Gravitational-Wave Detection

SPACE-TIME WARPS IN THE UNIVERSE
QUANTUM UNCERTAINTIES OF MACROSCOPIC OBJECTS

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California Institute of Technology

Lyncean Group Meeting, San Diego, California
June 25, 2008

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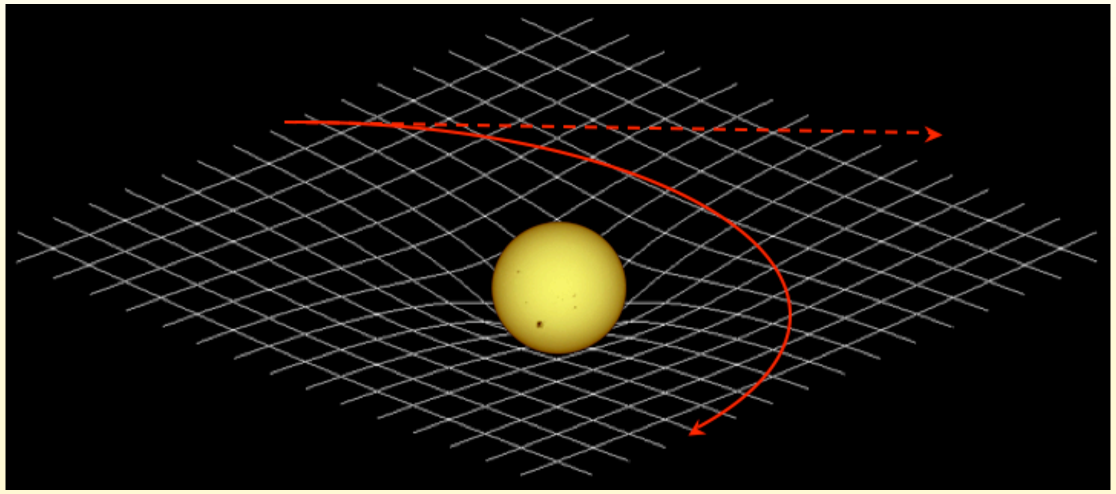

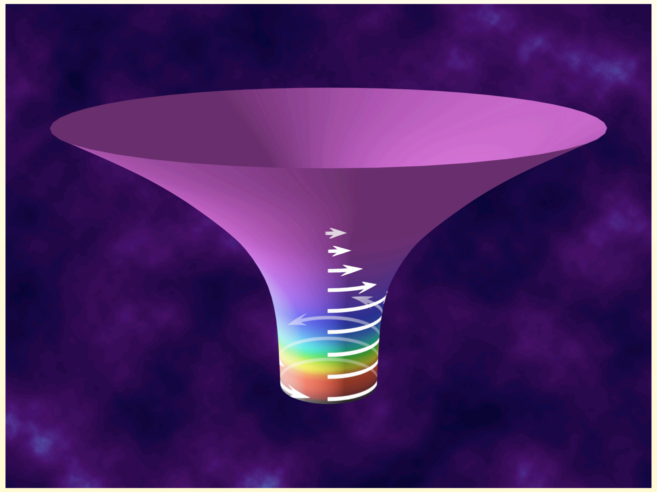

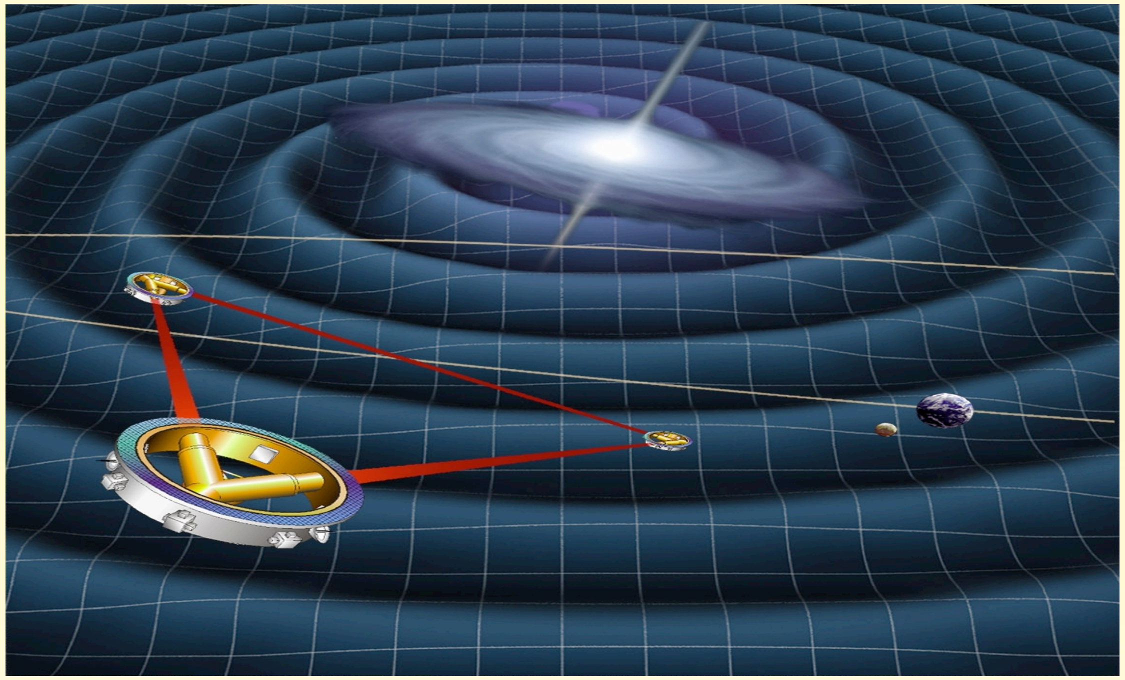

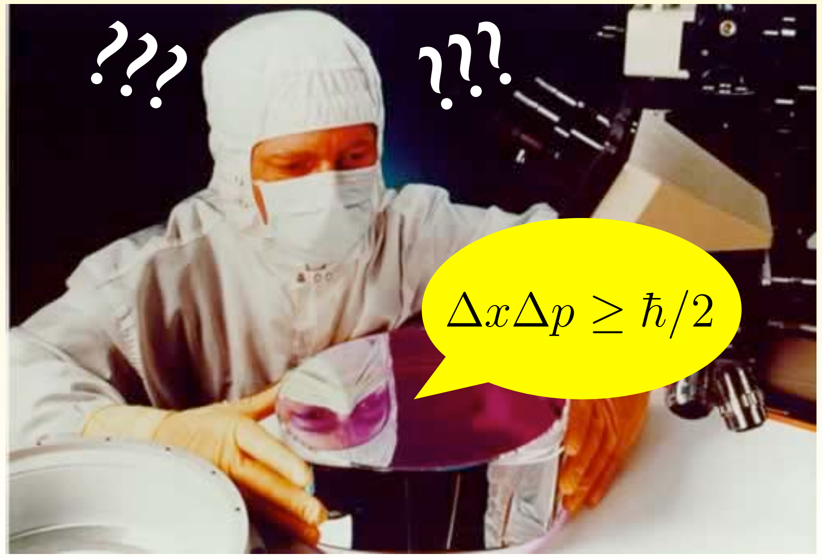

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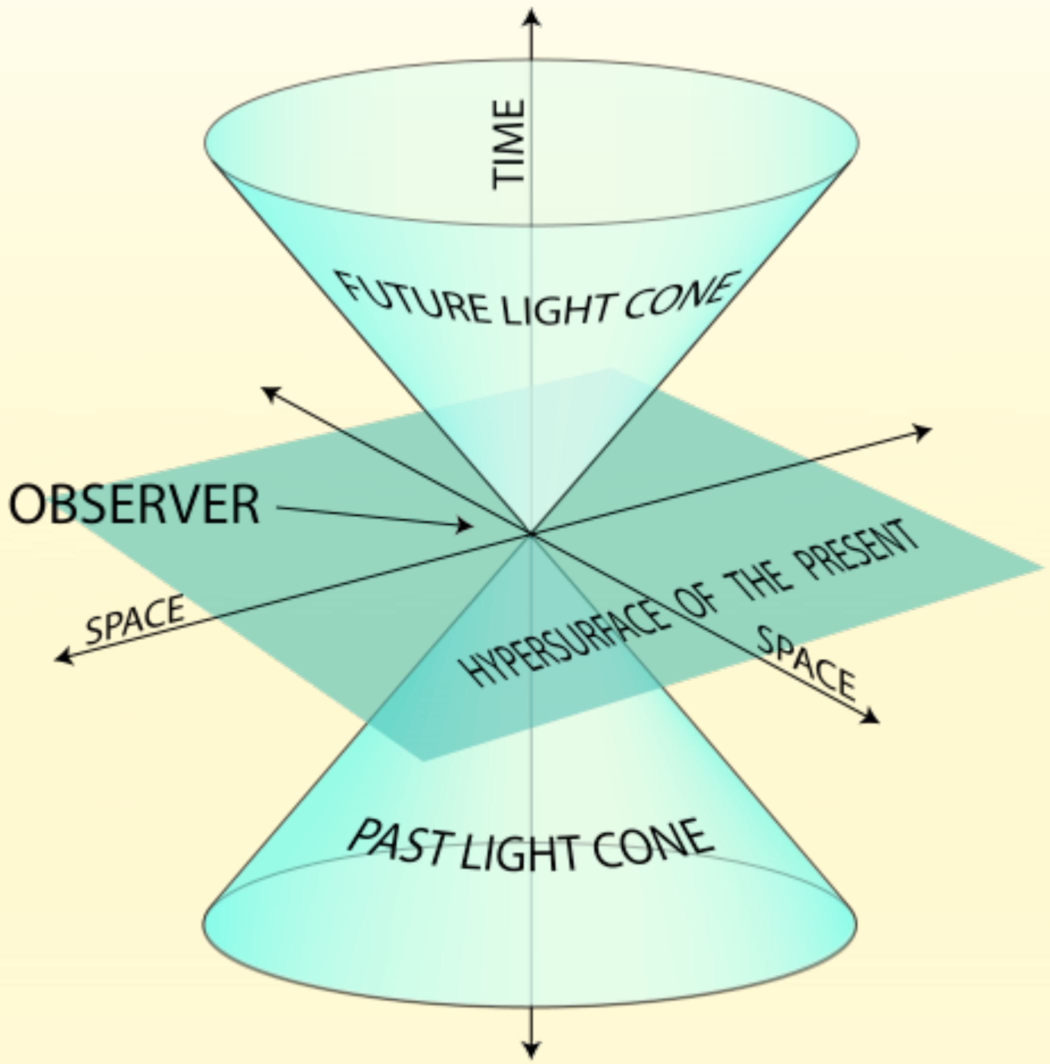
- Using Gravitational-Wave Experiments to Study Quantum Mechanics

Special Relativity

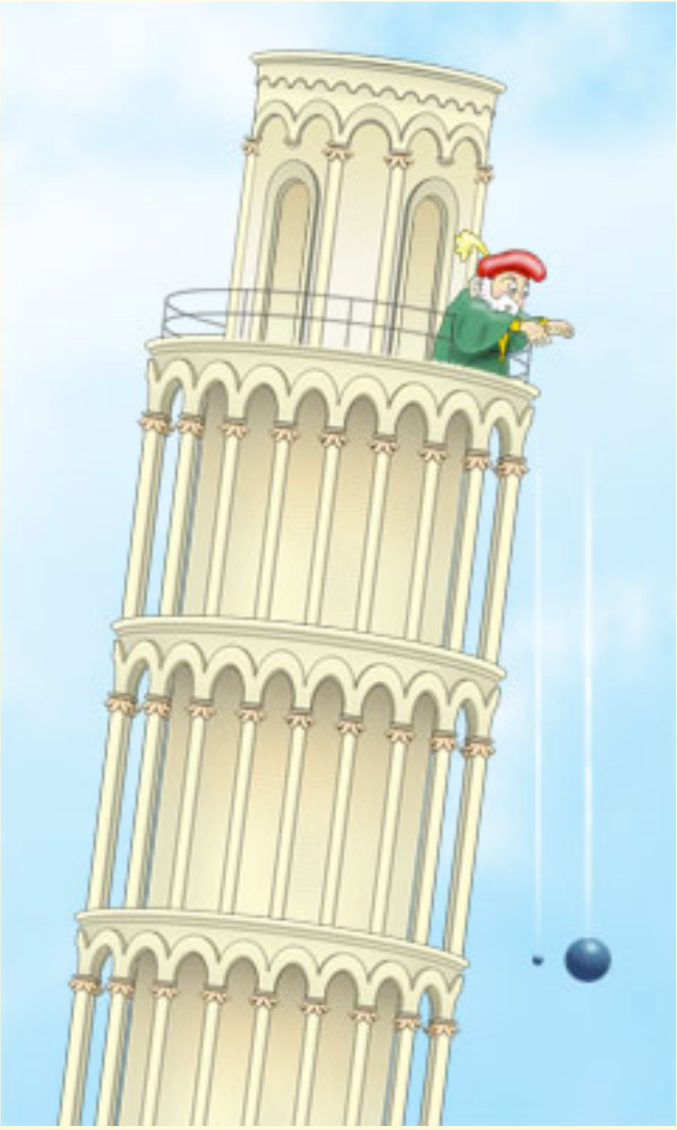
Albert Einstein

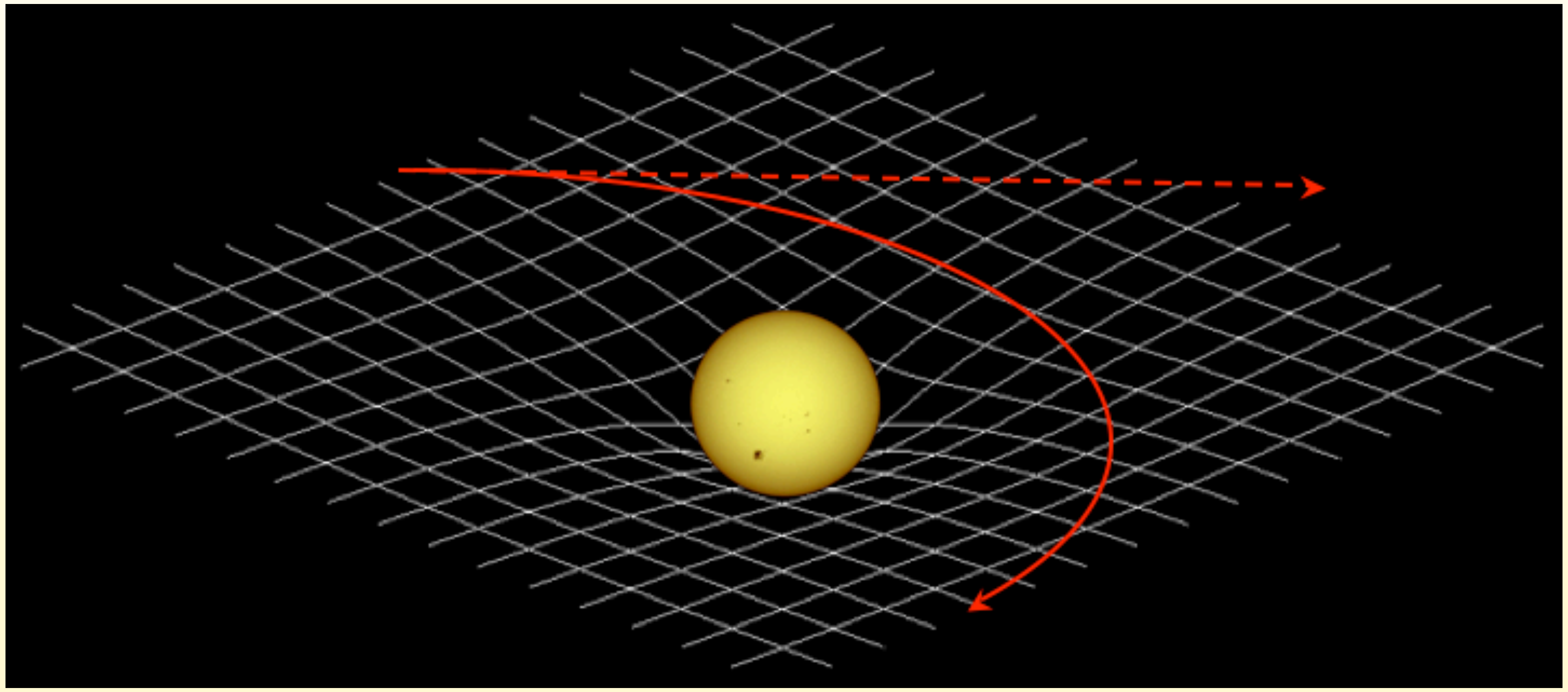


Hermann Minkowski

- Motivated by Maxwell's theory of Electromagnetism
- Unification of space and time: **spacetime**
- **The starting point for general relativity.**

General Relativity





- Motivation "Equivalence Principle": everything fall with the same acceleration
- Gravity is Geometry, not a "force"

Einstein Field Equation

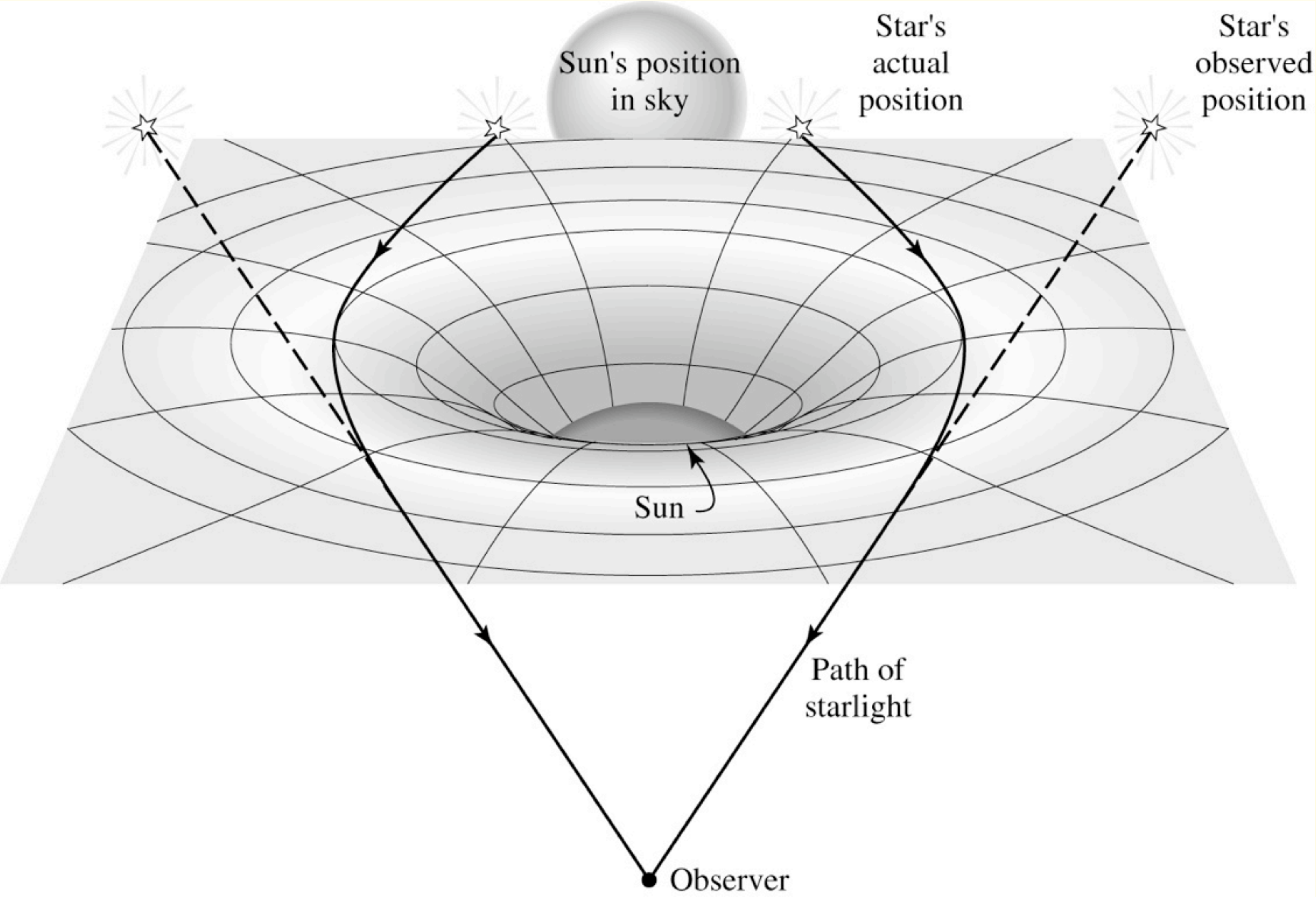
$$\underbrace{G_{\mu\nu}}_{\text{Geometry}} = \underbrace{8\pi T_{\mu\nu}}_{\text{Matter}}$$

Conservation Law

$$\nabla_\mu T^{\mu\nu} = 0$$

point particle follows time-like geodesic

Weak-Field Predictions of GR

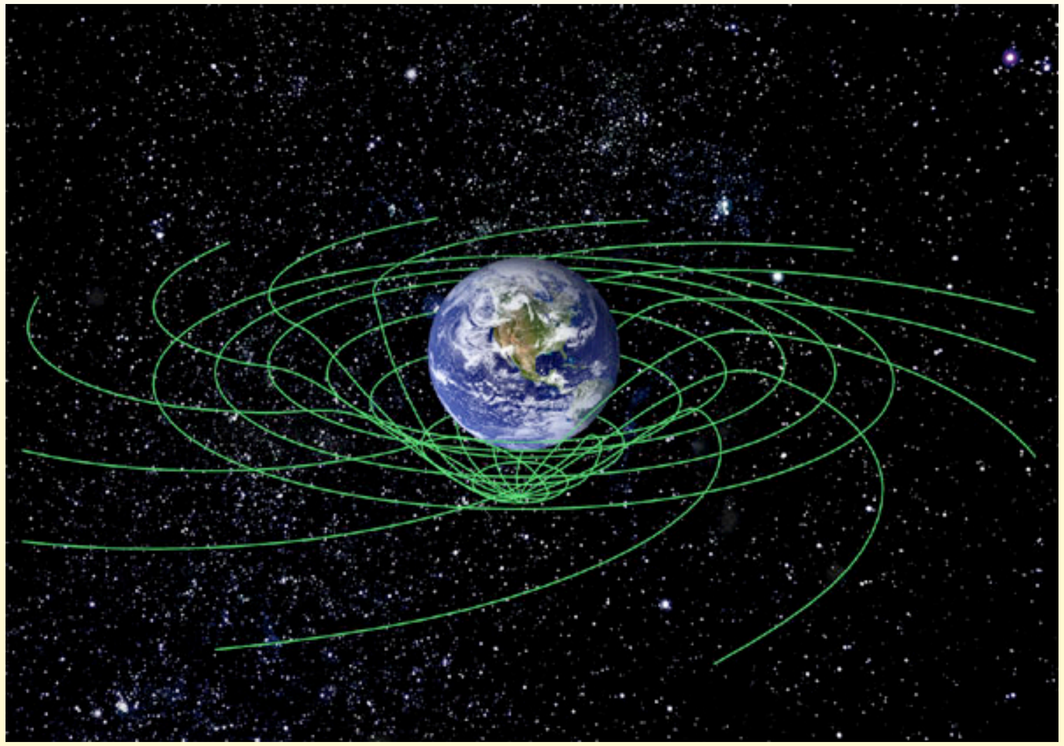


Bending of light by gravity (gravitational lensing)
Carroll & Ostlie, An Introduction to Modern Astrophysics

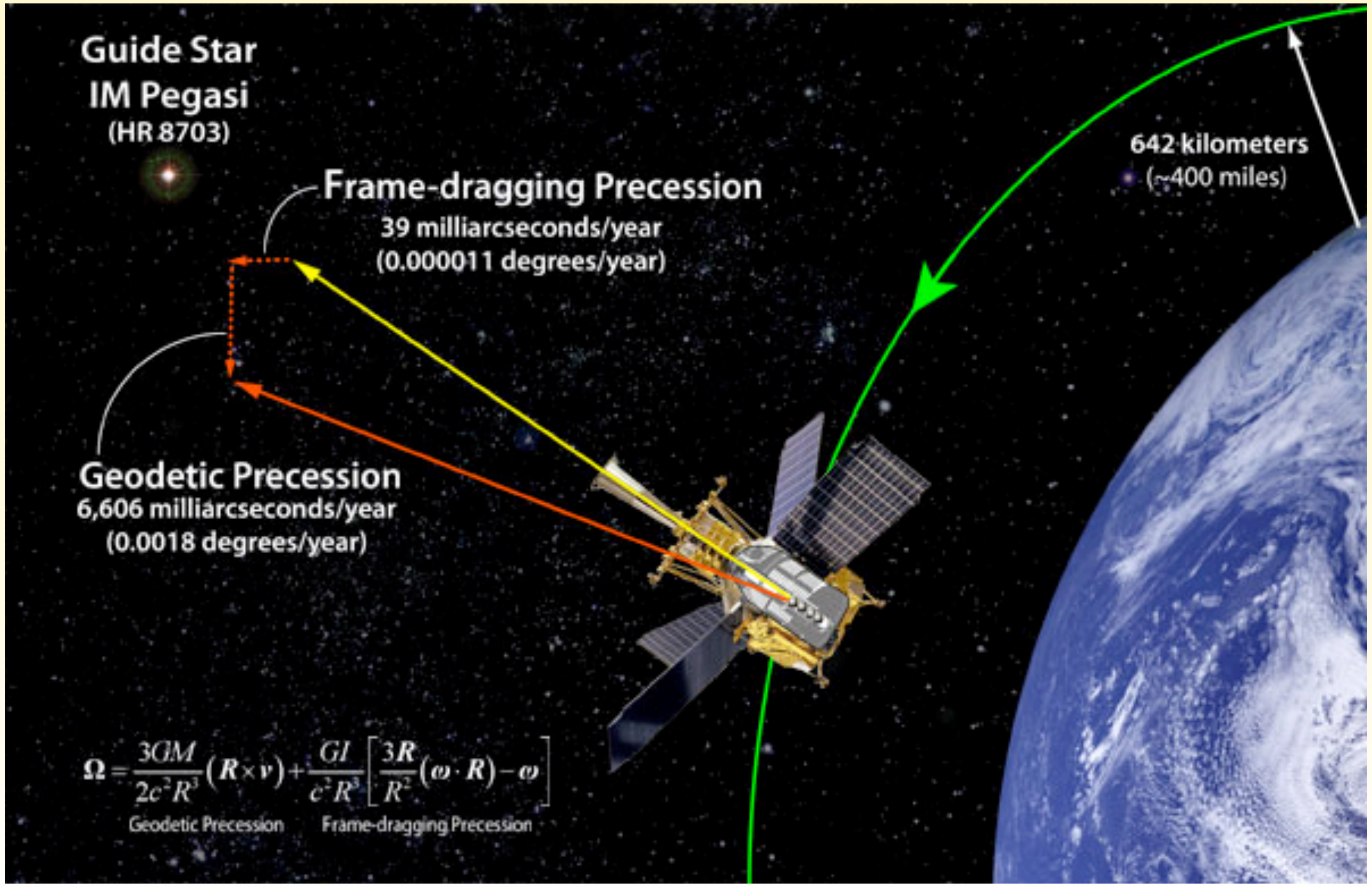
Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope • WFPC2

PRC96-10 • ST ScI OPO • April 24, 1996 • W. Colley (Princeton Univ.), NASA

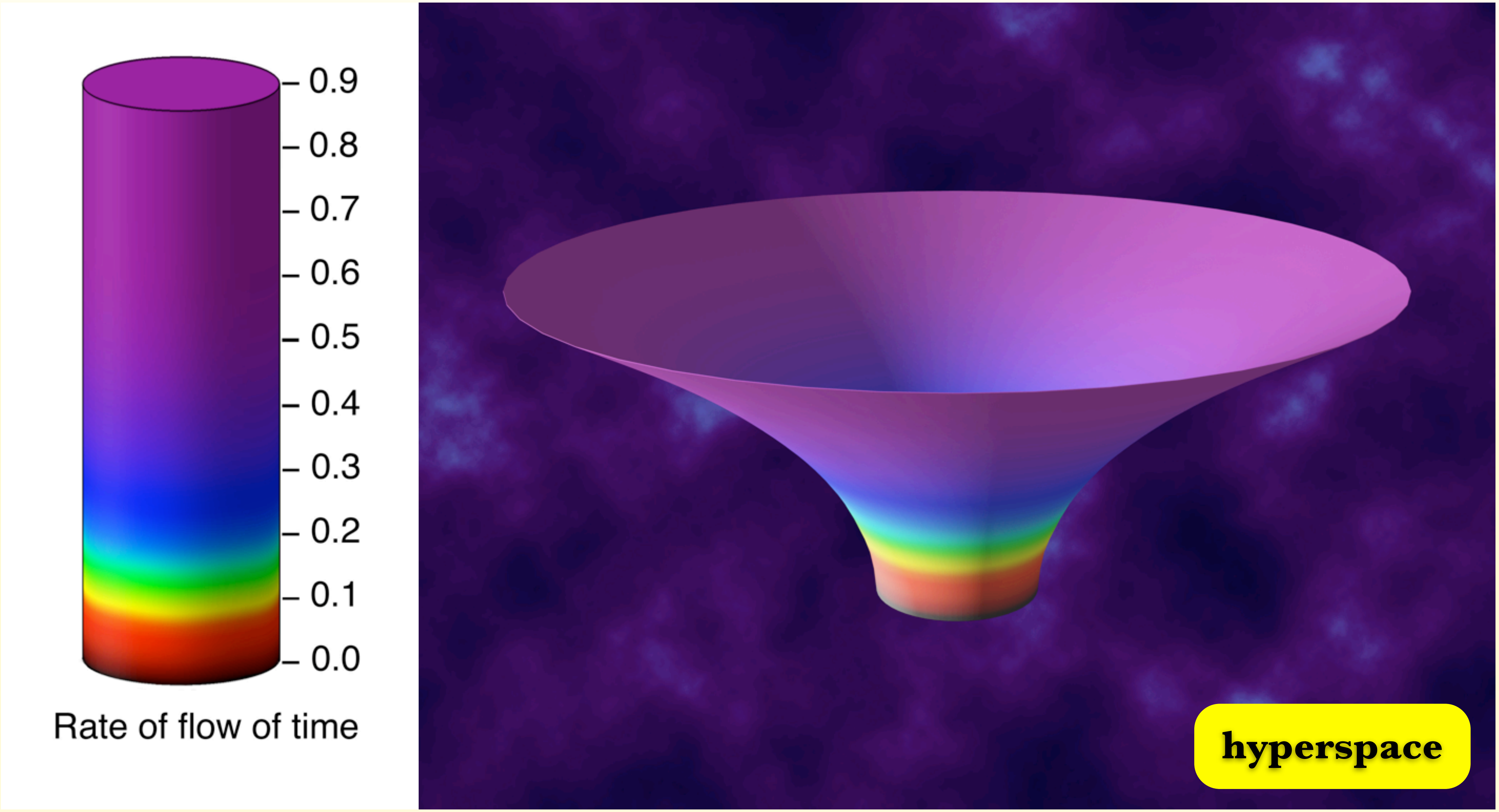
Weak-Field Predictions of GR



- Mass and rotation of the earth cause warp and whirl of nearby spacetime
- Gravity Probe B: aims at detecting both, using precession of gyroscopes.
- Warp already verified, whirl is more difficult ...

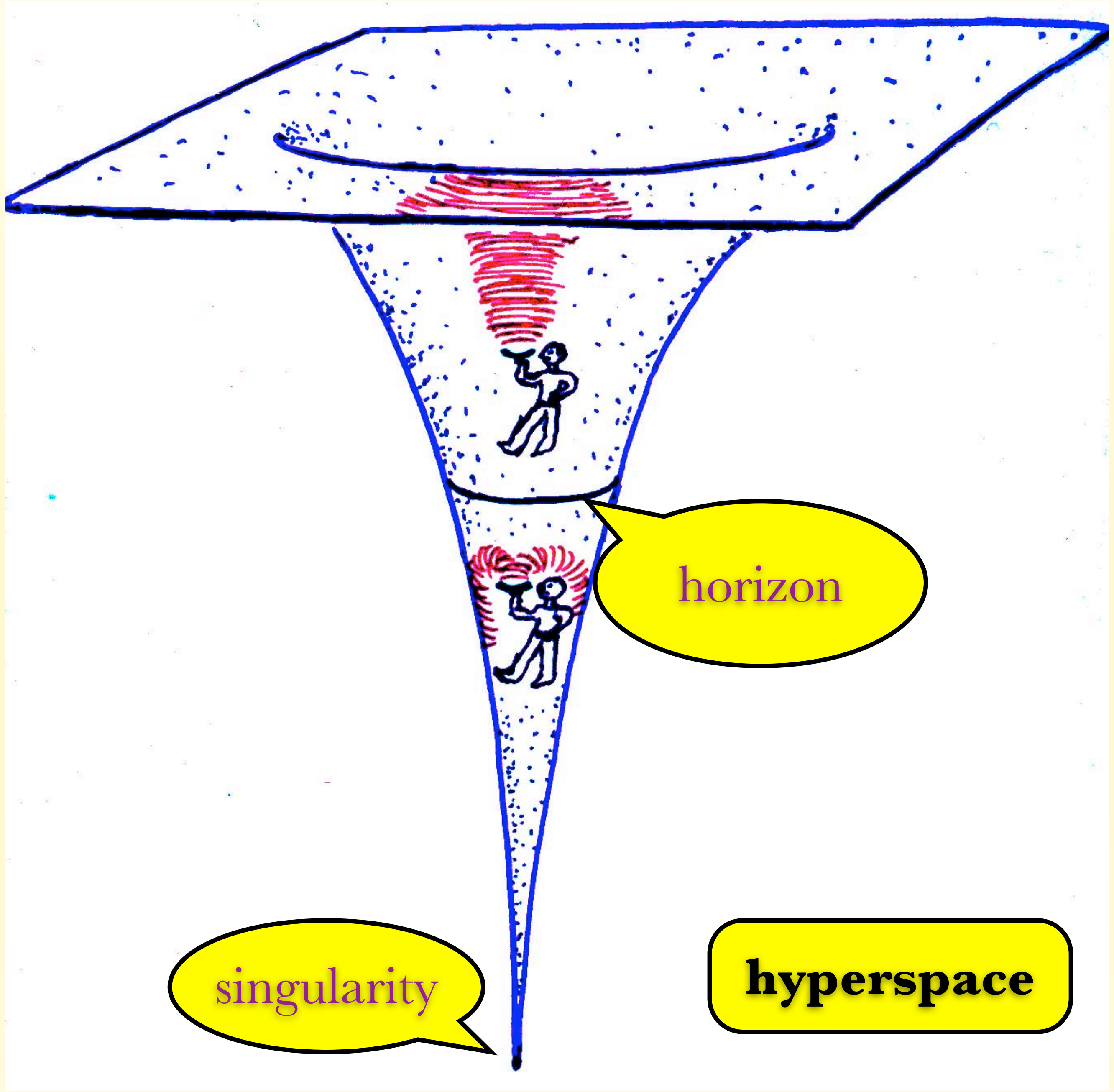


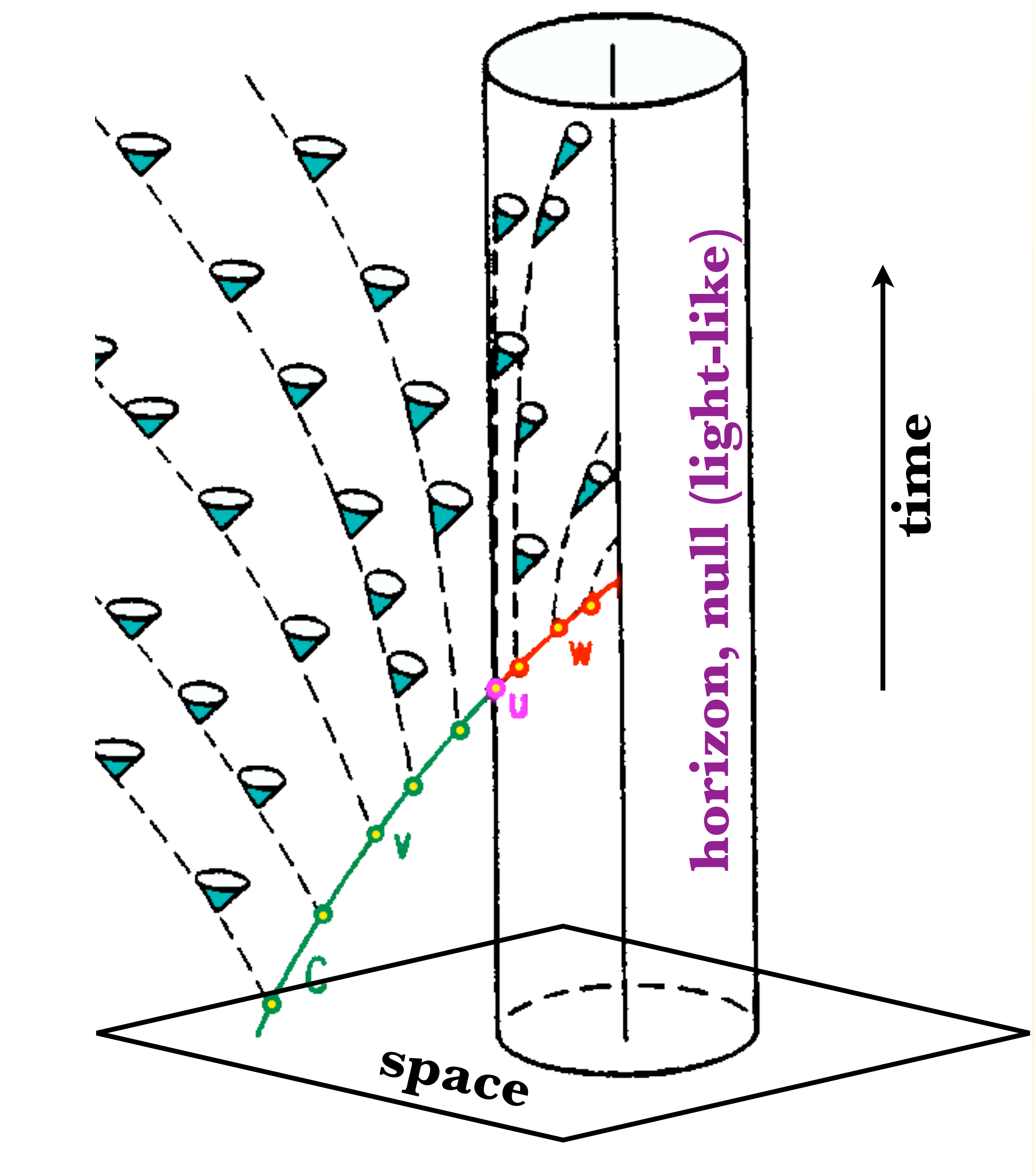
Black Holes: Pure, Nonlinear Spacetime



- Warp of spacetime: circumference > $2\pi\times$radius, time slows

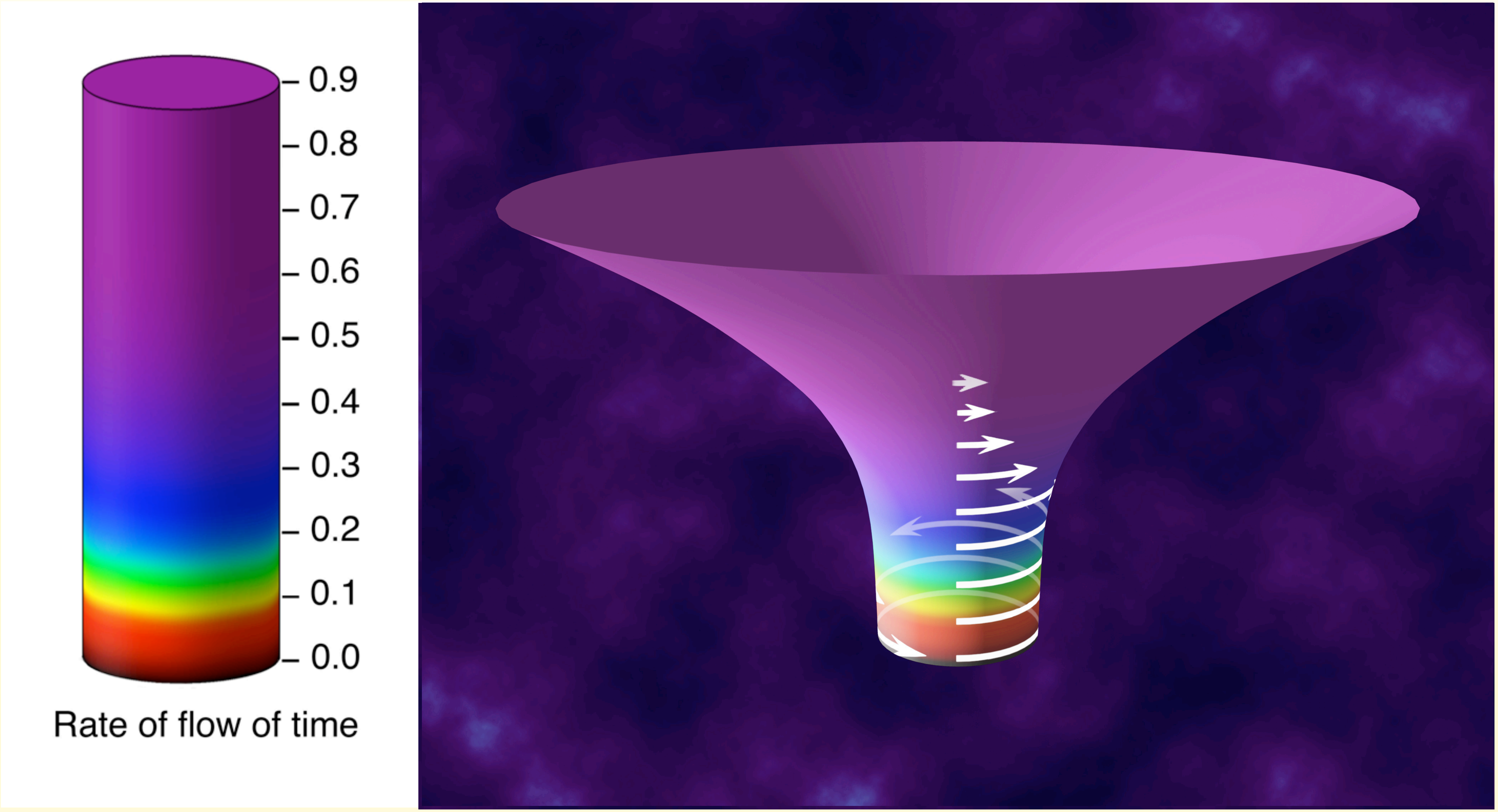
Black Holes: Pure Nonlinear Spacetime





- Warp of spacetime: circumference > 2π×radius, time slows
- Horizon: surface of no-escape

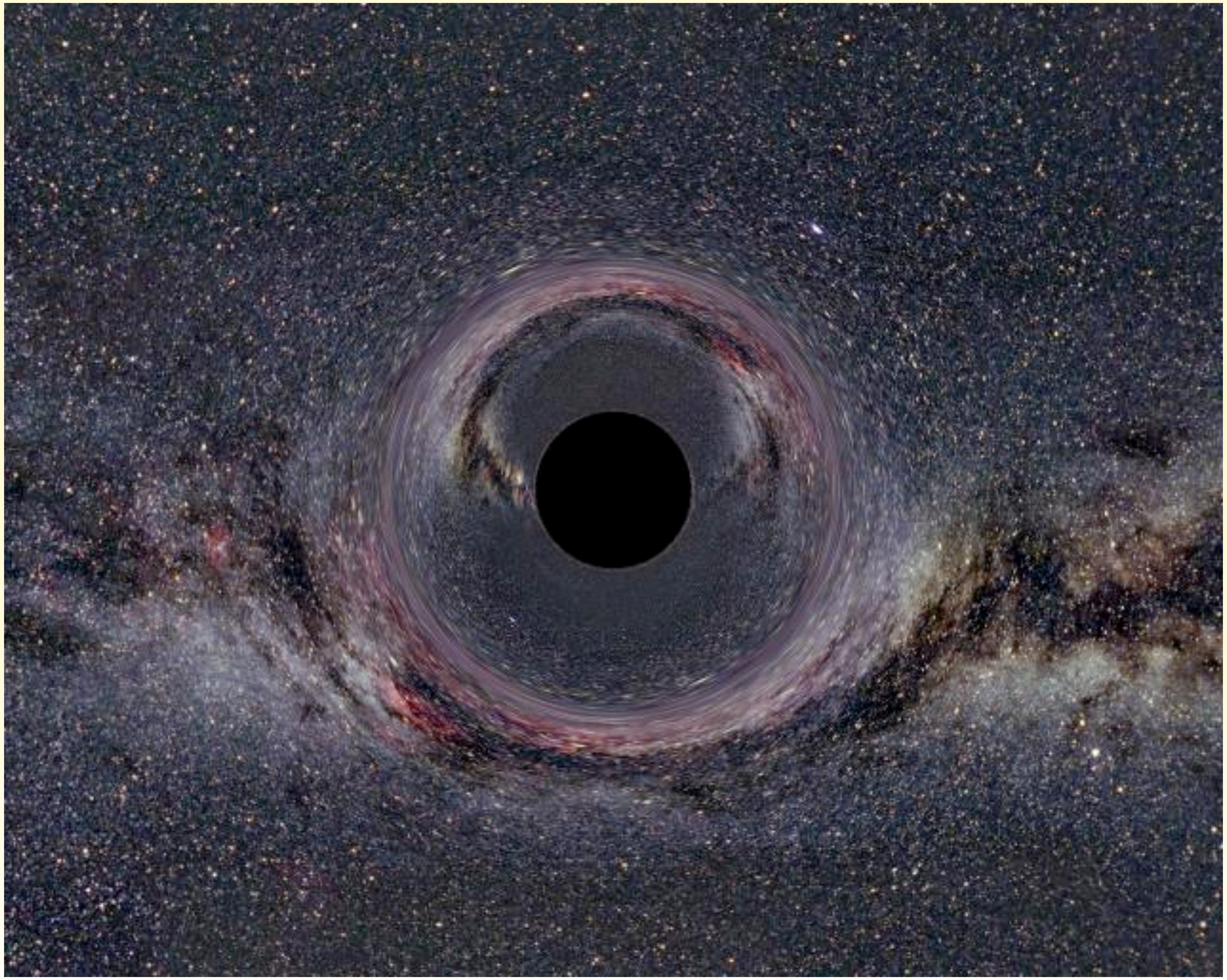
Black Holes: Pure Nonlinear Spacetime



- Warp of spacetime: circumference > 2π×radius, time slows
- Horizon: surface of no-escape
- Whirl of spacetime: nobody can stay non-rotating within the ergosphere

Formations of Black Holes

- Black Holes can form as final stage of stellar evolution
    - low-mass stars (like the sun) end up as White Dwarf stars
    - higher mass end up as Neutron Stars
    - massive stars (initially above 20 solar masses) end up as Black Holes

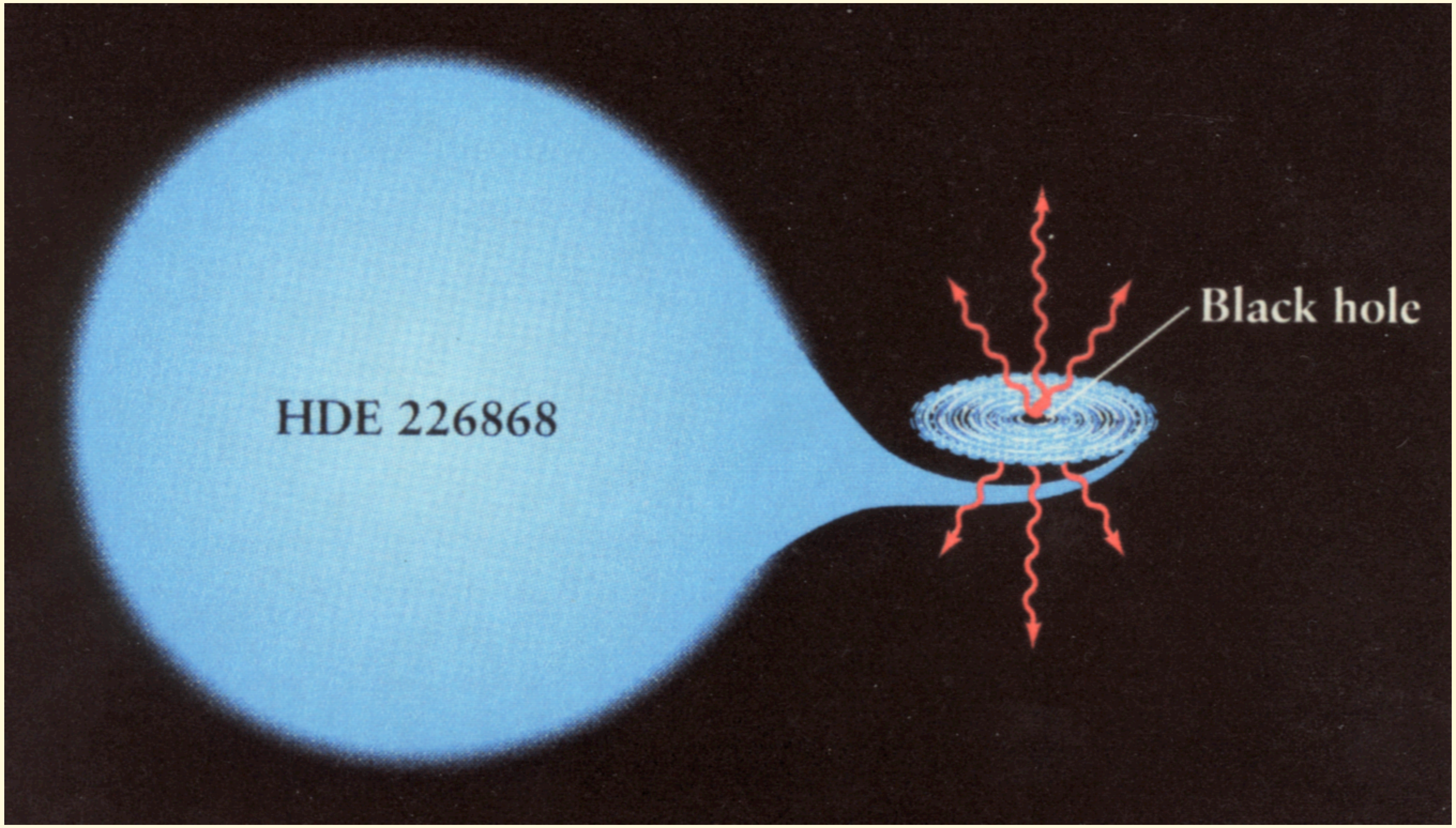


10 Solar Mass Schwarzschild Black Hole ("size" = 30km) viewed from 600 km away

Simulation by Ute Kraus, Max-Planck Institute and University of Tübingen

http://spacetimetravel.org

Stellar-Mass Black Holes

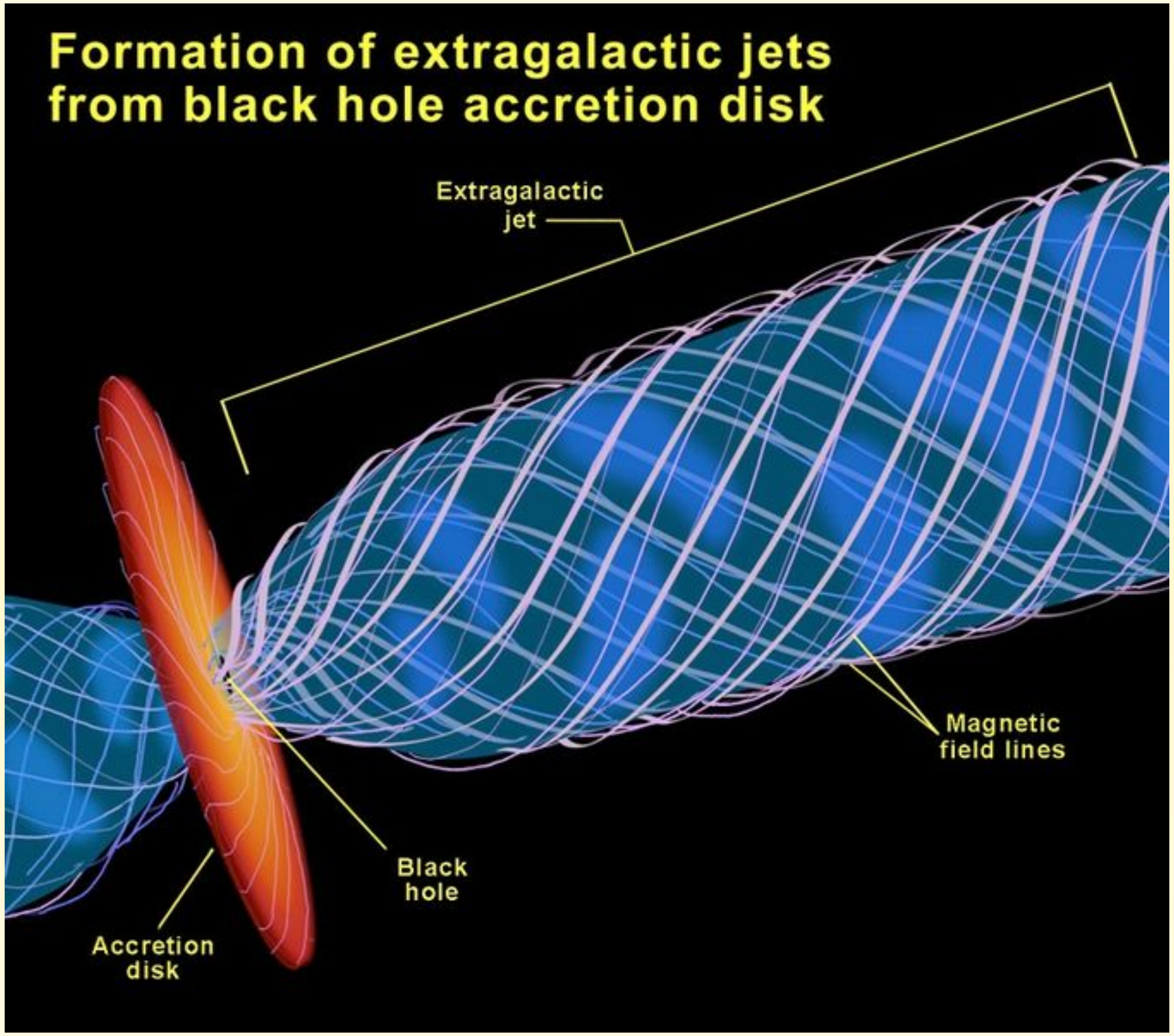


Black Holes are observable when they are in binaries

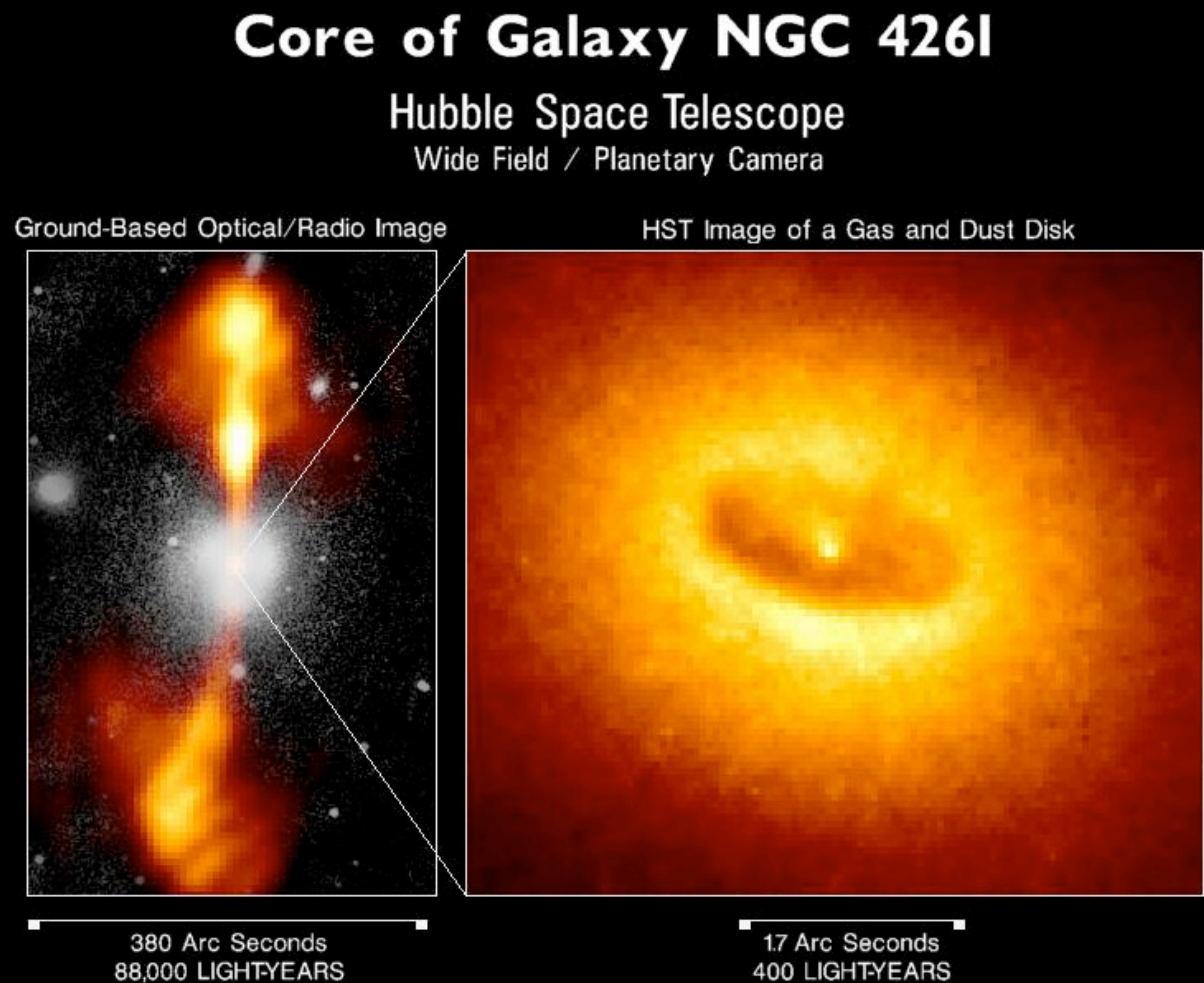
Primary criterion for being BH: mass > 3 solar mass

Supermassive Black Holes

- Quasars (1960s): supermassive Black Holes at centers of galaxies, with mass accretion

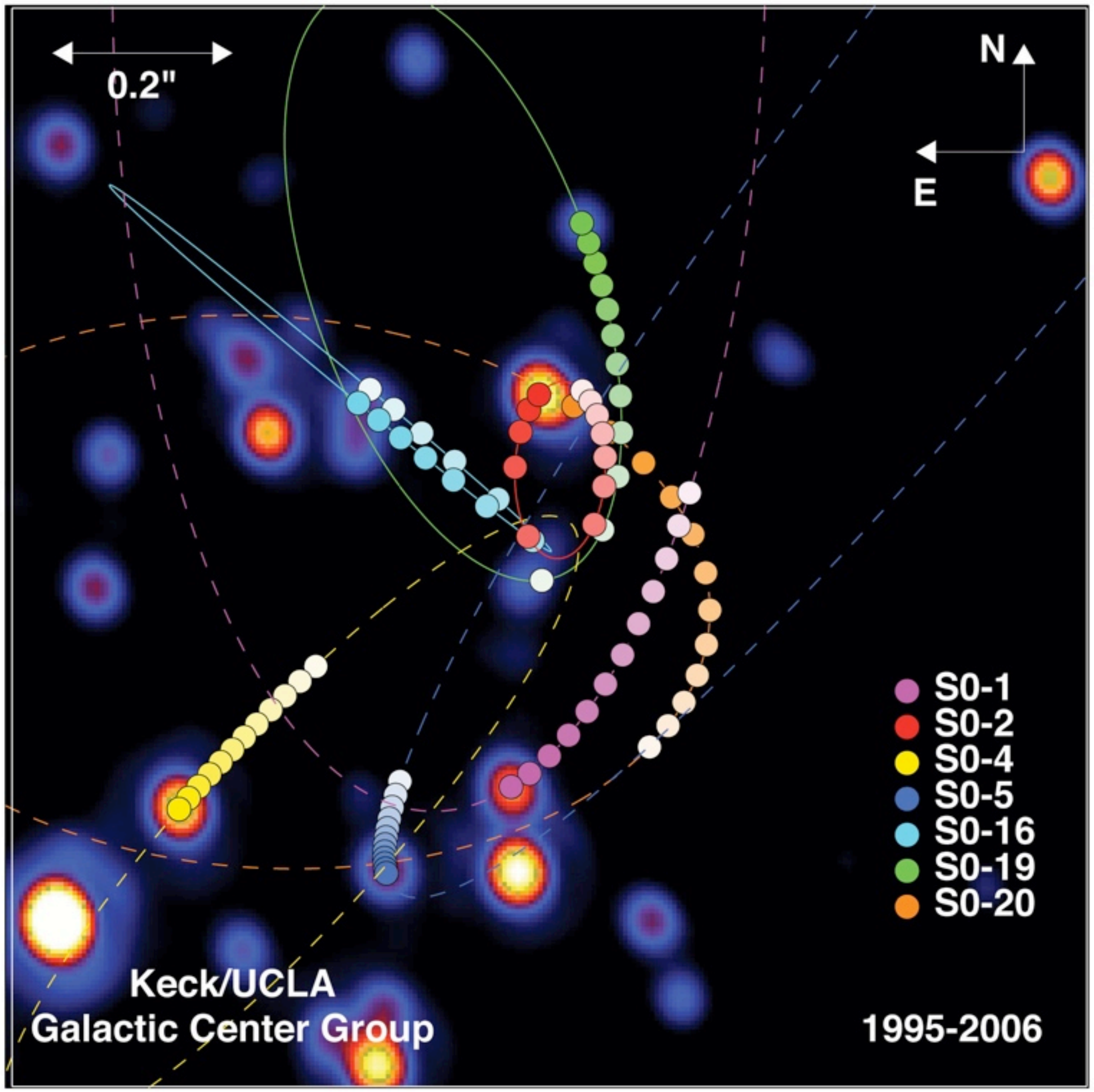


- 1% of all Galaxies are Active
- Every "respectable" nearby galaxy has a central black hole
- Origin of these black holes? Not entirely clear.



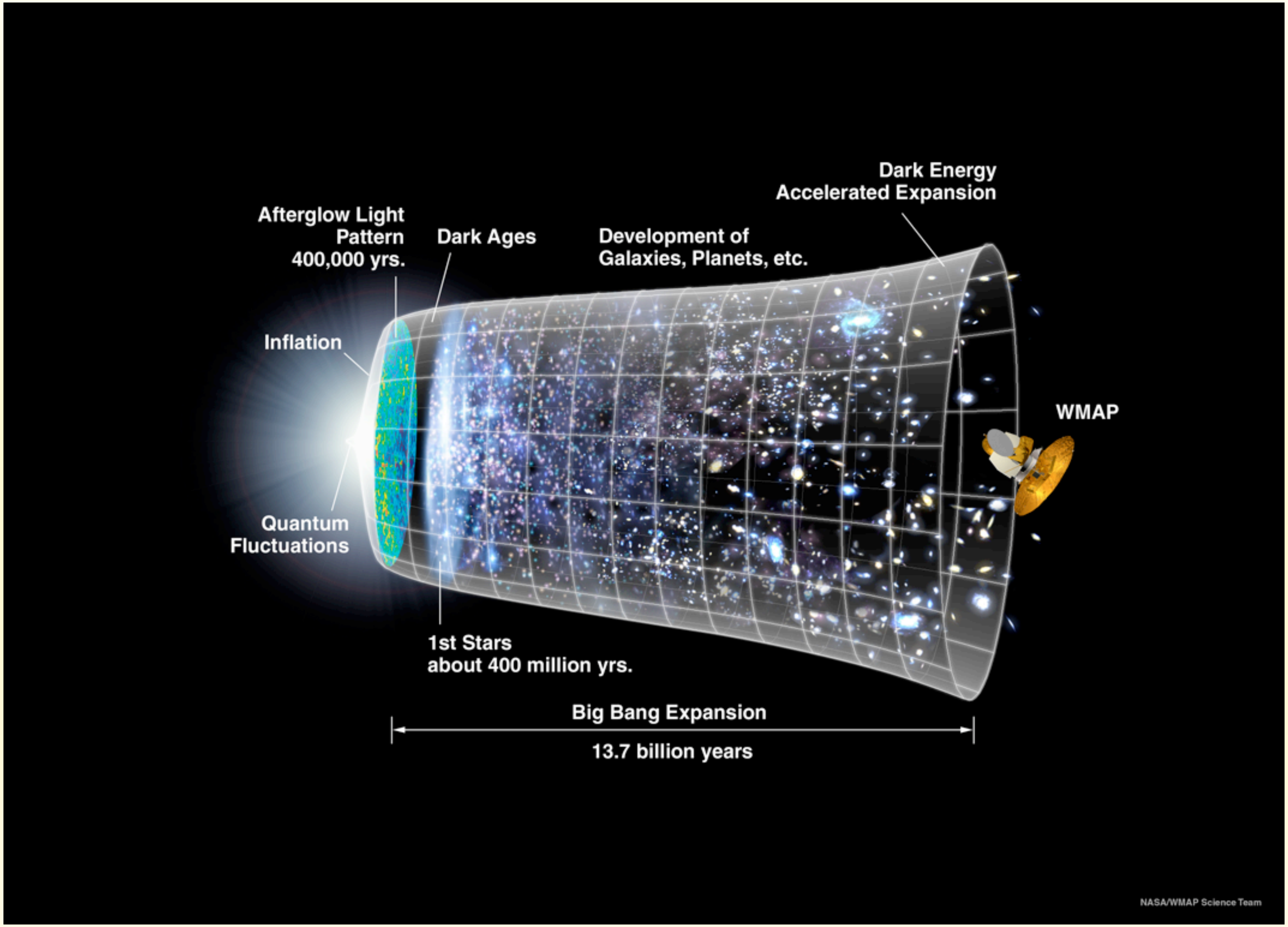
in the Virgo cluster, 59 Mly, or 18 Mpc

The Milky Way Black Hole



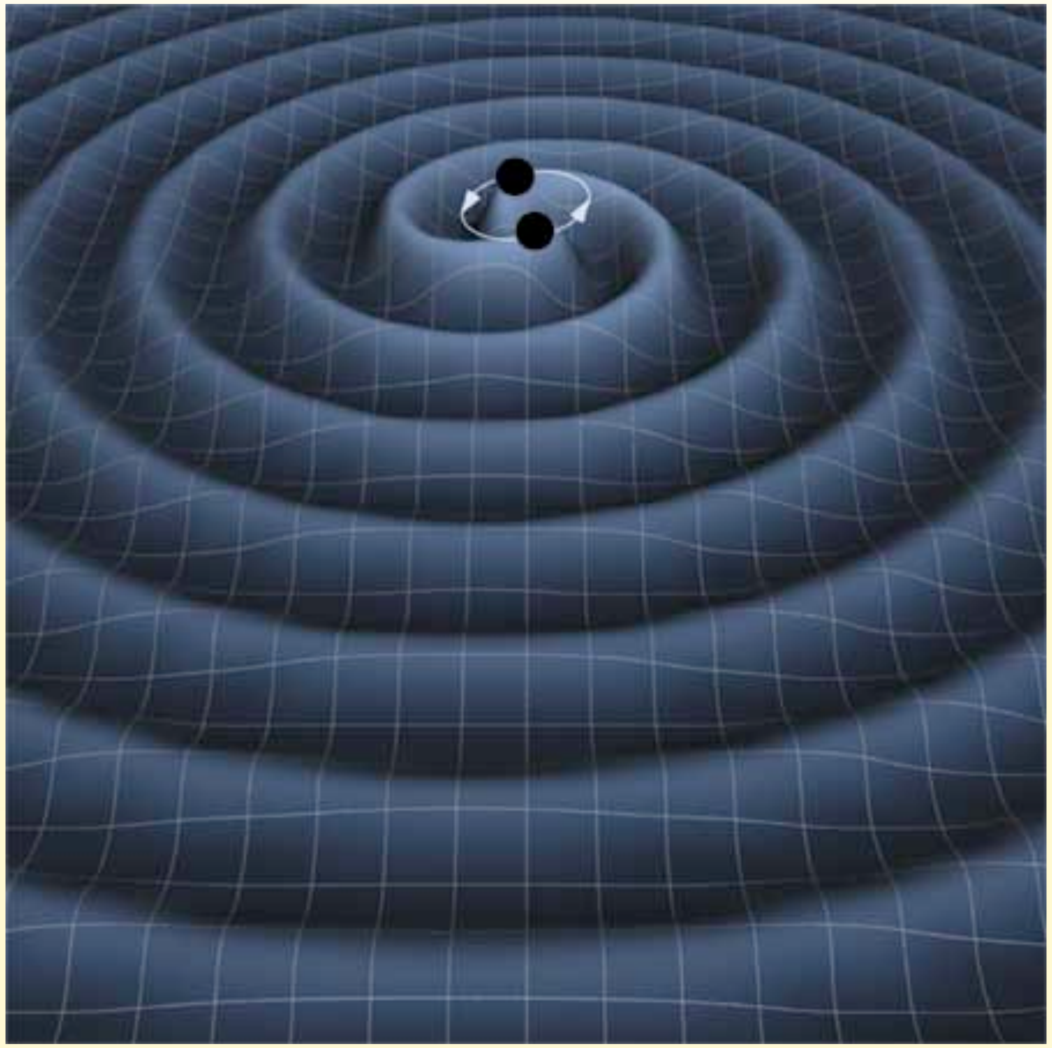
M= 4 Million Solar Masses

Cosmology, and the "Big Bang"



- General relativity also describes the dynamics of the universe

Gravitational Waves

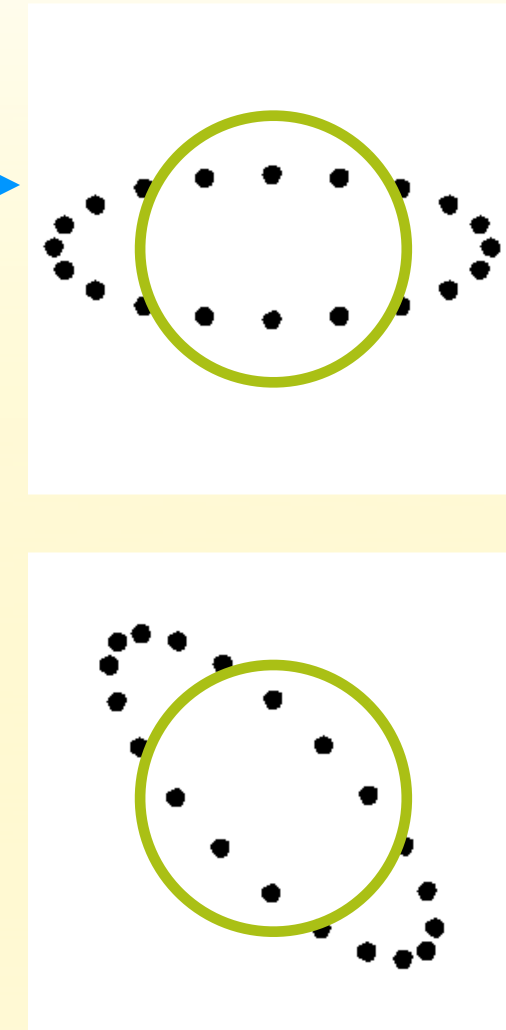


generation

distance = d

$h \sim H/d$

nearly free propagation (almost unaffected by matter)

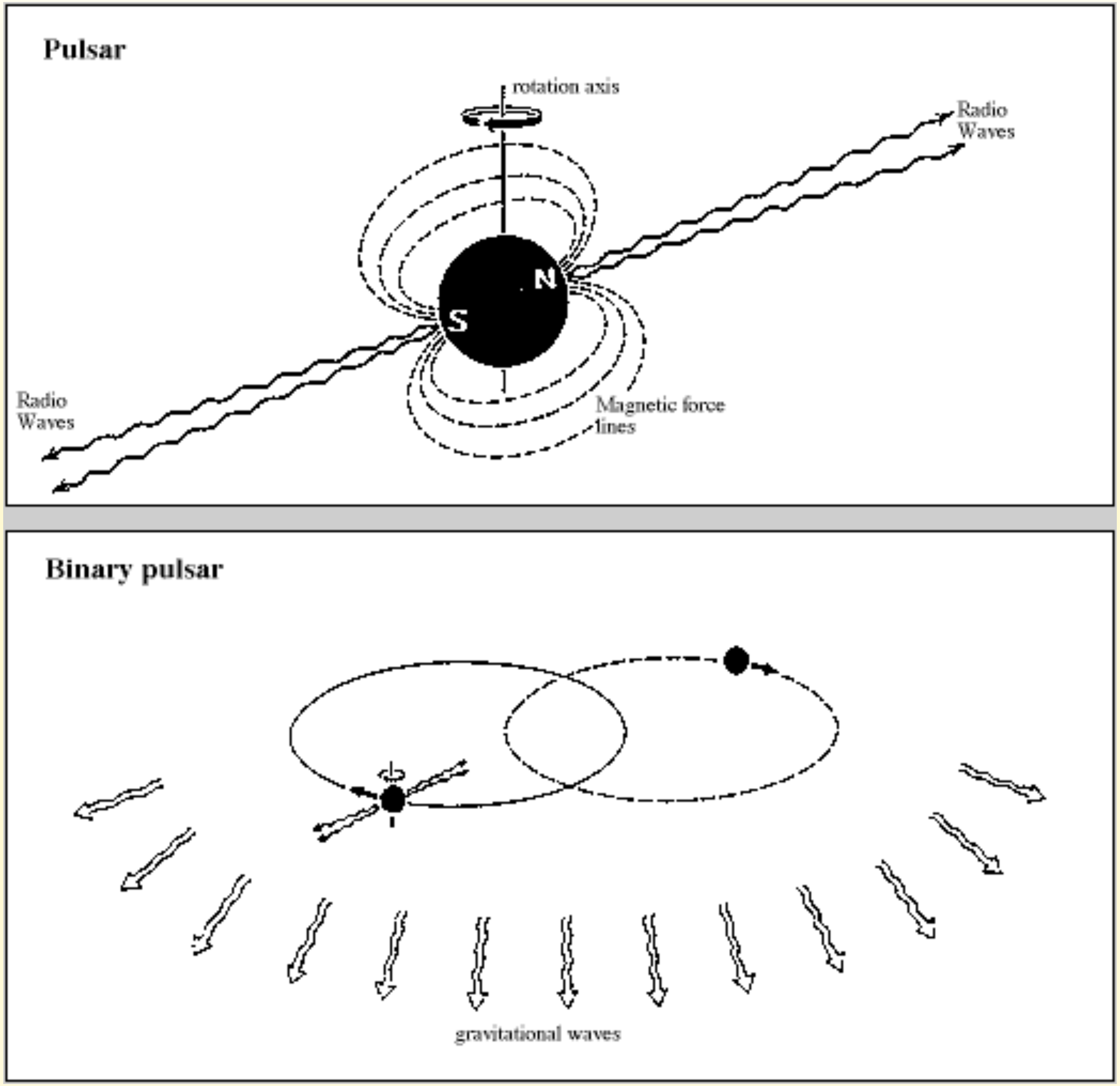


effect on free test masses

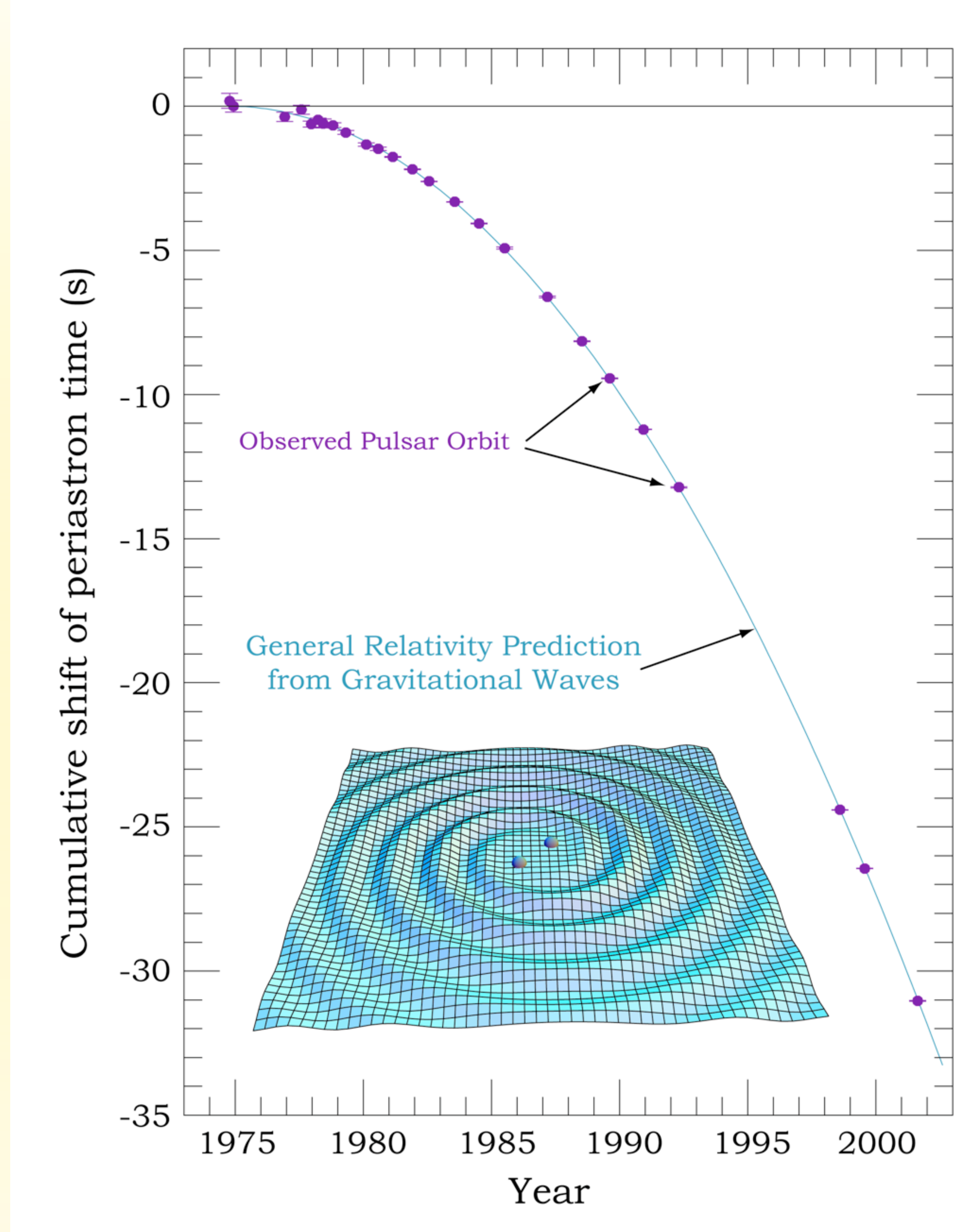
$\Delta L \sim L\, h$

- Oscillations of spacetime itself; generated by accelerated mass
- Propagates at speed of light
- Carry energy, momentum (similar to electromagnetic waves)
- Two polarizations

Evidence of Gravitational Radiation



Relativistic Binary Pulsars

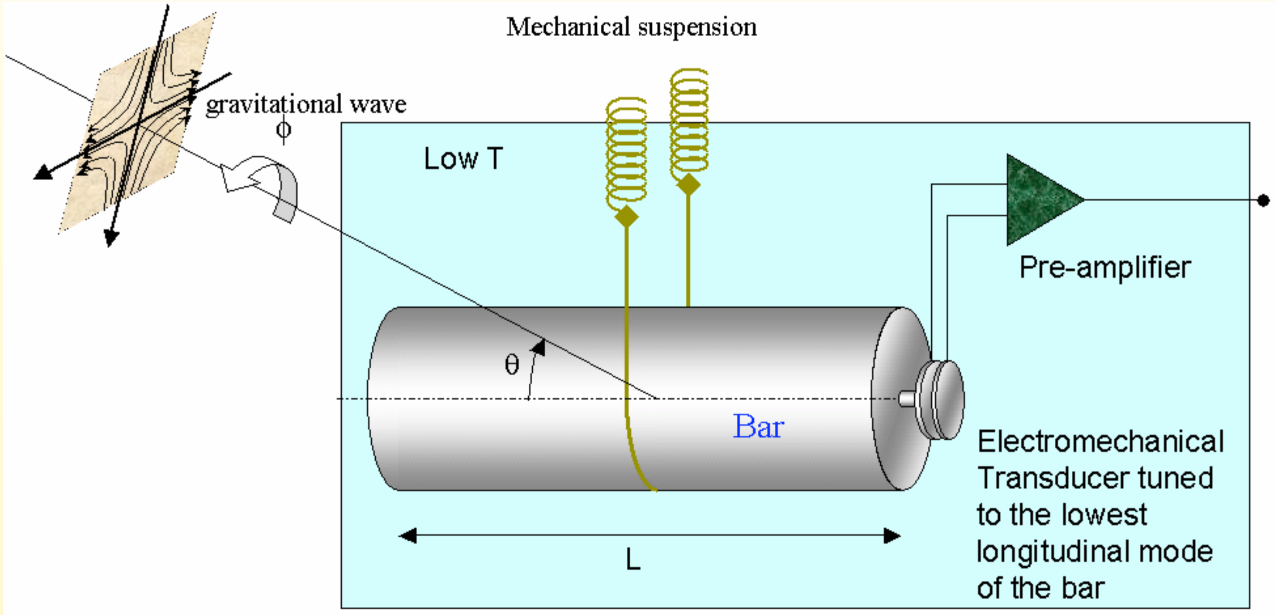


http://www.srl.caltech.edu/lisa/graphics/LISA_science.html

Data from Hulse-Taylor Pulsar

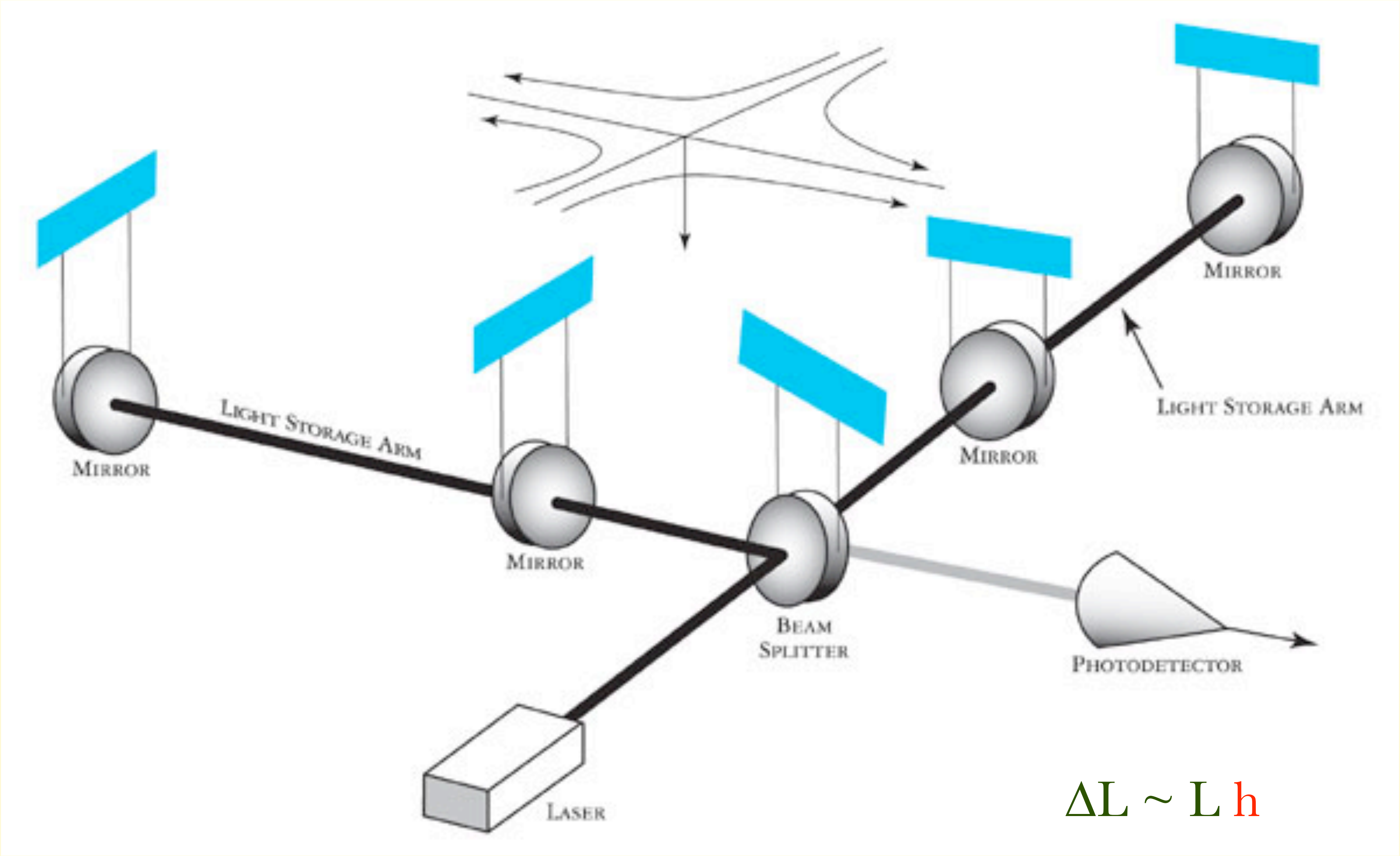
… will eventually merge in 85 Myrs

Early Days: Bar Detectors



- Resonant mass detector, invented by Joe Weber, 1960s. (Amplification around resonance)
- Claimed detections, but not verified.
- Modern bars stopped operations recently, replaced by laser interferometers

Laser Interferometers



- Comprehensive proposal by Rainer Weiss in 1972. *[In the USSR, Postovoit and Gertsenshtein, but not comprehensive ...]*
- Long arms (4 km = 2.5 miles): broadband amplification
- Sensing by laser light, with resonant enhancement

Laser Interferometer Gravitational-wave Observatory (LIGO)

Ronold Drever
Glasgow, then Caltech

Rainer Weiss
MIT

Kip Thorne
Caltech

- Funded by the NSF in 1992, operated by Caltech and MIT
- \$365M, largest project ever funded by the NSF
- "LIGO Scientific Collaboration" includes ~ 500 scientists
- Finished one year of operation, "Enhanced LIGO" starts 2009, with 2-3 times sensitivity
- \$205M for upgrade to Advanced LIGO, with 15 times sensitivity (start operation in 2014)

IMPLICATIONS FOR THE ORIGIN OF GRB 070201 FROM LIGO OBSERVATIONS

B. Abbott[14], R. Abbott[14], R. Adhikari[14], J. Agresti[14], P. Ajith[2], B. Allen[2,51], R. Amin[18], S. B. Anderson[14], W. G. Anderson[51], M. Arain[39], M. Araya[14], H. Armandula[14], M. Ashley[4], S. Aston[38], P. Aufmuth[36], C. Aulbert[1], S. Babak[1], S. Ballmer[14], H. Bantilan[8], B. C. Barish[14], C. Barker[15], D. Barker[15], B. Barr[40], P. Barriga[50], M. A. Barton[40], K. Bayer[17], J. Betzwieser[17], P. T. Beyersdorf[27], B. Bhawal[14], I. A. Bilenko[21], G. Billingsley[14], R. Biswas[51], E. Black[14], K. Blackburn[14], L. Blackburn[17], D. Blair[50], B. Bland[15], J. Bogenstahl[40], L. Bogue[16], R. Bork[14], V. Boschi[14], S. Bose[52], P. R. Brady[51], V. B. Braginsky[21], J. E. Brau[43], M. Brinkmann[2], A. Brooks[37], D. A. Brown[14,6], A. Bullington[30], A. Bunkowski[2], A. Buonanno[41], O. Burmeister[2], D. Busby[14], R. L. Byer[30], L. Cadonati[17], G. Cagnoli[40], J. B. Camp[22], J. Cannizzo[22], K. Cannon[51], C. A. Cantley[40], J. Cao[17], L. 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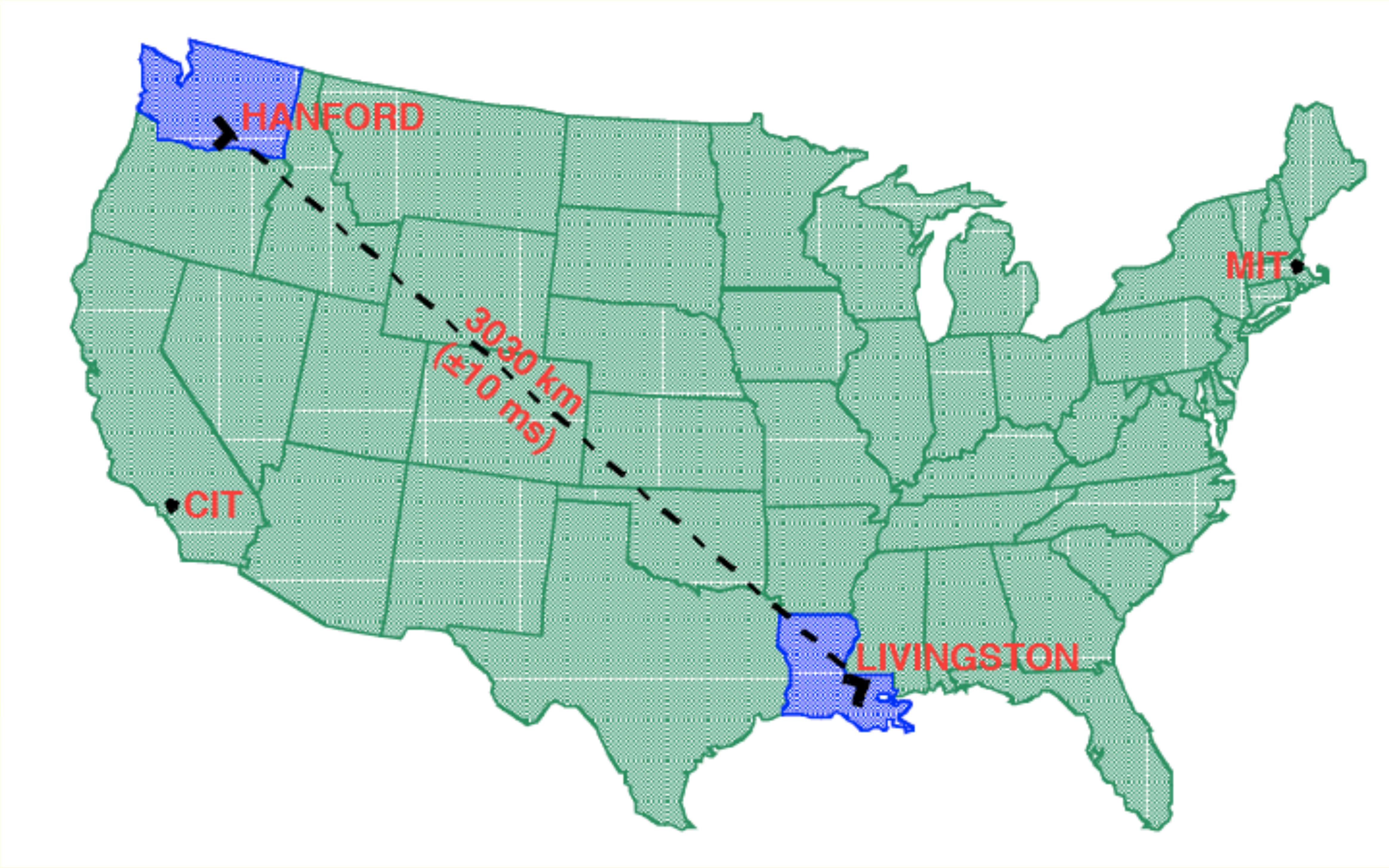
[39] University of Florida, Gainesville, FL 32611, USA
[40] University of Glasgow, Glasgow, G12 8QQ, United Kingdom
[41] University of Maryland, College Park, MD 20742 USA
[42] University of Michigan, Ann Arbor, MI 48109, USA
[43] University of Oregon, Eugene, OR 97403, USA
[44] University of Rochester, Rochester, NY 14627, USA
[45] University of Salerno, 84084 Fisciano (Salerno), Italy
[46] University of Sannio at Benevento, I-82100 Benevento, Italy
[47] University of Southampton, Southampton, SO17 1BJ, United Kingdom
[48] University of Strathclyde, Glasgow, G1 1XQ, United Kingdom
[49] University of Washington, Seattle, WA, 98195
[50] University of Western Australia, Crawley, WA 6009, Australia
[51] University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA
[52] Washington State University, Pullman, WA 99164, USA

LIGO Sites



Reason for two detectors: **coincident detection, and localization of source**

LIGO Hanford Observatory

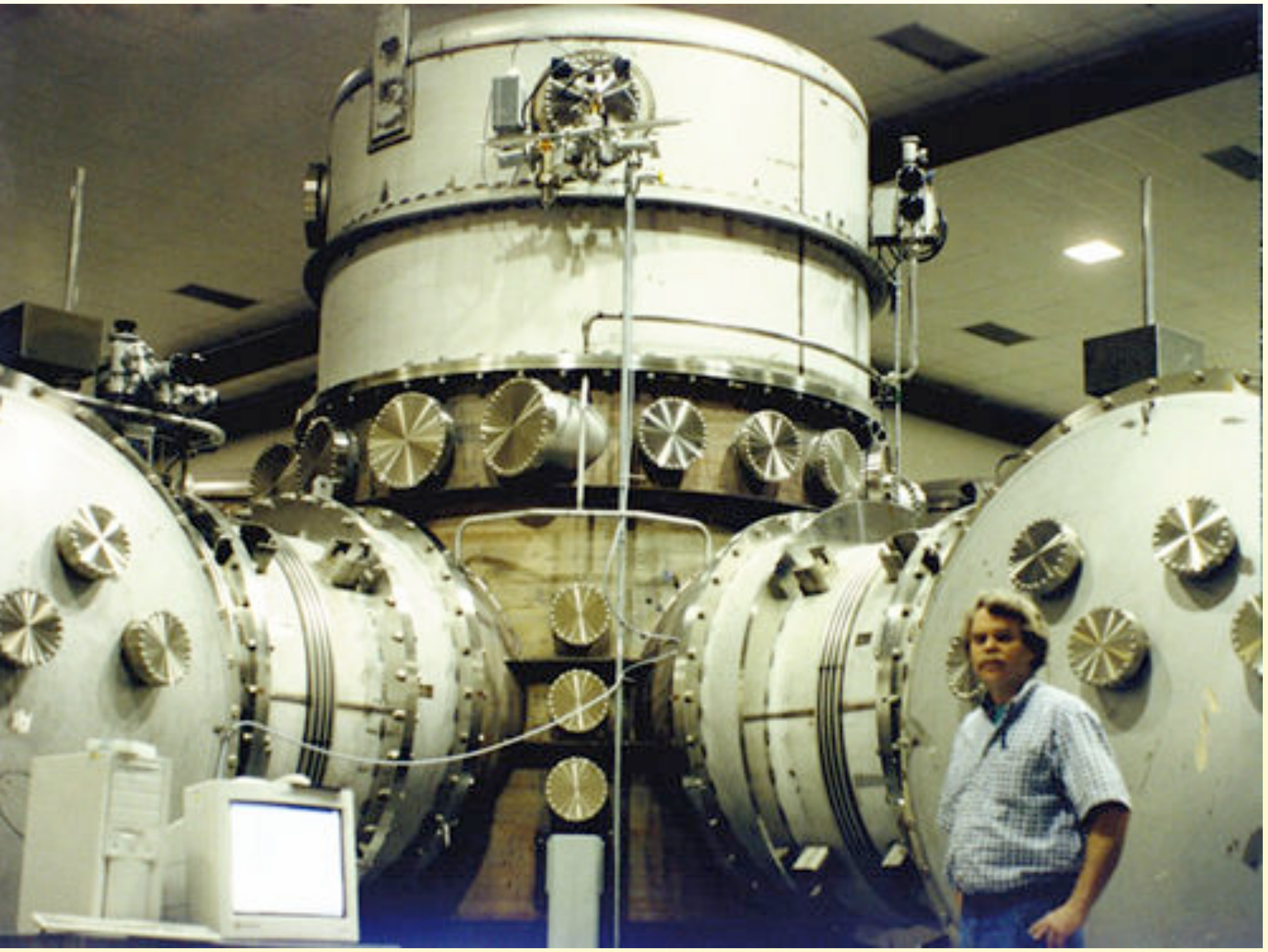
Hanford, WA (near Pasco-Richland-Kennewick, WA)

LIGO Livingston Observatory

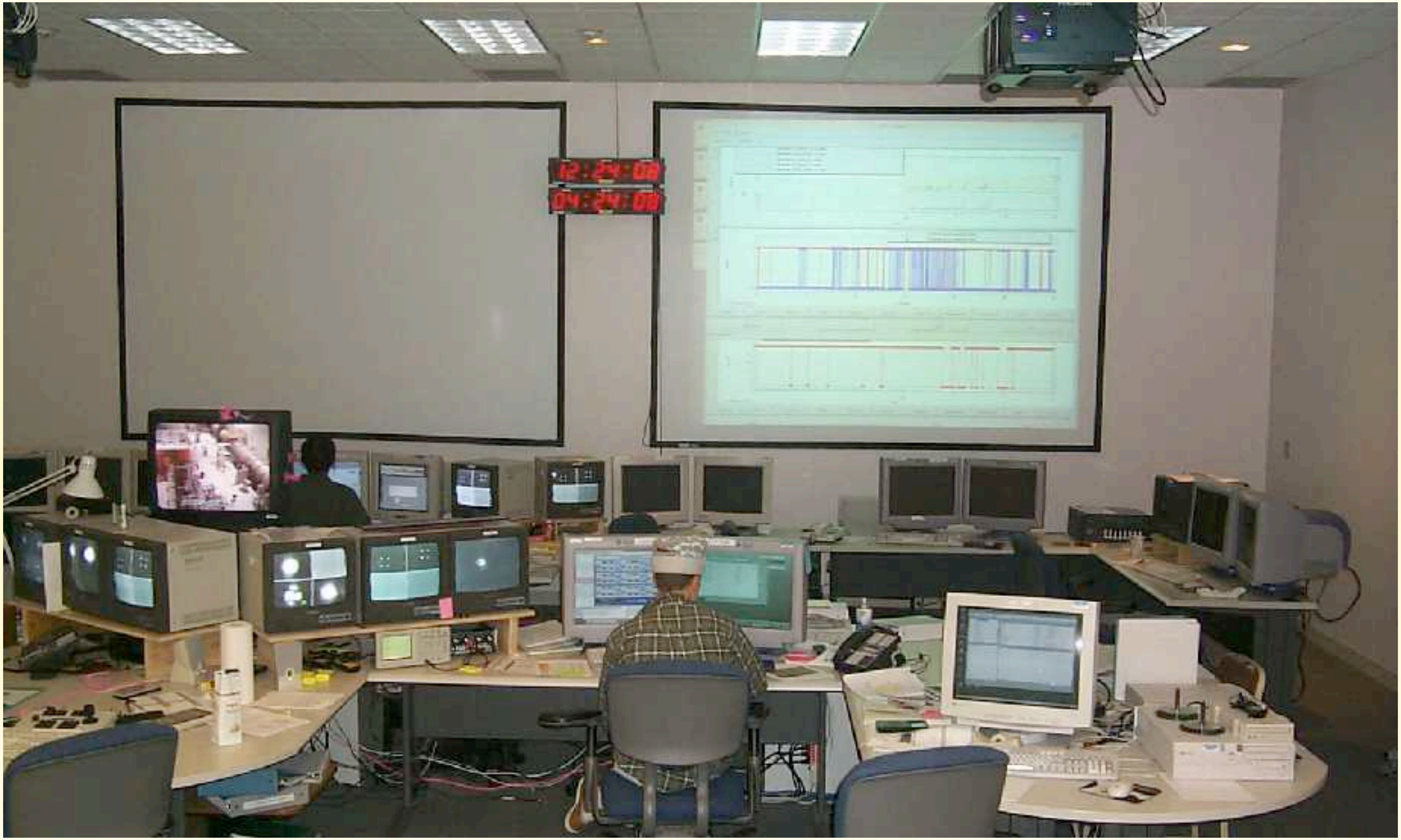
Livingston, LA (near Baton Rouge, LA)

The Beam Tubes

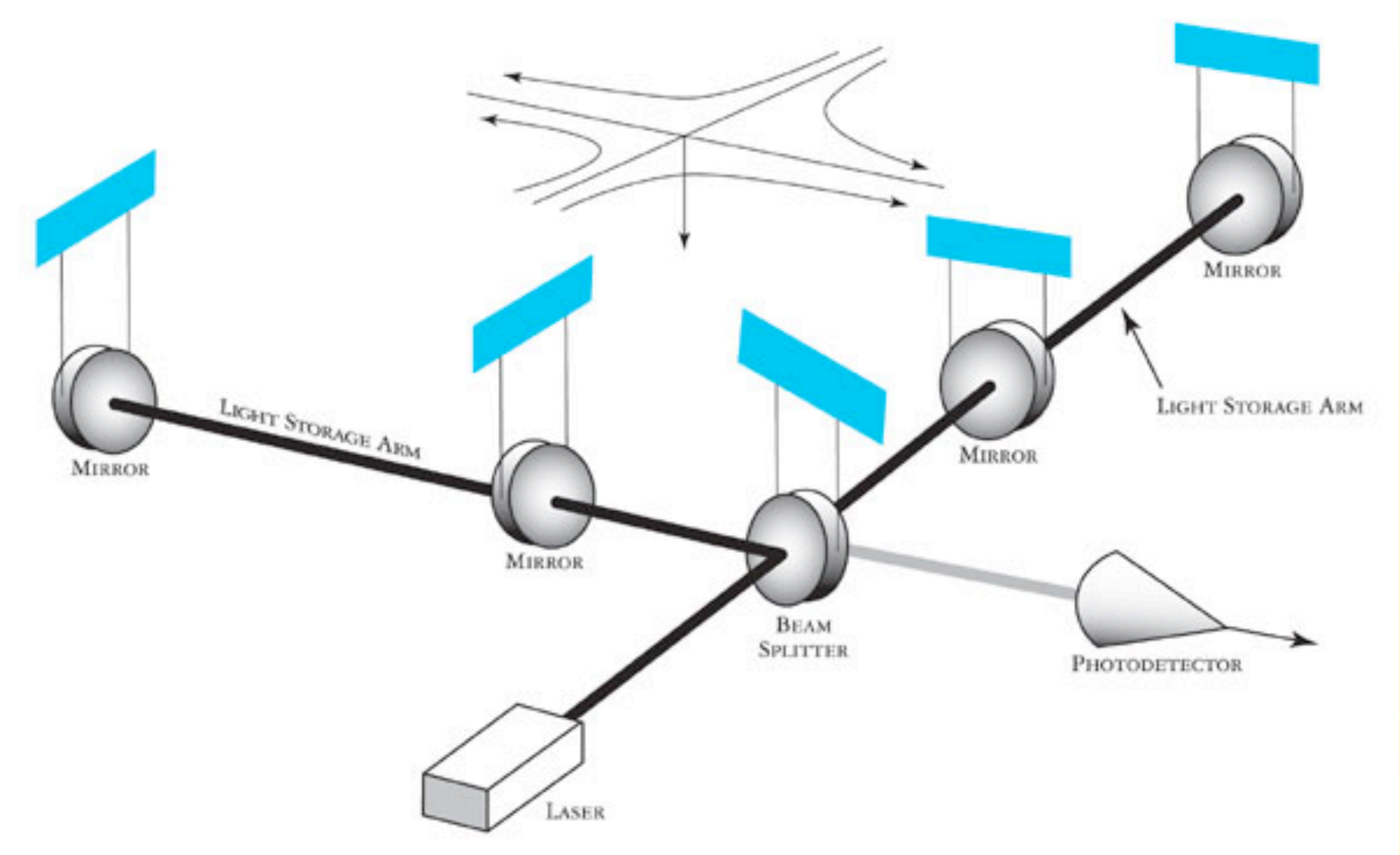
Vacuum Chambers



Control Room



LIGO sensitivity



$$\Delta L = L\,h = 4000\ m \times 10^{-21} = 4 \times 10^{-18}\ m$$

How small is 10^{-18} m? How is this possible?

	1-2 meter	height of an adult
÷ 10,000	10^{-4}m = 100 micron	human hair
÷ 100	10^{-6}m = 1 micron	wavelength of light (in LIGO)
÷ 10,000	10^{-10}m = 1 Angstrom	atom
÷ 100,000	10^{-15}m = 1 fm	atomic nucleus
÷ 1,000	10^{-18}m	current LIGO sensitivity
÷ 10	10^{-19}m	Advanced LIGO

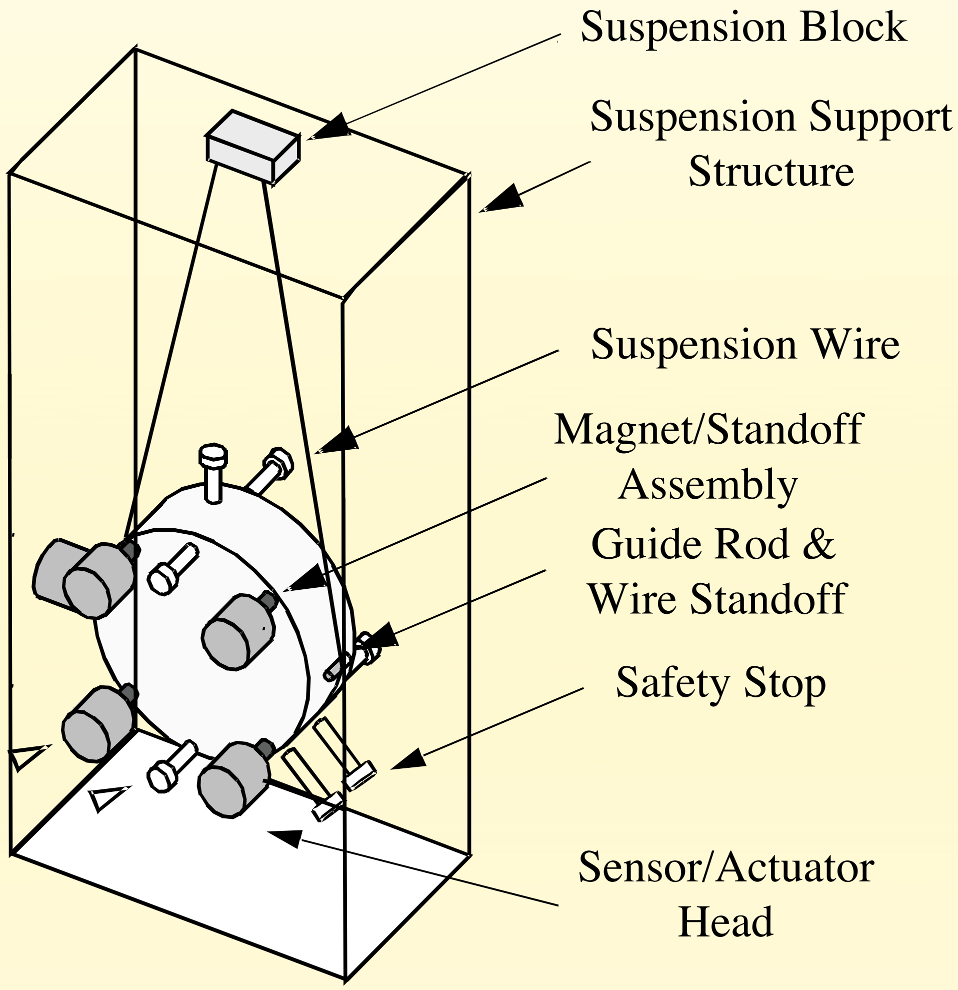
use a lot of photons (strong light) each samples mirrors many times (resonance)

average over many atoms (wide beam)

LIGO Mirrors

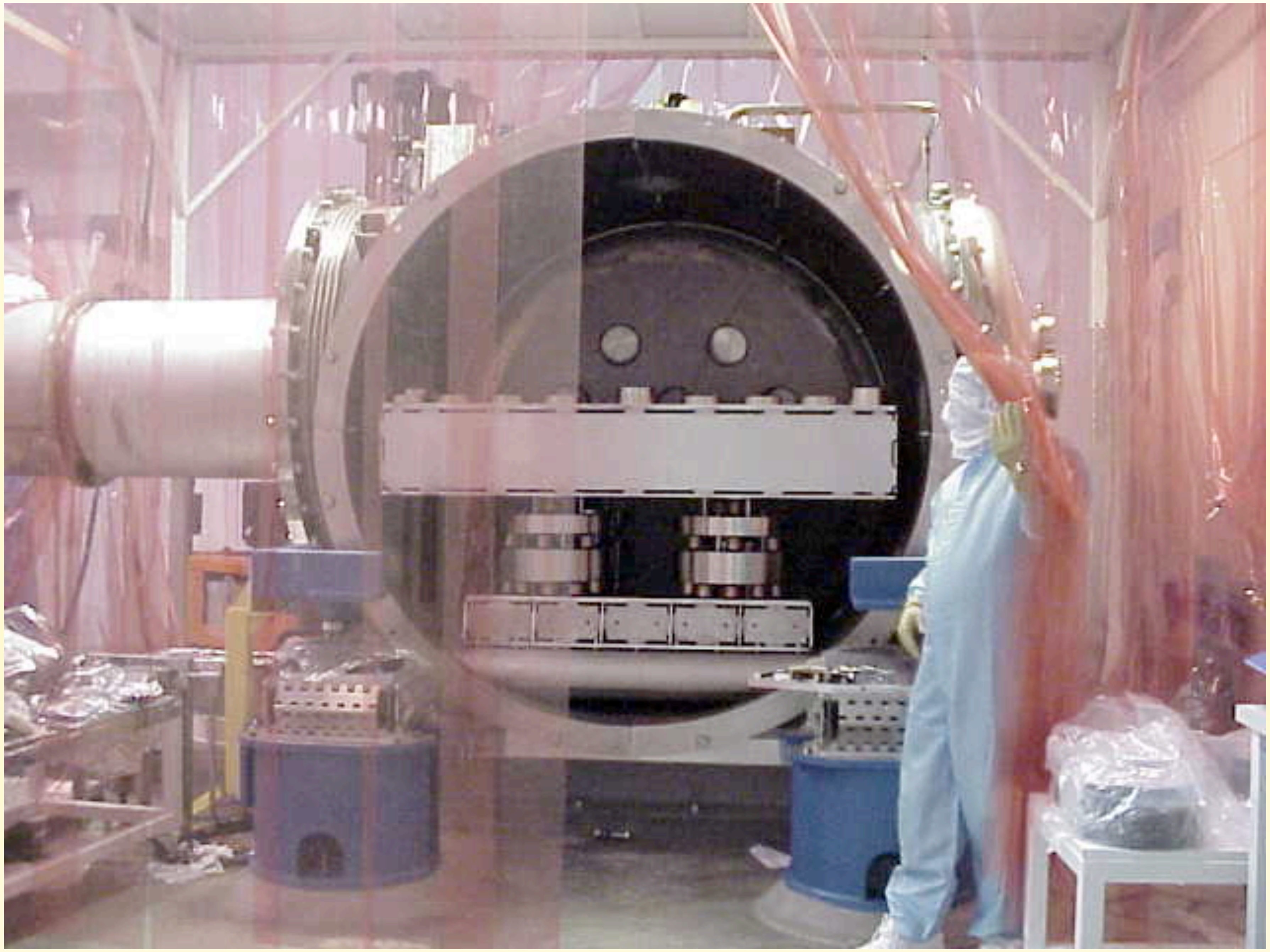
- Made from fused silica. Minimum size determined by diffraction.
- Weighs ~ 10 kg
- Light beam (~10 cm in diameter) averages over 10^{18} atoms
- Highly polished surface (with roughness ~ 10 nm, or ~100 atom layers)
- Low scattering and low optical loss (~ 100 ppm per bounce)

Mirror Suspension



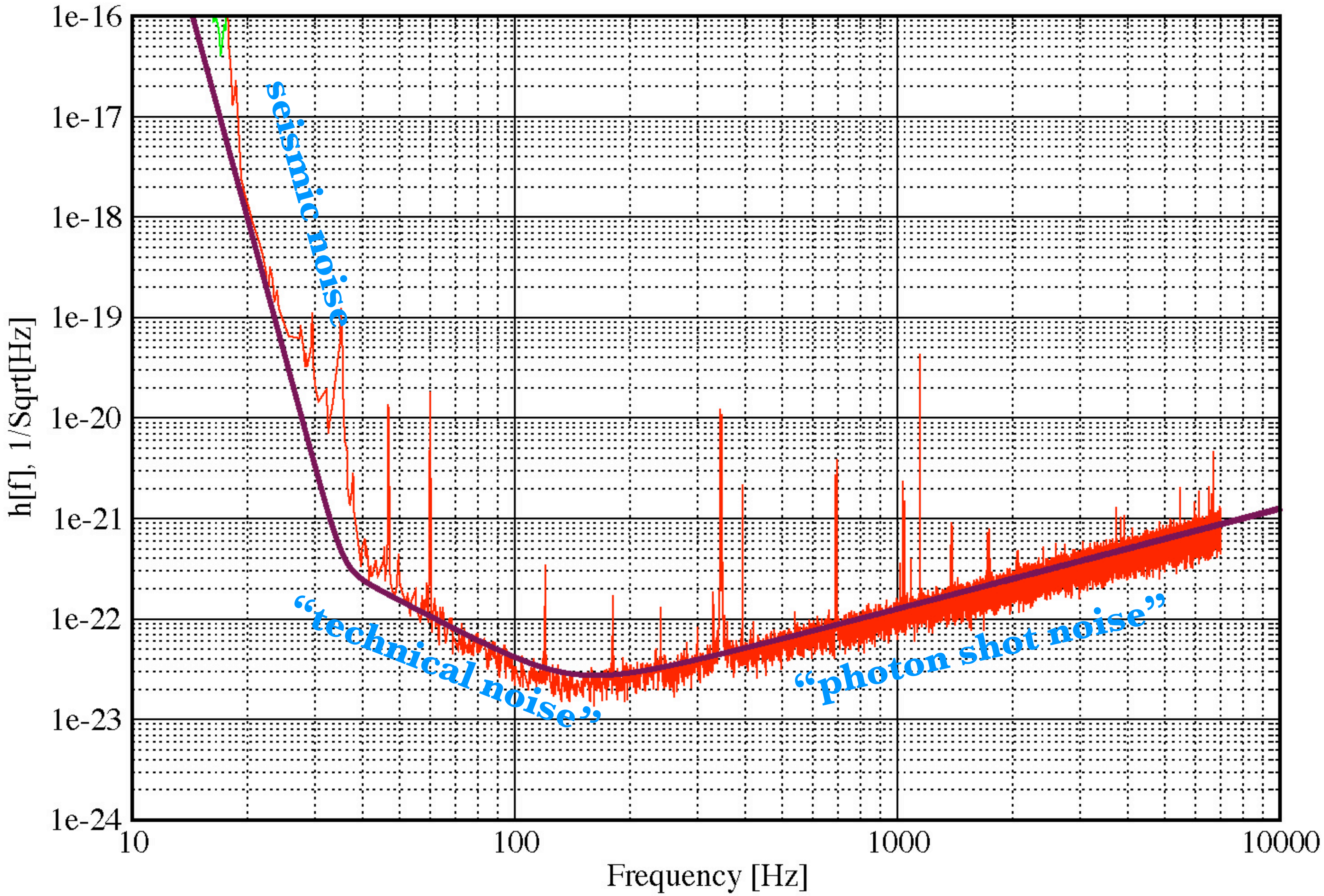
- Suspended by steel wires
- Controlled by magnets clued on the back of mirrors
- High Q factor (relaxation time ~ few years)

Seismic Isolation



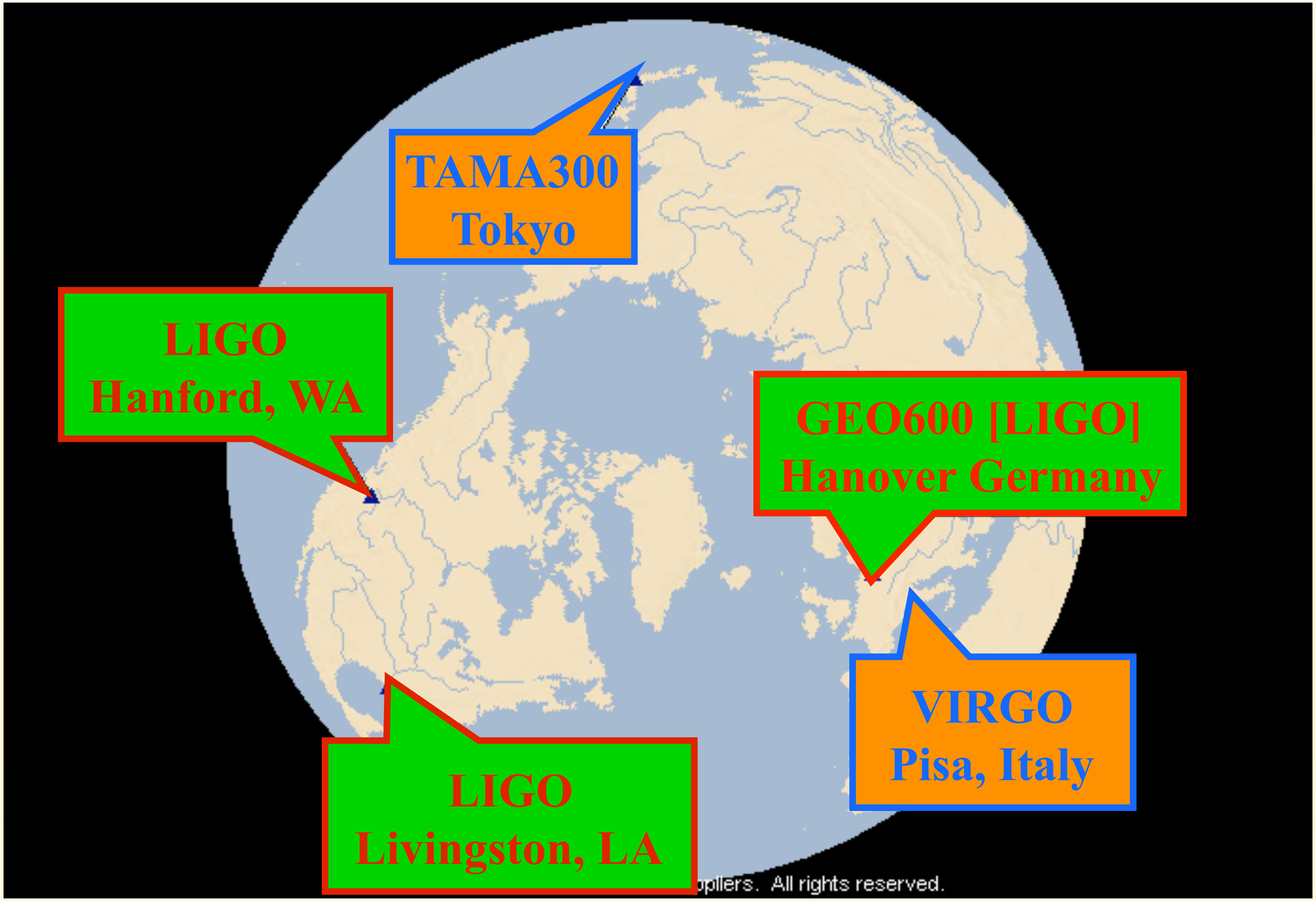
- Multiple stages of isolation

LIGO noise curve



Detection Band from 10Hz to 10000Hz

A Global Network



- Allows “angular localization” down to ~ 1 degree

A Global Network

VIRGO, Pisa, Italy, 3km
French-Italian Collaboration

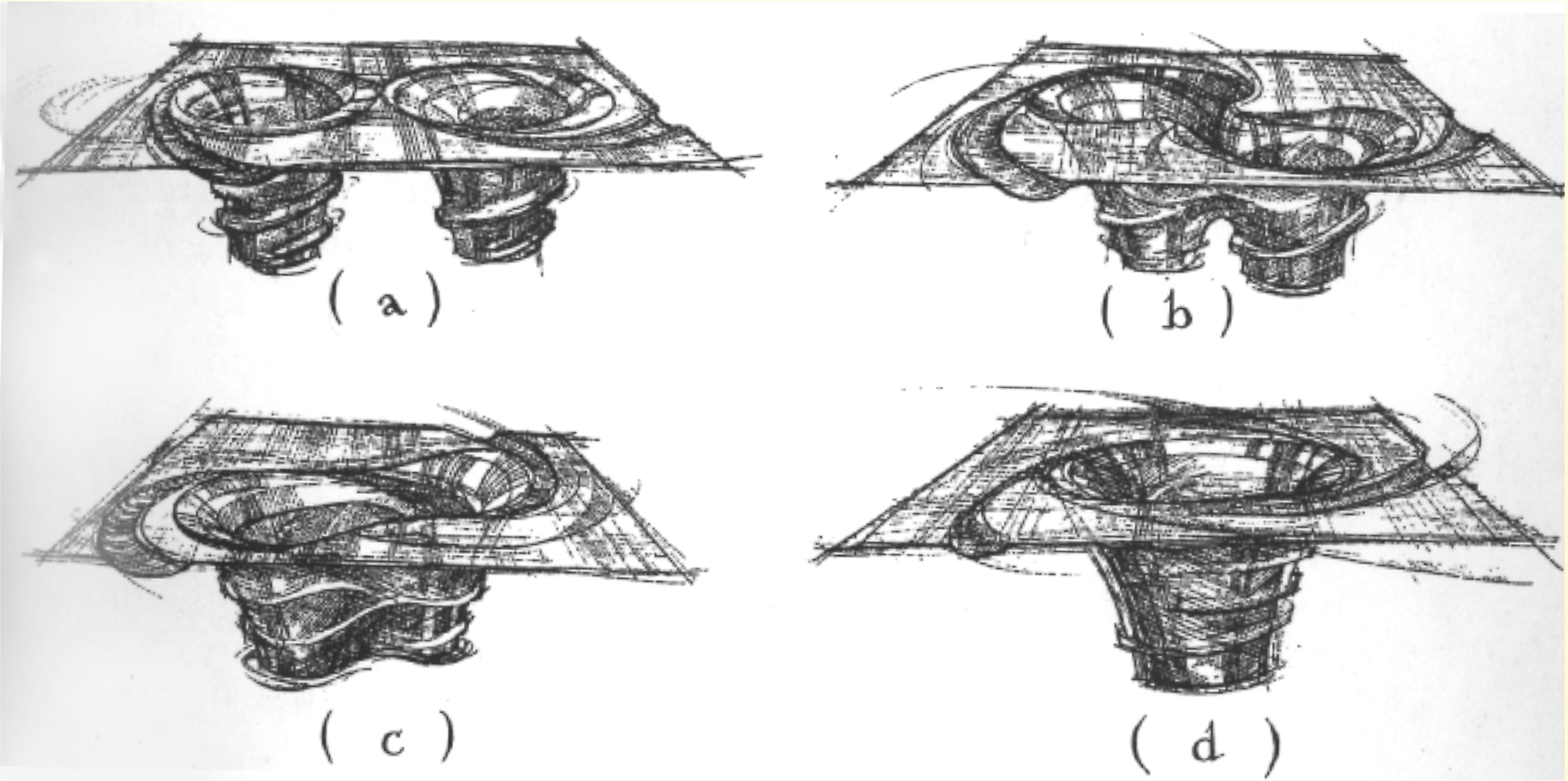
GEO 600, Hannover, Germany, 600m
British-German Collaboration

TAMA, Tokyo, Japan, 300m

Primary sources of LIGO

- **Collision of Black Holes/Neutron Stars**
- **Pulsars with asymmetry**
- **Explosions**
- **Stochastic Gravitational-Wave Background**

Black Hole Collisions



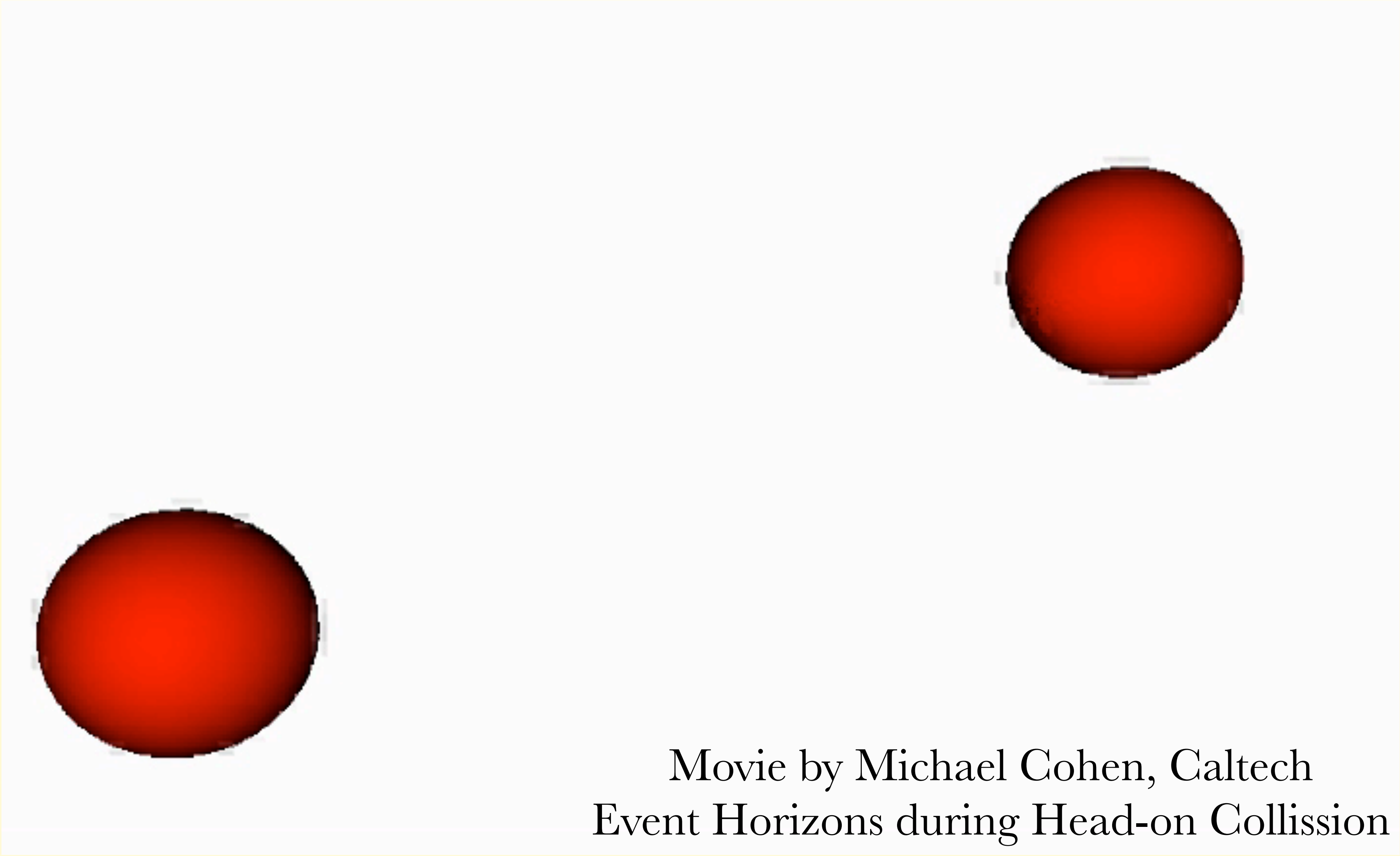
- Initial stage ("inspiral"): approximately a two-body motion
- Final stage ("ringdown"): perturbations to a single black hole
- Intermediate stage ("merger"): highly dynamical and nonlinear, can only be simulated numerically

Black Hole Collisions

Movie by Michael Cohen, Caltech
Event Horizons during Head-on Collission

- Started in the 1960s, difficult due to nonlinear nature of Einstein Equations, and freedom in the choice of frames.
- Waveforms very important for LIGO, because we need to "match" data with "templates". Crucial in verifying that they are indeed black holes.
- Head-on collision: 1990s
- Merger in circular orbits (astrophysically interesting): only since 2005, active field

Black Hole Collisions



Movie by Michael Cohen, Caltech
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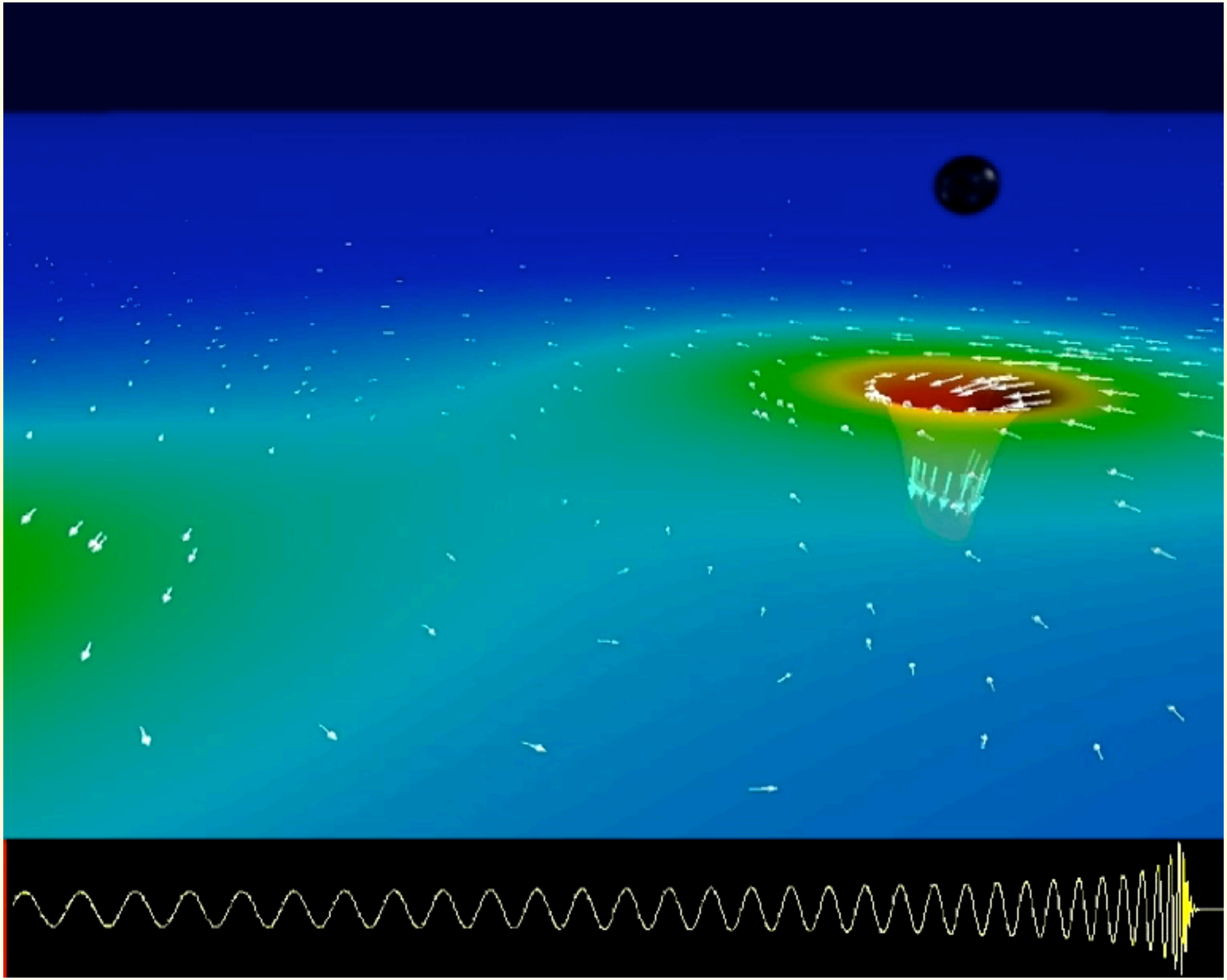
Black Hole Collisions

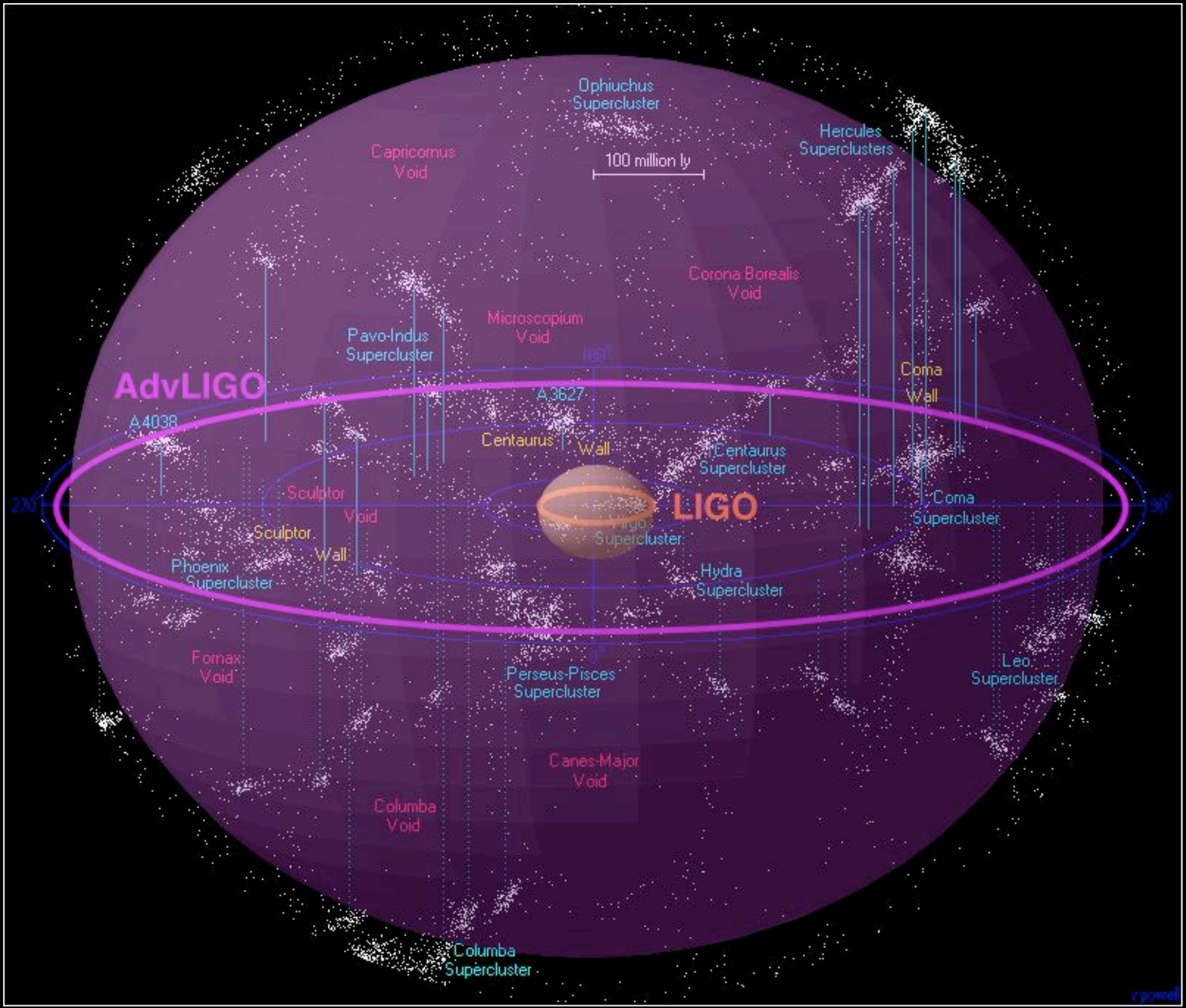


Movie by Caltech-Cornell Numerical Relativity Collaboration
Mark Scheel, Harald Pfeiffer, Lee Lindblom, et al.

initial LIGO (2005-07)
300 million light years
~1 BHBH/10 yr

Enhanced LIGO (2009-10)
600 million light years
~1 BHBH/yr

Advanced LIGO (2014-)
5 billion light years
~1 BHBH/day or week

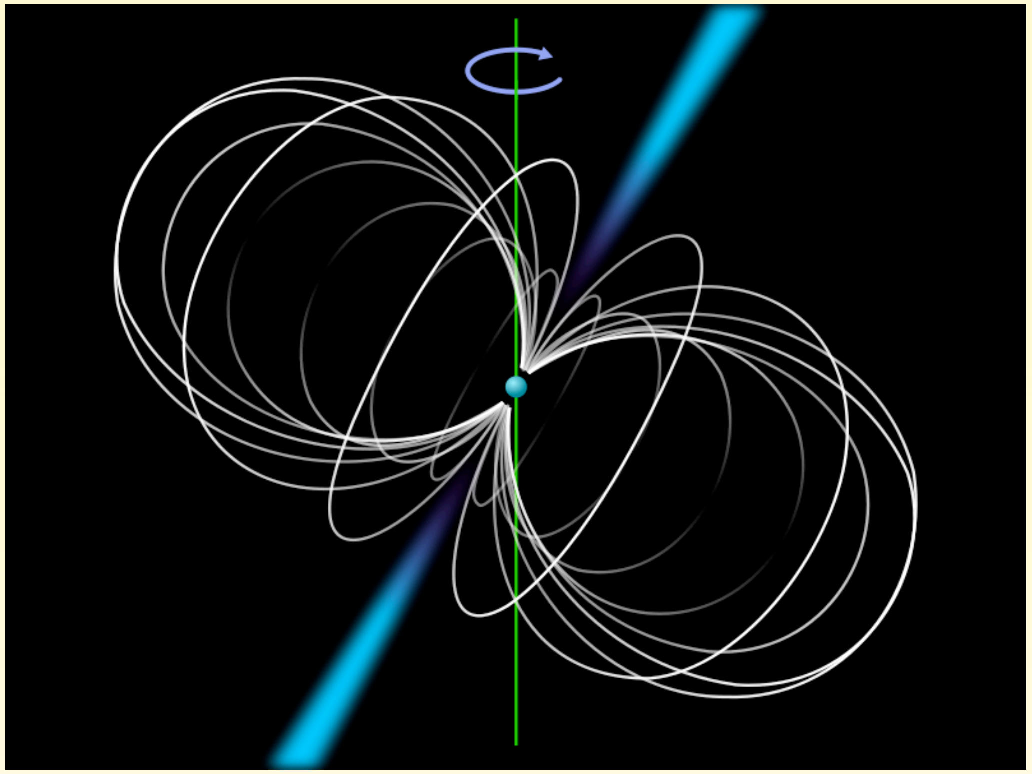


Pulsars (2005-07)

Asymmetric pulsars will emit gravitational waves

The Crab Pulsar (combined data from Hubble telescope and Chandra X-ray Telescope)

Result of a supernova in 1054



LIGO: less than 4% loss in rotation energy is released in gravitational waves

(rest of it released in driving charged particles)

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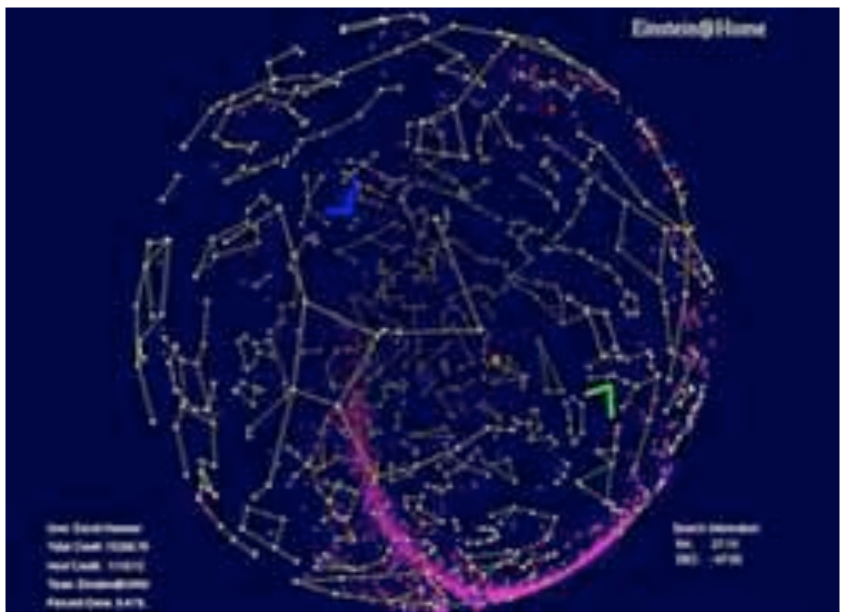
Welcome to Einstein@Home

Join Einstein@Home



Einstein@Home screensaver

According to Albert Einstein, we live in a universe full of gravitational waves. He suggested that the movements of heavy objects, such as black holes and dense stars, create waves that change space and time. We have a chance to detect these waves, but we need your help to do it!

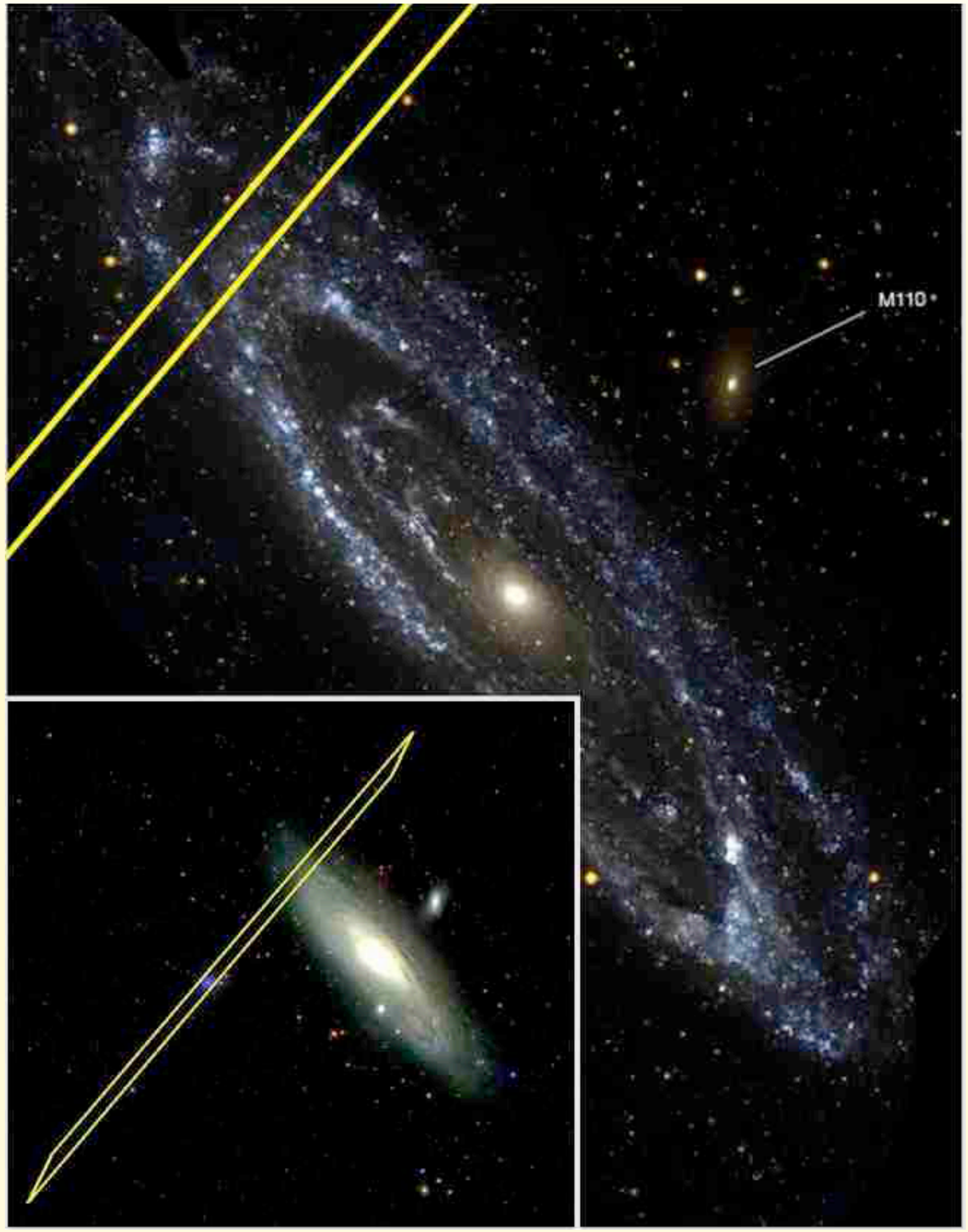
Einstein@Home uses computer time donated by computer owners all over the world to process data from gravitational wave detectors. Participants in Einstein@Home download software to their computers, which process gravitational wave data when not being used for other computer applications, like word processors or games. Einstein@Home doesn't affect the performance of computers and greatly speeds up this exciting research.

Learn more about the project.

APS physics

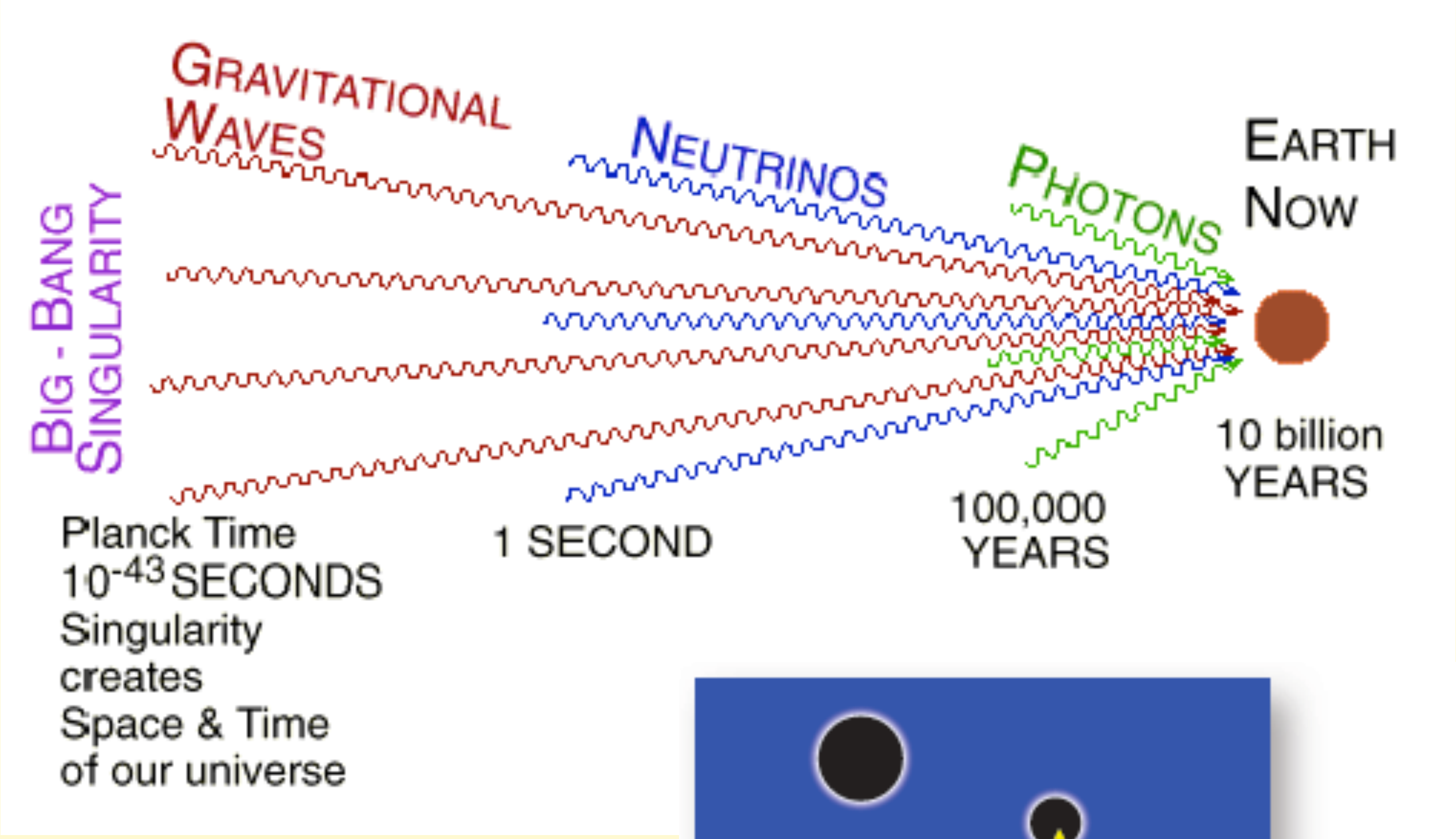
http://www.einsteinathome.org/index.html

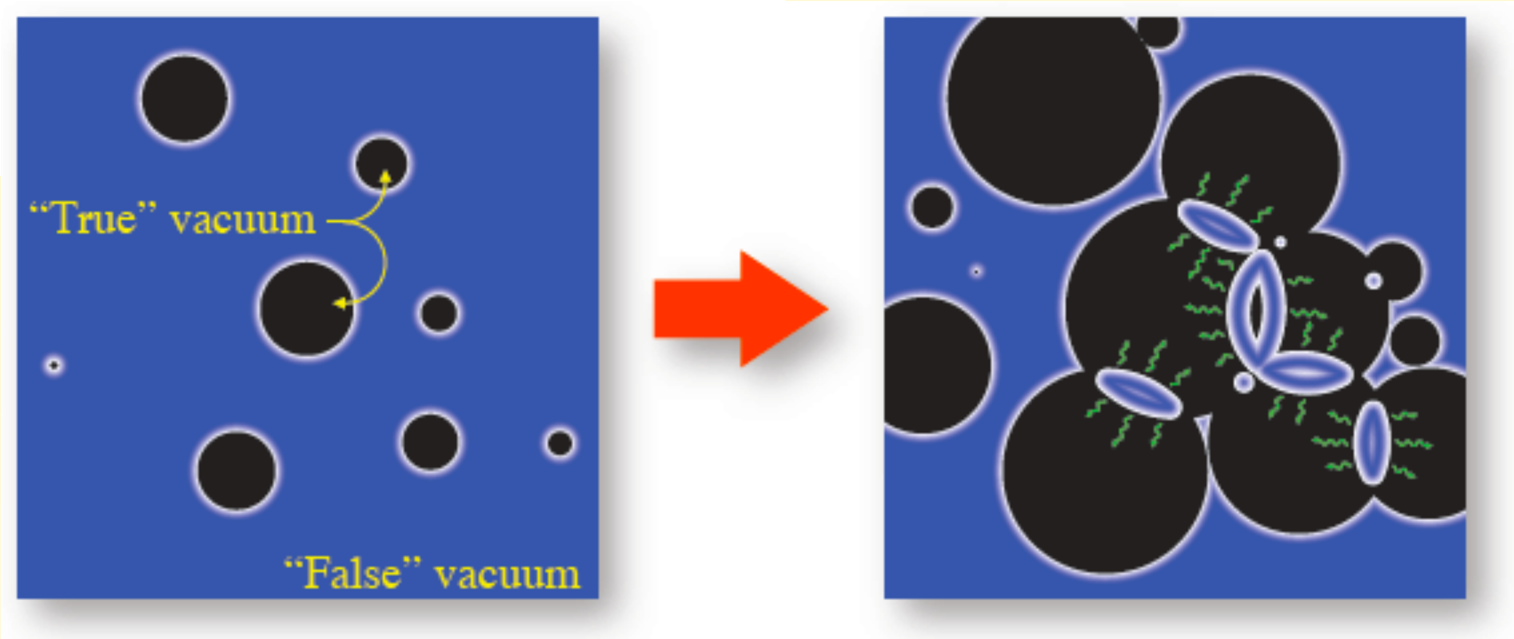
Gamma-Ray Bursts (2007)



- Gamma-Ray Burst 070201, **if in Andromeda Galaxy** (2.5Mly or 0.8 Mpc)**, then not a binary neutron-star merger.**

Stochastic Gravitational-Wave Background





- Quantum fluctuations of spacetime at the "birth" of the universe
- Stochastic waves generated by "phase transitions"

A test for string theory??

- Bursts from cosmic strings and/or cosmic superstrings??
- Highly speculative, but might provide evidence for string theory ...

Animation by Bret Underwood, University of Wisconsin

A test for string theory??

- Bursts from cosmic strings and/or cosmic superstrings??
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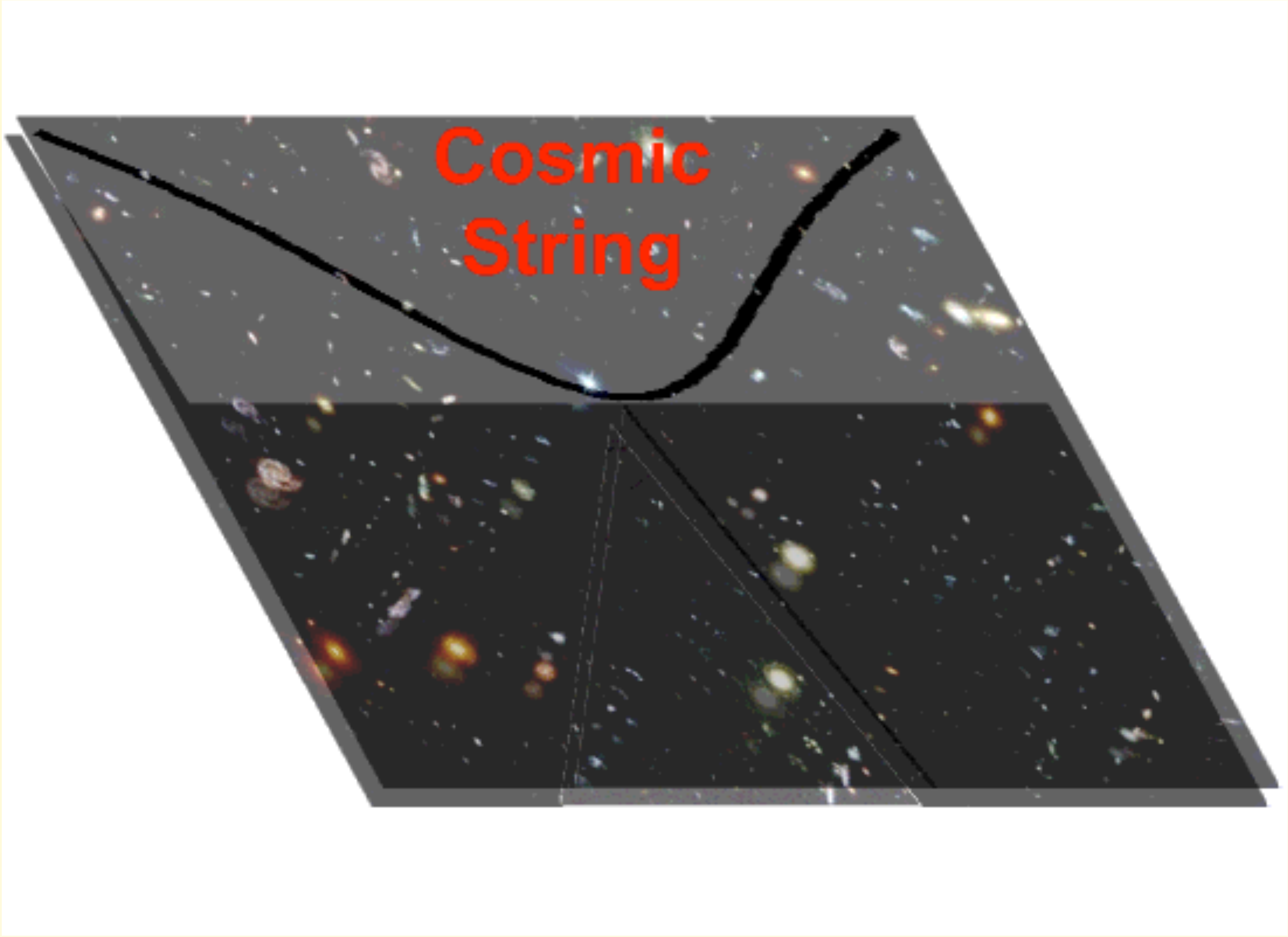
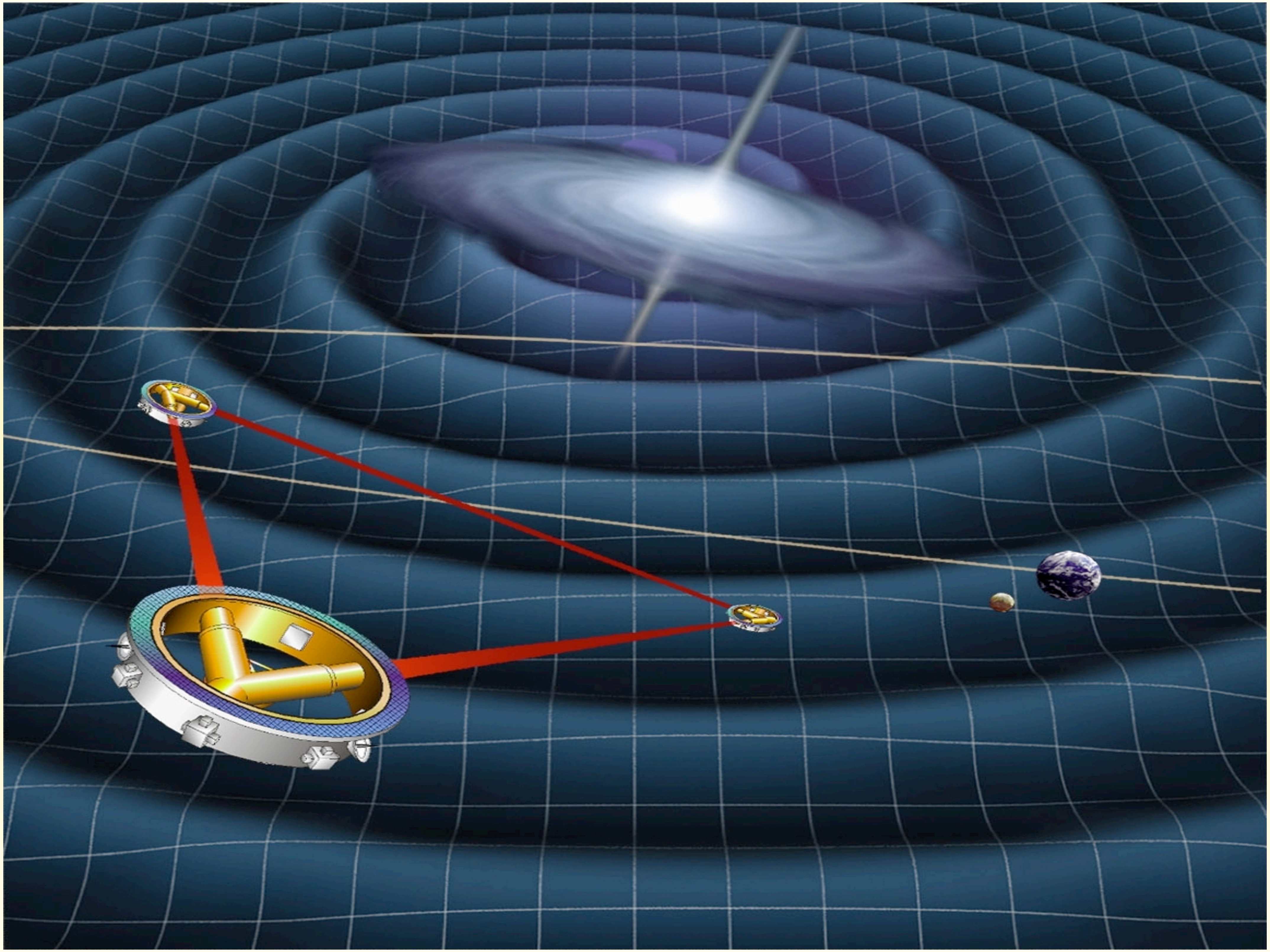


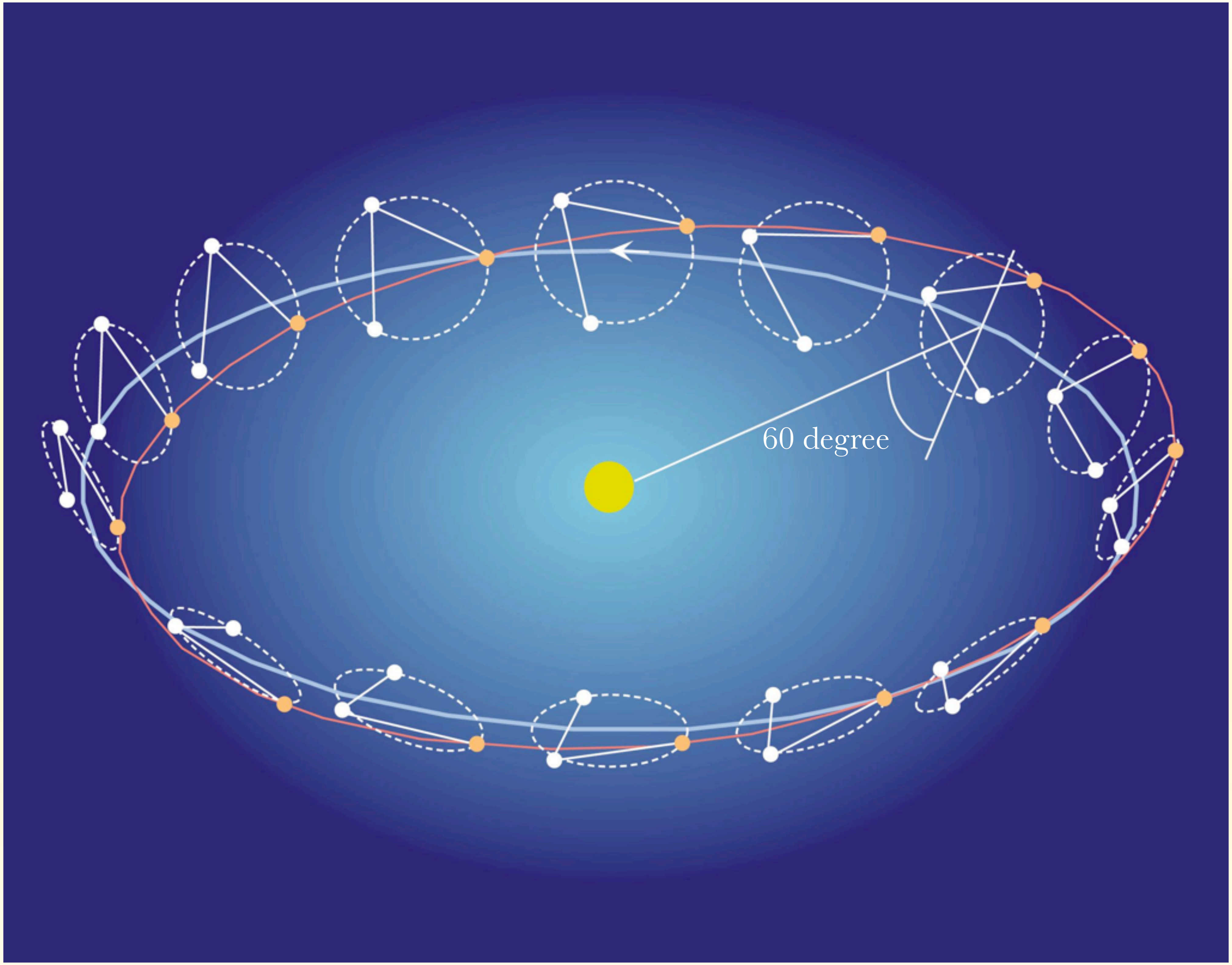
Animation by Bret Underwood, University of Wisconsin

Laser Interferometer Space Antenna



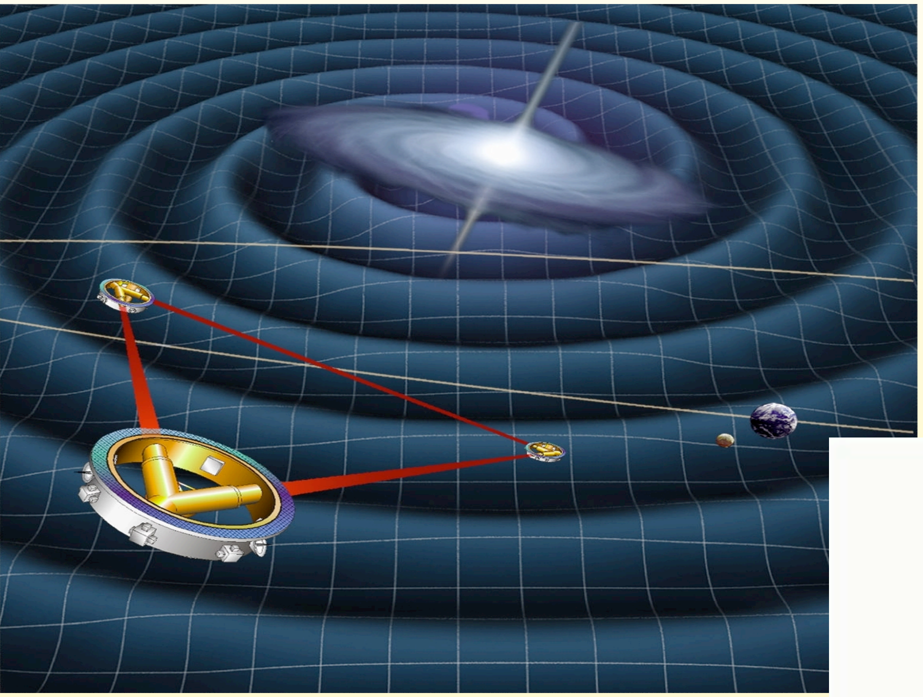
Joint NASA-ESA Project

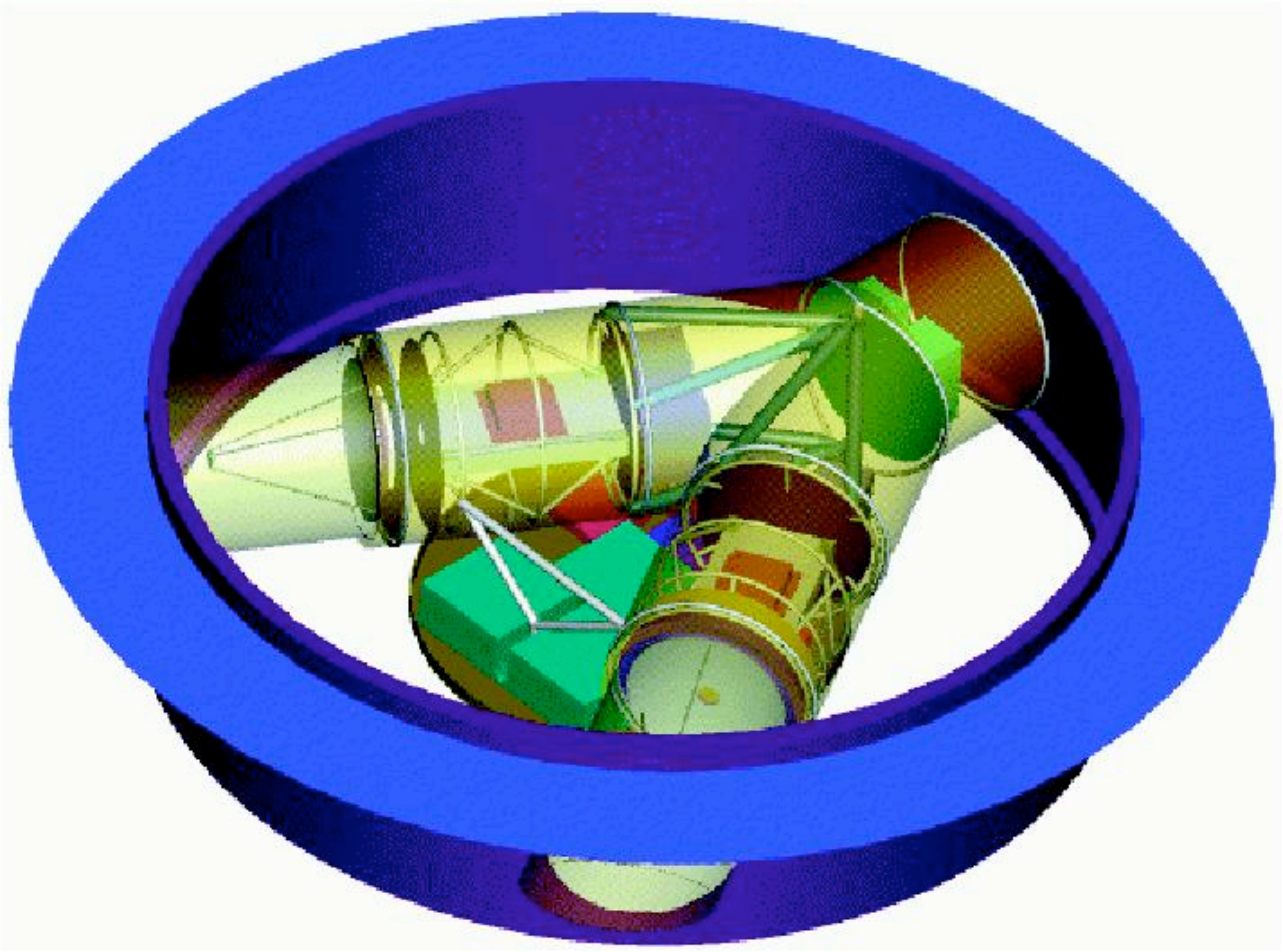
Laser Interferometer Space Antenna



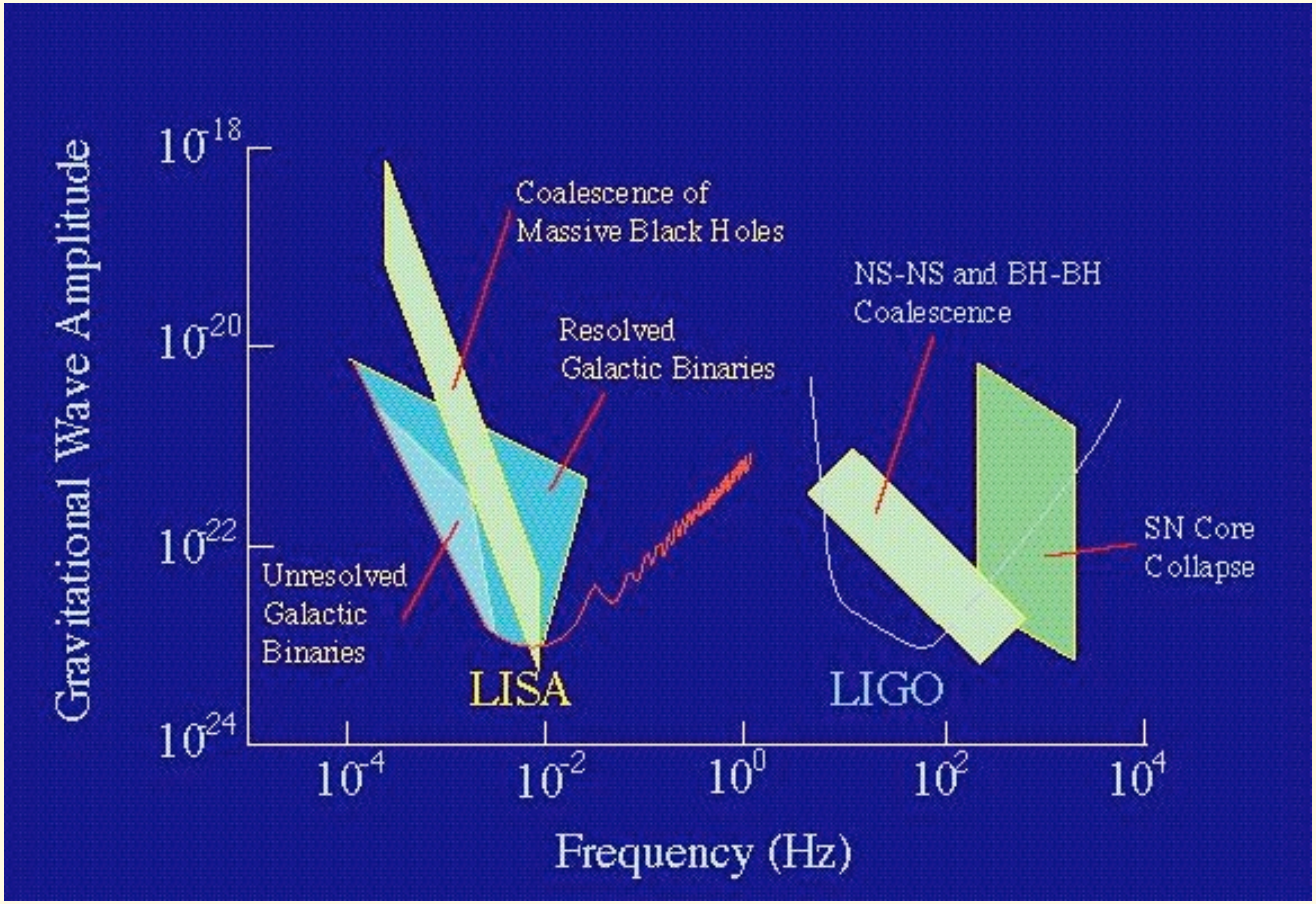
L = 5 million km
period = 1 year
operation time = 3 years (nominal)

LISA Spacecraft

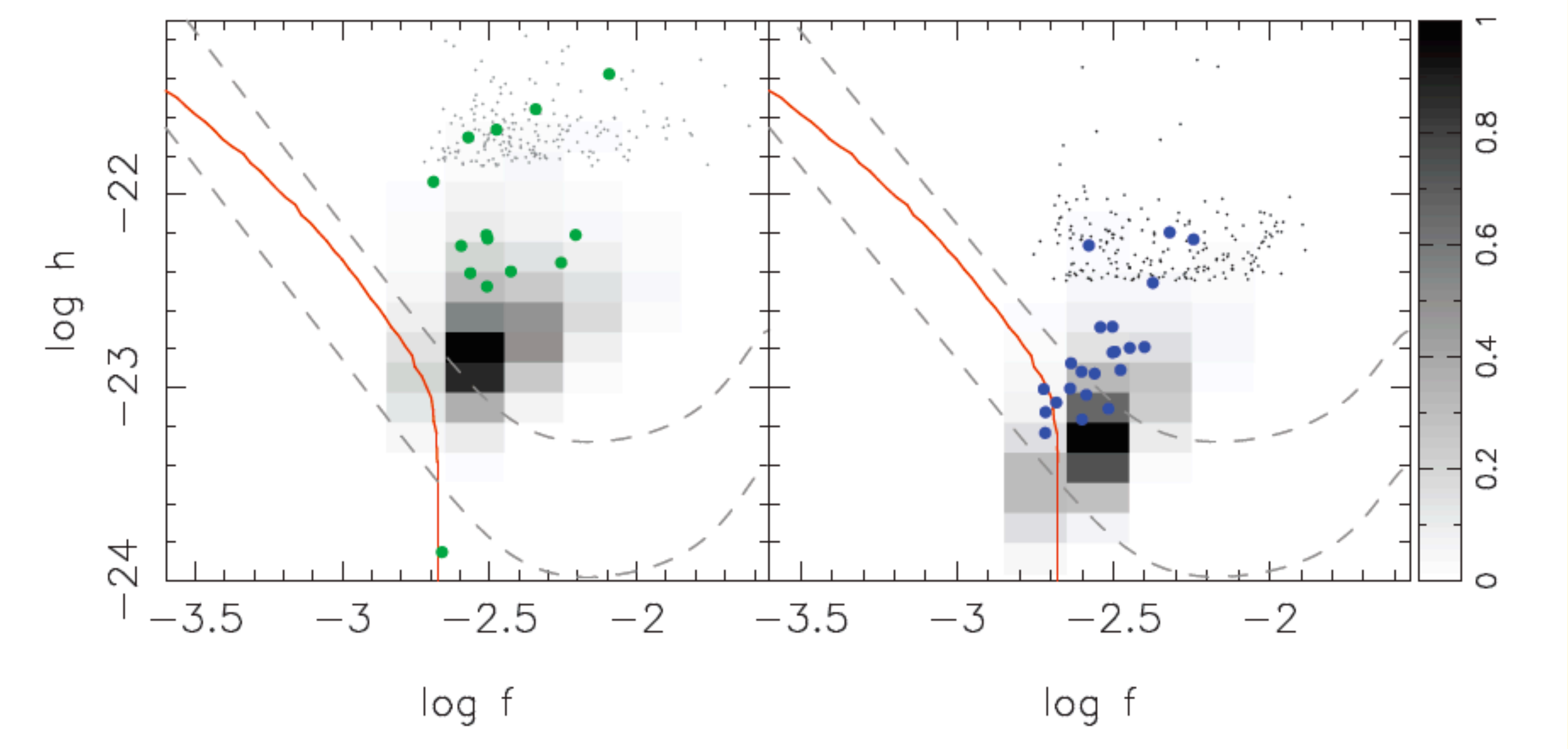




LISA Sensitivity



Binaries in the Milky Way Galaxy



- More than 10^4 White-Dwarf Binaries
- More than 10 known Neutron-Star Binaries
- Un-resolvable White Dwarf Binary signals increase noise level

Mergers of Galaxies

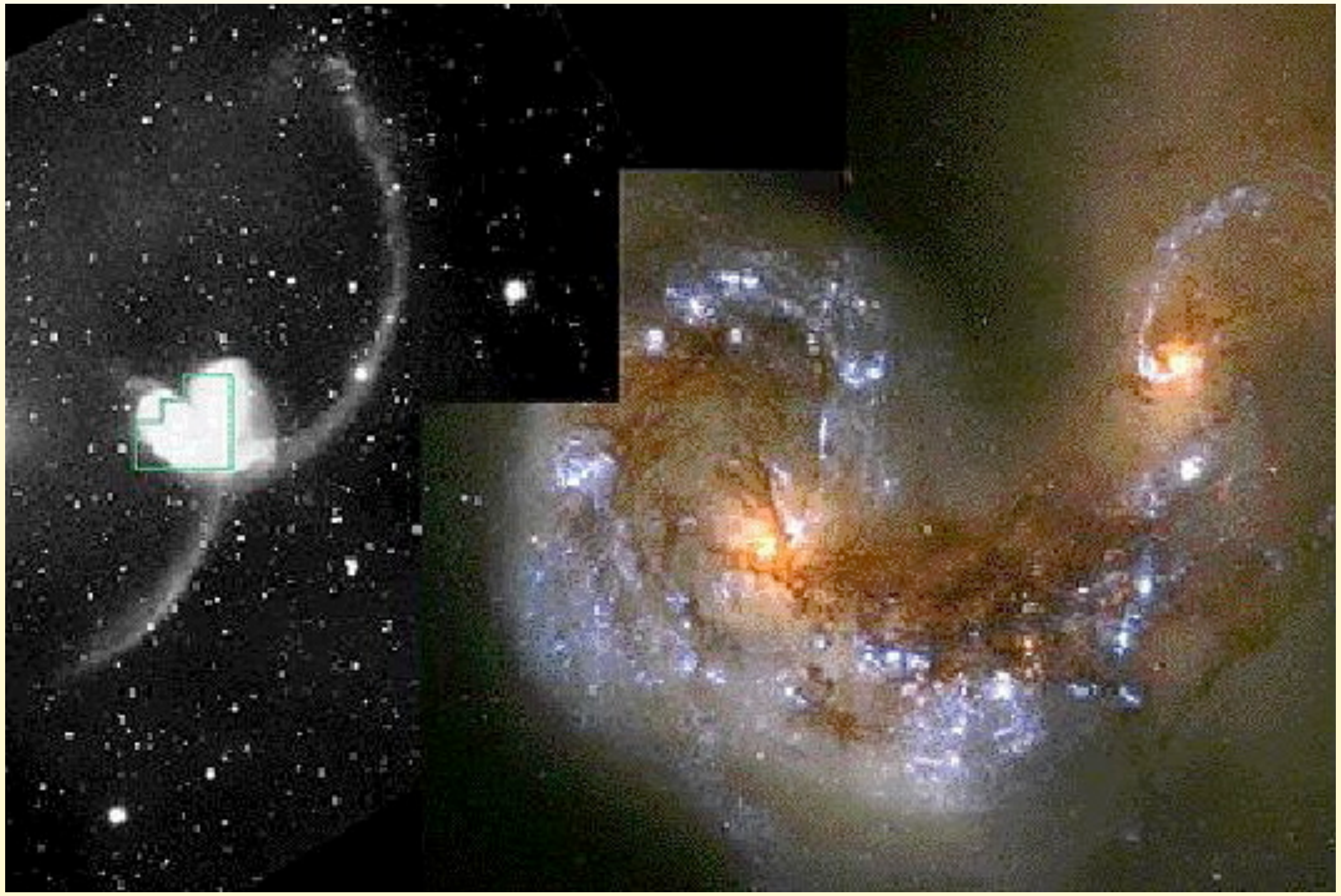


Image by B. Whitmore (STSci), F. Schweizer (DTM), NASA

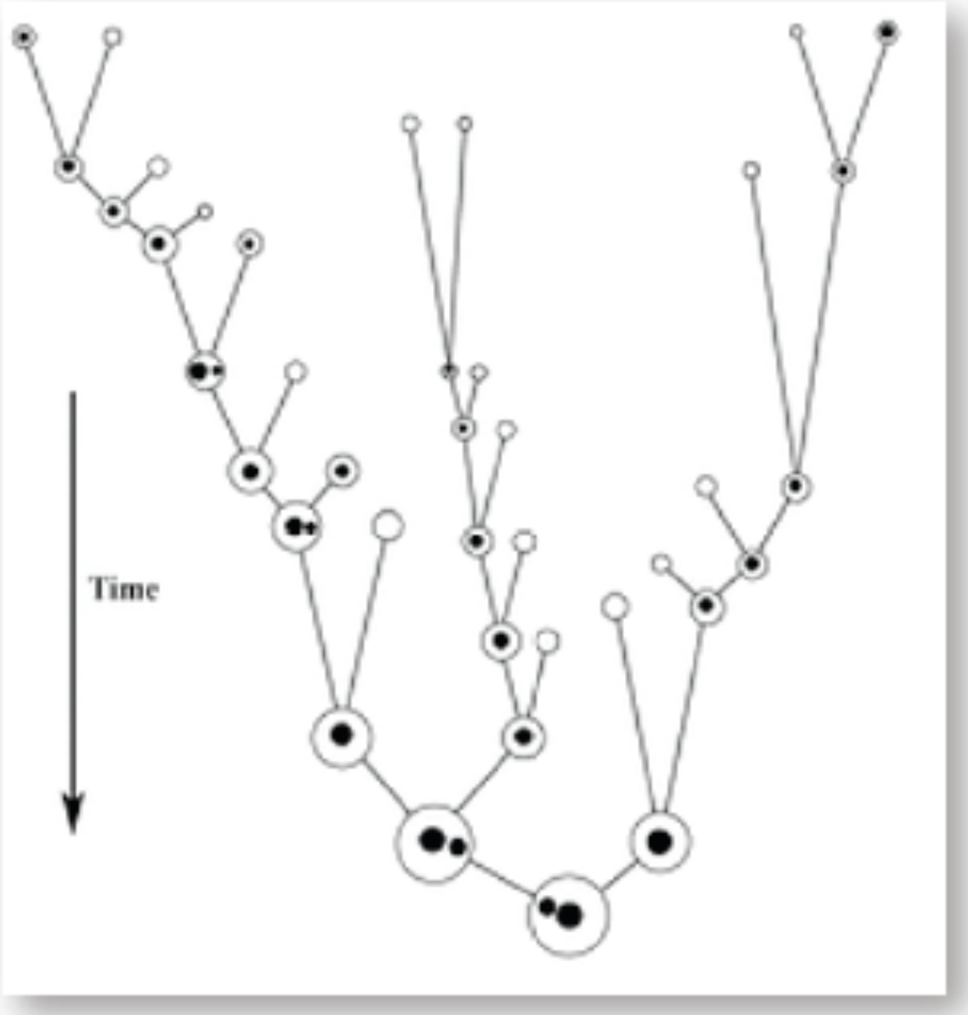
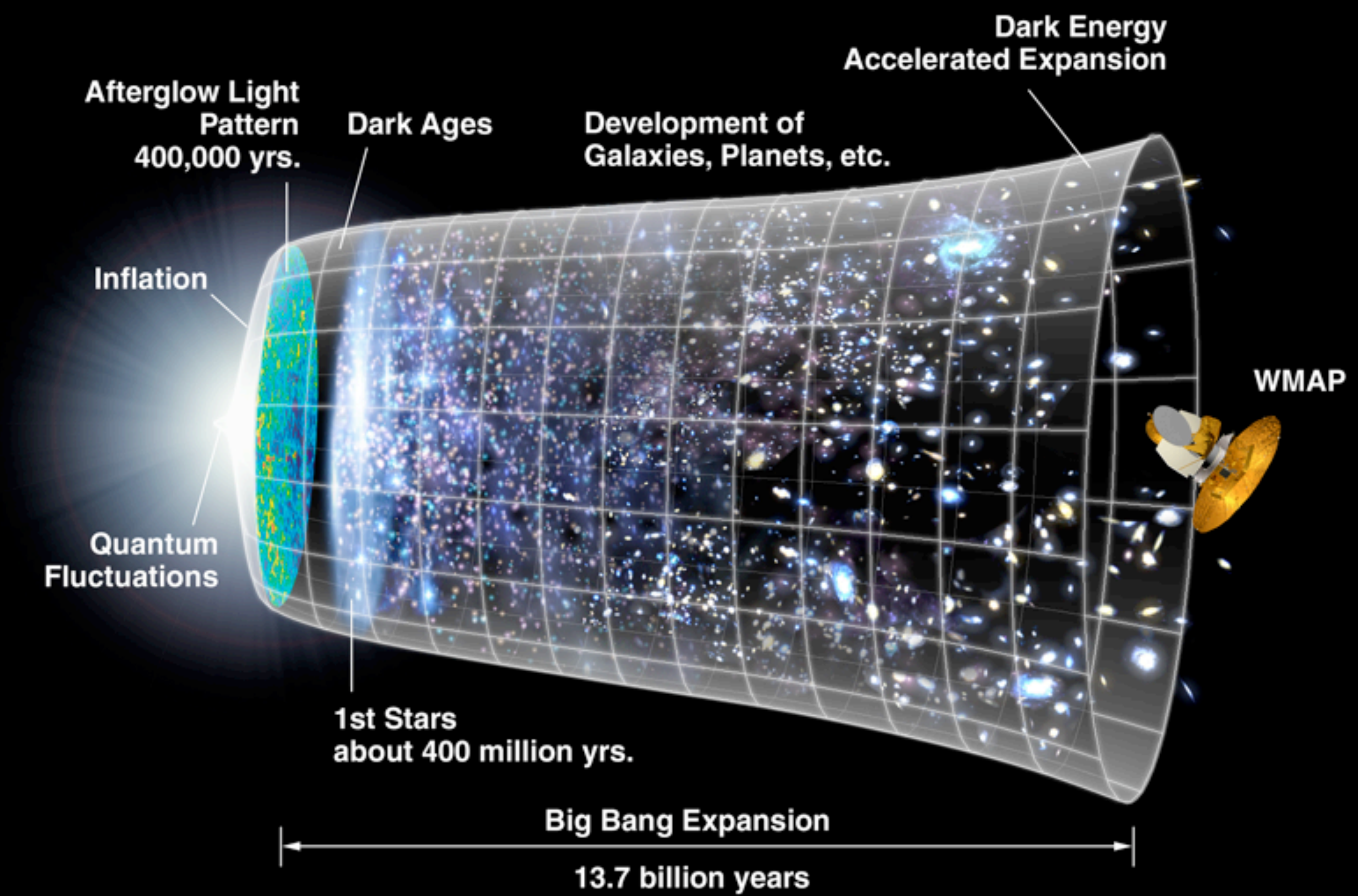


Figure 3-5: A cartoon of the merger-tree history of the assembly of a galaxy and its central black hole in cold-dark matter cosmology. Time increases from top to bottom, and the horizontal axis is a spatial direction. In this case the final galaxy is assembled from the merger of twenty smaller galaxies, containing a total of four seed black holes, and results in four mergers of binary black holes.

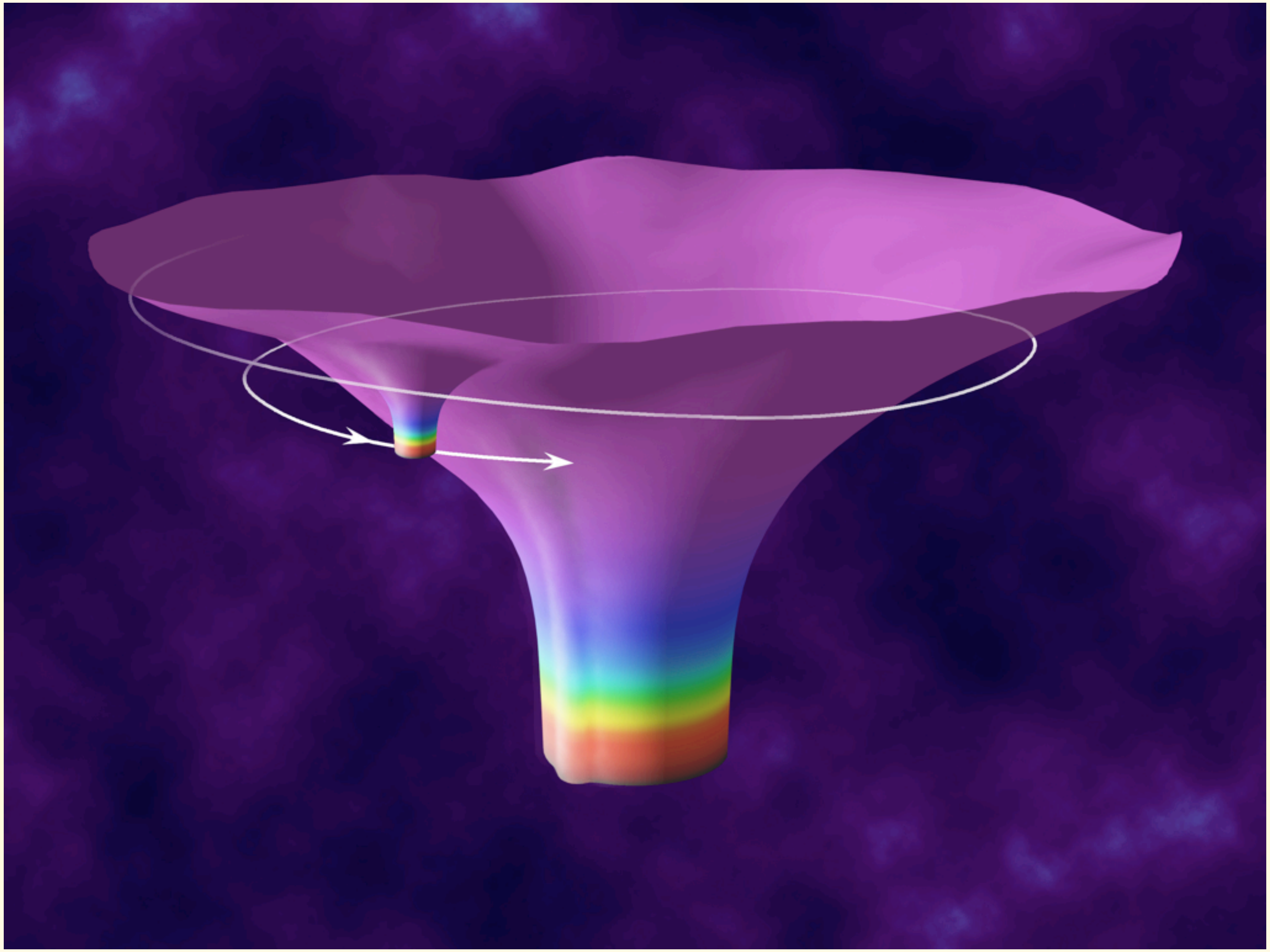
- Most galaxies have gone through merger, as a result of structure evolution of the universe
- Supermassive Black Hole Mergers offer clues to history of galaxy mergers and evolution of supermassive black holes



NASA/WMAP Science Team

Mapping Spacetime Around Black Holes

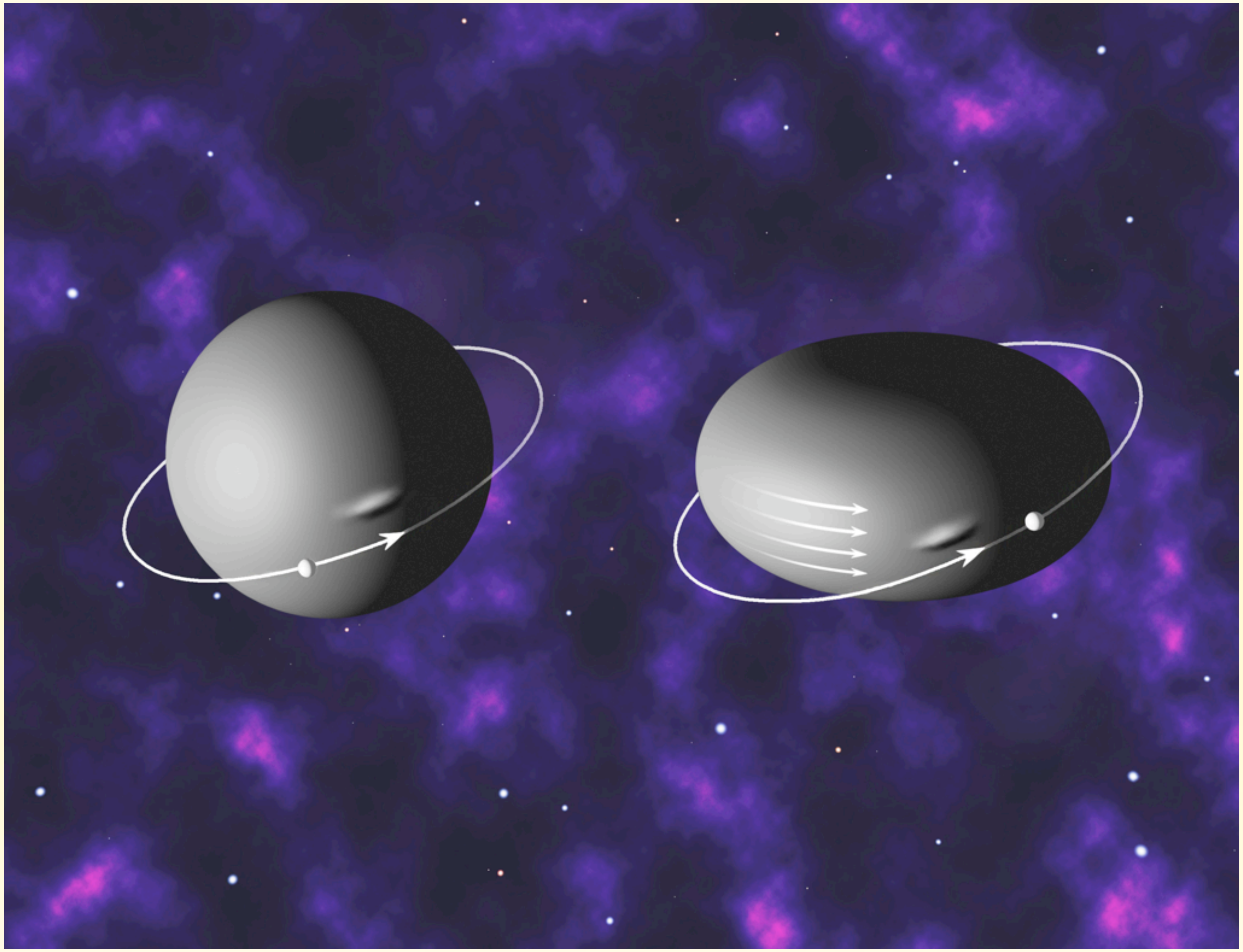
Are they really black holes?



10 solar mass into 10^6 solar mass, more than 10^5 wave cycles
provide fine map of spacetime geometry

Probing the Black Hole Horizon

Are they really black holes?

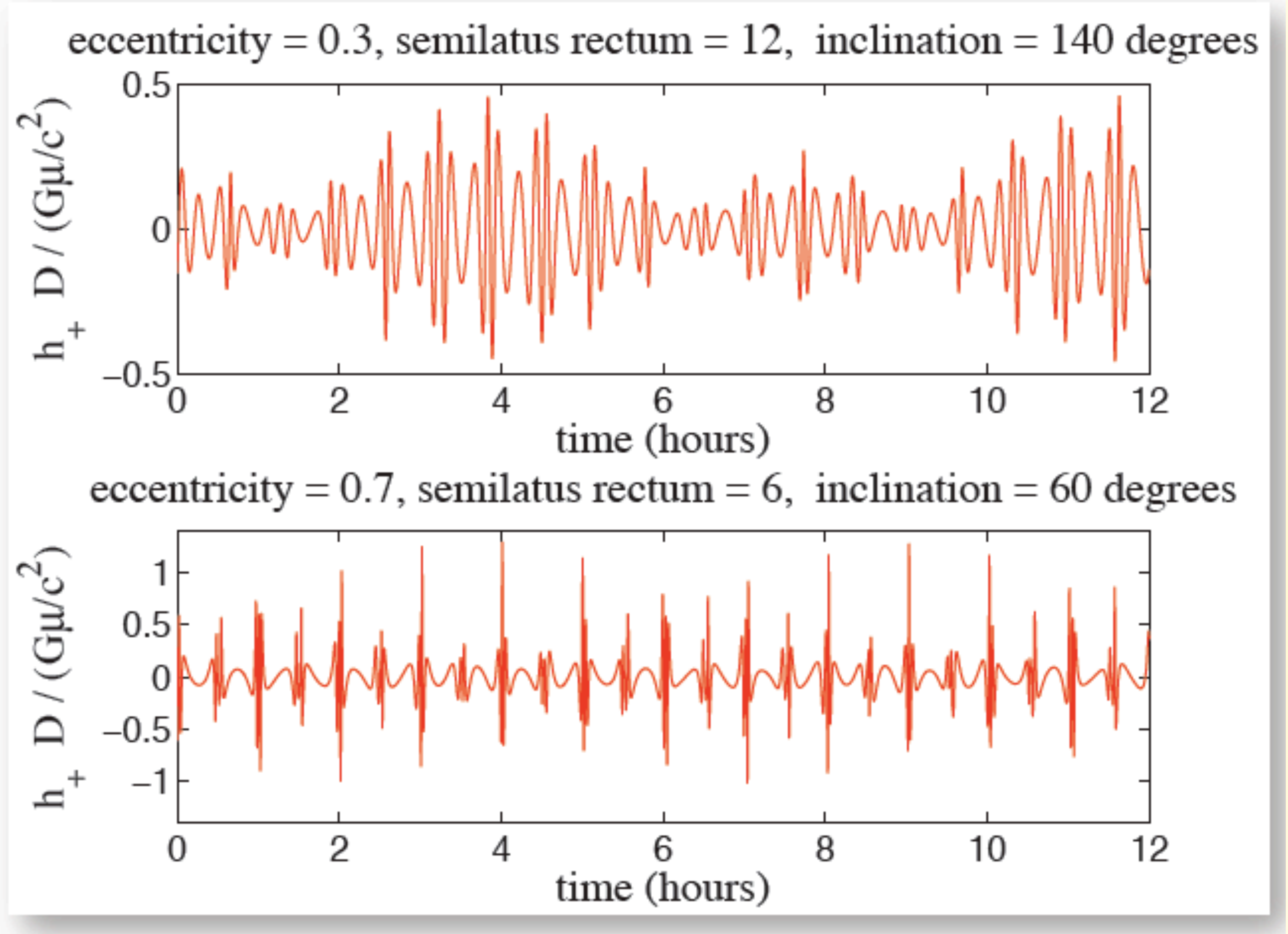


10 solar mass into 10^6 solar mass, more than 10^5 wave cycles

probing response of event horizon via tidal interaction

Mapping and Probing Black Holes

physical information must be decoded from waveforms like this



$$\times(2\times365\times3) = 2200$$

computationally and theoretically challenging

Summary

- Gravitational-Wave Astronomy has just started
- Eventually, we will be able to, **experimentally**
  - confirm Gravitational Waves by direct measurement (<<10)
  - detect waves from black hole/neutron star collisions, and study non-linear, highly dynamical spacetime (<<10)
  - study gravitational waves associated with gamma-ray bursts and other astrophysical explosions (<10)
  - study merger history of galaxies, understand evolution of supermassive black holes (~ 15-20)
  - map and probe black hole spacetime (~ 15-20)
  - study stochastic background, phase transitions in the early universe, and possible indictions of string theory (> 20)
- **In the mean time theoretically**
  - study of dynamics of highly non-linear spacetimes
  - foundations for space-time mapping and horizon probing
  - foundations for study quantum mechanics using gravitational-wave experiments ...

How small is 10^{-18} m? How is this possible?

	1-2 meter	height of an adult
÷ 10,000	10^{-4}m = 100 micron	human hair
÷ 100	10^{-6}m = 1 micron	wavelength of light (in LIGO)
÷ 10,000	10^{-10}m = 1 Angstrom	atom
÷ 100,000	10^{-15}m = 1 fm	atomic nucleus
÷ 1,000	10^{-18}m	current LIGO sensitivity
÷ 10	10^{-19}m	Advanced LIGO size of wave function

use a lot of photons (strong light) each samples mirrors many times (resonance)

only see time-dependent motion average over many atoms (wide beam)

Quantum Mechanics

- Heisenberg Uncertainty Principle: **position and momentum cannot be determined simultaneously**

$$\hbar = 10^{-34} \mathrm{Joule} \cdot \mathrm{sec}$$

"Standard Quantum Limit"

- Measurement of mirror location at two separate times

$$\Delta X_{\rm tot} = \Delta X + \tau \frac{\Delta P}{M} \geq 2\sqrt{\frac{\tau \Delta X \Delta P}{M}} \sim \sqrt{\hbar \tau / M}$$

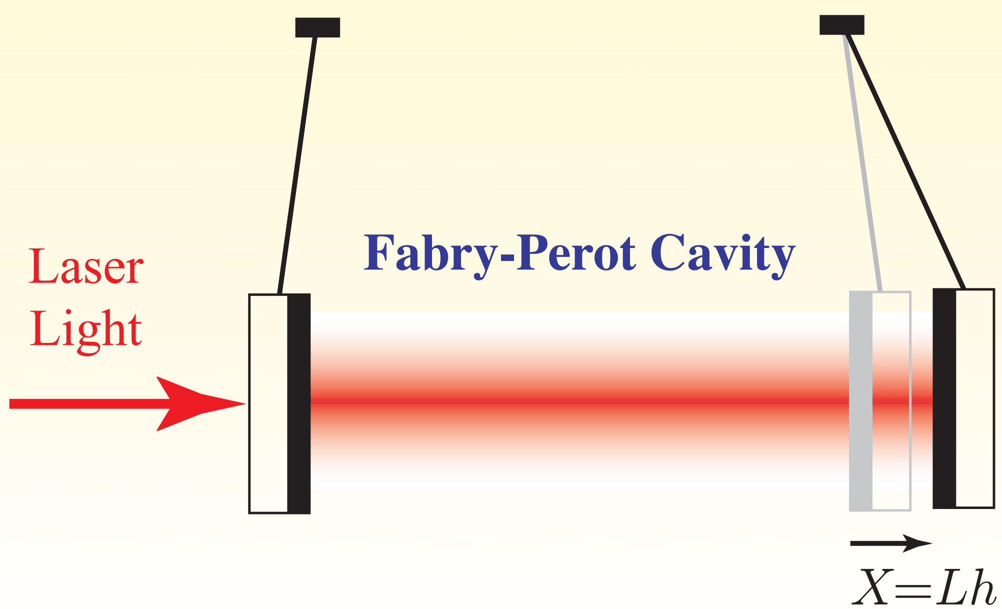
error in initial location

error in initial speed

- For M=10 kg and τ = 0.01 second

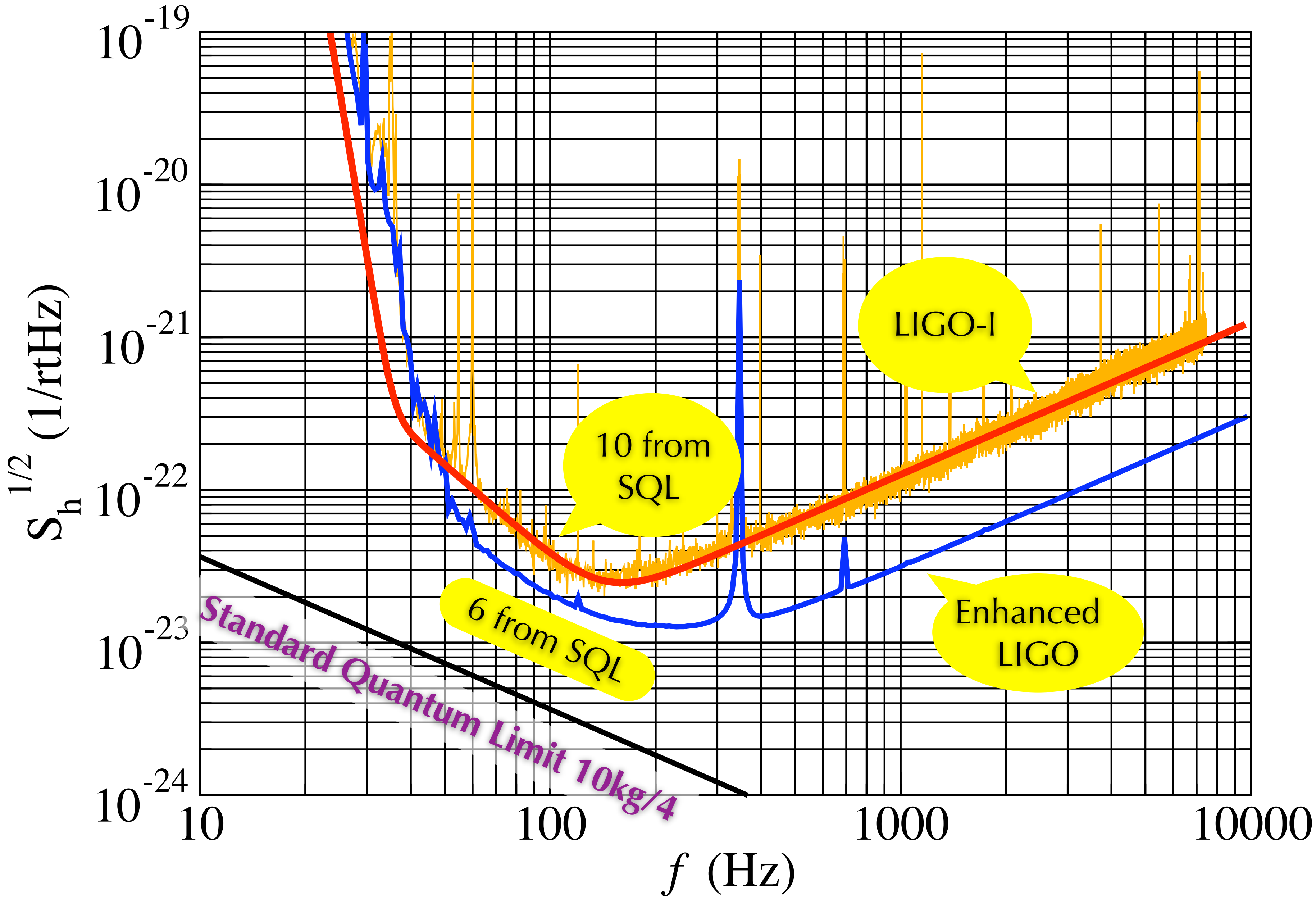
$$\Delta X_{\rm tot} > 10^{-19}\ {\rm m}$$

- In reality, this Limit will be imposed by Radiation-Pressure Noise



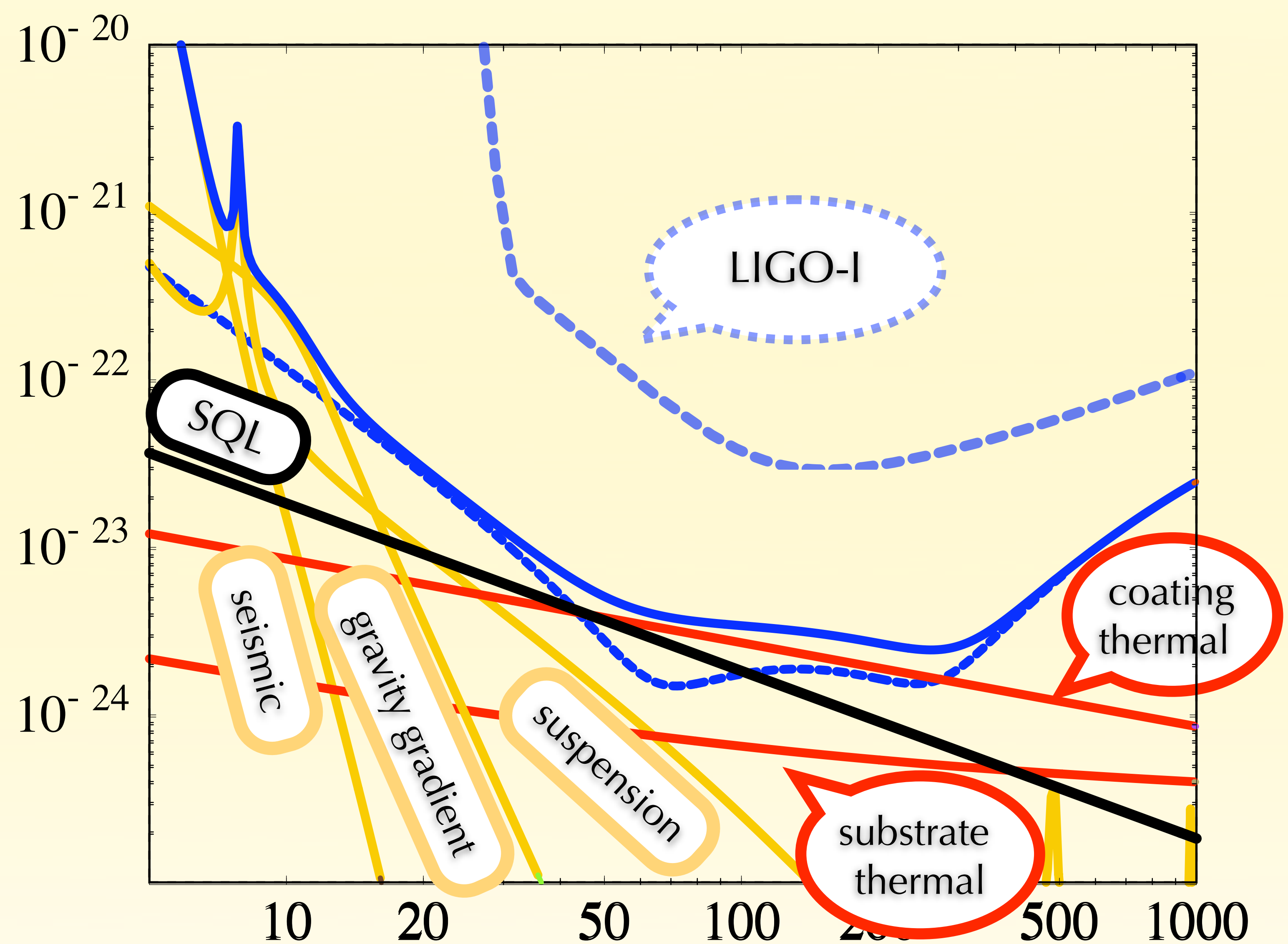
Photon number fluctuation causing noisy force
Radiation-Pressure Noise

"Standard Quantum Limit"



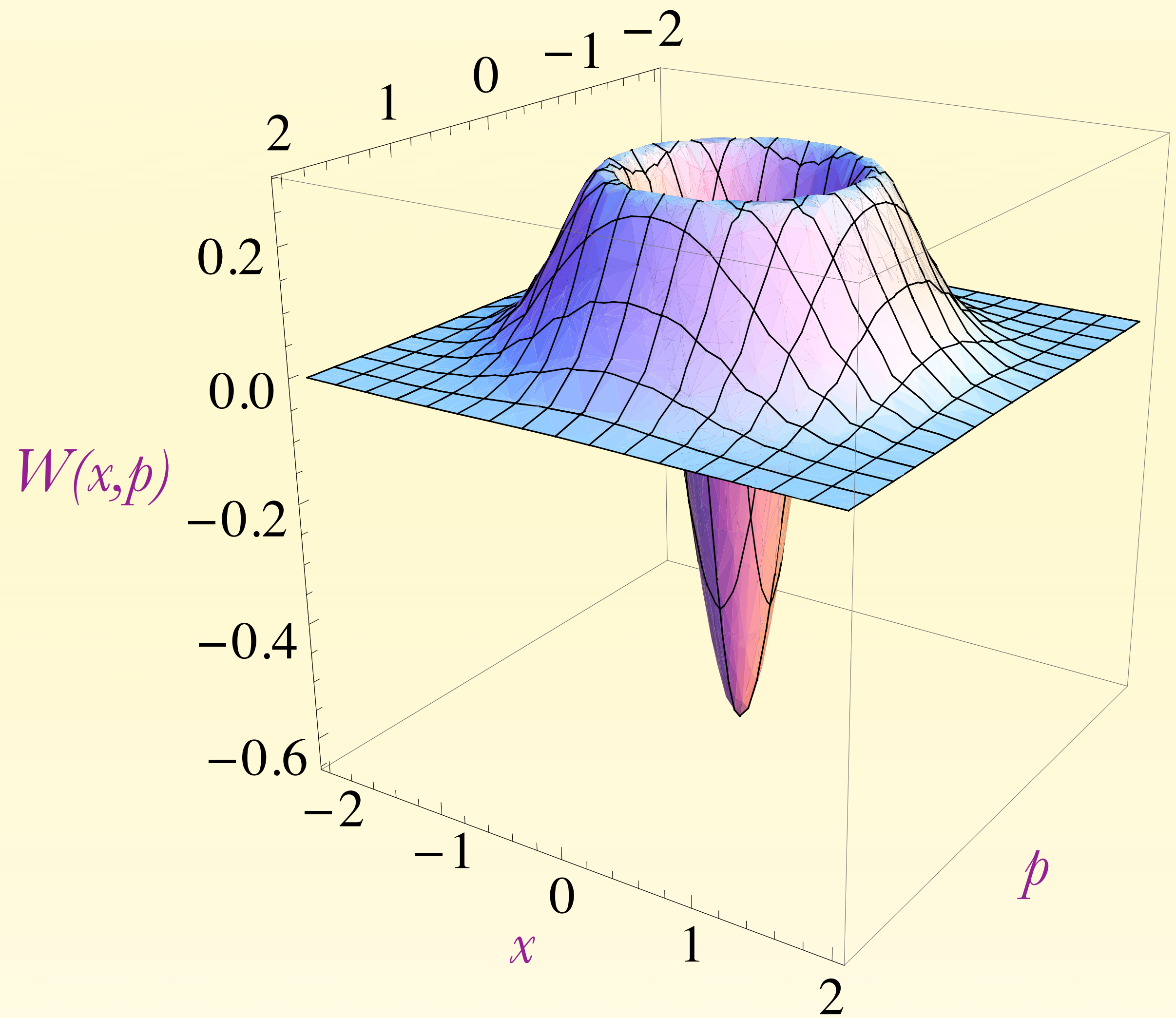
"Standard Quantum Limit"

- Advanced LIGO will "touch" the SQL
- Various prototype interferometers will reveal before Advanced LIGO

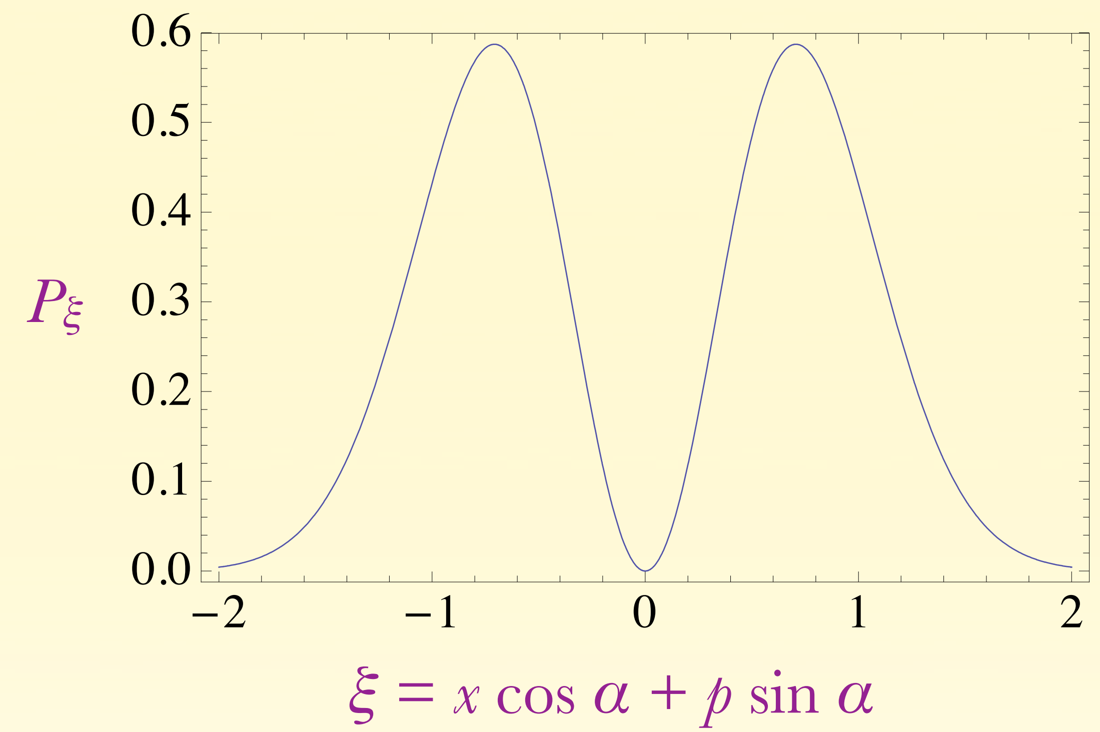


Macroscopic Quantum Mechanics

- With classical noises below the Standard Quantum Limit, light can be used to create and probe quantum mechanical states of mirrors
- Example, creation of a quantum state with **non-positive** effective joint probability distribution (Wigner Function) among *(x,p)*



effective joint distribution



marginal distribution

There is no classical correspondence!!