# Fluctuations, locality
# and
# the phase structure of quantum gravity

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**Universität Heidelberg & ExtreMe Matter Institute**

**Nordita, March 23rd 2015**

- **Locality & phase structure of quantum gravity**
  - **Functional RG and expansion schemes**
  - **locality in quantum gravity**
  - **phase structure of quantum gravity**
- **Coupling to matter**
  - **gauge-gravity system**
  - **fermions & scalars**

# Locality & phase structure of quantum gravity

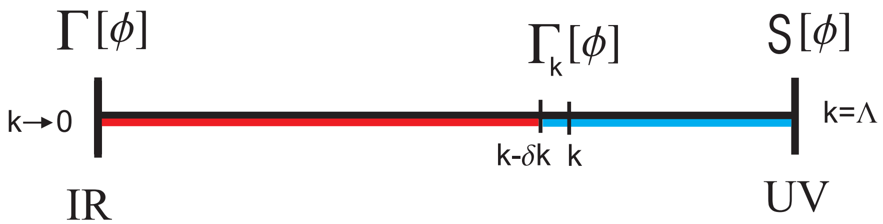
Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232

Christiansen, Knorr, Meibohm, JMP, Reichert, arXiv:1504.xxxx

# Functional approach to quantum gravity

## Functional RG

**free energy at momentum scale k**




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

# Functional approach to quantum gravity

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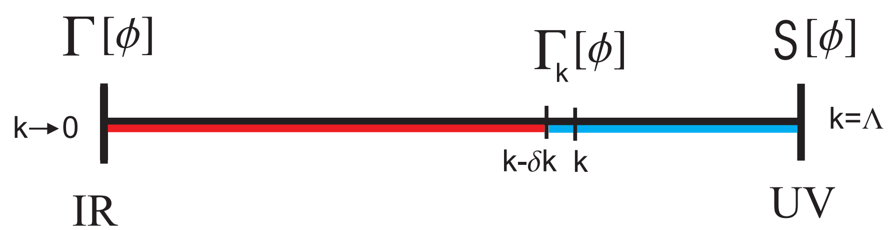


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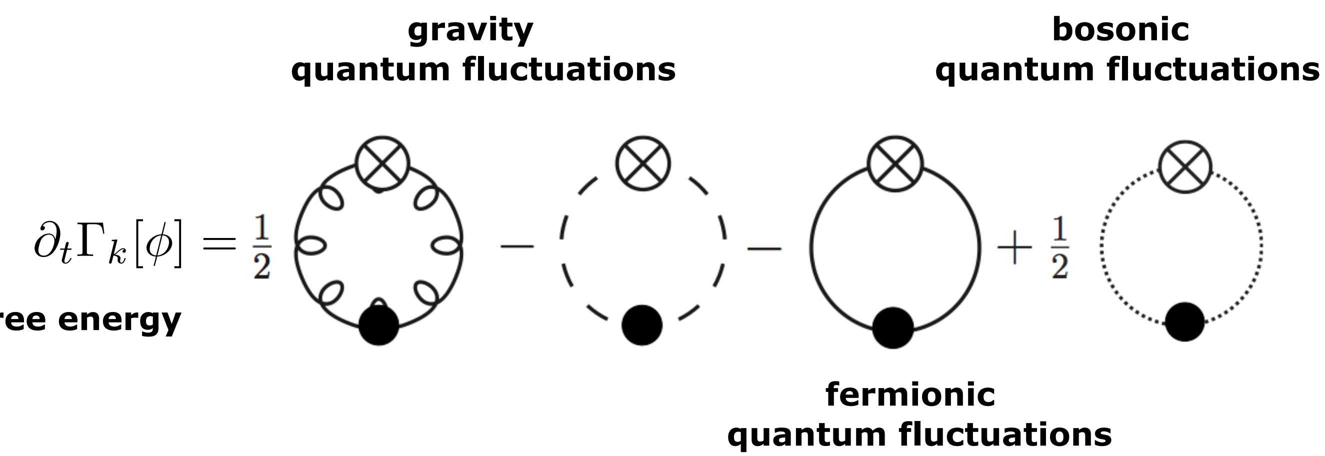


**Geometrical approach: fully diffeomorphism invariant**

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

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

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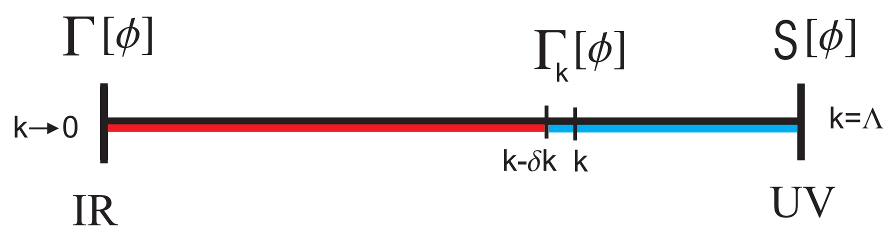


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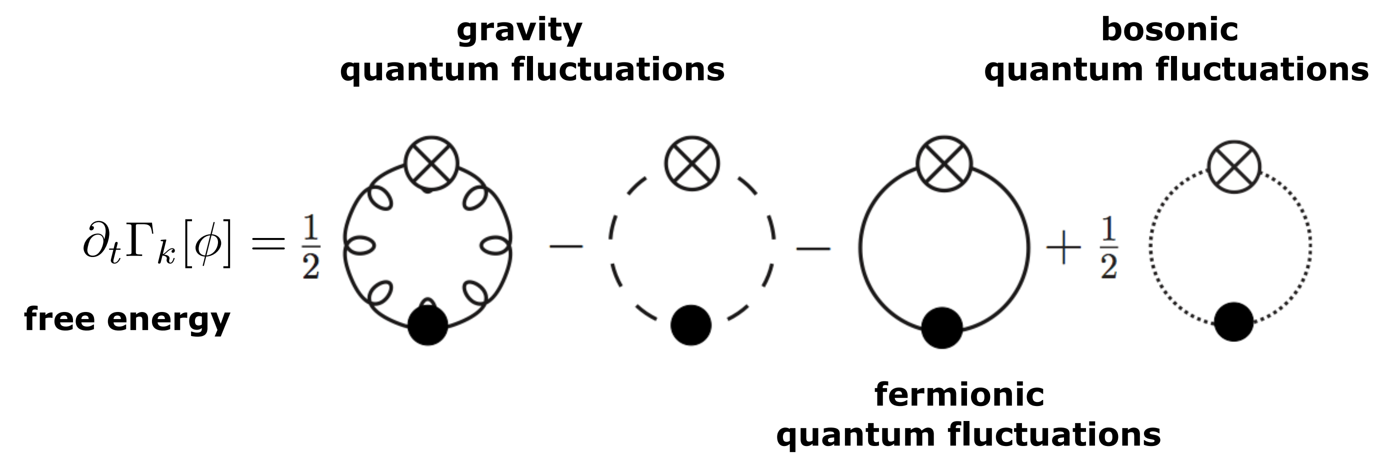



**Geometrical approach: fully diffeomorphism invariant**

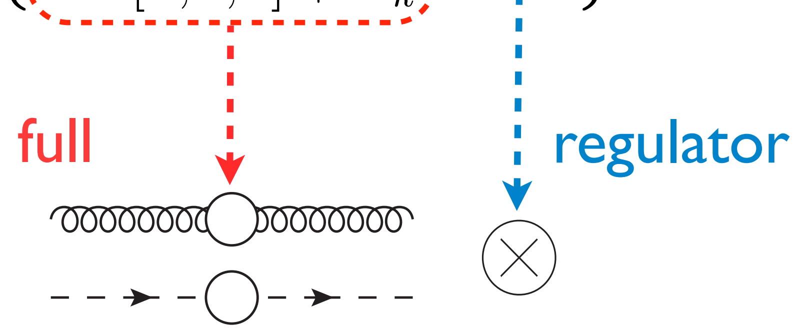
**1st global (UV-IR) phase structure: Donkin, JMP '12**

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

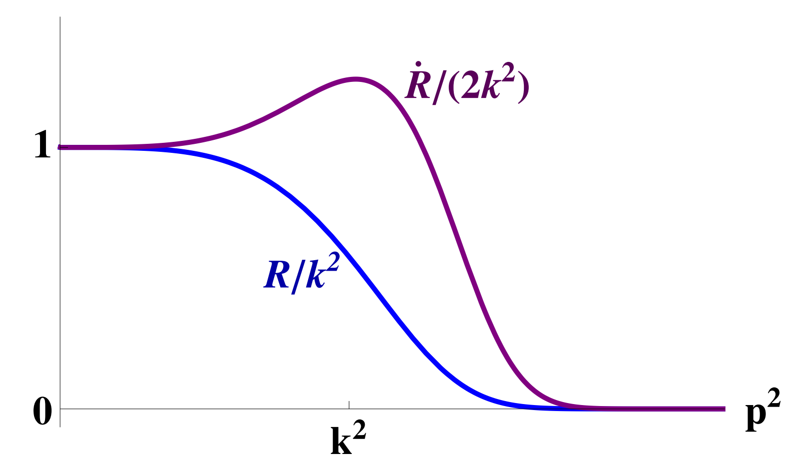
# pure gravity

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

$\partial_t = k\, \partial_k$




**fluctuation propagators**



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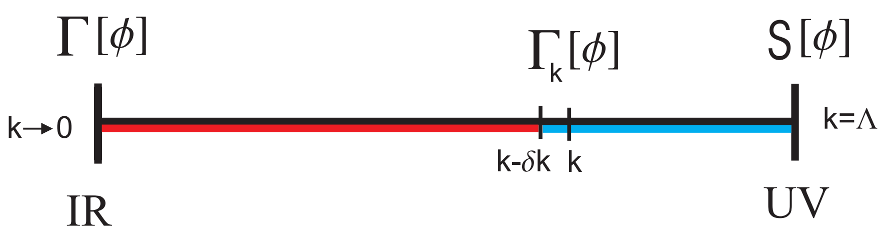


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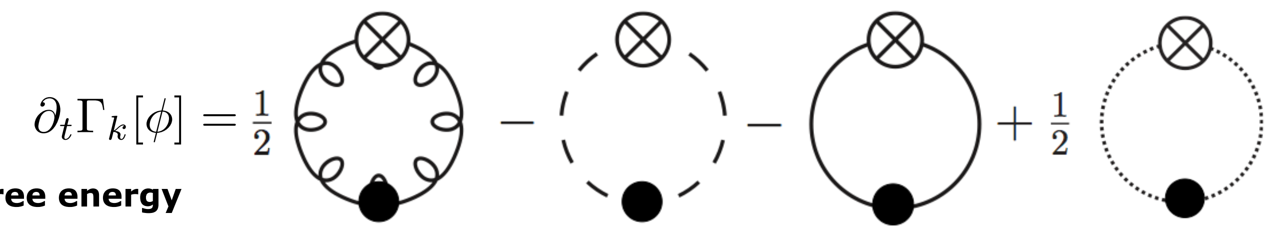


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$$g = \bar{g} + h + O(h^2)$$

**Effective action**

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

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

# Functional approach to quantum gravity

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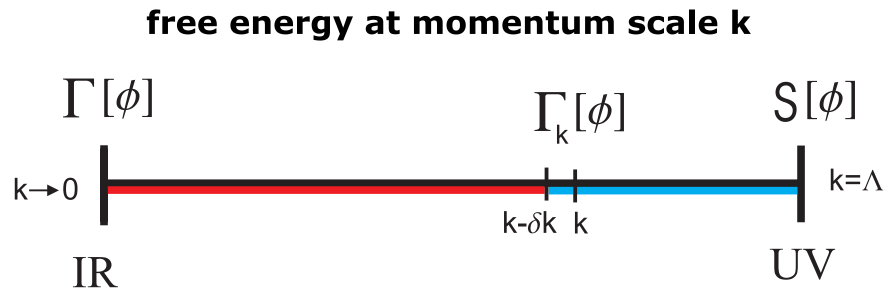


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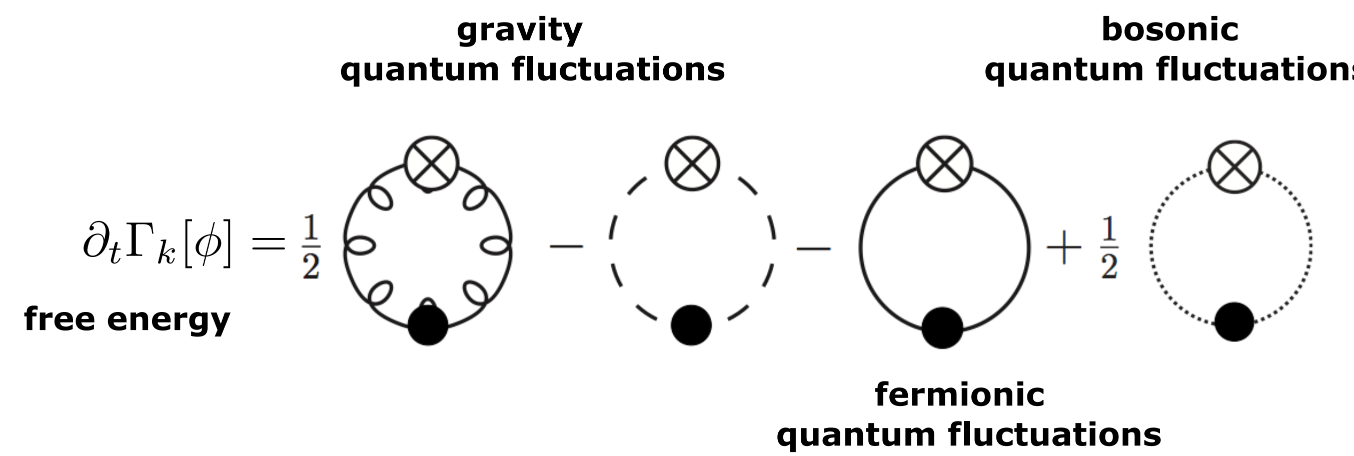


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$$\left\{ \Gamma_k[\bar{g}]\,,\ \Gamma_k^{(0,1)}[\bar{g}]\,,\ \Gamma_k^{(0,2)}[\bar{g}]\,,\ \Gamma_k^{(0,3)}[\bar{g}]\,,\ \ldots \right\}$$

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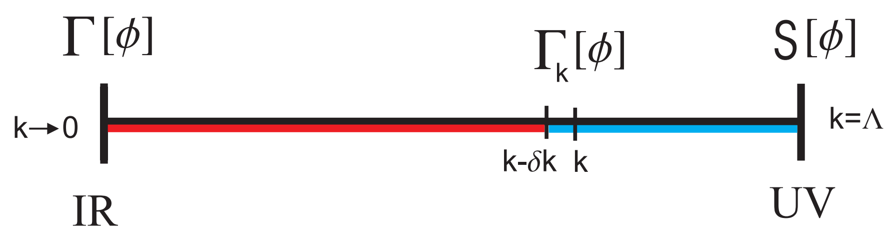


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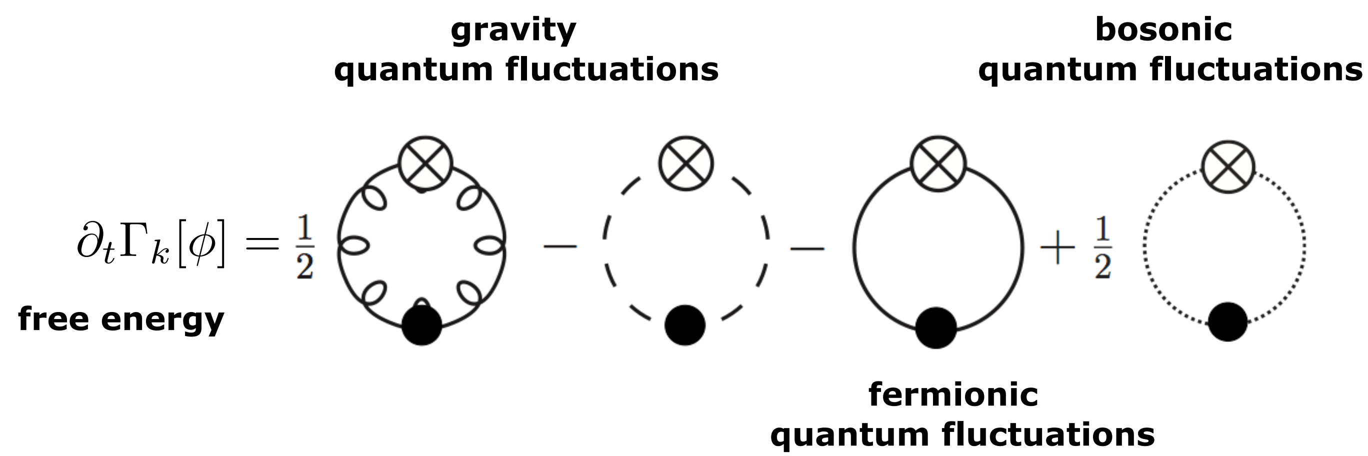


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$$\bar{h} = \langle h \rangle$$

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

*Se vogliamo che tutto rimanga come è,*

*bisogna che tutto cambi.*

*Il Gattopardo*

# Functional approach to quantum gravity

## expansion scheme

**Effective action**

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

# Functional approach to quantum gravity

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**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**

# Functional approach to quantum gravity

## expansion scheme

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- **no diffeomorphism-invariant expansion scheme**

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- **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**

# Functional approach to quantum gravity

## expansion scheme

**Effective action**

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

- **no diffeomorphism-invariant expansion scheme**

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- **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**

⋮

# Functional approach to quantum gravity

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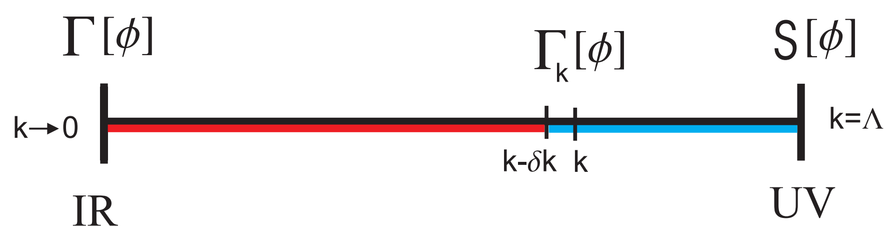


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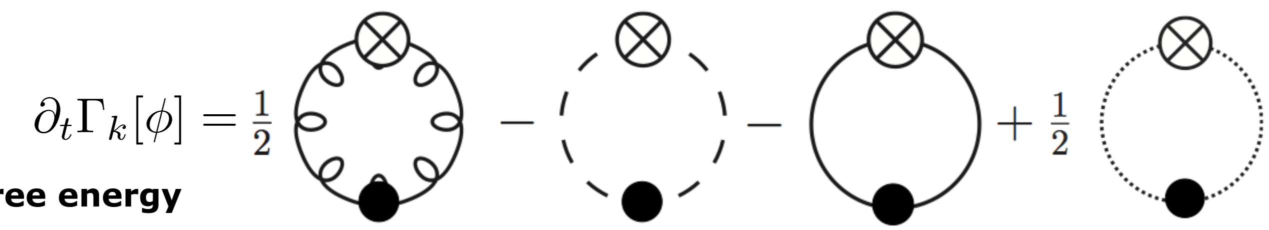


**Geometrical approach: fully diffeomorphism invariant**

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

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

**Flat expansion about Minkowski background**

**1st smooth global phase structure**

**Christiansen, Litim, JMP, Rodigast '12**

# Functional approach to quantum gravity

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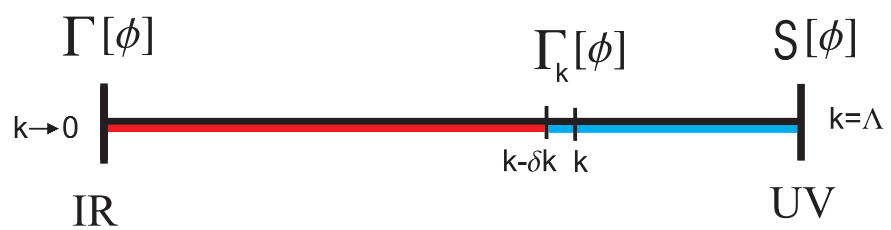
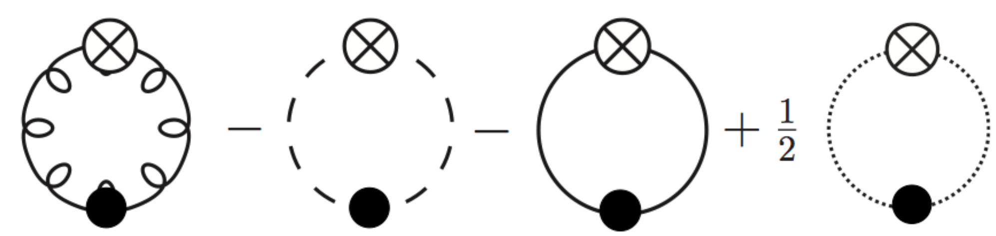



$$\text{RG-scale k: } t = \ln k$$

**gravity quantum fluctuations** | **bosonic quantum fluctuations**

$$\partial_t \Gamma_k[\phi] = \frac{1}{2}\;(\ldots) - (\ldots) - (\ldots) + \frac{1}{2}\;(\ldots)$$



**free energy**

**fermionic quantum fluctuations**

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**Flows**

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

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

**dynamical flow**

**Nielsen ID**

**background flow**

**JMP '03**

**Donkin, JMP '12**

# Functional approach to quantum gravity

## locality

Christiansen, Knorr, Meibohm, JMP, Reichert, arXiv:1504.xxxx

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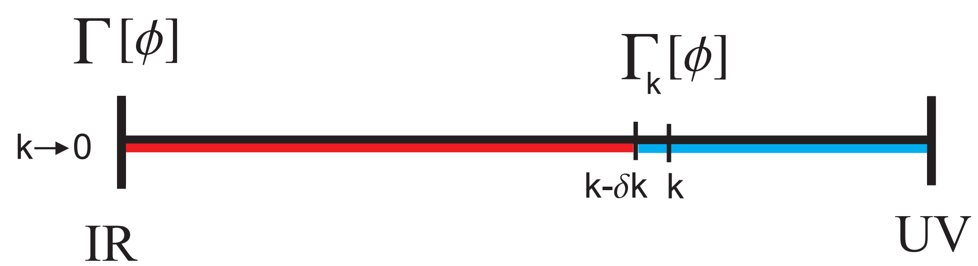

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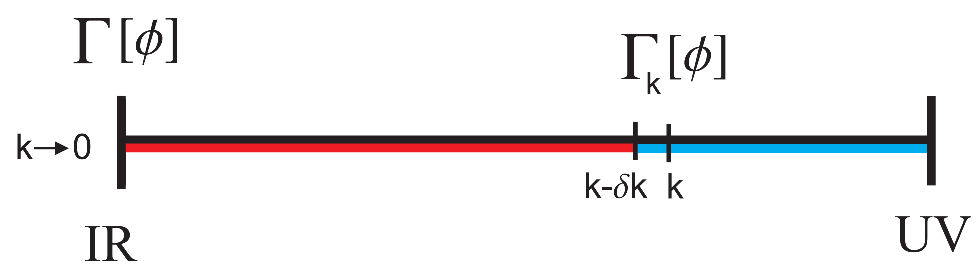


**Locality**

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

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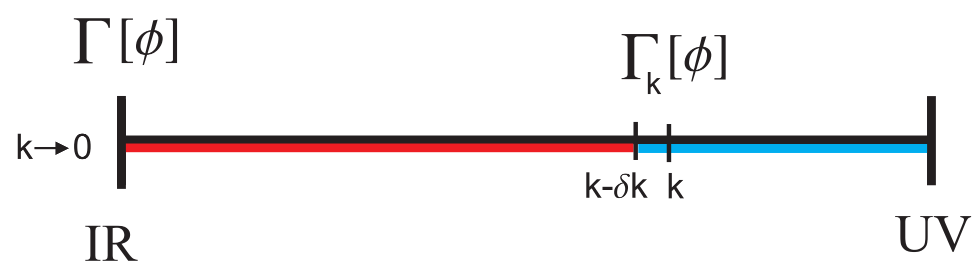


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- **local momentum space RG steps** ⟺ **local quantum field theory**

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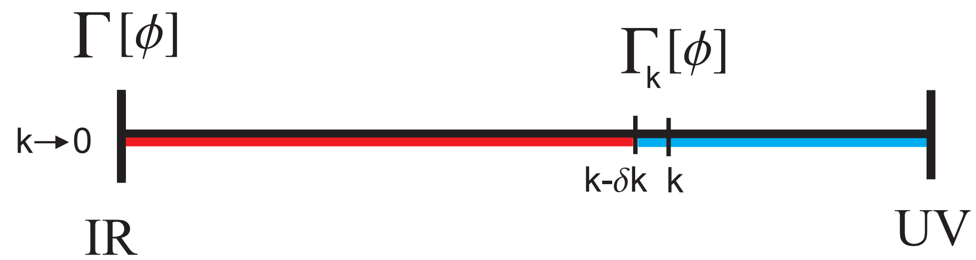


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- **local momentum space RG steps** $\Leftrightarrow$ **local quantum field theory**
- **gravity-matter systems: locality** $\Leftarrow$ **diffeomorphism invariance**

# Functional approach to quantum gravity

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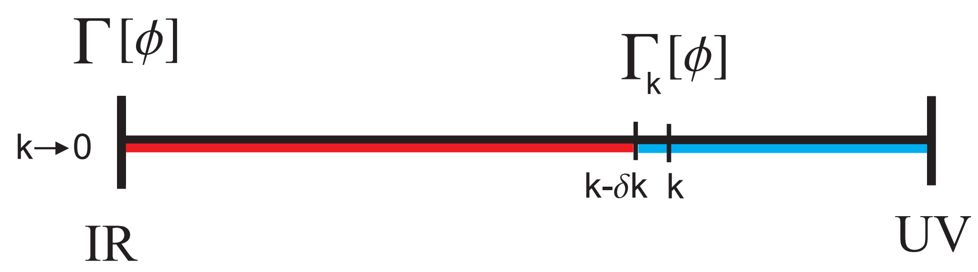


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- local momentum space RG steps ⇔ local quantum field theory
- gravity-matter systems: locality ⇐ diffeomorphism invariance

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

# Functional approach to quantum gravity

## approximation scheme

Christiansen, Knorr, Meibohm, JMP, Reichert, arXiv:1504.xxxx

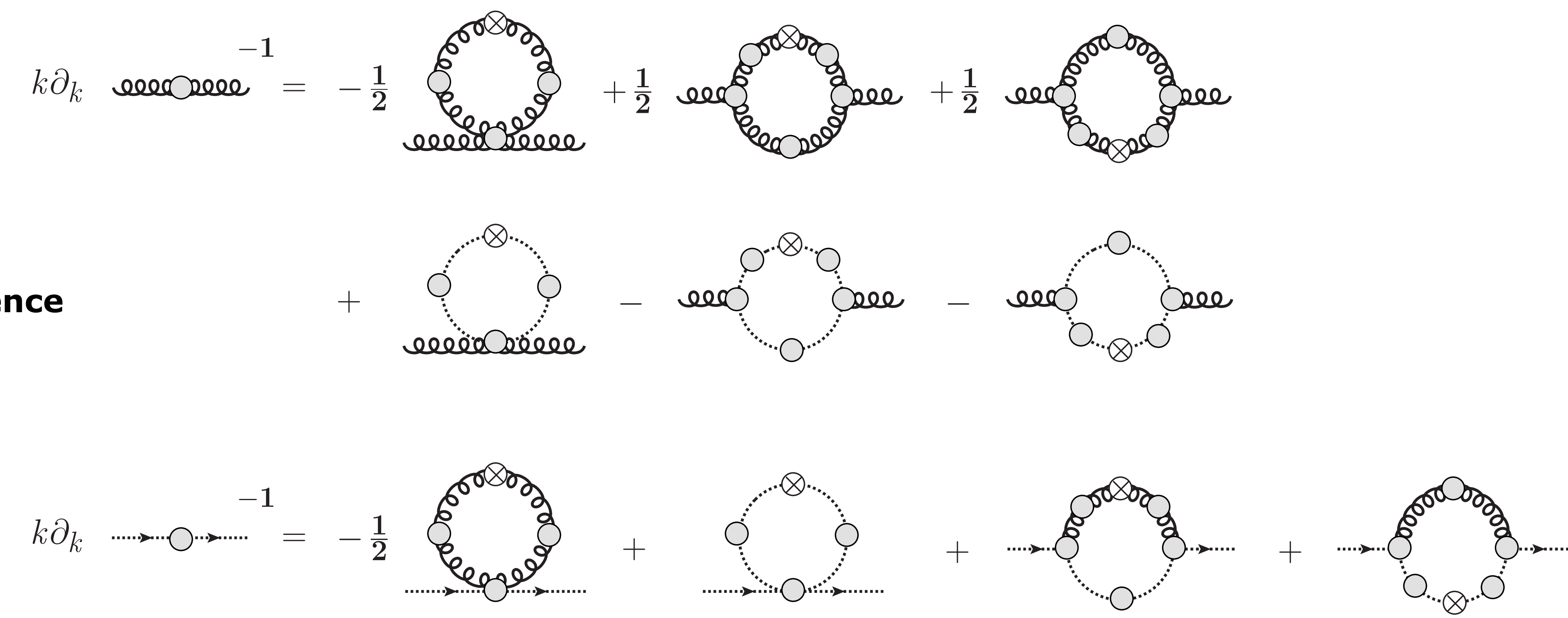
### Propagators

Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232

**graviton**

**full momentum dependence**

**ghost**

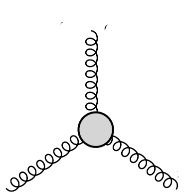



### Vertices

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

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

**flow**



**consistent momentum-dependent RG-dressing**

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

similar: Codello, D'Odorico, Pagani '13

# Functional approach to quantum gravity

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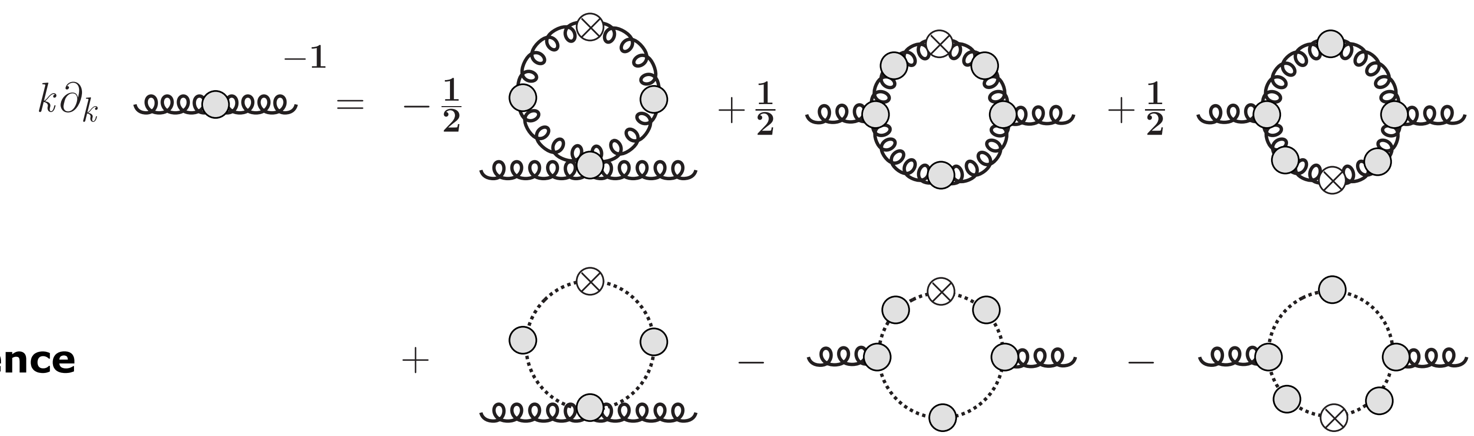
**graviton**

**full momentum dependence** New



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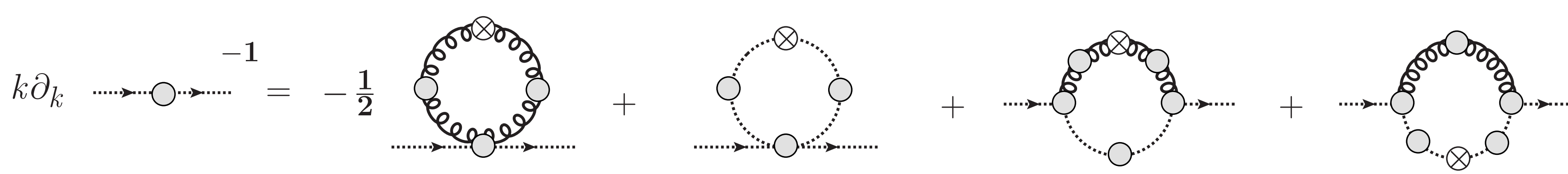

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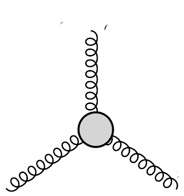

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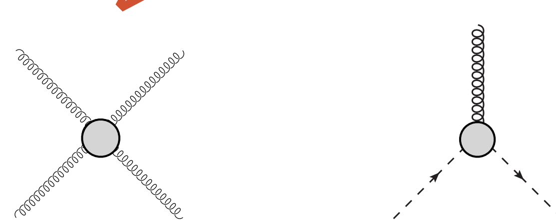

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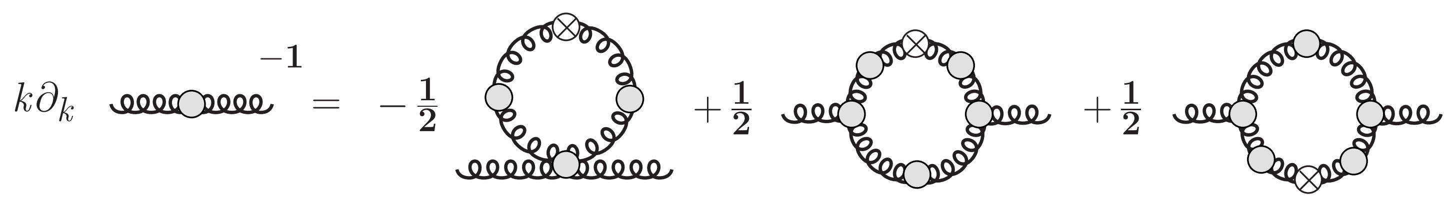

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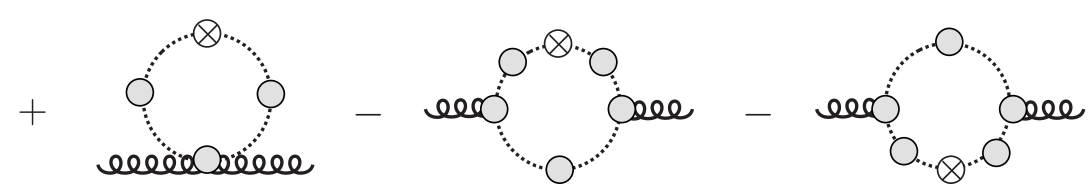

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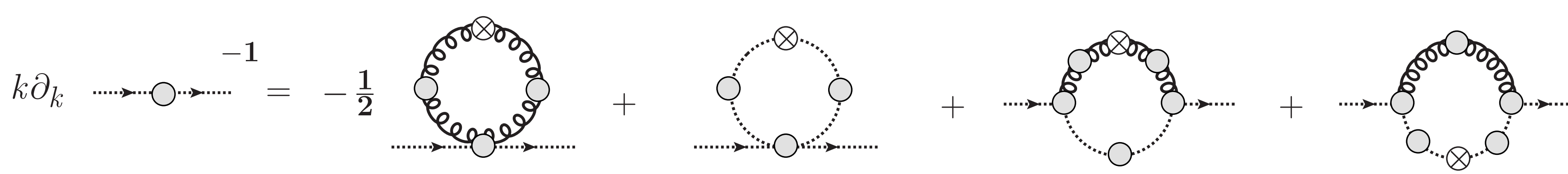

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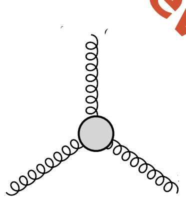
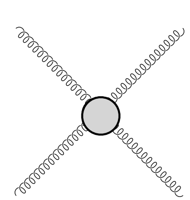
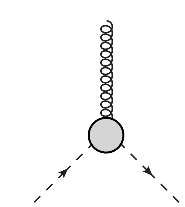
**flow** brand new

**consistent momentum-dependent RG-dressing** New







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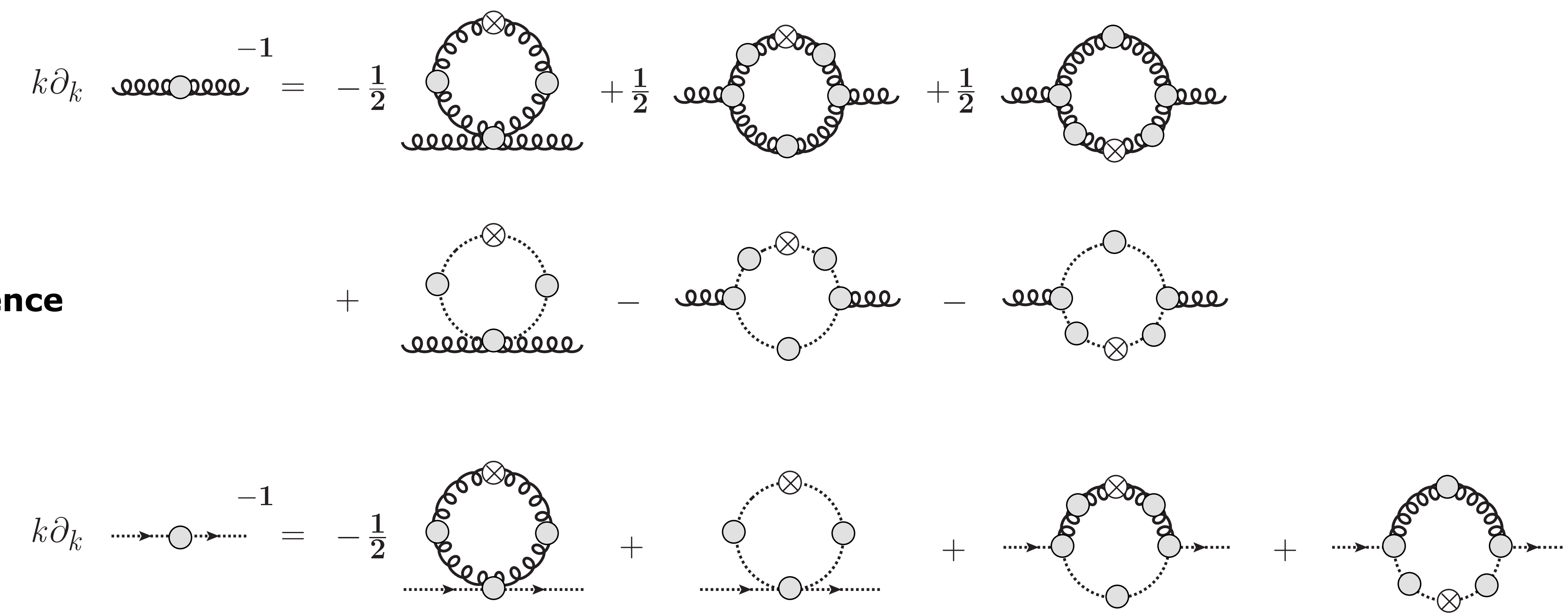


### Flows & scalings

**propagators**

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

**vertices**

$\Gamma^{(3)}_{hhh}(p_1, p_2, p_3)$ $G_N^{(3)}$ $G_N^{(4)}$ $\Lambda^{(3)}$ $\Lambda^{(4)}$

**background observables**

$\Lambda$ $\bar{G}_N$

**cosmological constant** **Newton constant**

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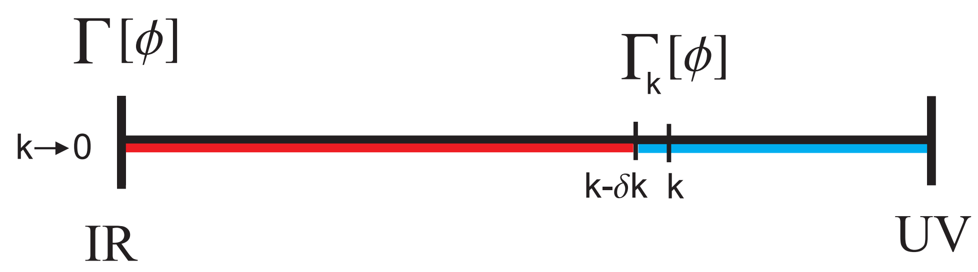


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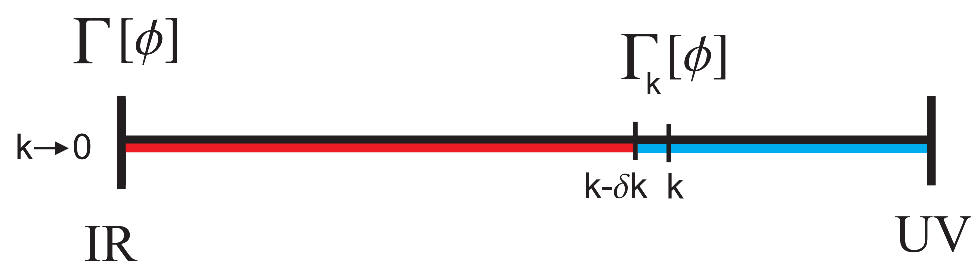


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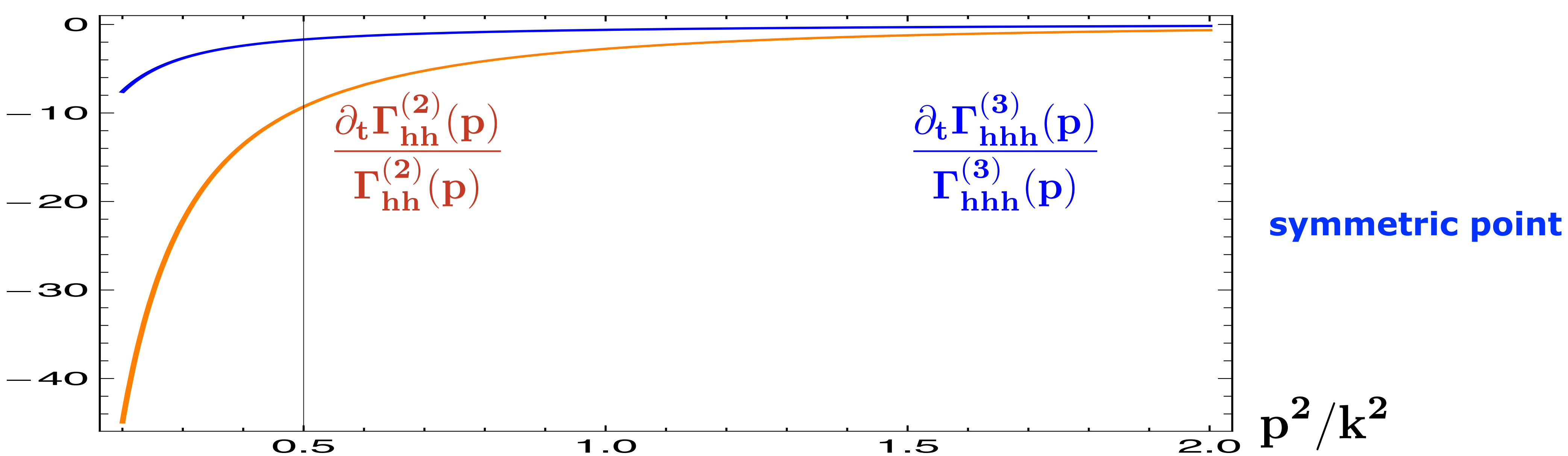

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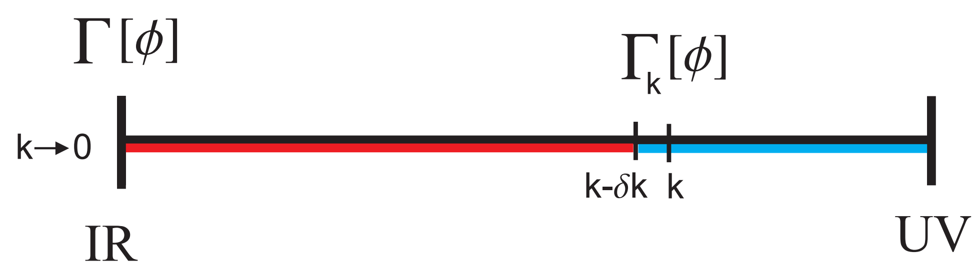
Christiansen, Knorr, Meibohm, JMP, Reichert, arXiv:1504.xxxx

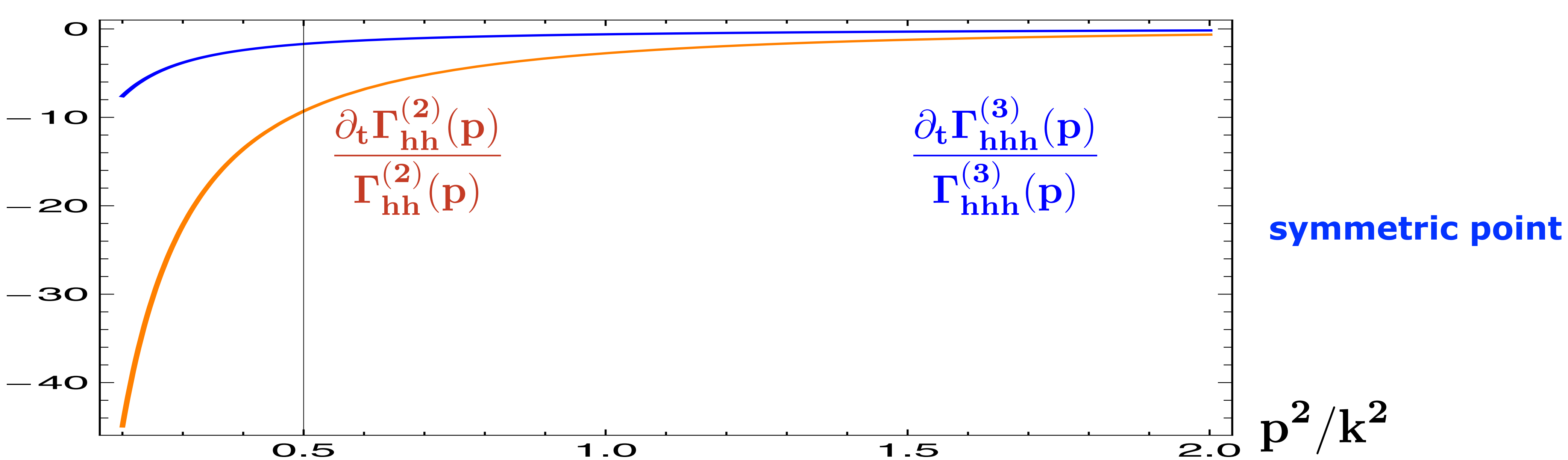
**free energy at momentum scale k**




**Locality**

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

**another brick in the wall**

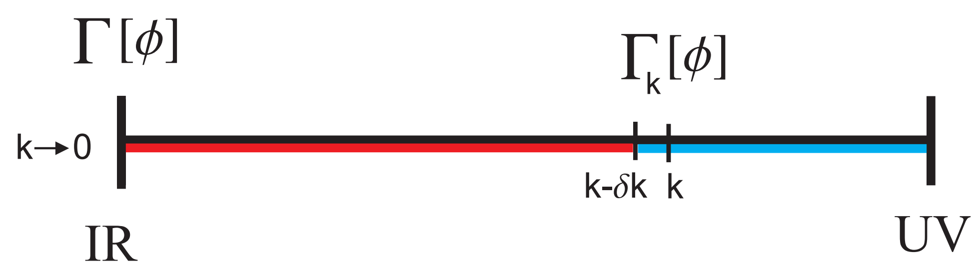


# Functional approach to quantum gravity

## locality

Christiansen, Knorr, Meibohm, JMP, Reichert, arXiv:1504.xxxx

**free energy at momentum scale k**




**Locality**

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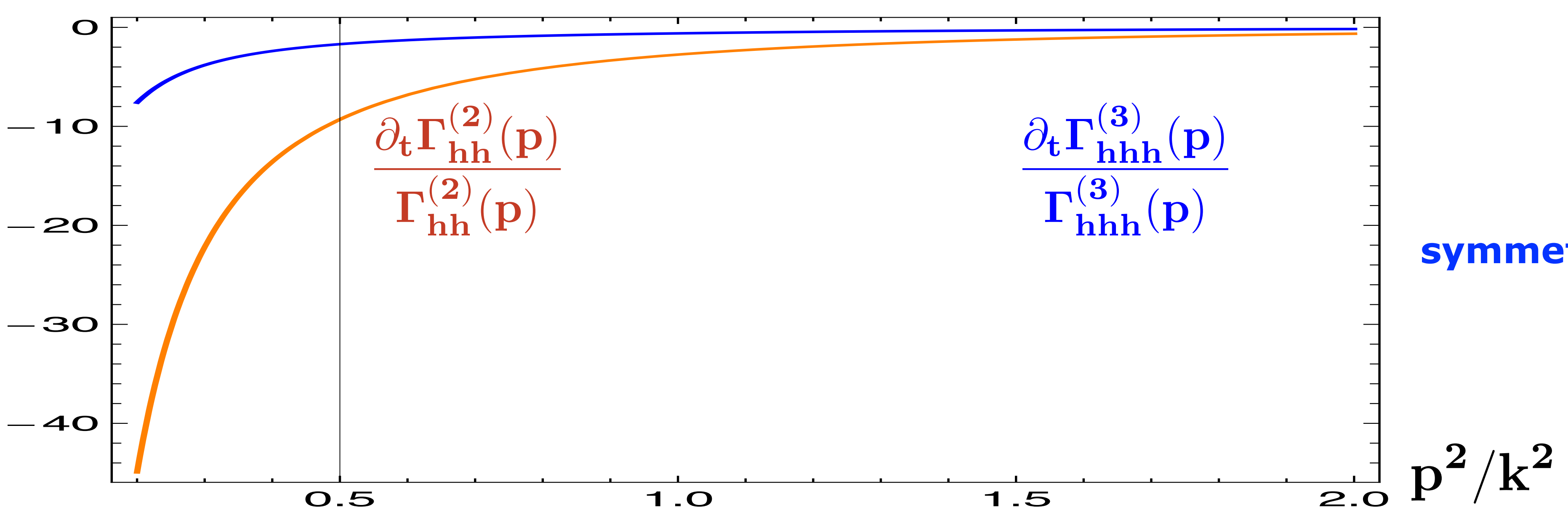
**another important brick in the asymptotic safety wall**




symmetric point

# Functional approach to quantum gravity

## locality

**Christiansen, Knorr, Meibohm, JMP, Reichert, arXiv:1504.xxxx**

**free energy at momentum scale k**


**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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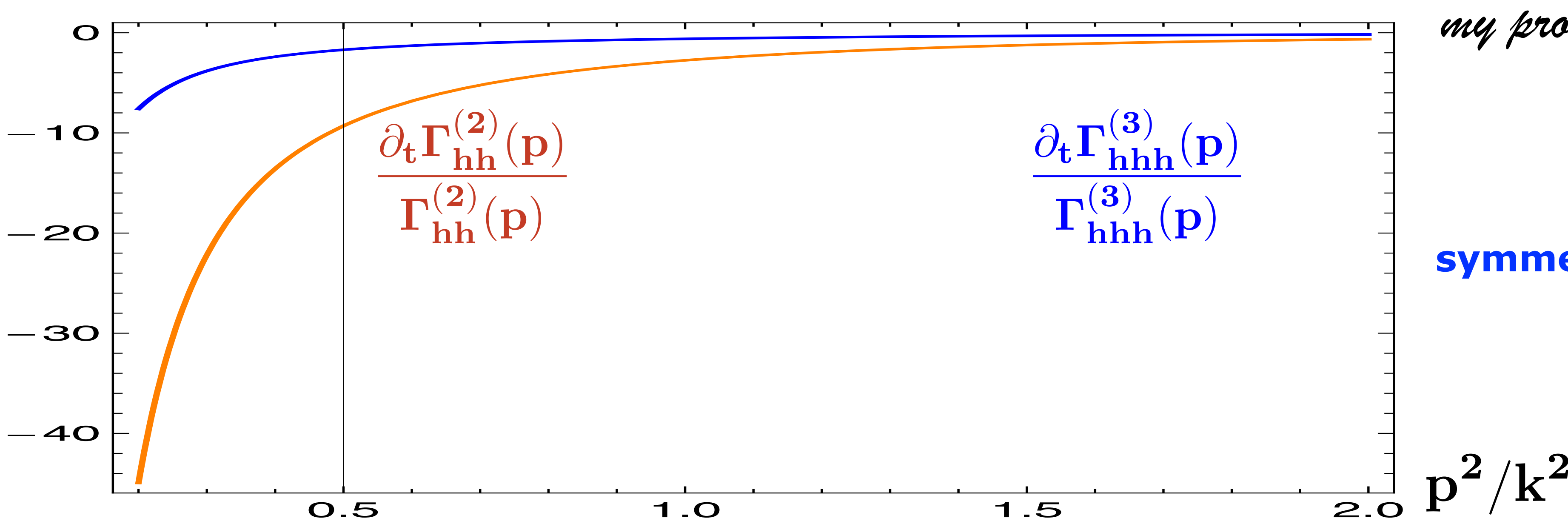


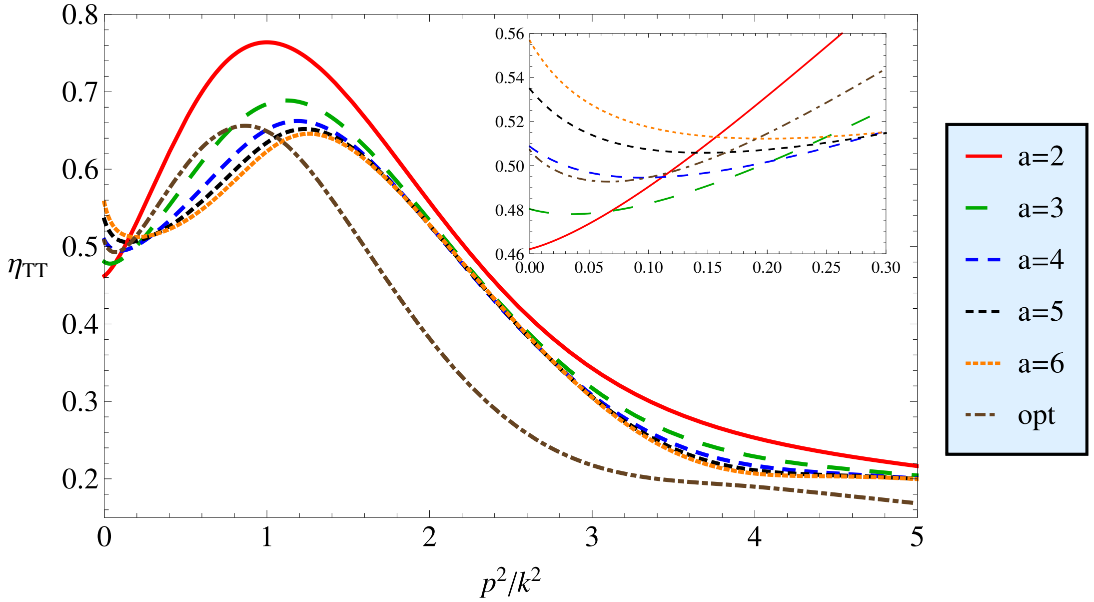

*my provocative statement*

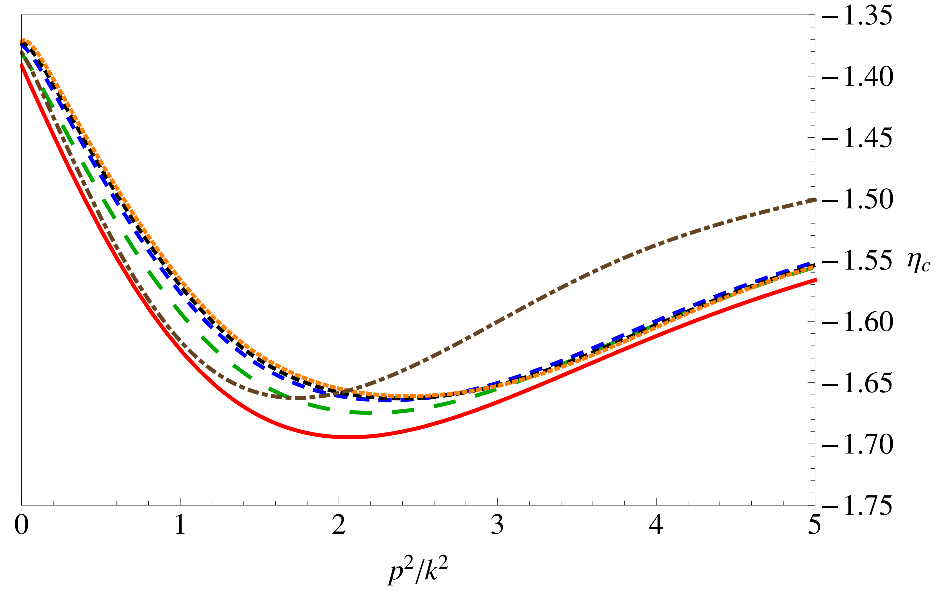
**symmetric point**

# Phase diagram of quantum gravity

## Propagators

**Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232**



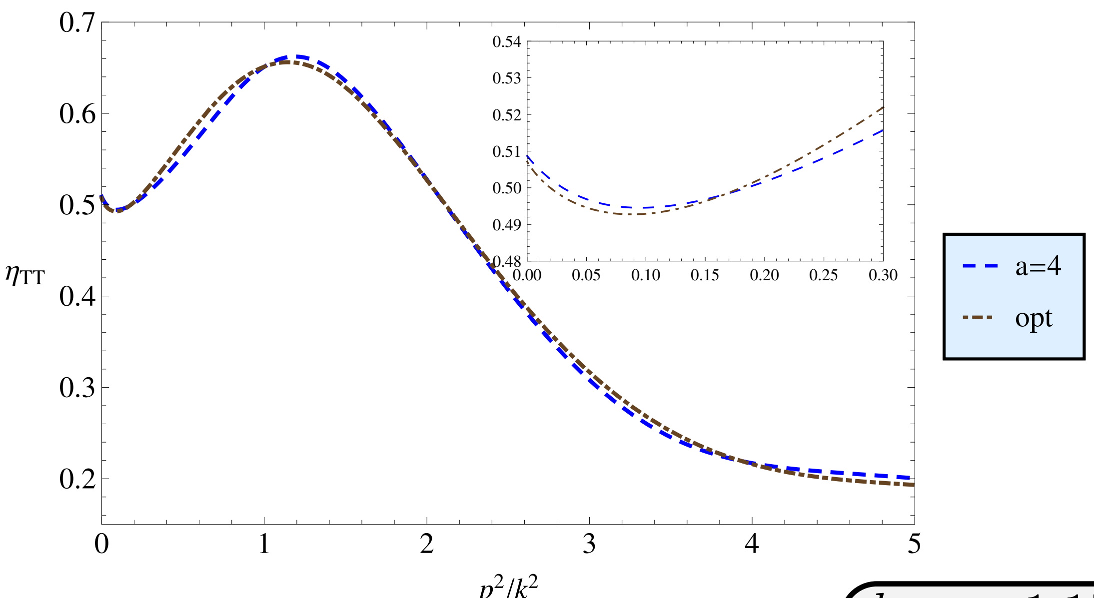

**graviton** **anomalous dimensions** **ghost**

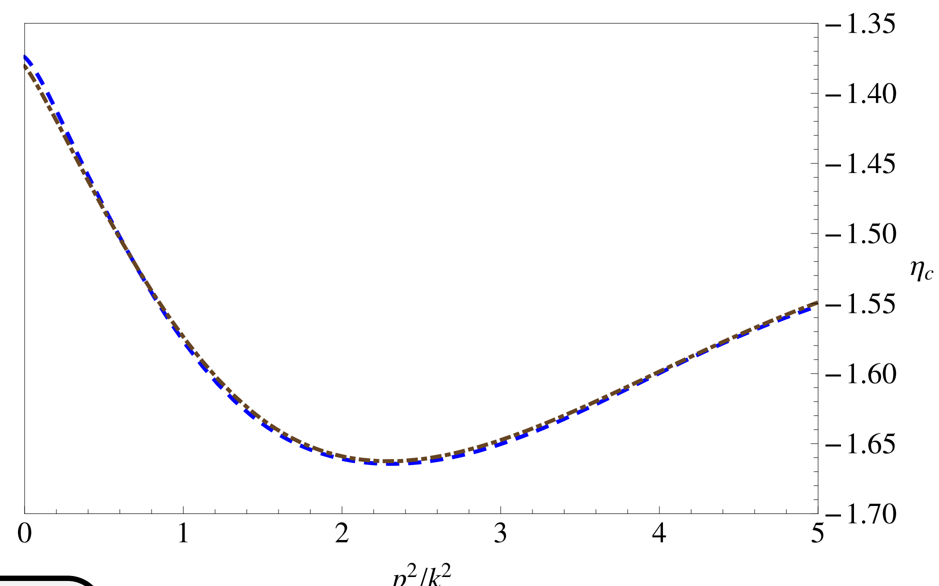
**regulators**

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

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

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



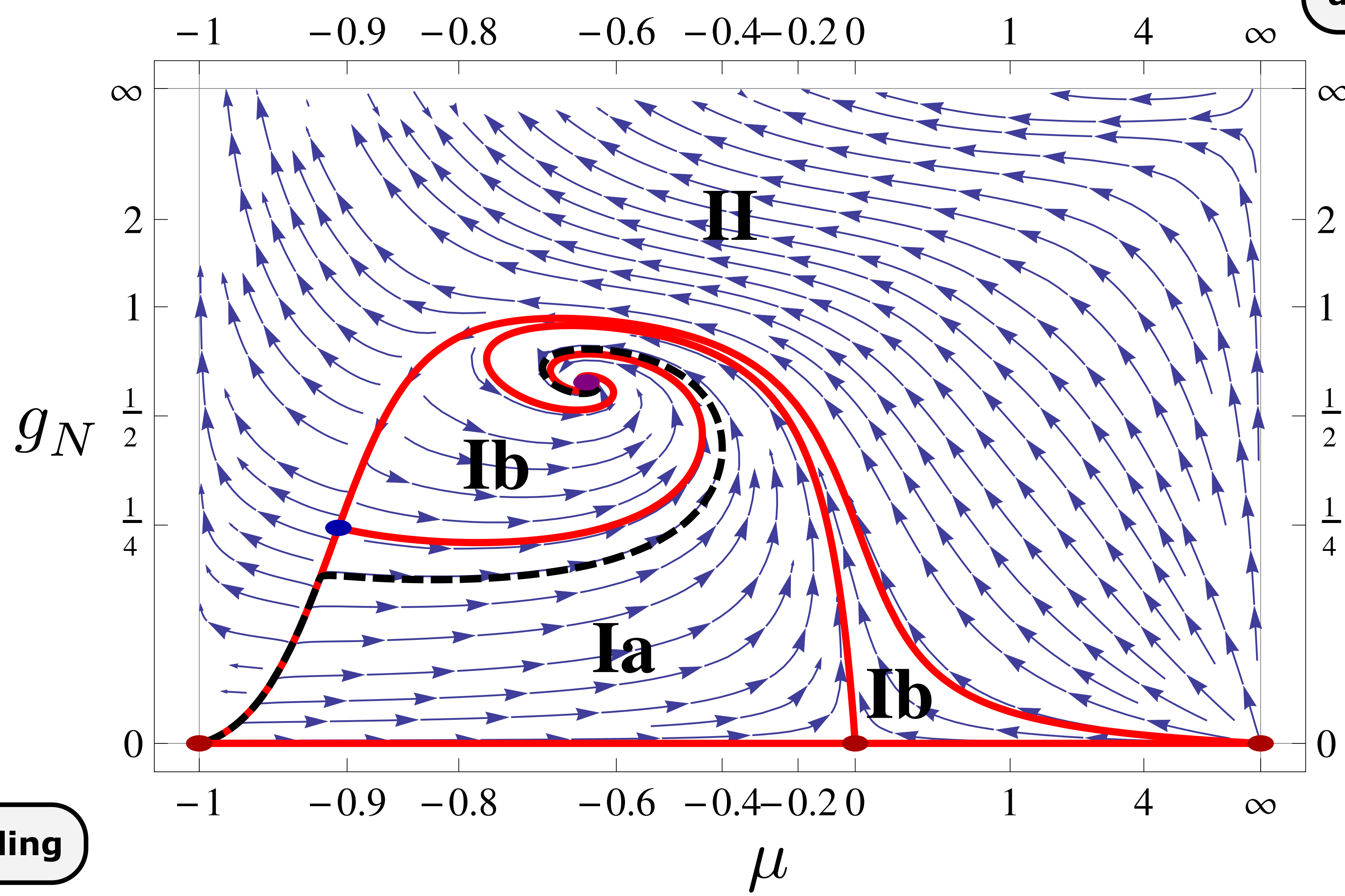

$$k_{\rm opt} = 1.15\, k_4$$

# Phase diagram of quantum gravity

## global phase diagram

Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232

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**

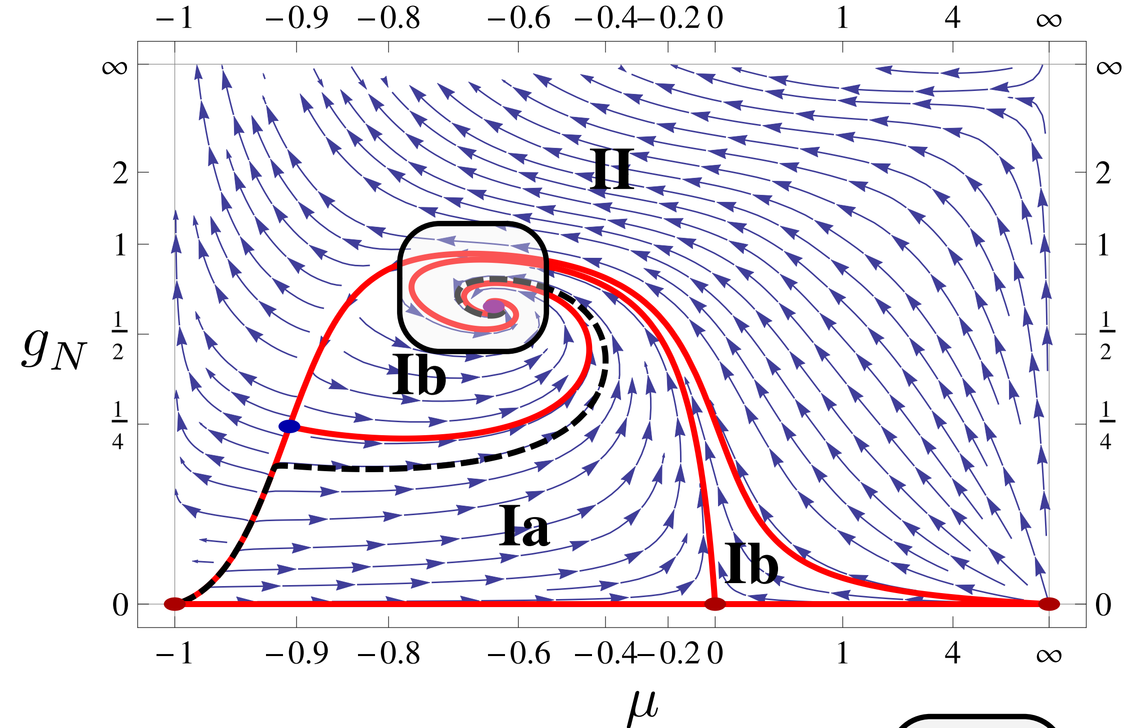
| $a$ | 2 | 3 | 4 | 5 | 6 | opt |
|---|---|---|---|---|---|---|
| $\mu_*$ | -0.637 | -0.641 | -0.645 | -0.649 | -0.651 | -0.489 |
| $g_*$ | 0.621 | 0.622 | 0.614 | 0.606 | 0.600 | 0.831 |
| $\overline{g}_*$ | 0.574 | 0.573 | 0.567 | 0.559 | 0.553 | 0.763 |
| $\lambda_*$ | 0.319 | 0.316 | 0.316 | 0.318 | 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**

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

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

Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232




$a = 4$

# Phase diagram of quantum gravity

## global phase diagram

**UV-fixed point**

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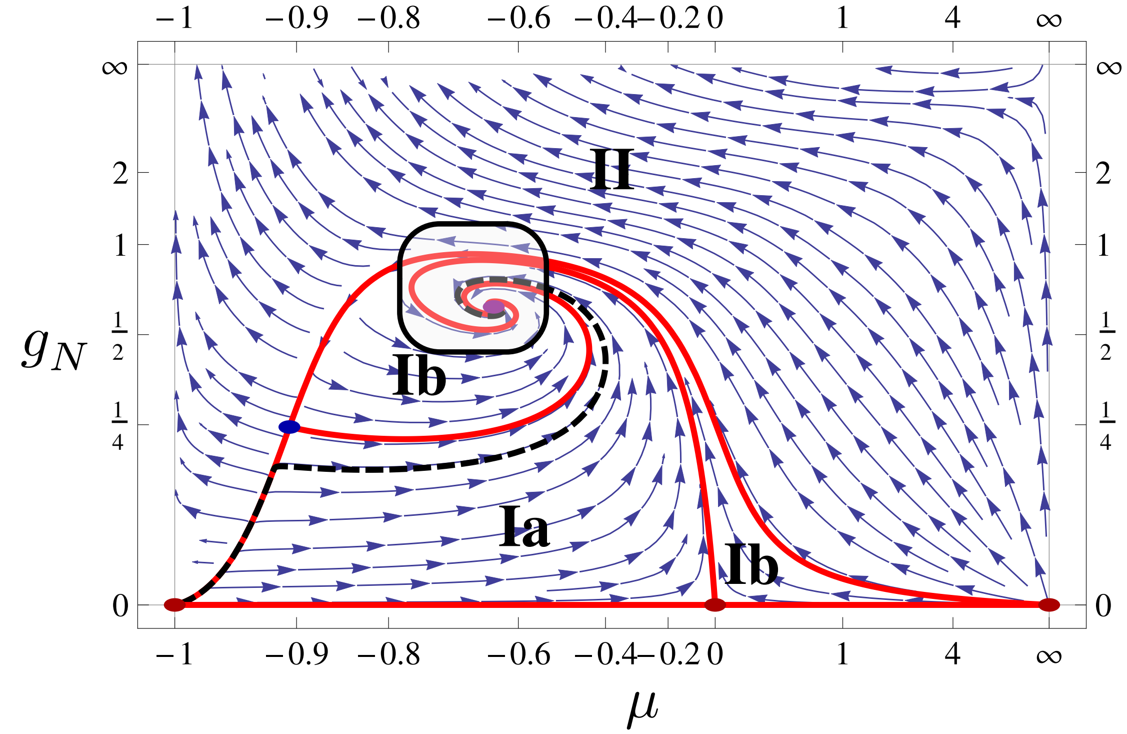
**Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232**




**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 |
| $\lambda_*$ | 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

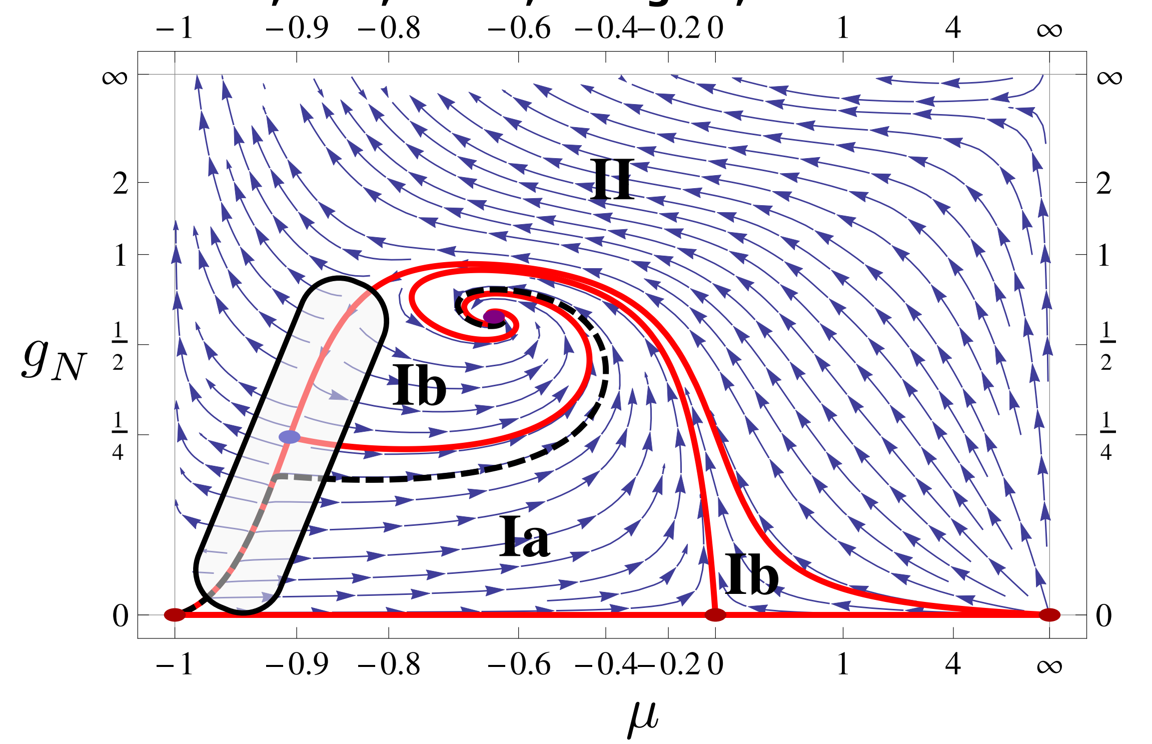
**Codello, D’Odorico, Pagani ’13** — flat expansion, mixed approach

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

# Phase diagram of quantum gravity

## global phase diagram

Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232




### UV-fixed point

**regulator-dependence**

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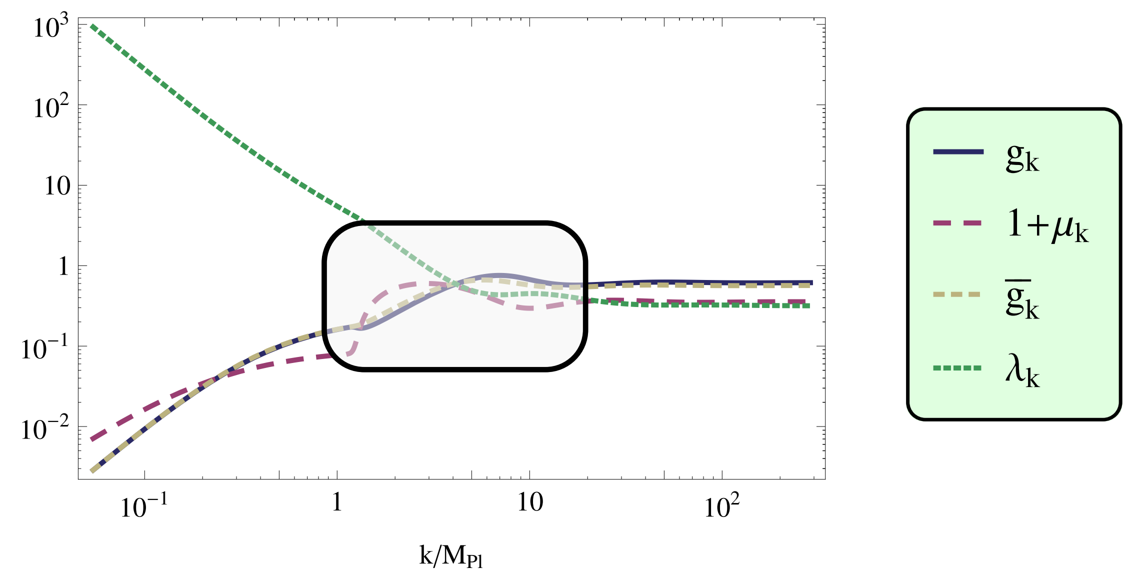
### UV-IR transition

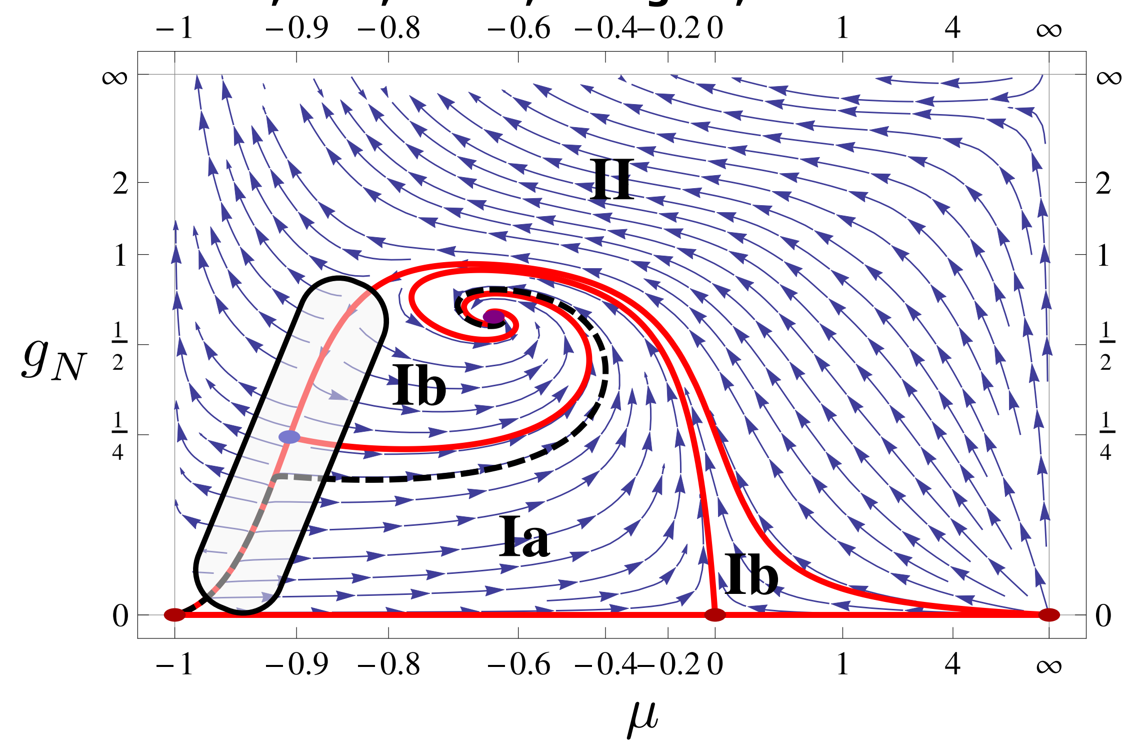
**dominance of constant parts** $\lambda^{(3)}, \lambda^{(4)}$ **of** $\Gamma^{(3)}, \Gamma^{(4)}$



# Phase diagram of quantum gravity

## global phase diagram

Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232

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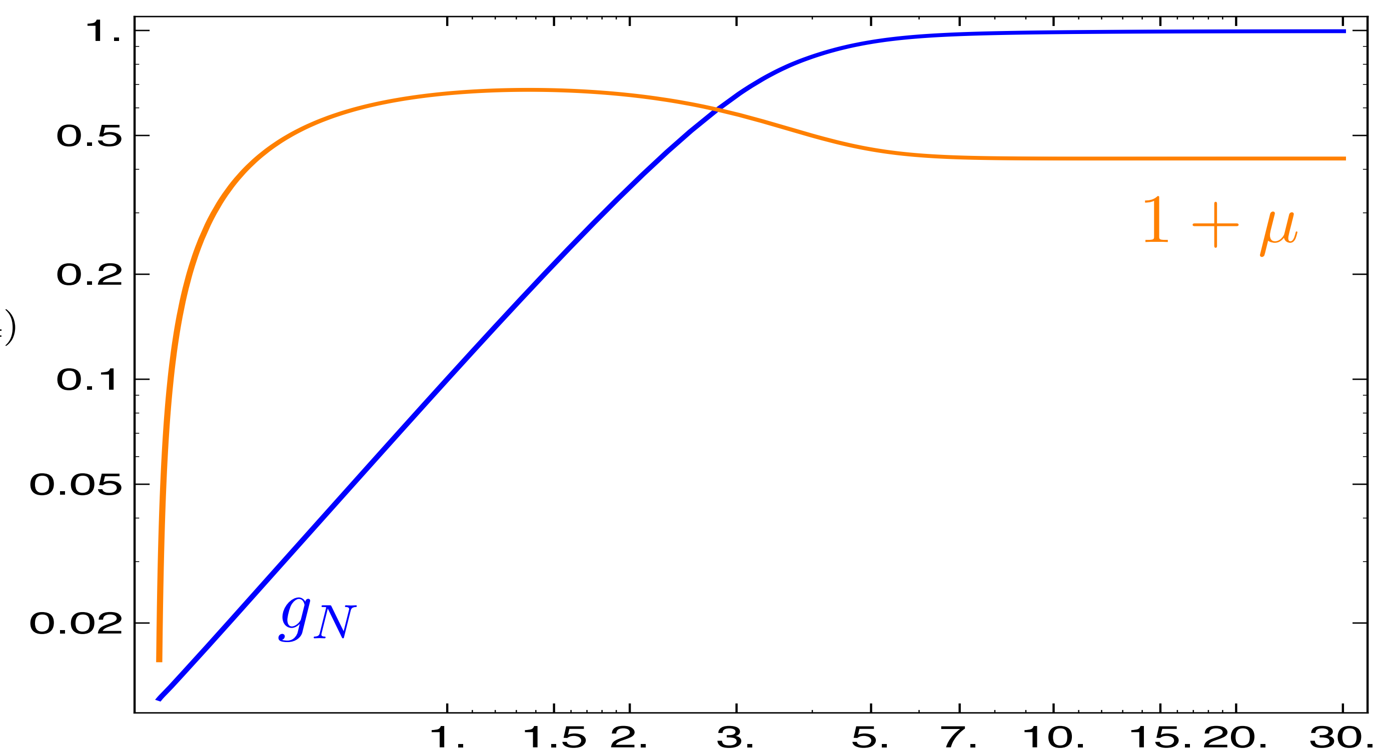
### UV-IR transition

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

**with flow of** $\Gamma^{(\mathbf{3})}_{\mathbf{hhh}}$




Christiansen, Knorr, Meibohm, JMP, Reichert, arXiv:1504.xxxx

# Phase diagram of quantum gravity

## global phase diagram

### UV-fixed point

**regulator-dependence**

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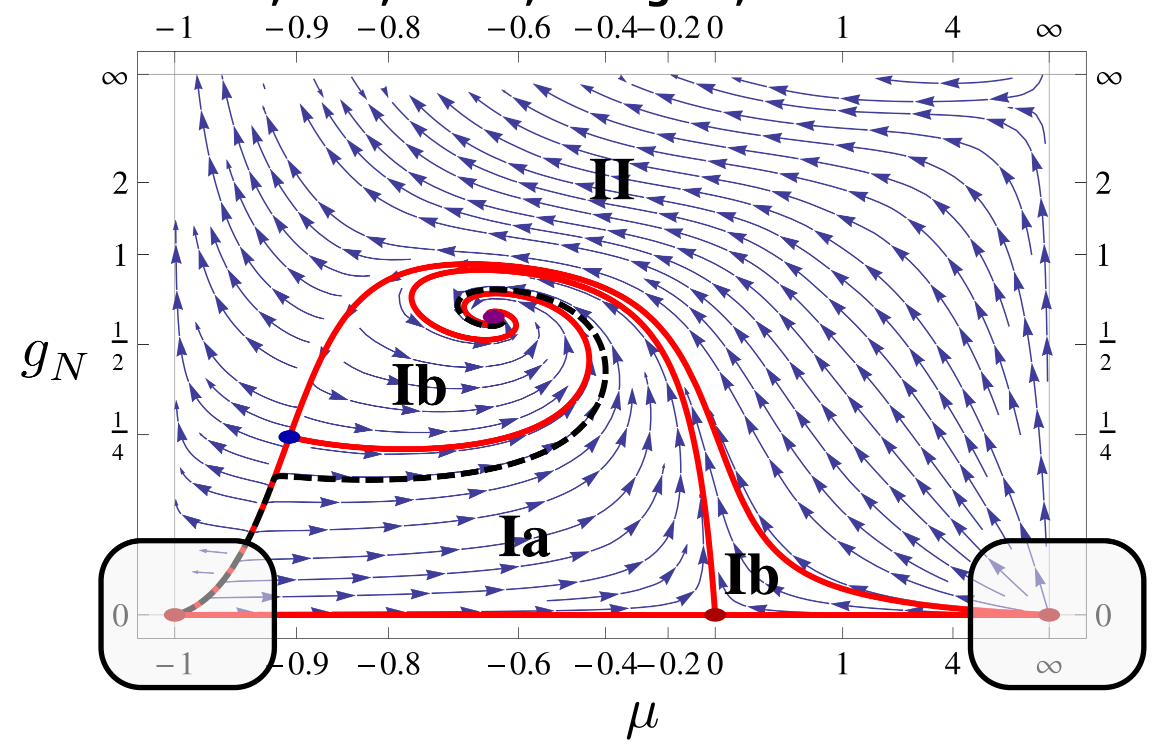
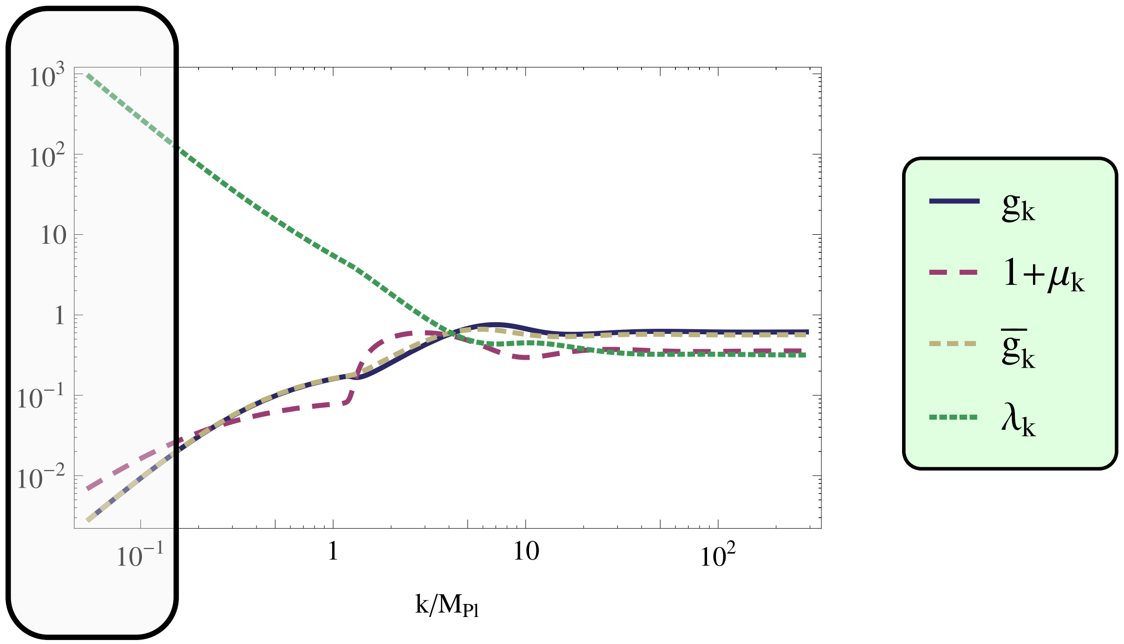
Christiansen, JMP, Knorr, Rodigast, arXiv:1403.1232




### IR-fixed points

$$g, \overline{g} \sim k^2 \qquad \lambda \sim \frac{1}{k^2}$$

$$\eta_h \to 0 \qquad \eta_c \to 0$$



# Coupling to matter

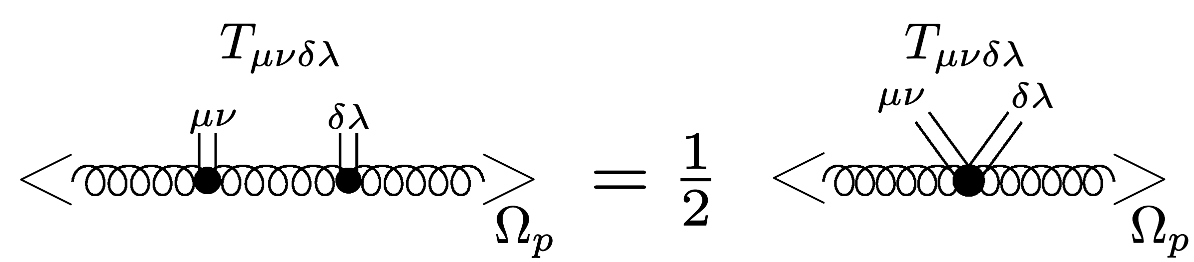
# Phase diagram of quantum gravity

## 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**

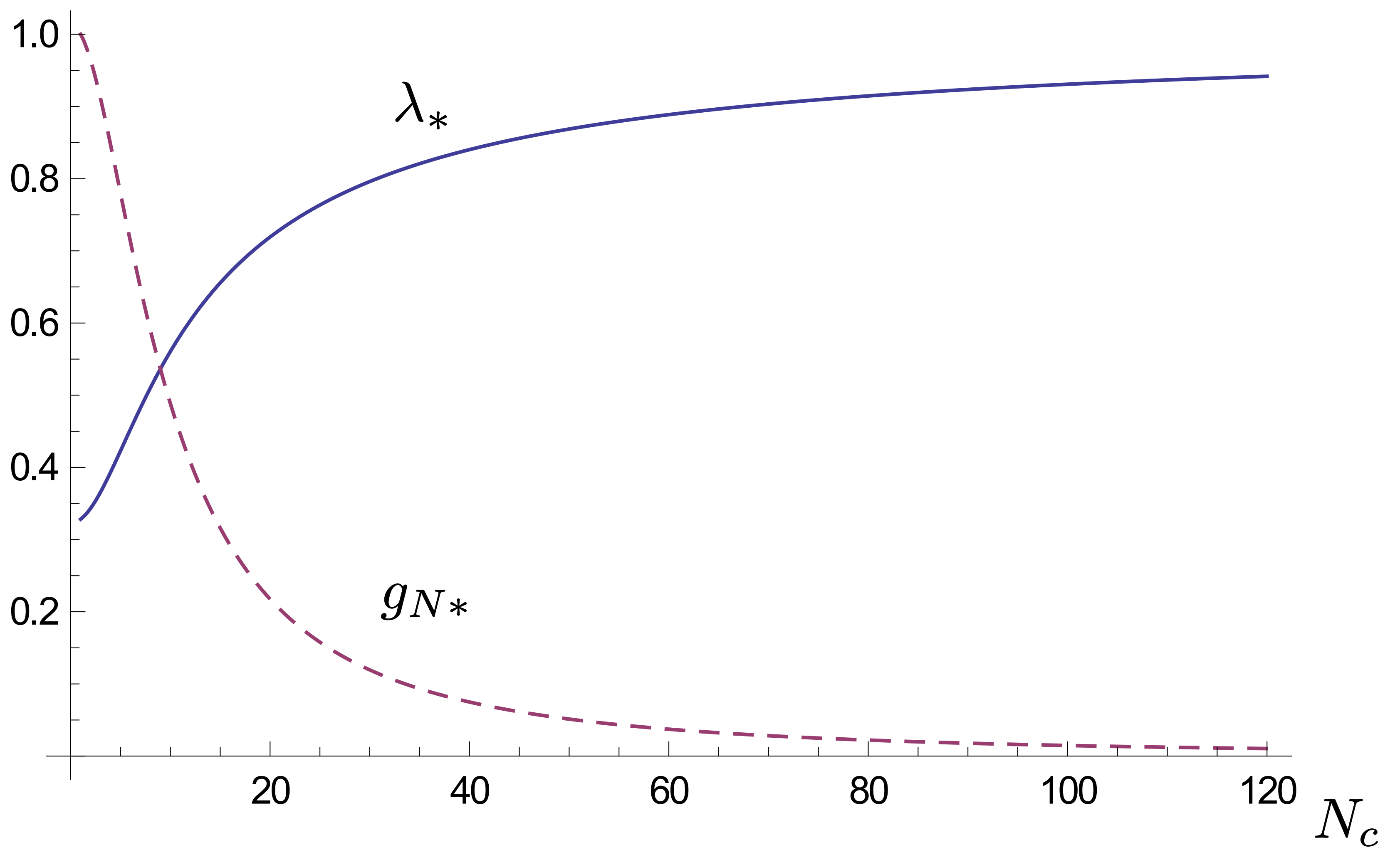


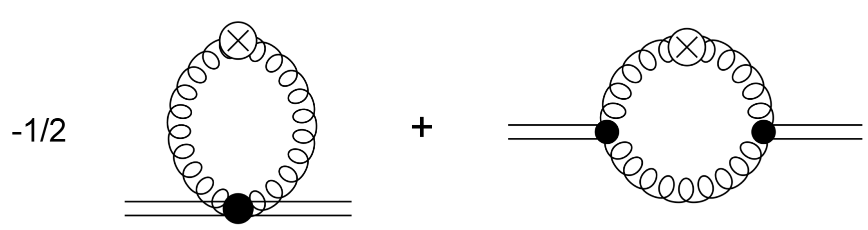

**kinematic identity**

# Phase diagram of quantum gravity

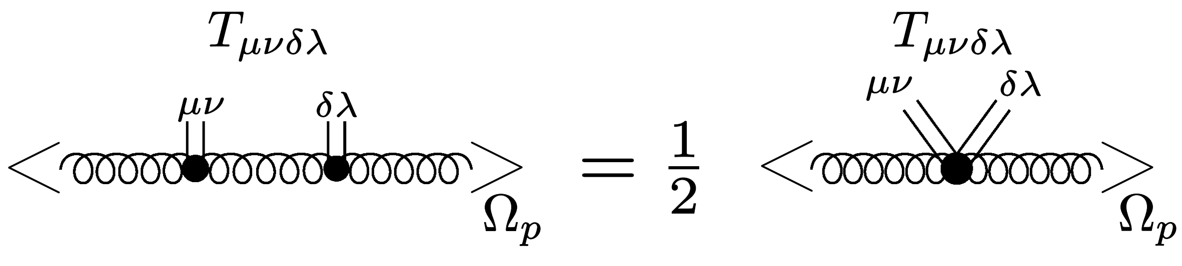
## UV stability of the gauge-gravity system

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




**gauge contribution to gravity**




**kinematic identity**

# Phase diagram of quantum gravity

## UV stability of the matter-gravity system

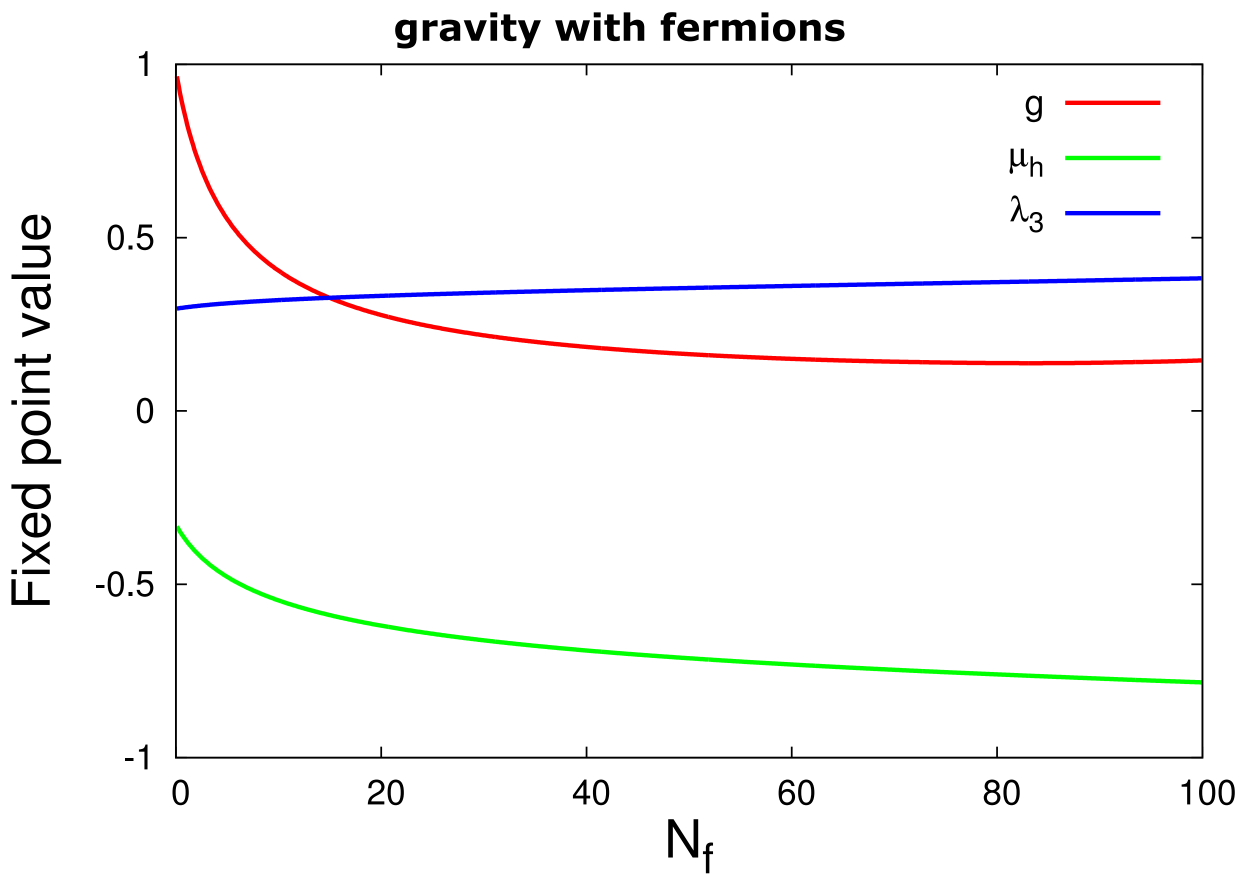
**Meibohm, JMP, Reichert, in preparation**

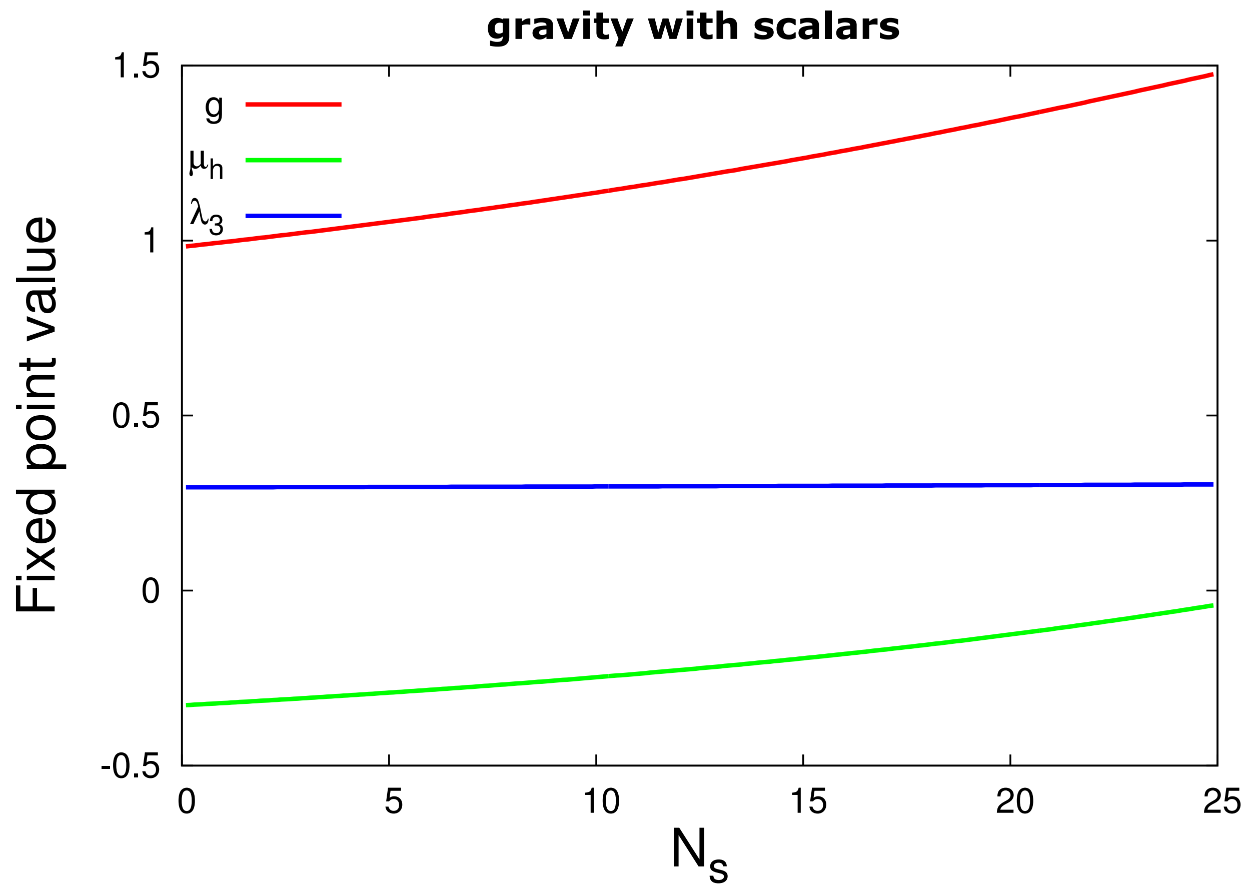
**propagators**

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

**vertices**

$$\Gamma^{(3)}_{hhh}(p_1, p_2, p_3) \qquad G_N^{(3)} \qquad G_N^{(4)} \qquad \Lambda^{(3)} \qquad \Lambda^{(4)}$$



# Summary & outlook

- **Locality & phase structure of quantum gravity**
    - **locality from diffeomorphism invariance**
    - **IR-stability and IR-classicality of quantum gravity**
    - **UV-stability of the matter-gravity systems**
- **Outlook**
    - **fully-coupled matter-gauge-gravity systems in the UV**
    - **long & short distance physics**

# Coupling to matter