Gravitational waves through the Amplitudes lens

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A review based on
Snowmass White Paper: Gravitational Waves and Scattering Amplitudes
with A. Buonanno, D. O'Connell, M. Solon, M. Zeng

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The detection of gravitational waves opened a new window on our Universe

- Probe aspects of dynamics in General Relativity in strong field regime
- Probe properties of black holes
- Probe/discriminate extensions of General Relativity
- Probe certain astrophysical environments, including dark matter
- Probe properties of (ultra-) dense nuclear matter
- Probe BH origin, formation mechanisms, population, etc
- …

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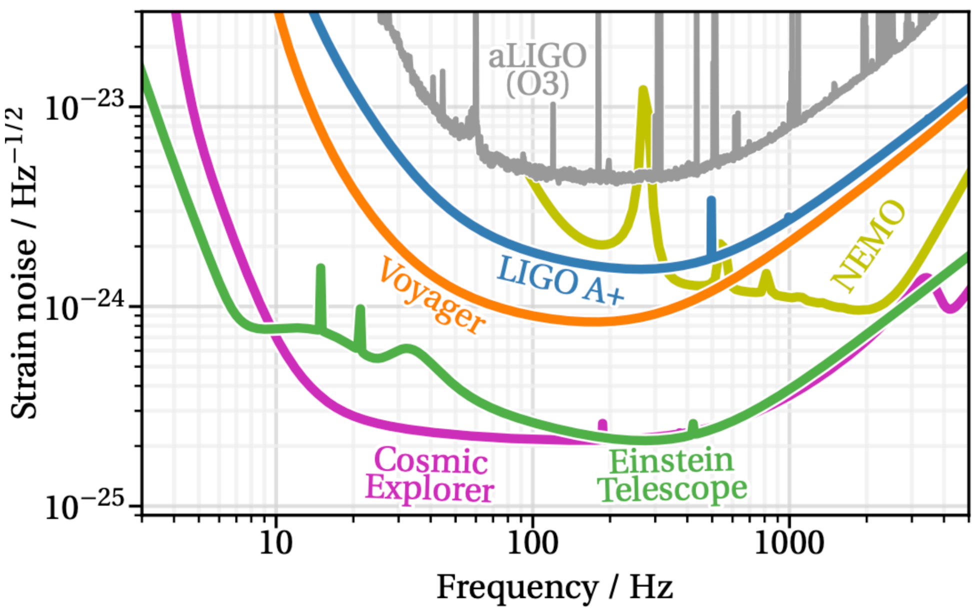
and gave new impetus towards new theoretical tools and structures

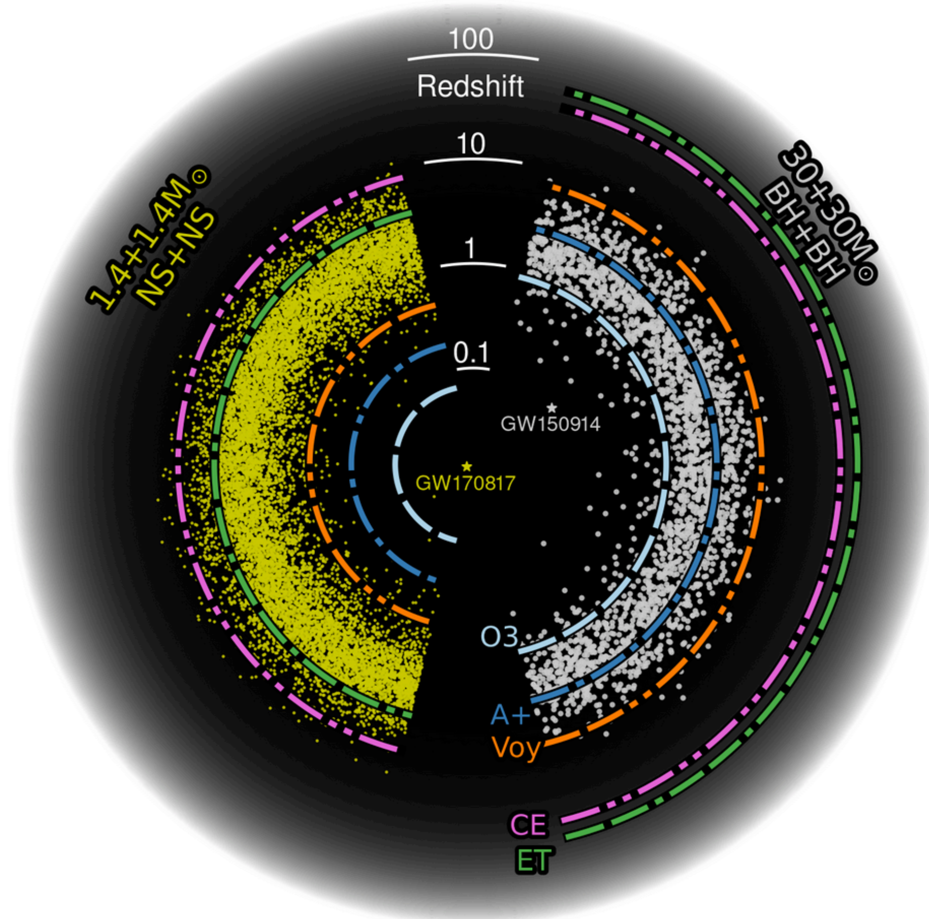
- Search for new symmetries
- Exploration of the structure of perturbation theory
- Resummation of perturbation theory
- Analytic continuations
- …

Future ground-based observatories

https://cosmicexplorer.org/sensitivity.html

- Advanced LIGO (A+)
- Einstein Telescope (ET)
- Cosmic Explorer (CE)





- Depending on parameters, sensitivity improvements by 10^2

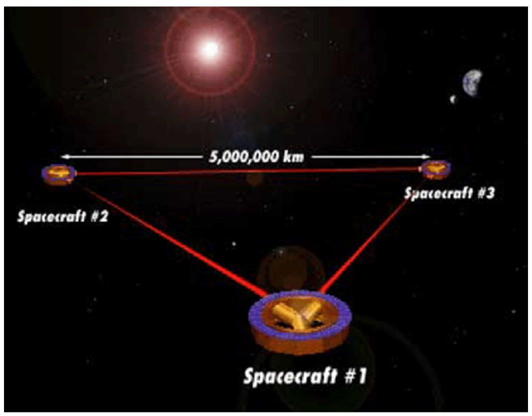
Future space-based observatories

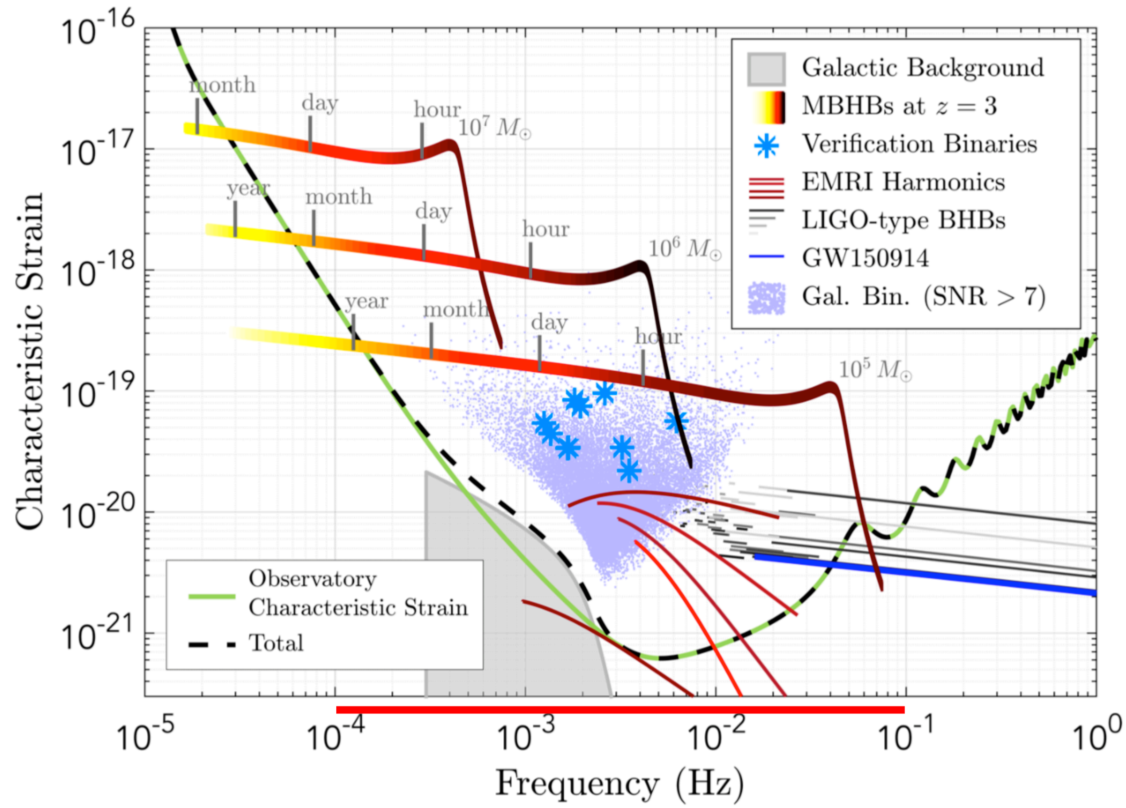
- LISA (2035+)
- TianQin (2035+)

From Danzmann et al 1702.00786
LISA proposal

Open three more decades of GW frequency

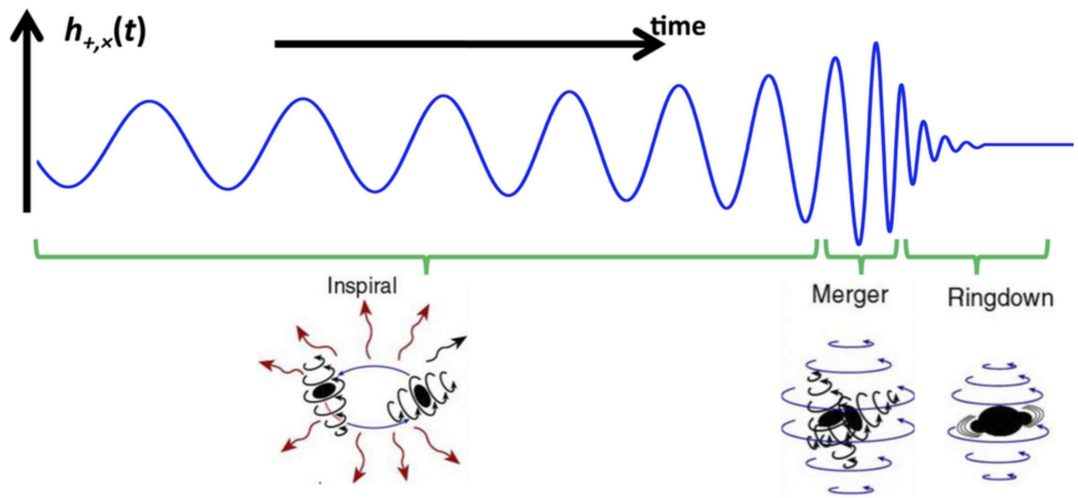
More sources: EMRIs, massive BHs,
galactic stellar-mass binaries





- Extended signals ⟶ long accurate waveforms are required
  ⟶ buildup of theoretical error over long-time evolution must be avoided
- Interplay of the various available approaches will be important to maximize theoretical output

Anatomy of an idealized binary merger



Favata/SXS/K.Thorne

- Numerical relativity – “the truth”, but expensive
- Post-Newtonian expansion (weak field, nonrelativistic): $\boldsymbol{v}^2 \sim \frac{GM}{|\boldsymbol{r}|} \ll 1$ — See Stefano Foffa’s talk
- Post-Minkowskian expansion (weak-field, relativistic): $\frac{GM}{|\boldsymbol{r}|} \ll \boldsymbol{v}^2 \sim 1$ — (this talk)
- Small mass ratio expansion/gravitational self-force $\boldsymbol{v}^2 \sim GM/|\boldsymbol{r}| \sim 1$ — See Chris Kavanagh’s talk
- Ringdown: black hole perturbation theory

→ Effective one-body theory (EOB) and phenomenological models consolidate available results

Precision, precision, even more precision…

Favata; Samajdar, Dietrich; Pürrer, Haster;
Huang, Haster, Vitale, Varma, Foucault, Biscoveanu

Depending on parameters: waveform accuracy needs two or more orders of magnitude improvement

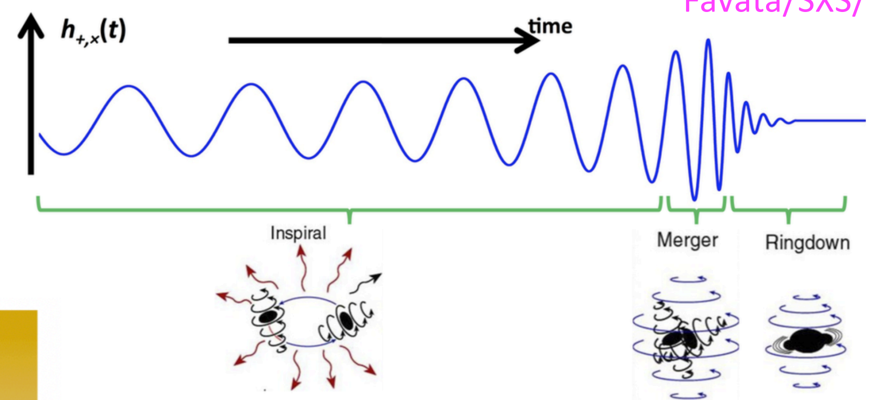
$\mathcal{O}(G^7)$ and $\mathcal{O}(v^{12})$

needed to keep modeling systematics below expected statistical errors

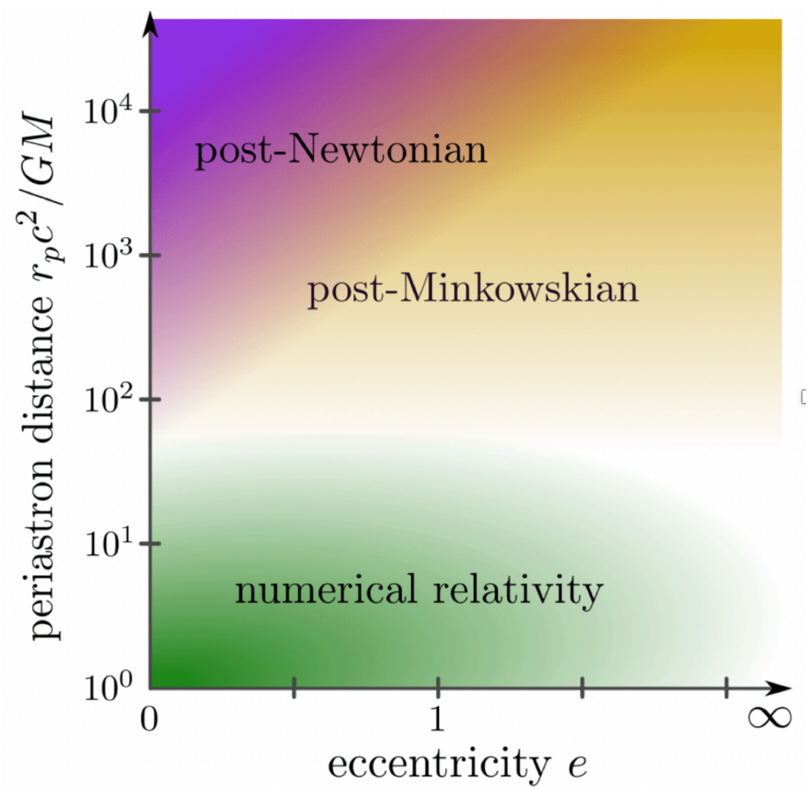
$$
\begin{aligned}
&G(1 + v^2 + v^4 + v^6 + v^8 + v^{10} + v^{12} + \cdots)\\
&G^2(1 + v^2 + v^4 + v^6 + v^8 + v^{10} + v^{12} + \cdots)\\
&G^3(1 + v^2 + v^4 + v^6 + v^8 + v^{10} + v^{12} + \cdots)\\
&G^4(1 + v^2 + v^4 + v^6 + v^8 + v^{10} + v^{12} + \cdots)\\
&G^5(1 + v^2 + v^4 + v^6 + v^8 + v^{10} + v^{12} + \cdots)\\
&G^6(1 + v^2 + v^4 + v^6 + v^8 + v^{10} + v^{12} + \cdots)\\
&G^7(1 + v^2 + v^4 + v^6 + v^8 + v^{10} + v^{12} + \cdots)
\end{aligned}
$$

- higher-order calculations are needed for the dissipative sector, the multipolar waveforms, and other physical effects such as spins, tides, and eccentricity.

Anatomy of an idealized binary merger



Favata/SXS/K.Thorne



Khalil, Buonanno, Steinhoff, Vines

Post-Minkowskian expansion is the relevant expansion for certail eccentric bounded motion and for hyperbolic motion

Why worry about the post-Minkowskian expansion:

- Motion on eccentrical orbits reaches high velocity at periastron

- Cleaner environment to sort out numerical and analytical theoretical subtleties

- Explore the structure of gravitational perturbation theory

  including symmetries, functional structures, etc

- Information for semi-analytic/semi-numerical approaches

  e.g. function basis required for fitting numerical data

See Oliver Long's talk

- Aid with post-Newtonian calculations

- Through resummation, contact between perturbation theory and strong-field gravity

  QCD-style resummation, EOB-style resummation, GSF-style resummation

- Explore structure of observables

A Plan:

- State of the art from amplitudes: spinless, spinning, radiation

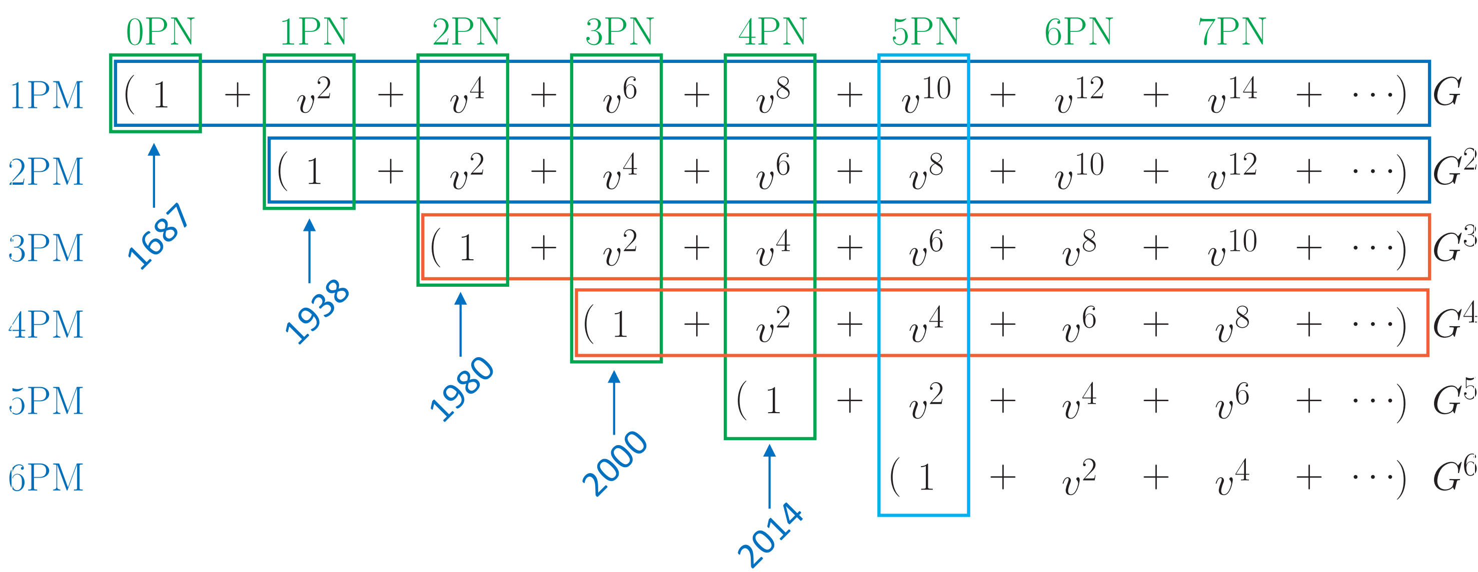
  See Stefano Foffa's talk for worldline EFT approach

- Theoretical structures

- Developing tools

- Future

Extensive work in the spinless PN theory, using (mostly) traditional methods:



Ohta, Okamura, Kimura, Hiida, Jaranowski, Schäfer, Damour, Jaranowski, Blanchet, Faye, Porto, Rothstein, Iyer, Will, Wiseman, Poisson, Cutler, Finn, Flanagan, Deruelle, Thorne, Sathyaprakash, Bini, Geralico, Goldberger, Rothstein, Buonanno, Le Tiec, Marsat, Foffa, Sturani, Mastrolia, Sturm, Torres Bobadilla, Blümlein, Maier, Marquard, *etc.*

Extensive perturbative QFT experience in gauge and gravity theories helps produce relativistic state of the art predictions

- Unitarity methods, recycles trees into loops — Bern, Dixon, Dunbar, Kosower; Cutkowski
- Double-copy: gravity from gauge theory — Kawai, Lewellen, Tye; Bern, Carrasco, Johansson; see also Henrik Johansson's talk
- NRQCD/HEFT and EFT methods — Caswell, Lepage; Luke, Manohar, Rothstein; Golberger, Rothstein; Cheung, Rothstein, Solon
- Method of regions: integrate out potential graviton modes — Beneke, Smirnov
- Reduction to master integrals/Integration-by-parts reduction — Chetyrkin, Tkachov; Laporta
- Method of differential equations for the evaluation of master integrals — Kotikov; Bern, Dixon, Kosower; Gehrmann, Remiddi; Henn, Smirnov

See talks by Christoph Dlapa, Gregor Kälin, David Kosower on Thursday for related developments in evaluation of Feynman integrals

Classical limit implemented as Bohr's correspondence principle (large angular momenta, masses, etc) or as explicit $\hbar \to 0$ helps tremendously

Spinless conservative PM scattering dynamics through G^4

$$\gamma = \frac{E}{m}, \quad \xi = \frac{E_1 E_2}{E^2}$$
$$\nu = \frac{m_1 m_2}{m_1 + m_2}$$
$$m = m_1 + m_2$$
$$\sigma = p_1 \cdot p_2$$

Westphal; Damour

Hamiltonian for hyperbolic motion: $H^{\mathrm{hyp}} = E_1 + E_2 + \sum_{n=1}^{\infty} \frac{G^n}{r^n} c_n(\boldsymbol{p}^2)$

$$c_1 = \frac{\nu^2 m^2}{\gamma^2 \xi}\left(1 - 2\sigma^2\right), \qquad c_2 = \frac{\nu^2 m^3}{\gamma^2 \xi}\left[\frac{3}{4}\left(1 - 5\sigma^2\right) - \frac{4\nu\sigma\left(1 - 2\sigma^2\right)}{\gamma\xi} - \frac{\nu^2(1-\xi)\left(1 - 2\sigma^2\right)^2}{2\gamma^3\xi^2}\right]$$

$$\begin{aligned} c_3 = \frac{\nu^2 m^4}{\gamma^2 \xi}\Bigg[& \frac{1}{12}\left(3 - 6\nu + 206\nu\sigma - 54\sigma^2 + 108\nu\sigma^2 + 4\nu\sigma^3\right) - \frac{4\nu\left(3 + 12\sigma^2 - 4\sigma^4\right)\operatorname{arcsinh}\sqrt{\frac{\sigma-1}{2}}}{\sqrt{\sigma^2-1}} \\ & - \frac{3\nu\gamma\left(1 - 2\sigma^2\right)\left(1 - 5\sigma^2\right)}{2(1+\gamma)(1+\sigma)} - \frac{3\nu\sigma\left(7 - 20\sigma^2\right)}{2\gamma\xi} - \frac{\nu^2\left(3 + 8\gamma - 3\xi - 15\sigma^2 - 80\gamma\sigma^2 + 15\xi\sigma^2\right)\left(1 - 2\sigma^2\right)}{4\gamma^3\xi^2} \\ & + \frac{2\nu^3(3 - 4\xi)\sigma\left(1 - 2\sigma^2\right)^2}{\gamma^4\xi^3} + \frac{\nu^4(1 - 2\xi)\left(1 - 2\sigma^2\right)^3}{2\gamma^6\xi^4}\Bigg] \end{aligned}$$

Bern, Cheung, RR, Solon, Shen, Zeng

$$\begin{aligned} c_4^{\mathrm{hyp}} = & \frac{m^7\nu^2}{4\xi E^2}\left[\mathcal{M}_4^{\mathrm{p}} + \nu\left(4\mathcal{M}_4^{\mathrm{t}}\log\left(\tfrac{p_\infty}{2}\right) + \mathcal{M}_4^{\pi^2} + \mathcal{M}_4^{\mathrm{rem}}\right)\right] + \mathcal{D}^3\left[\frac{E^3\xi^3}{3}c_1^4\right] + \mathcal{D}^2\left[\left(\frac{E^3\xi^3}{\boldsymbol{p}^2} + \frac{E\xi(3\xi-1)}{2}\right)c_1^4 - 2E^2\xi^2 c_1^2 c_2\right] \\ & + \left(\mathcal{D} + \frac{1}{\boldsymbol{p}^2}\right)\left[E\xi(2c_1c_3 + c_2^2) + \left(\frac{4\xi-1}{4E} + \frac{2E^3\xi^3}{\boldsymbol{p}^4} + \frac{E\xi(3\xi-1)}{\boldsymbol{p}^2}\right)c_1^4 + \left((1-3\xi) - \frac{4E^2\xi^2}{\boldsymbol{p}^2}\right)c_1^2 c_2\right] \end{aligned}$$

Bern, Parra-Martinez, RR, Ruf, Solon, Shen, Zeng

Parts of 4PM Hamiltonian from QFT techniques:

Bern, Parra-Martinez, RR, Ruf, Solon, Shen, Zeng

$$\mathcal{M}_4^{\rm p} = -\frac{35\left(1-18\sigma^2+33\sigma^4\right)}{8\left(\sigma^2-1\right)} \qquad \text{(p p p)}$$

$$\mathcal{M}_4^{\rm t} = r_1 + r_2 \log\left(\tfrac{\sigma+1}{2}\right) + r_3 \frac{\operatorname{arccosh}(\sigma)}{\sqrt{\sigma^2-1}} \qquad \text{(p r r)}$$

$$\mathcal{M}_4^{\pi^2} = r_4\pi^2 + r_5\,\mathrm{K}\left(\tfrac{\sigma-1}{\sigma+1}\right)\mathrm{E}\left(\tfrac{\sigma-1}{\sigma+1}\right) + r_6\,\mathrm{K}^2\left(\tfrac{\sigma-1}{\sigma+1}\right) + r_7\,\mathrm{E}^2\left(\tfrac{\sigma-1}{\sigma+1}\right) \qquad \text{(p p p)}$$

$$\mathcal{M}_4^{\rm rem} = r_8 + r_9 \log\left(\tfrac{\sigma+1}{2}\right) + r_{10}\tfrac{\operatorname{arccosh}(\sigma)}{\sqrt{\sigma^2-1}} + r_{11}\log(\sigma) + r_{12}\log^2\left(\tfrac{\sigma+1}{2}\right) + r_{13}\tfrac{\operatorname{arccosh}(\sigma)}{\sqrt{\sigma^2-1}}\log\left(\tfrac{\sigma+1}{2}\right) + r_{14}\tfrac{\operatorname{arccosh}^2(\sigma)}{\sigma^2-1}$$
$$+ r_{15}\,\mathrm{Li}_2\left(\tfrac{1-\sigma}{2}\right) + r_{16}\,\mathrm{Li}_2\left(\tfrac{1-\sigma}{1+\sigma}\right) + r_{17}\tfrac{1}{\sqrt{\sigma^2-1}}\left[\mathrm{Li}_2\left(-\sqrt{\tfrac{\sigma-1}{\sigma+1}}\right) - \mathrm{Li}_2\left(\sqrt{\tfrac{\sigma-1}{\sigma+1}}\right)\right] \qquad \text{(p p p) + (p r r)}$$

- Remarkably compact given that it is the result of higher-loop GR calculation
- Derived with Feynman prescription $i\epsilon$
- Real part identical with Damour’s principal-value prescription for conservative dynamics
- Amplitudes and scattering angles have simple mass dependence

$$\mathcal{M} \sim 1 \oplus \nu \oplus \cdots \oplus \nu^{[L/2]} \qquad \nu = \frac{m_1 m_2}{m_1+m_2}$$

  - Initially observed by Antonelli, Buonanno, Steinhoff, van de Meent, Vines in the 3PM angle
  - Thorough understanding by Damour: *good mass polynomiality rule*
  - From amplitudes perspective it is a consequence of Lorentz invariance

Parts of 4PM Hamiltonian from QFT techniques: Bern, Parra-Martinez, RR, Ruf, Solon, Shen, Zeng

$$\mathcal{M}_4^{\rm p} = -\frac{35\left(1-18\sigma^2+33\sigma^4\right)}{8\left(\sigma^2-1\right)} \qquad \text{(p p p)}$$

$$\mathcal{M}_4^{\rm t} = r_1 + r_2 \log\left(\tfrac{\sigma+1}{2}\right) + r_3 \frac{\operatorname{arccosh}(\sigma)}{\sqrt{\sigma^2-1}} \qquad \text{(p r r)}$$

$$\mathcal{M}_4^{\pi^2} = r_4\pi^2 + r_5\,\mathrm{K}\left(\tfrac{\sigma-1}{\sigma+1}\right)\mathrm{E}\left(\tfrac{\sigma-1}{\sigma+1}\right) + r_6\,\mathrm{K}^2\left(\tfrac{\sigma-1}{\sigma+1}\right) + r_7\,\mathrm{E}^2\left(\tfrac{\sigma-1}{\sigma+1}\right) \qquad \text{(p p p)}$$

$$\mathcal{M}_4^{\rm rem} = r_8 + r_9 \log\left(\tfrac{\sigma+1}{2}\right) + r_{10}\tfrac{\operatorname{arccosh}(\sigma)}{\sqrt{\sigma^2-1}} + r_{11}\log(\sigma) + r_{12}\log^2\left(\tfrac{\sigma+1}{2}\right) + r_{13}\tfrac{\operatorname{arccosh}(\sigma)}{\sqrt{\sigma^2-1}}\log\left(\tfrac{\sigma+1}{2}\right) + r_{14}\,\tfrac{\operatorname{arccosh}^2(\sigma)}{\sigma^2-1}$$
$$+ r_{15}\,\mathrm{Li}_2\left(\tfrac{1-\sigma}{2}\right) + r_{16}\,\mathrm{Li}_2\left(\tfrac{1-\sigma}{1+\sigma}\right) + r_{17}\,\tfrac{1}{\sqrt{\sigma^2-1}}\left[\mathrm{Li}_2\left(-\sqrt{\tfrac{\sigma-1}{\sigma+1}}\right) - \mathrm{Li}_2\left(\sqrt{\tfrac{\sigma-1}{\sigma+1}}\right)\right] \qquad \text{(p p p) + (p r r)}$$

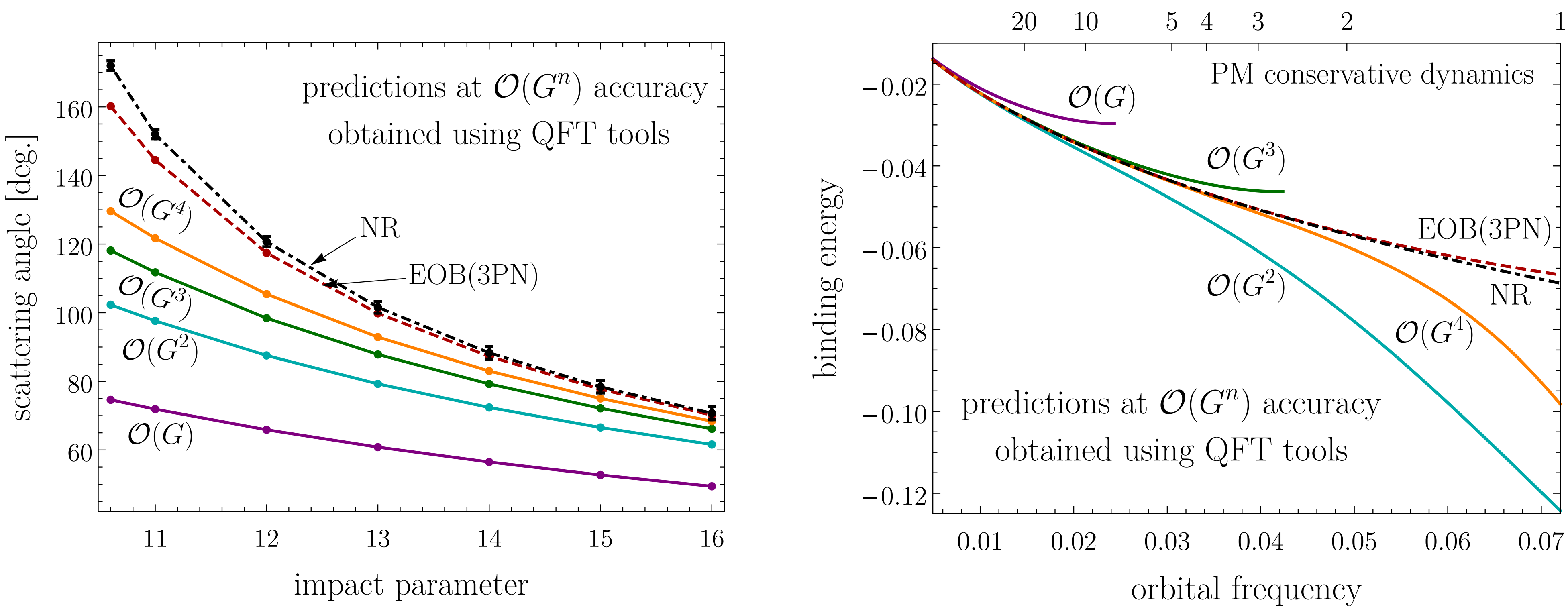
- Reproduces available 6PN results in the overlap and through $\mathcal{O}(\nu)$ — Bini, Damour, Geralico; Blümlein, Maier, Marquard, Schäfer

- All-order-in-velocity verification: Feynman graphs & PM EFT — 3PM: Cheung, Solon; Kälin, Liu, Porto; 4PM: Dlapa, Kälin, Liu, Porto

- $\mathcal{O}(\nu^2)$ difference with Blümlein et al. and Foffa, Sturani remains to be fully resolved, though consensus is that good mass polynomiality should hold — more in Stefano Foffa's talk

- Analytic continuation to bound motion is nontrivial because of the tail effect: boundary-to-bound map for local & universal non-local; complete understanding is an important open problem — Bini, Damour; Kälin, Porto; +Cho

Conservative binary dynamics: comparison with NR; no resummation



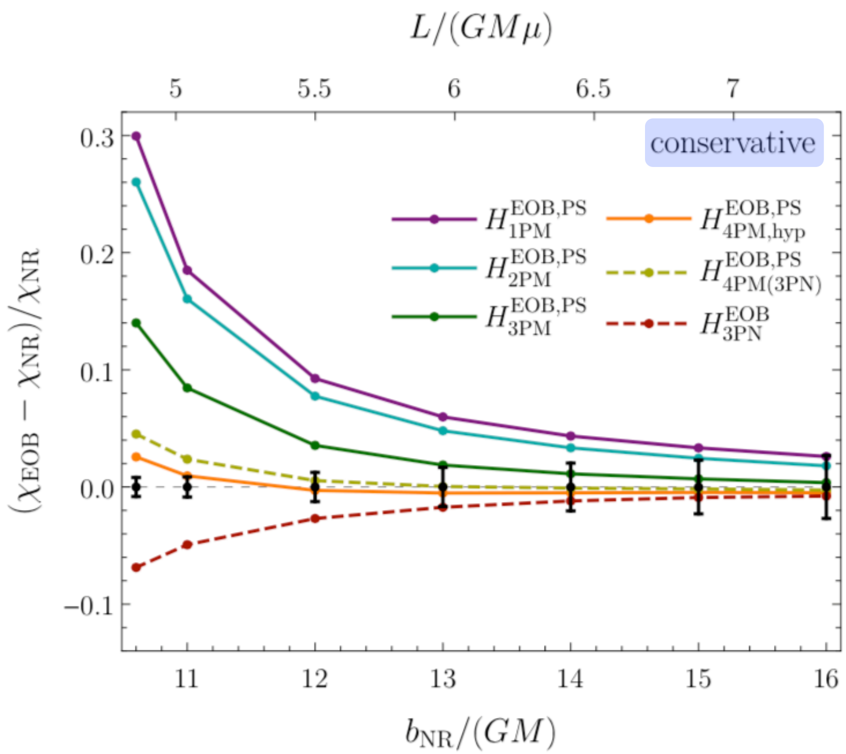
Khali, Buonanno, Steinhoff, Vines

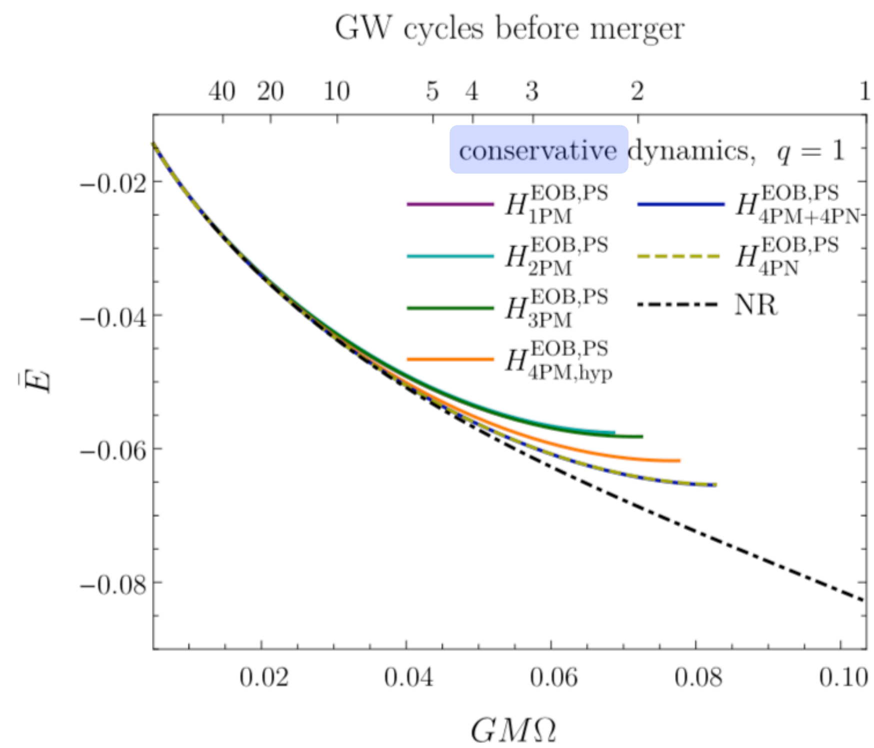
Snowmass white paper: Buonanno, Khalil,O'Connell RR, Solon, Zeng

Numerical Relativity data from Damour, Guercilena, Hinder, Hopper, Nagar, Rezzolla

Conservative binary dynamics through EOB

Khali, Buonanno, Steinhoff, Vines





- PN Hamiltonian is slightly better for circular orbits than the naively continued 4PM hyperbolic H and hyperbolic 4PM Hamiltonian is better on hyperbolic orbits than the 3PN Hamiltonian
- Better comparison should include radiative effects

Radiation reaction effects through $\mathcal{O}(G^4)$

3PM radiation reaction effect to scattering angle — Di Vecchia, Heisenberg, Russo, Veneziano; Damour

solves the infamous mass singularity puzzle $\chi^{\rm cons}_{\rm 3PM}\big|_{p\to\infty} \propto \ln \frac{p^2}{m^2}$

A general approach to incorporating leading-order radiated energy and angular momentum

$$2\chi^{\rm rr} = \frac{\partial \chi^{\rm cons}}{\partial E}\Delta E + \frac{\partial \chi^{\rm cons}}{\partial J}\Delta J$$

Bini, Damour

4PM radiation reacted impulse (or angle): $\Delta p = \Delta p^{\rm cons} + \Delta p^{\rm rr,\ even} + \Delta p^{\rm rr\ odd}$

dissipative/odd part:
- 3PM energy loss — Herrmann, Parra-Martinez, Ruf, Zeng
- 3PM angular momentum loss — Manohar, Ridgway, Shen

complete (even+odd) 4PM impulse — Dlapa, Kälin, Neef, Porto

Radiation reaction force ⟶ EOB

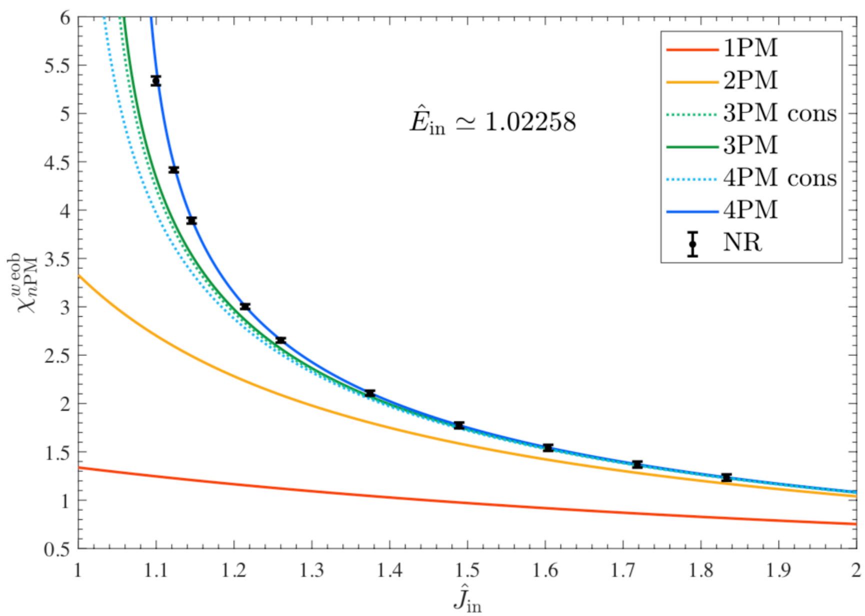
$$\chi_1 = \frac{2\sigma^2 - 1}{\sqrt{\sigma^2 - 1}} \qquad \chi_2 = \frac{3\pi}{8}\frac{5\sigma^2 - 1}{\sqrt{1 + 2\nu(\sigma^2 - 1)}}$$

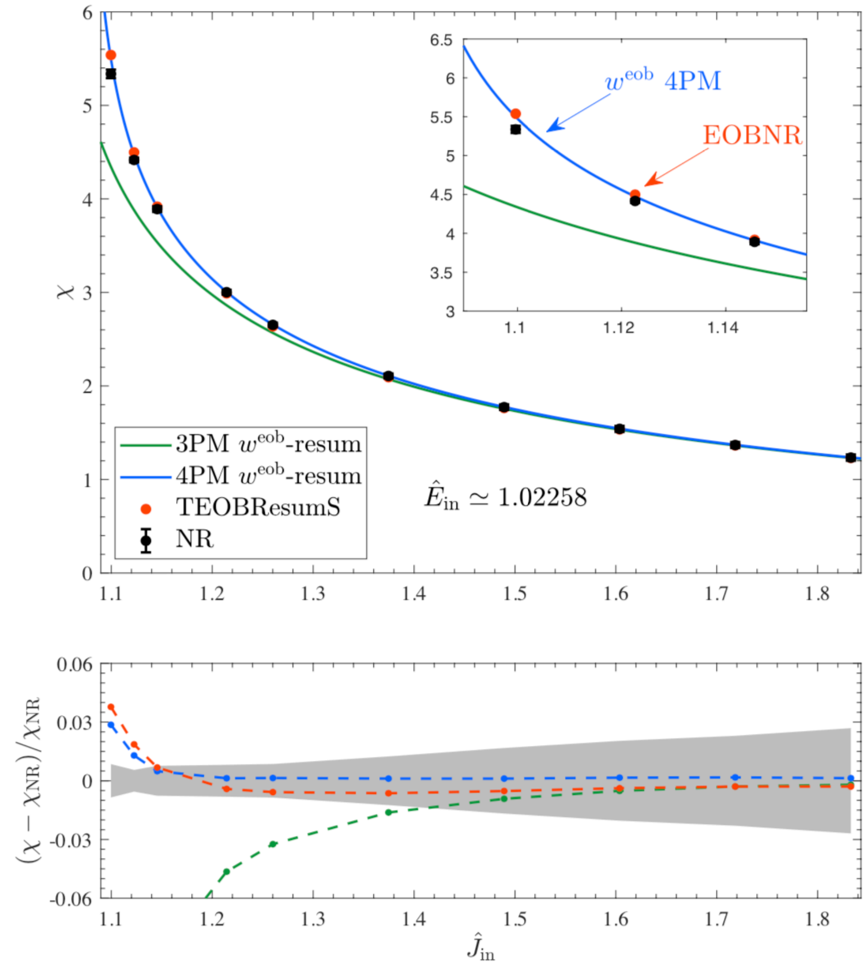
$$\chi_3 = \chi_3^{\rm cons} + \chi_3^{\rm rr} \qquad \chi_4 = \chi_4^{\rm cons} + \chi_4^{\rm rr,\ odd} + \chi_4^{\rm rr,\ even}$$

⟶

$$\dot{\boldsymbol{x}} = \frac{\partial H}{\partial \boldsymbol{p}} \qquad \dot{\boldsymbol{p}} = -\frac{\partial H}{\partial \boldsymbol{x}} + \boldsymbol{F}_{\rm rr}$$

One of the two EOB-style proposals of Damour, Retegno : $\chi_{\rm nPM}^{w\ eob}(\sigma,j) \equiv 2j\int_0^{\bar{u}_{\max}(\sigma,j)} \frac{d\bar{u}}{\sqrt{p_\infty^2 + w_{\rm nPM}(\bar{u},\sigma) - j^2\bar{u}^2}} - \pi$





- PM EOB with radiation reaction improves comparison w/ NR to percent level precision for spinless scattering
- New motivation for EOB studies of PM data for a precise analytic description of binary systems

Waveforms from amplitudes/(W)QFT – governed by 5-point amplitudes

- Leading order scattering waveform, leading order differential energy flux from WQFT

Jakobsen, Mogull, Plefka, Steinhoff

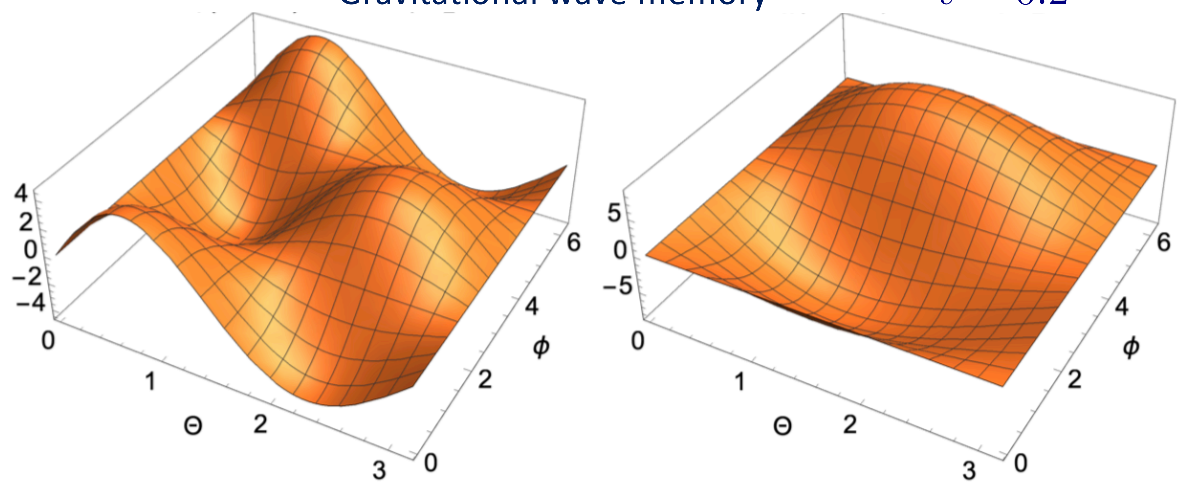
Gravitational wave memory $v = 0.2$

$$\kappa h_{ij}^{\mathrm{TT}} = \frac{f_{ij}}{r}$$

$$f_{ij} = f_{+}\,(e_{+})_{ij} + f_{\times}\,(e_{\times})_{ij}$$

$$e_{+/\times}^{\mu\nu} = \hat{\theta}^{\mu}\hat{\theta}^{\nu} - / + \hat{\phi}^{\mu}\hat{\phi}^{\nu}$$

$$\hat{\theta} = \partial_{\theta}\hat{x} \quad \hat{\theta} = \frac{1}{\sin\theta}\partial_{\phi}\hat{x}$$



- See Graham Brown's talk for progress towards classical one-loop 5-point amplitude

Brandhuber, Brown, Chen, De Angelis, Gowdy, Travaglini; Herderschee, RR, Teng

See also Matteo Sergola's talk

All things spinning: more spins and more loops

Extensive work in the PN expansion

Hanson, Regge, Bailey, Israel, Yee, Bander, Tulczyjew, Damour, Buonanno, Levi, Steinhoff, Porto, Rothstein, Perodin, Khriplovich, Pomeranski, Antonelli, Faye, Hinderer, Kavanagh, Khalil, Mandal, Mastrolia, Patil, Vines, Kunst, Mougiakakos, Kim, Yin, Morales, Vieira, McLeod, von Hippel, Teng, *etc.*

Systematic worldline all-orders-in-spin EFT approach

Levi, Steinhoff

PN order	0	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5
S^0	0PN	1PN		2PN		3PN		4PN		5PN		6PN	
S^1			LO		NLO		N2LO		N3LO		N4LO		
S^2				LO		NLO		N2LO		N3LO			
S^3							LO		NLO				
S^4								LO		NLO			
S^5											LO		NLO
S^6												LO	

(L+1)PM/loop order
tree
1-loop
2-loop
3-loop
4-loop
5-loop
6-loop
7-loop

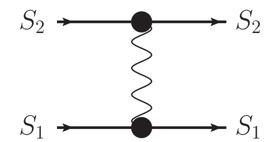
Credit: J. Vines

Six/Seven amplitudes-based approaches to higher-spin interactions

Conjectured to describe interactions of Kerr black holes

- 3-point ”minimal” amplitude for arbitrary-spin particles — Arkani-Hamed, Huang, Huang
  - Naïve higher-point amplitudes with spurious poles at $S^{\geq 5}$; fixed — (2022) Chen, Chung, Huang, Kim
- Exponentiated soft factors — Guevara, Ochirov, Vines
  - Same higher-point spurious pole issue as AHH at $S^{\geq 5}$
- 4d EFT for arbitrary-spin particles in classical limit — Bern, Luna, RR, Shen, Zeng
- Heavy-particle EFT-like theory — see Rafael Aoude’s talk — Aoude, Haddad, Helset
- Worldline QFT with spin (analogous to point-particle limit of NSR string theory) — Jakobsen, Mogull, Plefka, Steinhoff
- Fixed order in spin from fixed quantum spin — Spin ½ and 1: Holstein, Ross, Vaydia, Cachazo, Guevara, Bautista, Febres Cordero, Kraus, Lin, Ruf, Zeng; Damgaard, Haddad, Helset, …
  - $\text{spin-}k \longrightarrow S^{2k}$
  - see Paolo Pichini’s talk — spin 5/2: Chiodaroli, Johansson, Pichini
- See Alex Ochirov’s talk for the seventh

- “The truth”: Scattering of stuff off Kerr black holes



- Kerr gravitational form factor ⟶ 1PM amplitude:

Vines

$$\hat{T}^{\mu\nu}(a,q) = m\exp(ia*q)^{(\mu}{}_{\rho}u^{\nu)}u^{\rho} = m\cosh(a\cdot q)u^{\mu}u^{\nu} - \frac{i}{a\cdot q}\sinh(a\cdot q)\,q^{\rho}S(p)_{\rho}{}^{(\mu}u^{\nu)}$$

$$u_i^{\mu} = p_i^{\mu}/m_i \qquad a_i^{\mu} = S_i^{\mu}/m_i$$
$$\mathcal{E}_i = -i\epsilon^{\mu\nu\rho\lambda}u_{1\mu}u_{2\nu}q_{\rho}a_{i\lambda}$$

- Extension to general compact objects using a 4d EFT valid in the classical limit mirroring the worldline action of Levi & Steinhoff plus more QFT-specific operators

Bern, Luna, RR, Shen, Zeng

Bern, Kosmopoulos, Luna, RR, Teng

$$\mathcal{L} = -R(e,\omega) + \frac{1}{2}g^{\mu\nu}\nabla(\omega)_{\mu}\phi_s\nabla(\omega)_{\nu}\phi_s - \frac{1}{2}m^2\phi_s\phi_s + \mathcal{L}_{\mathrm{LS}} + \mathcal{L}_H + \mathcal{L}_{R^2}$$

$$\mathcal{L}_{\mathrm{LS}} = \sum_{n=1}^{\infty}\frac{(-1)^n}{(2n)!}\frac{C_{ES^{2n}}}{m^{2n}}\nabla(\omega)_{f_{2n}}\cdots\nabla(\omega)_{f_3}R_{f_1af_2b}\nabla(\omega)^a\phi_s\,\mathbb{S}^{(f_1}\ldots\mathbb{S}^{f_{2n})}\nabla(\omega)^b\phi_s$$
$$-\sum_{n=1}^{\infty}\frac{(-1)^n}{(2n+1)!}\frac{C_{BS^{2n}}}{m^{2n+1}}\nabla(\omega)_{f_{2n+1}}\cdots\nabla(\omega)_{f_3}\frac{1}{2}\epsilon_{ab(c|f_1}R^{ab}{}_{|d)\,f_2}\nabla(\omega)^c\phi_s\mathbb{S}^{(f_1}\ldots\mathbb{S}^{f_{2n+1})}\nabla(\omega)^d\phi_s$$

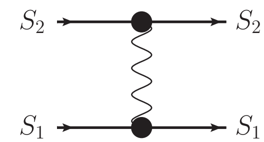
Equivalent classically and w/ covariant spin supplementary condition

Inequivalent q.m.

$$\mathcal{L}_H = -\sum_{n=1}^{\infty}\frac{(-1)^n(2n-1)}{(2n)!(2n+1)}\frac{H_{2n}}{m^{2n-2}}\nabla_{f_{2n}}\ldots\nabla_{f_3}R_{(a|f_1|b)f_2}\phi_s M^{a(f_1}M^{|b|f_2}\mathbb{S}^{f_3}\ldots\mathbb{S}^{f_{2n})}\phi_s$$
$$+\sum_{n=1}^{\infty}\frac{(-1)^n n}{(2n+1)!(n+1)}\frac{H_{2n+1}}{m^{2n-1}}\nabla_{f_{2n+1}}\ldots\nabla_{f_3}*R_{(a|f_1|b)f_2}\phi_s M^{a(f_1}M^{|b|f_2}\mathbb{S}^{f_3}\ldots\mathbb{S}^{f_{2n+1})}\phi_s$$

- Form factor exhibits double-copy structure; use/extension at higher points is an open question

- Kerr gravitational form factor ⟶ 1PM amplitude:



Vines

$$\hat{T}^{\mu\nu}(a,q) = m\exp(ia * q)^{(\mu}{}_\rho u^{\nu)} u^\rho = m\cosh(a\cdot q)u^\mu u^\nu - \frac{i}{a\cdot q}\sinh(a\cdot q)\, q^\rho S(p)_\rho{}^{(\mu} u^{\nu)}$$

$u_i^\mu = p_i^\mu/m_i \quad a_i^\mu = S_i^\mu/m_i$

$\mathcal{E}_i = -i\epsilon^{\mu\nu\rho\lambda} u_{1\mu} u_{2\nu} q_\rho a_{i\lambda}$

- Extension to general compact objects using a 4d EFT valid in the classical limit mirroring the worldline action of Levi & Steinhoff plus more QFT-specific operators

  Bern, Luna, RR, Shen, Zeng

  Bern, Kosmopoulos, Luna, RR, Teng

- Form factor exhibits double-copy structure; use/extension at higher points is an open question

- 2PM Kerr conservative amplitudes and observables

  - Aligned-spin configuration $S||L$; all spins $\sigma = (1-v^2)^{-1/2}$

    Guevara, Ochirov, Vines

$$\chi_2^{\text{aligned}} = \pi G^2 E \frac{m_2}{2v^4}\frac{\partial}{\partial b}\int_{C_{R>1/v}} \frac{dz}{2\pi i}\frac{(1-vz)^4}{(z^2-1)^{3/2}}\left|b - za_2 - \frac{z-v}{1-vz}a_1\right|^{-1} + (m_1 \leftrightarrow m_2, a_1 \leftrightarrow a_2)$$

  - Arbitrary spin orientations – more complicated (more in a bit)

- “Easier”: general compact objects (because there is no need to specify couplings)

E.g. through third power of the spin:

Bern, Kosmopoulos, Luna, RR, Teng

$$\mathcal{M}^{\triangle+\nabla}(q_\perp,p) = \frac{2\pi^2 G^2 \varepsilon_1\cdot\varepsilon_4 \varepsilon_2\cdot\varepsilon_3}{\sqrt{-q^2}} \sum_n \sum_i \alpha^{(n,i)} \mathcal{O}^{(n,i)}$$

	i		i		i	
$\mathcal{O}^{(2,i)}$	1	$\mathcal{E}_1^2$	2	$q^2(u_2\cdot a_1)^2$	3	$(q\cdot a_1)^2$
$\mathcal{O}^{(4,i)}$	1	$\mathcal{E}_1^4$	2	$q^2(u_2\cdot a_1)^2\mathcal{E}_1^2$	3	$q^4(u_2\cdot a_1)^4$
	4	$(q\cdot a_1)^2\mathcal{E}_1^2$	5	$q^2(q\cdot a_1)^2(u_2\cdot a_1)^2$	6	$(q\cdot a_1)^4$

$$\mathcal{O}^{(3,i)} = \mathcal{E}_1\mathcal{O}^{(2,i)} \qquad \mathcal{O}^{(5,i)} = \mathcal{E}_1\mathcal{O}^{(4,i)}$$

$$\alpha^{(2,i)} = \frac{m_1^2 m_2^2}{16(-1+\sigma^2)^2}(\gamma^{(2,i)}m_1 + \delta^{(2,i)}m_2) \qquad \alpha^{(3,i)} = \frac{m_1^2 m_2^2\sigma}{8(-1+\sigma^2)^2}(\gamma^{(3,i)}m_1 + 2\delta^{(3,i)}m_2)\,, \qquad \mathcal{E}_i = i\epsilon^{\mu\nu\rho\sigma}u_{1\mu}u_{2\nu}q_\rho a_{i\sigma}$$

$$\alpha^{(4,i)} = \frac{m_1^2 m_2^2}{1536(-1+\sigma^2)^3}\left(\gamma^{(4,i)}m_1 + \frac{8}{5}\delta^{(4,i)}m_2\right) \qquad \alpha^{(5,i)} = \frac{m_1^2 m_2^2\sigma}{768(-1+\sigma^2)^3}\left(\gamma^{(5,i)}m_1 + \frac{1}{75}\delta^{(5,i)}m_2\right) \qquad \delta^{(k,i)} = \sum_{\ell=0} \delta_\ell^{(k,i)}\sigma^{2\ell}$$

i	$\gamma^{(2,i)}$	i	$\gamma^{(2,i)}$
1	$7+23C_2 - Z_{2,1}\sigma^2(102-95\sigma^2)$	3	$12Z_{2,2}(\sigma^2-1)^2(5\sigma^2-1)$
2	$5-11C_2+5Z_{2,1}\sigma^2(6-7\sigma^2)$		
i	$\gamma^{(3,i)}$	i	$\gamma^{(3,i)}$
1	$Z_{3,1}(5-9\sigma^2)$	3	$4Z_{3,2}(\sigma^2-1)(5\sigma^2-3)$
2	$Z_{3,1}(7\sigma^2-3)$		

$Z_{2,1} = C_2 + 1$	$Z_{2,2} = C_2 - 1$
$Z_{3,1} = 3C_2 + C_3$	$Z_{3,2} = C_2 - C_3$

i	$\delta_0^{(2,i)}$	$\delta_1^{(2,i)}$	$\delta_2^{(2,i)}$	$\delta_3^{(2,i)}$
1	$8Z_{2,1}$	$-(68+52C_2)$	$60Z_{2,1}$	0
2	$4(3-C_2)$	$-12Z_{2,1}$	0	0
3	$-4Z_{2,2}$	$68Z_{2,2}$	$-124Z_{2,2}$	$60Z_{2,2}$

i	$\delta_0^{(3,i)}$	$\delta_1^{(3,i)}$
1	$3(H_2-2)H_2-(C_2-8)C_2$	$C_2(2C_2-13)-2C_3-3(H_2-2)H_2$
2	$C_2(4C_2-5)+2C_3-5(H_2-2)H_2$	$5(C_2-H_2)(2-C_2-H_2)$
3	$(5-2C_2)C_2-2C_3+(H_2-2)H_2$	$2\left[C_2(3C_2-8)+4C_3-(H_2-2)H_2\right]$

$$\delta_2^{(3,1)} = \delta_2^{(3,2)} = 0\,, \qquad \delta_2^{(3,3)} = (11-4C_2)C_2 - 6C_3 + (H_2-2)H_2$$

E.g. through third power of the spin:

Bern, Kosmopoulos, Luna, RR, Teng

$$\mathcal{M}^{\triangle+\nabla}(q_\perp, p) = \frac{2\pi^2 G^2 \varepsilon_1 \cdot \varepsilon_4 \varepsilon_2 \cdot \varepsilon_3}{\sqrt{-q^2}} \sum_n \sum_i \alpha^{(n,i)} \mathcal{O}^{(n,i)}$$

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$$\mathcal{O}^{(3,i)} = \mathcal{E}_1 \mathcal{O}^{(2,i)} \qquad \mathcal{O}^{(5,i)} = \mathcal{E}_1 \mathcal{O}^{(4,i)}$$

$$\alpha^{(2,i)} = \frac{m_1^2 m_2^2}{16(-1+\sigma^2)^2}(\gamma^{(2,i)} m_1 + \delta^{(2,i)} m_2) \qquad \alpha^{(3,i)} = \frac{m_1^2 m_2^2 \sigma}{8(-1+\sigma^2)^2}(\gamma^{(3,i)} m_1 + 2\delta^{(3,i)} m_2)\,, \qquad \mathcal{E}_i = i\epsilon^{\mu\nu\rho\sigma} u_{1\mu} u_{2\nu} q_\rho a_{i\sigma}$$

$$\alpha^{(4,i)} = \frac{m_1^2 m_2^2}{1536(-1+\sigma^2)^3}\left(\gamma^{(4,i)} m_1 + \frac{8}{5}\delta^{(4,i)} m_2\right) \qquad \alpha^{(5,i)} = \frac{m_1^2 m_2^2 \sigma}{768(-1+\sigma^2)^3}\left(\gamma^{(5,i)} m_1 + \frac{1}{75}\delta^{(5,i)} m_2\right) \qquad \delta^{(k,i)} = \sum_{\ell=0} \delta_\ell^{(k,i)} \sigma^{2\ell}$$

Aligned scattering angle:

in agreement with results of Vines and of Levi and Yin for $H_2 = 1$

$$\chi_{2,2}^{\text{alligned}} = \frac{3\pi {a_1}^2 G^2 {m_2}^2 \left(C_2\left(45\sigma^4 - 42\sigma^2 + 5\right) + 3\left(5\sigma^4 - 6\sigma^2 + 1\right)\right)}{16 b^4 \left(\sigma^2 - 1\right)^2}$$

$$\chi_{2,3}^{\text{alligned}} = -\frac{3\pi {a_1}^3 G^2 {m_2}^2 \sigma \left(C_2\left(15\sigma^2 - 11\right) + 2C_3\left(5\sigma^2 - 1\right) + 5(H_2 - 2)H_2\left(\sigma^2 - 1\right)\right)}{4 b^5 \left(\sigma^2 - 1\right)^{3/2}}$$

How many parameters does it take to describe a spinning compact object?

- Worldline description: one (multipole) per power of spin

Levi, Steinhoff

- 4D EFT: In the absence of further structure/constraints, gauge-invariant pieces of the gravitational Compton amplitude are independent, e.g.

$$\mathcal{A}^{+-}_{\text{Compton}}(S^2) \propto \frac{1}{2}\Big[(Q_3\cdot a - Q_4\cdot a)^2 + (C_2-1)\Big((Q_4\cdot a)^2 + (Q_3\cdot a)^2\Big)\Big]$$

Bern, Kosmopoulos, Luna, RR, Teng

$$\mathcal{A}^{+-}_{\text{Compton}}(S^3) \propto \frac{1}{6}\Big[(Q_3\cdot a - Q_4\cdot a)^3 - 3(C_2-1)(Q_3\cdot a)(Q_4\cdot a)(Q_3\cdot a - Q_4\cdot a) + 6(C_2-H_2)(C_2+H_2-2)(Q_4\cdot a)(Q_3\cdot a)(w_3\cdot a) + (C_3-1)\Big((Q_3\cdot a)^3 - (Q_4\cdot a)^3\Big)\Big]$$

Agree for $H_2 = 1$ with Saketh, Vines obtained by scattering plane gravitational waves off compact objects

Is there additional structure/constraints? If not, what is the physical meaning of the extra parameters?

see also Paolo Pichini's talk

What is the definition of a Kerr black hole from QFT perspective?

A proposal at 2PM order:

- symmetry/special spin-dependent structures $a_i^\mu \to a_i^\mu + \xi_i \frac{q^\mu}{q^2}$
- high energy behavior no worse than at tree level

Bern, Kosmopoulos, Luna, RR, Teng; Aoude, Haddad, Helset

The consequence(s):

- Certain operators are forbidden
  (use $u_2 \cdot q = q^2/2$)

	i		i		i	
$\mathcal{O}^{(2,i)}$	1	$\mathcal{E}_1^2$	2	$q^2(u_2\cdot a_1)^2$	3	~~$(q\cdot a_1)^2$~~
$\mathcal{O}^{(4,i)}$	1	$\mathcal{E}_1^4$	2	$q^2(u_2\cdot a_1)^2\mathcal{E}_1^2$	3	$q^4(u_2\cdot a_1)^4$
	4	~~$(q\cdot a_1)^2\mathcal{E}_1^2$~~	5	~~$q^2(q\cdot a_1)^2(u_2\cdot a_1)^2$~~	6	~~$(q\cdot a_1)^4$~~

consistent with results of Liu, Porto, Yang; Kosmopoulos, Luna (S^2); Chen, Chung, Huang, Kim (S^4)

- Uniquely fixes the amplitude at least through $S_1^n S_2^{5-n}$

Possible approach to a proof: symmetry must be rooted in GR study scattering off Kerr black holes

- Used to derive scattering matrix all orders in spin *S* on *S*=0 at 2PM

Aoude, Haddad, Helset

See Rafael Aoude's talk

State of the art spin-dependent results at 3PM order:

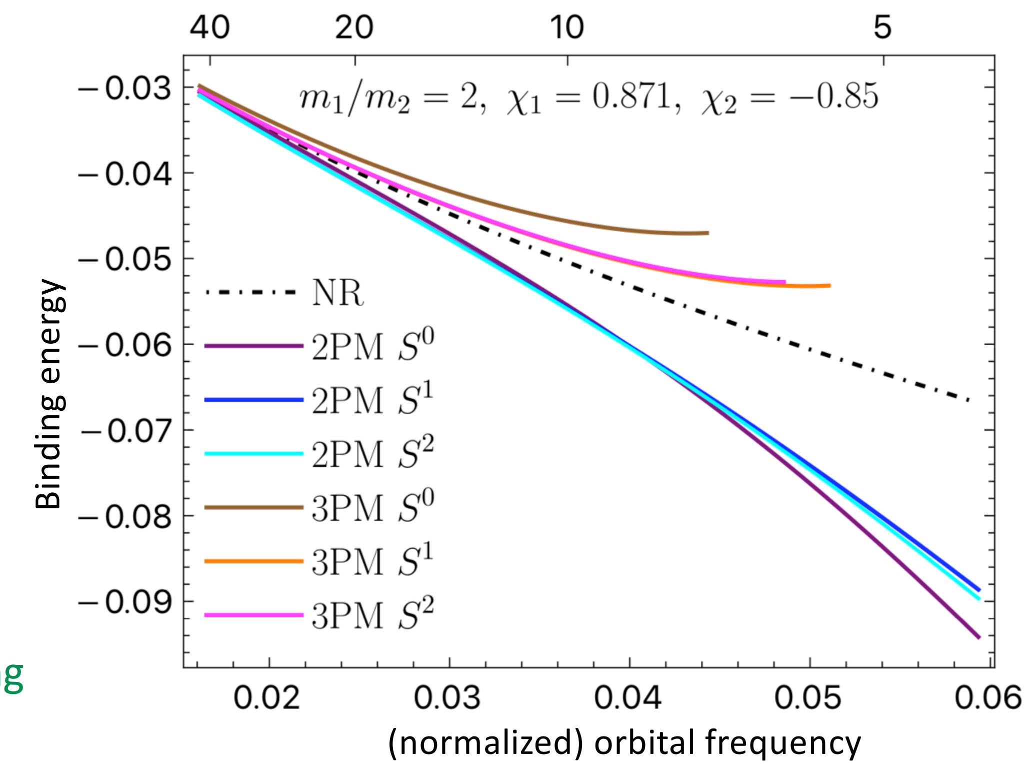
- Conservative $\mathcal{O}(S^2)$ Hamiltonian from matching with positive energy EFT Febres Cordero, Kraus, Lin, Ruf, Zeng
- Conservative and radiative $\mathcal{O}(S^2)$ impulse and spin kick, radiated *E*, Hamiltonian, from WQFT; arbitrary spin orientations Jakobsen, Mogull

B2B map to bound motion:

- Small change *SO* ⟶ S^2 at fixed PM order
- Large improvement between 2PM and 3PM next order should be interesting!

Scattering regime – better showcase of PM:

- Comparison with NR should be interesting – data needed!
- EOB resummation & suitable inclusion of radiation reaction effects should be interesting



numerical data from SXS

State of the art spin-dependent results at 3PM order:

- Conservative $\mathcal{O}(S^2)$ Hamiltonian from matching with positive energy EFT — Febres Cordero, Kraus, Lin, Ruf, Zeng

- Conservative and radiative $\mathcal{O}(S^2)$ impulse and spin kick, radiated *E*, Hamiltonian, from WQFT; aligned and arbitrary spin orientations — Jakobsen, Mogull

  $\mathcal{O}(S^2)$ radiated momentum also from a worldline Routhian-based formalism — Riva, Vernizzi, Wong

- From eikonal: radiative scattering angle for aligned spins, radiated angular momentum and $\omega \to 0$ of energy spectrum to all orders in spin and arbitrary orientations — Alessio, di Vecchia

See talk by Francesco Allesio

Results on tidal effects, beyond GR, and many-body problem from amplitudes

- Conservative effects for a variety of tidal operators; w & w/o spin

  Cheung, Solon; Kälin, Liu, Porto
  Haddad, Helset;+Aoude
  Bern, Parra-Martinez, RR, Sawyer, Shen; Cheung, Solon, Shah

- Leading-order waveforms from tidally-deformed spinless bodies

  Mougiakakos, Riva, Vernizzi

- Hamiltonians including beyond-GR physics

  Cheung, Solon; Bern, Parra-Martinez, RR, Sawyer, Shen
  Edmond, Moynihan; Christofoli; Accettulli Huber, Brandhuber, De Angelis, Travaglini;
  Carrillo-González, de Rham, Tolley

- Hamiltonians for N-body interactions

  Loebbert, Plefka, Shi, Wang;
  Solon, Jones

- Results and conjectures on vanishing Love nrs. for BH from standard methods; symmetries args

  Chia; Hui, Joyce, Penco, Santoni, Solomon; Charalambous, Dubovski, Ivanov
  Levi, Yin

  Relation between worldline and 4d QFT tidal operators?

Theoretical structures relevant in the classical limit

Theoretical structures relevant in the classical limit

- High energy limit – exposes interplay between inclusive and exclusive observables, soft graviton theorems and universality of gravitational interactions

  e.g. absence of collinear/mass singularities in inclusive observables

Block, Nordsiek;
Kinoshita, Lee, Nauenberg

$$\mathcal{M} \to -8\pi G^3 s^2 \log(-t) \log\left(\frac{m_1 m_2}{s}\right)$$

soft graviton theorem: Di Vecchia, Heissenberg, Russo, Veneziano

linear response: Damour

More information from 4 and 5-point amplitudes in simplifying limits?

- Nonperturbative structures: (1) exponentiation of amplitudes

  - Eikonal exponentiation with and without spin; relation to observables: $i\mathcal{M} = e^{i\delta} - 1$

$$\Delta\mathcal{O} = e^{-i\delta\mathcal{D}}[\mathcal{O}, e^{i\delta\mathcal{D}}] \qquad \delta\mathcal{D}g \equiv \delta g + \mathcal{D}_{SL}(\delta, g) \qquad \mathcal{D}_{SL}(\delta, g) \equiv -\sum_{a=1,2} \epsilon^{ijk} S_a^k \frac{\partial\delta}{\partial S_a^i} \frac{\partial g}{\partial L^j}$$

See Guilia Isabella's talk

Di Vecchia, Heissenberg, Russo, Veneziano; Damgaard, Plante, Vanhove;
Bern, Ita, Parra-Martinez, Ruf; Bern, Luna, RR, Shen, Zeng

  - Amplitude-(radial) action relation: $i\mathcal{M} = e^{iI_r} - 1$ $\qquad dI_r = \frac{\chi}{2\pi} dJ + \tau dE$

Bern, Parra-Martinez, RR, Ruf, Shen, Solon, Zeng

curved space: explicit demonstration in probe approx. to all orders in *G* — Kol, O'Connell, Telem

- Nonperturbative structures: (2) "impetus formula"

$$\mathcal{M}(r) = \frac{p(r)^2 - p(\infty)^2}{2E}$$

observed in Bern, Cheung, RR, Shen, Solon, Zeng
formalized by Kälin, Porto

e.g. derive (finite parts of) amplitudes from classical motion

(3) Newman-Janis shift $\phi_{\rm Kerr}(z) = \phi_{\rm Schw}(z + ia)$

Relation between Schwarschild and Kerr solutions through a complex shift

Used for leading order calculations impulse calculation — Arkani-Hamed, Huang, O'Connell

Other uses? (e.g. intriguing w.s. for Kerr) — Guevara, Maybee, Ochirov, O'Connell, Vines

- Analytic continuation and time non-locality
  - Newtonian mechanics: one Hamiltonian determines both bound and unbound motion
  - GR: suitable analytic continuation yields bound observables from unbound ones

  "Boundary to Bound" or "B2B", e.g. $\Delta\Phi(\mathcal{E}, J) = \Delta\chi(\mathcal{E}, J) + \Delta\chi(\mathcal{E}, -J) \quad \mathcal{E} < 0$ — Kälin, Porto

  Applicable for instantaneous + universal (log) nonlocal in time parts of *H* — Cho, Kälin, Porto

  and not for the rest of nonlocal *H* — Damour, Jaranowski, Schäfer

- Relations between amplitude fragments — Cristofoli, Gonzo, Moynihan, O'Connell, Ross, Sergola, White

- Relation to gravitational self-force: mass dep. of classical amplitude and angles (up to factor)

$$\mathcal{M} \sim 1 \oplus \nu \oplus \cdots \oplus \nu^{[L/2]}$$

observed at 3PM by Vines, Steinhoff, Buonanno

"good mass polynomiality rule"

thorough understanding provided by Damour

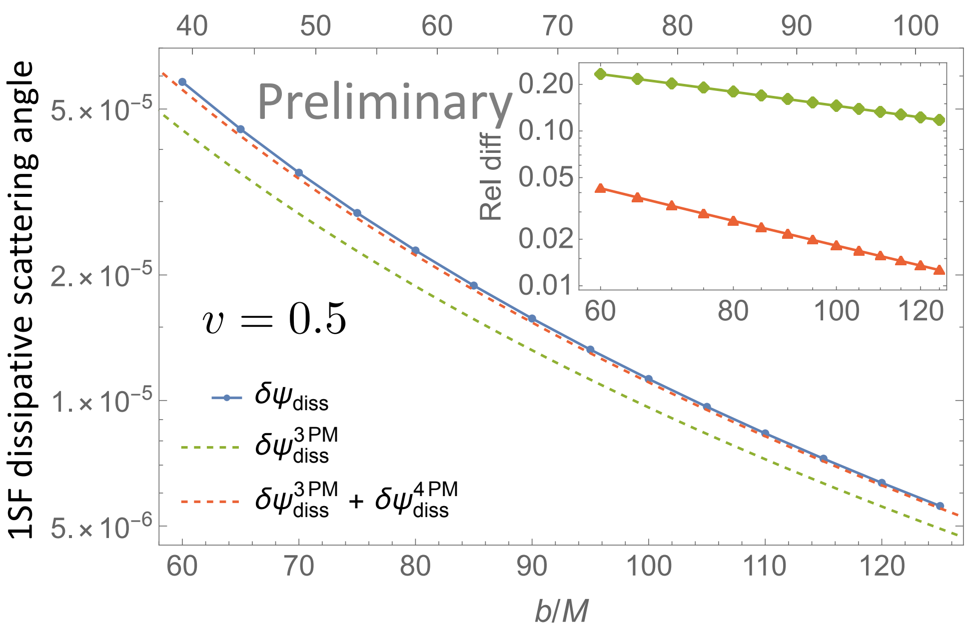
- Search for structure in simpler theories:

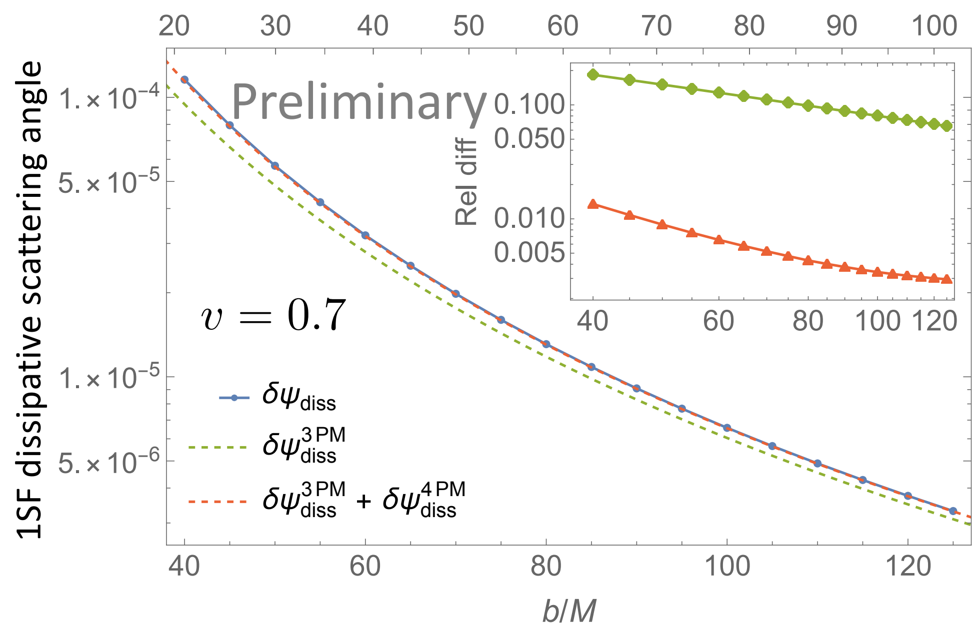
QED — De la Cruz, Maybee, O'Connell, Ross; Bern, Gatica, Herrmann, Luna, Zeng; Saketh, Vines, Steinhoff, Buonanno

a charged scalar model: SF + PM aim to extend both beyond respective validity regime

see Oliver Long's talk "soon" -- Barack, Bern, Herrmann, Long, Parra-Martinez, RR, Ruf, Shen, Solon, Teng, Zeng

1SF scattering angle vs. impact parameter in a particular scalar model “soon” -- Barack, Bern, Herrmann, Long, Parra-Martinez, RR, Shen, Solon, Teng, Zeng





- Percent-level agreement of analytic 4PM dissipative angle and the dissipative 1SF result in the overlap; better at larger impact parameters (as it should)

- Promise of higher-PM order extraction

see Oliver Long’s talk

Tools that enabled state of the art calculations

Developing (computational) tools

Effective field theories:
- positive energy — Cheung, Rothstein, Solon; Bern, Cheung, RR, Shen, Solon, Zeng
- relativistic, spin-dependent — Bern, RR, Shen, Zeng; + Kosmopoulos, Teng
- heavy mass — Brandhuber, Chen, Travaglini, Wen; Damgaard, Haddad, Helset

Observable-based formalism:
- inclusive observables — Kosower, Maybee, O'Connell
- differential observables — Cristofoli, Gonzo, Kosower, O'Connell

Generating functions for observables:
- radial action — Bern, Parra-Martinez, RR, Ruf, Solon, Shen, Zeng
- eikonal — Amati, Ciafaloni, Veneziano; di Vecchia, Heissenberg, Russo, Veneziano
- exponential rep. of S matrix — Damgaard, Planté, Vanhove

Amplitude building blocks & techniques in the classical limit
- Generalized unitarity + tree-level double copy + generalized gauge symmetry
- Loop-level double copy + dilaton projection — Carrasco, Vazquez-Holm
- New amplitudes for higher-spin particles/minimal amplitudes/… — Arkani-Hamed, Huang, O'Connell; Chiodaroli, Johansson, Pichini
- New amplitudes from classical scattering — Bautista, Guevara, Kavanagh, Vines

Developing (computational) tools

2d QFTs (worldline): NRGR, +spin, PM EFT, WQT

Goldberger, Rothstein; Levi Steinhoff; Kälin, Porto; Mogull, Plefka, Steinjoff; +Jakbosen;

new tools: in-in formalism in the PM EFT and WQFT

Dlapa, Kälin, Liu, Porto; Jakobsen, Mogull, Plefka, Sauer

See Gustav Jakobsen's talk

Multiloop integration technology: - automated programs for IBP

Anastasiou, Lazaropoulos; Smirnov, Smirnov; Maierhöffer, Usovitsch, Uwer; Studerus; Lee; Mandal, Mastrolia, Patil; etc

- differential equations

Bern, Dixon, Kosower; Henn, Smirnov

Synergy with traditional approached to the two-body problem

- Exploration of simpler theories

- QED

De la Cruz, Maybee, O'Connell, Ross;Bern, Gatica, Herrmann, Luna, Zeng Saketh, Vines, Steinhoff, Buonanno

- a charged scalar model -- SF + PM extension – see Oliver Long's talk

Barack, Bern, Herrmann, Long, Parra-Martinez, RR, Ruf, Shen, Solon, Teng, Zeng

- Boundary-to-bound map

Kälin, Liu, Porto

- Good mass polynomiality, developed into the Tutti-Frutti method

Vines, Steinhoff, Buonanno; Damour

- EOB – PM resummation

Khalil, Buonanno, Steinhoff, Vines; Damgaard, Vanhove; Damour, Retegno

My take on future advances

- Explicit higher-order computations, towards the precision needs of our GR friends

- Is there a QFT-intrinsic definition of a Kerr black hole and how many parameters does it take to describe a compact object

- Obtain bound state observables from amplitudes beyond those given by B2B
  - Bypass the current approaches that require Hamiltonian and radiation reaction forces

- Structure of high order gravitational perturbation theory and resummation
  - QCD-style resummation
  - Interface with gravitational self-force
  - Assist with EOB-style resummation

The talks today and on Thursday will offer a glimpse of what the future might bring.
Looking forward to learning them!

The Beginning