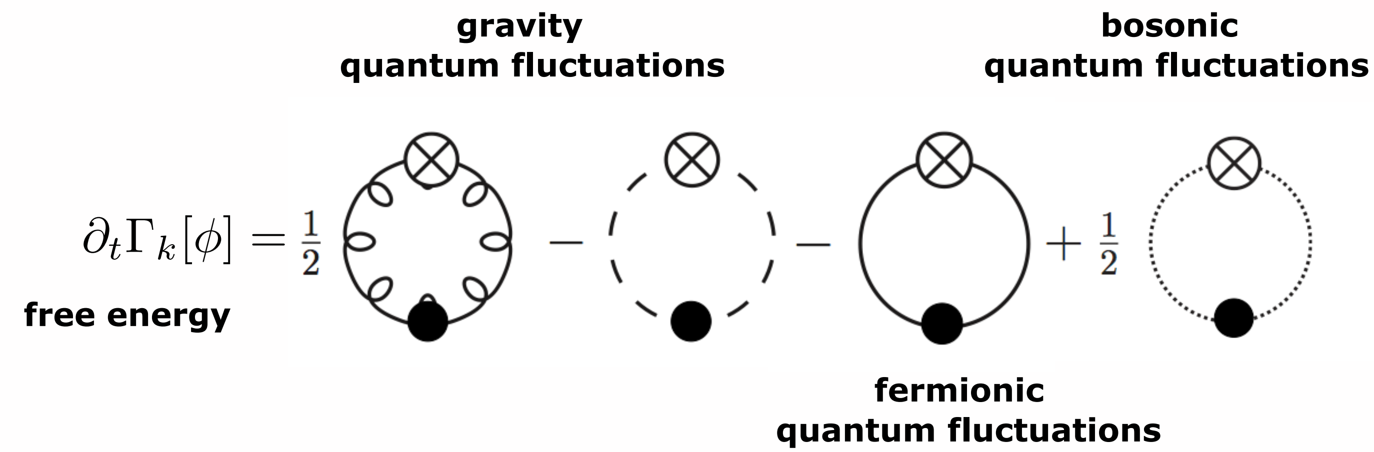

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$$\left\{ \Gamma_k[\bar{g}]\,,\ \Gamma_k^{(0,1)}[\bar{g}]\,,\ \Gamma_k^{(0,2)}[\bar{g}]\,,\ \Gamma_k^{(0,3)}[\bar{g}]\,,\ \ldots \right\}$$

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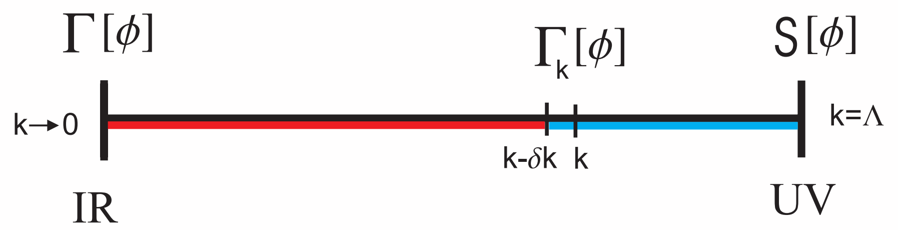

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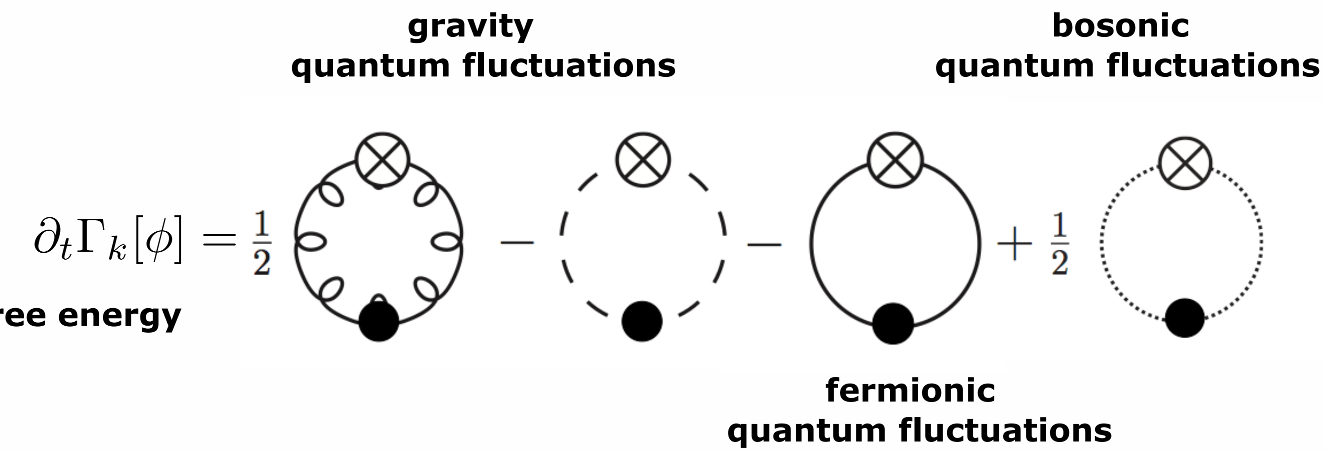

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Se vogliamo che tutto rimanga come è,

bisogna che tutto cambi.

Il Gattopardo

$$\left\{ \Gamma_k[\bar{g}], \Gamma_k^{(0,1)}[\bar{g}]\,,\, \Gamma_k^{(0,2)}[\bar{g}]\,,\, \Gamma_k^{(0,3)}[\bar{g}]\,,\, \ldots \right\}$$

Background (in)dependence in gravity

expansion schemes

Effective action

$$\left\{ \Gamma_k[\bar{g}]\,,\ \Gamma_k^{(0,1)}[\bar{g}]\,,\ \Gamma_k^{(0,2)}[\bar{g}]\,,\ \Gamma_k^{(0,3)}[\bar{g}]\,,\ \ldots \right\}$$

Background (in)dependence in gravity

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- **no diffeomorphism-invariant expansion scheme**

mSTIs/Nielsen IDs

Litim, JMP ’02

Background (in)dependence in gravity

expansion schemes

Effective action

$$\left\{ \Gamma_k[\bar g]\,,\, \Gamma_k^{(0,1)}[\bar g]\,,\, \Gamma_k^{(0,2)}[\bar g]\,,\, \Gamma_k^{(0,3)}[\bar g]\,,\, \ldots \right\}$$

- **no diffeomorphism-invariant expansion scheme**

mSTIs/Nielsen IDs

Litim, JMP '02

- **what is at stake?**

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

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

Braun, Gies, JMP '07

Braun, Eichhorn, Gies, JMP '10

Fister, JMP '13

Background (in)dependence in gravity

expansion schemes

Effective action

$$\left\{ \Gamma_k[\bar{g}]\,,\, \Gamma_k^{(0,1)}[\bar{g}]\,,\, \Gamma_k^{(0,2)}[\bar{g}]\,,\, \Gamma_k^{(0,3)}[\bar{g}]\,,\, \ldots \right\}$$

- **no diffeomorphism-invariant expansion scheme**

mSTIs/Nielsen IDs

Litim, JMP '02

- **what is at stake?**

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**

⋮

Background (in)dependence in gravity

expansion schemes

Effective action

$$\left\{ \Gamma_k[\bar g]\,,\, \Gamma_k^{(0,1)}[\bar g]\,,\, \Gamma_k^{(0,2)}[\bar g]\,,\, \Gamma_k^{(0,3)}[\bar g]\,,\, \ldots \right\}$$

- **no diffeomorphism-invariant expansion scheme** — **mSTIs/Nielsen IDs**, Litim, JMP '02

- **what is at stake?** **Does it matter?**

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- **no diffeomorphism-invariant expansion scheme**

mSTIs/Nielsen IDs

Litim, JMP '02

- **what is at stake?** **Does it matter?**

Examples in gravity-matter systems:

$$\text{sign}\left[\partial_t \Gamma^{(n)}_{\text{back}-\text{approx}}\right] \neq \text{sign}\left[\partial_t \Gamma^{(n)}_{\text{fluc}}\right]$$

Functional approach to quantum gravity

expansion schemes

Effective action

$$\left\{ \Gamma_k[\bar{g}]\,,\, \Gamma_k^{(0,1)}[\bar{g}]\,,\, \Gamma_k^{(0,2)}[\bar{g}]\,,\, \Gamma_k^{(0,3)}[\bar{g}]\,,\, \ldots \right\}$$

- **no diffeomorphism-invariant expansion scheme**

mSTIs/Nielsen IDs

Litim, JMP '02

Fluctuation flows determine the fixed point structure!

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

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

dynamical flow

Nielsen ID

background flow

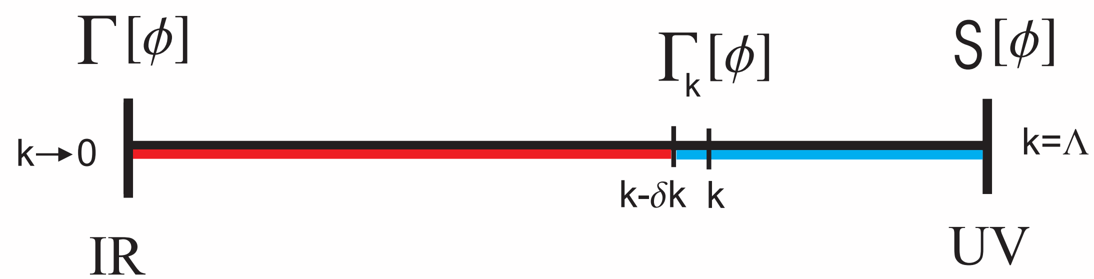
JMP '03

Donkin, JMP '12

Momentum locality of the RG

Christiansen, Knorr, Meibohm, JMP, Reichert, PRD 92 (2015) 12, 121501

free energy at momentum scale k



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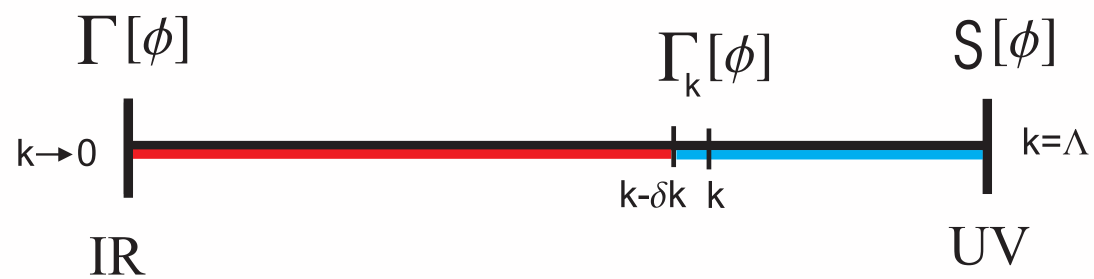

Locality

$$\lim_{p_1,\ldots,p_n\to\infty} \frac{|\partial_t \mathcal{O}_k(p_1,\ldots,p_n)|}{|\mathcal{O}_k(p_1,\ldots,p_n)|} \to 0$$

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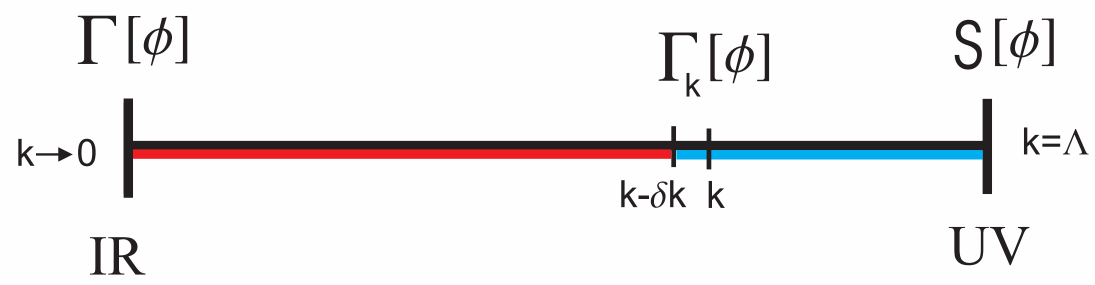

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- **local momentum space RG steps** ⟺ **local quantum field theory**

- **gravity-matter systems: locality** ⟸ **diffeomorphism invariance**

does not work in e.g. $\phi^2\Delta\phi^2$ -theories

Momentum locality of the RG

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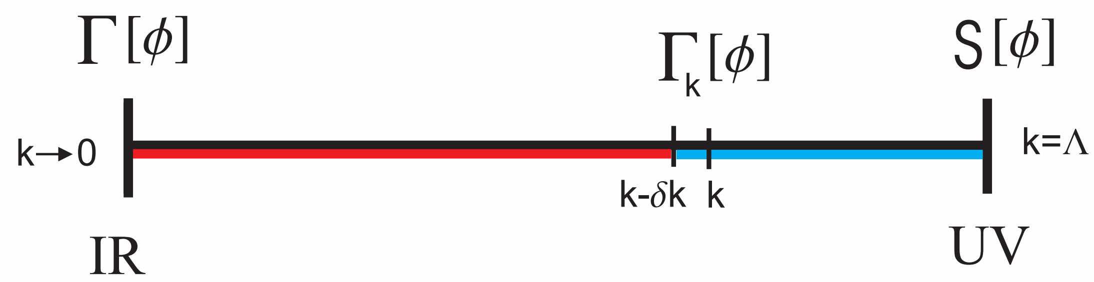

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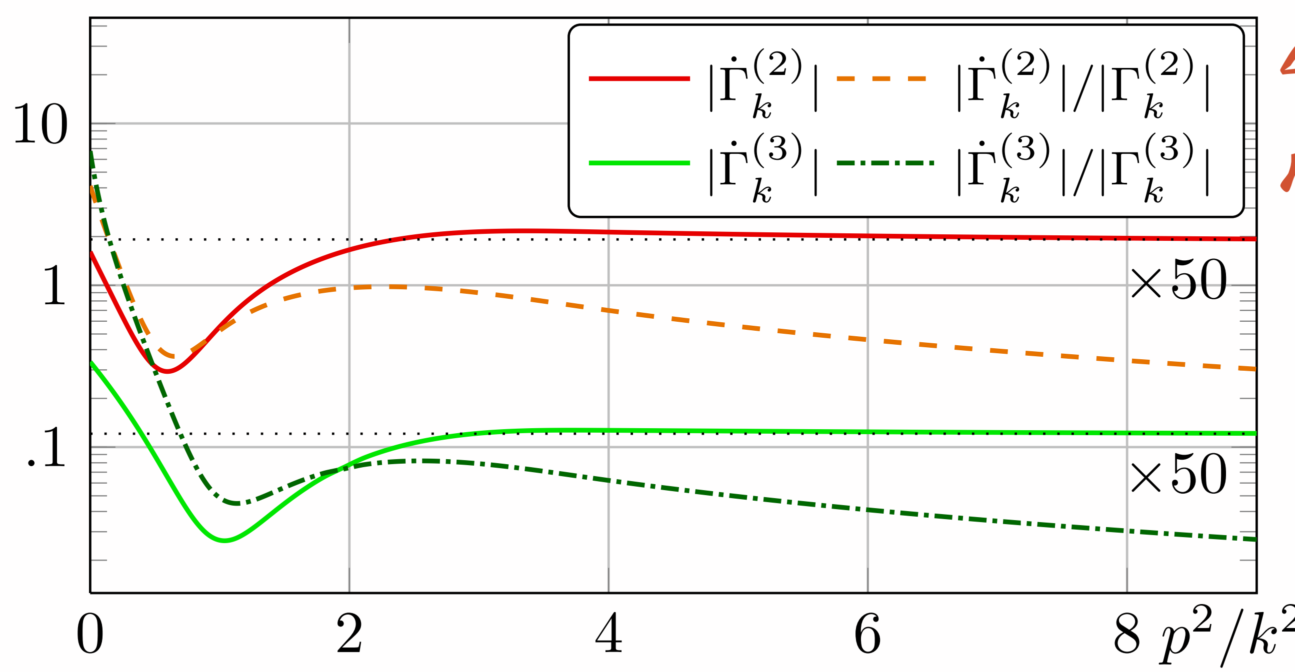


4-graviton vertex: see Poster of Tobias Denz

symmetric point

Approximation scheme

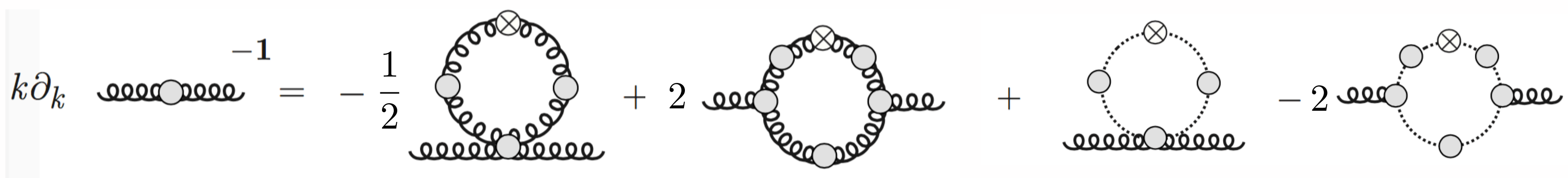
Christiansen, Knorr, Meibohm, JMP, Reichert, PRD 92 (2015) 12, 121501

Denz, JMP, Reichert, in preparation

Christiansen, Falls, JMP, Reichert, in preparation

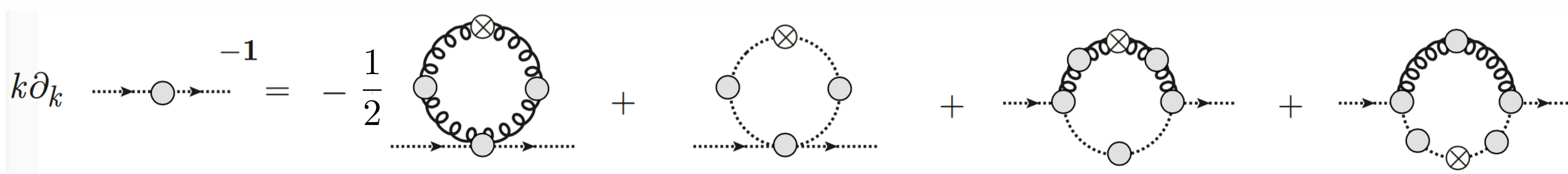
Propagators

graviton



full momentum dependence

ghost



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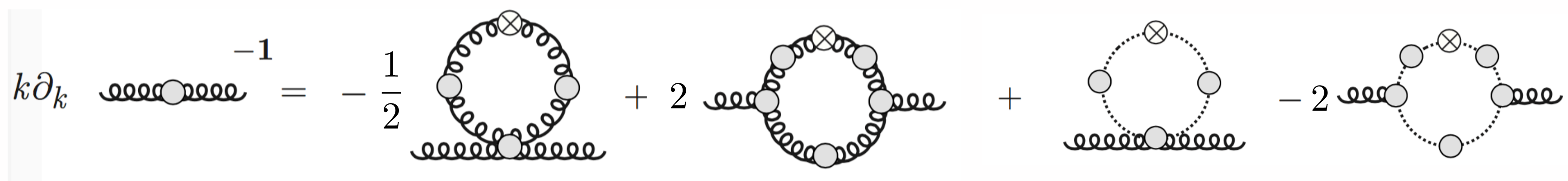

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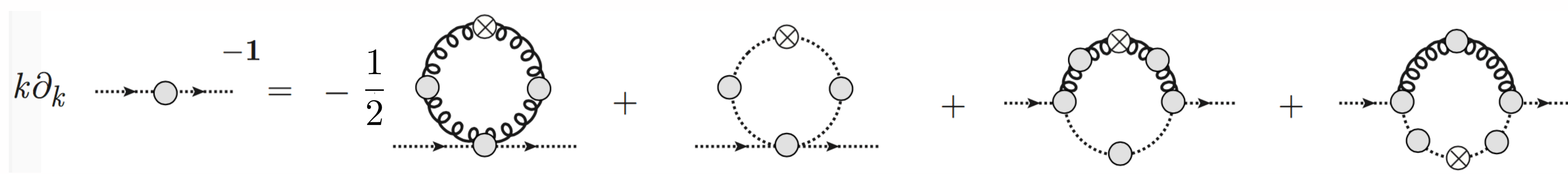
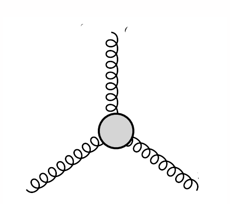


Vertices

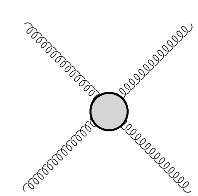
$$Z_{\text{graviton}} \neq Z_{g_N}$$

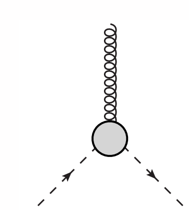
$$M^2_{\text{graviton}} \neq -2\Lambda$$

flow



consistent momentum-dependent RG-dressing





a la Fischer, JMP '09
Donkin, JMP '12

similar: Codello, D'Odorico, Pagani '13

Approximation scheme

Christiansen, Knorr, Meibohm, JMP, Reichert, PRD 92 (2015) 12, 121501

Denz, JMP, Reichert, in preparation

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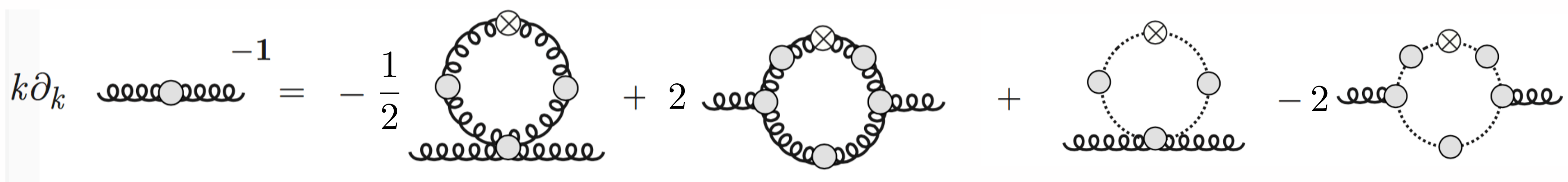
graviton



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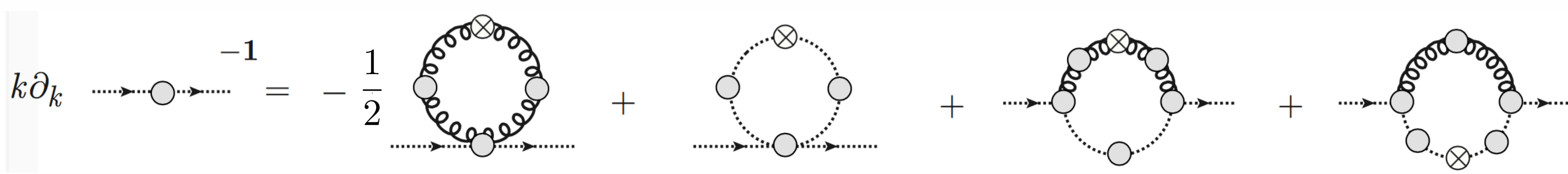

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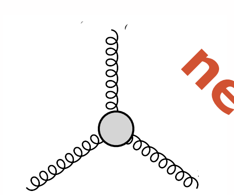
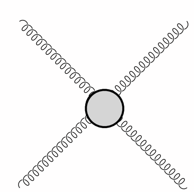
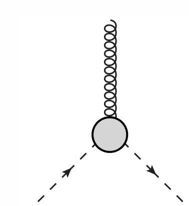


new





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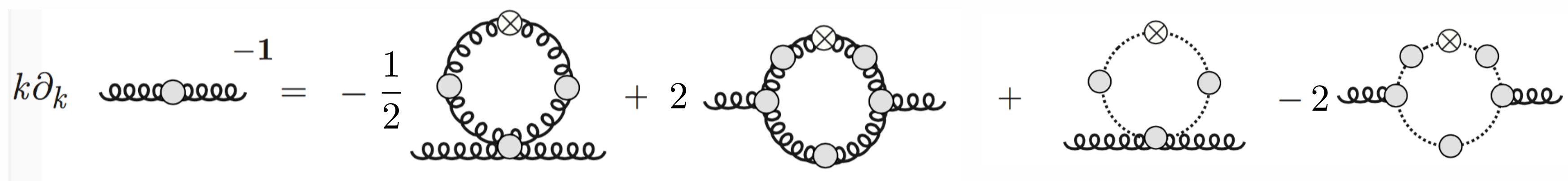

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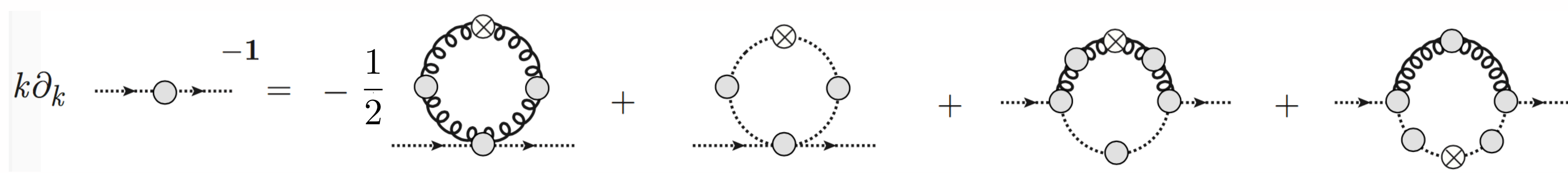

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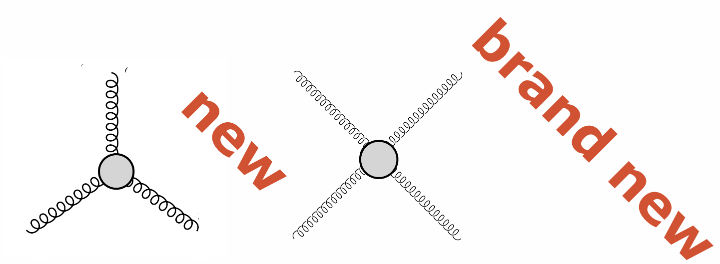

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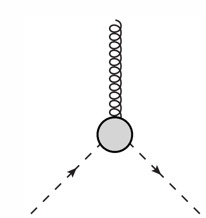

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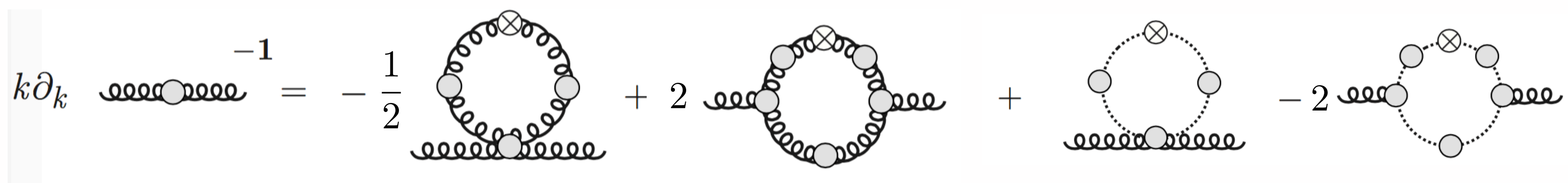

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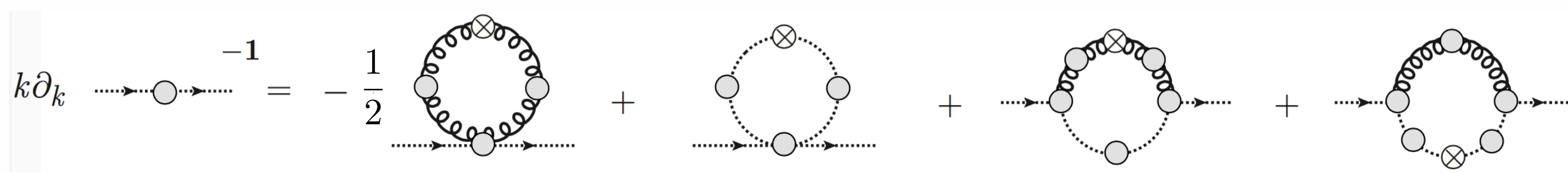

Flows & scalings

propagators

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

vertices

$\Gamma^{(3)}_{hhh}(p_1, p_2)$ $\quad G_3 \quad \Lambda_3$

$\Gamma^{(4)}_{hhh}(p_1, p_2, p_3)$ $\quad G_4 \quad \Lambda_4$

background observables

Λ — **cosmological constant**

$\bar{G}_N$ — **Newton constant**

Approximation scheme

Christiansen, Knorr, Meibohm, JMP, Reichert, PRD 92 (2015) 12, 121501

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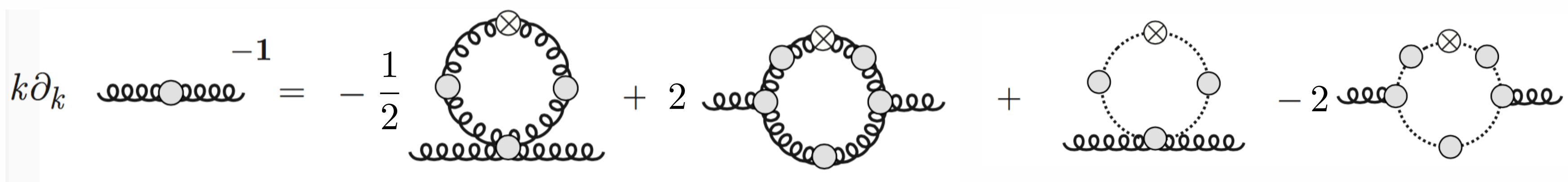

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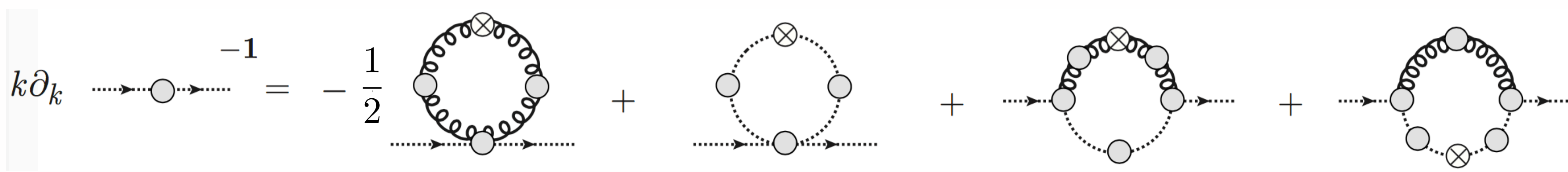

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background observables

Λ — **cosmological constant**

$\bar{G}_N$ — **Newton constant**

brand brand new: $G_n(R), \quad \Lambda_n(R)$ *see Poster of Manuel Reichert*

Summary & outlook

- **Background independence & Locality**
  - **background independence from background dependence**
  - **closed fluctuation flows**
  - **momentum locality from diffeomorphism invariance**
- **Applications**
  - **fully-coupled matter-gauge-gravity systems in the UV**
  - **long & short distance physics**