High-Energy, Cosmology and Strings
(IHP, Paris, 11-15 December 2006)

Transplanckian String Collisions and the information paradox

Gabriele Veneziano
(CERN-PH/TH & Collège de France)

Has string theory solved the information paradox?

•BH-entropy and counting of states agree for extremal BHs (Strominger-Vafa, ..)
•Spectra from quasi-extremal BH decay follow Hawking iff one traces over initial brane configuration (= density matrix)

Questions (see e.g. D. Amati, hep-th/0612061):

1. What happens if one starts from a pure state? Fails at weak coupling, may work at strong coupling.
2. Are there corrections to a pure thermal spectrum?
3. How does this extend to more conventional (Kerr) BHs?

Outline

1. The string-black hole correspondence curve
2. Transplanckian string collisions: why and how.

   2.1 MGO vs ACV approach to the problem

   2.2 Three scales/regimes in trans-planckian string collisions

I) $b > R, l_s$	Easy
II) $R > b, l_s$	Hard
III) $l_s > R, b$	Easy again?

   2.3 Approaching gravitational collapse from region III

   2.4 A unitary S-matrix with precocious black-hole-like behaviour
3. Conclusions

The string-black hole correspondence curve

String vs Black-Hole entropy

h = c = numerical factors =1

M_s , l_s = string mass, length scales

Tree-level string entropy

Counting states (FV, BM ('69), HW ('70))

$S_{st} = M/M_s = L/l_s$

= No. of string bits in the total string length

NB: no coupling, no G appears!

Black-Hole entropy

$S_{BH} = M R_S = (R_S/L_P)^2 \sim M^2$

$(GM = R_S$, $1/T_{BH} = dS/dM = R_S/h)$

to be contrasted with previous

$S_{st} = M/M_s = L/l_s$

****

$S_{st}/S_{BH} > 1$ @ small M, $S_{st}/S_{BH} < 1$ @ large M

Where do the two entropies meet? Obviously at

$R_S = l_s$ i.e. at $T_{BH} = M_s$!

"string holes" = states satisfying this entropy matching condition

Using string unification @ the string scale,

$$(L_P/l_s)^2 = g_s^2 \sim \alpha_{GUT}$$

entropy matching occurs for

$$M = M_{sh} \equiv g_s^{-2} M_s = g_s^{-1} M_P$$

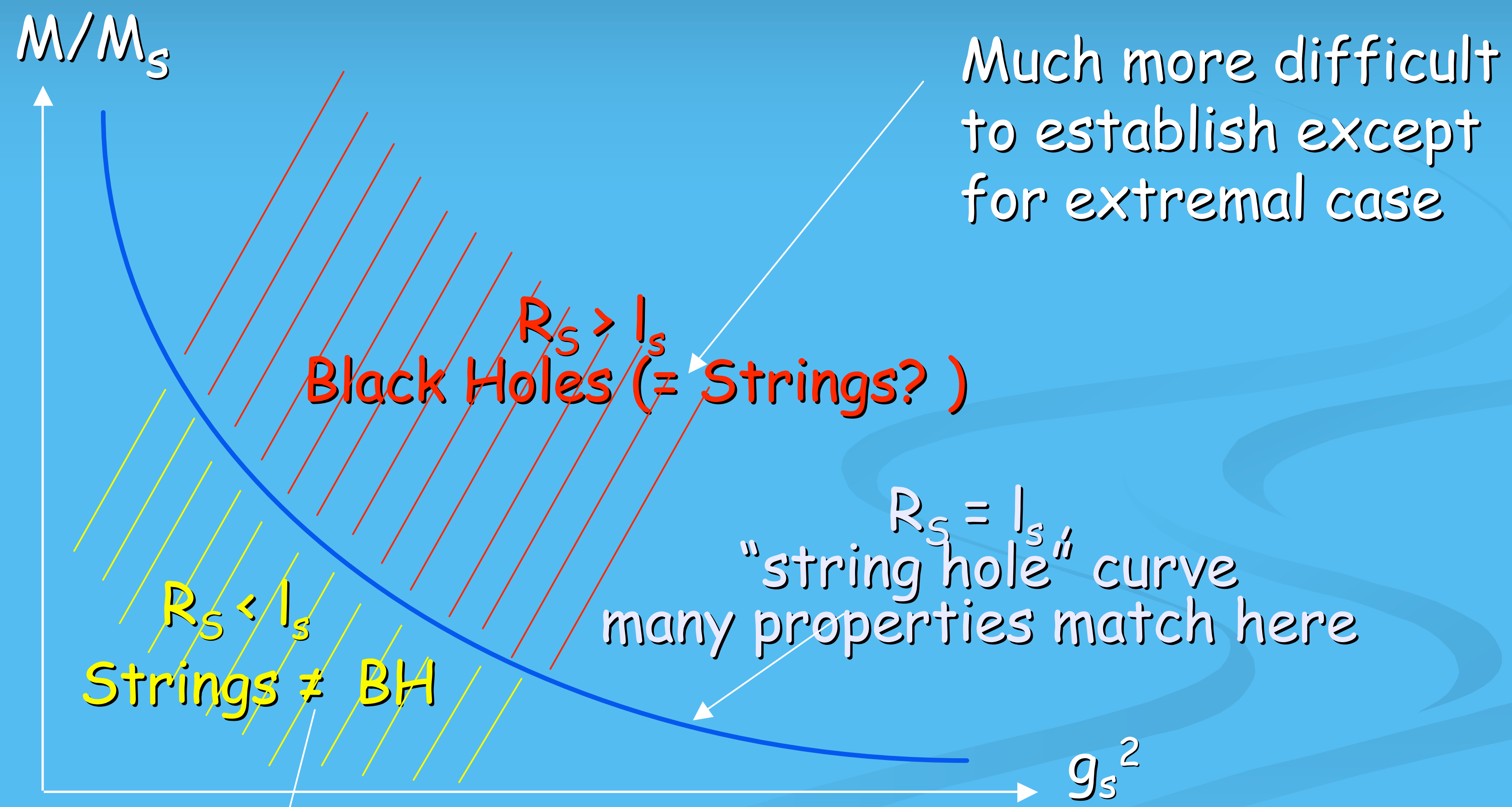
and the common value of S_{st} and S_{BH} is simply

$$S_{sh} = g_s^{-2} \sim \alpha_{GUT}^{-1}$$

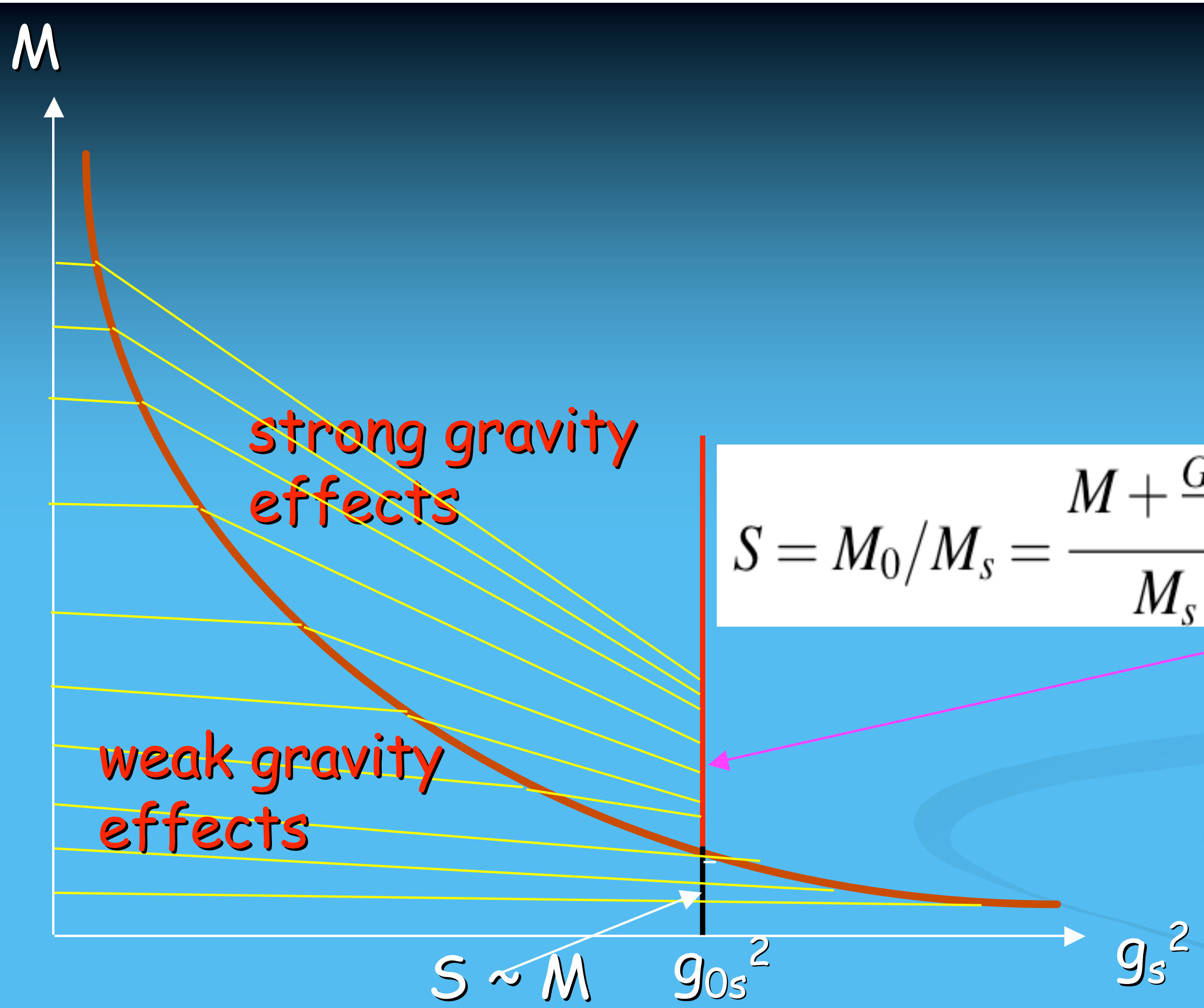
In string theory g_s^2 is actually a field, the dilaton. Its value is free in perturbation theory

Consider the (M, g_s^2) plane

The correspondence curve (critical collapse?)

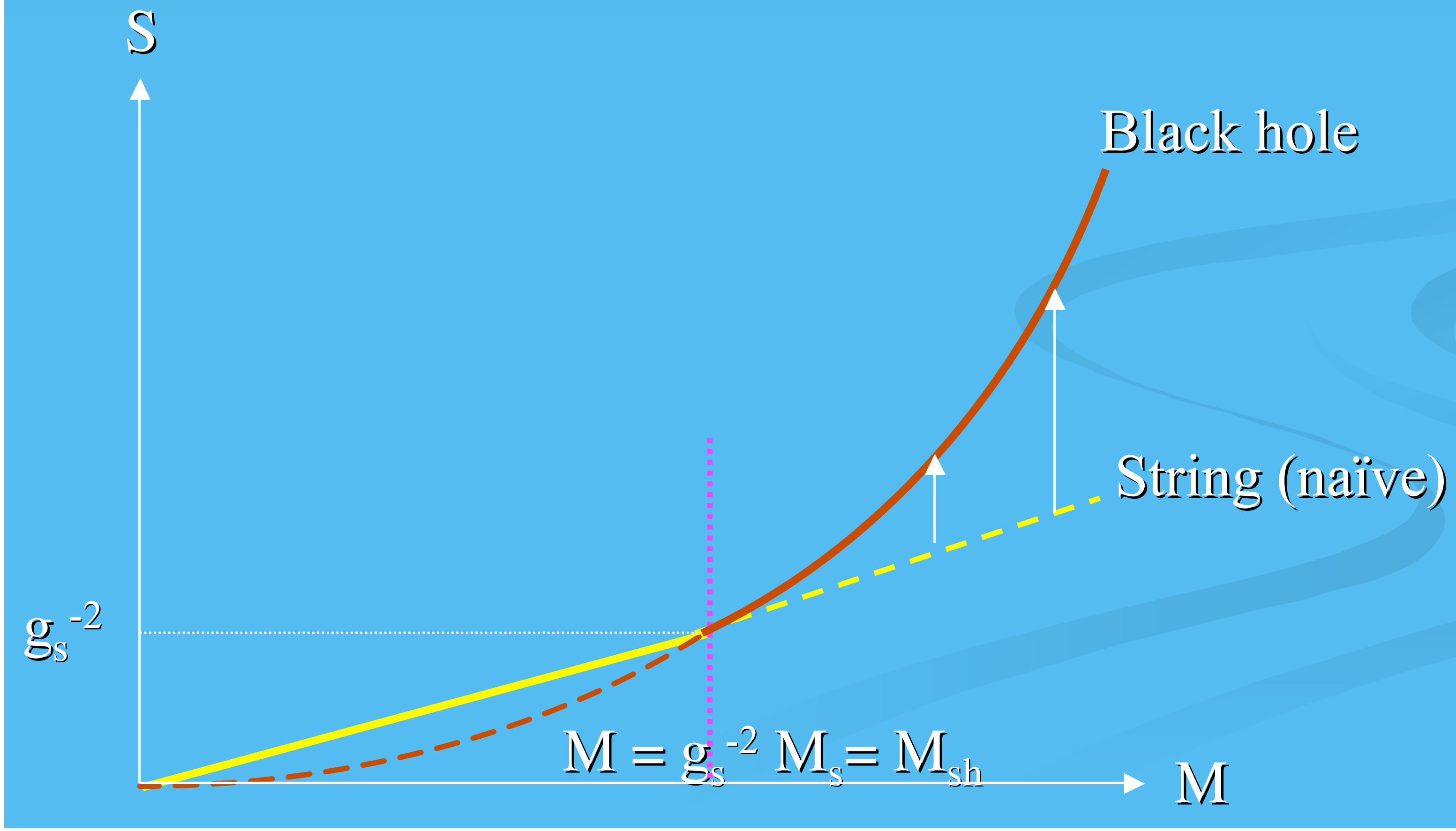


Safe conclusion since these strings are larger than R_S

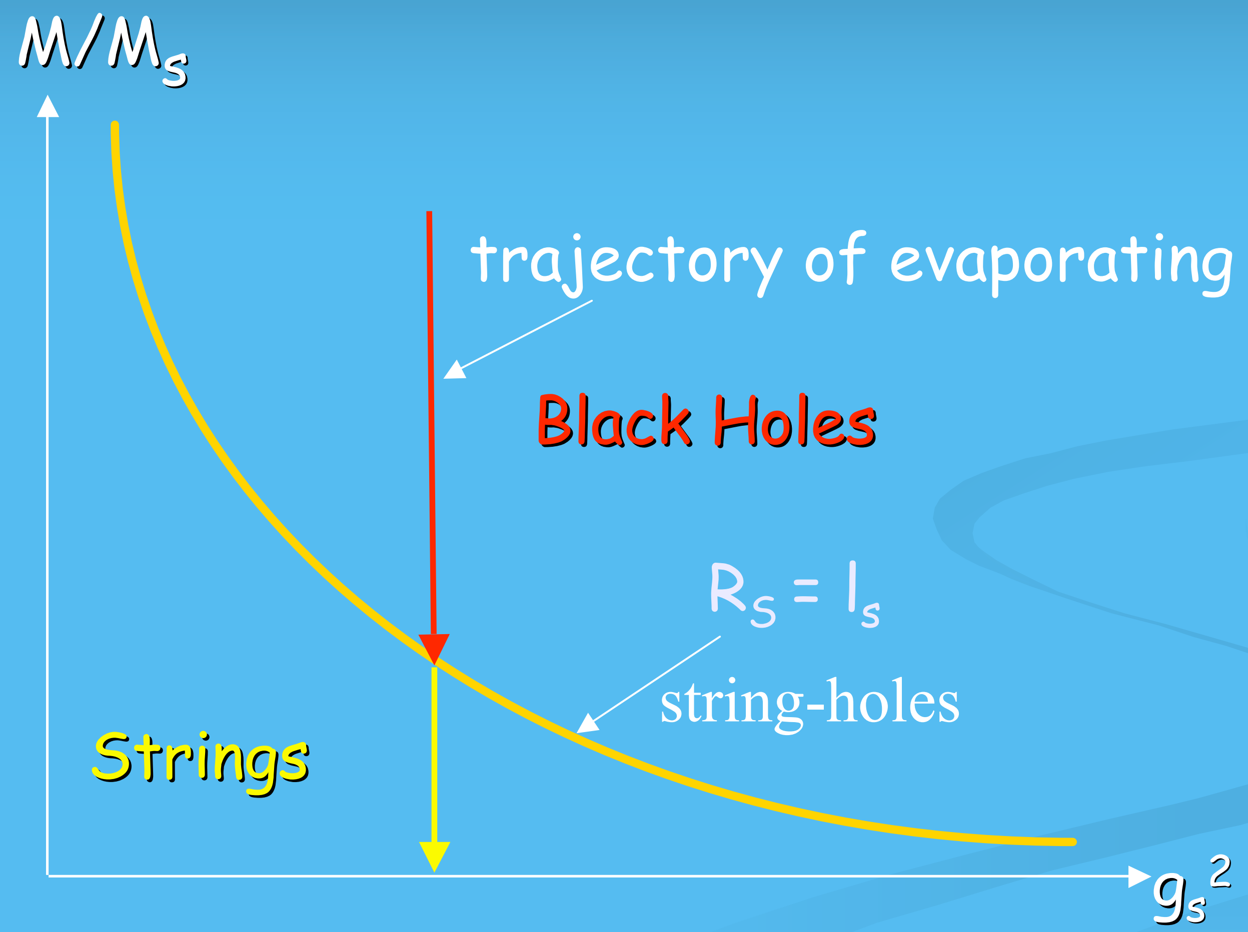


Collapse @ fixed M. Gravitational binding can increase (log of) density of states from linear to quadratic in the physical mass.

Turning string entropy into BH entropy



Evaporation at fixed g_s or how to turn a BH into a string (Bowick, Smolin,.. 1987)



Is singularity at the end of evaporation avoided thanks to l_s?

String S-matrix at E >> M_P

Super-planckian-energy collisions of light particles within superstring theory. Why care?

Theoretical Motivations

I) As a gedanken experiment

- To reproduce GR expectations at large distances
- To probe how ST modifies GR at short distances

II) Information paradox

“Phenomenological” Motivations

Signatures of string/quantum gravity @ colliders:

- In KK models with large extra dimensions;
- In brane-world scenarios; in general:
- If we can lower the true QG scale down to the TeV

NB. Future colliders at best marginal for producing BHs!

Two complementary approaches (> 1987):

A) Gross & Mende + Mende & Ooguri (1987-1990)

B) 't-Hooft; Muzinich & Soldate; ACV (>1987); Verlinde & Verlinde; Kabat & Ortiz; FPVV;...

de Haro; Arcioni; 't-Hooft; ... ('90s-'05)

The two approaches are very different. Yet they agree incredibly well in the (small) region of phase space where both can be justified

I will limit myself to describing B) and, in particular, the work of ACV (the only one, besides A) that considers the problem within string theory)

Gross-Mende-Ooguri (GMO)

Calculation (GM, 1987-'88) of elastic string scattering at very high energy and fixed scattering angle θ ($h+1$ = number of exchanged gravitons):

$$A_{el} \sim (g_s)^{2+2h} \exp\left(-\frac{\alpha' s f(\theta)}{1+h}\right)$$

The amplitude is exponentially suppressed but the suppression decreases as we increase the number of exchanged gravitons. A resummation was performed by Mende and Ooguri (see below)

Amati, Ciafaloni, GV (ACV) et al.

- Work in energy-impact parameter space, A(E,b) (b ~ J/E)
- Go to arbitrarily high E while increasing b correspondingly: $b > R_S(E) \sim GE$
- Go over to A(E, q~ θ E) by FT trusting saddle p. contributions from above region
- Reach the regime of fixed $\theta << 1$
- Compare w/ GMO in appropriate region

Tree level

- At fixed b we have to compute (D=4 when not specified)

$$\delta(E,b) = \frac{1}{(2\pi)^{D-2}} \int d^{D-2}q \frac{A_{tree}(s,t)}{4s} e^{-iqb}, \; s = E^2, \; t = -q^2$$

For the real part we get, at large b,

$$Re\delta \sim Gs \log b^2$$

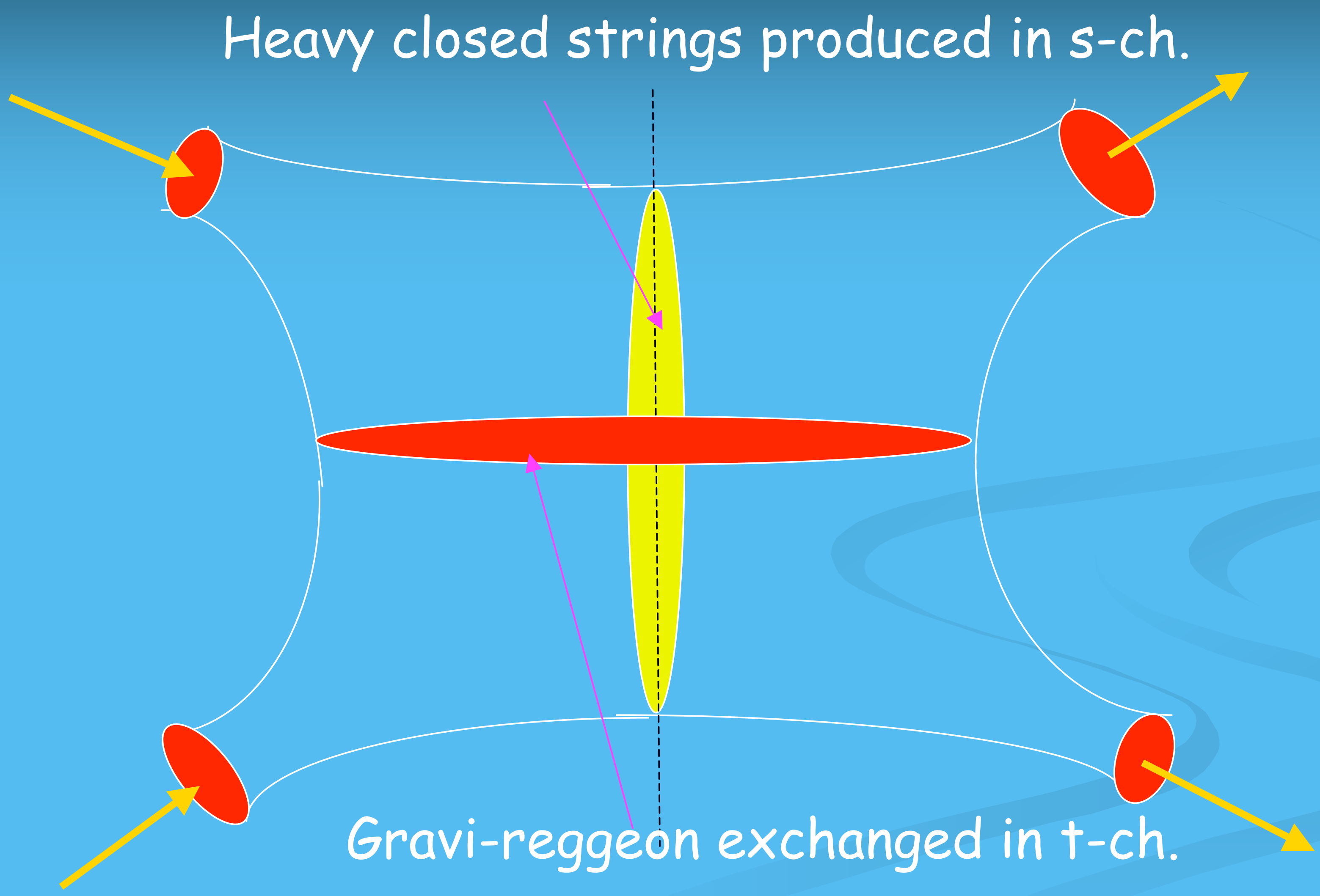
← Consequences discussed below

The graviton being "reggeized" in string theory, we also get

$$Im\delta \sim \frac{G_D \, s \, l_s^2}{(Y l_s)^{D-2}} e^{-b^2/b_I^2}, \; b_I^2 \equiv l_s^2 Y^2, \; Y = \sqrt{\log(\alpha' s)}$$

Since Im A has no Coulomb pole its FT is exp.^{lly} small at b >> b_I

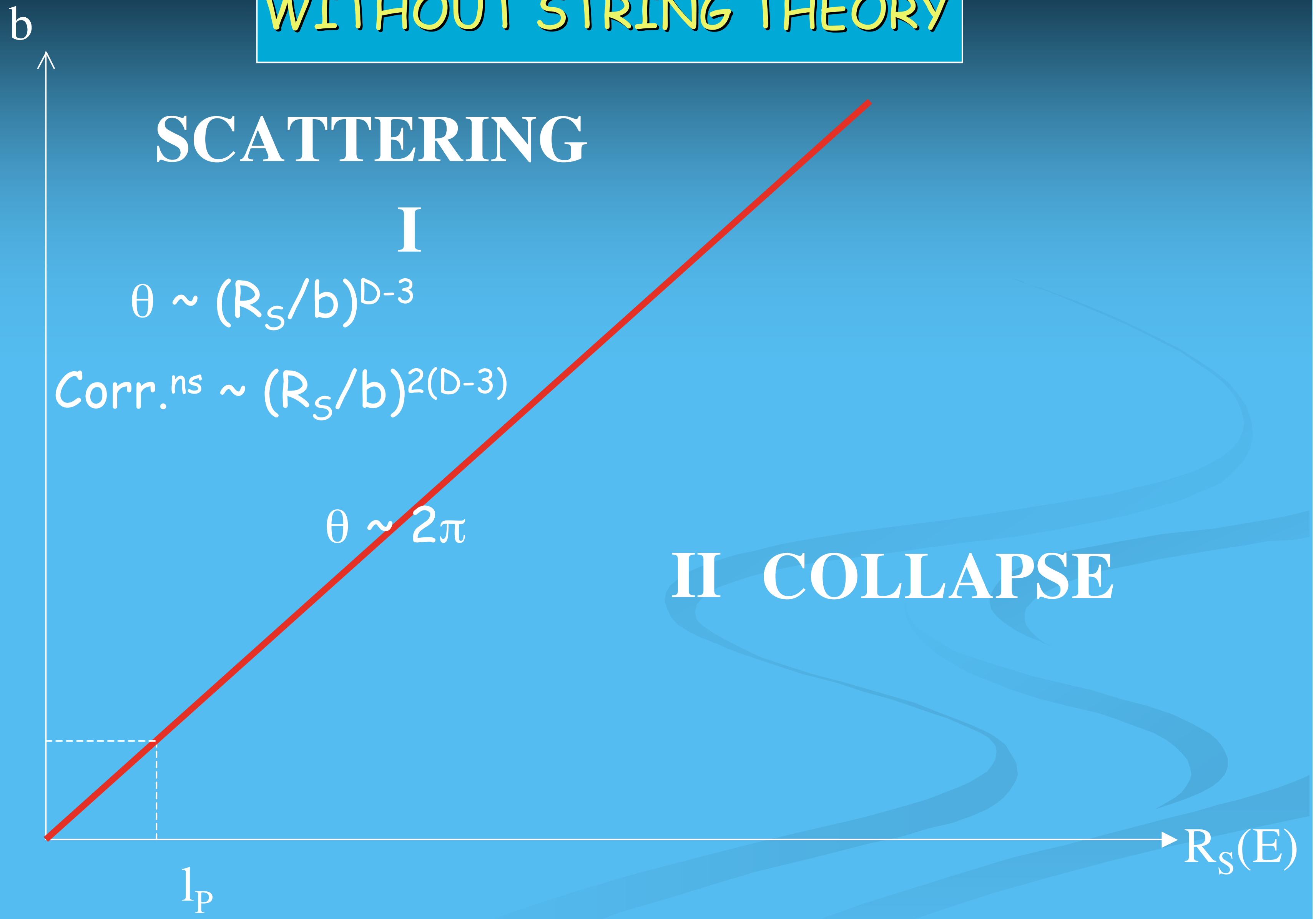
Im A is due to closed strings in s-channel (DHS duality)

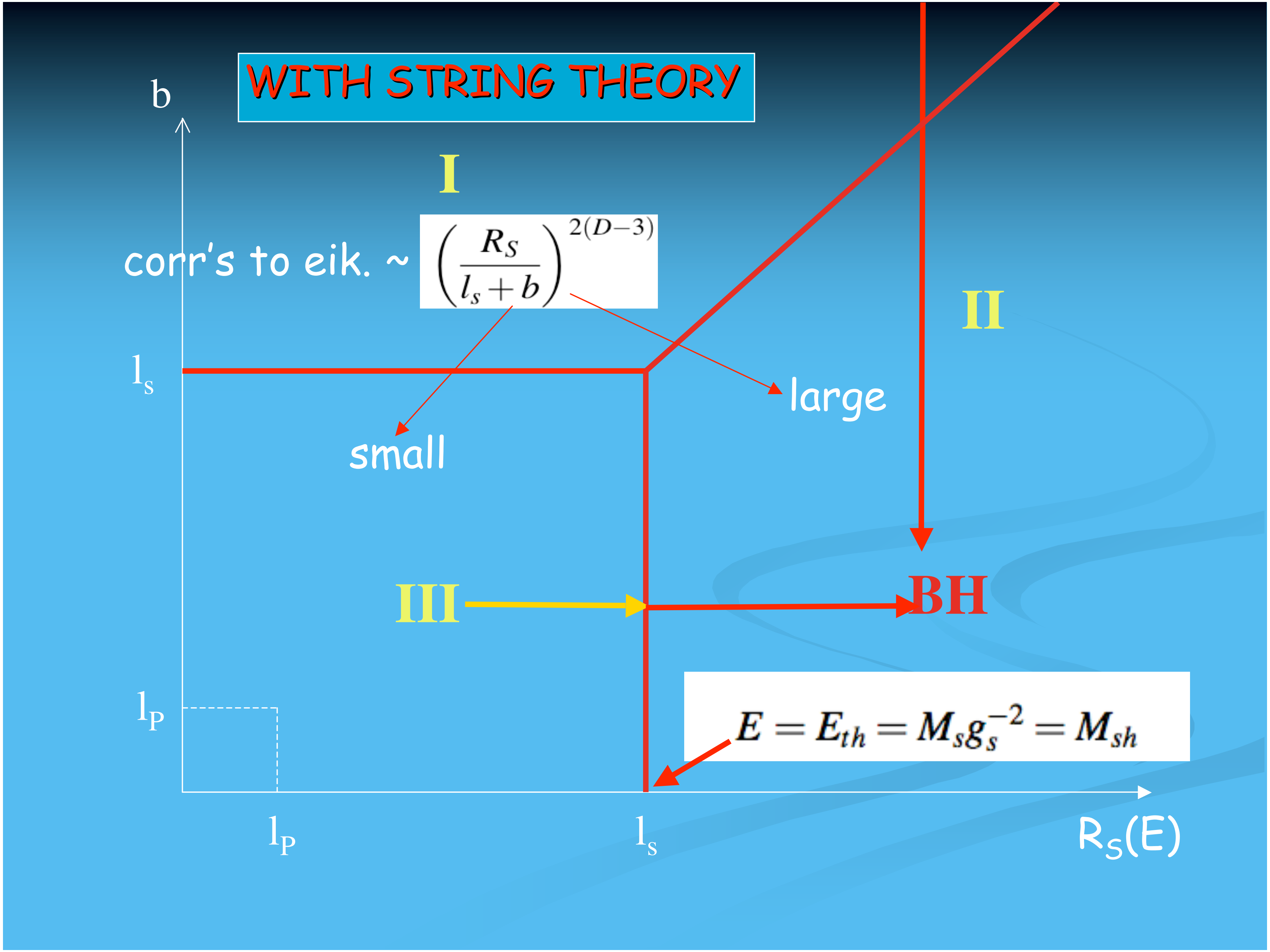


Tree level cont.[d]

- Tree level violates p.w. unitarity as s goes transplanckian
- Tree-level too large at fixed b, too small at fixed θ
- String loops take care of both problems!
- What do we expect from GR-type arguments?

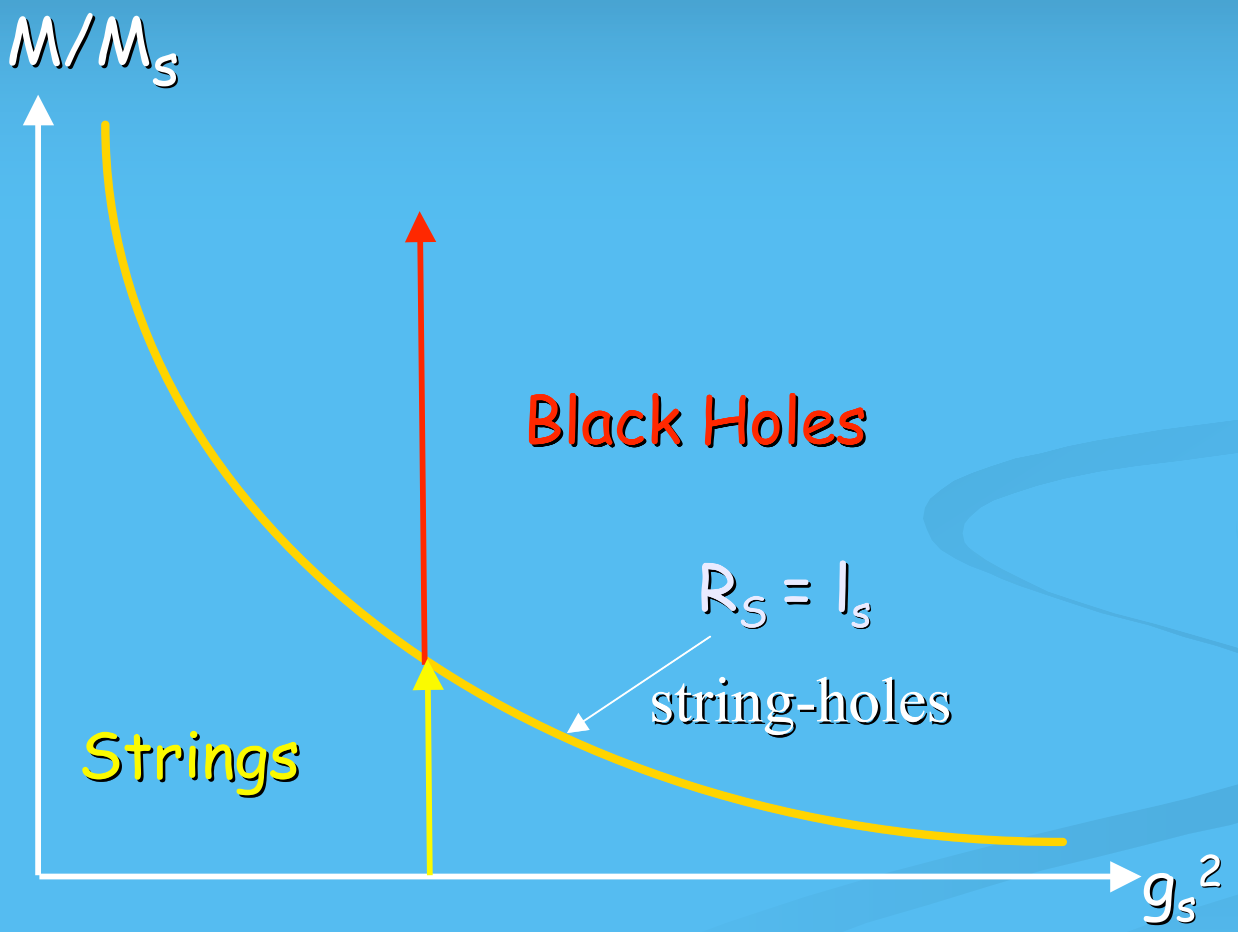
WITHOUT STRING THEORY





WITH STRING THEORY
b
I
corr's to eik. ~ $\left(\frac{R_S}{l_s+b}\right)^{2(D-3)}$
l_s
small
large
II
III
BH
l_P
$E = E_{th} = M_s g_s^{-2} = M_{sh}$
l_P
l_s
$R_S(E)$

Accretion at fixed g_s or how to turn a string into a black hole



- I) Small angle scattering: relatively easy
- II) Large angle, collapse: very hard, all attempts have failed so far
- III) Stringy (easy again)

A single, compact formula covers regions I and III!

Unitary S-matrix in regions I and III

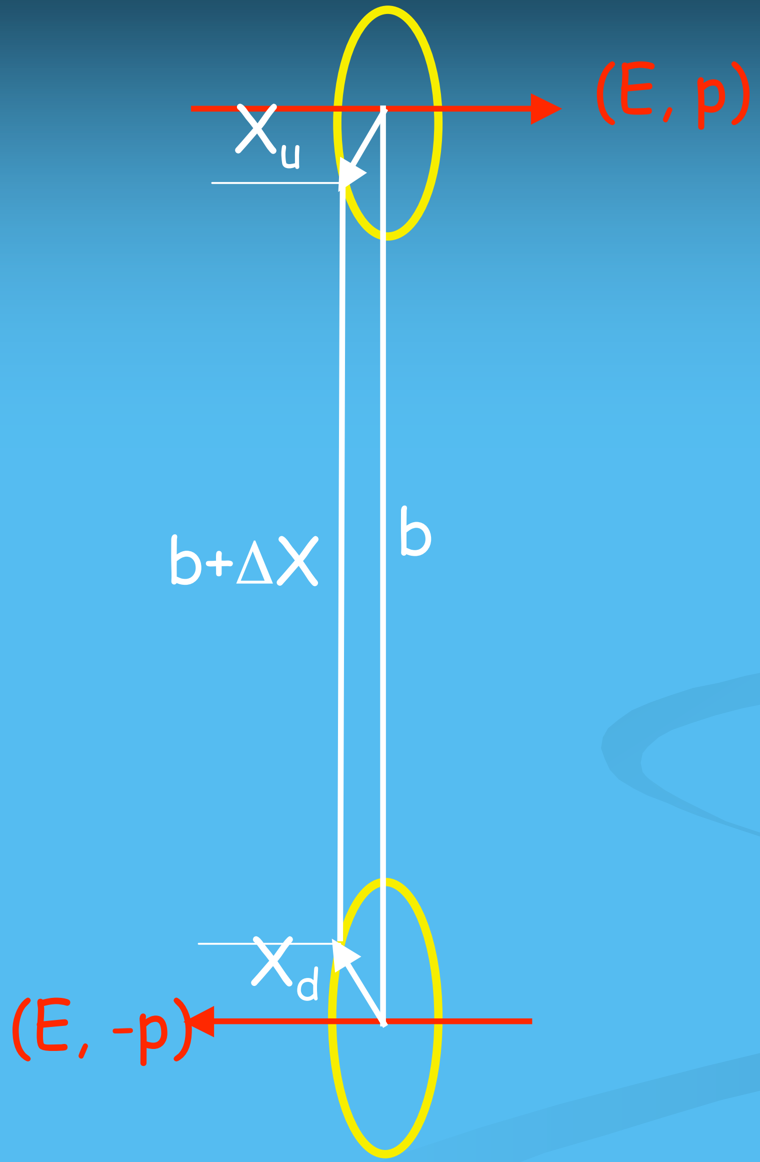
$$S = e^{2i\delta} e^{2i\sqrt{Im\delta}\, C^{\dagger}} e^{2i\sqrt{Im\delta}\, C}$$

$$[C, C^{\dagger}] = 1$$

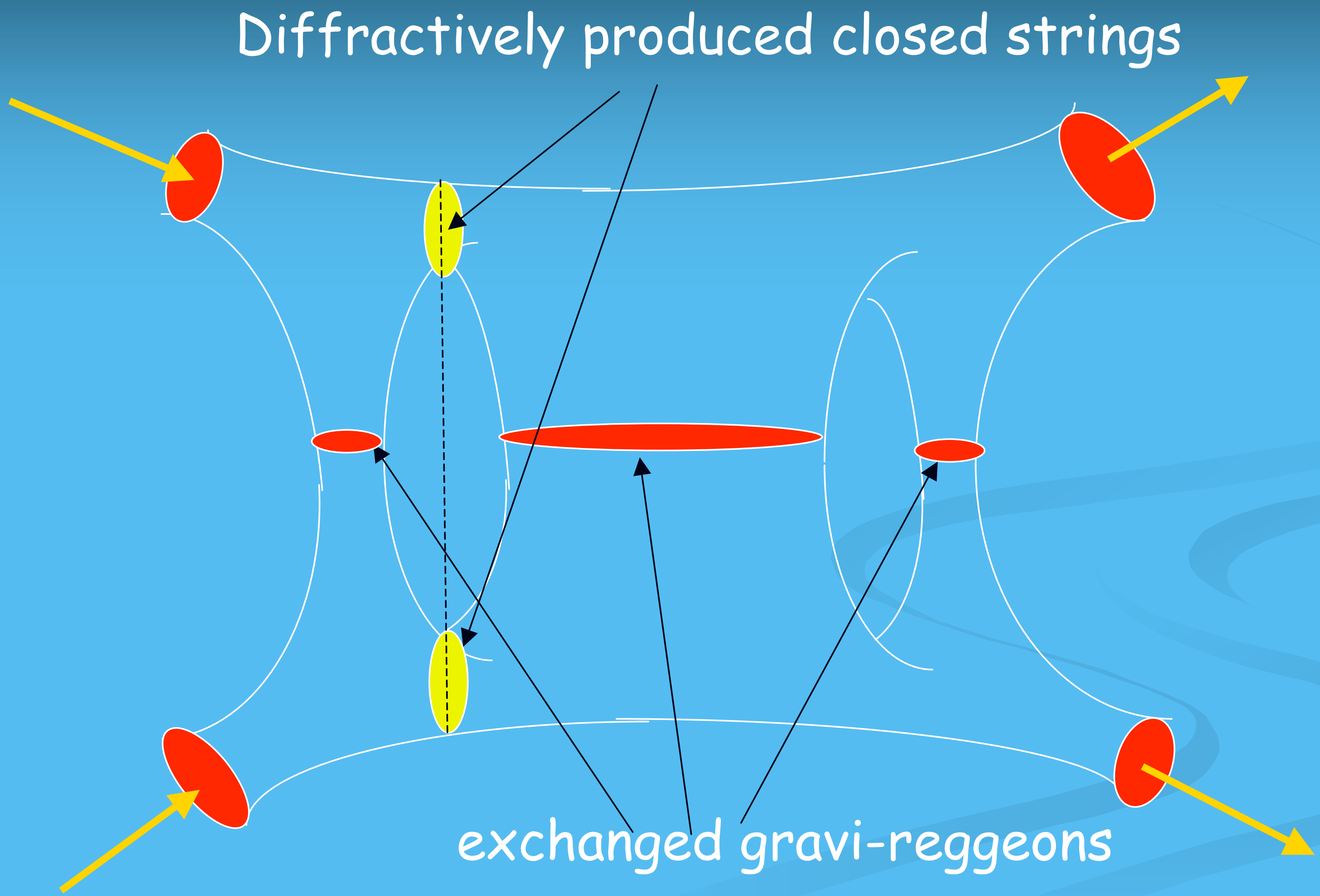
$$\delta(E,b) = \frac{1}{(2\pi)^{D-2}} \int d^{D-2}q \frac{A_{tree}(s,t)}{4s}\, e^{-iqb} \;,\; s = E^2,\; t = -q^2$$

Actually δ becomes an operator, but we shall neglect this complication physically related to the «diffractive» excitation of each string by the tidal forces due to the other string

Diffractive excitation from b --> b+ΔX

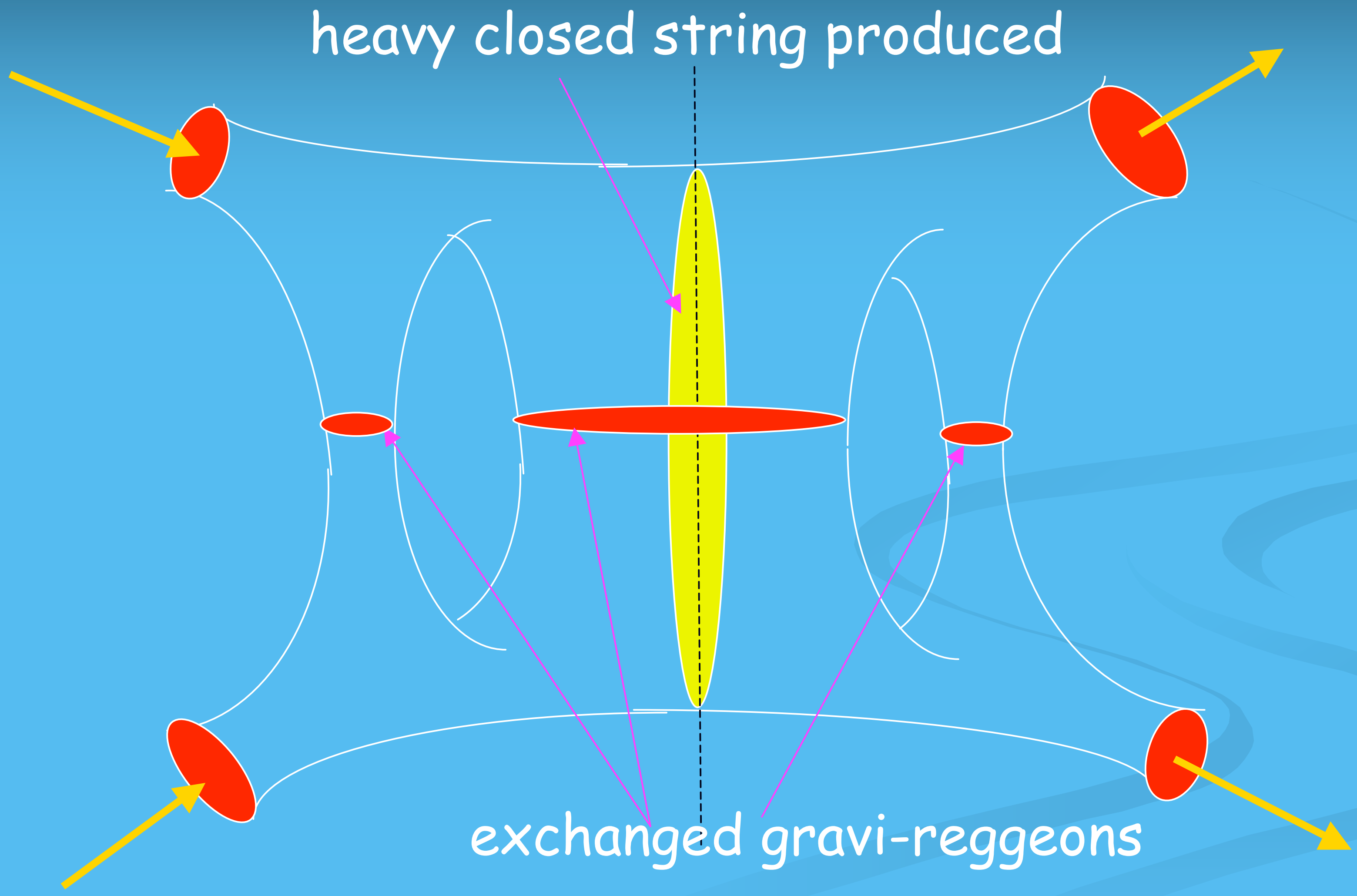


Another way of "cutting" the diagram



We will instead concentrate on the operators C, C^+ (appearing iff δ is not real) corresponding to the « Reggeization » and duality of graviton exchange in string theory.

NB: any number of gravi-Reggeons can be cut: AGK rules



Recall that:

$$Im\delta \sim \frac{G_D\, s\, l_s^2}{(Y l_s)^{D-2}} e^{-b^2/b_I^2}\,,\; b_I^2 \equiv l_s^2 Y^2\,,\; Y = \sqrt{log(\alpha' s)}$$

Thus, for b >> b_I (Region I), we can forget about C, C^+. Also:

$$Re\delta \sim G_D\, s\, \frac{b^{4-D}}{D-4}$$

Going over to scattering angle θ by FT, we find a saddle point:

$$b_s^{D-3} = \frac{8\pi G_D \sqrt{s}}{\Omega_{D-2}\theta} \quad \text{i.e.} \quad \theta = \frac{8\pi G_D \sqrt{s}}{\Omega_{D-2} b^{D-3}}$$

corresponding precisely to the relation between b and θ in an AS metric*): clearly, fixed θ , large E probes large b

******

*) metric produced by a pointlike relativistic particle

Region III

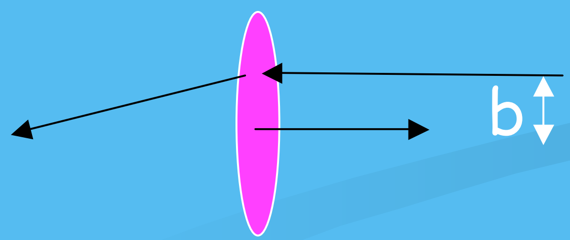
Let us neglect (for a moment!) Im $\delta \neq 0$, C and C^{+}

$$Re\delta = -\frac{G_D \, s \, b^2}{(Y l_s)^{D-2}}$$

The saddle point condition now gives the relation:

$$\theta = G_D \, \rho \, b \; , \; \rho = \frac{E}{(Y l_s)^{D-2}}$$

corresponding to deflection from an homogeneous beam of transverse size ~ l_s: θ_{max}~ GE/l_s^{D-3} reached for b ~ l_s



Analysis of final state in Region III

Take into account Im $\delta \neq 0$. C and C⁺ are now "activated". Recall:

$$S = e^{2i\delta} e^{2i\sqrt{Im\delta}\, C^\dagger} e^{2i\sqrt{Im\delta}\, C}$$

The elastic amplitude, ‹0|S|0›, is suppressed as exp(-2 Im δ):

$$\sigma_{el} \sim exp(-4Im\delta) = exp\left[-\frac{G_D\, s\, l_s^2}{(Y l_s)^{D-2}}\right] \equiv exp\left[-\frac{s}{M_*^2}\right]$$

$$M_* = \sqrt{M_s M_{sh}} \sim M_s g_s^{-1}$$

(= M_P in D=4, $M_* > M_P$ for D>4)

If we go to E= E_{th} we find: $\sigma_{el} \sim exp(-g_s^{-2}) \sim exp(-S_{sh})$

Amagingly: M_* is just the D0-brane mass scale!

Which final states saturate unitarity?

Recall once more:

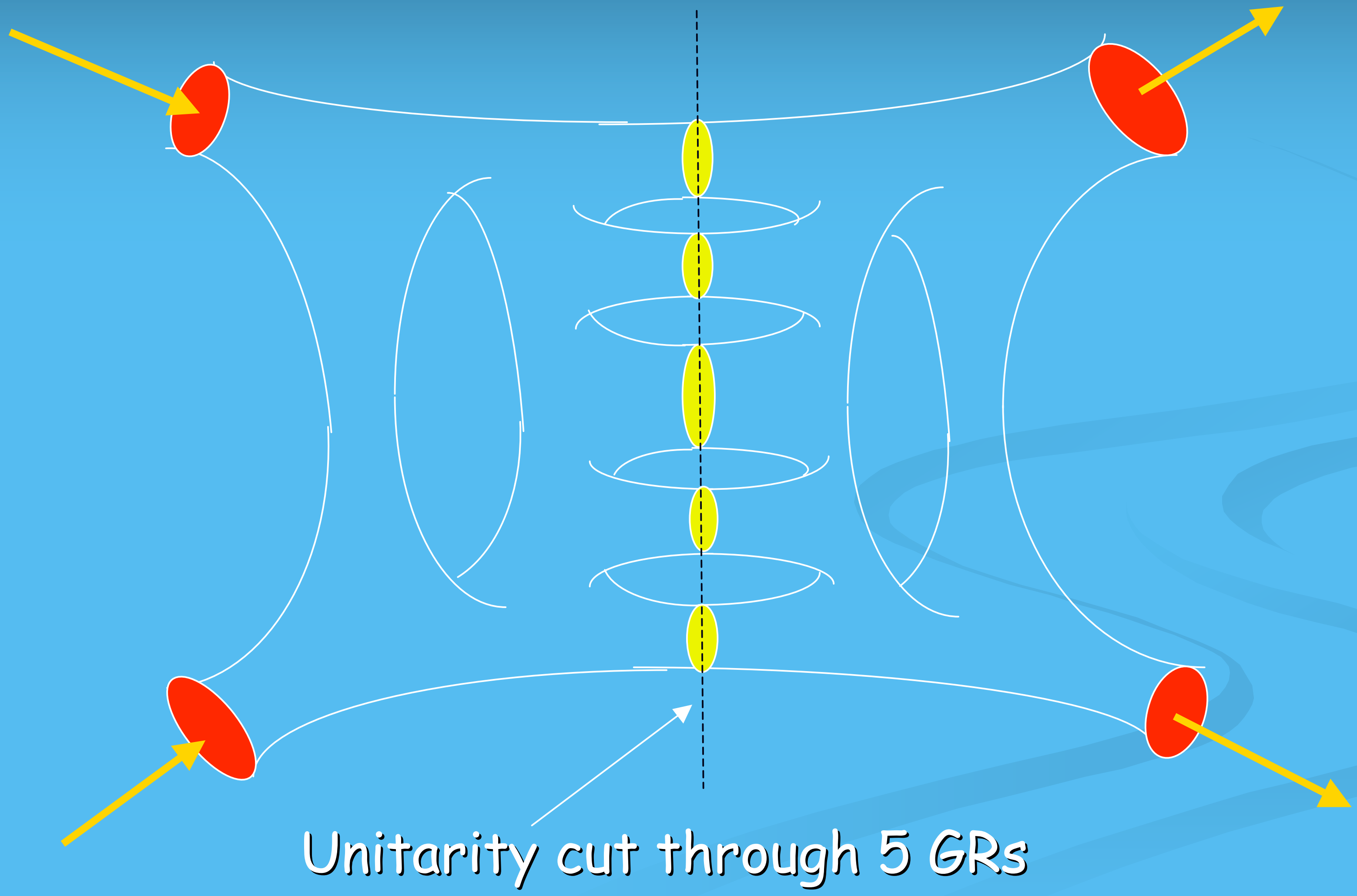
$$S = e^{2i\delta} e^{2i\sqrt{Im\delta}\, C^{\dagger}} e^{2i\sqrt{Im\delta}\, C}$$

➡The final state, S|0>, is a coherent state of quanta associated with C, C⁺. These quanta are just the closed strings dual to the gravi-reggeon (CGRs for "cut gravi-reggeons") The probability of producing n CGRs thus obeys a Poisson distribution with an average given by:

$$\langle N_{CGR} \rangle = 4Im\delta = \frac{G_D\, s\, l_s^2}{(Y l_s)^{D-2}} = O\left(\frac{s}{M_*^2}\right)$$

Final state via optical theorem & AGK rules

(NB: different CGRs overlap in rapidity)



At this point we can compute the average energy of a final state/string associated with a single CGR:

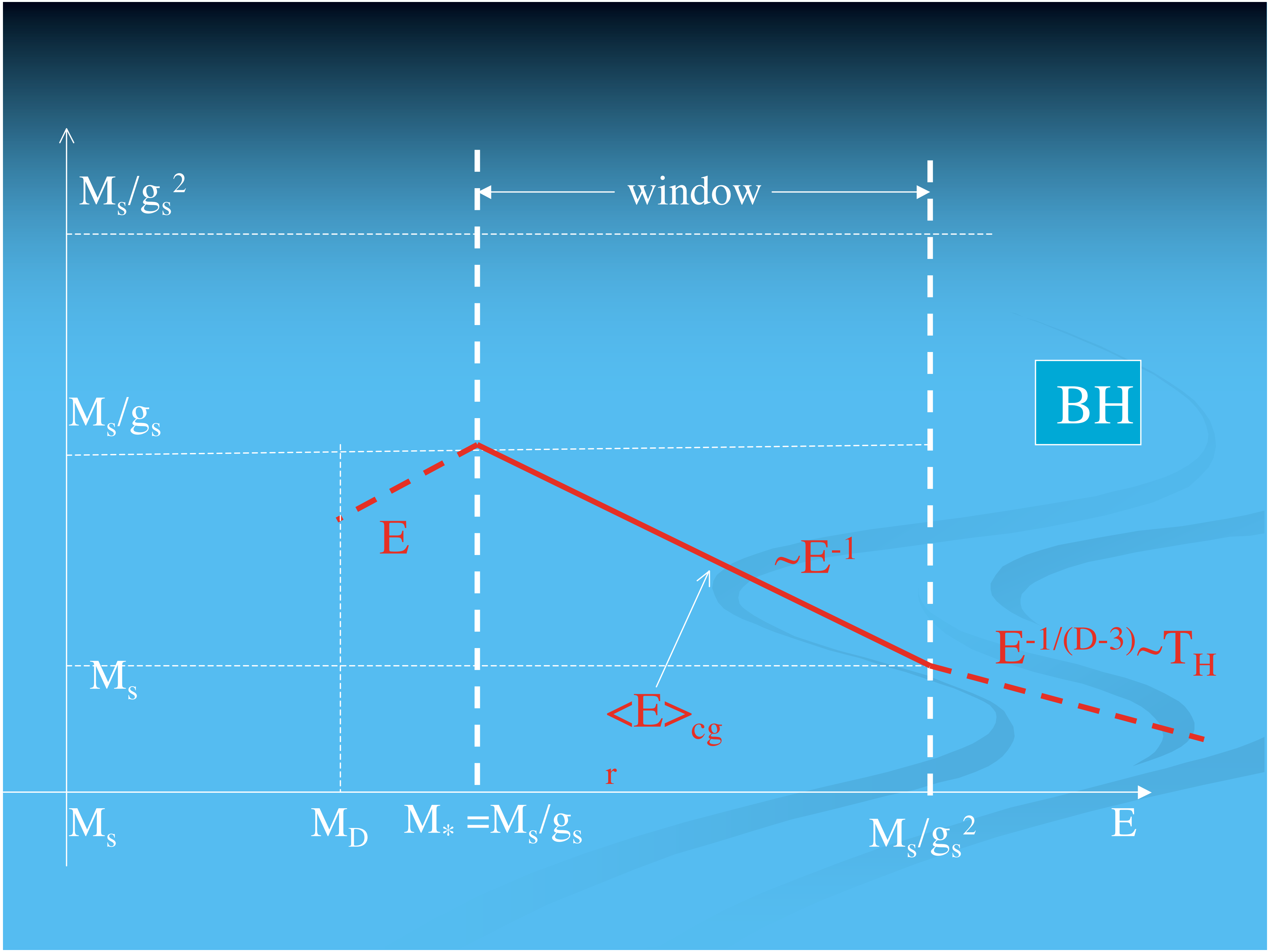
$$\langle E \rangle_{CGR} = \frac{\sqrt{s}}{\langle N_{CGR} \rangle} \sim M_s Y^{D-2} \left(\frac{l_s}{R_S} \right)^{D-3} \sim T_{eff} \equiv \frac{M_*^2}{E} = \frac{M_s^2}{g_s^2 E}$$

We have thus found that final-state energies obey a sort of «anti-scaling» law

$$\langle E \rangle_{CGR} \sqrt{s} = M_*^2 = M_s^2 g_s^{-2}$$

This antiscaling is very unlike what we are familiar with in HEP

It is however similar to what we expect in BH physics!
In particular: For D=4, $T_{eff} \sim T_{Haw}$ even at $E < E_{th}$



M_s/g_s^2
window
BH
M_s/g_s
E
~E^-1
E^-1/(D-3)~T_H
M_s
<E>_cg
r
M_s
M_D
M_* =M_s/g_s
M_s/g_s^2
E

We conclude that, at least below E_{th}, there is no loss of quantum coherence, but the spectra aren't thermal either

Above E_{th} we can no-longer neglect "classical" corrections corresponding to interactions among CGRs: these will hopefully turn the Poisson distribution into an approximately Planckian one

No reason to expect a breakdown of unitarity.

If we could prepare as initial state:

$$|in\rangle = S^{\dagger}|0\rangle = e^{-2i\delta^*} e^{-2i\sqrt{Im\delta}\, C^{\dagger}}|0\rangle$$

the final state would be just a two-particle state!

Summarizing

- String theory pretends to be the way to combine the principles of quantum mechanics and general relativity in a consistent framework. As such it should provide answers to the physics of black holes and cosmology in regimes where quantum effects are important/dominant
- So far, most of the progress has been in the former problem as seen from an outside observer (the physics inside a black hole is similar to that of a big crunch in cosmology)
- We have seen that string theory may be able to provide a microscopic, stat. mech. interpretation of black hole entropy

- We have also been able to recast the main results of ACV in the form of an approximate, but exactly unitary, S-matrix, whose range of validity covers a large region of the kinematic energy-angular-momentum plane;
- We have found a sort of precocious black-hole behaviour, in particular an « anti-scaling » dependence of $\langle E_f \rangle$ from E_i, reminiscent of the inverse relation between black-hole mass and temperature; this may have phenomenological applications in the context of the string/quantum-gravity signals expected at colliders in models with a low string/quantum-gravity scale.