Gravitational Waves: Measuring Ripples in Spacetime

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LIGO Press Conference

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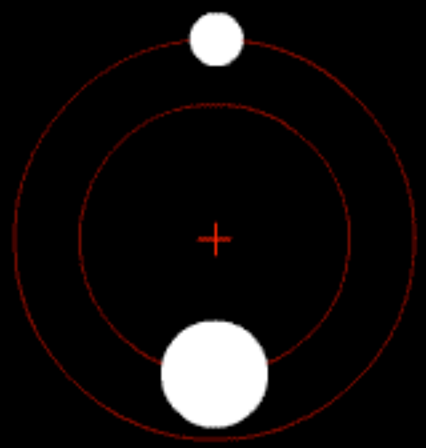
Earth and Its Moon
as seen from NASA's Mars Reconnaissance Orbiter, Nov. 20, 2016

Gravity + Relativity: General Relativity

Newton:

Falling and orbiting are explained by the same gravitational force

All masses attract each other

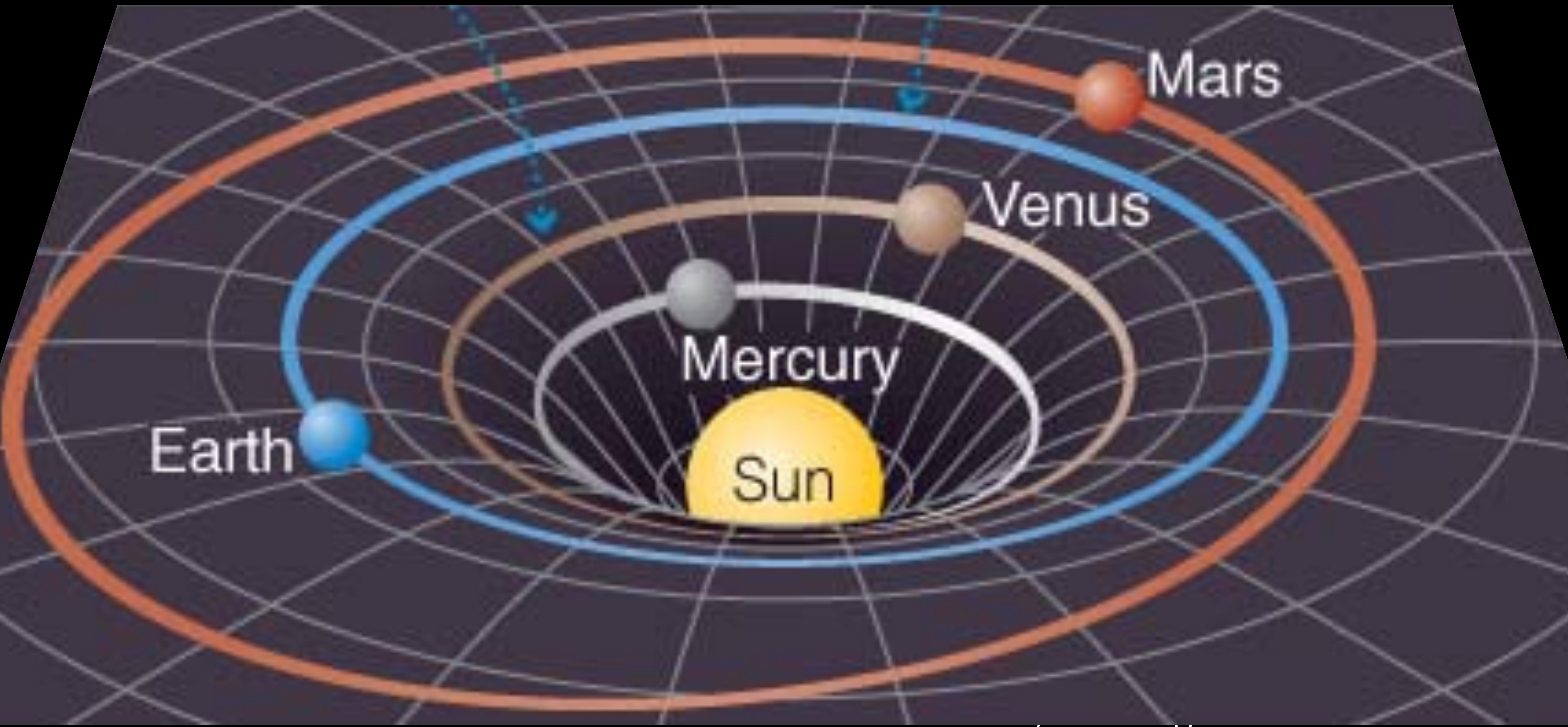


Relativity:

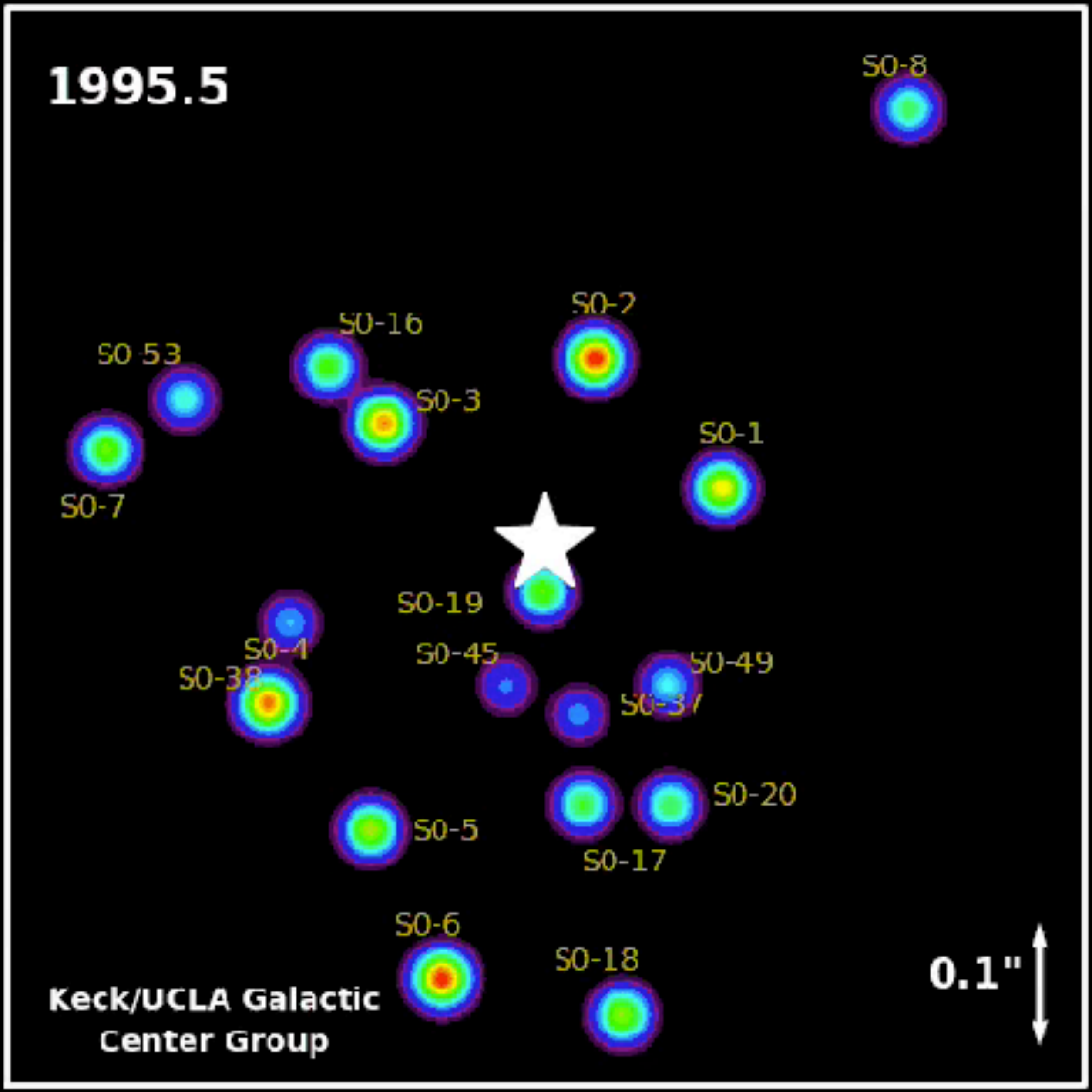
Space and time are not distinct

Nothing travels faster than light

"Matter tells space-time how to curve and space-time tells matter how to move."
- John A. Wheeler



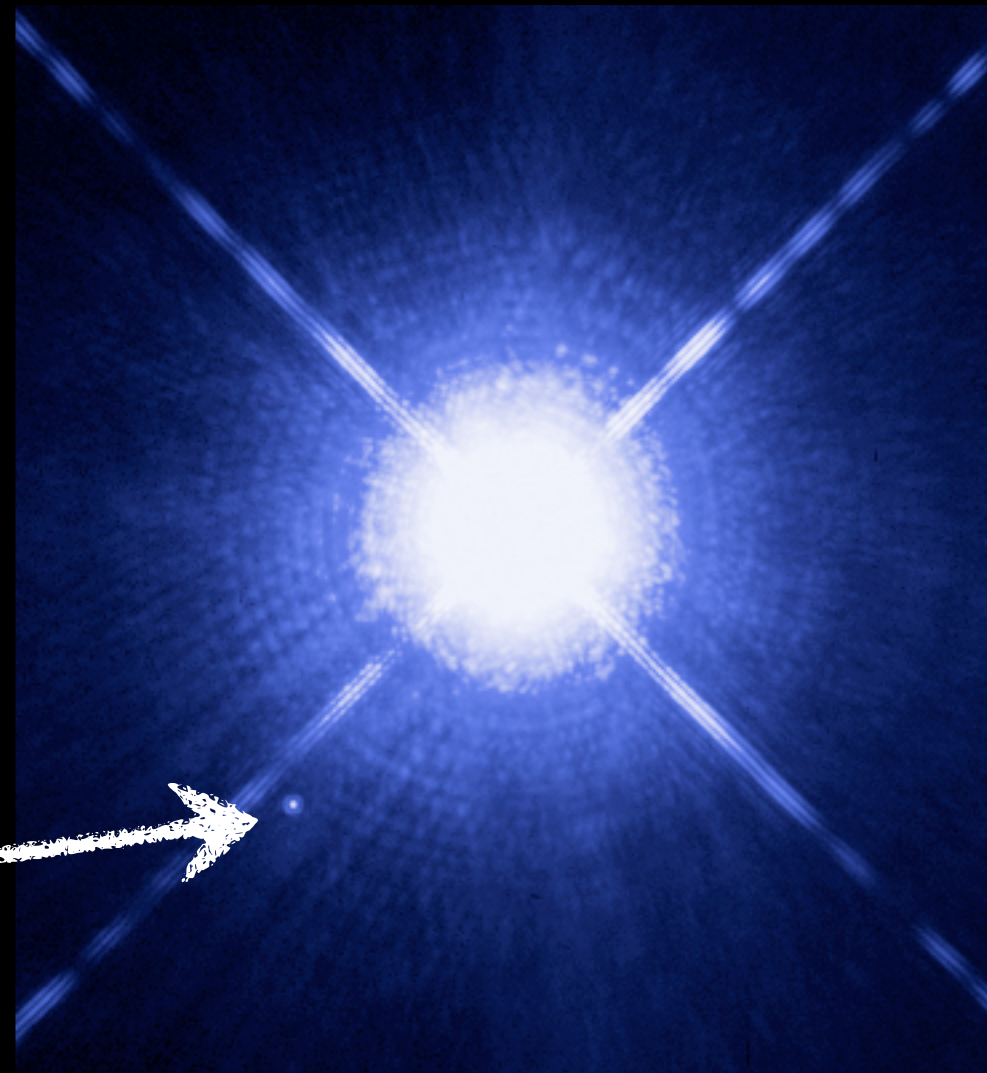
The movement of stars near the center of the Milky Way

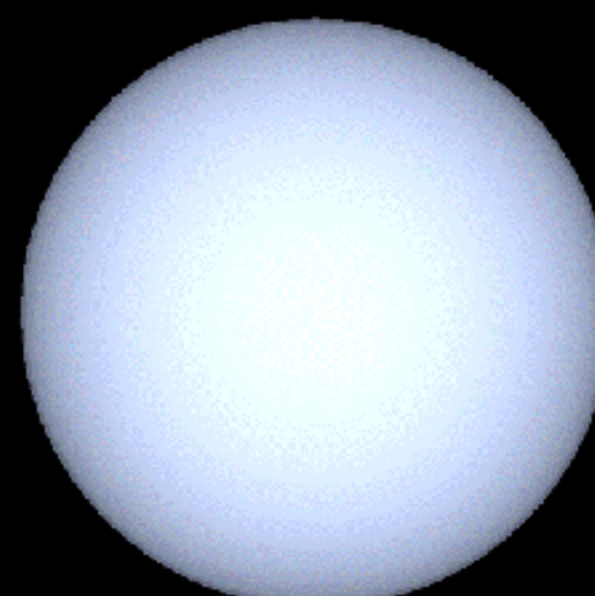


At the center: a mass 4 million times the mass of the Sun

$$F = G M m / r^2$$

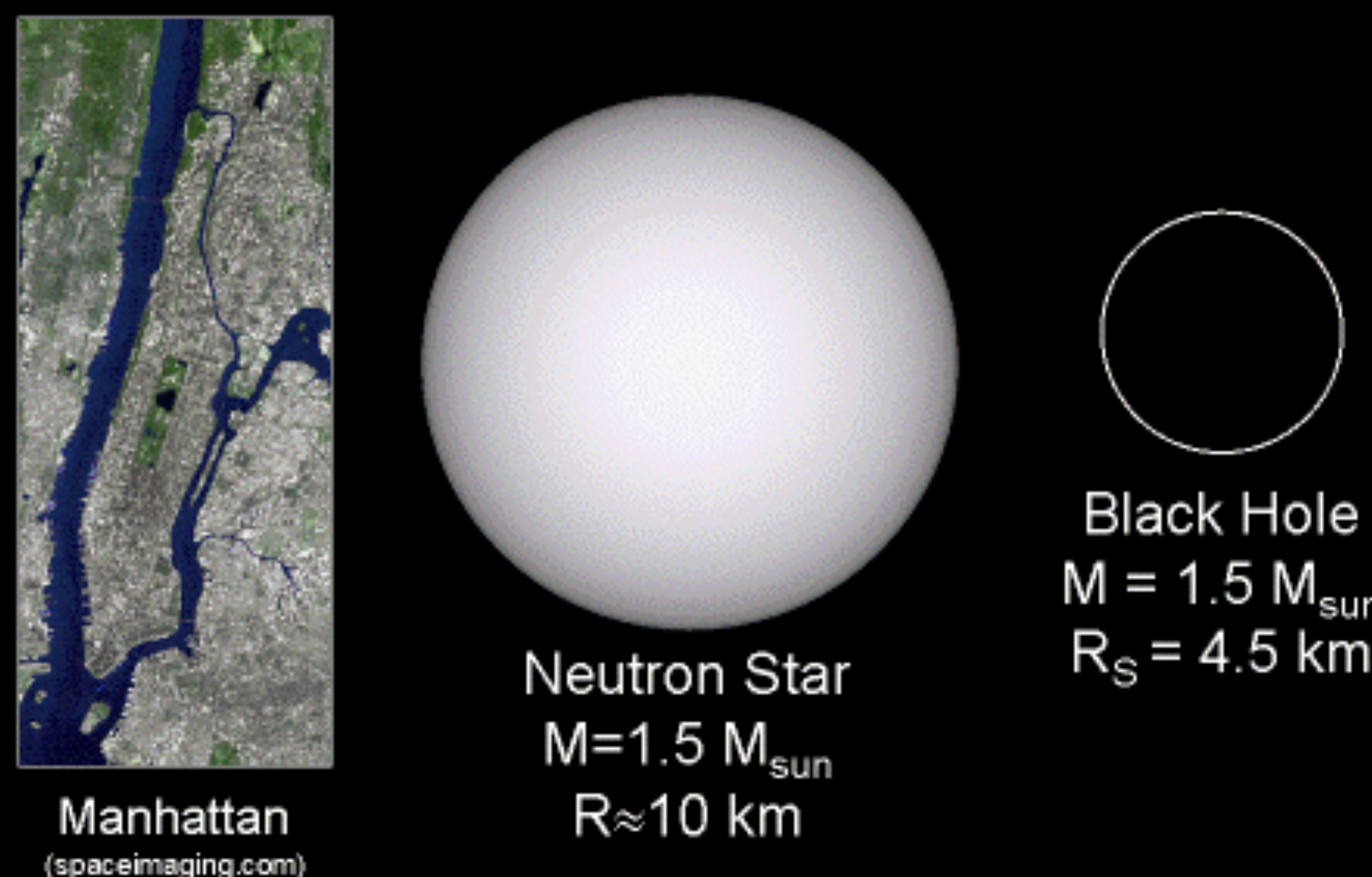
If you make an object smaller in size, but keep the mass the same, the gravitational effects get stronger





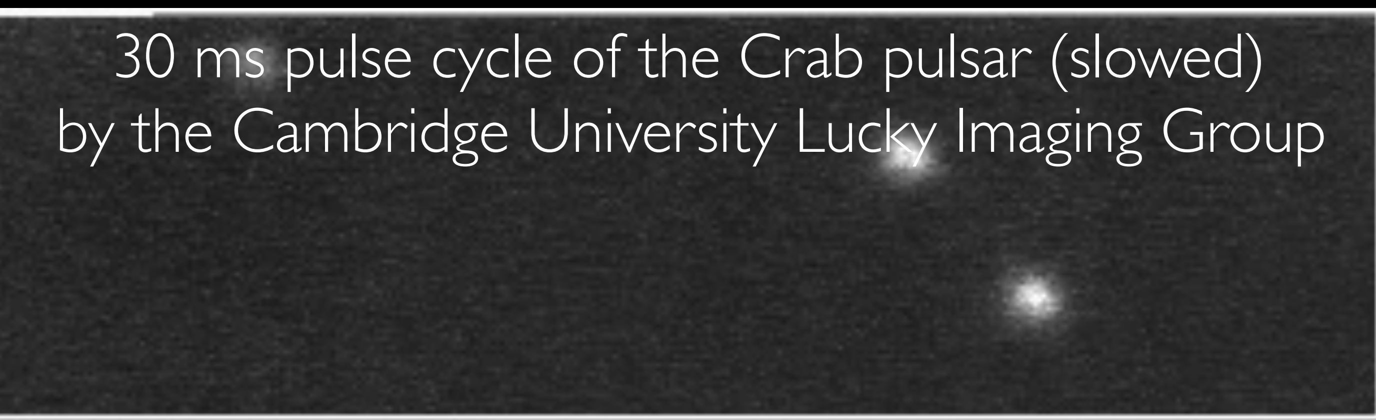
$M \approx 1.0\ M_{sun}$
$R \approx 5800$ km

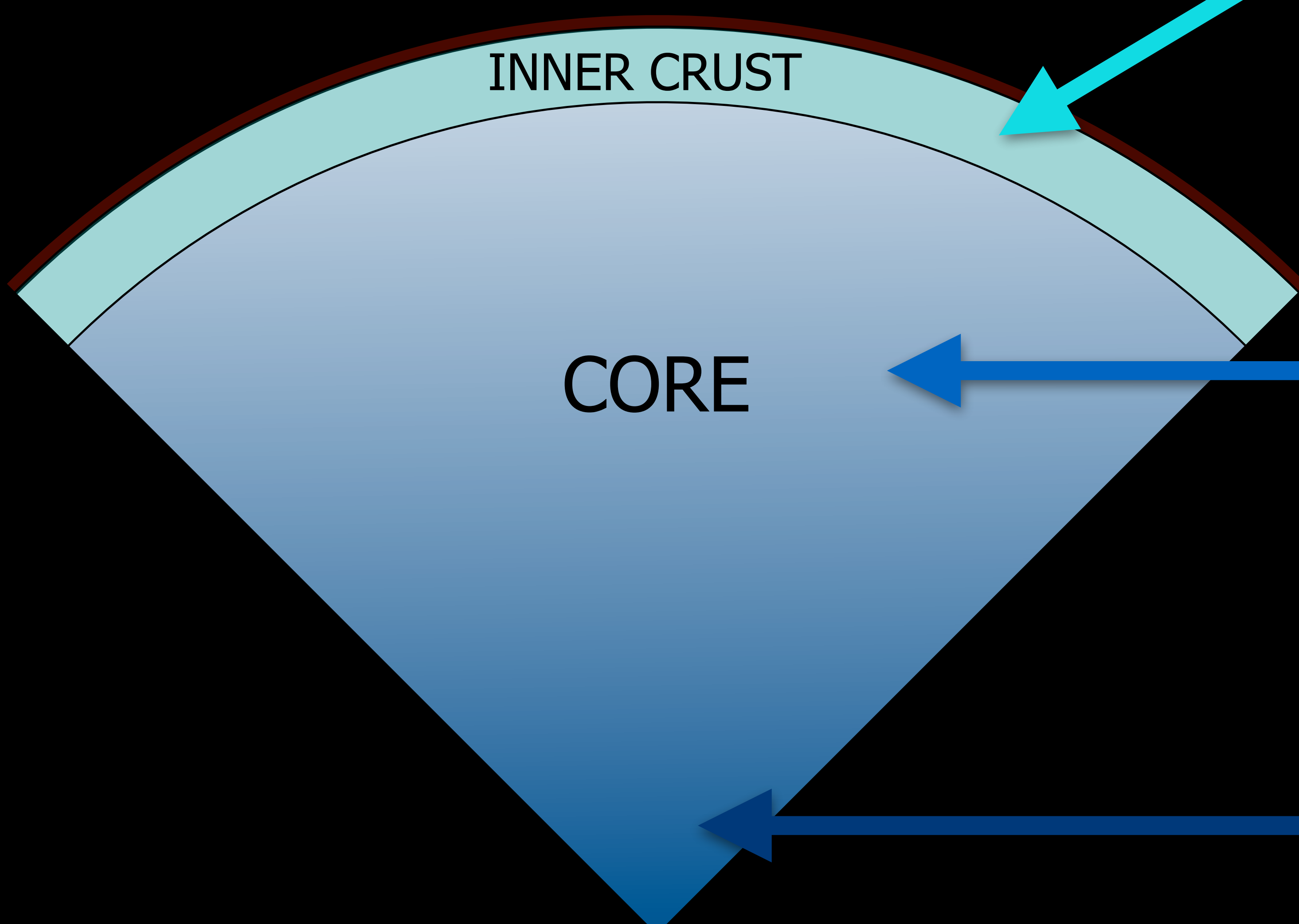
Strongest gravity: compact objects



Comparison by Richard Pogge, Ohio State

Neutron stars: matter's last stand against gravity





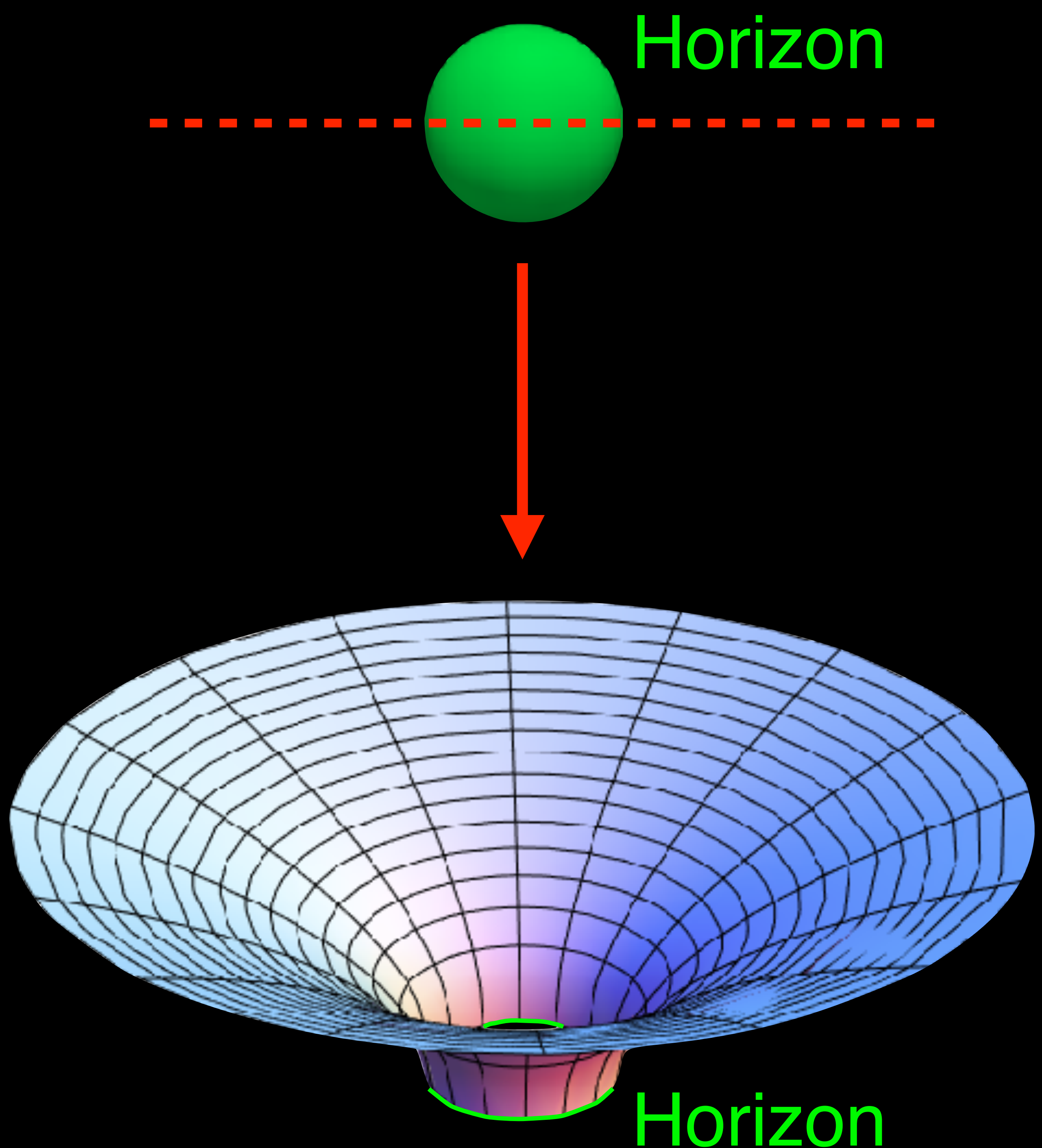
Atoms with heavy nuclei, up to a million times as dense as our Sun

Mostly neutrons, supported by quantum pressure

? ? ? ?

Black holes: extremes of space-time curvature

- Found in the centers of galaxies
- Formed when the most massive stars collapse
- Gravity so strong...
  - Nothing can escape from within the horizon (surface)
  - *Singularity* inside horizon



Images from Wikipedia

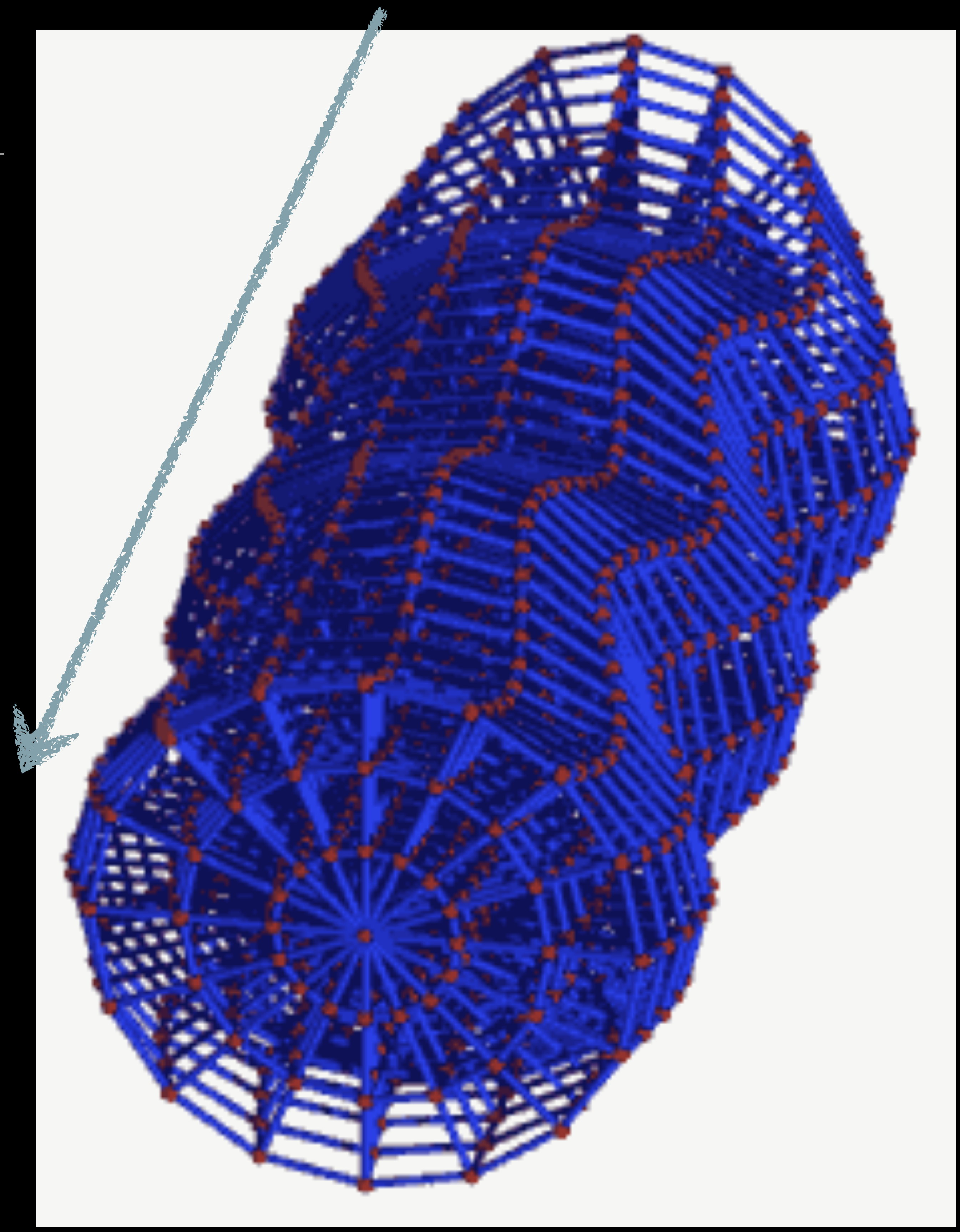
Mass in motion:

changes in spacetime travel at the speed of light

Moon passing Earth
as seen from NASA's DSCOVR spacecraft (NASA/NOAA)

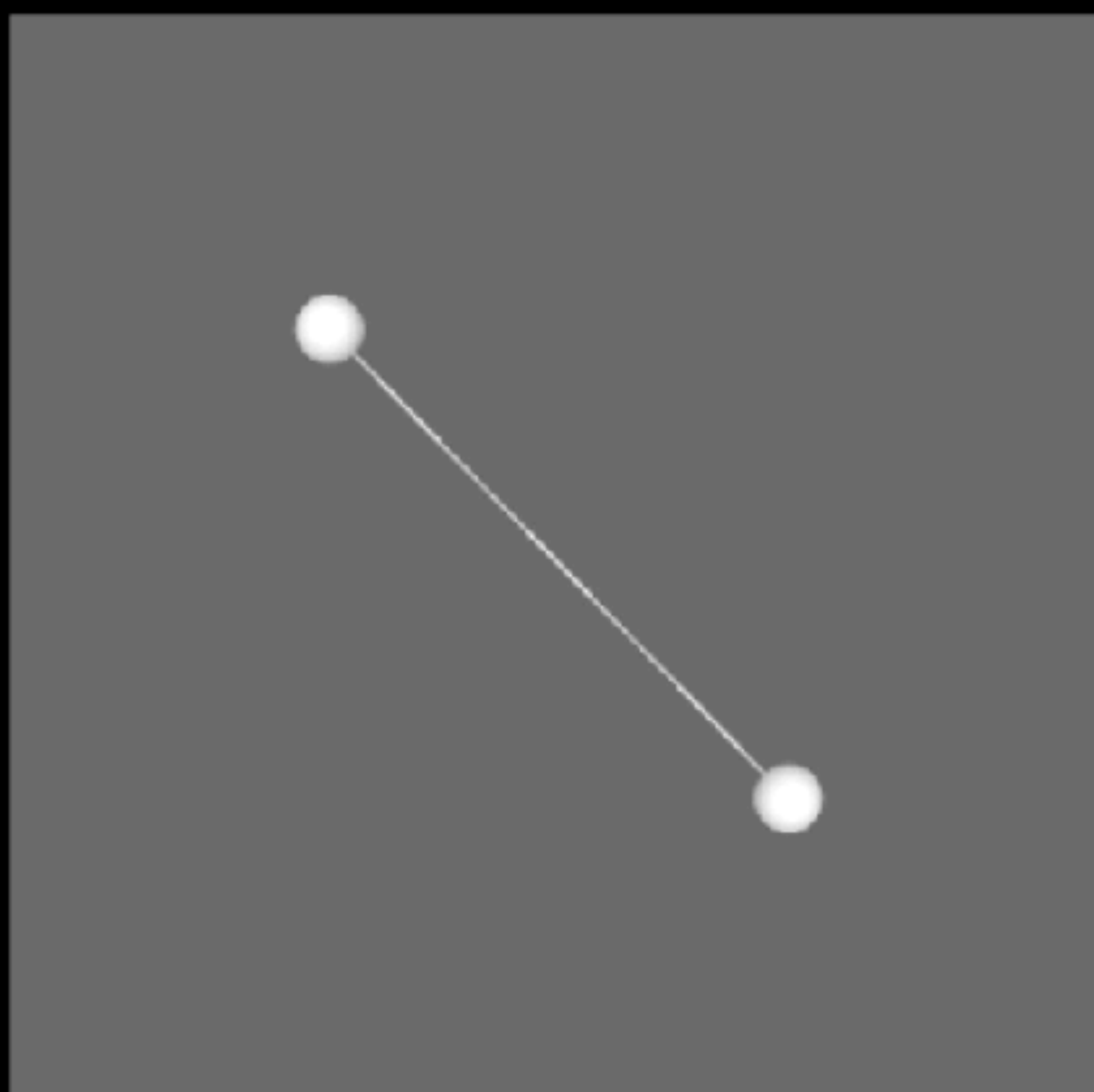
Gravitational wave

- Stretching and squeezing space
- Traveling at the speed of light

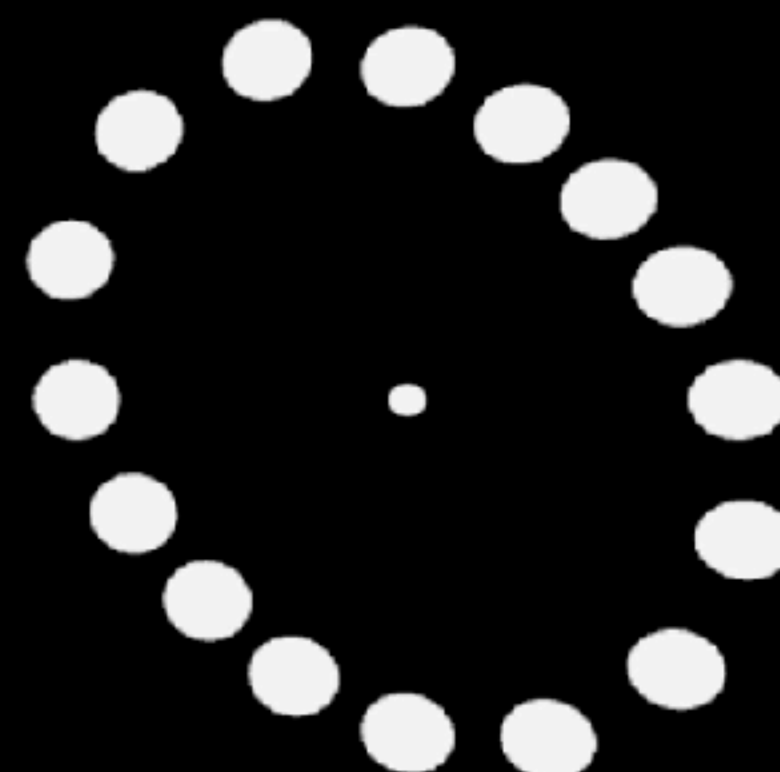


Animation from http://www.einstein-online.info/spotlights/gravWav

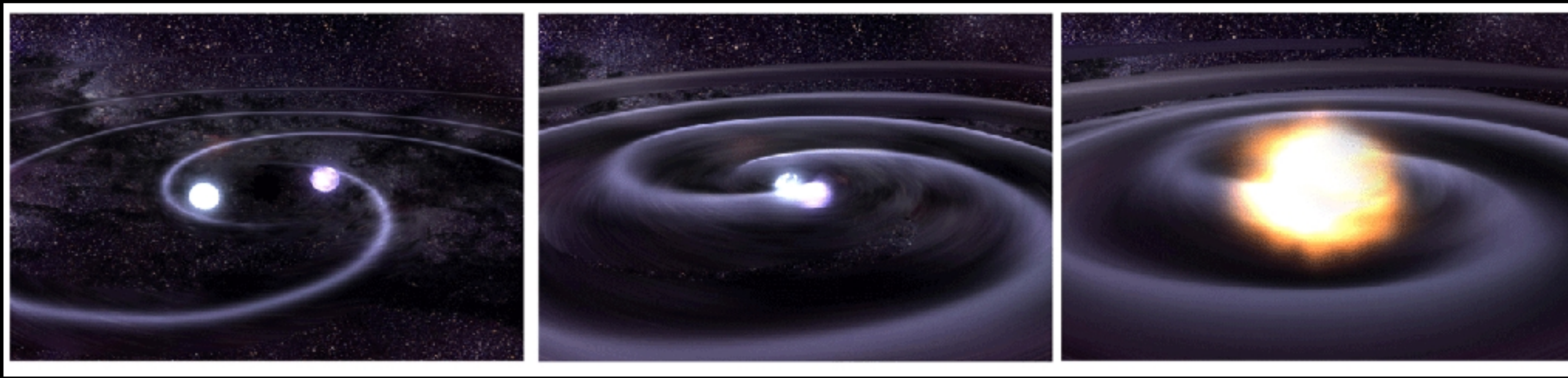
Two objects orbit



Far away, a ring of particles moves in response

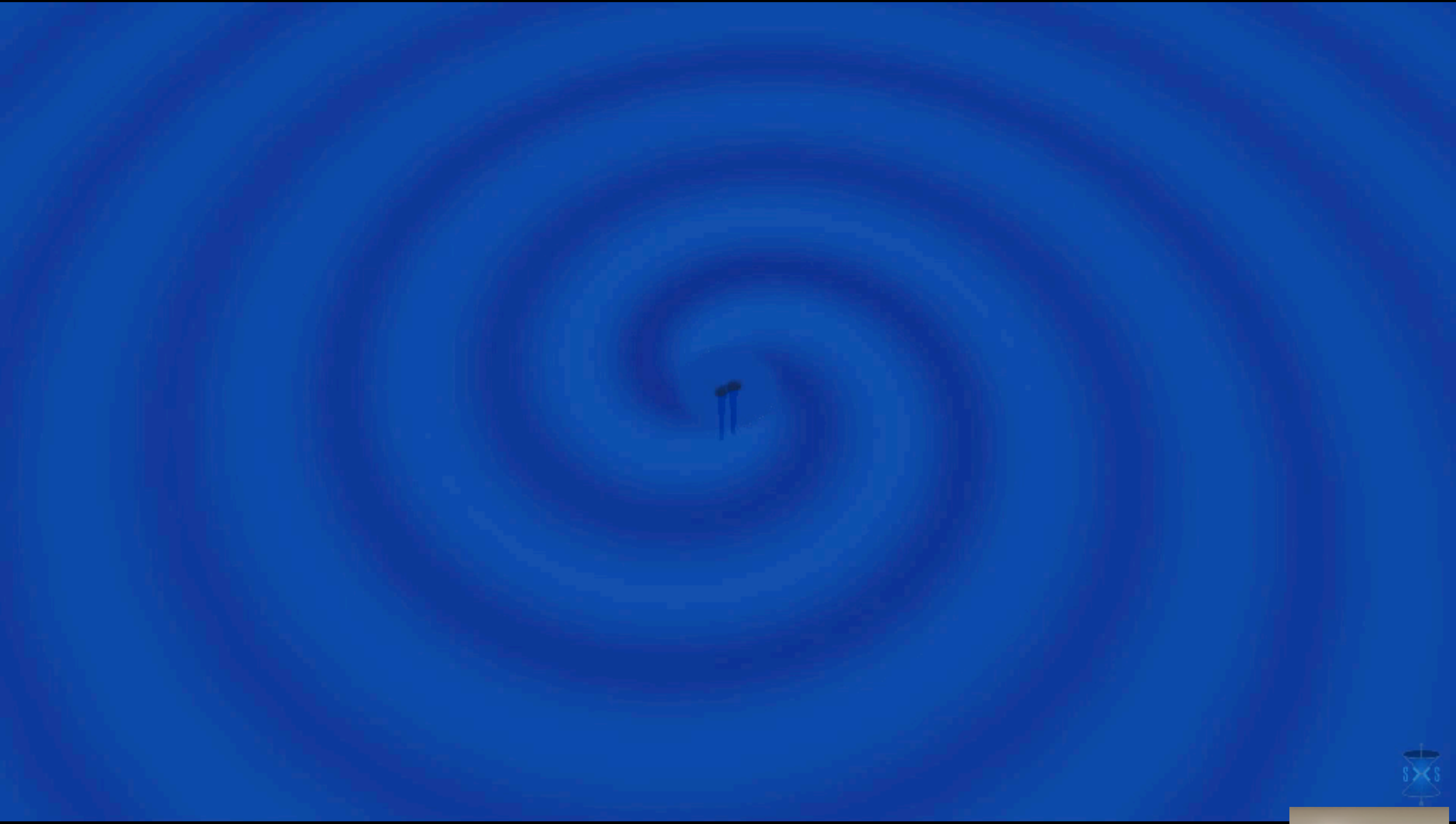


Demo by Eric Flynn, CSUF

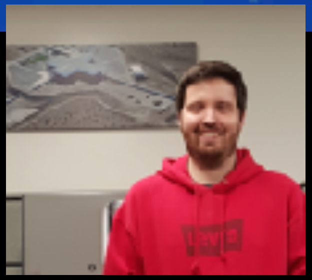


- Orbiting stars emit gravitational waves; waves carry away energy
- Orbits with lower energy are closer together
- Closer orbits produce stronger waves

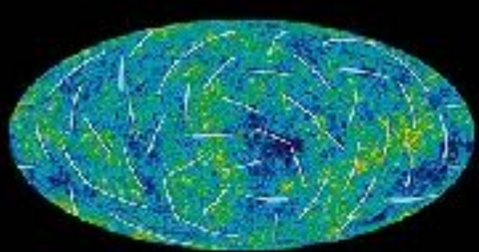
Gravitational Waves



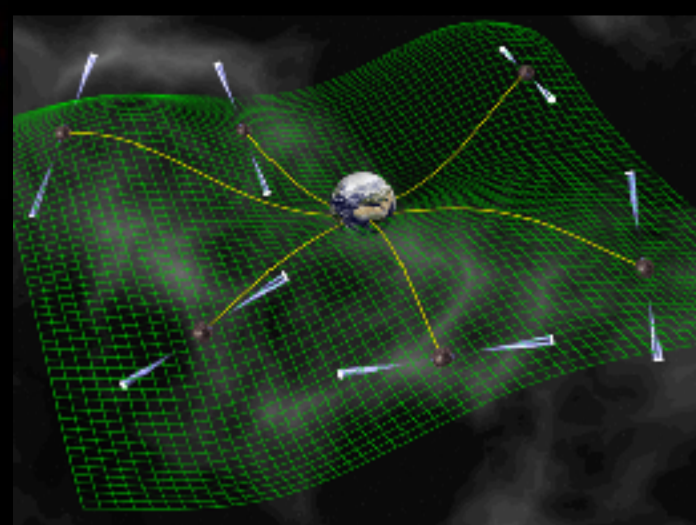
Movie by CSUF student Nick Demos,
Simulating eXtreme Spacetimes collaboration



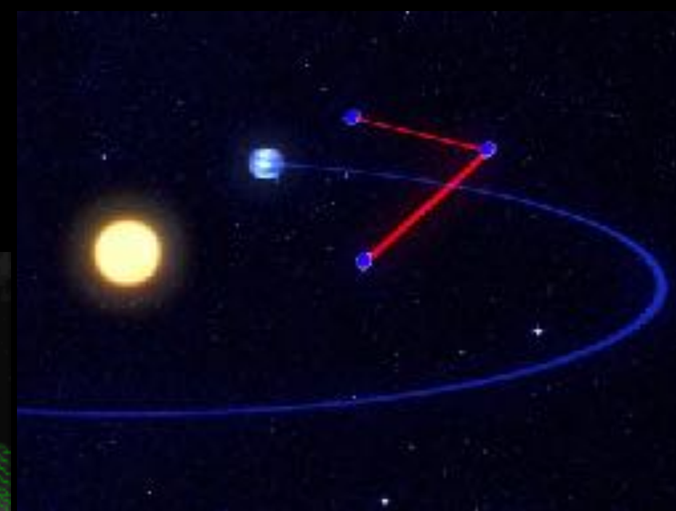
Measuring gravitational waves near Earth



Cosmic Microwave Background



Pulsar timing



Space-based interferometer

Ground-based interferometers

10^{-16} (today)

10^{-8} (~cycle/year)

10^{-4} (~cycle/hour)

10^{2} (audio)

GW frequency (Hz)

Sources of gravitational waves

Early Universe:

Inflation, Phase Transitions

Supermassive binary black hole mergers

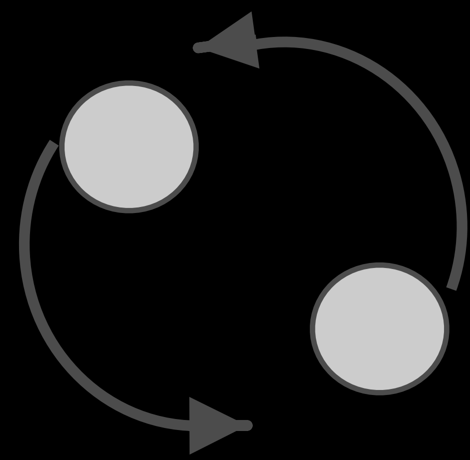
Compact objects captured by supermassive black holes

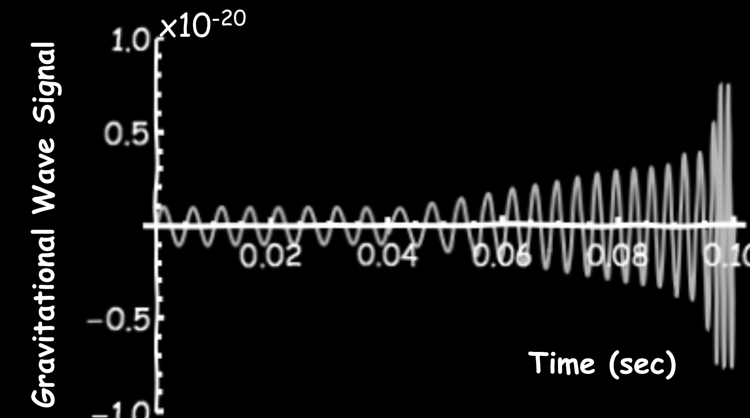
Merging compact object binaries

10^{-16} (today) | 10^{-8} (~cycle/year) | 10^{-4} (~cycle/hour) | 10^{2} (audio)

GW frequency (Hz)

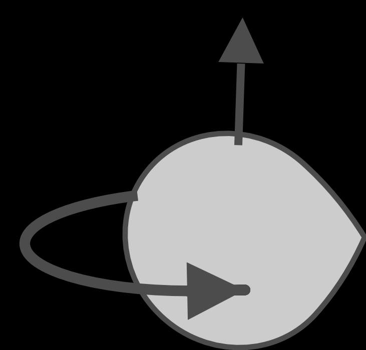
Colliding neutron stars & black holes

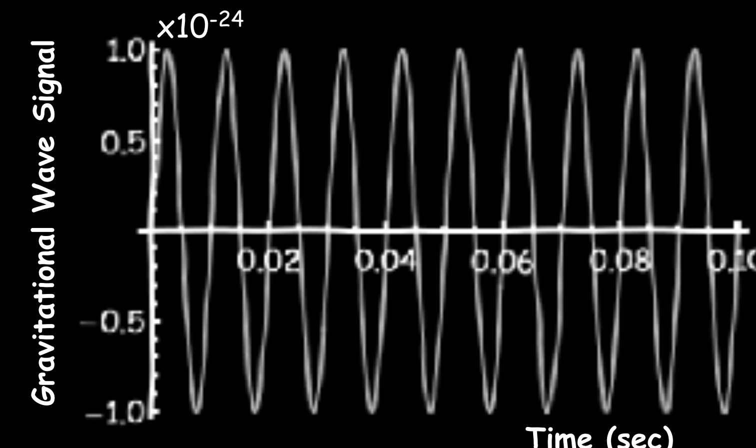




Chirp

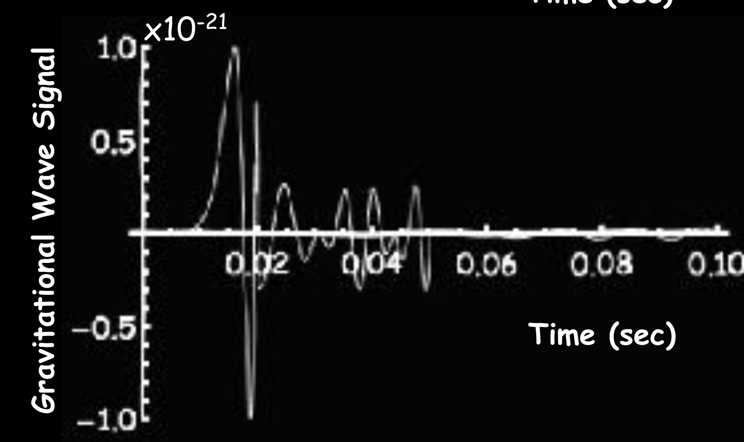
Spinning neutron star with a bump





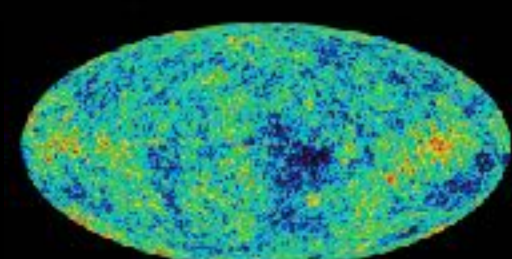
Sine wave

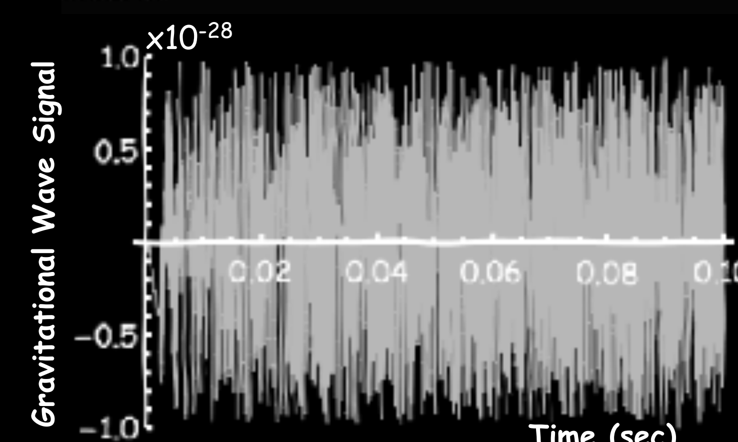
Non-spherical Supernova



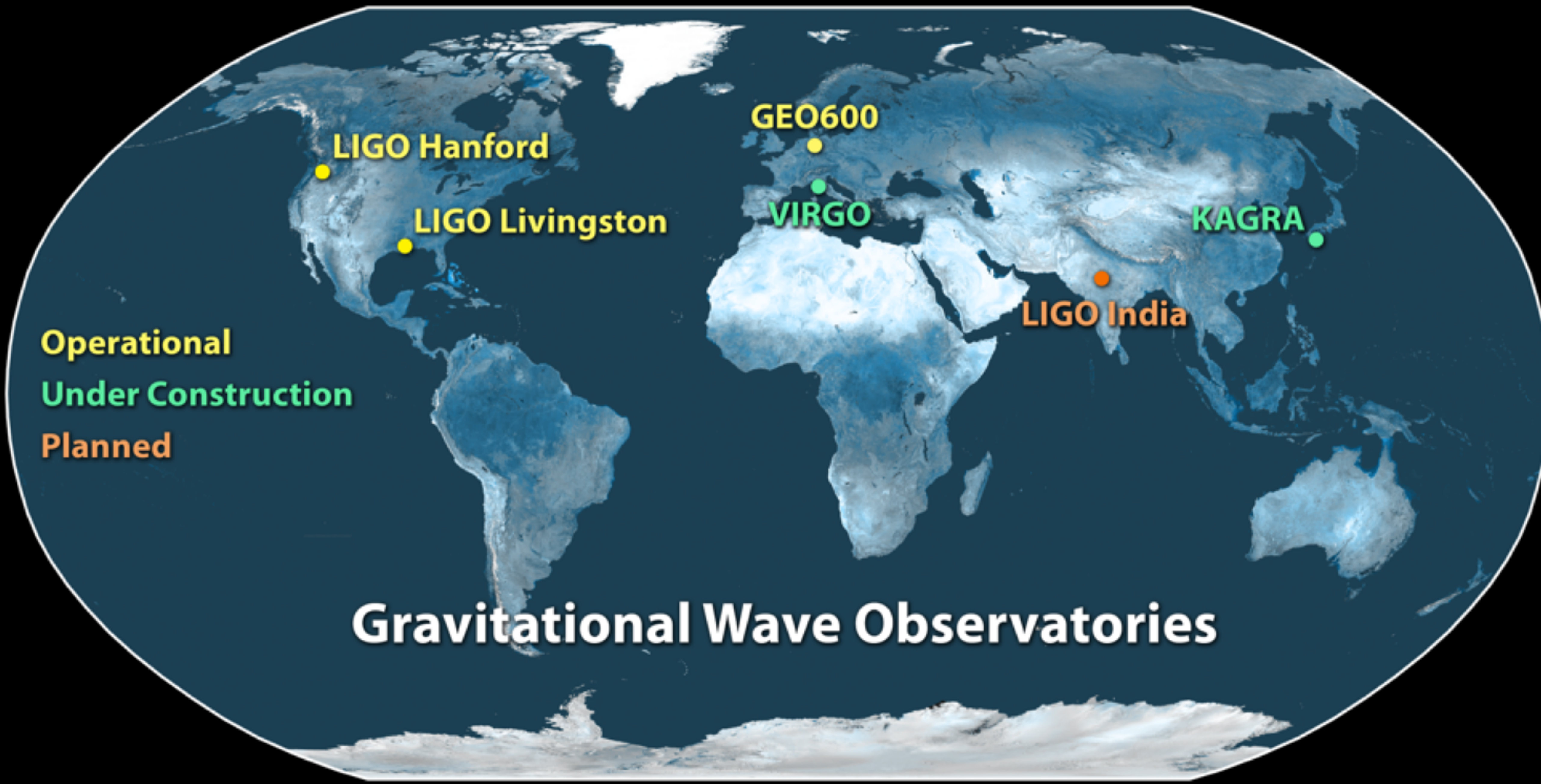
Burst

Cosmic Gravitational wave background



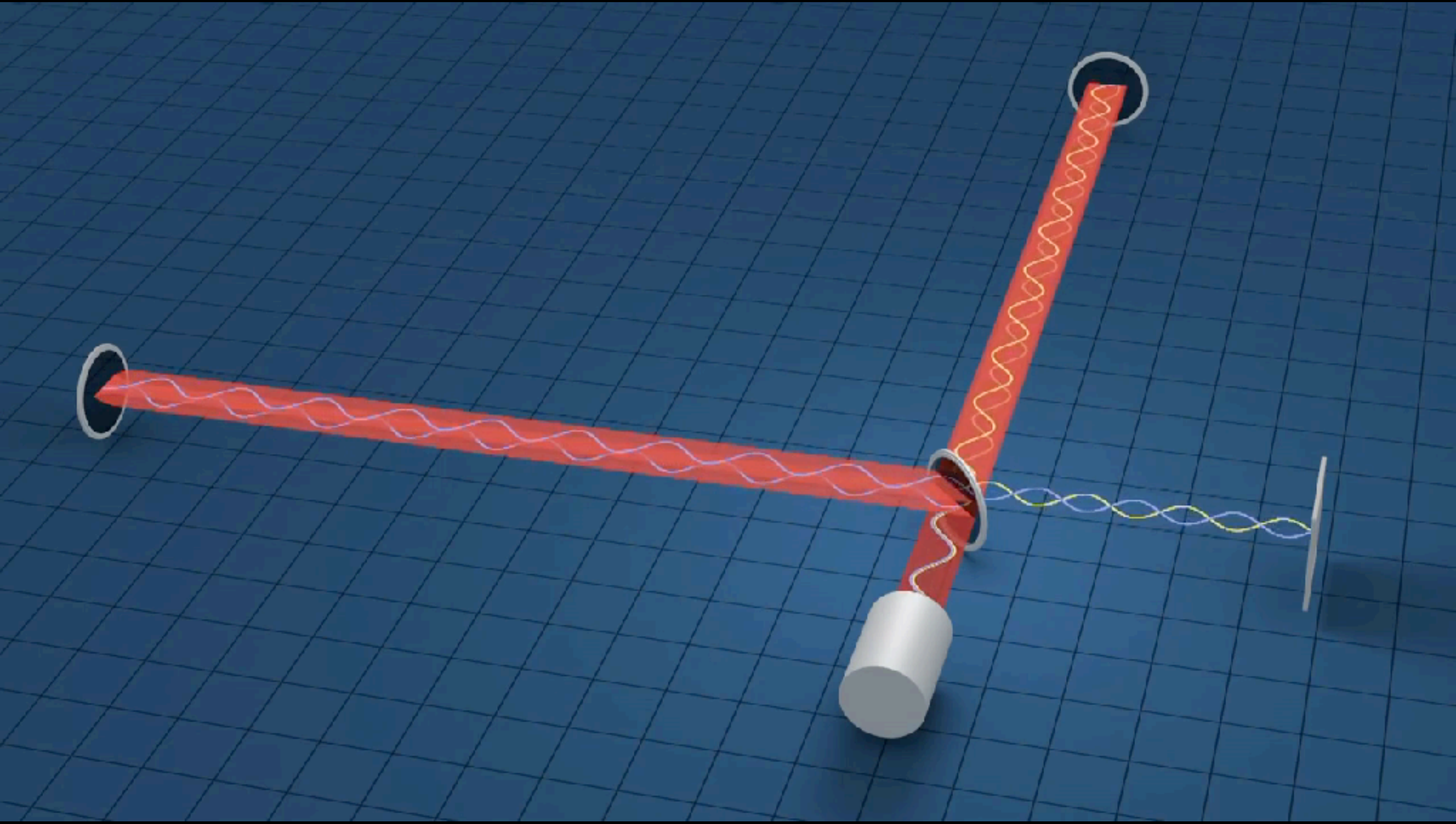


Random noise

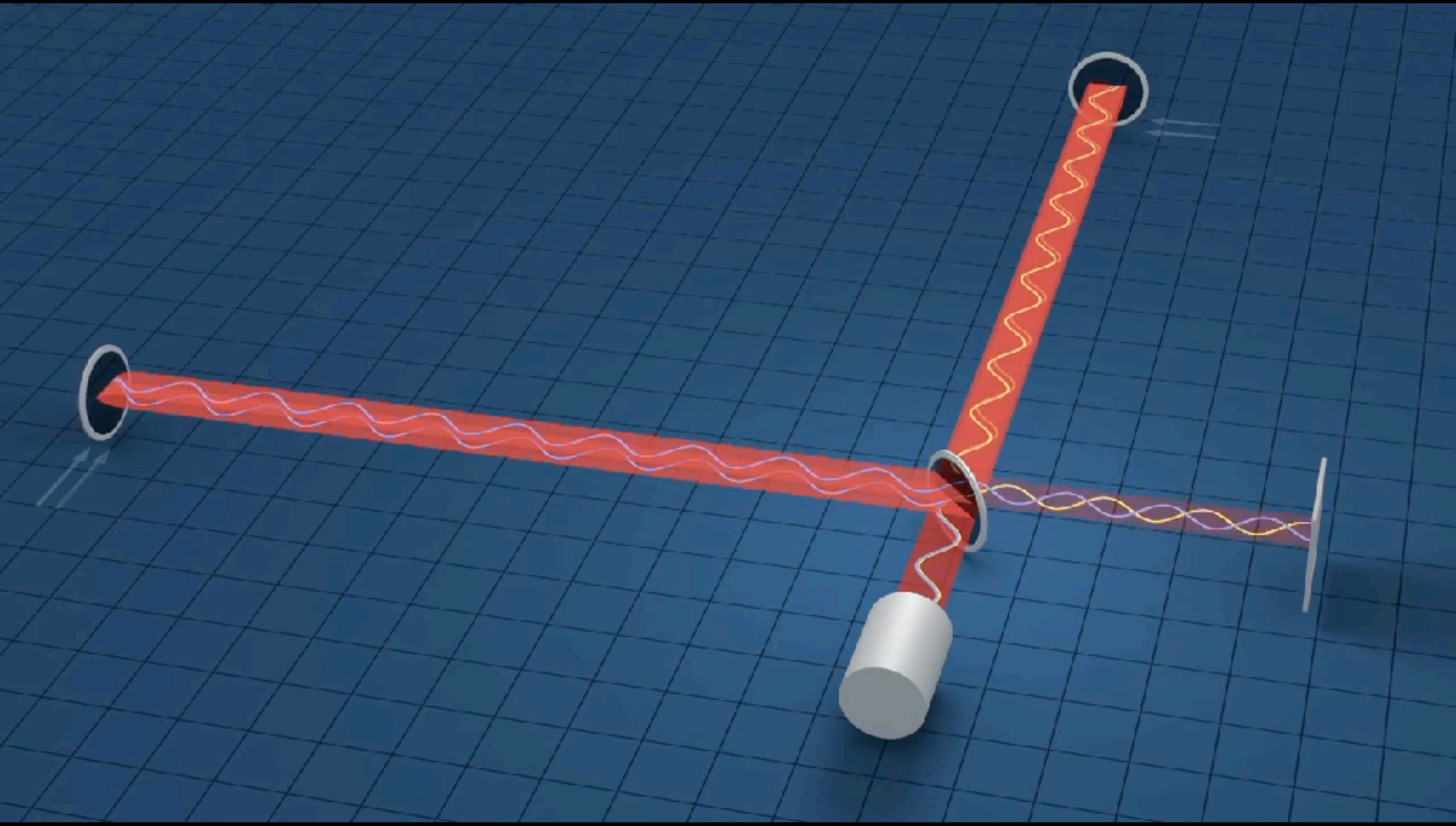


LIGO Hanford
LIGO Livingston
GEO600
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

LIGO: Laser Interferometer



Credit: LIGO

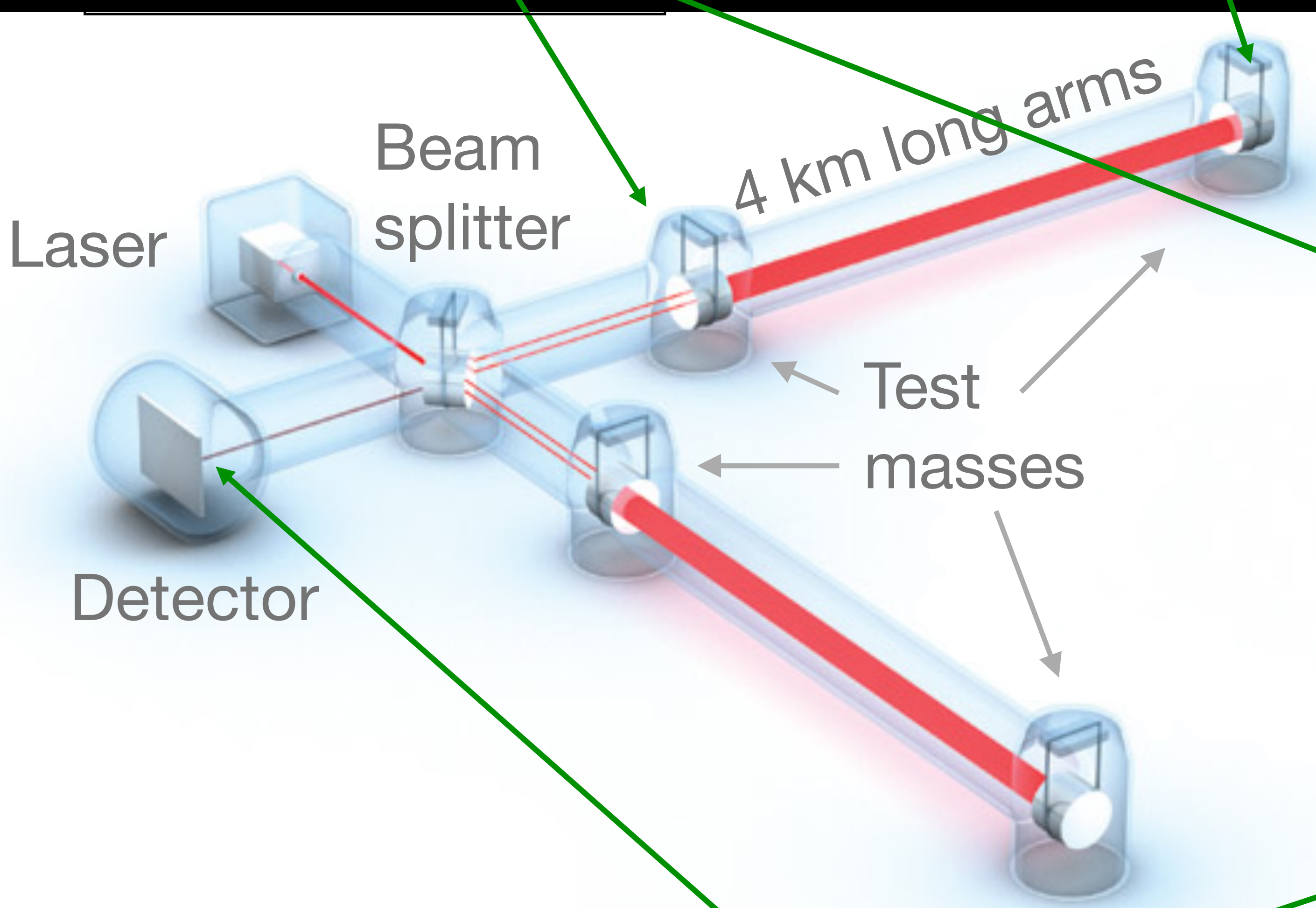


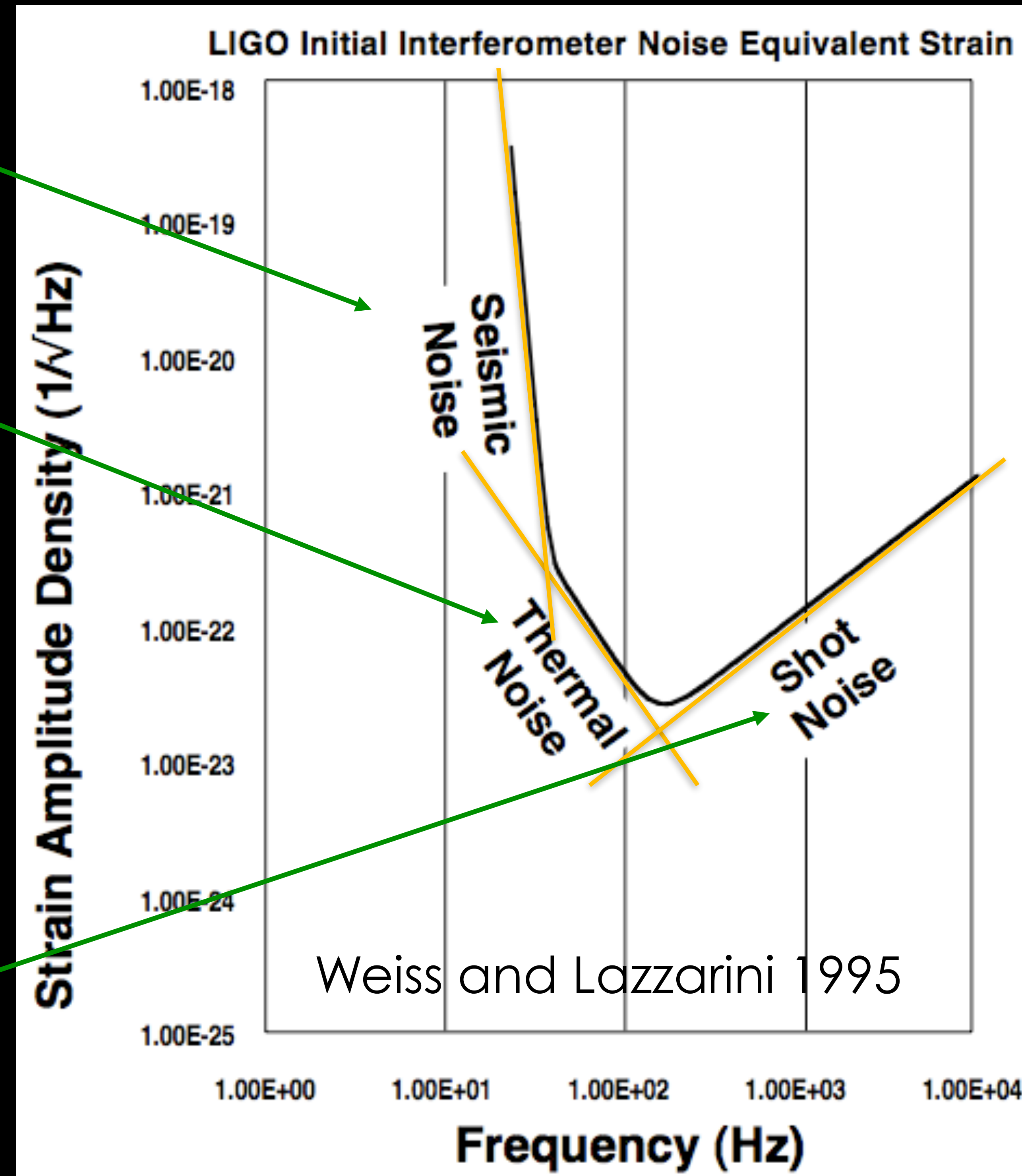
Animation: LIGO

What must Advanced LIGO overcome?

Thermal K_BT motion of molecules shakes mirrors

Seismic motion of ground shakes mirrors

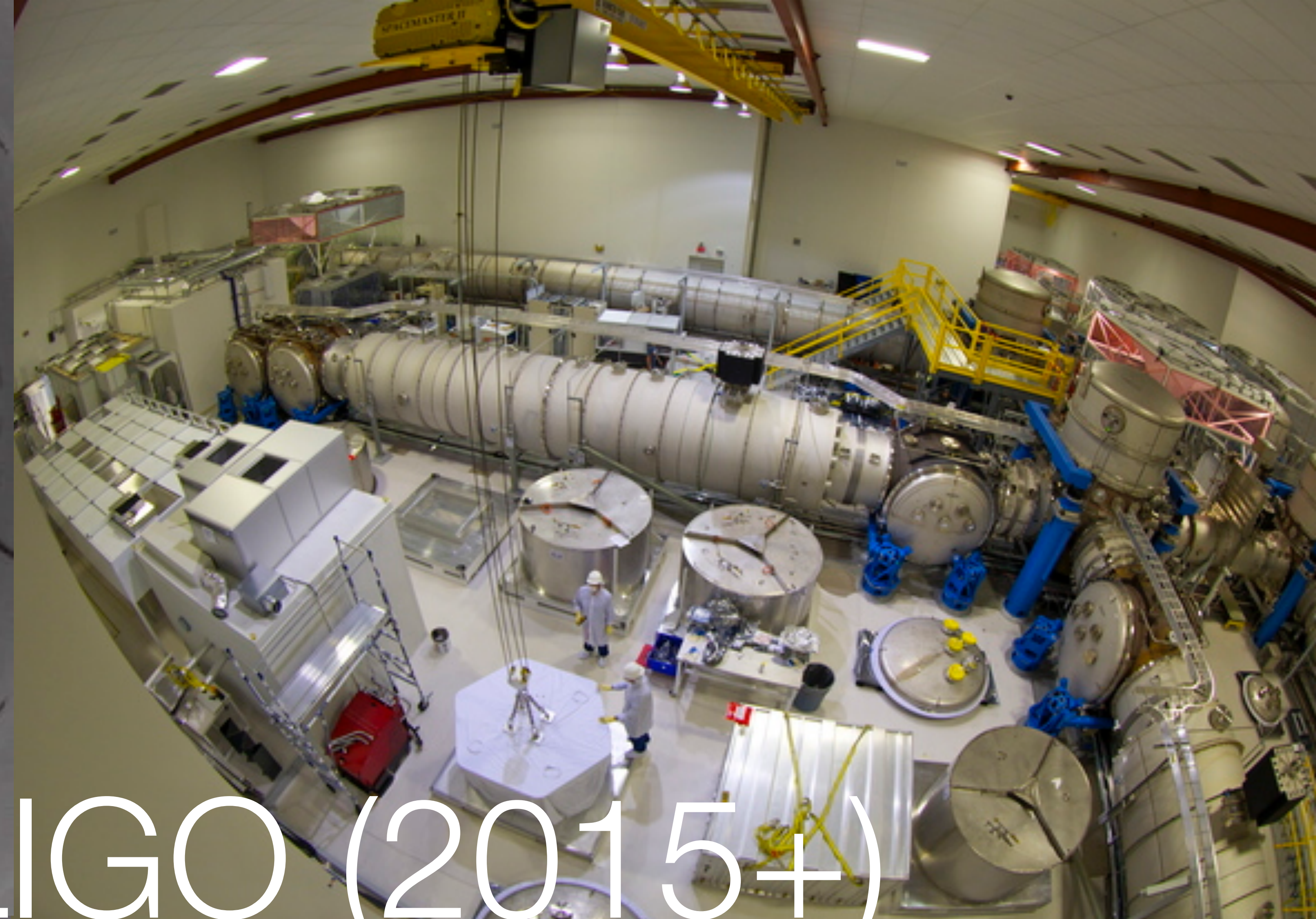


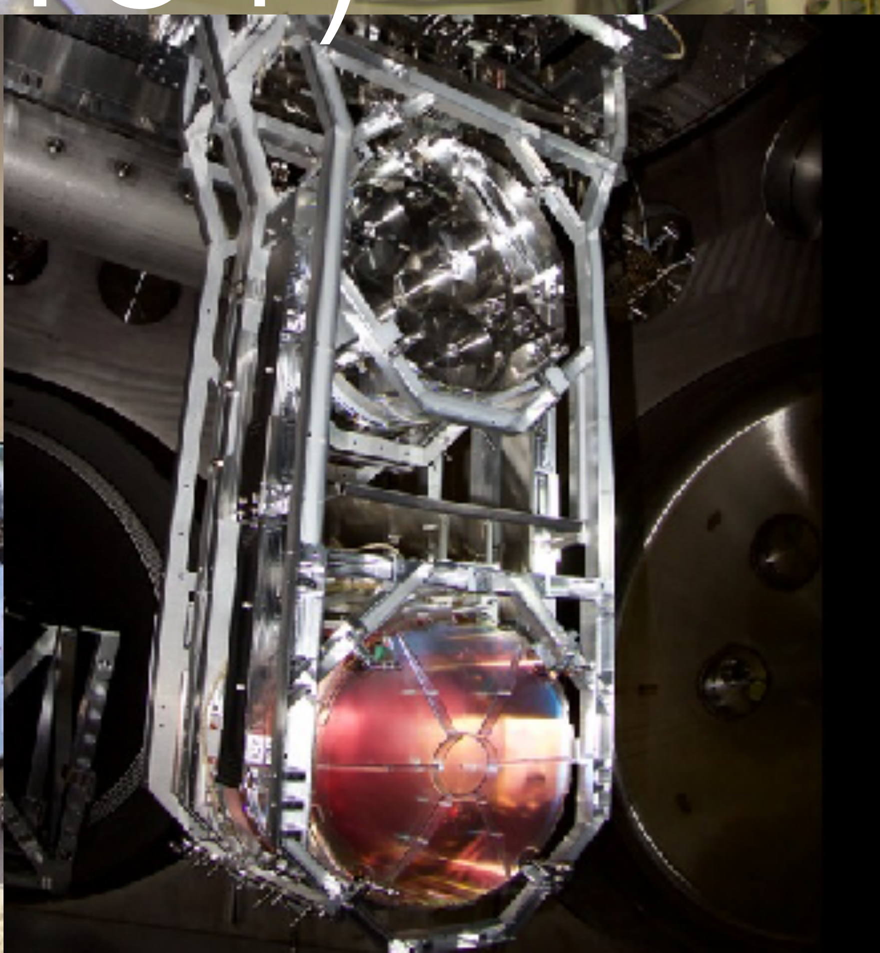


Photons arrive in a statistical pitter patter

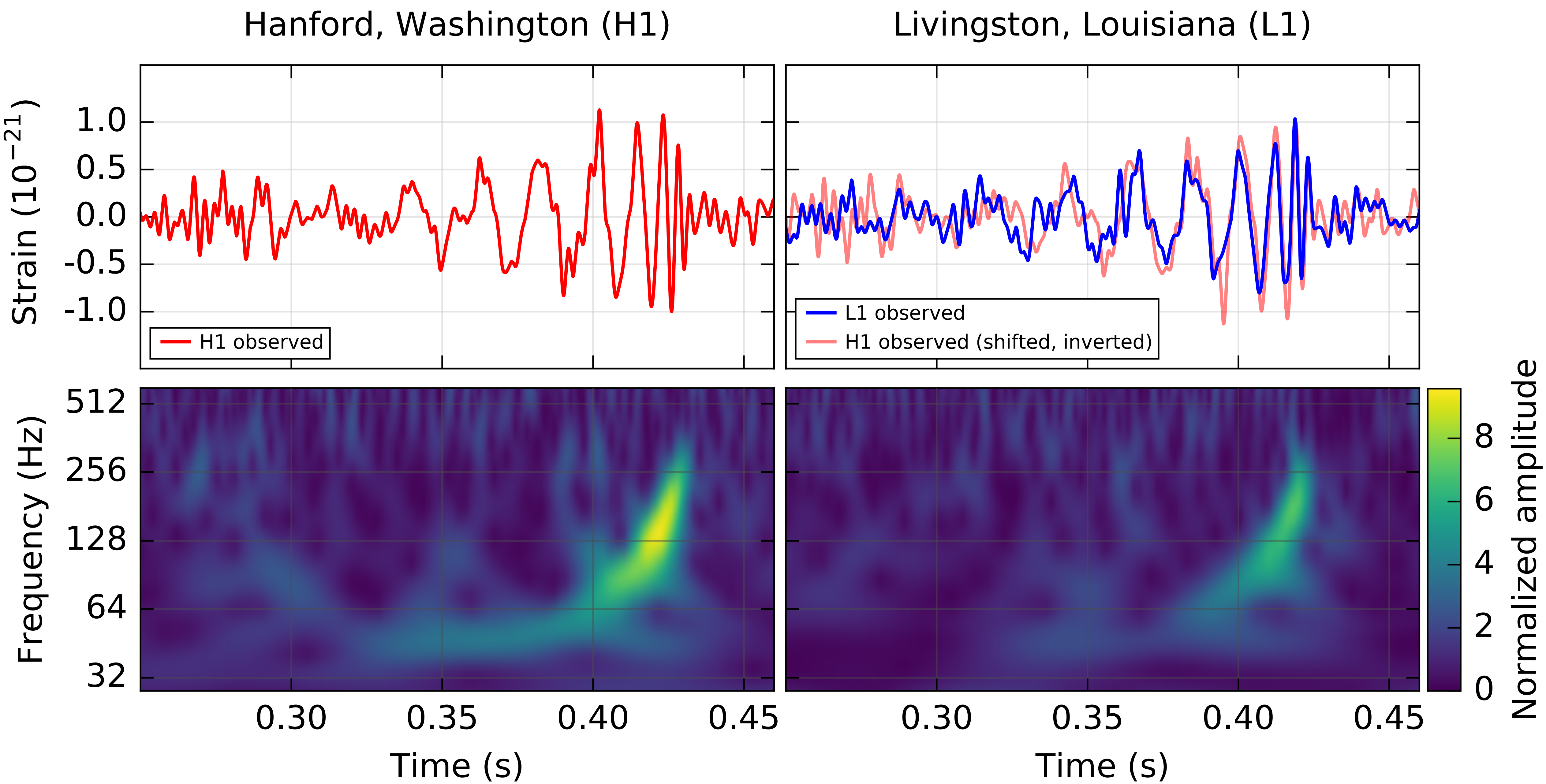
Slide courtesy Josh Smith, CSUF

Advanced LIGO (2015+)

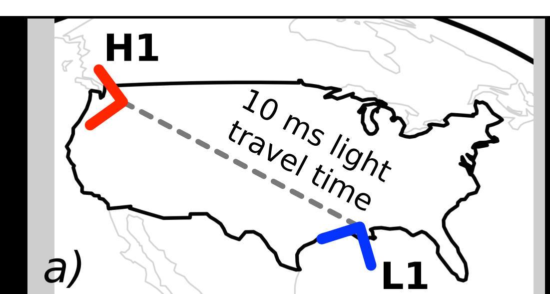




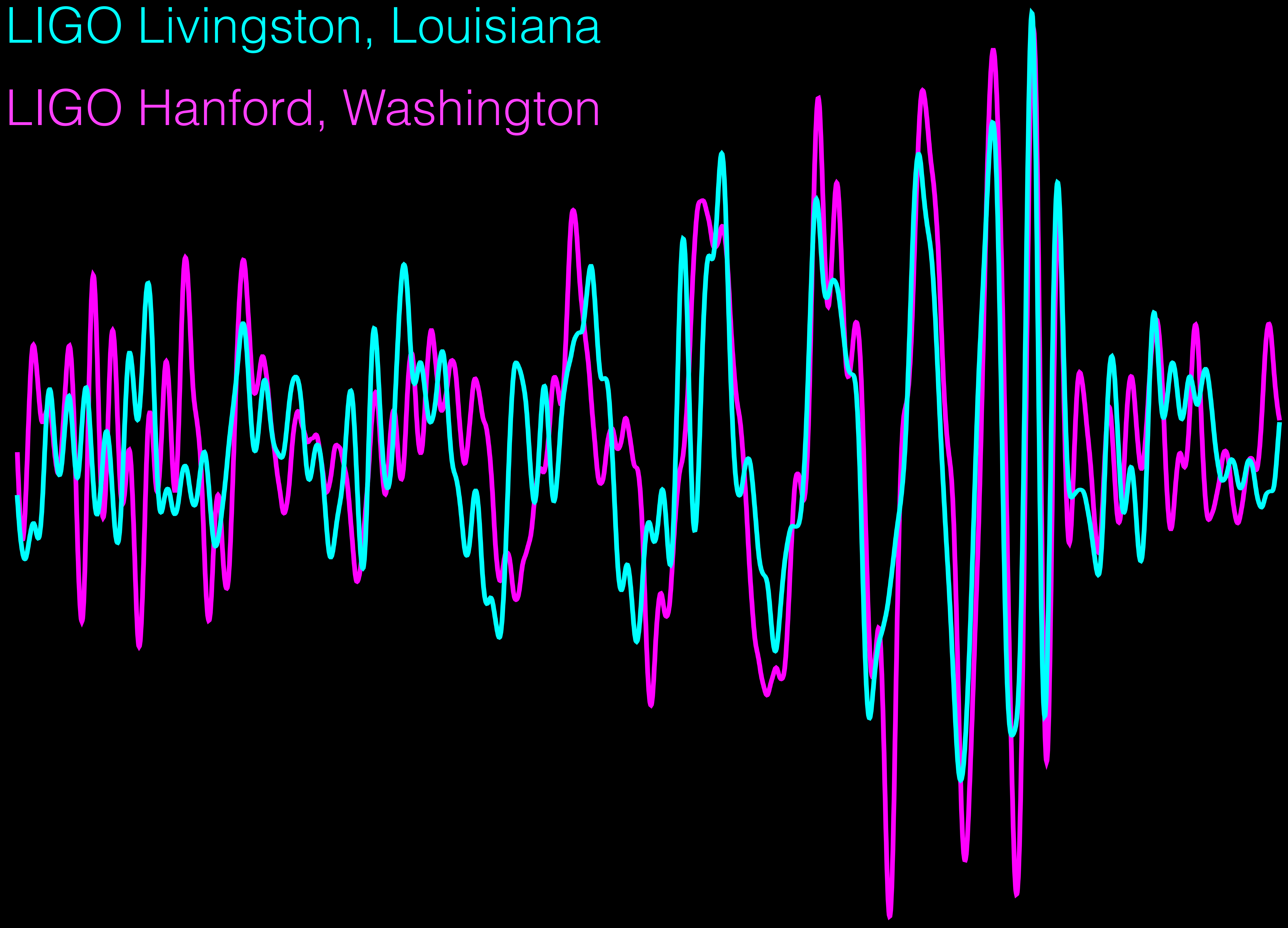
Observation of Gravitational Waves from a Binary Black Hole Merger

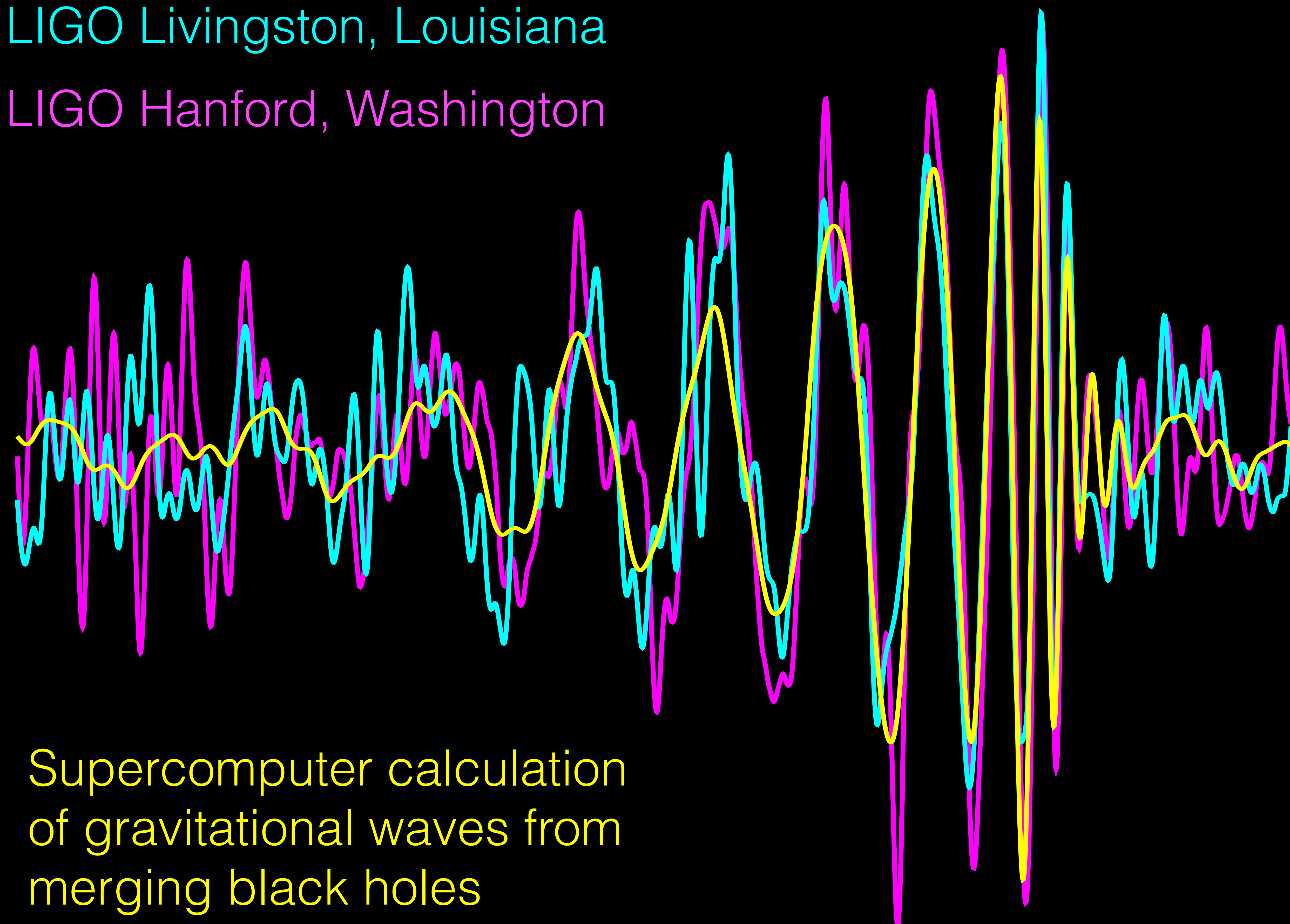


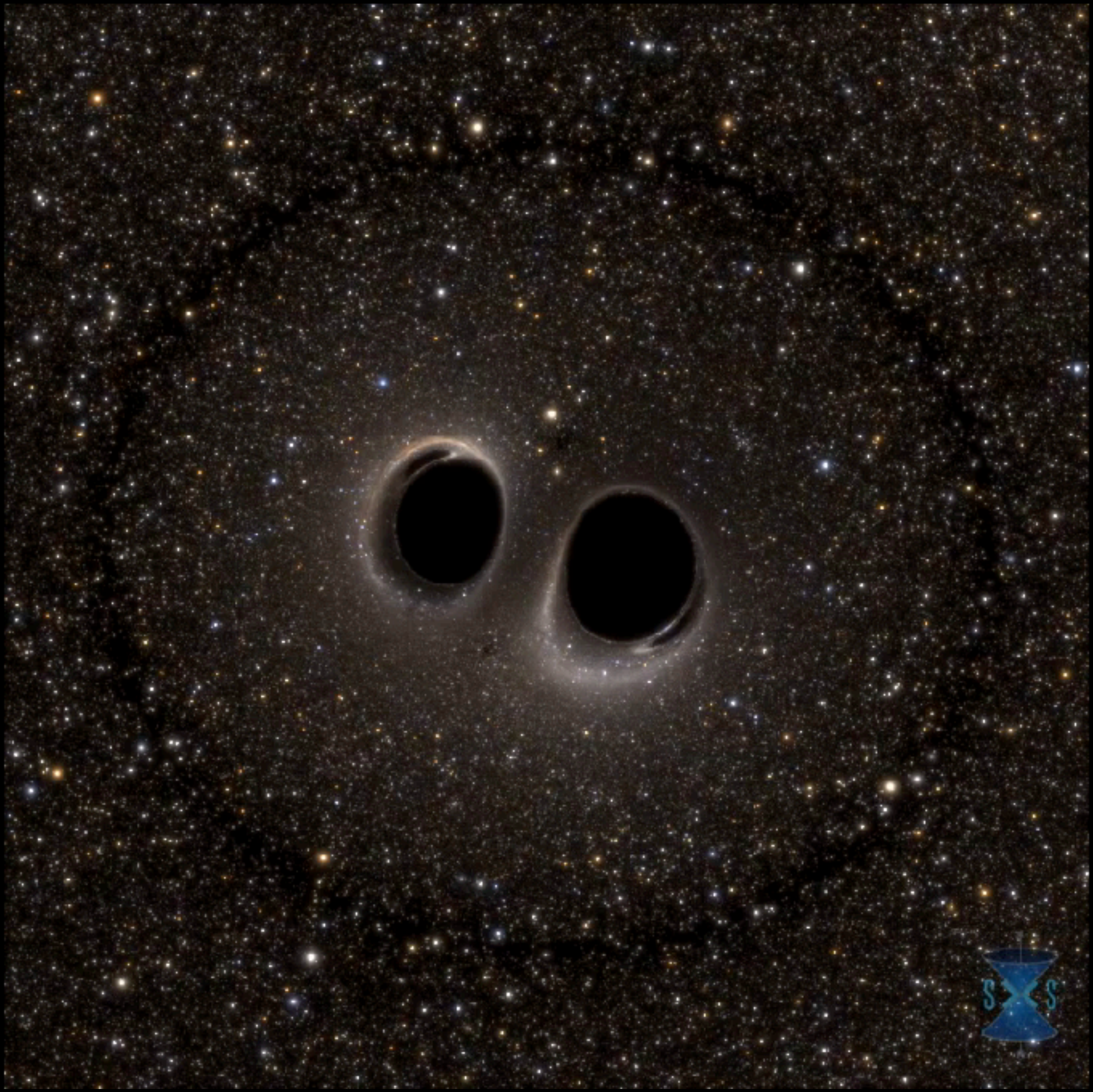
September 14, 2015 at 09:50:45 GMT



PRL 116, 061102 (2016)


LIGO Livingston, Louisiana
LIGO Hanford, Washington


LIGO Livingston, Louisiana
LIGO Hanford, Washington
Supercomputer calculation of gravitational waves from merging black holes



Movie by CSUF student Haroon Khan,
SXS collaboration

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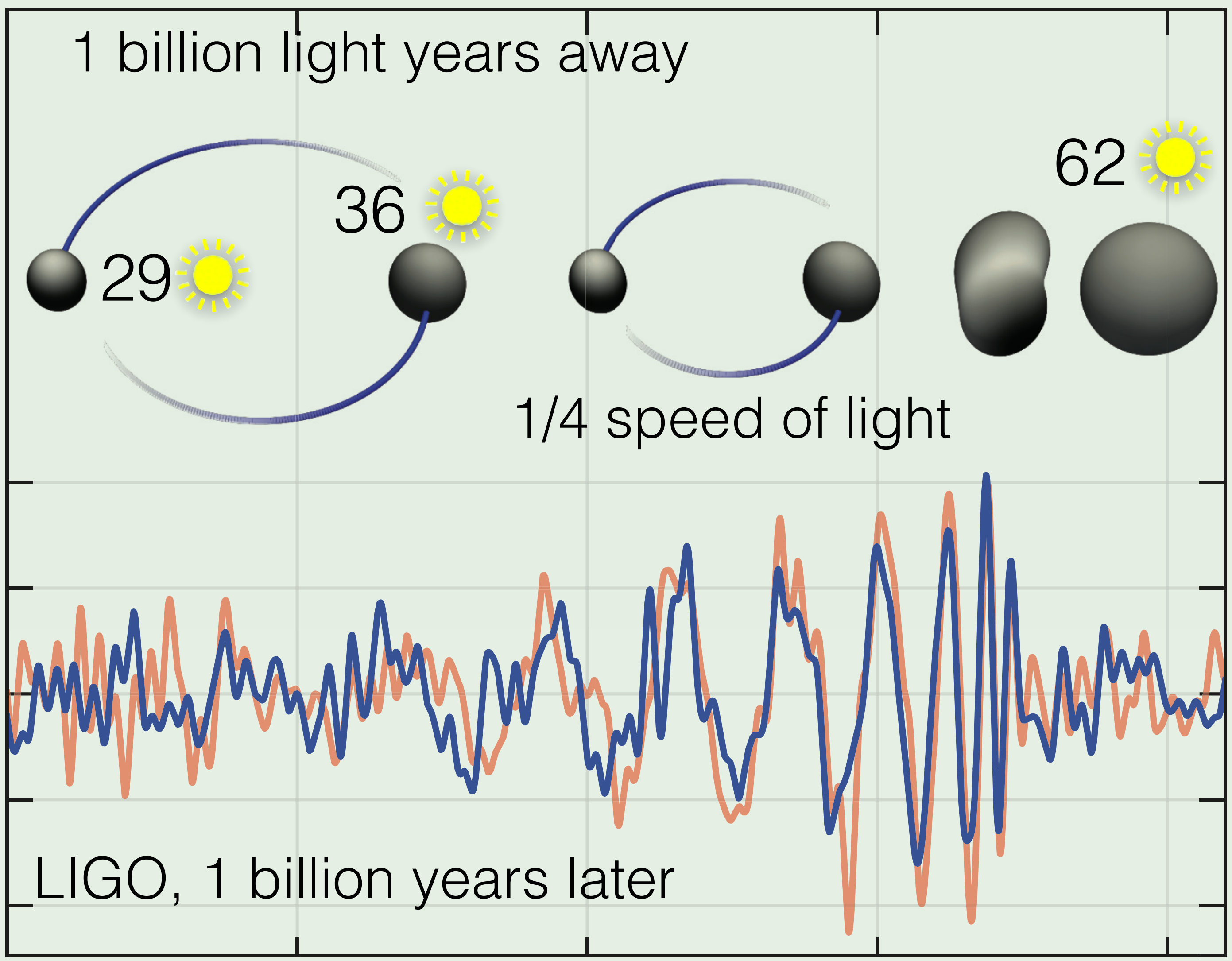
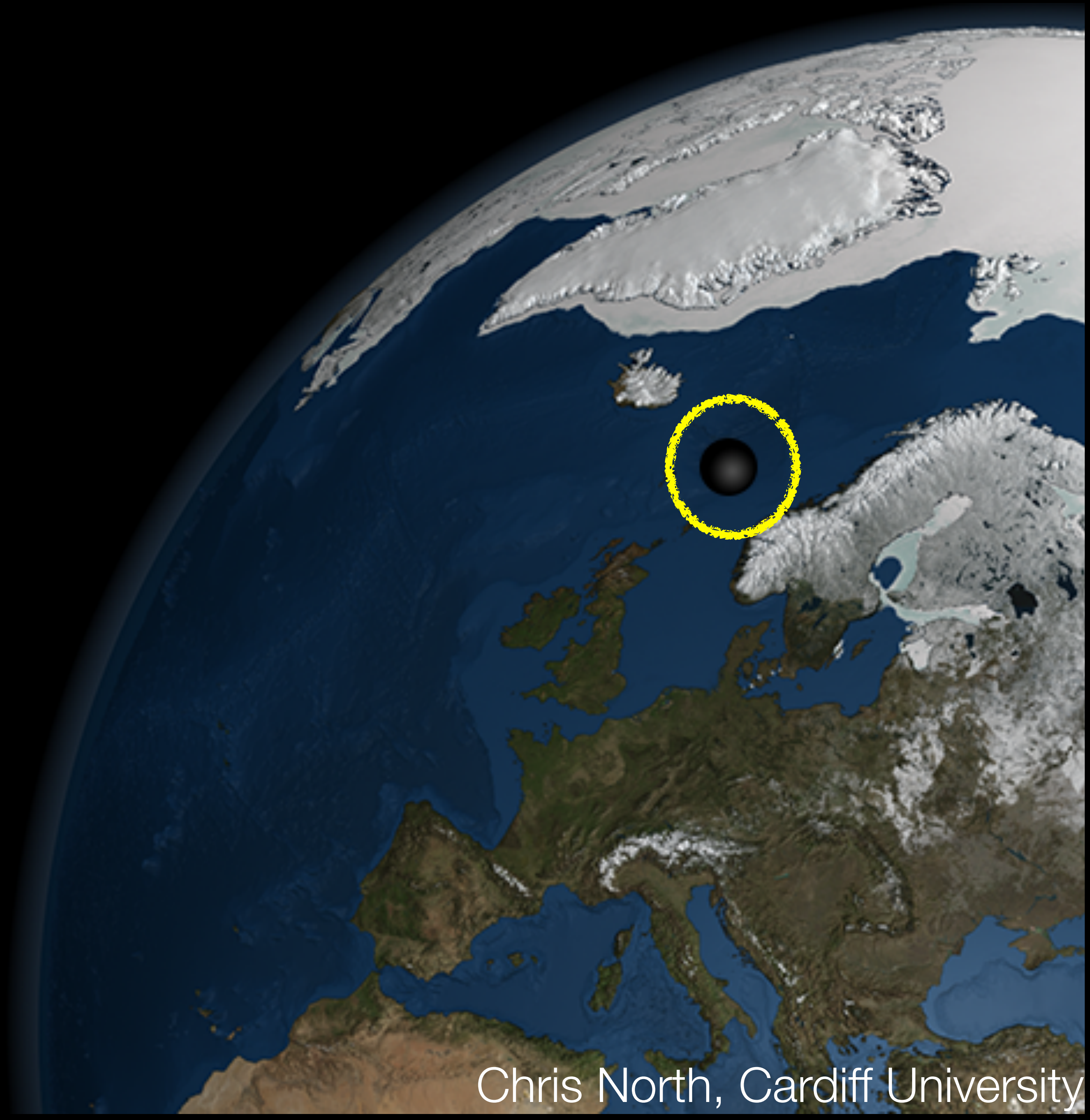
Articles published week ending 12 February 2016



Properties of the binary black hole merger GW150914: Result of merger

Final black hole:
62±4 solar
masses
spinning at
about 100 Hz

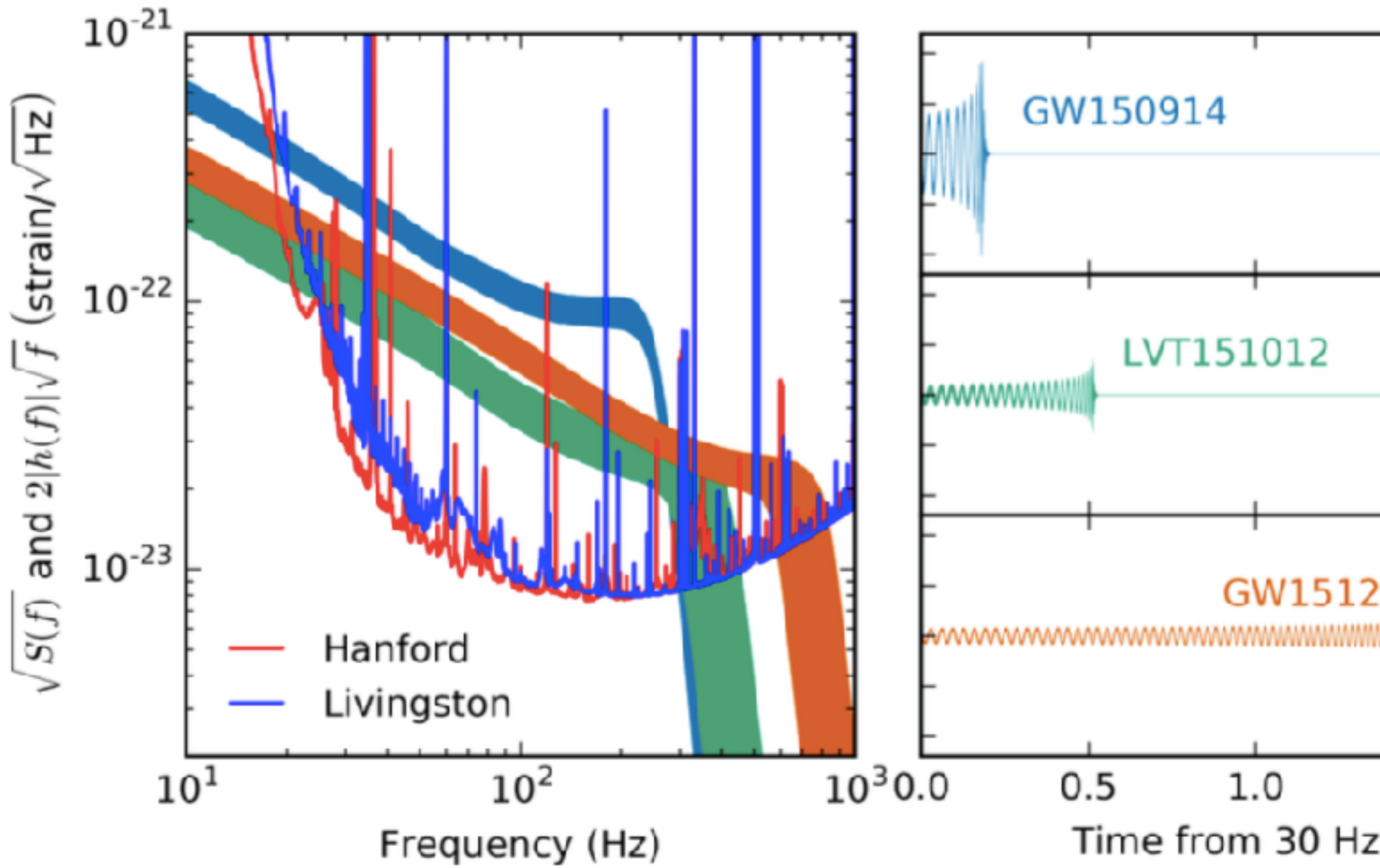
Estimated
luminosity (in GW)
~10^{56} erg/s



What did this mean?

- First direct detection of gravitational waves
    - opens the field of gravitational-wave astronomy
- First observation of stellar mass black holes (3!)
- First observation of two black holes merging to form one final black hole
- No deviations from General Relativity seen in this strong-field, high-velocity regime

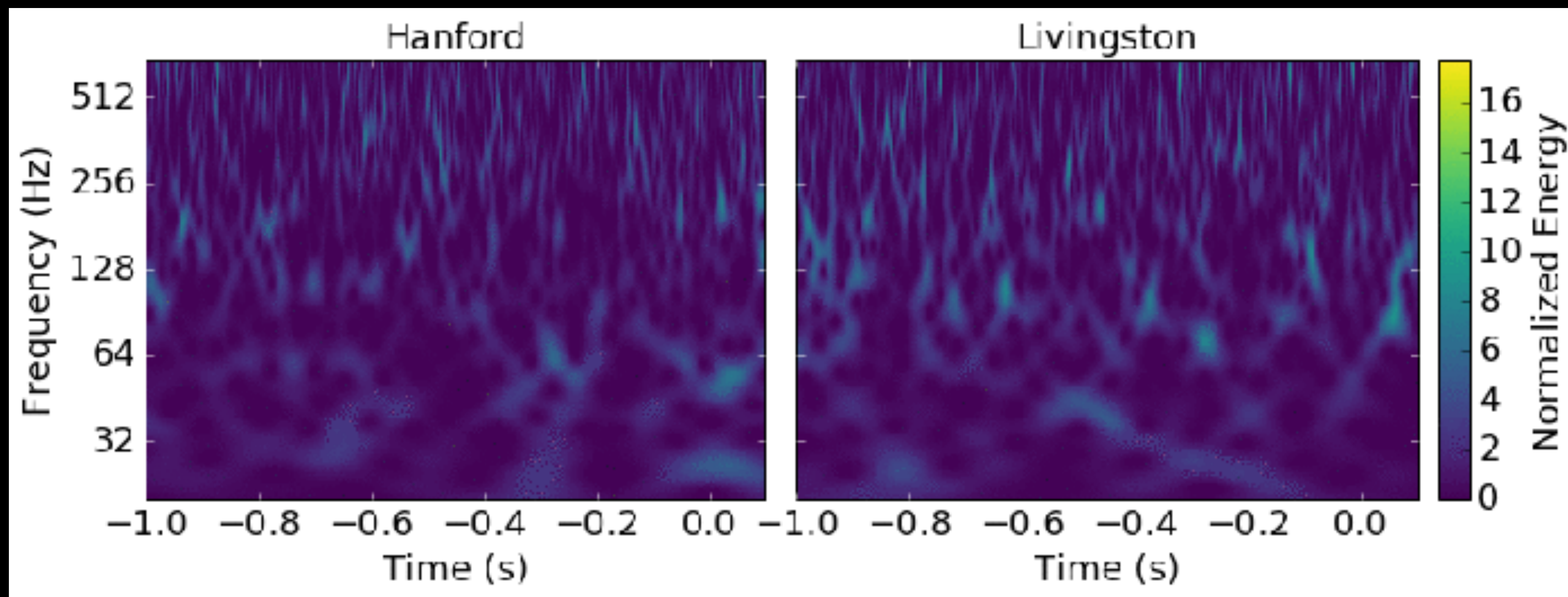
More black holes merge

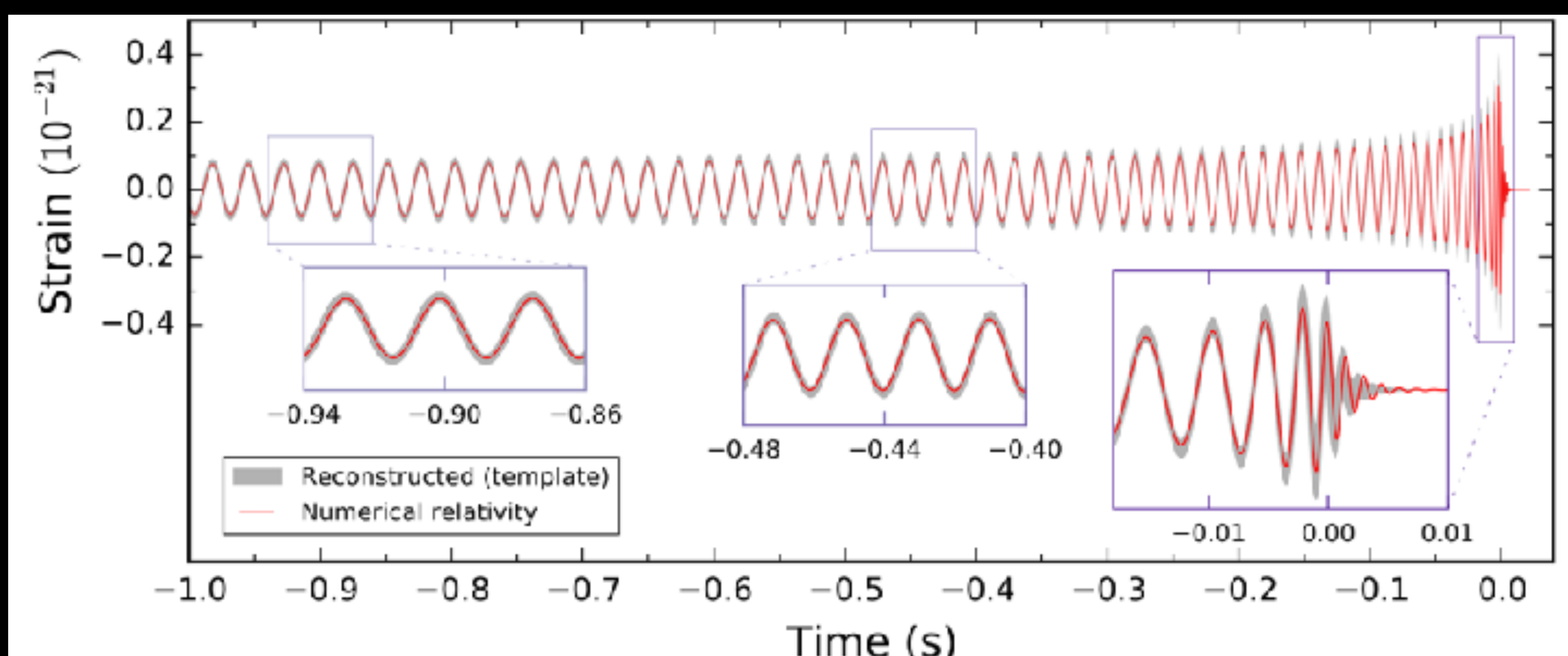


ArXiv 1606.04856

Image credit: LIGO

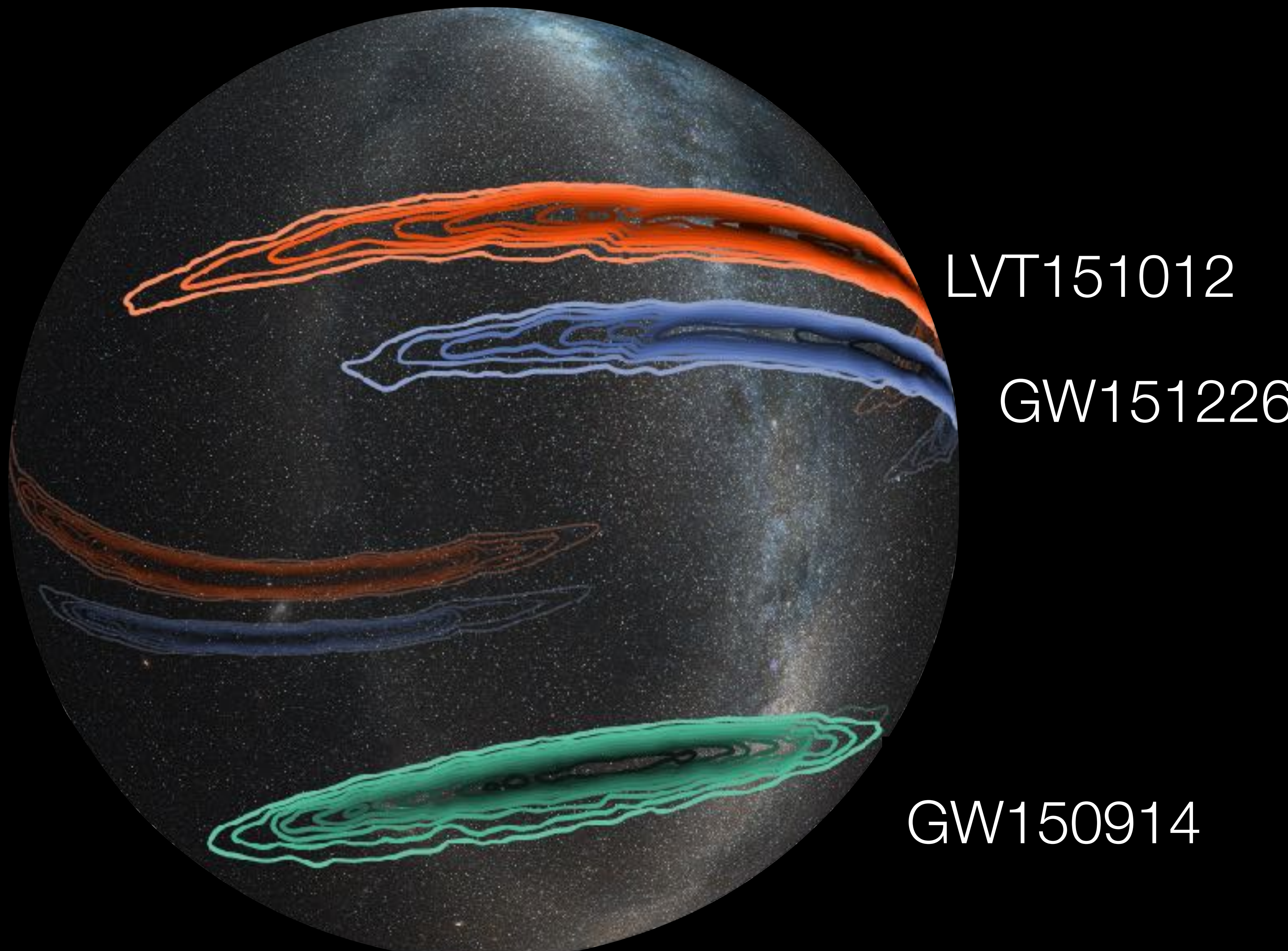
Observation of Gravitational Waves from a 22 Solar-mass Binary Black Hole Coalescence





http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.241103

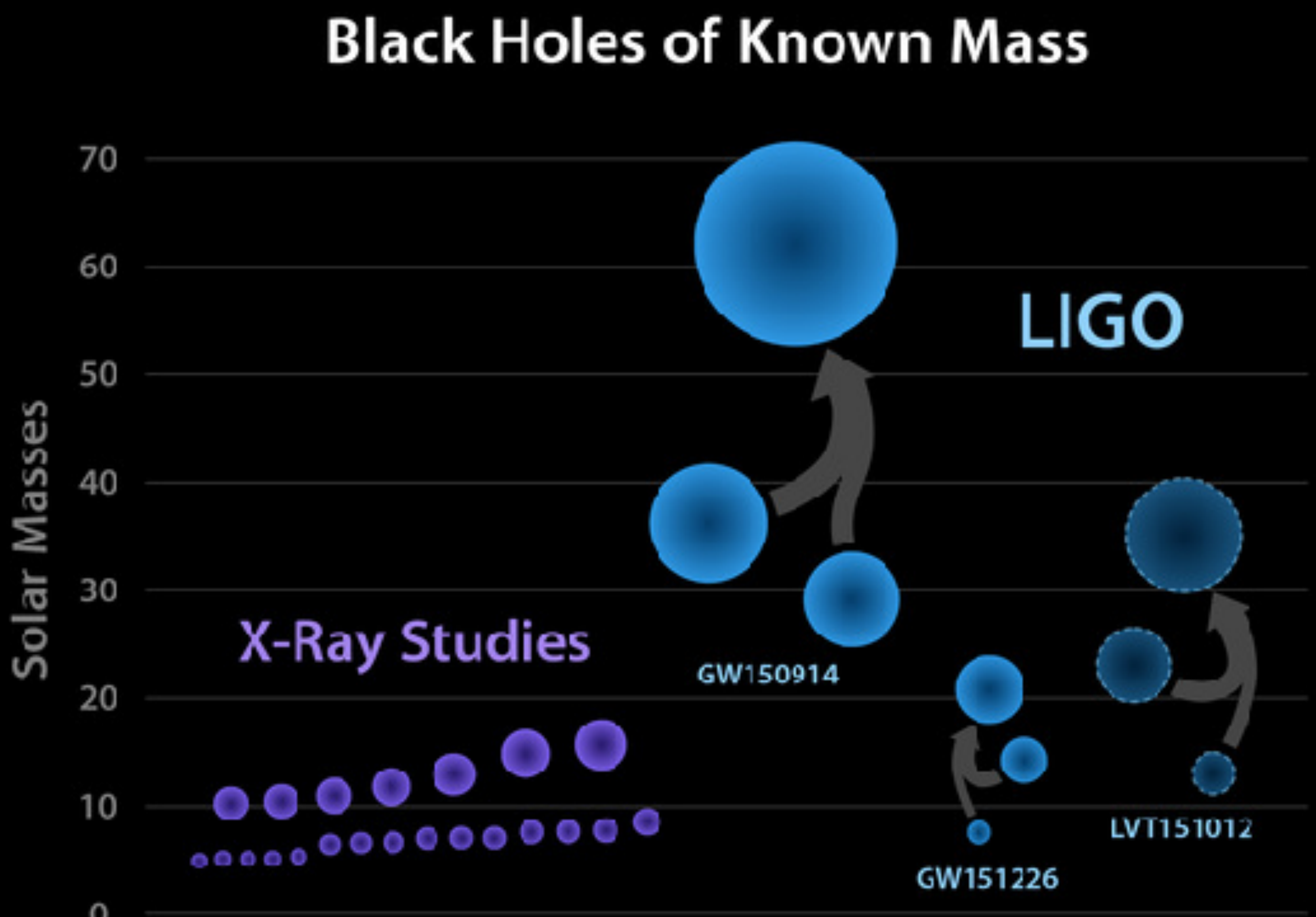
90%-10% sky localizations

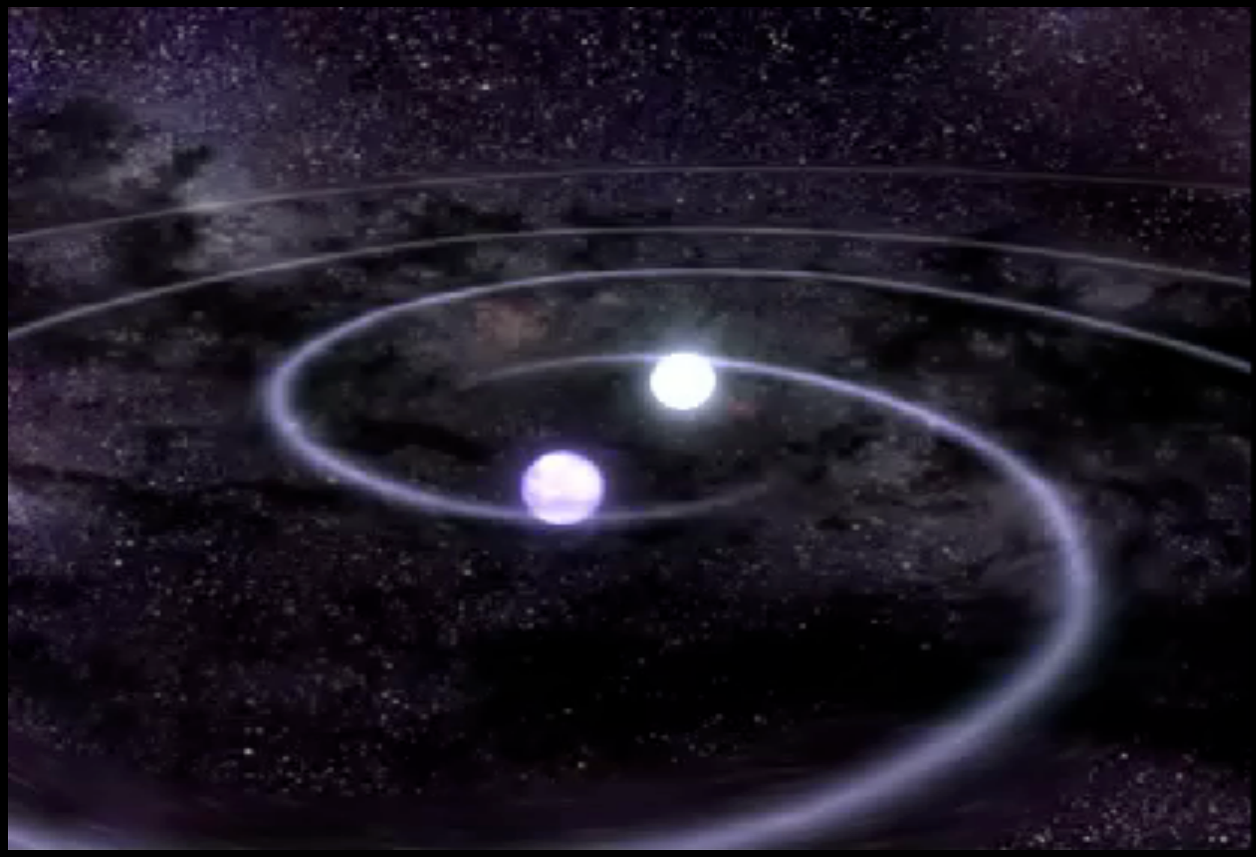


LIGO (Leo Singer)
Milky Way image (Axel Mellinger)

What's next for LIGO?

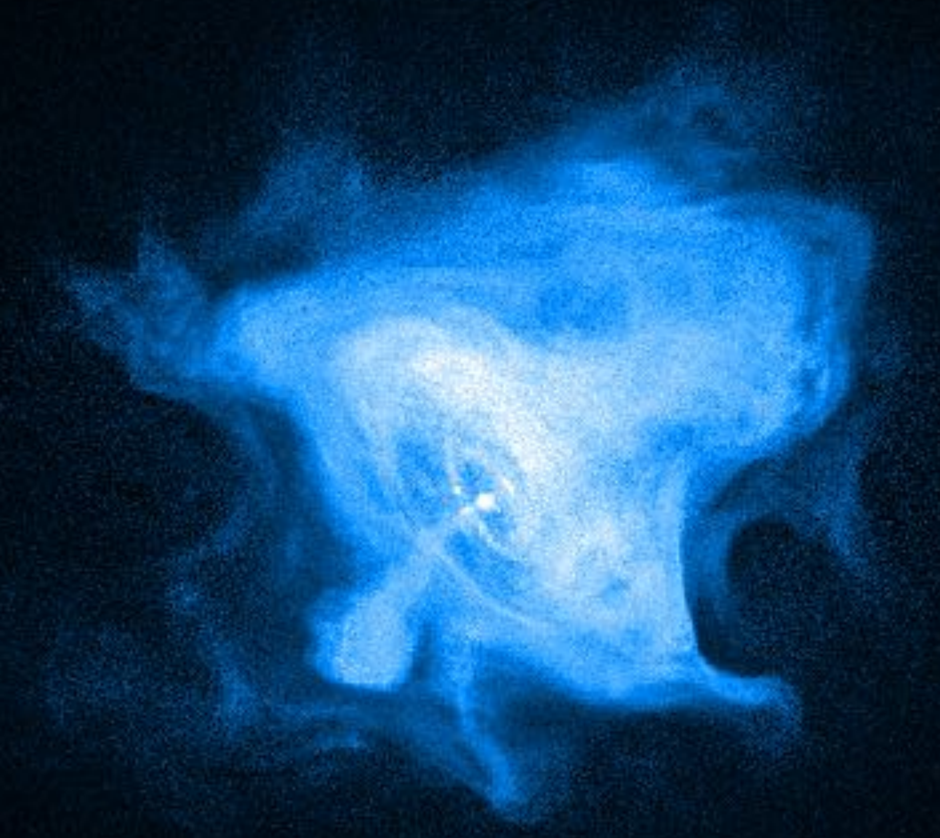
A population of black holes, merging neutron stars, multi-messenger astronomy?





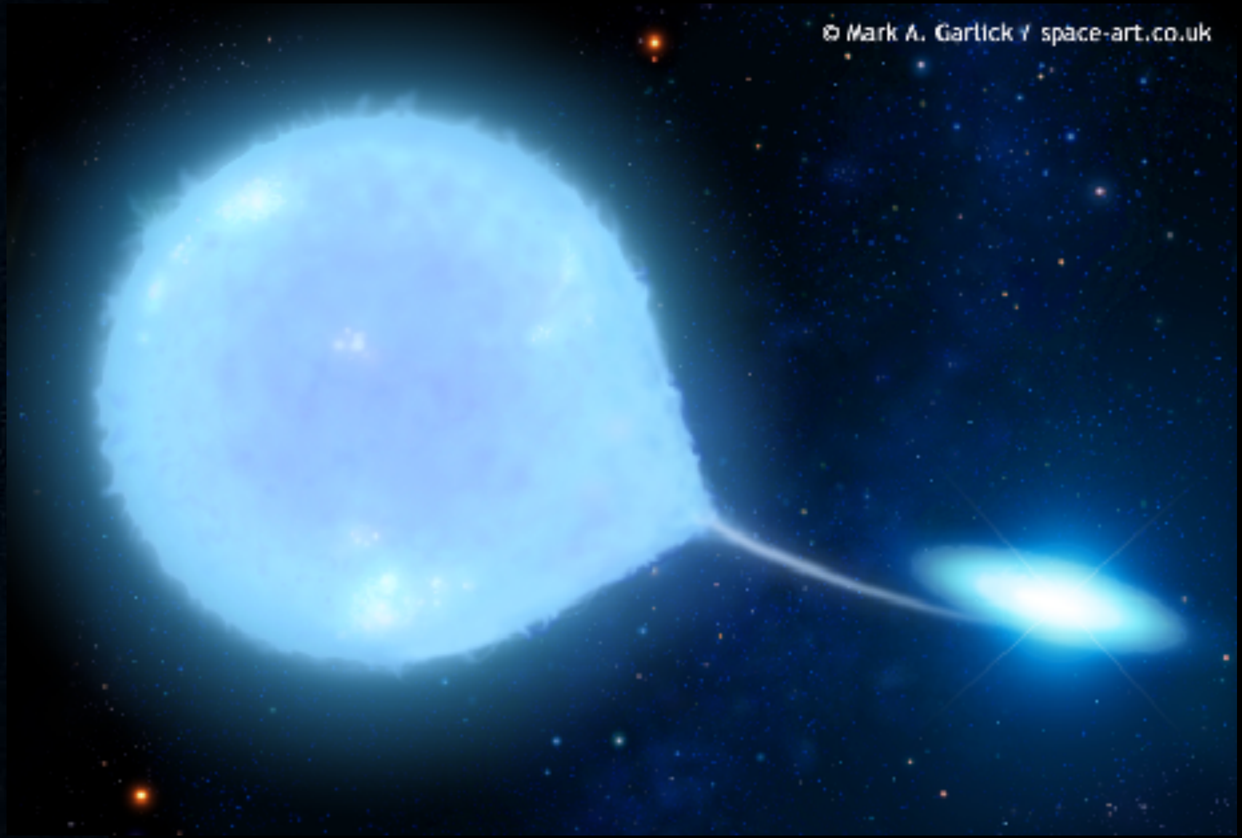
Searches for steady (“continuous”) sources

- Supernova remnants and pulsars



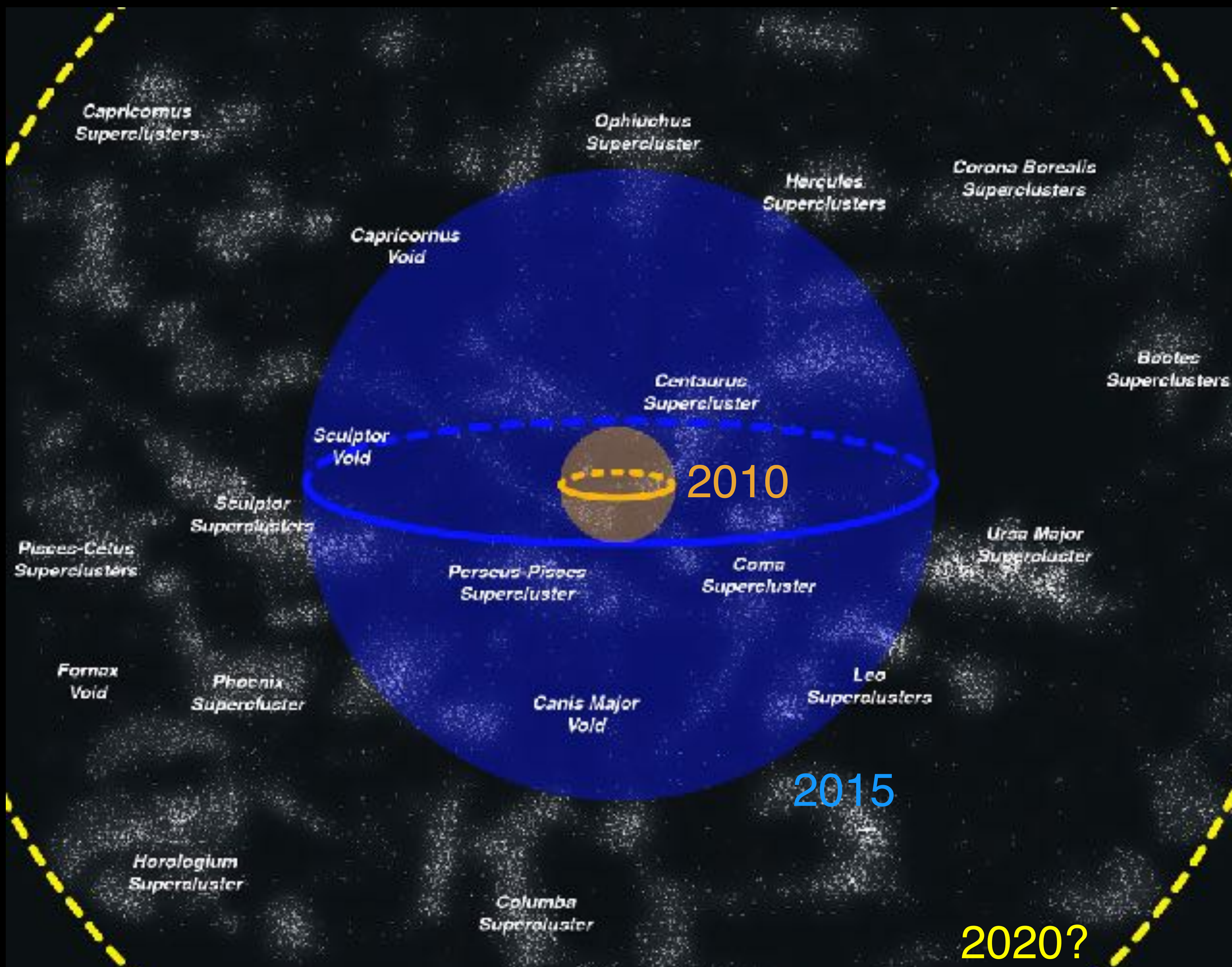
NASA's Chandra X-ray Observatory image of the Crab Nebula

- Accreting neutron stars



Artist image of an accreting neutron star (Mark A. Garlick)

Improved sensitivity



- Sensitivity to merging neutron stars shown

LIGO as an astrophysical-scale collider

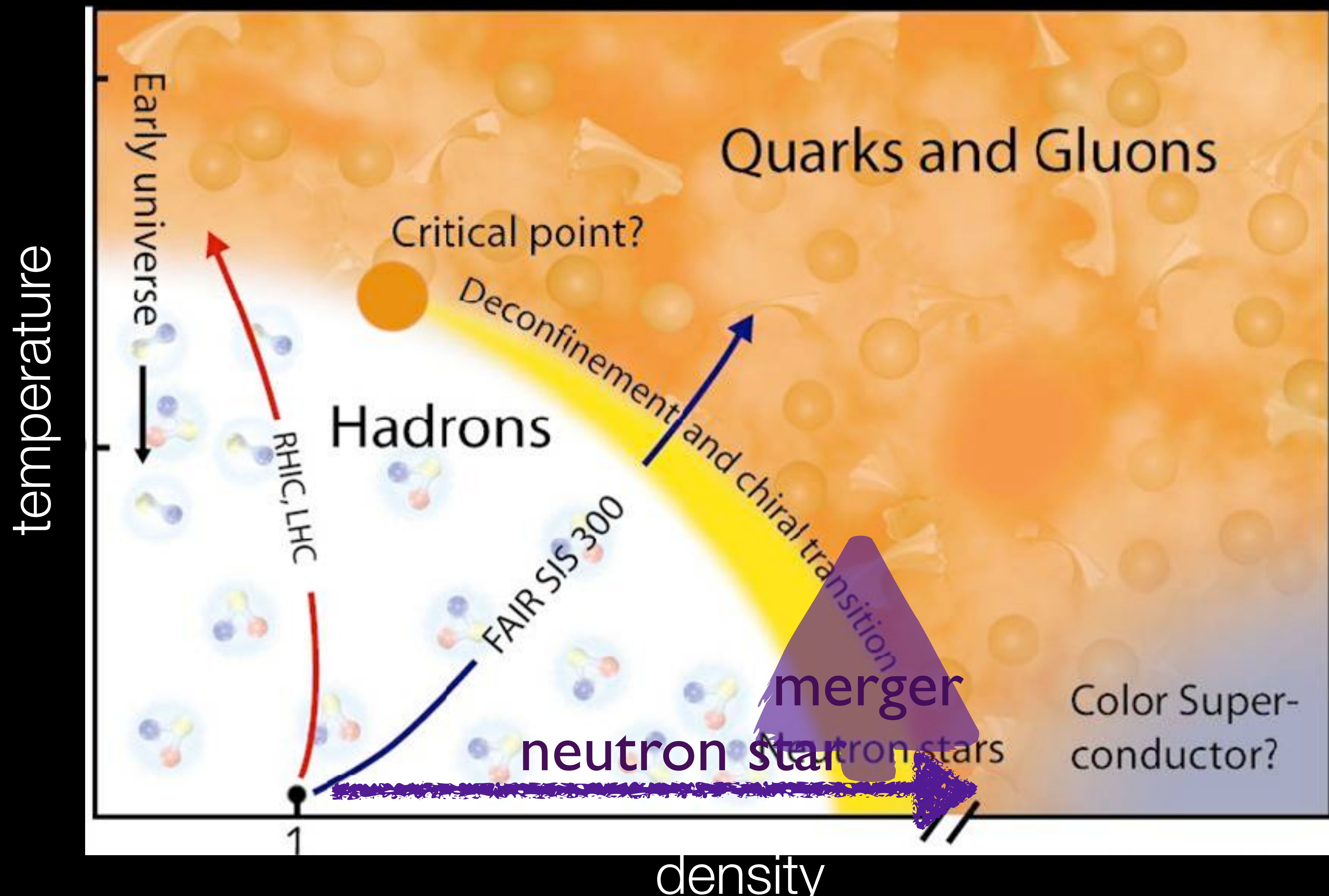
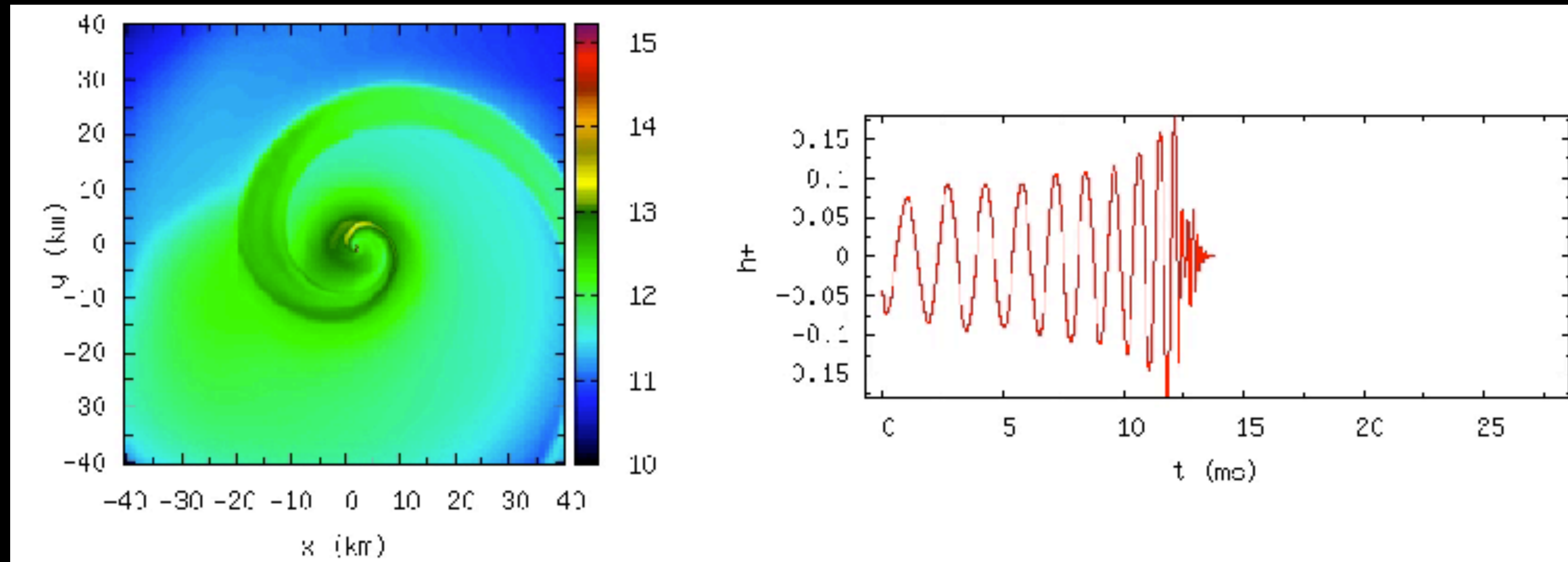
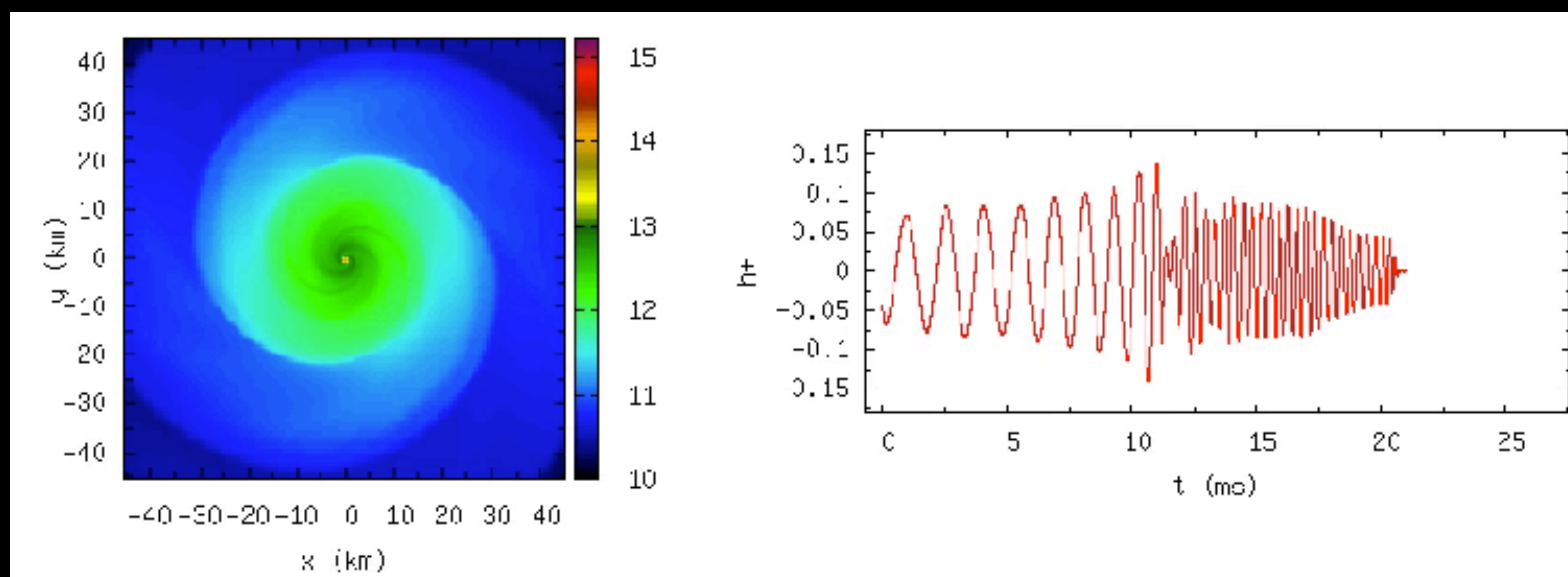


figure from FAIR CBM experiment

Merging compact stars

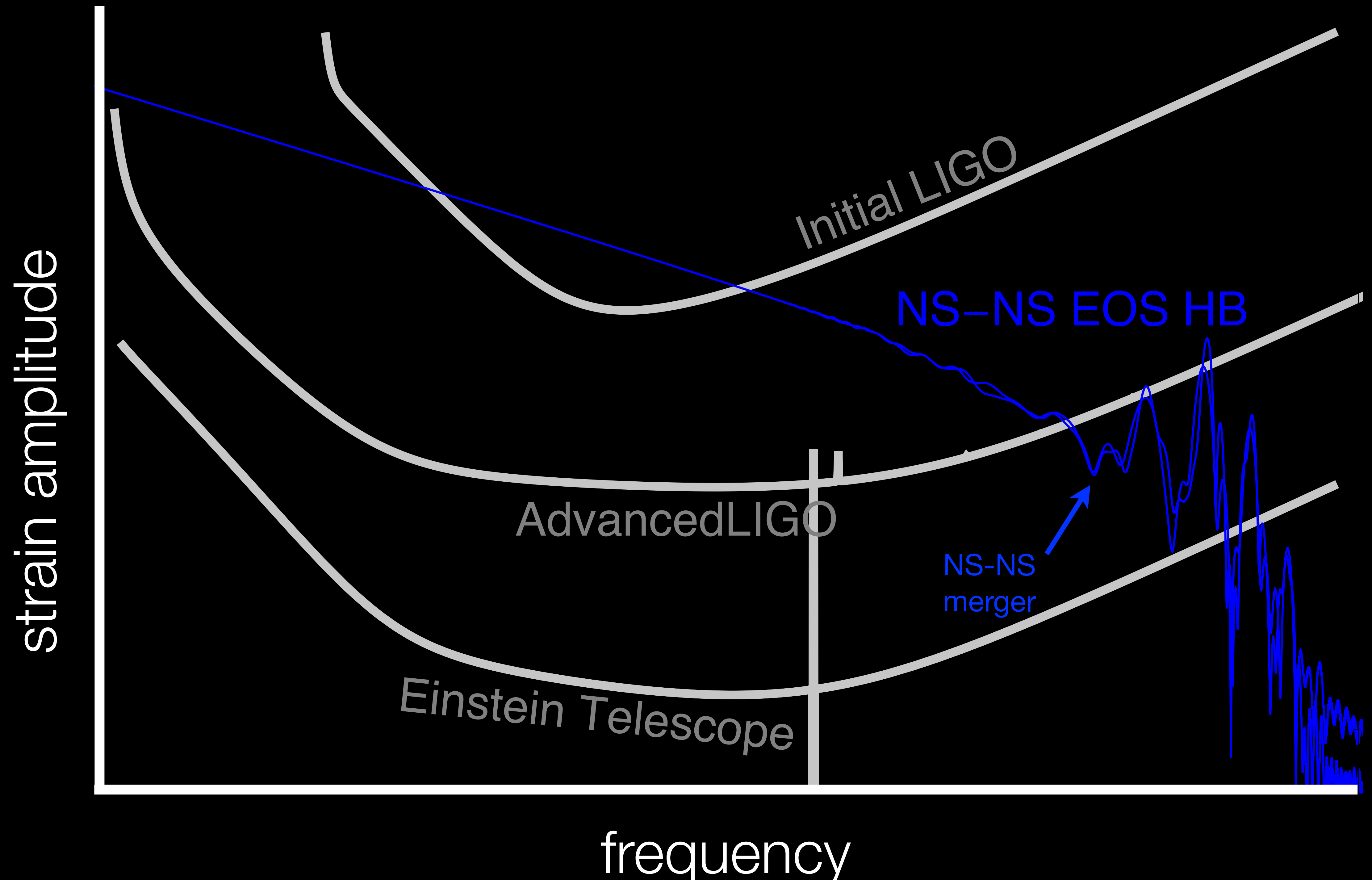


Merging large stars



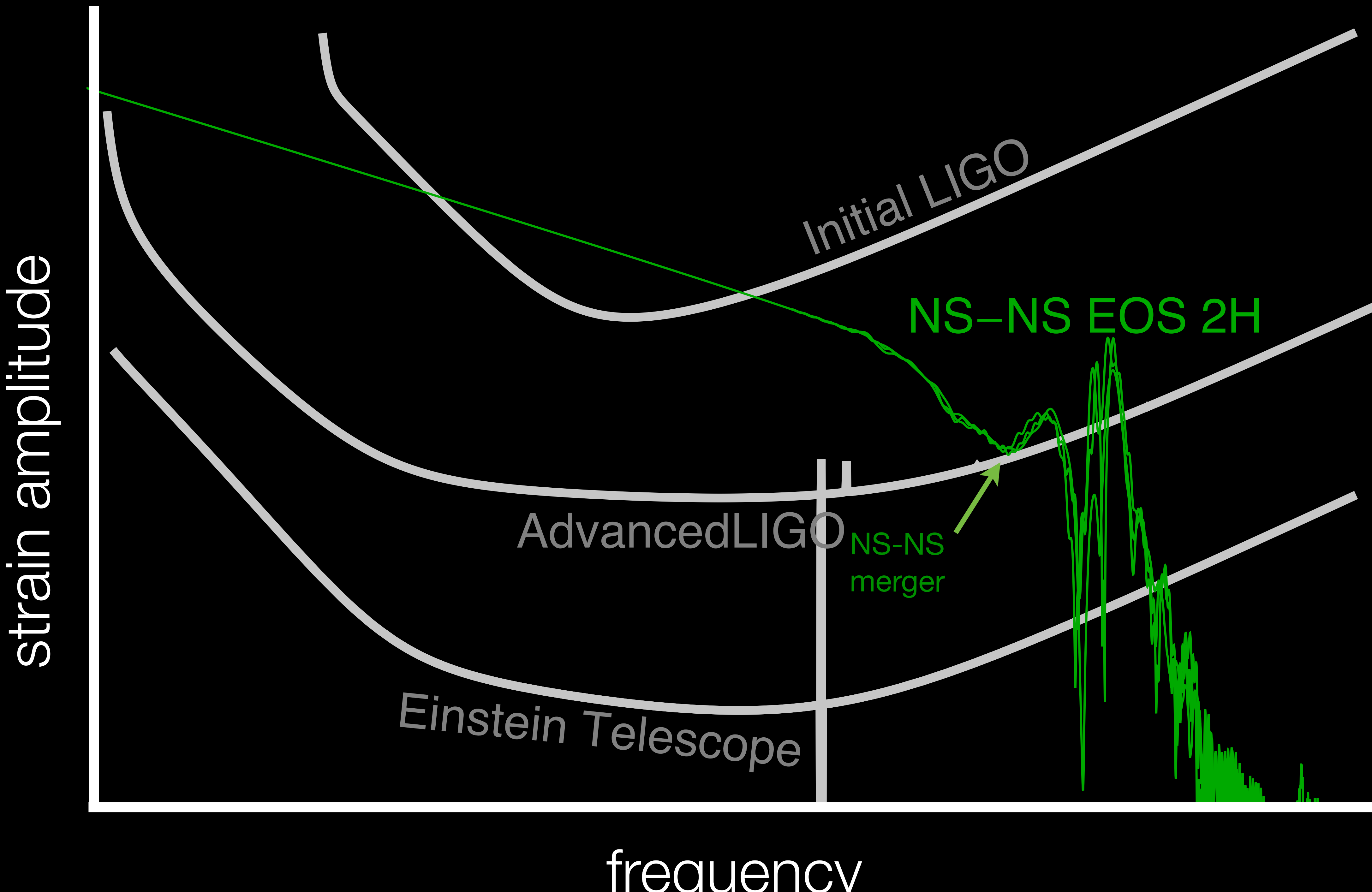
Numerical simulations: K. Hotokezaka, YITP

Learning about matter in neutron stars



Read et al

Learning about matter in neutron stars



Read et al

More information?

- Science summaries of LIGO collaboration results
    - http://www.ligo.org/science/outreach.php
- Educator guide and teacher courses
    - http://epo.sonoma.edu/ligo/
- Sounds of Spacetimehttp://www.soundsofspacetime.org/
- Documentaries on space.com
- “The basic physics of the binary black hole merger GW150914”
- LIGO on Facebook/Twitter!
    - https://www.facebook.com/LigoScientificCollaboration