Einstein's 1918 Legacy – Gravitational Waves

Rainer Weiss, MIT

Brown University

Einstein Lecture Series

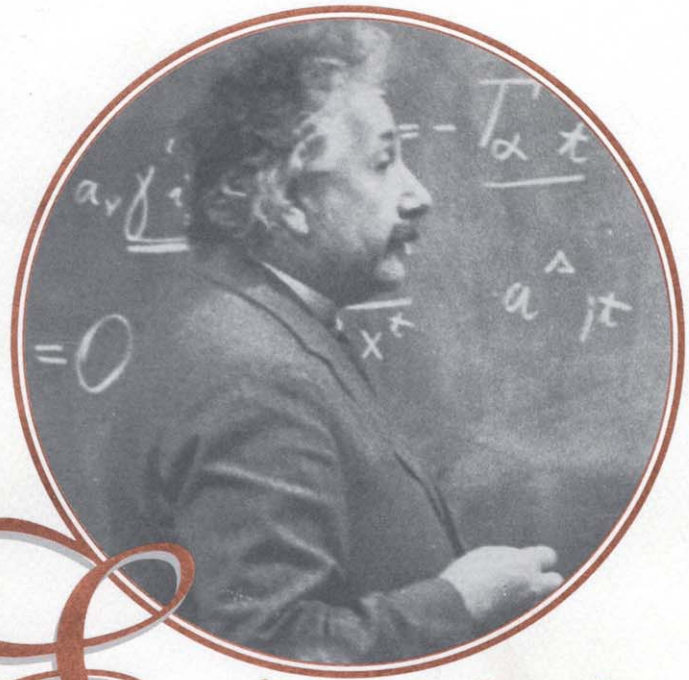
September 26, 2005

Subtle is the Lord – " the science and life of Albert Einstein"

Abraham Pais

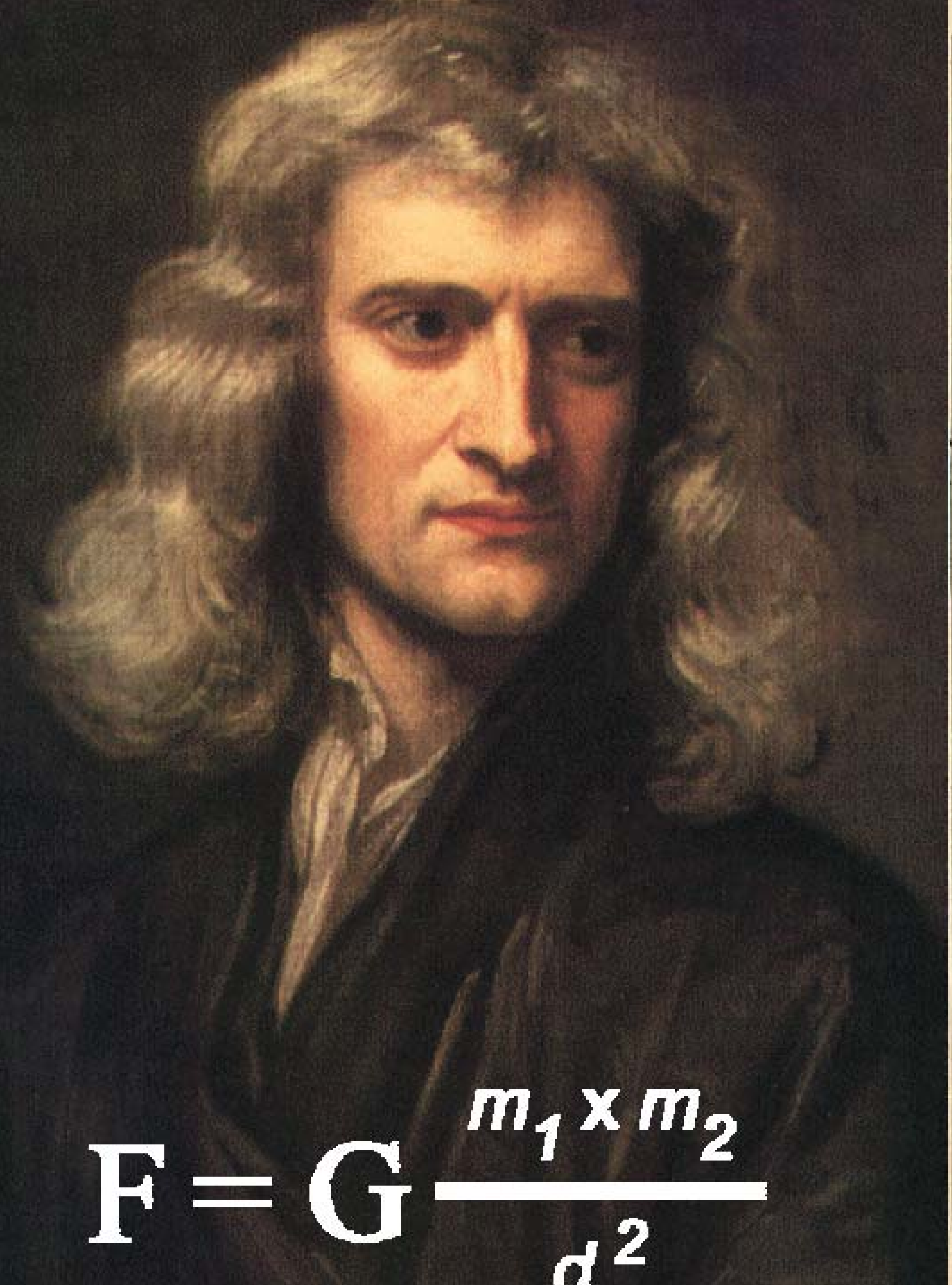
Oxford University Press 1982

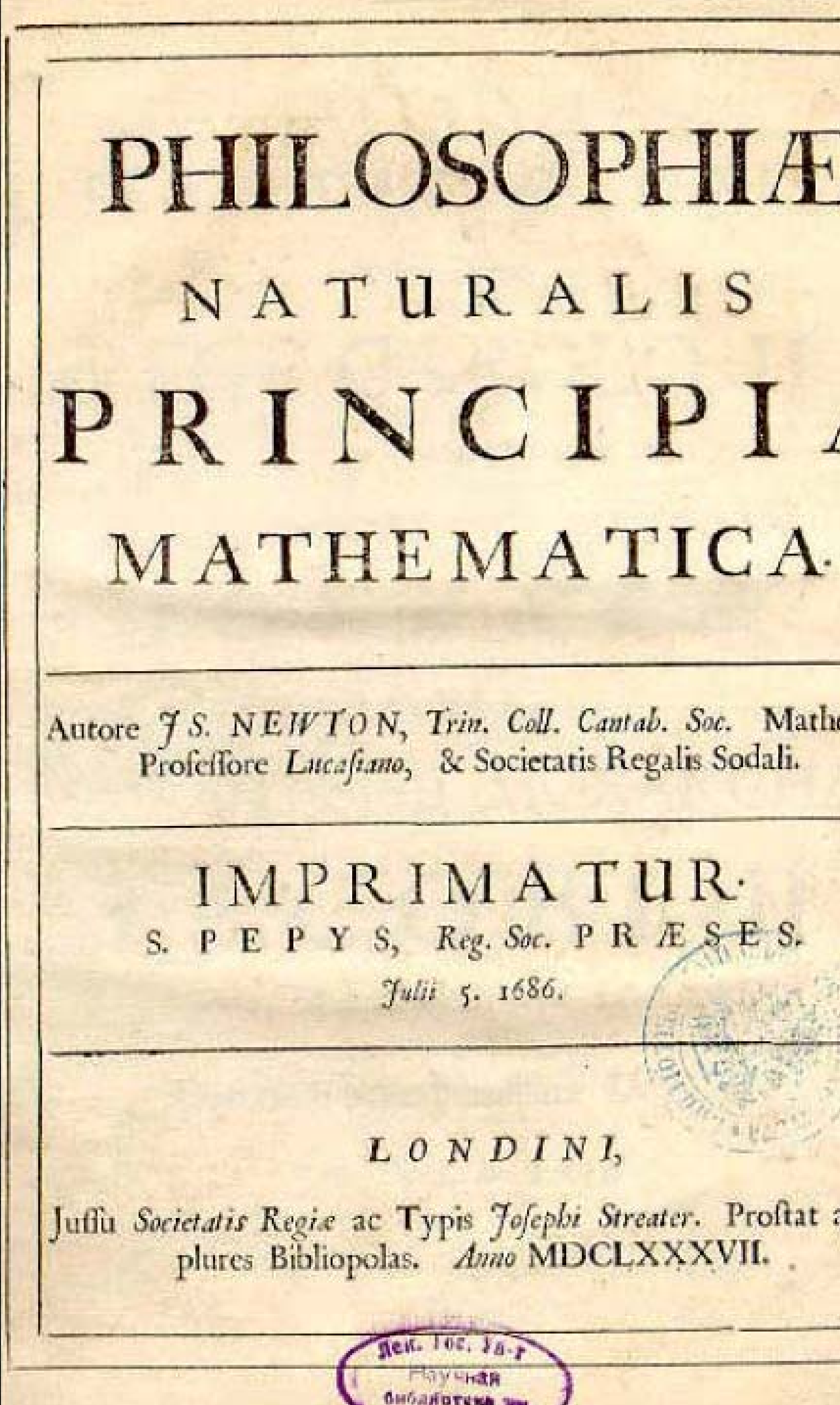
MARCIA BARTUSIAK



Einstein's Unfinished Symphony

Listening to the Sounds of Space-Time





PHILOSOPHIÆ

NATURALIS

PRINCIPIA

MATHEMATICA.

Autore *J S. NEWTON*, *Trin. Coll. Cantab. Soc.* Mathe
Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

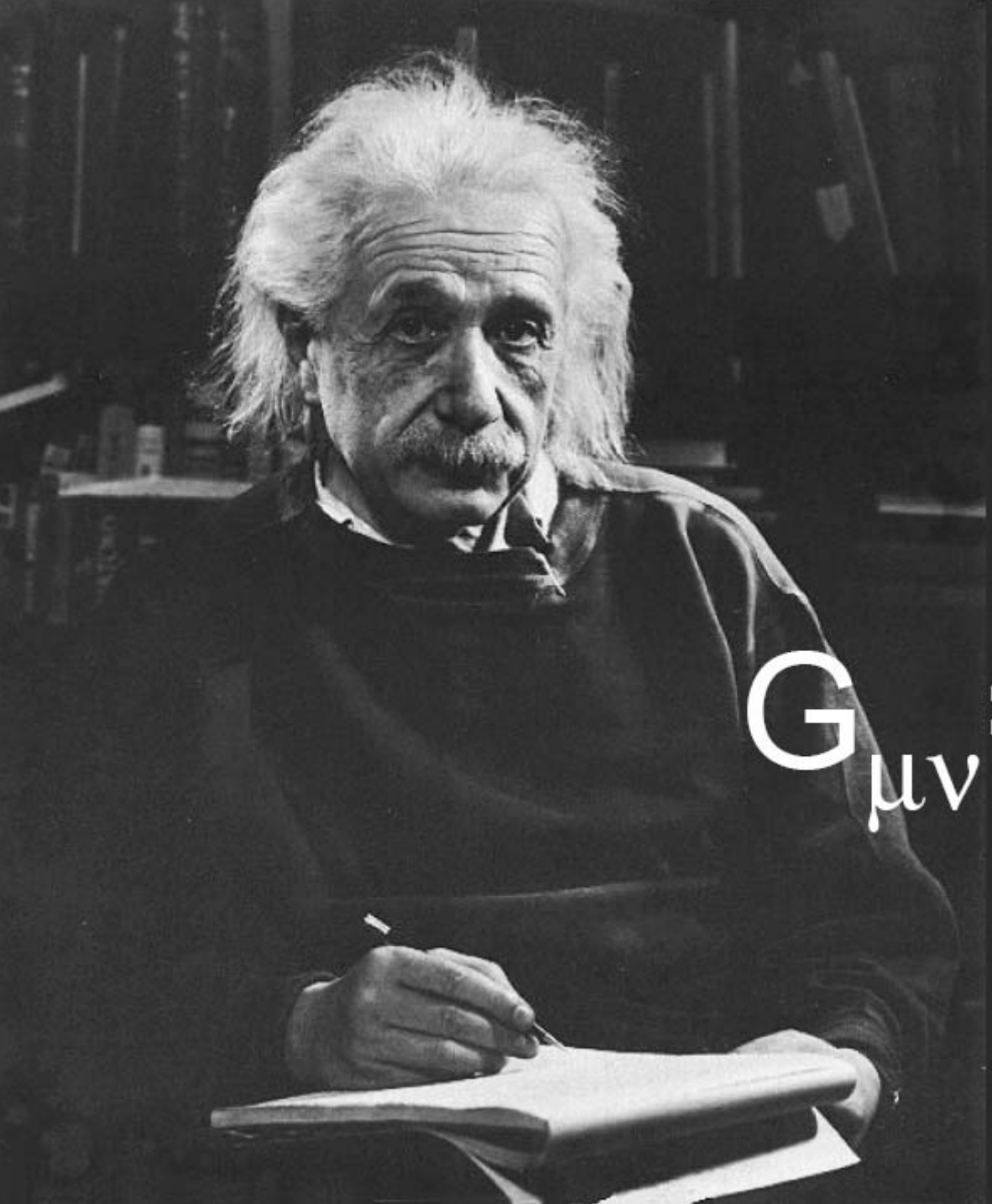
IMPRIMATUR.

S. PEPYS, *Reg. Soc.* PRÆSES.

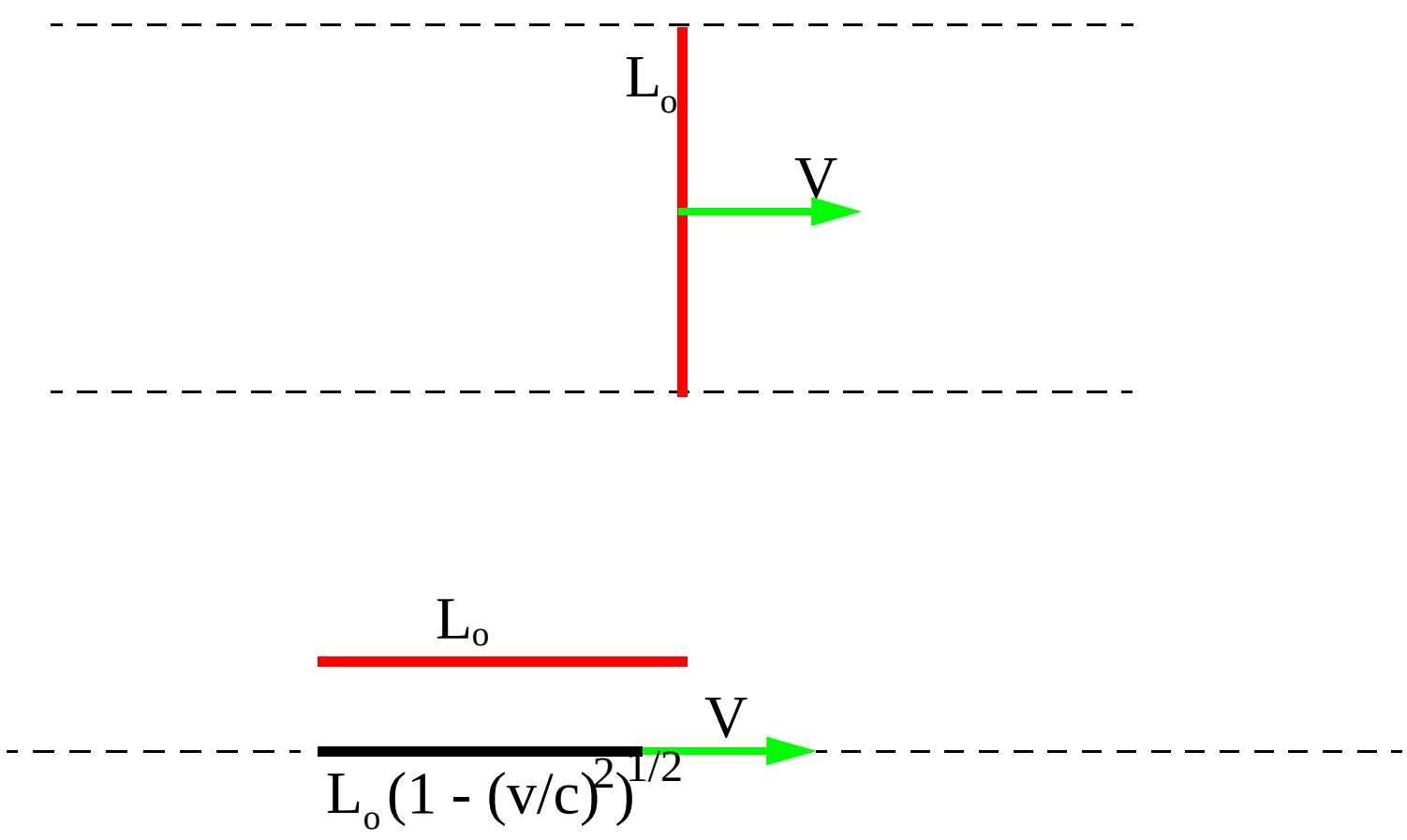
Julii 5. 1686.

LONDINI,

Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat a
plures Bibliopolas. *Anno* MDCLXXXVII.

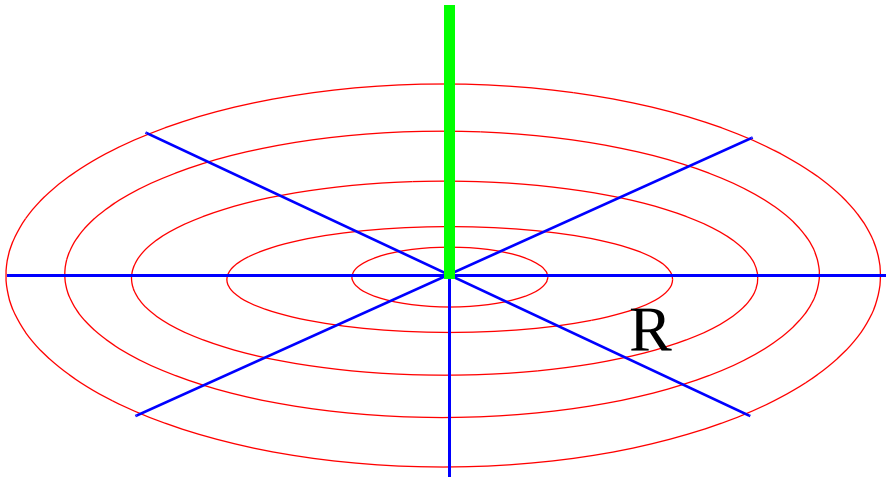


$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

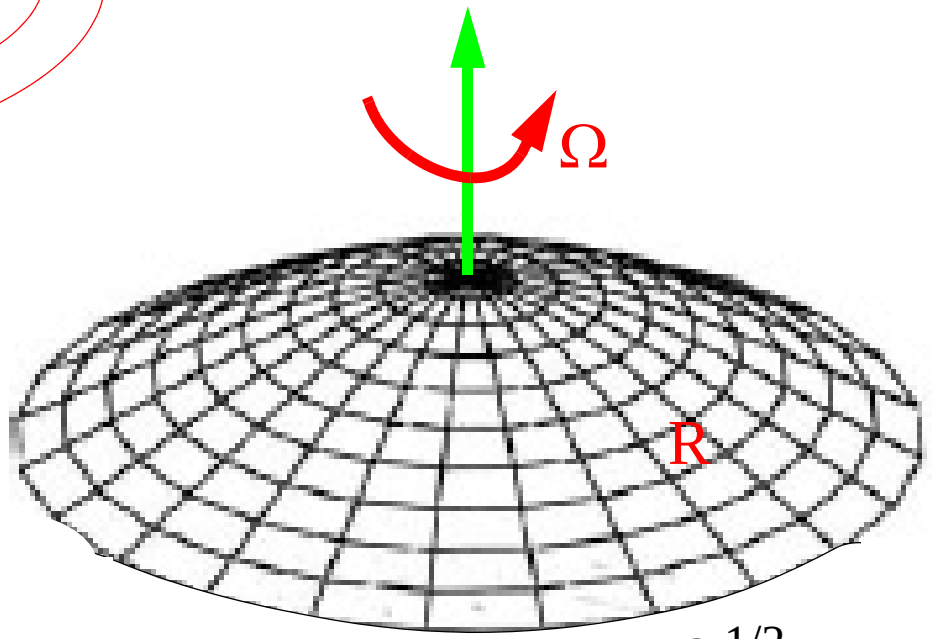


Special relativistic length contraction and simultaneous measurement

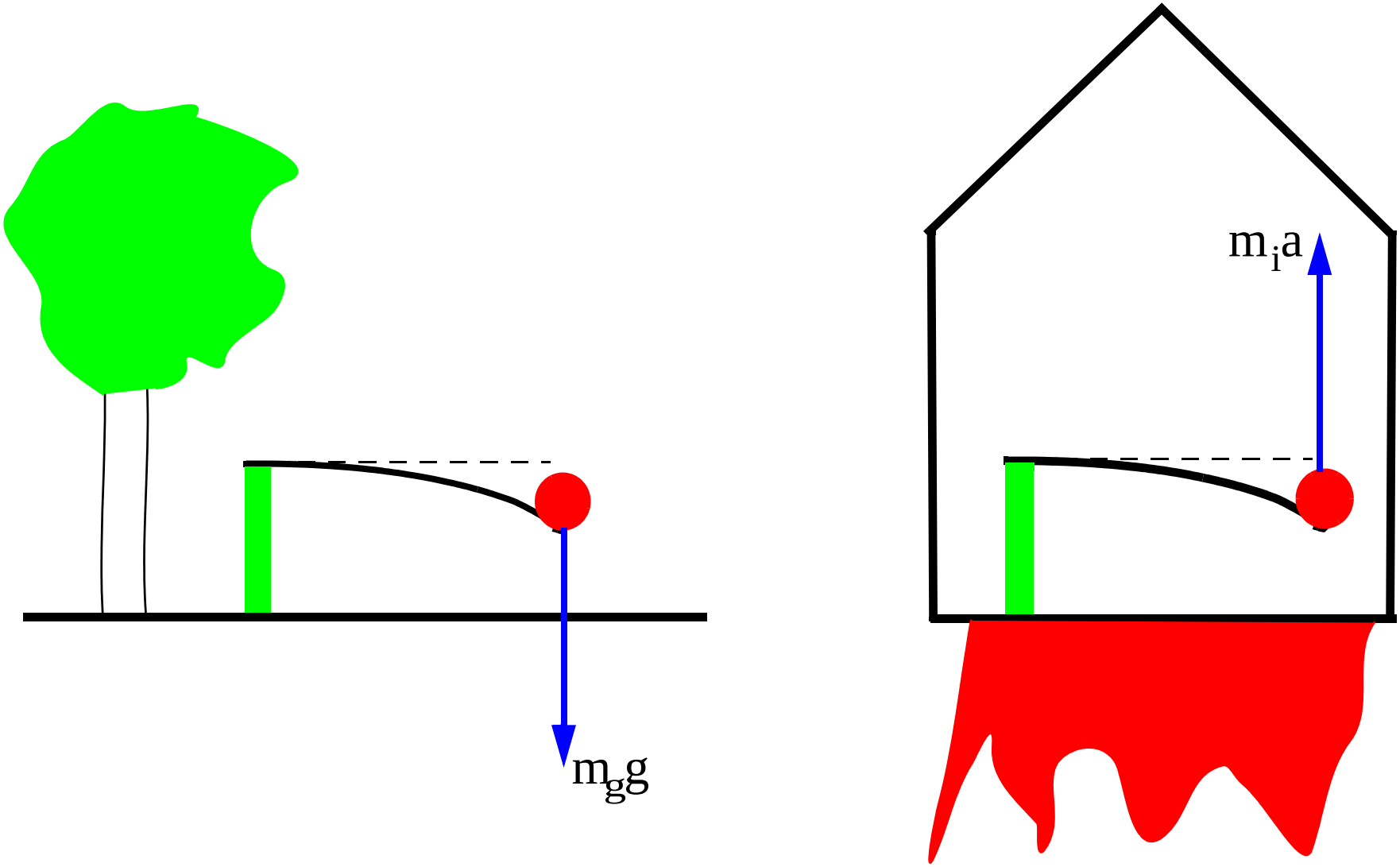
Imagining a rotating platform



$C = 2\pi R$



$$C = 2\pi R(1 - (\Omega R/c)^2)^{1/2}$$

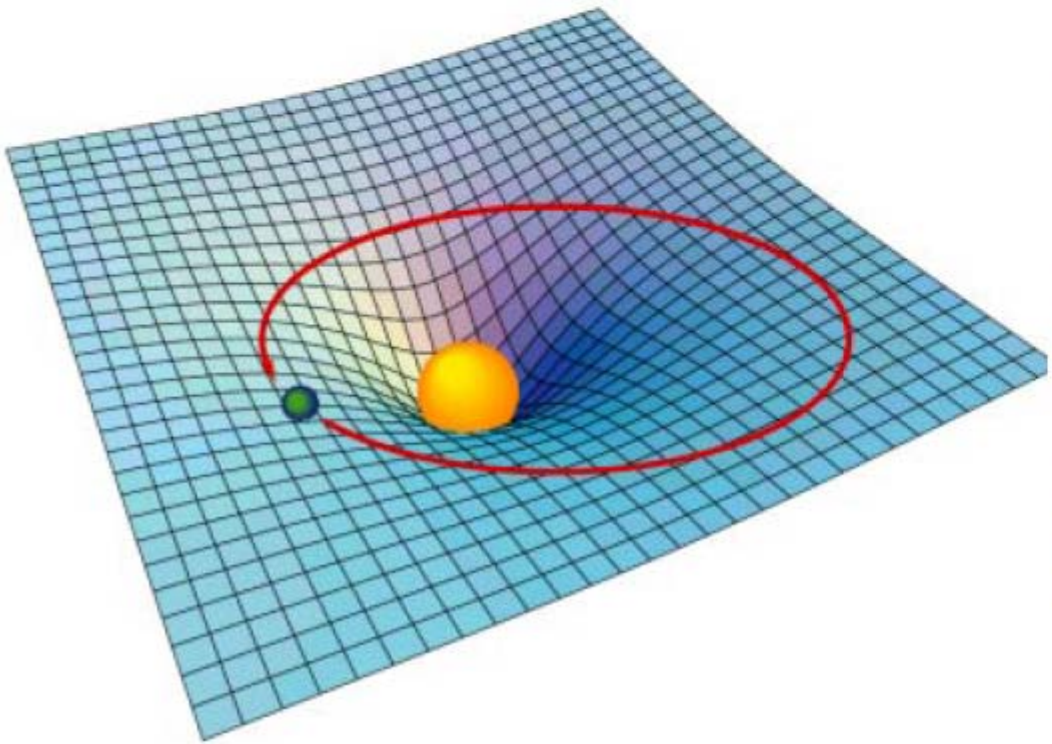


Principle of Equivalence

LIGO

General Relativity

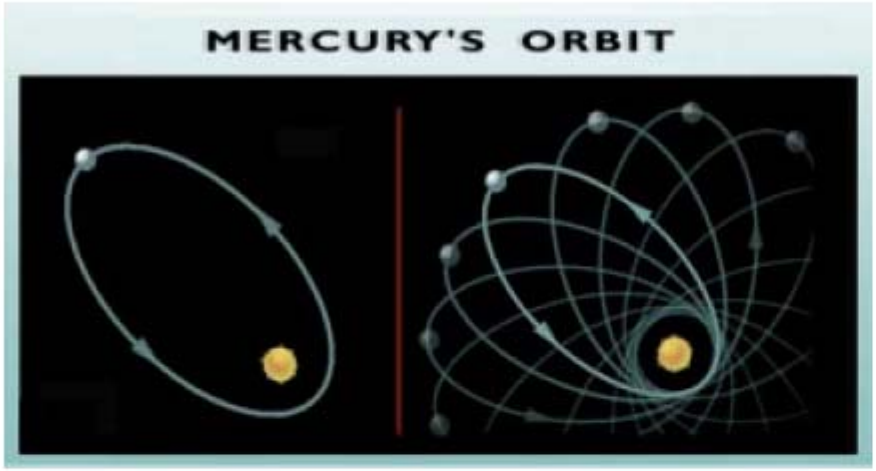
Einstein theorized that smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object



- Imagine space as a stretched rubber sheet.
- A mass on the surface will cause a deformation.
- Another mass dropped onto the sheet will roll toward that mass.

LIGO Einstein's Theory of Gravitation

experimental tests



Mercury's orbit

perihelion shifts forward an extra +43"/century compared to Newton's theory

Mercury's elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or "perihelion") shifts forward with each pass.

Astronomers had been aware for two centuries of a small flaw in the orbit, as predicted by Newton's laws.

Einstein's predictions exactly matched the observation.

LIGO

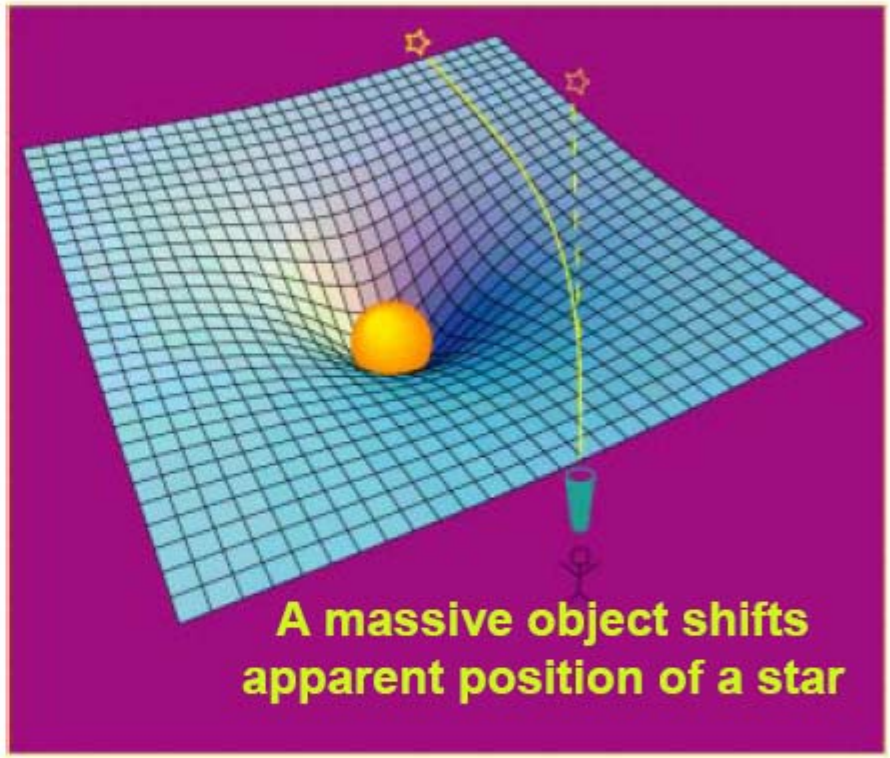
New Wrinkle on Equivalence

bending of light

- Not only the path of matter, but even the path of light is affected by gravity from massive objects

- First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

- Their measurements showed that the light from these stars was bent as it grazed the Sun, by the exact amount of Einstein's predictions.



The light never changes course, but merely follows the curvature of space. Astronomers now refer to this displacement of light as gravitational lensing.

SITZUNGSBERICHTE 1916.
XXXIII.
DER
KÖNIGLICH PREUSSISCHEN
AKADEMIE DER WISSENSCHAFTEN.

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

1918 VI. VII. VIII

SITZUNGSBERICHTE

DER

KÖNIGLICH PREUSSISCHEN

AKADEMIE DER WISSENSCHAFTEN

BERLIN 1918

VERLAG DER KÖNIGLICHEN AKADEMIE DER WISSENSCHAFTEN

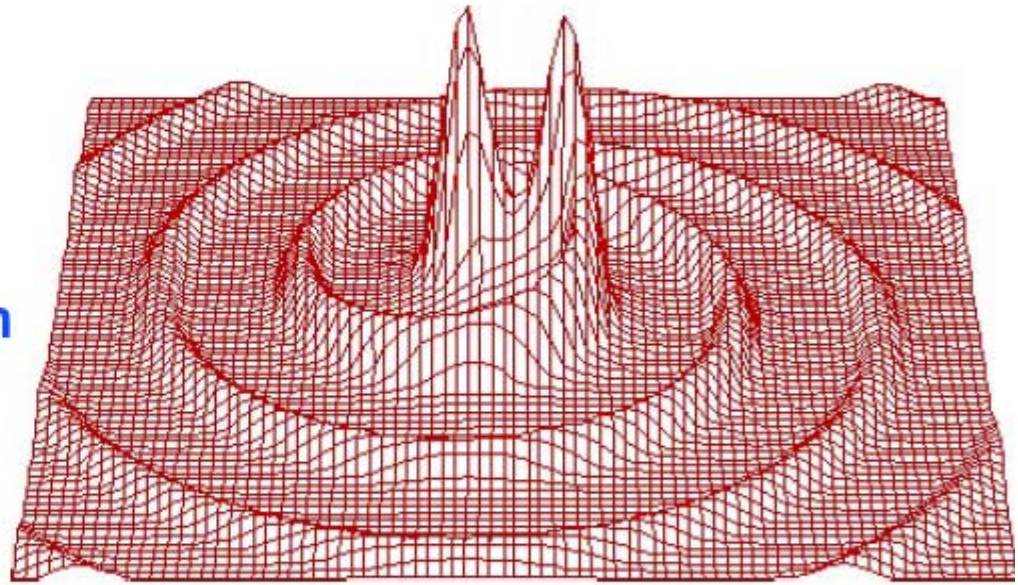
IN KOMMISSION BEI GEORG REIMER

LIGO Einstein's Theory of Gravitation

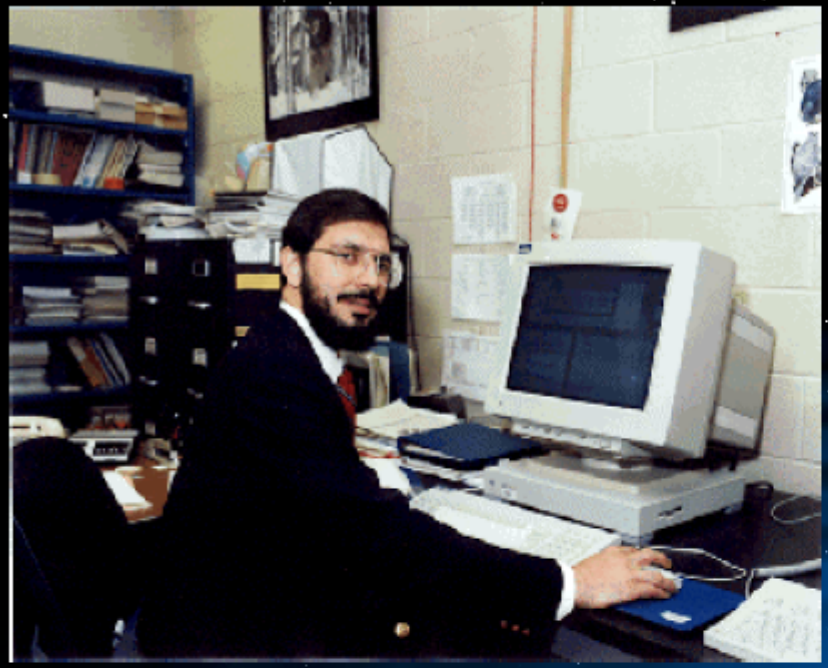
gravitational waves

- a necessary consequence of Special Relativity with its finite speed for information transfer

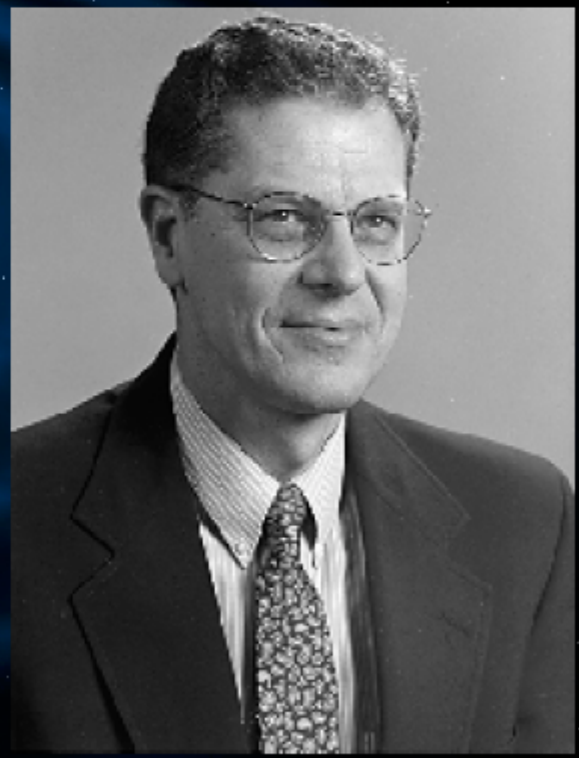
- time dependent gravitational fields come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light



gravitational radiation
binary inspiral of compact objects



Russel A. Hulse



Joseph H.Taylor Jr

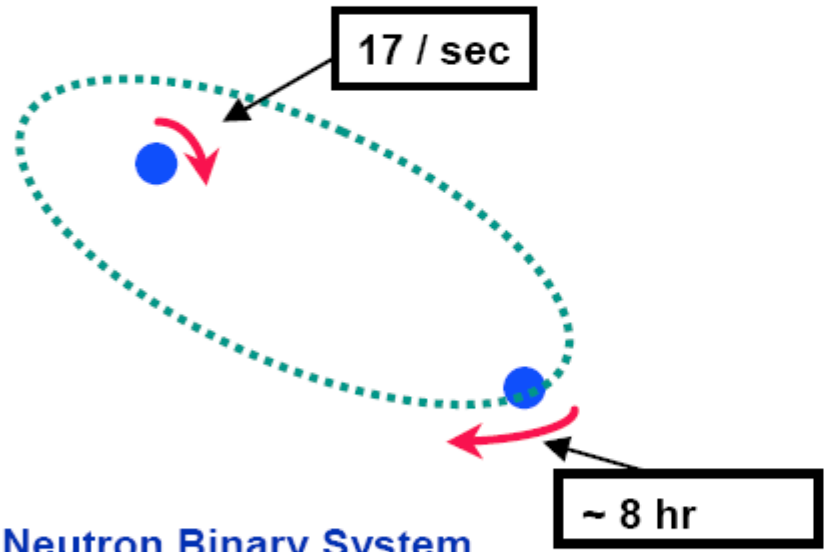
Source: www.NSF.gov

LIGO

Gravitational Waves
the evidence

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



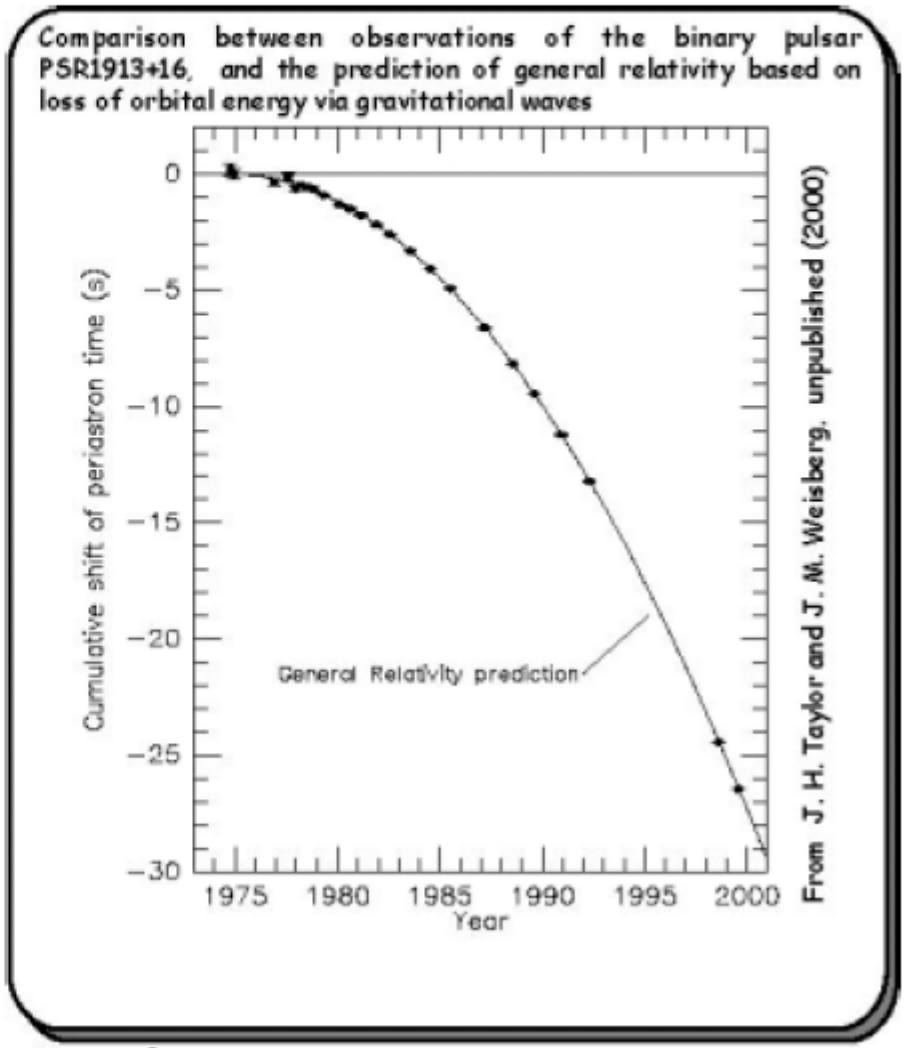
Neutron Binary System

- separated by 10^6 miles
- $m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity

- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves



Direct detection of gravitational waves from astrophysical sources

Physics

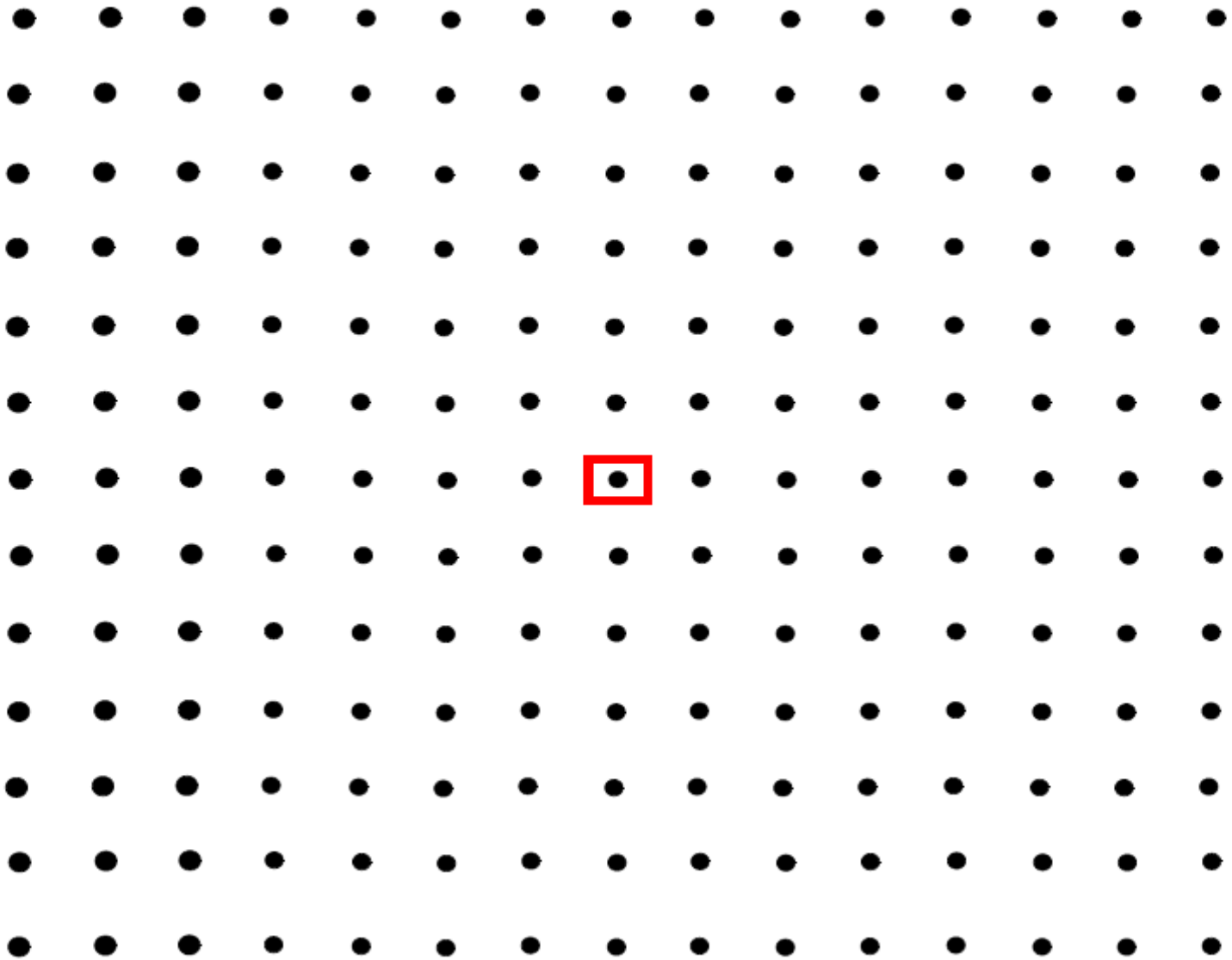
- Observations of gravitation in the strong field, high velocity limit
- Determination of wave kinematics – polarization and propagation
- Tests for alternative relativistic gravitational theories

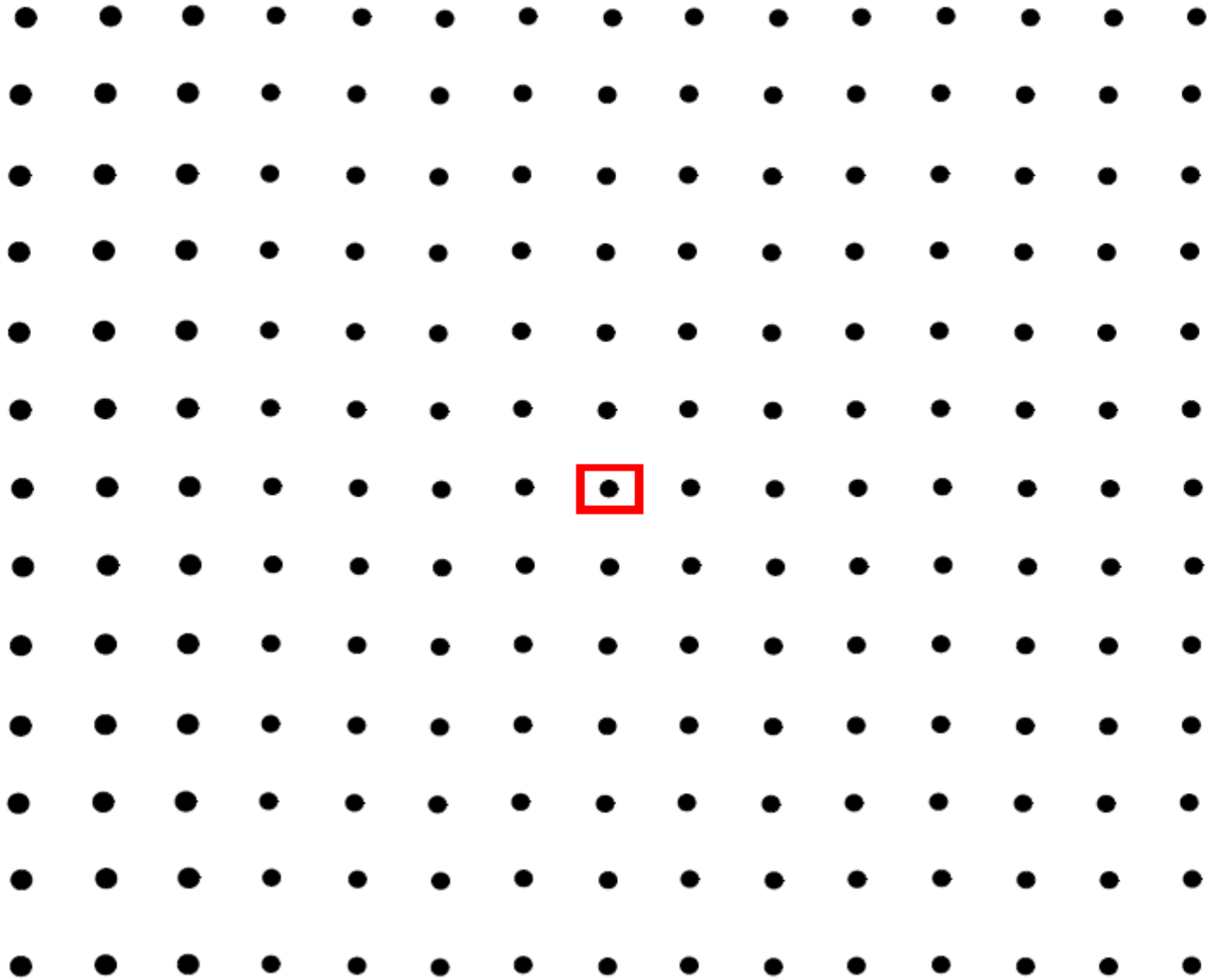
Astrophysics

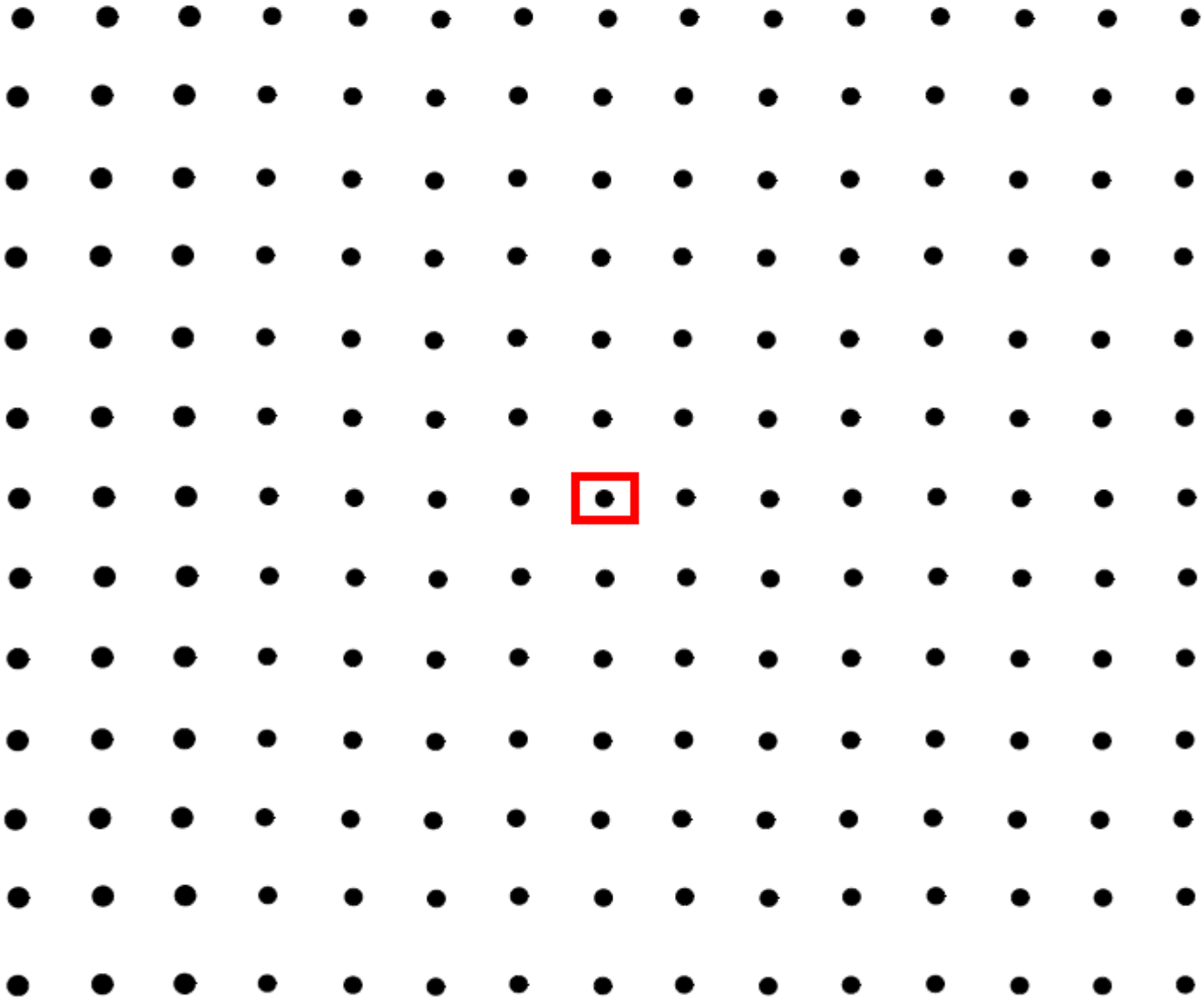
- Measurement of coherent inner dynamics – stellar collapse, pulsar formation….
- Compact binary coalescence – neutron star/neutron star, black hole/black hole
- Neutron star equation of state
- Primeval cosmic spectrum of gravitational waves

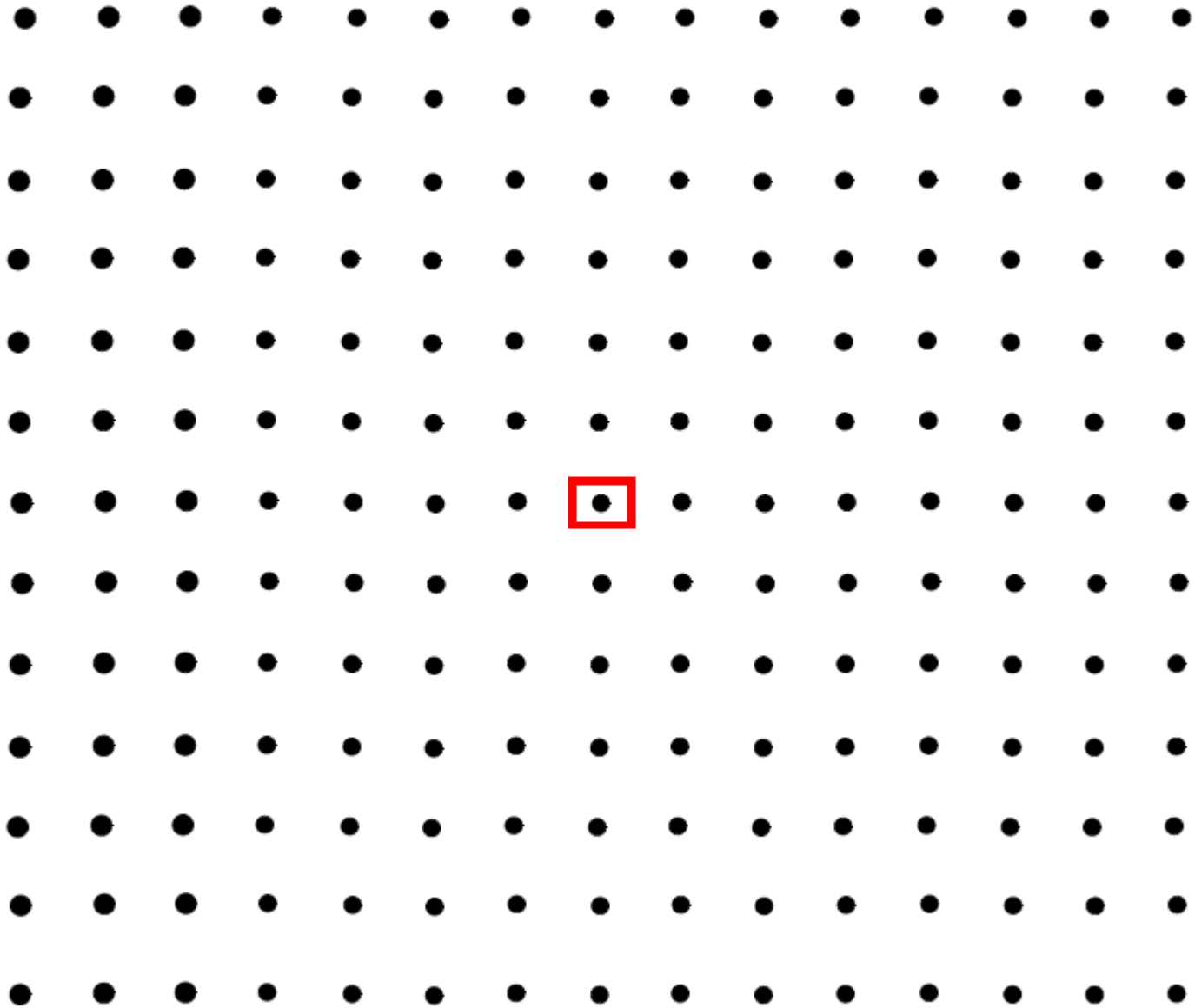
Gravitational wave survey of the universe

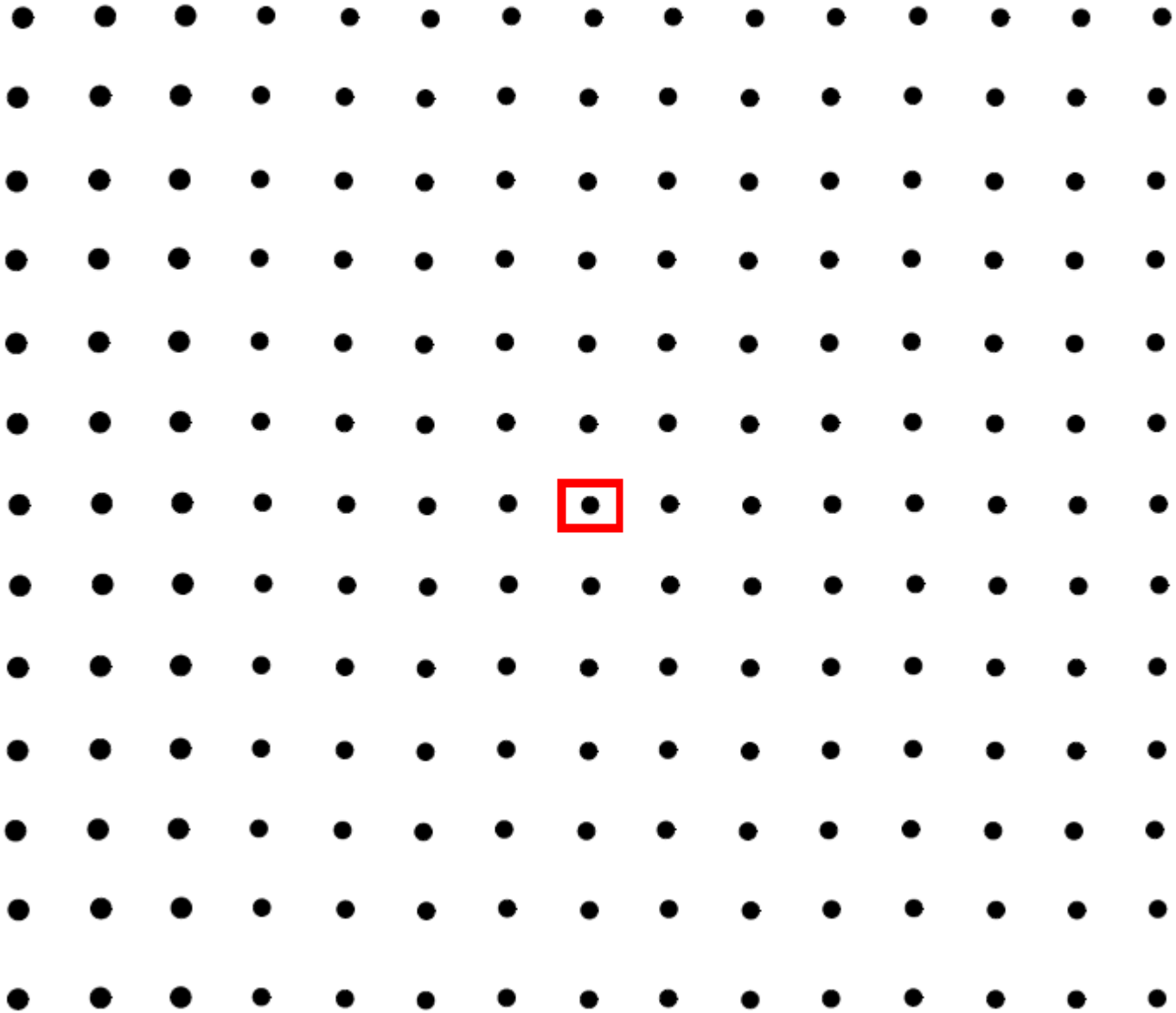
Joseph Weber 1919-2000

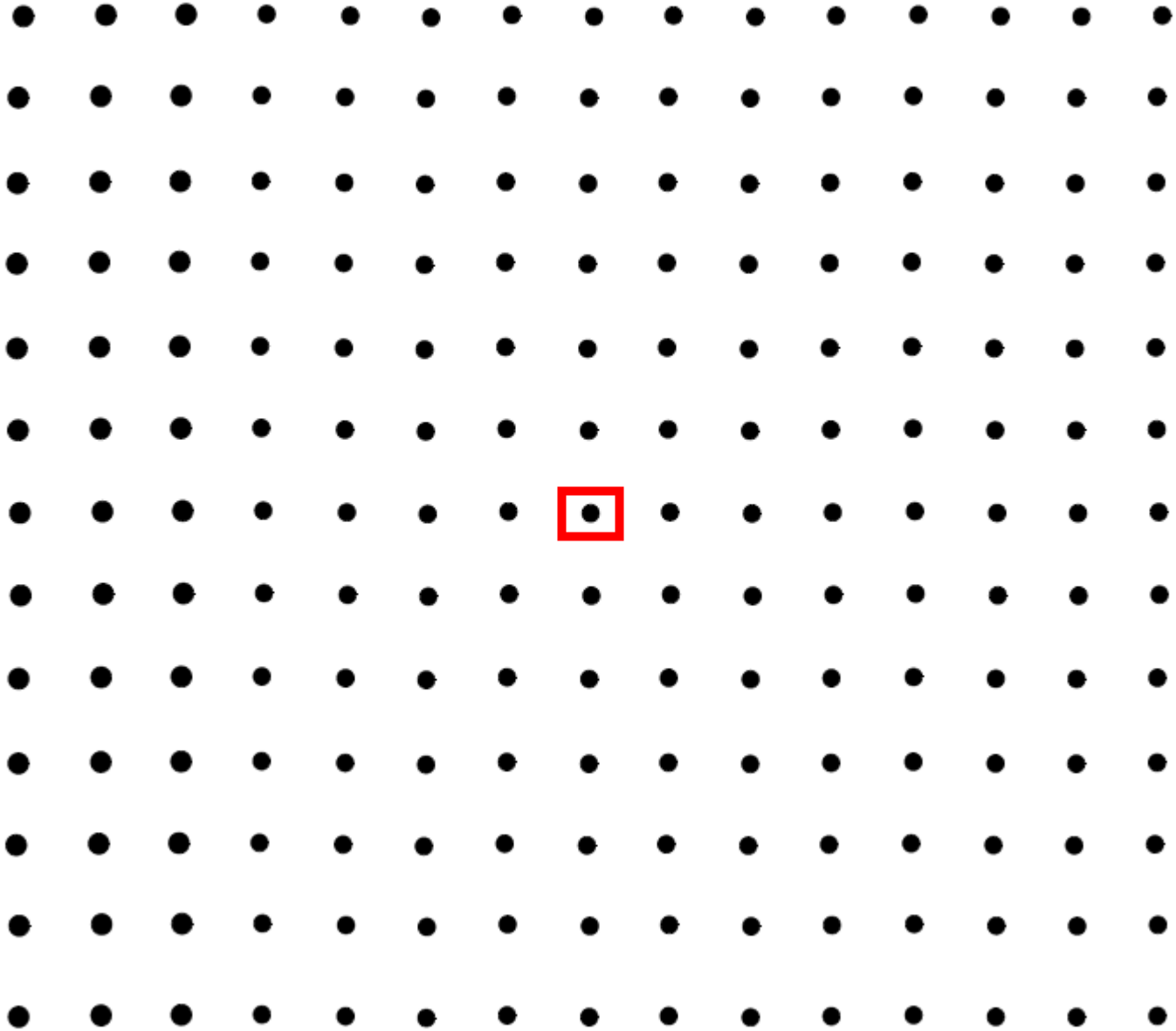


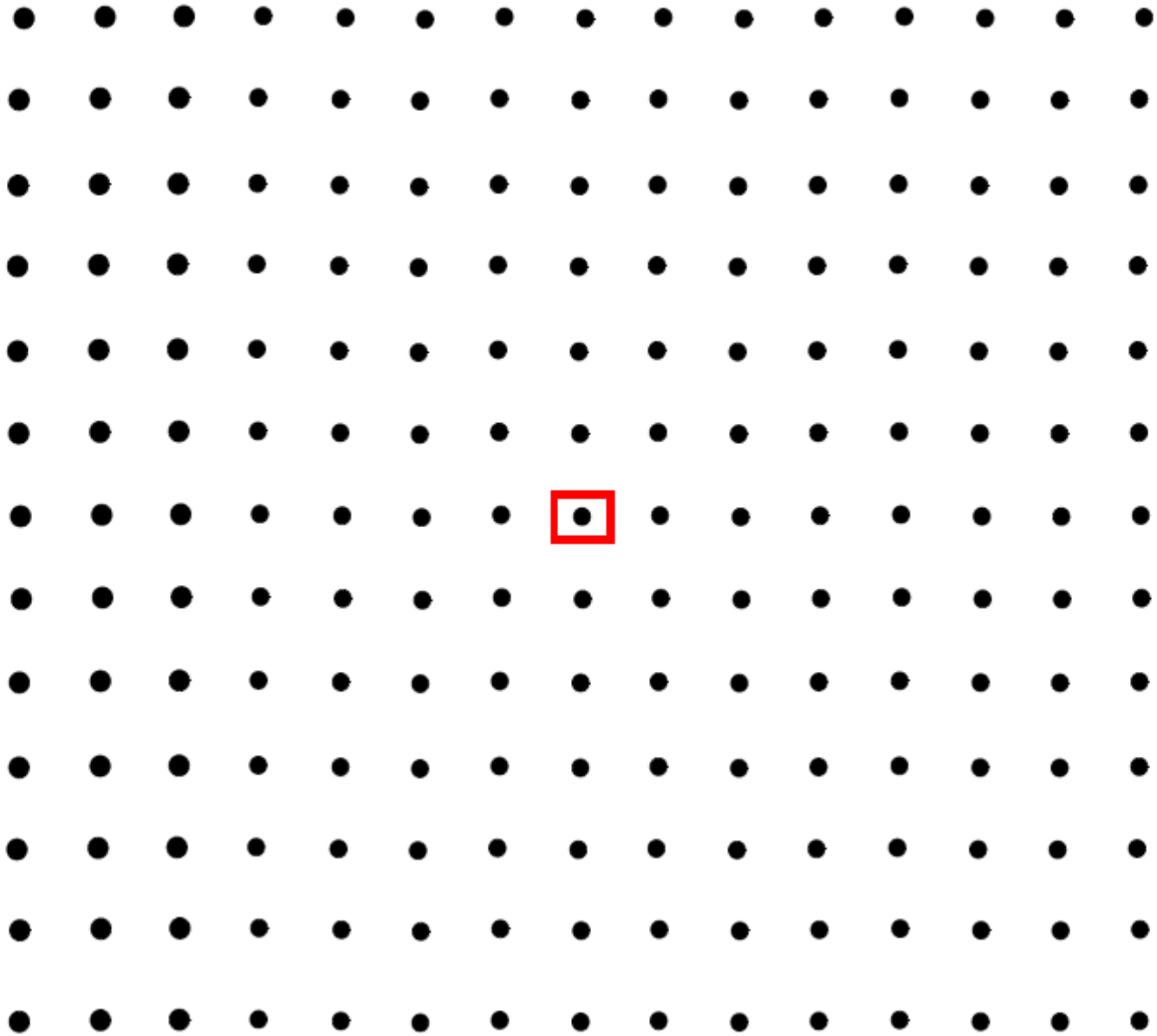


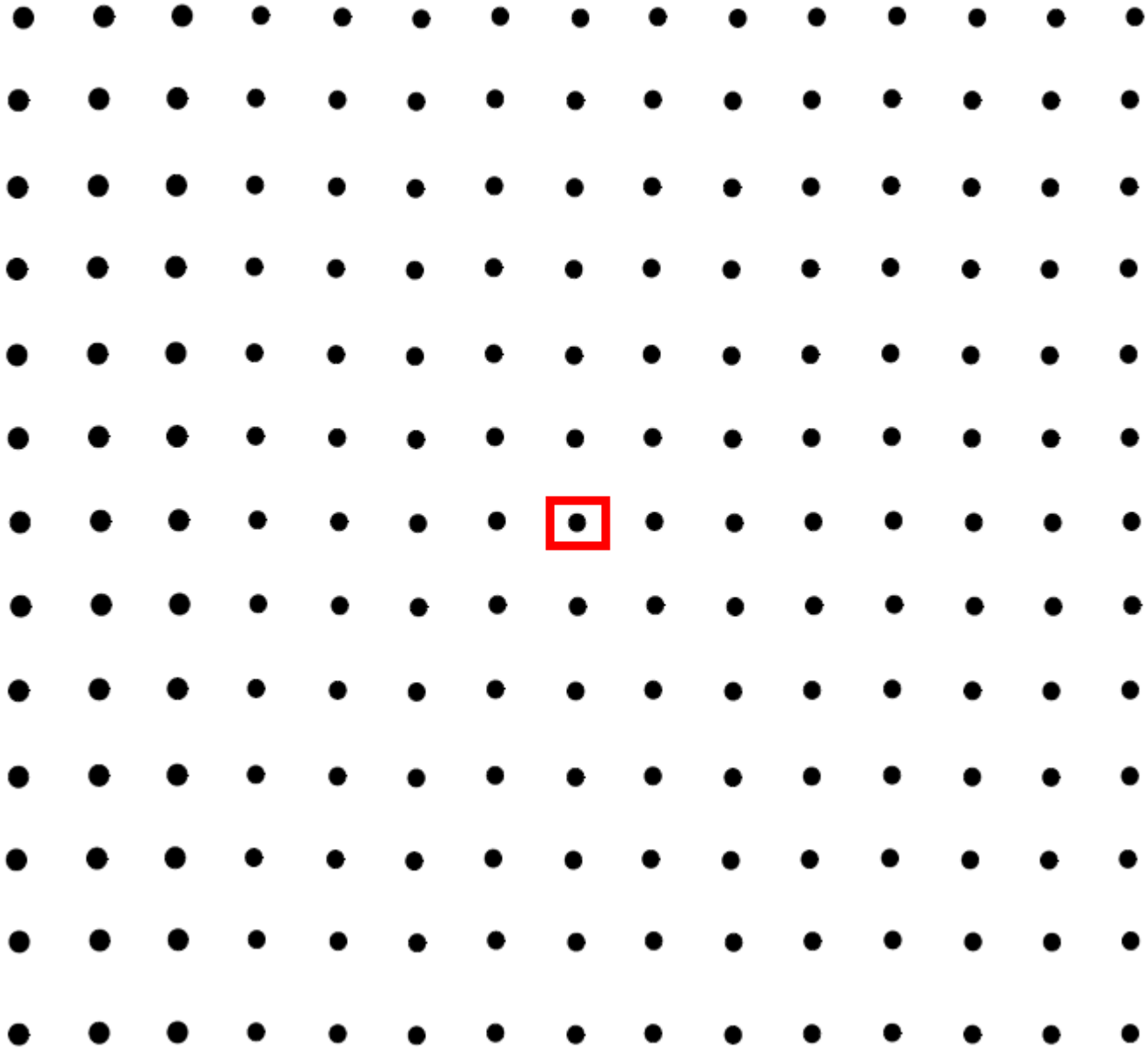


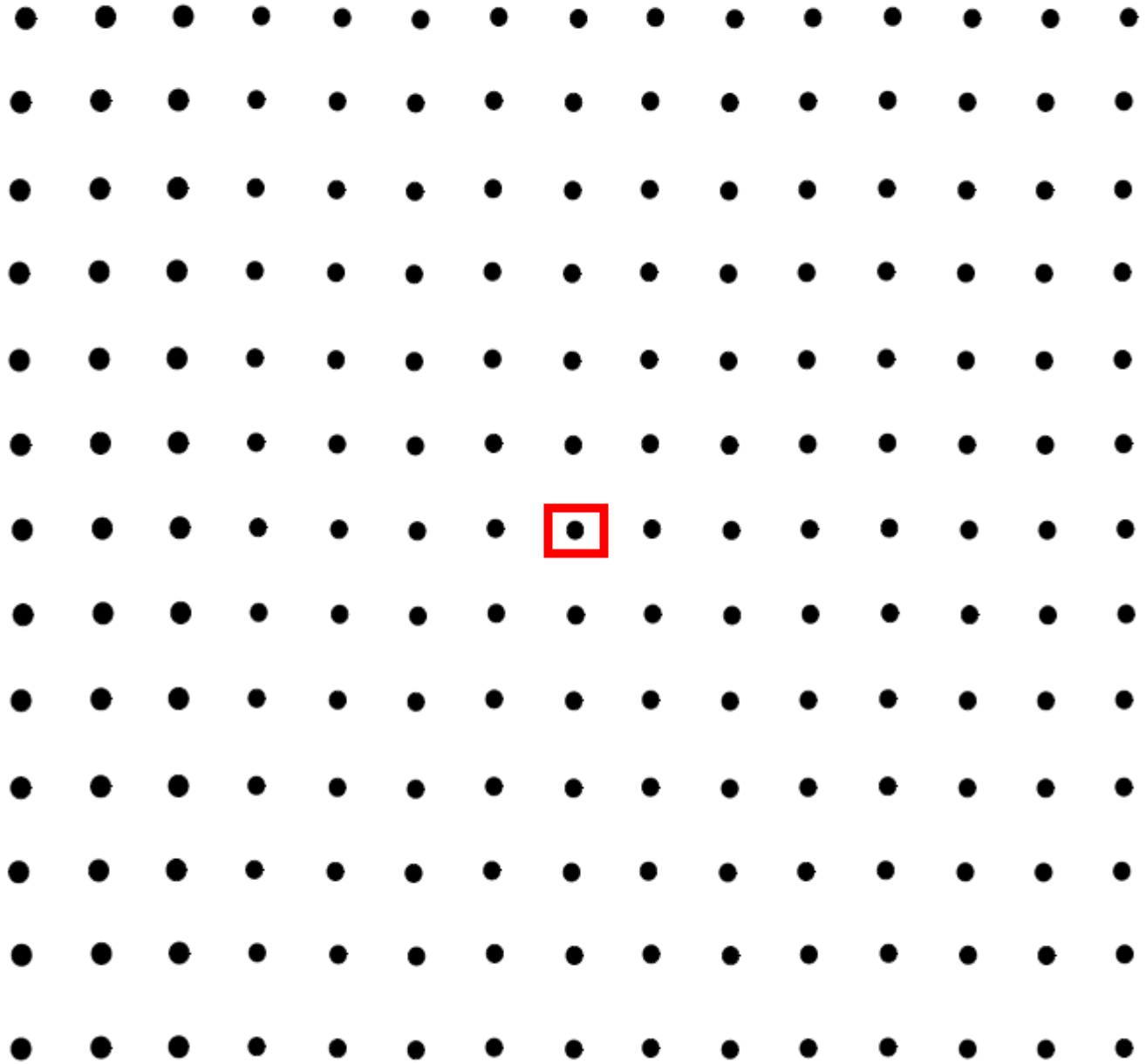


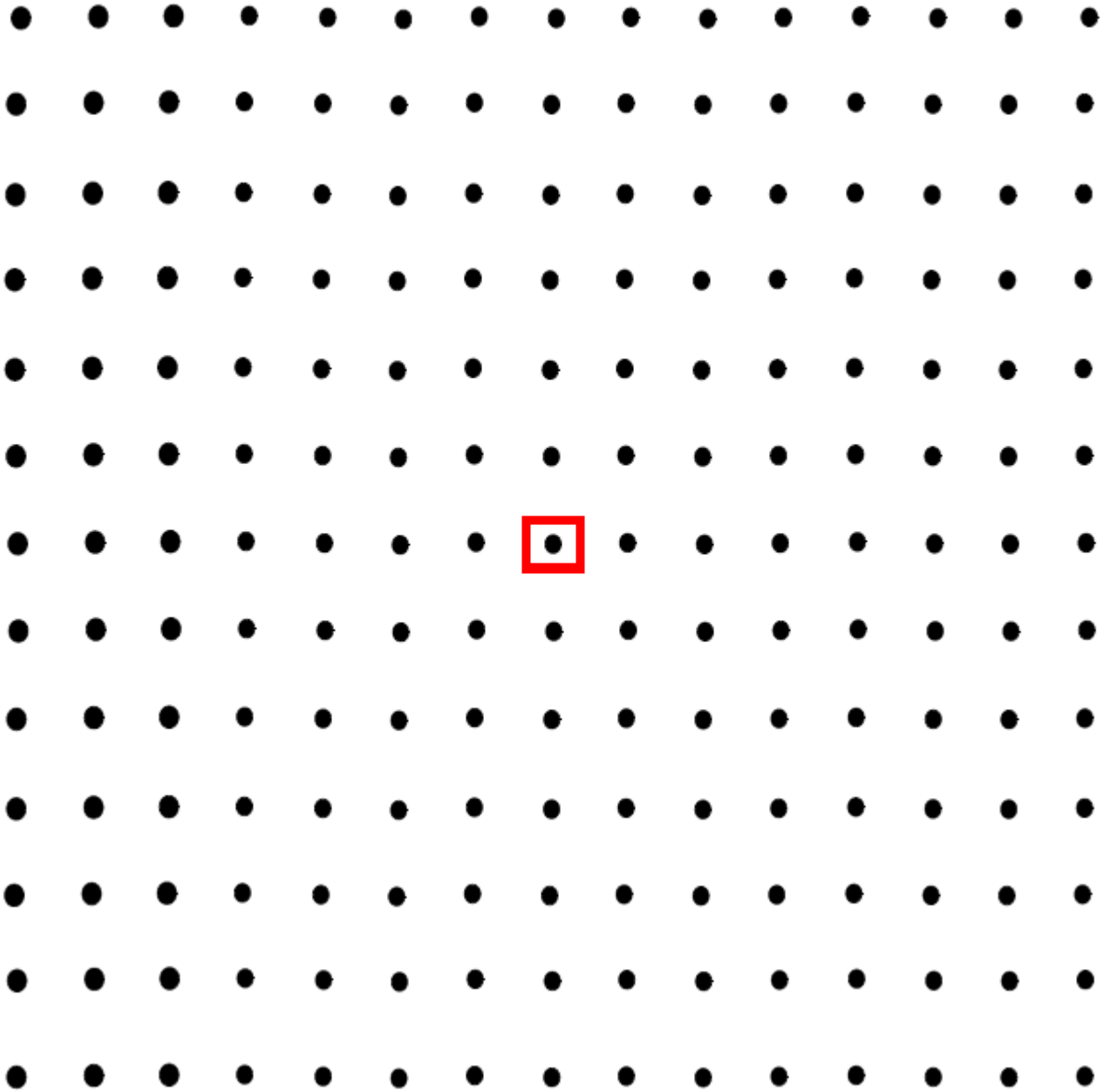


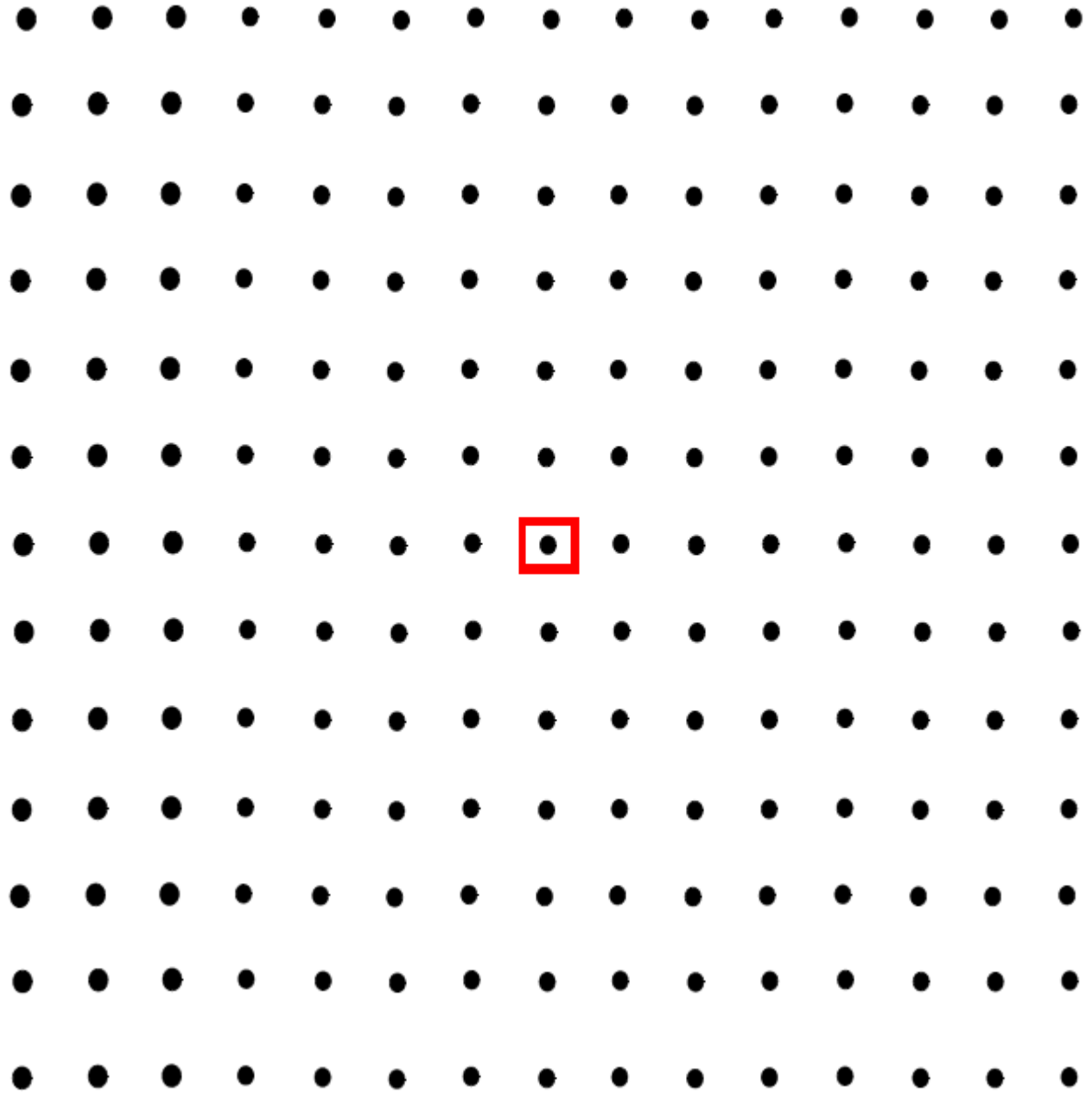


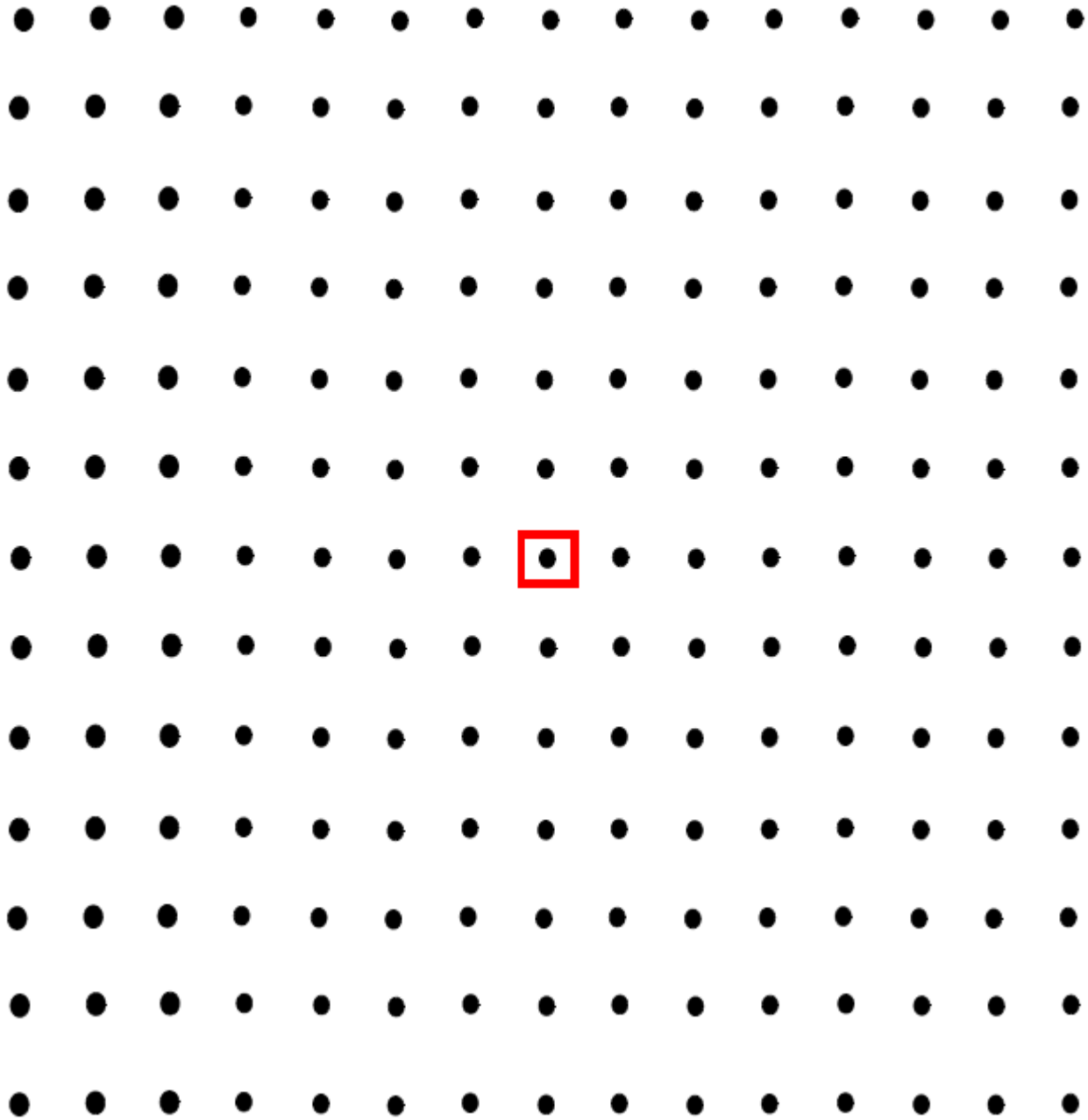












Measurement challenge

- Needed technology development to measure:

$$h = \Delta L/L < 10^{-21}$$

$$\Delta L < 4 \times 10^{-18} \text{ meters}$$

LIGO

How Small is 10^{-18} Meter?

One meter, about 40 inches

÷10,000

Human hair, about 100 microns

÷100

Wavelength of light, about 1 micron

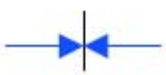
÷10,000

Atomic diameter, 10^{-10} meter

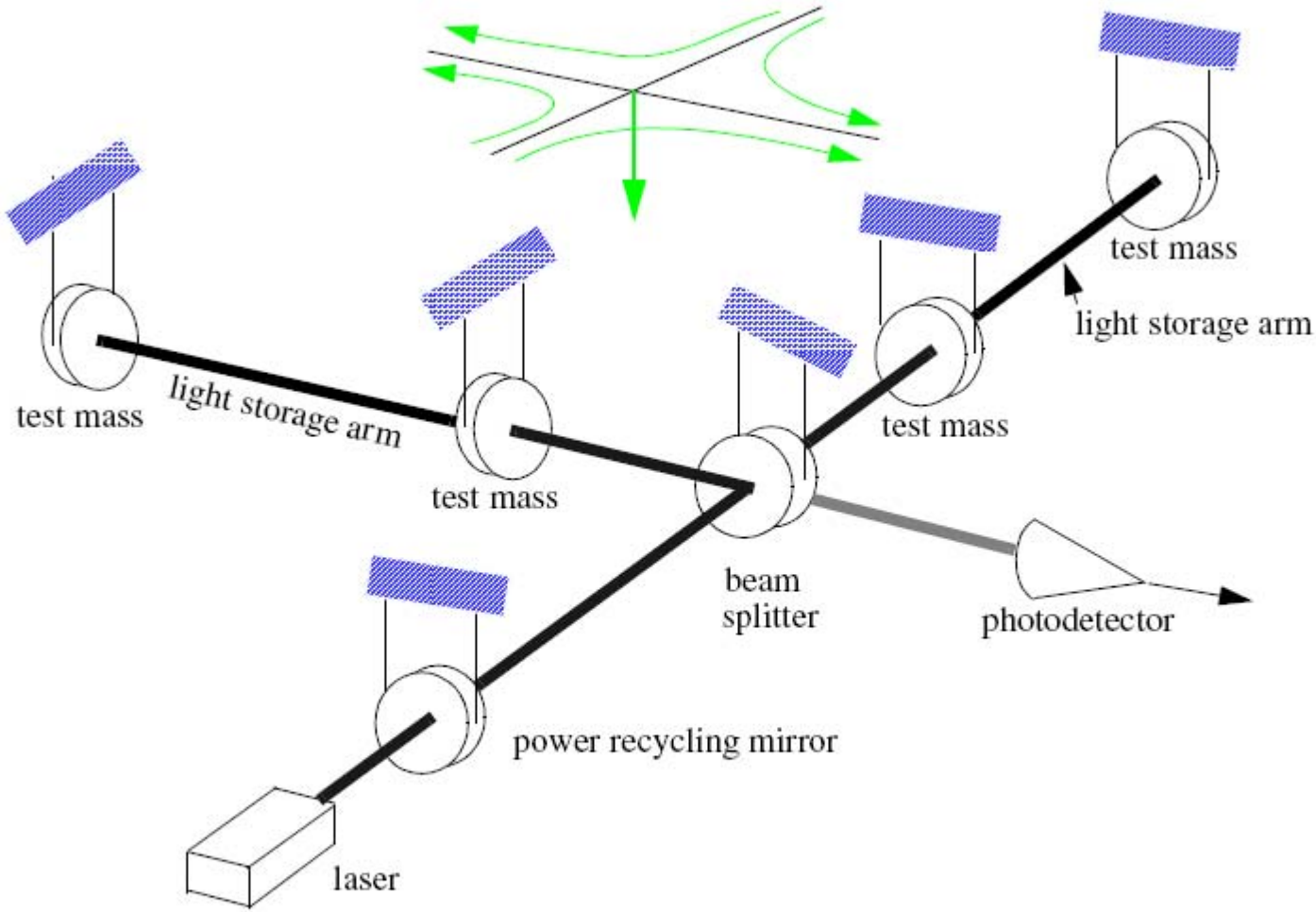
÷100,000

Nuclear diameter, 10^{-15} meter

÷1,000



LIGO sensitivity, 10^{-18} meter


test mass
light storage arm
test mass
beam
splitter
test mass
light storage arm
test mass
photodetector
power recycling mirror
laser

FRINGE SENSING

wavelength 1×10^{-6} m

$$h = \frac{x}{L} \sim \frac{\lambda}{Lb\sqrt{\dot{N}\tau}}$$

arm length = 4000 m

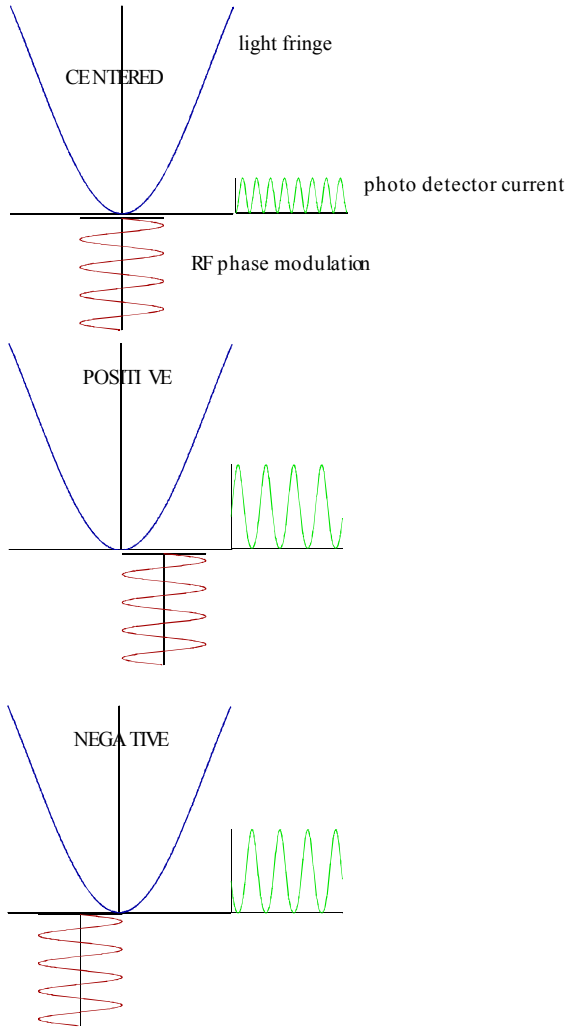
integration time

equivalent # of passes = 100

number of quanta/second at the beam splitter

300 watts at beam splitter = 10^{21} identical photons/sec

$h = 6 \times 10^{-22}$ integration time 10^{-2} sec



PENDULUM THERMAL NOISE

Pendulum Brownian motion

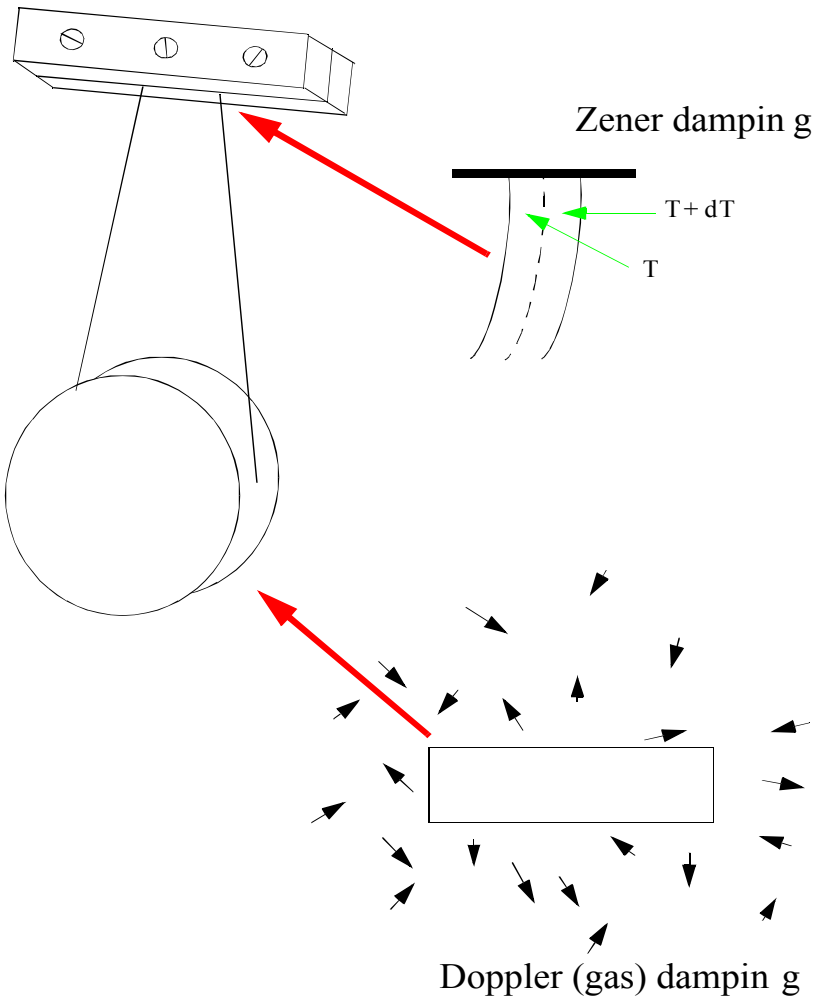
Dissipation leads to fluctuations

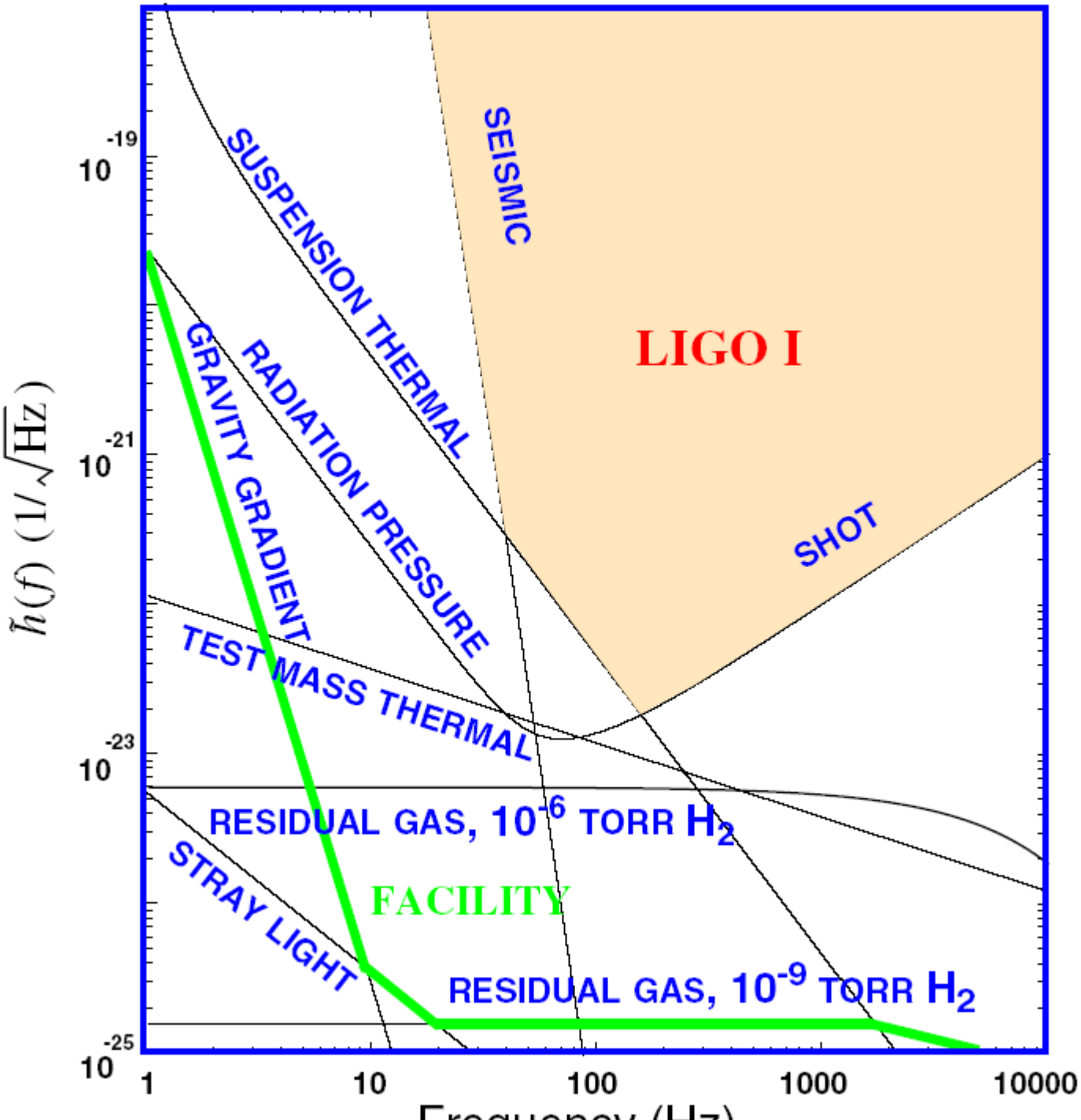
Tc = coherence or damping time
= Q x period of oscillator

Exchange with surroundings:

$$E(\text{thermal}) = \frac{kT\ t}{Tc}$$

Large Tc => smaller fluctuations

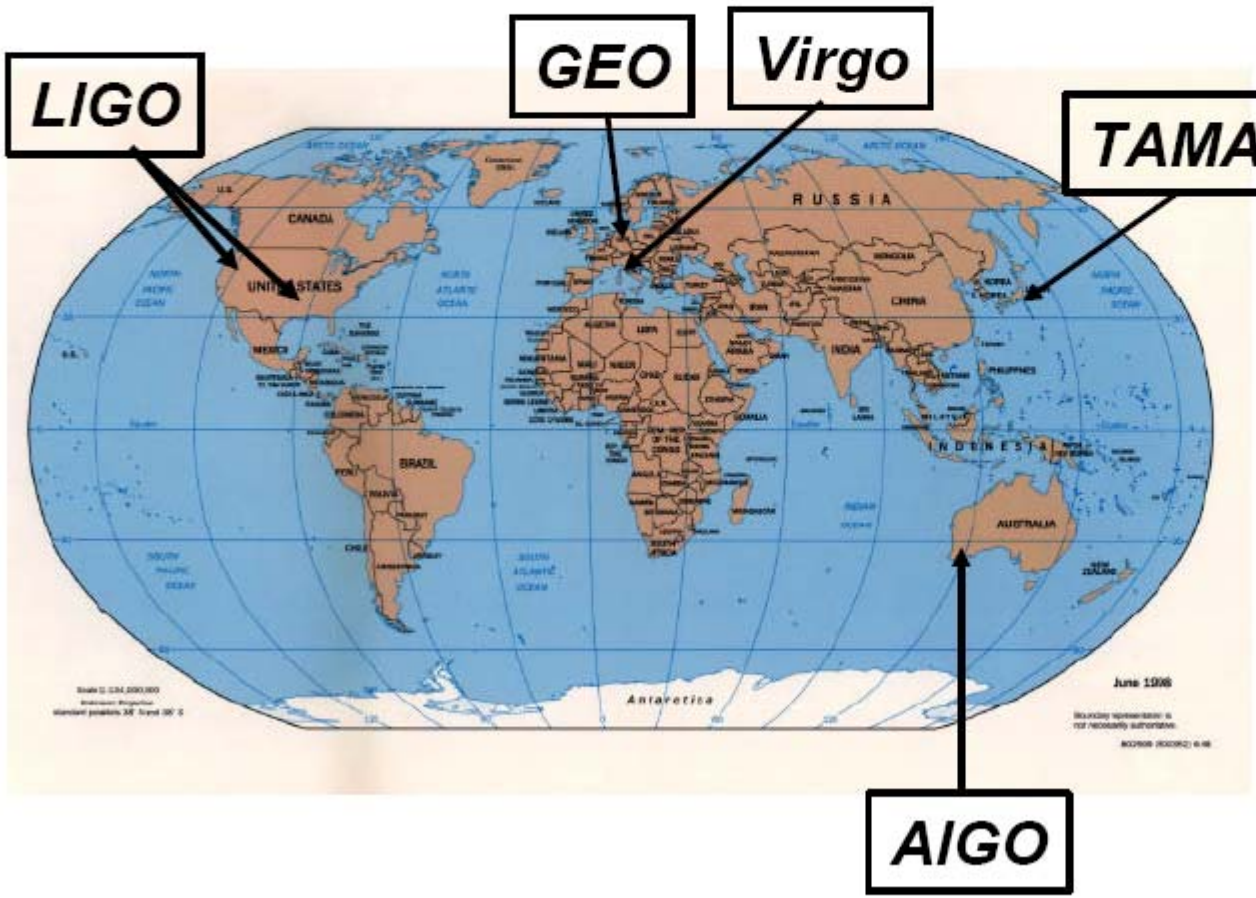



SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
TEST MASS THERMAL
SHOT
LIGO I
RESIDUAL GAS, 10-6 TORR H2
STRAY LIGHT
FACILITY
RESIDUAL GAS, 10-9 TORR H2
10-19
10-21
10-23
10-25
h(f) (1/√Hz)
1
10
100
1000
10000

Interferometers

international network

Simultaneously detect signal (within msec)

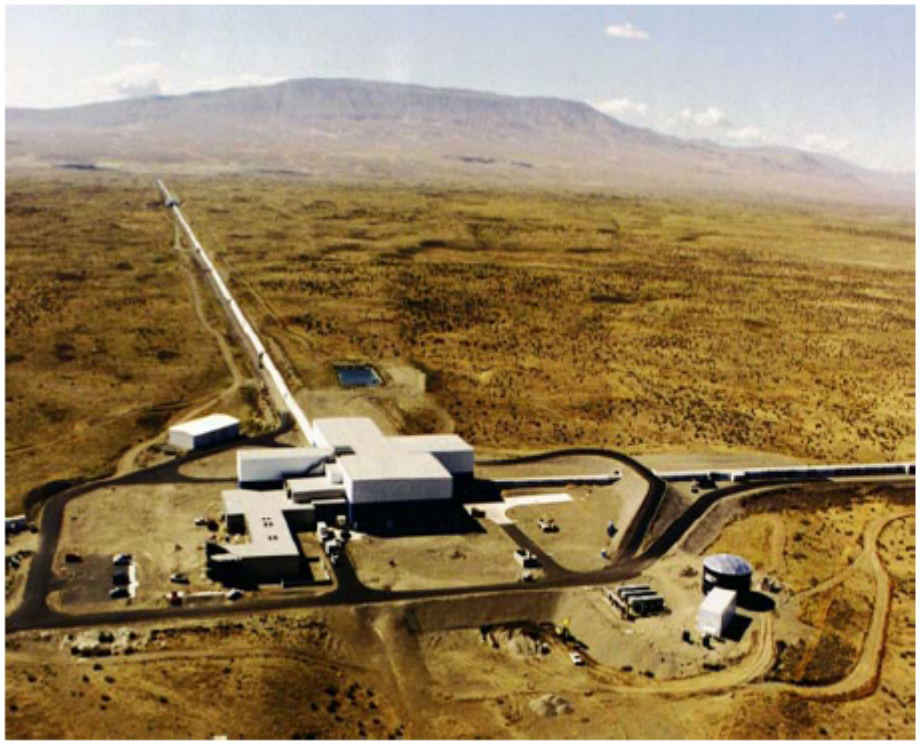


detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

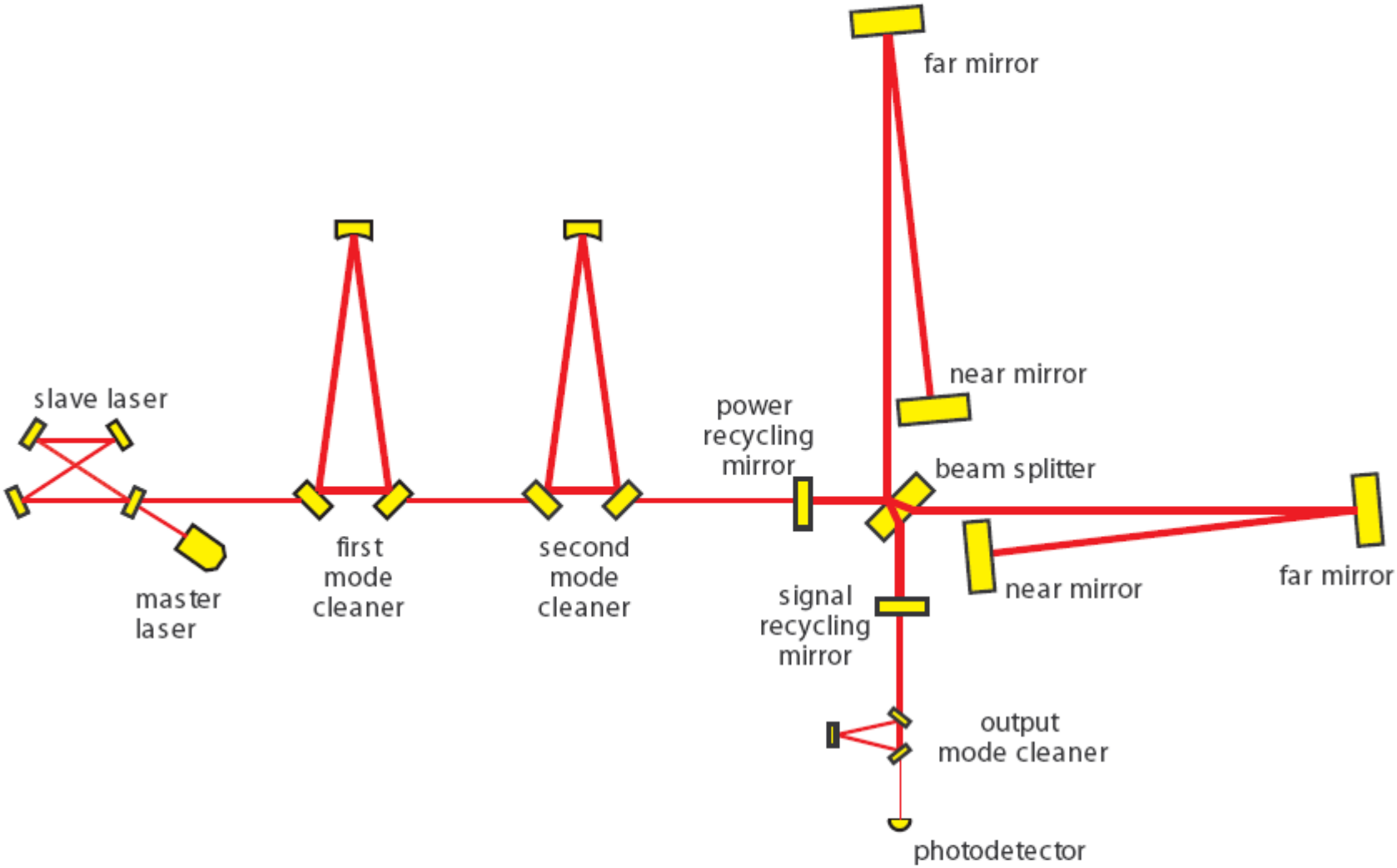
26 km north of Richland, WA

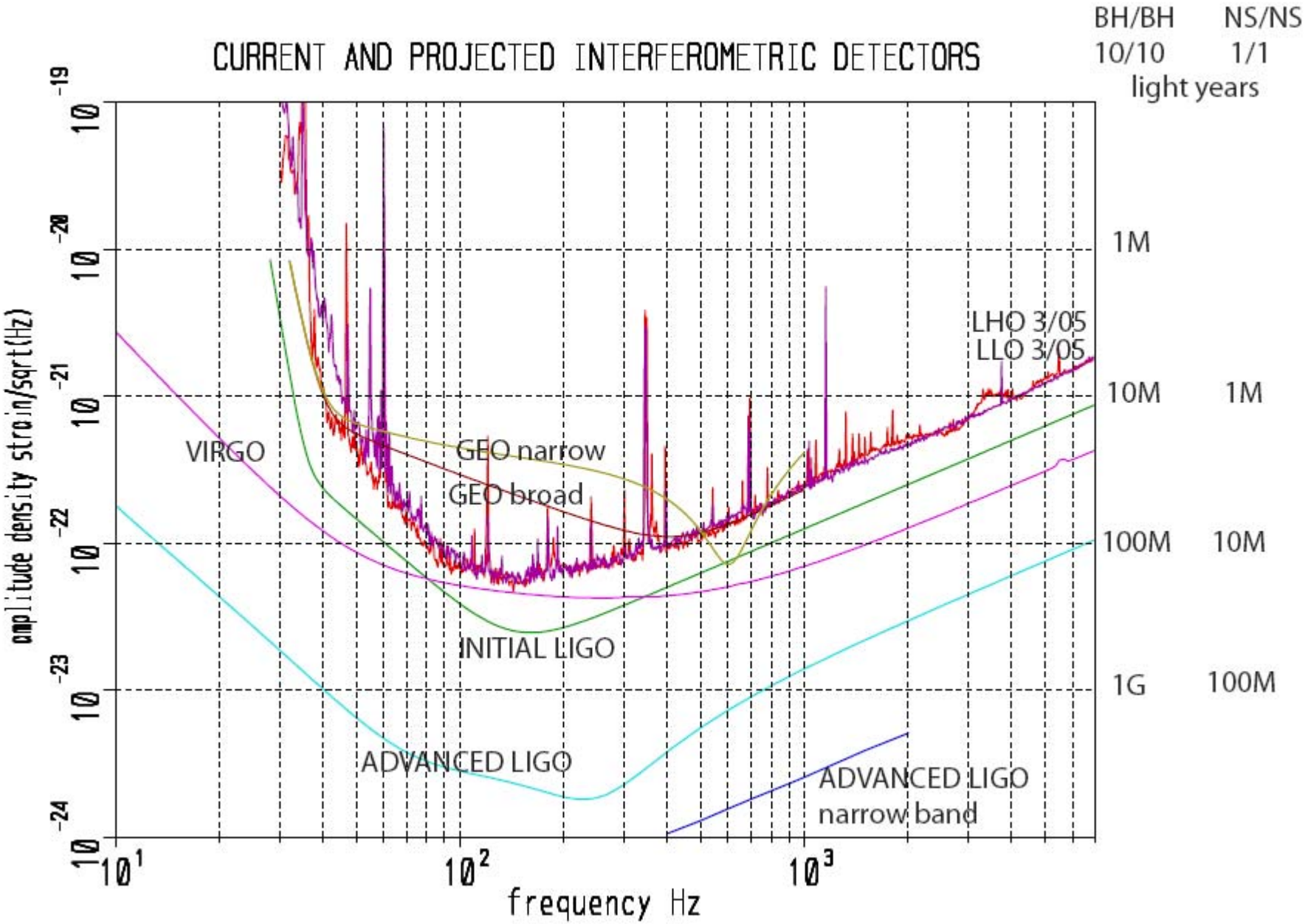
2 km + 4 km interferometers in same vacuum envelope

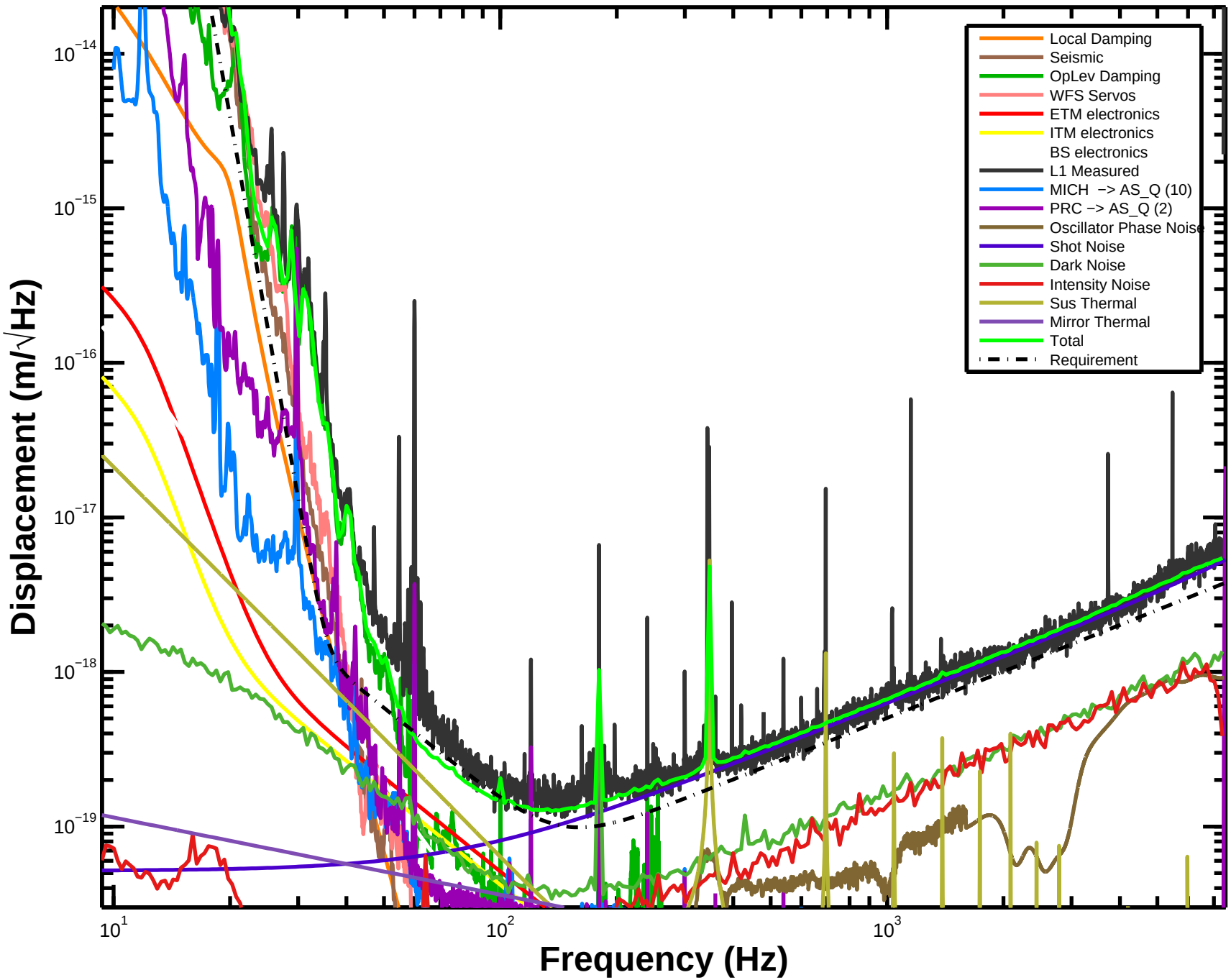
LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

Single 4 km interferometer


far mirror
near mirror
slave laser
power
recycling
mirror
beam splitter
first
mode
cleaner
second
mode
cleaner
near mirror
far mirror
master
laser
signal
recycling
mirror
output
mode cleaner
photodetector


CURRENT AND PROJECTED INTERFEROMETRIC DETECTORS
BH/BH
10/10
NS/NS
1/1
light years
1M
10M
1M
100M
10M
1G
100M
LHO 3/05
LLO 3/05
VIRGO
GEO narrow
GEO broad
INITIAL LIGO
ADVANCED LIGO
ADVANCED LIGO
narrow band
amplitude density strain/sqrt(Hz)
frequency Hz
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3


L1: 10.1 Mpc, Apr 20 2005 06:01:38 UTC
Displacement (m/√Hz)
Frequency (Hz)
Local Damping
Seismic
OpLev Damping
WFS Servos
ETM electronics
ITM electronics
BS electronics
L1 Measured
MICH −> AS_Q (10)
PRC −> AS_Q (2)
Oscillator Phase Noise
Shot Noise
Dark Noise
Intensity Noise
Sus Thermal
Mirror Thermal
Total
Requirement

LIGO

LIGO
beam tube

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

NO LEAKS !!

LIGO

LIGO

vacuum equipment

LIGO

LIGO Optic

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity < 5×10^{-7}

Internal mode Q's > 2×10^{6}

Polishing

Surface uniformity < 1 nm rms

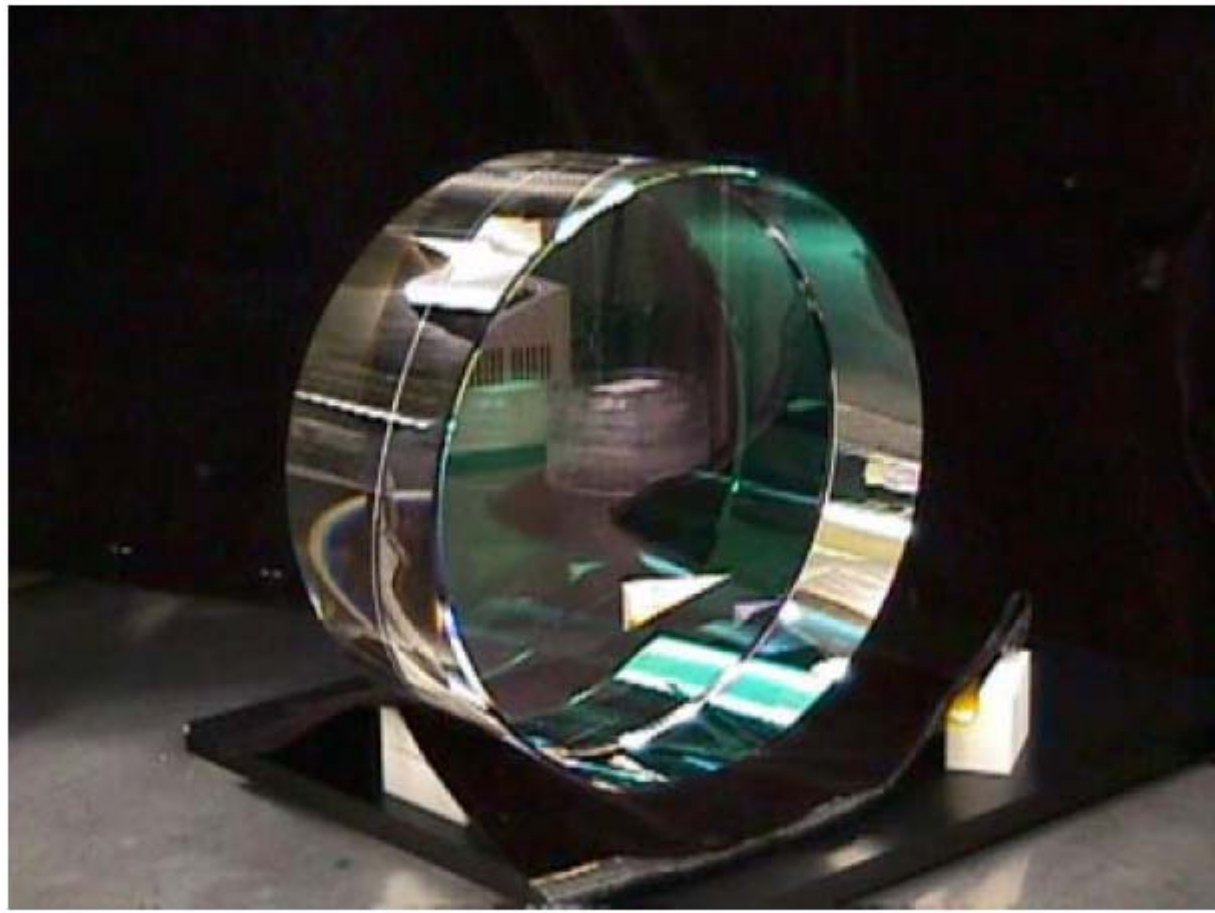
adii of curvature matched < 3%

Coating

Scatter < 50 ppm

Absorption < 2 ppm

Uniformity <10^{-3}



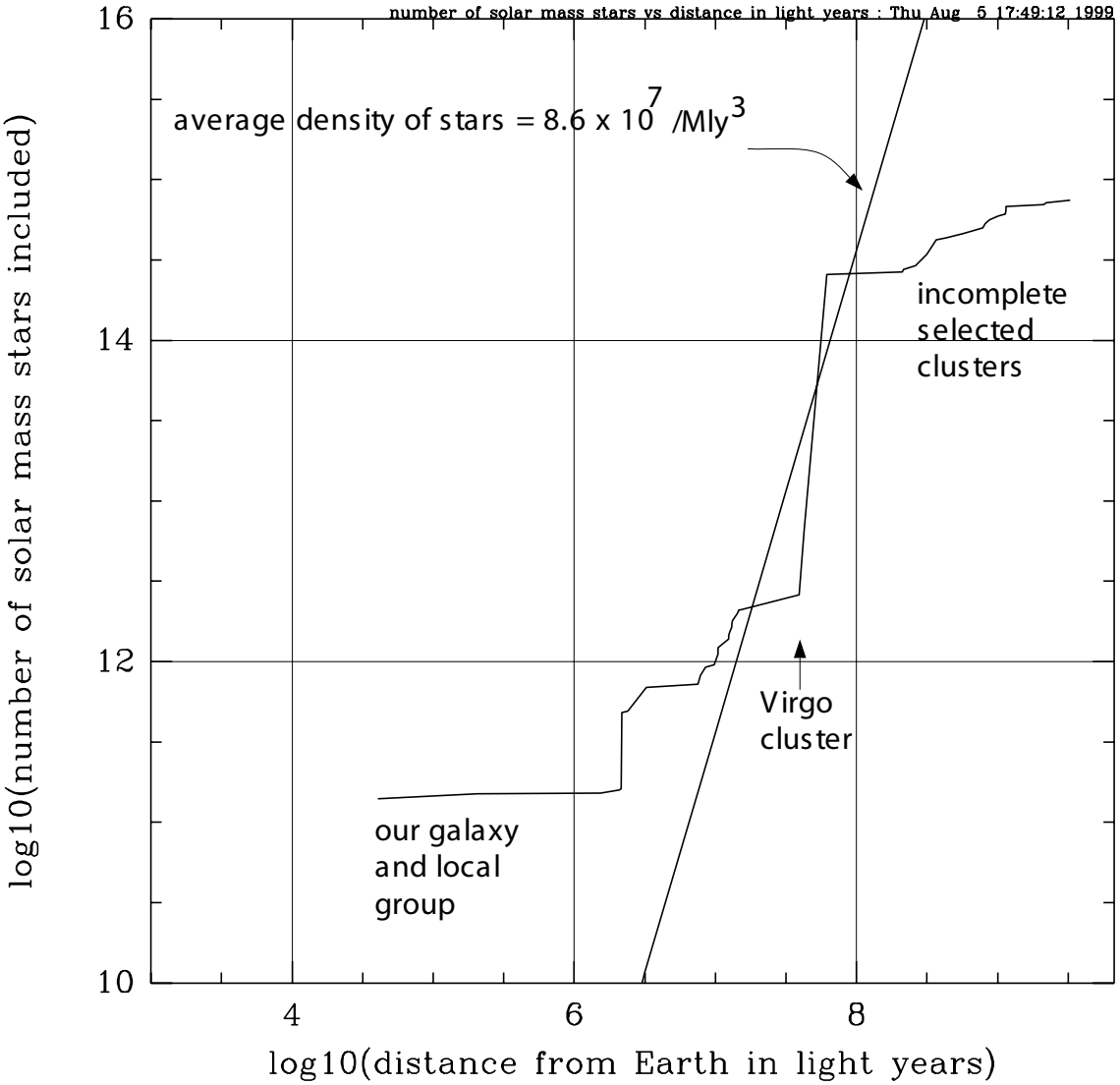
LIGO

Core Optics

installation and alignment

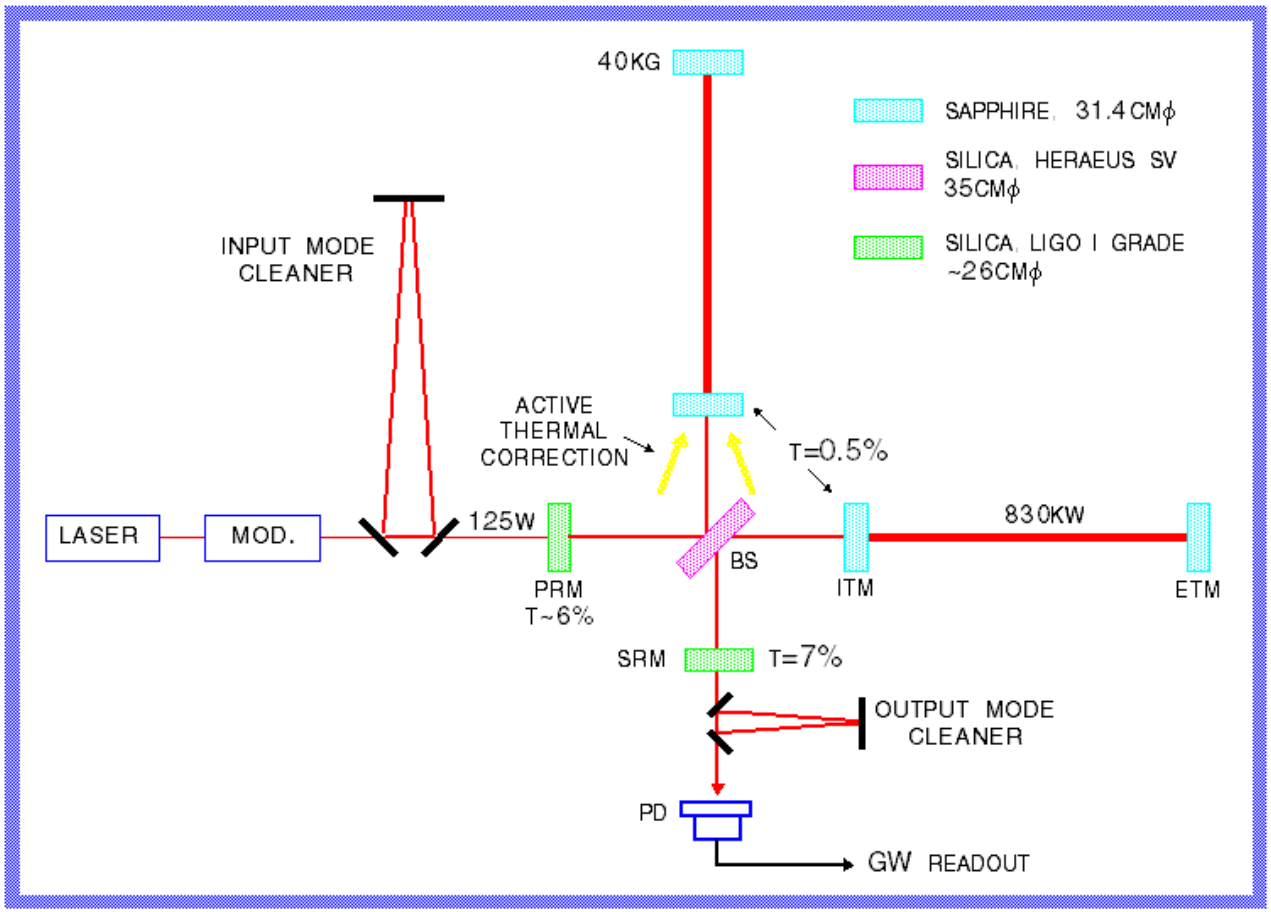
Classes of sources

- Compact binary inspiral: template search
  - BH/BH
  - NS/NS and BH/NS
- Low duty cycle transients: wavelets,T/f clusters
  - Supernova
  - BH normal modes
  - Unknown types of sources
- Periodic CW sources
  - Pulsars
  - Low mass x-ray binaries (quasi periodic)
- Stochastic background
  - Foreground sources : gravitational wave radiometry
  - Cosmological isotropic background



DATA: Cosmology of the Local Group G.Lake
Astrophysical Quantities C.W. Allen

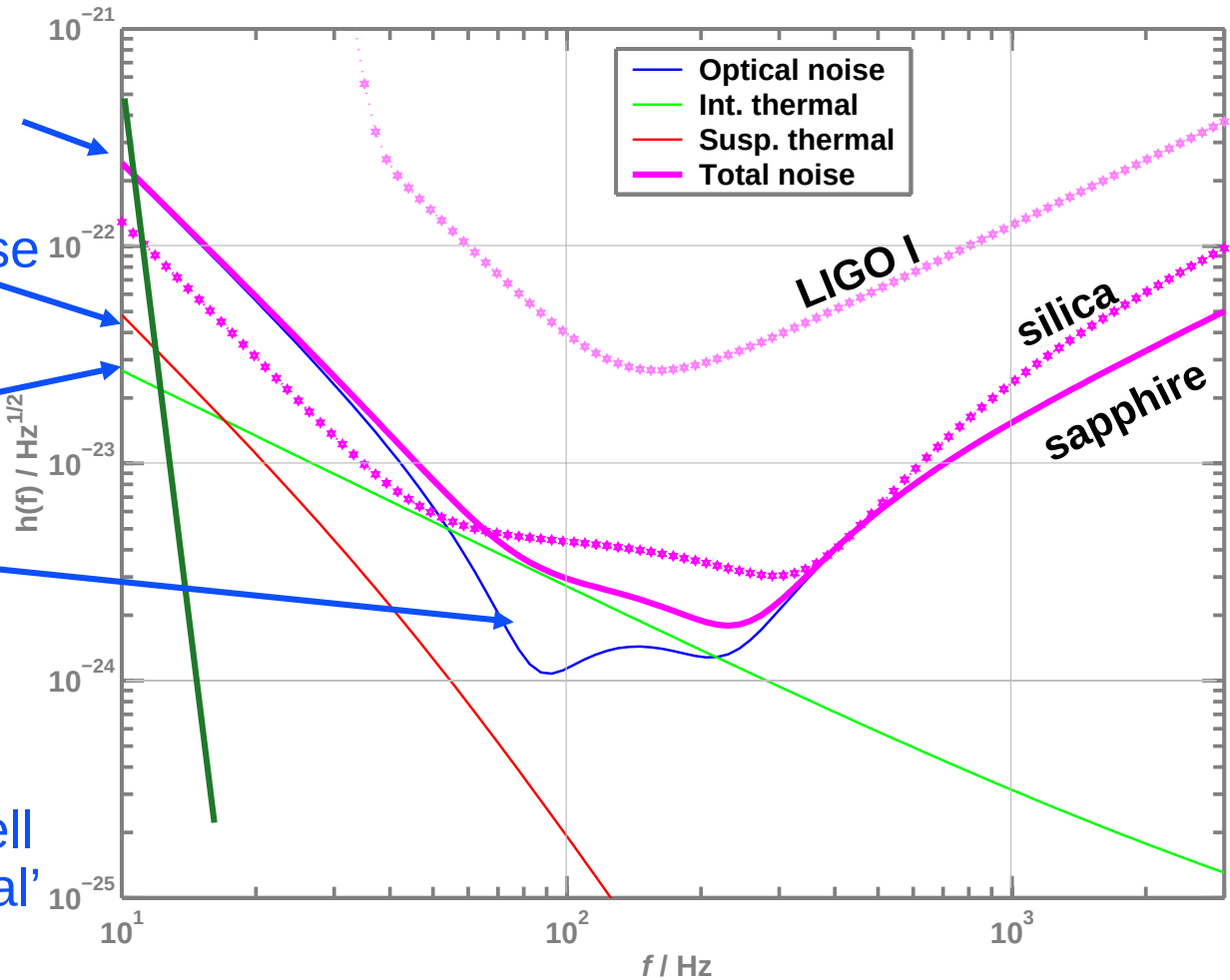
Advanced Interferometer Concept



- » Signal recycling
- » 180-watt laser
- » 40 kg Sapphire test masses
- » Larger beam size
- » Quadruple suspensions
- » Active seismic isolation
- » Active thermal correction
- » Output mode cleaner

Projected Performance

- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- ‘technical’ noise (e.g., laser frequency) levels held in general well below these ‘fundamental’ noises



Binary Coalescence Sources & Science:
Binary Neutron Stars: AdLIGO Range

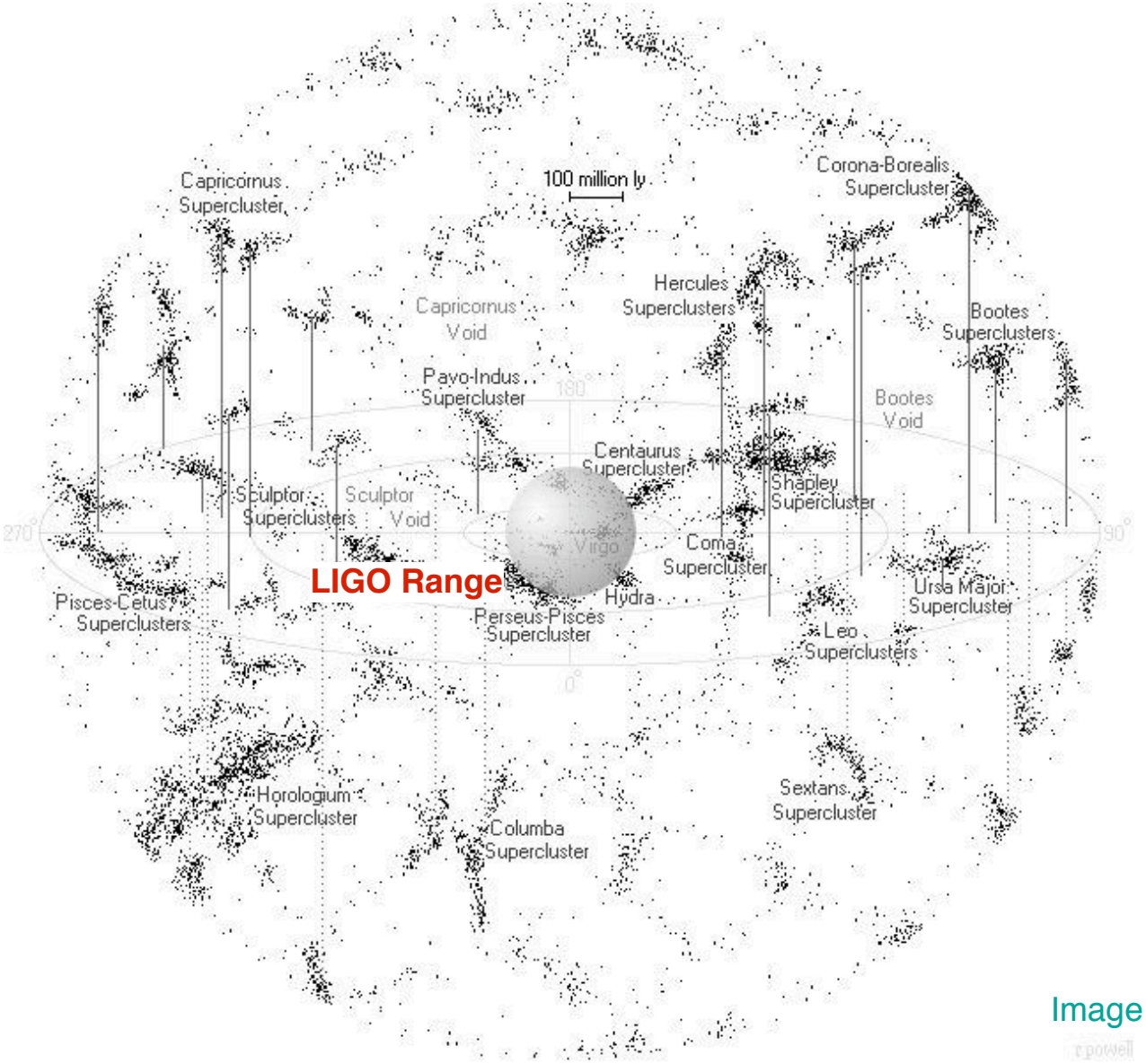
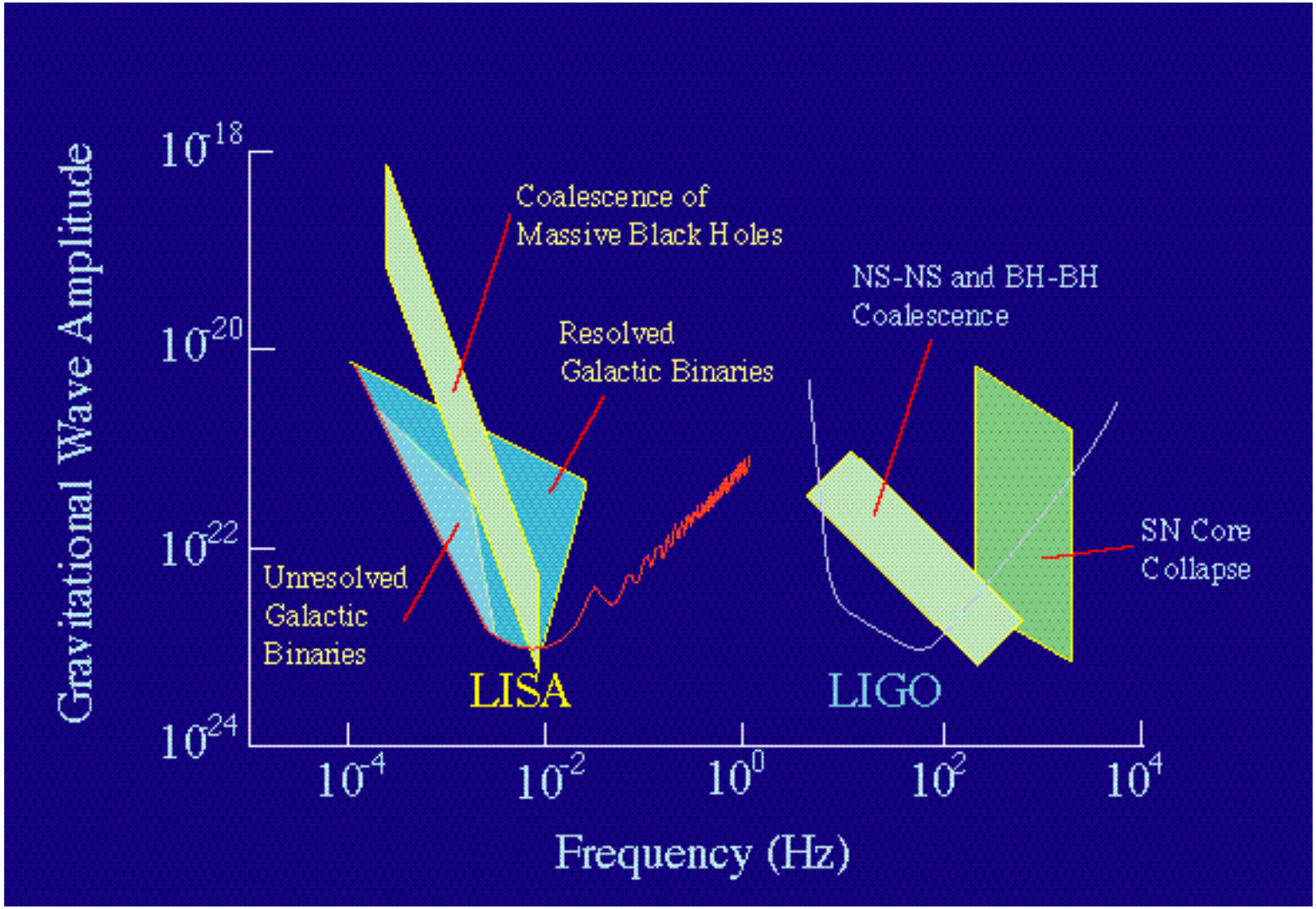
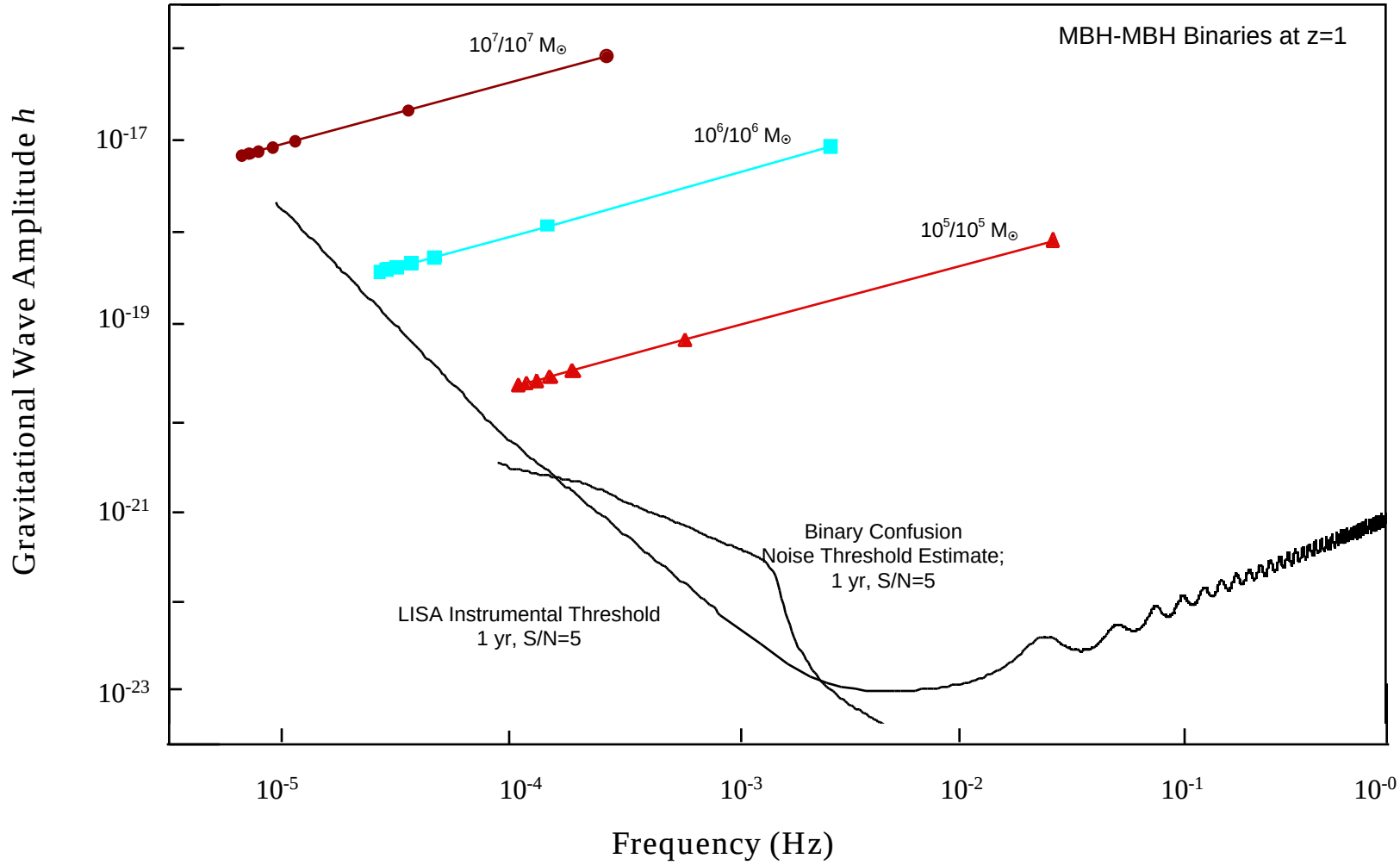


Image: R. Powell

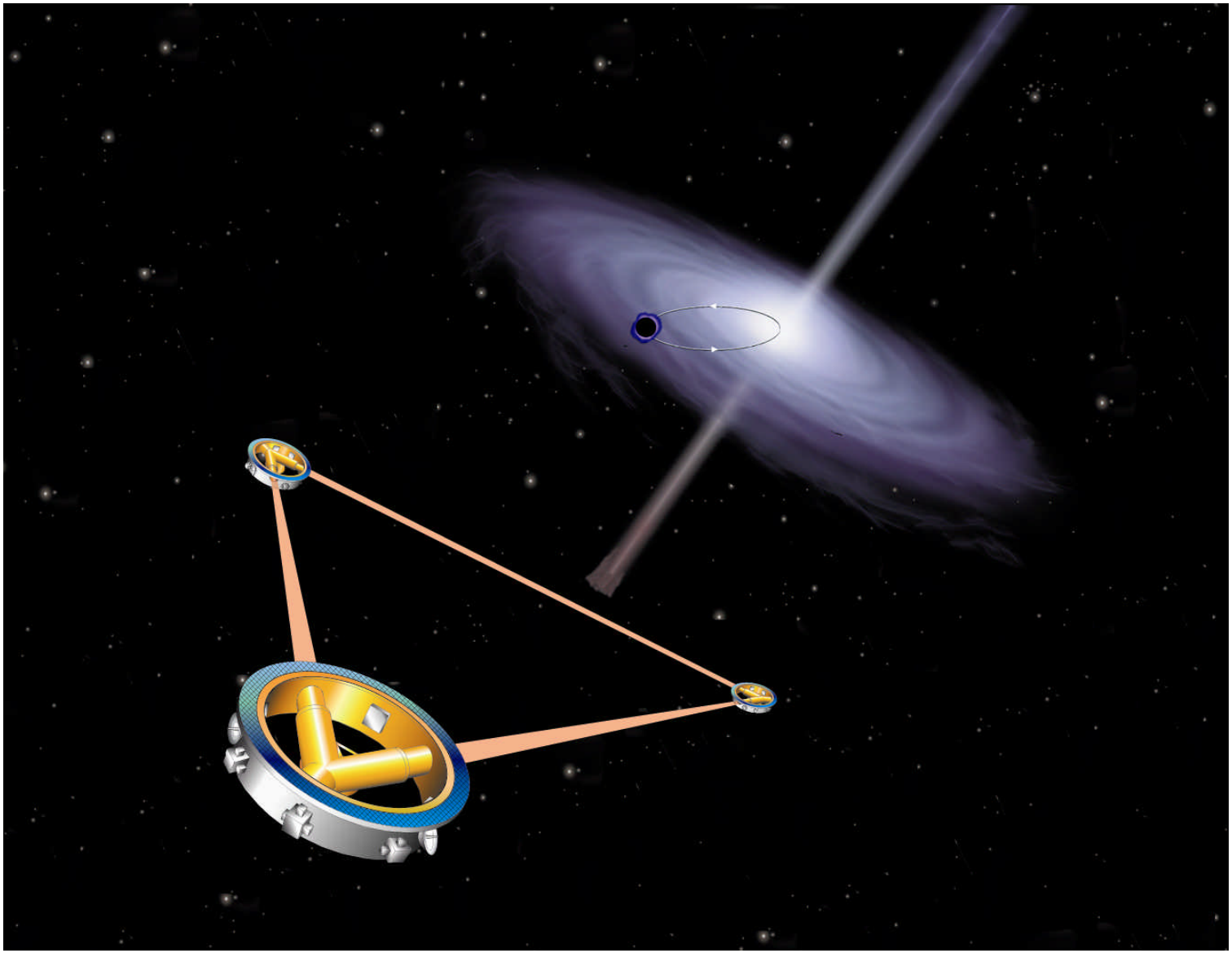
The Gravitational-Wave Spectrum



Massive Black Holes in Merging Galaxies

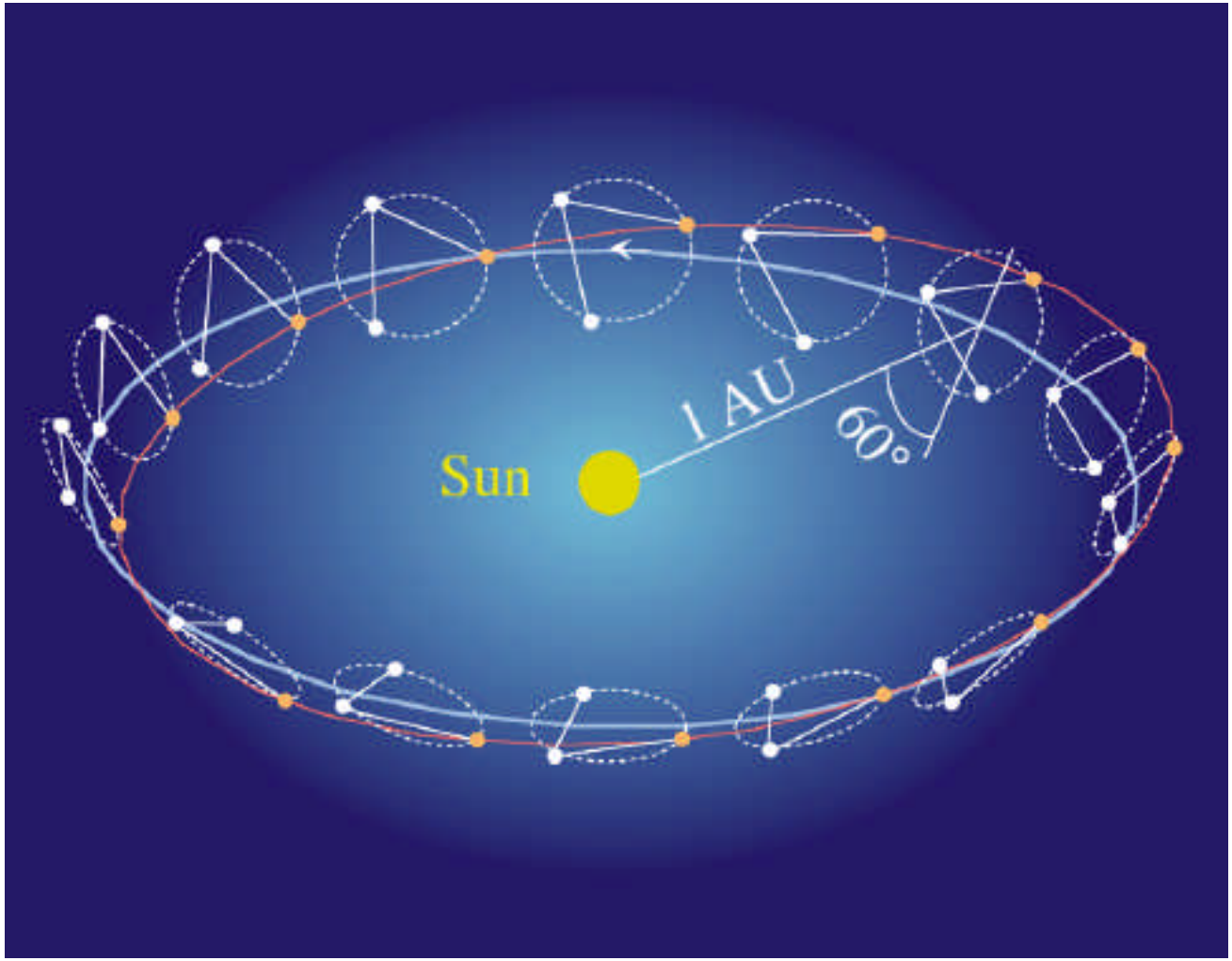


Mission Concept

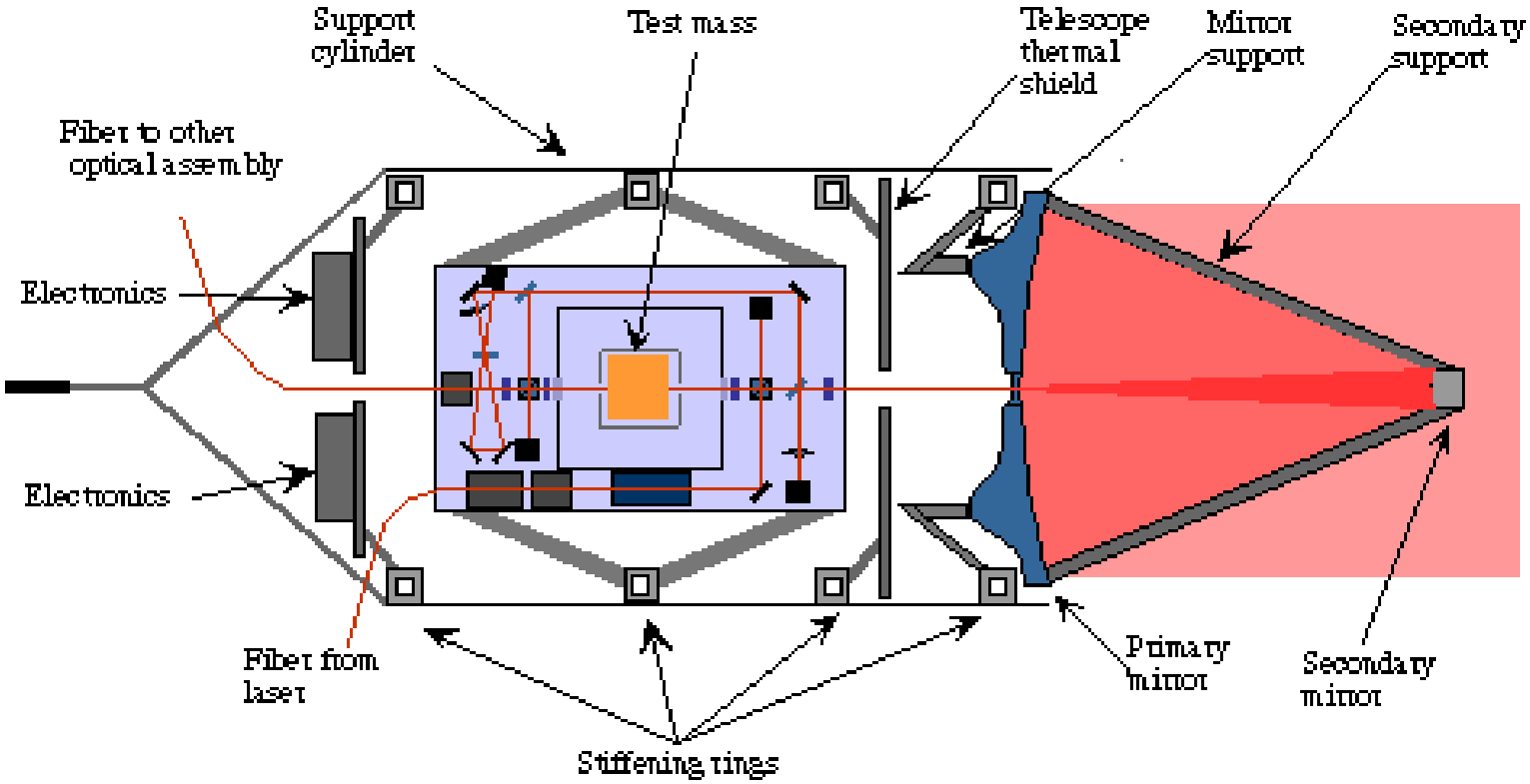


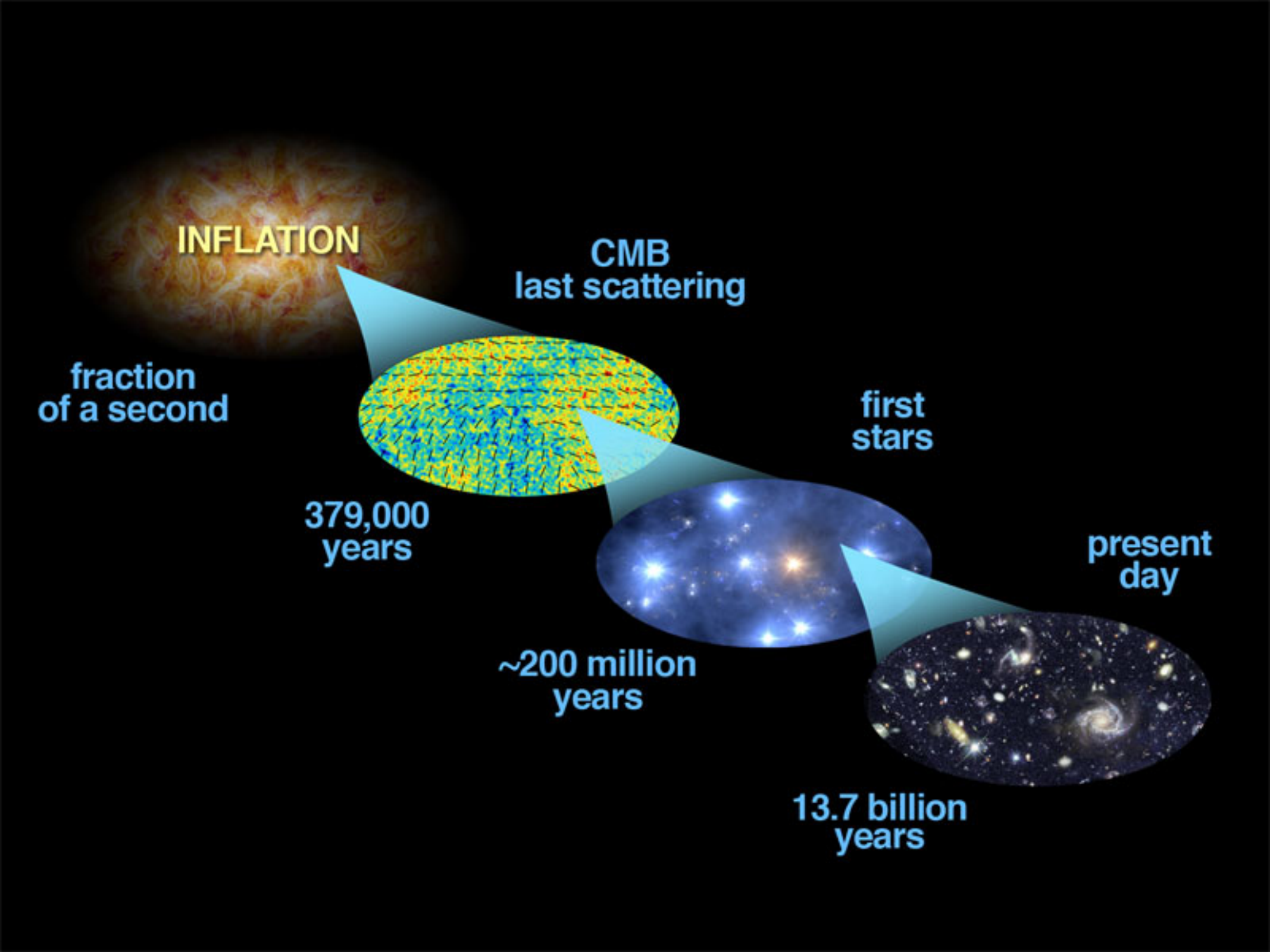
Spacecraft Orbits

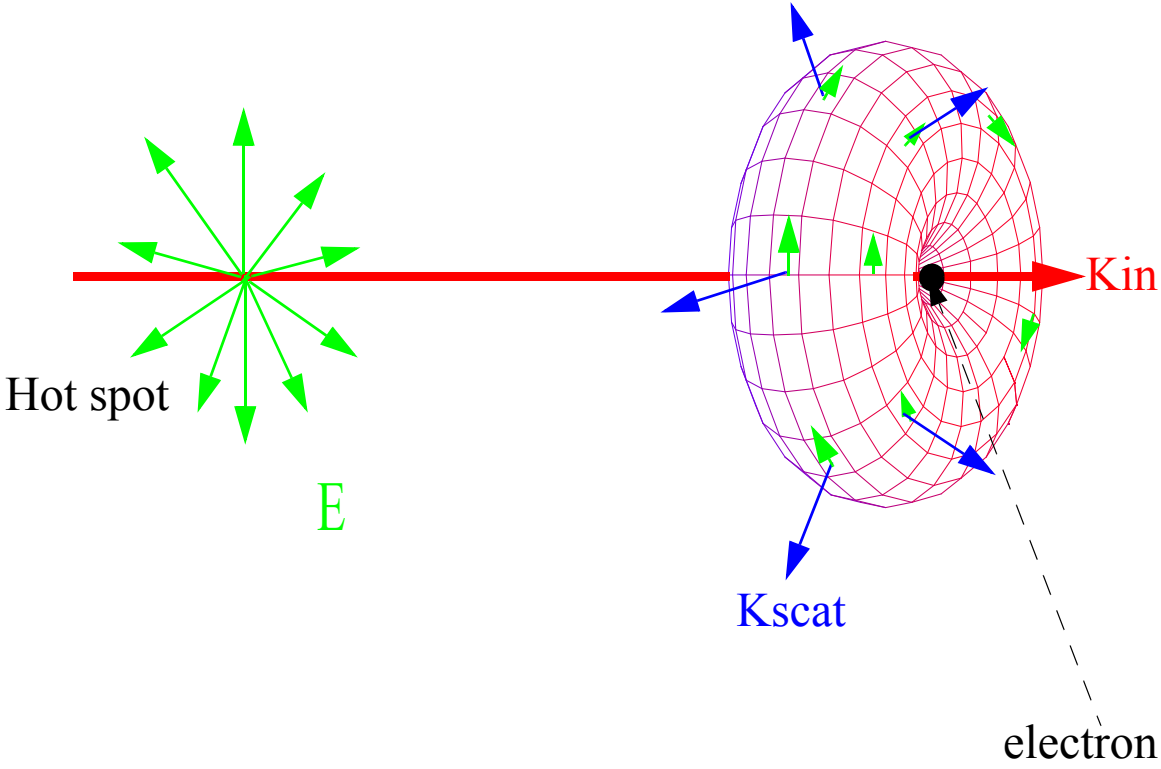
- Spacecraft orbits evolve under gravitational forces only
- Spacecraft fly “drag-free” to shield proof masses from non-gravitational forces



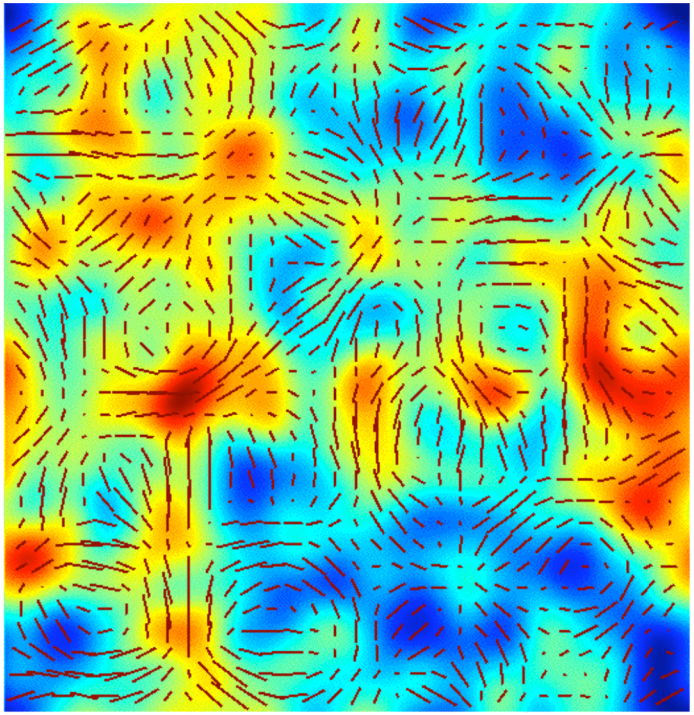
Optical System

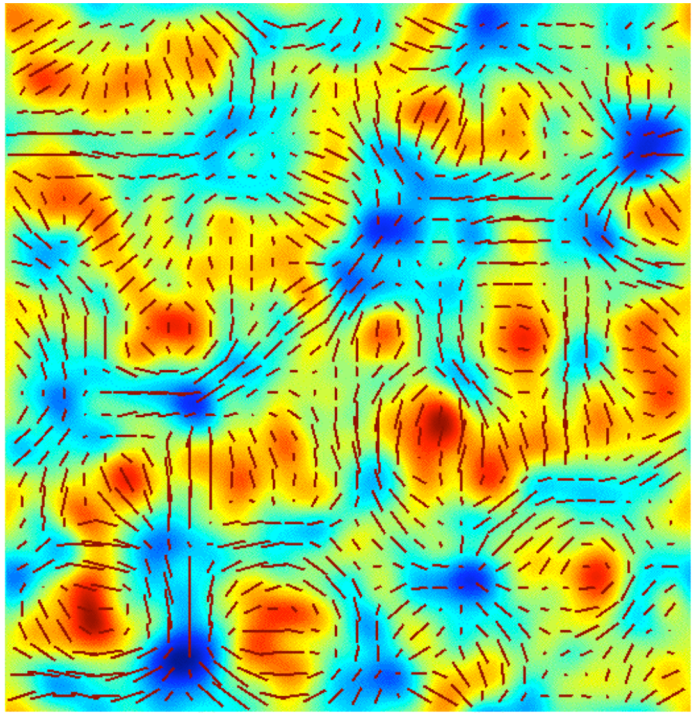


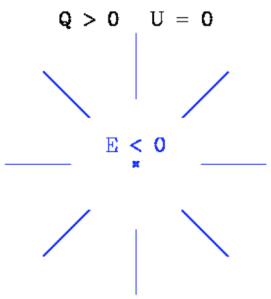

INFLATION
CMB
last scattering
fraction
of a second
379,000
years
first
stars
~200 million
years
present
day
13.7 billion
years

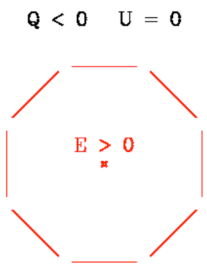

Hot spot
E
Kin
Kscat
electron

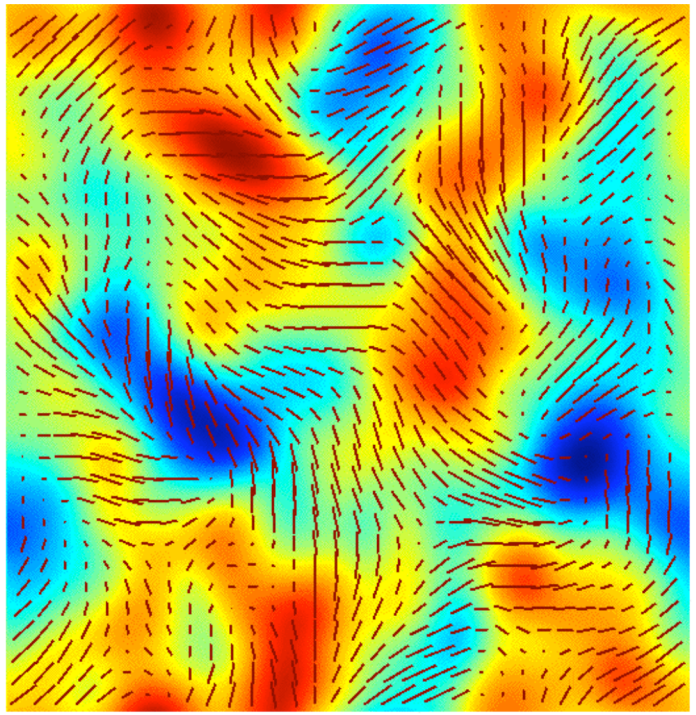
H. Edens

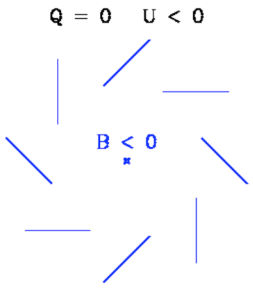


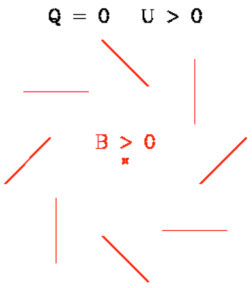




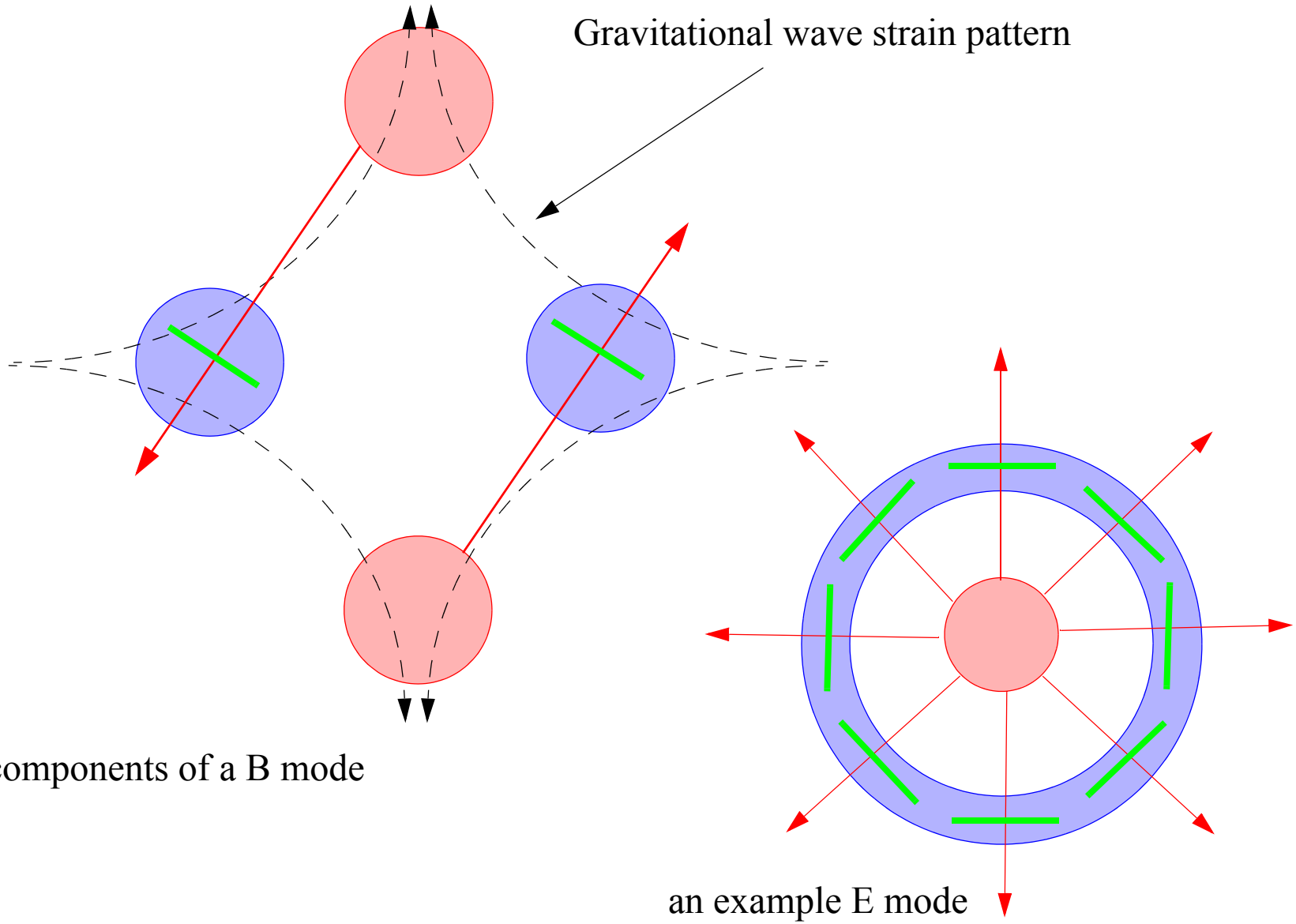


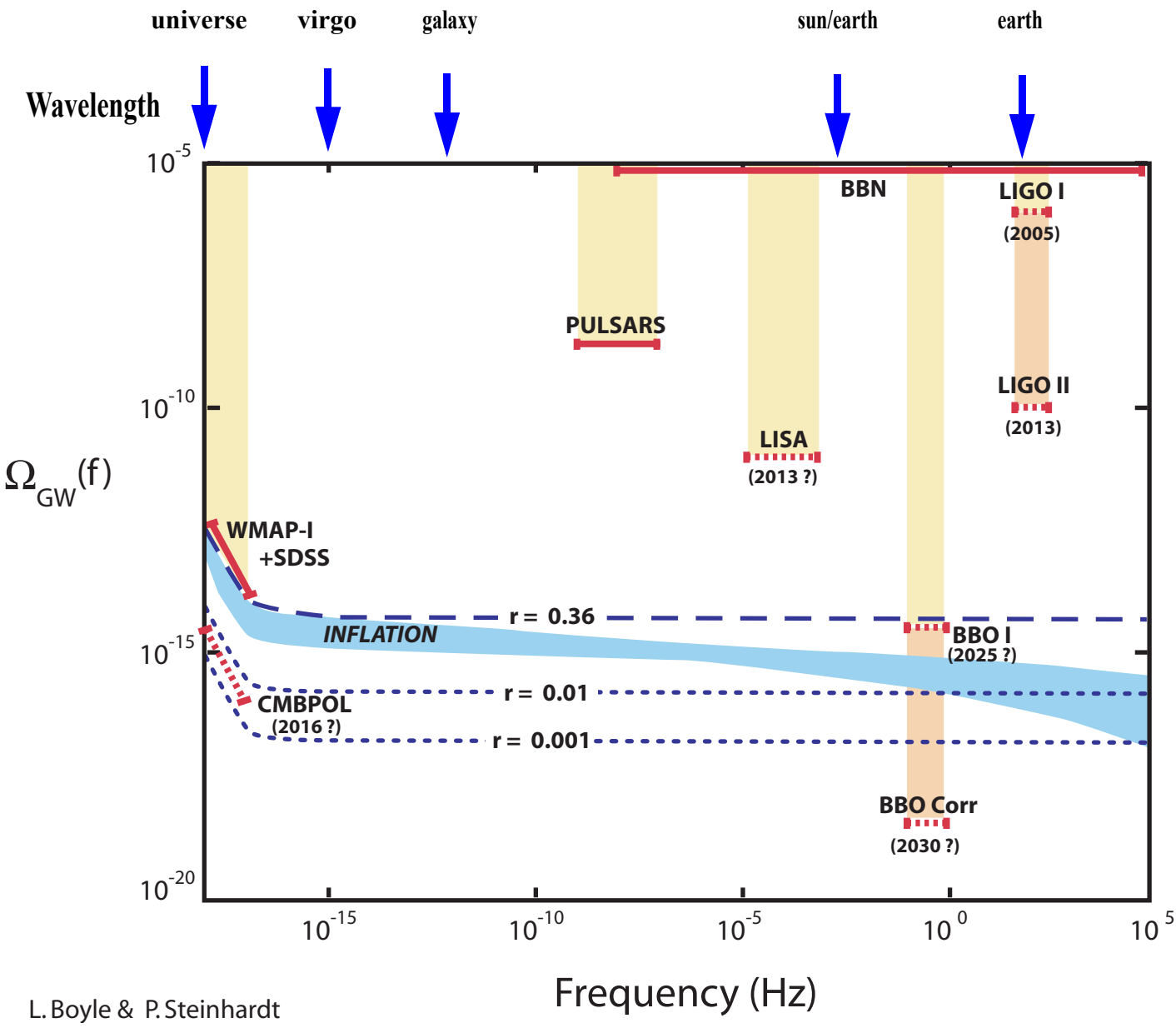






M. Zaldarriaga


Gravitational wave strain pattern
components of a B mode
an example E mode



L. Boyle & P. Steinhardt