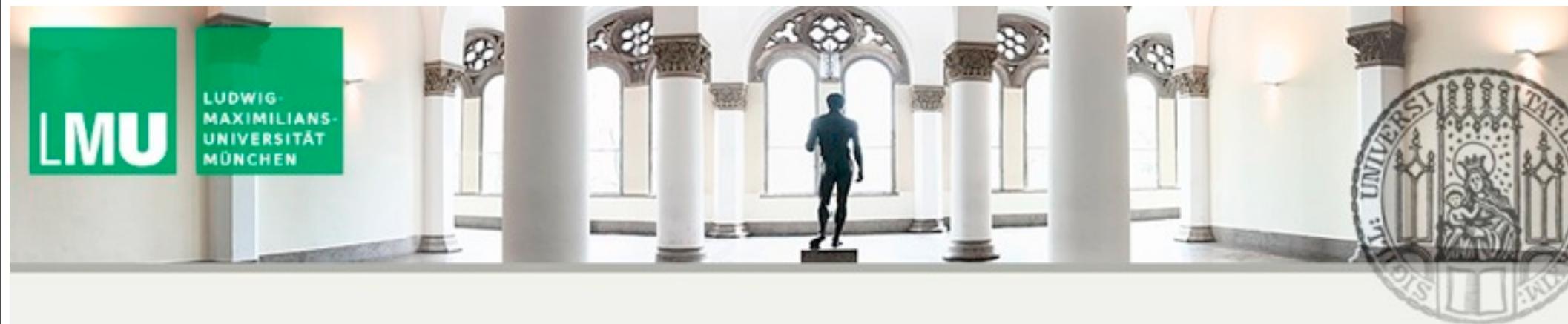


Large N Graviton Scattering and Black Hole Formation

DIETER LÜST (LMU-München, MPI)



STRINGS2015, Bengaluru, 24th. June 2015

Large N Graviton Scattering and Black Hole Formation

DIETER LÜST (LMU-München, MPI)

Work in collaboration with Gia Dvali, Cesar Gomez,
Reinke Isermann and Stephan Stieberger,
arXiv: 1409.7405

STRINGS2015, Bengaluru, 24th. June 2015

Outline:

- I) Unitarity in graviton scattering and black hole production
- II) Large N graviton scattering amplitudes at high energies in field and string theory
- III) Summary

In particular two questions and puzzles:

- What is the quantum nature of Black Holes ?
- What is the high energy behavior of graviton scattering amplitudes ?

Unitarity at tree level ?

In particular two questions and puzzles:

- **What is the quantum nature of Black Holes ?**

Two (interconnected ?) claims:
Solve these problems (partially) within Einstein gravity!

- **What is the high energy behavior of graviton scattering amplitudes ?**

Unitarity at tree level ?

In particular two questions and puzzles:

- **What is the quantum nature of Black Holes ?**

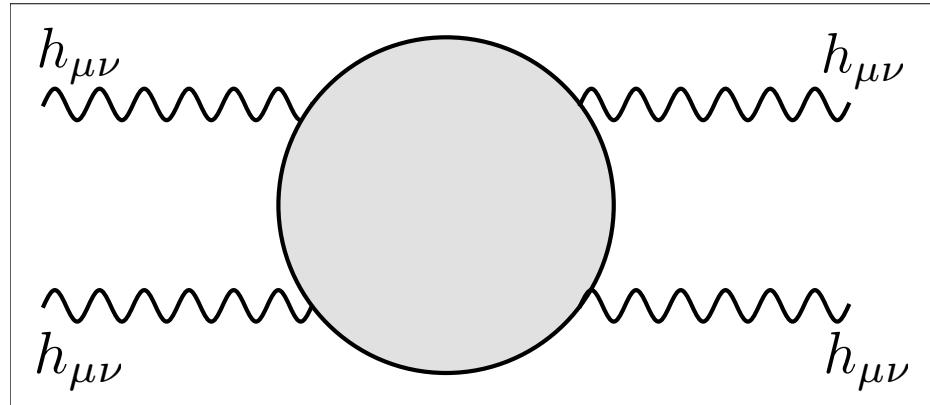
Two (interconnected ?) claims:
Solve these problems (partially) within Einstein gravity!

⇒ Classicalization & the black hole N-portrait

- **What is the high energy behavior of graviton scattering amplitudes ?**

Unitarity at tree level ?

Graviton scattering:



$$\sim s L_P^2$$

It is known that tree level graviton scattering amplitudes grow like s (center of mass energy).

⇒ **Violation of unitarity at $s = M_P^2$**

One possible solution: **Wilsonian approach:**

Amplitude is unitarized by integrating in new weakly coupled degrees of freedom of shorter and shorter wave lengths (at higher and higher energies).

However it is expected that black holes will be produced in particle scattering processes with high energies of the order

$$\sqrt{s}^{-1} < R_s \equiv \sqrt{s} L_P^2$$

['t Hooft (1987); Antoniadis, Arakani-Hamed, Dimopoulos, Dvali (1998); Banks, Fischler (1999); Dimopoulos, Landsberg (2001); Yoshino, Nambu (2002); Giddings, Thomas (2002); Eardley, Giddings (2002); Giddings, Rychkov (2004); ...]

Classicalization: Amplitudes get unitarized by classical black hole formation.

[G. Dvali, C. Gomez (2010); G. Dvali, G. Giudice, C. Gomez, A. Kehagias (2010)]

So we need a better understanding of how black holes are formed in graviton scattering amplitudes.

Black hole corpuscular N-portrait:

Quantum black hole = Bound state of N gravitons
(Bose-Einstein condensate)

[G. Dvali, C. Gomez (2011 - 2014); G. Dvali, C. Gomez, D.L. (2012)]

Black hole corpuscular N-portrait:

Quantum black hole = Bound state of N gravitons
(Bose-Einstein condensate)

Relevant properties:

[G. Dvali, C. Gomez (2011 - 2014); G. Dvali, C. Gomez, D.L. (2012)]

- N is large and the gravitons are soft.
- Interaction strength among individual gravitons is small:

$$\alpha = \frac{L_P^2}{R^2} \ll 1 \quad (R \dots \text{graviton wave length})$$

- Collective ('t Hooft like) coupling: $\lambda = \alpha N$
- Black holes are formed at the quantum critical point:

$$\lambda = 1$$

$$(R = \sqrt{N} L_P)$$

6

[G. Dvali, C. Gomez, arXiv:1207.4059;
Flassig, Pritzel, Wintergerst, arXiv:1212.3344]

Black hole bound state (at $\lambda = 1$):

- Mass and size: $M_{BH} = \sqrt{N}M_P$, $R_{BH} = \sqrt{N}L_P$
- Exponential degeneracy, entropy: $S \sim N$

Black hole bound state (at $\lambda = 1$):

- Mass and size: $M_{BH} = \sqrt{N}M_P$, $R_{BH} = \sqrt{N}L_P$
- Exponential degeneracy, entropy: $S \sim N$

Can we reconcile this picture in graviton scattering processes (expressed in terms of N and λ)?

Black hole bound state (at $\lambda = 1$):

- Mass and size: $M_{BH} = \sqrt{N}M_P$, $R_{BH} = \sqrt{N}L_P$
- Exponential degeneracy, entropy: $S \sim N$

Can we reconcile this picture in graviton scattering processes (expressed in terms of N and λ)?

Is there a signal of non-perturbative black hole physics in perturbative graviton amplitudes?

So far: computation of graviton N-point amplitudes with small N (N=4).

So far: computation of graviton N-point amplitudes with small N (N=4).

Our paper: new look at graviton scattering at trans-Planckian energy

- Explicit calculation of field theory and string amplitudes in a new kinematical large N regime, relevant for black hole production:

$$2 \longrightarrow N \quad \text{with} \quad N \rightarrow \infty$$

- We will argue that the perturbative $2 \longrightarrow N$ amplitude indeed contains relevant non-perturbative information supporting the picture of black hole production and classicalization.

Crossing the UV barrier:

The $2 \rightarrow N$ string amplitude exhibits an interesting transition property:

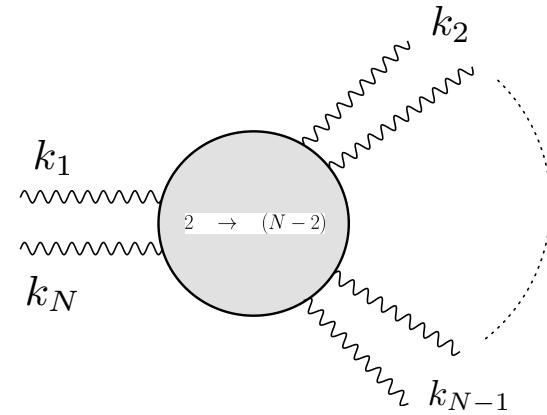
- Soft final gravitons: Unitarization by black holes.
- Hard final gravitons: Unitarization by string Regge states.

New trans-Planckian cross-over energy scale:

$$E_{\text{IR/UV}} = NM_{\text{string}}$$

II) Large N Graviton Scattering Amplitudes

$2 \rightarrow N$ graviton amplitude with high center of mass s:



$$s_{ij} = (k_i + k_j)^2 \sim \begin{cases} s, & i, j \in \{1, N\}, \\ -\frac{s}{N-2}, & i \in \{1, N\}, j \notin \{1, N\}, \\ \frac{s}{(N-2)^2}, & i, j \notin \{1, N\}. \end{cases}$$

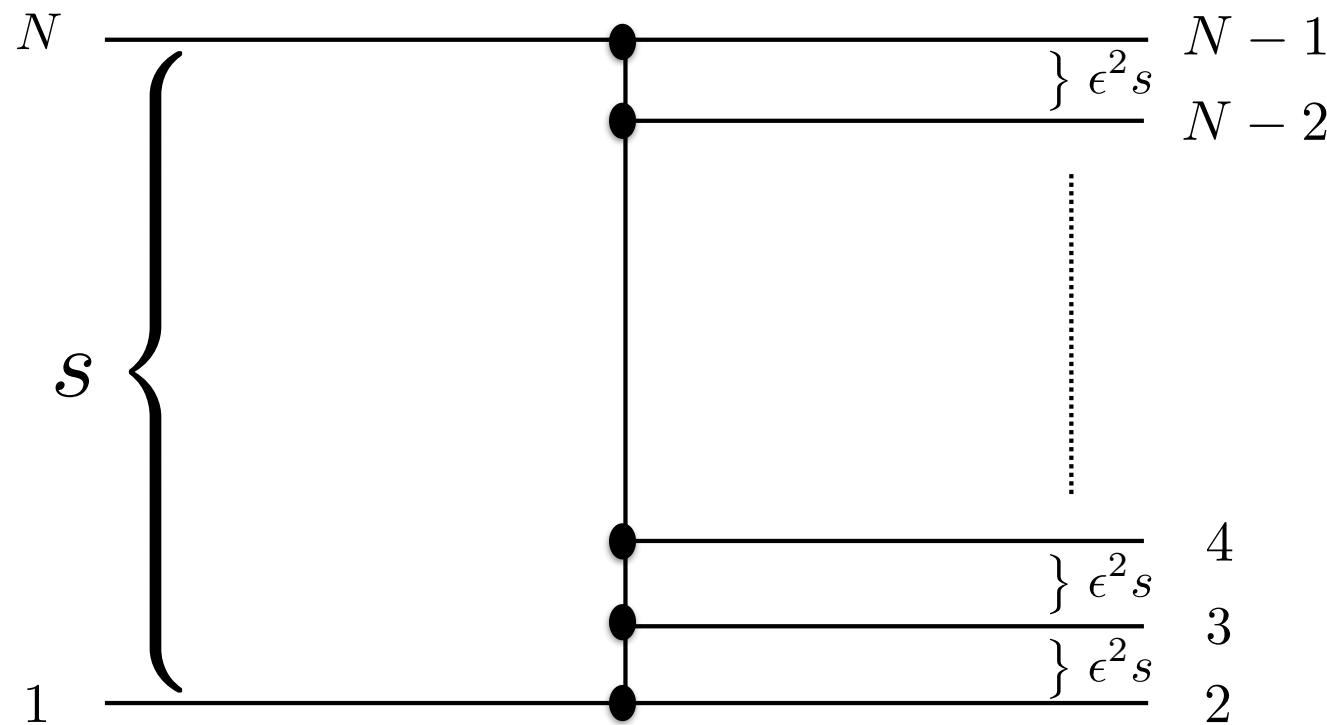
$$p_{in} \sim \sqrt{s} \text{ and } p_{out} \sim \frac{\sqrt{s}}{N-2}$$

Classicalization limit: soft gravitons in the final state.

$$s \rightarrow \infty, \quad \epsilon = \frac{1}{N-2} \rightarrow 0 \implies p_{out} < M_P$$

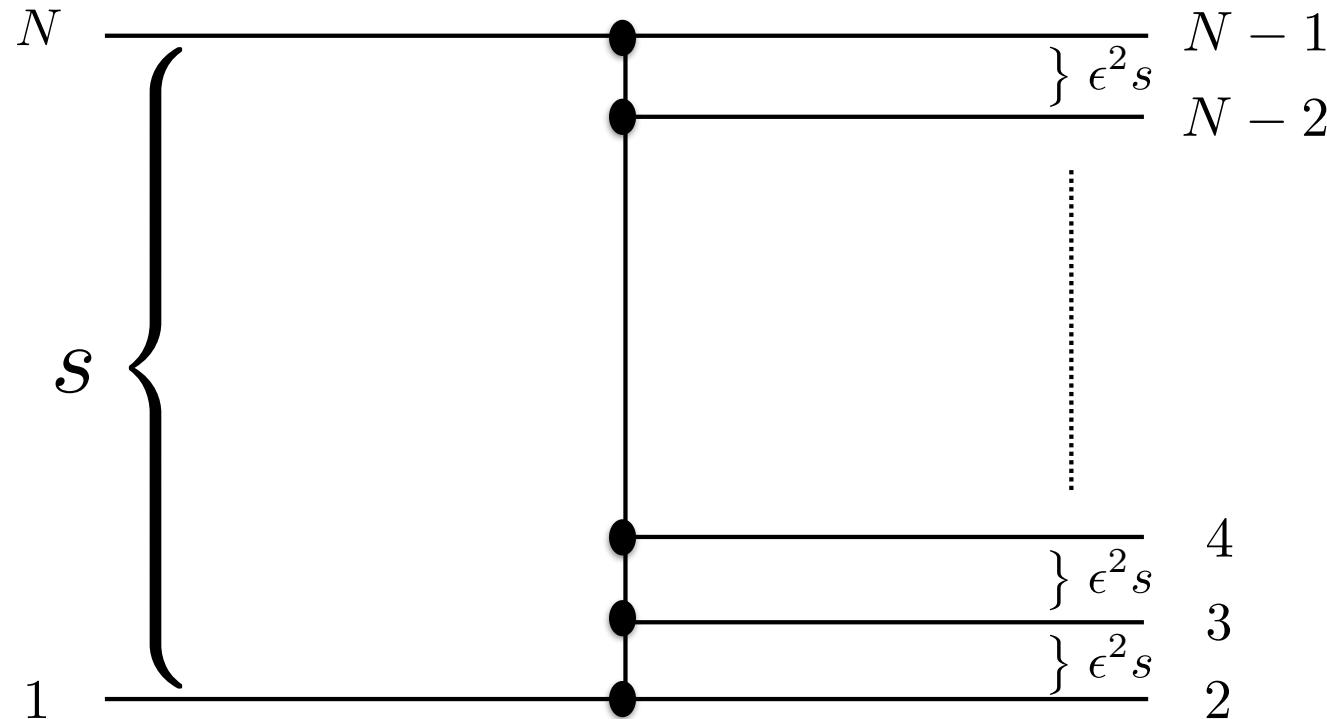
II) Large N Graviton Scattering Amplitudes

$2 \rightarrow N$ graviton amplitude with high center of mass s:



II) Large N Graviton Scattering Amplitudes

$2 \rightarrow N$ graviton amplitude with high center of mass s:



Double scaling limit: (\Rightarrow small impact parameter)

$$N \rightarrow \infty, \quad s \rightarrow \infty (\sqrt{s} \gg M_P) \quad \text{with} \quad \lambda = \frac{s}{M_P^2 N} \neq 0$$

(i) Field theory

To compute the graviton scattering amplitudes one can try on-shell methods and KLT techniques. [Kawai, Lewellen, Tye (1986)],

Problem: *KLT uses a double sum over $(N-3)!$ squares of Yang-Mills amplitudes
=> in practice very hard to perform $N \rightarrow \infty$ limit*

(i) Field theory

To compute the graviton scattering amplitudes one can try on-shell methods and KLT techniques. [Kawai, Lewellen, Tye (1986)],

Problem: KLT uses a double sum over $(N-3)!$ squares of Yang-Mills amplitudes
=> in practice very hard to perform $N \rightarrow \infty$ limit

Instead we use the CHY formula for the N-graviton amplitude:

[Cachazo, He, Yuan (2013, 2014)]

$$M_N = \int \frac{d^N \sigma}{\text{Vol } SL(2, \mathbf{C})} \prod_{a=1}^N \delta' \left(\sum_{b \neq a} \frac{s_{ab}}{\sigma_a - \sigma_b} \right) E_N^2(\{k, \xi, \sigma\})$$

integral over
N-punctured sphere

delta-function support
on solutions of
scattering equations

certain determinant (Pfaffian)
encoding external momenta k
and polarizations ξ

Scattering equations:

$$\sum_{b \neq a} \frac{s_{ab}}{\sigma_a - \sigma_b} = 0$$

$(N - 3)!$
solutions

relate space of kinematic invariants of N gravitons to that of the positions of N points on a sphere

[cfr. with twistor approach by E.Witten (2003)]

Problem: for $N > 5$ the scattering equations are very hard to solve for generic momenta.

[See L. Dolan and P. Goddard (2013/2014),
C. Baadsgaard, N. Bjerrum-Bohr, J. Bourjaily, P. Damgaard, arXiv:1506.06137]

Scattering equations:

$$\sum_{b \neq a} \frac{s_{ab}}{\sigma_a - \sigma_b} = 0$$

$(N - 3)!$
solutions

relate space of kinematic invariants of N gravitons to that of the positions of N points on a sphere

[cfr. with twistor approach by E.Witten (2003)]

Problem: for $N > 5$ the scattering equations are very hard to solve for generic momenta.

[See L. Dolan and P. Goddard (2013/2014),
C. Baadsgaard, N. Bjerrum-Bohr, J. Bourjaily, P. Damgaard, arXiv:1506.06137]

Fortunately in the **classicalization limit**, i.e. the limit we are interested in **scattering equations can be solved explicitly**

classicalization limit can be
parameterized as:

$$(\text{in units of } s/(N-2)^2) \quad \begin{aligned} s_{1,N} &= \frac{1}{2} (N-3) (N-a-b) , \\ s_{N-1,N} &= -\frac{1}{2} (N-3) (2-b) , \quad s_{1,N-1} = -\frac{1}{2} (N-3) (2-a) , \\ s_{1,i} &= -\frac{1}{2} (N-2-b) , \quad s_{i,N} = -\frac{1}{2} (N-2-a) , \\ s_{N-1,i} &= \frac{1}{2} (4-a-b) , \quad s_{ij} = 1 \quad , \quad i,j \in \{2, \dots, N-2\} , \end{aligned}$$

this gives rise to a two-parameter a, b solution, which is $(N-3)!$ -fold degenerate

This parametrization can be mapped to a problem
 Kalousios (2013) has already studied:
 Solutions of scattering equations are identified with the
 zeros of Jacobi polynomials.

$$M_N(1, \dots, N) = -\kappa^{N-2} 2^{8-N} \frac{s}{(N-2)^2} [(N-3)!!]^2 \frac{\Gamma(\frac{a}{2}) \Gamma(\frac{3}{2} + \frac{b-N}{2}) \Gamma(\frac{1-N+a+b}{2})}{\Gamma(1 + \frac{a-N}{2}) \Gamma(\frac{b-1}{2}) \Gamma(\frac{a+b-3}{2})} \\ \times \frac{\Gamma(\frac{3}{2} + \frac{a-N}{2}) \Gamma(\frac{b}{2}) \Gamma(\frac{a+b-2}{2})}{\Gamma(1 + \frac{b-N}{2}) \Gamma(\frac{a-1}{2}) \Gamma(\frac{a+b-N}{2})} H_N(a, b)^2$$

Exact in any real a,b and N

$$\xrightarrow{N \rightarrow \infty} \kappa^N \frac{s}{N^2} N!$$

This parametrization can be mapped to a problem
Kalousios (2013) has already studied:

Solutions of scattering equations are identified with the
zeros of Jacobi polynomials.

$$M_N(1, \dots, N) = -\kappa^{N-2} 2^{8-N} \frac{s}{(N-2)^2} [(N-3)!!]^2 \frac{\Gamma(\frac{a}{2}) \Gamma(\frac{3}{2} + \frac{b-N}{2}) \Gamma(\frac{1-N+a+b}{2})}{\Gamma(1 + \frac{a-N}{2}) \Gamma(\frac{b-1}{2}) \Gamma(\frac{a+b-3}{2})} \\ \times \frac{\Gamma(\frac{3}{2} + \frac{a-N}{2}) \Gamma(\frac{b}{2}) \Gamma(\frac{a+b-2}{2})}{\Gamma(1 + \frac{b-N}{2}) \Gamma(\frac{a-1}{2}) \Gamma(\frac{a+b-N}{2})} H_N(a, b)^2$$

Field
theory
amplitude!

Exact in any real a, b and N

$$N \rightarrow \infty \quad \kappa^N \frac{s}{N^2} N!$$

Note: Incidentally the solutions to the scattering
equations describe the saddle point contributions in the
high-energy limit of open and closed string amplitudes
(Gross, Mende) → see next part of the talk.

To obtain the physical probability, i.e. the S-matrix element, we have to consider phase space integral:

$$d|\langle 2|S|N-2\rangle|^2 = \frac{1}{(N-2)!} \prod_{i=2}^{N-1} dp_i^4 |M_N|^2 \delta^4(P_{total})$$

$$\left(p_{in} \sim \sqrt{s} , p_{out} \sim \frac{\sqrt{s}}{N-2} \right)$$

Physical $2 \rightarrow N-2$ perturbative, scattering probability in classicalization regime:

$$|\langle 2|S|N-2\rangle|^2 = \left(\frac{L_P^2 s}{N^2} \right)^N N! = \left(\frac{\lambda}{N} \right)^N N! \sim e^{-N} \lambda^N$$

Collective coupling $\lambda \equiv \alpha N = s/M_P^2 N$

This perturbative scattering probability possesses a maximum at the following critical value for N:

$$N_{crit} = sL_P^2 \iff \lambda_{crit} = 1$$

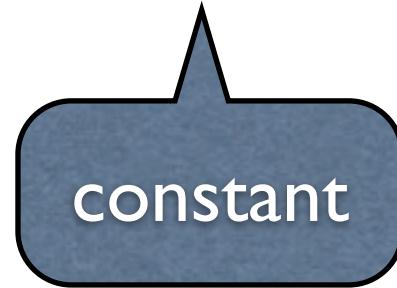
This perturbative scattering probability possesses a maximum at the following critical value for N:

$$N_{crit} = sL_P^2 \iff \lambda_{crit} = 1$$

Remark: similar calculations can be done for scalar field theories, like $\lambda\phi^4$.

In this case the amplitudes show a different large N behavior:

$$A_N^2 \simeq \lambda^N N!$$



Connection of the perturbative amplitude to the non-perturbative black hole bound state:

Connection of the perturbative amplitude to the non-perturbative black hole bound state:

The perturbative amplitude is suppressed by e^{-N} .

This is just the inverse of the degeneracy of states of a black hole with entropy $\mathcal{S} \sim N$.

Therefore this suppression factor is compensated at the critical point $\lambda = 1$ by e^N from the degeneracy of black hole states:

$$A_{BH} \sim \sum_j |\langle 2|S|N\rangle_p|^2 |\langle N|BH\rangle_j|_{np}^2 \sim \lambda^N e^{-N}|_p \times e^N|_{np}$$

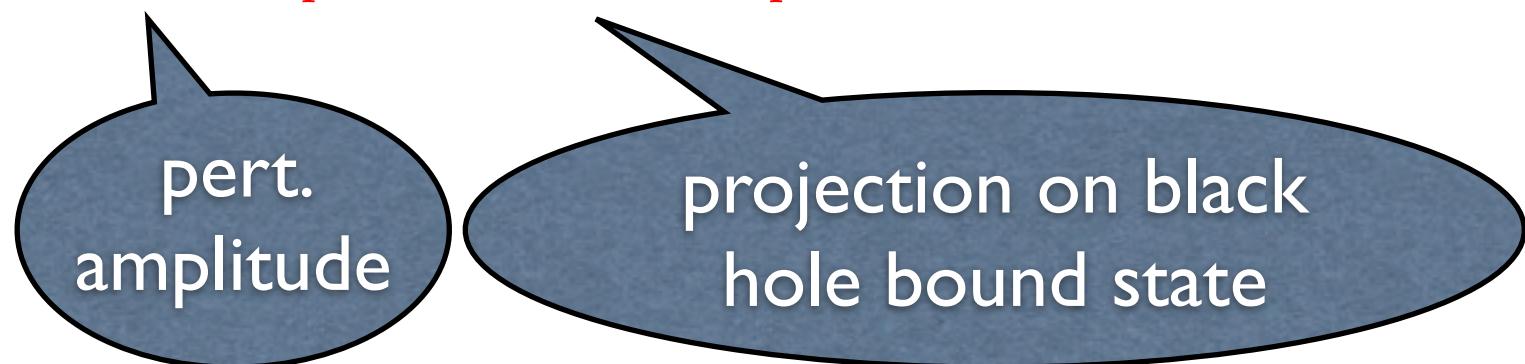
Connection of the perturbative amplitude to the non-perturbative black hole bound state:

The perturbative amplitude is suppressed by e^{-N} .

This is just the inverse of the degeneracy of states of a black hole with entropy $\mathcal{S} \sim N$.

Therefore this suppression factor is compensated at the critical point $\lambda = 1$ by e^N from the degeneracy of black hole states:

$$A_{BH} \sim \sum_j |\langle 2|S|N\rangle|_p^2 |\langle N|BH\rangle_j|_{np}^2 \sim \lambda^N e^{-N}|_p \times e^N|_{np}$$



Connection of the perturbative amplitude to the non-perturbative black hole bound state:

The perturbative amplitude is suppressed by e^{-N} .

This is just the inverse of the degeneracy of states of a black hole with entropy $\mathcal{S} \sim N$.

Therefore this suppression factor is compensated at the critical point $\lambda = 1$ by e^N from the degeneracy of black hole states:

$$A_{BH} \sim \sum_j |\langle 2|S|N\rangle_p|^2 |\langle N|BH\rangle_j|_{np}^2 \sim \lambda^N e^{-N}|_p \times e^N|_{np}$$

So, black hole is exactly dominating at $\lambda = 1$.

In summary:

- Perturbative $2 \rightarrow N$ graviton amplitude:

$$|M_N^{pert.}|^2 \simeq \lambda^N e^{-N}, \quad \lambda = s/(M_P^2 N)$$

In summary:

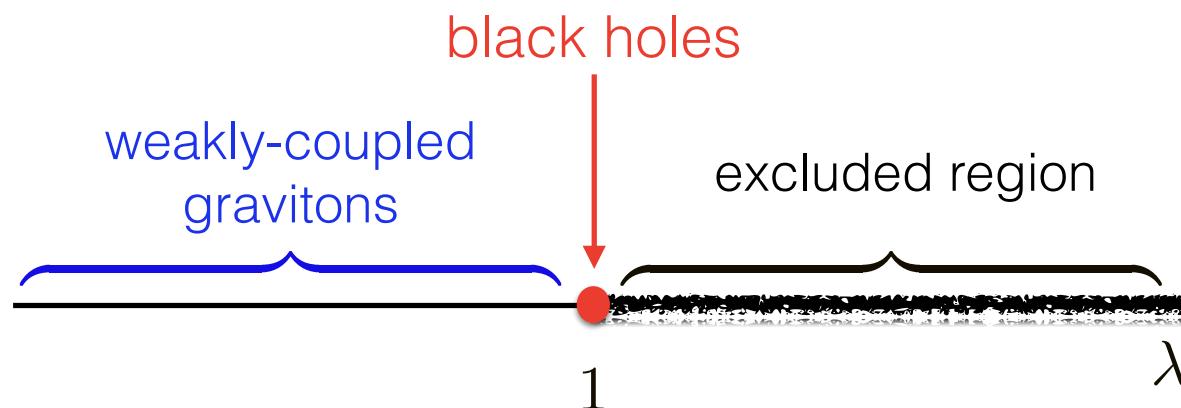
- Perturbative $2 \rightarrow N$ graviton amplitude:

$$|M_N^{\text{pert.}}|^2 \simeq \lambda^N e^{-N}, \quad \lambda = s/(M_P^2 N)$$

- Non-perturbative enhancement at $\lambda = 1$ due to black hole entropy factor : e^N

$$|M_N^{\text{n.p.}}|^2 \simeq \lambda^N$$

(fully saturated at $\lambda = 1$)



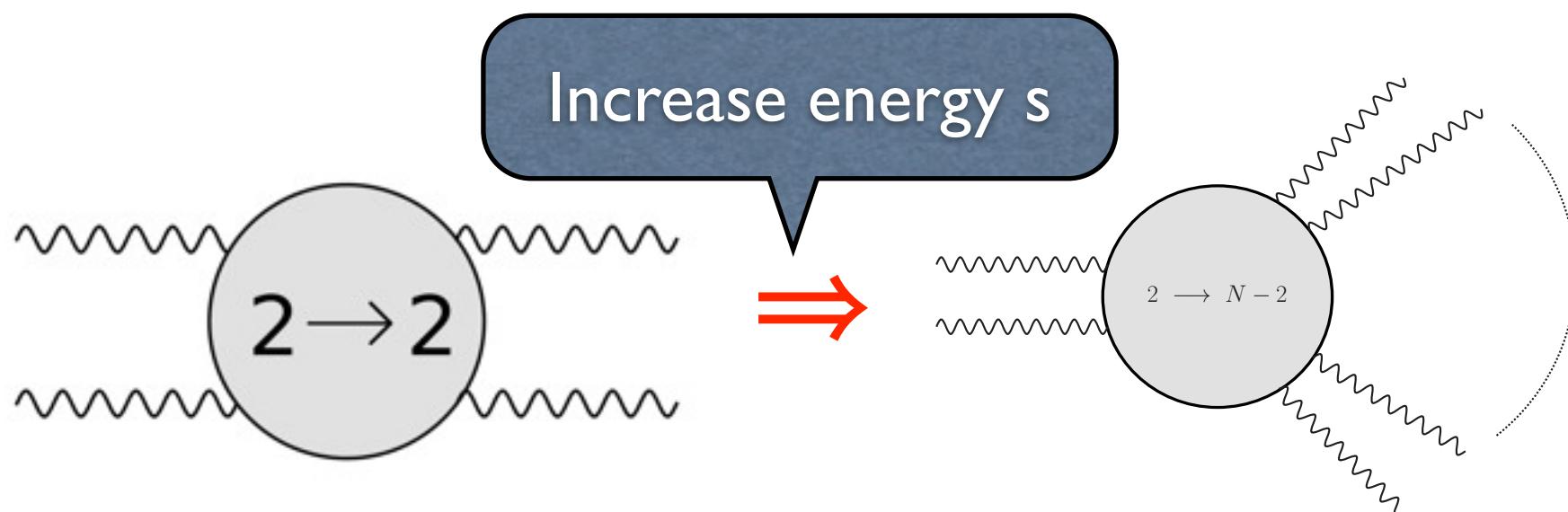
For large s unitarization occurs if N increases appropriately:

This bound implies that

$$N \gtrsim N_{crit} = sL_P^2$$

This is the core of the idea of classicalization!

N should be larger than the corresponding entropy of a black hole with mass equal to the center of mass energy.



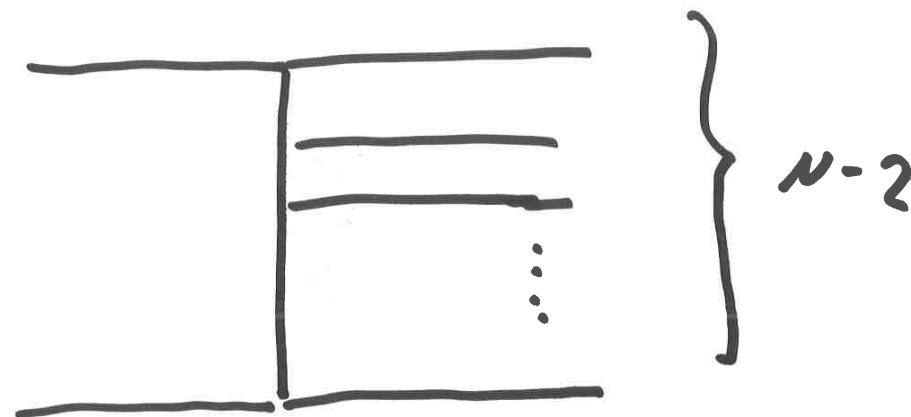
However there remain still some UV problems:

What is happening in the regime where $\lambda > 1$?

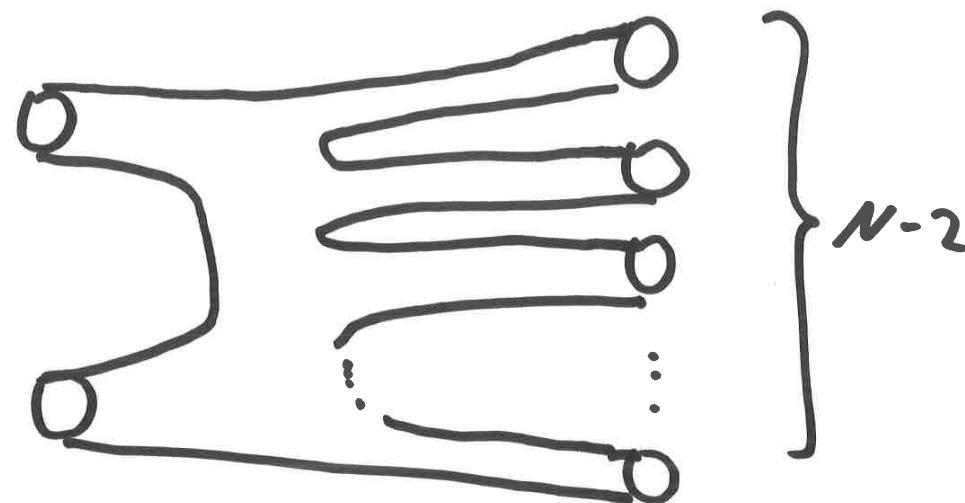
$$N < N_{crit} = sL_P^2$$

(ii) Closed string theory

F.T. :



S.T.



High energy behavior of open/closed string amplitudes shows exponential fall off due to Regge modes.

[Veneziano (1968); Amati, Ciafaloni, Veneziano (1987); Gross, Mende (1987), Gross, Manes (1989)]

Example: 4-point graviton amplitude

$$\mathcal{M}_4 \sim K \frac{\Gamma(-\frac{\alpha'}{4}s)\Gamma(-\frac{\alpha'}{4}t)\Gamma(-\frac{\alpha'}{4}u)}{\Gamma(\frac{\alpha'}{4}s)\Gamma(\frac{\alpha'}{4}t)\Gamma(\frac{\alpha'}{4}u)}$$
$$\longrightarrow_{\alpha' \rightarrow \infty} \kappa^2 |A_4|^2 \times 4\pi\alpha' \frac{st}{u} \exp\left\{ \frac{\alpha'}{2}(s \ln |s| + t \ln |t| + u \ln |u|) \right\}$$

High energy behavior of open/closed string amplitudes shows exponential fall off due to Regge modes.

[Veneziano (1968); Amati, Ciafaloni, Veneziano (1987); Gross, Mende (1987), Gross, Manes (1989)]

Example: 4-point graviton amplitude

$$\mathcal{M}_4 \sim K \frac{\Gamma(-\frac{\alpha'}{4}s)\Gamma(-\frac{\alpha'}{4}t)\Gamma(-\frac{\alpha'}{4}u)}{\Gamma(\frac{\alpha'}{4}s)\Gamma(\frac{\alpha'}{4}t)\Gamma(\frac{\alpha'}{4}u)}$$

$$\longrightarrow_{\alpha' \rightarrow \infty} \kappa^2 |A_4|^2 \times 4\pi \alpha' \frac{st}{u} \exp \left\{ \frac{\alpha'}{2} (s \ln |s| + t \ln |t| + u \ln |u|) \right\}$$

Square of
YM-amplitude

High energy behavior of open/closed string amplitudes shows exponential fall off due to Regge modes.

[Veneziano (1968); Amati, Ciafaloni, Veneziano (1987); Gross, Mende (1987), Gross, Manes (1989)]

Example: 4-point graviton amplitude

$$\mathcal{M}_4 \sim K \frac{\Gamma(-\frac{\alpha'}{4}s)\Gamma(-\frac{\alpha'}{4}t)\Gamma(-\frac{\alpha'}{4}u)}{\Gamma(\frac{\alpha'}{4}s)\Gamma(\frac{\alpha'}{4}t)\Gamma(\frac{\alpha'}{4}u)}$$

$$\longrightarrow_{\alpha' \rightarrow \infty} \kappa^2 |A_4|^2 \times 4\pi \alpha' \frac{st}{u} \exp \left\{ \frac{\alpha'}{2} (s \ln |s| + t \ln |t| + u \ln |u|) \right\}$$

Square of
YM-amplitude

Momentum
kernel

High energy behavior of open/closed string amplitudes shows exponential fall off due to Regge modes.

[Veneziano (1968); Amati, Ciafaloni, Veneziano (1987); Gross, Mende (1987), Gross, Manes (1989)]

Example: 4-point graviton amplitude

$$\mathcal{M}_4 \sim K \frac{\Gamma(-\frac{\alpha'}{4}s)\Gamma(-\frac{\alpha'}{4}t)\Gamma(-\frac{\alpha'}{4}u)}{\Gamma(\frac{\alpha'}{4}s)\Gamma(\frac{\alpha'}{4}t)\Gamma(\frac{\alpha'}{4}u)}$$

$$\longrightarrow_{\alpha' \rightarrow \infty} \kappa^2 |A_4|^2 \times 4\pi\alpha' \frac{st}{u} \exp\left\{ \frac{\alpha'}{2}(s \ln |s| + t \ln |t| + u \ln |u|) \right\}$$

Square of
YM-amplitude

Momentum
kernel

String
form factor

High energy behavior of open/closed string amplitudes shows exponential fall off due to Regge modes.

[Veneziano (1968); Amati, Ciafaloni, Veneziano (1987); Gross, Mende (1987), Gross, Manes (1989)]

Example: 4-point graviton amplitude

$$\mathcal{M}_4 \sim K \frac{\Gamma(-\frac{\alpha'}{4}s)\Gamma(-\frac{\alpha'}{4}t)\Gamma(-\frac{\alpha'}{4}u)}{\Gamma(\frac{\alpha'}{4}s)\Gamma(\frac{\alpha'}{4}t)\Gamma(\frac{\alpha'}{4}u)}$$

$$\longrightarrow_{\alpha' \rightarrow \infty} \kappa^2 |A_4|^2 \times 4\pi\alpha' \frac{st}{u} \exp\left\{ \frac{\alpha'}{2}(s \ln |s| + t \ln |t| + u \ln |u|) \right\}$$

Square of
YM-amplitude

Momentum
kernel

String
form factor

(Note: this was basically the state of the art before our paper.)

Generalization to arbitrary (large) N:

High energy limit: use of scattering equations:

$$\mathcal{M}(1, \dots, N) = \kappa^{N-2} (4\pi\alpha')^{N-3} \sum_{a=1}^{(N-3)!} \frac{\left(\prod_{i < j}^N |z_{ij}^{(a)}|^{\frac{\alpha'}{2}s_{ij}} \right)}{\det' \Phi(z^{(a)})^{1/2} \det' \Phi(\bar{z}^{(a)})^{1/2}} E_N(\{k, \xi, z^{(a)}\})^2 + \mathcal{O}(\alpha'^{-1})$$

↑
 ↑
 N closed string tree-level amplitude sum over the $(N-3)!$ solutions of scattering equations

← Koba-Nielsen factor
 ← Jacobian/Hessian from saddle point approximation

Again in the classicalization limit we obtain the explicit result for arbitrary N :

$$\begin{aligned} \mathcal{M}_N &= (4\pi\alpha')^{N-3} \prod_{\nu=1}^{N-3} \left(\frac{\nu^\nu (\alpha + \nu)^{\alpha+\nu} (\beta + \nu)^{\beta+\nu}}{(\alpha + \beta + N - 3 + \nu)^{\alpha+\beta+N-3+\nu}} \right)^{\frac{\alpha' s}{4}} \\ &\times M_N^{FT} + \mathcal{O}((\alpha' s)^{-1}) \end{aligned}$$

Generalization to arbitrary (large) N:

High energy limit: use of scattering equations:

$$\mathcal{M}(1, \dots, N) = \kappa^{N-2} (4\pi\alpha')^{N-3} \sum_{a=1}^{(N-3)!} \frac{\left(\prod_{i < j}^N |z_{ij}^{(a)}|^{\frac{\alpha'}{2}s_{ij}} \right)}{\det' \Phi(z^{(a)})^{1/2} \det' \Phi(\bar{z}^{(a)})^{1/2}} E_N(\{k, \xi, z^{(a)}\})^2 + \mathcal{O}(\alpha'^{-1})$$

↑
 N closed string tree-level amplitude
 ↑
 sum over the $(N-3)!$ solutions of scattering equations
 ↙
 Jacobian/Hessian from saddle point approximation

Again in the classicalization limit we obtain the explicit result for arbitrary N :

$$\begin{aligned} \mathcal{M}_N &= (4\pi\alpha')^{N-3} \prod_{\nu=1}^{N-3} \left(\frac{\nu^\nu (\alpha + \nu)^{\alpha+\nu} (\beta + \nu)^{\beta+\nu}}{(\alpha + \beta + N - 3 + \nu)^{\alpha+\beta+N-3+\nu}} \right)^{\frac{\alpha' s}{4}} \\ &\times M_N^{FT} + \mathcal{O}((\alpha' s)^{-1}) \end{aligned}$$

String form factor

Two different energy regimes:

$$(i) \quad \frac{\sqrt{s}}{N} < M_s : \iff \lambda < Ng_s^2$$

„infrared“, field theory regime

Field and ST theory amplitudes agree.

This was already conjectured for the MHV case up to 5 points by [Cheung, O'Connell, Wecht (2010)]

$$F_N = 1 \Rightarrow \mathcal{M}_N = M_N^{FT}$$

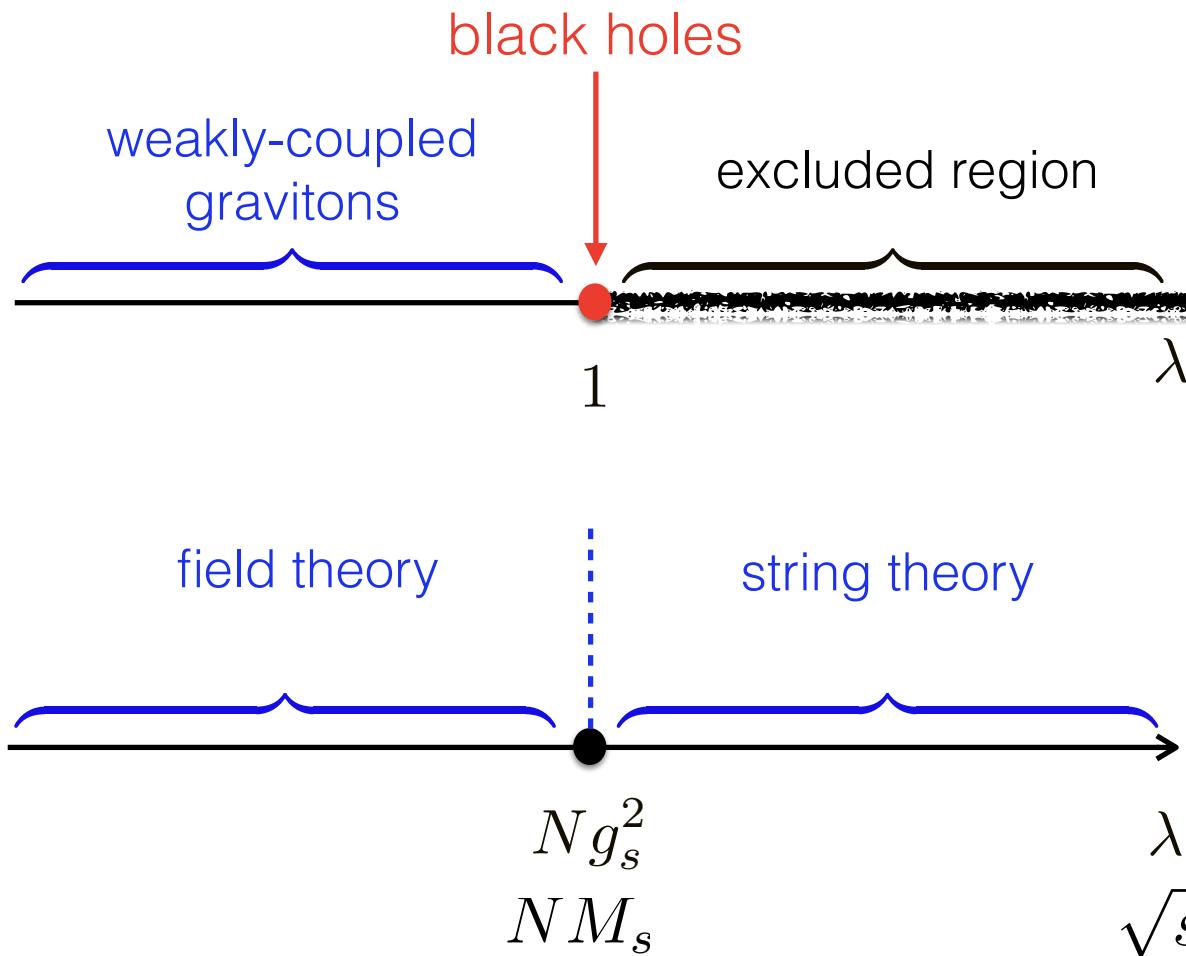
$$(ii) \quad \frac{\sqrt{s}}{N} > M_s : \iff \lambda > Ng_s^2$$

„ultraviolet“, string theory regime

$$\mathcal{M}_N \sim \kappa^{N-2} \alpha'^{N-3} s e^{-\frac{\alpha'}{2}(N-3)} s \ln(\alpha' s)$$

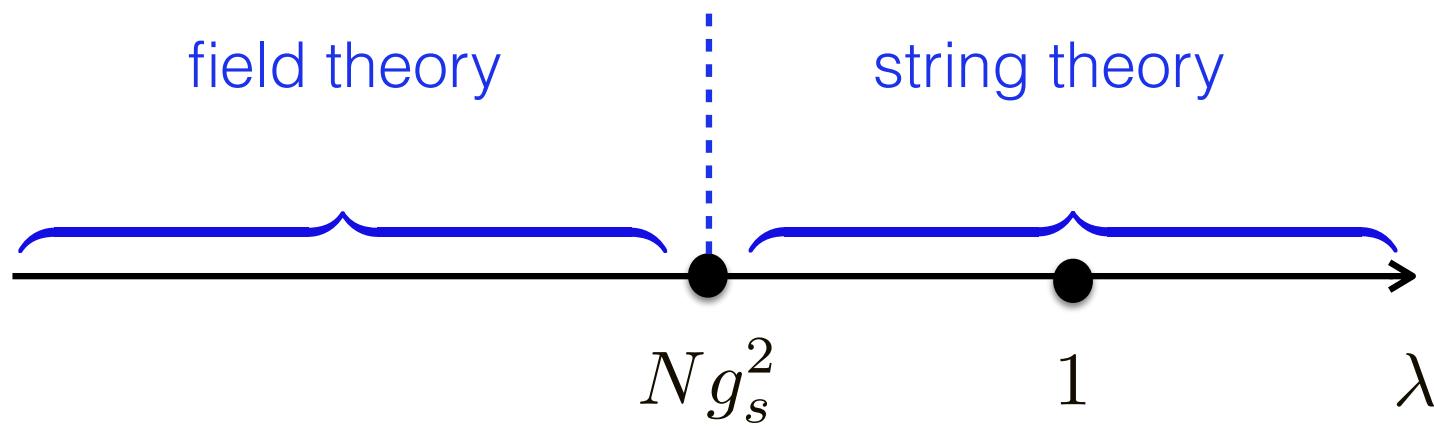
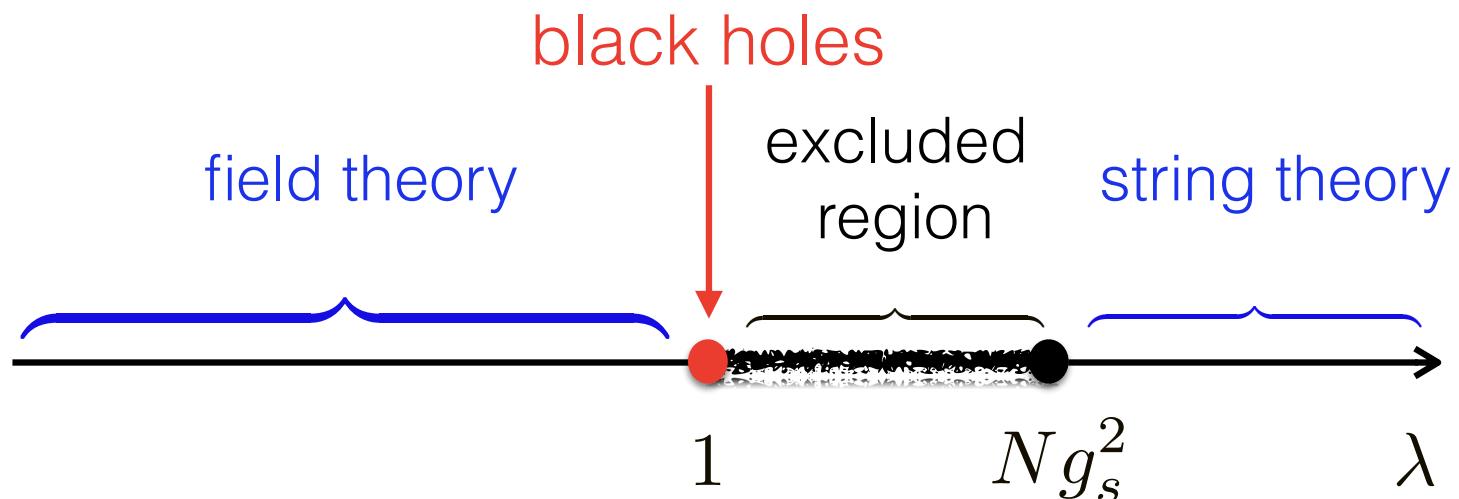
String states dominate.

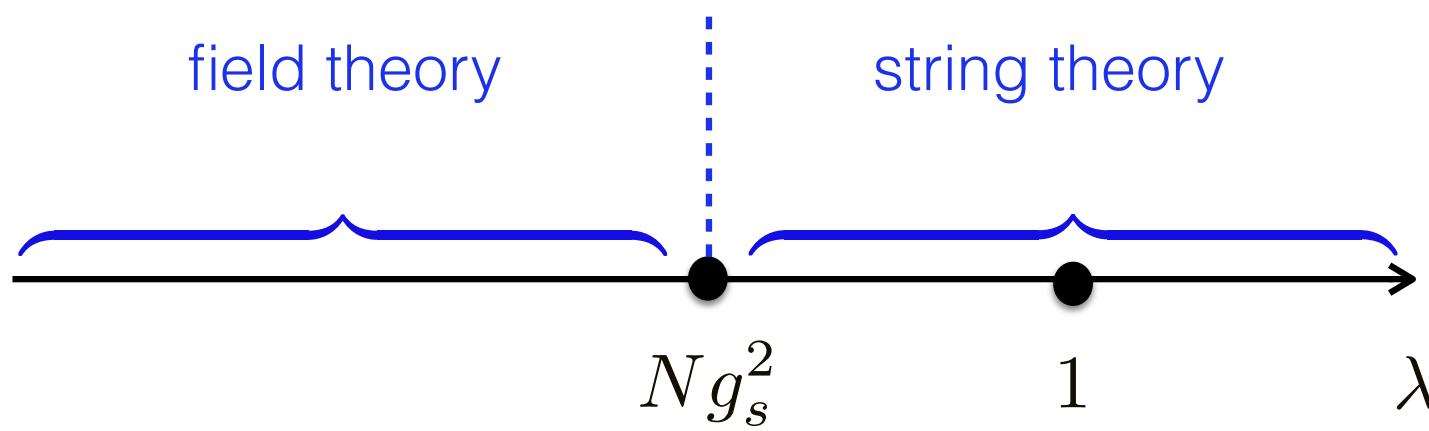
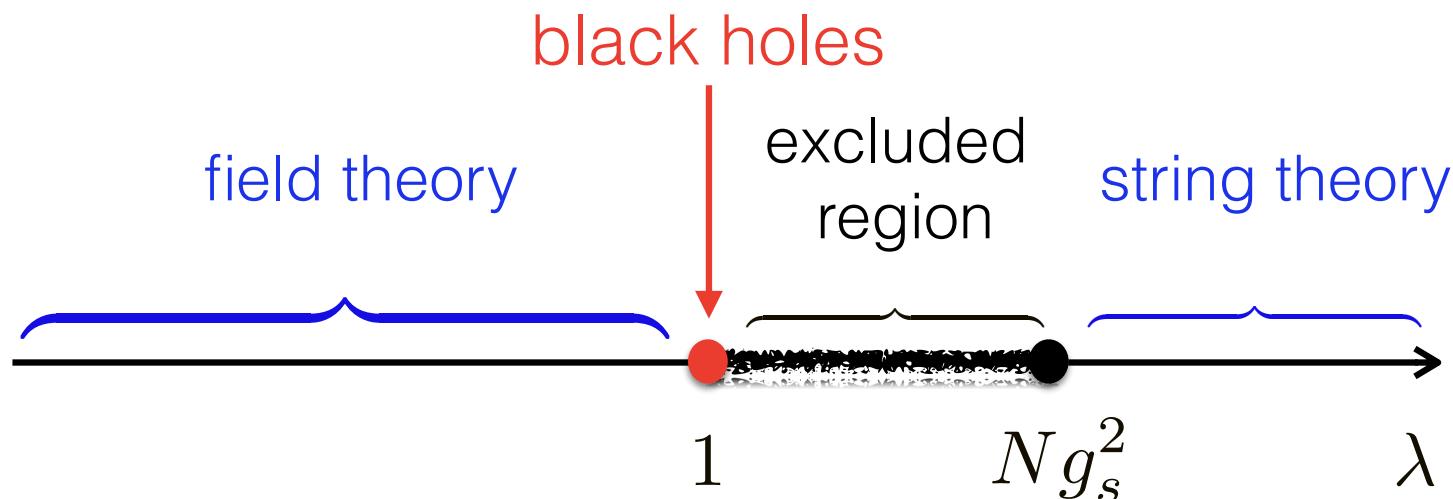
Amplitude gets tamed by string states (Regge modes).



Transition occurs at $E_{\text{IR/UV}} = NM_{\text{string}}$

Gravitons in final state become hard: $E_{\text{final}} > M_s$





Consistency for all λ

What is happening at the point $\lambda = Ng_s^2 = 1$?

Here the F.T. amplitude agrees with the string amplitude at the critical point $\lambda = 1$.

This the point where the **string effects** match the amplitude from the F.T. **black hole formation**.

$g_s = \frac{1}{\sqrt{N}}$ \Rightarrow **String - black hole correspondence:**

black hole can be described by a **state of strings**.

[Horowitz, Polchinski (1996); Dvali, D.L. (2009); Dvali, Gomez (2010)]

Here the **IR** is meeting the **UV**.

Is there possibly any relation between the limit of large number N of gravitons and the large N_c limit in Yang-Mills gauge theories?

Is there possibly any relation between the limit of large number N of gravitons and the large N_c limit in Yang-Mills gauge theories?

- Relation between open and closed string coupling:

$$g_s = g_{open}^2$$

- At point of string-bh correspondence: $g_s = 1/\sqrt{N}$

- Planar limit of gauge theory: $g_{open}^2 = 1/N_c$

Is there possibly any relation between the limit of large number N of gravitons and the large N_c limit in Yang-Mills gauge theories?

- Relation between open and closed string coupling:

$$g_s = g_{open}^2$$

- At point of string-bh correspondence: $g_s = 1/\sqrt{N}$

- Planar limit of gauge theory: $g_{open}^2 = 1/N_c$

So naively we get:

$$N = N_c^2$$

What is the interpretation of this relation?

Summary:

- New computation of N-point gravity (**string**) amplitudes in trans-planckian large N region in closed form
- We found evidence for classicalization and black hole production (black hole N-portrait) in field theory.
- We found an interesting trans-Planckian transition between field theory and string theory: string - black hole correspondence.

Next steps:

[Stieberger (2009); Stieberger, Taylor (2014); Cachazo, He, Yuan (2014)]

- Mixed gauge boson (open)/gravity (closed) amplitudes:
Bh N-portrait with matter
[Dvali, Gomez, D.L. (2013)]
- Bh N-portrait beyond tree level
First steps in [Kuhnel, Sundborg (2014)]