Gravity and Entanglement

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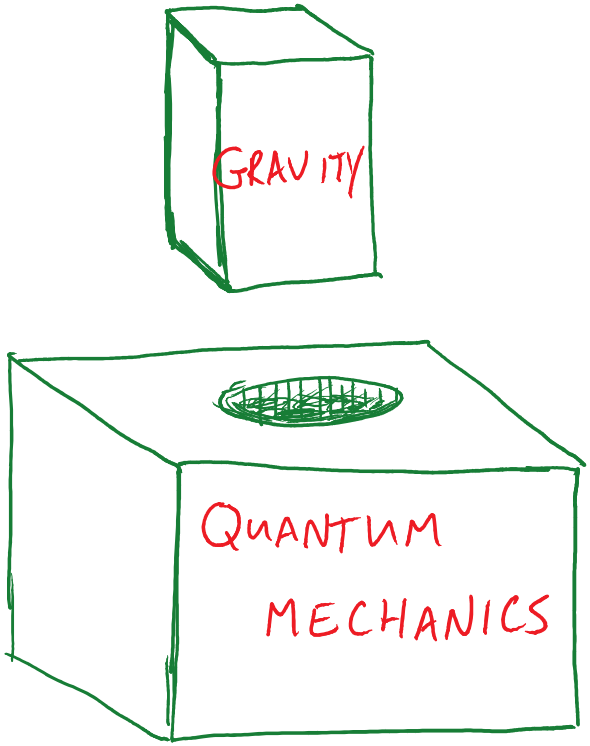
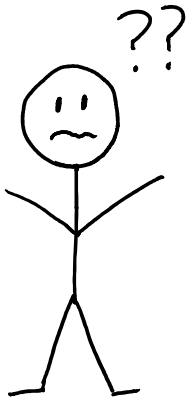
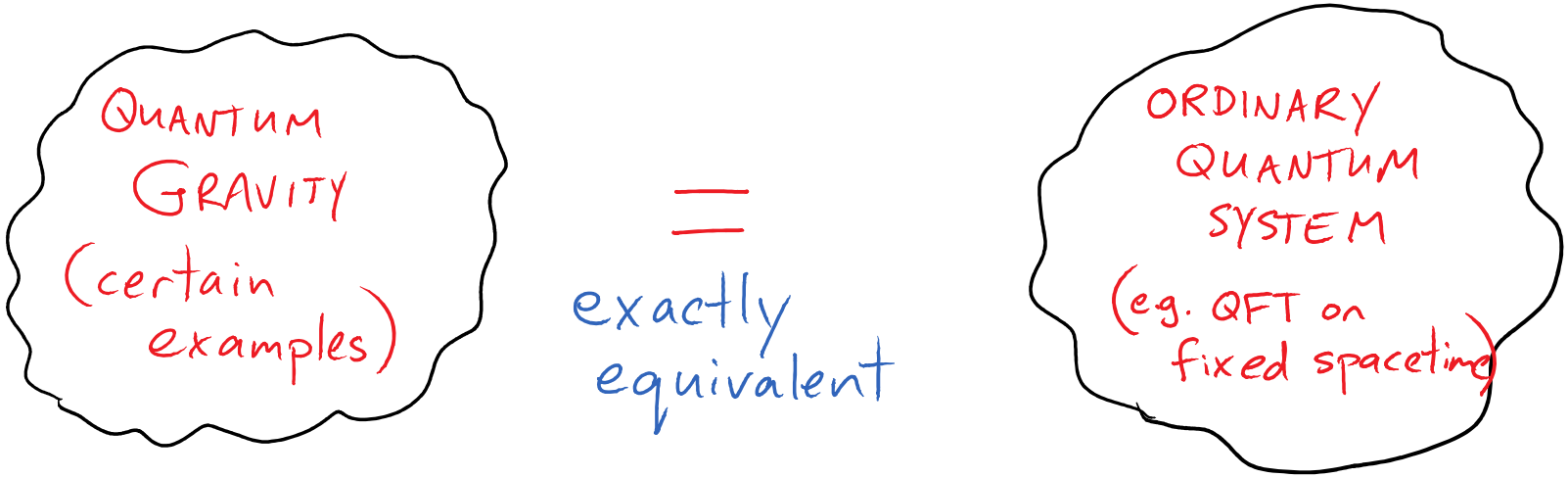
Testing Gravity 2015

One of the greatest challenges for theoretical physics:

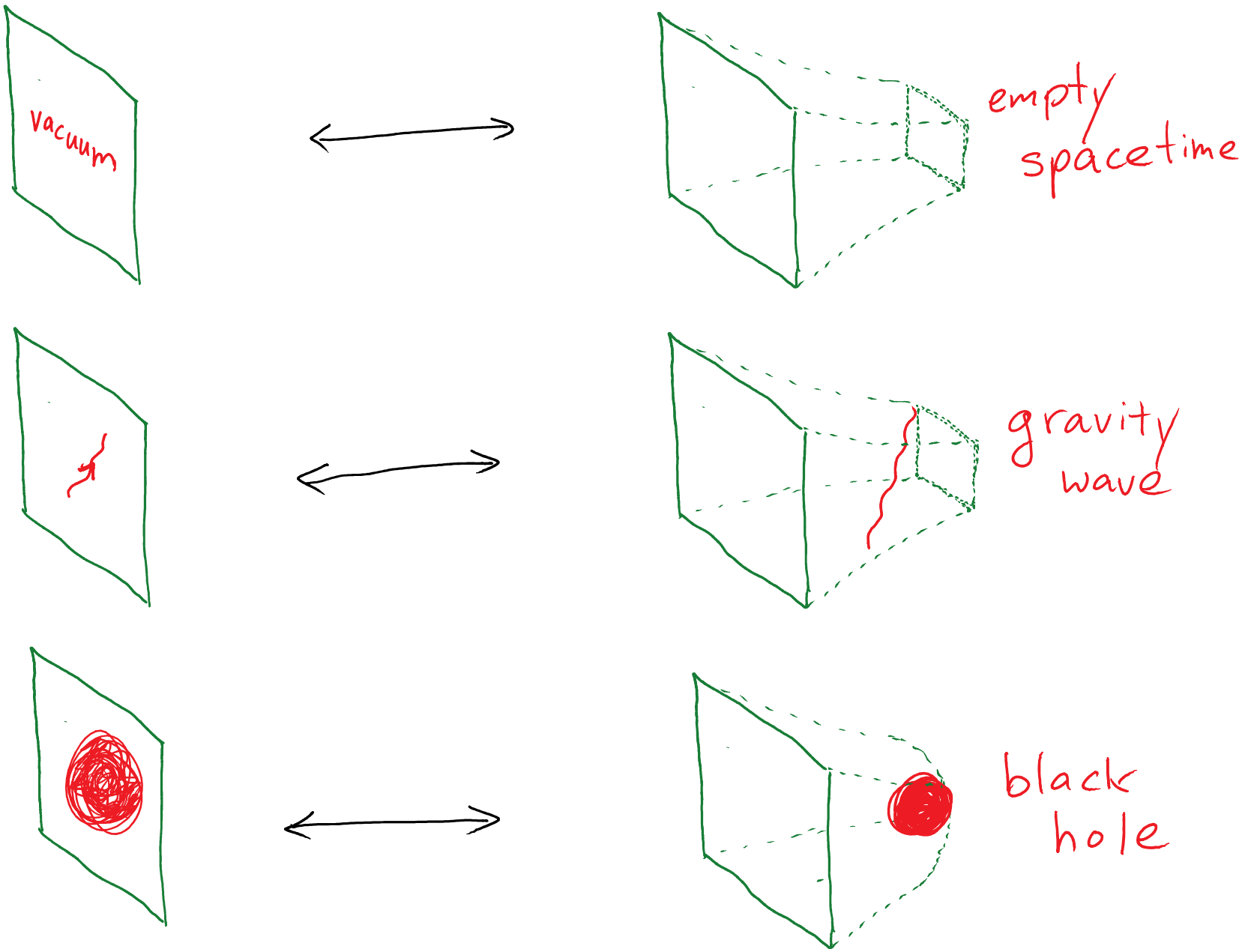




1997: Remarkable progress via AdS/CFT correspondence in string theory (Maldacena)



Different QFT states ⟷ Different spacetimes

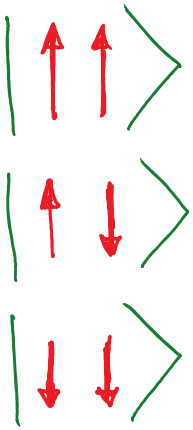


BIG QUESTION:

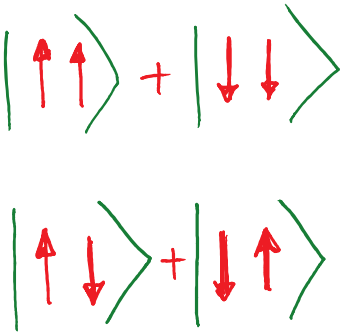
How/why do spacetime/gravity emerge from QFT physics?

Recent work: Quantum entanglement is crucial.

e.g. 2 spin system



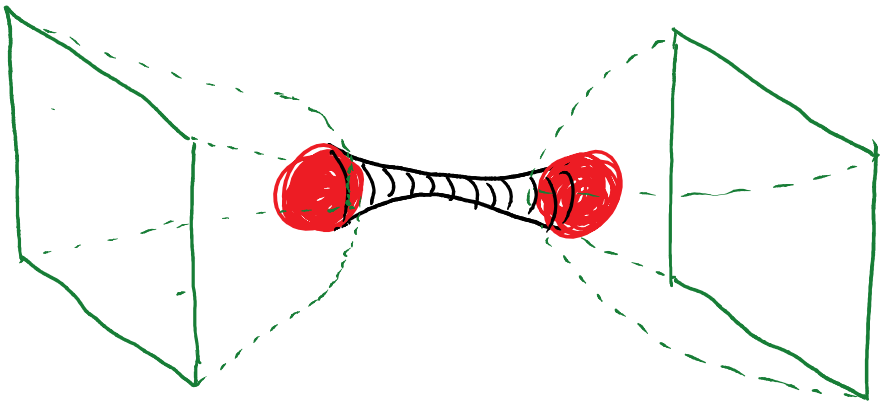
Not entangled



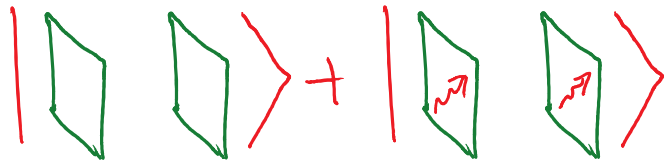
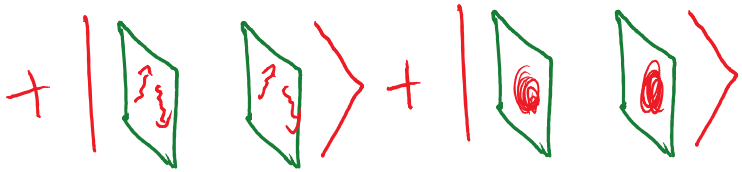
Entangled

Maldacena 2001:

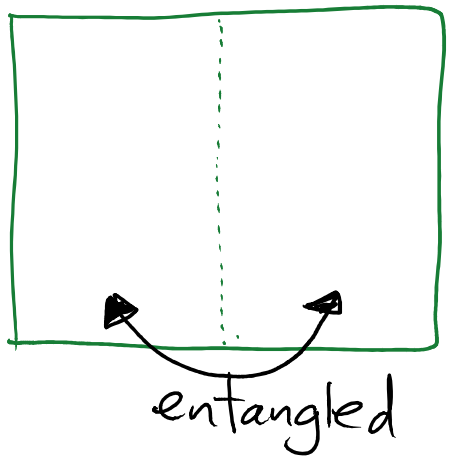
2 separate spacetimes connected by wormhole



2 separate QFTs entangled with one another

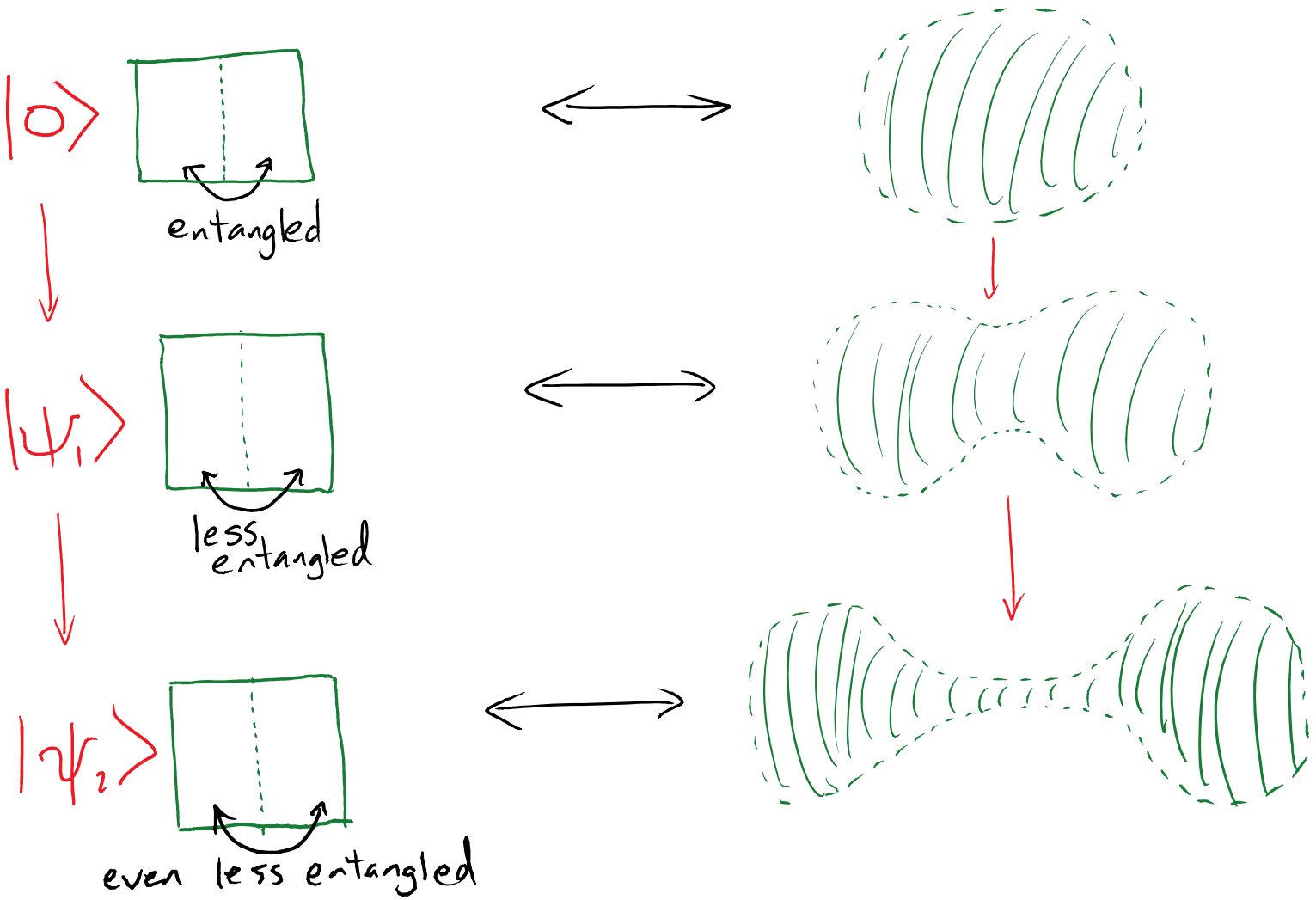
$|\psi\rangle =$  $+$  $+$  $+ \ldots$

BUT: lots of entanglement already in QFT ground state dual to empty spacetime.



QFT fields in any region entangled with fields outside

What happens if we remove this entanglement?



2 regions of space pinch off from each other!

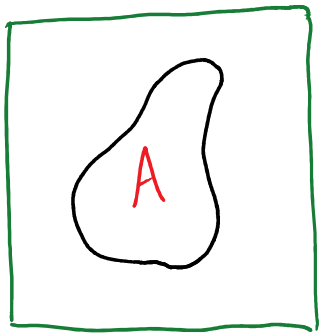
MIR; MVR, Czech, Noguiera, Karzmarek

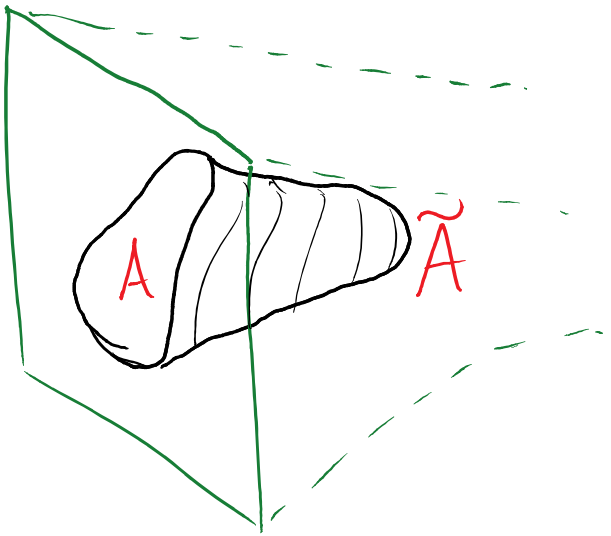
Suggests that classical spacetime geometry emerges via entanglement of degrees of freedom in dual QFT!

MVR, Swingle 2009

No classical spacetime without quantum entanglement.

A quantitative connection (Ryuto Takayanagi)



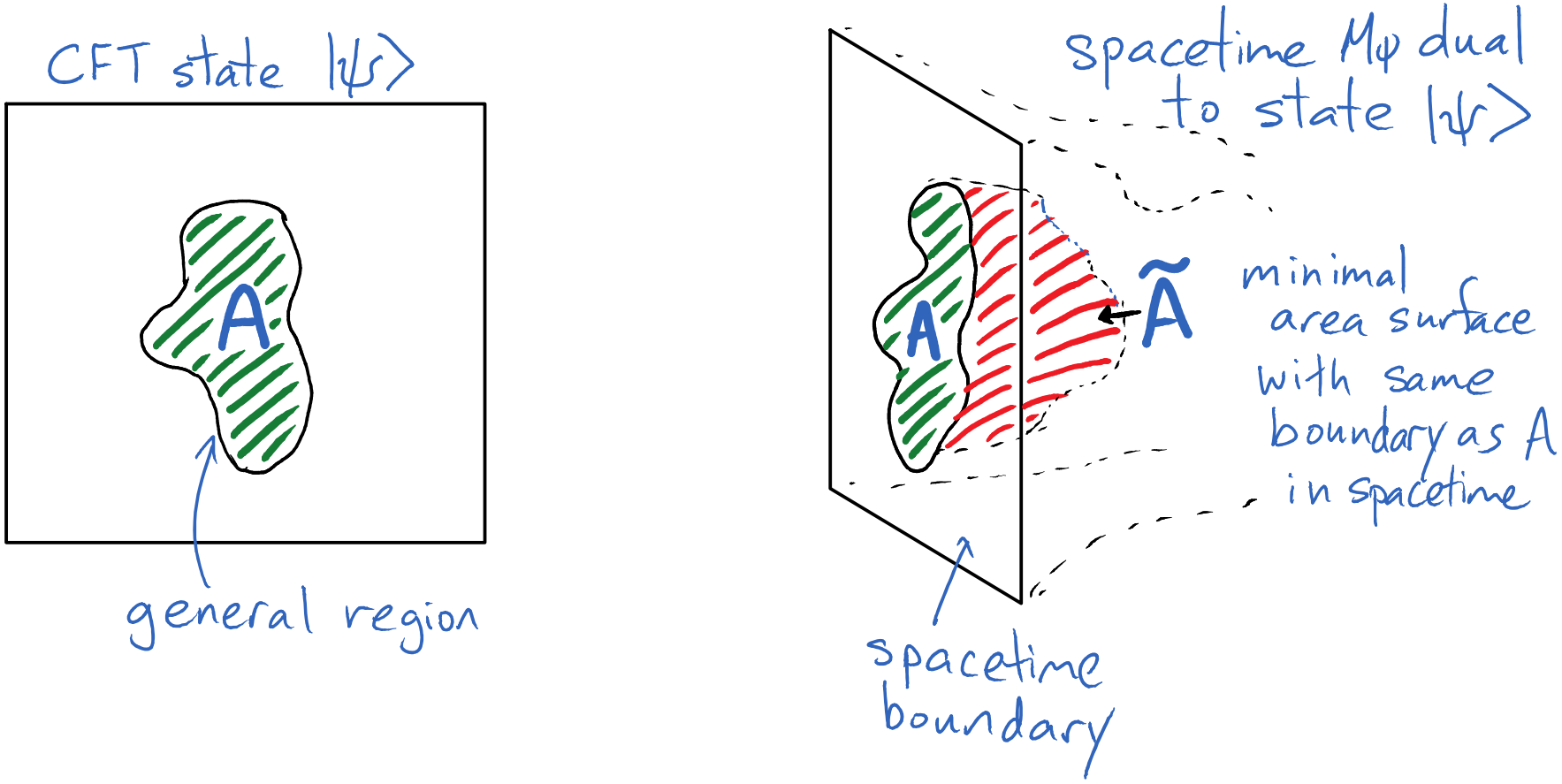


ENTANGLEMENT ENTROPY S_A (measures how much A is entangled w. rest of system)

$$= \frac{1}{4G} \times$$

Area of minimal surface $\tilde{A}$ in dual spacetime

Geometry From Entanglement



$|\psi\rangle \rightarrow$ calculate S_A for many A $\rightarrow$ find M_ψ s.t. $\text{Area}(\tilde{A}) = S_A$

Can (plausibly) reconstruct geometry from entanglement!

Past year: gravitational dynamics from entanglement

N. Lashkari, M. McDermott, MVR
T. Faulkner, M. Guica, T. Hartman, R. Myers, MVR
B. Swingle, MVR.

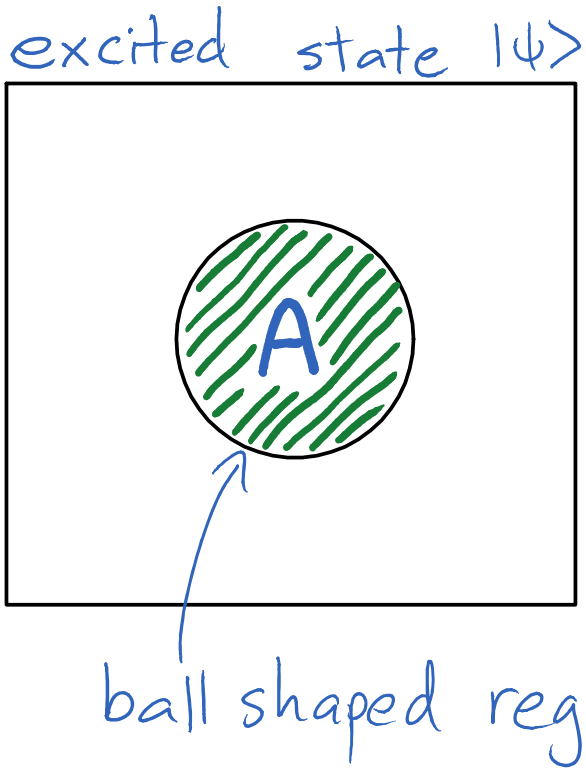
also:

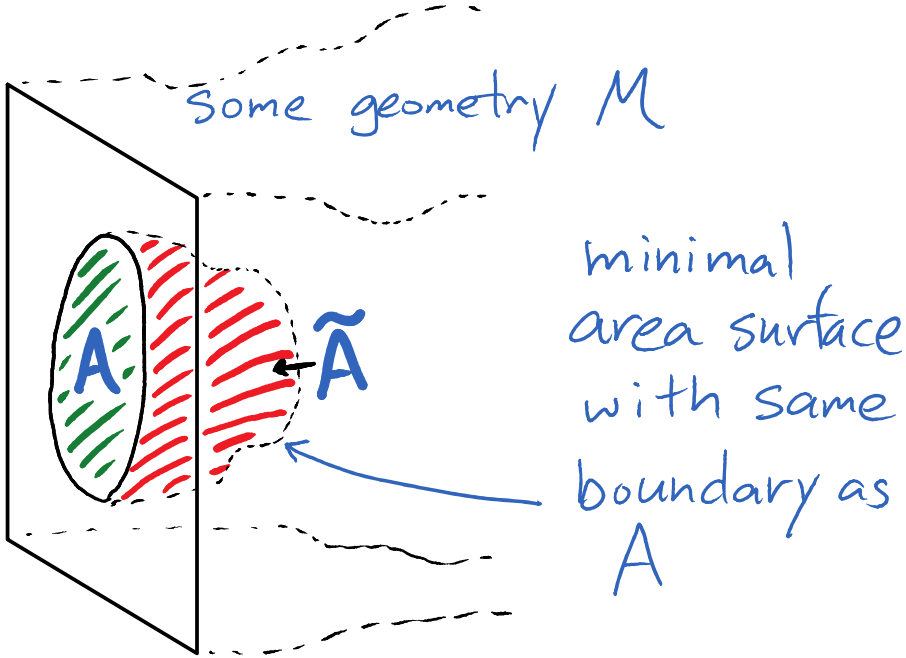
If spacetime geometry is a manifestation of QFT entanglement, can we understand spacetime dynamics from entanglement physics?

Geometries must satisfy Einstein's Equations

Will assume:

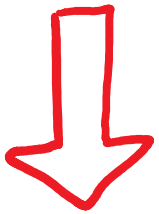
There exist CFTs for which entanglement entropies for family of states can be computed geometrically.





Which geometries are possible?

Entanglement entropies obey constraints

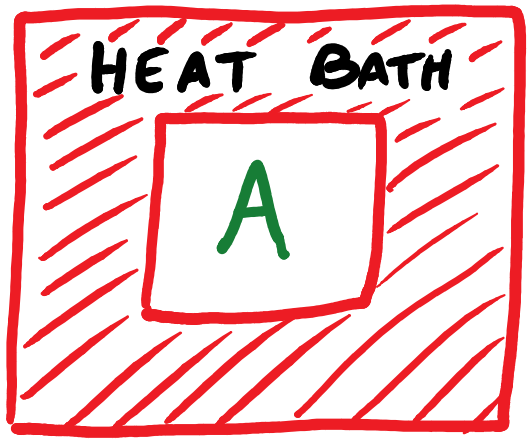


Entropy-area connection

Constraints on geometries

A Quantum First Law of Thermodynamics:

Starting in thermal state with temp. T:



For ANY variation of the state

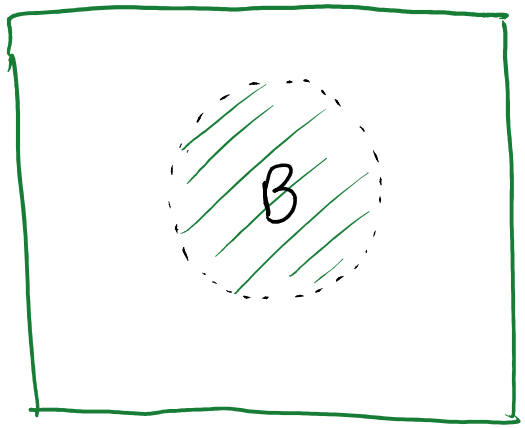
$$\delta S_A = \frac{1}{T} \delta \langle E \rangle$$

S_A: entanglement entropy

$\langle E \rangle$: energy (Hamiltonian)

Similar "First Law" for perturbations to ground state of a CFT

Blanco, Casini, Hung, Myers



$$|0\rangle \to |0\rangle + \delta|\psi\rangle$$

For any ball B:

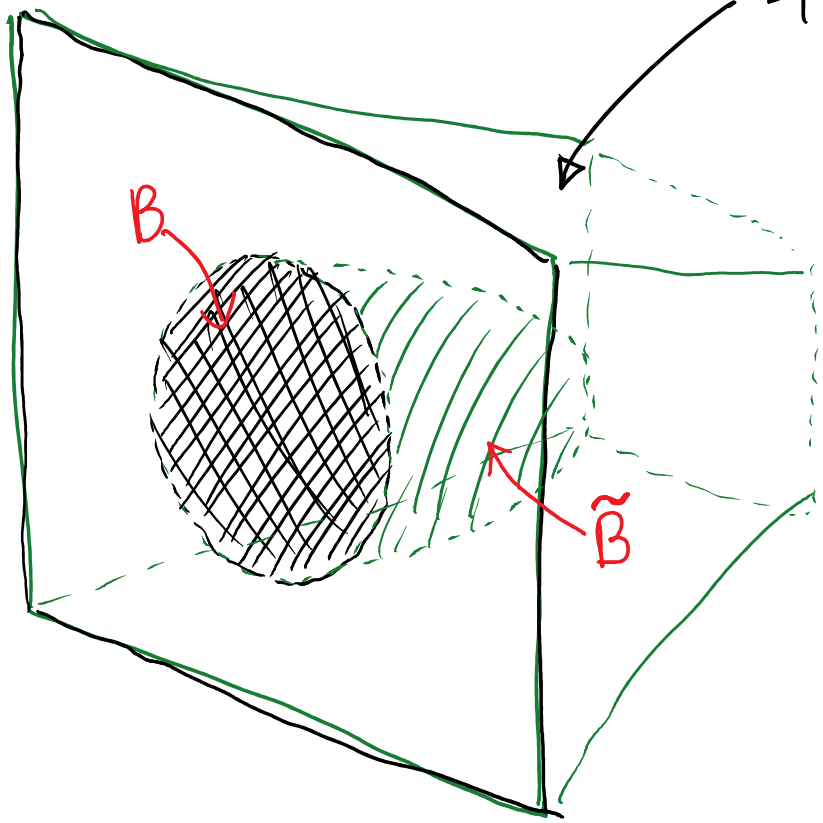
$$\delta S_B = \delta \langle E_B \rangle$$

$$E_B = \int_B dx \; f(x) \cdot \langle \rho(x) \rangle$$

specific function on B

Energy density

Translate to statement about dual spacetime:



spacetime dual to
$|0\rangle + \delta|\psi\rangle$

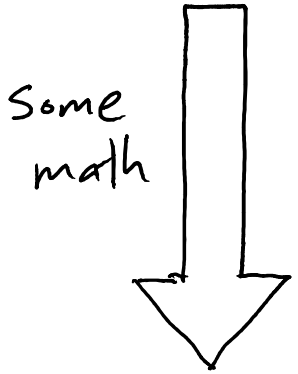
||

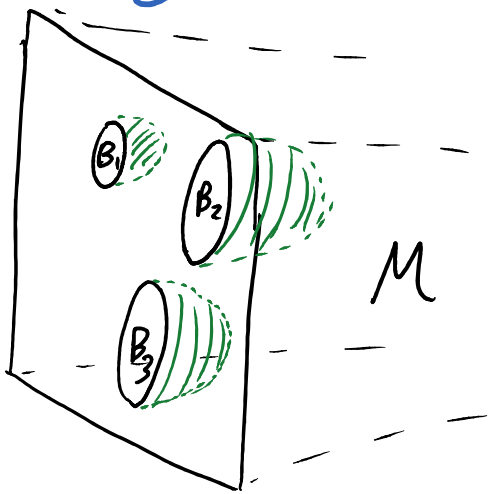
some perturbation
to empty AdS space

$dS_B = dE_B$ → relates metric perturbation on $\tilde{B}$ to metric perturbation on B (use Ryu+Takayanagi)

CONSTRAINT ON DUAL SPACETIME

Set of constraints for all ball-shaped regions B





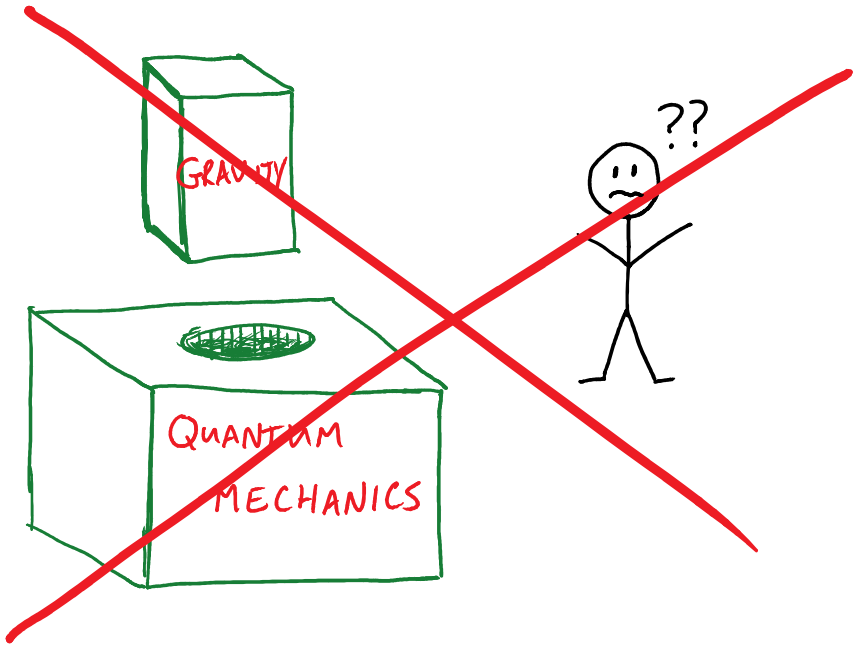
GEOMETRY M MUST SATISFY EINSTEIN'S EQUATIONS!!

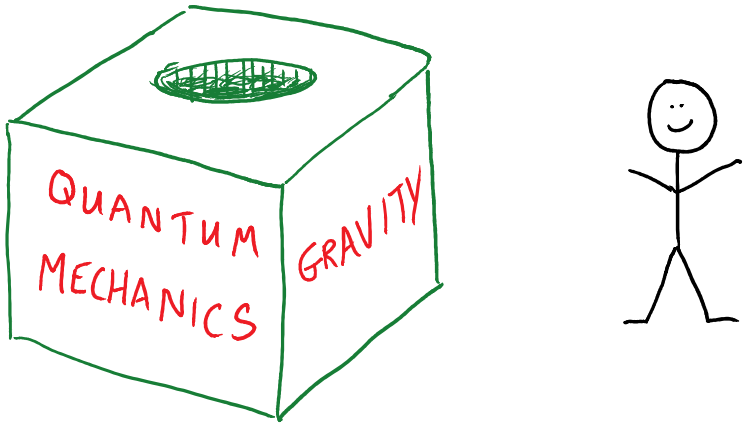
(linearized about Anti-de-Sitter)

Summary

structure of entanglement in QFT $\longleftrightarrow$ spacetime geometry

constraints on QFT entanglement $\longleftrightarrow$ Einstein Equations (so far: linearized)





Further results:

- Including first quantum corrections on gravity side gives $\langle T_{\mu\nu} \rangle$ as source for Einstein Equations

(linearized Einstein) + ($T_{\mu\nu}$ source) + (B.H. entropy = area)

$\longrightarrow$ Full non-linear Einstein (additional assumptions?)

- Entanglement constraints for finite perturbations imply (averaged) energy conditions