Probing Conformal Field Theories

Tomeu Fiol
Universitat de Barcelona

Overview of work done in collaboration with
Blai Garolera, Alberto Güijosa, Aitor Lewkowycz,
Juan Pedraza and Genís Torrents

Probing a CFT

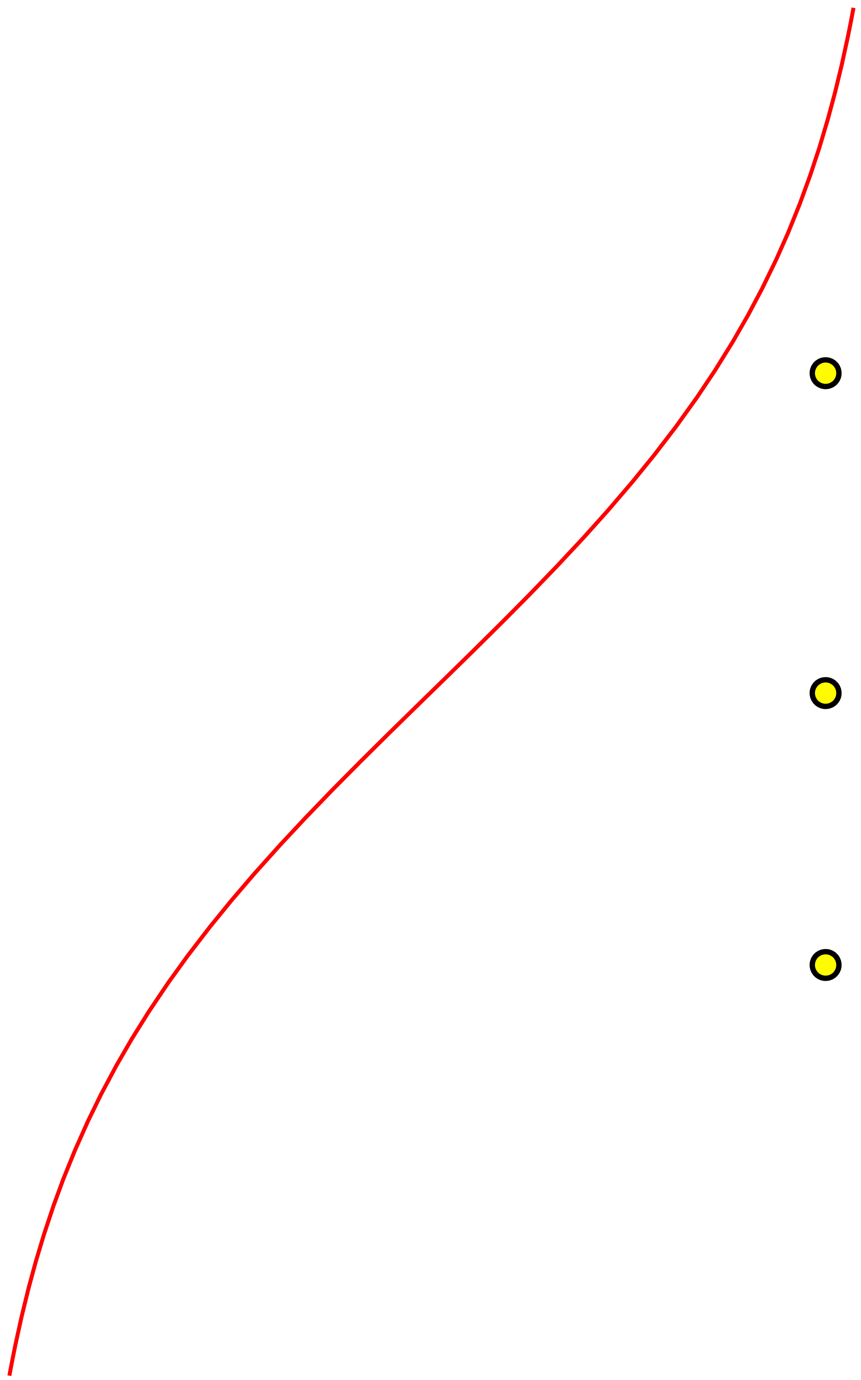
- Consider a heavy probe coupled to a CFT, in some rep. of the gauge group.

- It may be coupled to additional fields.

- Its world-line is prescribed. It defines a line operator (Wilson line,....).

- What are the fields it creates? Energy radiated? Momentum fluctuations?.....

Probing a CFT



- Timelike curve **C**
- Electrically/magnetically charged
- Representation **R** of **G**

→ Wilson operator, ‘t Hooft operator,….

An example: Maxwell theory

Static Particle

$$< \mathcal{L}(\vec{x}) > = q^2 \frac{1}{|\vec{x}|^4}$$

Coulomb

$$\mathcal{L} \sim F^2 \sim E^2 - \cancel{B^2}$$

Accelerated Particle

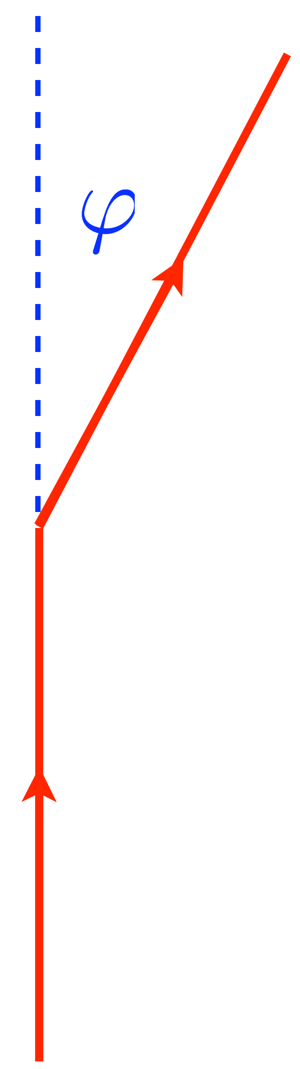
$$P = \frac{2}{3} q^2 \; a^\mu a_\mu$$

Larmor

Plan of the Talk

- External Probes in CFTs.
- Computing Bremsstrahlung functions.
  - AdS/CFT
  - Localization
- Two applications.
- Outlook.

Cusped Wilson line: Radiation

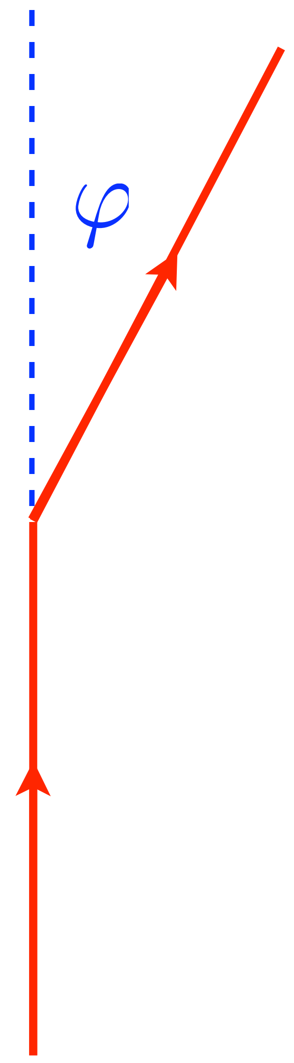


J.J. Thomson

Bremsstrahlung function

$$\Delta E = 2\pi B(\lambda, N) \int dt\ (\dot{v})^2$$

Cusped Wilson line

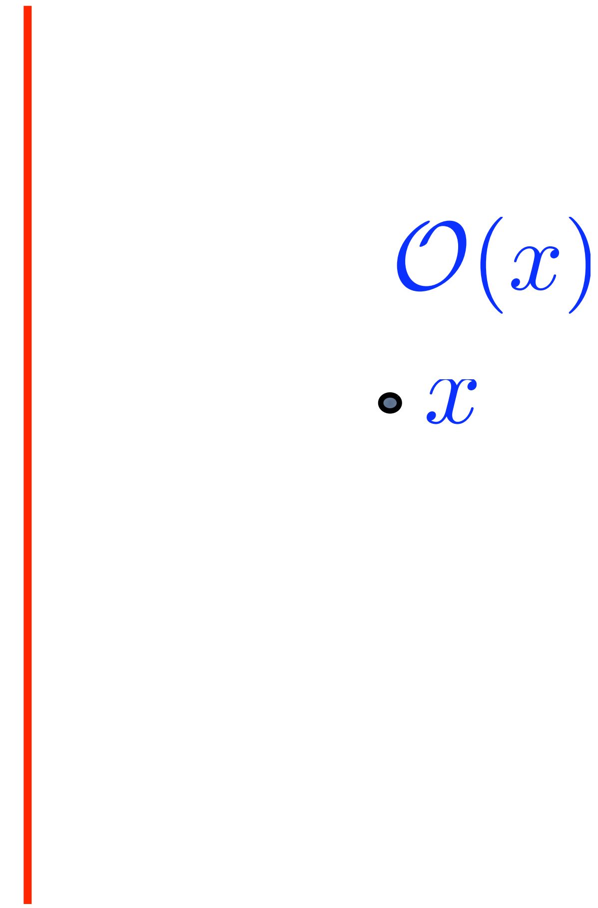


Cusp anomalous dimension

Polyakov 80

$$< W > \sim e^{-\,\Gamma_{cusp}(\varphi,\lambda)\; Log\frac{L}{\epsilon}}$$

Line operators and local operators



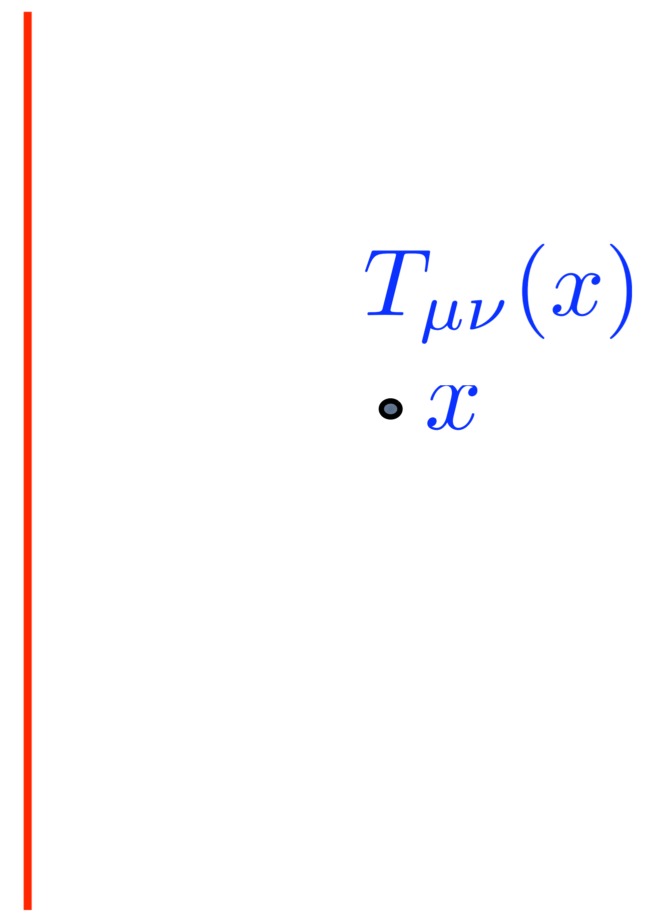
$$< \mathcal{O}(x) >_W \equiv \frac{< \mathcal{O}(x) W >}{< W >}$$

Kapustin 05

Conformal symmetry fixes $< \mathcal{O} >_W$ up to a coefficient.

Buchbinder, Tseytlin 12

Line operators and local operators



$$< T_{00}(x) >_W = h(\lambda, N)\,\frac{1}{|\vec{x}|^4}$$

$$< T_{ij}(x) >_W = h(\lambda, N)\;\frac{-\delta_{ij} + 2\frac{x_i x_j}{|\vec{x}|^2}}{|\vec{x}|^4}$$

Kapustin 05

World-line Operators: Displacement Operators

Polyakov, Rychkov 00
Semenoff, Young 04
Drukker, Kawamoto 06

$\mathbb{D}_j(t_2)$ $\delta x^j(t_2)$

$$\Delta(\mathbb{D}_i) = 2$$

$\mathbb{D}_i(t_1)$ $\delta x^i(t_1)$

$$<< \mathbb{D}_i(t_1)\mathbb{D}_j(t_2) >> = \tilde{\gamma}(\lambda, N) \; \frac{\delta_{ij}}{(t_1 - t_2)^4}$$

For any line operator in any 4d CFT, we have defined:

$$< W > \sim e^{-\ \Gamma_{cusp}(\varphi,\lambda)\ Log\frac{L}{\epsilon}}$$

$$\Delta E = 2\pi B(\lambda, N)\int dt\ (\dot{v})^2$$

$$<< \mathbb{D}_i(t_1)\mathbb{D}_j(t_2) >>= \ \tilde{\gamma}(\lambda, N)\ \ \frac{\delta_{ij}}{(t_1 - t_2)^4}$$

$$< T_{00}(x) >_W = h(\lambda, N)\,\frac{1}{|\vec{x}|^4}$$

$$< \mathcal{L}(x) >_W = f(\lambda, N)\ \frac{1}{|\vec{x}|^4}$$

These coefficients are actually not independent...

Expand the cusp anomalous dimension at small angles,

$$\Gamma(\varphi) = \Gamma(\lambda, N)\,\varphi^2 + \mathcal{O}(\varphi^4) + \ldots$$

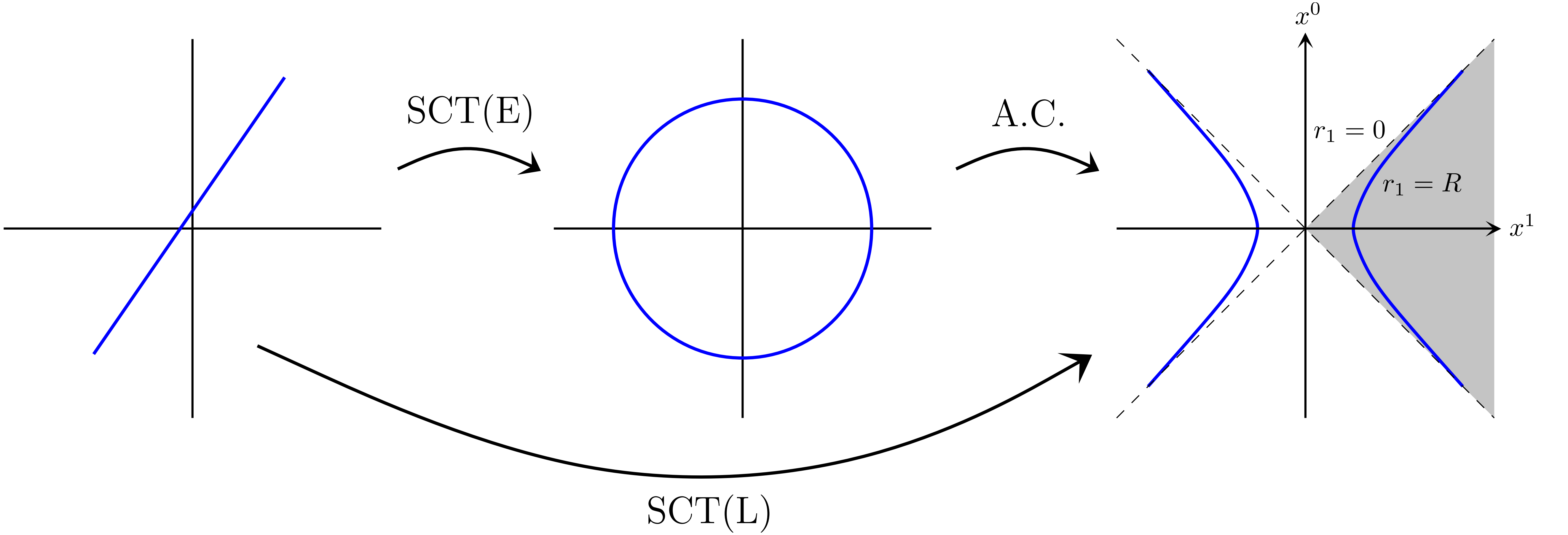
Then, for any line operator and any 4d CFT,

$$\Gamma = \frac{\tilde{\gamma}}{12} = B$$

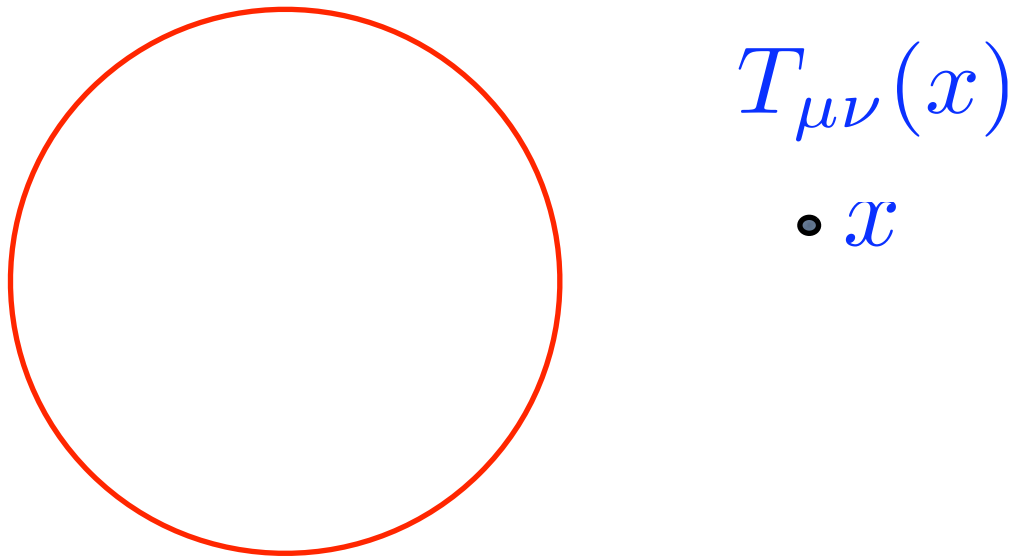
Correa, Henn, Maldacena, Sever 12

But wait!, there is more...

Hyperbolic Wilson line: accelerated probe



Hyperbolic Wilson line: accelerated probe



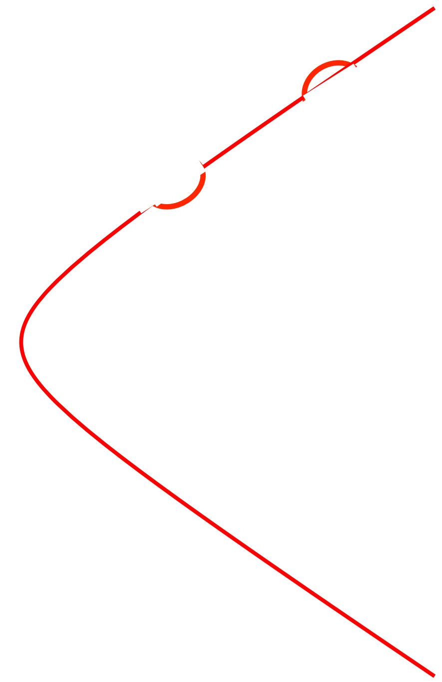
Since T^{0i} is the Poynting vector, this should give an alternative way to compute energy loss by radiation.

BF, Garolera, Lewkowycz 12

Actually, one needs to use an improved $\bar{T}_{0i}$.

Lewkowycz, Maldacena 13
Agón, Güijosa, Pedraza 14

Hyperbolic Wilson line: accelerated probe



BF, Garolera, Torrents 13

$$<< \mathbb{D}_i(\tau)\mathbb{D}_j(0) >>= 12\ B(\lambda, N)\ \frac{\delta_{ij}}{16R^4 \sinh^4(\frac{\tau}{2R})}$$

$$\kappa = \lim_{w\to 0} \int d\tau e^{iw\tau} << \mathbb{D}_i(\tau)\mathbb{D}_j(0) >>= 16\pi^3 B(\lambda, N)\, T^3$$

Unruh temperature

Very pretty.... but can we actually compute $B(\lambda, N)$ for any probe in any CFT?

Yes! 1/2-BPS probe coupled to $\mathcal{N}=4$ SYM.

A reminder: CFTs and local operators

- Conformal symmetry gives constraints on correlation functions, but it doesn't fix all coefficients.

$$< \mathcal{O}_i(x)\mathcal{O}_j(0) >= \frac{\delta_{ij}}{(x)^{2\Delta_i(\lambda,N)}}$$

$$< \mathcal{O}_i(x_i)\mathcal{O}_j(x_j)\mathcal{O}_k(x_k) >= \frac{c_{ijk}(\lambda,N)}{(x_{ij})^{2\alpha_{ijk}}(x_{ik})^{2\alpha_{ikj}}(x_{jk})^{2\alpha_{jki}}}$$

- We need additional tools to compute coefficients.

Computing the Bremsstrahlung function

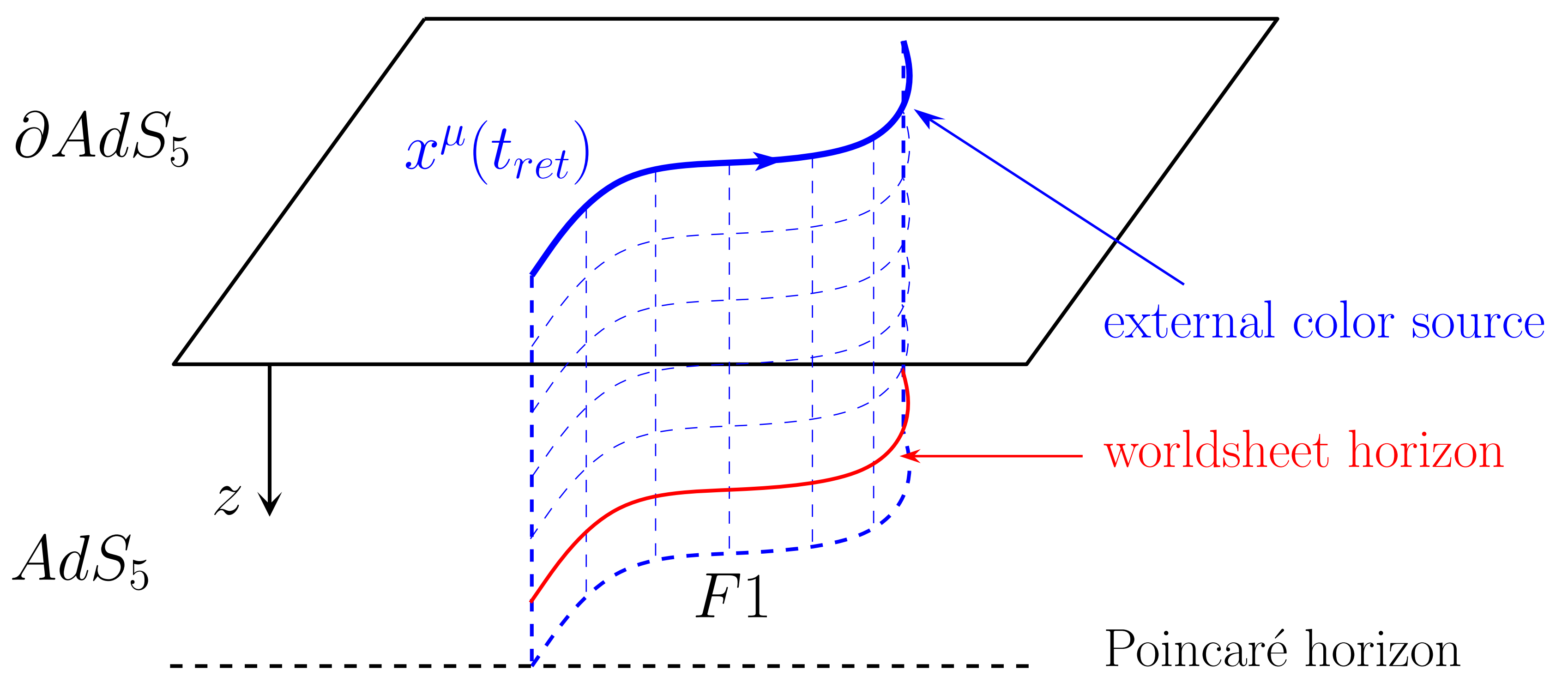
What additional tools can we consider?:

- Pert. Theory (finite N, small λ)
- Integrability (large N, finite λ)
- AdS/CFT (large N, large λ)
- Localization (finite N, finite λ)

External Probes in AdS/CFT

External Probes in AdS/CFT

Consider a particle in the fundamental representation. Its dual is a *fundamental string*, reaching the boundary of AdS at the particle world-line.



External Probes in AdS/CFT

In the absence of other scales, the effective charge is

$$\mathrm{e}^2_{\Box} \sim \sqrt{\lambda}$$

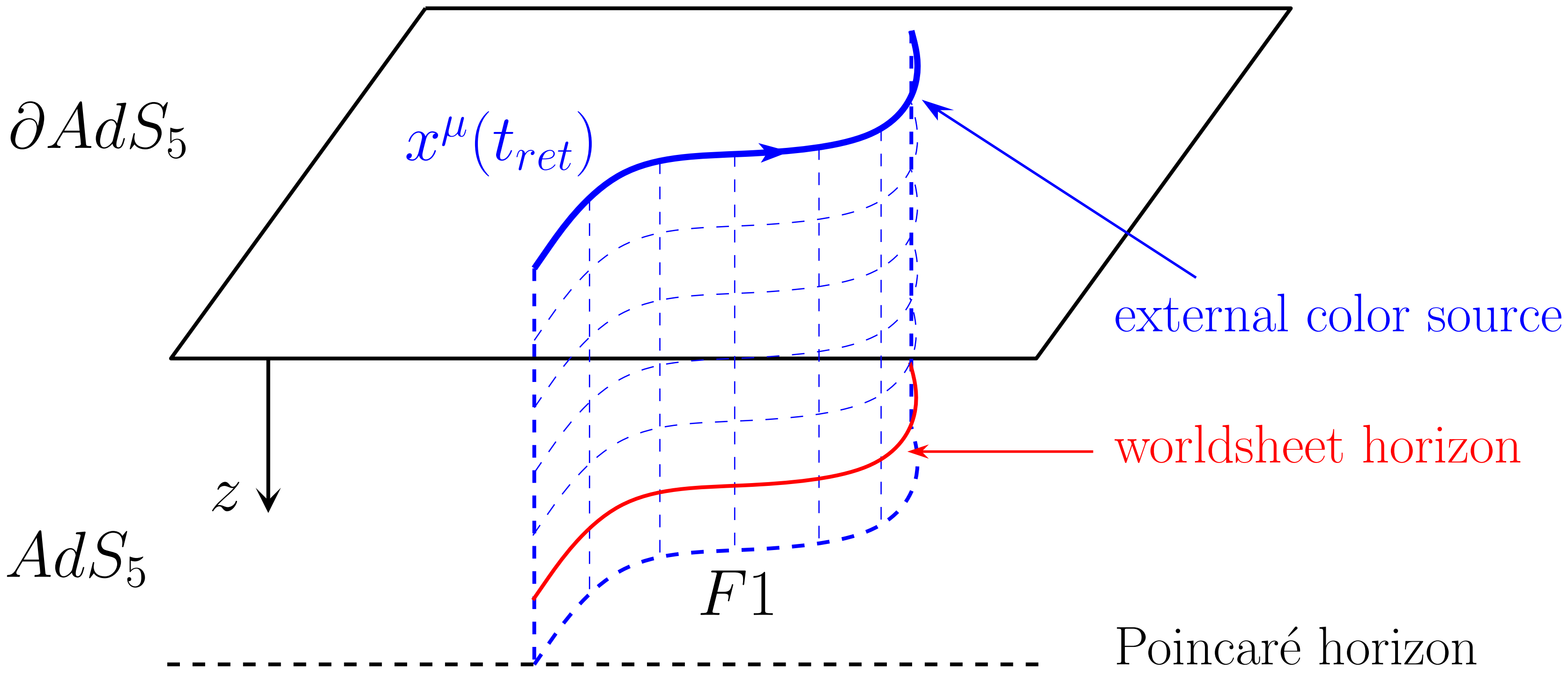
It signals screening of the charge at strong coupling.

$$S_{NG} = -\frac{1}{2\pi\alpha'}\int d^2\sigma\sqrt{-|g|} = -\frac{\sqrt{\lambda}}{2\pi L^2}\int d^2\sigma\sqrt{-|g|}$$

Example: accelerated particle

Mikhailov found the fundamental string dual to a particle following an *arbitrary* timelike trajectory.

Mikhailov 03

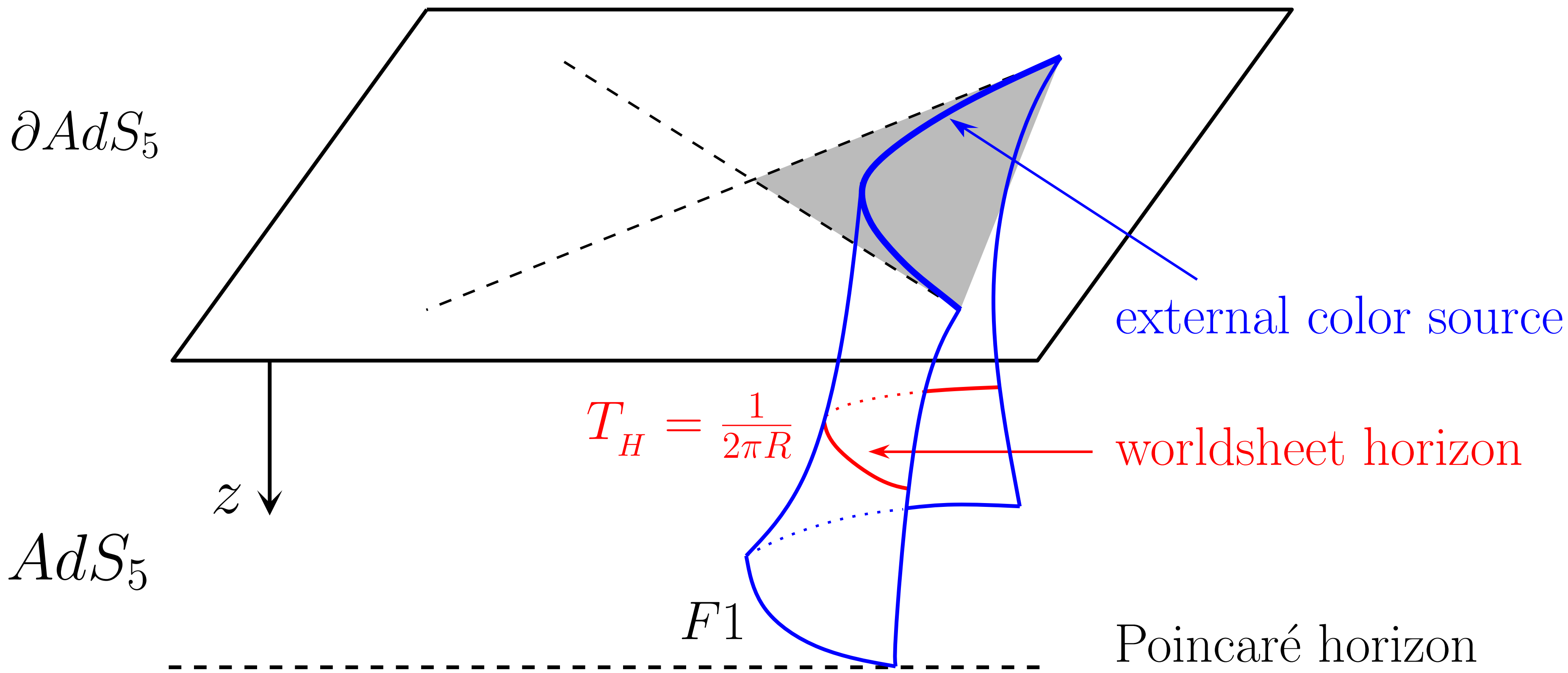


$$P = \frac{\sqrt{\lambda}}{2\pi} a^\mu a_\mu$$

Mikhailov 03

Example: accelerated particle

The world-sheet horizon splits the gluonic cloud into a *Coulombic and a radiative* part.



$$E = \int d\sigma \; \mathcal{E}$$

External Probes in AdS/CFT

Static Particle

$$< \mathcal{L}(\vec{x}) >= \frac{1}{16\pi^2}\frac{\sqrt{\lambda}}{|\vec{x}|^4}$$

Danielsson *et al.*
Callan, Güijosa 98

Cusped Wilson line

$$B(\lambda, N) = \frac{\sqrt{\lambda}}{4\pi^2}$$

Kruczenski 02

Accelerated particle

$$P = \frac{\sqrt{\lambda}}{2\pi} a^\mu a_\mu$$

Mikhailov 03

$$\kappa = 4\pi\sqrt{\lambda}\ T^3$$

Xiao 08

Circular Wilson loop

$$\ln\ < W_{\bigcirc} >= \sqrt{\lambda}$$

Berenstein *et al.* 98

External Probes in AdS/CFT

All these computations yield

$$B(\lambda, N) = \frac{\sqrt{\lambda}}{4\pi^2}$$

The $\sqrt{\lambda}$ in these results appears from evaluating classical string solutions to the NG action. There are two types of corrections:

- $1/\sqrt{\lambda}$ world-sheet fluctuations.
- $1/N$ higher genus world-sheets.

Forste, Ghoshal, Theisen 99
Drukker, Gross, Tseytlin 00
....
Buchbinder, Tseytlin 13

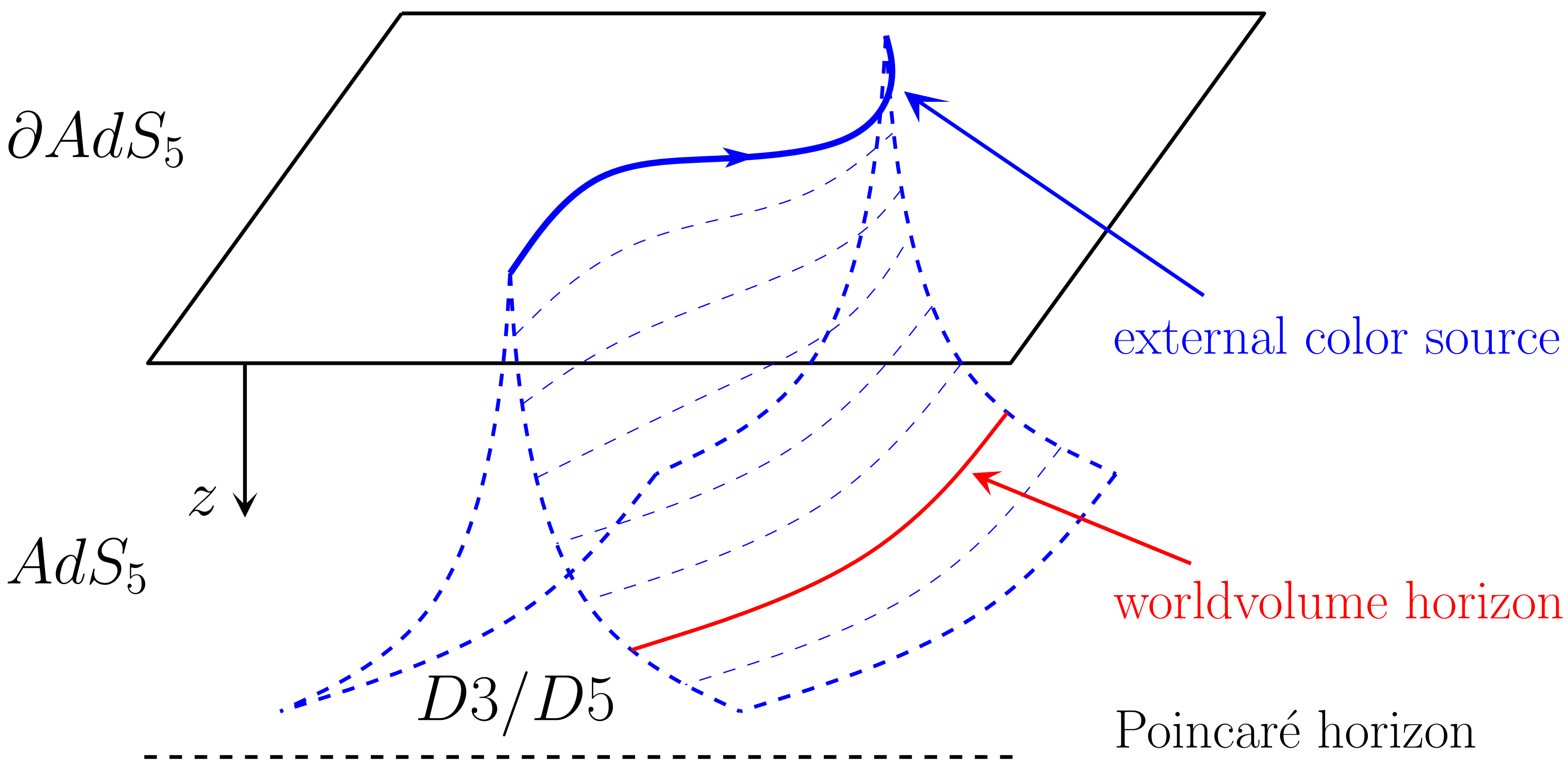
1/N Corrections with AdS/CFT

Probes in higher rank representations

D3, k-units of flux ⇔ **k-symmetric rep.**

D5, k-units of flux ⇔ **k-antisymmetric rep.**

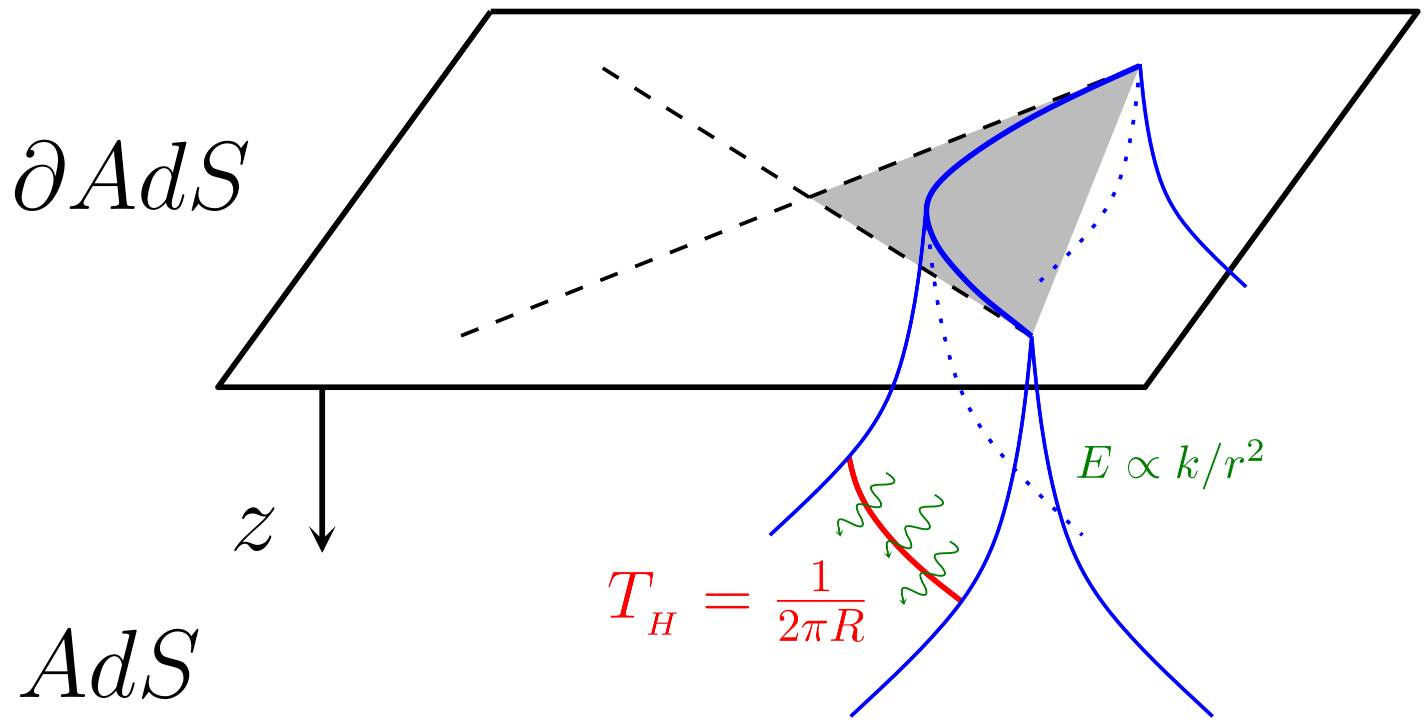
Hartnoll, Prem Kumar 06
Yamaguchi
Gomis, Passerini



Example: accelerated particle

It is possible to find a D3-brane that reaches the boundary at an arbitrary timelike trajectory.

BF, Güijosa, Pedraza 14



$$P = \frac{k\sqrt{\lambda}}{2\pi}\sqrt{1+\frac{k^2\lambda}{16N^2}}\; a^\mu a_\mu$$

BF, Garolera 11
BF, Güijosa, Pedraza 14

Probes in k-symmetric representation

Static Particle

$$< \mathcal{L}(\vec{x}) >_{S_k} = \frac{k\sqrt{\lambda}}{16\pi^2}\sqrt{1+\frac{k^2\lambda}{16N^2}}\,\frac{1}{|\vec{x}|^4}$$

BF, Garolera, Lewkowycz 12

Accelerated Particle

$$P = \frac{k\sqrt{\lambda}}{2\pi}\sqrt{1+\frac{k^2\lambda}{16N^2}}\; a^\mu a_\mu$$

BF, Garolera 11
BF, Güijosa, Pedraza 14

$$\kappa = 4\pi k\sqrt{\lambda}\sqrt{1+\frac{k^2\lambda}{16N^2}}\; T^3$$

BF, Garolera, Torrents 13

Circular Wilson loop

$$\ln\ < W(\bigcirc) > = \frac{k\sqrt{\lambda}}{2}\sqrt{1+\frac{k^2\lambda}{16N^2}} + 2N\sinh^{-1}\frac{k\sqrt{\lambda}}{4N}$$

Drukker, BF 05

Probes in k-symmetric representation

All these computations yield

$$B(\lambda, N) = \frac{k\sqrt{\lambda}}{4\pi^2}\sqrt{1+\frac{k^2\lambda}{16N^2}}$$

A priori, not justified to trust this result for k=1.

$$\underbrace{\frac{N^2}{\lambda^2} >> k}_{\text{probe approx.}} \qquad \overbrace{k >> \frac{N}{\lambda^{3/4}}}^{\text{SUGRA approx.}}$$

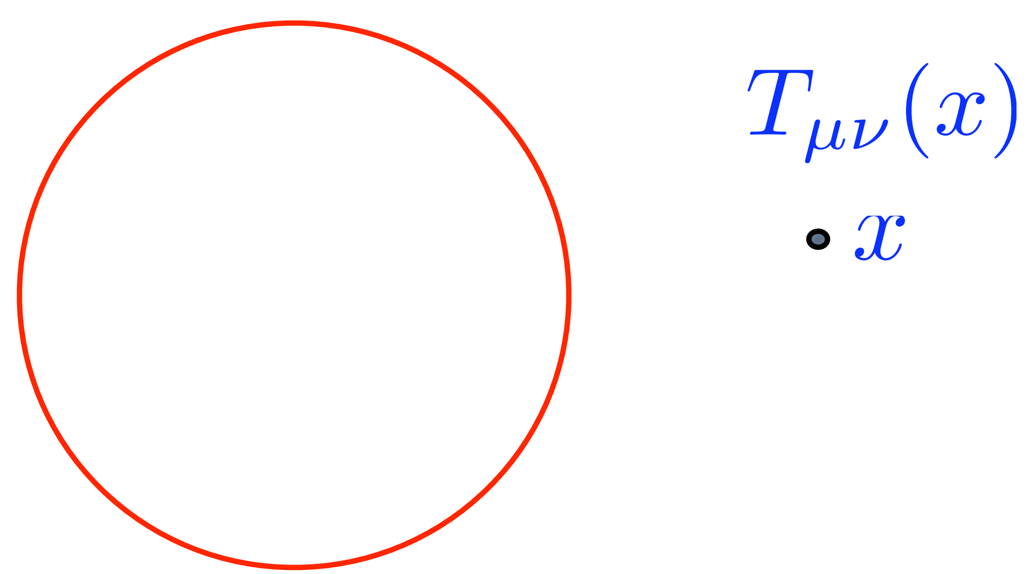
Nevertheless, it is a fact that for these quantities k=1 correctly captures 1/N corrections.

Exact Results for External Probes

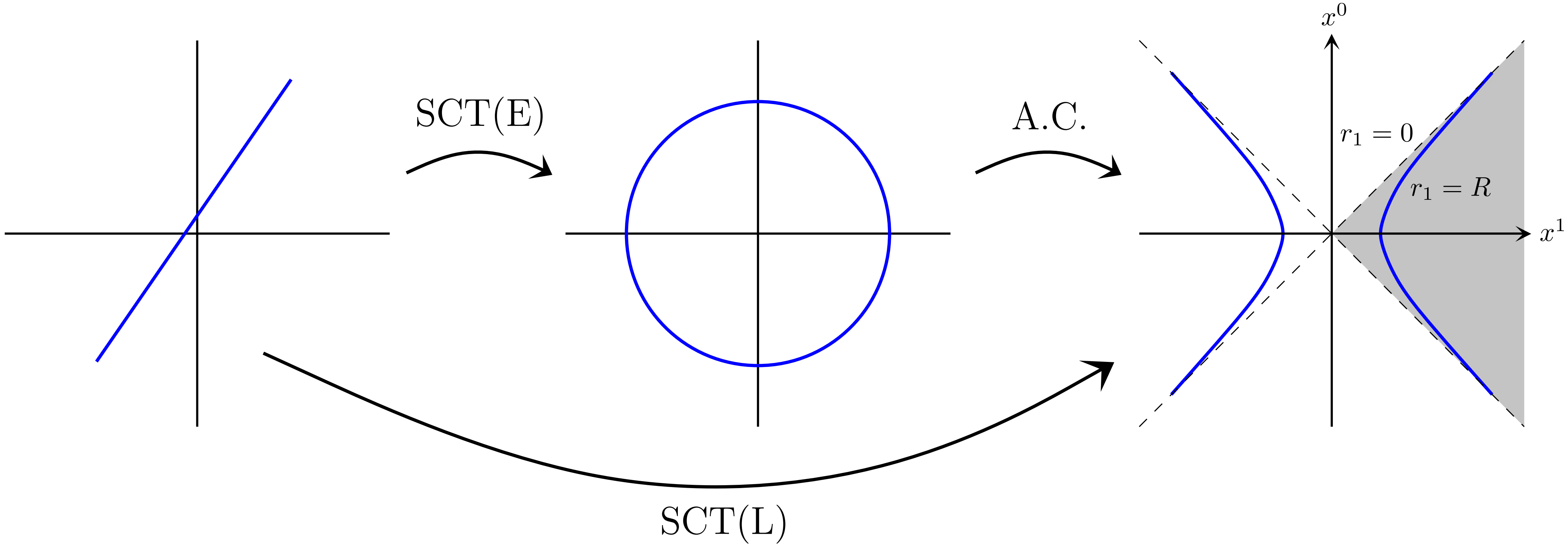
An exact Bremsstrahlung function

We will derive the Bremsstrahlung function for an electric 1/2 BPS probe in the fundamental rep. of N=4 U(N) SYM.

Our strategy: compute $$< T_{\mu\nu} >_W = \frac{< T_{\mu\nu}(x) W_{\bigcirc} >}{< W_{\bigcirc} >}$$



Start with <W>. Recall the Special Conformal Transformation,



$$< W_| >= 1 \qquad < W_\bigcirc > \neq 1$$

Conformal Anomaly !

The anomaly is localized at a point in space-time

⇩

It is perturbatively captured by a matrix model, guessed to be a Gaussian Hermitian matrix model.

$$< W_{\bigcirc} >= \frac{1}{N} L^{1}_{N-1}\left(-\frac{\lambda}{4N}\right) e^{\frac{\lambda}{8N}}$$

Erickson, Semenoff, Zarembo 00

Drukker, Gross 00

Using localization techniques, Pestun proved the result to be correct, and exact.

Pestun 07

What about $< T_{\mu\nu}(x) W_{\bigcirc} >$?

In $\mathcal{N}=4$ SYM, the Lagrangian density and the stress energy tensor belong to a short multiplet, the supercurrent multiplet.

$$\mathcal{O}_2 = \mathrm{Tr}\,\left(\Phi^{\{I}\Phi^{J\}}\right) \qquad T_{\mu\nu} \sim Q^2\bar{Q}^2\mathcal{O}_2 \qquad \mathcal{L} \sim Q^4\mathcal{O}_2$$

$< W_{\bigcirc}\mathcal{O}_2(x) >$ is computed with a normal matrix model

Okuyama, Semenoff 06

$$< W(\bigcirc)_{\square}\mathcal{O}_2 >= \frac{\sqrt{2}\lambda}{4N^3}\left[L^2_{N-1}\left(-\frac{\lambda}{4N}\right) + L^2_{N-2}\left(-\frac{\lambda}{4N}\right)\right]e^{\frac{\lambda}{8N}}$$

and finally we arrive at the Bremsstrahlung function for an electric 1/2 BPS probe in the fundamental rep. of N=4 U(N) SYM,

$$B_{U(N)}(\lambda, N) = \frac{\lambda}{16\pi^2 N} \frac{L^2_{N-1}\left(-\frac{\lambda}{4N}\right) + L^2_{N-2}\left(-\frac{\lambda}{4N}\right)}{L^1_{N-1}\left(-\frac{\lambda}{4N}\right)}$$

It is a rational function (why?)

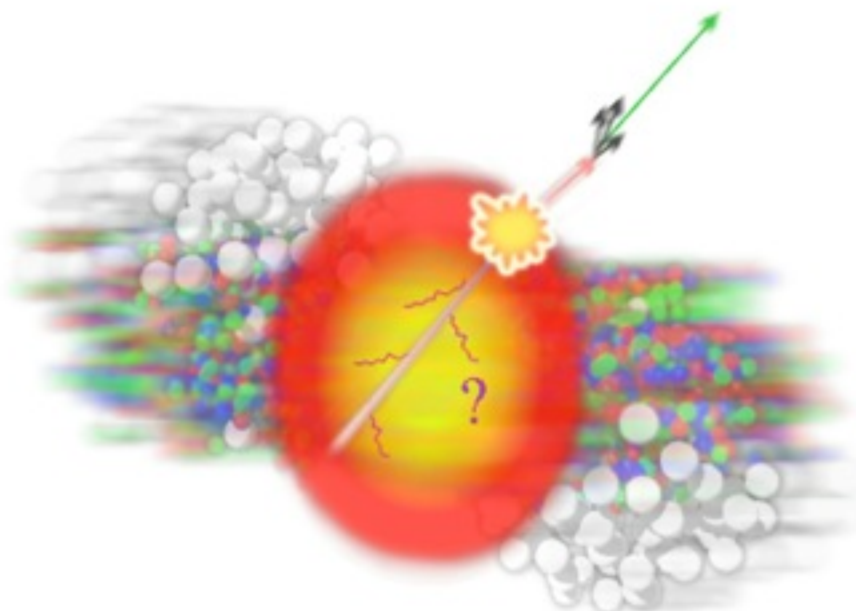
Equivalently,

$$B = \frac{1}{2\pi^2} \lambda \partial_\lambda \log \; < W_{\bigcirc} >$$

Correa, Henn, Maldacena, Sever 12

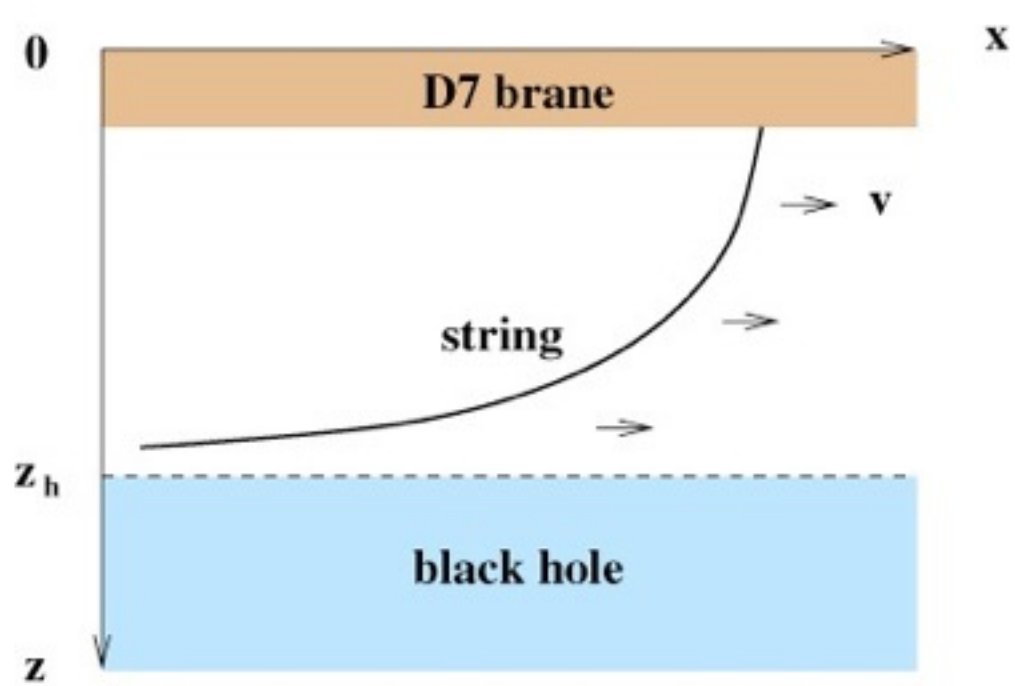
First application:
A benchmark for transport coefficients

Momentum broadening in Q.G.P.

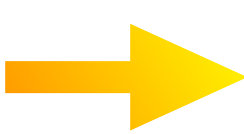


$$\kappa = g(\lambda, N)T^3$$

Modelling QGP by N=4 SYM : trailing string



Herzog *et al.* 06
Casalderrey-Solana, Teaney 06
Gubser 06

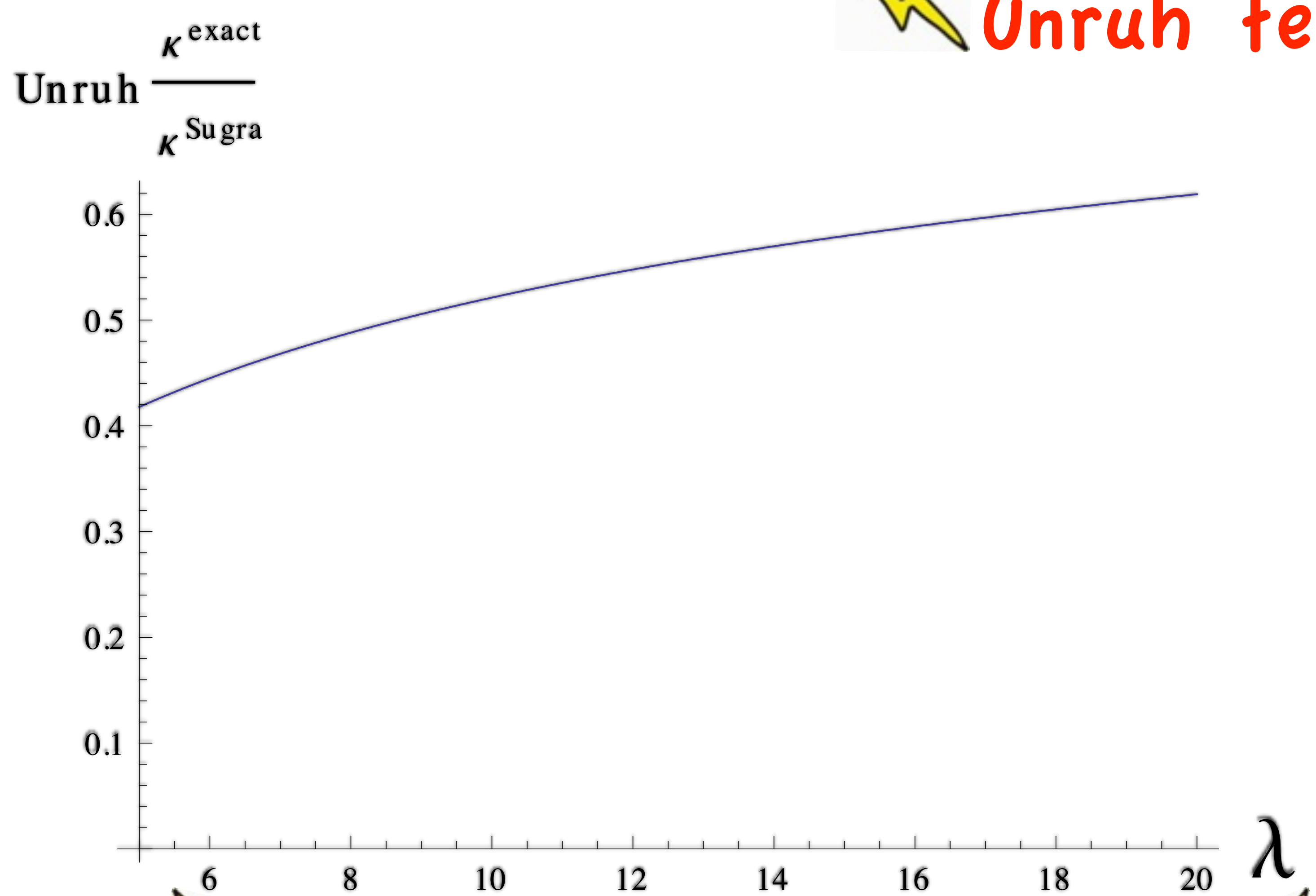
SUGRA  $\kappa = \pi\sqrt{\lambda}T^3$

SUGRA vs. exact results

SU(3), finite λ $$\kappa = 4\pi \frac{\lambda}{18} \frac{\lambda^2 + 144\lambda + 3456}{\lambda^2 + 72\lambda + 864} T^3$$

Large N, large λ $$\kappa = 4\pi\sqrt{\lambda}\, T^3$$

Unruh temperature



QGP-modelling range

Roughly, in this range

$$\kappa^{\text{SUGRA}}_{\text{Unruh}} \approx 2\,\kappa^{\text{Exact}}_{\text{Unruh}}$$

IF the same were true for κ_{thermal}

$$\mathbf{D}^{\text{Exact}}_{\text{thermal}} \approx 2\,\mathbf{D}^{\text{SUGRA}}_{\text{thermal}}$$

push towards QGP value ...

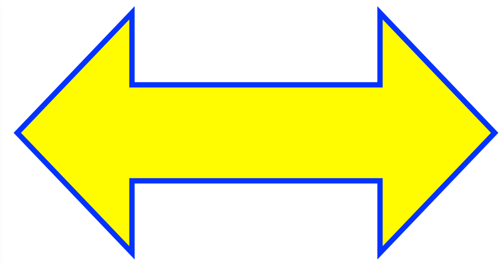
Second application:

Back to String Theory…

Two words about AdS/CFT

What we say....

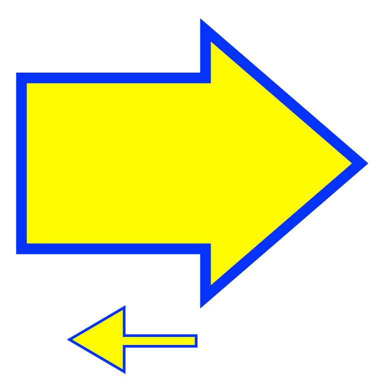
Quantum Gravity in AdS space



CFT in one less dimension

What we do....

Quantum Gravity in AdS space



CFT in one less dimension

From Localization to String Theory

We can compute exactly certain quantities in CFT. Can we use them to learn about string theory beyond the SUGRA regime?

"Ask not what the world-sheet can do for you;
ask what you can do for the world-sheet ."

(Understandably) Anonymous

From Localization to String Theory

$\mathcal{N}=4$ SYM
G=SO(N), Sp(N)

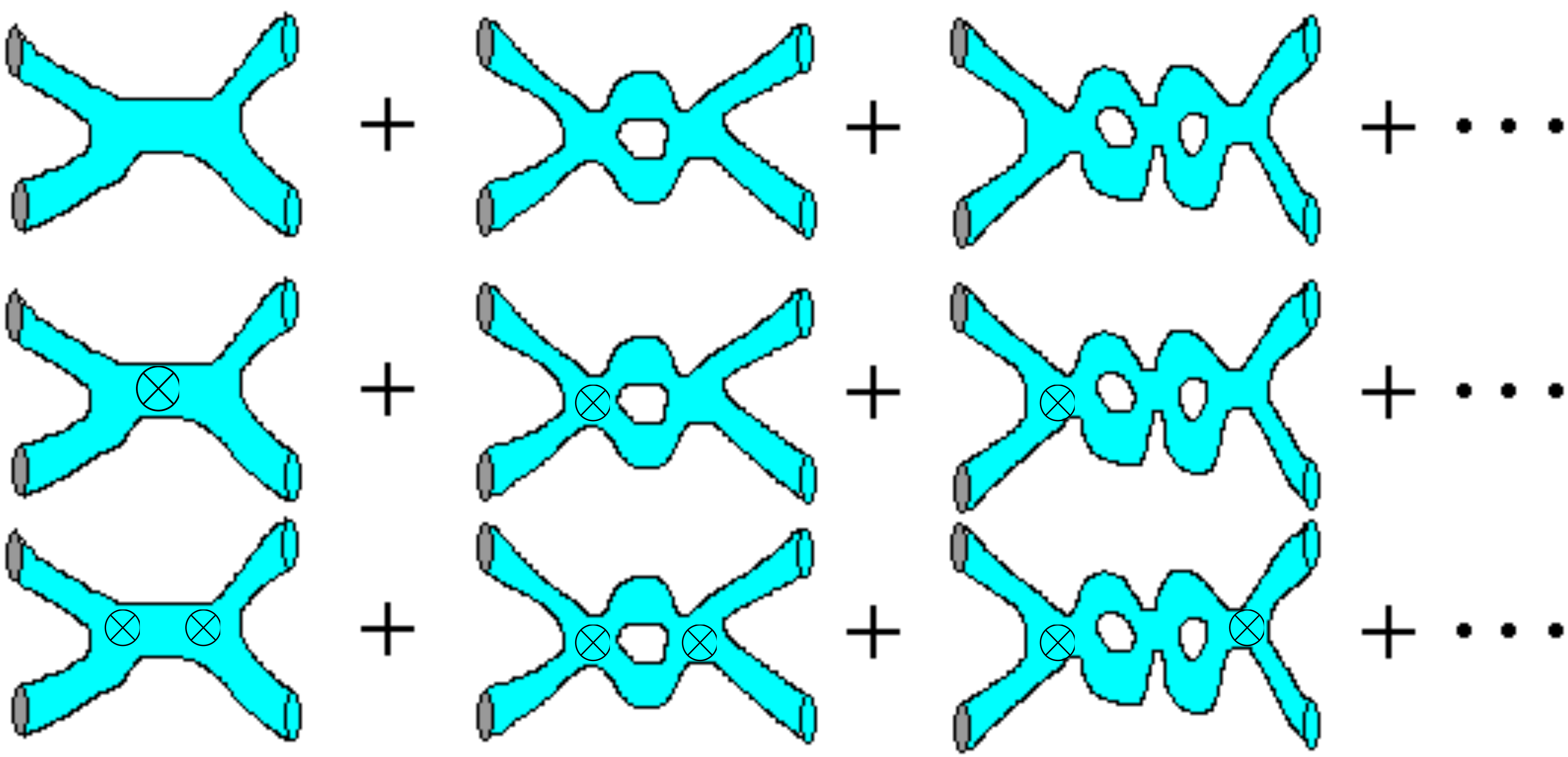
⟺

IIB string
$AdS_5 \times RP^5$

Witten 98

Novel feature: non-orientable surfaces in 1/N expansion

Cicuta 82



From Localization to String Theory

Possible to derive exact relations among vevs, even without doing the integrals:

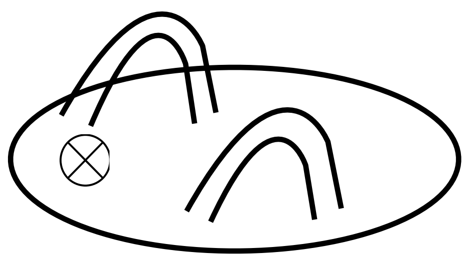
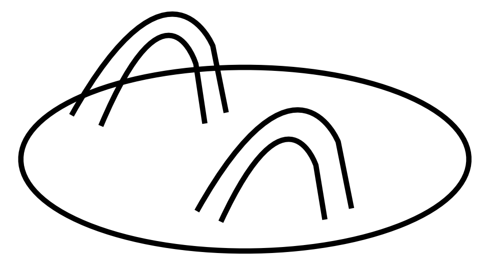
$$< W(g) >_{\substack{SO(2N) \\ Sp(N)}} = < W(g) >_{U(2N)} \mp \frac{1}{2} \int_0^g dg' \;\; < W(g') >_{U(2N)}$$

BF, Garolera, Torrents 14

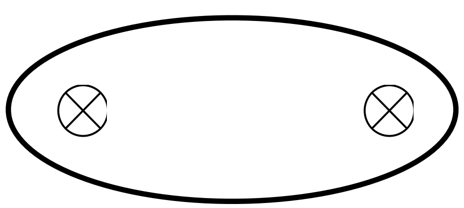
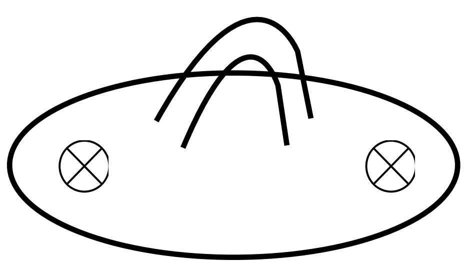
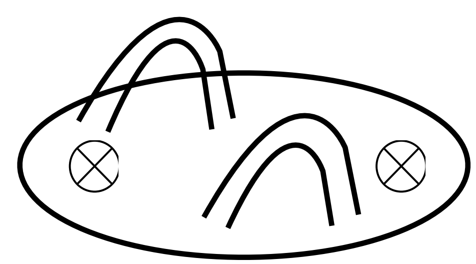
These relations have implications for the dual perturbative string expansion.

From Localization to String Theory

- **One-crosscap diagrams related to orientable ones:**

$$\frac{\partial}{\partial g}$$  = 

- **World-sheets with two crosscaps don't contribute:**

 +  +  + ...

= 0 + 0 + 0 + ...

Similar features seen before in orientifolds.

Sinha, Vafa 00

Corrado *et al* 02

Conclusions and Outlook

The **Bremsstrahlung function**, the small angle limit of the **cusp anomalous dimension**, determines many properties of **heavy probes** coupled to CFTs.

Thanks to **localization**, the **Bremsstrahlung functions** of probes in various reps. of **N=4 SU(N) SYM** can be determined exactly via **matrix model** computations.

In the regime of validity of SUGRA, these results reduce to functions of $\sqrt{\lambda}/N$, and **D-brane probe computations** capture them precisely.

Conclusions and Outlook

- Compute $B(\lambda, N)$ for other probes/CFTs.
- Exact entanglement entropy of a probe.

Lewkowycz, Maldacena 13

- Finite mass ?

  Adding Flavor

  Karch, Katz 02

  Schwinger effect and critical electric field

  Semenoff, Zarembo 11

$$E_c = \frac{2\pi m^2}{\sqrt{\lambda}}$$

- Beyond the vacuum state: modelling impurities, finite μ , finite T? ....