Title: Quantum information and the algebraic structure of quantum gravity

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Abstract: <p>Remote talk by teleconference</p>

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Quantum Information and the Algebraic Structure of Quantum Gravity

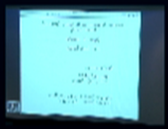
Steven B. Giddings

U.C. Santa Barbara

Based in part on:

arXiv: 1503.08207
WIP w/ Will Donnelly

Information Theoretic Foundations for Physics
Perimeter Institute May 13, 2015



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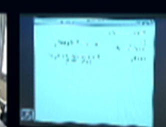
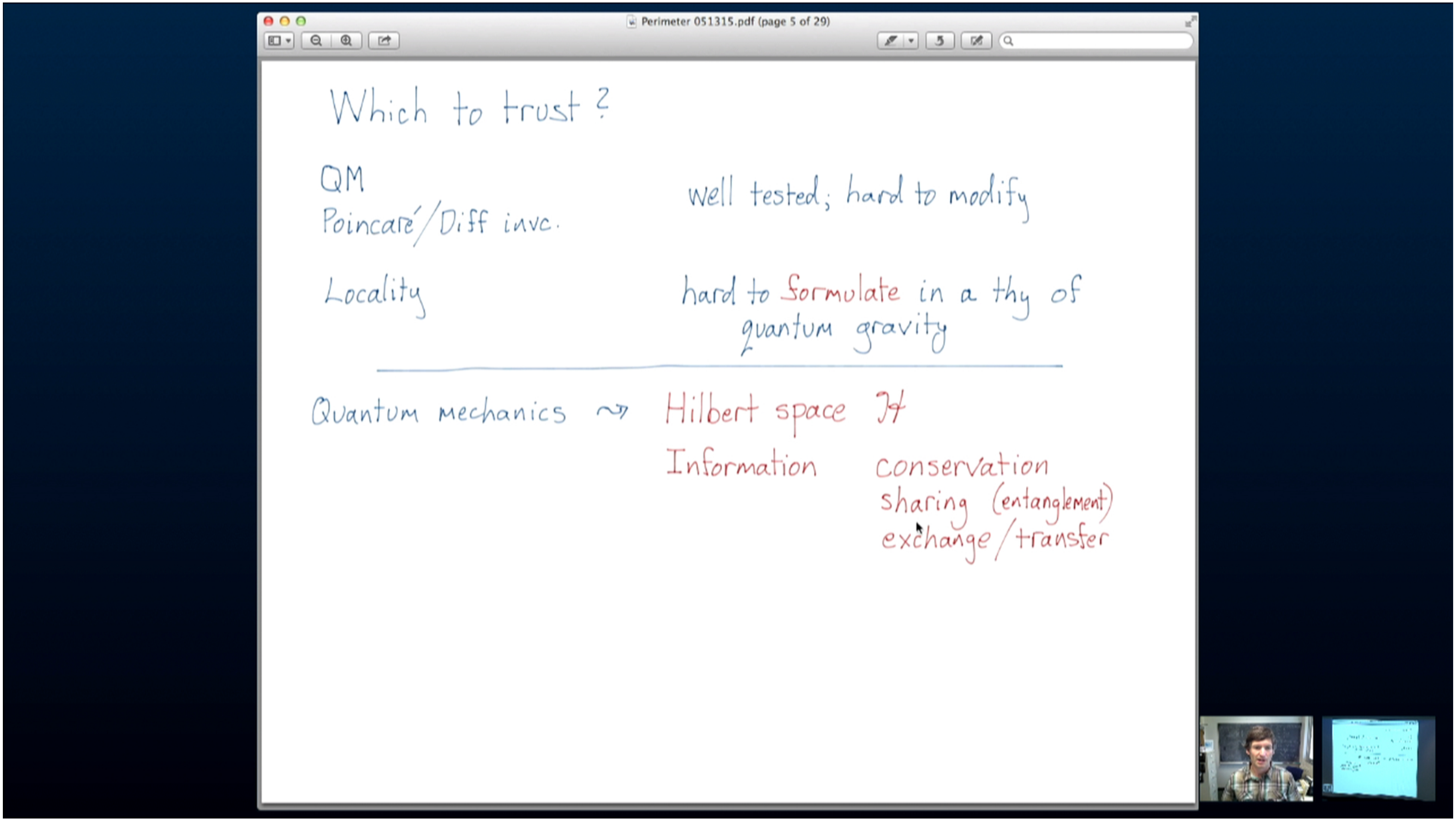
Which to trust?

QM | well tested; hard to modify
Poincaré/Diff invc.

Locality | hard to formulate in a thy of quantum gravity

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Which to trust?
QM
Poincaré/Diff invc.
well tested; hard to modify
Locality
hard to formulate in a thy of quantum gravity
Quantum mechanics ⇝ Hilbert space ℋ
Information
conservation
sharing (entanglement)
exchange/transfer

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The nature of this localization structure, and its relation to usual locality, appears a key question in quantum gravity.

How to provide?

Classic example: $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$

can entangle, transfer info.

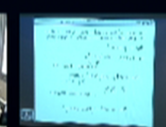
More generally, "locally finite" systems:

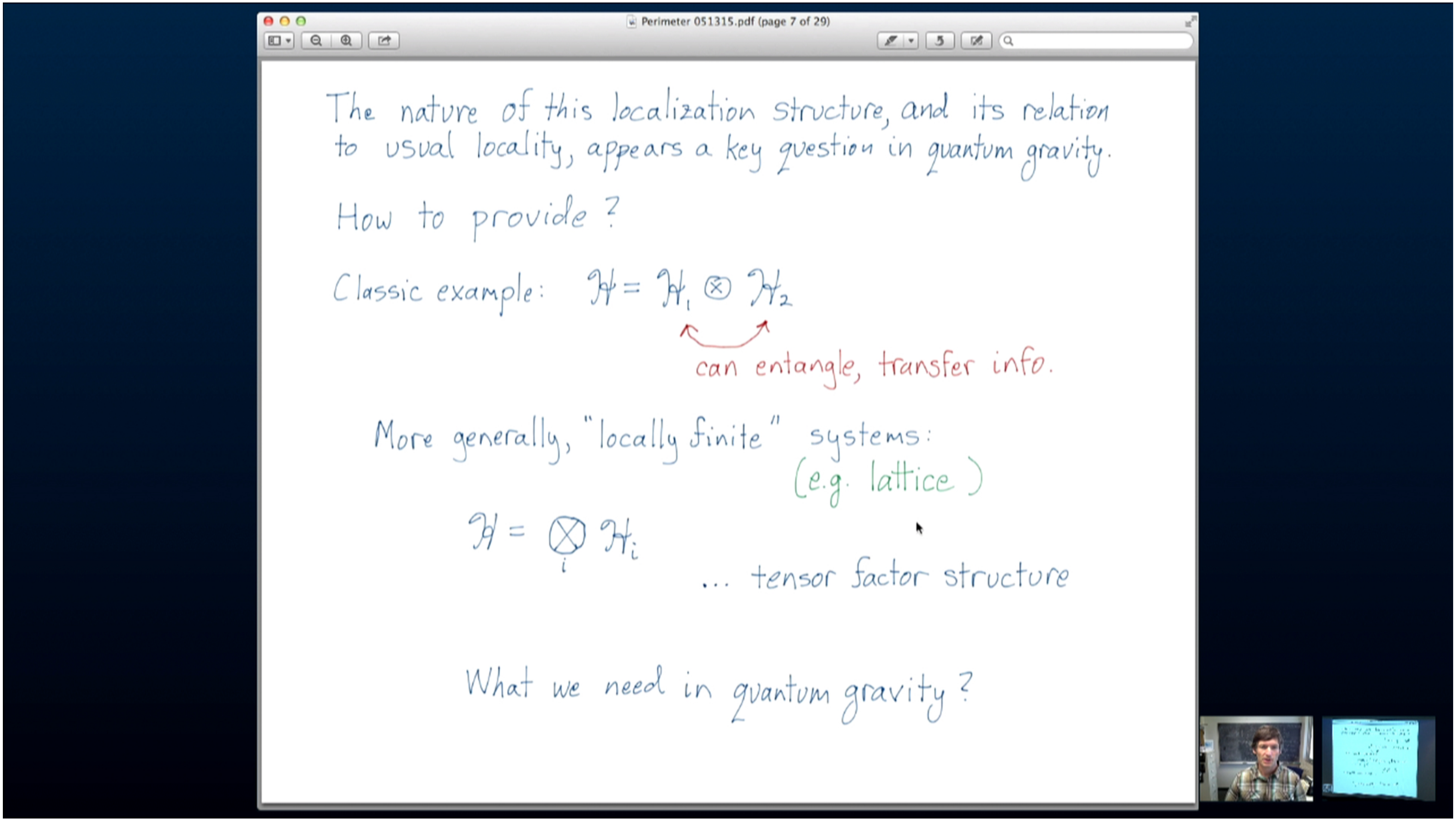
(e.g. lattice)

$$\mathcal{H} = \bigotimes_i \mathcal{H}_i$$

... tensor factor structure

What we need in quantum gravity?

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But: we expect a correspondence principle:

$$\text{Quantum gravity} \xrightarrow[\text{"weak fields"}]{} \text{Local Quantum Field Theory} \quad (\text{LQFT})$$

LQFT doesn't have tensor factorized $\mathcal{H}$ – for two reasons!

1. Long-range gauge fields (will return to)

2. Type III property: ∞ entanglement *

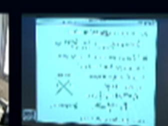
e.g. Rindler – left & right

$$|0\rangle_M \sim \prod_\omega \exp\left\{ z(\omega)\, \hat{b}^\dagger_\omega b^\dagger_\omega \right\} |\hat{0}\rangle |0\rangle$$

$$\sim \prod_{i=1}^{\infty} \left(\frac{|\hat{0}\rangle|0\rangle + |\hat{1}\rangle|1\rangle}{\sqrt{2}} \right)_i$$

(qubit approximation)

* Unless regulate: break symmetry of theory



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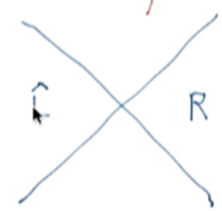
Mink. space



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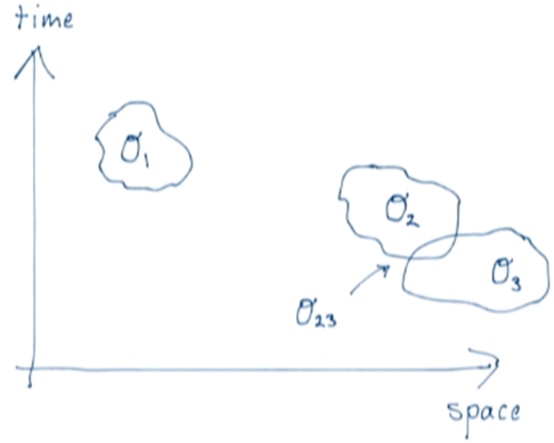
Handle the latter by working w/ algebra of observables.

Localization $\leftrightarrow$ Subalgebras



$$[A(\mathcal{O}_1), A(\mathcal{O}_2)] = 0$$

sugalgebras

(for $\mathcal{O}_1, \mathcal{O}_2$ spacelike separated)

"Net" of subalgebras; $\rightsquigarrow$ reconstructs spacetime manifold

Basic approach of Algebraic QFT - see e.g. Haag, Local Quantum Physics

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QED

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^2 - |D_\mu \phi|^2 - m^2 |\phi|^2 \quad ; \qquad D_\mu = \partial_\mu - i q A_\mu$$

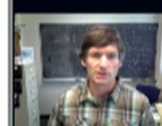
scalar

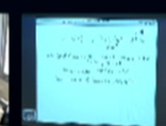
With $q = 0$, a basic observable is $\phi(x)$. Creates (or destroys) particle.

How to generalize?

$$\phi(x) \longrightarrow e^{-iq\Lambda(x)}\phi(x) \ : \ \text{not gauge invariant.}$$

$\longleftrightarrow$ "an electron is inseparable from its electric field"





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QED

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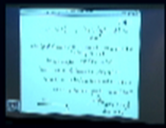
but, this can have different configurations = "dressings"

"Simple" example: Faraday (or Wilson) line (Dirac):

$$\Phi_{W_z}(0) = \phi(0)\, e^{iq\int_0^\infty dz\, A_z} \; :$$

gauge invt.



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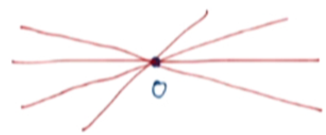
Indeed, $\left[E_z(\vec{x},0),\ \Phi_{W_z}(0)\right] \propto q\, \delta^2(x_\perp)\, \Theta(z)\ \Phi_{W_z}(0)$

Unnatural/unstable field config. Make symmetric : average $\frac{1}{4\pi}\int d\Omega$

$$\rightarrow\ \Phi_D(0) = \phi(0)\, \underbrace{e^{iq\int d^3x\, \frac{x^i}{x^3} A_i(0,\vec{x})}}_{V_D(0)} \qquad \text{Dirac dressing}$$



Now, $\left[E^i(x),\ \Phi_D(0)\right] \sim \frac{-q}{4\pi}\,\frac{x^i}{x^3}\ \Phi_D(0)\ \ldots$ Coulomb.

But: state of motion of particle ?

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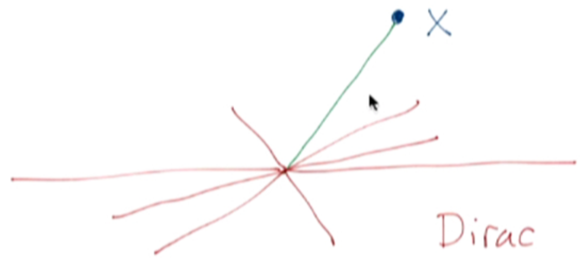
A more general dressing (see, e.g. Bagan, Lavelle, McMullan :)

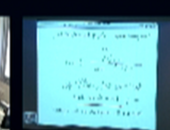


$(-T, \vec{x}_T)$

$$\Phi_{WL}(x) \sim V_D(-T, \vec{x}_T)\, e^{ig\int_{\text{worldline}} dx^\mu A_\mu}\, \phi(x)$$

$\rightsquigarrow$ e.g., boosted Coulomb field.

What are the consequences for the algebra?



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Gravity (in preparation, w/ Donnelly)

$$\mathcal{L} = \frac{2}{\kappa^2} R - \frac{1}{2}(\nabla\phi)^2 - \frac{1}{2} m^2 \phi^2$$

Gauge inv. $\quad x^\mu \to x^\mu + \kappa \xi^\mu$

$\phi(x)$: not gauge invariant

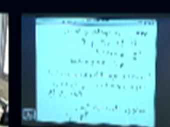
"an electron is inseparable from its <u>gravitational</u> field"

study in linearized theory: $\quad g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$

$$\delta h_{\mu\nu} = -\partial_\mu \xi_\nu - \partial_\nu \xi_\mu$$

Consider, e.g., $\quad \Phi(x) = \phi\left(x^\mu + V^\mu[h_{\lambda\sigma}]\right)$

"Dressing"



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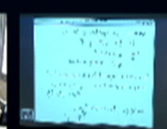

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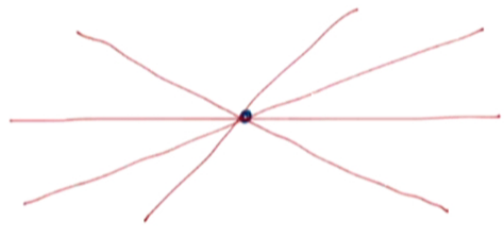
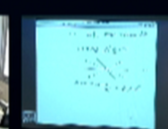
Make symmetric: average $\frac{1}{4\pi}\int d\Omega$ $\rightsquigarrow$

$$V_c^\mu = \frac{1}{4\pi}\int d^3x \, \frac{1}{r}\, \Gamma^\mu_{\alpha\beta}\, \hat{r}^\alpha \hat{r}^\beta + \text{s.t.}$$

$\rightsquigarrow$



$$[h_{\mu\nu}(x), \Phi_c] \sim h_{\mu\nu}^{\text{linearized Schwarzschild}}(x)$$



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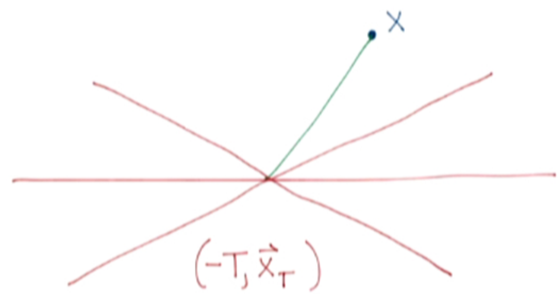
More general, accounting for state of motion:



$$\Phi_{WL}(x^\mu) = \phi(x^\mu + V_C^\mu + V_{WL}^\mu)$$

$$V_{WL}^\mu \sim \int dx^\lambda x^\sigma \, \Gamma^\mu_{\lambda\sigma}$$

$\rightsquigarrow$ e.g. boosted Schwarzschild, etc.

What are the consequences for the algebra?

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$$[\Phi_{W-Z}(x), \Phi_{W_Z}(x')] = 0.$$

(Though: also nonlin...)

$$[\Phi_{W_Z}(x), \dot{\Phi}_{W_Z}(x')] \neq 0.$$

$$[\Phi_C(x), \dot{\Phi}_C(x')] \neq 0$$

$$[\Phi_{WL}(x), \dot{\Phi}_{WL}(x')] \neq 0$$

$$\sim \frac{G E_1 E_2}{|\vec{x} - \vec{x}'|}$$

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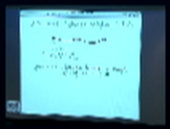
No local subalgebras in gravity? (contrast QED)

can't end

no screening in grav.

(except: $\Lambda > 0$ ...)

Appears to represent irreducible nonlocality in quantum gravity.



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No local subalgebras in gravity? (contrast QED)

can't end

no screening in grav.

(except: $\Lambda > 0$ ...)

Appears to represent irreducible nonlocality in quantum gravity.

$\Rightarrow$ no obvious def. of local subsystem;

Challenge to sharp definitions of

- information flow
- entanglement

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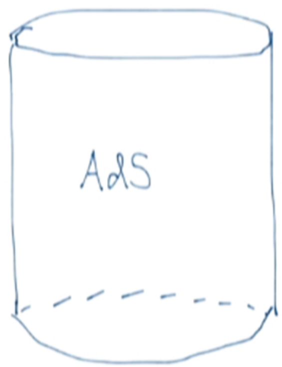
Further comments, cont'd:

2) Possible approach to AdS/CFT, <u>if</u> that can be used to define quantum gravity in AdS:

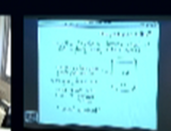


explore algebraic structure of boundary theory

note: boundary subalg. struct.

what ~ subalg. struct. associated w/ ~ bulk locality?

"decoding the hologram"



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More generally, a question, and a suggestion:

Q: How does approximate locality (approx. subalg. structure) emerge from the more basic quantum theory, and in what sense is it approximate? (Refine locality bound disc.)

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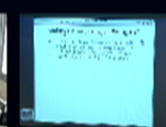

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A question, and a suggestion:

Q: How does approximate locality (approx. subalg. structure) emerge from the more basic quantum theory, and in what sense is it approximate? (Refine locality bound disc.)

S: The failure of exact locality underlies the info. transfer from BHs necessary for unitarization.

Possible effective description: (w.r.t. semiclass. geom.)
"Nonviolent nonlocality" 1108.2015
1201.1037
1211.7070 ...

Possible observable signatures at EHT?
1406.7001

Conclusion

- Reasonable expectation:

  quantum gravity $\subset$ quantum mechanics

- For physics: want "localization"/subsystem structure
  - tensor factors: problematic in LQFT
  - focus on algebra/subalgebras of observables

- Long range fields: added challenge
  - local subalgebras in QED
  - gravity: obstruction to local subalgebras

- This nonlocality of the algebra is plausibly an important element of the structure of the quantum theory

- Part of story of black hole unitarization?