LIGO Black Holes

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WHAT IS LIGO?

LIGO (Laser Interferometer Gravitational-Wave Observatory) is a national facility created to directly detect gravitational waves using laser interferometry.

LIGO consists of two interferometers across the U.S. that are operated in unison (one is in Washington and the other is in Louisiana).

Source: “About” page, ligo.caltech.edu

Gravitational waves

Light speed ripples in space-time, where the strongest ripples are created by high-energy cosmic events (like high mass/density objects orbiting each other at increasing speeds).

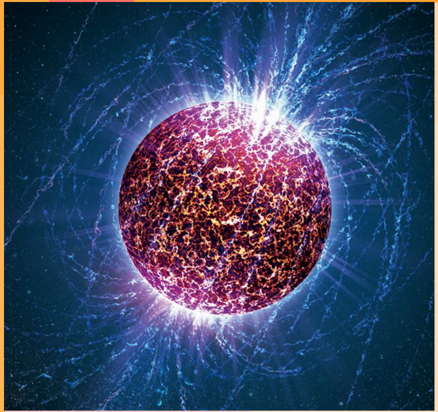
First predicted by Albert Einstein in 1916, but the first piece of proof was found by two researchers in New Jersey in 1974.

By the time gravitational waves reach the Earth, they are drastically different in size, usually around 10^{-3} times the size of a nucleus.

Gravitational waves interact weakly with matter, allowing them to travel through space essentially without disruption.

Source: "Gravitational Waves" page, ligo.caltech.edu

Types of Gravitational Waves: Continuous



Source: “Sources and …” page, ligo.caltech.edu

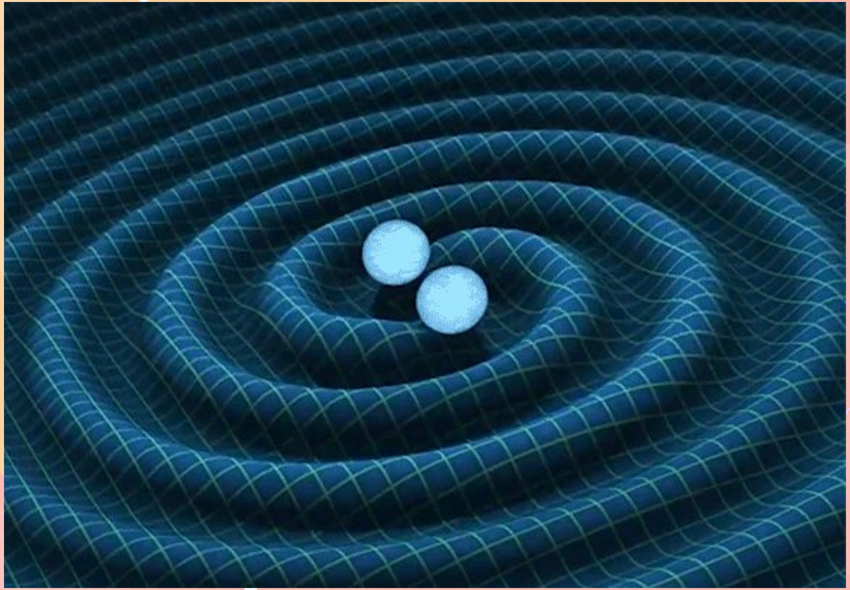
Continuous Gravitational Waves

- Believed to be generated by imperfections on the surface of lone, massive, spinning, spherical objects, such as neutron stars.
- The emission rate of continuous gravitational waves changes with the spin rate of the objects, therefore if the object spins at a (relatively) constant rate then the gravitational waves remain continuous at the same frequency and amplitude
- LIGO hopes to discover these with their “Advanced LIGO” detection

Types of Gravitational Waves: Compact Binary Inspiral

Compact Binary Inspiral Gravitational Waves (CBI)

- All gravitational waves detected by LIGO fall into this category
- CBI gravitational waves occur when two massively compact objects orbit each other at increasing rates
- Three subclasses of CBI systems:
    - Binary Black Hole (BBH)
    - Binary Neutron Star (BNS)
    - Neutron Star-Black Hole Binary (NSBH)
- Source: "Sources and ..." page, ligo.caltech.edu
- Image Source:



Types of Gravitational Waves: Compact Binary Inspiral

- Each binary pair has a unique gravitational wave pattern, but all are inspiral
    - Inspiral is a several million years long process where two massively compact object orbit each other and produce GW
    - The GW carries away some of the orbital energy of the system, bringing the objects closer together over time
    - As they move closer together, their orbital rates increase, creating stronger gravitational waves that take more orbital energy away, and so on till the pair collide
- The final inspiral length is determined by the mass of the objects, meaning black holes have a shorter final inspiral than neutron stars (the difference between two tenths of a second and over 100 seconds (10^3 difference))
- LIGO is tuned into a specific frequency range for the gravitational waves, allowing a brief window for data collection
- Source: “Sources and …” page, ligo.caltech.edu

Types of Gravitational Waves: Stochastic

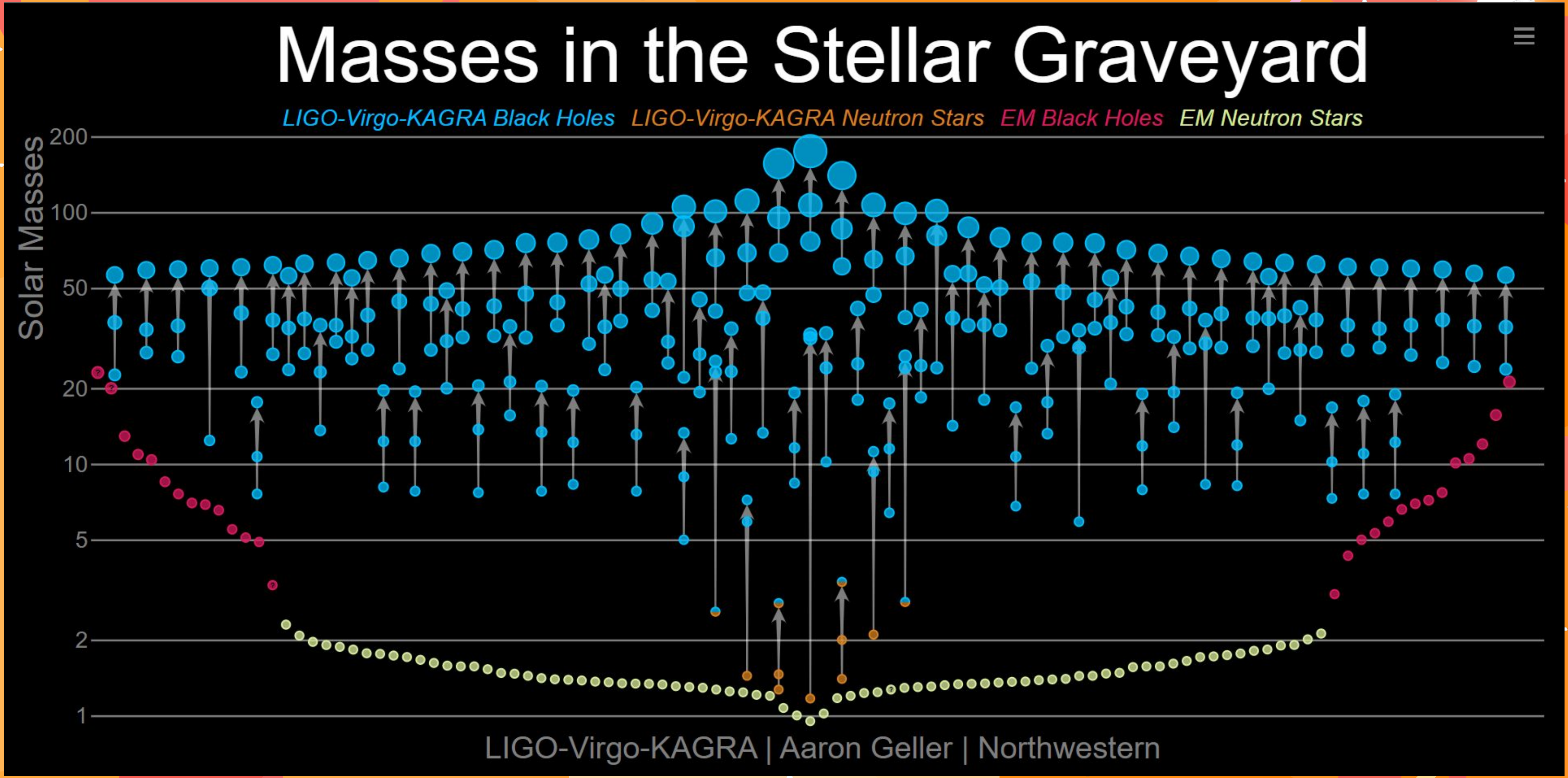
Stochastic Gravitational Waves

- Small, random, and hard to detect gravitational waves from a variety of potential sources, including the Big Bang
- These waves would be randomly mixed together and can create confusing signals for the detectors
- Source: “Sources and …” page, ligo.caltech.edu

Types of Gravitational Waves: Burst

Burst Gravitational Waves

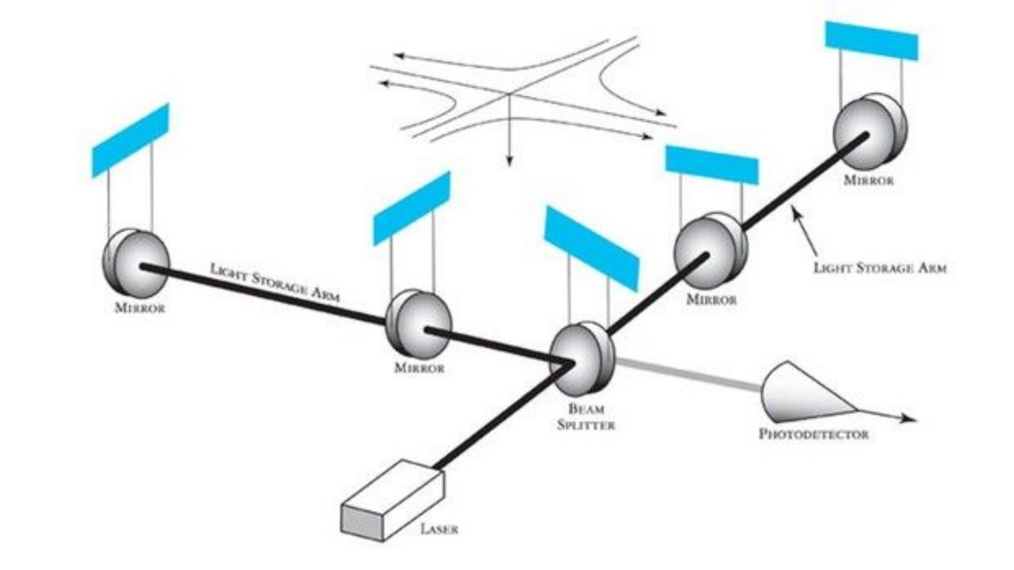
- Have not been detected, as it is hard to predict exactly where in a system GWs will appear and there numerous systems that are still unknown
- This keeps the search for gravitational waves open as there is no basis to assume the properties of GWs have been sufficiently defined
- Source: “Sources and …” page, ligo.caltech.edu



Source: [Ligo-Virgo Mass Plot]

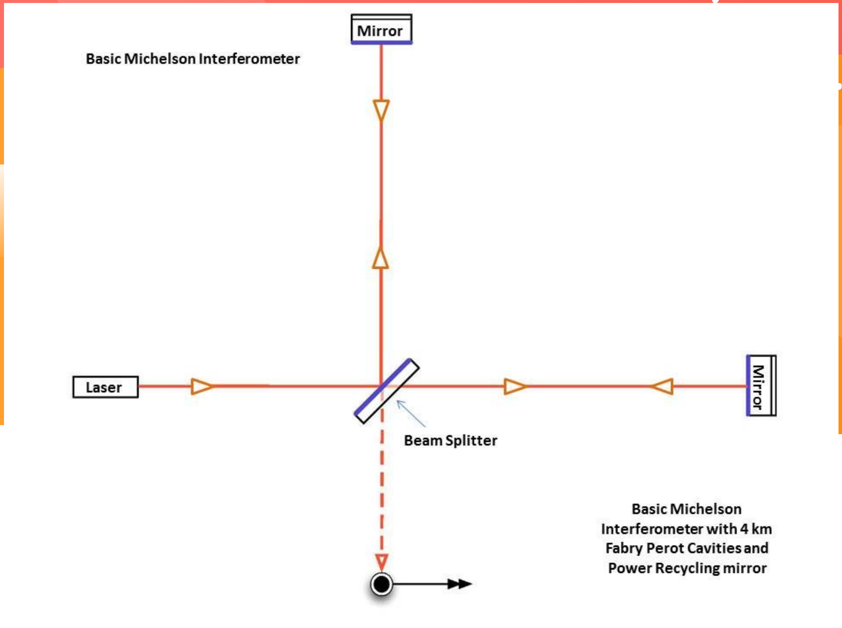
How does the Interferometer work?

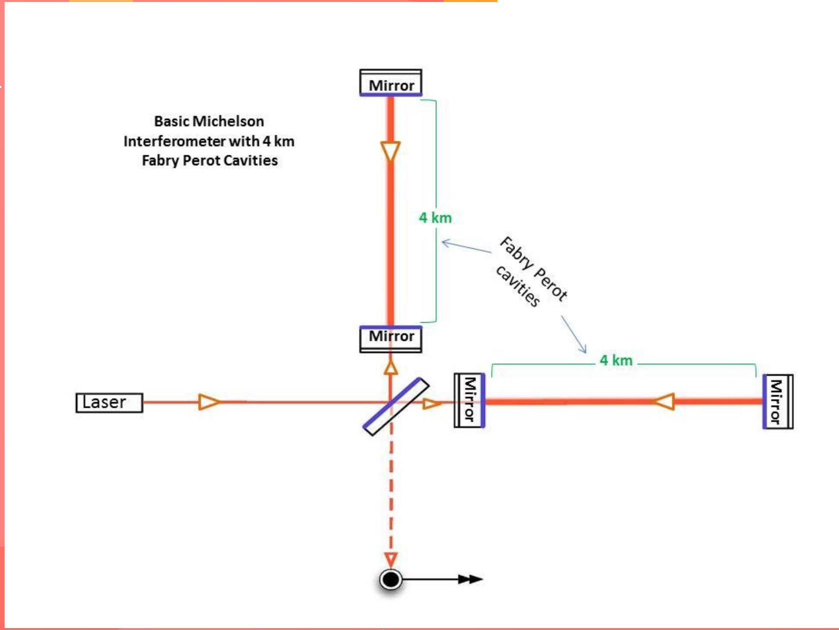
- Used to detect gravitational waves
- Laser is directed at a beam splitter
- Breaks into two beams that travel along interferometer arms
- Gravitational waves distort lengths of the arms
- Beams hit a mirror at the ends of the arms
- Time how long it takes for both beams to return
- https://www.ligo.caltech.edu/page/what-is-interferometer

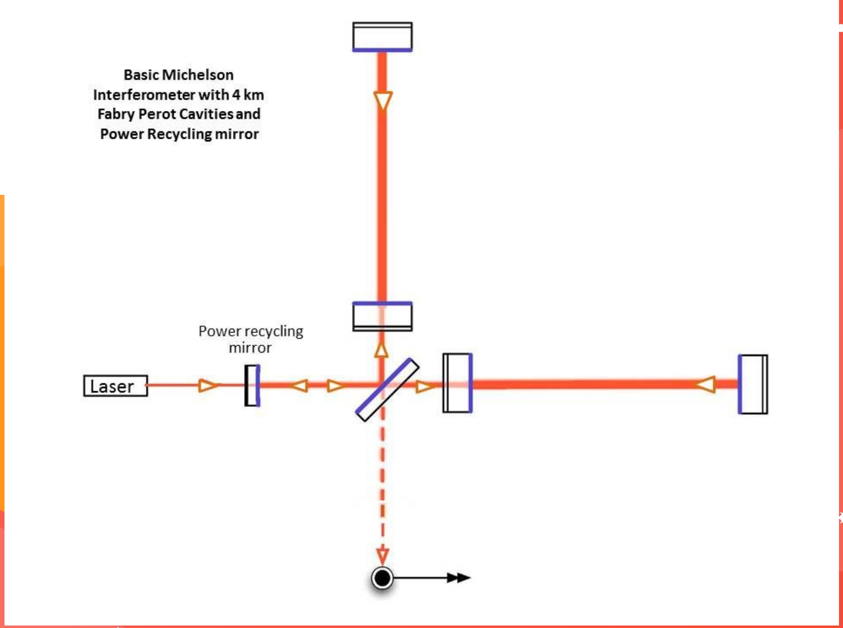


LIGO's Interferometer

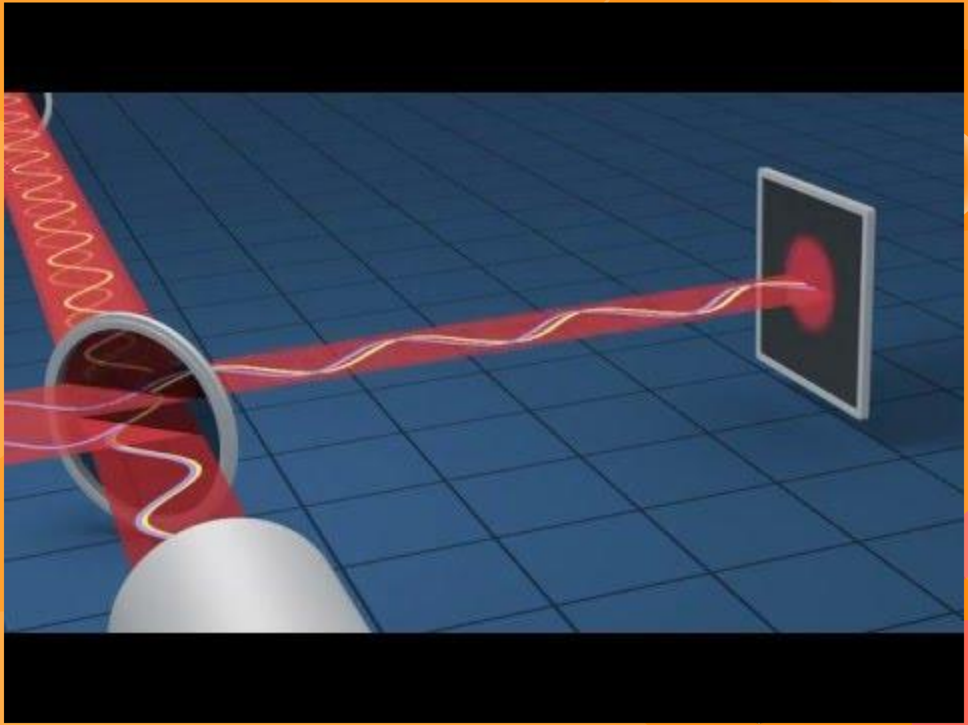
- 4 km long arms
- Mirrors are placed within arms
- Light bounces back and forth from the mirrors 300 times
- Cumulative 1200 km distance traveled
- Allows the interferometer to make more precise measurements
- Use power-recycling mirrors to increase beam wattage
- Reflects light back into interferometer and sends it back out more powerful
- Powers up from 40 Watts to 740 kW
- Sharpens interference fringes
- https://www.ligo.caltech.edu/page/ligos-ifo


Basic Michelson Interferometer
Mirror
Laser
Mirror
Beam Splitter


Basic Michelson Interferometer with 4 km Fabry Perot Cavities
Mirror
4 km
Fabry Perot cavities
Mirror
Laser
Mirror
4 km
Mirror


Basic Michelson Interferometer with 4 km Fabry Perot Cavities and Power Recycling mirror
Power recycling mirror
Laser

Interferometer Depiction



Neutron star merger animation ending with kilonova explosion

What information did we already extract?

- **Masses**: The individual black-hole masses span a range from ≃ 2.6M$_\odot$ to to ≃ 80M$_\odot$ → the mass distribution for the more massive black hole appears to be consistent with a power-law **p(M) ∝ M$^{-3.4}$**, reminiscent of the stellar initial mass function
    - Binaries mostly consistent with equal mass components, a few outliers with 3:1, 9:1 ratios
- **Distances and Sky Locations:** All of the observed binary black hole signals came from median redshifts between **z ~ 0.05** and **z ~ 0.9** (distances of around 250 Mpc to 6 Gpc
- **Merger Rate**: The uncertainty in the binary black hole mass distribution is related into the uncertainty on the inferred merger rate, [16,130] Gpc−3 yr−1, merger rate increases with redshift; the local merger rate at redshift z = 0 is [10,30] Gpc−3 yr−1

https://reader.elsevier.com/reader/sd/pii/S0370157322000175?token=924566C3DAF452118151BC2A7B54FE19781623EFF5A061E8CFB73C0C88F373B92556641F9E4FF4983C9D940F98C7D777&originRegion=us-east-1&originCreation=20220423030712

What can we find from these gravitational waves?

1) Questions about the interior of a neutron vs strange star

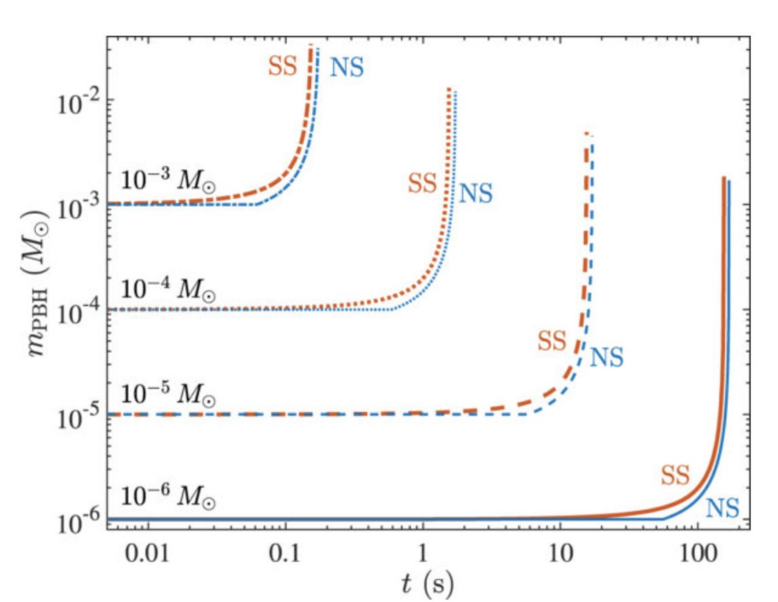
As the black hole tunnels into the star, its progress gradually slows as a result of accreting stellar material and emitting gravitational waves.

Modeled neutron star and strange star have the same mass and similar radii (12.6 and 11.0 km), but theorized to have different internal structures,

→ this should change the rate at which the black hole spirals inward.

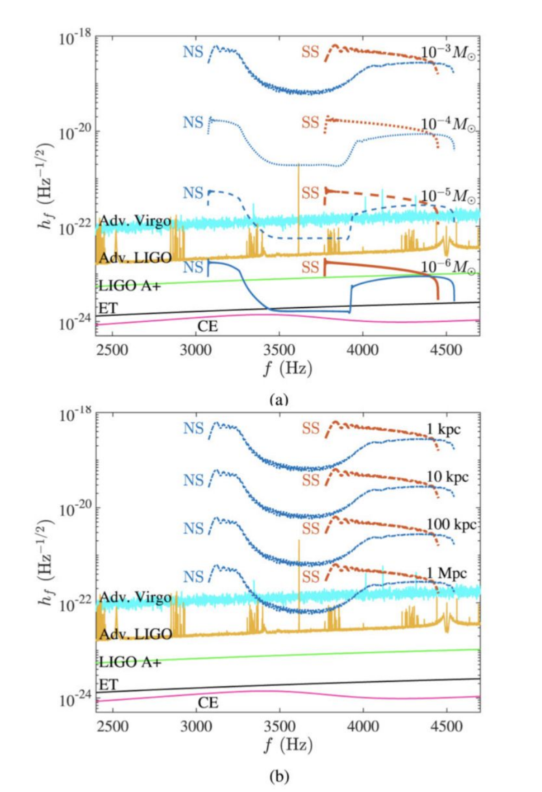
(accretion rate modeled to the right, λ eigenvalue depending on equation of state of accreted matter)

Conclusions from this graph → we can't tell much of a difference between NS and SS



$$\dot{m}_{\rm PBH} = \frac{4\pi\lambda\rho m_{\rm PBH}^2}{(c_s^2 + v^2)^{3/2}},$$

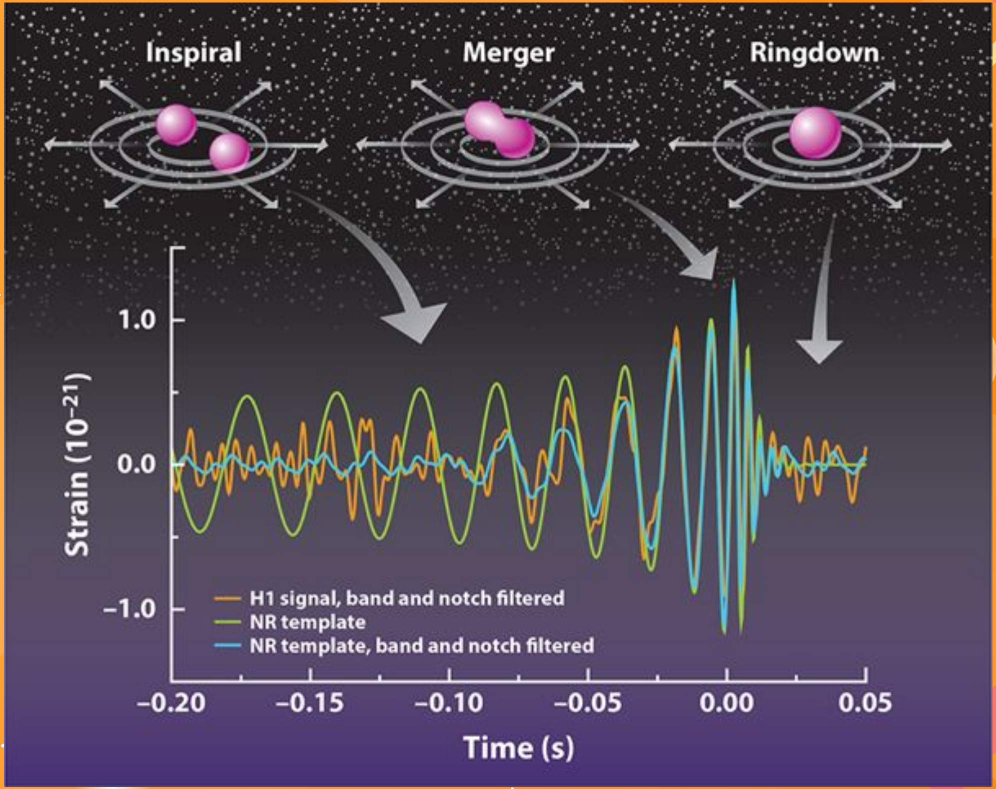
1 cont.) How can we tell the difference?



Though the two scenarios produce accretion waves with similar amplitudes from the previous slide, the shapes of the signals are different

the resulting GW signals show significant differences between the two cases

These tell that the mass of the black hole interacting with an SS increases faster than that of the corresponding NS case
→ due to the large surface density of the SS



Inspiral
Merger
Ringdown
Strain (10^{-21})
1.0
0.0
−1.0
H1 signal, band and notch filtered
NR template
NR template, band and notch filtered
−0.20
−0.15
−0.10
−0.05
0.00
0.05
Time (s)

2) Inconsistency with Merger and X-Ray Binaries

- **Spin observations:** X-Ray binaries such as three high-mass X-ray binaries with available spin measurements – Cygnus X-1, LMC X-1 and M33 X-7 – show evidence of rapid dimensionless spins in excess of $\gtrsim 0.85$
  - Note: 1 is the spin magnitude of a maximally spinning black hole
- **Why doesn't this make sense?**: high-mass X-ray binaries are too short-lived to enable significant spin changes due to accretion
- **How can we explain this difference:** observed high-mass X-ray binaries and merging binary black holes should predominantly sample different evolutionary histories

Formation questions and scenarios

These Binaries Shouldn't Exist...

1. **Only very tight binaries can merge via gravitational waves.**
   a. During a compact binary merger, the luminosity in gravitational waves is a few thousandths of the Planck luminosity, **c^5/G** at nearly 1057 ergs/s, such mergers "outshine" all the stars in the visible Universe combined
   b. Only very close binaries can be brought to merger by gravitational waves within the age of the universe
2. **But the black holes' parent stars cannot get so close**
   a. If the parent stars begin life in a close binary with a separation from which gravitational waves could bring their remnants together, the stars will expand to sizes much larger than their separation as they evolve
   b. expect that they would merge long before they collapse into black holes

HOW DO WE FIX THIS PROBLEM?

1) Binary evolution that brings the stars closer as they expand and interact

2) Stellar evolution that prevents the parent stars from expanding at all

3) Assembly of a close binary from black holes that formed from stars not born in the same binary

4) Stellar and binary evolution and dynamics operating jointly in triple systems

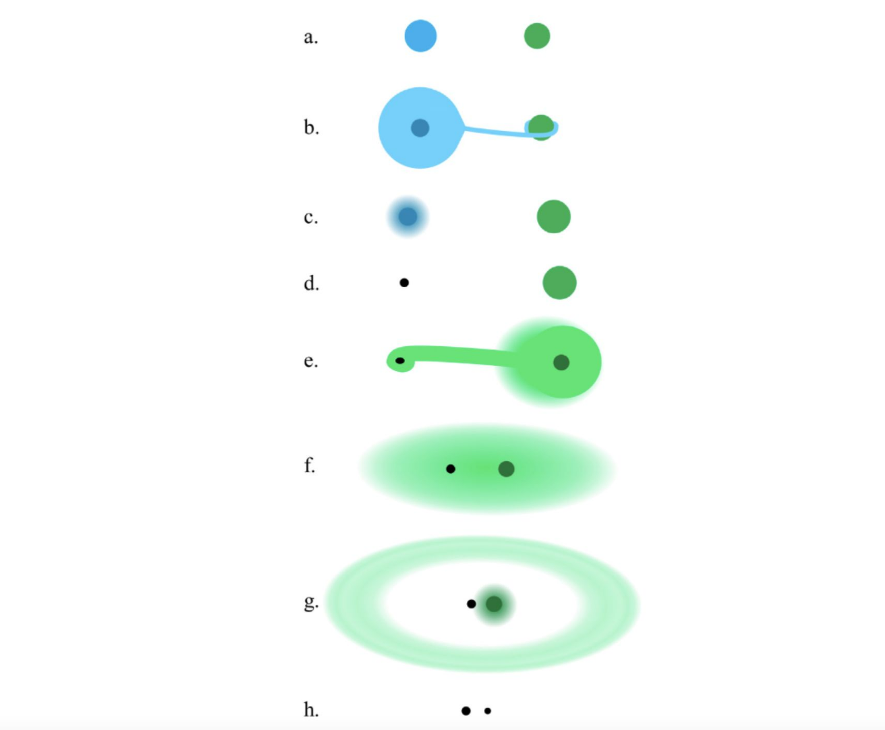
Possible Formations- Common Envelope Phase

In this scenario the two stars are born in a relatively wide binary, allowing them space to expand.

However, at a critical moment in its evolution, the binary is tightened by a factor of two or more orders of magnitude through dynamically unstable mass transfer, known as a common envelope phase

At b) completed fusing hydrogen into helium in its core, and with the loss of energy input, the core begins to contract → gravitational binding energy causes envelope to expand beyond Roche Lobe → mass transfer to secondary

At d) wind-driven mass loss, which further widens the system, the primary collapses into a black hole

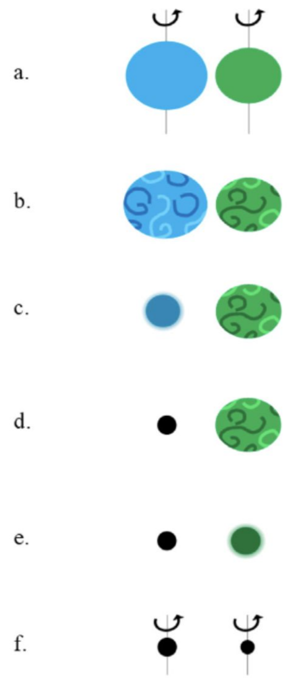


Possible Formations- Chemically Homogeneous Evolution

A massive binary could start at orbital period of a couple of days, close enough that if the stars produced black holes they would merge within the age of the Universe through gravitational-wave emission

Without an expansion phase, the parent stars would be in no danger of merger; if almost all of the star's mass was converted into a black hole ather than the ~30%–50% of the mass which typically becomes the helium core

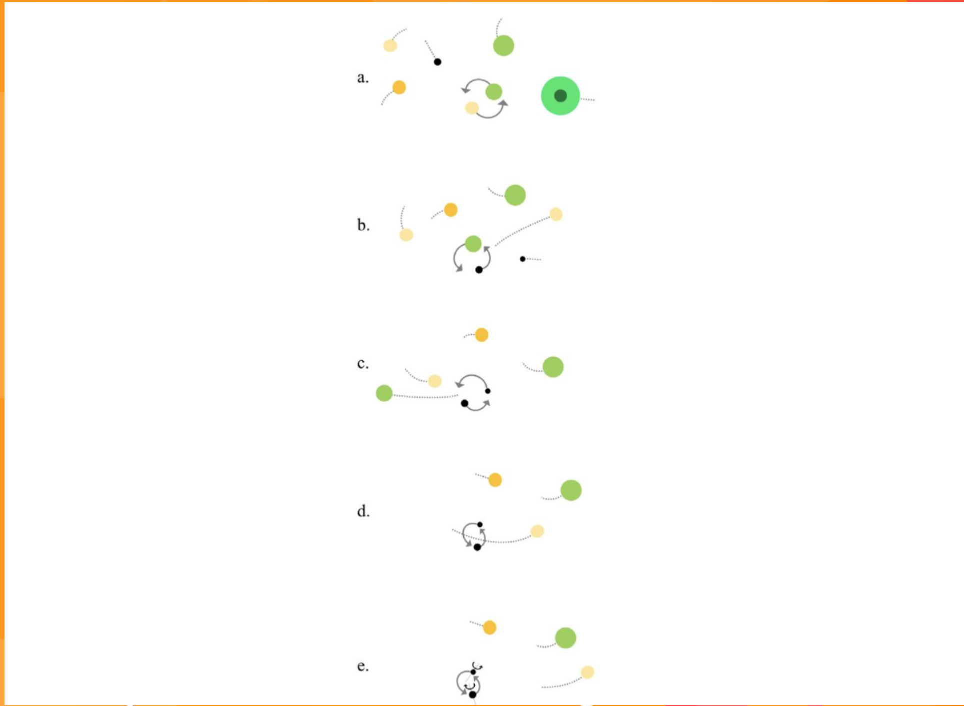
the merger timescale would shrink for a given separation, lifting the Roche lobe radius curve



Possible Formations- Dynamical Formation in Dense Stellar environments

The merging black holes may not have formed in the same binary at all. Instead, in this channel, they are remnants of independent massive stars

An accretion disk in an active galactic nucleus can act as a catalyst for binary black hole mergers. Compact objects in active galactic nuclei may form directly in the disk, be captured by the disk through gas drag, or settle into a disk through resonant relaxation against the stellar background



Relevant Equations and Derivations

Have to get the math of gravitational waves here
and probably understand them to at least a decent degree

Possible sources on source of GWs:

- https://www.pnas.org/doi/pdf/10.1073/pnas.1614681113
- https://www.ams.org/publications/journals/notices/201707/rnoti-p684.pdf
- http://www.physics.usu.edu/Wheeler/GenRel2013/Notes/GravitationalWaves.pdf
- http://www.tapir.caltech.edu/~teviet/Waves/gwave.html

Citations and sources

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Citations and Sources

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"Gravitational-wave Emission from a Primordial Black Hole Inspiraling inside a Compact Star: A Novel Probe for Dense Matter Equation of State," | *Ze-Cheng Zou and Yong-Feng Huang* 2022 *ApJL* **928** L13. doi:10.3847/2041-8213/ac5ea6

"Sources And Types Of Gravitational Waves". *LIGO Lab | Caltech*, 2022, https://www.ligo.caltech.edu/page/gw-sources