

# Einstein's 1918 Legacy

Gravitational waves and what they might tell us

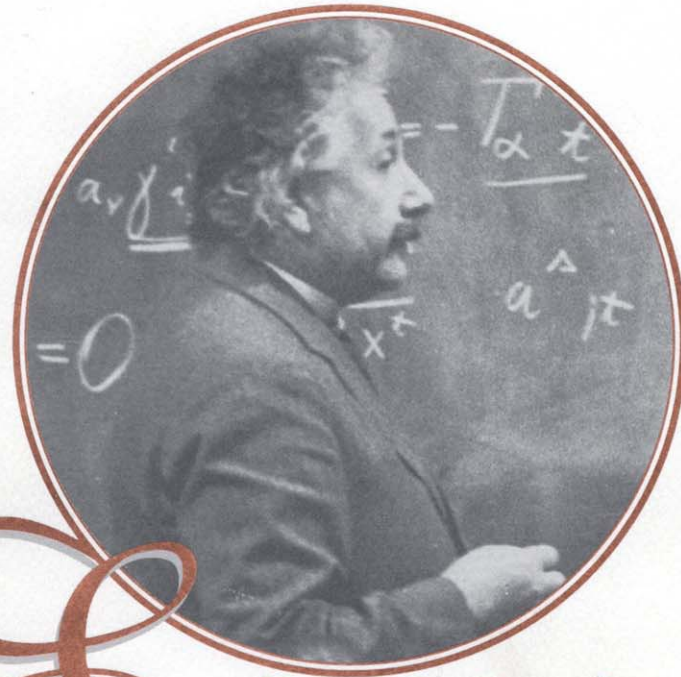
Rainer Weiss

MIT

Haverford College

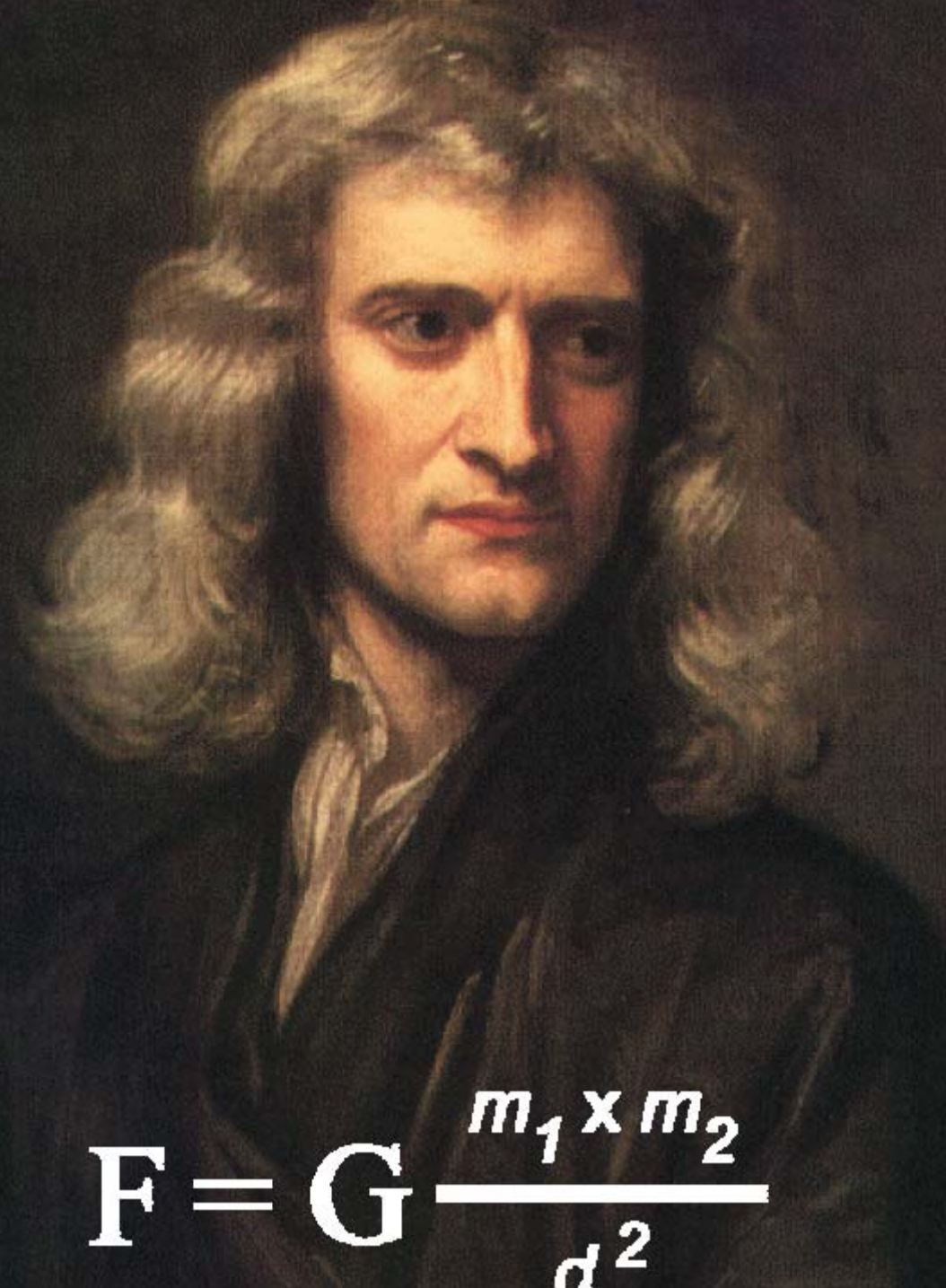
April 4, 2005

MARCIA BARTUSIAK



*E*instein's  
Unfinished Symphony

Listening to  
the Sounds of  
Space-Time



$$F = G \frac{m_1 \times m_2}{d^2}$$

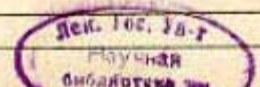
PHILOSOPHIÆ  
NATURALIS  
PRINCIPIA  
MATHEMATICÆ.

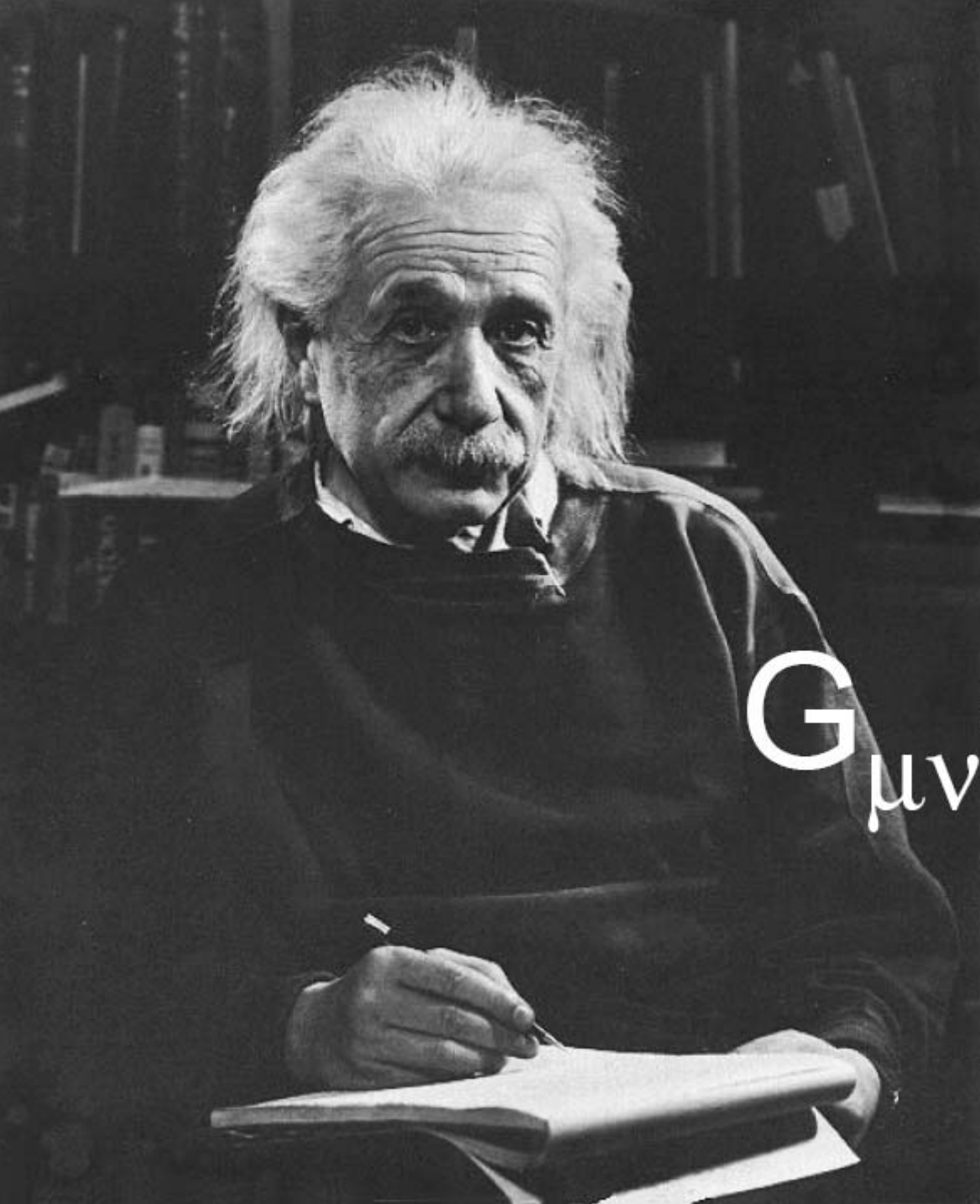
Autore J. S. NEWTON, Trin. Coll. Cantab. Soc. Math.  
Professore *Lucasiano*, & Societatis Regalis Sodali.

IMPRIMATUR.  
S. PEPYS, Reg. Soc. PRÆSES.  
Julii 5. 1686.

LONDINI,

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

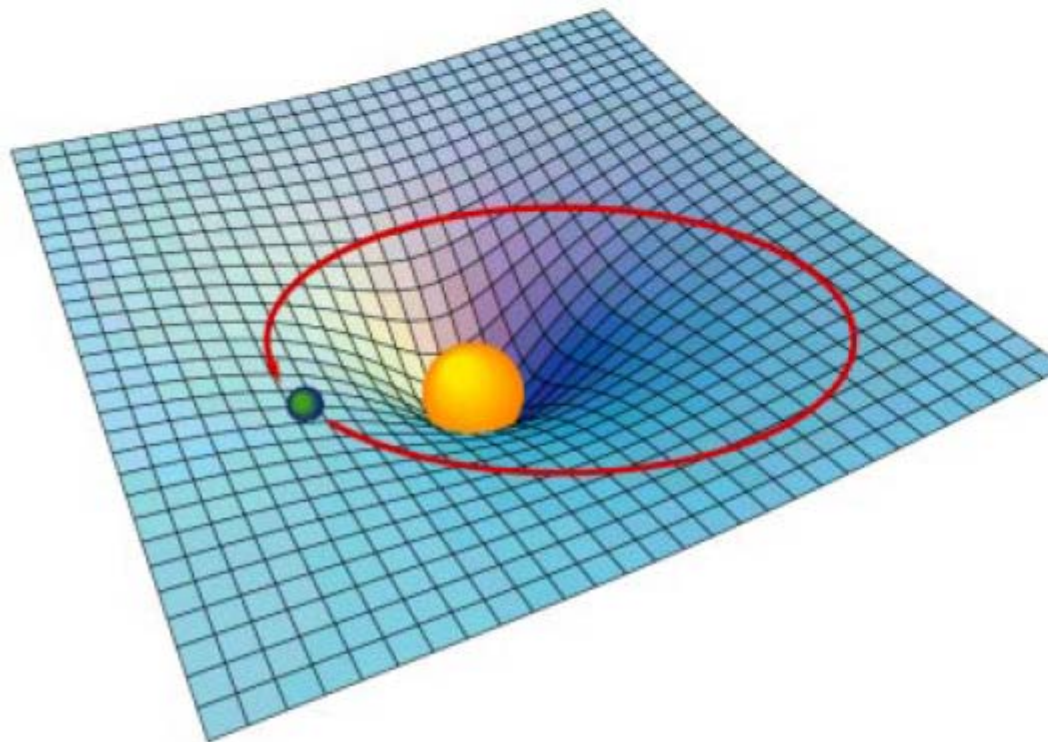




$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

# General Relativity

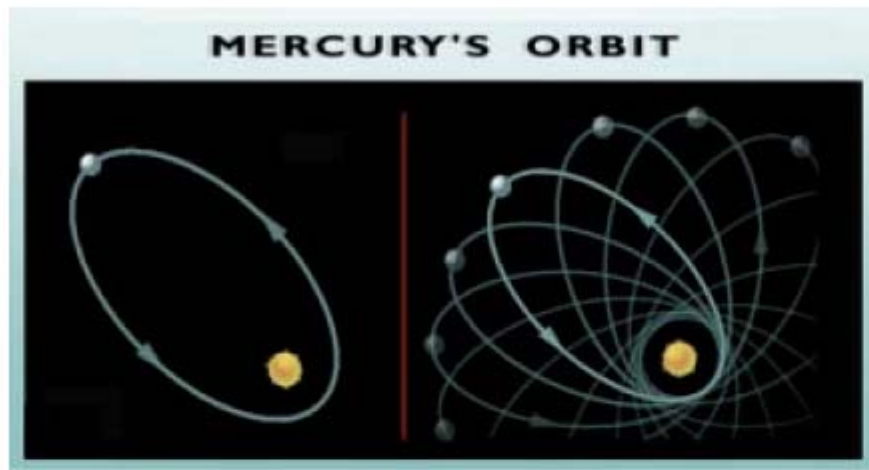
*Einstein theorized that smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object*



- 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*

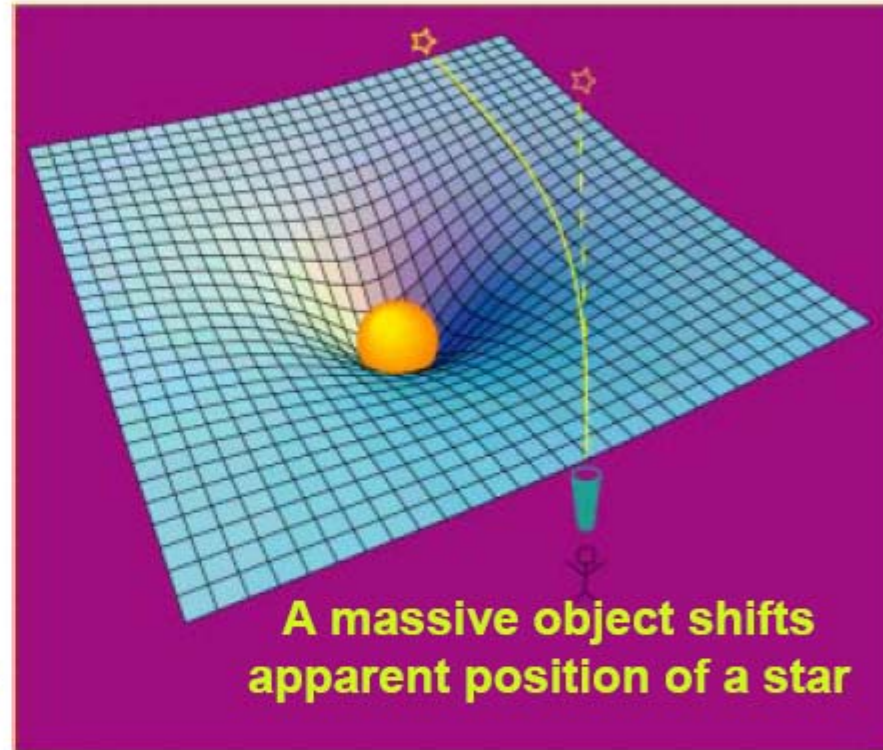
Mercury's elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or "perihelion") shifts forward with each pass.

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.

*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.*

697

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

688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

AS.A. 311

SCHEIDER LIBRARY MIT

Näherungsweise Integration der Feldgleichungen  
der Gravitation.

Von A. EINSTEIN.

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1918

VI. VII. VIII

# SITZUNGSBERICHTE

DER

KÖNIGLICH PREUSSISCHEN

# AKADEMIE DER WISSENSCHAFTEN

**Sitzung der physikalisch-mathematischen Klasse am 7. Februar.** (S. 139)

**Sitzung der philosophisch-historischen Klasse am 7. Februar.** (S. 141)

J. KIRCHNER: Archon Euthios. (S. 142)

**Gesamtsitzung am 14. Februar.** (S. 153)

EINSTEIN: Über Gravitationswellen. (Mitteilung vom 31. Januar.) (S. 154)

E. FREUNDLICH: Über die singulären Stellen der Lösungen des  $n$ -Körper-Problems. 1. Mitteilung.  
(Mitteilung vom 31. Januar.) (S. 168)

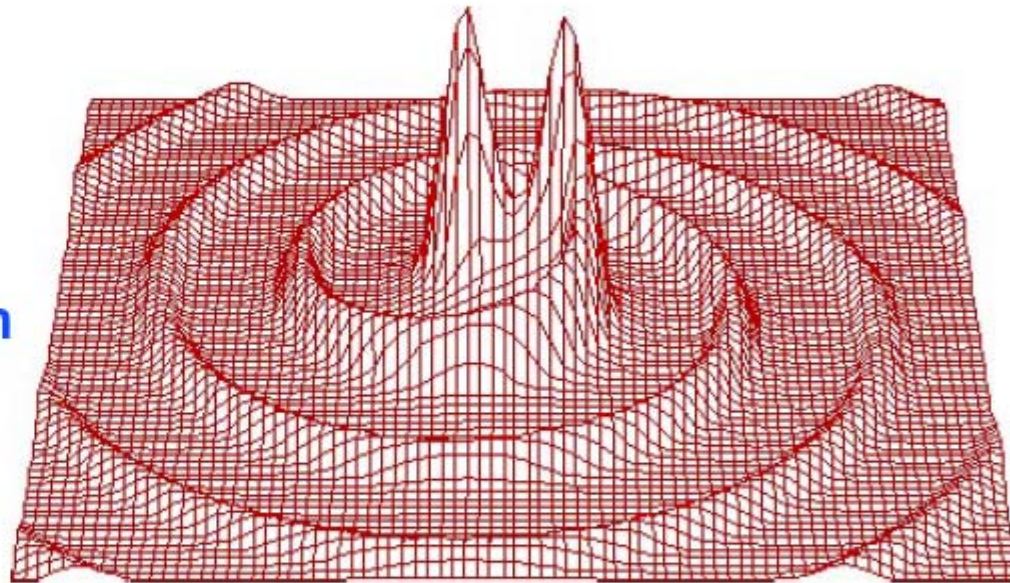
BERLIN 1918

VERLAG DER KÖNIGLICHEN AKADEMIE DER WISSENSCHAFTEN

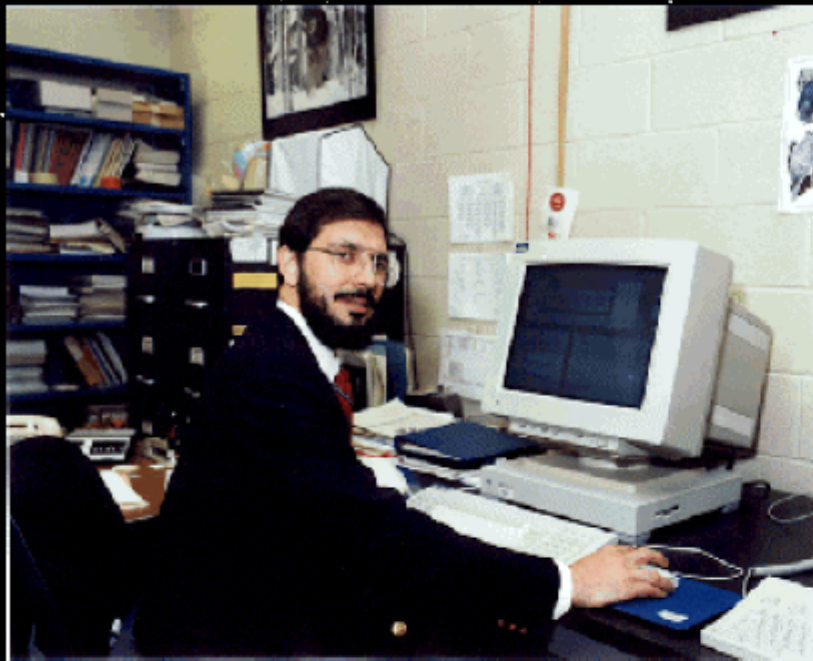
IN KOMMISSION BEI GEORG REIMER

*gravitational waves*

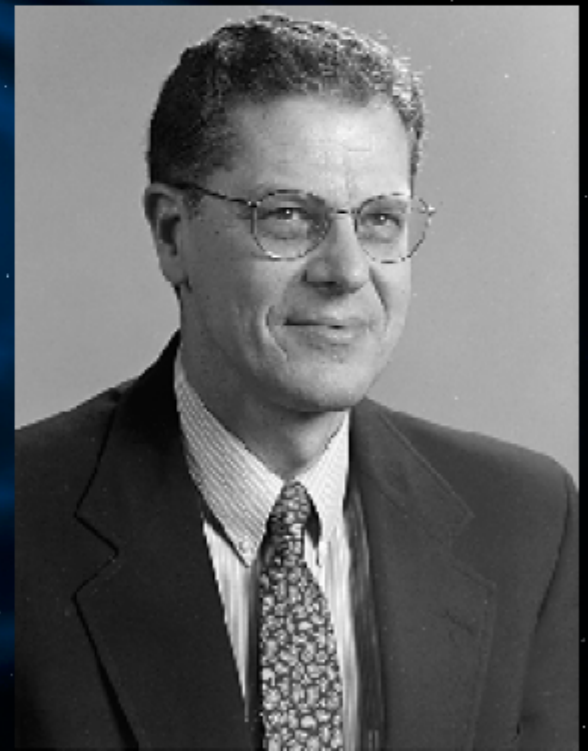
- a necessary consequence of Special Relativity with its finite speed for information transfer
- time dependent gravitational fields come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light



*gravitational radiation  
binary inspiral of compact objects*



Russel A. Hulse



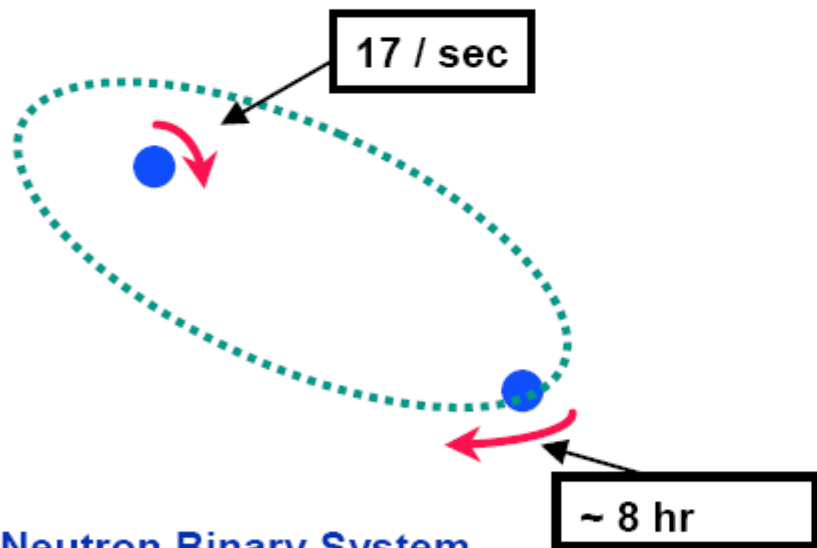
Joseph H. Taylor Jr

# Gravitational Waves

## *the evidence*

### Neutron Binary System – Hulse & Taylor

**PSR 1913 + 16 -- Timing of pulsars**



### Neutron Binary System

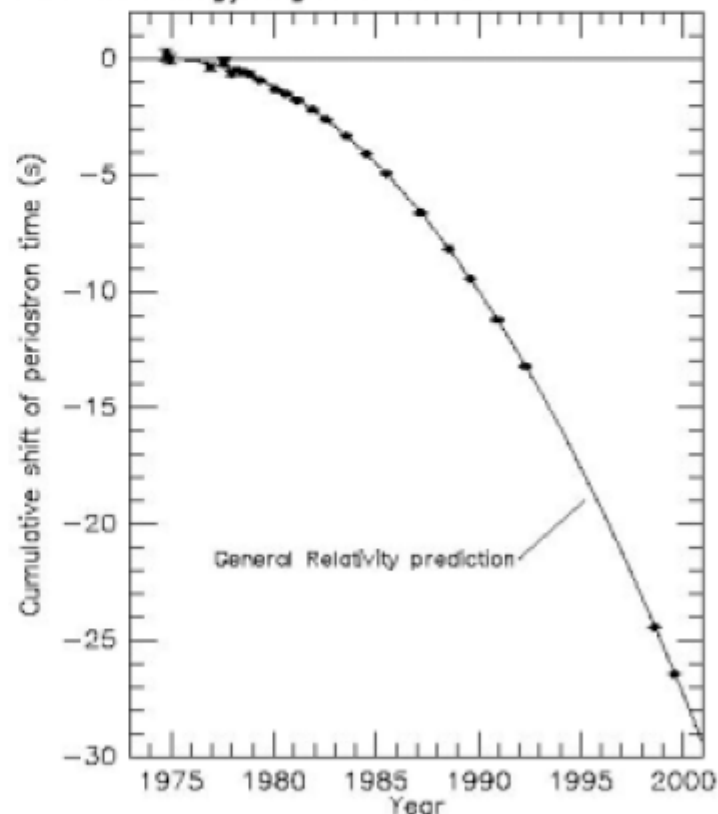
- separated by  $10^6$  miles
- $m_1 = 1.4m_{\odot}$ ;  $m_2 = 1.36m_{\odot}$ ;  $\epsilon = 0.617$

### Prediction from general relativity

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

### Emission of gravitational waves

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves



From J. H. Taylor and J. M. Weisberg, unpublished (2000)

# Direct detection of gravitational waves from astrophysical sources

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## 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

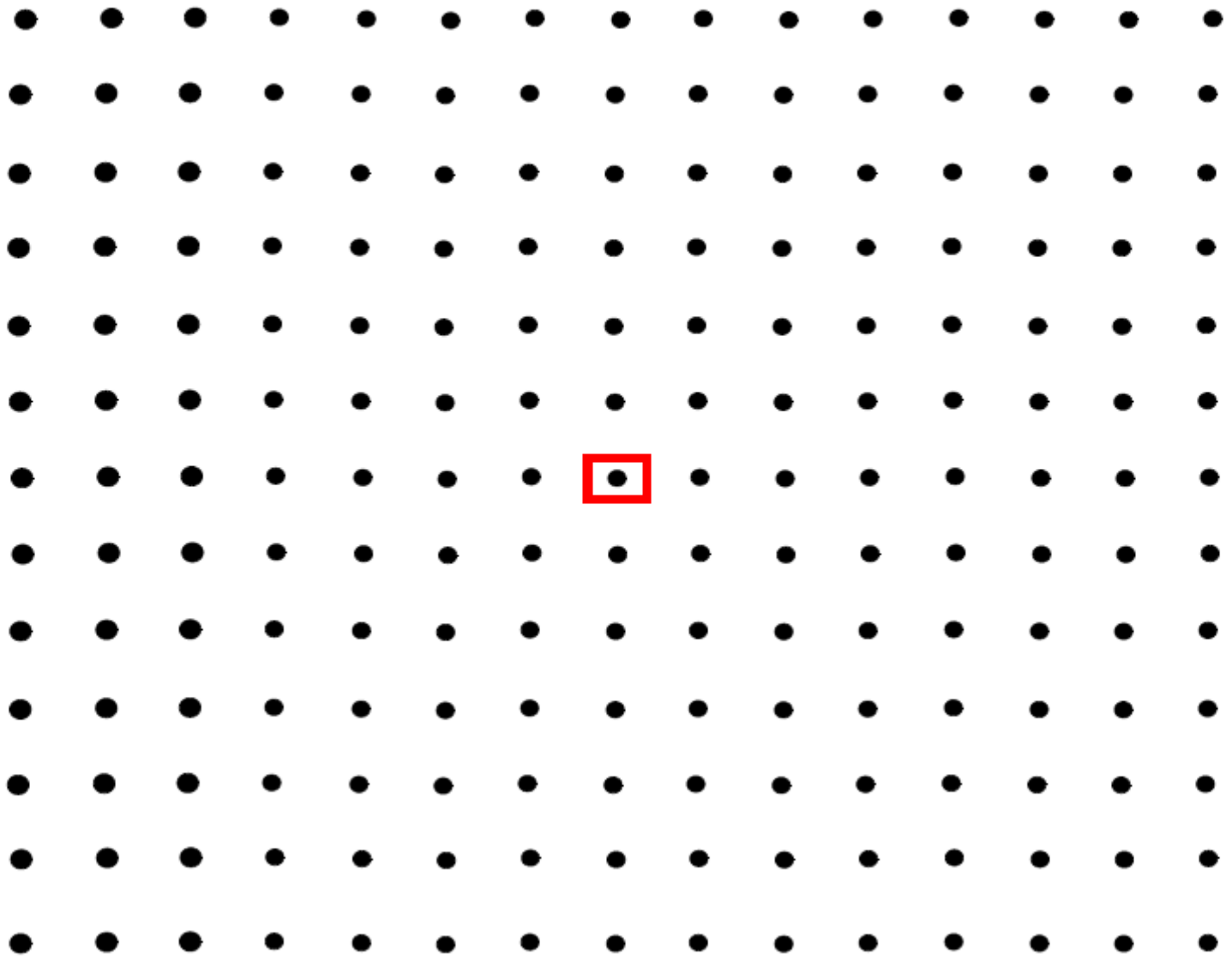
- » Measurement of coherent inner dynamics – stellar collapse, pulsar formation....
- » Compact binary coalescence – neutron star/neutron star, black hole/black hole
- » Neutron star equation of state
- » Primeval cosmic spectrum of gravitational waves

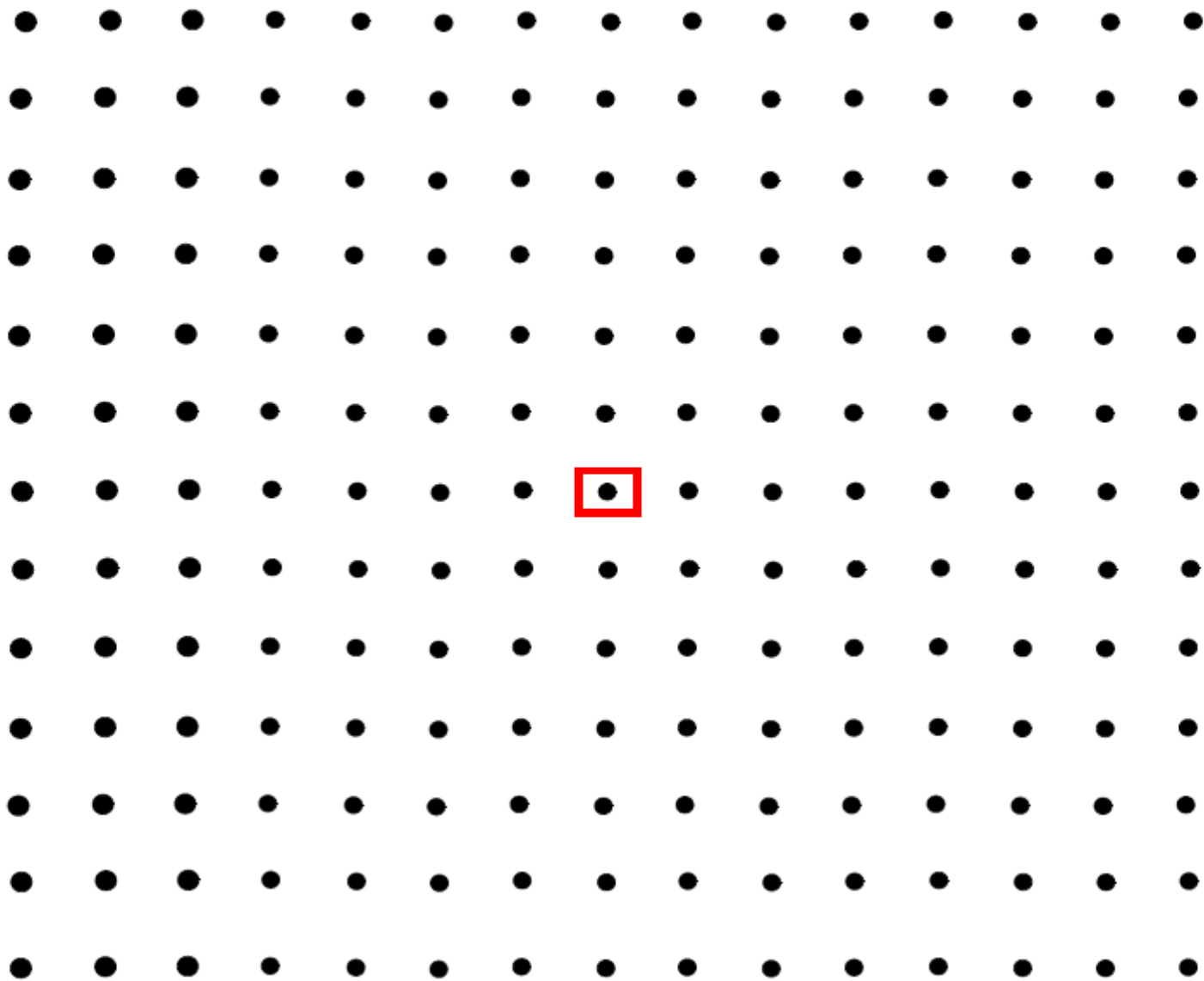
## Gravitational wave survey of the universe



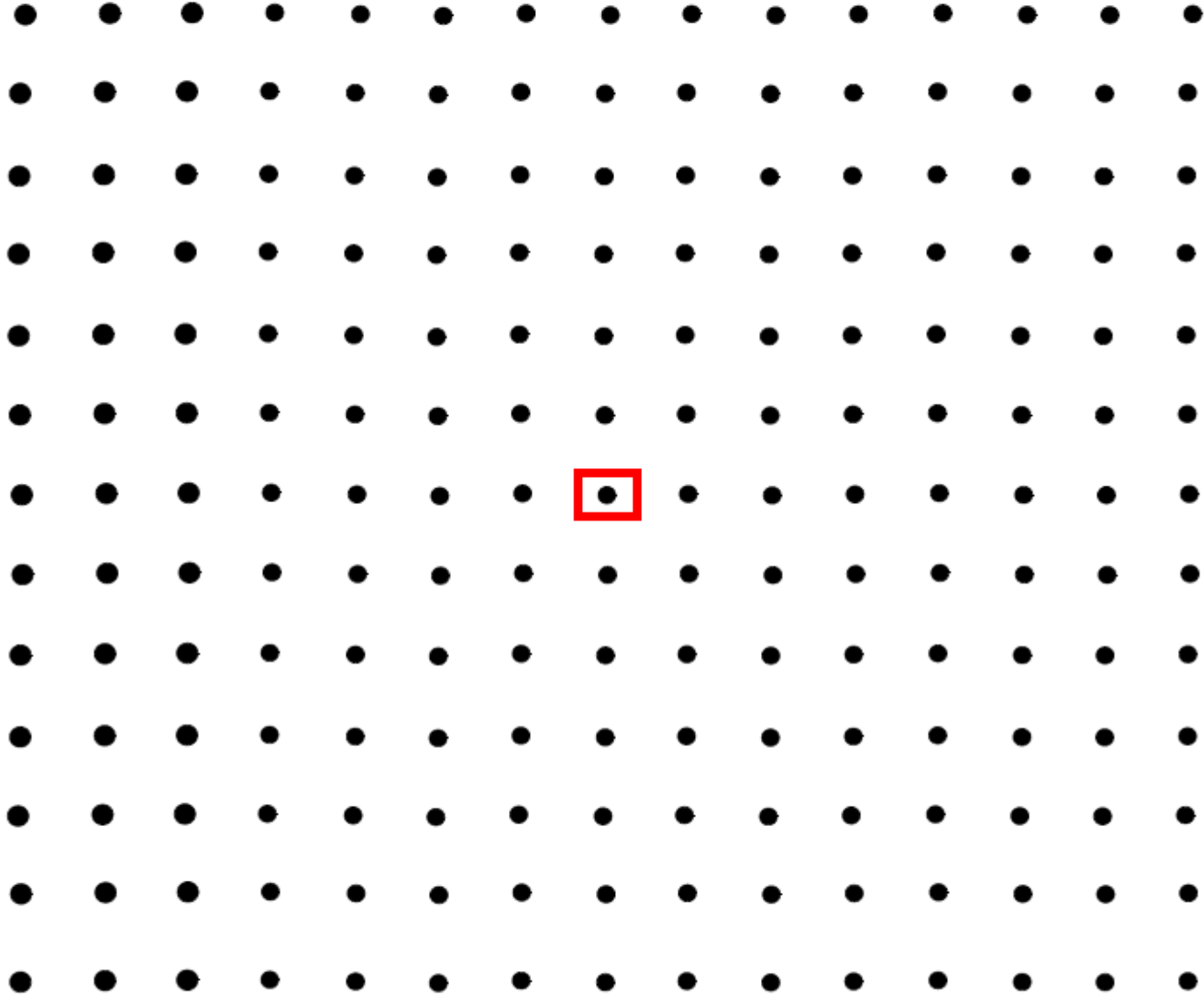
Joseph Weber 1919-2000

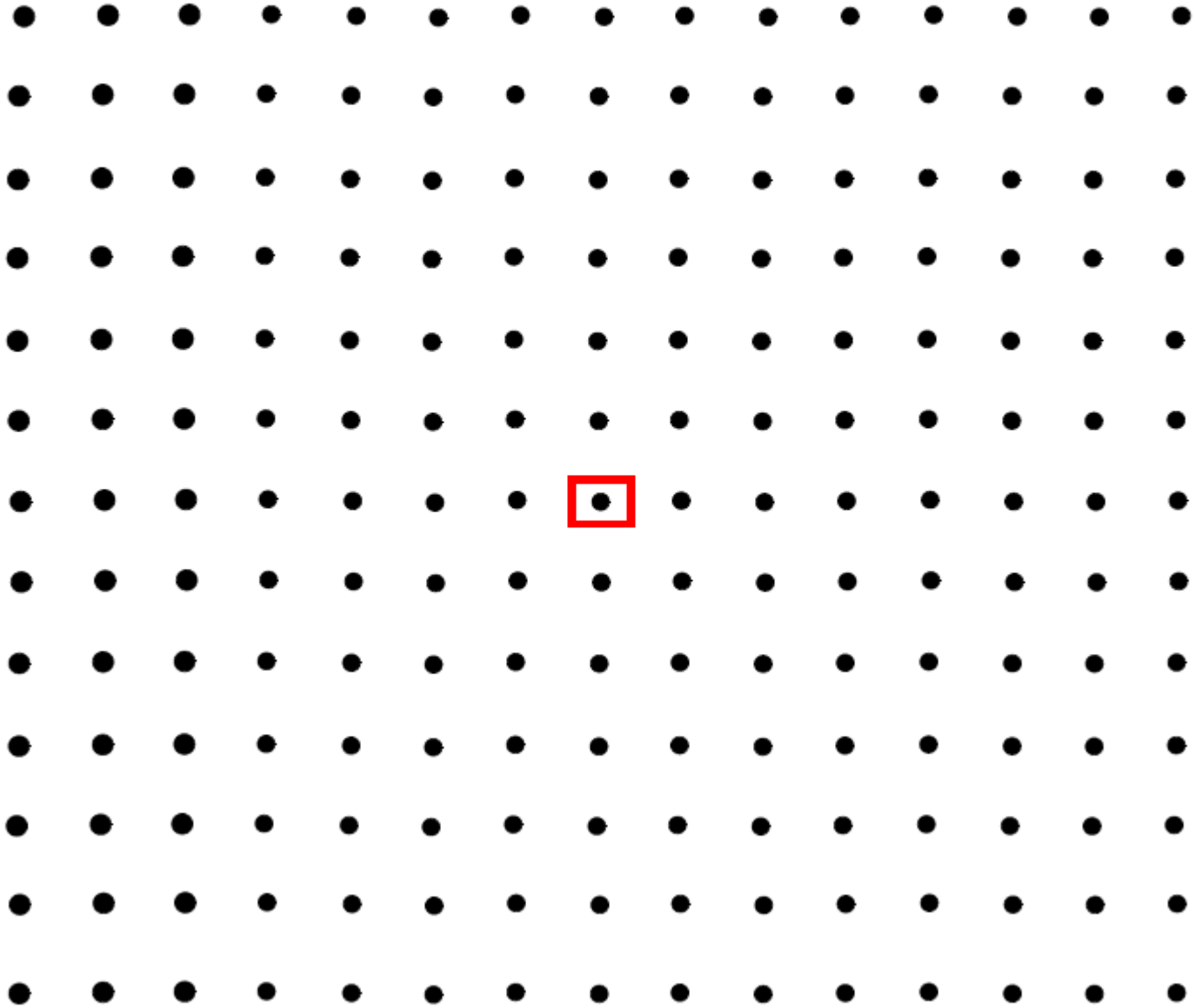


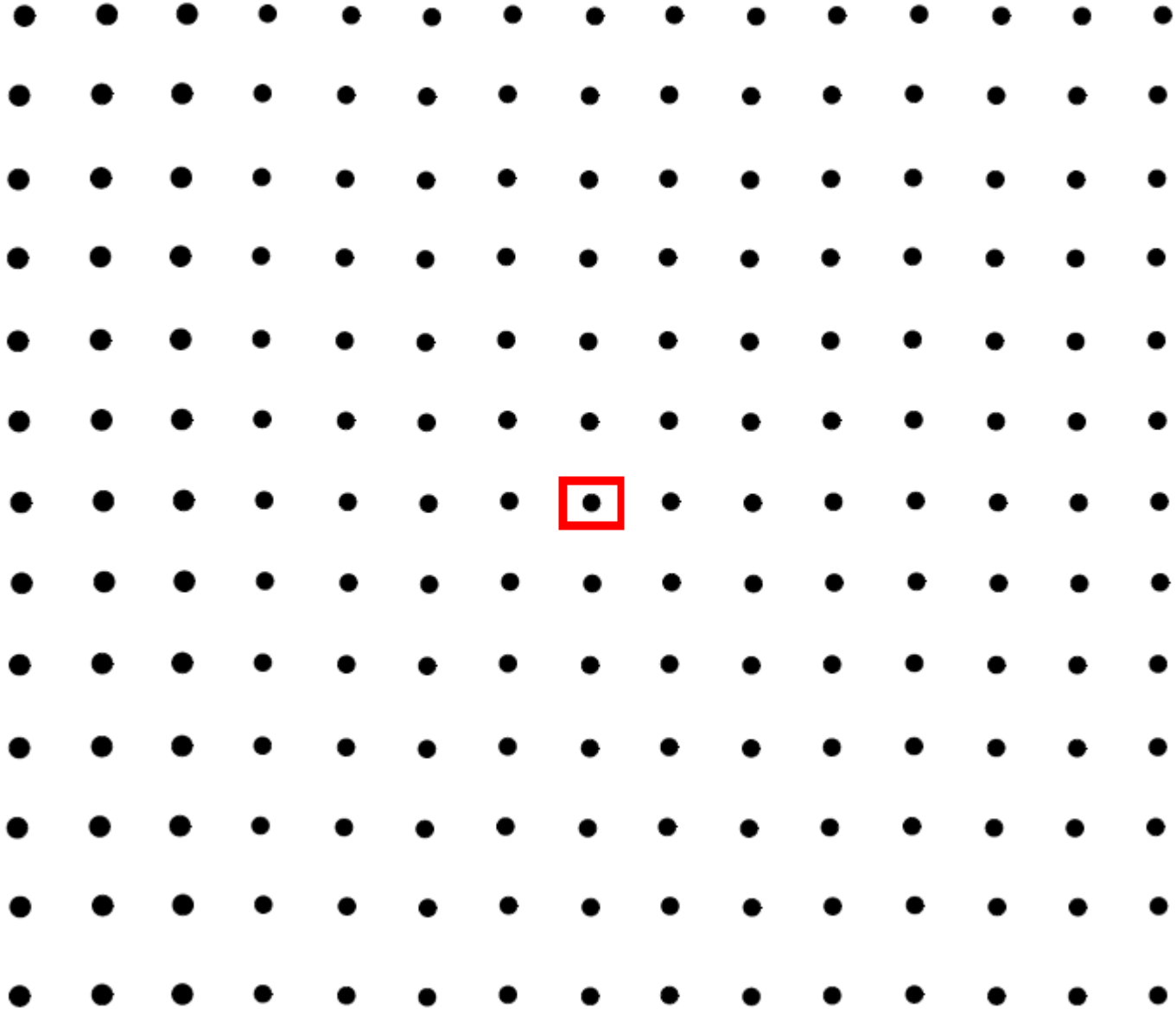


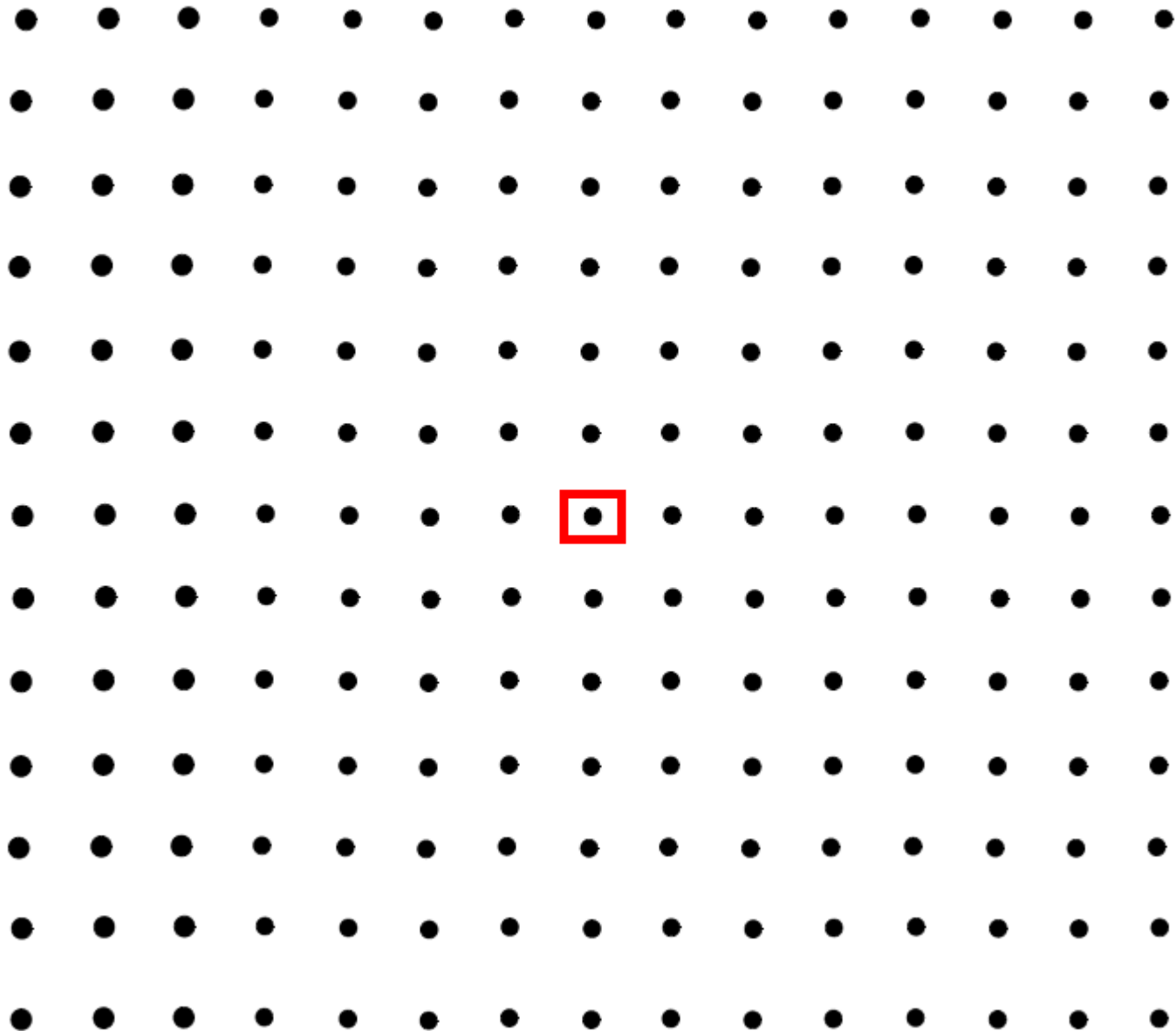


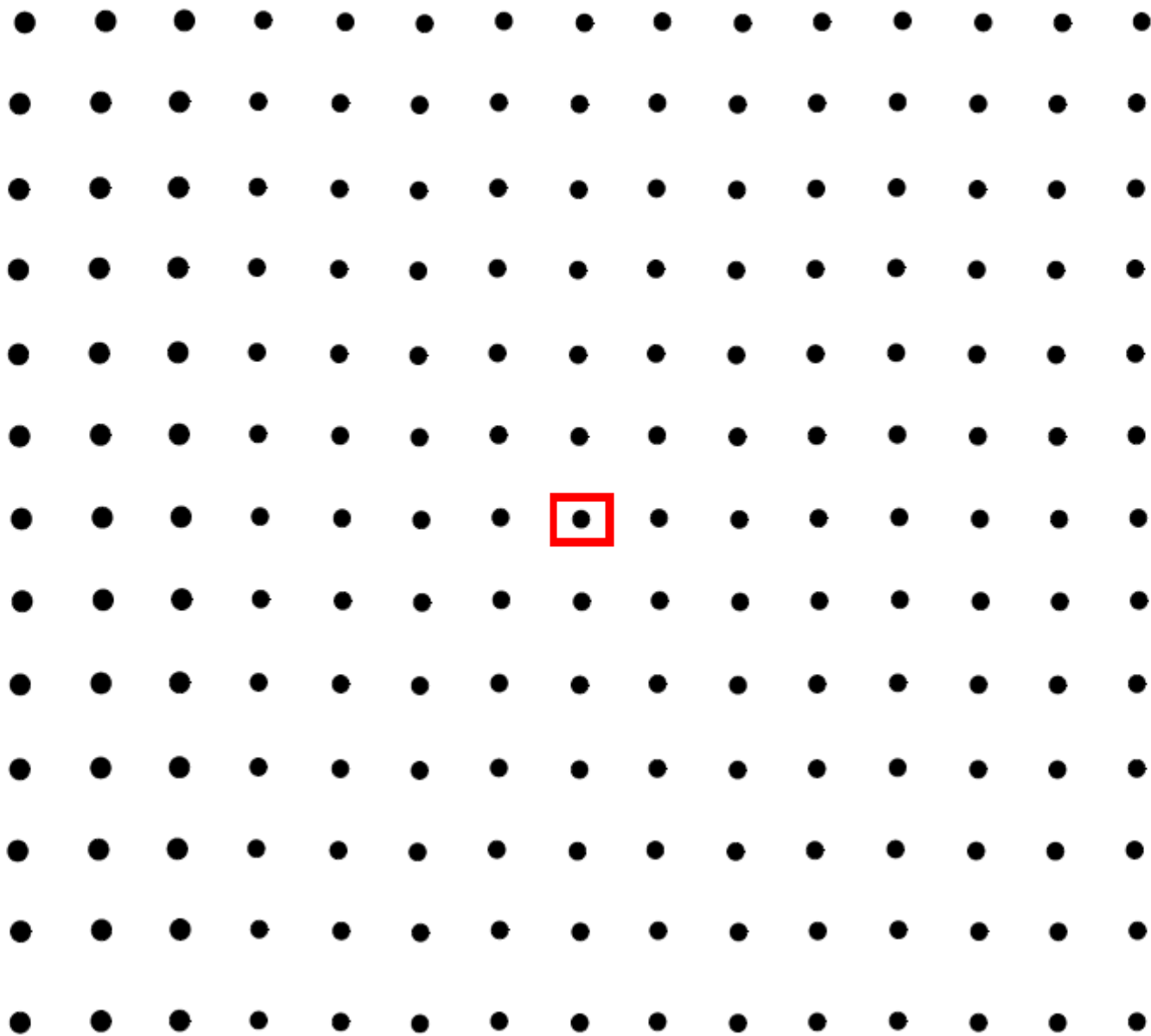


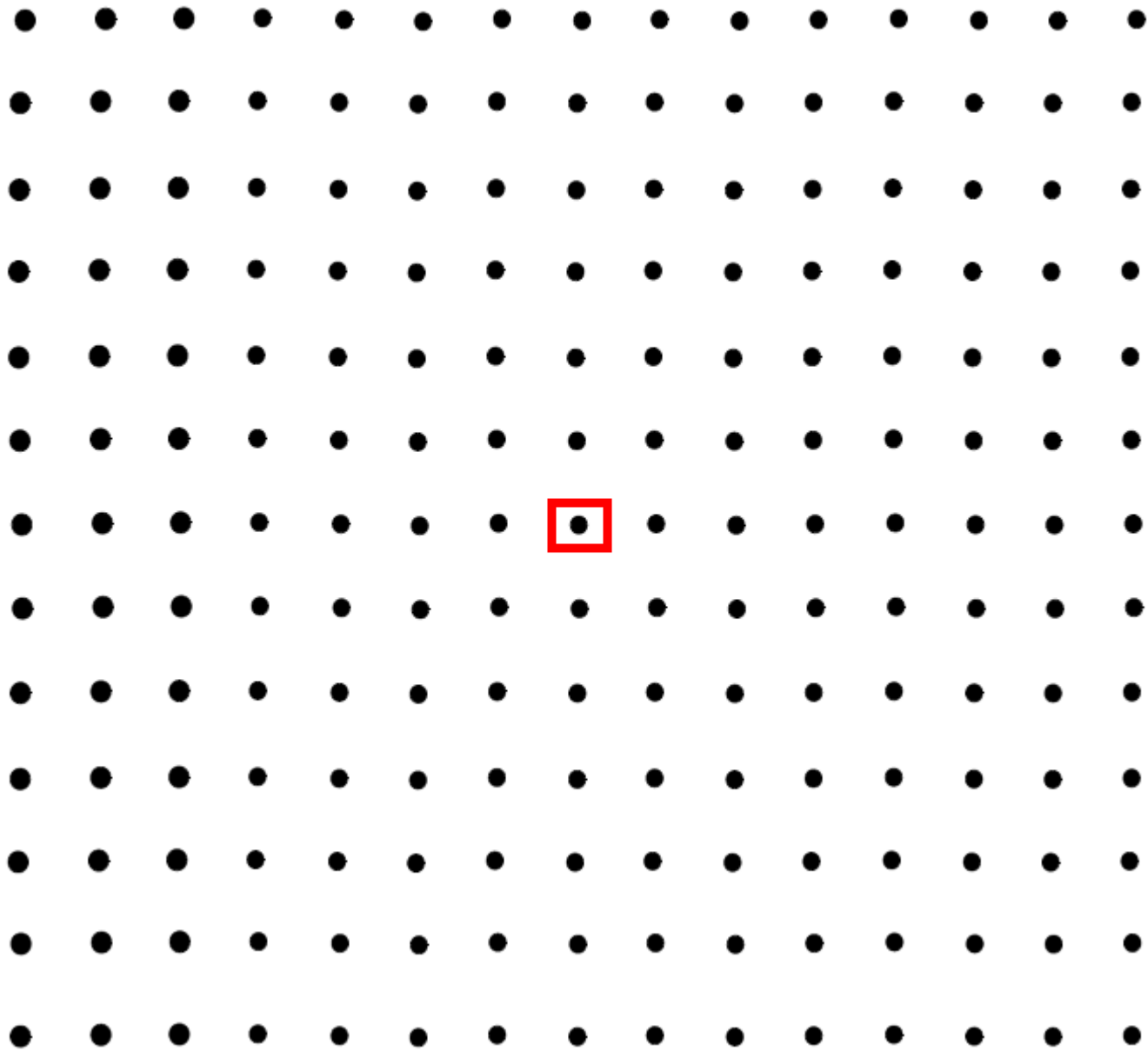


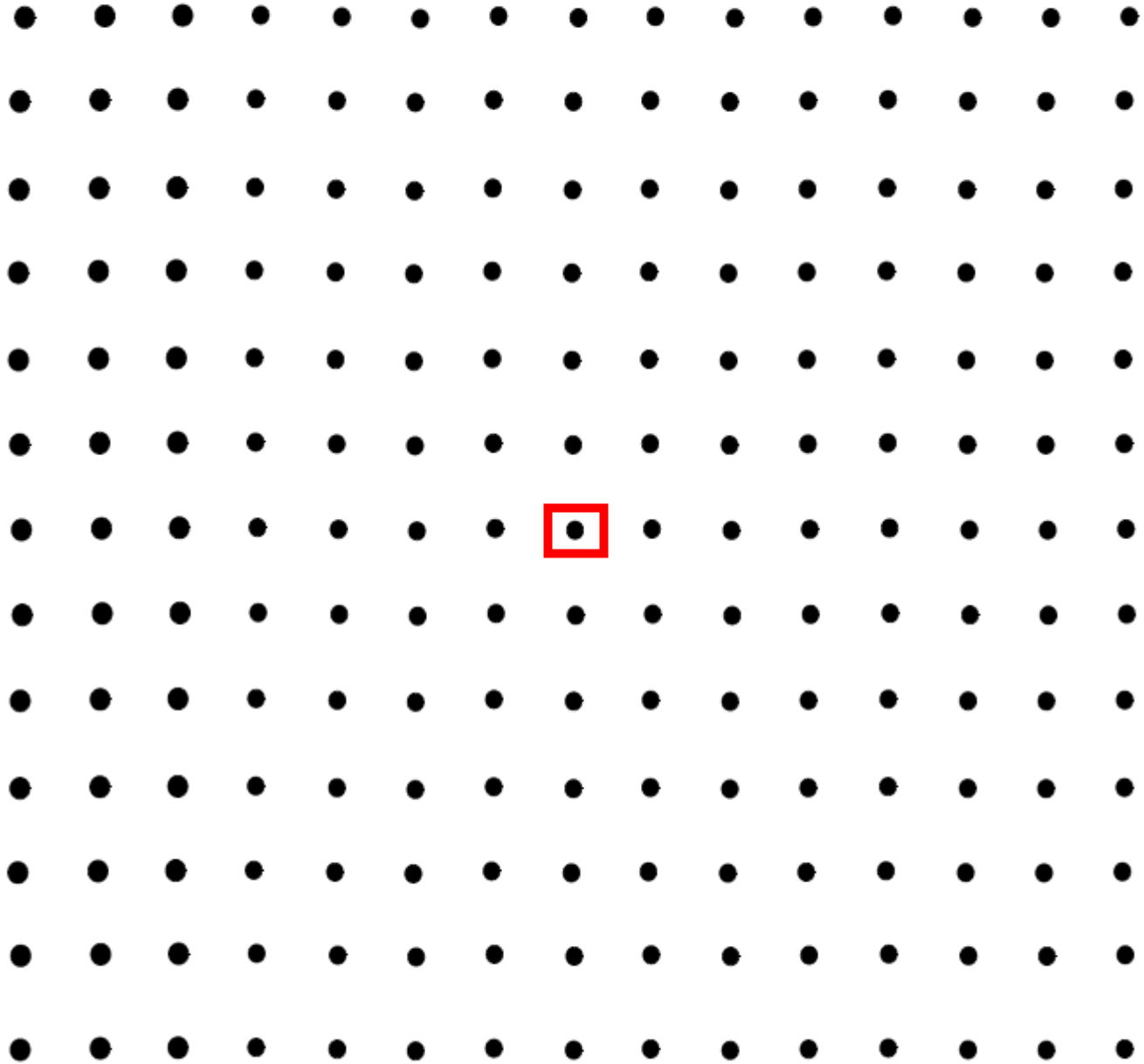


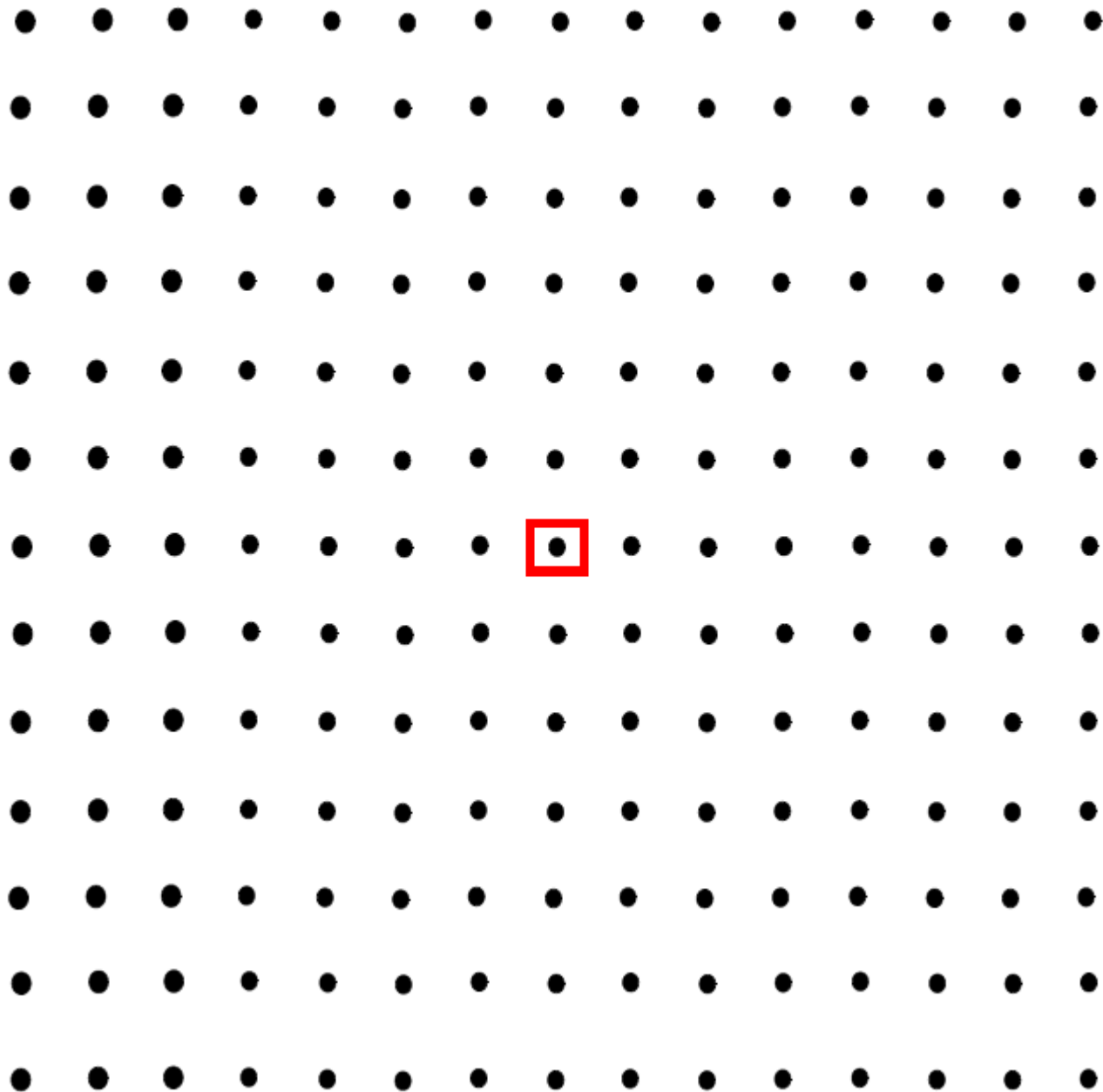




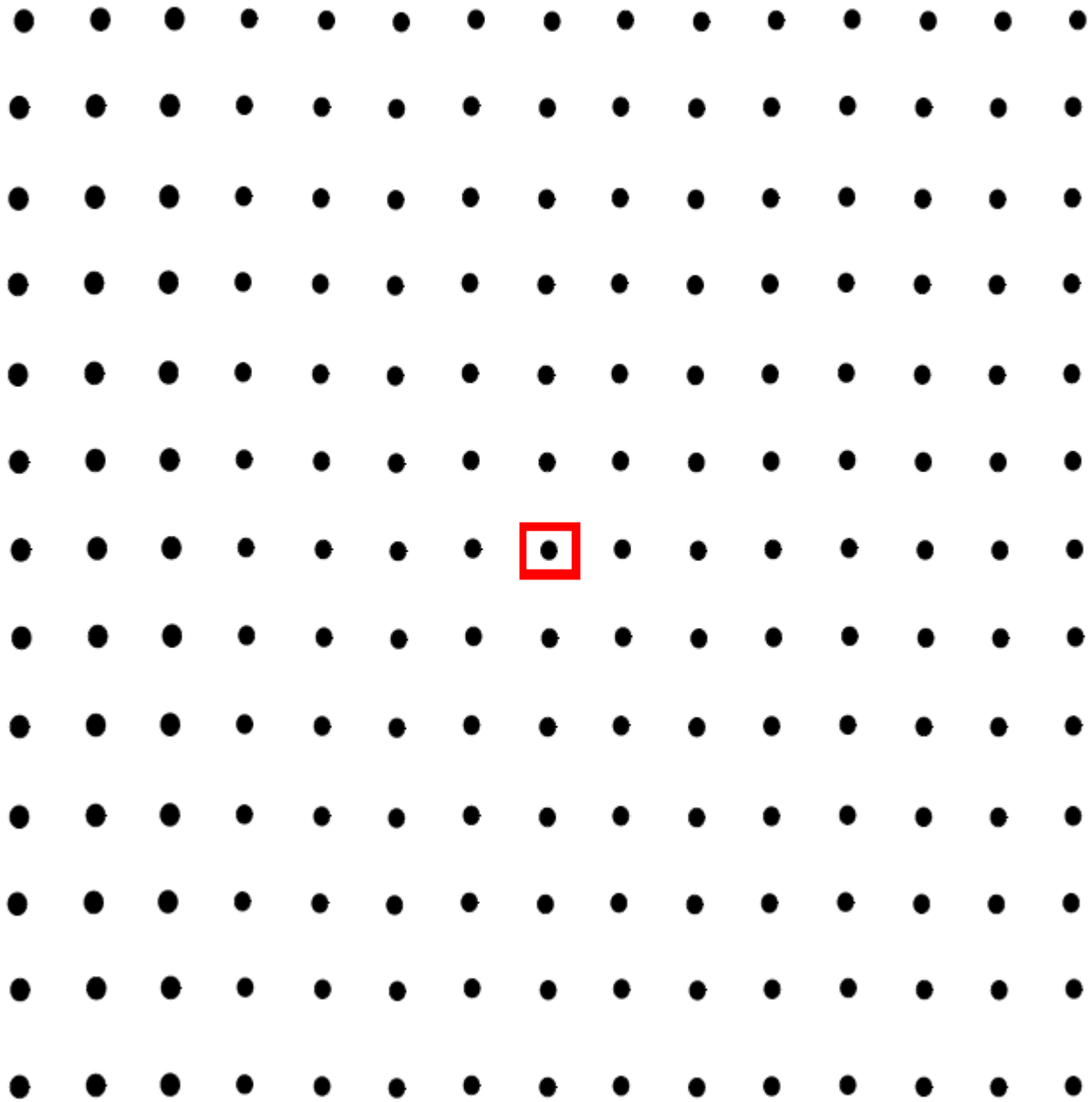


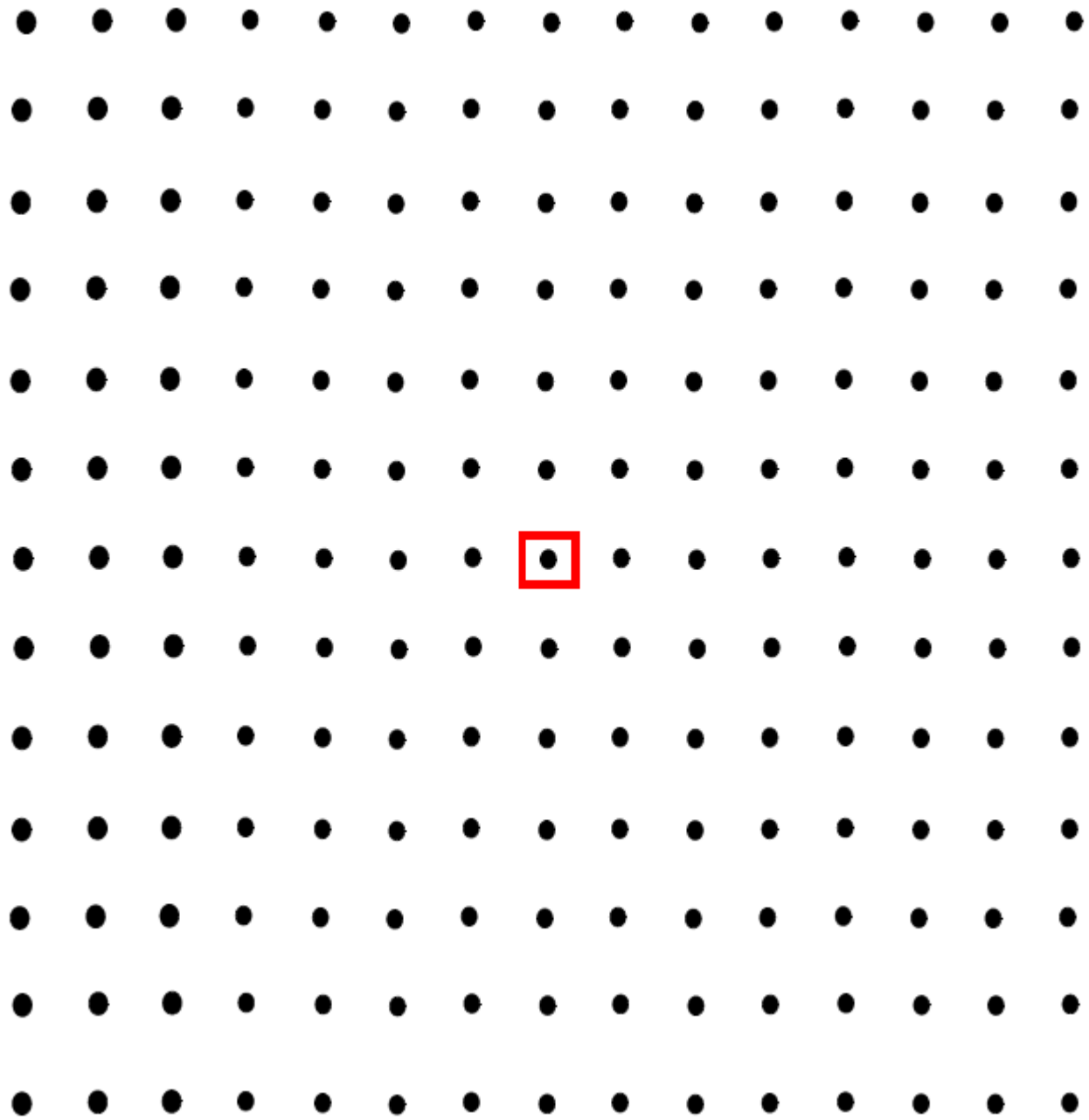












# Measurement challenge







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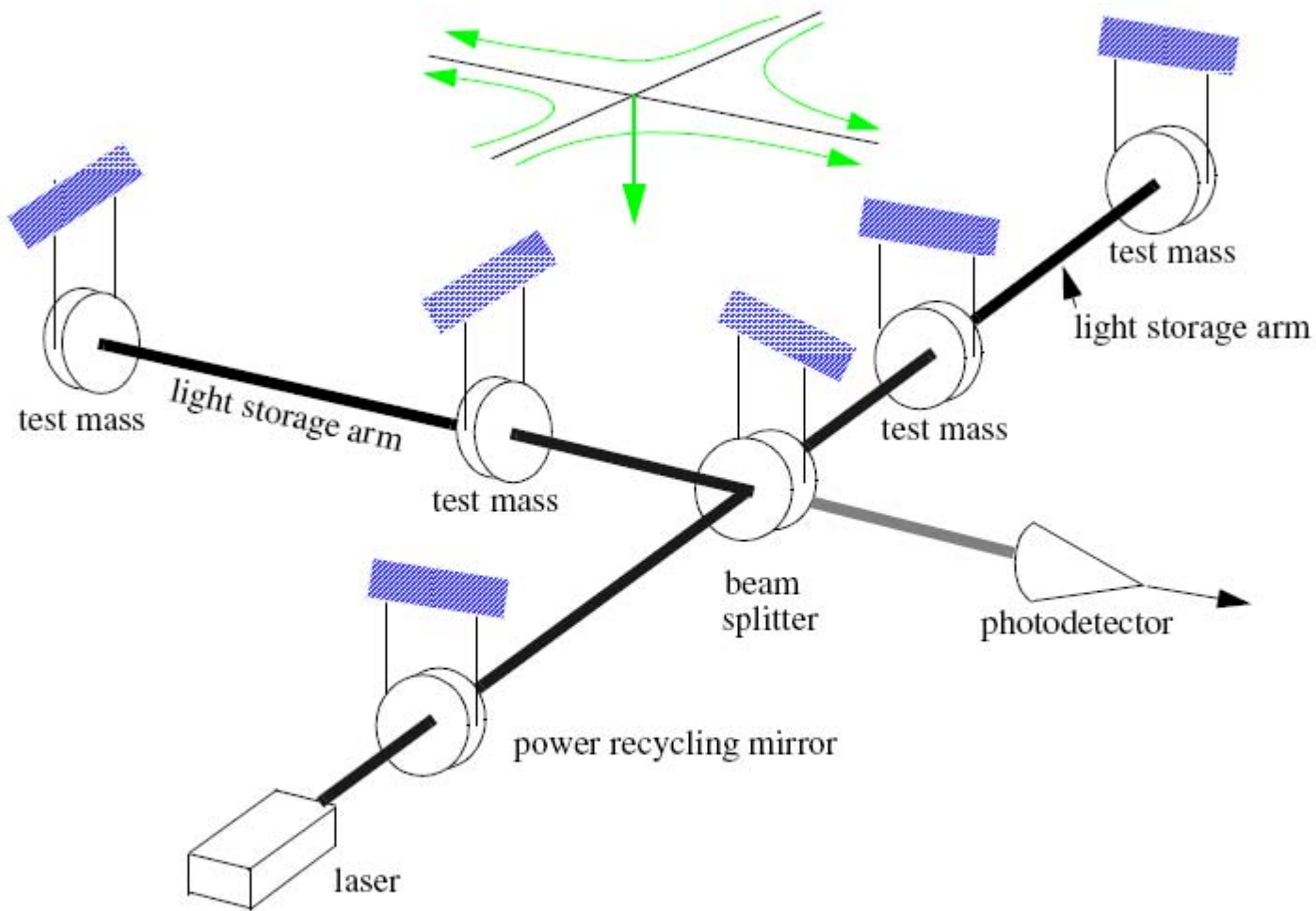
- Needed technology development to measure:

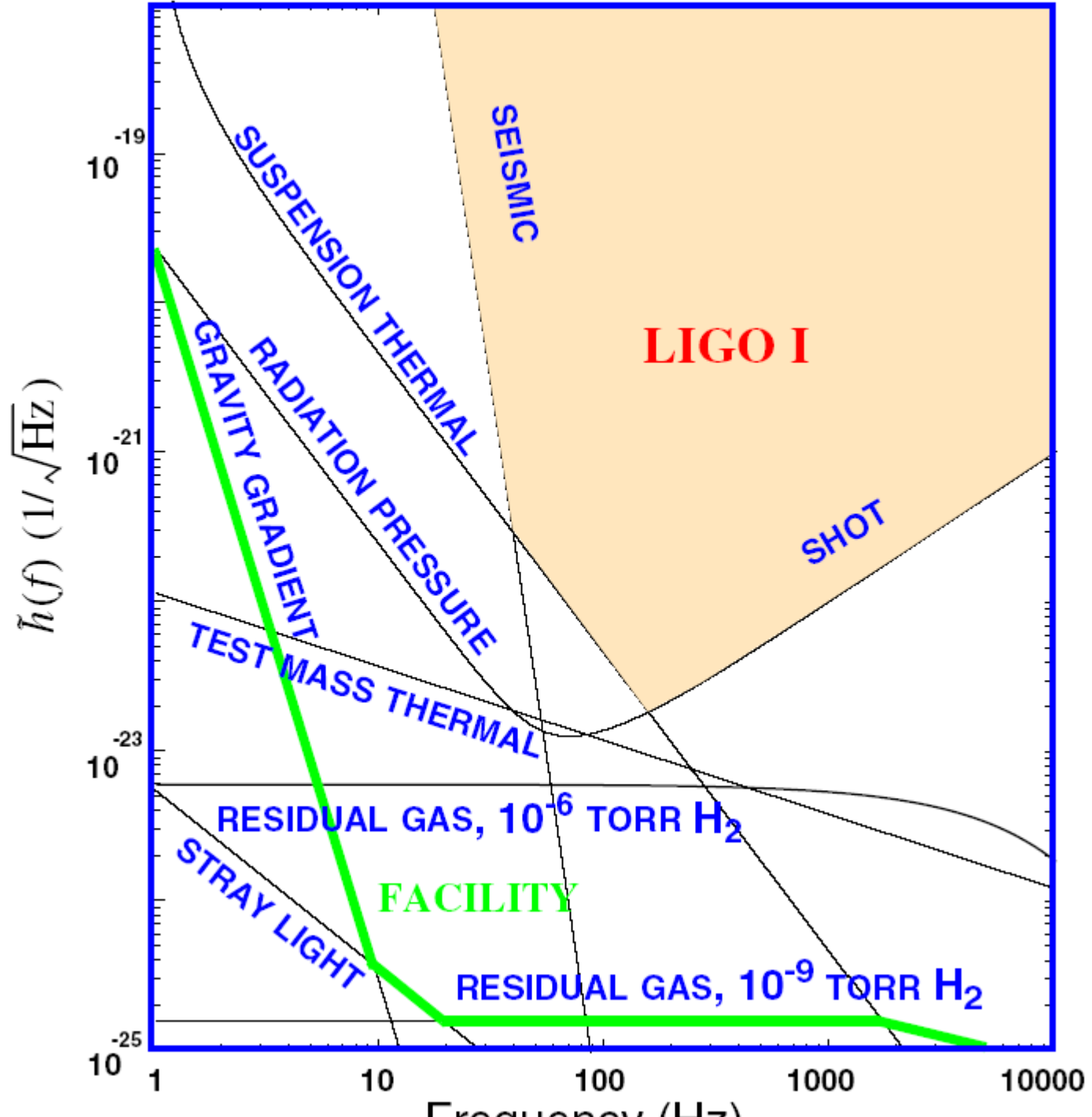
$$h = \Delta L/L < 10^{-21}$$

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

# How Small is $10^{-18}$ Meter?

		<i>One meter, about 40 inches</i>
$\div 10,000$		<i>Human hair, about 100 microns</i>
$\div 100$		<i>Wavelength of light, about 1 micron</i>
$\div 10,000$		<i>Atomic diameter, <math>10^{-10}</math> meter</i>
$\div 100,000$		<i>Nuclear diameter, <math>10^{-15}</math> meter</i>
$\div 1,000$		<i>LIGO sensitivity, <math>10^{-18}</math> meter</i>

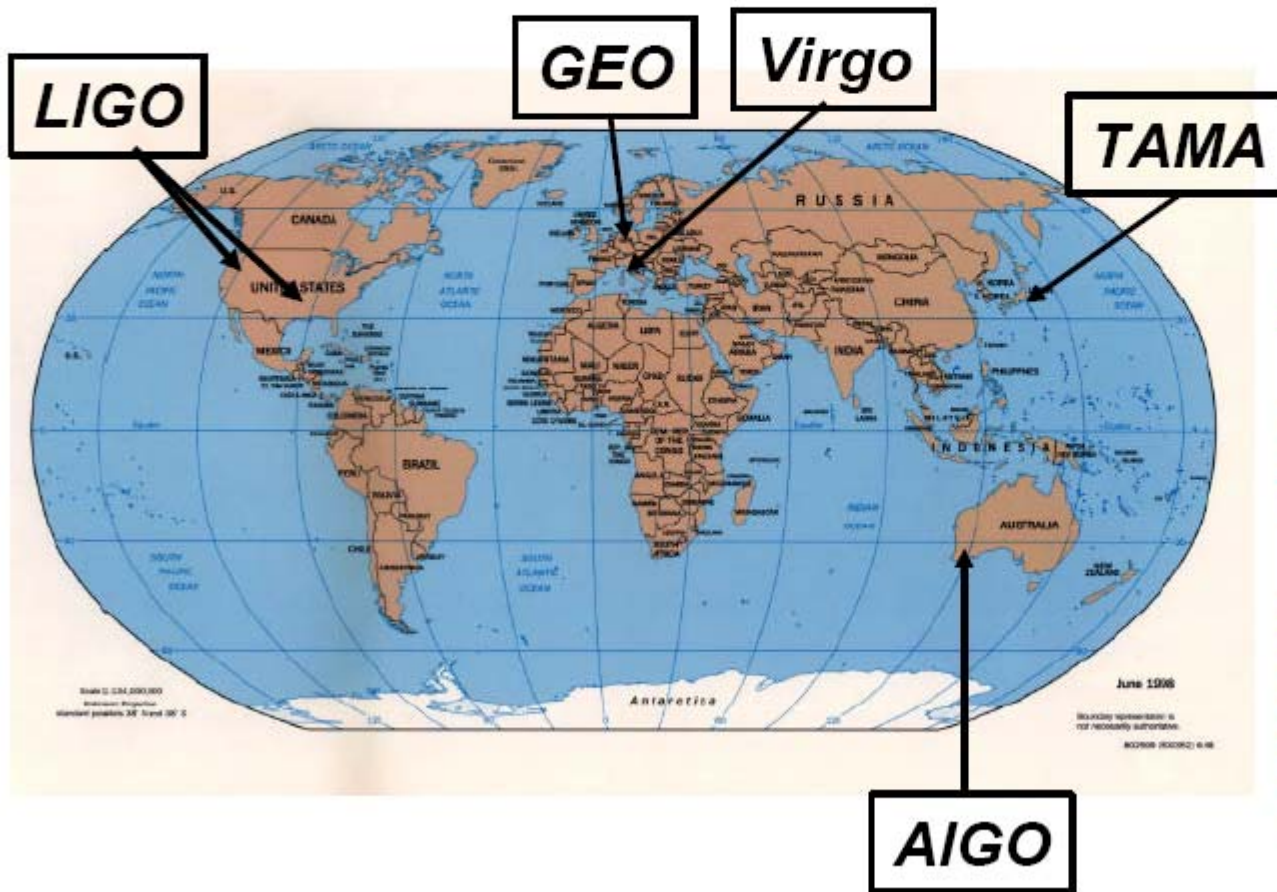




# Interferometers

## *international network*

Simultaneously detect signal (within msec)



detection  
confidence

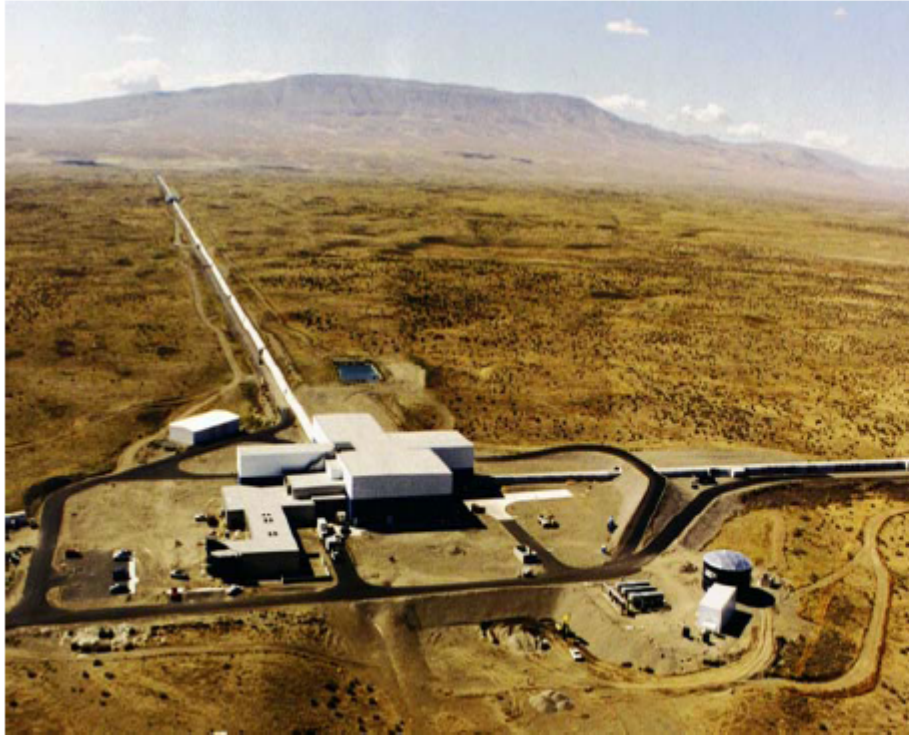
locate the  
sources

decompose the  
polarization of  
gravitational  
waves





# LIGO Observatory Facilities



***LIGO Hanford Observatory [LHO]***

*26 km north of Richland, WA*

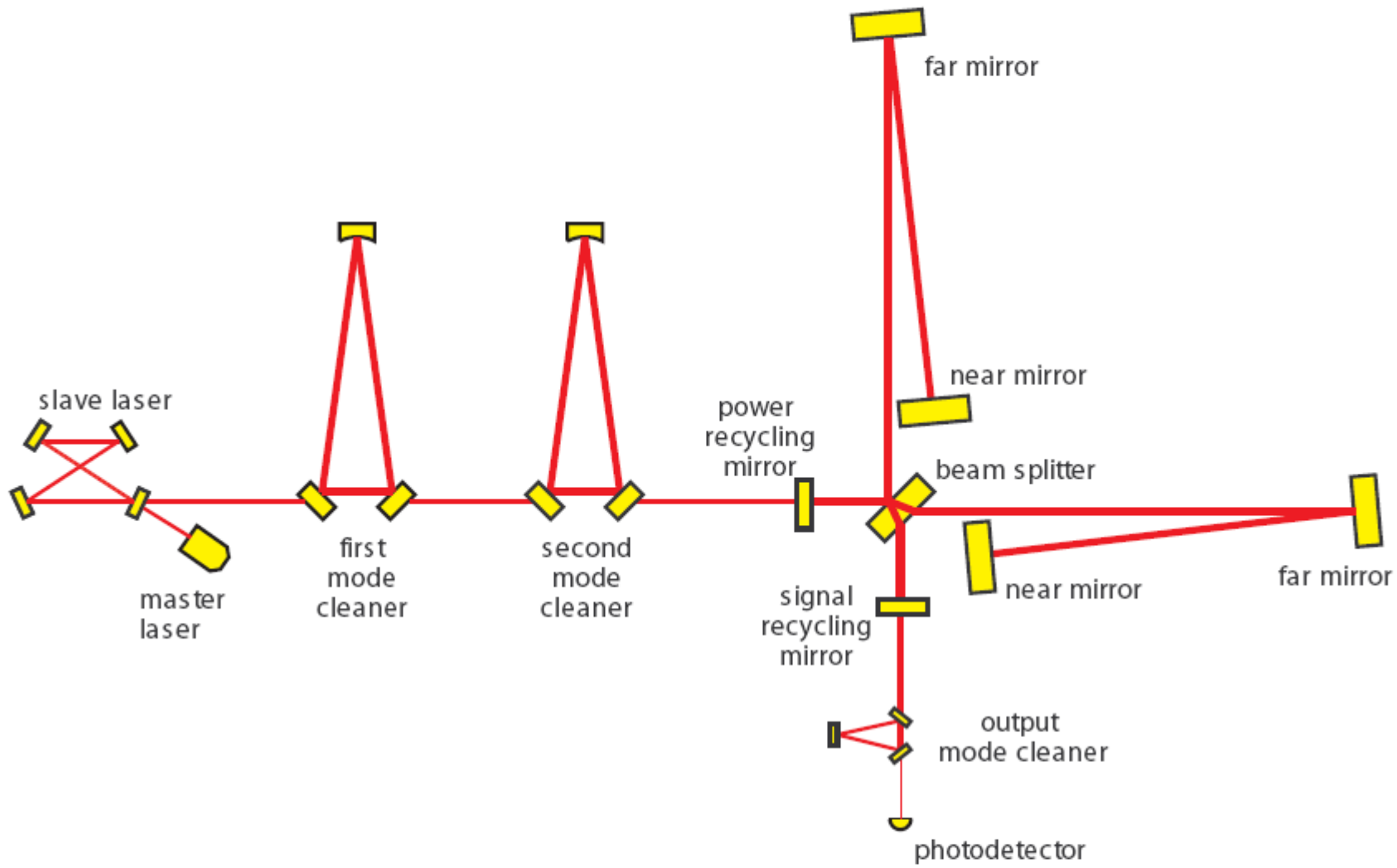
2 km + 4 km interferometers in same vacuum envelope



***LIGO Livingston Observatory [LLO]***

*42 km east of Baton Rouge, LA*

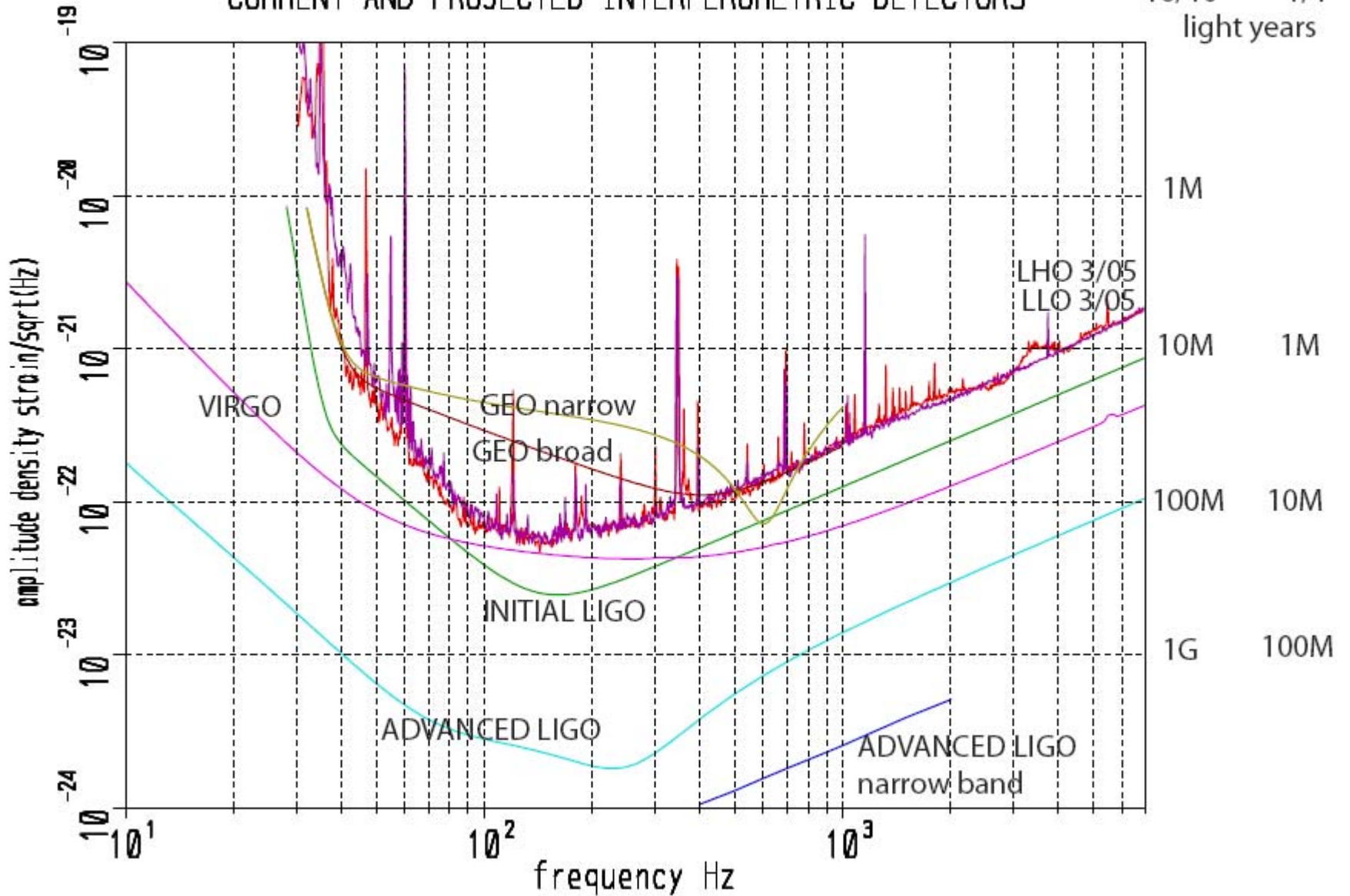
Single 4 km interferometer





# CURRENT AND PROJECTED INTERFEROMETRIC DETECTORS

BH/BH    NS/NS  
 10/10    1/1  
 light years



# 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 !!**

*vacuum equipment*



## Substrates: $\text{SiO}_2$

25 cm Diameter, 10 cm thick

Homogeneity  $< 5 \times 10^{-7}$

Internal mode Q's  $> 2 \times 10^6$

## Polishing

Surface uniformity  $< 1$  nm rms

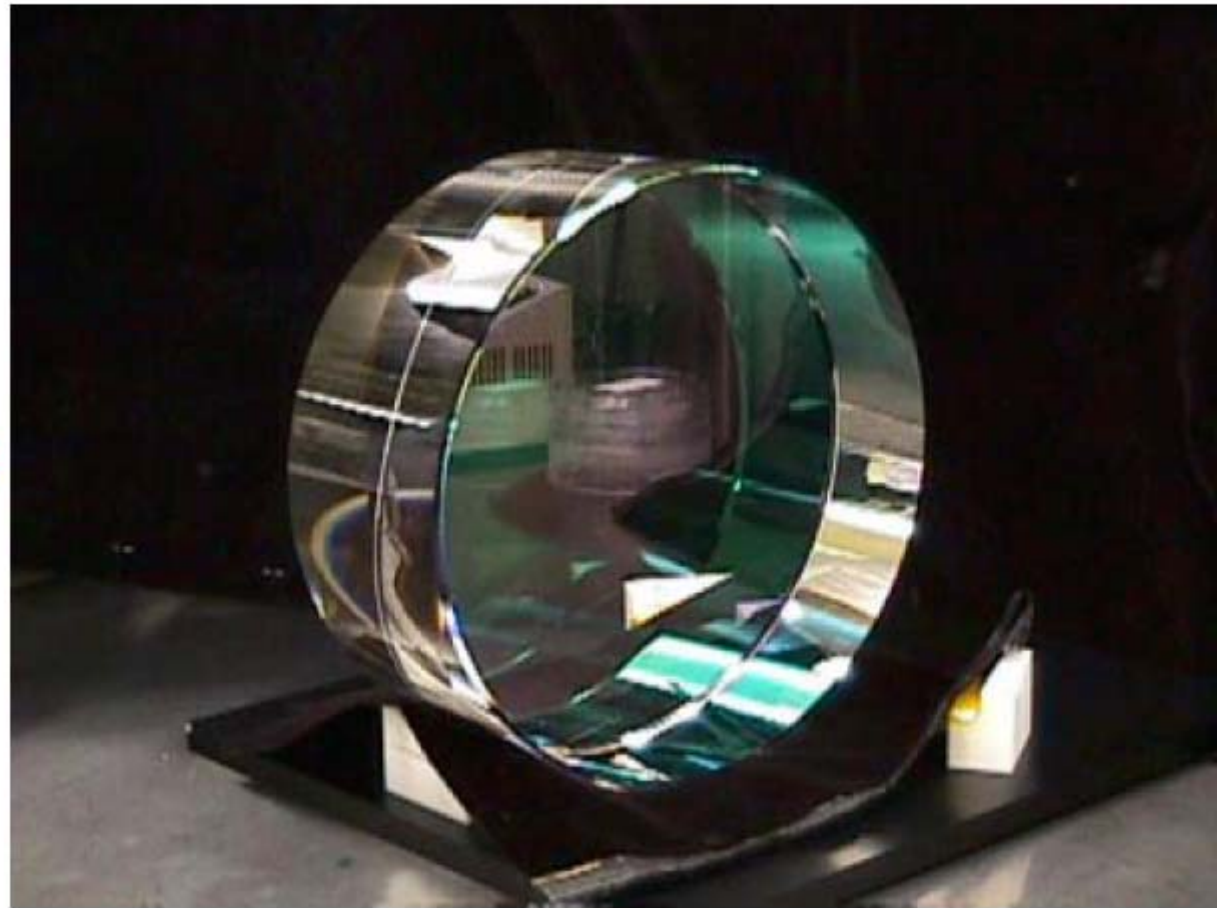
radii of curvature matched  $< 3\%$

## Coating

Scatter  $< 50$  ppm

Absorption  $< 2$  ppm

Uniformity  $< 10^{-3}$



# LIGO



## Core Optics

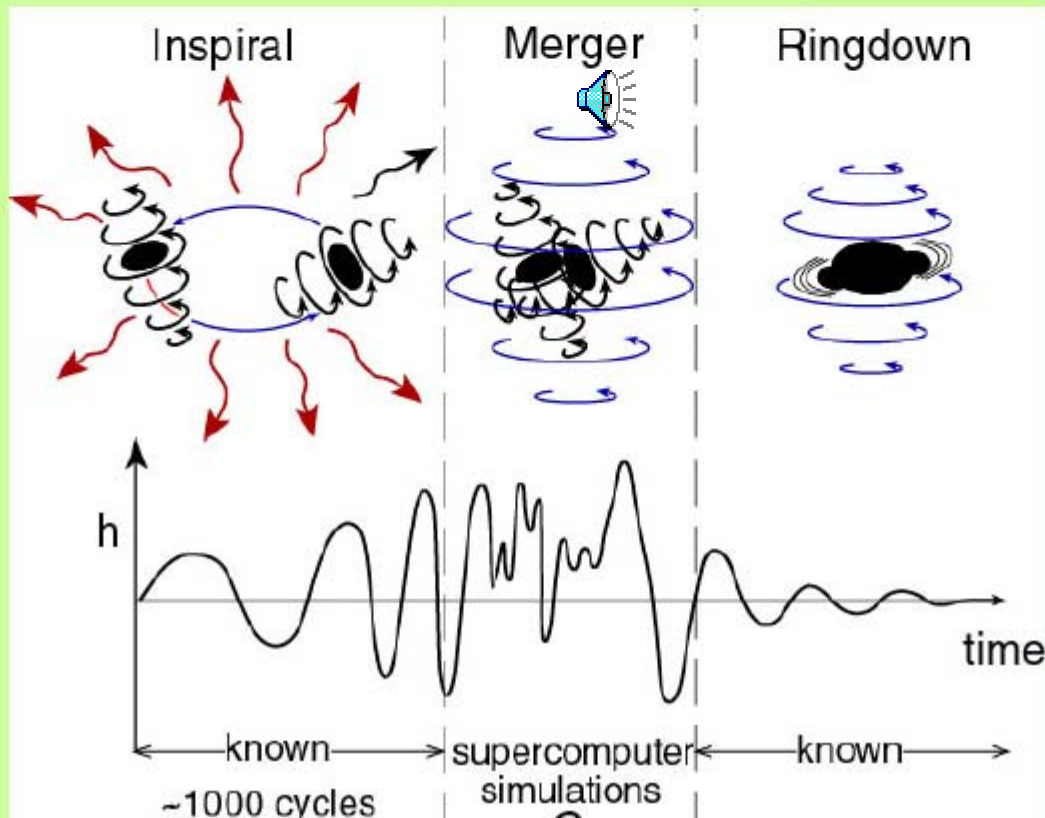
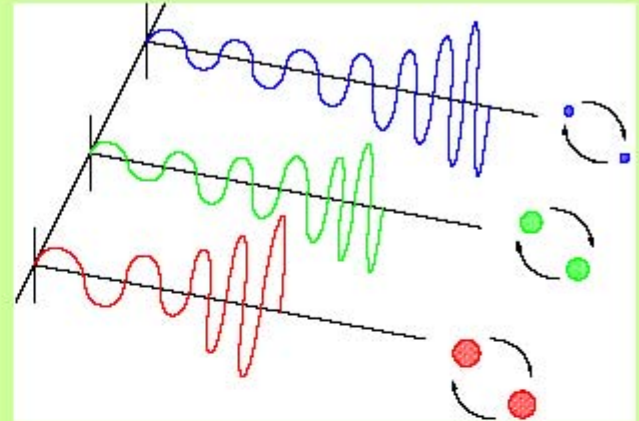
*installation and alignment*





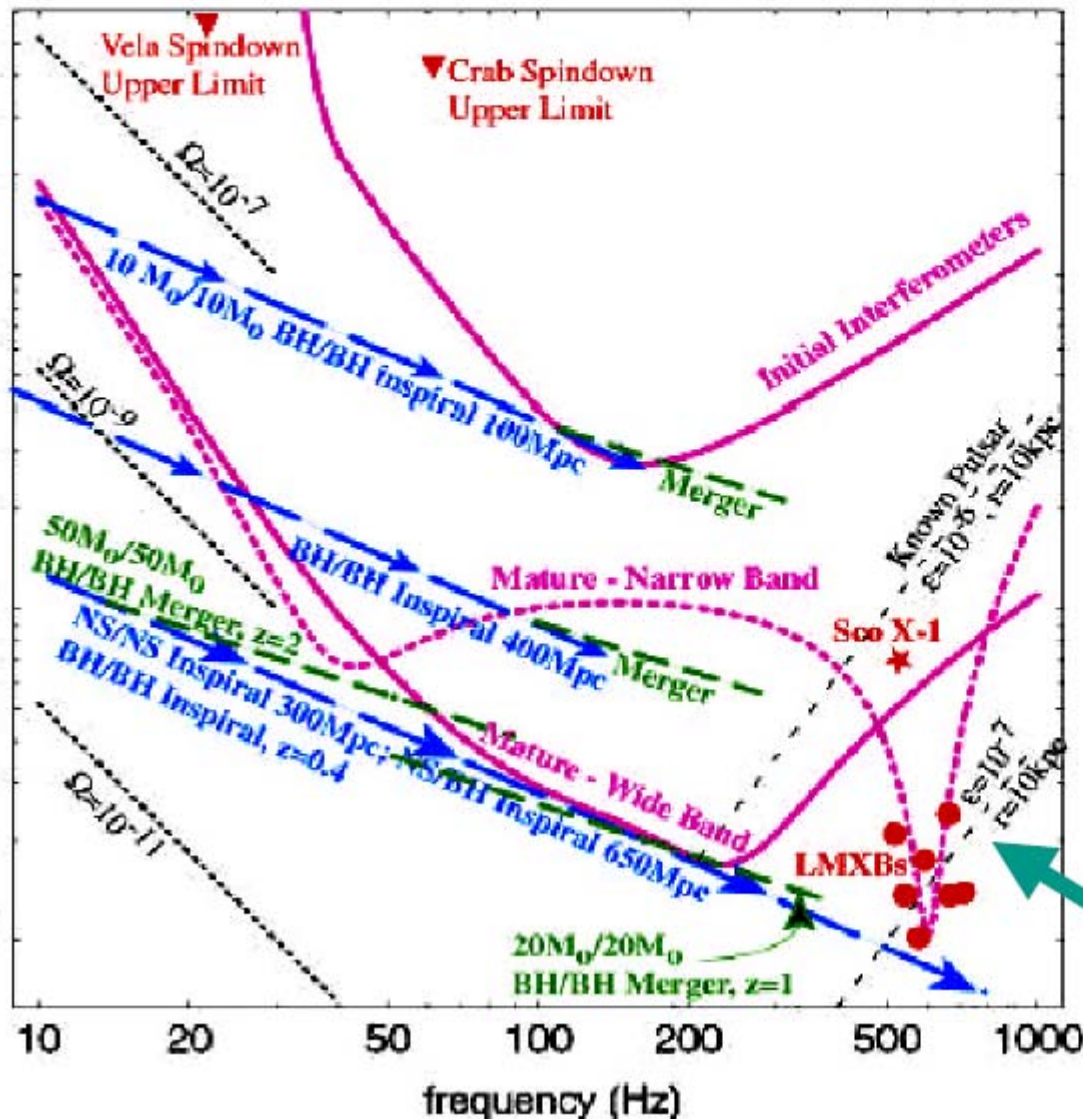
# Compact binary collisions

- » **Neutron Star – Neutron Star**
  - waveforms are well described
- » **Black Hole – Black Hole**
  - need better waveforms
- » **Search: **matched templates****



# Advanced LIGO

2007 +



## Enhanced Systems

- laser
- suspension
- seismic isolation
- test mass

Improvement  
factor in rate  
 $\sim 10^4$

+  
narrow band  
optical  
configuration

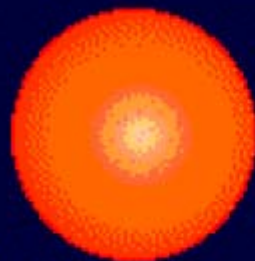
# The Lifecycle of Stars

**Sun-Like Stars**

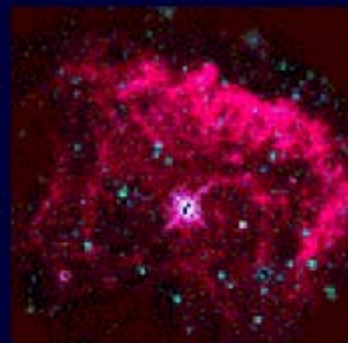
(up to 1.5 times the mass of the Sun)



**Red Giant**



**Planetary Nebula**



**White Dwarf**



**Black Dwarf**



**Stellar Nursery**



Stars form in a nebula, from collapsing clouds of interstellar gas and dust.

**Huge Stars**

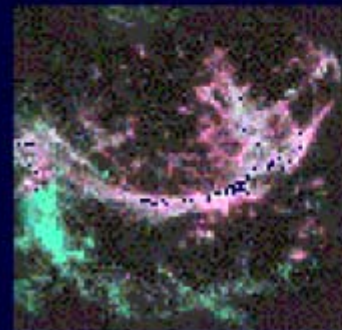
(from 1.5 to 3 times the mass of the Sun)



**Red Supergiant**



**Supernova**



**Neutron Star**



**Giant Stars**

(over 3 times the mass of the Sun)



**Red Supergiant**



**Supernova**



**Black Hole**

# Supernovae: “burst signals”



**The death of stars**

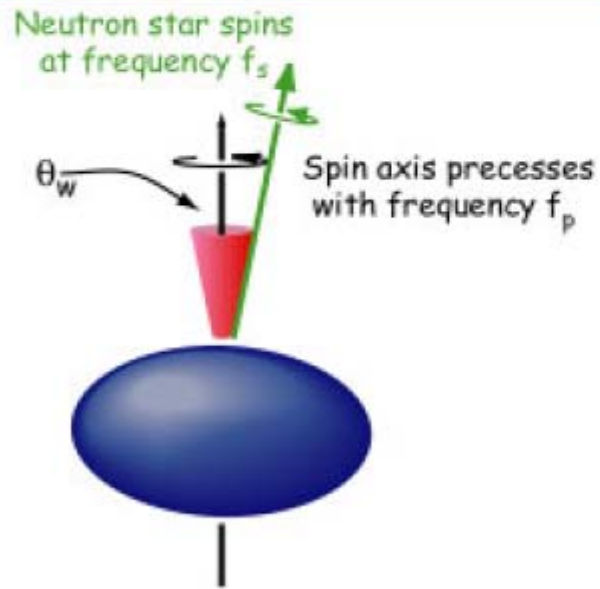
***time evolution***



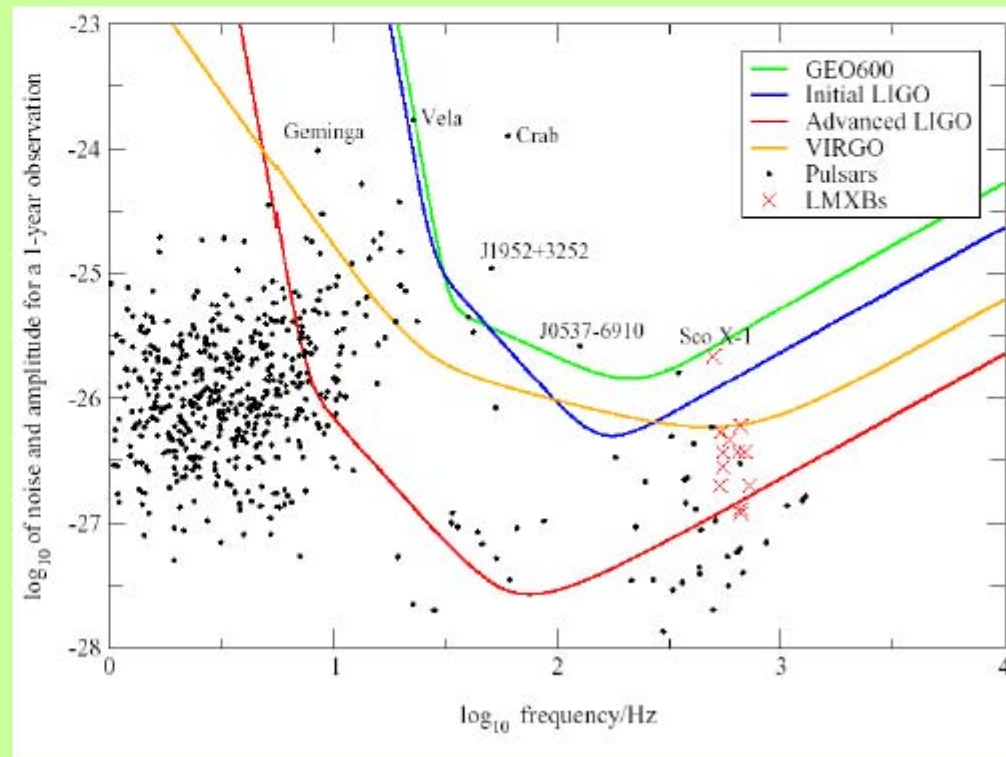
Images from NASA High Energy Astrophysics Research Archive

# Spinning Neutron Stars: “periodic”

## An afterlife of stars

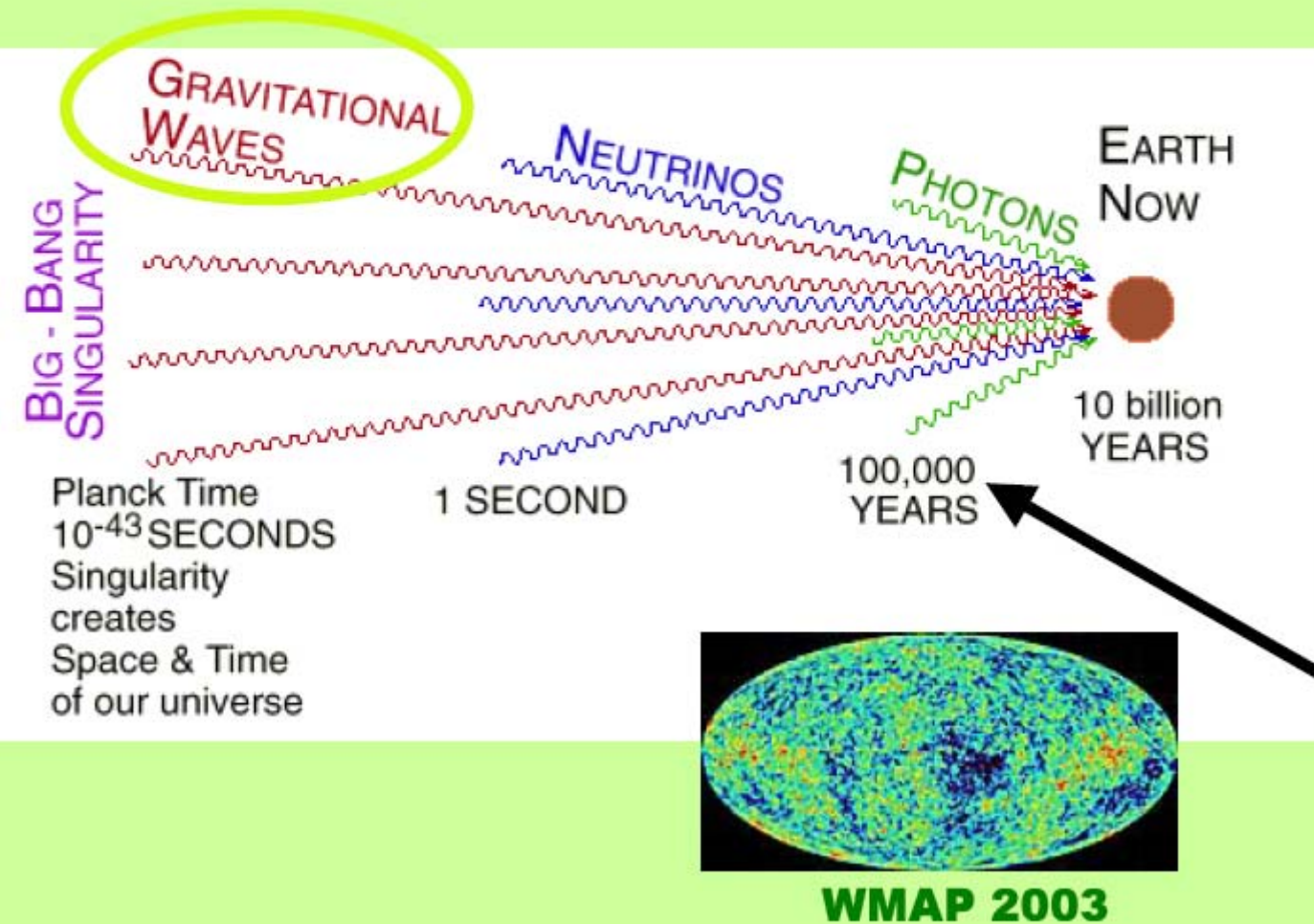


## Maximum gravitational wave luminosity of known pulsars

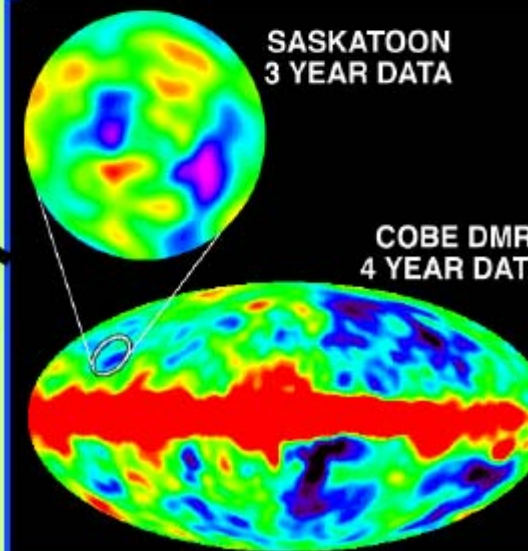


# Early Universe: *“correlated noise”*

## ‘Murmurs’ from the Big Bang

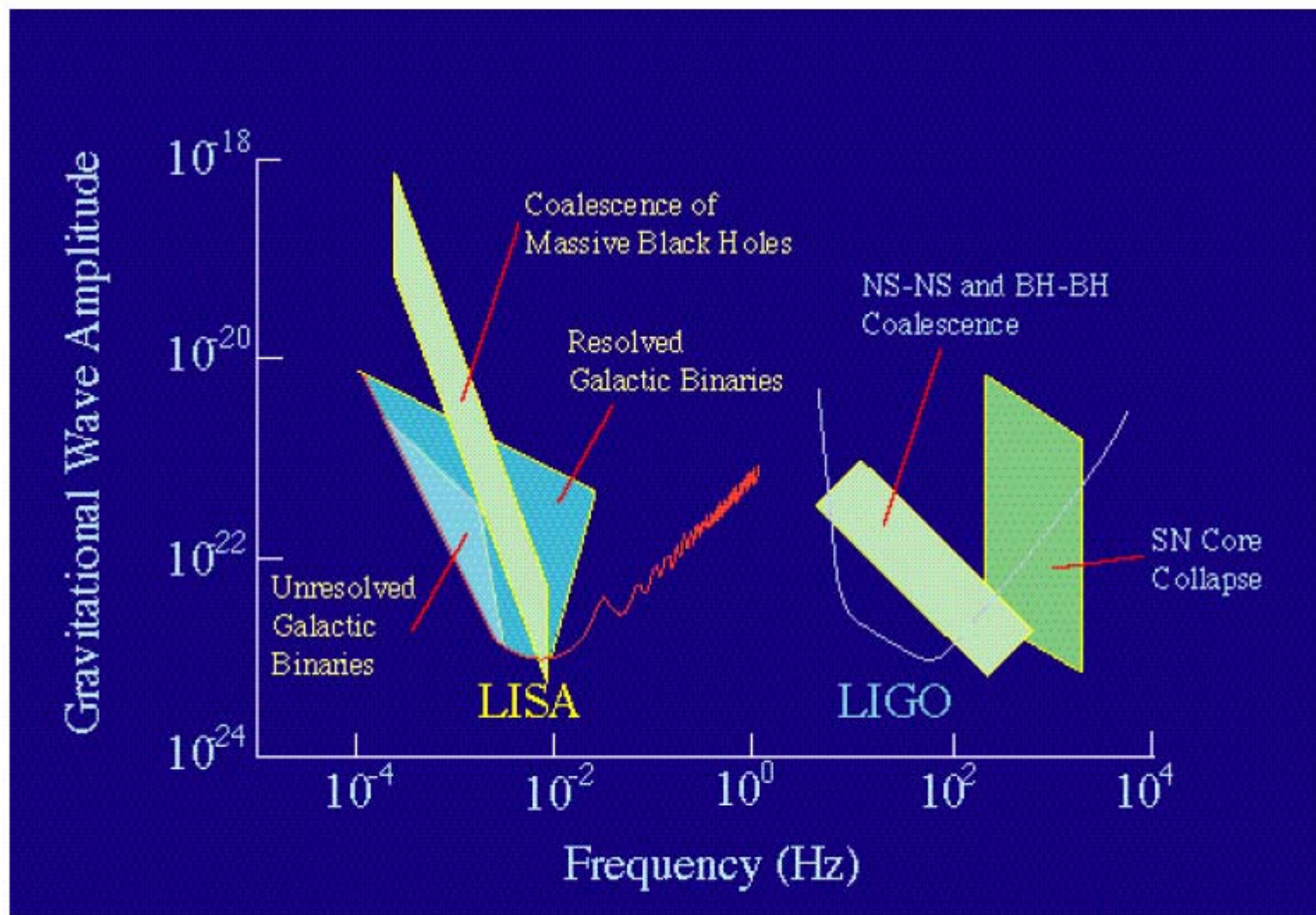


## **Cosmic Microwave background**



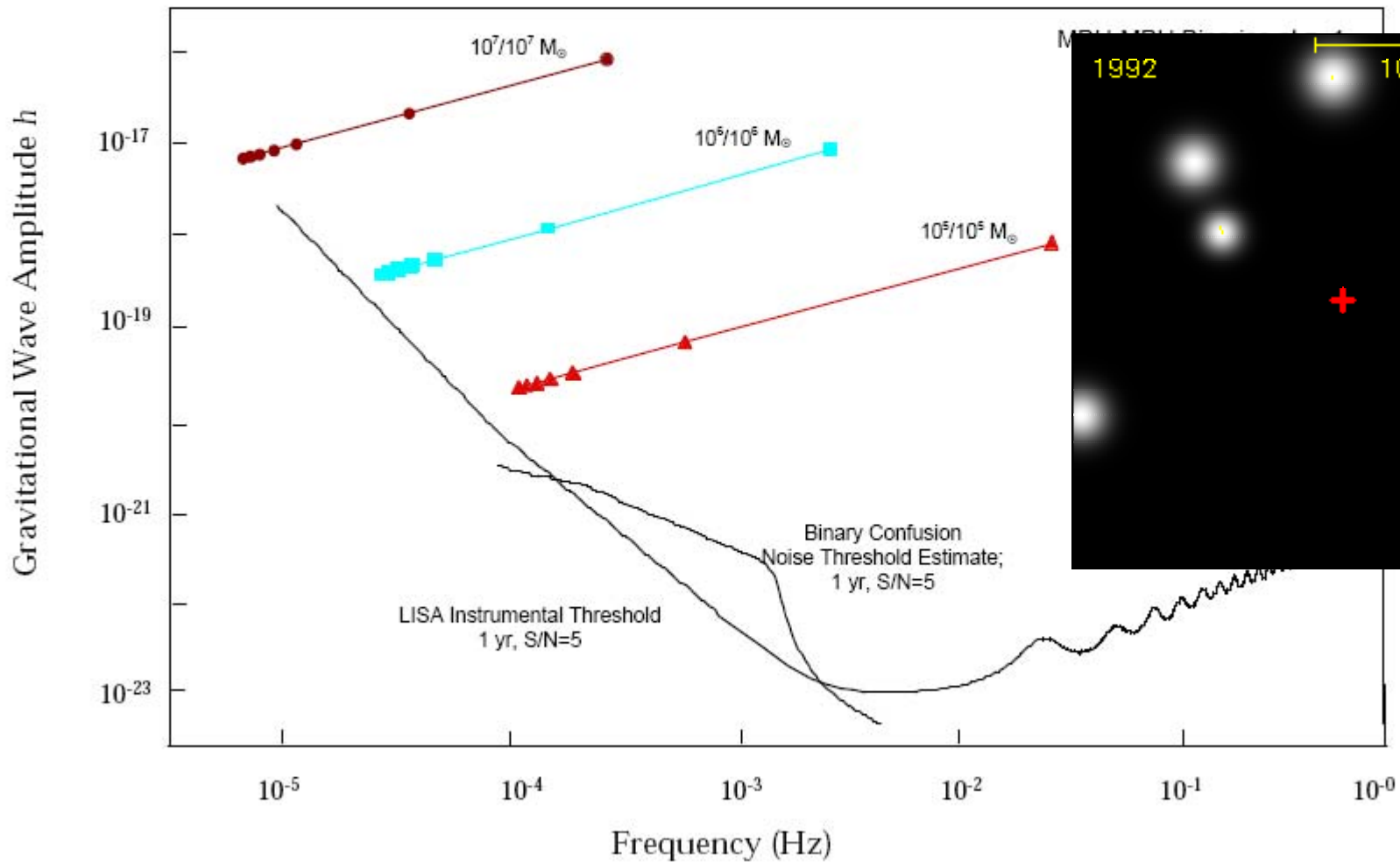


# The Gravitational-Wave Spectrum





# Massive Black Holes in Merging Galaxies



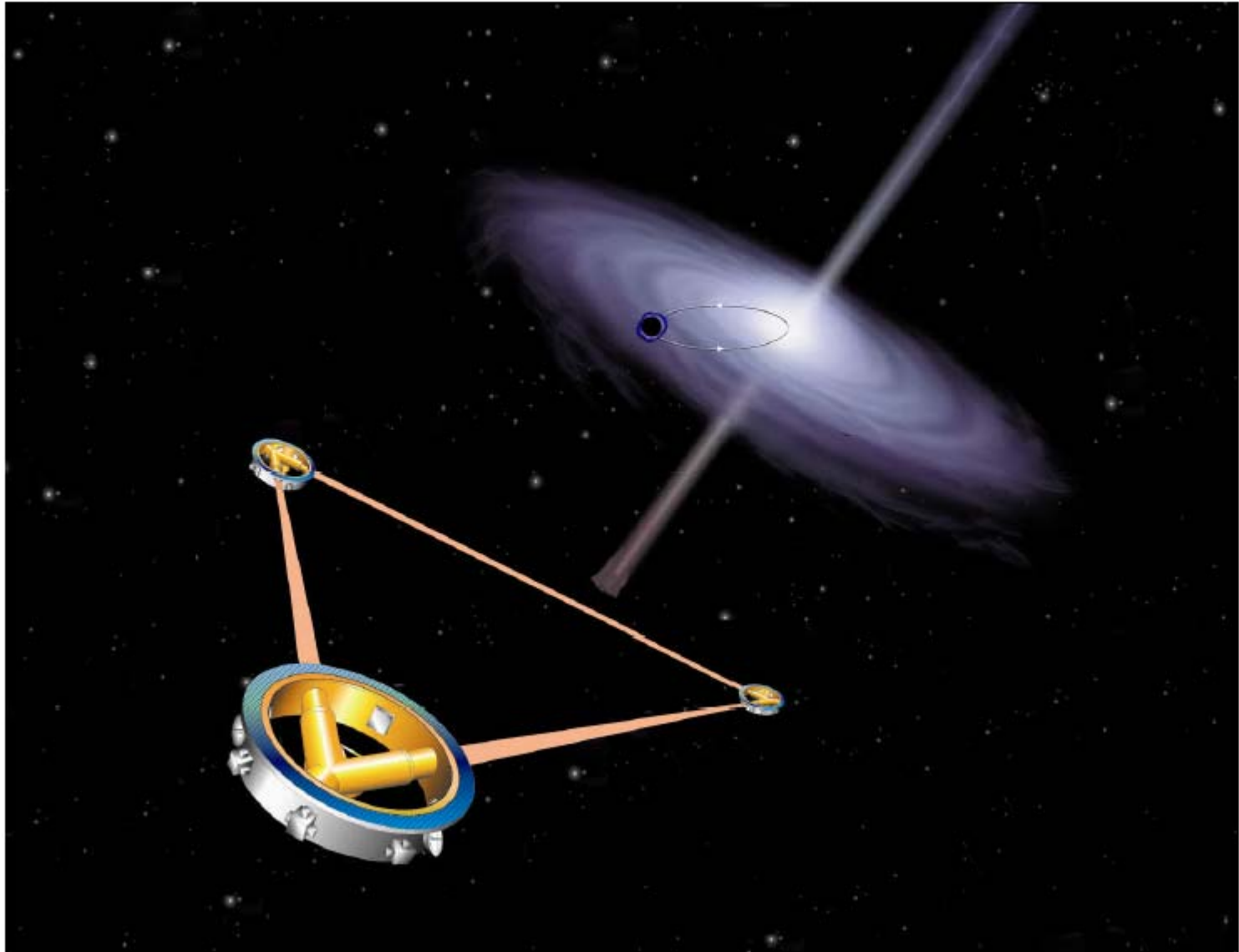




# Mission Concept

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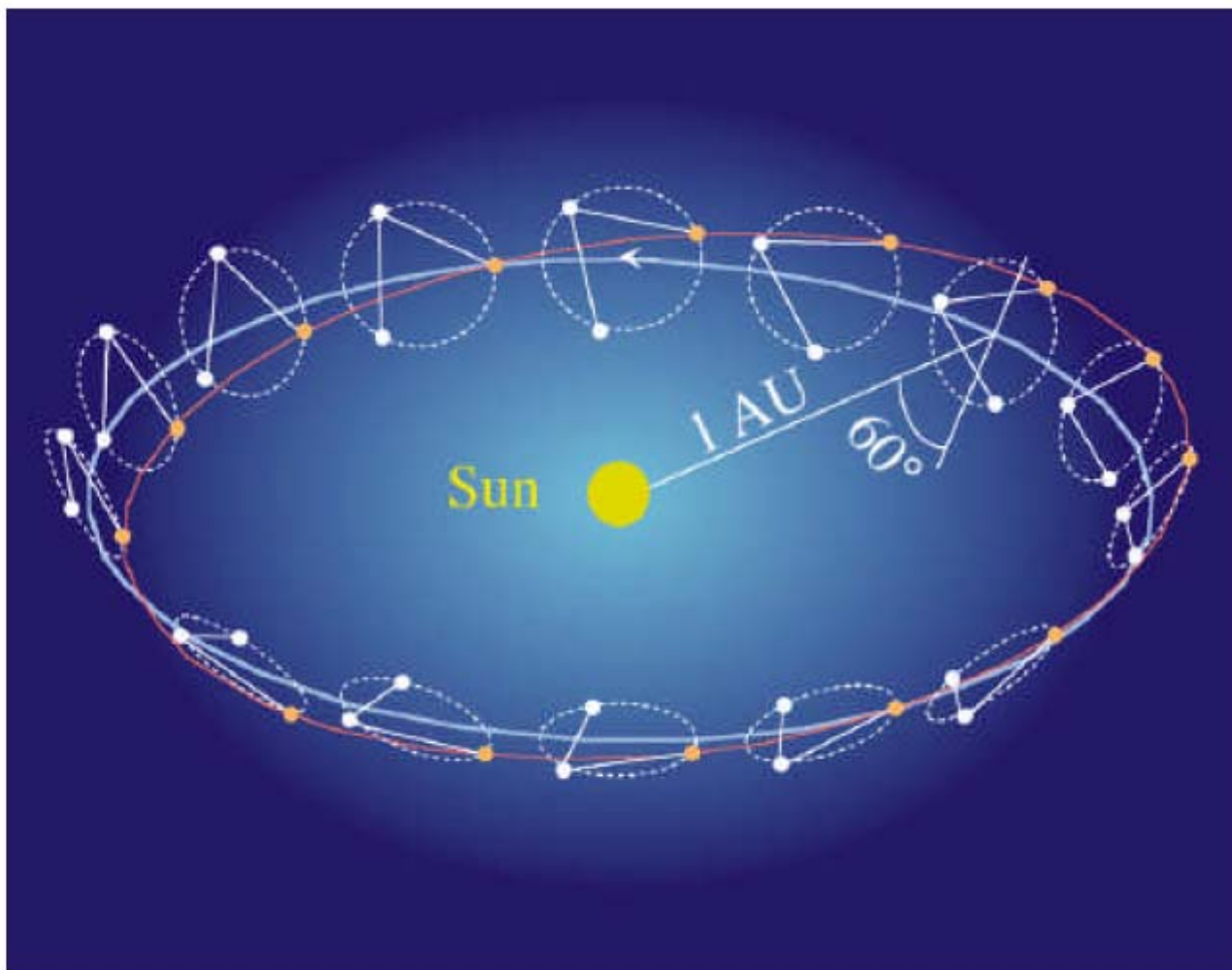
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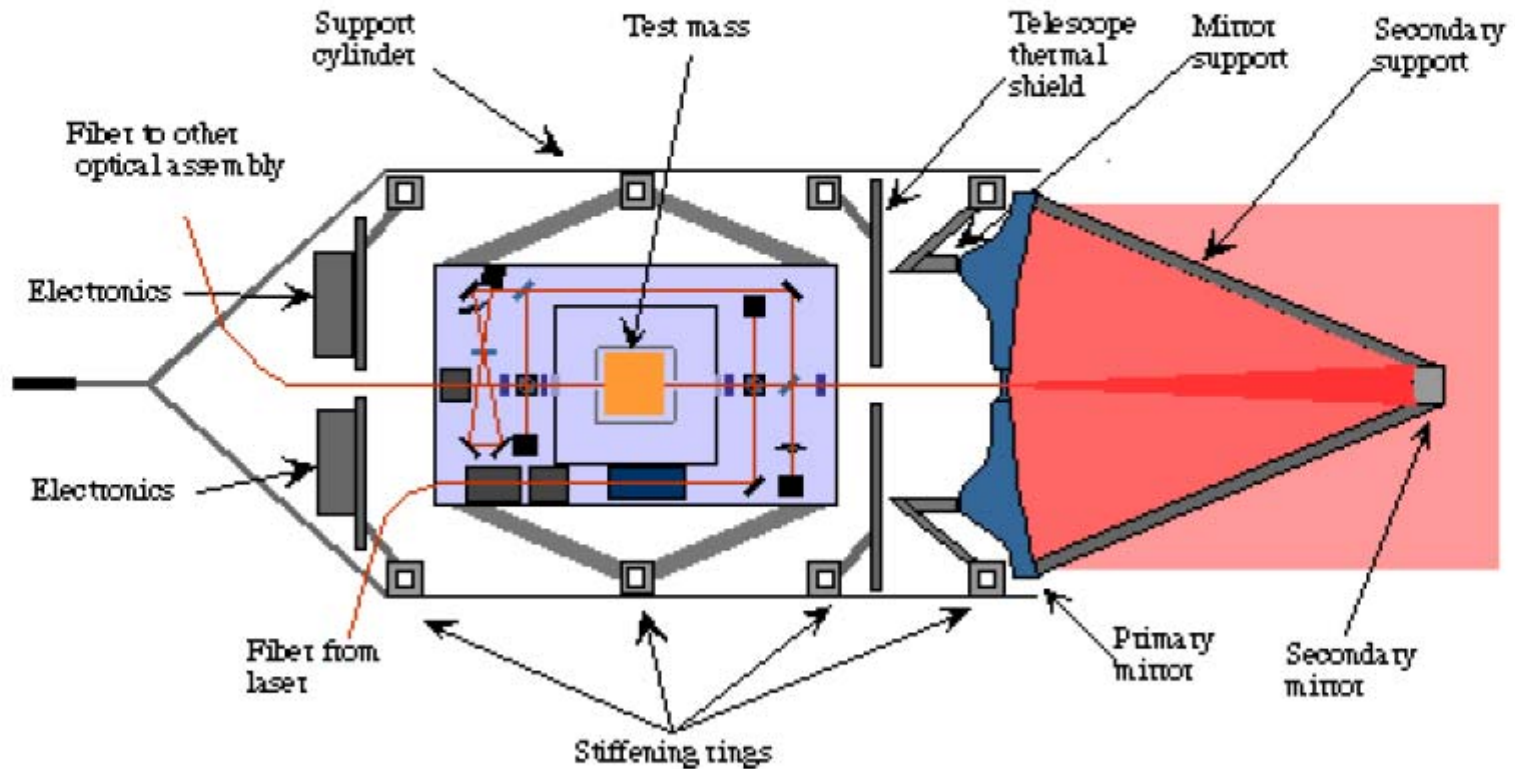


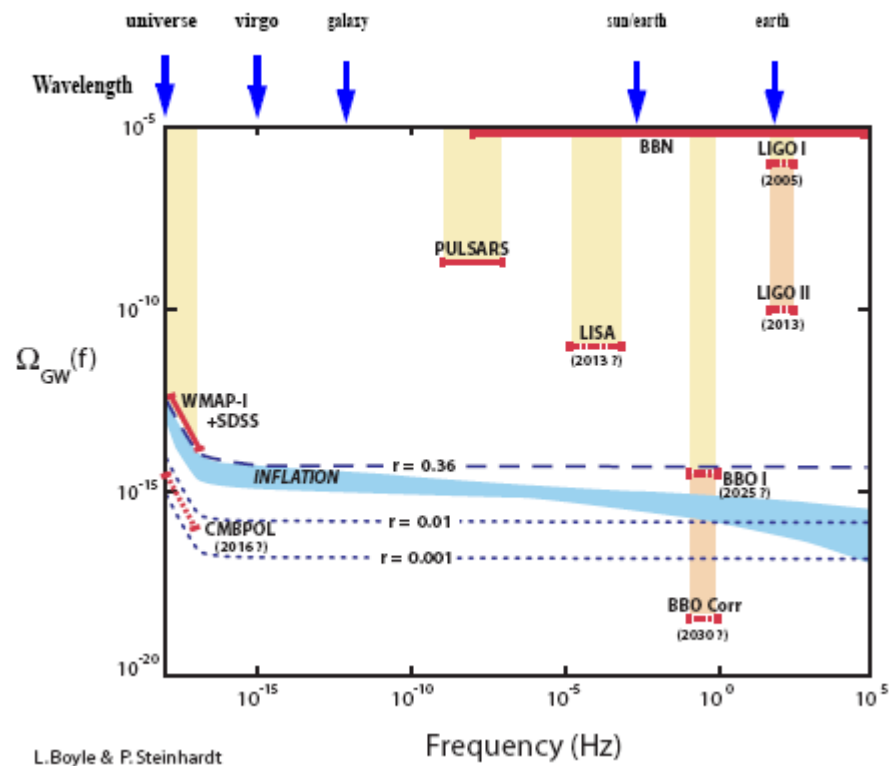
# Spacecraft Orbits

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



# Optical System





L. Boyle & P. Steinhardt