IHES, 24-27.10 2017

Quantum gravity: physics and philosophy

Quantum gravity or gravity from the quantum: string theory's lesson

Gabriele Veneziano

Outline

- Non-relativistic quantum mechanics & elimination of
  - UV divergences
  - Classical singularities
- Relativistic quantum mechanics, QFT
- UV divergences' comeback, renormalization
- The special case of gravity:
  - classical singularities
  - non renormalizability
- String theory and its quantum miracles
- A Copernican Revolution?

Outline (ctnd.)

- A worked out example: Transplanckian-energy string collisions
- Less desirable quantum effects
- Massless/light scalar fields: Achille's heel of QST?
- Quantum String gravity and classical singularities

Non-relativistic Quantum Mechanics

In 1900 Max Planck introduced a new constant of Nature: h.

This was the birth of non-relativistic Quantum Mechanics (NRQM), an extremely successful and internally consistent theory (see e.g. Dirac's formulation) in spite of some "interpretation" problems.

Eliminating a UV divergence

Planck's original motivation was the elimination of a divergence in the Black Body energy spectrum.

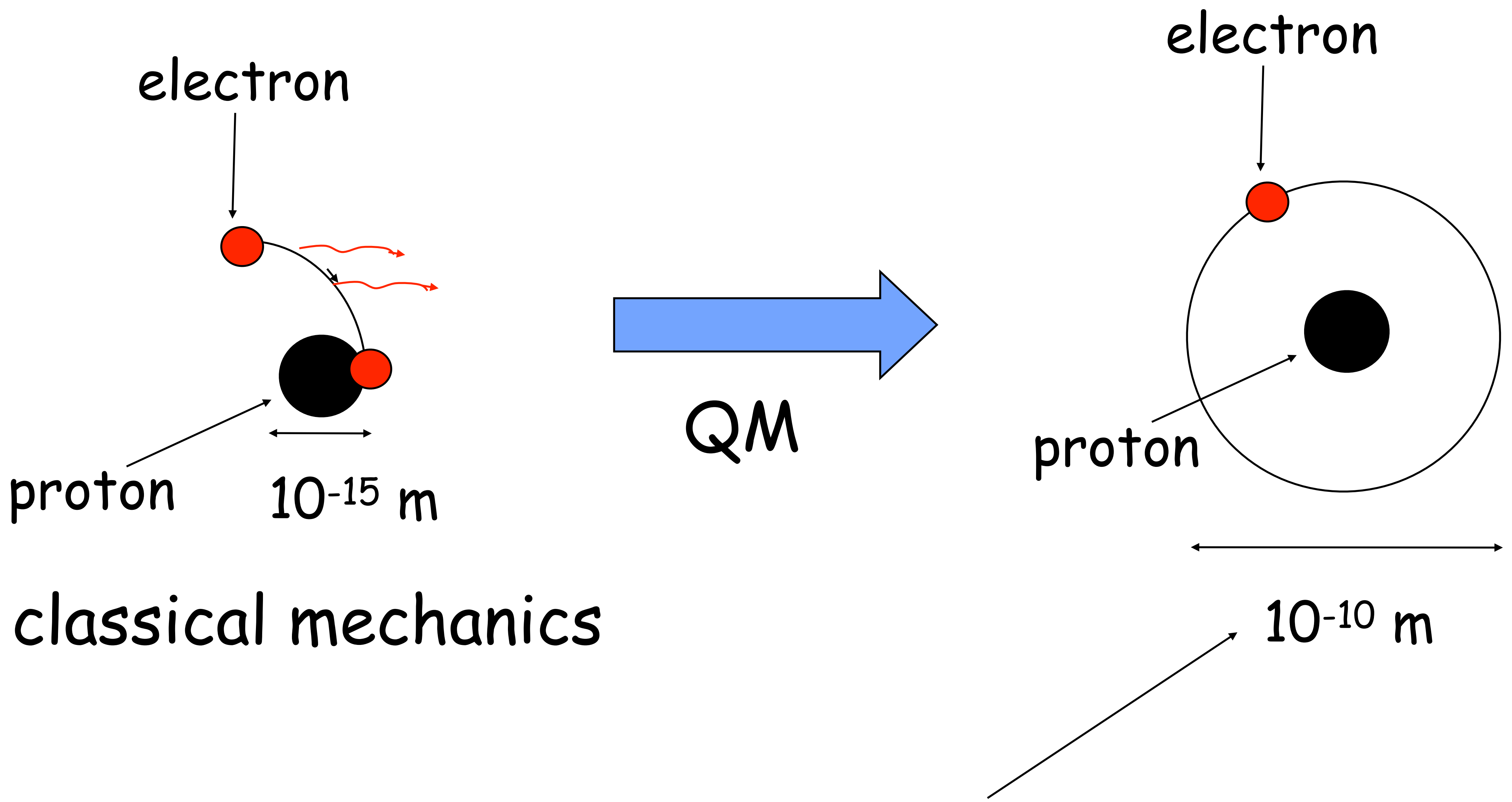
The divergence was an ultraviolet (UV) one i.e. had to do with the excessive emission of high-frequency radiation from the Black Body.

Quantum mechanics cures this problem by introducing an exponential high frequency cutoff

$$\boxed{\frac{dE}{d\nu} \sim \exp\left(-\frac{h\nu}{k_B T}\right)}$$

Eliminating classical singularities

Other successes of NRQM are well known.
I will only mention its explanation of the stability of atoms.
Classically a system made of a positive and a negative charge is unstable against emission of EM waves. In a short time the H-atom should collapse.
In QM it can live forever in its well-defined ground state (thanks to Heisenberg's uncertainty principle).



Best compromise satisfying $\Delta x \Delta p \sim h$

Relativistic Quantum Mechanics

Dirac himself was much aware of the problems that could originate from a relativistic extension of QM. Relativity allows for the transformation of energy into matter and back.
The number of particles/quanta is no longer conserved.

Quantum mechanics, on the other hand, allows for energy to be borrowed for very short time lapses (so-called E-t uncertainty principle).

Combining the two, an indefinite number of quanta of arbitrary energy can be created for a very short time interval. How can we check this quantitatively?

Quantum Field Theory (QFT)

Dealing with creation and destruction of quanta turned out to be a difficult task in the old NRQM formalism.

Historically people abandoned that formalism and turned to Quantum Field Theory (also known, somewhat improperly, as 2nd quantization)

The starting point is a classical field theory (e.g. Maxwell coupled to charged particles/fields, QED) to which one applies the rules of QM (PB-> i commutator).

The Fourier modes of the fields become creation and destruction operators for relativistic particles/quanta.

Reappearence of UV divergences

Special relativity and QM happily coexist in QFT.
But the problem with virtual creation of arbitrarily many energetic quanta pops out.

It appears through the UV divergence of radiative corrections (no Planck-like exp. cutoff!)

There is a classical counterpart: the EM energy of a pointlike charged particle is classically infinite.

This divergence is alleviated but not eliminated by QM.

Yet, for the non-gravitational interactions of the SM the infinities can be absorbed into a finite number of quantities

These quantities cannot be predicted. Even if they were given at the classical level quantum corrections would change them by an infinite amount.

The best that one can do it to "renormalize" the theory, i.e. give up to compute the above-mentioned quantities and, instead, take them for experiments.

Philosophically this is not very satisfactory. A better attitude, I think, is to say that QFTs are only valid up to a certain distance scale and then some (yet unknown) mechanism removes the infinities.

Precisely a finite number of quantities will depend on the details of how the theory is regularized…

These are the quantities that have to be measured (mass and charge of the electron, the fine-structure constant in QED).

The rest, in principle, is predictable (g-2 in QED).

Gravity is special!

Gravity is somewhat pathological even at the classical level. Ubiquitous singularities are generated even when starting from innocent looking smooth initial conditions or when we integrate backwards EEs. Most known examples:

1. Gravitational Collapse, BH formation, singularity behind a BH's horizon.

2. The cosmological singularity usually (and I think wrongly) associated with the Big Bang.

Non-renormalizability of Quantum Gravity

The problem with quantum gravity is that the renormalization strategy does not work in this case.

The ultimate reason for this failure is that, according to the Equivalence Principle of GR, gravity couples to energy. UV divergences are related to high energies and therefore they are enhanced by the gravitational interaction.

Virtual quanta of arbitrarily high energy are too copiously produced by gravitational interactions and make quantum GR non-renormalizable (infinities cannot be lumped into a finite number of quantities): predictivity is lost!

Another problem with quantum gravity are the difficulties one encounters with quantization in curved spacetimes.

Quantum effects appear to depend upon the reference frame (e.g. accelerated vs. inertial) while the EP would require that they do not.

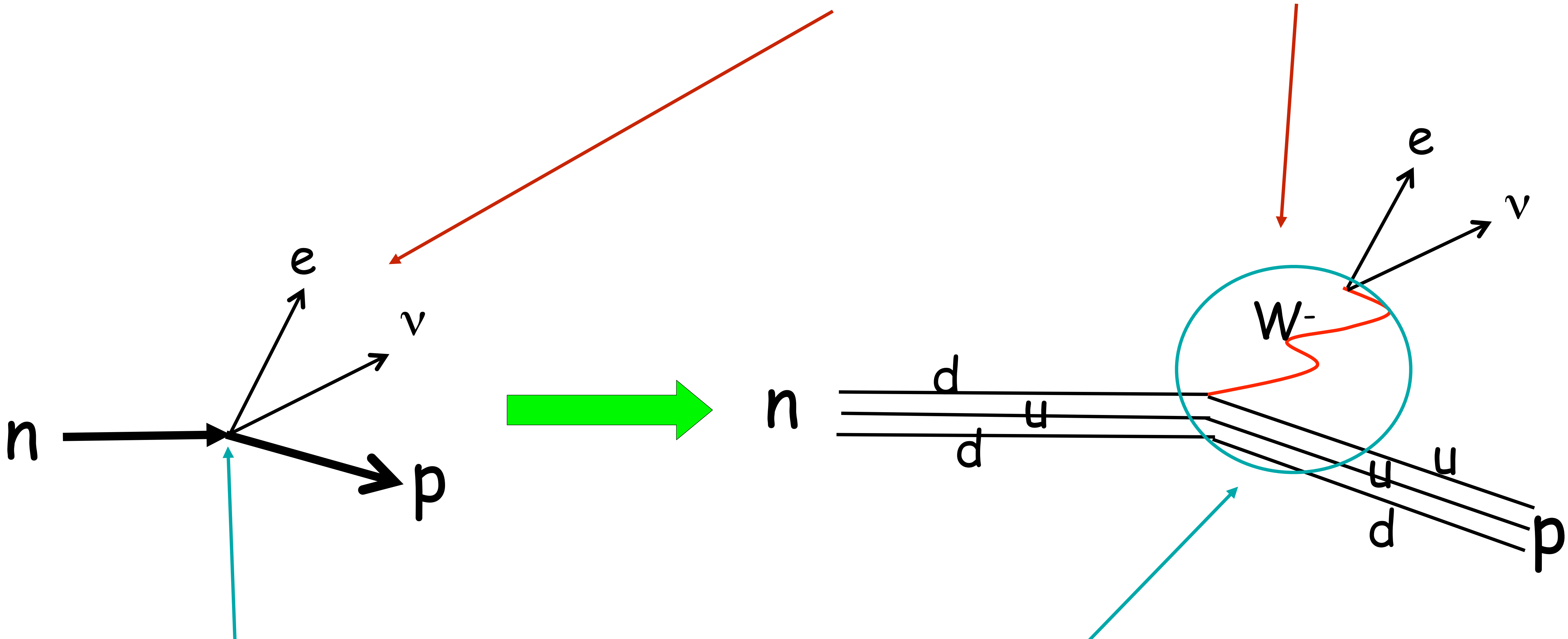
It is probably inconsistent to quantized matter fields in a fixed curved background, the background itself being subject to quantum fluctuations.

Is the information paradox a consequence of such an inconsistent mixture of classical and quantum?

Alternative approaches to QGR

The most interesting attempts to this date are those of Loop Quantum Gravity and of Asymptotic Safety. Both assume that one can make sense of quantum gravity by modifying the way to quantize GR, but not GR itself.

The EW lesson (Fermi vs. GWS)



The interaction takes place at a single point in space-time

The interaction is smeared over a finite region of space-time

It was not a matter of finding a smart trick to quantize the theory. We had to modify it!

A 2nd lesson from particle physics

According to our present understanding, at the most microscopic quantum level all fundamental interactions are transmitted by massless particles of spin 1 or 2.

The first (e.g. the photon) give rise to non-gravitational interactions, while the latter (the graviton) is responsible for gravity.

Both gauge invariance and general covariance follow from the consistency of those massless-particles' interactions

GR (and gauge theories) as a consequence of QM?

A Copernican Revolution
from String Theory!

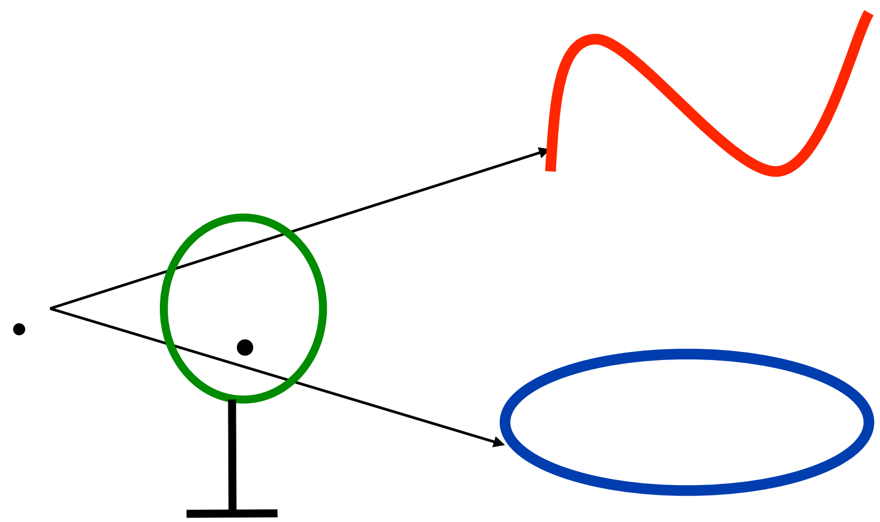
String theory: what's that?

best reply?

« String Theory is the theory of strings »

Replace the grand principles (gauge invariance, general covariance) by «just» the assumption that everything is made of

Relativistic Quantum Strings



open string

or

closed string

SR + QM + strings = Big Synthesis

I. Finite Size

Classical string theory is scale free. Classical strings have no characteristic size.
The characteristic size of quantum strings is determined by Quantum Mechanics:

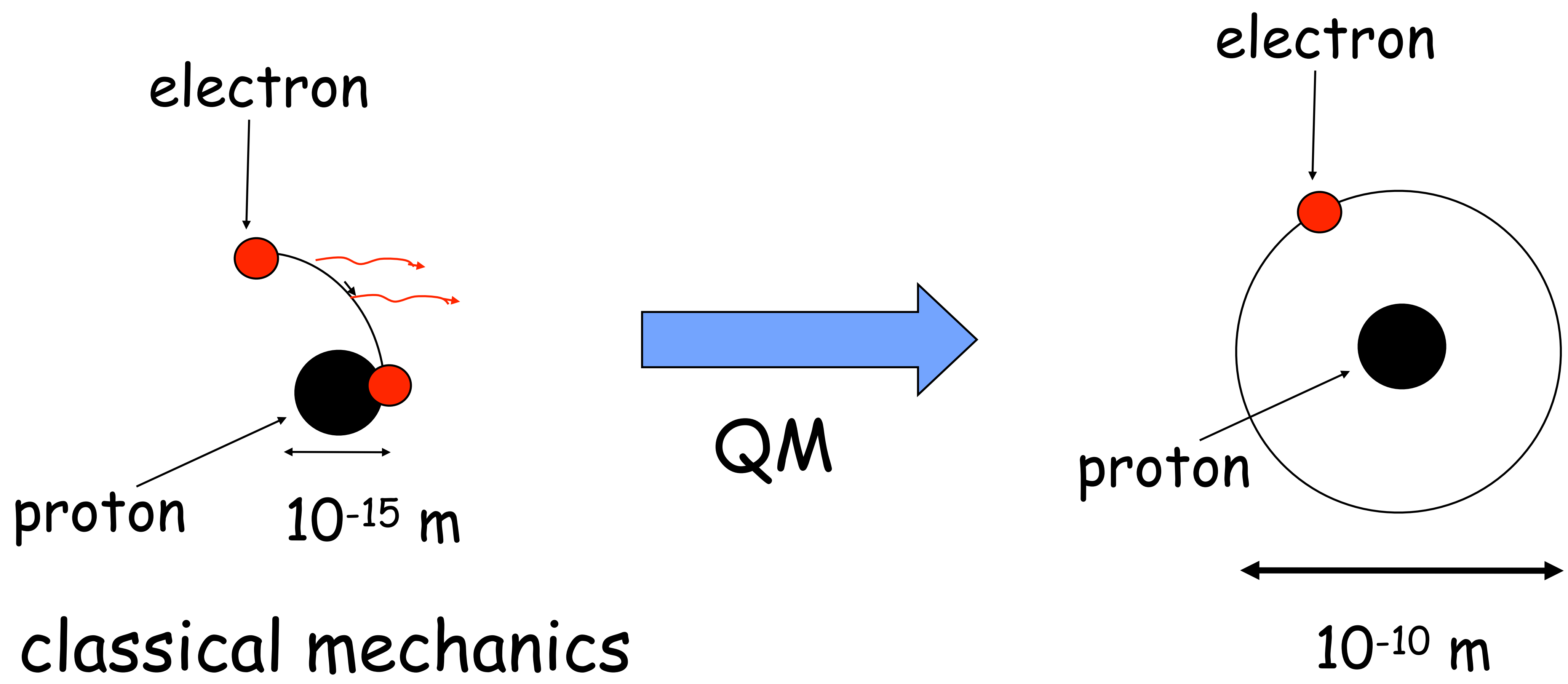
$$L_s = \sqrt{\frac{\hbar c}{T}}$$

T = string tension

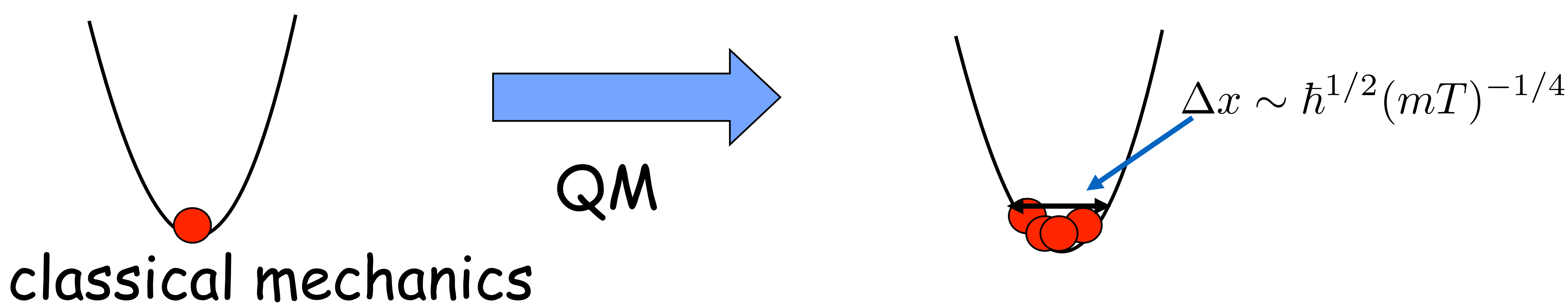
Note analogy (in D=4) with:

$$L_P = \sqrt{\frac{\hbar G_N}{c^3}}$$

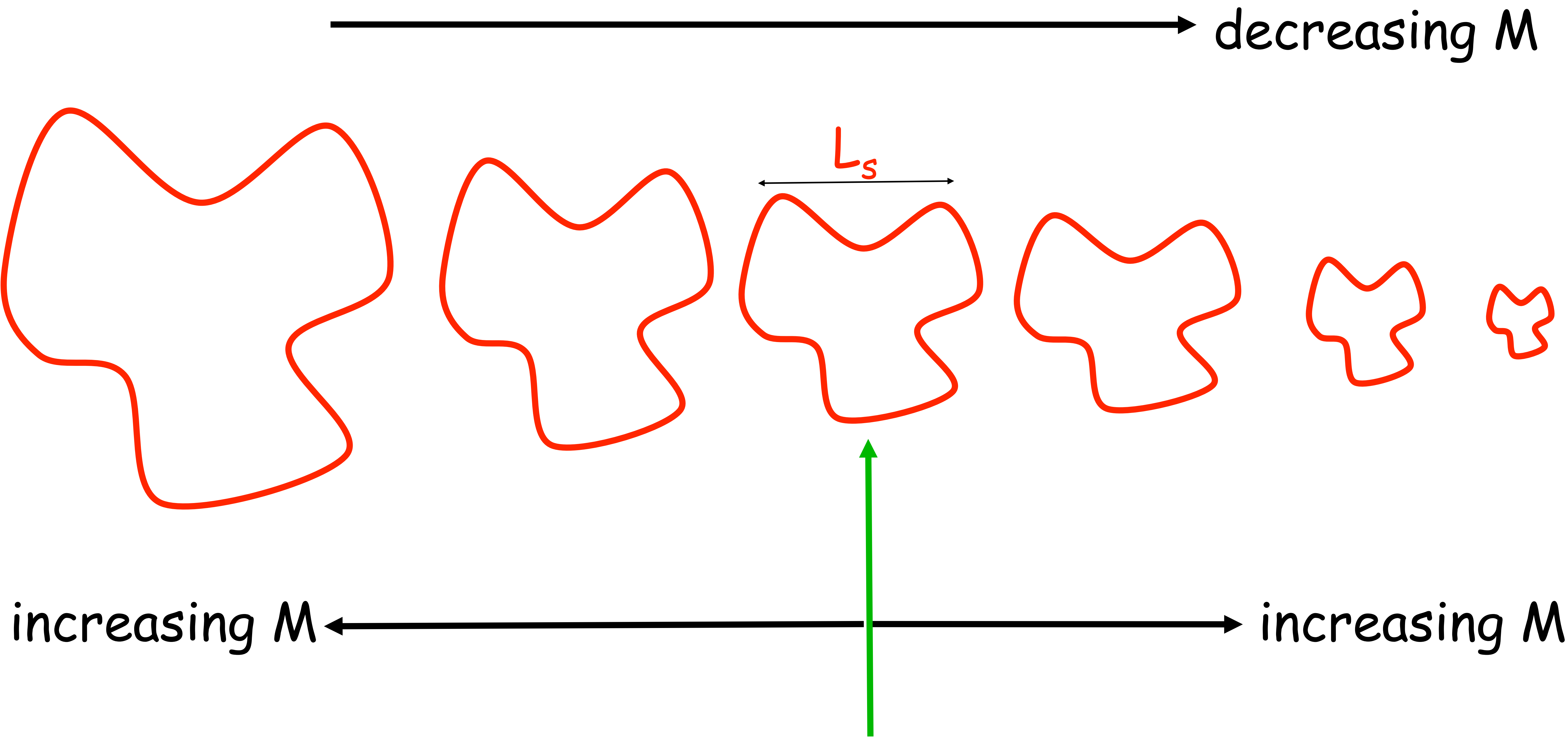
Analogy with atoms



Even closer with ground state of harmonic oscillator

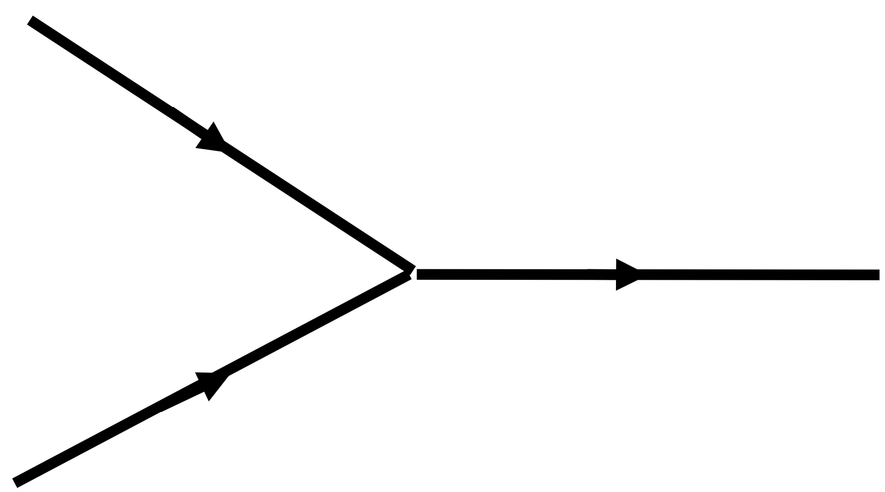


Without QM strings become lighter and lighter as they shrink

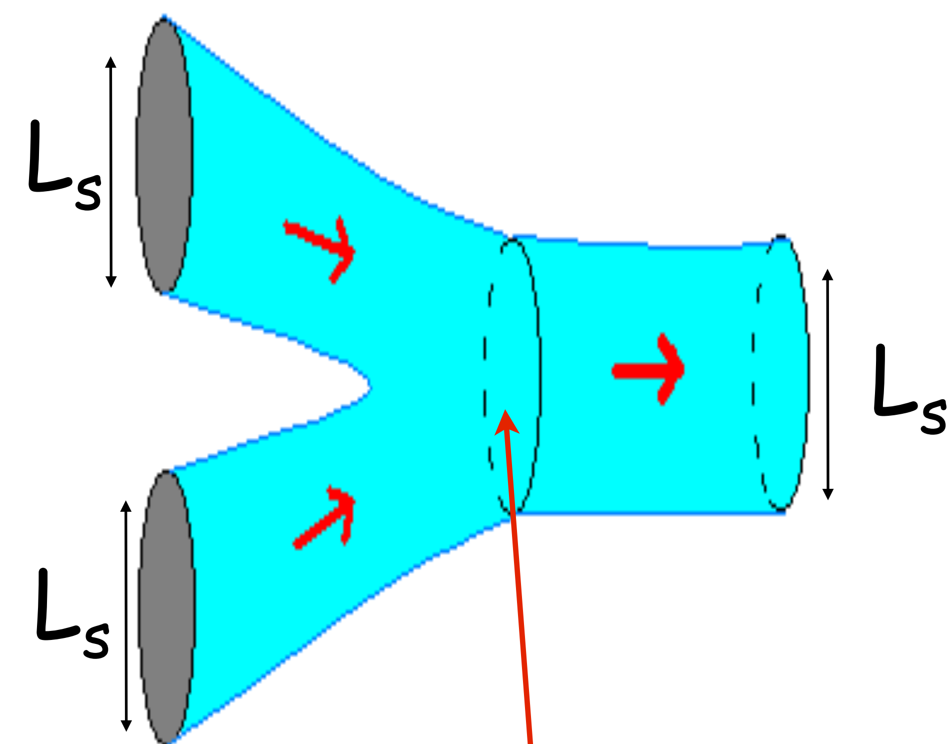


With QM strings are lightest when their size is L_s

Field Theory



String Theory



Interactions are smeared over regions of order L_s

This basic property of quantum strings cures the ultraviolet problems of conventional quantum gravity by removing UV divergences altogether

II. J without M

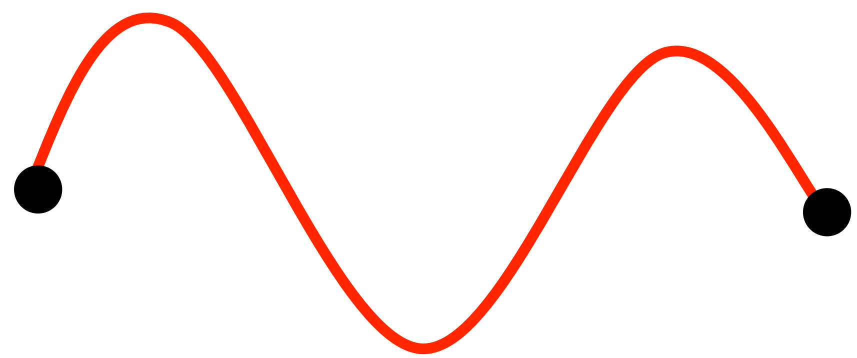
A classical string cannot have angular momentum without having a finite length, hence a finite mass. A quantum string, instead, can have up to two units of angular momentum without gaining mass.

after consistent regularization

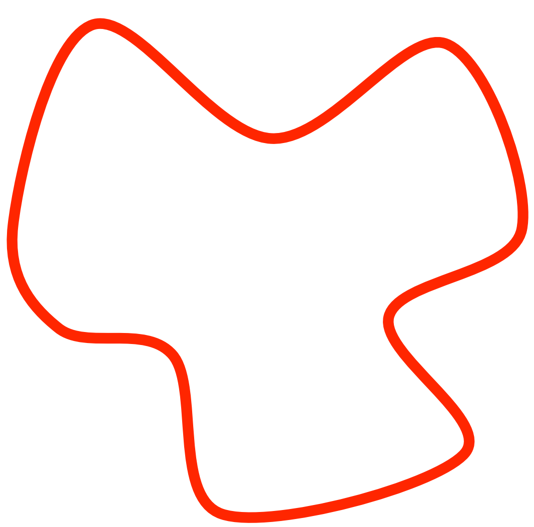
$$\frac{M^2}{2\pi T} \geq J + \hbar \sum_1^\infty \frac{n}{2} = J - \alpha_0 \hbar \qquad \alpha_0 = 0,\ \frac{1}{2},\ 1,\ \frac{3}{2},\ 2.$$

NB: The inevitability of massless spinning states was one reason for abandoning the old string theory in favor of QCD.
=>String theory CAN be falsified by large-distance experiments!

In particular our Copernican Revolution...



=> $m=0$, $J = 1$ => photon and other gauge bosons mediating the non-gravitational forces



$\Rightarrow m=0$, $J = 2$ => graviton, mediating the gravitational force

All elementary particles correspond to different vibrations of the same basic objects: open and closed strings!

Combining both miracles provides

A unified and finite theory of elementary particles, and of their gauge and gravitational interactions, not just compatible with, but based upon,

Quantum Mechanics!

QM gives rise, directly, to quantum versions of gauge and gravitational interactions whose classical limit is the conventional starting point of QFT.

However, it also provides short-distance corrections without which QFTs are plagued by UV divergences!

A worked-out example: transplanckian-energy string collisions (in Minkowski spacetime)

Trans-Planckian E string-string collisions

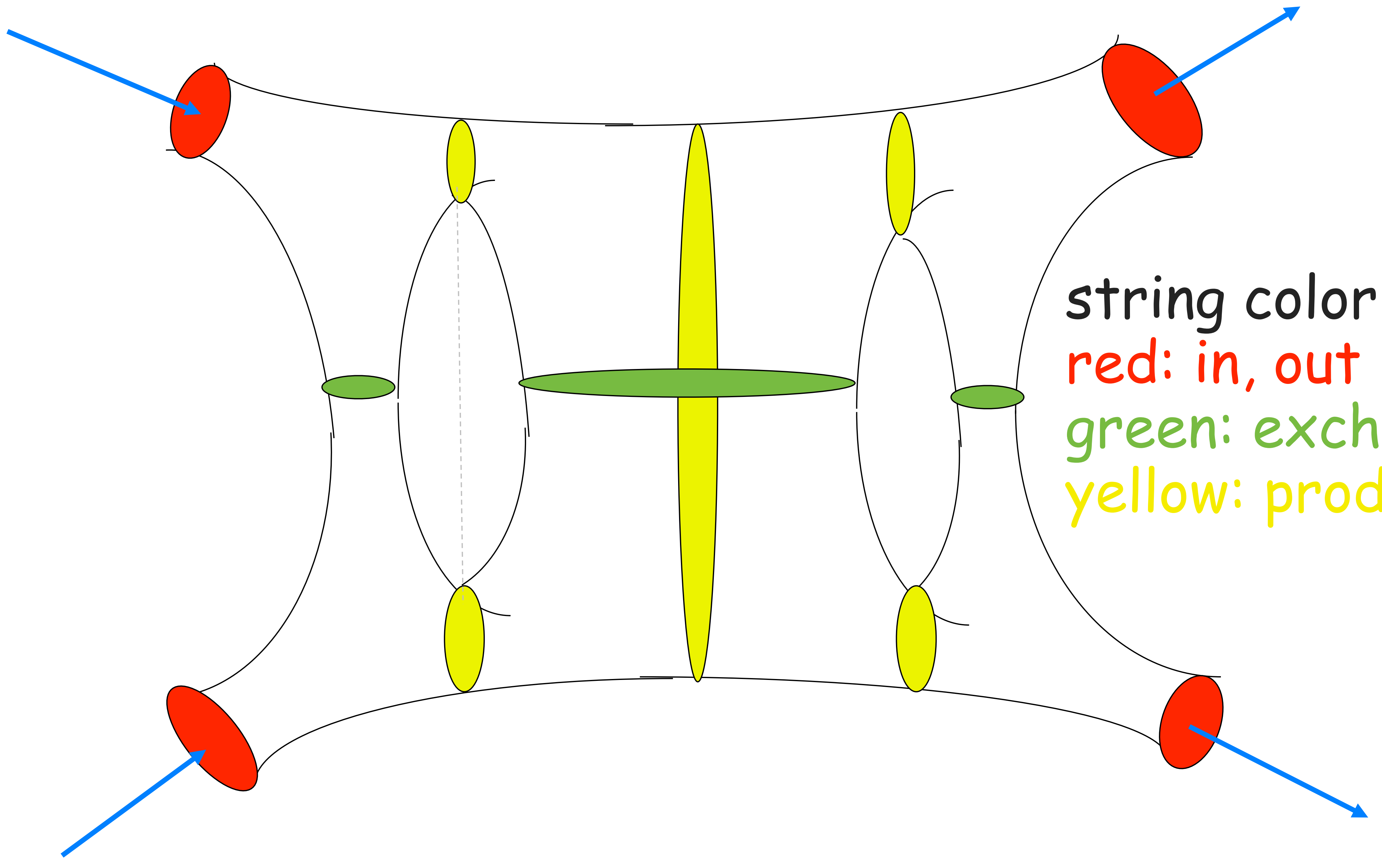
We can fix the two initial strings as well as $s = E^2$ and J.

Hard to imagine a simpler pure initial state that could lead to BH formation and whose unitary evolution we would like to understand/follow. An interesting gedanken experiment!

TPE simplifies the theoretical analysis by justifying a semiclassical approximation.

Calculations done in flat spacetime!

TPE (closed)string-string collisions
(a two-loop contribution)



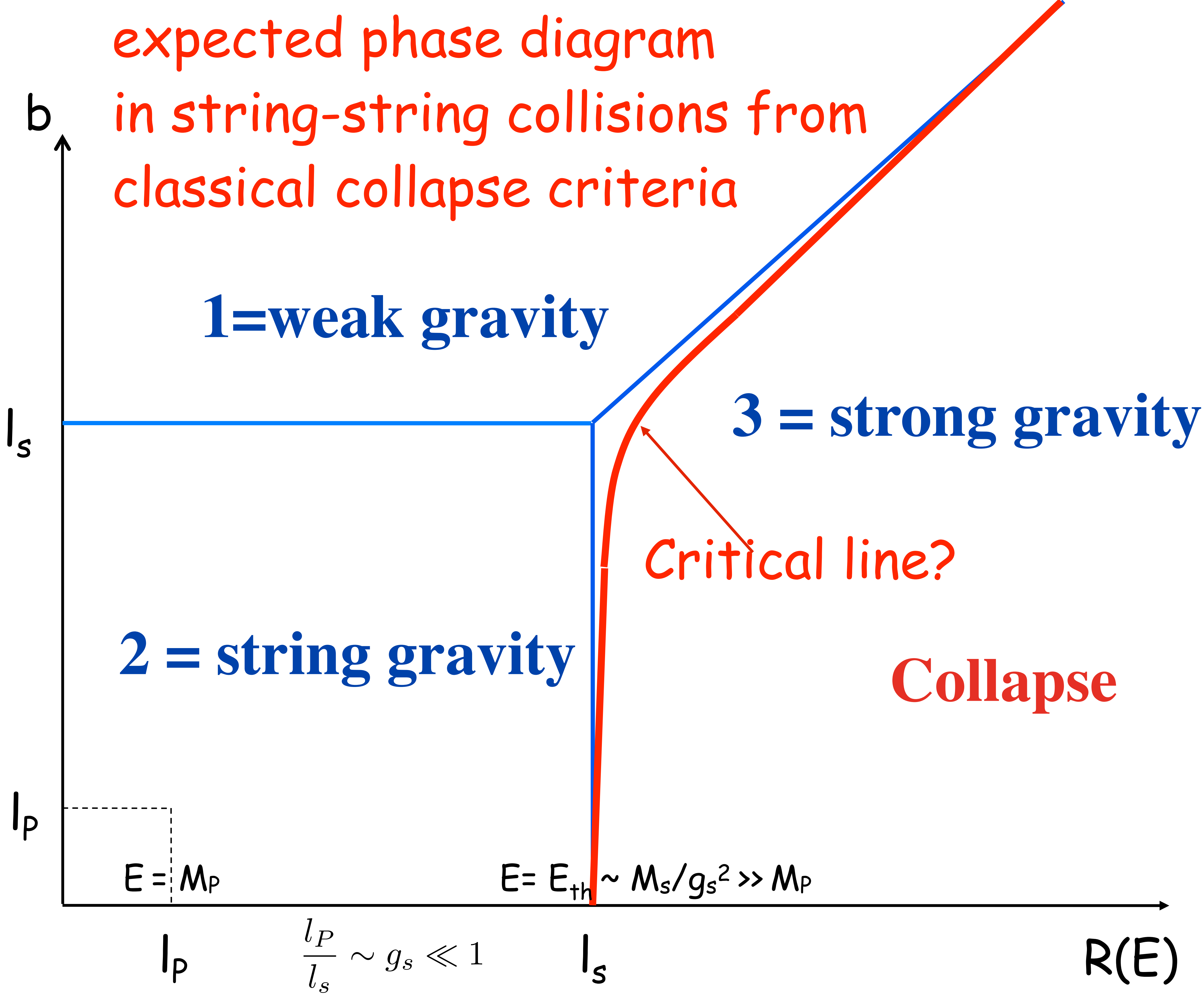
string color code:
red: in, out
green: exchanged
yellow: produced

Parameter-space for string-string collisions @ $s \gg M_P^2$

$$b \sim \frac{2J}{\sqrt{s}} \quad ; \quad R_D \sim \left(G\sqrt{s}\right)^{\frac{1}{D-3}} \quad ; \quad l_s \sim \sqrt{\alpha' \hbar} \quad ; \quad G\hbar = l_P^{D-2} \sim g_s^2 l_s^{D-2}$$

- 3 relevant length scales (neglecting l_P @ $g_s \ll 1$)
- Playing w/s and g_s we can make R_D/l_s arbitrary

expected phase diagram in string-string collisions from classical collapse criteria



Actually there are subregions: Why?

A semiclassical S-matrix @ high energy

General arguments and explicit calculations suggest the following form for the TPE string-string elastic S-matrix:

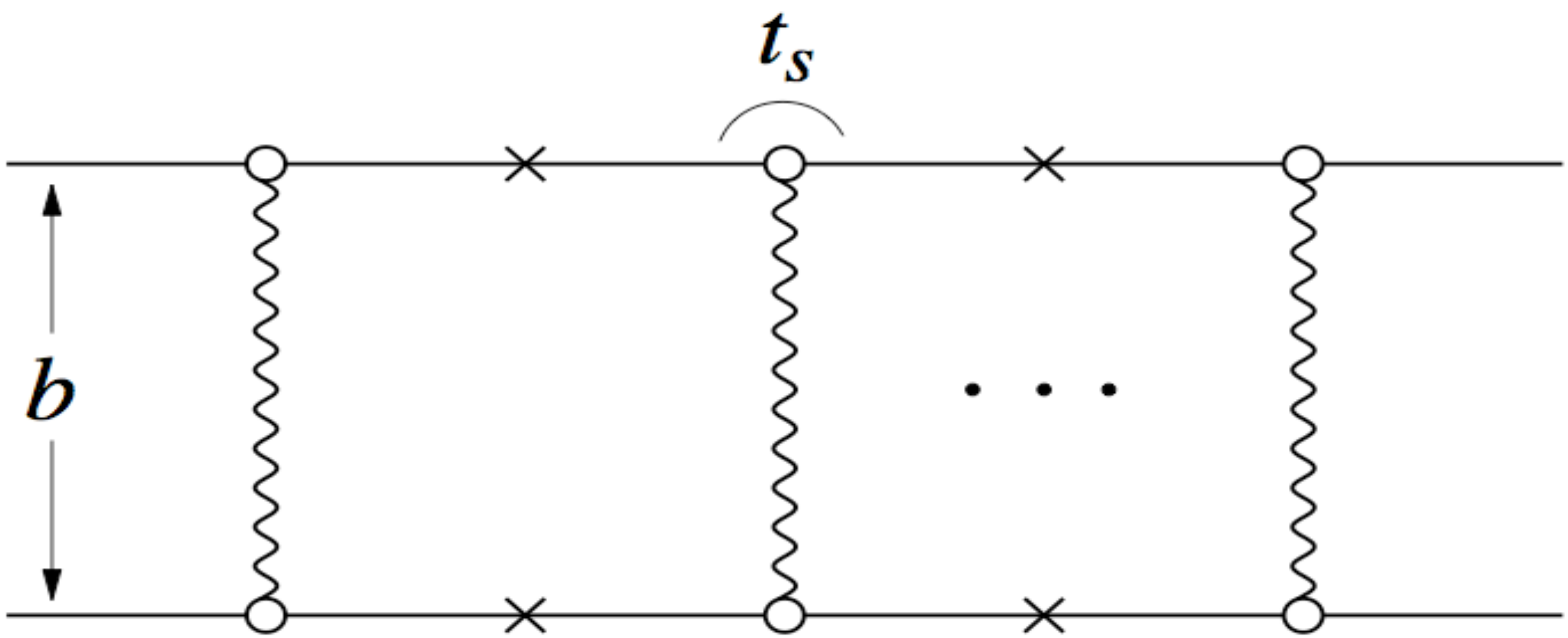
$$S(E,b) \sim exp\left(i\frac{A_{cl}}{\hbar}\right) \quad ; \quad \frac{A_{cl}}{\hbar} \sim \frac{Gs}{\hbar} c_D b^{4-D}\left(1 + O((R/b)^{2(D-3)}) + O(l_s^2/b^2) + O((l_P/b)^{D-2}) + \dots\right)$$

NB: Since leading term is real, for Im A_{cl} some terms may be more than just corrections. They give absorption ($|S_{el}| < 1$).
This i gives rise to subregions.

The weak-gravity QFT regime

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

Leading eikonal diagrams (crossed ladders included)



A unitary elastic S-matrix

$$S(E,b) \sim exp\left(i\frac{Gs}{\hbar}c_D b^{4-D}\right) \;;\; S(E,q) = \int d^{D-2}b\; e^{-iqb} S(E,b) \;\;;\;\; s = 4E^2 \;,\; q \sim \theta E$$

The integral is dominated by a saddle point at:

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

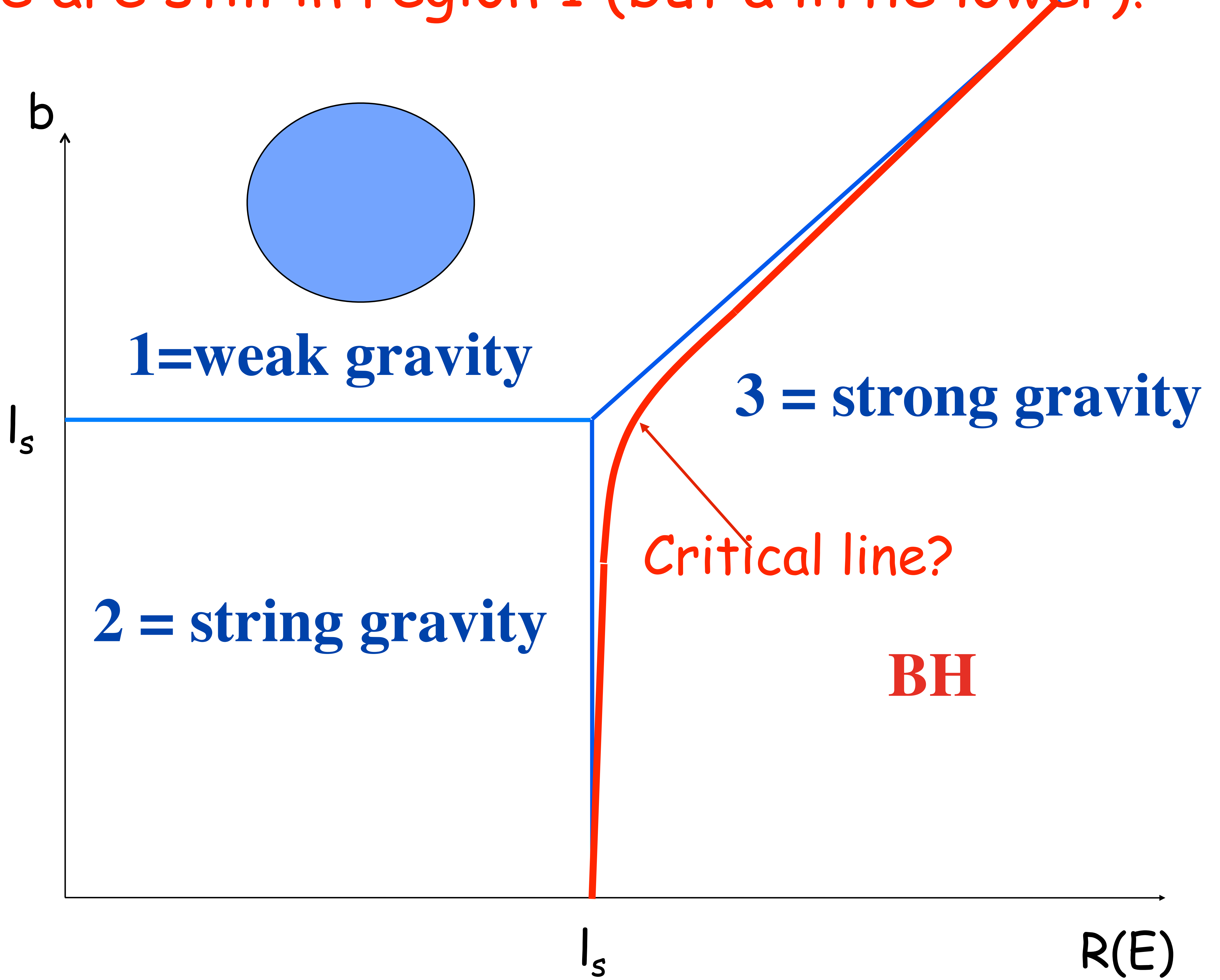
comments:

1. Deflection angle given by derivative of phase shift w.r.t. b. => correct generalization of Einstein's deflection formula to ultra-relativistic collisions & arbitrary D.
2. Derivative w.r.t. E gives correct Shapiro time delay.
3. Elastic unitarity is fullfilled.

The weak-gravity QST regime

(w/ exact inelastic unitarity)

We are still in region 1 (but a little lower)!



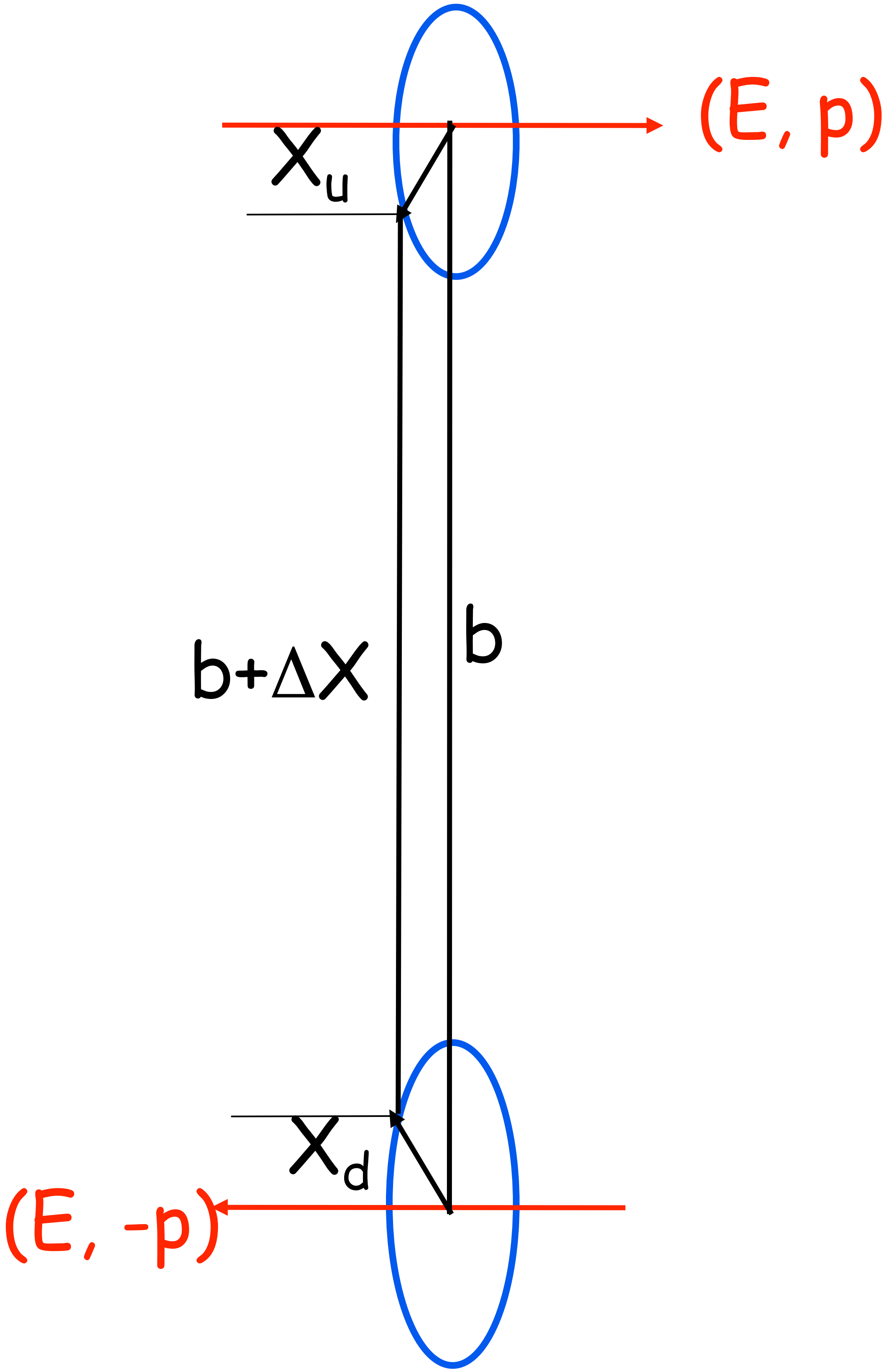
String-string scattering @ large b

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

String-size effects are simply captured, at the leading eikonal level, by replacing the impact parameter **b** by a shifted impact parameter, displayed by each string's position operator evaluated at $\tau = 0$ (= coll. time) and averaged over σ (see figure).

This leads to a unitary operator eikonal (as long as the phase shift is real).

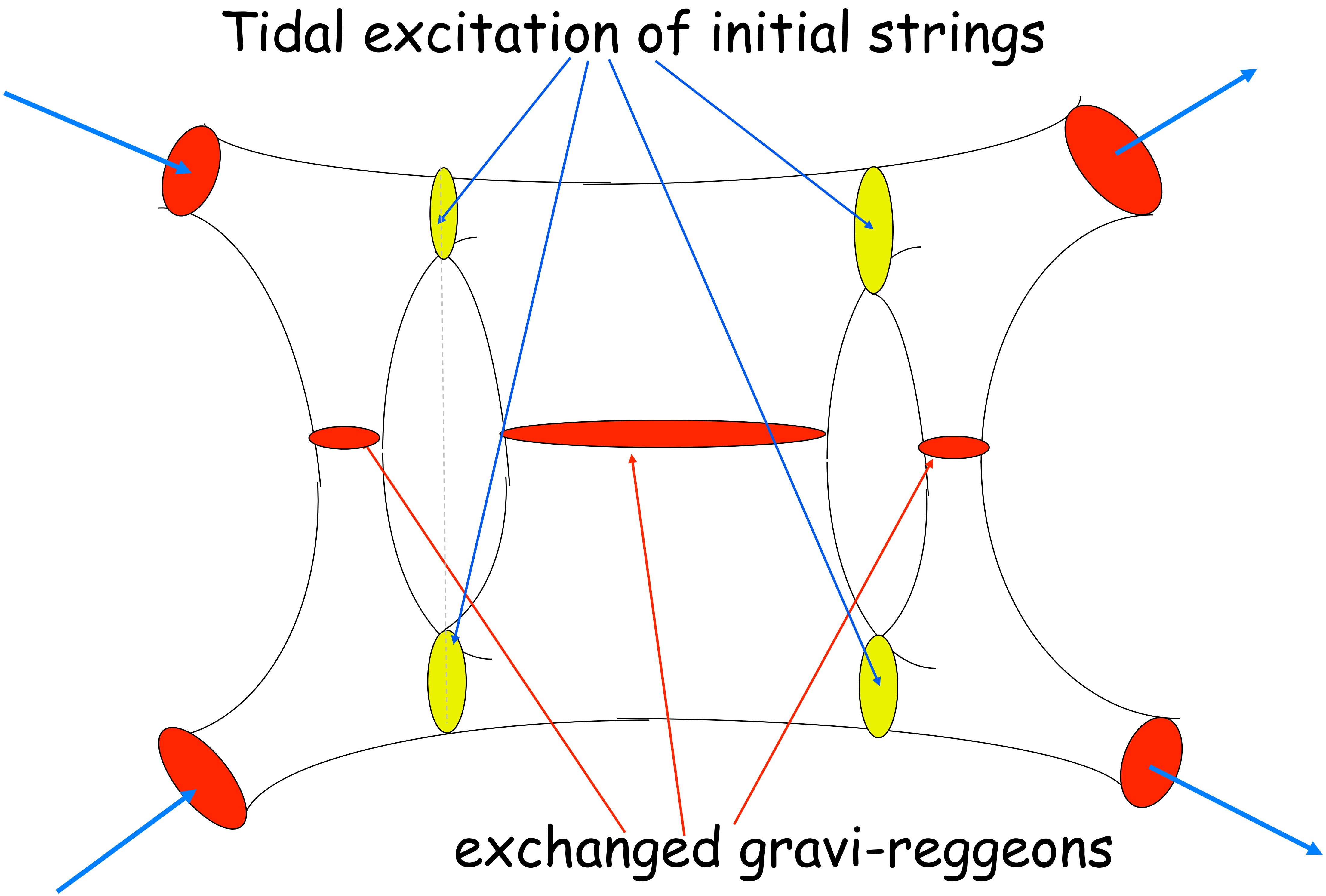
N.B. Elastic unitarity -> inelastic unitarity


(E, p)
X_u
b+ΔX
b
X_d
(E, -p)

Graviton exchange can excite one or both strings. Physical interpretation: a string moving in a non-trivial metric feels tidal forces as a result of its finite size.

Indeed the quantitative results so obtained are fully consistent with the classical tidal-effects picture.

Everything is fully consistent with a quantum-information preserving unitary evolution.


Tidal excitation of initial strings
exchanged gravi-reggeons

Gravitational waves from TPE collisions (in point-particle limit)

A highly non-trivial problem both analytically and numerically
(for further details see my talk at the IHES, June 2017)

S. Kovacs and K.Thorne 1977

THE GENERATION OF GRAVITATIONAL WAVES.
IV. BREMSSTRAHLUNG*†‡

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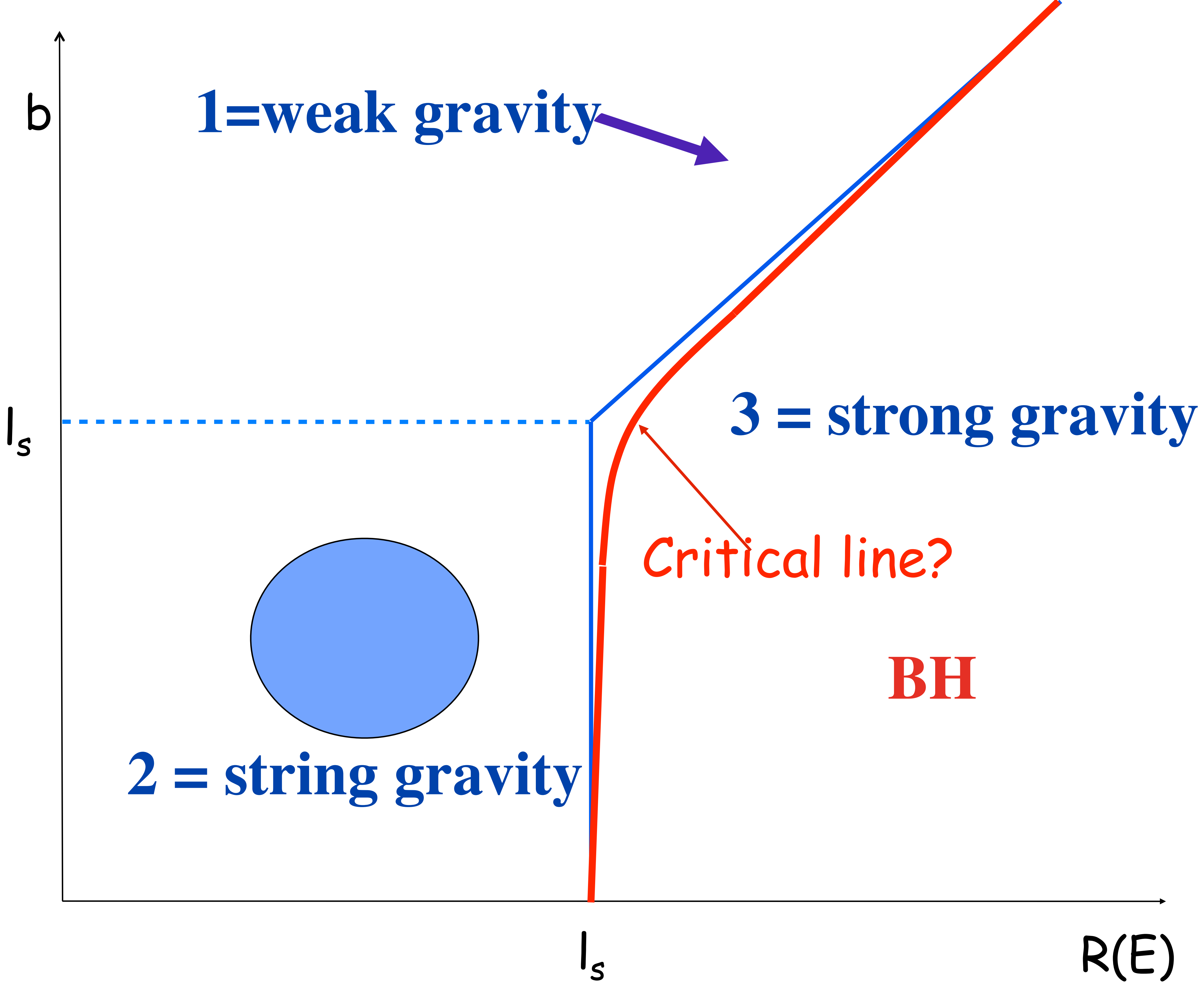
ABSTRACT

This paper attempts a definitive treatment of "classical gravitational bremsstrahlung"—i.e., of the gravitational waves produced when two stars of arbitrary relative mass fly past each other with arbitrary relative velocity v, but with large enough impact parameter that

$$\text{(angle of gravitational deflection of stars' orbits)} \ll (1 - v^2/c^2)^{1/2} .$$



b
1=weak gravity
l_s
3 = strong gravity
Critical line?
BH
2 = string gravity
l_s
R(E)

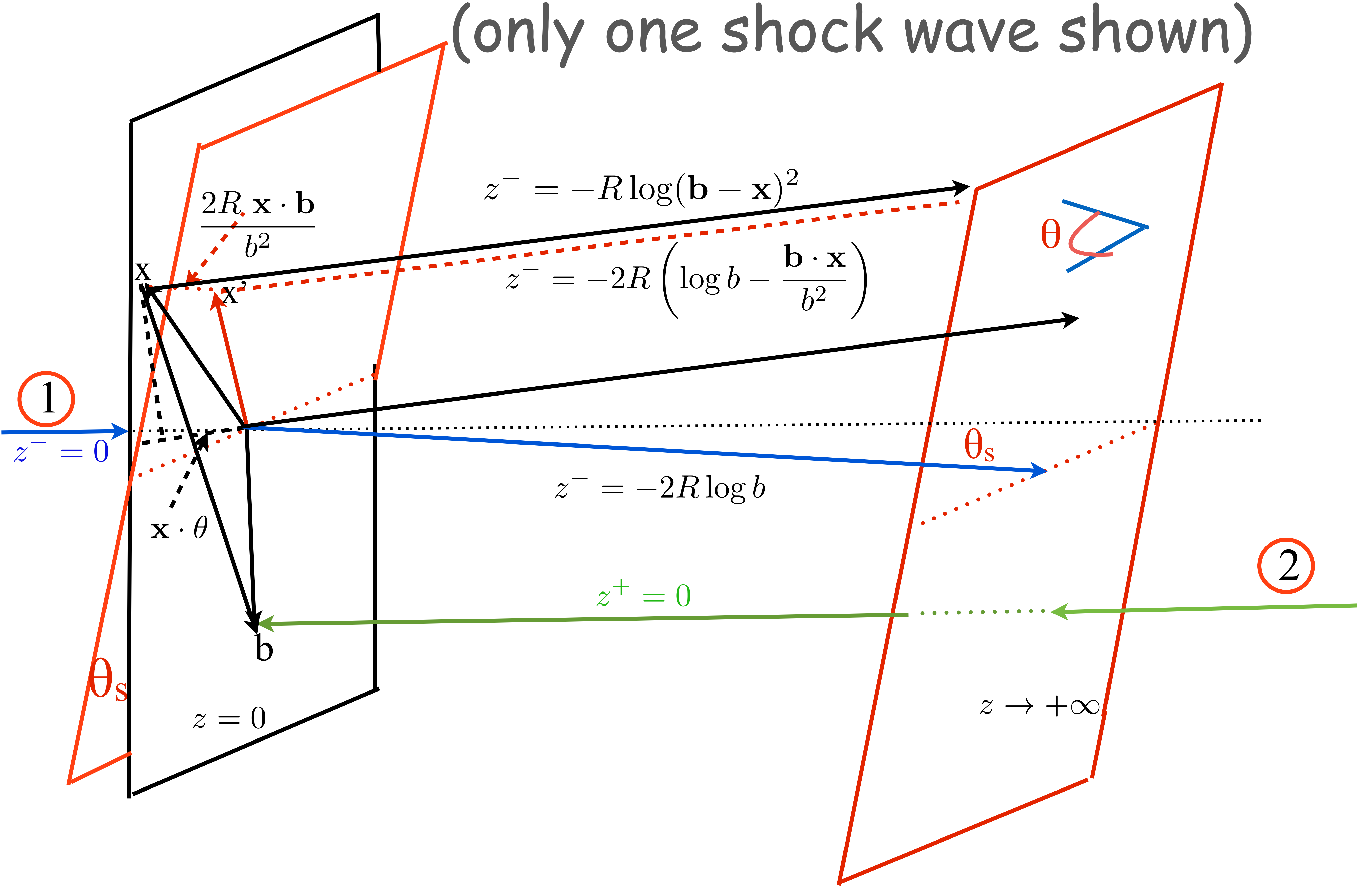
A classical treatment
(A. Gruzinov & GV, 1409.4555)

The calculation is done directly in the c.o.m. system for massless particles at small θ_s.

Obtained via Huygens principle in Fraunhofer approximation. For gravity this includes in an essential way the effects of gravitational time delay in an external metric.

Illustration of grav.^{al} Huygens-Fraunhofer

(only one shock wave shown)



Frequency and angular distribution of GW spectrum:

$$\frac{dE^{GW}}{d\omega\ d^2\tilde{\theta}} = \frac{GE^2}{\pi^4}|c|^2\ ;\ \tilde{\boldsymbol{\theta}} = \boldsymbol{\theta} - \boldsymbol{\theta}_s\ ;\ \boldsymbol{\theta}_s = 2R\frac{\boldsymbol{b}}{b^2}$$

$$c(\omega, \tilde{\boldsymbol{\theta}}) = \int \frac{d^2x\ \zeta^2}{|\zeta|^4}\ e^{-i\omega\mathbf{x}\cdot\tilde{\boldsymbol{\theta}}}\left[e^{-2iR\omega\Phi(\mathbf{x})} - 1\right]$$

$$\zeta = x + iy \qquad \Phi(\mathbf{x}) = \frac{1}{2}\ln\frac{(\mathbf{x}-\mathbf{b})^2}{b^2} + \frac{\mathbf{b}\cdot\mathbf{x}}{b^2}$$

$$c(\omega, \boldsymbol{\theta}) = \int \frac{d^2x\ \zeta^2}{|\zeta|^4} e^{-i\omega\mathbf{x}\cdot\boldsymbol{\theta}}\left[e^{-iR\omega\ln\frac{(\mathbf{x}-\mathbf{b})^2}{b^2}} - e^{+2iER\omega\frac{\mathbf{b}\cdot\mathbf{x}}{b^2}}\right]$$

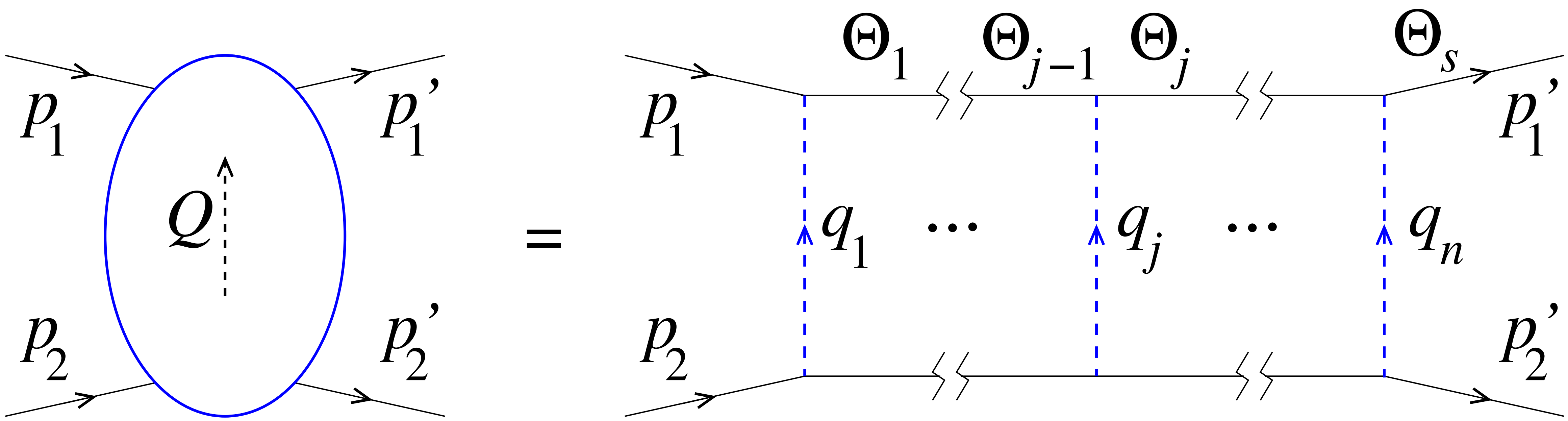
Re ζ^2 and Im ζ^2 correspond to the two GW polarizations.

Subtracting the deflected shock wave (cf. P. D'Eath) is crucial!

A quantum treatment in Minkowski spacetime

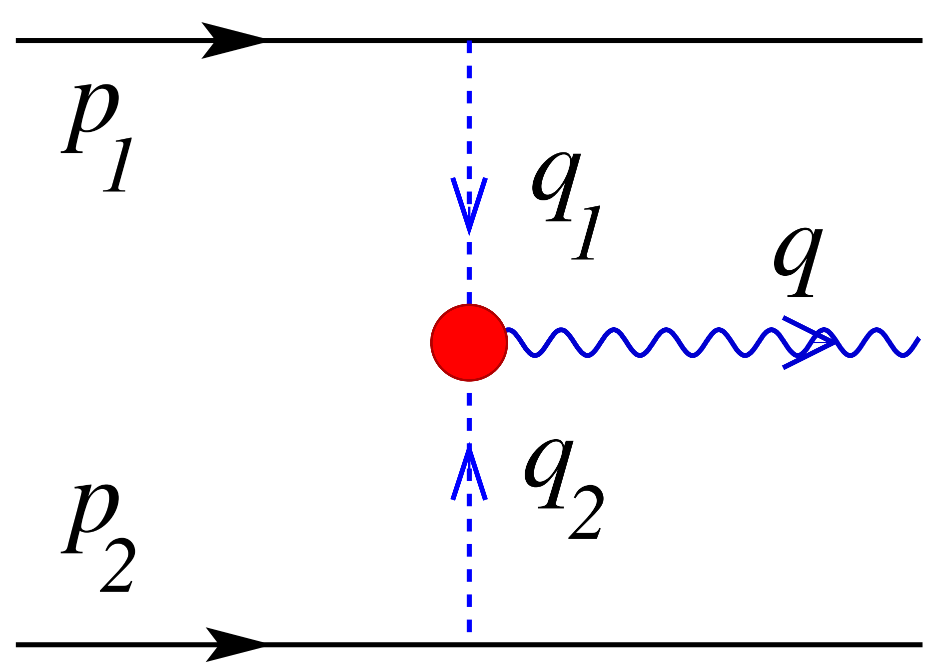
(Ciafaloni, Colferai & GV, 1505.06619),
CC&Coraldeschi & GV, 1512.00281)

In CC(C)V (1505.06619 & 1512.00281) the same problem has been addressed at the quantum level improving on the earlier (ACV07) treatment.

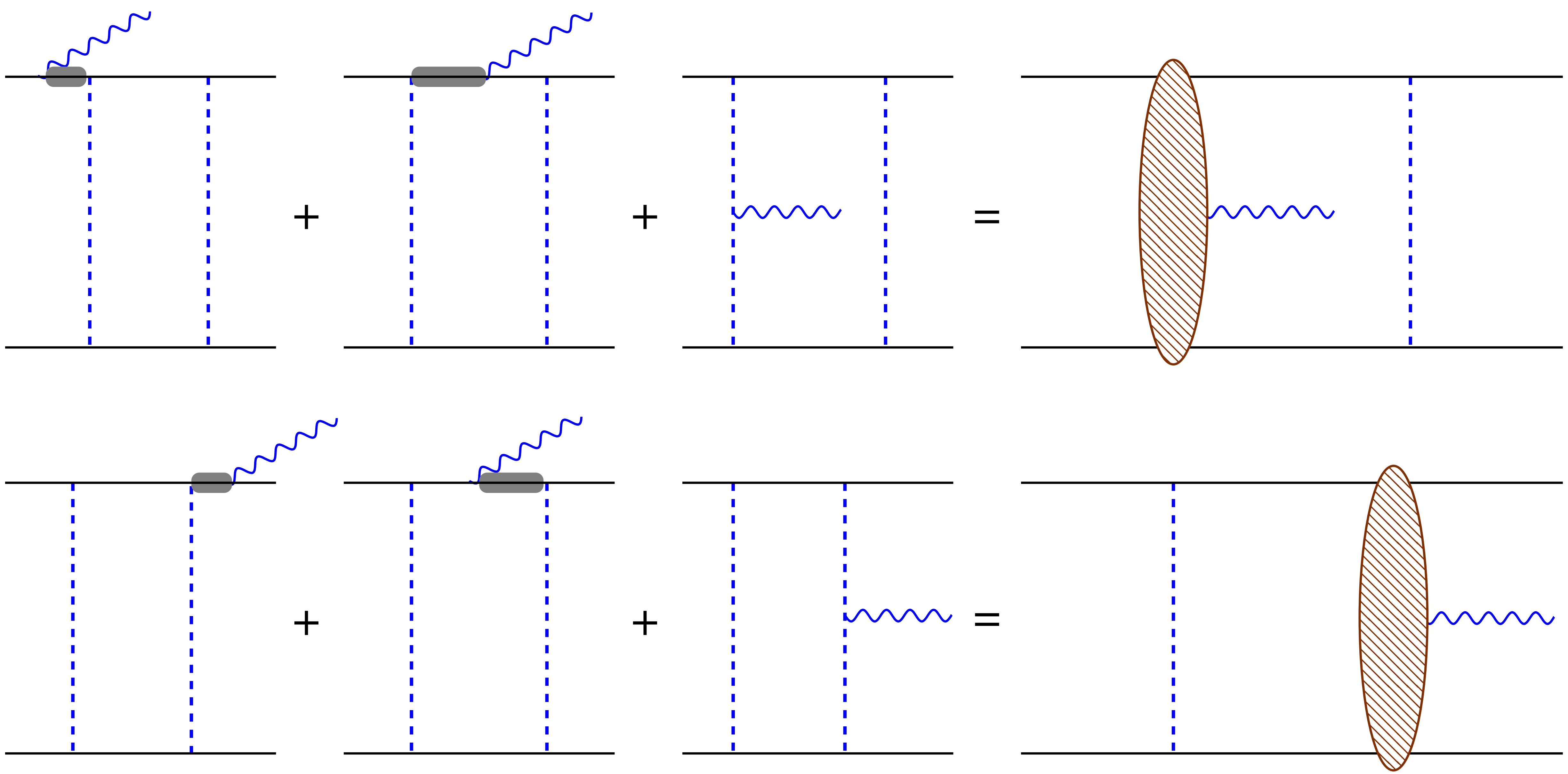


One observation is that the usual soft-graviton recipe (emission from external legs) has to be amended since the internal exchanged gravitons are almost on shell.

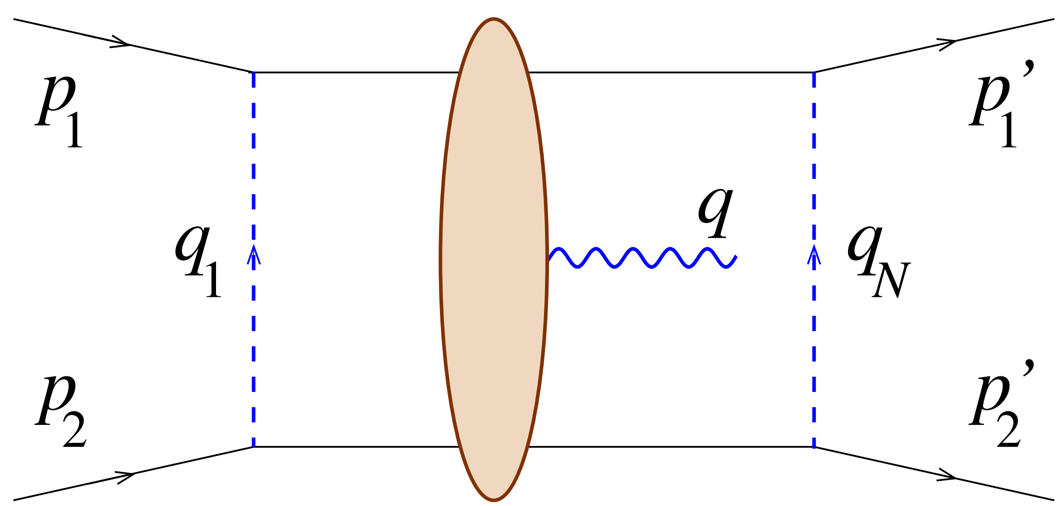
Emission from such internal lines is important for not-so-soft gravitons (hence for the energy loss).



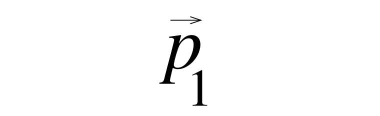
Emission from external and internal legs through the whole ladder has to be taken into account.



At fixed graviton helicity and momentum production amplitudes depend in a precise way upon the incidence angle, which changes along the fast-particle trajectory.



(a)



If this effect is kept into account the result for $c(\omega, \theta)$ is:

$$\int \mathrm{d}^2\boldsymbol{z} \int_0^1 \mathrm{d}\xi \; h_s(\boldsymbol{z}) \mathrm{e}^{\mathrm{i}\omega b \boldsymbol{z}\cdot(\boldsymbol{\theta} - \xi \boldsymbol{\Theta}_s(b))}$$

$$h_s(z) \equiv \frac{1}{\pi^2 z^{*2}} \left(\frac{E}{\omega} \log \left| \hat{\boldsymbol{b}} - \frac{\omega}{E} \boldsymbol{z} \right| - \log \left| \hat{\boldsymbol{b}} - \boldsymbol{z} \right| \right) \equiv - \frac{\Phi_R(\boldsymbol{z})}{\pi^2 z^{*2}}$$

$$\Phi_R(\boldsymbol{z}) \to \Phi(\boldsymbol{z}) \equiv \left(\hat{\boldsymbol{b}} \cdot \boldsymbol{z} + \log \left| \hat{\boldsymbol{b}} - \boldsymbol{z} \right| \right)$$

similar -but not identical- to the classical result of G+V.

However, as argued by CCCV, one should also take into account the difference between the phase of the final 3-particle state and that of an elastic 2-particle state.

When this is done, the classical result of G+V is exactly recovered in the limit $h\omega/E \ll 1$!

We have analyzed (mostly numerically) the properties of the spectrum in the classical limit and obtained several nice pictures (see my May-June talk here). Here I will only make some more qualitative remarks.

For $b^{-1} < \omega < R^{-1}$ the E-spectrum is almost flat in ω

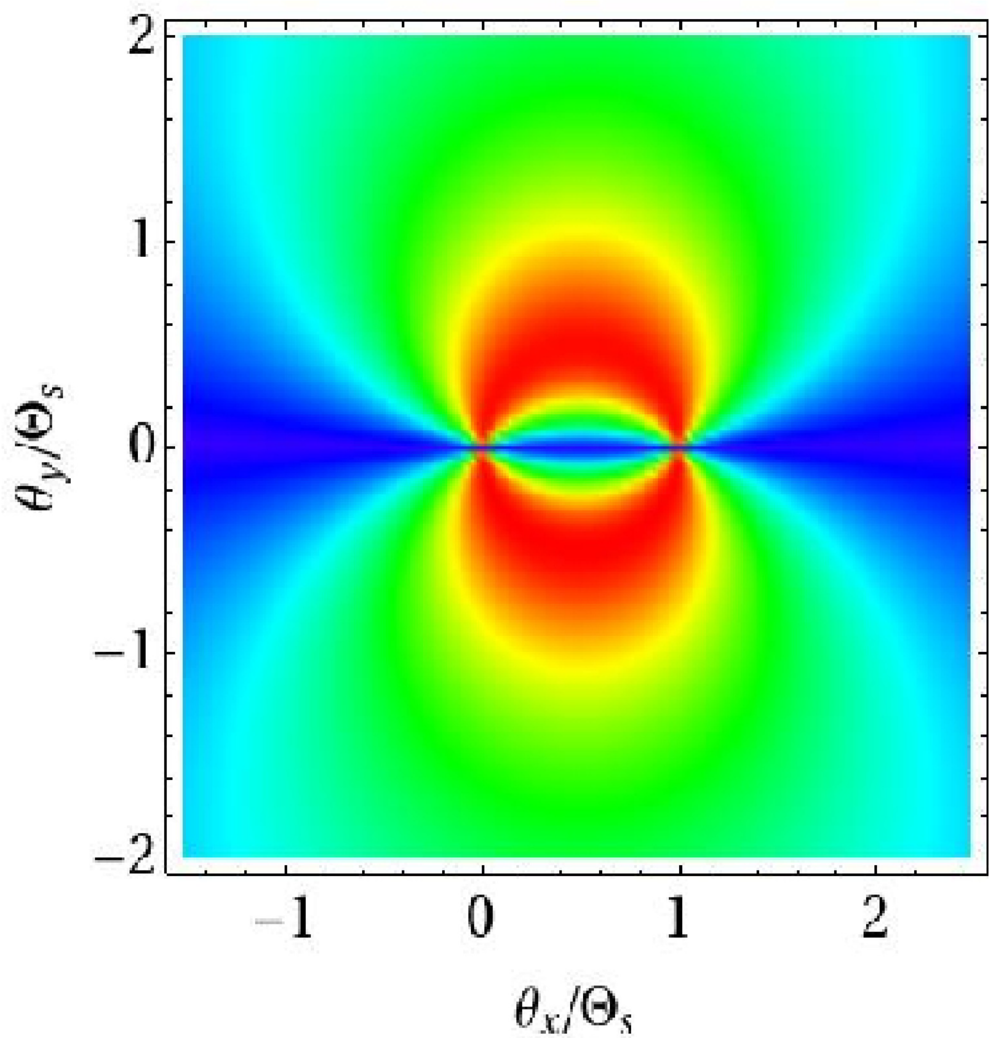
$$\boxed{\frac{dE^{GW}}{d\omega} \sim -\frac{8G}{\pi}\theta_s^2 \log(\omega R)}$$

Below $\omega = b^{-1}$ it freezes reproducing the ZFL

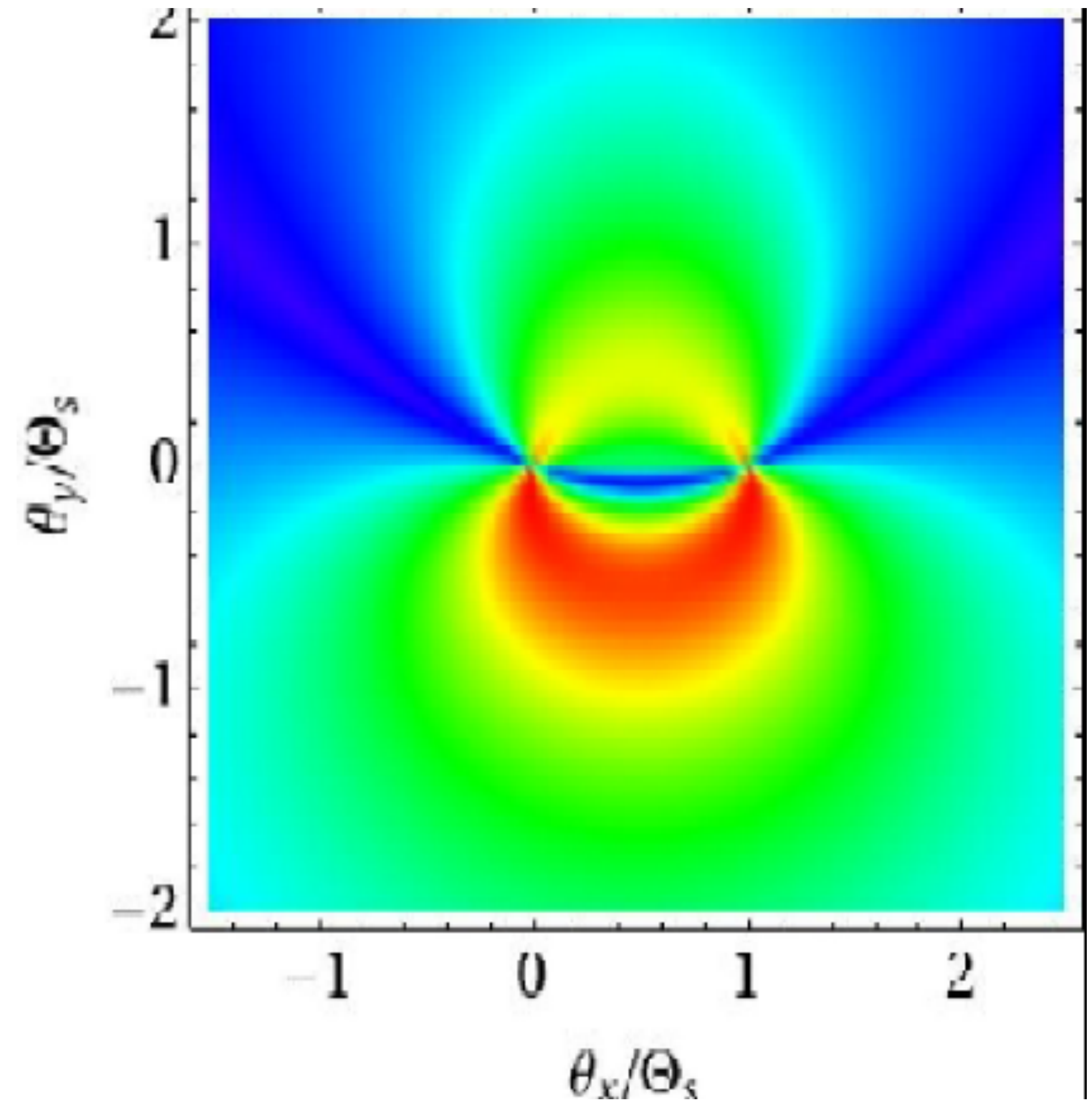
$$\boxed{\frac{dE^{GW}}{d\omega} \to \frac{4G}{\pi}\ \theta_s^2 E^2\ \log(\theta_s^{-2})}$$

Angular (polar and azimuthal) distribution

$\omega R = 10^{-3}$



$\omega R = 0.125$



M. Ciafaloni, D. Colferai, F. Coraldeschi & GV, 1512.00281

Above $\omega = R^{-1}$ the energy spectrum becomes scale-invariant

$$\boxed{\frac{dE^{GW}}{d\omega} \sim \theta_s^2 \frac{E}{\omega}}$$

This gives a log ω^* in the "efficiency" for a cutoff at ω^*

Using $\omega^* \sim R^{-1} \theta_s^{-2}$ (where our approximations break down and the "Dyson bound" $dE/dt < 1/G$ is saturated) we find (to leading-log accuracy) the suggestive result:

$$\boxed{\frac{E^{GW}}{\sqrt{s}} = \frac{1}{2\pi} \theta_s^2 \log(\theta_s^{-2})}$$

For $\omega > \omega^*$ G+V argued for an ω^{-2} spectrum (TBC): it turns out (extrapolating to $\theta_s \sim 1$) to be that of a time-integrated BH evaporation!

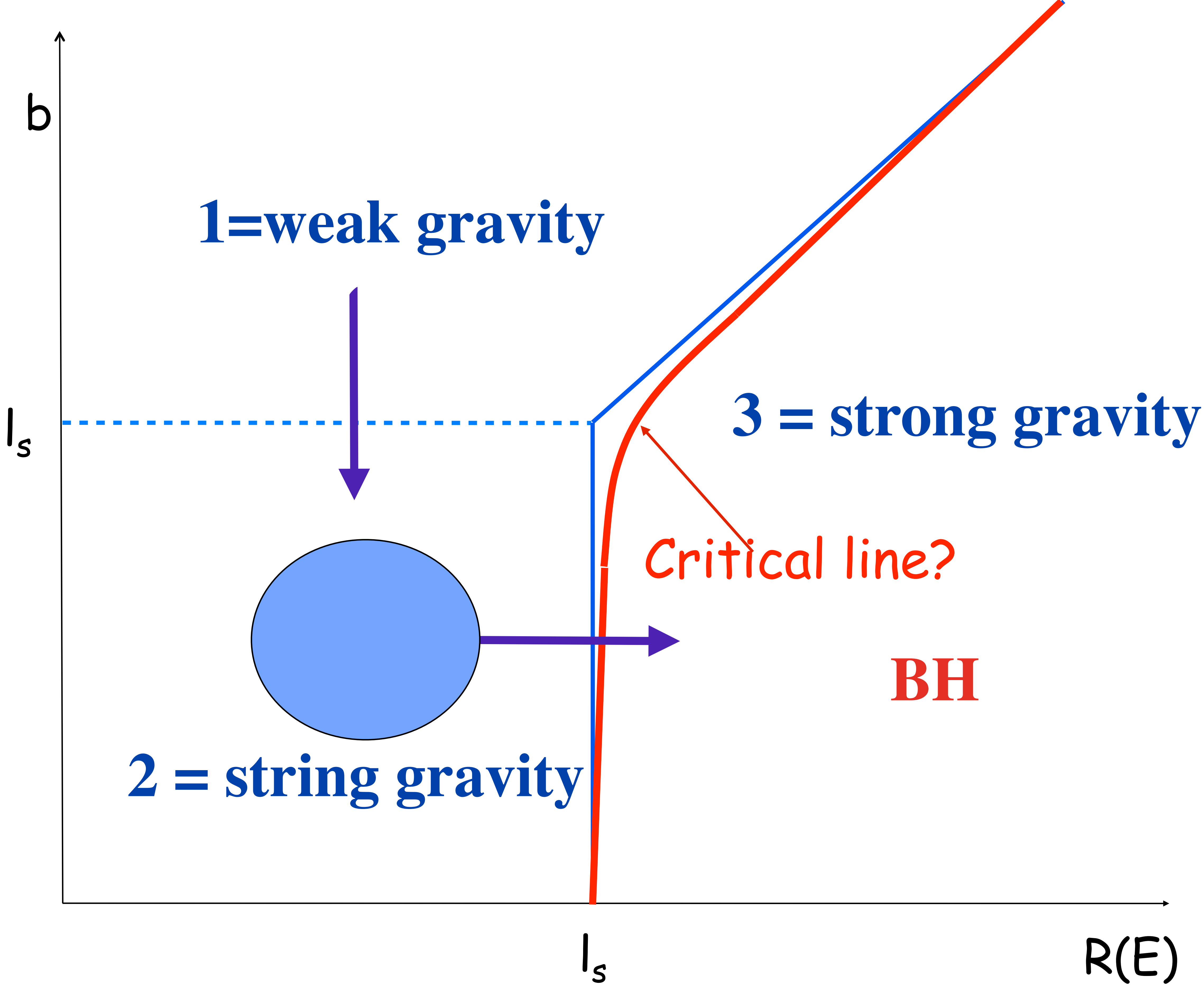
We now want to understand what, if any, provides a large-frequency cutoff and extend the reasoning towards the large-angle/collapse regime.
First steps (involving some educated guesses) already made by Ciafaloni & Colferai (1612.06923).

The emerging picture is quite appealing: transverse momenta are limited by $1/b$ while longitudinal ones (and energies) are controlled by the larger scale $1/R$ (with some leakage at higher frequencies)

If that behavior persists as $b \to b_c \sim R$, the GW/graviton distribution becomes more and more "isotropic" with $\langle n \rangle \sim Gs/\hbar$ and characteristic energy $O(\hbar/R \sim T_H)$.

How about short-distance modifications?

The string-gravity regime


b
1=weak gravity
l_s
3 = strong gravity
Critical line?
BH
2 = string gravity
l_s
R(E)

String-string scattering @ b,R < l_s

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

"Classical corrections" screened, string-corrected leading eikonal can be trusted even for b < R.

Phase shift is finite at b=0 and has a smooth expansion in $b^2/(l_s^2$ logs). Its derivative wrt E gives a well-behaved time delay even for b ->0.

Solves a potential "causality problem", pointed out by Maldacena et al (1407.5597), see DDRV (1502.01254).

The maximal classical deflection angle is ~ $(R/l_s)^{D-3} \ll 1$, and is reached when the two strings graze each other. Scales shorter than l_s cannot be explored =>

Generalized (effective) Uncertainty Principle

(GV, Gross, ACV)

$$\Delta x \geq \frac{\hbar}{\Delta p} + \alpha' \Delta p \geq l_s$$

Less desirable quantum effects

Quantum strings don't like D=4!

- Classical strings can move in any ambient space-time, flat, curved, and in an arbitrary number of dimensions.
- Quantum strings require suitable space-times (more generally backgrounds) in order to avoid lethal anomalies.
- In the case of weakly coupled superstring theories space-time, if nearly flat, must have 9 space and 1 time dimension.
- In order to reconcile this constraint with observations we have to assume that the extra dimensions of space are compact (or at least invisible to non-grav. interactions)
- QM pushes String Theory into a Kaluza-Klein scenario (or the waste basket?) to which it adds interesting twists… There too l_s plays a fundamental role.

Massless/light scalar fields: Achille's heel of QST?

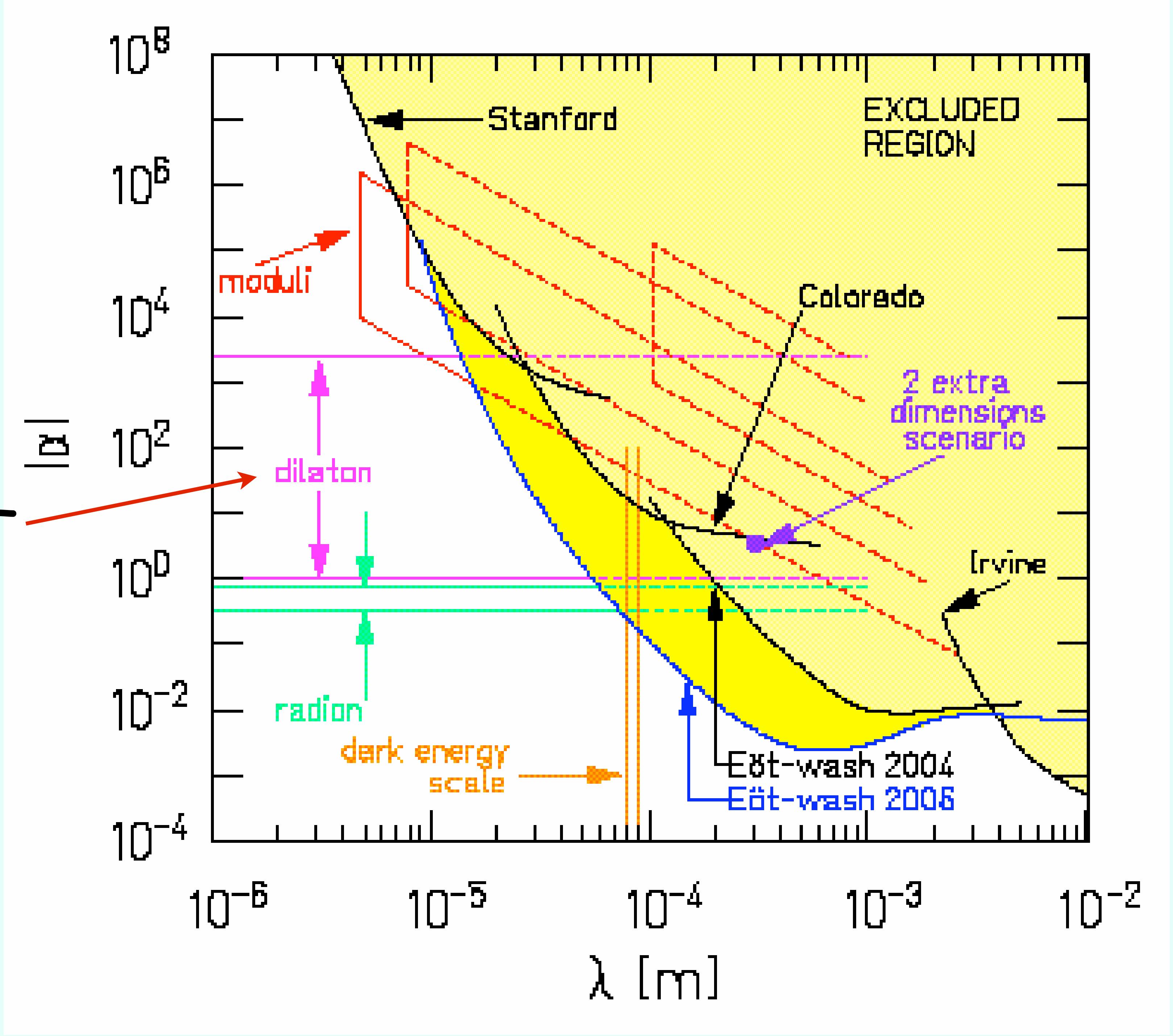
- QFT's parameters are replaced by (typically scalar) fields whose values provide the «Constants of Nature», e.g. the overall strength g_s of string interactions including α
- Are they dynamically determined? Computing α has been a long-time theorist's dream...
- While today these «constants» look to be space-time-independent, their variations may have played a role in early cosmology. The pre-big bang scenario uses it.
- If particles associated with above fields are too light, they induce long-range forces that threaten the EP (UFF).

? Very active field of experimental and theoretical research

- No need for Planck-scale experiments for testing string theory. True also for the old hadronic string!
- Tree-level QST is already ruled out! But so is the SM!

„Fifth Force" strengths now excluded at small distances

from ST



String Gravity and GR singularities

- One of the most difficult -but also most fascinating- questions in ST is the fate of GR's singularities (Big Bang, black hole interiors).
- At lowest order in derivatives and in the coupling the equations that insure a consistent string quantizations look like Classical Field Theory PDEs including (somewhat modified) Einstein equations.
- The singularity theorems of Hawking and Penrose apply. Hence the solution is typically driven towards regimes (high curvature, strong coupling, or both) in which the approximations break down.
- Q: Which are the correct equations in those non-perturbative regimes? What happens where there used to be a singularity? Can we go through the (would be) singularity and keep predictivity?
- We badly need techniques to study ST non perturbatively!

Thank You!

Abstract

After recalling how non-relativistic quantum mechanics (QM) removes the singularities of its classical counterpart, I will turn to relativistic quantum mechanics and to its conventional formulation known as Quantum Field Theory (QFT).

Because of a combination of quantum and relativistic effects, QFTs typically lead to new singularities associated with ultraviolet (UV) divergences. Although theorists have become accustomed to (and have found a way to live with) them, such divergences may signal a new crisis in our description of microscopic phenomena.

Furthermore, in the case of gravity there is no known way to deal with UV divergences without giving up predictivity. This is particularly unfortunate since Classical General Relativity (CGR) is plagued by its own singularities (e.g. the cosmological singularity and the one in a black-hole interior) and one would have hoped that QM helps to solve them. There are also conceptual problems with quantization in curved space times which could very well be at the origin of Hawking’s information puzzle.

Since several decades, quantum string theory (QST) has been proposed as a possible (though only theoretical so far) solution to the above-mentioned problems. In the second part of my talk I will try to explain how QST combines special relativity and quantum mechanics in a way that represents a truly Copernican revolution.

Rather than attempting to quantize classical field theories (such as Maxwell's or Einstein's), QST starts from the quantum spectrum of strings moving in particularly simple (e.g. flat) space times. Such a spectrum includes a set of massless spinning states which implies, at sufficiently large distances, a QFT description of gravitational and non-gravitational phenomena together with short-distance modifications that cure the UV diseases of conventional QFTs.

Finally, classical field theories, rather than representing the starting point of a problematic quantization procedure, are recovered in the appropriate limit of a fully quantum framework. The geometry of space-time of CGR is arguably the most amazing structure emerging from this revolutionary paradigm.