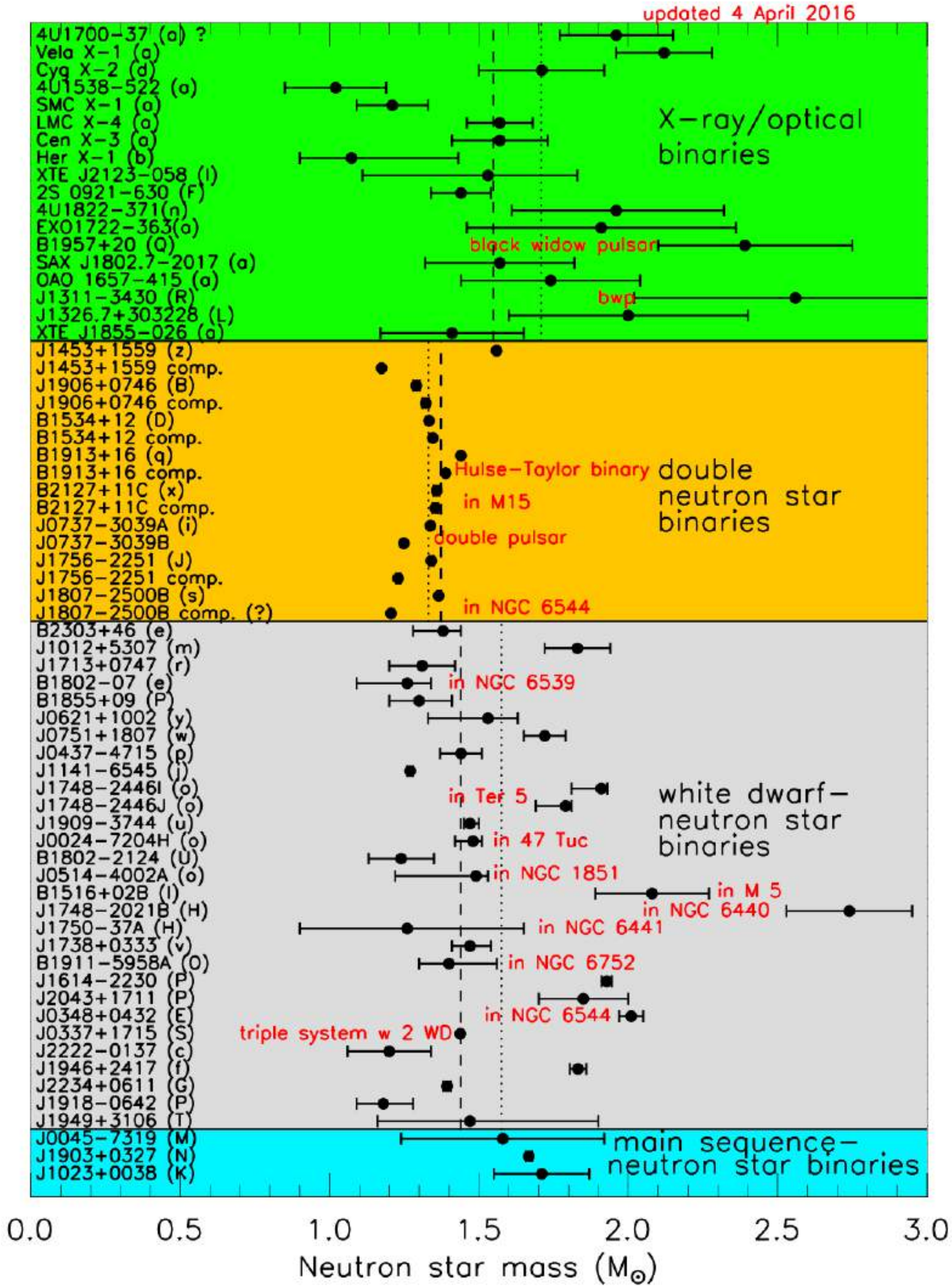
Observed neutron star masses



Credit: J. Lattimer

Two main kind of known black holes

- **Stellar**
  - 5-30 M_{sun}
  - there are ~10^8 in the Milky Way (out of ~10^{11} stars)
  - formed in core collapse of massive stars
- **Supermassive**
  - ~10^6-10^{10} M_{sun}
  - one at the center of each galaxy
  - formation mechanisms still subject of active research
  - two main models: 1) early stellar BHs that grew over time; 2) formed big in early Universe ("direct collapse")
- Intermediate mass? No solid evidence yet

Simulation of gravitational lensing by a BH moving in front of a galaxy (exaggerated for the visualization)

Black hole accretion power

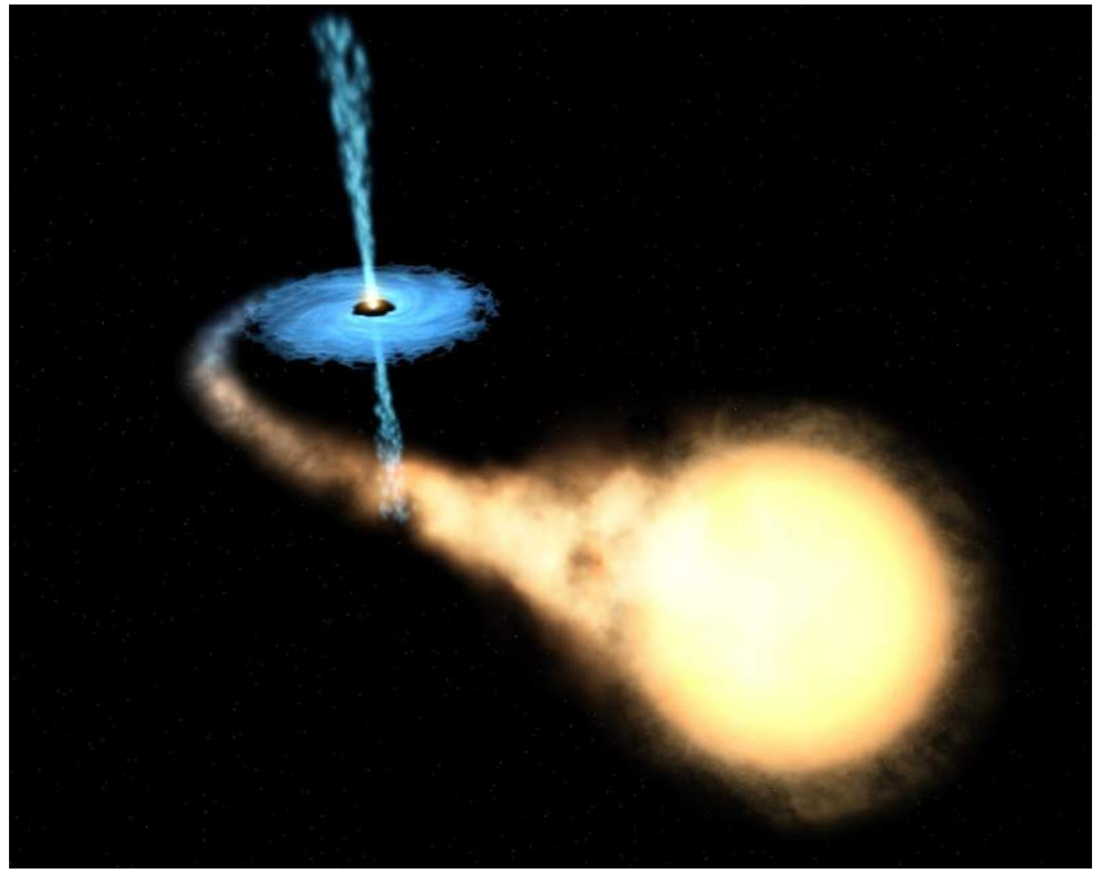
- In *X-ray binaries*, infalling gas circularizes and forms *accretion disk*
- Disk viscosity transports angular momentum, heating the disk and bringing the gas into the BH
- Radiative efficiency

$$L_{\rm acc} \sim 0.1 \dot{M} c^2$$

  exceeds H-burning efficiency

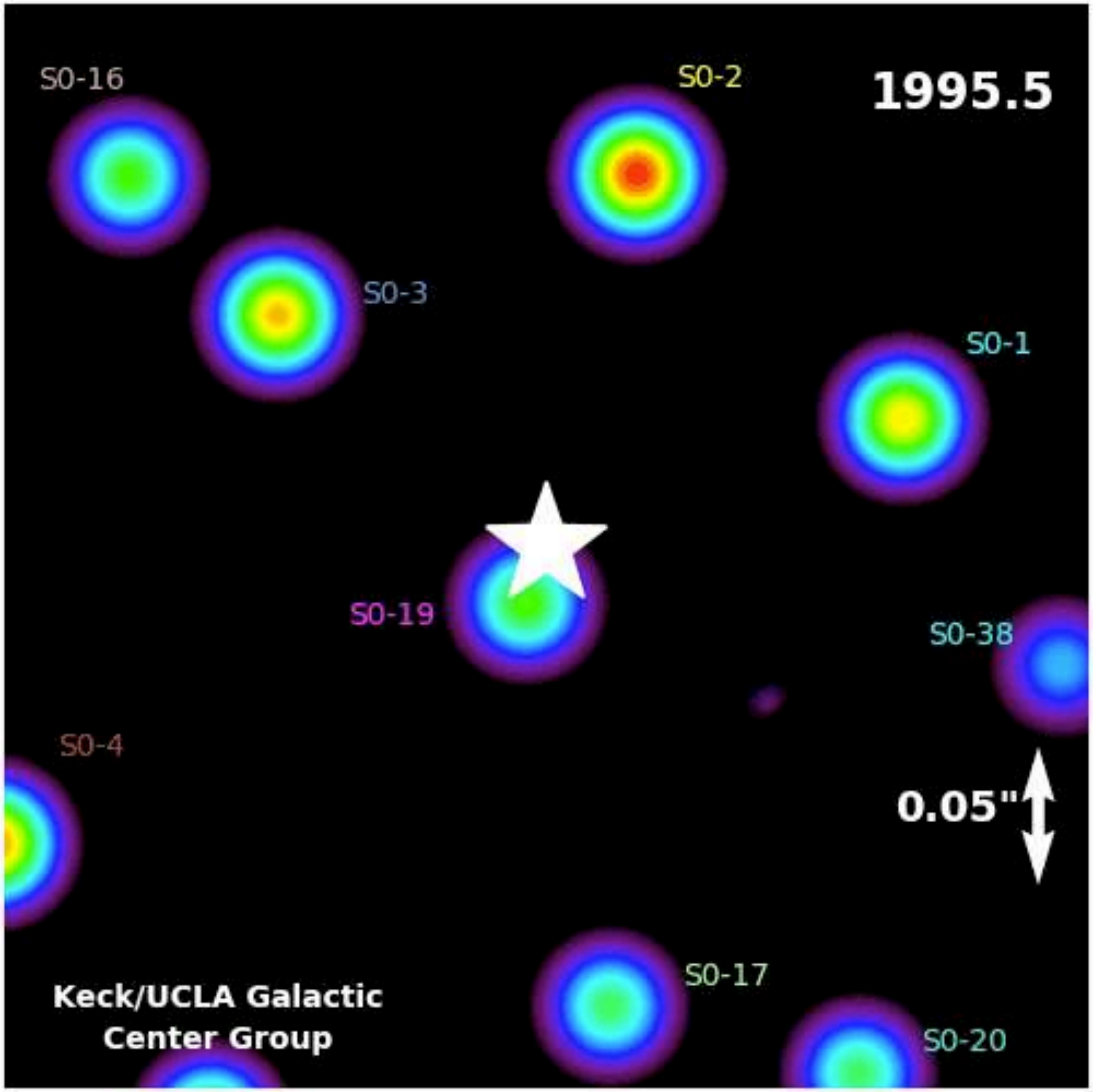
$$L_{\rm nuc} \sim 0.007 \dot{M} c^2$$

  by factor >10!



- Supermassive black holes can also accrete gas from their host galaxies

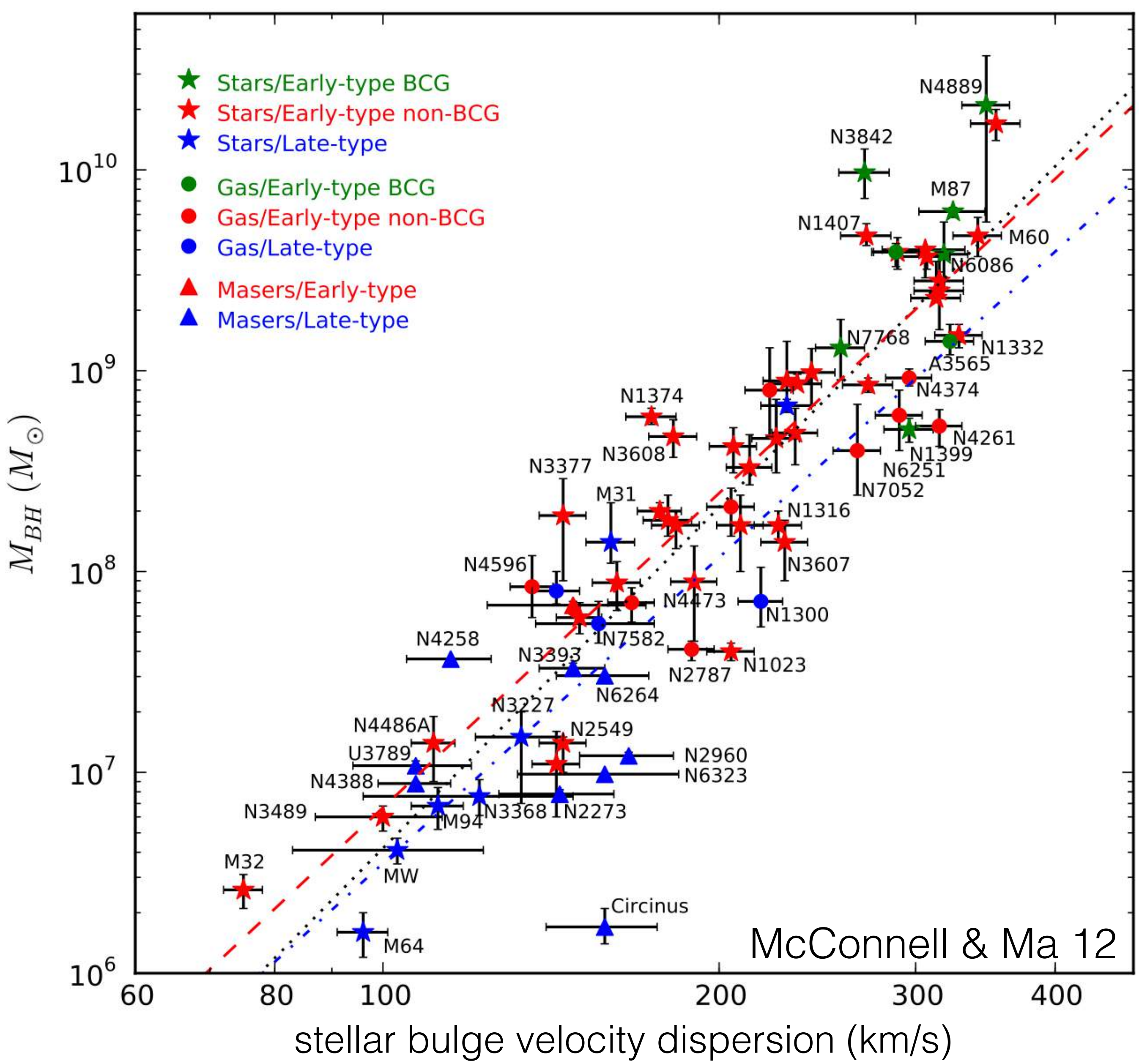
Supermassive black holes: our Galaxy



10^{-4} pc

- in MW (Sgr A*), M_{BH}=4×10^6 M_{sun}, measured using individual stellar orbits
- all (massive) galaxies appear to have one

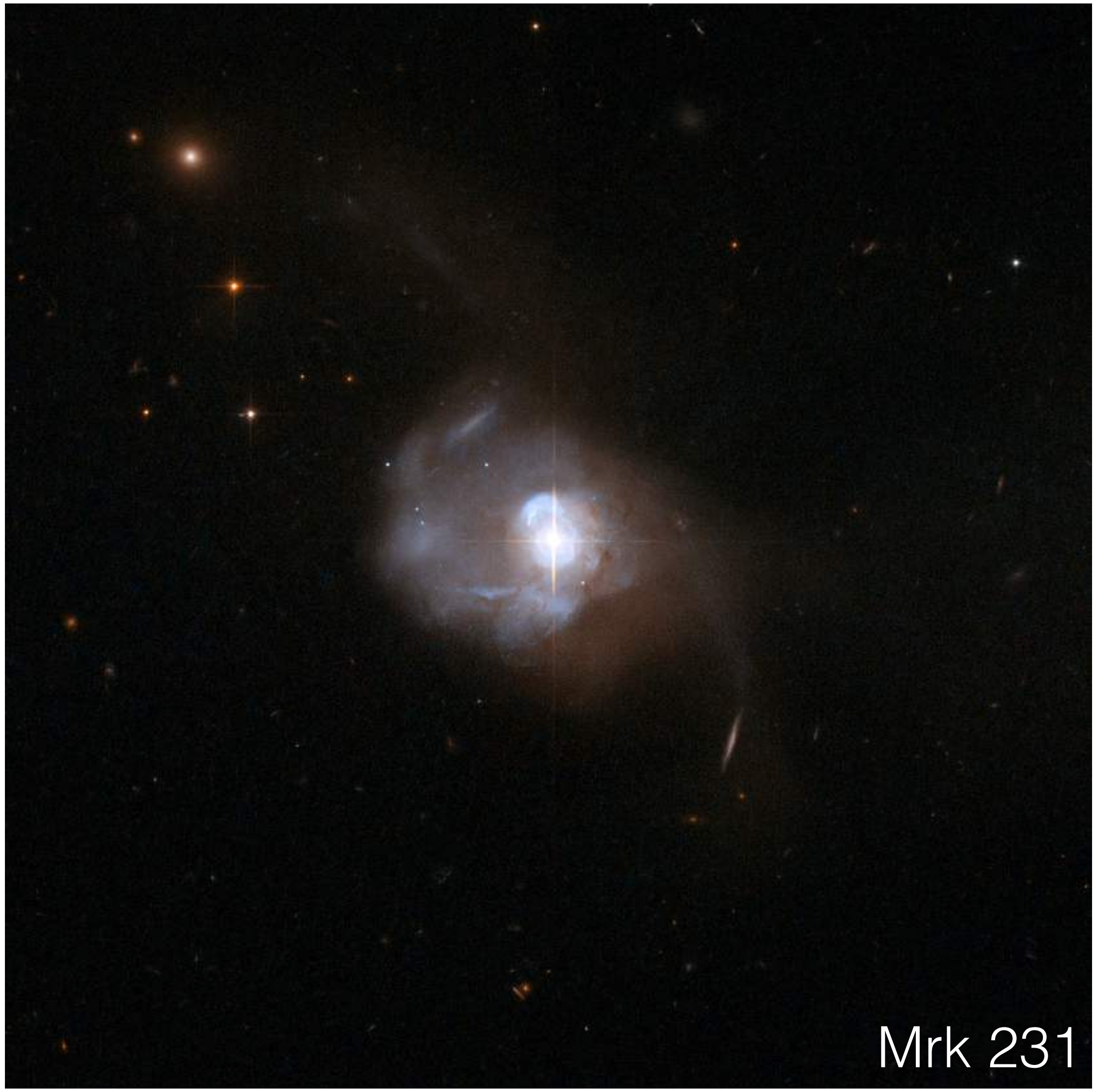
M-σ: black hole mass - stellar bulge velocity dispersion



$M_{\rm BH}$-$M_{\rm bulge}$ relation:

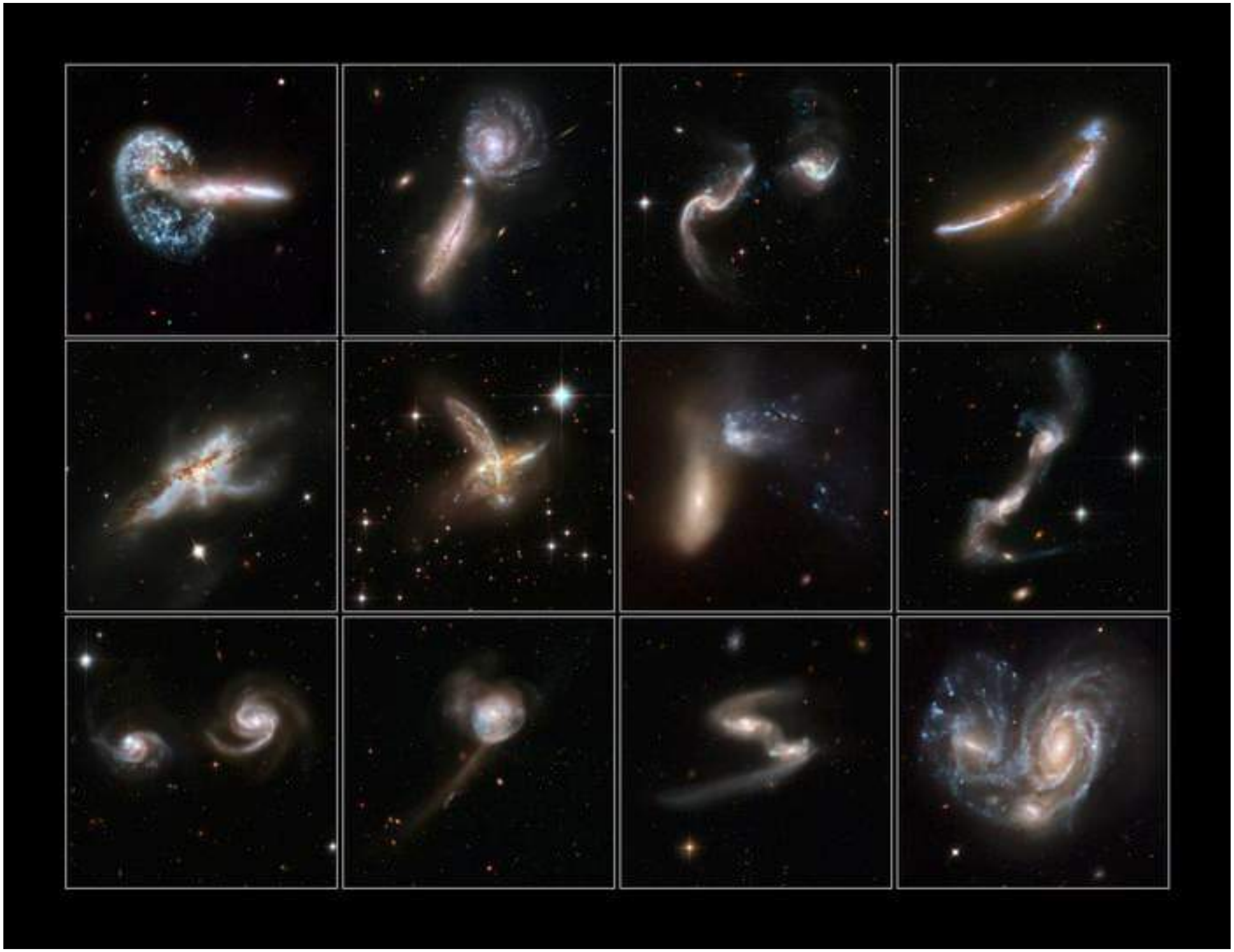
$M_{\rm BH} \sim 0.002\ M_{\rm bulge}$

Active galactic nuclei



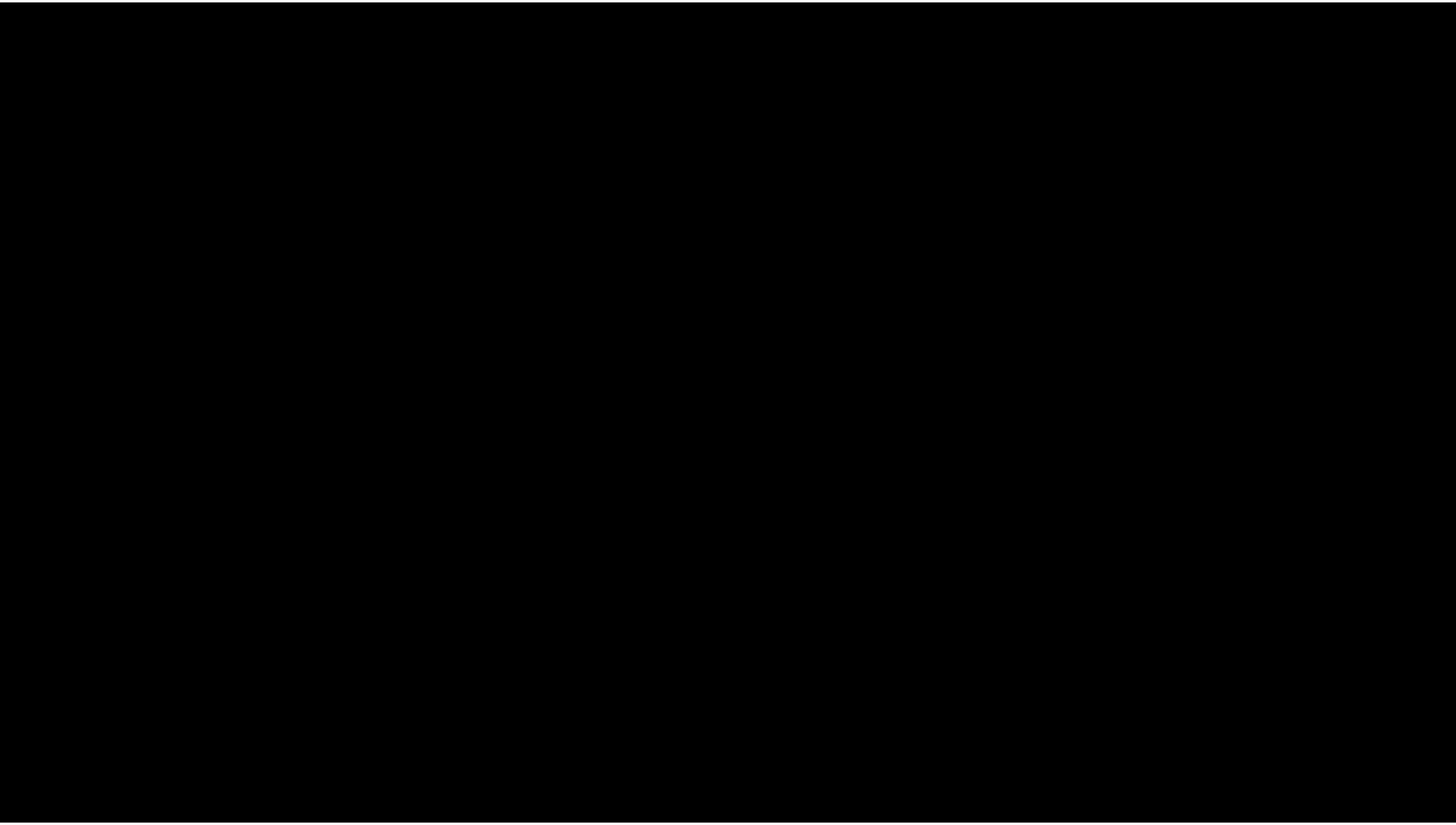
- accreting nuclear black holes visible as AGN
- the most luminous AGN are called quasars (can outshine entire host galaxy)
- in local Universe, quasars are associated with galaxy mergers

Galaxy collisions are relatively common: interacting galaxies observed by HST



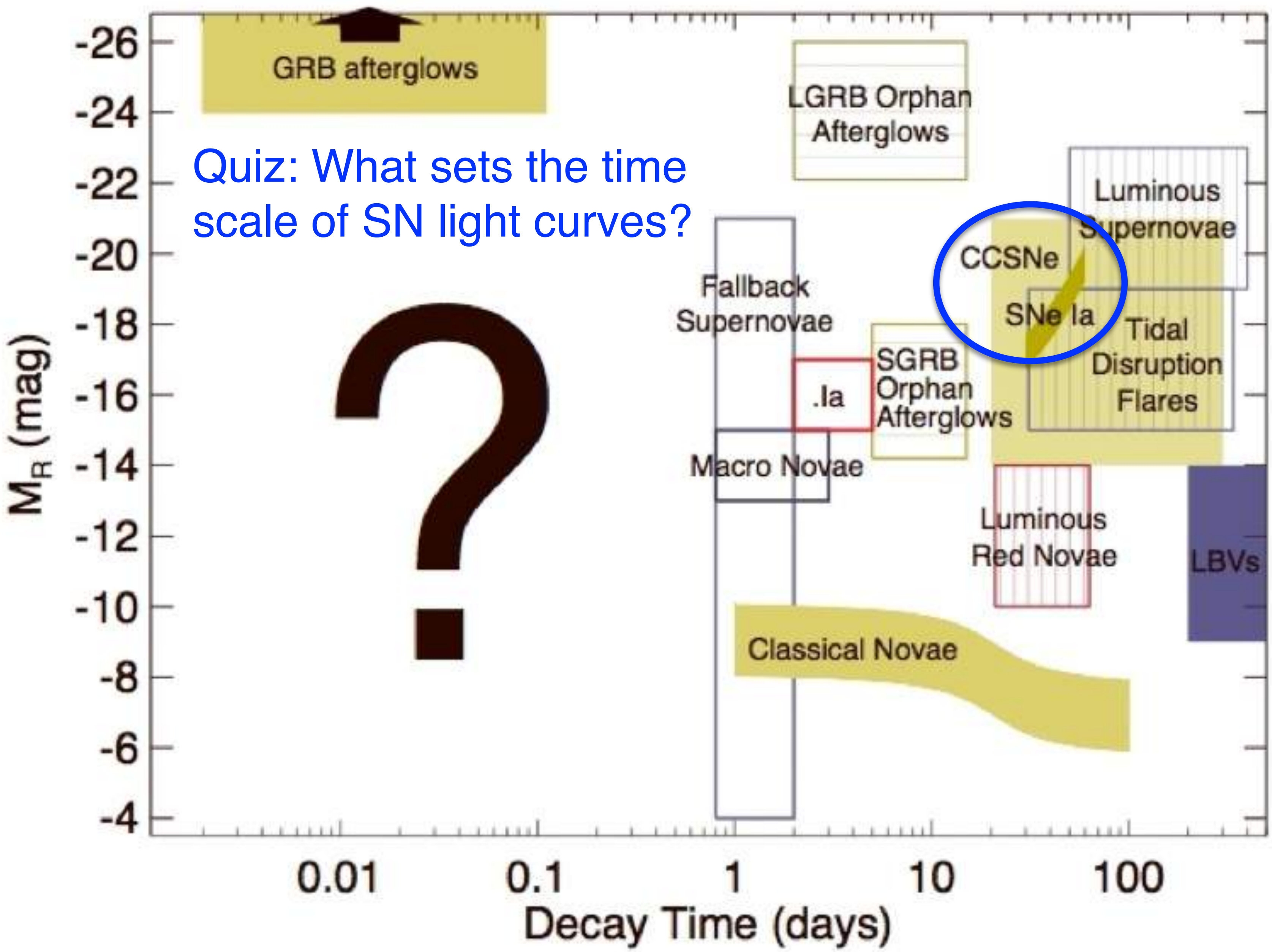
- galaxies collide with similar-mass galaxies several times during their evolution
- after galaxies collide, their supermassive black holes likely eventually also merge

Matching peculiar galaxies with stages of mergers in modern simulation



Toggling between galaxy merger simulation and HST images

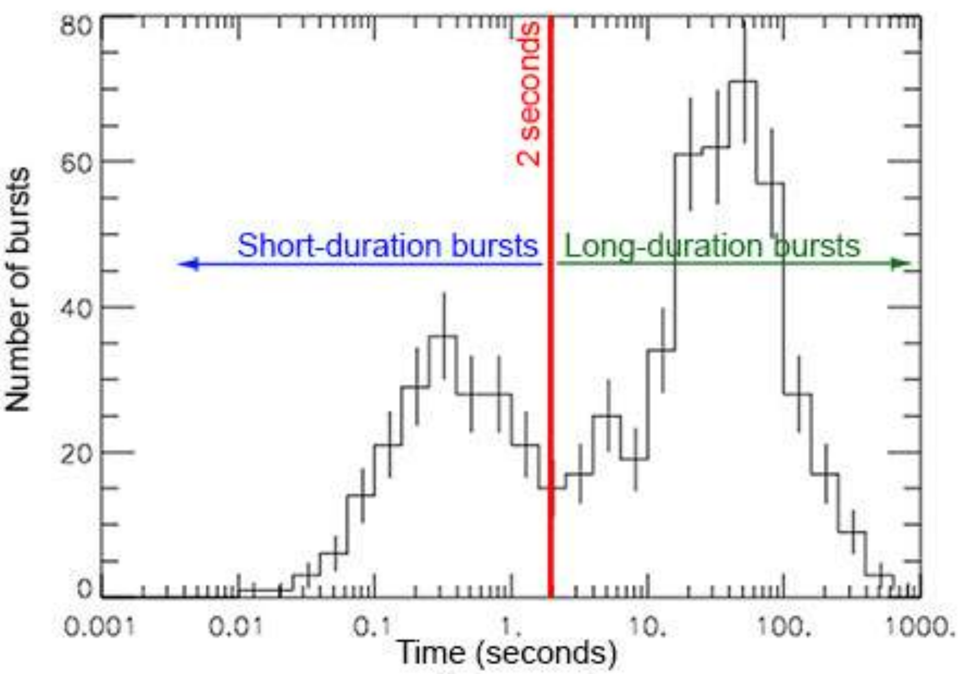
Time-domain (transient) astrophysics



Discovery space for cosmic transients (from the LSST Science Book)

γ-ray bursts

- Energetic, short bursts of γ-ray emission
- Discovered in 1967 by Vela military satellites designed to monitor nuclear explosions
- Two populations:
  - long (>2 s): powered by BH formation in the collapse of certain massive stars?
  - short (<2 s): powered by NS-NS mergers?



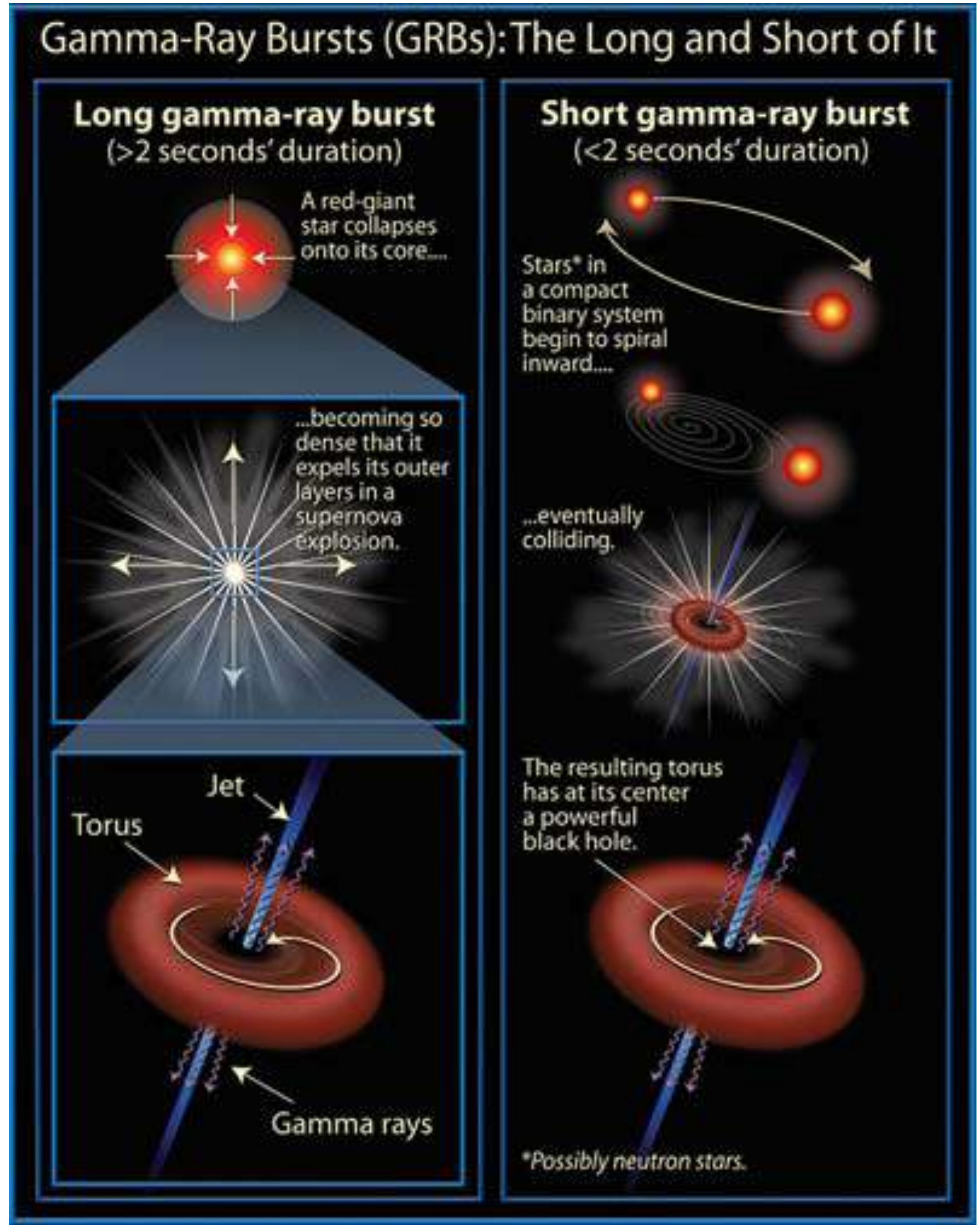
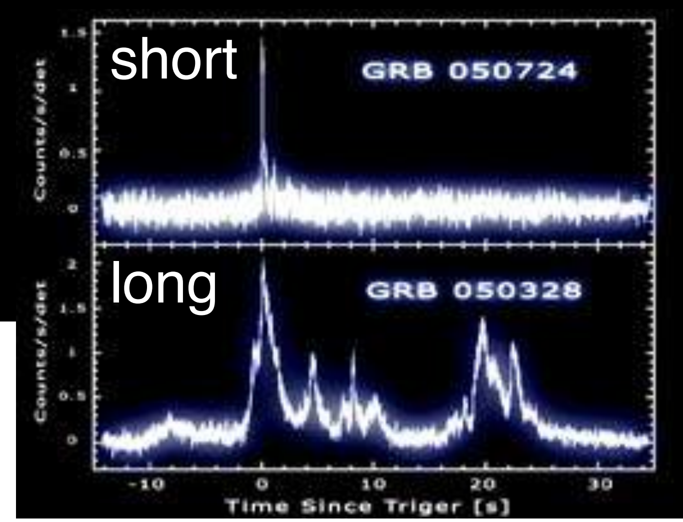


Figure credit: http://www.daviddarling.info/encyclopedia/G/gamma-ray_burst.html

γ-ray bursts, as detected by Swift satellite 2004-2010



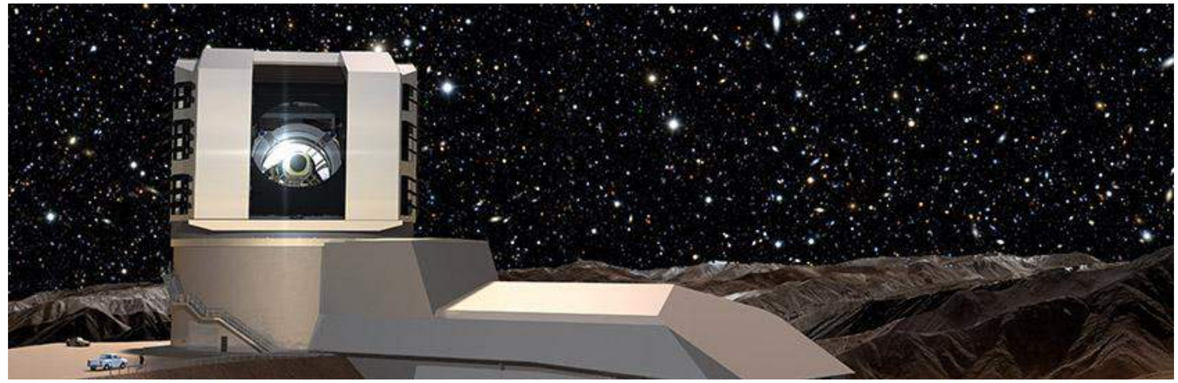
Animation credit: NASA Goddard Space Flight Center

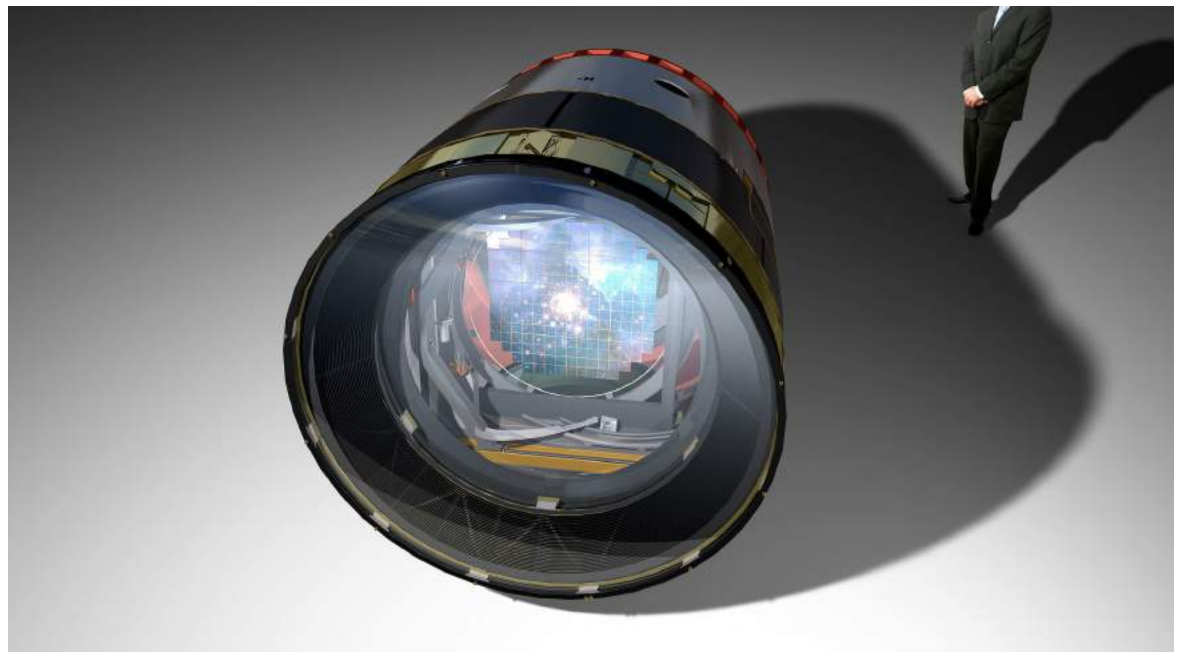
LSST

Large Synoptic Survey Telescope

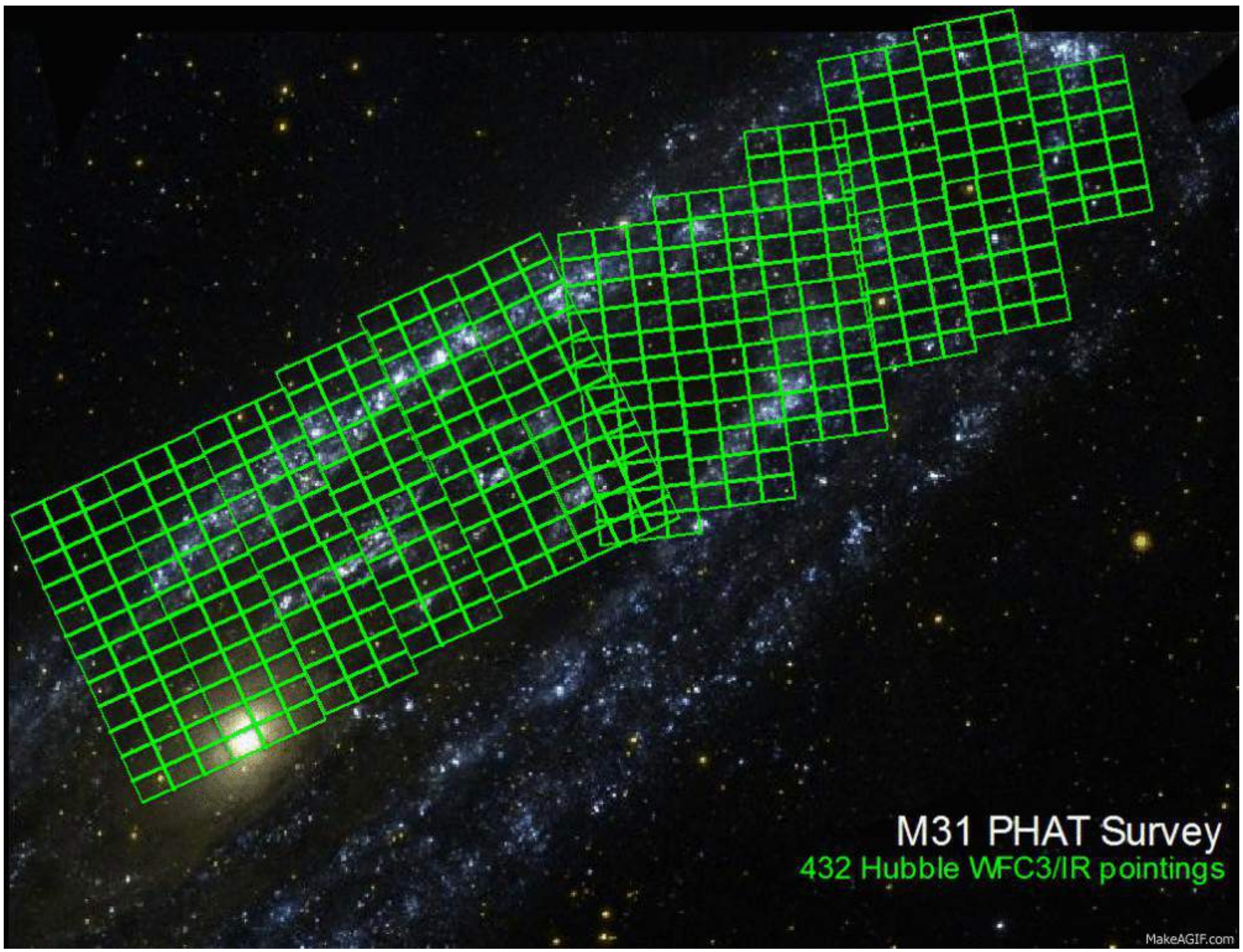
- 8.4-m ground-based optical telescope in Cerro Pachón, Chile
- 3.5 degree diameter field of view (very wide — Moon is 0.5 degree across)
- 3.2 gigapixel camera (largest digital camera ever constructed)
- will record the entire visible sky twice each week
- over period of 10 years, 1,000 images of the entire sky
- 15 Tb of data per night
- unprecedented data stream will require advances in automated data processing using supercomputers to identify the most interesting signals

Under construction. First-light anticipated in 2019.



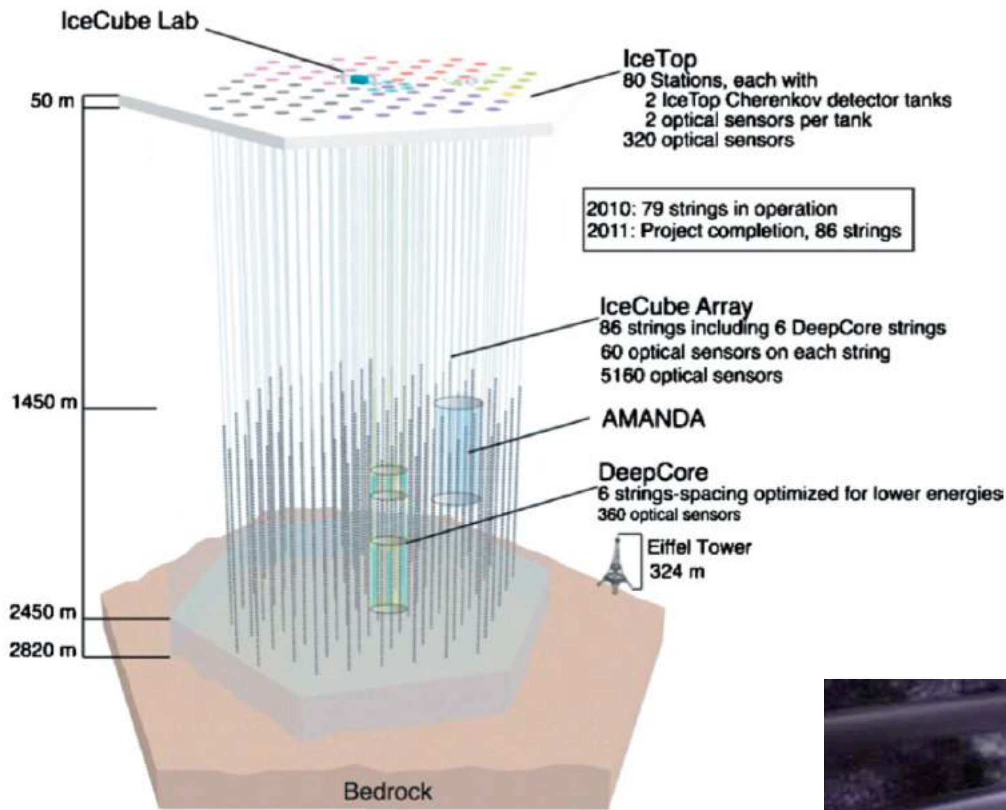


Planned for mid-2020s launch by NASA



- 2.4-m space telescope (same diameter as Hubble) with much larger field of view
- 288 megapixel near-infrared camera
- will cover in 2 pointings what required >400 pointings with the Hubble Space Telescope (at similar resolution)
- one of the key goals is to discover a large number of Type Ia SNe to map out the expansion history of the Universe with greater precision
- also exoplanets (microlensing and direct imaging)

Multi-messenger astrophysics: probing the Universe beyond the electromagnetic spectrum



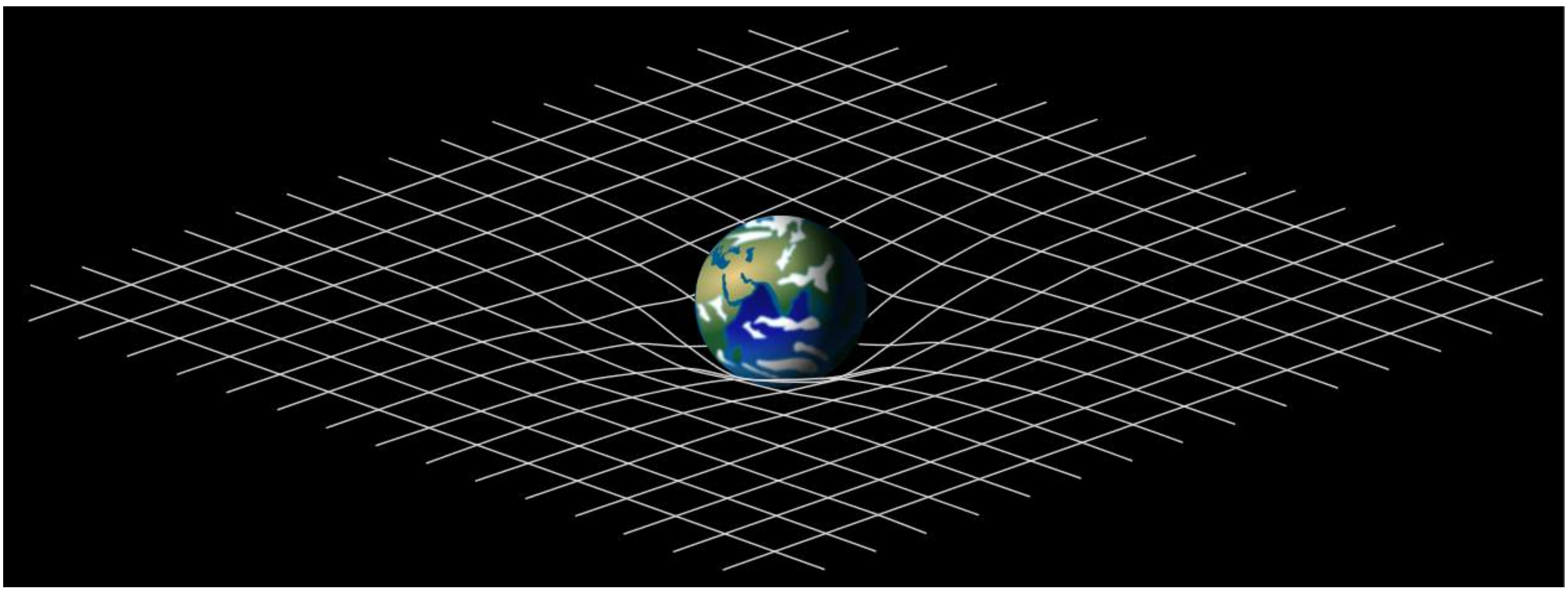
LIGO gravitational wave detector

GWs from inspiral of compact object binary (e.g., NS-NS)

- neutrinos
- gravitational waves
- sources tend to be energetic transients

Spacetime coordinates vs. physical quantities

- *Coordinates* are labels used to identify points in 4D spacetime, e.g. (t, x, y, z)
- Coordinates can be chosen arbitrarily (e.g., Cartesian, spherical, cylindrical, … for spatial part)
- Need a "tool" / "function" to convert coordinates into ***physical quantities*** that can be measured by clocks and meter sticks, ***proper distance*** and ***proper time***
- This function is called the ***metric*** and defines the ***curvature*** of spacetime



Spacetime metric

- Metric is a 4×4 matrix $g_{\mu\nu}$ defined such that spacetime *line element*

$$(ds)^2 = \sum_{\mu,\nu} g_{\mu\nu} dx_\mu dx_\nu$$

- E.g., *flat spacetime* — *Minkowski metric* of special relativity:

$$(ds)^2 = (cdt)^2 - (dx)^2 - (dy)^2 - (dz)^2$$
$$g_{00} = 1, \;\; g_{11} = -1, \;\; g_{22} = -1, \;\; g_{33} = -1$$

if using Cartesian coords for spatial

$$(ds)^2 = (cdt)^2 - (dr)^2 - (rd\theta)^2 - (r \sin\theta d\phi)^2$$
$$g_{00} = 1, \;\; g_{11} = -1, \;\; g_{22} = -r^2, \;\; g_{33} = -r^2 \sin^2\theta$$

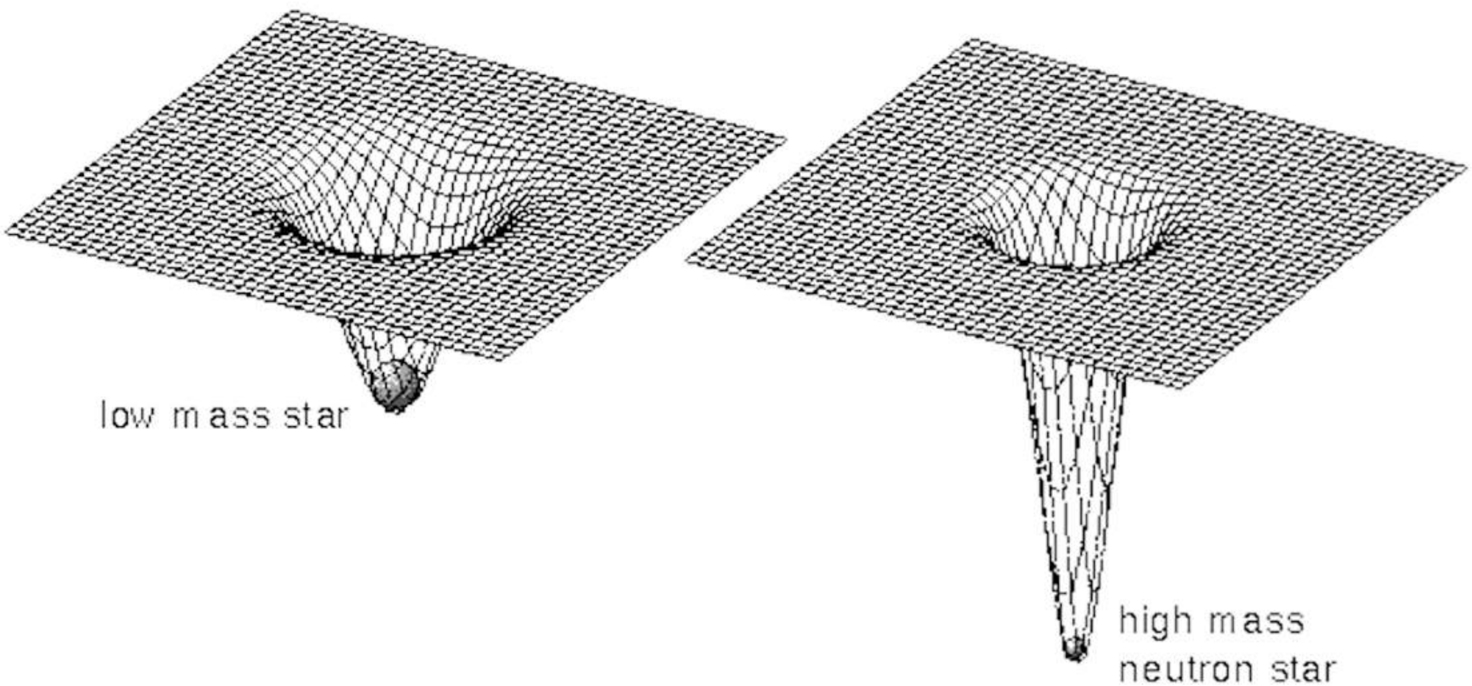
if using spherical coords for spatial

Energy & momentum determine the metric via Einstein's field equations

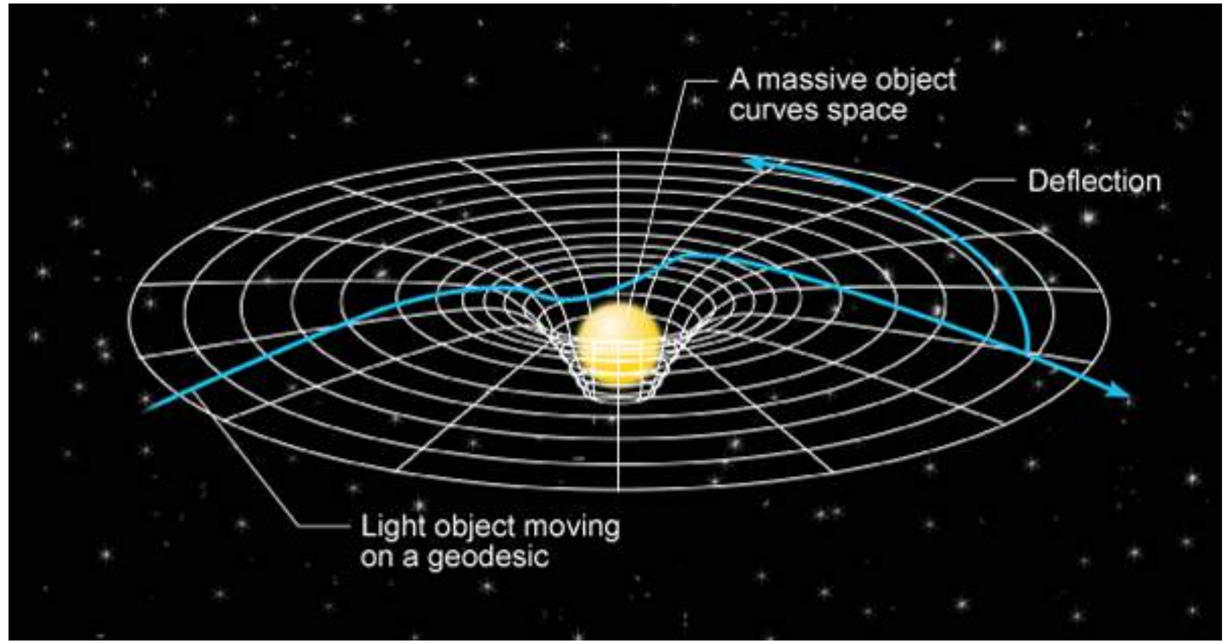
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein tensor
function of metric and its 1st and 2nd derivatives

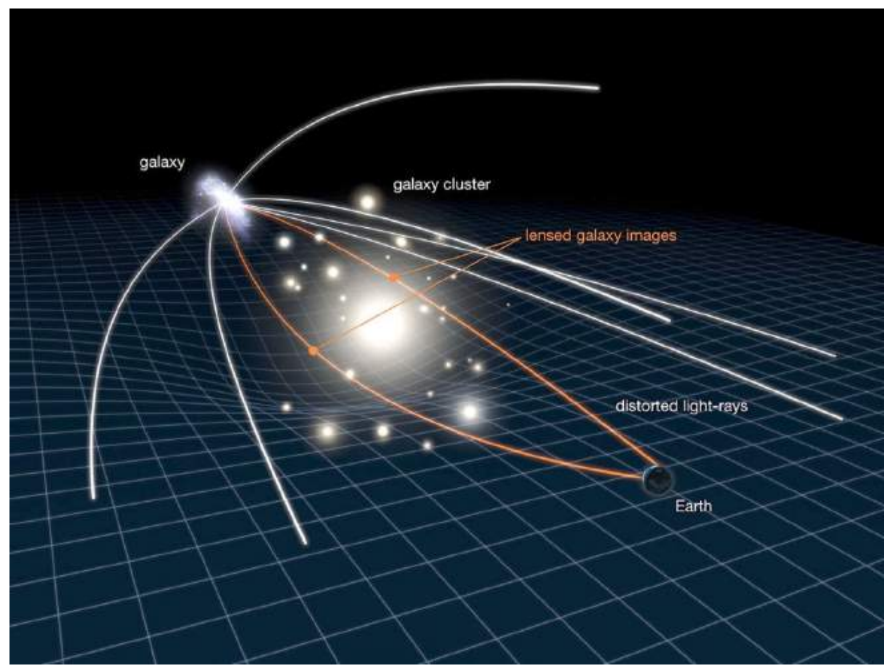
Stress-energy tensor
describes how energy and momentum are distributed in space



Motion of test particles follows geodesics



- Locally straightest paths



- In curved spacetimes, correspond to e.g.
  - planetary orbits
  - light deflected by foreground stars or galaxies

Schwarzschild metric

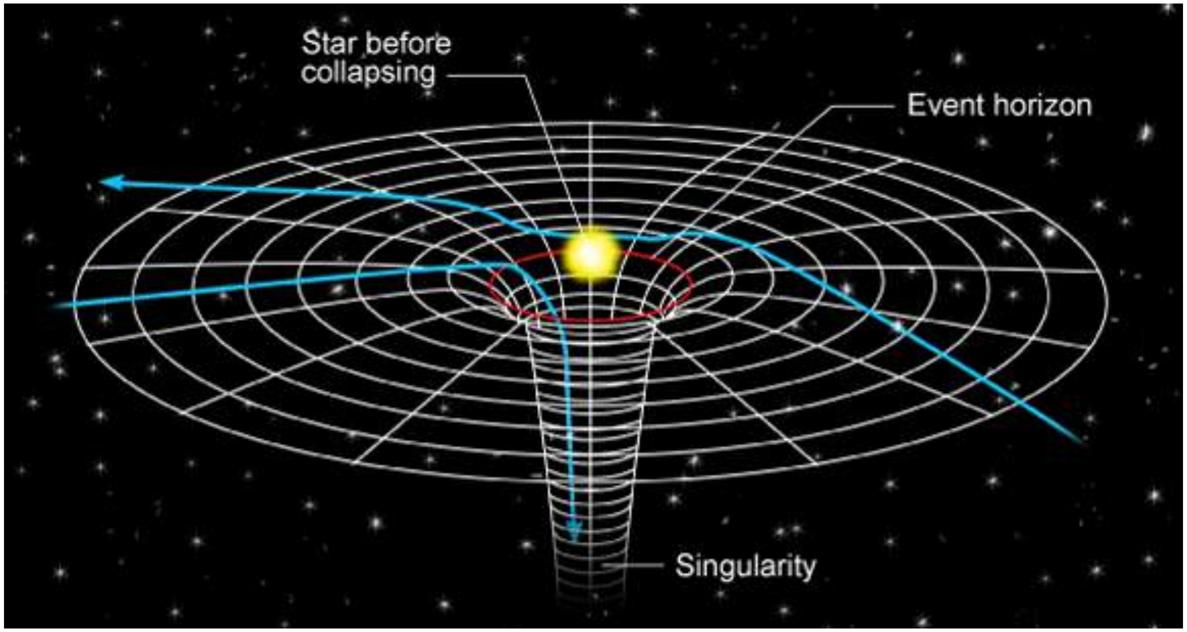
- Vacuum solution around spherically symmetric massive objects (Sun, NS, BH, …):

$$(ds)^2 = \left(1 - \frac{2GM}{rc^2}\right)(cdt)^2 - \left(1 - \frac{2GM}{rc^2}\right)^{-1}(dr)^2 - (rd\theta)^2 - (r\sin\theta d\phi)^2$$

- Matter or light that enters **event horizon** or **Schwarzschild radius**

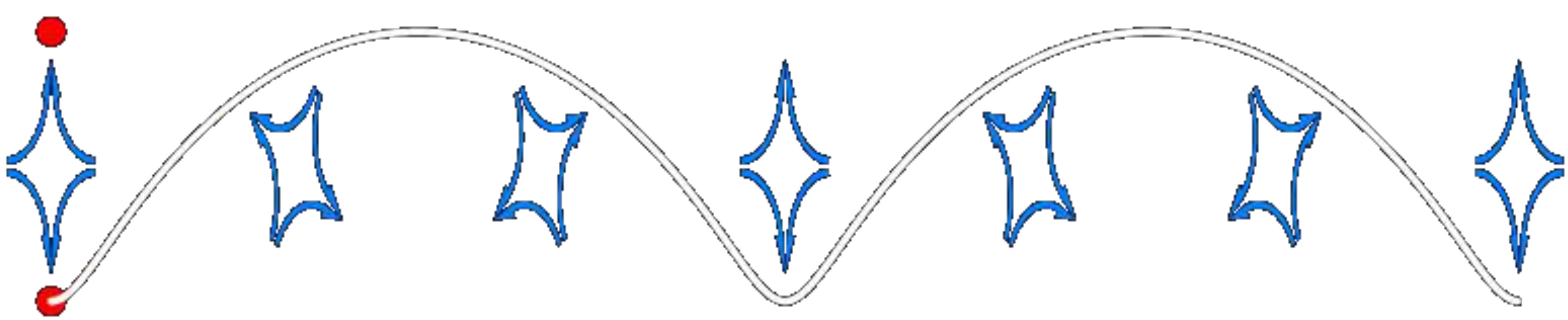
$$r_s = \frac{2GM}{c^2} = 3\,\mathrm{km}\frac{M}{M_\odot}$$

of black holes cannot escape



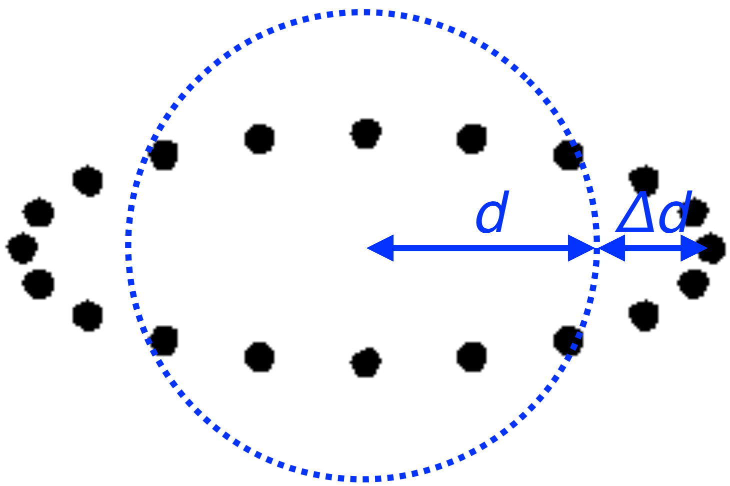
Gravitational waves

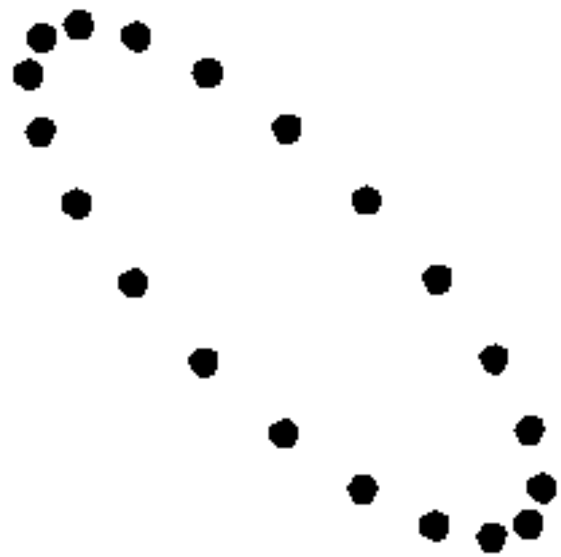
- Analogous to E&M radiation but ***generated by accelerated masses*** instead of accelerated electric charges
- ***Oscillations in the spacetime metric***, i.e. changes in physical distances
- ***Frequency*** is characteristic frequency of the source, e.g. ~1/orbital period
- Main stellar sources:
  - NS-NS, NS-BH and BH-BH binaries
  - asymmetric core collapse SNe
- Also produced by SMBH mergers (longer wavelengths)



Polarizations & strain

- General GW is superposition of “+” and “x” ***polarizations***. Effect on rings of test particles:





- ***Strain*** *h* = fractional change *2Δd/d*. Order-of-magnitude estimate:

$$h \sim \left(\frac{\text{system's Schwarzschild radius}}{\text{distance}} \right) \times \left(\frac{\text{characteristic velocity}}{c} \right)^2$$

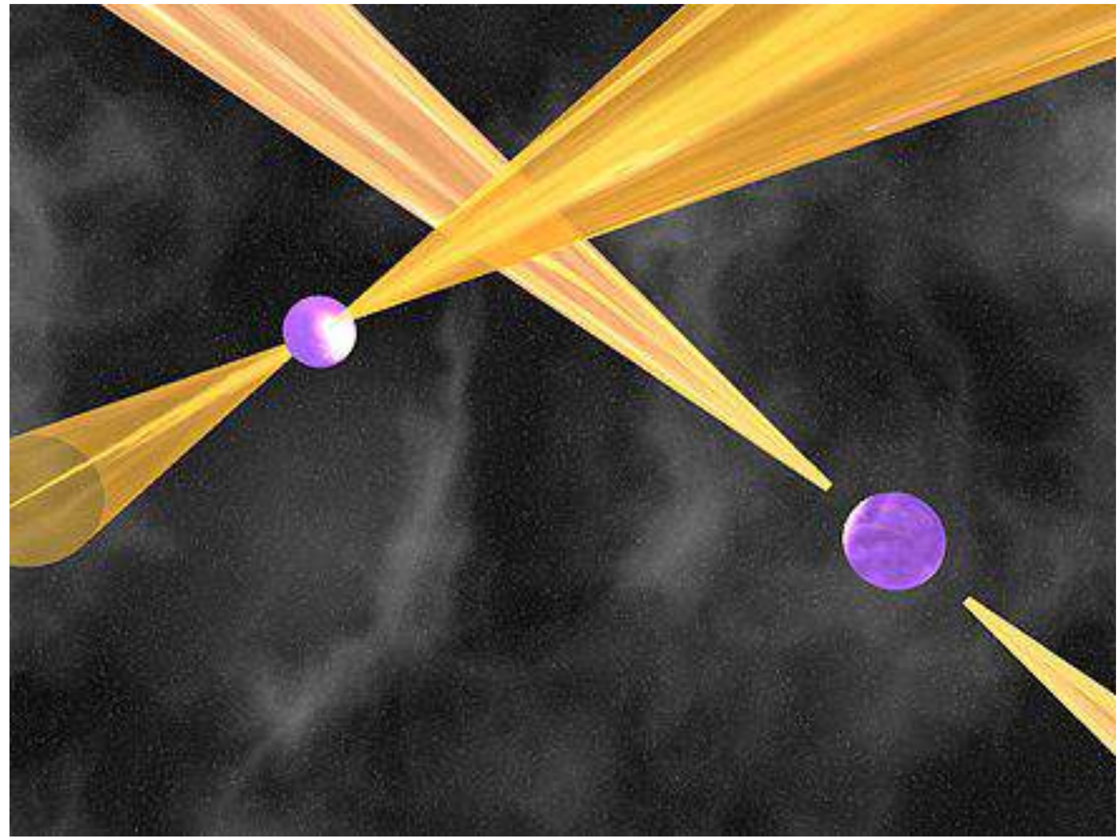
Indirect evidence for gravitational waves from NS-NS binaries

- First pulsar in binary orbit with another neutron star (PSR B1913+16) discovered by R. Hulse & J. Taylor in 1974

- Pulse time of arrivals are affected by Doppler effect, just like emission/ absorption lines in ordinary stars

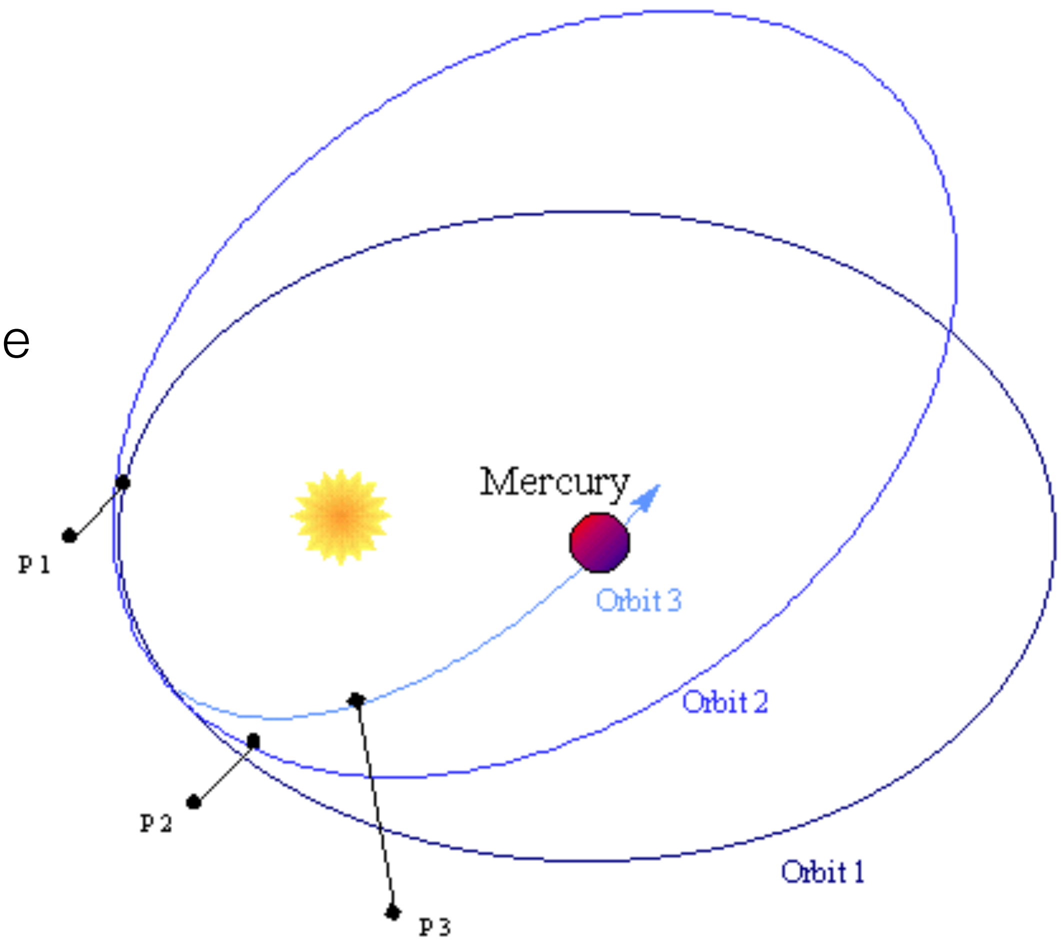
- By "timing" the pulsar, measurements analogous to those possible with spectroscopic binaries can be made

- In compact NS-NS binaries, relativistic effects are large — use to test Einstein's theory



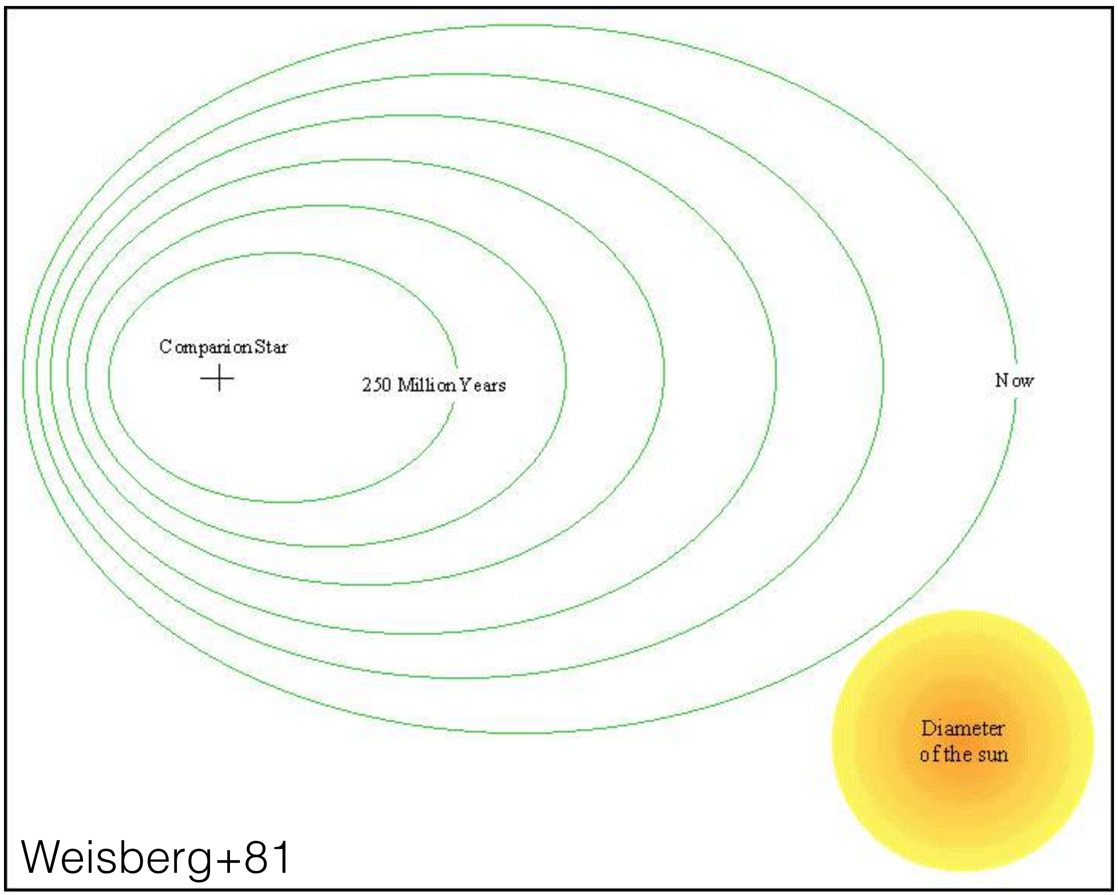
Relativistic periastron advance

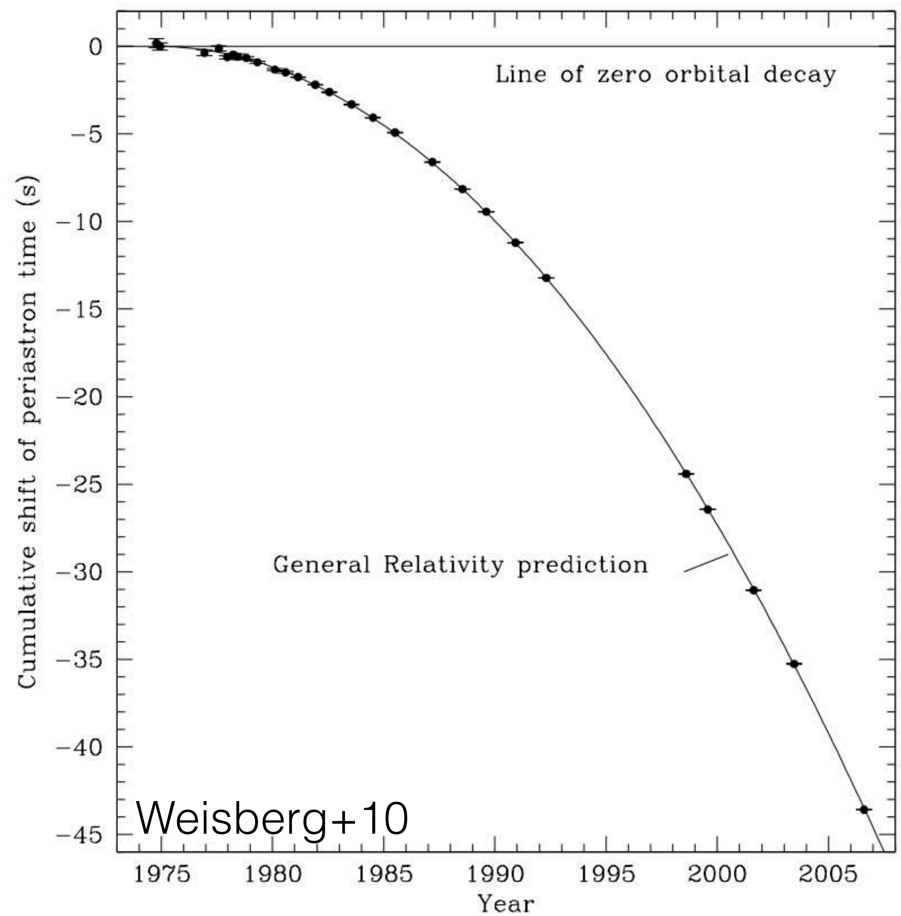
- In Newtonian mechanics, two point masses have elliptical orbits with fixed periastron
- In relativity, elliptic orbits precess and the position of periastron changes with time
- Effect small in Solar System: 43 arcsec **per century** for Mercury
- Much more dramatic in binary pulsar PSR B1913+16: 4.2 degrees **per year**



Orbit shrinks due to emission of gravitational waves

- Gravitational waves carry energy away from the NS-NS binary
- As energy is lost from the orbit, the orbit shrinks
- Orbital decay can be measured as a cumulative shift in the time of periastron, relative to what is predicted absent any orbital decay
- The measured shift in PSR B1913+16 matches with high accuracy the rate of orbital decay predicted to be induced by gravitational wave emission by Einstein's GR





The Nobel Prize in Physics 1993

Russell A. Hulse
Prize share: 1/2

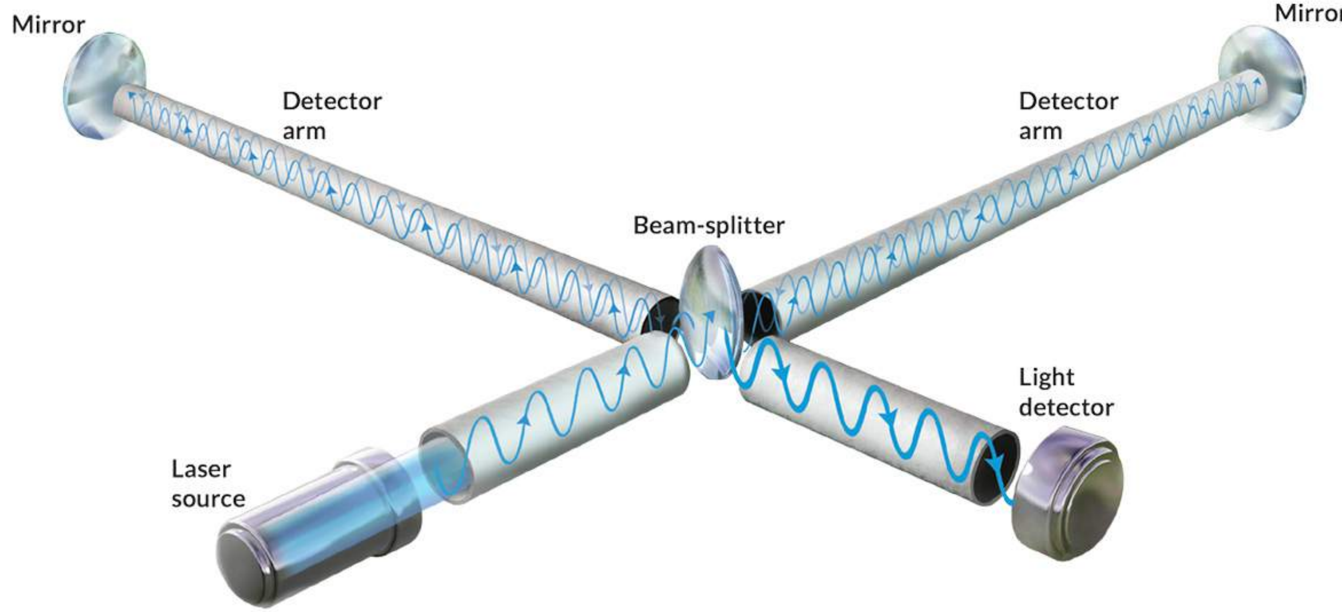
Joseph H. Taylor Jr.
Prize share: 1/2

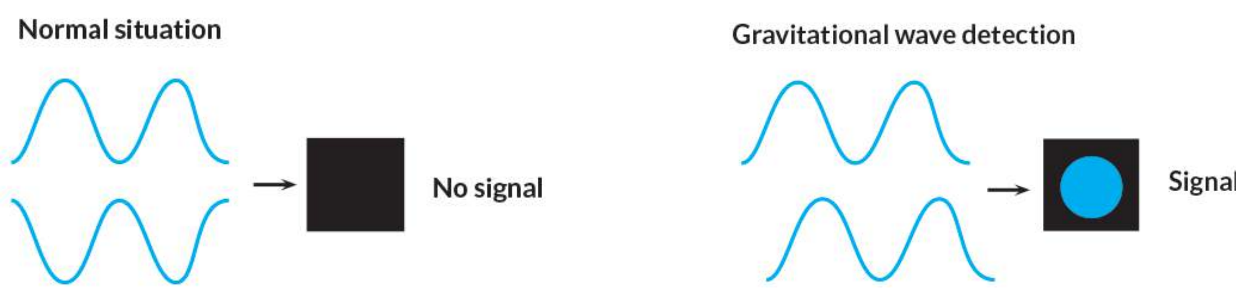
The Nobel Prize in Physics 1993 was awarded jointly to Russell A. Hulse and Joseph H. Taylor Jr. *"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"*

“Direct" gravitational wave detectors

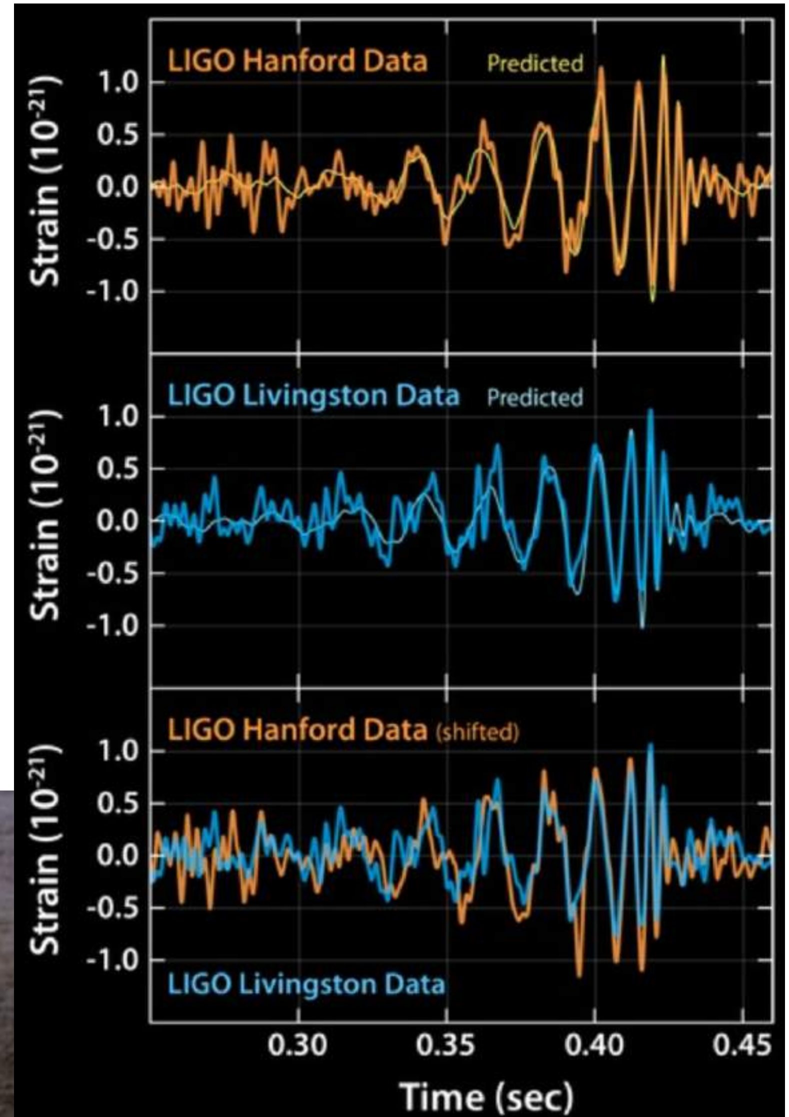
- Astrophysical strains are tiny, e.g. h=10^{-21} for first LIGO discovery of merging binary BHs

- LIGO observatory is based on a laser Michelson interferometer

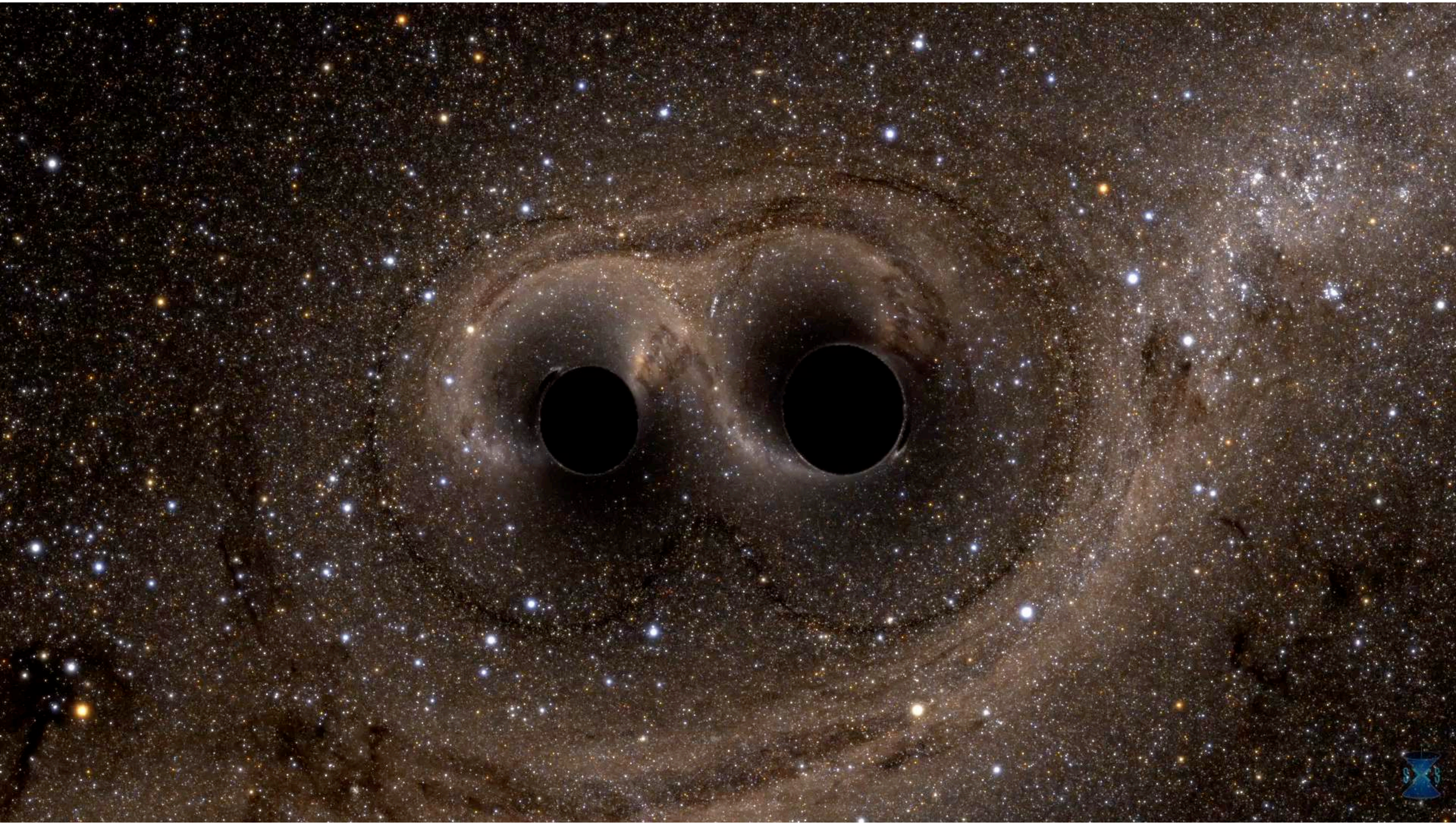




September 14, 2015: LIGO discovery of merging stellar black holes



Simulation of merging black holes



Other sources of gravitational waves and how to detect them

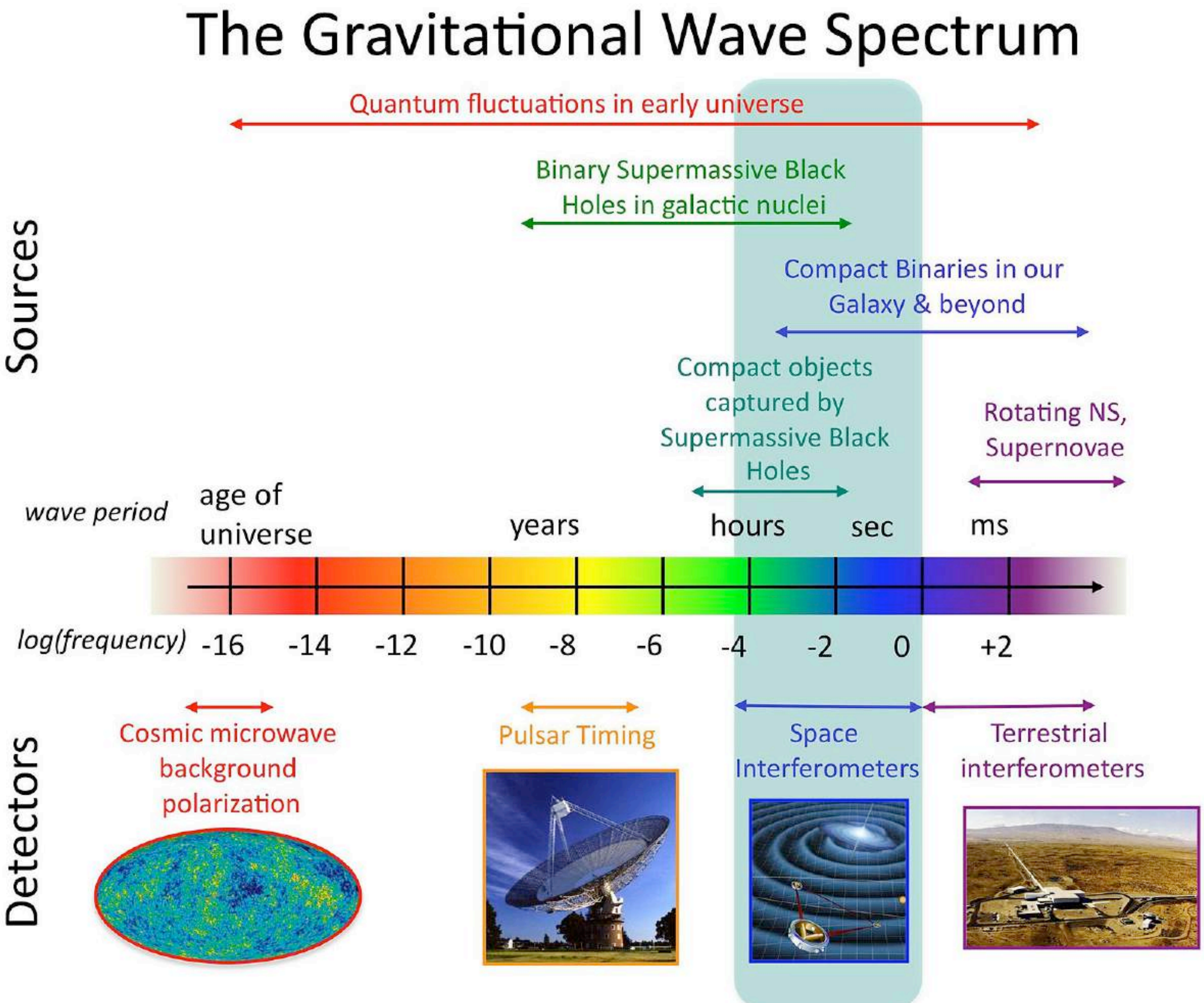


Figure credit: NASA Goddard Space Flight Center