

Towards ghost-free and unitary quantum gravity

2606.19321

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with Daniel Litim and Manuel Reichert

Graz, 09/2026



UNIVERSITY
OF SUSSEX

Asymptotically safe quantum gravity

UV complete quantum gravity based on additional UV symmetry

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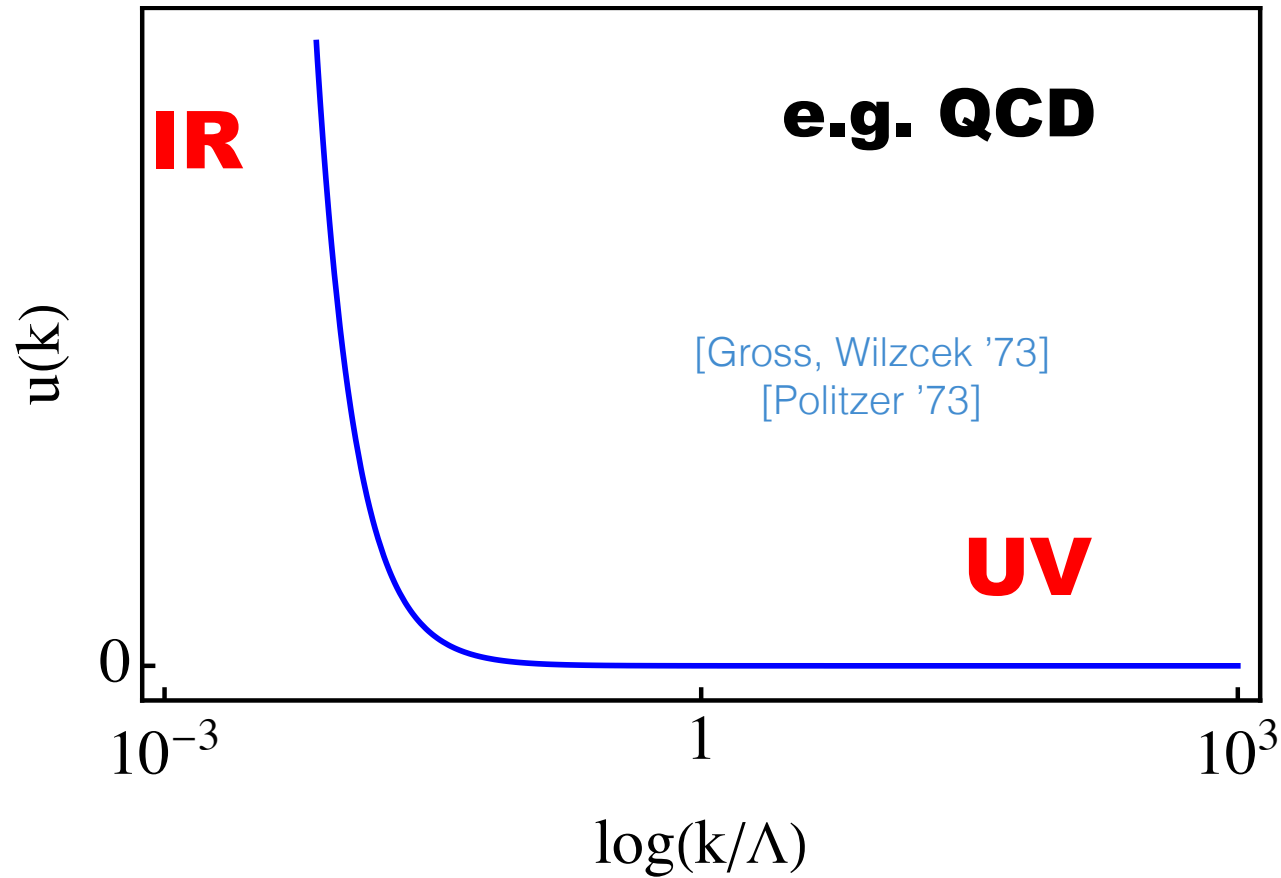
Quantum scale invariance

couplings reach UV fixed point under Renormalization Group running

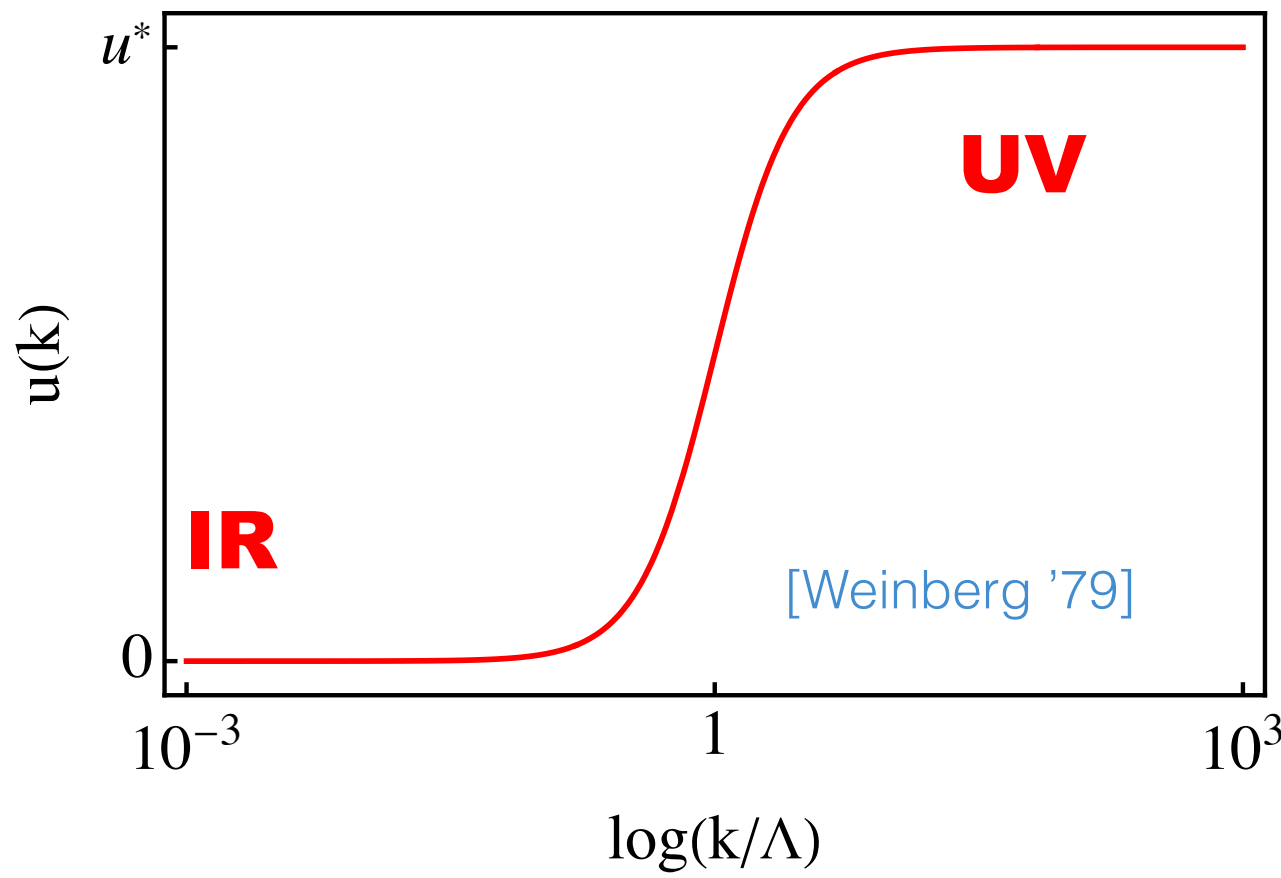
[Wilson '71]



**Asymptotic Freedom:
free fixed point**



**Asymptotic Safety:
interacting fixed point**



Asymptotically safe quantum gravity

UV complete quantum gravity based on additional UV symmetry

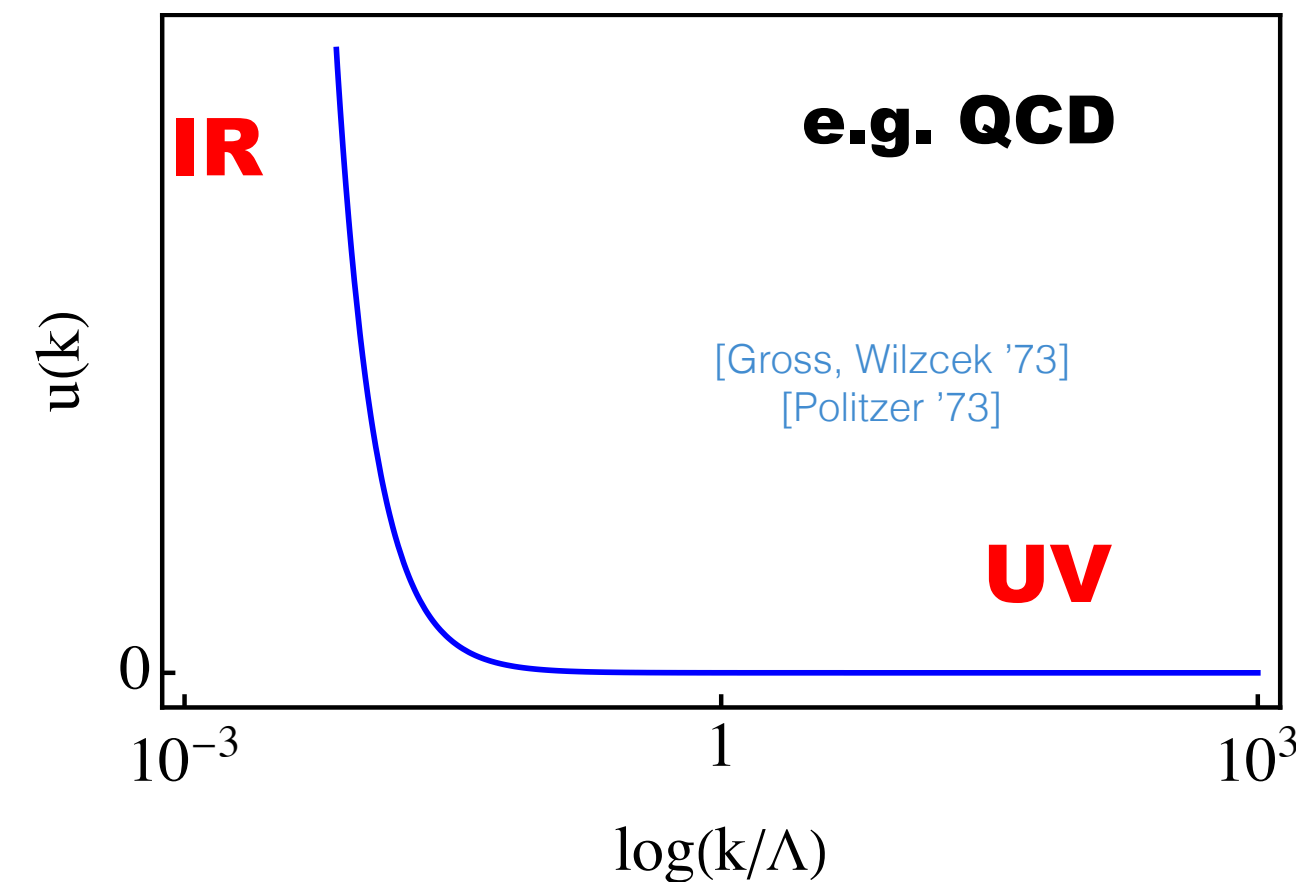
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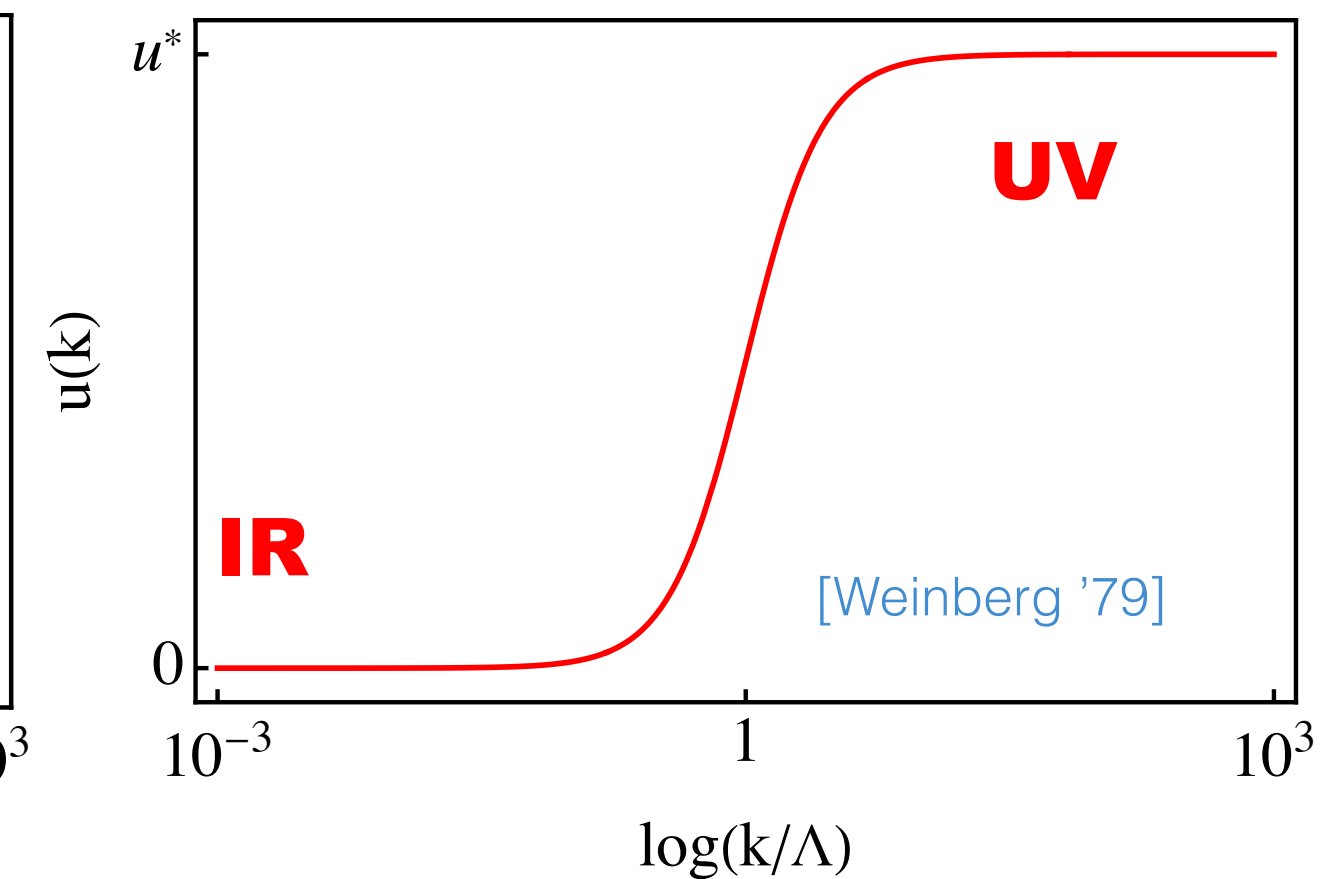
couplings reach UV fixed point under Renormalization Group running

[Wilson '71]

**Asymptotic Freedom:
free fixed point**



**Asymptotic Safety:
interacting fixed point**



Assumptions:

metric field carries degrees of freedom and diffeomorphism symmetry

Healthy and unitary quantum gravity

Healthy/unitary theory has **no ghosts or tachyons**.

e.g. GR

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

**2 on-shell
propagating dofs (GWs)**

Off-shell dofs

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

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

Fluctuation graviton

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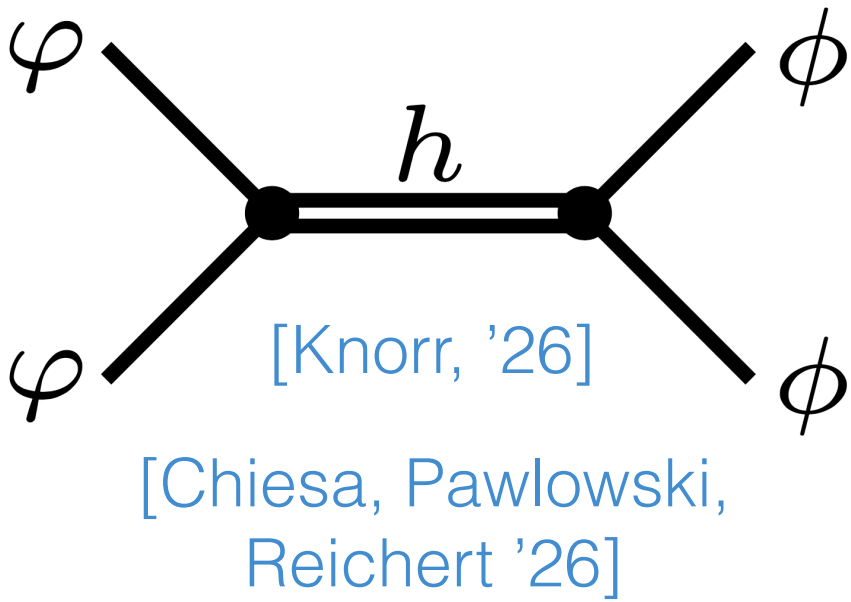
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Inflaton in R^2 gravity

Enters scattering



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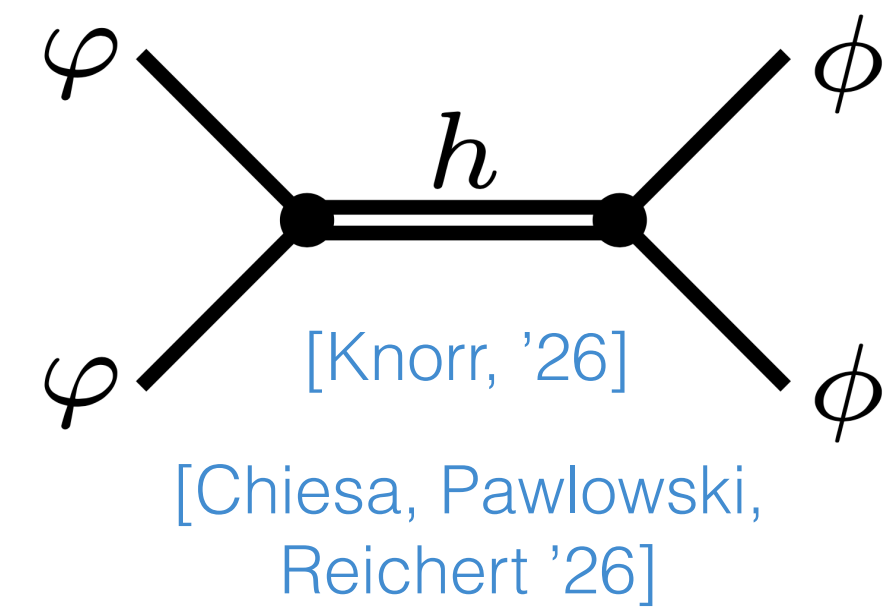
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2 on-shell propagating dofs (GWs)

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Spectral function: access to real time correlators

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

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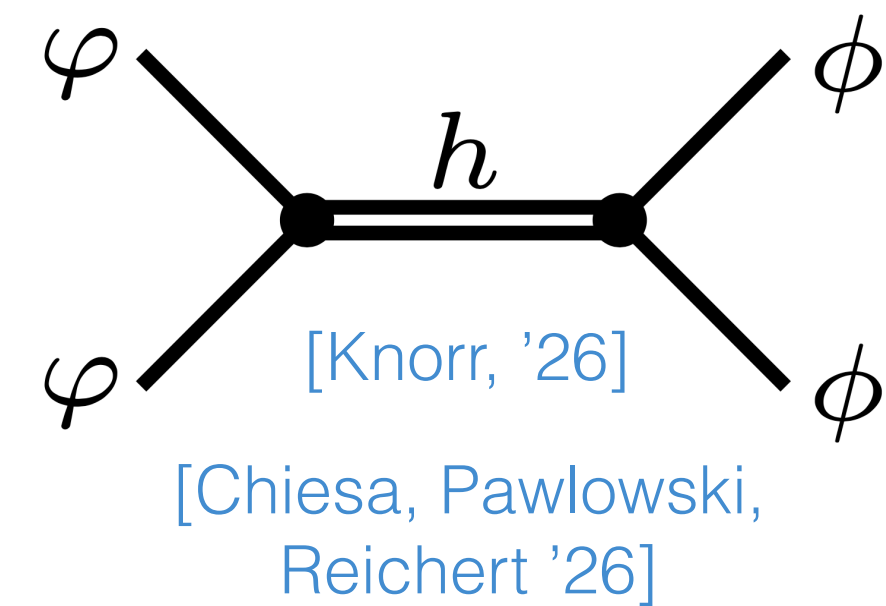
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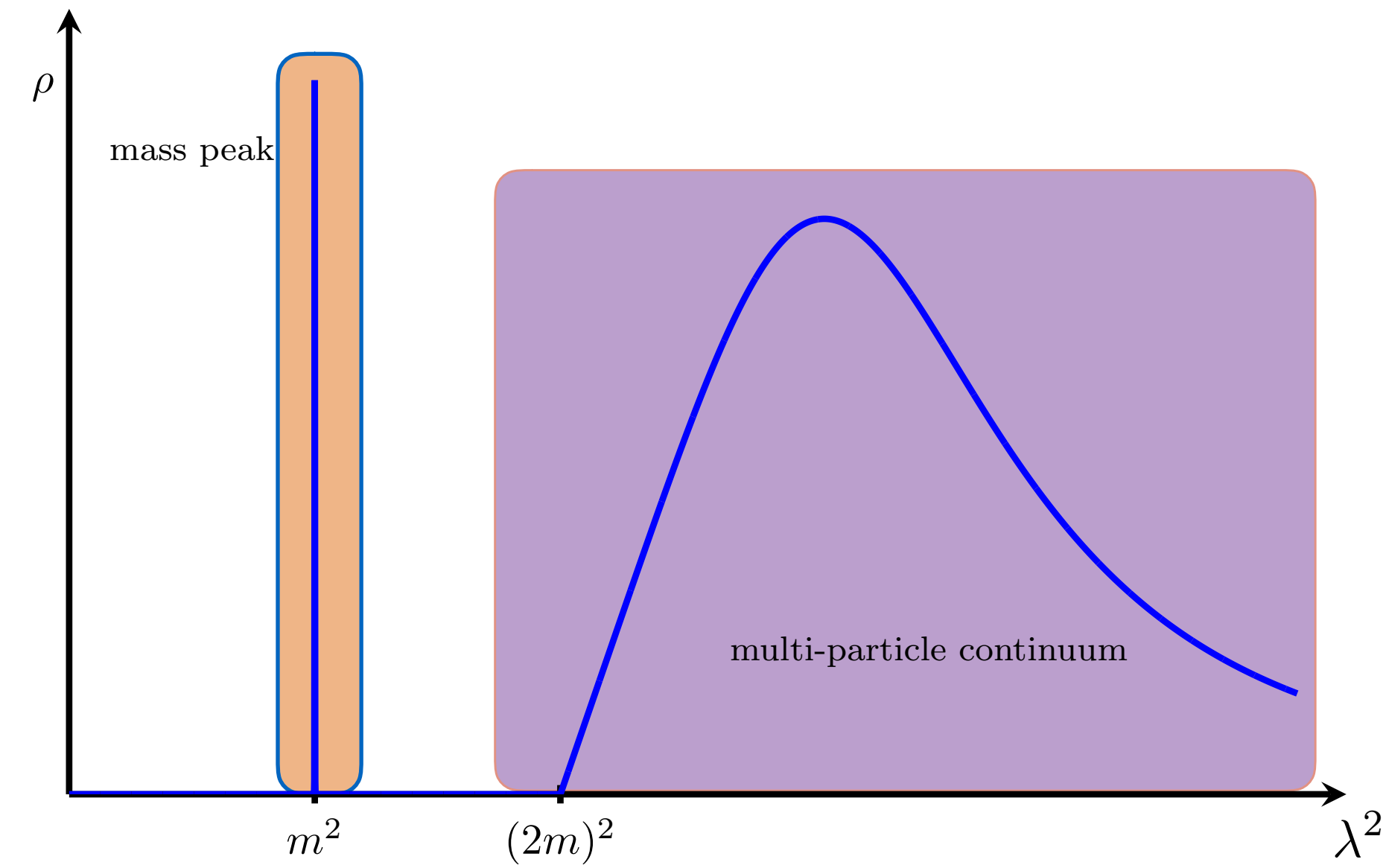
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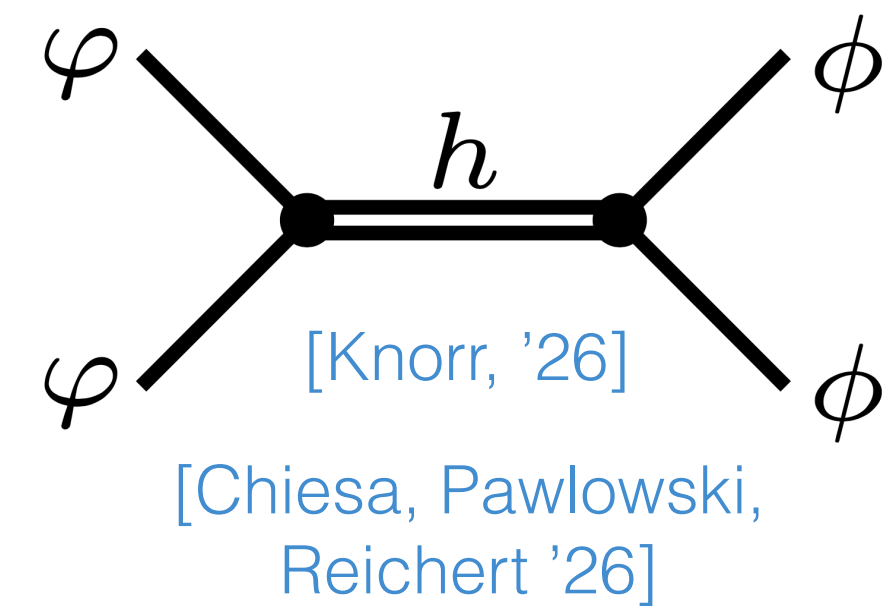
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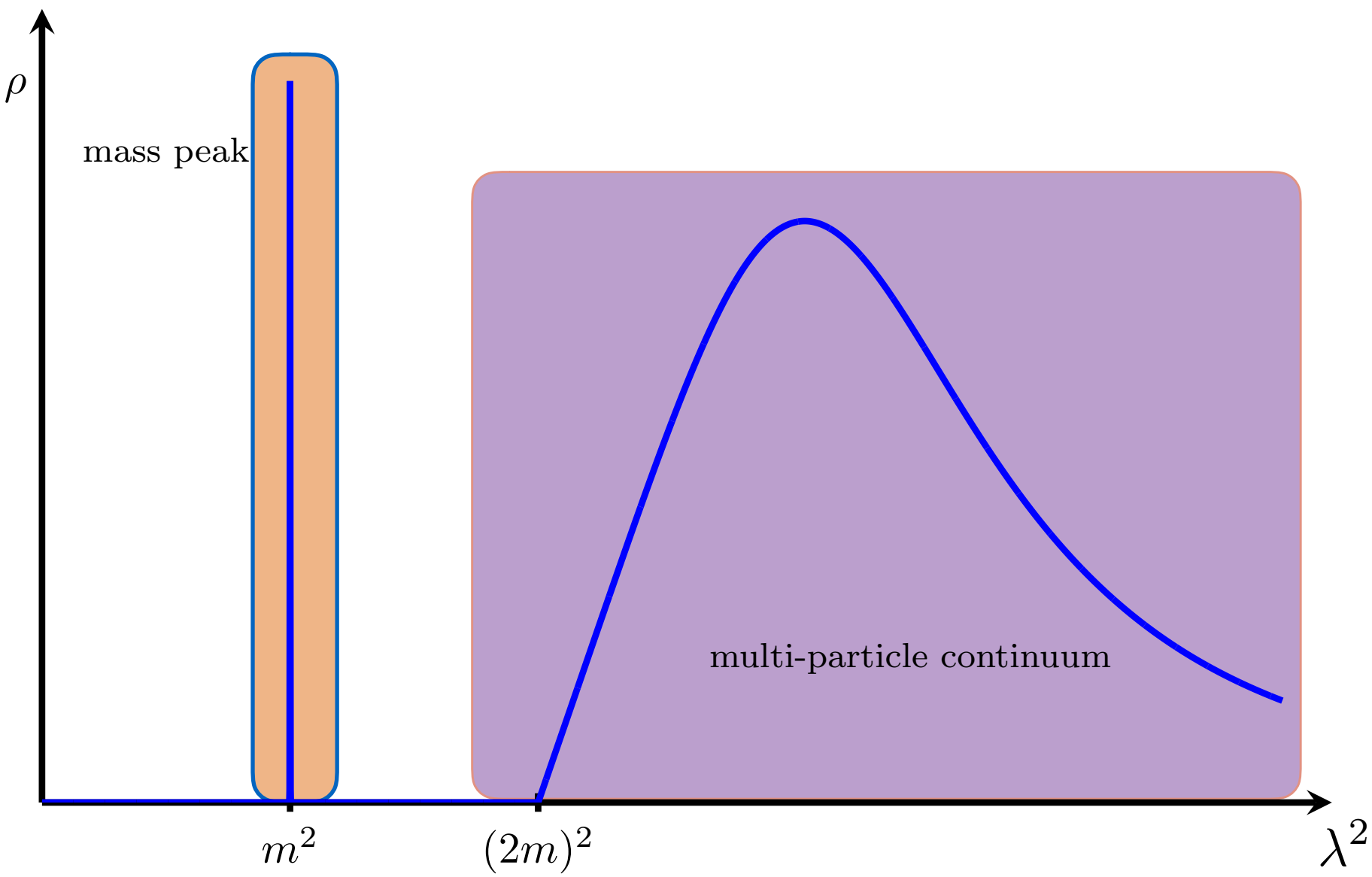


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Access to propagator for all momenta

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



Healthy and unitary quantum gravity

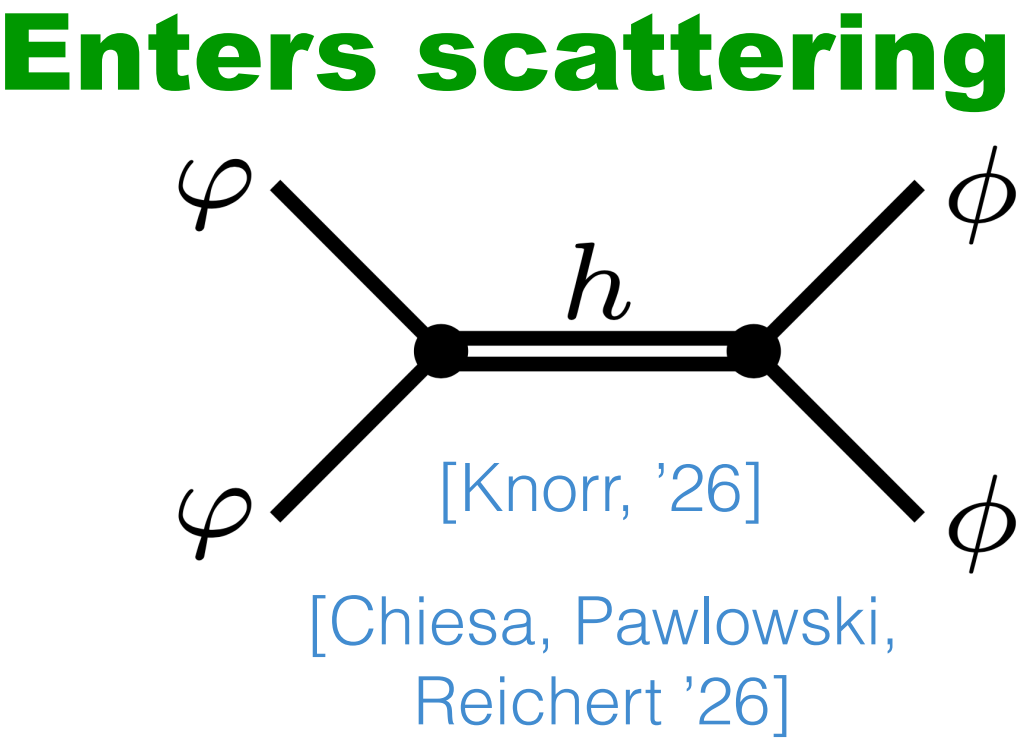
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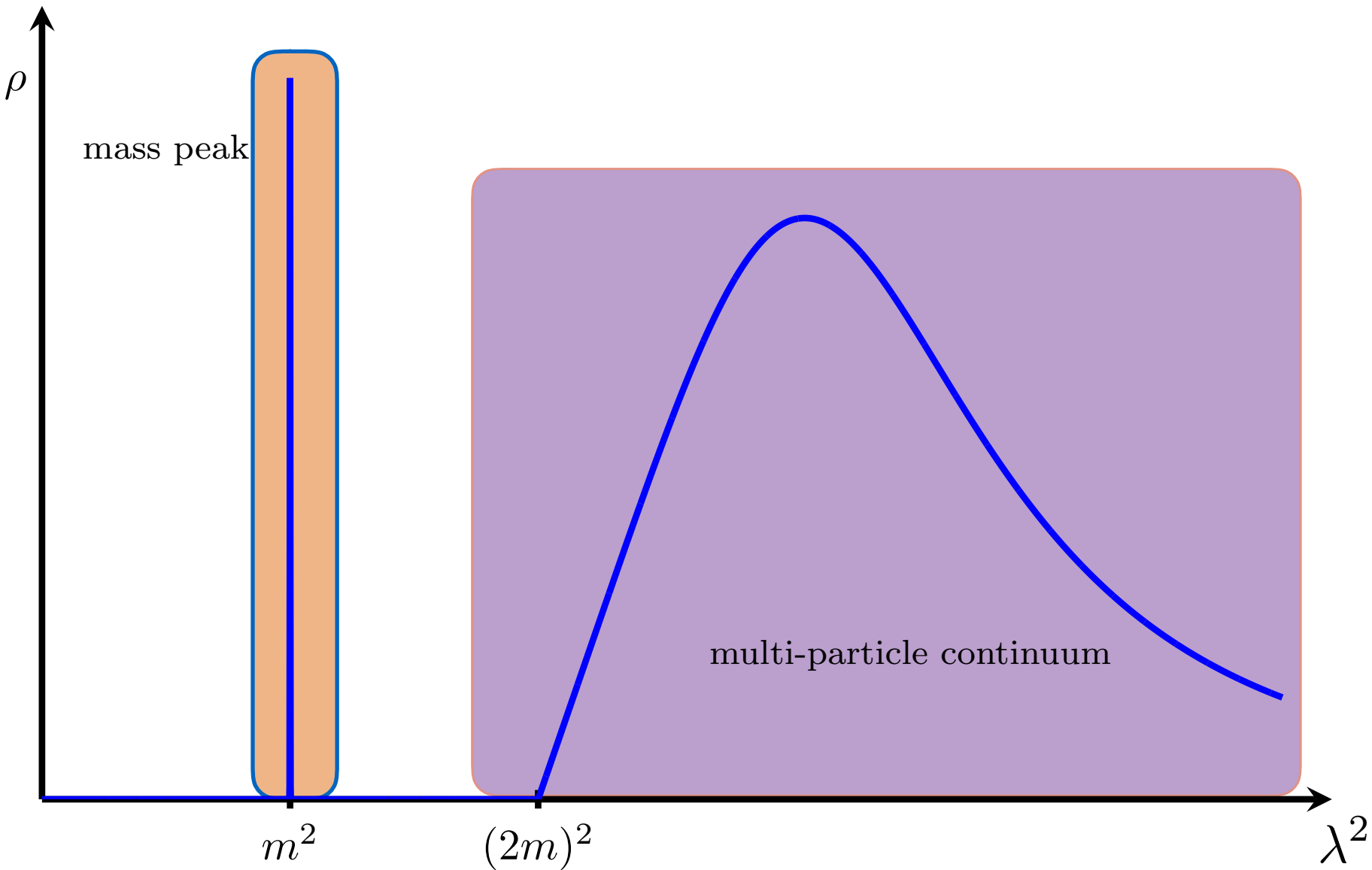


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Challenges

Need non-perturbative Lorentzian framework:
(Very new) Lorentzian functional RG

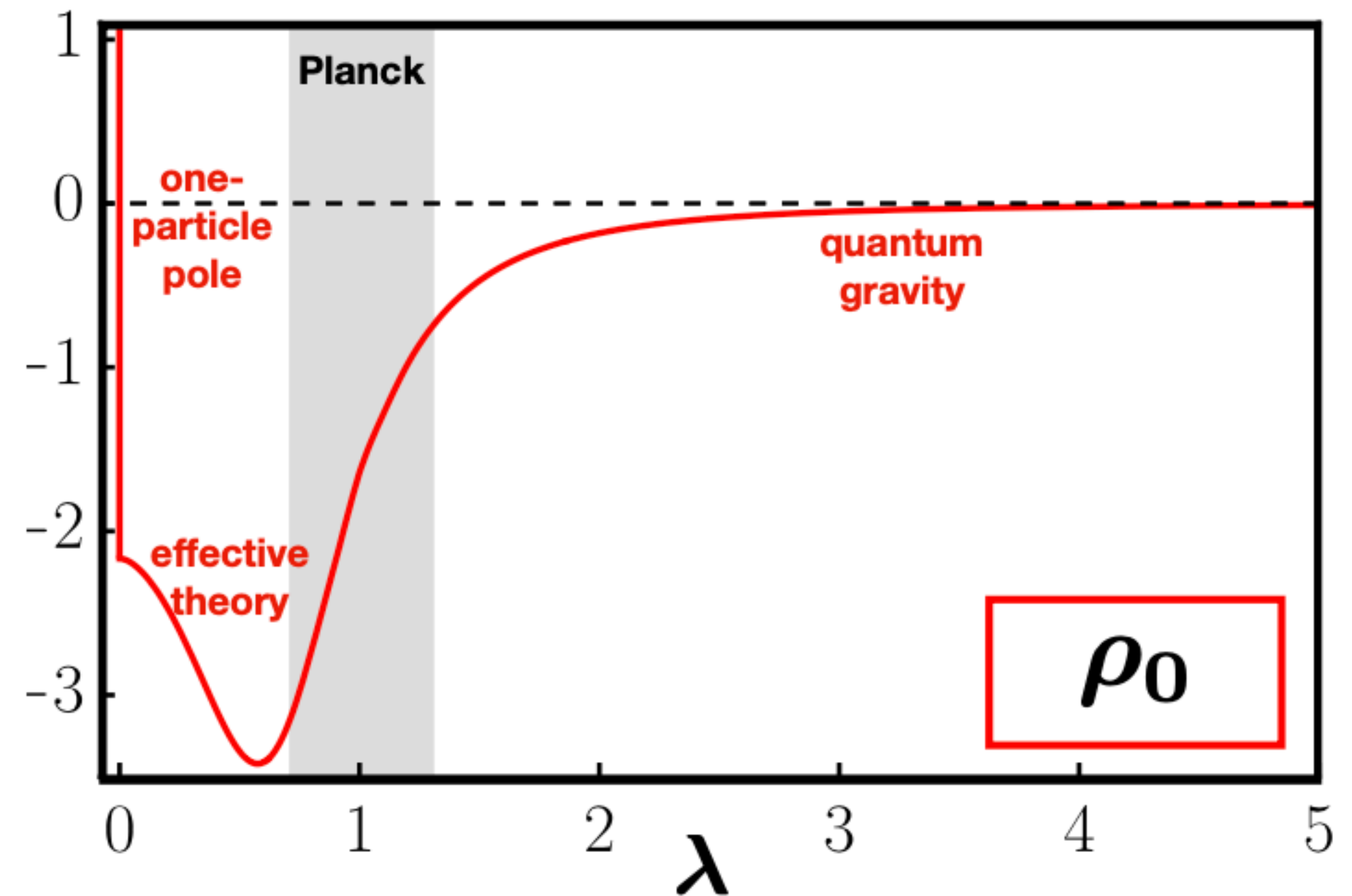
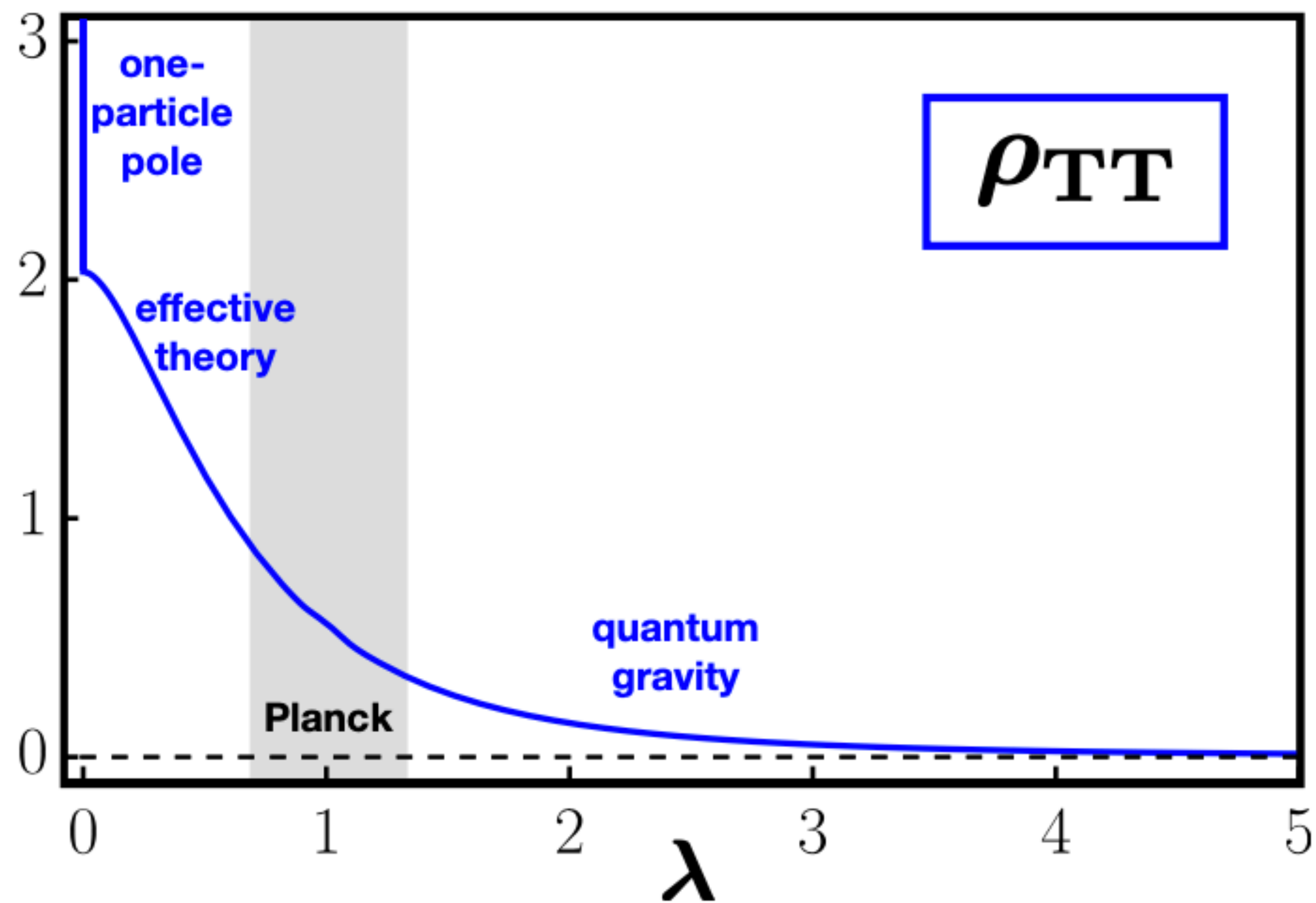


Spectral functions in on-shell renormalisation

The graviton is massless

Ghost and tachyon free

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

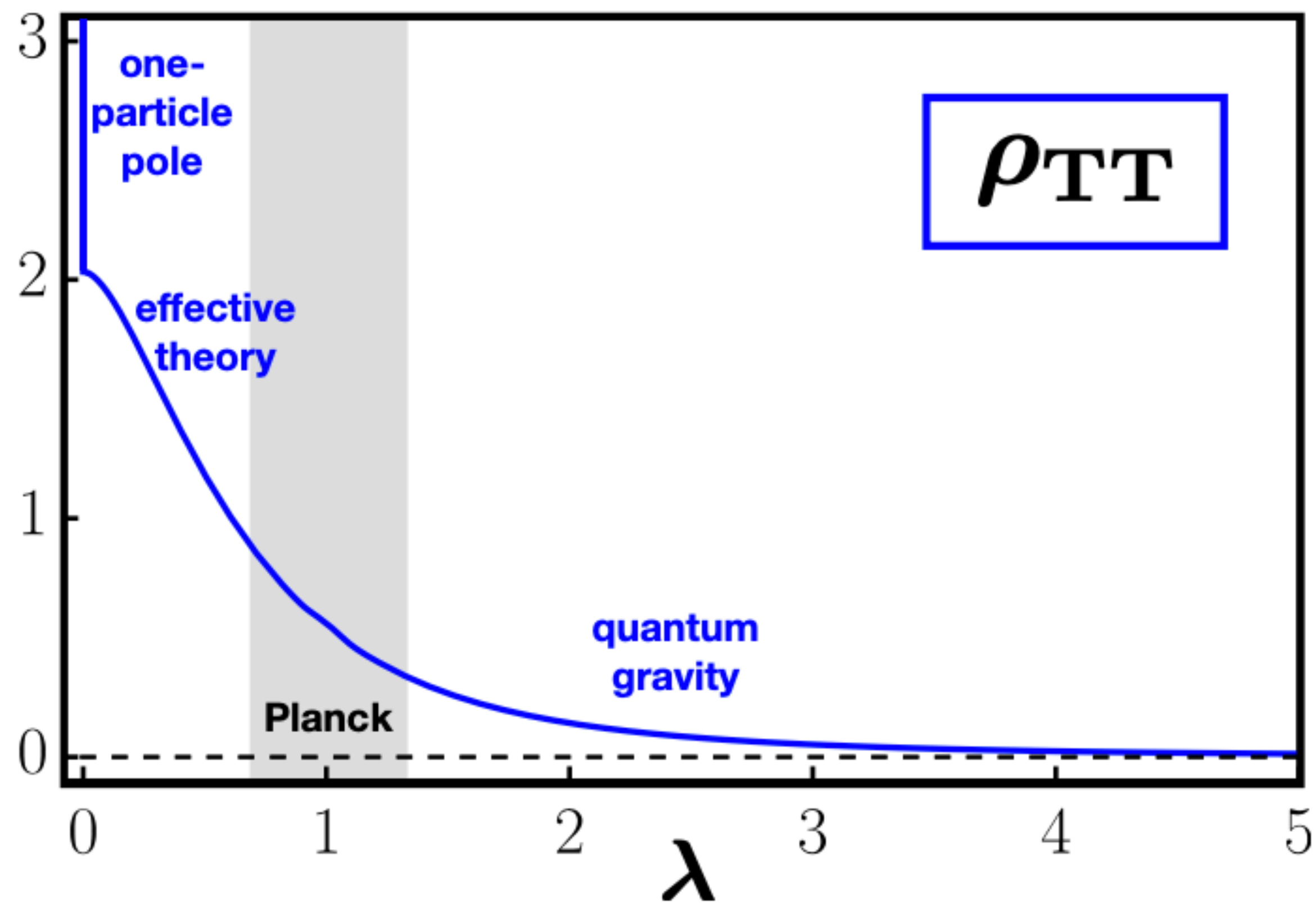


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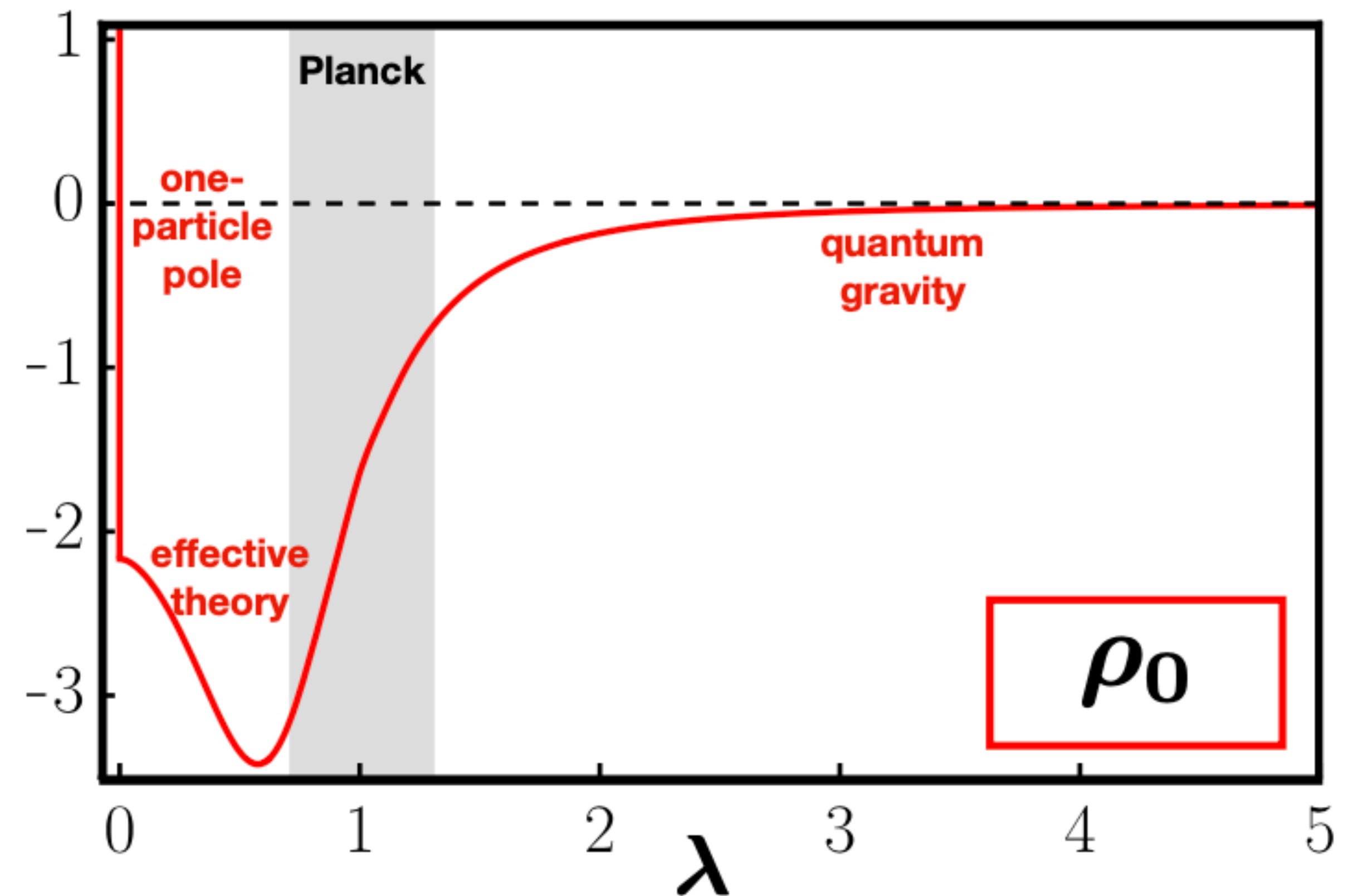
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TT agrees with numerical results

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



TT/0 agree with analytic results

[Knorr, '26]

Include graviton scalar mode

Set up differential equation for spectral functions

$$\rho_{\text{TT}/0}(\lambda) = 2 \operatorname{Im} \left[\mathcal{G}_{\text{TT}/0} \Big|_{\text{Wick}} \right]$$

$$\partial_t \rho_{\text{TT}/0}(\lambda) = -2 \operatorname{Im} \left[\mathcal{G}_{\text{TT}/0} \left(\partial_t \Gamma_{\text{TT}/0}^{(2)} \right) \Big|_{\text{Wick}} \right]$$

[Fehre, Litim, Pawłowski,
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Two-point quantum effective action

Fully dressed propagator: $\mathcal{G}_{\text{TT}/0} \propto \left(\Gamma_{\text{TT}/0}^{(2)} \right)^{-1}$

[Fehre, Litim, Pawłowski,
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Two-point quantum effective action
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How does it run?

Include graviton scalar mode

Set up differential equation for spectral functions

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Coupled RG flows two-point correlators

$$\begin{aligned} \partial_t \Gamma_{\text{TT}}^{(2)} &= \text{[diagrams]} - \frac{1}{2} \text{[diagram]} - \frac{1}{2} \text{[diagram]} - 2 \text{[diagram]} - \partial_t S_{\text{ct}, \text{TT}}^{(2)} \\ \partial_t \Gamma_0^{(2)} &= \text{[diagrams]} - \frac{1}{2} \text{[diagram]} - \frac{1}{2} \text{[diagram]} - 2 \text{[diagram]} - \partial_t S_{\text{ct}, 0}^{(2)} \end{aligned}$$

Blue lines: TT mode
Red lines: scalar + vector mode

Dashed black lines: ghost

Include graviton scalar mode

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Freedom in renormalisation condition

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RG fixed points, UV-IR trajectories

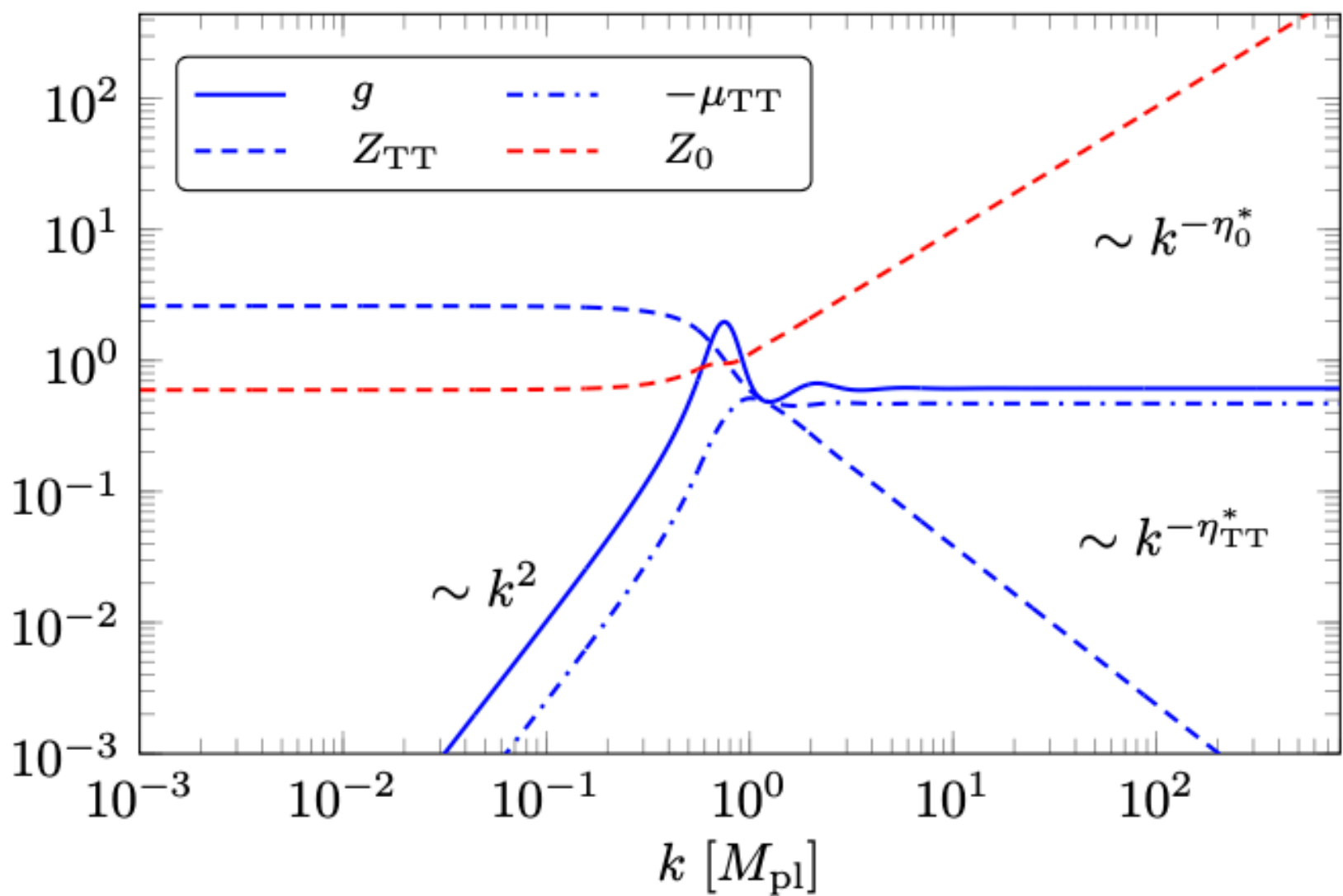
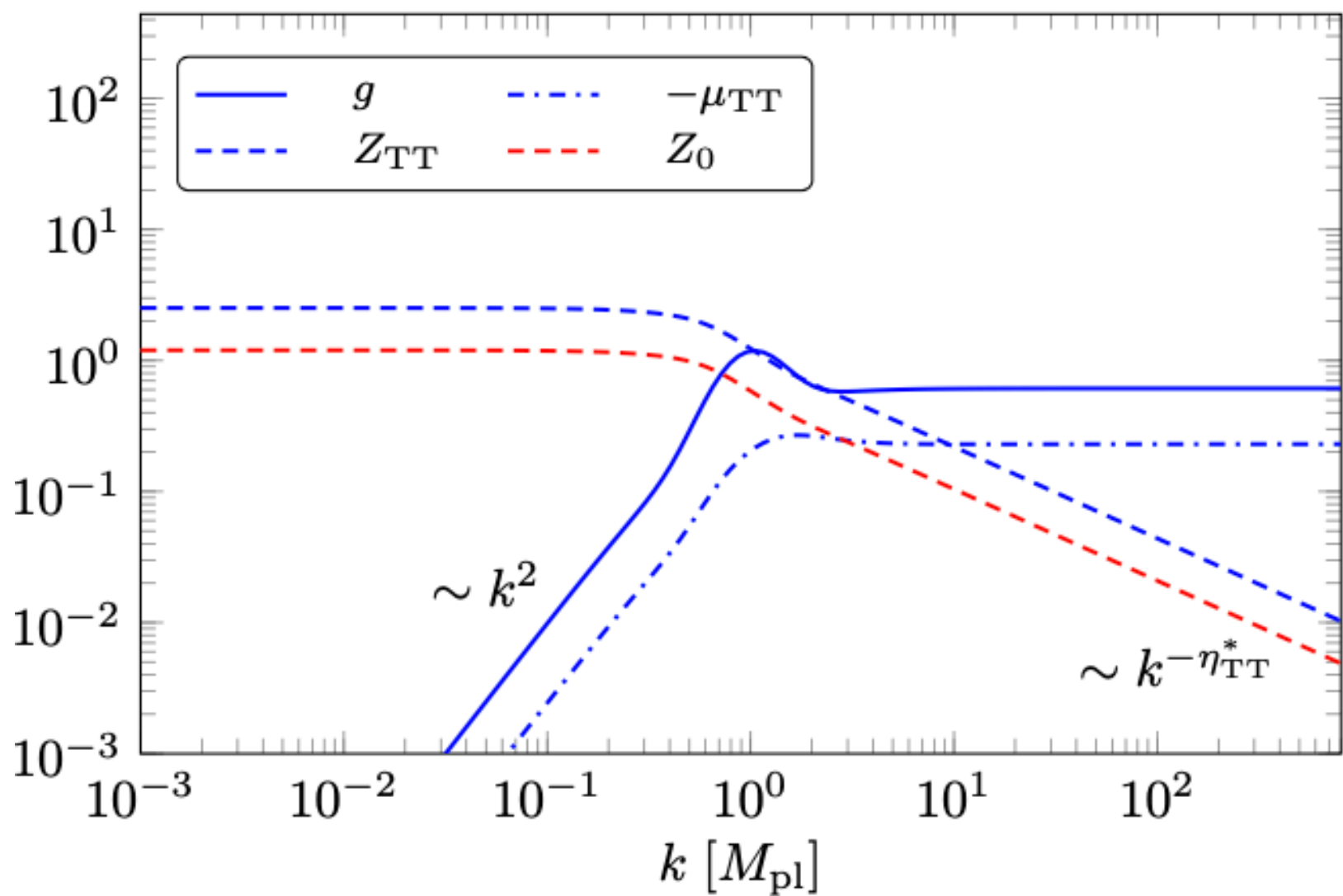
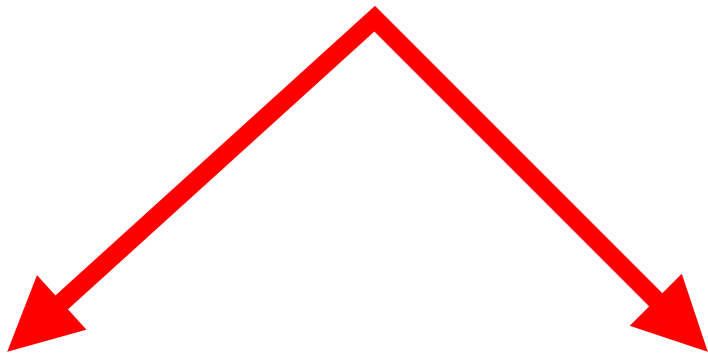
Counter-term action

$$\partial_t S_{\text{ct, TT}/0}^{(2)} = a_{\text{TT}/0} + b_{\text{TT}/0} p^2$$

p = 0 renormalisation

Fix pole location $\partial_t \Gamma_{\text{TT}/0}^{(2)}(p^2 = 0) = a_{\text{TT}/0}$

And height $\left. \partial_t \partial_{p^2} \Gamma_{\text{TT}/0}^{(2)}(p^2) \right|_{p^2=0} = b_{\text{TT}/0}$



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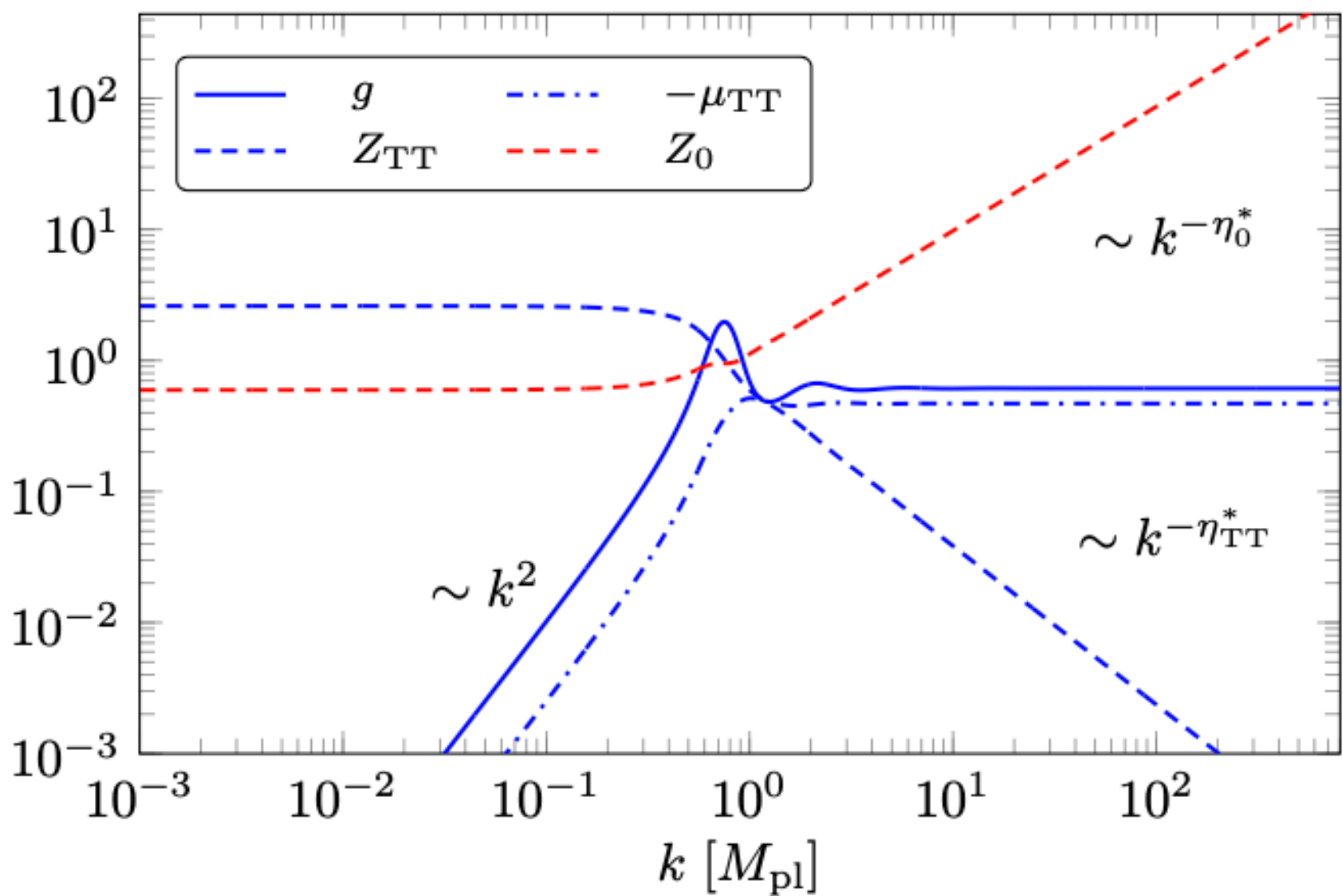
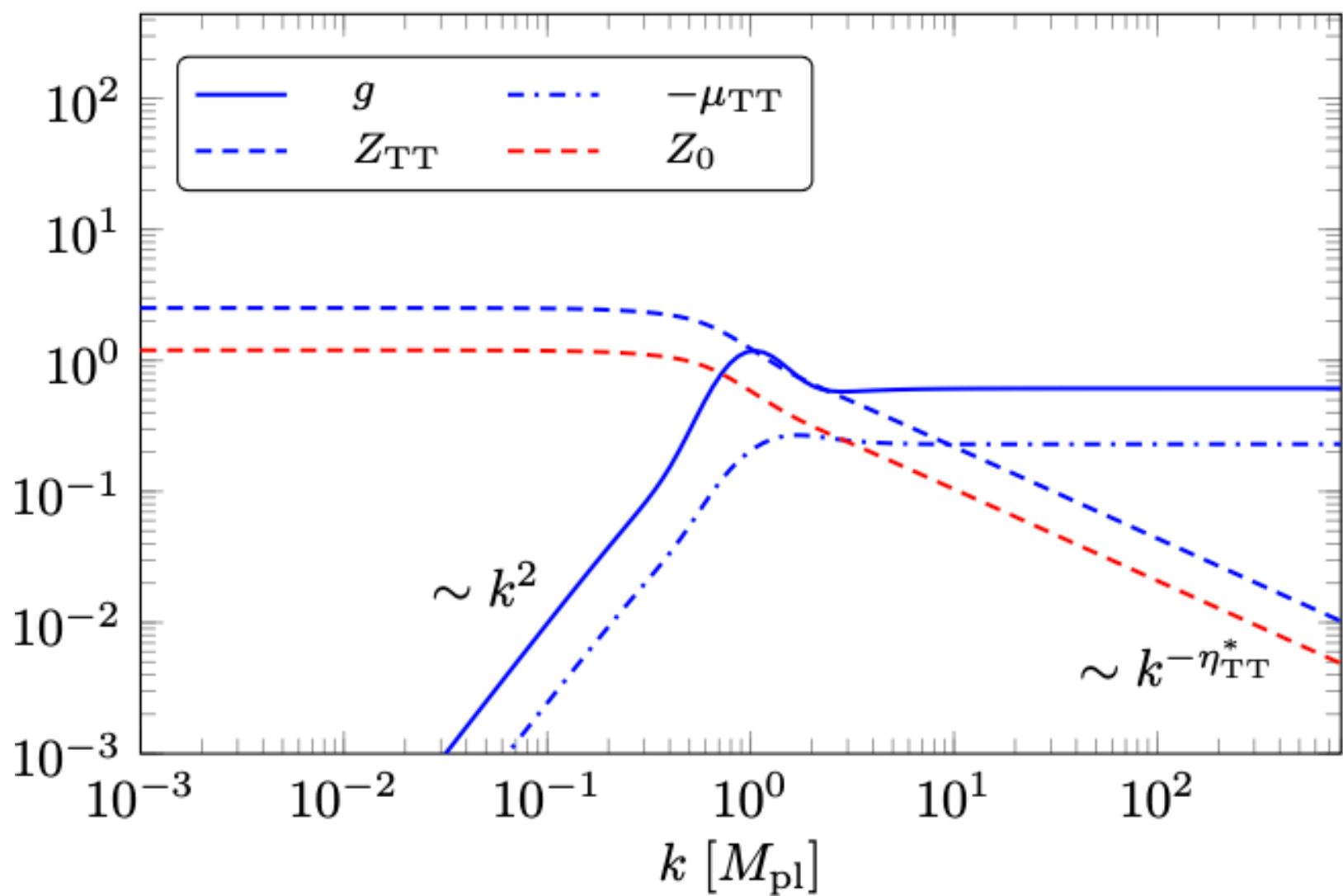
Renormalise on graviton mass pole $\partial_t \Gamma_{\text{TT}/0}^{(2)}(p^2 = -m_{\text{TT}/0}^2) = 0$

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[Pawlowski, Reichert, Wessely '25]

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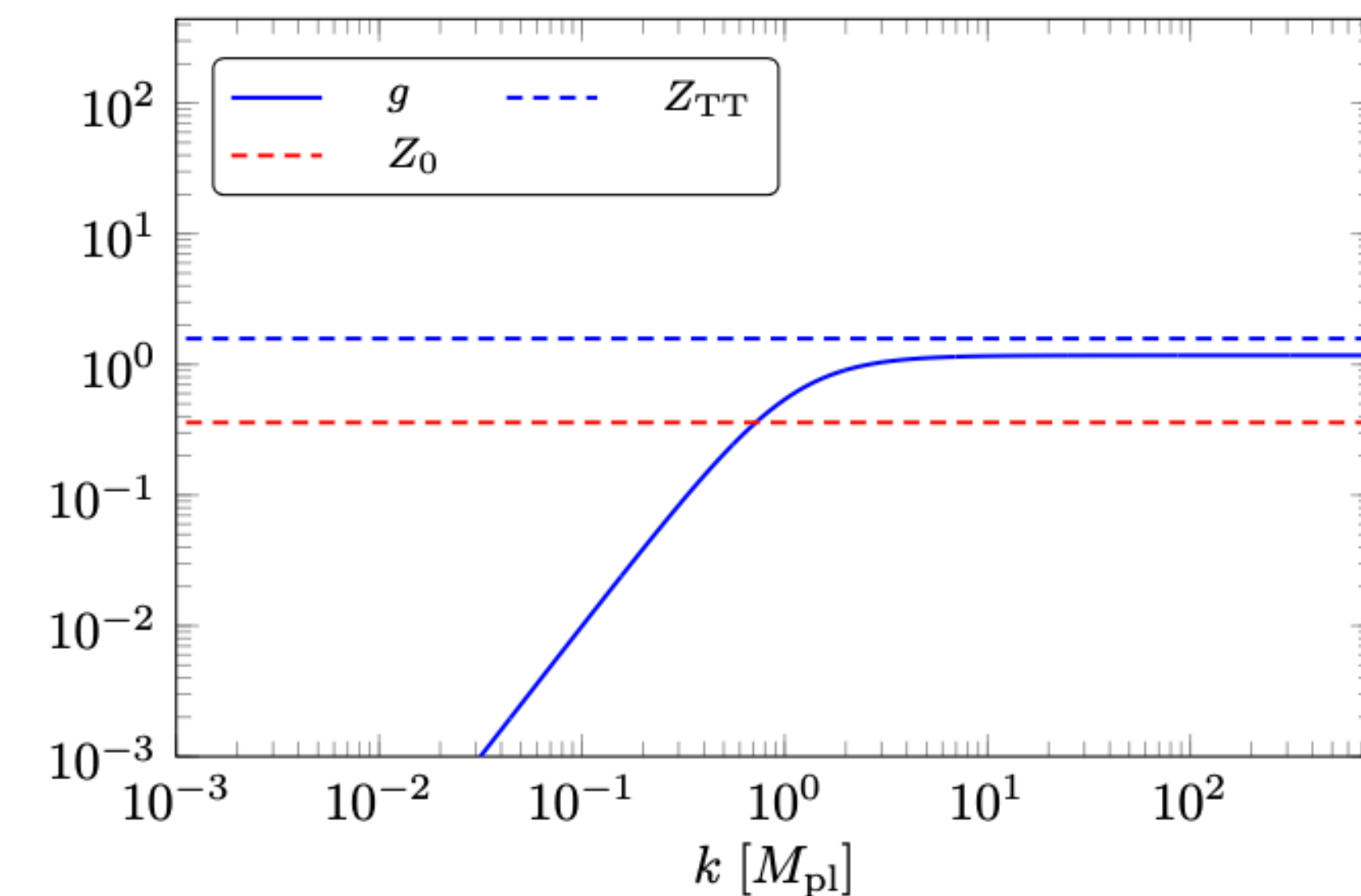
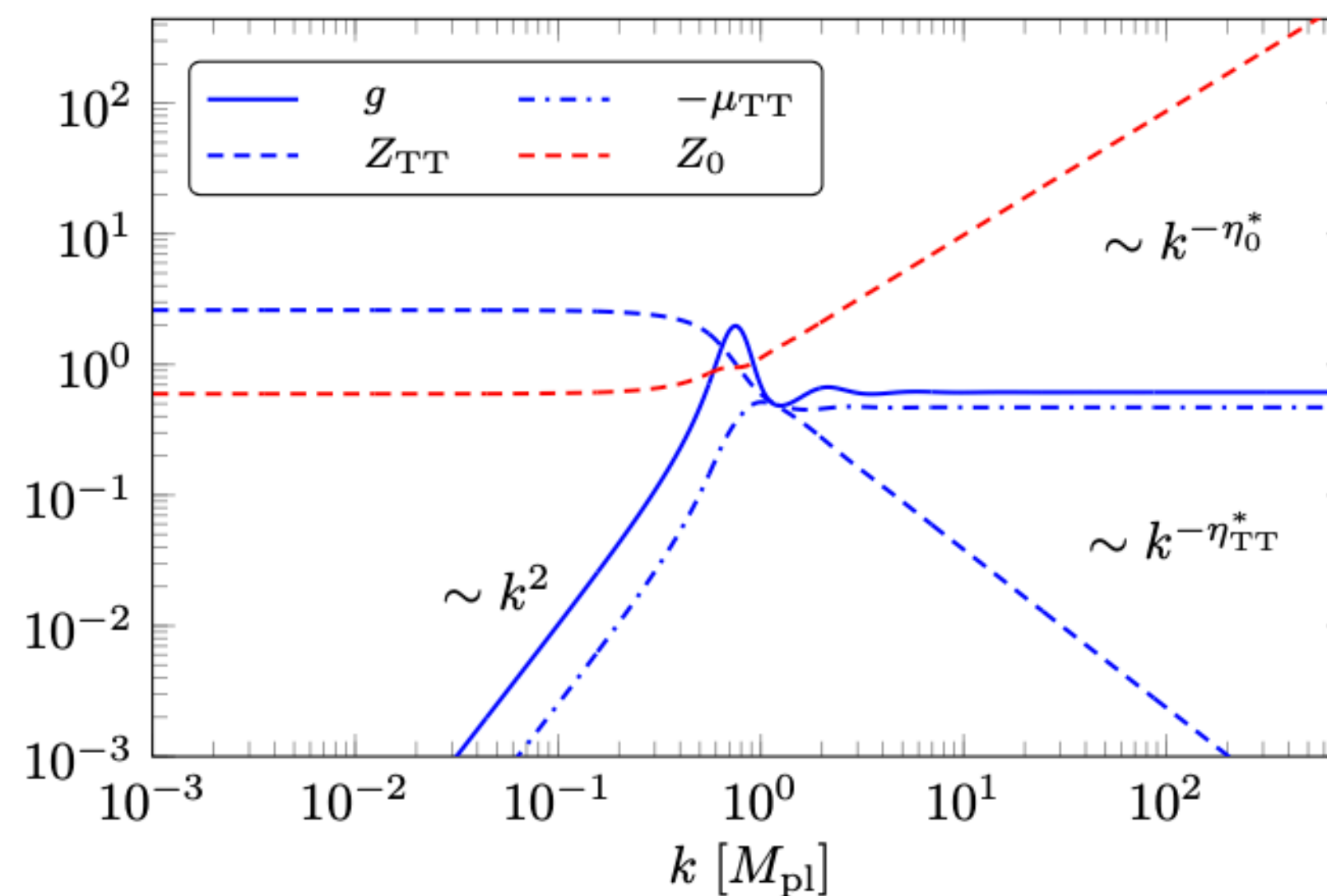
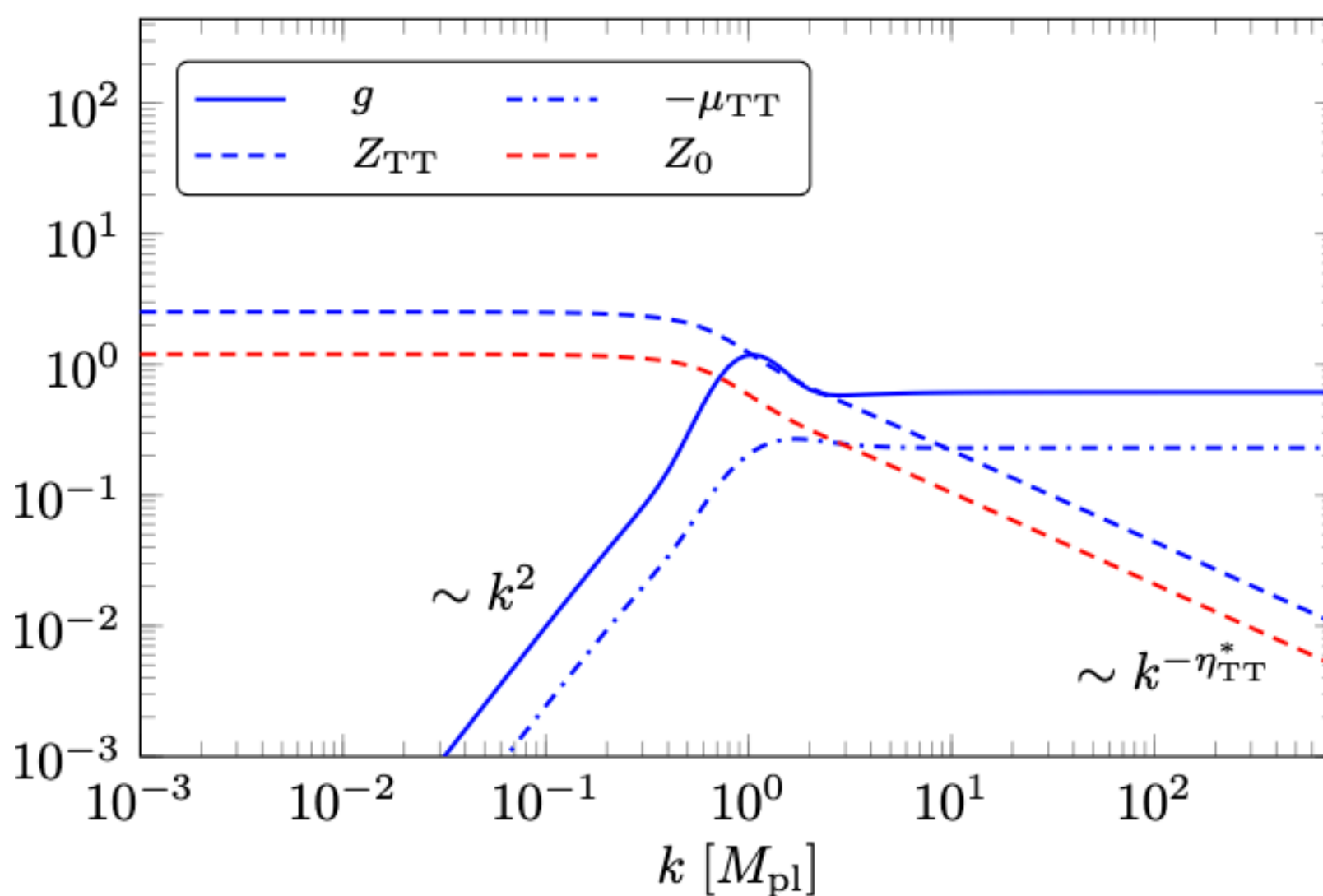
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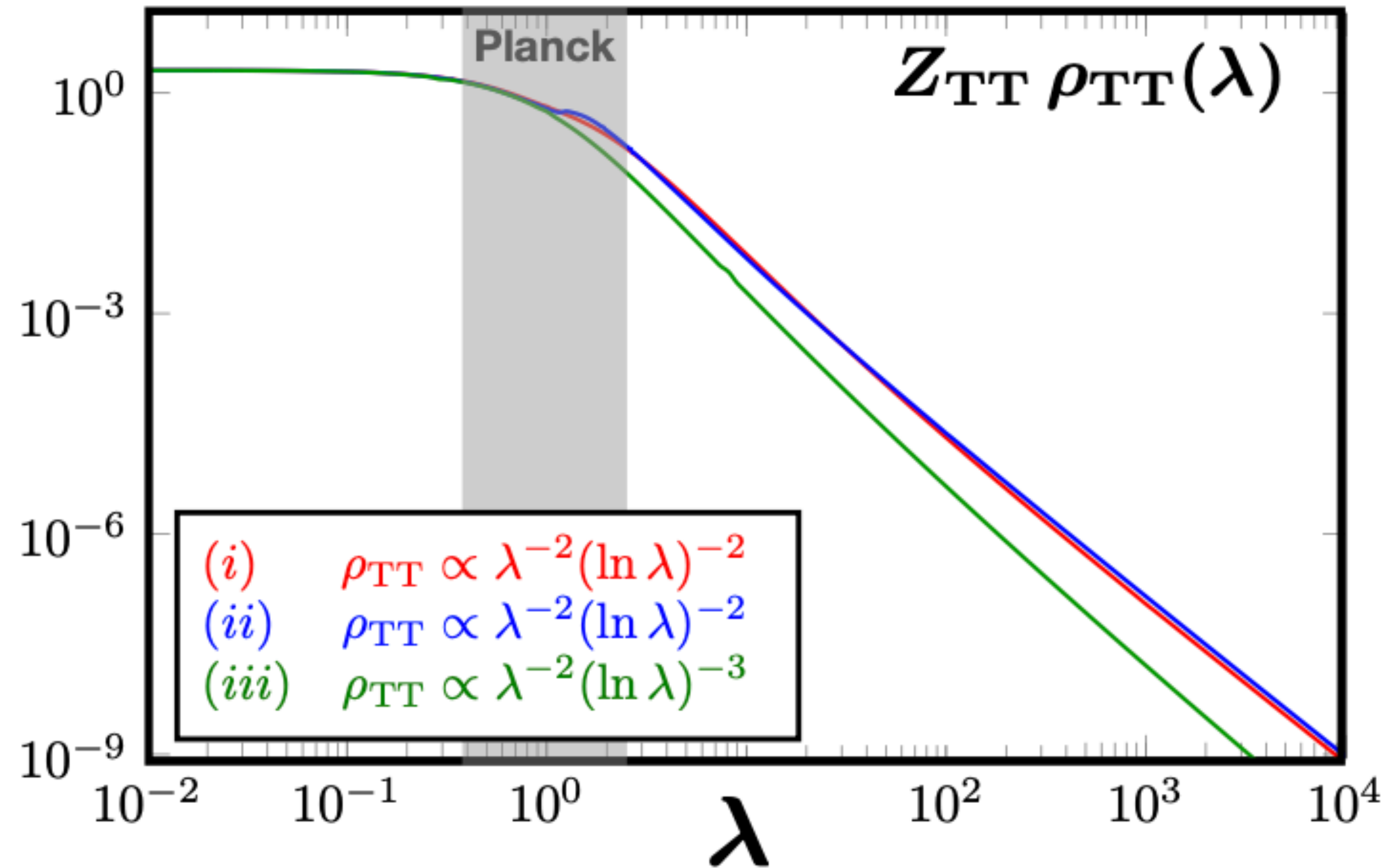
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Coupled spectral functions

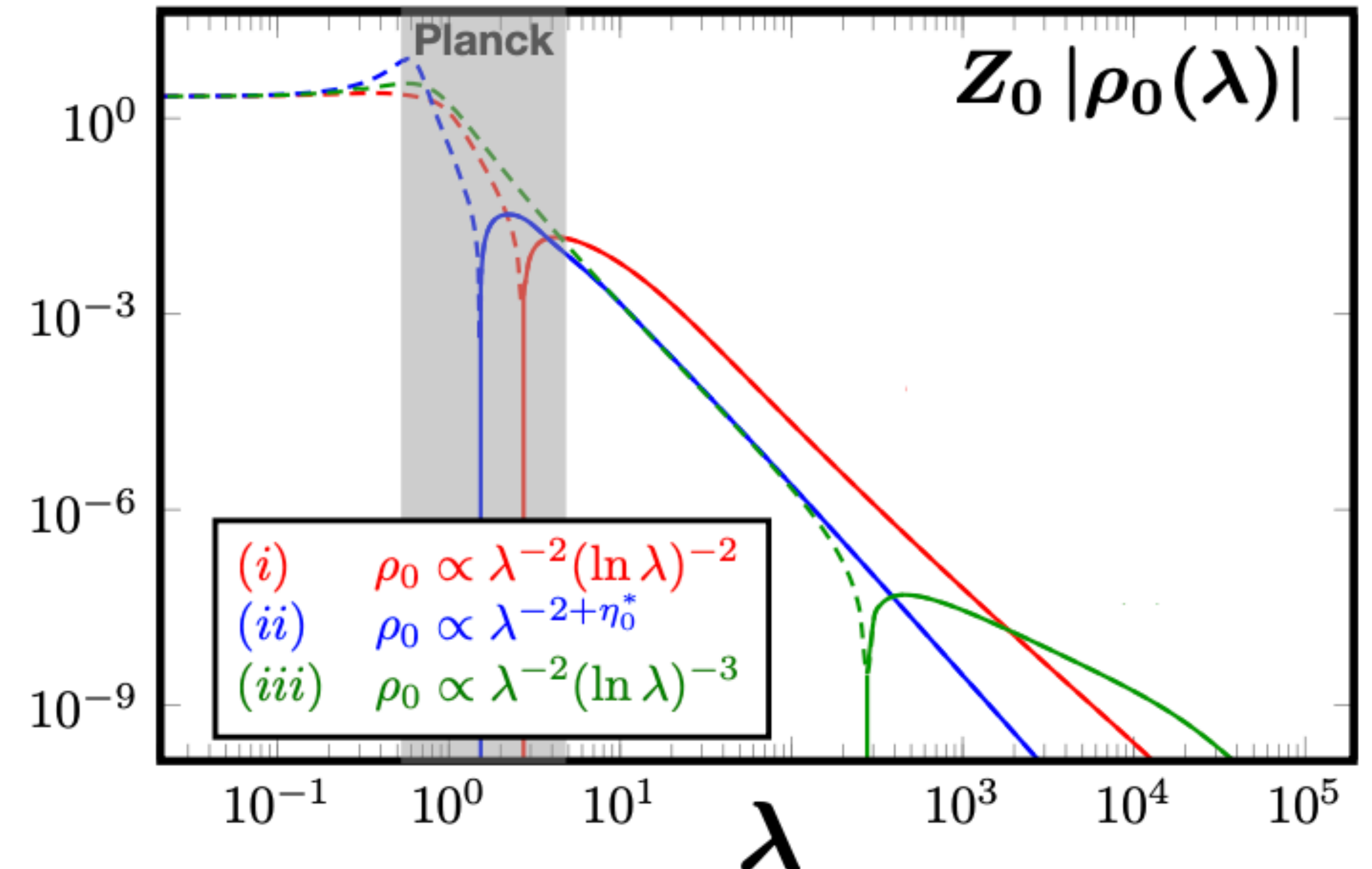
IR: matches EFT **exactly**



All spectral functions are **positive**

Transverse-traceless mode carries
on-shell dofs

UV: **Normalisable** spectral functions

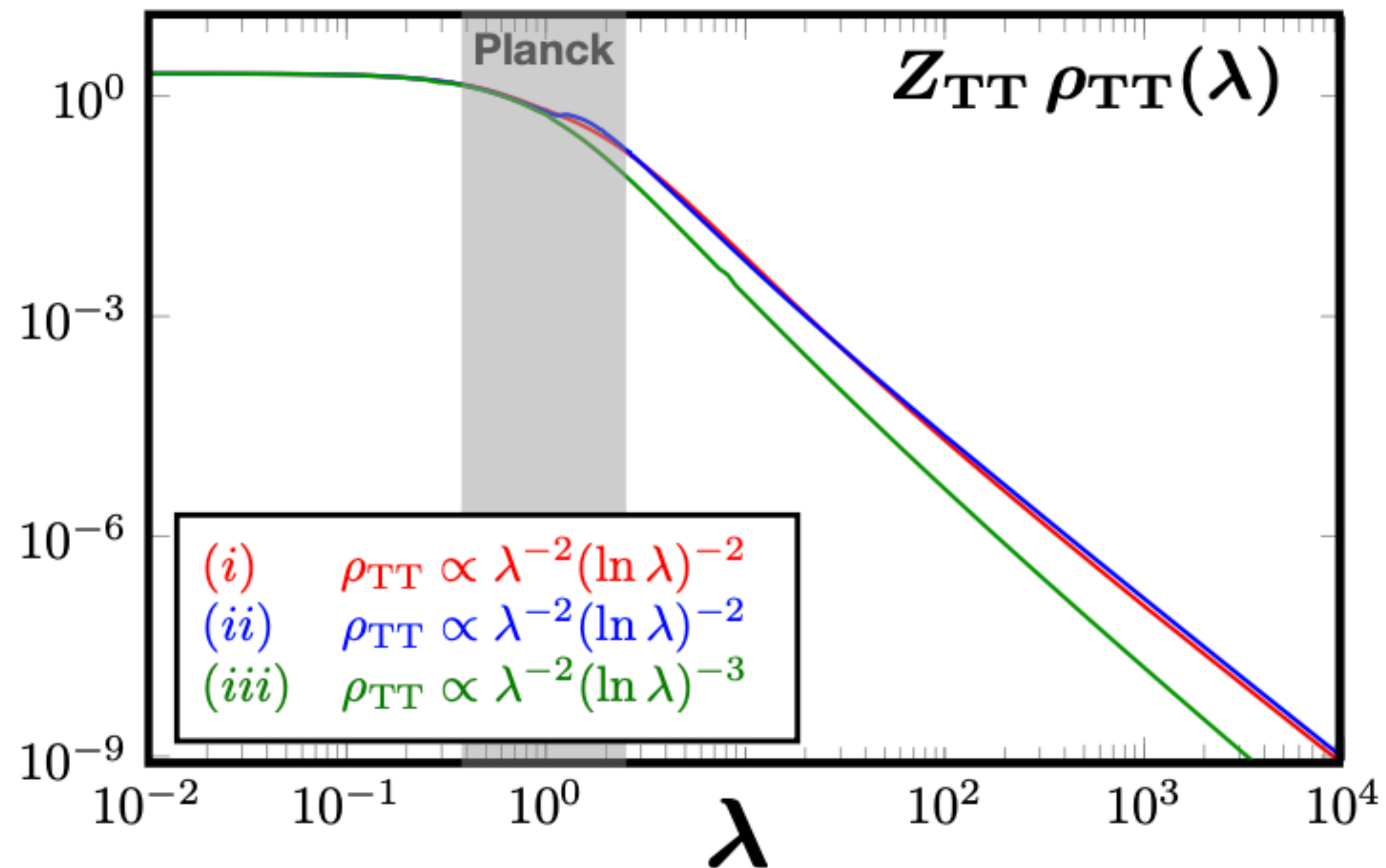


All spectral functions **change sign**

Physical scalar mode carries
off-shell dofs

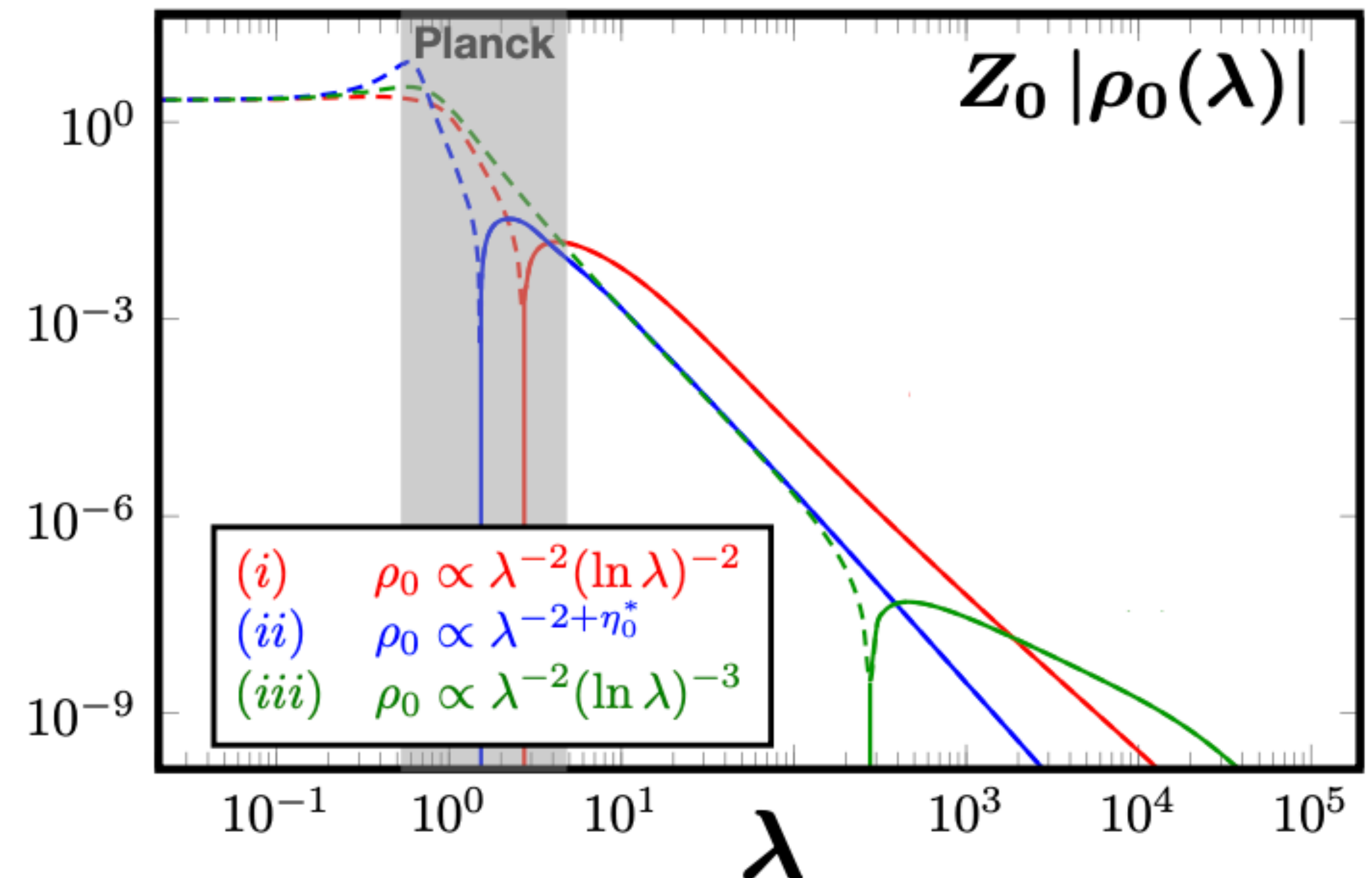
Coupled spectral functions

IR: matches EFT **exactly**



Propagator pole structure:
no additional modes

UV: **Normalisable** spectral functions

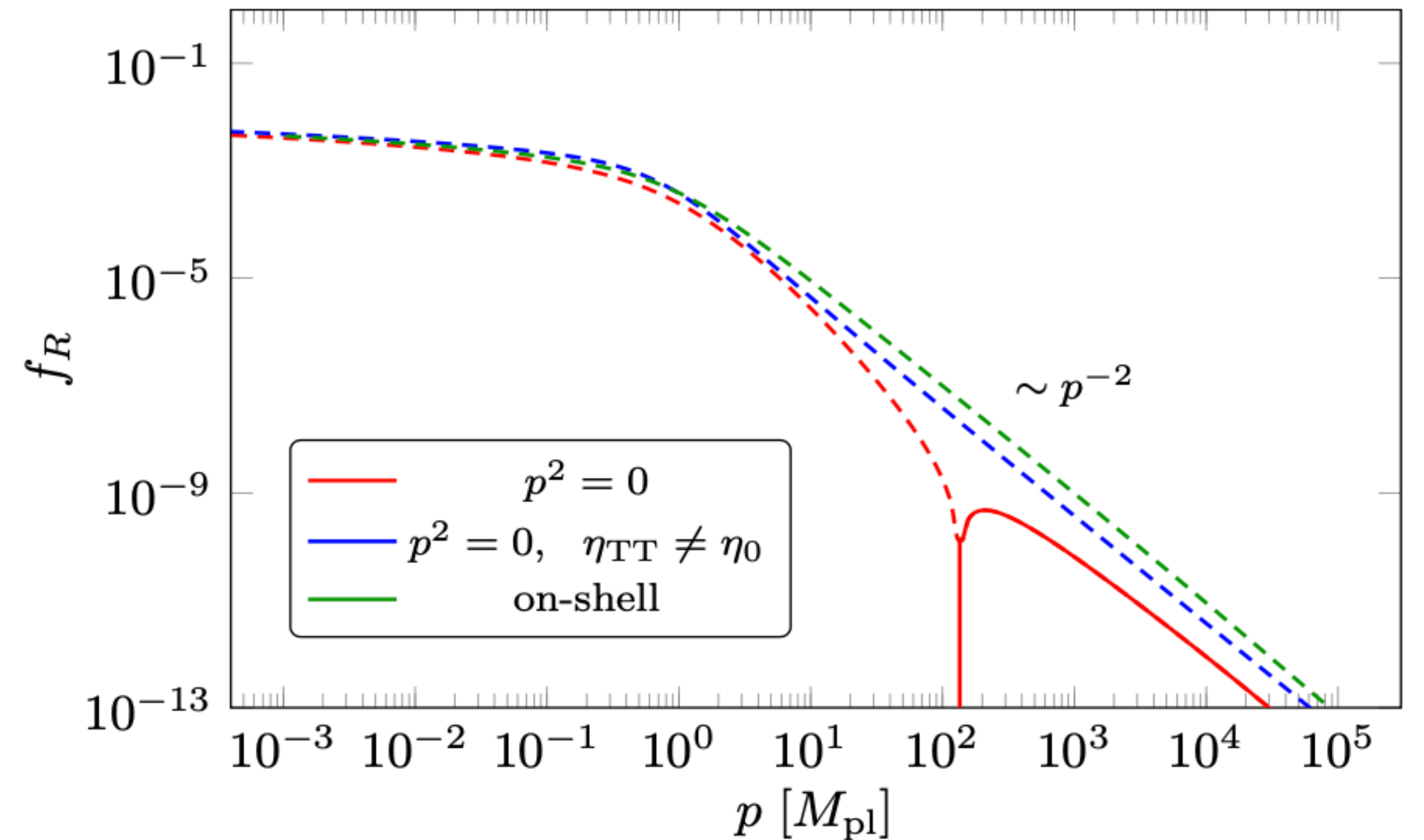
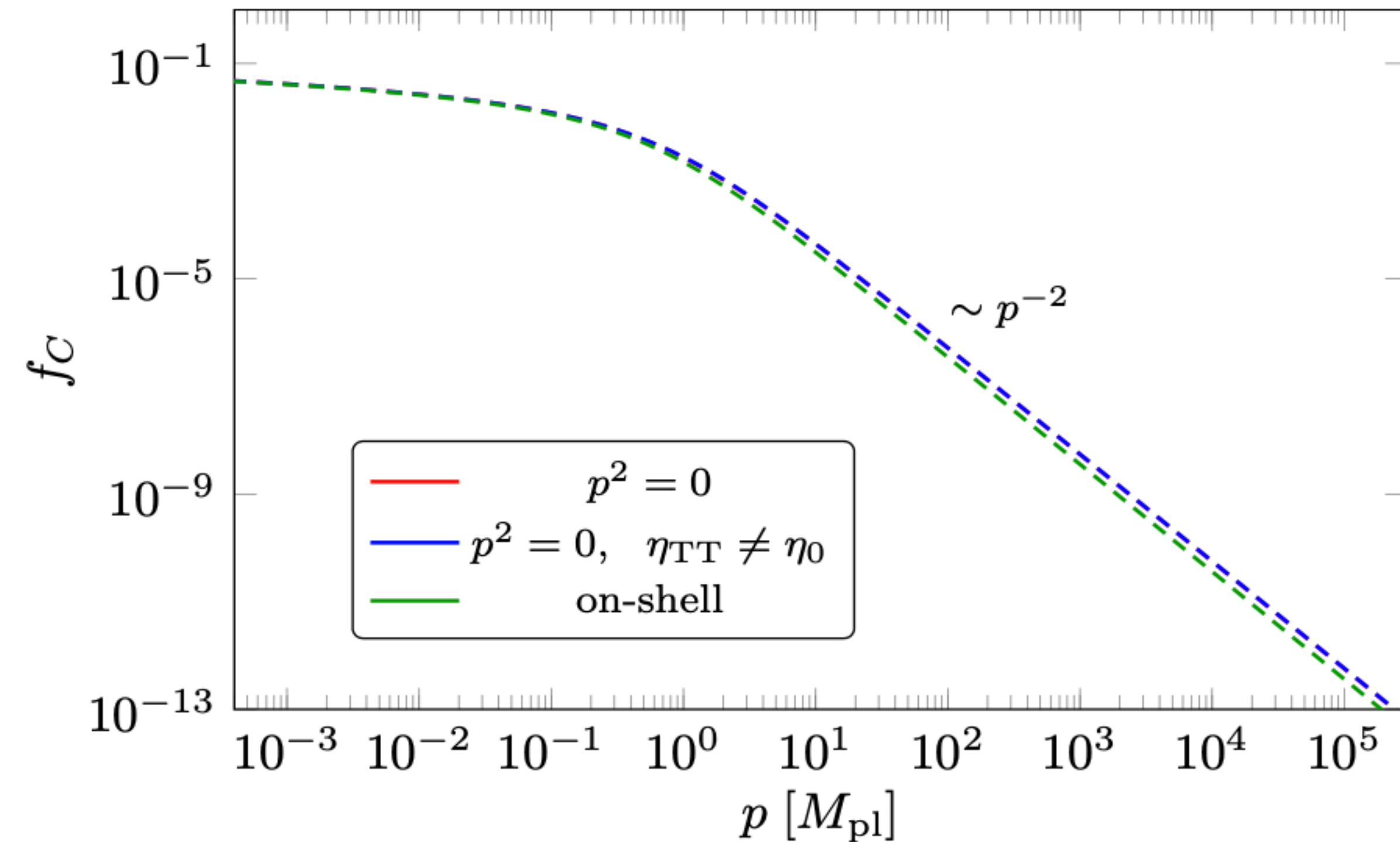


TT is compatible with all conditions
for unitary and causal
UV completion of gravity

Coupled form factors

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

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



Conclusions

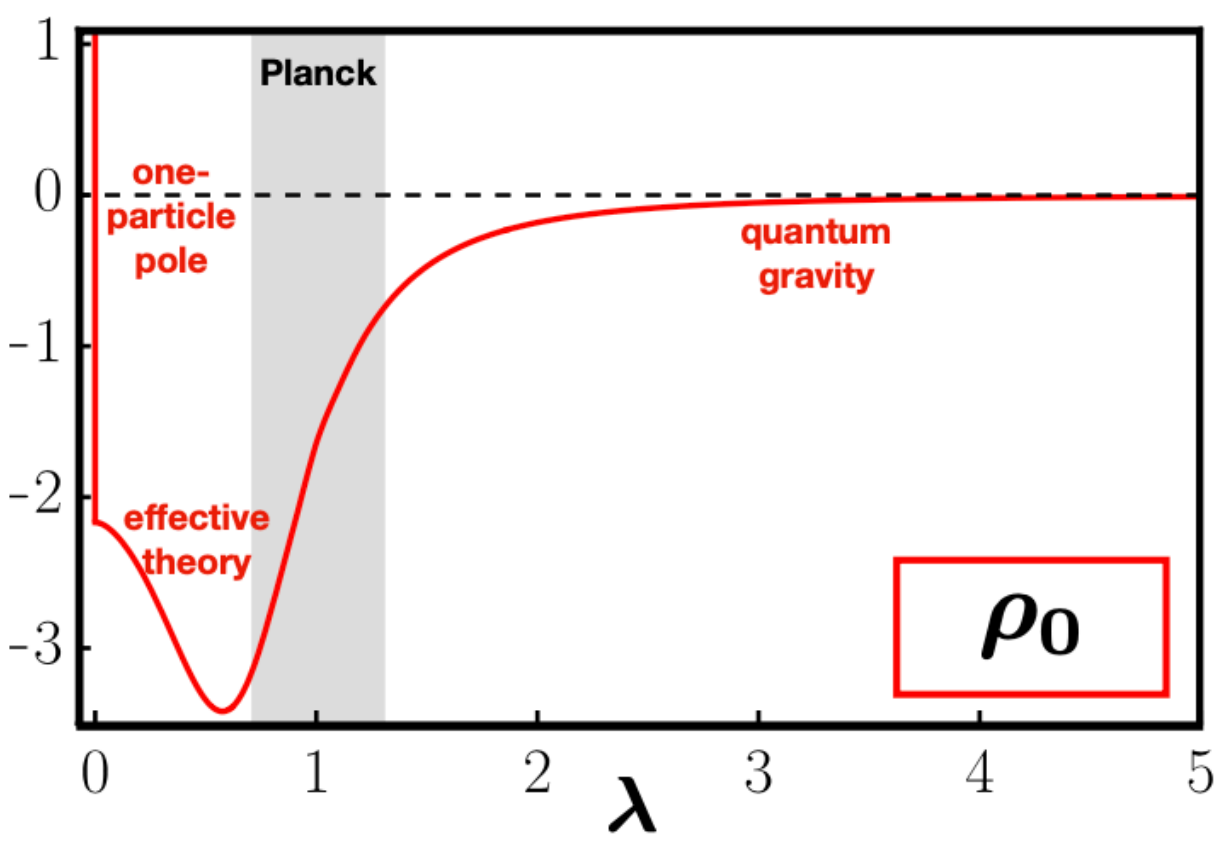
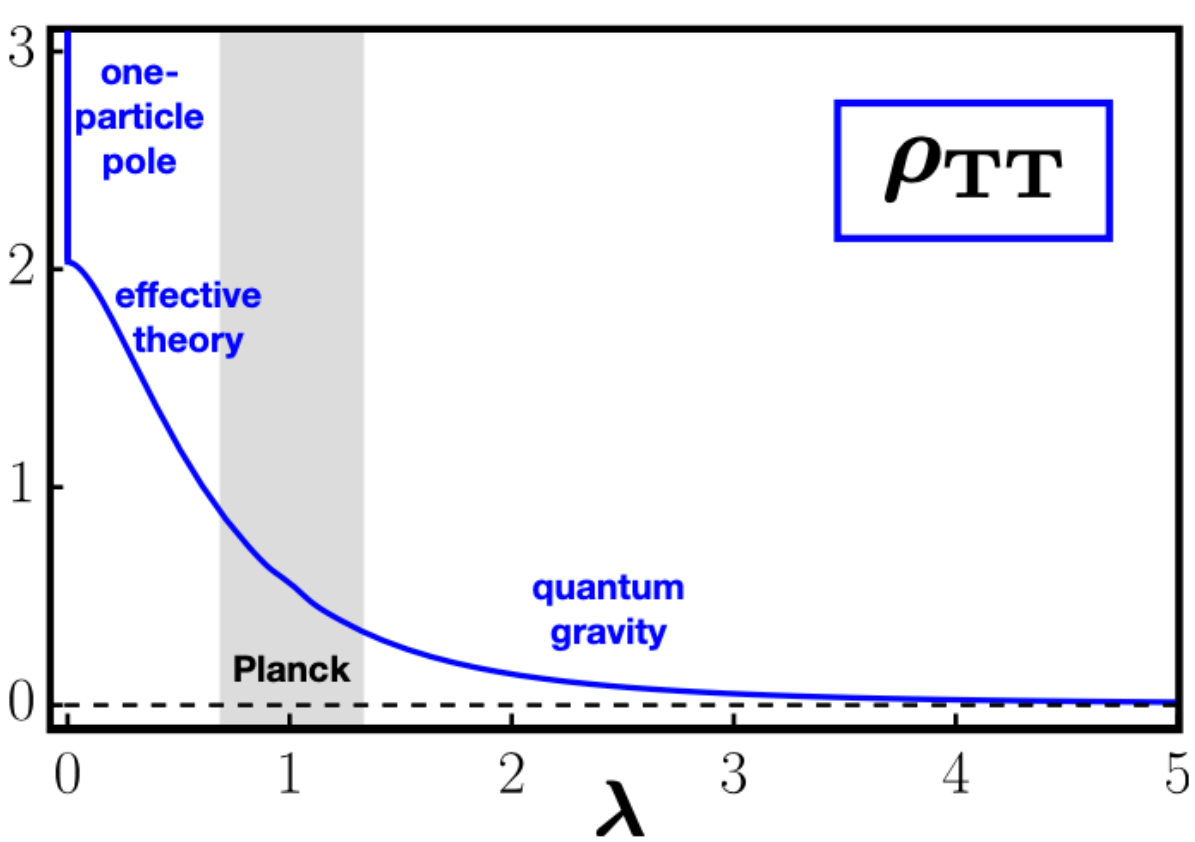
Lorentzian graviton spectral functions

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Direct Lorentzian computation

Coupled healthy spectral functions

Ghost and tachyon free: unitary and causal



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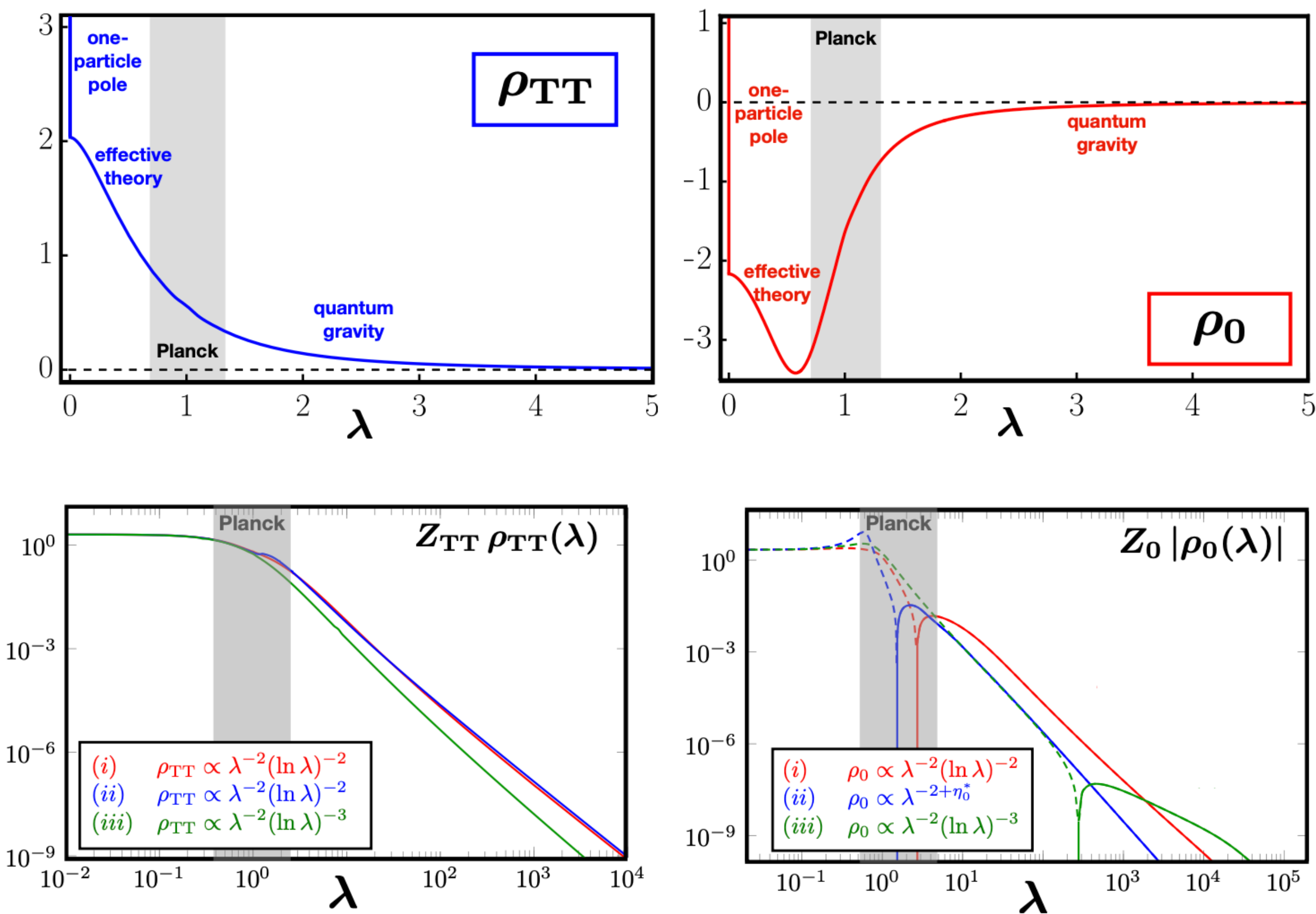
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Positive TT, all normalisable

Stable properties under changes of renormalisation scheme



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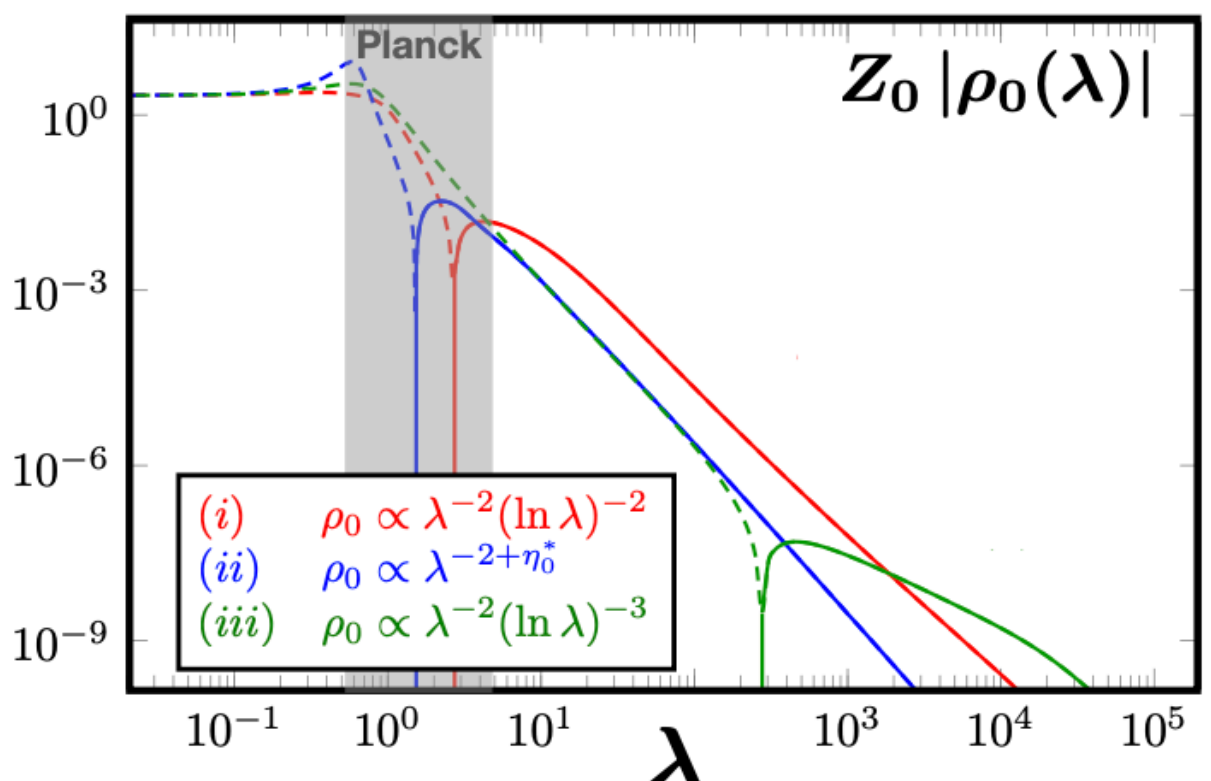
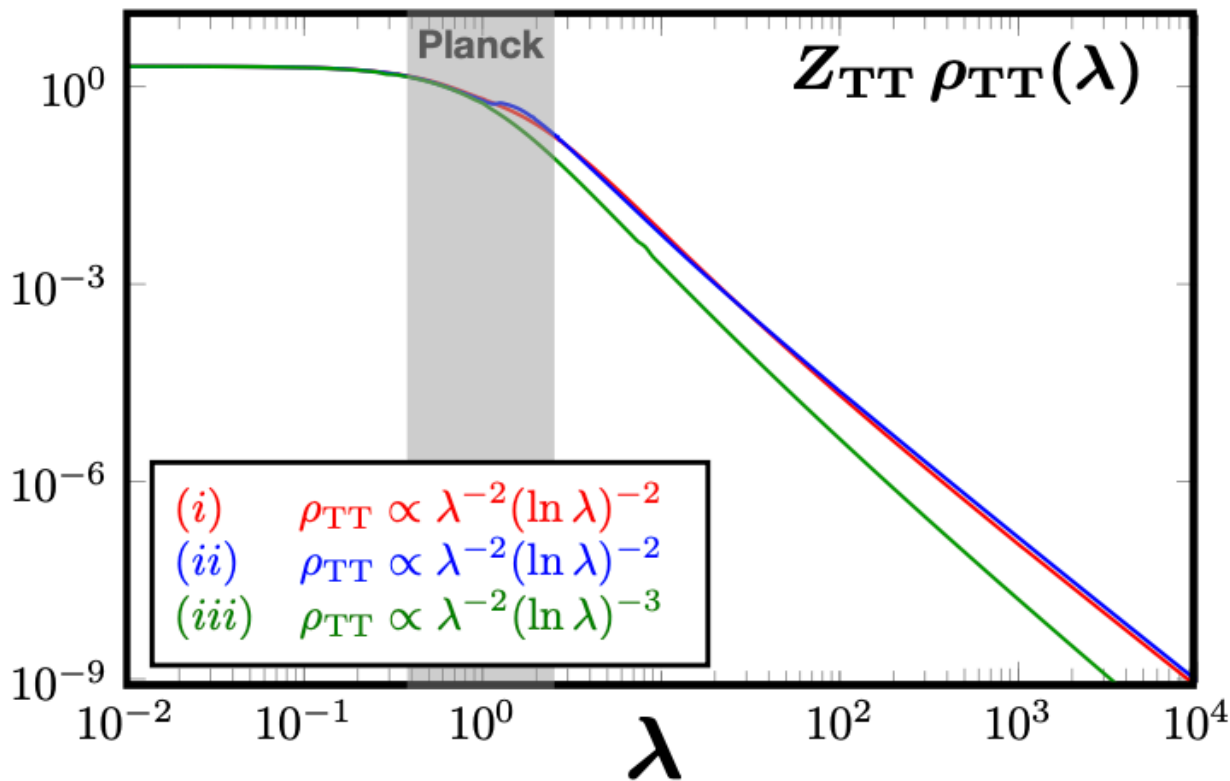
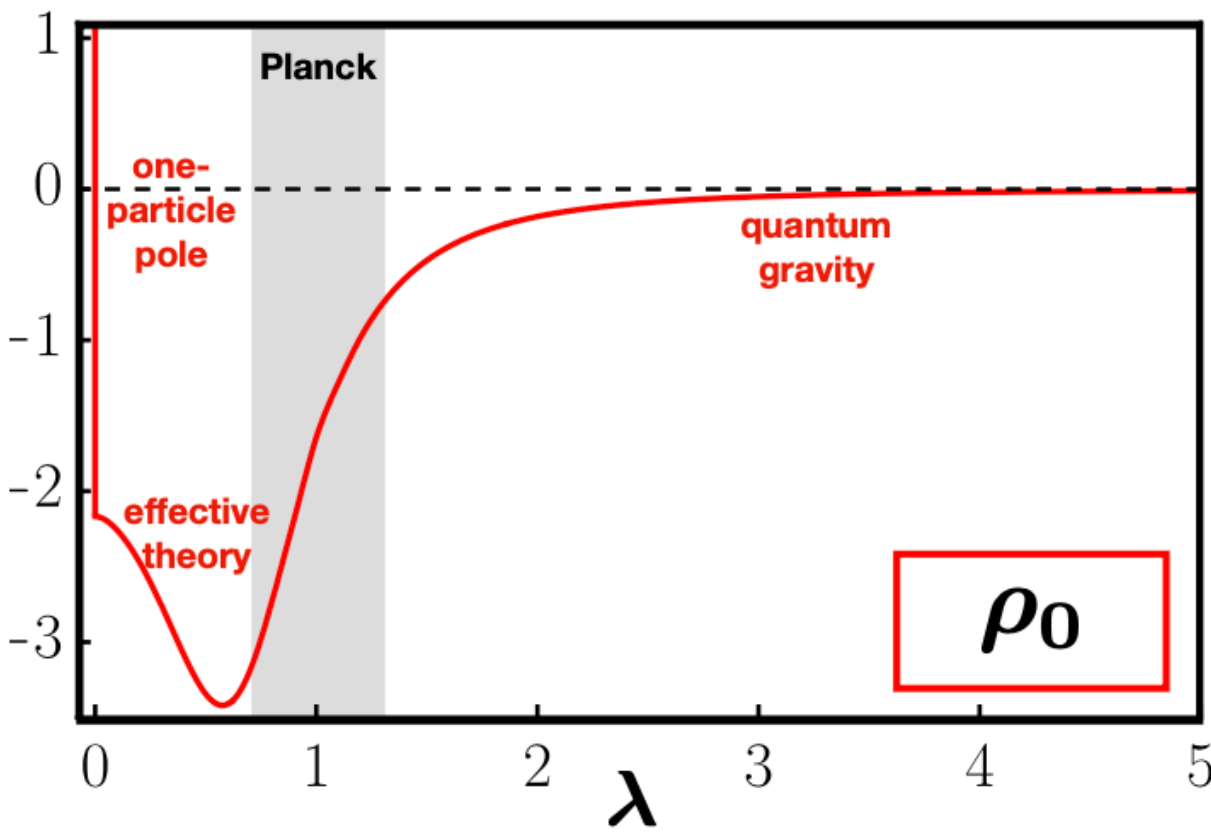
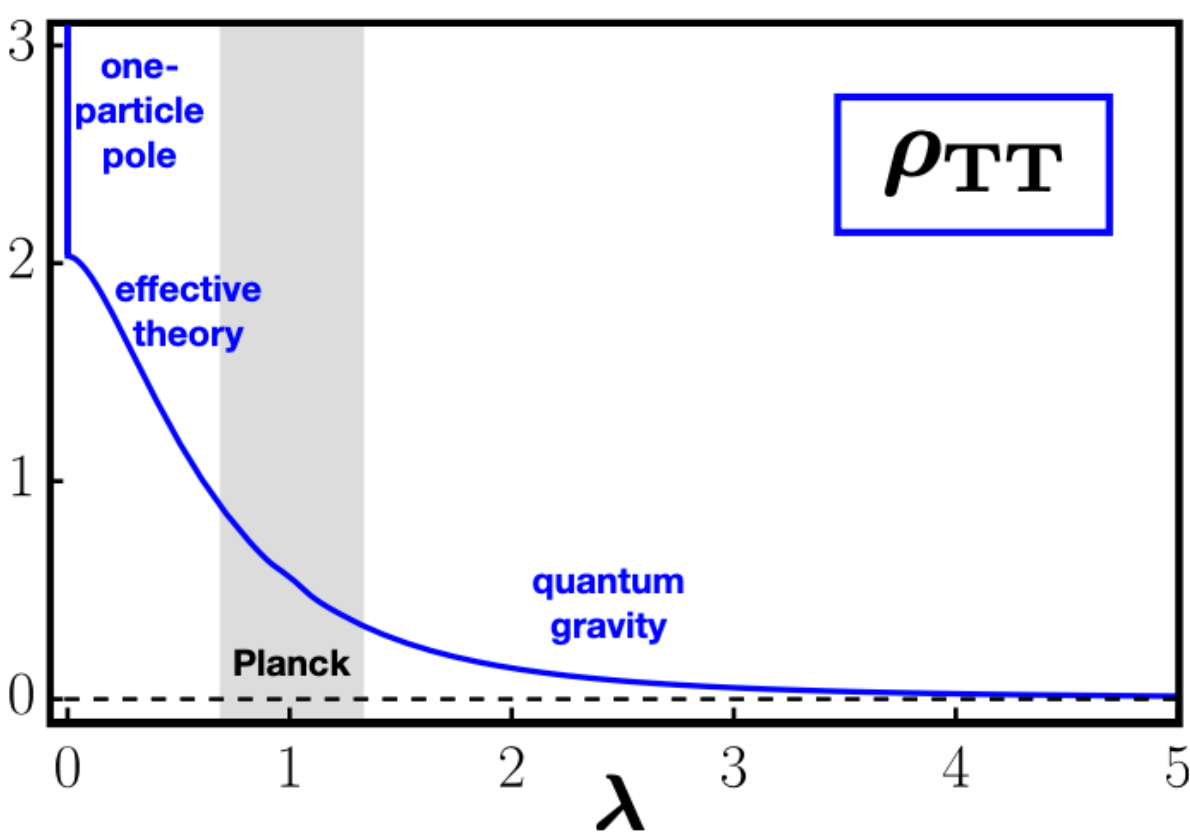
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Full form factors R^2, C^2 →

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Black holes, cosmology, scattering amplitudes...

Extra slides

(2) Scalar sector

Physical scalar mode projector
is **orthogonal to the gauge fixing**

$$\Pi^0 \cdot S_{\text{gf}}^{(2)} = 0$$

Projectors in the scalar sector

$$\Pi^0_{\mu\nu}{}^{\rho\sigma} = \frac{(3-\beta)^2}{12(3+\beta^2)} \left(\delta_{\mu\nu} + \frac{4\beta}{3-\beta} \Pi_{\mu\nu}^L \right) \left(\delta^{\rho\sigma} + \frac{4\beta}{3-\beta} \Pi^{L,\rho\sigma} \right),$$

$$\Pi^{\tilde{0}}_{\mu\nu}{}^{\rho\sigma} = \frac{(1+\beta)^2}{4(3+\beta^2)} \left(\delta_{\mu\nu} - \frac{4}{1+\beta} \Pi_{\mu\nu}^L \right) \left(\delta^{\rho\sigma} - \frac{4}{1+\beta} \Pi^{L,\rho\sigma} \right),$$

$$\Pi^{0\tilde{0}}_{\mu\nu}{}^{\rho\sigma} = \frac{(3-\beta)(1+\beta)}{4\sqrt{3}(3+\beta^2)} \left(\delta_{\mu\nu} + \frac{4\beta}{3-\beta} \Pi_{\mu\nu}^L \right) \left(\delta^{\rho\sigma} - \frac{4}{1+\beta} \Pi^{L,\rho\sigma} \right),$$

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

Tensor decomposed two-point function is

$$\Gamma^{(2),\mu\nu\rho\sigma} = \frac{1}{32\pi} \left(\Gamma_{\text{TT}}^{(2)} \Pi_{\text{TT}}^{\mu\nu\rho\sigma} + \Gamma_{\text{V}}^{(2)} \Pi_{\text{V}}^{\mu\nu\rho\sigma} - \frac{1}{2} \Gamma_0^{(2)} \Pi_0^{\mu\nu\rho\sigma} + \frac{1}{2} \Gamma_{\tilde{0}}^{(2)} \Pi_{\tilde{0}}^{\mu\nu\rho\sigma} - \frac{\sqrt{3}}{2} \Gamma_{0\tilde{0}}^{(2)} \left(\Pi_{0\tilde{0}}^{\mu\nu\rho\sigma} + \Pi_{\tilde{0}0}^{\mu\nu\rho\sigma} \right) \right)$$

We make a “uniform” approximation in the scalar sector

$$\Gamma_0^{(2)} = \Gamma_{\tilde{0}}^{(2)} = \Gamma_{0\tilde{0}}^{(2)}$$

**Breaks for feedback of
continua into the 2pt flow**

[Pawlowski, Reichert, Wessely, 2025]

(2) Mass identifications and complex poles

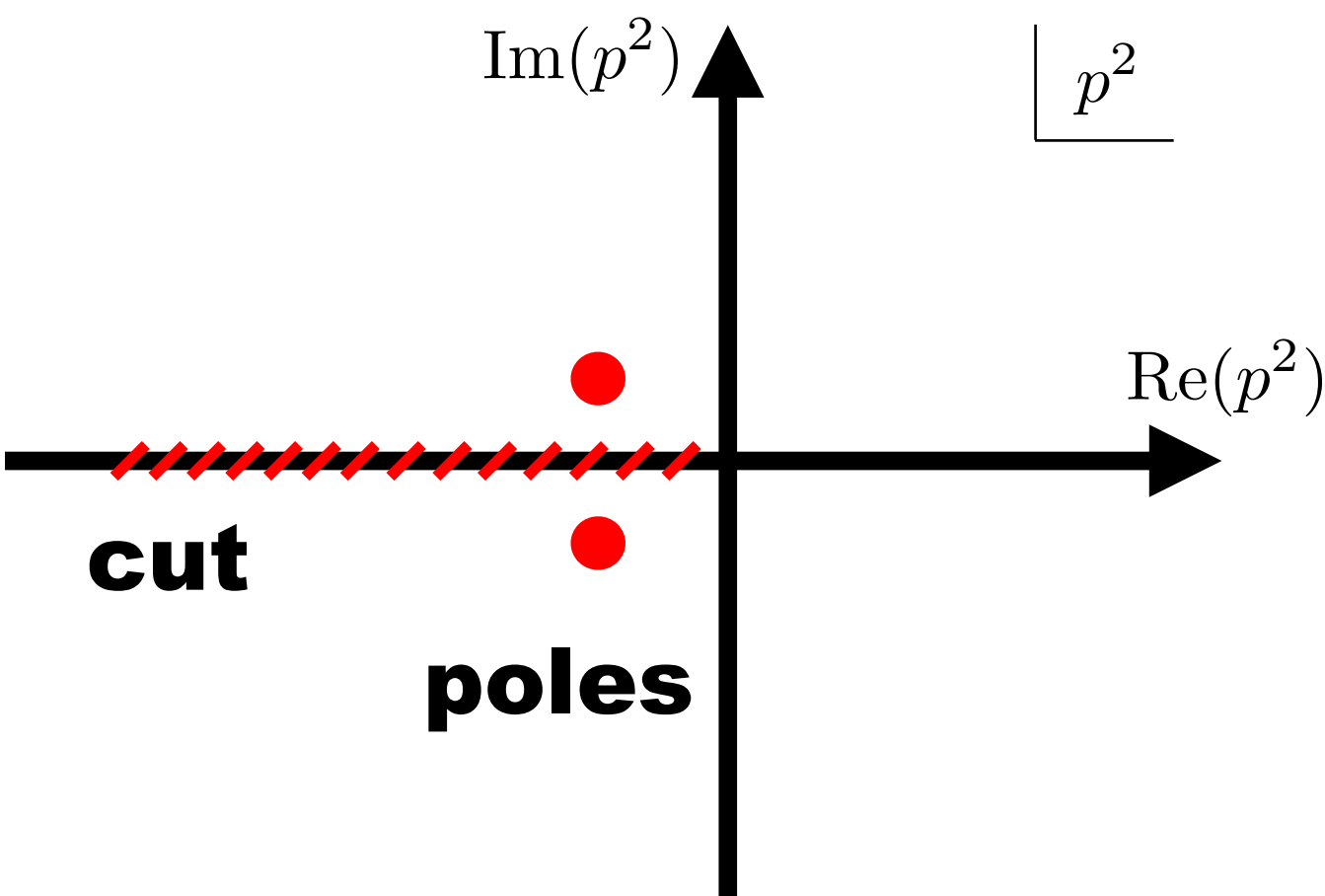
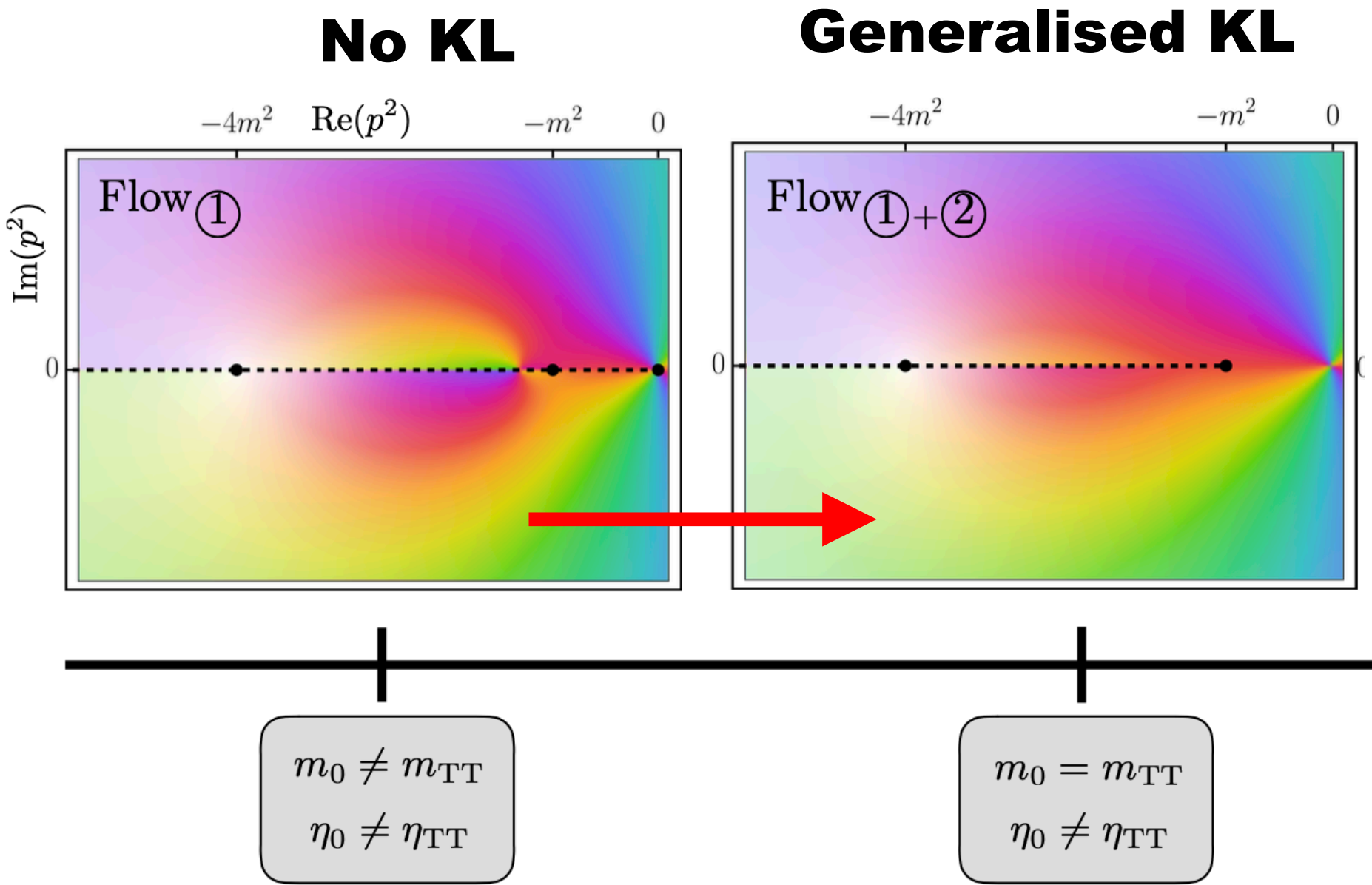
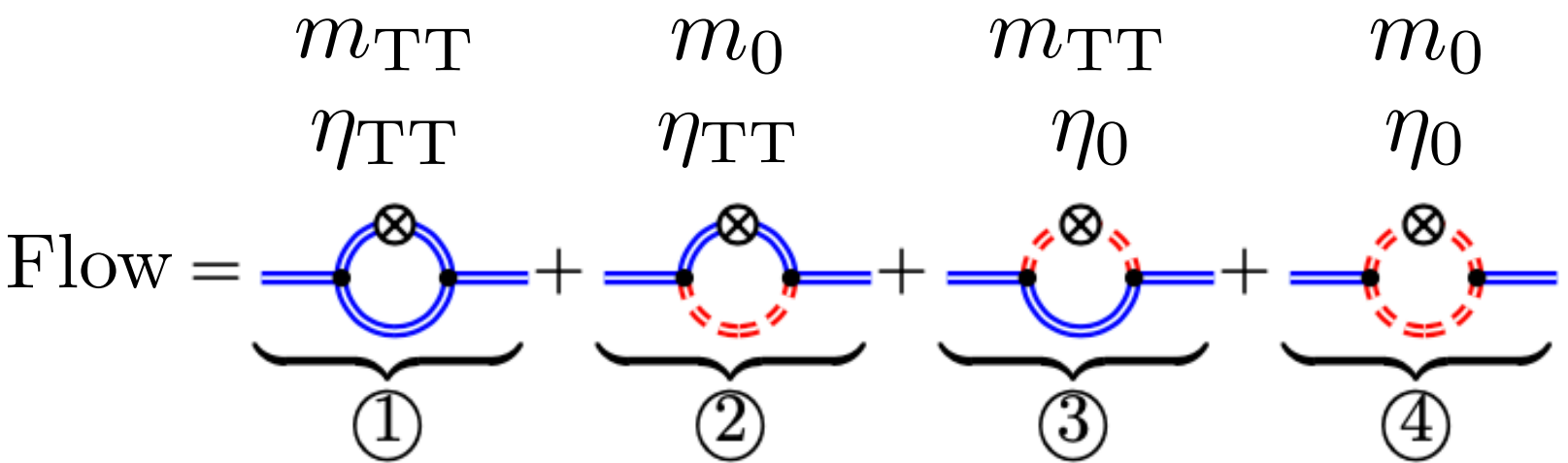
Expand the transverse-traceless
mode flow around

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

The transverse-traceless
mass parameter flow is

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

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



(1) UV completion of gravity

$$S_{\text{EH}} = \int_x \frac{1}{16\pi G_N} (2\Lambda - R)$$

**Naive perturbation
theory fails in d=4**

1 loop divergences:

2 loop divergences:

$\vdots$

$$\sim \sqrt{g}, \quad \sim \sqrt{g}R, \quad \sim \sqrt{g}R_{\mu\nu}R^{\mu\nu}, \quad \sim \sqrt{g}R^2$$

$$\sim \sqrt{g}C^3$$

$\vdots$

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UV complete QFT



**couplings reach UV fixed point under
Renormalization Group running**

[Wilson '71]

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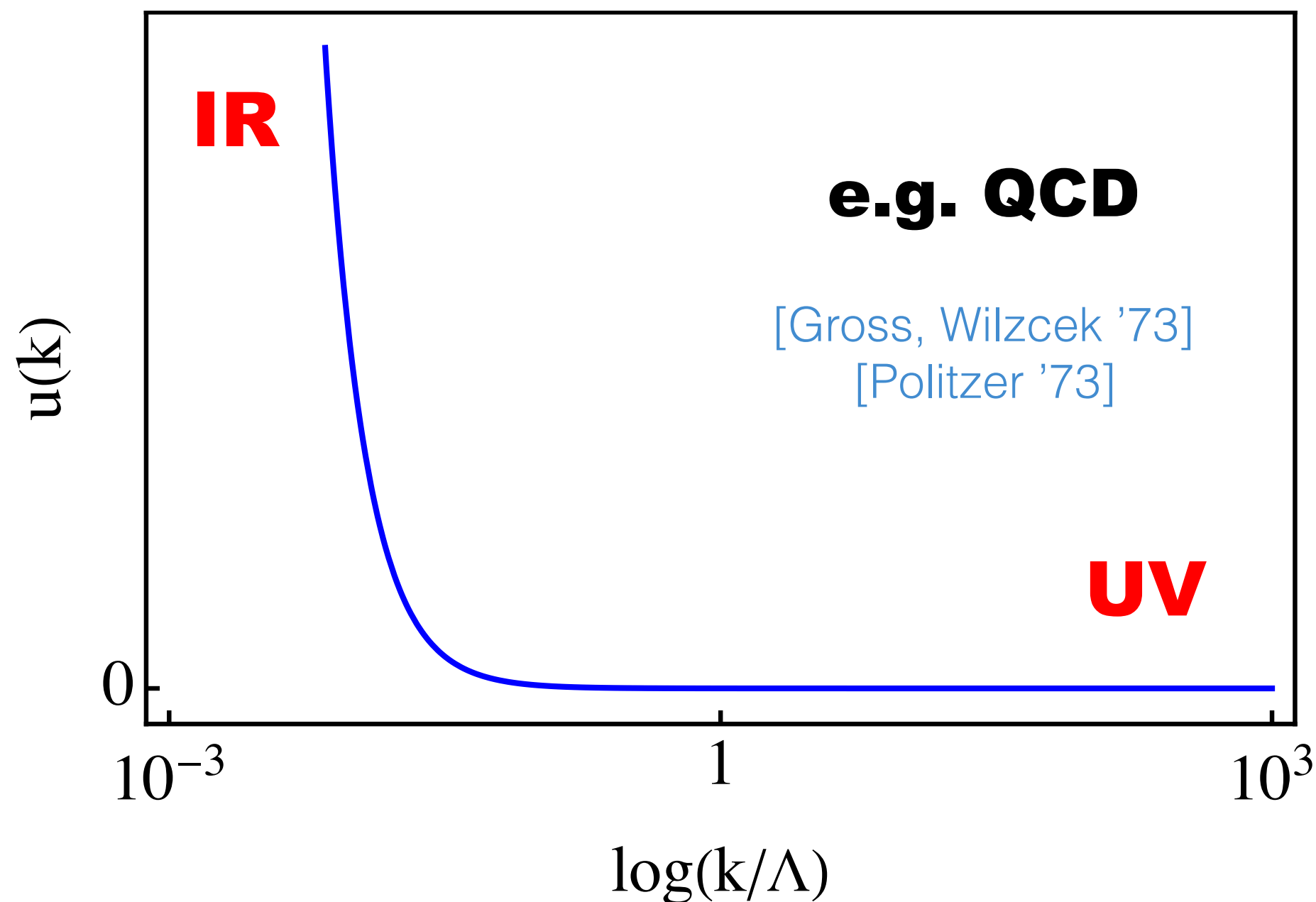
UV complete QFT



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[Wilson '71]

**Asymptotic Freedom:
reach free fixed point**



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$\vdots$ $\vdots$

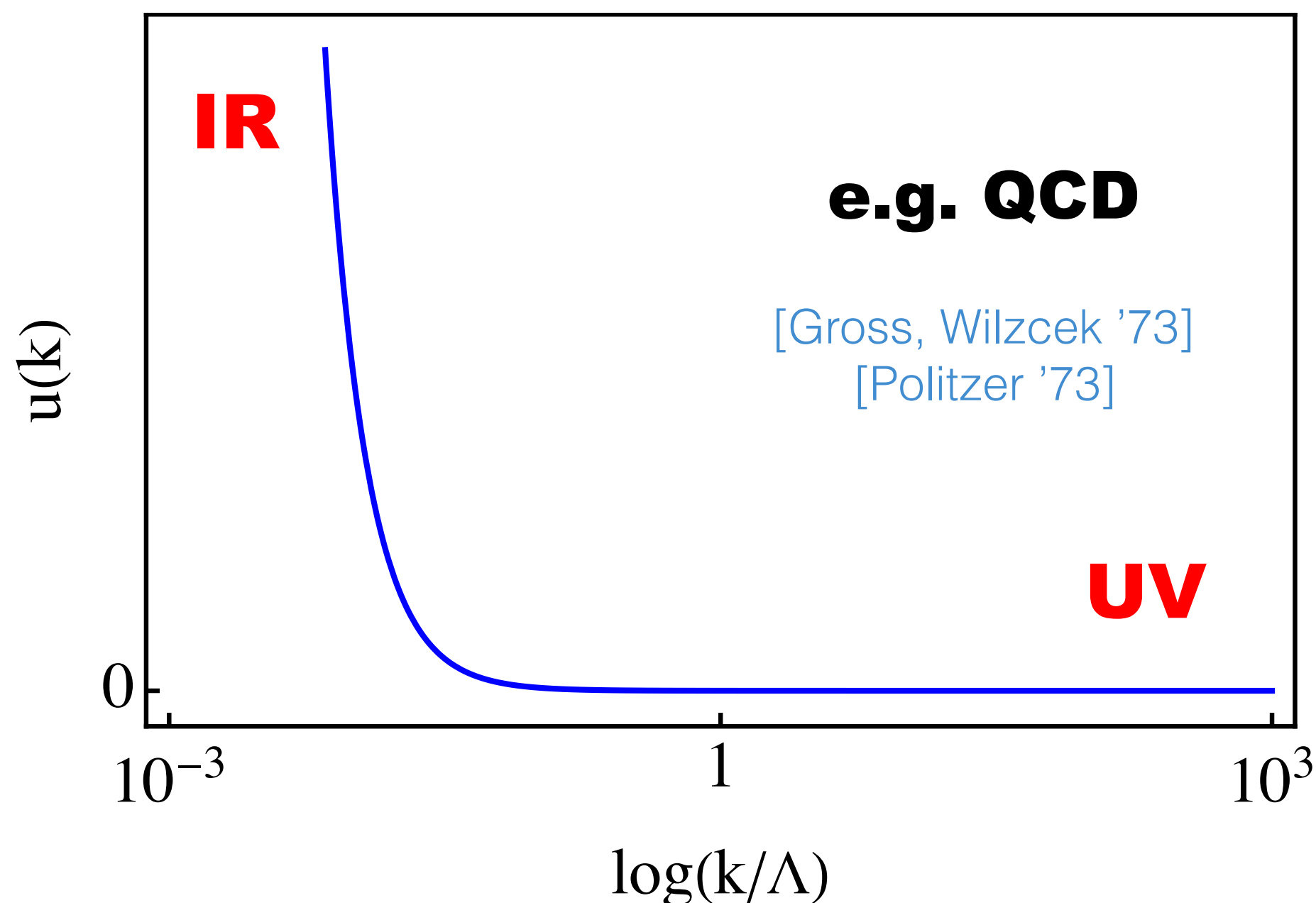
UV complete QFT



**couplings reach UV fixed point under
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[Wilson '71]

**Asymptotic Freedom:
reach free fixed point**



Fixed point condition

Flow stops

$$\beta_u \equiv k \partial_k u(k) = \partial_t u(k)$$

$$\beta_u|_{u*} = 0$$

Scale invariance

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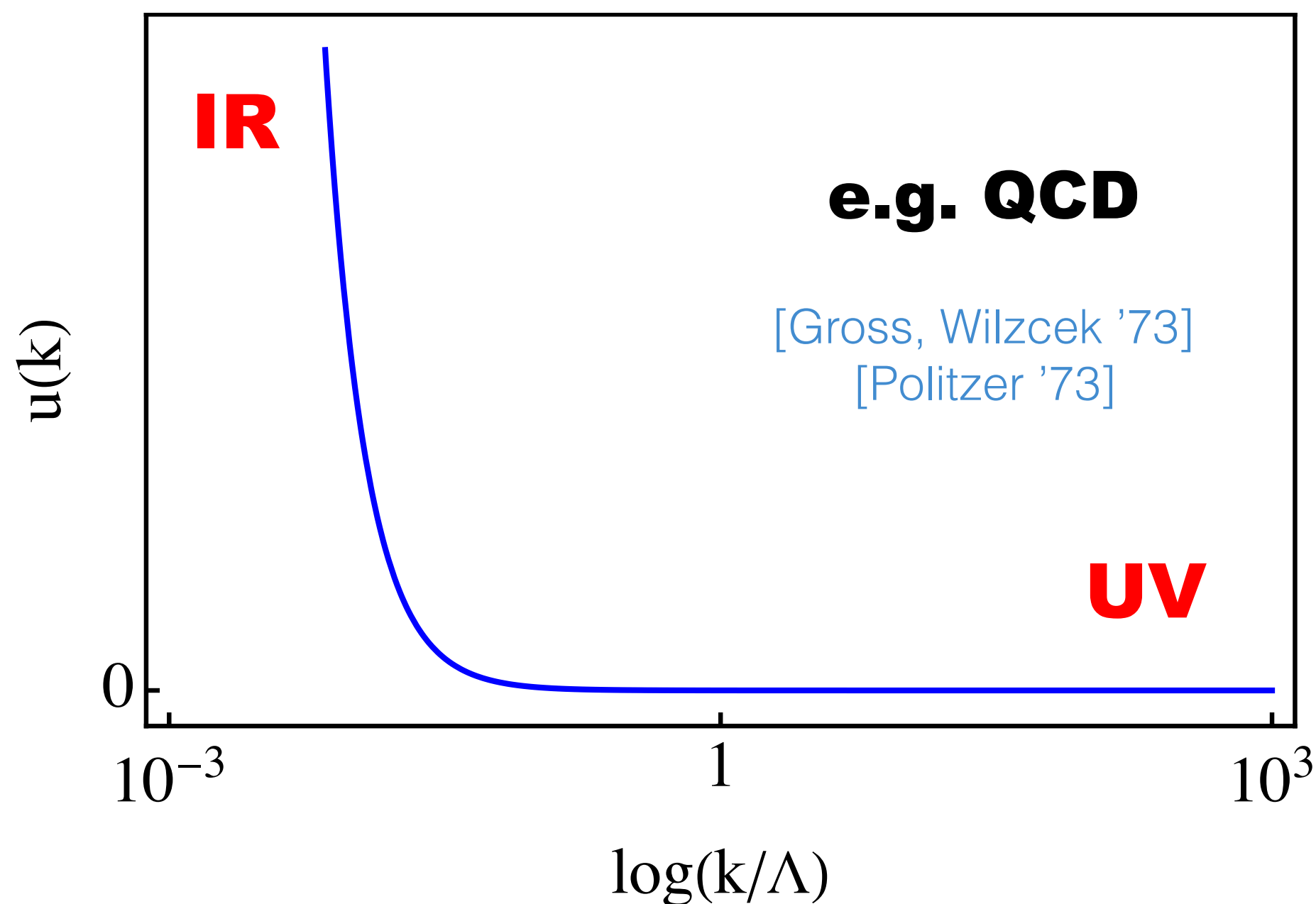
UV complete QFT



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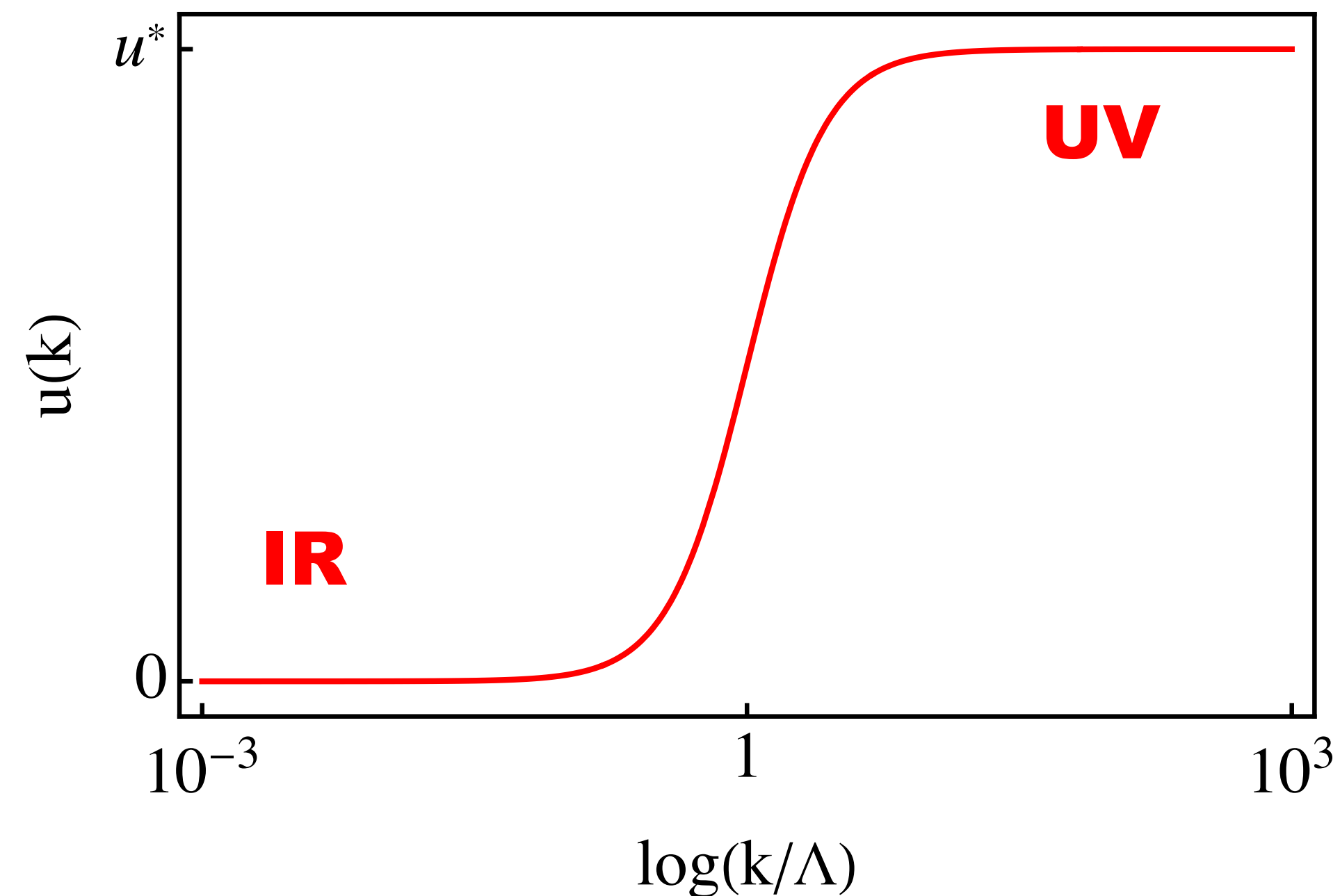
[Wilson '71]

**Asymptotic Freedom:
reach free fixed point**



**Asymptotic Safety:
reach interacting fixed point**

[Weinberg '79]



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 $\vdots$

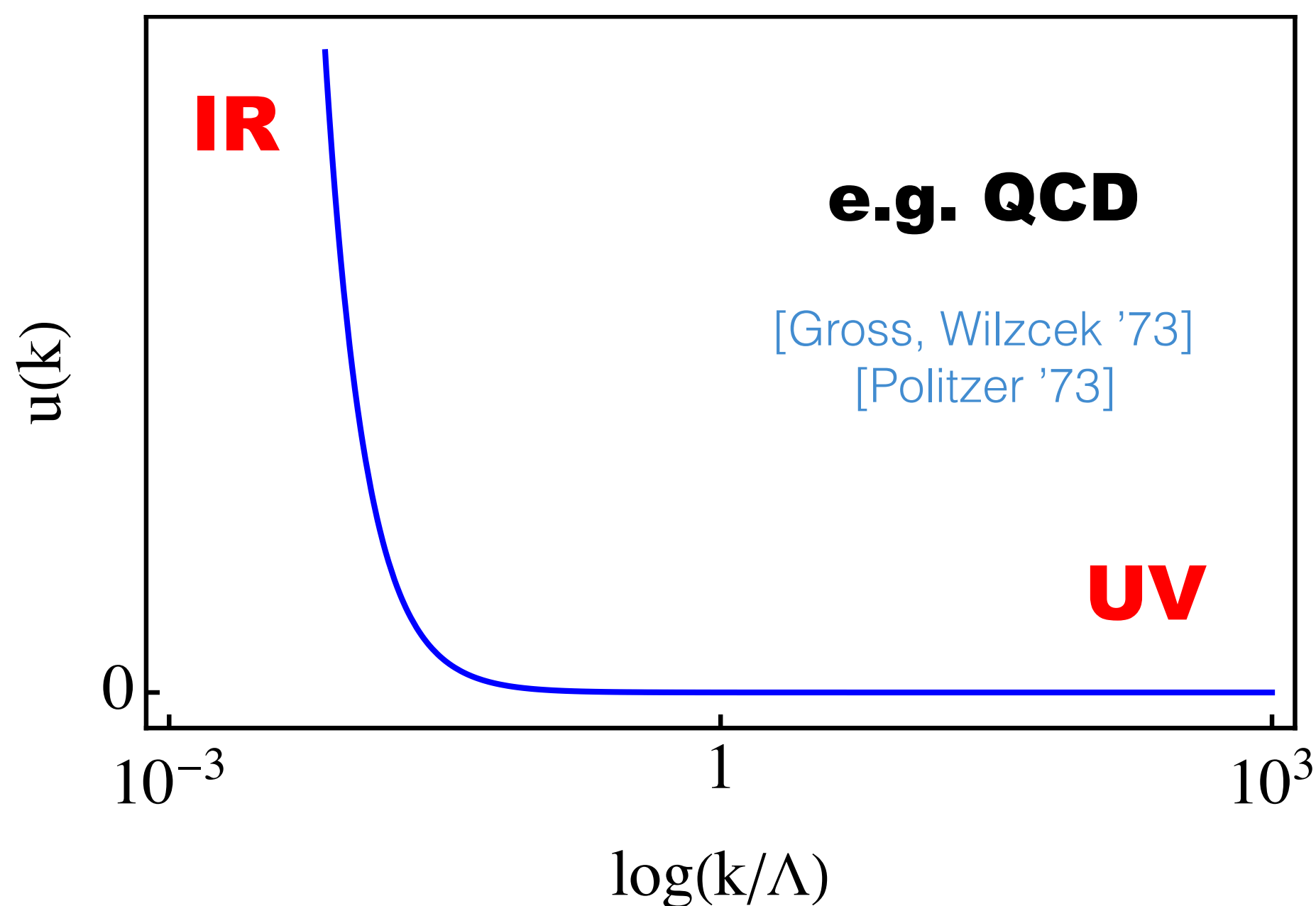
UV complete QFT



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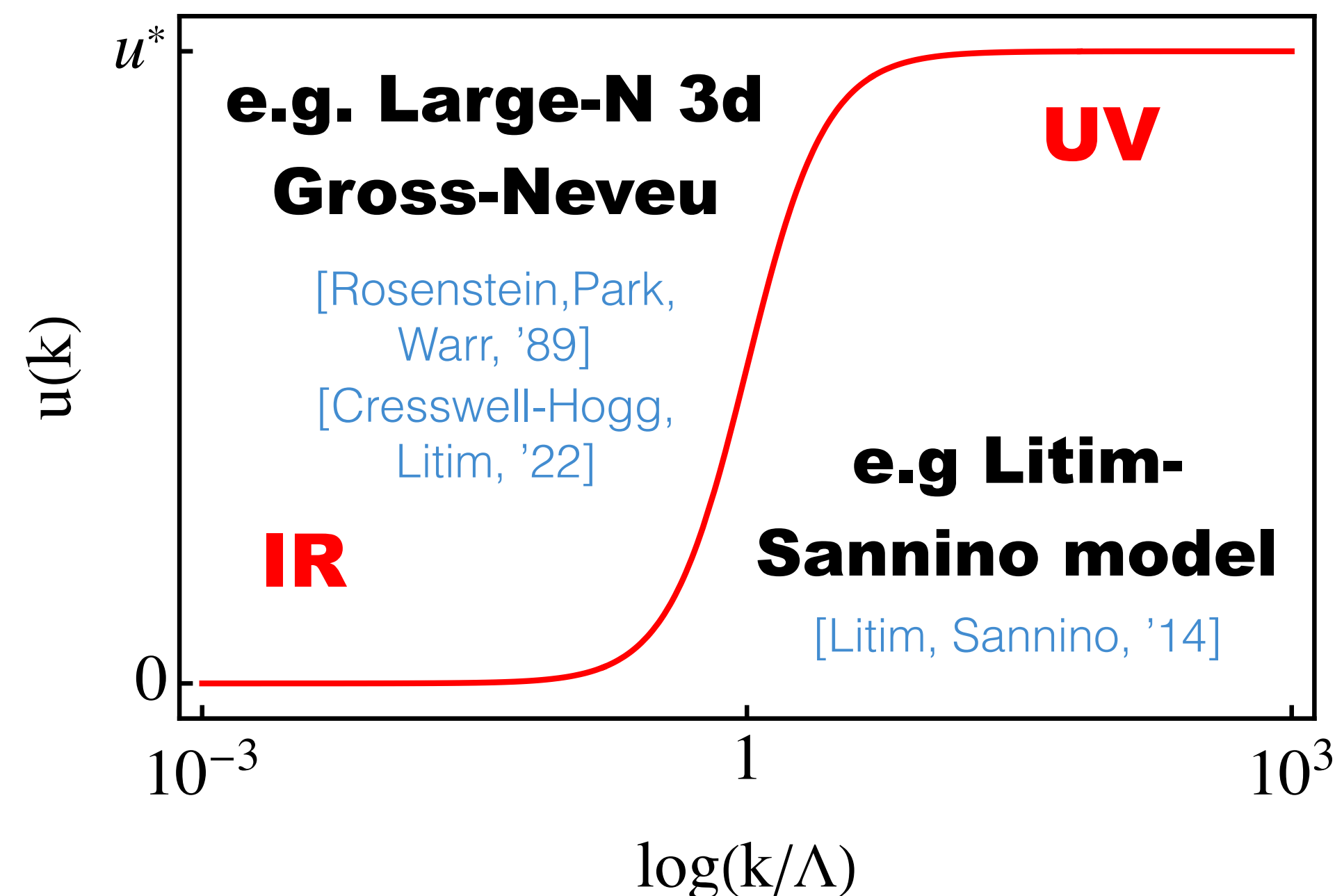
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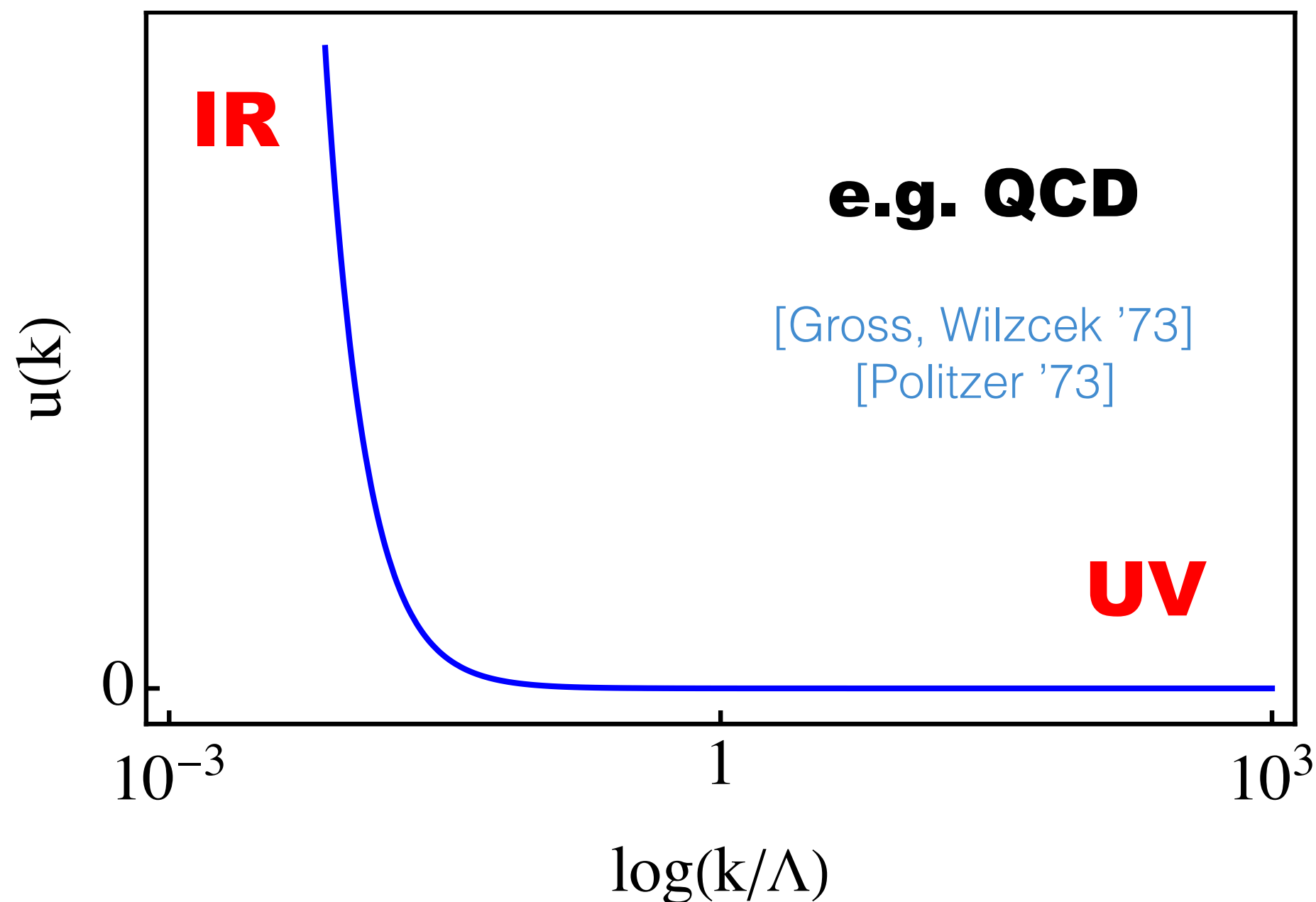
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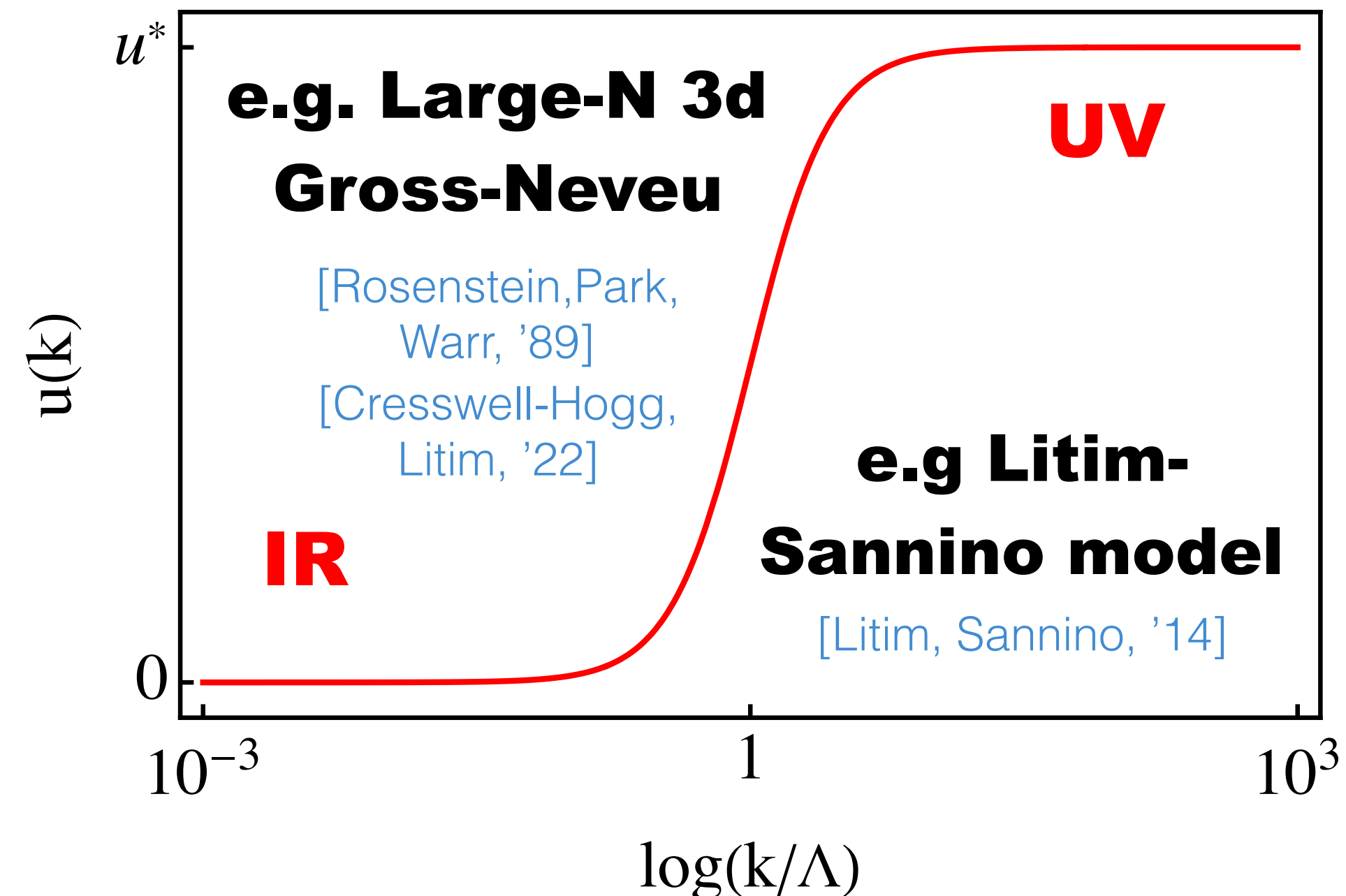
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**AS can make
gravity
predictive
and UV
complete**

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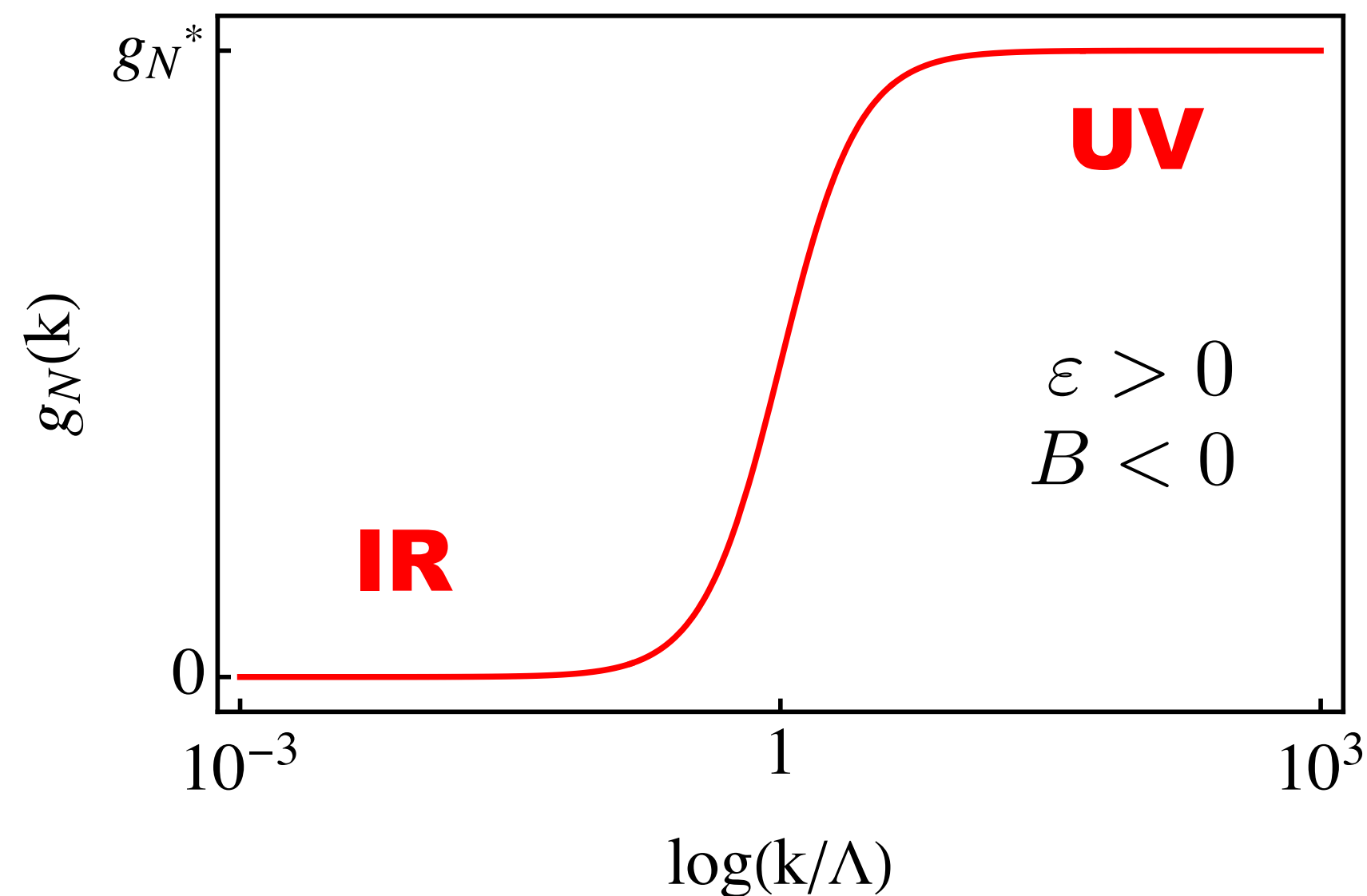
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$\vdots$

Asymptotic Safety in gravity



Hints from perturbation theory in d=2+eps:

$$\partial_t g_N = \underbrace{\varepsilon g_N}_{\text{dimension}} + \underbrace{B g_N^2}_{\text{one-loop}}$$

[Gastmans et al '78]
[Christensen, Duff '78]
[Weinberg '79]
[Kawai et al '90]

AS can make gravity predictive and UV complete

(1) UV completion of gravity

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Lose predictivity

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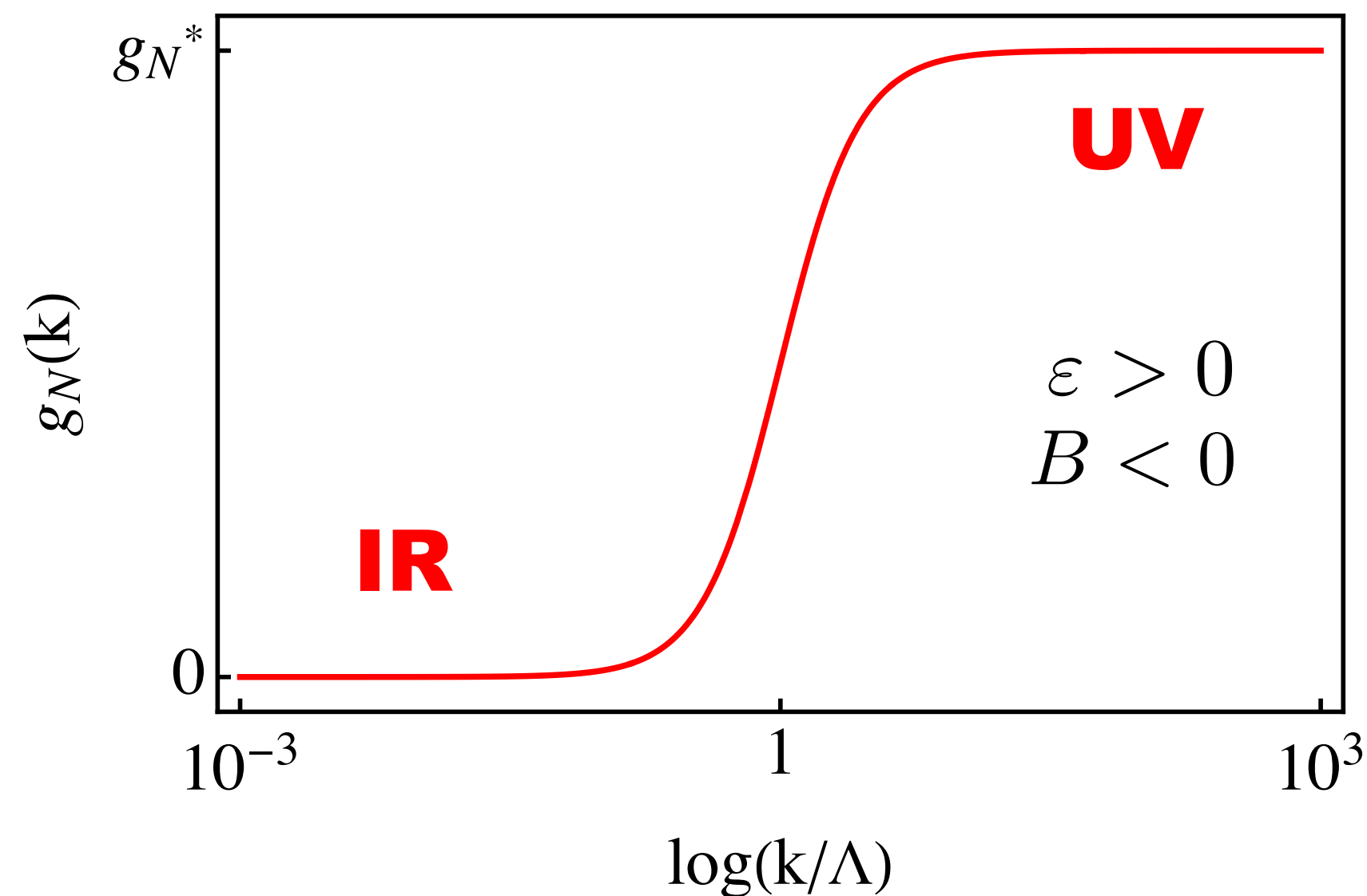
⋮

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$\varepsilon \rightarrow 2$ **is large!!**

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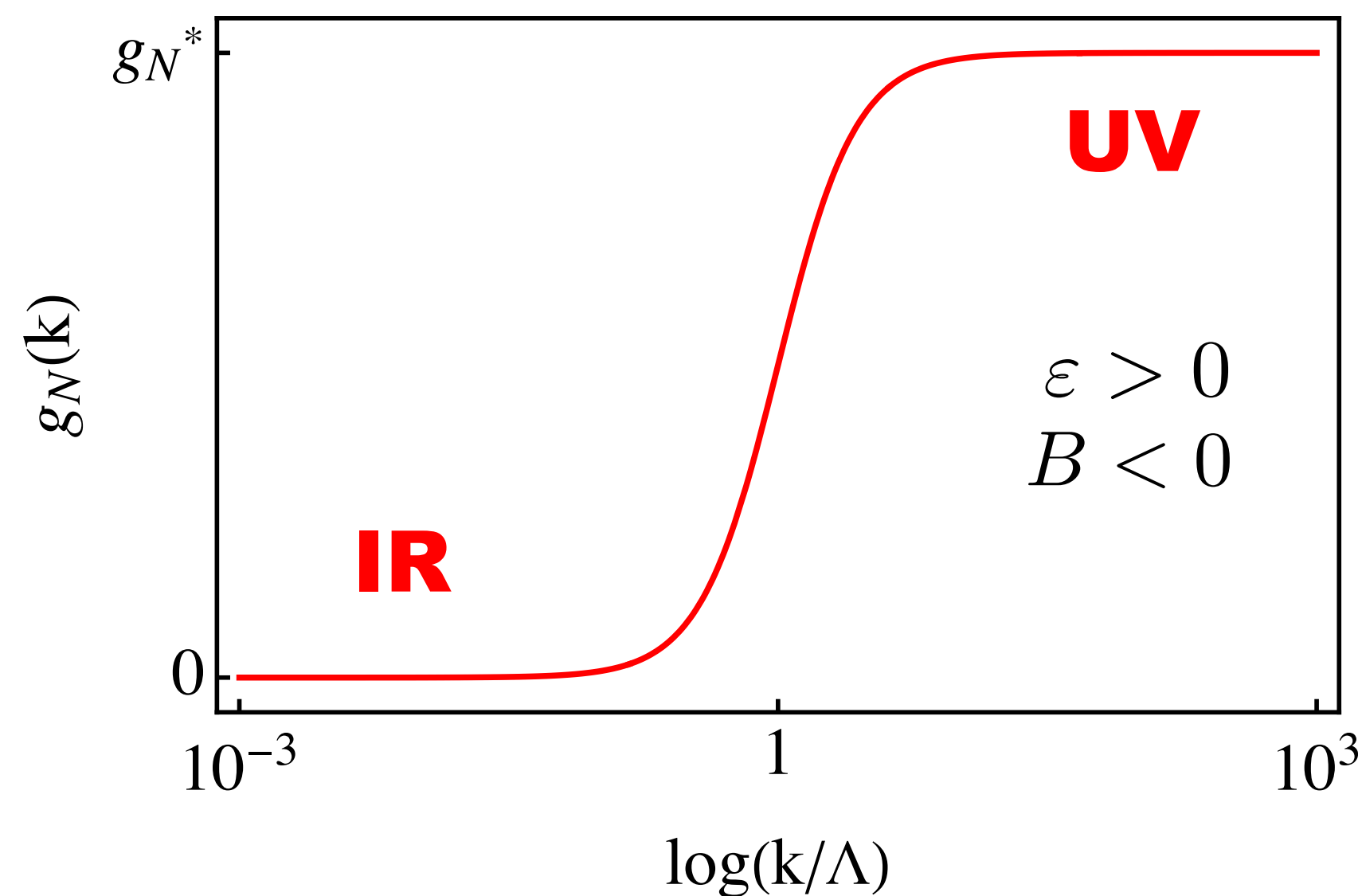
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Use non-perturbative methods

Lattice methods (CDT/EDT)

(1) UV completion of gravity

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Naive perturbation theory fails in d=4

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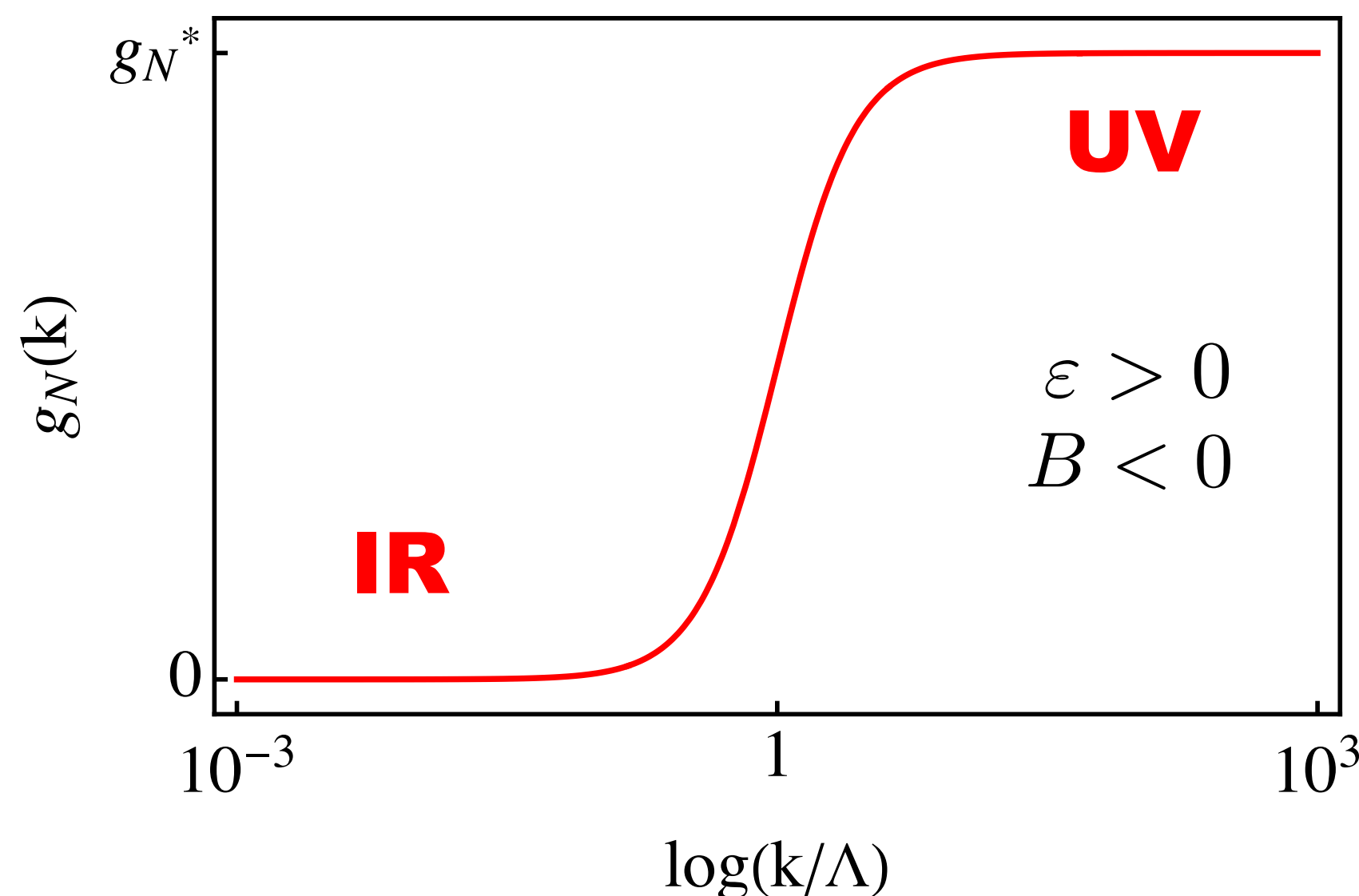
2 loop divergences:

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[Weinberg '79]
[Kawai et al '90]

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Lattice methods (CDT/EDT)

Functional Renormalisation Group:

Euclidean

[Lauscher, Reuter '02] [Codello, Percacci '05] [Codello, Percacci, Rahmede '08]
[Machado, Saueressig '09] [Niedermaier '09] [Benedetti, Caravelli '12] [Dietz, Morris '12]
[Falls, Litim, Nikolakopoulos, Rahmede '13,'14] [Falls, King, Litim, Nikolakopoulos, Rahmede '18] [Kluth, Litim '20] [Kluth, Litim '22]...

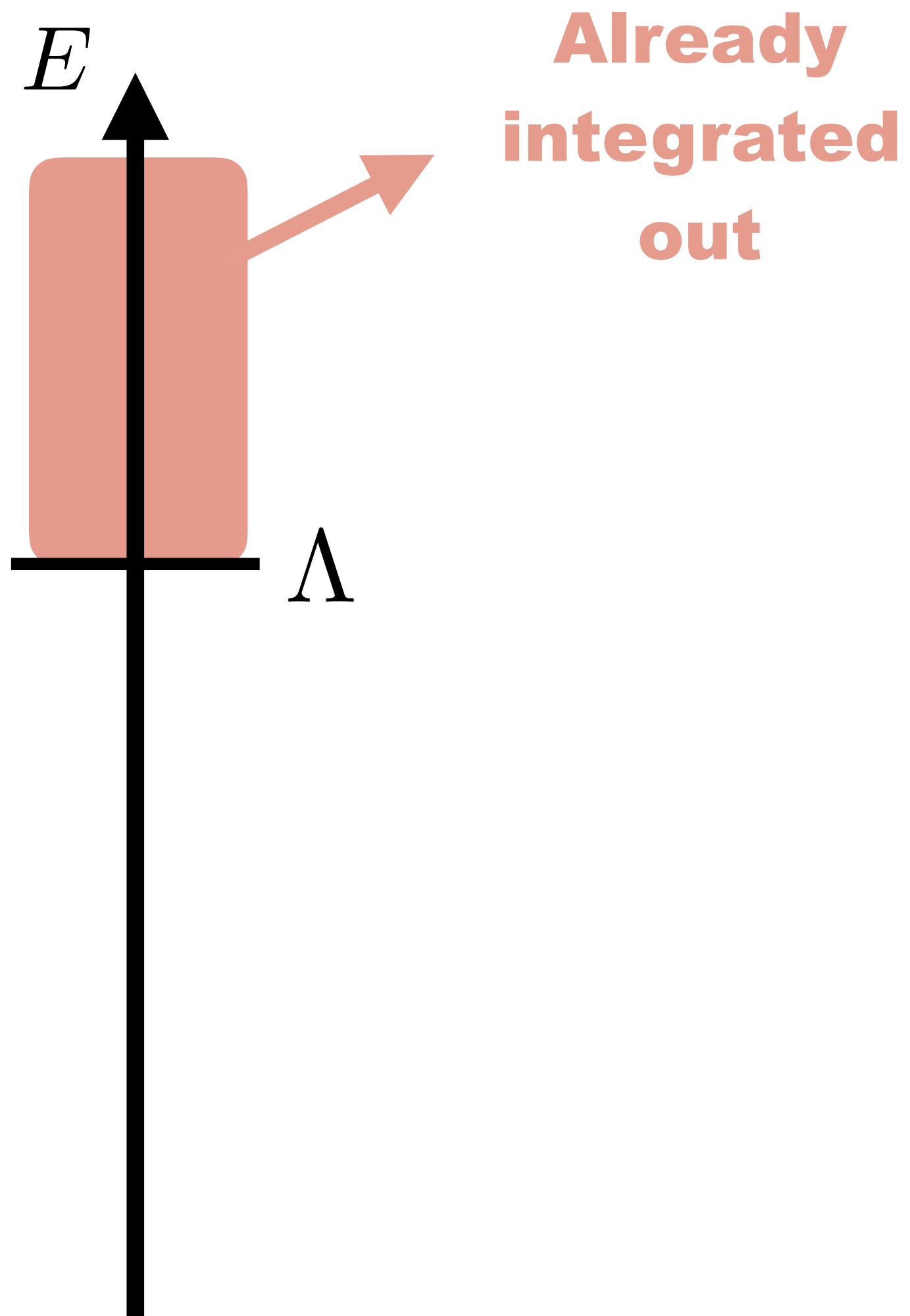
Recently, Lorentzian

[Fehre, Litim, Pawłowski, Reichert '21][Braun, et al '22][Pawłowski, Reichert, Wessely '25]
[d'Angelo, Rejzner '23][d'Angelo '24]

Introduction to functional RG

Wilsonian RG

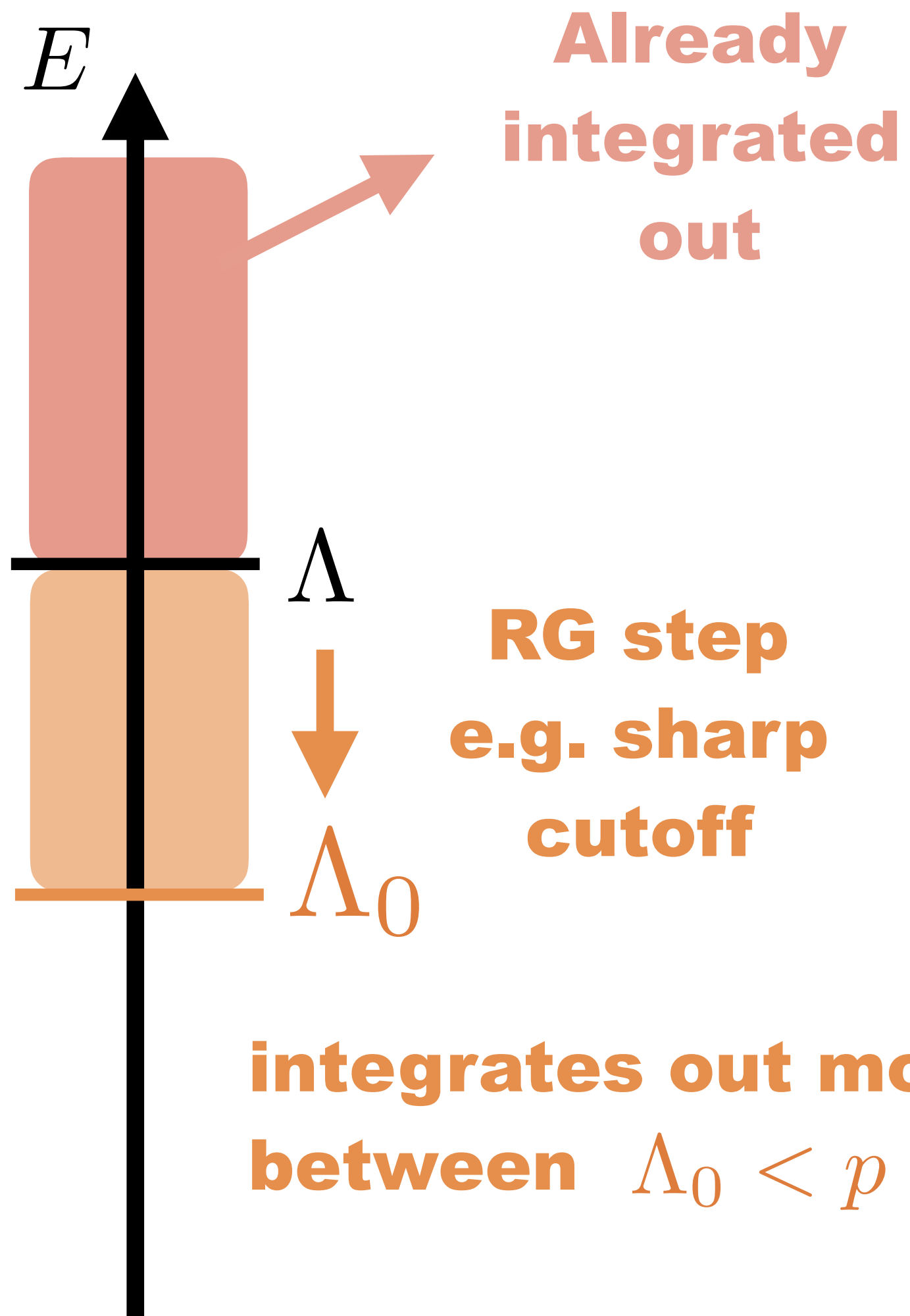
Integrate momentum shells



Introduction to functional RG

Wilsonian RG

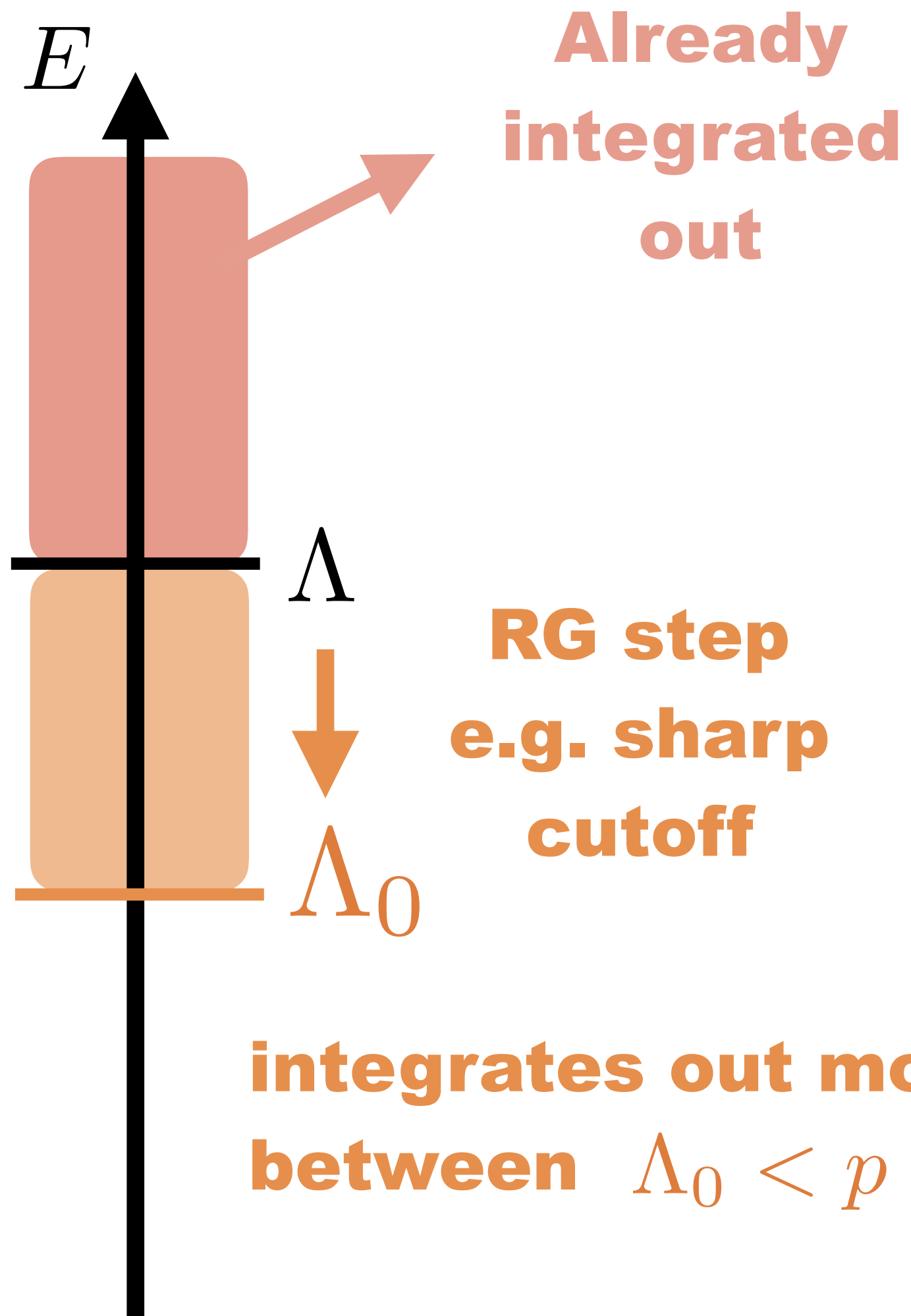
Integrate momentum shells



Introduction to functional RG

Wilsonian RG

Integrate momentum shells



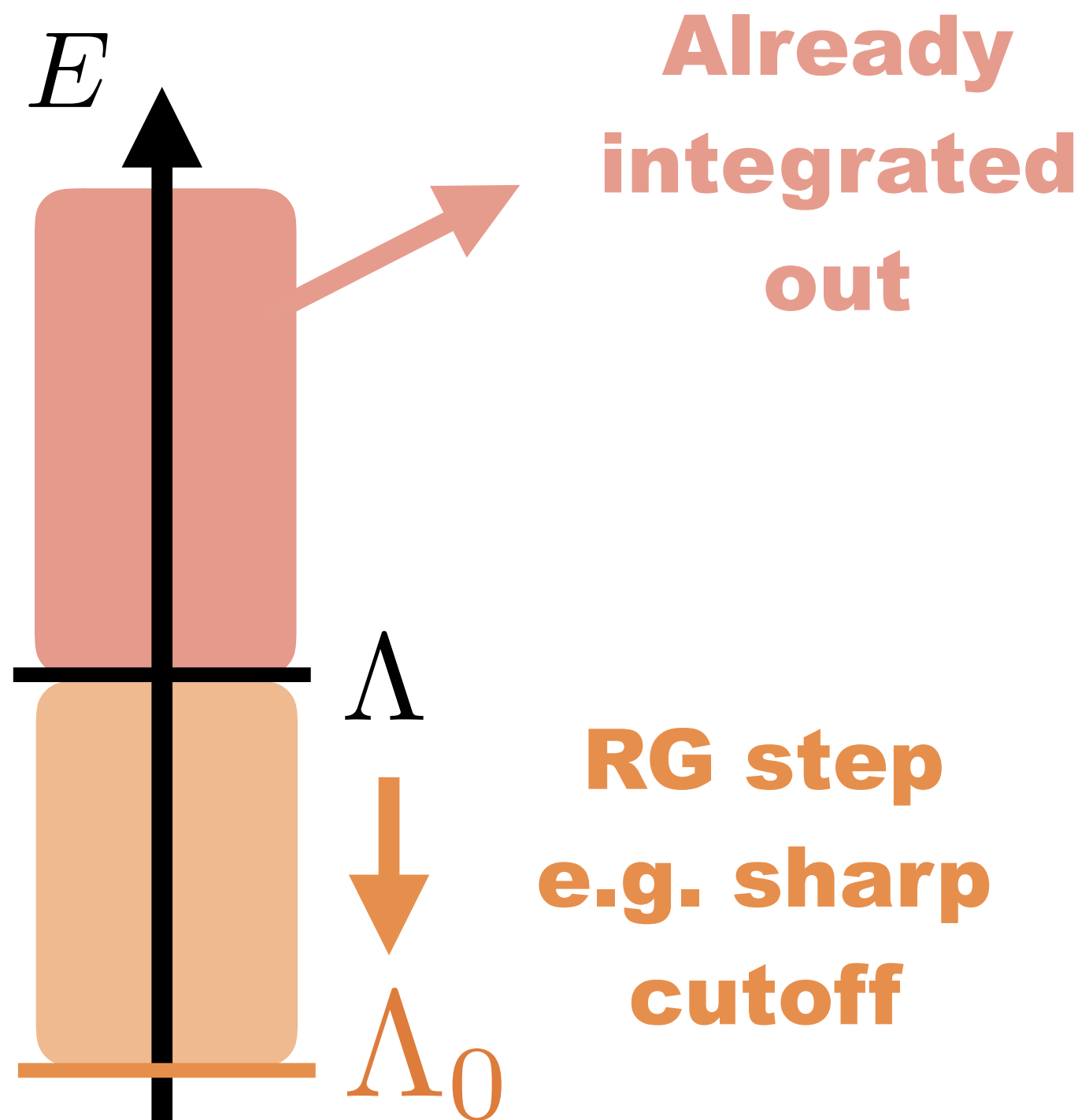
Functional identity for
Quantum effective action

$$\partial_t \Gamma_k = \frac{1}{2} \text{Tr} \left[\partial_t R_k \left(\Gamma_k^{(2)} + R_k \right)^{-1} \right]$$

Introduction to functional RG

Wilsonian RG

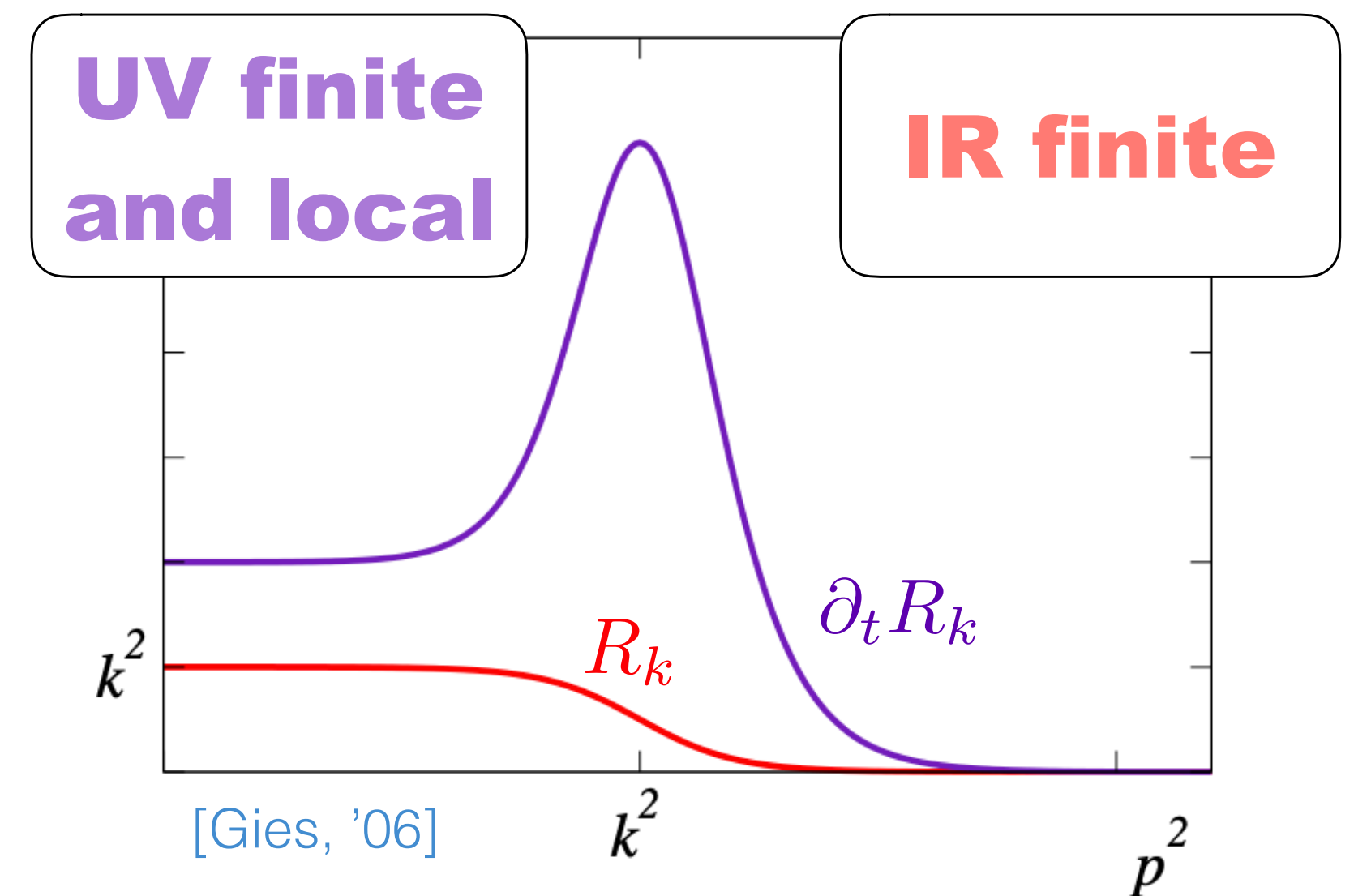
Integrate momentum shells



**integrates out modes
between $\Lambda_0 < p < \Lambda$**

Functional identity for Quantum effective action

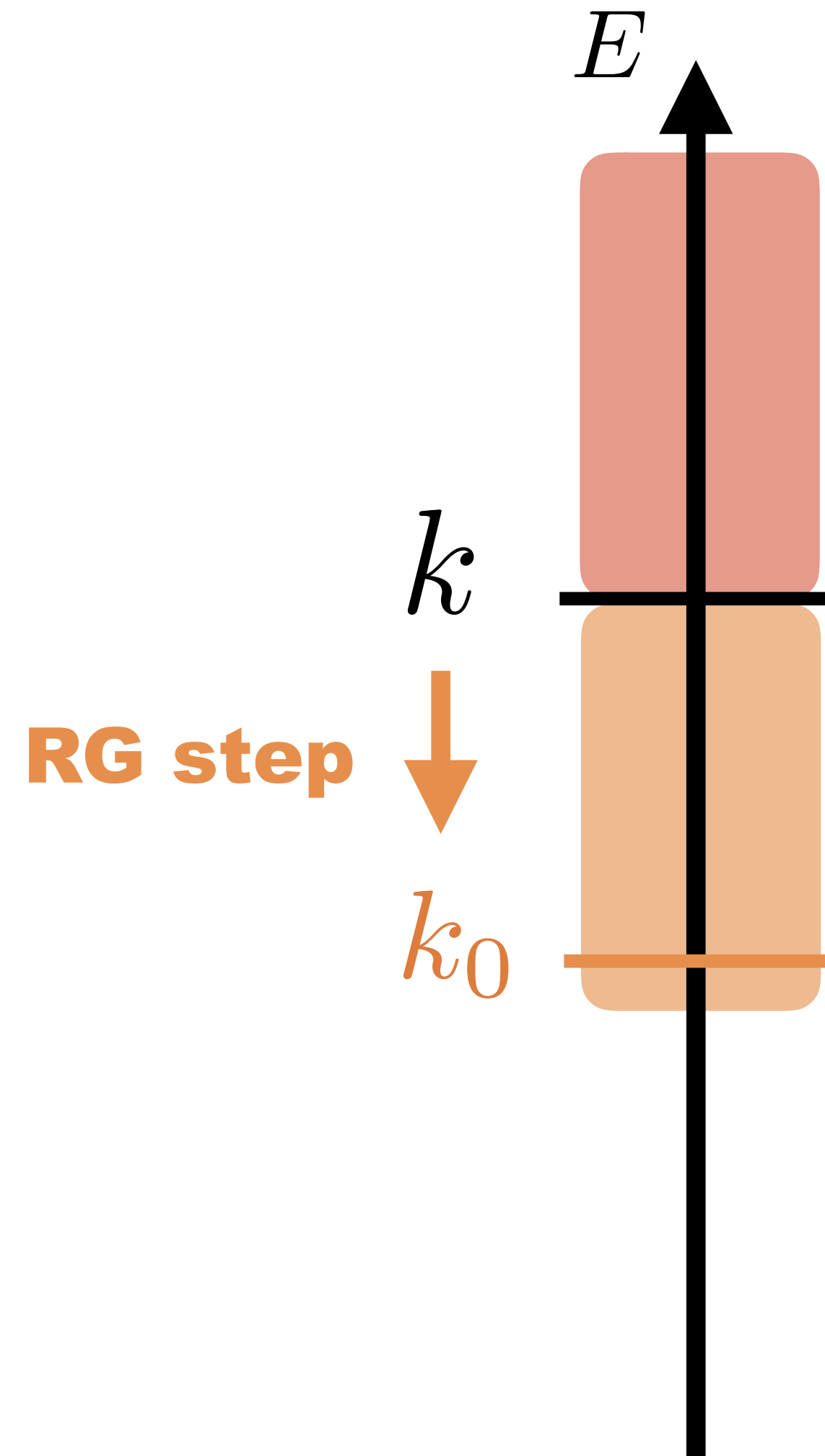
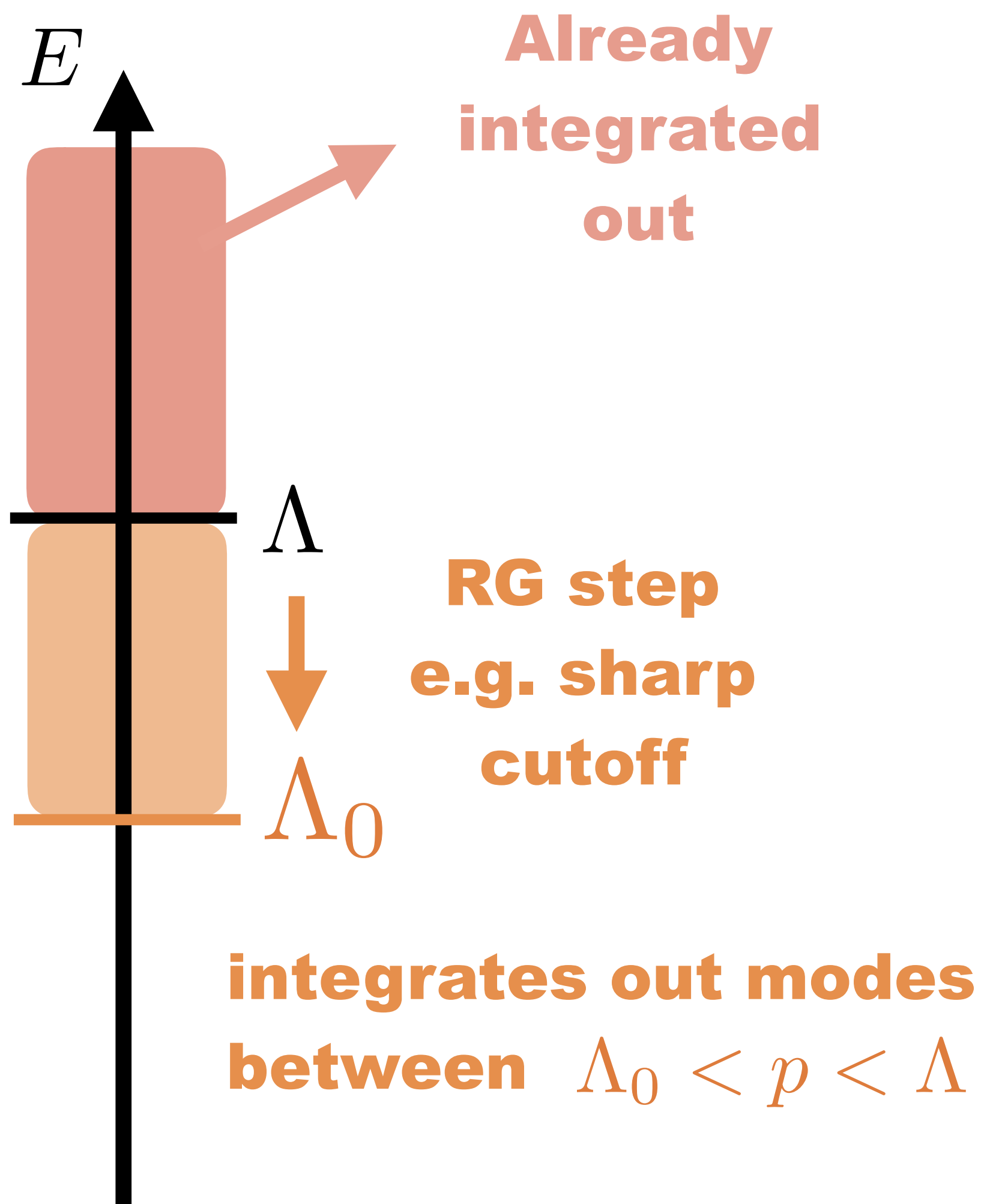
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Introduction to functional RG

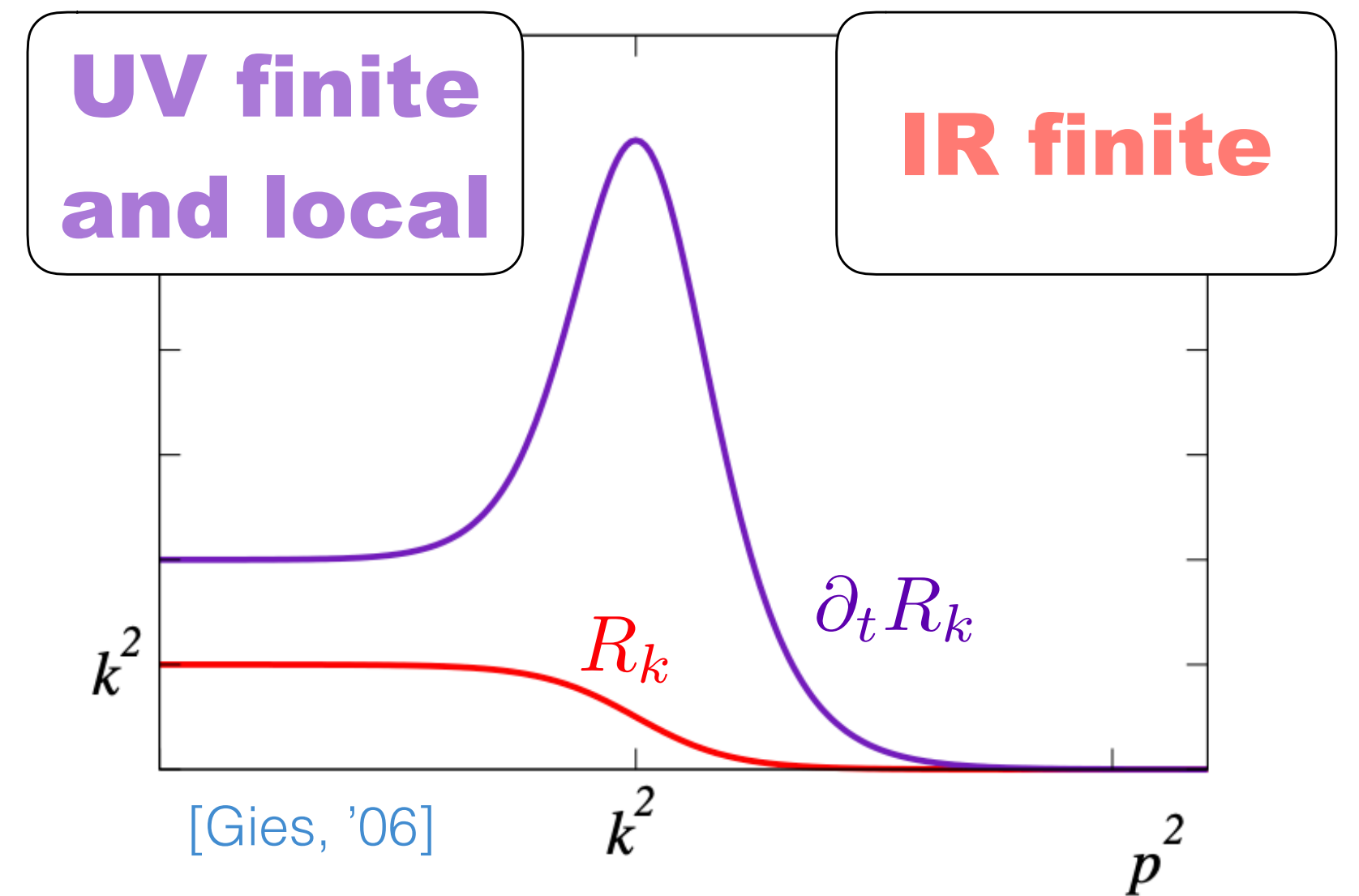
Wilsonian RG

Integrate momentum shells



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$$R_k(p^2 \gg k_0^2) \approx 0$$

$$R_k(p^2 \ll k_0^2) \approx k_0^2$$

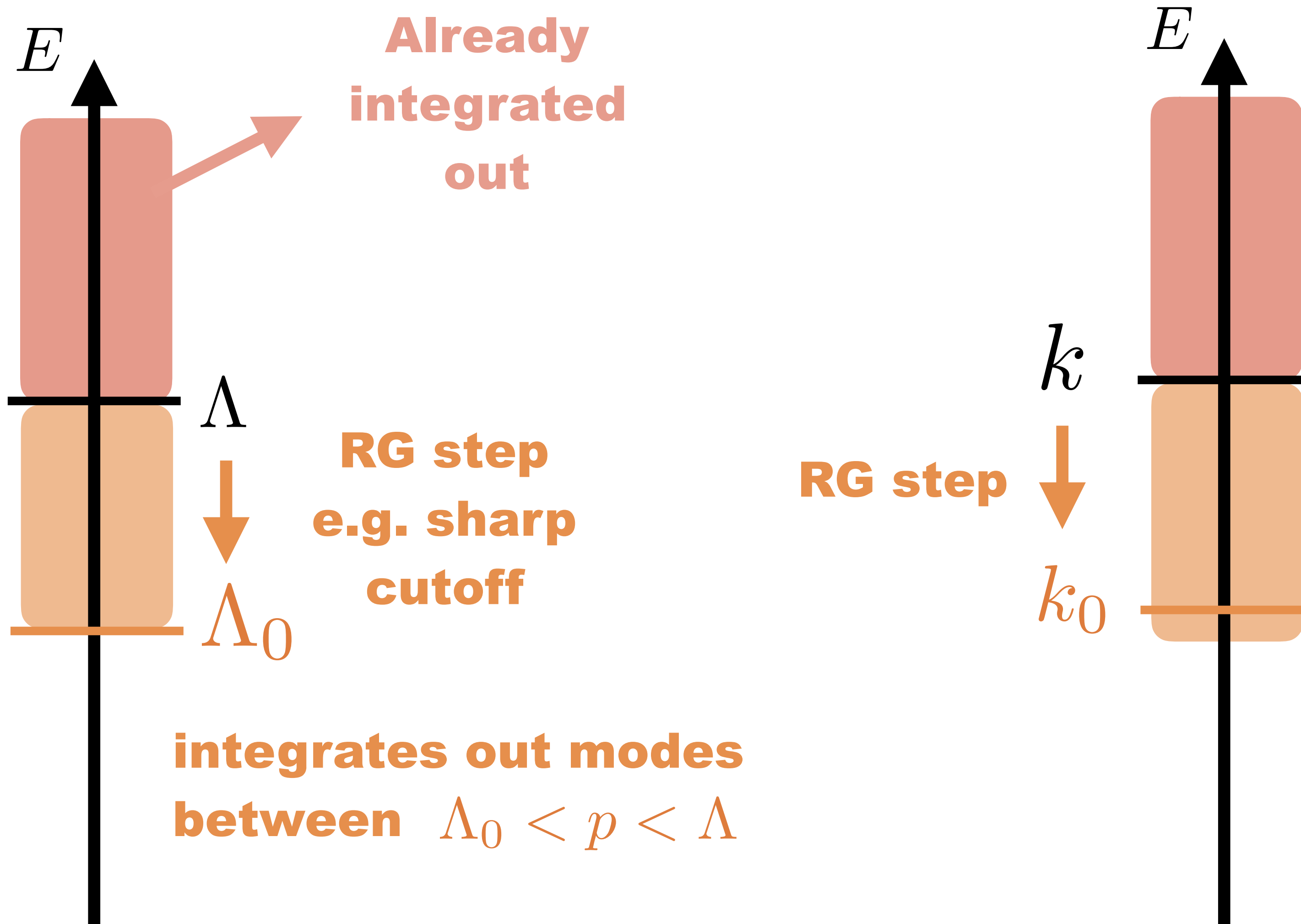
Modes unchanged

**Modes frozen/
suppressed**

Introduction to functional RG

Wilsonian RG

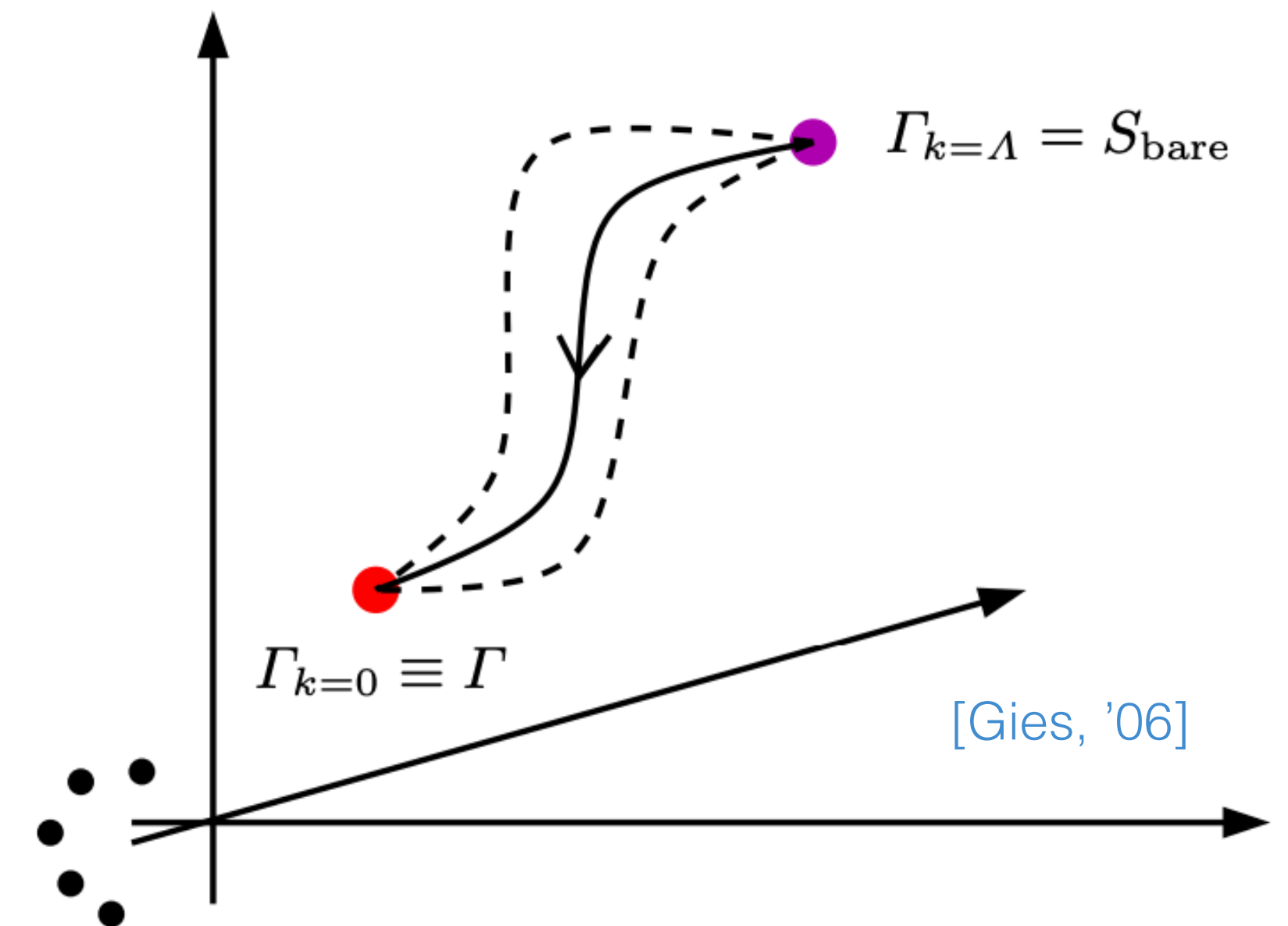
Integrate momentum shells



Functional identity for Quantum effective action

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Evolution in theory space



Work with running couplings

I have not told you everything...

The two-point function tensor decomposition

Goal: set up

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

$$\Gamma^{(2),\mu\nu\rho\sigma} = \frac{1}{32\pi} \left(\Gamma_{\text{TT}}^{(2)} \Pi_{\text{TT}}^{\mu\nu\rho\sigma} - \frac{1}{2} \Gamma_0^{(2)} \Pi_0^{\mu\nu\rho\sigma} + \text{gauge} \right)$$

[Fehre, Litim, Pawłowski, [Pawłowski, Reichert,
Reichert '21] Wessely, 2025]

[GA, Litim, Reichert, 2026]

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[Fehre, Litim, Pawłowski, Reichert '21]

[Pawłowski, Reichert, Wessely, 2025]

[GA, Litim, Reichert, 2026]

Recall RG flow

$$\partial_t \Gamma_{\text{TT}/0} = \frac{1}{2} \operatorname{Tr} \left[\partial_t R_{\text{TT}/0} \left(\Gamma_{\text{TT}/0}^{(2)} + R_{\text{TT}/0} \right)^{-1} \right]$$

I have not told you everything...

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$$\partial_t \rho_{\text{TT}/0}(\lambda) = -2 \operatorname{Im} \left[\mathcal{G}_{\text{TT}/0}^2 \left(\partial_t \Gamma_{\text{TT}/0}^{(2)} + \partial_t R_{\text{TT}/0} \right) \right]_{\text{Wick}}$$

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[GA, Litim, Reichert, 2026]

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$$\partial_t \Gamma_{\text{TT}/0} = \frac{1}{2} \operatorname{Tr} \left[\partial_t R_{\text{TT}/0} \left(\Gamma_{\text{TT}/0}^{(2)} + R_{\text{TT}/0} \right)^{-1} \right]$$

Regulated two-point function

$$\Gamma_{\text{TT}/0}^{(2)} + R_{\text{TT}/0} = Z_{\text{TT}/0}(p)(p^2 + m_{\text{TT}/0}^2)$$

With off-shell mass parameters

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

and anomalous dimensions

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

Healthy Källén-Lehmann flows

Single mode of gauge field:
Callan-Symanzik was enough

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

$$\partial_t \rho_{\text{TT}/0}(\lambda) = -2 \operatorname{Im} \left[\mathcal{G}_{\text{TT}/0}^2 \left(\partial_t \Gamma_{\text{TT}/0}^{(2)} + \partial_t R_{\text{TT}/0} \right) \right]_{\text{Wick}}$$

$$\partial_t \Gamma_{\text{TT}}^{(hh)} = -\frac{1}{2} \text{ (diagram 1) } + \text{ (diagram 2) } - 2 \text{ (diagram 3) } - \partial_t S_{\text{ct, TT}}^{(hh)}$$

The diagrams represent Feynman diagrams for the two-point function. Diagram 1 is a bubble diagram with a cross on the top arc and a solid dot on the bottom arc, connected by two horizontal lines. Diagram 2 is a bubble diagram with a cross on the top arc and two solid dots on the horizontal lines. Diagram 3 is a bubble diagram with a cross on the top arc and two solid dots on the horizontal lines, but the bubble is represented by a dotted line.

Healthy Källén-Lehmann flows

Single mode of gauge field:
Callan-Symanzik was enough

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

$$\partial_t \rho_{\text{TT}/0}(\lambda) = -2 \operatorname{Im} \left[\mathcal{G}_{\text{TT}/0}^2 \left(\partial_t \Gamma_{\text{TT}/0}^{(2)} + \partial_t R_{\text{TT}/0} \right) \right]_{\text{Wick}}$$

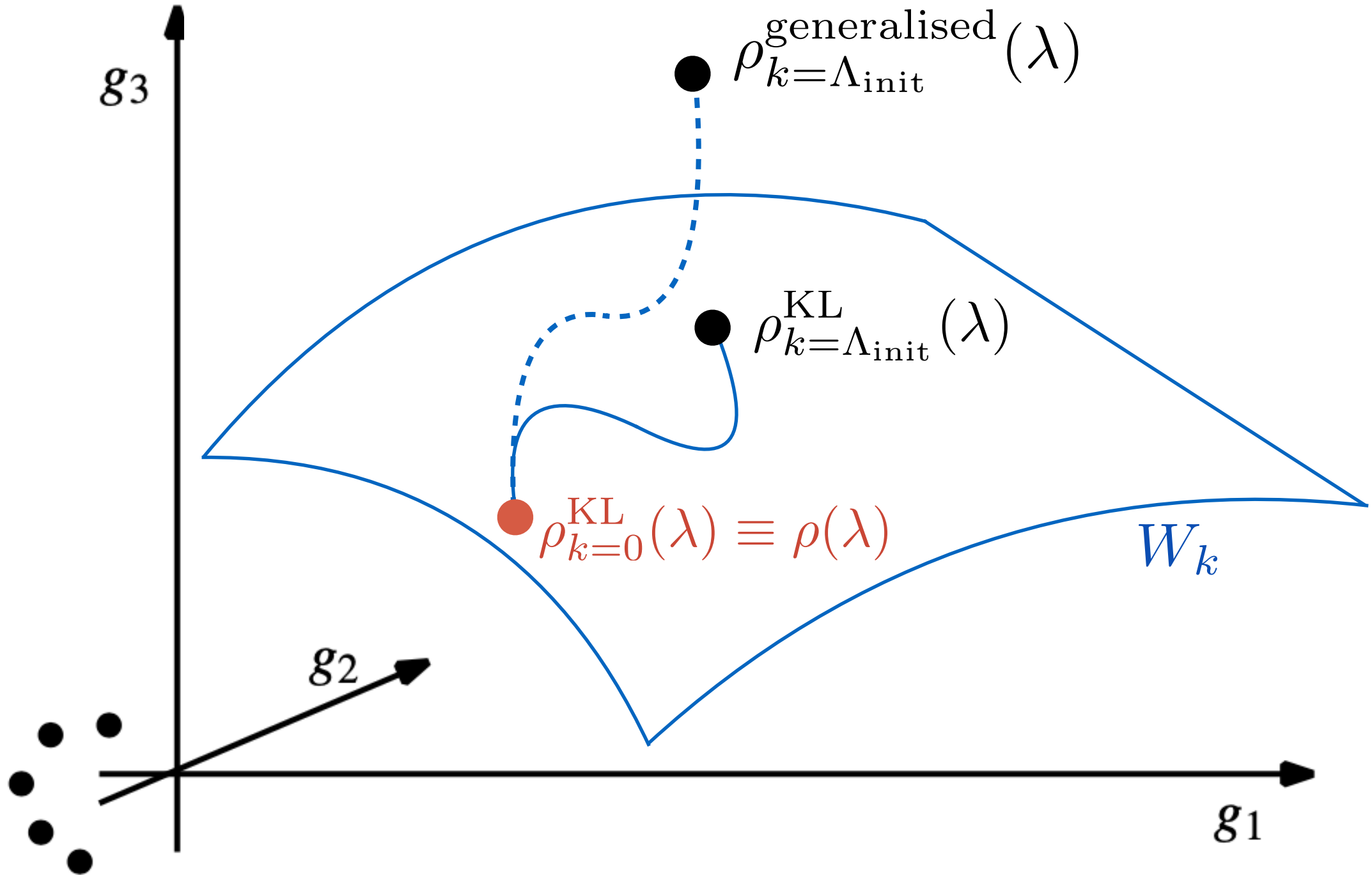
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$$\partial_t \Gamma_{\text{TT}}^{(hh)} = -\frac{1}{2} \text{[diagram 1]} + \text{[diagram 2]} - 2 \text{[diagram 3]} - \partial_t S_{\text{ct, TT}}^{(hh)}$$

$$\partial_t \Gamma_{\text{TT}}^{(2)} = \text{[diagram 4]} + \text{[diagram 5]} + \text{[diagram 6]} + \text{[diagram 7]} - \frac{1}{2} \text{[diagram 8]} - \frac{1}{2} \text{[diagram 9]} - 2 \text{[diagram 10]} - \partial_t S_{\text{ct, TT}}^{(2)}$$

$$\partial_t \Gamma_0^{(2)} = \text{[diagram 11]} + \text{[diagram 12]} + \text{[diagram 13]} + \text{[diagram 14]} - \frac{1}{2} \text{[diagram 15]} - \frac{1}{2} \text{[diagram 16]} - 2 \text{[diagram 17]} - \partial_t S_{\text{ct, 0}}^{(2)}$$

[GA, Litim, Reichert, '26]

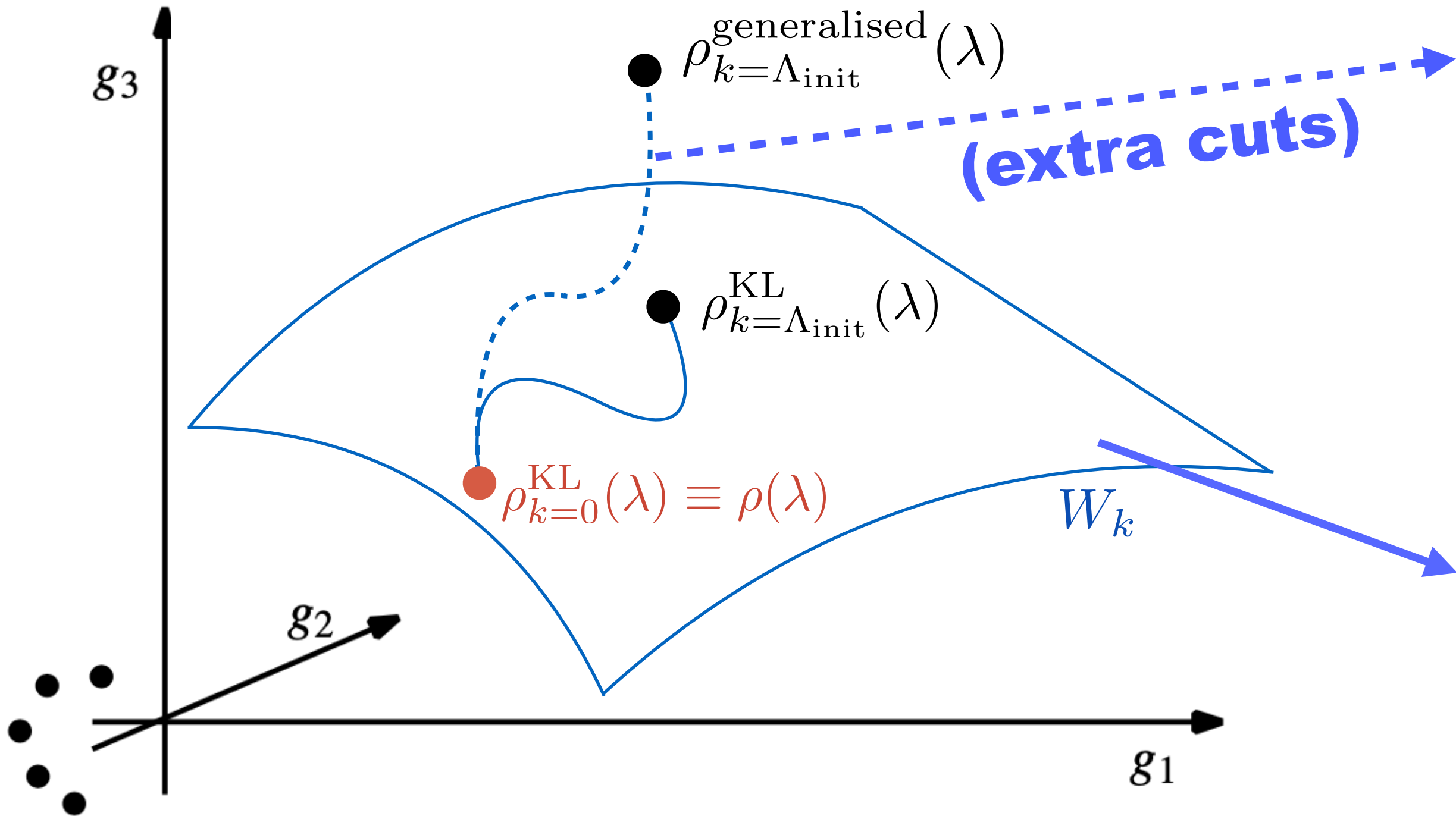


Healthy Källén-Lehmann flows

Single mode of gauge field: Callan-Symanzik was enough

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

[GA, Litim, Reichert, '26]



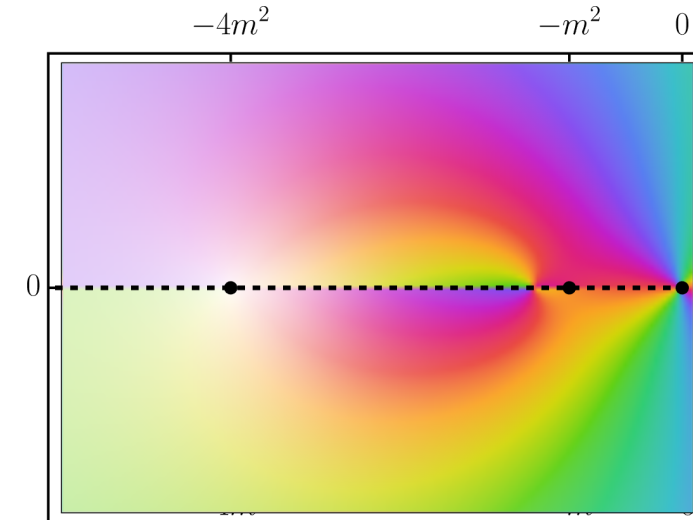
$$R_{\text{TT}} \propto k^2$$

$$\partial_t \Gamma_{\text{TT}}^{(hh)} = -\frac{1}{2} \left(\text{Diagram 1} + \text{Diagram 2} - 2 \text{Diagram 3} \right) - \partial_t S_{\text{ct, TT}}^{(hh)}$$

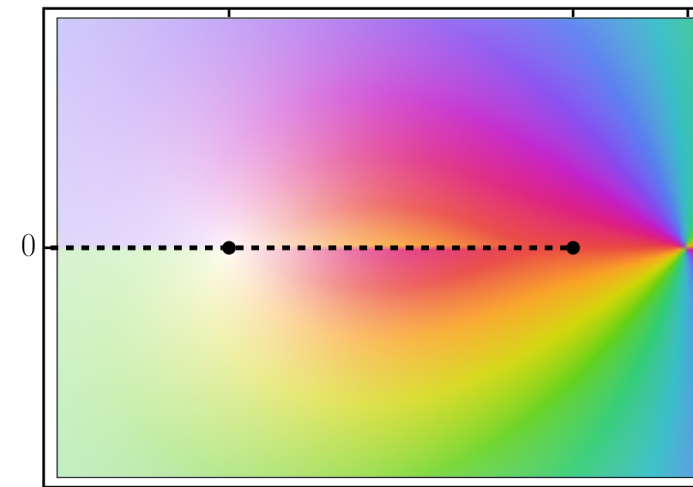
$$\partial_t \Gamma_{\text{TT}}^{(2)} = \text{[Diagram 1]} + \text{[Diagram 2]} + \text{[Diagram 3]} + \text{[Diagram 4]} - \frac{1}{2} \text{[Diagram 5]} - \frac{1}{2} \text{[Diagram 6]} - 2 \text{[Diagram 7]} - \partial_t S_{\text{ct, TT}}^{(2)}$$

$$\partial_t \Gamma_0^{(2)} = \text{diagram 1} + \text{diagram 2} + \text{diagram 3} + \text{diagram 4} - \frac{1}{2} \text{diagram 5} - \frac{1}{2} \text{diagram 6} - 2 \text{diagram 7} - \partial_t S_{\text{ct},0}^{(2)}$$

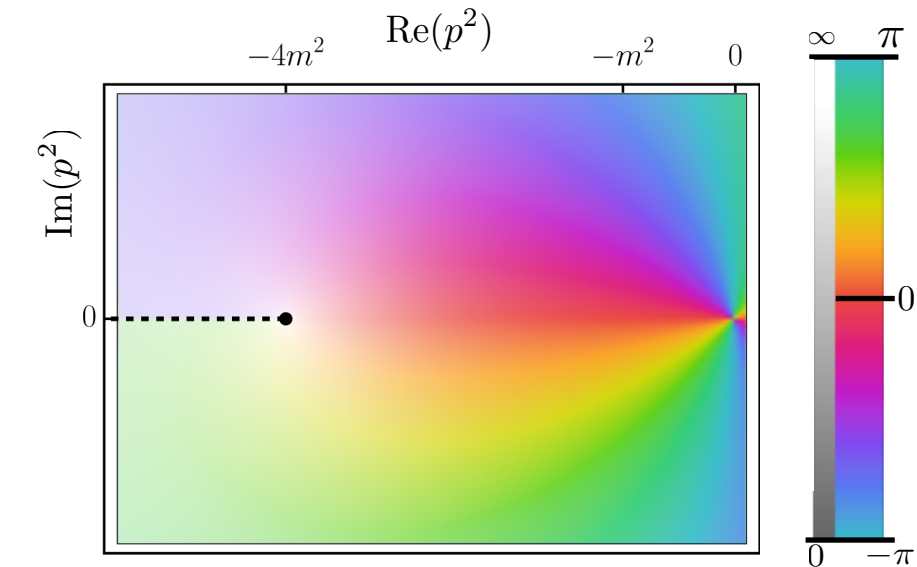
Unhealthy KL


$$\begin{aligned} m_0 &\neq m_{\text{TT}} \\ \eta_0 &\neq \eta_{\text{TT}} \end{aligned}$$

Generalised KL


$$\begin{array}{l} m_0 = m_{\text{TT}} \\ \eta_0 \neq \eta_{\text{TT}} \end{array}$$

Healthy KL

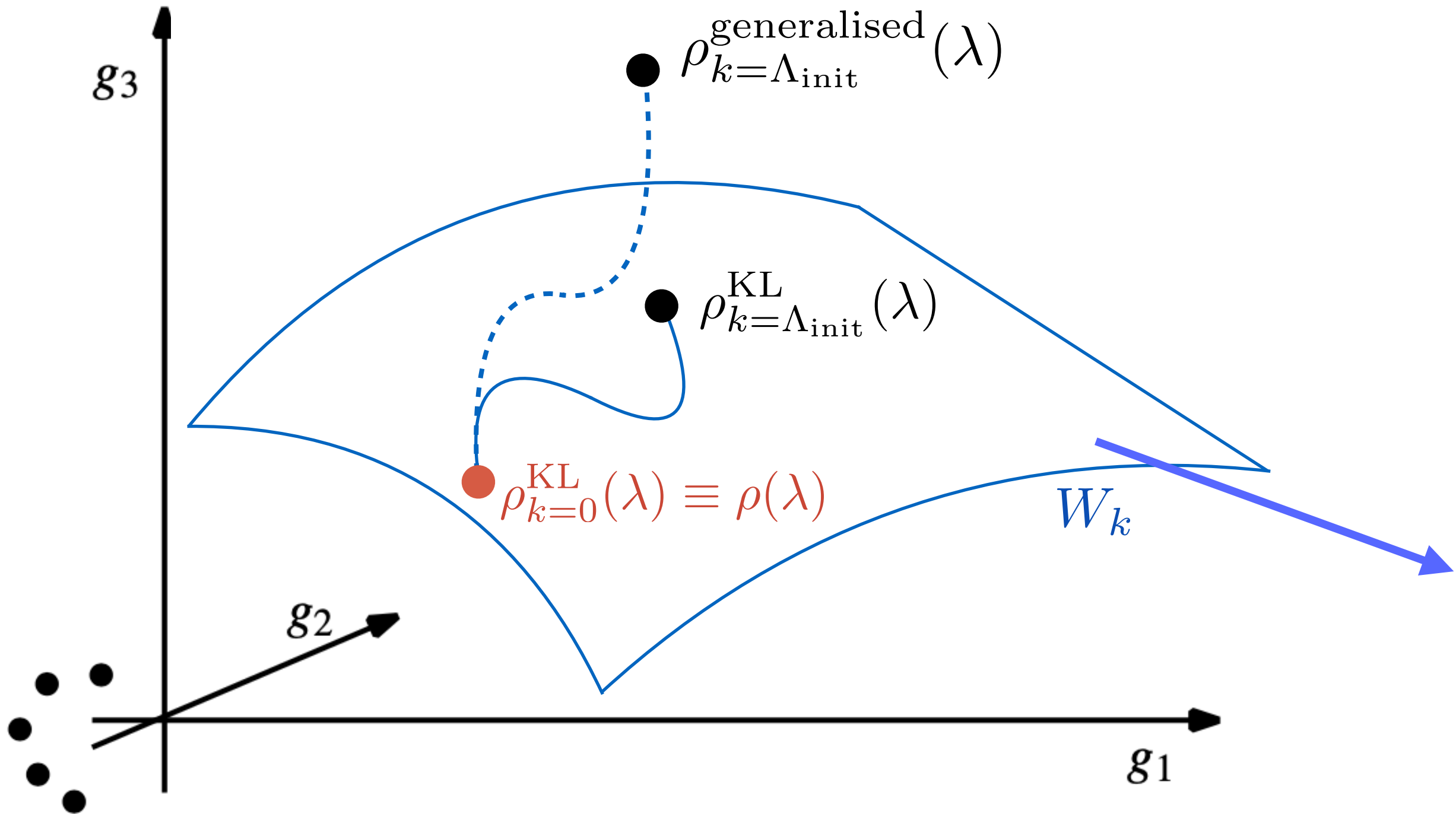

$$\begin{aligned} m_0 &= m_{\text{TT}} \\ \eta_0 &= \eta_{\text{TT}} \end{aligned}$$

Healthy Källén-Lehmann flows

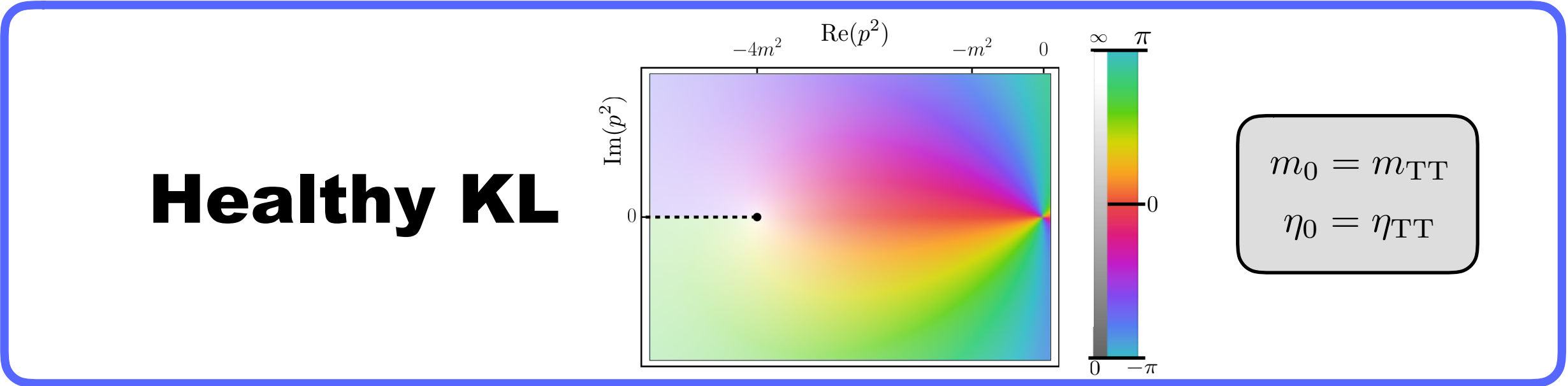
Single mode of gauge field:
Callan-Symanzik was enough

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

[GA, Litim, Reichert, '26]



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



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

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

$$\partial_t \Gamma_{\text{TT}}^{(hh)} = -\frac{1}{2} \text{ (diagram 1) } + \text{ (diagram 2) } - 2 \text{ (diagram 3) } - \partial_t S_{\text{ct, TT}}^{(hh)}$$

$$\partial_t \Gamma_{\text{TT}}^{(2)} = \text{ (diagram 1) } + \text{ (diagram 2) } + \text{ (diagram 3) } + \text{ (diagram 4) } - \frac{1}{2} \text{ (diagram 5) } - \frac{1}{2} \text{ (diagram 6) } - 2 \text{ (diagram 7) } - \partial_t S_{\text{ct, TT}}^{(2)}$$

$$\partial_t \Gamma_0^{(2)} = \text{ (diagram 1) } + \text{ (diagram 2) } + \text{ (diagram 3) } + \text{ (diagram 4) } - \frac{1}{2} \text{ (diagram 5) } - \frac{1}{2} \text{ (diagram 6) } - 2 \text{ (diagram 7) } - \partial_t S_{\text{ct, 0}}^{(2)}$$

Preserving symmetry

p = 0 renormalisation

Generalise [\[Fehre, Litim, Pawłowski, Reichert '21\]](#)

$$\partial_t \Gamma_{\text{TT}/0}^{(2)}(p^2 = 0) = a_{\text{TT}/0}$$

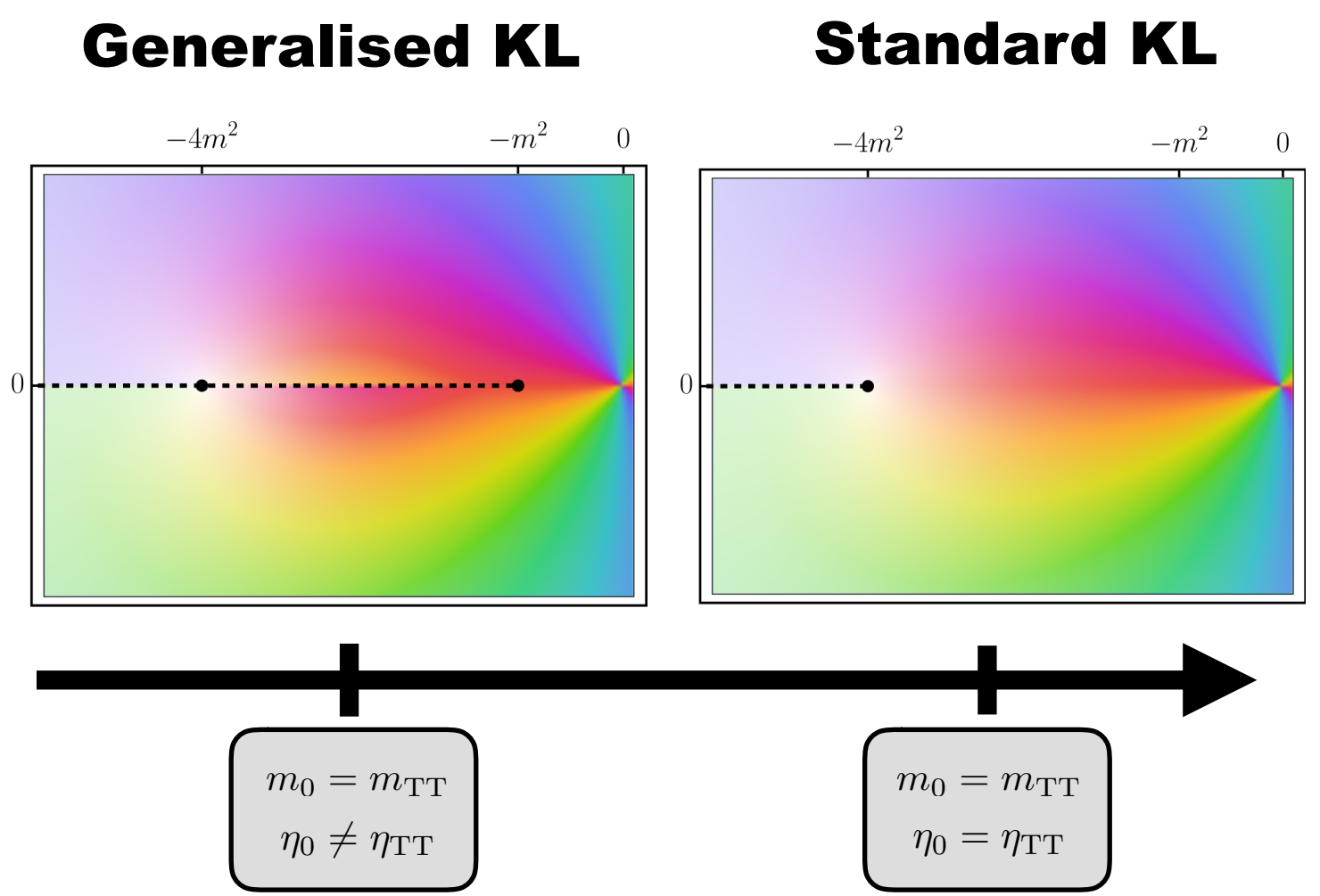
$$\partial_t \partial_{p^2} \Gamma_{\text{TT}/0}^{(2)}(p^2) \Big|_{p^2=0} = b_{\text{TT}/0}$$



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

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

Standard KL



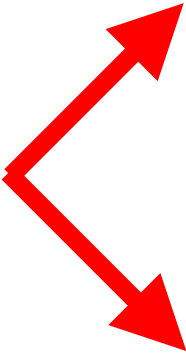
Preserving symmetry

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$$\partial_t \Gamma_{\text{TT}/0}^{(2)}(p^2 = 0) = a_{\text{TT}/0}$$

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



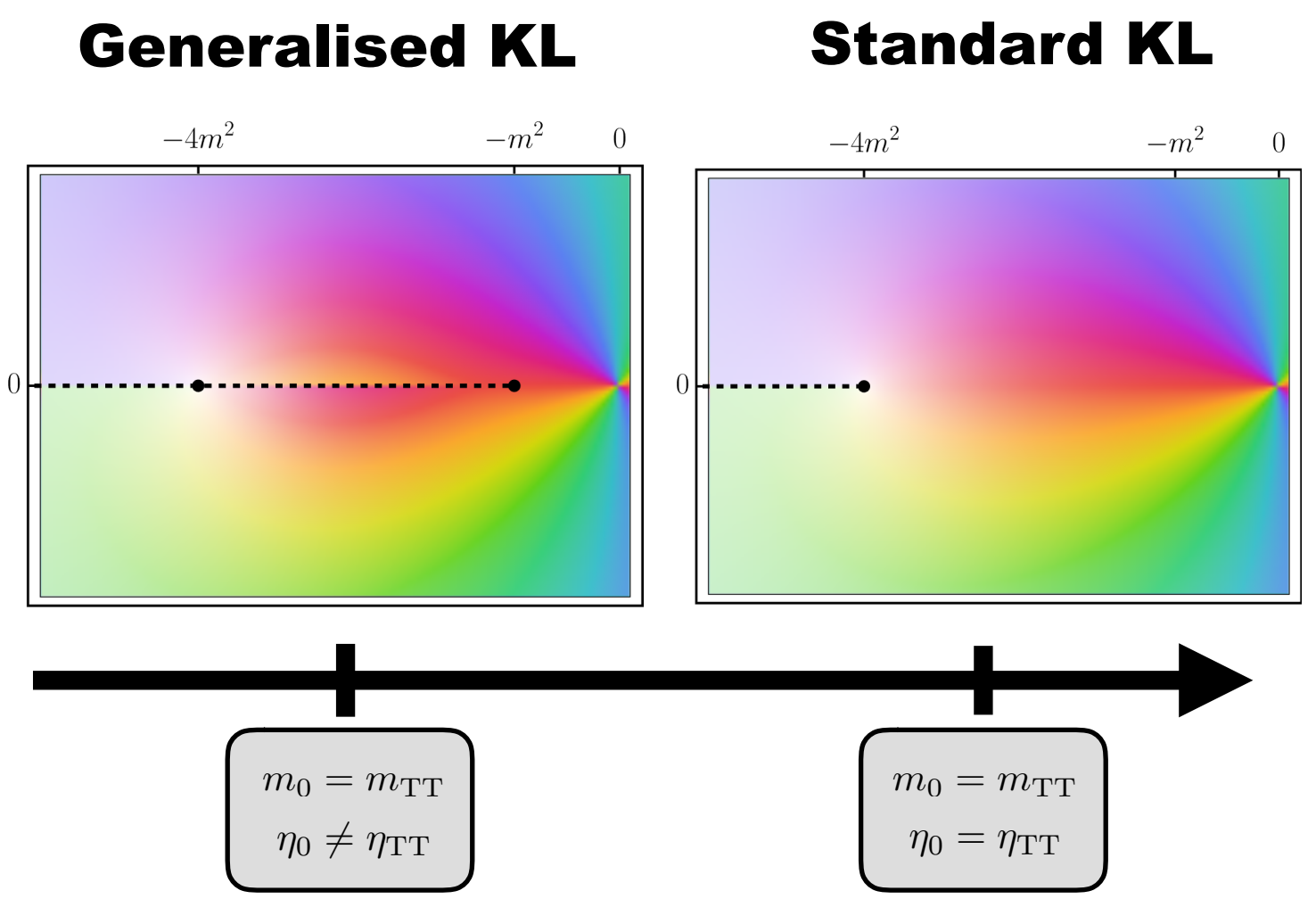
Fix $a_0 \implies m_{\text{TT}} = m_0$

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

Standard KL

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

Generalised KL



Preserving symmetry

p = 0 renormalisation

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

$$\partial_t \Gamma_{\text{TT}/0}^{(2)}(p^2 = 0) = a_{\text{TT}/0}$$

$$\left. \partial_t \partial_{p^2} \Gamma_{\text{TT}/0}^{(2)}(p^2) \right|_{p^2=0} = b_{\text{TT}/0}$$

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

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

Standard KL

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

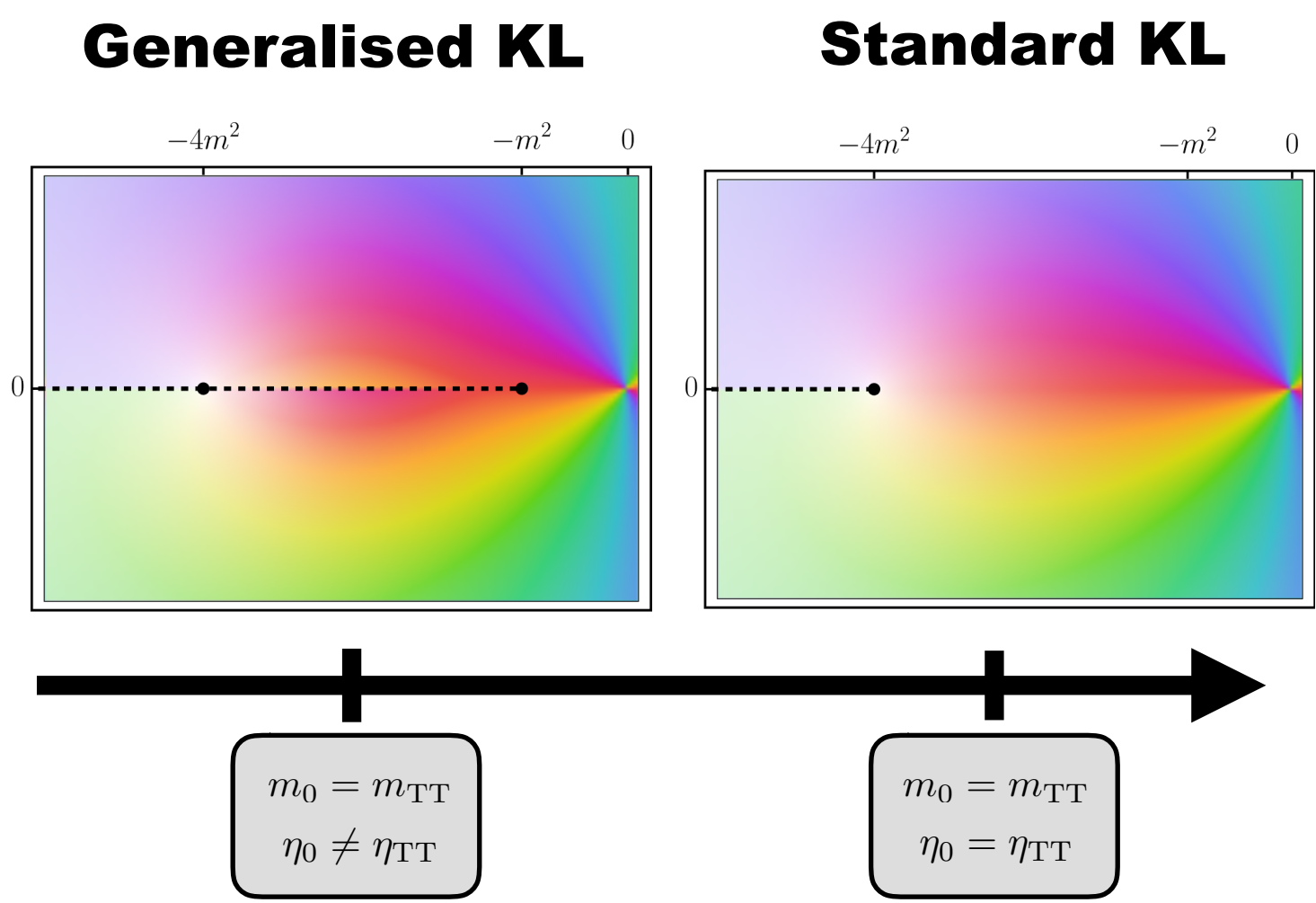
Generalised KL

On-shell renormalisation

$$\partial_t \Gamma_{\text{TT}/0}^{(2)}(p^2 = -m_{\text{TT}/0}^2) = 0$$

$$\left. \partial_t \partial_{p^2} \Gamma_{\text{TT}/0}^{(2)}(p^2) \right|_{p^2 = -m_{\text{TT}/0}^2} = 0$$

Renormalise on the graviton mass pole



Preserving symmetry

p = 0 renormalisation

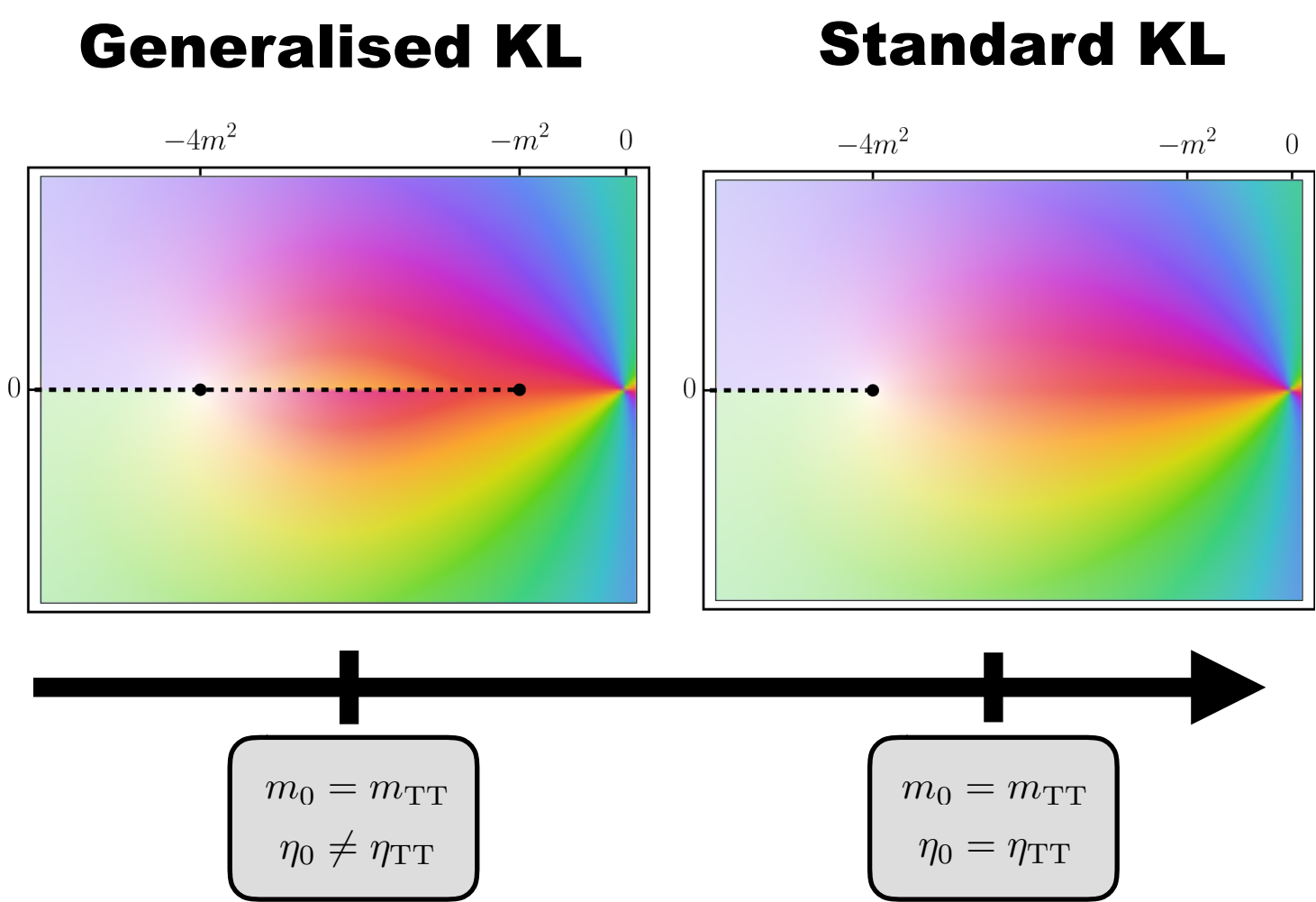
Generalise [Fehre, Litim, Pawłowski, Reichert '21]

$$\partial_t \Gamma_{\text{TT}/0}^{(2)}(p^2 = 0) = a_{\text{TT}/0}$$

$$\left. \partial_t \partial_{p^2} \Gamma_{\text{TT}/0}^{(2)}(p^2) \right|_{p^2=0} = b_{\text{TT}/0}$$

Fix $a_0 \implies m_{\text{TT}} = m_0$
 Fix $b_0 \implies \eta_{\text{TT}} = \eta_0$
Standard KL

Only fix $a_0 \implies m_{\text{TT}} = m_0$
Generalised KL



On-shell renormalisation

$$\partial_t \Gamma_{\text{TT}/0}^{(2)}(p^2 = -m_{\text{TT}/0}^2) = 0$$

$$\left. \partial_t \partial_{p^2} \Gamma_{\text{TT}/0}^{(2)}(p^2) \right|_{p^2 = -m_{\text{TT}/0}^2} = 0$$

Renormalise on the graviton mass pole

Naturally sets
 $m_{\text{TT}} = m_0 = k$
 $\eta_{\text{TT}} = \eta_0 = 0$
Standard KL

Simplifies computations

[Pawłowski, Reichert, Wessely '25]

[GA, Litim, Reichert, '26]

Preserving symmetry

p = 0 renormalisation

Generalise

$$\partial_t \Gamma_{\text{TT}/0}^{(2)}(p^2 = 0) = a_{\text{TT}/0}$$

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

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

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

Standard KL

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

Generalised KL

On-shell renormalisation

$$\partial_t \Gamma_{\text{TT}/0}^{(2)}(p^2 = -m_{\text{TT}/0}^2) = 0$$

$$\partial_t \partial_{p^2} \Gamma_{\text{TT}/0}^{(2)}(p^2) \Big|_{p^2 = -m_{\text{TT}/0}^2} = 0$$

**Renormalise on the graviton
mass pole**

Naturally sets

$$m_{\text{TT}} = m_0 = k$$

$$\eta_{\text{TT}} = \eta_0 = 0$$

Standard KL