Classroom Simulation of Gravitational Waves from Orbiting Binaries

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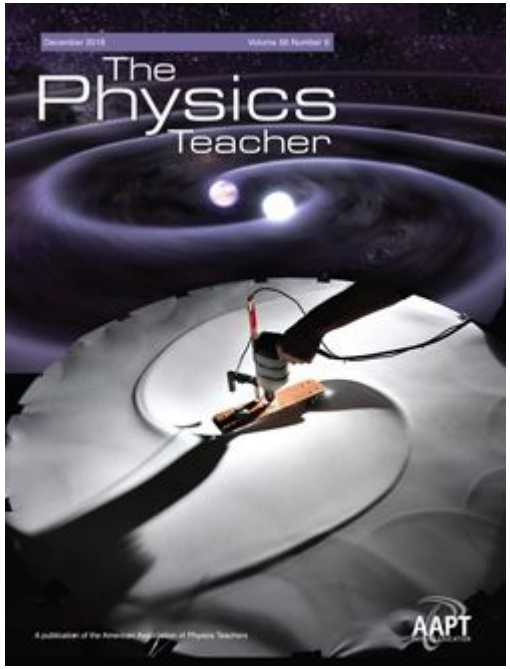
480 seconds / 18 slides = 26.7 seconds / slide



The Physics Teacher
Volume 56 Issue 9, December 2018

Gravitational Waves

The *2017 Nobel Prize in Physics* was awarded to **Rainer Weiss**, **Barry Barish**, and **Kip Thorne** for their contributions to LIGO and the observation of gravitational waves.

To date, **LIGO** and **Virgo** have observed 11 detections and 18 detection candidates over three runs.

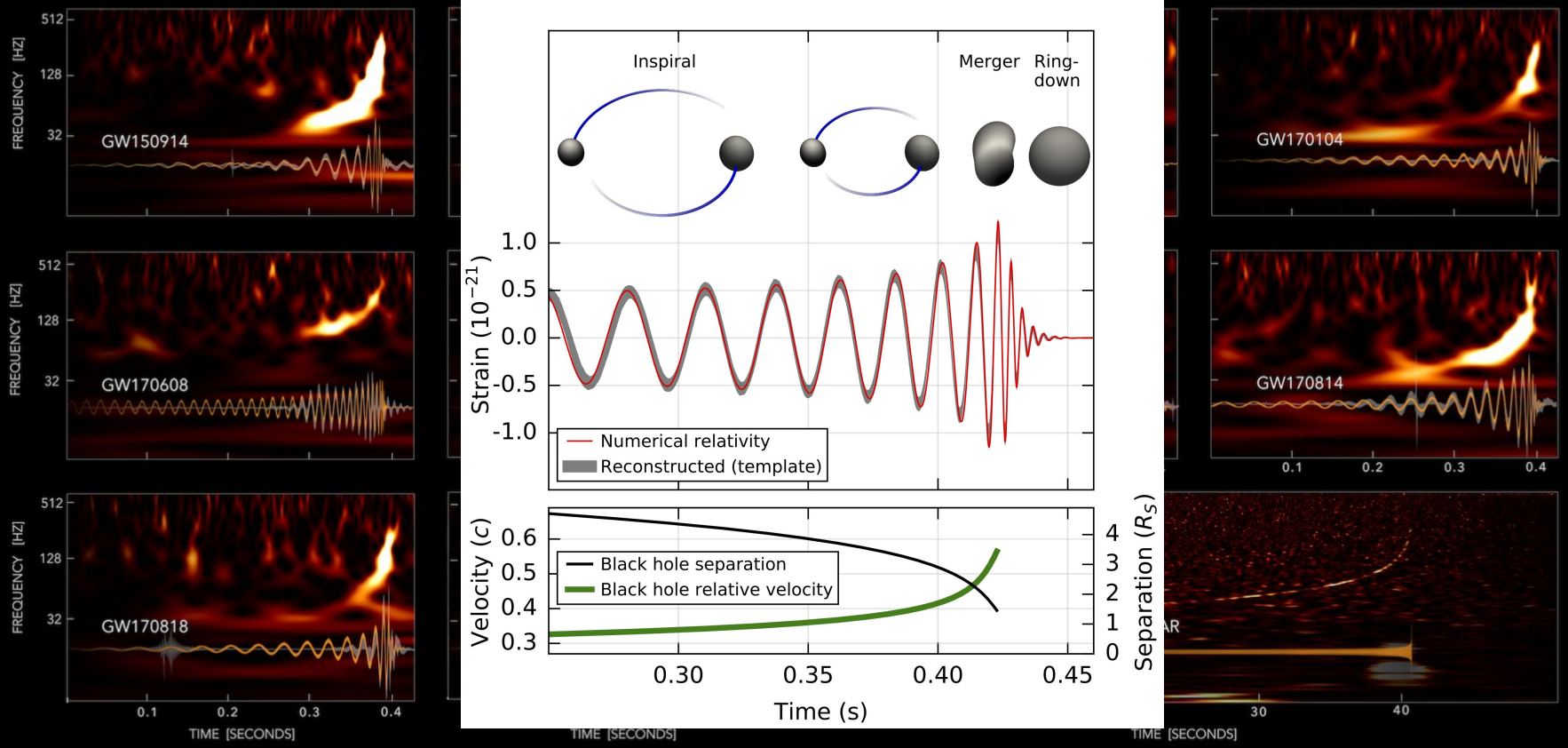
There are 3 phases to a gravitational wave signal: the **inspiral** phase, **merger** phase, and **ringdown** phase.

We are simulating a portion of the inspiral phase in the **plane** of the orbiting bodies.

Source: LIGO Caltech

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1

LIGO VIRGO Georgia Tech



LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23

WAVELET (UNMODELED) EINSTEIN'S THEORY

S. GHONGE, K. JANI | GEORGIA TECH

Fabric of Spacetime (Spandex)

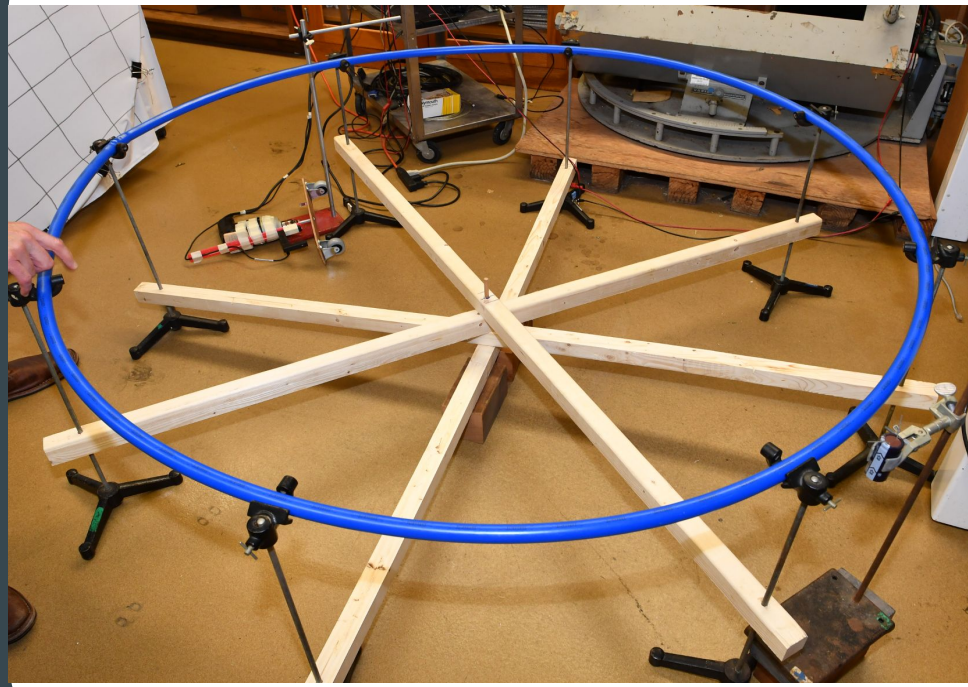
- Popular demonstration using spandex to mimic **force of gravity**
- **Significant pitfalls** to this approach
- But conveys some of the **wonder** to **non-specialists**

Could a **similar model** could be used to illustrate **gravitational waves** from orbiting binaries?

Dan Burns explaining his spacetime warping demonstration.

Our Demonstration

- Spandex stretched over **homemade** 60-in hoop
- Held up by **stands and clamps** commonly found in introductory physics labs
- Held in shape by four pieces of 2x2 **lumber** arranged like the spokes of a wheel



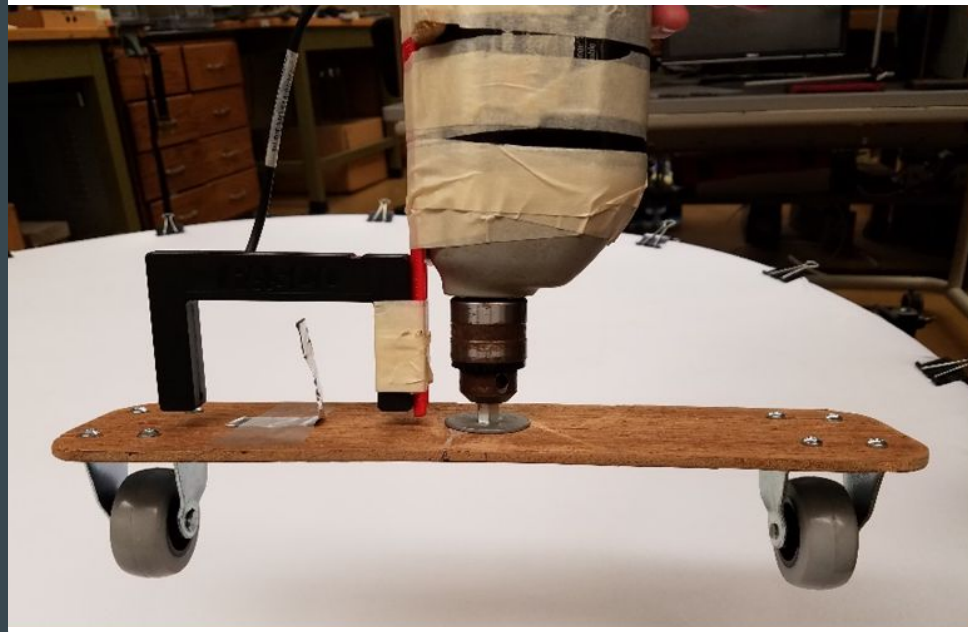
The Orbiting Binaries

Caster wheels mounted to a **wooden board**.

Secured to **variable speed** electric drill with **hex nut**.

Photogate sensor to measure the frequency.

Washers to distribute weight and minimize wobble.



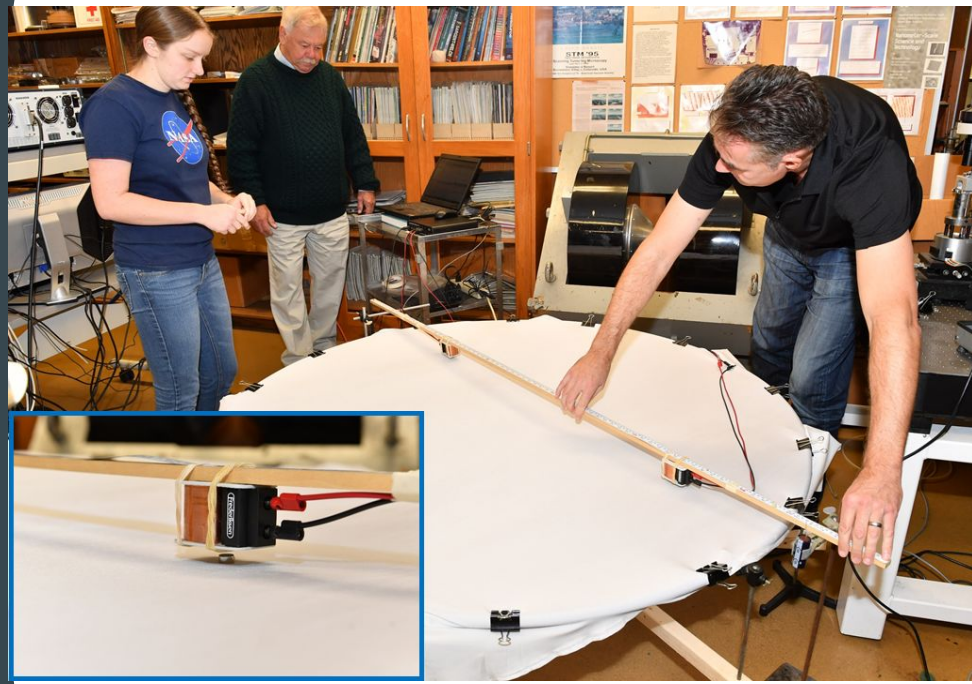
The Speed of Light

For real gravitational waves, amplitude reaches a **maximum** for orbital velocities near the **speed of light**.

Would the same hold here but with the **wave speed** set by the **tension**?

Used Faraday's law of **induction** with two small neodymium **magnets**.

We obtained best results with a **relatively slack** fabric (wave speed about **3 m/s**).



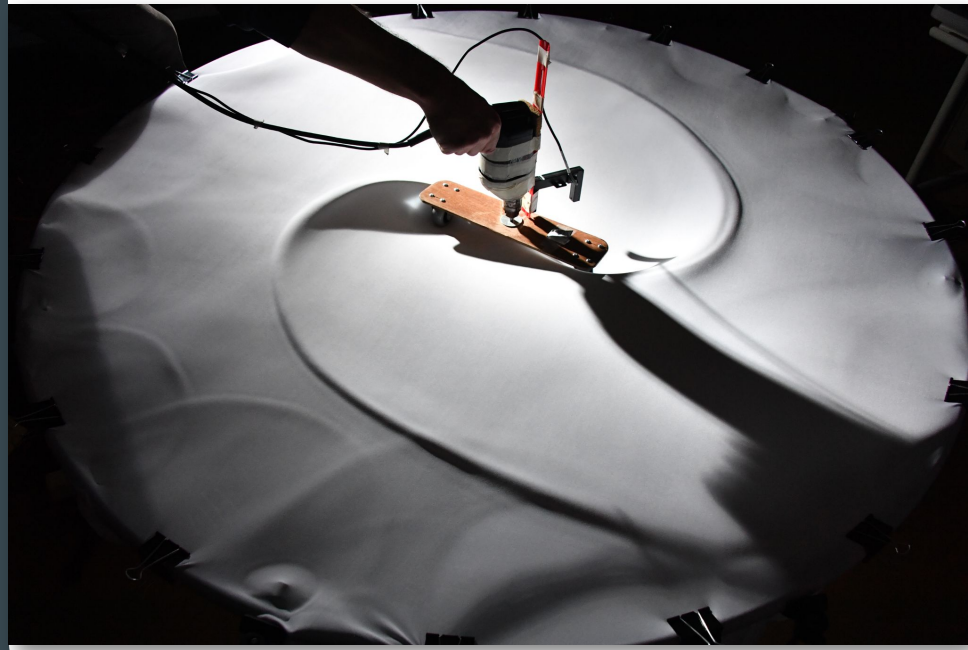
Strobe

To bring out the **wave pattern**, we **synchronized** the frequency of a strobe light with the rotational frequency of the binaries.

Rotation frequency is **half the frequency** of the strobe.

Also helped keep drill frequency **steady**.

Warning for those **sensitive to flashes**!



Amplitude

The dimensionless amplitude (or strain) h of real gravitational waves from coalescing binaries of mass M, orbital separation R, and orbital frequency f measured from a distance of r.

For GW150914 (where h is largest):
M ~ 70 solar masses
R ~ 350 km
f ~ 150 Hz
r ~ 300 Mpc
h ~ 1x10^-21

$$h \sim \frac{GMR^2 f^2}{rc^4}$$

Some Questions

For r, since $L \propto h^2$

$$L_{3D} \propto \frac{1}{r^2} \qquad L_{2D} \propto \frac{1}{r}$$

$$h_{3D} \propto \frac{1}{r} \qquad h_{2D} \propto \frac{1}{\sqrt{r}}$$

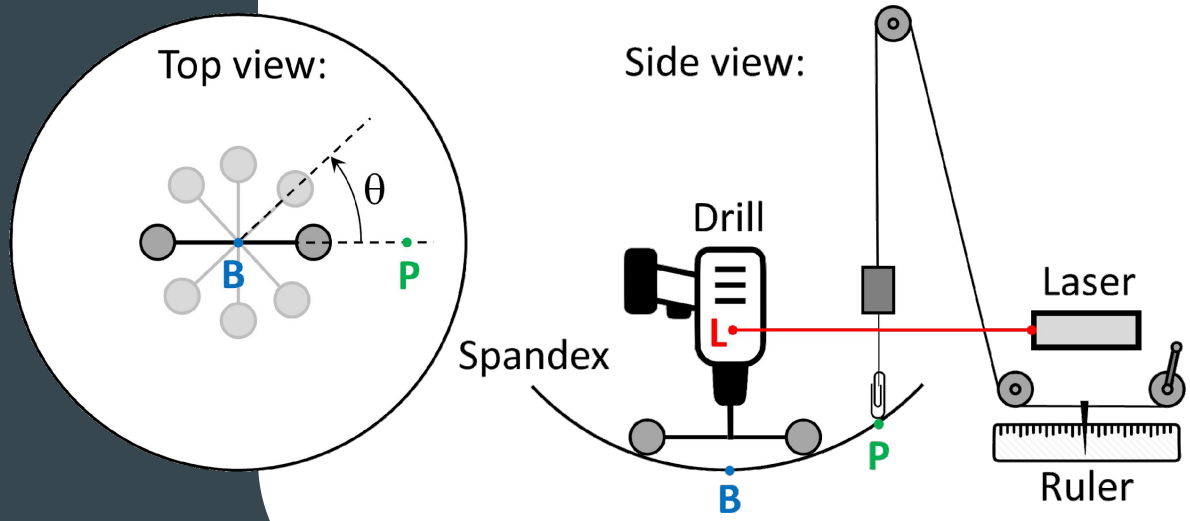
R and f dependence from **moment of inertia** and its **second time derivative**. But do these still apply for **spandex waves**? We tried to answer this **experimentally**.

$$h_{2D} \sim \frac{Rf}{\sqrt{r}}?$$

“Garage Depth” Detector

Inspired by **depth detectors** people often use in their garage to determine when the car is **fully** within the garage.

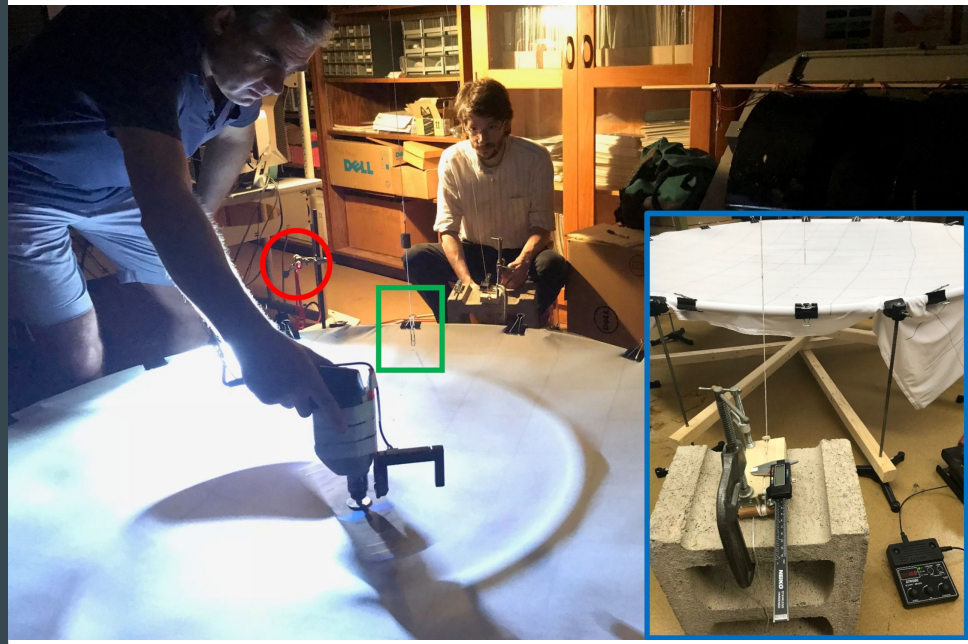
Two main parts:
1. Wave generation (B, L)
2. Amplitude measurer (P)



Measurement Procedure

Two operators; drill and *detector*.

1. Drill is positioned
2. *Paper clip detector is lowered*
3. *Mark as zero*
4. *Raise paper clip*
5. Generate waves
6. *Lower paper clip until disturbed*
7. *Record displacement*
8. Repeat



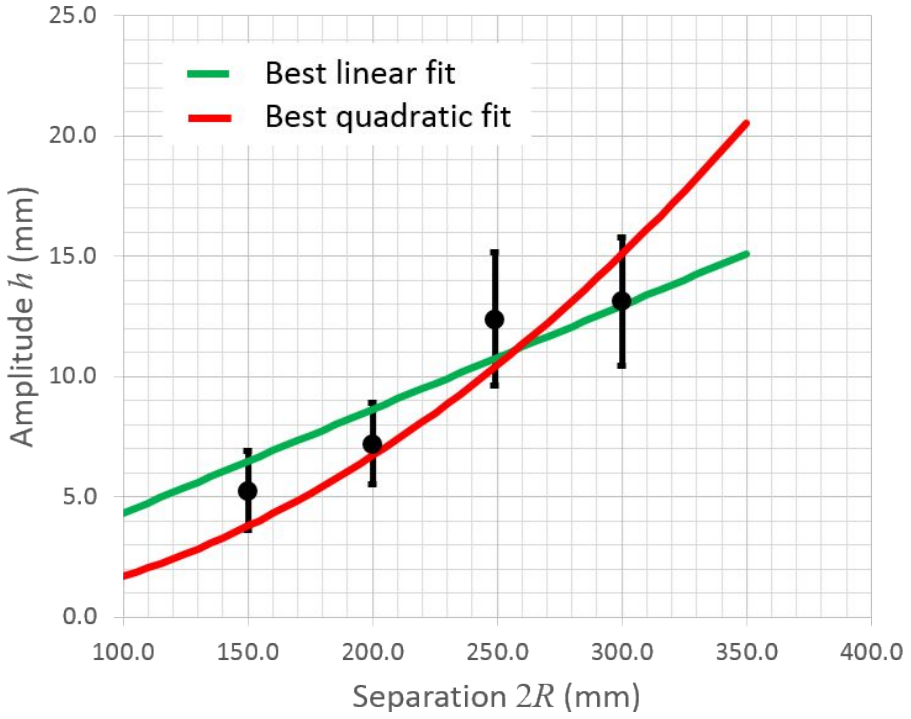
Amplitude vs Separation (2R)

Adjust **separation distance** of caster wheels.

Became **less stable** (more wobble) at greater distances.

Washers to help stabilize.

Best fit is **linear**, but cannot quite rule out **quadratic**.

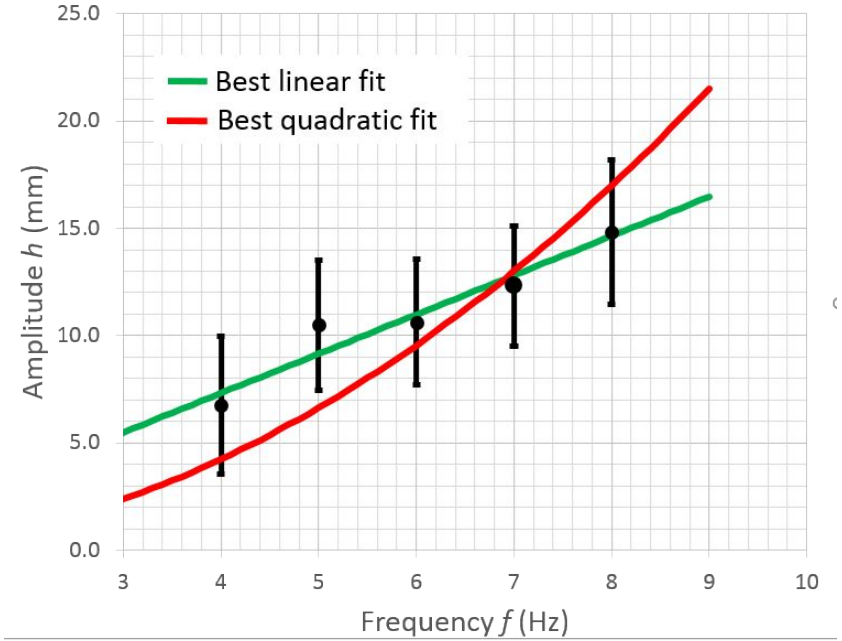


Amplitude vs Frequency (f)

Adjust **frequency** of the drill/strobe.

Again best fit is **linear**, though we cannot quite rule out **quadratic**.

Possible **systematic** effects.

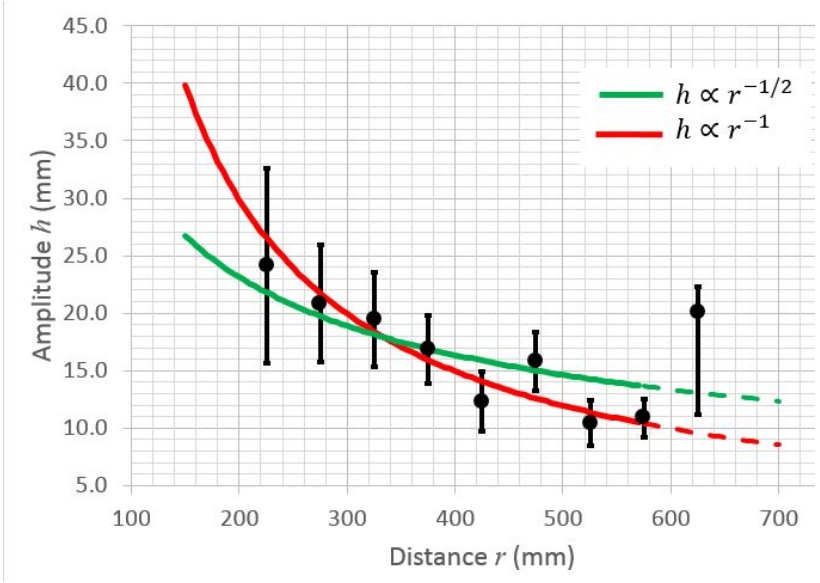


Amplitude vs Distance (r)

Disturbance from **air movement** near the spinning apparatus.

Measurements **near the edge** were difficult to read and increased due to reflecting waves **interfering constructively**.

Most difficult to determine better fit.



Summary of Results

Our data **suggests** that amplitude of 2D spandex waves is proportional to the square root of that of 3D gravitational waves but **further study** would be helpful.

Possible systematic errors:

- **Inflated** due to approaching from top
- Drill **stability** concerns (wobble/fatigue)
- Disturbance determined **visually**

$$h \sim \frac{Rf}{\sqrt{r}}$$

Conclusion

Inherently **classical** and **not relativistic**.

Entertaining and **educational** within limits.

Can only capture some aspects of GWs during **inspiral phase**.

Opens door to learning about general relativity in its **full glory**.