Spectral Functions of Lorentzian Quantum Gravity

2606.19321

Gabriel Assant
with Daniel Litim and Manuel Reichert

ERG, 09/2026

UNIVERSITY OF SUSSEX

Healthy and unitary quantum gravity

Healthy/unitary theory has no ghosts or tachyons.

e.g. GR

$$G^{hh}_{\mu\nu\rho\sigma} \propto \boxed{\mathcal{G}_{\mathrm{TT}}(p^2)\Pi^{\mathrm{TT}}_{\mu\nu\rho\sigma}} \boxed{- \frac{1}{2}\mathcal{G}_0(p^2)\Pi^0_{\mu\nu\rho\sigma} + \mathrm{gauge}}$$

2 on-shell propagating dofs (GWs)

Off-shell dofs

$$S_{EH} = \frac{1}{16\pi G_N}\int_x \sqrt{g}(2\Lambda_{cc} - R)$$

$$g_{\mu\nu} = \eta_{\mu\nu} + \boxed{h_{\mu\nu}}$$

Fluctuation graviton

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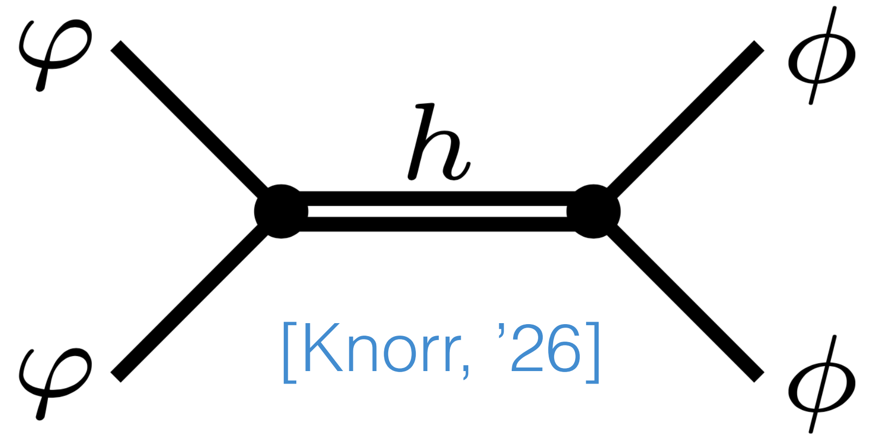
Enters scattering



[Knorr, '26]

[Chiesa, Pawlowski, Reichert '26]

Inflaton in R^2 gravity

See Angelo Portas Chiesa's talk!

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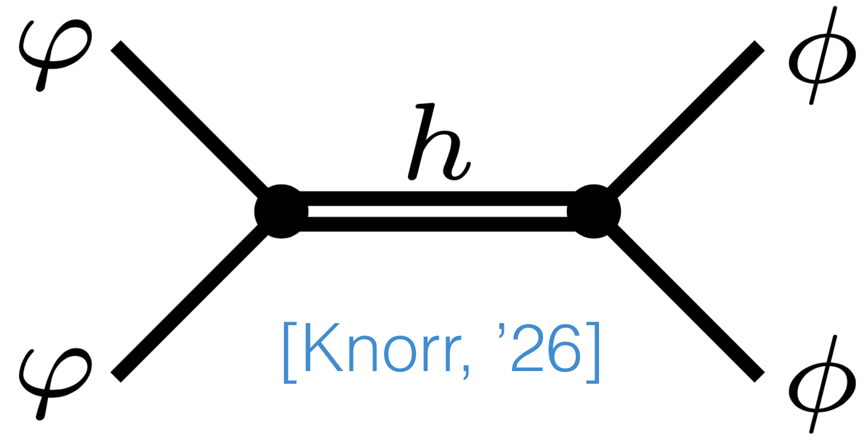

[Knorr, '26]

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Inflaton in R^2 gravity

<u>Spectral function:</u> access to real time correlators

$$\rho_{\rm TT/0}(\lambda) = \frac{1}{Z_{\rm TT/0}}\left[2\pi\delta\left(\lambda^2 - m^2_{\rm TT/0}\right) + \theta\left(\lambda^2 - 4m^2_{\rm TT/0}\right) f_{\rm TT/0}(\lambda)\right]$$

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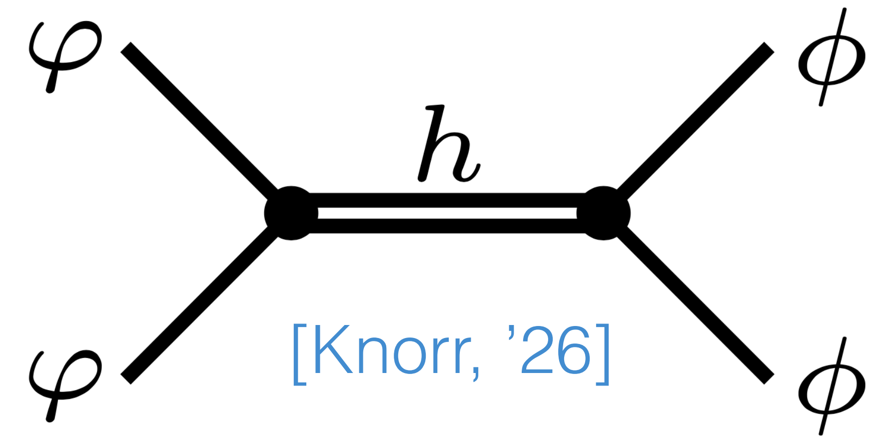

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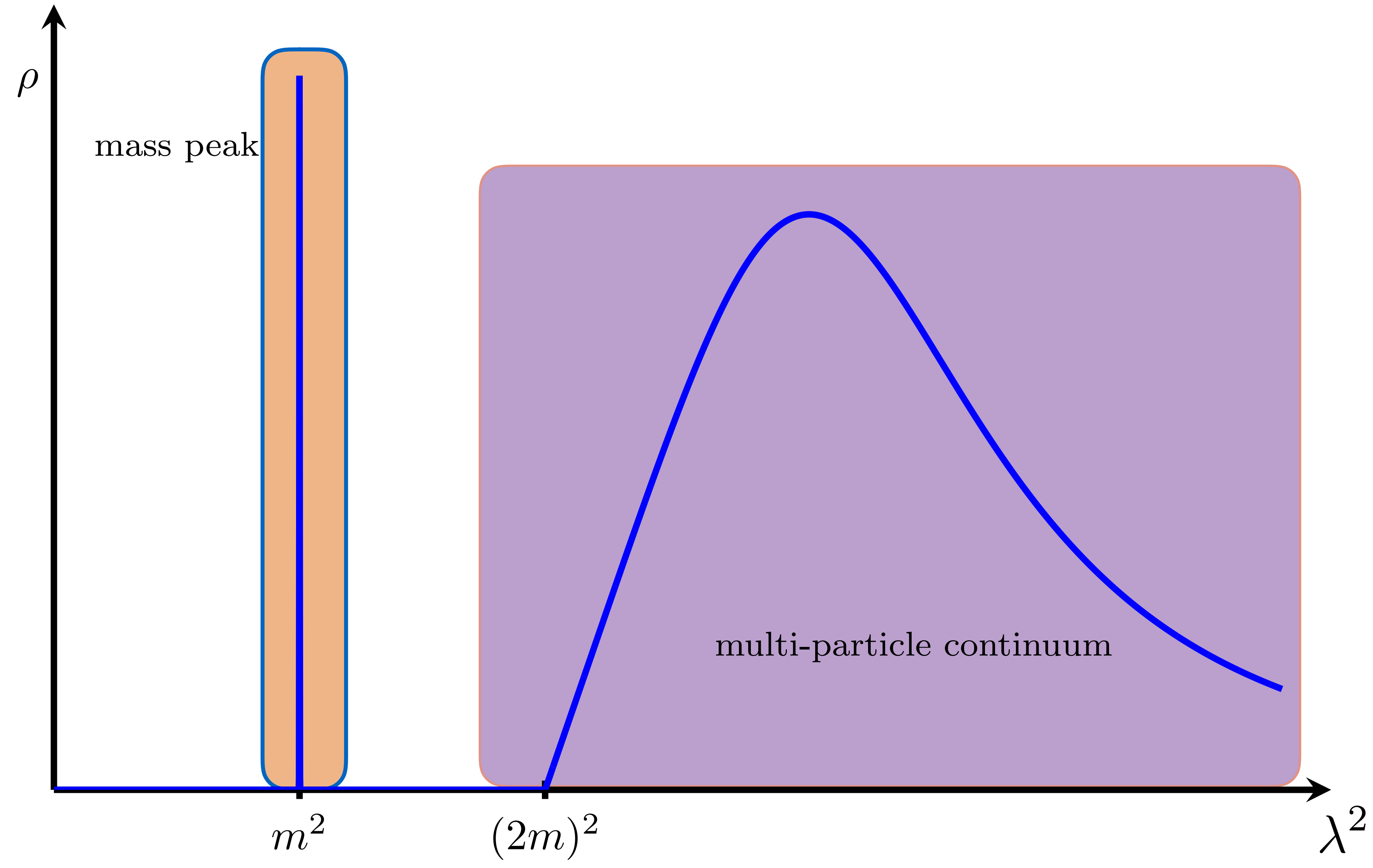

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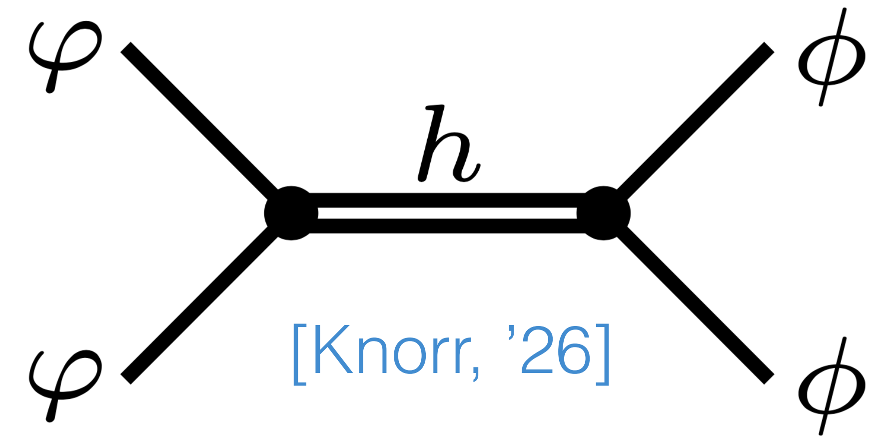

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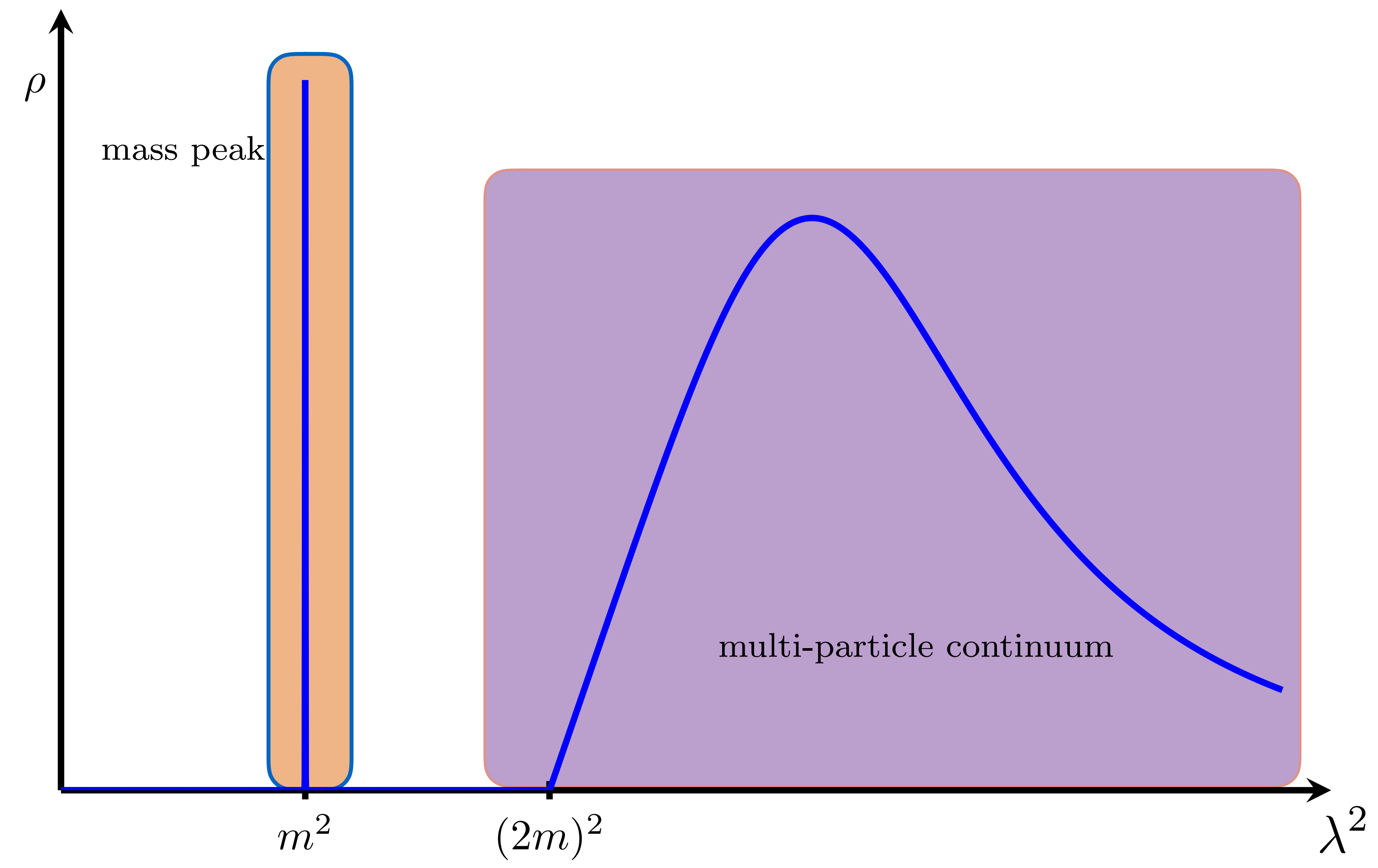

Access to propagator for all momenta

$$\mathcal{G}_{\mathrm{TT}/0}(p_0) = \int_0^\infty \frac{\lambda\,\mathrm{d}\lambda}{\pi}\frac{\rho_{\mathrm{TT}/0}(\lambda)}{\lambda^2 + p_0^2}$$

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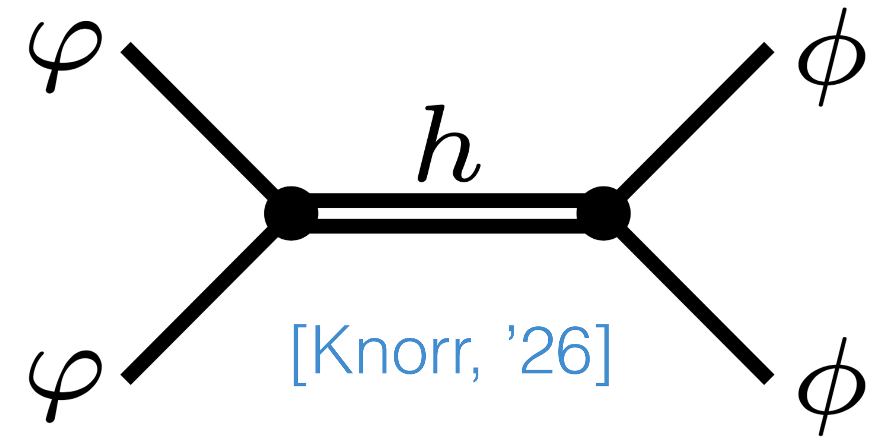

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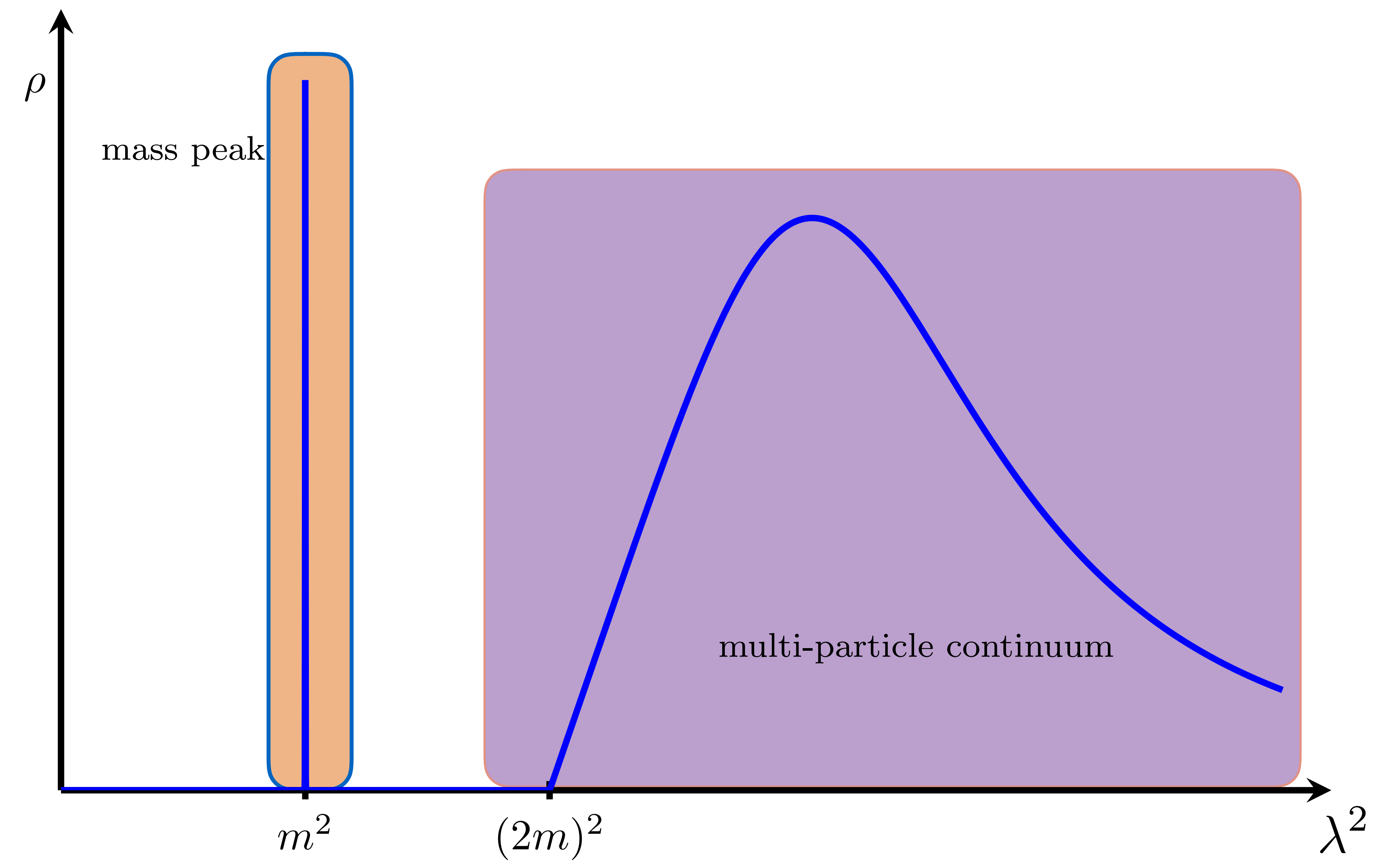

Challenges

Need non-perturbative Lorentzian framework

Regulators in the Functional Renormalisation Group

The regulator implements the Wilsonian integrating out of momentum shells

$$\partial_t \Gamma_k = \frac{1}{2} \mathrm{Tr}\left[G_k \partial_t R_k\right]$$

$$\boxed{R_k \propto k^2\, r_k(x)}$$

e.g.

$$r_{\mathrm{optimised}}(x) = x\left(\frac{1}{x} - 1\right)\theta(1-x)$$

[Litim '00]

$$r_{\exp}(x) = e^{-x}$$

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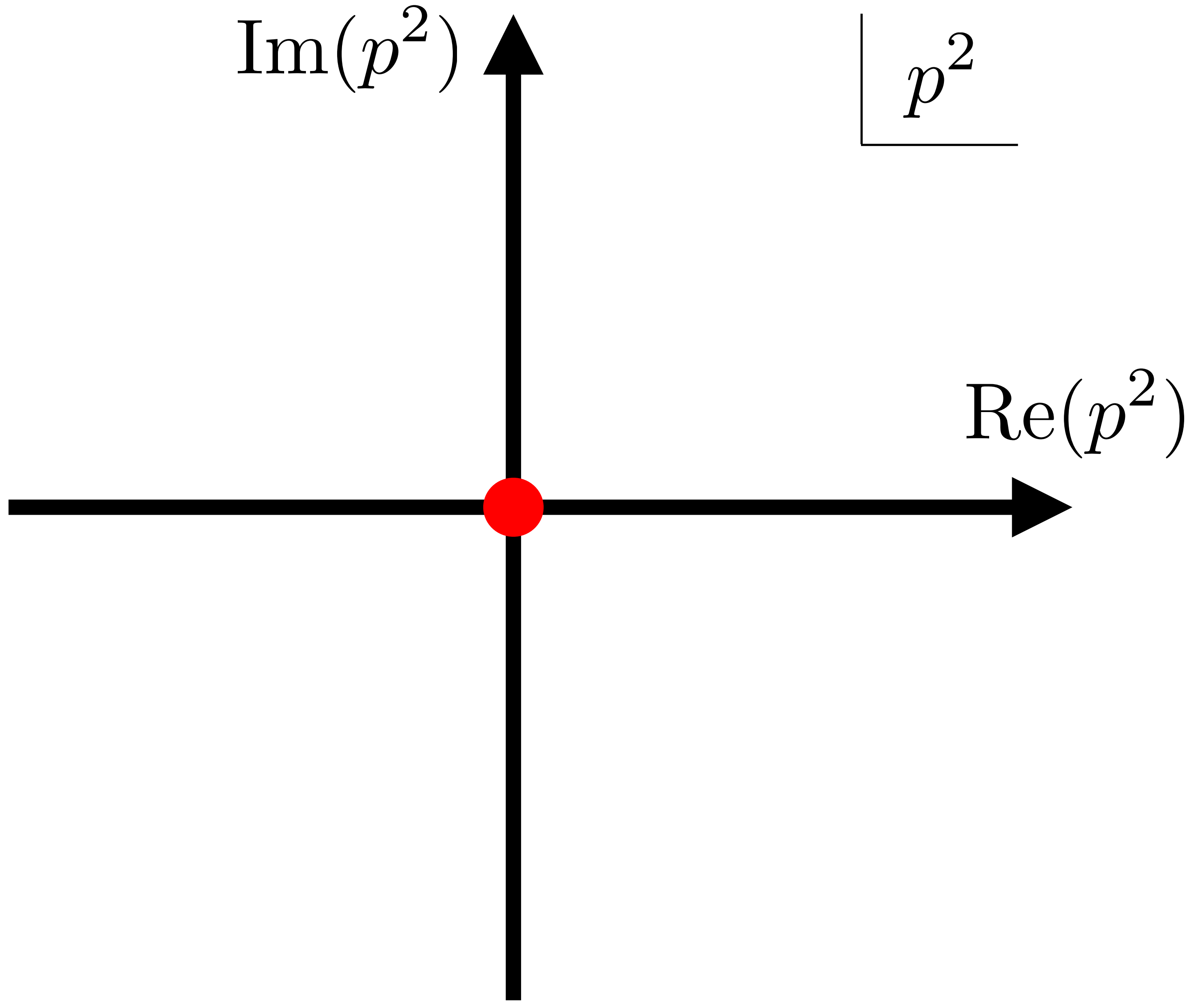
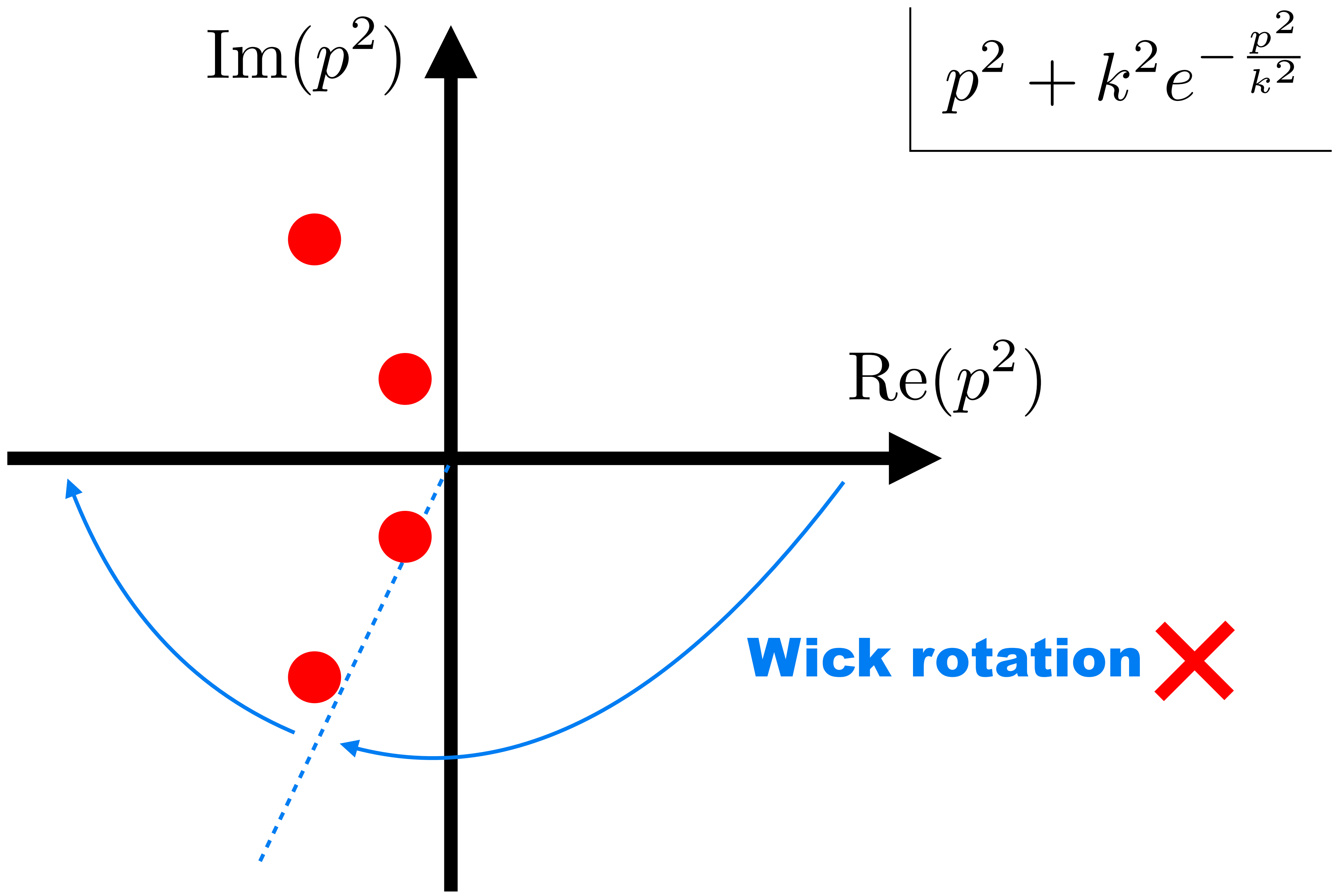
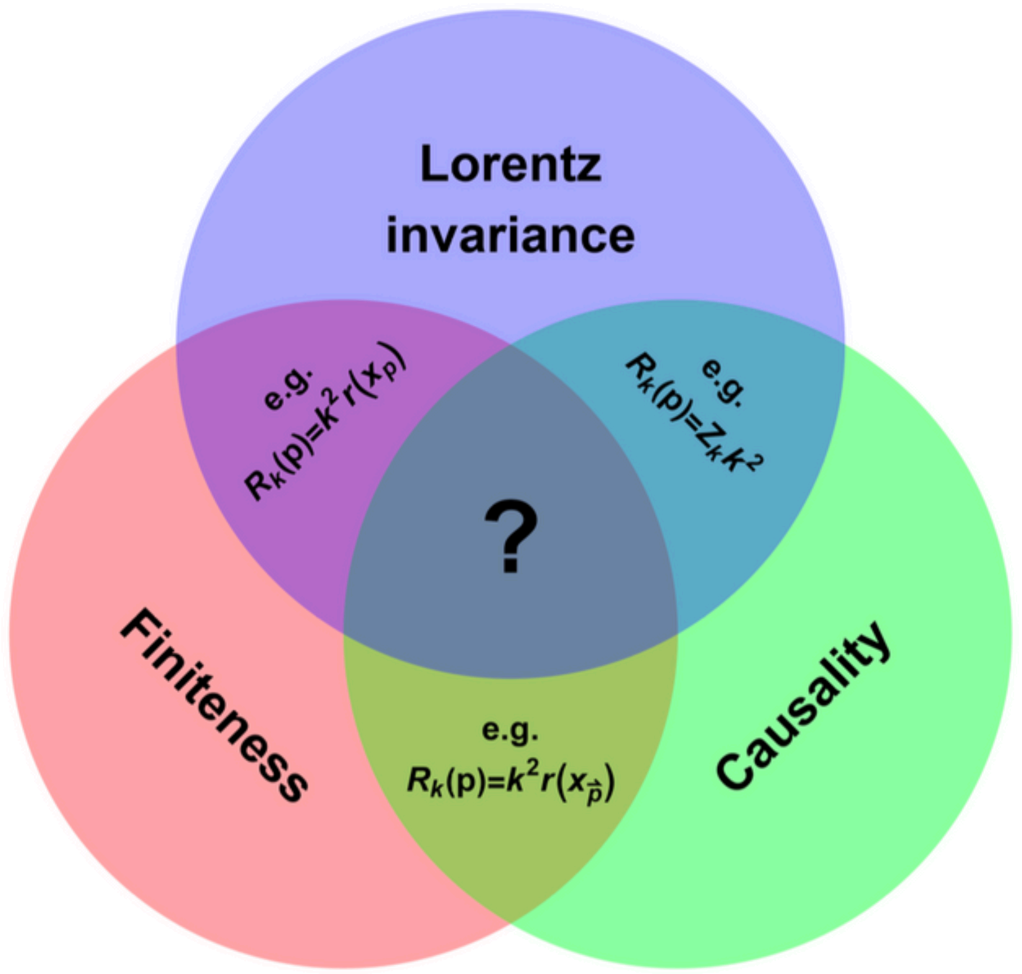
Modifies the two-point function





Want a regulator which allows analytic continuations for k>0

Callan-Symanzik Regulator

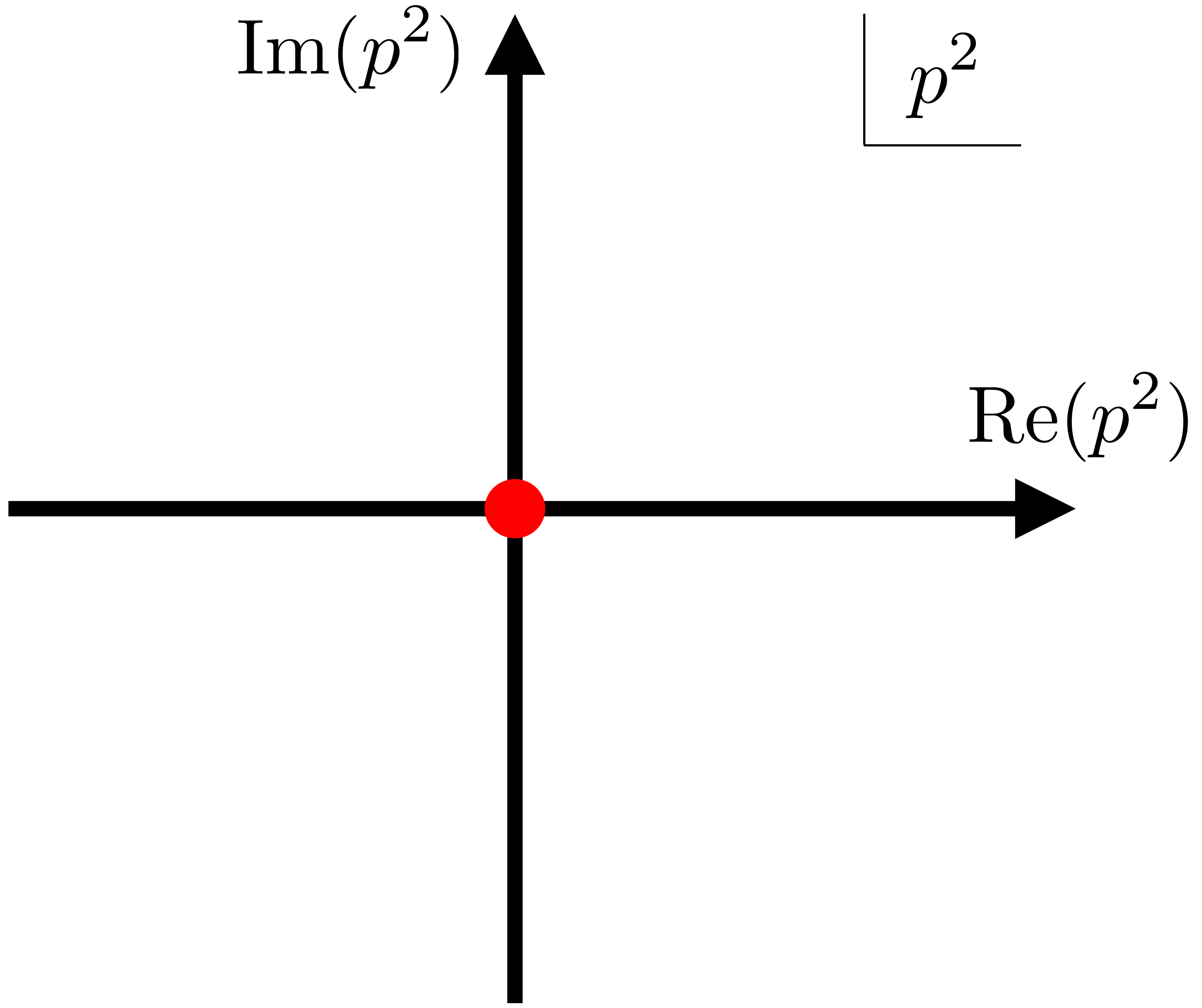


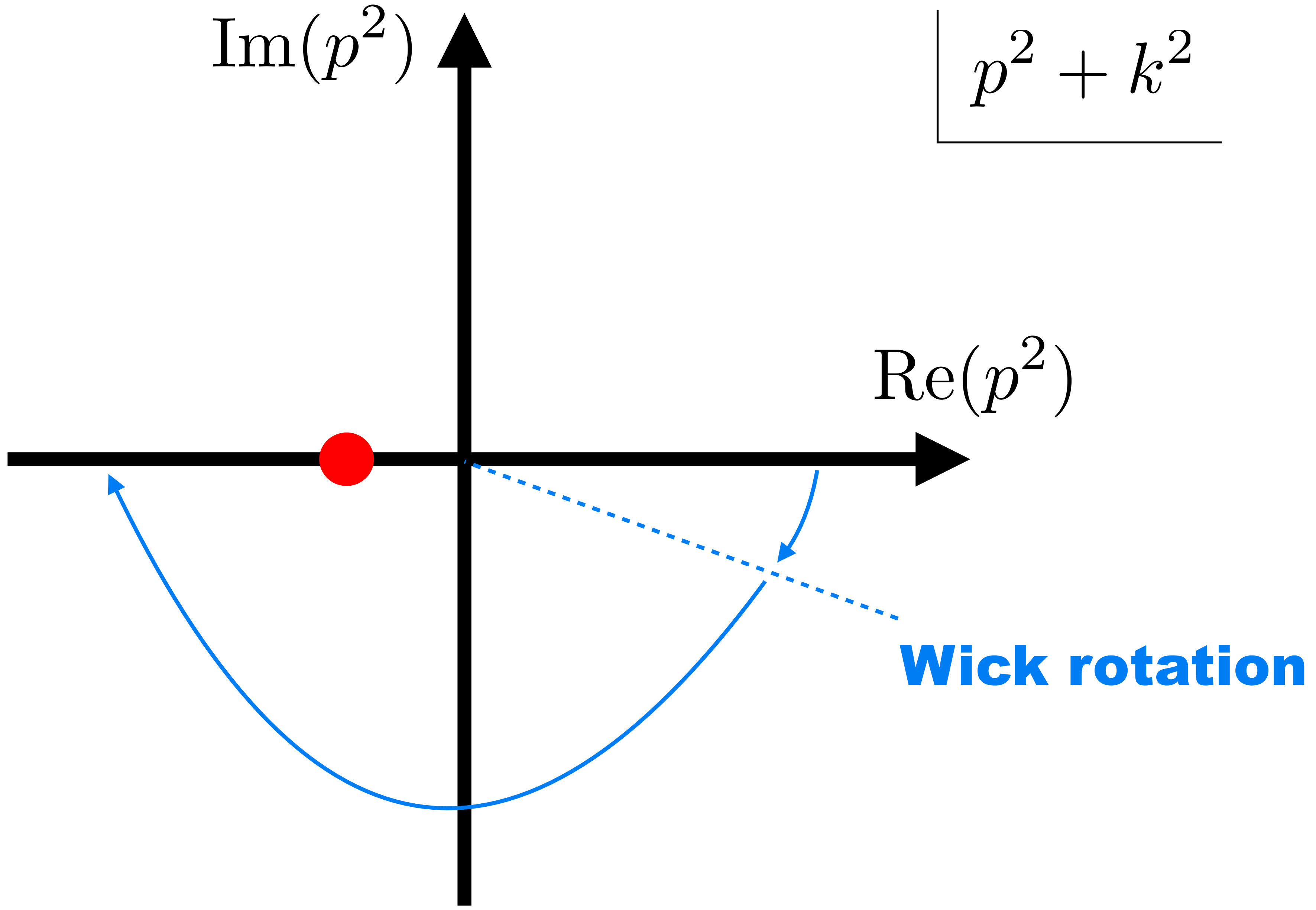
[Braun, et al '22]

Callan-Symanzik regulator preserves causality

$$R_k \propto k^2$$

Regulated two-point function





Can analytically continue to Lorentzian signature at k>0

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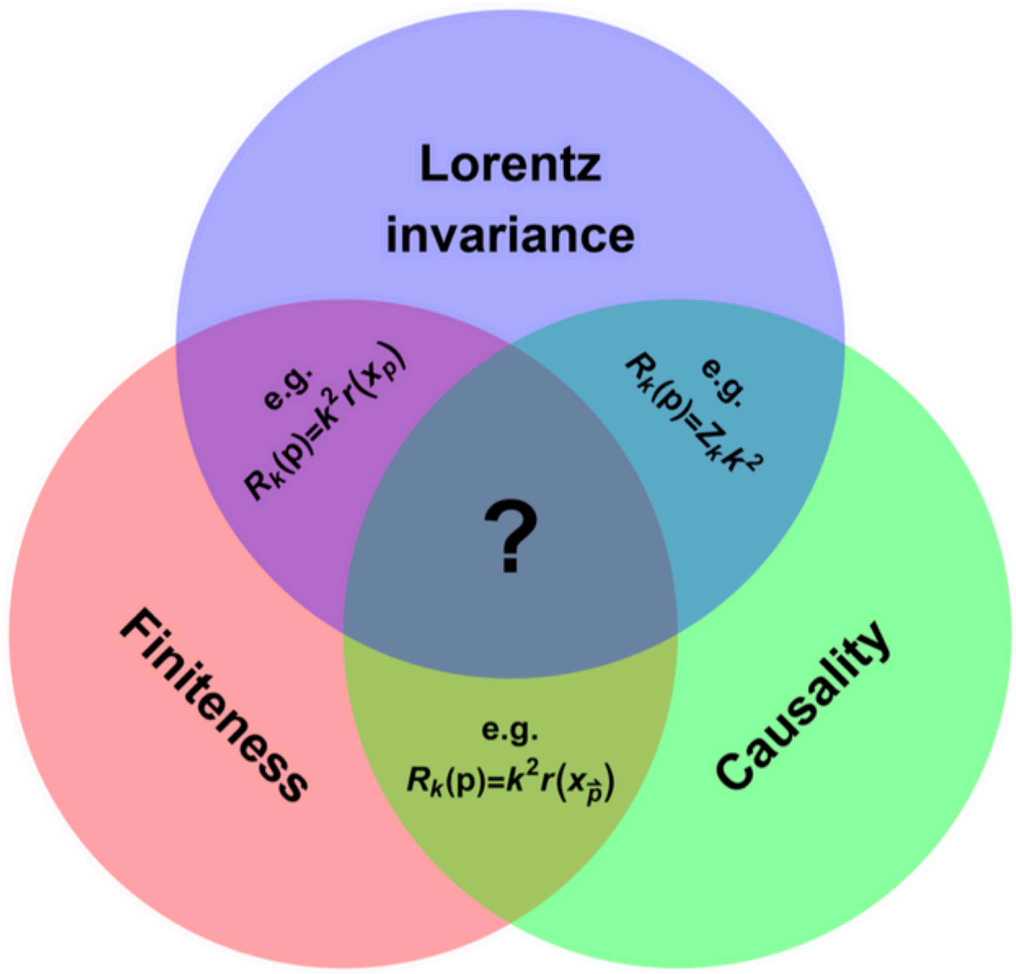

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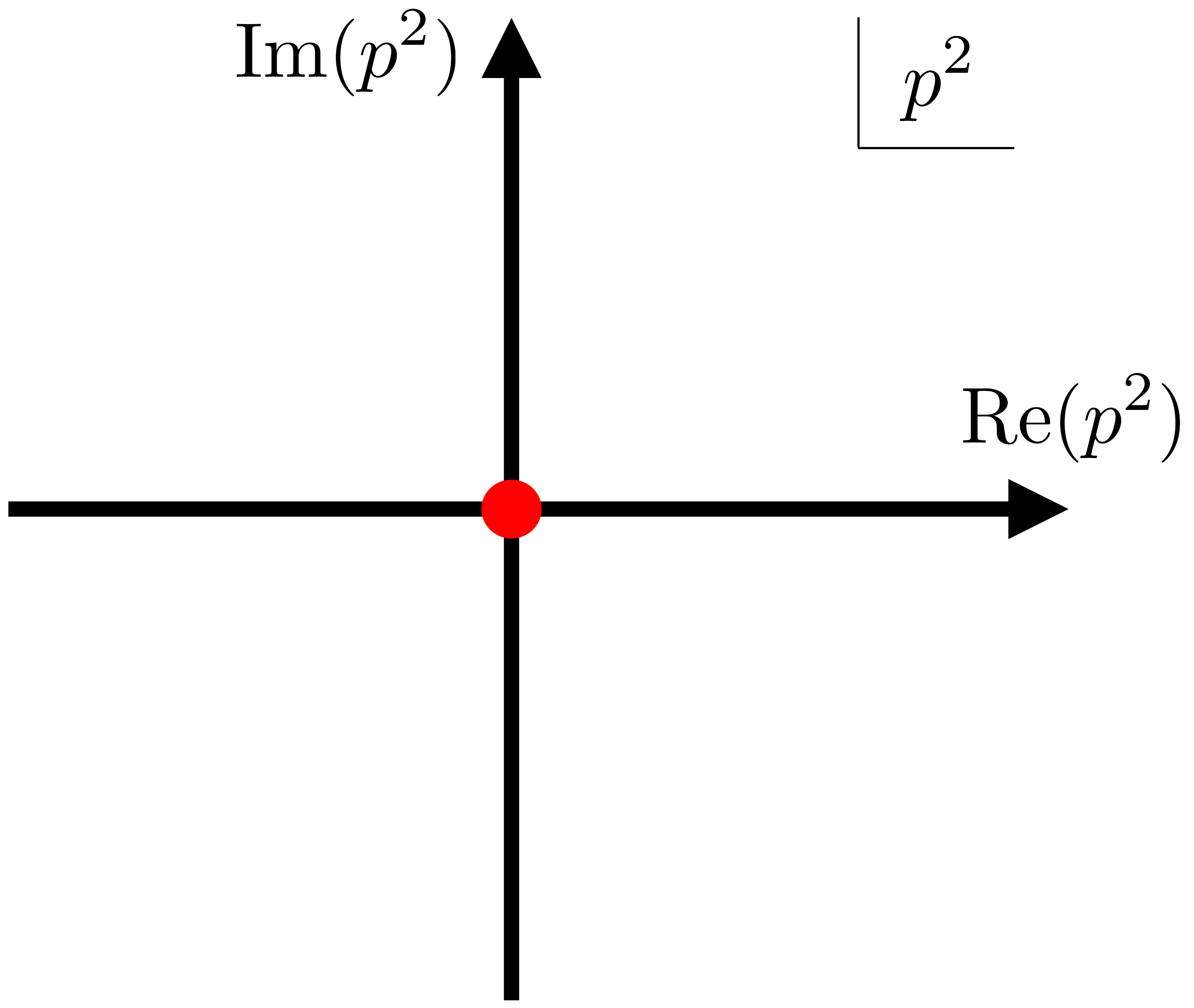

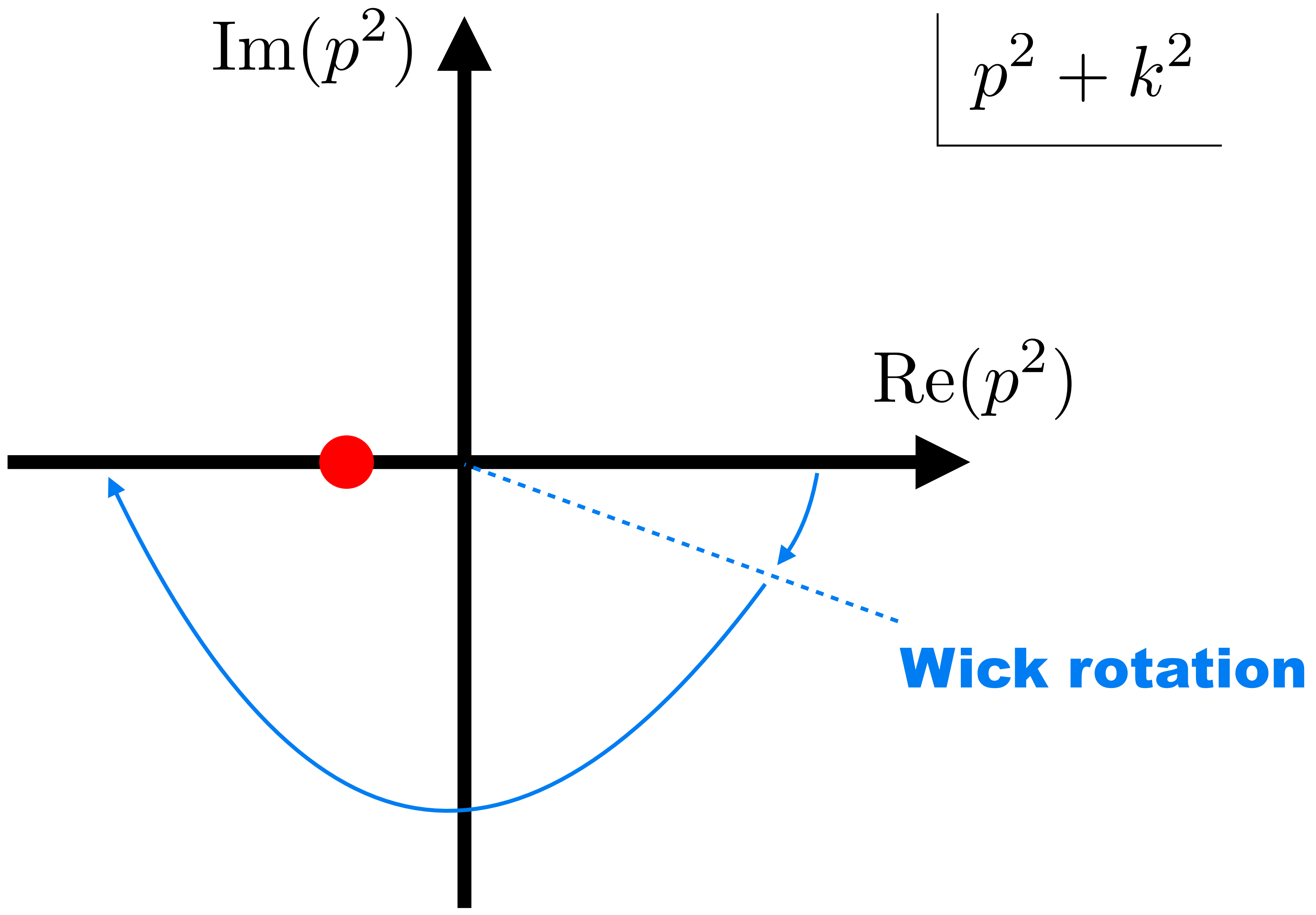

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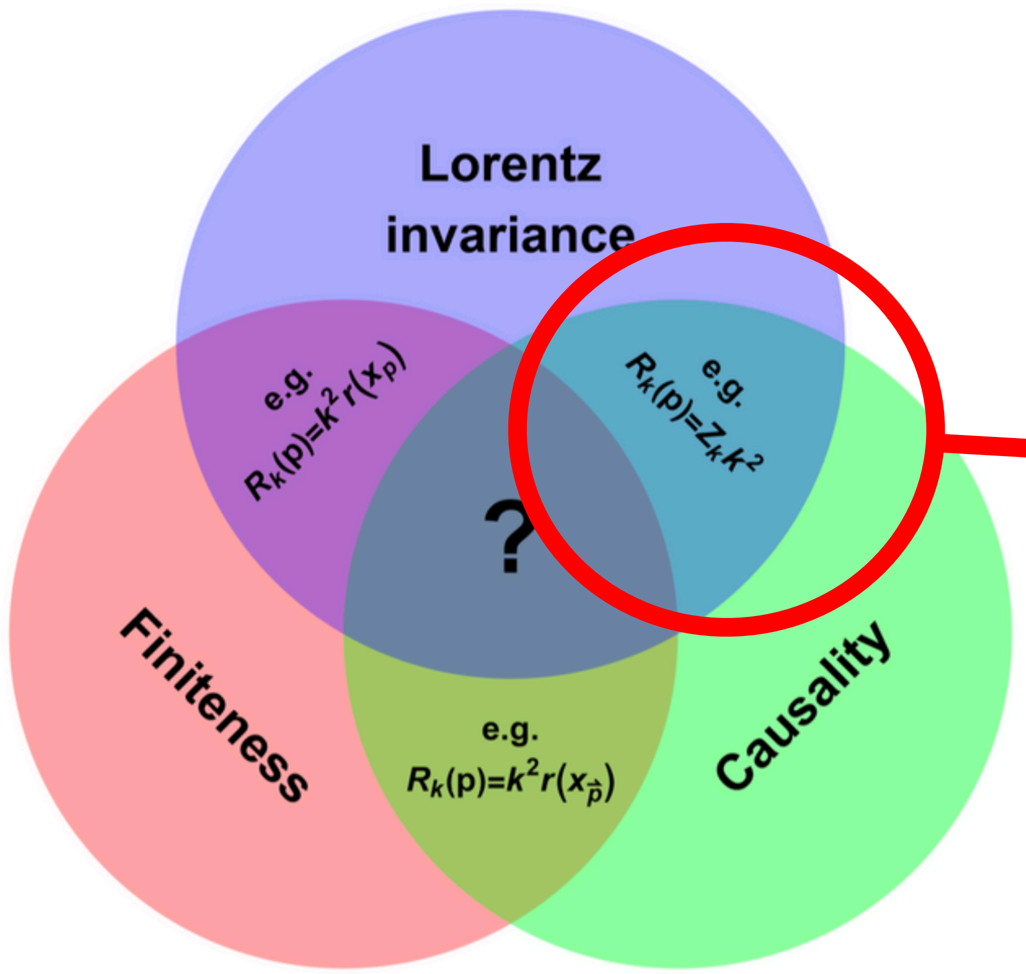

Give up finiteness

All loop momenta contribute above cutoff k

$$\boxed{R_k \propto k^2}$$

To guarantee finite UV

$$\partial_t \Gamma_k = \frac{1}{2} \mathrm{Tr} \mathcal{G}_k \partial_t R_k \boxed{- \partial_t S_{\mathrm{ct},k}}$$

[Fehre, Litim, Pawlowski, Reichert '21]
[Braun, et al '22]

UV divergences renormalised at every RG step using
BPHZ renormalisation in d=4

Include graviton scalar mode

Set up differential equation for spectral functions

[Fehre, Litim, Pawlowski, Reichert '21]

[Pawlowski, Reichert, Wessely, 2025]

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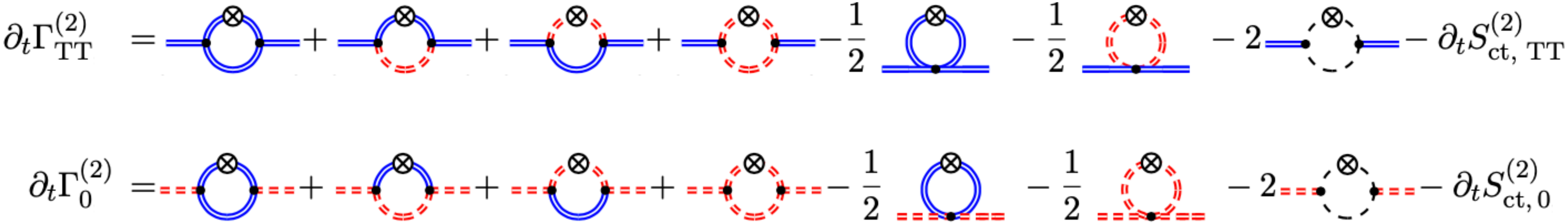
Coupled RG flows two-point correlators



Blue lines: TT mode

Red lines: scalar + vector mode

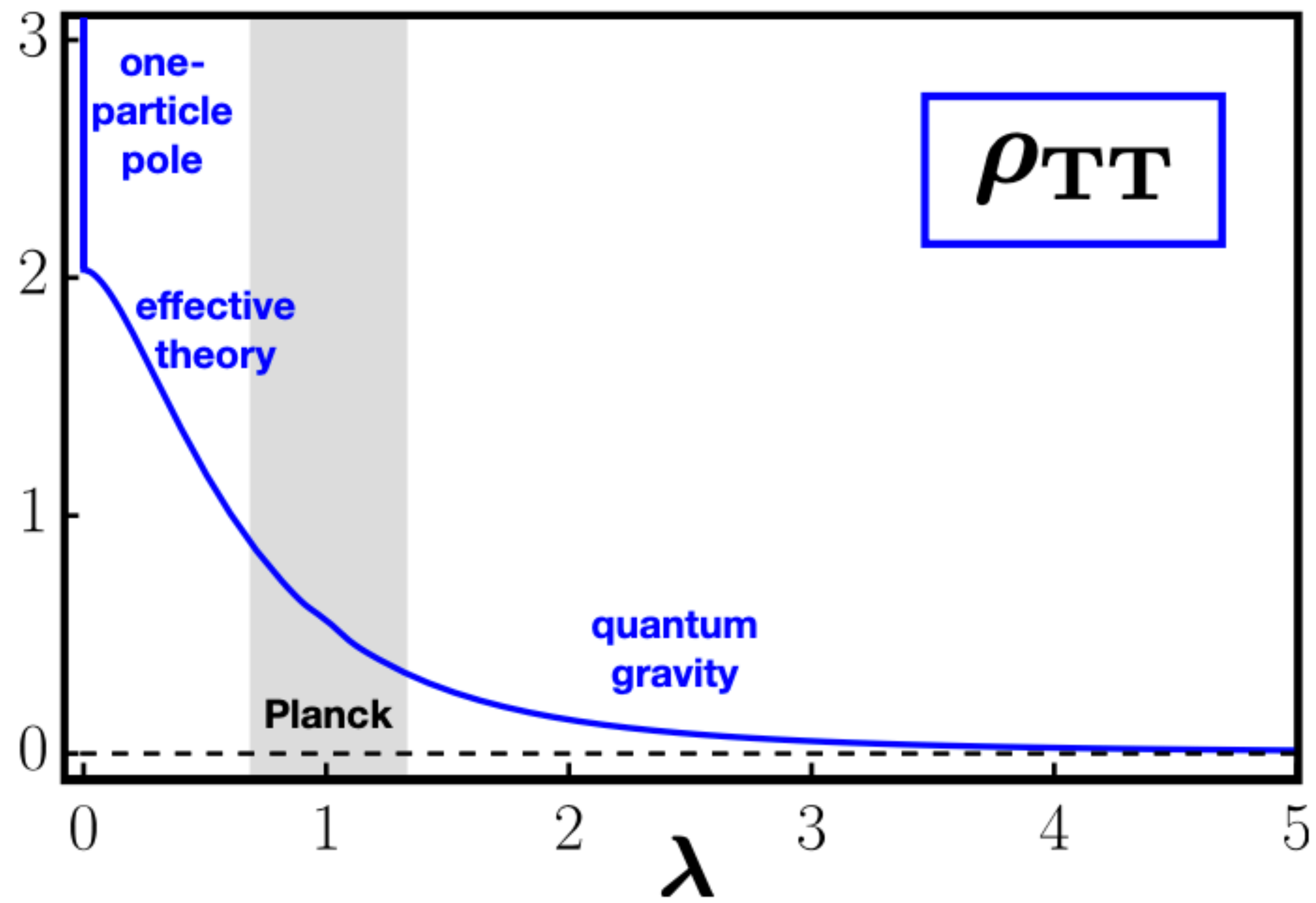
Dashed black lines: ghost

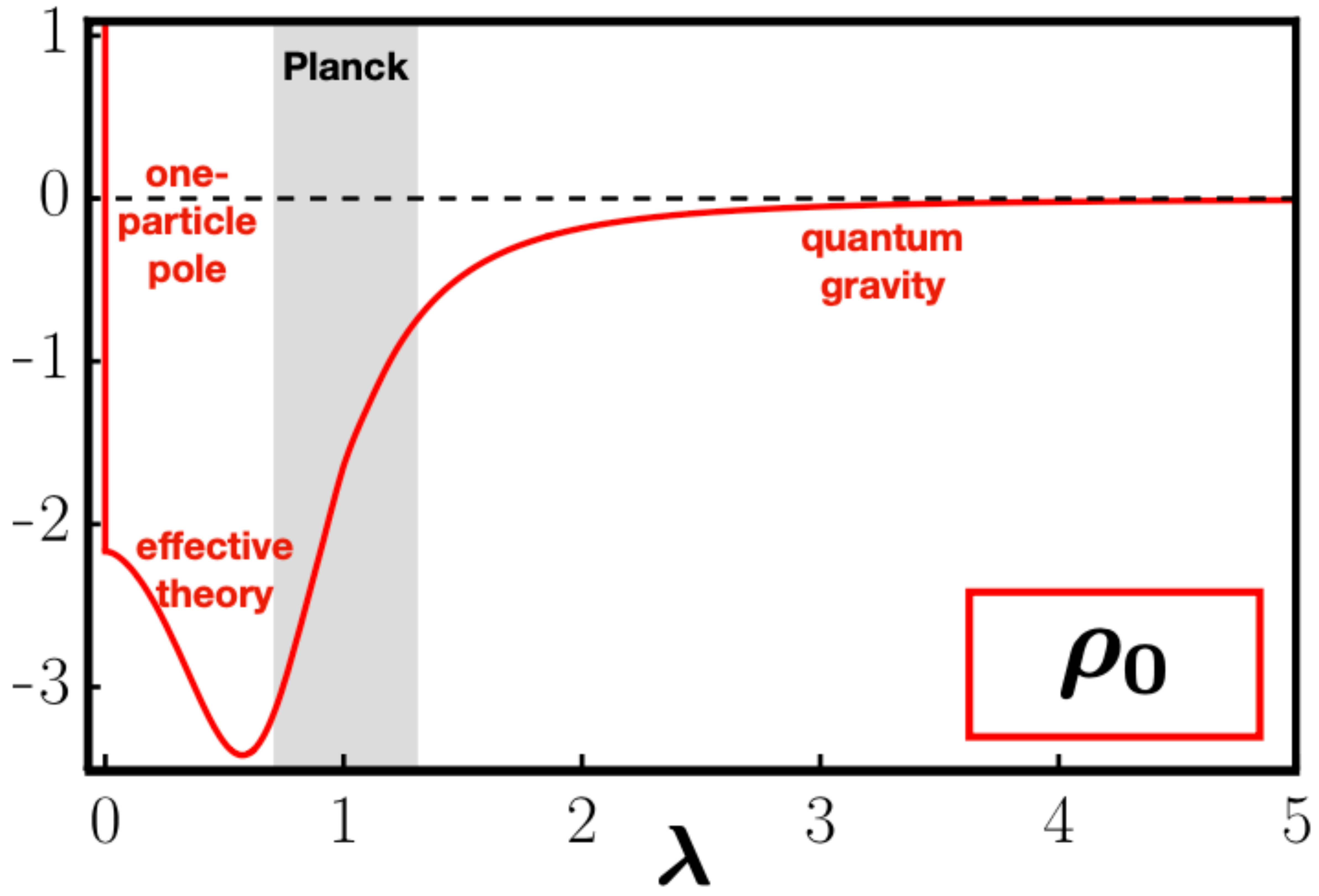
Spectral functions in on-shell renormalisation

The graviton is massless

Ghost and tachyon free

Spectral functions have the standard delta peak and continuum starting at the origin





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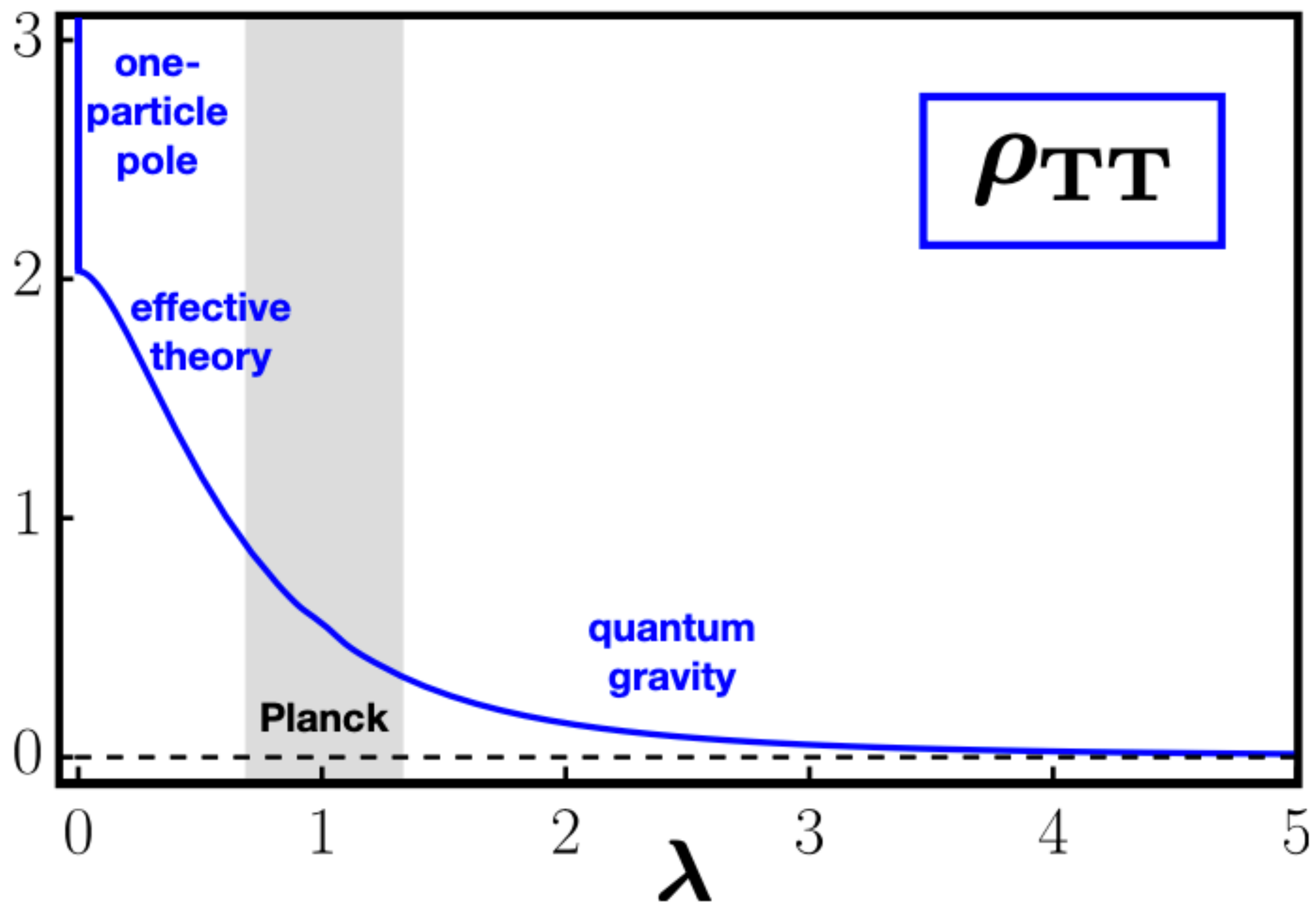

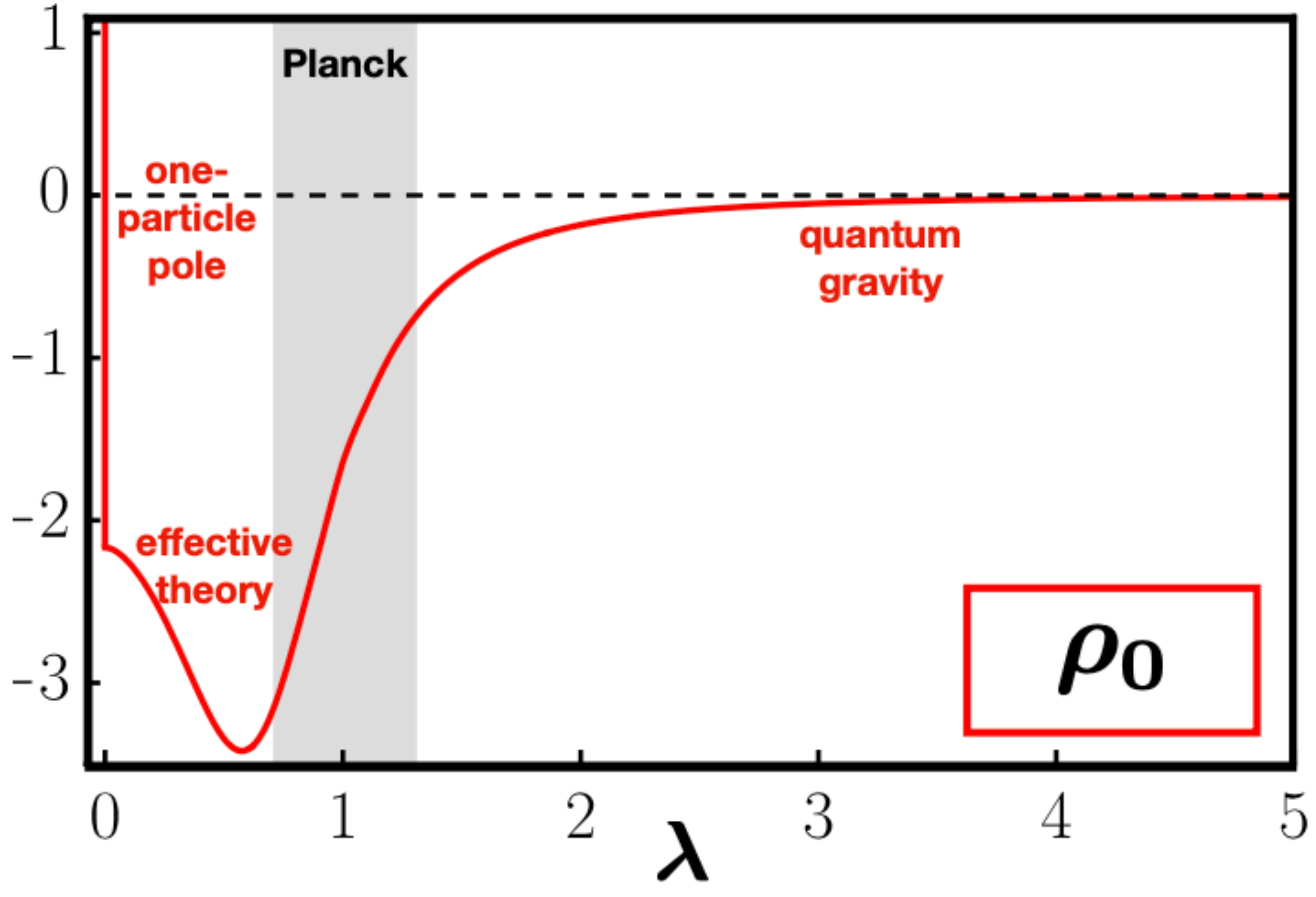

TT agrees with numerical results

[Fehre, Litim, Pawlowski, Reichert '21] [Pawlowski, Reichert, Wessely '25]

TT/0 agree with analytic results

See B. Knorr's talk! [Knorr, '26]

I have not told you everything…

Goal: set up

$$\partial_t \rho_{\mathrm{TT}/0}(\lambda) = -2\,\mathrm{Im}\left[\mathcal{G}^2_{\mathrm{TT}/0}\left(\partial_t \Gamma^{(2)}_{\mathrm{TT}/0} + \partial_t R_{\mathrm{TT}/0}\right)\Big|_{\mathrm{Wick}}\right]$$

The two-point function tensor decomposition

$$\Gamma^{(2),\mu\nu\rho\sigma} = \frac{1}{32\pi}\left(\boxed{\boxed{\Gamma^{(2)}_{\mathrm{TT}}\Pi^{\mu\nu\rho\sigma}_{\mathrm{TT}}} - \frac{1}{2}\Gamma^{(2)}_{0}\Pi^{\mu\nu\rho\sigma}_{0}} + \mathrm{gauge}\right)$$

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Regulated two-point function

$$\Gamma^{(2)}_{\mathrm{TT}/0} + R_{\mathrm{TT}/0} = Z_{\mathrm{TT}/0}(p)(p^2 + m^2_{\mathrm{TT}/0})$$

With off-shell mass parameters

$$m_{\mathrm{TT}/0}(\Lambda_{cc}, k)$$

and anomalous dimensions

$$\eta_{\mathrm{TT}/0} = -\partial_t \ln(Z_{\mathrm{TT}/0})$$

Healthy Källén-Lehmann flows

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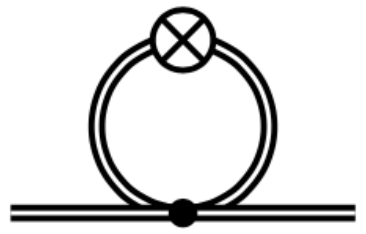
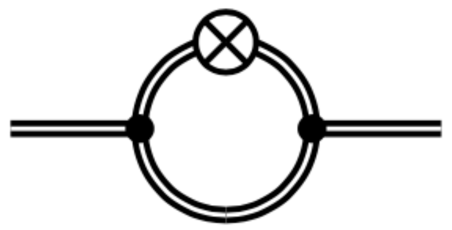
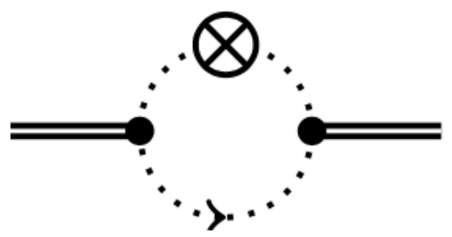
Single mode of gauge field:
Callan-Symanzik was enough

$$R_{\mathrm{TT}} \propto k^2$$

$\partial_t \Gamma^{(hh)}_{\mathrm{TT}} = -\dfrac{1}{2}$  $+$  $-\,2$  $-\,\partial_t S^{(hh)}_{\mathrm{ct,\,TT}}$

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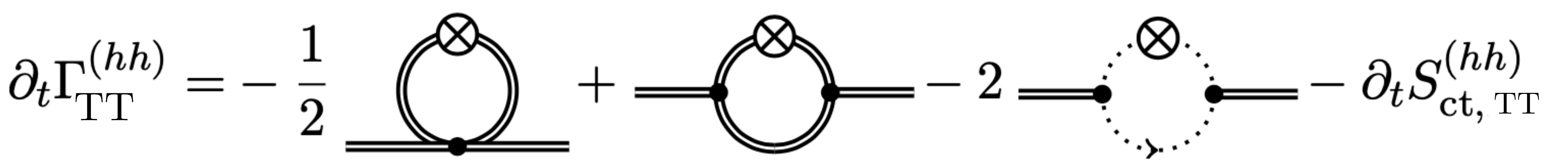
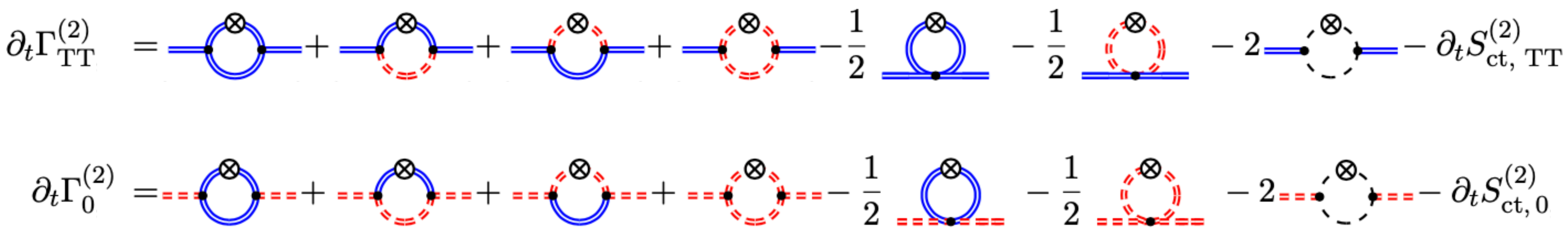
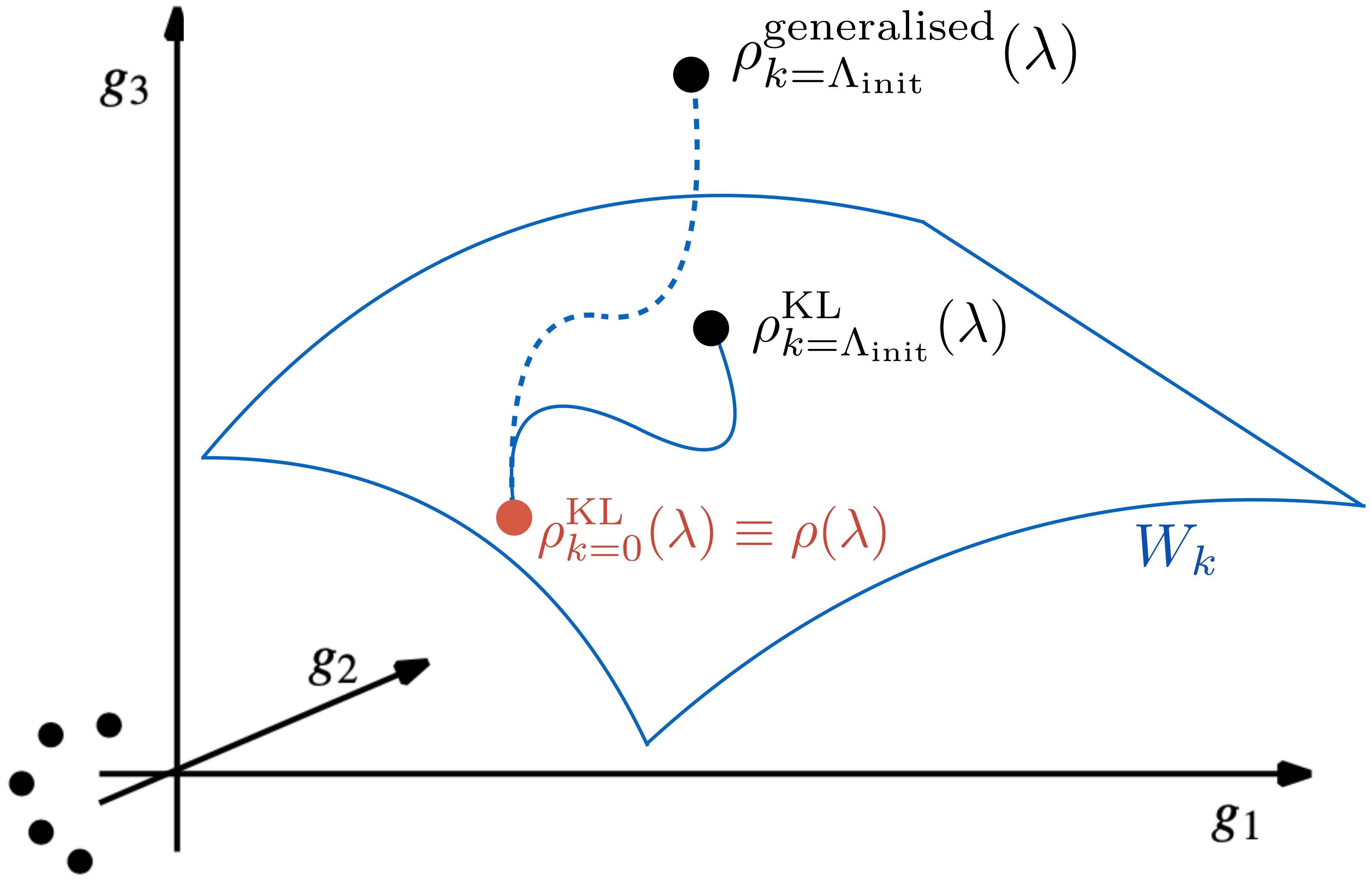


Coupled modes of gauge field:
Callan-Symanzik
+ symmetry identities



[**GA**, Litim, Reichert, '26]



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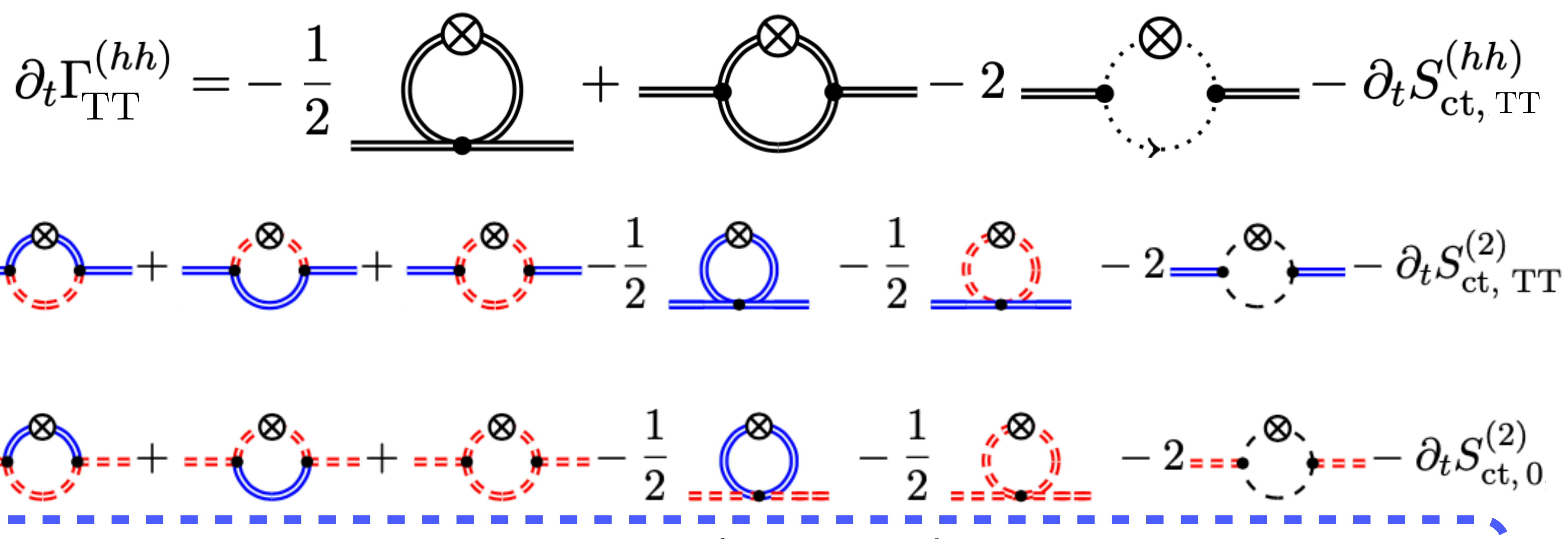

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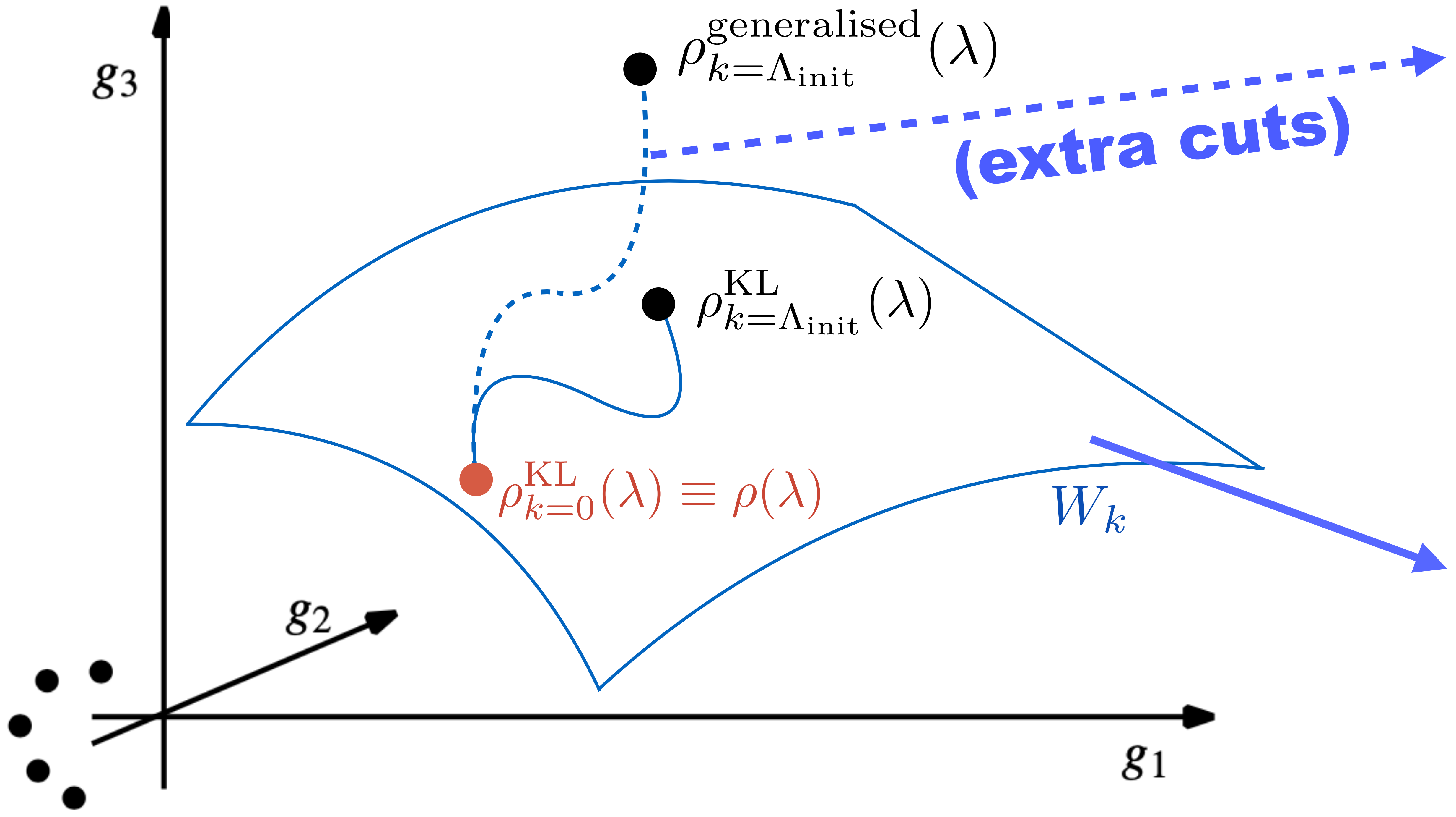

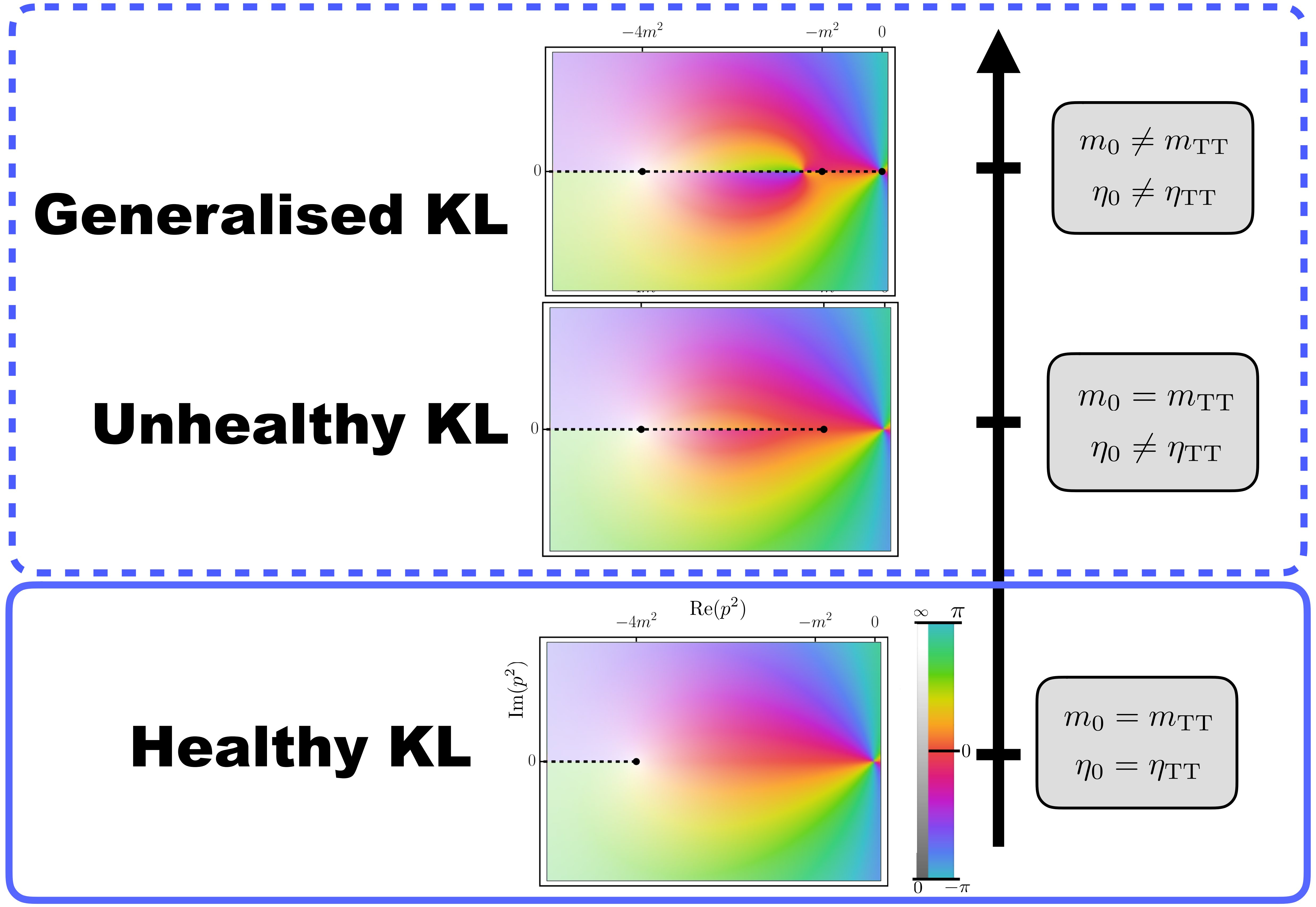

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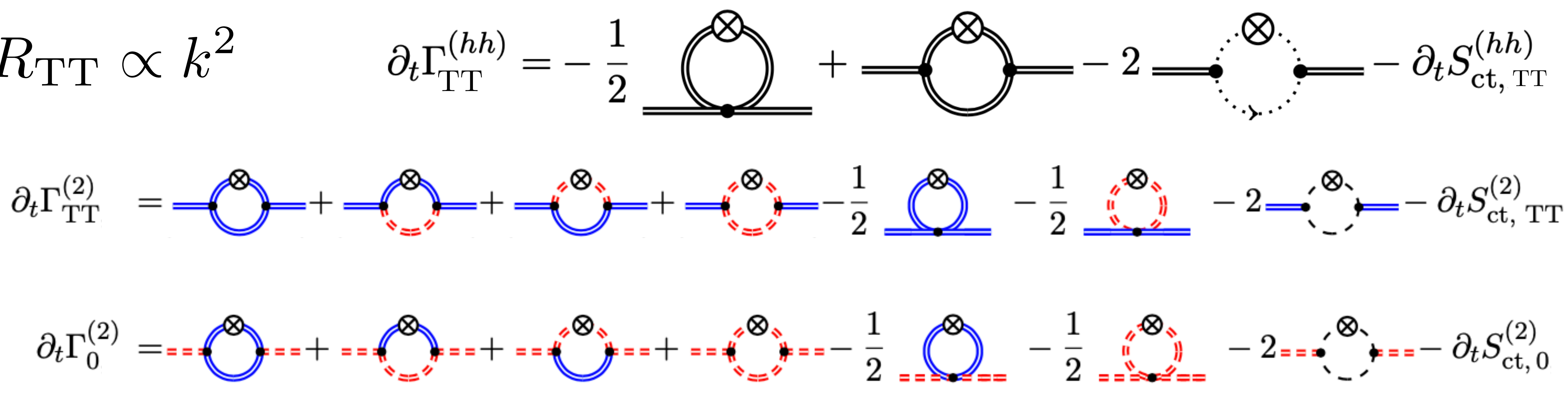

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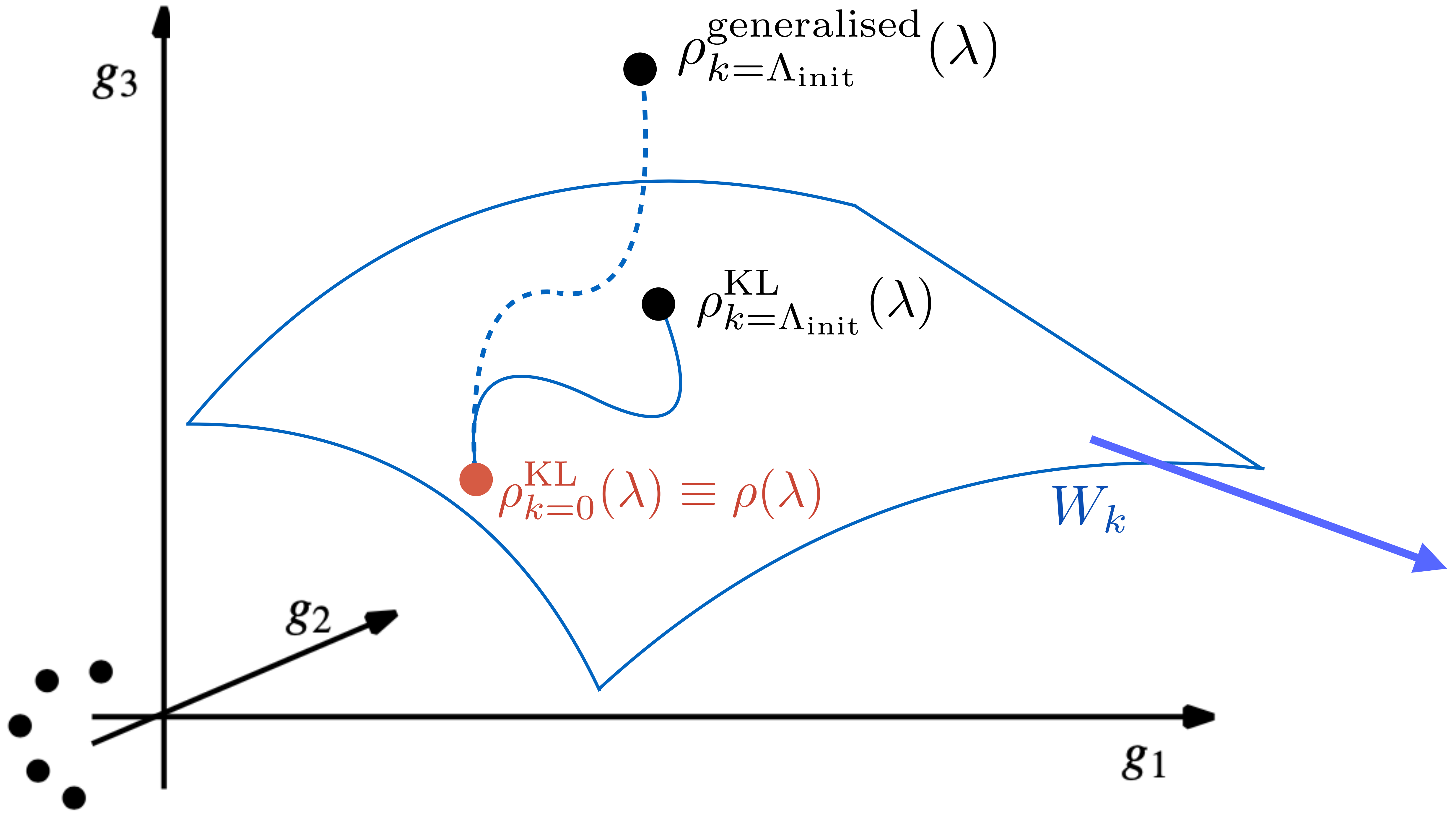
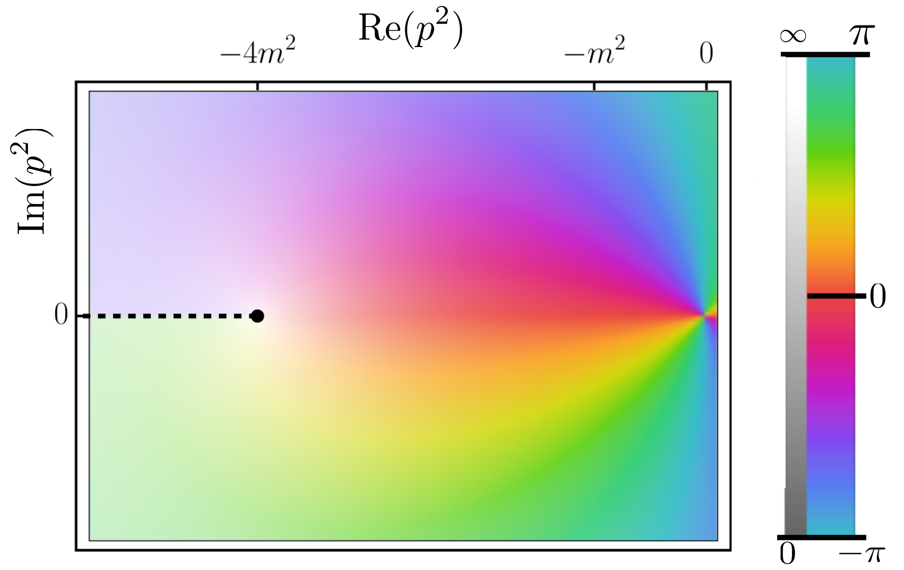
[**GA**, Litim, Reichert, '26]



Project on healthy hypersurface W_k
by appropriate choice of finite parts in diagrams

Healthy KL



$m_0 = m_{\mathrm{TT}}$
$\eta_0 = \eta_{\mathrm{TT}}$

Preserving symmetry

p = 0 renormalisation

Generalise [Fehre, Litim, Pawlowski, Reichert '21]

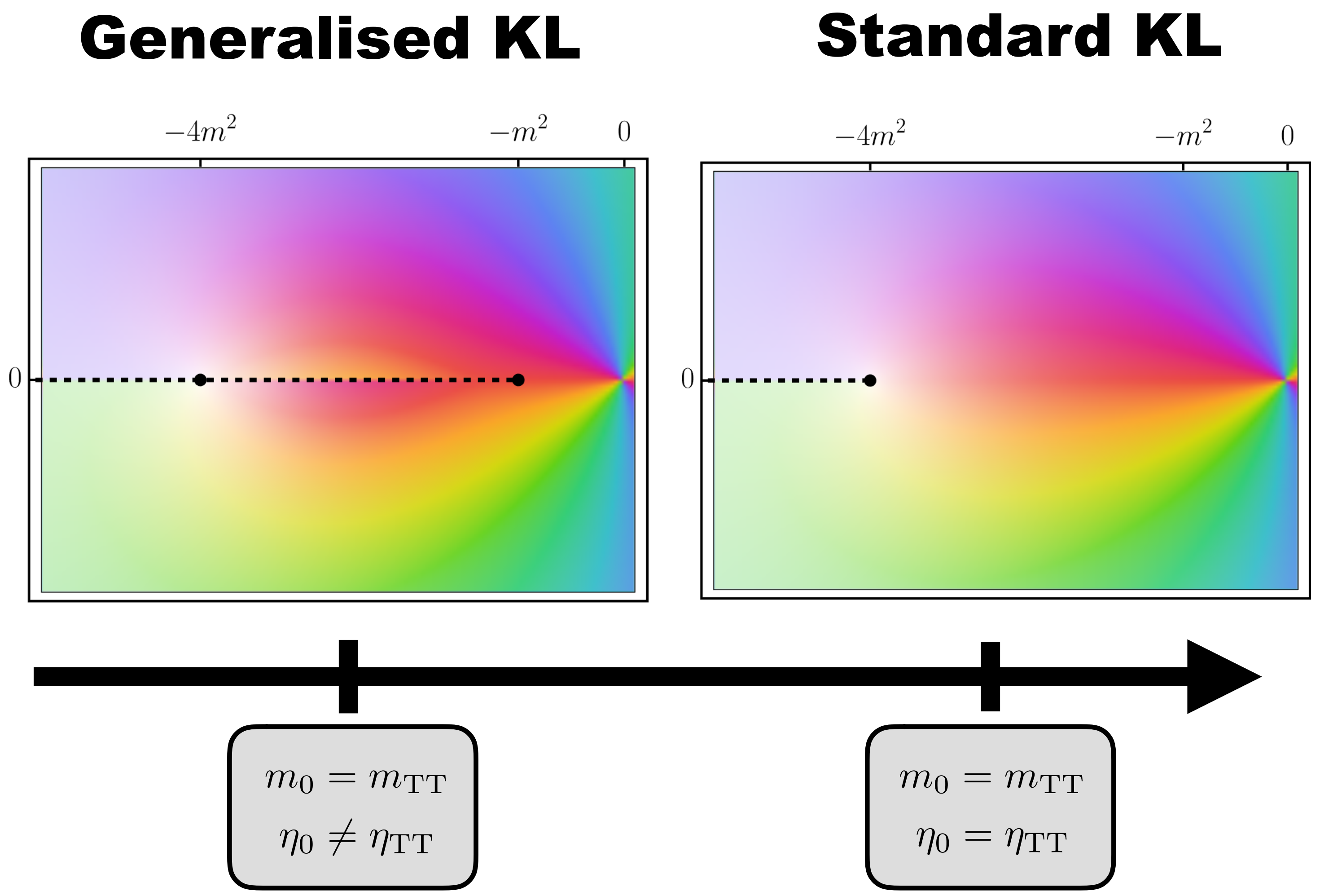
$$\partial_t \Gamma^{(2)}_{\mathrm{TT}/0}(p^2 = 0) = a_{\mathrm{TT}/0}$$

$$\partial_t \partial_{p^2} \Gamma^{(2)}_{\mathrm{TT}/0}(p^2)\Big|_{p^2=0} = b_{\mathrm{TT}/0}$$

$$\text{Fix } a_0 \implies m_{\mathrm{TT}} = m_0$$

$$\text{Fix } b_0 \implies \eta_{\mathrm{TT}} = \eta_0$$

Standard KL



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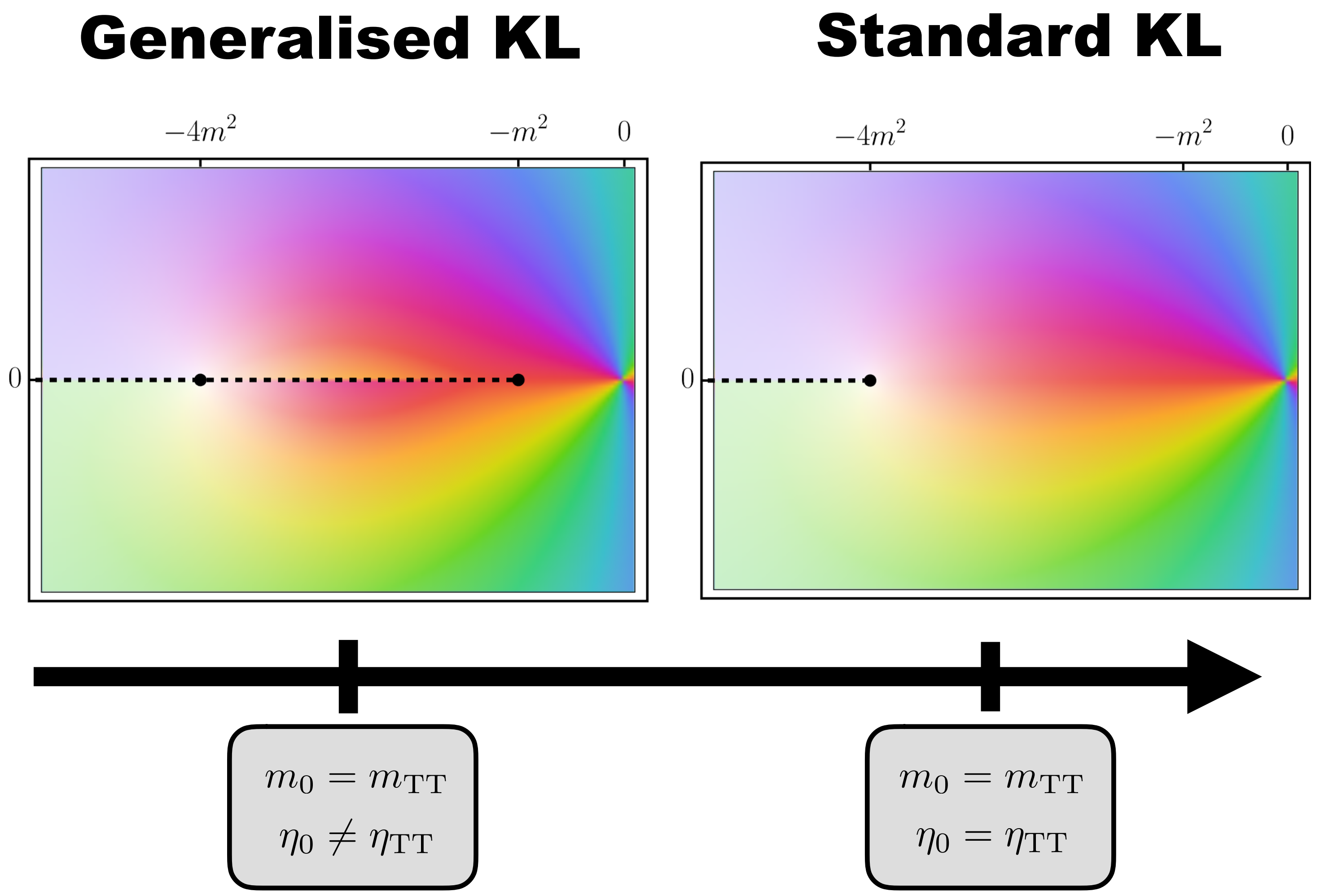
Standard KL

Only fix $a_0 \implies m_{\mathrm{TT}} = m_0$

Generalised KL



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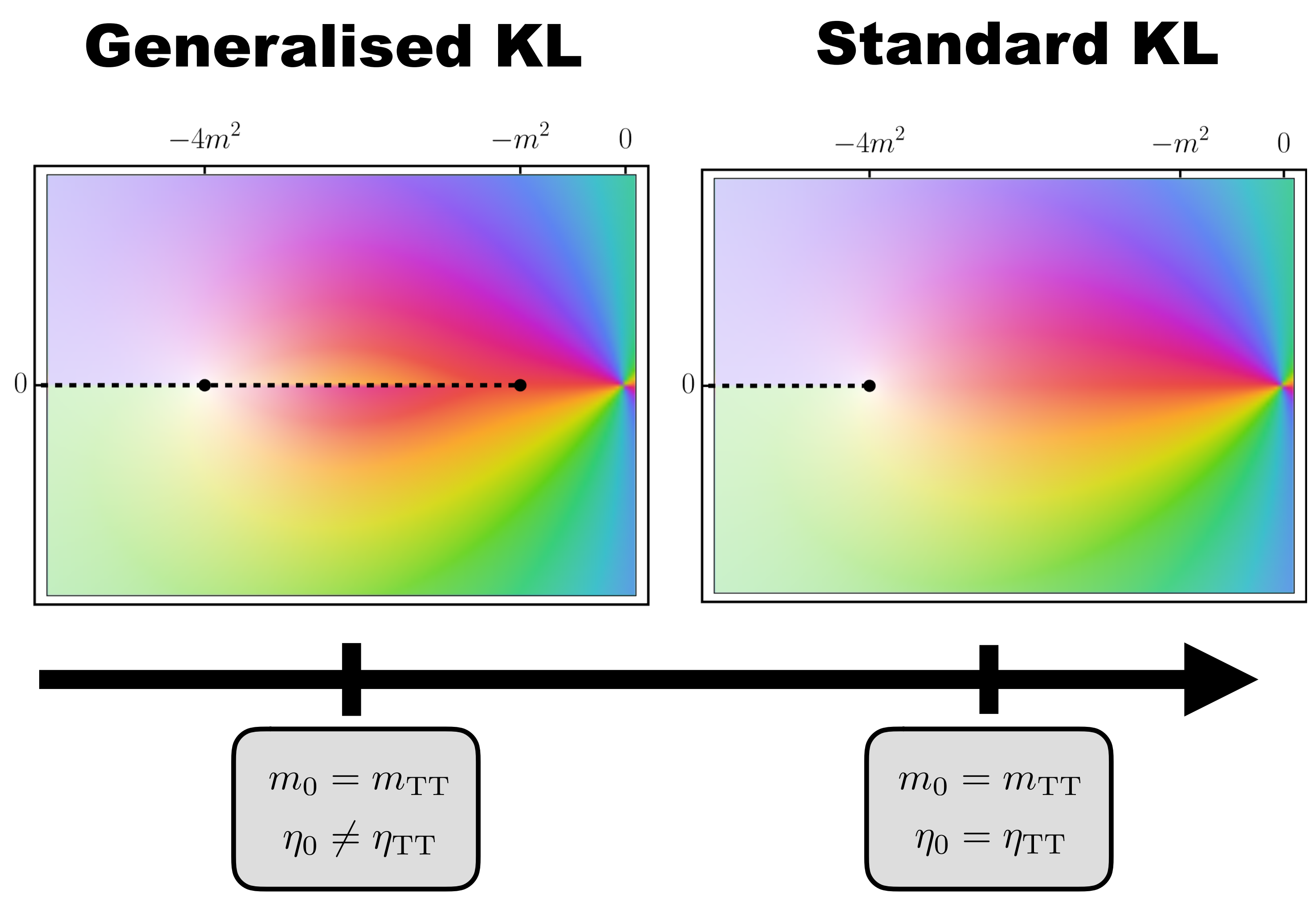


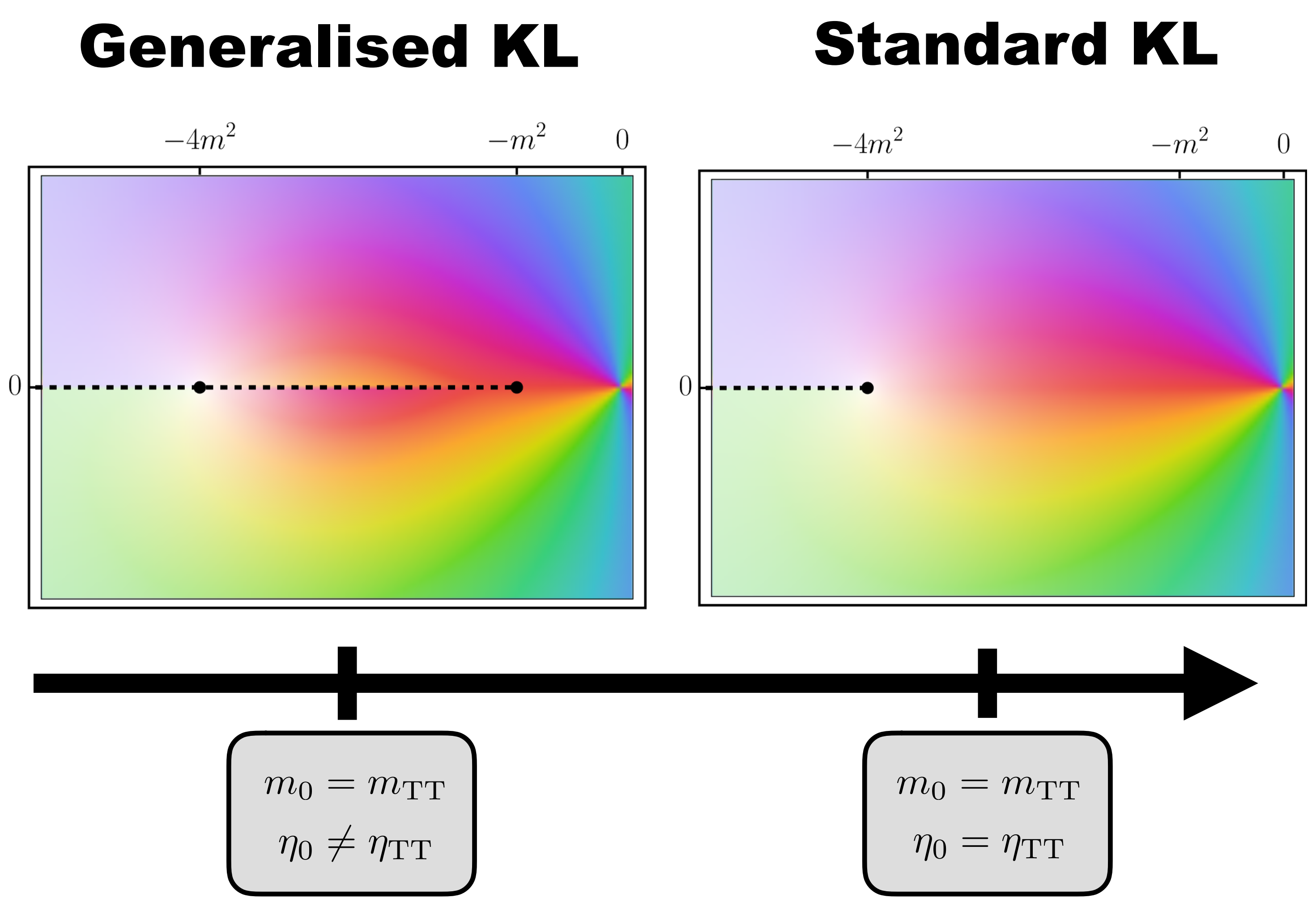
On-shell renormalisation

$$\partial_t \Gamma^{(2)}_{\mathrm{TT}/0}\boxed{(p^2 = -m^2_{\mathrm{TT}/0})} = 0$$

$$\partial_t \partial_{p^2} \Gamma^{(2)}_{\mathrm{TT}/0}(p^2)\Big|_{\boxed{p^2=-m^2_{\mathrm{TT}/0}}} = 0$$

Renormalise on the graviton mass pole

Preserving symmetry



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Generalise [Fehre, Litim, Pawlowski, Reichert '21]

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Standard KL

Only fix $a_0 \implies m_{\mathrm{TT}} = m_0$

Generalised KL

On-shell renormalisation

$$\partial_t \Gamma^{(2)}_{\mathrm{TT}/0}\left(p^2 = -m^2_{\mathrm{TT}/0}\right) = 0$$

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Renormalise on the graviton mass pole

Naturally sets

$$m_{\mathrm{TT}} = m_0 = k$$
$$\eta_{\mathrm{TT}} = \eta_0 = 0$$

Standard KL

Simplifies computations

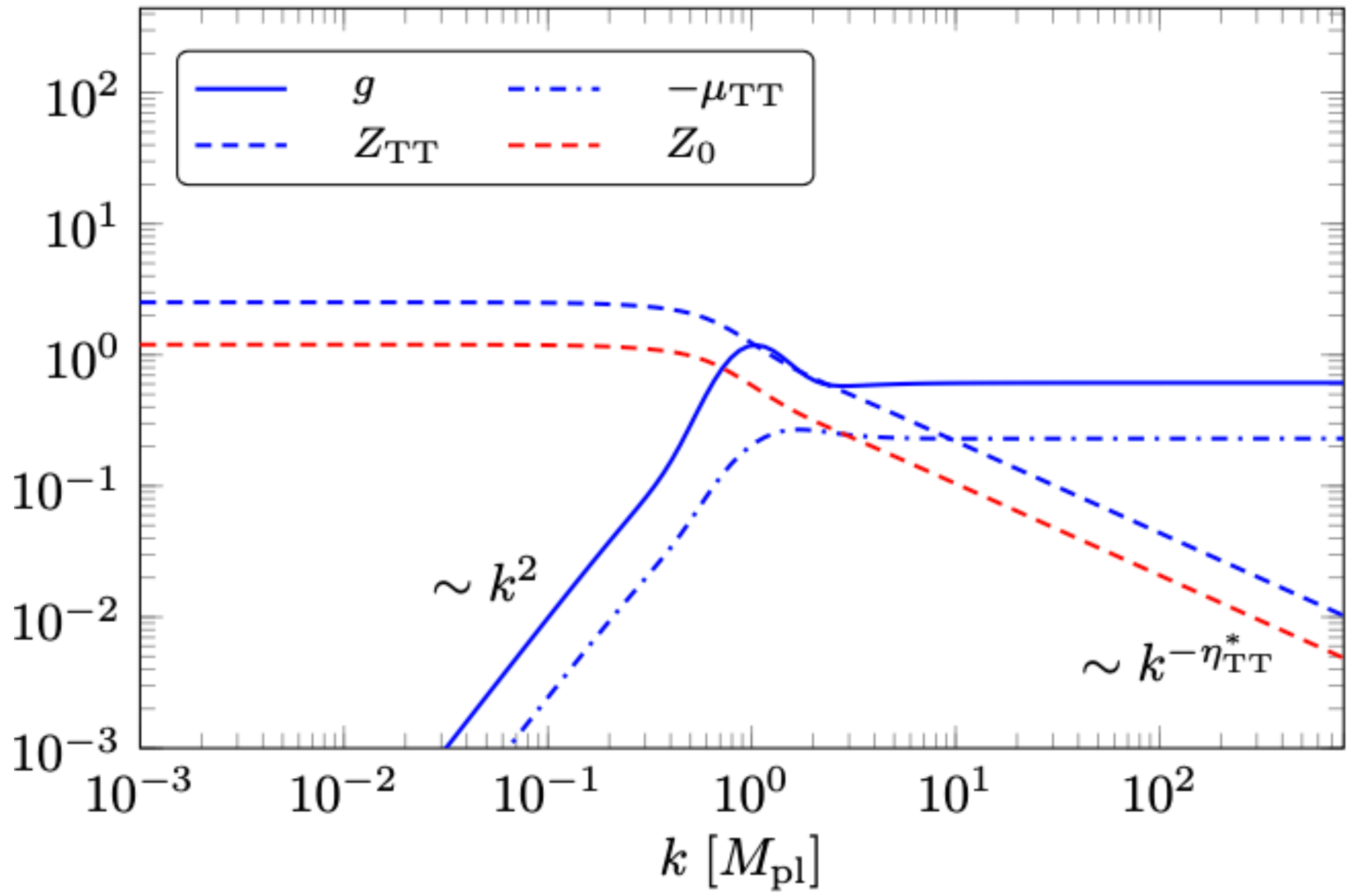
[Pawlowski, Reichert, Wessely '25]

[**GA**, Litim, Reichert, '26]

Fixed points, UV-IR connecting trajectories

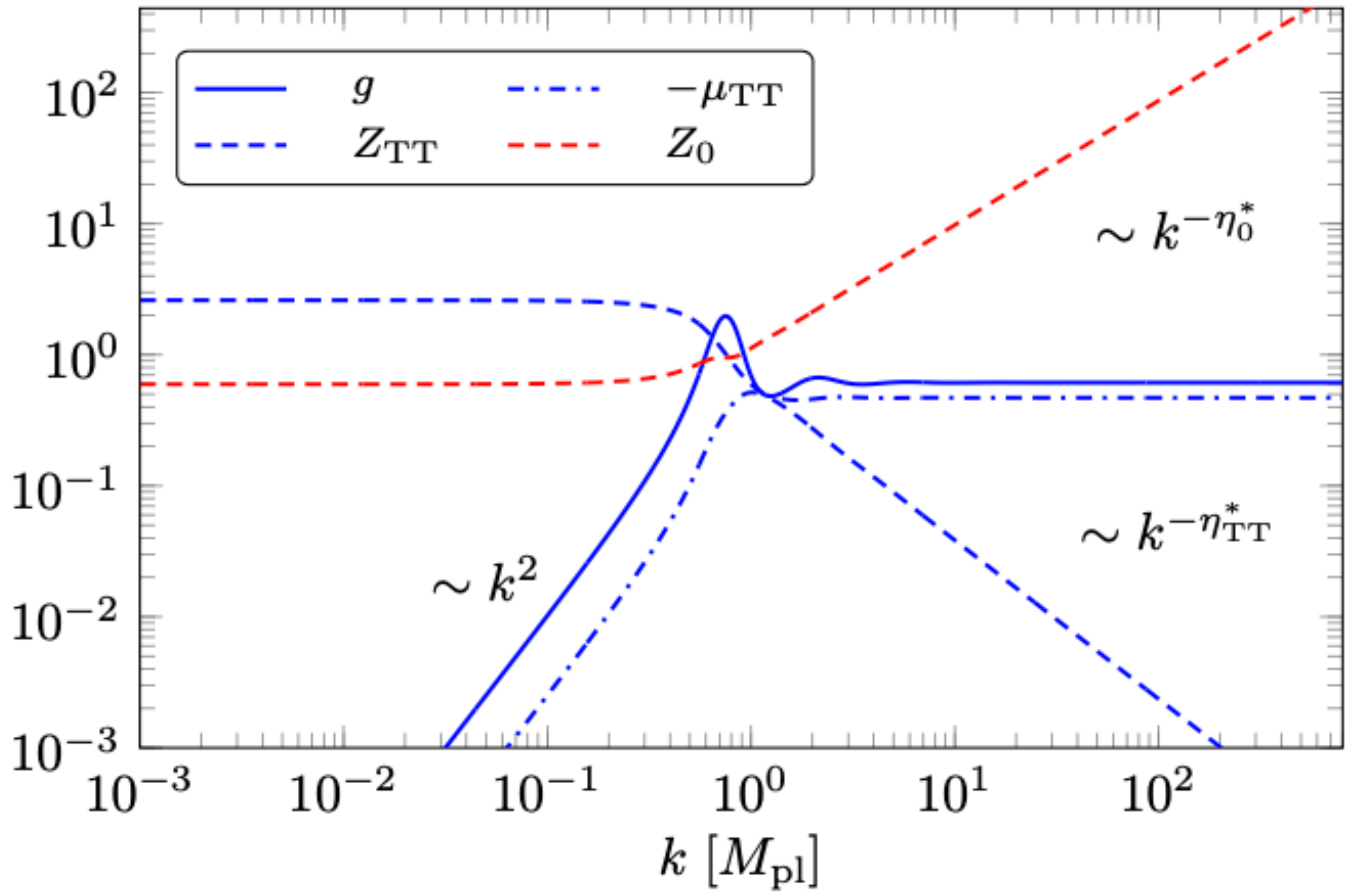
p = 0 renormalisation

On-shell renormalisation



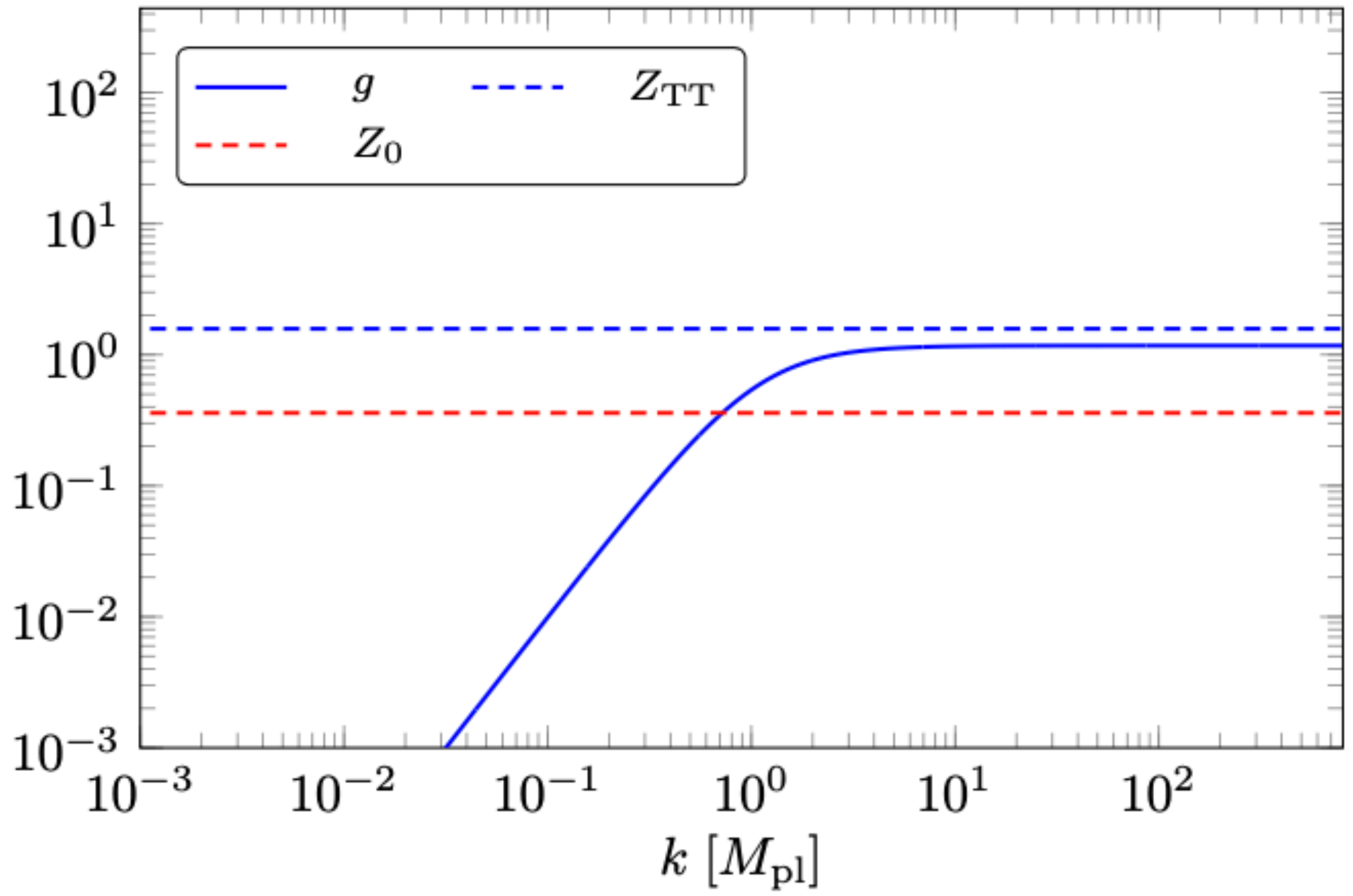
$$m_0 = m_{TT}$$
$$\eta_0 = \eta_{TT}$$

Standard KL for k>0



$$m_0 = m_{TT}$$
$$\eta_0 \neq \eta_{TT}$$

Generalised KL for k>0

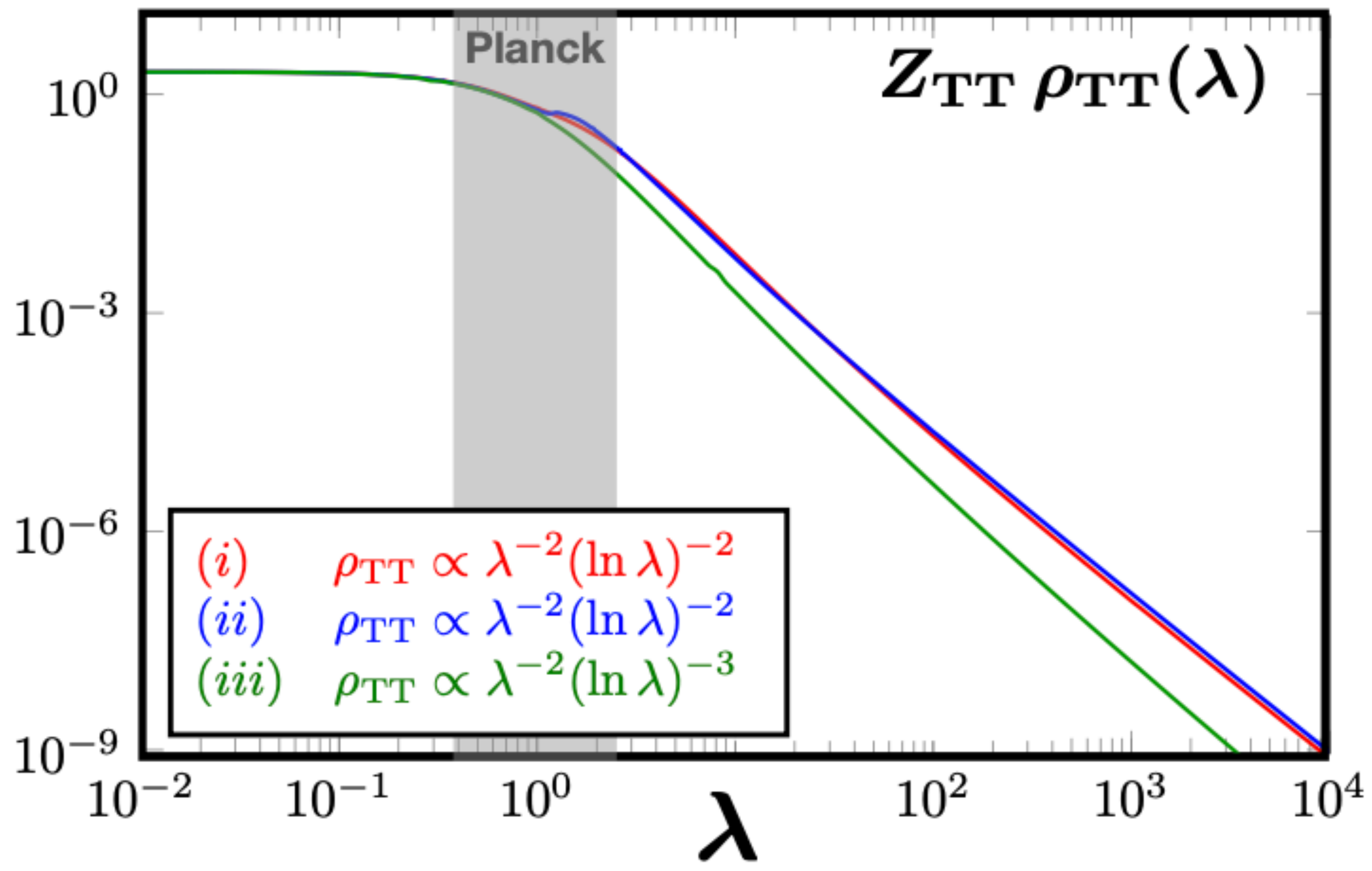


$$m_0 = m_{TT} = k$$
$$\eta_0 = \eta_{TT} = 0$$

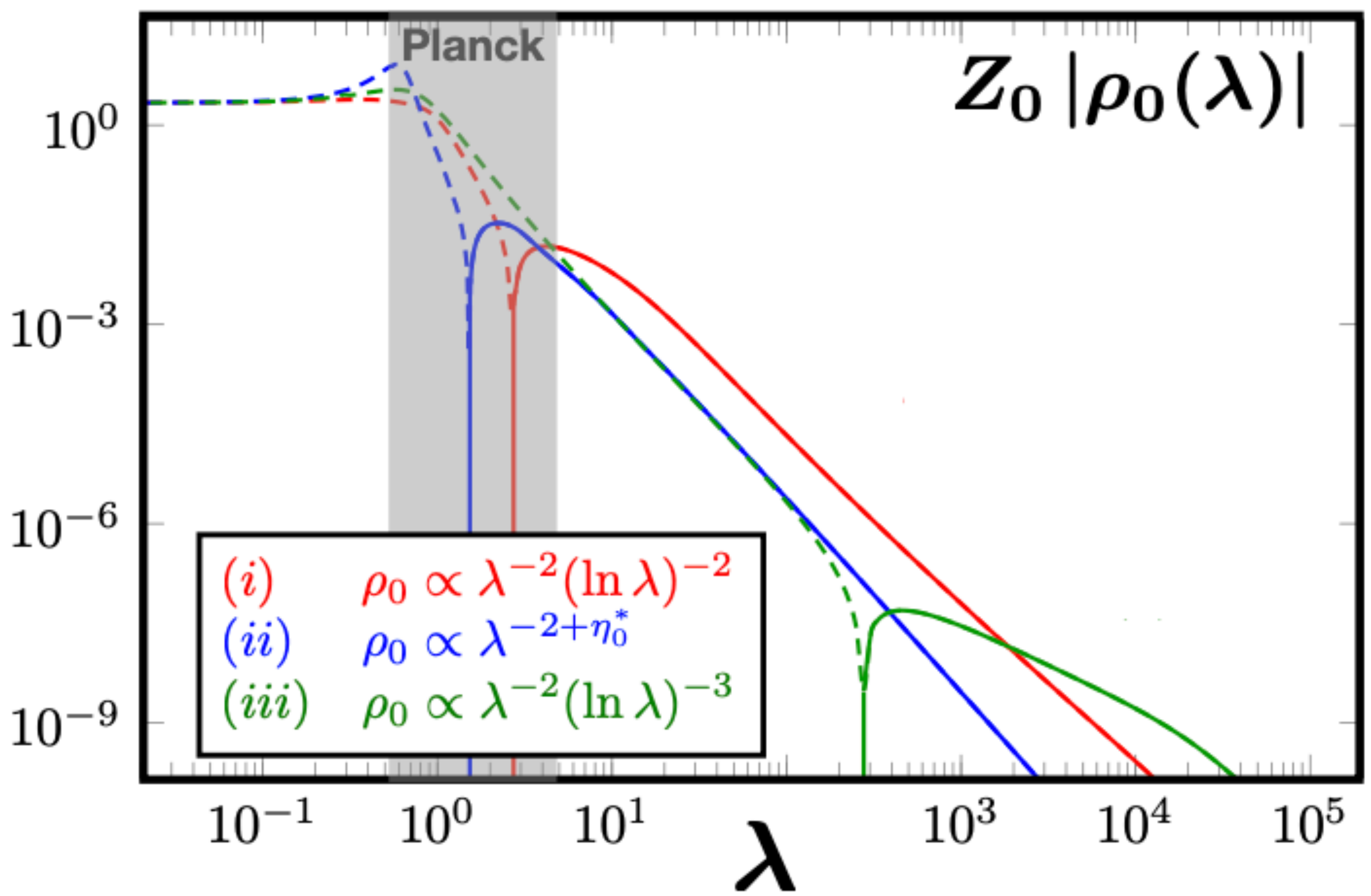
Standard KL for k>0

Coupled spectral functions

IR: matches EFT exactly



UV: Normalisable spectral functions



All spectral functions are positive

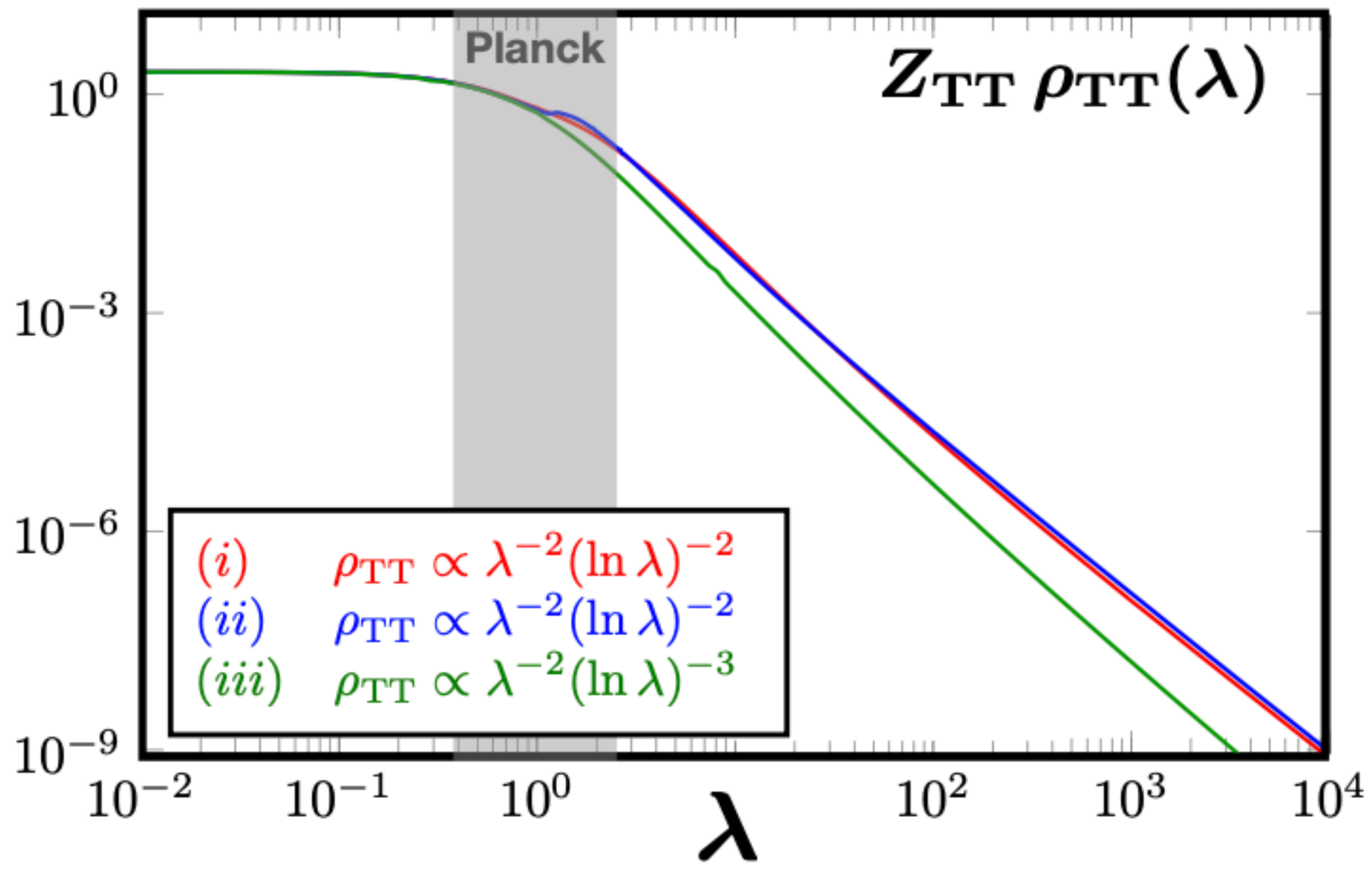
Transverse-traceless mode carries on-shell dofs

All spectral functions change sign

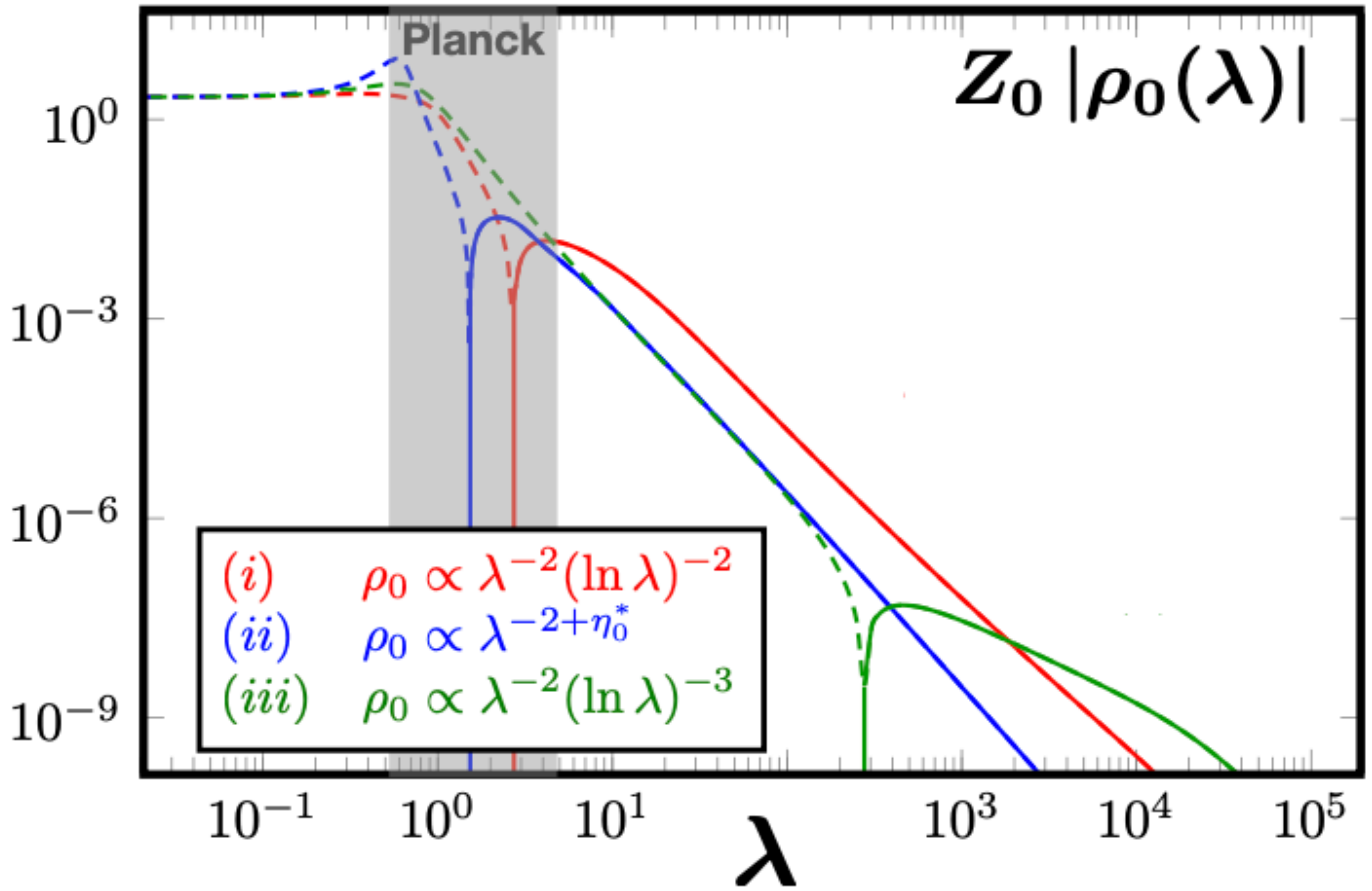
Physical scalar mode carries off-shell dofs

Coupled spectral functions

IR: matches EFT exactly



UV: Normalisable spectral functions



Propagator pole structure:
no additional modes

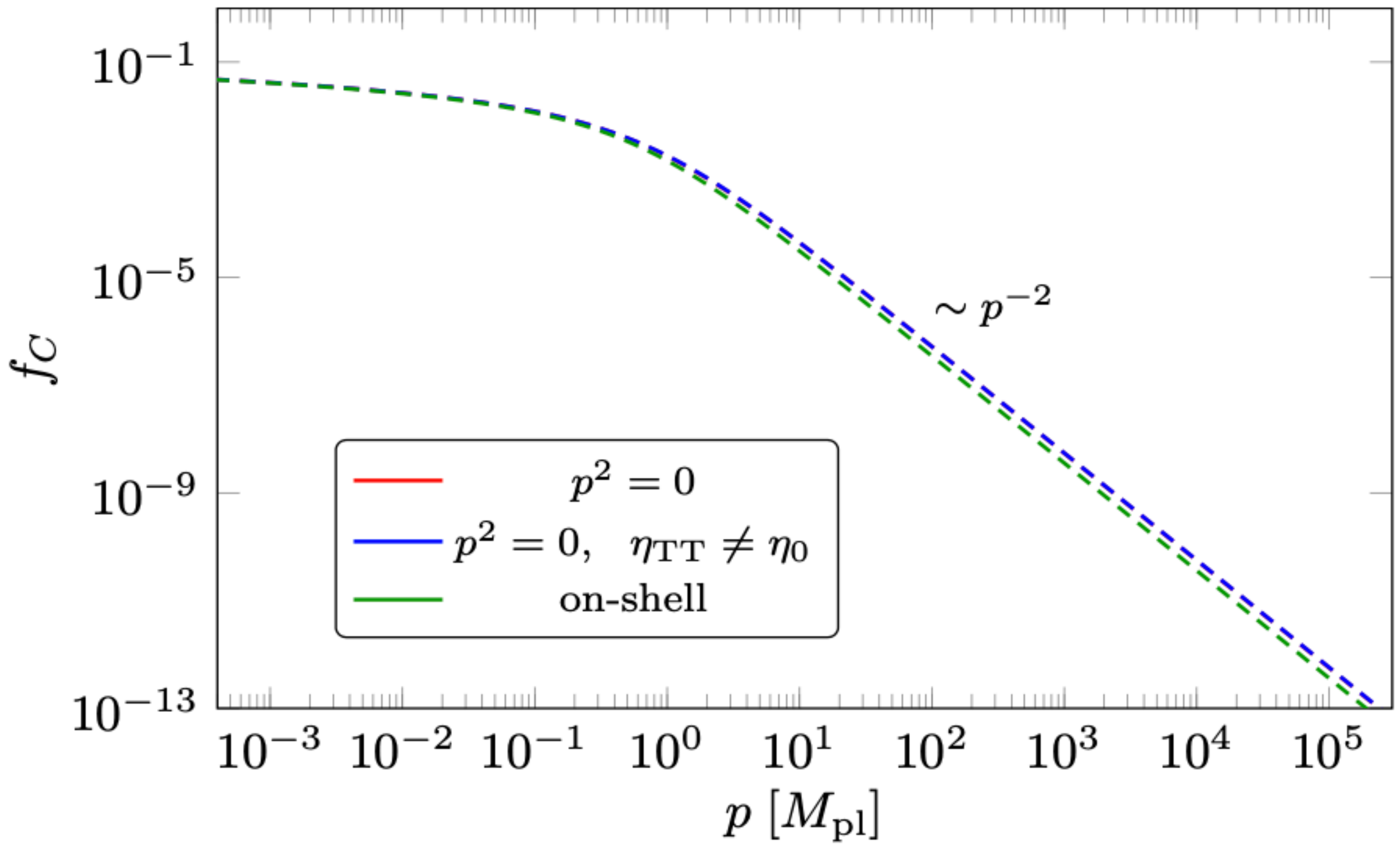
TT is compatible with all conditions
for unitary and causal
UV completion of gravity

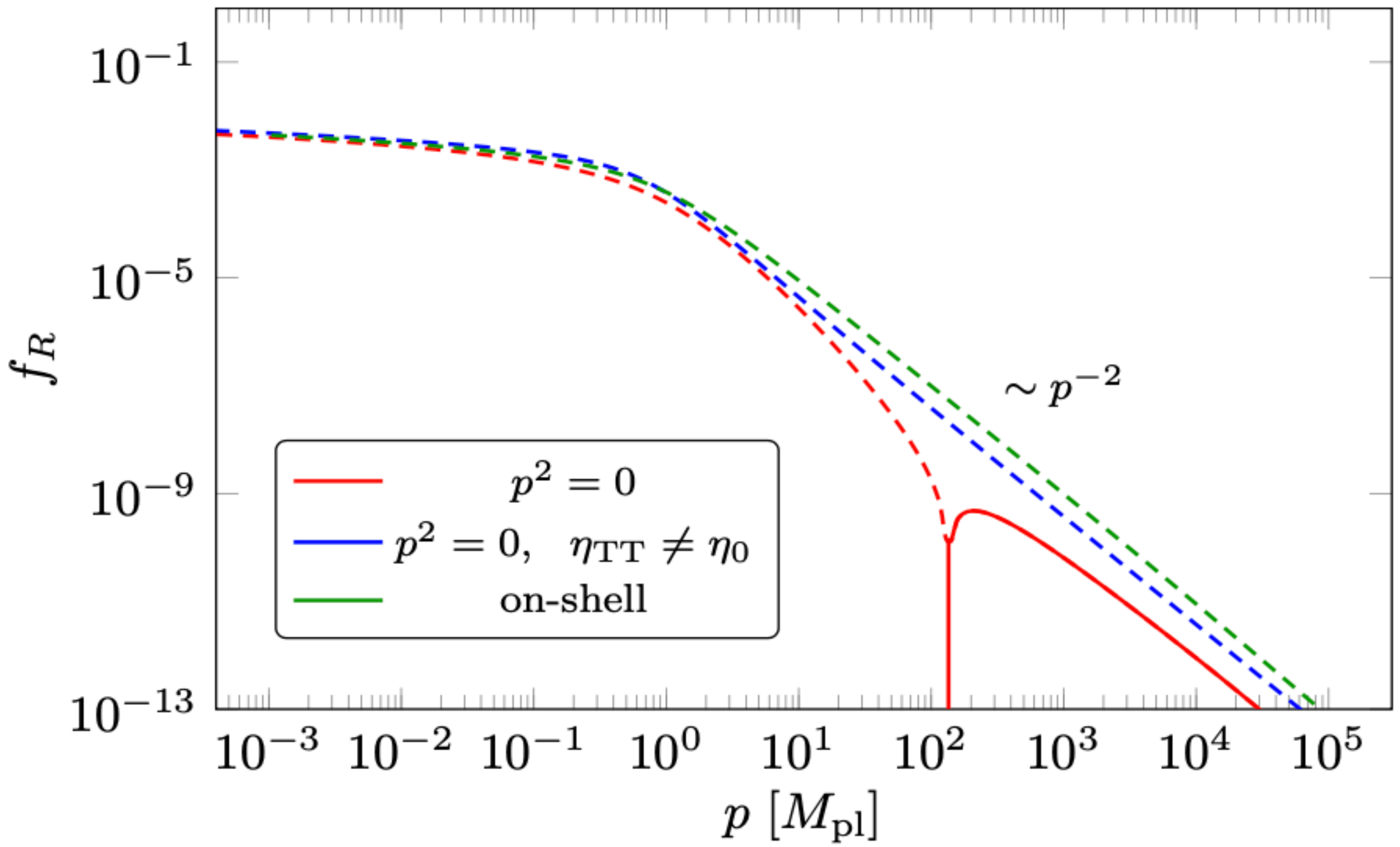
[Platania, Wetterich 2020]

Coupled form factors

First principles Lorentzian computation of non-perturbative form factors at k=0

$$\Gamma_{k=0} = \int d^4x\sqrt{g}\left(\frac{R}{16\pi G_N} + R f_R(\Box) R + C_{\mu\nu\rho\sigma} f_C(\Box) C^{\mu\nu\rho\sigma} + \cdots\right) + S_{gh} + S_{gf}$$





Conclusions

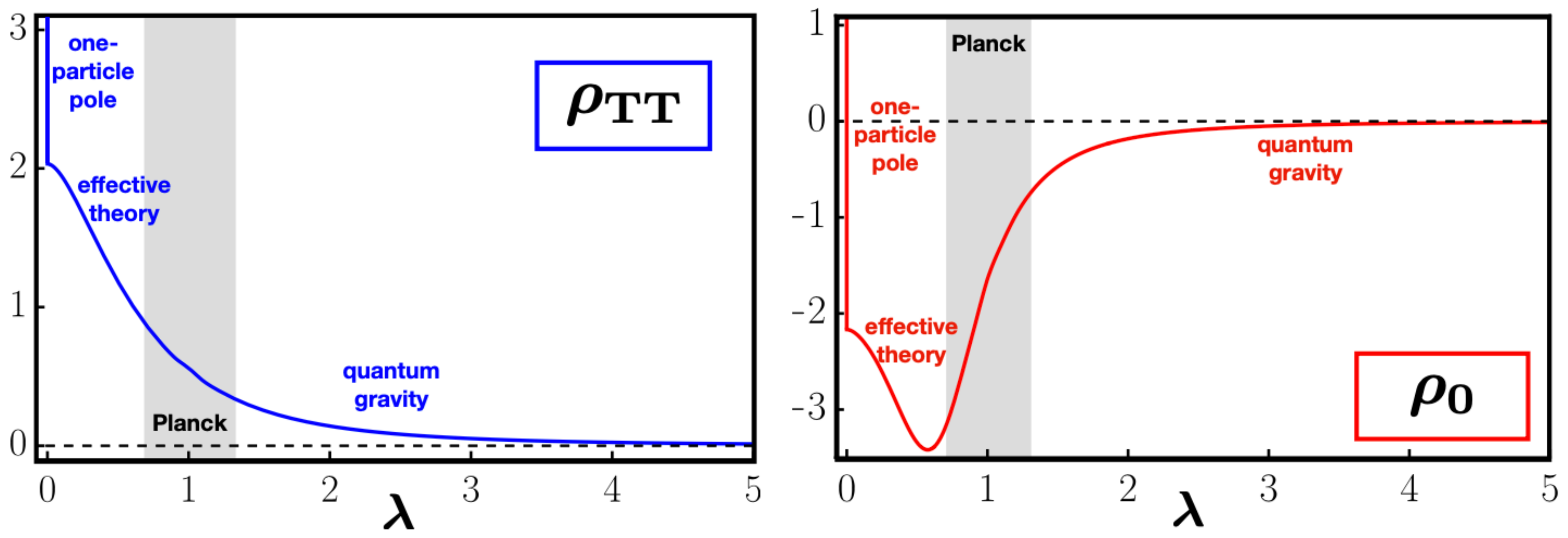
Lorentzian graviton spectral functions

2606.19321

Direct Lorentzian computation

Coupled healthy spectral functions

Ghost and tachyon free: unitary and causal



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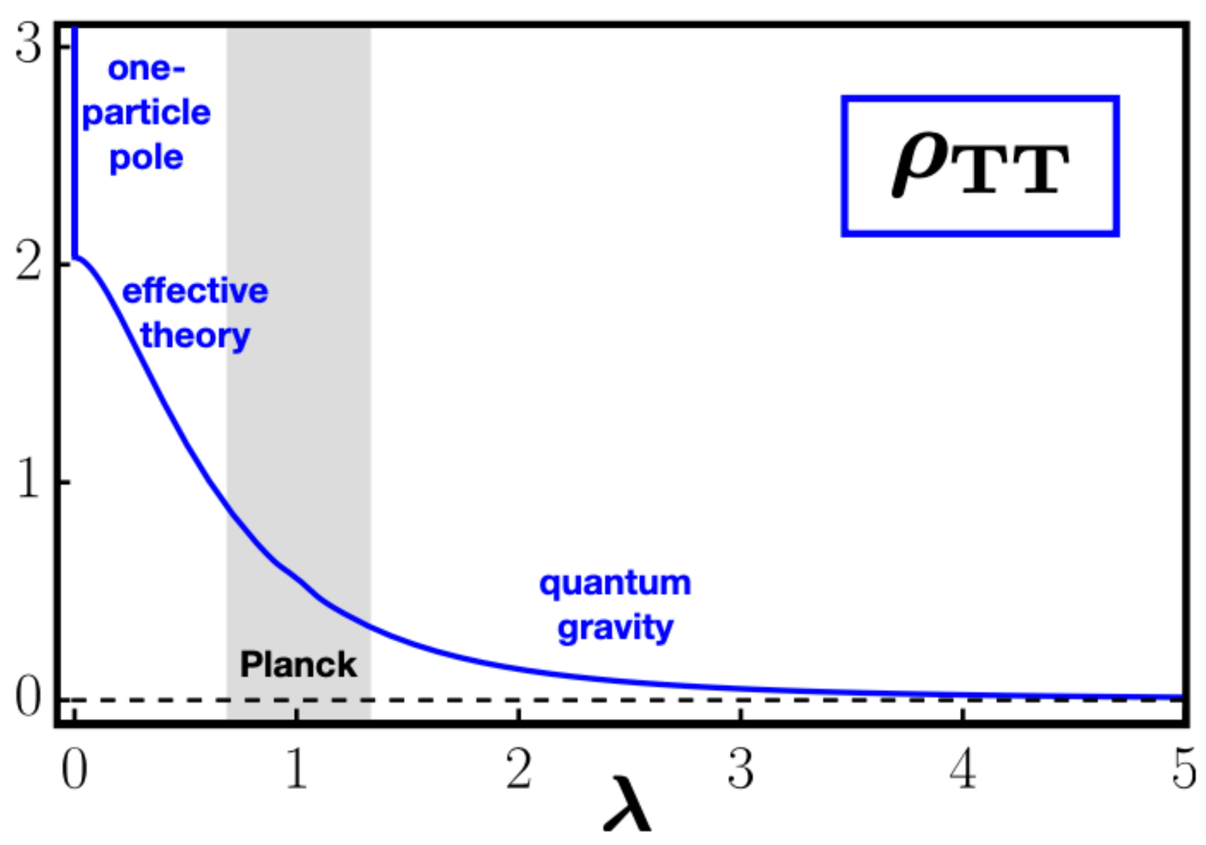
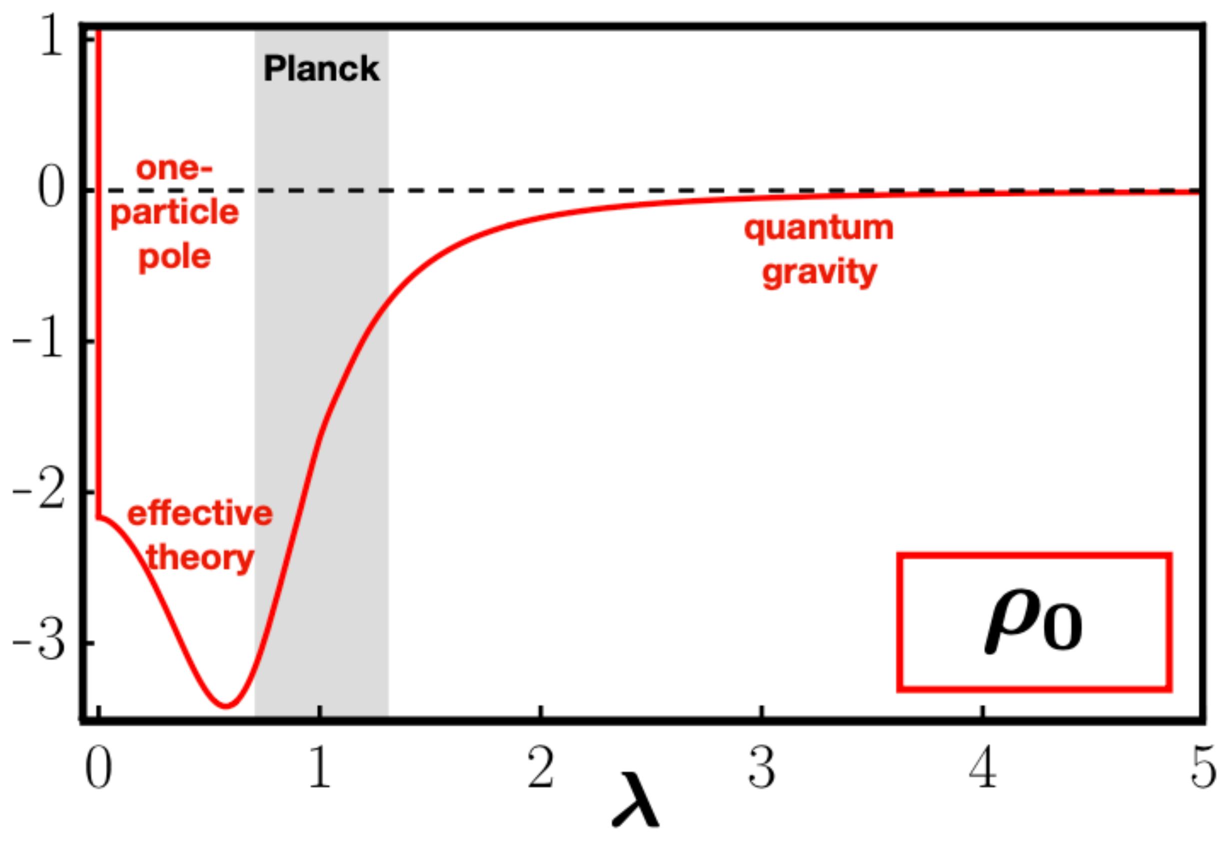
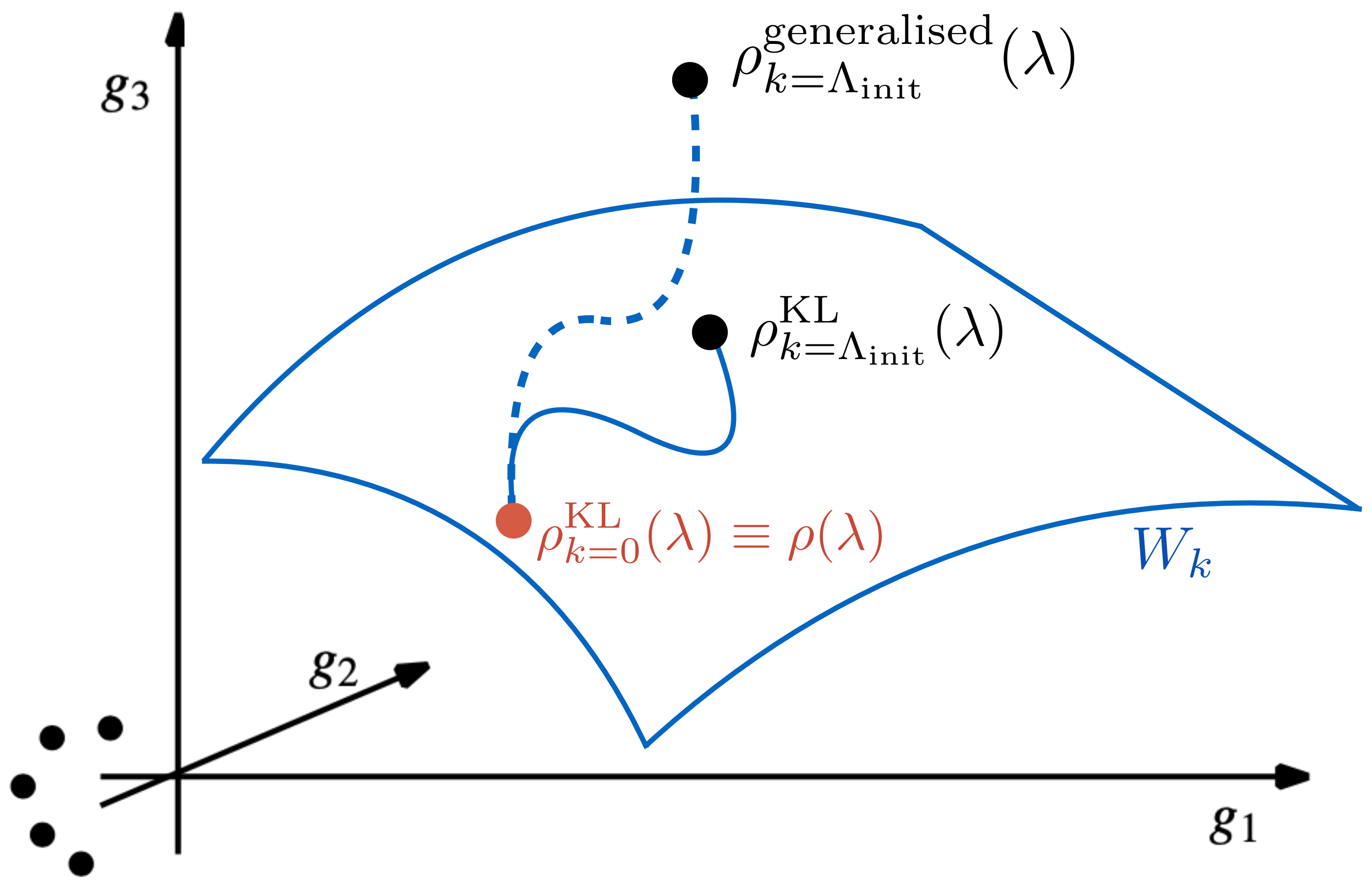




Callan-Symanzik is not enough to define spectral flow

→ **Constraints from diffeomorphism symmetry**



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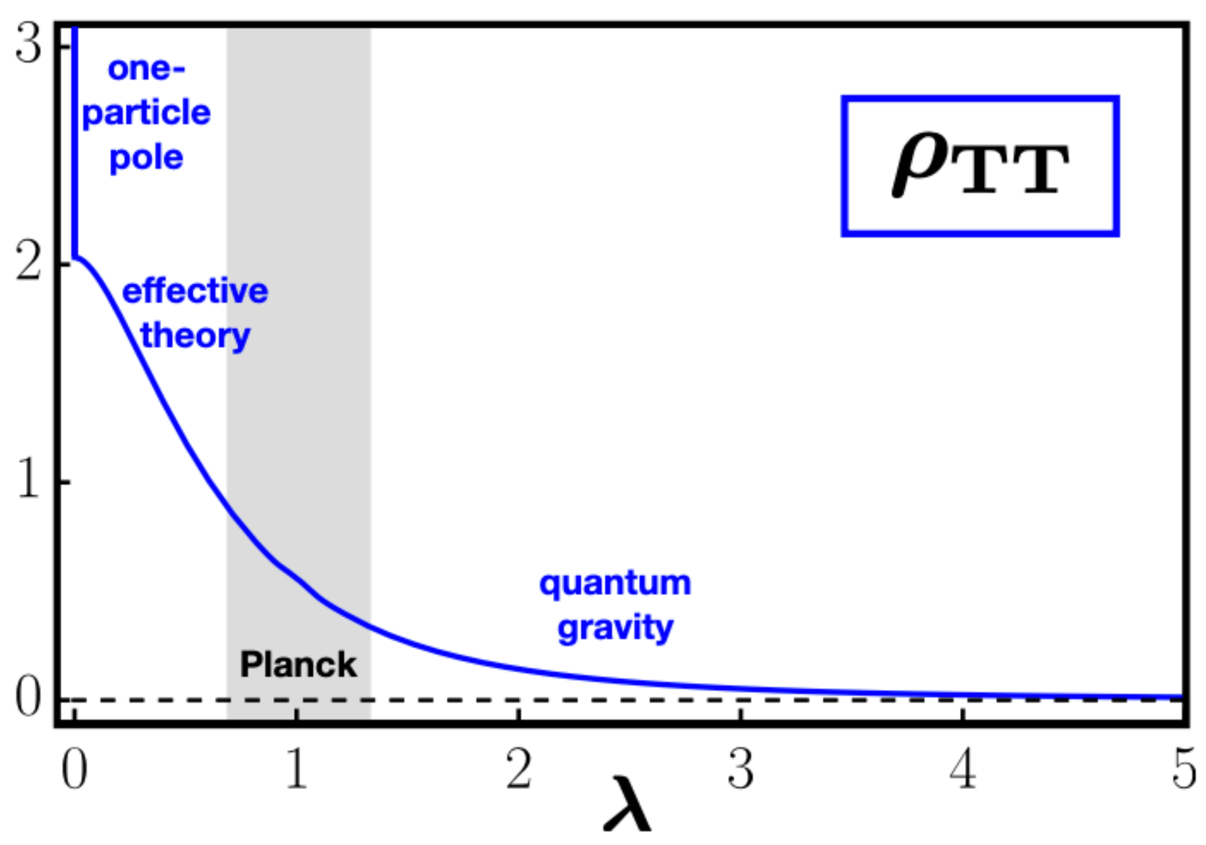

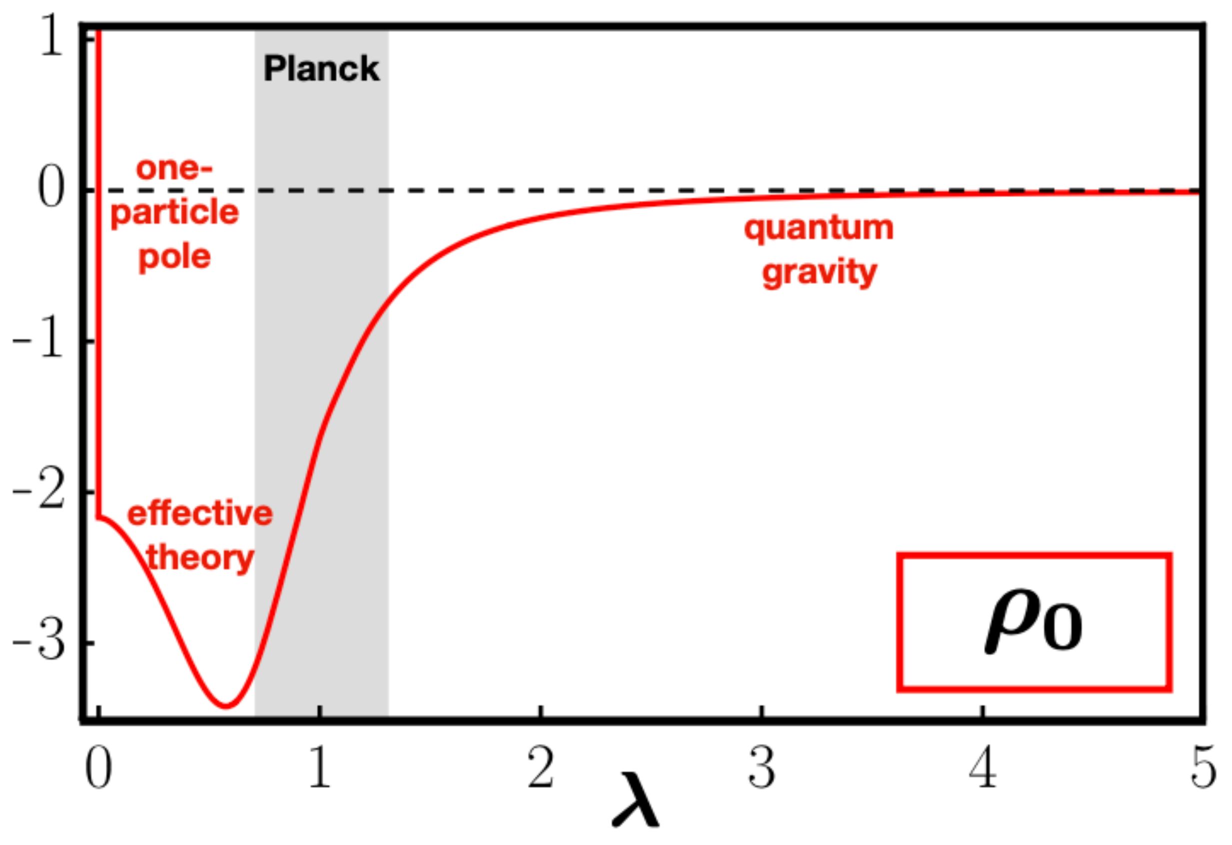

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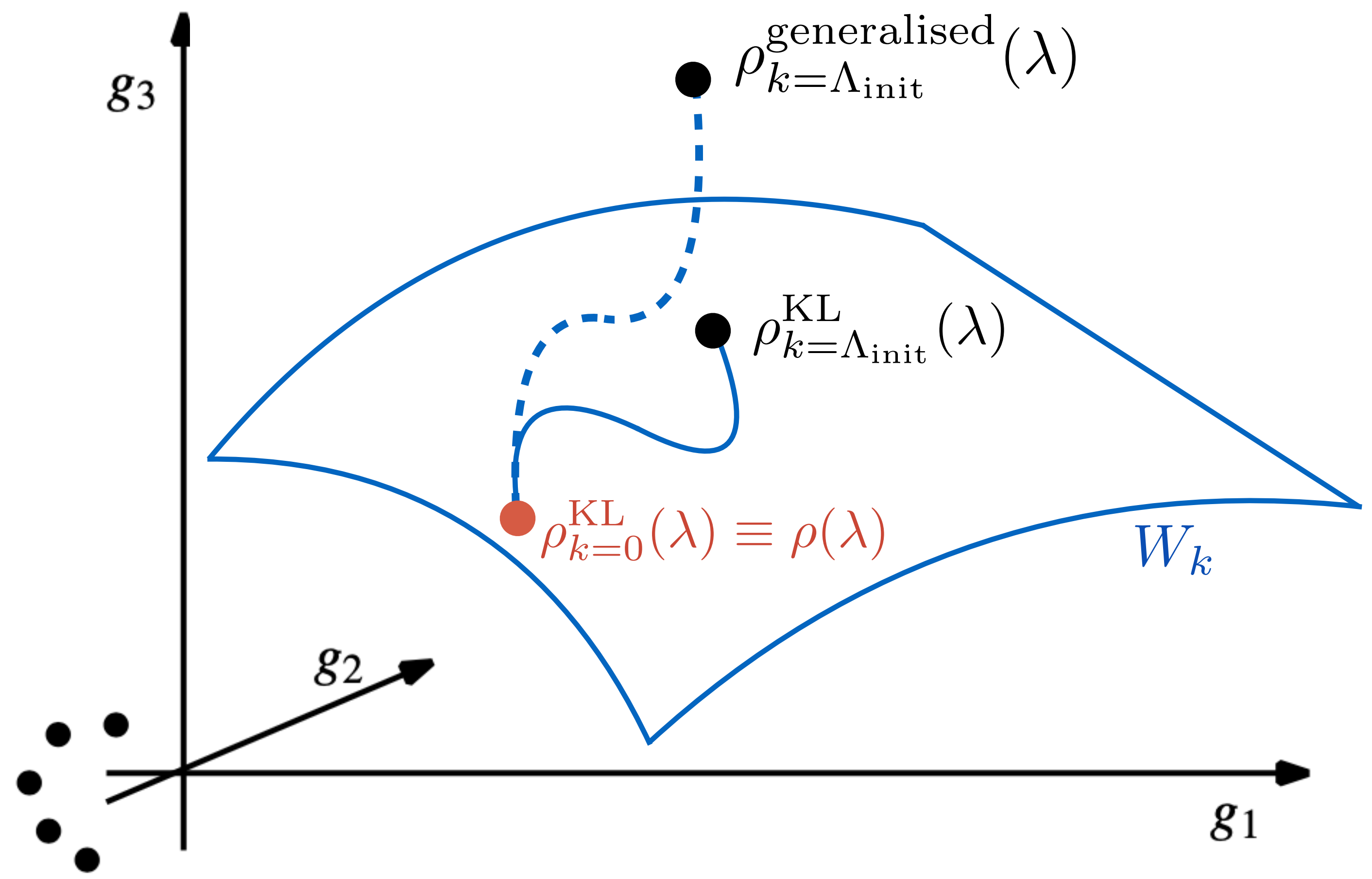


Full form factors R^2, C^2

$$\Gamma_{k=0} = \int d^4x \sqrt{g}\left(\frac{R}{16\pi G_N} + R f_R(\Box) R + C_{\mu\nu\rho\sigma} f_C(\Box) C^{\mu\nu\rho\sigma} + \cdots\right) + S_{gh} + S_{gf}$$

→ **Black holes, cosmology, scattering amplitudes...**

Extra slides

(2) Scalar sector

Projectors in the scalar sector

$$
\begin{aligned}
{\Pi^0}_{\mu\nu}{}^{\rho\sigma} &= \frac{(3-\beta)^2}{12(3+\beta^2)}\left(\delta_{\mu\nu} + \frac{4\,\beta}{3-\beta}\Pi^L_{\mu\nu}\right)\left(\delta^{\rho\sigma} + \frac{4\,\beta}{3-\beta}\Pi^{L,\,\rho\sigma}\right),\\
{\Pi^{\tilde{0}}}_{\mu\nu}{}^{\rho\sigma} &= \frac{(1+\beta)^2}{4(3+\beta^2)}\left(\delta_{\mu\nu} - \frac{4}{1+\beta}\Pi^L_{\mu\nu}\right)\left(\delta^{\rho\sigma} - \frac{4}{1+\beta}\Pi^{L,\,\rho\sigma}\right),\\
{\Pi^{0\tilde{0}}}_{\mu\nu}{}^{\rho\sigma} &= \frac{(3-\beta)(1+\beta)}{4\sqrt{3}(3+\beta^2)}\left(\delta_{\mu\nu} + \frac{4\,\beta}{3-\beta}\Pi^L_{\mu\nu}\right)\left(\delta^{\rho\sigma} - \frac{4}{1+\beta}\Pi^{L,\,\rho\sigma}\right),\\
{\Pi^{\tilde{0}0}}_{\mu\nu}{}^{\rho\sigma} &= \frac{(3-\beta)(1+\beta)}{4\sqrt{3}(3+\beta^2)}\left(\delta_{\mu\nu} - \frac{4}{1+\beta}\Pi^L_{\mu\nu}\right)\left(\delta^{\rho\sigma} + \frac{4\,\beta}{3-\beta}\Pi^{L,\,\rho\sigma}\right).
\end{aligned}
$$

Physical scalar mode projector is orthogonal to the gauge fixing

$$\Pi^0 \cdot S^{(2)}_{\rm gf} = 0$$

Tensor decomposed two-point function is

$$\Gamma^{(2),\mu\nu\rho\sigma} = \frac{1}{32\pi}\left(\Gamma^{(2)}_{\rm TT}\Pi^{\mu\nu\rho\sigma}_{\rm TT} + \Gamma^{(2)}_{\rm V}\Pi^{\mu\nu\rho\sigma}_{\rm V} - \frac{1}{2}\Gamma^{(2)}_{0}\Pi^{\mu\nu\rho\sigma}_{0} + \frac{1}{2}\Gamma^{(2)}_{\tilde{0}}\Pi^{\mu\nu\rho\sigma}_{\tilde{0}} - \frac{\sqrt{3}}{2}\Gamma^{(2)}_{0\tilde{0}}\left(\Pi^{\mu\nu\rho\sigma}_{0\tilde{0}} + \Pi^{\mu\nu\rho\sigma}_{\tilde{0}0}\right)\right)$$

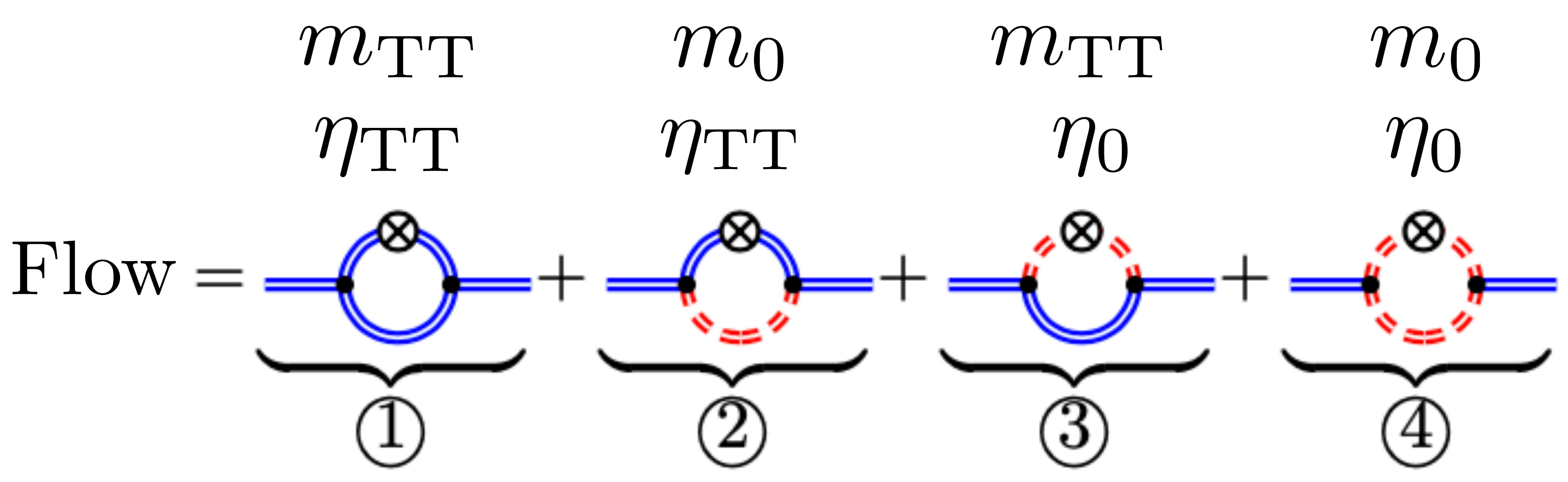
We make a "uniform" approximation in the scalar sector

$$\Gamma^{(2)}_{0} = \Gamma^{(2)}_{\tilde{0}} = \Gamma^{(2)}_{0\tilde{0}}$$

Breaks for feedback of continua into the 2pt flow

[Pawlowski, Reichert, Wessely, 2025]

(2) Mass identifications and complex poles



Expand the transverse-traceless mode flow around

$$m_0 = m_{TT} + \delta m$$

The transverse-traceless mass parameter flow is

$$\partial_t m_{TT}^2\big|_{3\text{-point}} = m_{TT}^2 \Bigg[\overbrace{g(2-\eta_{TT})\frac{-23600+9(513\sqrt{3}-31i)\pi}{6480\pi}}^{\textcircled{1}} + \overbrace{g(2-\eta_0)\frac{8390+9(-133\sqrt{3}+31i)\pi}{6480\pi}}^{\textcircled{3}} + \underbrace{g(2-\eta_{TT})\frac{-25360+9(575\sqrt{3}+31i)\pi}{6480\pi}}_{\textcircled{2}} + \underbrace{g(2-\eta_0)\frac{430+9(45\sqrt{3}-31i)\pi}{6480\pi}}_{\textcircled{4}} \Bigg] + \mathcal{O}(\delta m)$$

Which becomes complex for any $\delta m \neq 0$

No KL **Generalised KL**