Black Holes, Gravitational Waves, Simulations

and Frickin' LASER Beams

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Me

and my qualifications

- BIT (Hon. Class I), UQ, 2015
- Principal Software Engineer, Boeing Defence Australia
- Doctoral Candidate, UQ, School of Maths and Physics

My Research

what the heck am I doing?!

- Binary Black Holes
- Gravitational Waves
- Globular Clusters
- N-Body Gravitational Simulations


- History of Gravity
- Detecting Gravitational Waves
- Gravitational Wave Sources
- N-Body Gravitational Simulations

- Kopernikus, N., *De revolutionibus orbium coelestium*, 1543.

- Heliocentrism - the planets orbit the sun.
  This fool wishes to reverse the entire science of astronomy; but sacred Scripture tells us that Joshua commanded the sun to stand still, and not the earth. - Martin Luther 1539

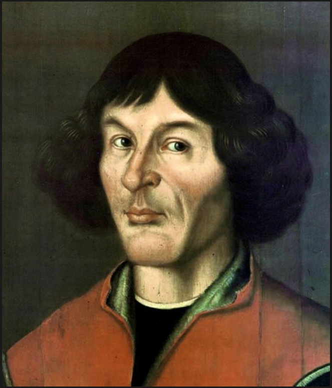
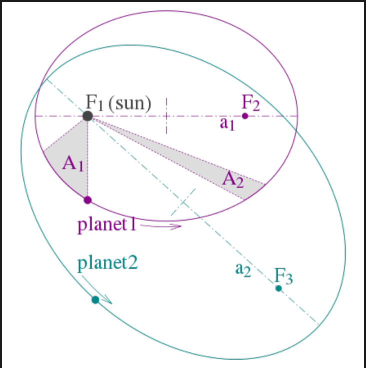


Figure: Nikolaus Kopernikus, 1473 - 1543

- Johannes Kepler, 1571 - 1630
- First Law: The orbit of every planet is an ellipse with the Sun at one of the two foci.
- His book, *Epitome Astronomiae Copernicanae*, was banned in 1619.



A Quick History
Gravity

Figure: Isaac Newton, 1642 - 1726

- Newton, I., *Philosophiæ Naturalis Principia Mathematica*, 1687.
- Universal Law of Gravitation
$$F = G\frac{m_1 m_2}{r^2}$$
- A very good approximation. I still use it!

- James C. Maxwell, 1831 - 1879.
- **Light is an electromagnetic wave!**
- Synthesized by Oliver Heaviside into four equations.

  There can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics. - Richard Feynman

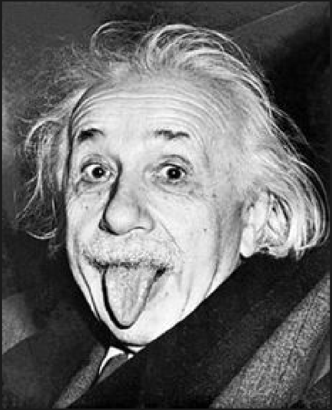
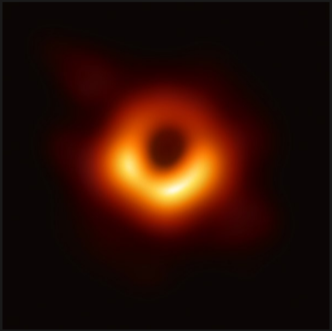


Figure: Albert Einstein, 1879 - 1955

- Einstein, A., *Die Feldgleichungen der Gravitation*, 1915.
- Einstein's Field Equations inspired by Maxwell's Equations.
- Relate spacetime curvature to matter, momentum and stress.
- Predicted time dilation, gravitational lensing, black holes and gravitational waves!

A region of spacetime where gravity is so strong that nothing, even light, can escape from it.

- Characterised by Swarzschild's solution to EFE in 1916.
- Cygnus X-1 discovered in 1971.
- Formed through various means, including at the end of a star's life.



A Crude Definition

Gravitational Waves

Spacetime curvature caused by the energy emitted by accelerating objects.

A Quick Video

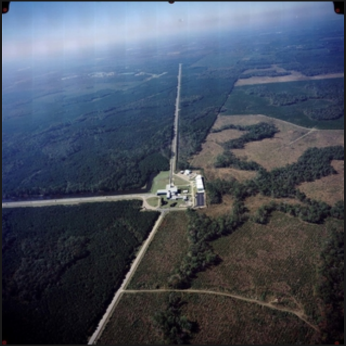
VIDEO

A Quick Example
Gravitational Waves

- Peters' formulae (1969) approximated EFE for two orbiting bodies.
- Decrease in orbital radius; inspiral.
- Energy leaves the system as gravitational radiation.

LASER Interferometers

LASER **I**nterferometer **G**ravitational-Wave **O**bservatory



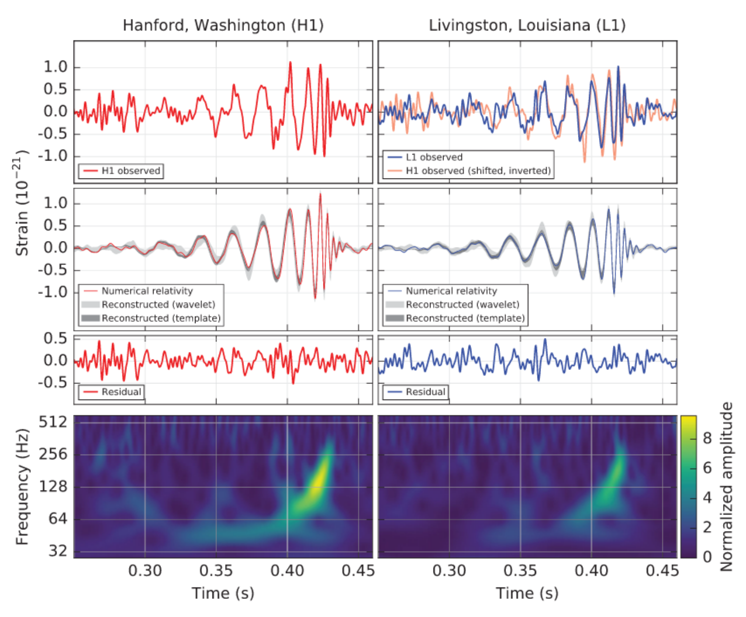
LASER Interferometry

How Does it Work?

- Two arms at right angles, 4km long, ultra high vacuum.
- LASER beams fired down vacuum tubes and reflected by a mirror.
- Interference pattern is measured.

VIDEO

Finding Black Holes

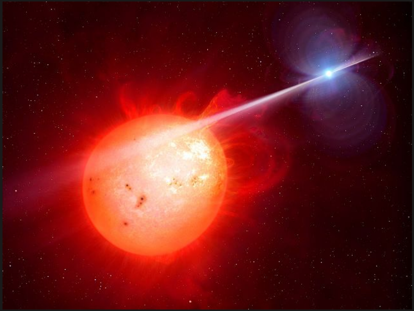


Gravitational Wave Events, Observing Runs 1 and 2

Event	Primary $M_\odot$	Secondary $M_\odot$	Remnant $M_\odot$
GW150914	35.6	30.6	63.1
GW151012	23.3	13.6	35.7
GW151226	13.7	7.7	20.5
GW170104	31.0	20.1	49.1
GW170608	10.9	7.6	17.8
GW170729	50.6	34.3	80.3
GW170809	35.2	23.8	56.4
GW170814	30.7	25.3	53.4
GW170817	1.46	1.27	≤ 2.8
GW170818	35.5	26.8	59.8
GW170823	39.6	29.4	65.6

Where do binary black holes come from?

Possible Scenarios



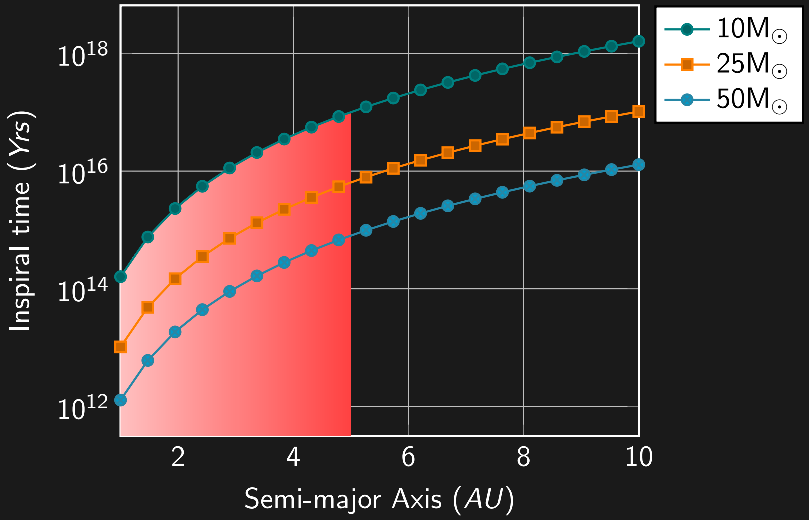
- Primordial black holes.
- Binary or triple stellar evolution.
- O-type main sequence stars form BH independently.

Problem

PROBLEM

Where do binary black holes come from?

Thought Experiment

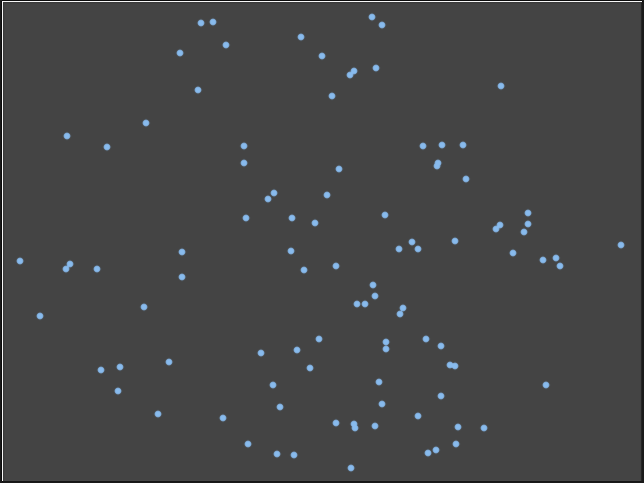


Globular Clusters

A Hole-y Site?

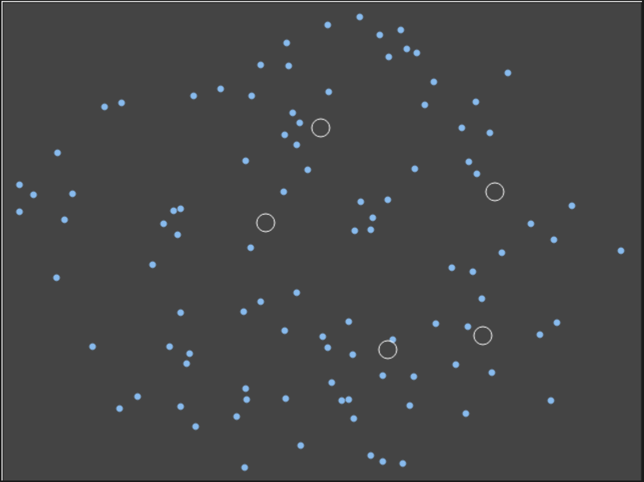
- Dense star clusters - gravitationally bound.
- Hundreds of thousands - millions of stars.
- Home of exotic phenomena; millisecond pulsars, neutron stars, black holes.

Globular Clusters



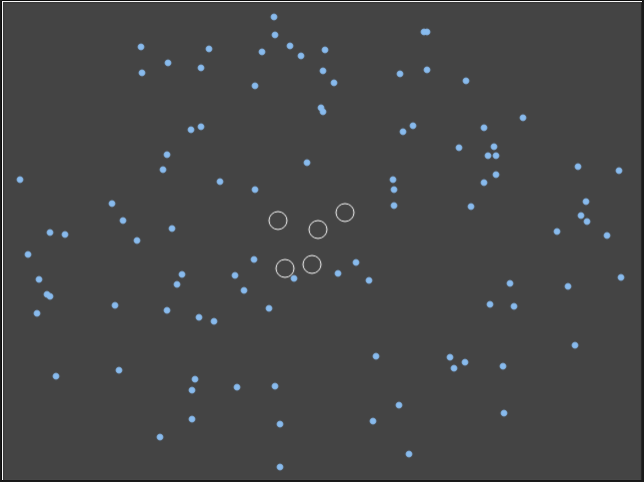
$T = 0$ dense cluster of stars.

Globular Clusters



$T \geq 10$Myr black holes start to form.

Globular Clusters



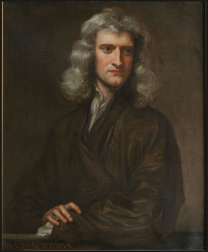
$T \geq 100$Myr black holes sink to the core.

PROBLEM

N-Body Simulations

My Research

Simulating the trajectory of millions of stars, over time.



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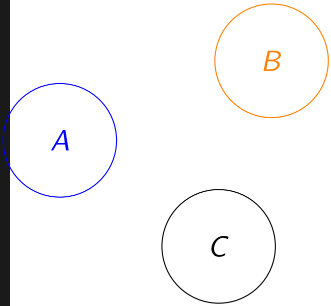
VIDEO

Formally

Given the initial positions and velocities at $T = 0$ of a system of celestial objects, predict their orbital motions for all $T > 0$.

$$\vec{F}_i = \sum_{j=1}^{n} \frac{Gm_i m_j}{|x_i - x_j|^2}$$

Example



$$\vec{F_A} = \frac{Gm_A m_B}{|x_A - x_B|^2} + \frac{Gm_A m_C}{|x_A - x_C|^2}$$

$$\vec{F_B} = \frac{Gm_B m_A}{|x_B - x_A|^2} + \frac{Gm_B m_C}{|x_B - x_C|^2}$$

$$\vec{F_C} = \frac{Gm_C m_A}{|x_C - x_A|^2} + \frac{Gm_C m_B}{|x_C - x_B|^2}$$

PROBLEM

Problem

Recall:

- $\vec{F}$ involves summing over every other body in the system.
- We need to determine $\vec{F}$ for every body at every step. $+$
- That's n^2 calculations per step!

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How many for a realistic star cluster?

$$10^6 \text{ stars} \Rightarrow 10^{12} \text{ calculations/step}$$

$$10^{15} \text{ steps} \Rightarrow 10^{27} \text{ calculations in total}$$

$$3 \times 10^9 \text{ calculations/s} \Rightarrow 10 \text{ Gyrs}$$

That's as slow as real time.

N-Body Simulations

It's Hard

N-Body Simulations

Solutions

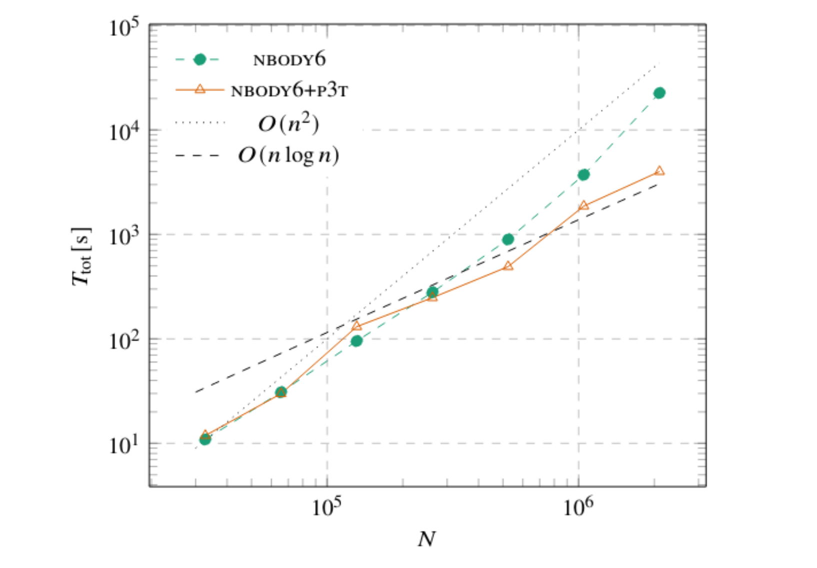
- Approximations
- Advanced Algorithms
- Better Hardware

The Kit

Heavy Lifting

How's it Going?

Results so far



The End

How did I do?

- History of Gravity
- Detecting Gravitational Waves
- Gravitational Wave Sources
- N-Body Gravitational Simulations

Fin

THANKS!