Research in theoretical high-energy physics at NBIA

Matthias Wilhelm

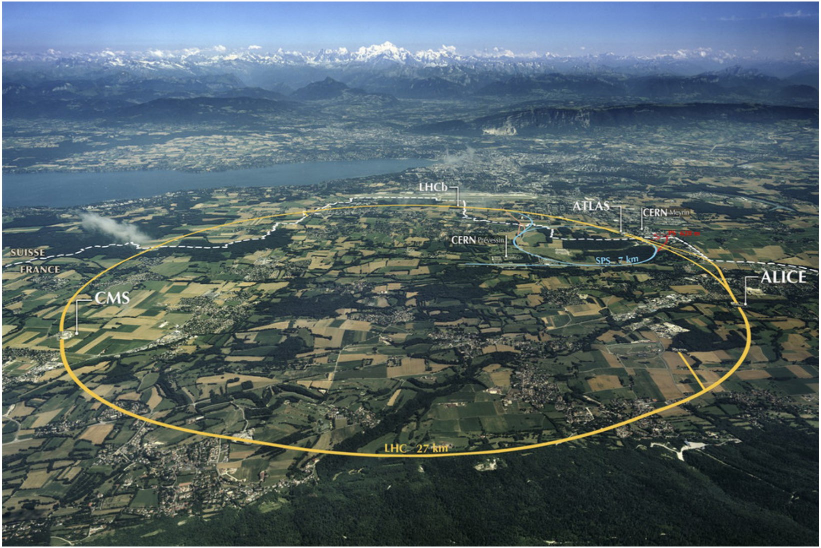
NBIA MSc Day 2022

October 12th, 2022

The Niels Bohr International Academy

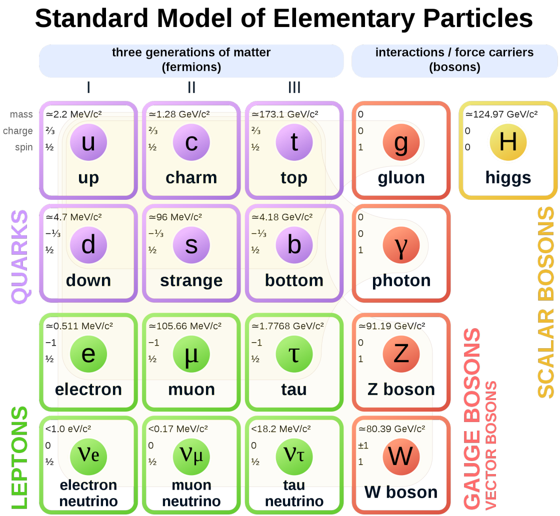
VILLUM FONDEN

Large Hadron Collider

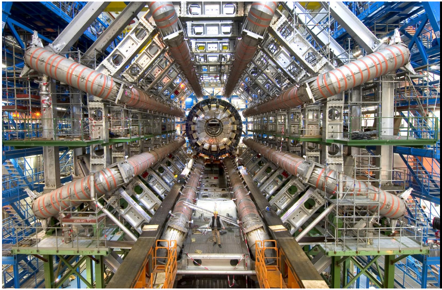


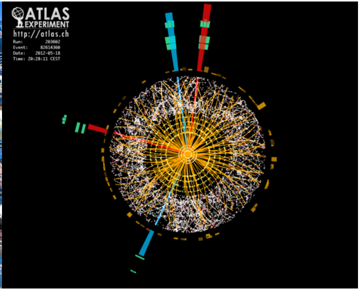
The world's largest machine = most powerful microscope

Standard model of particle physics



How do we see these particles?



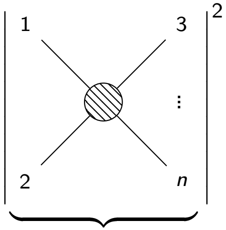


Short lived $\Rightarrow$ Only see decay products in detectors!

Theoretical description

Cross section = probability of two incoming particles to scatter into $n-2$ outgoing particles:

$\sigma =$



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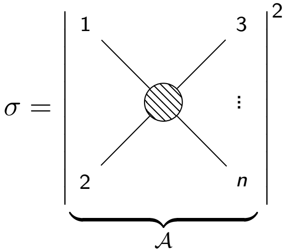


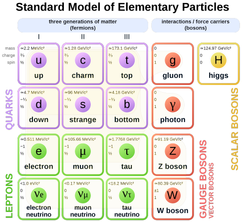
Amplitude $\mathcal{A}$ can be calculated using Quantum Field Theory

What is Quantum Field Theory?

Quantum Field Theory

= Quantum mechanics + special relativity

- describes all known interactions among all known particles except gravity via so-called gauge theories



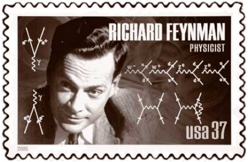
⊃ Quantum Electrodynamics (QED) and Quantum Chromodynamics (QCD)

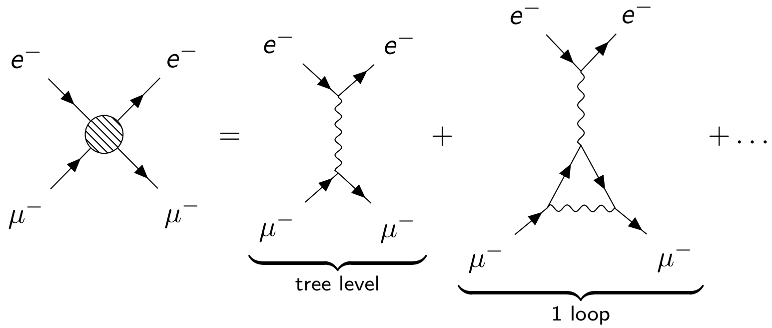
- describes classical gravity (general relativity) → Emil

→ Course “Quantum Field Theory I”

Amplitudes from Quantum Field Theory

Feynman diagrams
= sums over possible particle histories





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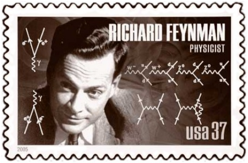

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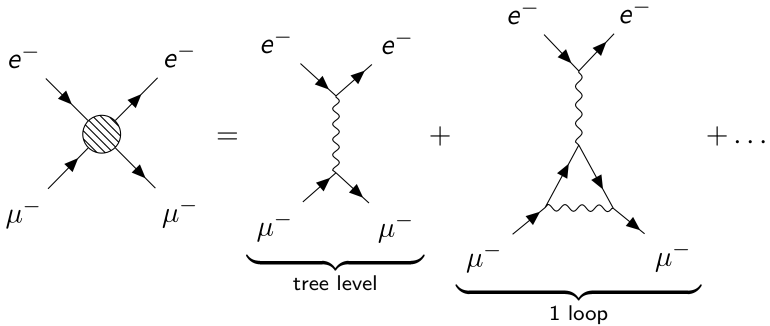
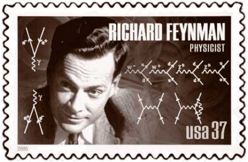


tree level leading order in perturbation theory

Amplitudes from Quantum Field Theory



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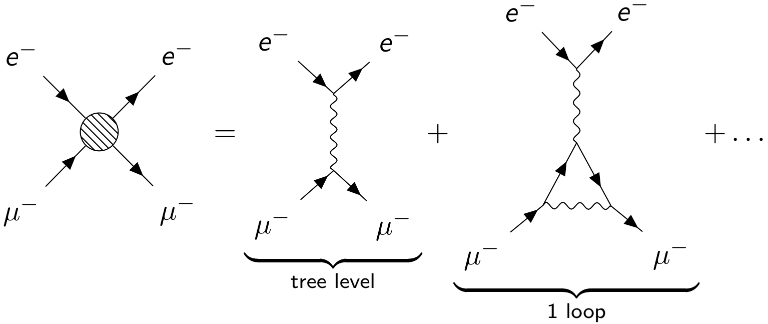

tree level — leading order in perturbation theory

1 loop — next-to-leading order in perturbation theory

Amplitudes from Quantum Field Theory

Feynman diagrams
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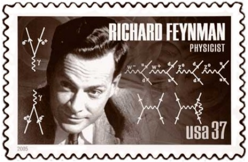

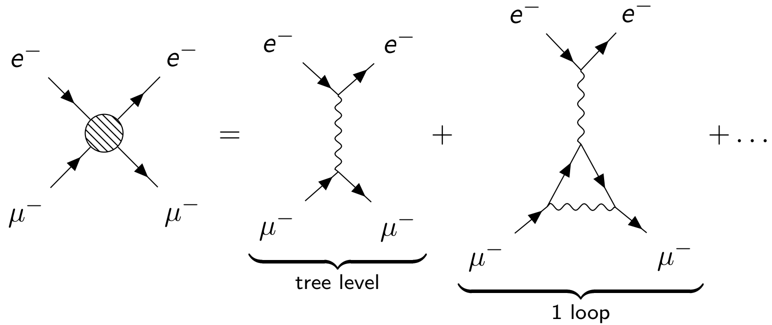

tree level	leading order in perturbation theory
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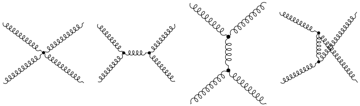
...	

Hidden simplicity I: Parke-Taylor amplitude



2 gluons $\rightarrow$ 2 gluons: 4 diagrams
2 gluons $\rightarrow$ 3 gluons: 25 diagrams
2 gluons $\rightarrow$ 4 gluons: 220 diagrams
...
2 gluons $\rightarrow$ 8 gluons: $>$ 1 million diagrams

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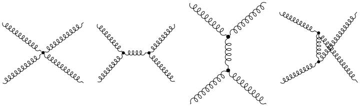

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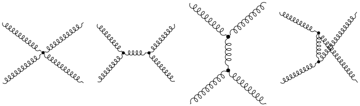

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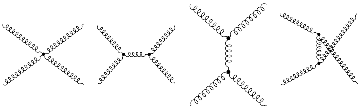
n-gluon helicity amplitude [Parke-Taylor (1986)] [Mangano, Parke, Xu (1987)]

$$\mathcal{A}_6(1^-,2^-,3^+,\dots,6^+) = \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\dots\langle 61\rangle}$$

$\pm$: polarization of the gluon with four-momentum p_i
$\langle ij\rangle = \sqrt{|s_{ij}|}e^{i\phi_{ij}}$ with $s_{ij} = (p_i + p_j)^2$



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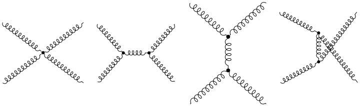

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Next step: Exploit this simplicity!
⇒ Recursion relations → all tree-level amplitudes

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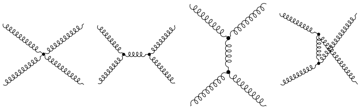

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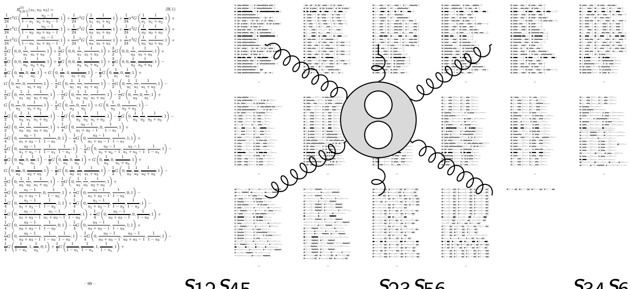
Next step: Exploit this simplicity!
⇒ Recursion relations → all tree-level amplitudes
→ Course "Modern methods in particle scattering"

Hidden simplicity II: Polylogarithms

Two-loop six-gluon reminder function (= non-trivial part of amplitude) in the maximally (super)symmetric gauge theory
[Del Duca, Duhr, Smirnov (2010)]



$$u_1 = \frac{s_{12}s_{45}}{s_{123}s_{345}} \quad u_2 = \frac{s_{23}s_{56}}{s_{234}s_{123}} \quad u_3 = \frac{s_{34}s_{61}}{s_{345}s_{234}}$$

Hidden simplicity II: Polylogarithms

$$18 \text{ pages} = \sum_{i=1}^{3}\left(L_4(x_i^+,x_i^-) - \frac{1}{2}\,\mathrm{Li}_4(1-1/u_i)\right) - \frac{1}{8}\left(\sum_{i=1}^{3}\mathrm{Li}_2(1-1/u_i)\right)^2 + \frac{1}{24}J^4 + \frac{\pi^2}{12}J^2 + \frac{\pi^4}{72}$$

[Gancharov, Spradlin, Vergu, Volovich (2010)]

$$x_i^\pm = u_i x^\pm, \qquad x^\pm = \frac{u_1+u_2+u_3-1\pm\sqrt{\Delta}}{2u_1u_2u_3}, \qquad \Delta = (u_1+u_2+u_3-1)^2 - 4u_1u_2u_3$$

$$L_4(x^+,x^-) = \frac{1}{8!!}\log(x^+x^-)^4 + \sum_{m=0}^{3}\frac{(-1)^m}{(2m)!!}\log(x^+x^-)^m(\ell_{4-m}(x^+)+\ell_{4-m}(x^-))$$

$$\ell_n(x) = \frac{1}{2}\left(\mathrm{Li}_n(x) - (-1)^n\,\mathrm{Li}_n(1/x)\right), \qquad J = \sum_{i=1}^{3}(\ell_1(x_i^+) - \ell_1(x_i^-))$$

Classical polylogarithms $\mathrm{Li}_n(x) = \int_0^x \frac{dt}{t}\,\mathrm{Li}_{n-1}$, $\qquad \mathrm{Li}_1(x) = -\log(1-x)$

Hidden simplicity II: Polylogarithms

Exploiting the simplicity:

Bootstrapping

$=$ ansatz for result from polylogarithms

$+$ fix coefficients via physical constraints

$\Rightarrow$ Avoid Feynman diagrams and Feynman integrals altogether!

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Exploiting the simplicity:

Bootstrapping

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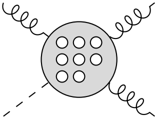
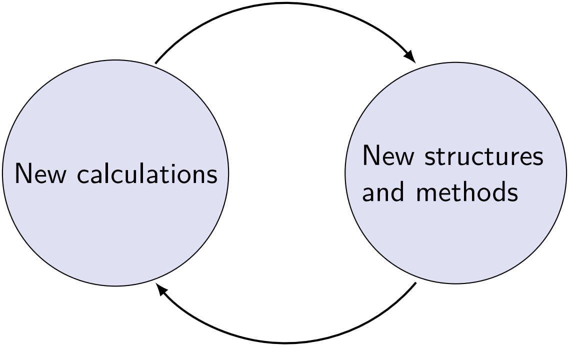
⇒ Avoid Feynman diagrams and Feynman integrals altogether!

Higgs → 3 gluons (in some approximation) up to 8-loop order!



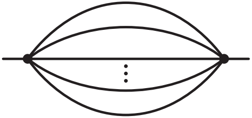
[Dixon, McLeod, MW (2020)], [Dixon, Gurdogan, McLeod, MW (2021)]

Virtuous circle



⇒ Precision predictions for the LHC to test our understanding of particle physics and to find new physics beyond the standard model of particle physics!

New functions for collider physics and gravitational waves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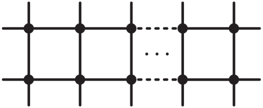
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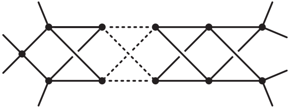
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Hidden structures and simplicity? How to exploit?

..., Morales, von Hippel, Vergu, Spiering, MW, Zhang,...

Interested?

Study track: High-Energy Theory and Cosmology

	Block 1	Block 2	Block 3	Block 4
Year 1	Advanced Quantum Mechanics	General Relativity and Cosmology	Quantum Field Theory 1	Fundaments of High-Energy Astrophysics and Particle Astrophysics
	Elementary Particle Physics	Particle Physics and the Early Universe	Modern Methods for Particle Scattering	*Choose one of:* Introduction to String Theory* Introduction to Gauge/Gravity Duality** Advanced Topics in QFT & Gravity***

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Potential supervisors → Talk to us!

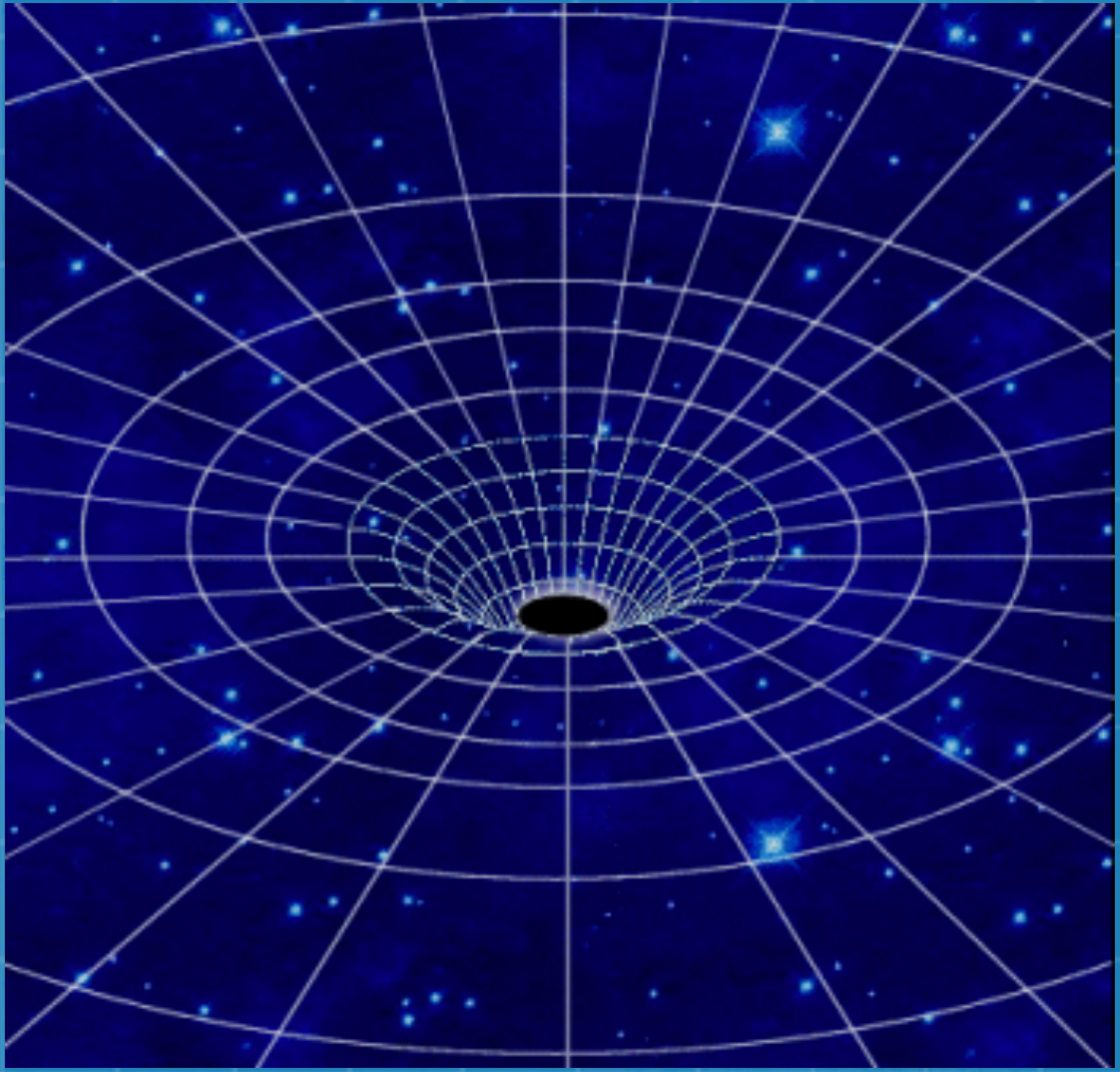

Anne Spiering


Matthias Wilhelm


N. Emil J. Bjerrum-Bohr
Gravity from Amplitudes
Illustration

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 :

$$\mathcal{L}_{\mathrm{E}H} = \int d^4x \left[\sqrt{-g}R\right] \qquad g_{\mu\nu} \equiv \eta_{\mu\nu} + \kappa h_{\mu\nu}$$

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

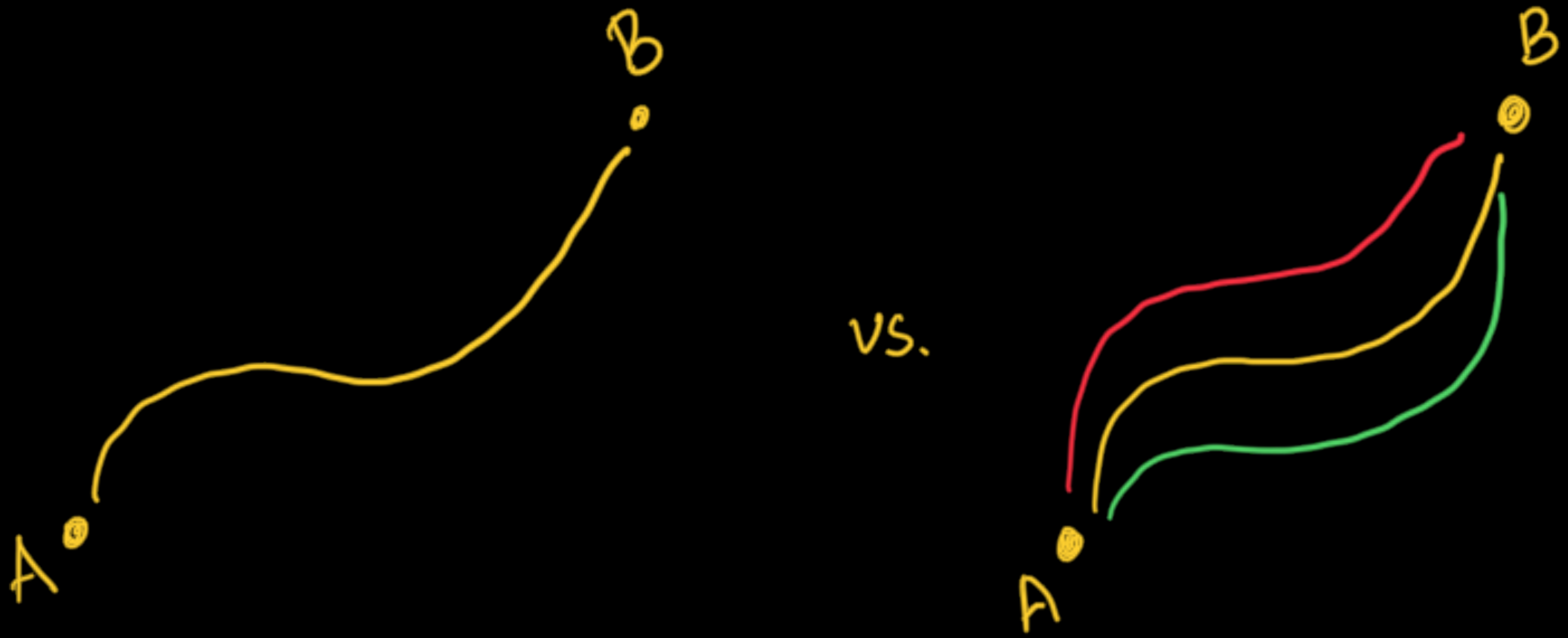
- (Weinberg) proposed to view the quantization of general relativity from the viewpoint of effective field theory

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

↓

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

Path integral for gravity

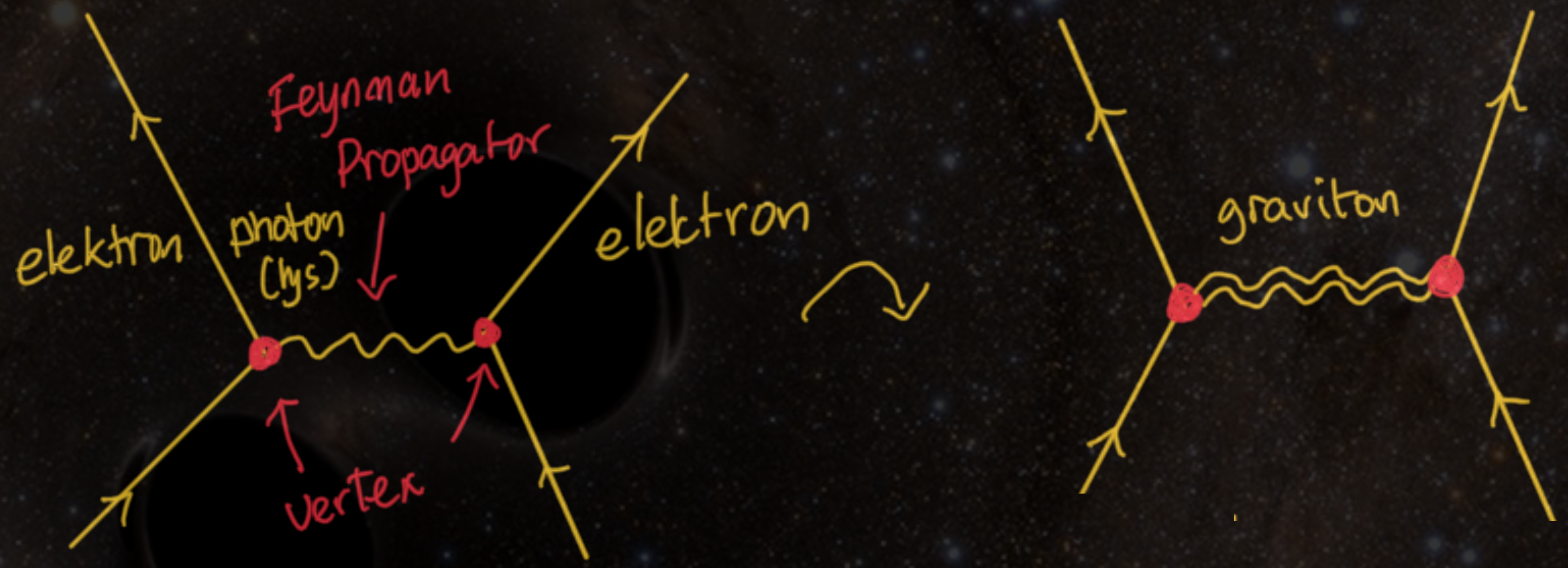


Feynman's integrals

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

The square of an amplitude gives probability

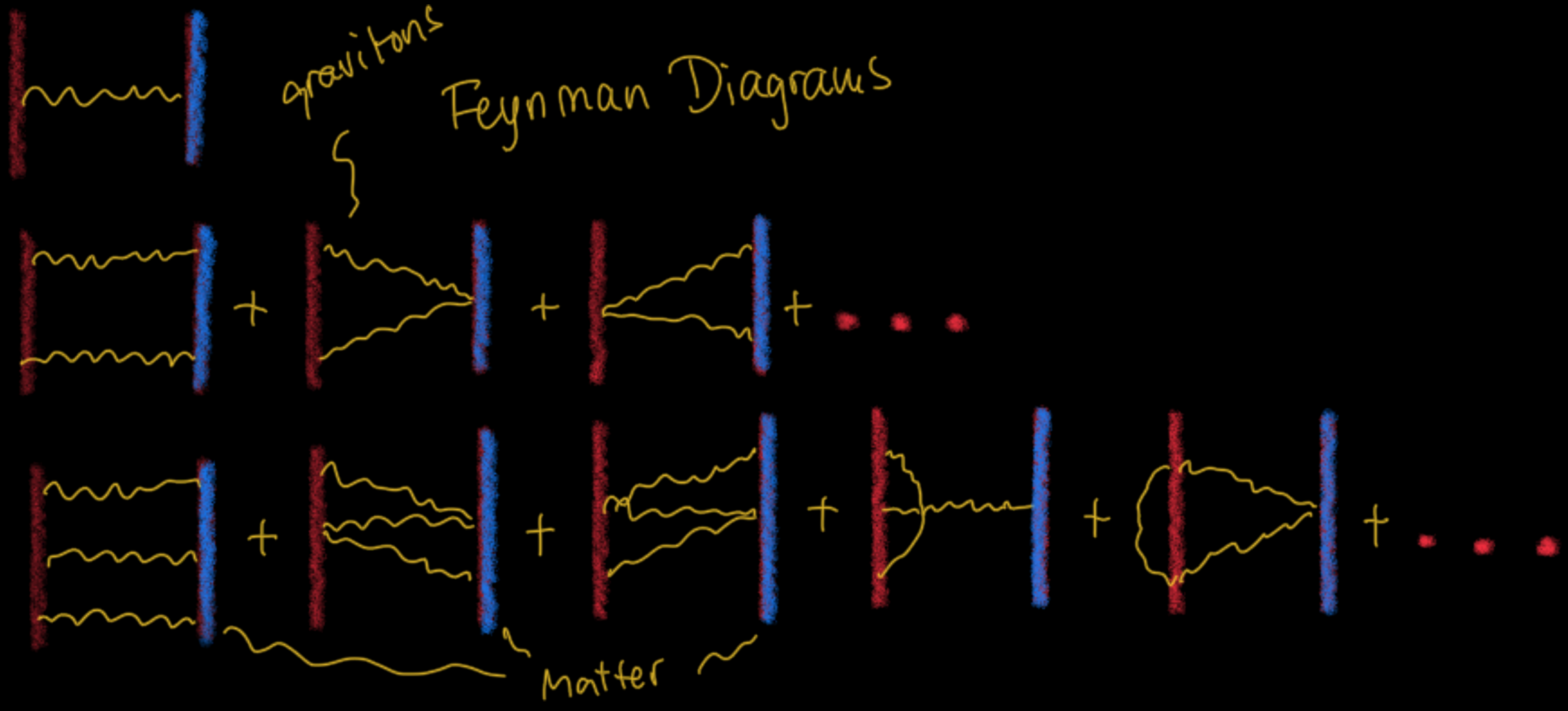
Probability of particle can be used for prediction eg Higgs particle... and .. gravity.



- 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)

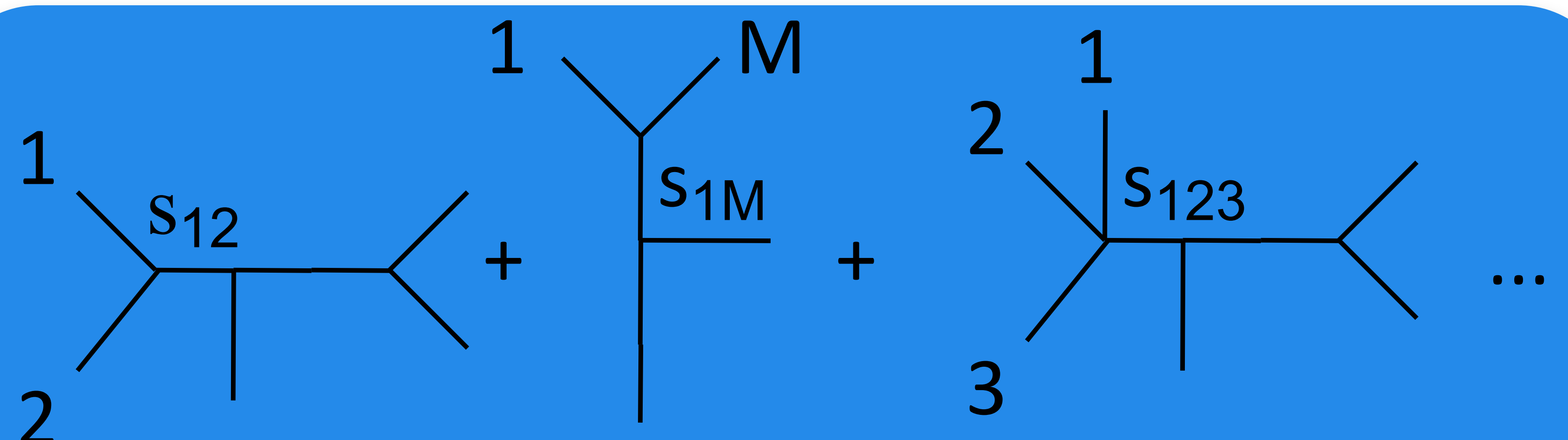
Classical contributions from the Path integral:

- 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

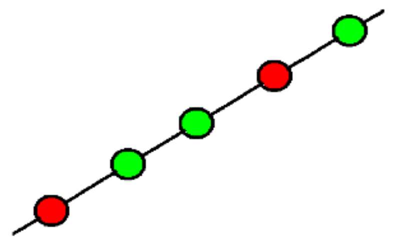
Tools for efficient computation

(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!!



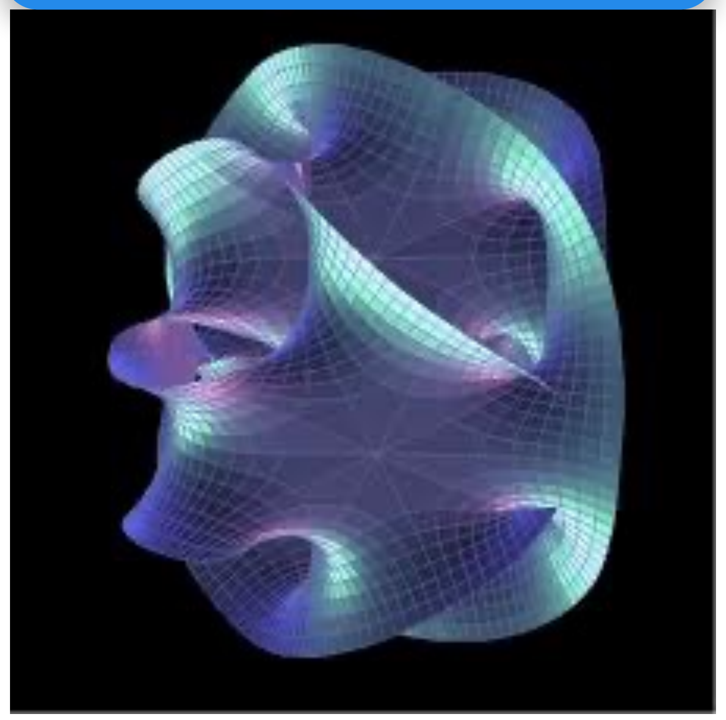
Rich hidden structure

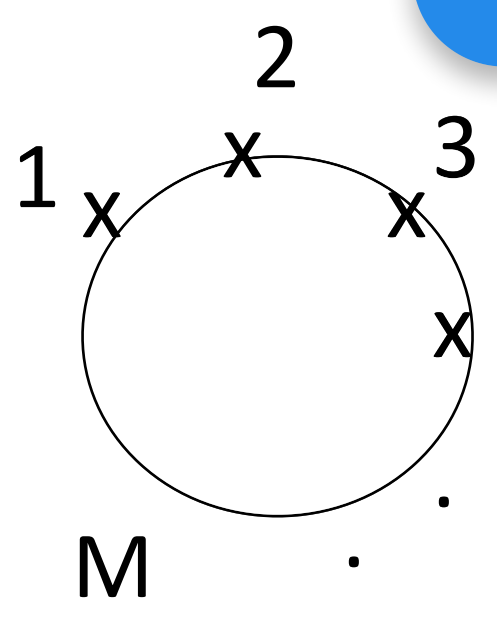
On-shell recursion
MHV only one term!

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

Inspiration across fields

String Theory





New relations

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

$$\mathcal{A}_n = \int \frac{d^n\sigma}{\mathrm{volSL}(2,\mathrm{c})} \prod_a{}' \delta\left(\sum_{a\neq b} \frac{k_a \cdot k_b}{z_a - z_b}\right) \left(\frac{\mathrm{Tr}(T^{a_1}T^{a_2}T^{a_3}\ldots T^{a_n})}{(z_1-z_2)(z_2-z_3)\cdots(z_n-z_1)} + \cdots\right)^{2-s} (\mathrm{Pf}'\Psi)^s$$

Exciting new framework for amplitudes

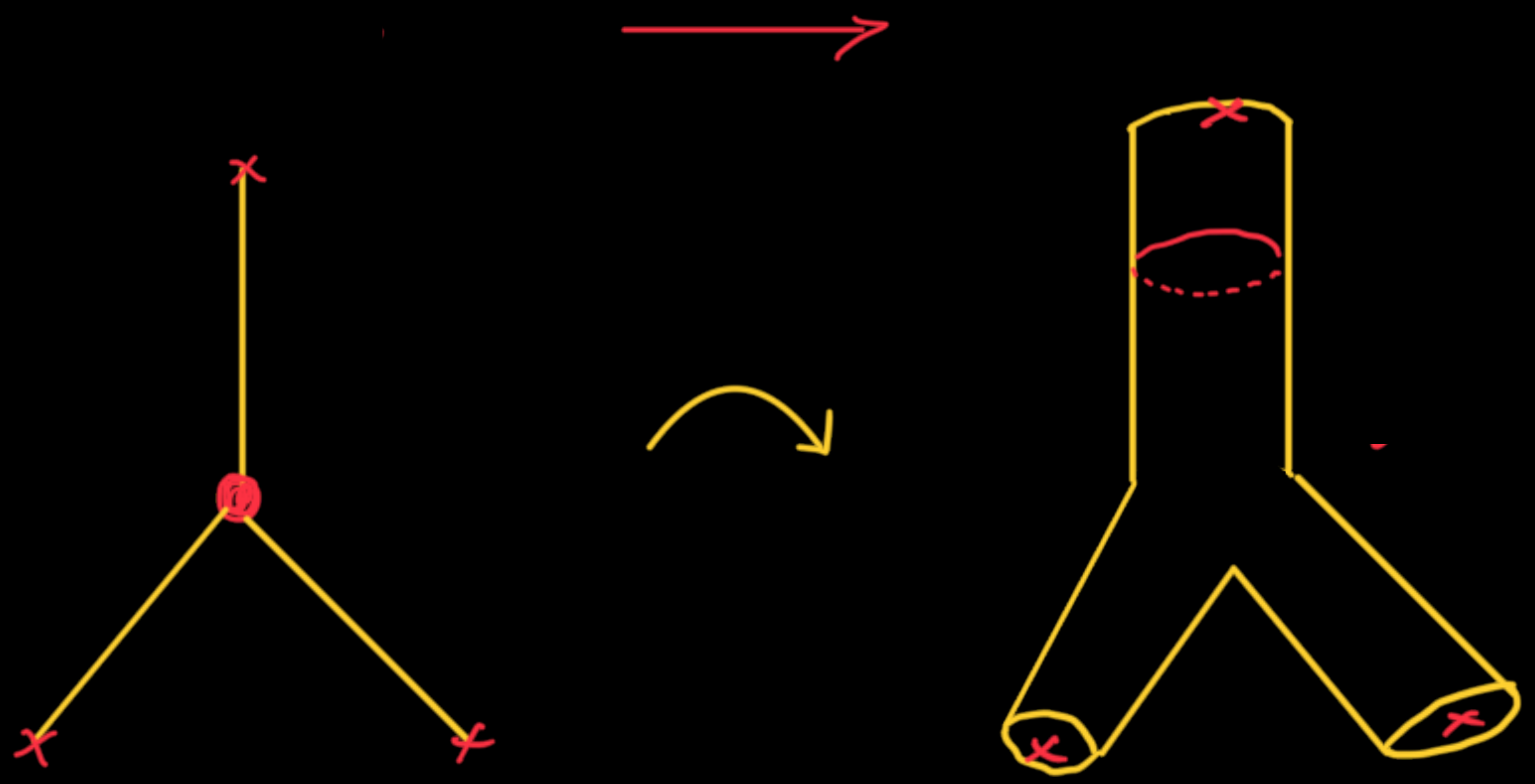
Color trace

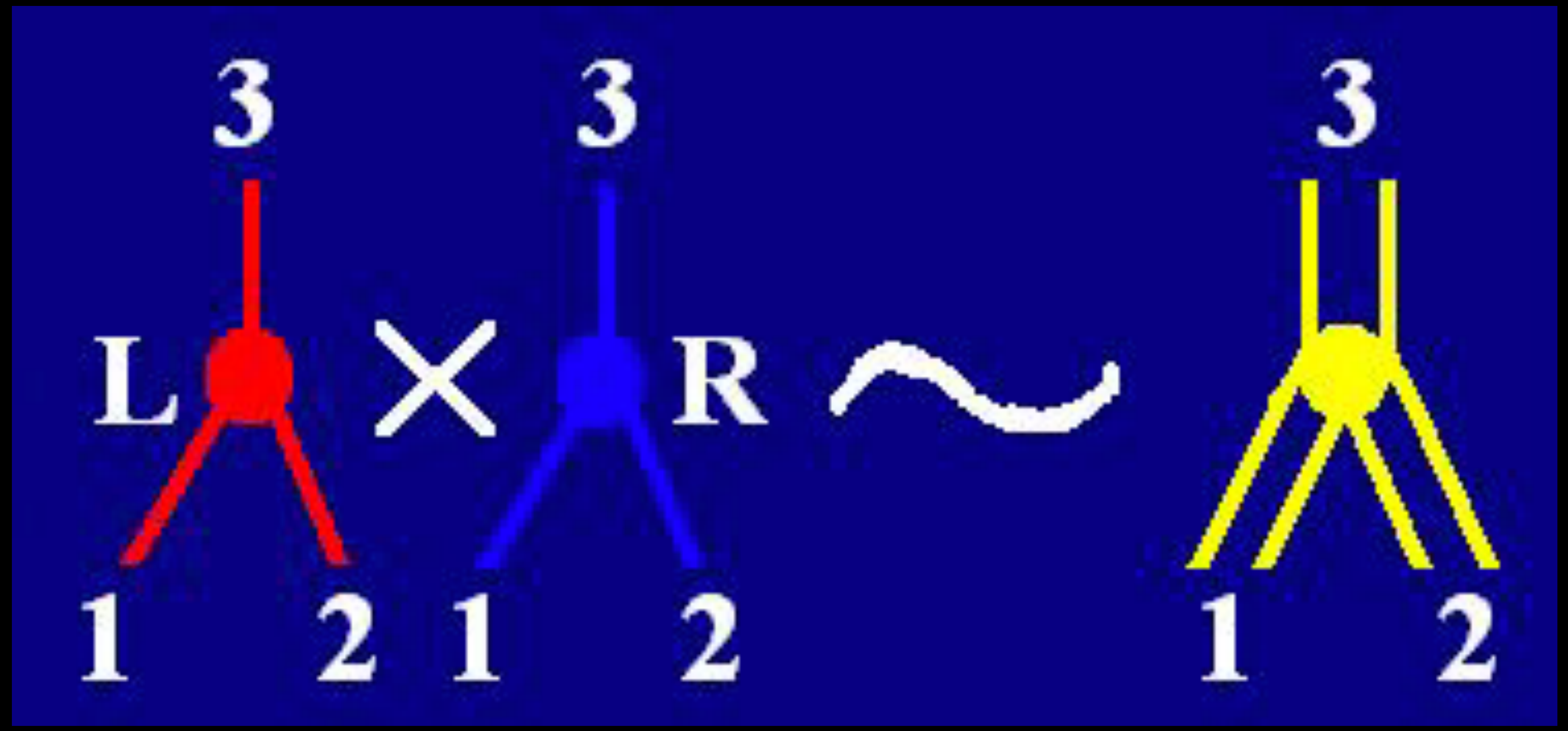
Algebraic solutions

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)





Quantum gravity from effective field theory

PRL 114, 061301 (2015) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2015

Bending of Light in Quantum Gravity

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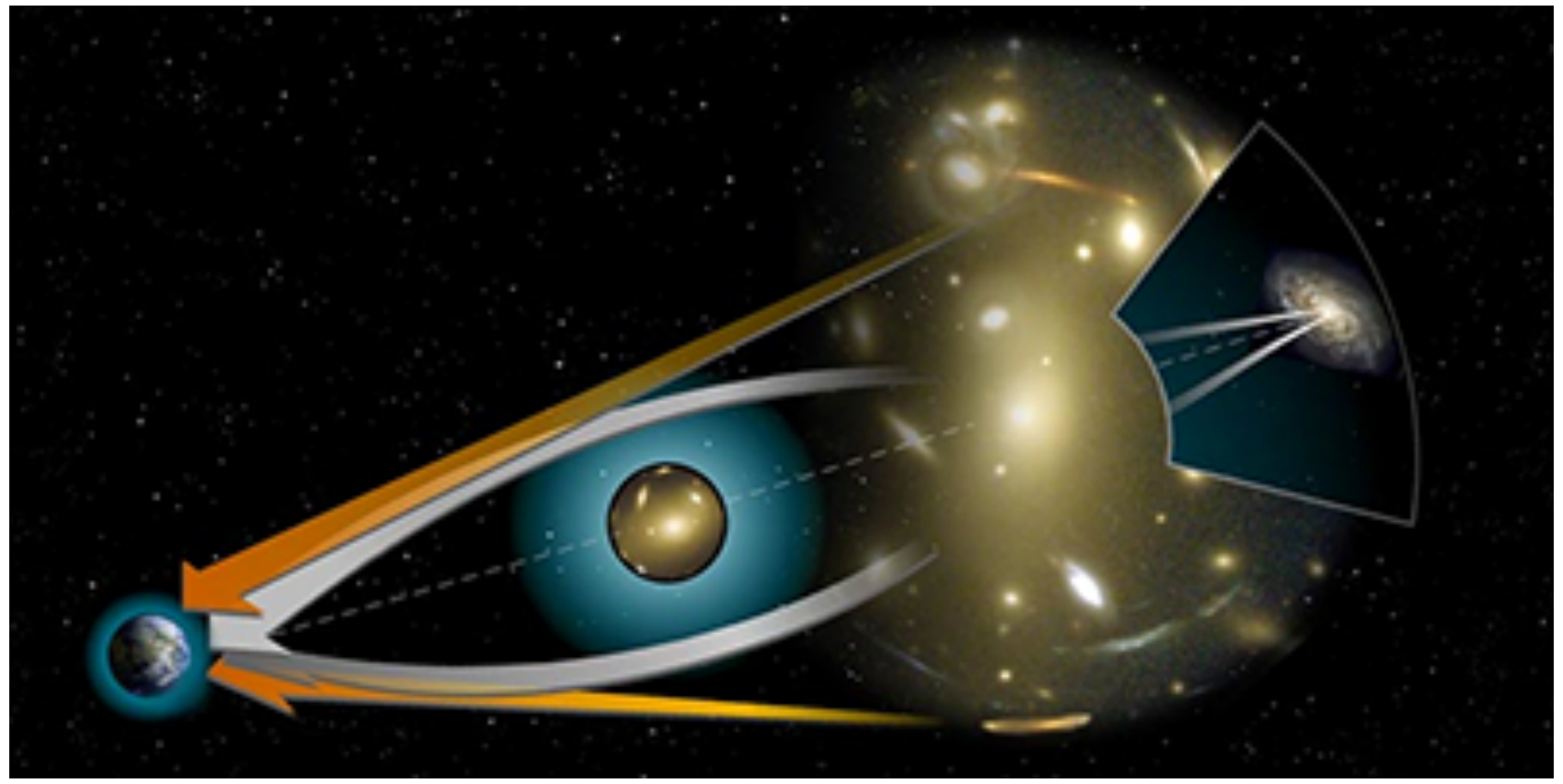
(Received 31 October 2014; revised manuscript received 18 November 2014; published 12 February 2015)

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.

DOI: 10.1103/PhysRevLett.114.061301 PACS numbers: 04.60.−m, 04.62.+v, 04.80.Cc

Using only a few computational tricks!

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



Precision physics and the experiment LIGO

Research visions

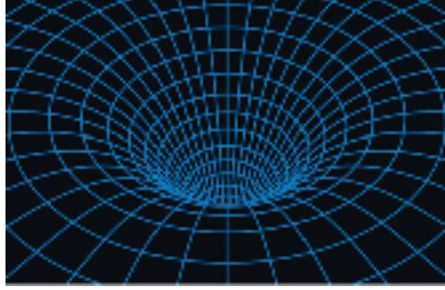
Still many things we do not know..

Many deep mysteries in quantum gravity research.

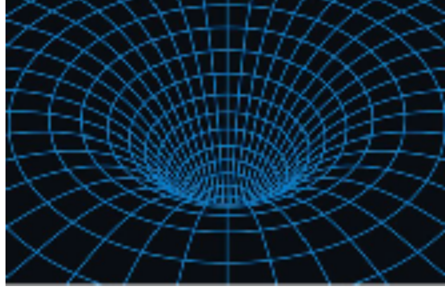
Developments no one would have believed of a few years ago.

Results now extend into for black-hole scattering and precision measurements of the gravitational attraction.

(Exact) Black holes and the double copy



(Exact) Black holes and the double copy



BCJ
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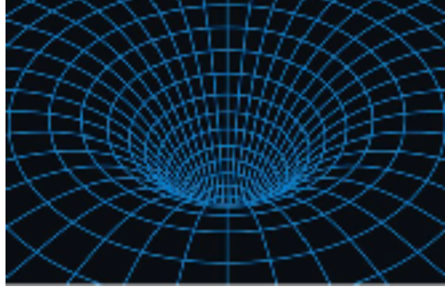

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$$A_a^\mu = c_a \phi k^\mu$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$
$$\equiv \eta_{\mu\nu} + k_\mu k_\nu \phi$$

...a relation between classical fields...

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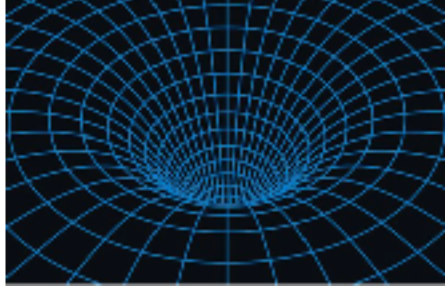

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$$C_{ABCD} = \frac{1}{S} f_{(AB} f_{CD)}$$

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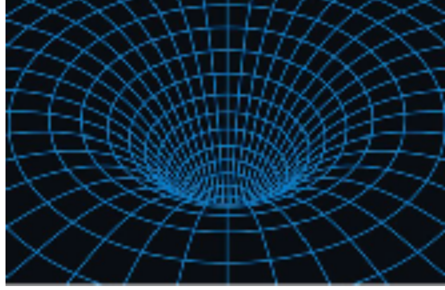

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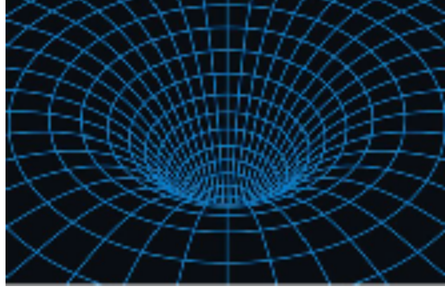

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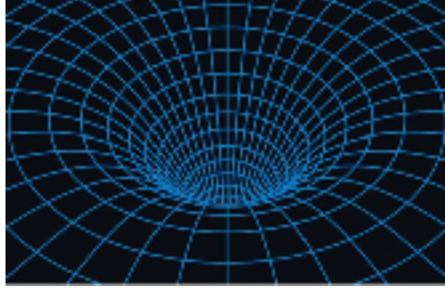

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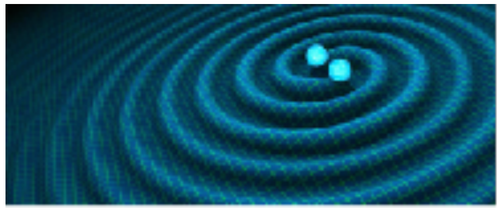

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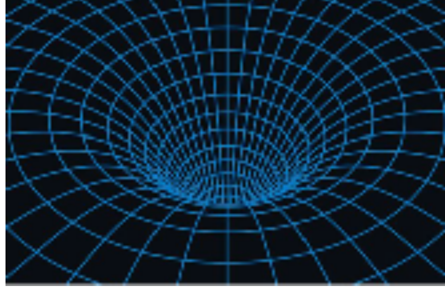

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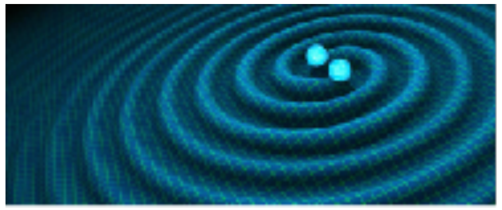
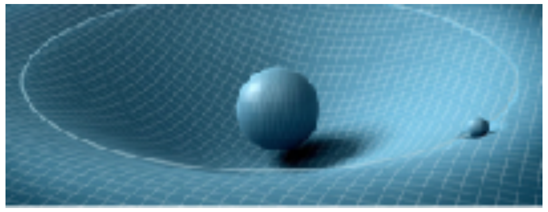


Yes, for geodesics (test bodies)



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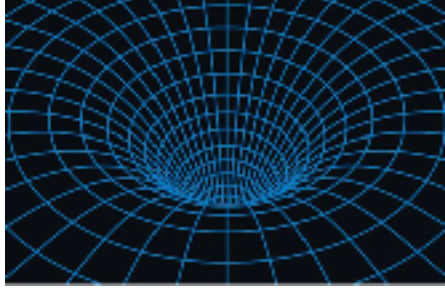

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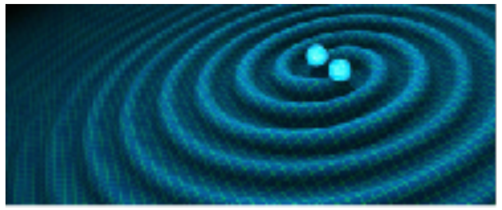

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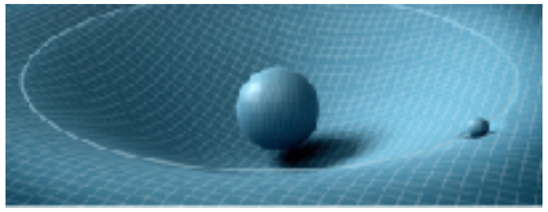

Related cool topic:

Descriptions of geodesics and (Weyl) double copy using twistors

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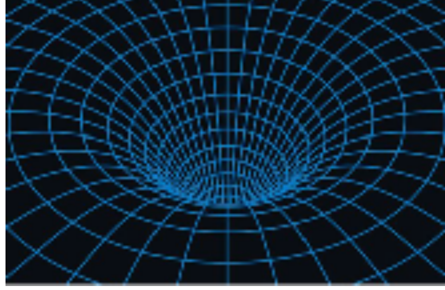

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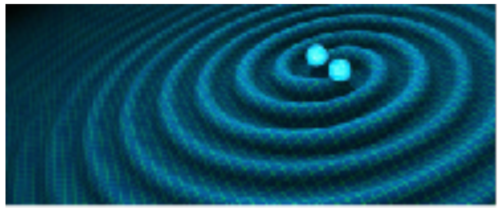

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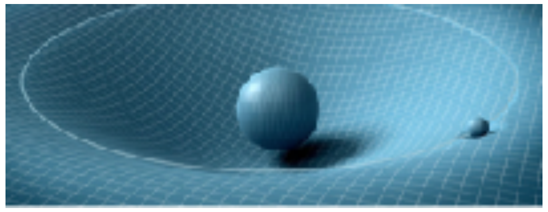

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Open questions:
Can we get exact dynamical results beyond geodesics?
How deep does the rabbit (black) hole go?
(or How fundamental is the classical double copy?)