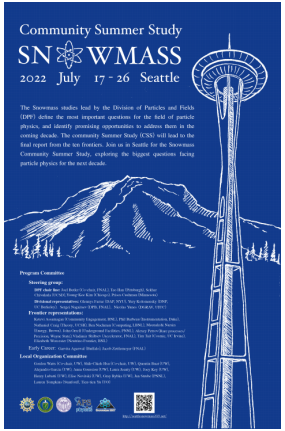
College | Physical Sciences
Physics & Astronomy

# Scattering Amplitudes and Gravitational Waves

Snowmass White Paper [Buonanno, Khalil, O'Connell, Roiban, Solon, Zeng; arXiv: 2204.05194]


## Enrico Herrmann

Mani L. Bhaumik Institute for Theoretical Physics
University of California, Los Angeles

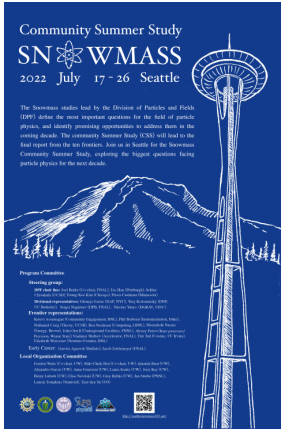
College | Physical Sciences
Physics & Astronomy

# Scattering Amplitudes and Gravitational Waves

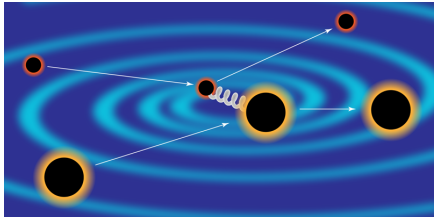
Snowmass White Paper [Buonanno, Khalil, O'Connell, Roiban, Solon, Zeng; arXiv: 2204.05194]


## Enrico Herrmann

Mani L. Bhaumik Institute for Theoretical Physics
University of California, Los Angeles

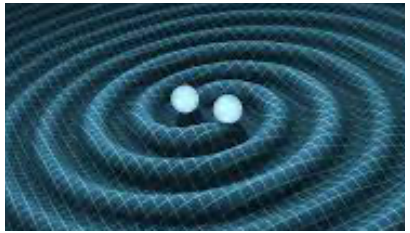



# “Black Hole Collider Physics”

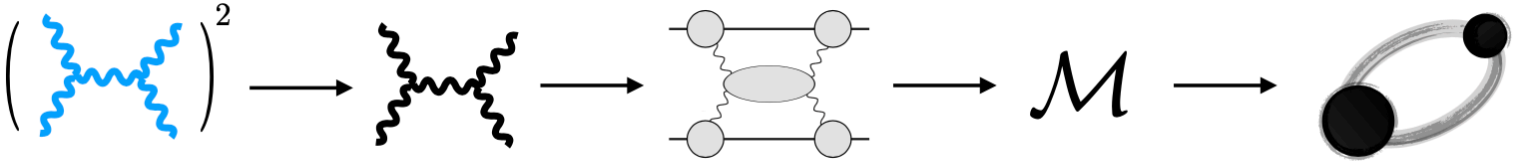


Black Hole collision

$\Leftrightarrow$



Binary inspiral process




Leverage advanced QFT methods for state-of-the-art gravitational wave predictions

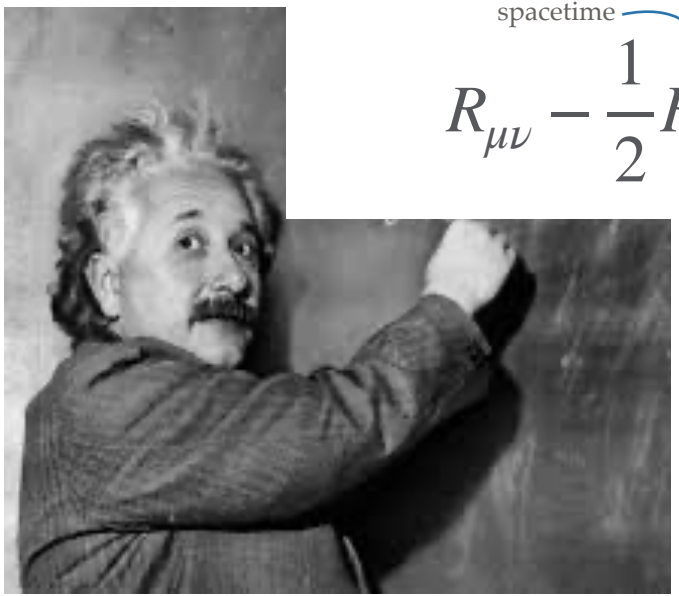
# Gravitational wave physics

## One Equation - Extremely Rich Physics

spacetime

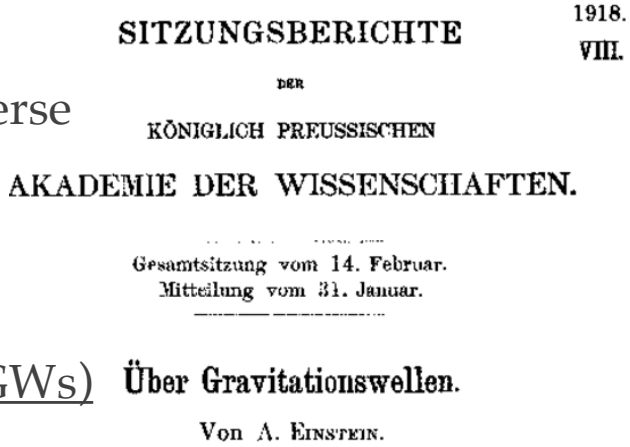
matter

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



[Einstein 1915]

- Expansion of the Universe
- Black Holes
- Gravitational Waves (GWs)



SITZUNGSBERICHTE 1918. VIII.

DER

KÖNIGLICH PREUSSISCHEN

AKADEMIE DER WISSENSCHAFTEN.

Gesamtsitzung vom 14. Februar.
Mitteilung vom 31. Januar.

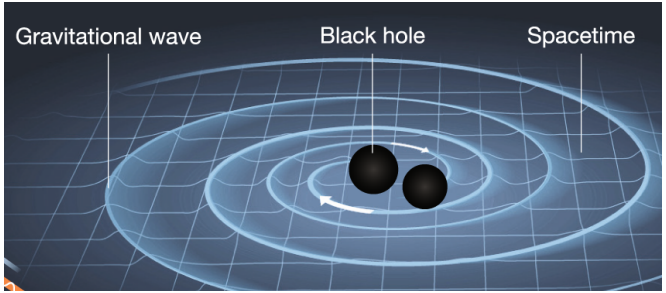
Über Gravitationswellen.

Von A. Einstein.

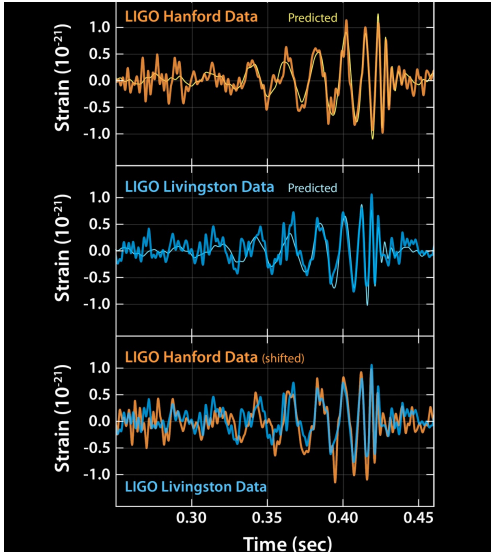
## Prediction of Gravitational Waves 1918

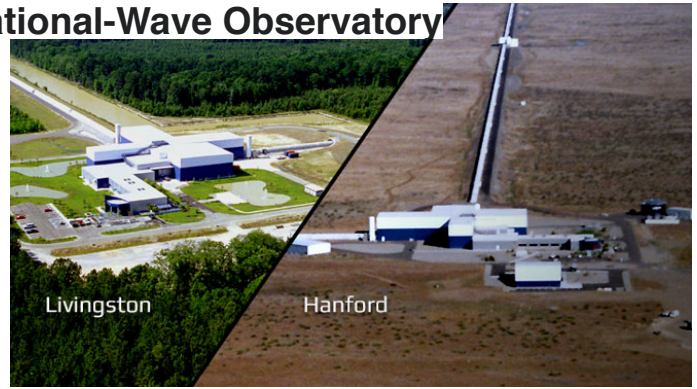
# Gravitational wave physics

## Direct detection of Gravitational Waves @ LIGO 2015




**Laser Interferometer Gravitational-Wave Observatory**



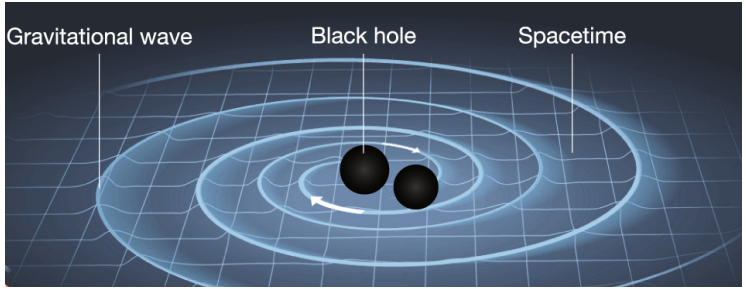

2015: direct detection of GWs from coalescence of two binary black holes

$m_1 = 65 M_\odot$ and $m_2 = 22 M_\odot$

## Gravitational waveform determined by General Relativity

# Gravitational wave physics

A promising scientific program ahead:



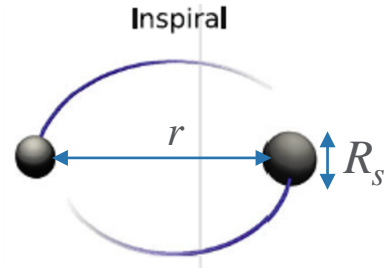

- Study General Relativity in strong field regime
- Constraints on Neutron star equations of state
- Precision tests of GR, modifications of gravity? New Physics? …

| 2015 | 2020 | 2025 | 2030+ |
|---|---|---|---|
| LIGO | LIGO / VIRGO | +KAGRA,… | Cosmic Explorer, Einstein Telescop, LISA,… |

requires theory precision

# Gravitational wave physics

Theory of gravitational waveforms:



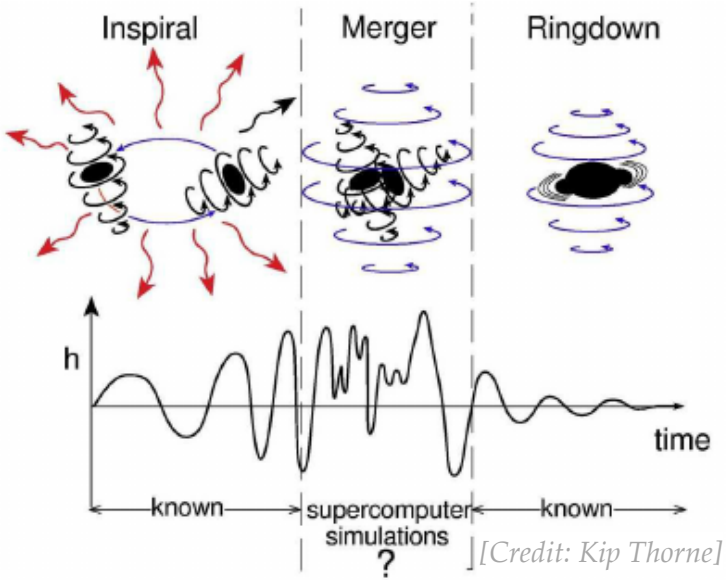

virialization

$$\left[\frac{v}{c}\right]^2 \sim \frac{GM}{r} = \frac{R_s}{r} \ll 1$$

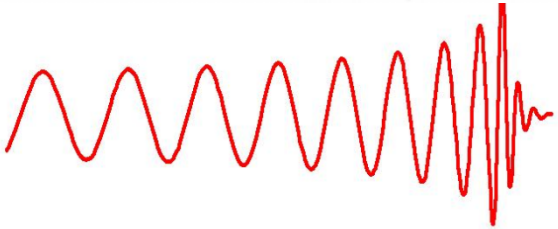
weak field, slow motion — *pert. theory*!

(velocities become large close to merger)

dynamics described by classical Hamiltonian $H$



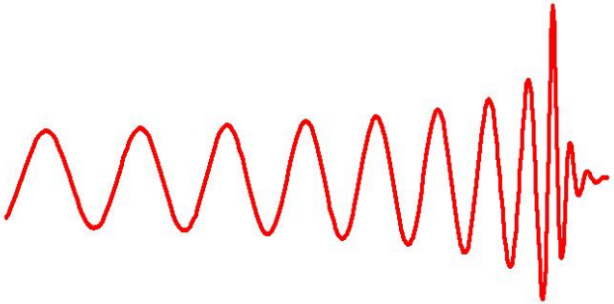

[Credit: Kip Thorne]

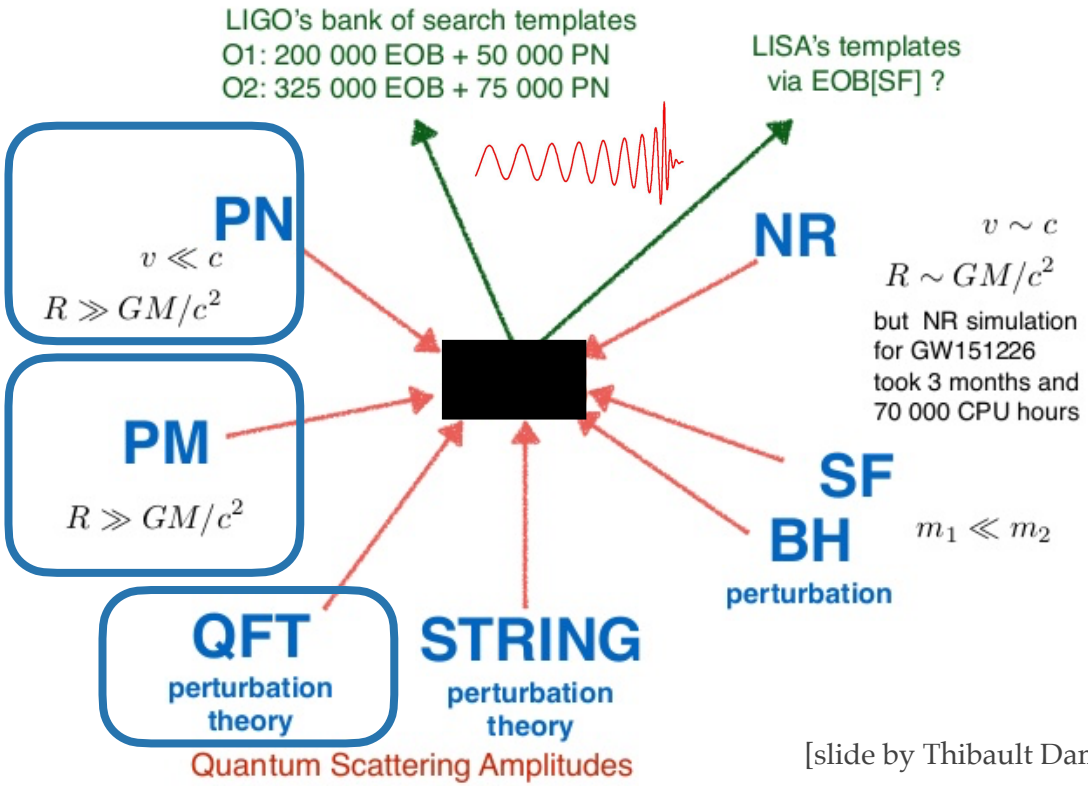


# Gravitational wave physics

## LIGO theorists: waveform modeling

[Buonanno; Damour; …]

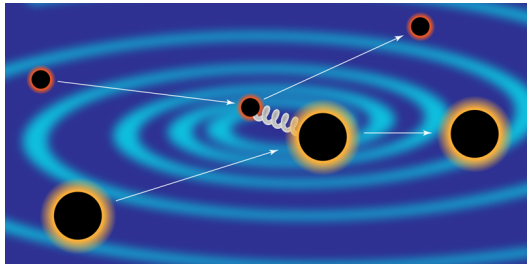





[slide by Thibault Damour]

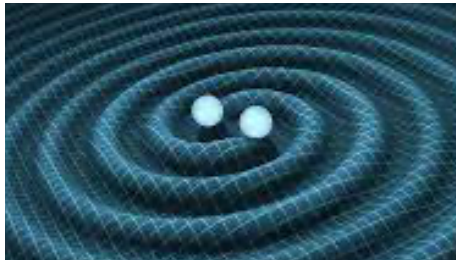
# QFT methods for classical General Relativity

"Black hole collider physics"



Black Hole collision

$\Leftrightarrow$



Binary inspiral process

New source of theory input

# Scattering Amplitudes

## Encouraged by general relativists:

[Kovacs, Thorne 1978]

*g) The Feynman-Diagram Approach*

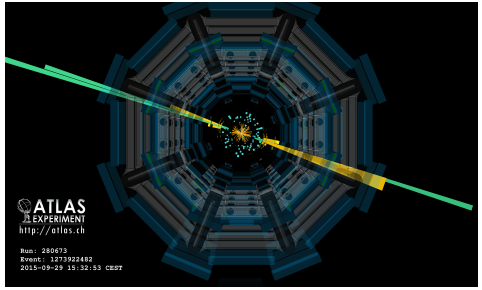
Any classical problem can be solved quantum-mechanically; and sometimes the quantum solution is easier than the classical. There is an extensive literature on the Feynman-diagram, quantum-mechanical treatment of gravita-

**High-energy gravitational scattering and the general relativistic two-body problem**

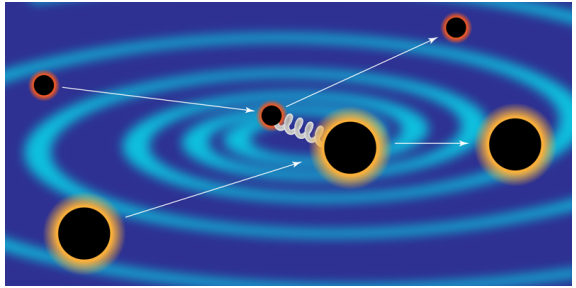
Thibault Damour*
*Institut des Hautes Etudes Scientifiques, 35 route de Chartres, 91440 Bures-sur-Yvette, France*
(Dated: October 31, 2017)

[...] tum gravitational scattering amplitude of two particles, and we urge amplitude experts to use their novel techniques to compute the 2-loop scattering amplitude of scalar masses, from which one could deduce the third post-Minkowskian effective one-body Hamiltonian

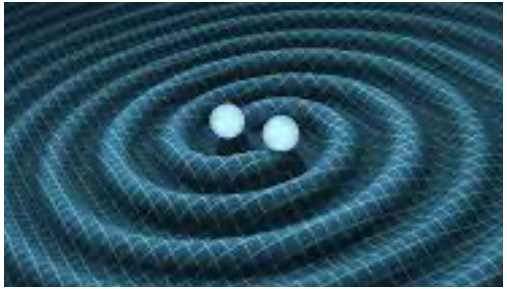
# Scattering Amplitudes




→



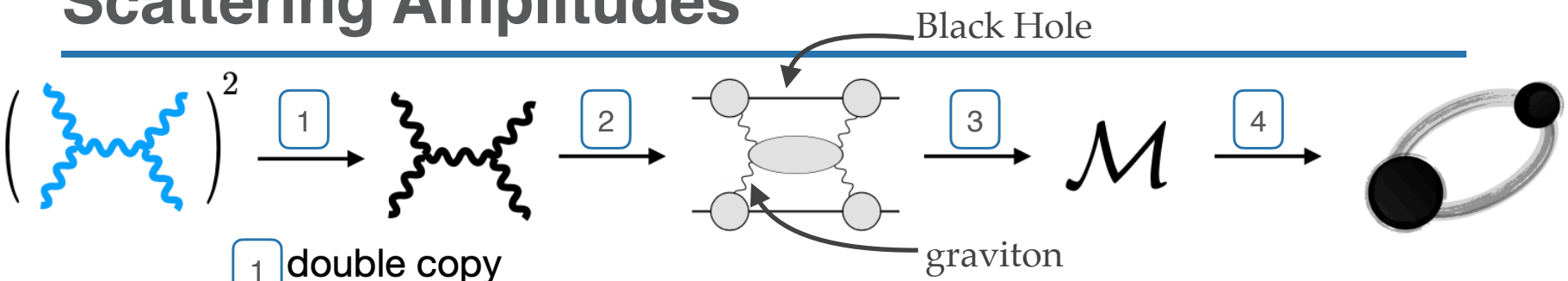
→



**What particle theorists bring to the table:**

- exploit scale separation: Effective Field Theory [Goldberger, Rothstein] [Beneke, Smirnov] [Cheung, Rothstein, Solon]
- export mature collider physics tools (loop computation) [Laporta; Tkachov; Chetyrkin; Kotikov; Remiddi, Gehrmann; Henn, Anastasiou, Melnikov, …]
- focus on physical, gauge-invariant quantities [Kosower, Maybee, O'Connell] [**EH**, Parra-Martinez, Ruf, Zeng]
- Boundary-to-Bound map between hyperbolic and bound motion [Porto, Kälin]

# Scattering Amplitudes




1 **double copy**

Kawai, Lewellen, Tye, Bern, Carrasco, Johansson, Ochirov, Chiodaroli, Jin, Roiban, Chen, Boucher-Veronneau, Dennen, Davies, Damgaard, Bjerrum-Bohr, Huang, Anastasiou, Borsten, Nagy, …

2 **on-shell methods**

Bern, Dixon, Dunbar, Kosower, Morgan, Britto, Cachazo, Feng, Witten, Ellis, Melnikov, Forde, Bader, Carrasco, Johansson, Arkani-Hamed, Y-T Huang, Trnka, Bourjaily …

3 **advanced multiloop integration**

Chetyrkin, Tkachov, Laporta, V. Smirnov, A. Smirnov, Kotikov, Bern, Dixon, Kosower, Remiddi, Gehrmann, Chuharev, Tarasov, Lee, Henn, Beneke, Czakon, Ita, Zeng, …

4 **effective field theory**

Caswell, Lepage, Braaten, Isgur, Wise, Manohar, Stewart, Donoghue, Beneke, Goldberger, Rothstein, Neill, Vaidya …

*[Credit: Mikhail Solon]*

# Scattering Amplitudes

Combination of QFT tools led to new state-of-the-art results in GR

(Post-Minkowskian [PM] expansion: Perturbation theory in Newton's constant G only)

$G^1\left(1+v^2+v^4+v^6+v^8+v^{10}+\cdots\right)$ 1 PM

$G^2\left(1+v^2+v^4+v^6+v^8+v^{10}+\cdots\right)$ 2 PM [Westpfahl 1985]

$G^3\left(1+v^2+v^4+v^6+v^8+v^{10}+\cdots\right)$ 3 PM [Bern, Cheung, Roiban, Shen, Solon, Zeng 2019] (conservative) [Kälin, Liu, Porto 2021] [**EH**, Parra-Martinez, Zeng 2021] [Vanhove et al. 2021] +(radiation)

$G^4\left(1+v^2+v^4+v^6+v^8+v^{10}+\cdots\right)$ 4 PM [Bern et al. 2021] [Porto et al. 2021] (conservative)

$G^5\left(1+v^2+v^4+v^6+v^8+v^{10}+\cdots\right)$ 5 PM ?

1-loop

2-loop

3-loop

4-loop

Relativity built into QFT approach – all orders in velocity results

# Scattering Amplitudes

Combination of QFT tools led to new state-of-the-art results in GR

(Post-Minkowskian [PM] expansion: Perturbation theory in Newton's constant G only)

$$G^1\left(1+v^2+v^4+v^6+v^8+v^{10}+\cdots\right) \quad \text{1 PM}$$

$$G^2\left(1+v^2+v^4+v^6+v^8+v^{10}+\cdots\right) \quad \text{2 PM}$$

$$G^3\left(1+v^2+v^4+v^6+v^8+v^{10}+\cdots\right) \quad \text{3 PM}$$

$$G^4\left(1+v^2+v^4+v^6+v^8+v^{10}+\cdots\right) \quad \text{4 PM}$$

$$G^5\left(1+v^2+v^4+v^6+v^8+v^{10}+\cdots\right) \quad \text{5 PM}$$

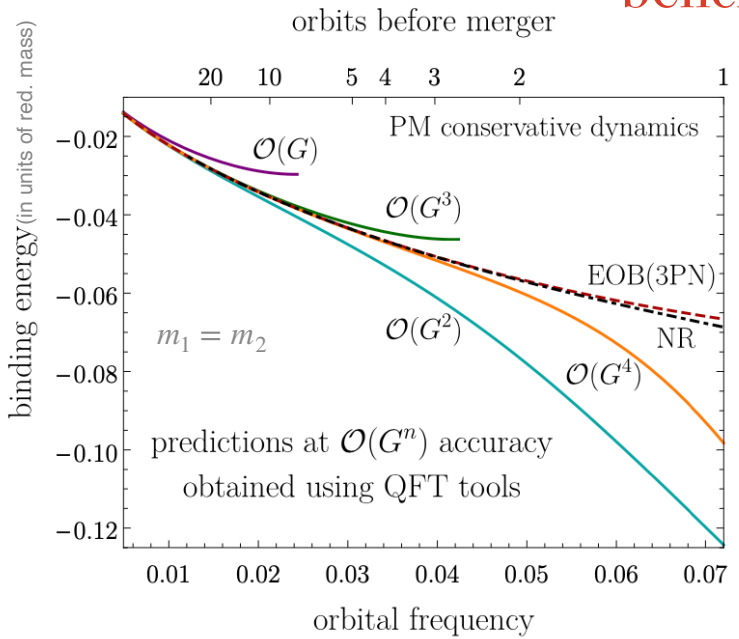
Bini, Damour, Geralico 19, 20
Damour 19, 20
Blümlein, Maier, Marquard, Schäfer 20
Di Vecchia, Heissenberg, Russo, Veneziano 20
EH, Parra-Martinez, Ruf, Zeng 21

Bini, Damour, Geralico 21
Blümlein, Maier, Marquard, Schäfer 21
Bern, Parra-Martinez, Roiban, Ruf, Shen, Solon, Zeng 21
Dlapa, Kälin, Liu, Porto 21

Relativity built into QFT approach – all orders in velocity results

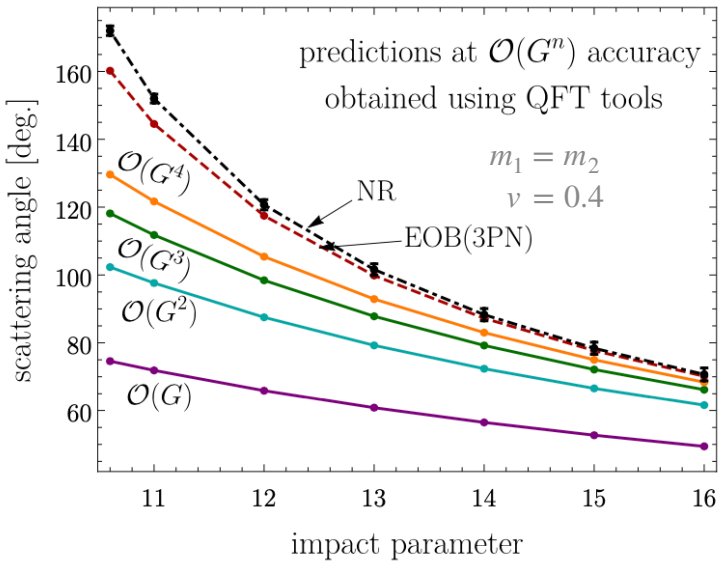
# Scattering Amplitudes [Buonanno, Khalil, O'Connell, Roiban, Solon, Zeng; arXiv:2204.05194]

benchmark quantities




[Antonelli, Buonanno, Steinhoff, van de Meent, Vines arXiv: 1901.07102]

bound




[Khalil, Buonanno, Steinhoff, Vines, arXiv: 2204.05047]

unbound

# Current status / Outlook

BH vs. Neutron Star

## spin and tidal effects

Guevara, Ochirov, Vines, Huang, Levi, Bern, Luna, Roiban, Shen, Zeng, Kosmopoulos, Jakobsen, Mogull, Cheung, Shah, Haddad, Helset, Chia, Charalambous, Dubovsky, Ivanov, Hui, Joyce, Penco, Santoni, Solomon, De Luca, Pani …

## radiation

Damour, Veneziano, Di Vecchia, Heissenberg, Russo, Herrmann, Parra-Martinez, Ruf, Zeng, Riva, Vernizzi, Cristofoli, Kosower, O'Connel, Jakobsen, Mogull, Plefka, Steinhoff, Bjerrum-Bohr, Damgaard, Plante, Vanhove, Shen, Manohar, Ridgway …

## classical double copy

Luna, Monteiro, O'Connell, White, Nicholson, Ridgway, Wise, Carrillo-Gonzalez, Penco, Trodden, Kol, Adamo, Casali, Mason, Nekovar, Ochirov, Goldberger, Ochirov, Plefka, Shi, Shen, Arkani-Hamed, Huang, Bjerrum-Bohr, Donoghue, Vanhove, Gonzo …

## theoretical structures

Cachazo, Guevarra, Ita, Ruf, Herrmann, Luna, Zeng, Jakobsen, Mogull, Plefka, Steinhoff, Bjerrum-Bohr, Damgaard, Vanhove, Kol, Telem, O'Connell, Cristofoli, Gonzo, Kosower, Britto, Brandhuber, Johannson, Travaglini, Carrillo-Gonzalez, de Rham, Tolley, Jones, Gralla …

## new methods

Kosower, Maybee, O'Connell, Bini, Damour, Geralico, Bjerrum-Bohr, Damgaard, Festuccia, Plante, Vanhove, Kalin, Porto, Parra-Martinez, Ruf, Zeng, Brandhuber, Chen, Johannson, Travaglini, Wen, Edison, Levi, Di Vecchia, Russo, Heissenberg, Veneziano, Chiodaroli, Johansson …

*[Credit: Mikhail Solon]*

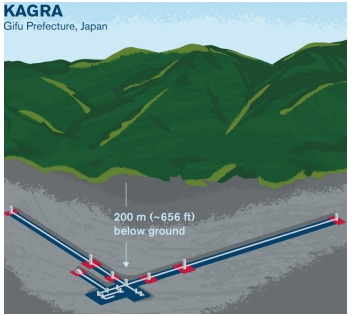
# Outlook

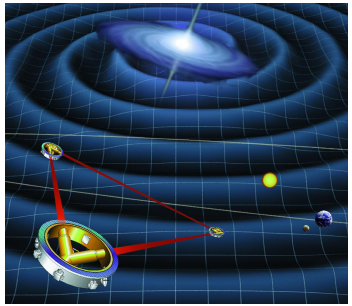
2015
LIGO

2020
LIGO / VIRGO

2025
+KAGRA,…

2030+
Cosmic Explorer
Einstein Telescop, LISA,…



The future of particle physics at interface with GW science is bright!

# Outlook

[Buonanno, Khalil, O'Connell, Roiban, Solon, Zeng; arXiv: 2204.05194]

## Snowmass White Paper: Gravitational Waves and Scattering Amplitudes

**Alessandra Buonanno,[1,2] Mohammed Khalil,[1,2] Donal O'Connell,[3] Radu Roiban,[4] Mikhail P. Solon,[5] Mao Zeng[3]**

lem in general relativity. Theorists developing waveform models for the LIGO-Virgo-KAGRA (LVK) collaboration [1–3] have performed initial studies [4, 5] of these early results, see Figure 1, and have strongly encouraged further developments. Indeed, if these calculations are pushed to higher orders, and are extended to include all physical effects (i.e., spins and tides), they can be used, in combination with other analytic methods [6–11][1] and with numerical-relativity (NR) simulations [16–19], to provide highly accurate waveform models of binary systems composed of black holes and/or neutron stars. Another aspect of this program that has drawn significant interest from

# Relevant Snowmass White Papers

[Buonanno, Khalil, O'Connell, Roiban, Solon, Zeng; arXiv: 2204.05194] **Snowmass White Paper: Gravitational Waves and Scattering Amplitudes**

[Adamo, Carrasco, Carrillo-Gonzalez, Chiodaroli, Elvang, et al.; arXiv: 2204.06547] **Snowmass White Paper: the Double Copy and its Applications**

[Goldberger; arXiv: 2206.14249] **Snowmass White Paper: Effective field theories of gravity and compact binary dynamics**

# Thank you!