Australian Research Council
Centre of Excellence for Gravitational Wave Discovery

Einsteinian Reality: A challenge for school education

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Australia-Norway-Germany-Scotland-LIGO Scientific Collaboration

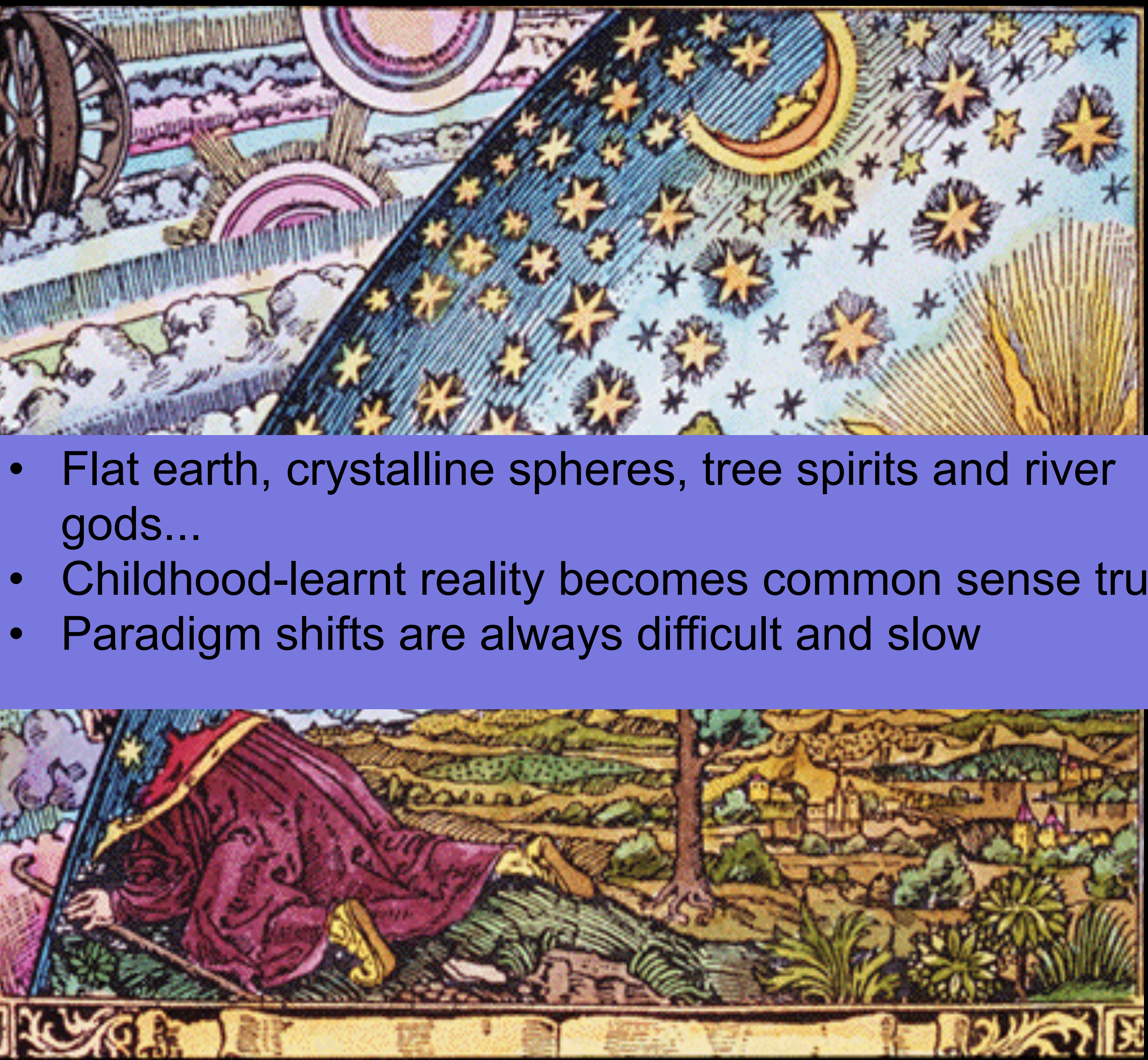
Every Child's Right

Every child has the right to share our best understanding of physical reality

Einsteinian Physics

- Two decades of discovery 1905-1924 changed everything.
  - Paradigm shift not noticed in schools
- Branding: *Einsteinian Physics*
- Relativity and quantum physics entwined
  - Neutron stars, Hawking radiation, quasars, GW detectors, CMB, big bang, atomic clocks
- Nature does not distinguish
- *Einstein-First* tries to bring GR and QM together

Changing Realities



- Flat earth, crystalline spheres, tree spirits and river gods...
- Childhood-learnt reality becomes common sense truth.
- Paradigm shifts are always difficult and slow

Language of reality

- *"The structure of language determines not only thought but reality itself"* - Noam Chomsky

  Deep structure expresses the underlying relations between words and conceptual meaning

- We learn not only spoken language but also a "language" of reality in our early years.
- Later learning is more difficult.
- It is easier to build on known language than introduce a new language

  Introduce the language of Einsteinian reality at an early age and then build on it.

“But” they say

- *You can’t learn Einsteinian concepts without first understanding Newtonian physics*
- *It’s too difficult*
- *Einsteinian concepts are not relevant to daily life*
- *Children can’t learn physics at primary school*
- *We would have to throw out important Newtonian physics.*
- *Teachers could not cope*

7 years ago: First trials with 11 year olds

- First surprise: children were not surprised
- No surprise: they loved doing it because it was all interactive, done in groups, fun activities.
- Second surprise: (16 year olds) Correlations

What was the most difficult topic? ⟷ What was the most interesting topic?

Primary School

- Replace implicit or untaught concepts with explicit Einsteinian concepts

What is space?

What is time?

What is light?

What is gravity?

Often the key question is *How can you measure it?*

Stone Age Running Races

Measuring space — Feet, paces, meters

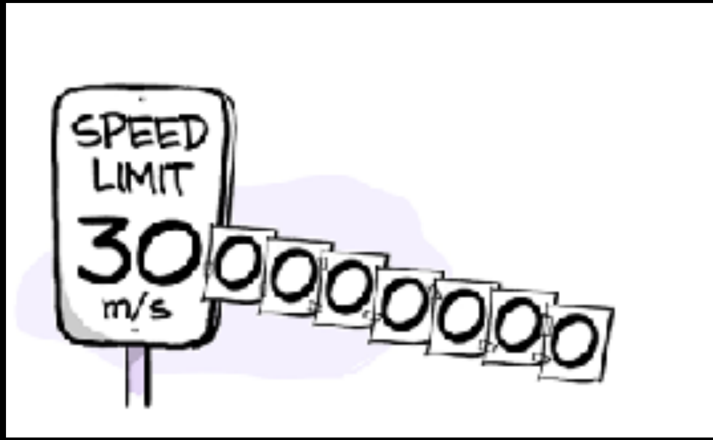
Measuring time — Heart beats, seconds

Measuring space with time

Space-time diagrams for journey to school

Speed limit of the universe

Spacetime diagram for falling balls



Measuring the Shape of Space

Experimental geometry

Shortest path = Line survey

Sum of angles vs Perimeter

Graphing skills

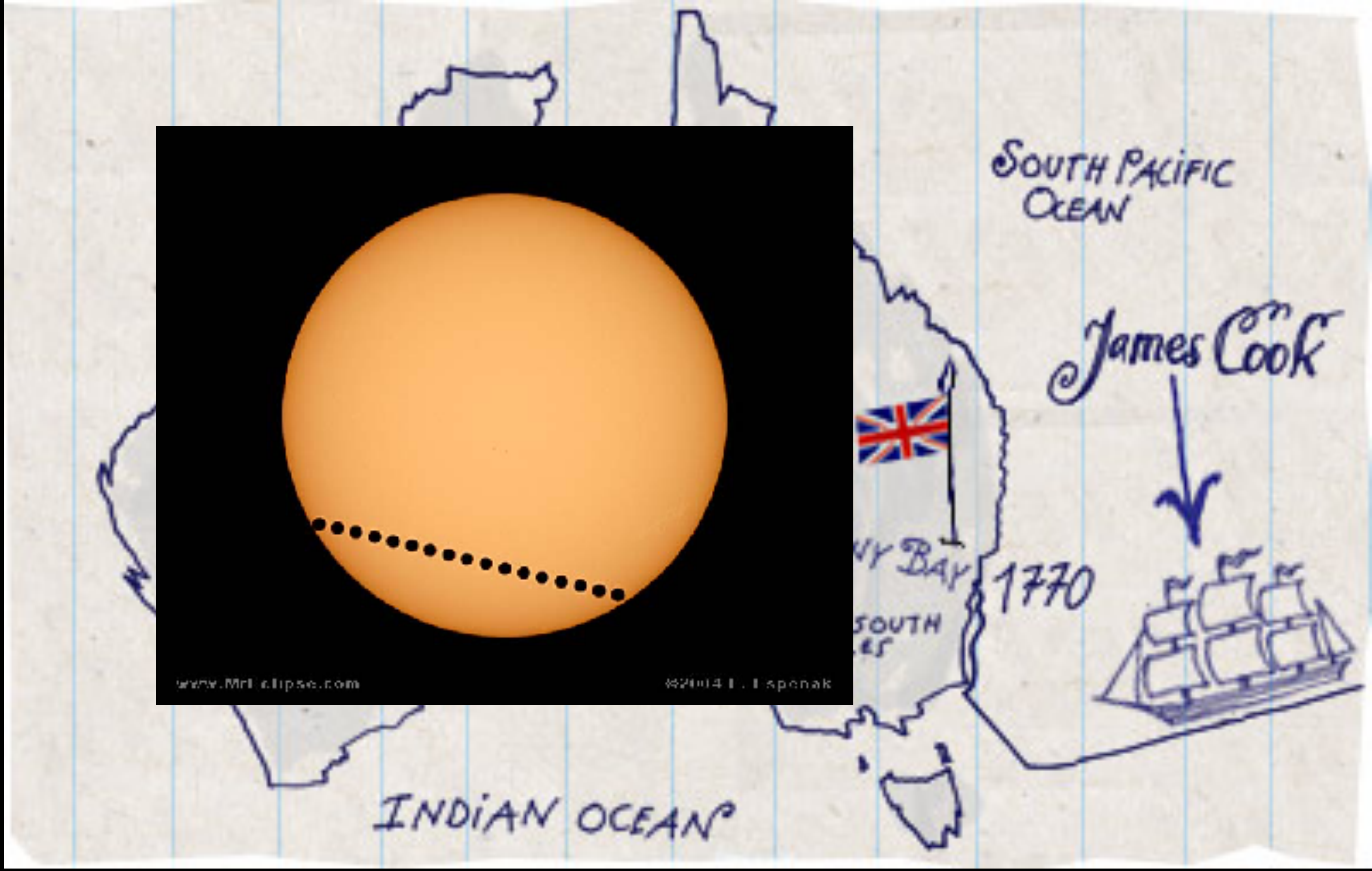
Newton's Law of Gravitation on a Lycra Sheet

Stories-of-Discovery Plays

- A simplified story (14 slides) tells how the new reality was discovered.
- We tell this story in various versions in simple plays and role play stories that involve most of the students in a class.
- Scripts available!

What is the size of the space we inhabit?

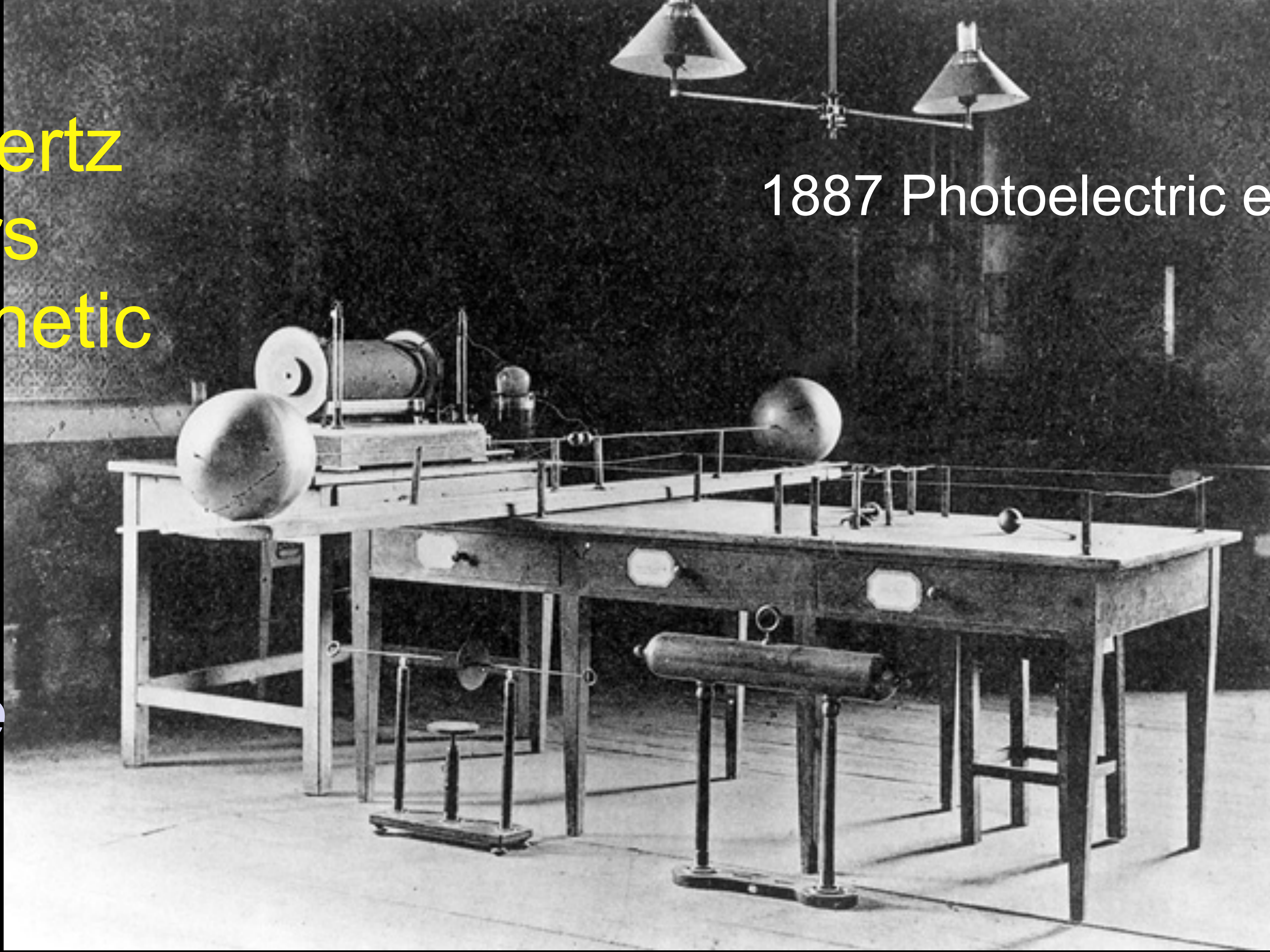
1769 Transit of Venus across the Sun



1886

Heinrich Hertz discovers electromagnetic waves

Of no possible use whatsoever



1905

Light comes as packets of energy later called photons

Speeds don't add up

Energy has mass

Speed limit of the universe

Einstein's happiest thought 1907

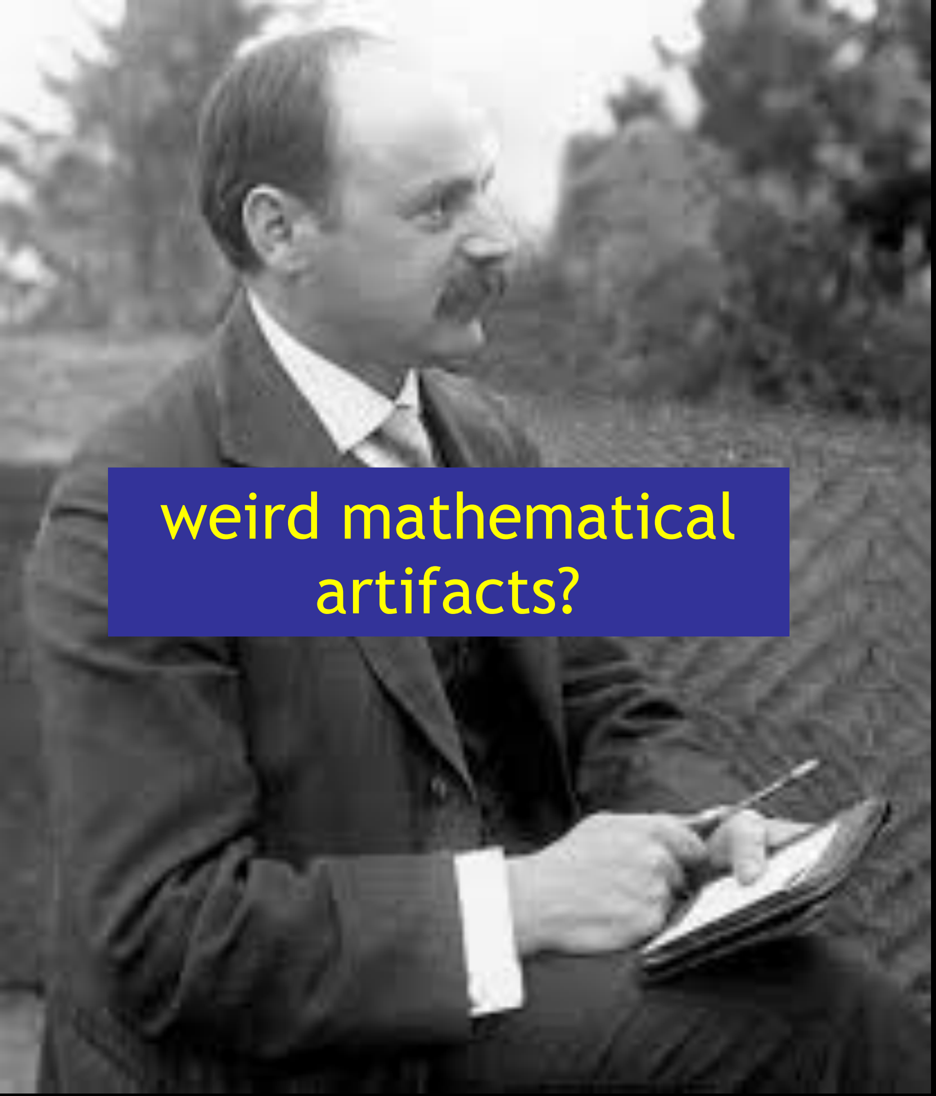
Gravity and acceleration are indistinguishable

Newton's gravity propagates instantaneously and violates relativity

Space is Elastic 1915

Matter tells spacetime how to curve
Spacetime tells matter how to move

1916: Karl Schwarzschild

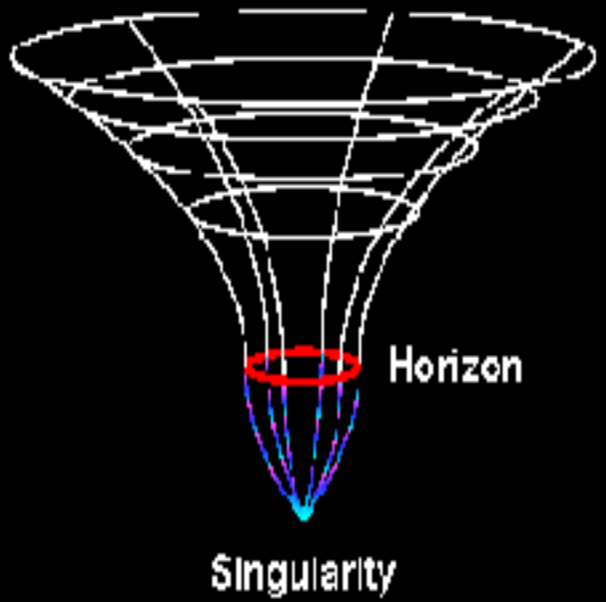


$$R_s = \frac{2GM}{c^2}$$

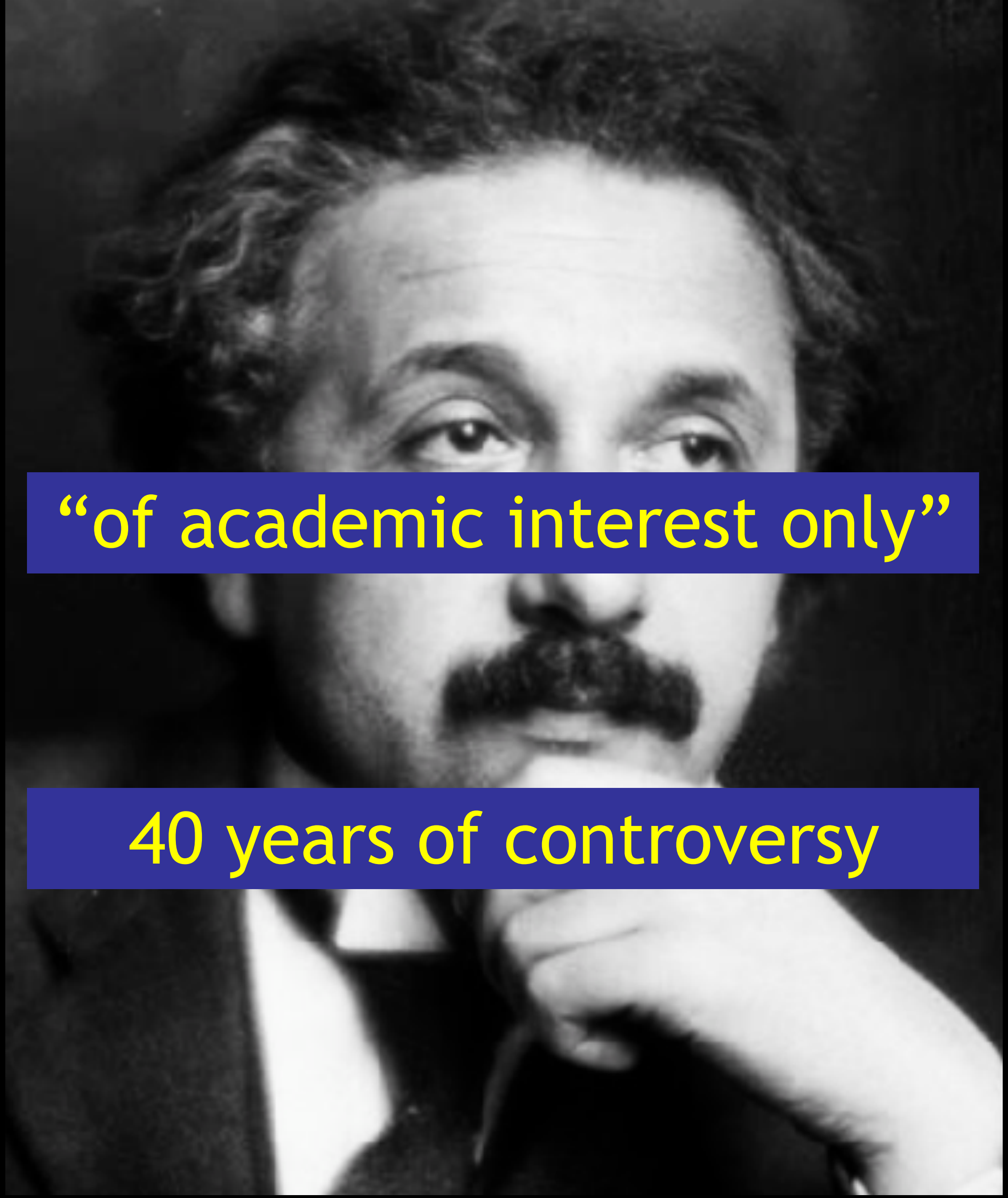
Earth mass

R_s =10mm

Holes in spacetime where space and time come to an end



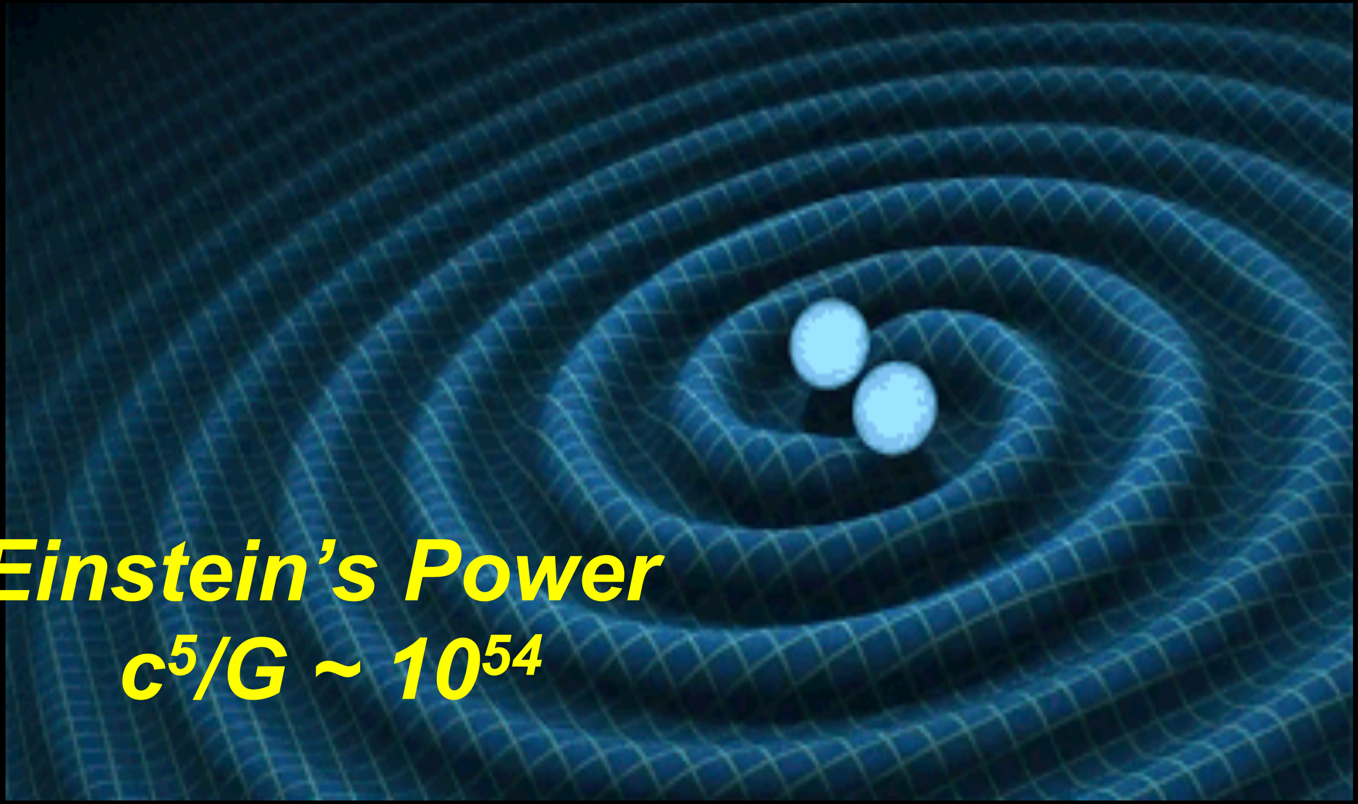
Einstein 1916



“of academic interest only”

40 years of controversy

Accelerating masses create ripples in spacetime which propagate at the speed of light - gravitational waves (June)

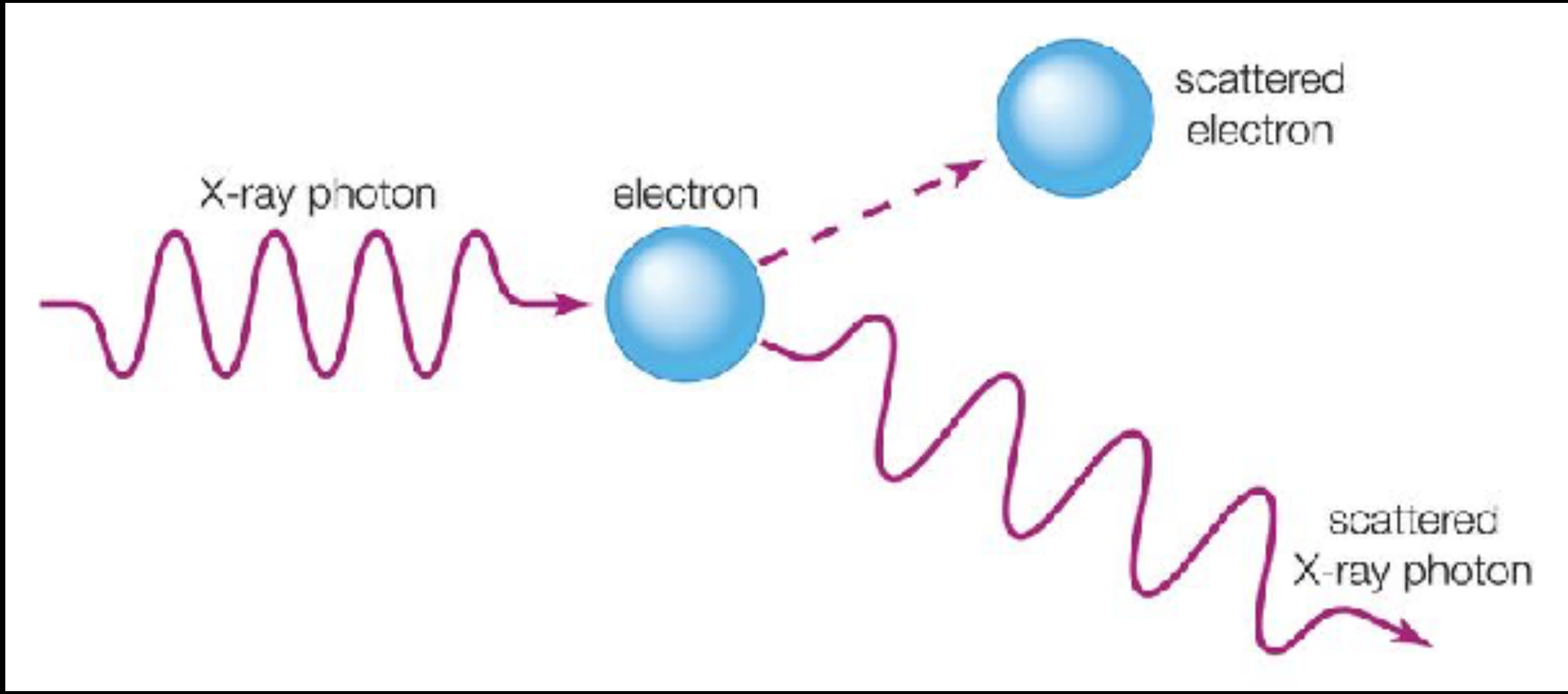


Einstein’s Power

$c^5/G \sim 10^{54}$

Einstein 1916 (again)

- Photons have momentum



1924

Louis de Broglie

A new picture of reality

Everything has waviness

Everything has bulletiness

Bulletiness follows the maths of numbers

Waviness follows the maths of arrows

Neutron star

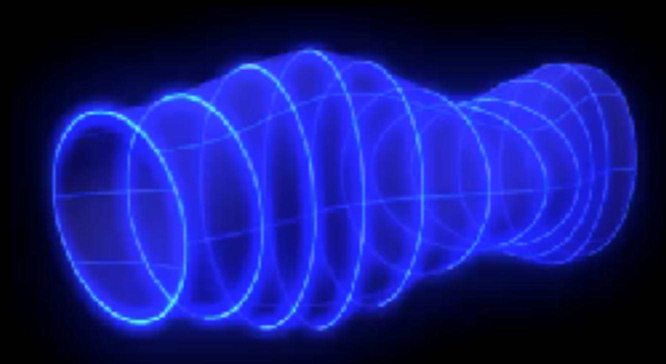
Ball of neutrons the size of Rottnest

I tsp =Mt Everest

1939 Oppenheimer

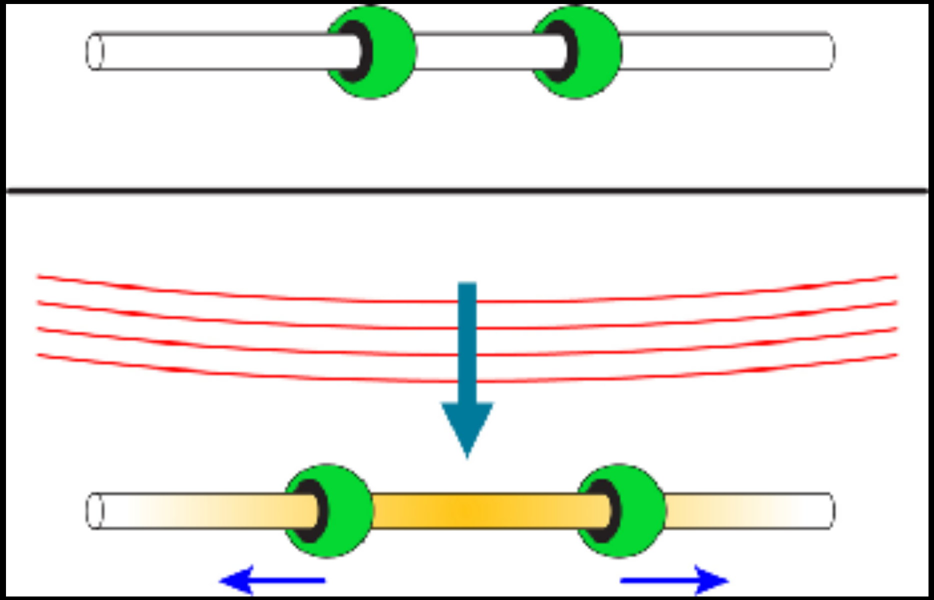
(1967 Jocelyn Bell)

1957: Feynman



How to detect gravitational waves

- **Inertia connects mass to space**
- **Stretching and shrinking space drags masses.**
- **Sticky beads on a rod will heat up by friction as they absorb gravitational wave energy**



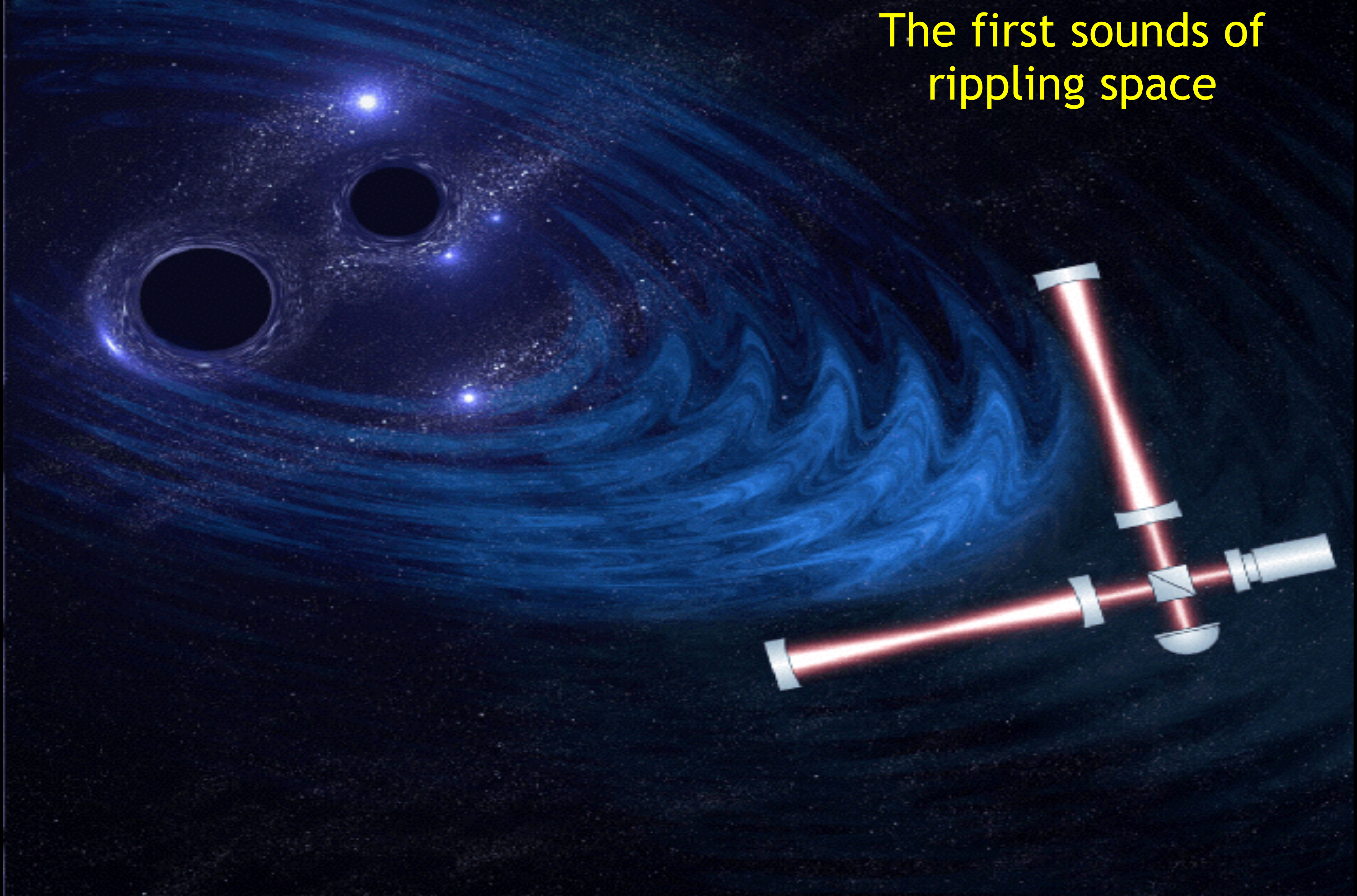
1973: Joseph Weber

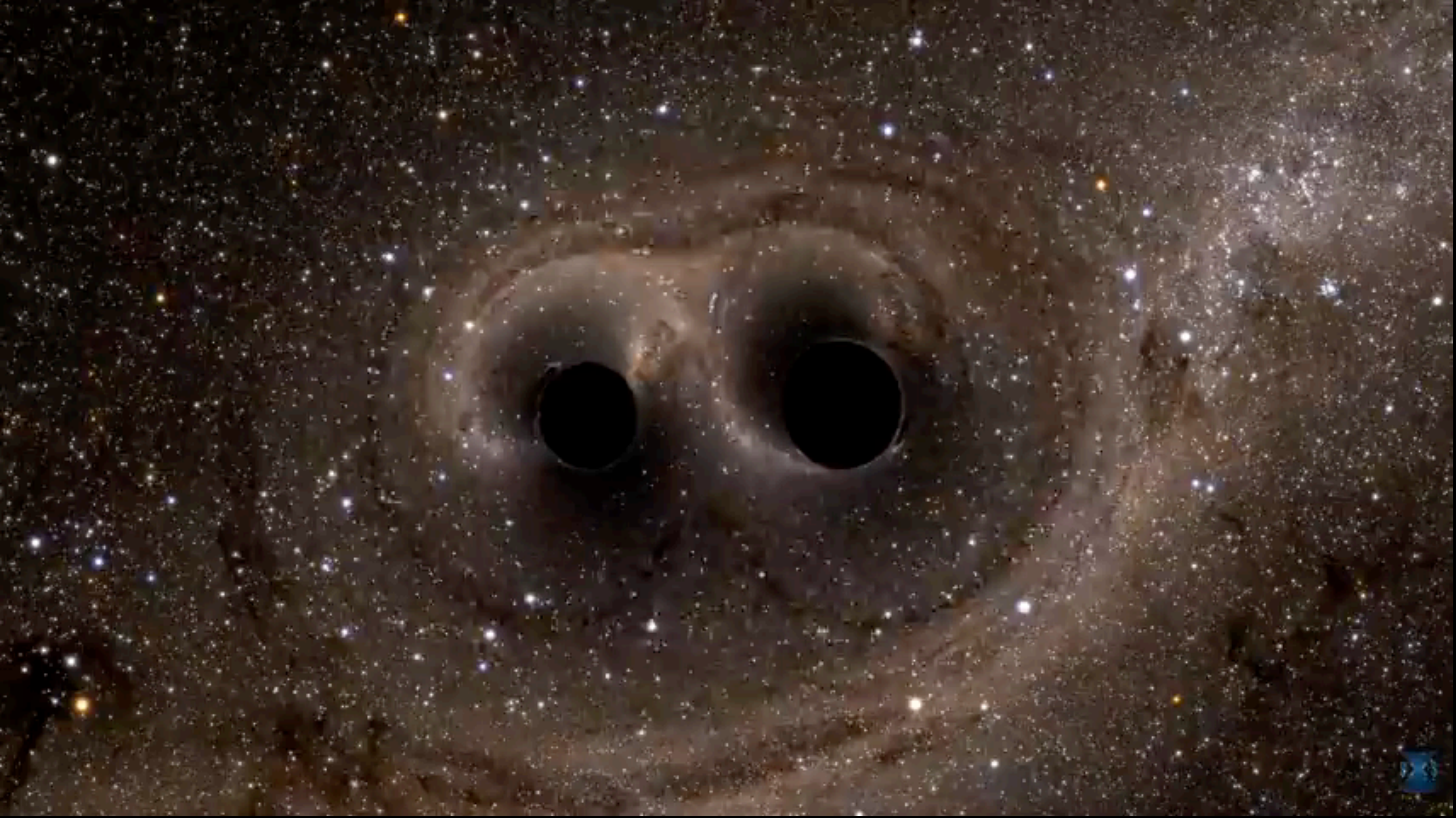
Precision measurement

Loss = Fluctuations

Can measure tiny changes if harmonic motion is pure enough

The first sounds of rippling space





Implicit Concepts in Primary Schools Today

- Space: undefined but implicitly Euclidean
- Geometry: Euclidean; exact truth
- Maths: only about numbers
- Time: undefined but implicitly absolute
- Matter: stuff with mass, momentum, inertia
- Waves: fluctuations that travel from one place to another.
- Speeds: implicitly Galilean or not addressed.

Schools Today	Modern Understanding
Rigid Euclidean space	Space flexible and curved
Time is absolute	Relative spacetime
Light is a wave Bullets are particles	Everything combines waviness and bulletiness
Energy is massless	$E = mc^2$
Newtonian determinism	Quantum uncertainty
Gravity: instantaneous force	Gravity: spacetime curvature, speed c

Weird Truths about Reality

(weird for adults who learnt Newtonian language)

1. Maths ………..1+1=0 - maths of arrows
2. Geometry…….parallel lines can meet
3. Light….like little bullets, that follow the maths of arrows
4. Molecules…also follow the maths of arrows
5. Gravity….is warped time and curved space
6. Time….changes with height and speed
7. Measuring always disturbs, creates uncertainty because photons have momentum.

What did you learn about light?

Year 3,
Mel Maria
Primary School,
Perth

Age 8

2018

8 year old students
Mel Maria Primary School
Perth, Australia

Presenters:
Rahul Choudhary
Alex Foppoli
Tejinder Kaur (Jyoti)

Maths of Arrows at Primary School

- Hand out equal size arrows

- Ask students to demonstrate 1 + 1 = 2
- Then ask them to demonstrate 1 + 1 = 0
- Go on to generalize as appropriate

- We are opening their minds to alternative forms of maths
- Maths is not just the maths of numbers.

Climbing Against the Time Gradient

When you climb the stairs you are working against a time gradient

Potential energy = mass energy x time dilation

- The change in time with height h above the Earth surface is given by $\Delta t/t = gh/c^2$
- The energy of a mass m is given by: $E = mc^2$

Combining these results $mgh = \Delta t/t \, . \, mc^2$
This equation shows a link between gravity and time dilation. Gravitational potential energy can be understood as a direct manifestation of time dilation.

Atomic clocks today can easily measure the warping of time by the earth!

Aphorisms for Einsteinian Reality

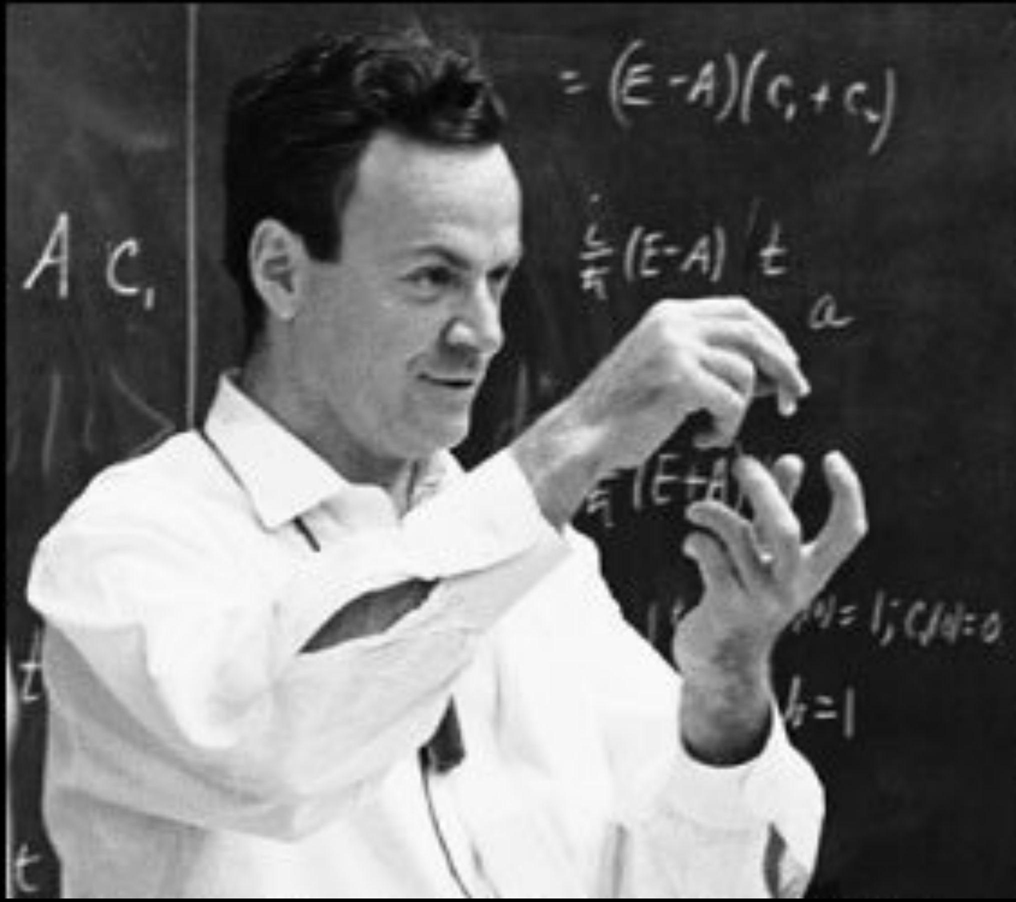
Waviness and bulletiness - everything has it!
Bulletiness follows the maths of numbers
Waviness follows the maths of arrows

Matter tells spacetime how to curve
Spacetime tells matter how to move

And remember, all of this physics is inside your phone!

"I want to emphasise that light comes as particles.
"It is very important to know that light behaves like particles,
"especially for those of you who have gone to school, where you were probably told something about light behaving like waves."

-Richard Feynman



Quantum Reality

- The world is not what it seems
- Even ordinary things like light reflections hide a mysterious reality.
- The mysterious reality is described by the maths of arrows

  It is called vector calculus. A vector is an arrow: it has length and direction

  The vectors we will be using are called phasors.

- First we will look at images
- Then we will play with little rolling objects that let you understand the connection between waves and wheels
- Then we will apply the maths of arrows to light reflecting from mirrors
- Then we will prove the ideas by tricking the light

Single molecules
in a quantum movie

History

- 1801 and 1816: Scientists prove that light is a wave.
- 1905: Einstein proved that light comes as particles called **photons**
- 1916: Einstein said light has momentum: light acts like bullets
- 1924: Count Louis de Broglie said if light waves act like bullets, then maybe bullets act like waves

Waviness and bulletiness

Everything has it!

Bulletiness follows the maths of numbers

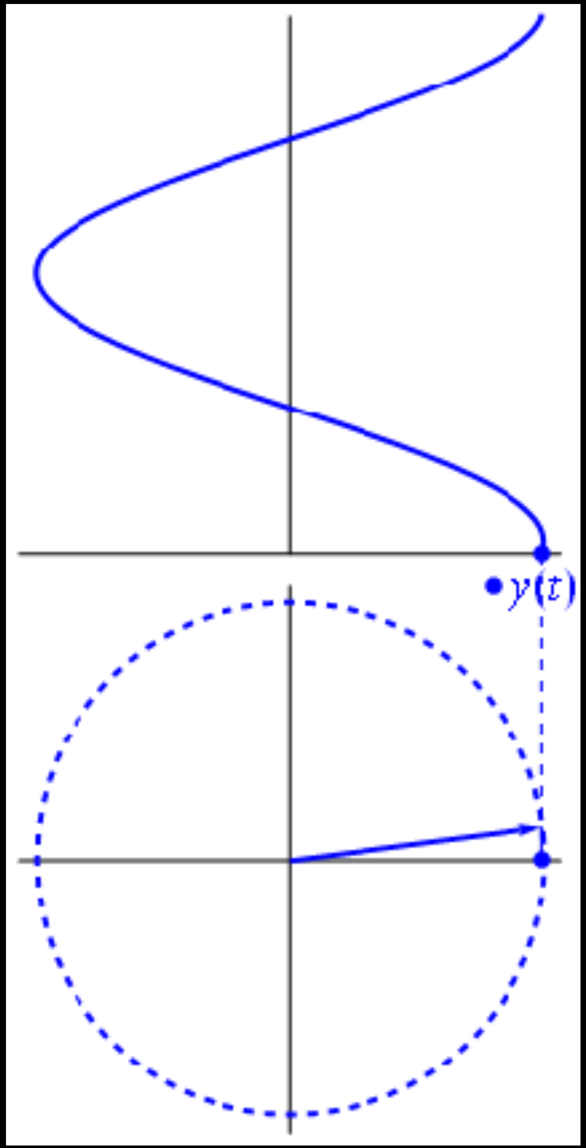
Waviness follows the maths of arrows

Simultaneous brilliant discovery 1893

Phasors

Charles Steinmetz

Oliver Heaviside



2018 Challenge: can we teach students Feynman's beautiful path integral approach to QED
Phasor/Wheel Activity

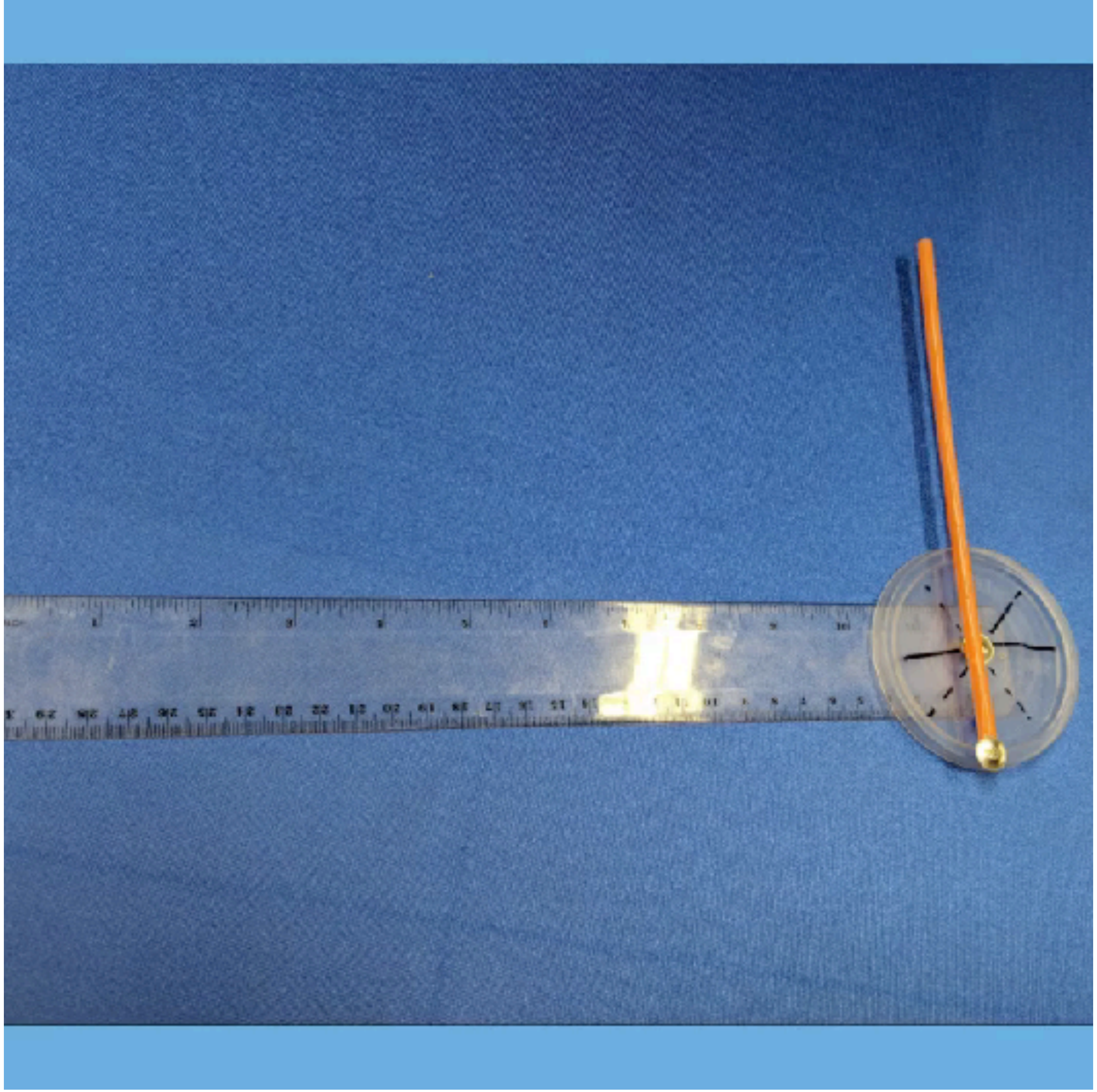
- Activity in small groups using rolling ruler
  - Students need one A3 sheet.
  - Plot graph of straw position for rolling straight
  - Plot phasors for two trajectories: straight along edge and diagonal
  - Identify the wavelength and the phasor angle for a few points along the trajectory

  - Tested with students from Mt Lawley SHS and Guildford Grammar School thanks to Richard and Gary.

All possible paths

Phasor-Roller Activity for Feynman Path Integrals for Quantum Interference

Video by Rahul Choudhary



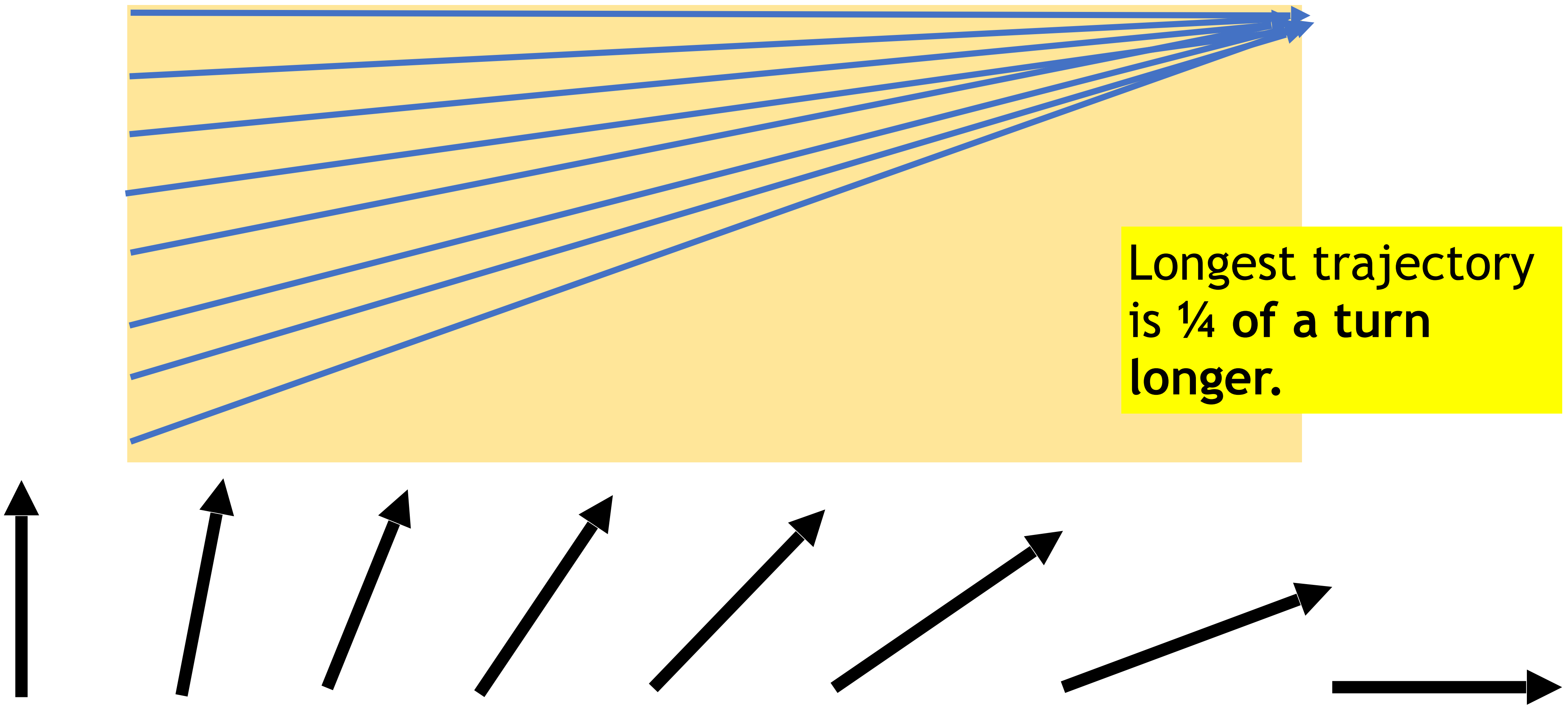
How do phasors connect to probability of particles arriving at a certain place

- The adding of the arrows is equivalent to the adding of the waves.
- For waves like water waves the length of the combined arrows tell you size of the wave.
- For single particles like atoms or molecules or photons the maths is identical but the length of the combined arrow tells you the ***probability*** that a particle will arrive at a certain place.

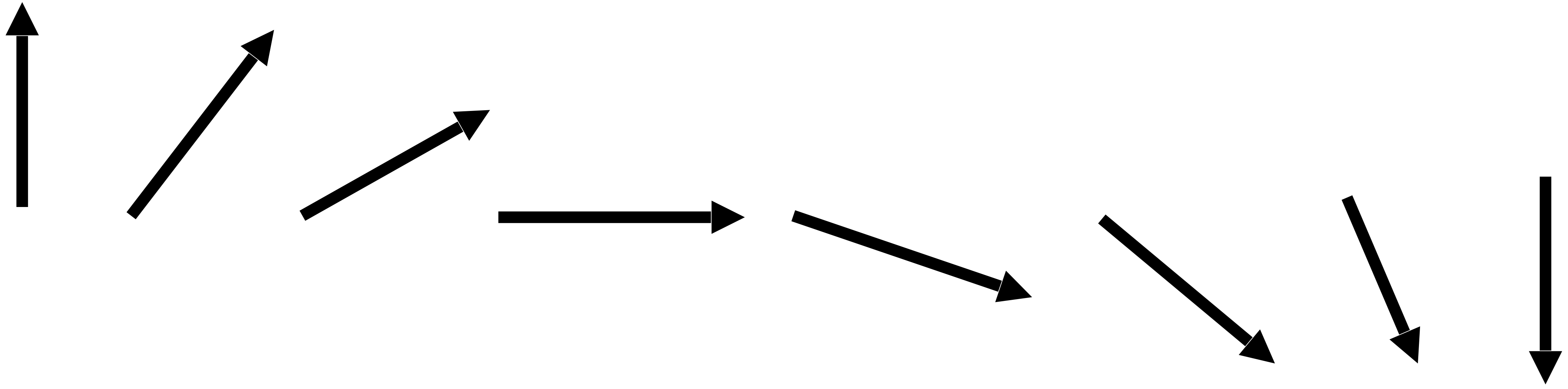
- **In reality** everything that we see is the arrival of photons. Every image your eye sees is because photons follow the quantum probability.
- When there are enough photons the images look smooth.

Because the maths is the same, we can pretend that light is like a water wave even though it isn't.

8 waves arriving at the same point

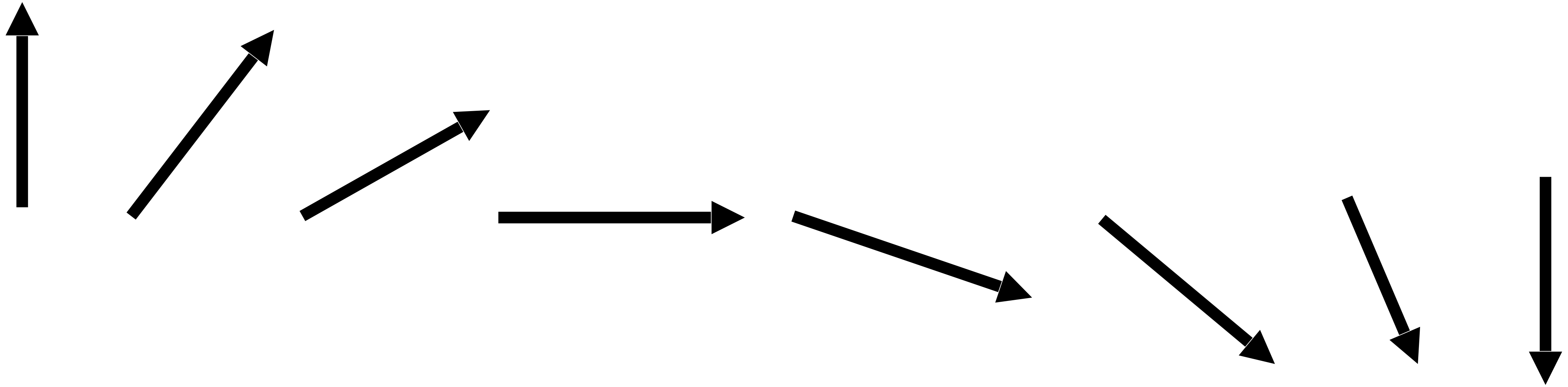


How much longer is the longest trajectory this time?



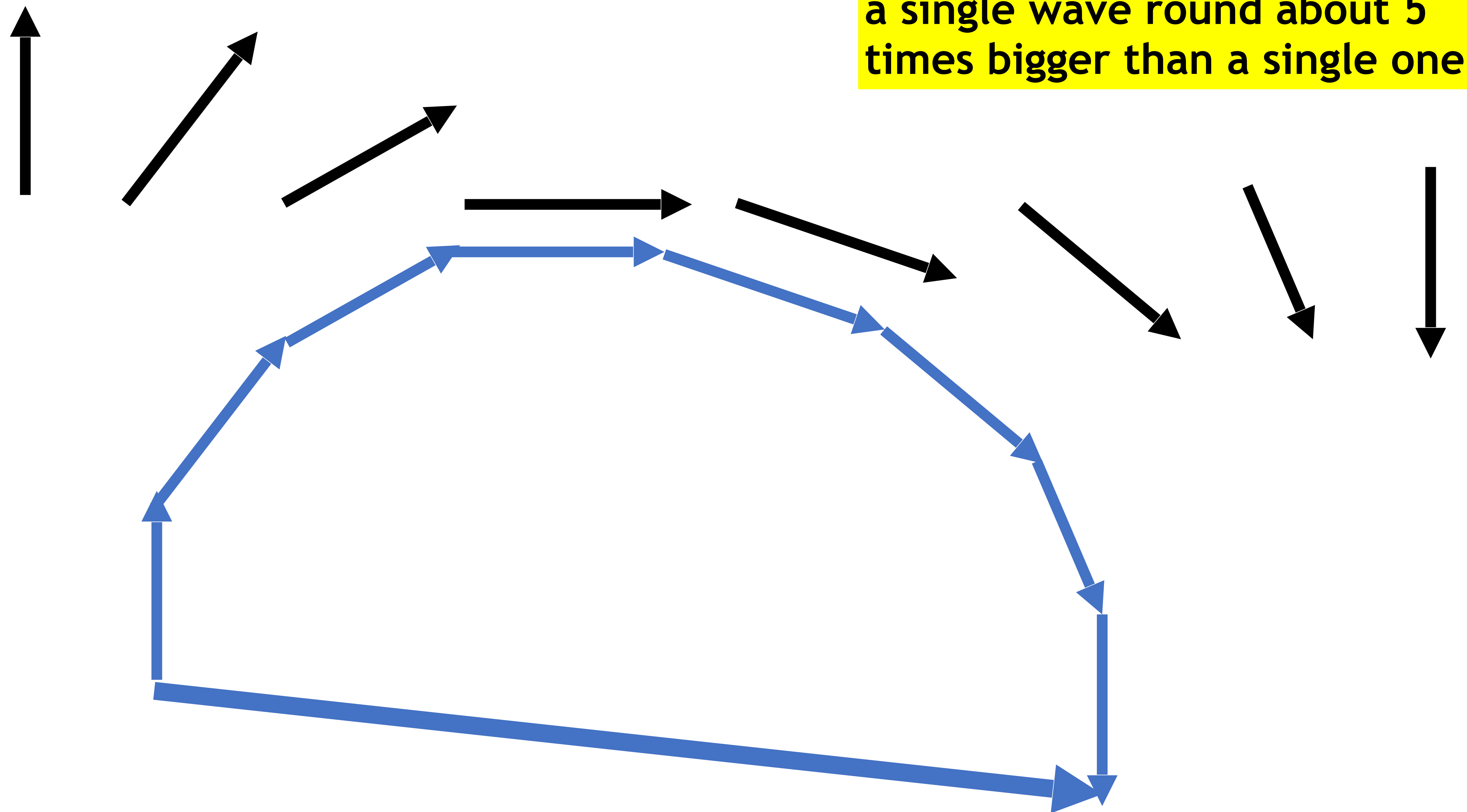
half a turn

Lets add up the 8 separate waves.

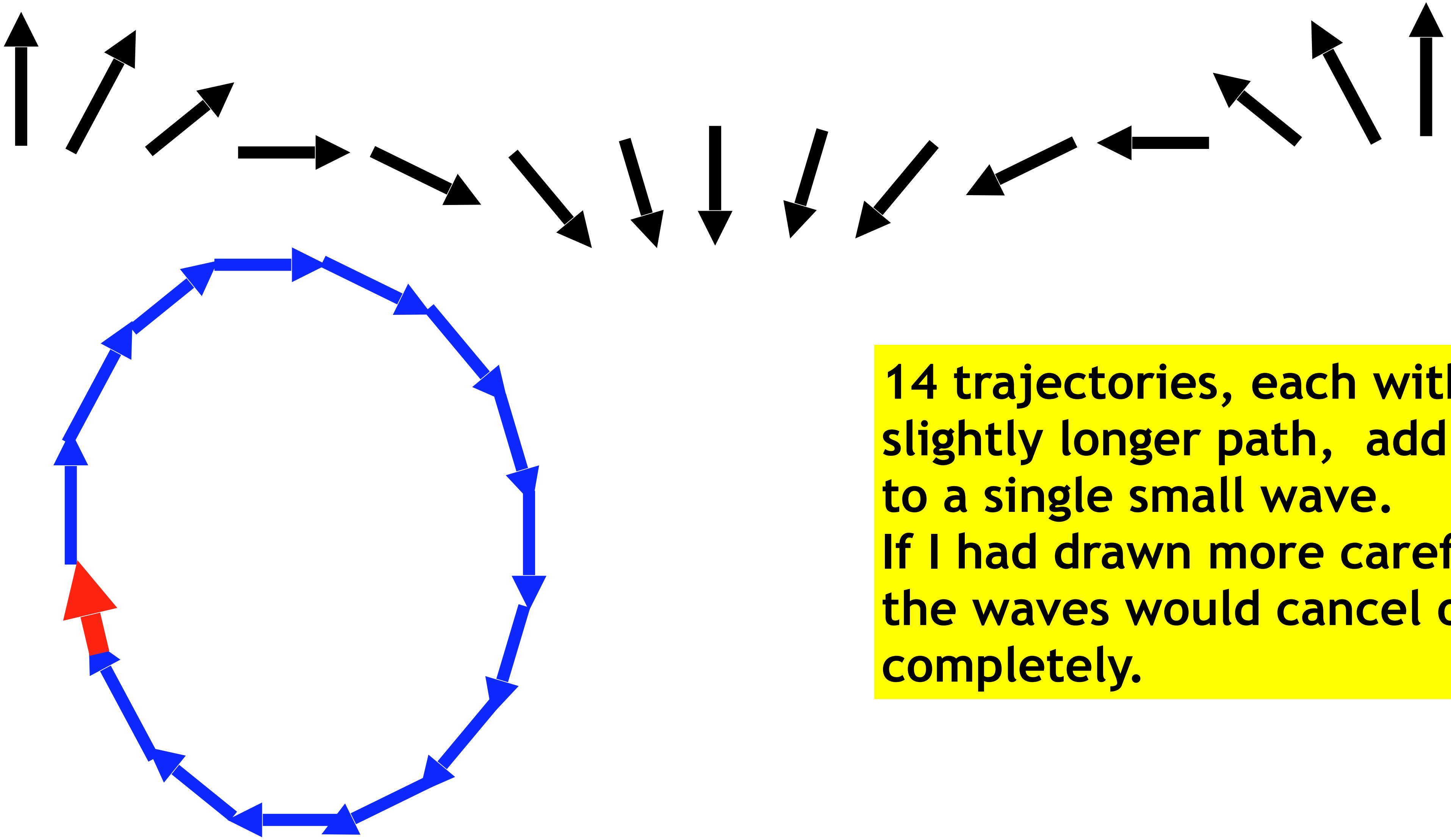


Lets add them all up?

Eight waves, each with a slightly longer path add up to a single wave round about 5 times bigger than a single one



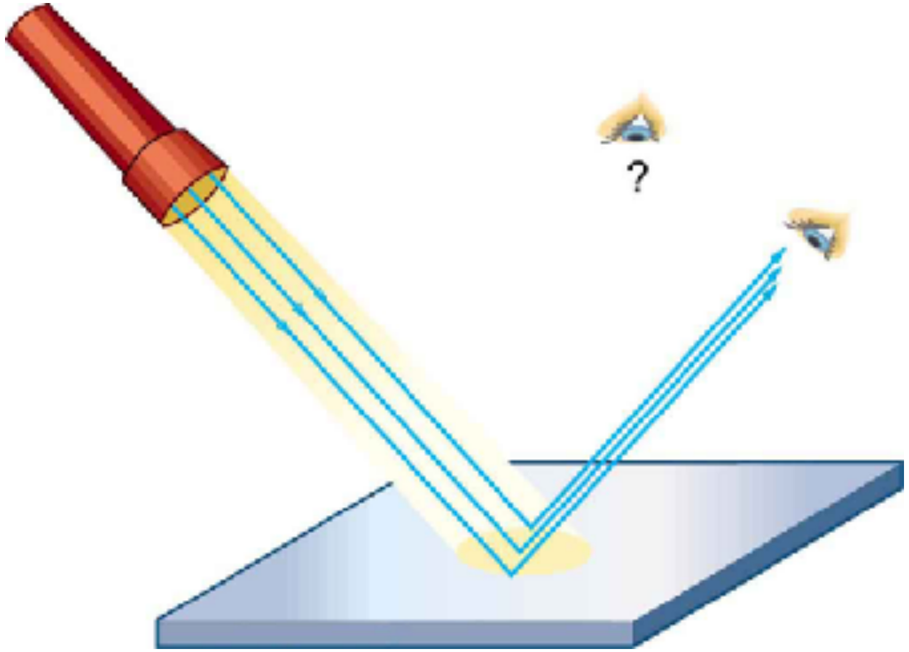
What would happen if I added more longer trajectories



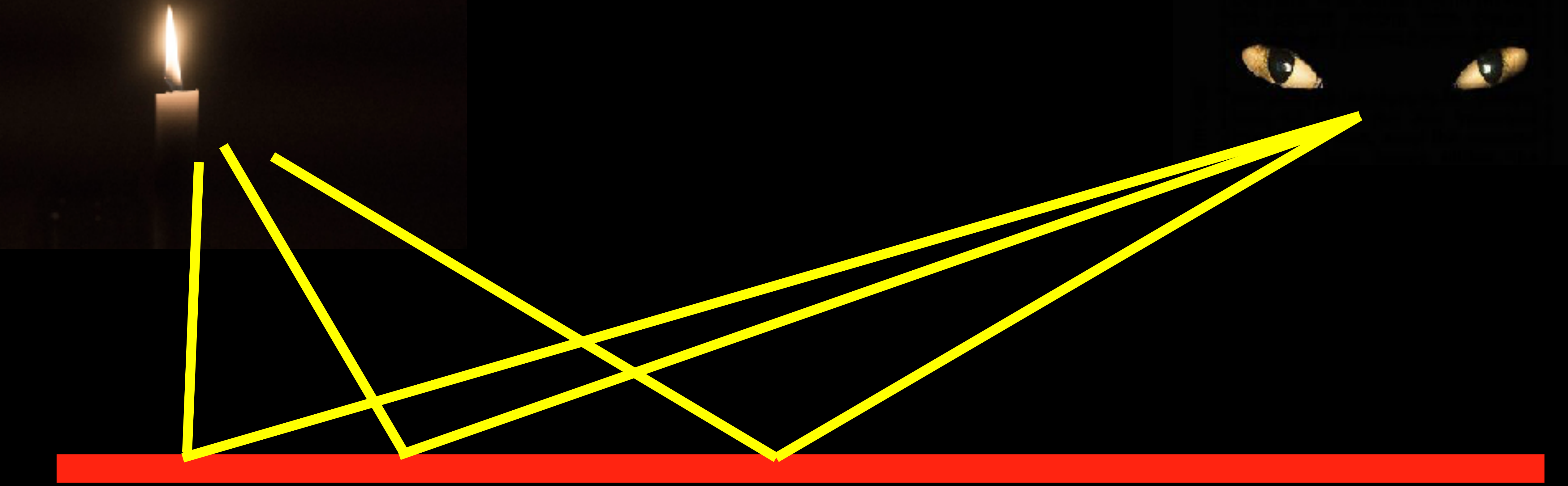
14 trajectories, each with a slightly longer path, add up to a single small wave. If I had drawn more carefully the waves would cancel out completely.

Reflection in a Mirror

- Why does the light take this path?
- We are going to see something extraordinary!
- All possible paths contribute.
- For most paths there is cancellation.
- We will trick some of the paths into not-cancelling.
- You will record photos of light that has been tricked to take alternative paths

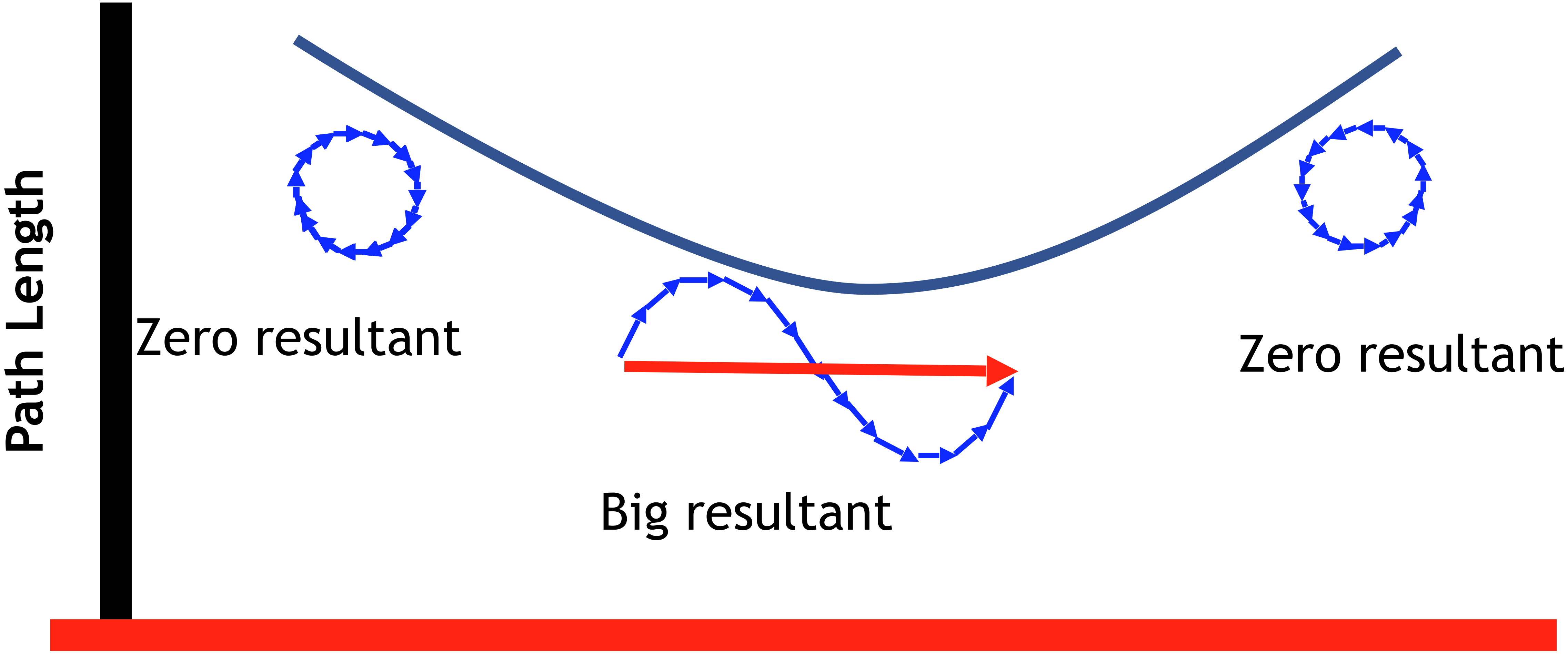


What is different about these alternative paths?



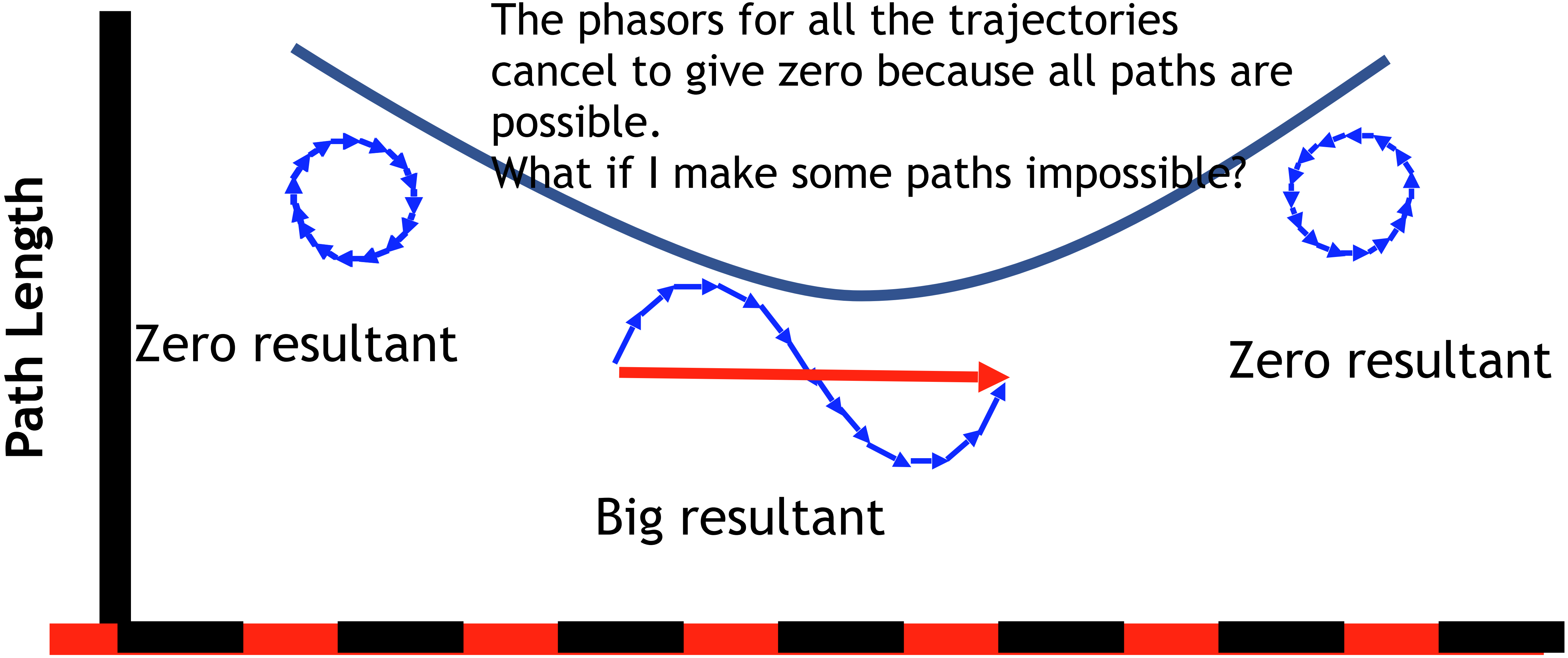
- Which is the shortest path?
- How does path length depend on trajectory?

Path Length vs position on Mirror



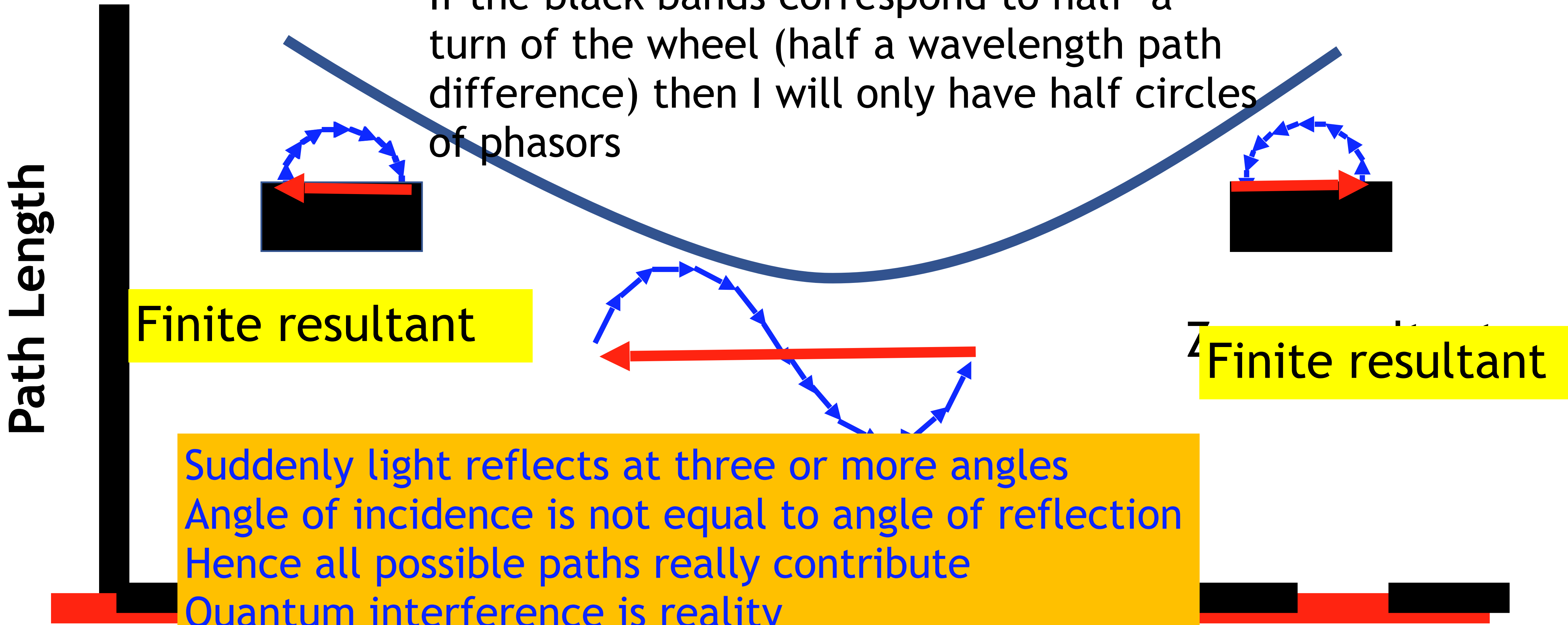
Can I trick the Photons

The phasors for all the trajectories cancel to give zero because all paths are possible.
What if I make some paths impossible?



Can I trick the Photons

If the black bands correspond to half a turn of the wheel (half a wavelength path difference) then I will only have half circles of phasors



Suddenly light reflects at three or more angles
Angle of incidence is not equal to angle of reflection
Hence all possible paths really contribute
Quantum interference is reality
Easily seen with a laser pointer and a CD (student activity)

7 years of Trials

a) Children accept Einsteinian concepts with ease
b) Children are aware that they learn old stuff at school
c) They want to learn Einsteinian concepts
d) They are extremely motivated by the activity based Einsteinian curriculum.
e) Teachers like it, especially those with minimal physics background.
f) Evidence of gender levelling: girls improve more than boys.
g) Positive responses from teachers workshops and from parents

Ages tested: 8 - 16

See our published papers which are full of histograms for very impressive improvements in both attitude and ability

Strong evidence that the core concepts are accepted by all students independent of aptitude

It is time now to develop an integrated curriculum!

Primary: Introductory Concepts

-Activities and qualitative understanding

Space and geometry: experimental geometry

Space and Time: measuring space with time

Limiting velocities and speed limit of the universe

What is gravity?

Matter tells spacetime…Spacetime tells matter

What is light ?

Waviness and bulletiness: everything has it!

Black holes and gravitational waves

Toy photons and Gravitational wave detectors

Two types of maths

Maths of numbers and maths of arrows

Middle School: Consolidation

- quantitative experiments and activities with models and on-line

Space and geometry:
gravitational lensing, stars askew, mapping space, understanding curvature.

Space and Time:
quantitative examples: space time diagrams, falling objects

Limiting velocity
mechanisms: graphing terminal velocities of balloons, relativistic mass enforces the speed limit

Spacetime tells matter how to move
Newtonian gravity on lycra sheets, Kepler’s law of orbits, gravitational lensing

Waviness and bulletiness….
spacing between photons, uncertainty principle, single photon interference and interference experiments

Maths of arrows:
Experiments with phasor wheels

Black holes and gravitational waves
GR and QM of GW detectors

Upper School: Quantitative Einsteinian Physics

Space and geometry: quantitative estimates of gravitational lensing, time dilation and gravitational waves

Geometry near the earth and the sun, neutron stars and black holes: curvature and sector models,

Time on Earth, Sun, neutron stars and black holes: **Time dilation**: CMB, time dilation of supernovae

Photons and particles: momentum, wavelength: Measurement uncertainty from random arrival of photons, angular uncertainty: telescope resolution. Quantum noise in gravitational wave detectors. Simple applications of statistics of photon number.

Einsteinian-Newtonian connection

Gravity and time: potential energy, inverse square law.

Clocks and GPS, relativity of time

Cosmology, red shifts, big bang and cosmic microwave background

Critique of models and analogies!

Modern physics*: Introduction to modern quantum physics applications*

Development of vector approach to interference

Quantum entanglement, quantum squeezing, vacuum fluctuations

The physics of gravitational wave detection

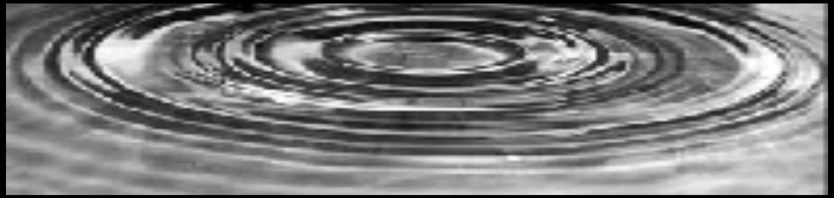
Physics literacy*: Students should have moderate literacy about the physics of the last 20 years*

Still under development!

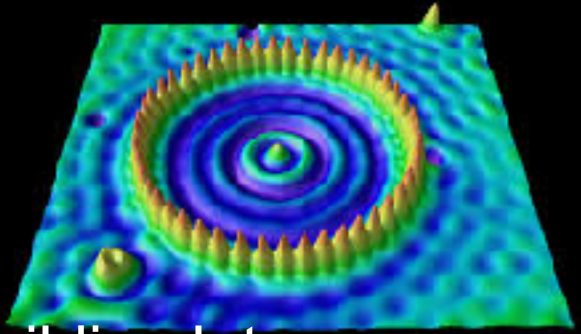
2012 slide

Ideas Everyone Could Know

- We live in curved space with rippling geometry and warping time.



- The world is quantum. Quantum reality underpins technology. Matter has wave behaviour and waves have particle behaviour.



- Old approximations are still useful.
  - Flat earth is useful when you mark out building lots
  - Euclidean geometry is useful for architects
  - Wave properties are useful for radio engineers
  - Galilean relativity is ok for car crashes

2012 slide

Making the Impossible Possible

- Einstein said his waves were only academic
- Many said detection was impossible
- A small band of physicists in the 1970s has grown to thousands.
- Our “gravity radio receivers” have improved more than 1 trillion-fold
- New LIGO detectors will begin to operate 2015: expect 20 signals per year by 2018.

Conclusion

- We found the first signals in 2015
- We have found 11 signals up to December 2018
- Gravitational waves provides essential relevance to Einsteinian physics education.
- Space ripples and 40kg mirrors + laser light obey the laws of quantum physics
- See posters by Ju Li, Rahul, Richard and Gary