Particle Physics Perspectives on Gravity

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Relativity Perspective (Einstein)

- SPACE TIME IS A SEMI-RIEMANNIAN MANIFOLD
- PHYSICAL OBJECTS ARE CONSTRUCTED FROM GEOMETRIC OBJECTS (COVARIANT QUANTITES)

Particle Physics Perspective (Kraichnan, Gupta, Feynman, Weinberg)

- THERE EXISTS A MASSLESS SPIN TWO PARTICLE S-Matrix
- ALL THEORIES MUST BE POINCARE INVARIANT

Approaches are NOT logically independent, but the tool kits are quite distinct.

Particle Physics Perspective

Formal Progress

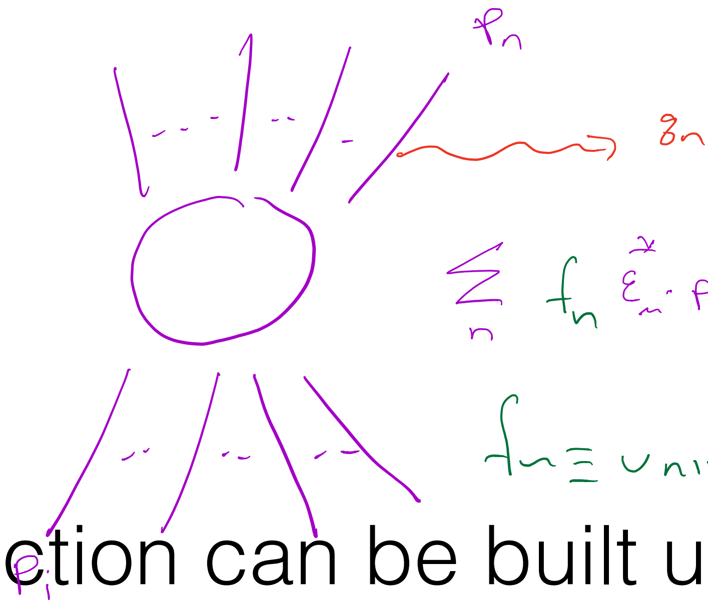
- String World Sheet Expansion/ Large N YM, Gauge/ Gravity Duality (AdS/CFT)
- BCJ Relation between scattering amplitudes
- Generating Classical Solutions

Phenomenological Progress

- LIGO discovery of GW150914, New Field of Gravity Wave Phenomenology, fertile ground for studying fundamental physics.
- Particle Physics Perspective : Effective Field Theory

Formalism: "Just Another Gauge Theory"

- Lorentz Invariance of S implies weak equivalence principle (Weinberg)

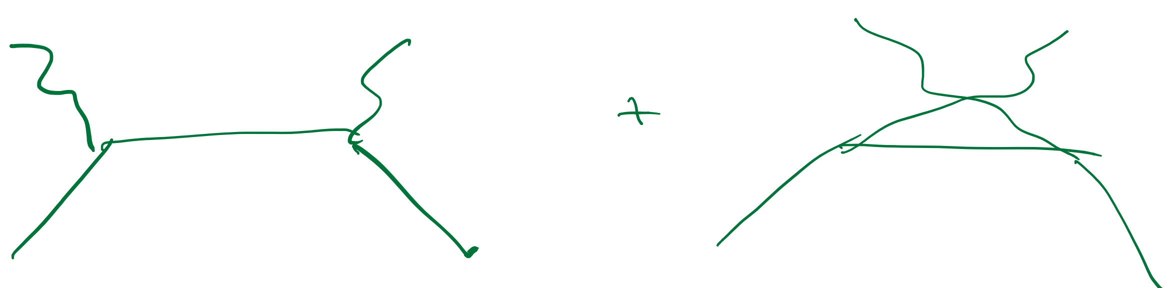


$\sum_n f_n \, \varepsilon_n^* \cdot p_n = 0$

$f_n \equiv$ universal

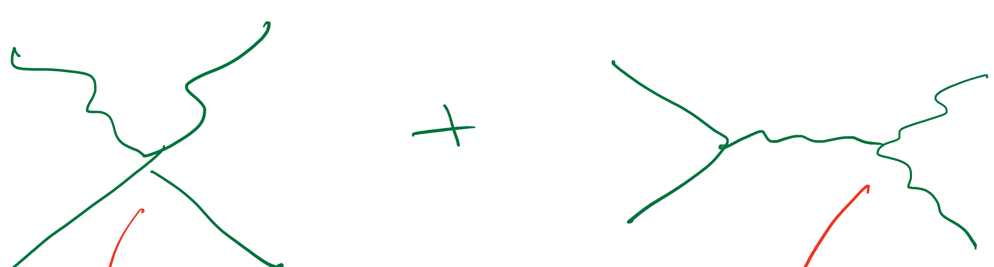
(Weinberg)

- Einstein-Hilbert action can be built up from consistency, current conservation.



NOT GAUGE INV.

Builds up diff. invariance order by order



Builds up $\sqrt{g}$

Builds up $R_{\mu\nu}$

(Deser) Full Einstein-Hilbert

Modern Understanding: Action carries with it unphysical, off shell information that obscures the underlying physics.

Little Group Covariance + Locality

uniquely fixes 3-pnt S-Matrix

$$A_g(1^- 2^- 3^+) = \frac{\langle 12\rangle^6}{\langle 23\rangle^2 \langle 31\rangle^2}$$

$$A_g(1^+ 2^+ 3^-) = \frac{[12]^6}{[23]^2 \langle 31\rangle^2}$$

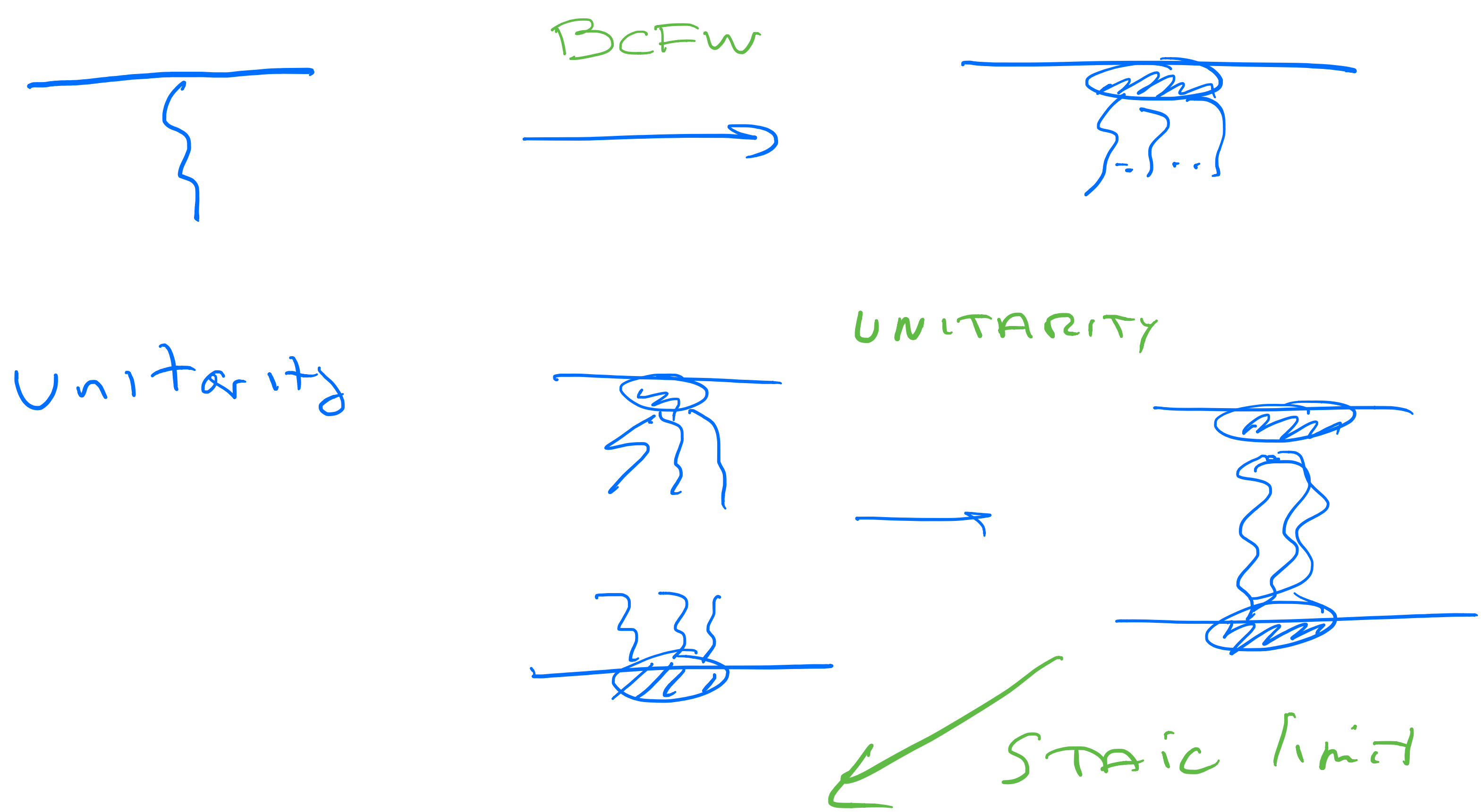
From these seeds BCFW bootstrap allows for the construction of all n-point tree level S matrix elements

Use this methodology to show that Classical Spacetimes emerge from the S-matrix, no need for Einstein Equations

- Reconstruct metric (AF) from geodesics

(D. Neill, IZR)

- Geodesics determined by a set of potentials in NR limit.
- Potentials are generated from S-matrix elements with static external states
- Only input is Lorentz invariance and unitarity, no Lagrangian, or Feynman rules



Schwarzschild, as well as Kerr (Vaidya)

potentials: $\sum_i c_i V_i(r)$

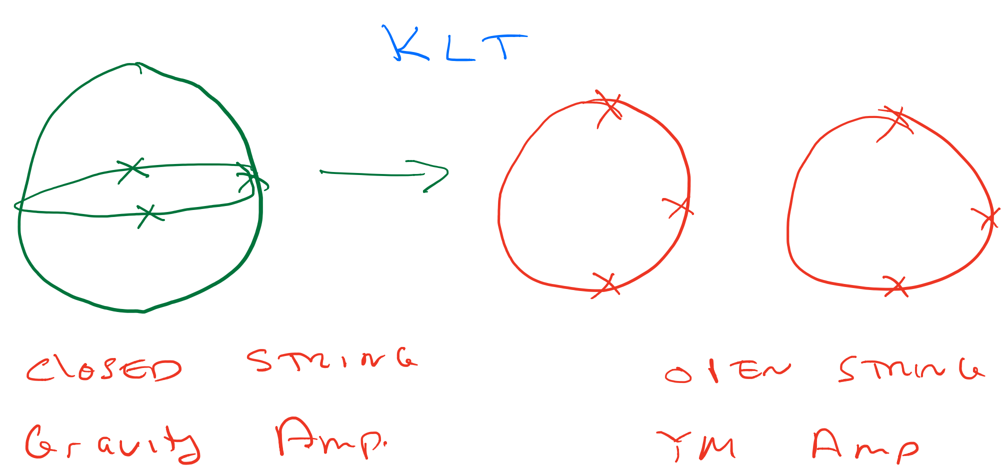
This approach also shed light on the relation between YM and GR

Little Group Covariance + Locality

uniquely fixes 3-pnt S-Matrix

$$A_g(1^-2^-3^+) = \frac{\langle 12\rangle^6}{\langle 23\rangle^2\langle 31\rangle^2} = A_{YM}^2(1^-2^-3^+)$$

$$A_g(1^+2^+3^-) = \frac{[12]^6}{[23]^2\langle 31\rangle^2} = A_{YM}^2(1^+2^+3^-)$$



KLT only valid at tree and involves multiple color ordering, BCJ generalizes and works at loop level (even w/o busy)

Is there a classical double copy? Given the mapping between S-matrices and space-times one might hope so.

Saotome-Akhoury showed (by resuming ladder diagrams) that leading order Regge scattering obeys the double copy relation

Monteiro, Oconnel and White consider space times that can be written in Kerr-Schild form

$$g_{\mu\nu} = \eta_{\mu\nu} + \phi(x) k_\mu k_\nu \qquad g_{\mu\nu} k_\mu k_\nu = \eta_{\mu\nu} k_\mu k_\nu = 0$$

Null geodesic $\quad k^\mu \partial_\mu k^\nu = 0$

$$A_\mu = k_\mu \phi$$

Consider Schwarzschild Solution

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{2GM}{r} k_\mu k_\nu \qquad\qquad k^\mu = (1, \frac{x^i}{r})$$

$$A^\mu = \frac{gc^aT^a}{4\pi r}(1, \frac{\vec{x}}{r}) \;\equiv (\frac{gc^aT^a}{4\pi r}, \vec{0})$$

$C^aT^a \leftrightarrow M$ Charge Map $\frac{\sqrt{16\pi G}}{2} \leftrightarrow g$

Inherently Abelian choose a gauge where charges commute, force is simply Coulombic (Mandula, Sikivie, Weiss)

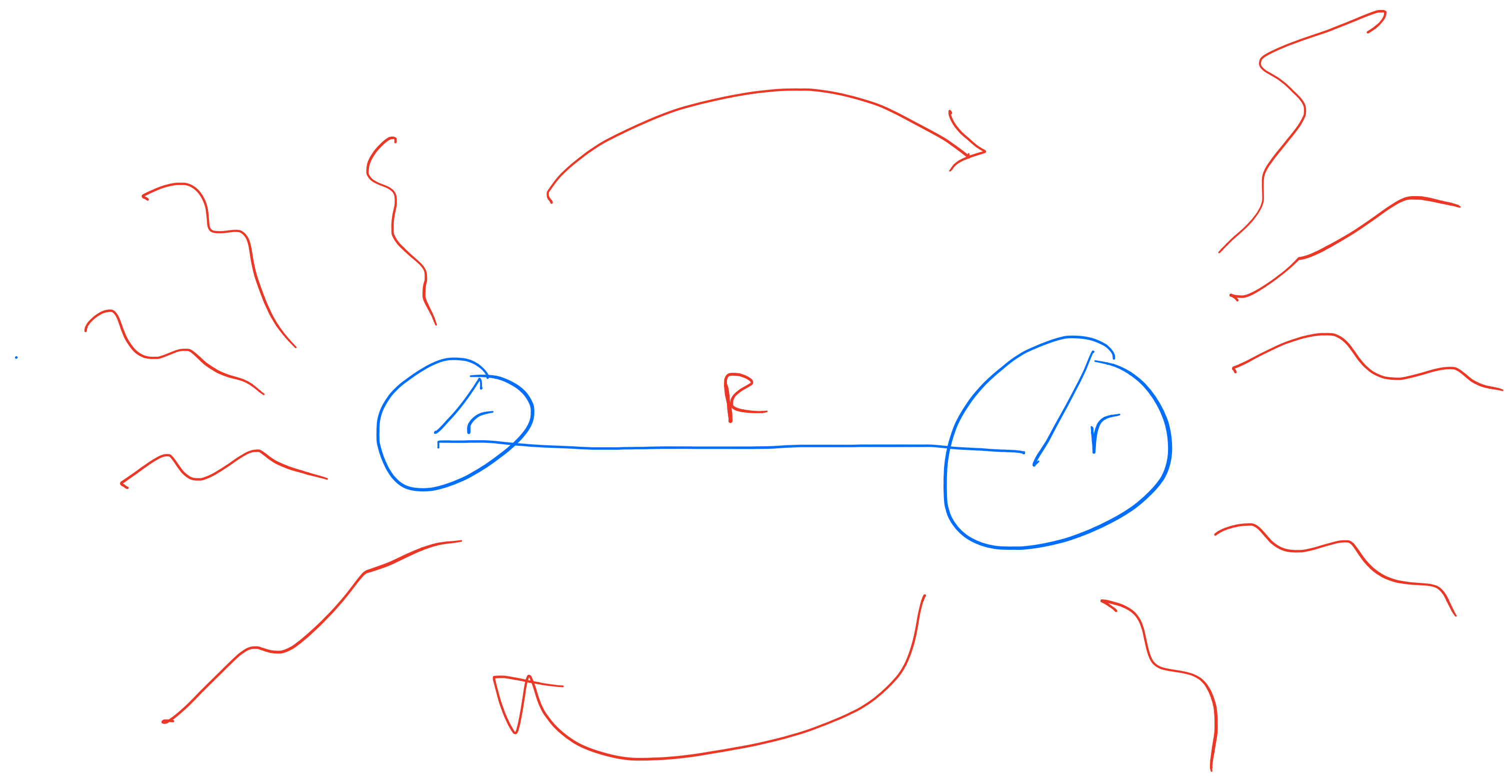
Gravity Wave Pheno-16

Implications for fundamental physics:

- Implications for Dark Matter
- Alternate Theories of Gravity
- Precision measurements of cosmological parameters

Our ability to extract information from data is predicated on our ability to make precision predictions with well defined systematic errors.

Binary Inspiral



In early stages of inspired system is non-relativistic bound state.

Multi scale classical non-linear field theory problem

NRGR: EFT of GR for describing gravitational dynamics of compact objects

Tower of Effective Field Theories:

(W. Goldberger, IZR)

Extended objects (BH/NS) + GR (the "full theory")

match $\qquad \frac{1}{\mu} = r_s$

Relativistic point particle + GR $(\mathcal{ZOSO})$

↓ non-trivial RG running

2-body NR problem or m/M

match $\qquad \frac{1}{\mu} = r$

Composite object + radiation gravitons (NRGR)

↓ non-trivial RG running?

$\frac{1}{\mu} = \frac{r}{v}$

1) Integrate out internal degrees of freedom

$k \sim 1/R$

$$S = \sum_i \int (m_i + C_E^i E^2 + C_B^i B_+^2 \ldots\ldots) d\tau$$

$C_E \sim C_B \sim R^3$

Tidal Love Numbers

Vanish for black holes, extreme fine tuning!

2) Integrate out orbital scale

Potential Gravitons: $k^0 \sim v/r, \quad |\vec{k}| \sim 1/r$

mediate binding forces, generate orbits. Never on-shell, so must integrate out.

Integrate out

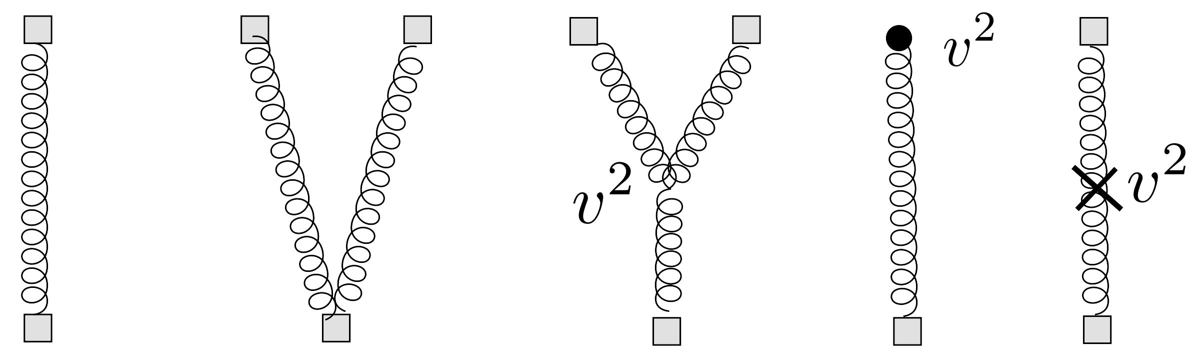
Radiation Gravitons: $k^\mu \sim v/r$ These are the modes that propagate to the detector. They generate cuts in diagrams.

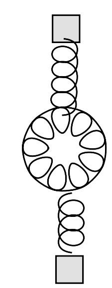
keep

$$e^{iS_{eff}(x_i,v_i,h)} = \int DH e^{iS(g_{\mu\nu},,x_i,v_i)}$$

$$S_{eff} = K.E + \sum_i V(x_i, v_i) + \int dt(Q_{ij}E_{ij} + I_{ij}B_{ij} + ...)$$

Potentials calculated by vacuum amplitudes





Drop quantum diagrams

$$L_{EIH} = \frac{1}{8}\sum_a m_a \mathbf{v}_a^4 + \frac{G_N m_1 m_2}{2|\mathbf{x}_1 - \mathbf{x}_2|}\left[3(\mathbf{v}_1^2 + \mathbf{v}_2^2) - 7(\mathbf{v}_1 \cdot \mathbf{v}_2) - \frac{(\mathbf{v}_1 \cdot \mathbf{x}_{12})(\mathbf{v}_2 \cdot \mathbf{x}_{12})}{|\mathbf{x}_1 - \mathbf{x}_2|^2}\right] - \frac{G_N^2 m_1 m_2 (m_1 + m_2)}{2|\mathbf{x}_1 - \mathbf{x}_2|^2}$$

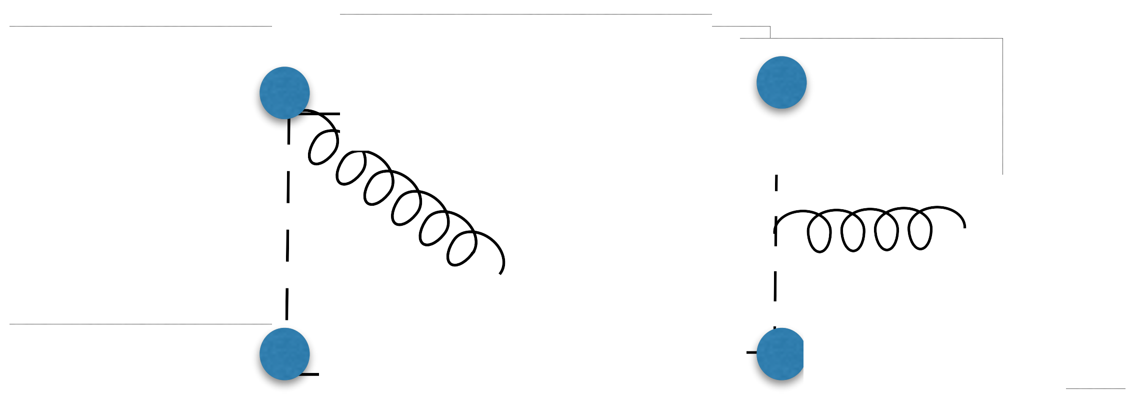
State of the art is v^8

Blanchet, Schaefer (GR)
Foffa/Sturani (NRGR)

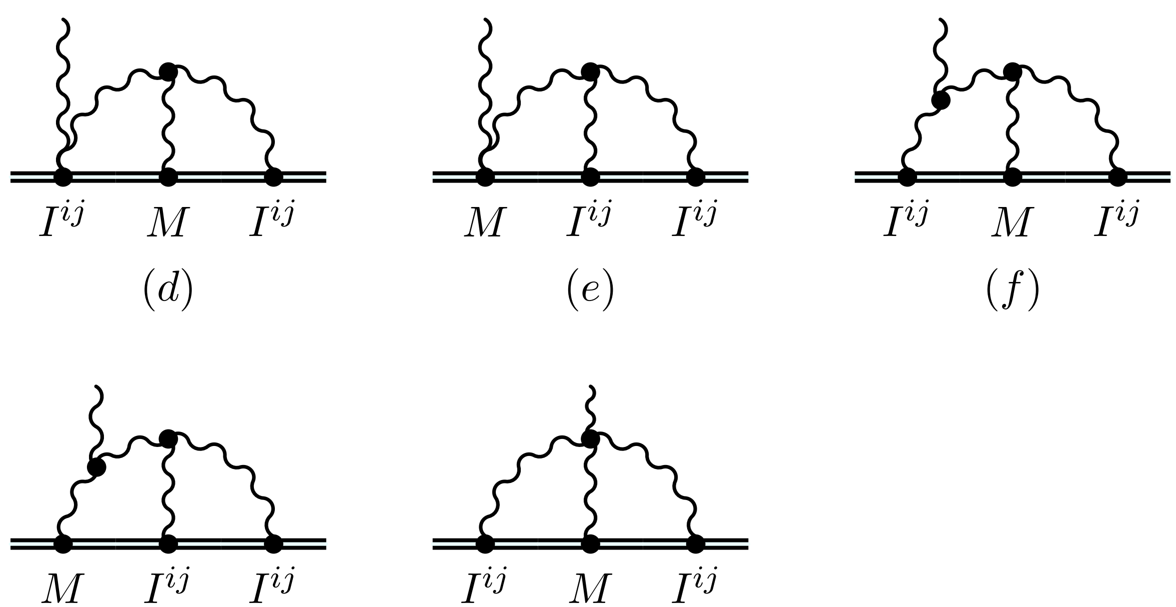
I_{ij}

Dynamical Quadruple moment of composite system, function of worldliness coordinates and velocities. Calculated by matching in a systematic expansion in relative velocity

Match by calculating one point function



At higher orders we run into UV divergences



Non-Trivial RG flow for mass as well as multipole moments

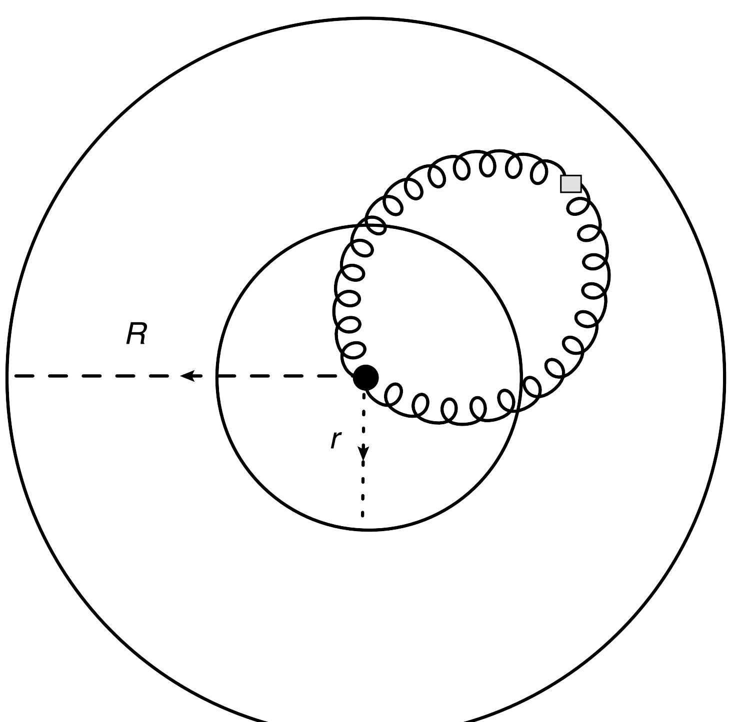
$$\mu \frac{d}{d\mu} M(t,\mu) = -\frac{2G^2\bar{M}}{5}\left(2I_{ij}^{(5)}I_{ij}^{(1)} - 2I_{ij}^{(4)}I_{ij}^{(2)} + I_{ij}^{(3)}I_{ij}^{(3)}\right)(t)$$ (Goldberger, Ross, IZR)

$$\mu \frac{dI_{ij}}{d\mu}(\omega,\mu) = -\frac{214}{105}(G\bar{M}\omega)^2 I_{ij}(\omega,\mu)$$ (Goldberger and Ross)

Solution to RG eq.

$$\frac{\bar{M}(\mu)}{\bar{M}_0} = \exp\left[\frac{\langle I_{ij}^{(2)} I_{ij}^{(2)}\rangle_{\mu_0} - \langle I_{ij}^{(2)} I_{ij}^{(2)}\rangle_{\mu}}{\beta_I \bar{M}_0^2}\right]$$

$$I_{ij}(\omega,\mu) = \left(\frac{\mu}{\mu_0}\right)^{\beta_I (G\bar{M}_0\omega)^2} I_{ij}(\omega,\mu_0)$$



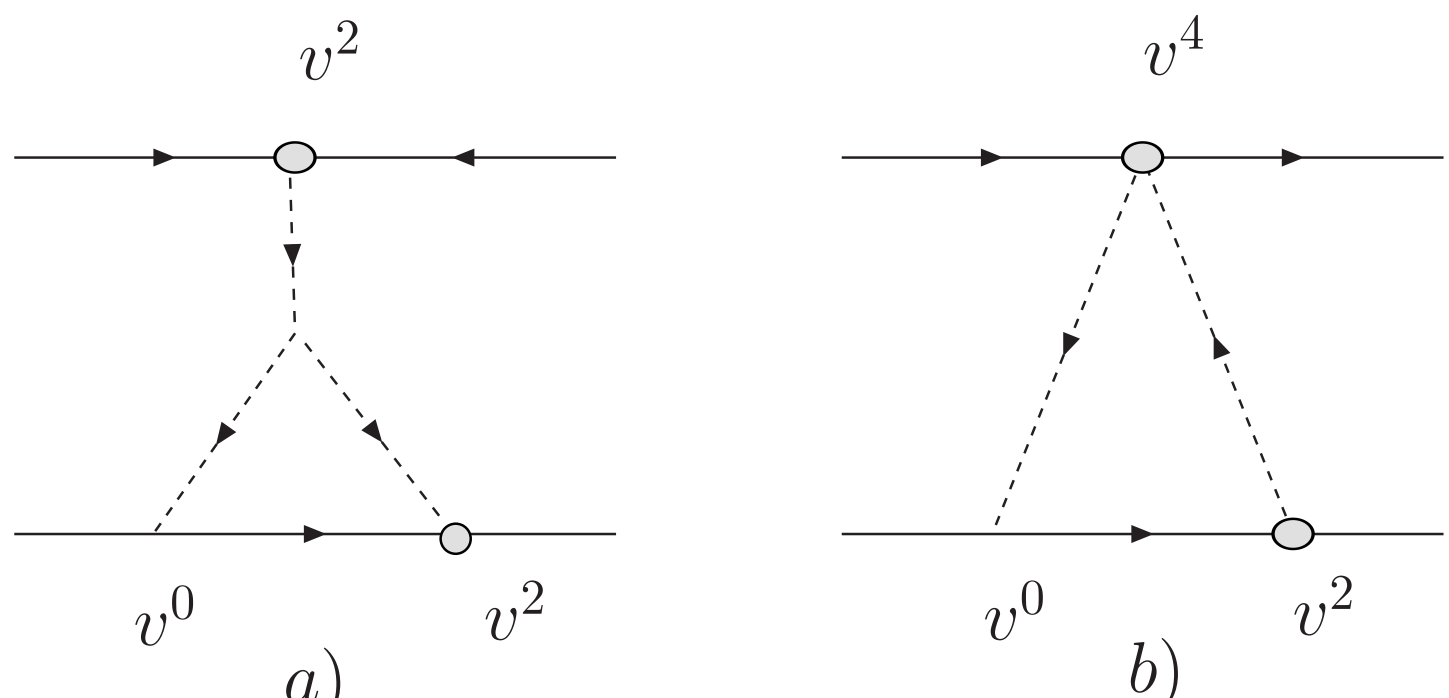
Mass is "asymptotically free"

Log contributes to binding energy v^8

$$E(\Omega) = -\frac{\mu}{2}\,\frac{448}{15}\nu x^5 \ln x + \ldots ,$$

Including Spin Effects (R. Porto)

Introduce spin degrees of freedom that live on the world-lines $S^i_{\mu\nu}(\tau)$



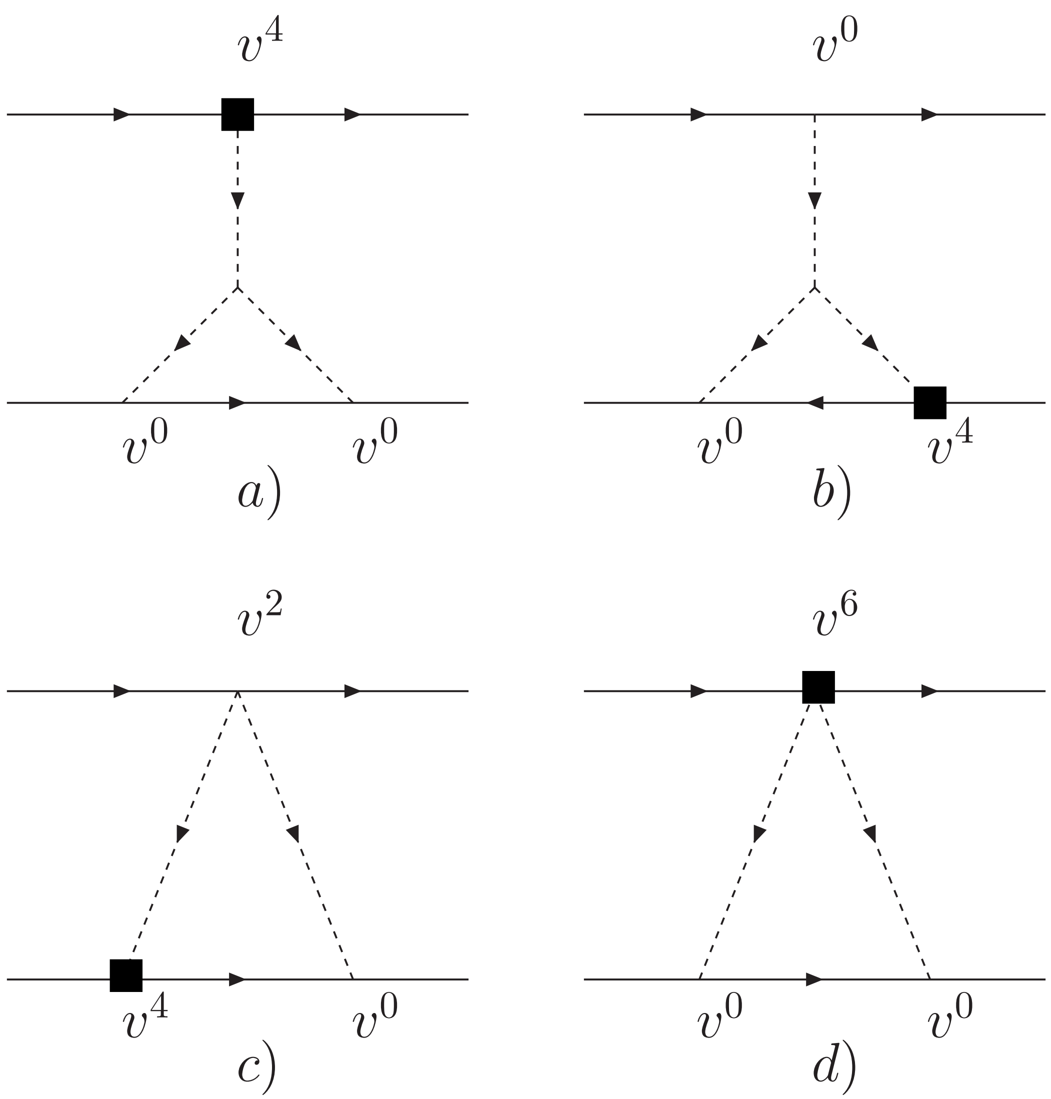
State of the art spin-spin potential (Porto, IZR)

$$\begin{aligned}V^{spin}_{3PN} = \frac{-G_N}{2r^3}\Big[&\vec{S}_1\cdot\vec{S}_2\left(\frac{3}{2}\vec{v}_1\cdot\vec{v}_2 - 3\vec{v}_1\cdot n\vec{v}_2\cdot n - \left(\vec{v}_1^2+\vec{v}_2^2\right)\right) - \vec{S}_1\cdot\vec{v}_1\vec{S}_2\cdot\vec{v}_2 - \frac{3}{2}\vec{S}_1\cdot\vec{v}_2\vec{S}_2\cdot\vec{v}_1 + \vec{S}_1\cdot\vec{v}_2\vec{S}_2\cdot\vec{v}_2\\
&+\vec{S}_2\cdot\vec{v}_1\vec{S}_1\cdot\vec{v}_1 + 3\vec{S}_1\cdot\vec{n}\vec{S}_2\cdot\vec{n}\left(\vec{v}_1\cdot\vec{v}_2 + 5\vec{v}_1\cdot\vec{n}\vec{v}_2\cdot\vec{n}\right) + 3\vec{S}_1\cdot\vec{v}_1\vec{S}_2\cdot\vec{n}\vec{v}_2\cdot\vec{n} + 3\vec{S}_2\cdot\vec{v}_2\vec{S}_1\cdot\vec{n}\vec{v}_1\cdot\vec{n}\\
&+3(\vec{v}_2\times\vec{S}_1)\cdot\vec{n}(\vec{v}_2\times\vec{S}_2)\cdot\vec{n} + 3(\vec{v}_1\times\vec{S}_1)\cdot\vec{n}(\vec{v}_1\times\vec{S}_2)\cdot\vec{n} - \frac{3}{2}(\vec{v}_1\times\vec{S}_1)\cdot\vec{n}(\vec{v}_2\times\vec{S}_2)\cdot\vec{n}\\
&-6(\vec{v}_1\times\vec{S}_2)\cdot\vec{n}(\vec{v}_2\times\vec{S}_1)\cdot\vec{n}\Big] + \frac{3G_N^2(m_1+m_2)}{r^4}\left(\vec{S}_1\cdot\vec{S}_2 - 3\vec{S}_1\cdot\vec{n}\vec{S}_2\cdot\vec{n}\right).\end{aligned}$$

S_i^2 Potential

1 for BH

finite size effects: $$L_{E\mathcal{S}^2} = \frac{C^{(q)}_{ES^2}}{2mm_p}\frac{E_{ab}}{\sqrt{u^2}}\mathcal{S}^a{}_c\mathcal{S}^{cb}.$$



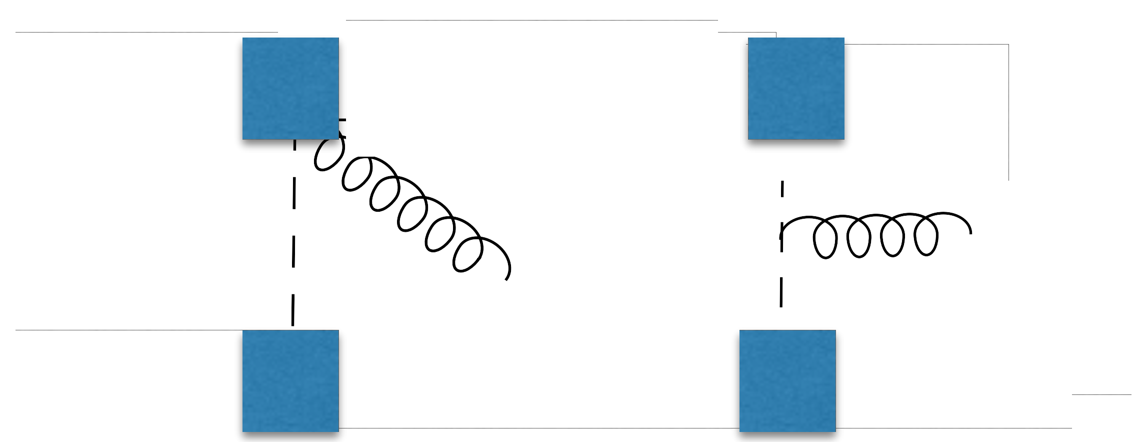
v^6 SS potential, state of the art.

(Porto, Rothstein)

Effects of Spin on Radiation

$$I \to I(S)$$

Insertion of spin operators



State of the Art Spin moments at v^6
(Porto, IZR)

Other topics uncovered

- Radiation Reaction Forces (Galley, Leibovich,Porto, IZR)
- Dissipation (Goldberger, IZR)
- Spin-Orbit Couplings (Levi, Steinhoff)
- Modifications of Gravity
- Analytically solving EOM via DRG.

Just the beginning of new field, PP perspective significant utility