Gravitational Waves

Wind Crest Learners

Academy for Lifelong Learning

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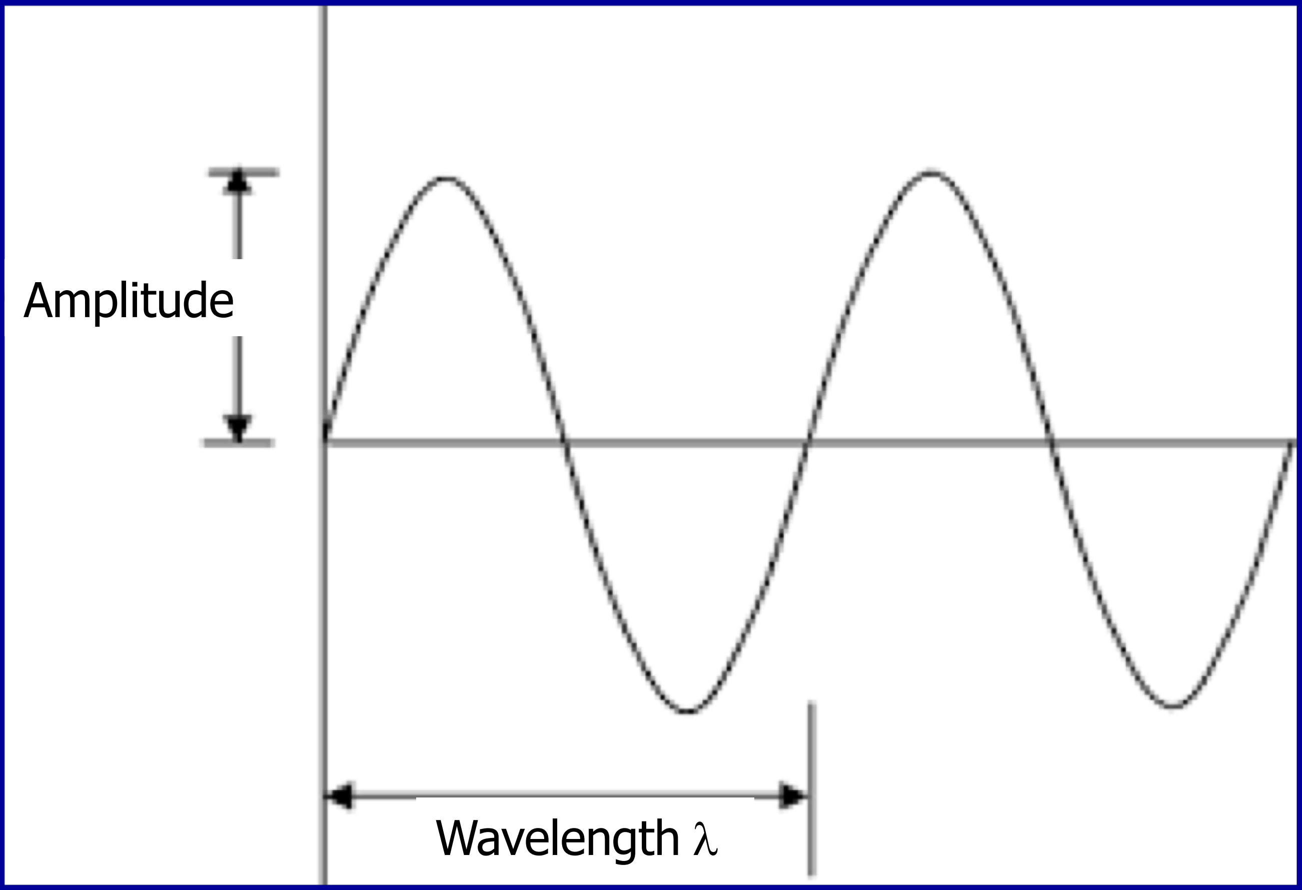
Electromagnetic waves

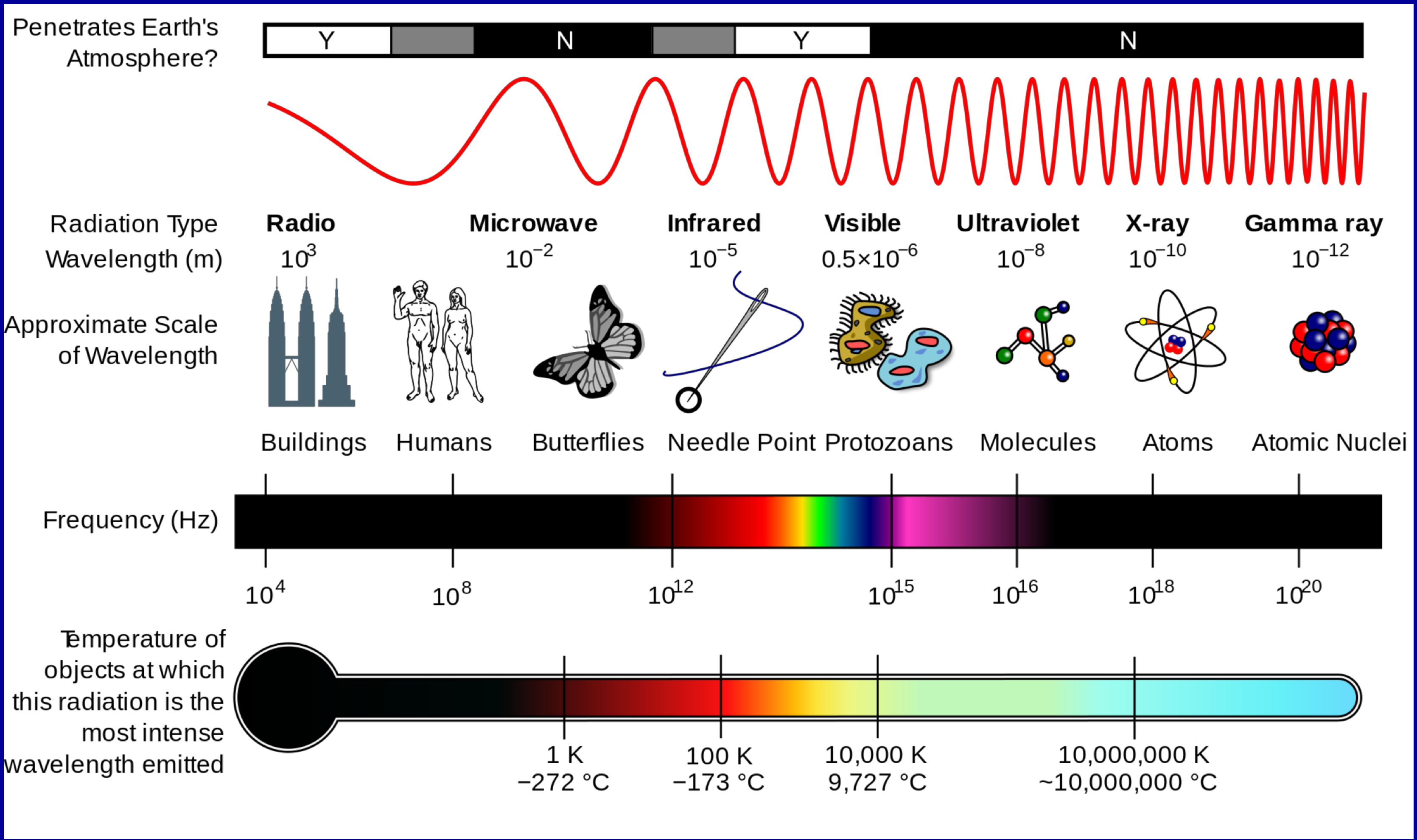
$f=c/\lambda$

Frequency is measured in cycles per second, a unit we call Hertz or symbolize Hz.

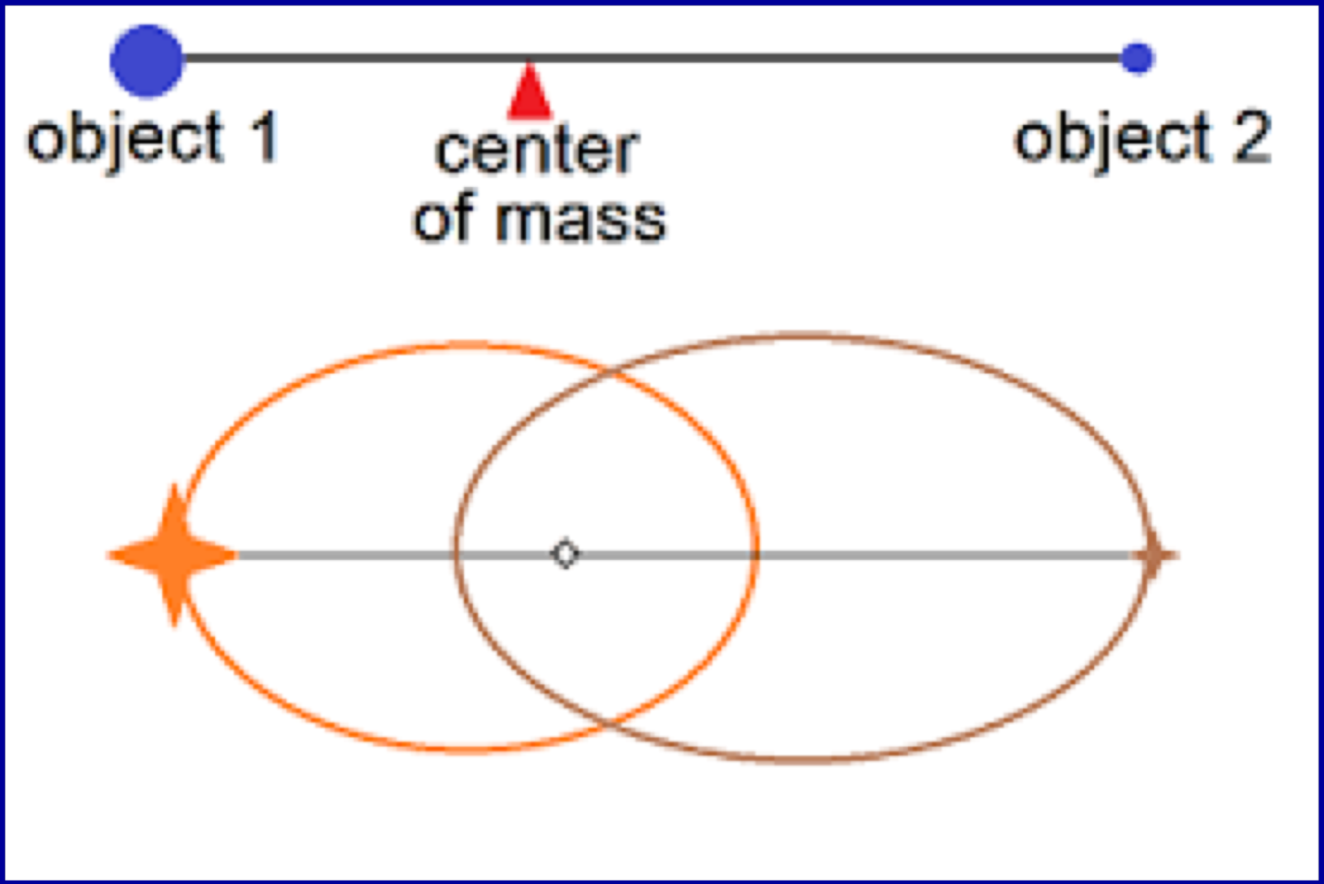


As wavelength gets longer (bigger), cycles per second gets slower (frequency decreases).

The electromagnetic spectrum



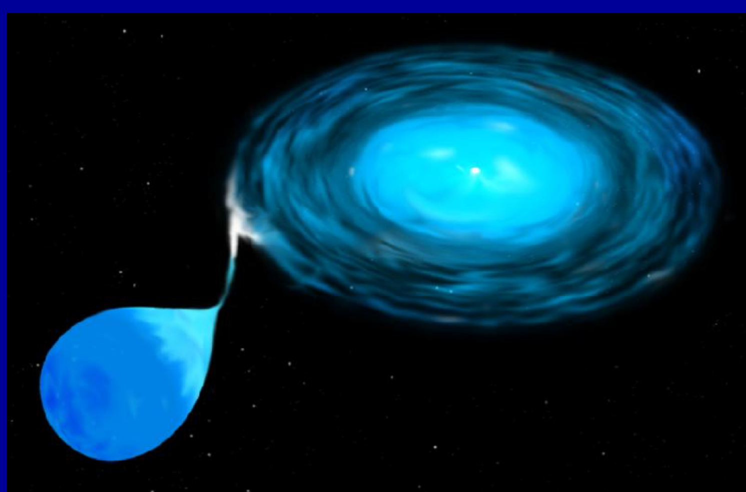
Binary orbits

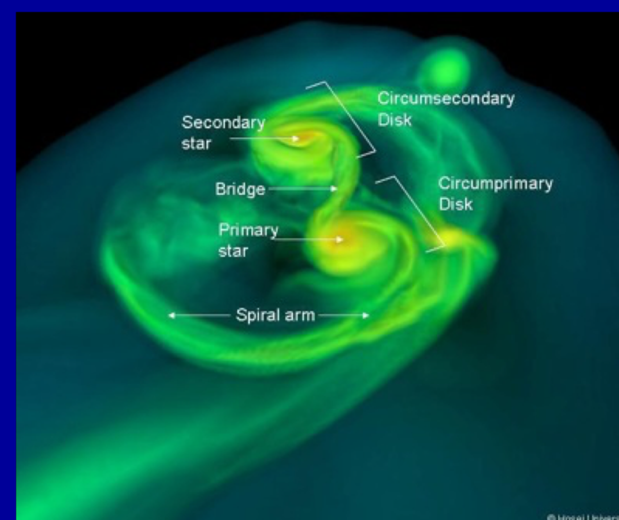


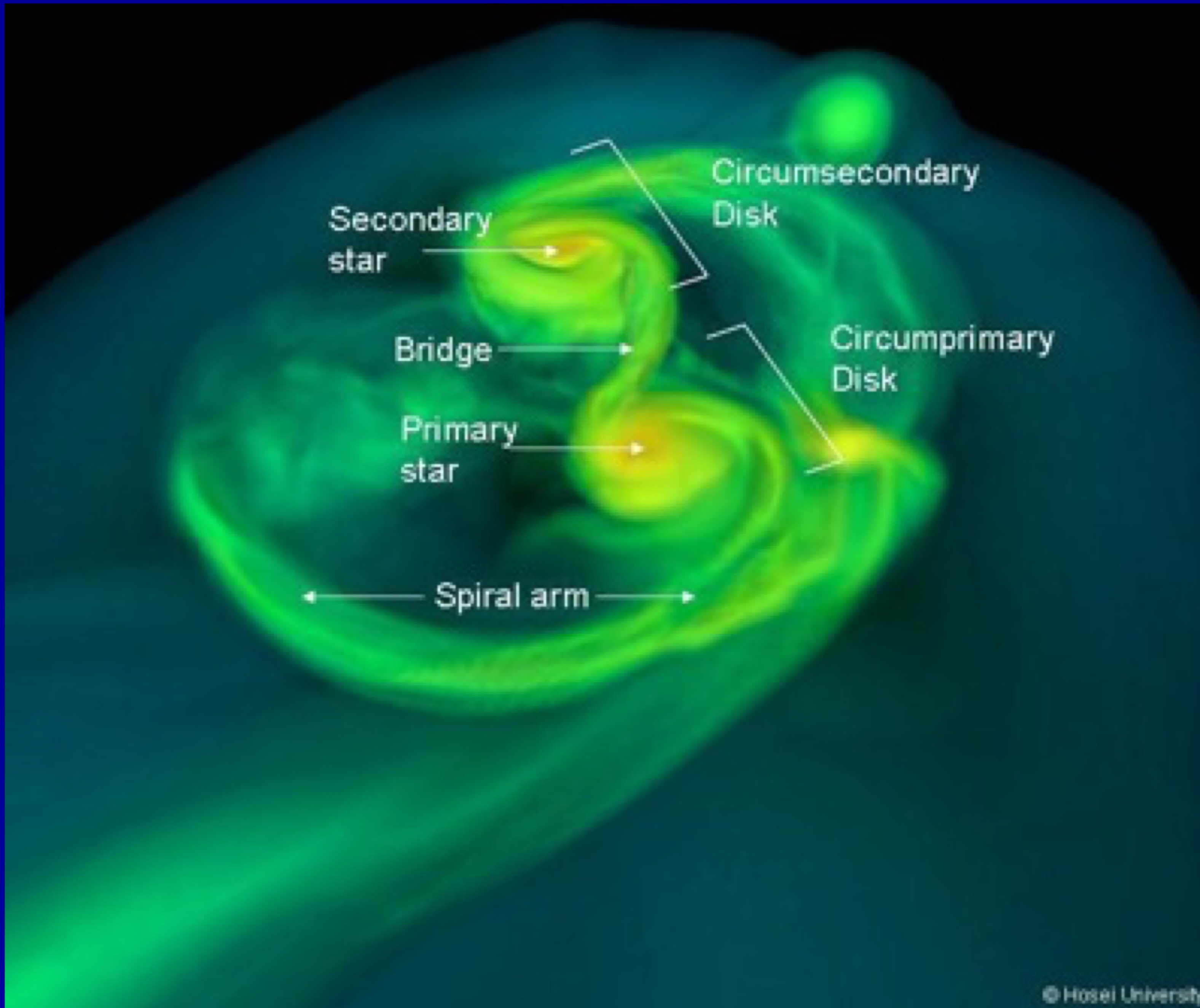
Collapsed objects

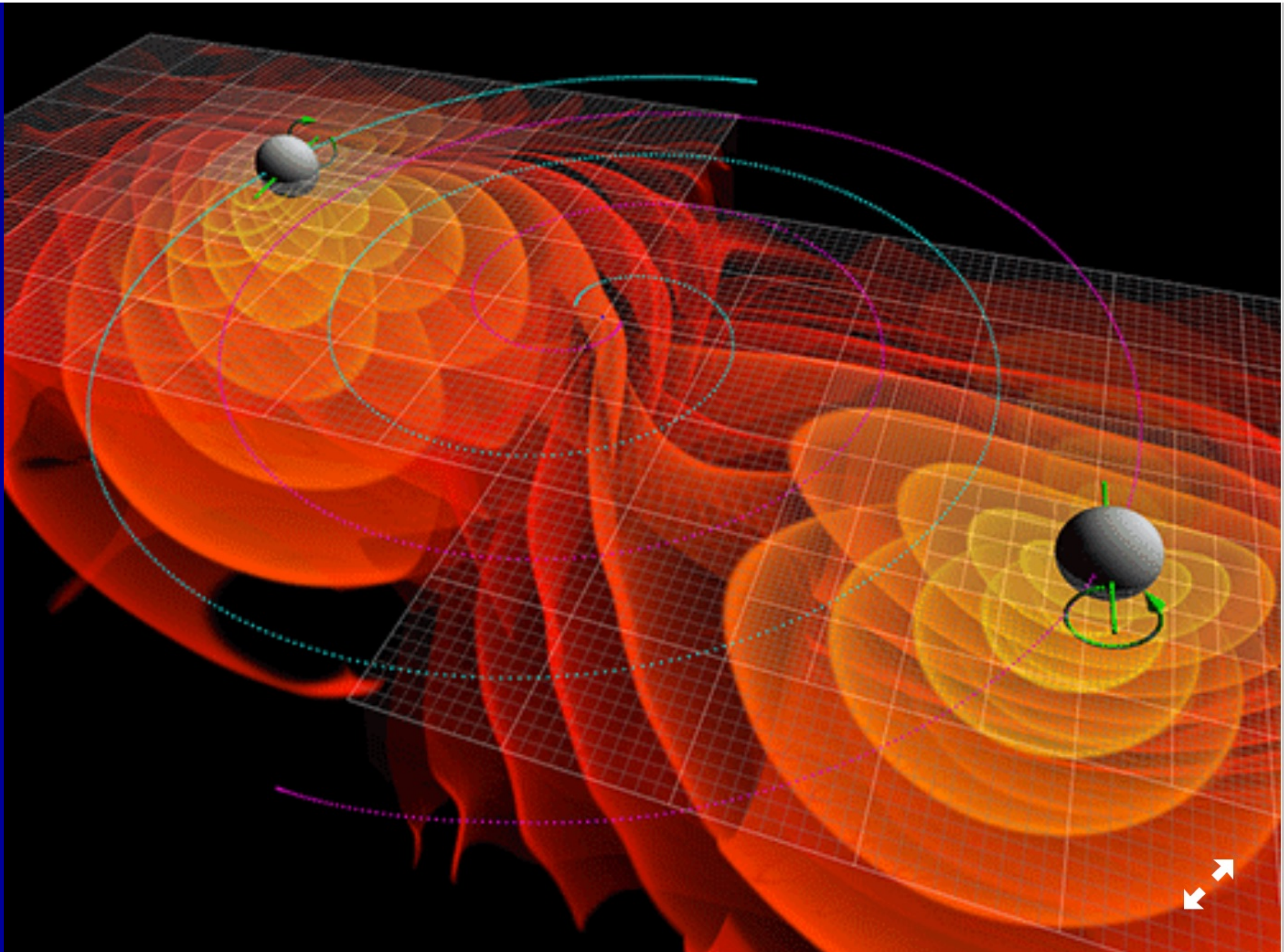
- $0.6 < M_o < 1.4$ => white dwarf
- $1.1 < M_o < 3.3$ => neutron star (pulsars)
- $3.8 < M_o < 10^9$ => black hole

Many stars end up in binary systems, and one or both of the stars can collapse once its internal fuel is burned up.

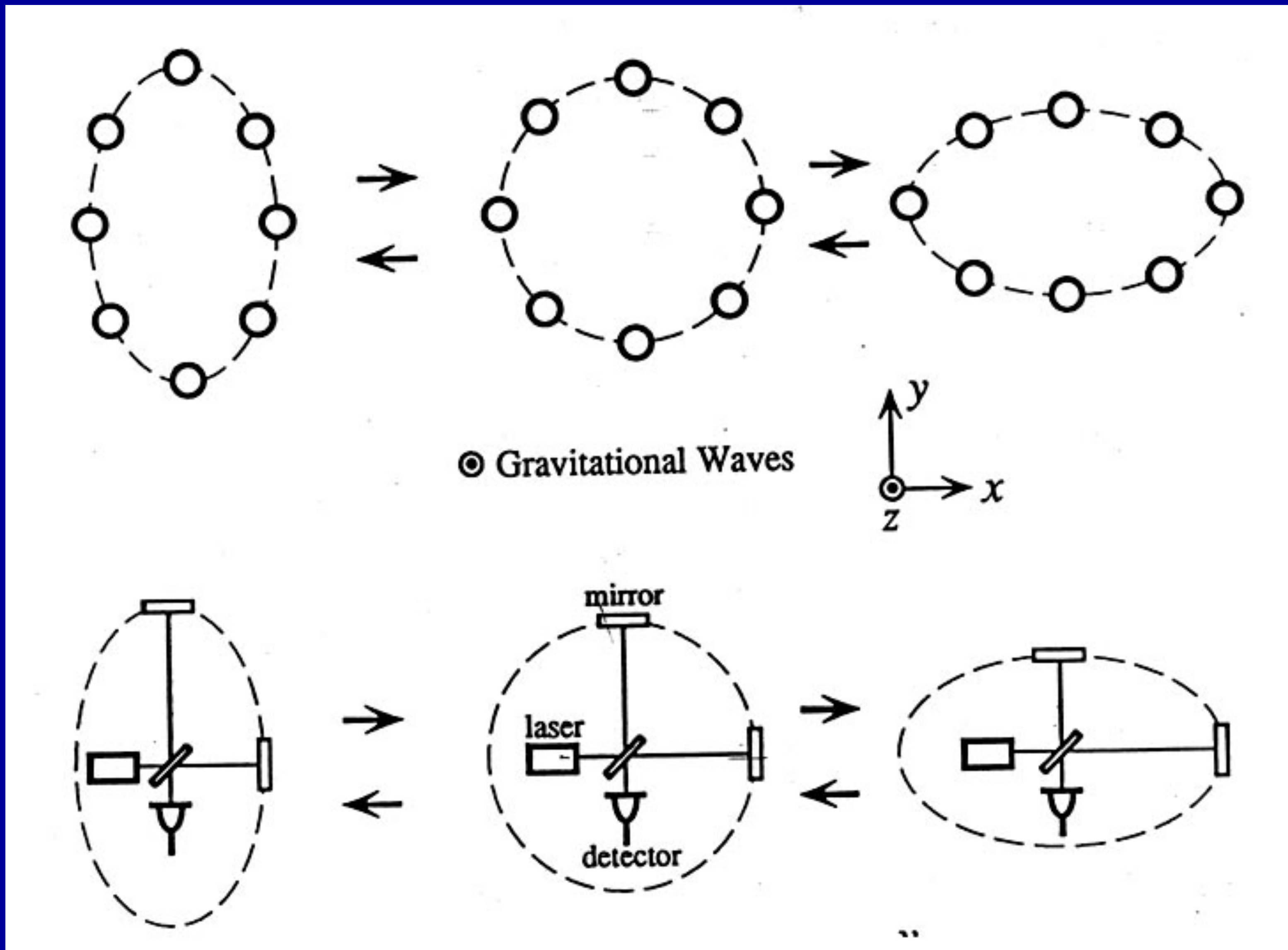





Circumsecondary
Disk
Secondary
star
Bridge
Circumprimary
Disk
Primary
star
Spiral arm
© Hosei University



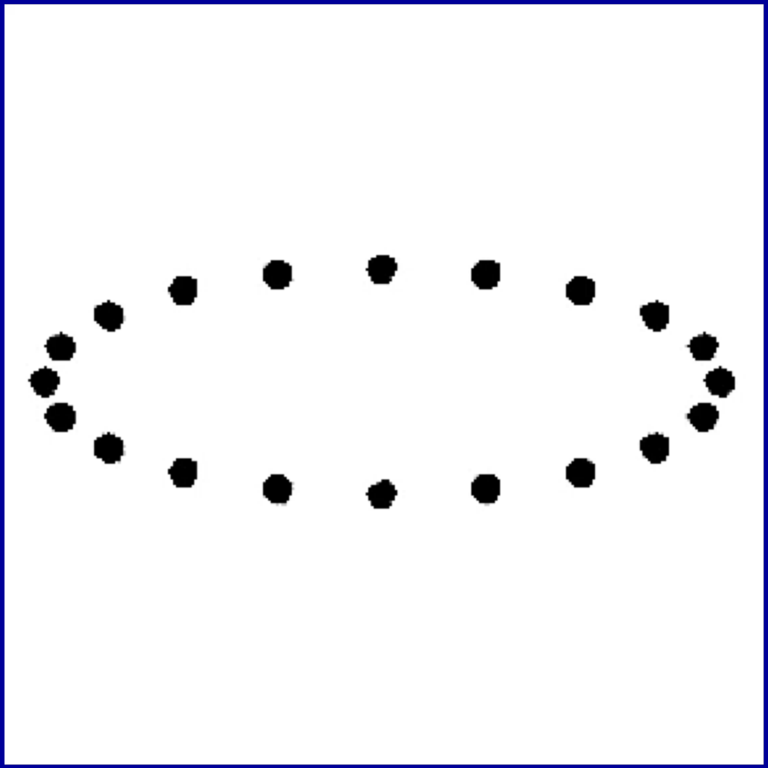
C. Henze/NASA Ames Research Center



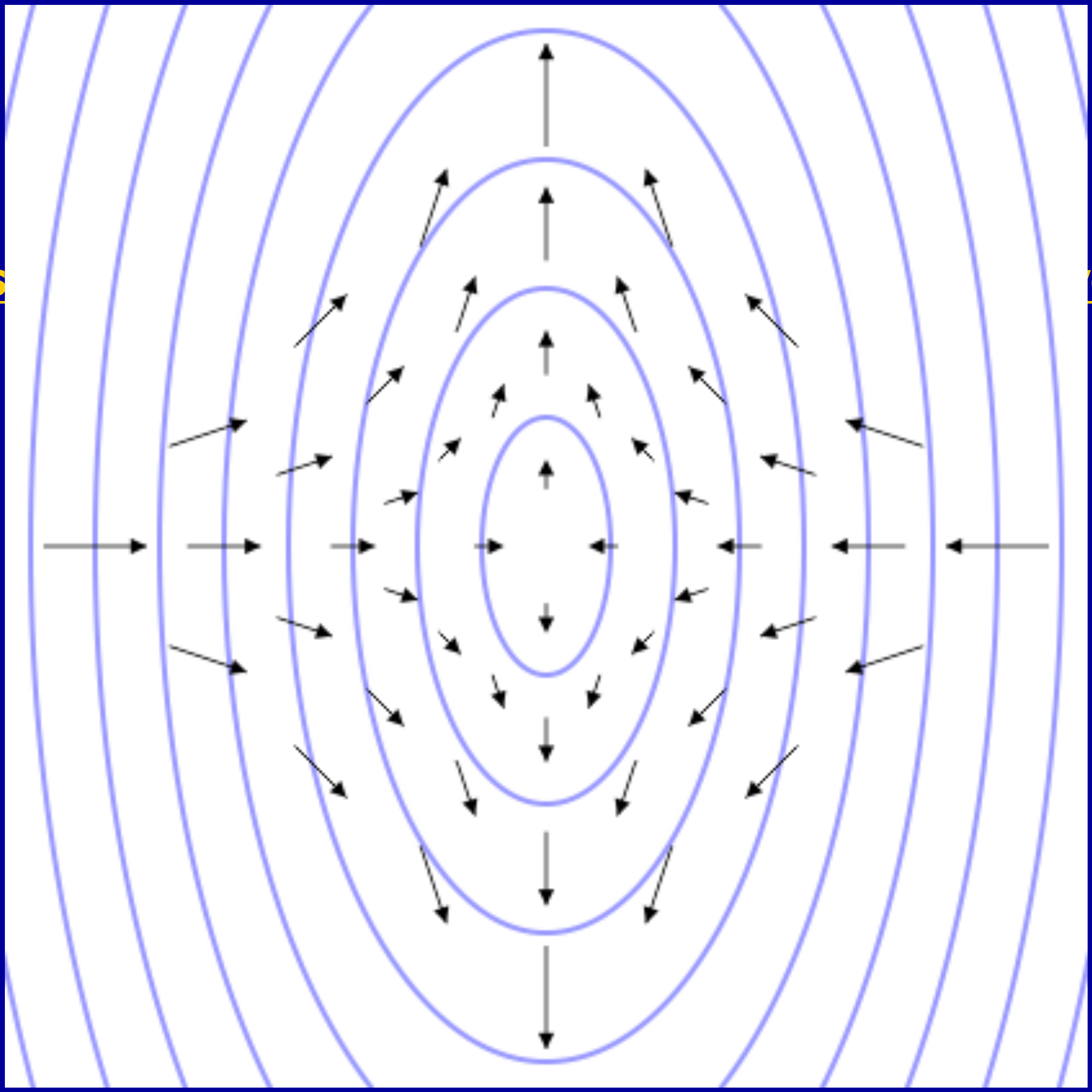
graphic courtesy of B. Barish, LIGO-Caltech
hula hoop courtesy of Craig and Arlene's grandchildren

Quadrupole wave

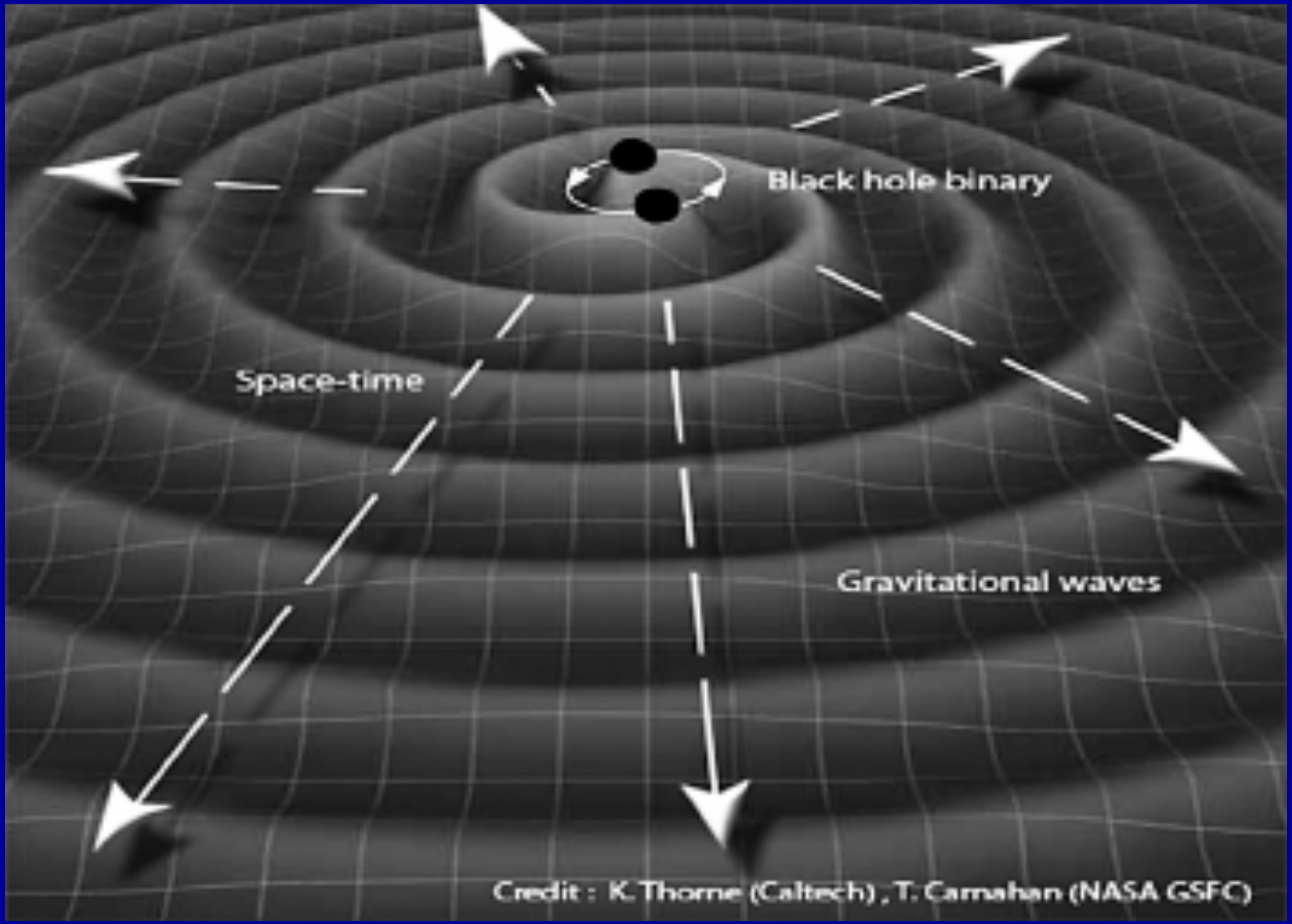
https://en.wikipedia.org/wiki/File:Quadrupol_Wave.gif



https … e.gif



Black Hole merger



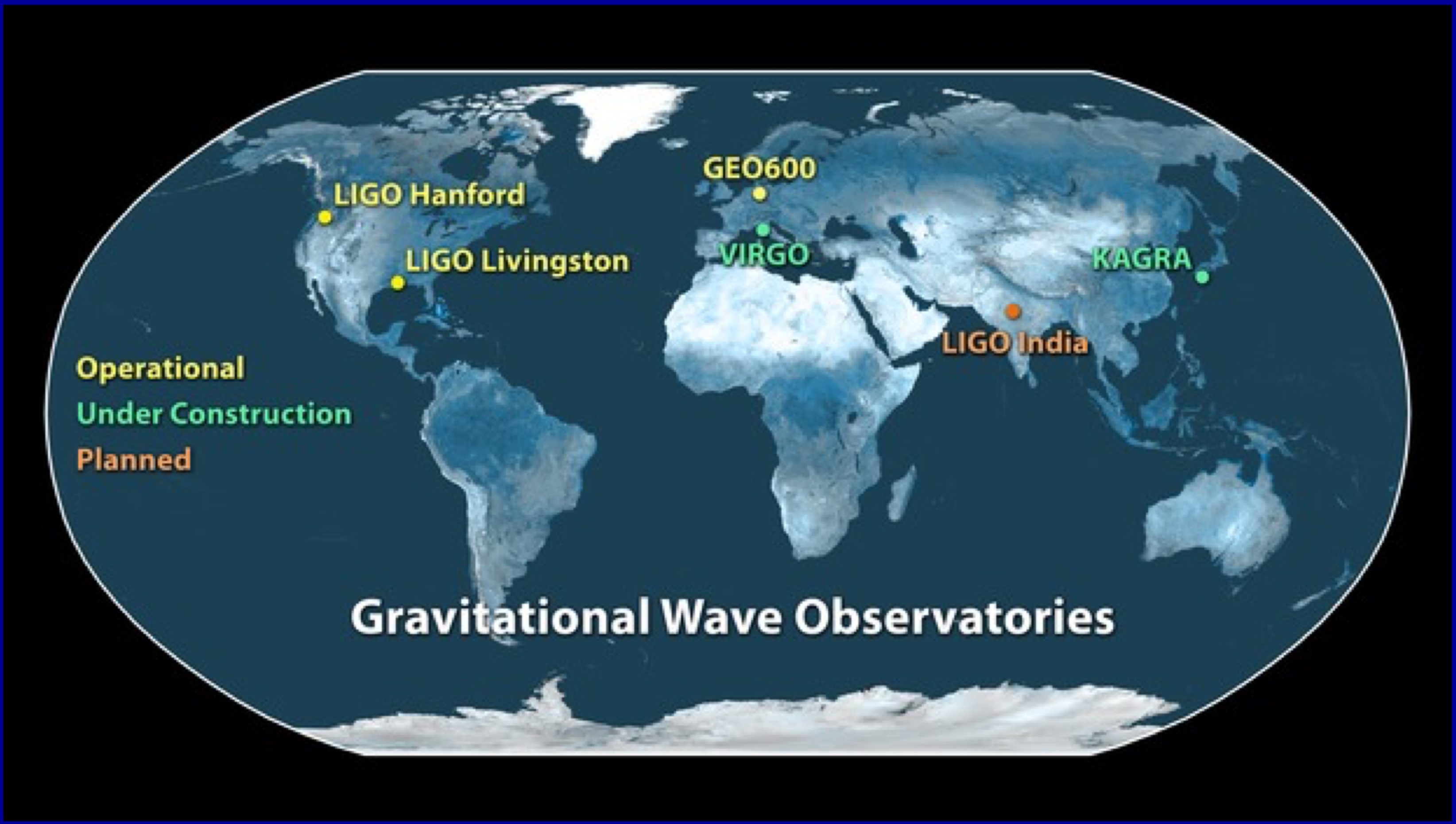
Pulse timing is important

LIGO, late 1990s (first funding 1995)

Arms 4 km long, masses 40 kg, basically mirrors. Motion detected 10^{-19} m (aLIGO).

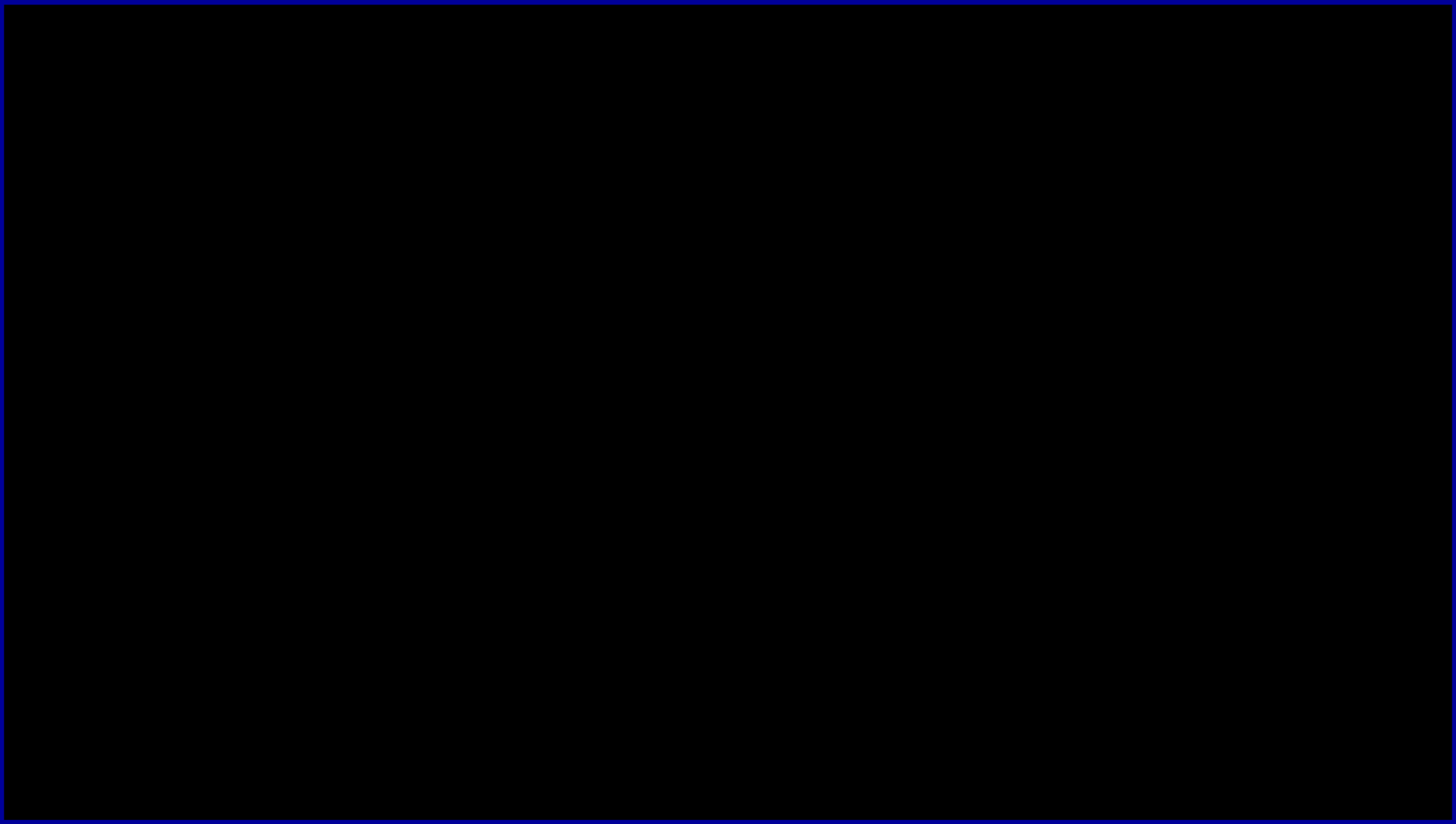
Coincidence by aLIGO: Hanford, Washington and Livingston, Louisiana, (Italy)

Gravity wave detectors



GEO600 was not operating on Sept. 15 2015

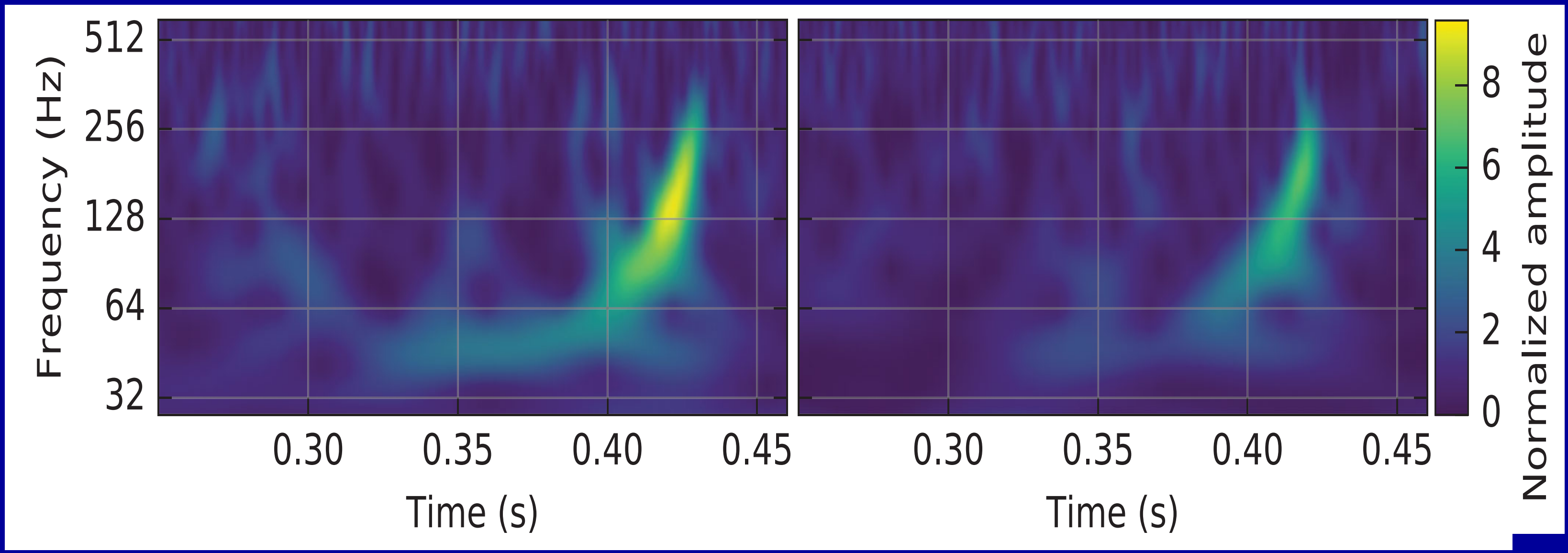
What are gravitational waves



The sound chirp

The sound ends around middle C for those of you who know your piano.

Started about G, two and a half octaves lower.



Mass ranges

- We use the Sun’s mass as a unit for studying stars
- We designate it as M_o; we say the mass of our sun is $M_{sun} = 1\ M_o$

- $M_{dwarf} < 1.39\ M_o$ => white dwarf
- $1.39\ M_o < M_{ns} < 3.2\ M_o$ => neutron star
- $M_{BH} > 3.2\ M_o$ => black hole
  - stellar sized black holes
  - The original stars lose blow off a lot of mass in their explosions
- Black hole at the center of our galaxy $M = 10^6\ M_o$
- Supermassive Black holes $10^9\ M_o$

Coalescing black holes

3.26 x Mpc = Mly: all are in our local supercluster

Event	$m_1/M_\odot$	$m_2/M_\odot$	d_L/Mpc	χ_{eff}	$M_f/M_\odot$	Dist/Bly
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	430^{+150}_{-170}	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	1.4 B ly
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	1060^{+540}_{-480}	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	3.4 B ly
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	440^{+180}_{-190}	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	1.43 B ly
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	960^{+430}_{-410}	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	3.1 B ly
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	320^{+120}_{-110}	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	1.0 B ly
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	2750^{+1350}_{-1320}	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	9.0 B ly
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	990^{+320}_{-380}	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	3.2 B ly
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	580^{+160}_{-210}	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	1.9 Bly
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	40^{+10}_{-10}	$0.00^{+0.02}_{-0.01}$	≤ 2.8	0.13 B ly
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	1020^{+430}_{-360}	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	3.3 B ly
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	1850^{+840}_{-840}	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	6.0 B ly

The major players in LIGO

Nobel Prize 2018

Kip Thorn, Caltech

Rainer Weiss, MIT

Laser Interferometer Gravitational-Wave Observatory (LIGO) is a large-scale, very high-precision, physics experiment and observatory to detect gravitational waves. Sponsored by NSF.

Arms are 4 km long

They want to detect $h = \Delta L/L = 10^{-22}$

The laser travels 8 km, so $L = 8 \times 10^{3}$ m

$\Delta L = 10^{-22} \times 8 \times 10^{3}\ \text{m} = 8 \times 10^{-19}\ \text{m}$

$\Delta L = 8 \times 10^{-17}$ cm

Size of proton 1.6×10^{-13} cm

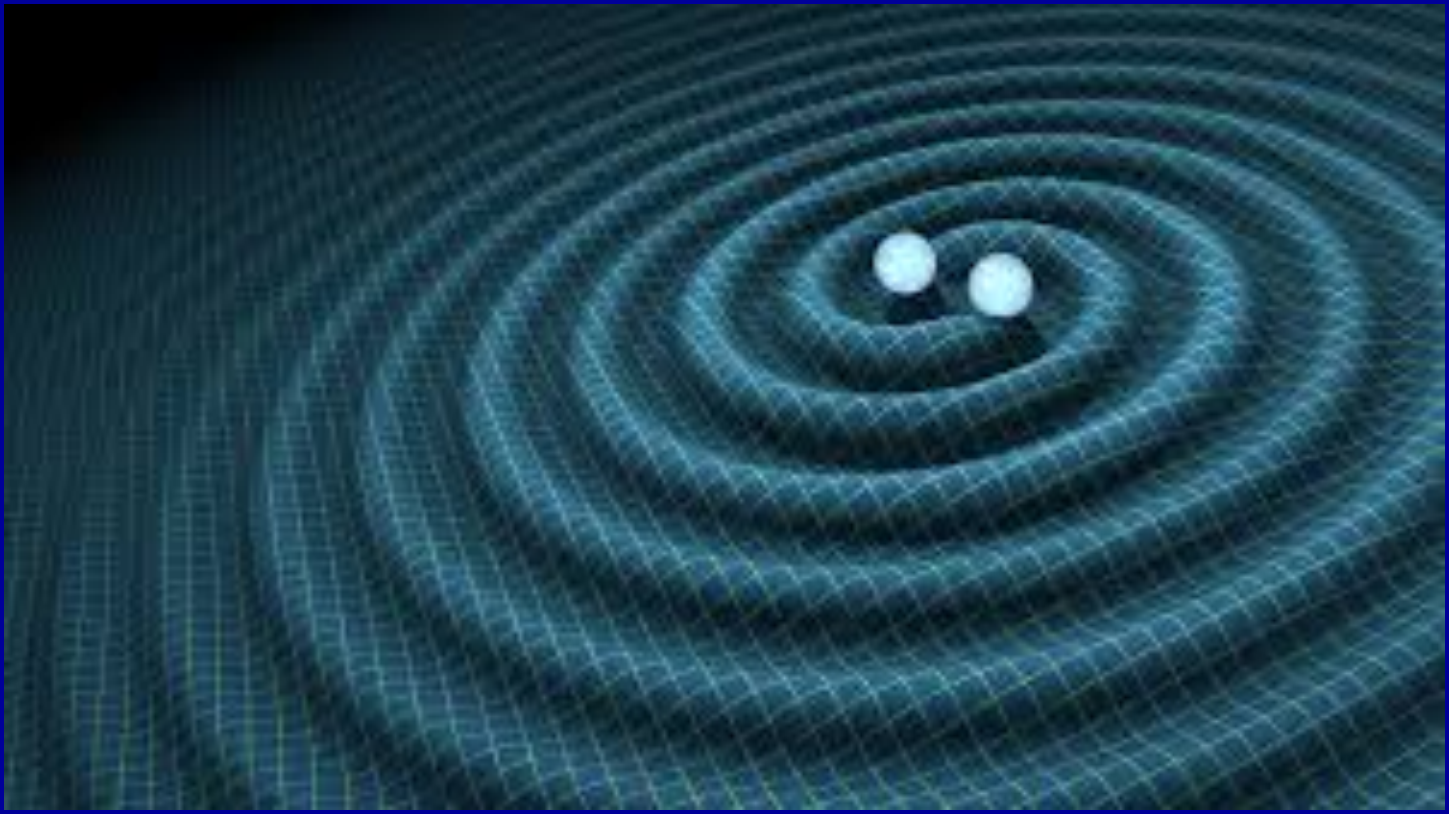
How big is 10^{-17} cm?

An amazing technical 'tour de force'!!

- So 10^{-17} cm is *two thousandth of the size of a proton*. The motion detected was one tenth of a millionth of a billionth of a milliimeter.
  - If you compare this and put the number into dollars, with a millimeter being like a dollar, it is like having 2 thousand trillion dollars or something like 20 times the size of our national debt.

Stop here

36 M_o and 29 M_o -> 62 M_o (+/-4 M_o)
distance 1.3 billion light years
Note: 36 M_o+ 29 M_o= 65 M_o
3 $M_o c^2$ energy in gravitational waves

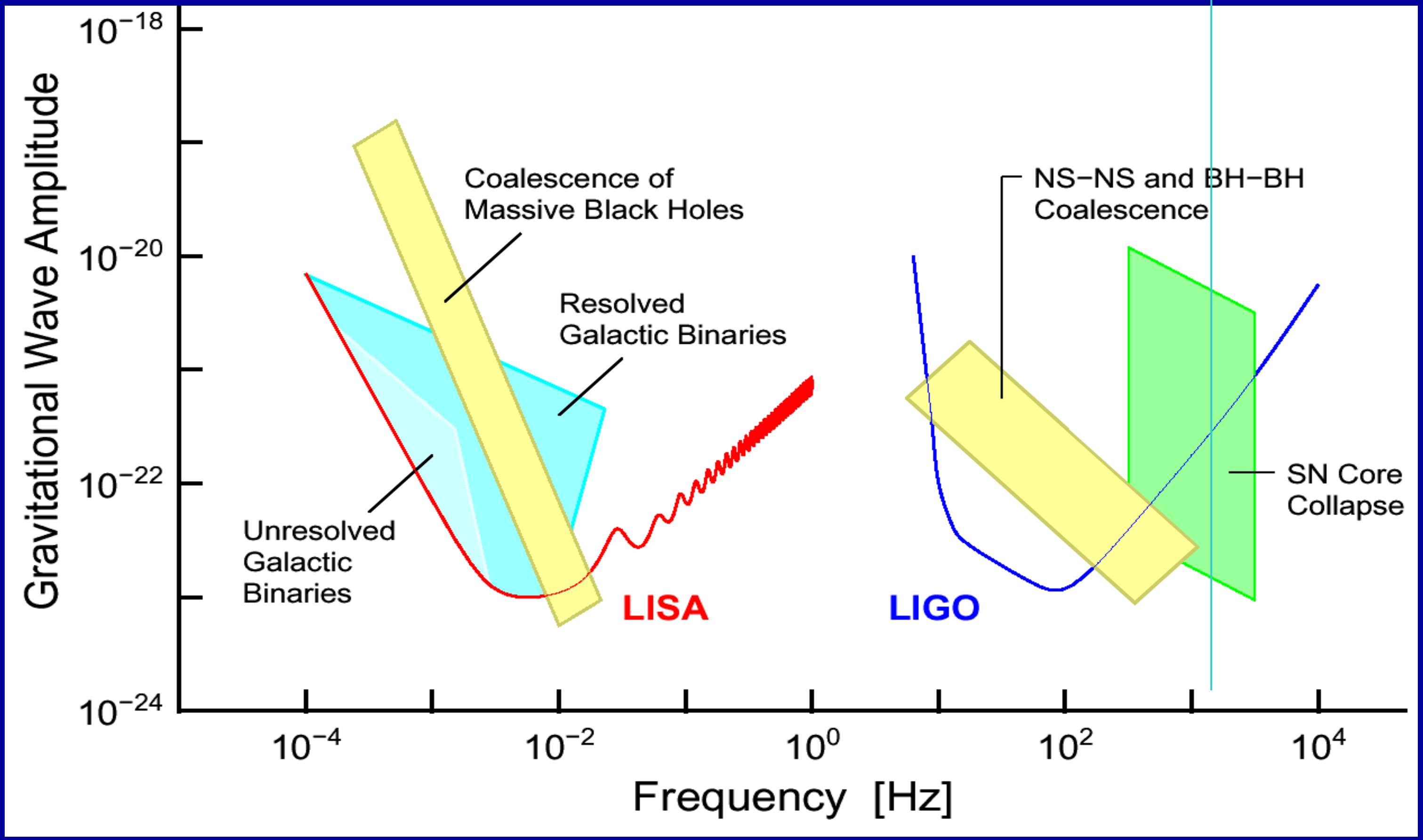


Sept 14, 2015 during the aLIGO calibration run

LISA-LIGO wave bands

Weber bar 10^{-16}

1660 Hz



An outstanding paper

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

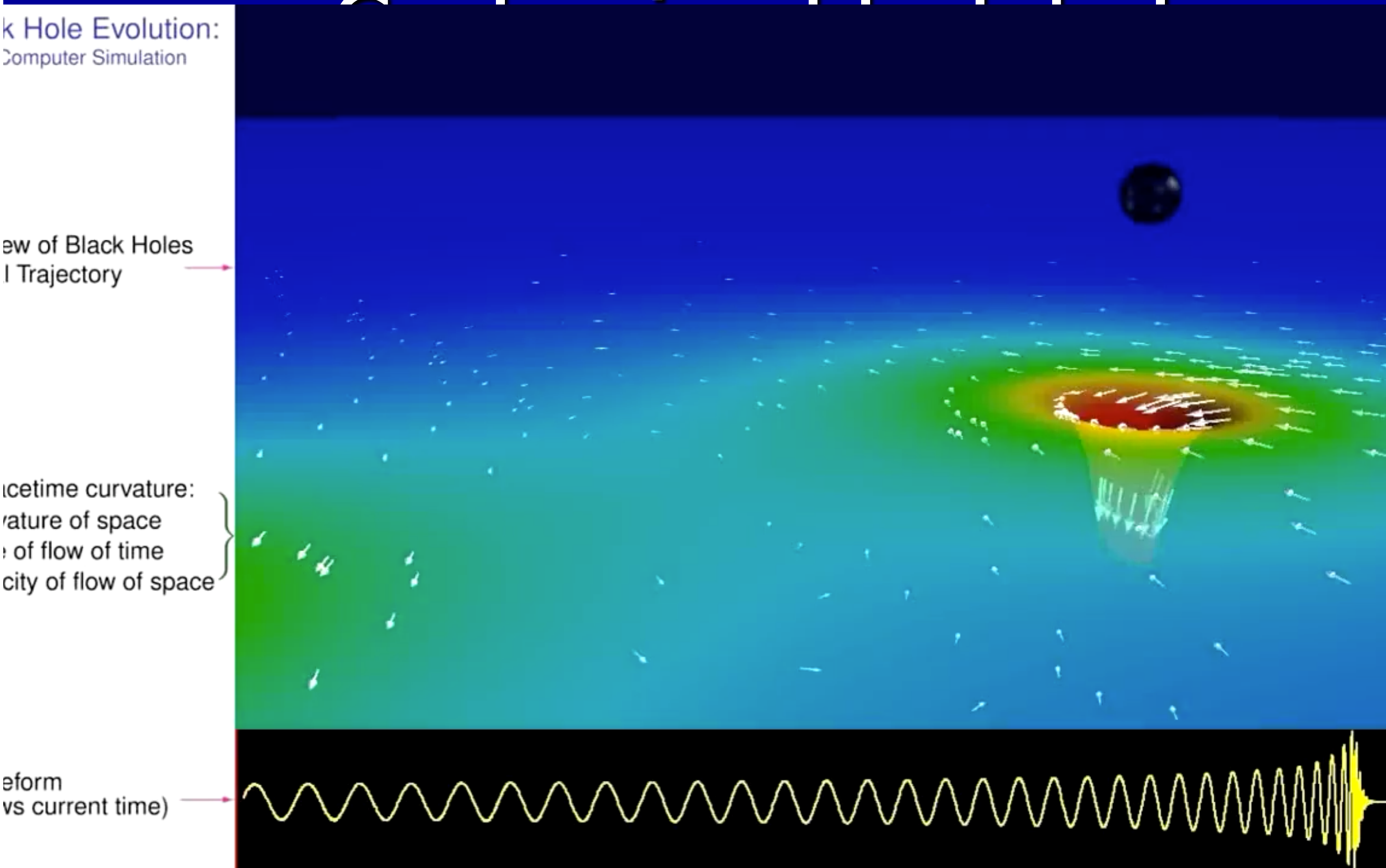
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

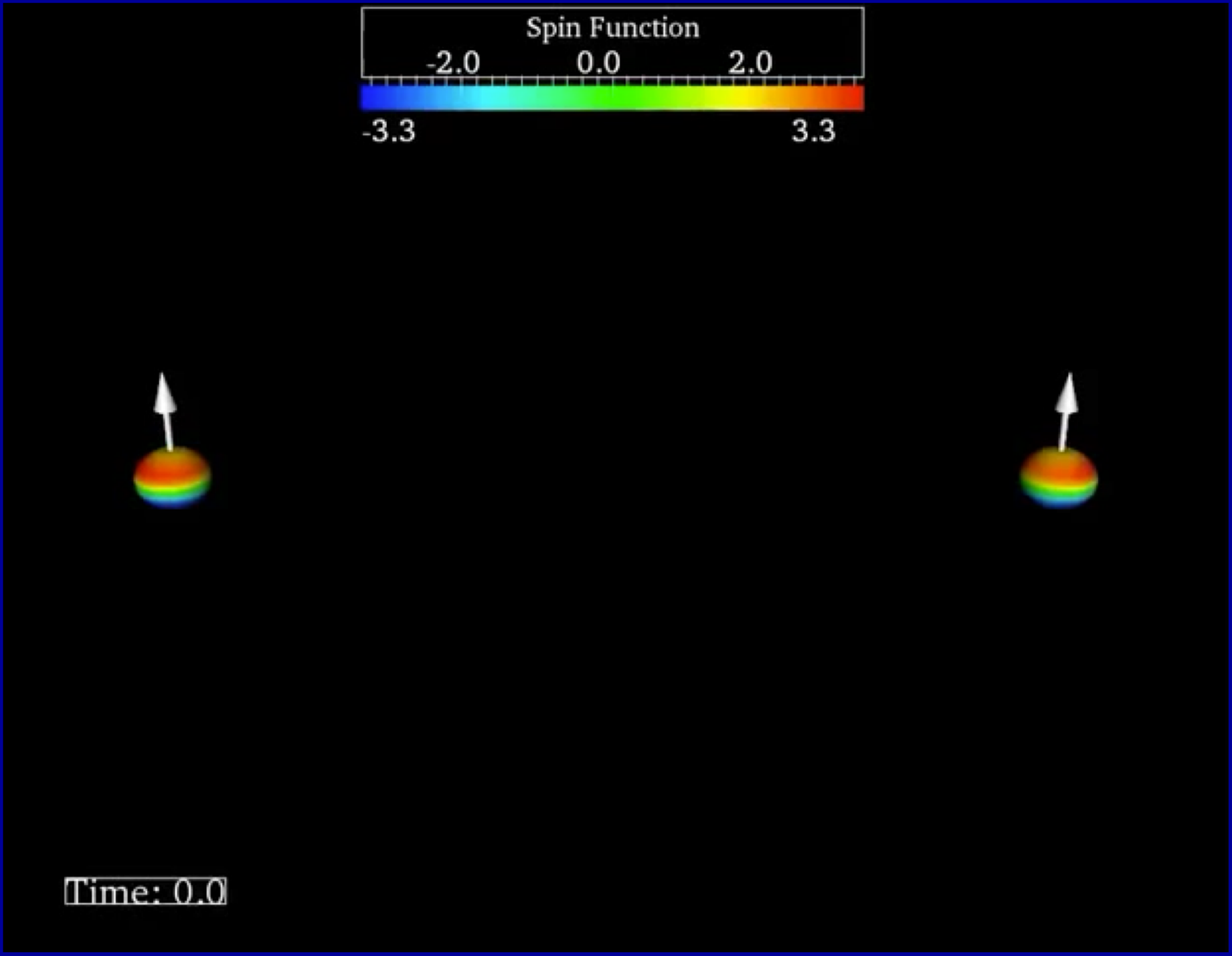
Conclusions

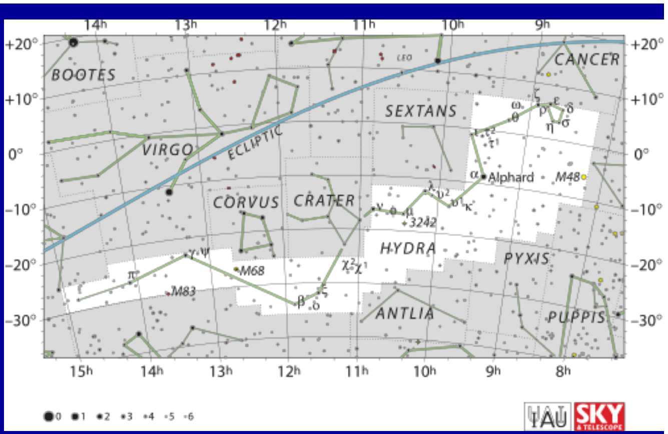
- Observations demonstrate that gravitational waves travel at the speed of light and that gravity has no mass, as predicted by Einstein’s general relativity.
- We can now estimate the rate at which Black hole coalescences are taking place in the nearby (100 M ly).



https://www.youtube.com/watch?v=L478ZPy_2Ys

Coalescing black hole simulations





GW170817

Discovered by LIGO and Virgo Observatories
Chirp 100 sec by LIGP

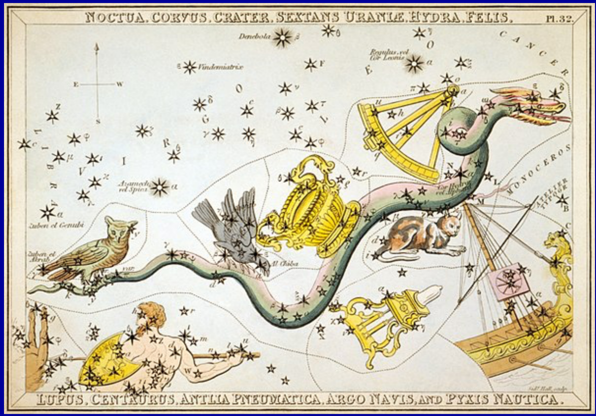
1.7 s later by Fermi and INTEGRAL – gamma-rays
11 hours later optical counterpart
Observed from radio to X-rays -> kilonova

- another similar event found without GW counterpart
- Swift, Chandra and 70 other observatories
- Jet outflows probably not directed towards Earth
- Region now neutron rich
- Paper with 4000 authors (2/3 of world's astronomers)

Distance 40 Mpc
2 kpc from center of NGC4993 in constellation Hydra

Binary neutron star system
Gravitational waves when they coalesced
M_1 in the range 1.36-2.26 M_o
M_2 in the range 0.86-1.36 M_o

Such events produce the elements heavier than iron – called r-process nuclei



Amplitudes of Gravitational Wave Sources . . .

- Strongest sources have large masses moving with $v \sim c$

Characteristic GW amplitude h

Estimated upper limits (circa 2003):

- $10\ M_o$ Black Hole at
  - r = 50,000 light-years, $h \sim 10^{-16}$
  - r = 50 million light-years, $h \sim 10^{-19}$
  - r = 650 million light-years, $h \sim 10^{-20}$
  - r = 10 billion light-years, $h \sim 10^{-21}$
- $2.5 \times 10^6\ M_o$ Massive Black Hole at
  - r = 10 billion light-years, $h \sim 10^{-16}$