

The Functional Renormalisation Group

**From strongly correlated QCD
to
asymptotically safe quantum gravity**

Jan M. Pawłowski

Universität Heidelberg & ExtreMe Matter Institute

Maynooth, August 4th 2018

GEFÖRDERT VOM



Bundesministerium
für Bildung
und Forschung

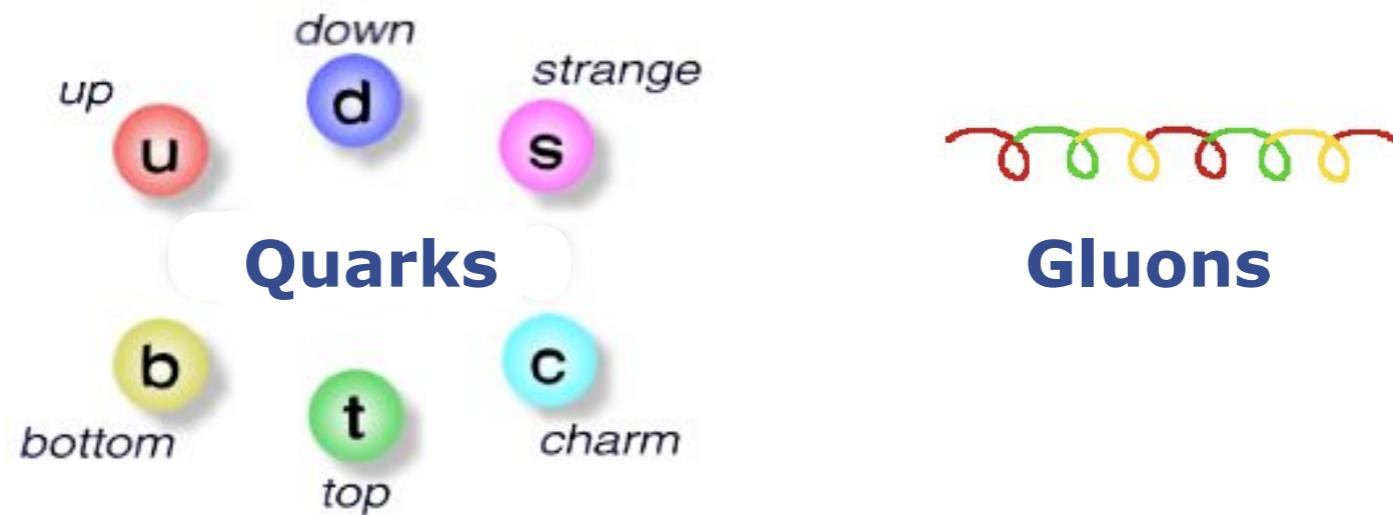


strongly correlated QCD

no introduction, but

Trento summer school QCD 2018 ‘QCD under extreme conditions’:
The Functional Renormalisation Group and the Phase Structure of QCD

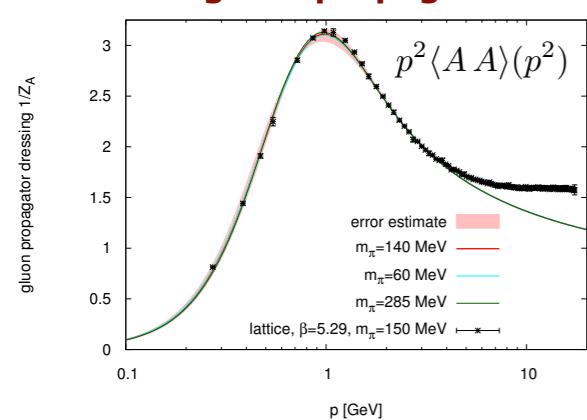
JMP



Snapshots QCD

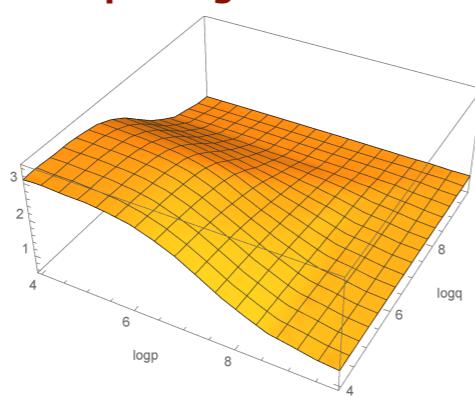
QCD correlation functions

gluon propagator

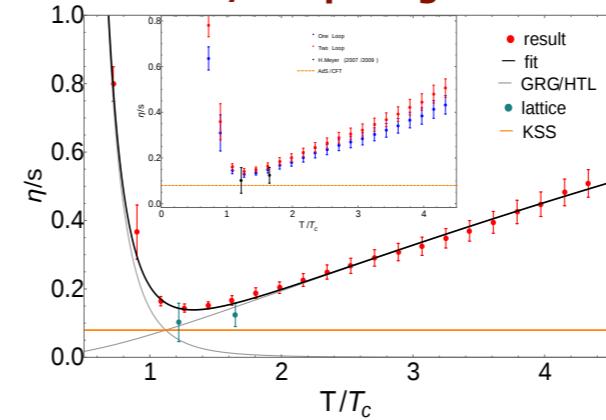


Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006

quark-gluon vertex

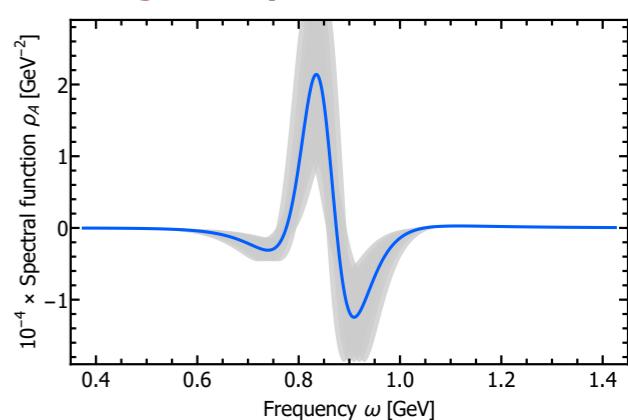


eta/s in pure glue



Christiansen, Haas, JMP, Strodthoff,
PRL 115 (2015) 112002

gluon spectral function



Cyrol, JMP, Rothkopf, Wink,
arXiv:1804.00945

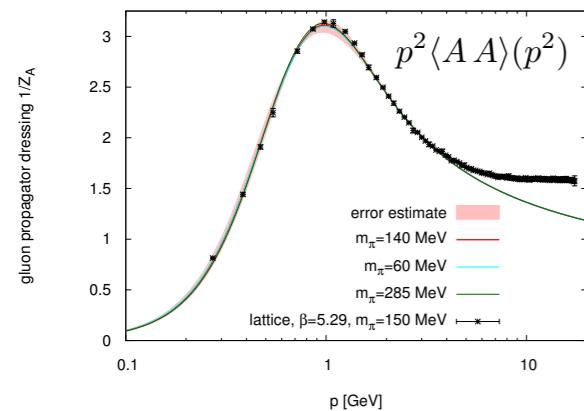
see talk of Mario Mitter
Thursday, 14:30

slight violation of causality

Snapshots QCD

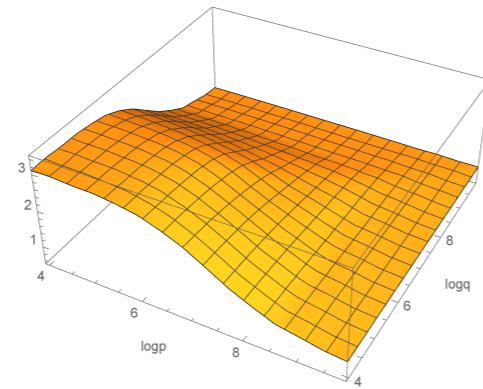
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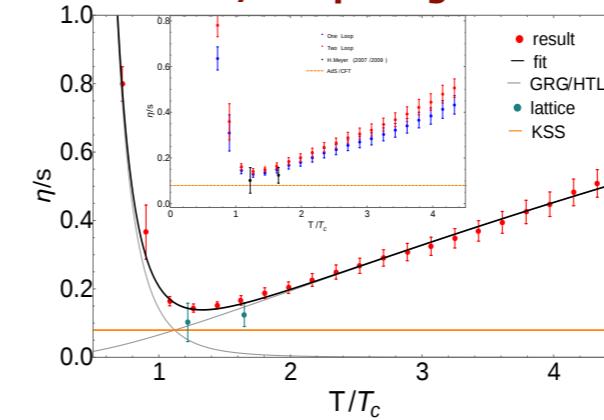


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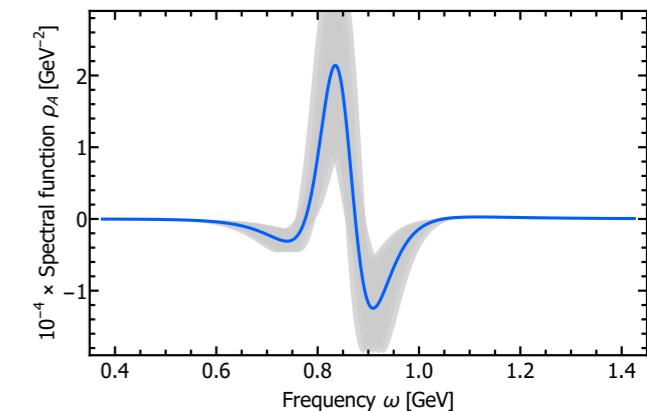


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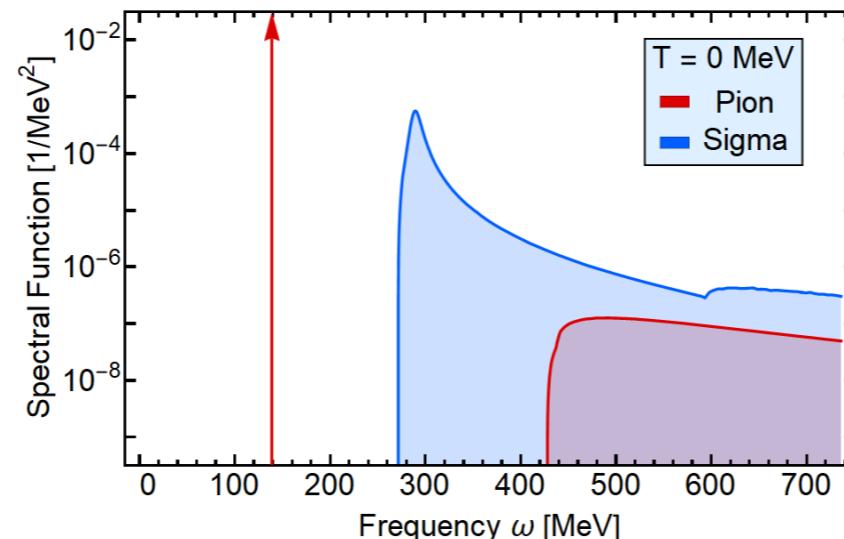
Christiansen, Haas, JMP, Strodthoff,
PRL 115 (2015) 112002

gluon spectral function



Cyrol, JMP, Rothkopf, Wink,
arXiv:1804.00945

Sigma & Pion spectral functions



JMP, Strodthoff, Wink, arXiv:1711.07444

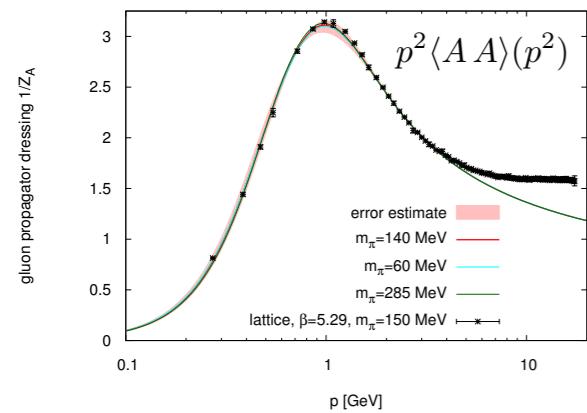
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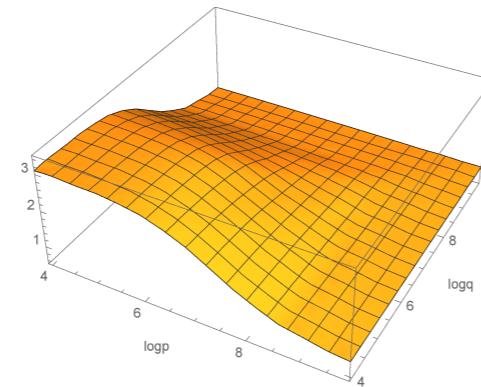
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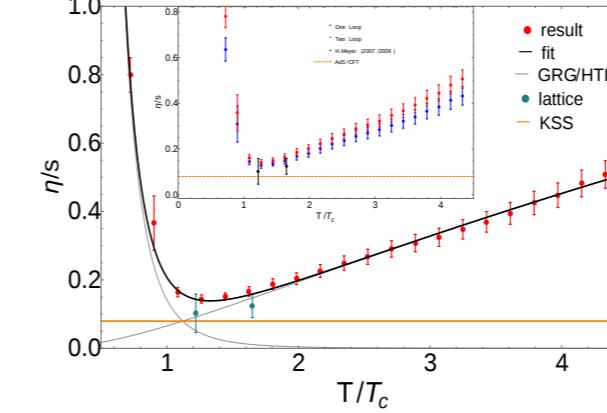
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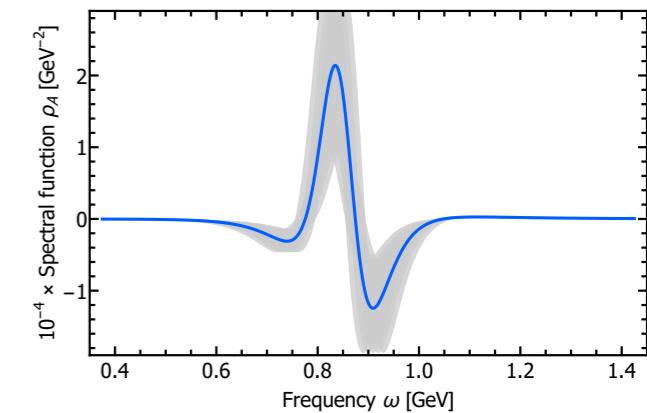
quark-gluon vertex



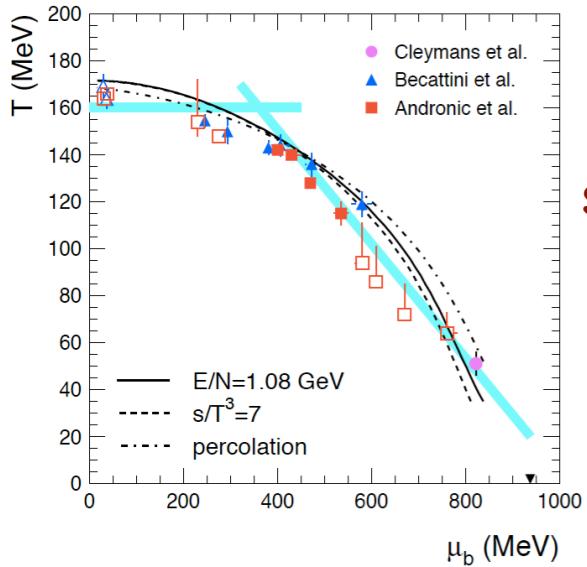
eta/s in pure glue



gluon spectral function



Phase structure



see talk of Marc Leonhardt
Thursday, 15:20

- Braun, Haas, Marhauser, JMP, PRL 106 (2011) 022002
Skokov, Friman, Redlich, PRC 83 (2011) 054904
Fu, JMP, Schaefer, Rennecke, PRD 94 (2016) 116020
Braun, Leonhardt, Pospiech, PRD 96 (2017) 076003
Rennecke, Schaefer, PRD 96 (2017) 016009
Andersen, Tranberg, JHEP 1404 (2014) 187

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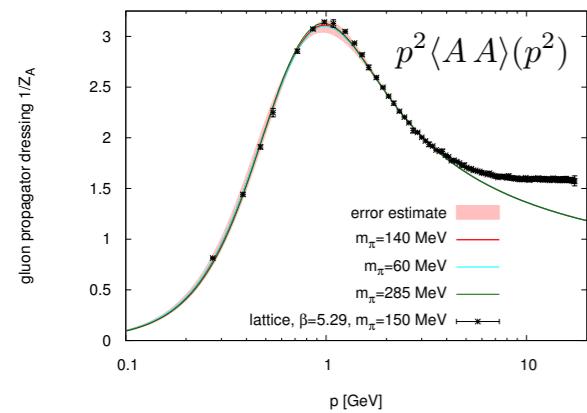
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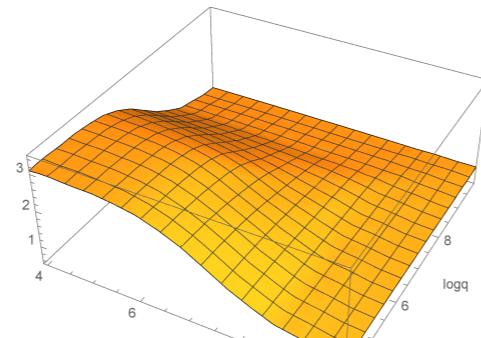
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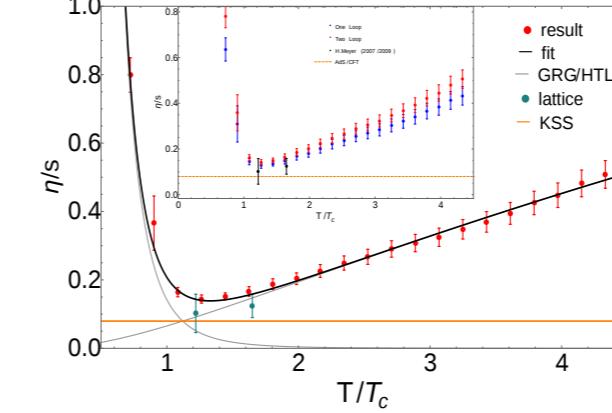
gluon propagator



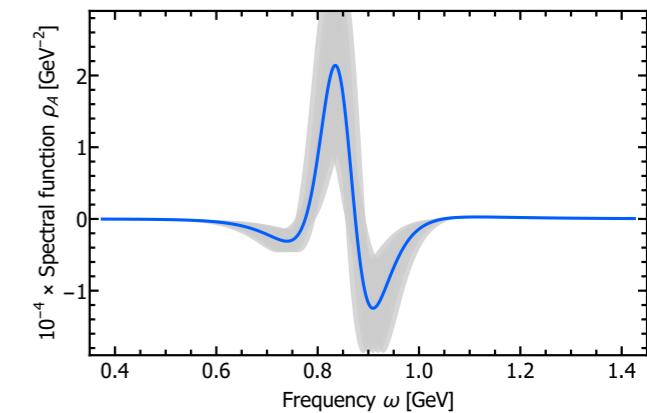
quark-gluon vertex



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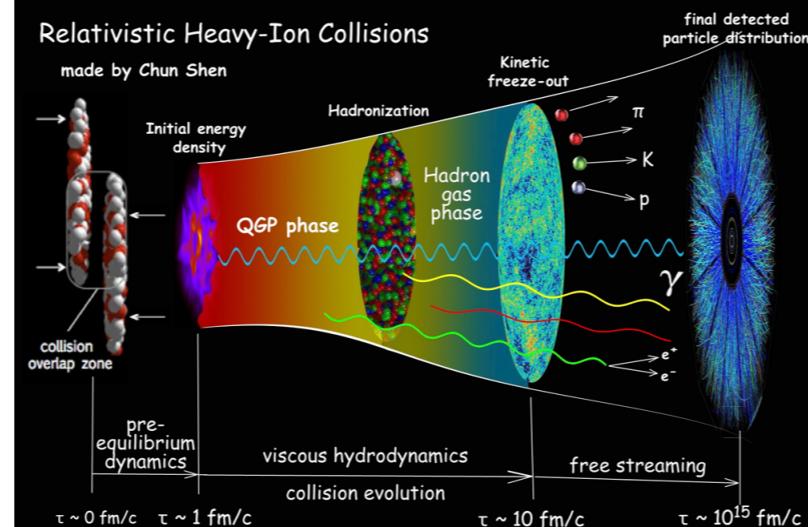
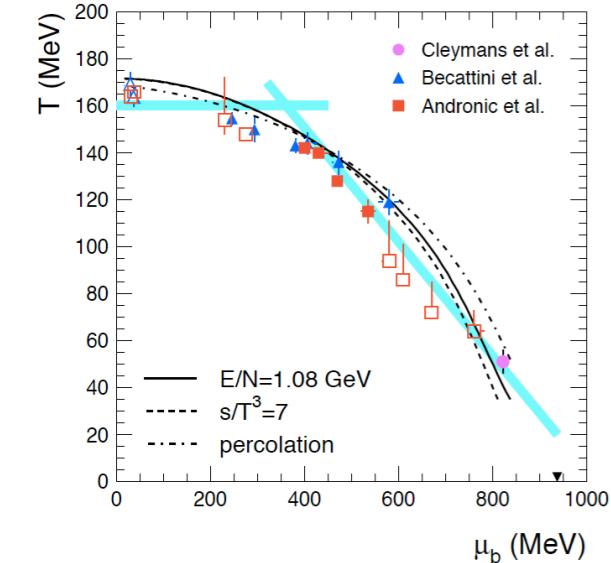


gluon spectral function



transport & dynamics

Phase structure



Christiansen, Haas, JMP, Strodthoff, PRL 115 (2015) 112002
Bluhm, Jiang, Nahrgang, JMP, Rennecke, Wink, arXiv:1808.monday

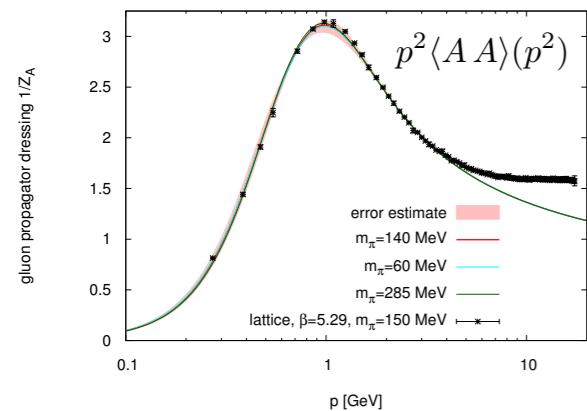
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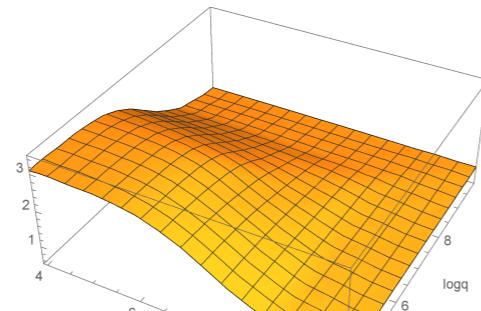
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QCD correlation functions

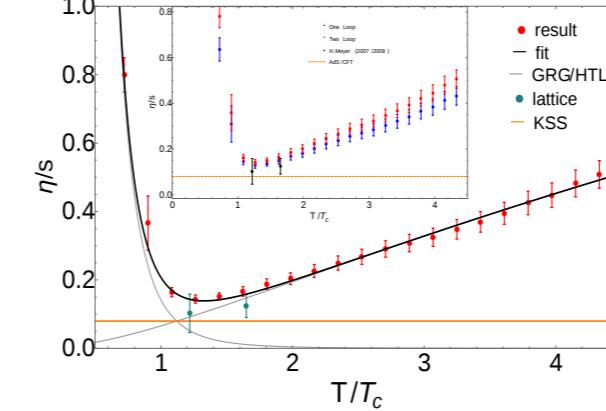
gluon propagator



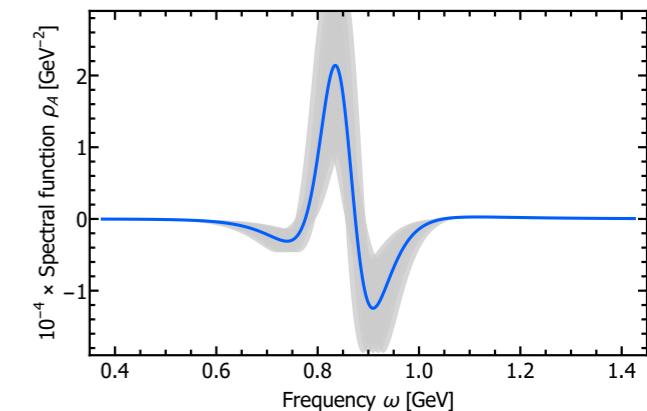
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eta/s in pure glue

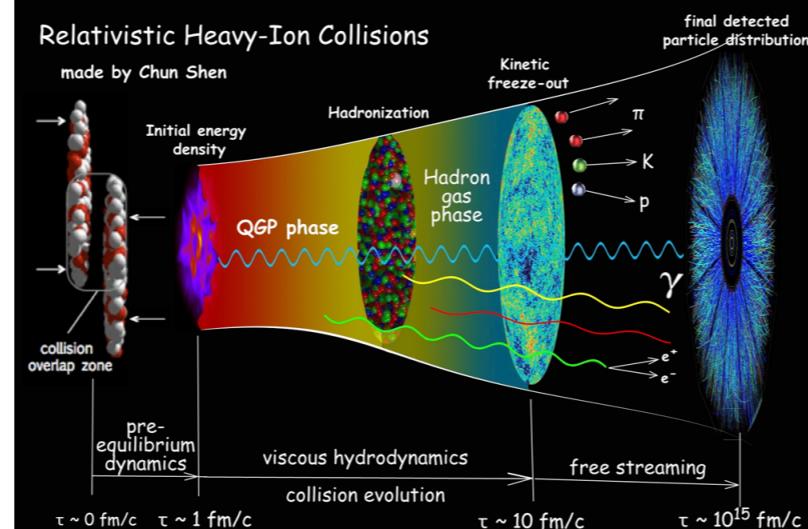
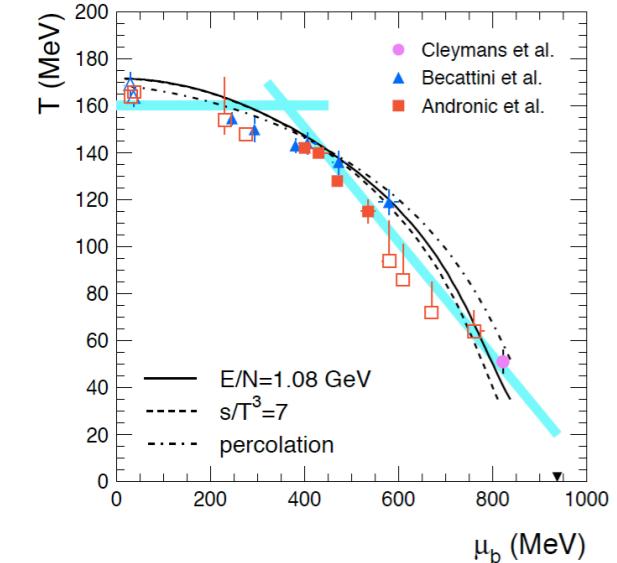


gluon spectral function

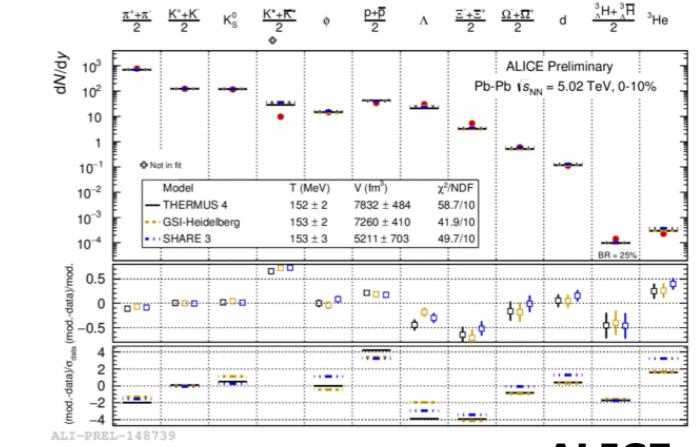


transport & dynamics

Phase structure



Spectral properties



ALICE

Braun, Fister, Haas, JMP, Rennecke, PRD 94 (2016) 034016
Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006

Flörchinger, JHEP 1205 (2012) 021
Tripolt, Strodthoff, von Smekal, Wambach, PRD 89 (2014) 034010
Yokota, Kunihiro, Morita, PRD 96 (2017) 074028
JMP, Strodthoff, Wink, arXiv:1711.07444
Tripolt, Weyrich, von Smekal, Wambach, arXiv:1807.11708

⋮

⋮

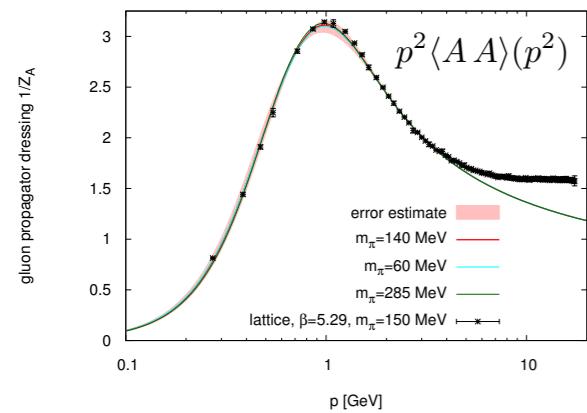
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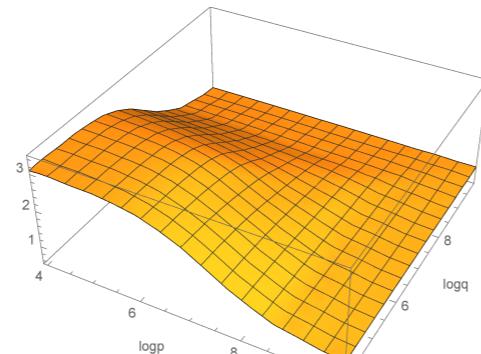
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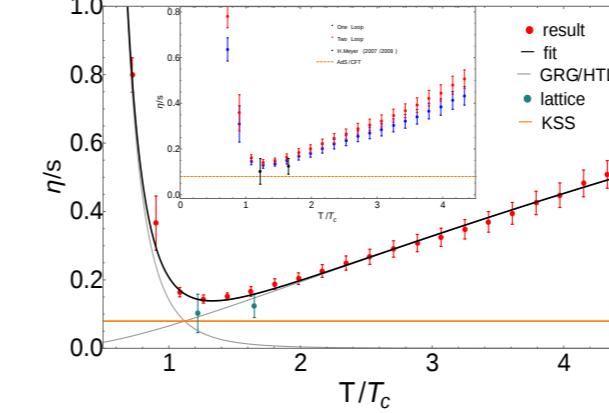
gluon propagator



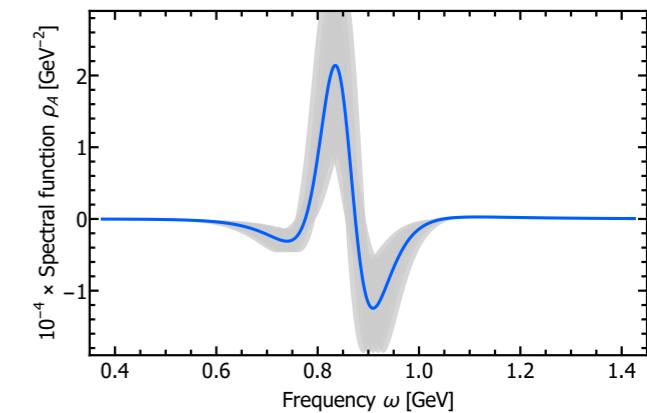
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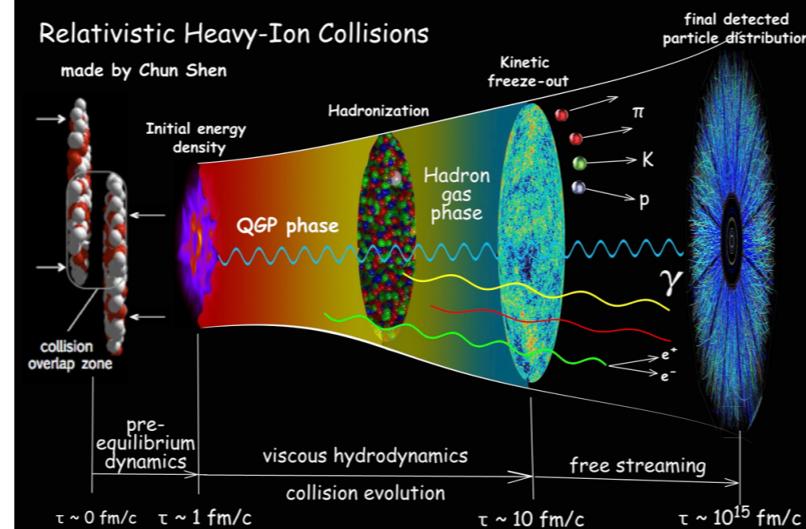
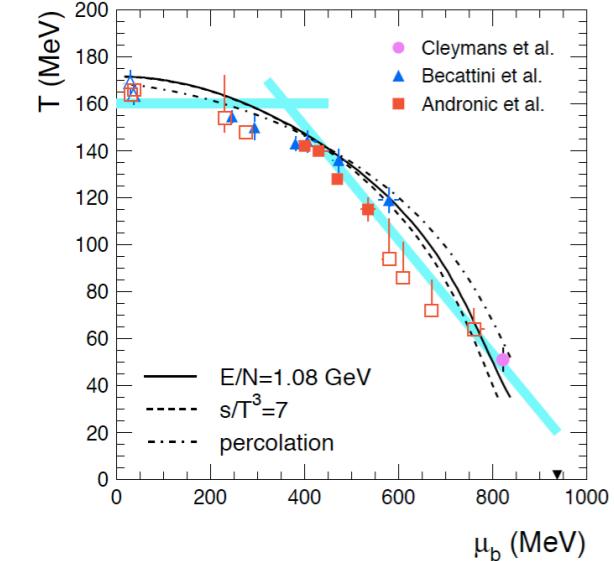


gluon spectral function

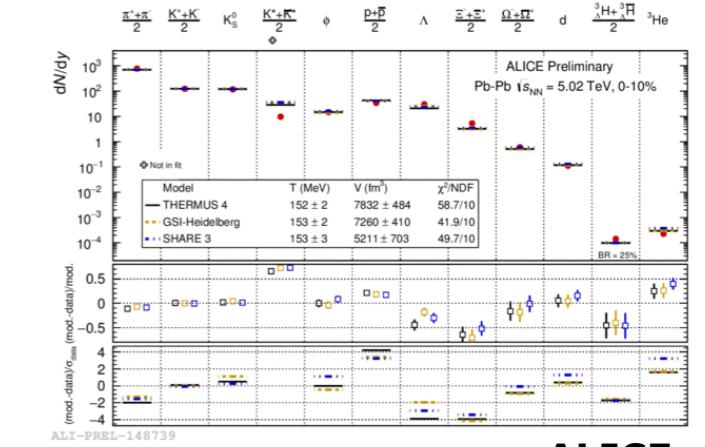


transport & dynamics

Phase structure



Spectral properties



ALICE

Vision: solve coherently for the timeline of a heavy ion collision

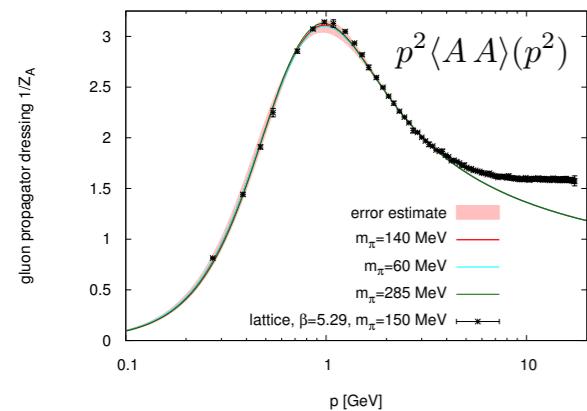
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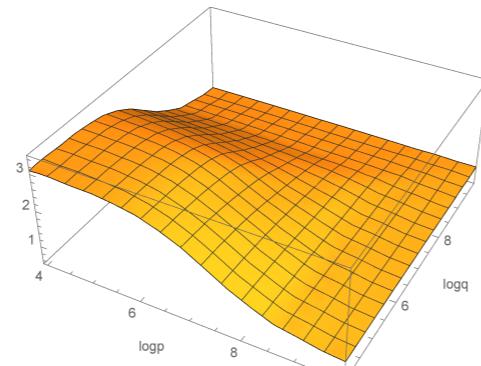
Snapshots QCD

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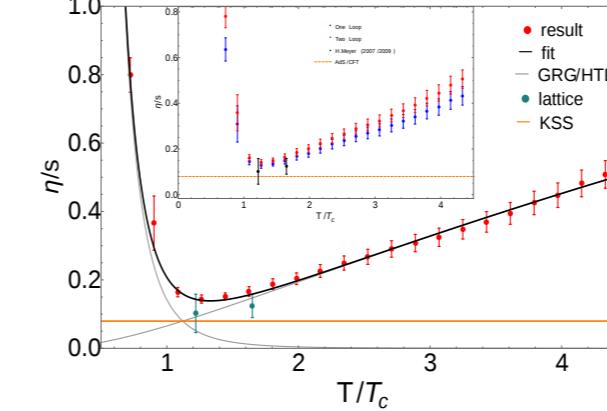
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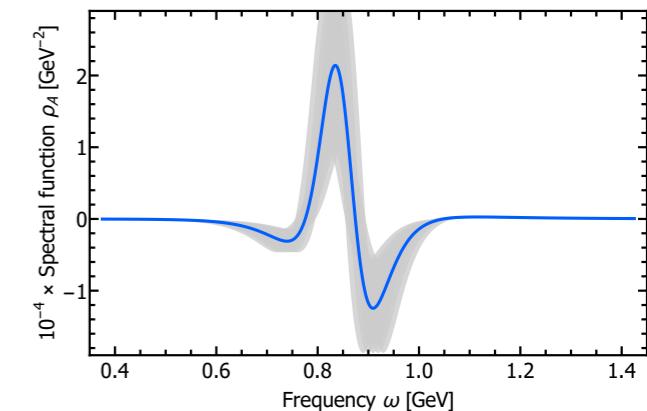
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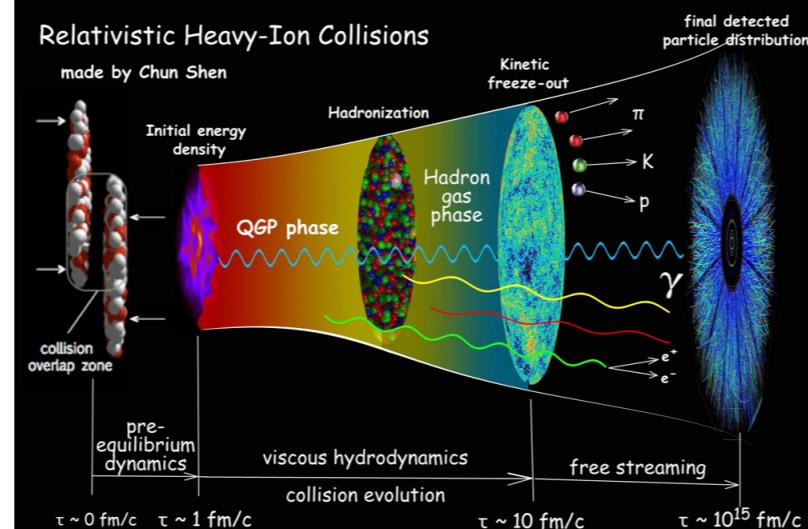
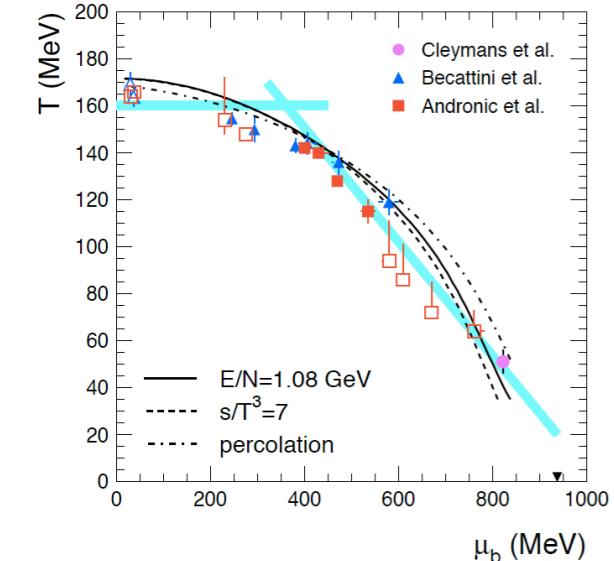


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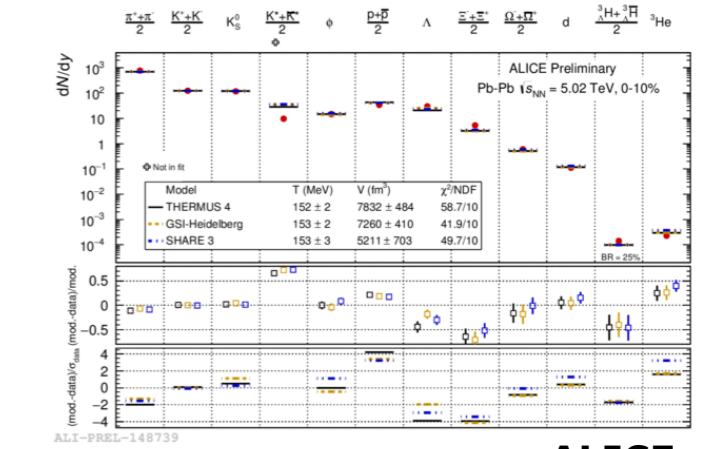


transport & dynamics

Phase structure



Spectral properties



ALICE

Vision: solve coherently for the timeline of a heavy ion collision

'Wer Visionen hat, sollte zum Arzt gehen'

Helmut Schmidt '80

asymptotically safe quantum gravity

a brief introduction

Asymptotic safety

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 $R(g)$

Asymptotic safety

Einstein-Hilbert action

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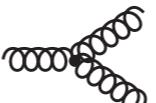
Momentum dimension of couplings

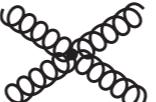
$$\dim G_N = -2$$

$$\dim \Lambda = 2$$

perturbatively non-renormalisable

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

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

4 – grav. vertex :  $\propto G_N p^2$
⋮

Asymptotic safety

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perturbatively non-renormalisable

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

Asymptotic safety

Weinberg '79: Ultraviolet Divergences in Quantum Theories of Gravitation

Consider an observable $\mathcal{O}(g)$ with fundamental coupling g

Asymptotic safety

Weinberg '79: Ultraviolet Divergences in Quantum Theories of Gravitation

Consider an observable $\mathcal{O}(g)$ with fundamental coupling g

- **Standard perturbation theory**

$$\mathcal{O}(g) = O_0 + O_1 g + \frac{1}{2} O_2 g^2 + \dots$$

Asymptotic safety

Weinberg '79: Ultraviolet Divergences in Quantum Theories of Gravitation

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- **Generalised perturbation theory**

$$\mathcal{O}(g) = O^* + O_1^* (g - g^*) + \frac{1}{2} O_2^* (g - g^*)^2 + \dots$$

e.g. aiming at better convergence fundamental coupling
non-perturbative example: analytic perturbation theory in QCD

Asymptotic safety

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- Renormalisation group fixed points

beta functions

$$\partial_t g = \beta_g(g, \mu)$$

Logarithmic momentum (RG) scale: $t = \log \frac{k}{k_0}$

$$\partial_t \mu = \beta_\mu(g, \mu)$$

Asymptotic safety

Weinberg '79: Ultraviolet Divergences in Quantum Theories of Gravitation

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Fixed points

$$\beta_g(g^*, \mu^*) = 0$$

$$\partial_t \mu = \beta_\mu(g, \mu)$$

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Asymptotic safety

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Consider an Observable $\mathcal{O}(g)$ with fundamental coupling g

▪ Ultraviolet running

QCD	quantum gravity
$\beta_g(g) = -\frac{1}{16\pi^2} \frac{22 N_c}{3} g^3$	$\beta_{g_N} = [2 + \eta_N(g_N, \lambda)] g_N$
Asymptotic freedom	Asymptotic safety
	
	$g_N = G_n k^2 \qquad \lambda = \frac{\Lambda}{k^2}$

▪ Renormalisation group fixed points

Logarithmic momentum scale

beta functions

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Weinberg '79: Ultraviolet Divergences in Quantum Theories of Gravitation

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$\beta_g(g) = -\frac{1}{16\pi^2} \frac{22 N_c}{3} g^3$	$\beta_{g_N} = [2 + \eta_N(g_N, \lambda)] g_N$
	↑ dimensional running ↑ quantum fluctuations
Asymptotic freedom	Asymptotic safety
Gaußian fixed point	non-Gaußian fixed point
$\eta_N = -2$	

▪ Renormalisation group fixed points

Logarithmic momentum scale

$$(g_N^*, \lambda^*) \neq 0$$

beta functions

$$\partial_t g = \beta_g(g, \mu)$$

Fixed points

$$\beta_g(g^*, \mu^*) = 0$$

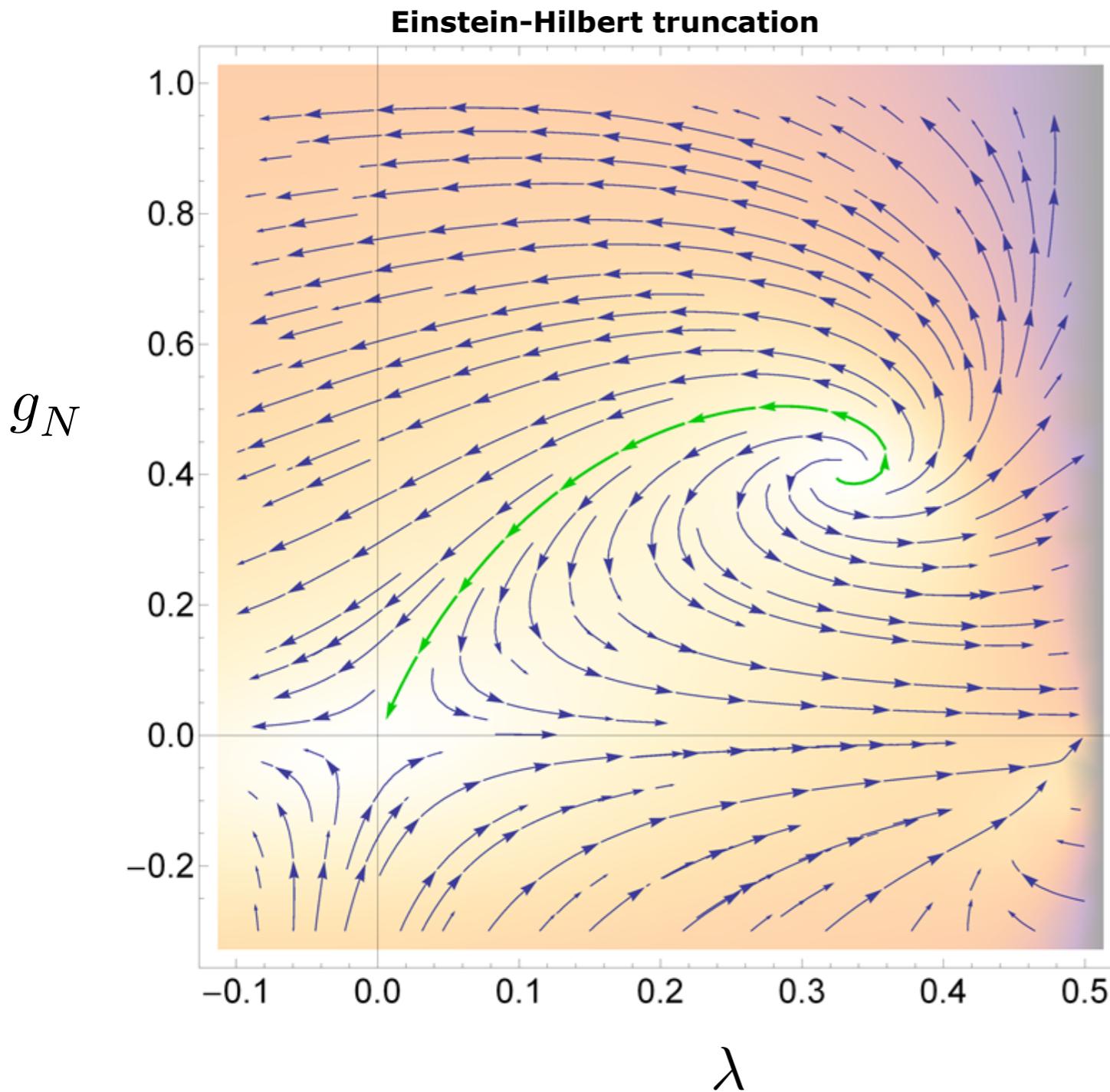
$$\partial_t \mu = \beta_\mu(g, \mu)$$

$$\beta_\mu(g^*, \mu^*) = 0$$

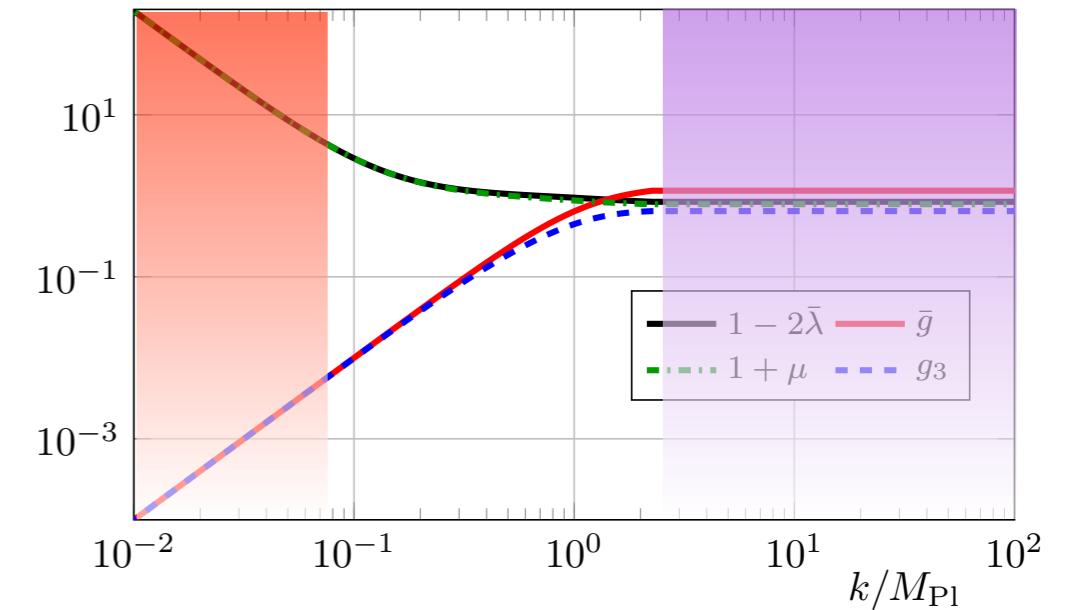
Asymptotic safety

Weinberg '79: Ultraviolet Divergences in Quantum Theories of Gravitation

Phase Structure of Quantum Gravity



IR fine-tuning of diffeomorphism invariance



Denz, JMP, Reichert, EPJ C78 (2018) 4, 336



classical general relativity



asymptotically safe fixed point scaling

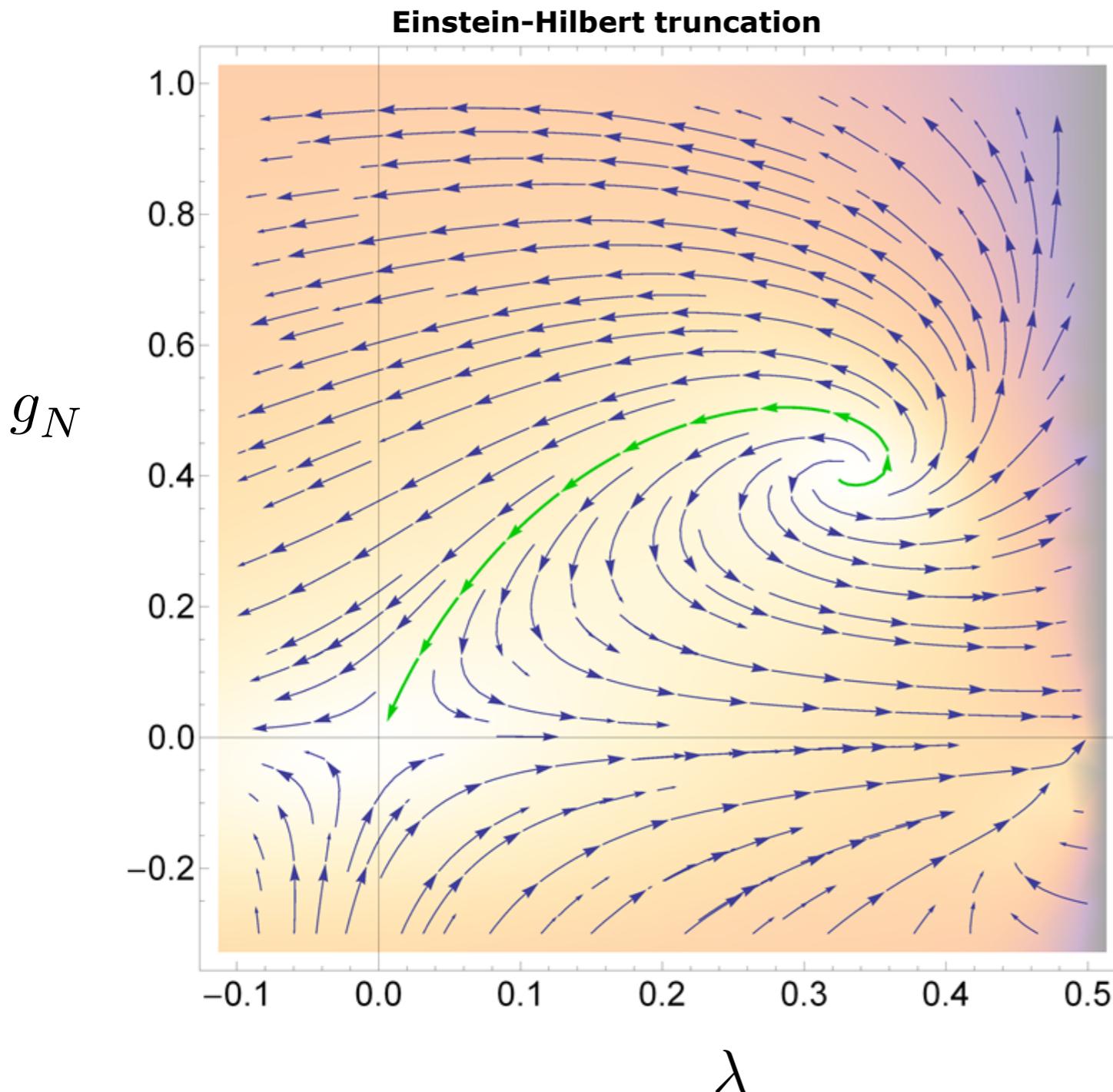
Reuter '96

⋮

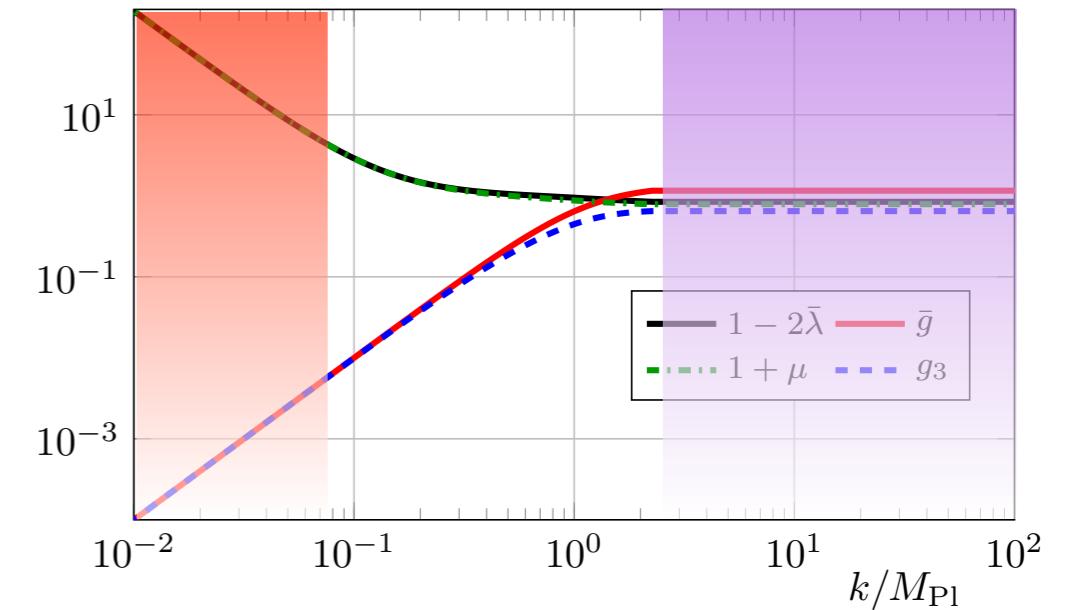
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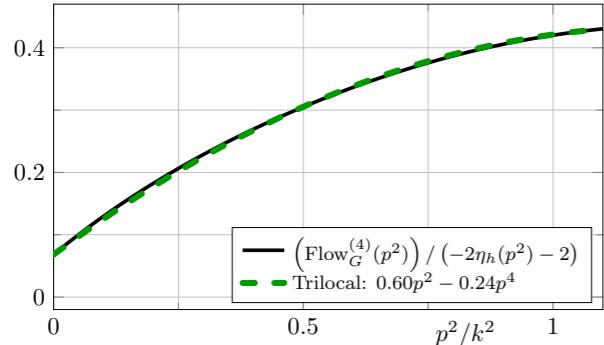
Reuter, Saueressig, PRD 65 (2002) 065016

QG as perturbative as possible?

Overview Quantum Gravity

QG correlation functions

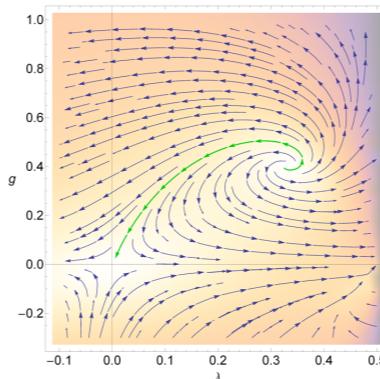
Flow of four-graviton vertex



Denz, JMP, Reichert, EPJ C78 (2018) 4, 336

⋮

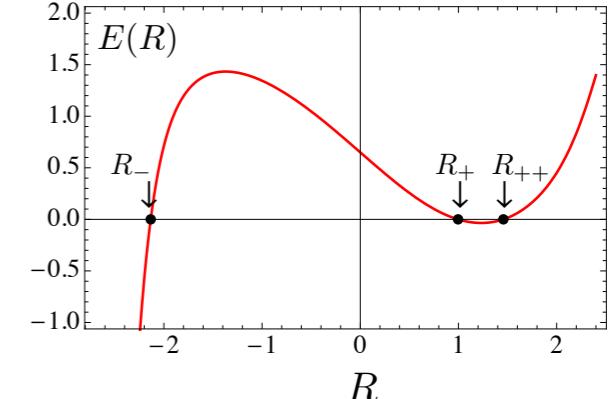
phase structure of QG



Reuter, Saueressig, PRD 65 (2002) 065016

⋮

EoM of quantum gravity



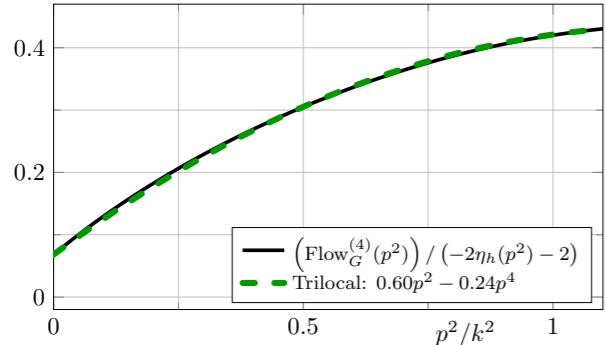
Falls, Litim, Nikolopoulos, Rahmede, PRD 97 (2018) 086006

⋮

Snapshots Quantum Gravity

QG correlation functions

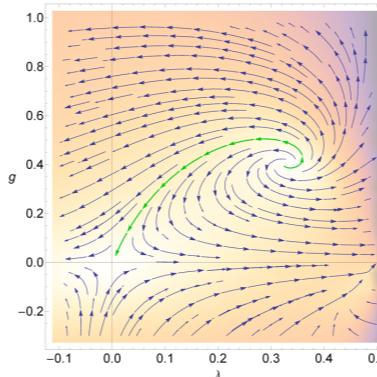
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⋮

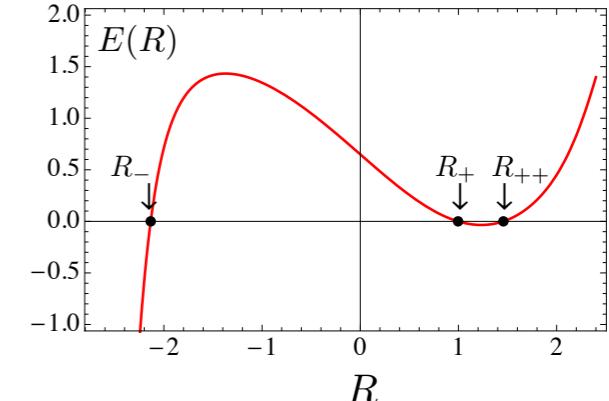
phase structure of QG



Reuter, Saueressig, PRD 65 (2002) 065016

⋮

EoM of quantum gravity

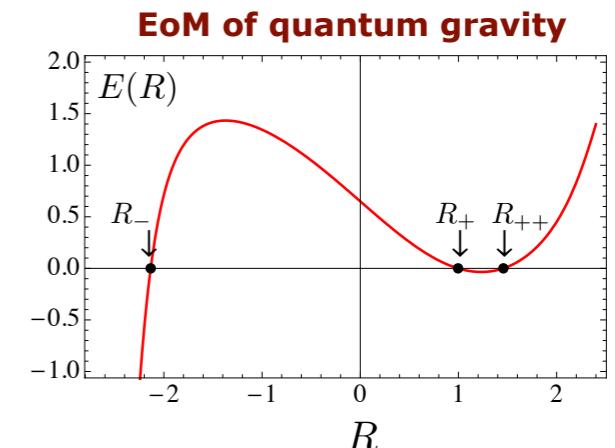
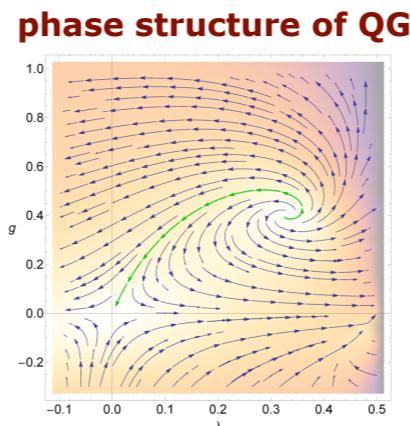
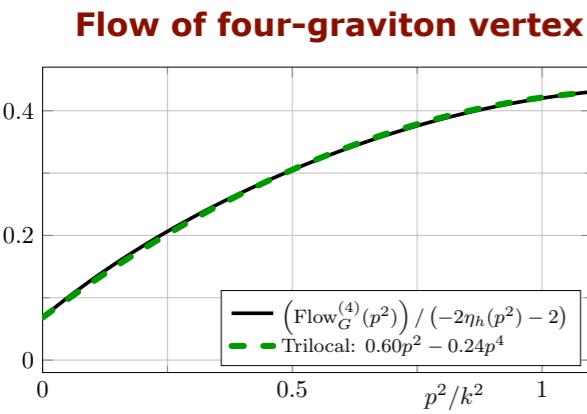


Falls, Litim, Nikolakopoulos, Rahmede, PRD 97 (2018) 086006

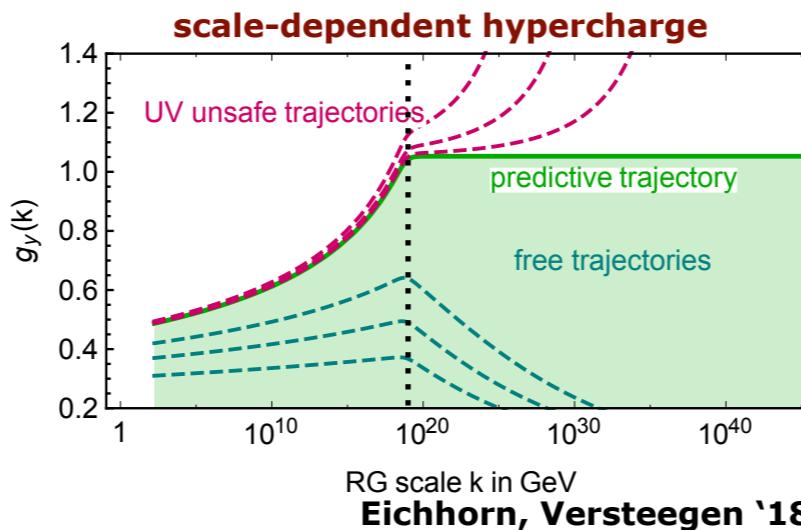
⋮

Snapshots Quantum Gravity

QG correlation functions



asymptotically safe Standard Model



Dona, Eichhorn, Percacci, PRD 89 (2014) 084035
Meibohm, JMP, Reichert, EPJC 76 (2016) 285

⋮

⋮

⋮

Shaposhnikov, Wetterich, PLB 683 (2010) 196
Eichhorn, Versteegen, JHEP 1801 (2018) 030

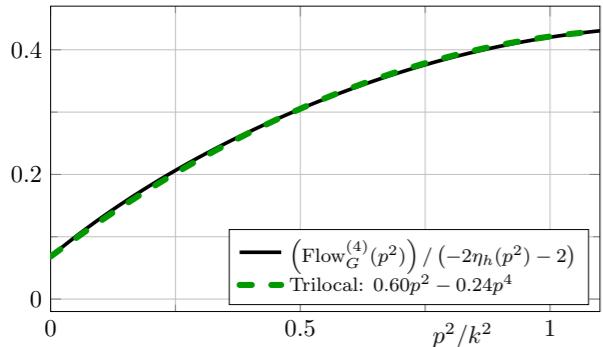
⋮

⋮

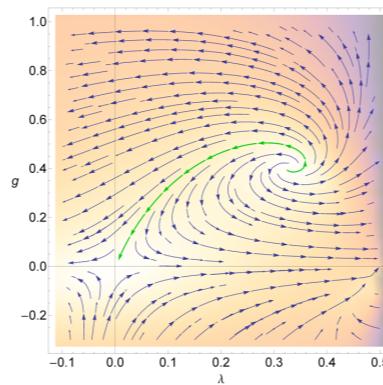
Snapshots Quantum Gravity

QG correlation functions

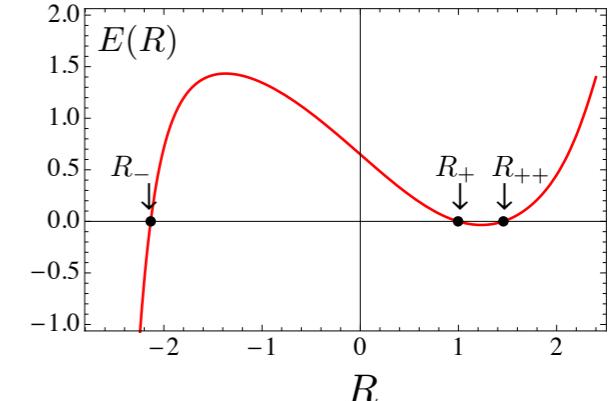
Flow of four-graviton vertex



phase structure of QG

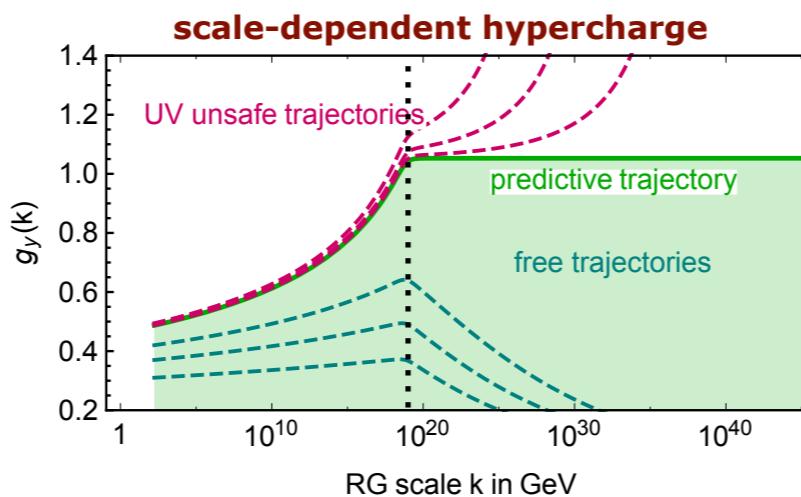
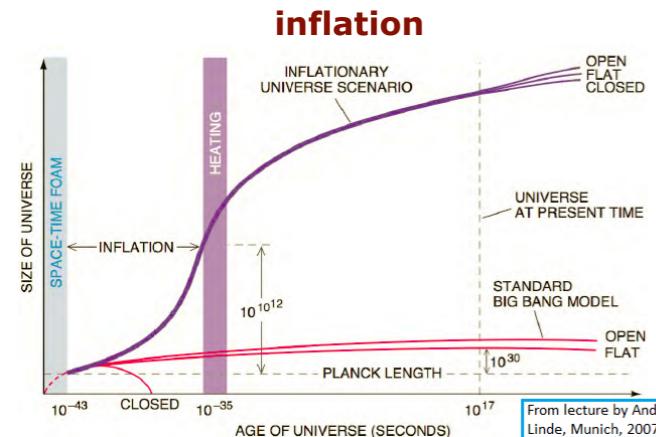


EoM of quantum gravity



asymptotically safe Standard Model

quantum cosmology



Bonanno, Reuter PRD 65 (2002) 043508

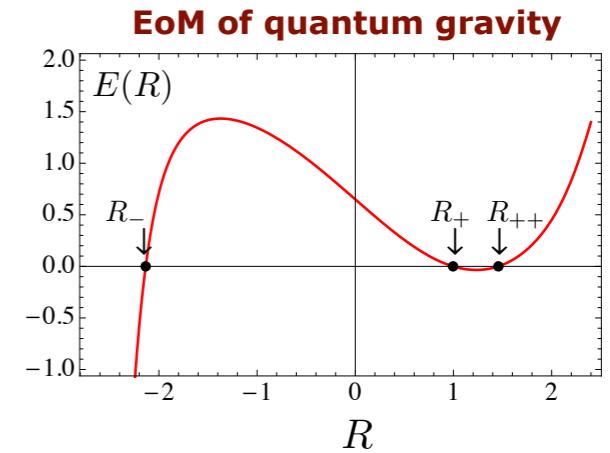
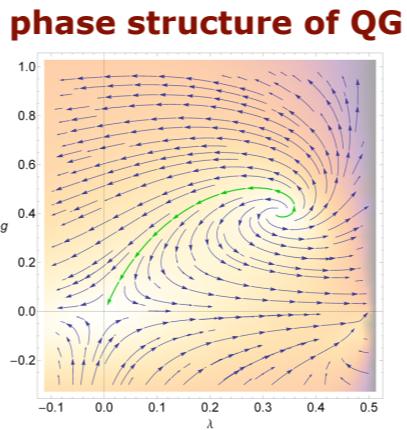
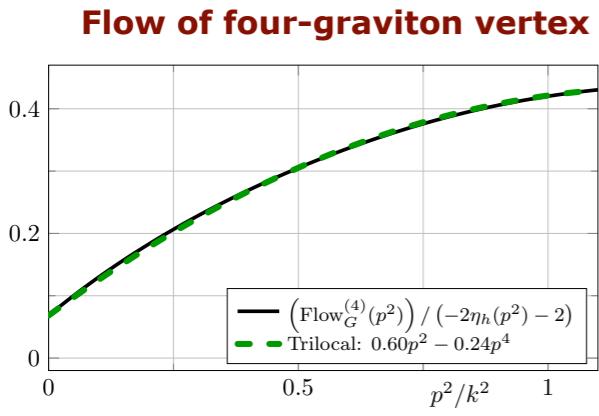
Bonanno, Contillo, Percacci, CQG 28 (2011) 145026

Hindmarsh, Litim, Rahmede, JCAP 1107 (2011) 019

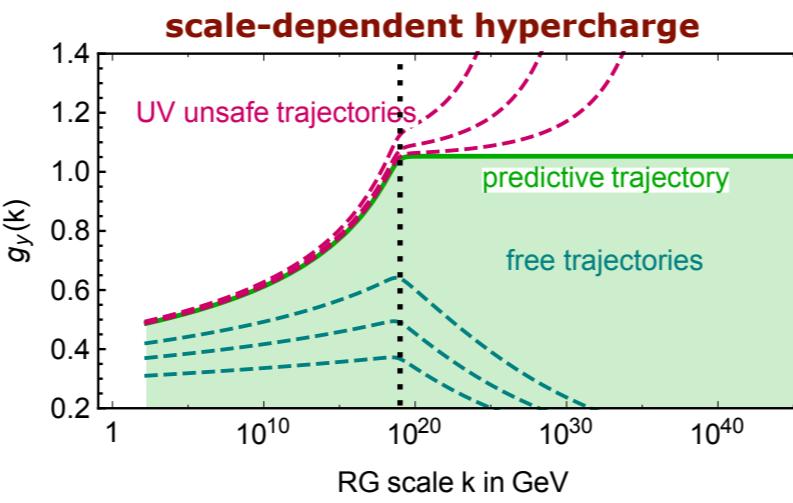
⋮

Snapshots Quantum Gravity

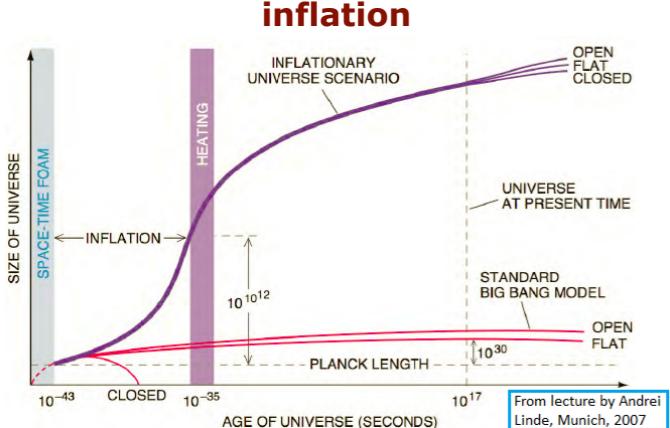
QG correlation functions



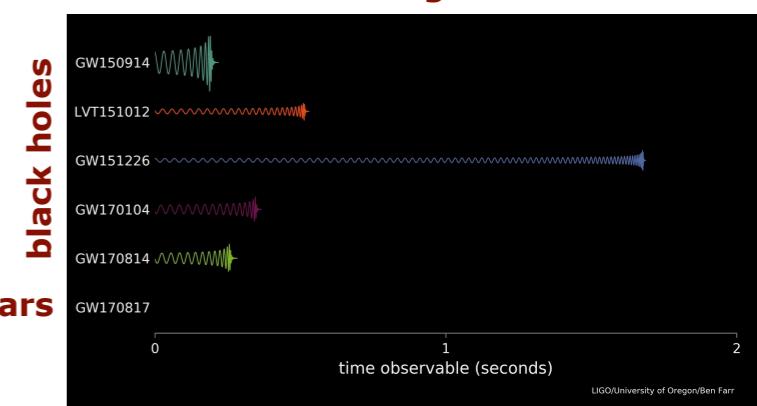
asymptotically safe Standard Model



quantum cosmology



quantum black holes



LIGO, VIRGO

asymptotically save black holes

Bonanno, Reuter PRD 60 (1999) 084011
Falls, Litim, IJMP A27 (2012) 1250019
JMP, Stock, arXiv:1807.10512

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•
•

The functional renormalisation group

a brief introduction

Functional Renormalisation Group

quantum gravity

$$\phi = (g_{\mu\nu}, C_\mu, \bar{C}_\mu, \phi_{\text{matter}})$$

graviton ghosts matter

QCD

$$\phi = (A_\mu, C, \bar{C}, \phi_{\text{matter}})$$

gluons ghosts matter

correlation functions $\langle \phi(x_1) \cdots \phi(x_n) \rangle$

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correlation functions $\langle \phi(x_1) \cdots \phi(x_n) \rangle$

flow equation

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \text{ (orange loop)} - \text{ (dashed loop)} - \text{ (solid loop)} + \frac{1}{2} \text{ (blue loop)}$$

free energy/
grand potential gluons ghosts matter

Functional Renormalisation Group

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correlation functions $\langle \phi(x_1) \cdots \phi(x_n) \rangle$

generates correlation functions

$$n>2: \Gamma^{(n)}[\phi]$$

flow equation

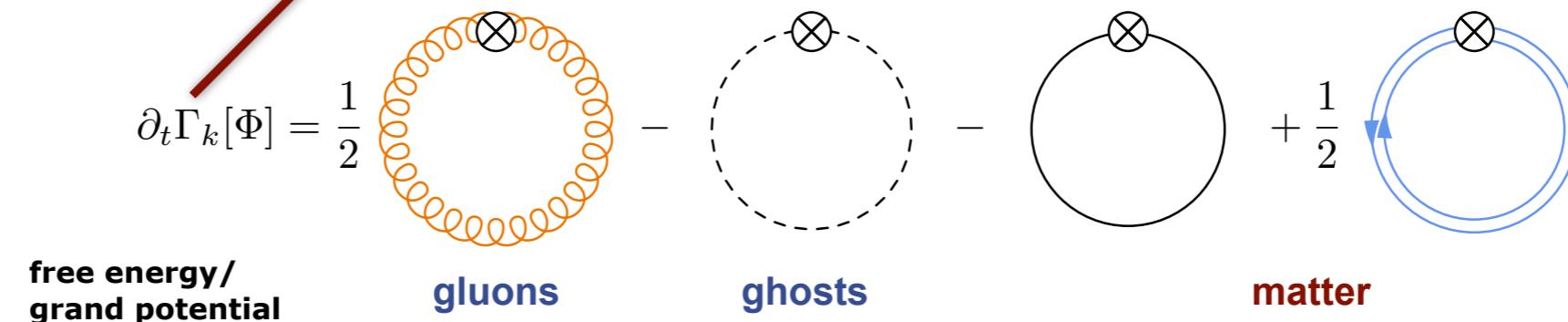
$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \left[\text{gluons loop} - \text{ghosts loop} - \text{matter loop} + \frac{1}{2} \right]$$

free energy/
grand potential

gluons

ghosts

matter



Functional Renormalisation Group

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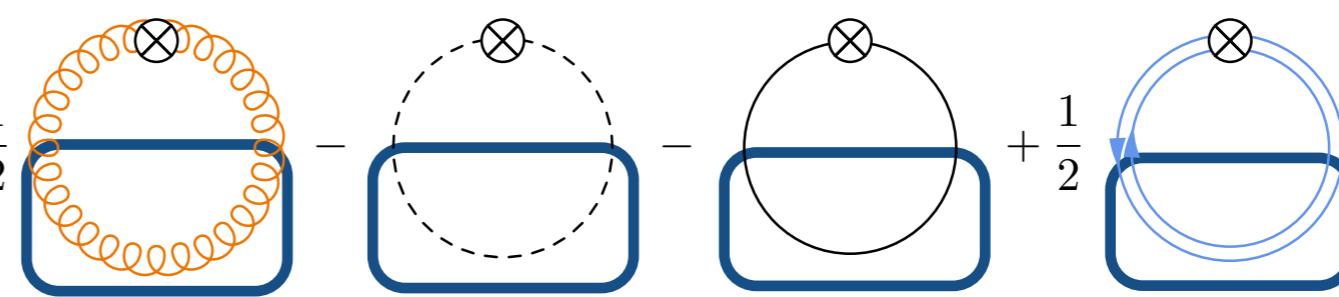
gluons ghosts matter

correlation functions $\langle \phi(x_1) \cdots \phi(x_n) \rangle$

flow equation

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \left[\text{gluons loop} - \text{ghosts loop} - \text{matter loop} + \frac{1}{2} \text{matter loop} \right]$$

free energy/
grand potential



$$\langle \phi_1 \phi_2 \rangle = \frac{1}{\frac{\delta^2 \Gamma_k}{\delta \phi_1 \delta \phi_2} + R_k}$$

Functional Renormalisation Group

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graviton ghosts matter

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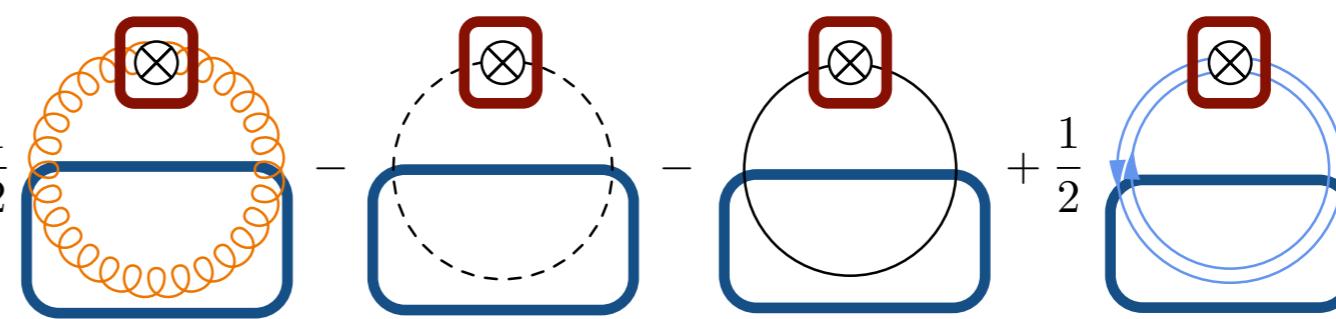
gluons ghosts matter

correlation functions $\langle \phi(x_1) \cdots \phi(x_n) \rangle$

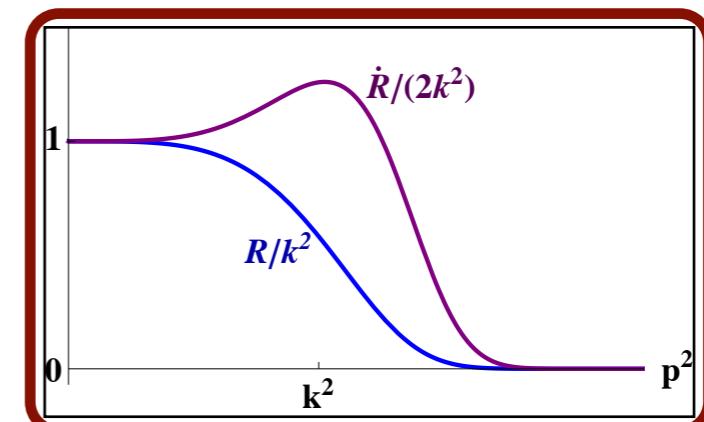
flow equation

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \left[\text{gluons loop} - \text{ghosts loop} - \text{matter loop} + \frac{1}{2} \right]$$

free energy/
grand potential



$$\langle \phi_1 \phi_2 \rangle = \frac{1}{\delta^2 \Gamma_k} + R_k$$



Functional Renormalisation Group

quantum gravity

$$\phi = (g_{\mu\nu}, C_\mu, \bar{C}_\mu, \phi_{\text{matter}})$$

graviton ghosts matter

QCD

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gluons ghosts matter

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flow equation

Universal!

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \text{graviton} - \text{ghosts} - \text{matter} + \frac{1}{2} \text{matter}$$

free energy/
grand potential

graviton ghosts matter

gluons ghosts matter

Functional Renormalisation Group

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$$\phi = (g_{\mu\nu}, C_\mu, \bar{C}_\mu, \phi_{\text{matter}})$$

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QCD

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gluons ghosts matter

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flow equation

Universal!

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \left(\text{graviton loop} - \text{ghosts loop} - \text{matter loop} + \frac{1}{2} \text{graviton loop} \right)$$

free energy/
grand potential

graviton ghosts matter

gluons ghosts matter

graviton

The diagram illustrates the flow equation for the effective action $\Gamma_k[\Phi]$. It shows the time derivative $\partial_t \Gamma_k[\Phi]$ as a sum of loop corrections. The loops are labeled by their respective fields: graviton (orange), ghosts (dashed), matter (black), and a self-energy correction for the graviton (blue). A red arrow points from the ghost loop to the graviton loop, indicating the flow direction.

Functional Renormalisation Group

quantum gravity

Pure quantum gravity

$$\partial_t \Gamma_k = \frac{1}{2} \text{ (blue loop diagram)} - \text{ (red loop diagram)}$$

$$\partial_t \Gamma_k^{(h)} = -\frac{1}{2} \text{ (blue loop diagram)} + \text{ (red loop diagram)}$$

$$\partial_t \Gamma_k^{(2h)} = -\frac{1}{2} \text{ (blue loop diagram)} + \text{ (blue loop diagram)} - 2 \text{ (blue loop diagram)} - \text{ (red loop diagram)}$$

$$\partial_t \Gamma_k^{(c\bar{c})} = \dots + \dots + \text{ (red F diagram)}$$

$$\partial_t \Gamma_k^{(3h)} = -\frac{1}{2} \text{ (blue loop diagram)} + 3 \text{ (blue loop diagram)} - 3 \text{ (blue loop diagram)} + 6 \text{ (blue loop diagram)} - \text{ (red loop diagram)}$$

$$\begin{aligned} \partial_t \Gamma_k^{(4h)} = & -\frac{1}{2} \text{ (blue loop diagram)} + 3 \text{ (blue loop diagram)} + 4 \text{ (blue loop diagram)} - 6 \text{ (blue loop diagram)} \\ & - 12 \text{ (blue loop diagram)} + 12 \text{ (blue loop diagram)} - 24 \text{ (blue loop diagram)} - \text{ (red loop diagram)} \end{aligned}$$

⋮

QCD

Pure glue part

$$\partial_t \longrightarrow^{-1} = \text{ (blue loop diagram)} + \text{ (blue loop diagram)}$$

$$\partial_t \text{ (wavy line)}^{-1} = \text{ (wavy line loop)} - 2 \text{ (wavy line loop)} - \frac{1}{2} \text{ (wavy line loop)}$$

$$\partial_t \text{ (triangle)} = - \text{ (triangle)} - \text{ (triangle)} + \text{ perm.}$$

$$\partial_t \text{ (triangle)} = - \text{ (triangle)} + 2 \text{ (triangle)} + \text{ (triangle)} + \text{ perm.}$$

$$\partial_t \text{ (cross)} = + \text{ (cross)} + \text{ (square)} - 2 \text{ (cross)} - \text{ (cross)} + \text{ perm.}$$

+ diagrams with matter lines

Glue-matter part

$$\begin{aligned} \partial_t \longrightarrow^{-1} = & \text{ (blue loop diagram)} + \text{ (blue loop diagram)} + \frac{1}{2} \text{ (blue loop diagram)} \\ & + \text{ (dashed loop diagram)} + \text{ (dashed loop diagram)} - \text{ (dashed loop diagram)} \end{aligned}$$

$$\begin{aligned} \partial_t \text{ (triangle)} = & - \text{ (triangle)} - \text{ (triangle)} - \text{ (triangle)} - \text{ (triangle)} - \frac{1}{2} \text{ (triangle)} \\ & + 2 \text{ (triangle)} - \text{ (triangle)} + \text{ perm.} \end{aligned}$$

$$\begin{aligned} \partial_t \text{ (cross)} = & 2 \text{ (cross)} - \text{ (cross)} - \text{ (cross)} - \text{ (cross)} - \text{ (cross)} \\ & - \text{ (cross)} - \text{ (cross)} - \text{ (cross)} + \text{ perm.} \end{aligned}$$

⋮

Functional Renormalisation Group

quantum gravity

Pure quantum gravity

$$\begin{aligned}\partial_t \Gamma_k &= \frac{1}{2} \text{ (blue loop)} - \text{ (red loop)} \\ \partial_t \Gamma_k^{(h)} &= -\frac{1}{2} \text{ (blue loop)} + \text{ (red loop)} \\ \partial_t \Gamma_k^{(2h)} &= -\frac{1}{2} \text{ (blue loop)} + \text{ (blue loop)} - 2 \text{ (red loop)} \\ \partial_t \Gamma_k^{(c\bar{c})} &= \dots + \text{ (red loop)} F \dots\end{aligned}$$

$$\partial_t \Gamma_k^{(3h)} = -\frac{1}{2} \text{ (blue loop)} + 3 \text{ (blue loop)} - 3 \text{ (blue loop)} + 6 \text{ (red loop)}$$

$$\begin{aligned}\partial_t \Gamma_k^{(4h)} &= -\frac{1}{2} \text{ (blue loop)} + 3 \text{ (blue loop)} + 4 \text{ (blue loop)} - 6 \text{ (blue loop)} \\ &\quad - 12 \text{ (blue loop)} + 12 \text{ (blue loop)} - 24 \text{ (red loop)}\end{aligned}$$

⋮

QCD

Pure glue part

$$\begin{aligned}\partial_t \text{ (wavy line)}^{-1} &= \text{ (wavy loop)} + \text{ (wavy loop)} \\ \partial_t \text{ (wavy line)}^{-1} &= \text{ (wavy loop)} - 2 \text{ (wavy loop)} - \frac{1}{2} \text{ (wavy loop)} \\ \partial_t \text{ (wavy line)} &= - \text{ (triangle)} - \text{ (triangle)} + \text{ perm.} \\ \partial_t \text{ (wavy line)} &= - \text{ (triangle)} + 2 \text{ (triangle)} + \text{ (loop)} + \text{ perm.} \\ \partial_t \text{ (wavy line)} &= + \text{ (double loop)} + \text{ (square)} - 2 \text{ (double loop)} - \text{ (double loop)} + \text{ perm.}\end{aligned}$$

+ diagrams with matter lines

Glue-matter part

$$\begin{aligned}\partial_t \text{ (wavy line)}^{-1} &= \text{ (wavy loop)} + \text{ (wavy loop)} + \frac{1}{2} \text{ (wavy loop)} \\ &\quad + \text{ (dashed loop)} + \text{ (dashed loop)} - \text{ (wavy loop)} \\ \partial_t \text{ (wavy line)} &= - \text{ (triangle)} - \text{ (triangle)} - \text{ (loop)} - \text{ (loop)} - \frac{1}{2} \text{ (loop)} \\ &\quad + 2 \text{ (loop)} - \text{ (loop)} + \text{ perm.} \\ \partial_t \text{ (wavy line)} &= 2 \text{ (double loop)} - \text{ (double loop)} - \text{ (square)} - \text{ (square)} - \text{ (loop)} - \text{ (loop)} \\ &\quad - \text{ (dashed loop)} - \text{ (dashed loop)} - \text{ (dashed loop)} + \text{ perm.}\end{aligned}$$

Aiming at apparent convergence

⋮

Towards apparent convergence in QCD & quantum gravity

Why does/could it work?

Typically diagrams with higher order vertices are strongly suppressed

Towards apparent convergence in QCD & quantum gravity

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(a) couplings stay finite

Towards apparent convergence in QCD & quantum gravity

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Gies, Wetterich, PRD 65 (2002) 0650016

JMP, AP 322 (2007) 2831

Flörchinger, Wetterich, PLB 680 (2009) 371

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JMP, AP 322 (2007) 2831

(c) graviballs in gravity

Flörchinger, Wetterich, PLB 680 (2009) 371

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Gies, Wetterich, PRD 65 (2002) 0650016
JMP, AP 322 (2007) 2831
Flörchinger, Wetterich, PLB 680 (2009) 371

QCD strongly correlated!

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Gies, Wetterich, PRD 65 (2002) 0650016
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QG as perturbative as possible?

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Towards apparent convergence in QCD & quantum gravity

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Gies, Wetterich, PRD 65 (2002) 0650016

JMP, AP 322 (2007) 2831

Flörchinger, Wetterich, PLB 680 (2009) 371

QG as perturbative as possible?

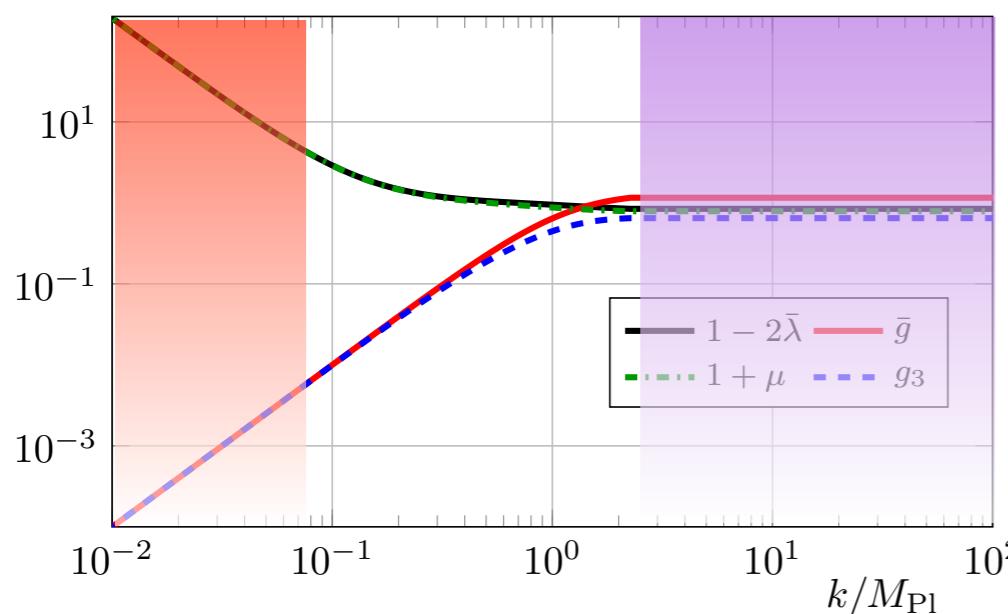
QCD strongly correlated!

... slight oversimplification for the sake of this talk ...

Towards apparent convergence in QCD & quantum gravity

Couplings stay finite

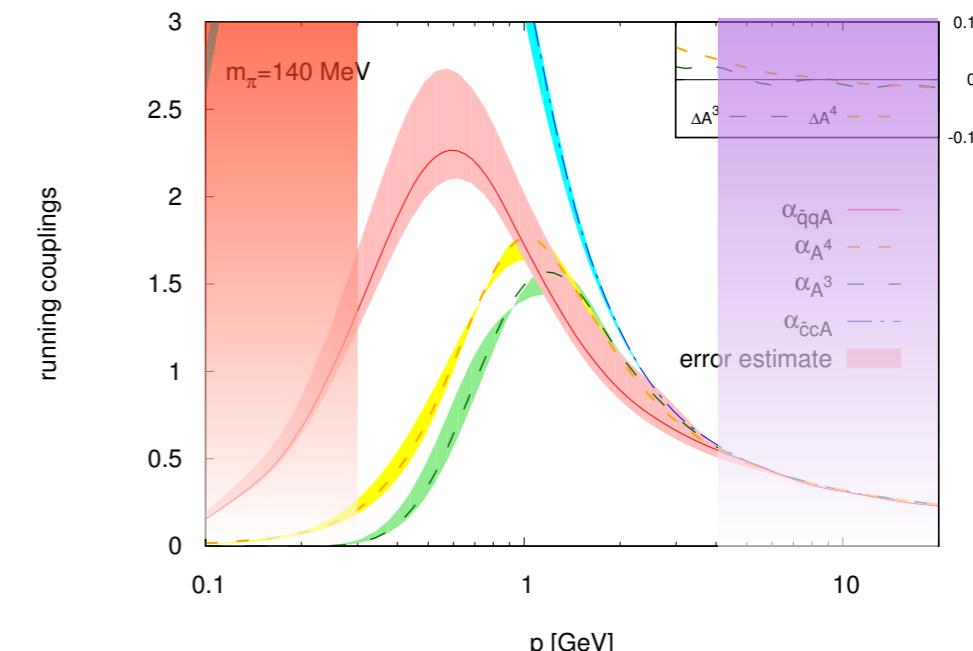
quantum gravity



Denz, JMP, Reichert, EPJ C78 (2018) 4, 336

QCD

Beware of BRST



Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006



classical general relativity



asymptotically safe fixed point scaling



decoupling of glue dynamics



perturbative QCD

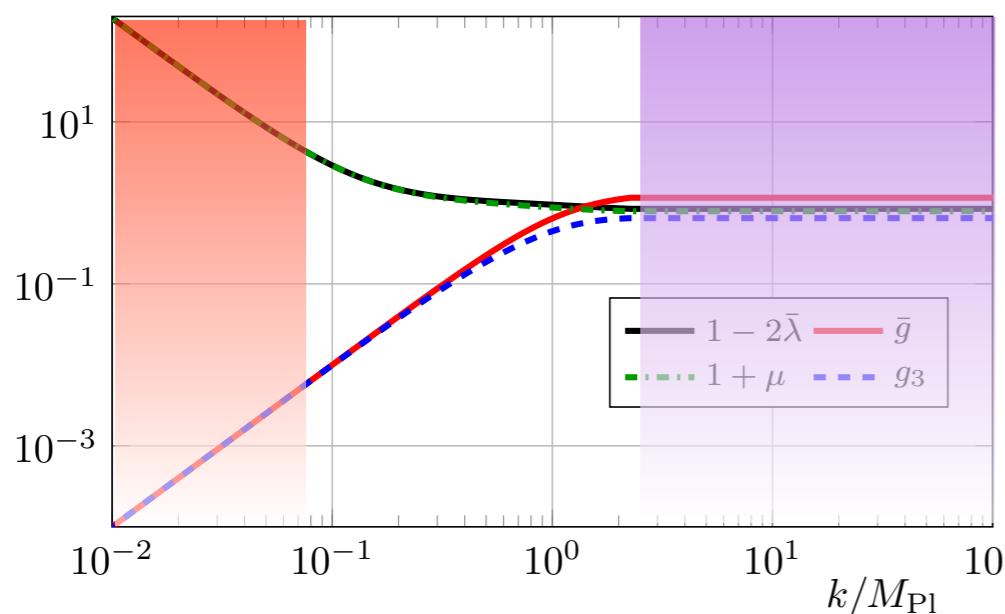
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Towards apparent convergence in QCD & quantum gravity

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quantum gravity



Denz, JMP, Reichert, EPJ C78 (2018) 4, 336



classical general relativity



asymptotically safe fixed point scaling

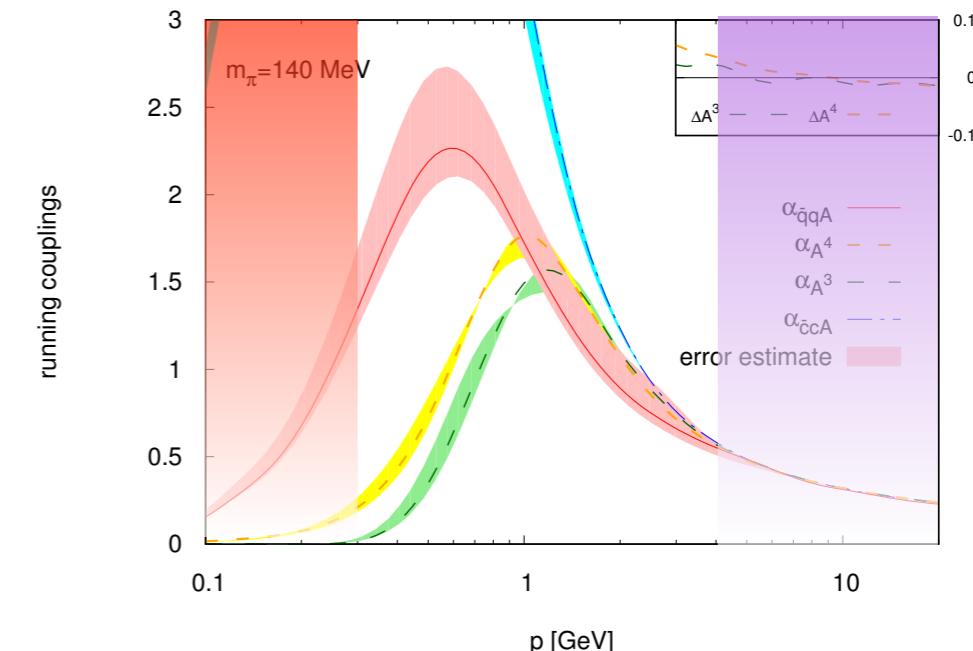
QG as perturbative as possible?

QG enjoys effective universality!?

Eichhorn, Labus, JMP, Reichert, arXiv:1804.00012

QCD

Beware of BRST



Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006



decoupling of glue dynamics



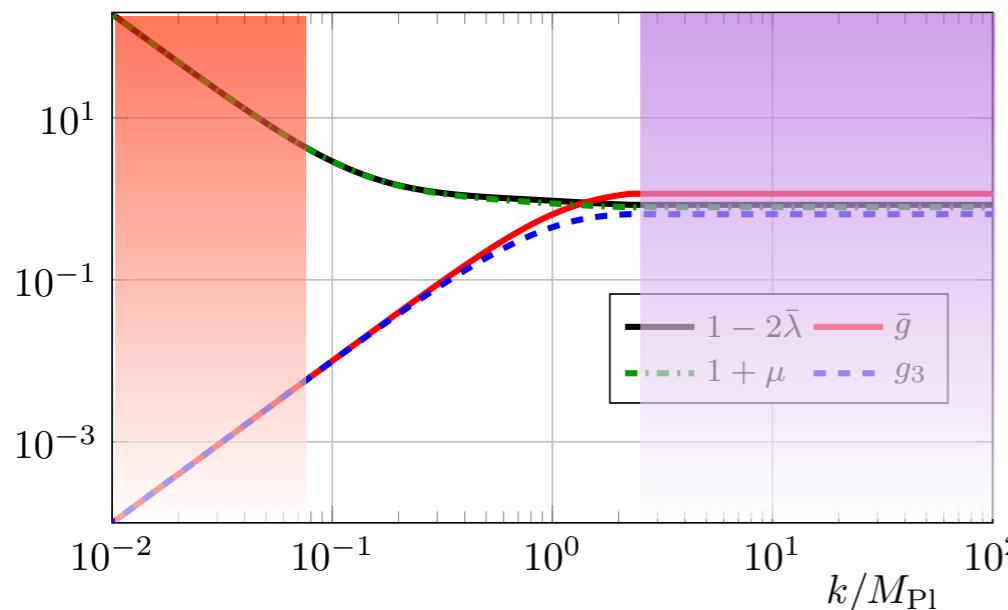
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Towards apparent convergence in QCD & quantum gravity

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Denz, JMP, Reichert, EPJ C78 (2018) 4, 336



classical general relativity



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QG as perturbative as possible?

QG enjoys effective universality!?

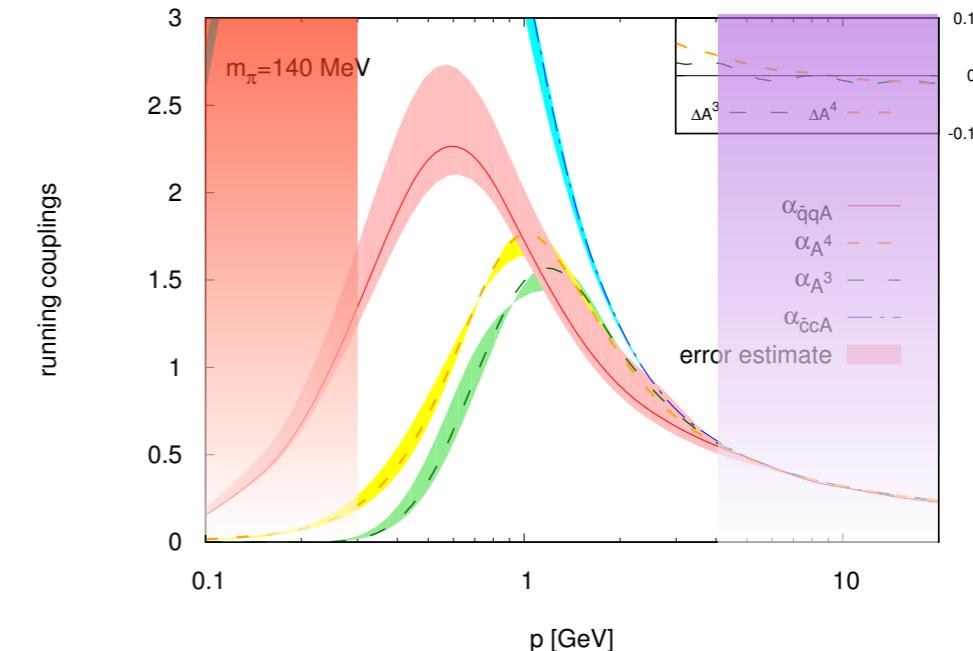
Eichhorn, Labus, JMP, Reichert, arXiv:1804.00012

'One force to rule them all'!?

Christiansen, Litim, JMP, Reichert, PRD 97 (2018) 106012

QCD

Beware of BRST



Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006



decoupling of glue dynamics



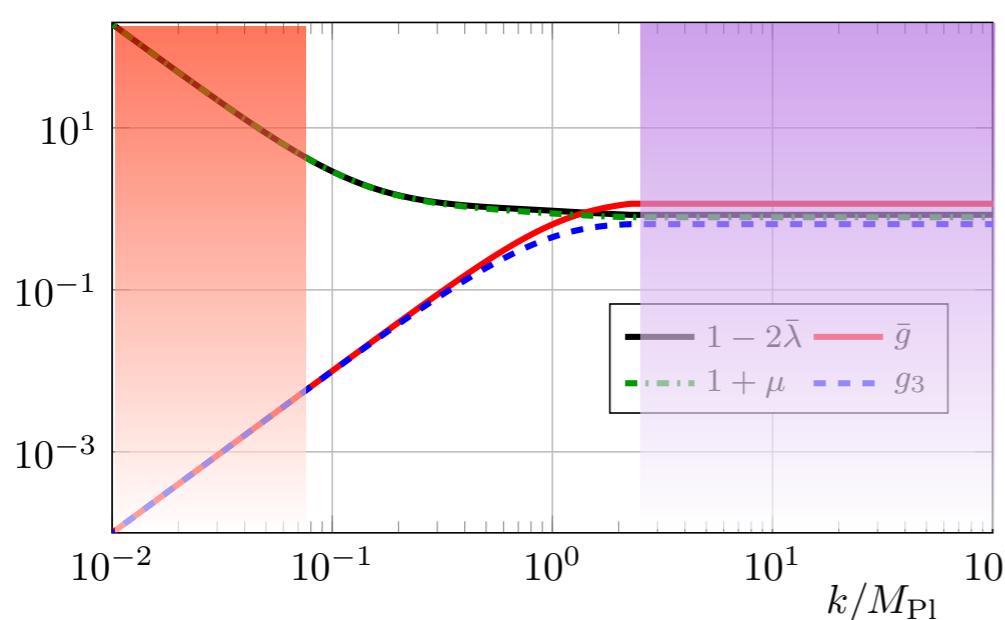
perturbative QCD

QCD strongly correlated!

Towards apparent convergence in QCD & quantum gravity

Couplings stay finite

quantum gravity



Denz, JMP, Reichert, EPJ C78 (2018) 4, 336



classical general relativity



asymptotically safe fixed point scaling

QG as perturbative as possible?

QG enjoys effective universality!?

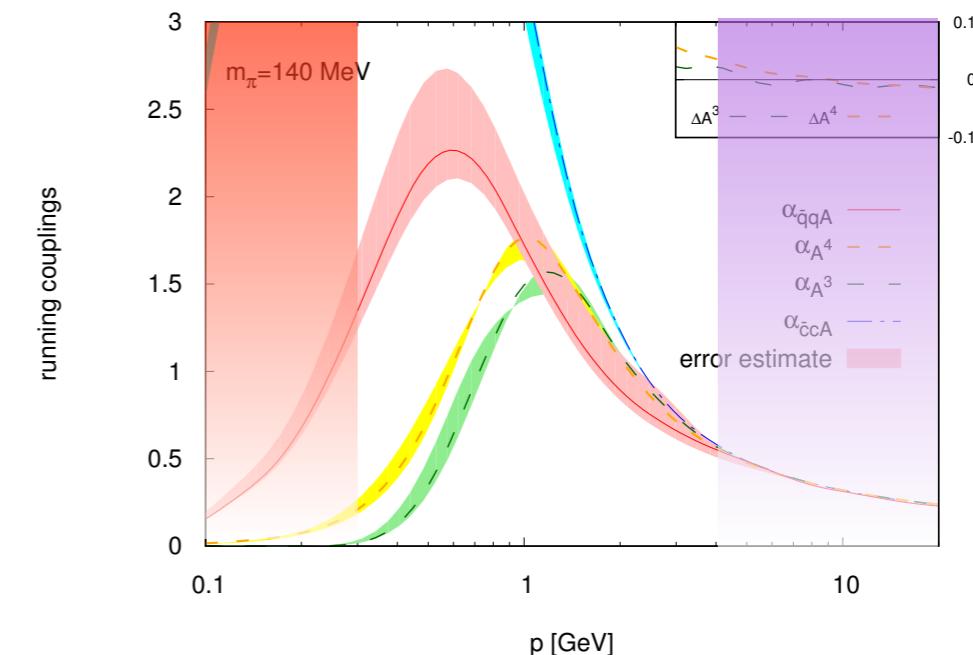
Eichhorn, Labus, JMP, Reichert, arXiv:1804.00012

'One force to rule them all'!?

Christiansen, Litim, JMP, Reichert, PRD 97 (2018) 106012

QCD

Beware of BRST



Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006



decoupling of glue dynamics



perturbative QCD

QCD strongly correlated!

Dynamical hadronisation

Mitter, JMP, Strodthoff, PRD 91 (2015) 054035
Braun, Fister, Haas, JMP, Rennecke, PRD 94 (2016) 034016
Cyrol, Mitter, JMP, Strodthoff, PRD 97 (2018) 054006

Towards apparent convergence in quantum gravity I expansion in curvature invariants

Quantum Effective Action: $\Gamma[g] = \sum_n c_{n,k} \int d^4x \sqrt{g} \mathcal{O}_n(g)$



Λ, R

Reuter, PRD 57 (1998) 971

Λ, R, R^2

Lauscher, Reuter, PRD 66 (2002) 025026

$\Lambda, f(R)$

**Codello, Percacci, Rahmede, AP 324 (2009) 414,
Falls, Litim, Nikolakopoulos, Rahmede,
arXiv:1301.4191, PRD 93 (2016) 10, 104022**

$\Lambda, R, C^{\mu\nu\kappa\lambda} C^{\kappa\lambda\rho\sigma} C^{\rho\sigma\mu\nu}$

Gies, Knorr, Lippoldt, Saueressig, PRL 116 (2016) 21, 211302

Towards apparent convergence in quantum gravity I

expansion in curvature invariants

Quantum Effective Action: $\Gamma[g] = \sum_n c_{n,k} \int d^4x \sqrt{g} \mathcal{O}_n(g)$

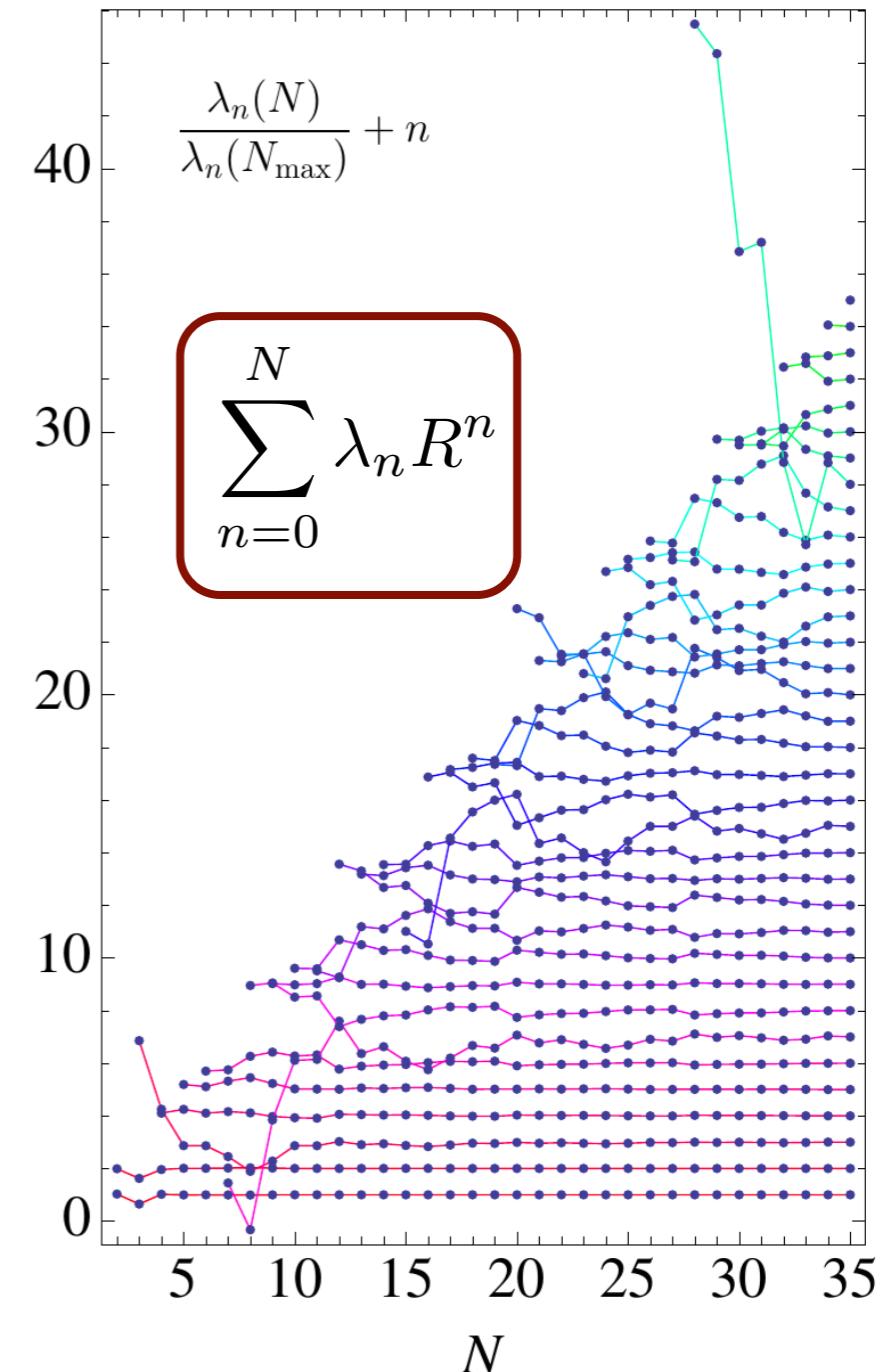
\mathcal{O}_n

Λ, R

Λ, R, R^2

$\Lambda, f(R)$

$\Lambda, R, C^{\mu\nu\kappa\lambda}C^{\kappa\lambda\rho\sigma}C^{\rho\sigma\mu\nu}$



Towards apparent convergence in quantum gravity II

vertex expansion

$$\Gamma^{(m,n \geq 2)}$$

$$\begin{aligned} \partial_t \Gamma_k &= \frac{1}{2} \text{ (blue loop with } \otimes \text{)} - \text{ (red dashed loop with } \otimes \text{)} \\ \partial_t \Gamma_k^{(h)} &= -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (red dashed loop with } \otimes \text{)} \\ \partial_t \Gamma_k^{(2h)} &= -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (blue loop with } \otimes \text{)} - 2 \text{ (red dashed loop with } \otimes \text{)} \\ \partial_t \Gamma_k^{(c\bar{c})} &= \dots \text{ (red dashed loop with } \otimes \text{)} + \dots \text{ (red dashed loop with } \otimes \text{)} \\ \partial_t \Gamma_k^{(3h)} &= -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} - 3 \text{ (blue loop with } \otimes \text{)} + 6 \text{ (red dashed loop with } \otimes \text{)} \\ \partial_t \Gamma_k^{(4h)} &= -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} + 4 \text{ (blue loop with } \otimes \text{)} - 6 \text{ (blue loop with } \otimes \text{)} \\ &\quad - 12 \text{ (blue loop with } \otimes \text{)} + 12 \text{ (blue loop with } \otimes \text{)} - 24 \text{ (red dashed loop with } \otimes \text{)} \end{aligned}$$

Towards apparent convergence in quantum gravity II

vertex expansion

$$\Gamma^{(m,n \geq 2)}$$

Reuter, PRD 57 (1998) 971, ...

$$\partial_t \Gamma_k = \frac{1}{2} \text{ (blue loop with } \otimes \text{)} - \text{ (red dashed loop with } \otimes \text{)}$$

background approximation: $\Gamma^{(m,n)} \approx \Gamma^{(m+n,0)}$

$$\partial_t \Gamma_k^{(h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(2h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (blue loop with } \otimes \text{)} - 2 \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(c\bar{c})} = \dots \text{ (red dashed loop with } \otimes \text{)} + \dots \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(3h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} - 3 \text{ (blue loop with } \otimes \text{)} + 6 \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(4h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} + 4 \text{ (blue loop with } \otimes \text{)} - 6 \text{ (blue loop with } \otimes \text{)}$$

$$- 12 \text{ (blue loop with } \otimes \text{)} + 12 \text{ (blue loop with } \otimes \text{)} - 24 \text{ (red dashed loop with } \otimes \text{)}$$

Towards apparent convergence in quantum gravity II

vertex expansion

$$\Gamma^{(m,n \geq 2)}$$

bi-metric approach: Manrique, Reuter, Saueressig, Annals Phys. 326 (2011) 463

$$\partial_t \Gamma_k = \frac{1}{2} \text{ (blue loop with } \otimes \text{)} - \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (red dashed loop with } \otimes \text{)}$$

level 1: $\Gamma^{(m,n)} \approx \Gamma^{(m+n-1,1)}$

$$\partial_t \Gamma_k^{(2h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (blue loop with } \otimes \text{)} - 2 \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(c\bar{c})} = \dots \text{ (blue loop with } \otimes \text{)} + \dots \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(3h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} - 3 \text{ (blue loop with } \otimes \text{)} + 6 \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(4h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} + 4 \text{ (blue loop with } \otimes \text{)} - 6 \text{ (blue loop with } \otimes \text{)}$$

$$- 12 \text{ (blue loop with } \otimes \text{)} + 12 \text{ (blue loop with } \otimes \text{)} - 24 \text{ (red dashed loop with } \otimes \text{)}$$

Aiming at apparent convergence

Towards apparent convergence in quantum gravity II

vertex expansion

$$\Gamma^{(m,n \geq 2)}$$

geometrical approach: Donkin, JMP, arXiv:1203.4207

flat expansion: Christiansen, Litim, JMP, Rodigast, PLB 728 (2014) 114

$$\partial_t \Gamma_k = \frac{1}{2} \text{ (blue loop with } \otimes \text{)} - \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(2h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (blue loop with } \otimes \text{)} - 2 \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(c\bar{c})} = \text{ (red dashed loop with } \otimes \text{)} + \text{ (red dashed loop with } \otimes \text{)}$$

level 2: $\Gamma^{(m,n)} \approx \Gamma^{(m+n-2,2)}$

$$Z_h(p), Z_c(p), \mu = -2\lambda_2$$

$$\partial_t \Gamma_k^{(3h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} - 3 \text{ (blue loop with } \otimes \text{)} + 6 \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(4h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} + 4 \text{ (blue loop with } \otimes \text{)} - 6 \text{ (blue loop with } \otimes \text{)}$$

$$- 12 \text{ (blue loop with } \otimes \text{)} + 12 \text{ (blue loop with } \otimes \text{)} - 24 \text{ (red dashed loop with } \otimes \text{)}$$

Aiming at apparent convergence

Towards apparent convergence in quantum gravity II

vertex expansion

$$\Gamma^{(m,n \geq 2)}$$

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

$$\partial_t \Gamma_k = \frac{1}{2} \text{ (blue loop with } \otimes \text{)} - \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(2h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (blue loop with } \otimes \text{)} - 2 \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(c\bar{c})} = \dots \text{ (red dashed loop with } \otimes \text{)} + \dots \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(3h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} - 3 \text{ (blue loop with } \otimes \text{)} + 6 \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(4h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} + 4 \text{ (blue loop with } \otimes \text{)} - 6 \text{ (blue loop with } \otimes \text{)}$$

$$- 12 \text{ (blue loop with } \otimes \text{)} + 12 \text{ (blue loop with } \otimes \text{)} - 24 \text{ (red dashed loop with } \otimes \text{)}$$

level 3: $\Gamma^{(m,n)} \approx \Gamma^{(m+n-3,3)}$

$Z_h(p), Z_c(p), \mu = -2\lambda_2$

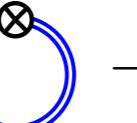
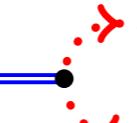
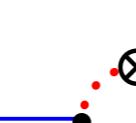
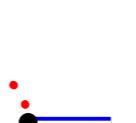
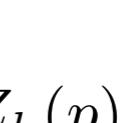
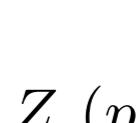
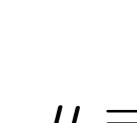
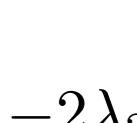
$g_3(p), \lambda_3$

Towards apparent convergence in quantum gravity II

vertex expansion

$$\Gamma^{(m,n \geq 2)}$$

Denz, JMP, Reichert, EPJ C78 (2018) 4, 336

$\partial_t \Gamma_k = \frac{1}{2}$		$-$					
$\partial_t \Gamma_k^{(h)} = -\frac{1}{2}$		$+$					
$\partial_t \Gamma_k^{(2h)} = -\frac{1}{2}$		$+$		$- 2$			
$\partial_t \Gamma_k^{(c\bar{c})} =$		$+$					
$\partial_t \Gamma_k^{(3h)} = -\frac{1}{2}$		$+$		$- 3$		$+ 6$	
$\partial_t \Gamma_k^{(4h)} = -\frac{1}{2}$		$+$		$+ 4$		$- 6$	
	$- 12$		$+ 12$		$- 24$		

level 4: $\Gamma^{(m,n)} \approx \Gamma^{(m+n-4,4)}$

$Z_h(p), Z_c(p), \mu = -2\lambda_2$

$g_3(p), \lambda_3$

$g_4(p), \lambda_4$

Towards apparent convergence in quantum gravity II

vertex expansion

$$\Gamma^{(m,n \geq 2)}$$

Denz, JMP, Reichert, EPJ C78 (2018) 4, 336

$$\partial_t \Gamma_k = \frac{1}{2} \text{ (blue loop with } \otimes \text{)} - \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(2h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + \text{ (blue loop with } \otimes \text{)} - 2 \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(c\bar{c})} = \dots \text{ (red dashed loop with } \otimes \text{)} + \dots \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(3h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} - 3 \text{ (blue loop with } \otimes \text{)} + 6 \text{ (red dashed loop with } \otimes \text{)}$$

$$\partial_t \Gamma_k^{(4h)} = -\frac{1}{2} \text{ (blue loop with } \otimes \text{)} + 3 \text{ (blue loop with } \otimes \text{)} + 4 \text{ (blue loop with } \otimes \text{)} - 6 \text{ (blue loop with } \otimes \text{)}$$

$$- 12 \text{ (blue loop with } \otimes \text{)} + 12 \text{ (green box with } \otimes \text{)} - 24 \text{ (red dashed loop with } \otimes \text{)}$$

level 4: $\Gamma^{(m,n)} \approx \Gamma^{(m+n-4,4)}$

$Z_h(p), Z_c(p), \mu = -2\lambda_2$

$g_3(p), \lambda_3$

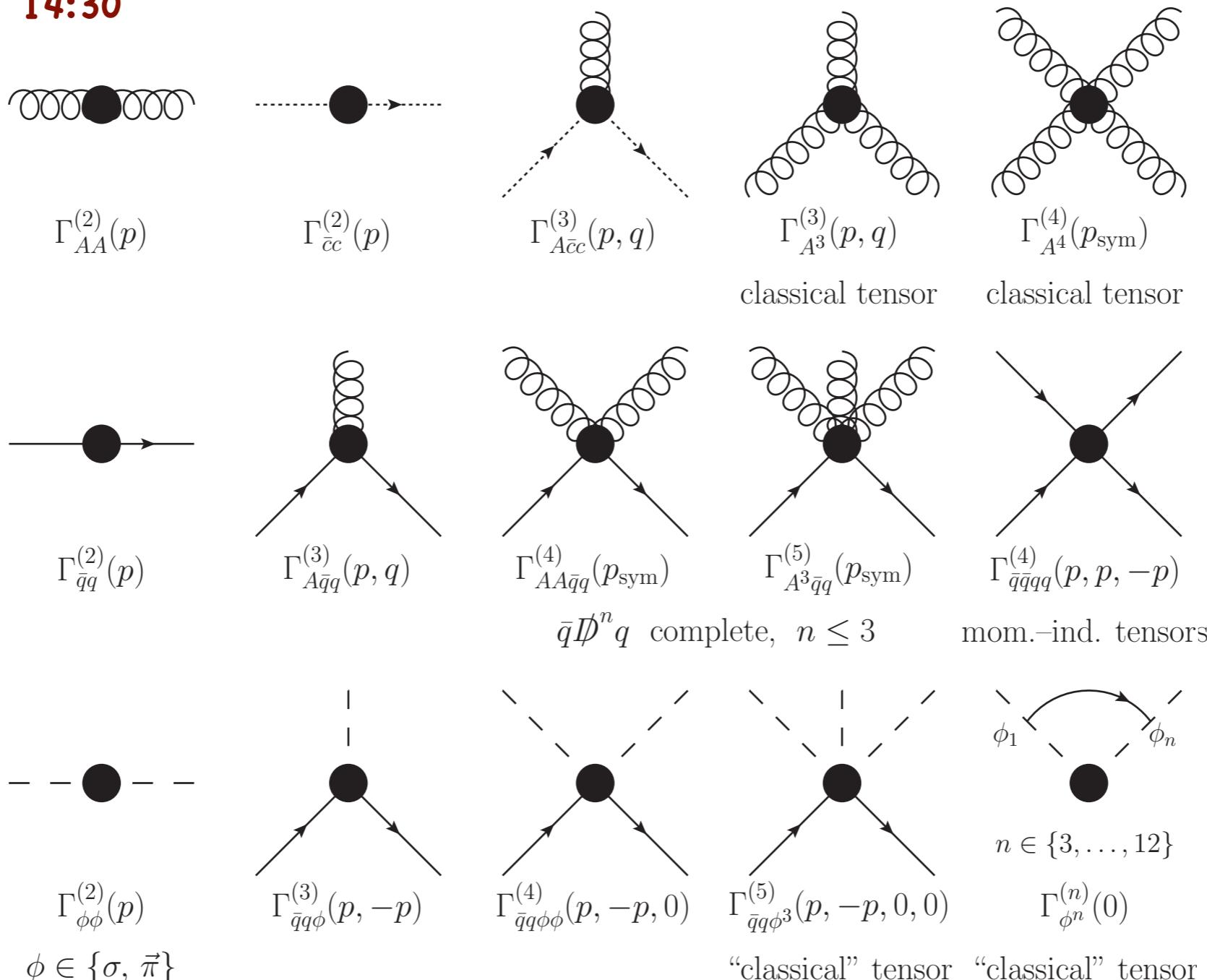
$g_4(p), \lambda_4$

$\sim 10^{12}$ terms

Towards apparent convergence in QCD

see talk of Mario Mitter
Thursday, 14:30

vertex expansion



Cyrol, Mitter, JMP, Strodthoff,
PRD 97 (2018) 054006,
PRD 97 (2018) 054015

Cyrol, Fister, Mitter, JMP, Strodthoff,
PRD 94 (2016) 054005

Mitter, JMP, Strodthoff,
PRD 91 (2015) 054035

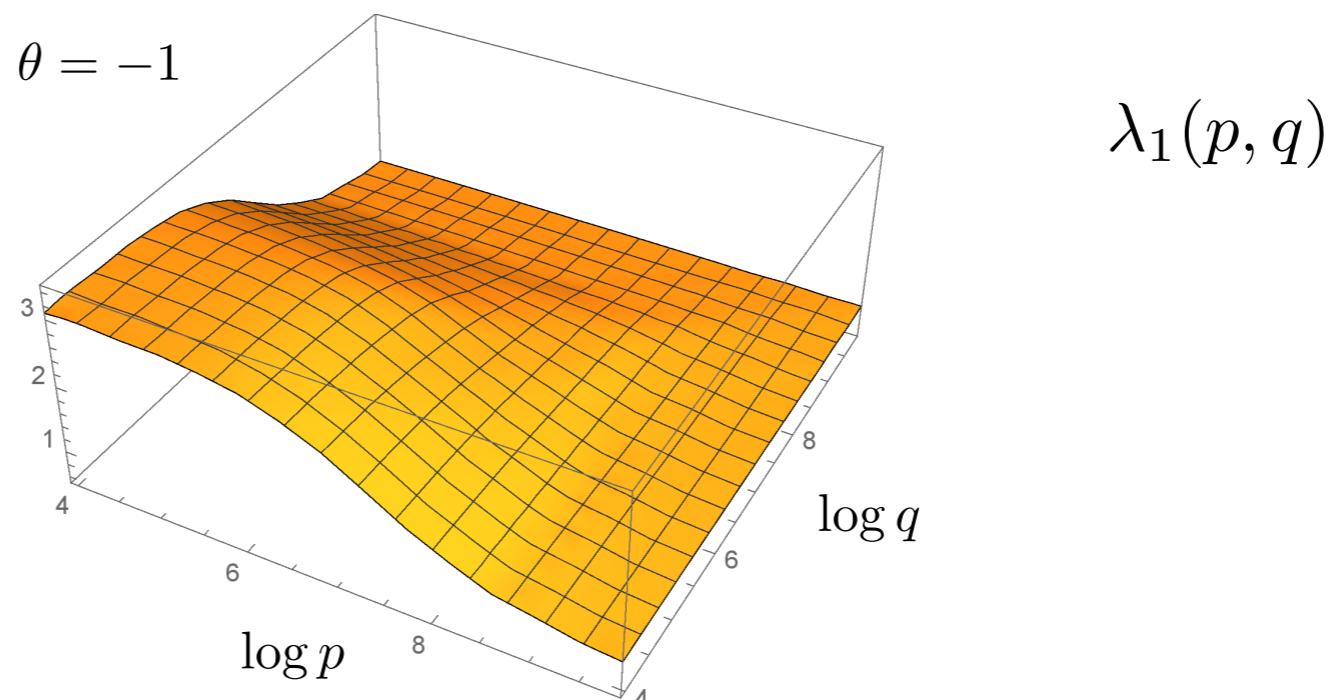
Aiming at apparent convergence



QCD: Quark-gluon vertex

$$\theta = \frac{p \cdot q}{\sqrt{p^2 q^2}}$$

p,q in MeV



up-to-date 1st principles works:

FunMethods: Williams, EPJ A51 (2015) 57
 Sanchis-Alepuz, Williams, PLB 749 (2015) 592
 Williams, Fischer, Heupel, PRD 93 (2016) 034026

Aguilar, Binosi, Ibanez, Papavassiliou, PRD 89 (2014) 065027
 Binosi, Chang, Papavassiliou, Qin, Roberts, PRD 95 (2017) 031501
 Aguilar, Cardona, Ferreira, Papavassiliou, arXiv:1610.06158

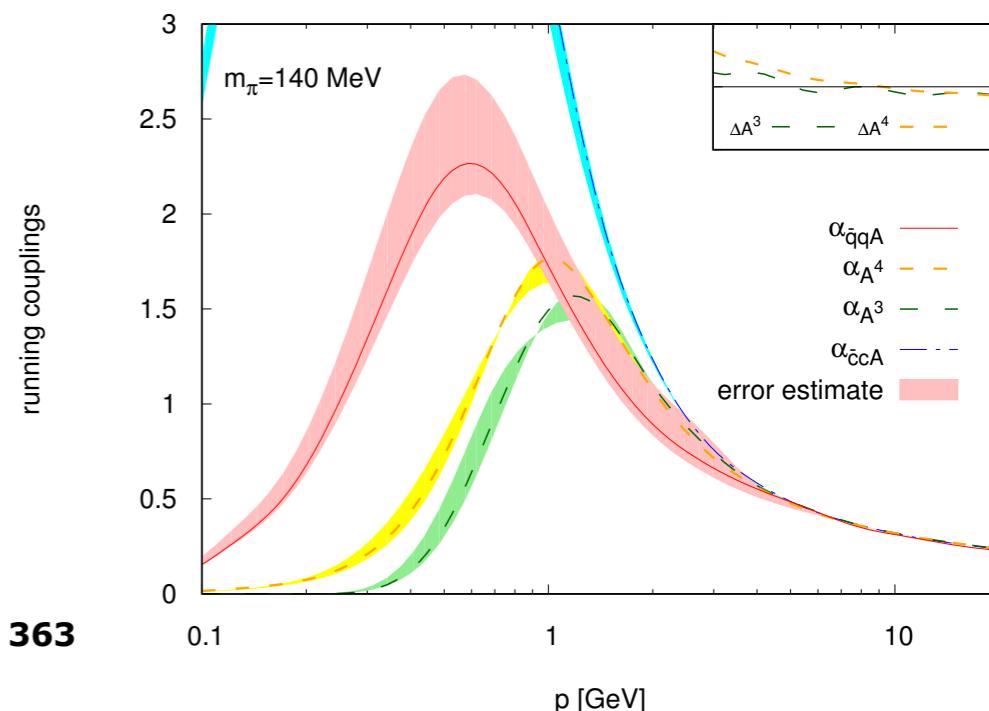
Mitter, JMP, Strodthoff, PRD 91 (2015) 054035

Pelaez, Tissier, Wschebor, PRD 92 (2015) 045012

Eichmann, Sanchis-Alepuz, Williams, Alkofer, Fischer, PPNP 91 (2016) 1

lattice: Oliveira, Kizilersü, Silva, Skullerud, Sternbeck, Williams, APP Suppl. 9 (2016) 363

Beware of BRST



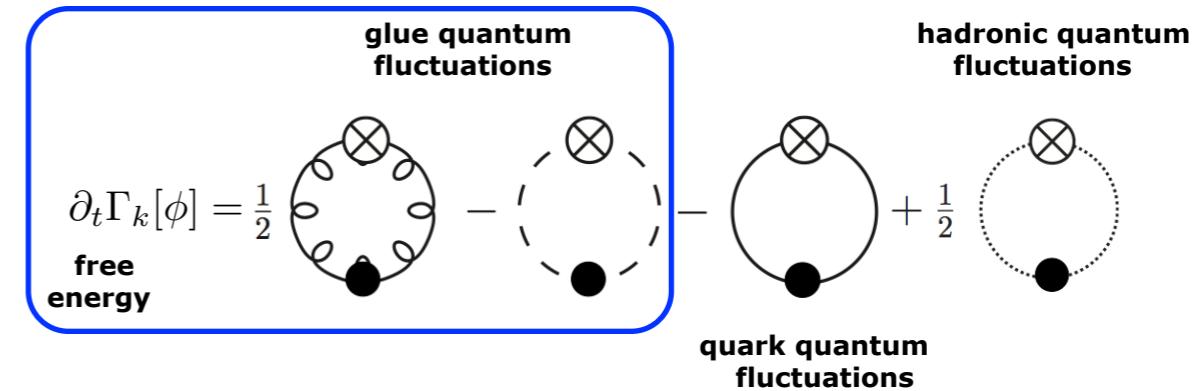
Aiming at apparent convergence

Confinement

FRG: Braun, Gies, JMP, PLB 684 (2010) 262

FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

$$L[A_0] = \frac{1}{N_c} \text{tr} \mathcal{P} e^{i g \int_0^\beta A_0(x)}$$

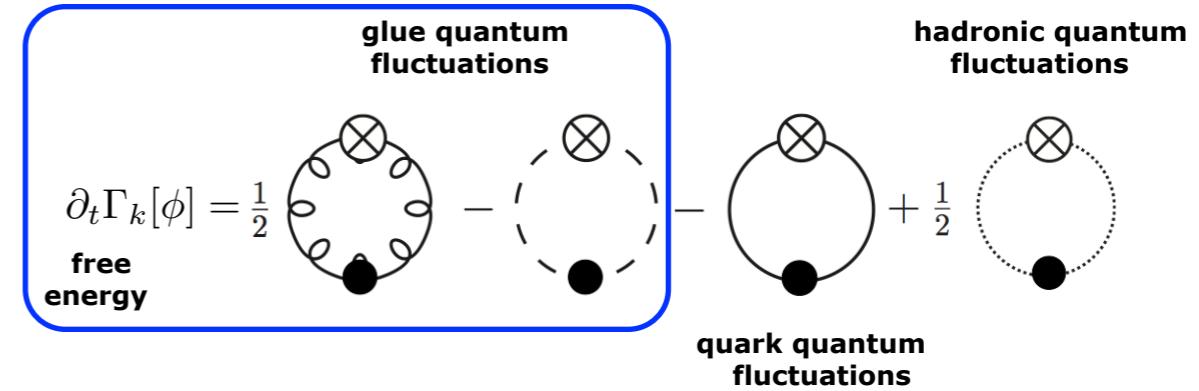


Confinement

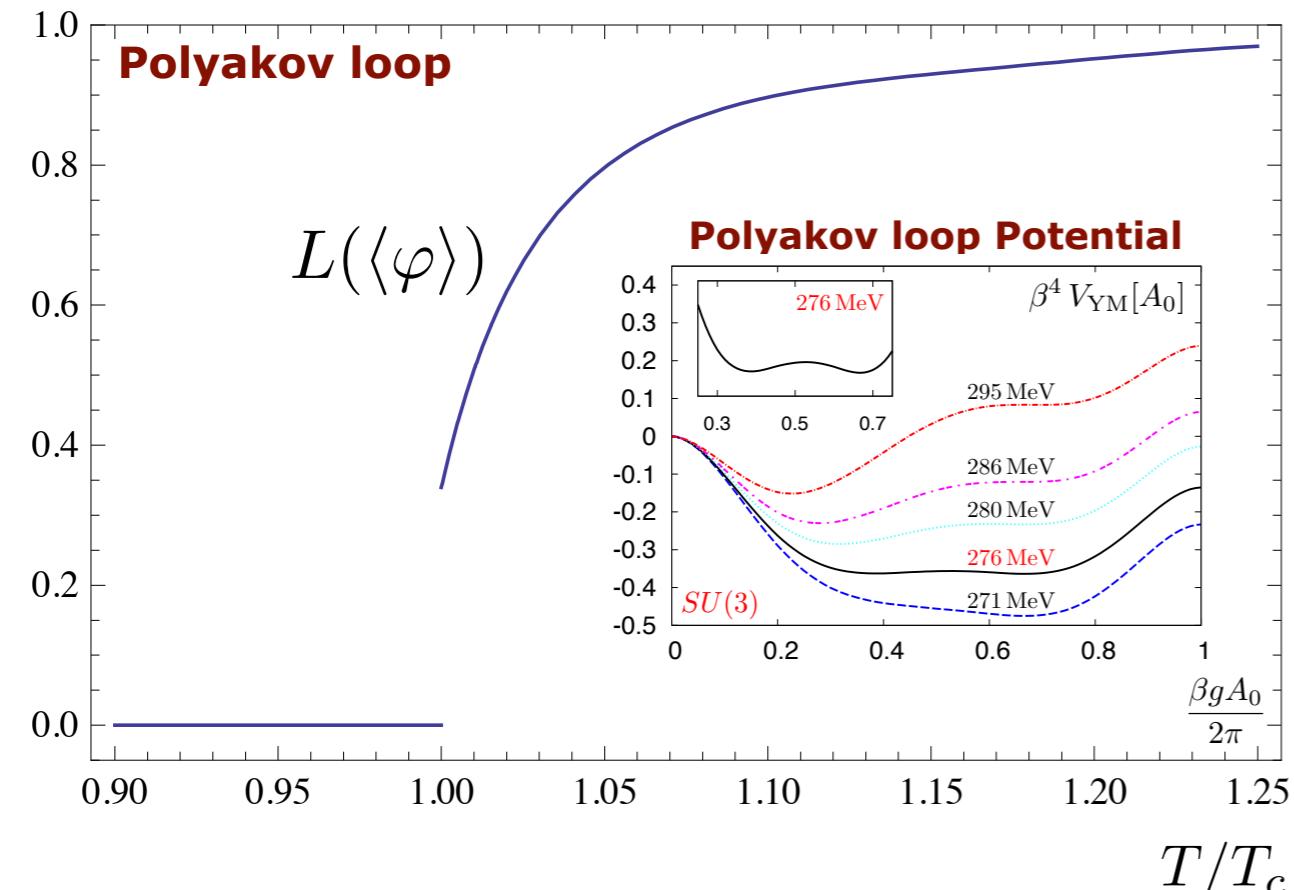
FRG: Braun, Gies, JMP, PLB 684 (2010) 262

FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

$$L[A_0] = \frac{1}{N_c} \text{tr } \mathcal{P} e^{i g \int_0^\beta A_0(x)}$$



$$\mathcal{P} e^{i g \int_0^\beta A_0(x)} = e^{i\varphi}$$



$$T_c/\sqrt{\sigma} = 0.658 \pm 0.023$$

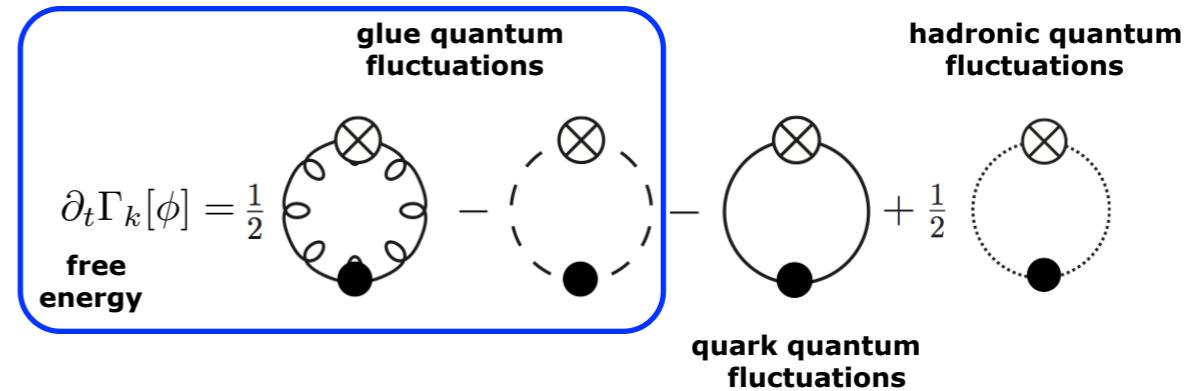
$$\text{lattice : } T_c/\sqrt{\sigma} = 0.646$$

Confinement

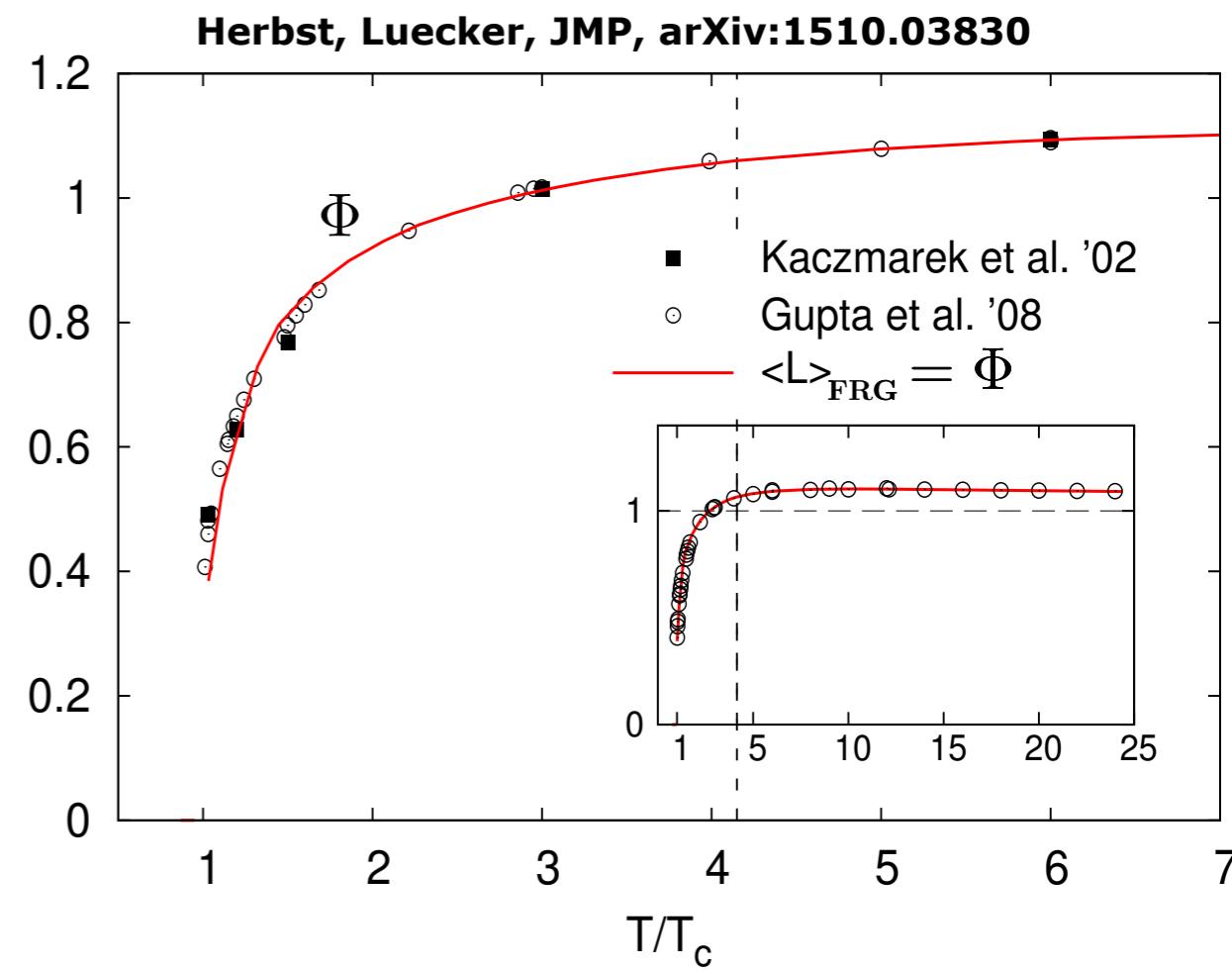
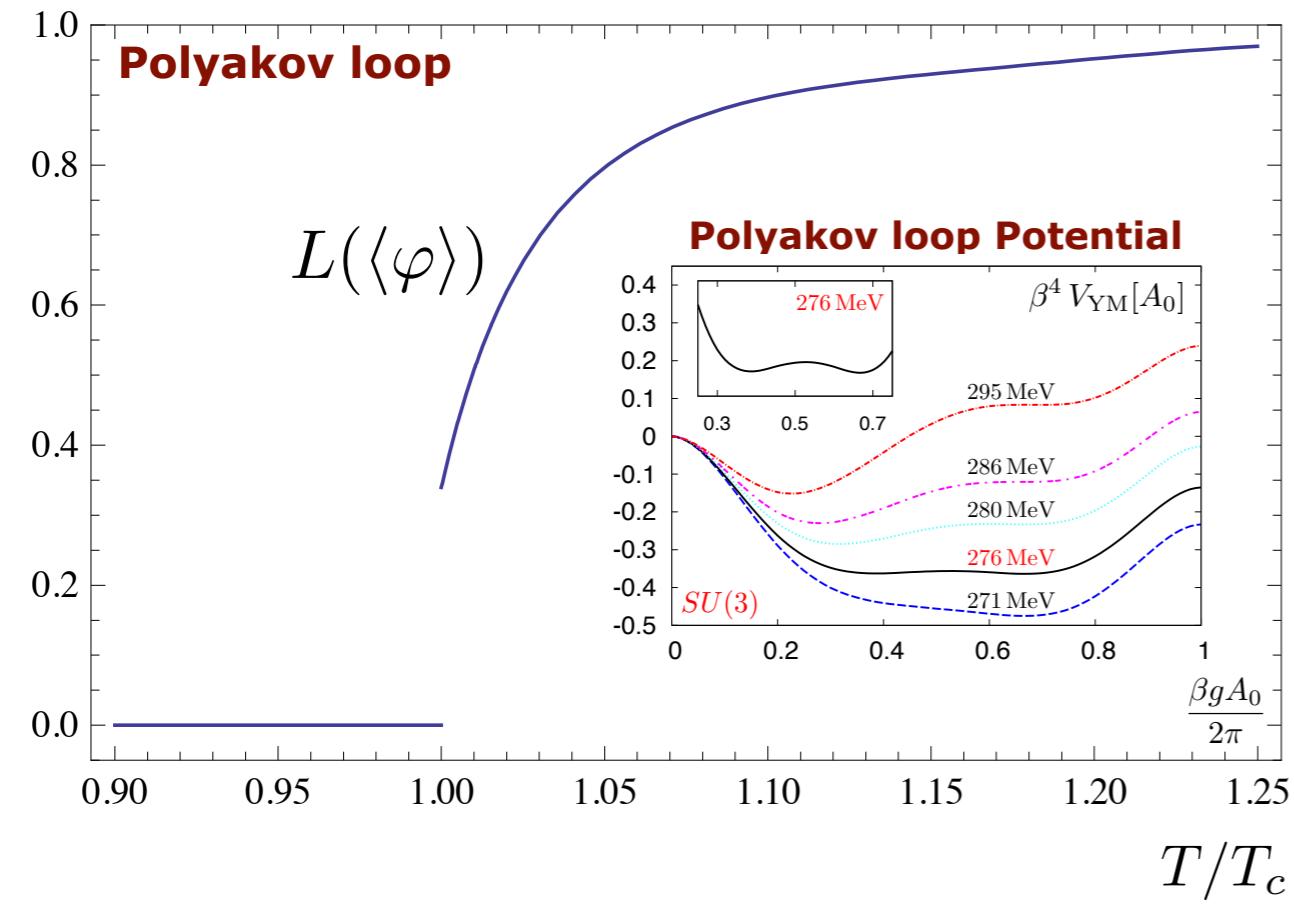
FRG: Braun, Gies, JMP, PLB 684 (2010) 262

FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

$$L[A_0] = \frac{1}{N_c} \text{tr } \mathcal{P} e^{ig \int_0^\beta A_0(x)}$$



$$\mathcal{P} e^{ig \int_0^\beta A_0(x)} = e^{i\varphi}$$



Summary

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \text{ (orange loop with } \otimes \text{) - } \text{ (dashed loop with } \otimes \text{) - } \text{ (solid loop with } \otimes \text{) + } \frac{1}{2} \text{ (blue loop with } \otimes \text{)}$$

asymptotically safe QG

correlation functions

asymptotically safe phase structure

asymptotically safe Standard Model

asymptotically safe inflation

asymptotically safe black holes

⋮

strongly correlated QCD

correlation functions

phase structure for small densities

spectral functions

transport coefficients

QCD-assisted hydrodynamics & transport

⋮

QG as perturbative as possible?

QG enjoys effective universality!?

'One force to rule them all'!?

QCD strongly correlated!

Dynamical hadronisation