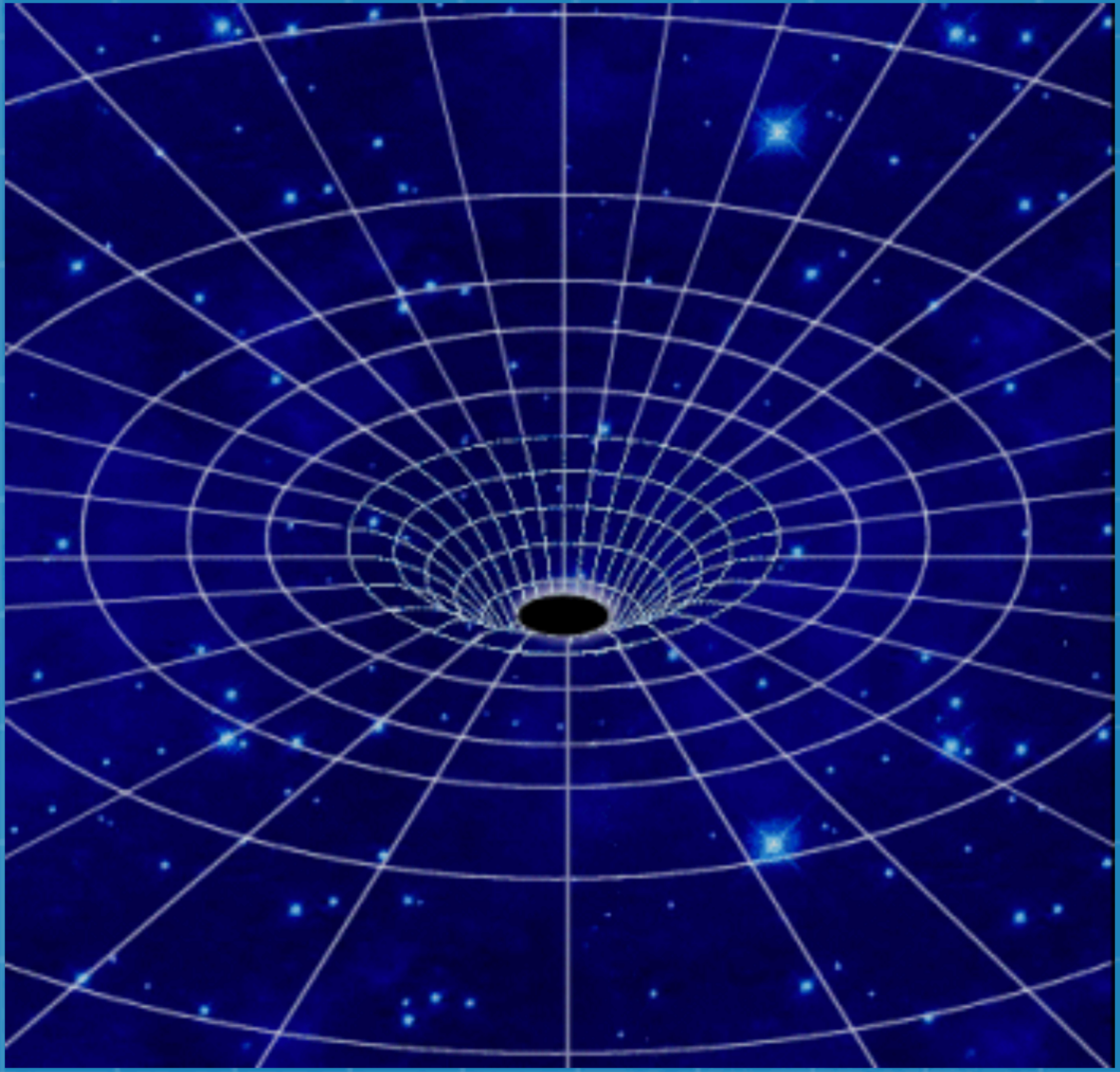
N. Emil J. Bjerrum-Bohr

Gravity from Amplitudes

Gravity as a particle theory?

- Einstein’s theory presents us with a beautiful theory for gravity.
- However geometrical description that does not fit well with a generic (flat space) formulation of quantum mechanics.
- Quantum mechanical extension of General Relativity?



- Known since the 1960ties that a particle version of General Relativity can be derived from the Einstein Hilbert Lagrangian (Feynman, DeWitt)

- Expand Einstein-Hilbert Lagrangian :

$$\mathcal{L}_{\mathrm{E}H} = \int d^4x \left[\sqrt{-g}R\right]$$

$$g_{\mu\nu} \equiv \eta_{\mu\nu} + \kappa h_{\mu\nu}$$

- Derive vertices as in a particle theory - compute amplitudes as Feynman diagrams!

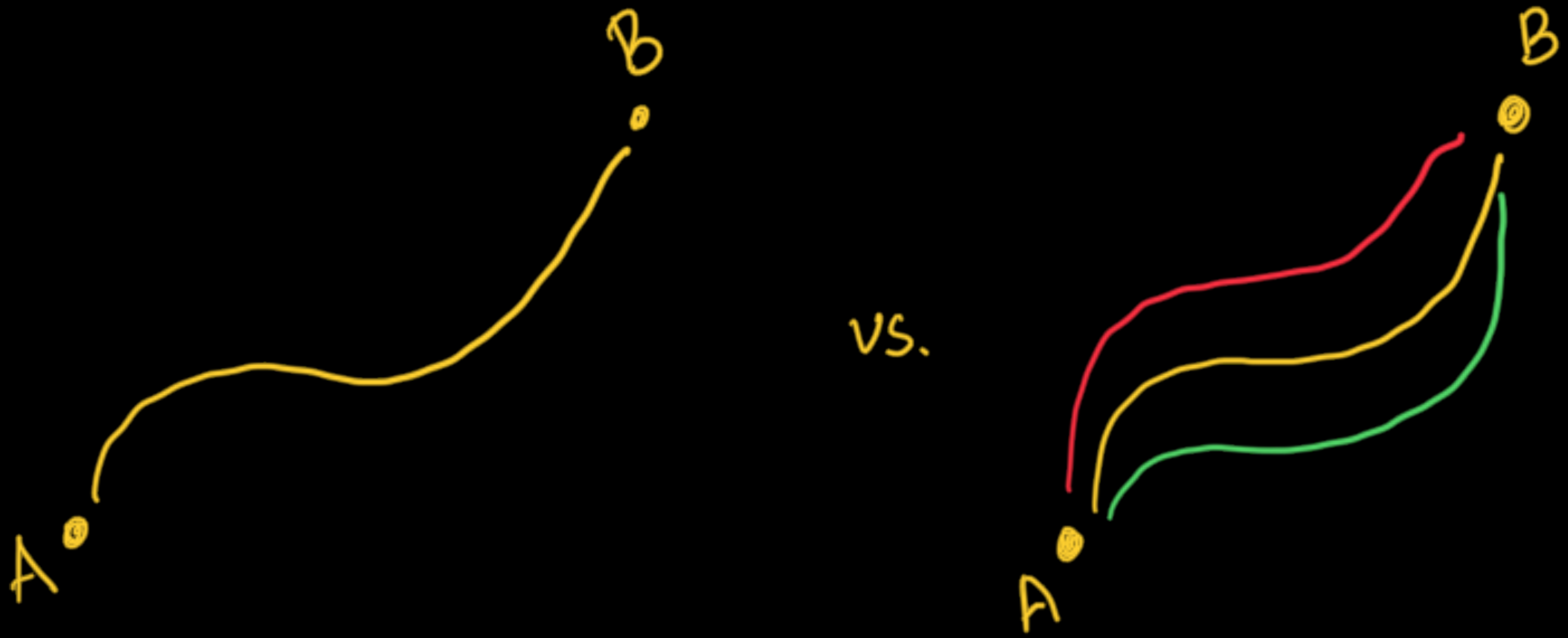
- (Weinberg) proposed to view the quantization of general relativity from the viewpoint of effective field theory

$$\mathcal{L} = \sqrt{-g}\left[\frac{2R}{\kappa^2} + \mathcal{L}_{\text{matter}}\right]$$

↓

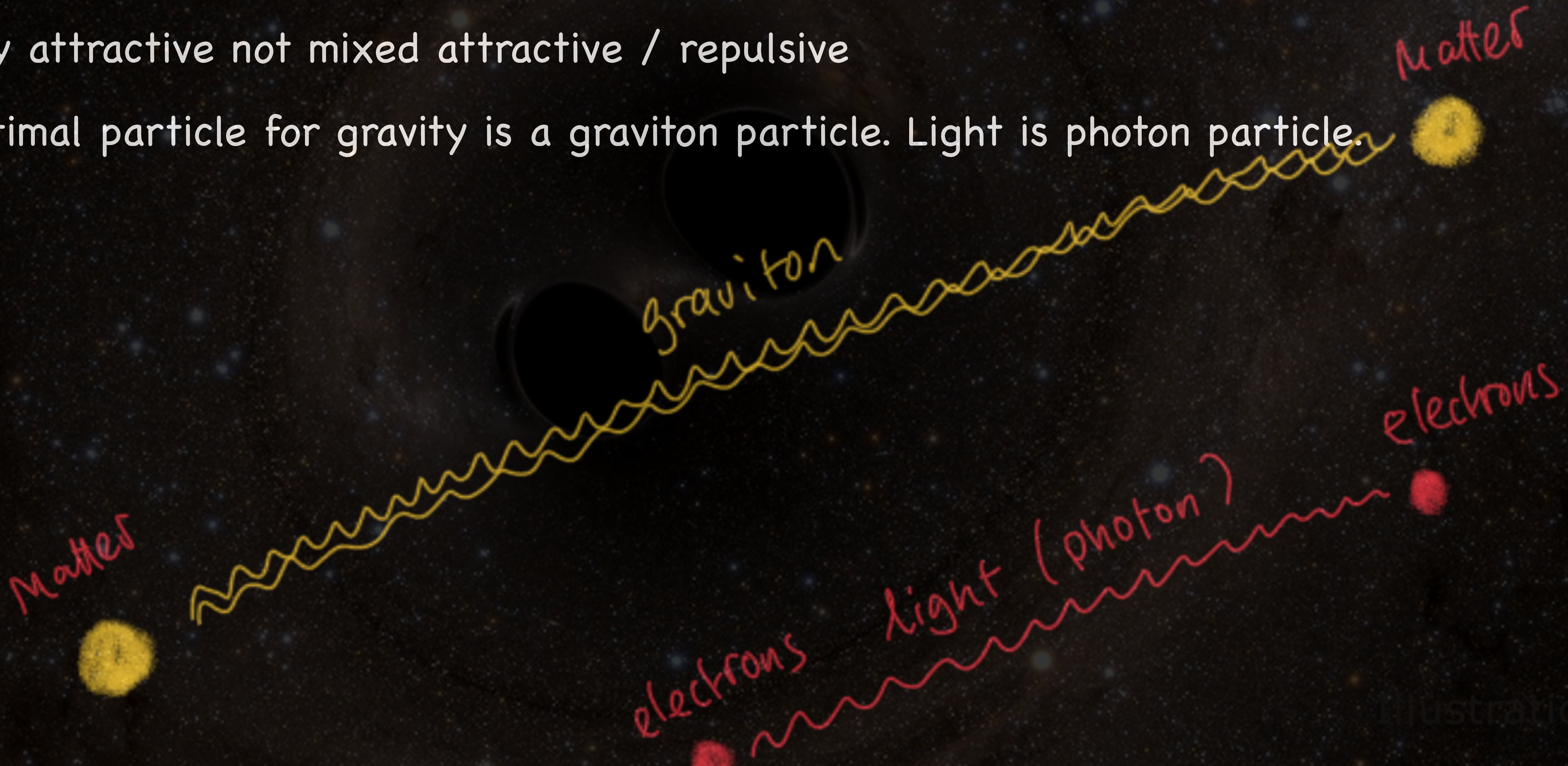
$$\mathcal{L} = \sqrt{-g}\left\{\frac{2R}{\kappa^2} + c_1 R^2 + c_2 R^{\mu\nu} R_{\mu\nu} + \dots\right\}$$

Path integral for gravity



Gravitons – Feynman diagrams

- The graviton is emitted from all matter not like light from charges.
- Gravity attractive not mixed attractive / repulsive
- The optimal particle for gravity is a graviton particle. Light is photon particle.

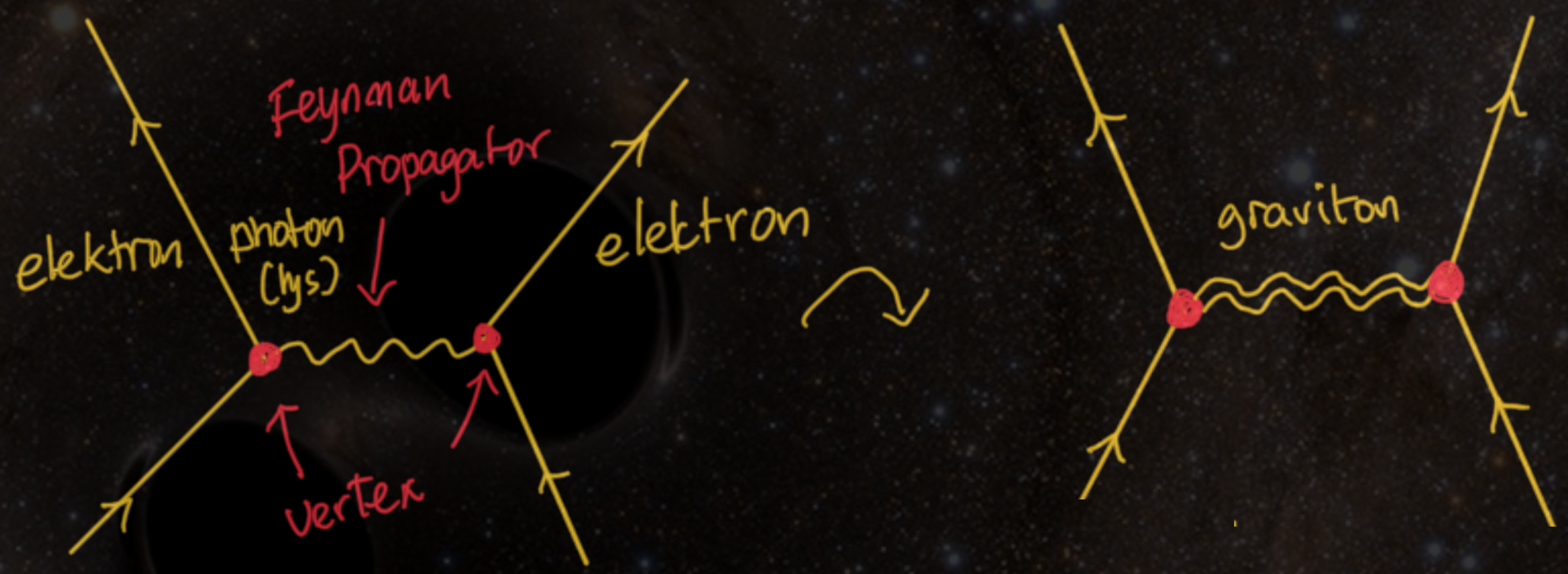


Feynman's integrals

Amplitudes can calculate quantum mechanics via Feynman graphs also when the physics is relativistic

The square of an amplitude gives probability

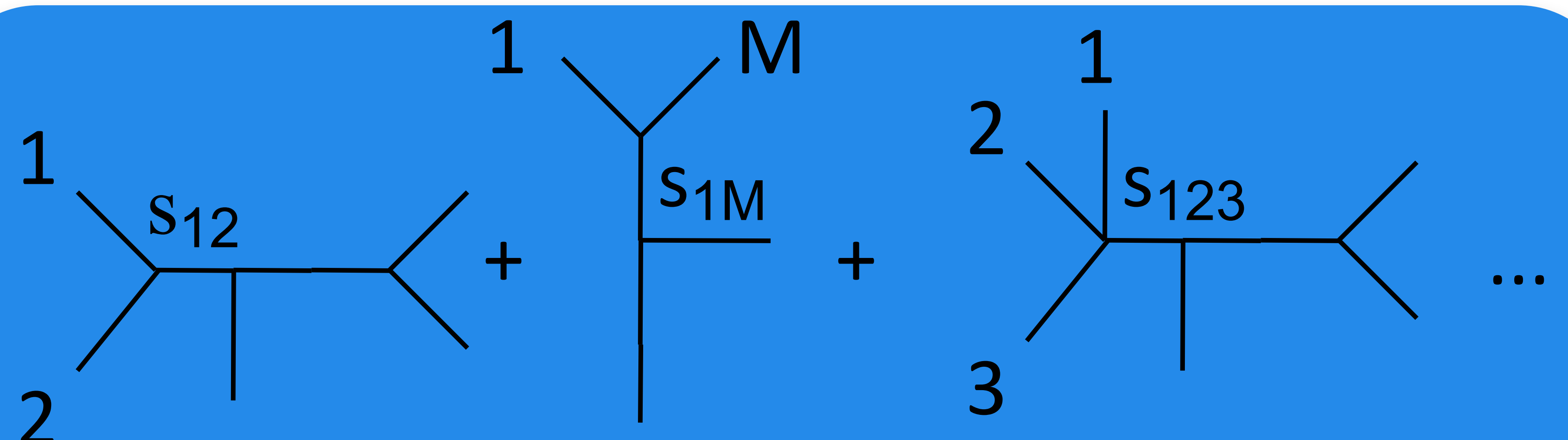
Probability of particle can be used for prediction eg Higgs particle... and .. gravity.



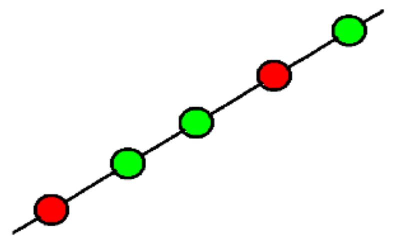
Tools for efficient computation

(If you are interested in learning more — check out my modern methods for particle scattering course) (block 3)

MHV amplitude (geometric) revolution!



Factorial growth ~ billions of terms!!



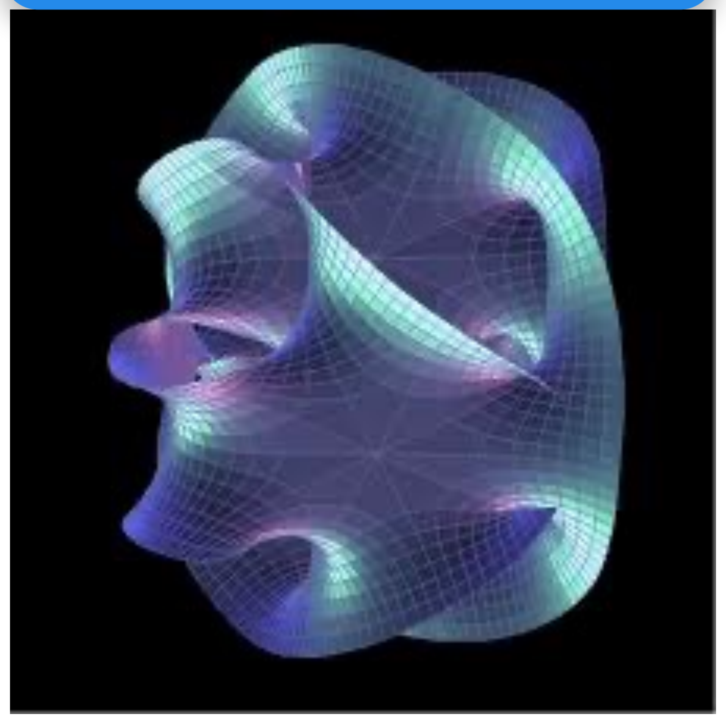
Rich hidden structure

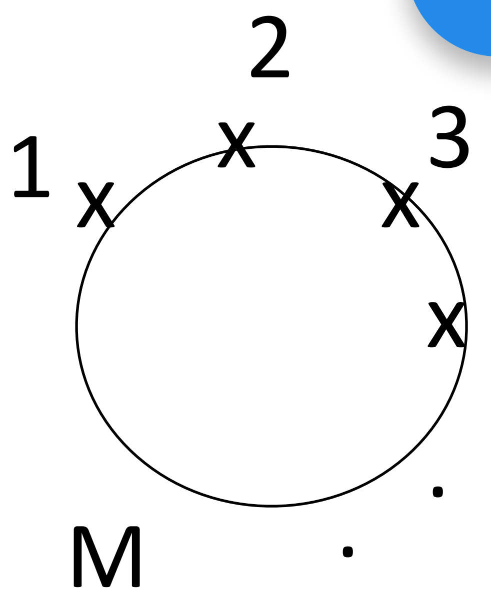
On-shell recursion
MHV only one term!

$$\sim \frac{\langle jk \rangle^4}{\langle 12\rangle\langle 23\rangle\cdots\langle M1\rangle}$$

Inspiration across fields

String Theory





New relations

It was suggested recently by Cachazo, He and Yuan that one can compute amplitudes via

$$\mathcal{A}_n = \int \frac{d^n\sigma}{\mathrm{volSL}(2,\mathrm{c})} \prod_a{}' \delta\left(\sum_{a\neq b} \frac{k_a \cdot k_b}{z_a - z_b}\right)$$

$$\left(\frac{\mathrm{Tr}(T^{a_1} T^{a_2} T^{a_3} \dots T^{a_n})}{(z_1 - z_2)(z_2 - z_3)\cdots(z_n - z_1)} + \cdots\right)^{2-s} (\mathrm{Pf}'\Psi)^s$$

Exciting new framework for amplitudes

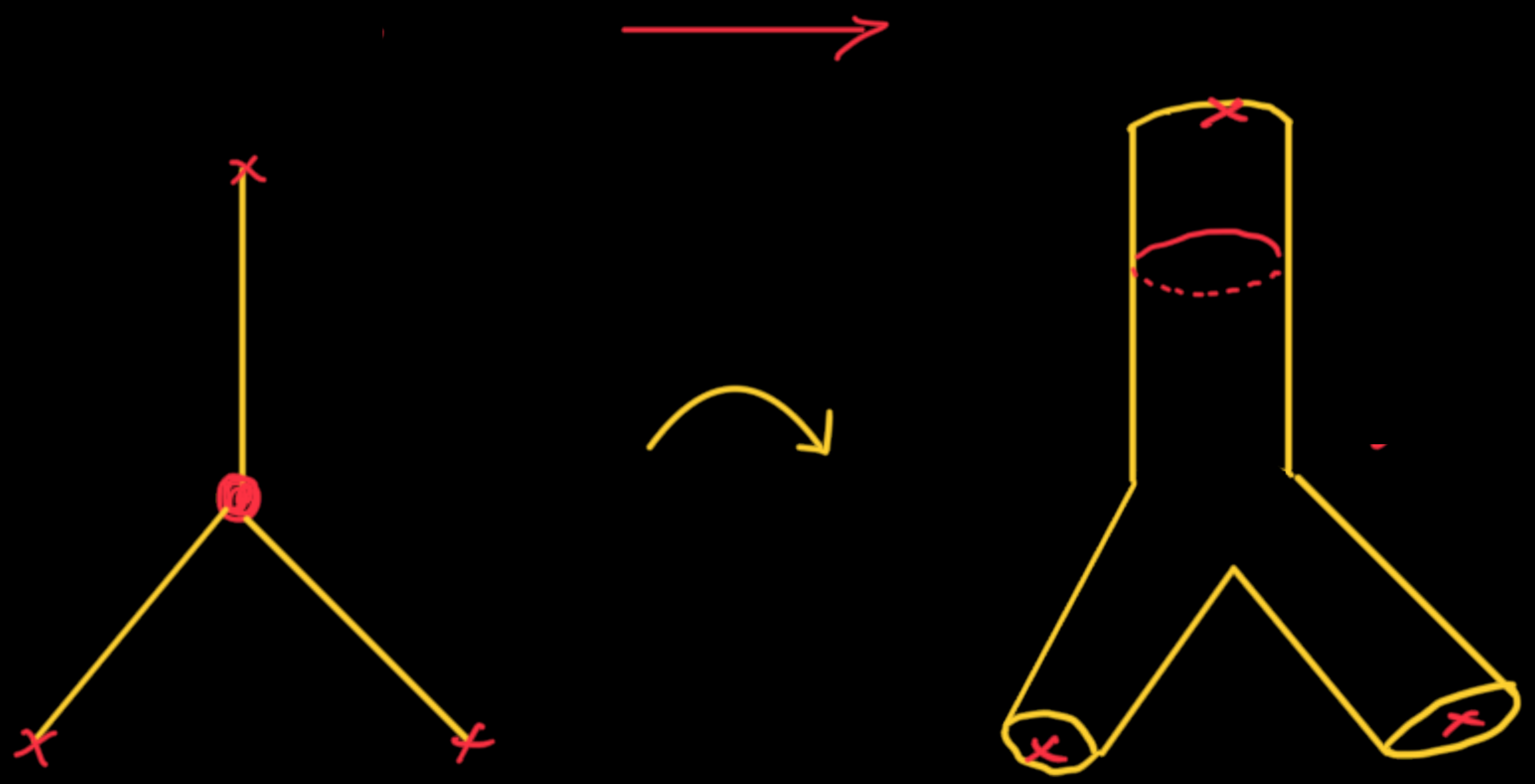
Color trace

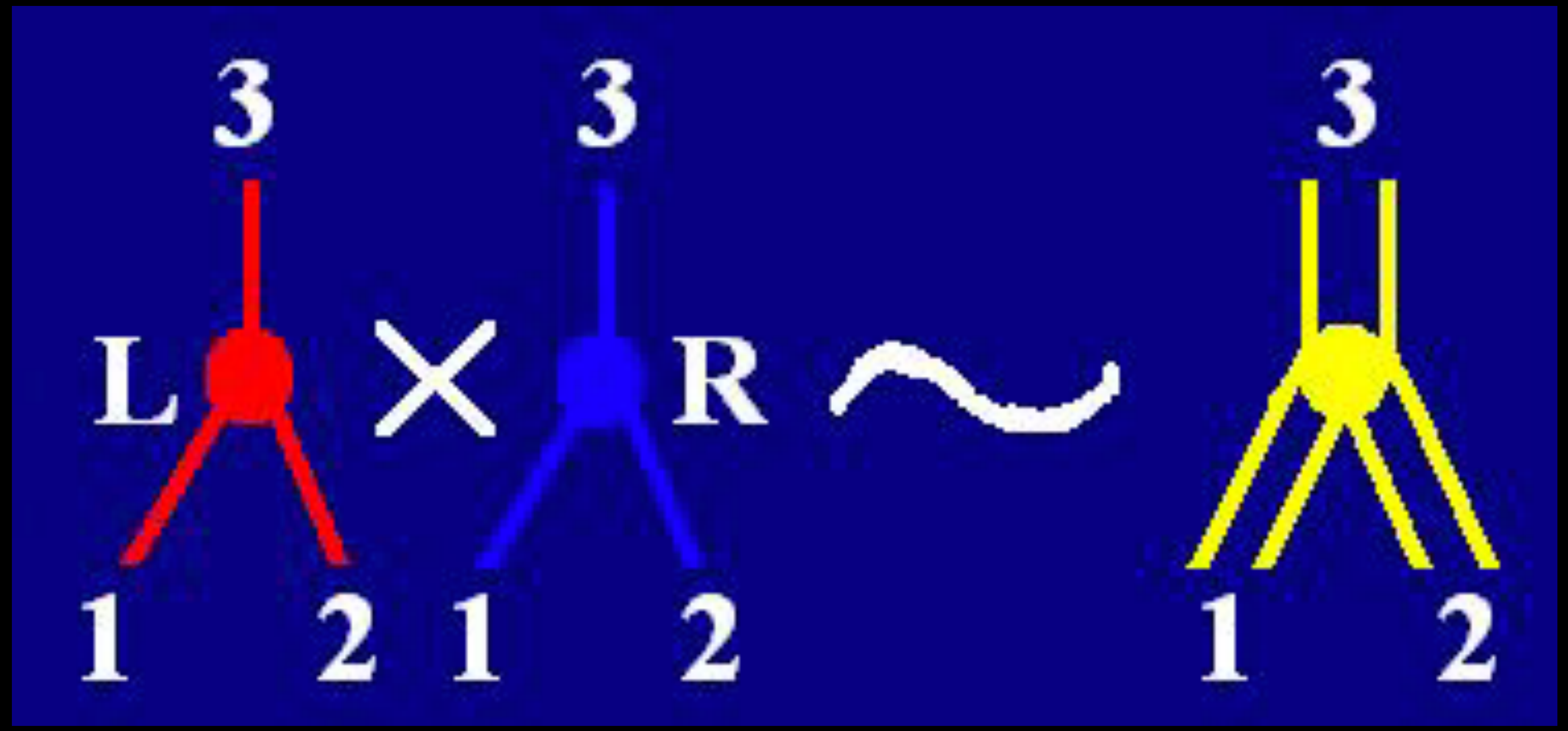
Algebraic solutions

Pfaffian (dependent on polarisations and momenta)

Applications of String theory

- Gives naturally a quantum gravity
- Important principle: gravity is like the product of something simpler (double-copy in particle physics)





Classical contributions from the Path integral:

- Novel ways to compute observables in General Relativity
- Bending of light – a new take on Quantum Gravity and potential quantum corrections in General Relativity?
- Applications for the physics behind LIGO and observations of gravitational waves

Quantum gravity from effective field theory

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Bending of Light in Quantum Gravity

N. E. J. Bjerrum-Bohr,[1,*] John F. Donoghue,[2,†] Barry R. Holstein,[2,‡] Ludovic Planté,[3,§] and Pierre Vanhove[3,4,¶]
[1]*Niels Bohr International Academy and Discovery Center, The Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark*
[2]*Department of Physics-LGRT, University of Massachusetts, Amherst, Massachusetts 01003, USA*
[3]*CEA, DSM, Institut de Physique Théorique, IPhT, CNRS, MPPU, URA2306, Saclay, F-91191 Gif-sur-Yvette, France*
[4]*Institut des Hautes Études Scientifiques, Bures-sur-Yvette, F-91440, France*

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We consider the scattering of lightlike matter in the presence of a heavy scalar object (such as the Sun or a Schwarzschild black hole). By treating general relativity as an effective field theory we directly compute the nonanalytic components of the one-loop gravitational amplitude for the scattering of massless scalars or photons from an external massive scalar field. These results allow a semiclassical computation of the bending angle for light rays grazing the Sun, including long-range $\hbar$ contributions. We discuss implications of this computation, in particular, the violation of some classical formulations of the equivalence principle.

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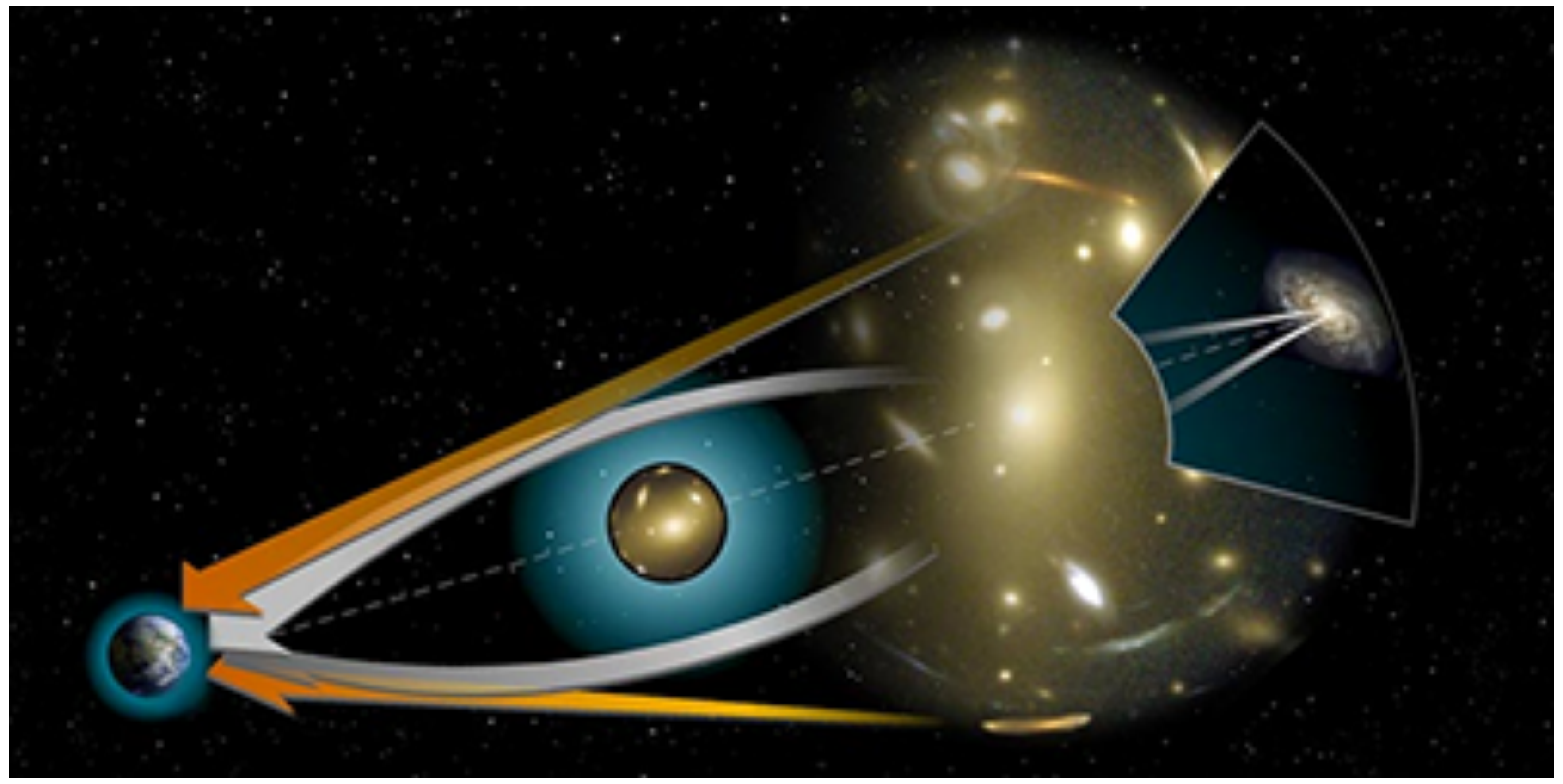
Using only a few computational tricks!

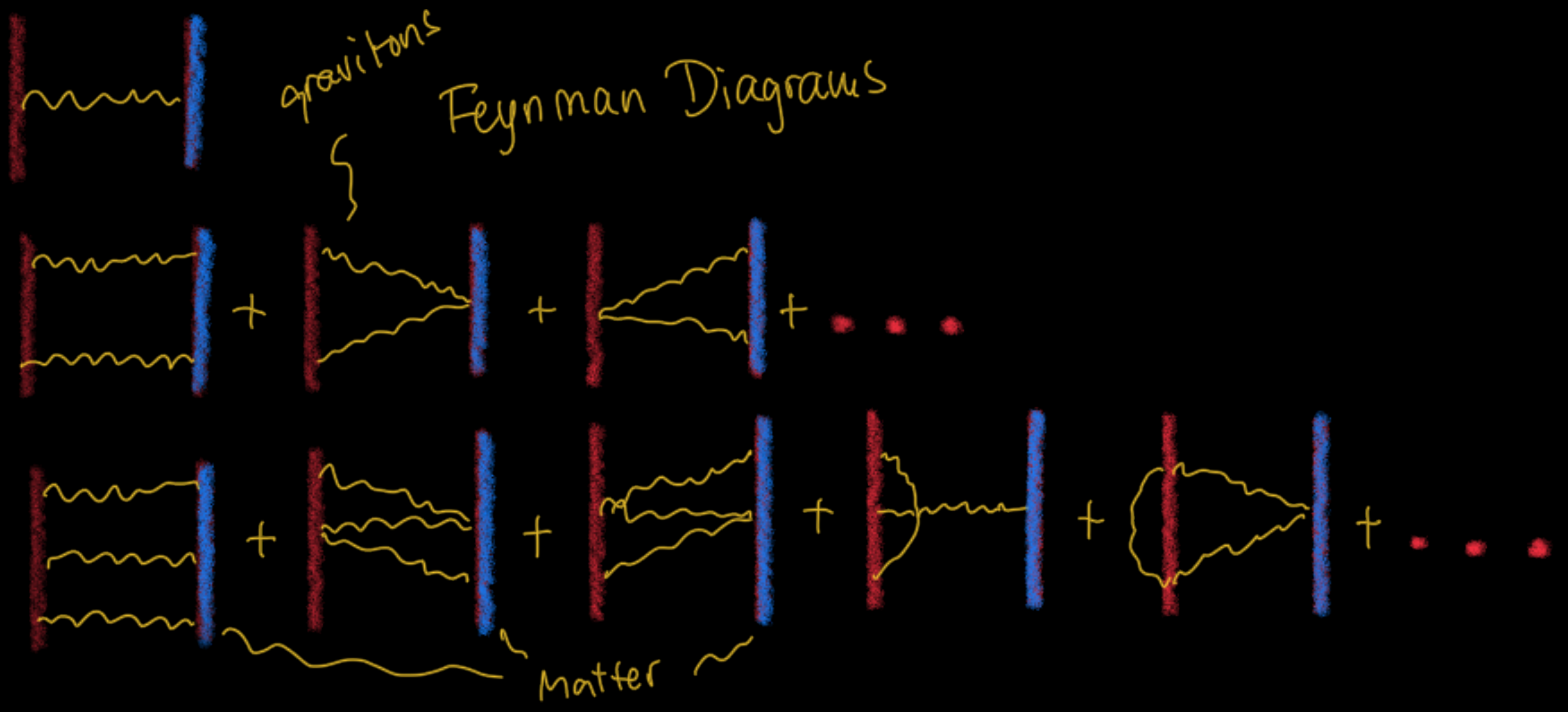
Reproduces Einstein's result plus quantum effects in particle theory!



- Consistent quantization
  - Working low energy version of quantum gravity

- New point of view:
  - General relativity hbar-> 0 limit of multi-loop expansion
  - Classical pieces comes from loop diagrams!
  - Explanation: contributions appear in loop diagrams feature a cancellation of the loop diagram hbar factor
    - (mass/hbar) expansion.

Quantum mechanical description of black scattering?



- Classical potential from quantum mechanical propagation via quantum / classical correspondence principle.

Large quantum numbers (angular impulse enormous) -> Classical physics (gravity) (essence of Bohr's correspondence principle)

Precision physics and the experiment LIGO

Conclusions

- Gravity remains a mystery and we are working on a better understanding of the phenomena we know about ..
- Gravity wave measurements are a new exciting experimental field.
- A new window to the Universe. Perhaps a new opportunity to understand quantum physics for a new field / astrophysical observatory.

Conclusions

- An important task is accurate theoretical prediction to understand any deviations in observations.
- Interesting observation that we can use Niels Bohr's quantum mechanical correspondence principle to calculate classical physics. We hope to use exciting ideas for extensions of particle physics at high energies.
- We can use some of these ideas as theoretical inspiration to better understand gravity....