The Breakdown of the Narrow Width Approximation and other Aspects of Timelike Processes in AdS

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2002.12335
2011.06603
+ upcoming work

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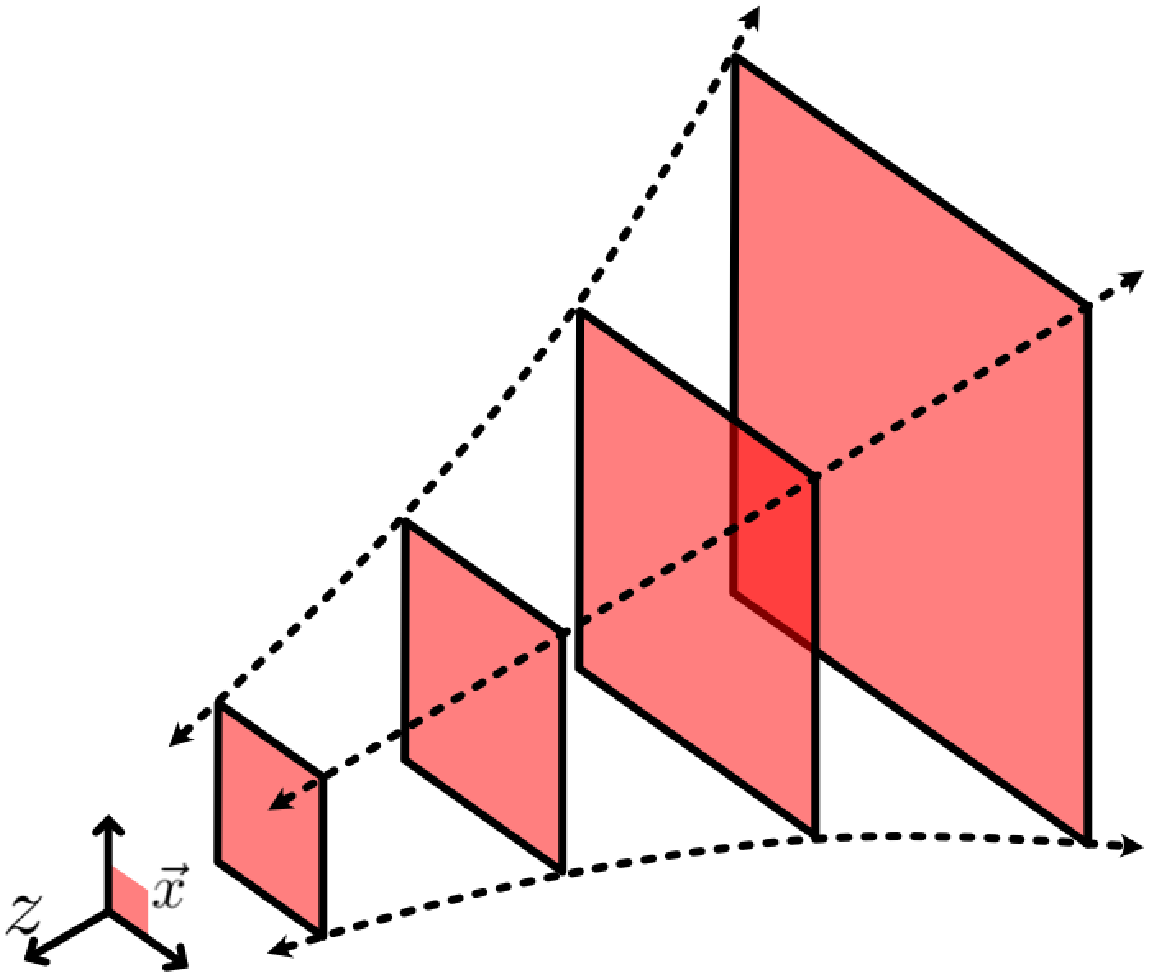
Why Anti-de Sitter spacetime?

- Dual to a conformal field theory via AdS/CFT correspondence (hep-th/9711200 by Maldacena, hep-th/9802109 by Gubser et al., hep-th/9802150 by Witten)

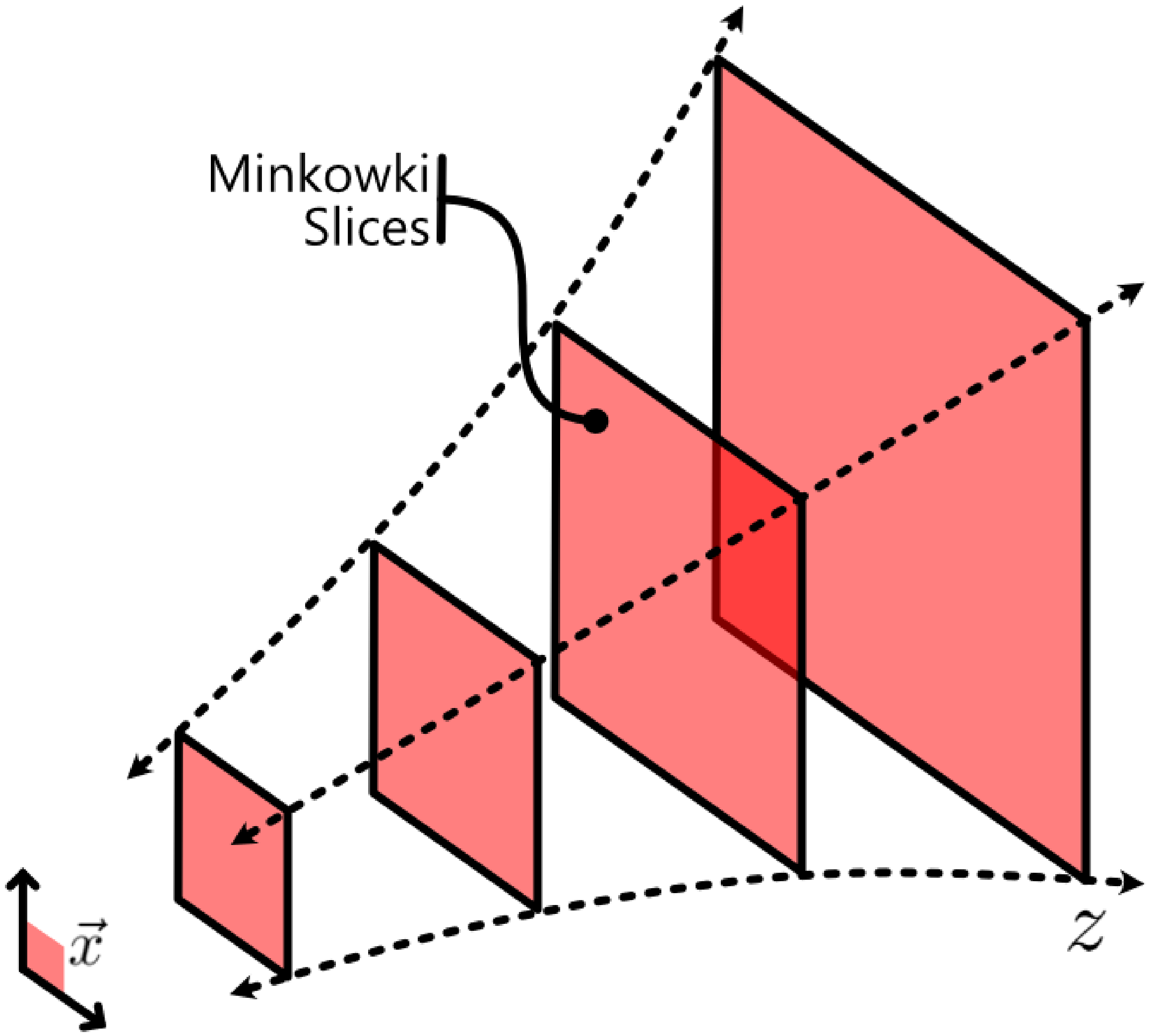
- Strongly coupled CFTs can produce novel phenomenon:

    - Non-integer forces, ``Unparticles'' (see e.g. Georgi hep-ph/0703260 and 0704.2457. See also 0804.0424 by Cacciapaglia, Marandella, Terning, and 0902.3676 by Friedland et al.)

    - Quasi-spherical cascade decays (see e.g. Csaki, Reece, Terning 0811.3001)



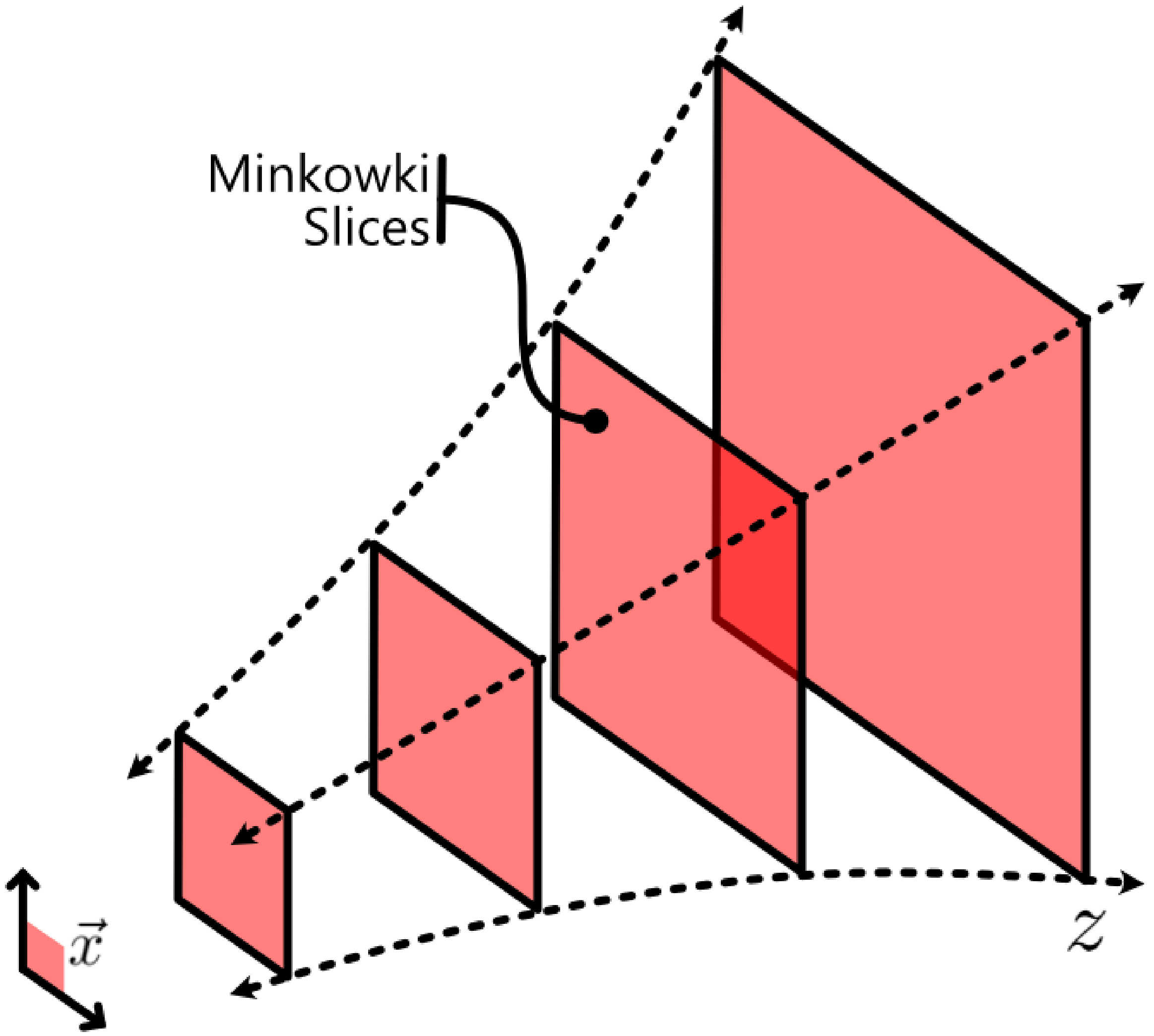
Anti-de Sitter Spacetime



$$ds^2 = \frac{1}{(kz)^2}\left(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2\right)$$

$\eta_{\mu\nu} \rightarrow (+,-,-,-)$

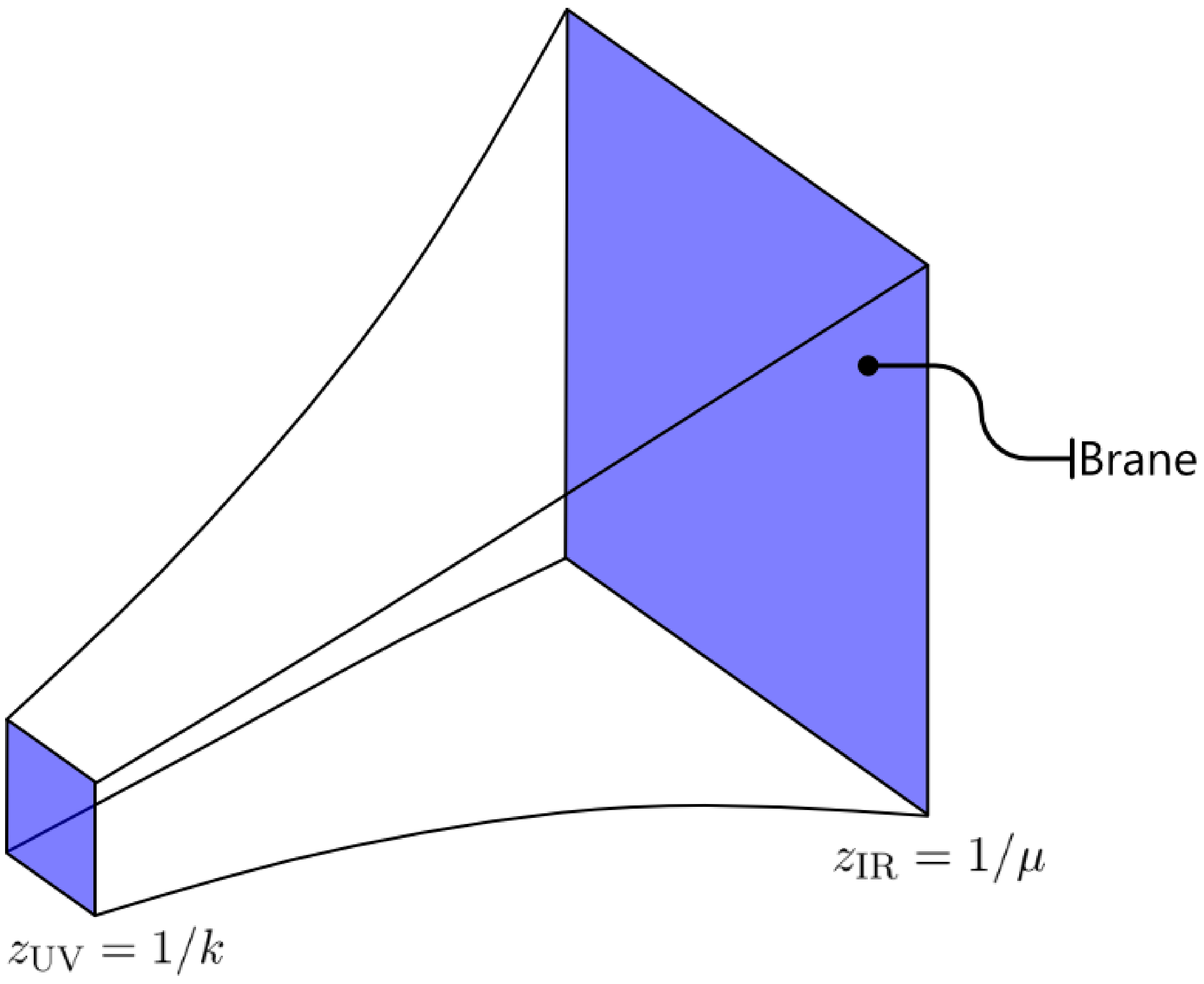
Anti-de Sitter Spacetime



Warp Factor

$$ds^2 = \frac{1}{(kz)^2}\left(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2\right)$$

AdS with Branes



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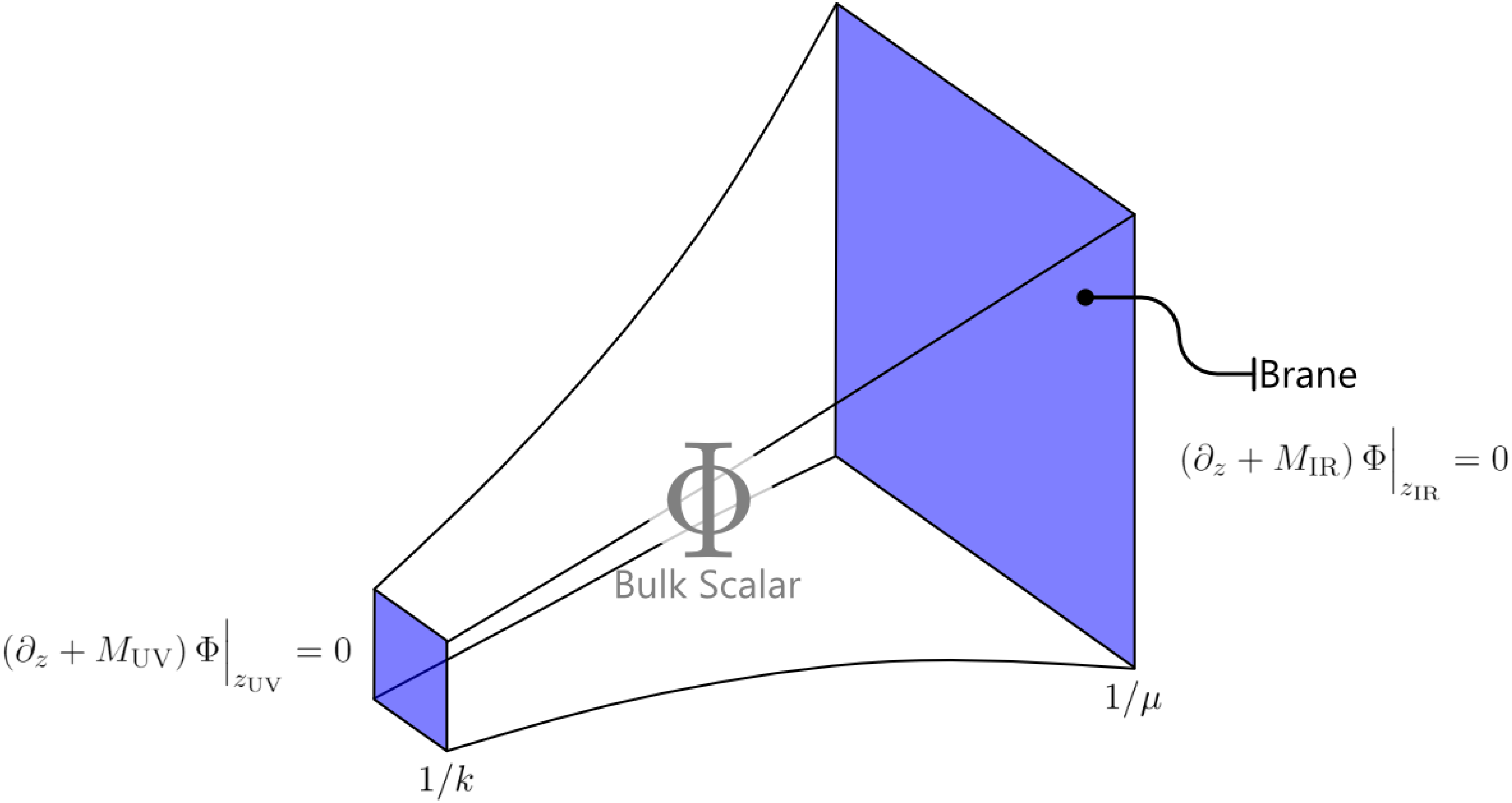

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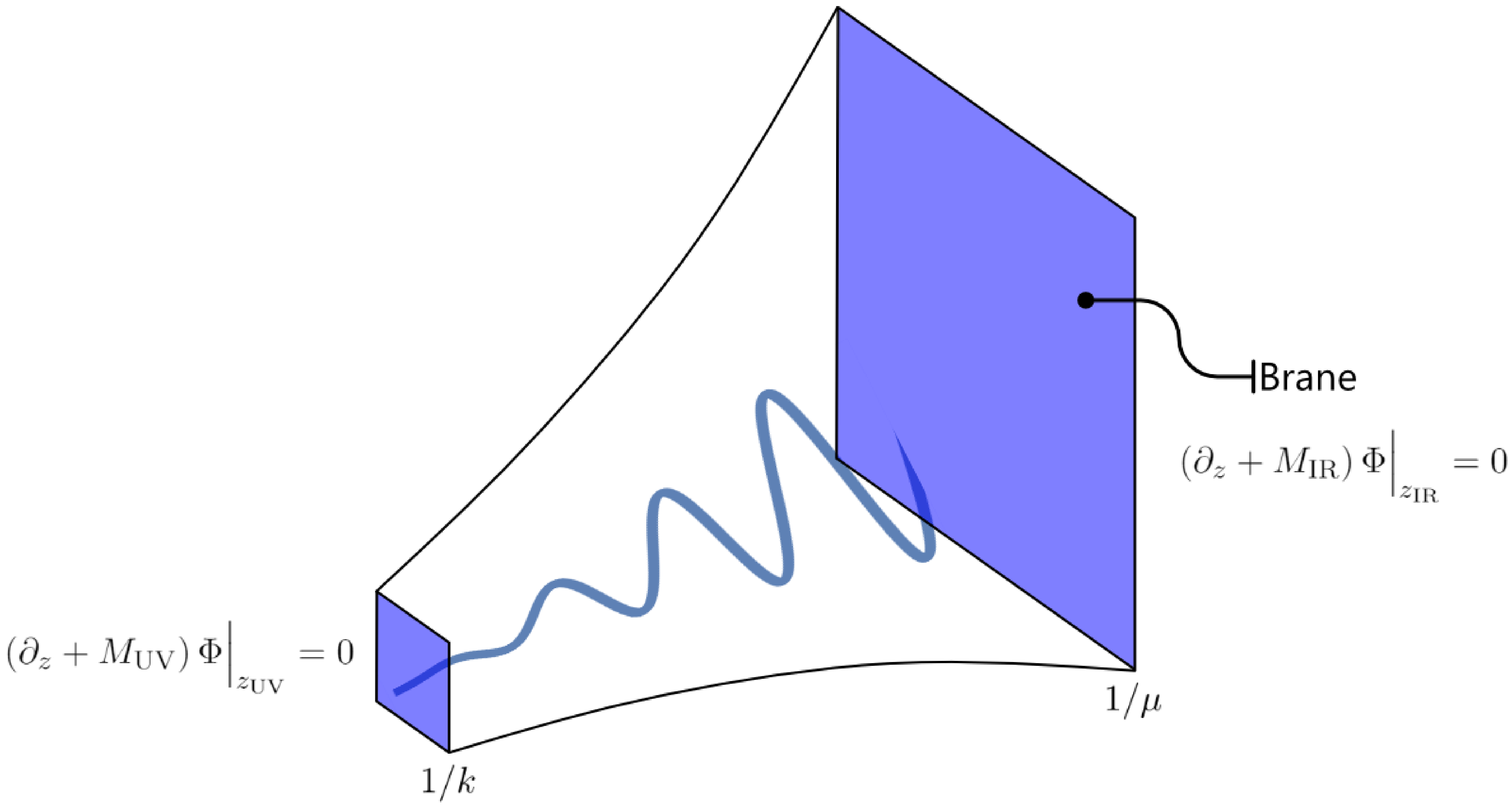
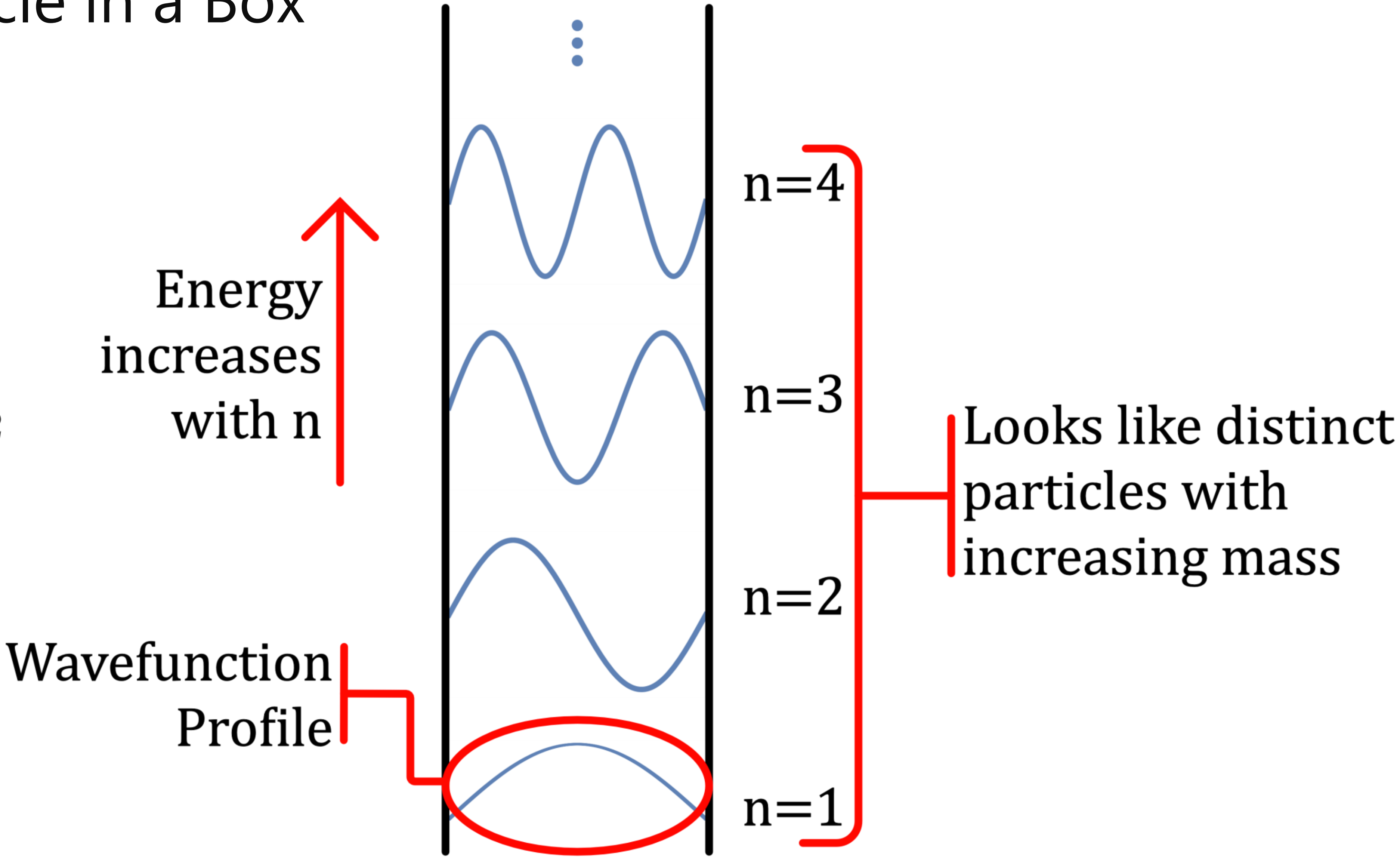


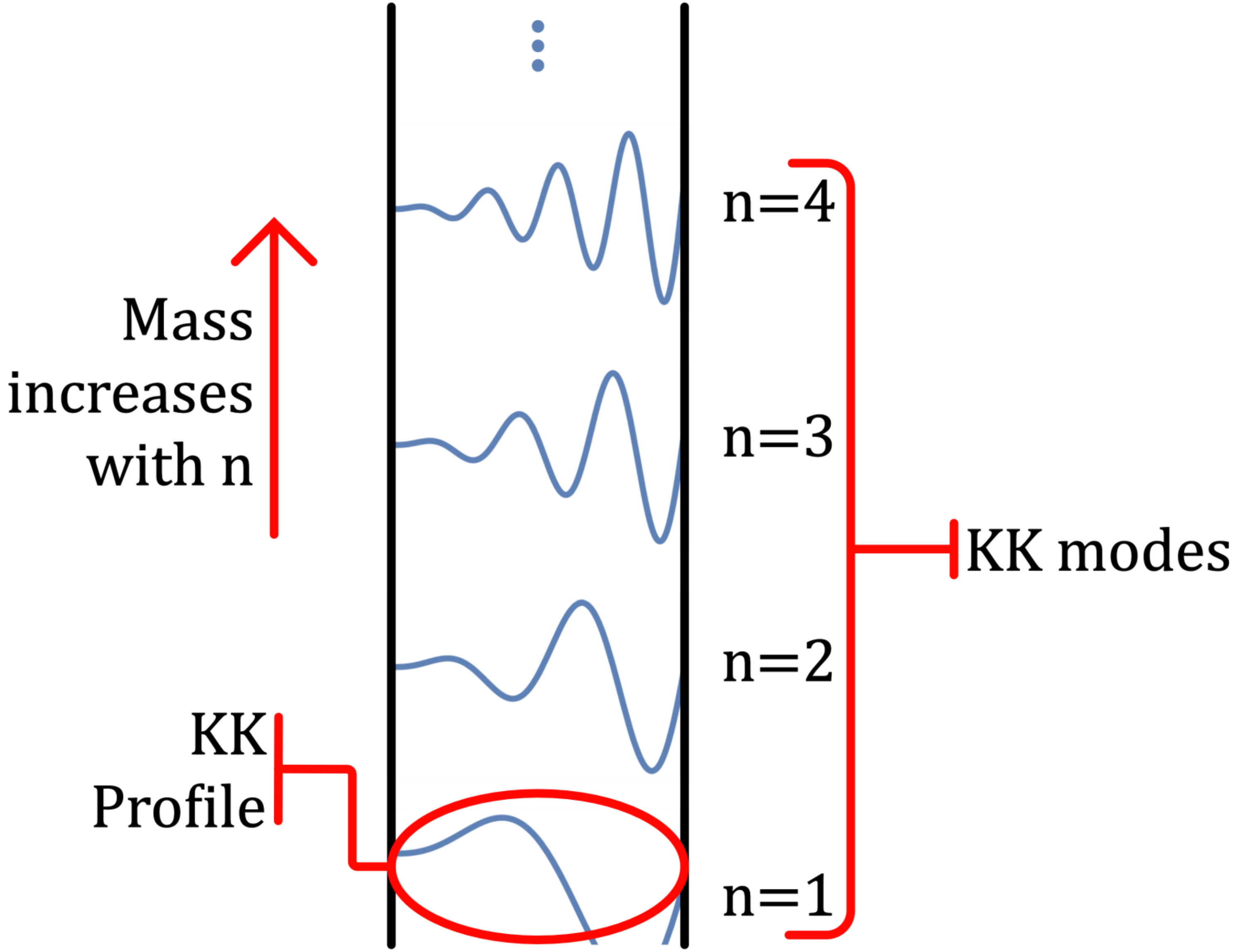
Review: Particle in a Box

$$E_n \propto n^2$$



KK Modes

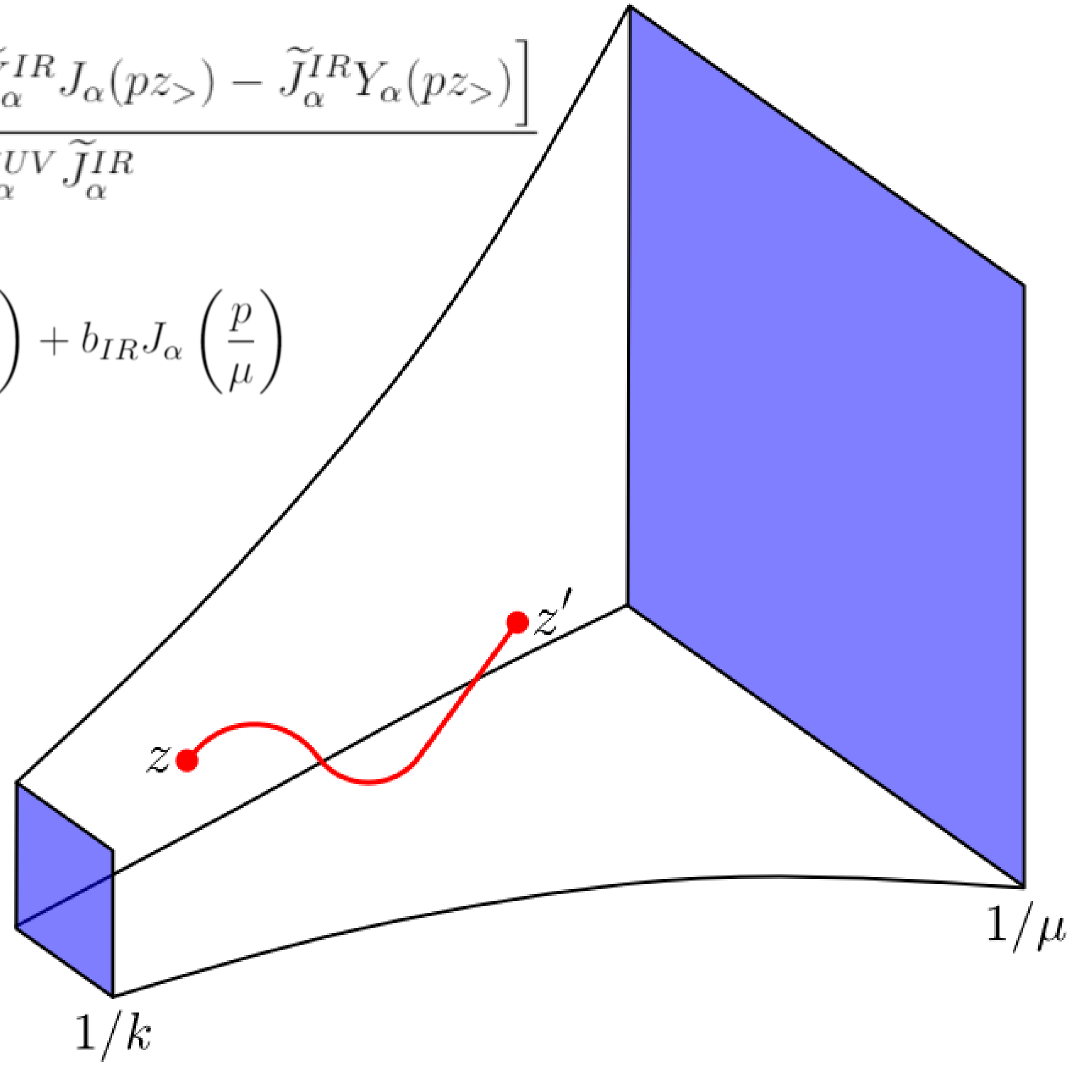
$$m_n \sim n\pi\mu$$



5D Propagator

$$G_p(z,z') = i\frac{\pi k^3 (zz')^2}{2}\frac{\left[\widetilde{Y}_\alpha^{UV} J_\alpha(pz_<) - \widetilde{J}_\alpha^{UV} Y_\alpha(pz_<)\right]\left[\widetilde{Y}_\alpha^{IR} J_\alpha(pz_>) - \widetilde{J}_\alpha^{IR} Y_\alpha(pz_>)\right]}{\widetilde{J}_\alpha^{UV}\widetilde{Y}_\alpha^{IR} - \widetilde{Y}_\alpha^{UV}\widetilde{J}_\alpha^{IR}}$$

$$\widetilde{J}_\alpha^{UV} = \frac{p}{k}J_{\alpha-1}\left(\frac{p}{k}\right) - b_{UV}J_\alpha\left(\frac{p}{k}\right) \qquad \widetilde{J}_\alpha^{IR} = \frac{p}{\mu}J_{\alpha-1}\left(\frac{p}{\mu}\right) + b_{IR}J_\alpha\left(\frac{p}{\mu}\right)$$



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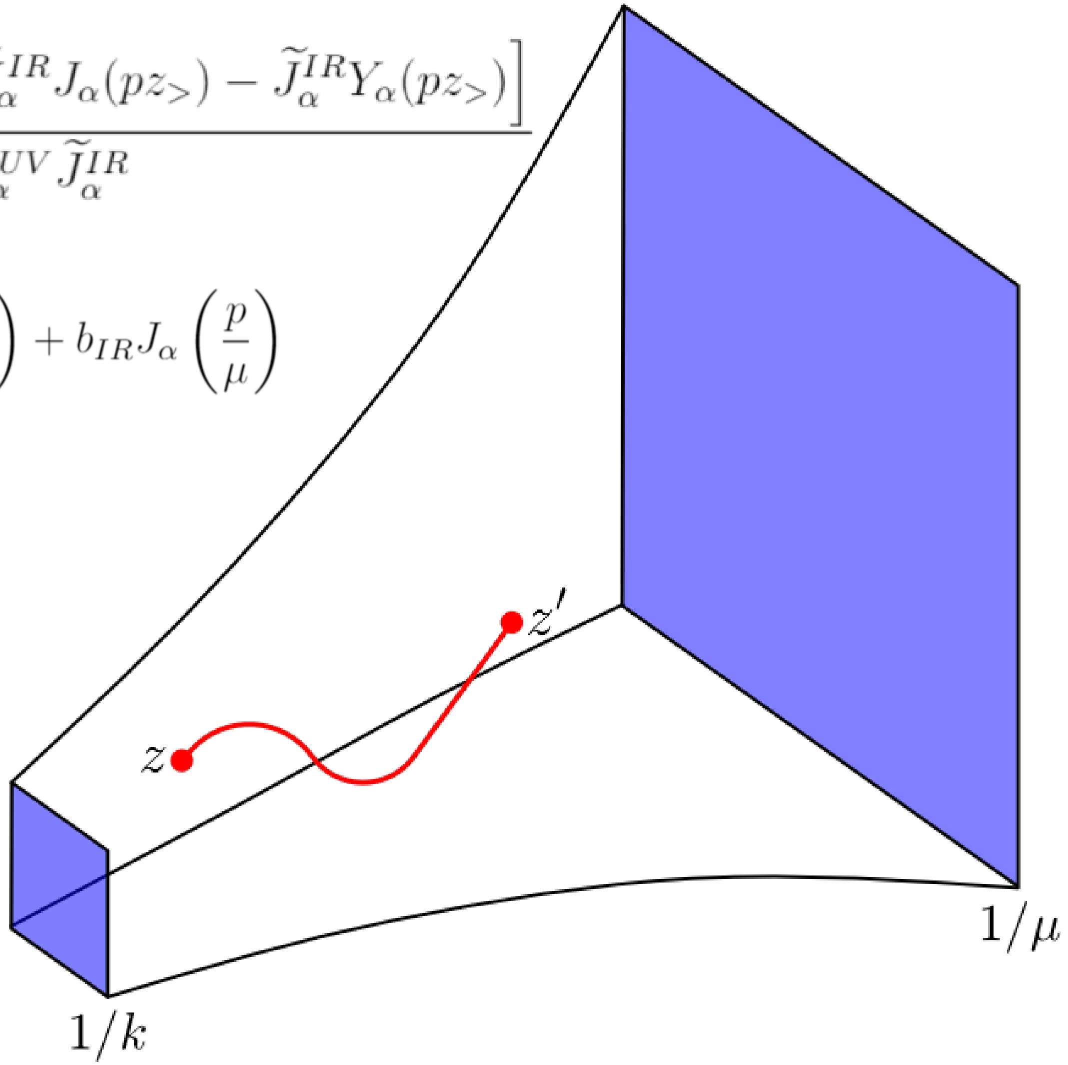
KK profiles

$$G_p(z,z') = i\sum_{n=0}^{\infty}\frac{f_n(z)f_n(z')}{p^2 - m_n^2}$$



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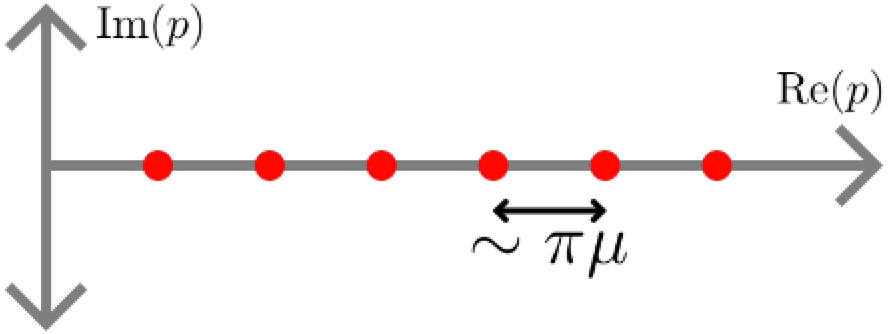
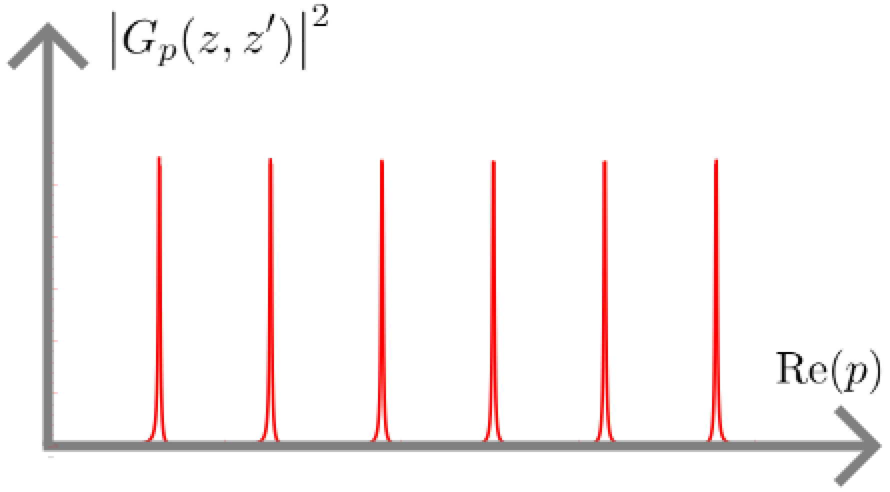
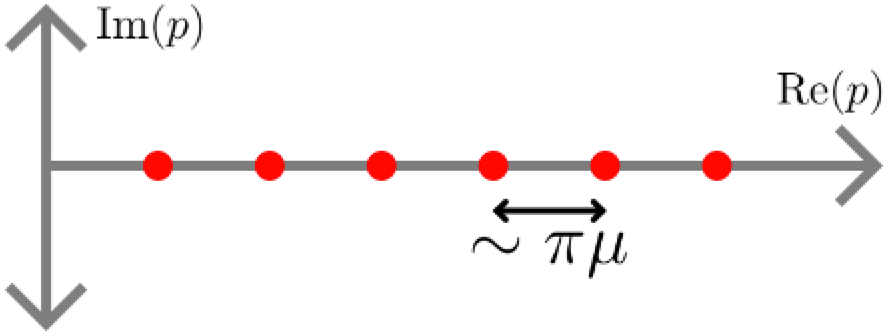
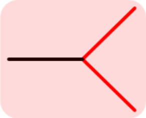


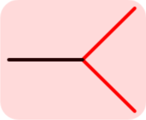
5D Propagator

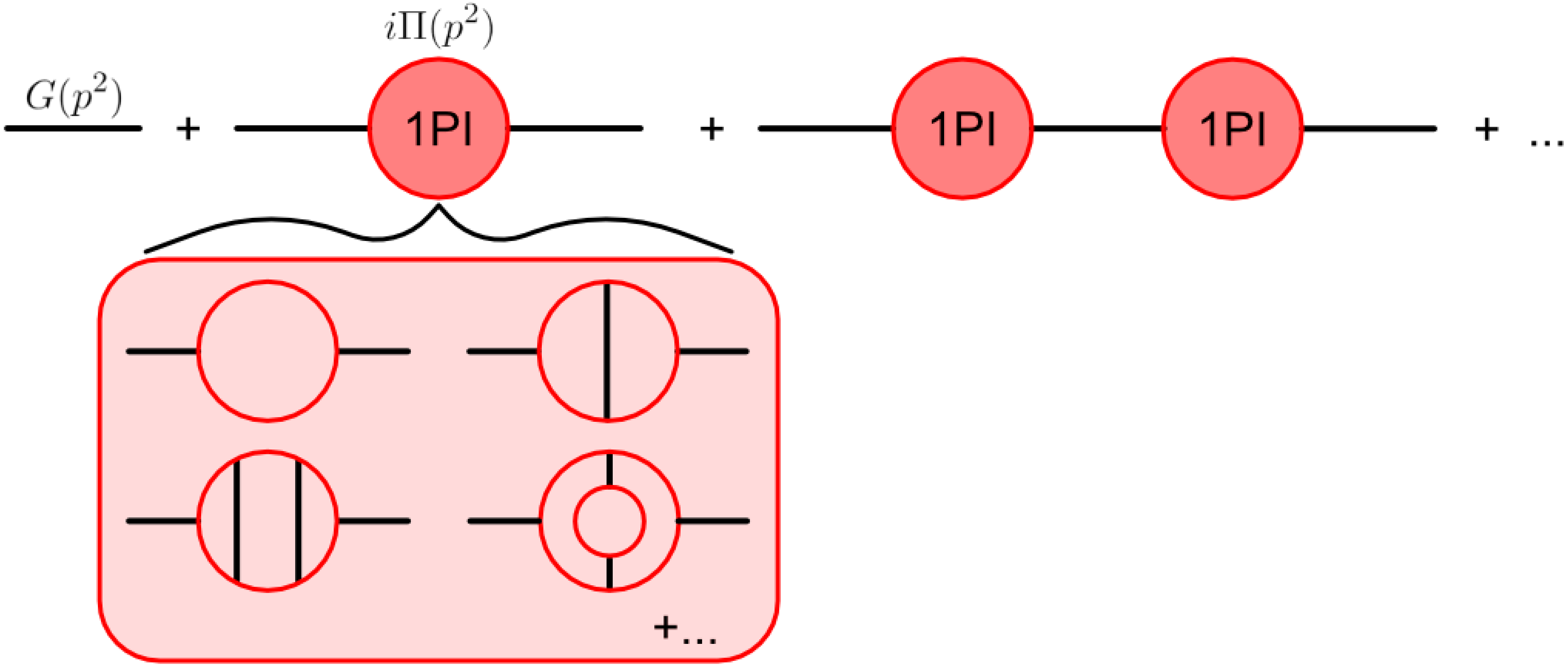


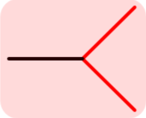
$$G_p(z,z') = i\sum_{n=0}^{\infty}\frac{f_n(z)f_n(z')}{p^2-m_n^2}$$

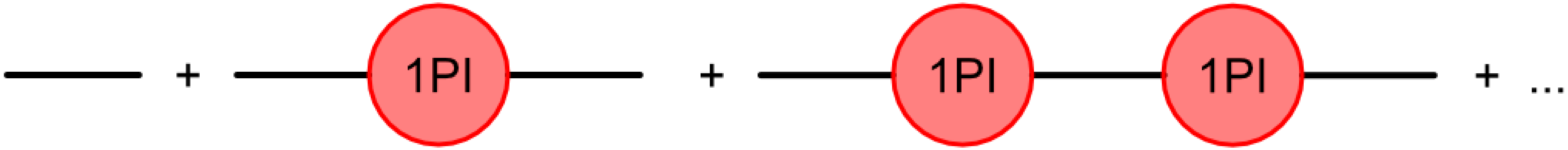


How does  impact particle propagation?

How does  impact particle propagation?



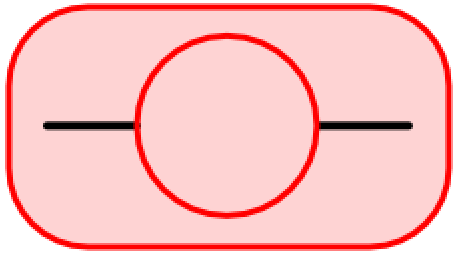
How does  impact particle propagation?



$$G_{\rm dr}(p^2) = G + Gi\Pi G + \cdots = \frac{i}{iG^{-1} + \Pi}$$

$$G_{\rm dr}(p^2) = \frac{i}{p^2 - m_1^2 + \Pi(p^2)}$$

Resummed Propagator



$$G_p(z,z') = i\sum_{n=0}^{\infty}\frac{f_n(z)f_n(z')}{p^2 - m_n^2 + \Pi_n(p^2)}$$

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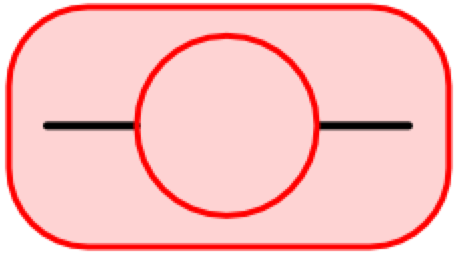

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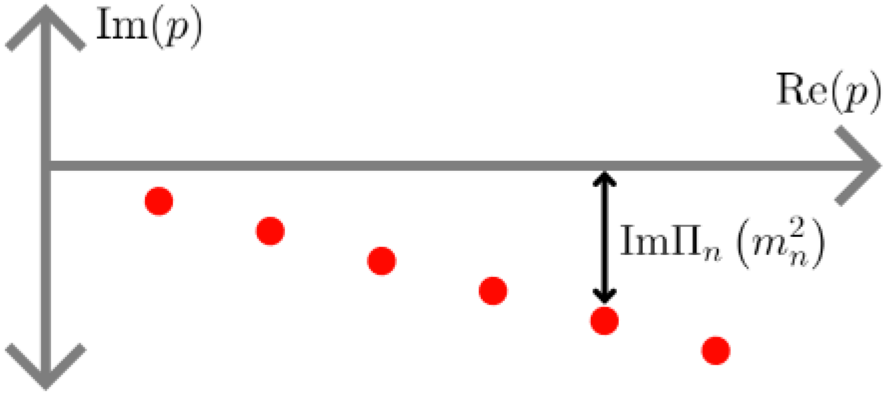

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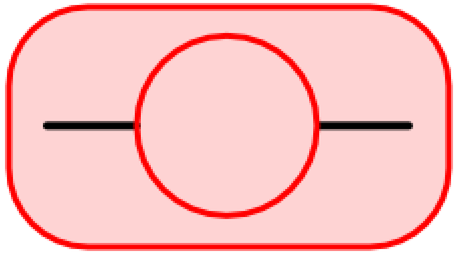

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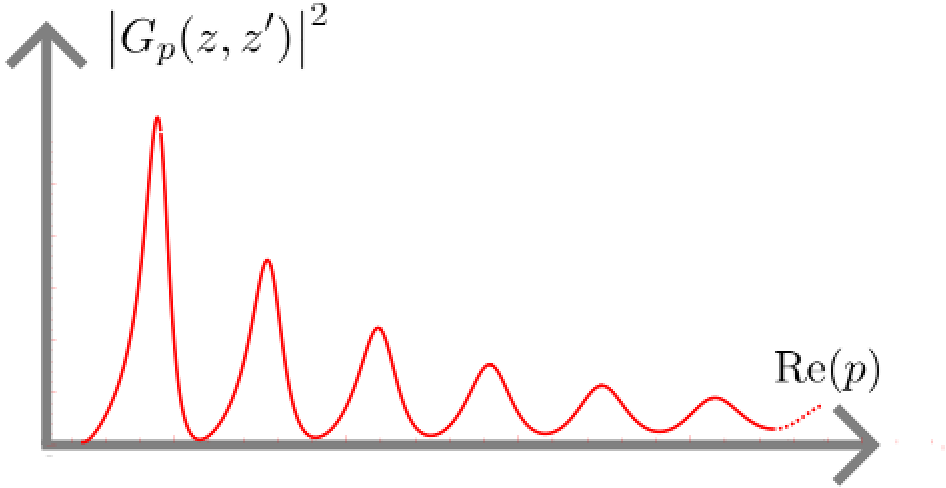

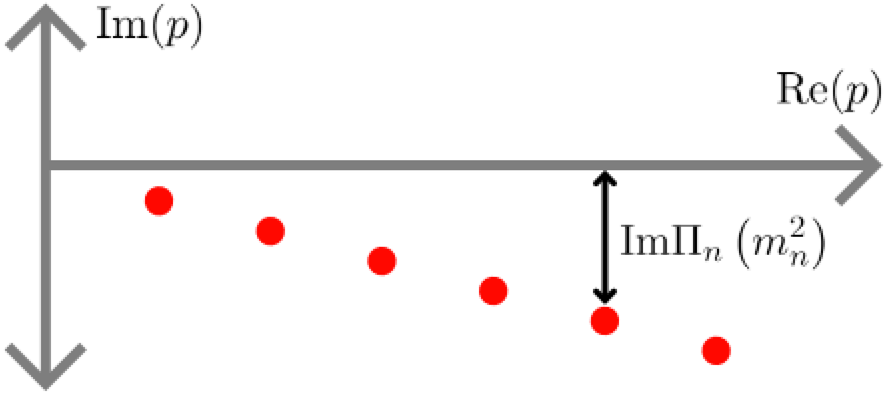

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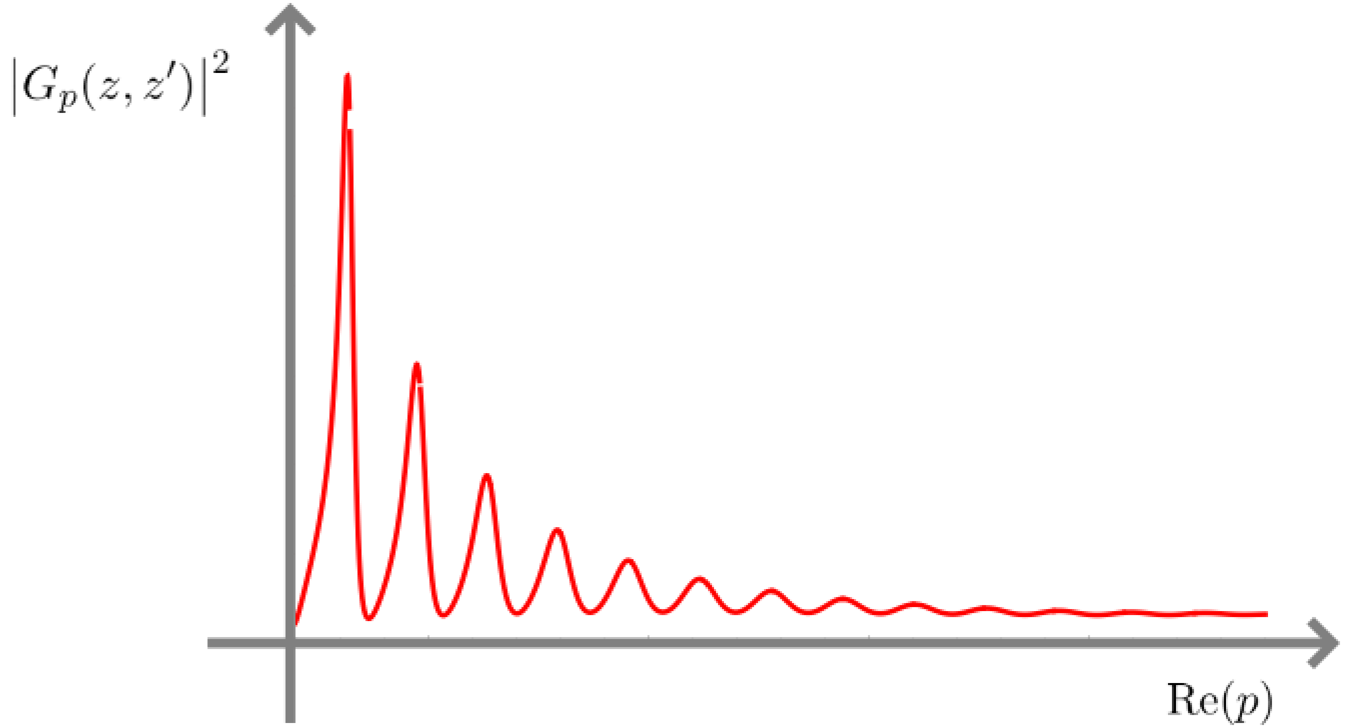

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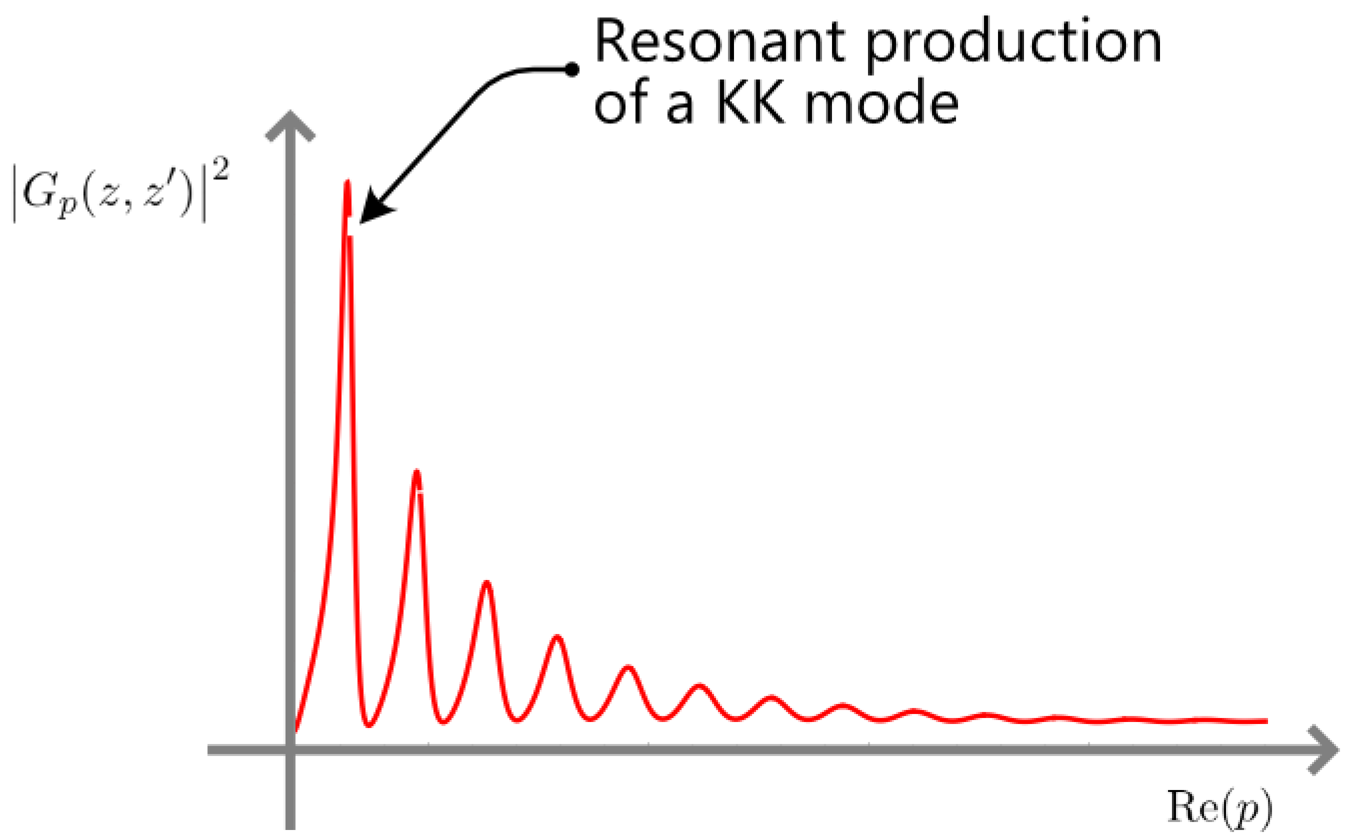

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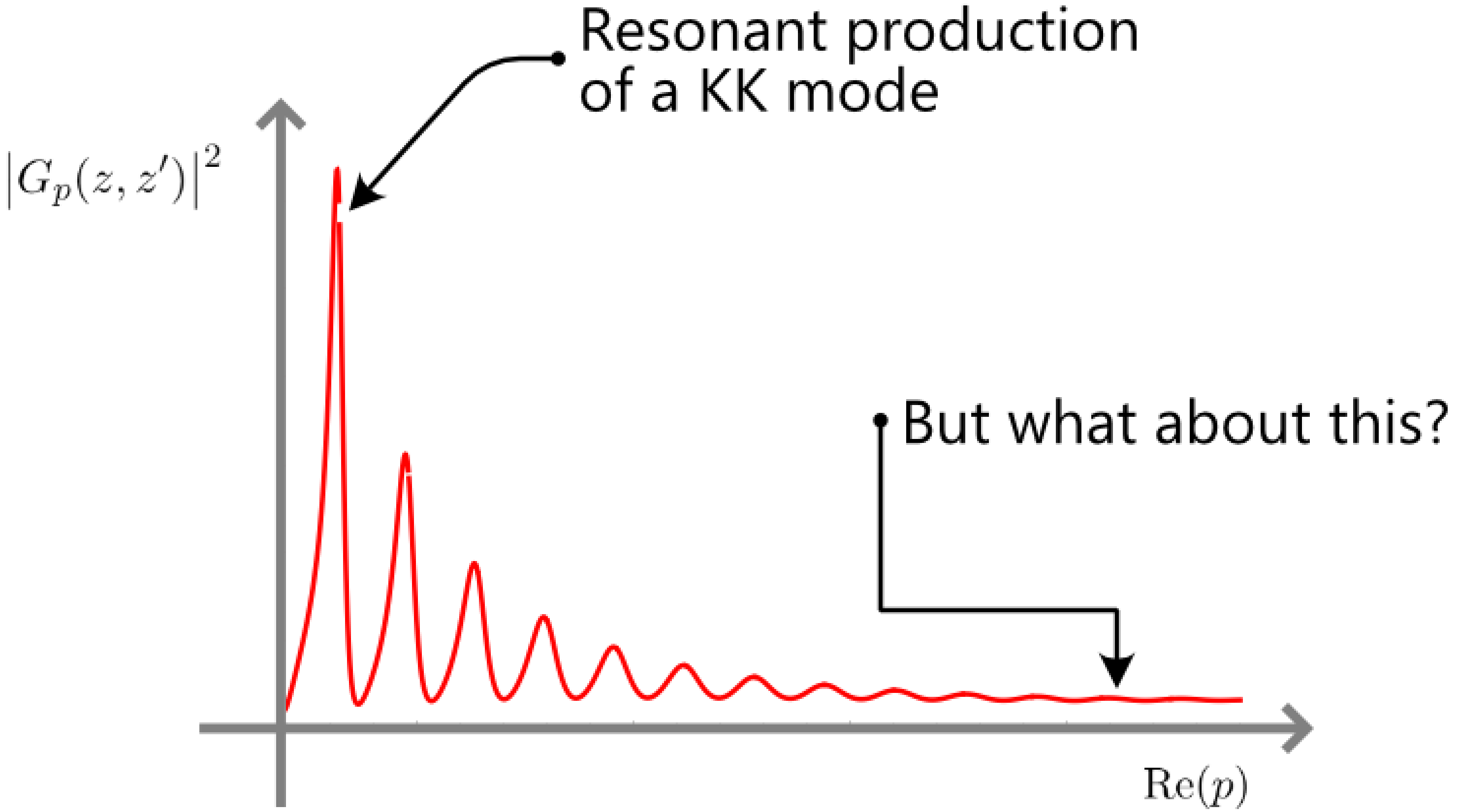
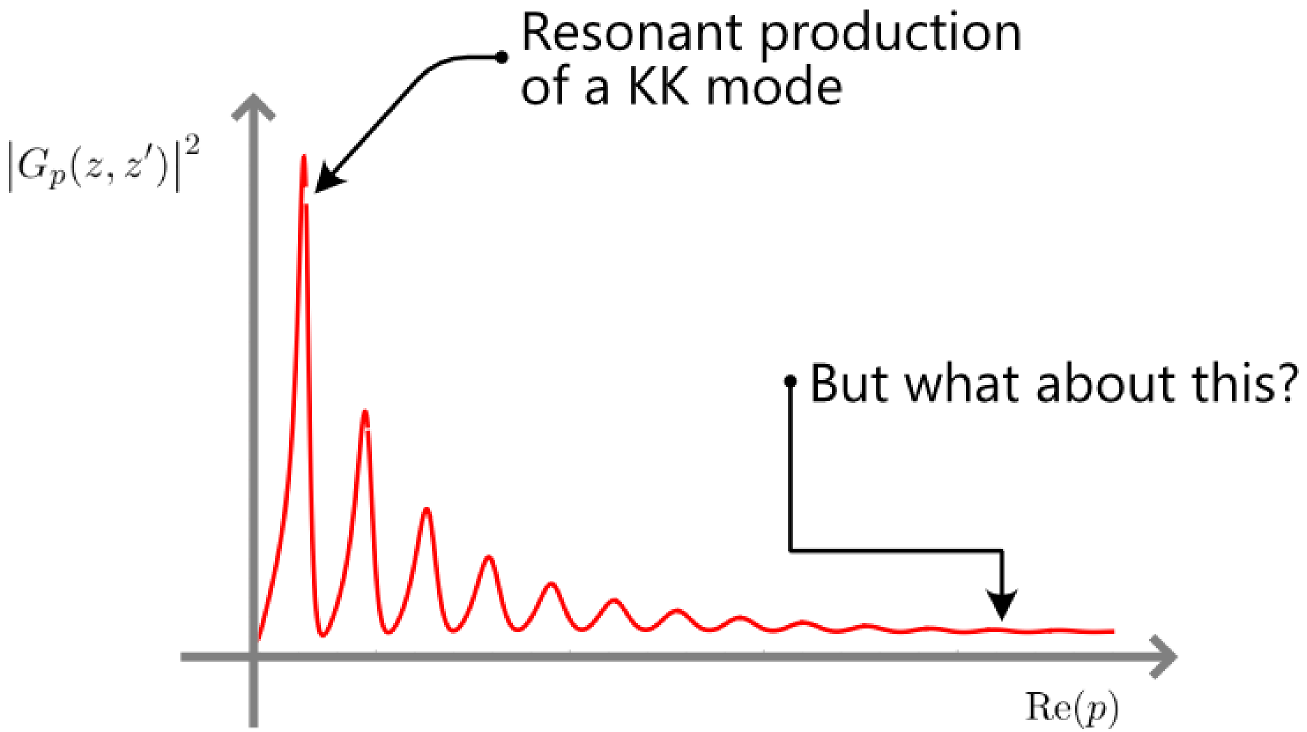


Resummed Propagator

$$G_p(z, z') = i \sum_{n=0}^{\infty} \frac{f_n(z) f_n(z')}{p^2 - m_n^2 + \Pi_n(p^2)}$$



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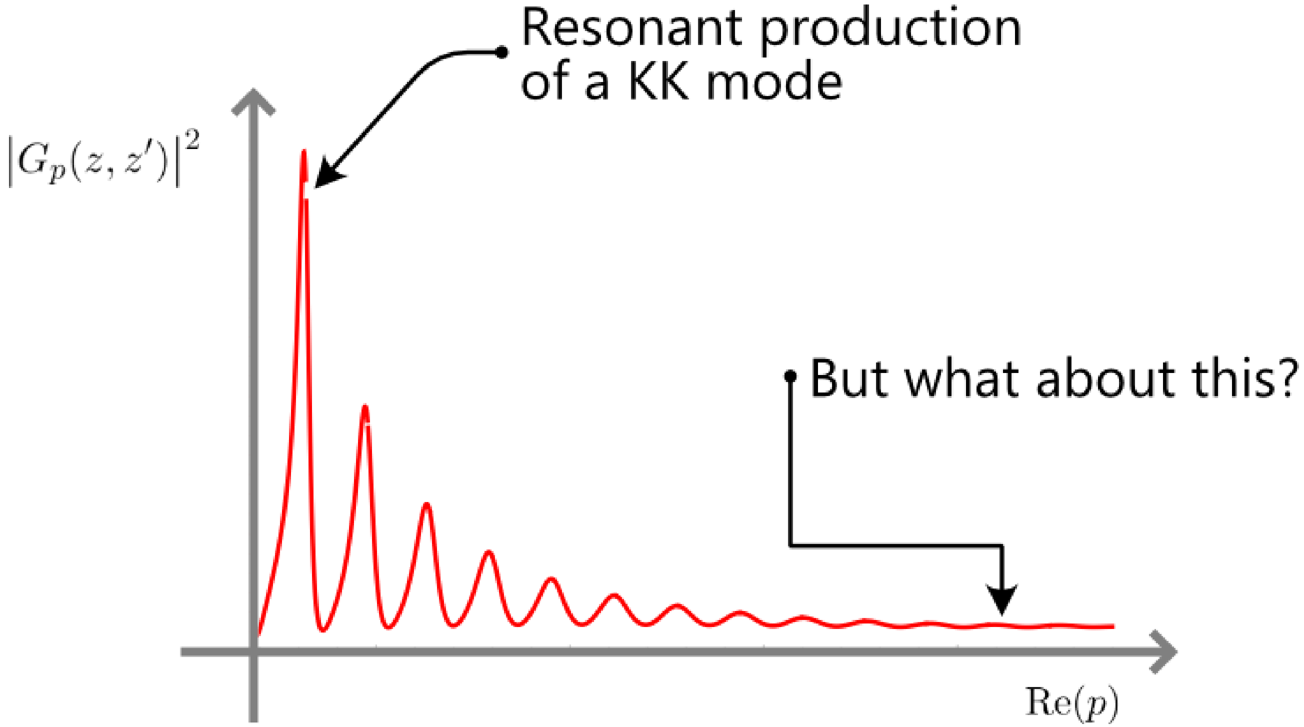

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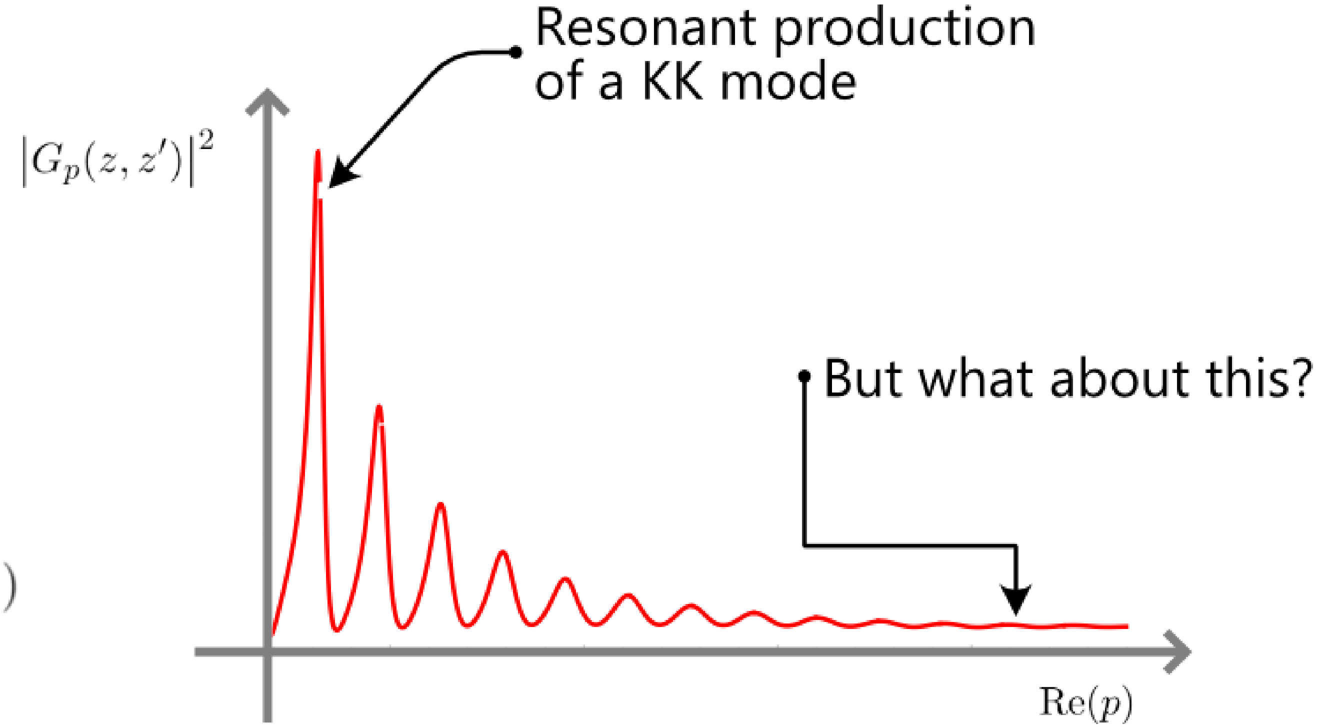
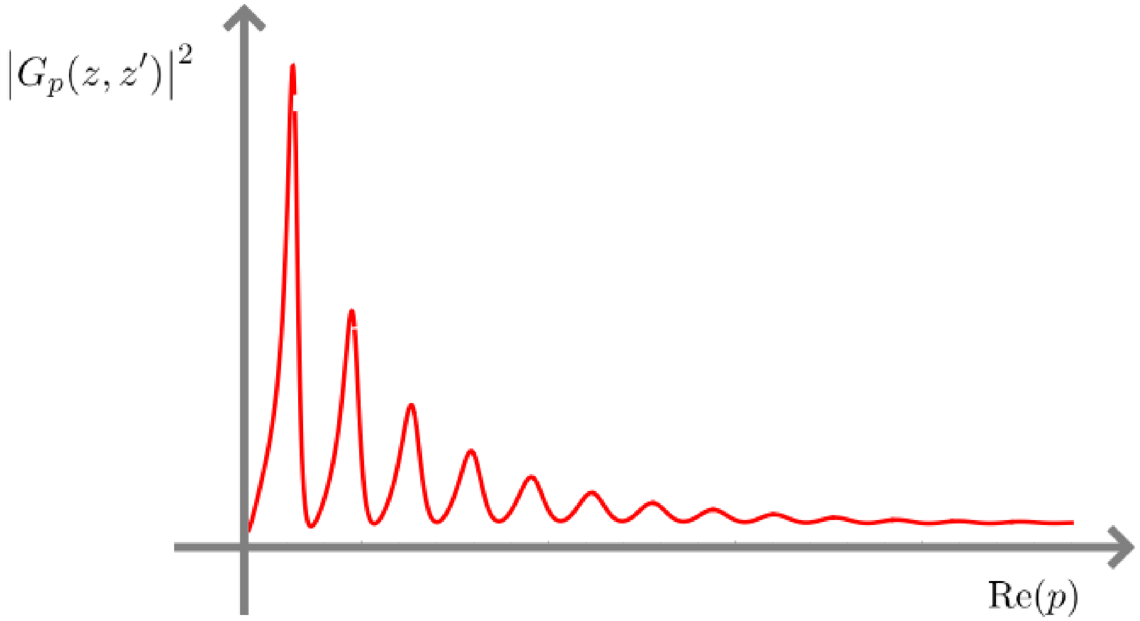
$$G_p(z,z') = i\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} f_m(z)\left(p^2 - m^2 + \Pi\right)^{-1}_{mn} f_n(z')$$



Open Questions

- Is the high energy continuum regime physically realizable?
- By treating heavy KK modes as narrow modes and good asymptotic states, could we miss something?



$$G_p(z,z') = i \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} f_m(z) \left(p^2 - m^2 + \Pi\right)^{-1}_{mn} f_n(z')$$

Outline

Solve equation of motion subject to brane boundary conditions

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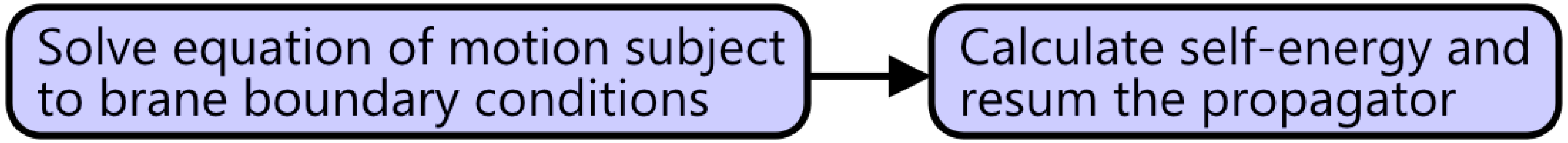
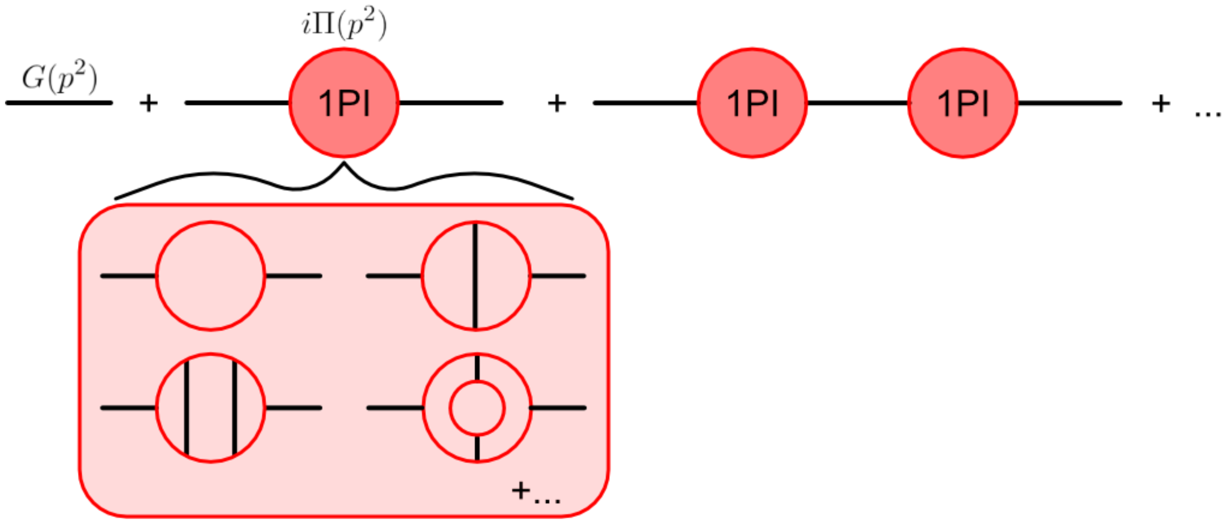
$$G_p(z,z') = i\frac{\pi k^3 (zz')^2}{2}\frac{\left[\widetilde{Y}_\alpha^{UV} J_\alpha(pz_<) - \widetilde{J}_\alpha^{UV} Y_\alpha(pz_<)\right]\left[\widetilde{Y}_\alpha^{IR} J_\alpha(pz_>) - \widetilde{J}_\alpha^{IR} Y_\alpha(pz_>)\right]}{\widetilde{J}_\alpha^{UV}\widetilde{Y}_\alpha^{IR} - \widetilde{Y}_\alpha^{UV}\widetilde{J}_\alpha^{IR}}$$

Outline

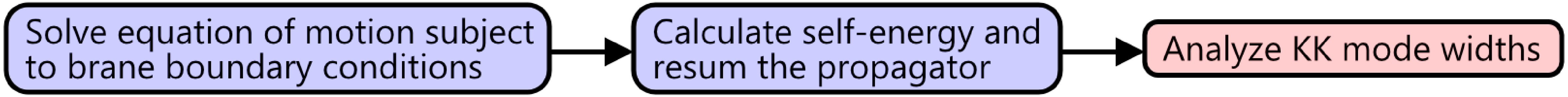

Solve equation of motion subject to brane boundary conditions
Calculate self-energy and resum the propagator

Outline

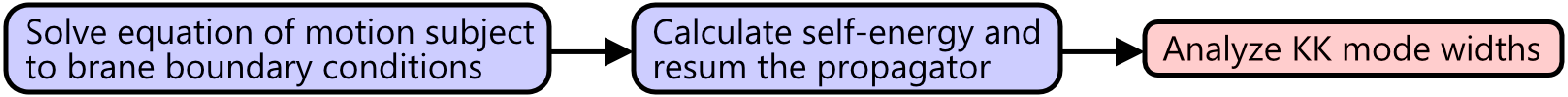
Solve equation of motion subject to brane boundary conditions → Calculate self-energy and resum the propagator



Outline


Solve equation of motion subject to brane boundary conditions
Calculate self-energy and resum the propagator
Analyze KK mode widths

Outline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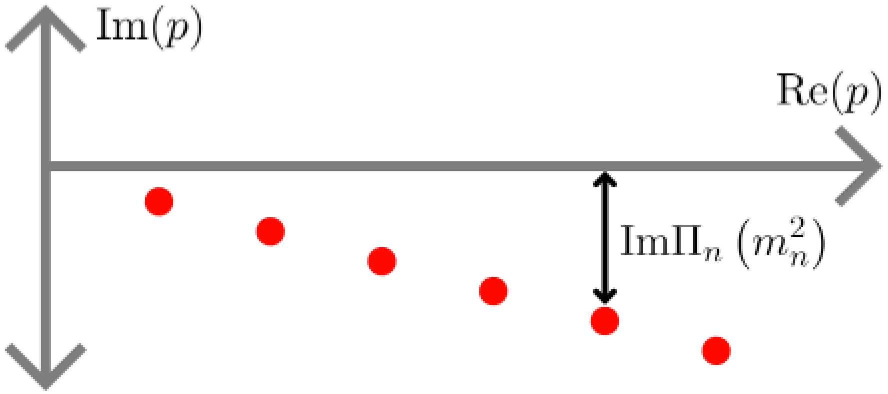
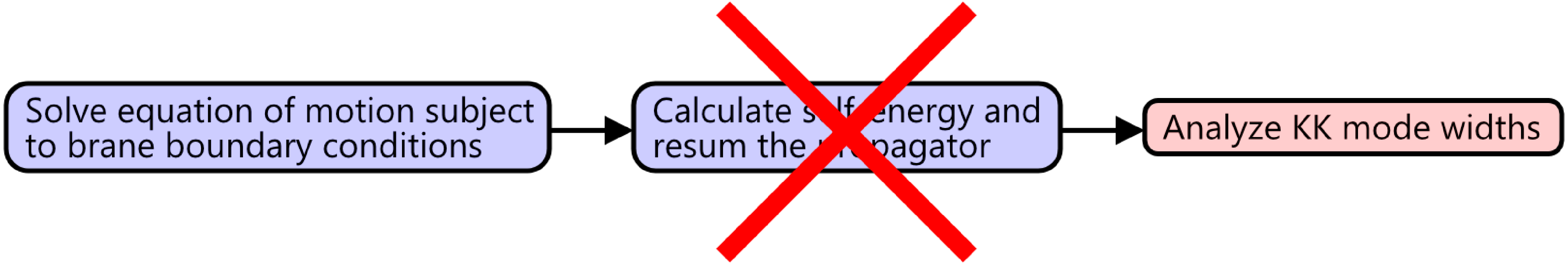
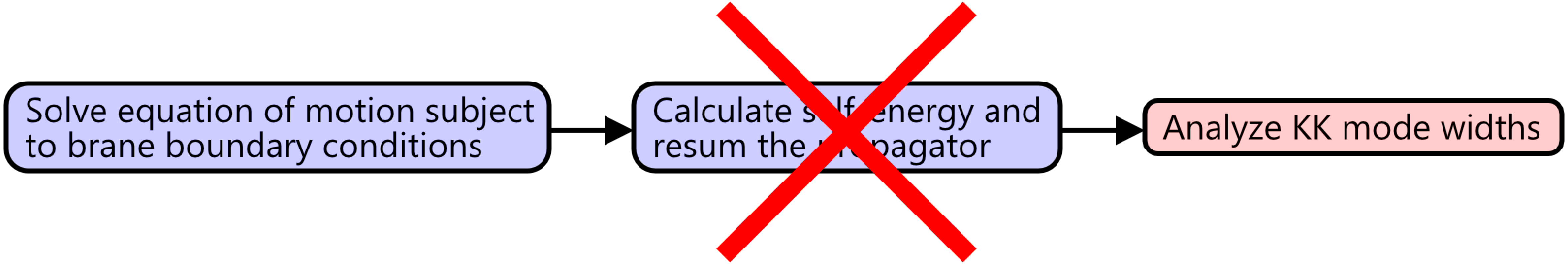

$\mathrm{Im}(p)$
$\mathrm{Re}(p)$
$\mathrm{Im}\Pi_n\left(m_n^2\right)$

Outline


Solve equation of motion subject to brane boundary conditions
Calculate s lf energy and resum the pagator
Analyze KK mode widths

Outline



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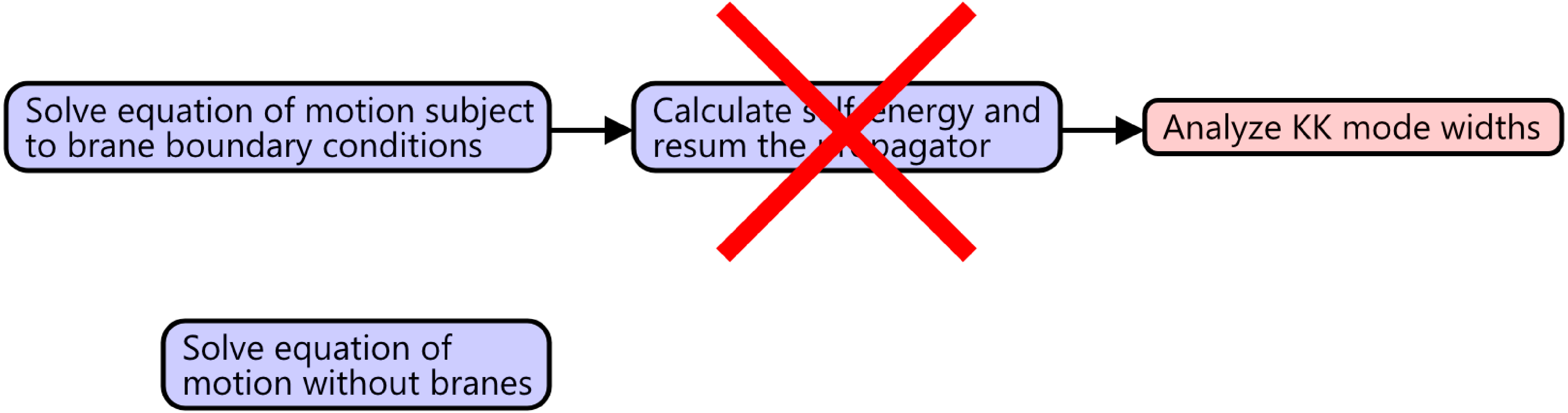
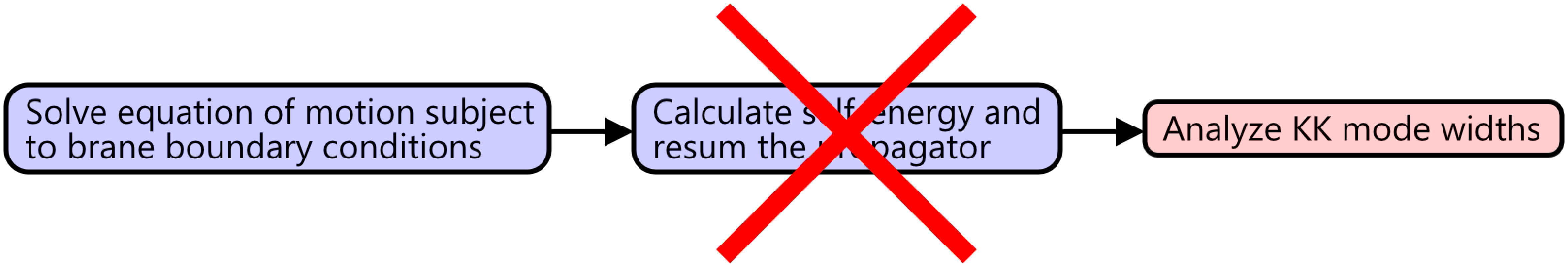
Outline


Solve equation of motion subject to brane boundary conditions
Calculate s lf energy and resum the pagator
Analyze KK mode widths
Solve equation of motion without branes

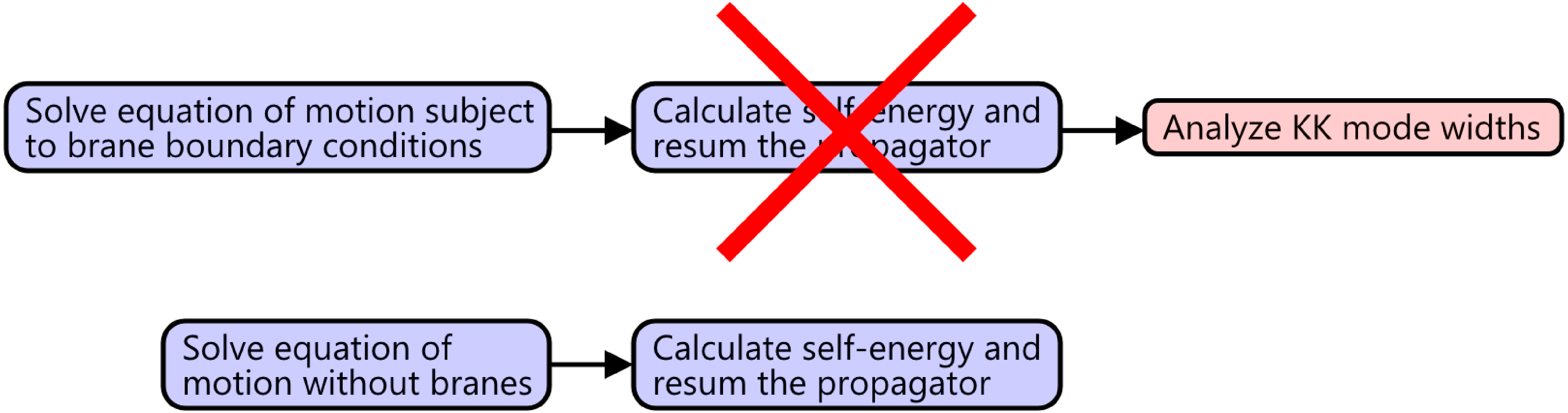
Outline



Solve equation of motion without branes

$$G_p(z, z') = \frac{\pi}{2k}(kz)^2(kz')^2 J_\alpha(pz_<)H_\alpha^{(1)}(pz_>)$$

Outline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Solve equation of motion without branes
Calculate self-energy and resum the propagator

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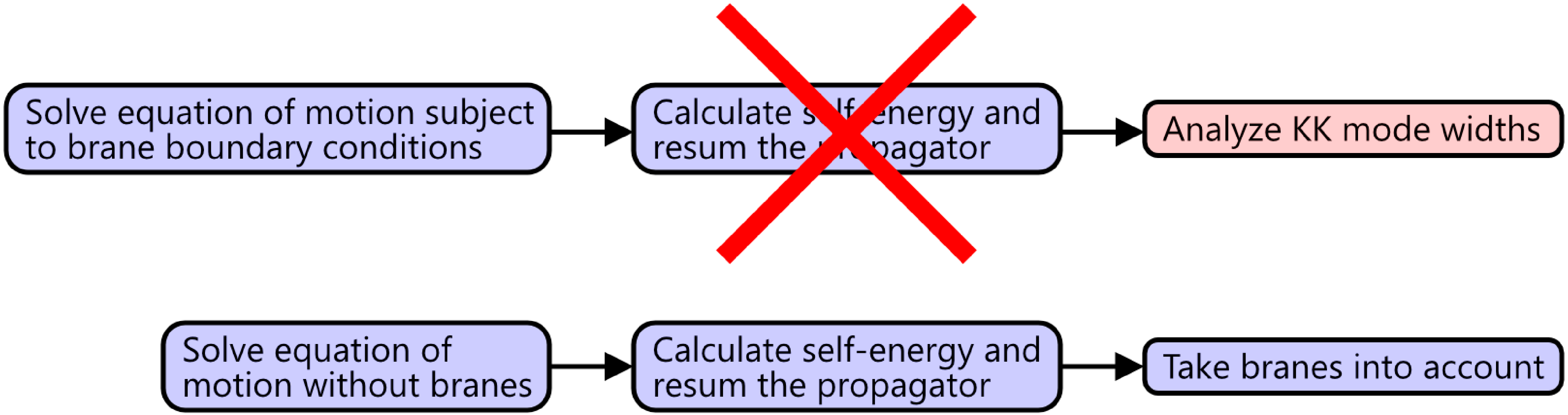
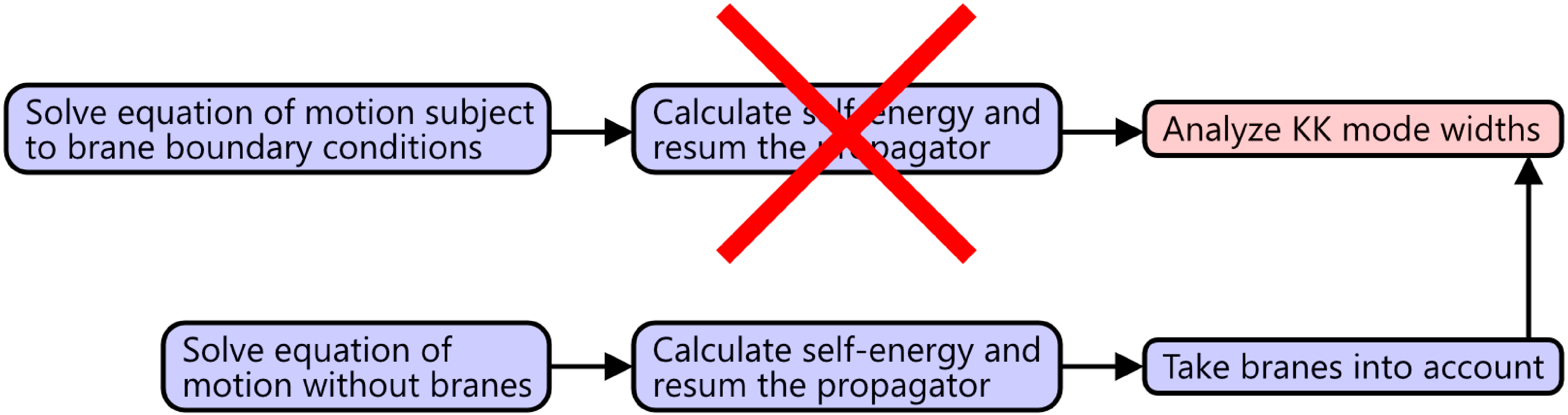


Solve equation of motion subject to brane boundary conditions
Calculate s lf energy and resum the pagator
Analyze KK mode widths
Solve equation of motion without branes
Calculate self-energy and resum the propagator
Take branes into account

Outline



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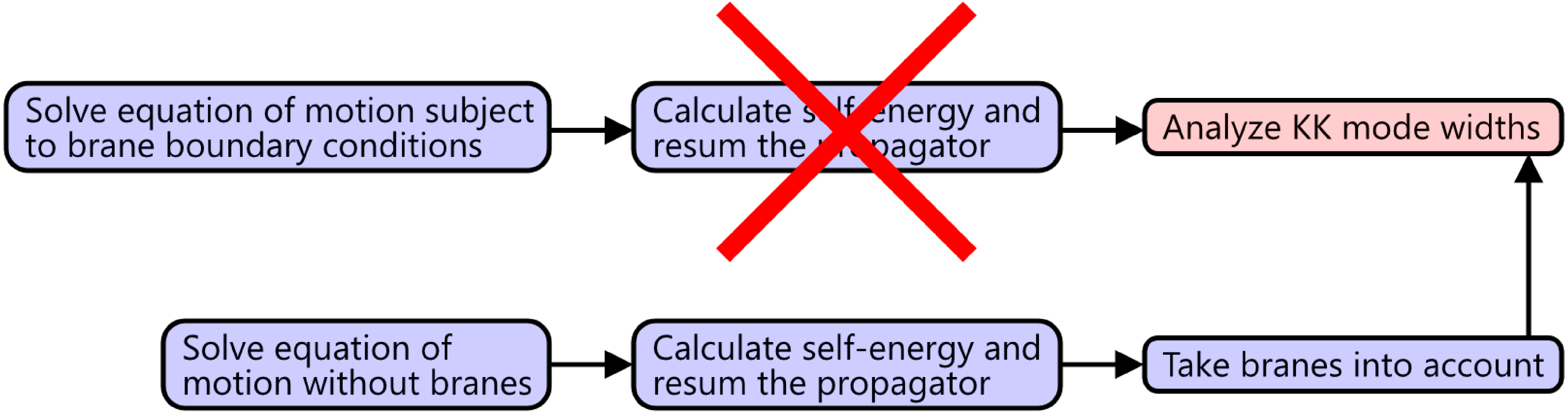

$$G_p(z, z') = \frac{\pi}{2k}(kz)^2(kz')^2 J_\alpha(pz_<)H_\alpha^{(1)}(pz_>)$$

Effective Field Theory in AdS

$$S \supset \int d^5X \sqrt{|\gamma|} \left(\lambda \Phi \Phi_1 \Phi_2 - \zeta \Phi \partial_M \Phi_1 \partial^M \Phi_2 + \ldots \right)$$

Effective Field Theory in AdS

$$S \supset \int d^5X \sqrt{|\gamma|} \left(\lambda \Phi \Phi_1 \Phi_2 - \zeta \Phi \partial_M \Phi_1 \partial^M \Phi_2 + \ldots\right)$$

metric factor

Effective Field Theory in AdS

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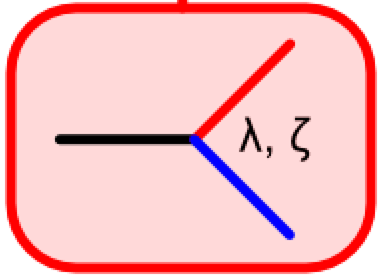
metric factor



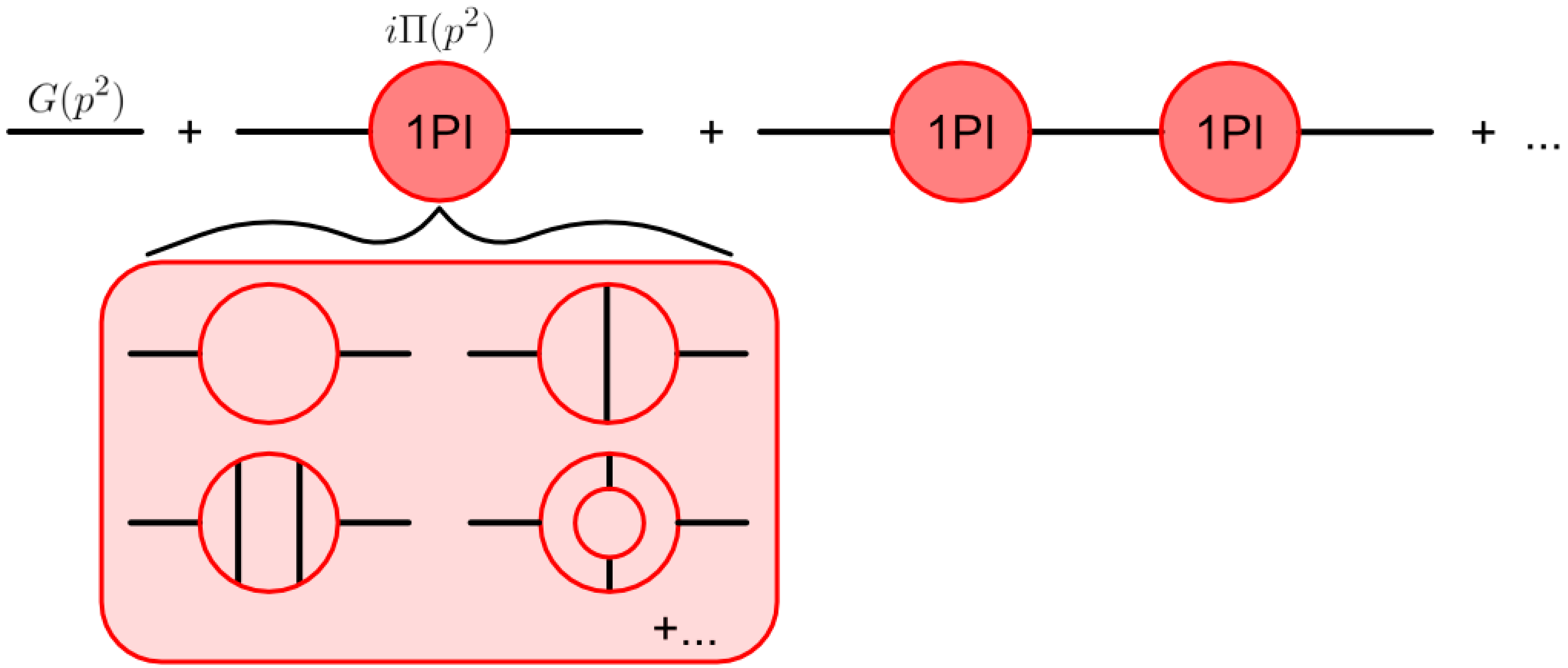
Effective Field Theory in AdS

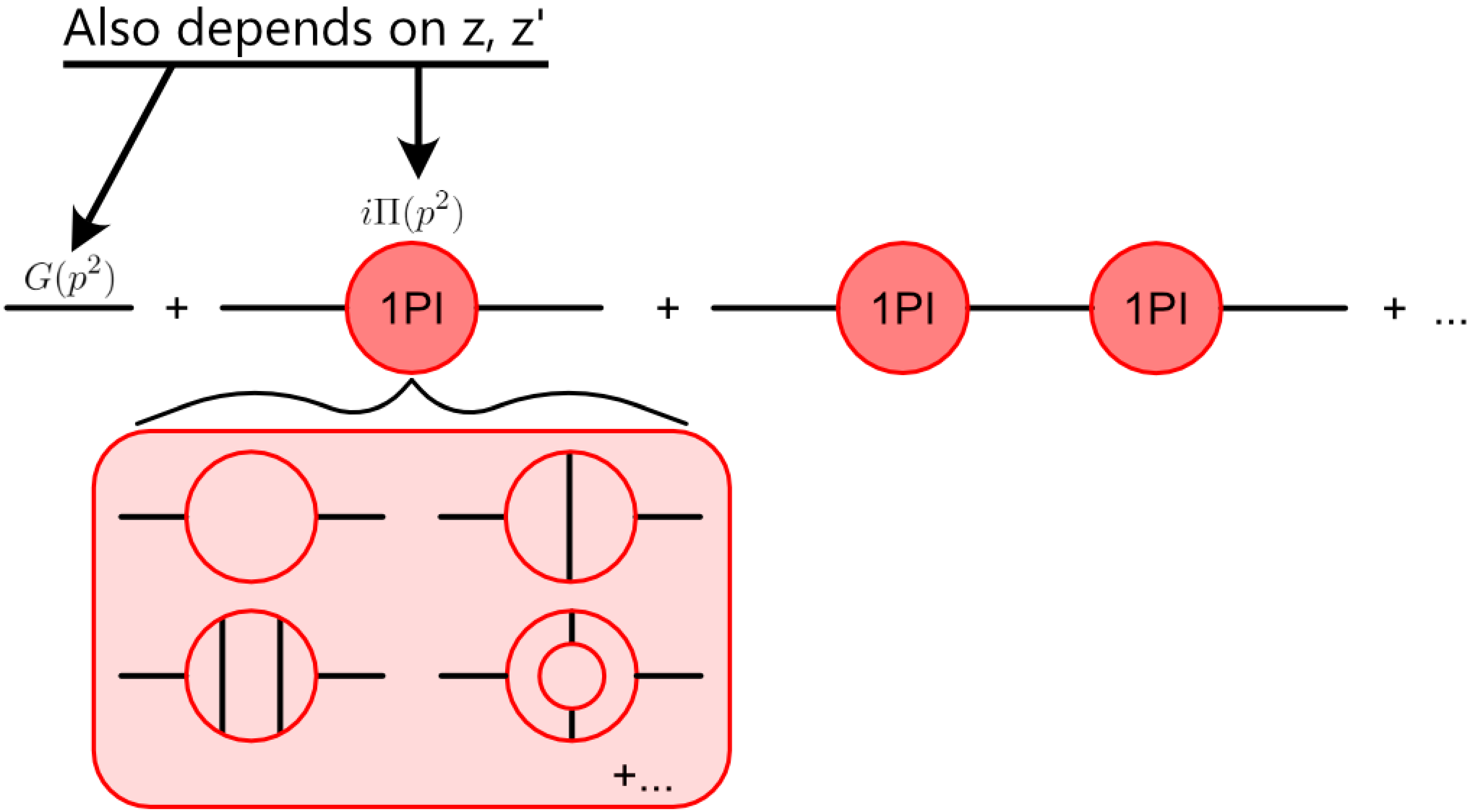
$$S \supset \int d^5X \sqrt{|\gamma|} \left(\lambda \Phi \Phi_1 \Phi_2 - \zeta \Phi \partial_M \Phi_1 \partial^M \Phi_2 + \ldots \right)$$

metric factor

$$\lambda \sim \sqrt{24\pi^3 \Lambda} \qquad \zeta \sim \sqrt{\frac{24\pi^3}{\Lambda^3}}$$

For details on "naïve" dimensional analysis, see hep-ph/9909248 by Chacko, Luty, and Ponton. Also, see the Ponton TASI lectures.


$i\Pi(p^2)$
$G(p^2)$
+
1PI
+
1PI
1PI
+ ...
+...


Also depends on z, z'
$i\Pi(p^2)$
$G(p^2)$
+
1PI
+
1PI
1PI
+ ...
+...

Better way: Schwinger-Dyson equation for the 2-point function

$$\mathcal{D}_X G_{\mathrm{dr}}(X,X') - \int d^4Y\, \Pi(X,Y) G_{\mathrm{dr}}(Y,X') = -i\delta^4(X-X')$$

Schwinger-Dyson equation for the 2-point function

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$\partial_X^2 + m^2$

Schwinger-Dyson equation for the 2-point function

$$\mathcal{D}_X G_{\rm dr}(X,X') - \int d^4Y\,\Pi(X,Y)G_{\rm dr}(Y,X') = -i\delta^4(X-X')$$

$$\partial_X^2 + m^2$$

$$G_{\rm dr}(X,X') = G_0(X,X') + G_1(X,X') + \ldots$$

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Regroup terms

$$\mathcal{D}_X G_0(X,X') = -i\delta^4(X-X')$$

$$\mathcal{D}_X G_1(X,X') = \int d^4Y\, \Pi(X,Y) G_0(Y,X')$$

Schwinger-Dyson equation for the 2-point function

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$$\mathcal{D}_X G_0(X,X') = -i\delta^4(X-X') \quad \xrightarrow[\text{Transform}]{\text{Fourier}} \quad \mathcal{D}G_0 \sim -i$$

$$\mathcal{D}_X G_1(X,X') = \int d^4Y\, \Pi(X,Y) G_0(Y,X') \quad \xrightarrow[\text{Transform}]{\text{Fourier}} \quad \mathcal{D}G_1 \sim \Pi G_0$$

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$$(iG_0\mathcal{D})\, G_1 \sim G_1 \sim G_0 i\Pi G_0$$

2-point Schwinger-Dyson equation in AdS_5

$$\sqrt{|\gamma|}\mathcal{D}_{p;z}G(p^2;z,z') - \int du\,\Pi(p^2;z,u)G(p^2;u,z') = -i\delta(z-z')$$

2-point Schwinger-Dyson equation in AdS_5

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$$\Big\downarrow \; pz_> \gg \left|\alpha^2 - \tfrac{1}{4}\right|$$

$$G_{\rm dr}(p^2;z,z')\Big|_{pz_> \gg \left|\alpha^2-\frac{1}{4}\right|} \propto e^{ipz_> - S(z_>)}$$

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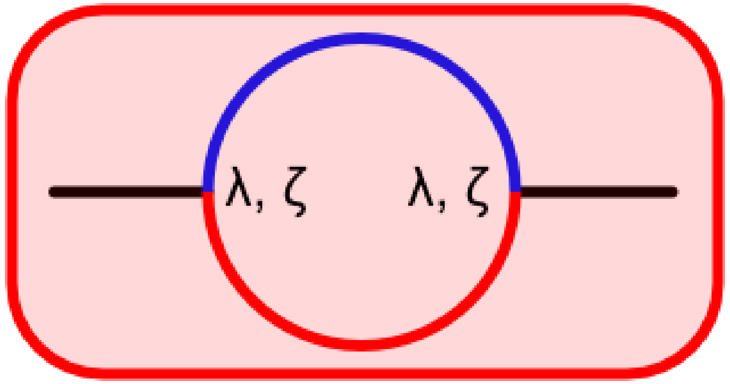
$$G_{\rm dr}(p^2;z,z')\Big|_{pz_> \gg \left|\alpha^2-\frac{1}{4}\right|} \propto e^{ipz_> - S(z_>)}$$

If we know the function S(z), then we know the resummed propagator!

WKB Analysis

$$G_{\rm dr} \sim e^{-S(z_>)}$$



WKB Analysis

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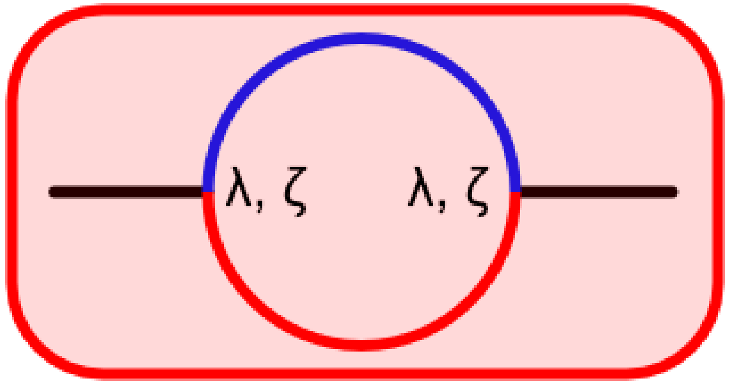


$$S_{\lambda\lambda}(z) \approx 3 \cdot 10^{-5}\, \frac{\lambda^2}{k} \log{(pz)}$$ Renormalizable Interaction

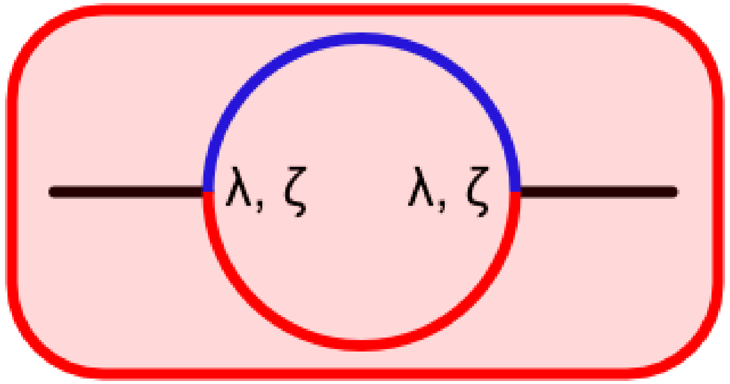
$$S_{\lambda\zeta}(z) \approx 1 \cdot 10^{-5}\, \lambda\zeta k\, (pz)^2$$

$$S_{\zeta\zeta}(z) \approx 5 \cdot 10^{-7}\, \zeta^2 k^3\, (pz)^4$$

Higher Dim. Operators

WKB Analysis

$$G_{\mathrm{dr}} \sim e^{-S(z_>)}$$



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Higher Dim. Operators

$$G_{\mathrm{dr}}\left(p; z, z'\right) \propto e^{ipz_> - C(pz_>)^2}$$

$$C = 10^{-5}\lambda\zeta k$$

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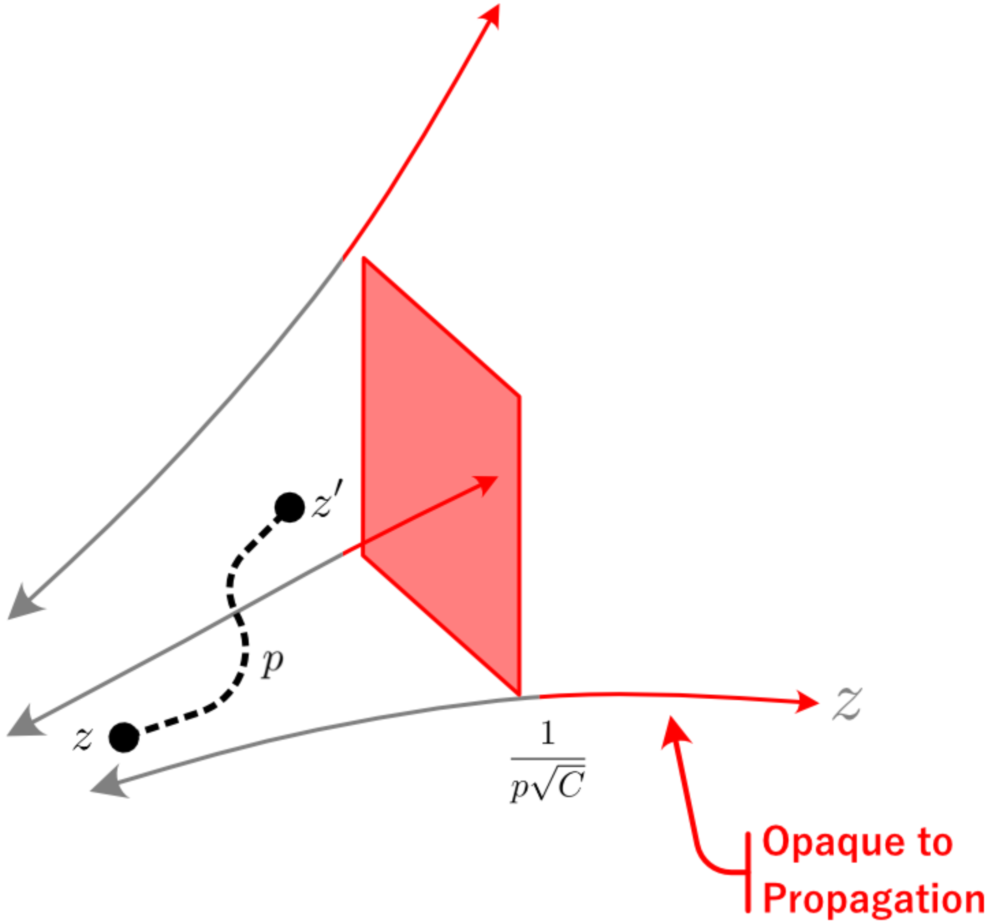

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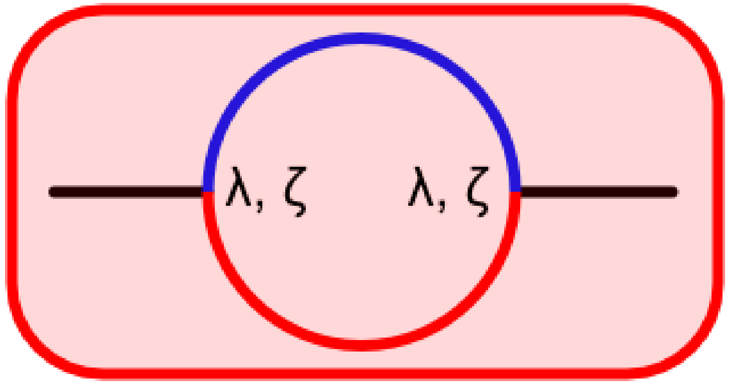

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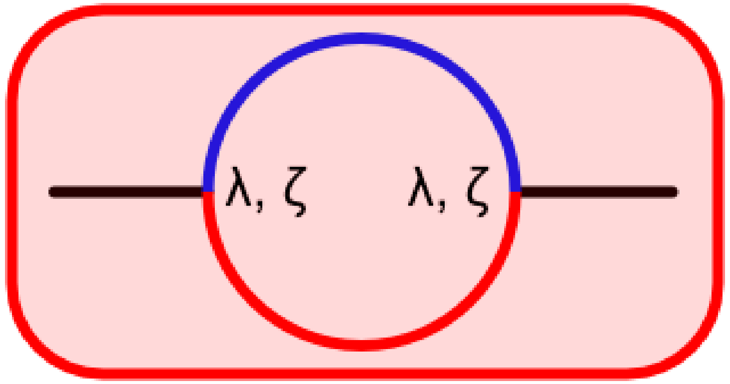

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Higher Dim. Operators → Same order when EFT breaks down

Is $S \sim \mathcal{O}(1)$ possible in the EFT?

$$S_{\lambda\zeta}(z) \approx 7 \cdot 10^{-3}\, \frac{k}{\Lambda}\, (pz)^2$$

$$S_{\zeta\zeta}(z) \approx 4 \cdot 10^{-4}\, \frac{k^3}{\Lambda^3} (pz)^4$$

Is $S \sim \mathcal{O}(1)$ possible in the EFT?

$$S_{\lambda\zeta}(z) \approx 7 \cdot 10^{-3}\,\frac{k}{\Lambda}\,(pz)^2 \xrightarrow{S_{\lambda\zeta} \sim \mathcal{O}(1)} (pz)_{\text{opacity}} \sim 10\sqrt{\frac{\Lambda}{k}}$$

$$S_{\zeta\zeta}(z) \approx 4 \cdot 10^{-4}\,\frac{k^3}{\Lambda^3}\,(pz)^4$$

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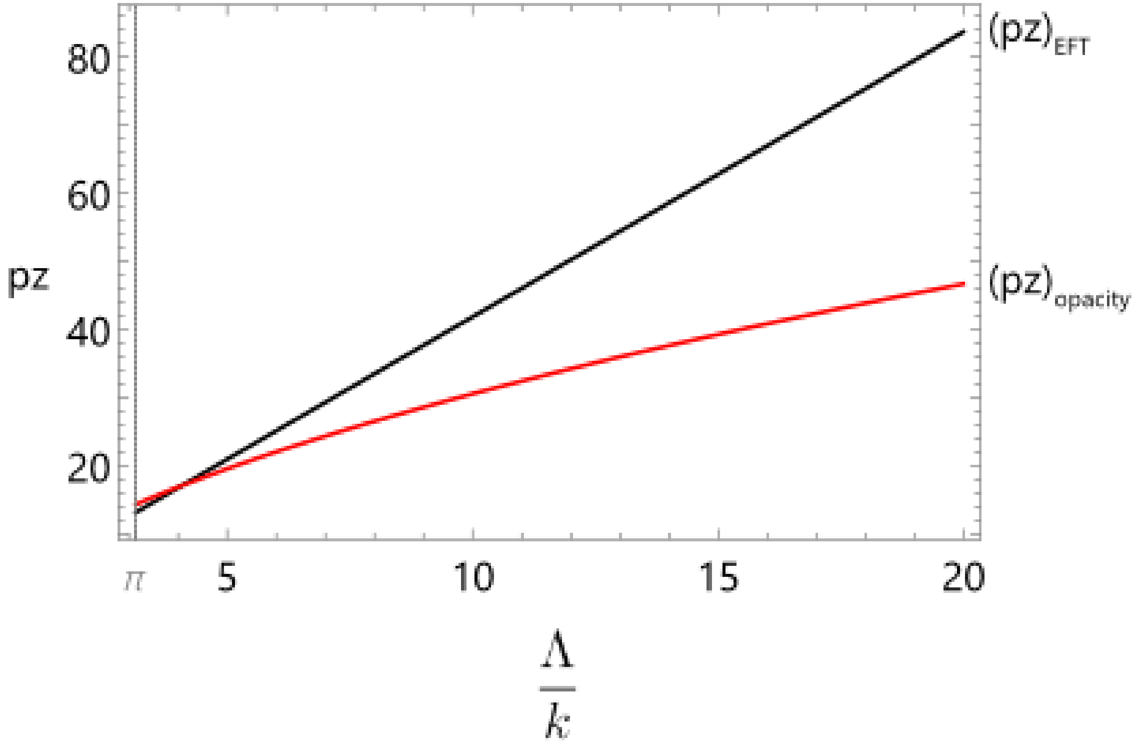
$$S_{\lambda\zeta}(z) \approx 7 \cdot 10^{-3}\,\frac{k}{\Lambda}\,(pz)^2$$

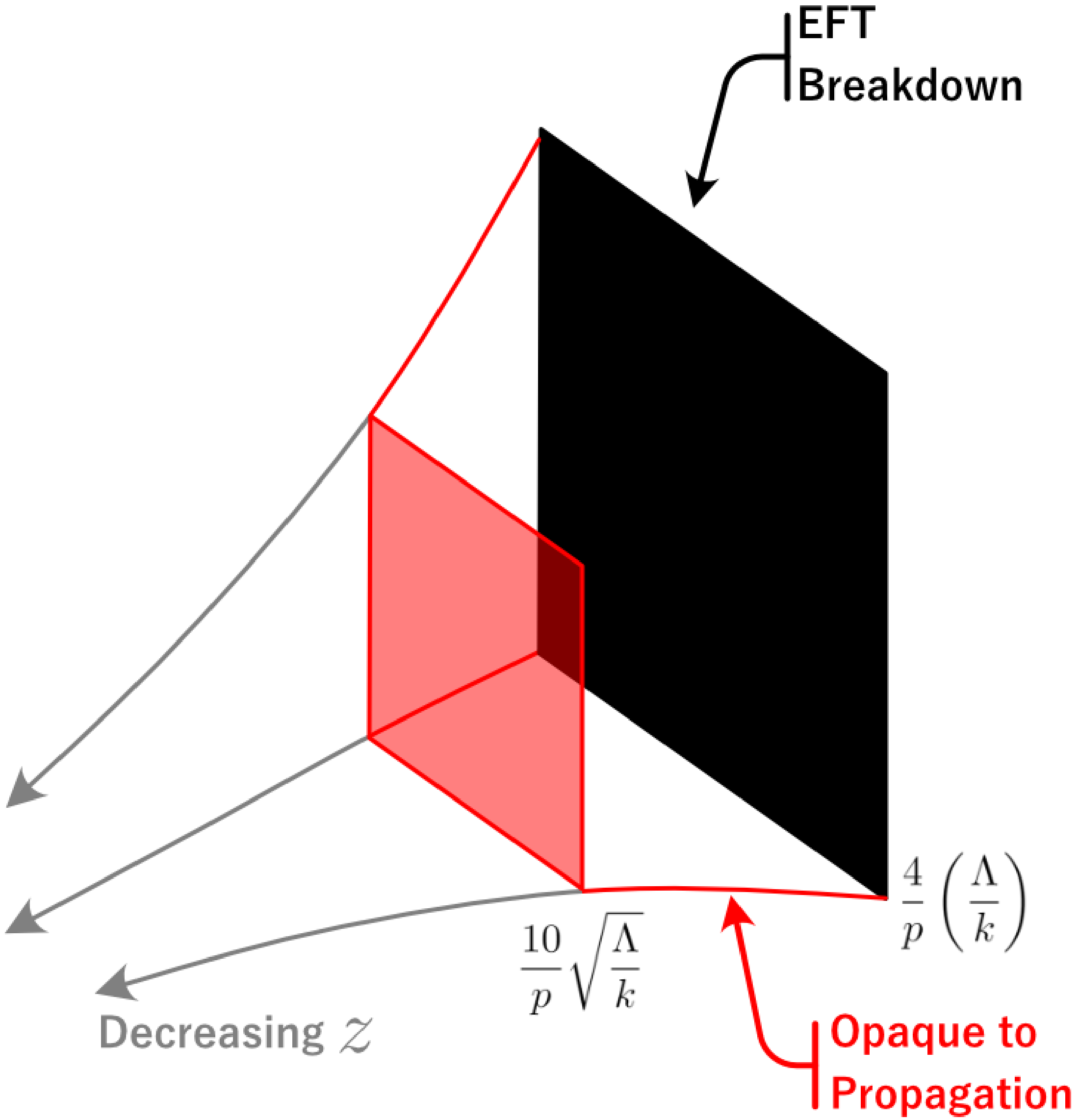
$$S_{\zeta\zeta}(z) \approx 4 \cdot 10^{-4}\,\frac{k^3}{\Lambda^3}\,(pz)^4$$

$$(pz)_{\text{opacity}} \sim 10\sqrt{\frac{\Lambda}{k}}$$

$$S_{\lambda\zeta} \sim S_{\zeta\zeta} \rightarrow (pz)_{\text{EFT}} \sim \frac{4\Lambda}{k}$$

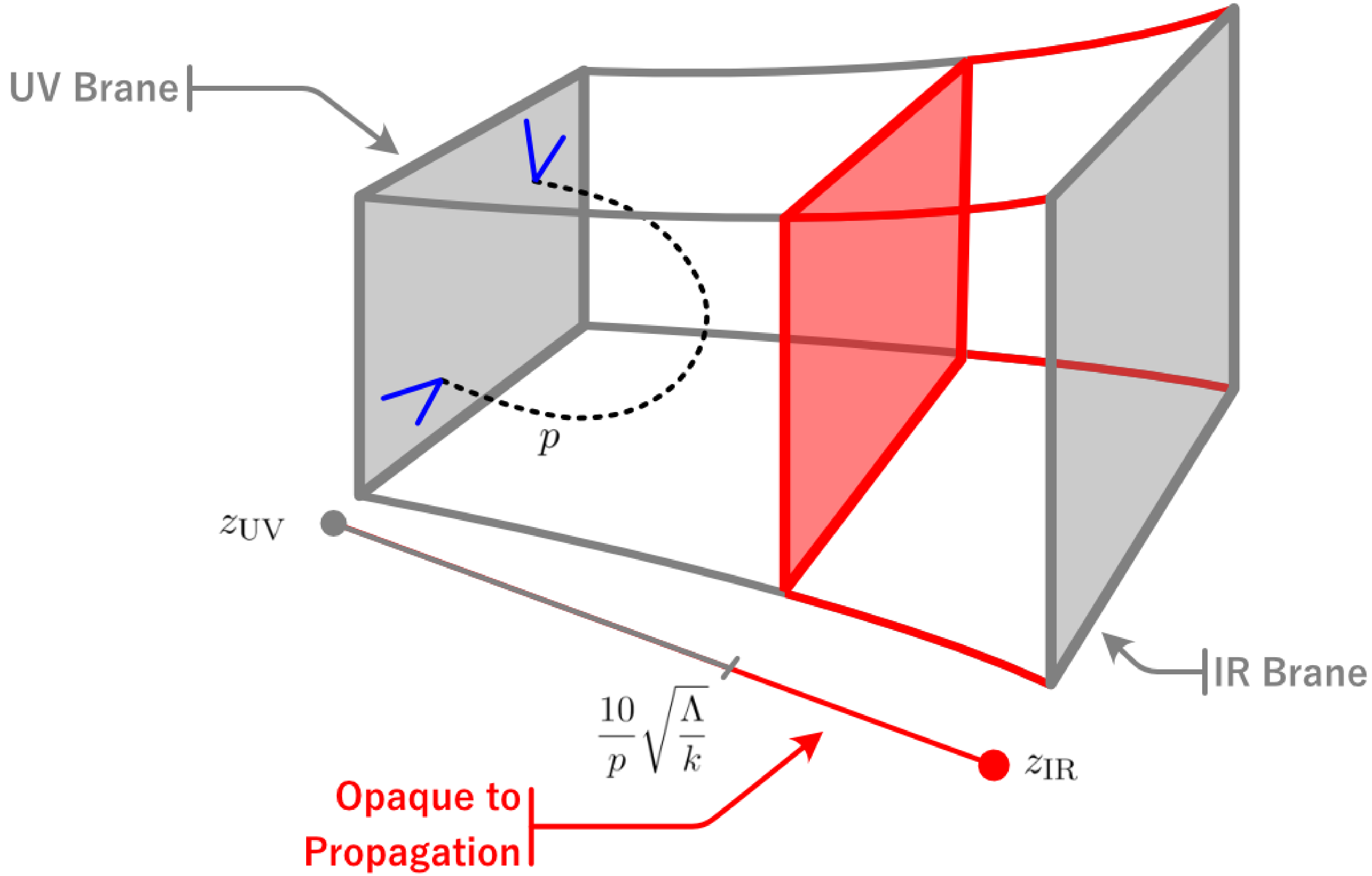
Is $S \sim \mathcal{O}(1)$ possible in the EFT?



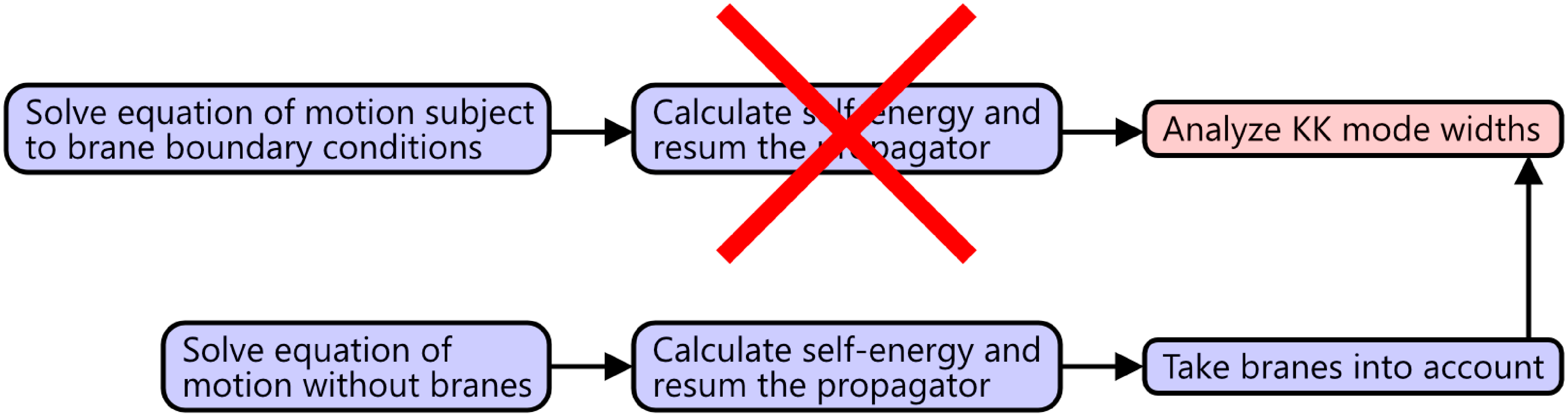


See also hep-th/0012148, where Arkani-Hamed et al. hint at a large z censorship property.

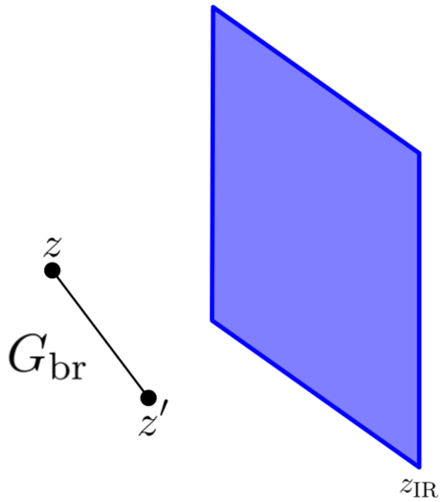
Propagation to the IR brane can be suppressed!



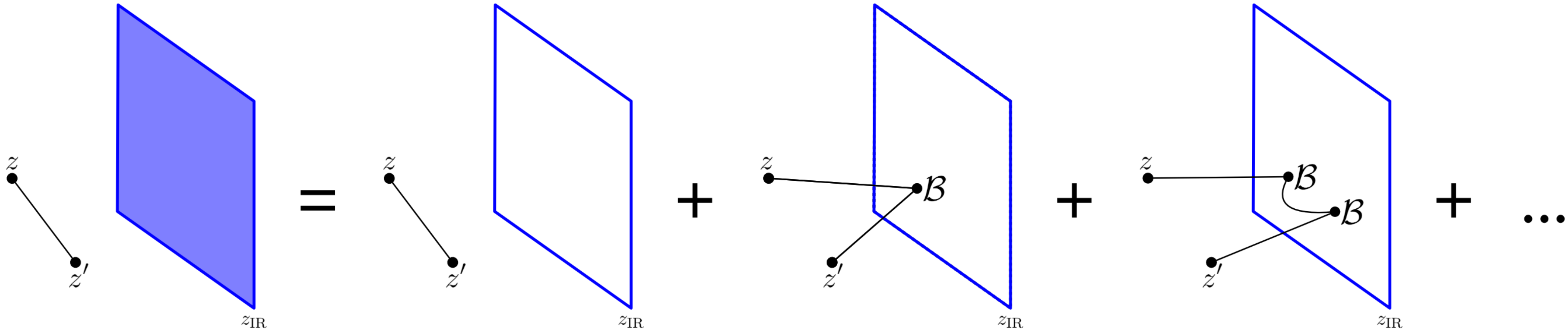
Outline


Solve equation of motion subject to brane boundary conditions
Calculate s lf energy and resum the pagator
Analyze KK mode widths
Solve equation of motion without branes
Calculate self-energy and resum the propagator
Take branes into account

$$\sqrt{\gamma}\mathcal{D}_{p;z}G\left(p^2;z,z'\right) = -i\delta(z-z')$$
$$\mathcal{B}\left(G_{\mathrm{br}}\right)\Big|_{z=z_{\mathrm{IR}}} = 0$$



Details will appear in an upcoming paper
by AC and Sylvain Fichet, 2106.xxxxx :-)



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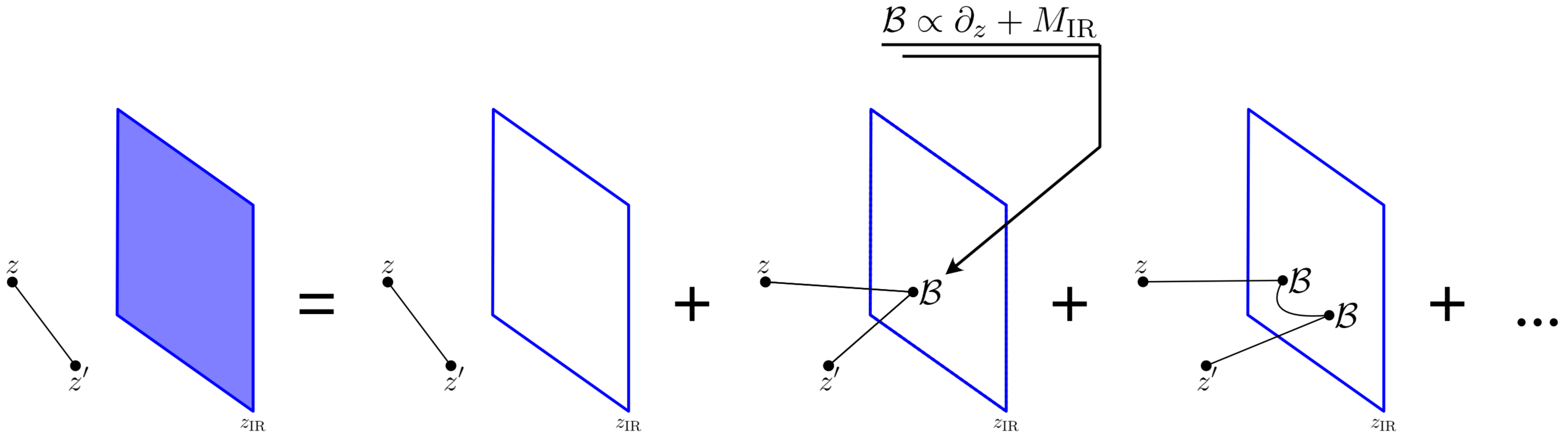
$$G_p(z,z') = \frac{\pi}{2k}(kz)^2(kz')^2 J_\alpha(pz_<)H_\alpha^{(1)}(pz_>)$$

$$G_p(z,z') = i\frac{\pi k^3(zz')^2}{2}\frac{\left[\widetilde{Y}_\alpha^{UV}J_\alpha(pz_<) - \widetilde{J}_\alpha^{UV}Y_\alpha(pz_<)\right]\left[\widetilde{Y}_\alpha^{IR}J_\alpha(pz_>) - \widetilde{J}_\alpha^{IR}Y_\alpha(pz_>)\right]}{\widetilde{J}_\alpha^{UV}\widetilde{Y}_\alpha^{IR} - \widetilde{Y}_\alpha^{UV}\widetilde{J}_\alpha^{IR}}$$



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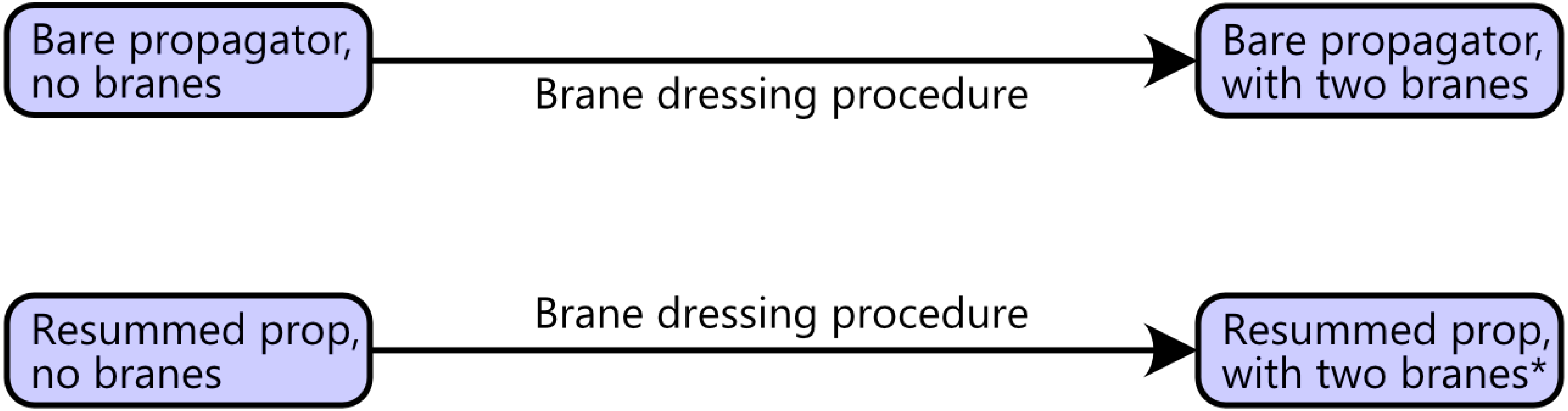
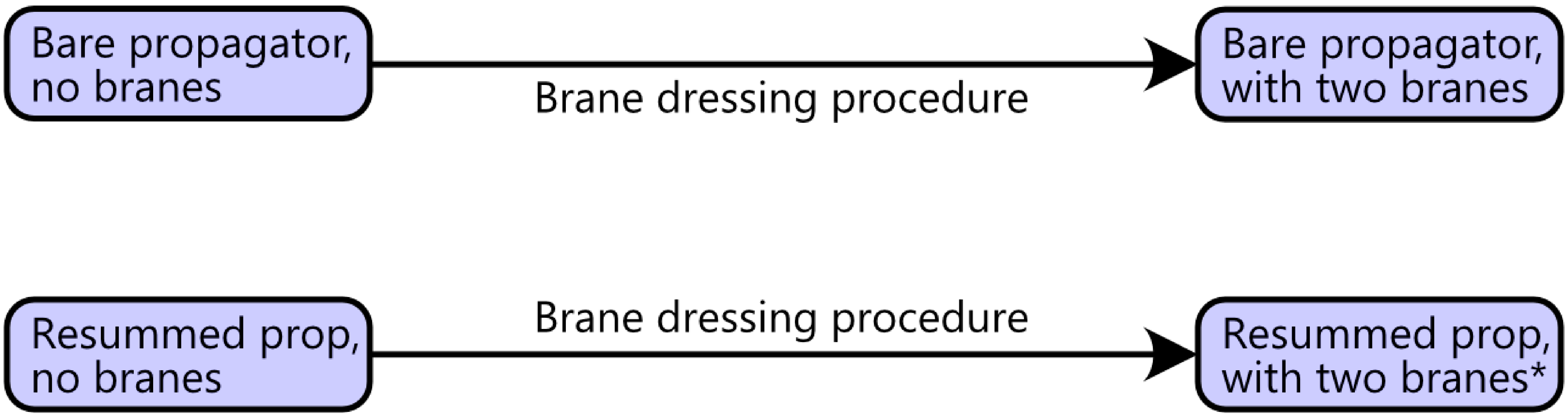
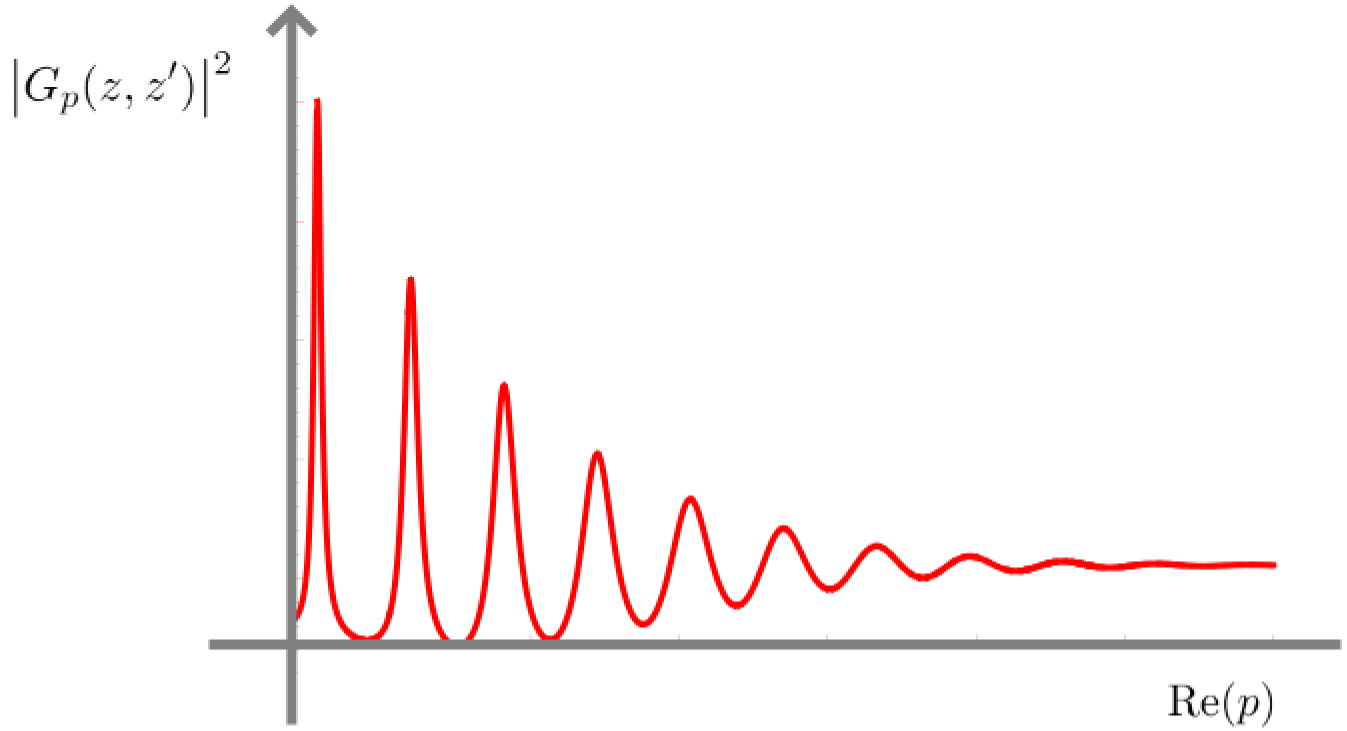
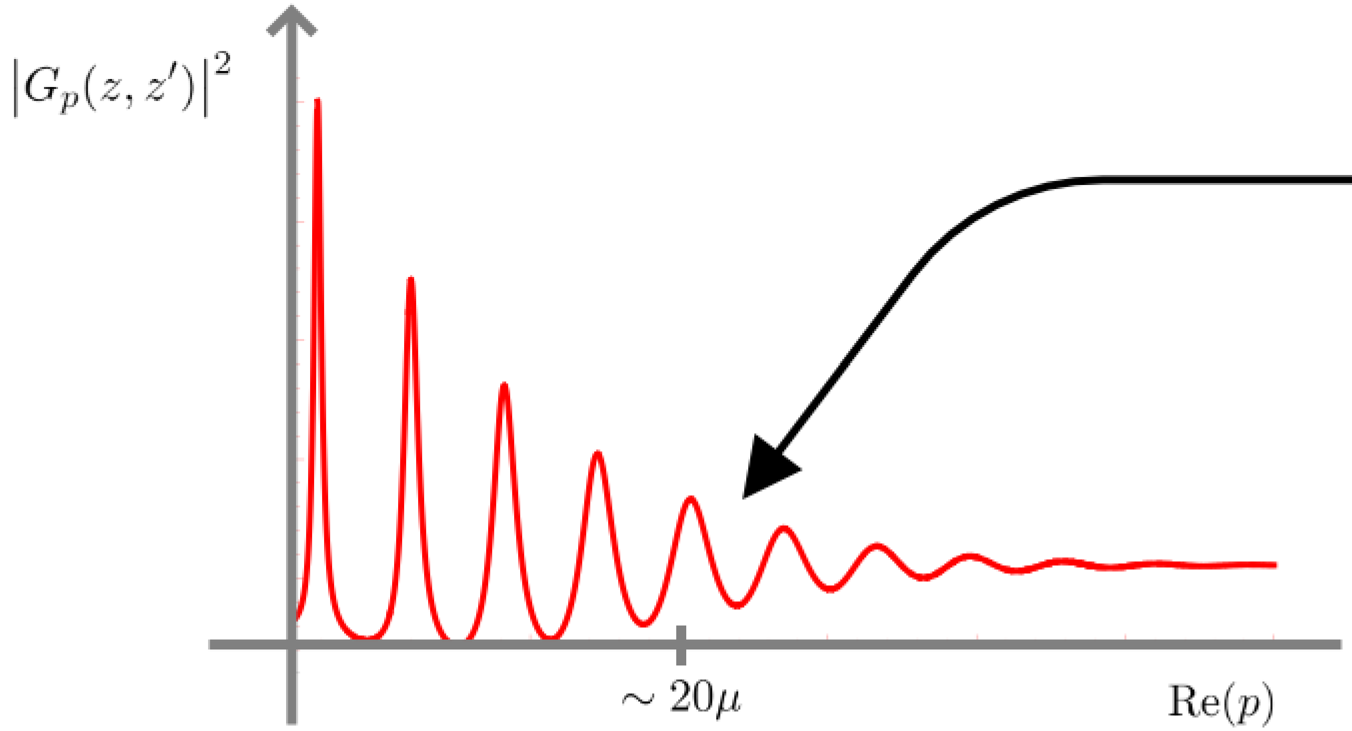
Bare propagator, no branes
Brane dressing procedure
Bare propagator, with two branes


Bare propagator, no branes
Brane dressing procedure
Bare propagator, with two branes
Resummed prop, no branes
Brane dressing procedure
Resummed prop, with two branes*

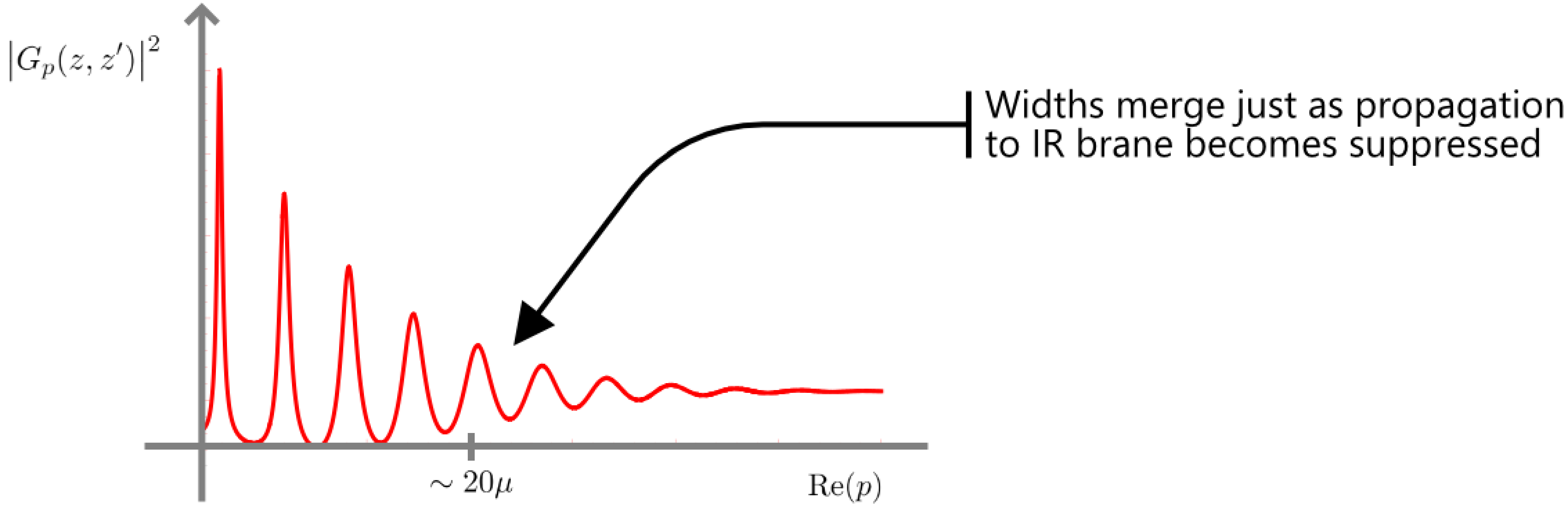


*self-energy was calculated without branes, and this isn't updated by the brane dressing procedure

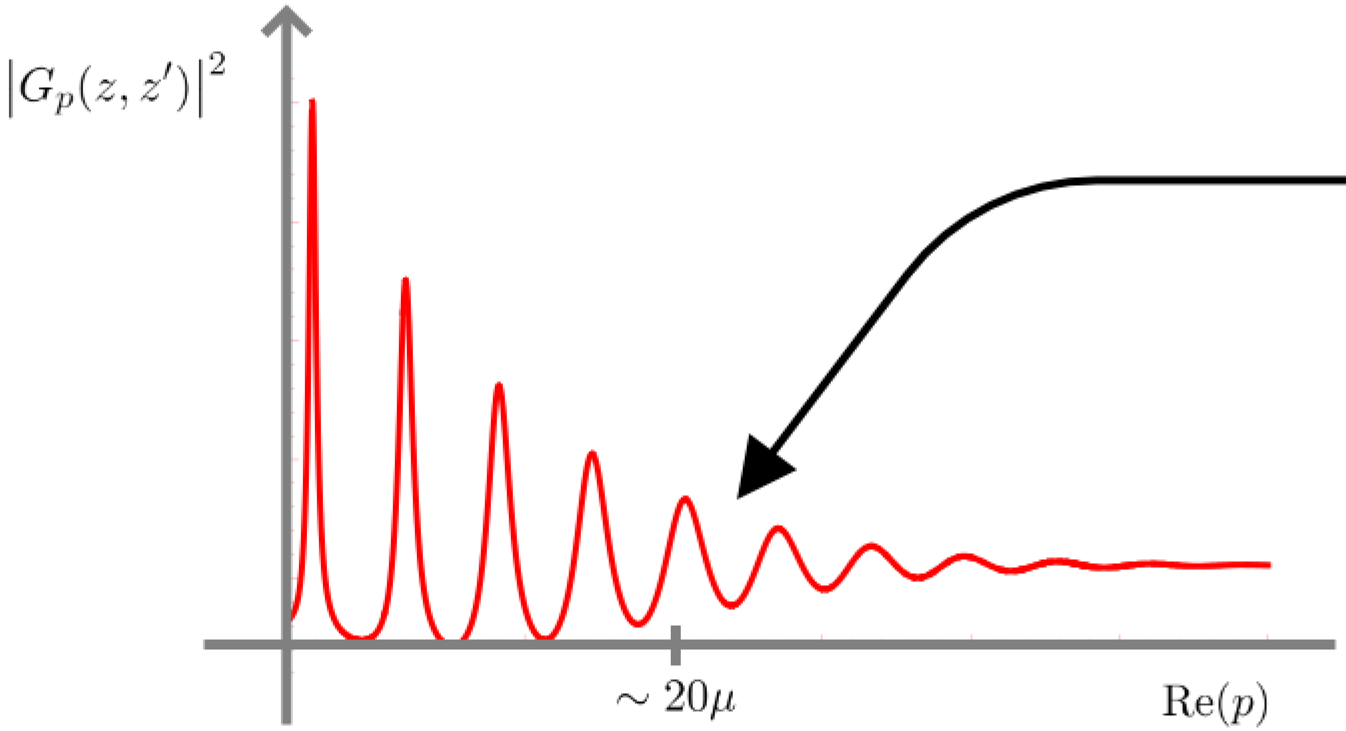

$|G_p(z,z')|^2$
$\mathrm{Re}(p)$



Widths merge just as propagation to IR brane becomes suppressed



$$G_p(z,z') = i\sum_{n=0}^{\infty} \frac{f_n(z) f_n(z')}{p^2 - m_n^2 + \Pi_n(p^2)}$$



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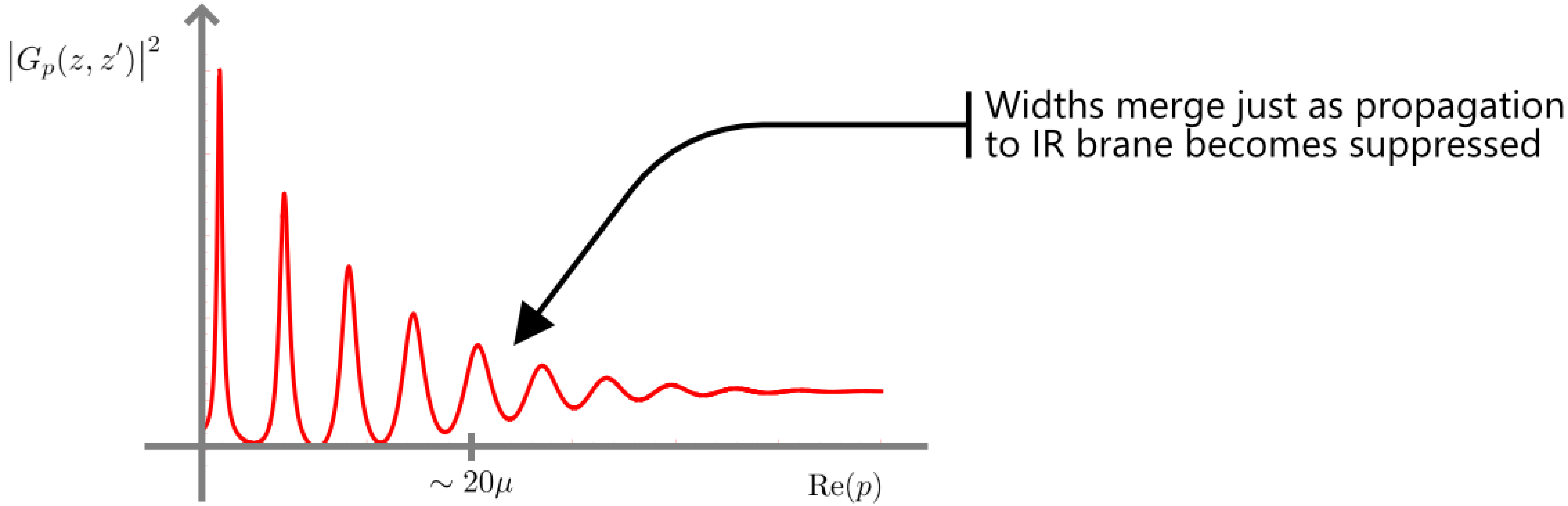
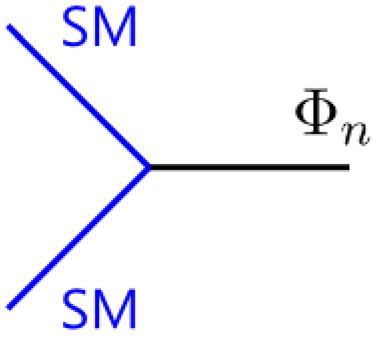
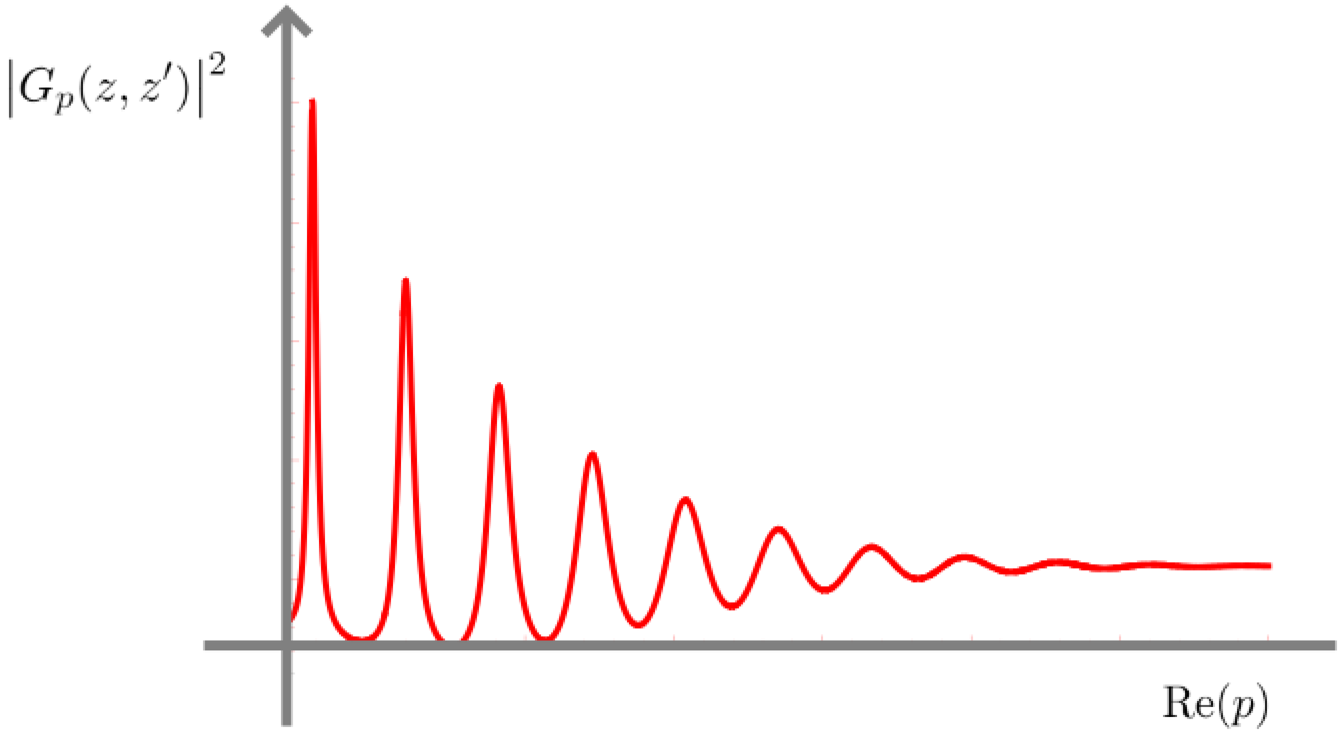


$$G_p(z,z') = i\sum_{n=0}^{\infty} \frac{f_n(z)\, f_n(z')}{p^2 - m_n^2 + \Pi_n(p^2)}$$

$$G_p(z,z') = i\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} f_m(z)\left(p^2 - m^2 + \Pi\right)^{-1}_{mn} f_n(z')$$

There is a really nice paper by Cacciapaglia et al. on interference from nondiagonal width matrices: 0906.3417





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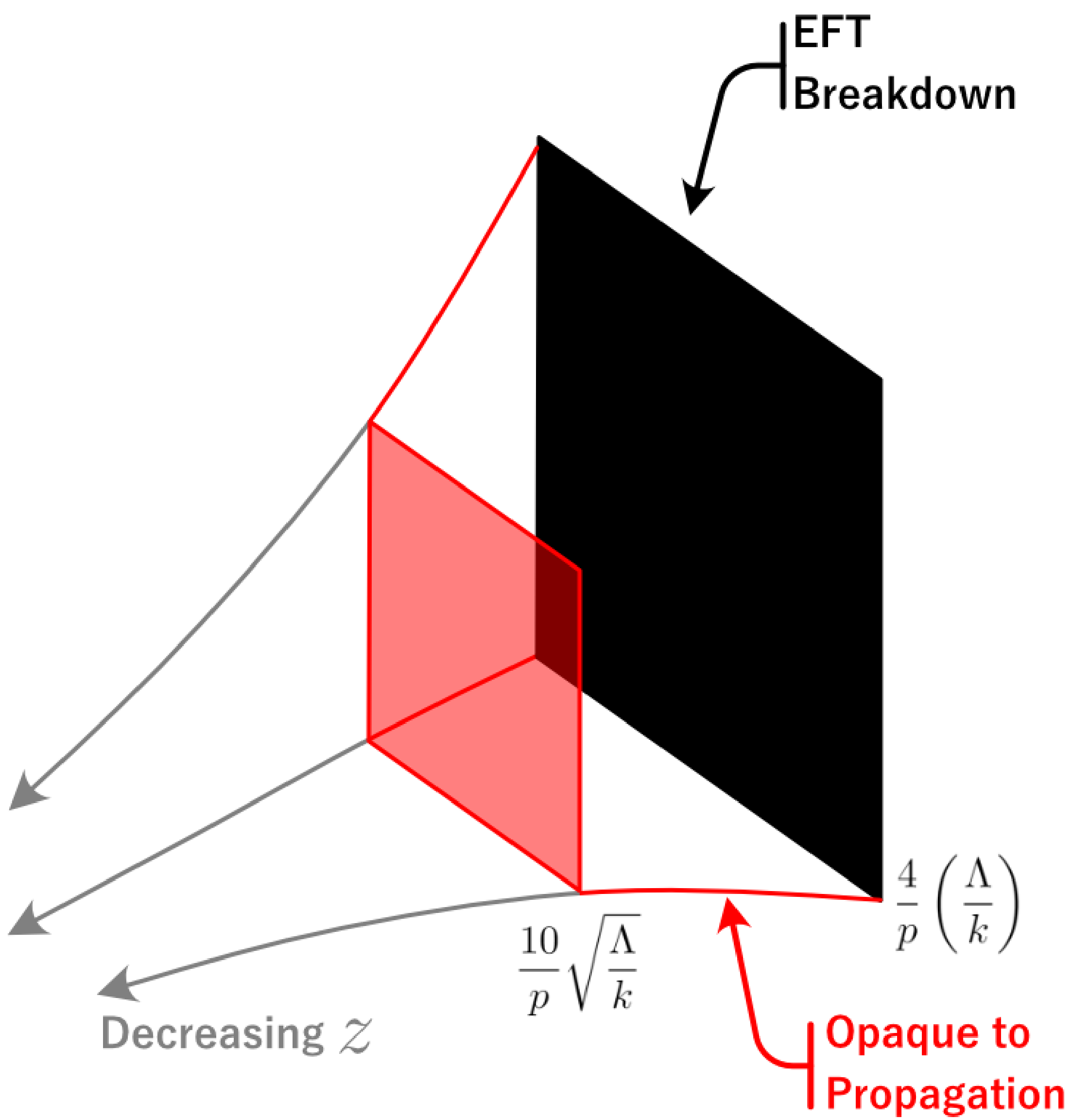
Summary

- When interactions are present, propagation into the IR region can be suppressed at high energies.
- Region of EFT breakdown is censored by this suppression
- Widths mix and merge to form a continuum at energies when the IR brane becomes opaque to propagation



Thanks!