Particle Physics meets Gravitational Wave Physics
- QFT for the Era of Precision Gravitational Wave Physics -

Jung-Wook Kim [MPI for Gravitational Physics (Albert Einstein Institute)]

Talk overview

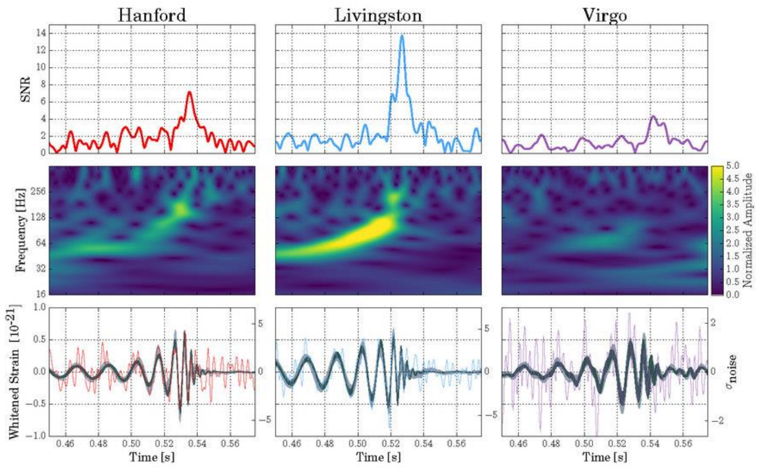
- Overview of QFT-based approaches to binary dynamics
  - Motivation to study the two-body problem
  - Advantage of using QFT (or EFT-based approaches)
  - Perturbative GR (PN/PM) & their QFT-based approaches

- My research: specialisation to spin
  - Describing spin and its effects / importance
  - Current research topic: spin resummation in PM dynamics

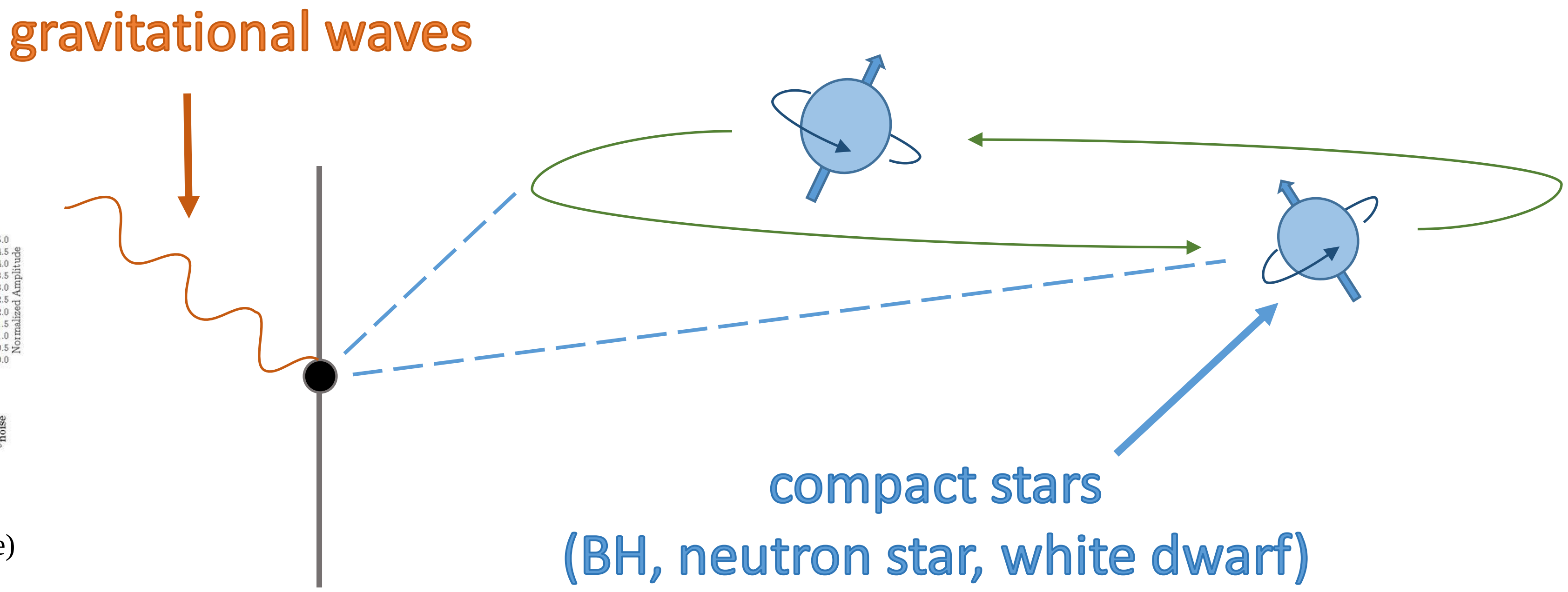
- Outlook

Motivation

- Era of gravitational wave observatories (LIGO-Virgo-KAGRA)
  - Targets: Compact Binary Coalescence (CBC)
  - Next-gen ('30s): LISA, Einstein Telescope, Cosmic Explorer, …

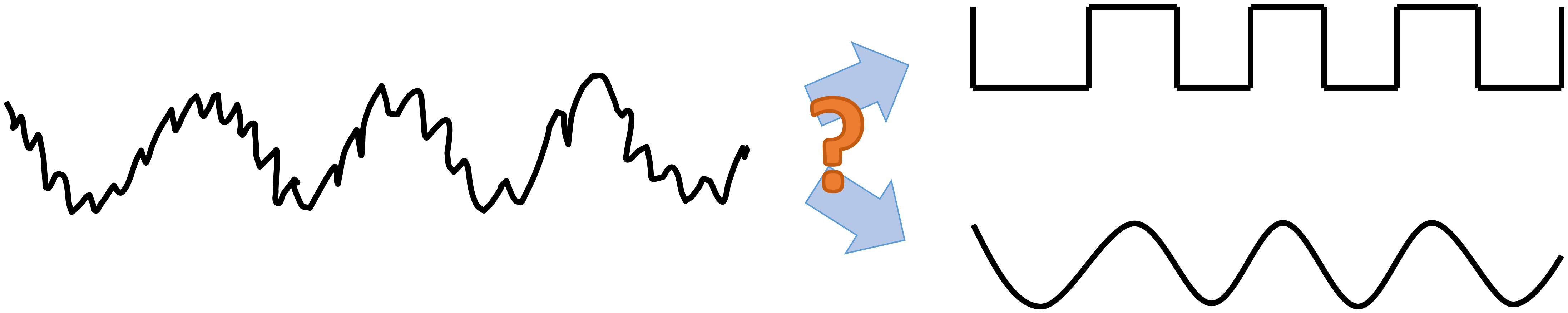


(Image source: LIGO homepage)



Motivation

- Main detection / parameter estimation method: matched filter
  - Crucial for parameter estimation (mass, spin, eccentricity, etc.)



- Need "expected waveforms"
  - Required template bank size: $\sim 10^{3-6}$
  - Binary dynamics from **analytic calculations** & numerical relativity (NR)

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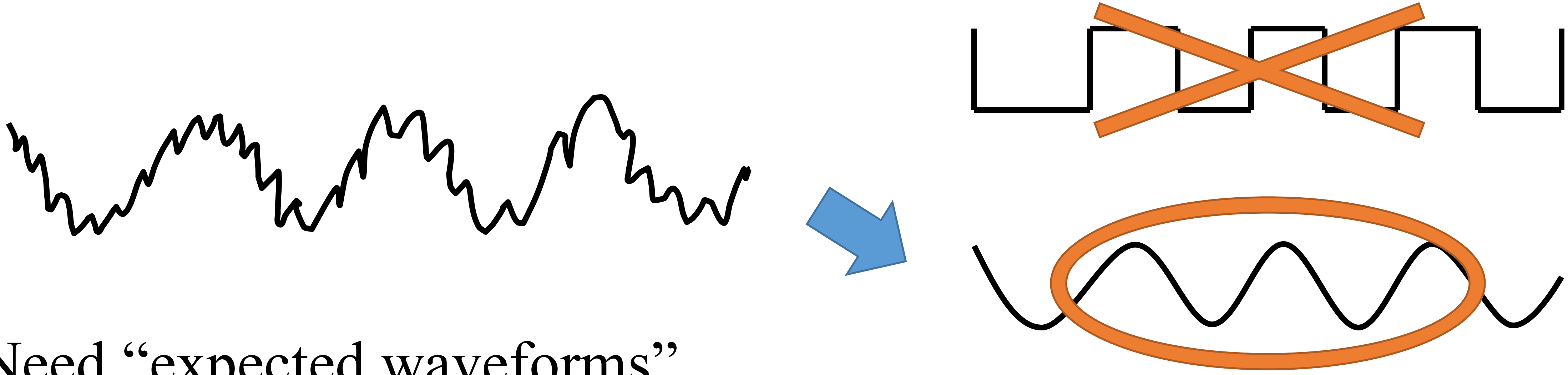

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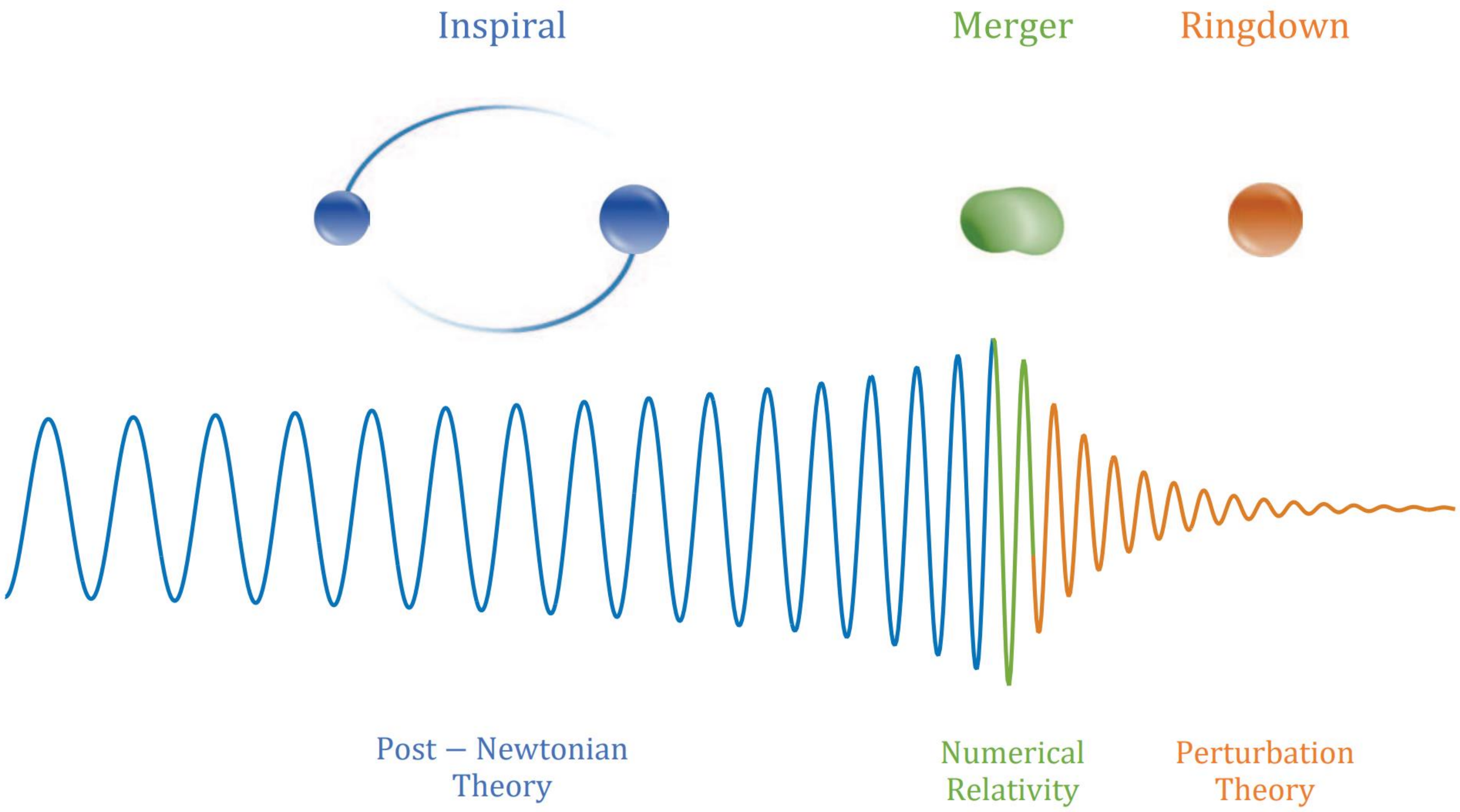
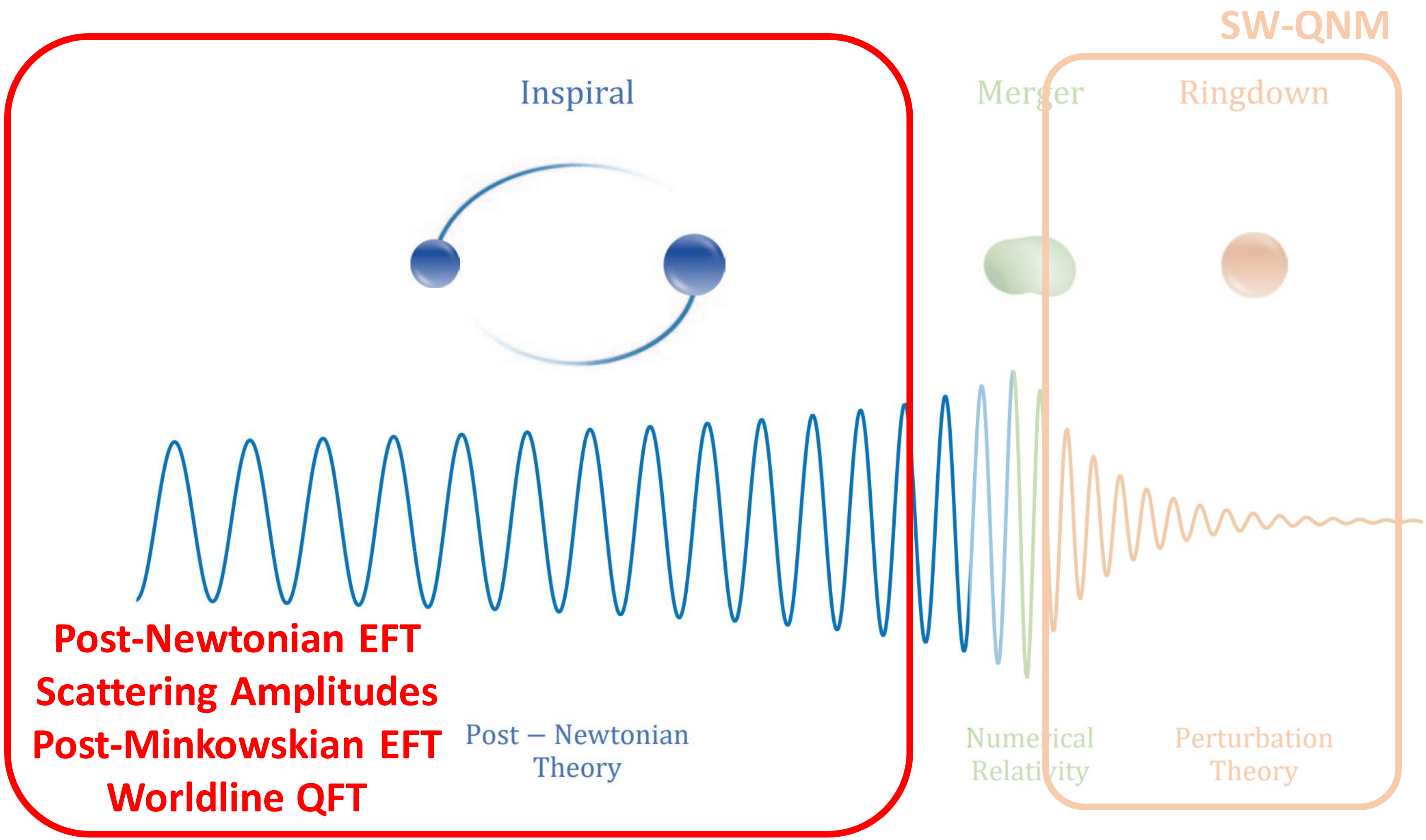
Structure of a typical waveform



(Image source : [1610.03567])

Structure of a typical waveform



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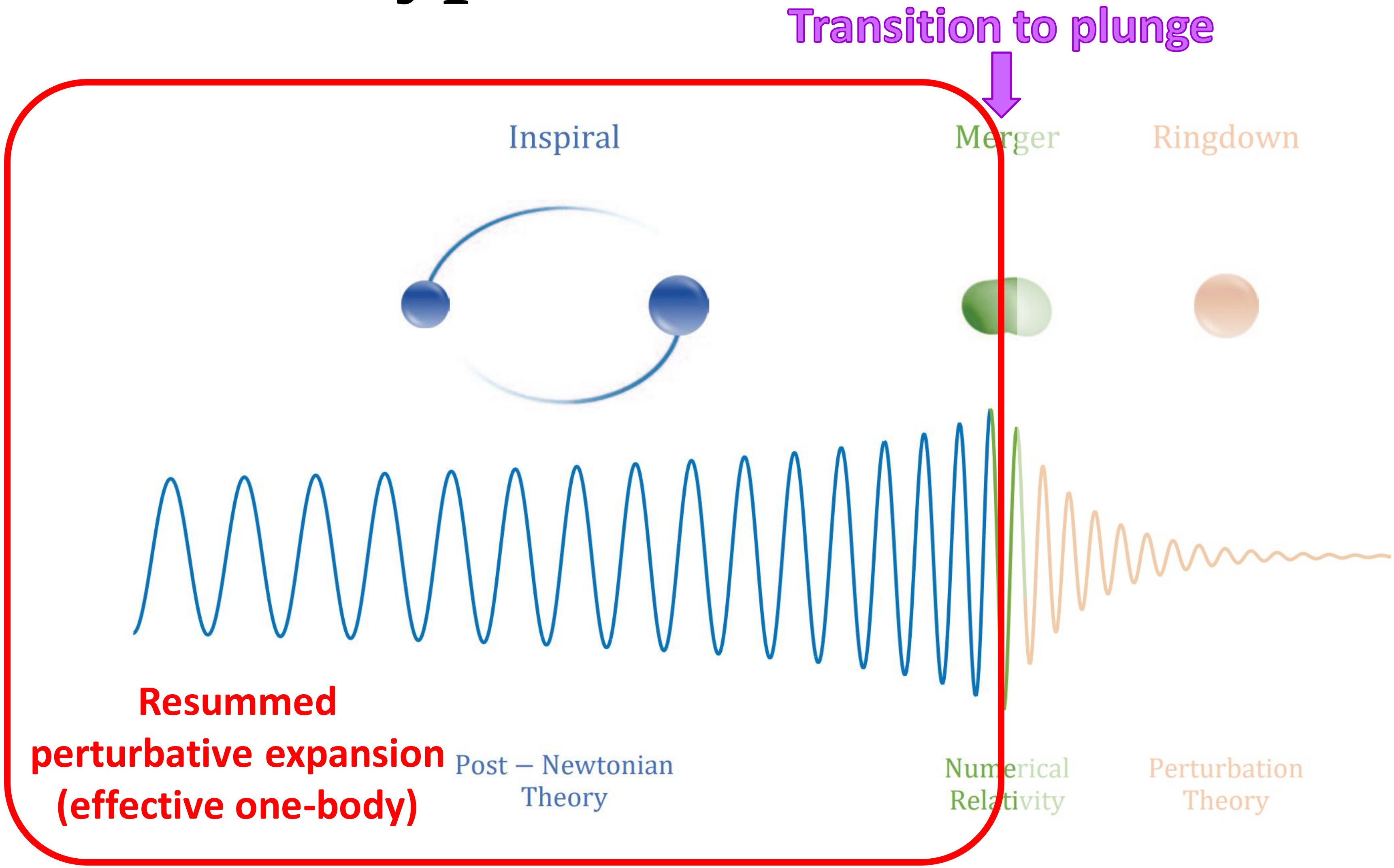
Structure of a typical waveform

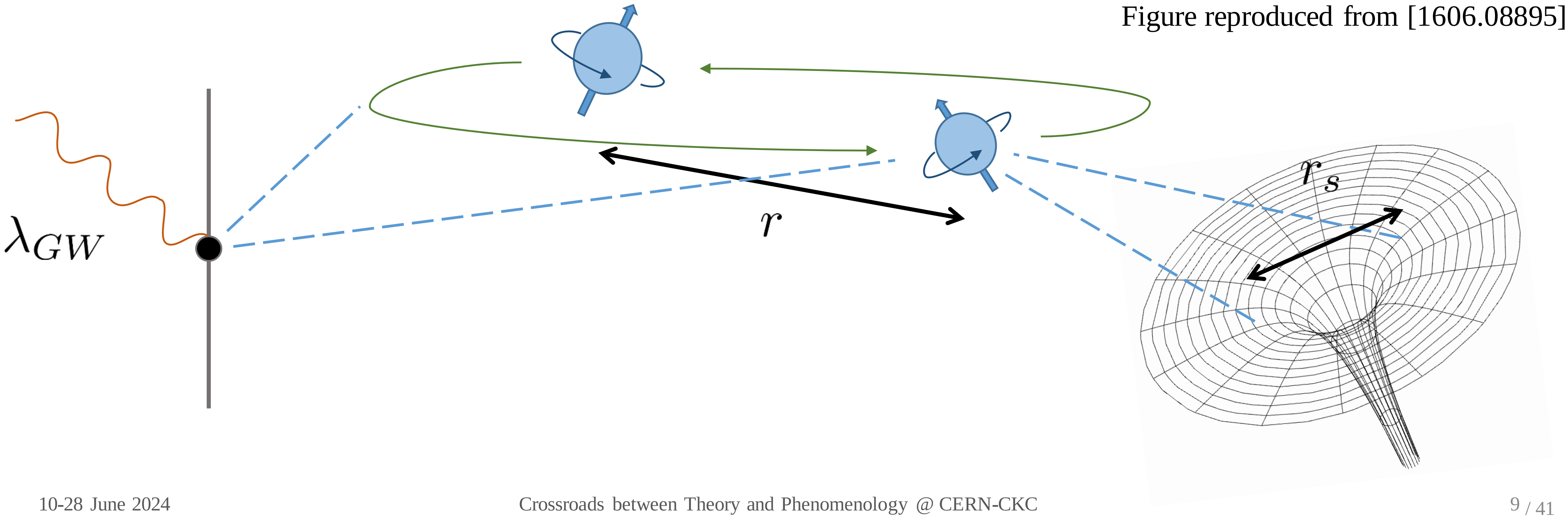


(Image source : [1610.03567])

Physics of the inspiral phase

- Separation of scales: $\lambda_{GW} \gg r \gg r_s$
  - Analytic treatment using perturbation theory
  - Scale separation ⇒ effective field theory (EFT)

Figure reproduced from [1606.08895]



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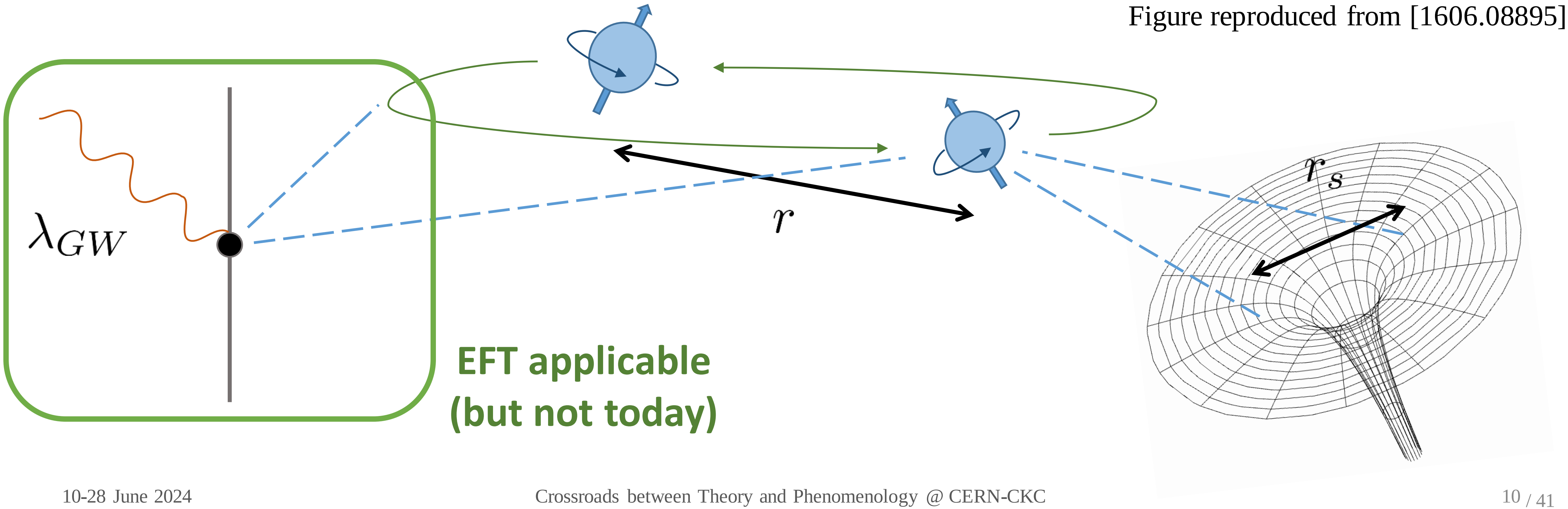

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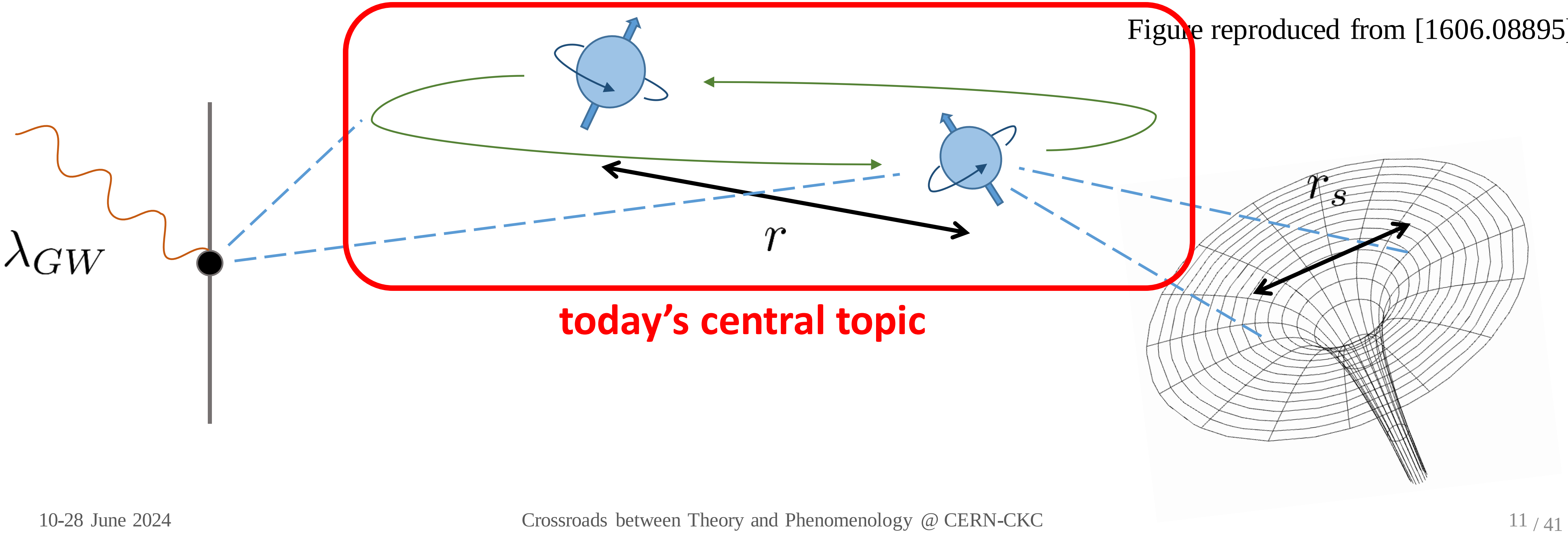

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Advantage of QFT/EFT based methods

- EFT-based approaches provide cleaner interpretation
  - Example: spinning point-particle motion on a background
    - Conventional approach: closure of equations of motion
    - EFT-based approach: each expansion encodes UV properties of the particle
  - Practically the only known approach to incorporate beyond-GR effects

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spin-independent dynamics

required by closure of EOM (unclear physical meaning)

$$\frac{Ds^\mu}{d\tau} = \mathcal{O}(s^0) + \mathcal{O}(s^1) + \mathcal{O}(s^2) + \mathcal{O}(s^3) + \cdots$$

$$\frac{Dp^\mu}{d\tau} = \mathcal{O}(s^0) + \mathcal{O}(s^1) + \mathcal{O}(s^2) + \mathcal{O}(s^3) + \cdots$$

spin interactions

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spin-independent dynamics (spin-induced) quadrupole effects

$$\frac{Ds^\mu}{d\tau} = \mathcal{O}(s^0) + \mathcal{O}(s^1) + \mathcal{O}(s^2) + \mathcal{O}(s^3) + \cdots$$

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spin interactions (spin-induced) octupole effects

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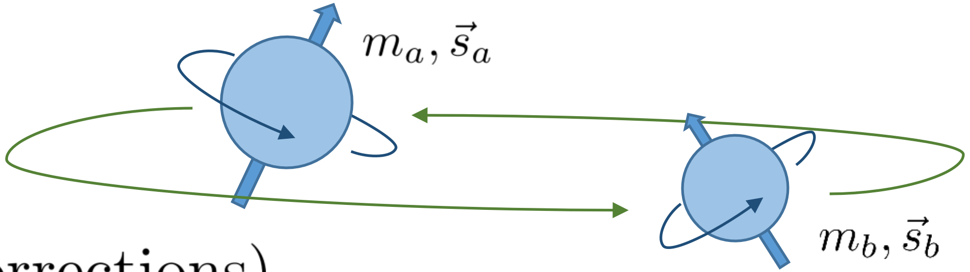
- Amplitudes-inspired approaches provide compact results
  - “Gauge-invariant” description of dynamics (up to BMS)
    - Scattering/hyperbolic motion: initial/final states $\approx$ free states
  - Simpler expression $\Rightarrow$ potentially new/better resummation schemes

Perturbative general relativity



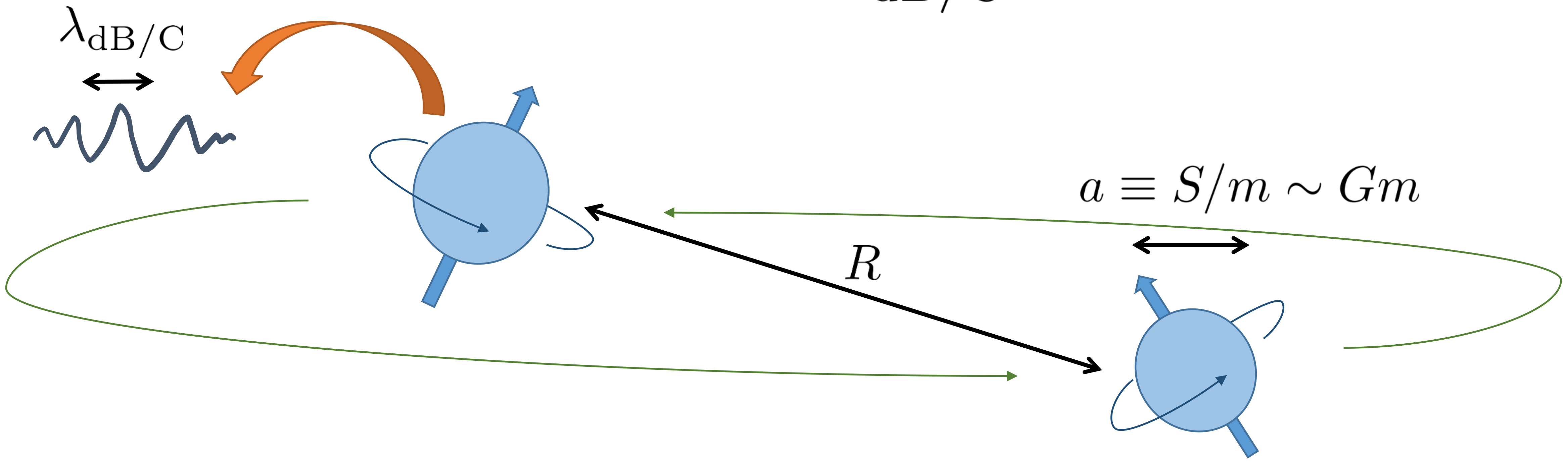
- Effective two-body Hamiltonian

$$H = \frac{p_a^2}{2m_a} + \frac{p_b^2}{2m_b} - \frac{Gm_a m_b}{r_{ab}} + (\text{relativistic corrections})$$

Classification	Post-Minkowskian (PM)	Post-Newtonian (PN)
Corrections to	GR corrections to SR	GR & SR corrections to NG
Expansion in	Newton's constant G	Newton's constant G, velocity v^2/c^2
Small numbers	$Gm/r \ll 1$ $(\lvert\vec{s}\rvert/mr \ll 1)$	Gm/r & $p^2/m^2 \ll 1$ $(\lvert\vec{s}\rvert/mr \ll 1)$
Dynamics	Scattering (p^2/m^2 unconstrained)	Bound motion ($Gm/r \approx p^2/m^2$)
QFT methods	Amplitudes, WQFT, PMEFT	PNEFT

Scale separation in the two-body problem

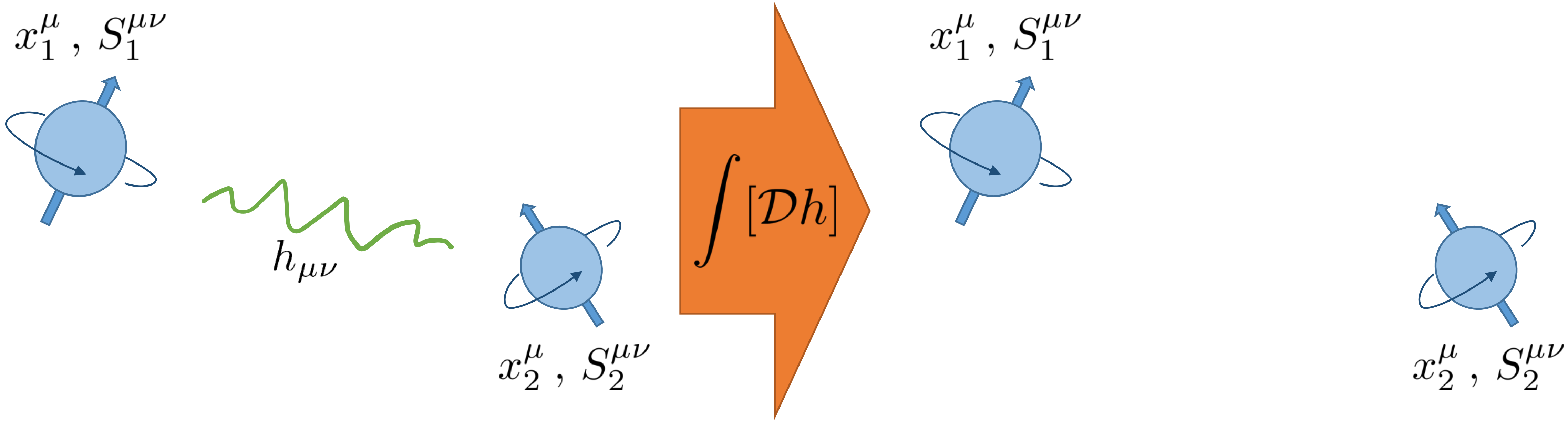
$$R \gg a \gg \lambda_{\rm dB/C}$$



$$\frac{\lambda_{\rm dB}}{R} \simeq \frac{\hbar}{|\vec{L}|} \ll 1 \qquad \frac{\lambda_{\rm C}}{a} \simeq \frac{\hbar}{|\vec{S}|} \ll 1 \qquad \frac{a}{R} \simeq \frac{|\vec{S}|}{|\vec{L}|} \sim \frac{G\mu}{R} \ll 1$$

Set-up of PNEFT approach

[Goldberger, Rothstein; Porto]



$$e^{iS_{\mathrm{pp}}[x^\mu,S^{\mu\nu}]+iS_g[h_{\mu\nu}]} \qquad\qquad e^{iS_{\mathrm{pp,eff}}[x^\mu,S^{\mu\nu}]}$$

Set-up of PNEFT approach

[Goldberger, Rothstein; Porto]

- Effective point-particle worldline action
  - Worldline proper time + "finite-sized" effects (spin, tidal, beyond-GR, etc.)
  - Polyakov type action also possible [Jakobsen, Mogull, Plefka, Steinhoff]

$$S_{\rm pp}[x^\mu, S^{\mu\nu}] = -\int d\tau \left[m\sqrt{\dot{x}^2} + \frac{1}{2}\Omega_{\mu\nu}S^{\mu\nu} + \cdots\right]$$

- Graviton action: Einstein-Hilbert (+ gauge fixing & beyond-GR)
  - KK decomposition for simpler PN counting

$$S_g[h_{\mu\nu}] = S_g[\phi, A_i, \sigma_{ij}] = \int d^D x \left[-\frac{1}{16\pi G}\sqrt{-g}R + \Gamma_\mu\Gamma^\mu\right]$$

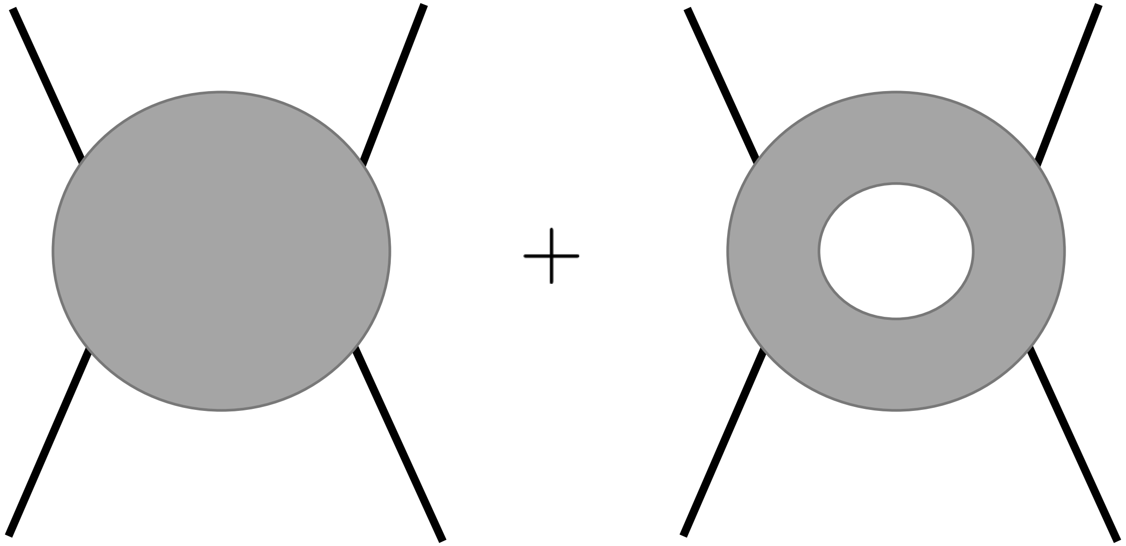
$$ds^2 = e^{2\phi}(dt - A_i dx^i)^2 - e^{-2\phi}(\delta_{ij} + \sigma_{ij})dx^i dx^j$$

Beyond-GR effects in the PN(EFT) approach

- Extra scalar field: scalar-tensor, dilaton, axion, dark matter, etc.
  - Generally has N^{-1}LO (-1PN) waveform corrections compared to GR
    - Scalar dipolar radiation (LO GR radiation quadrupolar) [Yagi, Stein, Yunes, Tanaka]
  - Scalarisation of black holes: Einstein-scalar-Gauss-Bonnet [Sotiriou, Zhou]
    - Scalarisation as background-scalar-dependent mass on the worldline [Eardley]
  - Binary Hamiltonian known to 3PN (Scalar tensor & EsGB) [Bernard; Julié, Berti]
    - 2PN from EFT calculations [Almeida]
- Observational constraints from LIGO-Virgo-KAGRA
  - EsGB coupling from GW230529 [2406.03568]: $\ell_{\rm GB} \lesssim 0.51\,\mathrm{M}_\odot$
  - *"Tests of General Relativity with GWTC-3"* [2112.06861]: $m_g \leq 1.27 \times 10^{-23}\,\mathrm{eV}$

Set-up of scattering amplitudes approach

[Iwasaki; Cheung, Rothstein, Solon; Bern, Parra-Martinez, Roiban, Ruf, Shen, Solon, Zeng]



$$+ \cdots = \begin{cases} e^{i\chi[b]} \\ \mathcal{T} e^{-i\int H dt} \end{cases}$$

Set-up of scattering amplitudes approach

[Iwasaki; Cheung, Rothstein, Solon; Bern, Parra-Martinez, Roiban, Ruf, Shen, Solon, Zeng]

$$iM_{i\to f} = \langle f | i \rangle$$

Dyson series element

$$iM_{i\to f} = {}_0\langle f | \mathcal{T} e^{-i\int H_{\text{int}} d\tau} | i \rangle_0$$

Effective Hamiltonian
from EFT amplitude matching

$$\begin{aligned} 1 + iM_{i\to f} &= 1 - i\int H_{\text{int}} - \frac{1}{2}\iint H_{\text{int}}^2 + \cdots \\ &= 1 - i\int H_{\text{eff,int}} - \frac{1}{2}\iint H_{\text{eff,int}}^2 + \cdots \end{aligned}$$

PI transition amplitude

$$\langle f | i \rangle = \int_i^f [\mathcal{D}x] e^{iS[x]}$$

Hamilton's principal function (action)
from logarithm ("eikonal phase")

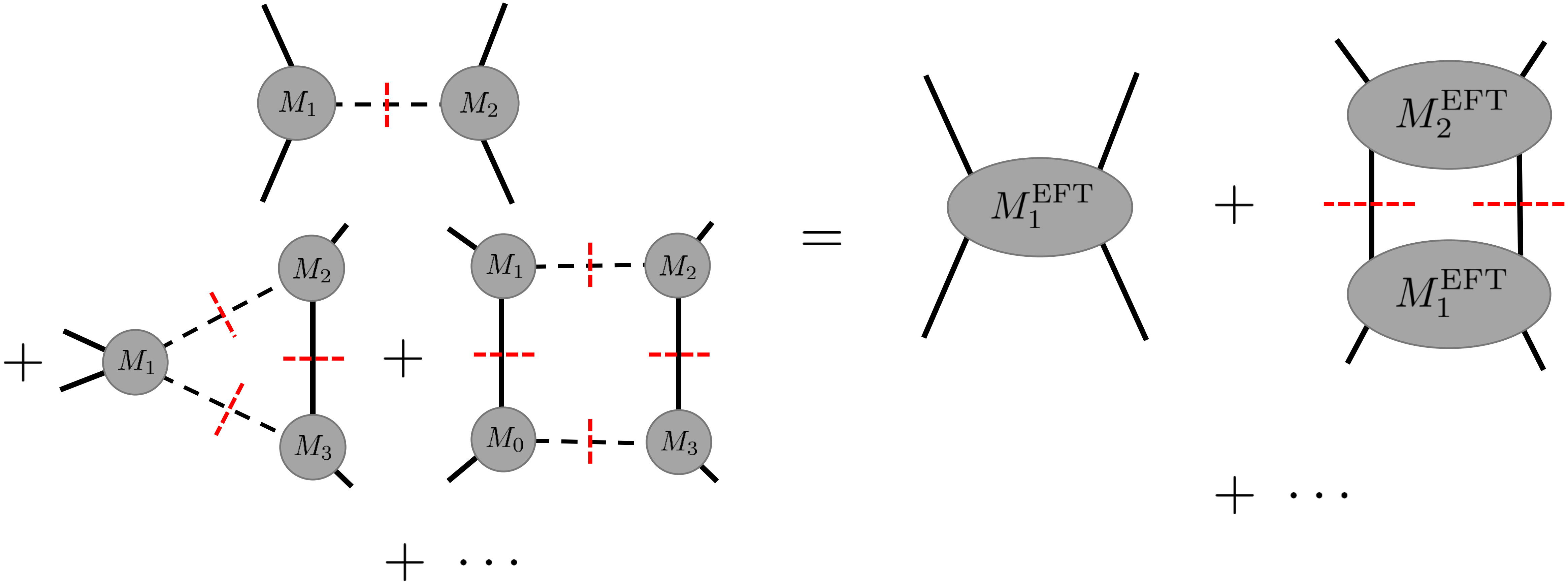
$$1 + iM_{i\to f} = e^{i\chi_{i\to f}} = e^{iS[x]}$$

Effective Hamiltonian from amplitude matching

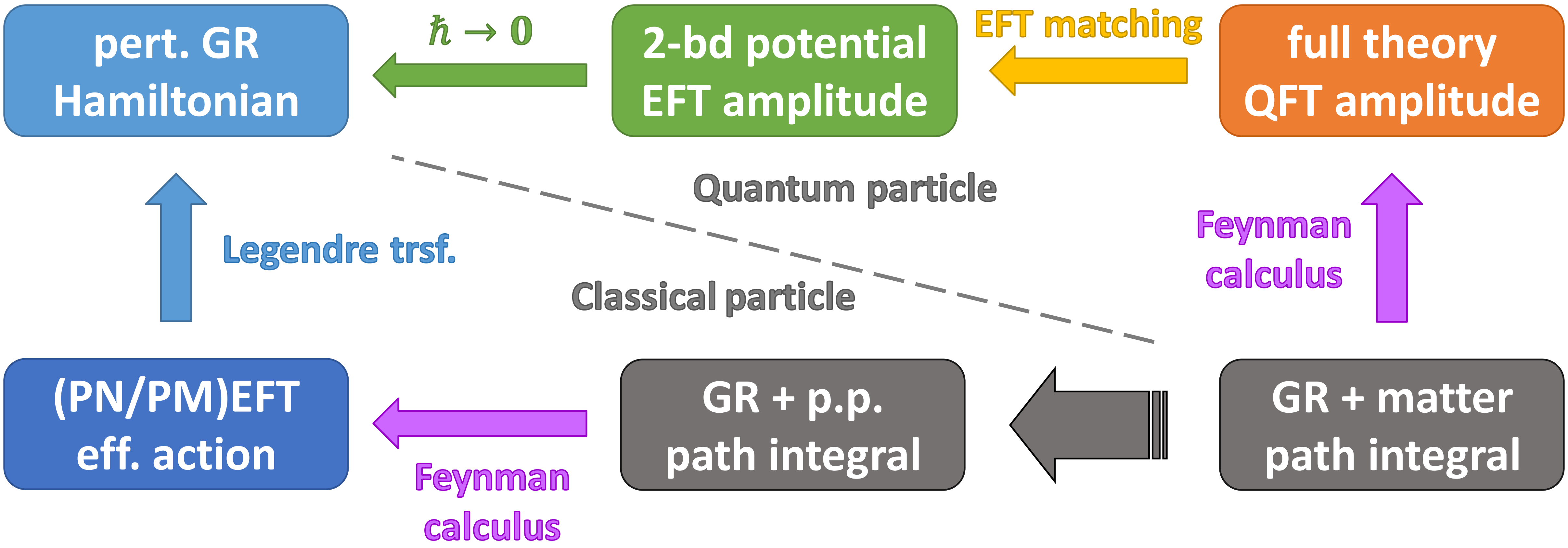
[Cheung, Rothstein, Solon; Bern, Cheung, Roiban, Shen, Solon, Zeng]

Full theory amplitude

Effective theory amplitude



Classical mechanics from QFT: flowchart



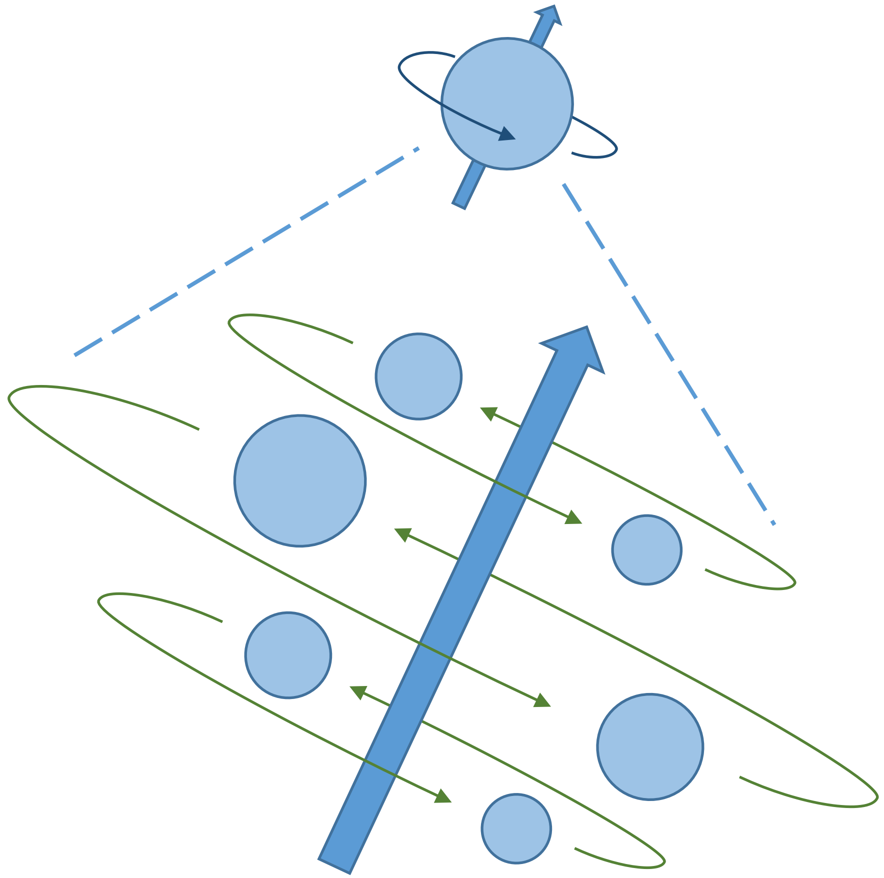
Describing “spin” in relativity

- Every rotational rigid motion is isometric [Herglotz, Noether]
  - Born rigidity: const. distance btw. every pair of neighbouring worldlines
  - Implies impossibility of linear/angular accelerations

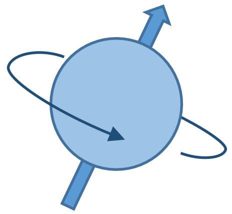
- Spinning objects **exist**
  - Exact rigidity conditions are unnecessarily too constraining
  - (Classical) spin must be treated as an **effective description**

Spin in classical and quantum mechanics

Classical mechanics



Quantum mechanics



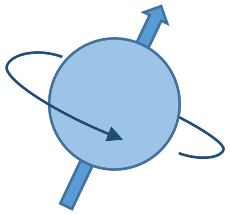
Elementary property

Upper bound ($|s| \leq 2$)
for "elementary" particles

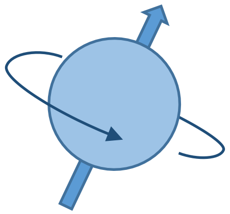
Higher spin ($|s| > 2$) $\Rightarrow$ composite
(effective description)

Spin in classical and quantum mechanics

Classical mechanics



Quantum mechanics

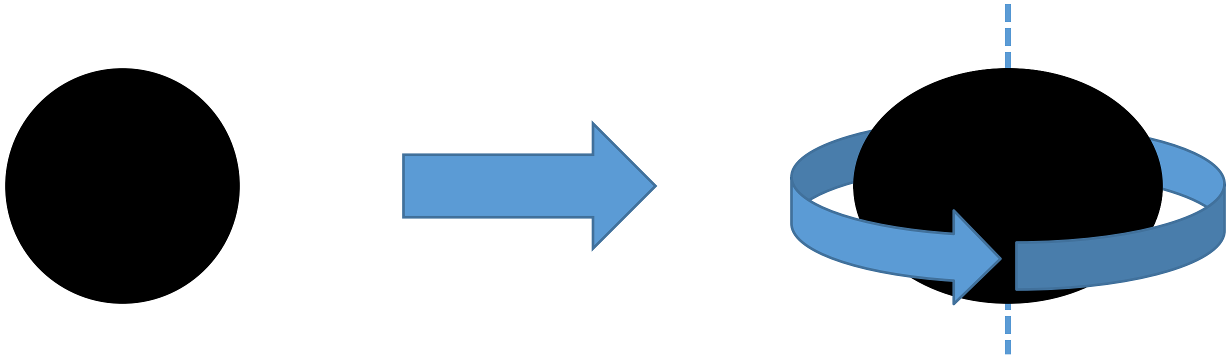


Classical mechanics		Quantum mechanics
WL tetrad & local Lorentz generators	**Full DOF**	Symmetric traceless rank-s tensor
Rotational DOF	**Spin DOF**	Spatial(transverse) components
Spin supplementary condition	**Constraint**	Transversality condition

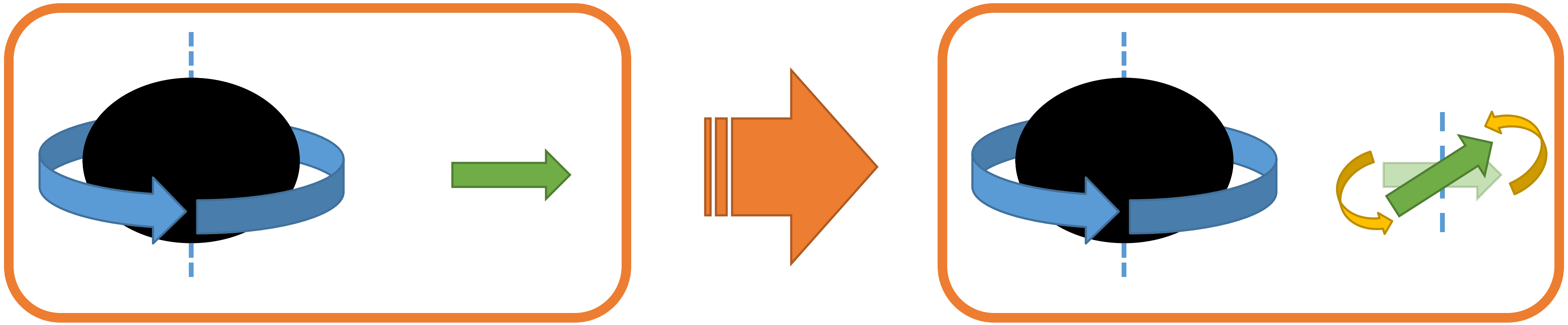
Local boost DOFs can have **<u>classical</u>** contributions [JWK, Steinhoff; Bern et al.]

Effects of spin

- Spin-induced multipole moments

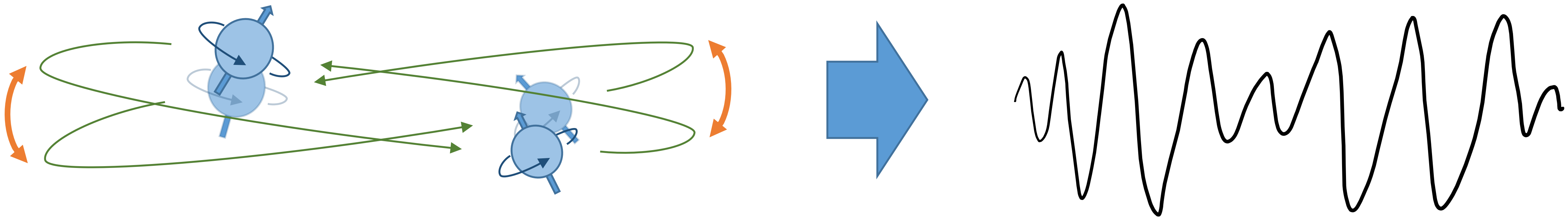


- Frame-dragging effect



Effects of spin

- Orbital precession
  - $\vec{J} = \vec{L} + \vec{S}_1 + \vec{S}_2$ conserved, but **not separately**
  - Distinct signature (modulation) in waveform [Apostolatos, Cutler, Sussman, Thorne]



- Applications
  - Astrophysics: spin orientation ⇒ binary formation history
  - QCD in extreme conditions: SI multipole moments ⇒ Neutron star EOS

Importance of spin

- Waveform models perform worse for high spins/mass ratios
  - Comparison with numerical relativity (NR) simulations

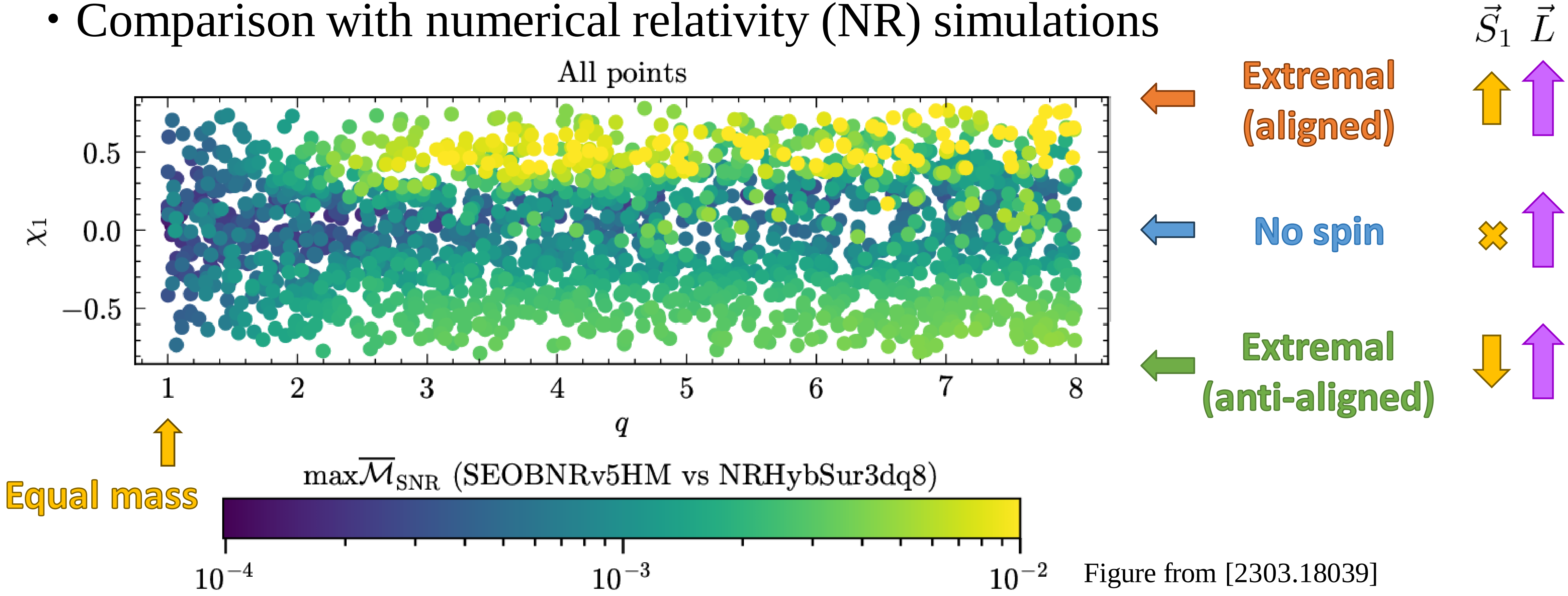
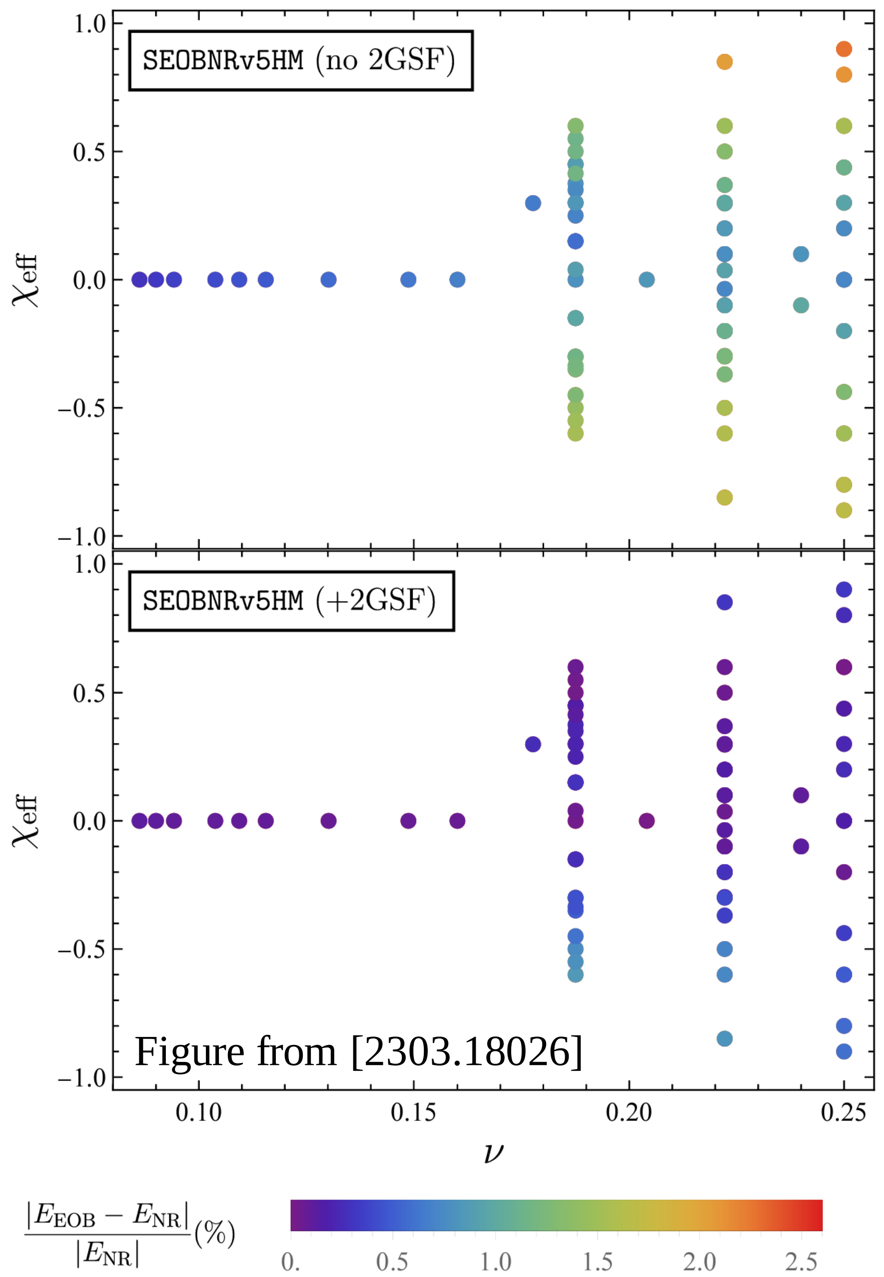


Figure from [2303.18039]

Importance of spin

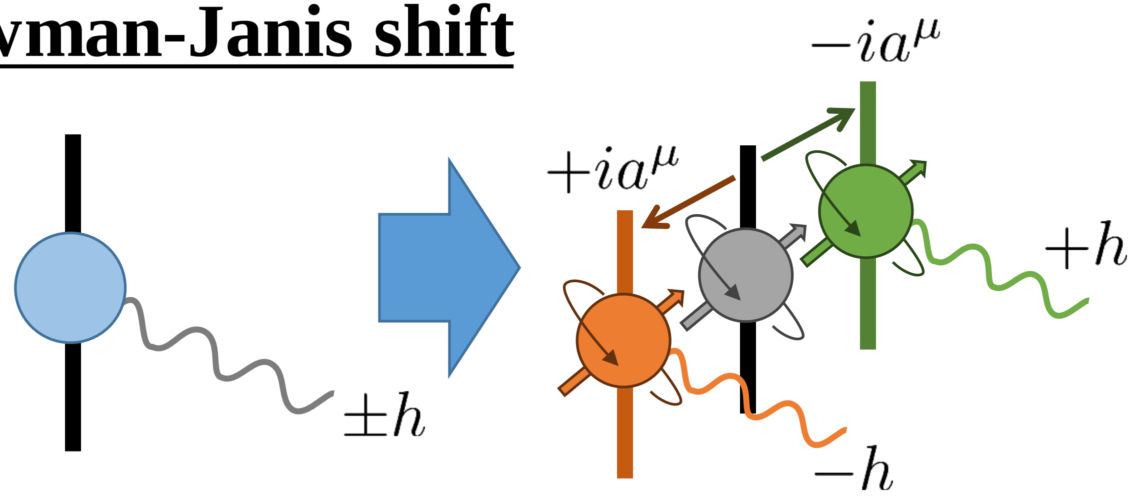
- Waveform models perform worse for high spins/mass ratios
- Limiting factor for (next-gen) GW physics
  - "we ascertain that current waveforms can accurately recover the distribution of masses in the LVK astrophysical population, **but not spins**"

    [Dhani, Völkel, Buonanno, Estelles, Gair, Pfeiffer, Pompili, Toubiana]



Current interest: resummation of spin effects

- Waveform models resum perturbative dynamics (PN/PM + spin)
  - E.g. effective-one-body formalism in SEOBNRv5 (LVK data analysis)
- Why expect spin to be resummable?
  - Black hole spin moments given by **Newman-Janis shift**
  - Kerr couples minimally* to gravitons
    [Guevara, Ochirov, Vines; Chung, Huang, JWK, Lee]
    - Minimal coupling from high-E limit
      [Arkani-Hamed, Huang, Huang]
    - Minimal coupling ≈ on-shell NJ shift
      [Arkani-Hamed, Huang, O'Connell]



- Expectation: singularities of binary dynamics governed by NJ shift

Spin resummation in electrodynamics

[Kim, JWK, Lee]

- Twistor worldline model for spinning particles
  - Allows **dynamical** Newman-Janis shift of the worldline
- Target: eikonal (phase) χ
  - Generator of scattering observables [Kim, JWK, Lee; Gonzo, Shi]

$$\mathcal{O}_f = e^{\{\chi,\bullet\}}[\mathcal{O}] = \mathcal{O} + \{\chi,\mathcal{O}\} + \frac{1}{2!}\{\chi,\{\chi,\mathcal{O}\}\} + \frac{1}{3!}\{\chi,\{\chi,\{\chi,\mathcal{O}\}\}\} + \cdots$$

- Spin-resummed 1PL (post-Lorentzian) twistor worldline eikonal

$$\chi_{(1)} = \frac{q_1 q_2 \gamma}{4\pi\sqrt{\gamma^2-1}}\left[\frac{1}{\epsilon} + \Re\left(\log\frac{(b^\mu - i a_\perp^\mu)^2}{b_0^2}\right) + \frac{\epsilon[b, v_1, v_2, a_\perp]}{2\gamma\sqrt{b^2 a_\perp^2 - (b\cdot a_\perp)^2}}\log\left(\frac{b^2 + a_\perp^2 + 2\sqrt{b^2 a_\perp^2 - (b\cdot a_\perp)^2}}{b^2 + a_\perp^2 - 2\sqrt{b^2 a_\perp^2 - (b\cdot a_\perp)^2}}\right)\right]$$

$$a^\mu = a_1^\mu + a_2^\mu\,,\ a_1^\mu = \frac{S_1^\mu}{m_1}$$

Spin resummation in electrodynamics

[Kim, JWK, Lee]

- Spin-resummed 2PL twistor worldline eikonal
  - Eikonal is a double infinite sum of 2F1, but simplifies in special kinematics

$$\Bigg(\pi^{3/2}\,\mathrm{dot}[b,b]^{-\frac{5}{2}-l-m}\big(-\mathrm{dot}[y,y]-\mathrm{dot}[y1,v2]^2\big)^m\Big(-(1+2l)\,\mathrm{dot}[b,ymb]\,\mathrm{dot}[b,ypb]+2(1+2m)\,\mathrm{dot}[b,b]\,\big(\mathrm{dot}[y1,v2]^2+\mathrm{dot}[y1,y1]+\mathrm{dot}[y1,y2]\big)+(1+2l)\,\mathrm{dot}[b,b]\,\mathrm{dot}[ypb,ymb]\Big)$$

$$\big(-\mathrm{dot}[ypb,ypb]\big)^l\,\mathrm{Gamma}\Big[\frac{1}{2}+l\Big]\,\mathrm{Gamma}\Big[\frac{1}{2}+m\Big]\,\mathrm{GegenbauerC}\Big[2l,\frac{3}{2}+m,\frac{\mathrm{dot}[b,ypb]}{\sqrt{\mathrm{dot}[b,b]\,\mathrm{dot}[ypb,ypb]}}\Big]\Bigg)\Big/\Big(2\,\mathrm{Gamma}\Big[-\frac{1}{2}-m\Big]\,\mathrm{Gamma}[1+m]\,\mathrm{Gamma}[2+l+m]\Big)+$$

$$\Bigg((-1)^l\,\pi^{3/2}\,\mathrm{dot}[b,b]^{-2-l-m}\,\mathrm{dot}[b,ymb]\,\big(-\mathrm{dot}[y,y]-\mathrm{dot}[y1,v2]^2\big)^m\,\mathrm{dot}[ypb,ypb]^{\frac{1}{2}+l}\,\mathrm{Gamma}\Big[\frac{3}{2}+l\Big]\,\mathrm{Gamma}\Big[\frac{1}{2}+m\Big]\,\mathrm{GegenbauerC}\Big[1+2l,\frac{1}{2}+m,\frac{\mathrm{dot}[b,ypb]}{\sqrt{\mathrm{dot}[b,b]\,\mathrm{dot}[ypb,ypb]}}\Big]\Bigg)\Big/$$

$$\Big(\mathrm{Gamma}\Big[\frac{1}{2}-m\Big]\,\mathrm{Gamma}[1+m]\,\mathrm{Gamma}[1+l+m]\Big)+\Bigg(\pi^{3/2}\,\mathrm{dot}[b,b]^{-\frac{1}{2}-l-m}\,\big(-\mathrm{dot}[y,y]-\mathrm{dot}[y1,v2]^2\big)^m\,\big(-\mathrm{dot}[ypb,ypb]\big)^l$$

$$\mathrm{Gamma}\Big[\frac{1}{2}+l\Big]\,\mathrm{Gamma}\Big[\frac{1}{2}+m\Big]\,\mathrm{GegenbauerC}\Big[2l,\frac{1}{2}+m,\frac{\mathrm{dot}[b,ypb]}{\sqrt{\mathrm{dot}[b,b]\,\mathrm{dot}[ypb,ypb]}}\Big]\,\Big(\big(-1+\mathrm{gamma}^2\big)\,\big(\mathrm{gamma}\,\mathrm{dot}[y1,v2]-\mathrm{dot}[y2,v1]\big)+$$

$$2(l+m)\,\Big(2\,\mathrm{gamma}\,\big(-1+\mathrm{gamma}^2\big)\,\mathrm{dot}[y1,v2]+\big(\mathrm{dot}[y2,v1]+\mathrm{gamma}\,(\mathrm{dot}[y1,v2]-2\,\mathrm{gamma}\,\mathrm{dot}[y2,v1])\big)\Big)\,\mathrm{Hypergeometric2F1}\Big[1,-m,\frac{1}{2},\frac{\big(-\mathrm{gamma}\,\mathrm{dot}[y1,v2]+\mathrm{dot}[y2,v1]\big)^2}{\big(-1+\mathrm{gamma}^2\big)\,\big(\mathrm{dot}[y,y]+\mathrm{dot}[y1,v2]^2\big)}\Big]\Big)\Bigg)\Big/$$

$$\Big(\big(-1+\mathrm{gamma}^2\big)\,\big(\mathrm{gamma}\,\mathrm{dot}[y1,v2]-\mathrm{dot}[y2,v1]\big)\,\mathrm{Gamma}\Big[\frac{1}{2}-m\Big]\,\mathrm{Gamma}[1+m]\,\mathrm{Gamma}[1+l+m]\Big)+\Bigg(\pi^2\,\mathrm{dot}[b,b]^{-\frac{3}{2}-l-m}\,\big(-\mathrm{dot}[y,y]-\mathrm{dot}[y1,v2]^2\big)^m\,\big(-\mathrm{dot}[ypb,ypb]\big)^l$$

$$\mathrm{dot}[ypb,ypb]\,\mathrm{Gamma}\Big[\frac{3}{2}+l+m\Big]\,\mathrm{Hypergeometric2F1Regularized}\Big[-2(1+l),3+2l+2m,1+m,\frac{1}{2}-\frac{\mathrm{dot}[b,ypb]}{2\sqrt{\mathrm{dot}[b,b]\,\mathrm{dot}[ypb,ypb]}}\Big]\Bigg)\Big/\Big(\mathrm{Gamma}[1+l]\,\mathrm{Gamma}\Big[\frac{1}{2}-m\Big]\,\mathrm{Gamma}[1+m]\Big)$$

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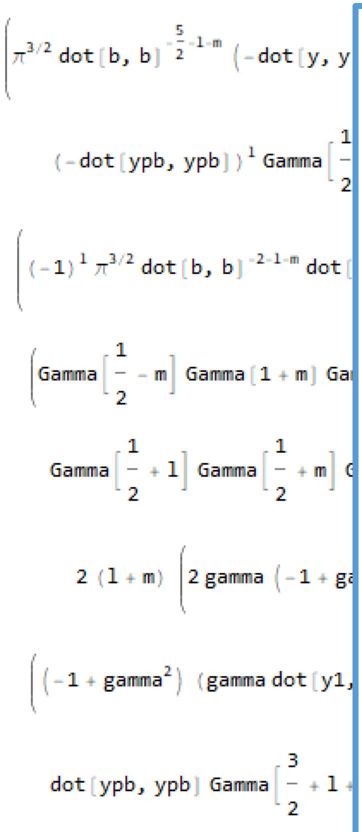
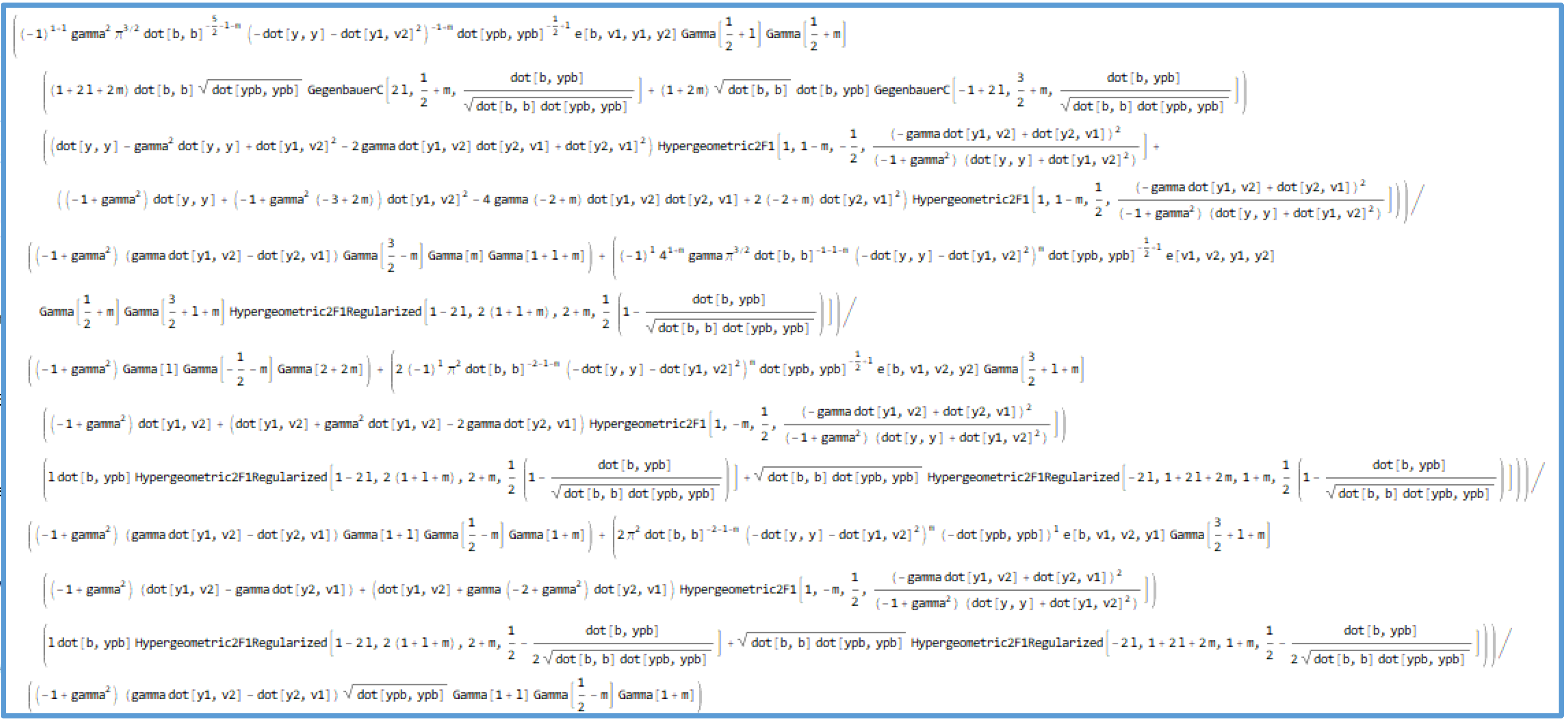
  - Eikonal is a double infinite sum of 2F1, but simplifies in special kinematics



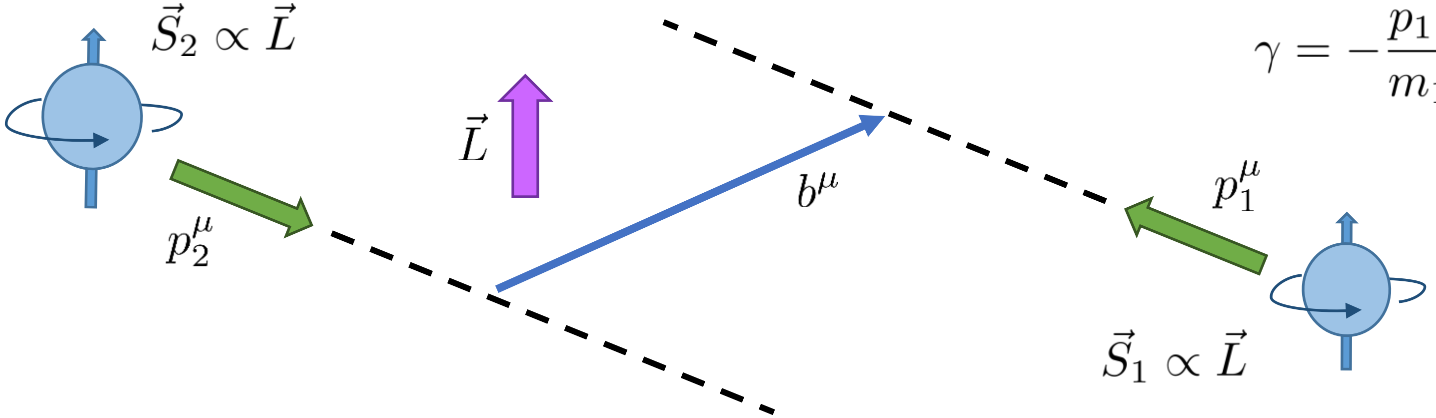


Spin resummation in electrodynamics

[Kim, JWK, Lee]

- Spin-resummed 2PL twistor worldline eikonal
  - Eikonal is a double infinite sum of 2F1, but simplifies in special kinematics
  - Aligned-spin configuration

$$\chi_{(2,\text{aligned})} = \frac{(q_1 q_2)^2 \left(b^2 + \frac{(\zeta-2)\gamma}{(\gamma^2-1)}\,\epsilon[b, v_1, v_2, a] + \frac{\gamma^2(1-\zeta)+\zeta}{\gamma^2-1}\,a^2\right)}{32\pi m_1 \sqrt{\gamma^2-1}\,(b^2-a^2)^{3/2}} + (1 \leftrightarrow 2)$$



$$\gamma = -\frac{p_1 \cdot p_2}{m_1 m_2}\,,\; a_1^\mu = \frac{S_1^\mu}{m_1} = \zeta a^\mu\,,\; a^\mu = a_1^\mu + a_2^\mu$$

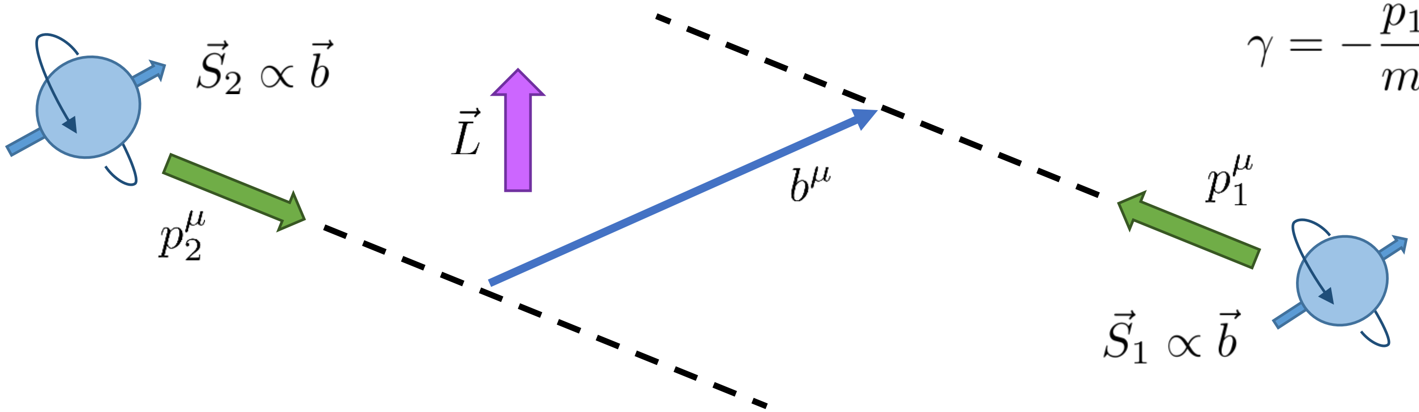
Spin resummation in electrodynamics

[Kim, JWK, Lee]

- Spin-resummed 2PL twistor worldline eikonal
  - Eikonal is a double infinite sum of 2F1, but simplifies in special kinematics
  - Axial scattering configuration

$$\chi_{(2,\text{axial})} = \frac{(q_1 q_2)^2 \sqrt{b^2}}{16\pi^2 m_1 (\gamma^2 - 1)^{3/2}} \left[\frac{\gamma^2(\zeta - 1) - \zeta}{b^2} K(-\frac{a^2}{b^2}) - \frac{\gamma^2(\zeta - 2) - (\zeta - 1)}{b^2 + a^2} E(-\frac{a^2}{b^2}) \right] + (1 \leftrightarrow 2)$$

$$\gamma = -\frac{p_1 \cdot p_2}{m_1 m_2} \,,\; a_1^\mu = \frac{S_1^\mu}{m_1} = \zeta a^\mu \,,\; a^\mu = a_1^\mu + a_2^\mu$$



Challenges for the future

- Pushing the precision frontier: more efficient loop integrations
  - Completing non-spinning 5PM (4-loop)
    - NLO in mass-ratio computed; NNLO remaining
      [Driesse, Jakobsen, Mogull, Plefka, Sauer, Usovitsch;
      Bern, Herrmann, Roiban, Ruf, Smirnov, Smirnov, Zeng]
  - NNLO scattering waveform (2-loop 2 → 3 process)
    - NLO non-spinning computed by various groups
      [Brandhuber, Brown, Chen, De Angelis, Gowdy, Travaglini; Herderschee, Roiban, Teng;
      Elkhidir, O'Connell, Sergola, Vazquez-Holm; Georgoudis, Heissenberg, Vazquez-Holm]
    - NLO linear-in-spin computed [Bohnenblust, Ita, Kraus, Schlenk]
  - Spin resummation in gravity, 2PM (1-loop) [Chen, JWK, Wang (WIP)]
    - Spin resummation at 3PL/PM (2-loop): first beyond-probe-limit computation

Challenges for the future

- From scattering (PM) dynamics to waveform models
  - Obstacle: scattering-to-bound continuation of nonlocal-in-time (tail) effects
    - Various prescriptions exist [Dlapa, Kälin, Liu, Porto; Buonanno, Mogull, Patil, Pompili]
  - Partial success: SEOBNR-PM [Buonanno, Mogull, Patil, Pompili]
    - Quasi-circular orbit / tail contribution from PN computations
    - Less NR calibration compared to PN-based waveform (SEOBNRv5)
  - Improved spin resummation schemes

- Exploring beyond-GR binary dynamics from scattering amplitudes
  [Brandhuber, Travaglini; Emond, Moynihan; Accettulli Huber, De Angelis; Burger; Brown, Pichini, Matasan]

Returning to particle physics

- Tensor Integral Generating Functions [Feng]
  - Feynman integrals deformed by an exponential factor
    - Generally encountered in spin-resummed PM dynamics: $e^{(ia)\cdot\nabla} \Leftrightarrow e^{a\cdot k}$

$$\mathcal{I}_{\lambda_k}[\alpha_i^\mu] = \int \prod_{j=1}^{L} d^D\ell_j \frac{\exp(\sum_{j=1}^{L} \alpha_j \cdot \ell_j)}{\mathcal{D}_1^{\lambda_1} \cdots \mathcal{D}_n^{\lambda_n}}$$

$$\mathcal{D}_j = (\ell + q_j)^2 - m_j^2$$

  - Provides alternative methods for tensor reduction: $\frac{\partial}{\partial \alpha_j^\mu} \Leftrightarrow \ell_j^\mu$
  - Can be computed by <u>*conventional*</u> multiloop techniques [Chen, JWK, Wang (WIP)]
  - Can we reduce irreducible numerators more efficiently?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