GRAVITY AND ENTANGLEMENT

Mark Van Raamsdonk, UBC

A  Lecture on Quantum Phenomena

The goal of physics:

- Observe the universe
- Figure out the rules

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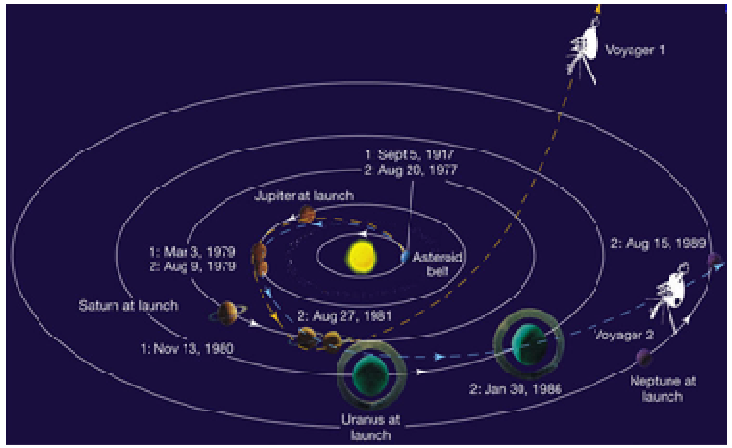
Predict the future



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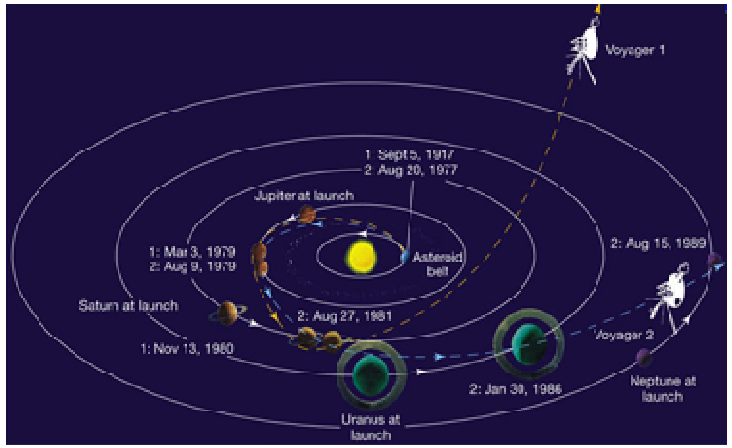
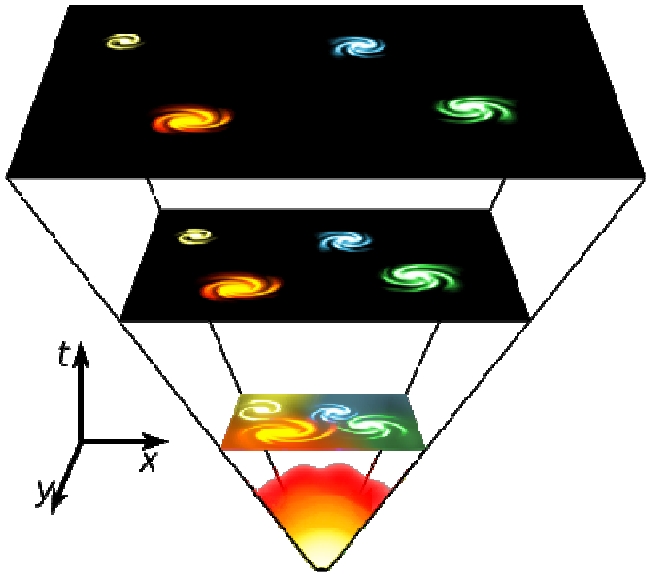


Understand the past



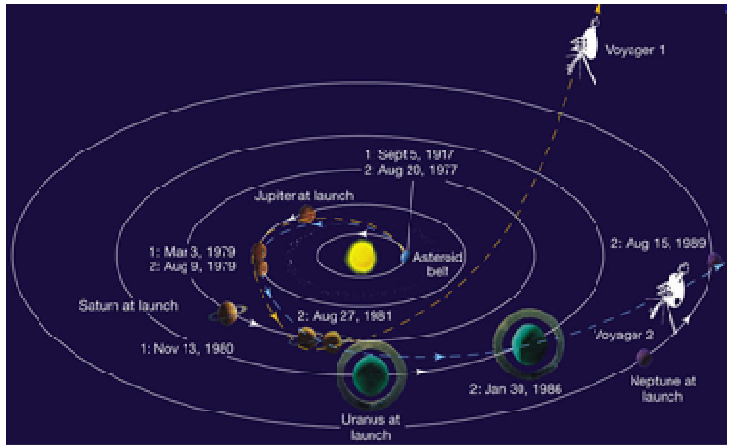
The goal of physics:

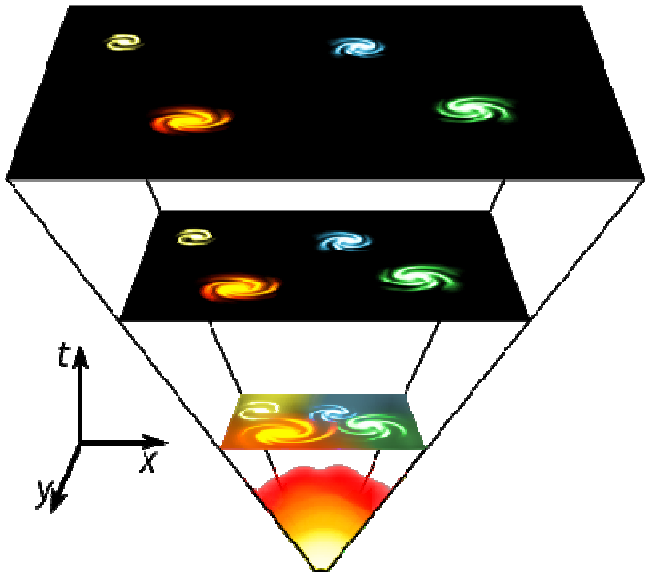
- Observe the universe
- Figure out the rules

Make better mobile devices

Predict the future

Understand the past

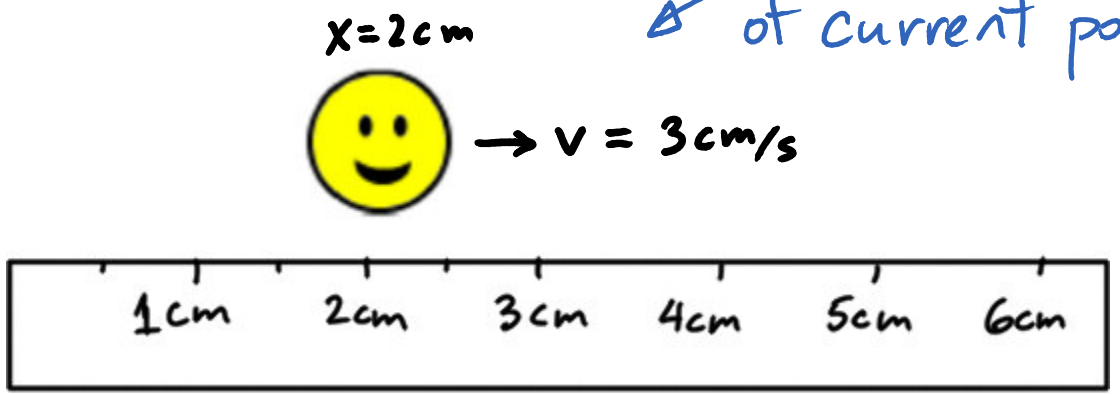




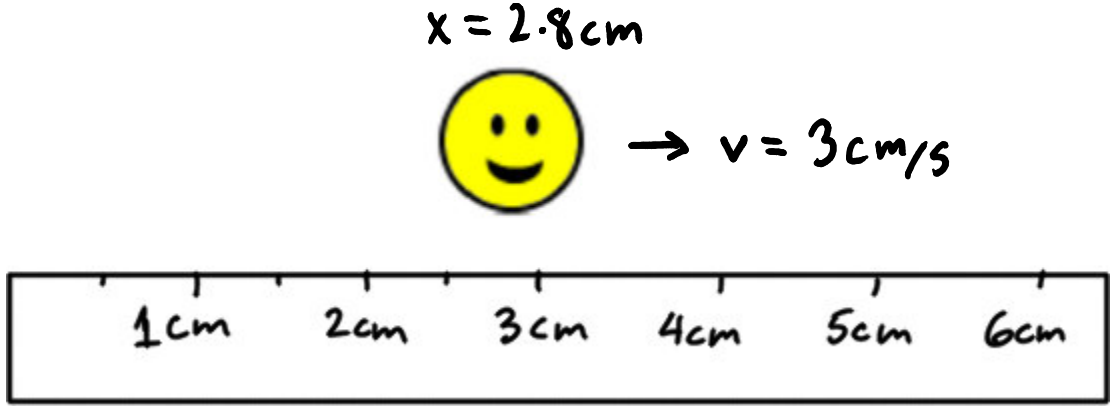
"Classical" physics:

i.e. ordinary non-quantum

Mathematical representation of current position + velocity



Physics = rule for figuring out what x and v are at slightly later time eg. NEWTON's LAWS

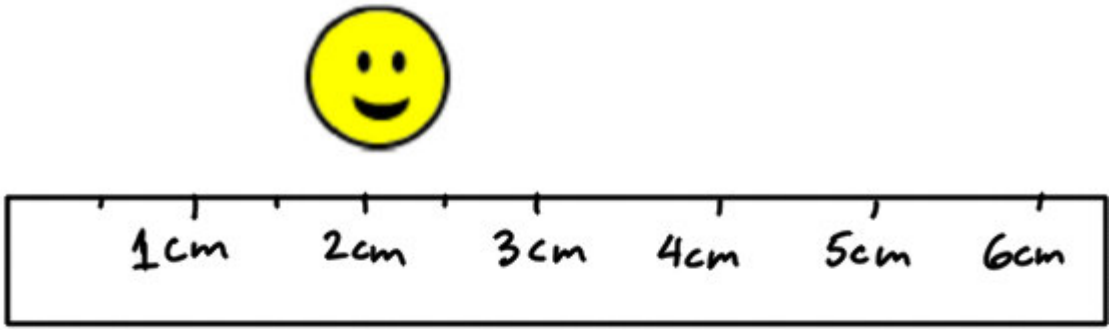


These classical rules are only approximations.

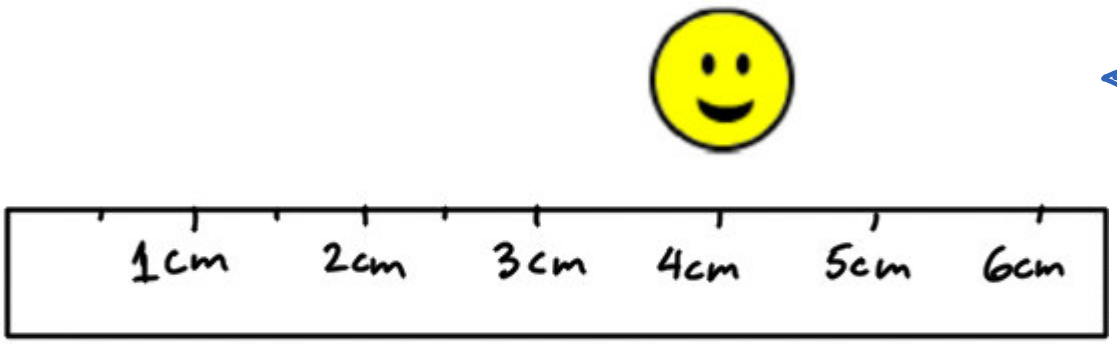
At atomic/subatomic scales (and sometimes at macroscopic scales) we need a more complete theory:

QUANTUM MECHANICS

Most important feature: objects can be in QUANTUM SUPERPOSITIONS



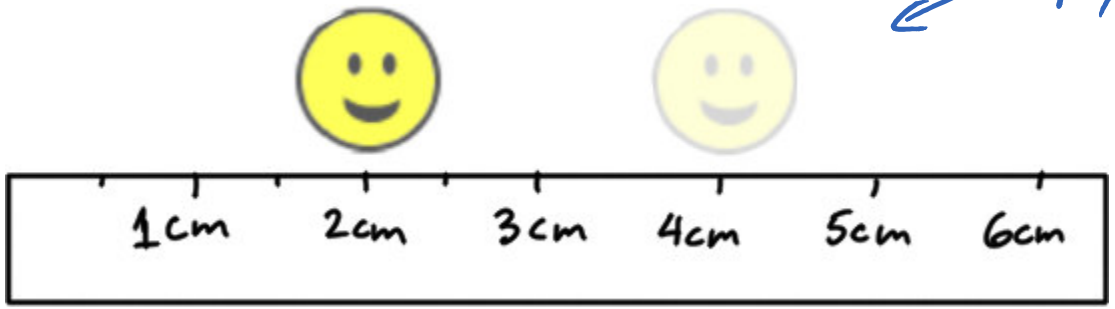
STATE #1:
object at x=2cm



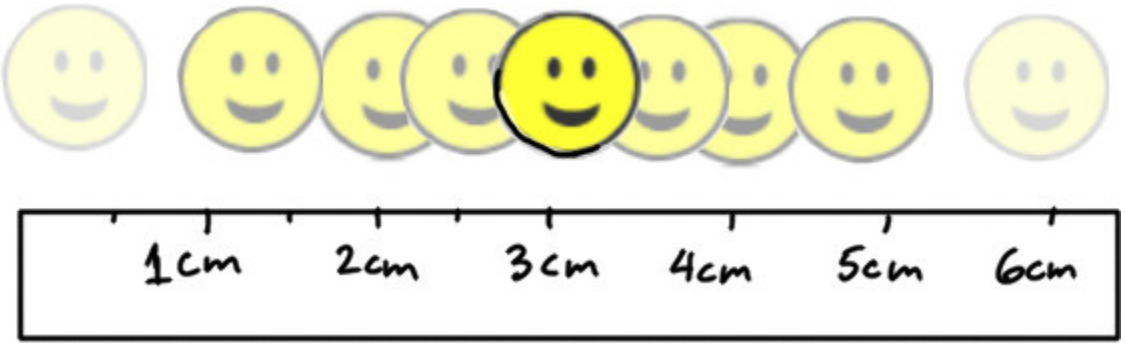
STATE #2:
object at x=4cm

50/50 SUPERPOSITION
- no definite position
- "collapses" to state #1 or #2 if we observe it

More general superpositions:



70/30 superposition: more likely to become x=2cm state if observed



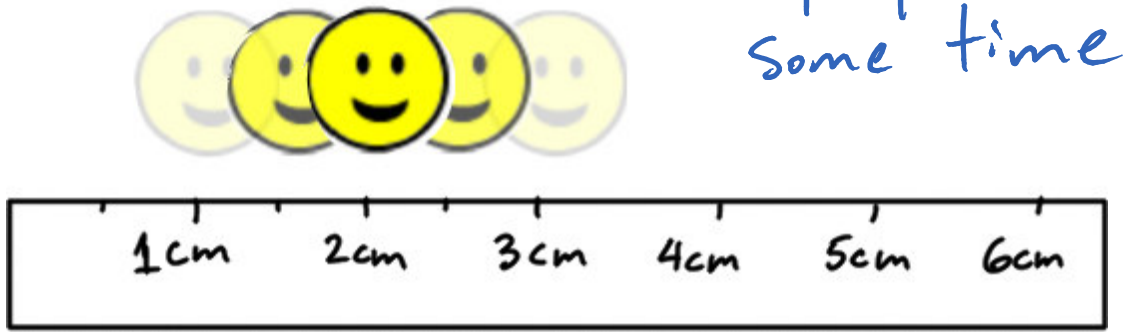
superposition of many locations:

WAVEFUNCTION describes fraction of each state in superposition

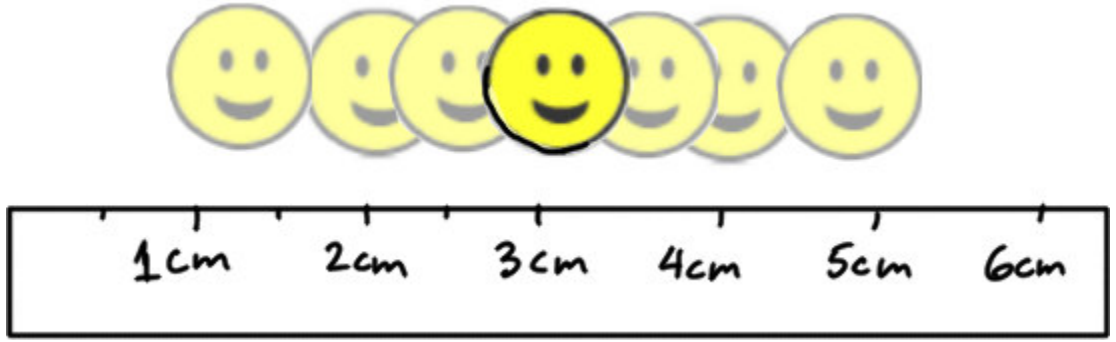
still only a single object here!

Quantum Physics

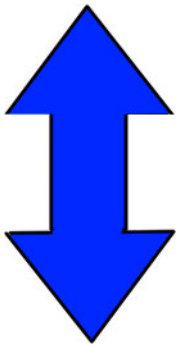
superposition state at some time



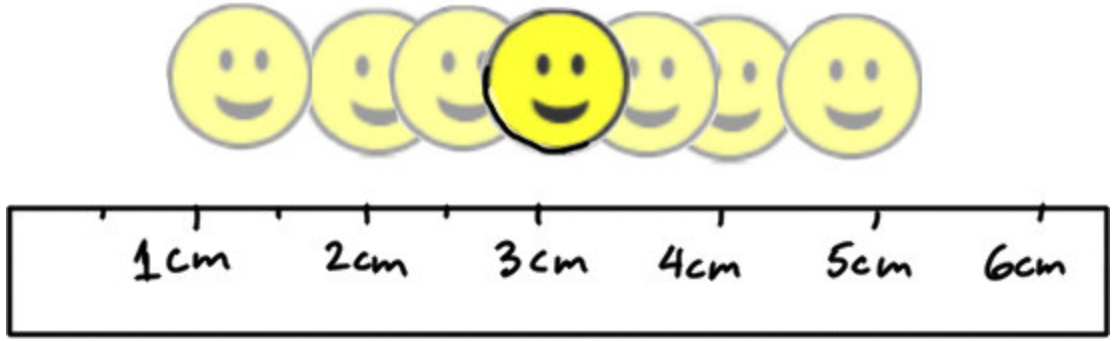
SCHRÖDINGER EQUATION: rule for figuring out superposition state at slightly later time



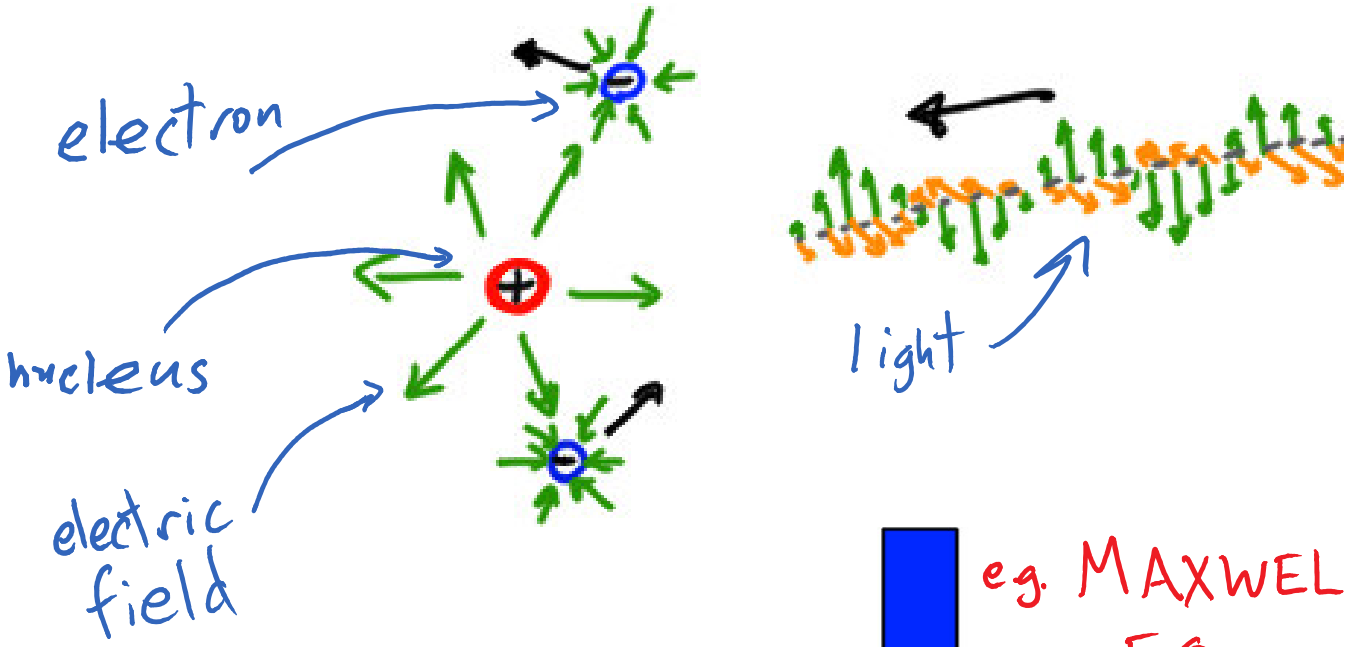
Quantum physics is REVERSIBLE



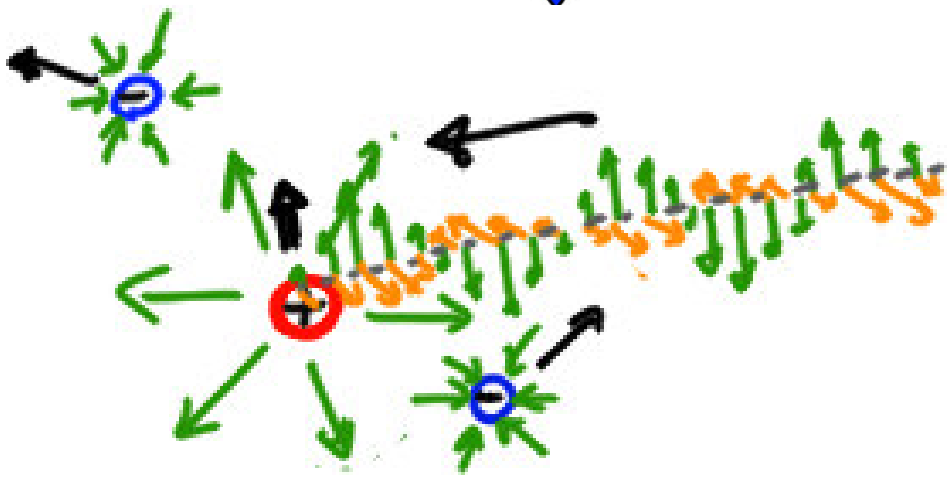
can also figure out past state from future state



We have found quantum versions of most physical laws.



e.g. MAXWELL'S EQUATIONS



classical version fails badly at atomic scale

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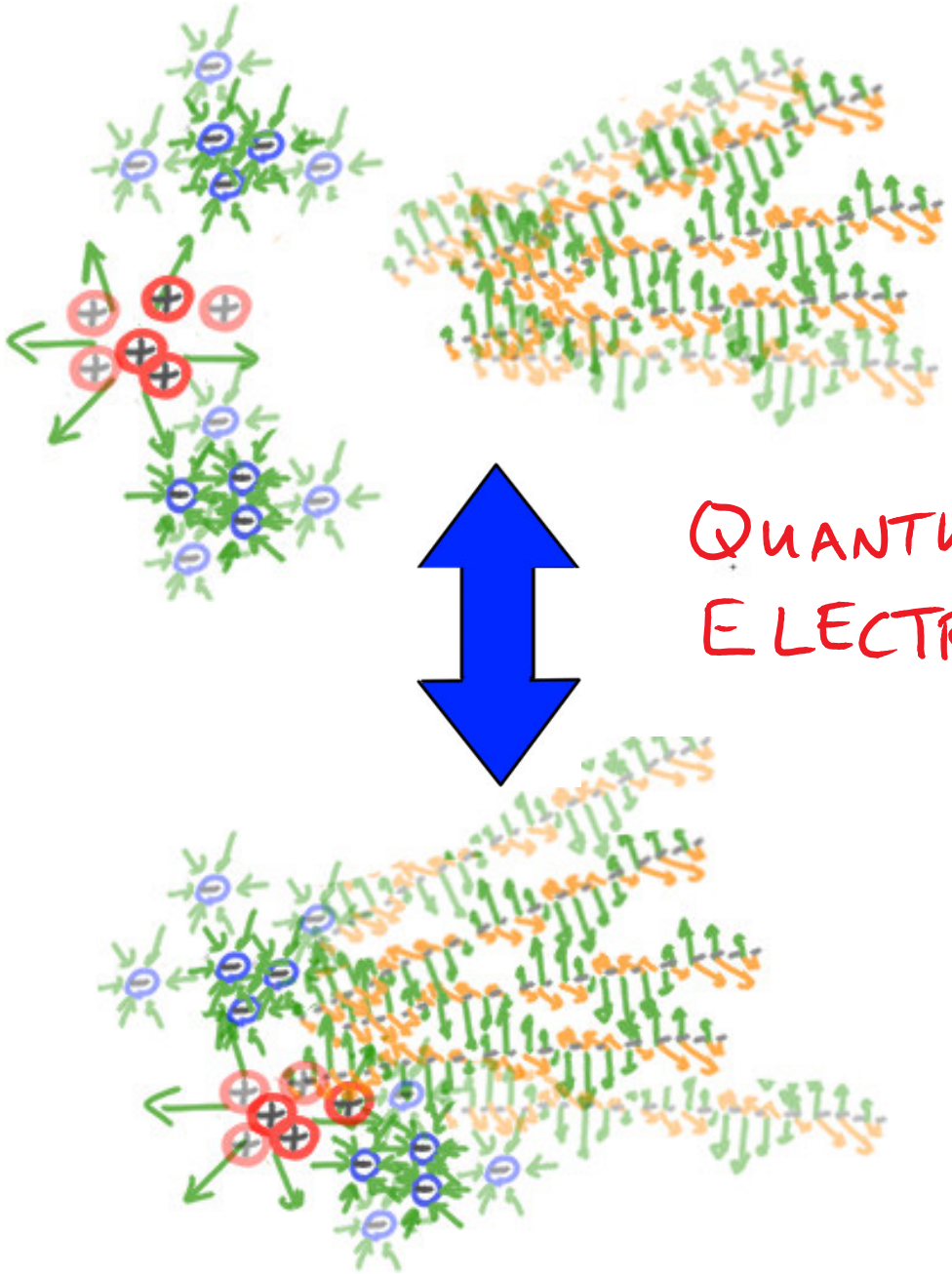
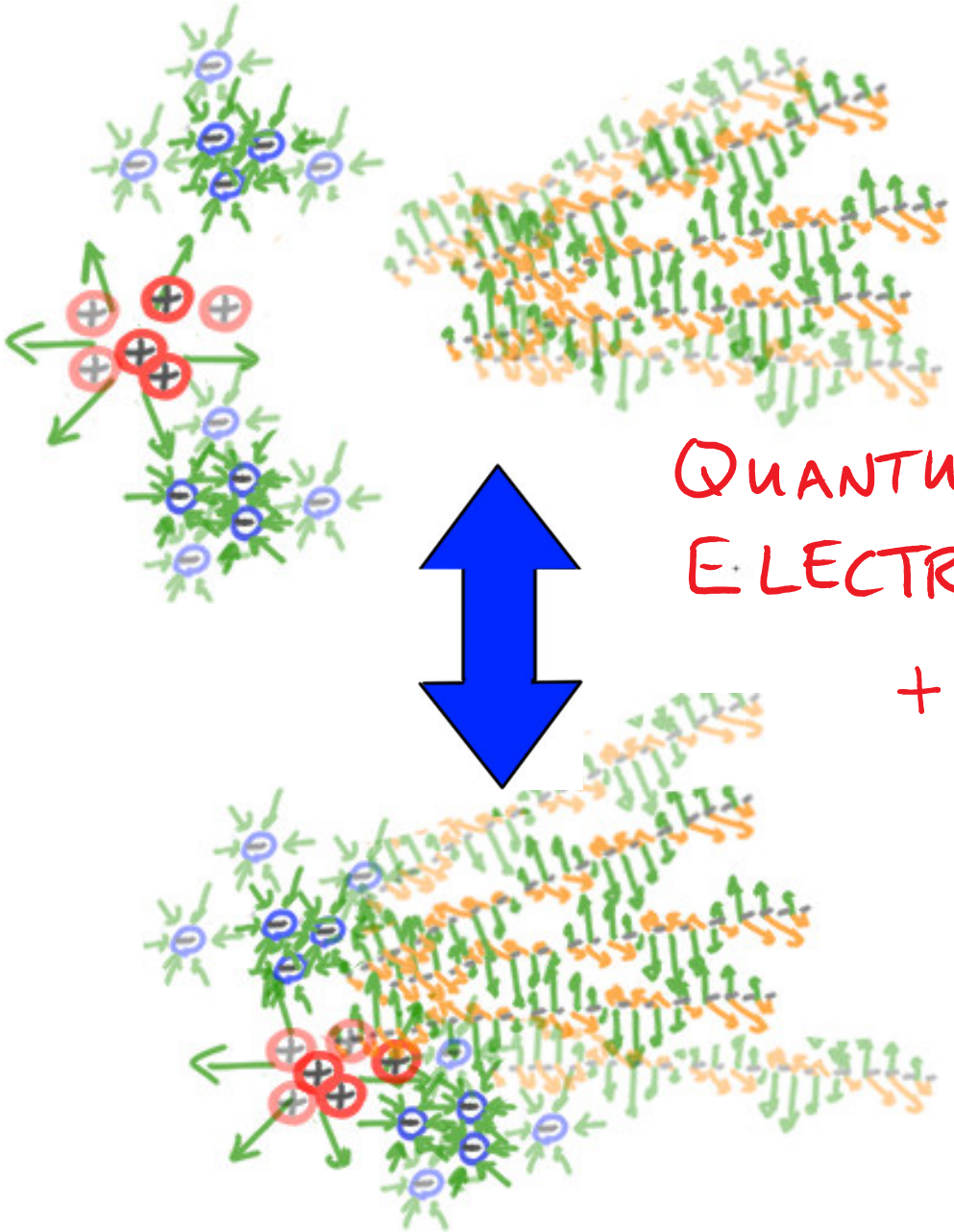


QUANTUM ELECTRODYNAMICS

We have found quantum versions of most physical laws...



QUANTUM ELECTRODYNAMICS

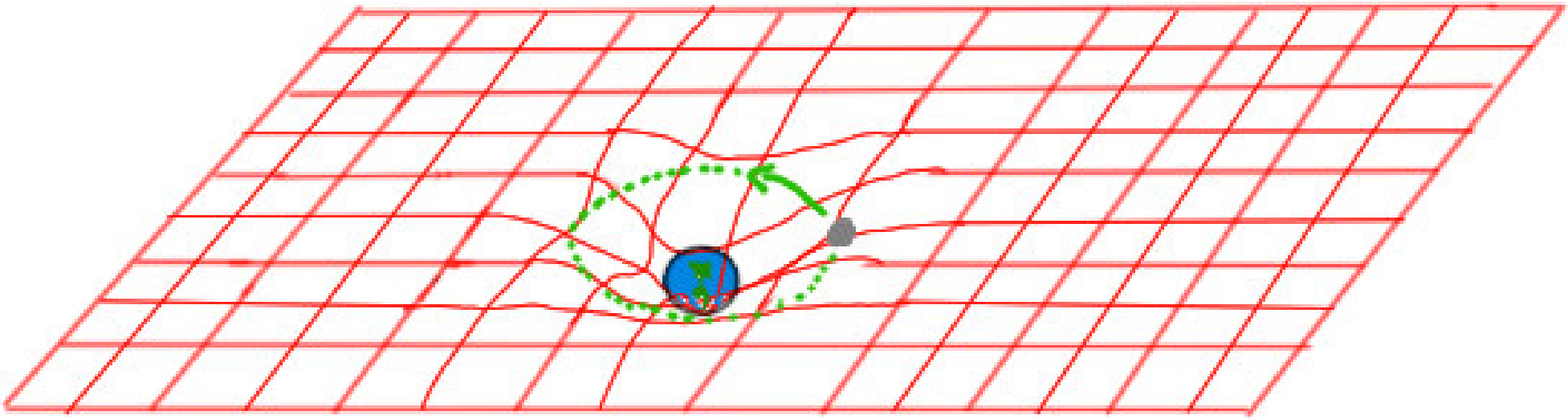
+ weak + strong forces

↓

STANDARD MODEL OF PARTICLE PHYSICS

... except gravity

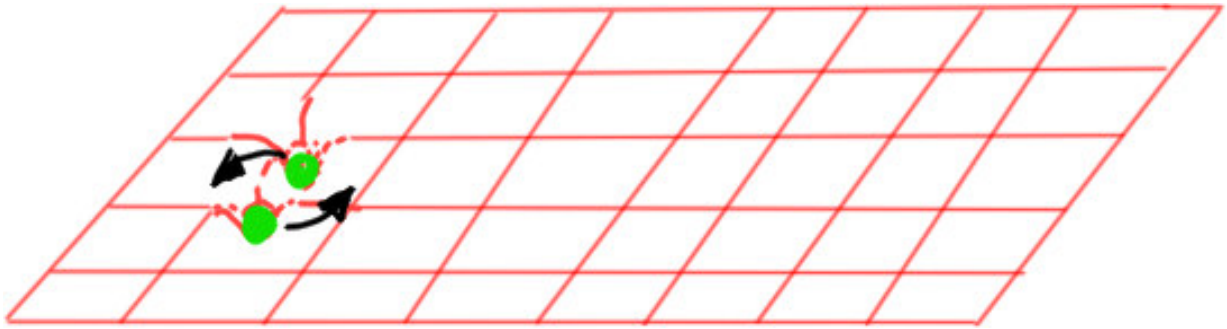
Einstein: classical gravity describes bending of space + time by mass + energy:



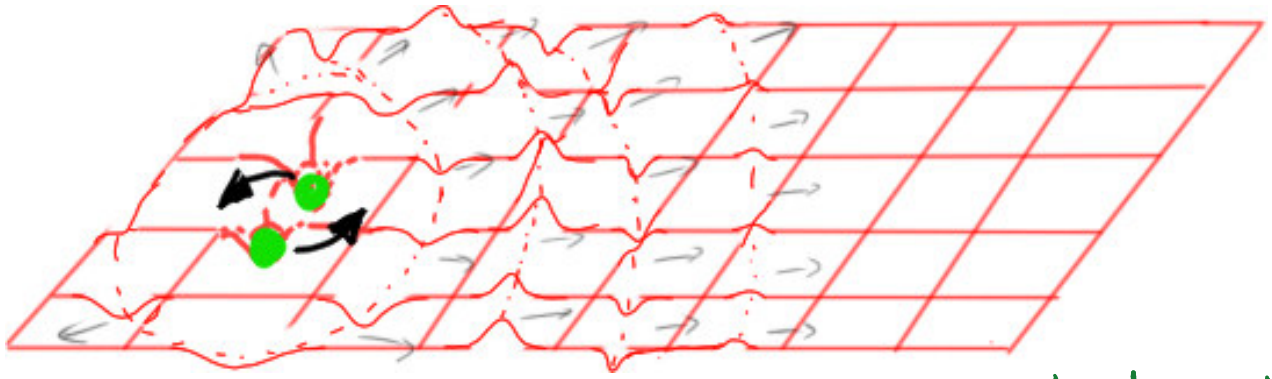
* Matter + energy cause space to bend / warp

* Effects of gravity explained by objects moving on natural paths in this curved space

Classical rules for gravity



EINSTEIN'S EQUATIONS - describe dynamics of spacetime + interactions with matter



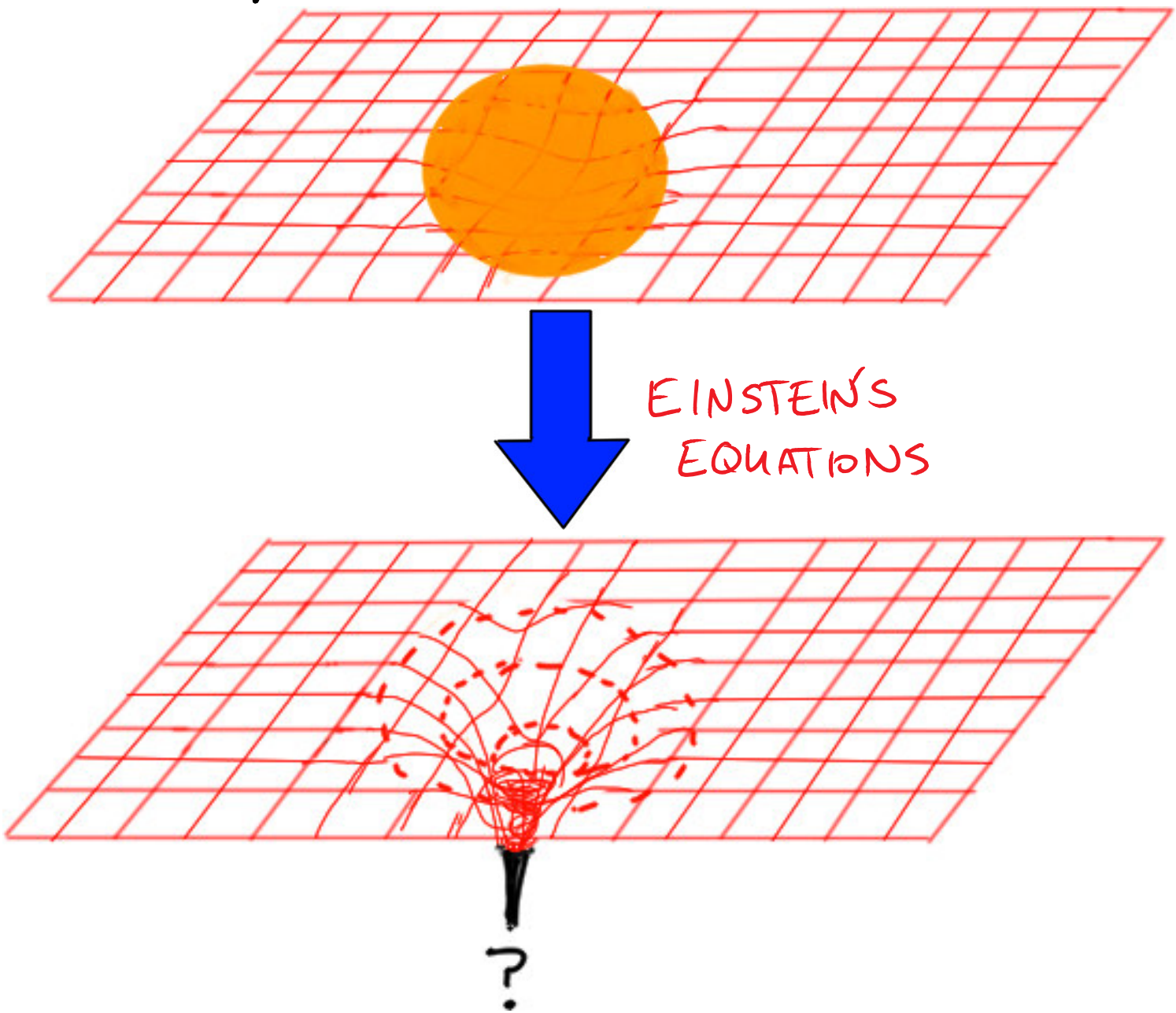
gravitational waves

What are the quantum rules?

Can different spacetimes be in superpositions?

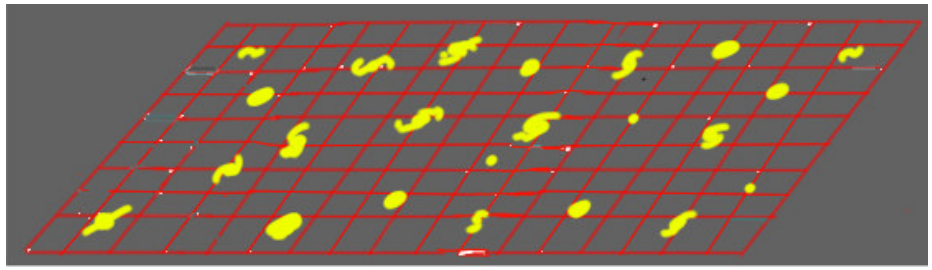
Do we even need quantum gravity since we can basically ignore gravity at atomic scales?

Einstein's equations predict black holes



Einstein's equations + observations suggest expanding universe → BIG BANG

???



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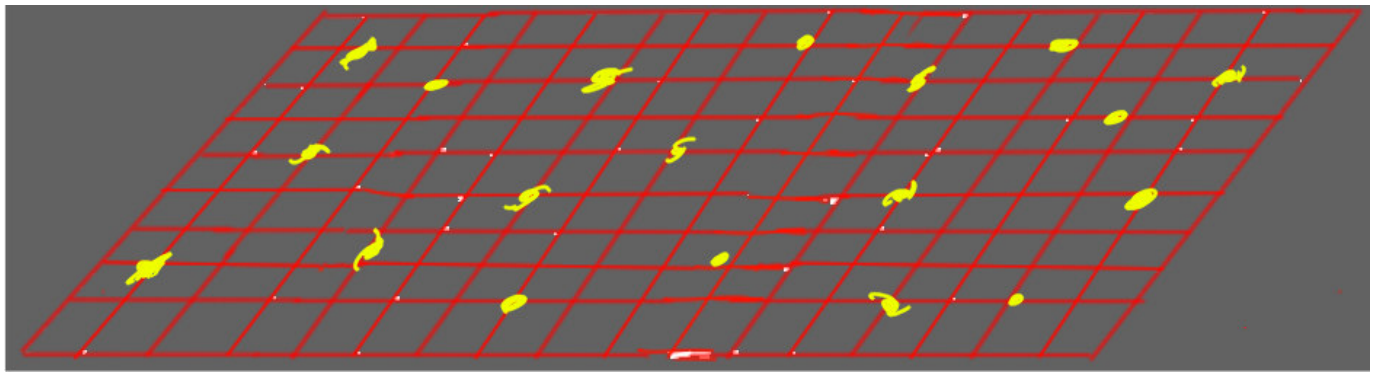


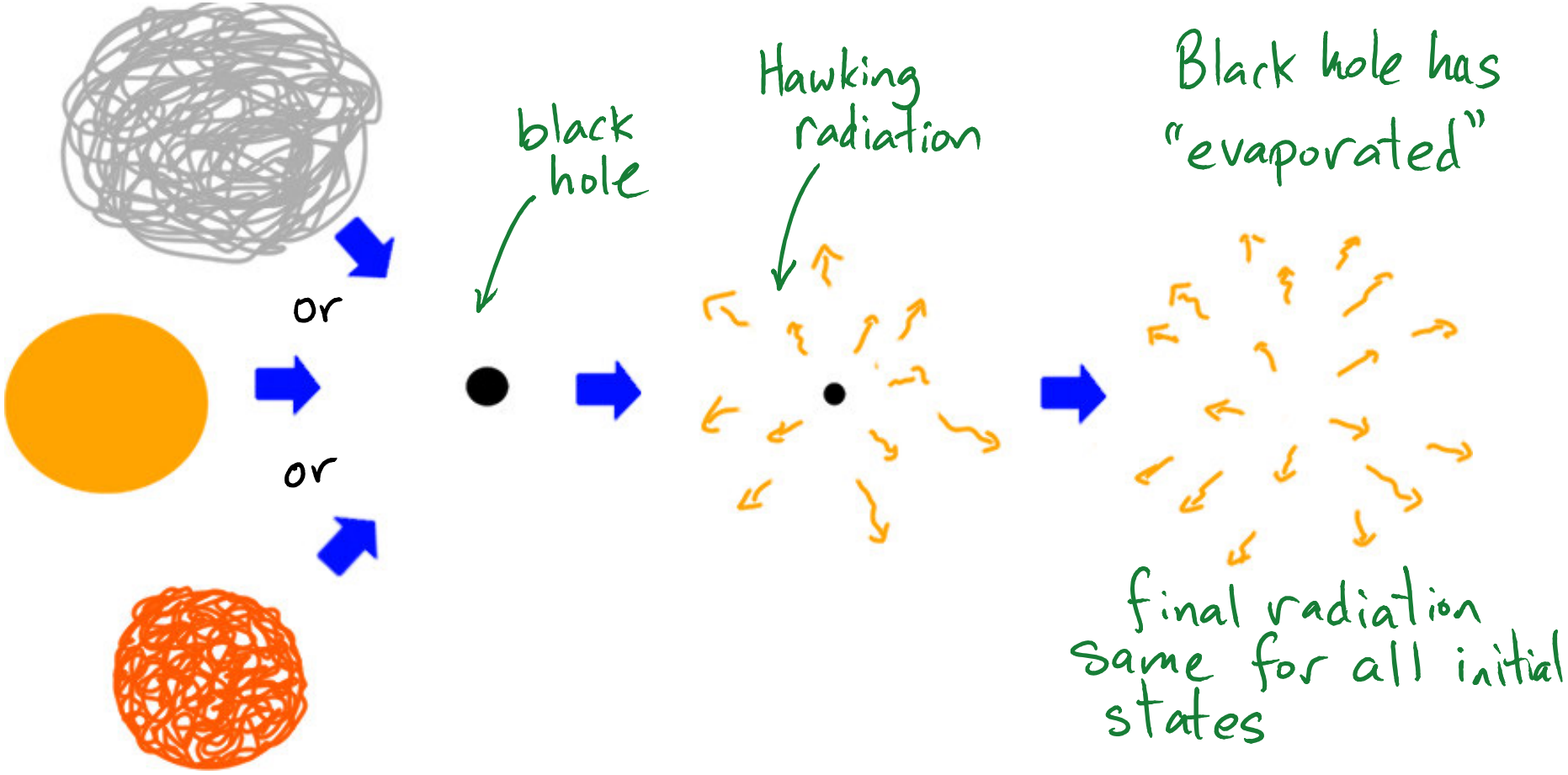
Black holes + big bang:

Matter is so dense that gravity will be important even at atomic scales.

We need a quantum theory to understand them.

* much harder than other cases since space itself is dynamical. *

1970s: Hawking suggests black hole physics is irreversible



Not consistent with quantum mechanics

BUT: Hawking's calculations were approximate.

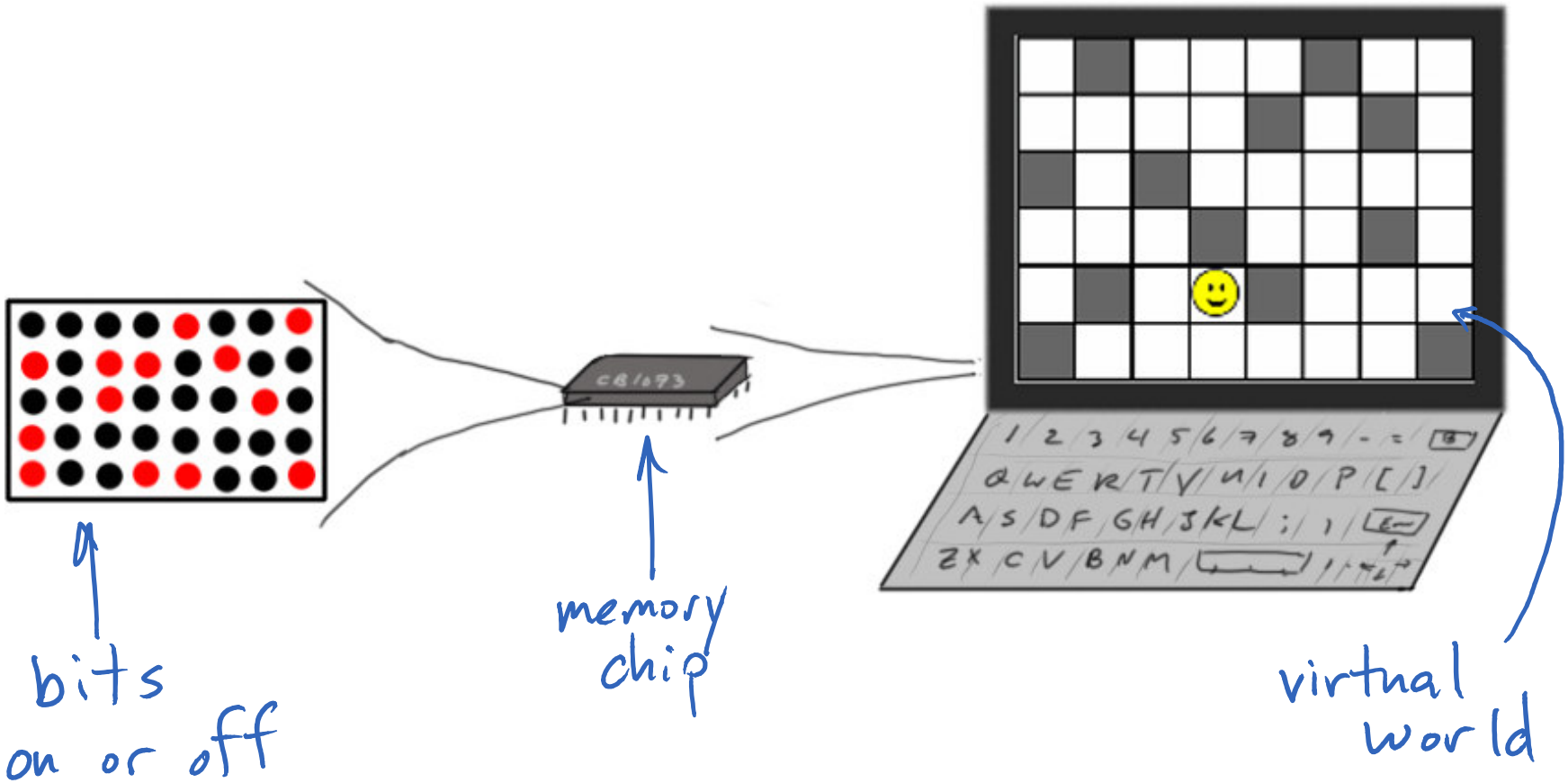
No complete model with quantum mechanics + gravity until...

- 20 years of string theory research
- deeper understanding of gravity, black holes, connections with thermodynamics

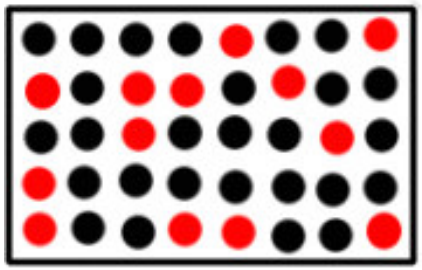
1997 Juan Maldacena

"the AdS/CFT correspondence"

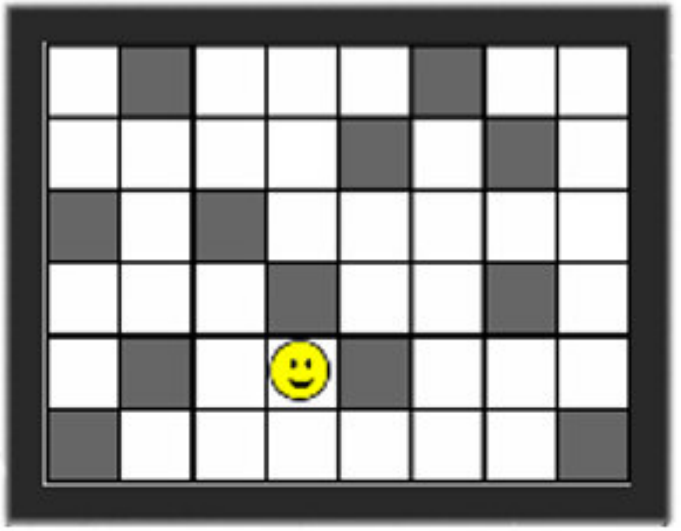
Analogy:



Evolution in virtual world related to physical changes of bits on memory chip:

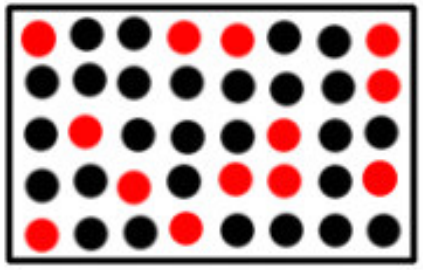


code

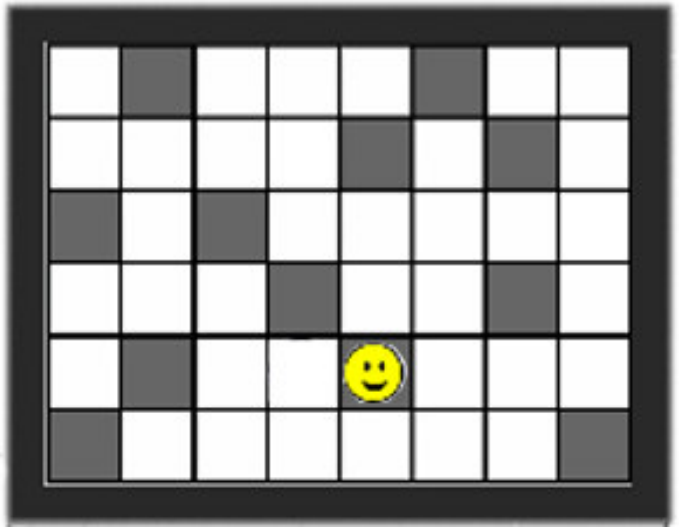


evolution of bits on memory chip

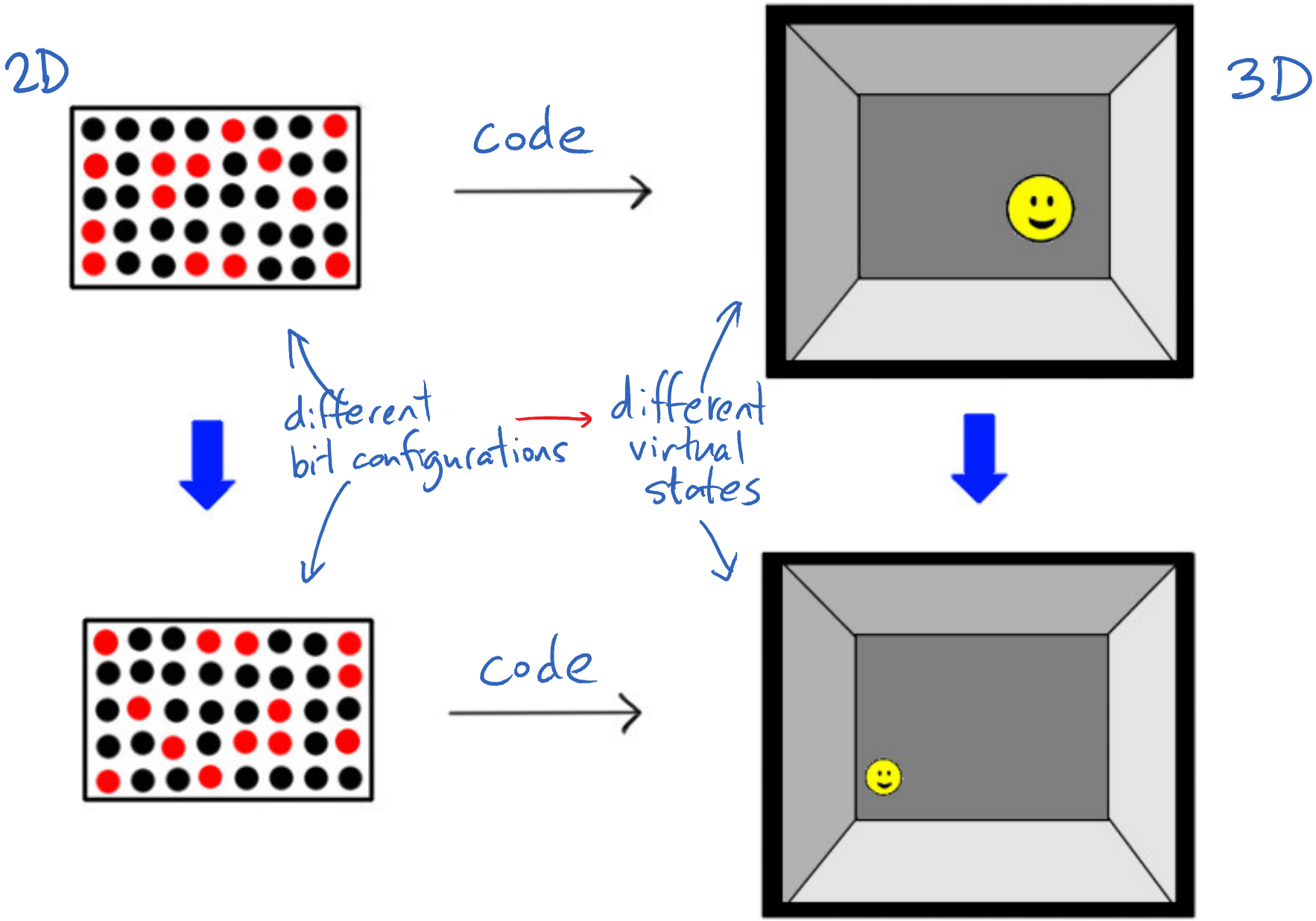
evolution in virtual world



code

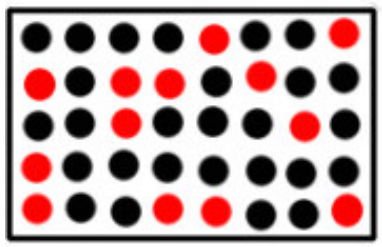


"Physics" in virtual world can be like our world



Maldacena: 3D gravitational physics is actually controlled by some underlying 2D system

(anticipated by 't Hooft & Susskind based on work of Bekenstein)



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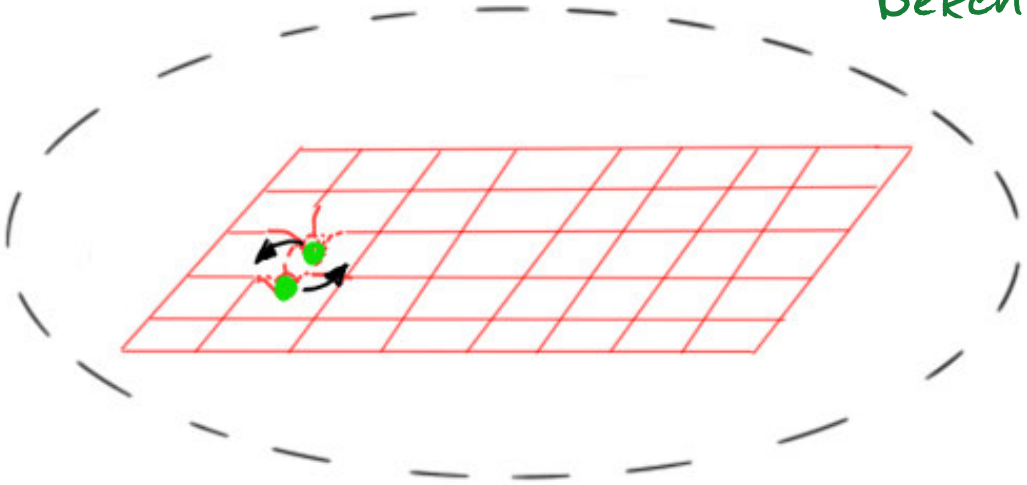
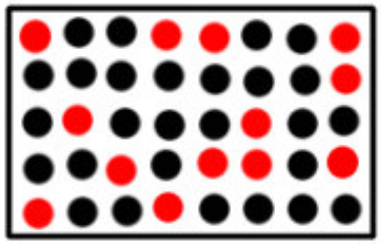


simpler 2D physics

EINSTEIN'S EQUATIONS + other physics



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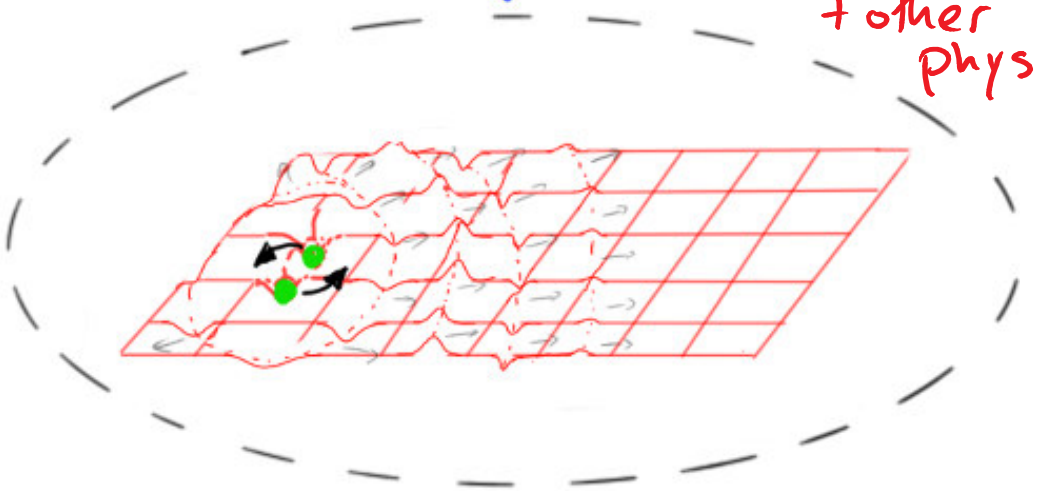


Much easier to find quantum rules for this 2D system. This quantum 2D system defines the quantum gravity theory.

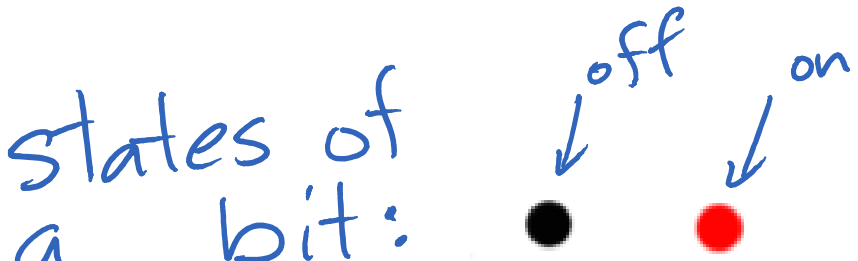
★ Defined in this way, gravity is clearly consistent with quantum mechanics ★

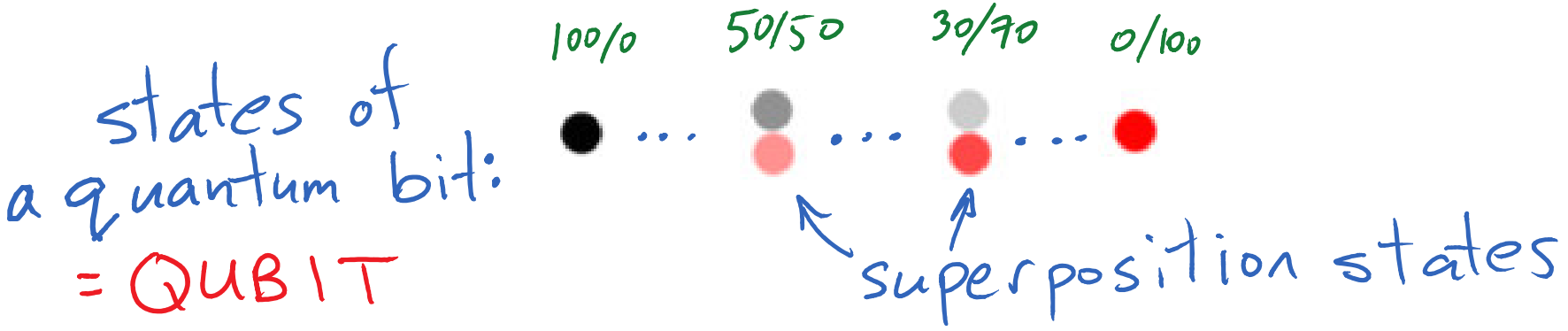
(...and Hawking has agreed)

BUT: need to understand the code!

How is spacetime encoded in the chip?

Maldacena's 2D system is like a quantum computer chip.





states of 2 bits:  4 possibilities

some states of 2 qubits:

100%/0/0/0 

30/20/30/20 

50/0/0/50 

0/70/30/0 

many possibilities

states of 2 bits:  4 possibilities

some states of 2 qubits:

100/0/0/0 30/20/30/20 50/0/0/50 0/70/30/0

many possibilities

most states have ENTANGLEMENT:
neither bit in definite state but states are correlated.

Examples of entanglement:

superposition of

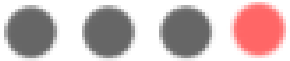
50% 

and

50% 

will always find first bit on/off ; if second bit on/off

superposition of

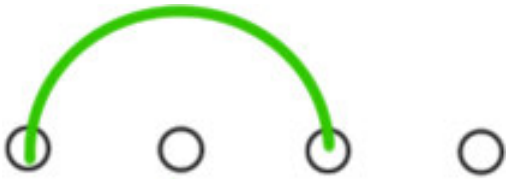
50% 

and

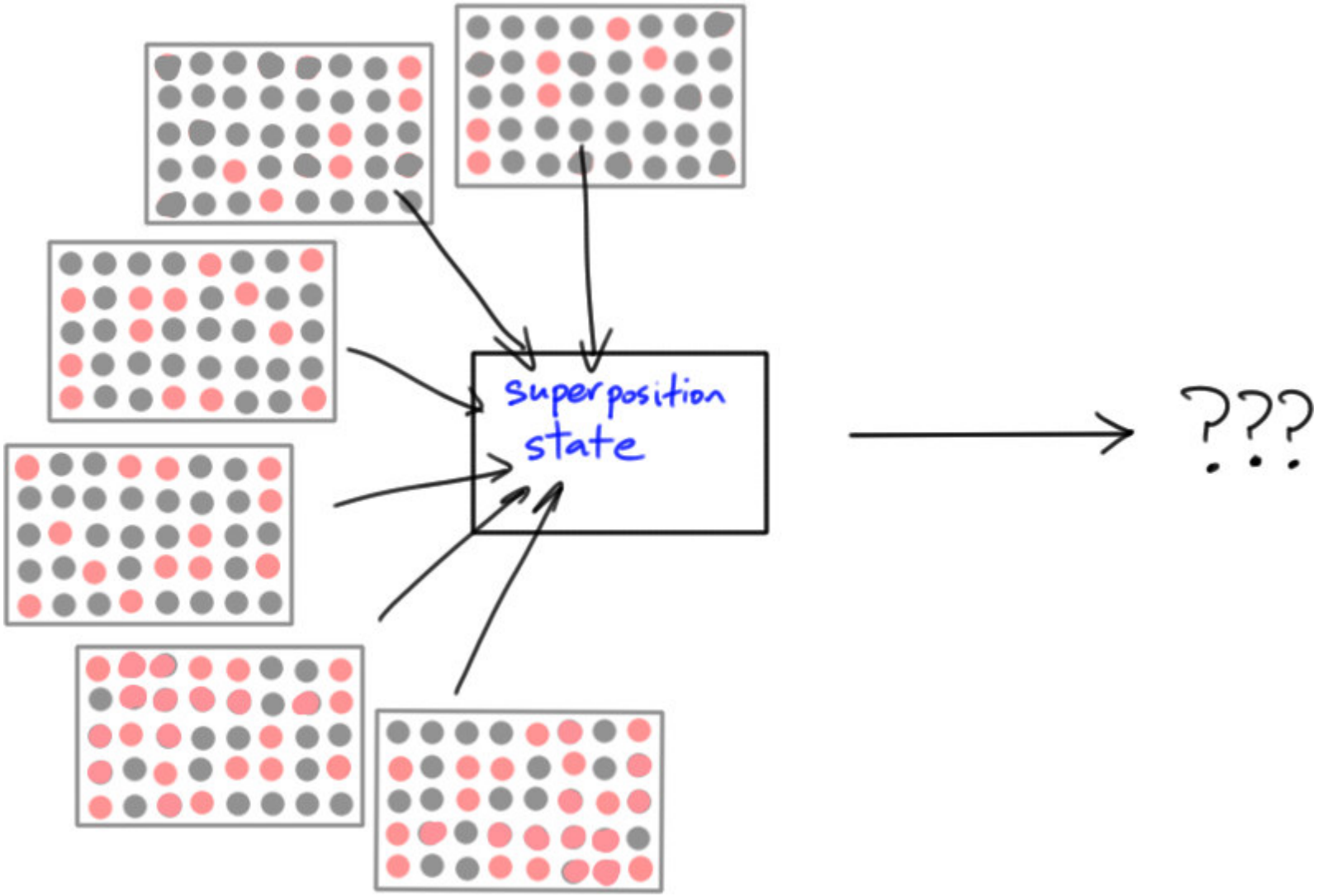
50% 

1st and 3rd bits are entangled

represent as

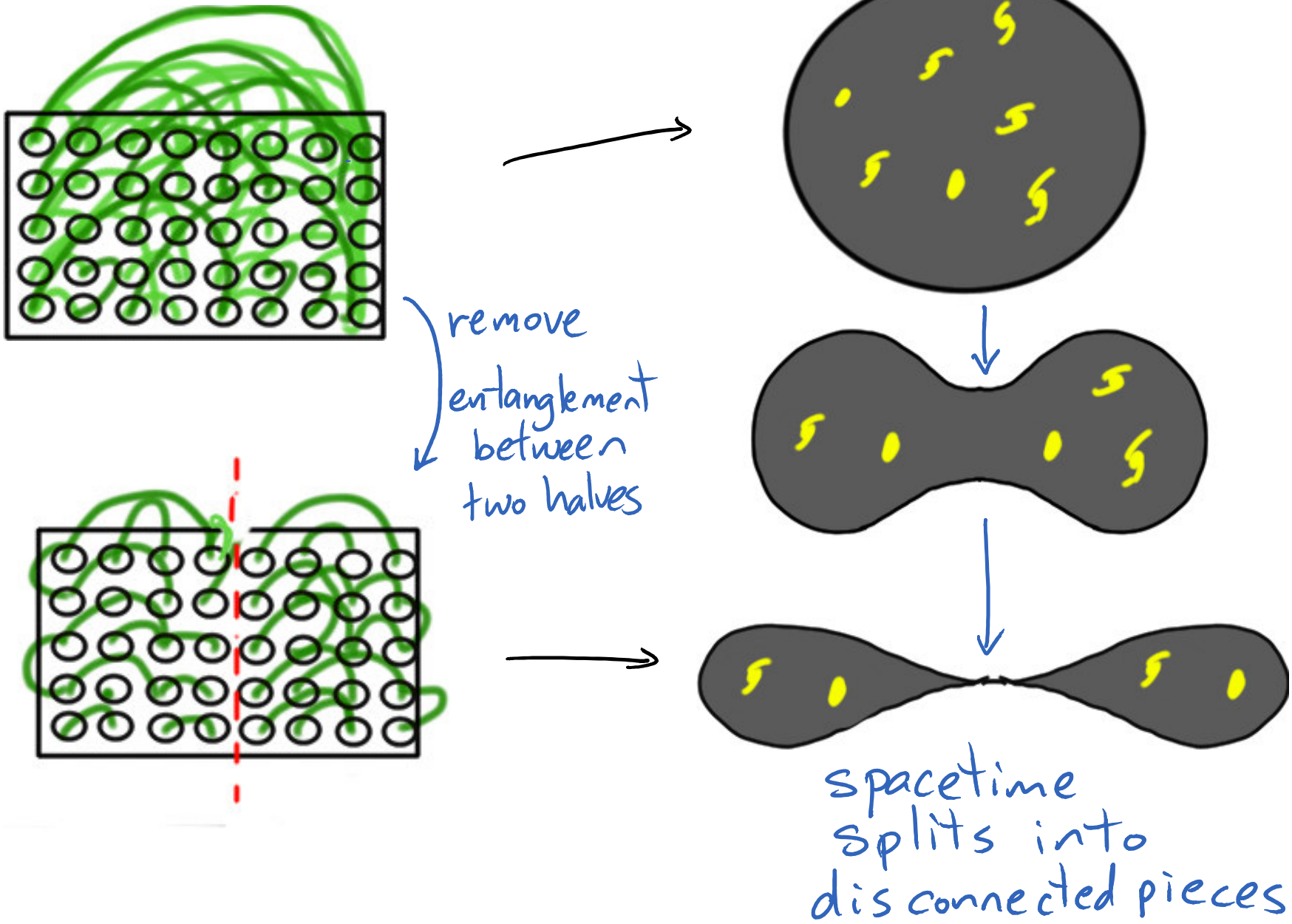


Q: How is geometry/shape of space encoded in the quantum memory chip?

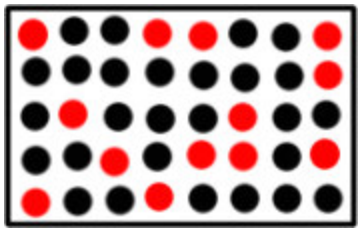


Recent work: seems to be encoded in ENTANGLEMENT

Ryu-Takayanagi:



"Classical" state
with no superposition



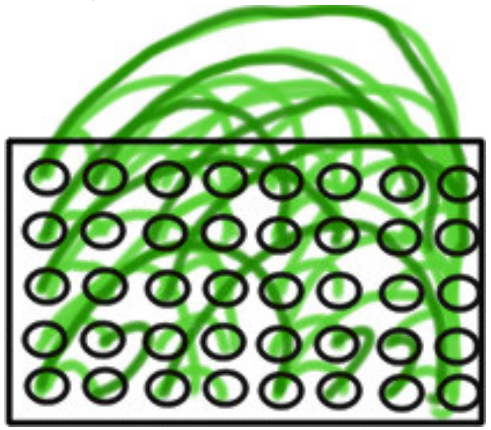
no entanglement →

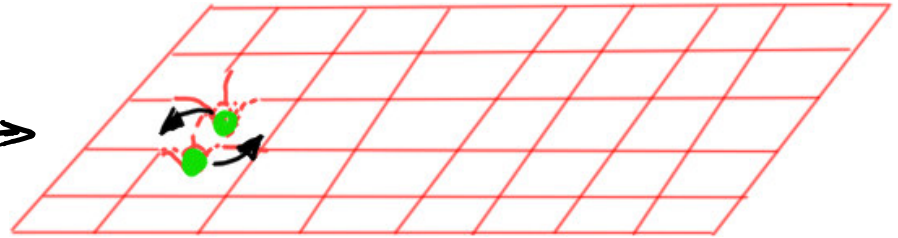
no spacetime at all.

Quantum mechanics underlies even classical gravity!

According to this model, quantum entanglement is the "fabric of spacetime"

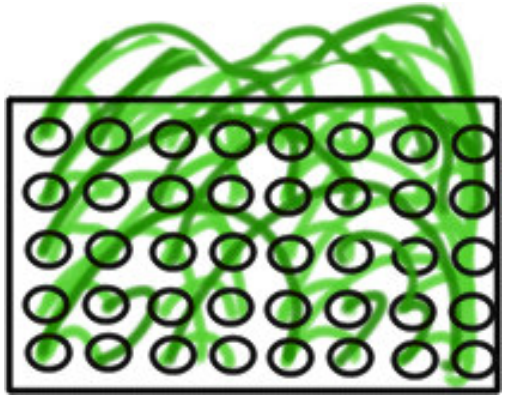
All of this can be made quantitative

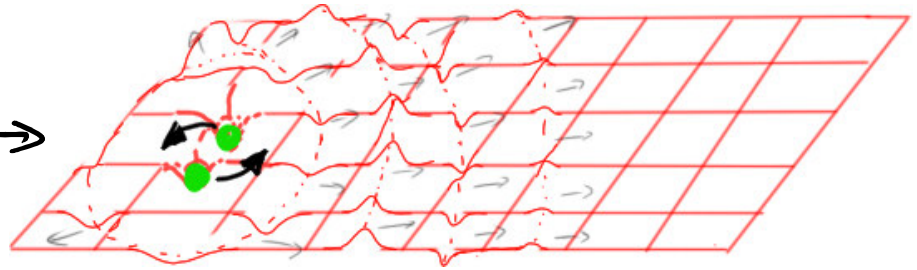




Quantum rules

EINSTEIN'S EQUATIONS

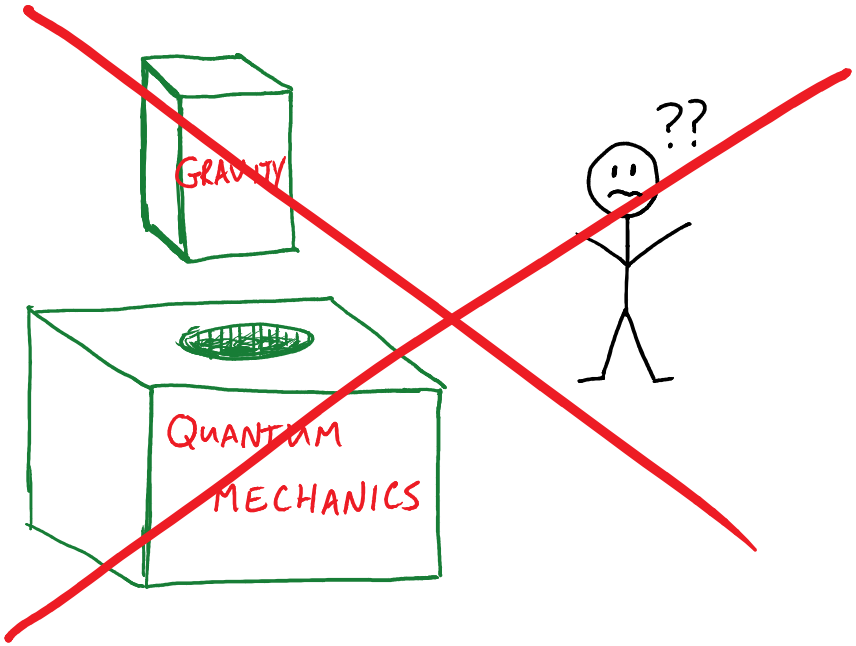


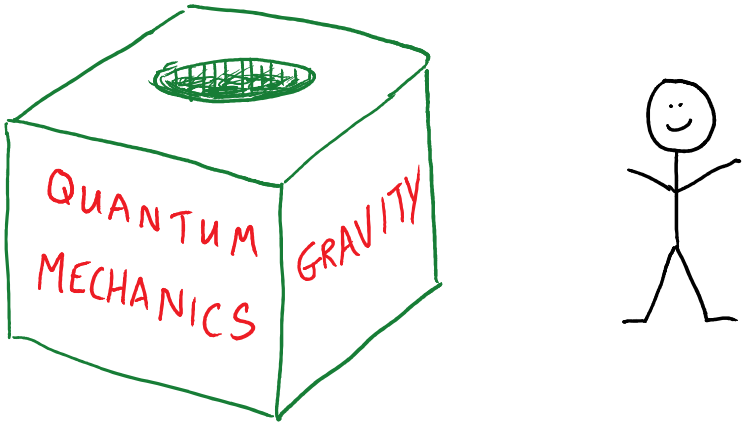


gravitational waves

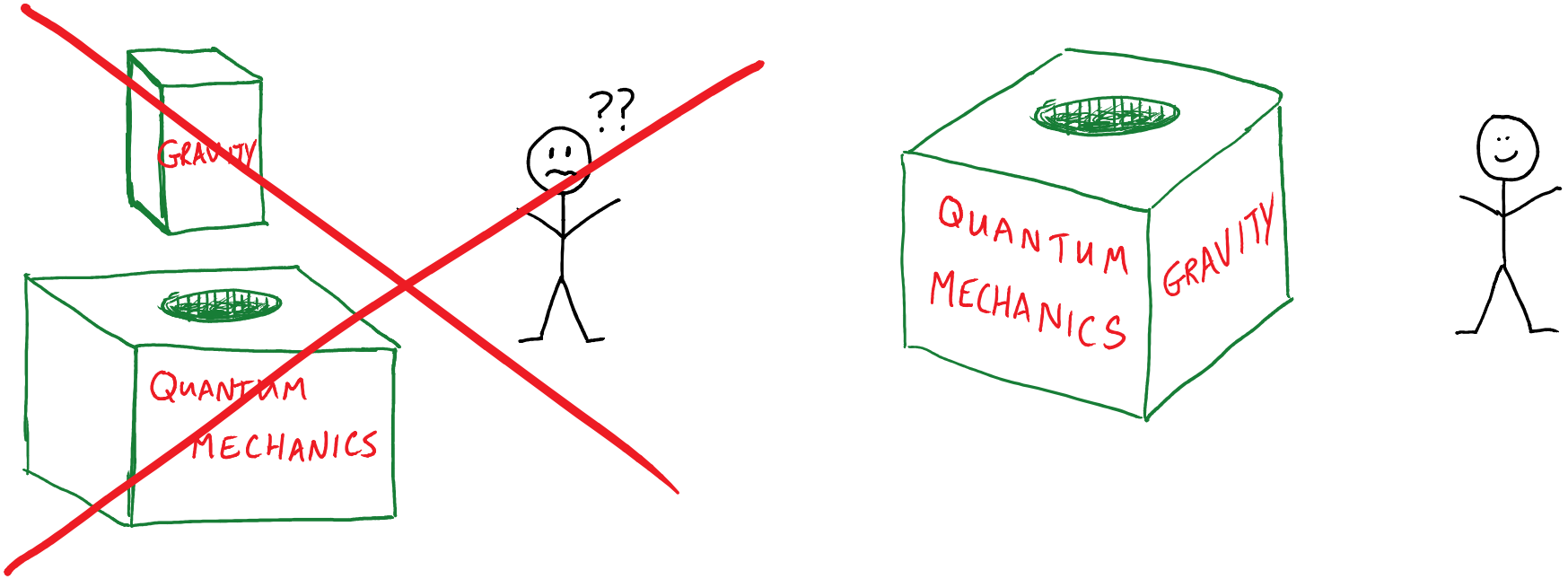
* Can derive (weak gravity) Einstein's Equations from entanglement physics

Summary





Summary



Ongoing: still need to understand code better to answer some questions about black holes

- need to generalize to say something about "big bang"