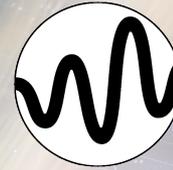


Christopher Berry
Institute of Gravitational Wave Astronomy
LIGO Scientific & Virgo Collaboration



Discoveries of gravitational wave astronomy



The multiwavelength universe

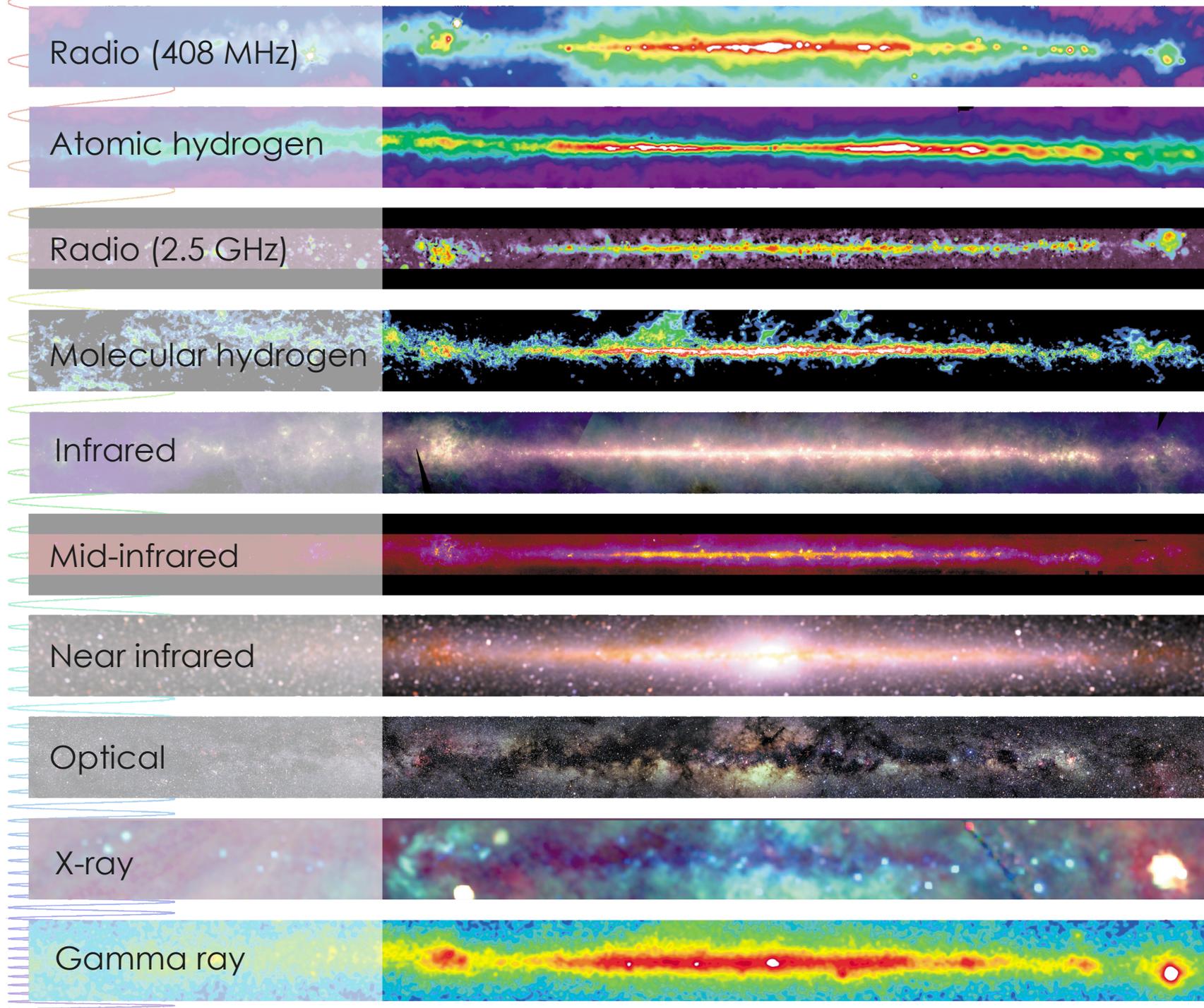


Image:
NASA

Pulsars

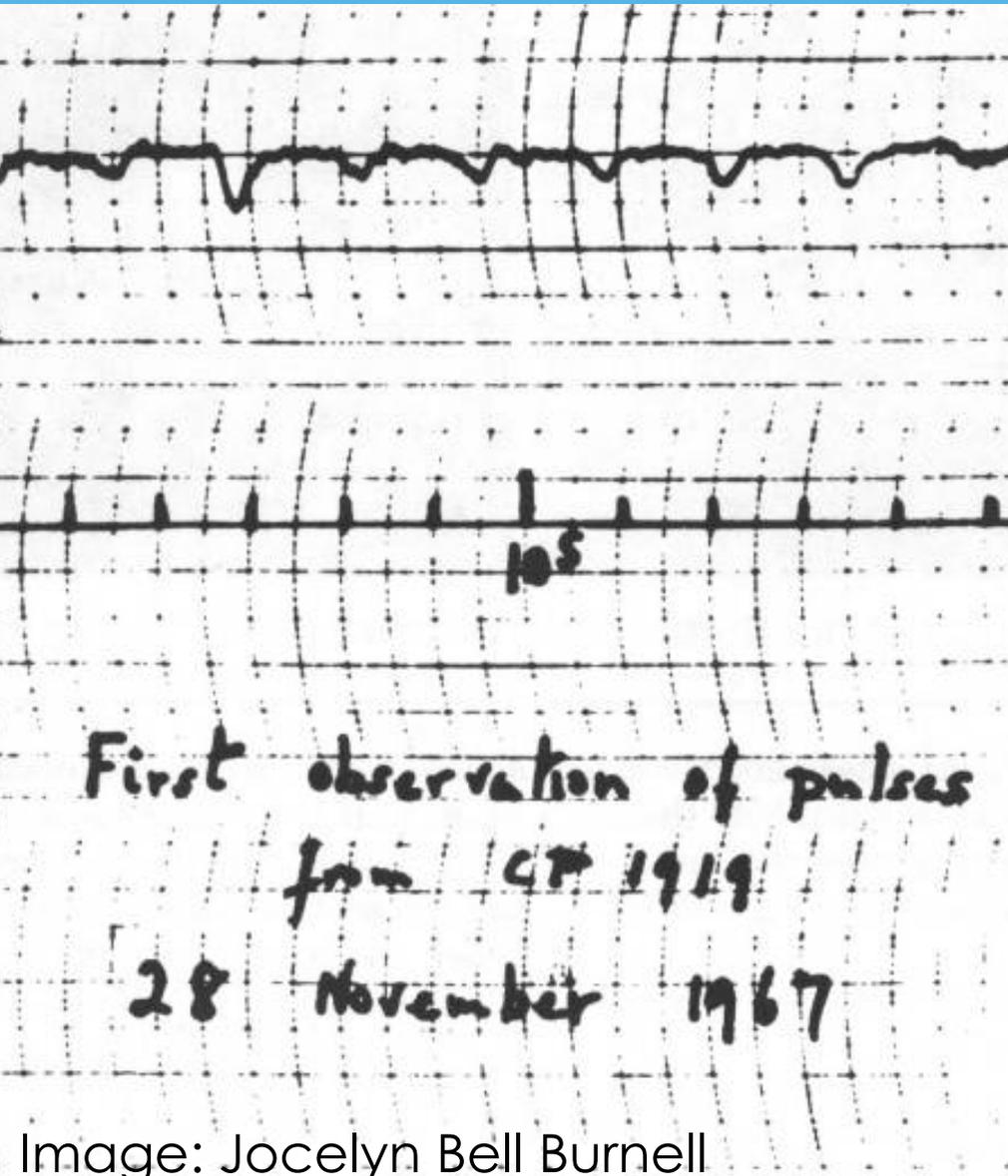
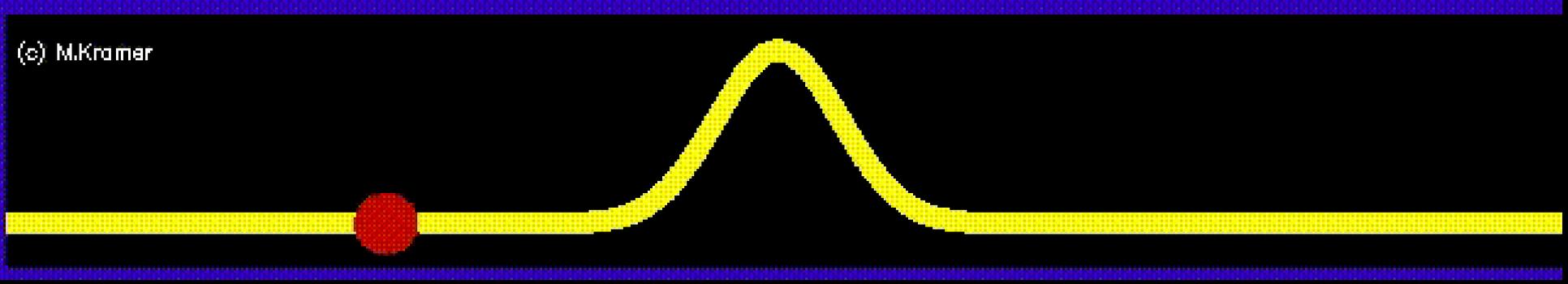
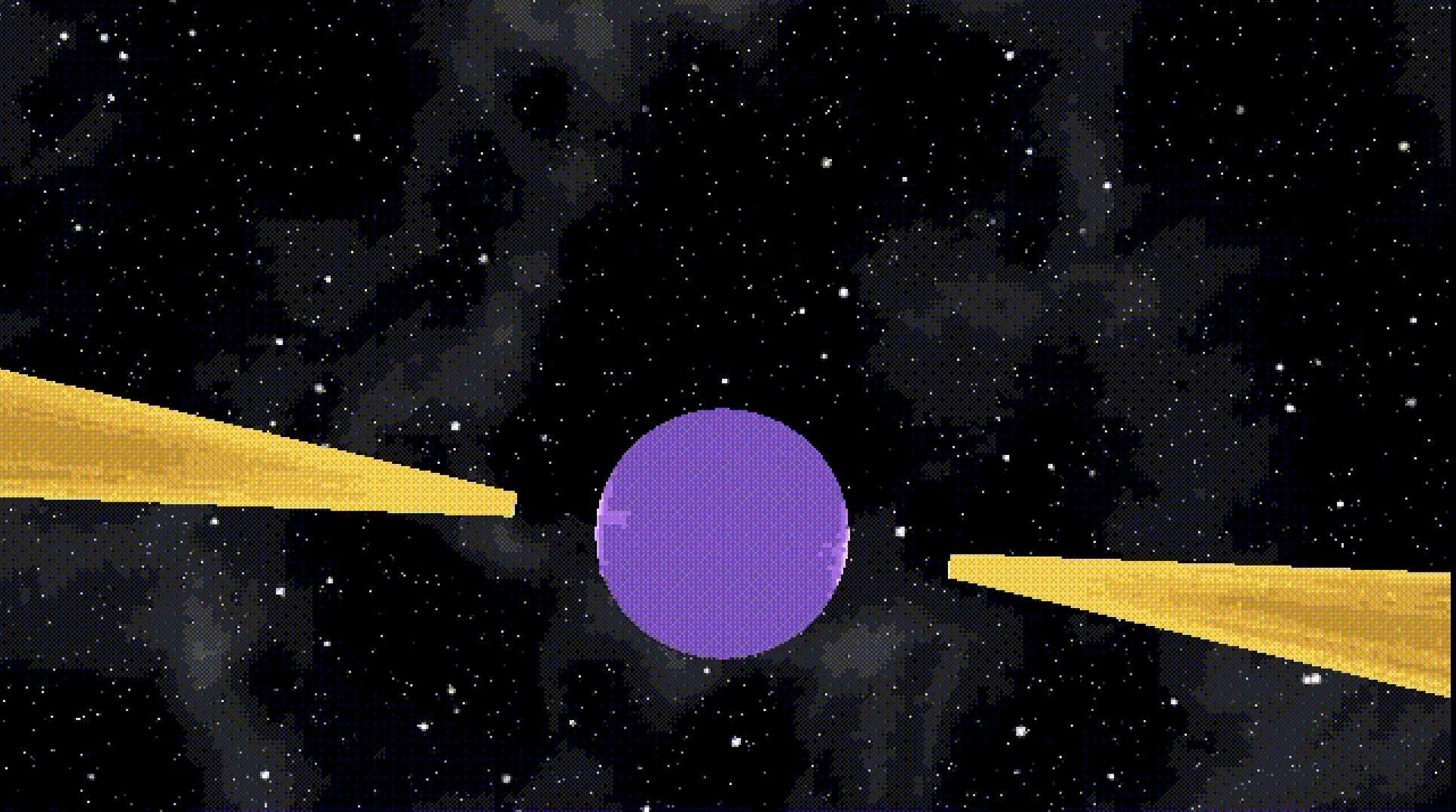


Image: Jocelyn Bell Burnell



(c) M.Kramer

The multiwavelength universe

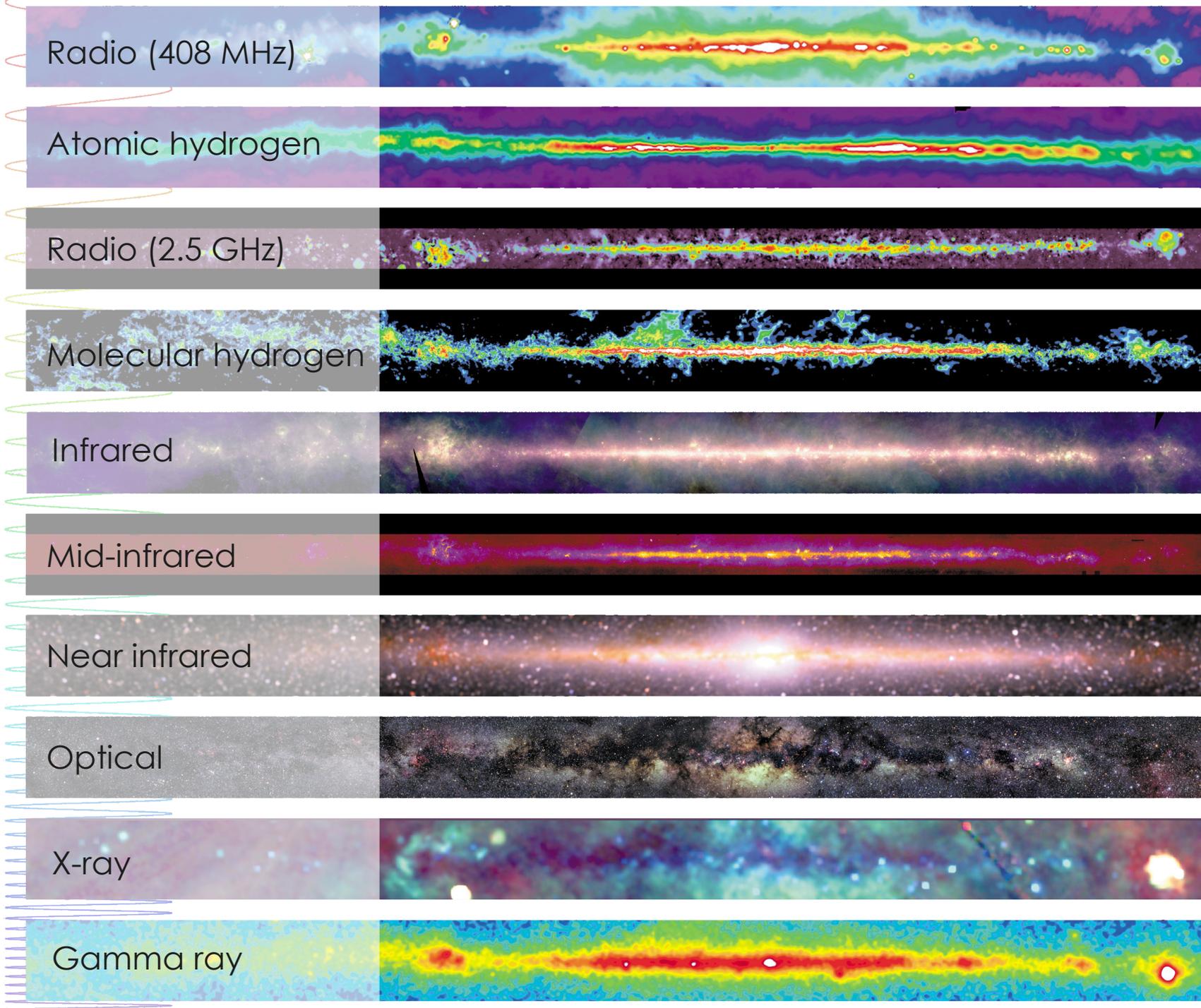
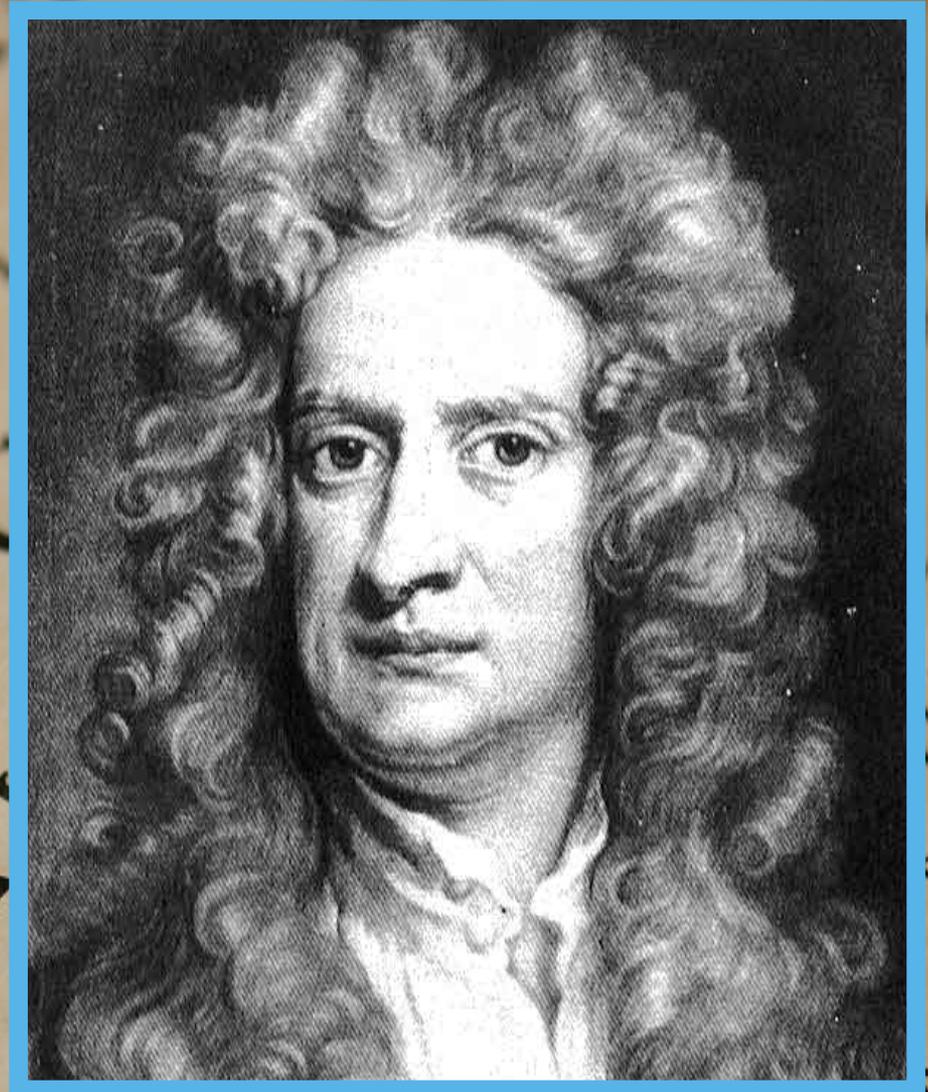


Image:
NASA

Image:
Daniel Berehulak/
Getty Images

Gravitation is universal

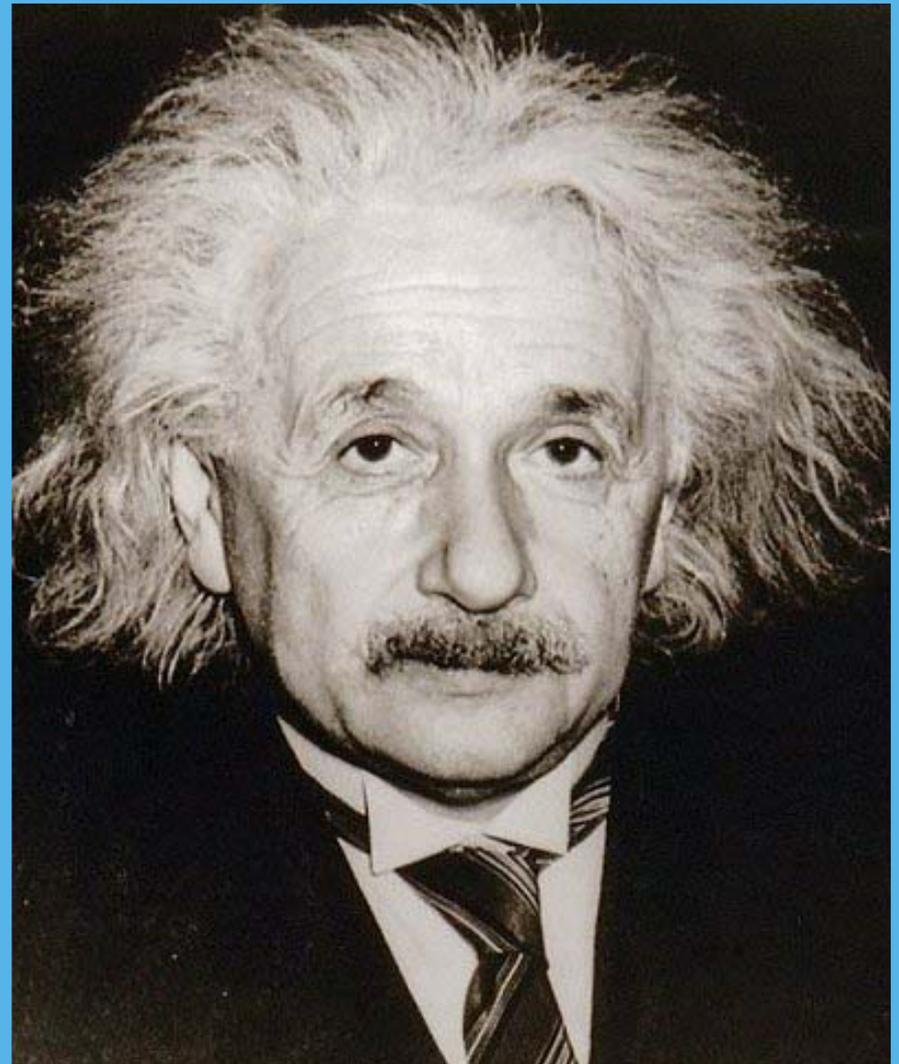
Objects move in
straight lines



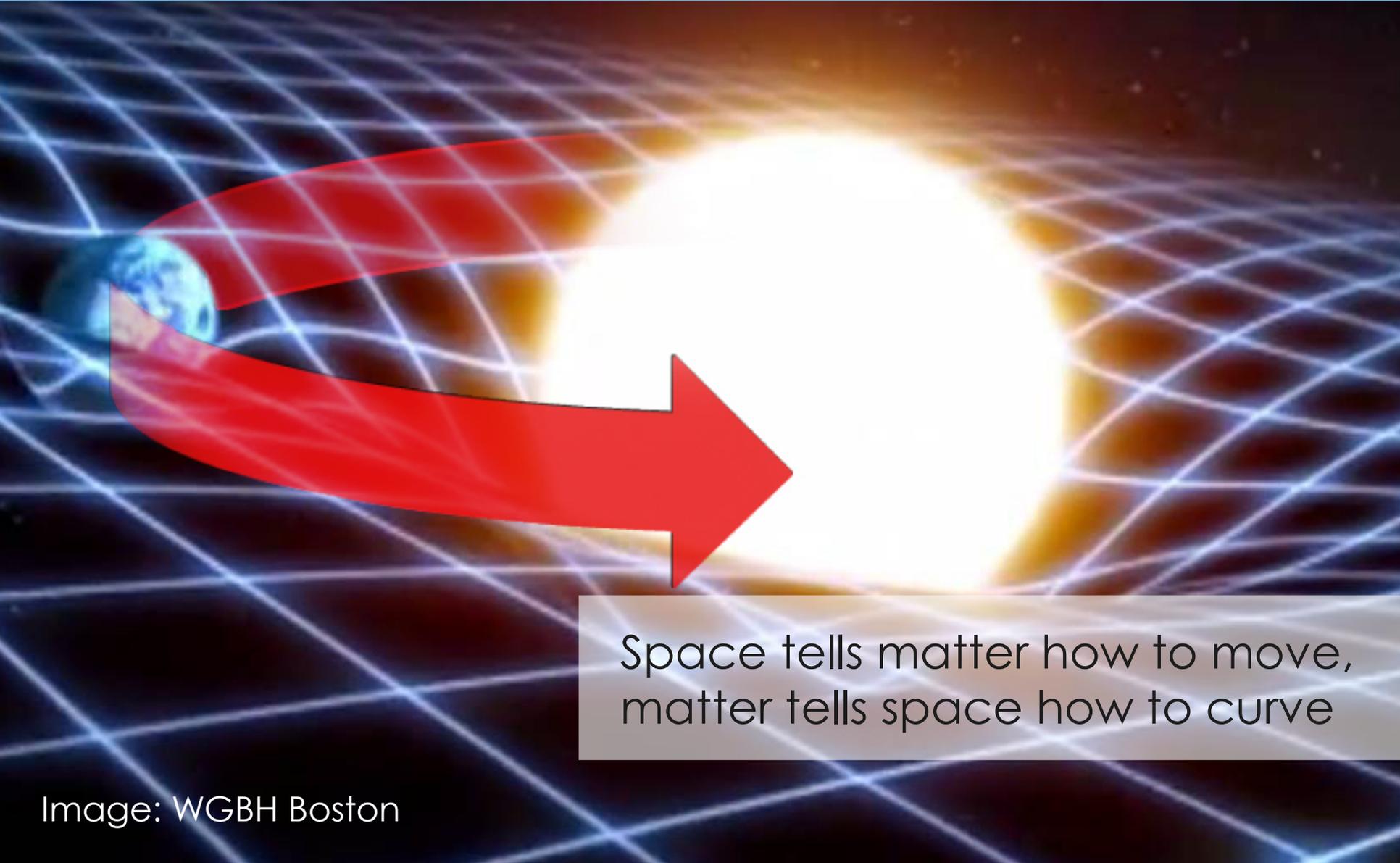
Relativity

Space and time are linked

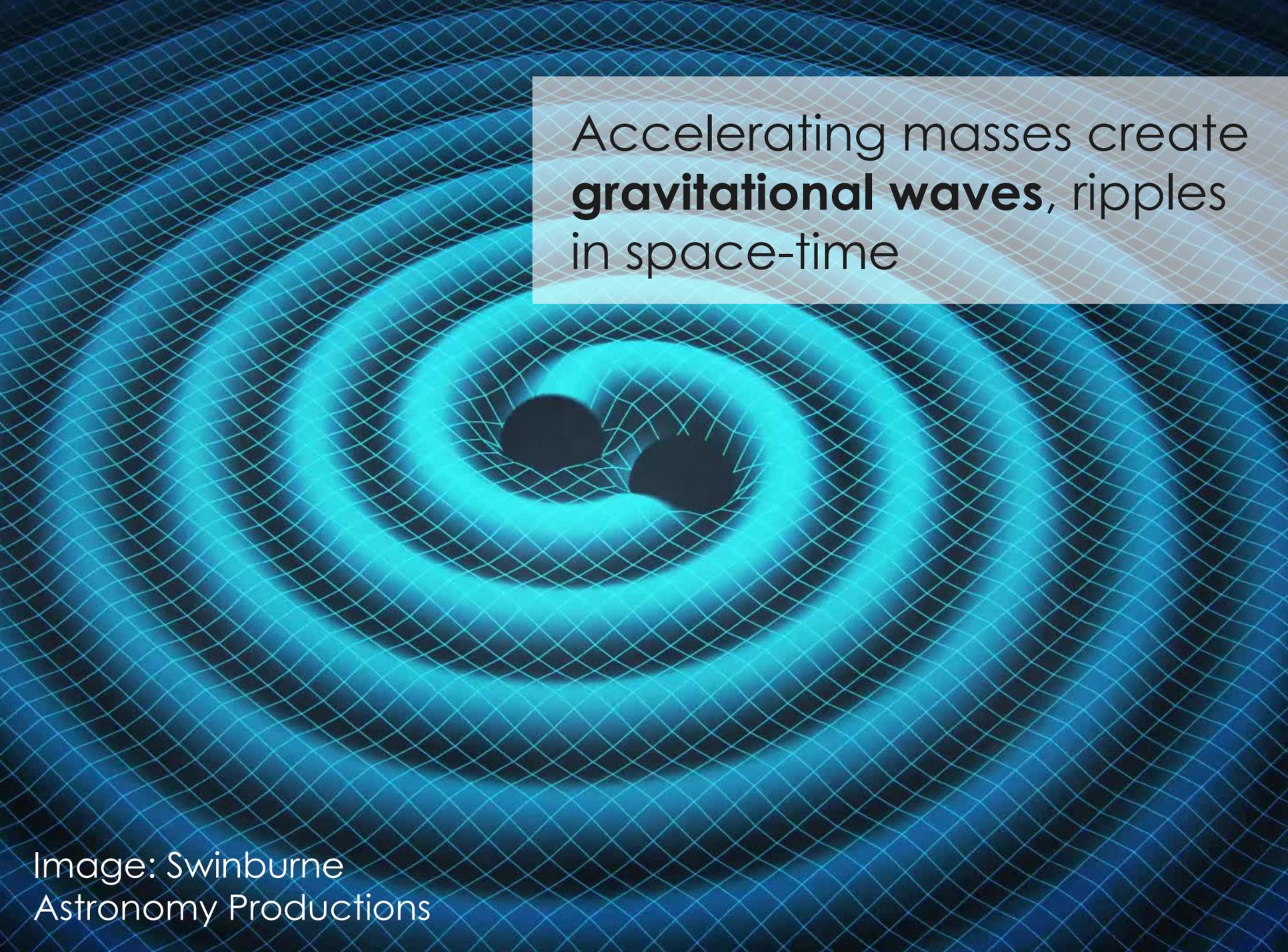
Nothing can travel faster than the speed of light



Space-time

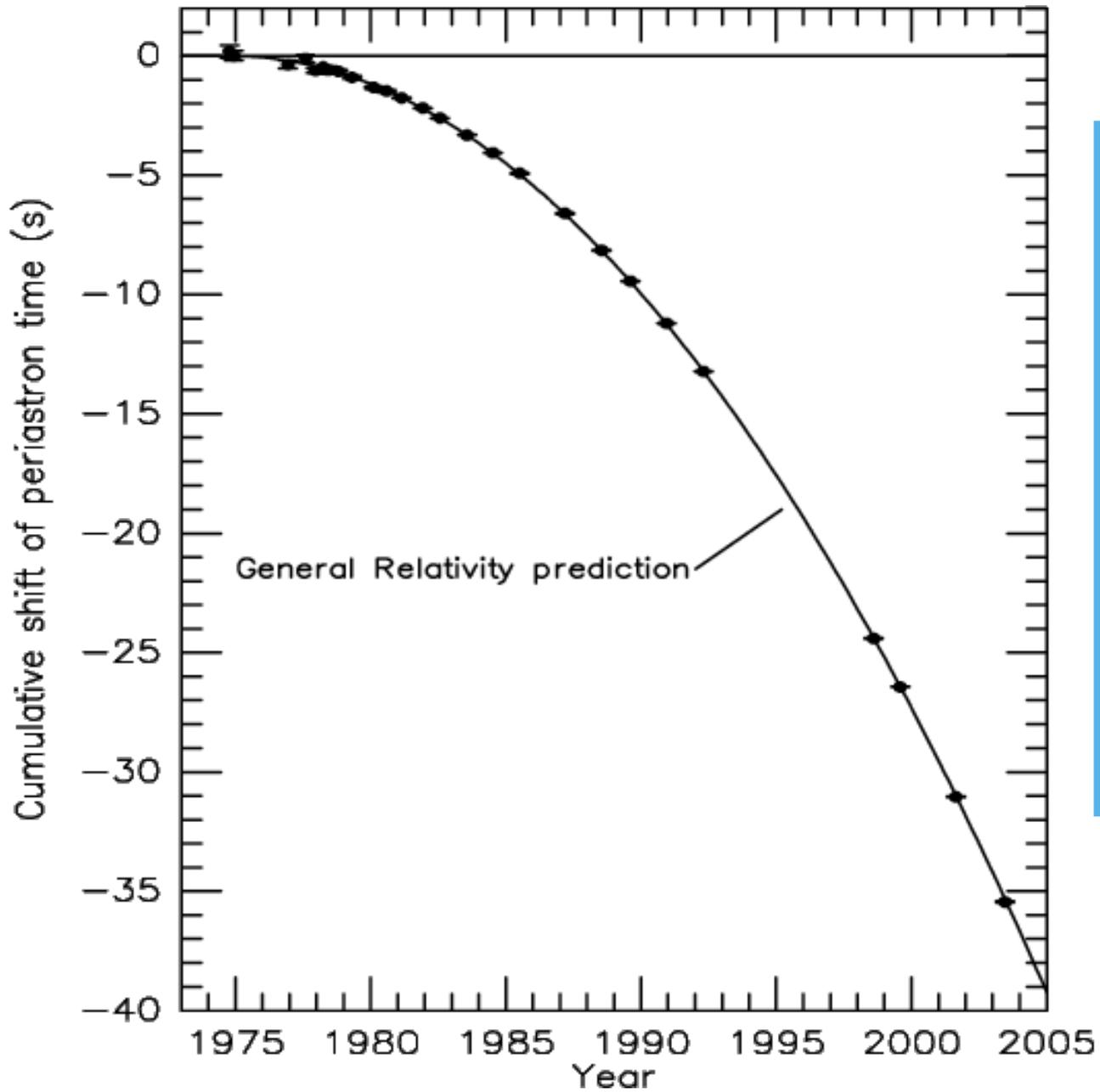


Space tells matter how to move,
matter tells space how to curve



Accelerating masses create **gravitational waves**, ripples in space-time

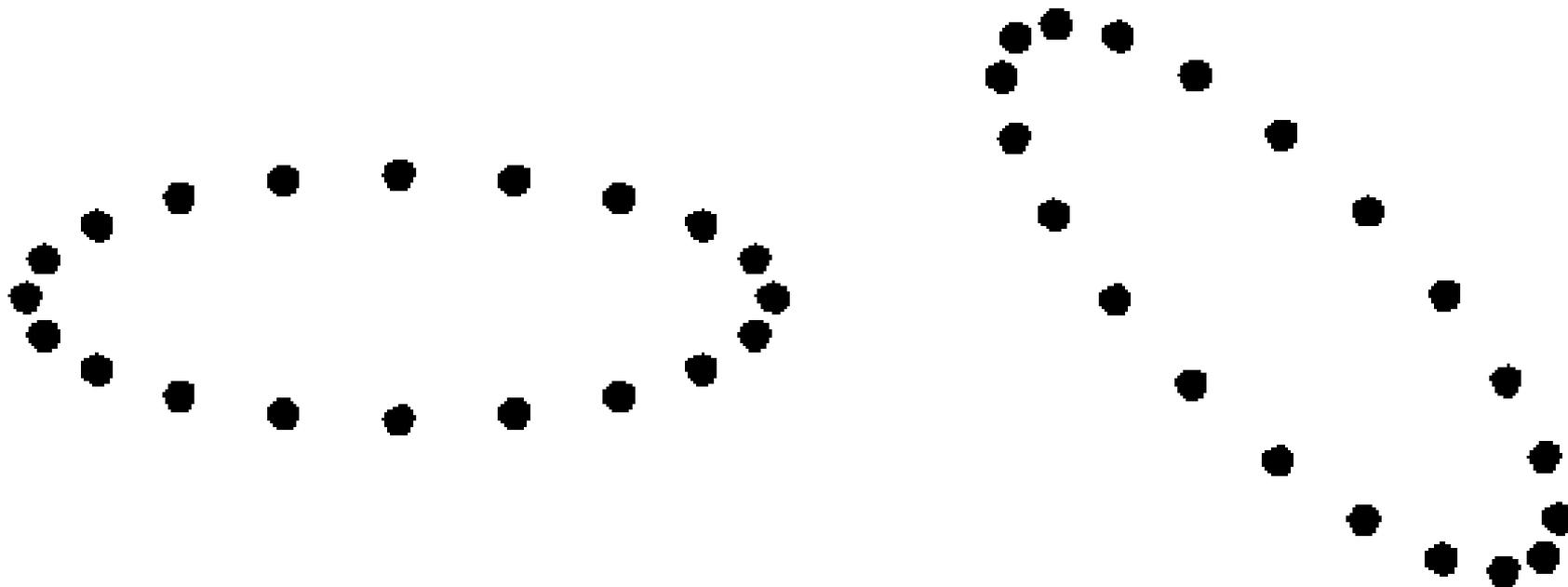
Image: Swinburne
Astronomy Productions



Pulsars confirm theoretical predictions to superb accuracy

Credit: Weisberg & Taylor

Stretch and squash





LIGO Livingston
4 km arms

Image: LIGO

Detector network



15 September
2015

We observed
gravitational
waves

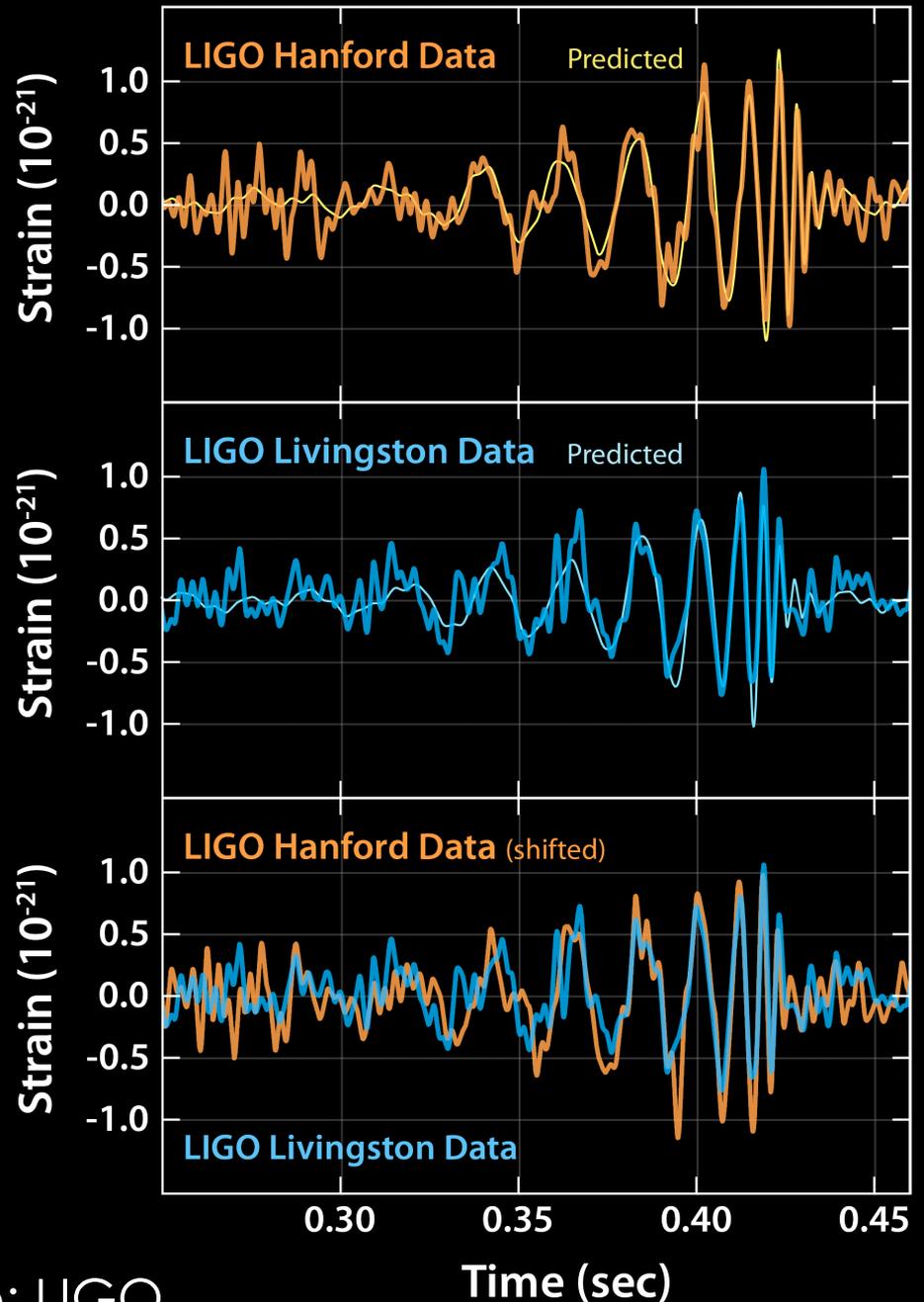
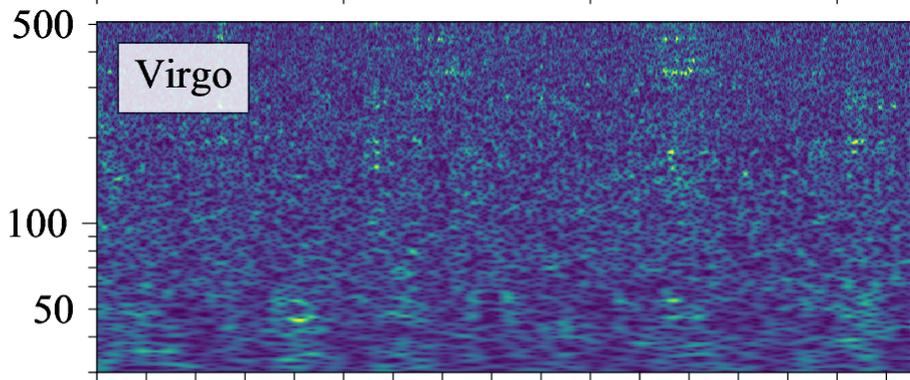
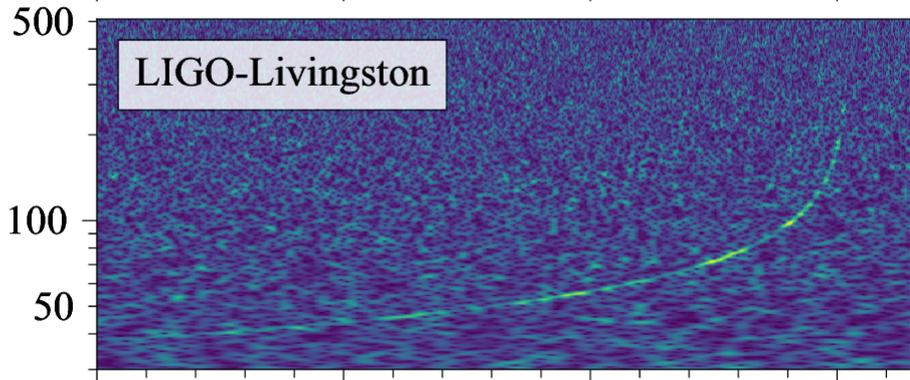
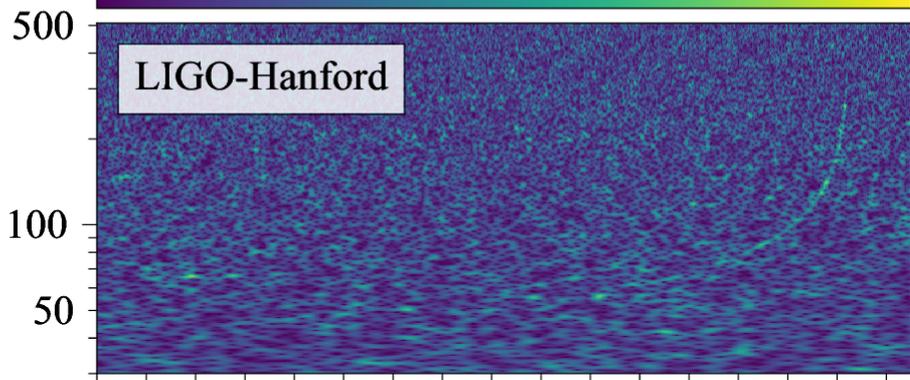


Image: LIGO

Normalized amplitude

0 2 4 6

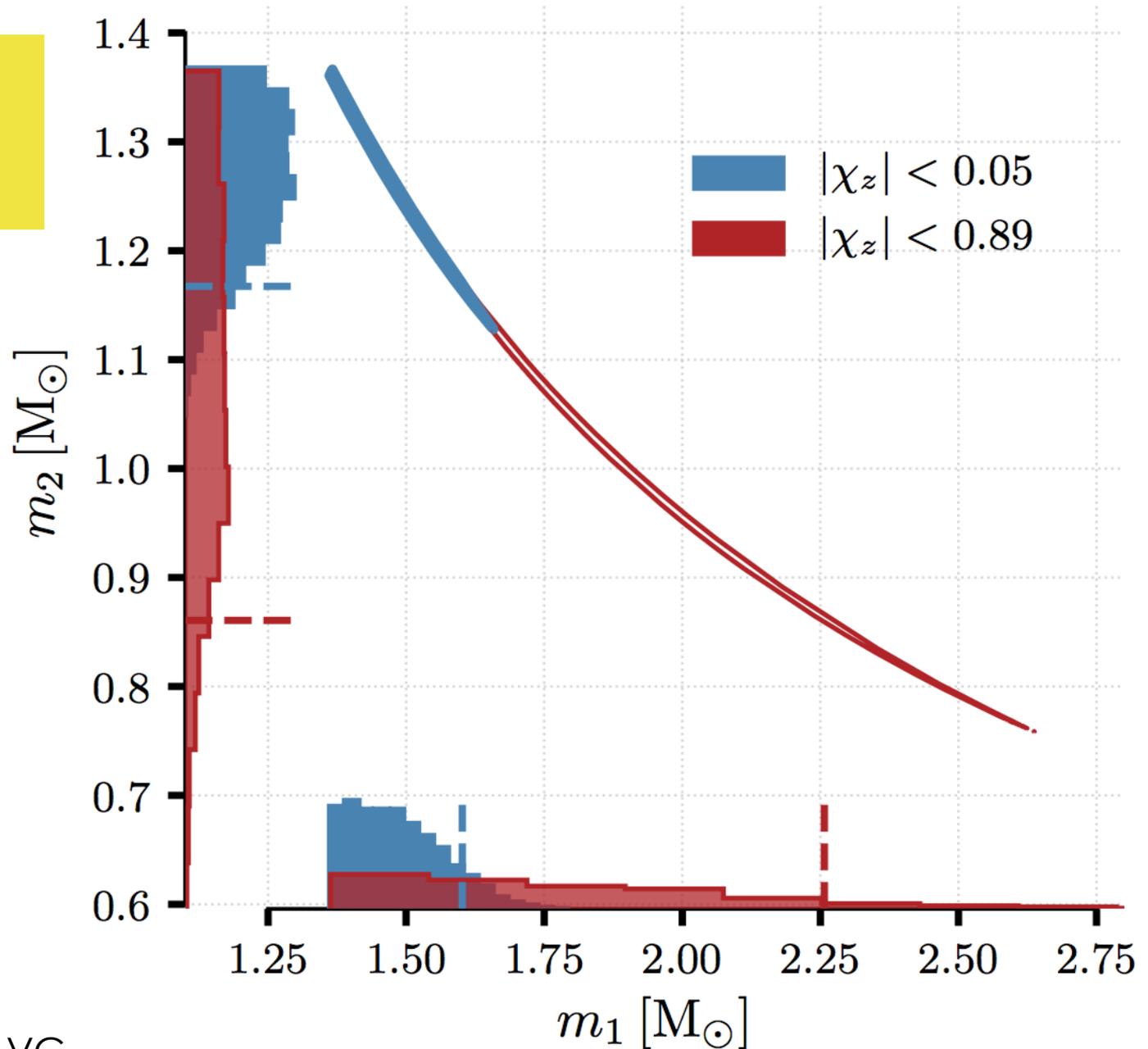


GW170817

17 August 2017

Credit: LVC

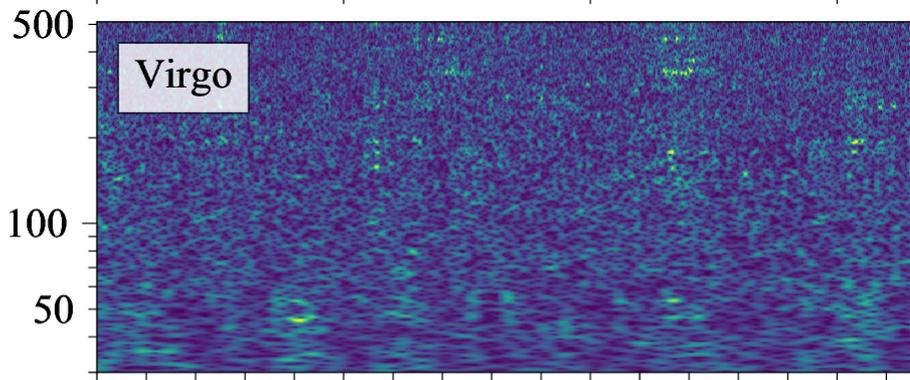
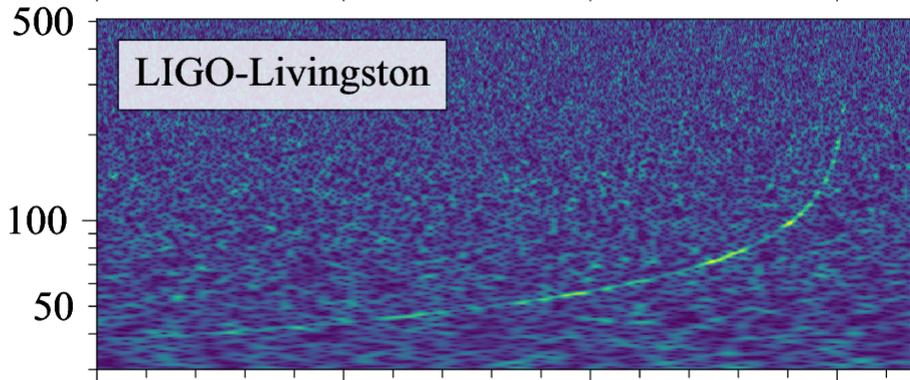
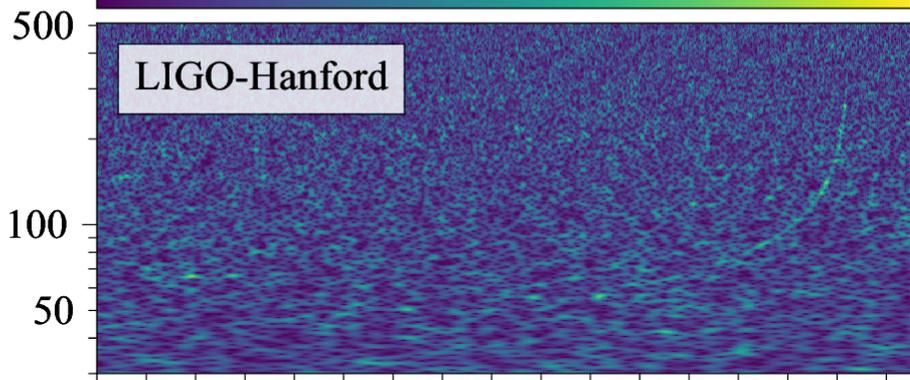
Masses



Credit: LVC

Normalized amplitude

0 2 4 6



GW170817

17 August 2017

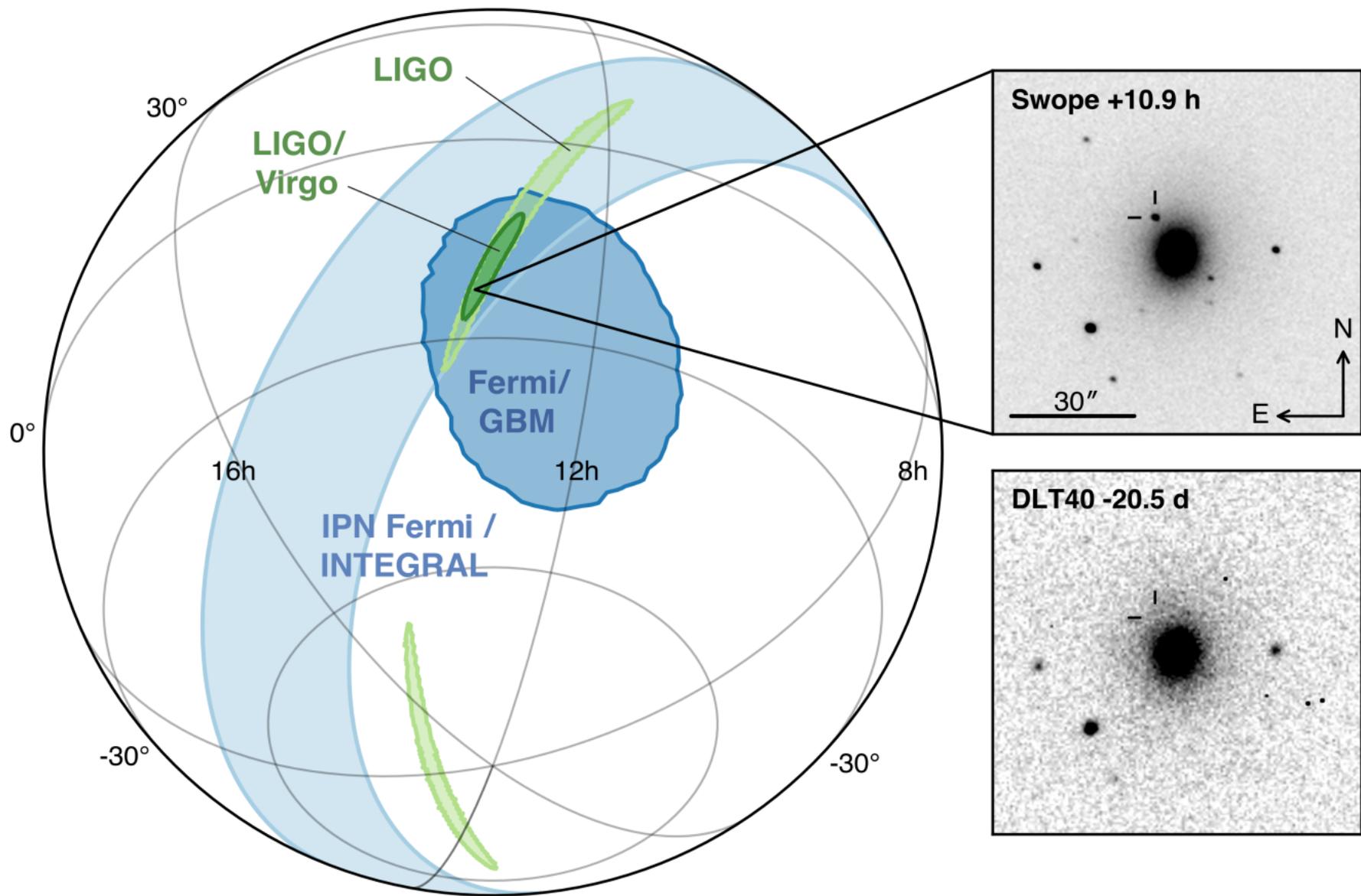
Credit: LVC

Video: LVC/NASA/L. Singer

Earth

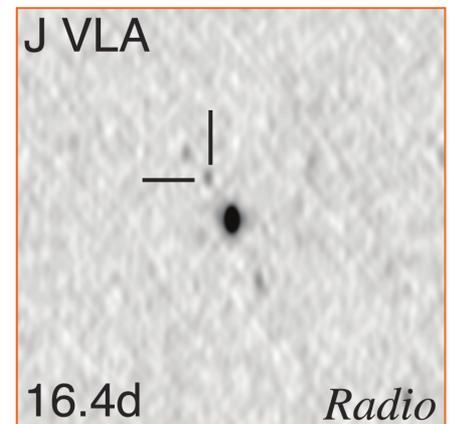
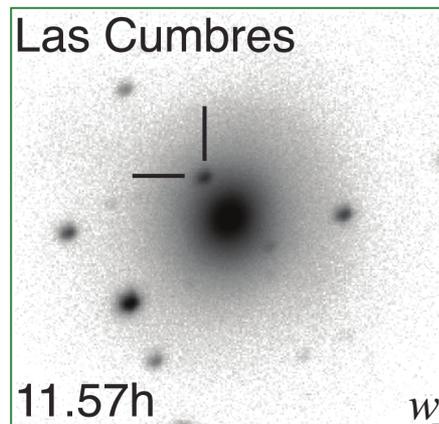
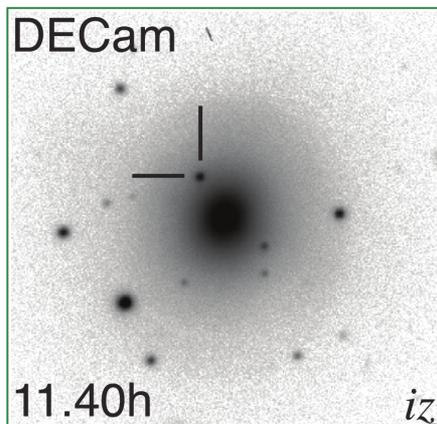
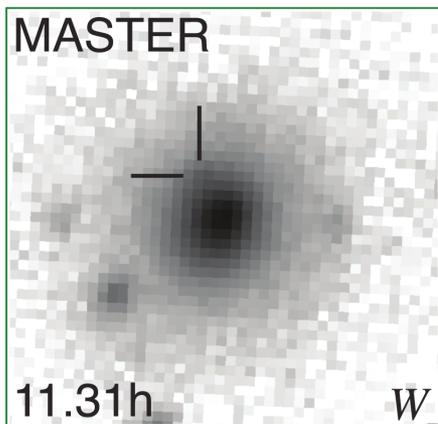
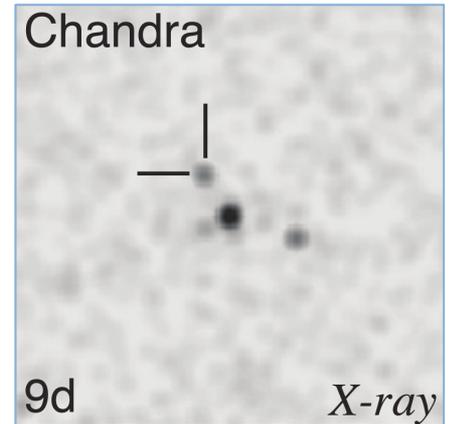
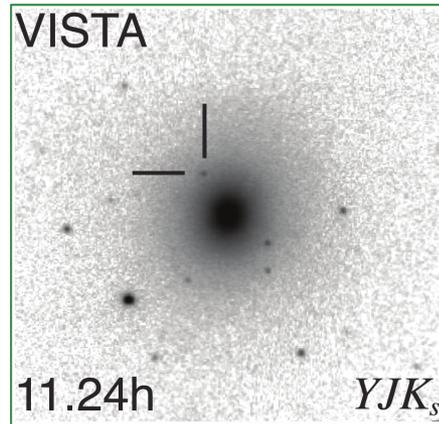
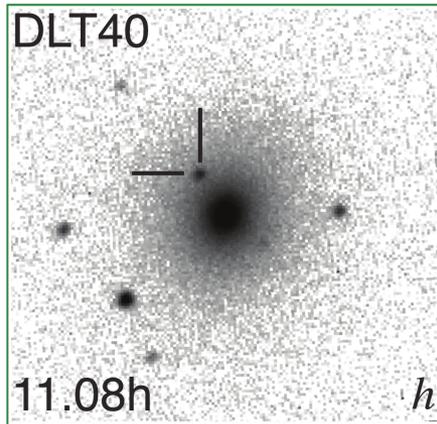
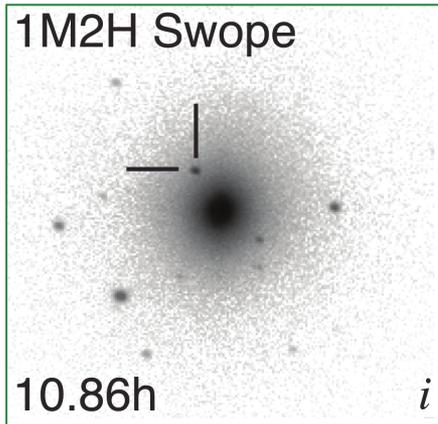
Space





Credit: LVC+

Spectrum of observations



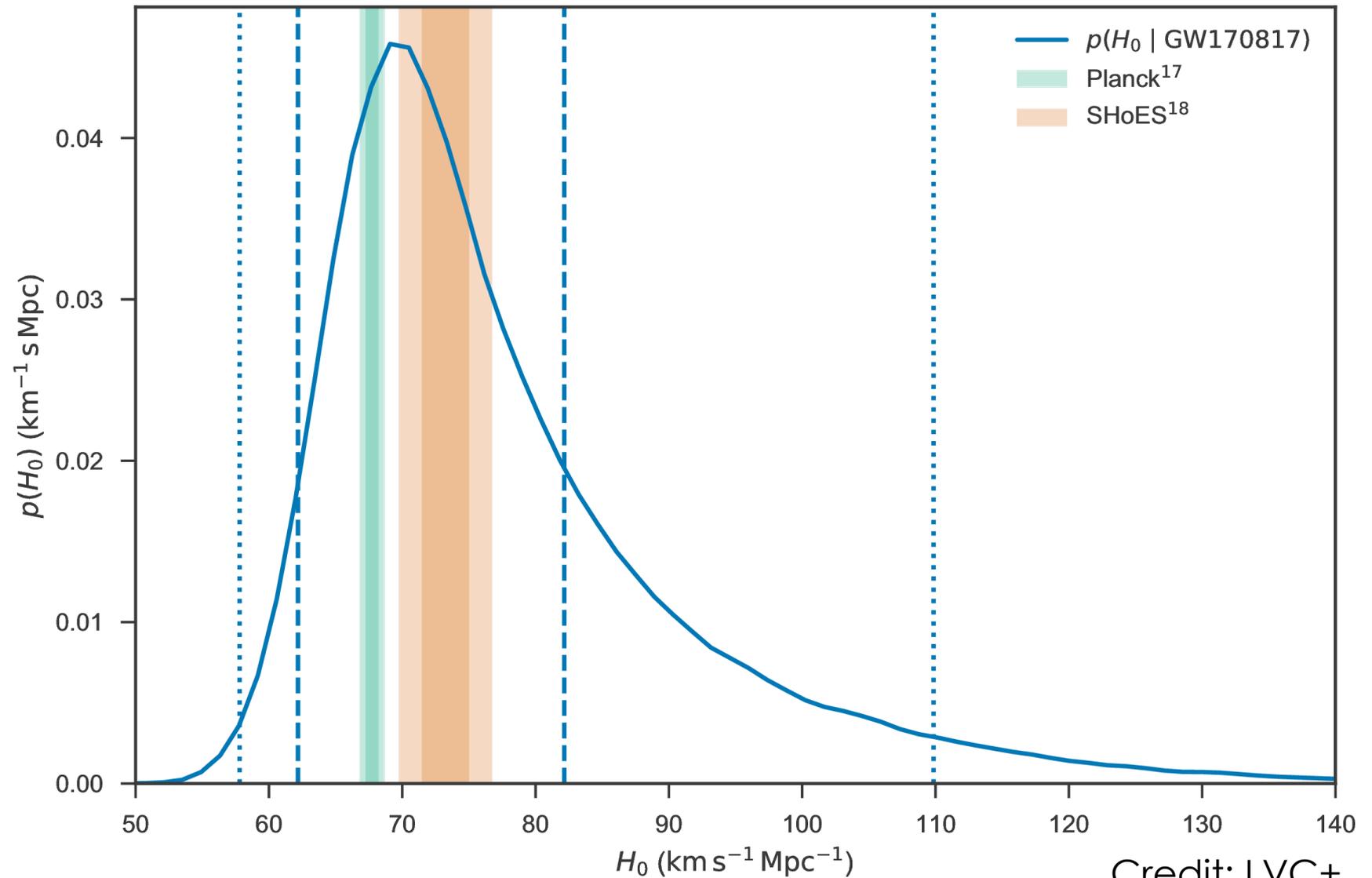
Credit: LVC+

Heavy elements



Credit: AP/F. Vergara

Hubble constant

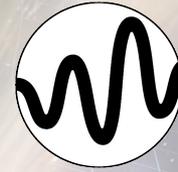


Gravitational waves are a new way to do astronomy

We have observed the first neutron star coalescence

Neutron stars are the source of short gamma-ray bursts and kilonovae

birmingham.ac.uk/gravitational-waves/
ligo.org/science/



Combined observations tell a
more complete story

Image: NSF/LIGO/Sonoma State University/A. Simonnet

The neutrino sky

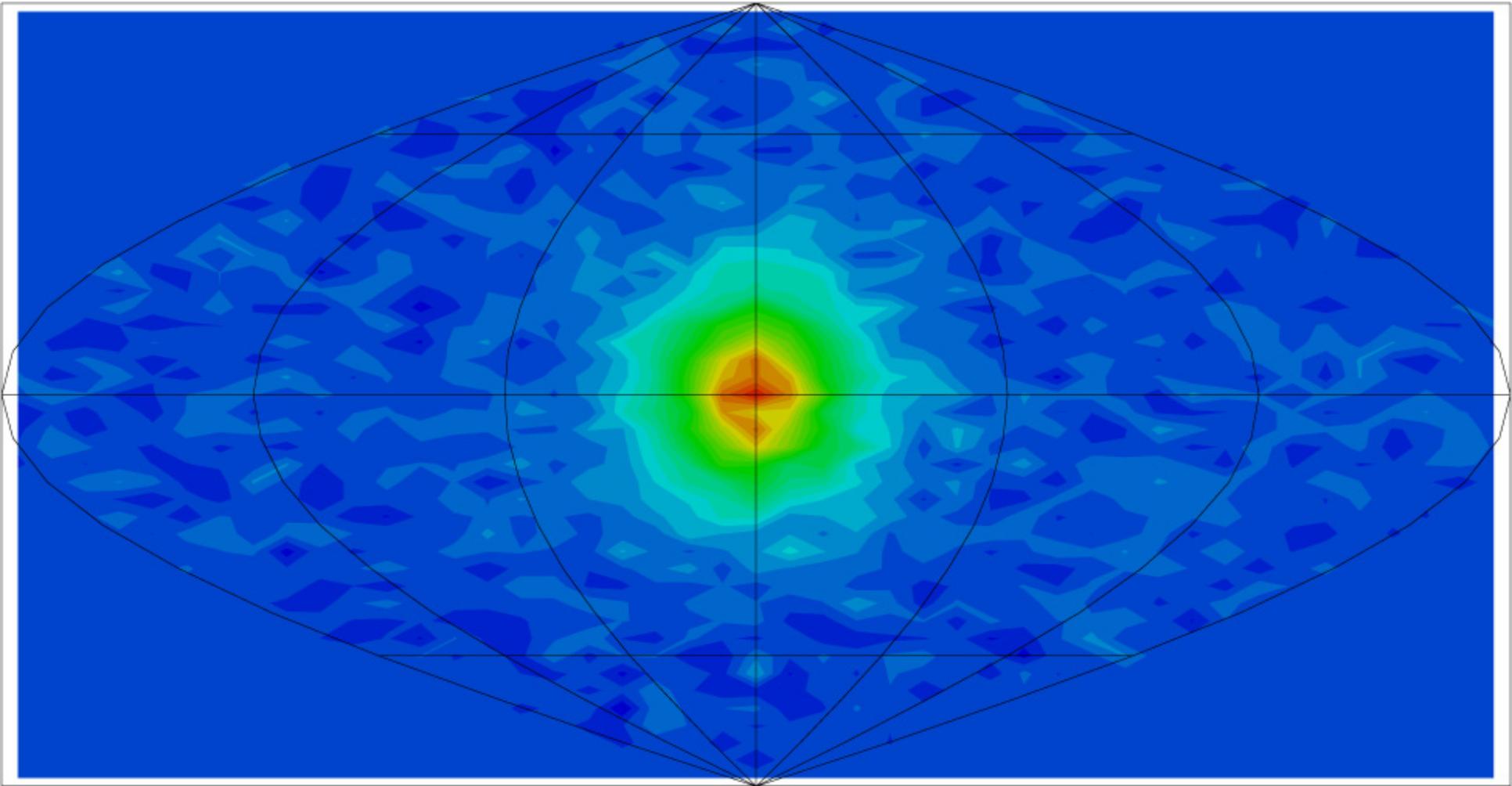
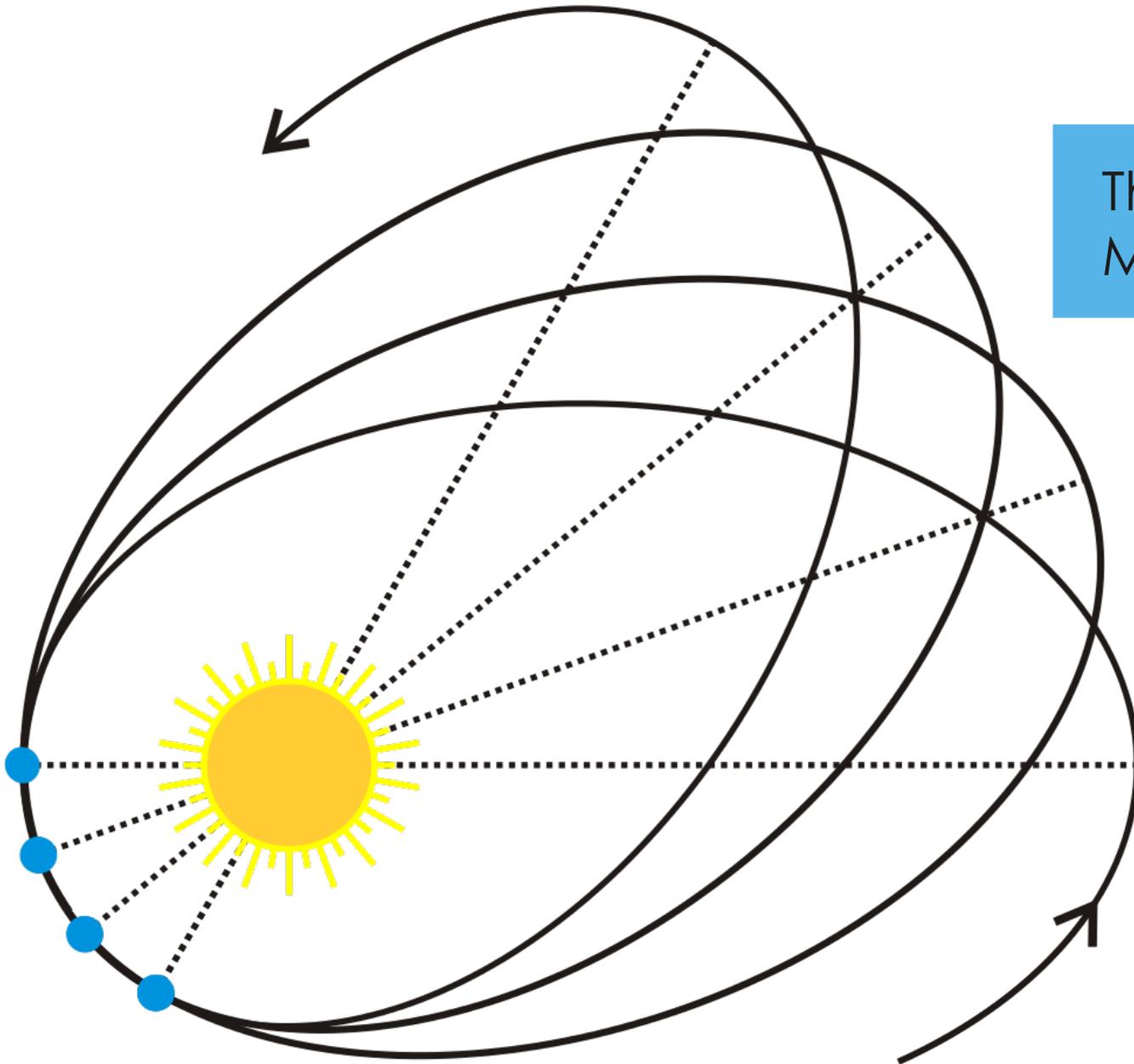


Image: Super-Kamiokande

The puzzle of
Mercury's orbit



General relativity

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Curvature

Mass

Dark energy

Cosmological constant

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Curvature

Mass

The black hole
from *Interstellar*

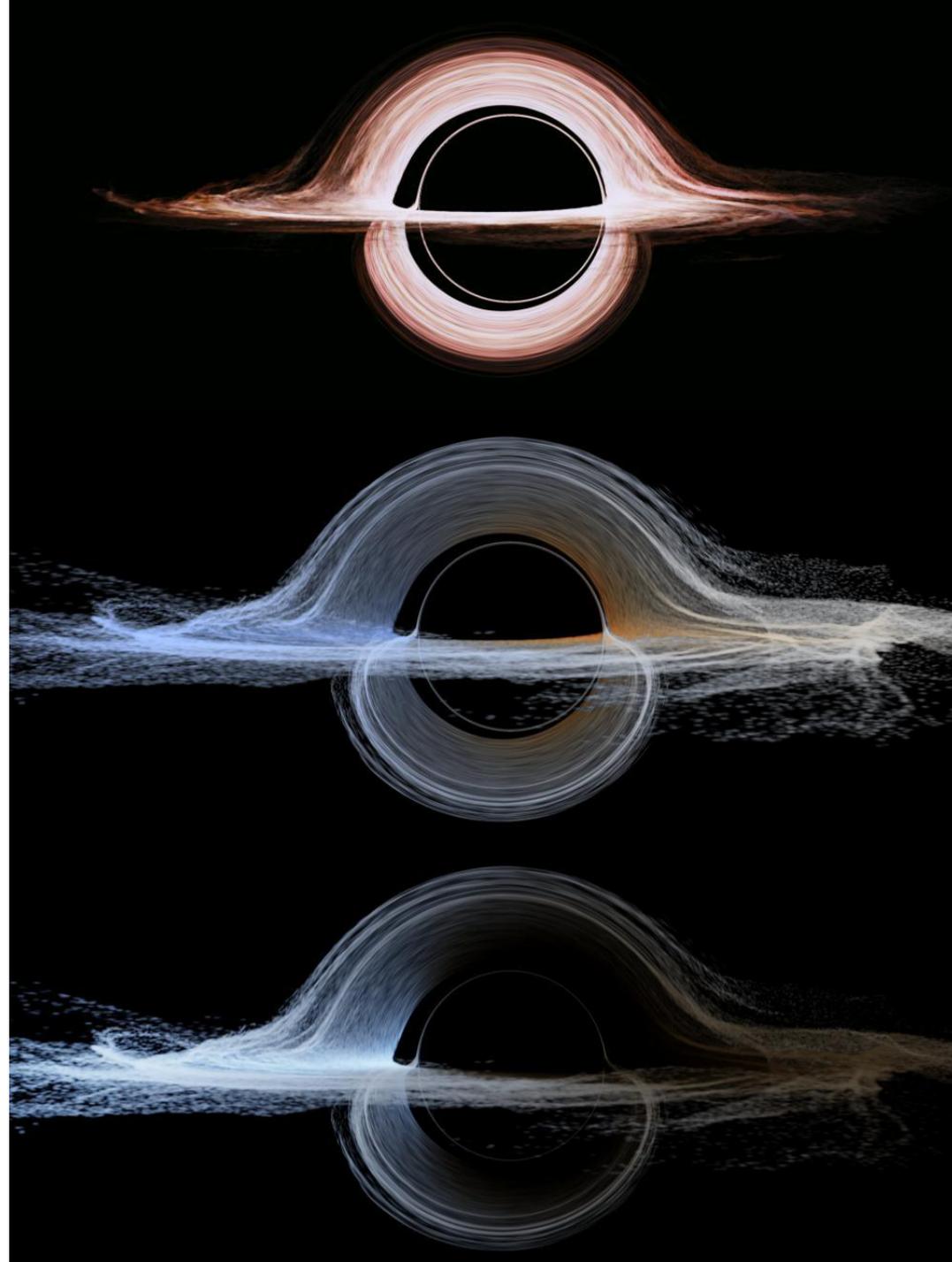


Image: James *et al.* (2015)

LIGO Scientific Collaboration

Abilene Christian University
 Albert-Einstein Institut
 Andrews University
 American University
 California Institute of Technology
 California State Univ., Fullerton
 Canadian Inst. Th. Astrophysics
 Carleton College
 College of William and Mary
 Columbia U. in the City of New York
 Embry-Riddle Aeronautical Univ.
 Eötvös Loránd University
 Georgia Institute of Technology
 Goddard Space Flight Center
 Hobart & William Smith Colleges
 ICTP-SAIFR
 IndIGO
 IAP-Russian Acad. of Sciences
 Inst. Nacional Pesquisas Espaciais
 Kenyon College
 Korean Gravitational-Wave Group
 Louisiana State University
 Montana State University
 Montclair State University
 Moscow State University
 National Tsinghua University
 Northwestern University



Penn State University
 Rochester Institute of Technology
 Sonoma State University
 Southern Univ. and A&M College
 Stanford University
 Syracuse University
 Szeged University
 Texas Tech University
 Trinity University
 Tsinghua University
 Universitat de les Illes Balears
 University of Alabama in Huntsville
 University of Brussels
 University of Chicago
 University of Florida
 University of Maryland
 University of Michigan
 University of Minnesota
 University of Mississippi
 University of Oregon
 University of Sannio
 Univ. of Texas-Rio Grande Valley
 University of Washington
 University of Wisconsin-Milwaukee
 Washington State University
 West Virginia University
 Whitman College

LIGO Laboratory: California Institute of Technology, Massachusetts Institute of Technology, LIGO Hanford Observatory, LIGO Livingston Observatory

Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):

Australian National University, Charles Sturt University, Monash University, University of Adelaide, University of Melbourne, University of Western Australia

German/British Collaboration for the Detection of Gravitational Waves (GEO600):

Cardiff University, Leibniz Universität Hannover, Albert-Einstein Institut, Hannover, King's College London, Rutherford Appleton Laboratory, University of Birmingham, University of Cambridge, University of Glasgow, University of Hamburg, University of Sheffield, University of Southampton, University of Strathclyde, University of the West of Scotland

Waves

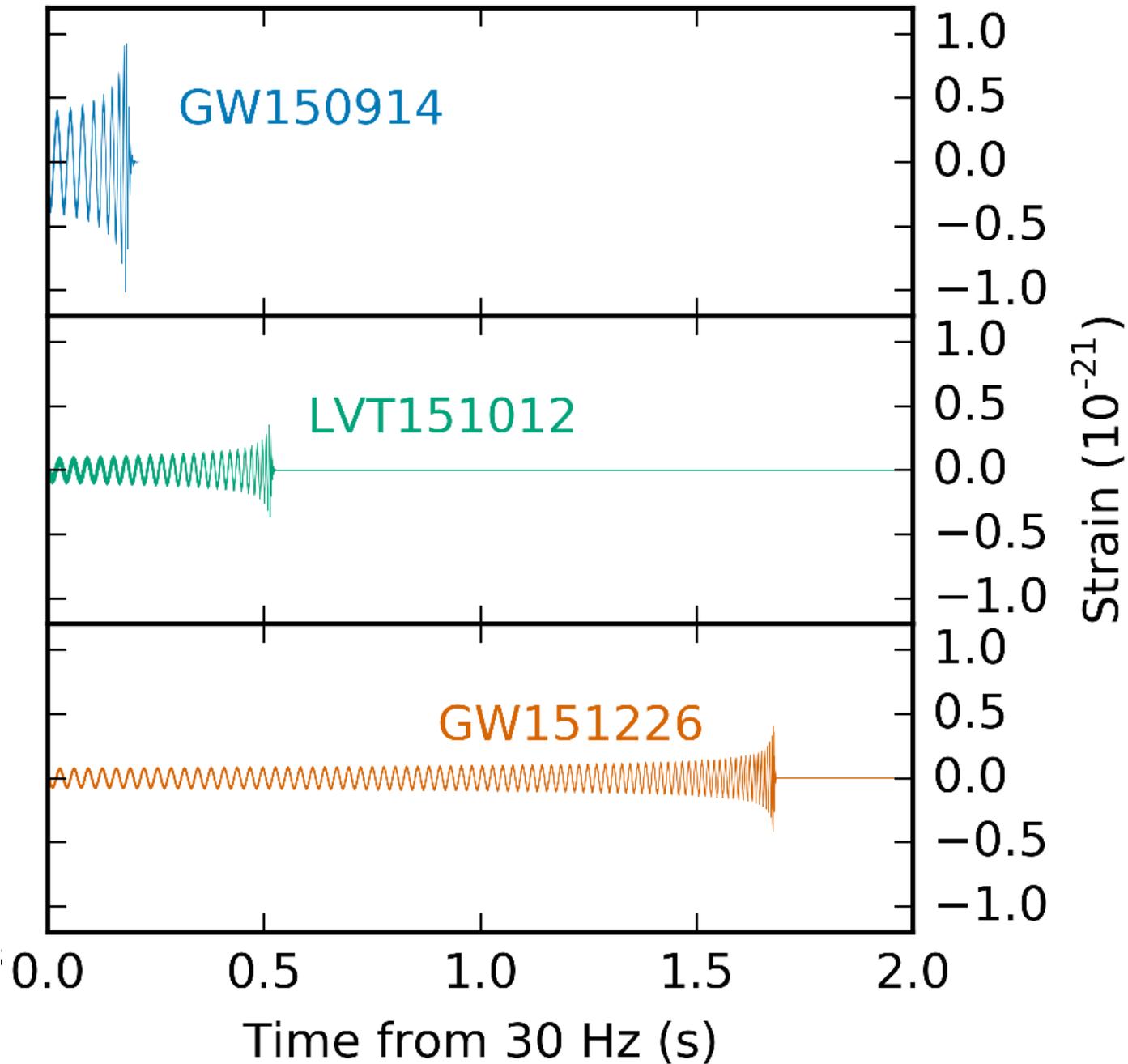




Image: ButterflyLove1

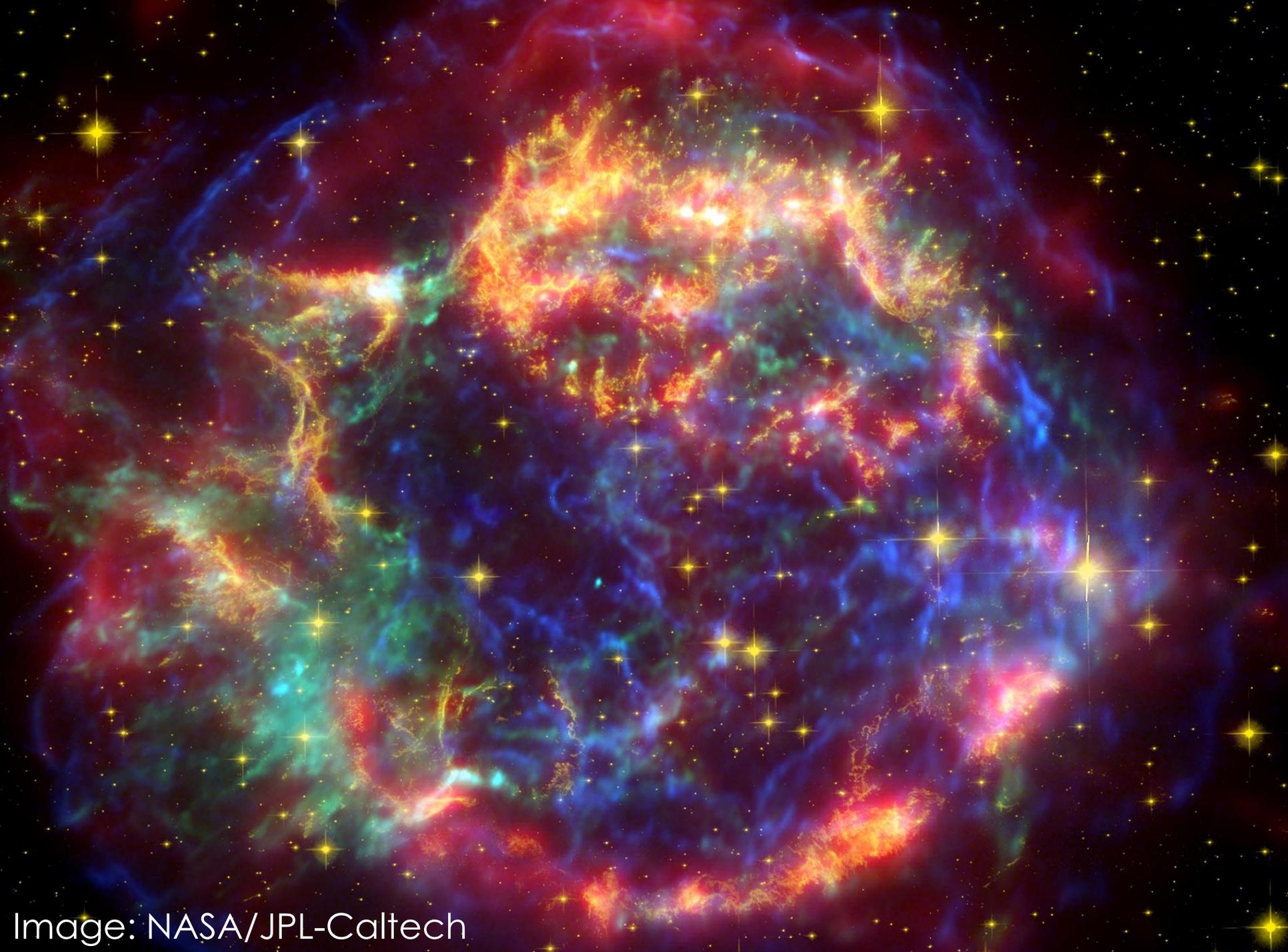
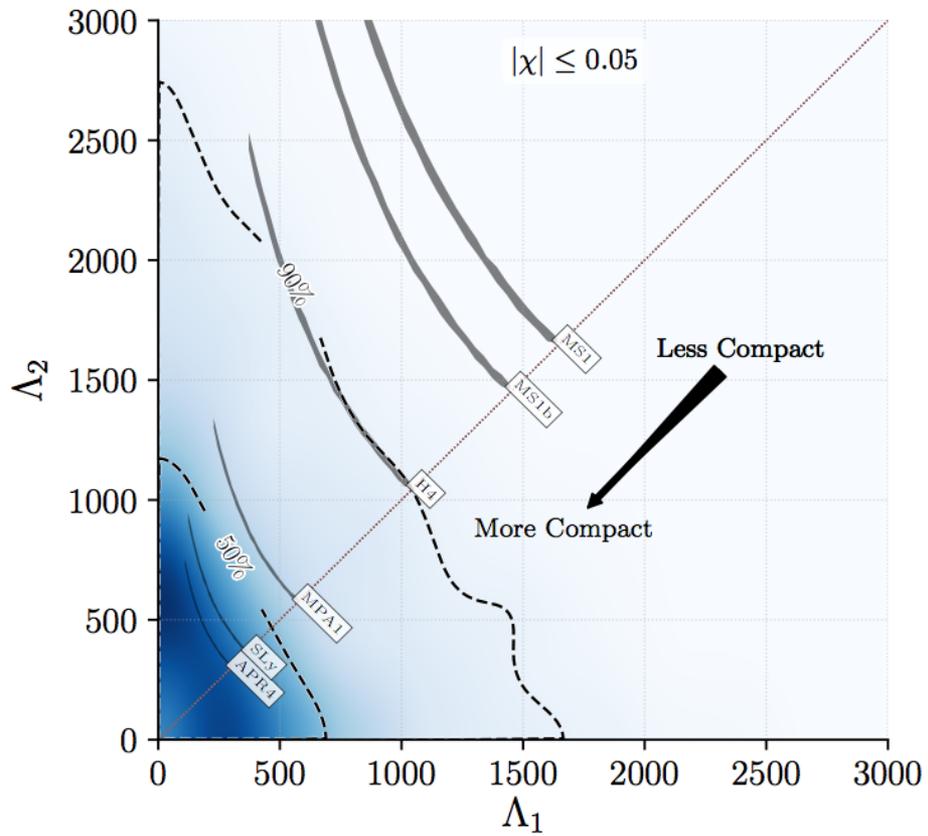
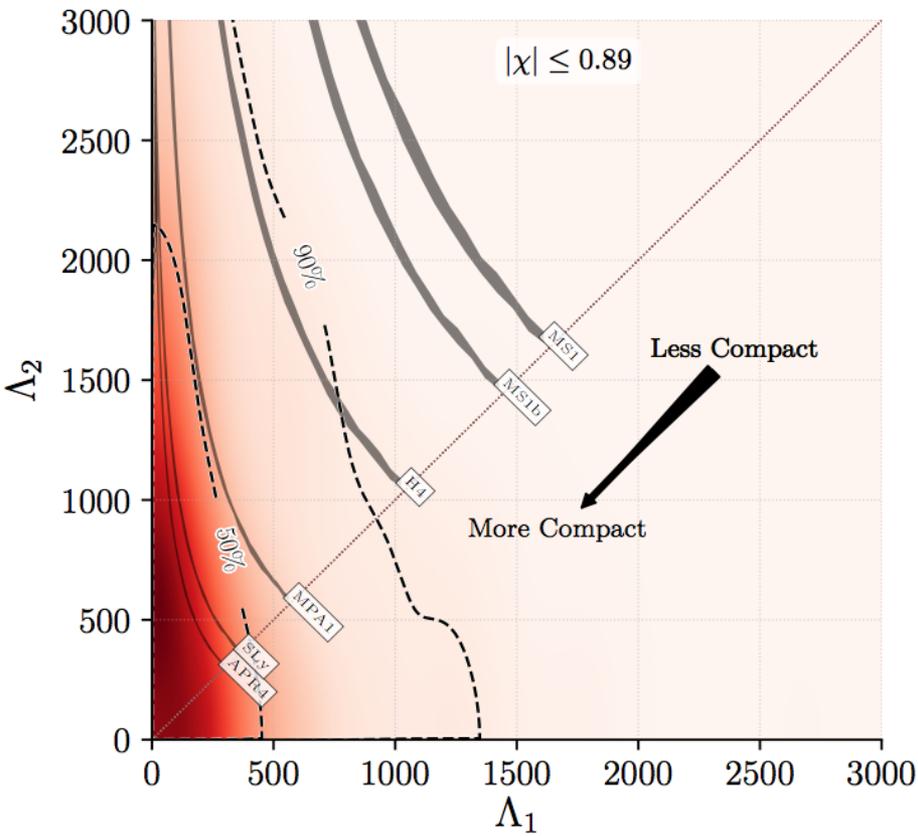


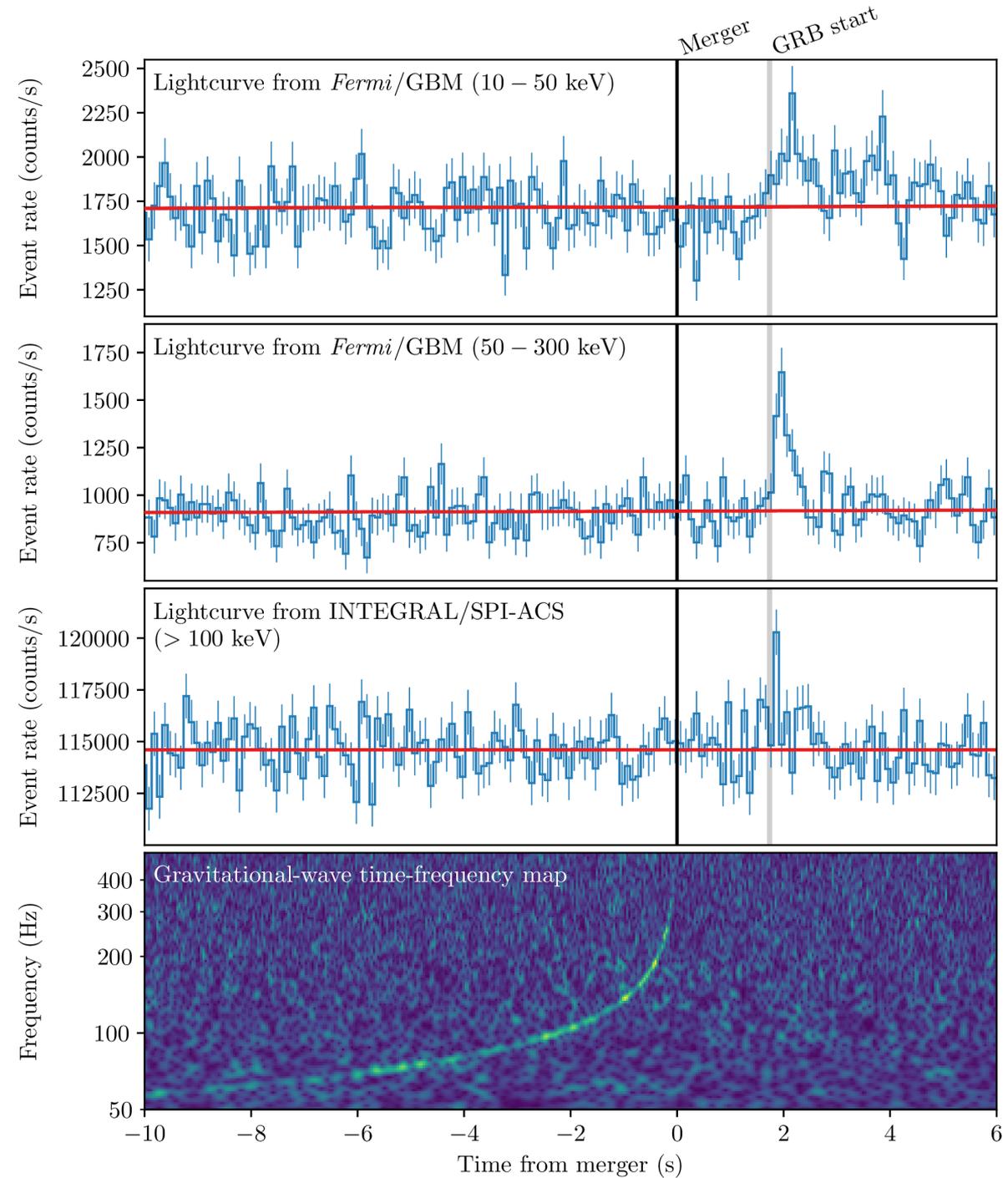
Image: NASA/JPL-Caltech

Tidal distortion



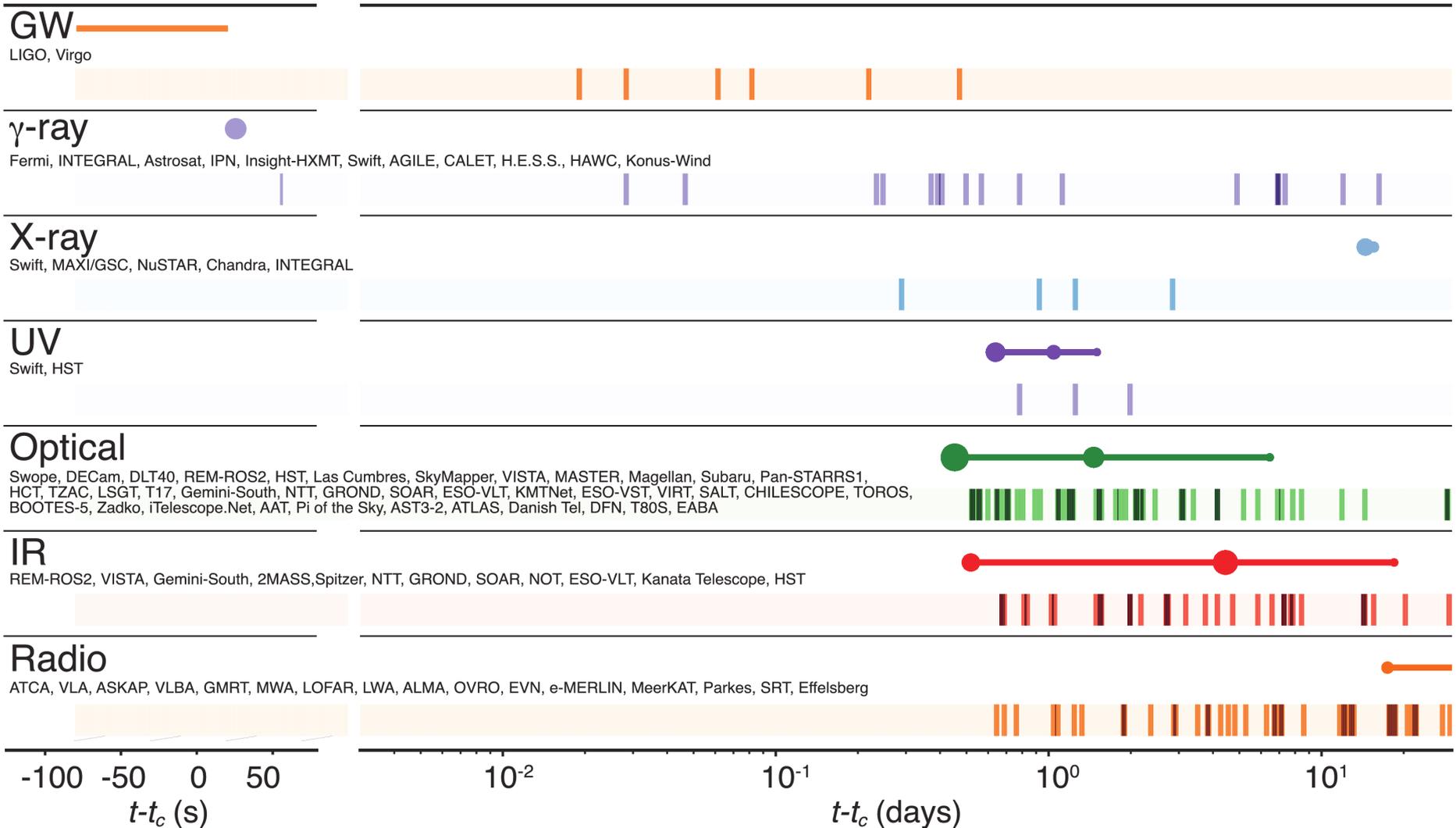
Credit: LVC

Gamma-rays



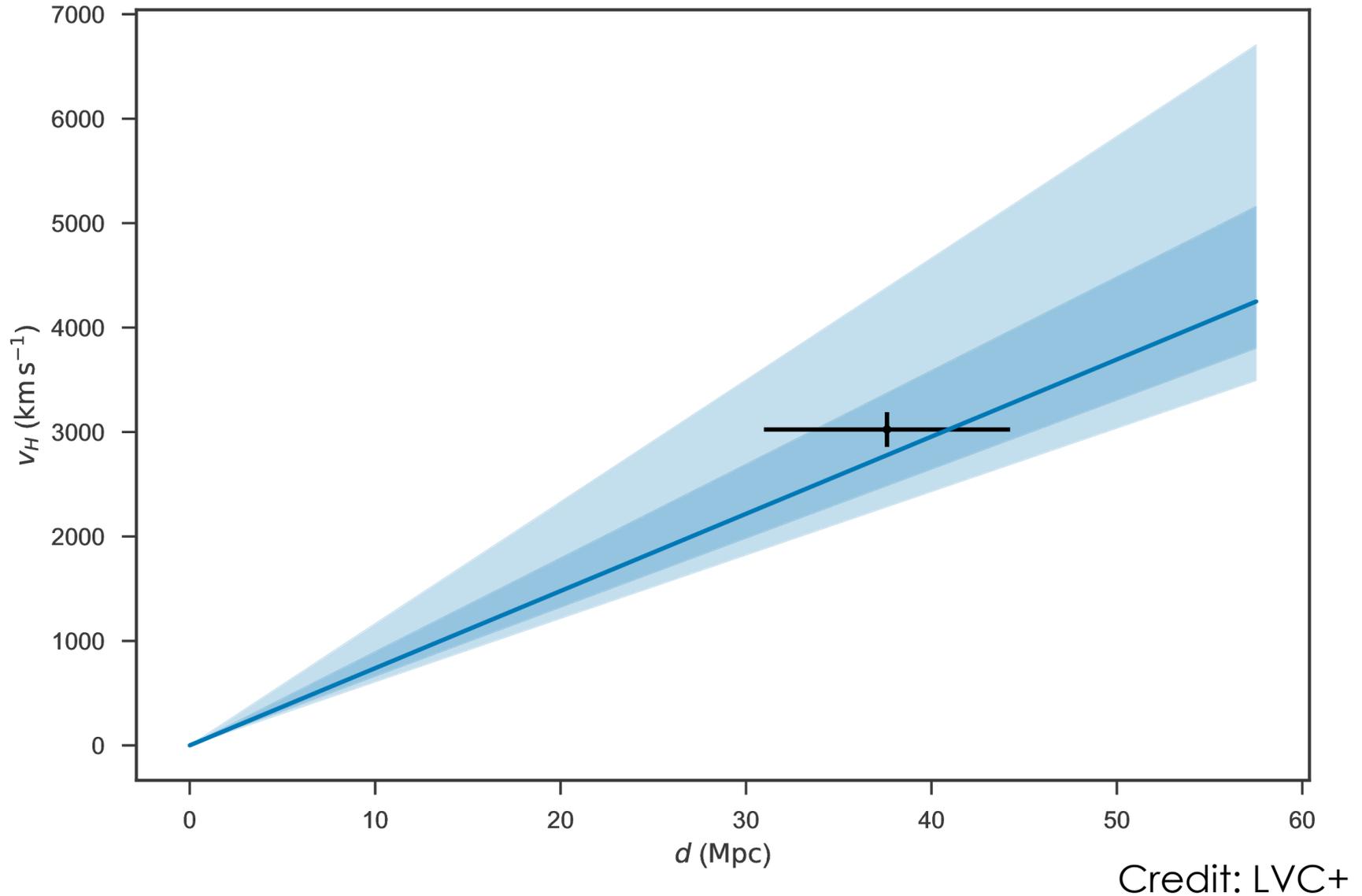
Credit: LVC/*Fermi*/INTEGRAL

Spectrum of observations



Credit: LVC+

Expansion of the Universe



Black holes and neutron stars are the remains of stars

Gravitational waves give us a new way to observe these remarkable objects

@cplberry

Image: Double Negative