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Classical and quantum gravity from (gedanken?) string collisions

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General introduction

- So far, the SM of EP appears to work extremely well (see MM's lectures) at least at scales below 100 GeV
- CGR also works very well in a vast range of scales (see TD's lectures)
- There are problems with GR at very short scales (singularities) and possibly also at very large scales (dark energy)
- CGR is bound to fail in extreme-curvature regimes
- Wide-spread belief that a consistent theory of QG may avoid the short-distance problems of CGR (BTW: having a consistent theory of QG is not just a theoretical luxury if LSS does originate from primordial quantum fluctuations)

- When appied to GR, QM appears to bring new problems instead of new solutions (UV divergences, information paradox, a huge cosmological constant).
- Although a serious candidate for a quantum theory of gravity does exists, ST, we still lack a full understanding of how it provides answers to the abovementioned questions
- QG today reminds us (me?) of the early days of QM about a century ago: trying to learn its basic rules and to extract its physical consequences
- A century ago much progress was made (both in QM and in R) by considering *gedanken* experiments. Will history repeat itself?
- This is the question I will try to adress in the context of superstring theory, using QM and SR, but without appealing to any GR prejudice:
- Class. and Quant. Gravity not an input, hopefully an output!

TPE collisions as a GE

Trans-Planckian-Energy (TPE => $E \gg M_P$, or $Gs/\hbar \gg 1$) collisions represent a very rich theoretical laboratory for addressing the physics of Black Holes (BH).

The need for TPE comes from our wish to understand the physics of semiclassical -rather than Planck size- BH's

There are many classical results on whether and how smooth initial data can either lead to black-hole formation or to a completely dispersed final state (Christodoulou & Kleinermann, Christodoulou..., Choptuik,... CTS criteria, ... Christodoulou '08)

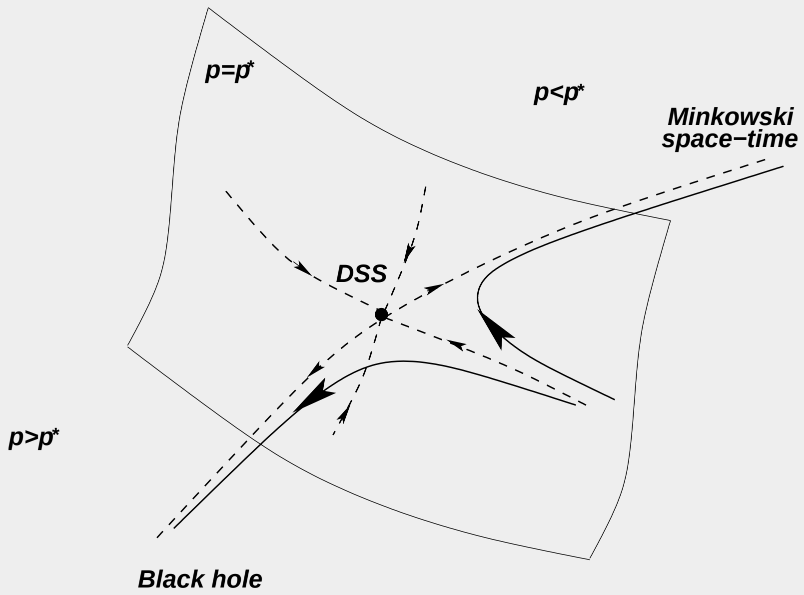


Figure 1: Phase space picture of the critical gravitational collapse.

In general, one expects to find a critical hypersurface $S_{cr}^{(Cl)}$ (in the parameter space $P^{(Cl)}$ of the initial state) separating the two phases

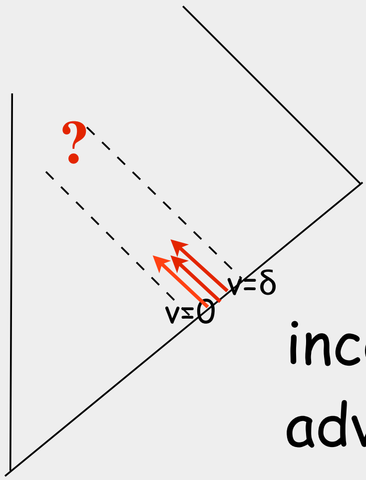
The approach to criticality looks like that of phase transitions in Stat. Mech. (order of transition, crit. exp's,..)

0805.3880 [gr-qc] 26 May 2008, 594 pages

The Formation of Black Holes in General Relativity

Demetrios Christodoulou

May 18, 2008



incoming energy (G=1) per unit advanced time & solid angle

$$\text{If} \quad M(\theta,\phi,\delta) = \int_0^\delta dv \frac{d\mathcal{M}(v,\phi,\delta)}{dv\ dcos\theta\ d\phi} \geq \frac{k}{8\pi} \quad \text{for all} \quad \theta,\phi$$

then a CTS forms with $R \geq k - O(\delta) \quad (\text{provided } R > 0)$

At the quantum level we can prepare pure initial states that correspond, roughly, to the classical data. They define a parameter space $P^{(Q)}$. We may ask:

- Is there a unitary S-matrix (unitary evolution operator) describing the evolution of the system?
- If yes, does such an S-matrix develop singularities as one approaches a critical surface $S_{cr}^{(Q)}$ in $P^{(Q)}$?
- If yes, what happens in the vicinity of this critical surface? Does the nature of the final state change as one goes through it? Is there any connection between $S_{cr}^{(Cl)}$ and $S_{cr}^{(Q)}$?
- What happens to the final state deep inside the BH region? Does it resemble at all Hawking's thermal spectrum for each initial pure state?

A phenomenological motivation?
(from gedanken to real experiments!)

Finding signatures of string/quantum gravity @ LHC:

- In KK models with large extra dimensions;
- In brane-world scenarios; in general:
- If the true Quantum Gravity scale is O(few TeV)

NB: In the most optimistic situation the LHC will be very marginal for producing BH, let alone semiclassical ones

Q: Can there be some precursors of BH behaviour even below the expected production threshold?

Outine of the two talks

1st talk (12/09)

- 3 scales & 3 regimes in TPE string collisions
- The small-angle regime
    - Leading eikonal
    - Tidal excitations
    - s-channel production of heavy strings
- The "stringy" regime and precocious BH behaviour

2^{nd} talk (13/09)

- Classical corrections in the large-angle regime
  - Identification of the relevant diagrams
  - Resumming classical corrections via an eff. action
  - The axisymmetric case: critical lines and comparison with CTS criteria
  - Two-body scattering at $b \neq 0$: critical point
  - Graviton spectra below and near criticality
  - What happens above criticality?
- Summary and outlook

Part 1

Classical expectations

based on the construction of

Closed Trapped Surfaces

in two-body scattering

(DC's criterion not so useful for this problem)

CTS (sufficiency) criteria => bounds

- Point-particle collisions:

1. b=0: Penrose ('74) : $M_{BH} > E/\sqrt{2} \sim 0.71E$

   D'Eath & Payne ('92), Pretorius ('08): $M_{BH} \sim 0.86\ E$
2. b≠0: Eardley and Giddings, gr-qc/0201034, Yoshino & Nambu, hep-th/0209003: one example:

$$\left(\frac{R}{b}\right)_{cr} \leq 1.25\ ,\ \ D = 4 \qquad\qquad (R = 2G\sqrt{s} = 4GE_1 = 4GE_2)$$

- Extended sources:

- Yurtsever ('88) gave arguments for critical size O(R)
- Kohlprath and GV, gr-qc/0203093: one example:

$$\left(\frac{R}{L}\right)_{cr} \leq 1\ ,\ \ D = 4$$

for central collision of 2 homogeneous null beams of radius L

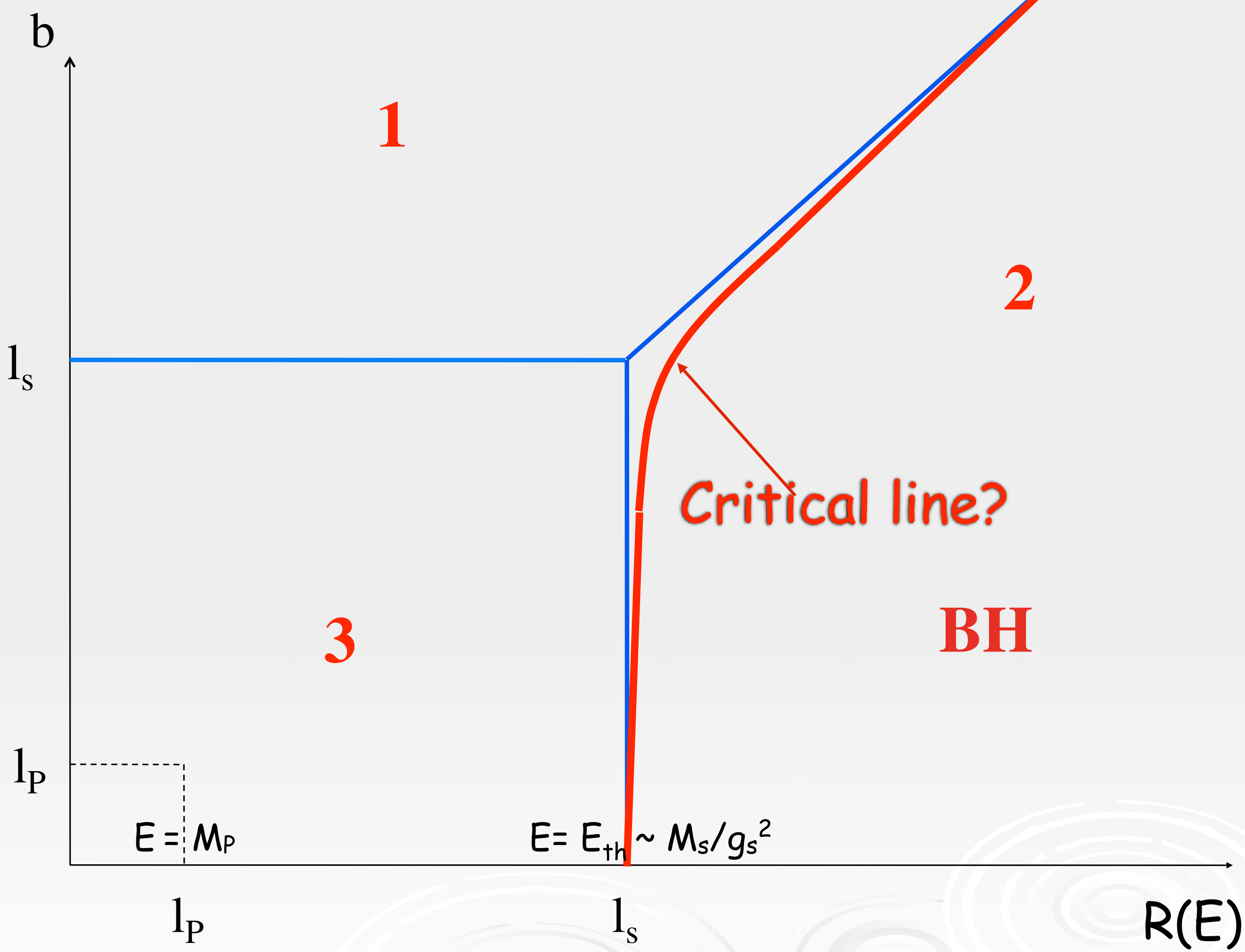
The string length parameter l_s plays the role of the beam size!

3 length scales: b, R and l_s =>

3 broad-band regimes in trans-Planckian superstring scattering

1) Small angle scattering ($b \gg R, l_s$)
2) Large angle scattering ($b \sim R > l_s$), collapse ($b, l_s < R$)
3) Stringy ($l_s > R, b$)

They will become 6 narrow-band regimes



NB: we take the string coupling g_s very small so that $l_s \gg l_P$

Two complementary approaches

Reconsidered recently within AdS/CFT (AM, CCP, BPST)

1. Gross-Mende, Mende-Ooguri ('87-'90)
2. 't-Hooft; Muzinich & Soldate; ACV; Verlinde^2; FPVV…, Arcioni, de Haro, 't-Hooft; …('87-'05); Giddings; Giddings, Gross, Maharana Jr. ('07); Giddings and Srednicki ('07); ACV07, Marchesini & Onofri (08), GV & Wosiek (08), Ciafaloni & Colferai (08)

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Two very different approaches; agree incredibly well in the region of ph. sp. where they can be both justified.

ACV approach (1987-2007)

- Work in energy-impact parameter space, A(E,b)
- Go to arbitrarily high energy while increasing b

$$b > R_S(E) \sim (G_N E)^{\frac{1}{D-3}}$$ (NB: $R=R_S$)

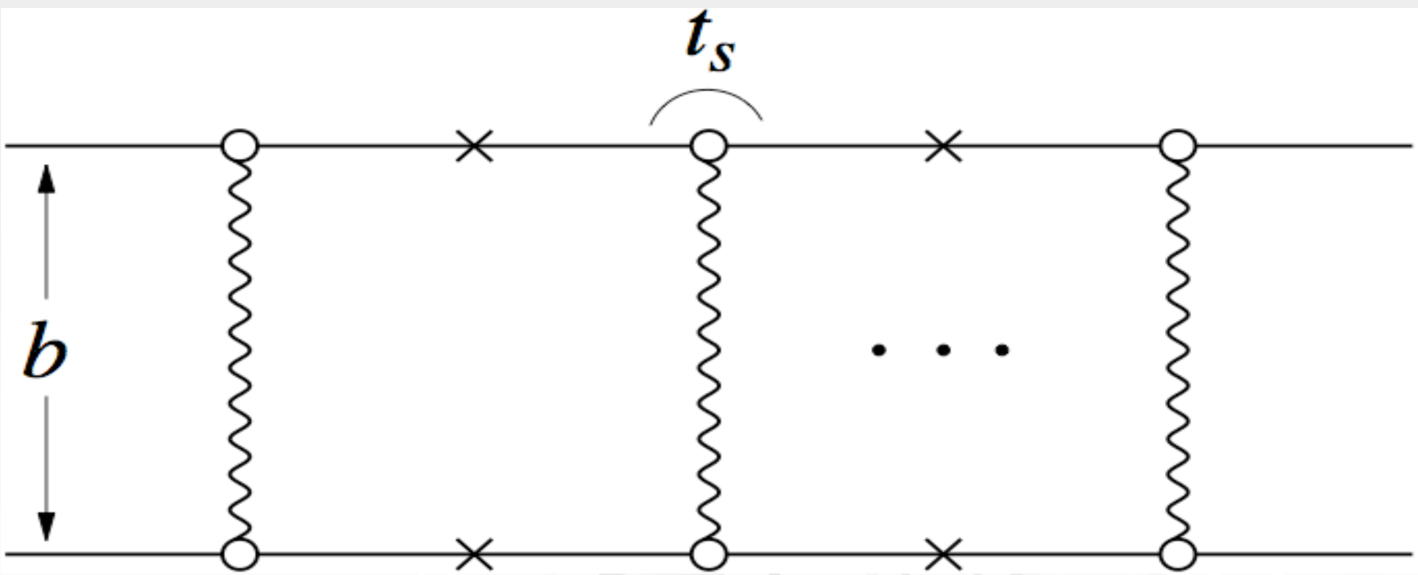
- Go over to $A(E, q \sim \theta E)$ by FT and reach the regime of fixed $\theta \ll 1$ by picking up contributions from saddle point in the above region of b ($b_s \sim R/\theta \gg R$)
- Extend to large angle (collapse) i.e. to $b \sim R$ ($b < R$)
- Cross fingers throughout!

The semiclassical S-matrix

General arguments as well as string-loop calculations suggest the following form for the TPE S-matrix:

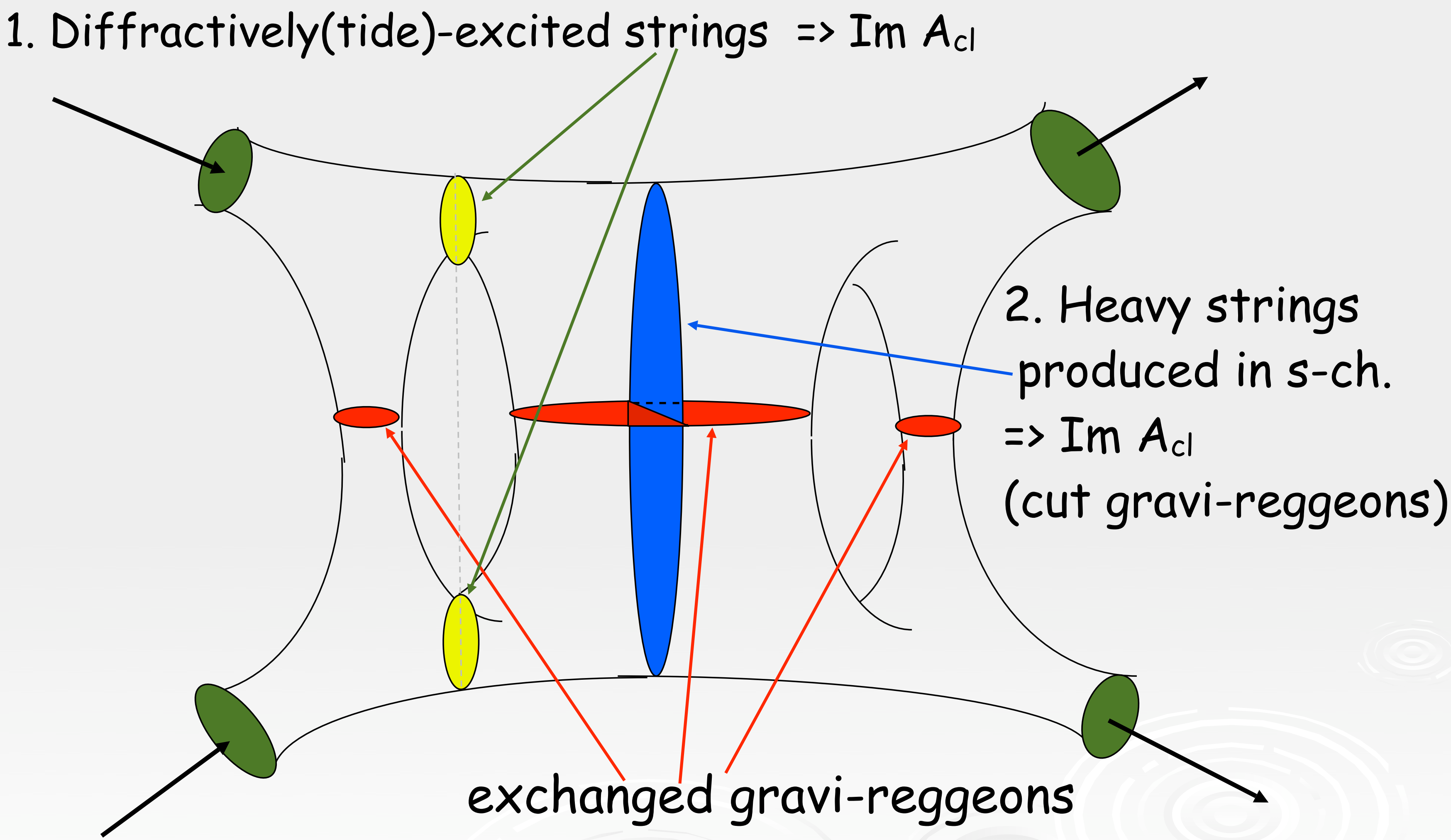
$$S(E,b) \sim exp\left(i\frac{A_{cl}}{\hbar}\right) \quad ; \quad \frac{A_{cl}}{\hbar} \sim \frac{Gs}{\hbar} c_D b^{4-D} \left(1 + O((R/b)^{2(D-3)}) + O(l_s^2/b^2) + \cancel{O((l_P/b)^{D-2})} + \cancel{\ldots}\right)$$

Leading eikonal diagrams (crossed ladders included)



NB: For Im A_{cl} some terms may be more than just corrections...

Two examples of string corrections (controlled by l_s)



Classical corrections (controlled by R/b) to be discussed later

The existence of these corrections complicates the previous diagram with new regions appearing in our parameter space. We may roughly distinguish 6 (increasingly difficult) regimes:

I) Small-angle elastic scattering (leading eikonal)

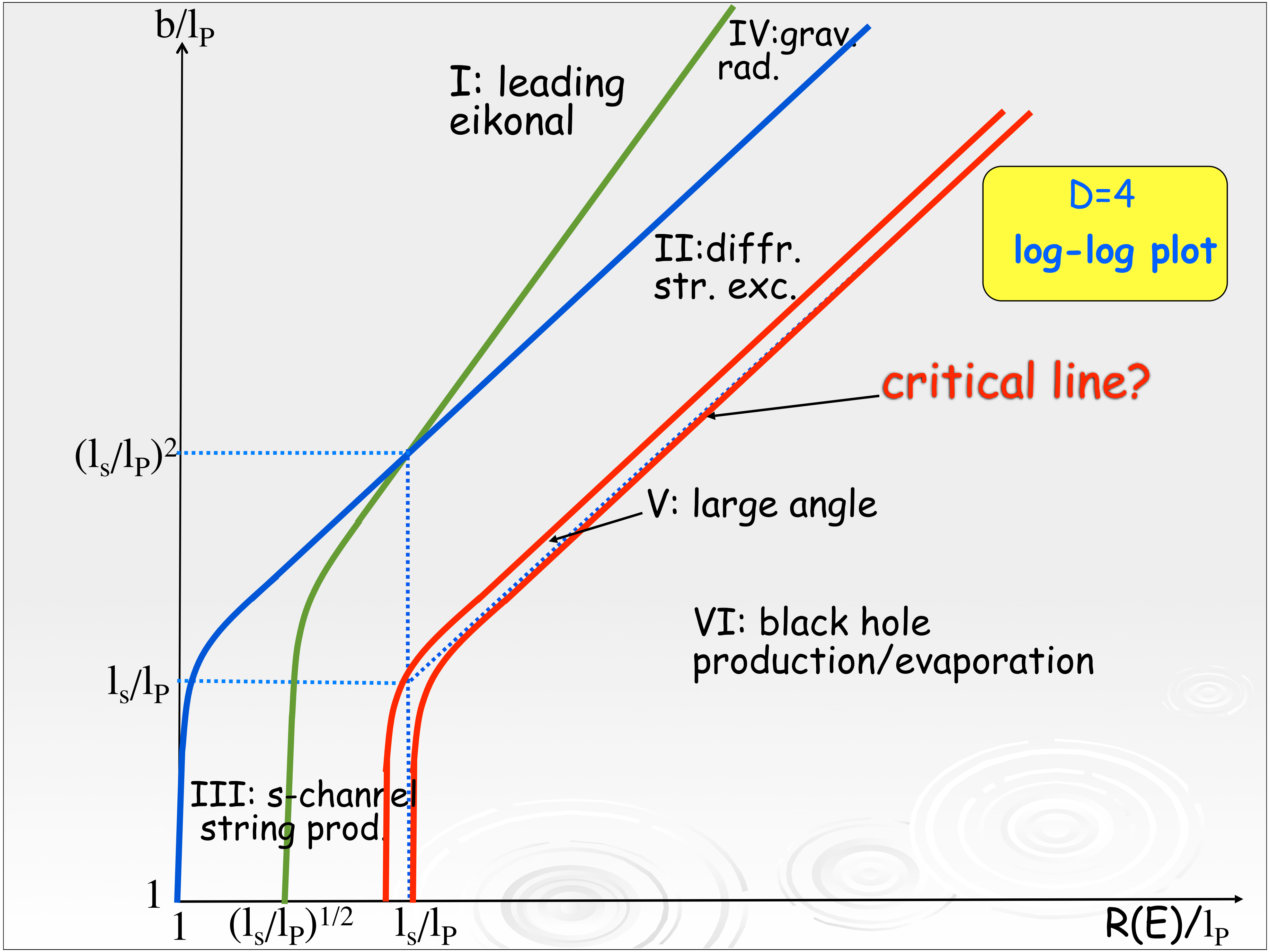
II) Small-angle inelastic scattering (a.string excitation)

III) Small-angle inelastic scattering (b.string formation)

IV) Small-angle inelastic scattering (c.graviton emission)

V) Large-angle inelastic scattering

VI) Classical Collapse

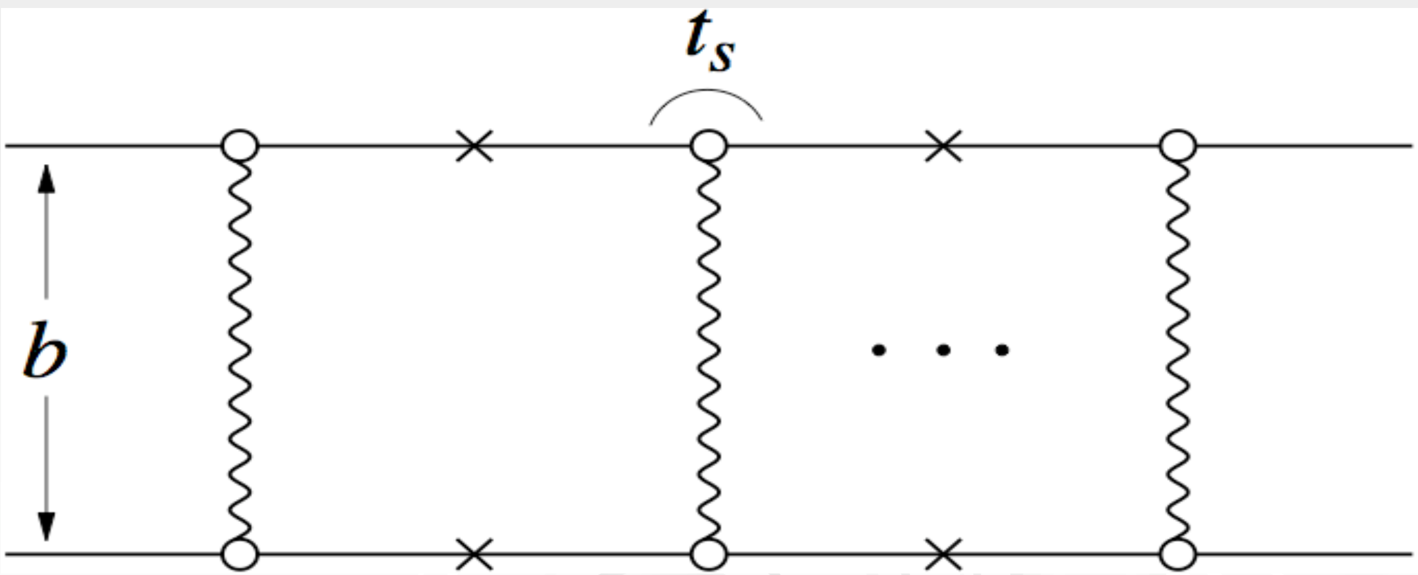


b/l_P
I: leading eikonal
IV:grav. rad.
D=4
log-log plot
II:diffr. str. exc.
critical line?
(l_s/l_P)^2
V: large angle
VI: black hole production/evaporation
l_s/l_P
III: s-channel string prod.
1
1
(l_s/l_P)^1/2
l_s/l_P
R(E)/l_P

I: Small-angle elastic scattering (leading eikonal)

$$S(E,b) \sim exp\left(i\frac{A_{cl}}{\hbar}\right) \quad ; \quad \frac{A_{cl}}{\hbar} \sim \frac{Gs}{\hbar} c_D b^{4-D}\left(1 + \cancel{O((R/b)^{2(D-3)})} + \cancel{O(l_s^2/b^2)} + \cancel{O((l_P/b)^{D-2})} + \ldots\right)$$

Leading eikonal diagrams (crossed ladders included)



Recovering CGR expectations @ large distance

$$S = \mathrm{e}^{2i\delta} \qquad\qquad Re\delta \sim Gsb^{4-D}$$

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

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

For b >> l_sY (Region I), we can forget about Im δ

Going over to scattering angle θ, we find a saddle point at

$$b_s^{D-3} \sim \frac{G\sqrt{s}}{\theta} \quad ; \quad \theta \sim \left(\frac{R_S}{b}\right)^{D-3}$$

corresponding **precisely** to the relation between impact parameter and deflection angle in the (emerging!) AS metric generated by a relativistic **point-particle** of energy E.

- Note that at fixed θ, larger E probe larger b
- The reason is quite simple: because of eikonal exponentiation, Re δ also gives the average loop-number. The total (huge) momentum transfer $q = \theta E$ is shared among many many exchanged gravitons to give:

$$q_{ind.} \sim \frac{q}{Gsb^{4-D}} \sim \frac{\theta}{R_S^{D-3} b^{4-D}} \sim b_s^{-1}$$

meaning that the process is soft at large s

II: Small-angle inelastic scattering

(a. diffractive/tidal string excitation)

When a string moves in an AS metric it suffers tidal forces as a result of its finite size (Giddings 0604072)
Grav. counterpart to diffractive excitation?

When does DE kick-in? Tidal-force argument (SG/GV):

$$\theta_1 \sim G_D \; E_2 \; b^{3-D} \;\; \Rightarrow \Delta\theta_1 \sim G_D \; E_2 \; l_s \; b^{2-D}$$

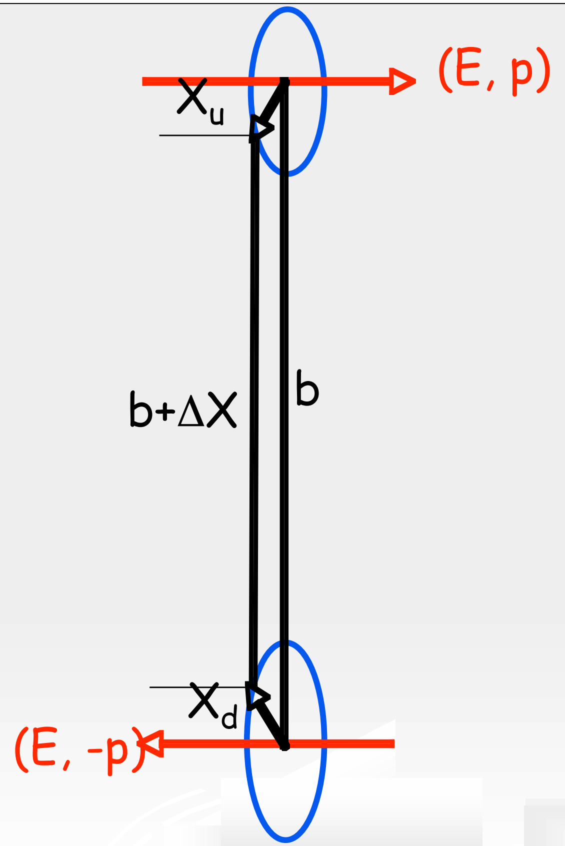
This angular spread provides an invariant mass:

$$M_1 \sim E_1 \Delta\theta_1 \sim G_D \; s \; l_s \; b^{2-D} = M_2$$ strings get excited if

$$M_{1,2} \sim M_s = \hbar l_s^{-1} \Rightarrow b = b_D \sim \left(\frac{G s l_s^2}{\hbar}\right)^{\frac{1}{D-2}}$$

... as in ACV '87

$$\sigma_{el} \sim \exp(-S(M)) \sim \exp(-M/M_s) \sim \exp(-\frac{Gs}{\hbar}\frac{l_s^2}{b^{D-2}}) \to \exp(-\frac{Gs}{\hbar} l_s^{4-D})$$



(E, p)
X_u
b+ΔX
b
X_d
(E, -p)

III: Small-angle inelastic scattering

(b. string formation @ b, R < l_s)

Because of Im $\delta \neq 0$, S_{el} is suppressed as exp(-2 Im δ):

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

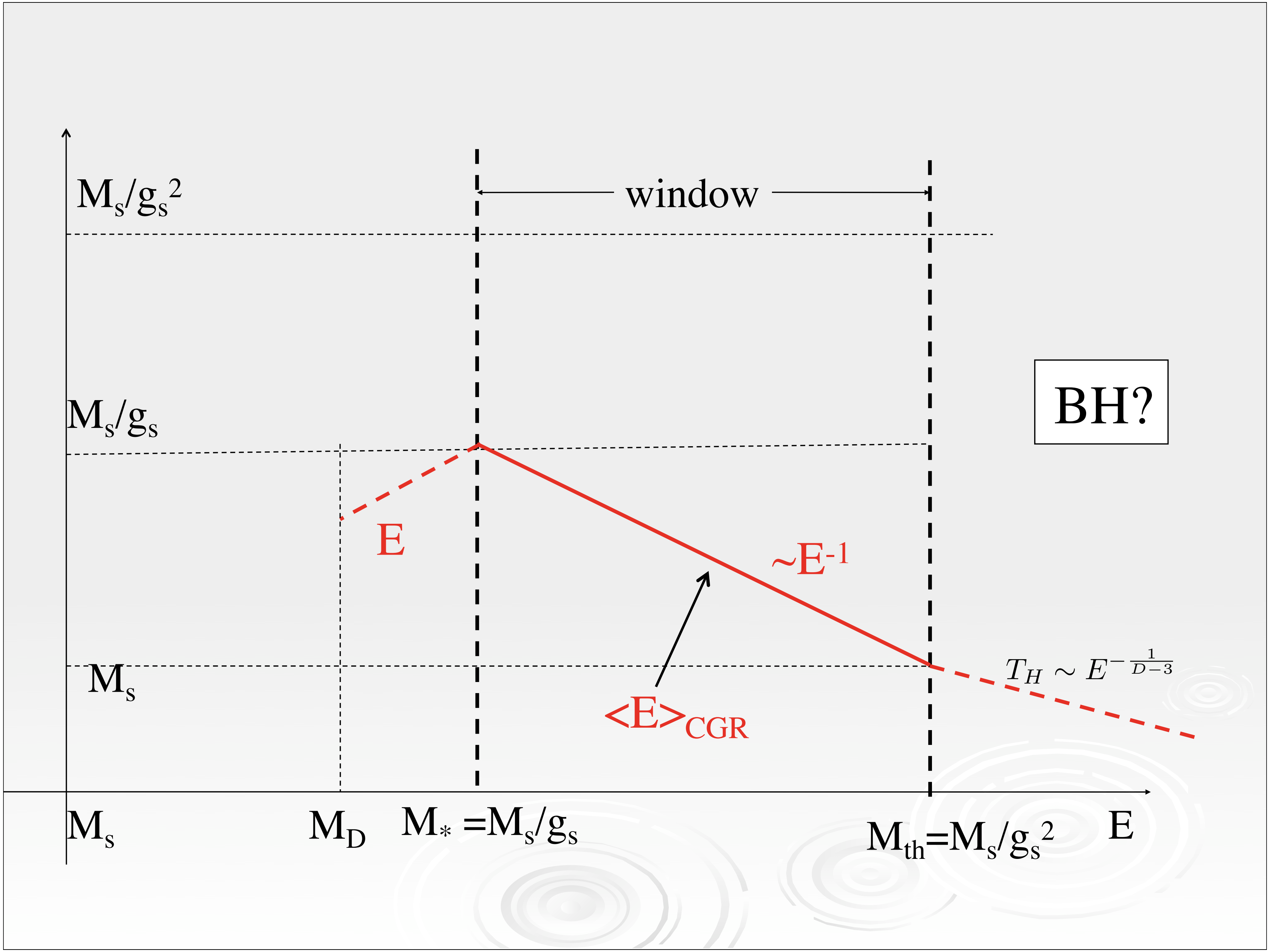
$$M_* = \sqrt{M_s M_{th}} \sim M_s g_s^{-1}$$ NB: same as DE abs. @ b = l_s!

At $E = E_{th} = M_s/g_s^2$

$$\sigma_{\rm el} \sim \exp(-g_s^{-2}) \sim \exp(-S_{sh})$$ (S_{sh} = entropy of a BH/string of M=E_{th})

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

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



M_s/g_s^2
window
BH?
M_s/g_s
E
~E^{-1}
M_s
$T_H \sim E^{-\frac{1}{D-3}}$
<E>$_{CGR}$
M_s
M_D
$M_* = M_s/g_s$
$M_{th}=M_s/g_s^2$
E