International School of Theoretical Physics,

(Parma, 8-13 Sept. 2008)

Classical and quantum gravity from (gedanken?) string collisions

Gabriele Veneziano

(Collège de France & CERN)

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 $Gs/h \gg 1$) 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)

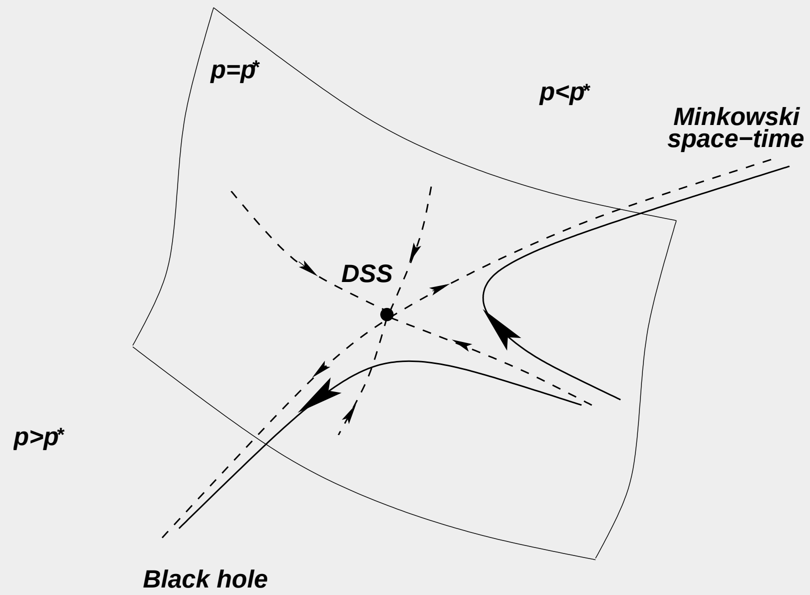


Figure 1: Phase space picture of the critical gravitational collapse.

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

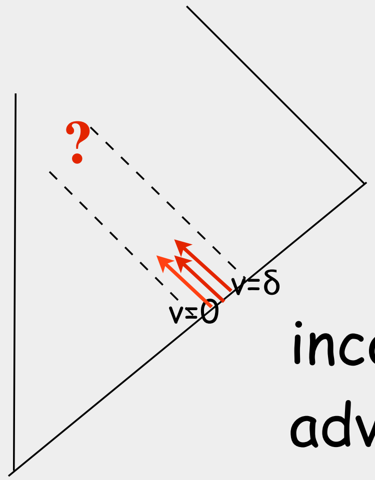
The approach to criticality looks like that of phase transitions in Stat. Mech. (order of transition, crit. exp's,..)

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 =>

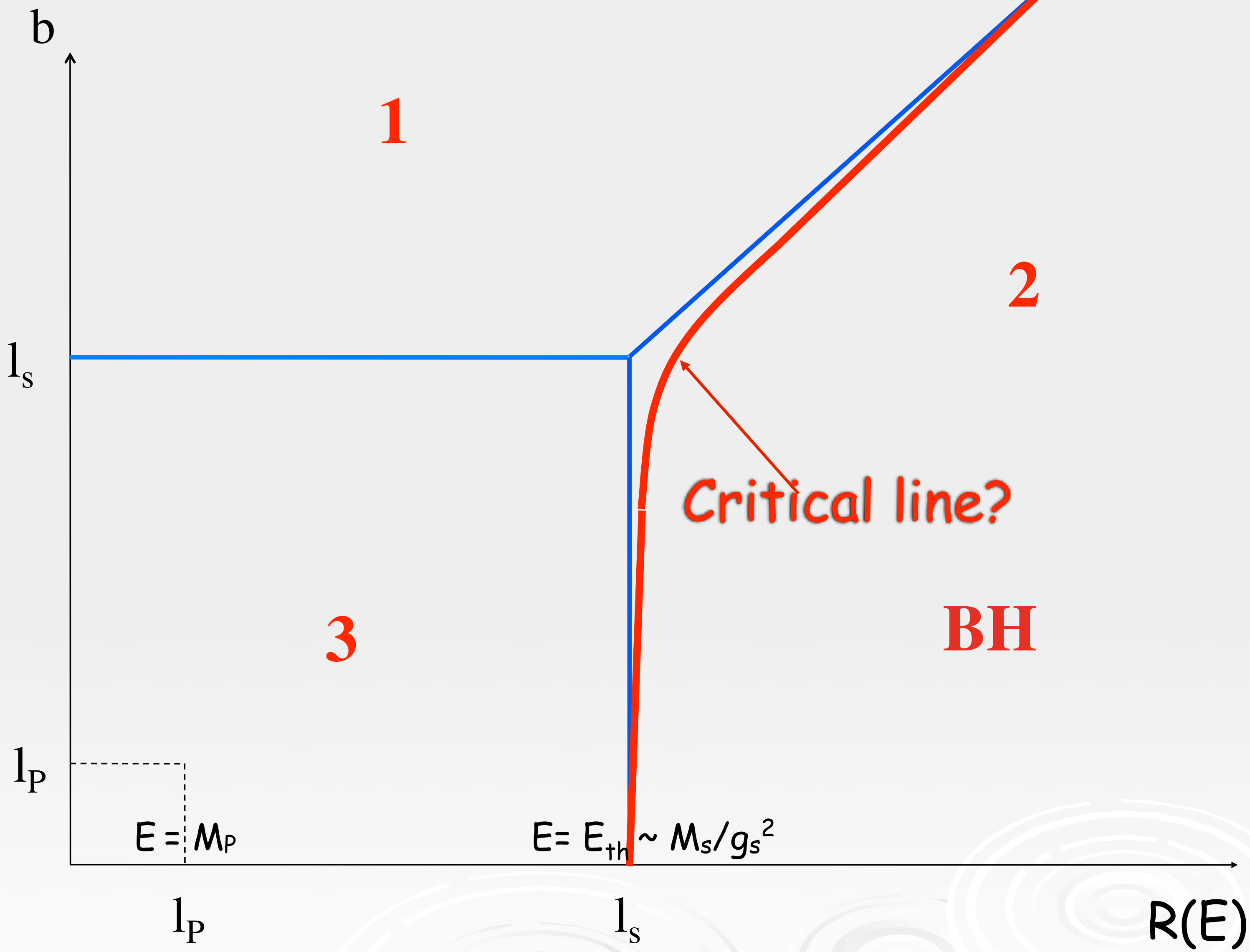
3 broad-band regimes in trans-Planckian superstring scattering

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: $R=R_S$)

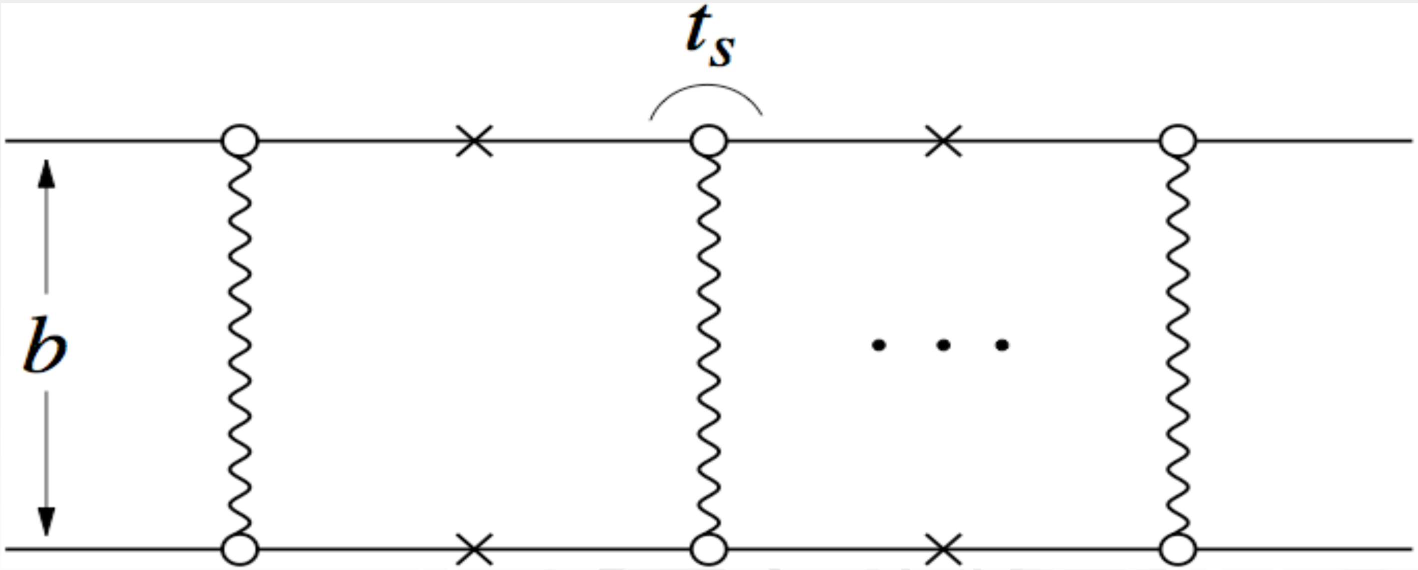
- Go over to A(E, $q \sim \theta$ E) by FT and reach the regime of fixed $\theta \ll 1$ by picking up contributions from saddle point in the above region of b ($b_s \sim R/\theta \gg R$)
- Extend to large angle (collapse) i.e. to $b \sim R$ ($b < R$)
- Cross fingers throughout!

The semiclassical S-matrix

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

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

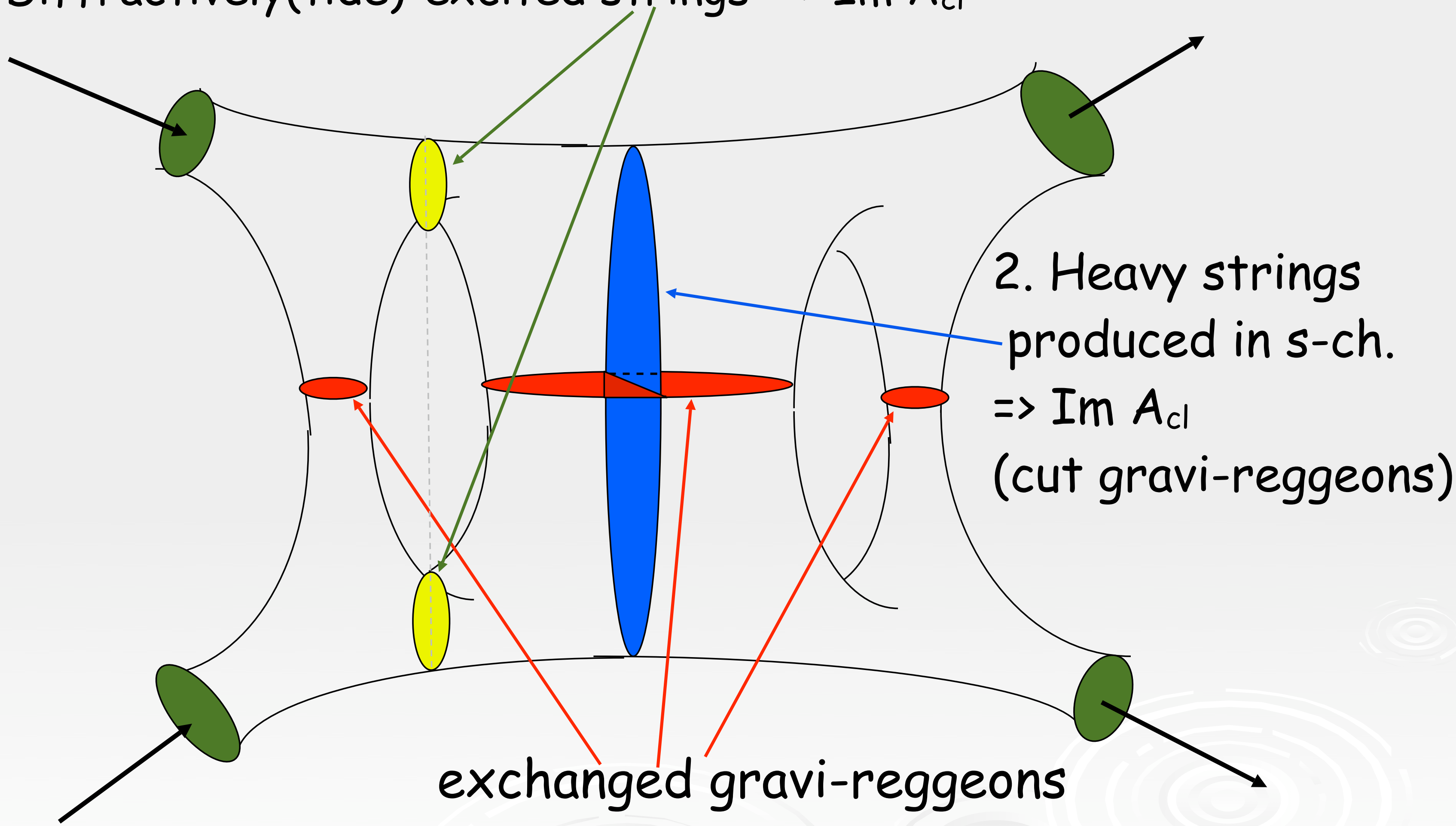
Leading eikonal diagrams (crossed ladders included)



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

Two examples of string corrections (controlled by l_s)

1. Diffractively(tide)-excited strings => Im A_{cl}



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)

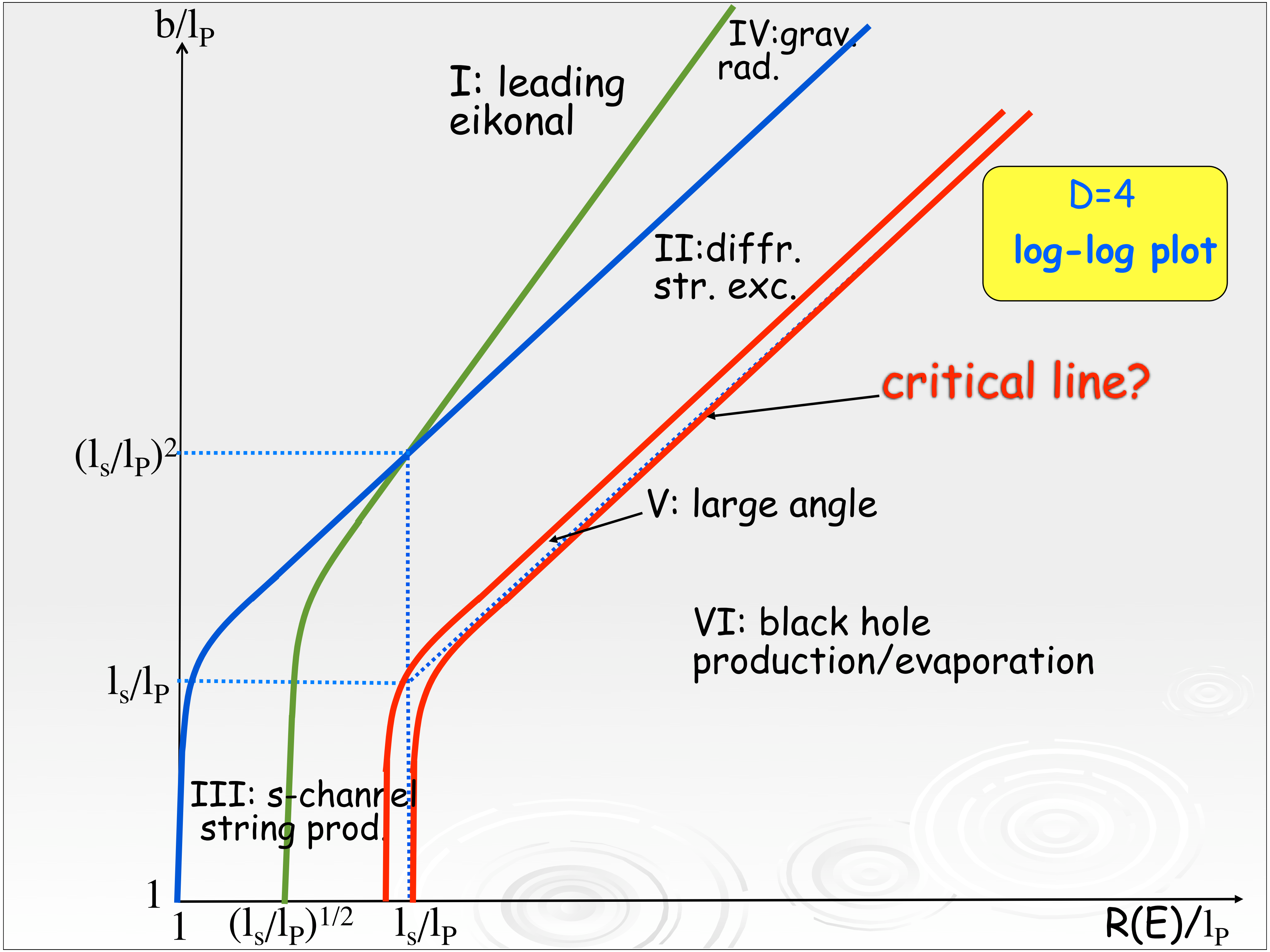
II) Small-angle inelastic scattering (a.string excitation)

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

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

V) Large-angle inelastic scattering

VI) Classical Collapse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1
1
(ls/lP)1/2
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I: Small-angle elastic scattering
(leading eikonal)

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

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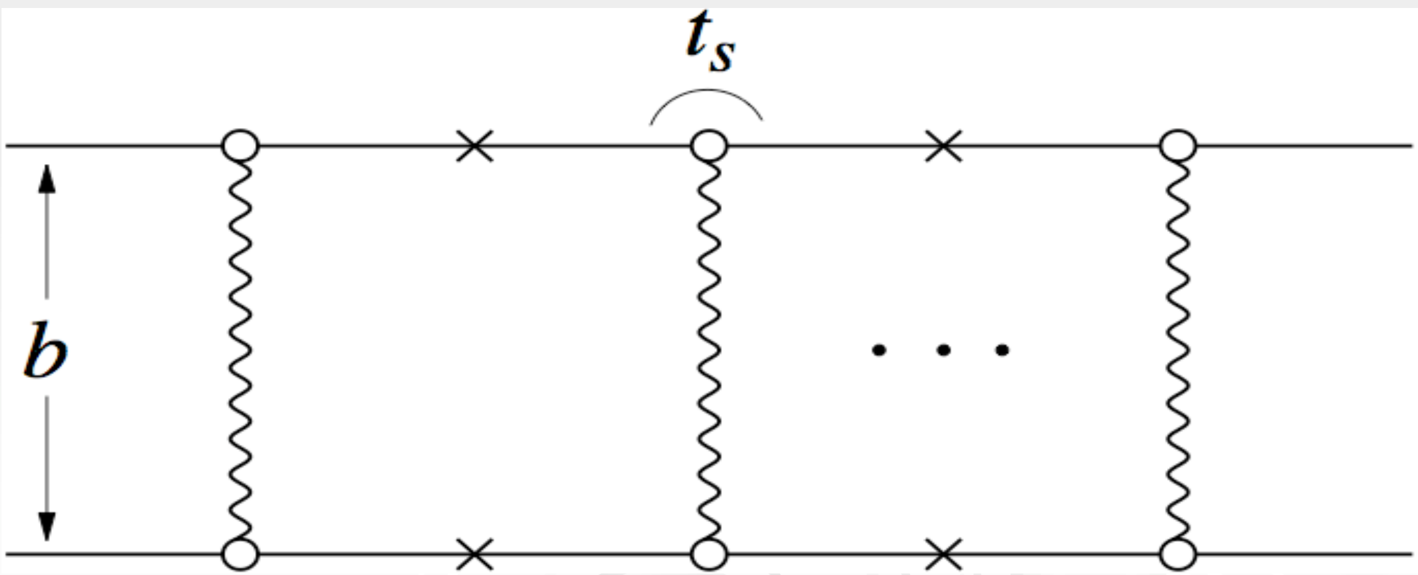


Recovering CGR expectations @ large distance

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

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

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

For b >> $l_s Y$ (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):

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

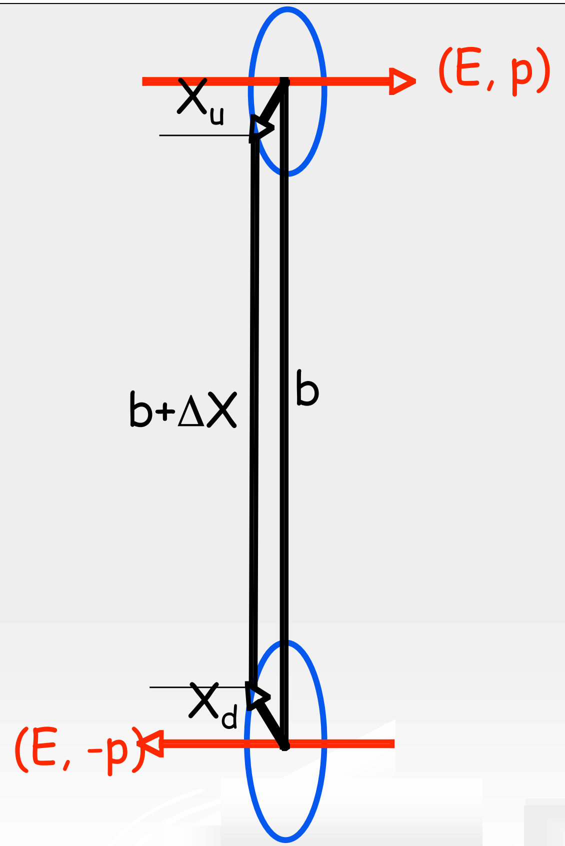
This angular spread provides an invariant mass:

$$M_1 \sim E_1 \Delta\theta_1 \sim G_D \ s \ l_s \ b^{2-D} = M_2$$ 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

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


(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 δ≠0, S_{el} is suppressed as exp(-2 Im δ):

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

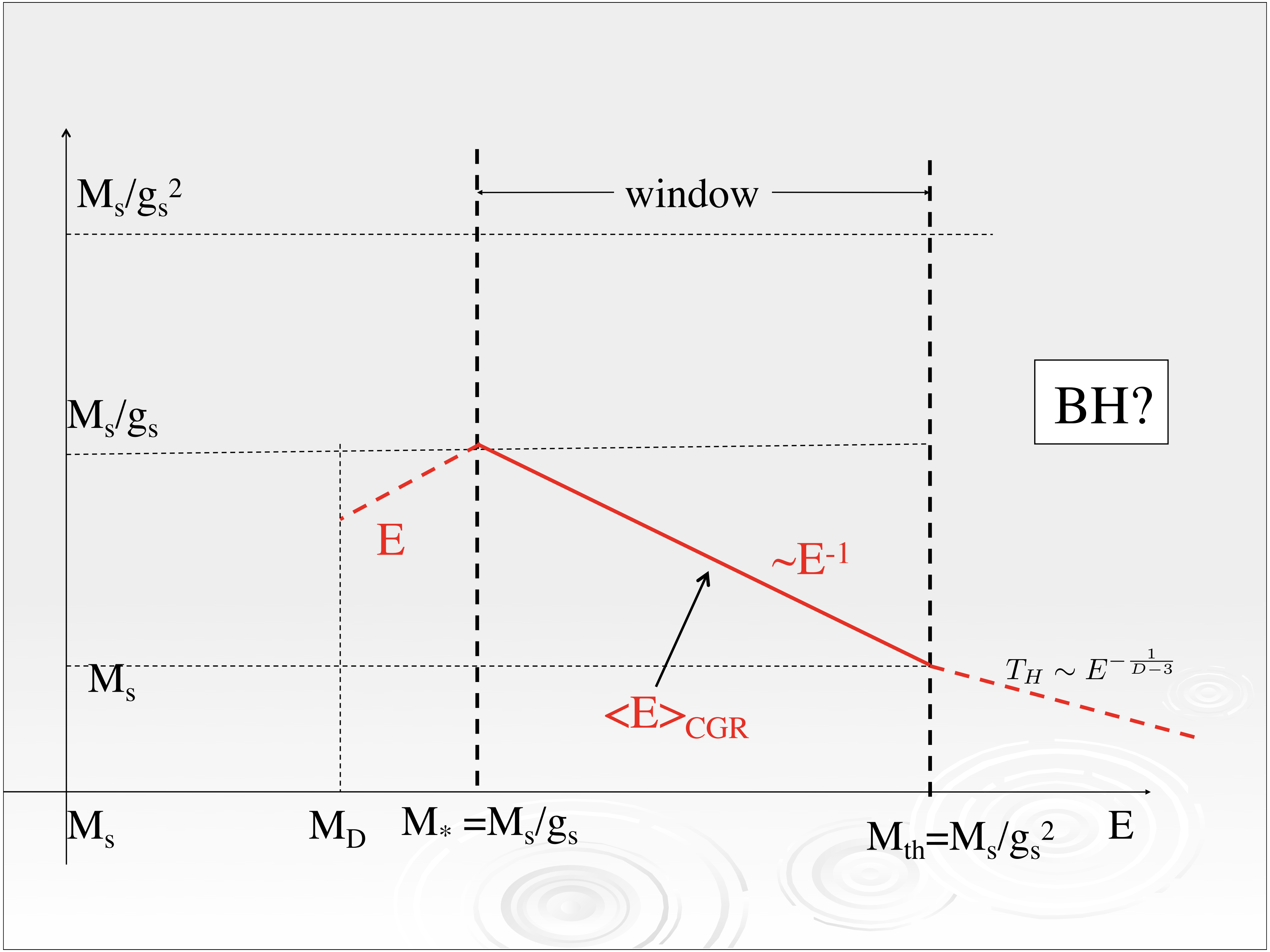
$$M_* = \sqrt{M_s M_{th}} \sim M_s g_s^{-1}$$ NB: same as DE abs. @ b = l_s!

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:

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



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

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

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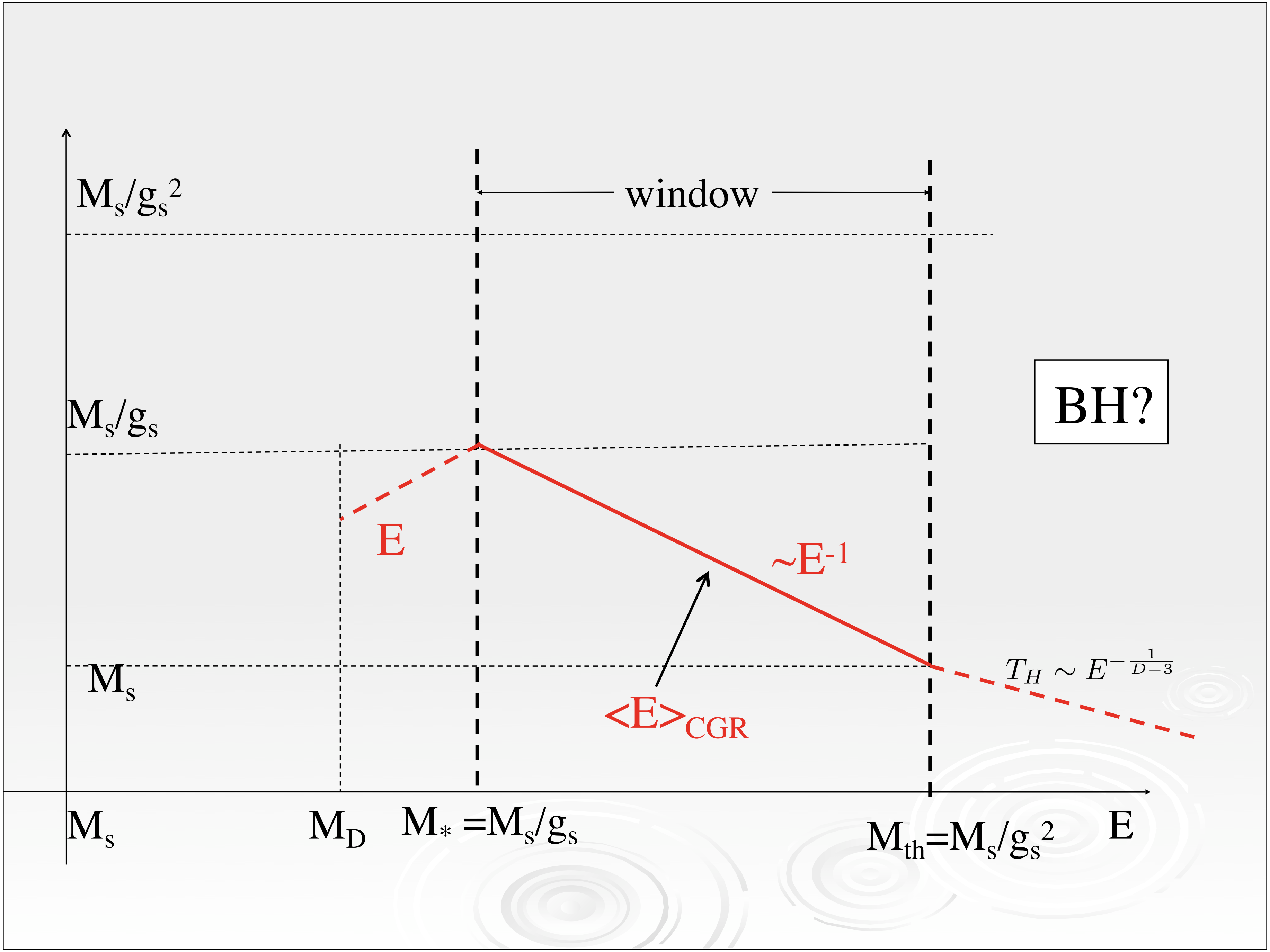
$$\langle E\rangle_{\rm CGR} = \frac{\sqrt{s}}{\langle N_{\rm CGR}\rangle} \sim M_s Y^{D-2}\left(\frac{l_s}{R_S}\right)^{D-3} \sim T_{\rm eff} \equiv \frac{M_*^2}{E} = \frac{M_s^2}{g_s^2 E}$$



M_s/g_s^2
window
M_s/g_s
BH?
E
$\sim E^{-1}$
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

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
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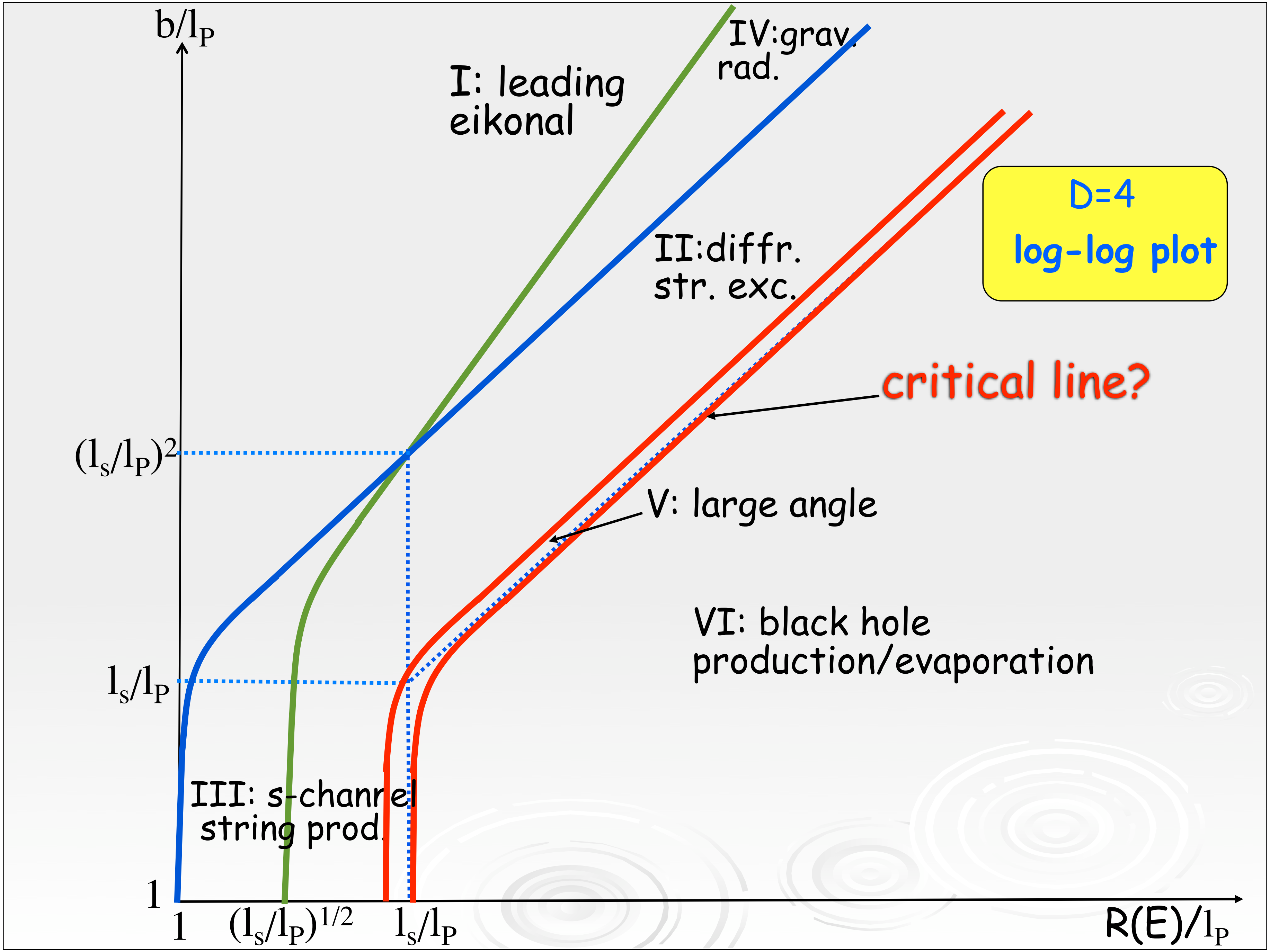
- Summary and outlook

Part 2



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1
1
(l_s/l_P)^1/2
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IV: Small-angle inelastic scattering

(ACV-90's)

=> Classical corrections to leading eikonal

$$S(E,b) \sim exp\left(i\frac{A_{cl}}{\hbar}\right) \sim exp\left(-i\frac{Gs}{\hbar}(logb^2 + O(R^2/b^2) + \cancel{O(l_s^2/b^2)} + \cancel{O(l_P^2/b^2)} + \ldots)\right)$$

V: Large-angle inelastic scattering

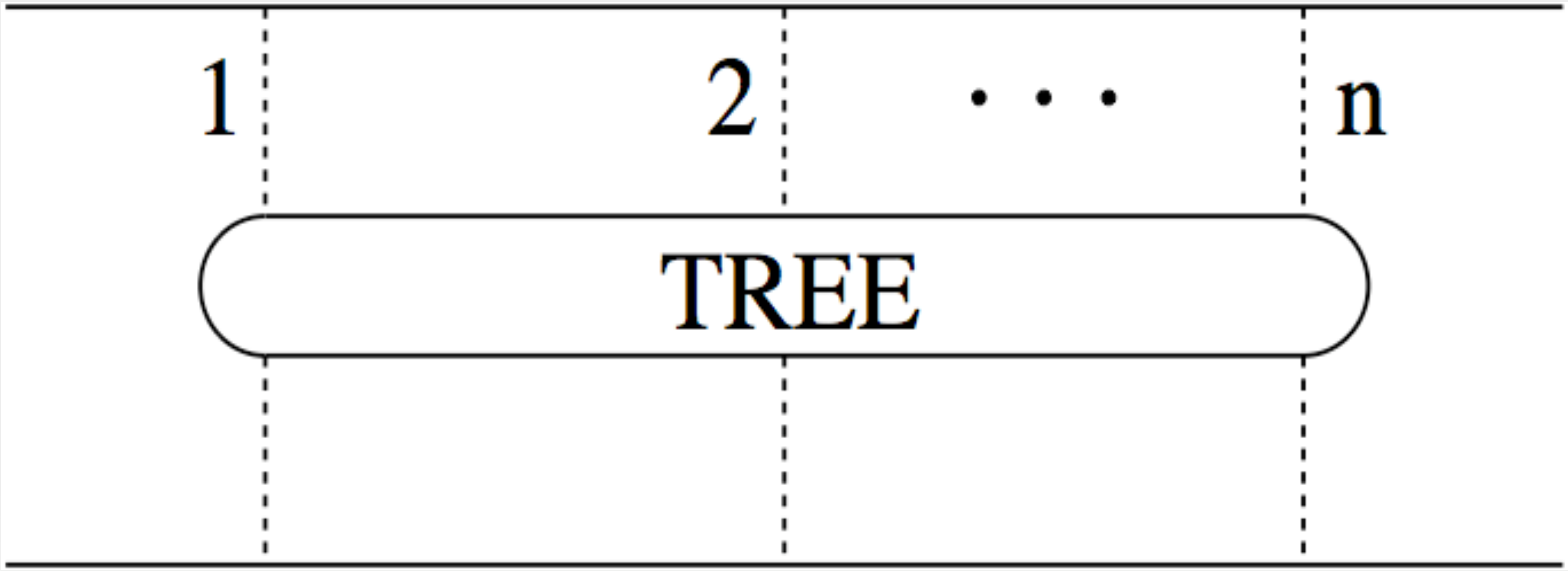
VI: Collapse?

=> Resumming classical corrections

(ACV, hep/th-0712.1209, MO, VW, CC...'08)

D=4 hereafter

Classical corrections characterized by absence of h. Not surprisingly, they are related to tree diagrams once the coupling to the external energetic particles is replaced by a classical source

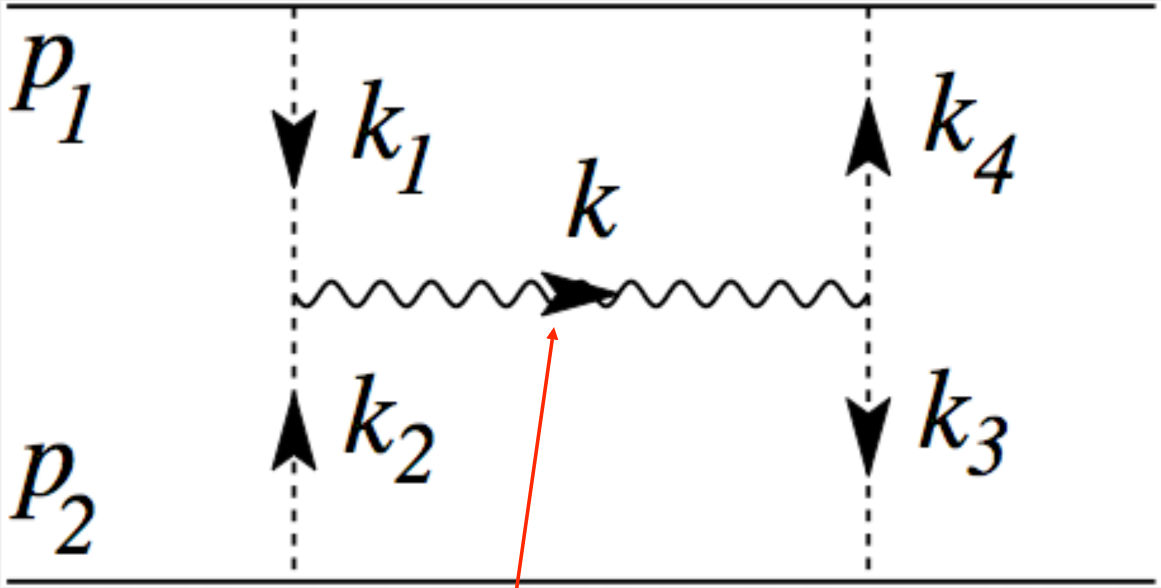


When considering the exponent (the "phase") one should restrict to connected trees

Power counting for connected trees:

$$\delta(E,b) \sim G^{2n-1}s^n \sim Gs\ R^{2(n-1)} \to Gs\ (R/b)^{2(n-1)}$$

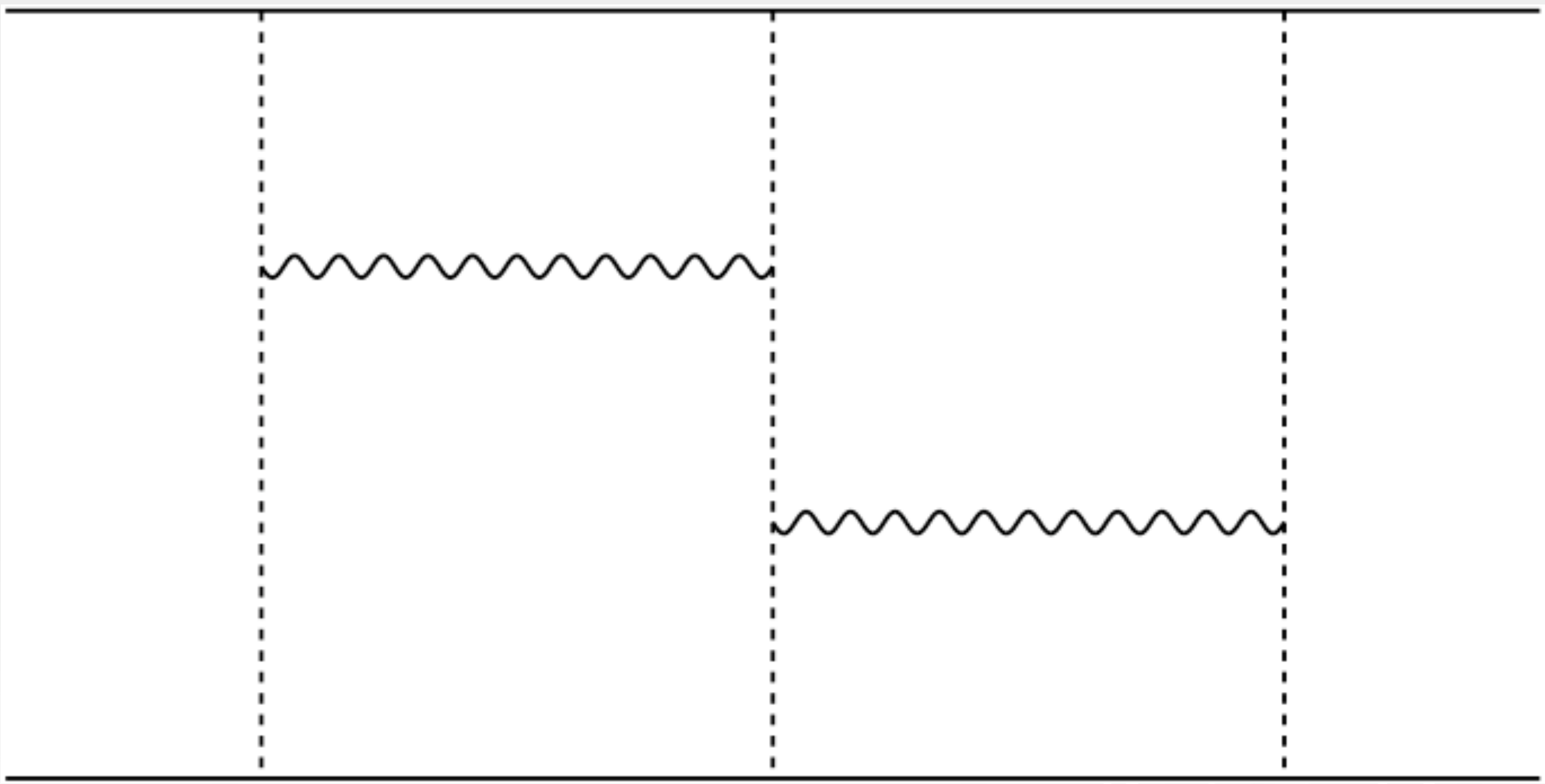
Next to leading order: the H diagram



$$\sim G^3 s^2 = Gs\ G^2 s = GsR^2 \rightarrow Gs\ (R/b)^2$$

One of the produced graviton's polarizations ("TT") is IR-safe
the other ("LT") is not

NNL-order



$$\sim G^5 s^3 = Gs\ G^4 s^2 = GsR^4 \to Gs\ (R/b)^4$$

Reduced effective action & field equations

There is a simple D=2 effective action generating the leading diagrams (Lipatov, ACV '93)

Neglecting the IR-unsafe (LT) polarization, it contains:
a and $\bar{a}$, representing the longitudinal (++ and --) components of the gravitational field, coupled to the corresponding components of the EMT;
ϕ, representing the TT graviton-emission field. Besides source and kinetic terms there is a trilinear derivative coupling of a, $\bar{a}$ and ϕ

The action

$$\frac{\mathcal{A}}{2\pi G s} = \int d^2x \left[a(x)\bar{s}(x) + \bar{a}(x)s(x) - \frac{1}{2}\nabla_i \bar{a} \nabla_i a \right]$$
$$+ \frac{(\pi R)^2}{2} \int d^2x \left(-(\nabla^2\phi)^2 + 2\phi\nabla^2\mathcal{H} \right) ,$$
$$-\nabla^2\mathcal{H} \equiv \nabla^2 a \, \nabla^2 \bar{a} - \nabla_i\nabla_j a \, \nabla_i\nabla_j \bar{a} \, ,$$

and the corresponding eom

$$\nabla^2 a + 2\delta(x) = 2(\pi R)^2 (\nabla^2 a \, \nabla^2\phi - \nabla_i\nabla_j a \, \nabla_i\nabla_j\phi), \quad \bar{a}(x) = a(b-x)$$

$$\nabla^4\phi = -(\nabla^2 a \, \nabla^2\bar{a} - \nabla_i\nabla_j a \, \nabla_i\nabla_j \bar{a})$$

The semiclassical approximation corresponds to solving the eom and computing the classical action on the solution. This is why we took Gs/h >> 1!

Still too hard for analytic study!

Axisymmetric Solutions

(ACV07, J. Wosiek & G.V. 08/1 & 08/2)

I. Particle-particle collisions @ b=0

Equations can be studied (ACV, 07121209) but are unreliable: lesson unclear

II. Central beam-beam collisions

One example in ACV07, more systematically explored in VW (0804.3321 & 0805.2973)

Central beam-beam collisions

In spite of its restrictive symmetry it is a very rich problem:

1. The two beams contain several parameters (total intensity, shape; same or different) & we can look for critical surfaces in their multi-dim.^{al} space
2. The CTS (KV) criterion is simple (see below)
3. Numerical results should be next on line (see recent talks by Choptuik & Pretorius)

Two major simplifications occur in ACV eqns:

1. PDEs become ODEs
2. The IR-singular polarization is just not produced

Axisymmetric action and eqns (t=r^2)

$$\frac{\mathcal{A}}{2\pi^2 G s} = \int dt \left[a(t)\bar{s}(t) + \bar{a}(t)s(t) - 2\rho\dot{\bar{a}}\dot{a}\right] - \frac{2}{(2\pi R)^2}\int dt(1-\dot{\rho})^2$$

$$\rho = t\left(1-(2\pi R)^2\dot{\phi}\right) \qquad \pi\int^t dt' s_i(t') = R_i(t)/R$$

$$\dot{a}_i = -\frac{1}{2\pi\rho}\frac{R_i(r)}{R}$$

$$\ddot{\rho} = \frac{1}{2}(2\pi R)^2\dot{a}_1\dot{a}_2 = \frac{1}{2}\frac{R_1(r)R_2(r)}{\rho^2}$$

2nd order ODE w/ Sturm-Liouville-like b. conditions

CTS criterion (KV gr-qc/0203093)

If there exists an r_c such that

$$R_1(r_c)R_2(r_c) = r_c^2$$

we can construct a CTS and therefore expect a BH to form.

Theorem (VW08): whenever the KV criterion holds*) the ACV field equations do not admit regular (at r=0) real solutions. Thus:

KV criterion ==> ACV criterion

but of course not the other way around!

*) actually the r.h.s. can be replaced by $\frac{2}{3\sqrt{3}} r_c^2$

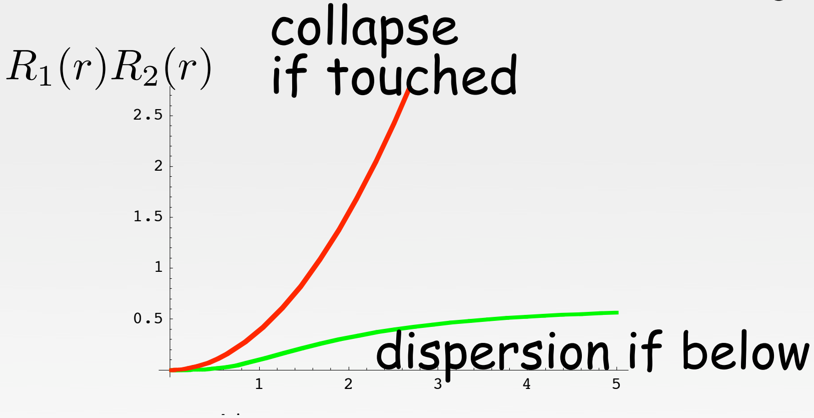
A sufficient criterion for dispersion

(P.-L. Lions, private comm.)

If $$R_1(r)R_2(r) \leq \frac{8}{27}\frac{r^4}{(1+r^2)^2}\left[1+\frac{1}{2}\left(1-\frac{log(1+r^2)}{r^2}\right)\right]^2$$

the ACV eqns do admit regular, real solutions.

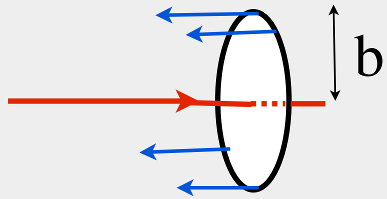
To summarize



clearly, there is room for improvement...

Examples

Example 1: particle-scattering off a ring



Can be dealt with analytically:

$$\ddot{\rho} = \frac{R^2}{2\rho^2}\Theta(r^2 - b^2)$$

$$\begin{aligned} \rho &= \rho(0) + r^2\dot{\rho}(0) \quad , \quad (r < b) \\ \dot{\rho} &= \sqrt{1 - R^2/\rho} \quad , \quad (r > b) \end{aligned}$$

Since ρ(0) =0:

$$\rho(b^2) = b^2\dot{\rho}(b^2) = b^2\sqrt{1 - R^2/\rho(b^2)}$$

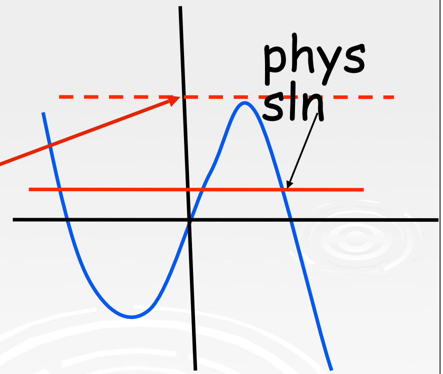
This (cubic) equation has positive real solutions iff $b^2 > \frac{3\sqrt{3}}{2}R^2 \equiv b_c^2$

$(b/R)_c \sim 1.61$

CTS: $(b/R)_c > 1$

Amusing analogy with turning point in Schwarzschild metric

$$\frac{R}{b} = x - x^3, x \equiv \frac{r*}{b} \Rightarrow b > b_c = \frac{3\sqrt{3}}{2} R$$



Example 2: Two hom. beams of radius L.

The equation for ρ becomes

$$\ddot{\rho}(r^2) = \frac{R^2}{2\rho^2}\Theta(r-L) + \frac{R^2 r^4}{2L^4\rho^2}\Theta(L-r)$$

We can compute the critical value numerically:

$$\left(\frac{R}{L}\right)_{cr} \sim 0.47$$

It is compatible with (and close to) the CTS upper bound of KV:

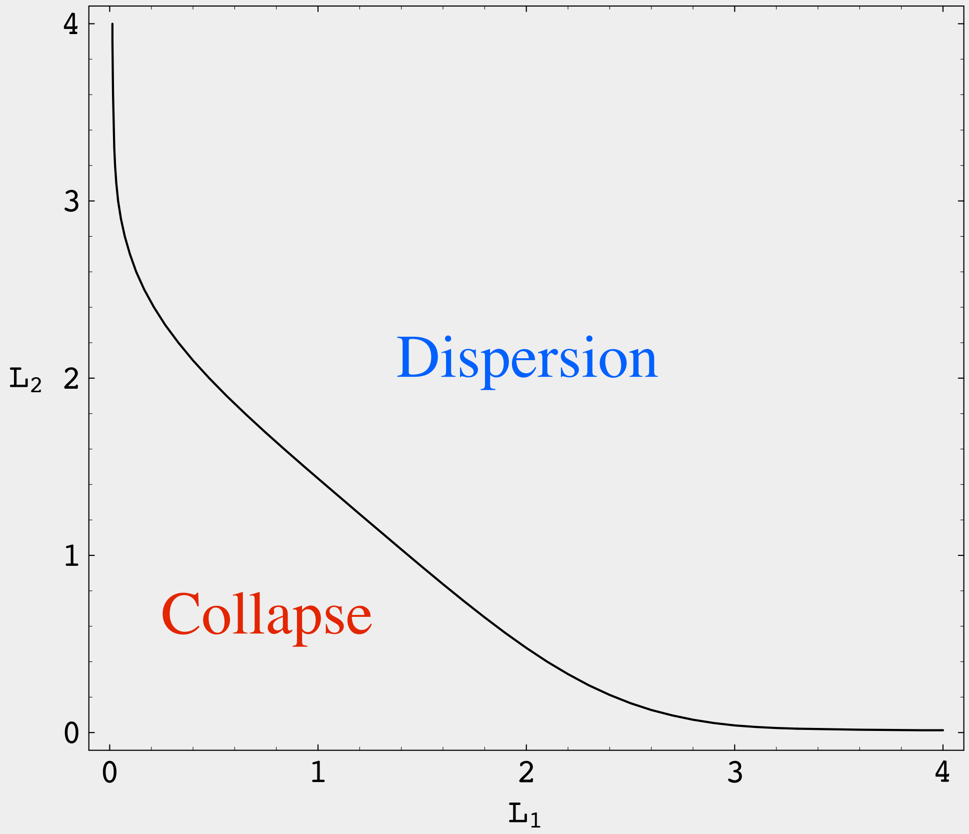
$$\left(\frac{R}{L}\right)_{cr} < 1.0$$

Example 3:
Two different Gaussian Beams
(GV&J.Wosiek '08)

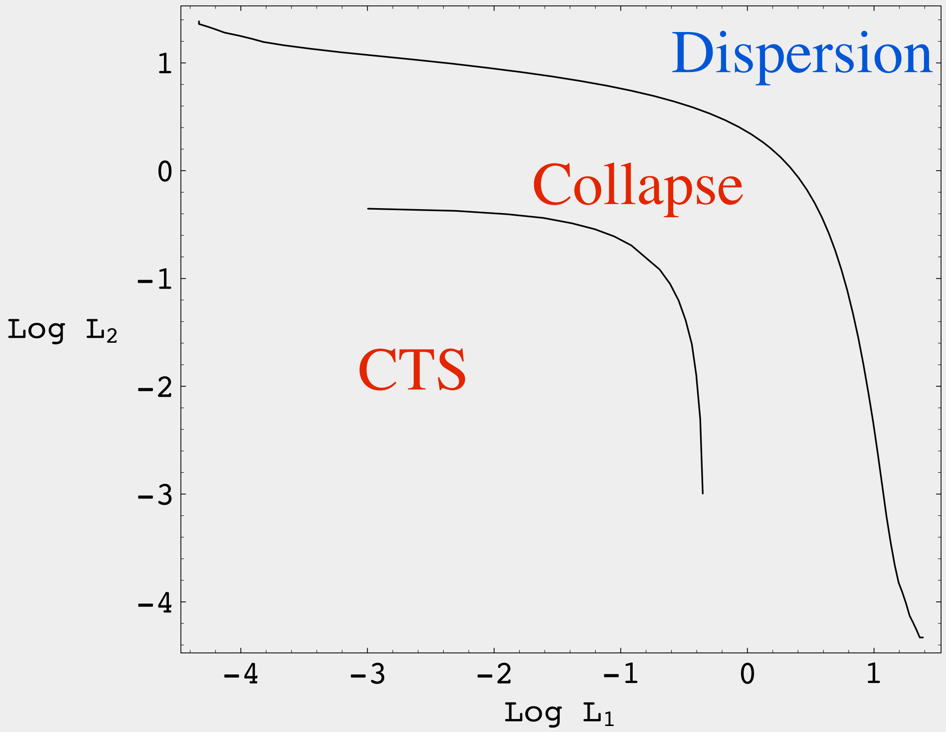
We took two extended sources (beams) with the same fixed total energy and two Gaussian profiles centered at r=0 and characterized by two widths L_1 and L_2

$$s_i(t) = \frac{1}{2\pi L_i^2} exp\left(-\frac{t}{2L_i^2}\right) \quad , \quad \frac{R_i(t)}{R} = 1 - exp\left(-\frac{t}{2L_i^2}\right)$$

We determined the critical line in the (L_1 , L_2) plane and compared it with the one coming from the CTS criterion.



Dispersion
Collapse
L_2
L_1
0
1
2
3
4
0
1
2
3
4


Dispersion
Collapse
CTS
1
0
-1
-2
-3
-4
Log L_2
-4
-3
-2
-1
0
1
Log L_1

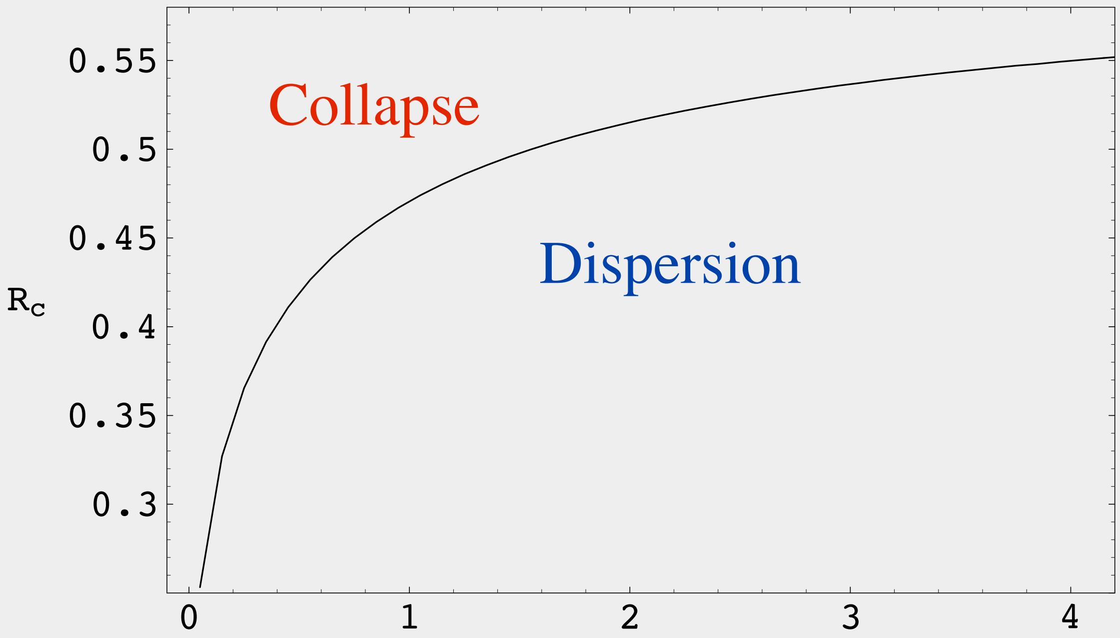
Example 4:
two identical non-hom. beams
(GV&Wosiek '08/1)

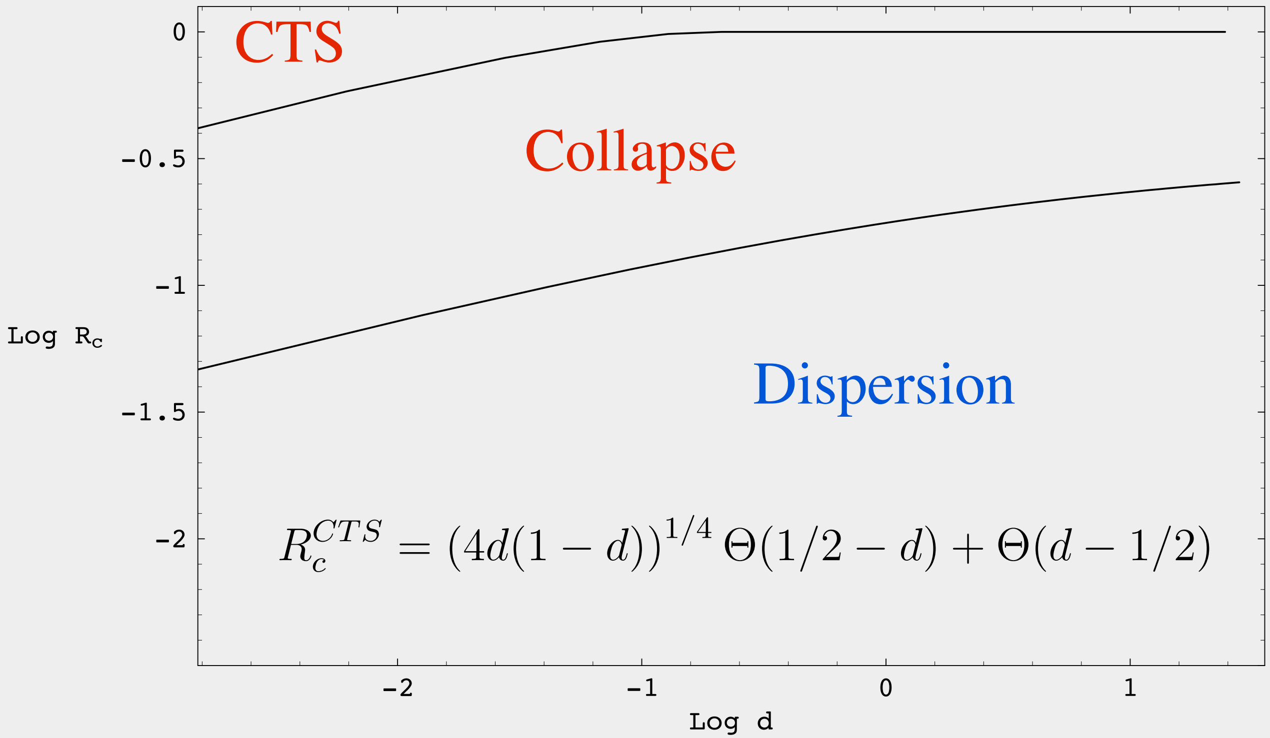
Two extended sources with fixed total energy and a profile characterized by the overall size L and a shape-parameter d:

$$s_1(t) = s_2(t) = \frac{d}{\pi \left(d + (1-d)t^2\right)^{3/2}} \Theta(1-t)$$

We determined the critical line in the (d, L) plane and compared it with the one coming from KV's CTS criterion.

$$R_c^{CTS} = (4d(1-d))^{1/4}\,\Theta(1/2-d) + \Theta(d-1/2)$$




CTS
Collapse
Dispersion
$R_c^{CTS} = (4d(1-d))^{1/4}\,\Theta(1/2-d) + \Theta(d-1/2)$
Log R_c
Log d
0
-0.5
-1
-1.5
-2
-2
-1
0
1

Particle-particle collisions at finite b

Analytic approach by ACV07
(using an azimuth-average approximation)
gave $b_c \sim 1.61R$

Numerical solutions

(G. Marchesini & E. Onofri, 0803.0250)

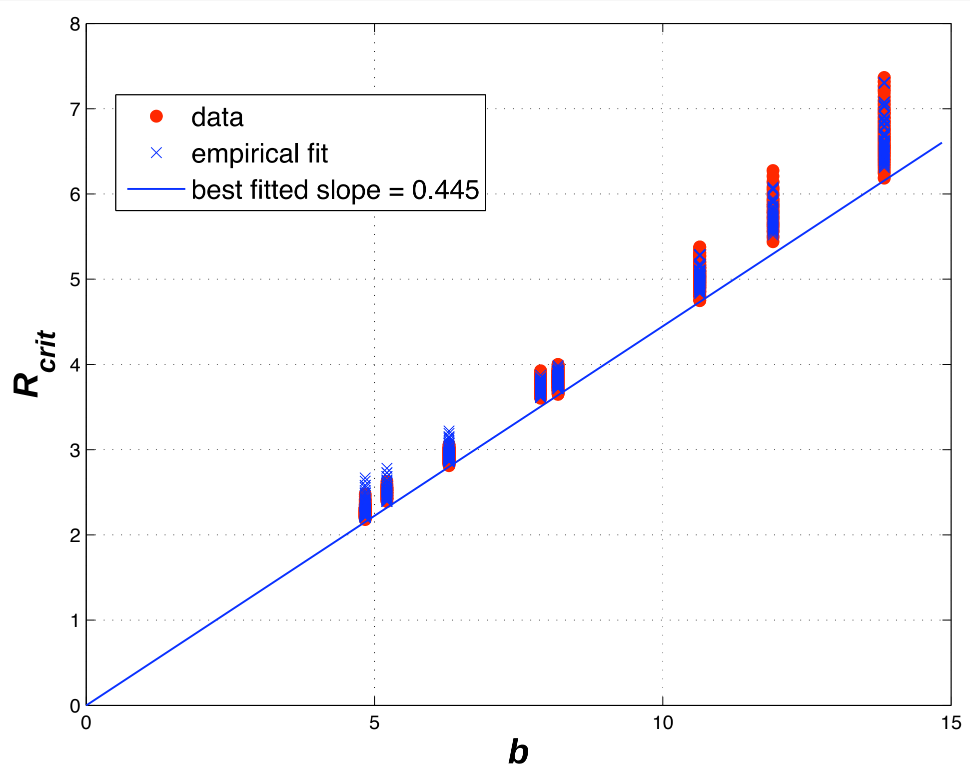
Solve directly PDEs by FFT methods in Matlab

Result: real solutions only exist for

$$b > b_c \sim 2.28R$$

Compare with EG's CTS lower bound on b_c

$$b_c > 0.80R$$



G. Marchesini & E. Onofri, 0803.0250

Particle Spectra

(ACV07, VW08/2, & Ciafaloni GV in progress)

We can study the spectrum of the produced particles by looking at various contributions to the imaginary part of the elastic amplitude at fixed E & b (E-cons. important)

The final spectrum is roughly as follows (for extended sources b--> beam size):

$$\frac{1}{\sigma}\frac{d\sigma}{d^2k\,dy} = \frac{Gs}{\hbar}R^2 \exp\left(-\frac{|k||b|}{\hbar}(1+\cosh y\; R^3/b^3)\right)$$

This shows that, while for b >> R gravitons are produced at small angles, as b -> b_c ~ R their distribution becomes more and more spherical w/ <n> ~ Gs and characteristic energy O(1/R ~T_H)

Near & beyond b_c

Approach to b_c can be studied. Leaving aside the imaginary part due to graviton production, for b-->b_c^+ the on-shell action behaves as follows

$$\frac{A - A_c}{Gs} = \sqrt{3}\left(1 - \frac{b^2}{b_c^2}\right) + \frac{2\sqrt{2}}{3}\left(\frac{b^2}{b_c^2} - 1\right)^{3/2}$$

The elastic amplitude picks up an extra damping below b_c meaning that some new channels must have opened up.
Q: Do these correspond to the formation of BHs?

Ciafaloni and Colferai (see next talk) have formulated this as a QM tunnelling problem (r^2 having role of time)

Just below b_c the new imaginary part of the action behaves like

$$ImA \sim Gs(1 - J/Gs)^{3/2} \ , \ \sigma_{el} \sim exp(-ImA)$$

Q: Can we make the identification: $\sigma_{el} \sim \exp(-S_{BH})$?

A: We can if the mass of the BH goes to zero as $b \to b_c$ (Type-II critical collapse)

In order to recover our result we would need:

$$M_{BH} \sim \sqrt{s}(1 - b/b_c)^{3/4}$$

fixing the value of Choptuik's exponent to about twice his 0.37 (depends on $w = p/\rho$ and kinematics)

Clearly our understanding of the physics below b_c is still far from complete (to say the least)!

Conclusions

- Gedanken HE collisions (e.g. $\pi\pi \to \pi\omega$) have played an important role in the early developments of ST.
- After the 1984 revolution TPE collisions may well play a similar role for understanding whether & how QM & GR are mutually compatible in a string theory framework
- Superstring theory in flat space-time (and in other consistent backgrounds) offers a concrete framework where the quantum scattering problem is well-posed.

- The problem simplifies by considering $Gs/\hbar \gg 1$ so that a suitable semiclassical approximation can be justified. Within that kinematical constraint we have considered various regimes, roughly classified as follows:

- A large impact parameter regime, where an eikonal approximation w/ small corrections holds and GR expectations are recovered (AS effective metric..)
- A stringy regime, where one finds an approximate S-matrix with some characteristics of BH-physics as the expected BH threshold is approached from below
- A strong-gravity (large R) regime where an effective action approach can be (partly) justified and tested

•Critical points (lines) have emerged matching well CTS-based GR criteria

•As the critical line is approached, the final state starts resembling a Hawking-like spectrum: a fast growth (~ E^2) of multiplicity w/ a related softening of the final state.

•Progress was made towards constructing a unitary S-matrix and understanding the physics of the process as the critical surface is reached and possibly crossed

•Much more work remains to be done, but an understanding of the quantum analog/replacement of GR's gravitational collapse does no-longer look completely out of reach...

International School of Theoretical Physics,
(Parma, 8-13 Sept. 2008)

Closing Remarks:

Some personal thoughts at the dawn of the LHC era

Gabriele Veneziano

(Collège de France & CERN)

Lessons from accelerator physics

- The SM of PP works extremely well: a great achievement of 20th-century physics
- Is this a confirmation of LQFT?
- QM + SR => LQFT as an effective low-E approximation (S. Weinberg).
- Is the validity of the SM just a confirmation of QM & SR?
- Yes, modulo a crucial new point:the effective LQFT is a gauge theory!

Lessons from gravity and cosmology

- GR works very well on scales at which it has been tested
- GR, perhaps with a small cosmological constant, is the effective classical theory of gravity
- GR appears to be badly behaved at short scales (singularity theorems). Is QM the cure to those problems?
- QM appears to make things worse (UV divergences, induced cosmological constant, ...)!

The mystery of quantum corrections

- Radiative corections to marginal and irrelevant perators in the SM have been seen in precision experiments (e.g. LEP)
    - running of gauge couplings
    - effective 4-fermi interactions
    - anomalies
- Radiative corrections to relevant operators have not been seen (w/ exception of Newton's constant?):
    - scalar masses
    - cosmological constant
- Because of a (well-known?) IR-UV connection this may tell us something. The SM and GR are not the full story: they need an ultraviolet completion!

Why GT and GR?

- GTs are the only consistent way to deal with massless J=1 particles in a quantum-relativistic theory
- GR is the only consistent way to deal with massless J=2 particles in a Lorentz invariant way
- The question then becomes: Why does Nature like massless J=1, 2 particles?
- The answer could very well be: because She likes String Theory!

Does Quantum Gravity need a cutoff?

- Some people have still some hope to cure the deseases of QGR. I will give some arguments towards the opposite conclusion...
- They are based on invoking a bound on Newton's constant in terms of the UV cutoff. Then G_N-->0 as we remove the cutoff
- Old model-dependent arguments (GV, Dvali & Gabadaze, '02)
- More recently model-independent arguments (Dvali et al.,...., Dvali & GV to appear?)

A robust bound (?) .....

Let us make two assumptions in QG
w/ UV cutoff = $\Lambda_{UV} = 1/\lambda_{UV}$

1. A BH of radius R > λ_{UV} can be treated semiclassically using the standard formulae, for S, T, ev. rate etc

2. At least one of the following inequalities is satisfied by a semiclassical evaporating BH (c=1):

$$-\frac{d(2GM)}{dt} \leq 1 \;\; ; \;\; \frac{\hbar}{T^2}\frac{dT}{dt} \leq 1 \;\; ; \;\; \frac{\Gamma}{M} \leq 1$$

Then: $\lambda_{UV}^{D-2} \geq N_{eff}(\Lambda_{UV}) l_P^{D-2}$

Proof: If opposite true, take a BH of radius between λ_{UV} and $N^\gamma l_P$ ...

...and its implications

If one accepts above argument there two important consequences

1. A lower bound on M_P/Λ_{UV} implying that QG becomes trivial if cutoff is sent to infinity
2. The infinite bare coupling (Sakharov) limit of QG is non-singular

Too good to be true?

Farewell