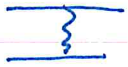
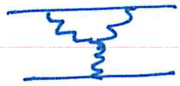
John Donoghue

Lessons of QGR + causality

QGR vs QG , ~~EFT~~

EFT

1) HE effects local – U.P.
2) LE effects non local  +  + ...

In calculation $1, q^2, q^4, \ldots \sim \delta(x), \delta'(x) \equiv$ local. (some prediction here)

$\sqrt{-q^2}, \; q^2 \ln(-q^2) \sim$ nonlocal

3) Energy expansion $G[1 + Gq^2 + Gq^2 \ln q^2 + \cdots]$

local $\mathcal{L} \sim \frac{1}{G} R + c_1 R^2 + G d_i R^3 + \cdots$

tree, one loop, 2 loop

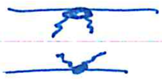
divergences ~ $c R^2$, ~ R^3

Samples: (Low energy theorems) classical

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

HE divergence

$$\mathcal{M}(q) \sim \frac{1}{q^2}\left[1 + a\,G(M+m)\sqrt{q^2} + b\,G q^2 \ln q^2 + c' q^2\right]$$

Universal  soft theorem → one loop

US + Chi Bai Huang

Light bending

$$\Theta = \frac{4GM}{b} + \frac{15G^2M^2\pi}{b^2} + \left(8 c_i - 39 + 48 \log \tfrac{b}{b_0}\right)\frac{G^2\hbar M}{\pi b^3}$$

$c_i = 371/120$ spin 0
$= +113/120$ photon not universal
$= -\frac{29}{8}$ graviton

– peak of eikonal amplitude

Graviton scattering $\kappa^2 = 32\pi G$

Dunbar Norridge

$$M_{++++} = i\frac{\kappa^2 s^3}{tu}\left[1 + \frac{\kappa^2 s}{32\pi^2}\left[\ln\frac{-t}{s} \cdot \ln\frac{-u}{s} + \cdots + \frac{1}{\epsilon_{IR}}\right]\right]$$

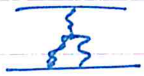
· one loop finite

IR divergence

Lessons:

1) Not a quantum corrected metric
   - can't define new metric which gives these results
   - even if you try  - not particularly meaningful - gauge variant
     - not related to real answer

2) Light cones ill defined
   - non universality of trajectory of massless particle
   - also spread of QM amplitude

3) No ~~classical~~ "test masses"  =  for quantum part

3b) No point particle

4) Non-local in space + time
   - many effects are "tidal effects" - no point particle

   - also holds in cosmology

$$\frac{2}{\kappa^2} R + \underbrace{c(\mu) R^2}_{2\text{ terms}} + \overset{\text{known}}{\#} \underbrace{R \ln \Box R}_{3\text{ terms}}$$

Barvinsky
Vilkovisky

$$\cancel{\left(\frac{\dot a}{a}\right)^2 \sim \rho + \int^t dt'}$$

$$\left(\frac{\dot a}{a}\right)^2_t + \#\left(\frac{\dot a(t)}{a}\right)^2 \rho \int_{-\infty}^{t} \frac{dt'}{t-t'} \underbrace{\left(\frac{\dot a}{a}\right)^2_{t'}}_{} \simeq G\rho$$

schematic

5) No ~~running~~ gravitational running couplings in EFT region

Comment: there is some log running
RGE relates $\log^n$ at diff loop orders
But comments here on $f(GE^2)$ – based also on experience with C[illegible]

~~First: No running C~~
– logic of usual running: 1) universal – $\ln q^2$ with $\frac{1}{\epsilon}$ ~ [illegible]

$$e^2 = e_0^2 + \# e_0^4 \left[\frac{1}{\epsilon} \dots + \ln q^2 \right]$$

– every e^2_{ren} comes with $\ln q^2$

2) ~~Universal~~ Useful
– sums up common large logs
– applies in all processes
$\ln(-s)$, $\ln(-t)$ ~ $\ln(\mu^2)$
$\ln(-s) = \ln|s| - i\pi$

Problem with grav running: 1) Not universal – because not renorm of original diag – it's power counts

IFD + Anber

2) Not useful $G(1+aGs)$
$G(1+aGt)$
– does not capture quantum corrections

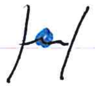
Evidence: – look at predictions – numbers are not the same
– crossing reaction
– Perhaps could renorm at some kin. point
i.e. $s=t=u=\mu^2/3$
– also # wildly diff
– does not work away from point

Could graviton propagator give running?

$$D_2(q) = \frac{P_2}{\left[q^2 - \frac{\kappa^2 q^4}{2\xi^2(\mu)} - \frac{\kappa^2 q^4 N}{640\pi^2} \ln \frac{-q^2}{\mu^2} \right]}$$ Spin 2

with Harmonic gauge

$$D_0(q) = \frac{P_0}{\left[-q^2 + \frac{\kappa^2 q^4}{2 f_0^2} - \frac{\kappa^2 q^4 N_0}{640\pi^2} \ln \frac{-q^2}{\mu^2} \right]}$$ spin zero ~~check~~

This is like  $\frac{G}{q^2} = \frac{G}{q^2[1 + \# q^2]}$

But: 1) kinematic problem $q^2 > 0$ vs $q^2 < 0$

2) Not universal D_2 vs D_0

3) Not useful – other contributions equally important

Also hold for other couplings?

$$e^2(E) = e^2[1 + aGE^2] \;?$$ Robinson + Wilczek + many

but – not universal $e^2(s)$ vs $e^2(t)$ kinematic flaw universality

– not useful

really higher order operator $R^{\mu\nu} D_\mu \phi^\dagger D_\nu \phi$

or $(D_\mu \phi)^\dagger D^2 (D_\mu \phi)$

motivation
work with G Menezes
on quadratic gravity
– does have causality "violation" ④

Causality Uncertainty

1) Lack of well defined geodesics — no Penrose diagrams
   - some fuzziness about timing
   - but EFT does have local causality – but global?
     – scattering etc?

2) Colloquially "No effect before cause"

But  interpretation – vac fluctuat

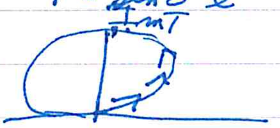
D_F

can you see final vertex before collision? No, Uncertainty Princ..
   – can't prepare initial state

3) More concretely Potential Scatt. Wigner $\Delta t \sim \frac{\partial \delta}{\partial E} > 0$ (really $> -R$)

This is why resonances move counterclockwise on Argand diagram 

Review: $T = \sin\delta\, e^{i\delta}$ $\quad \mathrm{Im}\, T = |T|^2$

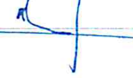


resonance = time delay

Here gravity QG starts off different

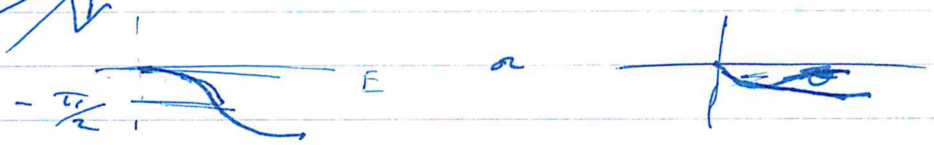
large N T_2 = 

$$T_2 = \frac{-\frac{NK^2 s}{640\pi}}{\left[1 - \frac{K^2 s}{2\xi^2} - \frac{NK^2 s}{64\pi^2}\left(\ln\frac{s}{\mu^2} - i\pi\right)\right]} = -\frac{NK^2 s^2}{640\pi} D_2(s)$$



Beyond EFT

plot out δ vs EV



$-\frac{s}{2\xi^2} \to +\frac{s}{2\xi^2}$

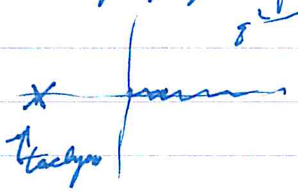
$$\frac{A(s)}{f(s) - i A(s)} = \frac{A(s)\,(f(s) + i A(s))}{f^2 + A^2}$$

4) Microcausality $[\mathcal{O}(x), \mathcal{O}(y)] = 0$ for $(x-y)^2 < 0$

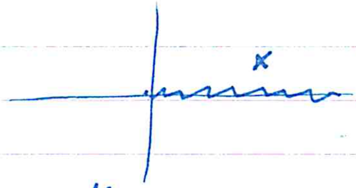
But with PI quantization?
Translates into analyticity $(q^2 - m^2 + i\epsilon)$

— ~~again~~ is this sacrosanct? vac fluct influence both operators

But spin 2 propagator [beyond EFT!]
Either



or



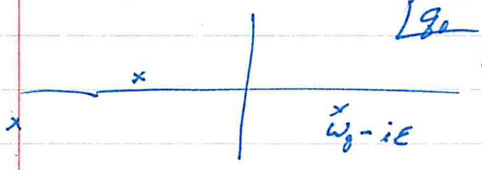
Reject

unstable ghost $\frac{1}{q^2 - \frac{\kappa^2 q^4}{2\xi^2} - i\delta} = \frac{1}{q^2} - \frac{1}{q^2 - \frac{2\xi^2}{\kappa^2}}$

Maybe One conclusion — change theory before this point!
But maybe not!

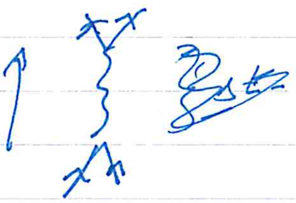
This ~~does~~ leads to $(D_F(x) = D^+(x)\,\theta(x_0) + D^-(x)\,\theta(-x_0))$

$$D^-(x) = \int \frac{d^3q}{(2\pi)^3}\left[\frac{e^{+i(\omega_q t - q\cdot x)}}{2\omega_q} + \frac{e^{-i(E_q t - q\cdot x)}}{2(E_q - i\frac{\gamma}{2E_q})}\, e^{-\frac{\gamma}{2E_q}|t|}\right]$$



note change in sign

Now t



$+$

$\Big\}\ \Delta t \sim \frac{1}{\xi^2 M_P}$

longer time difference

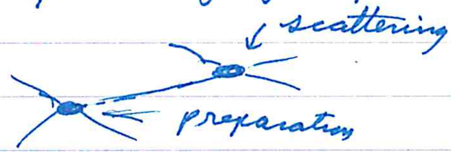
5) Features of Lee Wick theories

- ~ late '60s - dynamical pauli villars => finite QED
- Coleman 1969 Erice "Acausality"
- GOW 2009 "Causality as Emergent ...

Basic summary
- unstable ghost
- seems stable theory
- seems unitary
- microcausality violation

GOW wavepackets in scattering
Quadratic gravity is a LW theory

6) Causality uncertainty

- wavepackets for grav particles an idealization
- 

is it more "uncertainty" than "violation"?

QFT effects are similar to other QFTs

- but with gravity we have an extra classical construct:
  - we construct notions of spacetime ~~then~~ with light rays + geodesics
  - these fail in quantum theory