Title: EFT of Gravity

Speakers: John Donoghue

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EFT Techniques for Gravity #3

John Donoghue
June 21, 2023
Trisep

Recap: EFT thinking

High energy $\Rightarrow$ local

Low energy $\longrightarrow$ non local

Renormalization = measurement (matching)

Expansion in energy $\sim \Box^n$

Example: $Z = \int [d\sigma][d\vec{\pi}]\, e^{i\int d^4x\, \mathcal{L}_\sigma(\sigma, \vec{\pi})}$

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$$= \int [d\vec{\pi}]_{\Lambda = m_\sigma}\, e^{i\int d^4x\, \mathcal{L}_{eff}(\vec{\pi})}$$

With $\mathcal{L} = \frac{v^2}{4} Tr(\partial_\mu U^\dagger \partial^\mu U) + \ell_1 [Tr(\partial_\mu U^\dagger \partial^\mu U)]^2$

High energy $\Rightarrow$ local Trisep

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Example: $Z = \int [d\sigma][d\vec{\pi}]\, e^{i\int d^4x\, \mathcal{L}_0(\sigma,\vec{\pi})}$

$= \int [d\vec{\pi}]_{\Lambda = m_\sigma}\, e^{i\int d^4x\, \mathcal{L}_{eff}(\vec{\pi})}$

With $\mathcal{L} = \frac{v^2}{4} \mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U) + \ell_1 \left[\mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U)\right]^2 +$

$+ \ell_2 \mathrm{Tr}[\partial_\mu U^\dagger \partial_\nu U] \mathrm{Tr}(\partial^\mu U^\dagger \partial^\nu U)$

with
$U = \exp i\vec{\tau}\cdot\vec{\pi}$

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$$\ell_1^r = \frac{v^2}{8m_\sigma^2} + \frac{1}{192\pi^2}\left[\ln \frac{m_\sigma^2}{\mu^2} - \frac{35}{6}\right]$$

$$\ell_2^r = \frac{1}{384\pi^2}\left[\ln \frac{m_\sigma^2}{\mu^2} - \frac{11}{6}\right].$$

Note $\Lambda = m_\sigma \Rightarrow$ Limits

Renormalize a "nonrenormalizable" theory

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Renormalize a "nonrenormalizable" theory
— locality + general $\mathcal{L}$

Full QFT calculation:

$$\mathcal{M}_{\rm eff} = \frac{t}{v^2} + \left[8\ell_1^r + 2\ell_2^r + \frac{5}{192\pi^2}\right]\frac{t^2}{v^4}$$
$$+ \left[2\ell_2^r + \frac{7}{576\pi^2}\right][s(s-u) + u(u-s)]/v^4$$
$$- \frac{1}{96\pi^2 v^4}\left[3t^2\ln\frac{-t}{\mu^2} + s(s-u)\ln\frac{-s}{\mu^2} + u(u-s)\ln\frac{-u}{\mu^2}\right] \leftarrow *$$

See DSM and C. Burgess "Introduction to EFT"

$$\check{\Gamma}^{\lambda}_{\mu\nu} = \bar{\Gamma}^{\lambda}_{\mu\nu} + \underline{\Gamma}^{\lambda}_{\mu\nu} + \cdots$$

Maintain bkgd gauge invariance

$$\underline{\Gamma}^{\lambda}_{\mu\nu} = \frac{1}{2}\,\bar{g}^{\lambda\sigma}\left[\bar{D}_{\mu} h_{\sigma\nu} + \cdots\right.$$

$$\kappa\alpha$$

$$\underline{\quad_{\mu\nu}} = \frac{1}{2} g \quad \left(D_{\mu} h_{\sigma\nu} + - - \right.$$

$$\qquad\qquad\qquad\qquad \kappa \quad \alpha$$

Also gauge inv for $h_{\mu\nu}$

$$h'_{\mu\nu} = h_{\mu\nu} + \bar{D}_{\mu} \xi_{\nu} + \bar{D}_{\nu} \xi_{\mu}$$

ideal gauge inv for $h_{\mu\nu}$

$$h'_{\mu\nu} = h_{\mu\nu} + \bar{D}_\mu \xi_\nu + \bar{D}_\nu \xi_\mu$$

Gauge fixing

$$C_\nu = \left(\bar{D}^\mu h_{\mu\nu} - \bar{D}_\nu h^\lambda{}_\lambda \right)$$

$$\mathcal{L}_{gf} - \frac{1}{2} C_\nu C^\nu$$

Ghosts

physical

 −  = physical

unphysical   ghosts

QUANTUM THEORY OF GRAVITATION*

BY R. P. FEYNMAN

(Received July 3, 1963)

My subject is the quantum theory of gravitation. My interest in it is primarily in the relation of one part of nature to another. There's a certain irrationality to any work in gravitation, so it's hard to explain why you do any of it; for example, as far as quantum effects are concerned let us consider the effect of the gravitational attraction between an electron

This made me investigate the entire subject in great detail to find out what the trouble is. I discovered in the process two things. First, I discovered a number of theorems, which as far as I know are new, which relate closed loop diagrams and diagrams without closed loop diagrams (I shall call the latter diagrams "trees"). The unitarity relation which I have just been describing, is one connection between a closed loop diagram and a tree; but I found a whole lot of other ones, and this gives me more tests on my machinery. So let me just tell you a little bit about this theorem, which gives other rules. It is rather interesting. As a matter

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Tree theorem

There is another theory, more well-known to meson physicists, called the Yang-Mills theory, and I take the one with zero mass; it is a special theory that has never been investigated in great detail. It is very analogous to gravitation; instead of the coordinate transformation group being the source of everything, it's the isotopic spin rotation group that's the source of everything. It is a non-linear theory, that's like the gravitation theory, and so forth. At

Tree theorem

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been opened, take only real transverse graviton to represent that term. This then serves as the definition of how to calculate closed-loop diagrams; the old rules, involving a propagator $1/k^2+i\varepsilon$ *etc.* being superseded. The advantage of this is, first, that it will be gauge invariant, second, it will be unitary, because unitarity is a relation between a closed diagram and an open one, and is one of the class of relations I was talking about, so there's no difficulty. And third, it's completely unique as to what the answer is; there's no arbitrary fiddling around with different gauges and so forth, in the inside ring as there was before. So that's the plan.

it no longer singular. That's the first thing; I found it out by trial and error before, when I made it gauge invariant. But then secondly, you must subtract from the answer, the result that you get by imagining that in the ring which involves only a graviton going around, instead you calculate with a different particle going around, an artificial, dopey particle is coupled to it. It's a vector particle, artificially coupled to the external field, so designed as to correct the error in this one. The forms are evidently invariant,

DeWitt: Because of the interest of the tricky extra particle that you mentioned at the end, and its possible connection, perhaps, with some work of Dr Białynicki-Birula, when I made it gauge invariant. But then secondly, you must subtract from the answer, the result that you get by imagining that in the ring which involves only a graviton going around, instead you calculate with a different particle going around, an artificial, dopey particle is coupled to it. It's a vector particle, artificially coupled to the external field, so designed as to correct the error in this one. The forms are evidently invariant,

DeWitt: Because of the interest of the tricky extra particle that you mentioned at the end, and its possible connection, perhaps, with some work of Dr Białynicki-Birula, have you got far enough on that so that you could repeat it with just a little more detail? The structure of it and what sort of an equation it satisfies, and what is its propagator? These are technical points, but they have an interest.

Feynman: Give me ten minutes. And let me show how the analysis of these tree diagrams, loop diagrams and all this other stuff is done mathematical way. Now I will show you that I too can write equations that nobody can understand. Before I do that I should like to say that there are a few properties that this result has that are interesting. First of

$$\boxed{\begin{aligned}\mathcal{L} = &\sqrt{-\bar{g}}\Big[\frac{2\bar{R}}{\kappa^2} + \frac{1}{\kappa}\left[h^\alpha_\alpha \bar{R} - 2\bar{R}^\alpha_\nu h^\nu_\alpha\right] + \bar{R}\left[\frac{1}{4}[h^\alpha_\alpha]^2 - \frac{1}{2}h^\alpha_\beta h^\beta_\alpha\right] \\ &- h^\alpha_\alpha h^\nu_\beta \bar{R}^\beta_\nu + 2h^\nu_\beta h^\beta_\alpha \bar{R}^\alpha_\nu + h^\alpha_{\alpha,\nu} h^{\nu,\beta}_\beta - h^{\nu,\alpha}_\beta h^\beta_{\alpha,\nu} + \frac{1}{2}h^\beta_{\alpha,\nu} h^{\alpha,\nu}_\beta - \frac{1}{2}h^{\alpha,\nu}_\alpha h^\beta_{\beta,\nu}\Big]\end{aligned}}$$

$$\theta = \frac{4GM}{b} + \frac{15}{4}\frac{G^2M^2\pi}{b^2} + \frac{8c_b - 47 + 64\log(2r_0/b)}{\pi}\frac{G^2M\hbar}{b^3} \tag{21}$$

where $c_b = (371/120,\ 113/120,\ -29/8)$ for scalars, photons and gravitons re-

$$\begin{aligned}
\mathcal{A}^{1\ loop}(++;--) &= -i\frac{\kappa^4}{30720\pi^2}\left(s^2+t^2+u^2\right)\\
\mathcal{A}^{1\ loop}(++;+-) &= -\frac{1}{3}\mathcal{A}^{1\ loop}(++;--)\\
\mathcal{A}^{1\ loop}(++;++) &= \frac{\kappa^2}{4(4\pi)^{2-\epsilon}}\frac{\Gamma^2(1-\epsilon)\Gamma(1+\epsilon)}{\Gamma(1-2\epsilon)}\mathcal{A}^{tree}(++;++)\times(s\,t\,u) \qquad (3)\\
&\times\left[\frac{2}{\epsilon}\left(\frac{\ln(-u)}{st}+\frac{\ln(-t)}{su}+\frac{\ln(-s)}{tu}\right)+\frac{1}{s^2}f\left(\frac{-t}{s},\frac{-u}{s}\right)\right.
\end{aligned}$$

Ghosts

physical

 −  = physical

unphysical ghosts

Logic

$$1 = \int dx_i \, \delta(f(x_i)) \, \det\left(\frac{\partial f}{\partial x_i}\right)$$

$$\text{P.I} \Rightarrow 1 = \underbrace{\int d\theta}_{\text{Vol.}} \, \underbrace{\delta(f(A^\theta))}_{\text{constant}} \, \underbrace{\det \frac{\partial f}{\partial \theta}}$$

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FDFP trick

$$\det \frac{\partial f}{\partial \theta} = \int dc \, d\bar{c} \; e^{i\int d^4x \, \bar{c} \frac{\partial f}{\partial \theta} c}$$

For QED:

$$A^{\theta}_{\mu} = A_{\mu} + \partial_{\mu}\theta$$

$$f(A^{\theta}) = \partial^{\mu}A_{\mu} = 0$$

$$\partial^{\mu}A^{\theta}_{\mu} = \Box\theta$$

$$\frac{\partial f}{\partial \theta} = \Box \qquad \mathcal{L}_{g} = \bar{c}\,\Box\,c$$

dont need ghost

$$\frac{\delta f}{\delta G} = \Box \qquad \mathcal{L}_g = \bar{c}\,\Box\, c$$

dont need ghost

QCD $\quad c \to c^A$

$$\frac{\delta f^A}{\delta \theta^B} = \left[\delta^{AB}\,\Box - g f^{ABC} \partial^\mu A_\mu^C \right]$$

int

GR: $f_{\nu} = D^{\mu} h_{\mu\nu} - ?$

GR:

$$f_\nu = D^\mu h_{\mu\nu} - \frac{1}{2} D_\mu h^\lambda{}_\lambda$$

$$\delta f_\nu = \bar{D}_\nu \left(\bar{D}_\nu \xi_\mu + \bar{D}_\mu \xi_\nu \right) - \frac{1}{2} \bar{D}_\mu \bar{D}_\nu \xi^\nu$$

GR: $f_\nu = D^\mu h_{\mu\nu} - \frac{1}{2} D_\nu h^\lambda{}_\lambda$

$$\delta f_\nu = \underset{1}{\bar D^\mu} \left(\bar D_\nu \xi_\mu + \underset{1}{\bar D_\mu \xi_\nu} \right) - \frac{2}{2} \underset{2}{\bar D_\nu \bar D_\lambda \xi^\lambda}$$

$$= \bar D^2 \xi_\nu + \bar R_{\mu\nu} \xi^\mu$$

$$\frac{\delta f_\nu}{\delta \xi^\mu} = \left(g^{\mu\nu} \bar D^2 + \bar R_{\mu\nu} \right.$$

$$\frac{}{\partial \xi^{\mu}} \quad (\quad \quad g_{\mu\nu})$$

$$\mathcal{L}_{gh} = \bar{\eta}^{\mu} \left[\bar{g}_{\mu\nu} \bar{D}^2 + R_{\mu\nu} \right] \eta^{\nu}$$

$$\mathcal{L}_{gh} = \bar{\eta}^{\mu}\left[\bar{g}_{\mu\nu}\bar{D}^2 + \bar{R}_{\mu\nu}\right]\eta^{\nu}$$

$$\underset{\xi_\eta}{\text{-----}} = -i\beta\left[k_\mu k_\nu \eta_{\alpha\beta} + \cdots\right]$$

EFT of gravity

$$S = \int d^4x \sqrt{g} \left[-\Lambda - \frac{2}{\kappa^2} R + \underbrace{c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu}}_{\text{Gauss Bonnet}} + \dots \right]$$

$$G = R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta} - 4 R_{\mu\nu} R^{\mu\nu} + R^2$$

$$\frac{1}{8\pi^2} \int d^4x \sqrt{g}\, G = \chi$$

EFT of gravity

$$S = \int d^4x \sqrt{g} \left[-\Lambda - \frac{2}{\kappa^2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \dots \right]$$

Measure:

$\Lambda = (10^{-3}\, eV)^4$ neglect

$\kappa^2 = 32\pi G$

$c_1, c_2 < 10^{+65}$ (millimeter)

Gauss Bonnet

$G = R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta} - 4 R_{\mu\nu} R^{\mu\nu} + R^2$

$\frac{1}{32\pi^2} \int d^4x \sqrt{g}\, G = \chi$

$\kappa = 8\pi G$

$C_1, C_2 < 10^{+65}$ (millikanda)

$\frac{1}{8\pi^2}\int d^4x \sqrt{g}\, G = \chi$

<u>Renormalize</u>

Scalar loop $\sim \underbrace{g^{\mu\nu} g^{\lambda\sigma} g^{\alpha} g^{\beta}}_{R^2} + \cdots$

Background field + Heat Kernel

$$a_2 = \frac{1}{180}\left(R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta} + R_{\mu\nu}R^{\mu\nu} + \frac{5}{2}(6\xi - 1)^2 R^2 - 6\,\Box R\right)$$

$\xi R \phi^2$

Background field + Heat Kernel $\quad R^2$

$$a_2 = \frac{1}{180}\left(R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta} + R_{\mu\nu} R^{\mu\nu} + \frac{5}{2}(6\xi - 1)^2 R^2 - 6\Box R \right)$$

ξ $\qquad\qquad$ $\xi R \phi^2$

$$\Delta \mathcal{L} = \frac{1}{16\pi^2} a_2$$

Background field + Heat kernel $\quad R^2$

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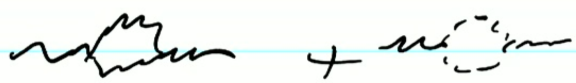
<u>Graviton:</u> 't Hooft Veltman



$$\Delta \mathcal{L} = \frac{1}{16\pi^2}\left[\frac{1}{120} R^2 + \frac{7}{20} R_{\mu\nu} R^{\mu\nu}\right] \frac{1}{\cdot}$$

Background field + Heat Kernel $\qquad R^2$

$$a_2 = \frac{1}{180}\left(R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta} + R_{\mu\nu}R^{\mu\nu} + \frac{\xi}{2}(6\xi-1)^2R^2 - 6\Box R\right)$$

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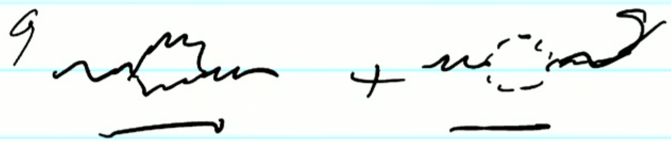

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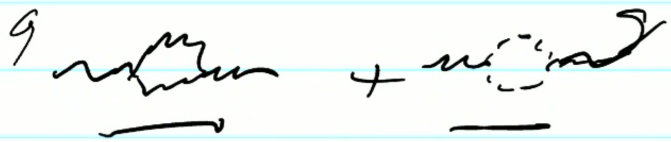
$$\ldots \frac{1}{16\pi^2} \ldots \frac{1}{\varepsilon}$$

Graviton: 't Hooft Veltman



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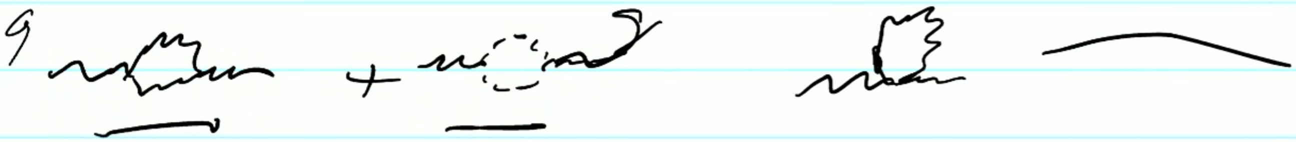

$$\int d^4 l \, \frac{l}{l^2}$$

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Example Newton Potential

— Scattering Potential

NR & FI

$$\mathcal{M} = \frac{GMm}{q^2}\left[1 + aG(M+m)\sqrt{-q^2} + bGq^2 \ln q^2 + cGq^2\right]$$

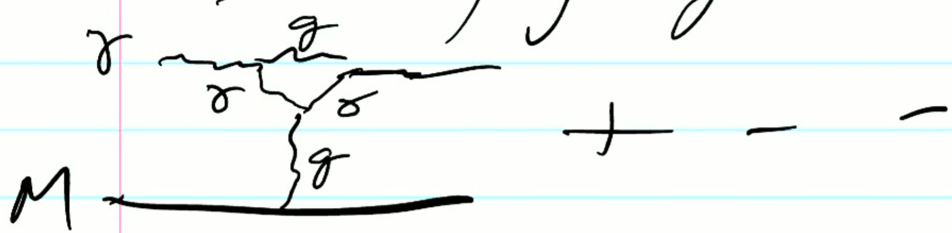
$$V(r) \quad \frac{GMm}{r}\left[1 + \frac{G(M+m)}{r} + \frac{G\hbar}{r^2}\right] + \delta^3(\vec{x})$$

classical quantum

Calculate:

$$V(r) = -\frac{GMm}{r}\left[1 + \frac{3G(M+m)}{r} + \frac{41}{10\pi^2}\frac{G\hbar}{r^2}\right]$$

Bending of light



Eikonal:

$$\Theta = \frac{4GM}{b} + \frac{15}{4}\frac{GM^2\pi}{b^2} + \left(\frac{8c_b - 47 + 64\ln(b/r_0)}{\pi}\right)\frac{G\hbar}{b^3}$$

$$c_b = \frac{371}{120}, \quad \frac{113}{120}, \quad -\frac{29}{8}$$

spin 0 γ graviton

Bending of light

$0, g, \gamma$

M

$+ \quad - \quad -$

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↖ spin 0 ↖ γ ↖ graviton

Bending of light

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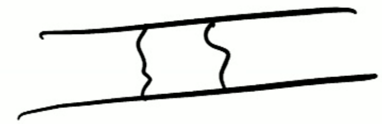

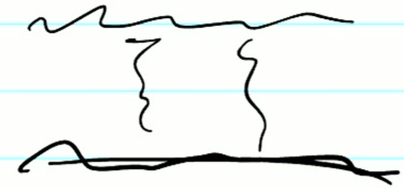

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$$C_b = \frac{371}{120}, \quad \frac{113}{120}, \quad -\frac{29}{8}$$

$\uparrow$ spin 0 $\quad \uparrow \gamma \quad \uparrow$ graviton

Discussion

1) Potential correction is universal

a) Redone calc Tree theorem

 → ✓

a) On shell soft theorems tree level
~~Low~~ Weinberg, Jackiw, Gross

2) Classical effect at one loop!

loop ≠ $\hbar$ expansion

$$\bar{\Psi}(i\hbar\partial\!\!\!/ - m)\Psi \rightarrow \hbar\, \bar{\Psi}\left(i\partial\!\!\!/ - \frac{m}{\hbar}\right)\Psi$$

$$\hbar \frac{M}{\hbar}\sqrt{-q^2}$$

$\hbar \frac{M}{\hbar} \sqrt{1-q^2}$

Industry

3) Bending is not universal

- geodesics, Penrose diagrams become uncontrolled

3) Bending is not universal

- geodesics, Penrose diagrams become uncontrolled

4) ~~B~~ No "quantum metric"

- not quantum question
- Kirilin: field redef: $h \to h + h^2$

violates Haag's theorem

Limits of EFT

High energy / large curvature

$$\mathcal{L} \quad R + R^2 + R^3 + \cdots$$

$$\mathcal{M} = E^2 + E^4 + E^6 + \cdots$$

IR Limits?

Gravity builds up

$$g_{\mu\nu}(x') = \eta_{\mu\nu} + \frac{1}{3} R_{\mu\nu\alpha\beta}(x)\,(x'-x)^\alpha (x'-x)^\beta$$

Technical issue?

$\mathcal{L} \sim R + R^2 + R^3 + \cdots$

$$\mathcal{M} = E^2 + E^4 + E^6 + \cdots$$

IR Limits?

Gravity builds up

$$g_{\mu\nu}(x') = \eta_{\mu\nu} + \frac{1}{3} R_{\mu\nu\alpha\beta}(x)\,(x'-x)^\alpha (x'-x)^\beta$$

Technical issue?

BH

- Kirilin: field redef $h \to h + \tilde{h}$

violates Haag's theorem

Hawking Hambli Burgess

$$(\text{Flux}) \sim T_{tr} \lim_{x \to x'} \partial_t \partial_r \langle \phi(x) \phi(x') \rangle$$

~~Good~~ God Quantum question?

Limit

~~Goo~~ God Quantum question?

Limit to QM?

~~macros~~ macroscopicity