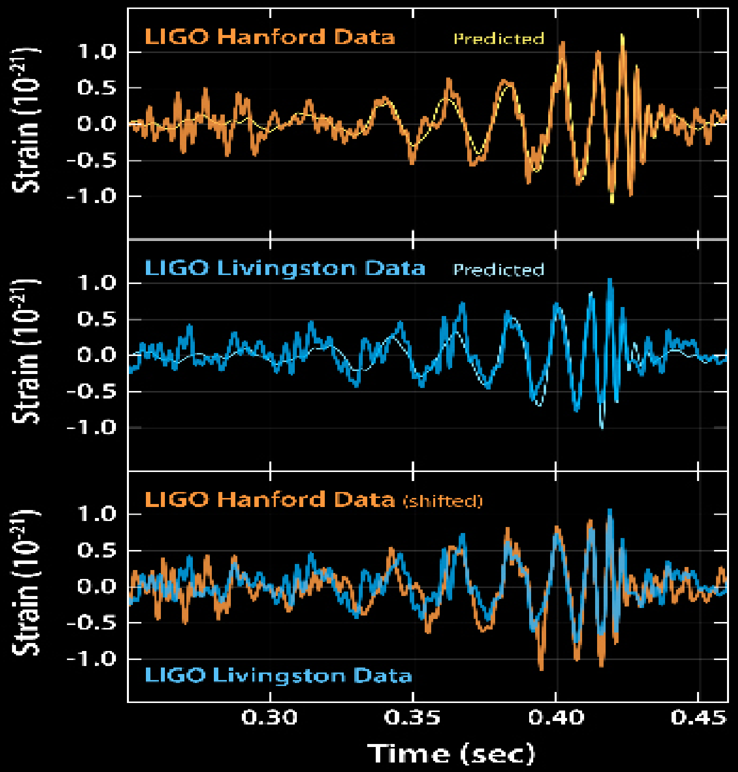
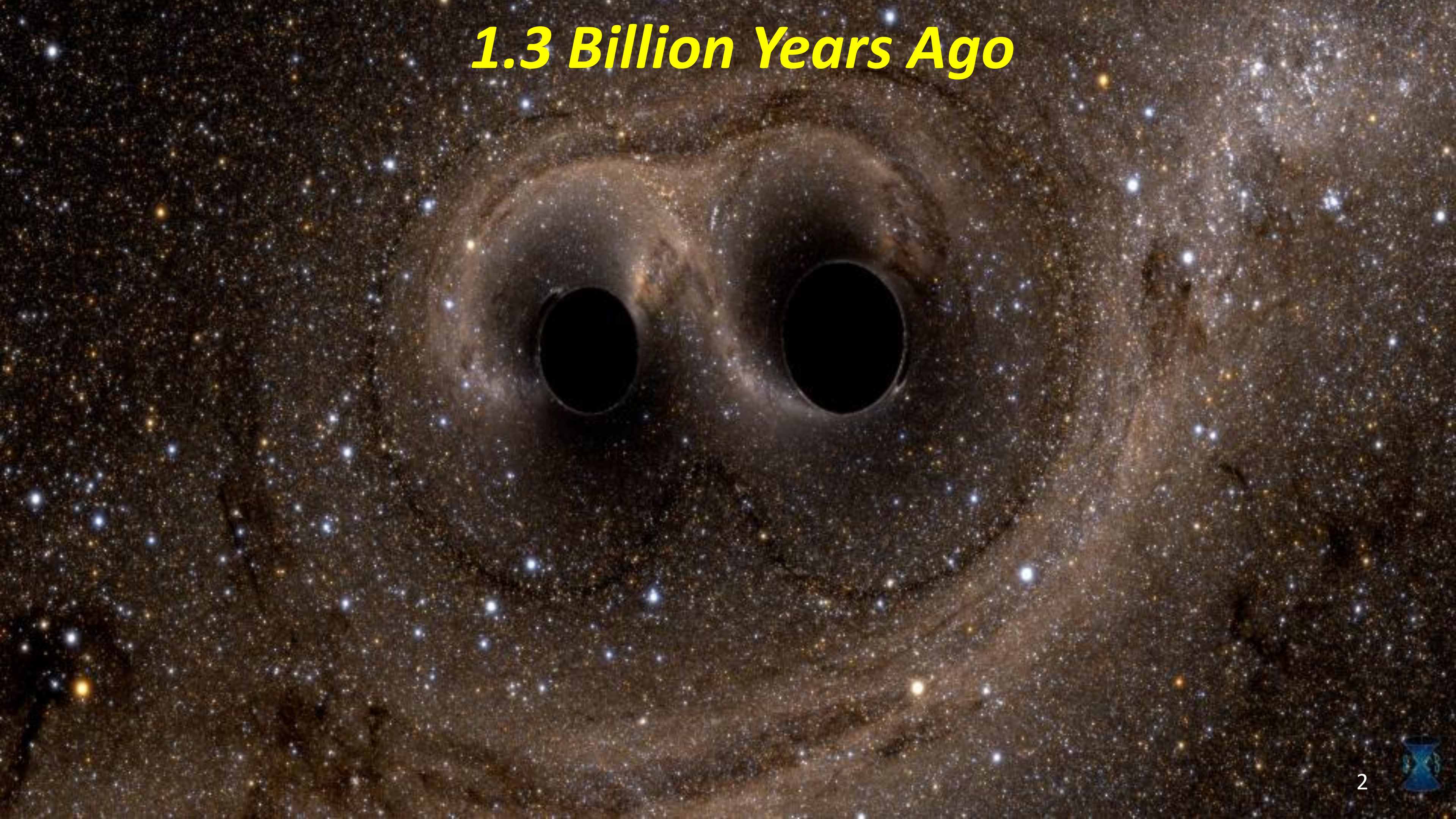
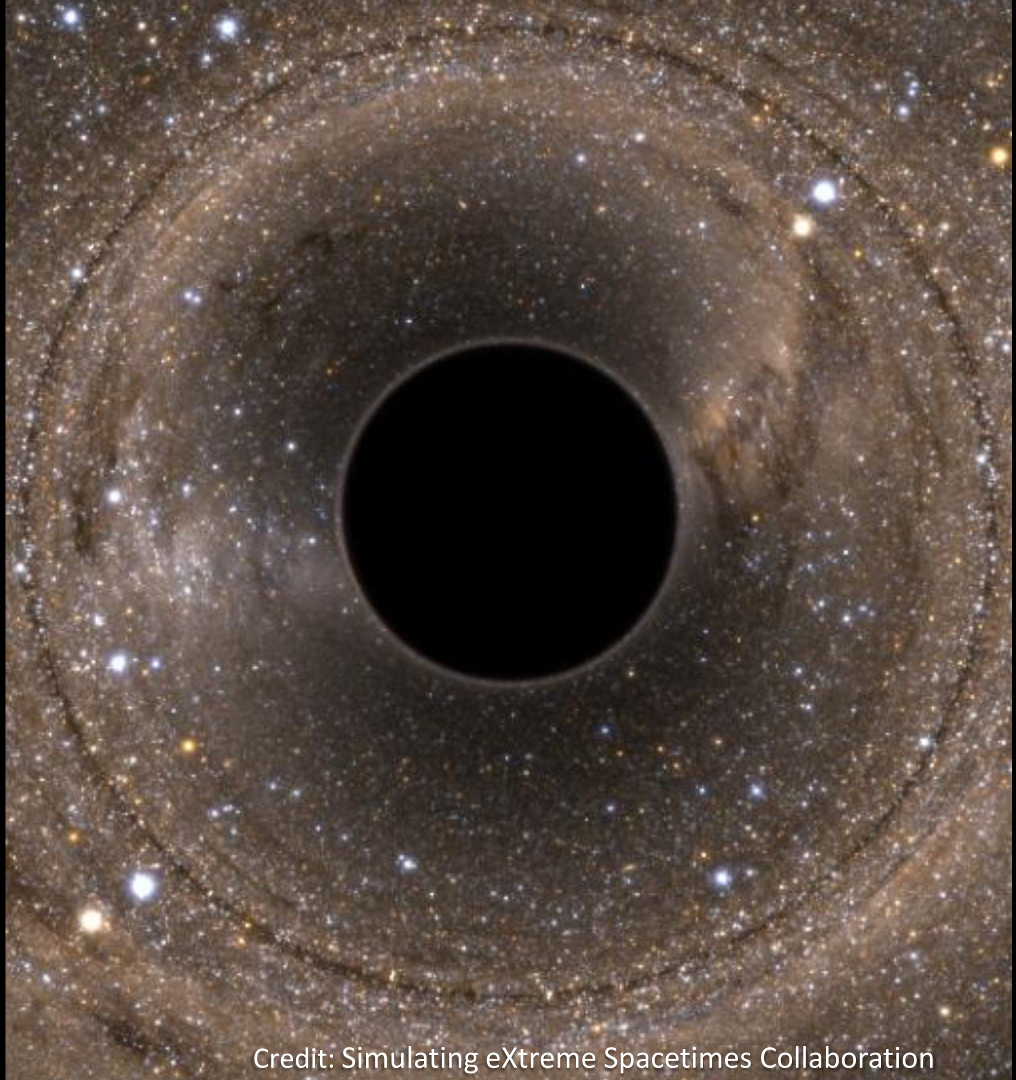


Gravitational Waves: From Einstein to a New Science

Barry C Barish
Caltech - LIGO

1.3 Billion Years Ago





Credit: Simulating eXtreme Spacetimes Collaboration

Black Holes

- Regions of space created by super dense matter from where nothing can escape due to the strength of gravity
- Some may form when very large stars collapse and die
- Expected to have masses from around 3 to 100s of times the mass of the Sun
- Others may have been created in the Big Bang
- Supermassive black holes weighing as much as millions of stars reside in the centers of most galaxies (including our own)


Albi
A65
Auch
Toulouse
Montpellier
A63
Santander
E-70
Bilbao
San Sebastián
Pau
A64
A61
Béziers
A9
Sète
Torrelavega
Carcassonne
Lourdes
Park
Parc naturel régional des Pyrénées ariégeoises
Vitoria-Gasteiz
Pamplona
Parc national des Pyrénées
A9
León
Logroño
Andorra
Perpignan
Burgos
E-15
E-80
Huesca
Palencia
E-804
Girona
E-5
Soria
Valladolid
Zaragoza
Lleida
E-15
Barcelona
Tarragona
Salou
E-5
E-90
E-15
E-803
Alcala de Henares
Teruel
Peniscola
Getafe
Balearic Sea
Castellón de la Plana
Cuenca
Google
Toledo
E-901
E-901
Palma
Valencia


29 M_sun
36 M_sun
V ~ 0.5 c
V ~ 0.5 c
Santander
Bilbao
San Sebastián
Torrelavega
Vitoria-Gasteiz
Pamplona
León
Burgos
Logroño
Soria
Zaragoza
Huesca
Lleida
Barcelona
Girona
Perpignan
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Toulouse
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Pau
Lourdes
Albi
Montpellier
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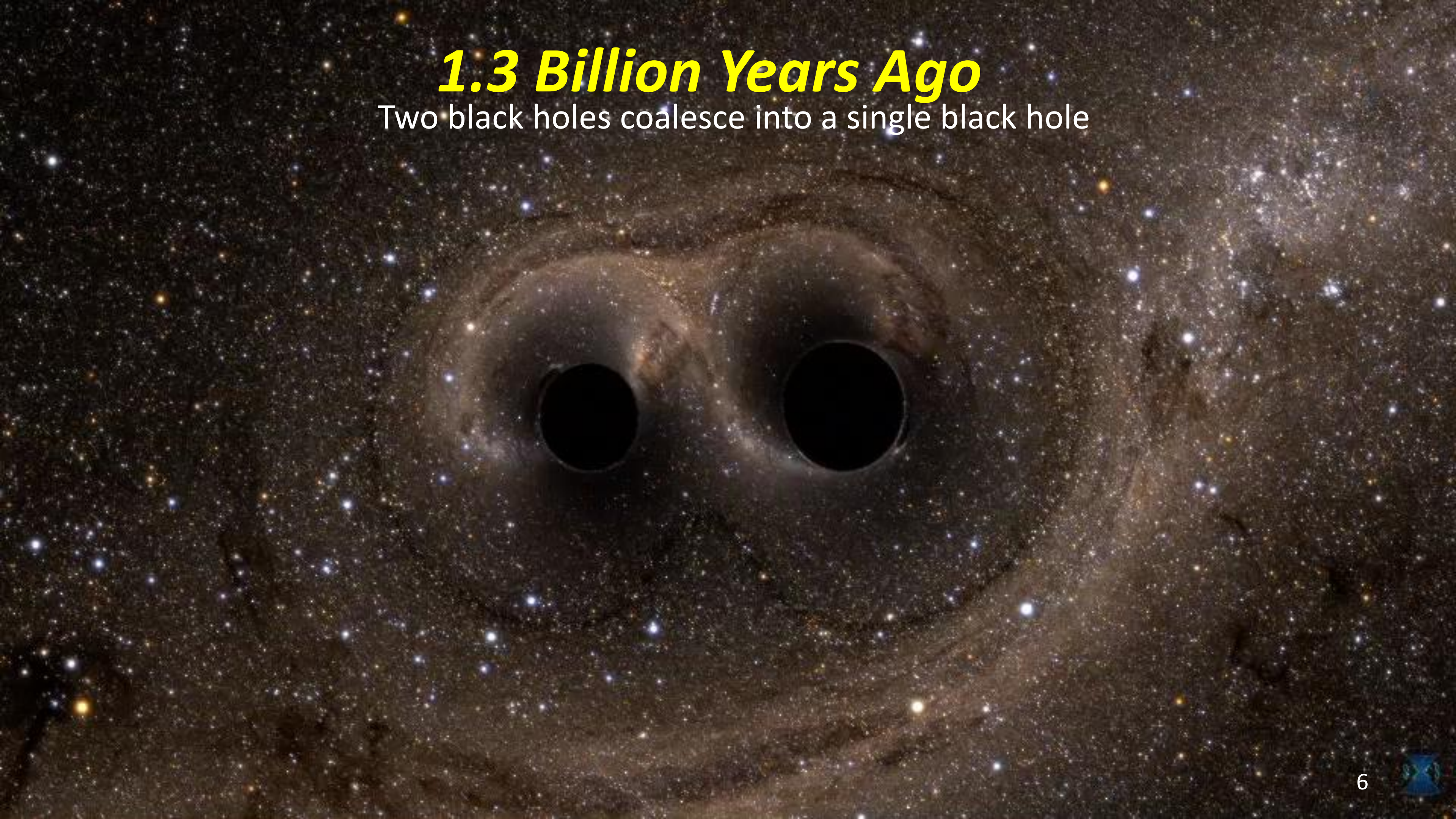
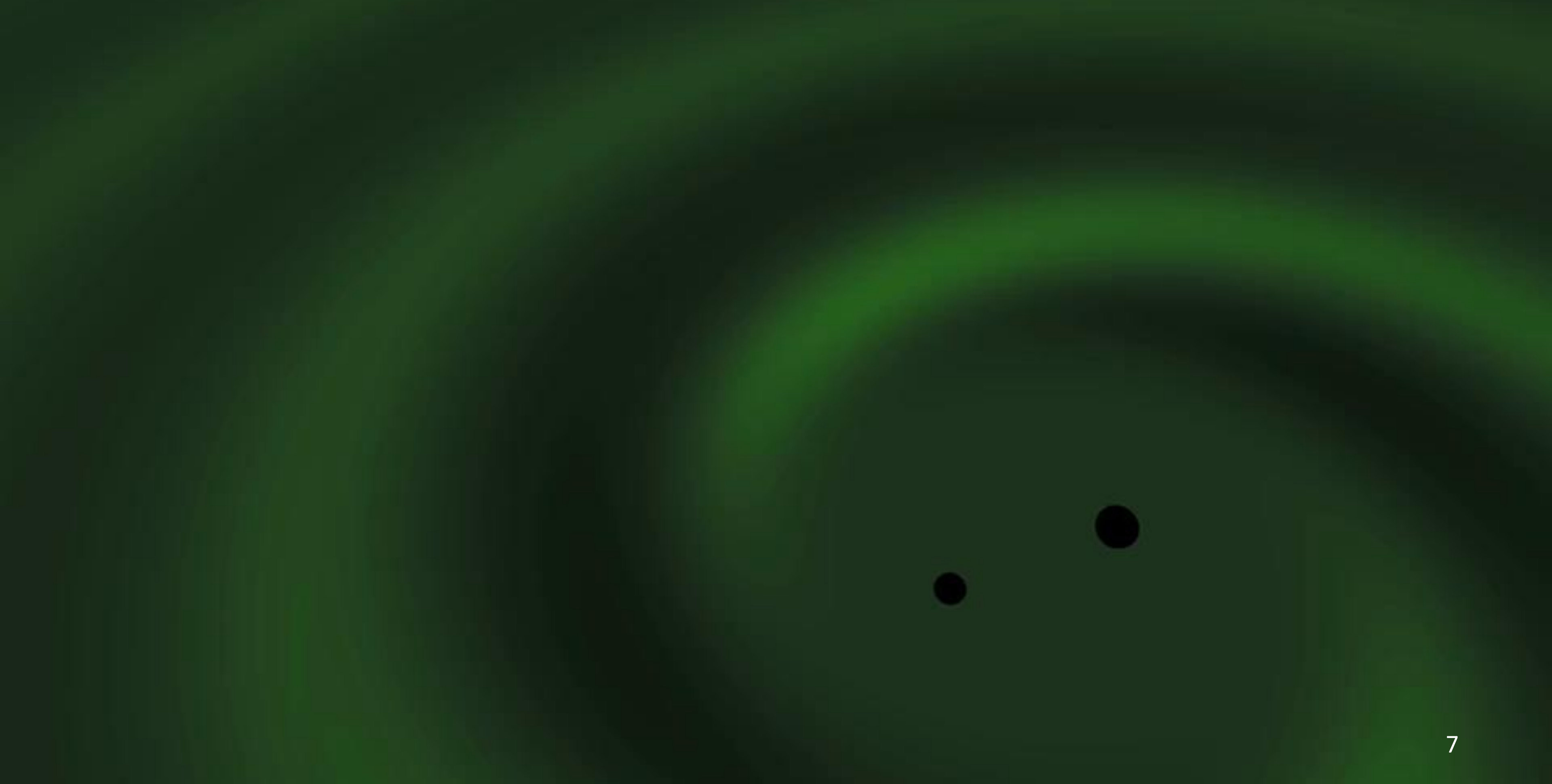
Alcala de Henares
Getafe
Cuenca
Teruel
Castellón de la Plana
Valencia
Palma
Google

1.3 Billion Years Ago

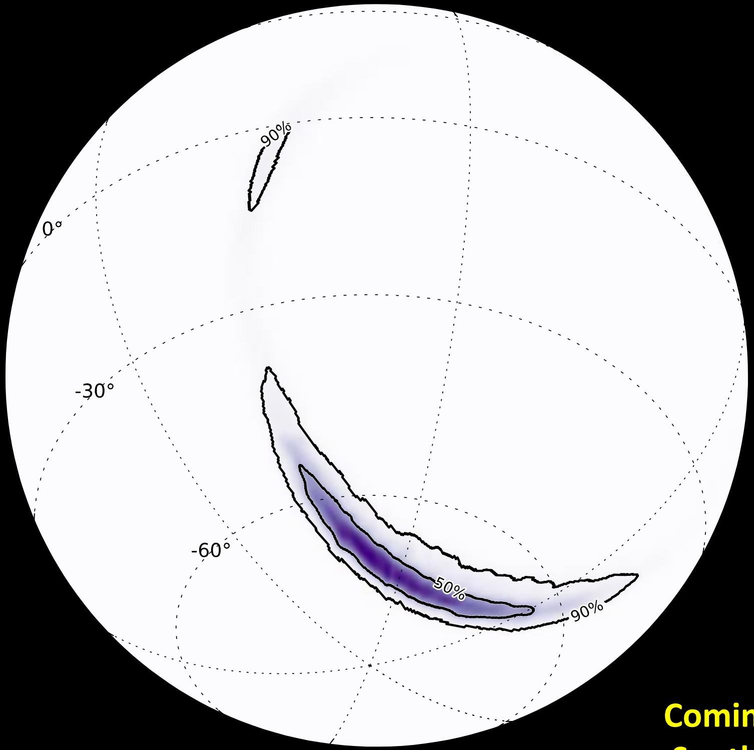
Two black holes coalesce into a single black hole



Gravitational Waves Travel to the Earth

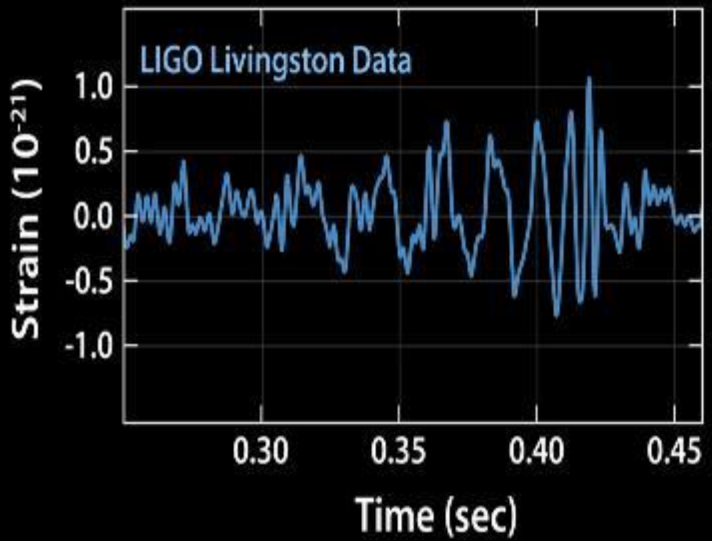


Sept 14, 2015

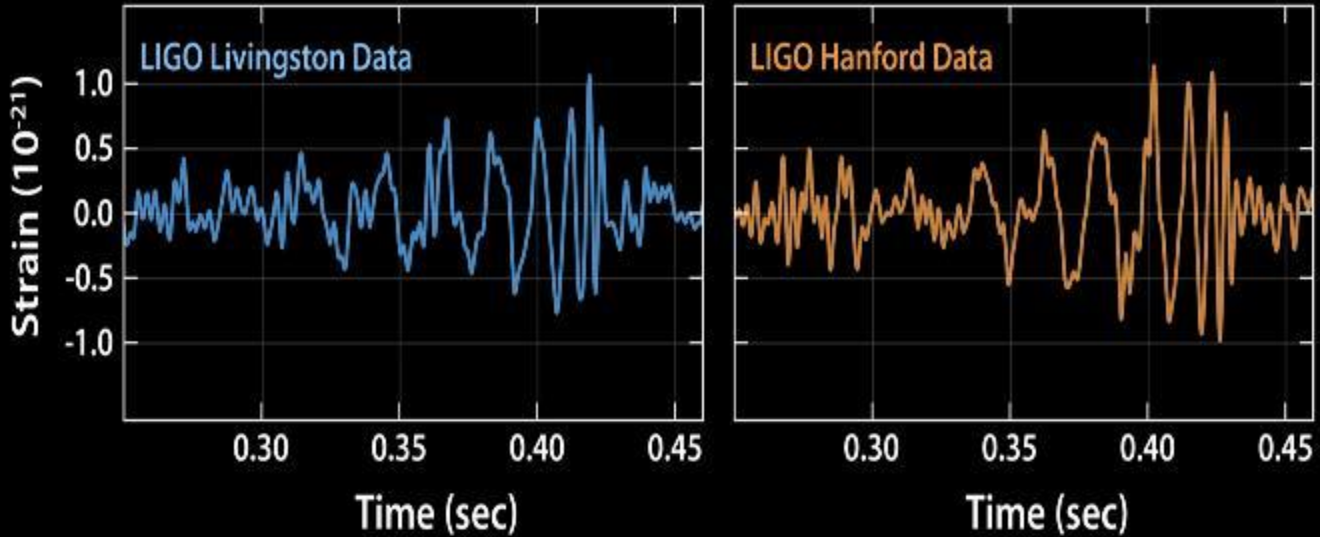


Coming up from
Southern Hemisphere

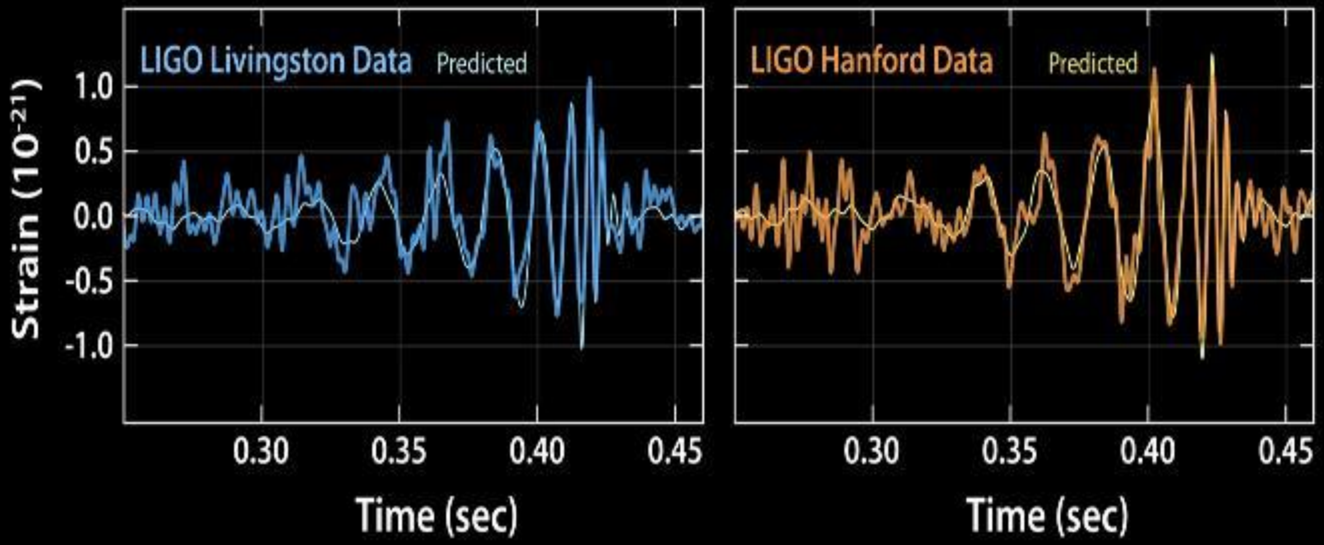
~ 20 msec later



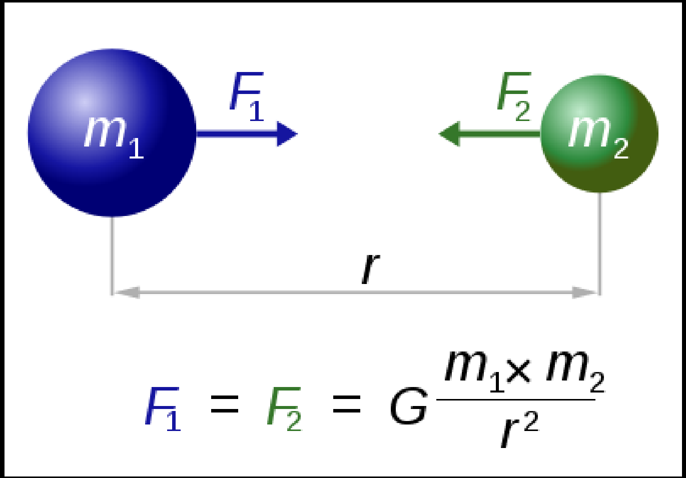
After another 7 msec



GR Prediction for BH merger



Newton's Theory of Gravity
1687



Universal Gravity: force between massive objects is directly proportional to the product of their masses, and inversely proportional to the square of the distance between them.

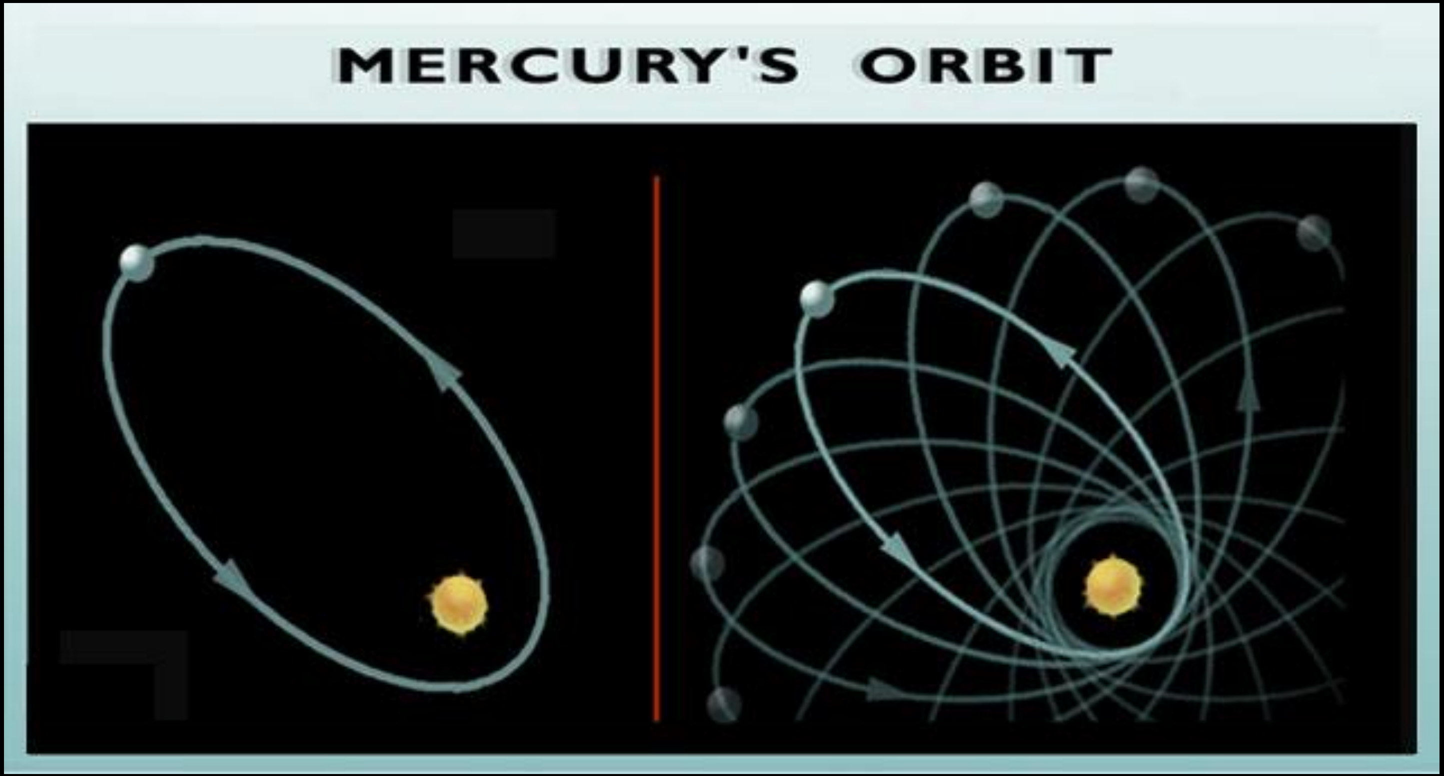
Urban le Verrier

Mathematician – Celestial Mechanics.

Famous for validation of "Celestial Mechanics." He **predicted the existence and position of Neptune** by calculating the discrepancies between Uranus's orbit and the laws of Kepler and Newton.

He sent his prediction to a German astronomer who found Neptune within 1 degree of prediction the same night. (1846)

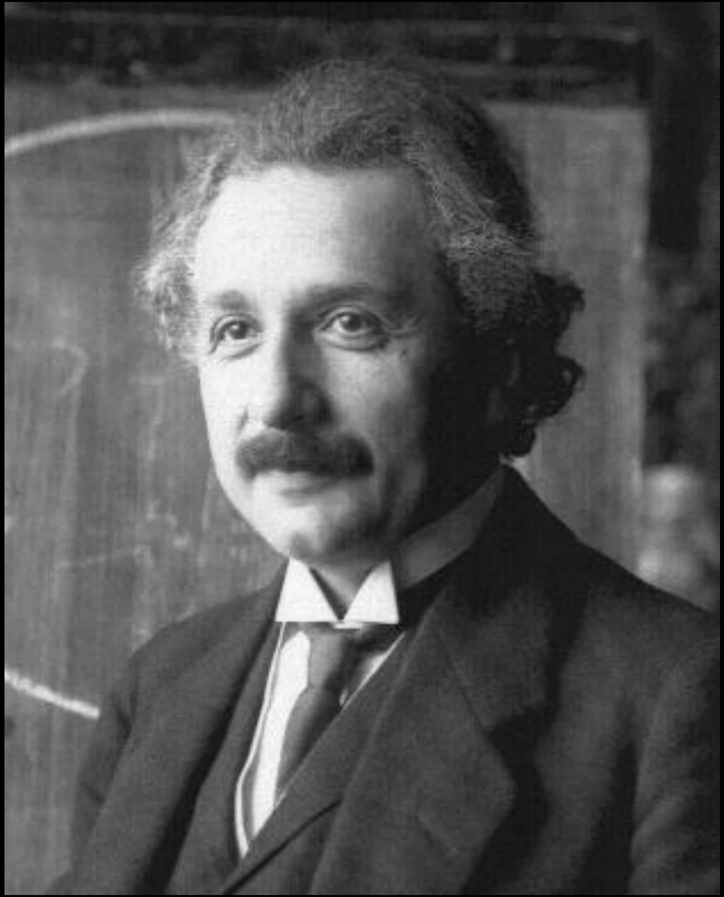
Then, in the 1850s he discovered a problem with the orbit of Mercury around the sun



Mercury's elliptical path around the Sun. Perihelion shifts forward with each pass. (Newton 532 arc-sec/century vs Observed 575 arc-sec/century)

(1 arc-sec = 1/3600 degree).

Einstein's Theory of Gravity

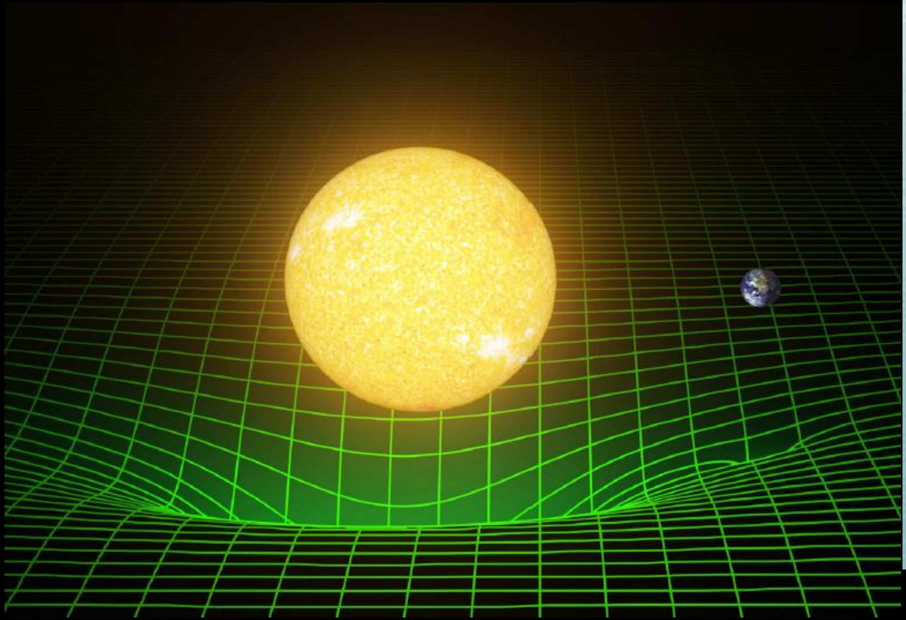


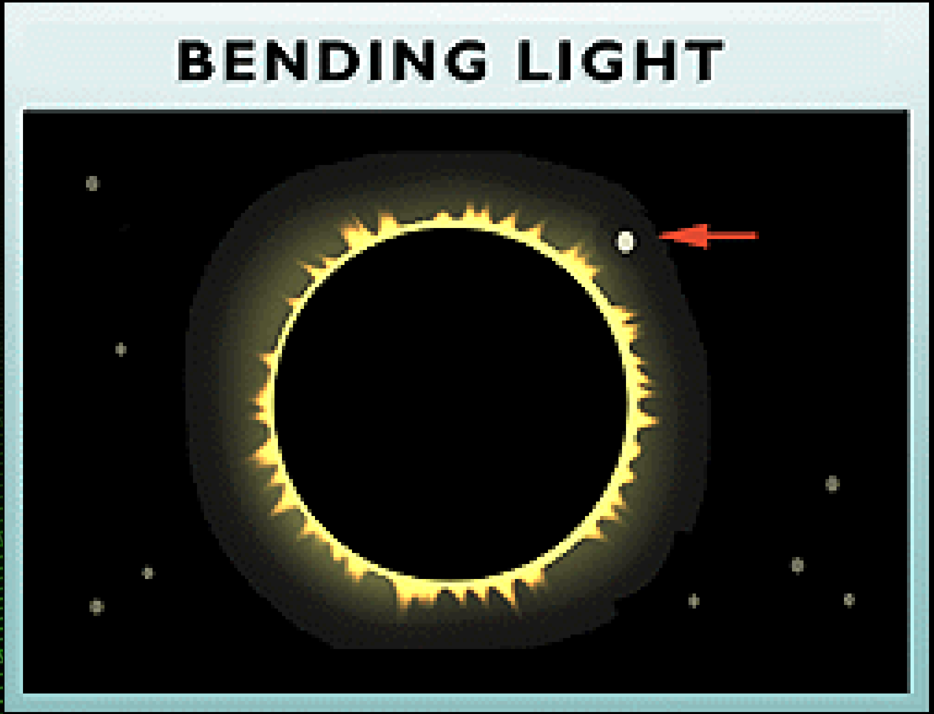
1915

$$G_{ab} \equiv R_{ab} - \frac{1}{2} g_{ab} R = \frac{8\pi G}{c^4} T_{ab}$$

Space *and* Time are ***unified*** in a four dimensional

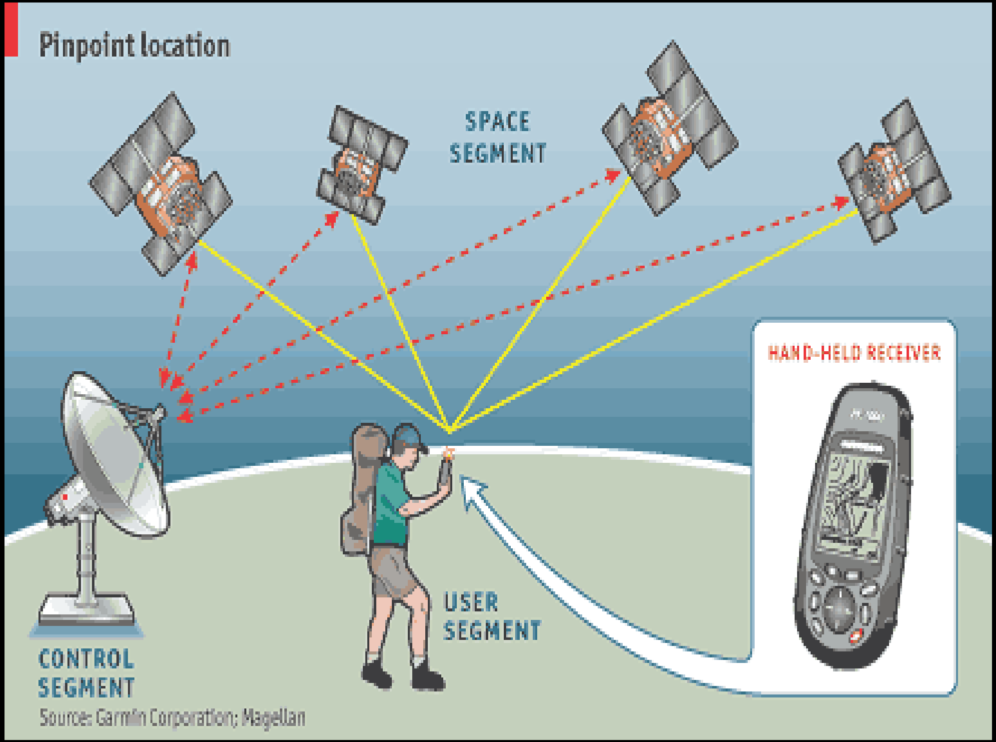
spacetime





First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

GPS: General Relativity in Everyday Life



Special Relativity

(Satellites v = 14,000 km/hour
"moving clocks tick more slowly"
Correction = - 7 microsec/day

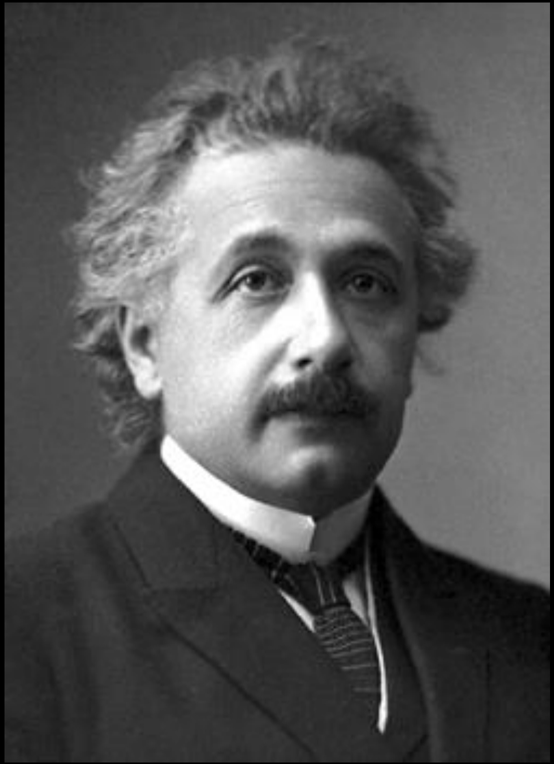
General Relativity

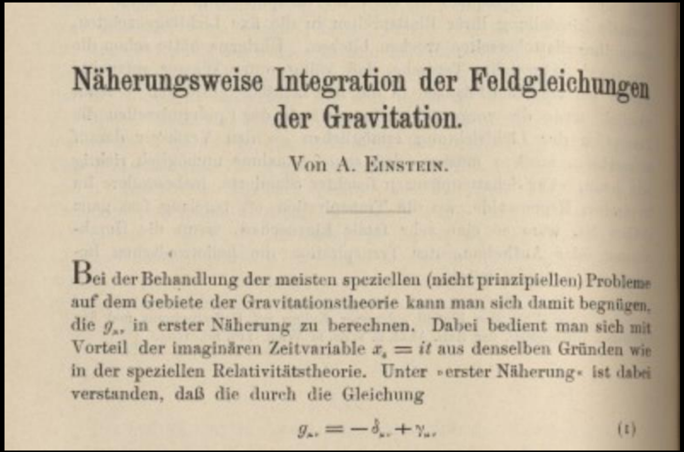
Gravity: Satellites = 1/4 x Earth
Clocks faster = + 45 microsec/day

GPS Correction = + 38 microsec/day

(Accuracy required ~ 30 nanoseconds
to give 10 meter resolution

Einstein Predicted Gravitational Waves in 1916





Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

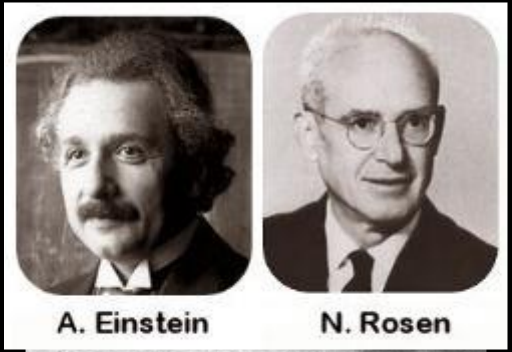
- 1st publication indicating the existence of gravitational waves by Einstein in 1916
  - Contained errors relating wave amplitude to source motions
- 1918 paper corrected earlier errors (factor of 2), and it contains the quadrupole formula for radiating source

Einstein vs Physical Review

1936

Einstein and Rosen Submited an article to Physical Review

"Do Gravitational Waves Exist?"



The Chapel Hill Conference

Could the waves be a coordinate effect only, with no physical reality? Einstein didn't live long enough to learn the answer.

In January 1957, the U.S. Air Force sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1.

The organizers were Bryce and Cecile DeWitt. 44 of the world's leading relativists attended.

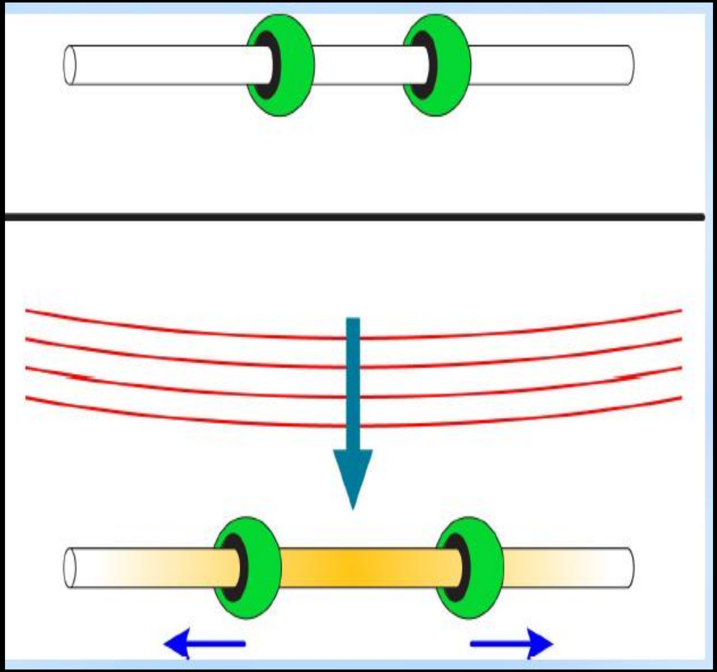
The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born.

(Pirani, Feynman and Babson)

Agreement: Gravitational Waves are Real

- Felix Pirani presentation: relative acceleraton of particle pairs can be associated with the Riemann tensor. The interpretation of the attendees was that non-zero components of the Riemann tensor were due to gravitational waves.

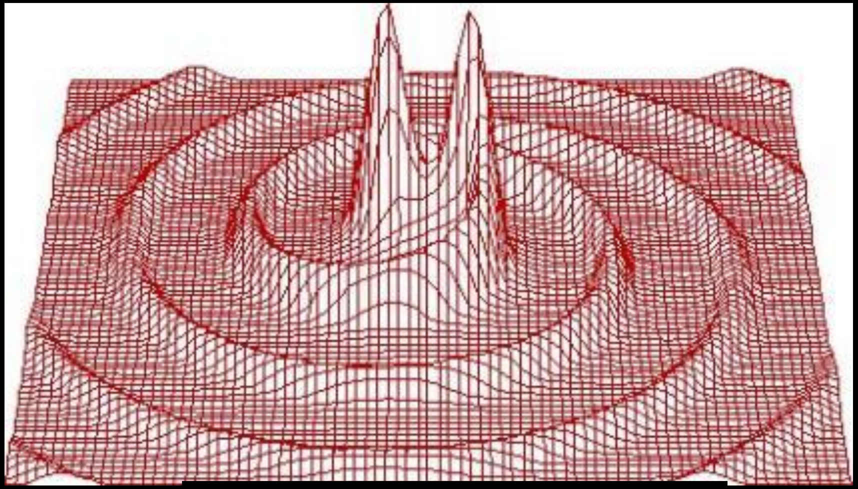
- Sticky bead argument (Feynman)
  - Gravitational waves can transfer energy?



Einstein's Theory of Gravitation

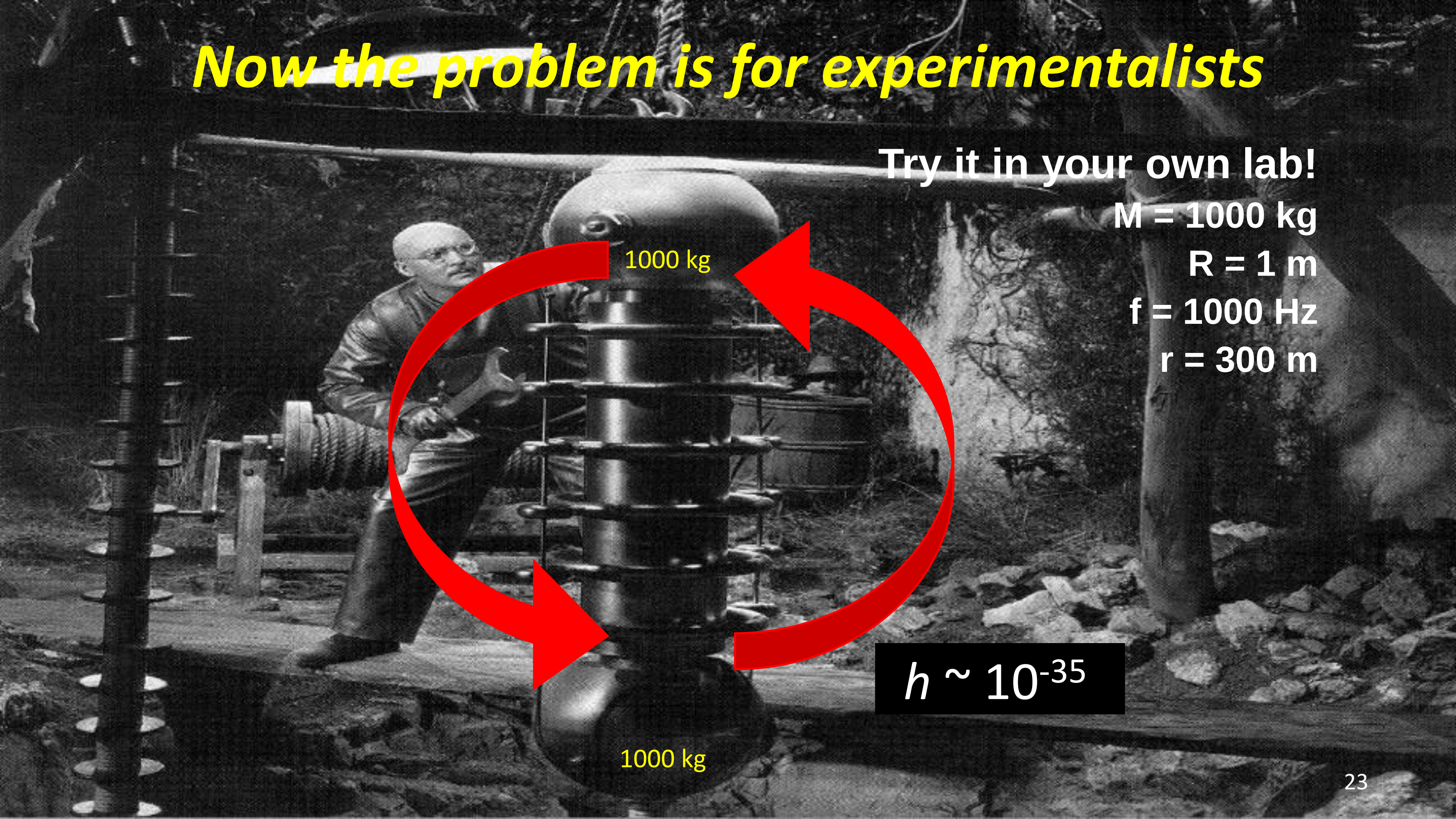
A necessary consequence of Special Relativity with its finite speed for information transfer

Gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light



gravitational radiation
binary inspiral
of
compact objects

Now the problem is for experimentalists



Try it in your own lab!

M = 1000 kg

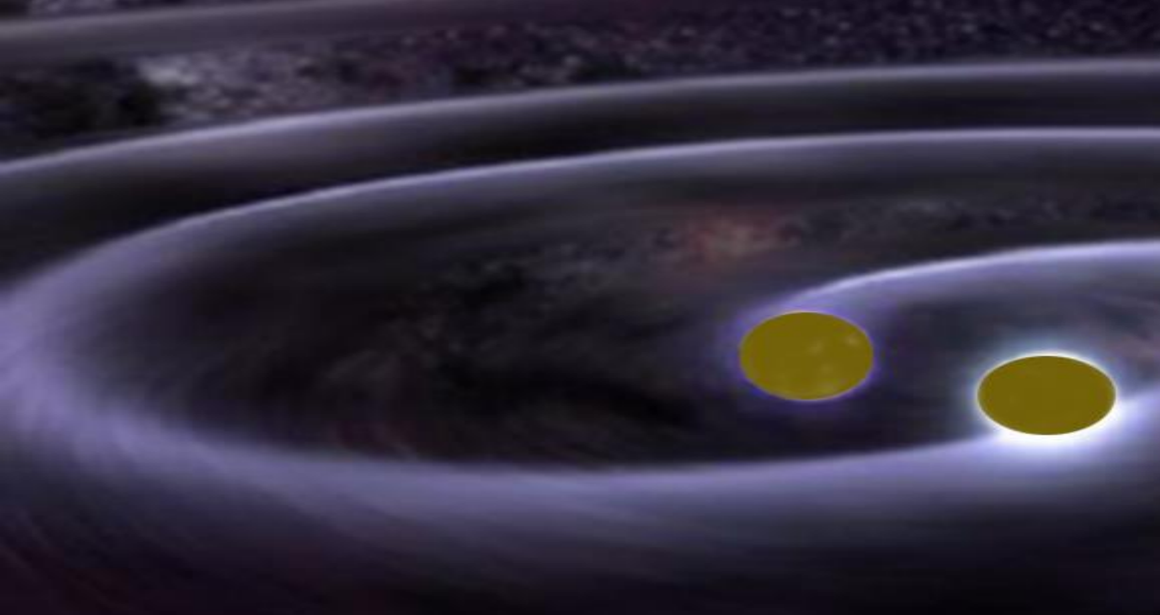
R = 1 m

f = 1000 Hz

r = 300 m

$h \sim 10^{-35}$

BUT, the effect is incredibly small

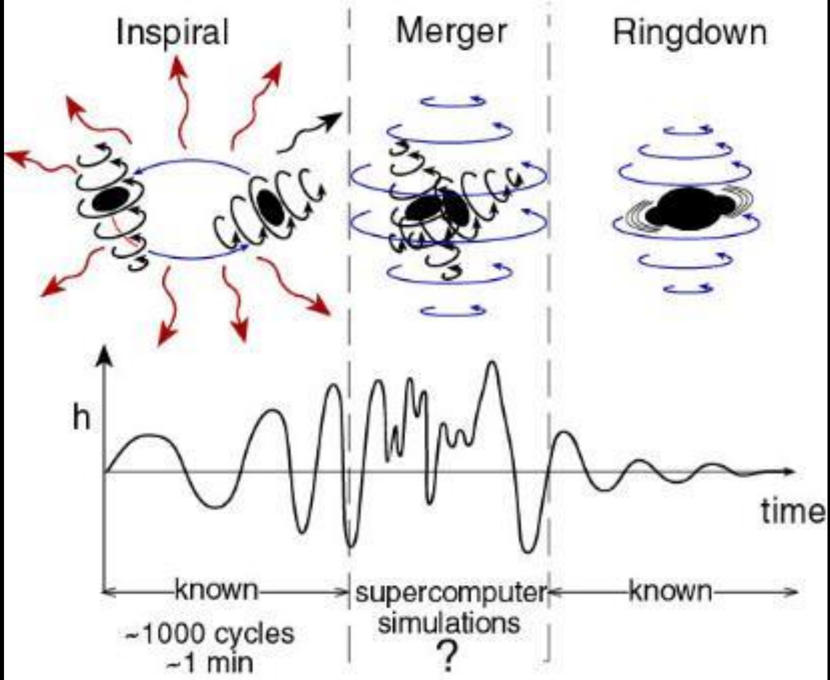


- Consider ~30 solar mass binary Merging Black Holes
  - $M = 30\ M_{\odot}$
    $R = 100$ km
    $f = 100$ Hz
    $r = 3\ 10^{24}$ m (500 Mpc)

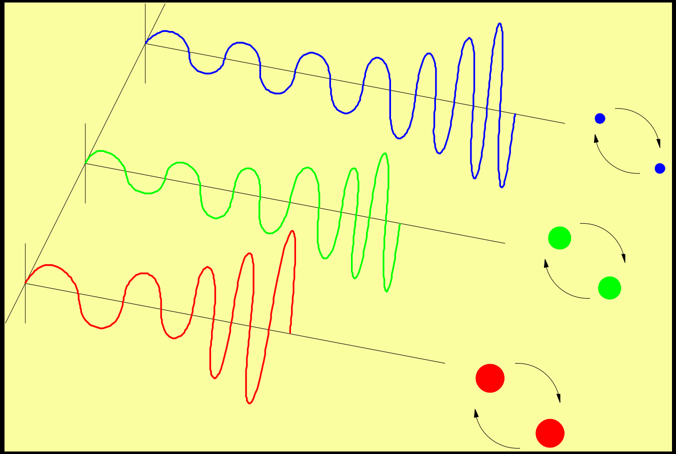
$$h = \Delta L / L \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r} \Rightarrow h \sim 10^{-21}$$

Credit: T. Strohmayer and D. Berry

Compact Binary Collisions



– Neutron Star – Neutron Star
  - **waveforms are well described**
– Black Hole – Black Hole
  - **Numerical Relativity waveforms**
– Search: <u>*matched templates*</u>

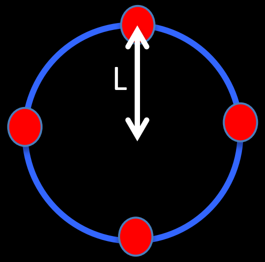


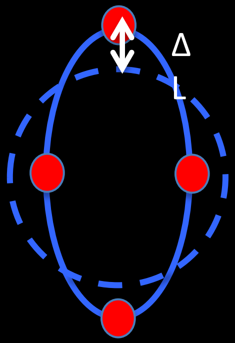
"chirps"

Gravitational Waves

- Ripples of spacetime that stretch and compress spacetime itself
- The amplitude of the wave is h ≈ 10^{-21}
- Change the distance between masses that are free to move by $\Delta L = h \times L$
- Spacetime is “stiff” so changes in distance are very small

$$\Delta L = h \times L = 10^{-21} \times 1\,\mathrm{m} = 10^{-21}\,\mathrm{m}$$

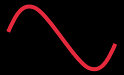




How Small is 10^{-18} Meter?

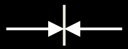
One meter

÷10,000  Human hair, about 100 microns

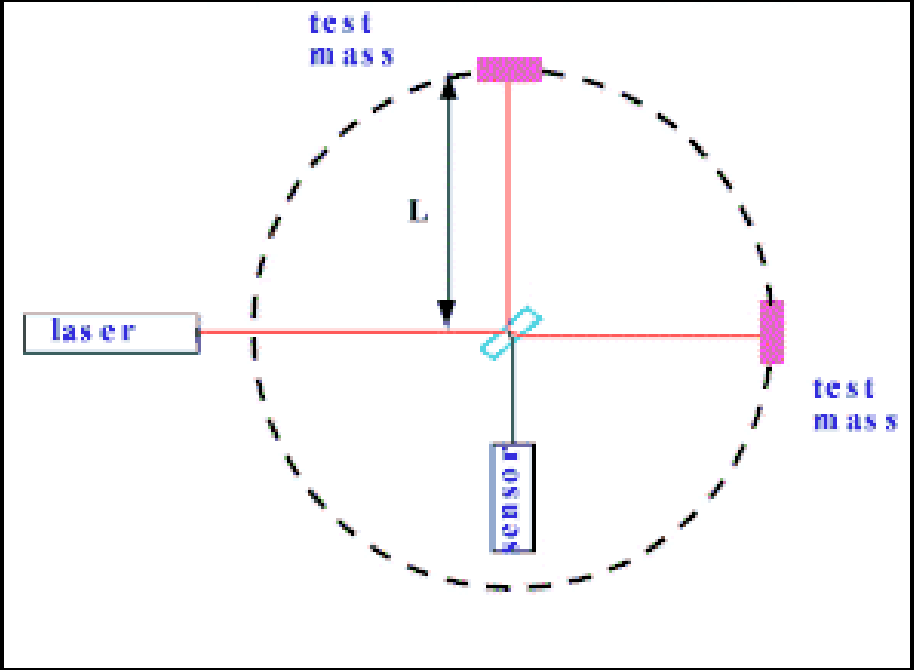
÷100  Wavelength of light, about 1 micron

÷10,000  Atomic diameter, 10^{-10} meter

÷100,000  Proton diameter, 10^{-15} meter

÷1,000  LIGO sensitivity, 10^{-18} meter

Suspended Mass Interferometry



$$h = \frac{DL}{L} \leq 10^{-21}$$

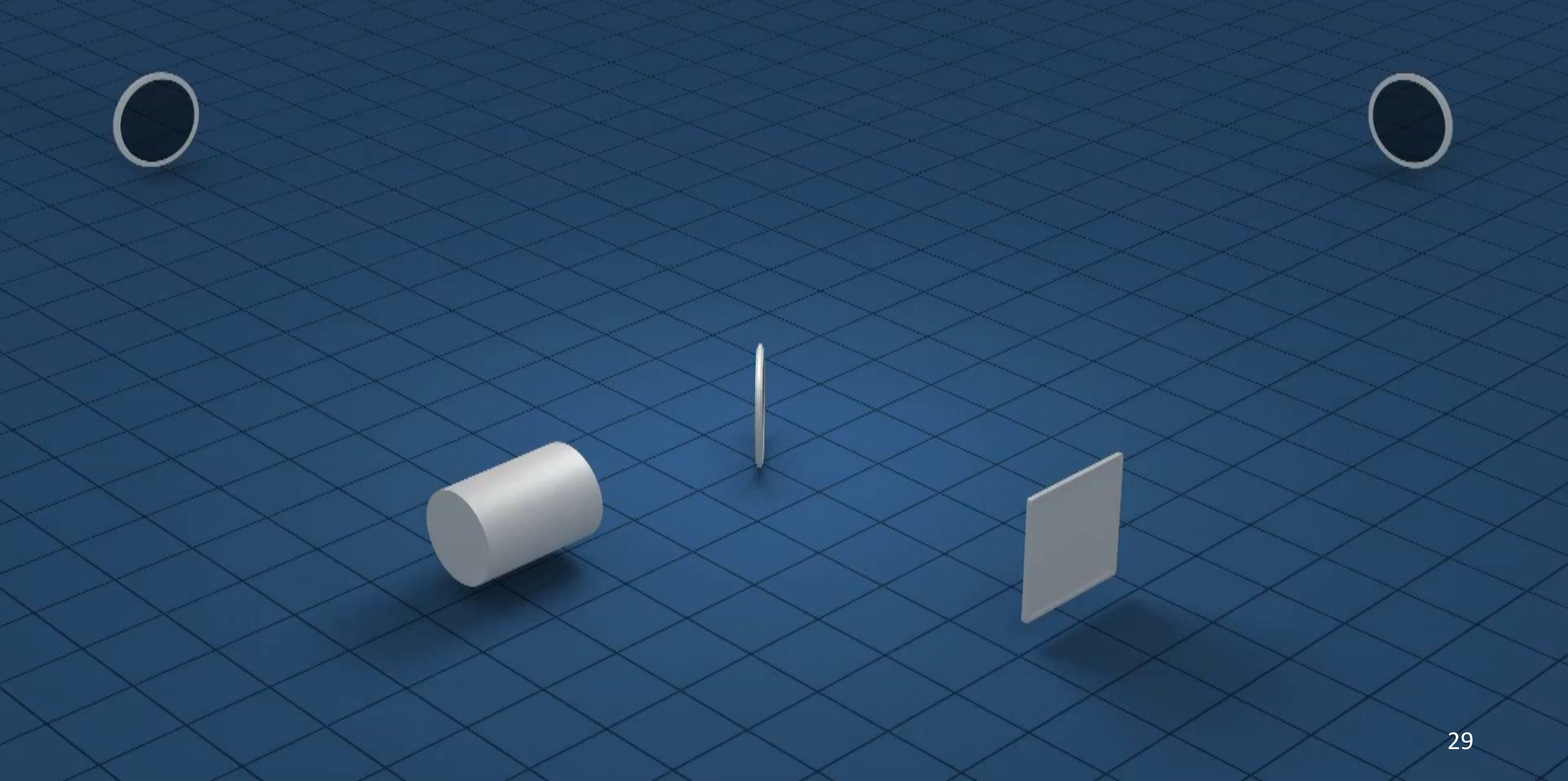
$$L = 4\text{km} \quad DL \leq 4\text{x}10^{-18}\text{ meters}$$

$$DL \sim 10^{-12}\text{ wavelength of light}$$

$$DL \sim 10^{-12}\text{ vibrations at earth's surface}$$

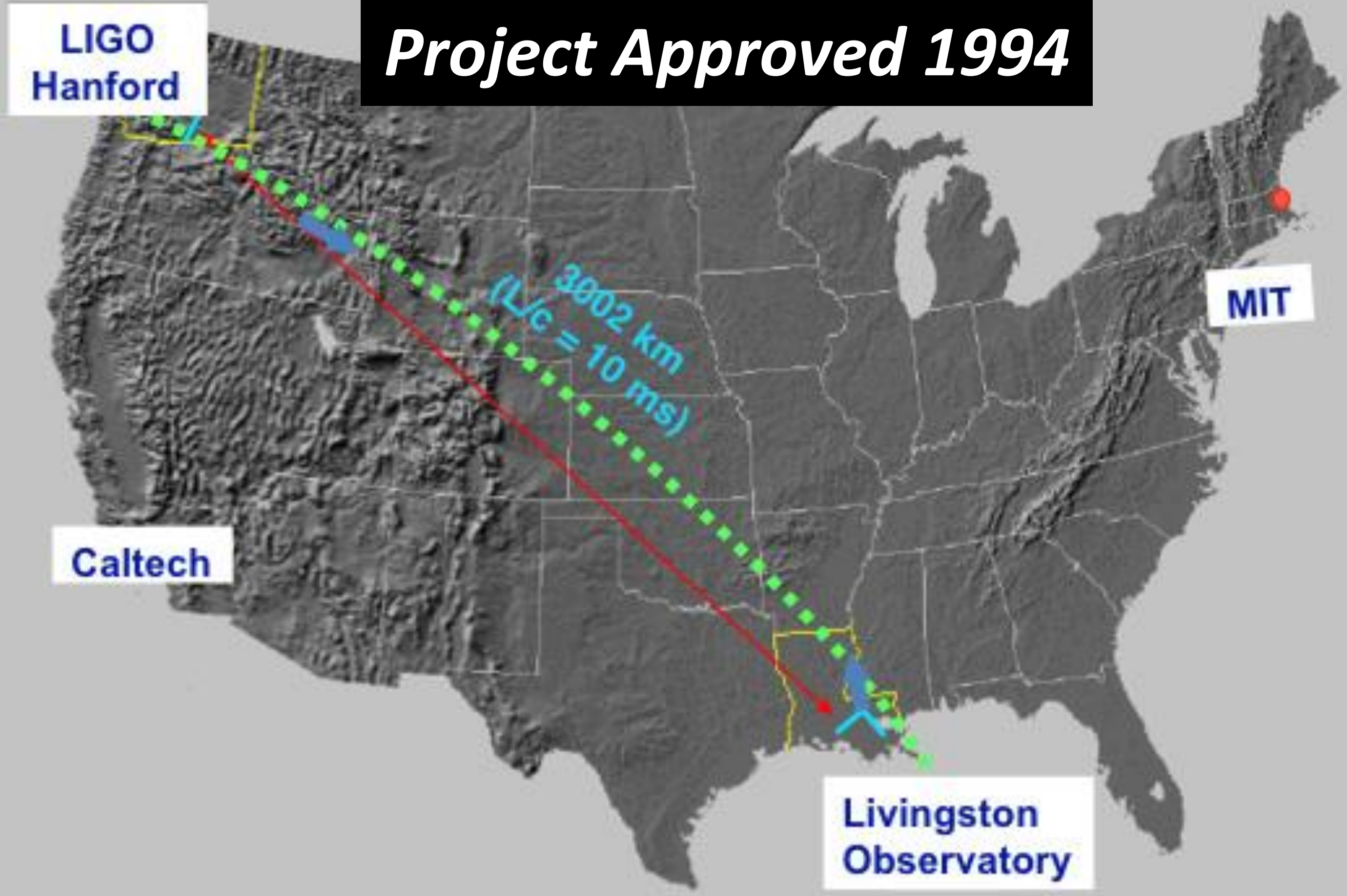
Credit: LIGO/T. Pyle

Interferometry – The scheme



LIGO Sites

Project Approved 1994



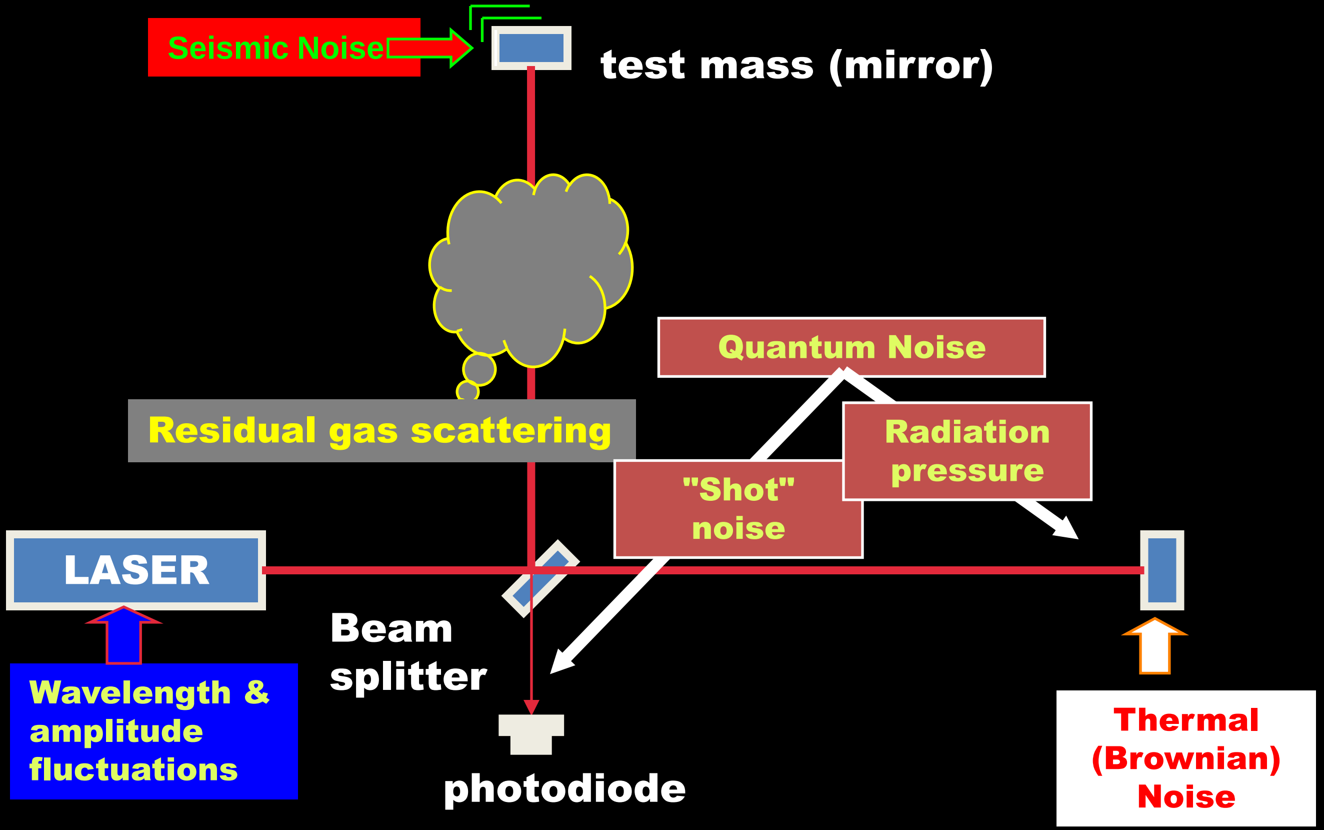
LIGO Interferometers

Hanford, WA

Livingston, LA

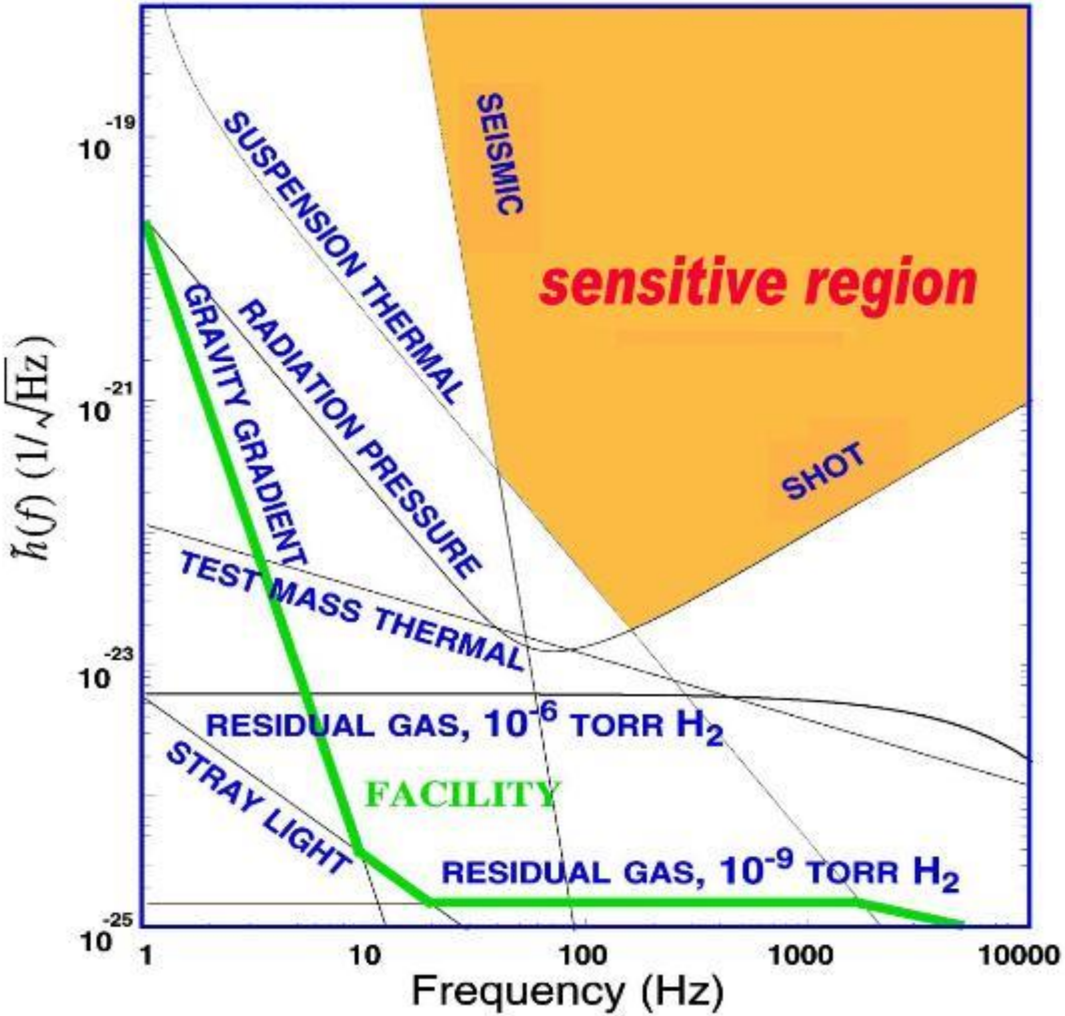
LIGO Interferometer Infrastructure

Interferometer Noise Limits

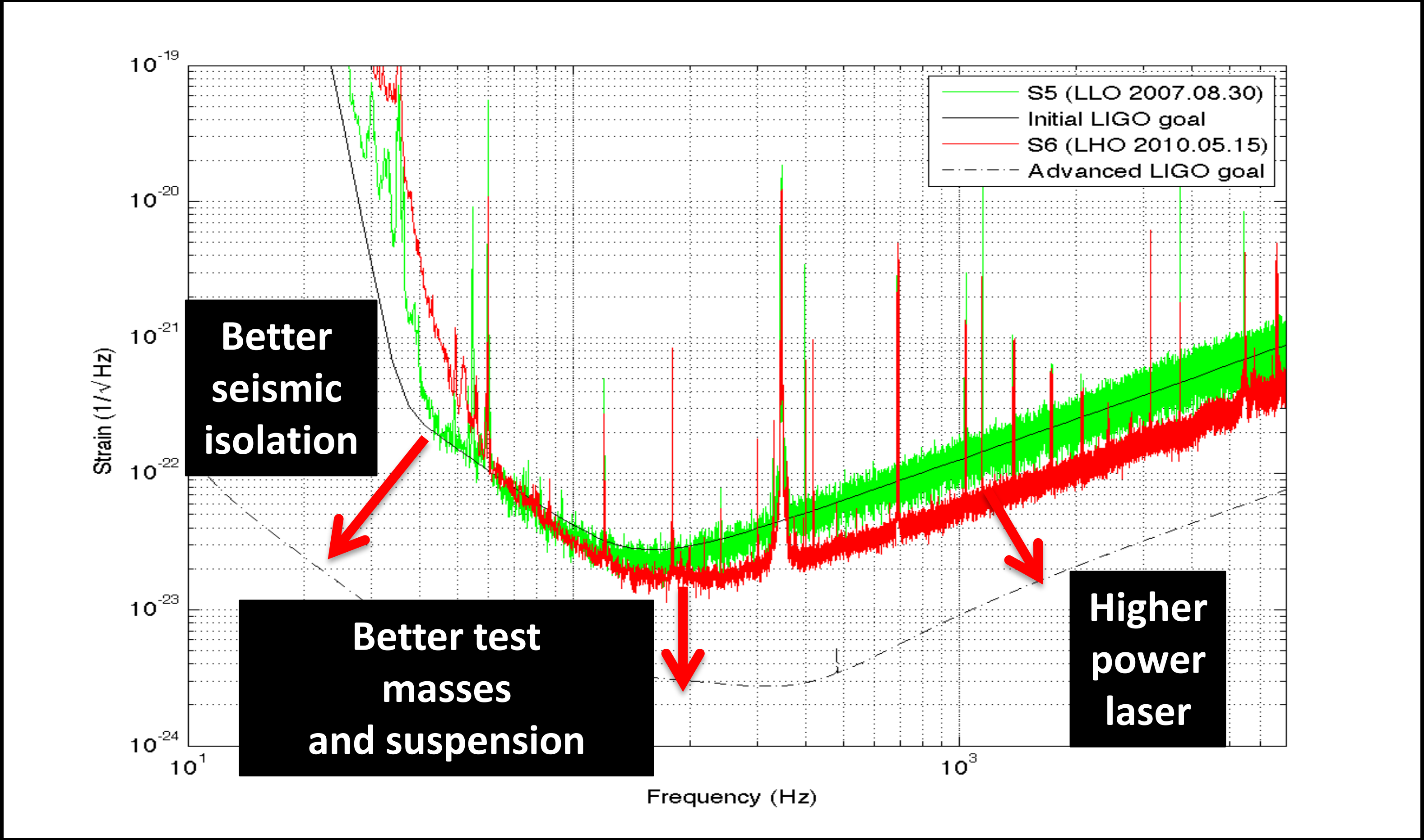


What Limits LIGO Sensitivity?

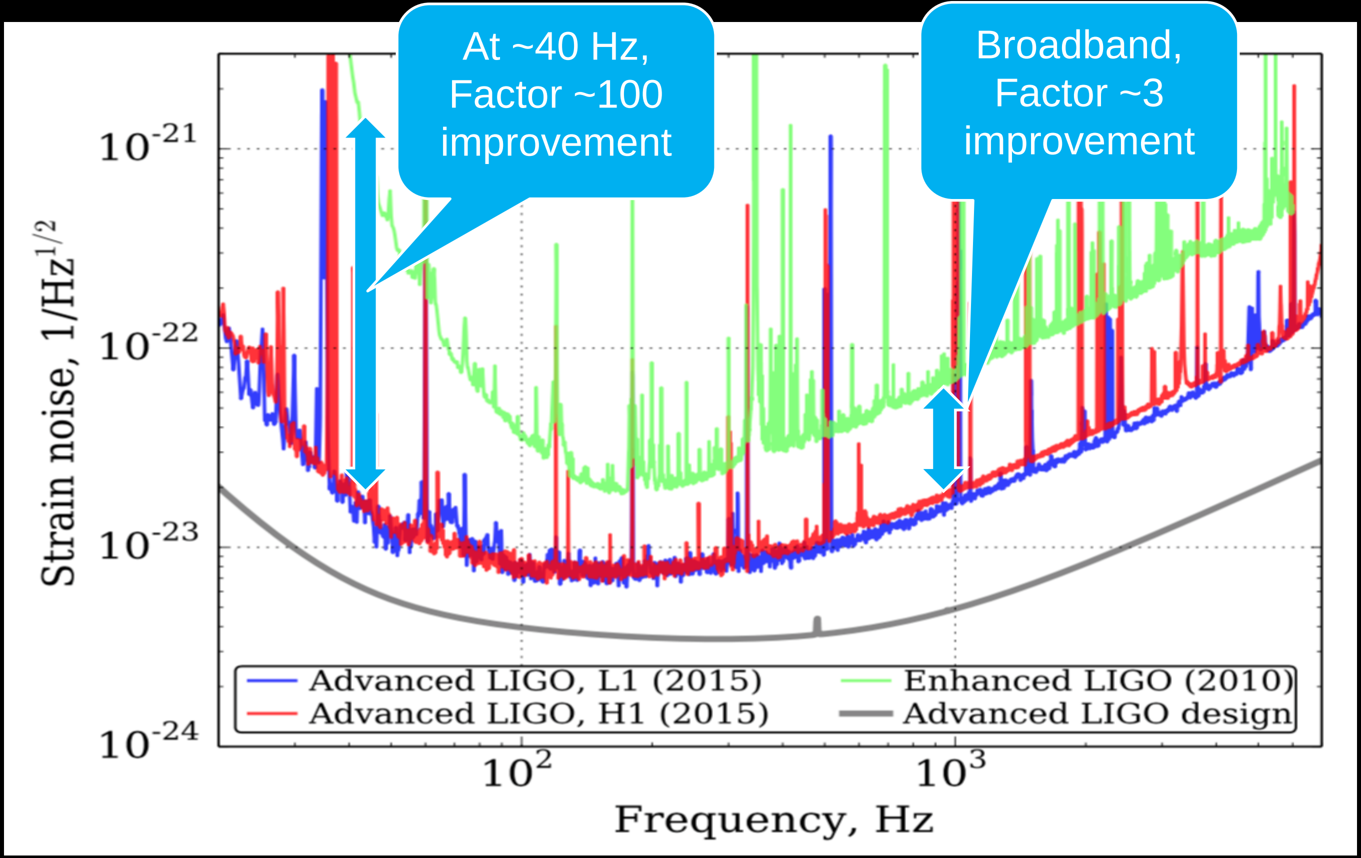
- **Seismic noise limits low frequencies**
- **Thermal Noise limits middle frequencies**
- **Quantum nature of light (Shot Noise) limits high frequencies**
- **Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals**



Advanced LIGO GOALS



Sensitivity for Advanced LIGO

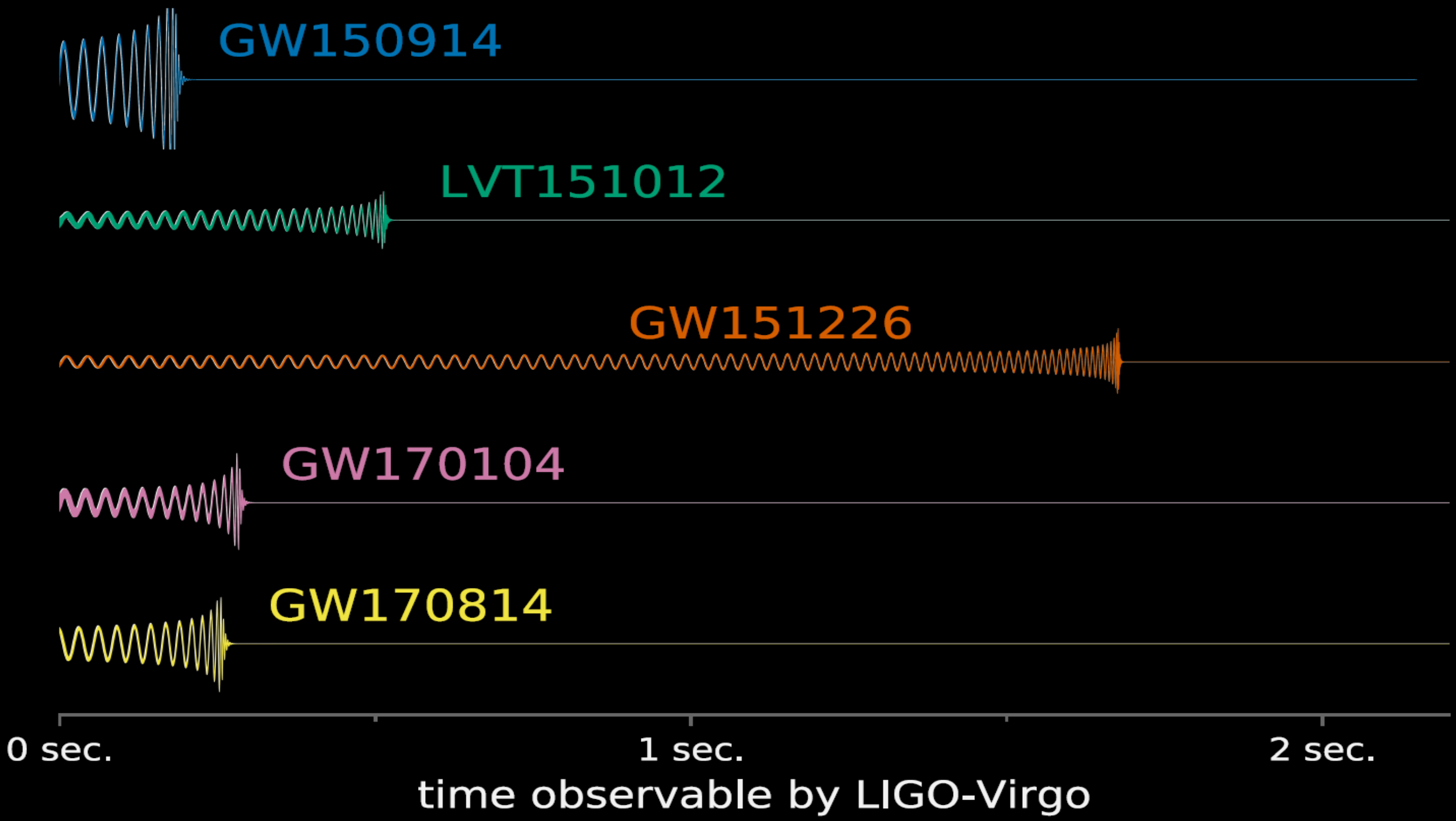


Initial LIGO

O1 aLIGO

Design aLIGO

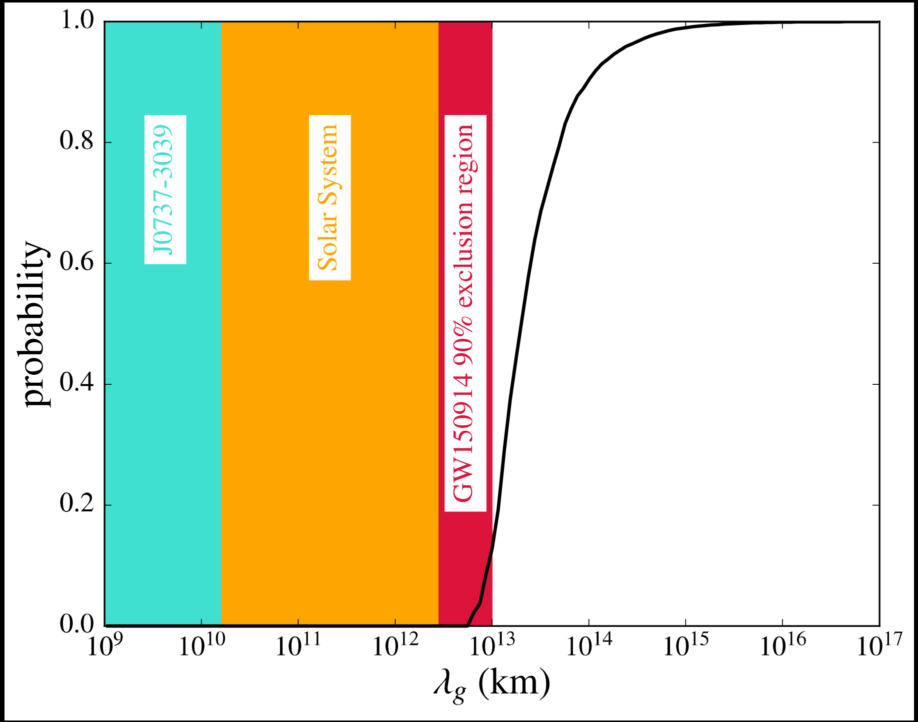
Reported Black Holes Mergers



Testing General Relativity

graviton mass

If $v_{GW} < c$, gravitational waves then have a modified dispersion relation. There is no evidence of a modified inspiral



$$\lambda_g > 10^{13}\ \mathrm{km}$$

$$m_g < 1.2 \times 10^{-22}\ \mathrm{eV}/c^2$$

LIMIT 90% Confidence

Phys. Rev. Lett. 116, 221102 (2016)

New Astrophysics

- Stellar binary black holes exist
- They form into binary pairs
- They merge within the lifetime of the universe
- The masses ($M > 20\, M_{\odot}$) are much larger than what was known about stellar mass Black Holes.

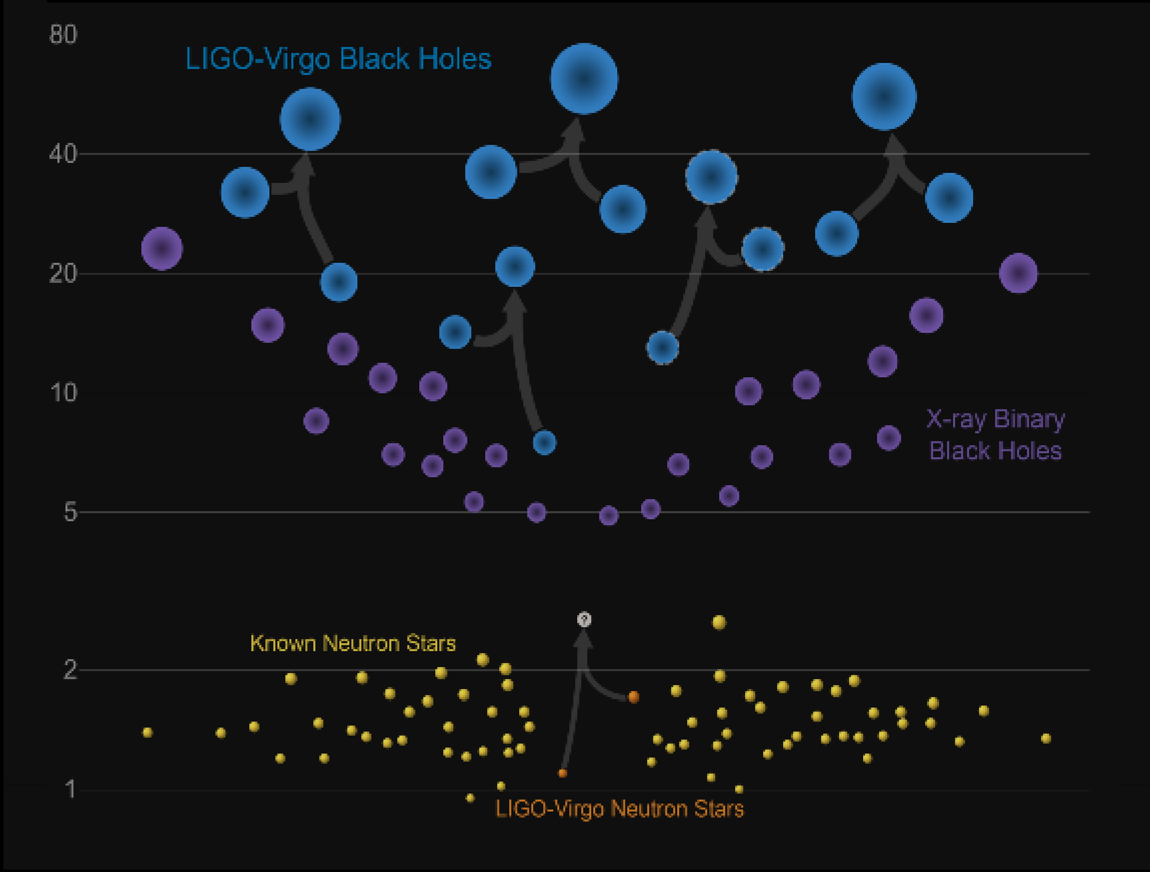
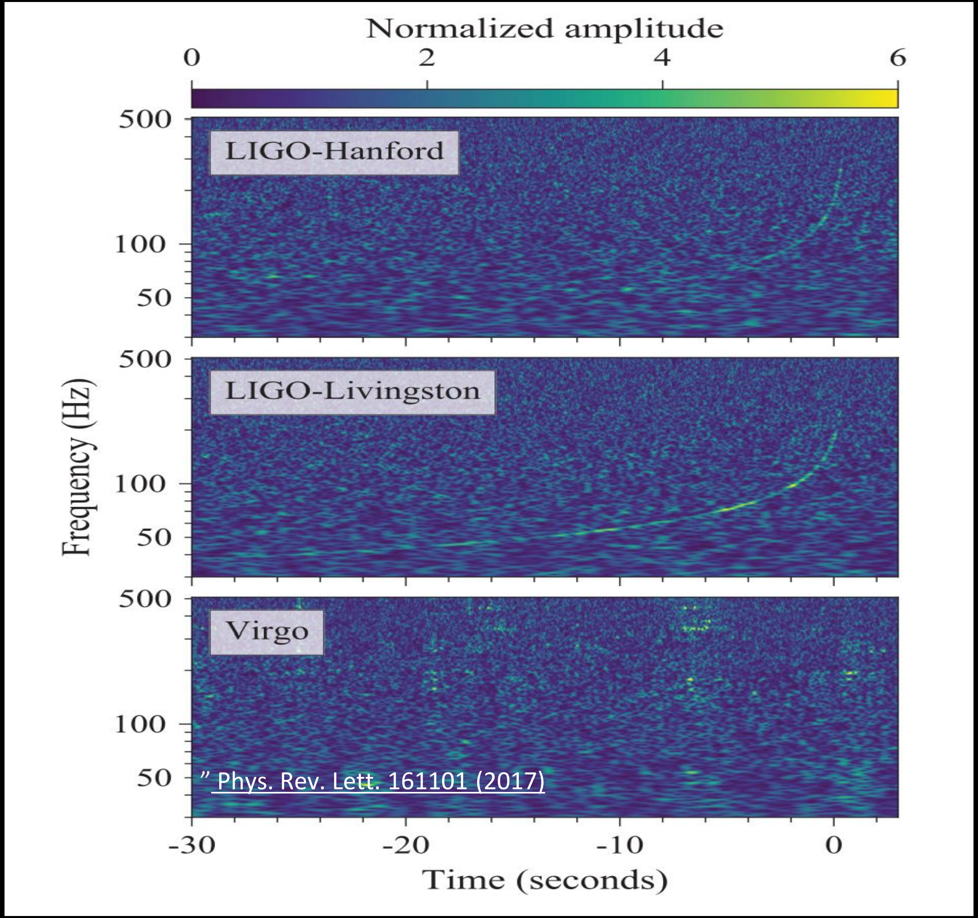


Image credit: LIGO

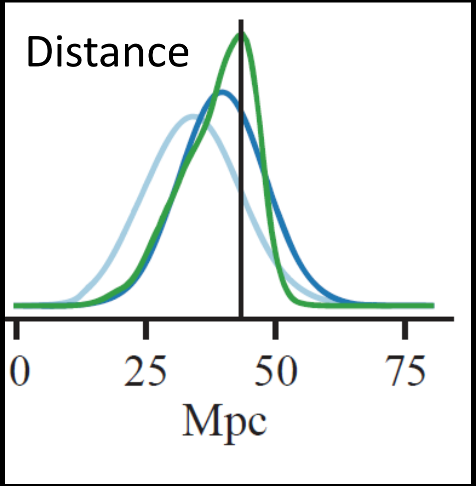
First Binary Neutron Star Merger



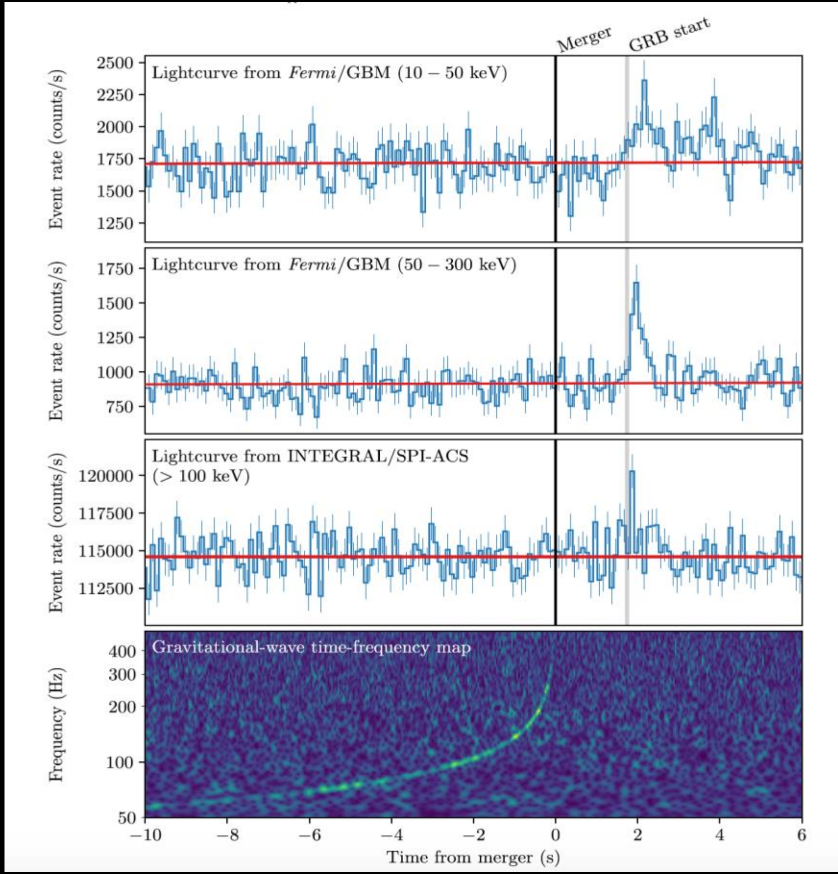
” Phys. Rev. Lett. 161101 (2017)

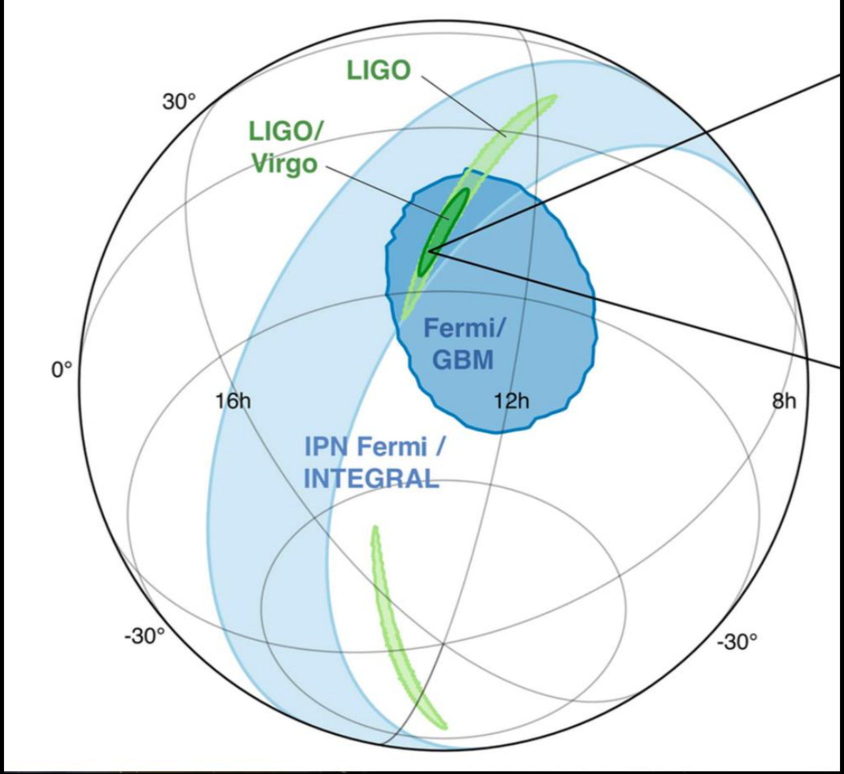
	Low-spin priors ($|\chi| \leq 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$

	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	1.36–2.26 $M_\odot$
Secondary mass m_2	0.86–1.36 $M_\odot$



Fermi Satellite GRB detection 2 seconds later

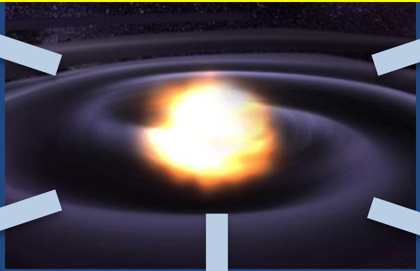




170817A" Astrophys. J. Lett., 848:L13, (2017)

Multi-messenger Astronomy with Gravitational Waves

Binary Neutron Star Merger

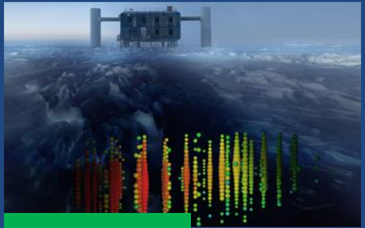


Gravitational Waves

X-rays/Gamma-rays

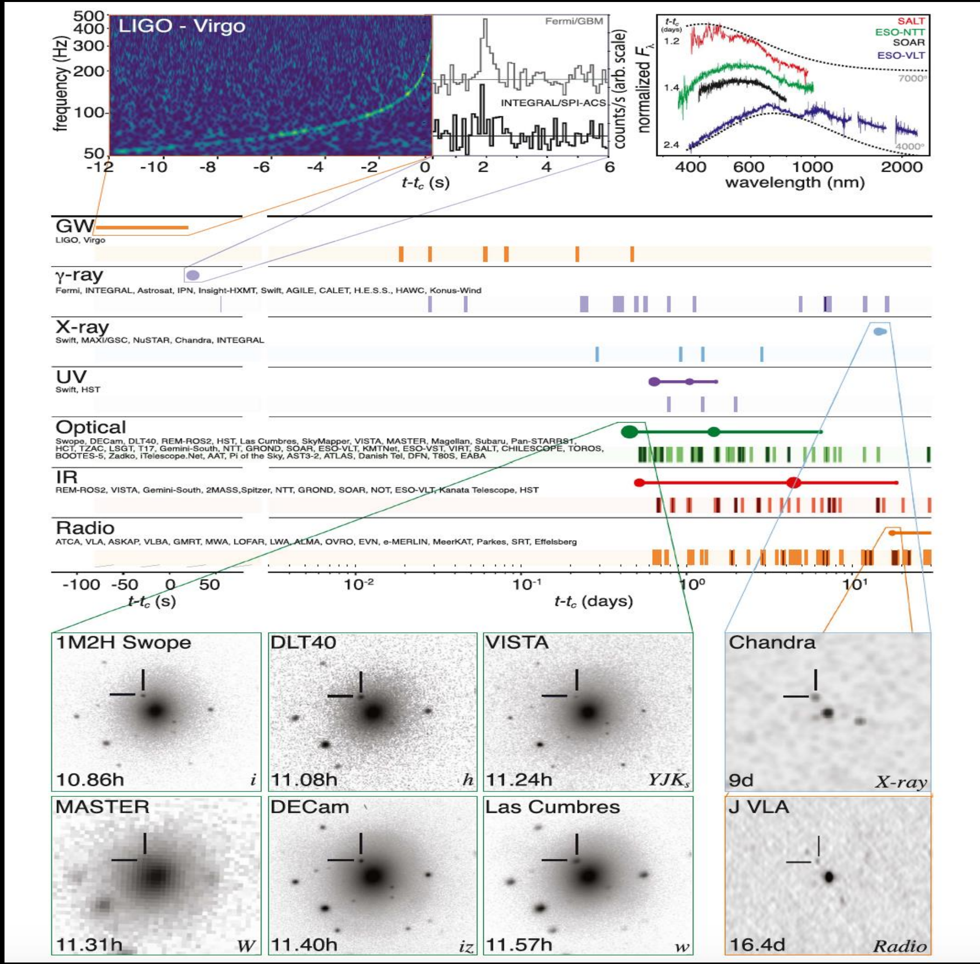
Visible/Infrared Light

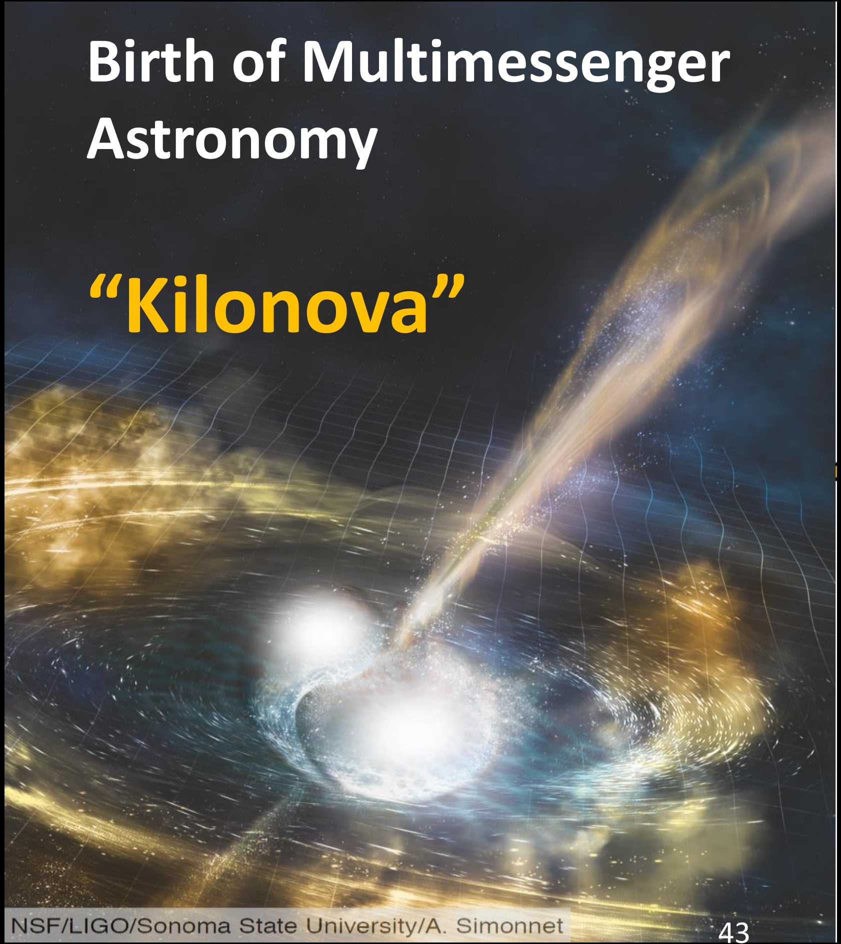
Radio Waves



Neutrinos

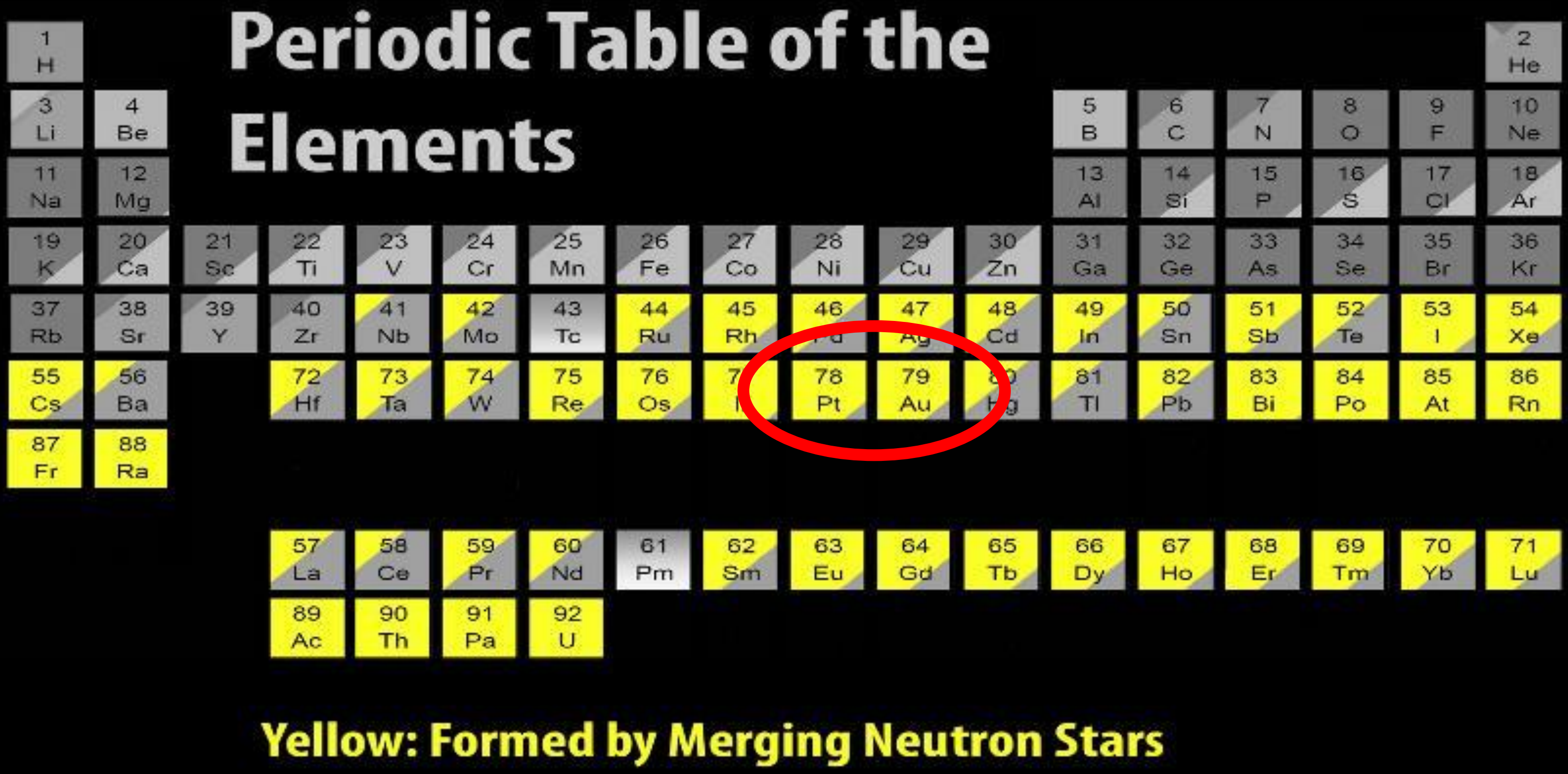
Observations Across the Electromagnetic Spectrum



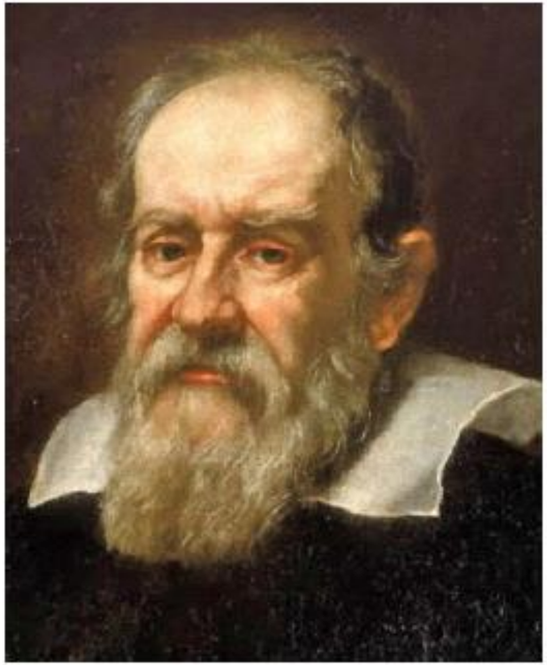


The Origin of Heavy Elements

Gold Factory in the Sky



The Birth of a New Astronomy



Thanks!