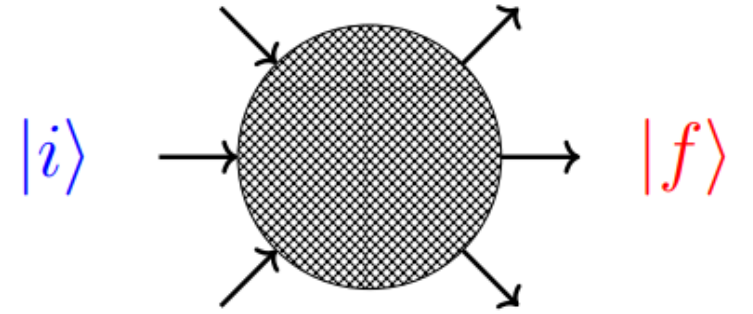# The Double Copy: A Duality for Particles and Gravity

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Introduction

$|i\rangle$ → ⬤ → $|f\rangle$

- Theories of particle physics (such as the standard model) are best described by a special type of quantum field theory called *non-abelian gauge theories*.

- Recently, a new relationship between scattering amplitudes for *non-abelian gauge theories* and *gravity* has been discovered, known as the **<u>Double Copy</u>** *(Bern, Carrasco, and Johansson).*

- The Double Copy has allowed us to calculate previously unobtainable scattering amplitudes results in gravity, by "building" them out of analogous results in non-abelian gauge theories. (used as a tool in *gravitational scattering problems and gravitational waveform corrections*)

Weyl Double Copy in Practice

The Double Copy also exists at the level of *classical physics* for **certain exact** solutions between **General Relativity** and **Classical** Non-abelian Gauge theories (e.g *Yang-Mills Theory*) *(Luna, Monteiro, Nicholson, O'Connell, White)*.

For vacuum solutions in General Relativity that are of Petrov type **D** or **N**, we can express them in terms of analogous solutions in electromagnetism: *(Nicholson, O'Connell, Godazgar, Godazgar, Peinador Veiga, Pope)*

Gravity $$\Psi_{ABCD} = \frac{\Phi_{(AB}\Phi_{CD)}}{\phi}$$ **Electromagnetism**

ϕ is some scalar which is a harmonic function.

Weyl Double Copy with Sources

The Weyl Double Copy has now been extended to work with non-vacuum solutions for Einstein-Maxwell Gravity. *(KAW, Moynihan, White, Manton, Easson, Svesko)*

Einstein-Maxwell Gravity = **General Relativity** + **Classical Electromagnetism**
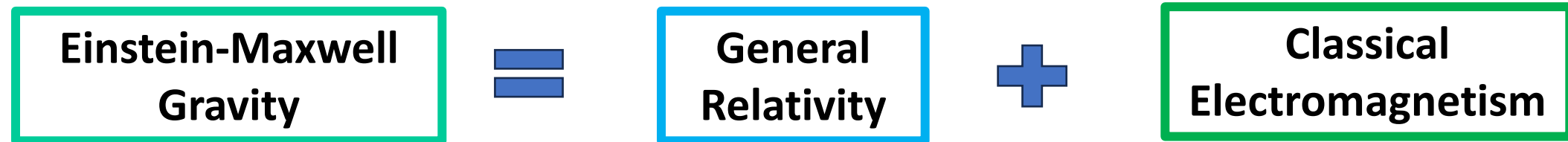
These results were derived using methods inspired by methods from Twistor Theory and Quantum Field Theory. *(KAW, Moynihan, White)*

Weyl Double Copy with Sources

For scalar fields which admit radial power like solutions $\phi^{(n)} = \frac{1}{r^n}$:

Gravity $\quad \Psi_{ABCD} = \displaystyle\sum_{n=1}^{m} \frac{1}{\phi^{(n)}} \Phi^{(n)}{}_{(AB} \Phi^{(n)}{}_{CD)}$ **Electromagnetism**

Where for $n > 1$:

$$\partial^\mu F^{(n)}{}_{\mu\nu} = j^{(n)}{}_\nu$$

$$\partial^2 \phi^{(n)} = \rho_s{}^{(n)}$$

Conclusions and Open Questions

- The Double Copy is a duality between Non-abelian Gauge Theories and Gravity for both scattering amplitudes in quantum field theory and exact solutions in Classical Physics.

- The Classical Double Copy has been recently extended to work in non-vacuum solutions (Einstein-Maxwell Gravity).

- Can we find (Classical) Double Copies for more exotic theories (CFT, AdS, Supergravity, condensed matter, de sitter, cosmology)?

- The Double Copy has some relation to new mysterious structures in gauge theory known as **Kinematic Algebras.** By studying kinematic algebras, what else can we learn ?