Australian Government
Australian Research Council

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Gravitational-wave Astronomy: Decoding the dark Universe

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Monash University & OzGrav

Swinburne University of Technology · Australian National University · Monash University · The University of Adelaide · The University of Melbourne · The University of Western Australia · AAO · CSIRO

About this mini course

This course will demonstrate how we learn astrophysical information from gravitational waves that are buried in Advanced LIGO/Virgo data

The other topics covered will be (astro)physics and theory (Paul Lasky), galaxy evolution (Middleton), and detectors (Rob Ward)

The course is designed to be interactive and is contained within jupyter notebooks which can be run in Google colaboratory (colab)

- You can run the notebooks in Google Drive(!) without having to install anything on your laptops

The main techniques we will encounter are those of ***Bayesian Inference***

We'll also look at LIGO data and how to build our intuition about how we can see detect gravitational waves

The techniques that are central to this mini course are foundational in data science and are widely applicable outside of gravitational-wave astronomy

Astronomy, pre 2015

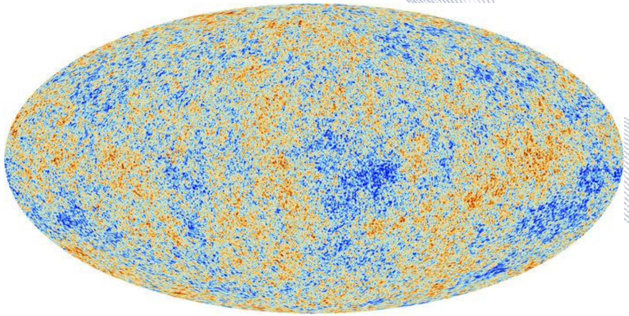
Electromagnetic

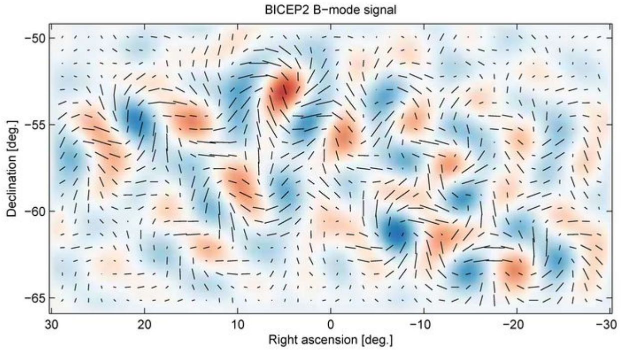
- Optical
- Radio
- X-ray
- Gamma ray
- Infrared
- Microwave

Non-EM

- Neutrinos
- Cosmic rays

Microwave

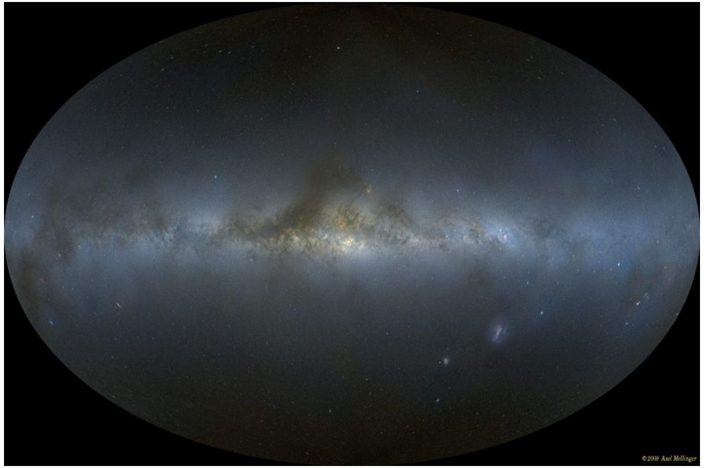




Cosmic Microwave Background (CMB), Planck 2013

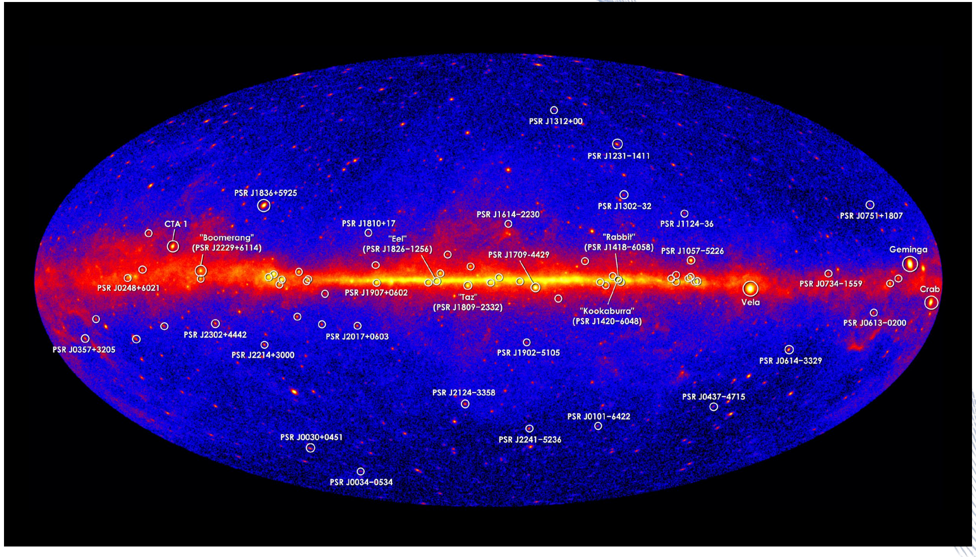
Optical to infrared

Hubble eXtreme Deep Field



All-sky Milky Way Panorama Project

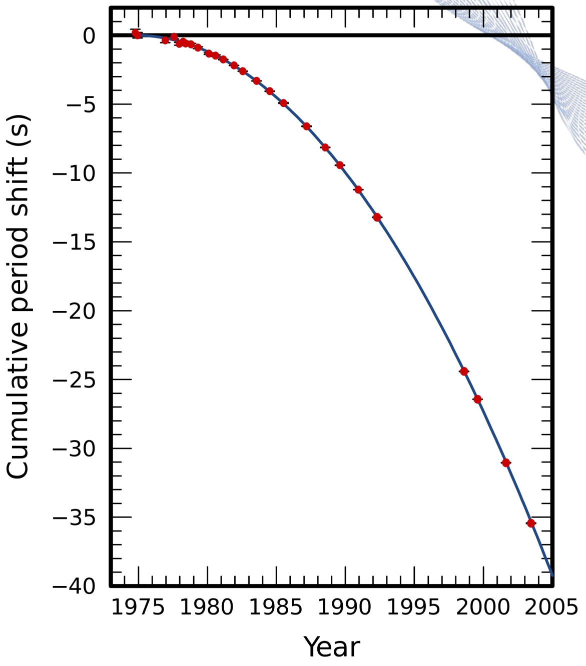
Gamma rays



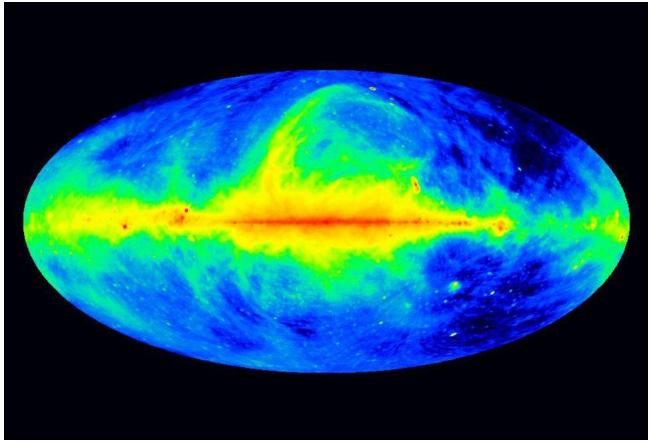
This is the sky at energies above 1 GeV (Fermi)

The circles are pulsars: rapidly rotating neutron stars

Radio



Orbital decay of **PSR B1913+16** (Hulse-Taylor binary) due to gravitational-wave emission

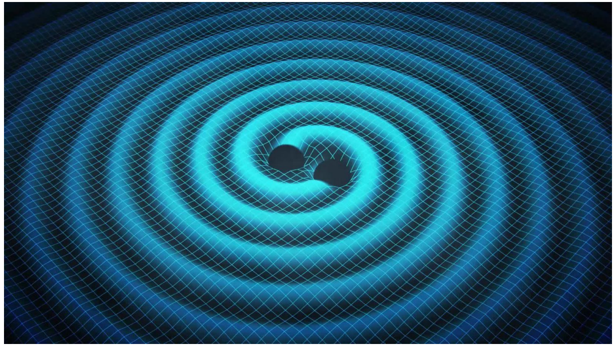


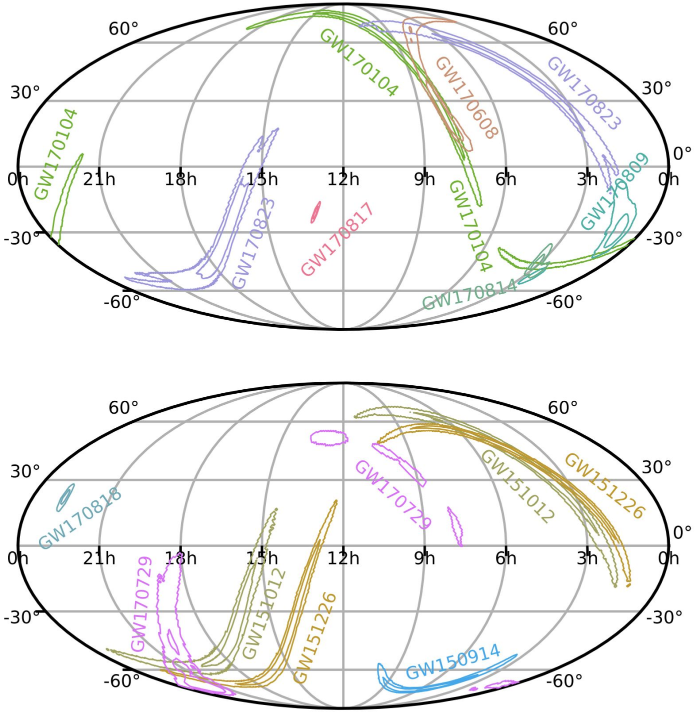
408 mHz all sky survey (Jodrell Bank & Parkes)

Gravitational waves

The gravitational-wave sky before 2015

Gravitational waves #UpToEleven



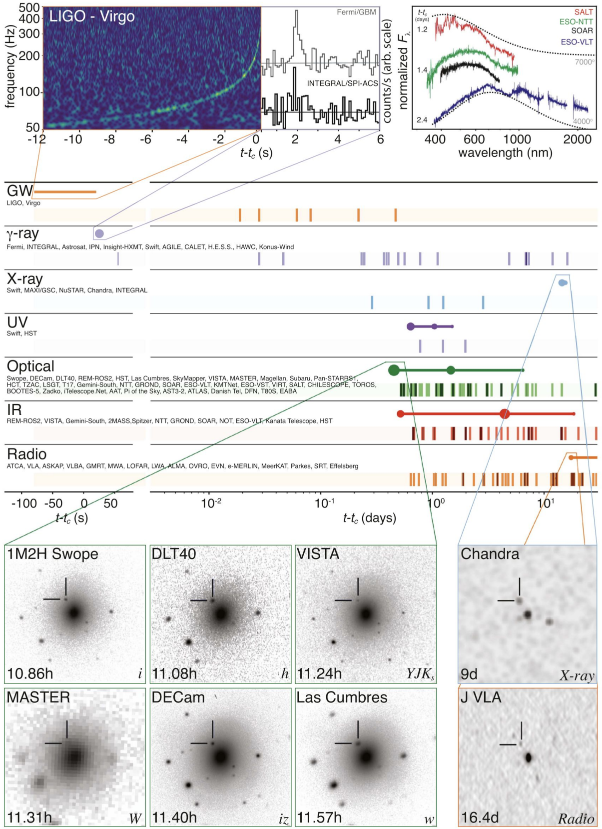


The gravitational-wave sky today

- 11 confirmed observations
  - 10 binary black hole coalescences
  - 1 binary neutron star coalescence

GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs (Abbott et al - LSC)

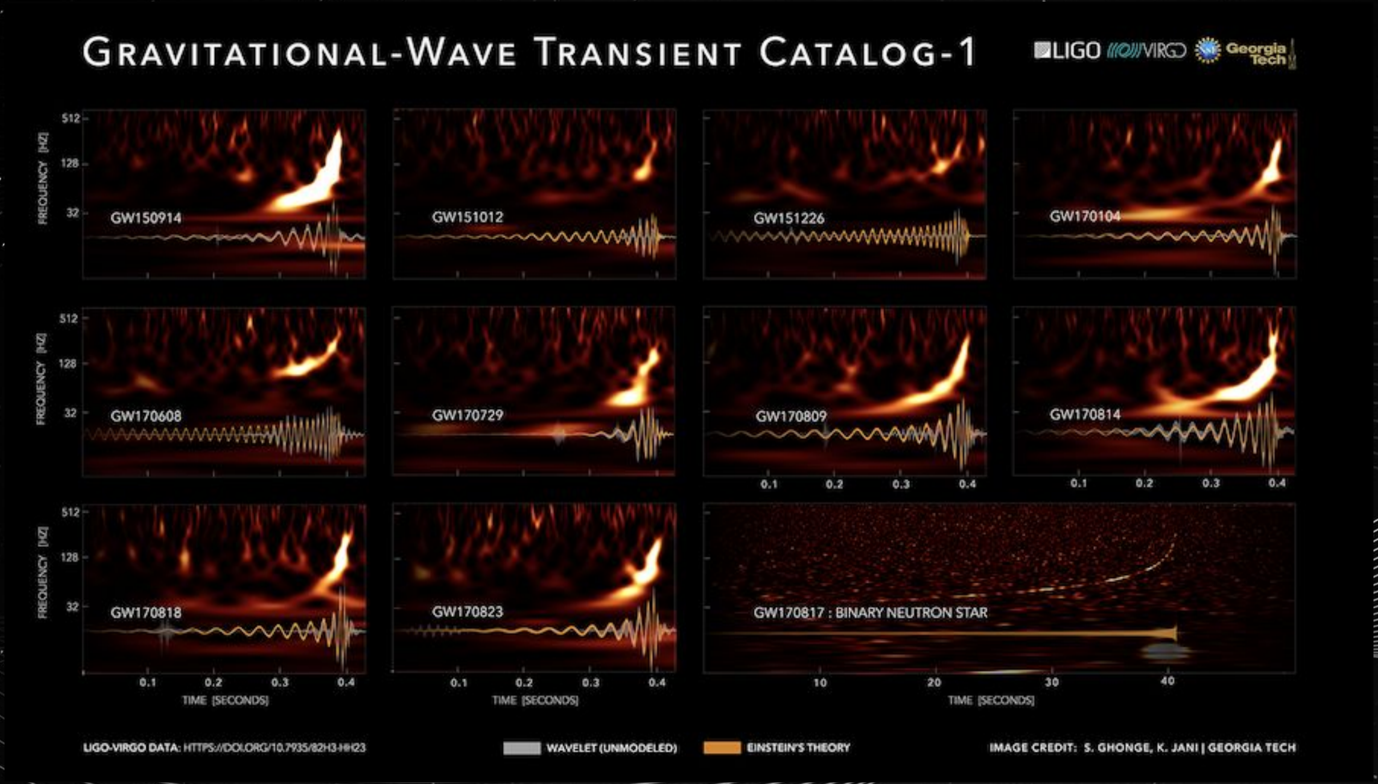
Multi-messenger astronomy: Gravitational waves + electromagnetic radiation



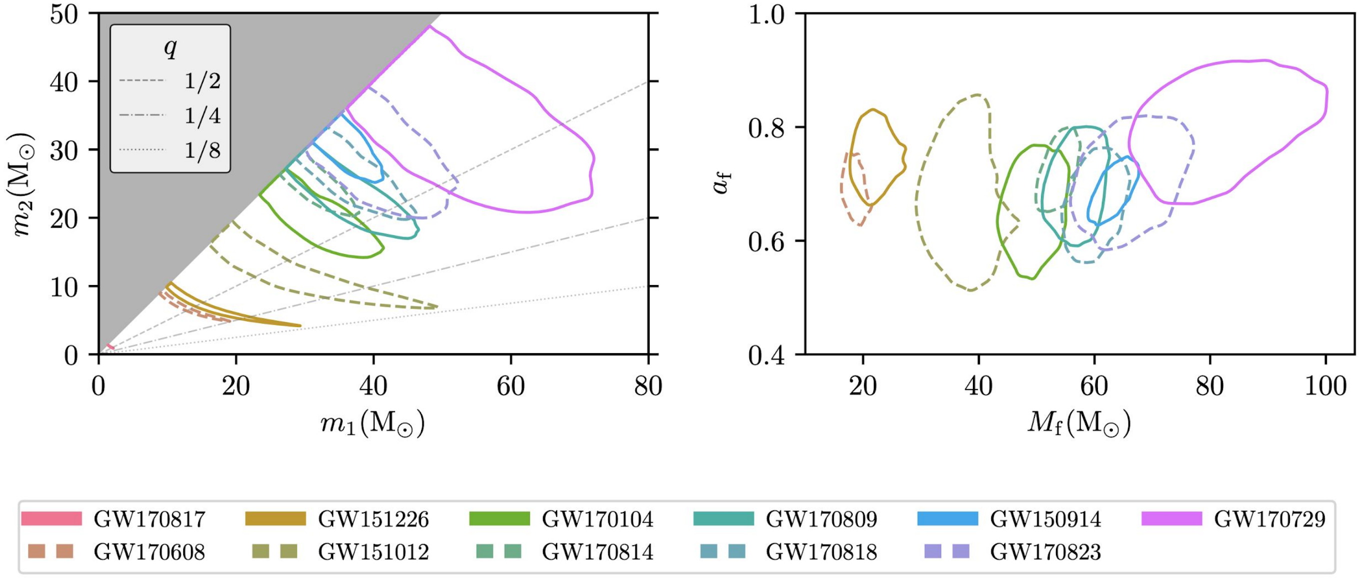
- The binary neutron star merger (GW170817 in GWs) was accompanied by a range of electromagnetic counterparts
  - This was one of the most observed events in the history of astronomy
- The gravitational waves contain information about nuclear matter at extreme pressure and densities (see lectures by Paul Lasky)

Multi-messenger Observations of a Binary Neutron Star Merger (Abbot et al - LSC), Figure 2 http://iopscience.iop.org/article/10.3847/2041-8213/aa91c9

Gravitational waves #UpToEleven



Binary black hole and binary neutron star properties



These are some of the properties of the black holes and neutron stars

- The contours in the plots represent 90% -probability regions
- All of these properties were inferred *directly from the gravitational waves*

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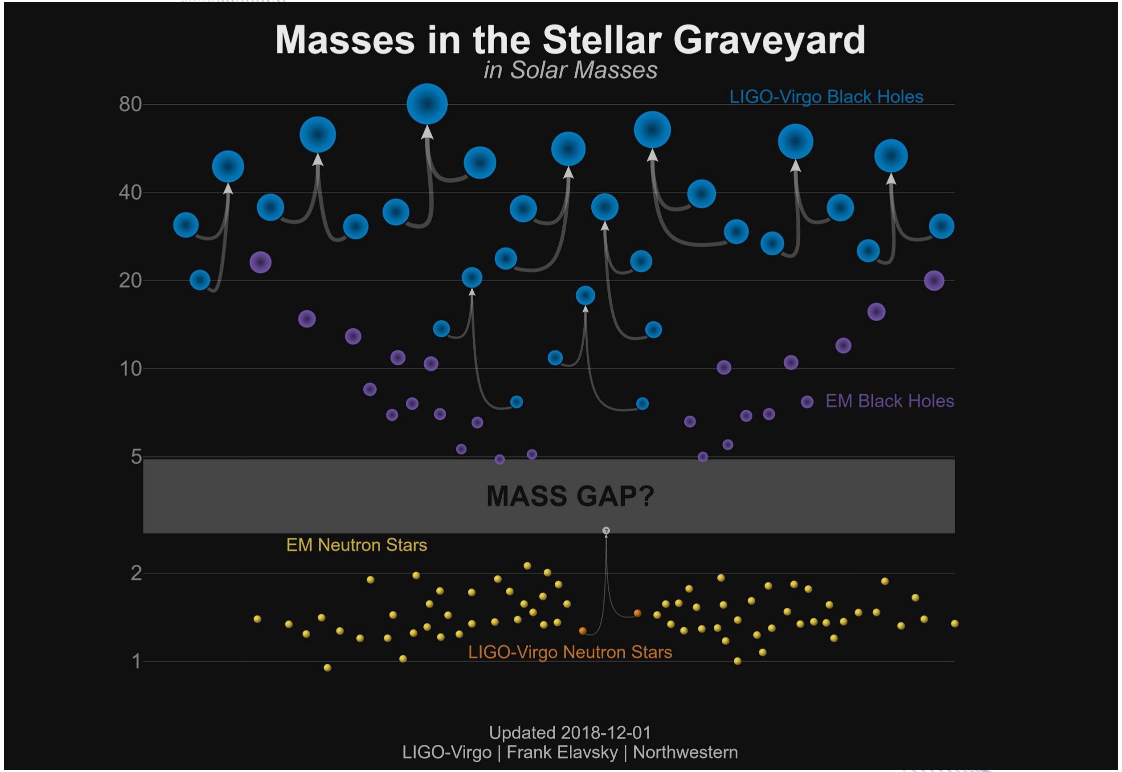
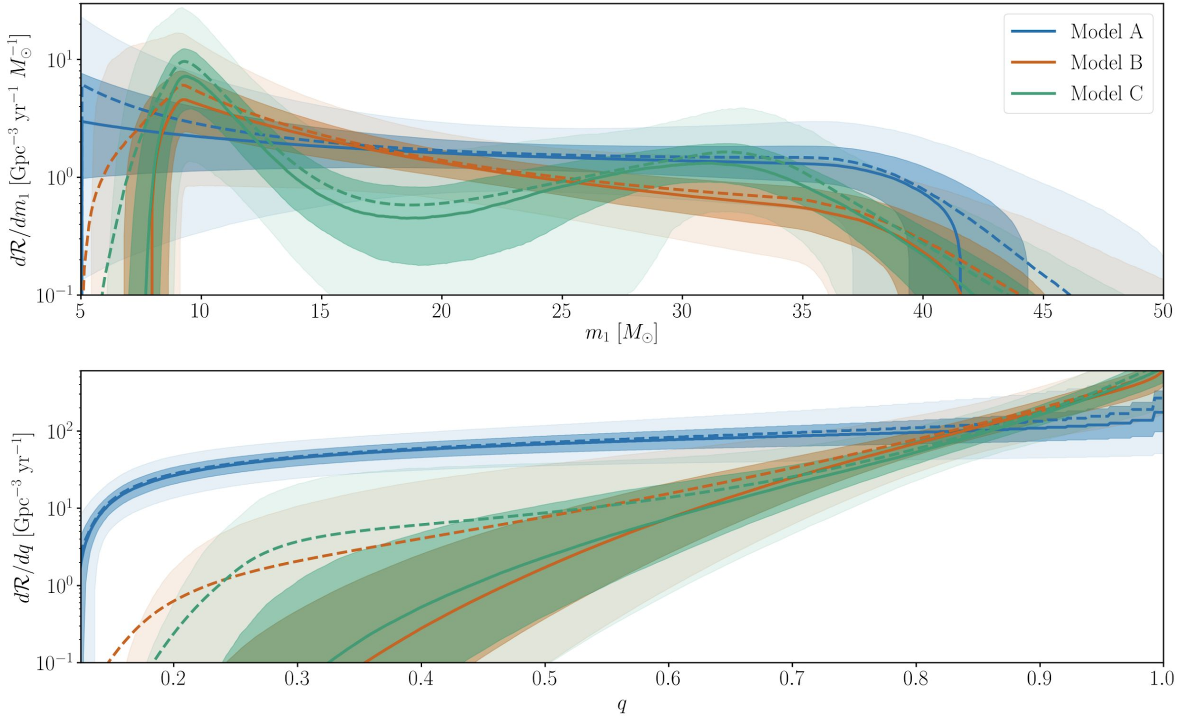
Binary black hole and binary neutron star properties



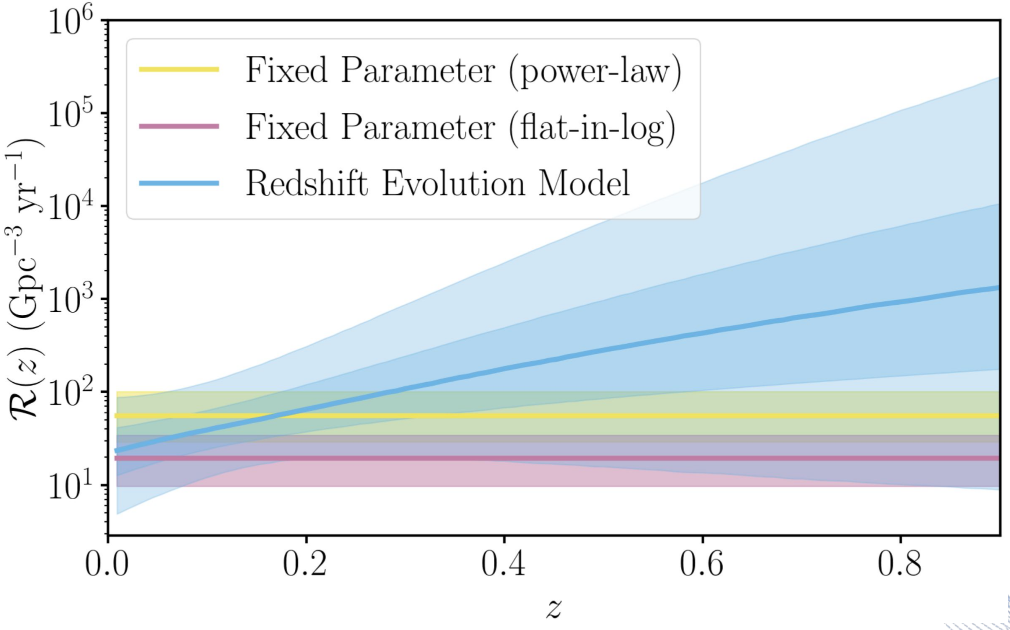
Binary black hole population properties



- From the 10 detections we're starting to learn about the population of binary black holes in the universe
  - e.g., their mass distributions
  - And merger rates
- Black hole populations could be a proxy for star formation in galaxies

Binary Black Hole Population Properties Inferred from the First and Second Observing Runs of Advanced LIGO and Advanced Virgo (Abbott et al - LSC)

Binary black hole population properties



- From the 10 detections we're starting to learn about the population of binary black holes in the universe
  - e.g., their mass distributions
  - And merger rates
- Roughly, 1 binary black hole merger every 200s somewhere in the universe

Binary Black Hole Population Properties Inferred from the First and Second Observing Runs of Advanced LIGO and Advanced Virgo (Abbott et al - LSC)

Open questions

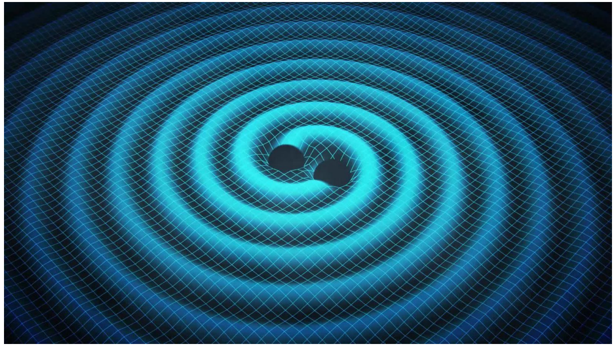
Stellar Astrophysics

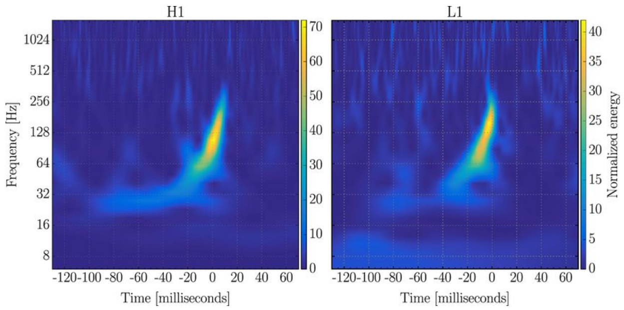
- Does the formation rate of binary black holes follow star formation rates in the universe?
  - Are there primordial black holes?
- Is there a mass gap?
  - Compact objects with masses between 2.5-5 solar masses?
- What can black hole and neutron star mergers telling us about the environments in which they form?
  - e.g., globular clusters

Fundamental Physics

- Can we find evidence for new physics beyond general relativity in gravitational waves?
  - Are there extra polarizations?
- Are there more exotic compact objects than black holes and neutron stars?
  - e.g., boson or quark stars
- How does matter behave at the extreme pressure and densities in neutron stars?
  - The nuclear equation of state of neutron stars

How do we perform GW astronomy?



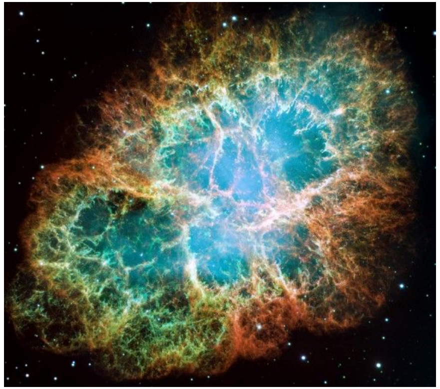


Sources

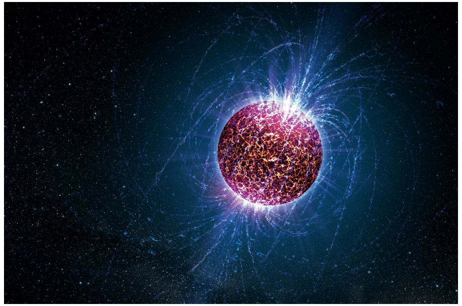
Compact binary coalescence

Sources

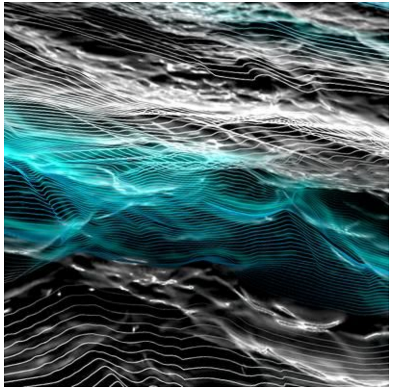
"Bursts" of GWs from, e.g., nearby supernovae



Continuous waves from, e.g., rapidly rotating neutron stars



Stochastic GWs from, e.g., unresolved binaries, the big bang



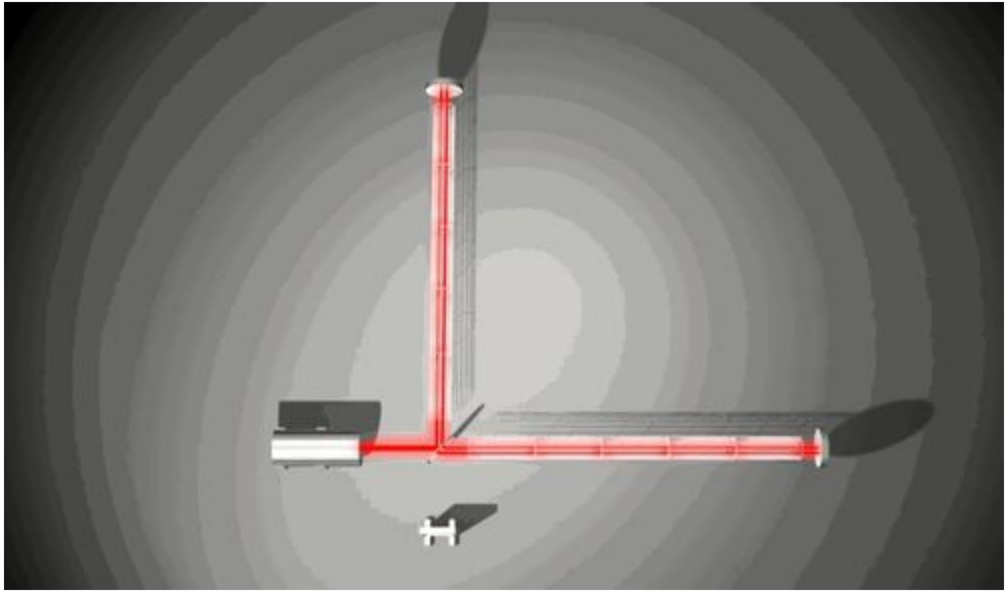
Exotica, e.g., GWs from cosmic string cusps

Signals

- Gravitational waves cause a *strain* in spacetime

$$\text{strain} = \Delta L / L$$

- Interferometers transduce spacetime strain into optical power



Animation: Aurore Simone (Sonoma State U.)

Signals

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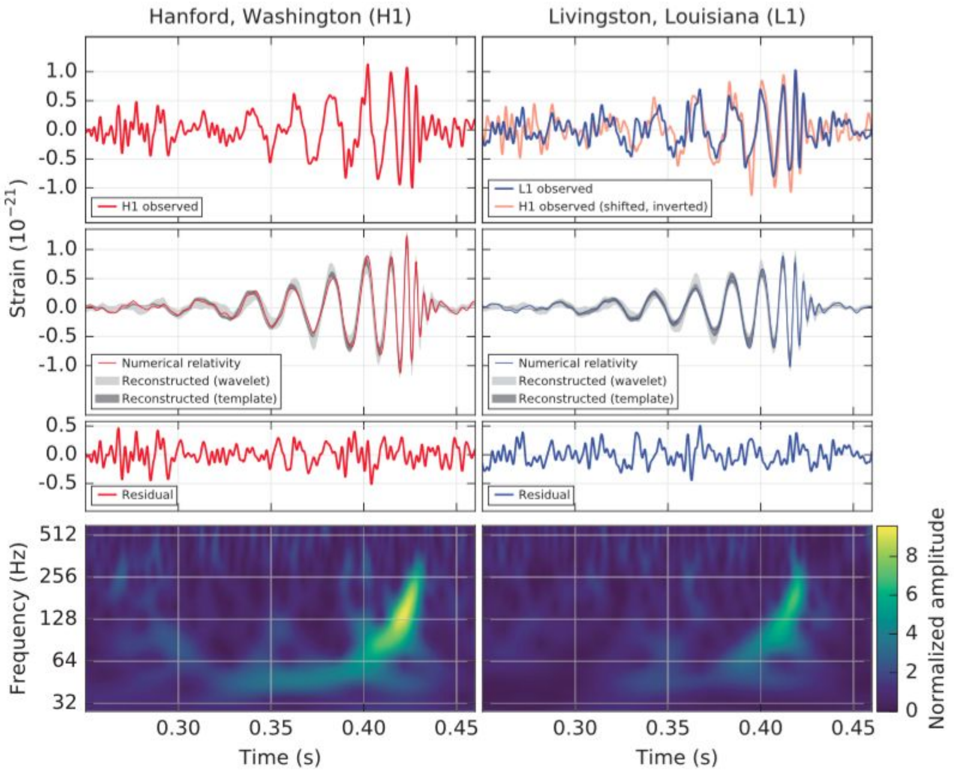
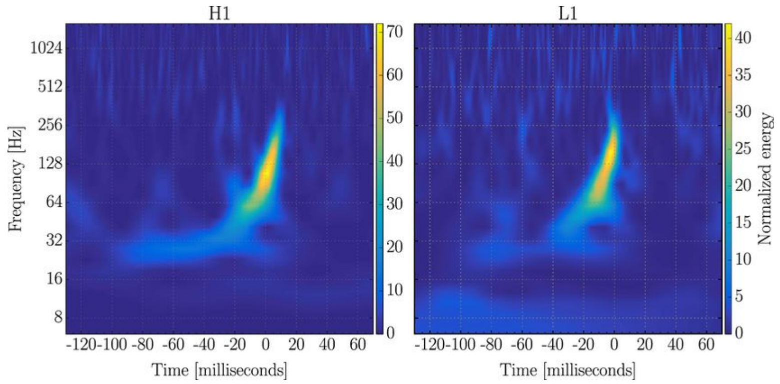
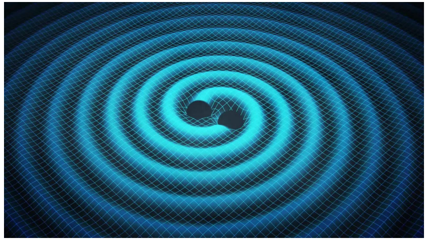


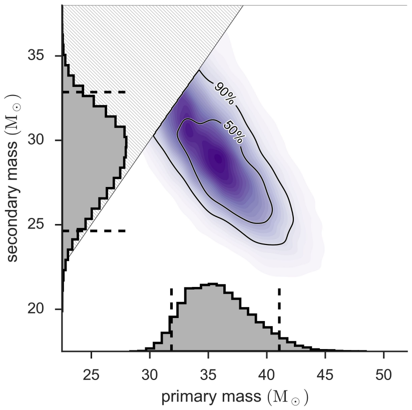
Observation of Gravitational Waves from a Binary Black Hole Merger (Abbott et al - LSC)

Astrophysics: Inference on data



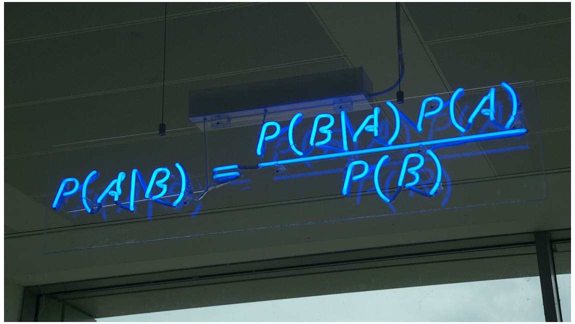
Inference





Bayesian Inference: 18th Century insight to 21st Century data science

Bayes Theorem



- Gravitational waves *encode* information about black holes, neutron stars, spacetime, etc…
- Bayesian inference *decodes* the information

Bayesian Inference: 18th Century insight to 21st Century data science

- Optimal framework for *statistical inference*
- Gives a *unified* framework for hypothesis testing, parameter estimation/feature extraction and hierarchical inference

Assign probabilities to hypotheses such as:

- How much more likely is it that the data contains a GW signal vs noise; Did we see evidence for new physics when black holes merge? Is the speed of gravity the same as the speed of light?: ***Hypothesis testing***
- If the data contains a GW signal, what is the source; if it's a binary black hole, what are the masses, spins etc… ***Parameter estimation***
- How do we learn about populations (such as mass distributions and merger rates) from ensembles of measurements? ***Hierarchical inference***

Overview of topic 1

Topic 1: A brief introduction to Advanced LIGO data and black-hole signals

- Characteristics of coalescing compact signals
- Understanding LIGO data
  - Data surrounding GW150914
  - The strain time series and Fourier series
  - The Power Spectral Density (PSD)

Overview of topic 2

Topic 2: Inference on gravitational-wave signals in LIGO data

- Basics of Bayesian inference
  - Conditional probabilities
- Hypothesis testing and model selection
  - Odds
  - Bayes factors
- Parameter estimation
  - Likelihoods, priors, evidences
  - Posterior probability density functions

Overview of topic 3

Topic 2: Algorithms

- Scalability and high-dimensional models
  - The curse of dimensionality
- Parameter estimation and hypothesis testing for high-dimensional models
  - Learning about binary black hole source properties (from GWs) using nested sampling
  - Uncertainty quantification

Before we begin...

- The aim here is to build up complexity from the ground up
    - The coded examples are intended to demystify what I think can be fairly opaque and cumbersome notation

- We will only cover a very small number of topics: but we will demonstrate how elementary questions about data can be answered within a single framework

Local

NEWS IN BRIEF

Explanation Of Board Game Rules Peppered With Reassurances That It Will Be Fun

1/27/17 8:00am • SEE MORE: LOCAL

X-Ray

A selection of images from the Chandra X-Ray Observatory (2015: *International year of light*)