Title: Field theory for gravity at all scales

Speakers: Michele Levi

Series: Quantum Fields and Strings

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Abstract: In this talk I will review the state of the art in PN gravity, and in particular its significant advancement via the EFT of spinning gravitating objects. First, I will introduce the concept of a tower of EFTs for the binary inspiral problem. I will then present the intricate formulation of the EFT of spinning objects. Finally, I will present some advanced results accomplished within this framework.

# Field Theory for Gravity at All Scales

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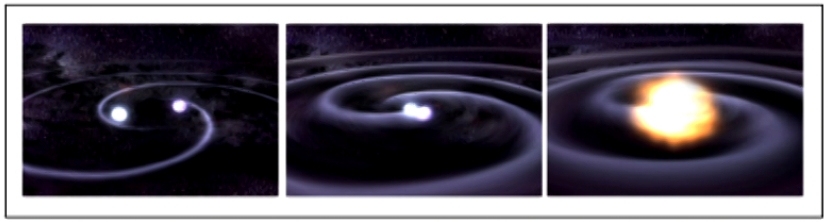
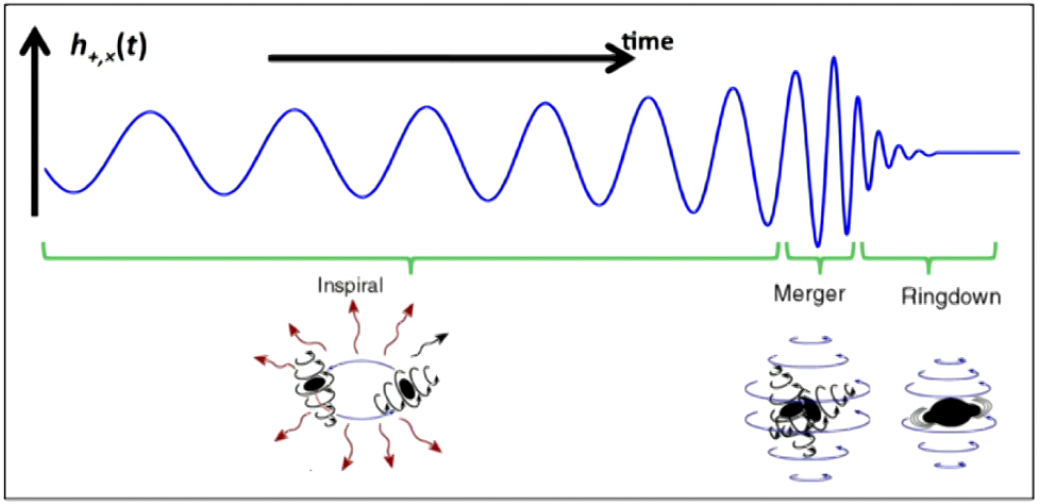
Joint Gravity & Quantum Fields Seminar
Perimeter Institute
February 4, 2020

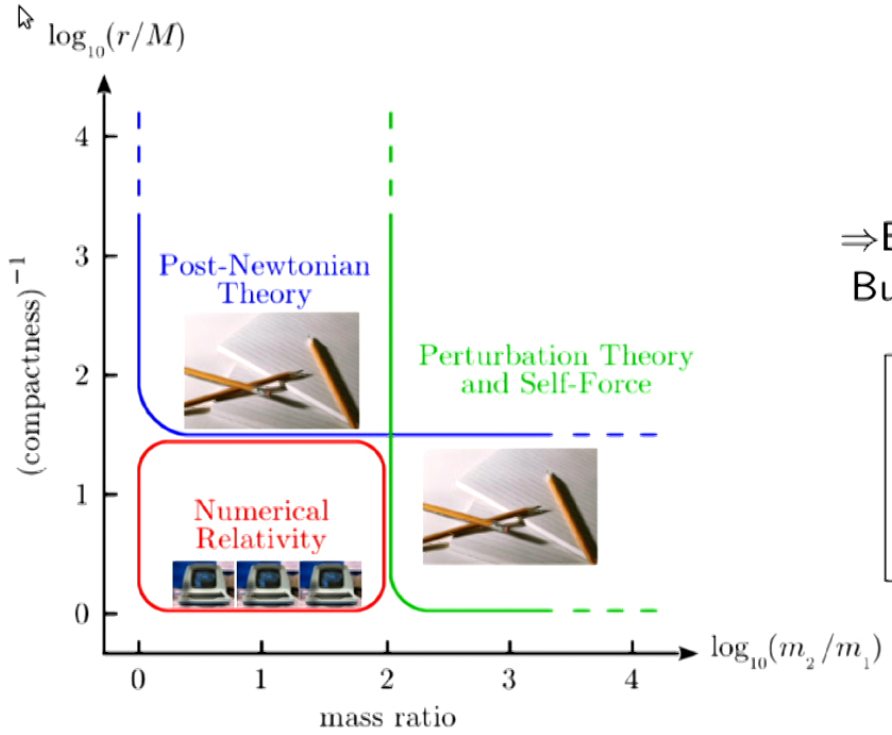
# GW signal from compact binaries



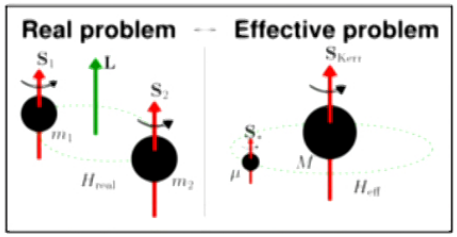
## 3 phases in the life of a compact binary



# Physics of GW templates




⇒Effective One-Body (EOB)
Buonanno & Damour 1999




- Real world: High demand on accurate theoretical waveform templates
- Pure science: How well can PN theory capture strong gravity in general?

# State of the Art in PN Gravity

## Complete state-of-the-art of PN theory for compact binary dynamics

| l \ n | (N$^0$)LO | N$^{(1)}$LO | N$^2$LO | N$^3$LO | N$^4$LO |
|---|---|---|---|---|---|
| S$^0$ | 1 | 0 | 3 | 0 | 25 |
| S$^1$ | 2 | 7 | 32 | | |
| S$^2$ | 2 | 2 | **18** | | |
| S$^3$ | 4 | **24** | | | |
| S$^4$ | **3** | | | | |

- Each entry at the PN order $n + l + \text{Parity}(l)/2$
- A measure for loop computational scale: number of (highest) $n$-loop graphs that enter at N$^n$LO of up to the $l$th multipole moment $S^l$.
- All (but top right one) are derived in the public "EFTofPNG" code: `https://github.com/miche-levi/pncbc-eftofpng`

# EFTs are Universal

## There is a Hierarchy of Scales

1. $r_s$, scale of internal structure, $r_s \sim m$
2. $r$, orbital separation scale, $\dfrac{r_s}{r} \sim v^2$
3. $\lambda$, radiation wavelength scale, $\dfrac{r}{\lambda} \sim v$

$v \ll 1 \rightarrow nPN \equiv v^{2n}$ correction in classical gravity to Newtonian gravity

## Multistage strategy for EFTs of inspiraling binaries

[Goldberger & Rothstein 2007]

It's a multiscale!

1. One-Particle EFT
2. EFT of a Composite Particle
3. Effective Theory of Dynamical Multipoles

# Setup of EFTs is Universal

## Top-Down or Bottom-Up?

Kenneth Wilson

Thomas Appelquist

Two generic procedures to construct Effective Field Theories:

1. Top-Down, perturbative theory in high resolution/close-up is known, so we reduce resolution by systematically removing extra pixels. Feynman formalism/technology enables that.
   – *"Wilsonian approach", Wilson 1971-1974*
2. Bottom-Up, no perturbative theory for the system in close-up, so we look from afar, and gradually zoom in. This is done by identifying the Degrees Of Freedom and Symmetries.
   – *"Decoupling theorem", Appelquist & Carazzone 1975*

# One-Particle EFT

## 1st Stage Remove scale $r_S$ of isolated compact object

In the full theory we only have a vacuum gravitational field:

$$S\left[g_{\mu\nu}\right] = -\frac{1}{16\pi G}\int d^4x\sqrt{g}R\left[g_{\mu\nu}\right]$$

Integrate out strong field modes $g^s_{\mu\nu}$, $g_{\mu\nu} \equiv g^s_{\mu\nu} + \bar{g}_{\mu\nu}$ via bottom-up approach:

$$S_{\text{eff}}\left[\bar{g}_{\mu\nu}, y^\mu(\sigma), e^\mu_A(\sigma)\right] = -\frac{1}{16\pi G}\int d^4x\sqrt{\bar{g}}R\left[\bar{g}_{\mu\nu}(x)\right] + \underbrace{\sum_{i=1}^{\infty} C_i(r_s)\int d\sigma\mathcal{O}_i(\sigma)}_{\equiv S_{pp}(\sigma)\text{ with Wilson coefficients}}$$

The operators $\mathcal{O}_i(\sigma)$ must respect the symmetries that pertain at low energies.

$$S_{\text{eff}}[\bar{g}_{\mu\nu}, y^\mu] = -\frac{1}{16\pi G}\int d^4x\sqrt{\bar{g}}R\left[\bar{g}_{\mu\nu}(x)\right] - \int m d\sigma + \underbrace{c_{5\text{PN}}\int d\sigma\left(R_{\mu\alpha\nu\beta}\dot{y}^\alpha\dot{y}^\beta\right)^2 + \cdots}_{\text{finite size effects}}$$

# EFT of Composite Particle

2nd Stage Remove orbital scale $r$ of binary, first via the top-down approach:

$$\bar{g}_{\mu\nu} \equiv \eta_{\mu\nu} + \underbrace{H_{\mu\nu}}_{\text{orbital}} + \underbrace{\widetilde{h}_{\mu\nu}}_{\text{radiation}}$$

$$\partial_t H_{\mu\nu} \sim \frac{v}{r} H_{\mu\nu}, \quad \partial_i H_{\mu\nu} \sim \frac{1}{r} H_{\mu\nu}, \quad \partial_\rho \widetilde{h}_{\mu\nu} \sim \frac{v}{r} \widetilde{h}_{\mu\nu}$$

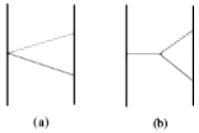
$$S_{\text{eff}}\left[\bar{g}_{\mu\nu}, y_1^\mu, y_2^\mu, e_{(1)A}^{\ \ \mu}, e_{(2)A}^{\ \ \mu}\right] = -\frac{1}{16\pi G}\int d^4x\sqrt{\bar{g}}R\left[\bar{g}_{\mu\nu}\right] + S_{\text{pp}}(\sigma_1) + S_{\text{pp}}(\sigma_2)$$

Integrate out orbital field modes - in this classical context - only tree level

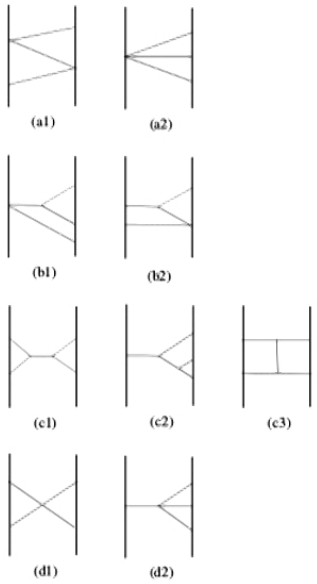
$$\Rightarrow e^{iS_{\text{eff(composite)}}\left[\widetilde{h}_{\mu\nu}, y^\mu, e^\mu_{(Comp)A}\right]} \equiv \int \mathcal{D}H_{\mu\nu}\ e^{iS_{\text{eff}}\left[\bar{g}_{\mu\nu}, y_1^\mu, y_2^\mu, e_{(1)A}^{\ \ \mu}, e_{(2)A}^{\ \ \mu}\right]}$$

Stop here for effective action strictly in conservative sector, that is
**WITHOUT** any remaining (orbital scale) field modes

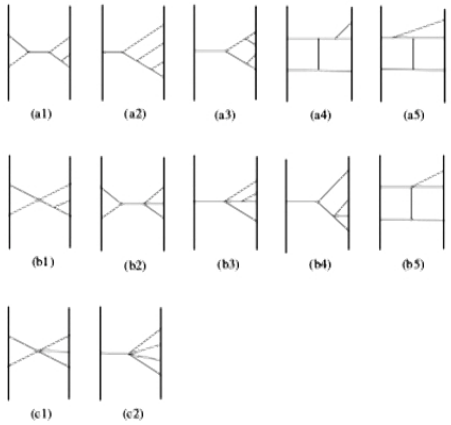
# Graph topologies in conservative sector




Topologies at $O(G^2)$:
(a) Two-graviton exchange;
(b) Cubic self-interaction
$\equiv$ One-loop topology.

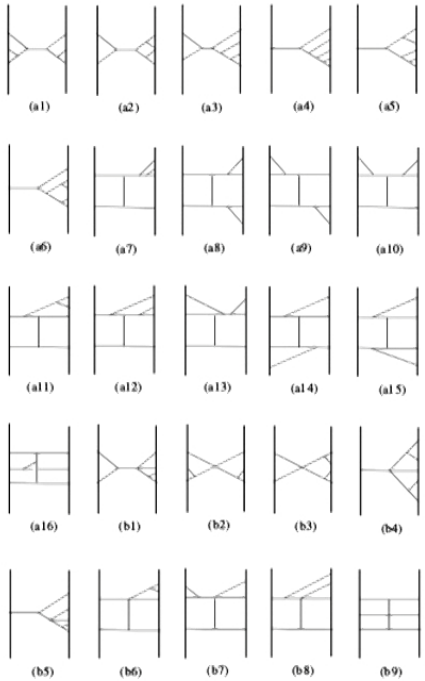



Topologies at $O(G^3)$



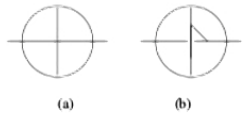

3-loop topologies
(out of total 32)
at $O(G^4)$

# Graph topologies in conservative sector




4-loop topologies at $O(G^5)$ at 4PN using KK metric

Standard QFT multi-loop techniques based on $n$-loop master integrals, and IBPs




4-loop two-point topologies at 4PN

# EFT of a Composite Particle

Remove orbital scale via bottom-up approach:

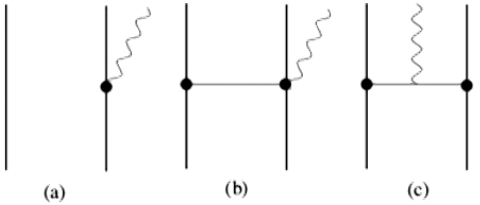
$$S_{\text{eff(comp)}}[\widetilde{g}_{\mu\nu}, y_c^\mu, e_{c\,A}^{\ \mu}] = -\frac{1}{16\pi G}\int d^4x\sqrt{\widetilde{g}}\,R\,[\widetilde{g}_{\mu\nu}] + S_{\text{pp(comp)}}[\widetilde{g}_{\mu\nu}(y_c), y_c^\mu, e_{c\,A}^{\ \mu}](\sigma_c)$$

The point-particle action of the composite particle is a multipole expansion:

$$S_{\text{pp(comp)}}[\widetilde{h}_{\mu\nu}, y_c^\mu, e_{c\,A}^{\ \mu}](t) = -\int dt\sqrt{\widetilde{g}_{00}}\left[M(t) + \frac{1}{2}\epsilon_{ijk}L^k(t)\left(\Omega_{\text{LF}}^{ij} + \omega_\mu^{ij}u^\mu\right) - \sum_{l=2}^{\infty}\left(\frac{1}{l!}I^L(t)\nabla_{L-2}E_{i_{l-1}i_l} - \frac{2l}{(l+1)!}J^L(t)\nabla_{L-2}B_{i_{l-1}i_l}\right)\right]$$

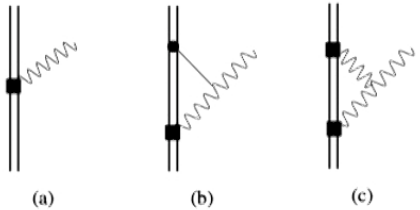
$L$ abbreviated notation for $i_1\cdots i_l (l \geq 2)$

# Graphs in radiative sector

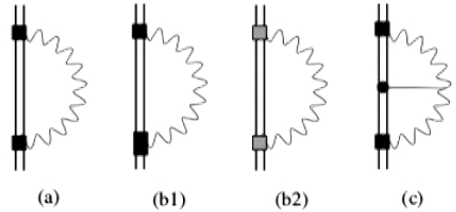



1PN mass quadrupole $I^{ij}$

$\Longrightarrow$




Radiation and hereditary effects.
Black square boxes $I^{ij}$ and sphere total mass monopole $M$.
(a) Diagrams on the left match onto this one.
(b) Leading tail effect
(c) Leading memory effect




Radiation reaction

# Spinning Particle: DOFs

Assume isolated object has no intrinsic permanent multipoles beyond mass (monopole) and spin (dipole)

1. *Gravitational field*
   - Metric $g_{\mu\nu}(x)$
   - Tetrad field $\eta^{ab}\tilde{e}_a{}^{\mu}(x)\tilde{e}_b{}^{\nu}(x) = g^{\mu\nu}(x)$

2. *Particle Coordinate*

   $y^{\mu}(\sigma)$ function of arbitrary affine parameter $\sigma$
   Particle worldline position does not in general coincide with object's 'center'

3. *Particle rotating DOFs*

   Worldline tetrad, $\eta^{AB}e_A{}^{\mu}(\sigma)e_B{}^{\nu}(\sigma) = g^{\mu\nu}$

   $\Rightarrow$ Angular velocity $\Omega^{\mu\nu}(\sigma) \equiv e^{\mu}_A \frac{De^{A\nu}}{D\sigma}$ + conjugate Spin $S_{\mu\nu}(\sigma)$

   $\Rightarrow$ Lorentz matrices $\eta^{AB}\Lambda_A{}^{a}(\sigma)\Lambda_B{}^{b}(\sigma) = \eta^{ab}$ + conjugate local spin $S_{ab}(\sigma)$

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# Where is our spinning 'particle'?

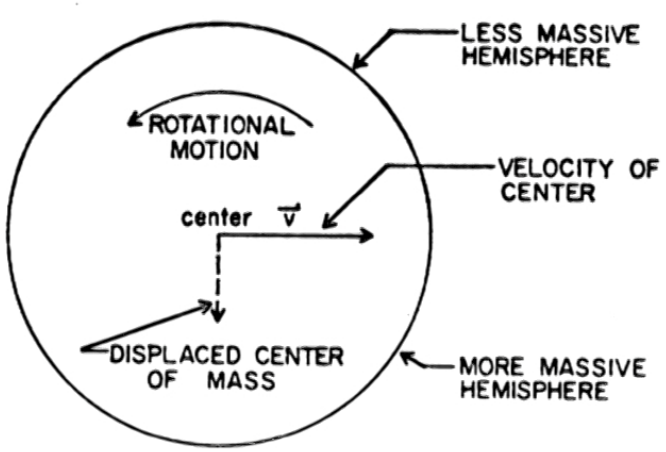
Spin is WIDE:

- Special Relativity already requires a minimal finite measure, $S/Mc$, for the rotational velocity not to exceed the speed limit!
- Also in General Relativity, where this is the ring singularity of Kerr

In Newtonian physics a unique notion of a center, with the 3 nice properties:

1. 3-vector
2. Forms canonical pair together with the total momentum
3. Center of spatial mass distribution

No unique 'center' in relativistic physics!




Fleming 1965

# Spinning Particle: Symmetries

1. General coordinate invariance, and parity invariance
2. Worldline reparametrization invariance
3. Internal Lorentz invariance of local frame field
4. SO(3) invariance of 'body-fixed' spatial triad
5. Spin gauge invariance, that is invariance under choice of completion of 'body-fixed' spatial triad through timelike vector

# Spin as extra particle DOF

## Effective action of spinning particle

[Hanson & Regge 1974, Bailey & Israel 1975]

- $u^\mu \equiv dy^\mu/d\sigma$, $\Omega^{\mu\nu} \equiv e_A^\mu \frac{De^{A\nu}}{D\sigma} \Rightarrow L_{\rm pp}\left[\bar{g}_{\mu\nu}, u_\mu, \Omega^{\mu\nu}\right]$
- $S_{\mu\nu} \equiv -2\frac{\partial L}{\partial \Omega^{\mu\nu}}$ spin as further particle DOF – classical source

$$\Rightarrow S_{\rm pp}(\sigma) = \int d\sigma \left[-p_\mu u^\mu - \frac{1}{2} S_{\mu\nu}\Omega^{\mu\nu} + L_{\rm NMC}\left[\bar{g}_{\mu\nu}\left(y^\mu\right), u^\mu, S_{\mu\nu}\right]\right]$$

- This form assumes implicit "covariant gauge": $e^\mu_{[0]} = \frac{p^\mu}{\sqrt{p^2}}$, $\quad S_{\mu\nu}p^\nu = 0$
- Linear momentum $p_\mu \equiv -\frac{\partial L}{\partial u^\mu} = m\frac{u^\mu}{\sqrt{u^2}} + \mathcal{O}(S^2)$

For EFT of spin – gauge of both rotational DOFs
should be fixed at level of one-particle action

# Introduce gauge freedom in tetrad & spin

## Introduce gauge freedom into tetrad

Transform from a gauge condition

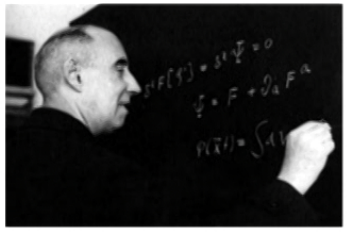
$$e_{A\mu} q^{\mu} = \eta_{[0]A} \Leftrightarrow e_{[0]\mu} = q_{\mu}$$

to

$$\hat{e}_{A\mu} w^{\mu} = \eta_{[0]A} \Leftrightarrow \hat{e}_{[0]\mu} = w_{\mu}$$

with a boost-like transformation in covariant form

$$\hat{e}^{A\mu} = L^{\mu}{}_{\nu}(w, q) e^{A\nu}$$



Ernst Stueckelberg

with $q_\mu$, $w_\mu$ timelike unit 4-vectors

## Generic gauge for the tetrad entails the generic "SSC"

$$\hat{e}_{[0]\mu} = w_{\mu} \quad \Rightarrow \quad \hat{S}^{\mu\nu} \left( p_{\nu} + \sqrt{p^2} w_{\nu} \right) = 0$$

# Extra term in minimal coupling

$$\Rightarrow \hat{S}^{\mu\nu} = S^{\mu\nu} - \delta z^\mu p^\nu + \delta z^\nu p^\mu$$

$$\delta z^\mu = \frac{S^{\mu\rho} w_\rho}{\sqrt{p^2} + pw} = -\frac{\hat{S}^{\mu\rho} p_\rho}{p^2}, \qquad \delta z^\mu p_\mu = 0$$

$\Rightarrow$ Extra term in action appears!

- From minimal coupling

$$\frac{1}{2} S_{\mu\nu} \Omega^{\mu\nu} = \frac{1}{2} \hat{S}_{\mu\nu} \hat{\Omega}^{\mu\nu} + \frac{\hat{S}^{\mu\rho} p_\rho}{p^2} \frac{Dp_\mu}{D\sigma}$$

- Extra term with covariant derivative of momentum, contributes to finite size effects, yet carries no Wilson coefficient
- As of LO with spin, to all orders in spin!
- Essentially Thomas precession

- Beyond minimal coupling we transform between spin variables by projecting

# Non-minimal coupling: Under construction

## Spin-induced higher multipoles

- Consider the spin vector

$$S^\mu \equiv {}^*S^{\mu\nu}\frac{p_\nu}{\sqrt{p^2}} \simeq {}^*S^{\mu\nu}\frac{u_\nu}{\sqrt{u^2}}, \qquad {}^*S_{\alpha\beta} \equiv \frac{1}{2}\epsilon_{\alpha\beta\mu\nu}S^{\mu\nu}$$

$$\Rightarrow \; S_\mu S^\mu = -\frac{1}{2}S_{\mu\nu}S^{\mu\nu} \equiv -S^2$$

- Consider dependence of higher powers of spin:

$$S^\alpha{}_\mu S^\mu{}_\beta = -S^\alpha S_\beta - S^2\left(\delta^\alpha{}_\beta - \frac{u^\alpha u_\beta}{u^2}\right)$$

$$S^\alpha{}_\mu S^\mu{}_\nu S^\nu{}_\beta = -S^2 S^\alpha{}_\beta$$

$$\Rightarrow X(X+iS)(X-iS) = 0$$

$\Rightarrow$ Independent combinations: $S^\alpha$, $S^\alpha{}_\mu S^\mu{}_\beta \sim S^\alpha S_\beta \ldots$

# Non-minimal coupling: Under construction

## Spin-induced higher multipoles

- Considering body-fixed frame: Spin multipoles are SO(3) irreps tensors
- Recall we start from "covariant gauge": $e_{[0]}{}^{\mu} = u^{\mu}/\sqrt{u^2}$, $e_{[i]}{}^{\mu} u_{\mu} = 0$

$\Rightarrow$ Spin-induced higher multipoles are symmetric, traceless, and spatial, constant tensors in body-fixed frame

## Curvature

- Electric component $E_{\mu\nu} \equiv R_{\mu\alpha\nu\beta} u^{\alpha} u^{\beta}$
- Magnetic component $B_{\mu\nu} \equiv \frac{1}{2} \epsilon_{\alpha\beta\gamma\mu} R^{\alpha\beta}{}_{\delta\nu} u^{\gamma} u^{\delta}$

Field is vacuum solution at LO, properties of Riemann, Bianchi identities
$\Rightarrow$ $E/B$ are symmetric, traceless, and orthogonal to $u^{\mu}$, also when projected to body-fixed frame, where they are spatial

Building blocks $\sim$ Riemann components $\bullet$ Spin-induced multipoles

Even/odd spin-induced multipoles couple to even/odd parity electric/magnetic curvature components, and their covariant derivatives

# Non-minimal coupling: Under Construction

## Adding covariant derivatives

- Covariant derivatives of electric/magnetic tensors also projected to body-fixed frame $D_{[i]} = e^{\mu}_{[i]} D_{\mu}$
- Time derivative $D_{[0]} = u^{\mu} D_{\mu} \equiv D/D\sigma$ can be ignored at linear order in curvature, i.e. for non-tidal effects
- In analogy to Maxwell's equations

$$\epsilon_{[ikl]} D_{[k]} E_{[lj]} = \dot{B}_{[ij]} \simeq 0$$
$$\epsilon_{[ikl]} D_{[k]} B_{[lj]} = -\dot{E}_{[ij]} \simeq 0$$
$$\Rightarrow D_{[i]} E_{[ij]} = D_{[i]} B_{[ij]} = 0, \quad \Box E_{[ij]} = \Box B_{[ij]} = 0$$

$\Rightarrow$ Indices of covariant derivatives would be symmetrized with respect to indices of electric/magnetic tensors

$\Rightarrow$ Covariant derivatives of these tensors also traceless

# Leading non-minimal couplings to all orders in spin

New spin-induced Wilson coefficients:

$$L_{\rm NMC} = \sum_{n=1}^{\infty} \frac{(-1)^n}{(2n)!} \frac{C_{ES^{2n}}}{m^{2n-1}} D_{\mu_{2n}} \cdots D_{\mu_3} \frac{E_{\mu_1\mu_2}}{\sqrt{u^2}} S^{\mu_1} S^{\mu_2} \cdots S^{\mu_{2n-1}} S^{\mu_{2n}}$$
$$+ \sum_{n=1}^{\infty} \frac{(-1)^n}{(2n+1)!} \frac{C_{BS^{2n+1}}}{m^{2n}} D_{\mu_{2n+1}} \cdots D_{\mu_3} \frac{B_{\mu_1\mu_2}}{\sqrt{u^2}} S^{\mu_1} S^{\mu_2} \cdots S^{\mu_{2n-1}} S^{\mu_{2n}} S^{\mu_{2n+1}}$$

## Leading spin couplings up to 5PN order

- $L_{ES^2} = -\frac{C_{ES^2}}{2m} \frac{E_{\mu\nu}}{\sqrt{u^2}} S^\mu S^\nu$, Quadrupole @2PN
- $L_{BS^3} = -\frac{C_{BS^3}}{6m^2} \frac{D_\lambda B_{\mu\nu}}{\sqrt{u^2}} S^\mu S^\nu S^\lambda$, Octupole @3.5PN
- $L_{ES^4} = \frac{C_{ES^4}}{24m^3} \frac{D_\lambda D_\kappa E_{\mu\nu}}{\sqrt{u^2}} S^\mu S^\nu S^\lambda S^\kappa$, Hexadecapole @4PN

# Disentangling graviton and particle DOFs

## Particle tetrad contains both rotational and graviton DOFs

- $\hat{e}_A{}^\mu = \hat{\Lambda}_A{}^b \tilde{e}_b{}^\mu$: $\eta^{AB}\hat{\Lambda}_A{}^a\hat{\Lambda}_B{}^b = \eta^{ab}$, tetrad field $\eta_{ab}\tilde{e}^a{}_\mu\tilde{e}^b{}_\nu = g_{\mu\nu}$
- $\frac{1}{2}\hat{S}_{\mu\nu}\hat{\Omega}^{\mu\nu} = \frac{1}{2}\hat{S}_{ab}\hat{\Omega}^{ab}_{\text{LocFlat}} + \frac{1}{2}\hat{S}_{ab}\omega_\mu{}^{ab}u^\mu$, $\omega_\mu{}^{ab} \equiv \tilde{e}^b{}_\nu D_\mu \tilde{e}^{a\nu}$ Ricci rotation coeffs.

  $\Rightarrow$ New rotational variables: $\hat{\Omega}^{ab}_{\text{LocFlat}} \equiv \hat{\Lambda}^{Aa}\frac{d\hat{\Lambda}_A{}^b}{d\sigma}$, $\hat{S}_{ab}$

## Separation of graviton from particle DOFs is not completed

- $\hat{\Lambda}_{[0]}{}^a = w^a = \tilde{e}^a{}_\mu w^\mu$ may contain further graviton dependence
- $\hat{S}_{0i}$ components contain further graviton dependence

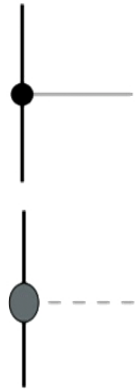
  $\Rightarrow$ Graviton completely disentangled from particle DOFs only once gauge for rotational variables is fixed

# Kaluza-Klein decomposition of field

## Reduction over time dimension à la Kaluza-Klein

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu \equiv e^{2\phi}(dt - A_i dx^i)^2 - e^{-2\phi}\gamma_{ij}dx^i dx^j$$

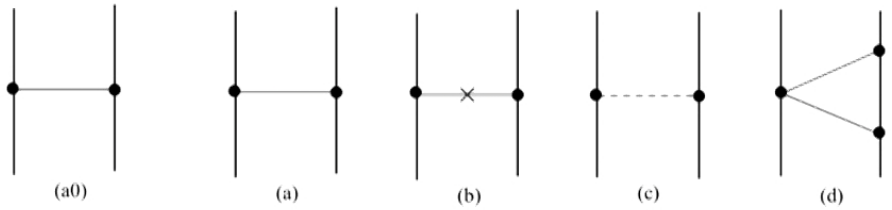
- $\phi, A_i, \gamma_{ij} \equiv \delta_{ij} + \sigma_{ij}$, KK fields
- Newtonian potential scalar $\phi$

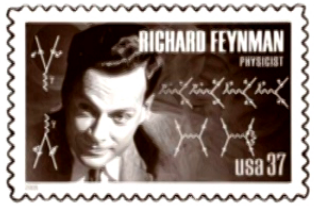


- Gravitomagnetic vector $A_i$
- Hierarchy in coupling to mass and to spin
- Advantageous, preferable e.g. over Lorentz covariant, ADM decompositions...

# LO sectors beyond Newtonian

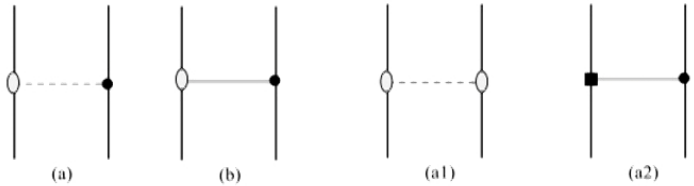
## Feynman graphs of non-spinning sector to 1PN order




Newton . One-loop diagram – absent from 1PN with KK parametrization of field

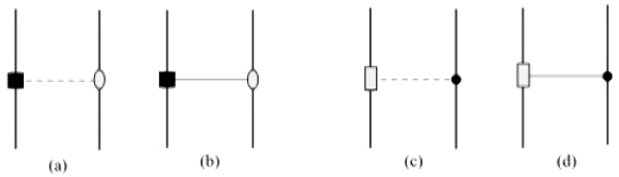
## LO Feynman diagrams with spin – to quadratic-in-spin




Spin-Orbit Spin-Spin

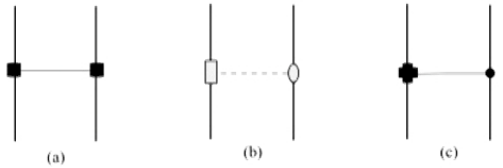
# LO cubic & quartic in spin

## Feynman diagrams of LO **cubic** in spin sector




- On left pair – quadrupole-dipole, on right – octupole-monopole
- Note analogy of each pair with LO spin-orbit

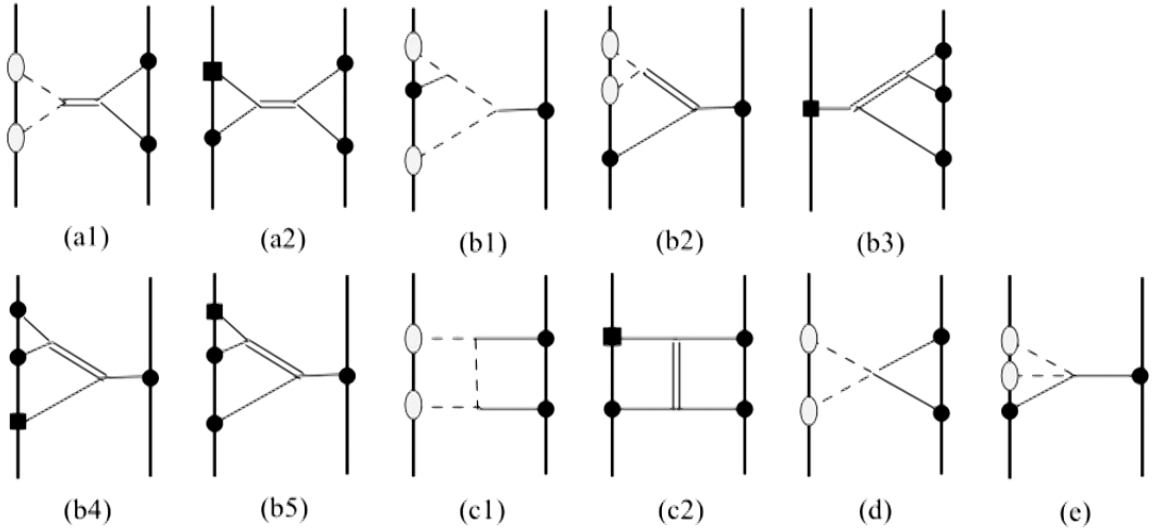
## Feynman diagrams of LO **quartic** in spin sector




- On left and right – quadrupole-quadrupole and hexadecapole-monopole
  Each is analogous to LO spin-squared
- In middle – octupole-dipole analogous to LO spin1-spin2

# NNLO spin-squared sector

## Feynman diagrams of order $G^3$ with 2 loops

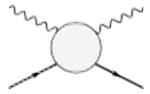



- In general (in particular with spin!) at N$^n$LO – $n$-loop graphs are realized
- Five 2-loop topologies actually fall into 3 kinds
- I (or H rotated) topology (c1,c2) – is the leading nasty one (i.e. IBP needed)!

# State of the Art in PN Gravity Theory

## Complete state-of-the-art of PN theory for compact binary dynamics

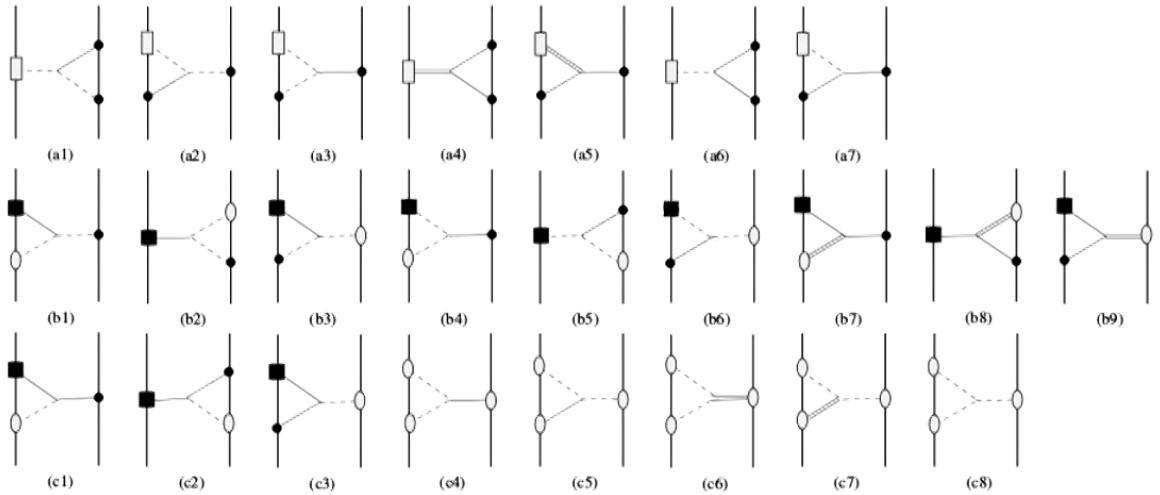
| l \ n | $(N^0)LO$ | $N^{(1)}LO$ | $N^2LO$ | $N^3LO$ | $N^4LO$ |
|---|---|---|---|---|---|
| $S^0$ | 1 | 0 | 3 | 0 | 25 |
| $S^1$ | 2 | 7 | 32 | | |
| $S^2$ | 2 | 2 | **18** | | |
| $S^3$ | 4 | **24** | | | |
| $S^4$ | **3** | | | | |

- Gray area corresponds to where we can no longer take $p^\mu \simeq \frac{m}{u} u^\mu$, but have to take into account corrections from non-minimal coupling part of spinning particle action. What happens then?
- Also corresponds to gravitational Compton scattering  with $s \geq 3/2$ as classical $S^l$ corresponds to quantum $s = l/2$
- Can we get insight on the graviton Compton amplitude with $s \geq 5/2$ from PN gravity?

# NLO cubic-in spin sector

**ML**, Mougiakakos, Vieira,  arXiv:1912.06276

## Feynman graphs of one-loop




- Graphs include all relevant interactions among the spin-induced quadrupole, octupole, and the mass and spin
- There are nonlinearities originating strictly from minimal coupling
- Cubic vertices with time derivatives, similar to NLO (odd P) spin-orbit sector

# NLO cubic-in spin sector

**ML**, Mougiakakos, Vieira, arXiv:1912.06276

## New Feature: Extra one- and two-graviton exchange

- $p_\mu = \frac{m}{u} u_\mu + \Delta p_\mu(RS^2) \Rightarrow L_{S^3}$
- New type of worldline-graviton couplings to "composite" octupole expressed in terms of "elementary" spin multipoles

# Field Theory for Gravity at All Scales

**ML**, Rept. Prog. Phys. 2019

- Knowledge can → should be exchanged between the 2 fields
- EFT of gravitating spinning objects has pushed state of the art in Gravity
- NLO cubic-in-spin - 1st complete sector beyond current precision frontier
- Continuous development of public computational tools
- PN gravity does tell us about gravity in general
- Even-in-spin easier than odd-in-spin ≡ Bosons are nicer than fermions
- New feature in NLO cubic-in-spin resonates with picture of composite (rather than elementary) particles at higher spins
- Going into the "gray area" becomes extremely intricate also classically
- Can amplitudes approaches capture such classical effects?
- Possible insight for graviton Compton amplitude with higher spins