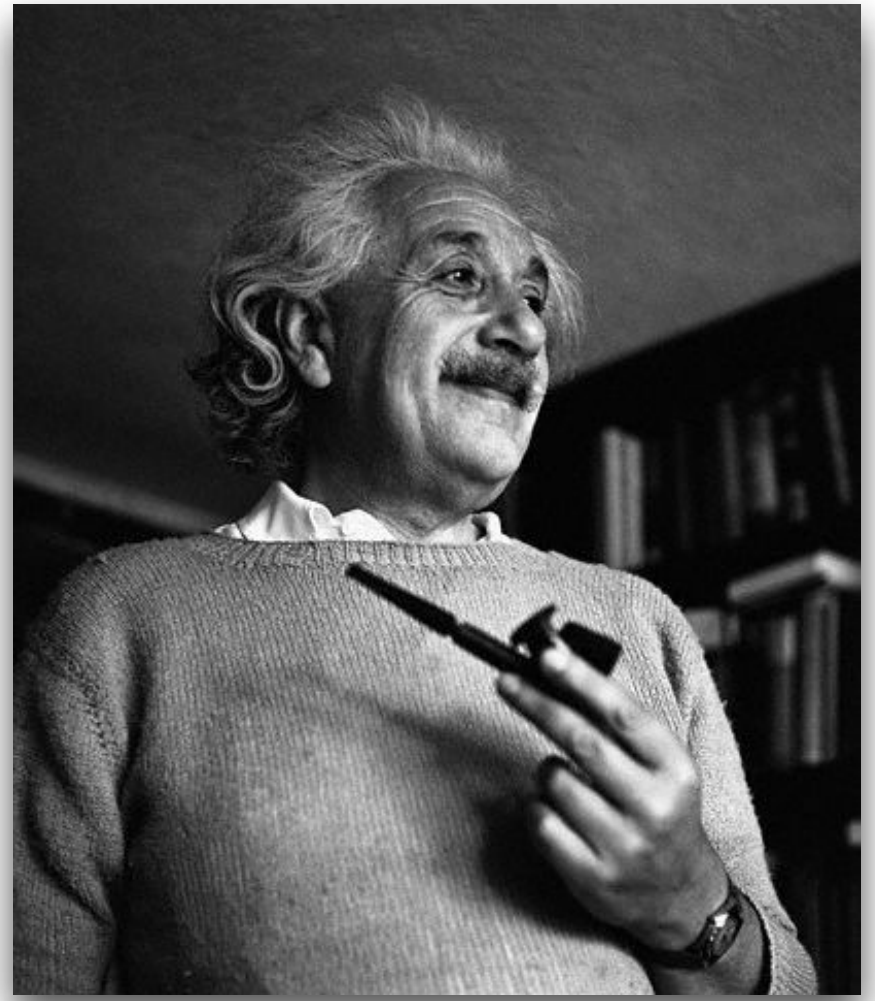
100 Years Of Gravity: Notes From A Research Frontier



Lee Samuel Finn

The Pennsylvania State University

Gravitational Waves: The Last of The First?

- Gravity, Space-Time, & Space-Time Curvature
- Gravitational Waves & Gravitational Wave Detectors
- Gravitational Wave Astronomy

Gravity, space-time, & space-time curvature

What holds you in your seat?

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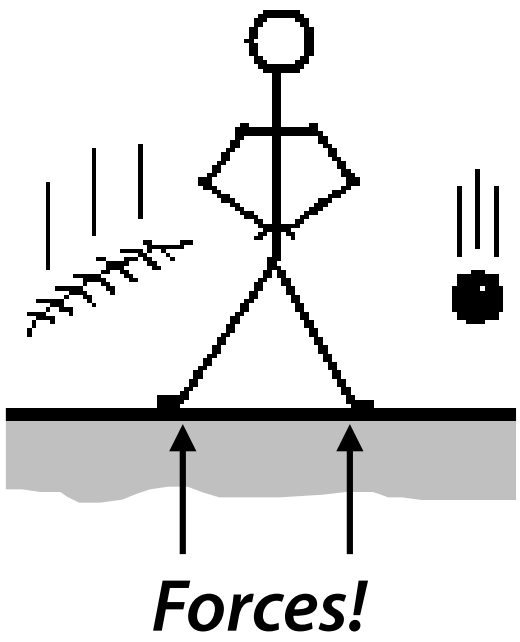
Where's the force?



Newton's First Law:

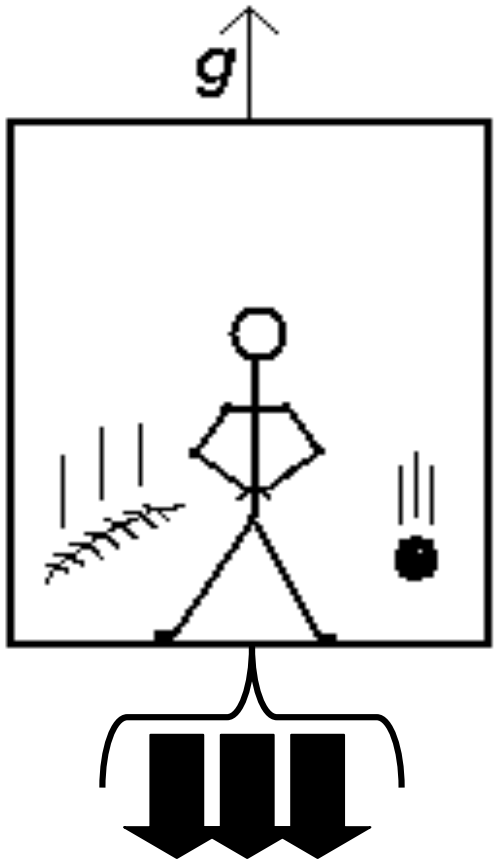
Every object in a state of uniform [straight line] motion tends to remain in that state of motion unless an external force is applied to it.

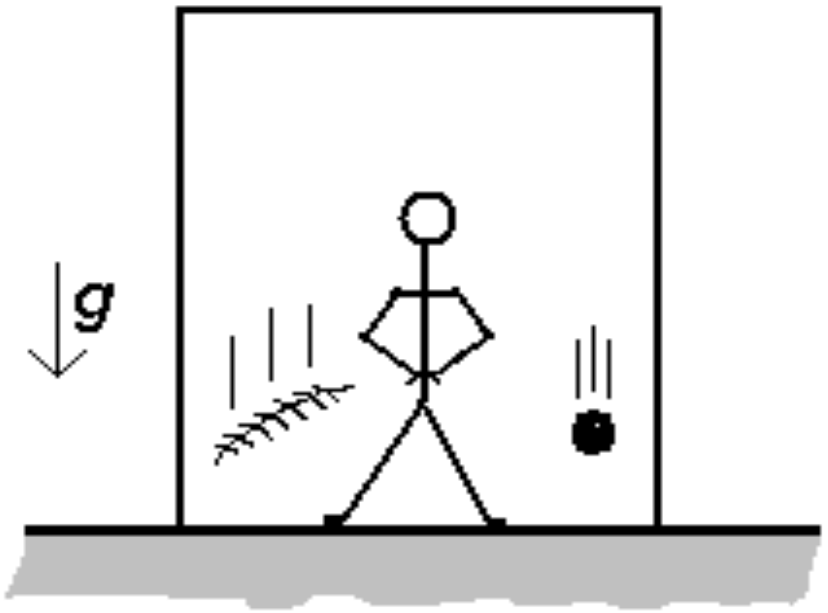
Einstein's Revision

Uniform [straight line] motion is the state of motion of objects upon which no force acts

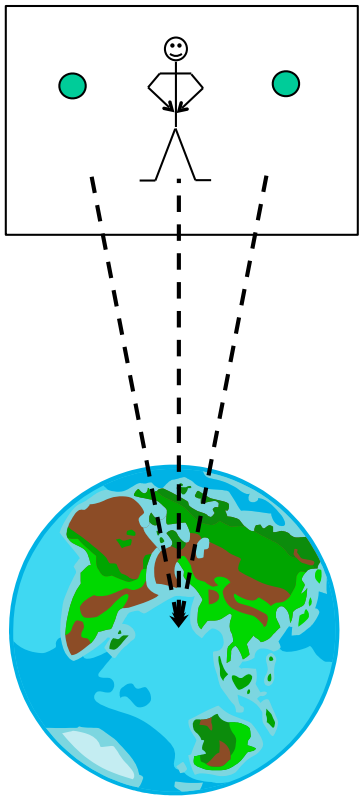
What holds you in your seat? The Earth getting in the way of your natural state of motion!

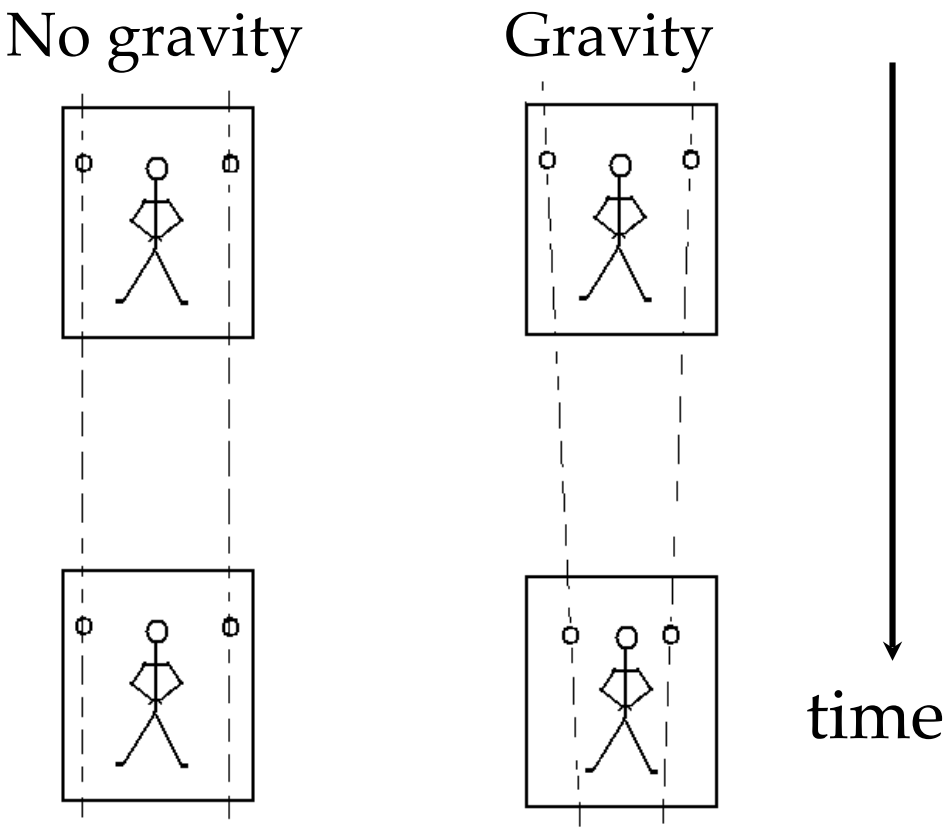
Where is Gravity?



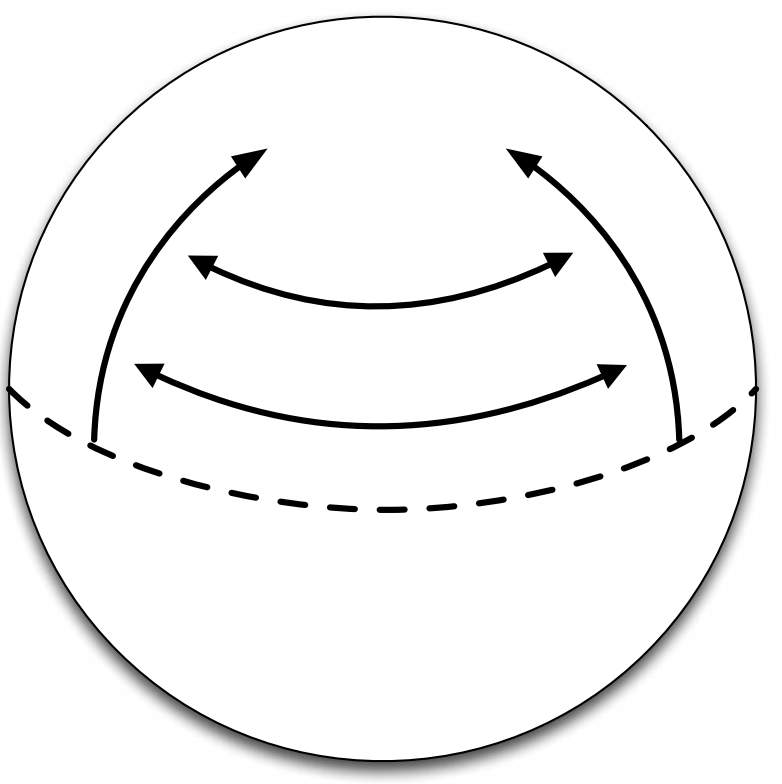


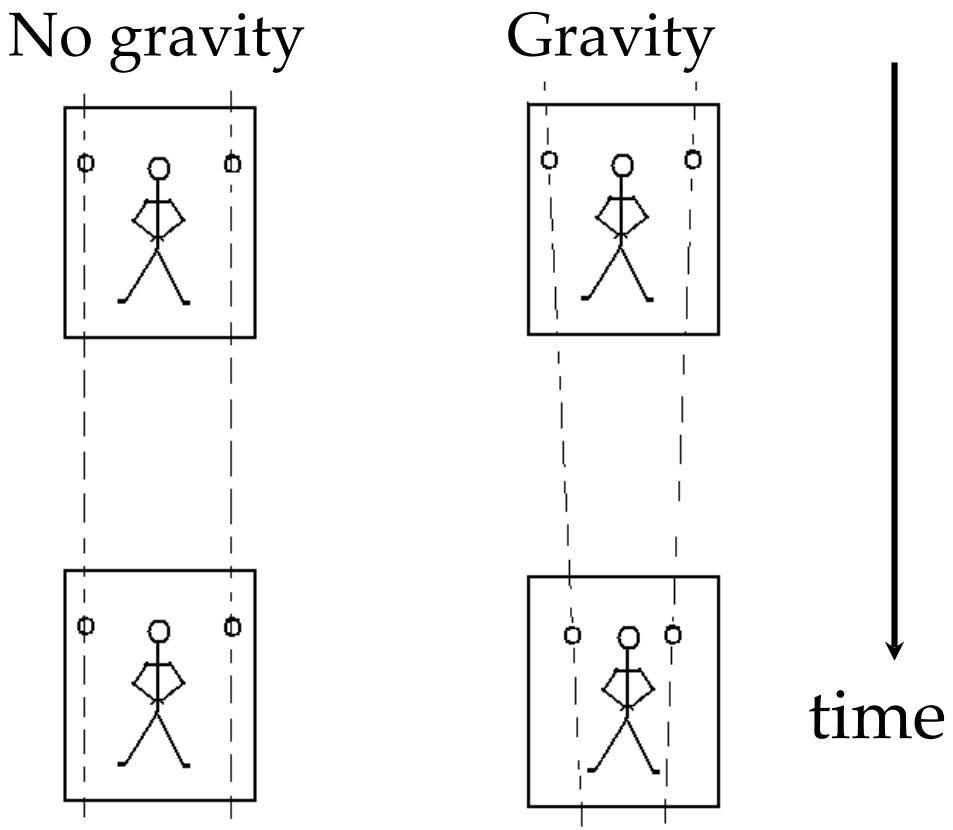
Gravity *does* make a difference …





Curvature leads to an acceleration of the deviation between initially parallel straight-line trajectories





Gravity is the physical manifestation of space-time curvature

Directions of travel initially parallel

Astronauts in orbit feel no forces acting on them: "weightless"

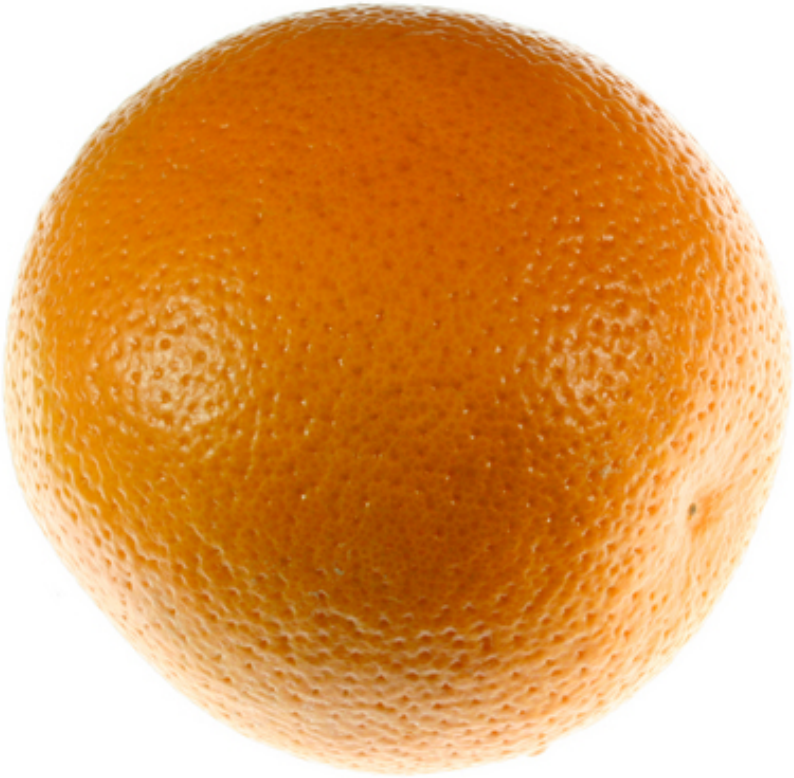
Relative separations and directions of motion undergo periodic change

Space-time curvature radius is $Pc/2\pi$: i.e., proportional to orbital period times light speed

Gravitational waves & gravitational wave detectors

Gravitational waves are short-scale space-time curvature fluctuations

Surface of orange is on average smooth; in detail, it has small dimples and ripples

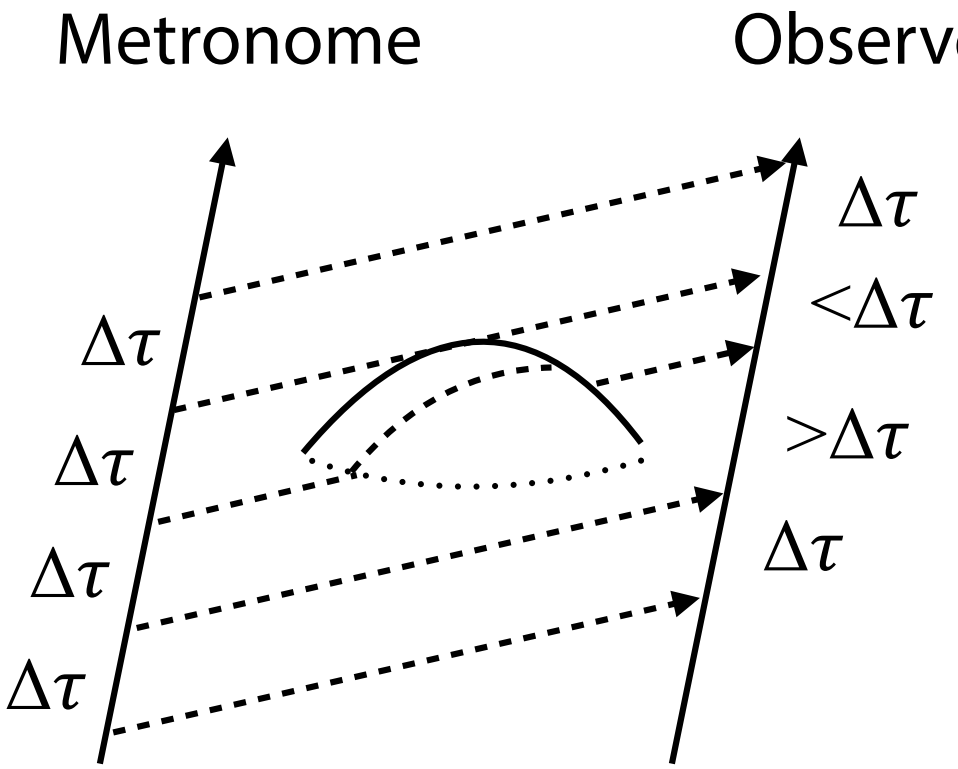


Radius of "average" orange is large compared to radius of orange "details"

Gravitational waves are spacetime curvature ripples

Nomenclature: we say "curvature" is large when the radius is small, and curvature is small when the radius is large

Gravitational wave detectors measure *fluctuations* in *curvature* throughout detector

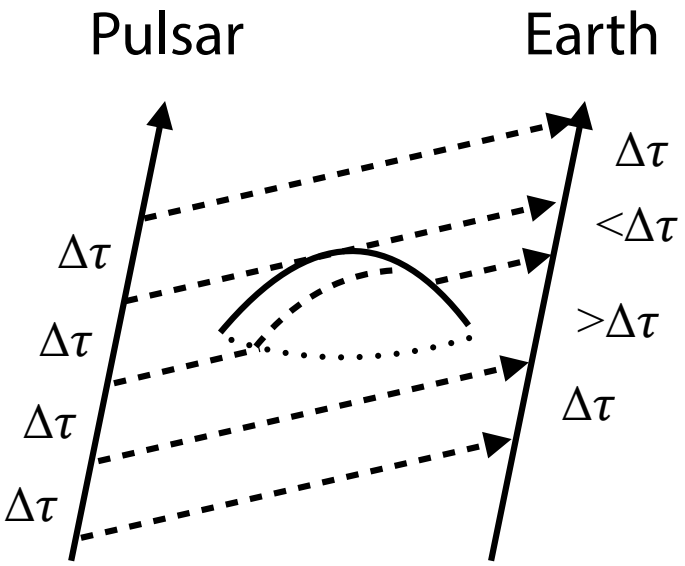


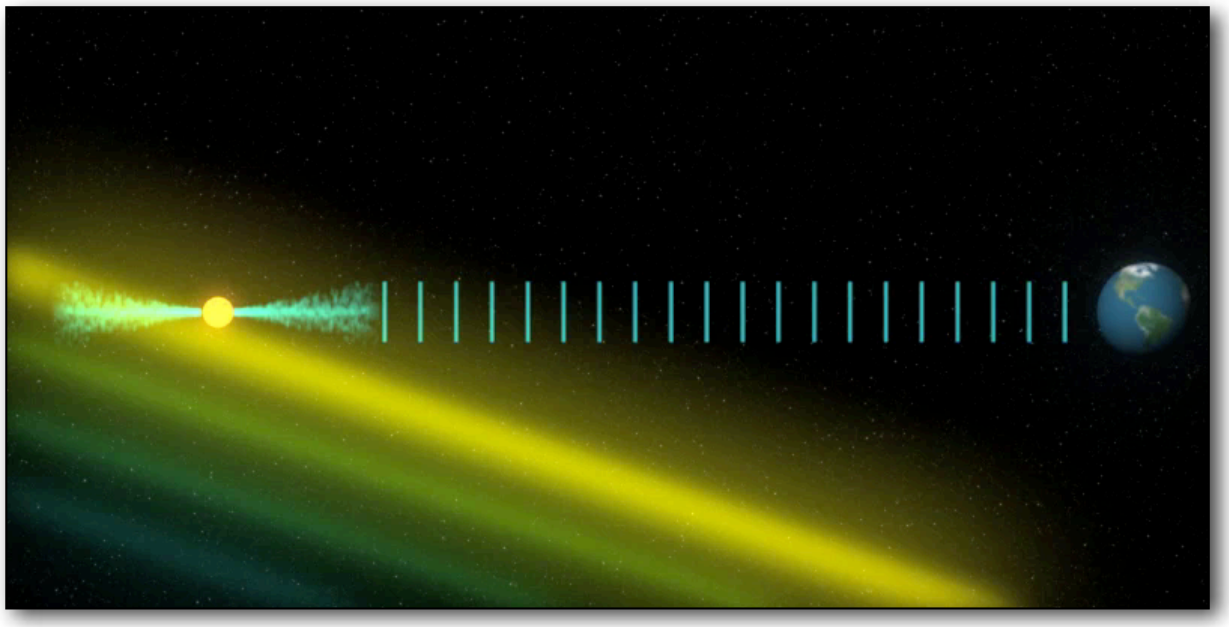
Regular light pulses propagate from metronome to observer

Changing curvature along light pulse paths change *observed* pulse rate

Equivalence Principle: spacetime curvature does not affect metronome, observer, or light

Rapidly rotating neutron stars emitting regular pulses can be used to detect gravitational waves

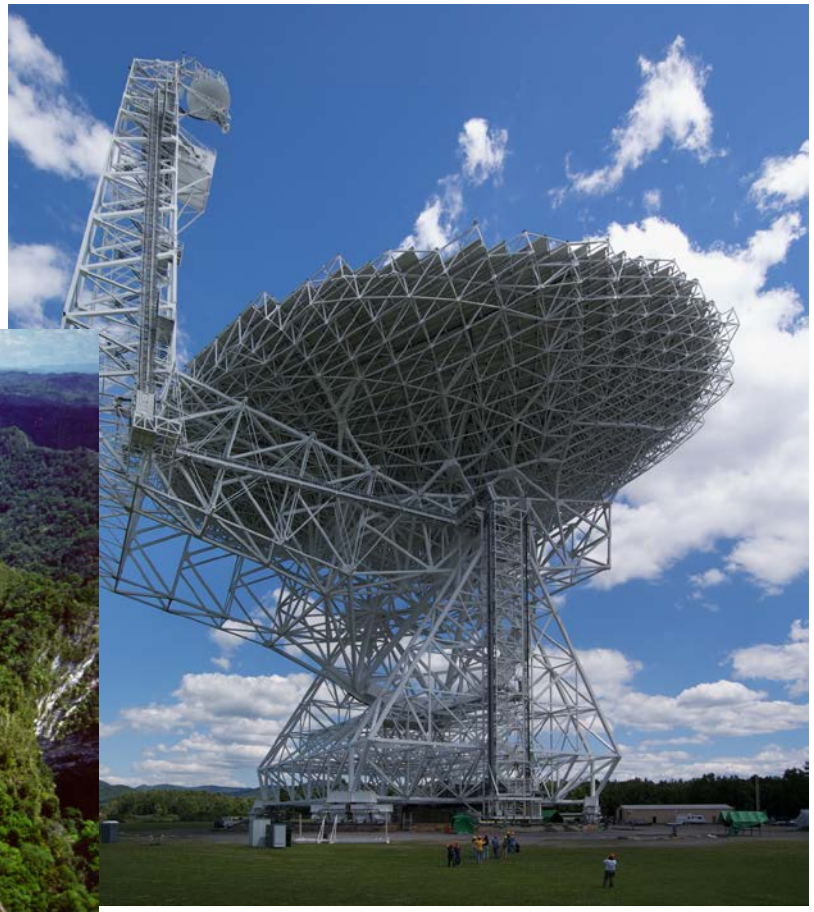




Current sensitivity: ~100 ns fluctuations in pulse arrival times over ~year timescales

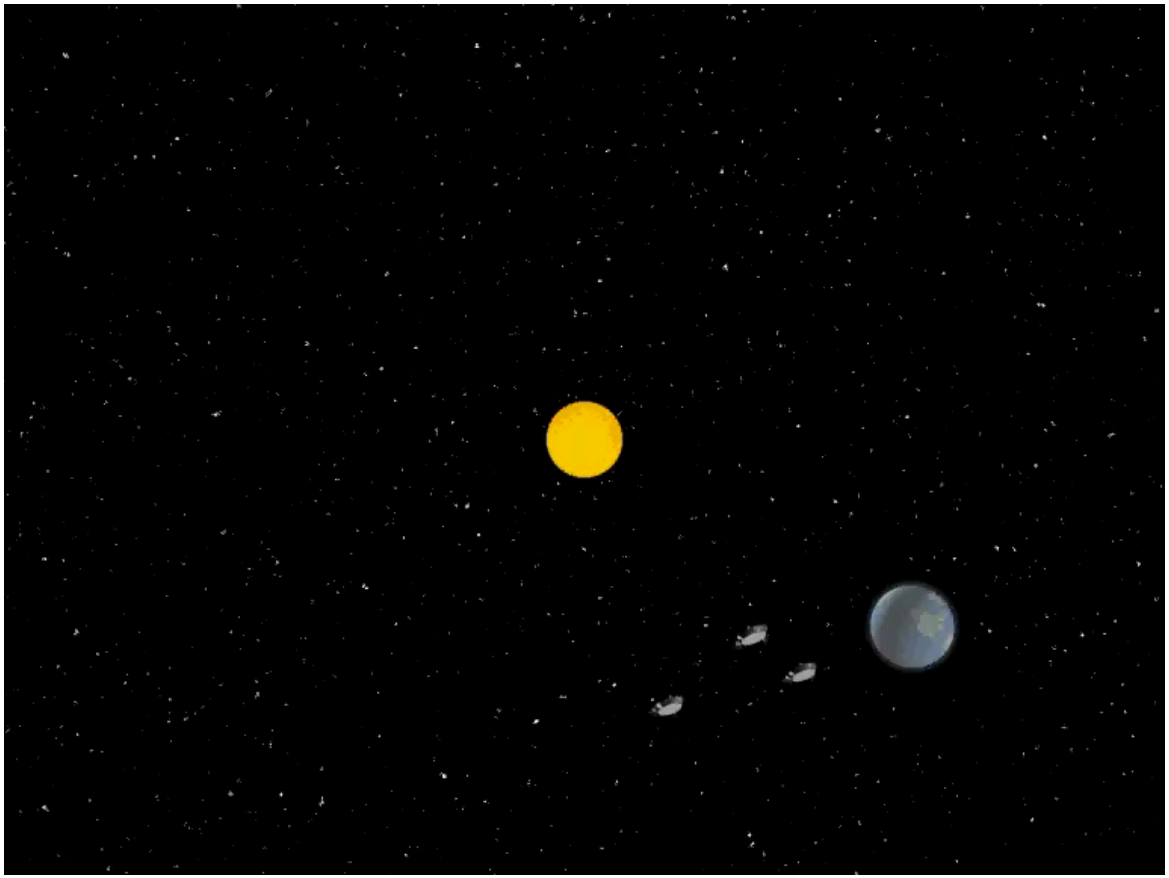
European Pulsar Timing Array

Parkes Pulsar Timing Array and North American Nanohertz Gravitational Wave Observatory

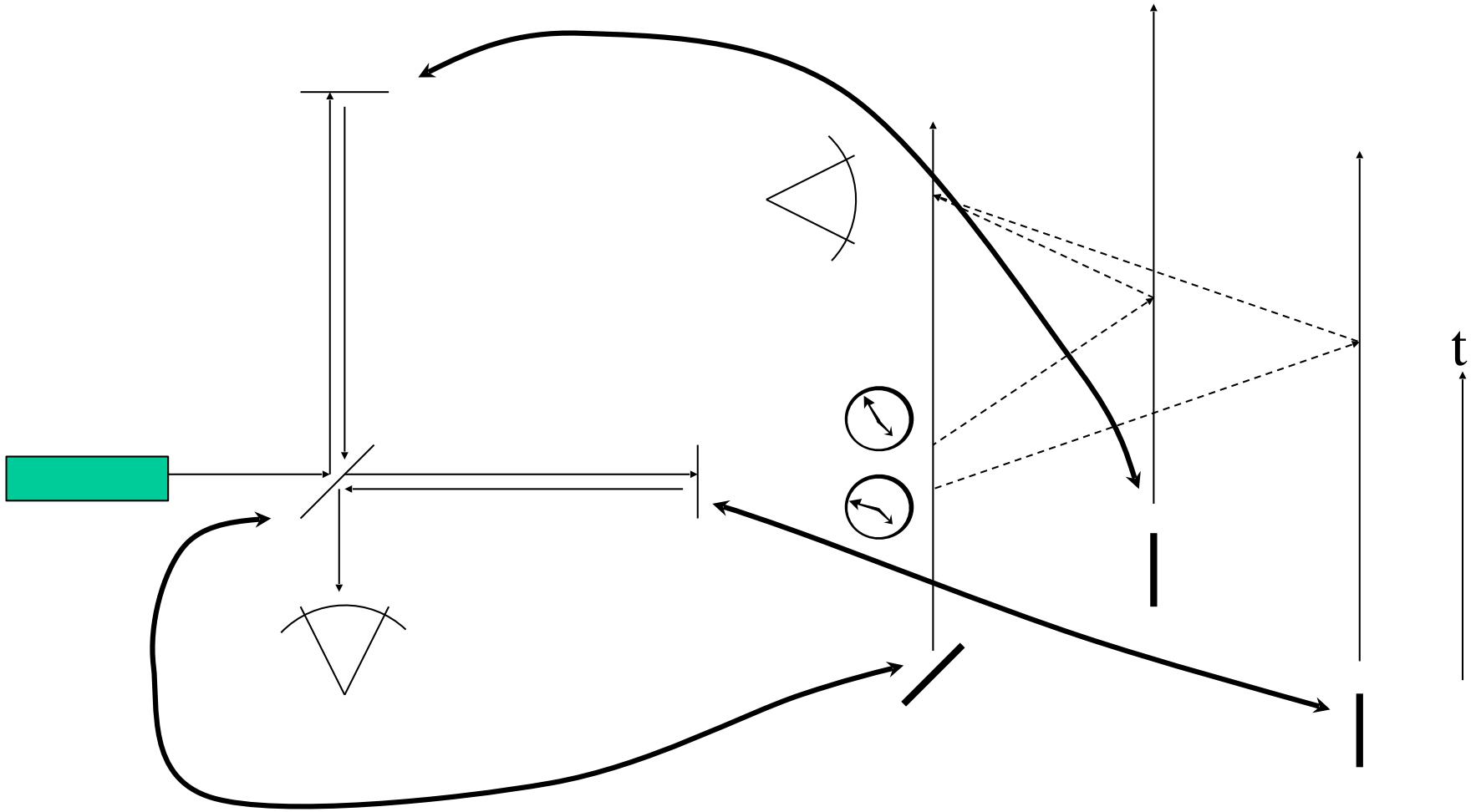


LISA: Laser Interferometer Space Antenna

- Three spacecraft separated from each other by ~10^6 km
- Modulated laser light transponded between s'craft measures changes owing intervening grav. waves
  - *Projected sensitivity: femtosecond changes over ~minute timescales*
- 40 years of study: mature design
- Pathfinder to test critical technologies flies Dec 11!



Detecting Gravitational Waves: Laser Interferometry



Advanced detectors projected sensitivity: light-time fluctuations of ~1/10 of a nano-femto-second at frequencies of ~100/sec

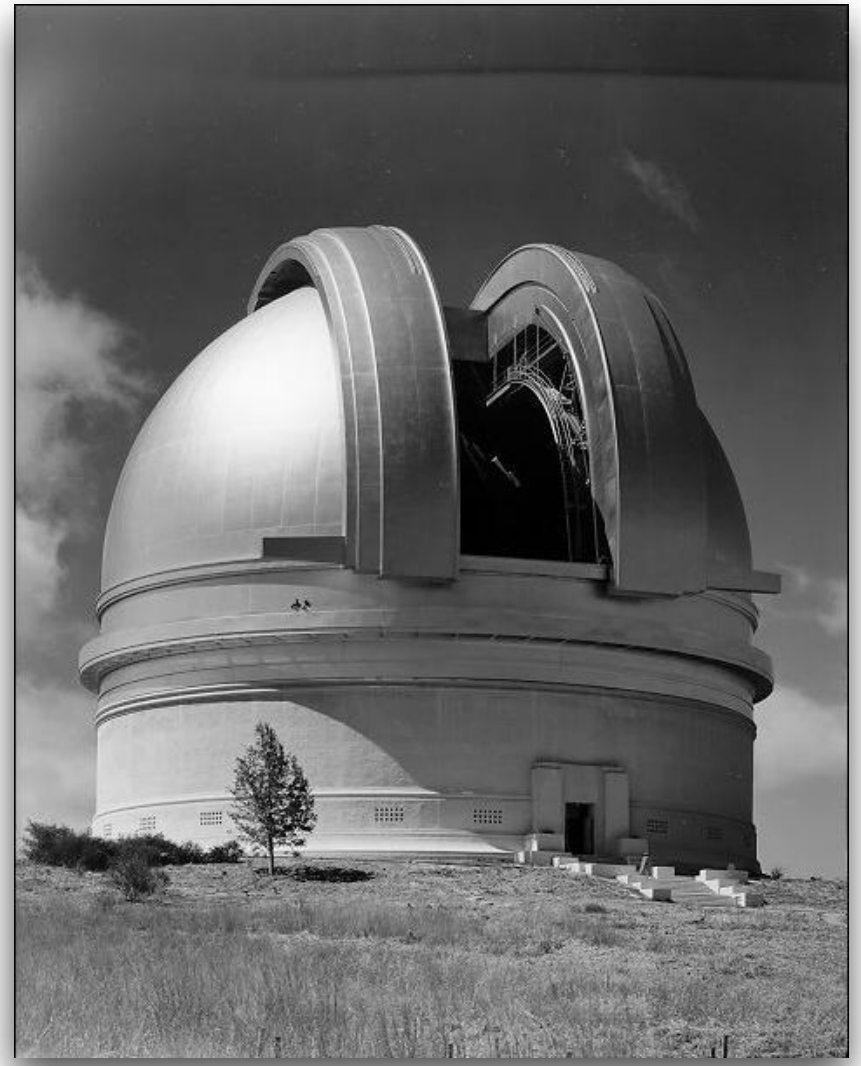
Laser interferometric gravitational wave detectors

Gravitational wave astronomy

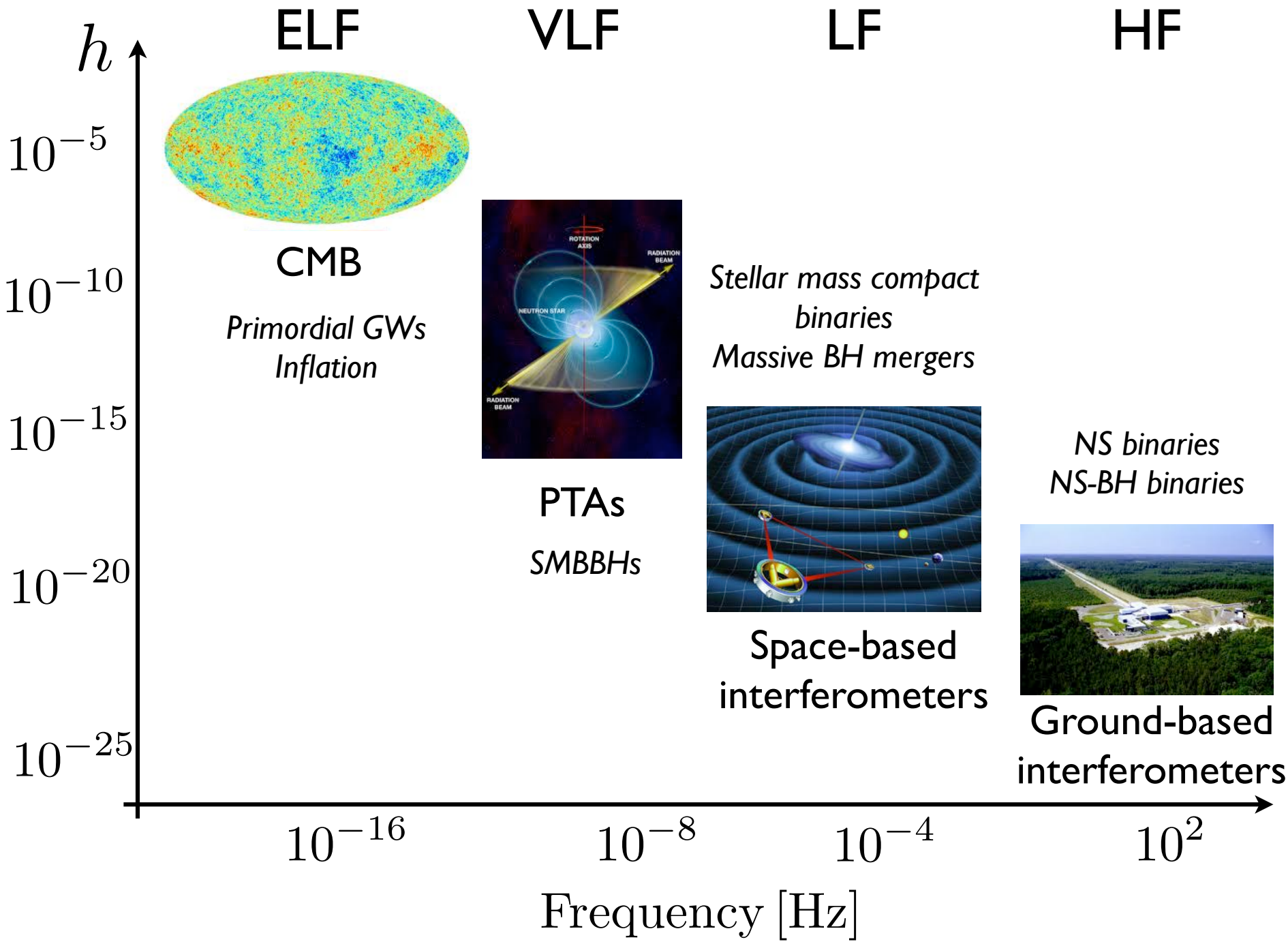
Astronomers Observe

Observation, v.

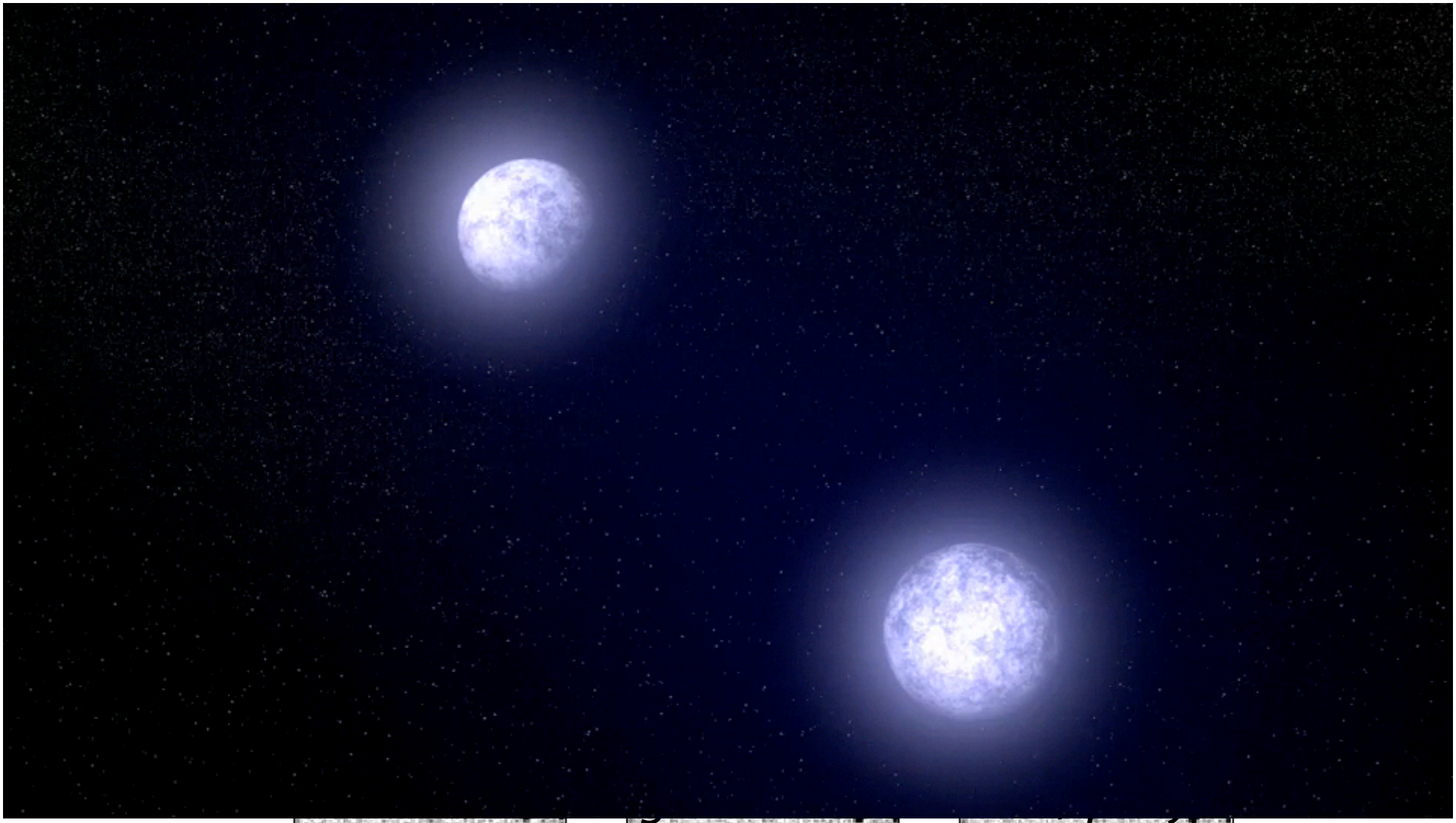
… esp. the careful watching and noting of an object or phenomenon in regard to its cause or effect, or of objects or phenomena in regard to their mutual relations (contrasted with experiment).



The big picture of gravitational wave astronomy



Gravitational Waves and Gamma-ray Bursts



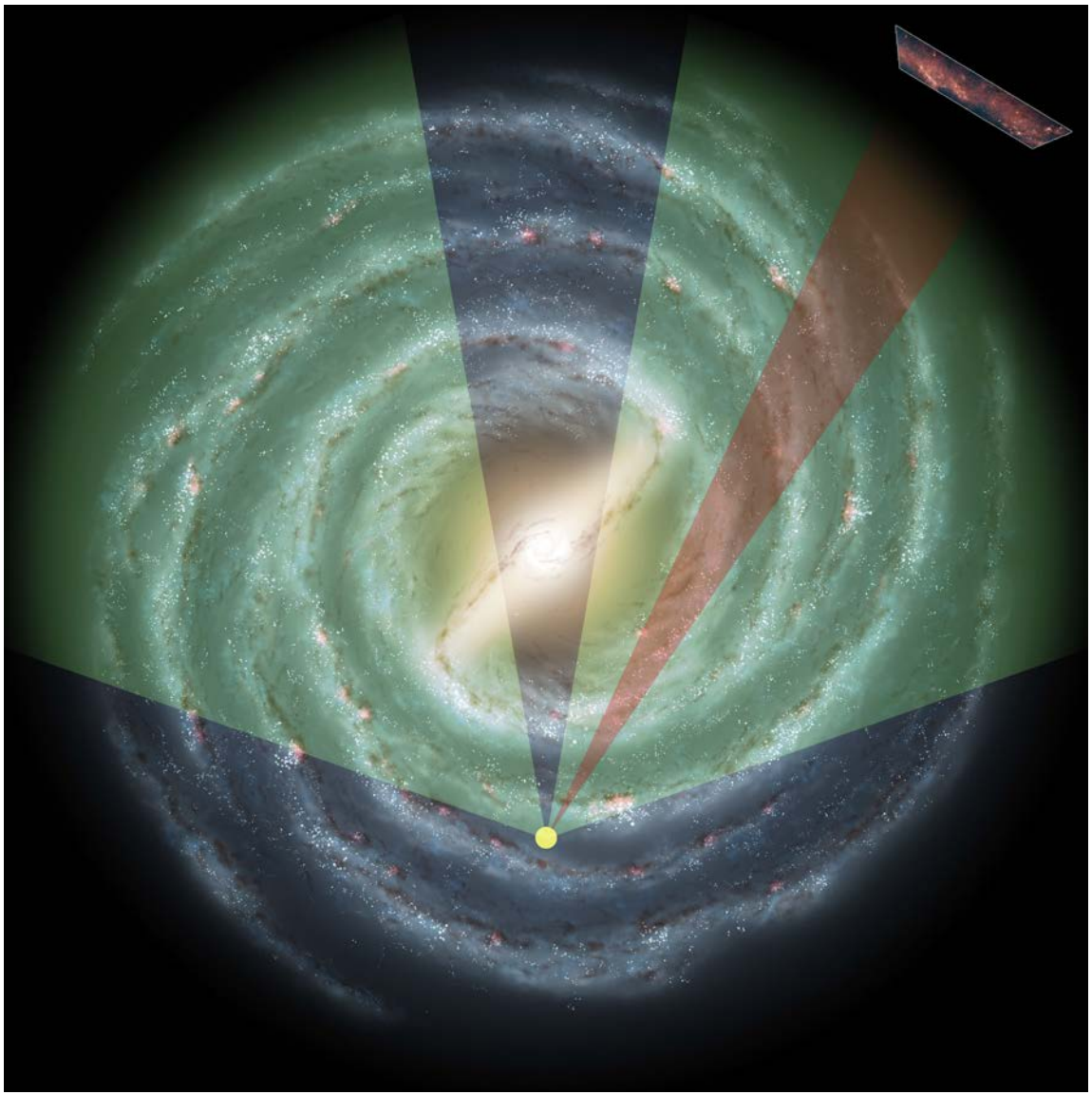
observations answer these questions!

Black hole binary coalescence and merger

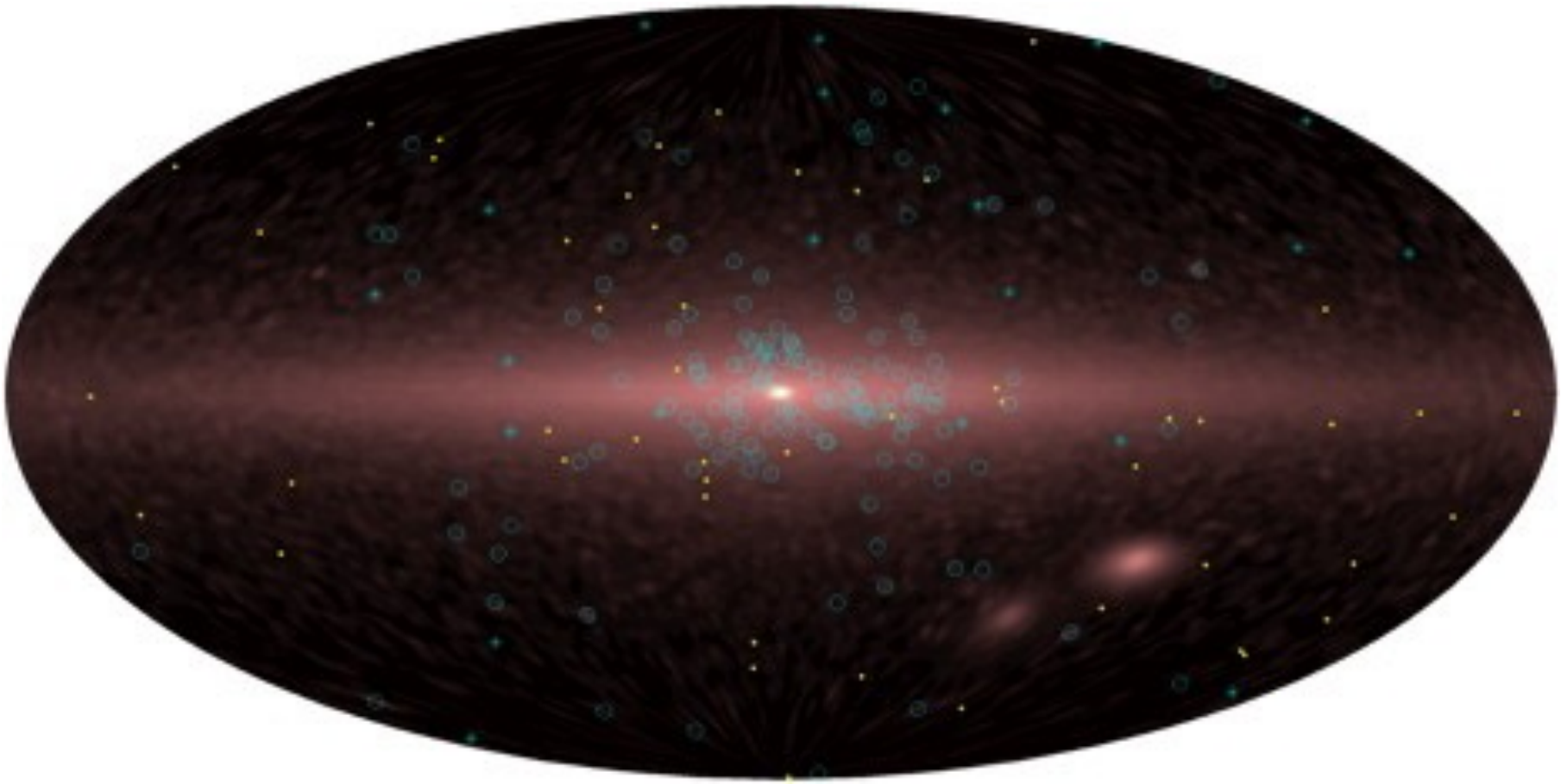
- How many? How far? How massive?
- How the stars that made them lived and died

Ground-based detectors: Observing through the Zone of Avoidance

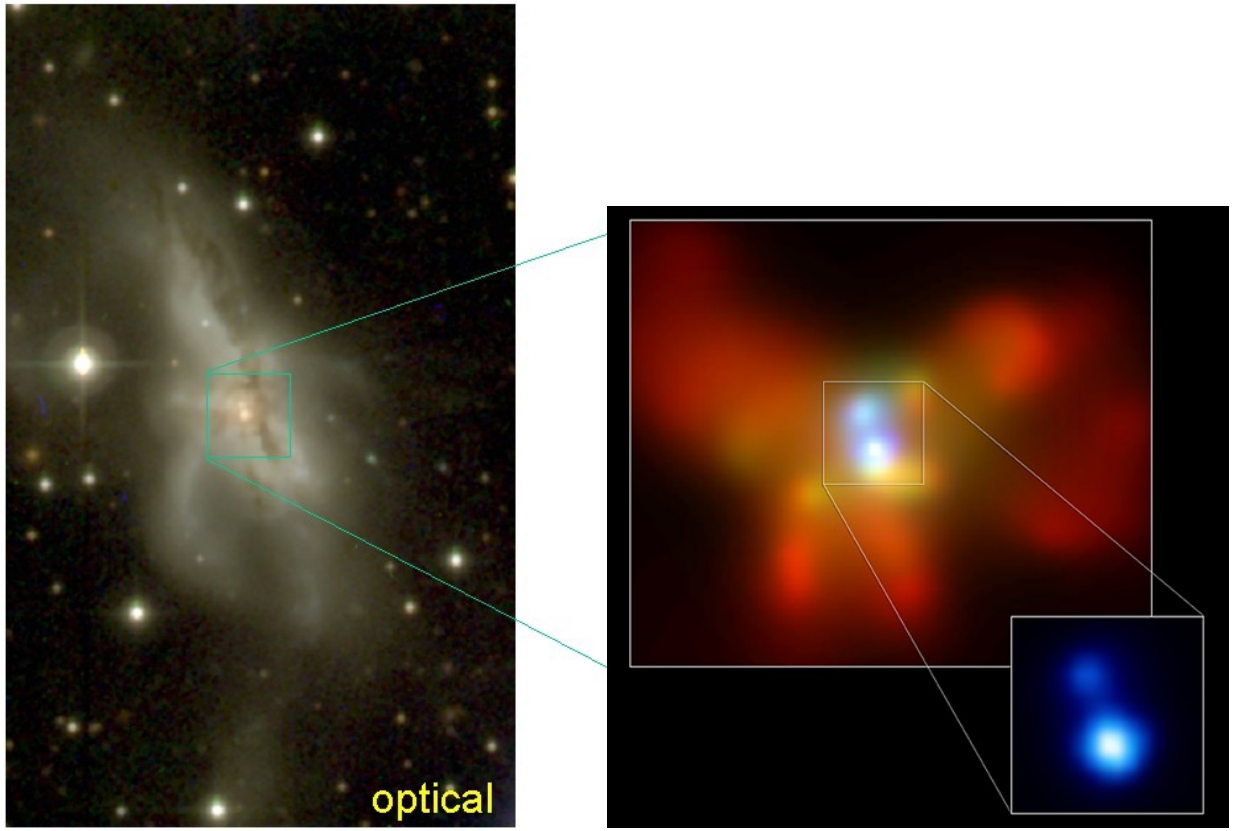
- Galactic center gas, dust obscure universe beyond
- Gravitational waves penetrate unimpeded
- What lies beyond?



LISA's Gravitational Wave Sky: The Galaxy in White Dwarf Binaries



Coalescing Galaxies and Colliding Black Holes



Galaxy mergers lead to supermassive black hole mergers

Dynamical friction drives SMBHs to galactic nucleus, forming a binary that evolves to ~ **pc orbital radius**

Believe gas, slingshot ejections with loss-cone refilling drive binary through greater part of final pc

Believe transition to gravitational wave dominated inspiral when orbital radius ~ $\mathbf{10^2 - 10^3}\ R_s$

Orbital period months to centuries for binaries of $\mathbf{10^8 - 10^{11}}\ M_\odot$