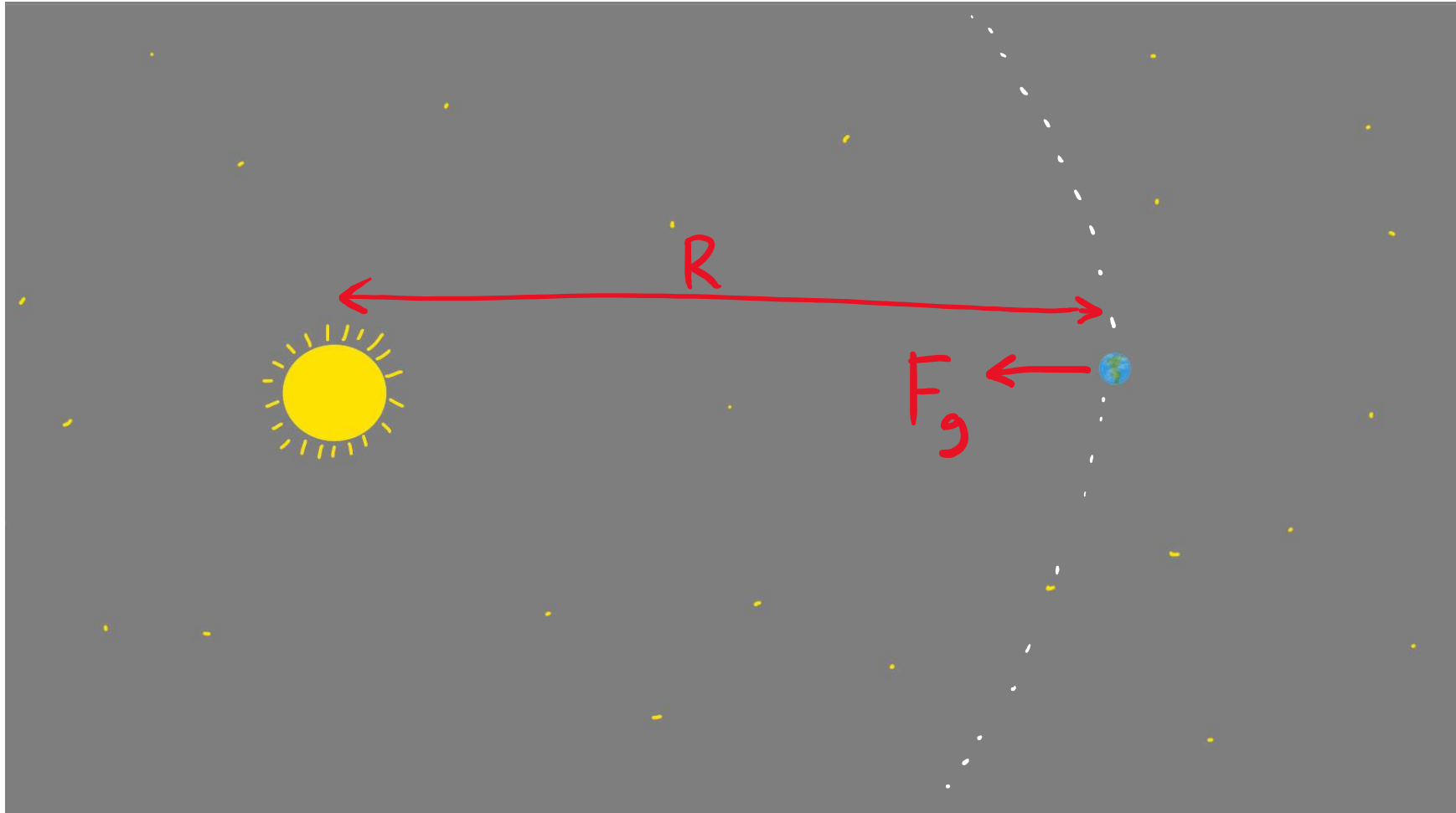


EINSTEIN'S GRAVITY, BLACK HOLES, AND OSCILLATIONS OF SPACETIME

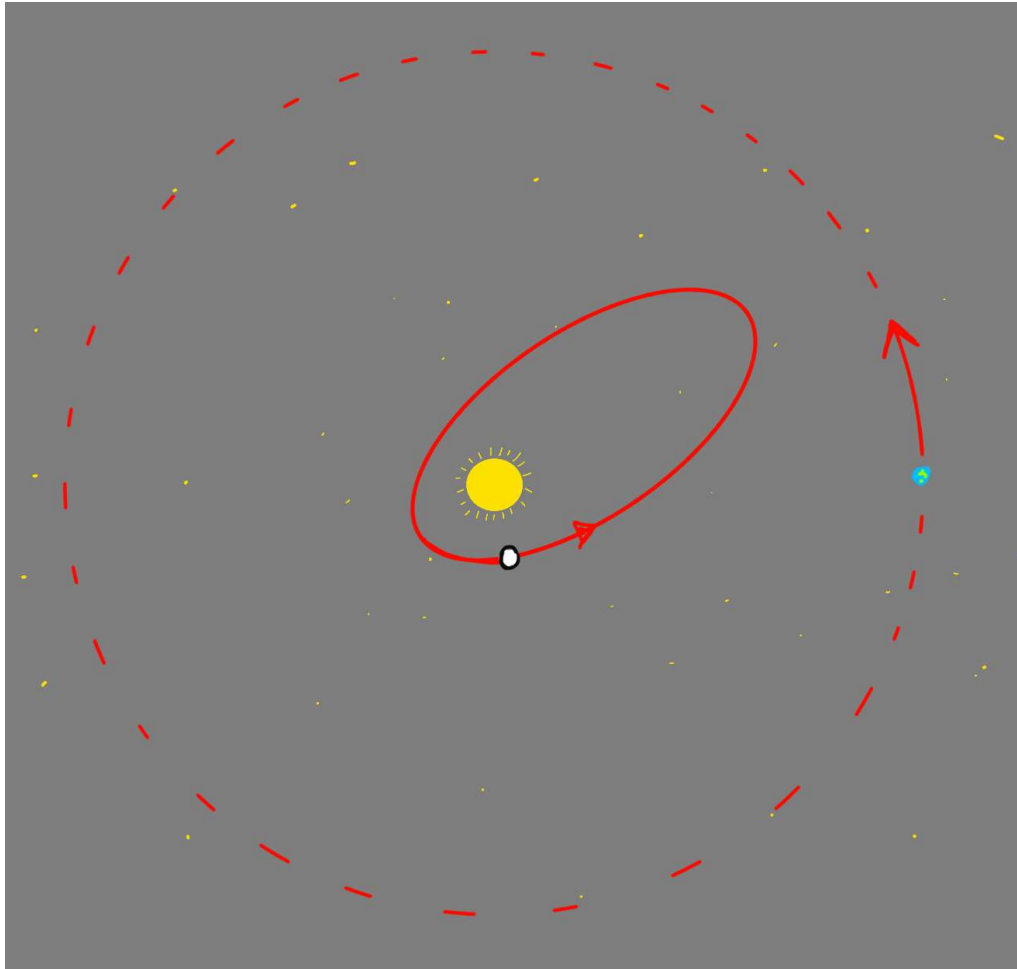
Gravity according to Newton: $F_g = G \frac{Mm}{R^2}$



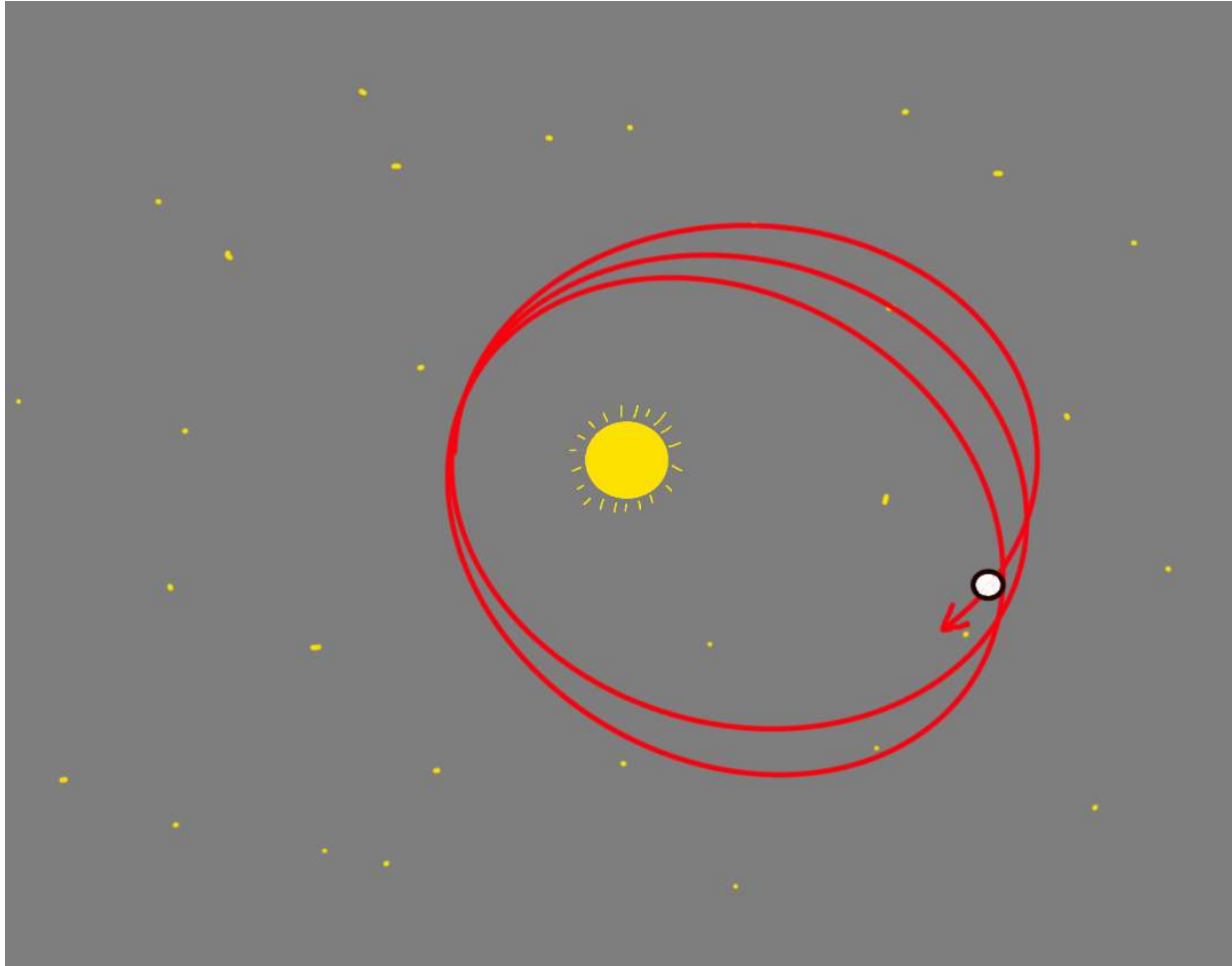
Gravity according to Newton:

$$F_g = G \frac{Mm}{R^2}$$

Predicts elliptical
orbits

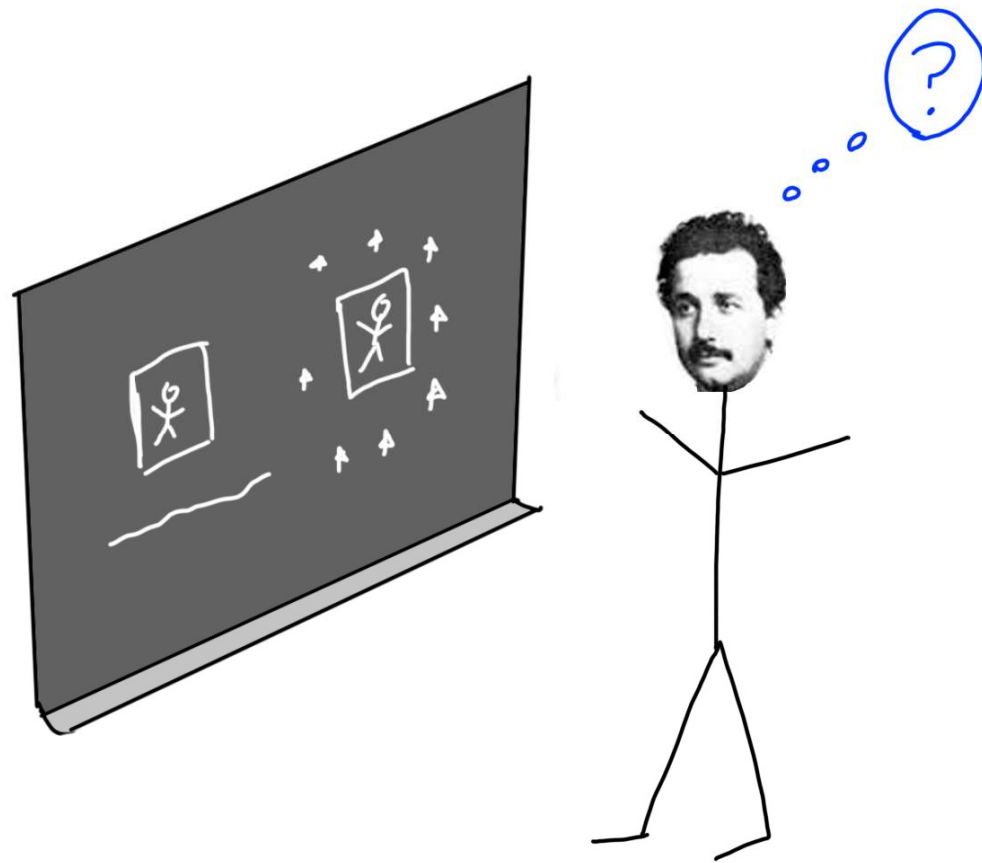


Actual orbit of mercury

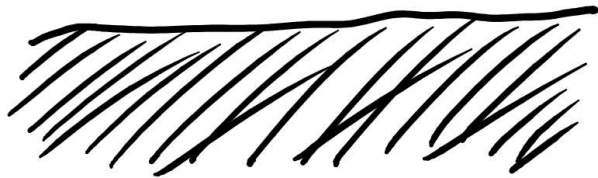
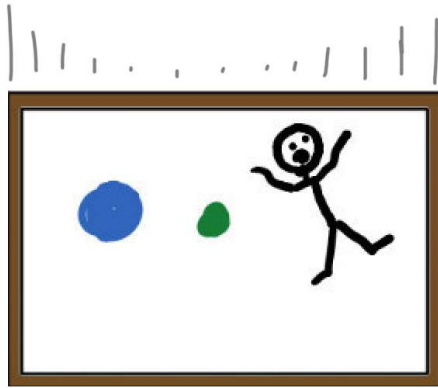


★ couldn't be explained using Newtonian gravity★

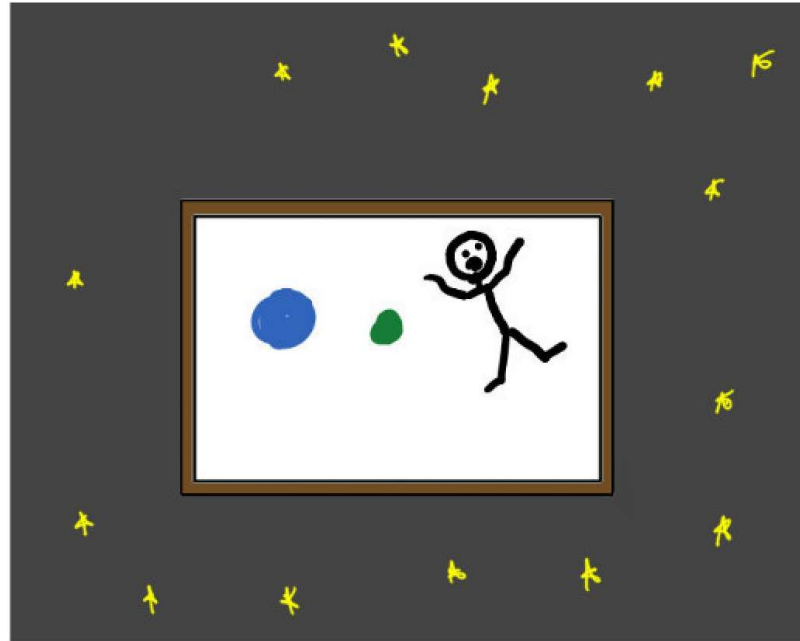
Meanwhile...



Weird fact: can't tell difference between free fall and situation with no forces...

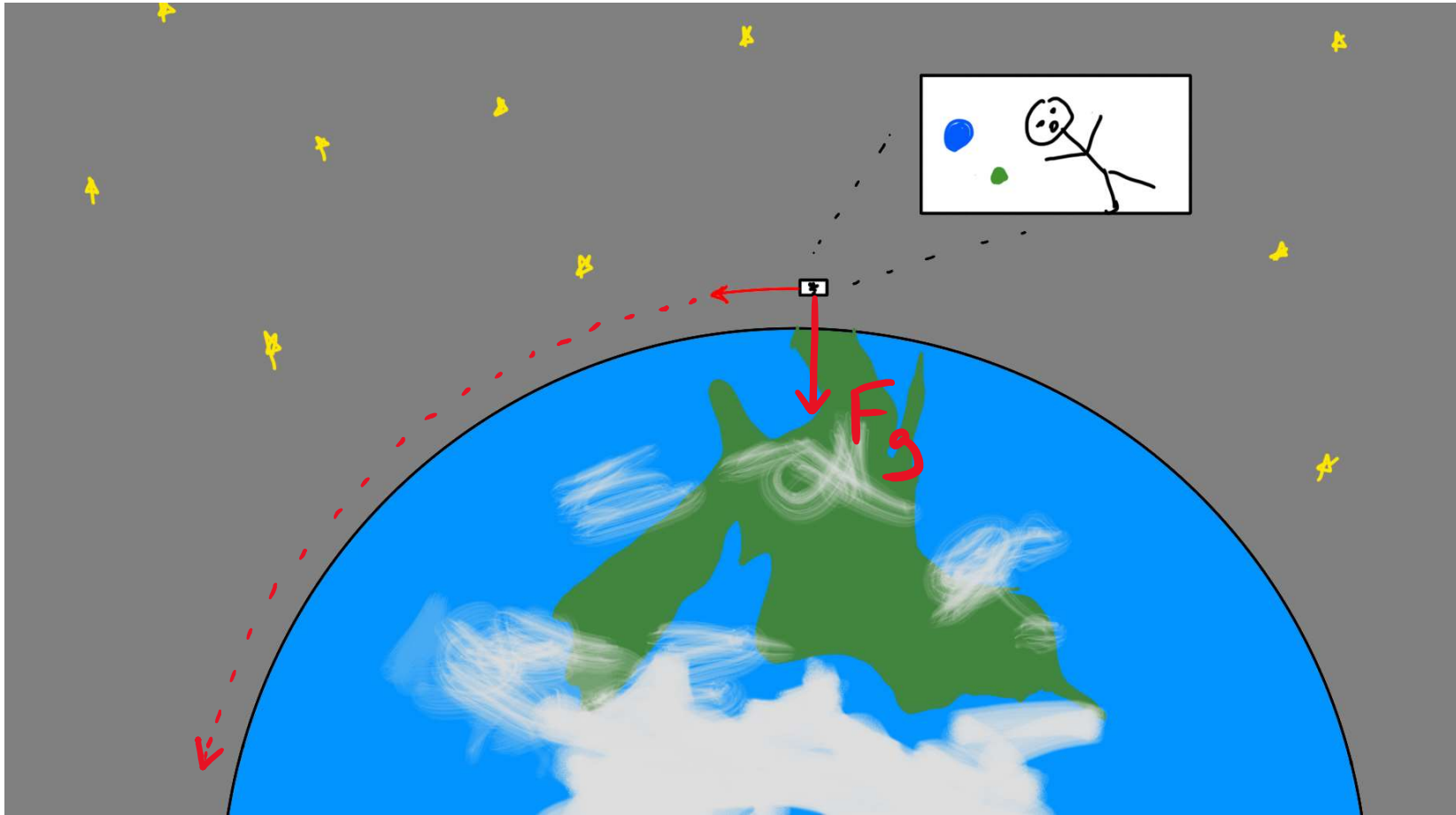


Free fall

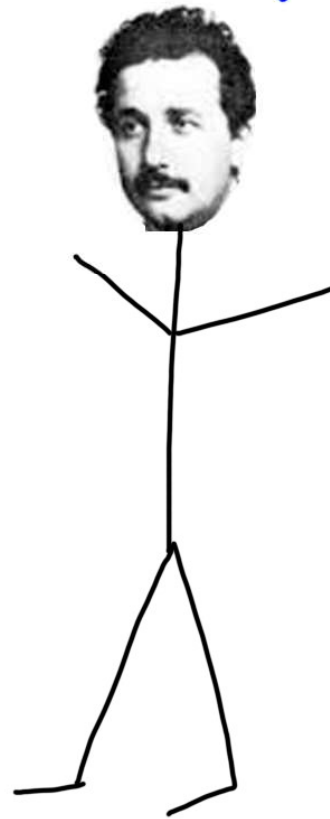
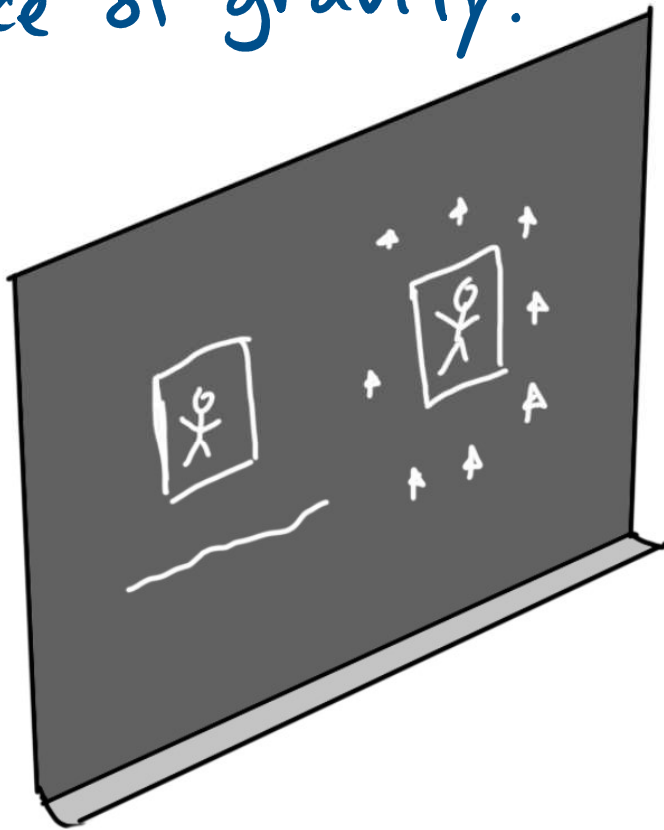


Outer space

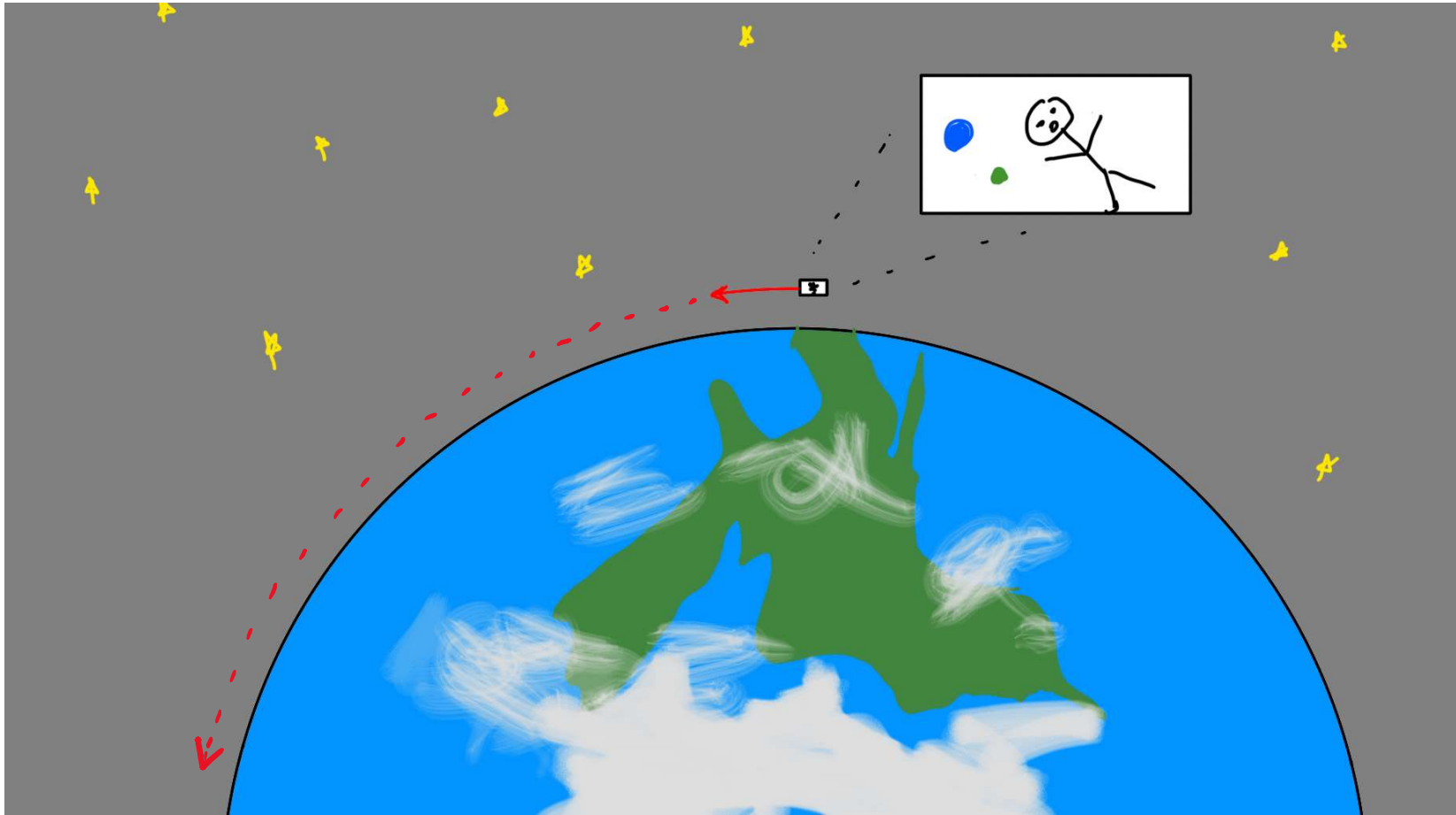
Why don't we feel gravity in space near the Earth?



Einstein: maybe there is no
force of gravity!



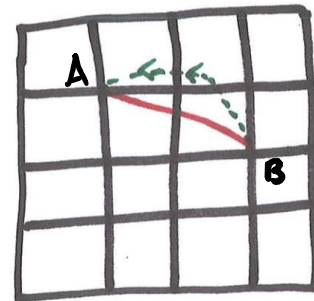
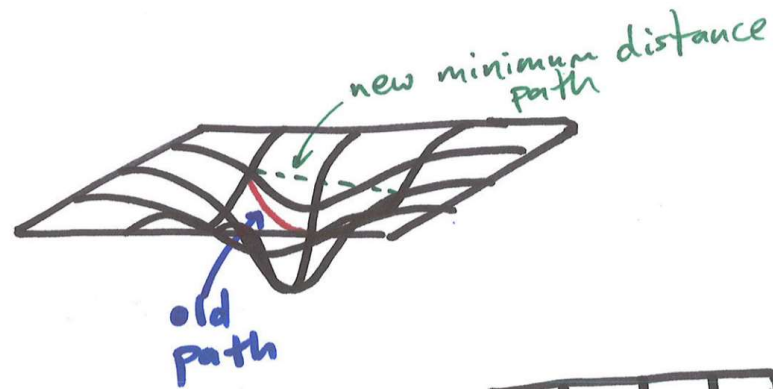
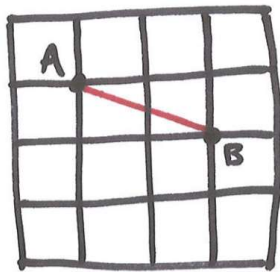
New puzzle: if no force of gravity, why don't objects near the Earth just move in a straight line.



Newton's 1st Law: In the absence of forces, objects will move in a straight line with a constant velocity.

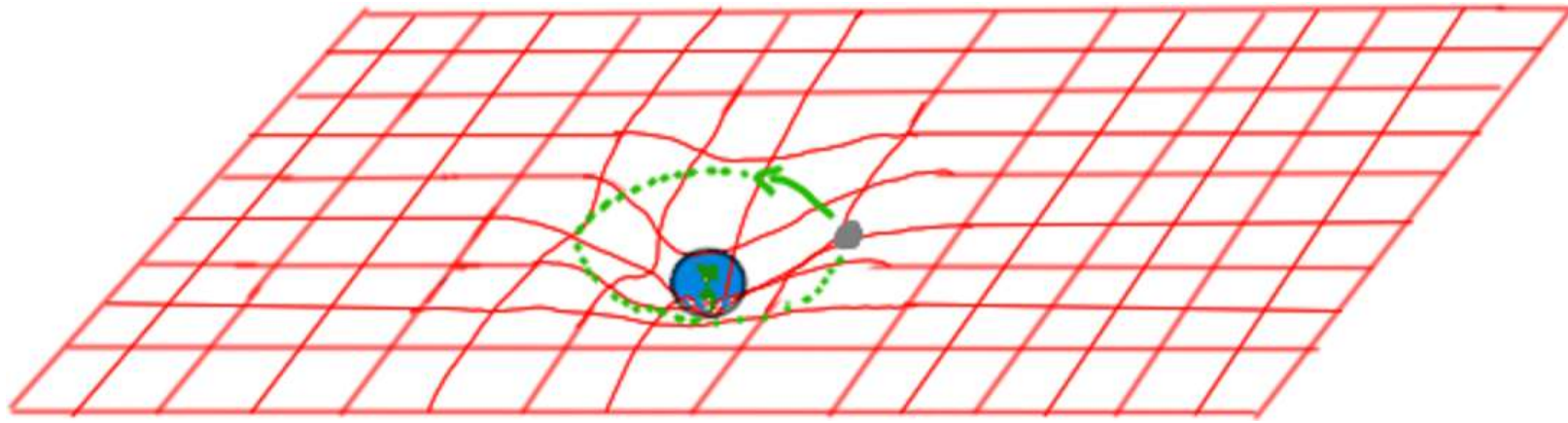
Einstein: Maybe the objects are trying to move straight, but the space is curved!

Curved space:



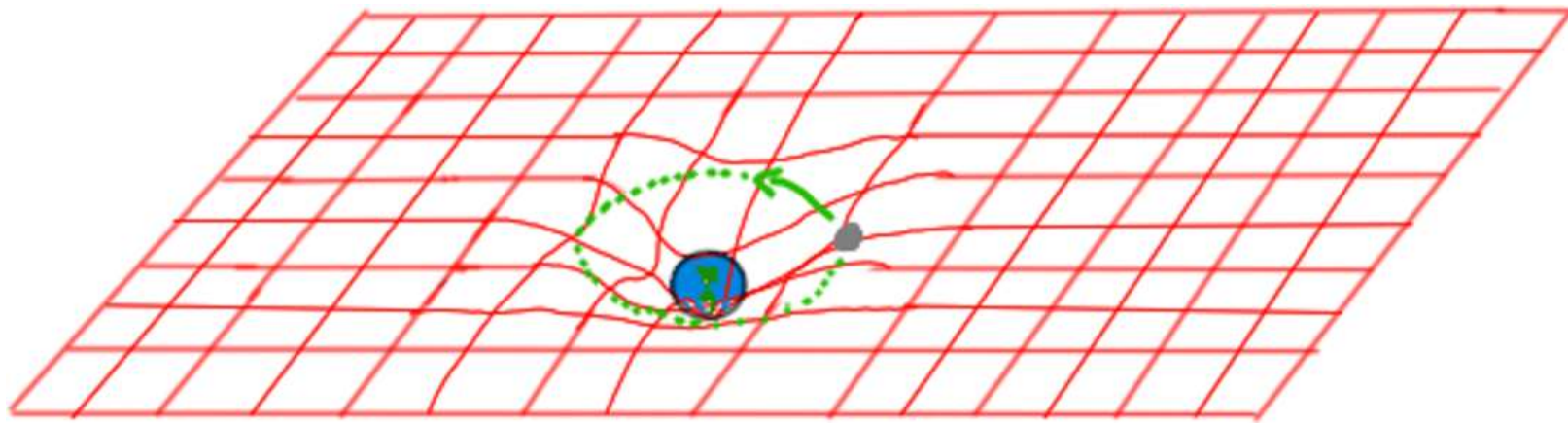
Gravity according to Einstein:

"General Relativity"



- * Matter + energy cause space to bend/warp
- * Effects of gravity explained by objects moving on natural paths in this curved space

Gravity according to Einstein:

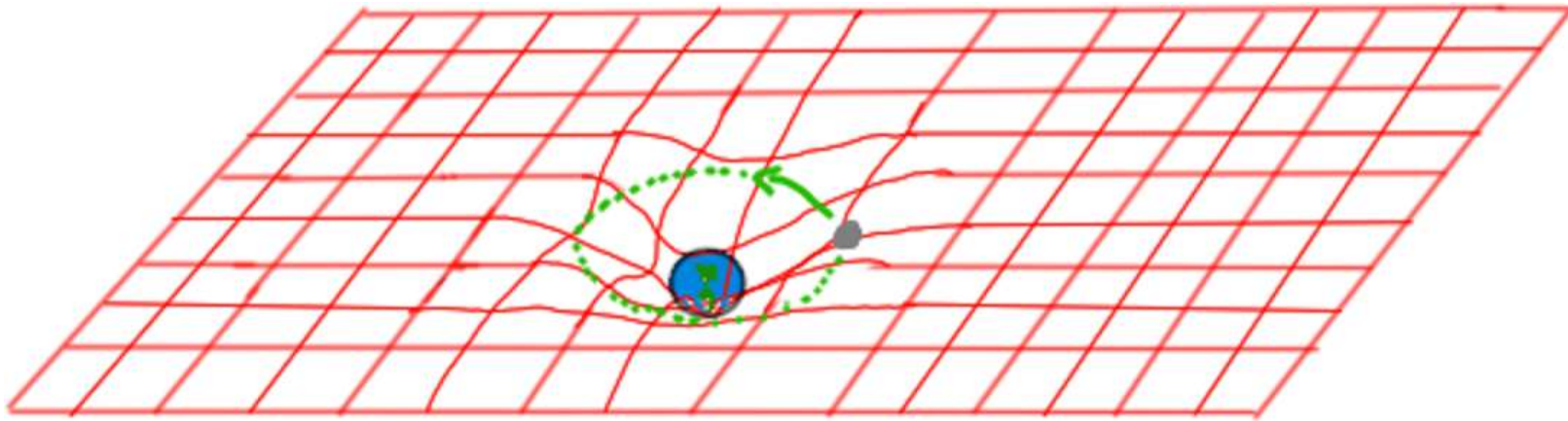


Einstein's equation: $G_{\mu\nu} = 8\pi G_N \cdot T_{\mu\nu}$

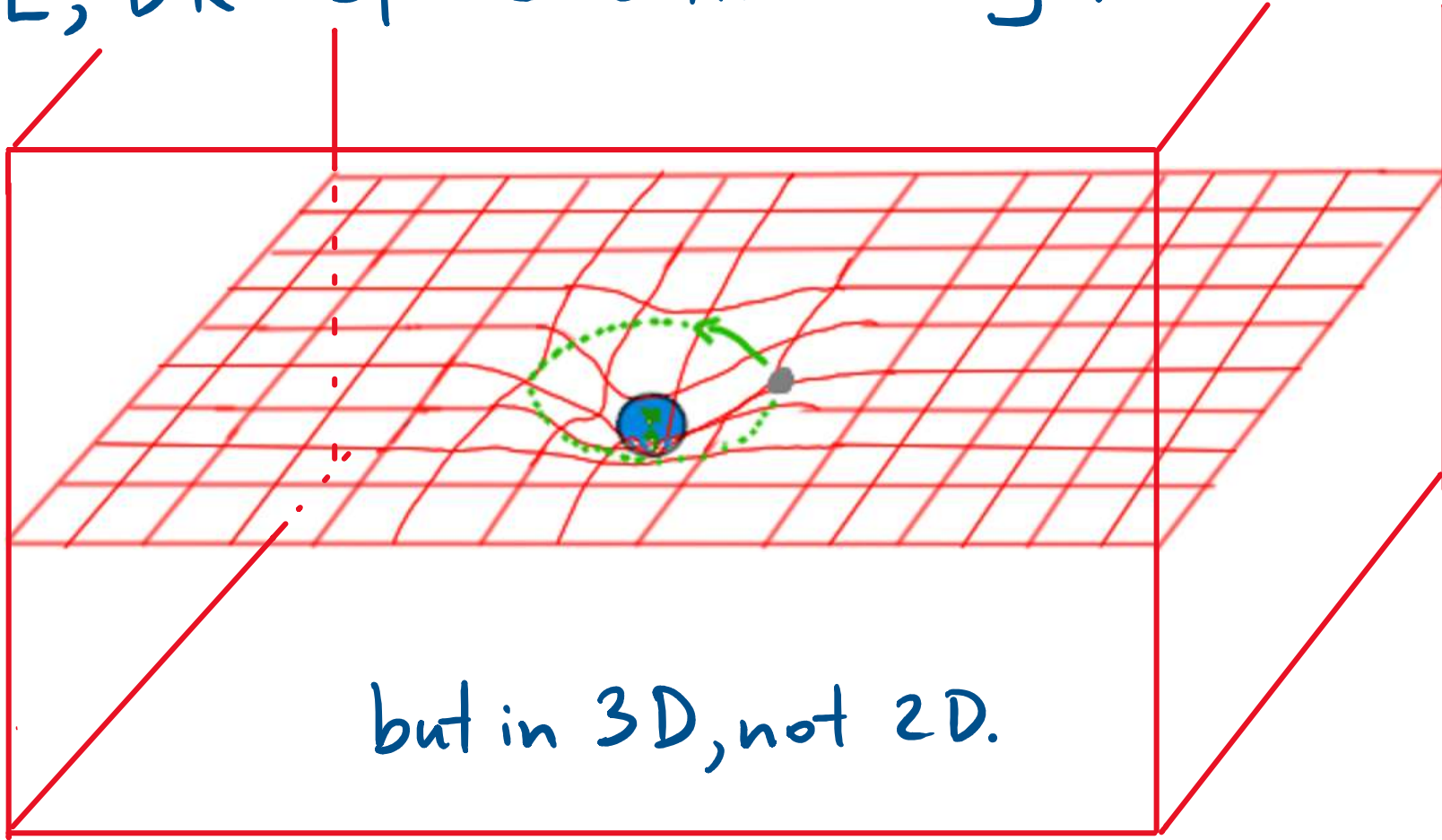
describes curvature of space Newton's constant. describes density of matter

Describes dynamics of spacetime + interaction with matter

TL; DR : space is like a big rubber sheet

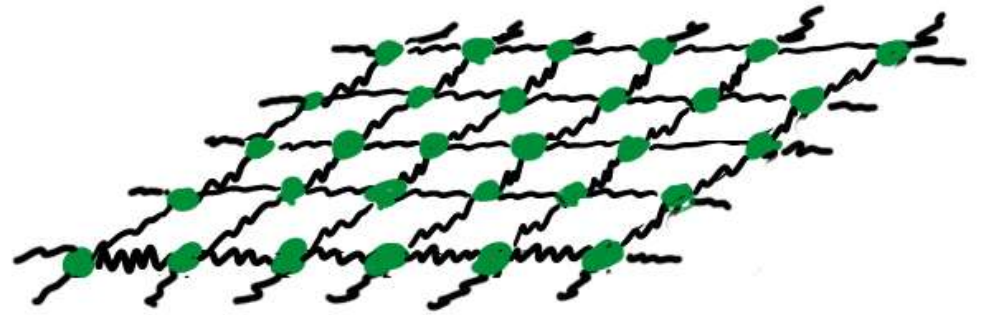
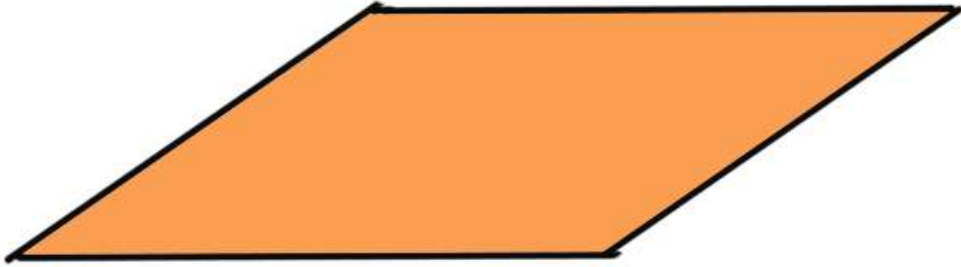


TL; DR : space is like a big rubber sheet,

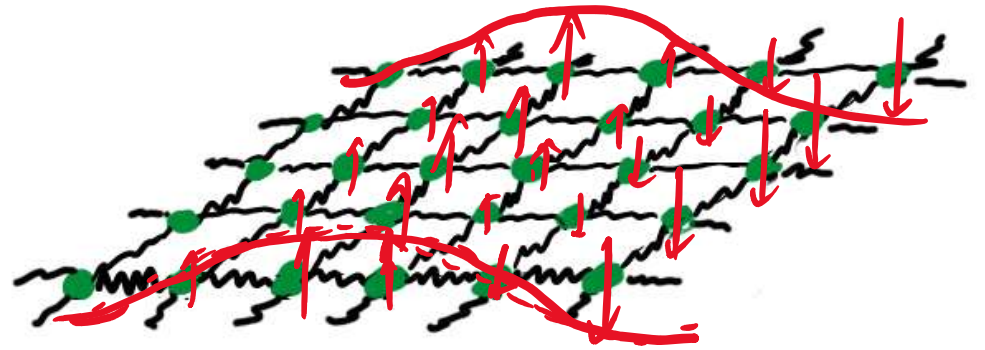
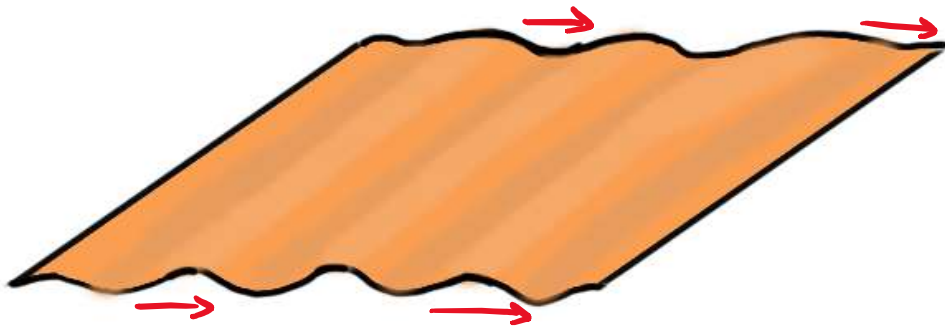


but in 3D, not 2D.

Actual rubber sheet: model by coupled oscillators



Actual rubber sheet: model by coupled oscillators



can have travelling waves

Can space itself oscillate
and have waves?

Can space itself oscillate
and have waves?

Einstein's equation says yes!

$$G_{\mu\nu} = 8\pi G_N \cdot T_{\mu\nu}$$

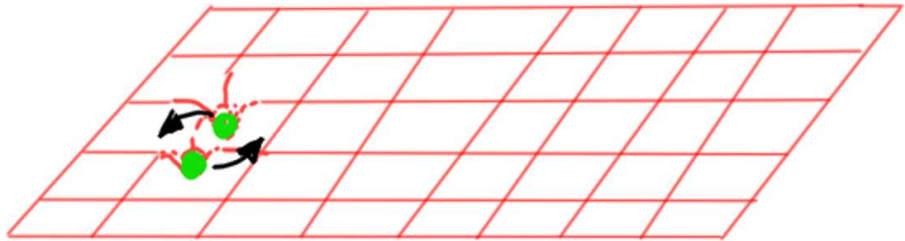
→ for small ripples,
gives same math
as waves in a solid!

How do we drive this oscillation?

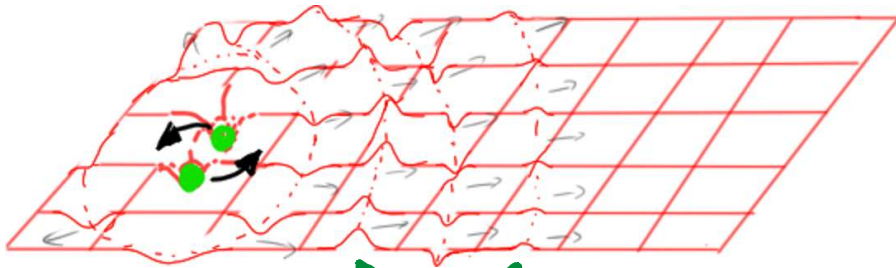
How do we drive this oscillation?

★ oscillating matter system!

GRAVITATIONAL WAVES



oscillating matter system
e.g. stars orbiting

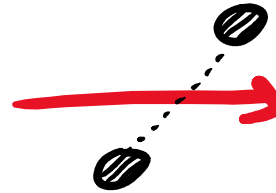


energy carried
away by ripples of space/time

Can we observe these gravitational waves?

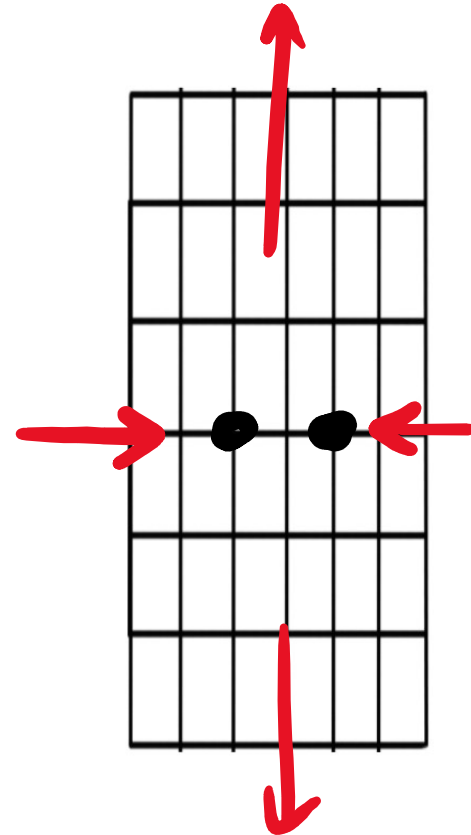
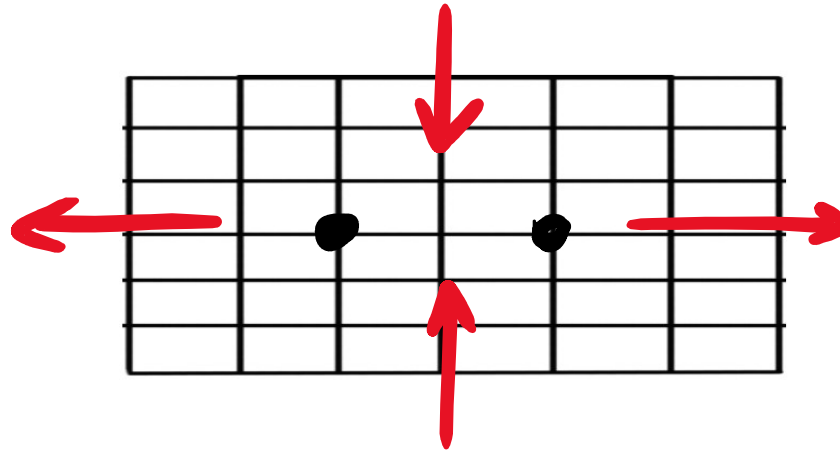
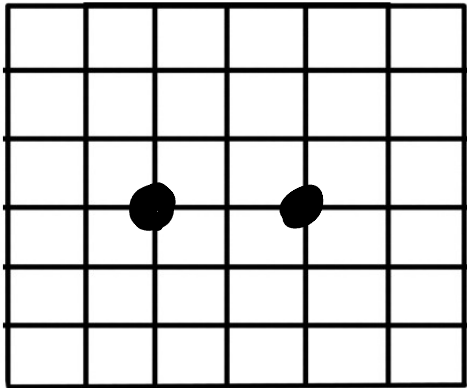
How would we detect them?

gravitational
wave direction

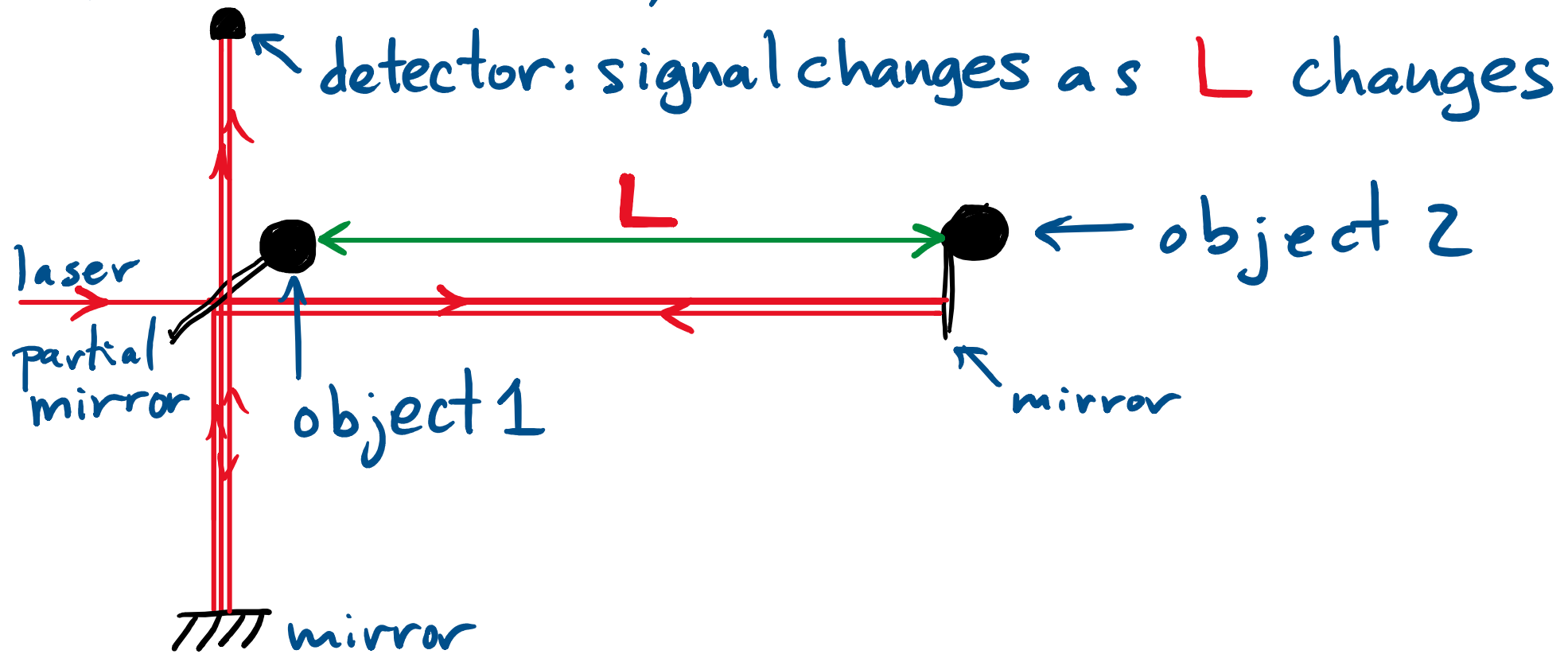


distance oscillates
as gravitational
wave passes.

Head on view



LIGO experiment : try to measure these changes in distance directly using "interferometer"



Most gravitational waves too small to measure.

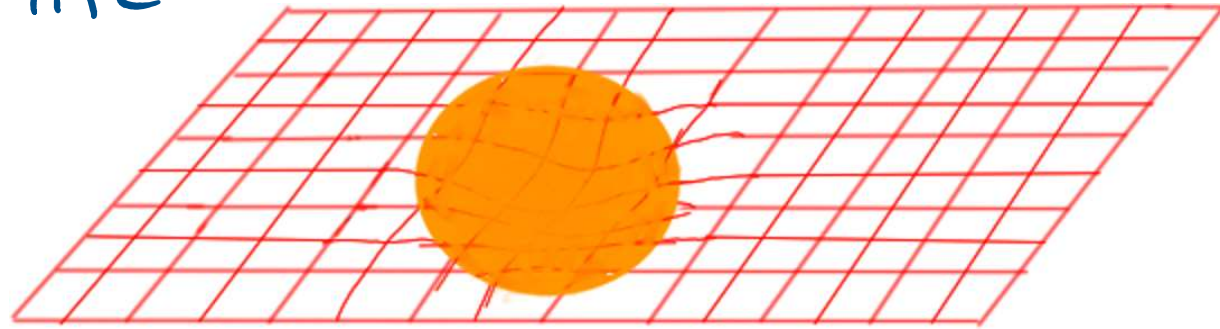
What is the strongest source?

Most gravitational waves too small to measure.

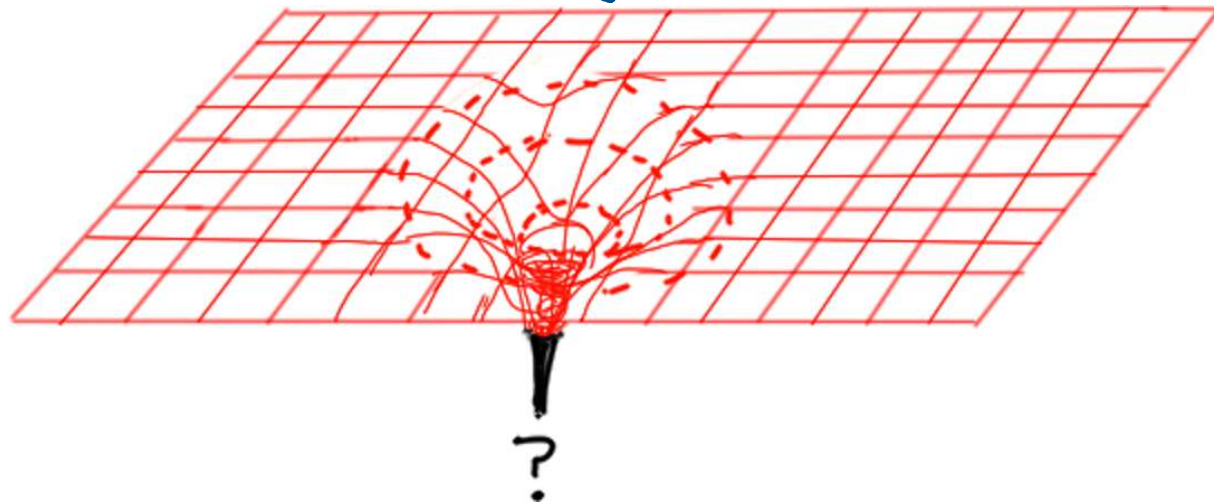
What is the strongest source?

black holes!

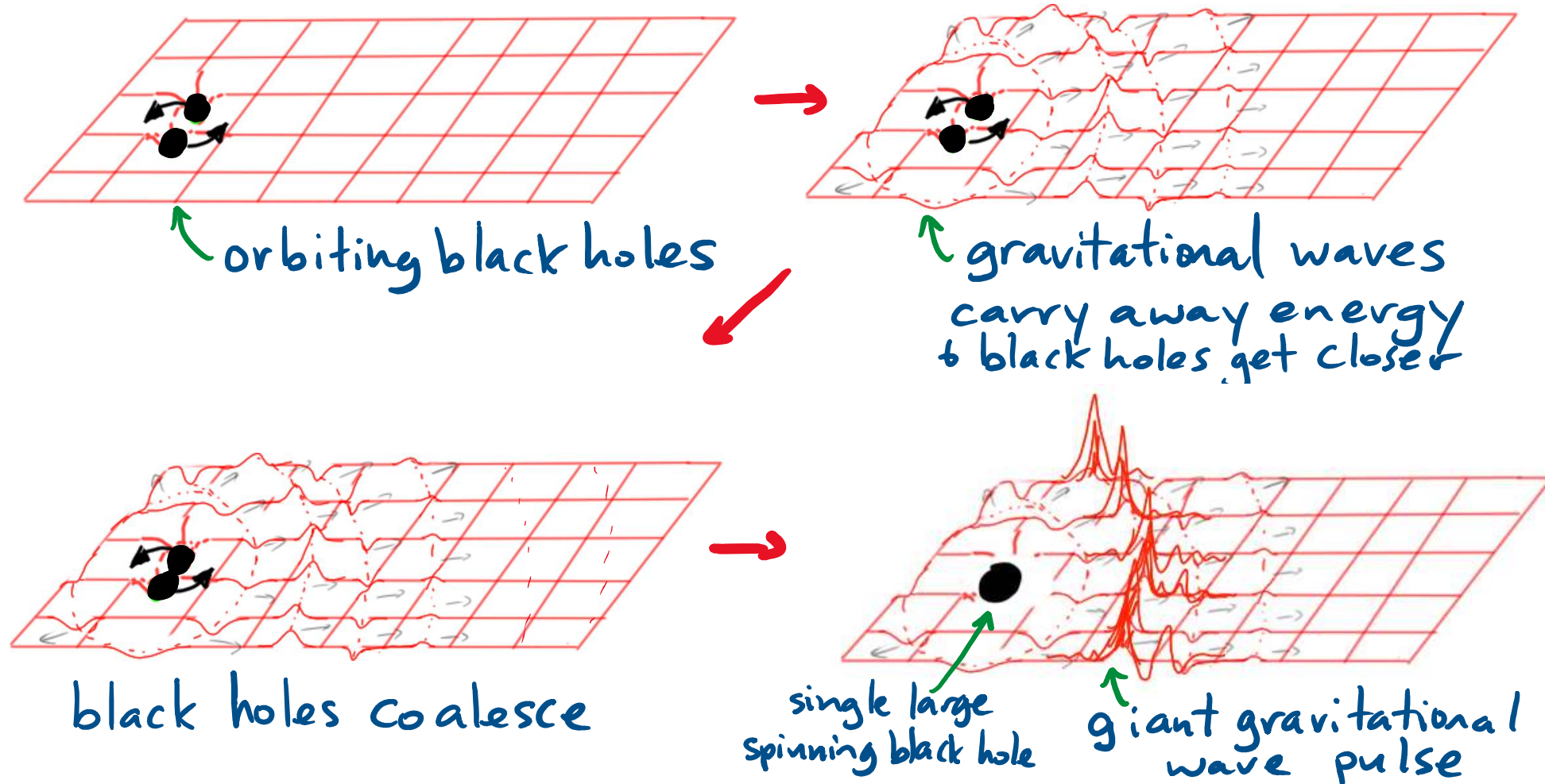
BLACK HOLES: largest stars have unbounded collapse
at end of life

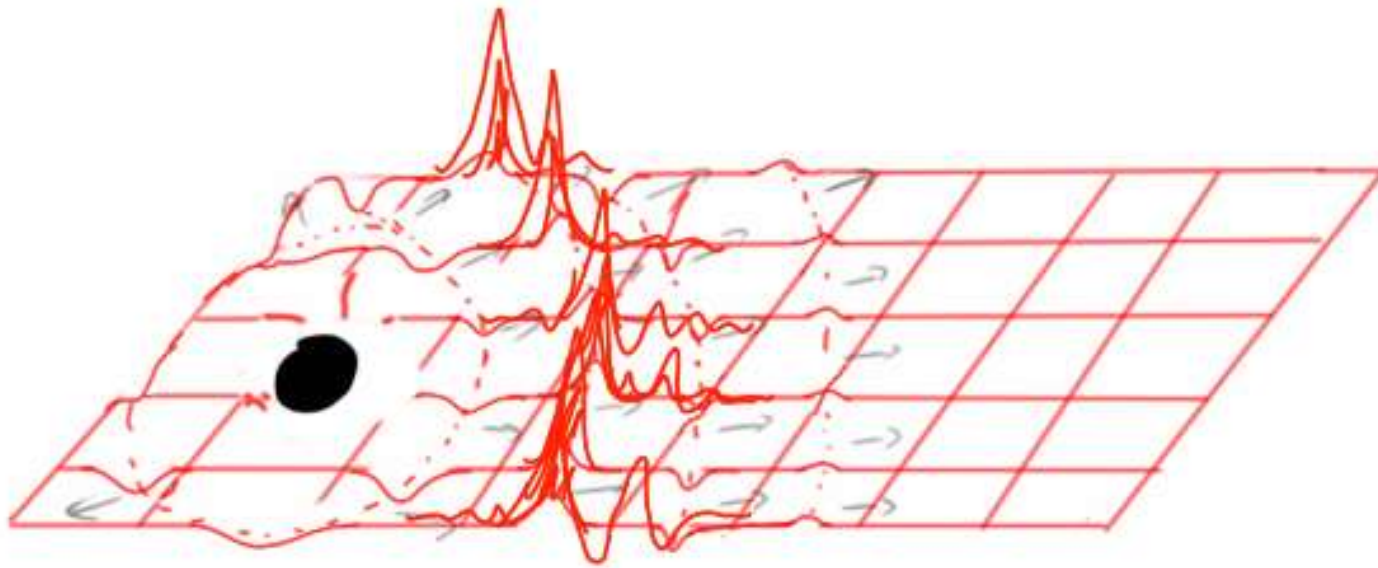


Einstein's equations



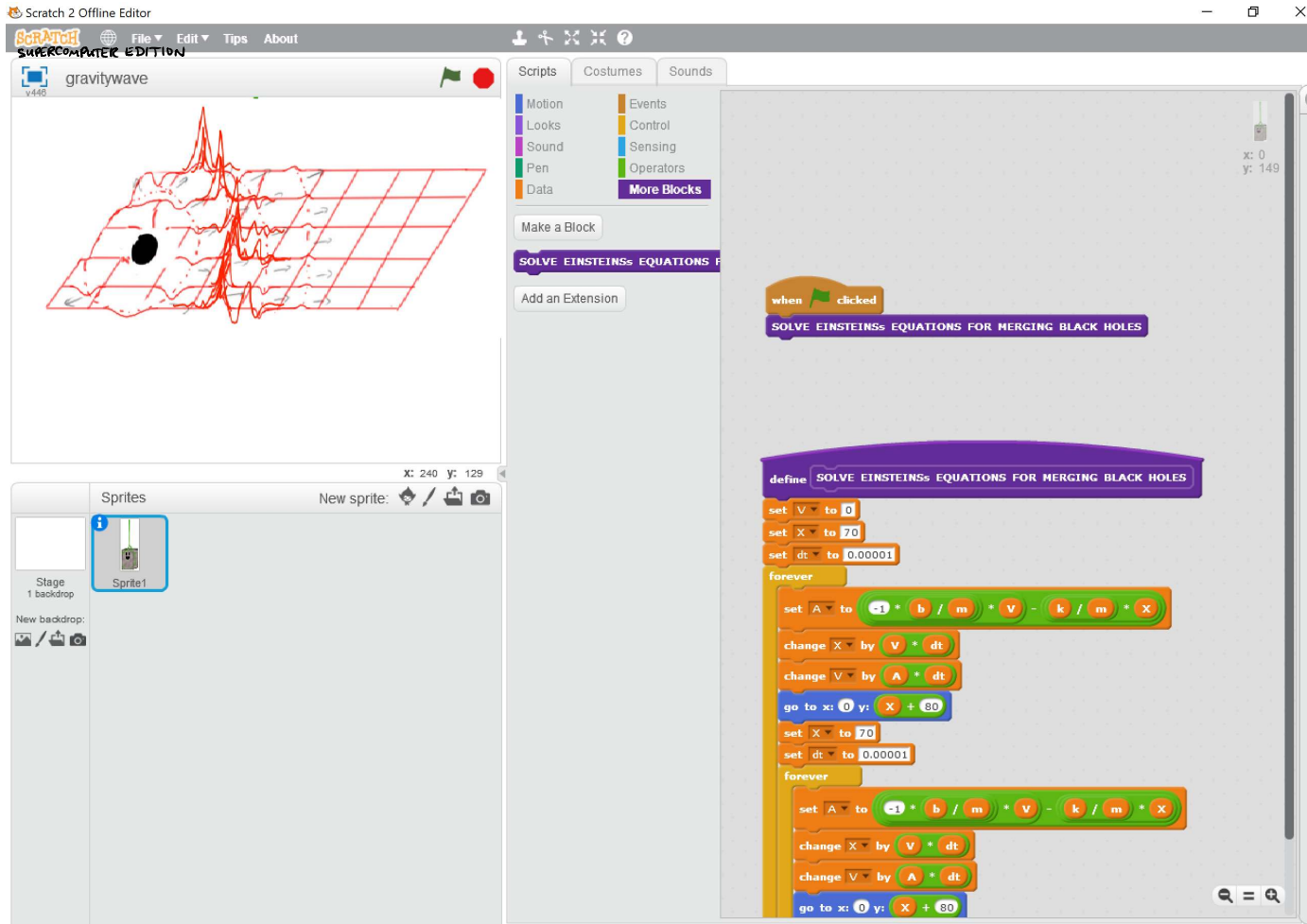
GRAVITATIONAL WAVES





Shape of this wave pulse
determined by Einstein's
equations

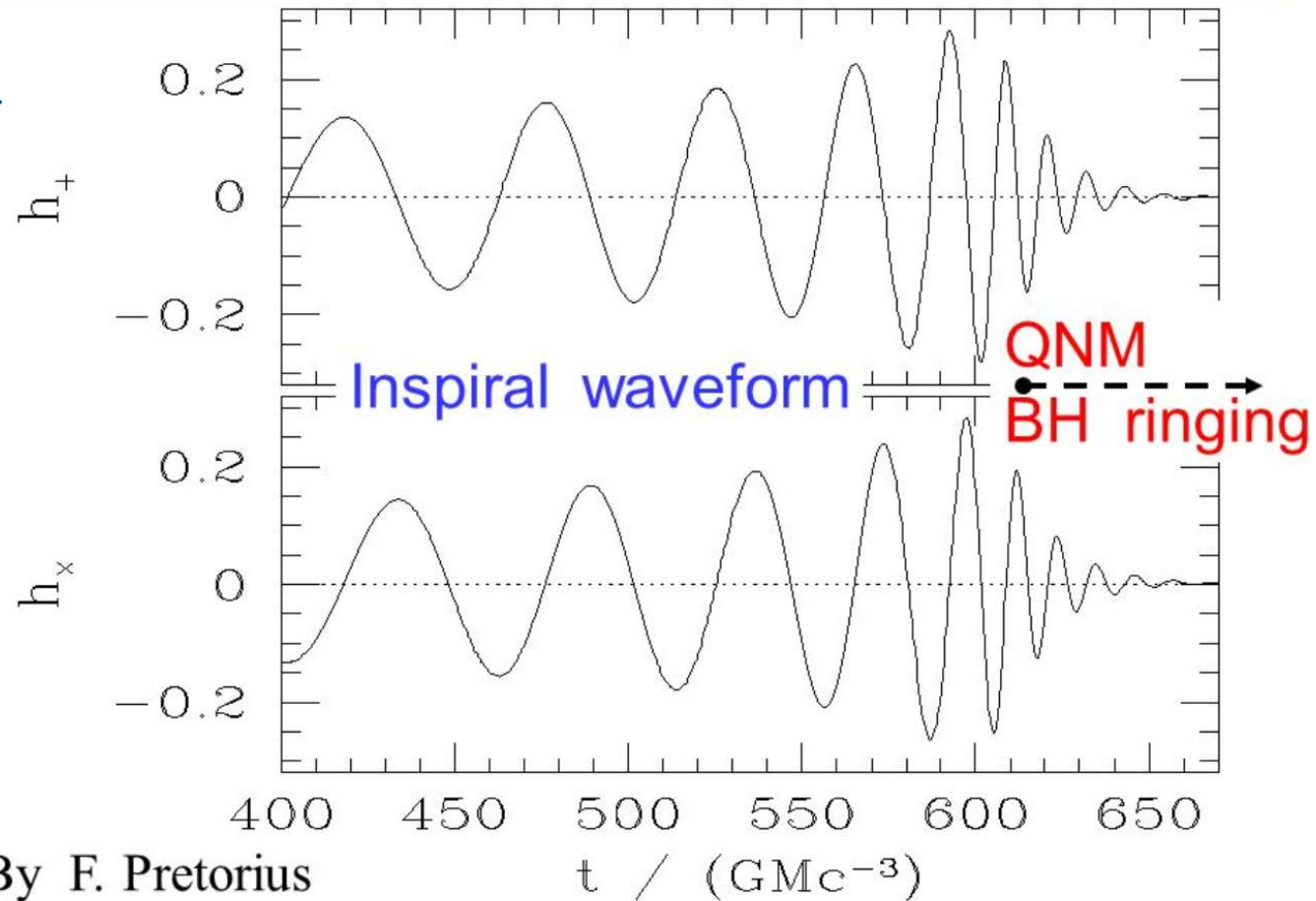
★ Need to simulate via supercomputer ★



Prediction:

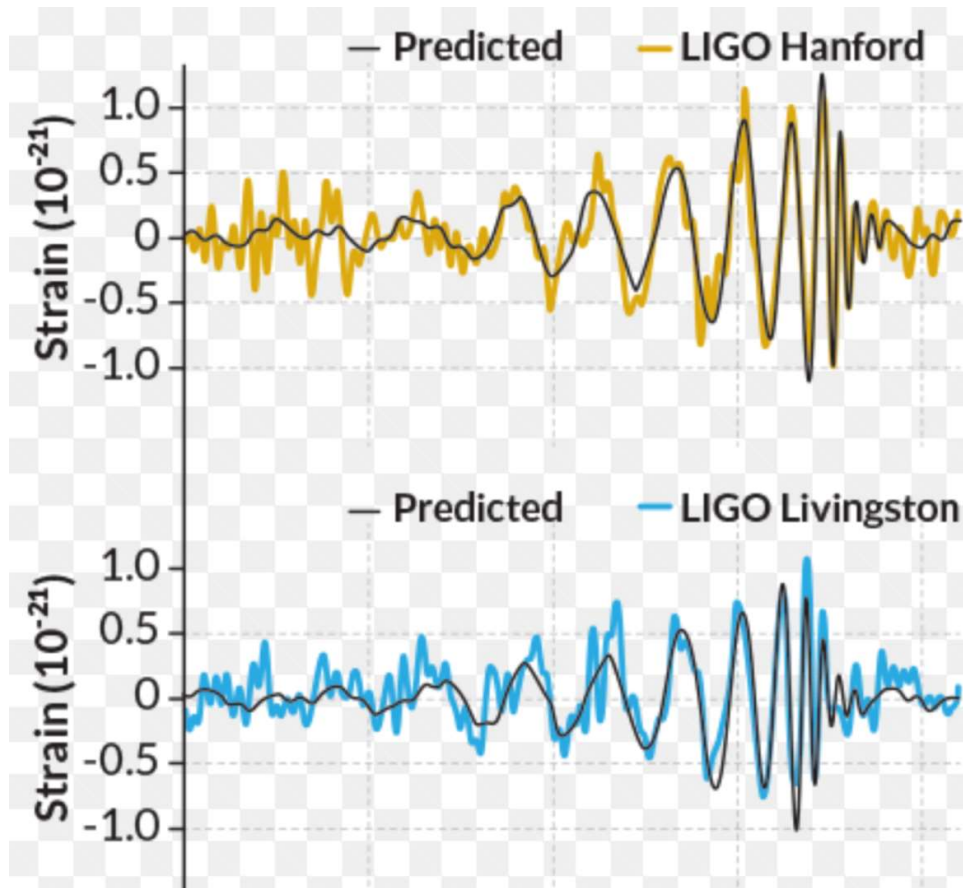
Gravitational waves from BBH merger

- Shape depends on
black hole
masses
amount of
rotation



Observed signal: September 14th, 2015

(reported 2016)



detectors at
different location

excellent
match to
wave shape
for

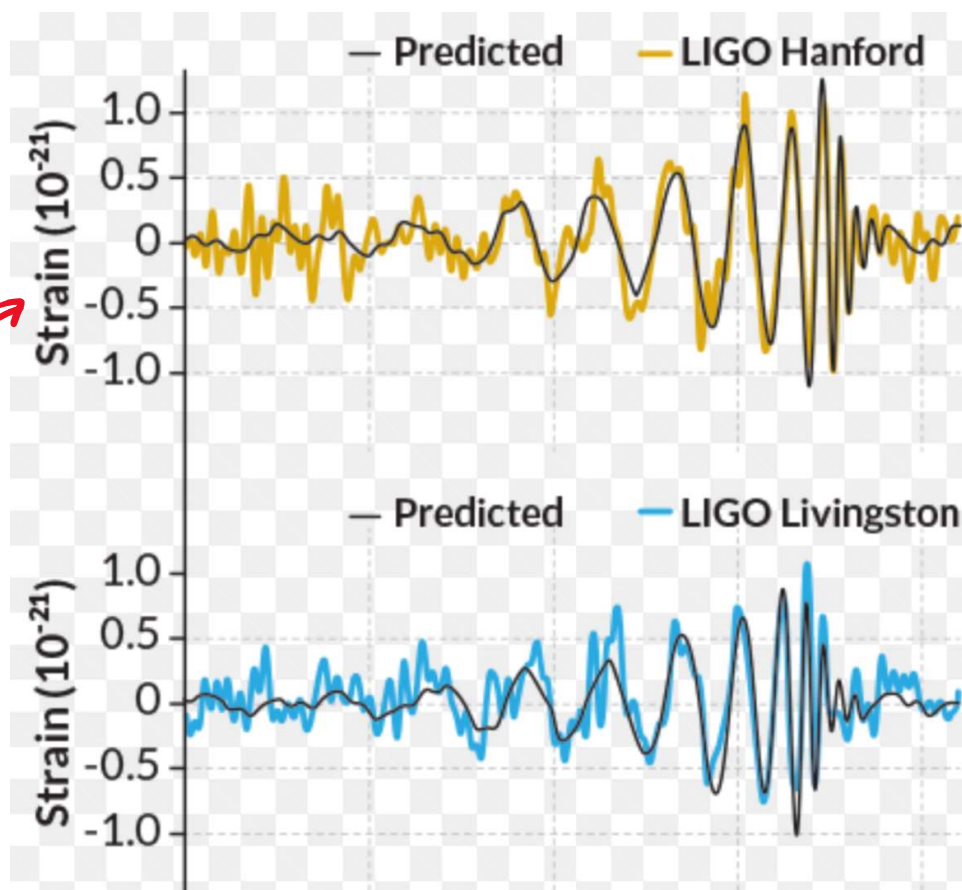
$$M_1 = 36 M_{\text{sun}}$$

$$M_2 = 29 M_{\text{sun}}$$

Amplitude:



$$\frac{\Delta l}{l_0}$$

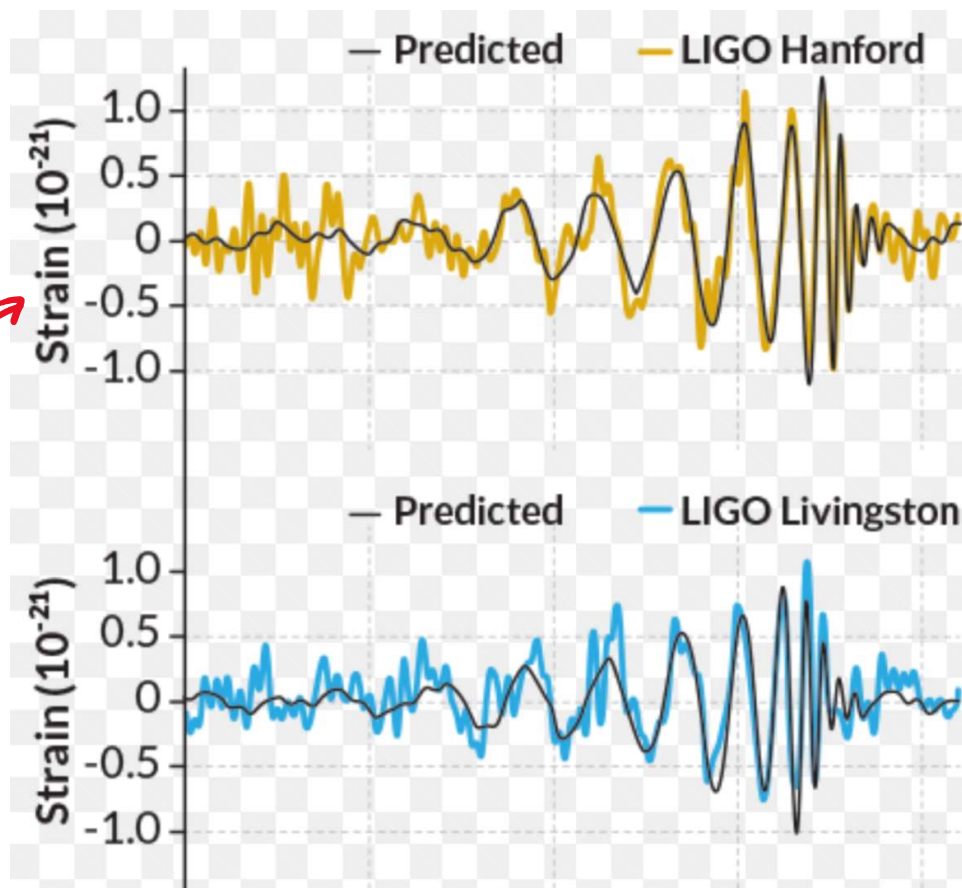


MV1

Amplitude:



$$\frac{\Delta l}{l_0}$$



$$\begin{aligned}\Delta l &= 4\text{ km} \times 10^{-21} \\ &= 4 \times 10^{-18}\text{ m}\end{aligned}$$

less than

$\frac{1}{1000} \times \text{proton size!}$

