Advances in gravitational-wave predictions through quantum field theory methods

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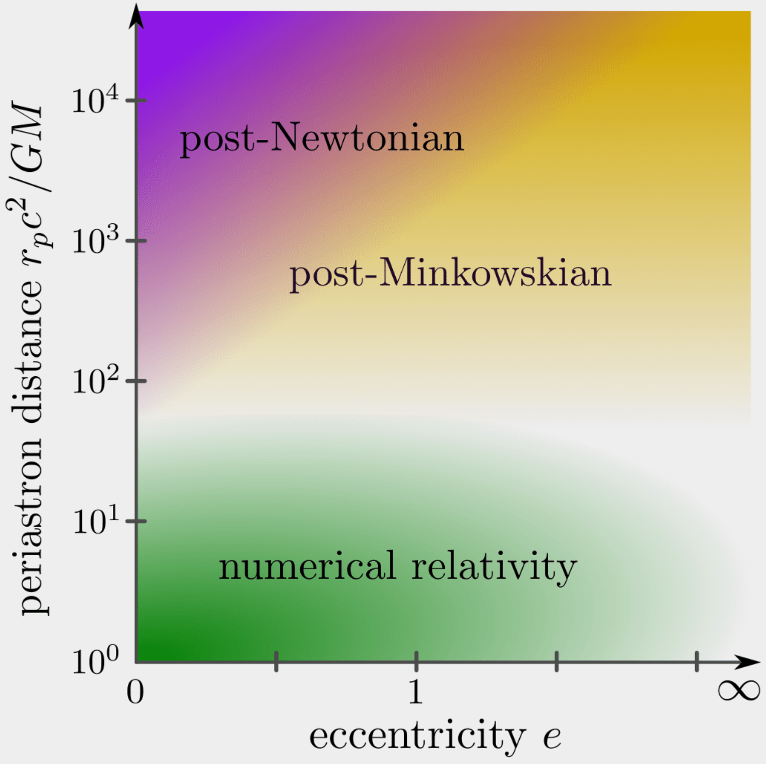
Post-Minkowskian (PM) expansion

- Natural pQFT approach $\Rightarrow$ recycle tools $G \ll 1$
- PM incorporates PN $(v^2 \ll 1) \Rightarrow$ similar results for overlap
- PM velocity resummation increases accuracy for scattering-like events
  - large-eccentricity, hyperbolic
  - detection rate is expected to increase in 3G detectors!
  - [Khalil, Buananno, Steinhoff, Vines, '22; Damour, Rettegno, '23]
  - higher accuracy needed
  - [Pürrer, Haster, '20]



[Khalil, Buananno, Steinhoff, Vines, '22]

Post-Minkowskian expansion for non-spinning BH

	0PN	1PN	2PN	3PN	4PN	5PN	6PN	
1PM	1	v^2	v^4	v^6	v^8	v^{10}	v^{12}	$\times G^1$
2PM		1	v^2	v^4	v^6	v^8	v^{10}	$\times G^2$
3PM			1	v^2	v^4	v^6	v^8	$\times G^3$
4PM				1	v^2	v^4	v^6	$\times G^4$
5PM					1	v^2	v^4	$\times G^5$
6PM						1	v^2	$\times G^6$

- State of the art for non-spinning BH:
  - 4PM conservative [Bern, Parra-Martinez, Roiban, Ruf, Shen, Solon, Zeng, '21; CD, Kälin, Liu, Porto, '21]
  - 4PM dissipative [CD, Kälin, Liu, Neef, Porto, '22]
  - 4PN [Rothstein, Porto, Sturani, Foffa, Mastrolia, Marchand; Bernard, Blanchet, Faye; Damour, Jaranowski, Schäfer, ...]
  - 5PN & 6PN (conservative): [Foffa, Mastrolia, Sturani, Sturm Bobadilla, '19; Blümlein, Maier, Marquard, '19; Bini, Damour, Geralico, Laporta, Mastrolia, '20]

PM-EFT

[Kälin, Porto, 20';
Kälin, Neef, Porto, 21']

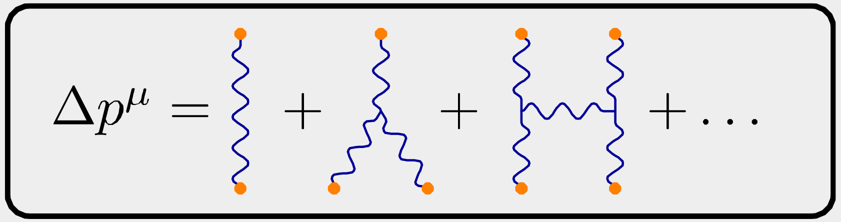
- EFT approach:

$$e^{iS_{\text{eff}}[x_a]} = \int \mathcal{D}h_{\mu\nu} e^{iS_{\text{EH}}[h]+iS_{\text{GF}}[h]+iS_{\text{pp}}[x_a,h]}$$

  - Post-Minkowskian expansion:

$$S_{\text{eff}} = \sum_{n=0}^{\infty} \int \mathrm{d}\tau_1 G^n \mathcal{L}_n[x_1(\tau_1), x_2(\tau_2)]$$

  - Total momentum change through EOM:



Other approaches:

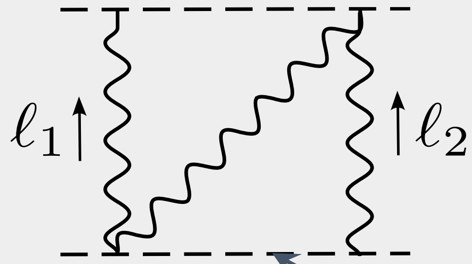
- Scattering amplitudes [Cheung, Rothstein, Solon; Bern, Parra-Martinez,Roiban, Ruf, Shen, Zeng, ...]
- WL-QFT [Jakobsen, Mogull, Plefka, Steinhoff, '21]
- Eikonal [Di Vecchia, Heissenberg, Russo, Veneziano]
- ...

Loop integrals

- Integrand construction: [Passarino, Veltman, '79]
  - standard techniques in QFT [FORM, xAct, C++, GiNaC]
- Example integral family:
- Dimensional regularization:

$$D = 4 - 2\epsilon$$

$I =$



integrals very similar to Heavy Quark Effective Theory

[Goldberger, Rothstein, '06]

- Kinematic dependence fixed by DE: $\partial_v \vec{f} = A(D, v)\vec{f}$ ← integrals to compute
  - solve by transforming to canonical form [Henn, '13]
  - available algorithms: [Lee, '15; Libra, epsilon, Fuchsia; CANONICA]

[INITIAL:
CD, Henn, Wagner, '22;
CD, Henn, Yan, '20]

$\Longrightarrow$

used before for HQET integrals:
[Brüser, CD, Henn, Yan, '20]

Boundary conditions

- From PN-like limit $v^2 \ll 1$
  - method of regions:

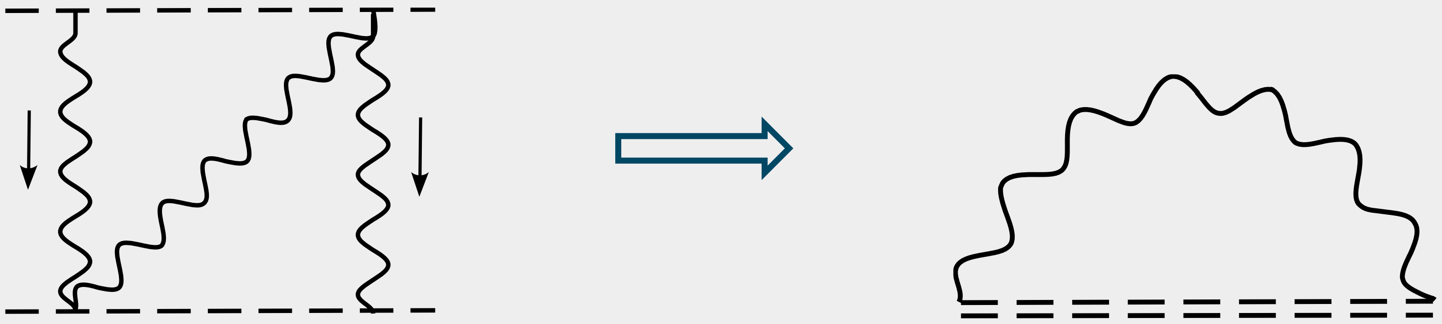
[Beneke, Smirnov, ‘97]
[asy2.m, Jantzen, Smirnov, Smirnov, ‘12; Pak, Smirnov, ‘10]

potential graviton: $(\ell^0, \boldsymbol{\ell}) \sim (1, v)$

radiation graviton: $(\ell^0, \boldsymbol{\ell}) \sim (v, v)$

[Goldberger, Rothstein, ‘06]

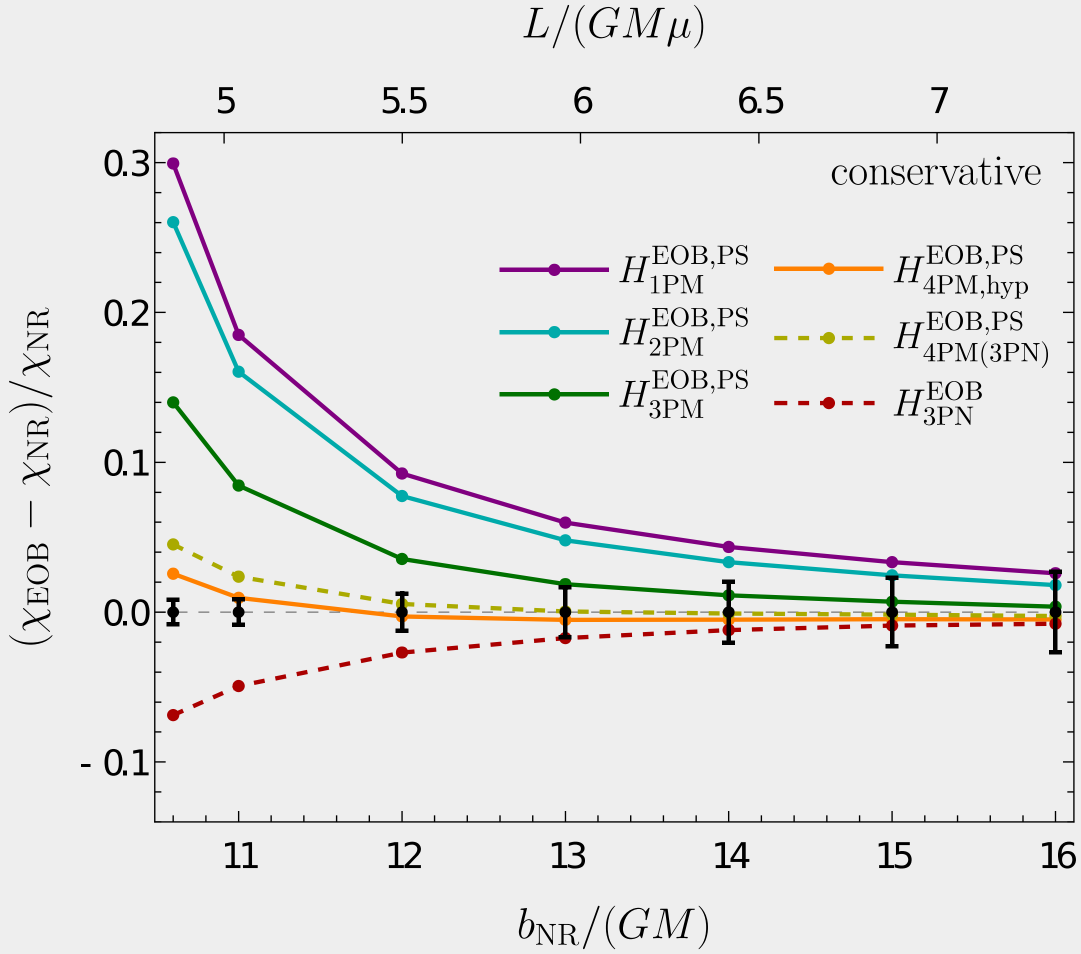
  - correspond nicely to PN regions and (3d) integrals

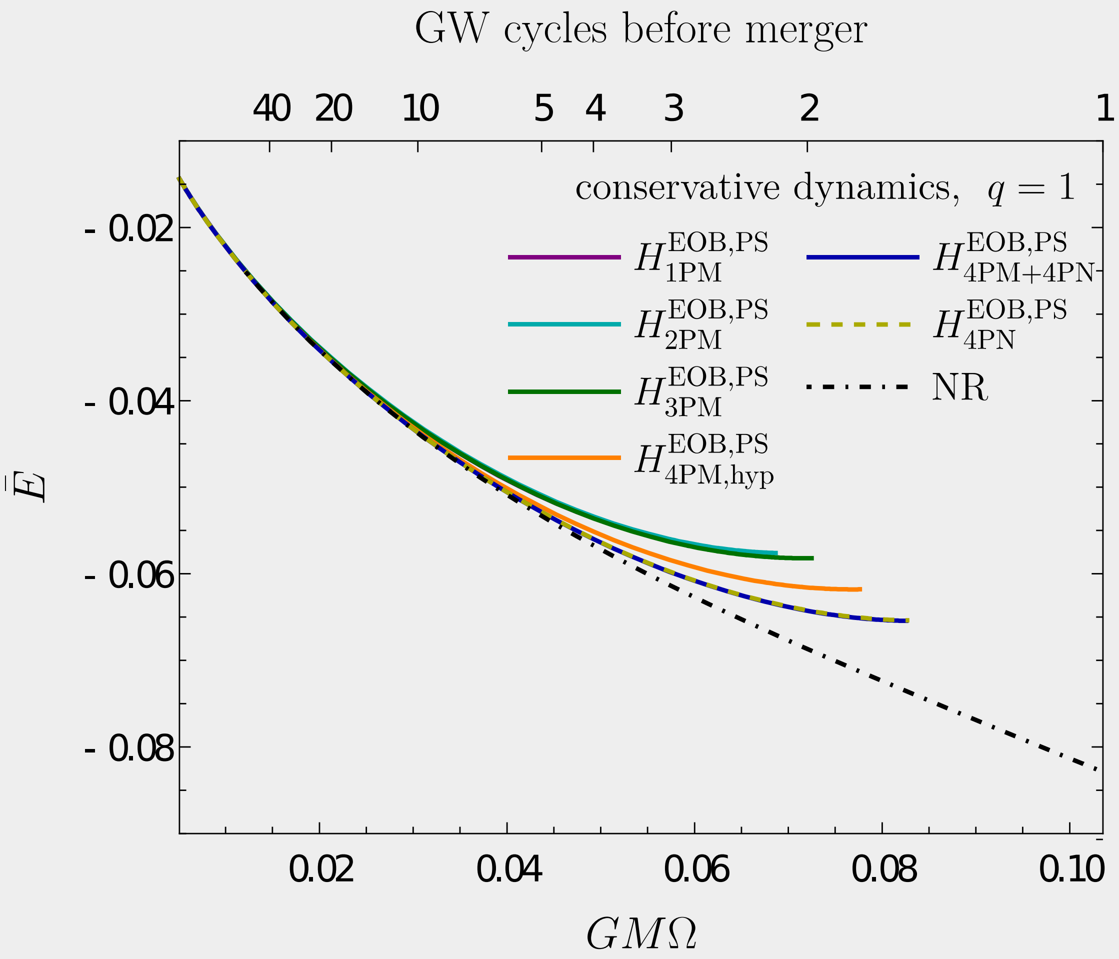


[Galley, Leibovich, Porto, Ross, ‘15]

PM conservative accuracy

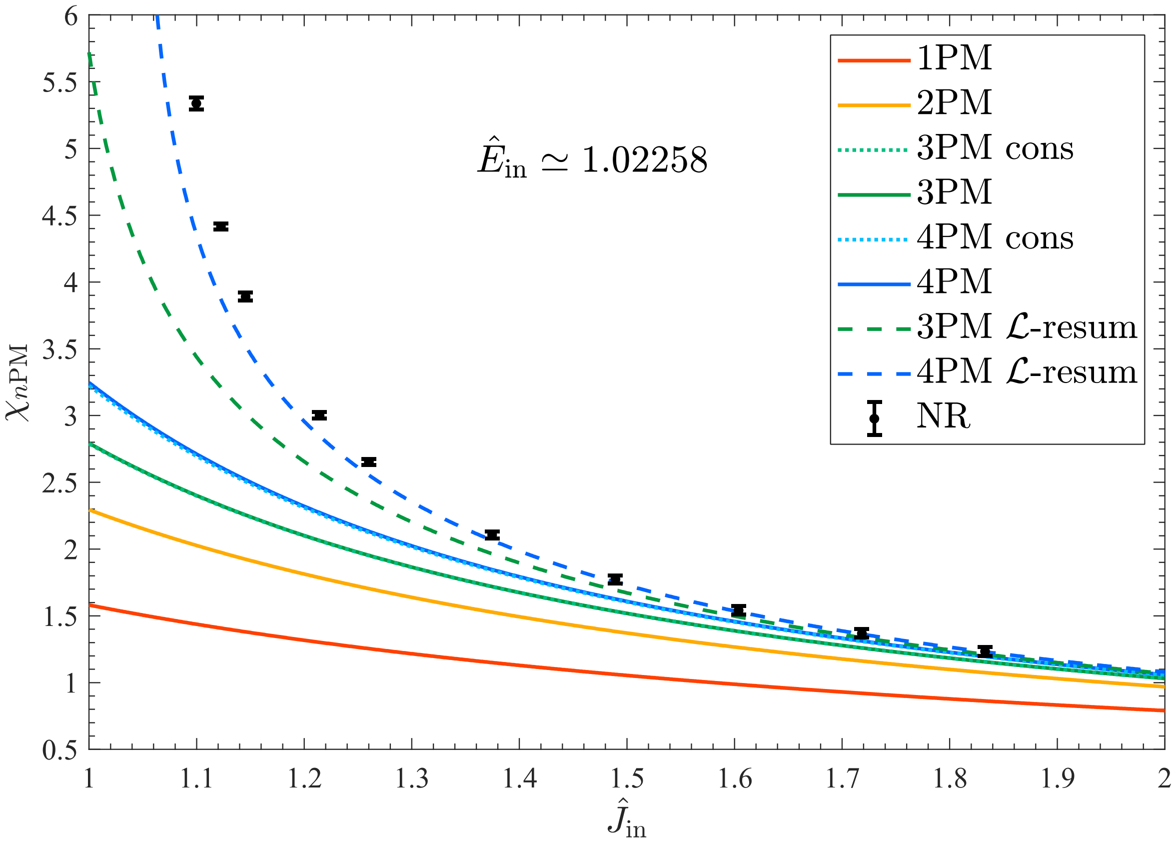
[Khalil, Buananno, Steinhoff, Vines, '22]

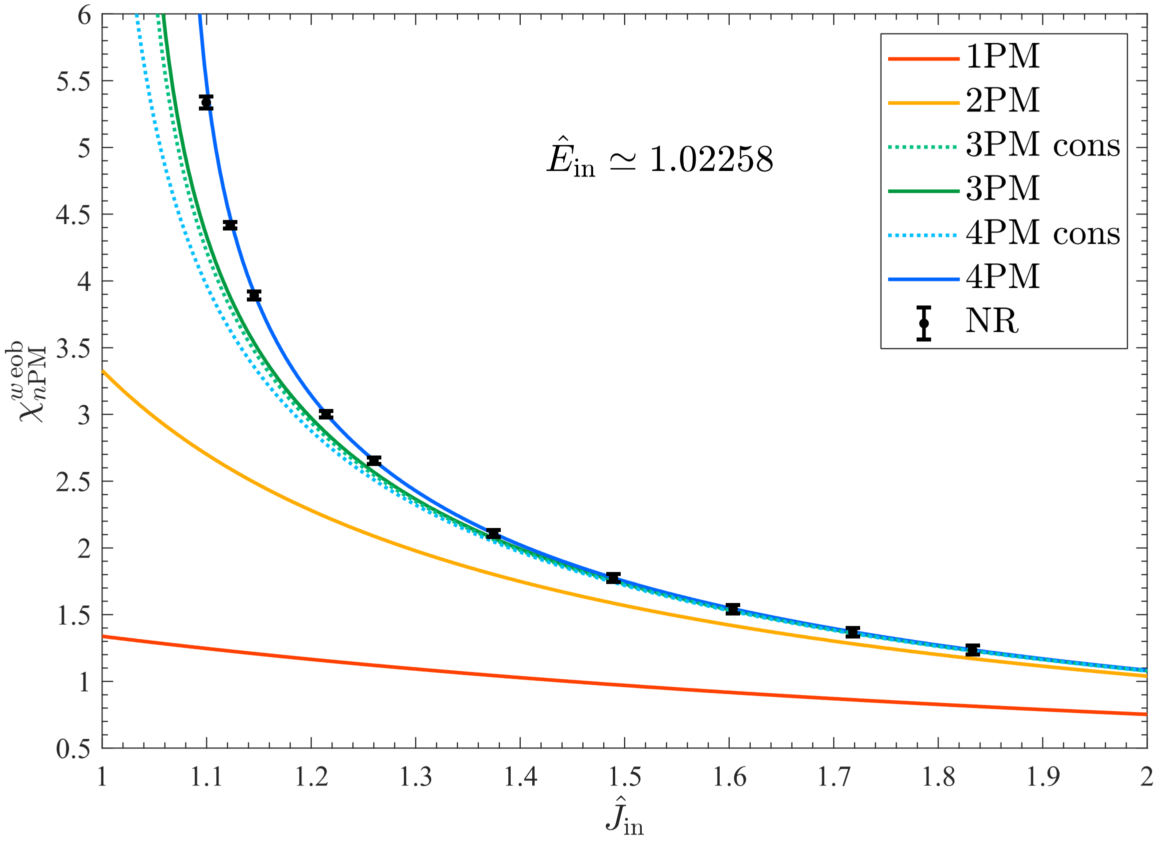




PM radiative state-of-the-art accuracy

[Damour, Rettegno, '22]





Challenges

- Detector accuracy
  - Higher PM, spin, internal structure, ...
  - Adjust QFT tools more to our needs
  - Continue scattering to bound state data

    [B2B: Kälin, Porto, '19; Cho, Kälin, Porto, '21]
  - Incorporate PM more directly into waveform generation (EOB)

    [Damour, '16; Damgaard, Vanhove, ' 21; Khalil, Buananno, Steinhoff, Vines, '22; Damour, Rettegno, '23; ...]