Axion mass from the UV

Alex Pomarol, IFAE/UAB, Barcelona

The axion, the neatest solution to the strong CP problem

Axion physics claim to be fully IR determined

from QCD quantities

lead to precise predictions for its
DM abundance and the range of exp. searches

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How robust is this?

How easy/difficult is for the Axion to get mass from UV physics?

(of course, without spoiling the axion solution to the strong CP problem)

Axion mass dependence with the UV

Not to spoil the solution to the strong CP problem:

Mass from the anomaly: $\frac{a}{f} G^{\mu\nu}\widetilde{G}_{\mu\nu}$ ☛ **from instantons**

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Pure YM:

instanton amplitude

$$\int \mathcal{D}A \; e^{-\frac{2\pi}{\alpha_s}}$$

'tHooft 76

integrating over **fluctuations** around the instanton

$$A_\mu^{(I)a}(x) = \frac{2\,\eta^a_{\mu\nu}(x-x_0)_\nu}{(x-x_0)^2+\rho^2}$$

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integrating over the instanton size ρ

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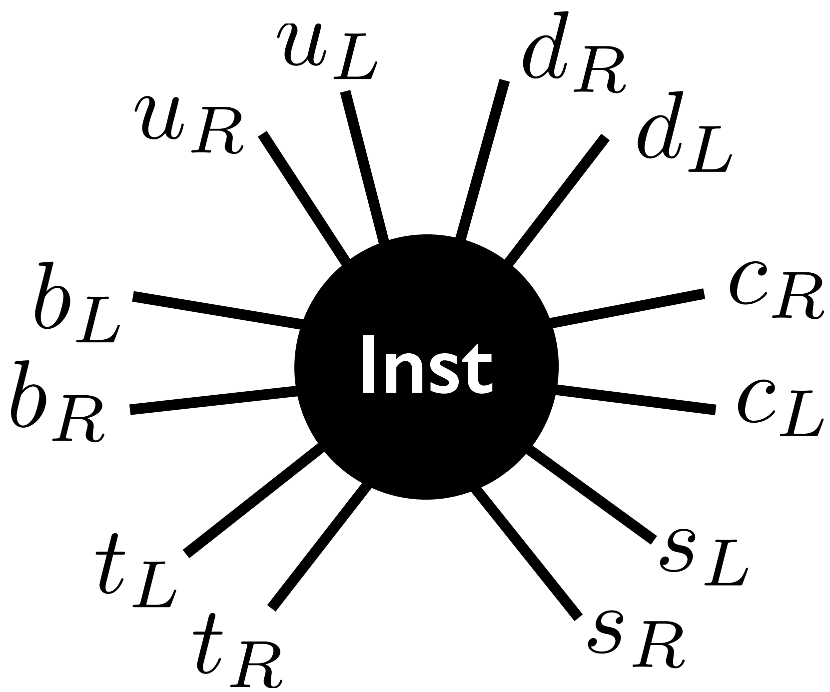
dominated by the IR: Large instanton

Including fermions:

'tHooft 76

$$\partial_\mu J_\mu{}^5 = -i(Ng^2/16\pi^2)G_{\mu\nu}{}^a\tilde{G}_{\mu\nu}{}^a \quad \rightarrow \quad \Delta Q^5 = 2N$$

chiral breaking process



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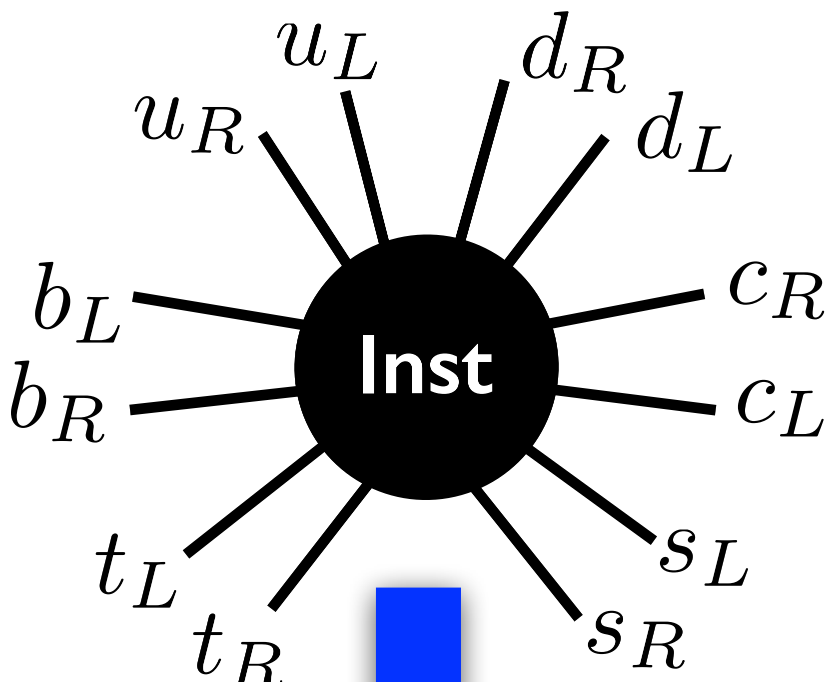
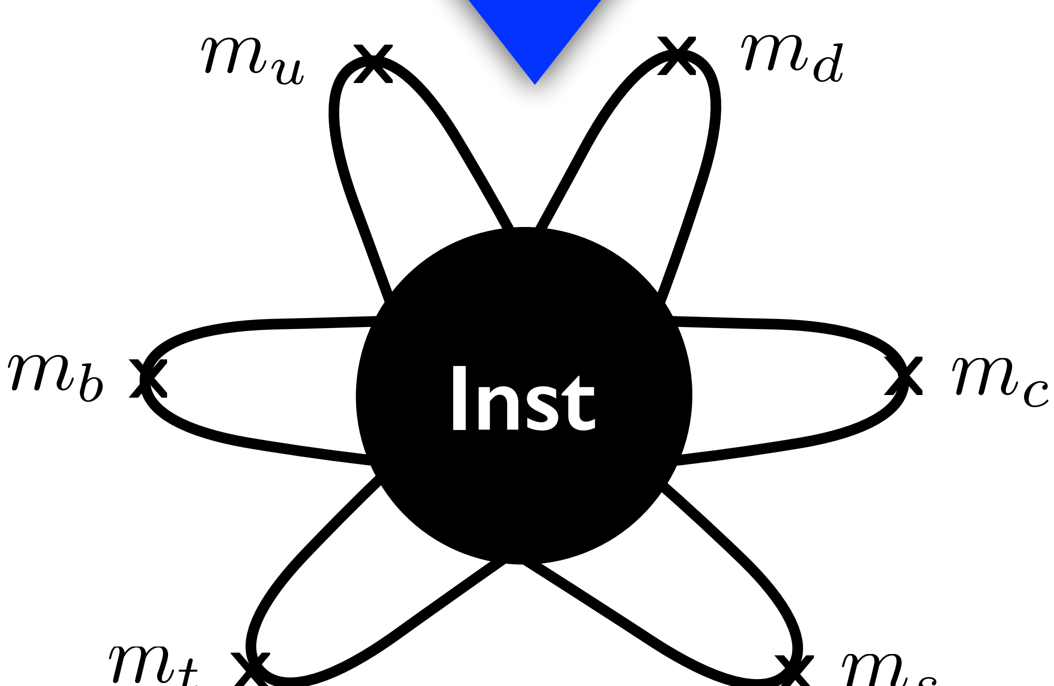




$$\frac{m_u m_d m_c m_s m_t m_b}{\Lambda^6}$$

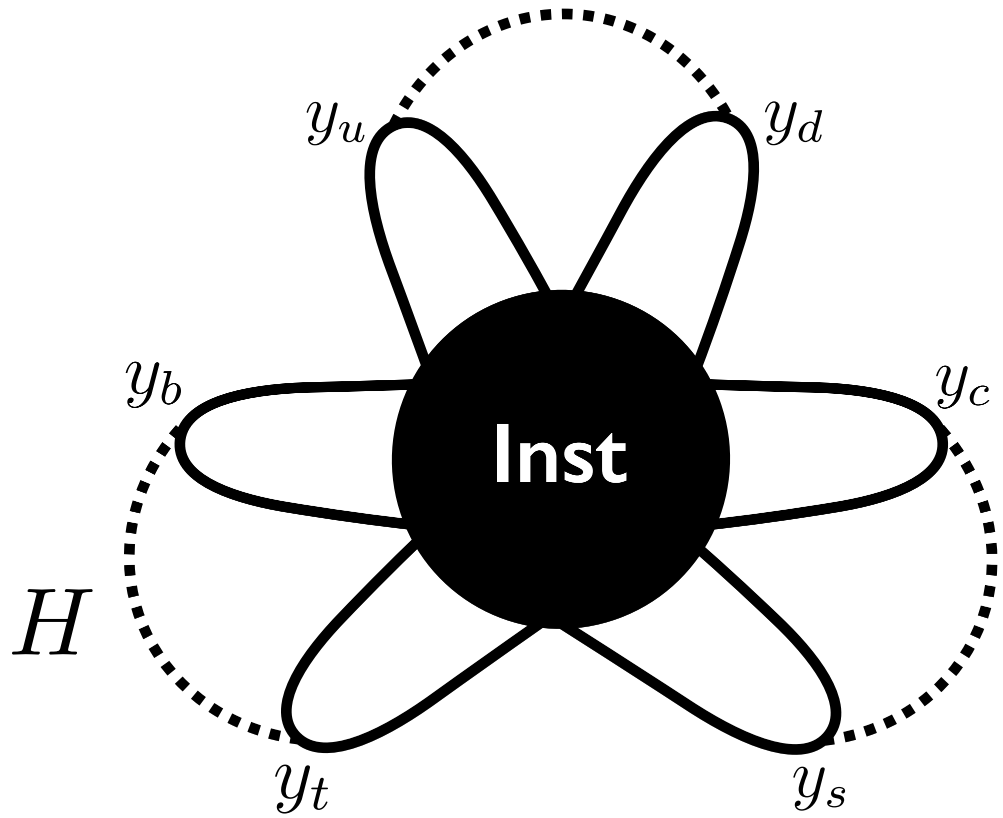
$\Lambda \sim 1/\rho$

UV instanton highly suppressed

Simplest way to enhance the UV contributions:

I) Larger α_s at the UV to enhance $e^{-\frac{2\pi}{\alpha_s(\Lambda)}}$

II) Closing fermion lines by Higgs:

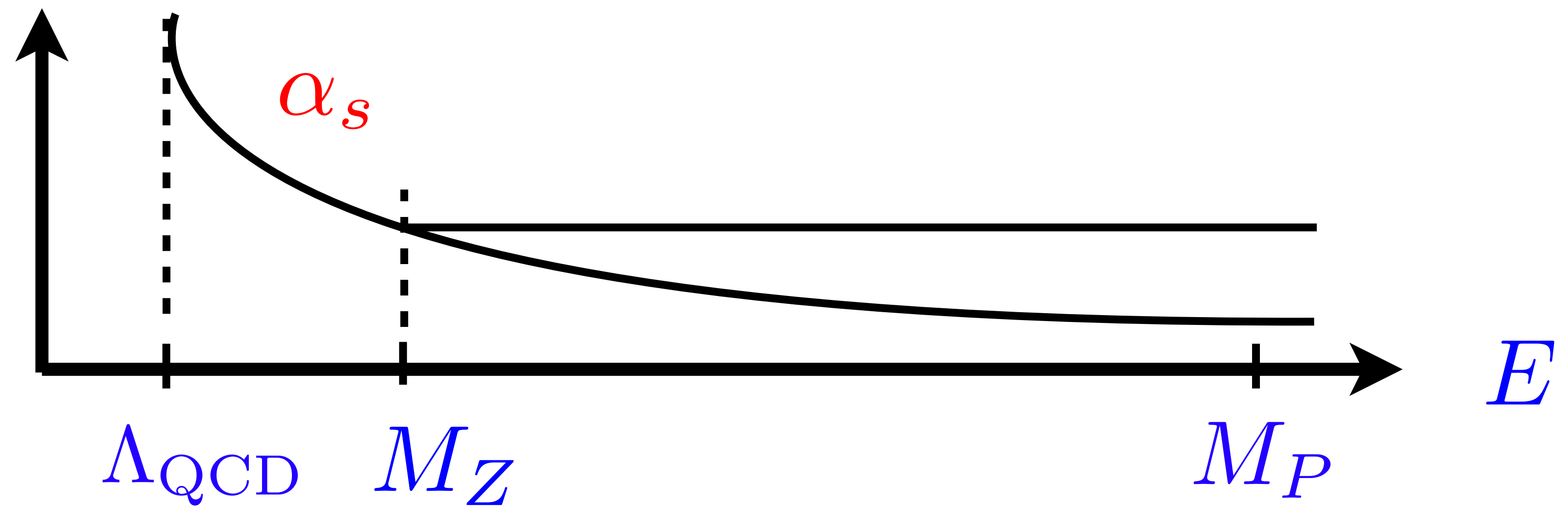


$$\kappa_f = \frac{y_u}{4\pi}\frac{y_d}{4\pi}\frac{y_c}{4\pi}\frac{y_s}{4\pi}\frac{y_t}{4\pi}\frac{y_b}{4\pi} \approx 10^{-23}$$

Or extra "Higgs" at the UV with larger couplings,
but danger to generate extra phases

Simplest model:

Extra color scalars (e.g. at the TeV) ☛ freezing α_s at the TeV



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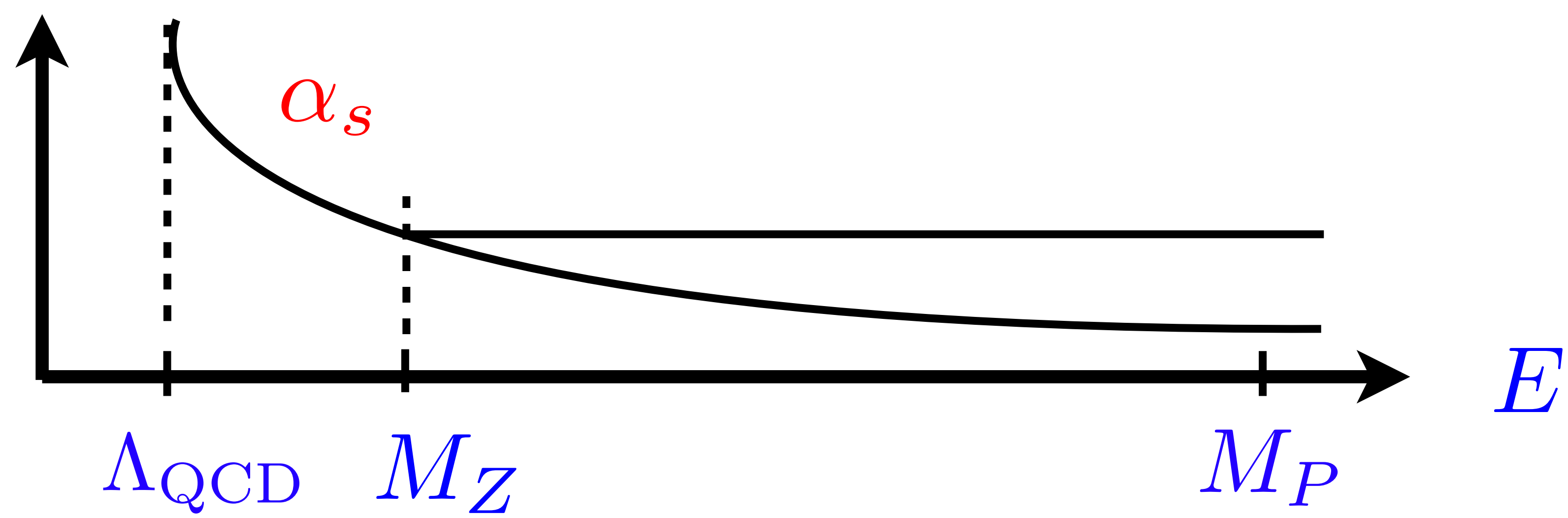

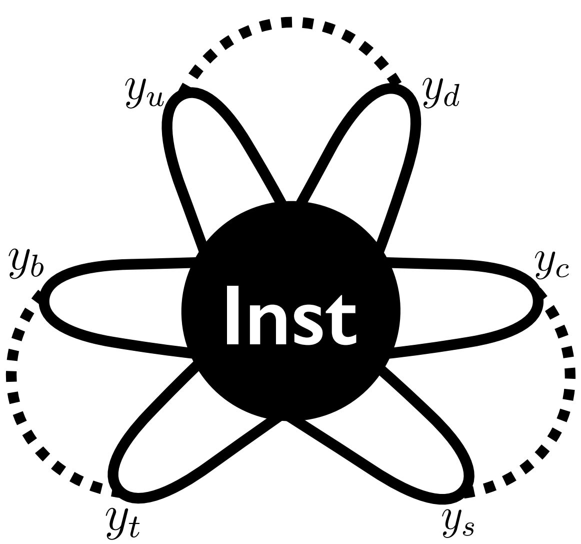

$$\kappa_f \; M_P^4 \; e^{-\frac{2\pi}{\alpha_s(M_P)}}$$

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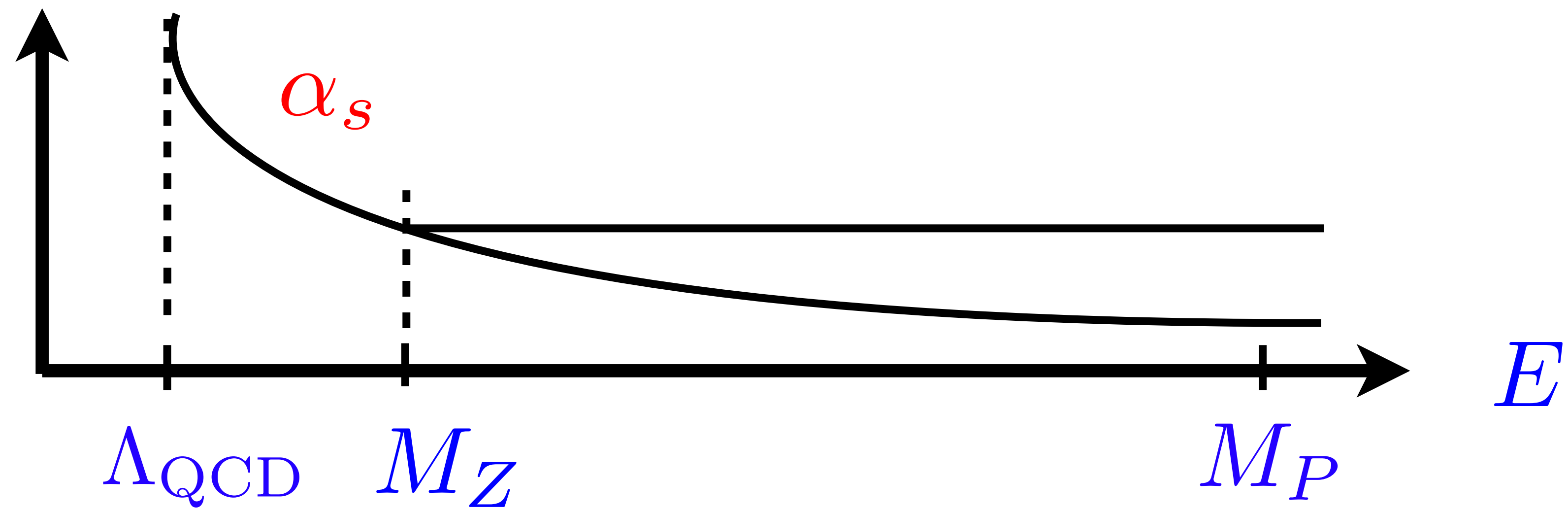

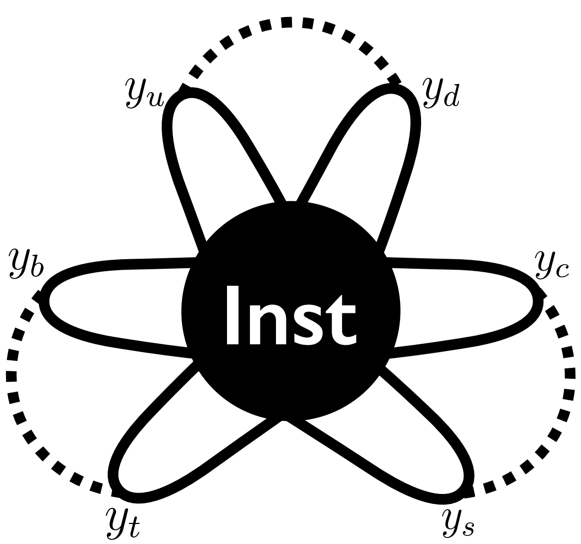

$$\kappa_f \; M_P^4 \; e^{-\frac{2\pi}{\alpha_s(M_P)}} \sim m_a^2 f_a^2$$

10^{-23} $\quad 10^{72}$ $\quad 10^{-25}$

$(10^{12})^2$ GeV^4

much larger than QCD!

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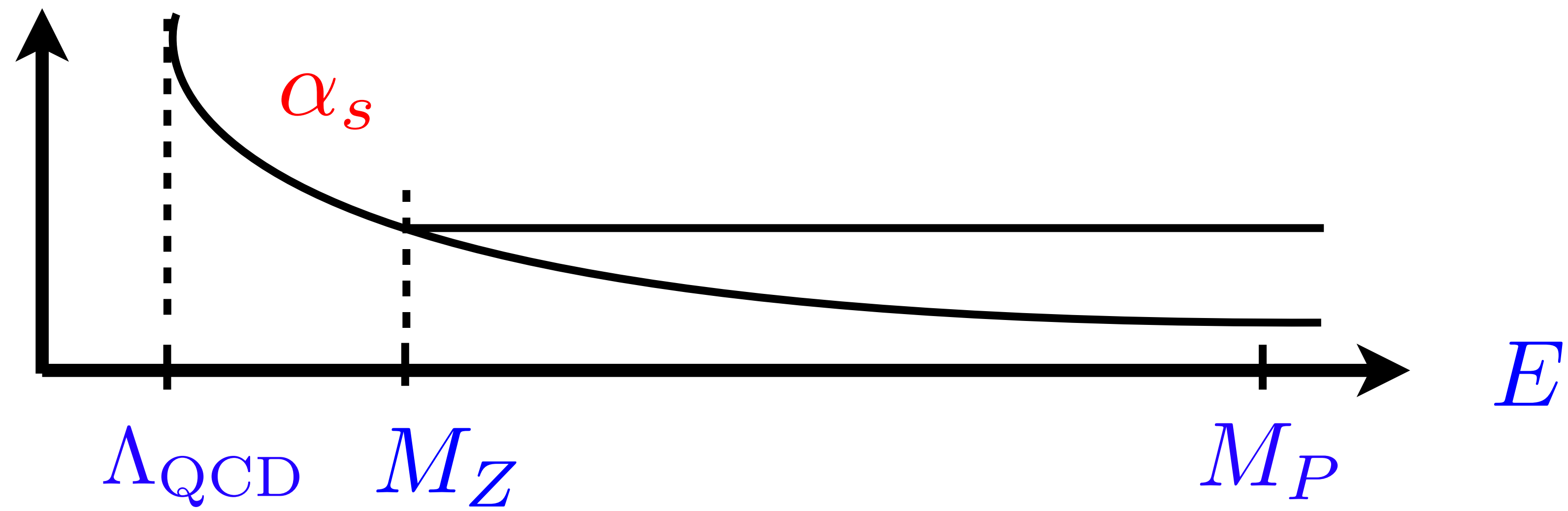

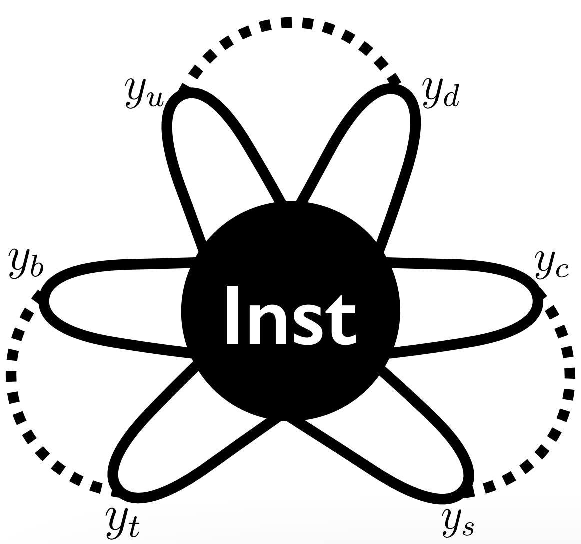

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10^{-23} 10^{72} 10^{-25}

But, how to keep the scalars light?

(plenty of new hierarchy problems)

GeV

much larger than QCD!

Other options:

I) $SU(3)_1 \times SU(3)_2 \times \ldots \times SU(3)_k \to SU(3)_{QCD}$

Agrawal, Howe 17

II) Mirror worlds

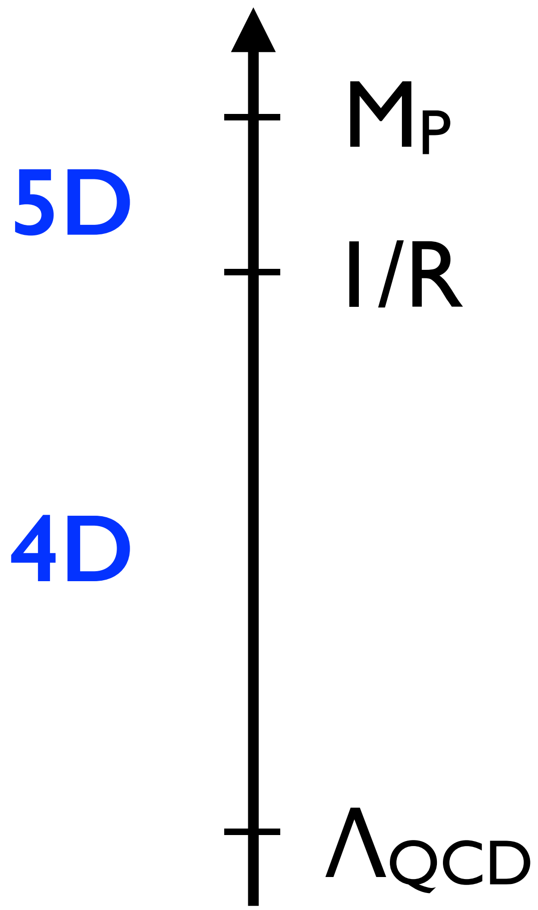
Dimopoulos, Hook, Huang, Marques-Tavares 16

$\vdots$

UV completing QCD with an extra dimension

T.Gherghetta, V.V.Khoze, AP, Y.Shirman arXiv:2001.05610

For concreteness, orbifold with localized matter on the boundary



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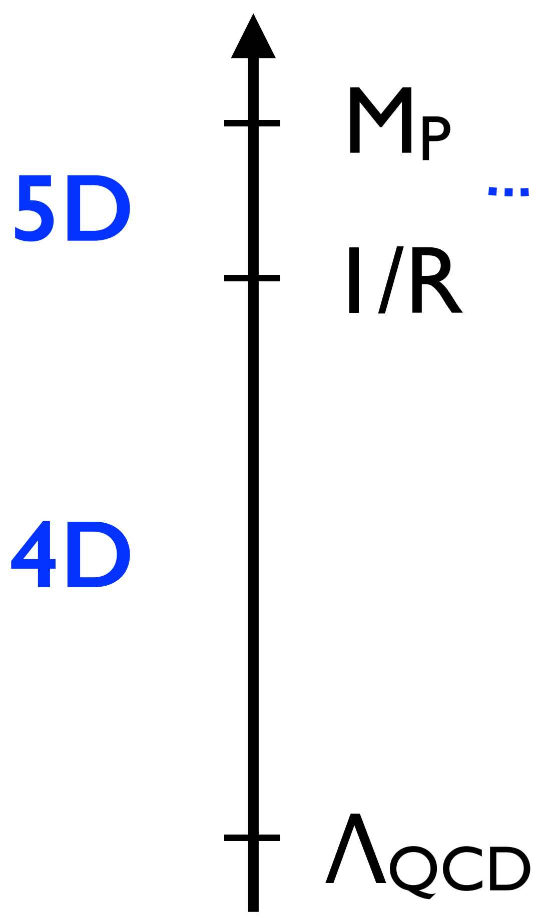

$$\int \mathcal{D}A \; e^{-\frac{2\pi}{\alpha_s}}$$

integrating over **5D fluctuations** around the uplifted 4D instanton:

$$A^a_\mu(x,y) = A^{(I)a}_\mu(x), \qquad A^a_5(x,y) = 0$$

$$A^{(I)a}_\mu(x) = \frac{2\,\eta^a_{\mu\nu}(x-x_0)_\nu}{(x-x_0)^2+\rho^2}$$

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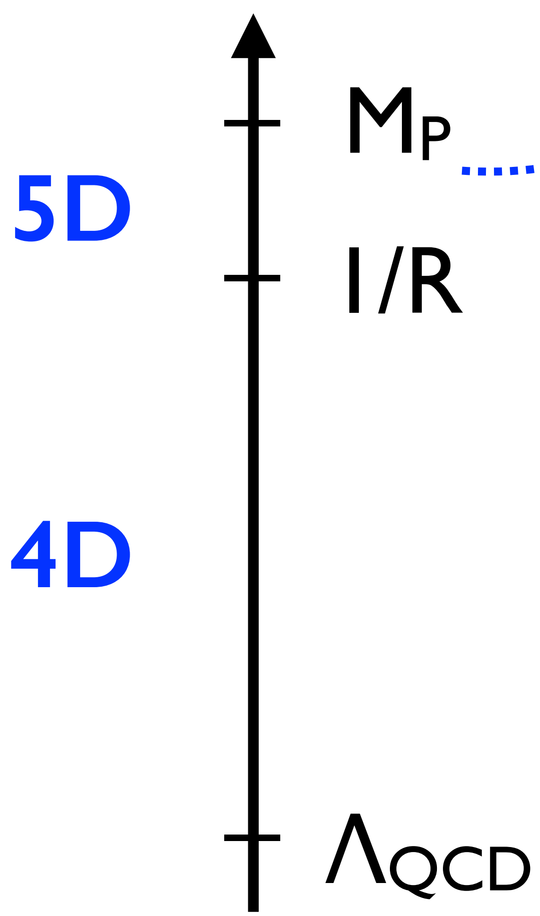
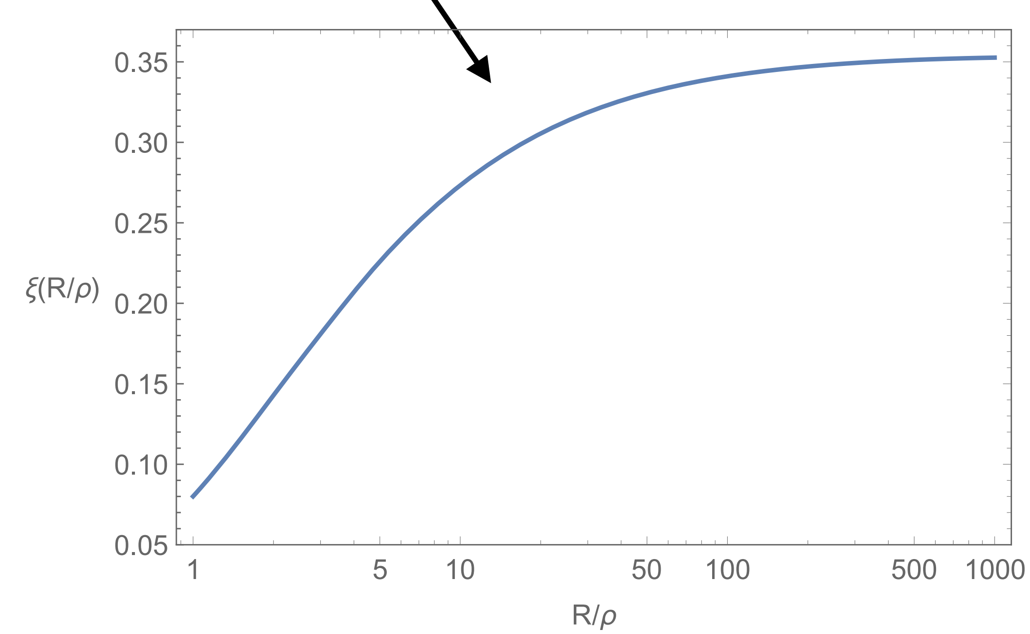


$$e^{-S_{\rm eff}}$$

$$S_{\rm eff} = \frac{2\pi}{\alpha_s(1/R)} - 3\xi(R/\rho)\frac{R}{\rho} + b_0 \ln\frac{R}{\rho}$$



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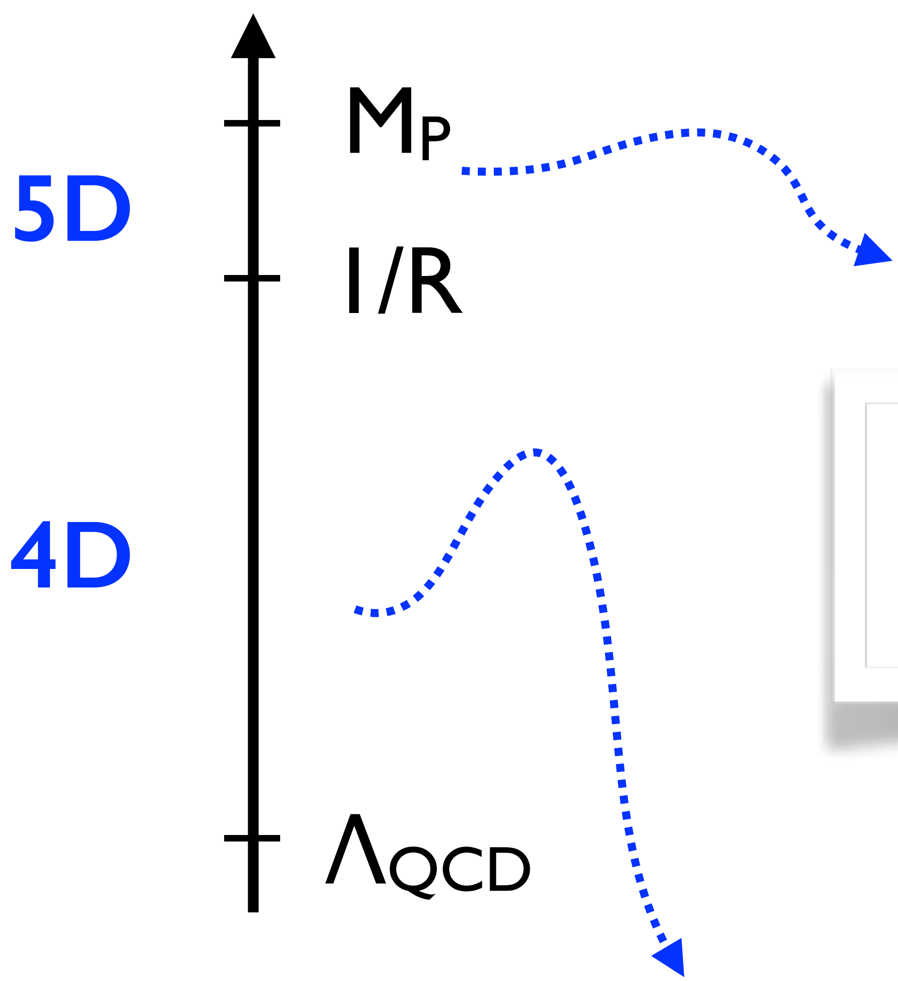

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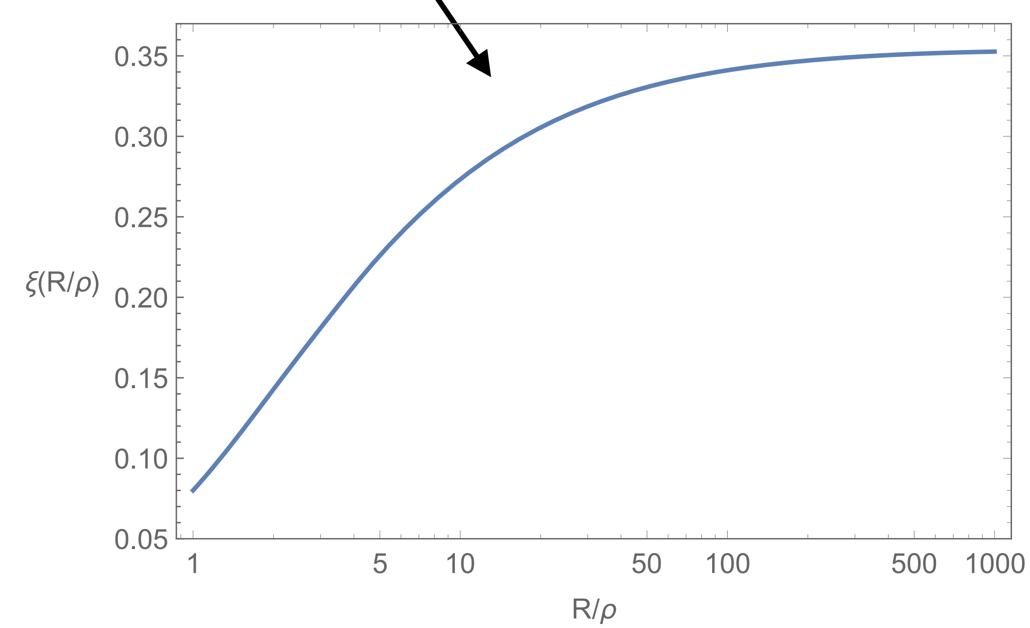

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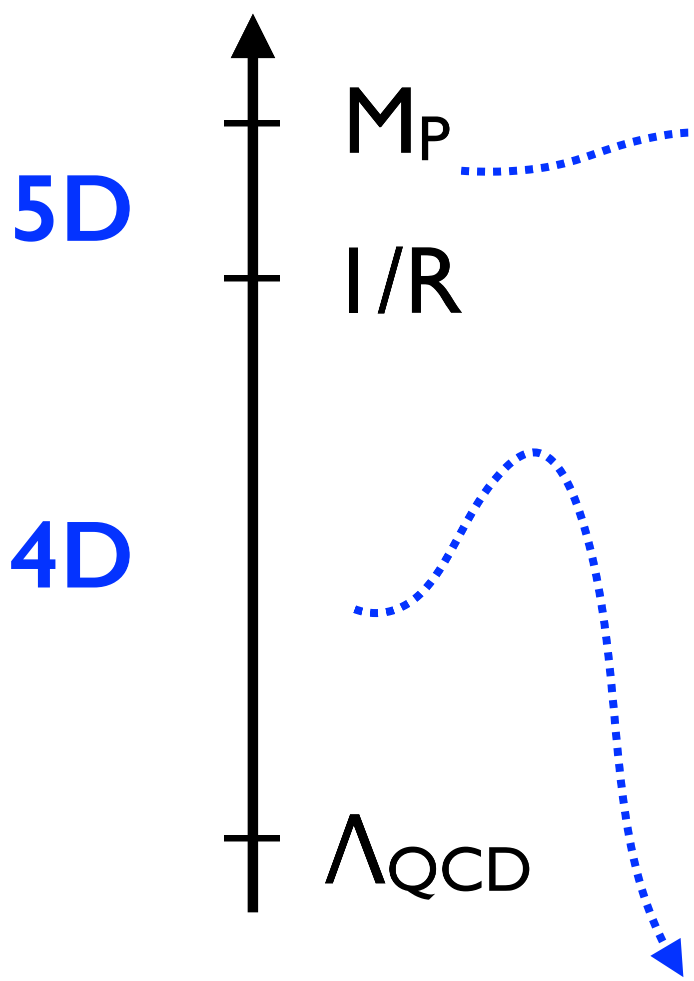
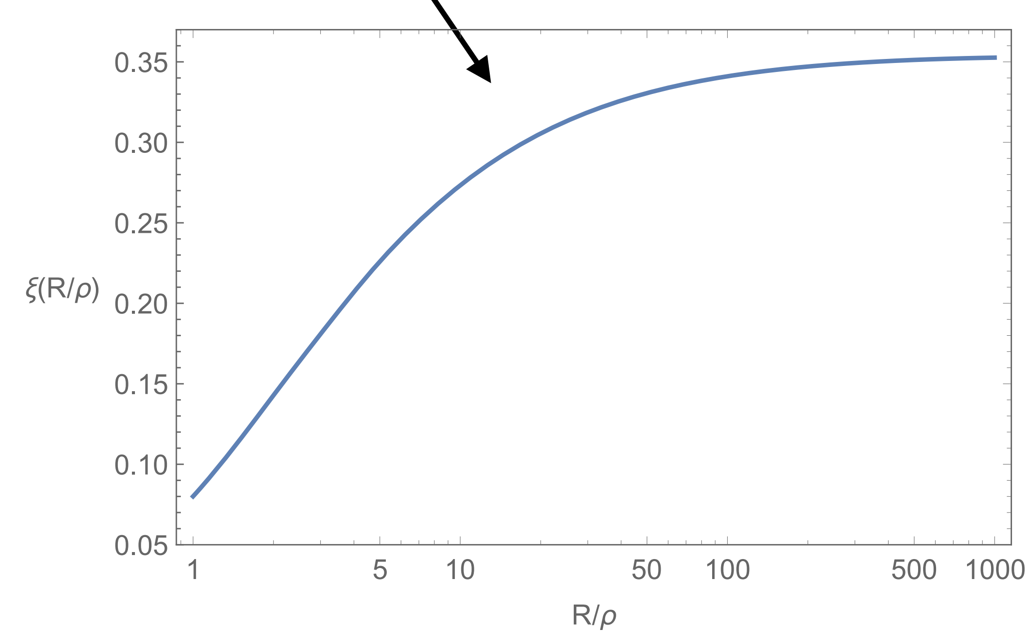


$$e^{-S_{\rm eff}}$$

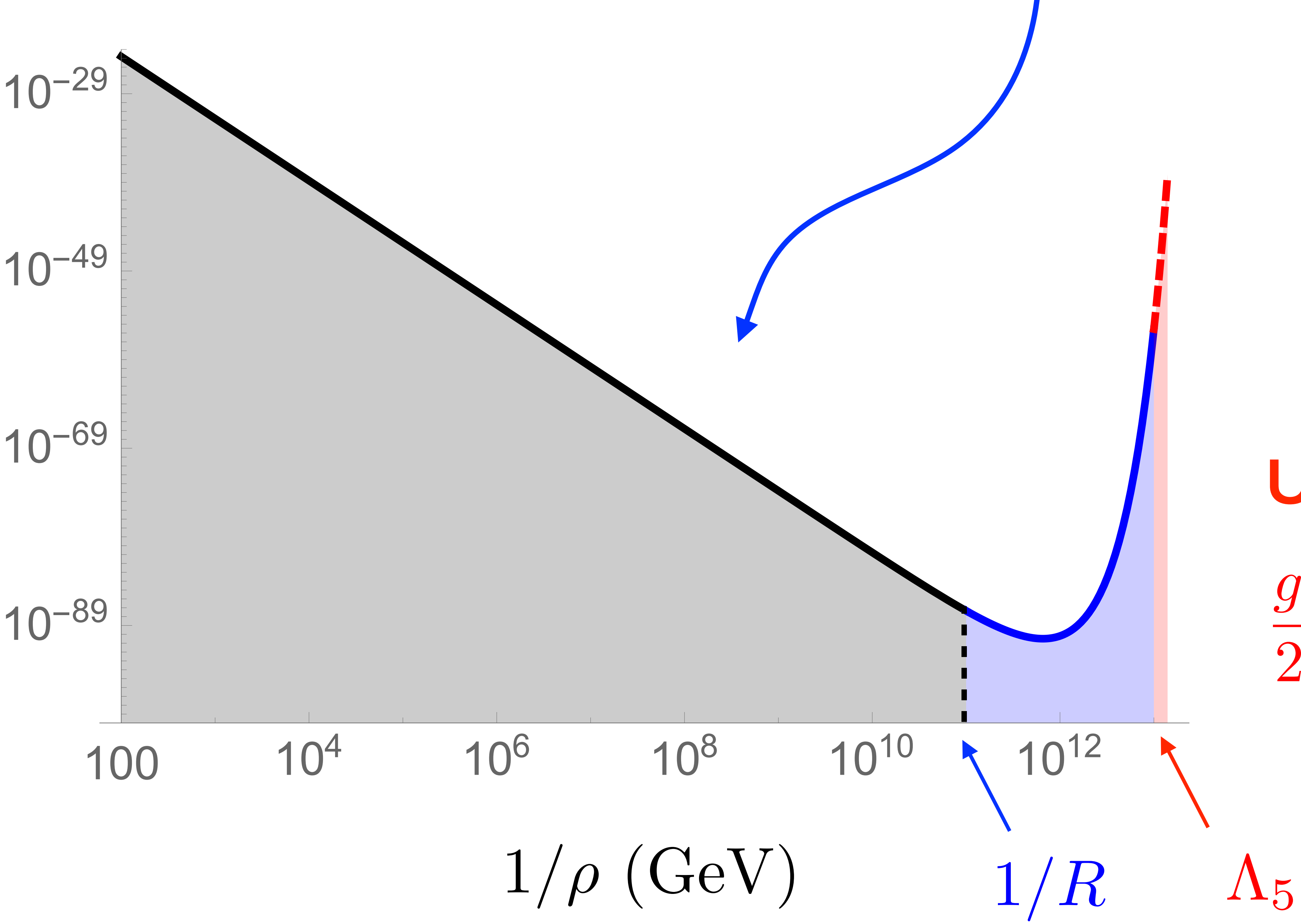
Power-law growth

$$S_{\rm eff} = \frac{2\pi}{\alpha_s(1/R)} - 3\xi(R/\rho)\frac{R}{\rho} + b_0 \ln\frac{R}{\rho}$$

$$S_{\rm eff} = \frac{2\pi}{\alpha_s(\rho)}$$



$$\kappa_f \int \frac{d\rho}{\rho^5}\, C[3] \left(\frac{2\pi}{\alpha_s(1/R)}\right)^6 e^{-S_{\text{eff}}}$$



UV-cutoff:

$$\frac{g_5^2 \Lambda_5}{24\pi^3} = \frac{\alpha_s \Lambda_5 R}{6\pi} \sim 1$$

loops are *O(1)*

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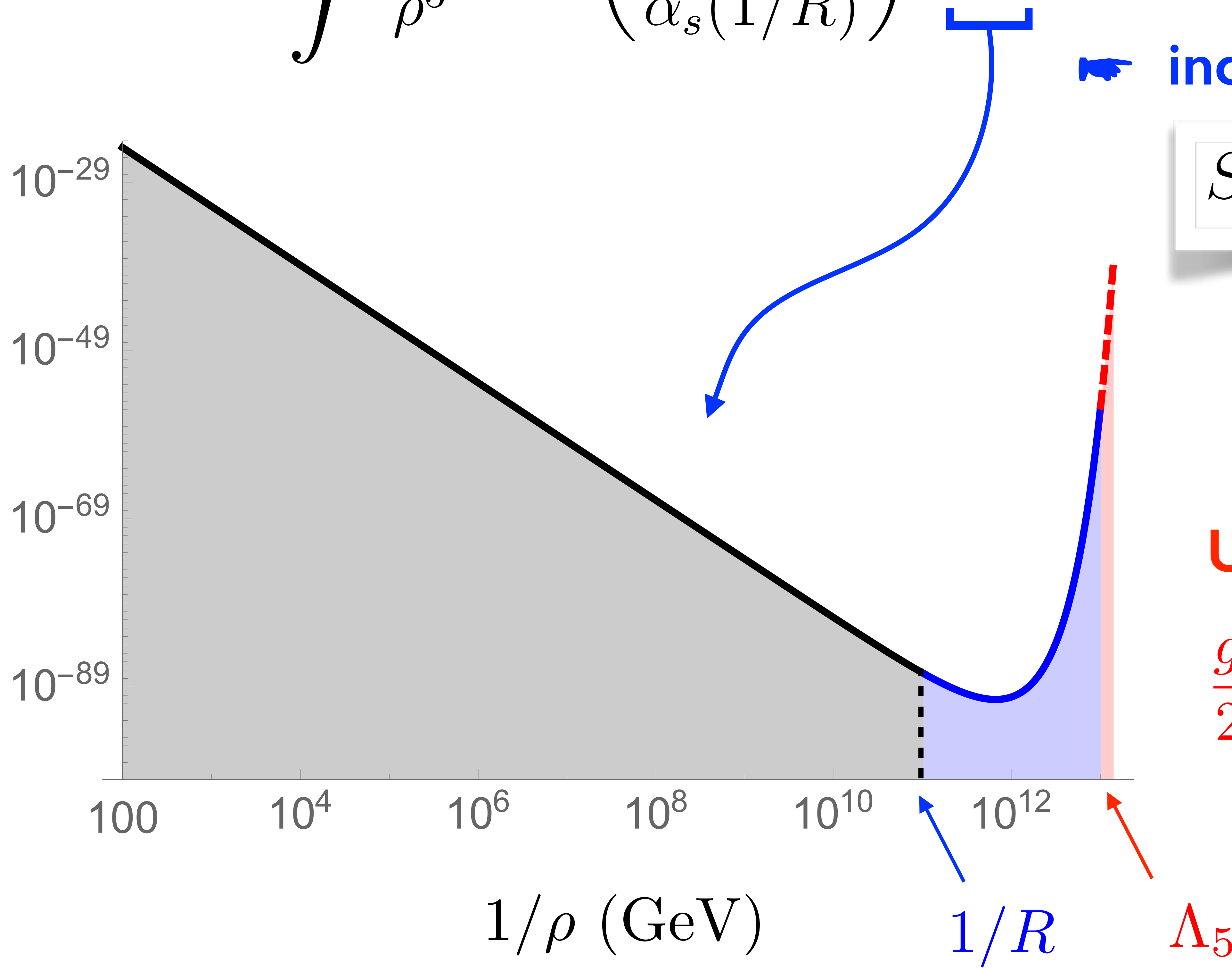

including the axion:

$$S_{\text{eff}} \to S_{\text{eff}} - ia/f$$

since $a\int G\tilde{G}|_{inst} = a$

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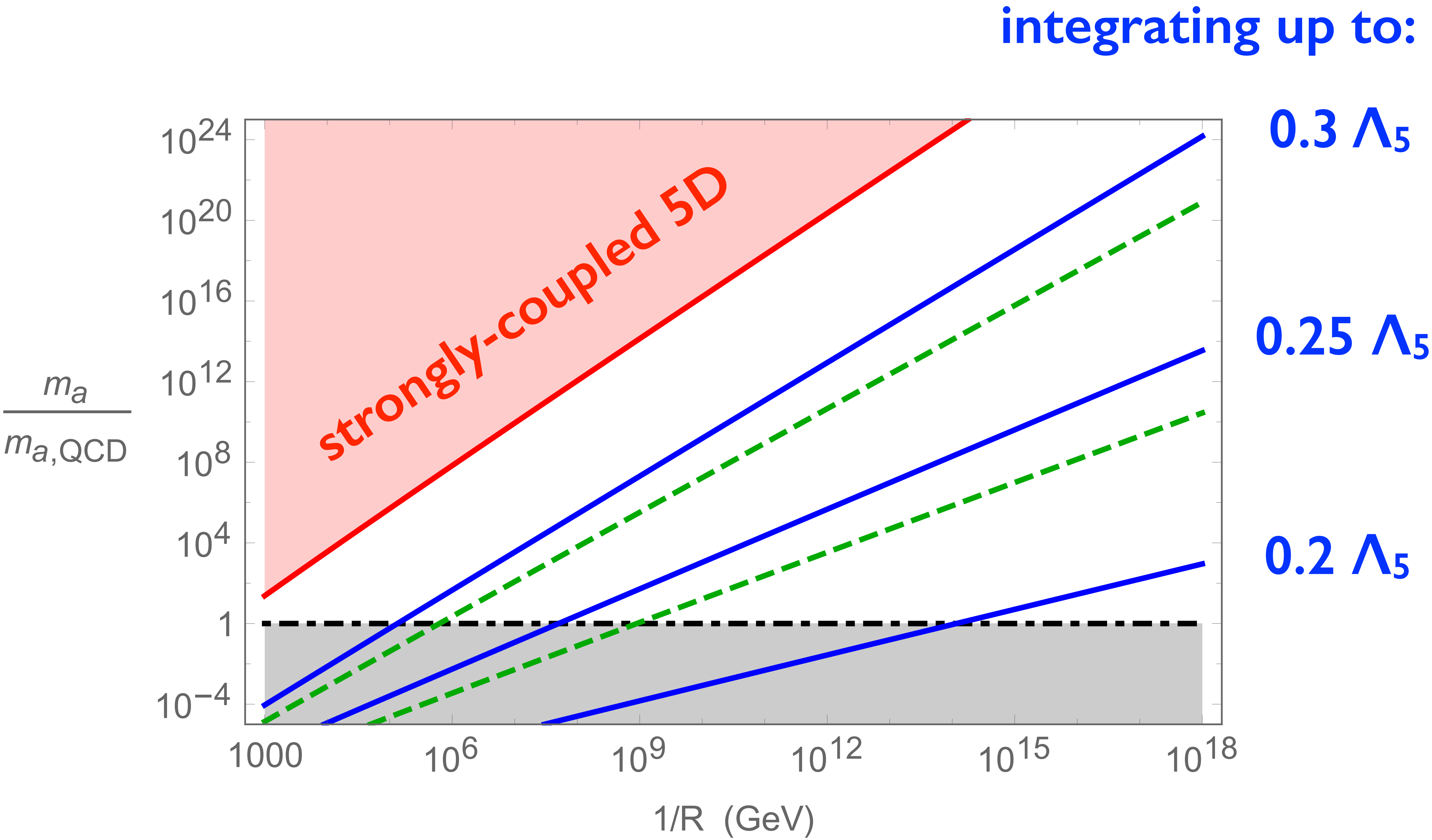
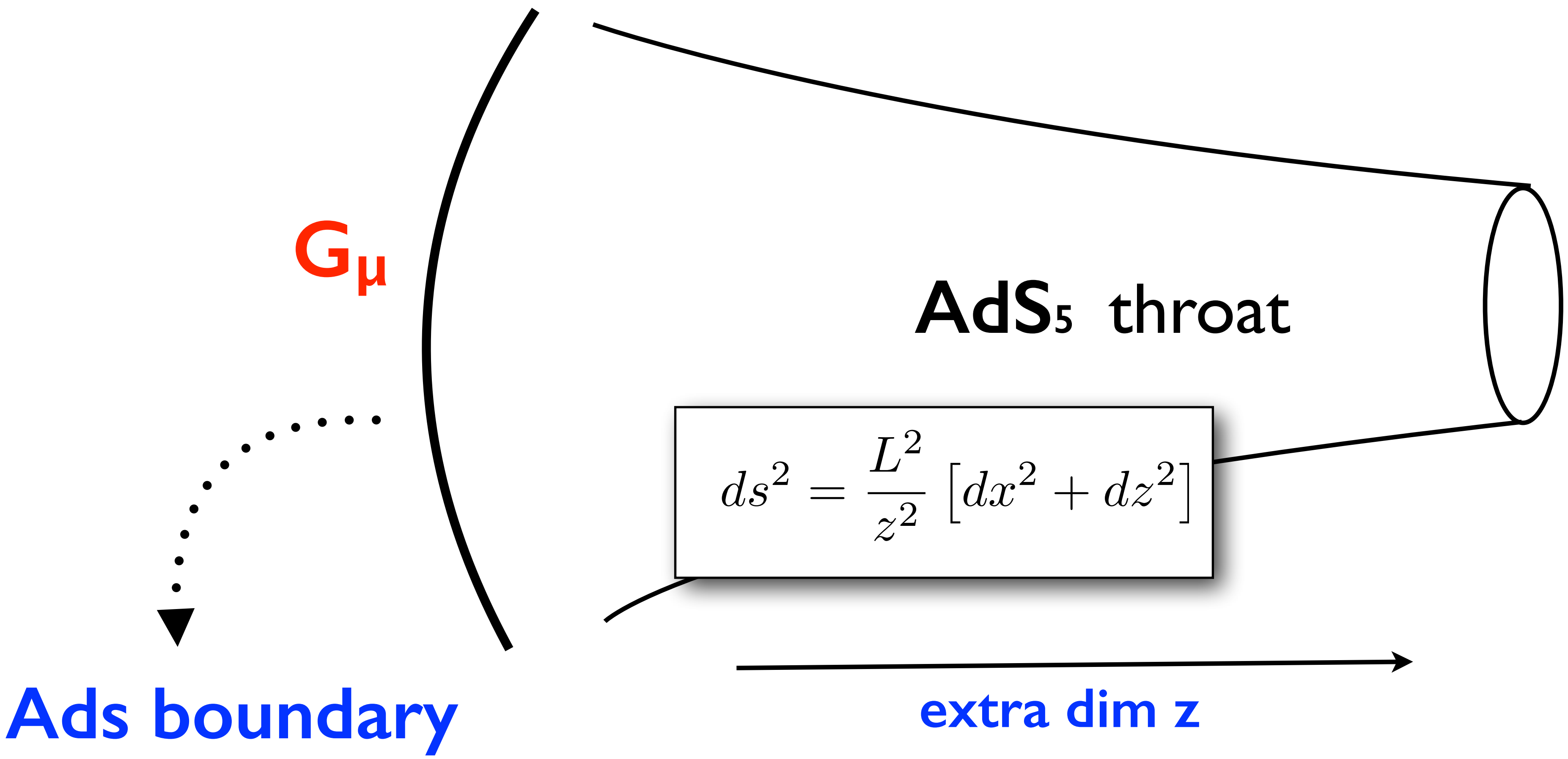

integrating up to:
0.3 Λ_5
0.25 Λ_5
0.2 Λ_5
strongly-coupled 5D
$\frac{m_a}{m_{a,QCD}}$
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
1000
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
1/R (GeV)

Extra dimensional AdS$_5$

T. Gherghetta, AP, arXiv:2109.xxx



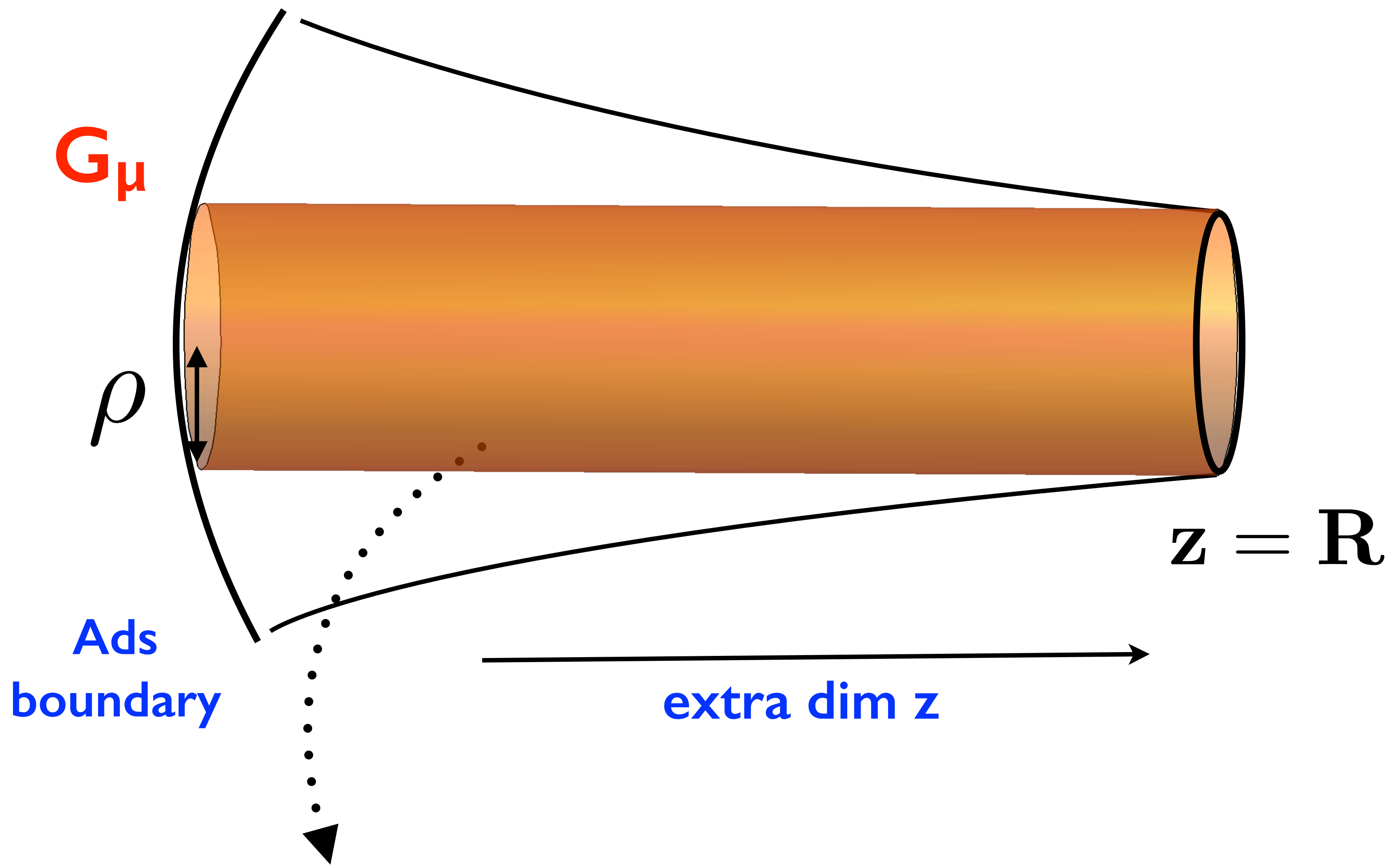
Logarithmic correction to the gauge coupling of the gluon on the AdS boundary

Expected from the AdS/CFT correspondence: $\langle \mathbf{JJ} \rangle \sim \log \mathbf{p}$

AdS$_5$ ↔ CFT charged under QCD

Extra dimensional AdS$_5$

T. Gherghetta, AP, arXiv:2109.xxx



The only instanton found in the AdS$_5$ is a "cylindrical" one:

no z dependence

$$A_\mu^a(x,y) = A_\mu^{(I)a}(x), \qquad A_5^a(x,y) = 0$$

Extra dimensional AdS$_5$

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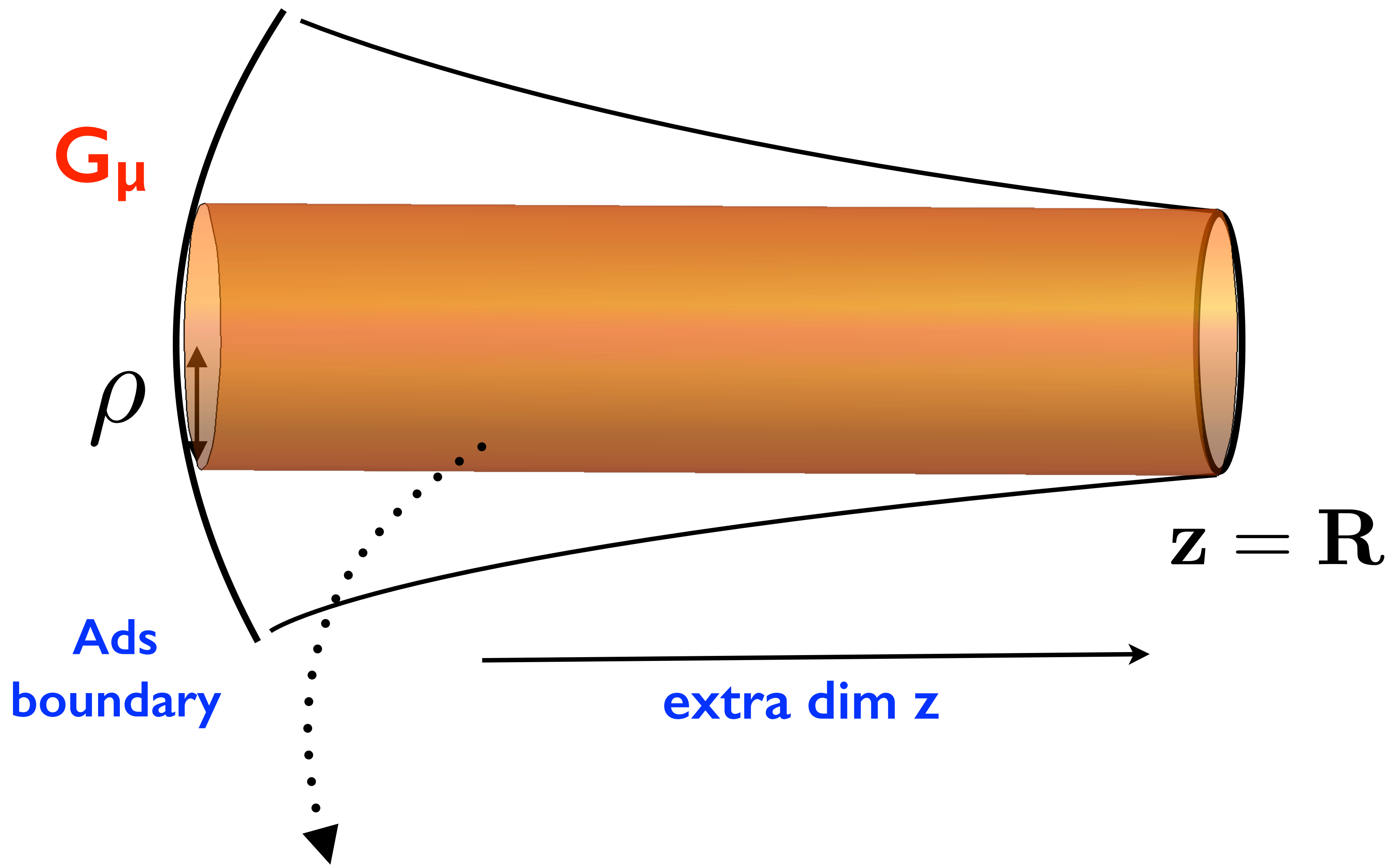


The only instanton found in the AdS$_5$ is a "cylindrical" one:

no z dependence

$$S_{inst} = \frac{8\pi^2}{g^2(1/R)} \gg \frac{8\pi^2}{g^2(1/\rho)}$$

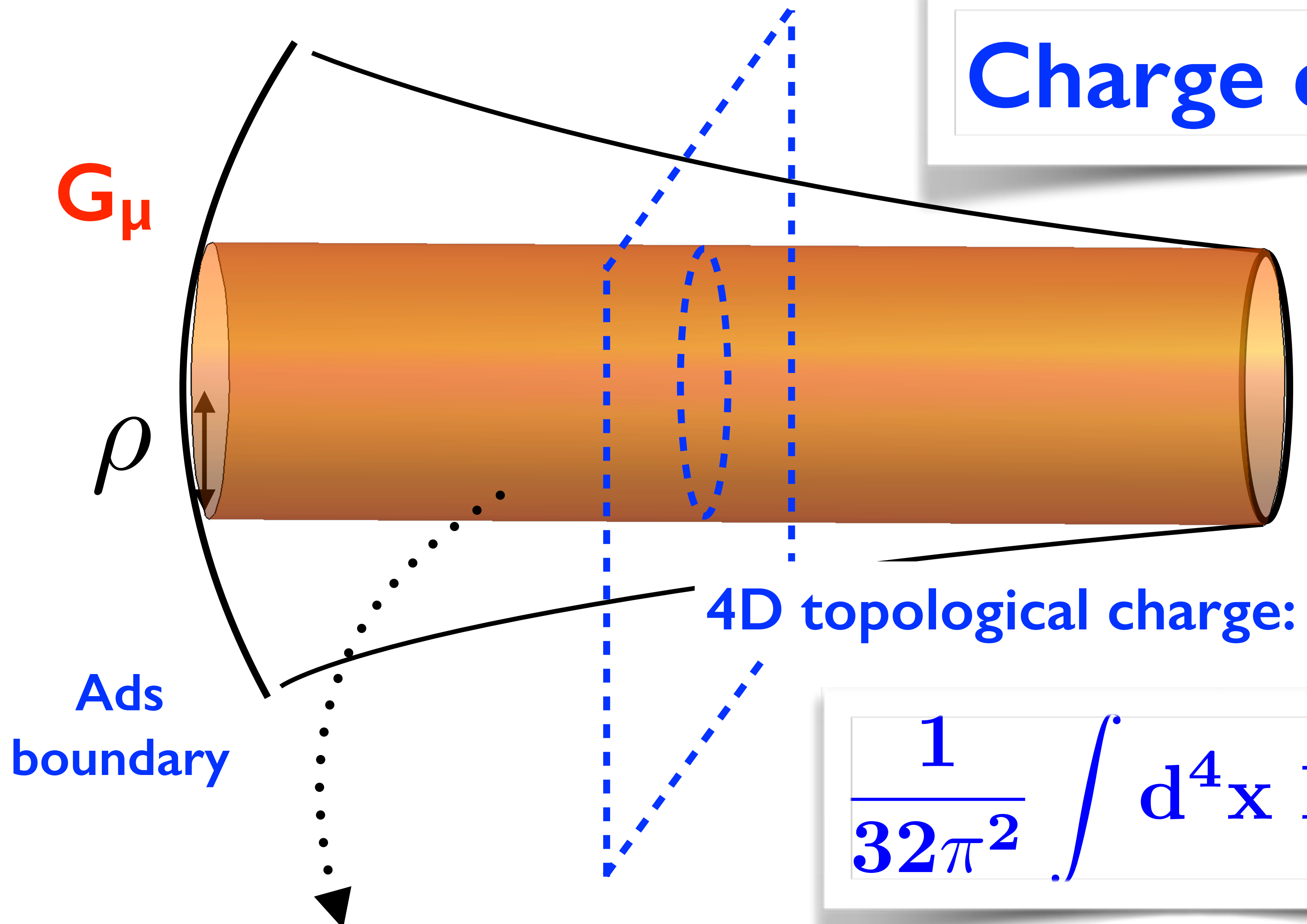
compactification scale

Small instanton are suppressed!

Extra dimensional AdS5

T. Gherghetta, AP, arXiv:2109.xxx

Charge conservation!



4D topological charge:

$$\frac{1}{32\pi^2}\int d^4x\, F\widetilde{F} = 1$$

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no z dependence

$$S_{inst} = \frac{8\pi^2}{g^2(1/R)} \gg \frac{8\pi^2}{g^2(1/\rho)}$$

R: compactification scale

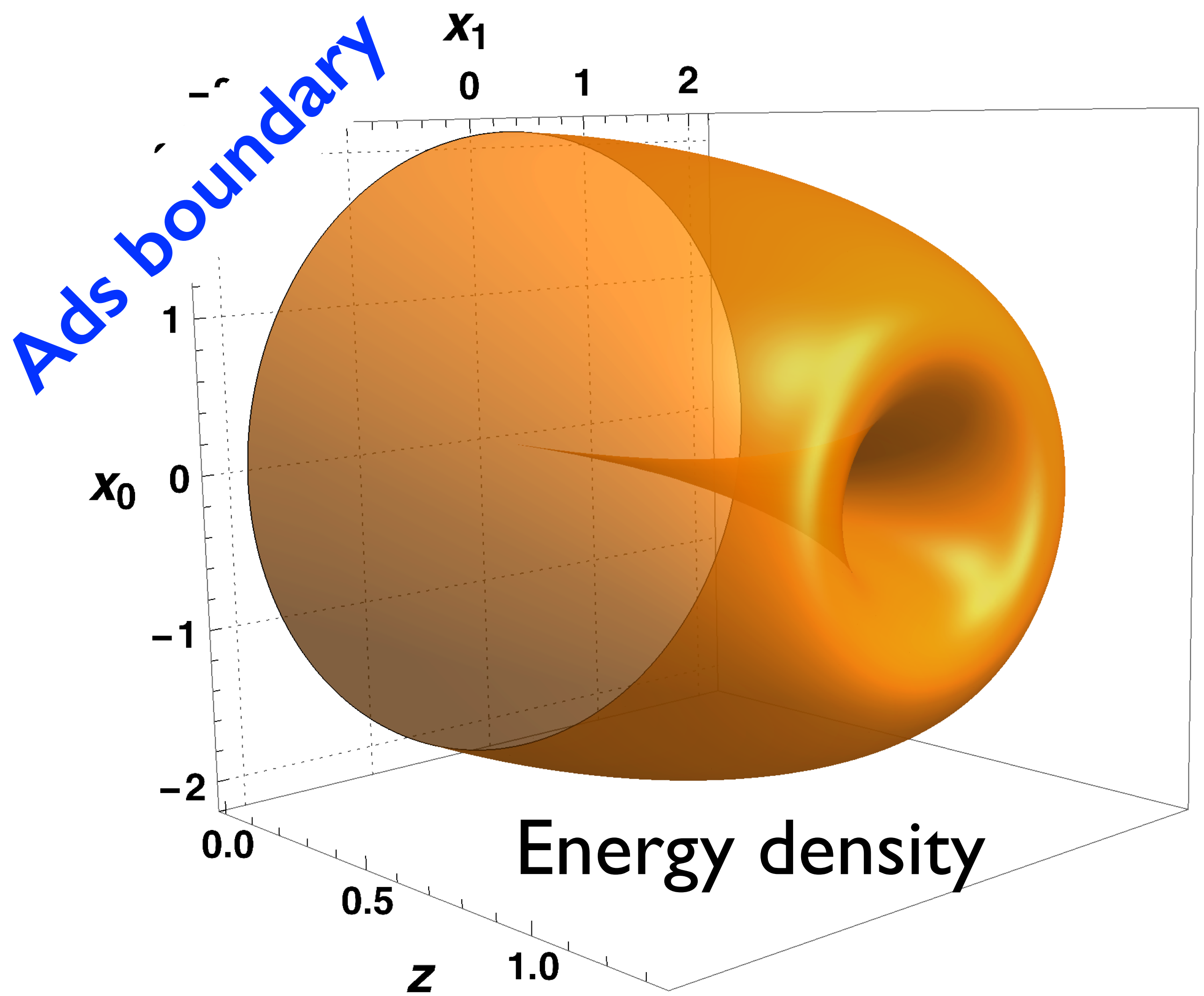
Small instanton are suppressed!

(

In the way… we have found plenty of simple analytical Instanton-Anti-instanton solutions

$$A^a_\mu(x,z) = 2\eta^a_{\mu\nu}\frac{x_\nu}{x^2}f(x,z)\ , \quad A^a_5(x,z) = 0$$

$$f(x,z) = \frac{(x^2+z^2)^2}{x^2\rho^2 + (x^2+z^2)^2}$$



obtained by conformal transformations

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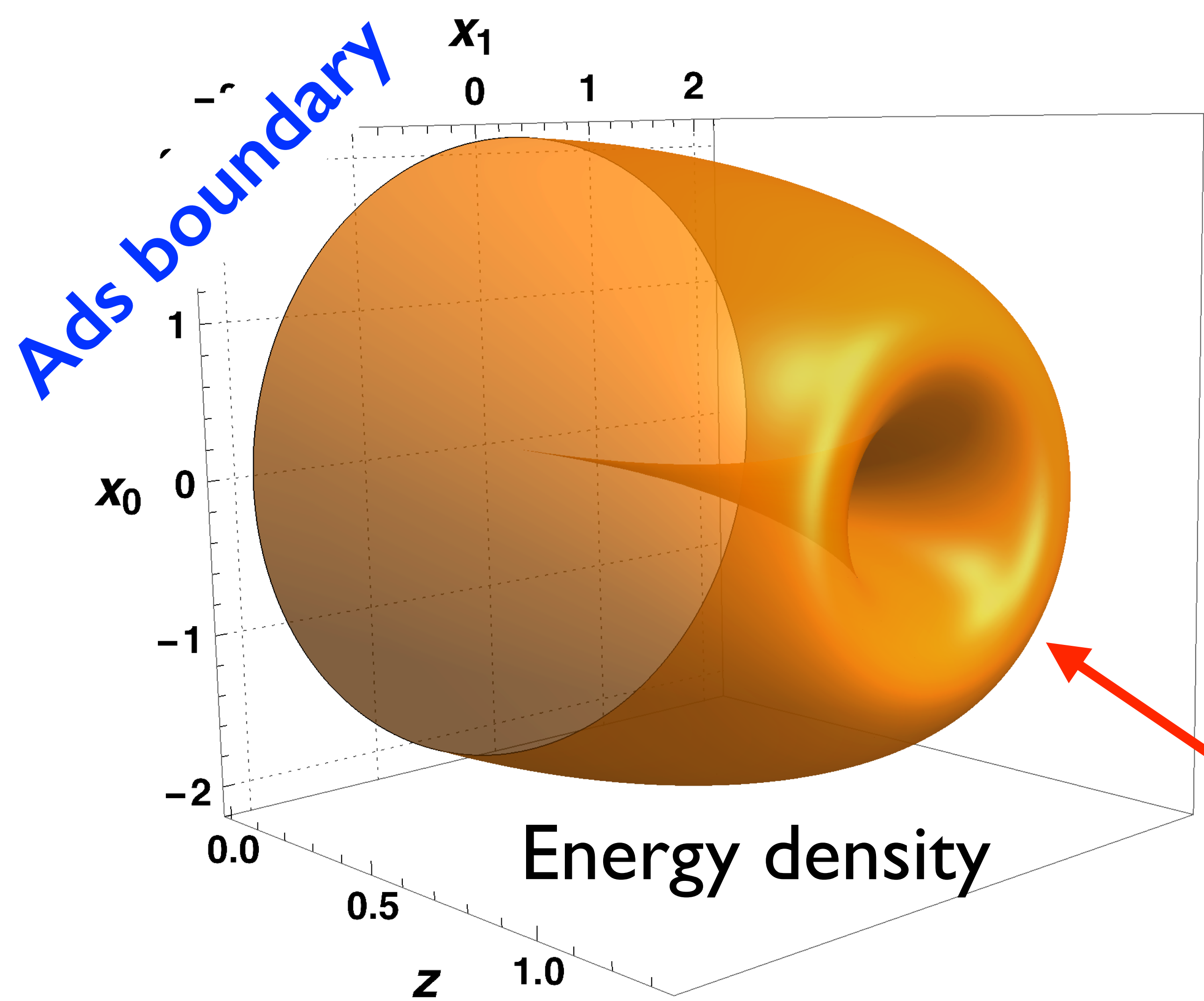
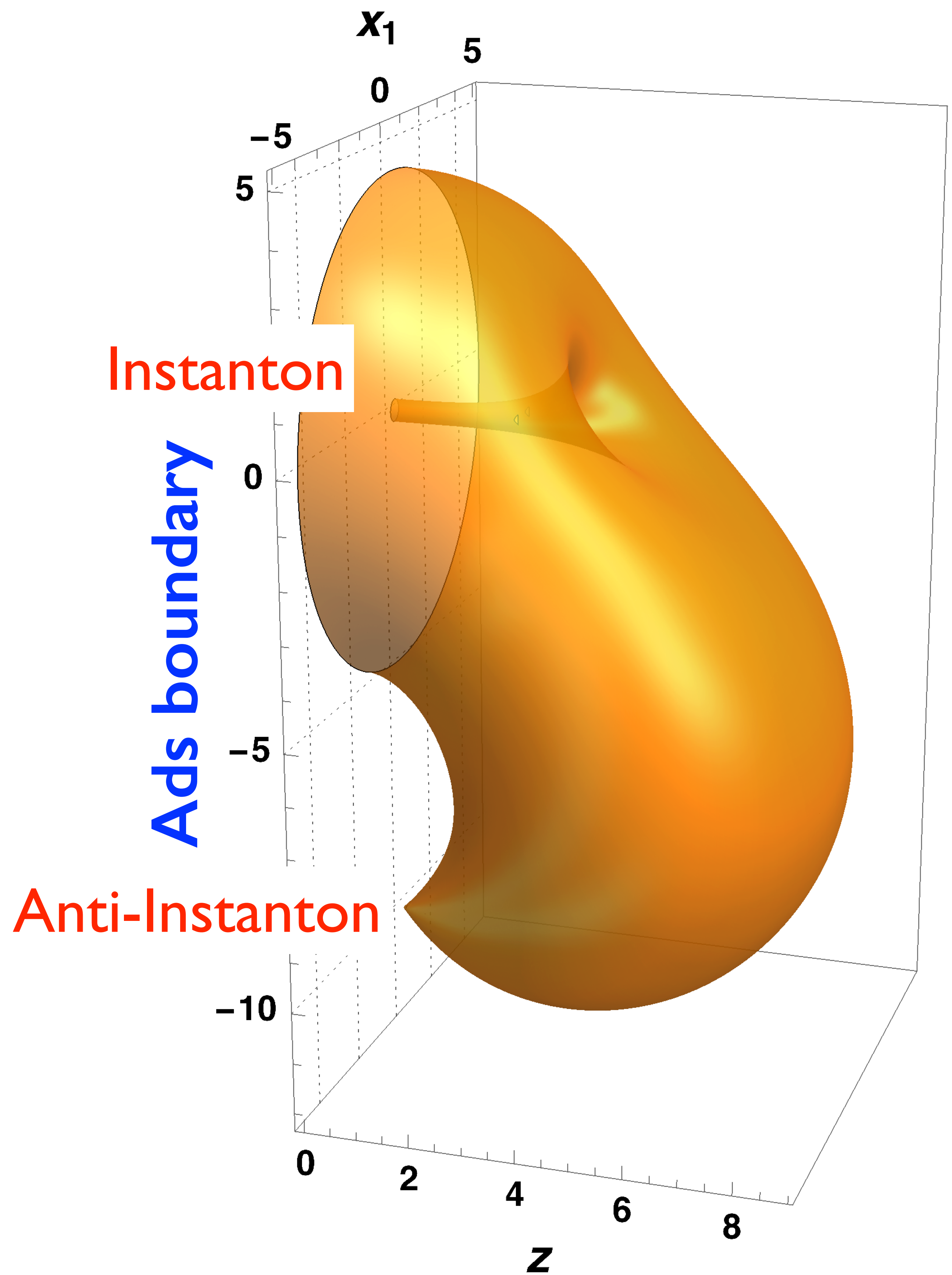


Instanton and anti-instanton annihilate at z~ρ!

consistently with charge conservarion (q=0)

obtained by conformal transformations



x_1
5
0
−5
5
Instanton
Ads boundary
0
−5
Anti-Instanton
−10
0
2
4
6
8
z

)

Conclusions

- There is the **possibility** to give contributions to the axion mass from the UV = Small instantons

- We can enhance the small instanton contribution by **enhancing the gauge coupling** in the UV

- A flat extra dimension can do it, but we must be close to the non-perturbative limit

- Small instantons in AdS_5 seem to be suppressed!

Not UV localized instantons!

although plenty of nice analytical instanton-anti-instanton solutions