LIGO, the Laser Interferometer Gravitational-wave Observatory

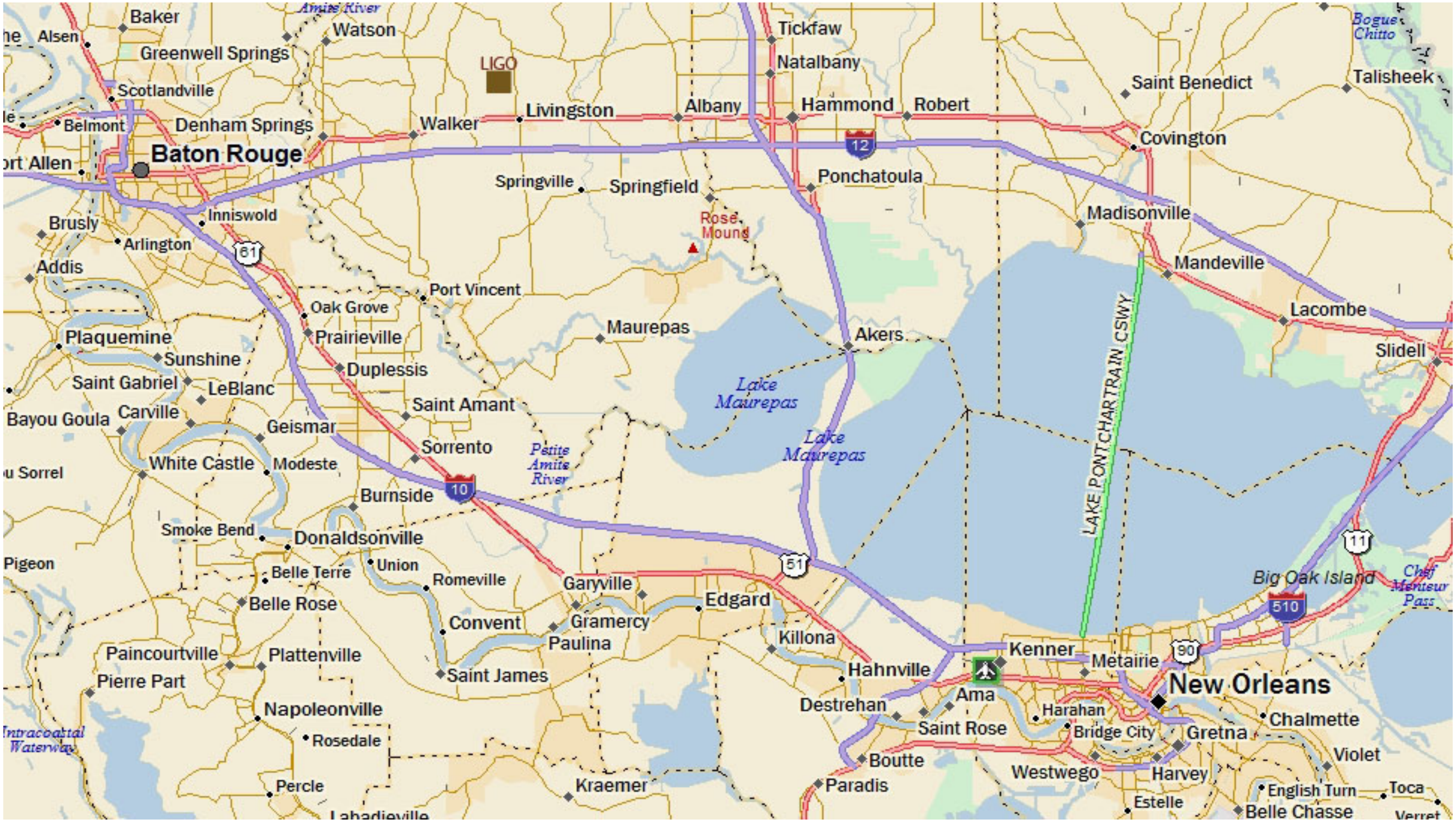
Rainer Weiss, MIT

on behalf of the LIGO/GEO/VIRGO Collaboration

IPAC 12

New Orleans

May 25,2012



Tour to LIGO Saturday May 26
Leave Morial Convention Ct 12:30PM return before7:00PM
Bus tickets available at the Conference Registration Desk

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravit[illegible]
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

Direct detection of gravitational waves from astrophysical sources

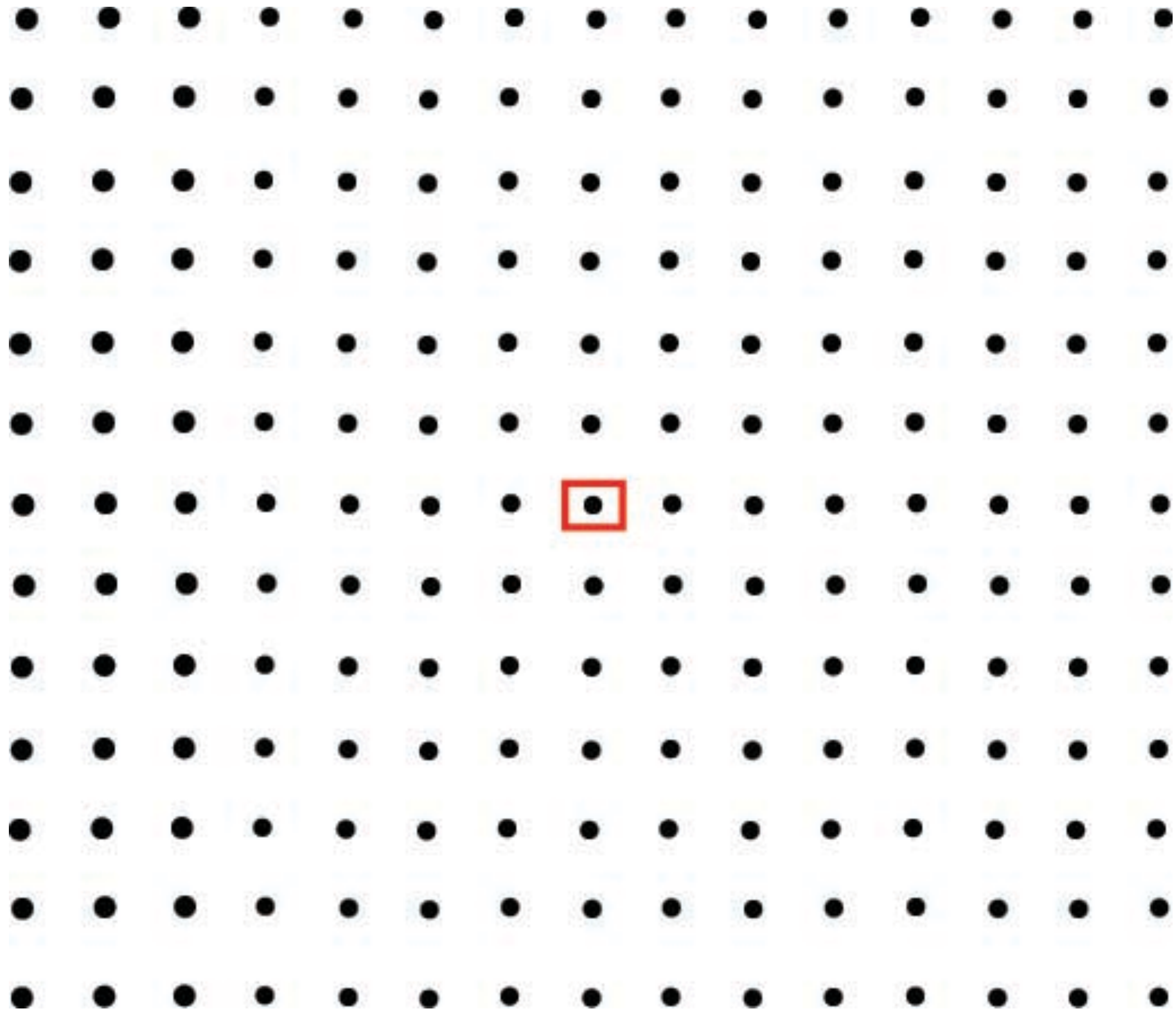
Physics

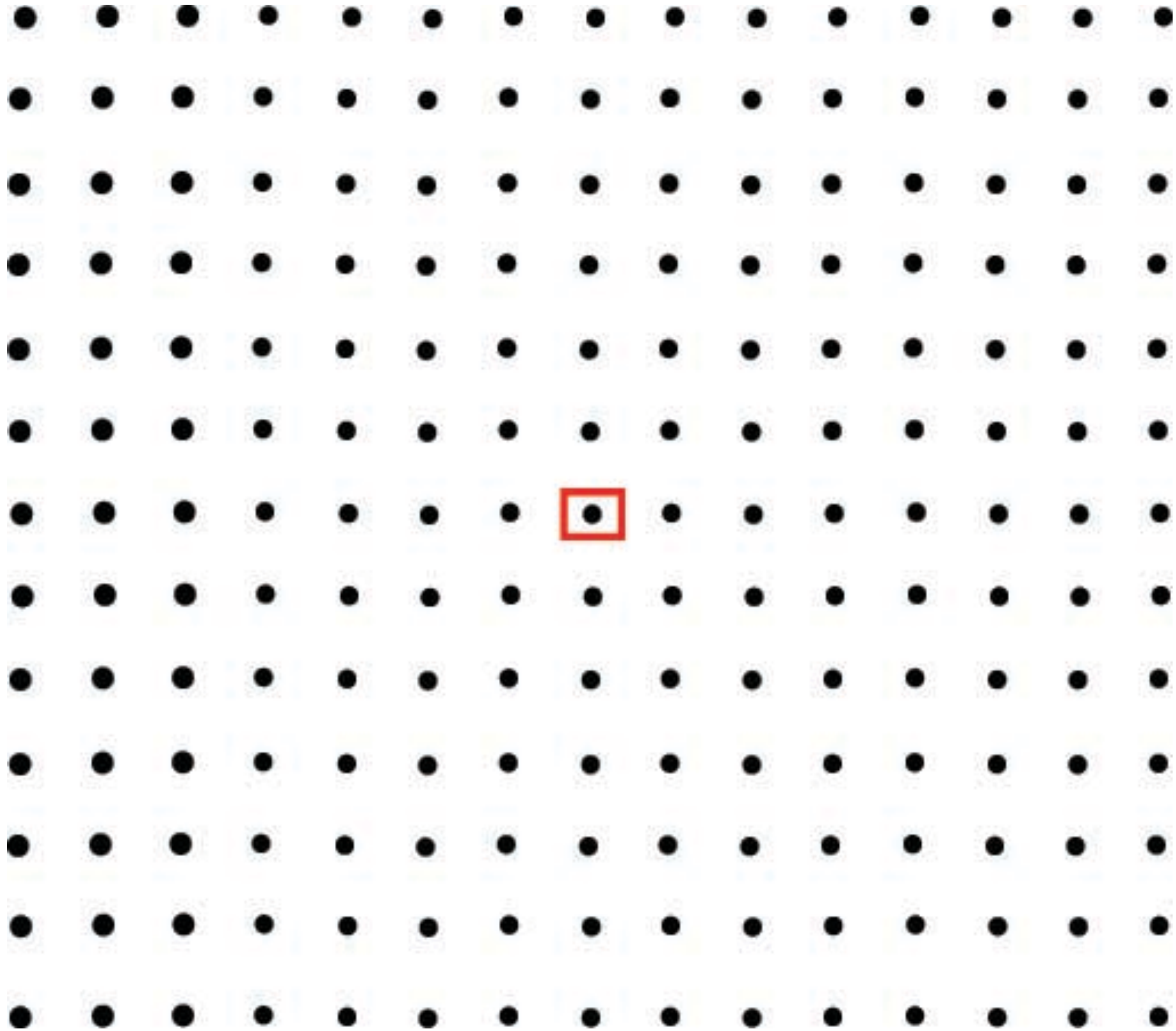
- » Observations of gravitation in the strong field, high velocity limit
- » Determination of wave kinematics – polarization and propagation
- » Tests for alternative relativistic gravitational theories

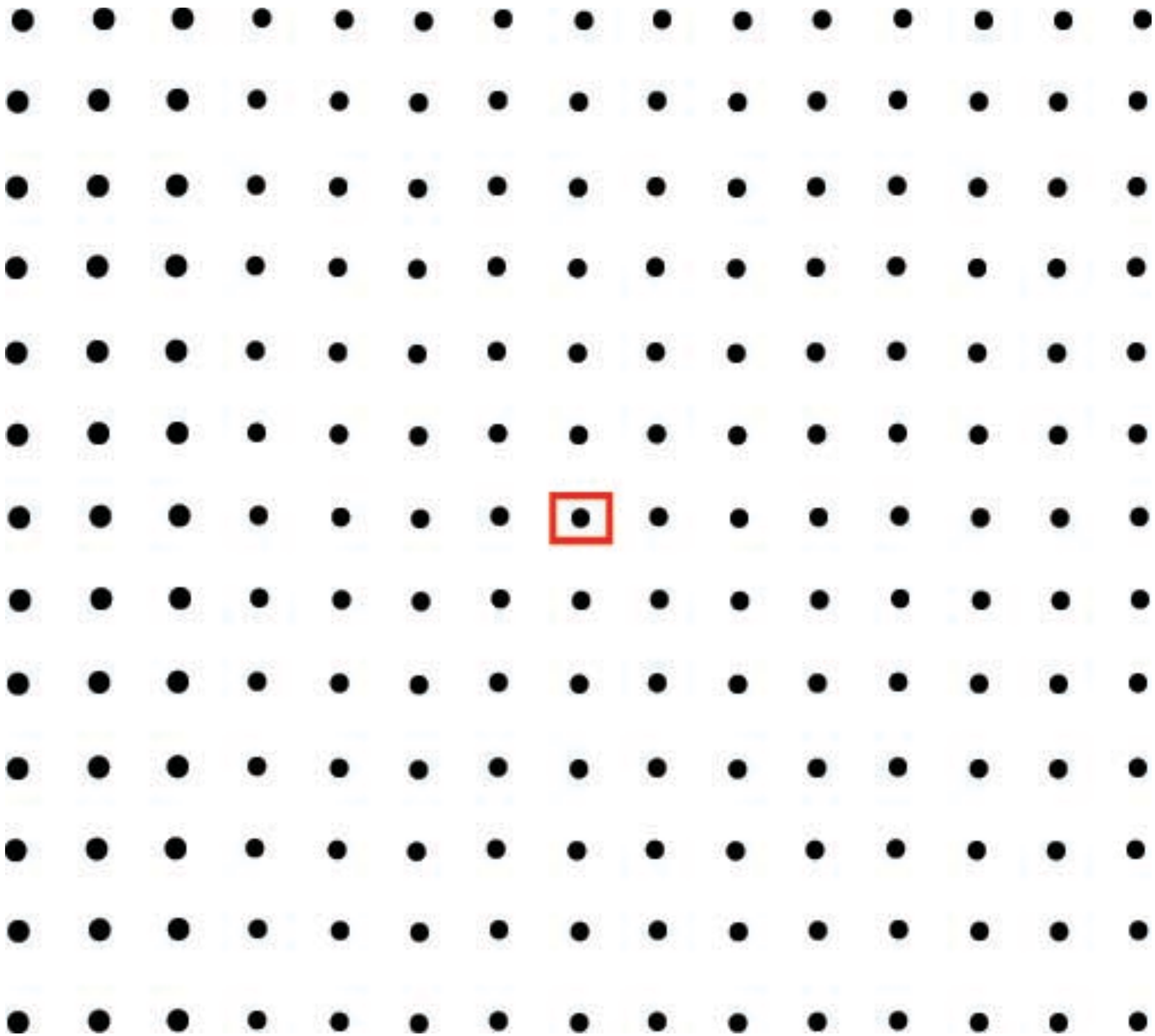
Astrophysics

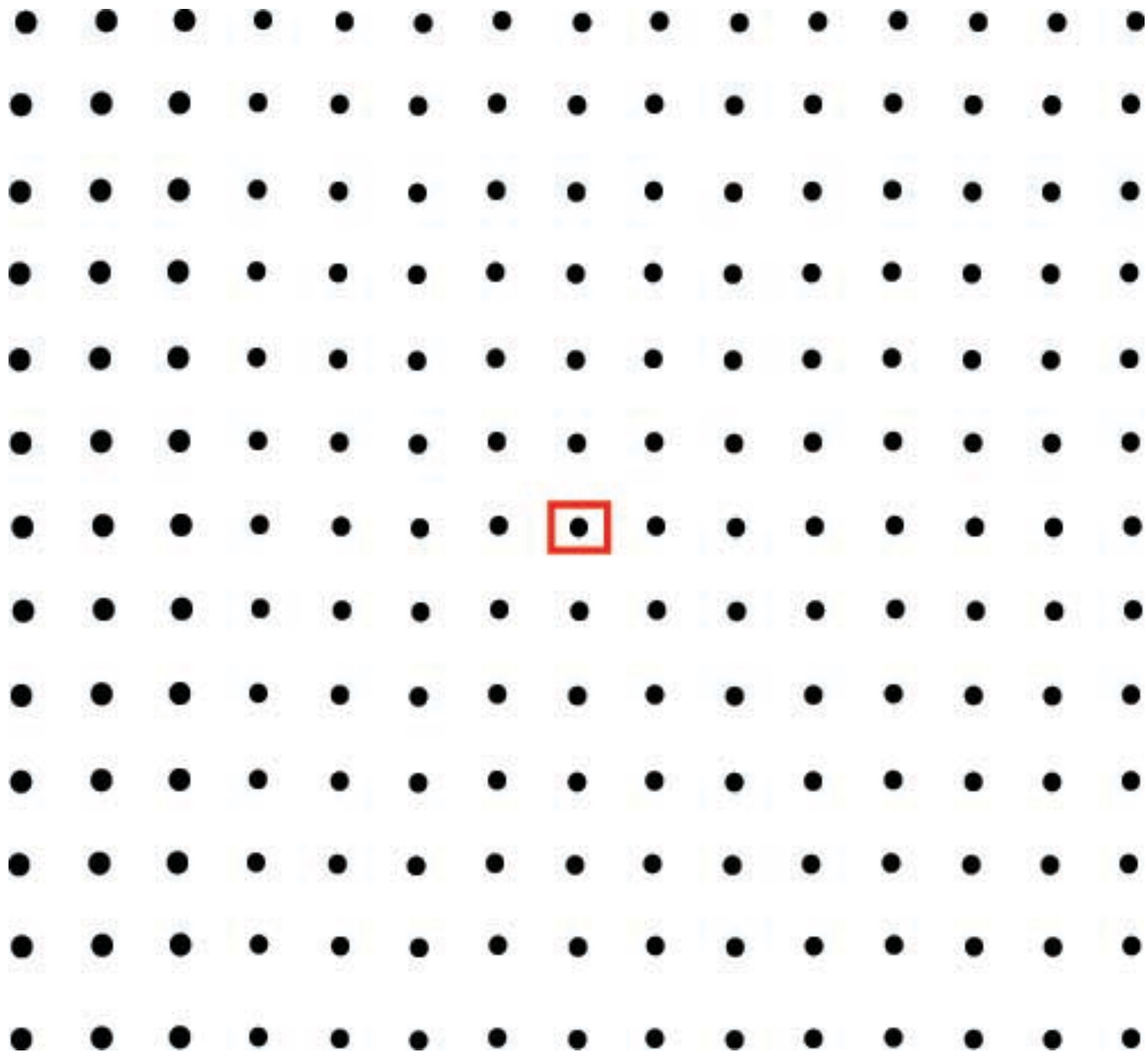
- » Measurement of coherent inner dynamics – stellar collapse, pulsar formation….
- » Compact binary coalescence – neutron star/neutron star, black hole/black hole
- » Neutron star equation of state
- » Primeval cosmic spectrum of gravitational waves

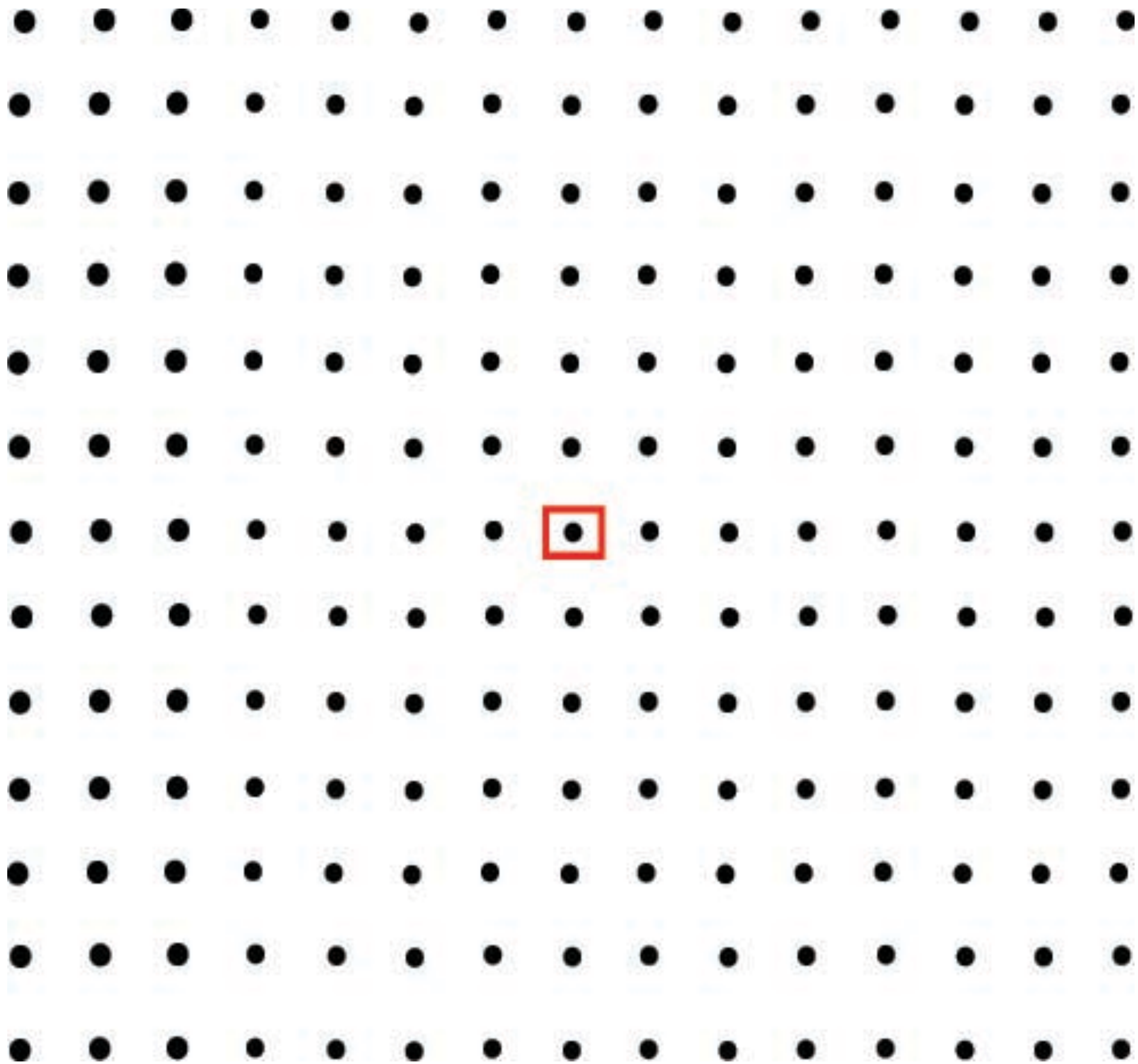
Gravitational wave survey of the universe

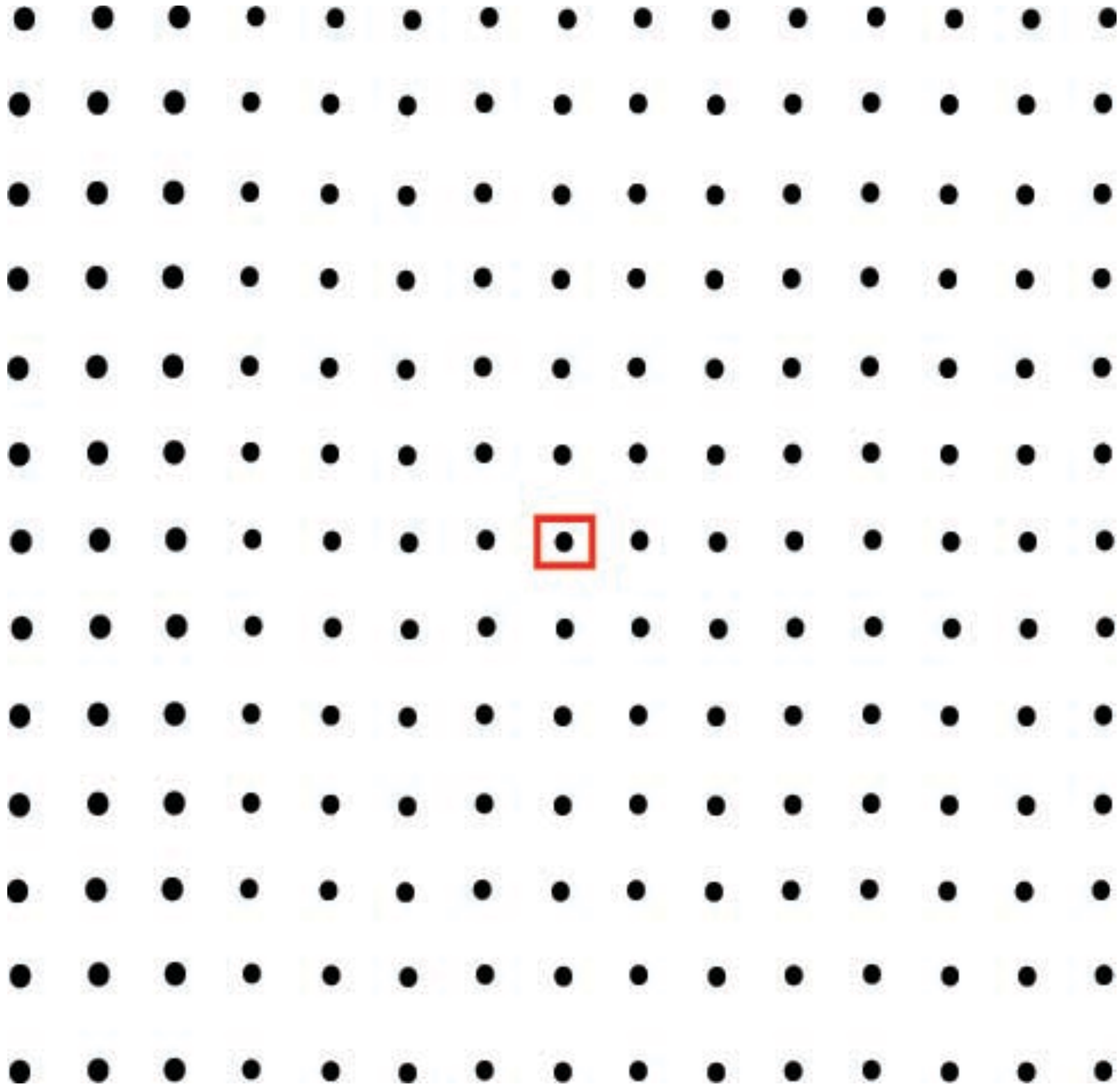


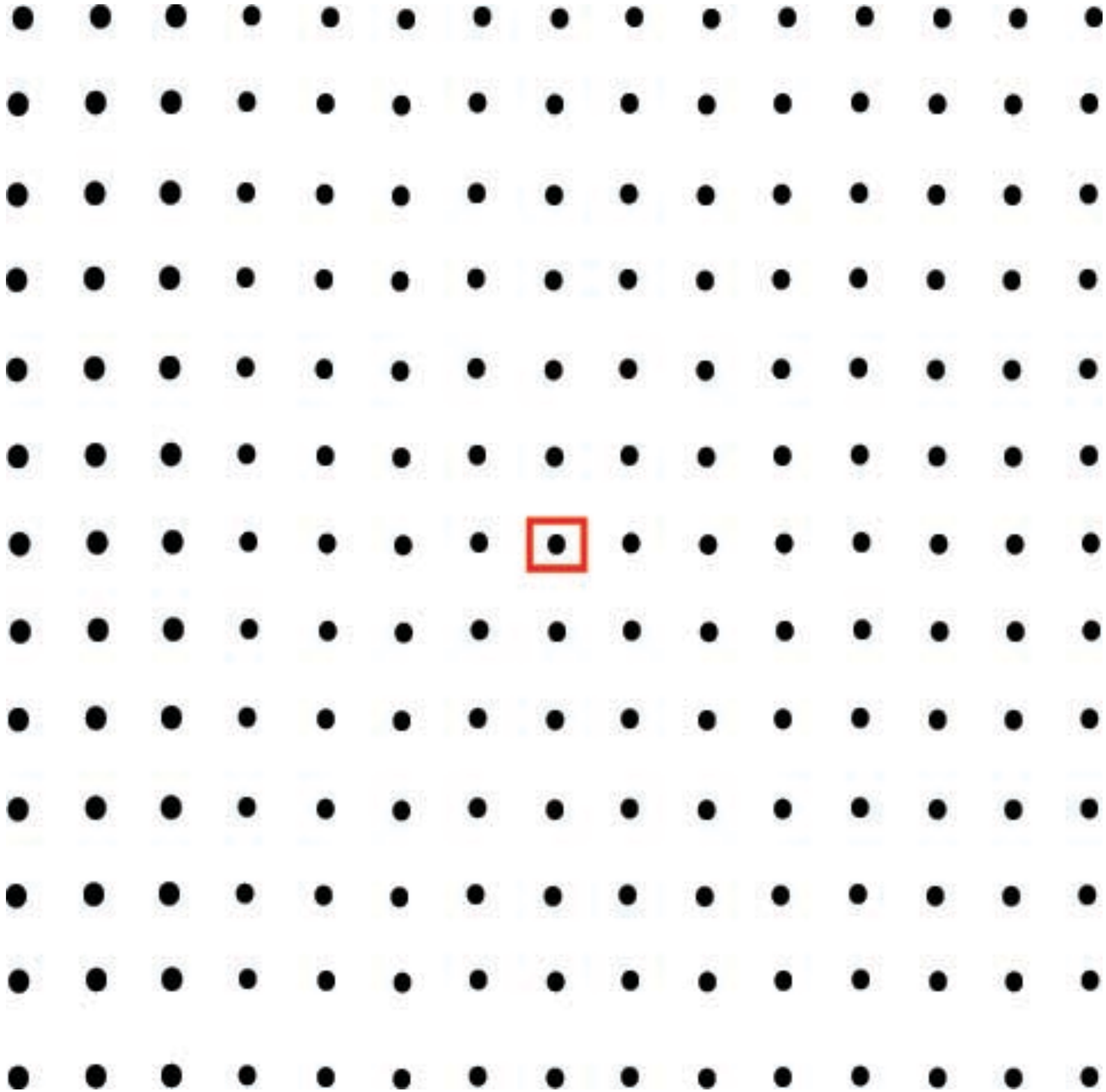


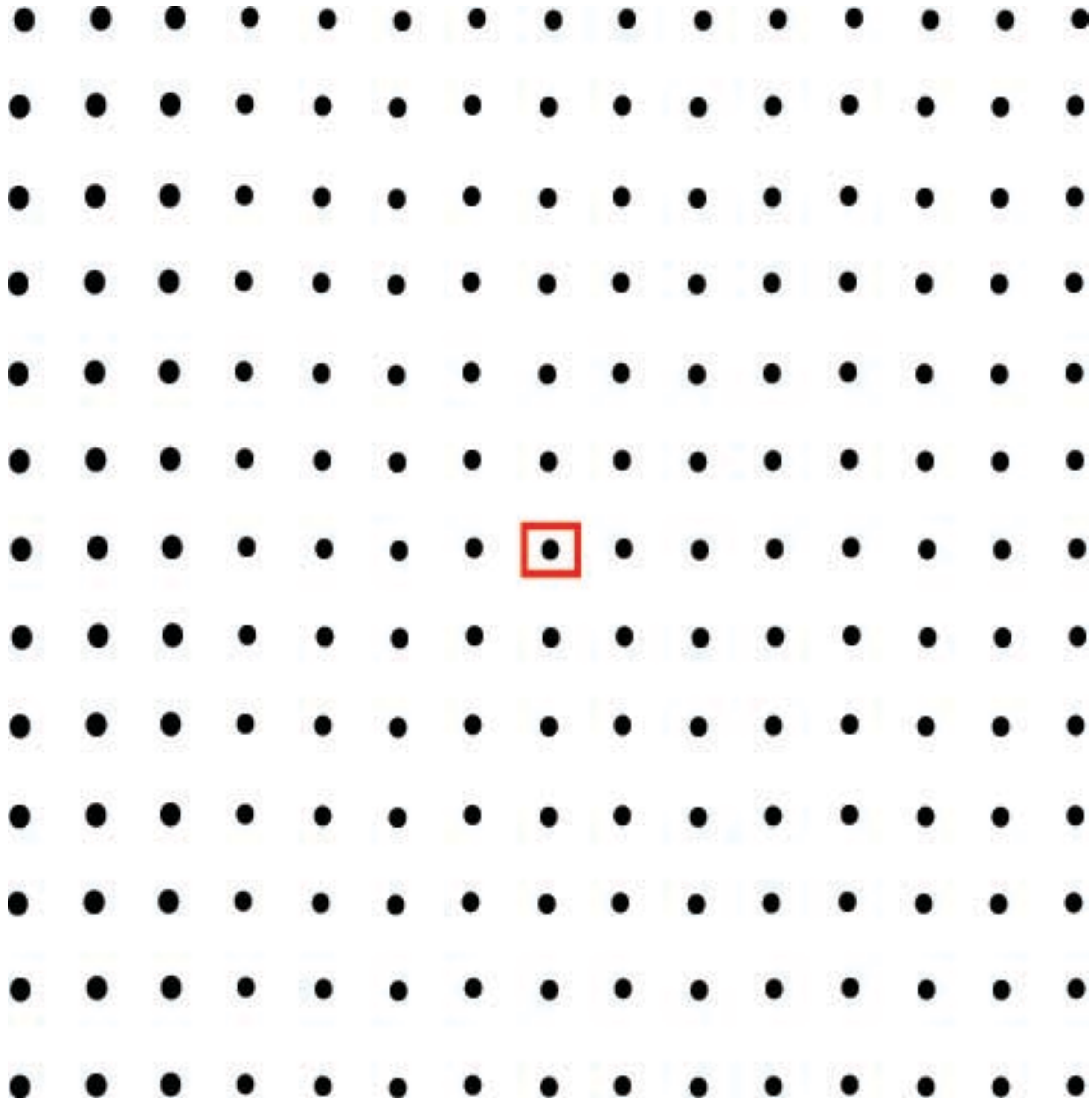


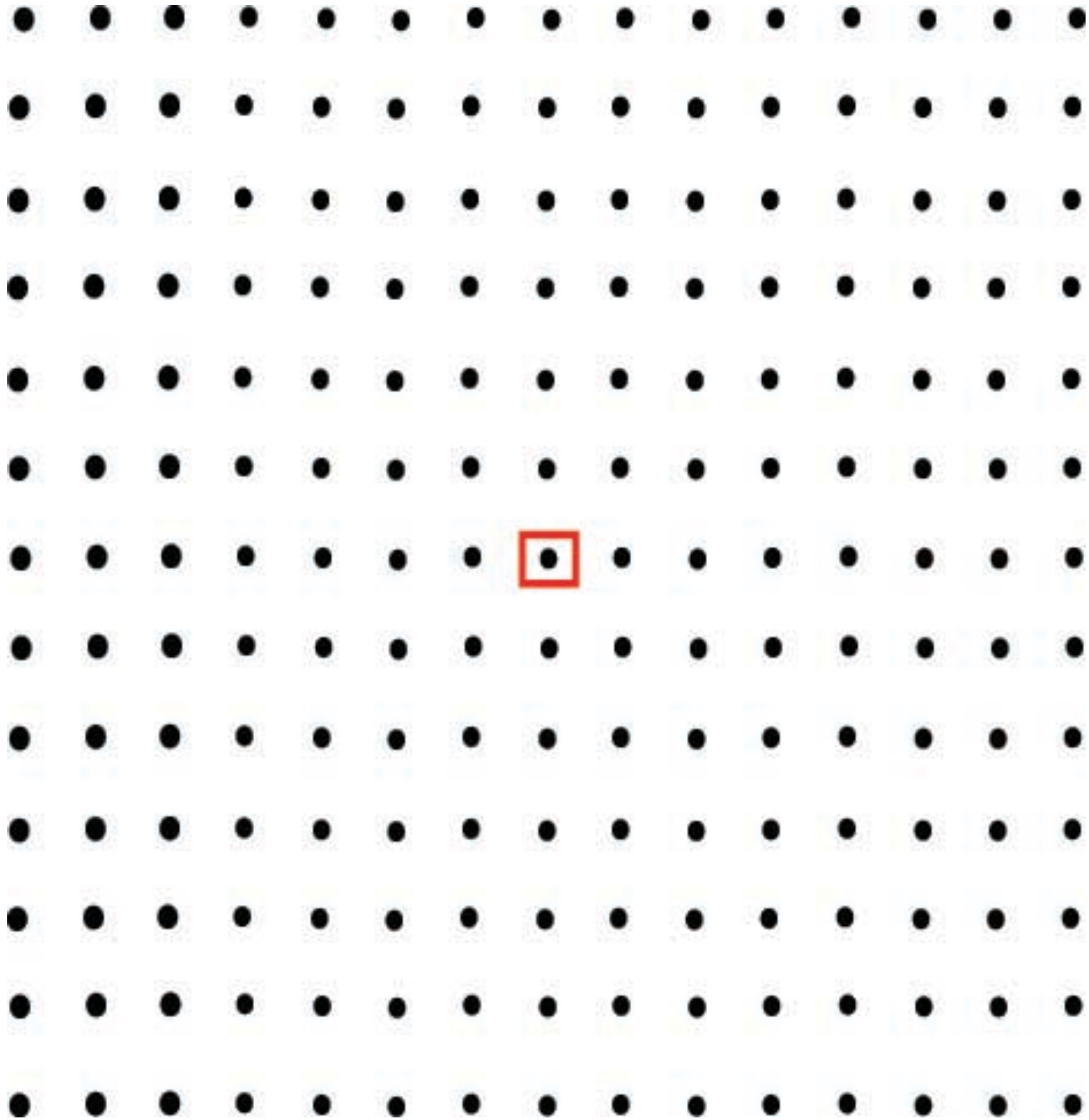


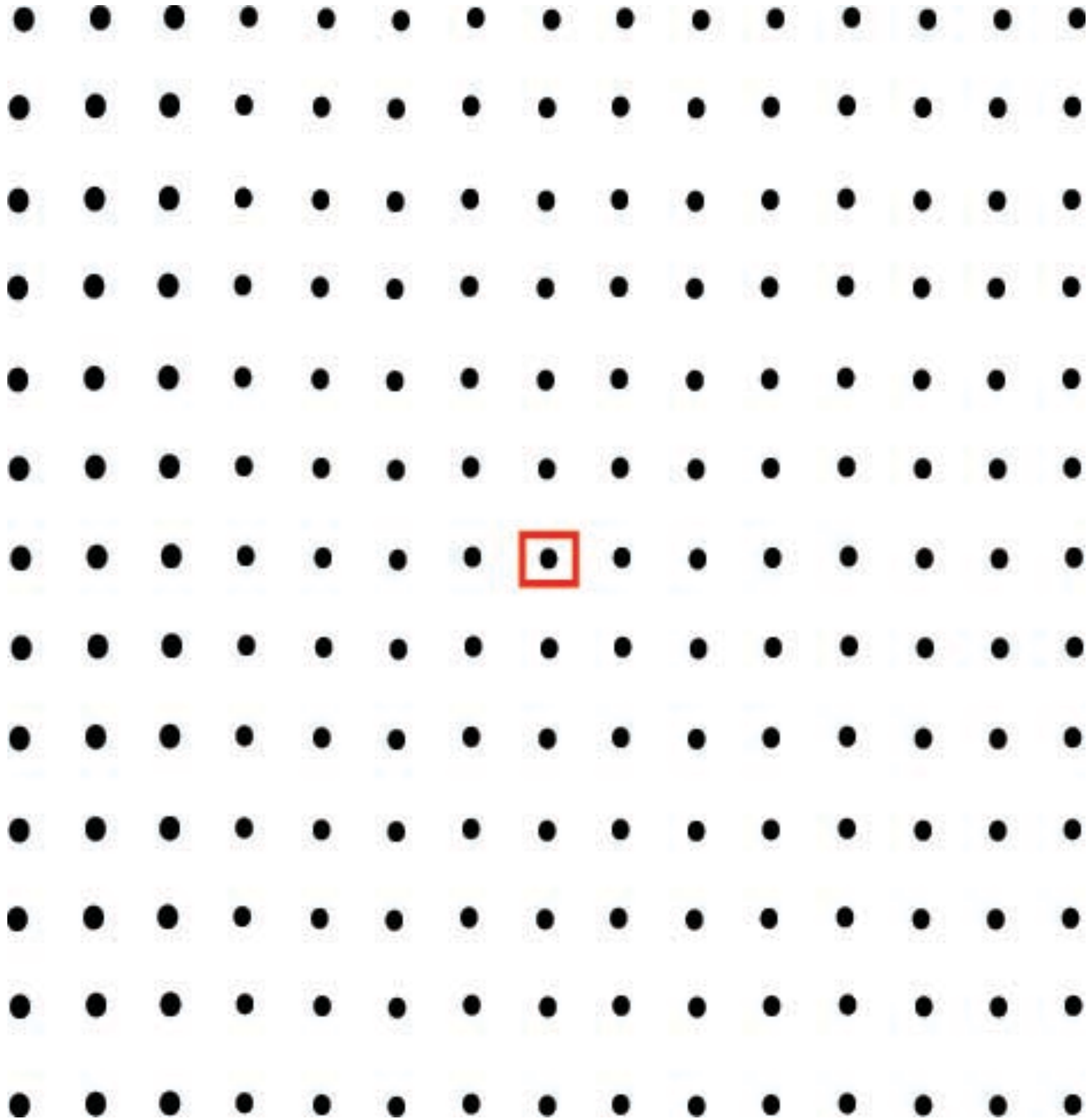


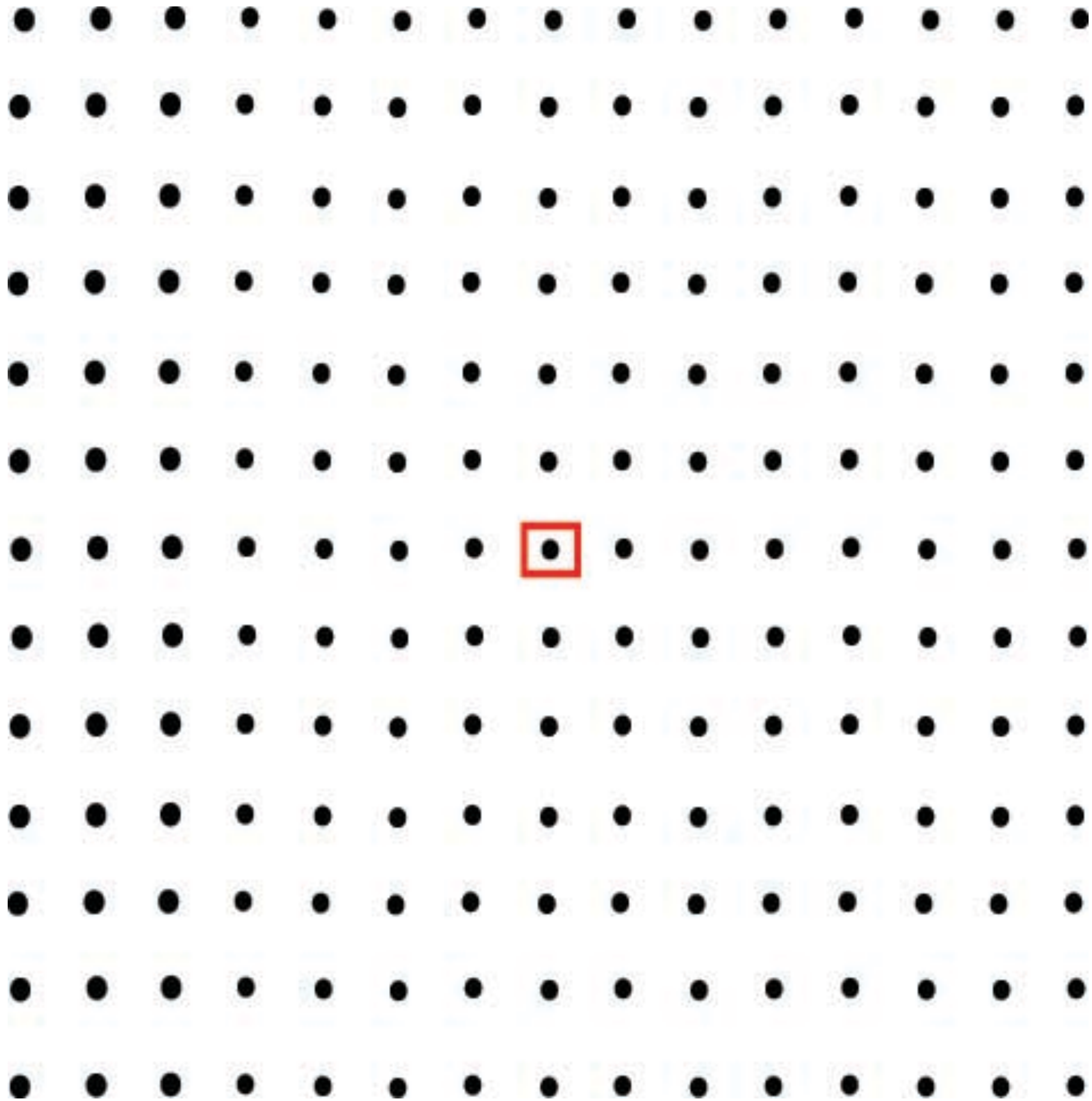


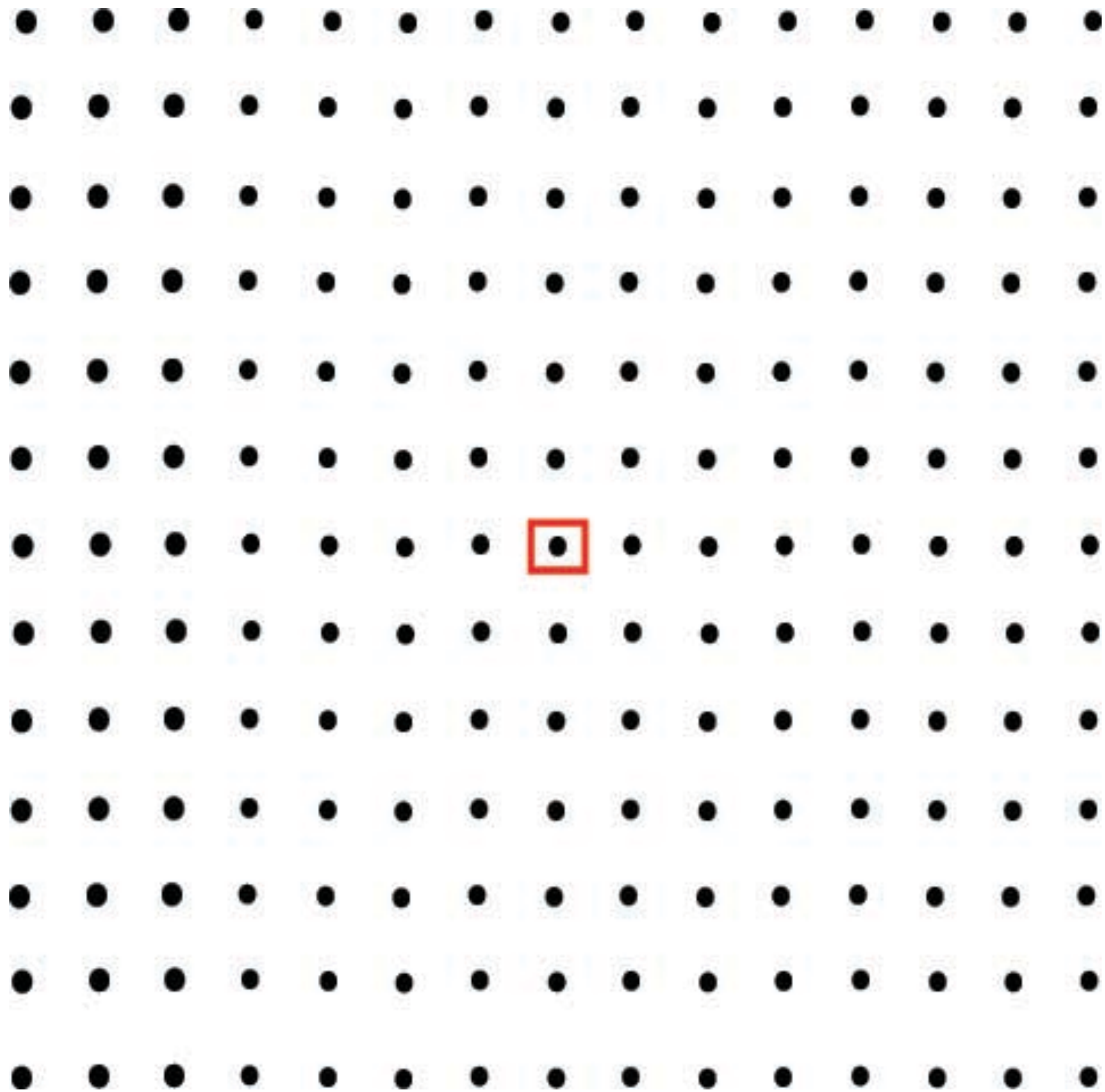


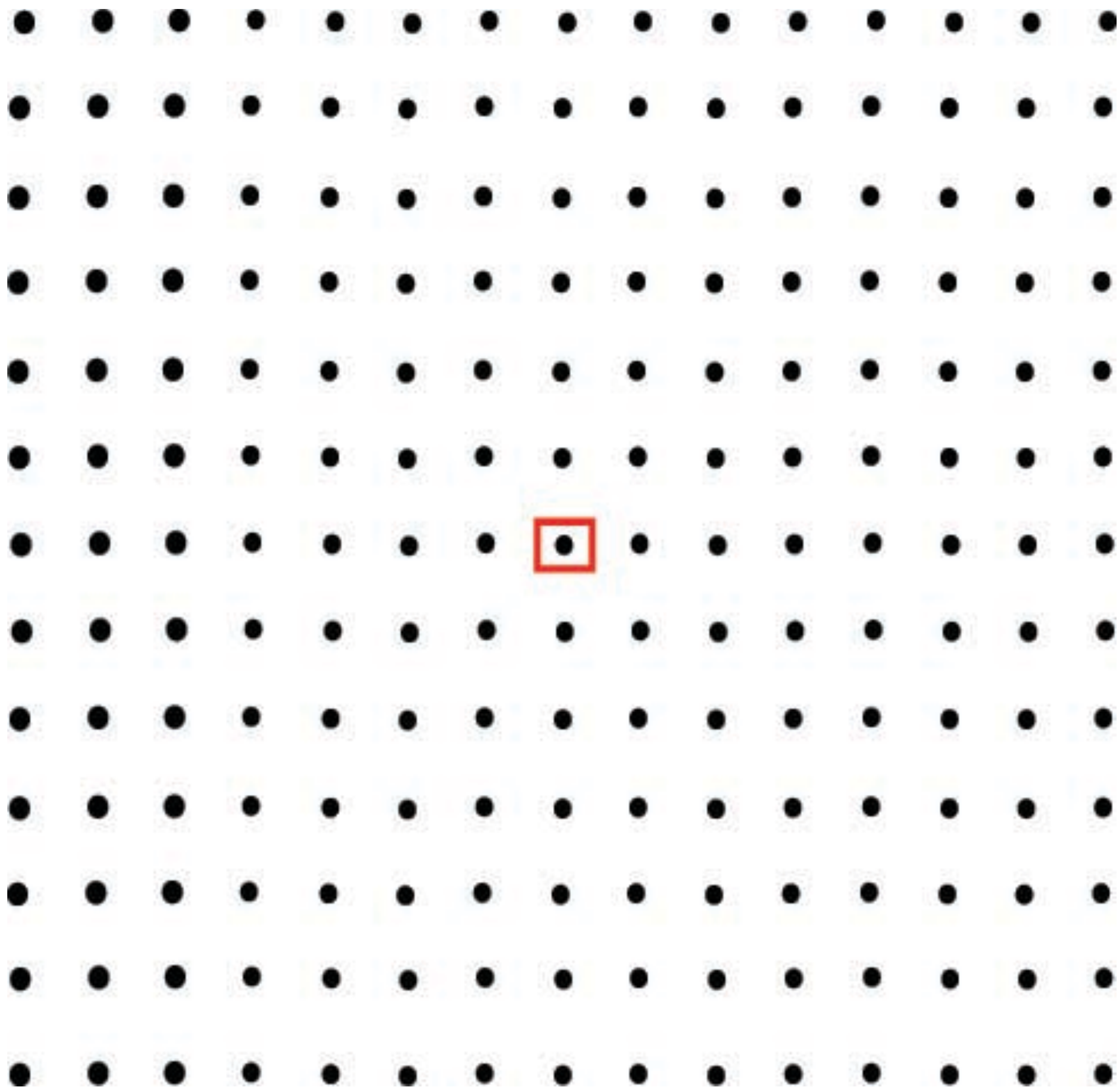


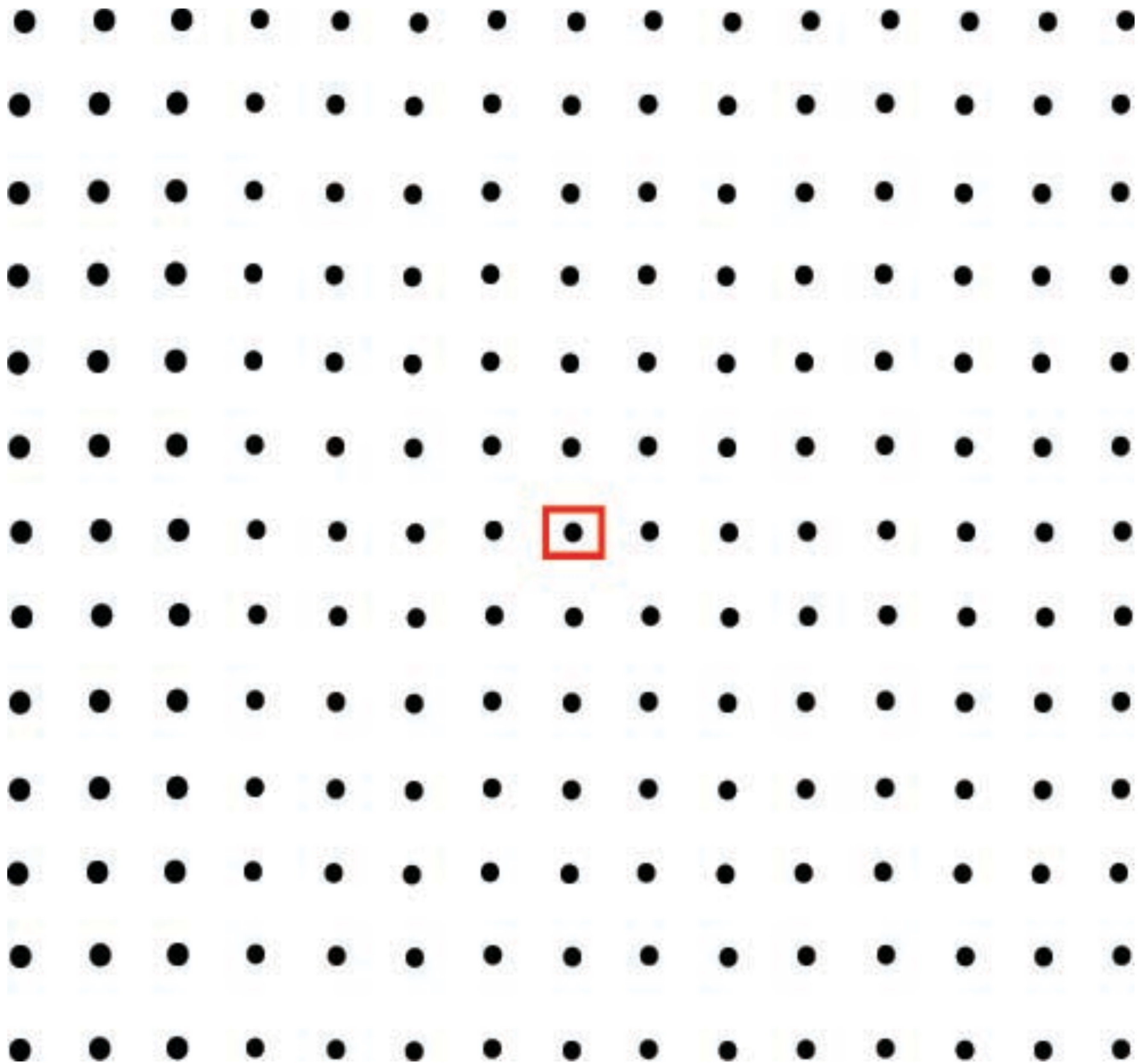


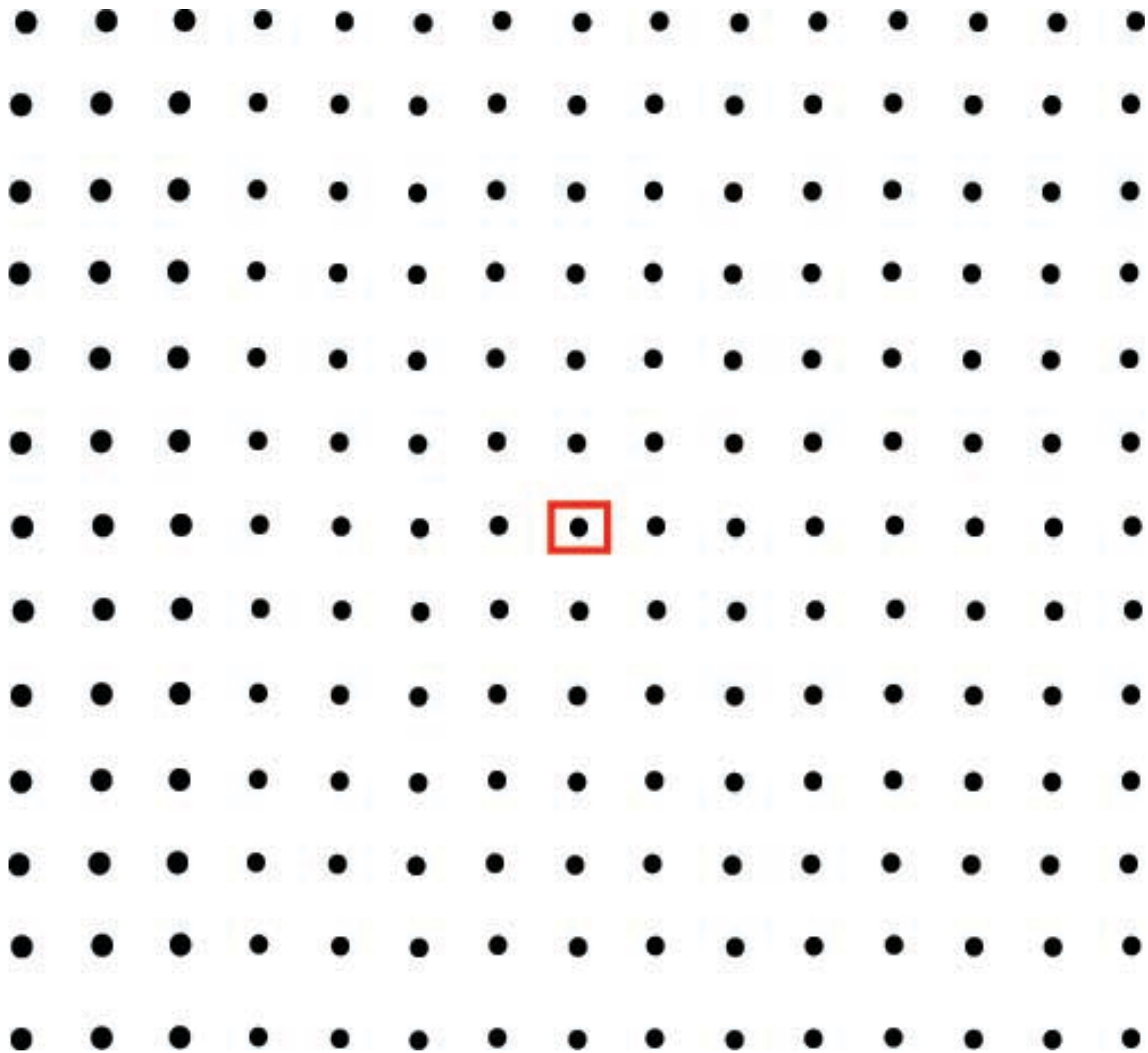


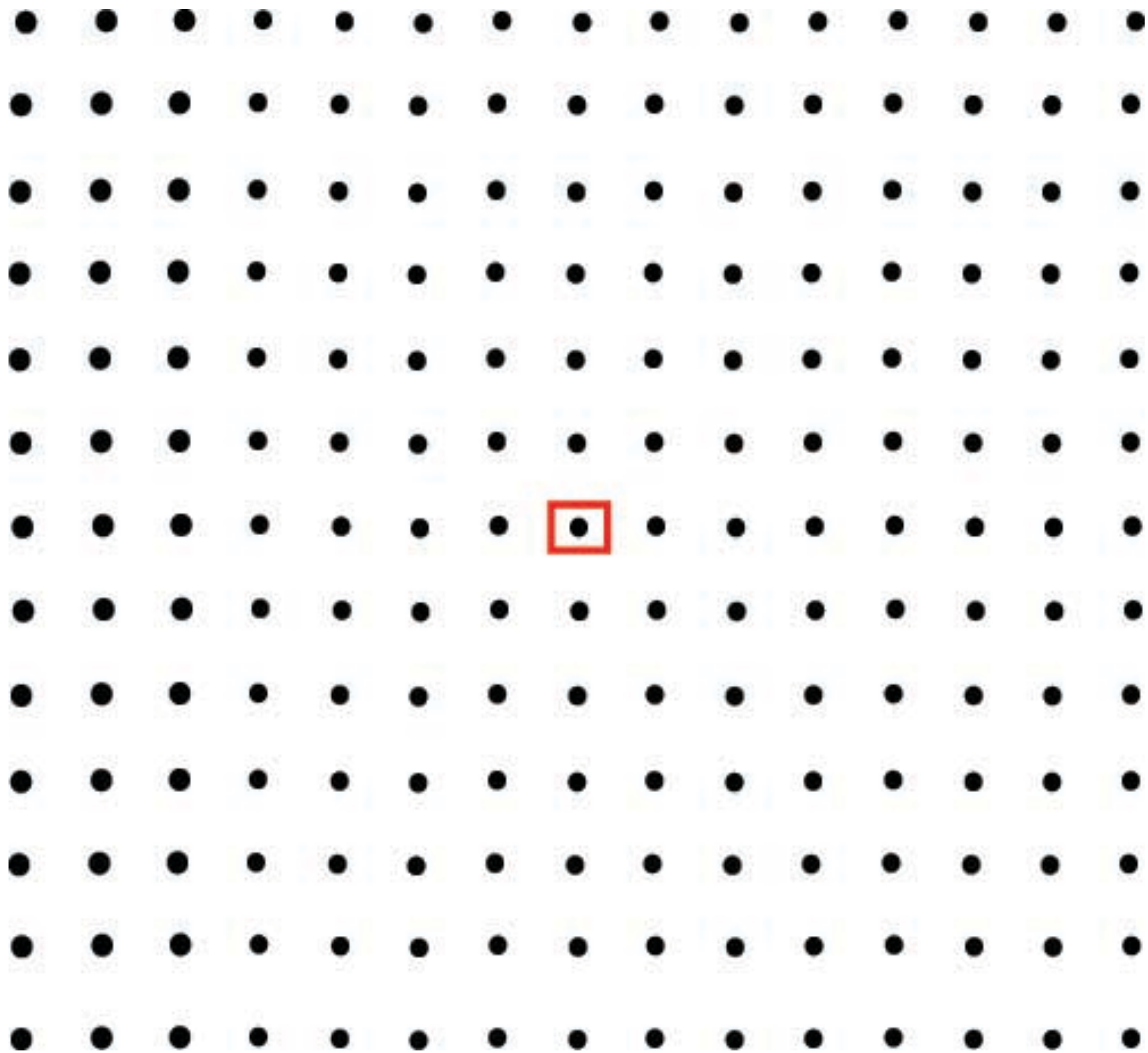


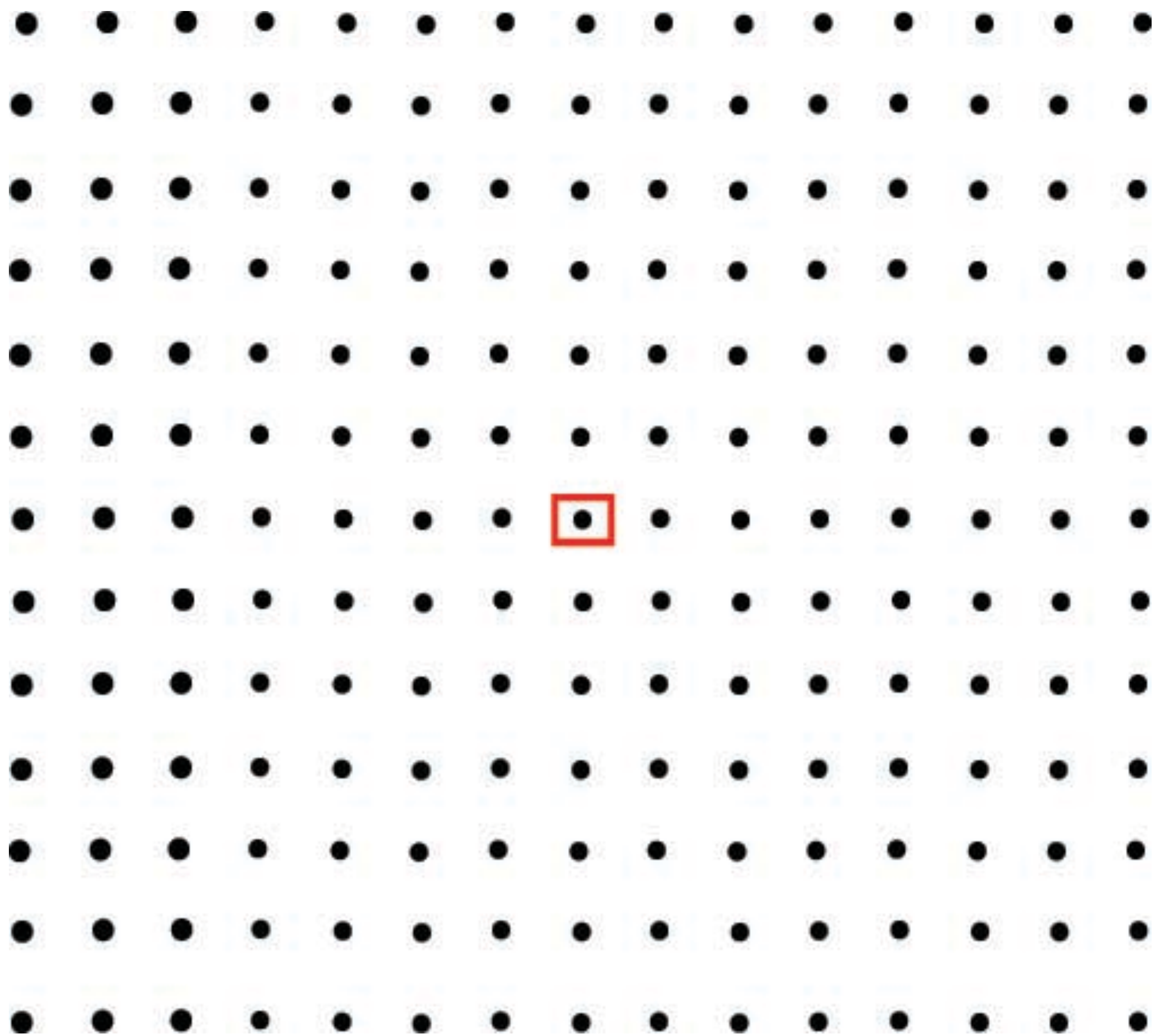


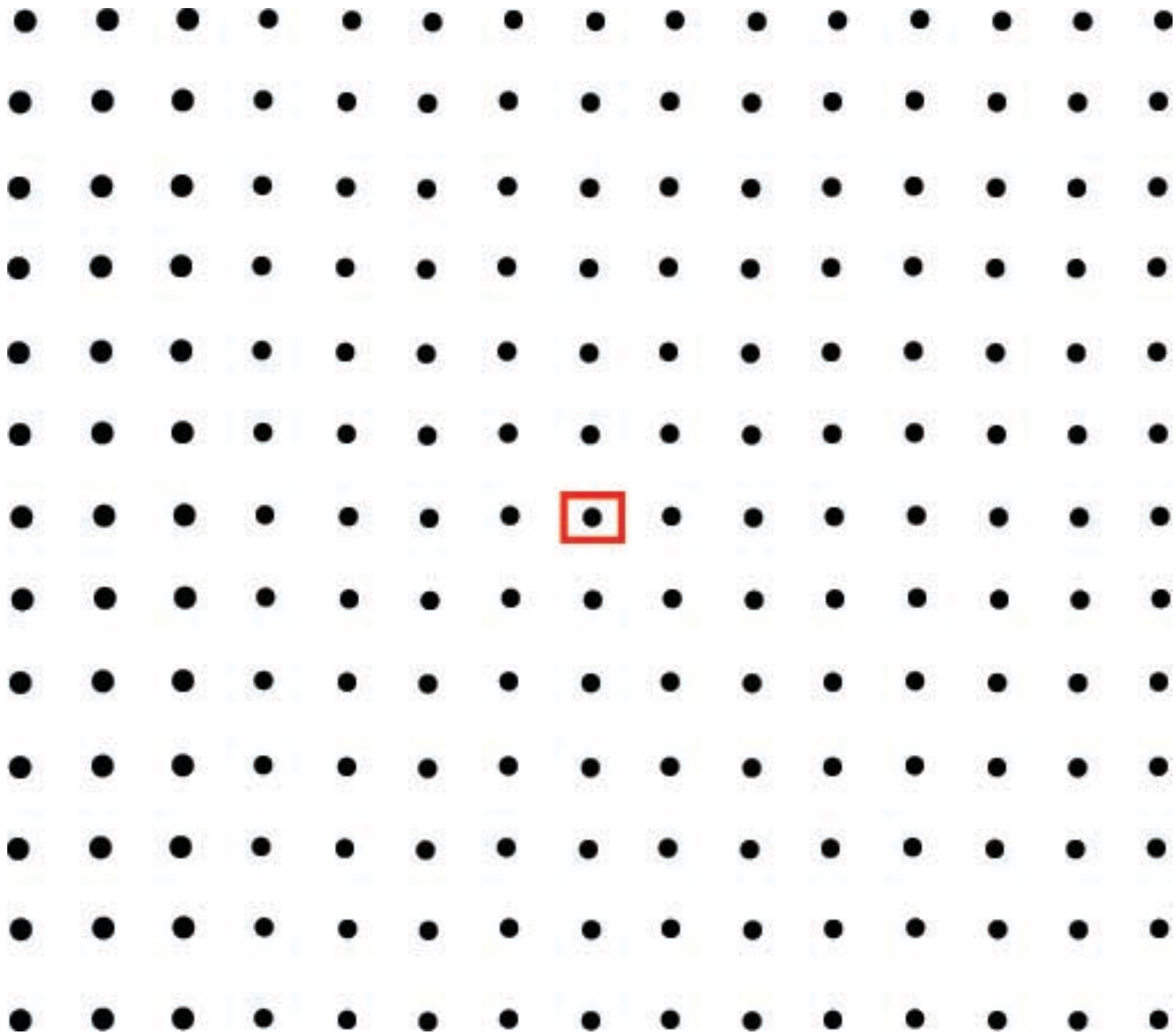


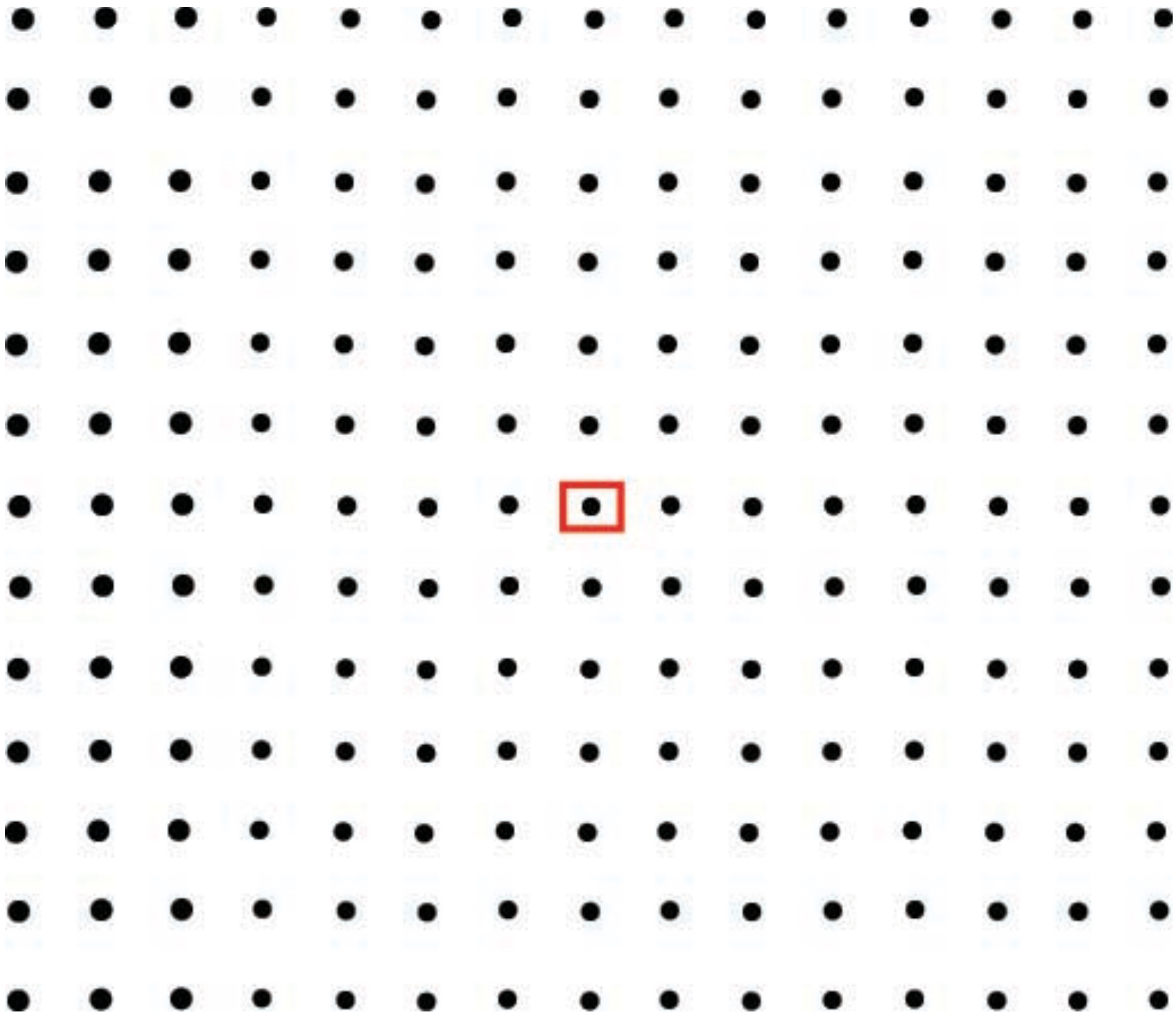


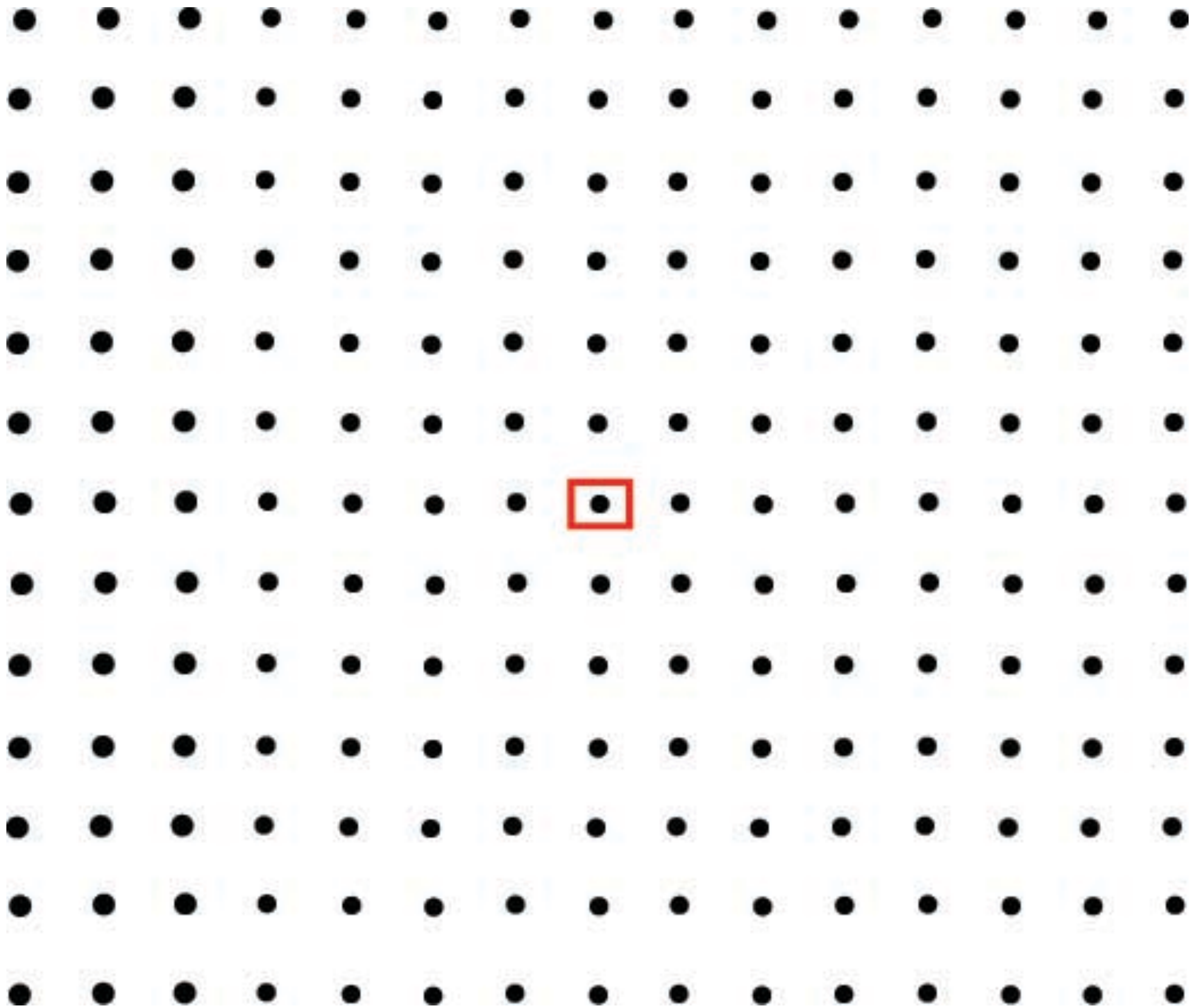


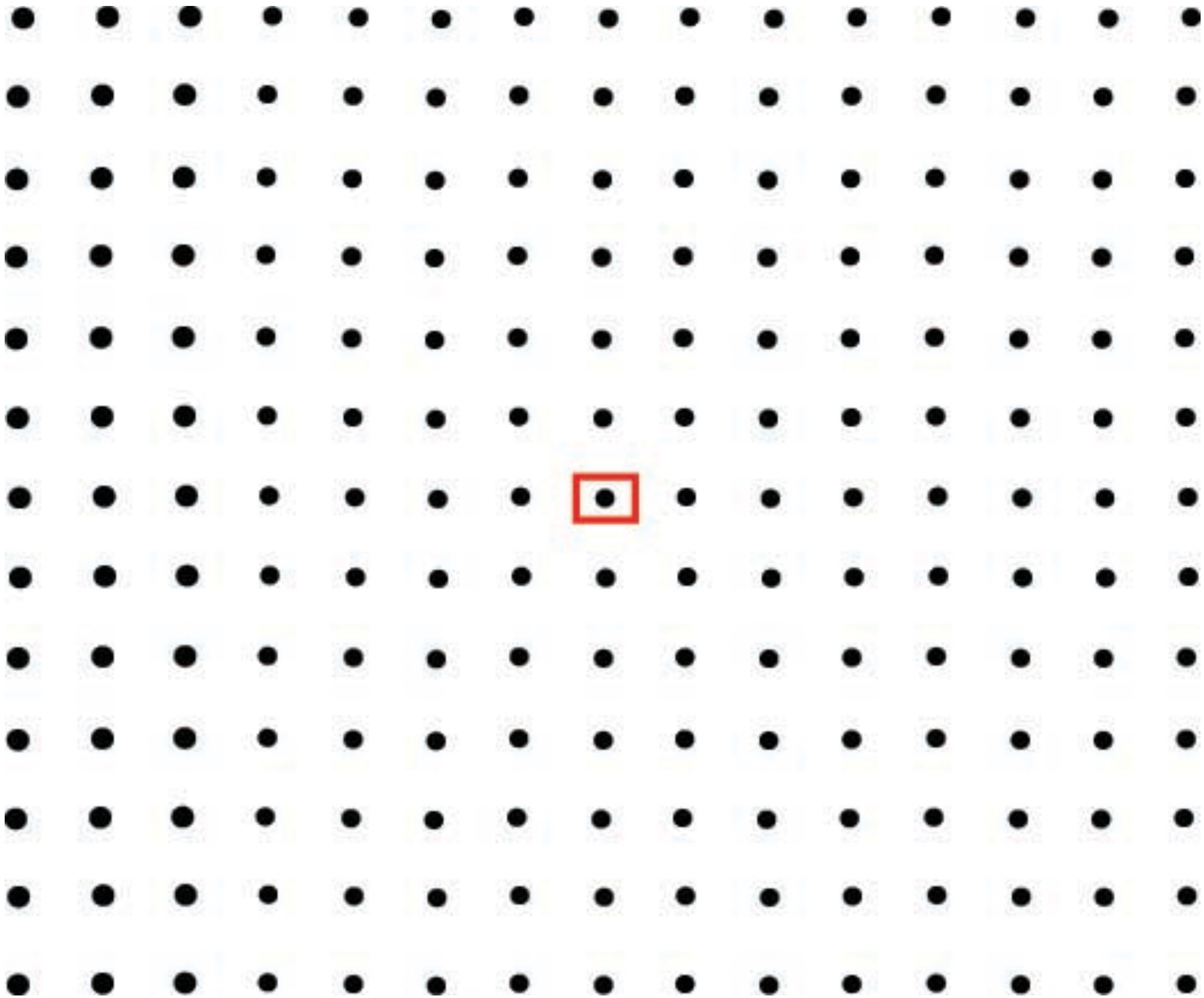


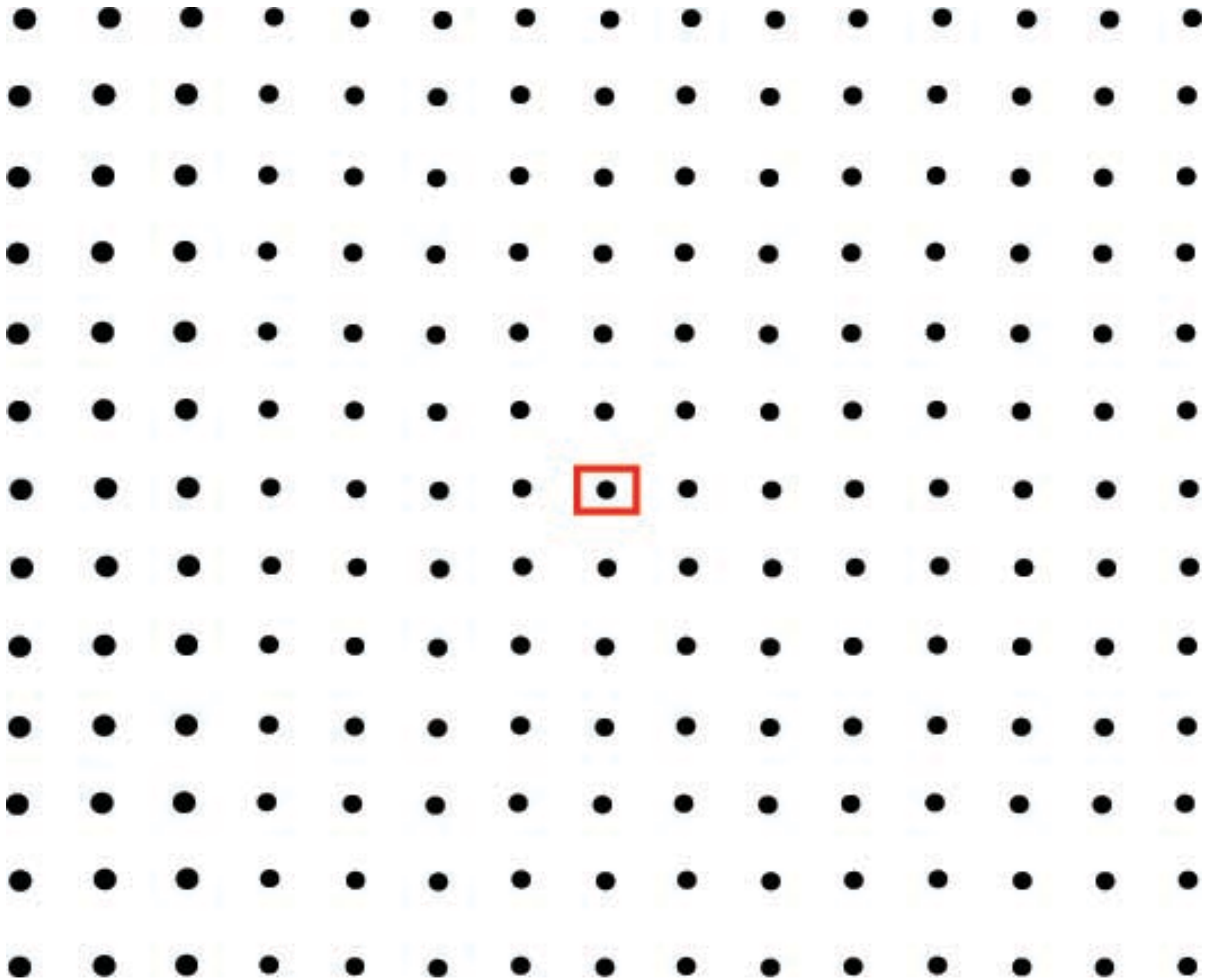


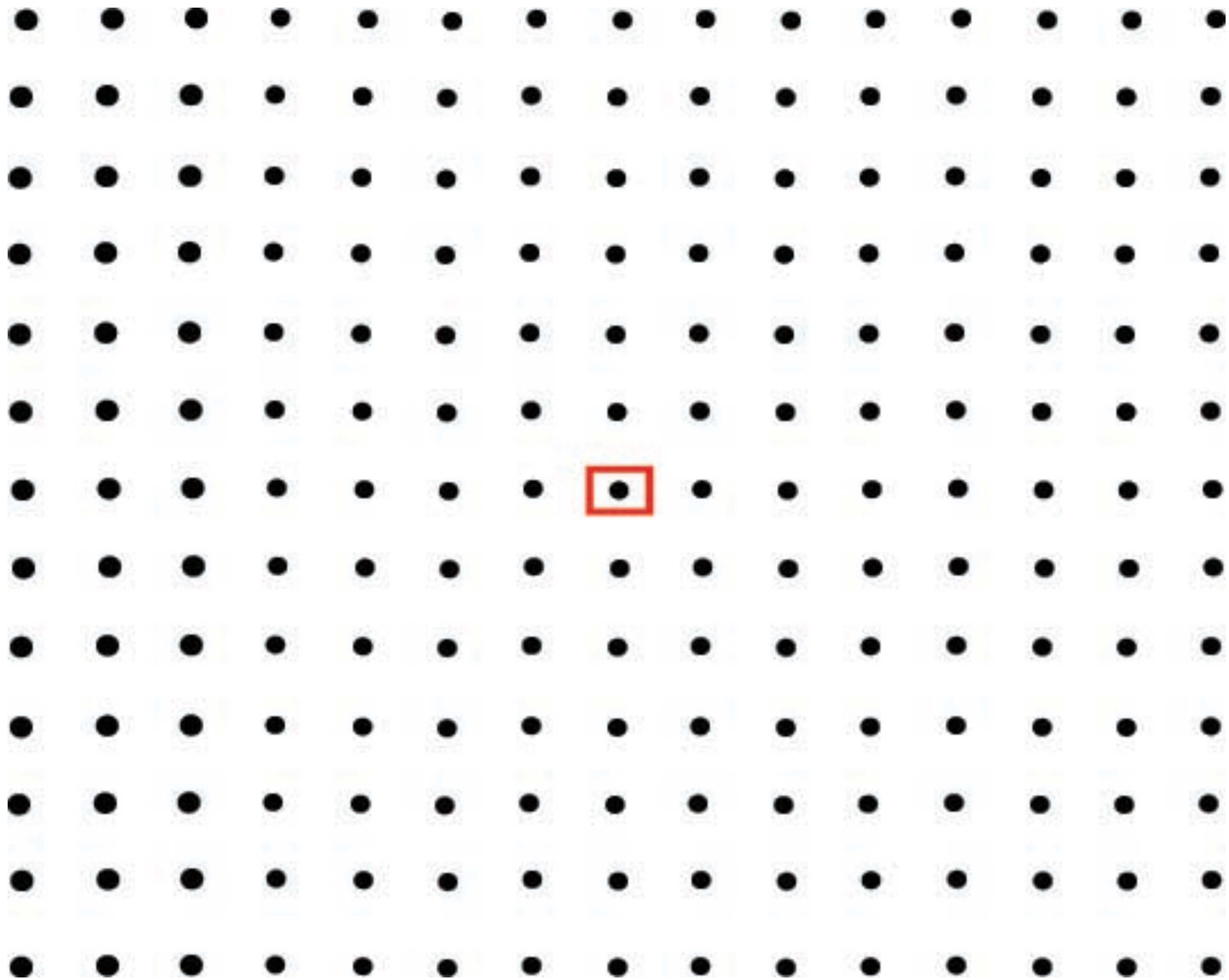


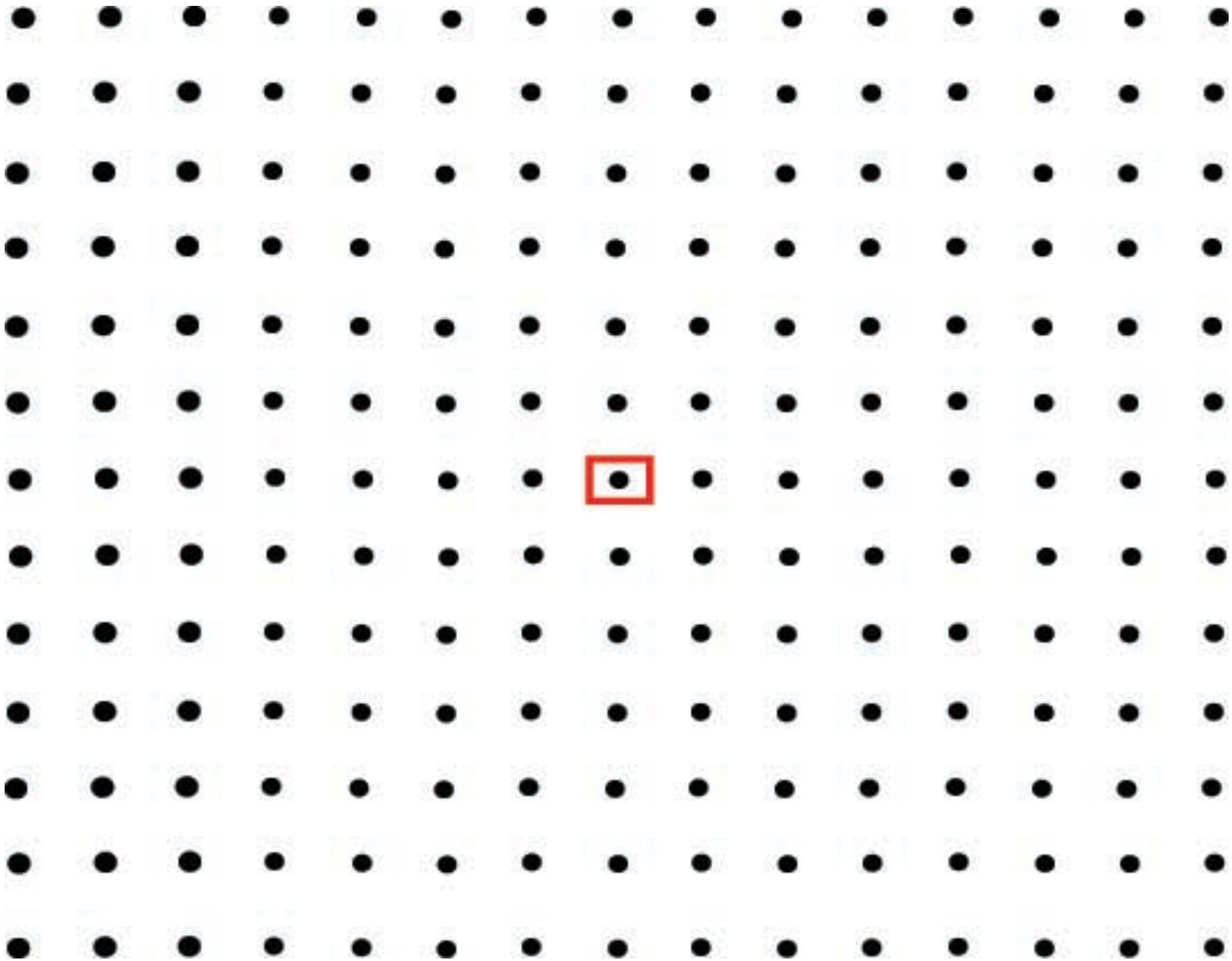


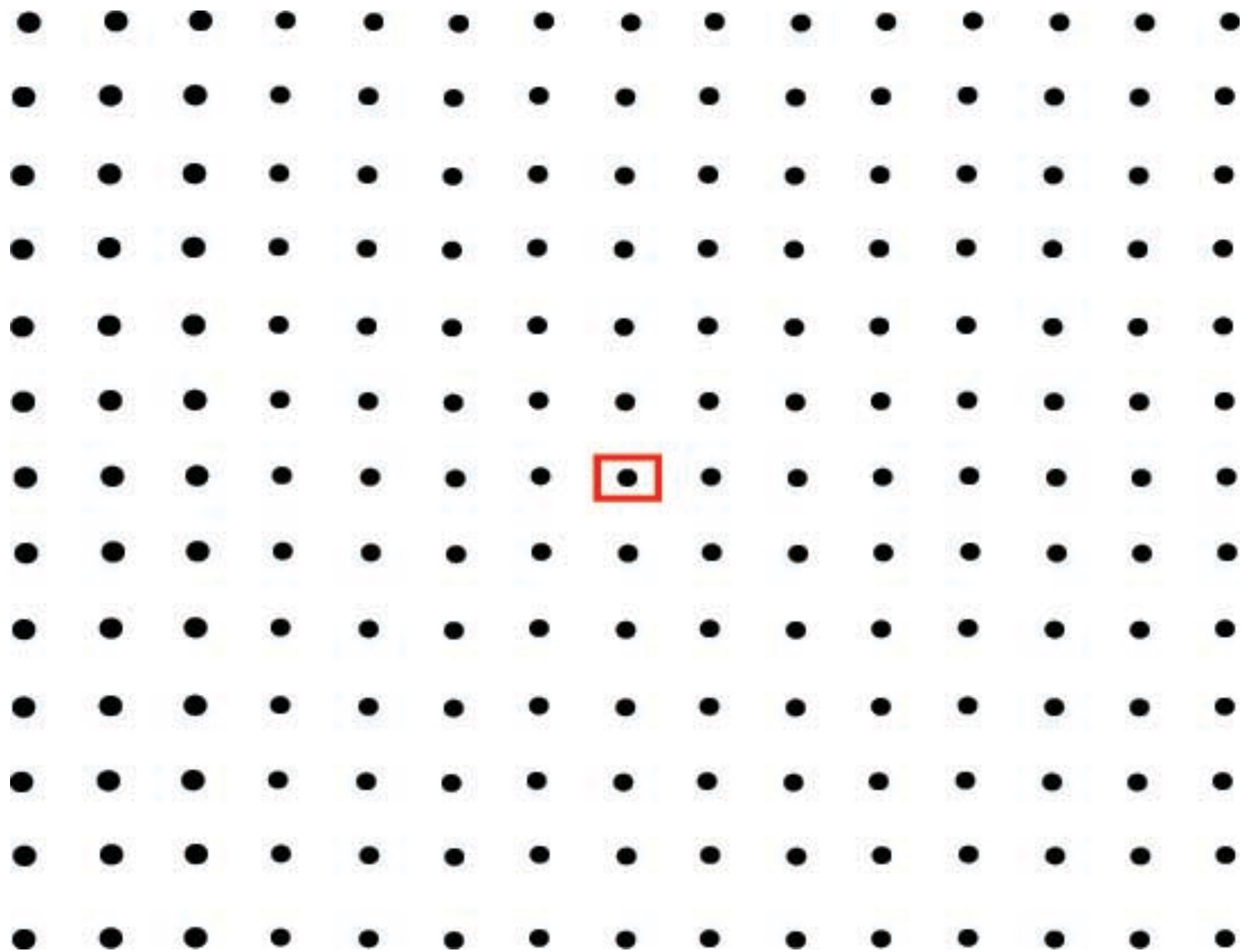


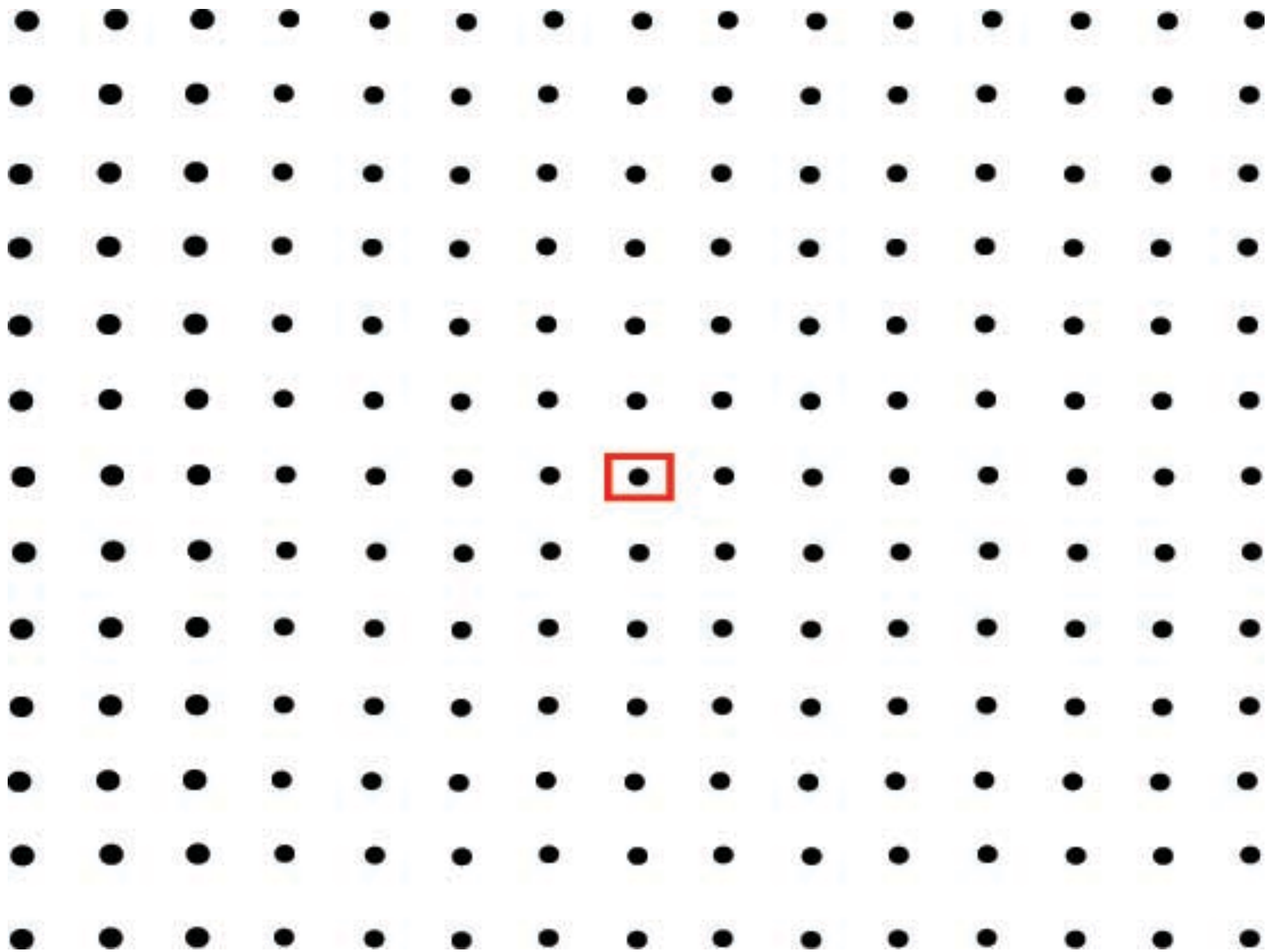


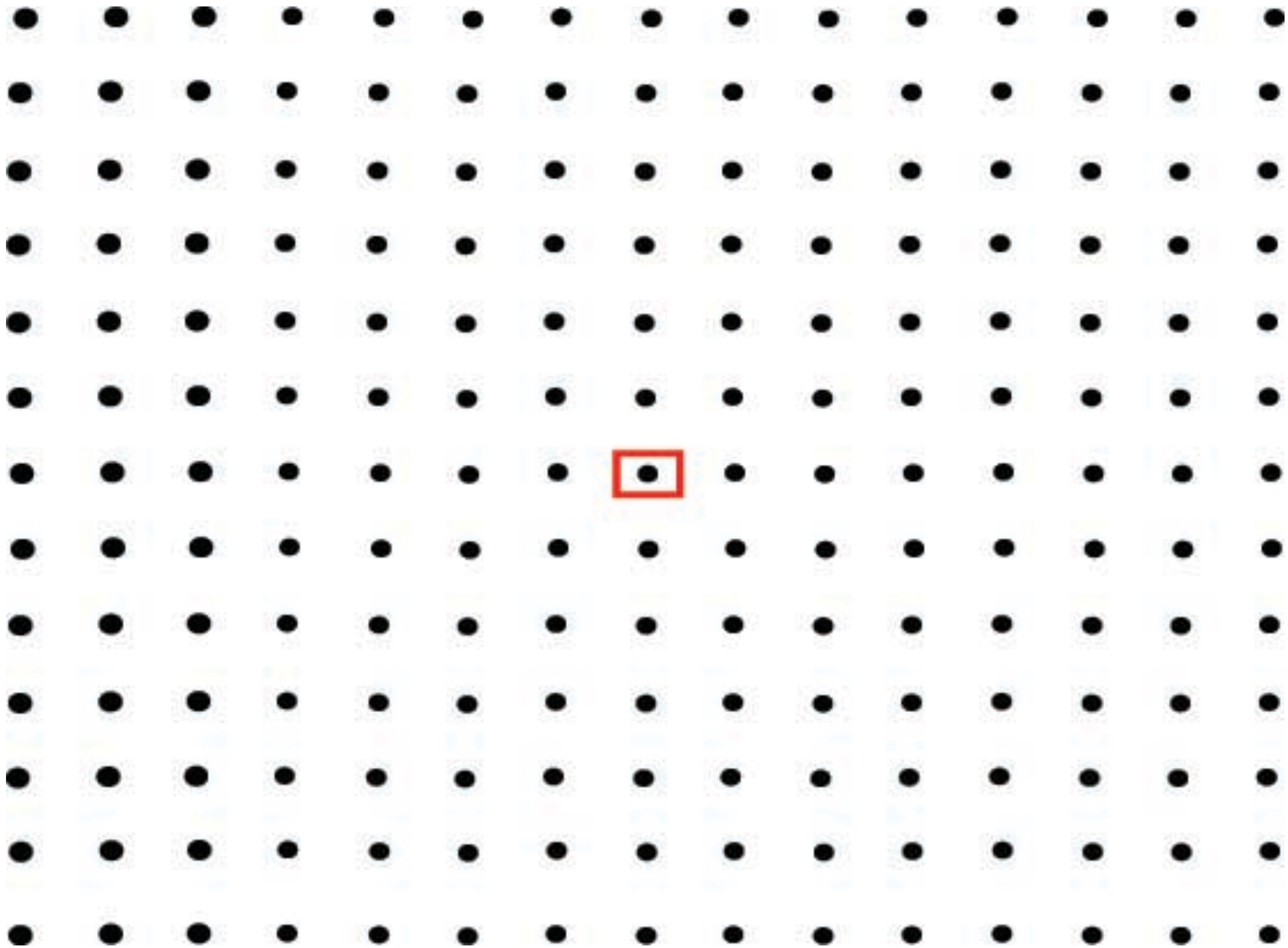


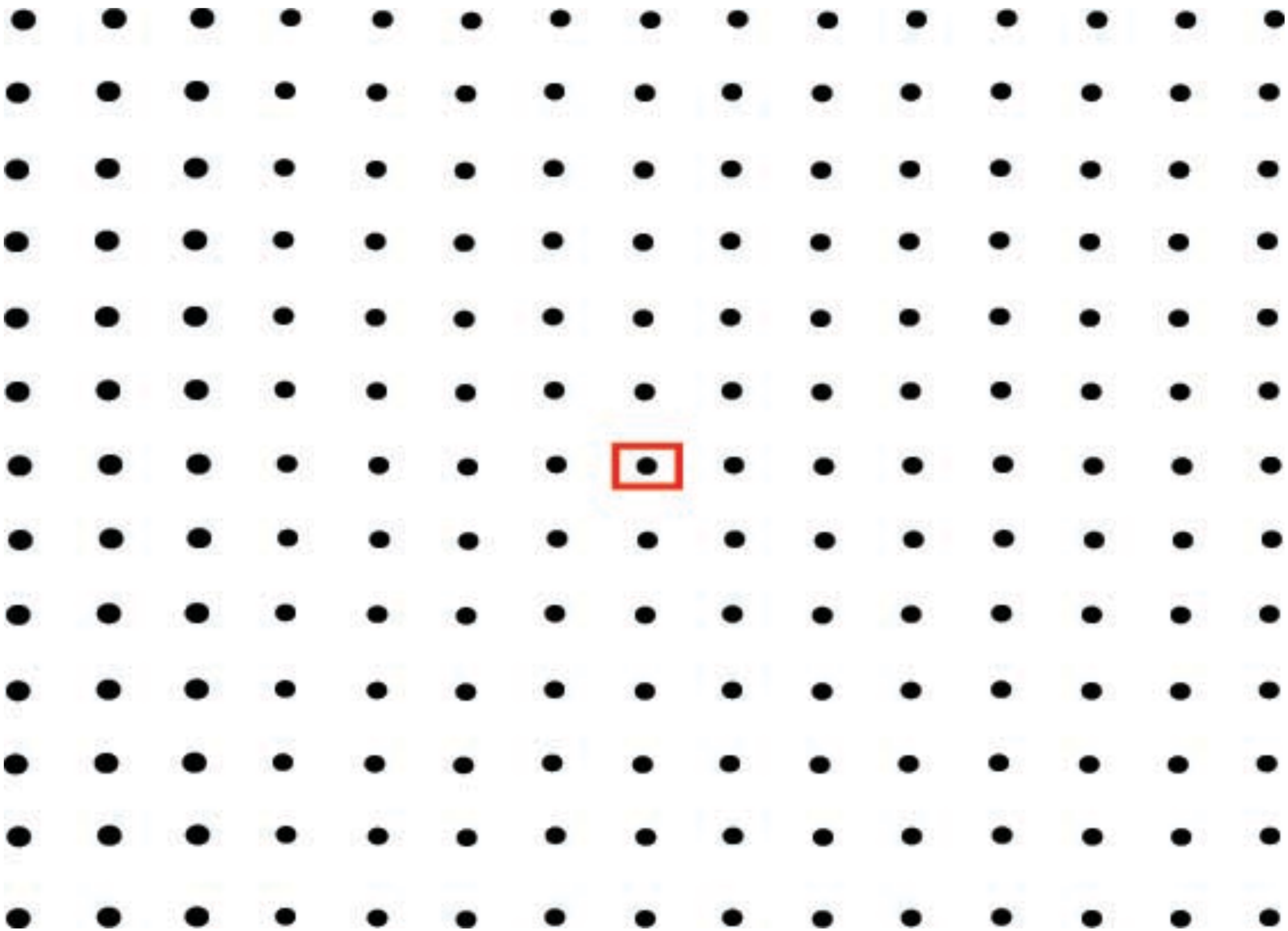


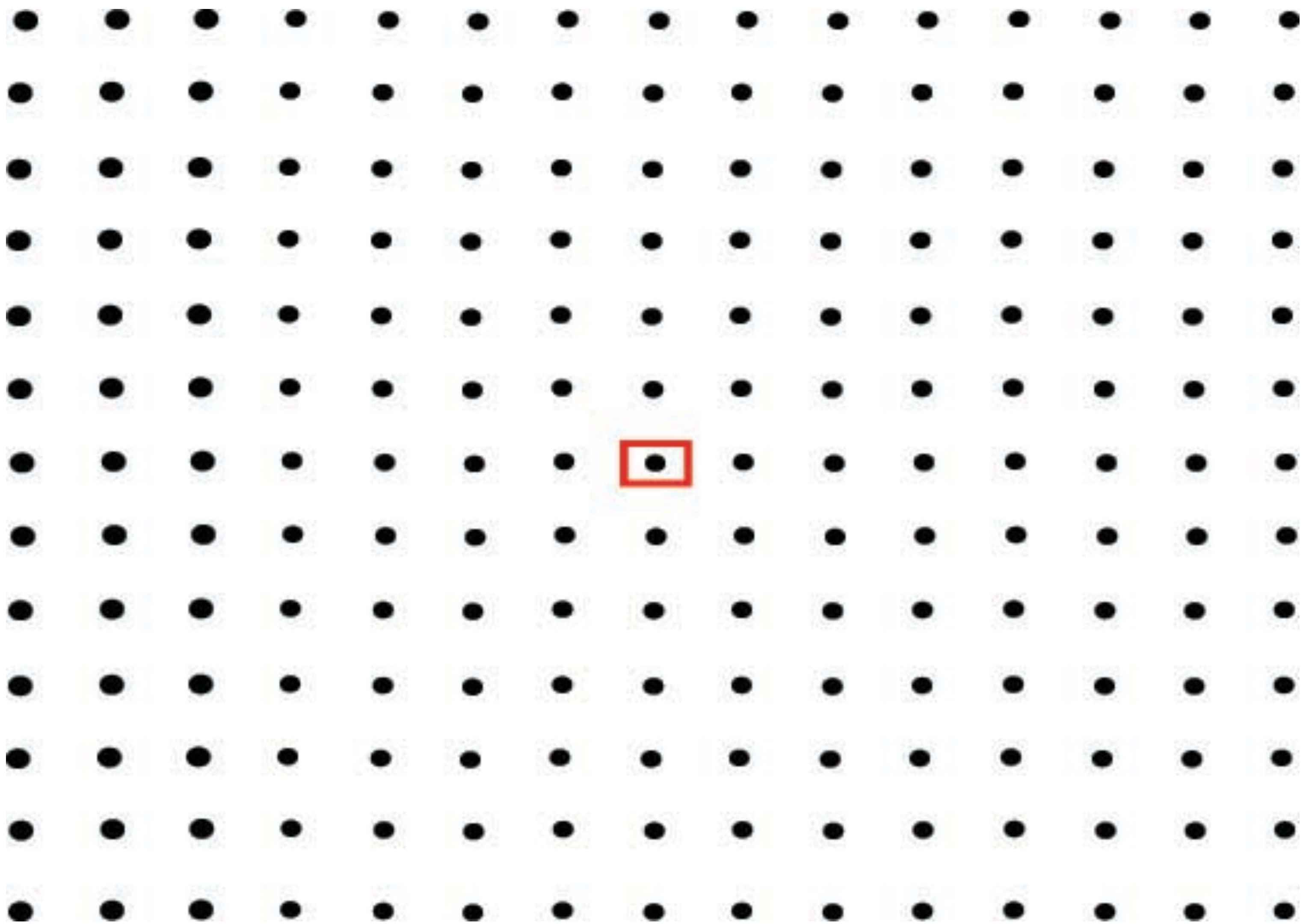


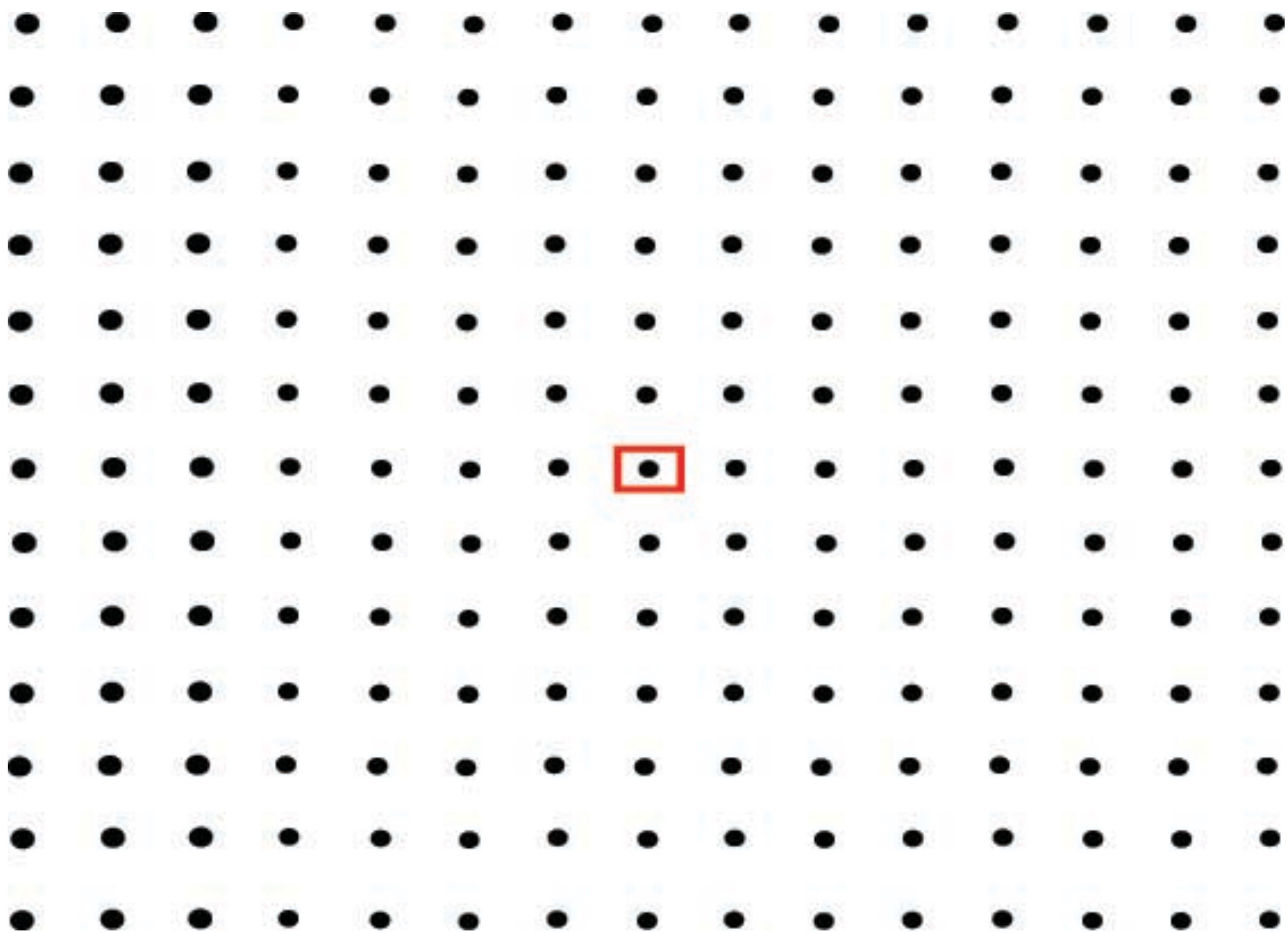


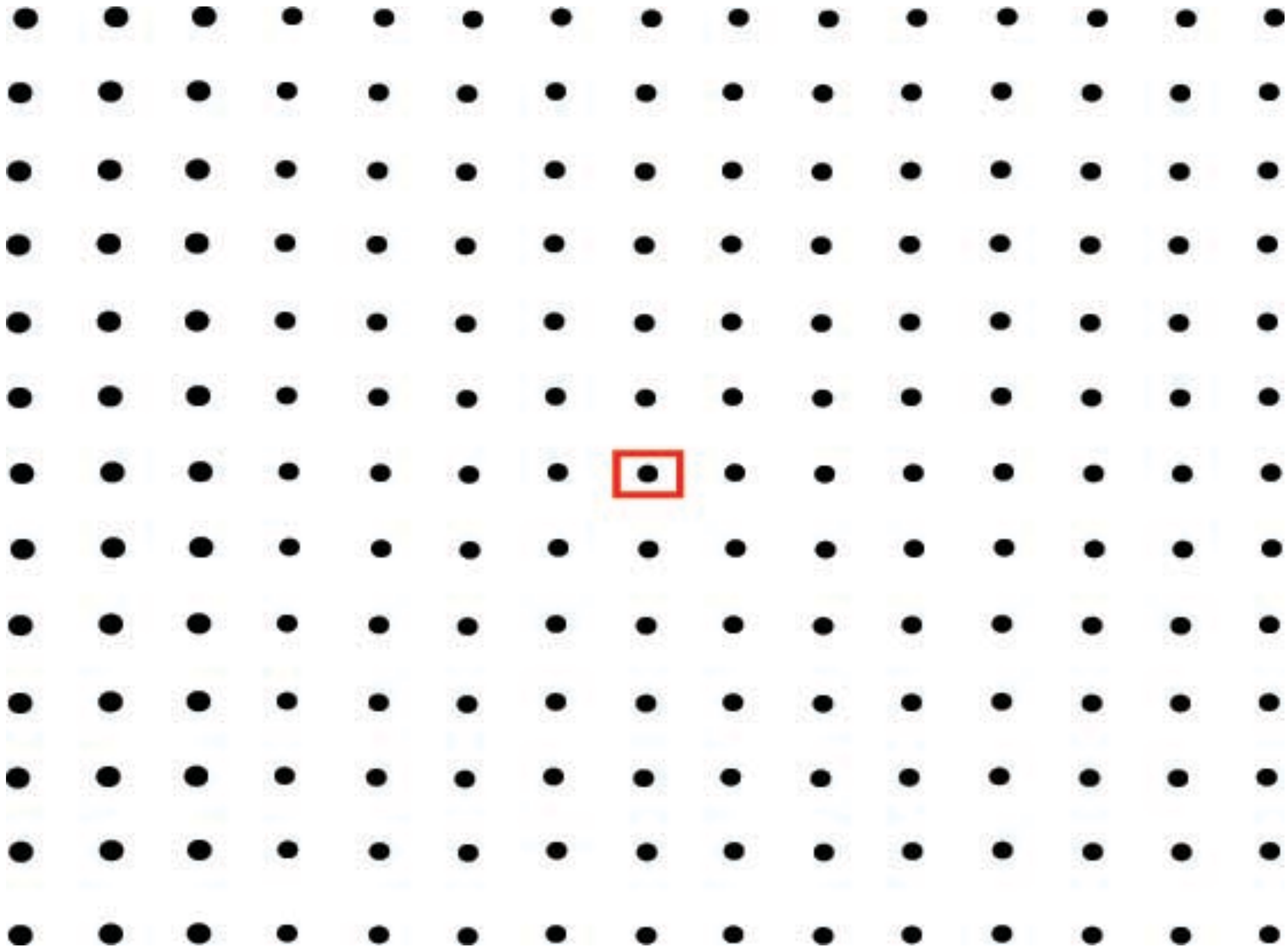


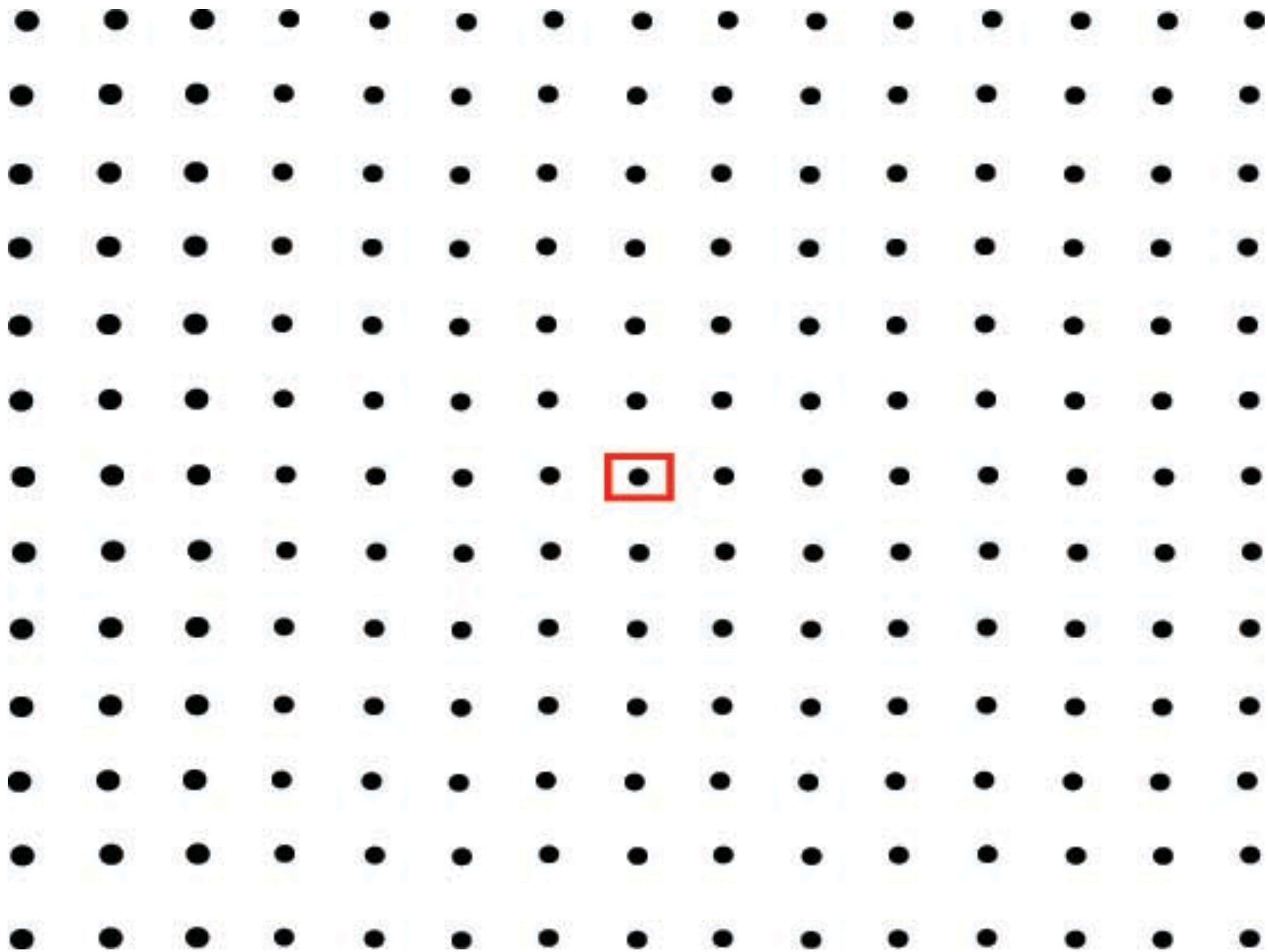


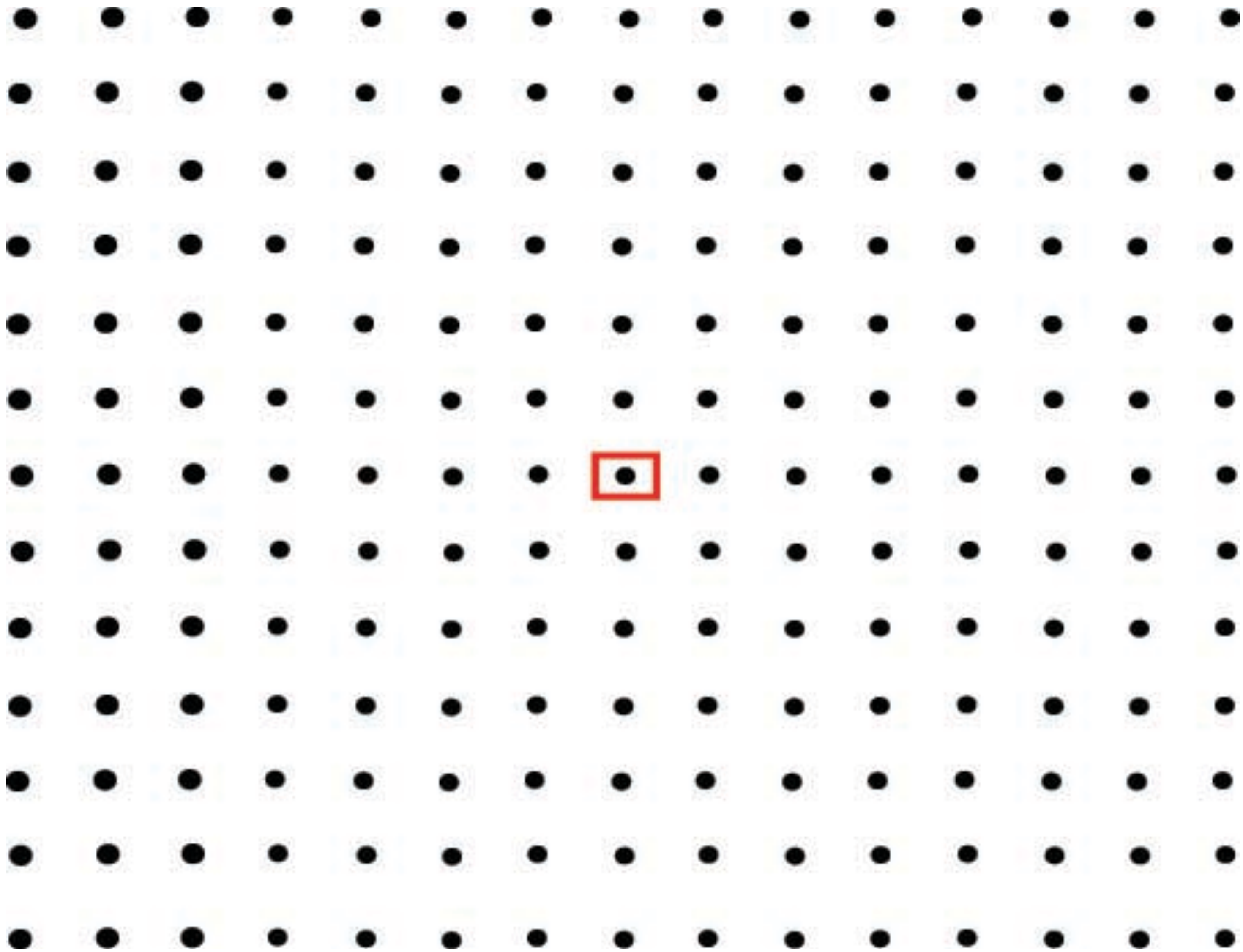


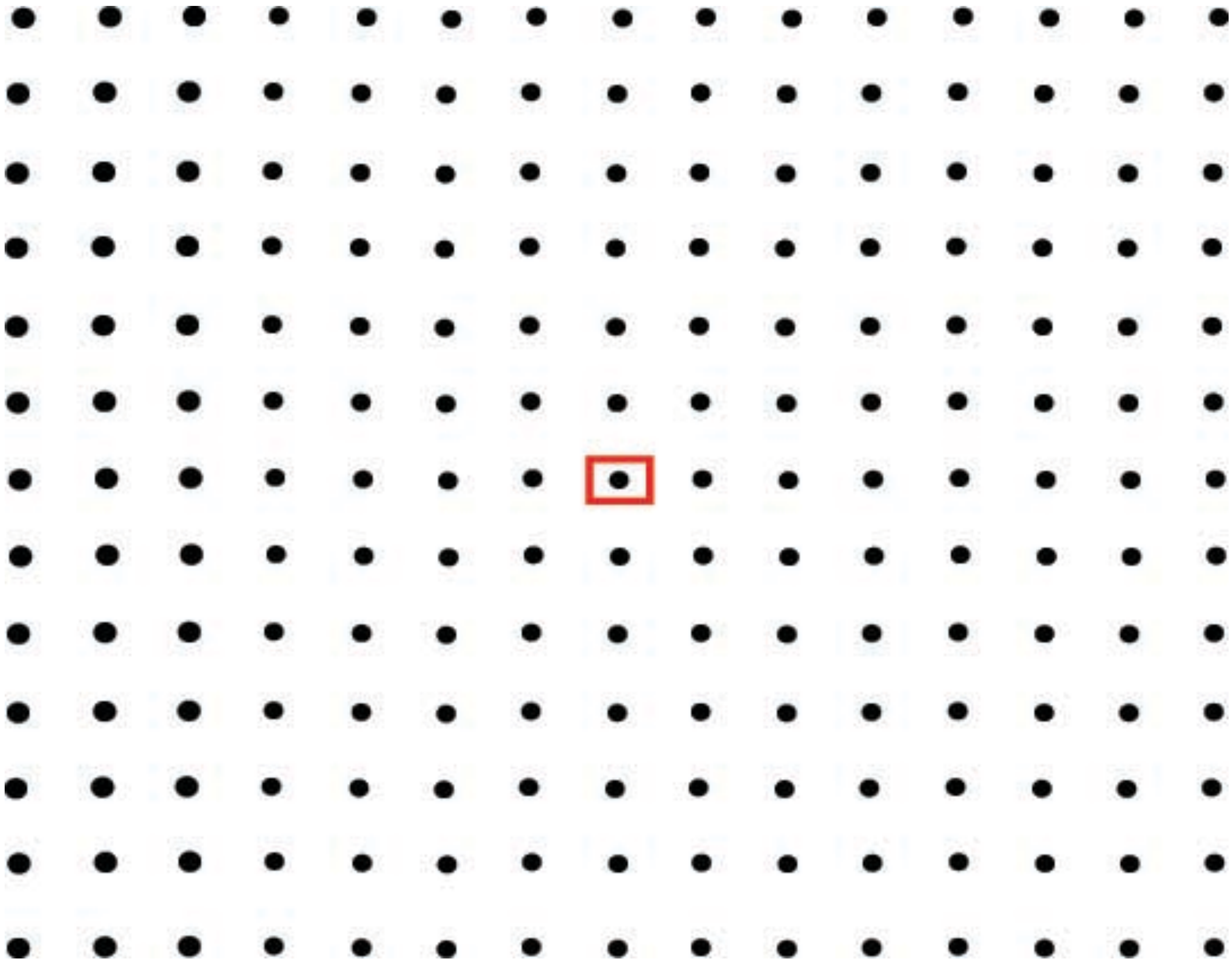


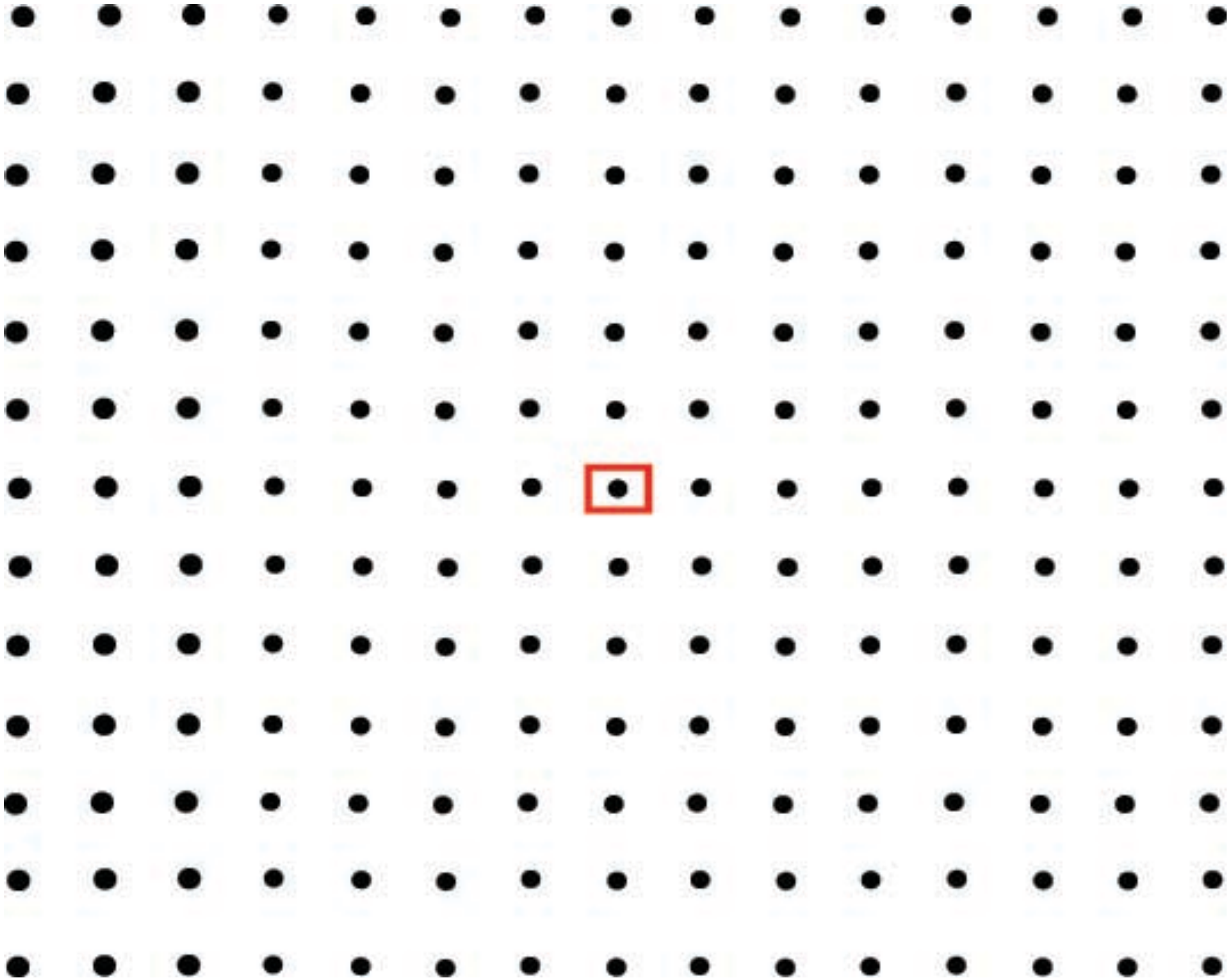


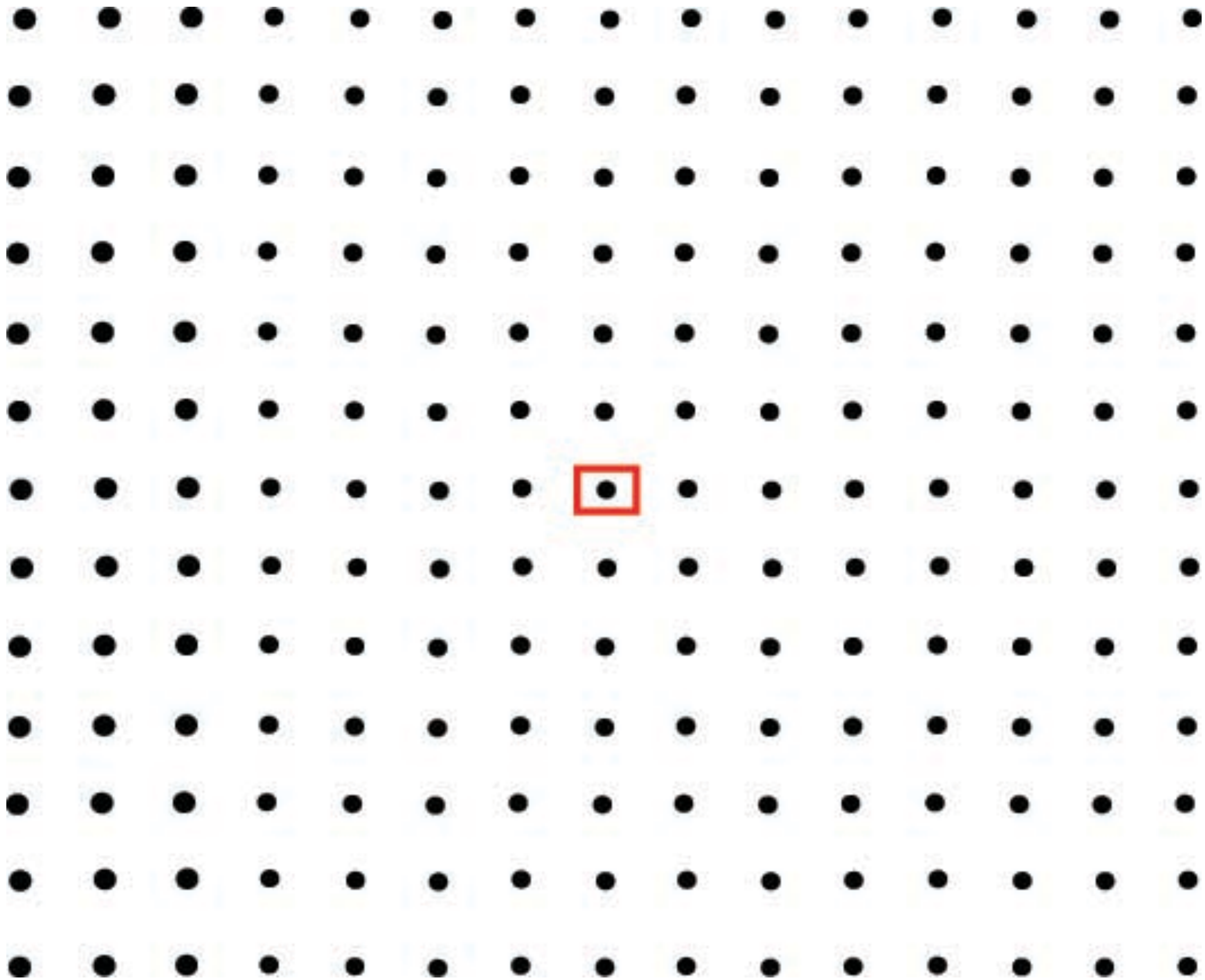


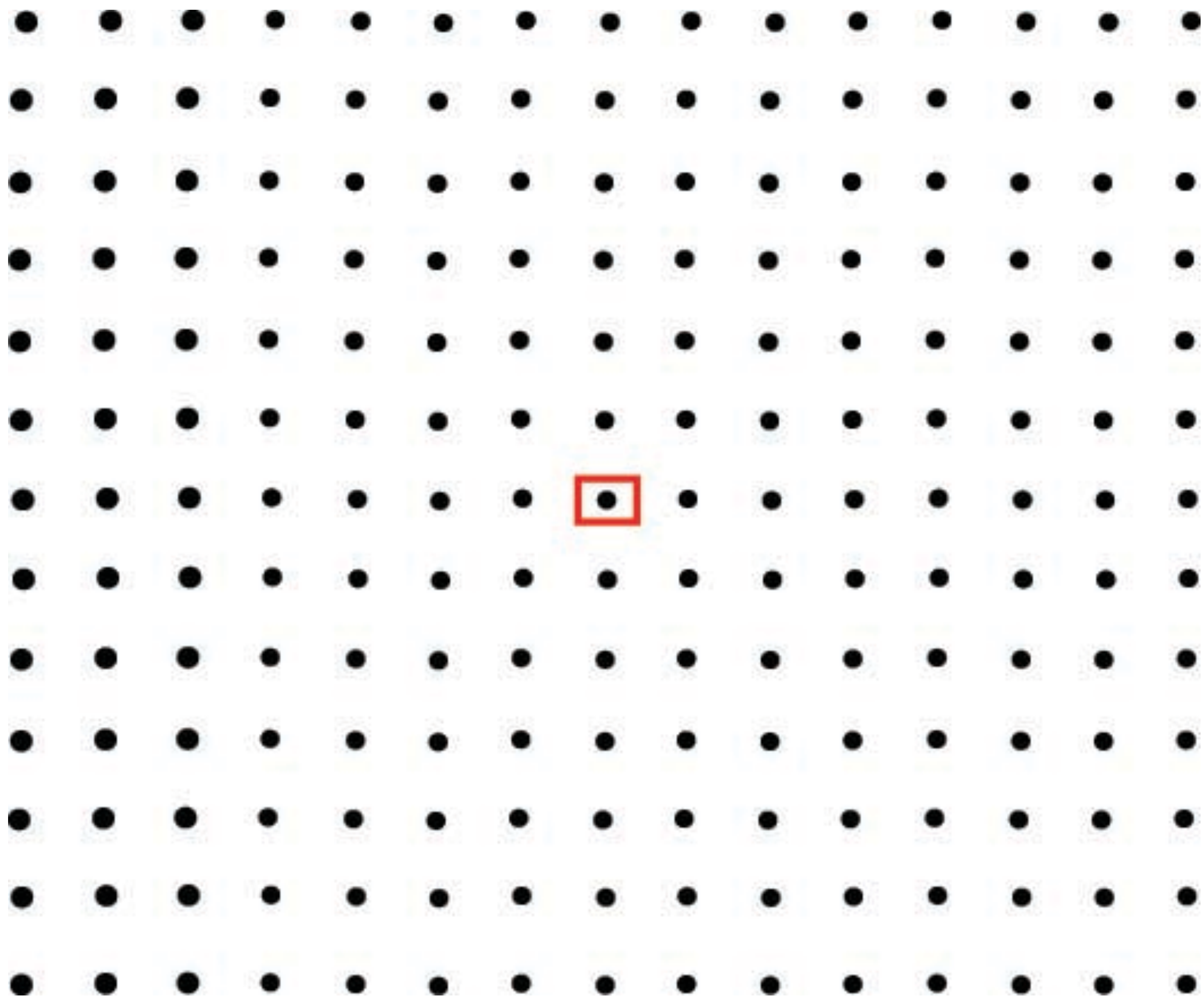


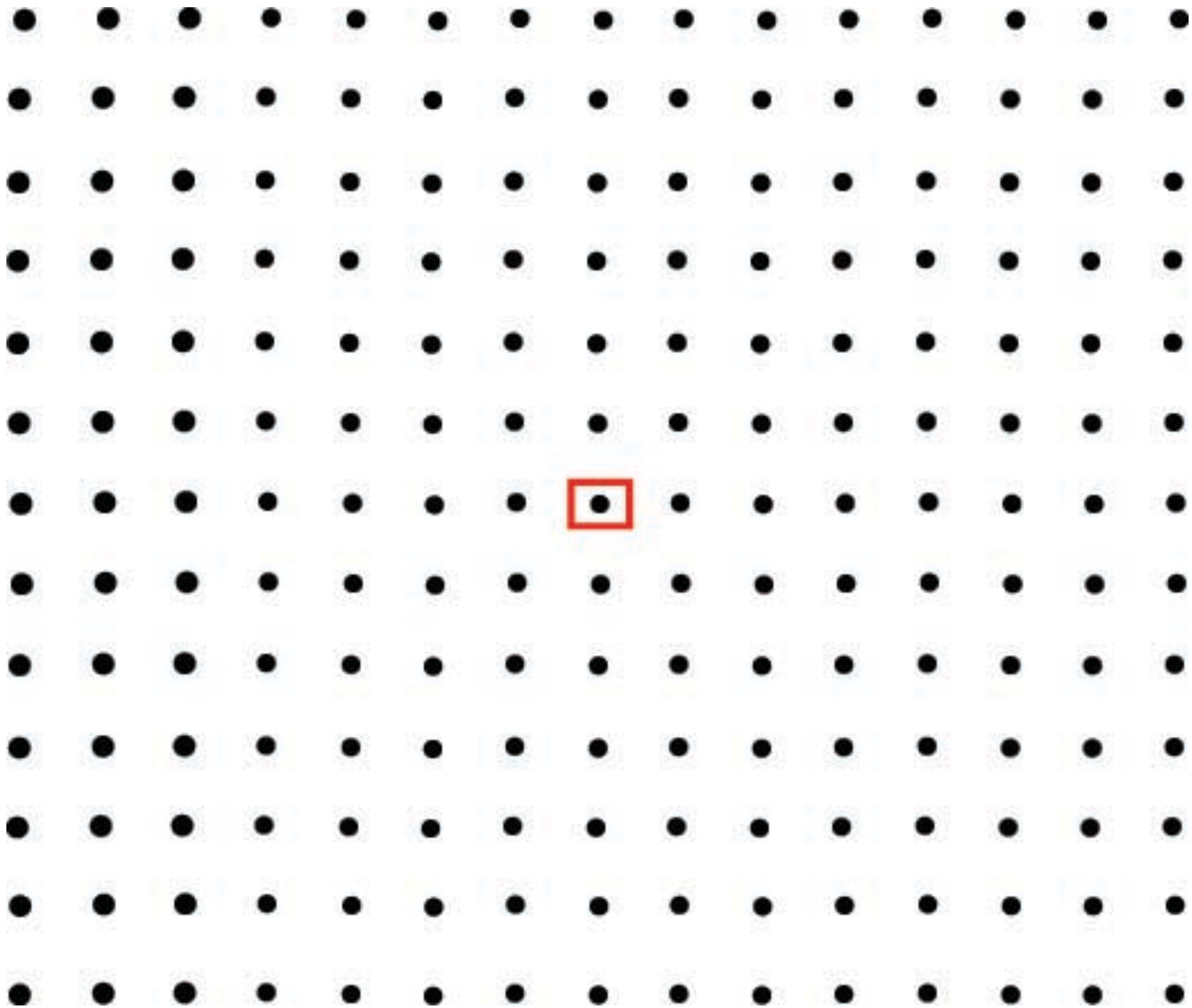










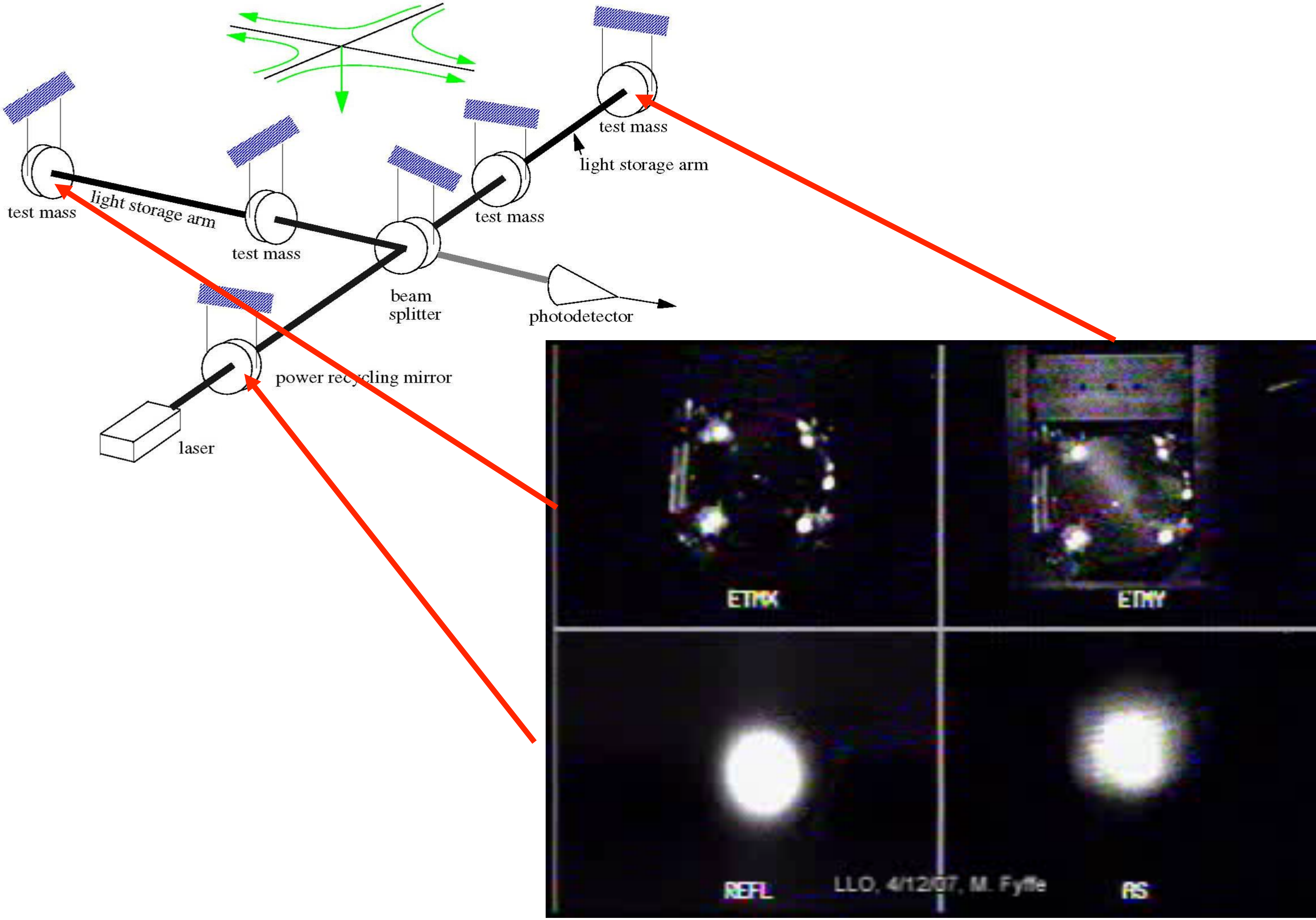


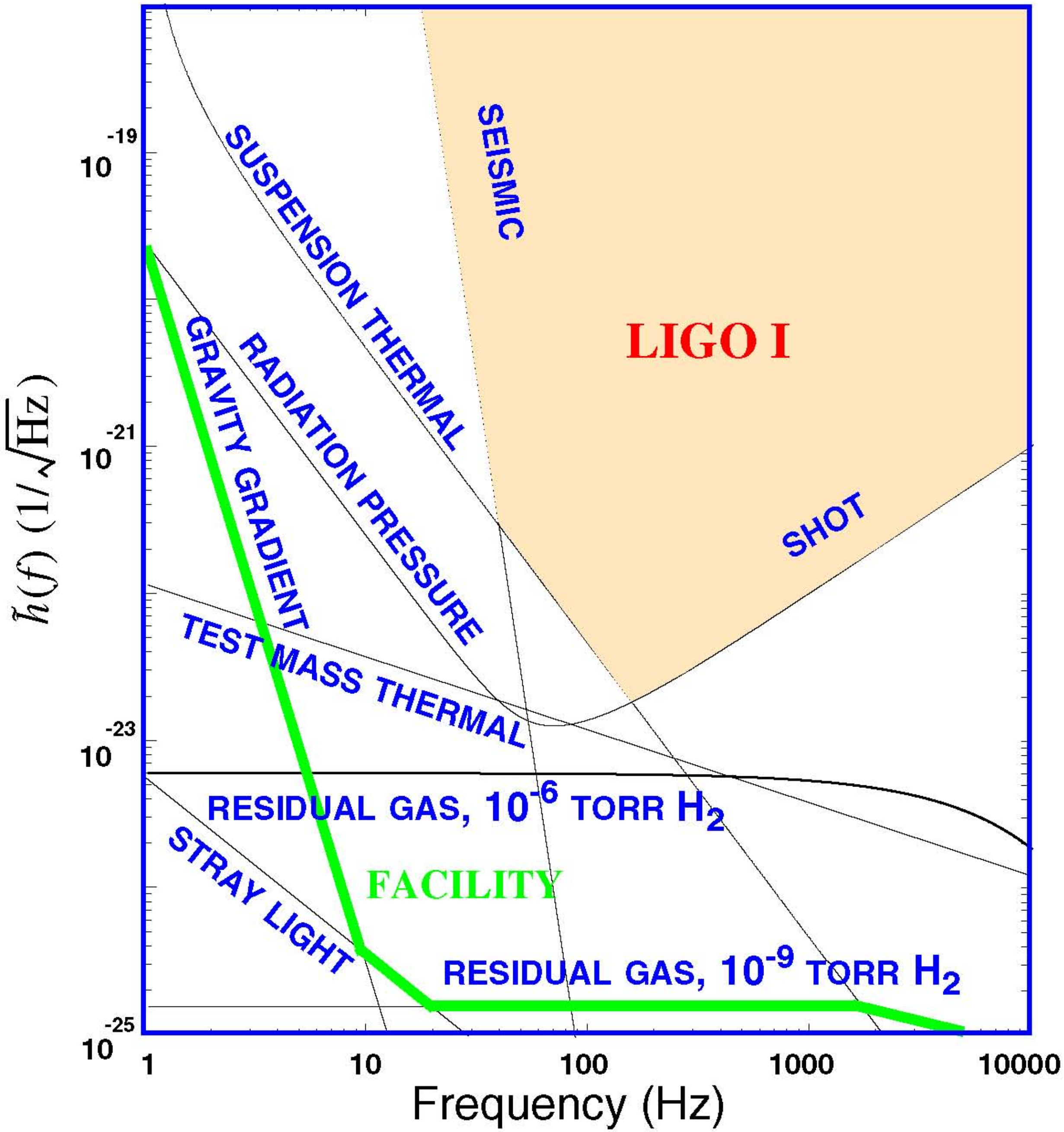
Measurement challenge

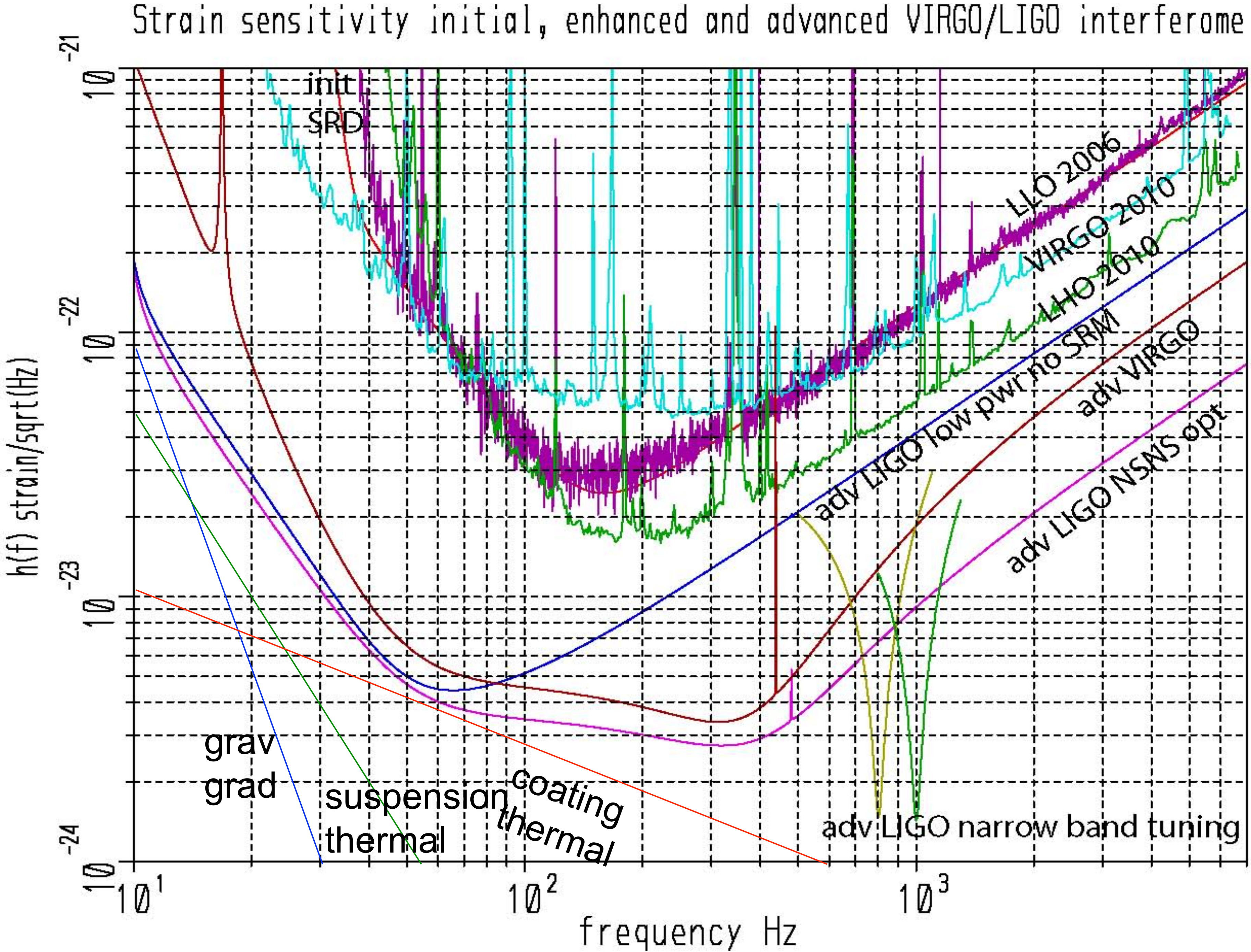
- Needed technology development to measure:

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

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


test mass
light storage arm
test mass
test mass
test mass
light storage arm
beam
splitter
photodetector
power recycling mirror
laser
ETMX
ETMY
REFL
LLO, 4/12/07, M. Fyffe
AS


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



Strain sensitivity initial, enhanced and advanced VIRGO/LIGO interferome
h(f) strain/sqrt(Hz)
init
SRD
LLO 2006
VIRGO 2010
LHO 2010
adv LIGO low pwr no SRM
adv VIRGO
adv LIGO NSNS opt
grav
grad
suspension
thermal
coating
thermal
adv LIGO narrow band tuning
frequency Hz

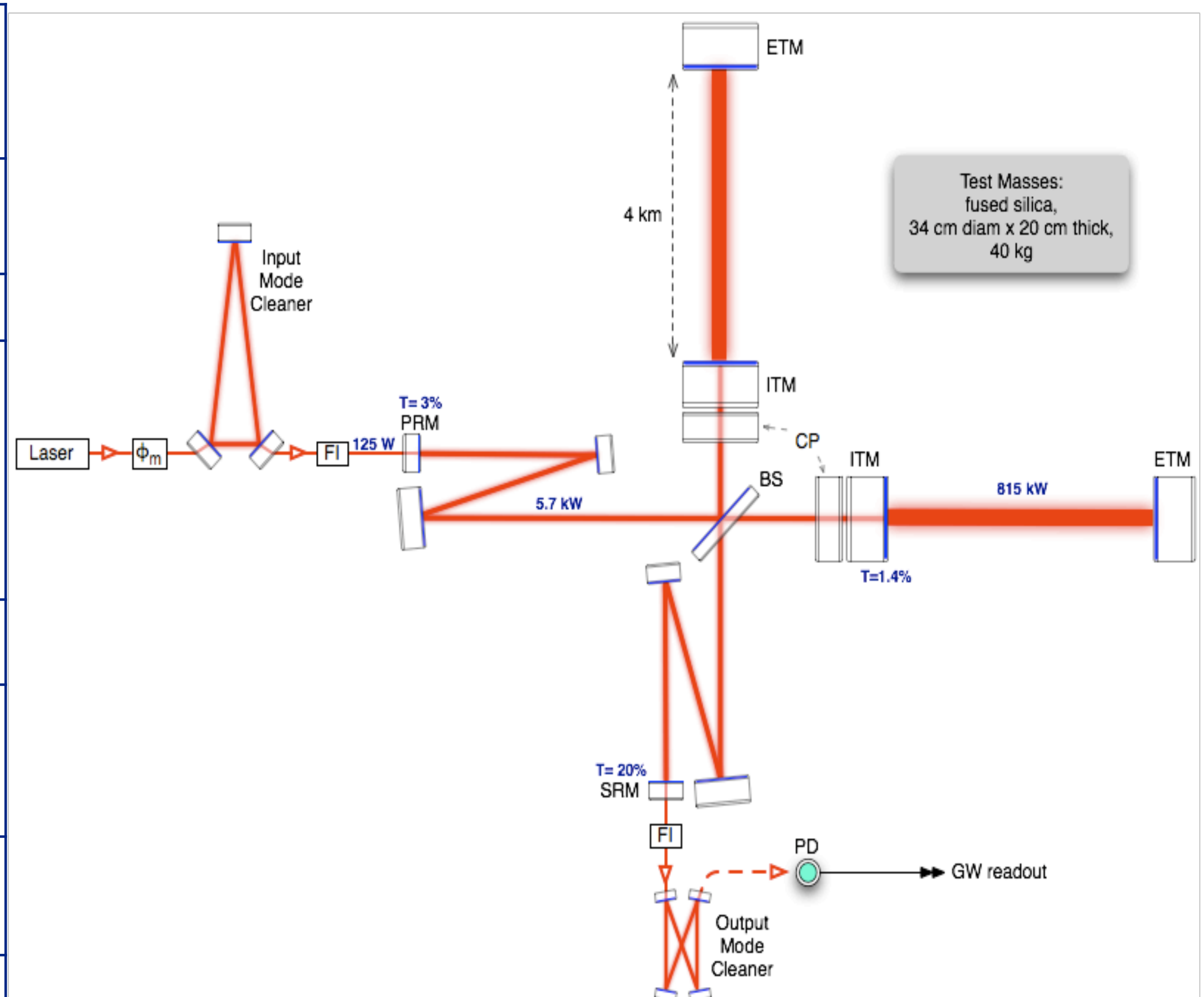
Classes of sources and searches

inspiral S5

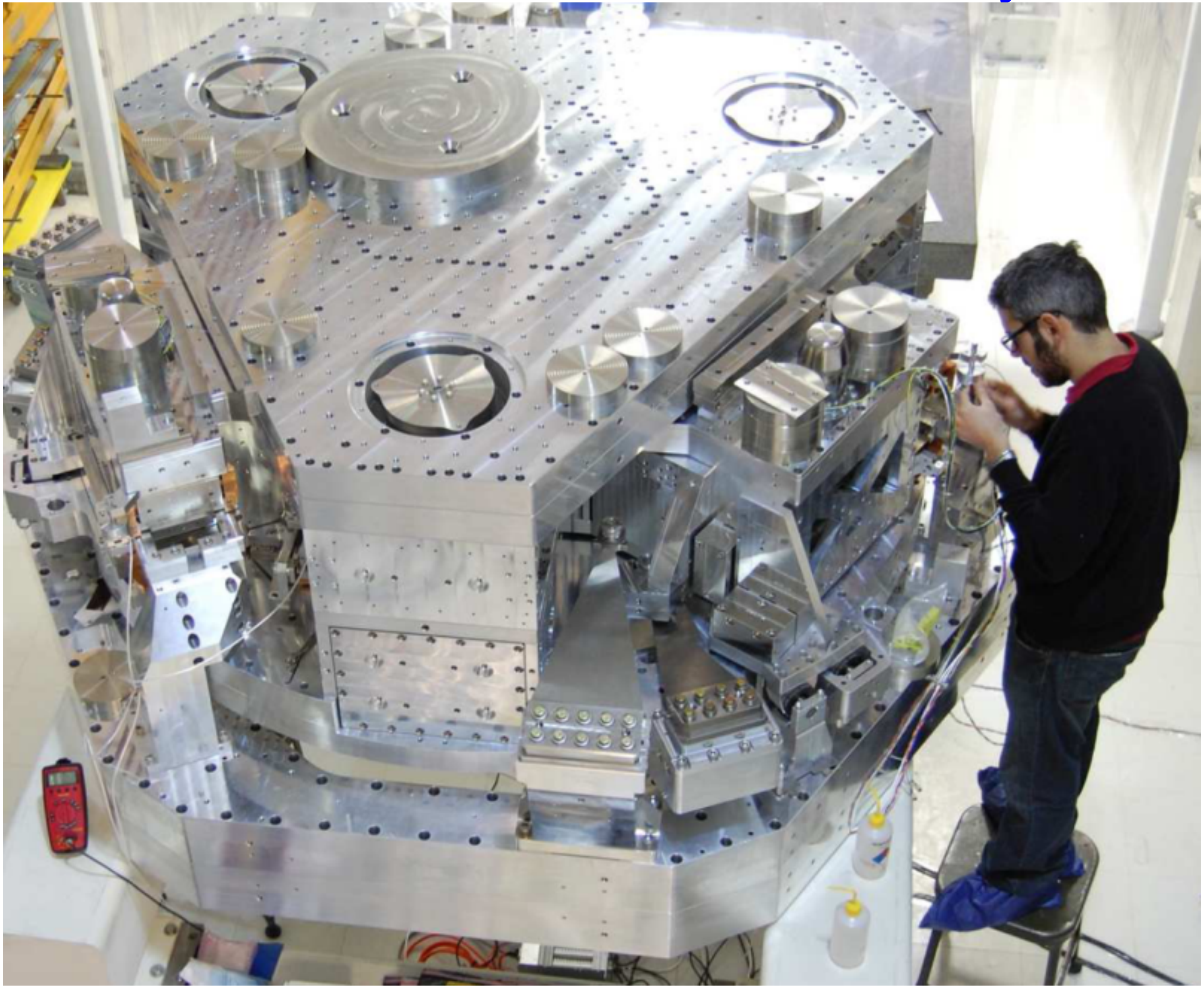
- Compact binary inspiral: template search
  - BH/BH
  - NS/NS and BH/NS
- Low duty cycle transients: wavelets,T/f clusters
  - Supernova
  - BH normal modes
  - Unknown types of sources
- Externally triggered searches
  - Gamma bursts
  - EM transients
- Periodic CW sources
  - Pulsars
  - Low mass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

Systems: Interferometer Design

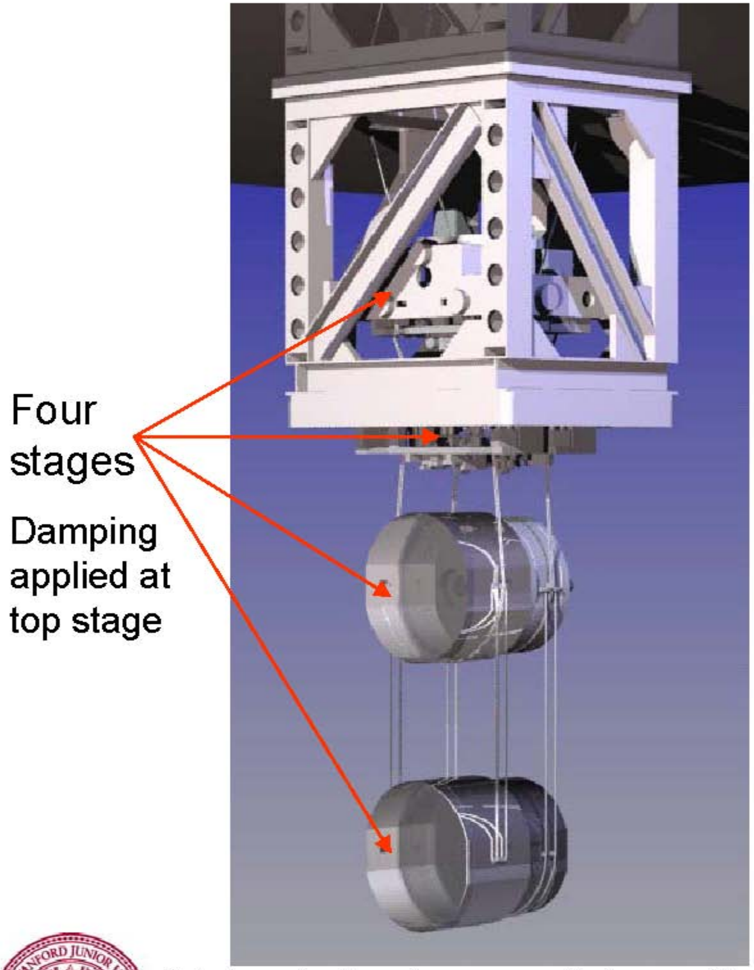
Parameter	***Initial LIGO***	***Advanced LIGO***
Input Laser Power	10 W (10 kW arm)	180 W (>700 kW arm)
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson (stable recycling cavities)
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in broadband
Seismic Isolation Performance	$f_{low} \sim 50$ Hz	$f_{low} \sim 12$ Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum



Advanced LIGO seismic isolation system

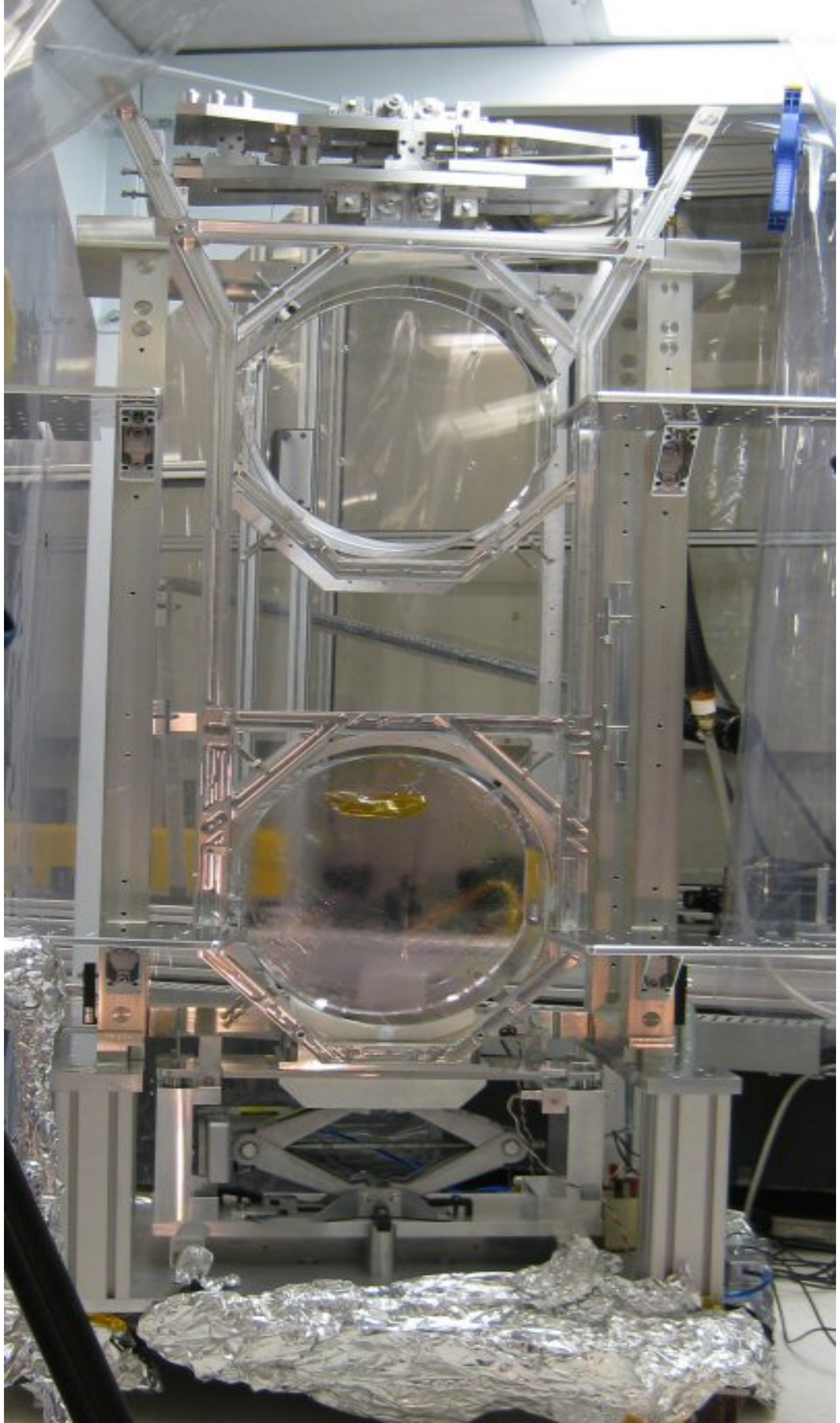


Schematic

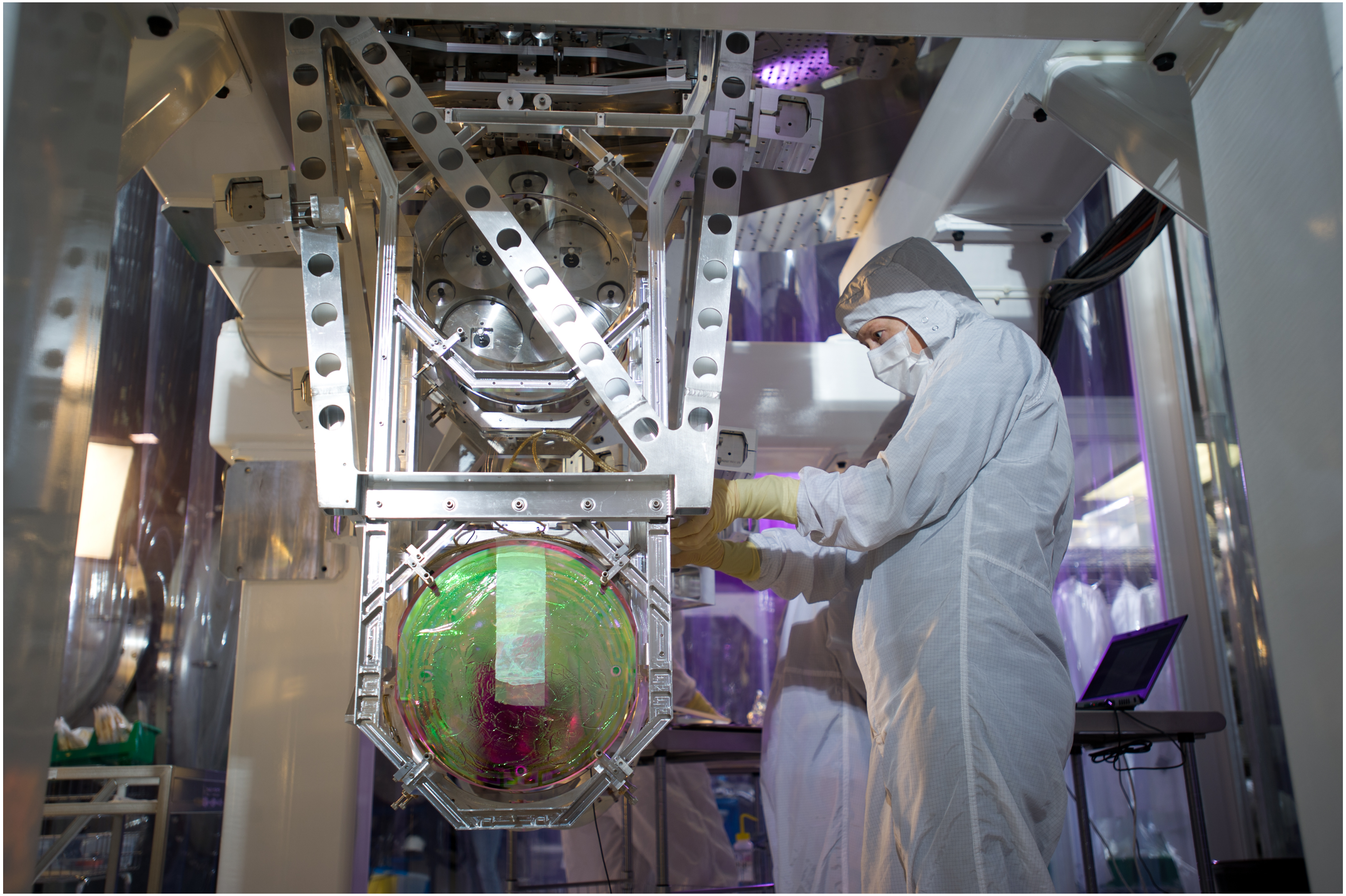


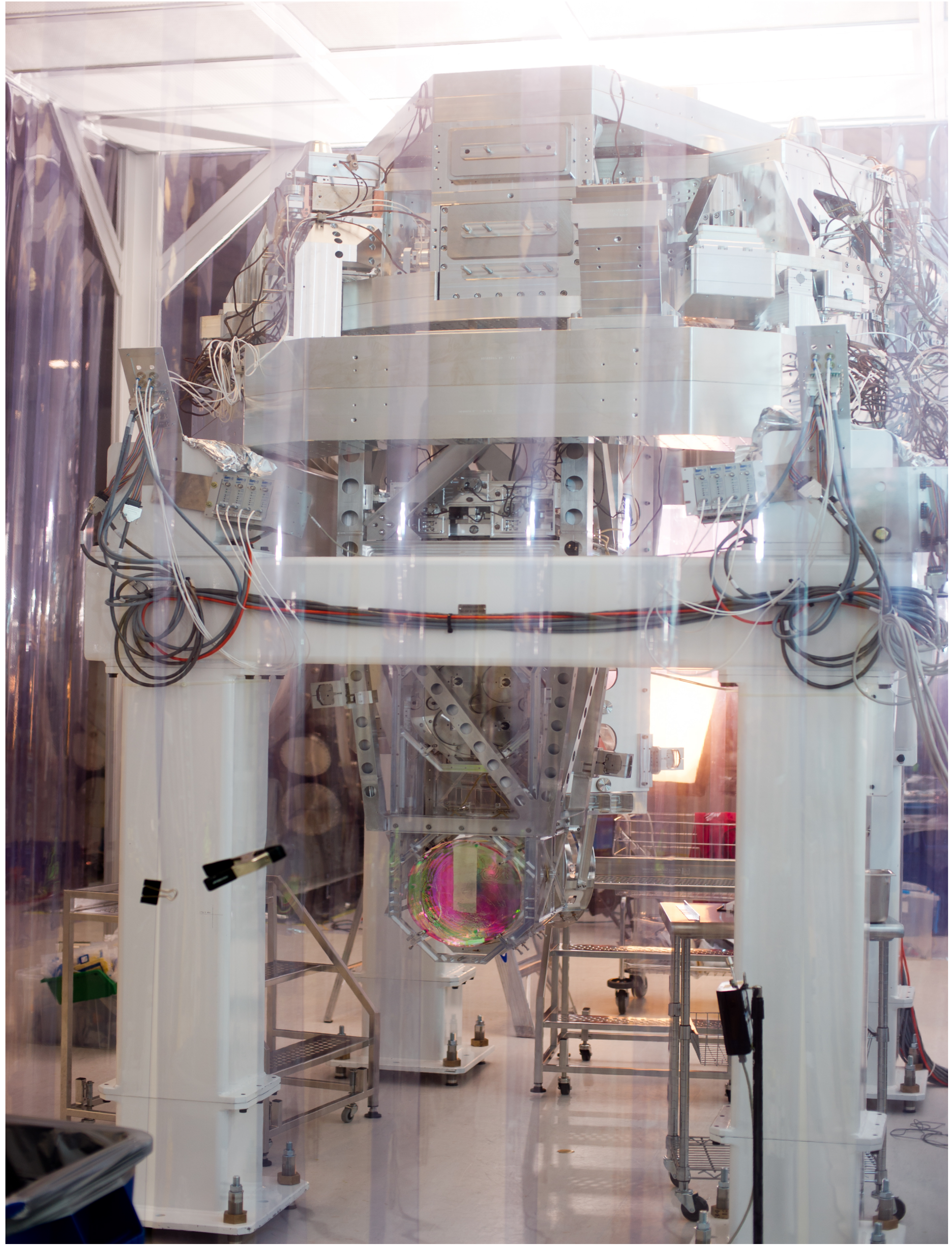
Main chain plus parallel reaction chain for control actuation

(Lower support structure removed for clarity)

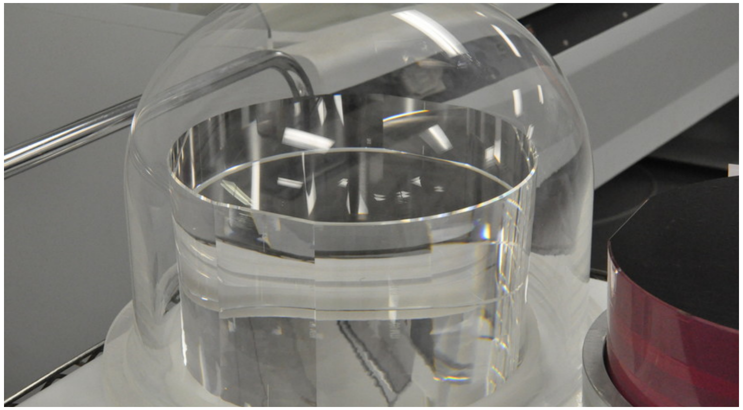


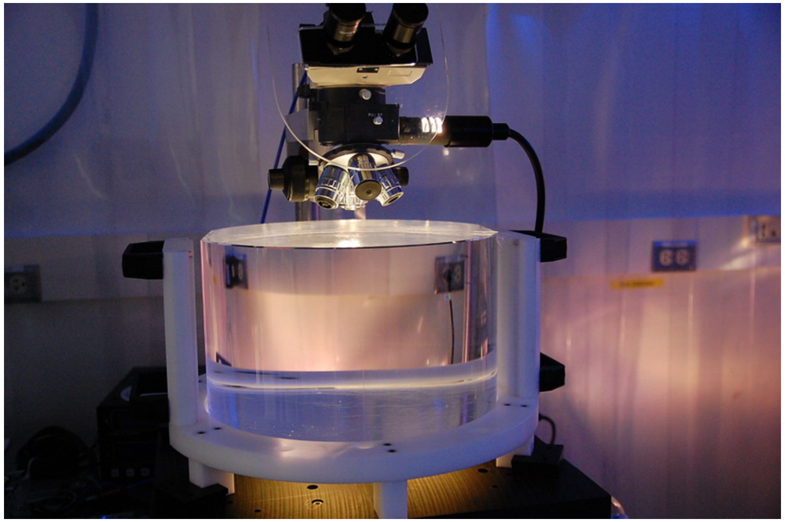
Suspension and isolation system



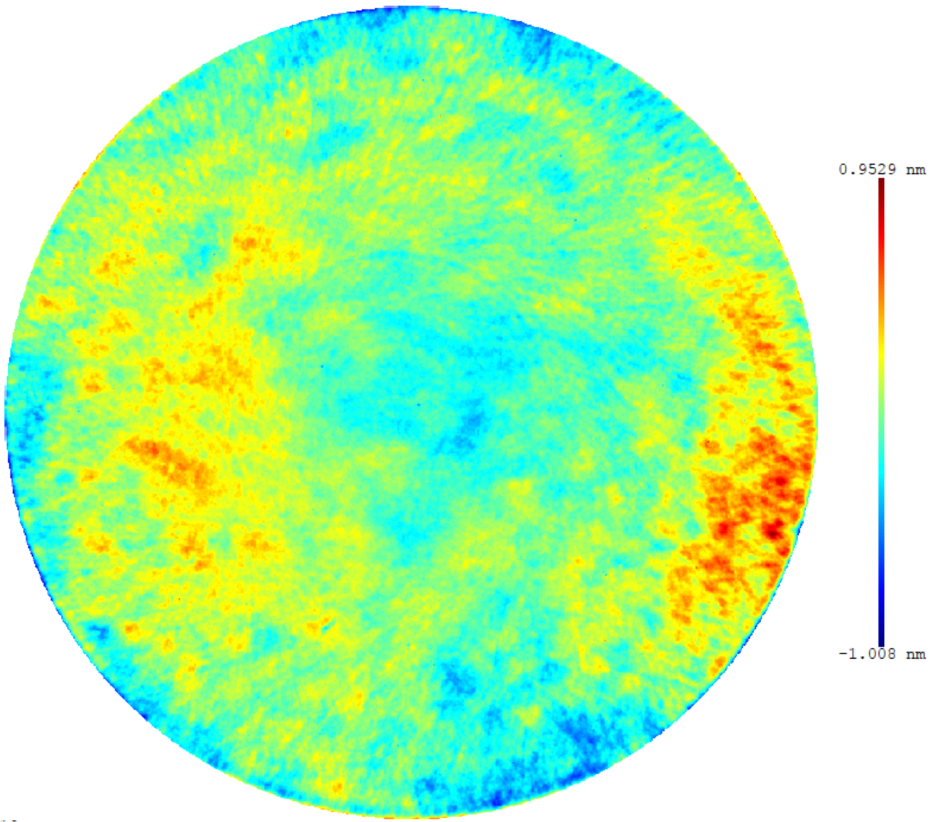


Advanced LIGO Core Optics

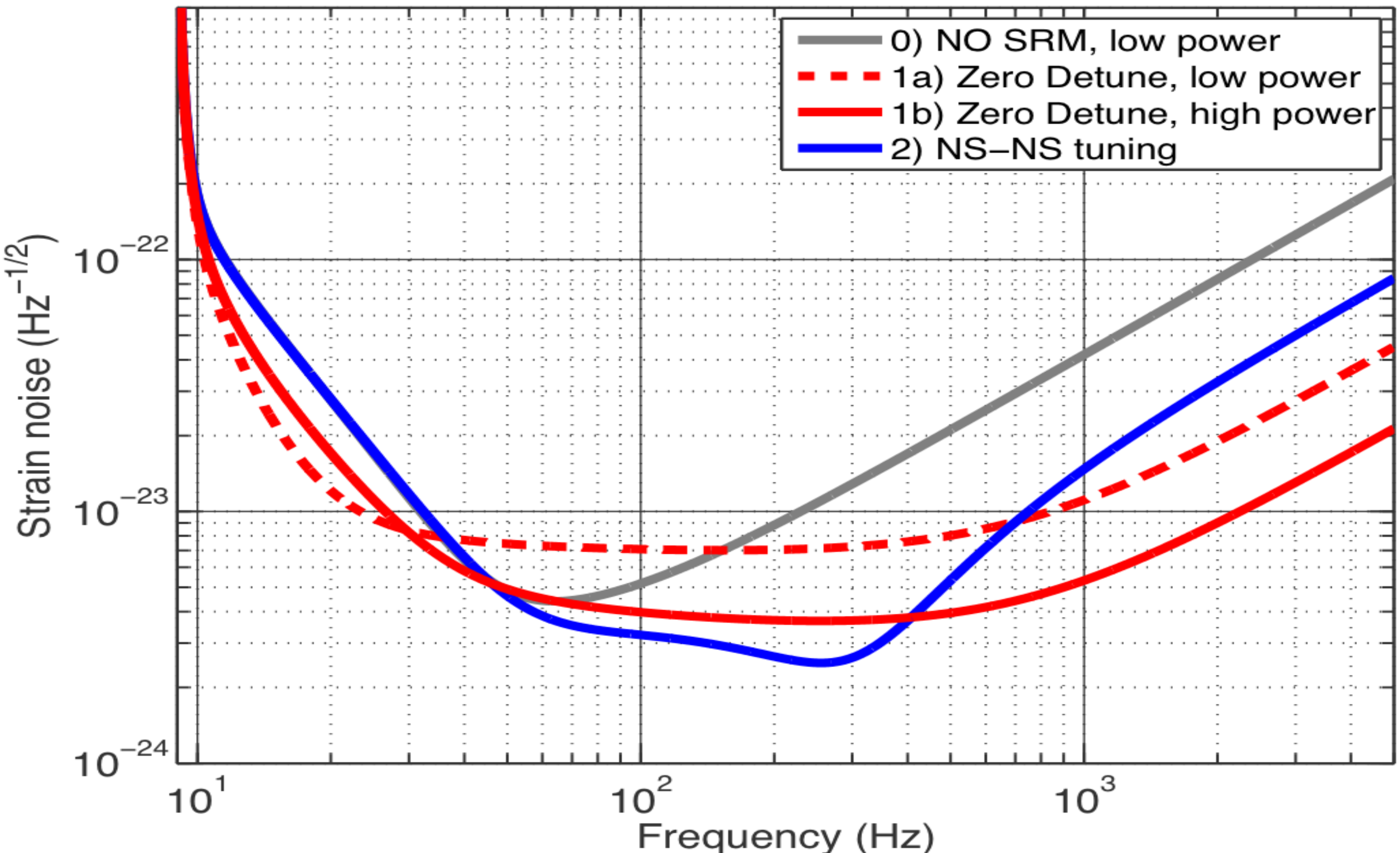




- 40 kg masses, 38 cm in diameter, and figured to 0.15 nm rms
- Optical coatings are challenging

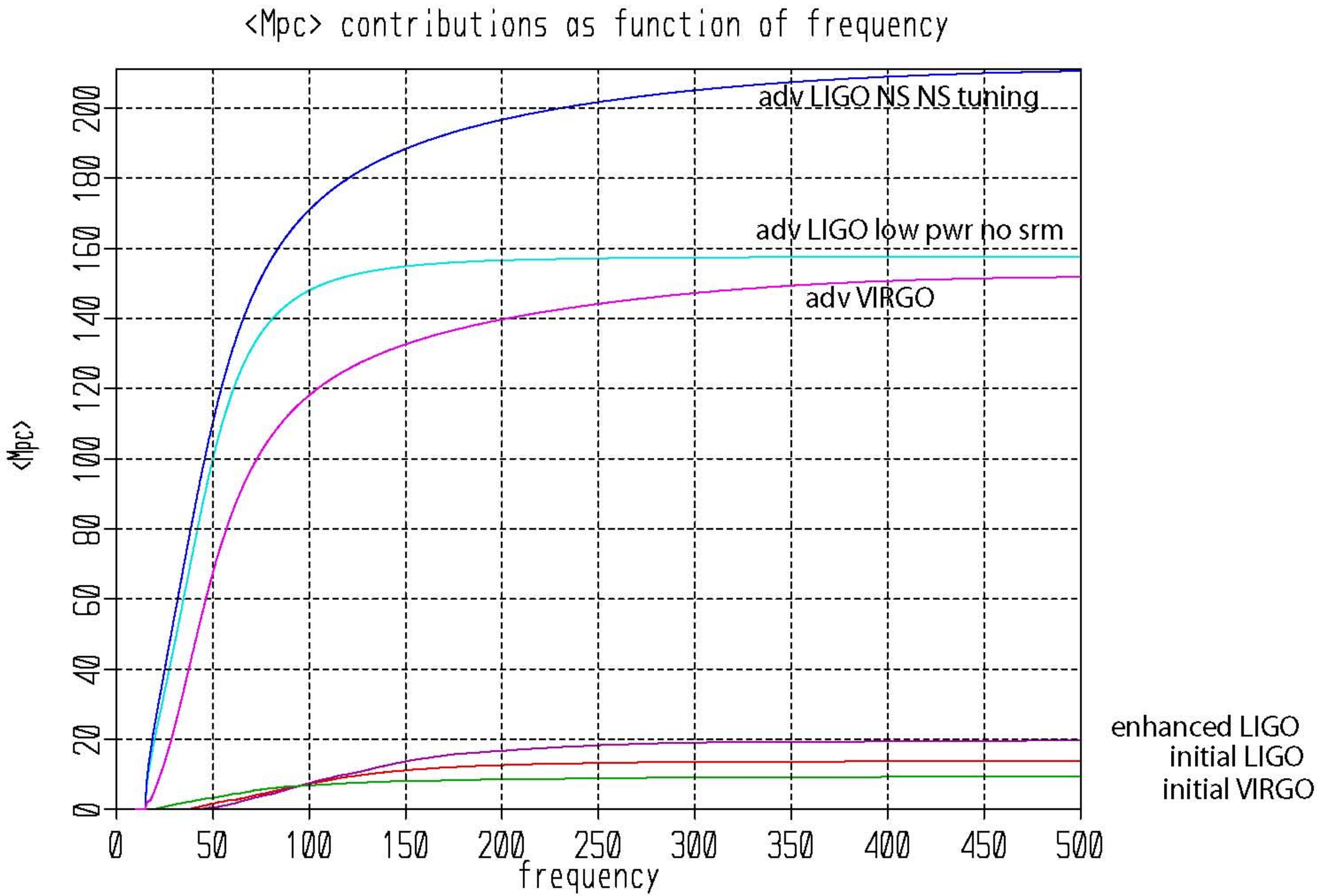


Advanced LIGO broadband operational modes

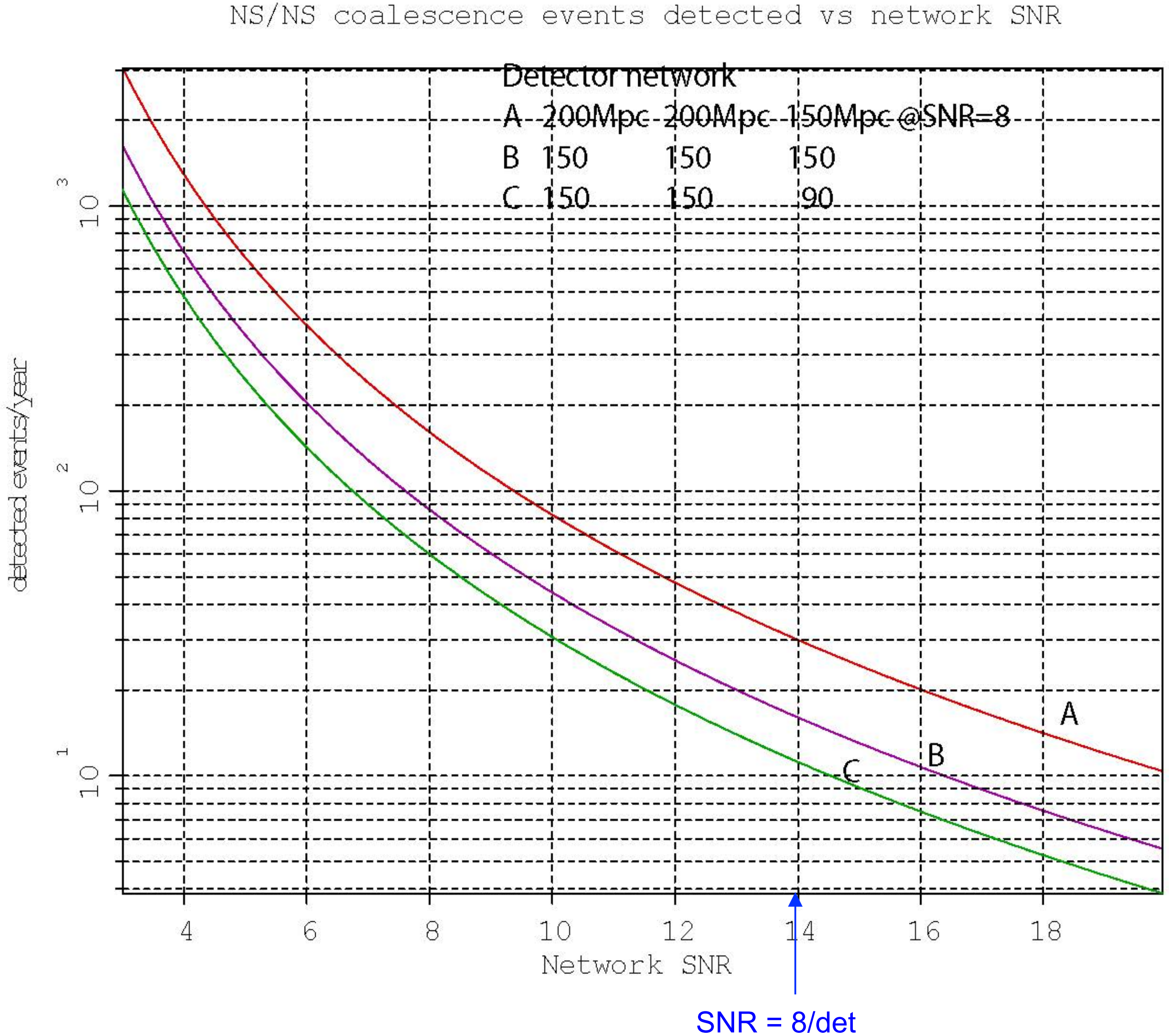


P.Fritschel Advanced LIGO Systems Design (2009)

Mode	*NS-NS Range*	*BH-BH Range*	P_{in}	T_{SRM}	ϕ_{SRC}	h_{RMS}, 10^{-22} (band)
0	150 Mpc	1.60 Gpc	25 W	100%	–	0.53 (40 – 140 Hz)
1a	145 Mpc	1.65 Gpc	25 W	20%	0 deg.	0.70 (110 – 210 Hz)
1b	190 Mpc	1.85 Gpc	125 W	20%	0 deg.	0.37 (205 – 305 Hz)
2	200 Mpc	1.65 Gpc	125 W	20%	16 deg.	0.25 (205 – 305 Hz)



<Mpc> contributions as function of frequency
adv LIGO NS NS tuning
adv LIGO low pwr no srm
adv VIRGO
enhanced LIGO
initial LIGO
initial VIRGO
<Mpc>
frequency
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400
450
500



Conditions:

False alarm rates reduced to Gaussian statistics.

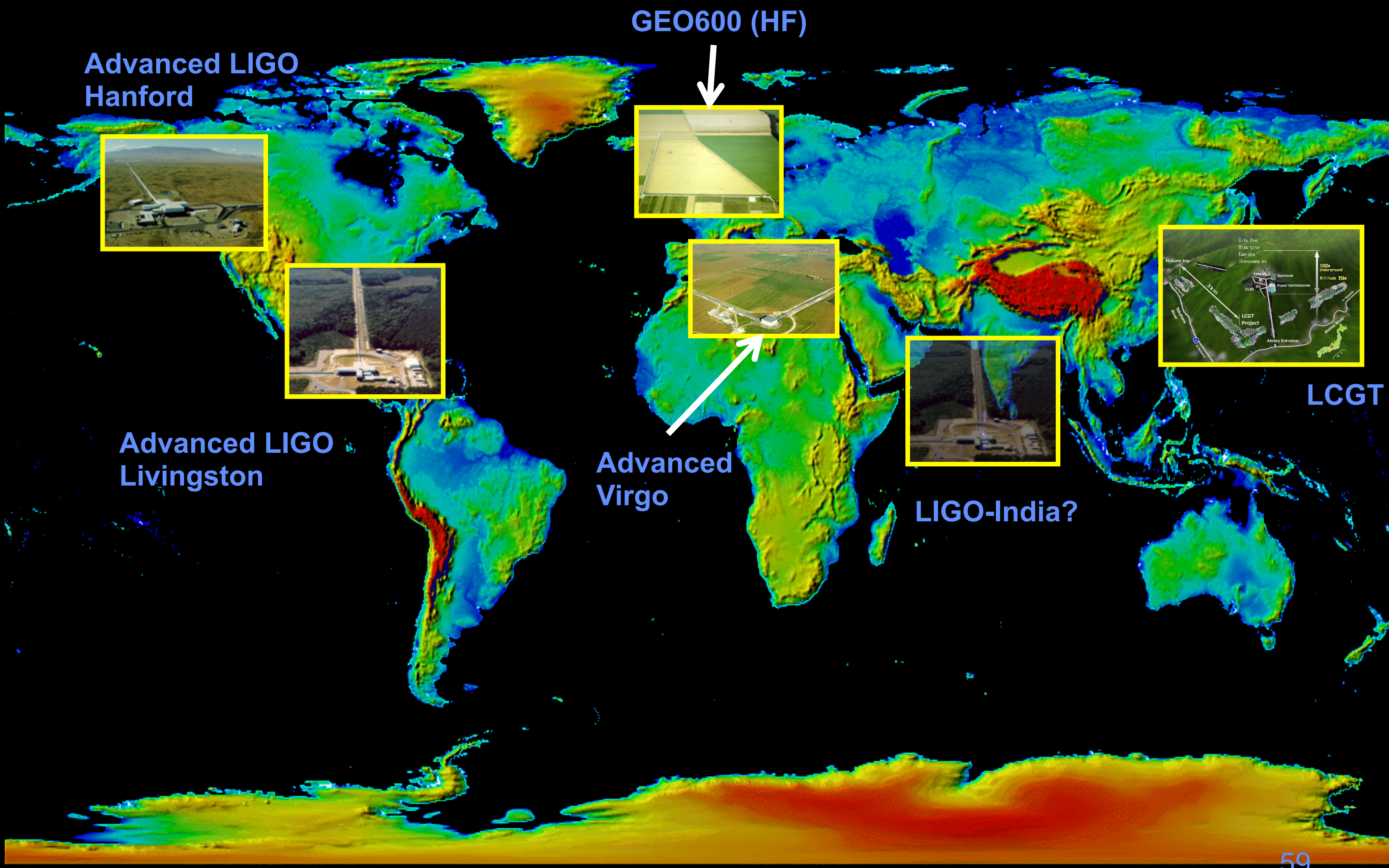
Coherent detection

$$\mathrm{MWEG/Mpc^3} = 0.012$$

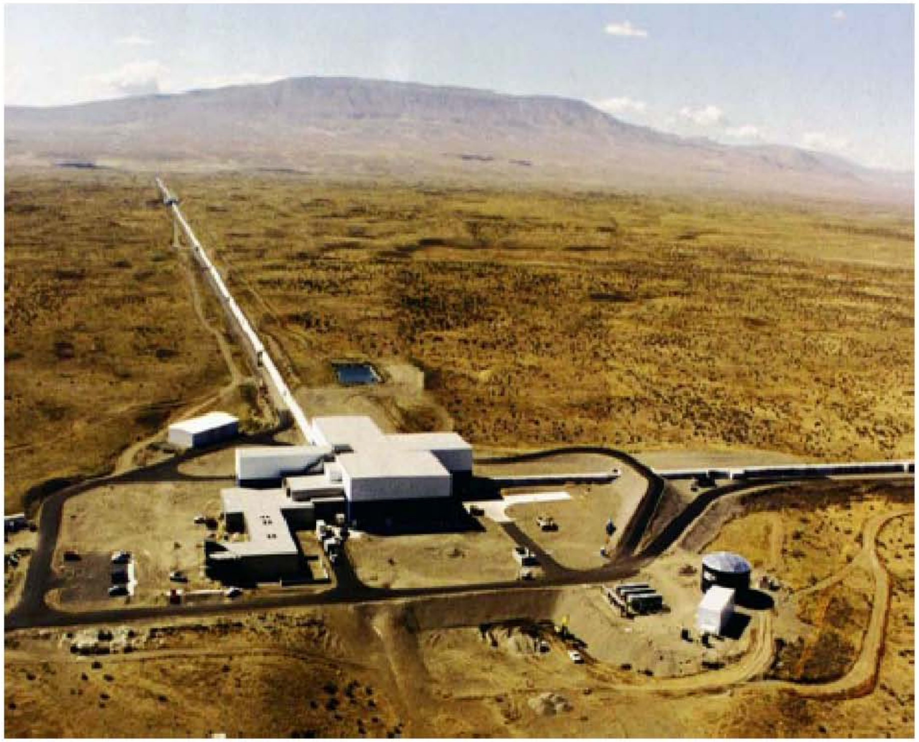
$$\mathrm{\#NS/NS\ insp/MWEG/yr} = 10^{-4}$$

$$\text{NSNS events/year} = \frac{4\pi}{3}\left(\frac{8}{\mathrm{SNR_{network}}}\sqrt{\sum_{1}^{\mathrm{n\,det}}\left\langle \mathrm{R(Mpc)}\right\rangle^2_{\mathrm{SNR}=8}}\right)^3\left(\frac{\mathrm{MWEG}}{\mathrm{Mpc^3}}\right)\left(\frac{\mathrm{\#NSNS\ insp}}{\mathrm{MWEG/yr}}\right)$$

The Advanced GW Detector Network



LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

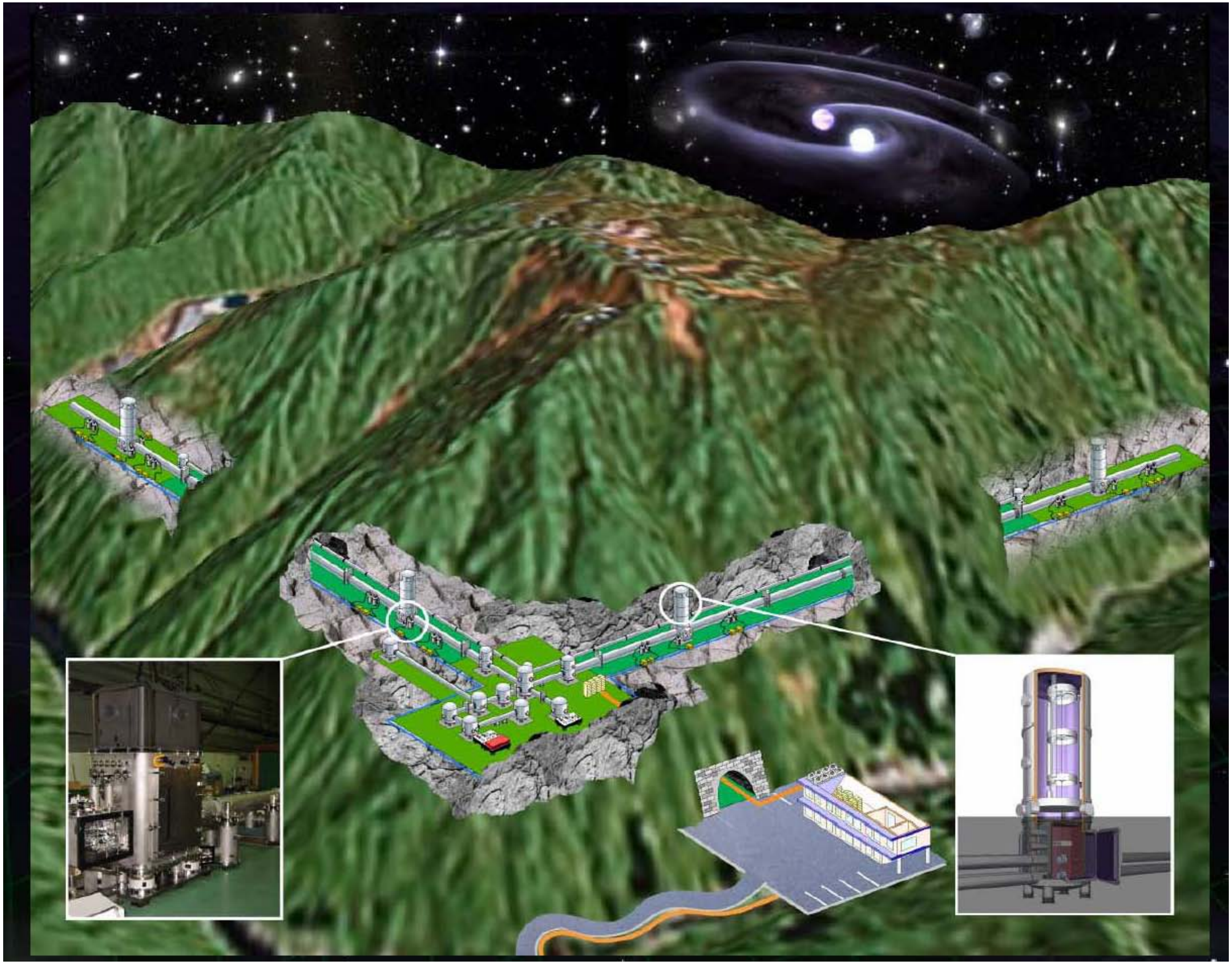
26 km north of Richland, WA

2 km + 4 km interferometers in same vacuum envelope

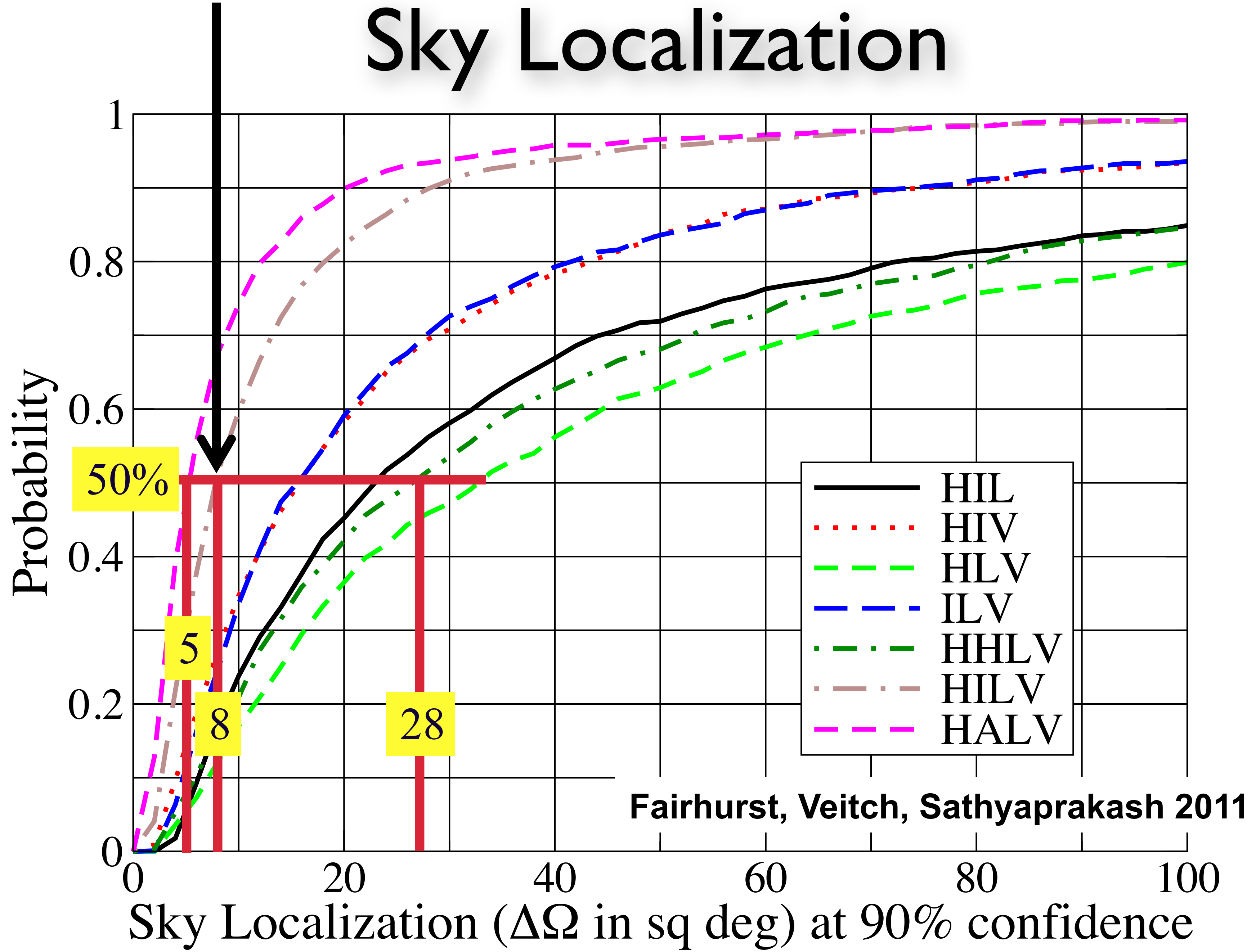
LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

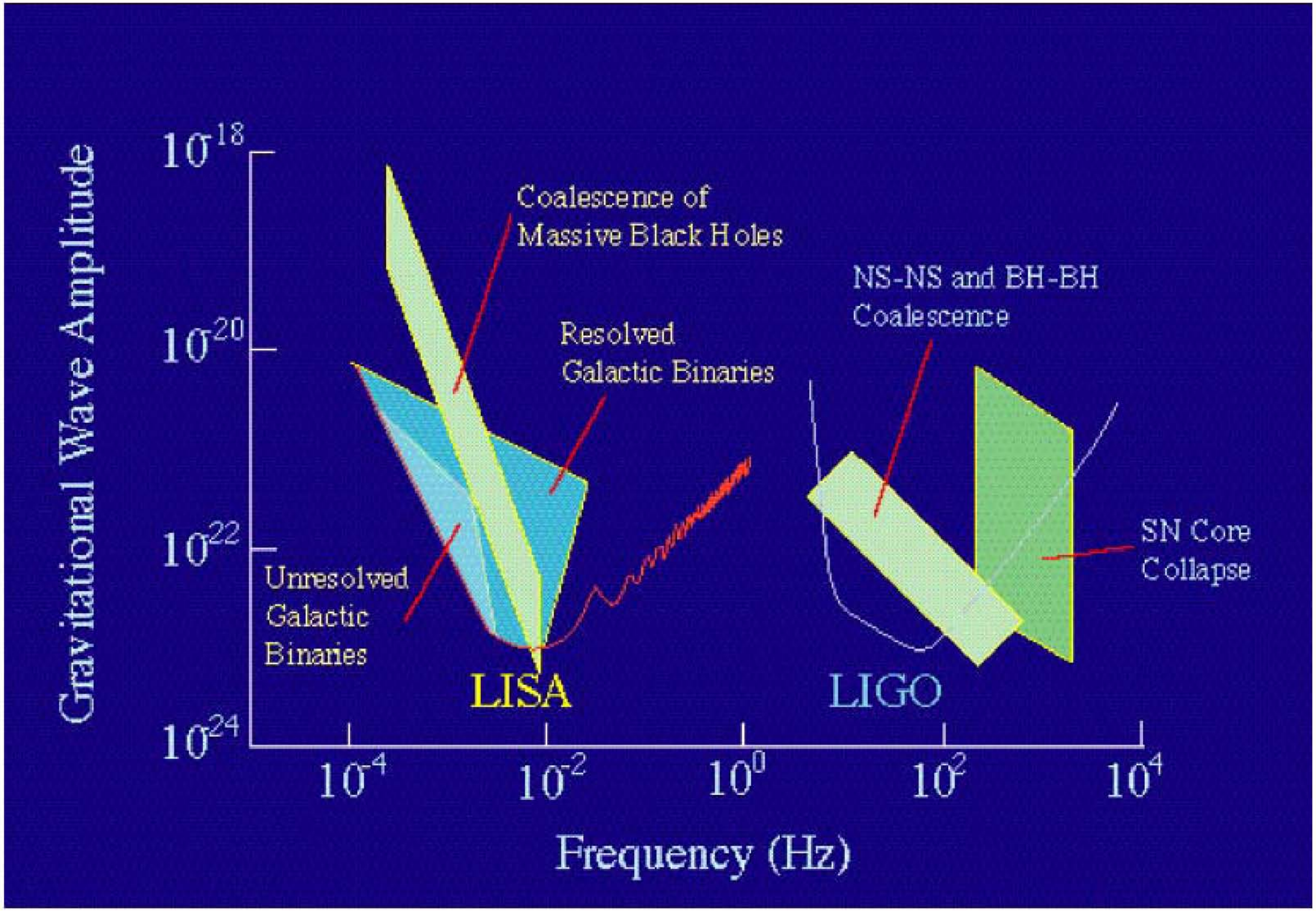
Single 4 km interferometer



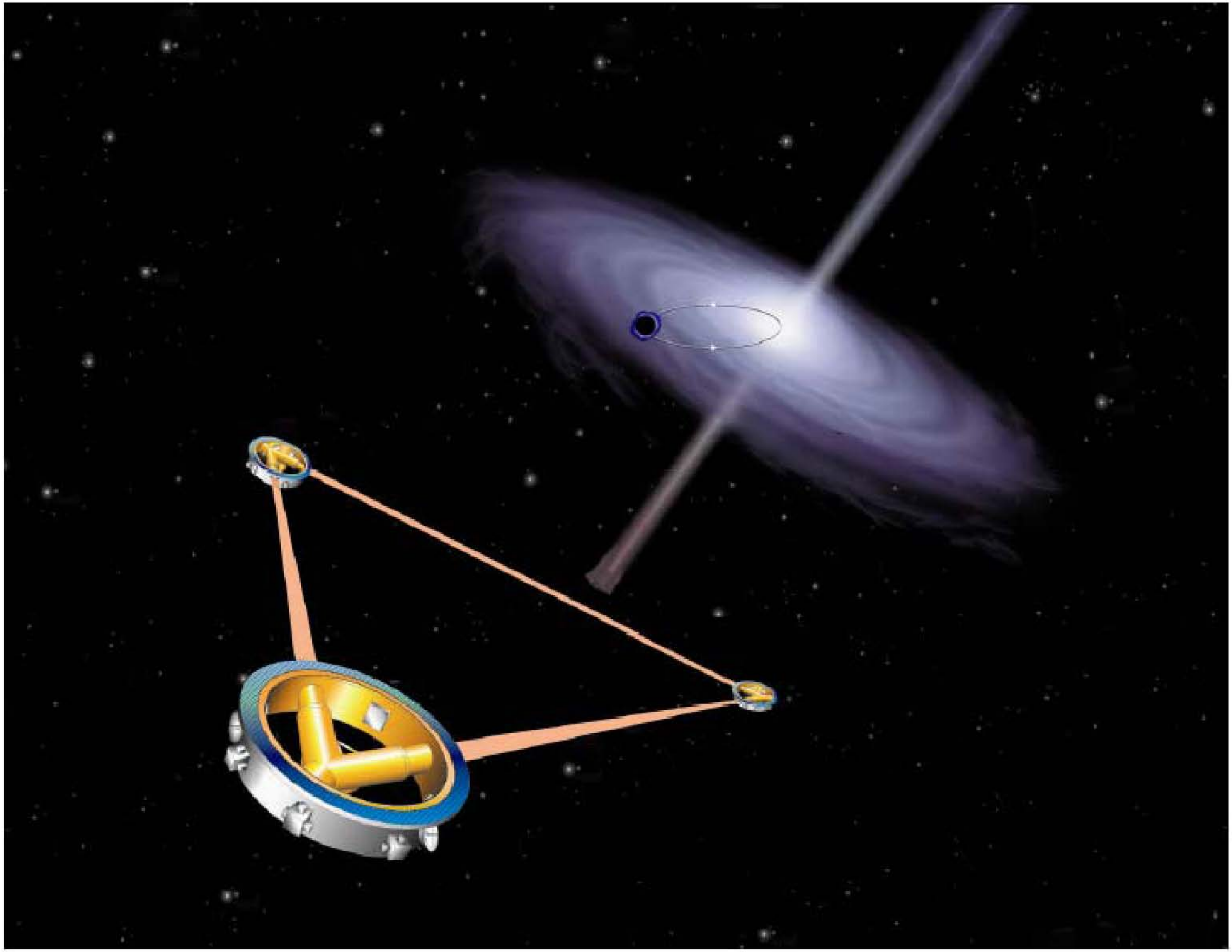
Sky Localization



The Gravitational-Wave Spectrum

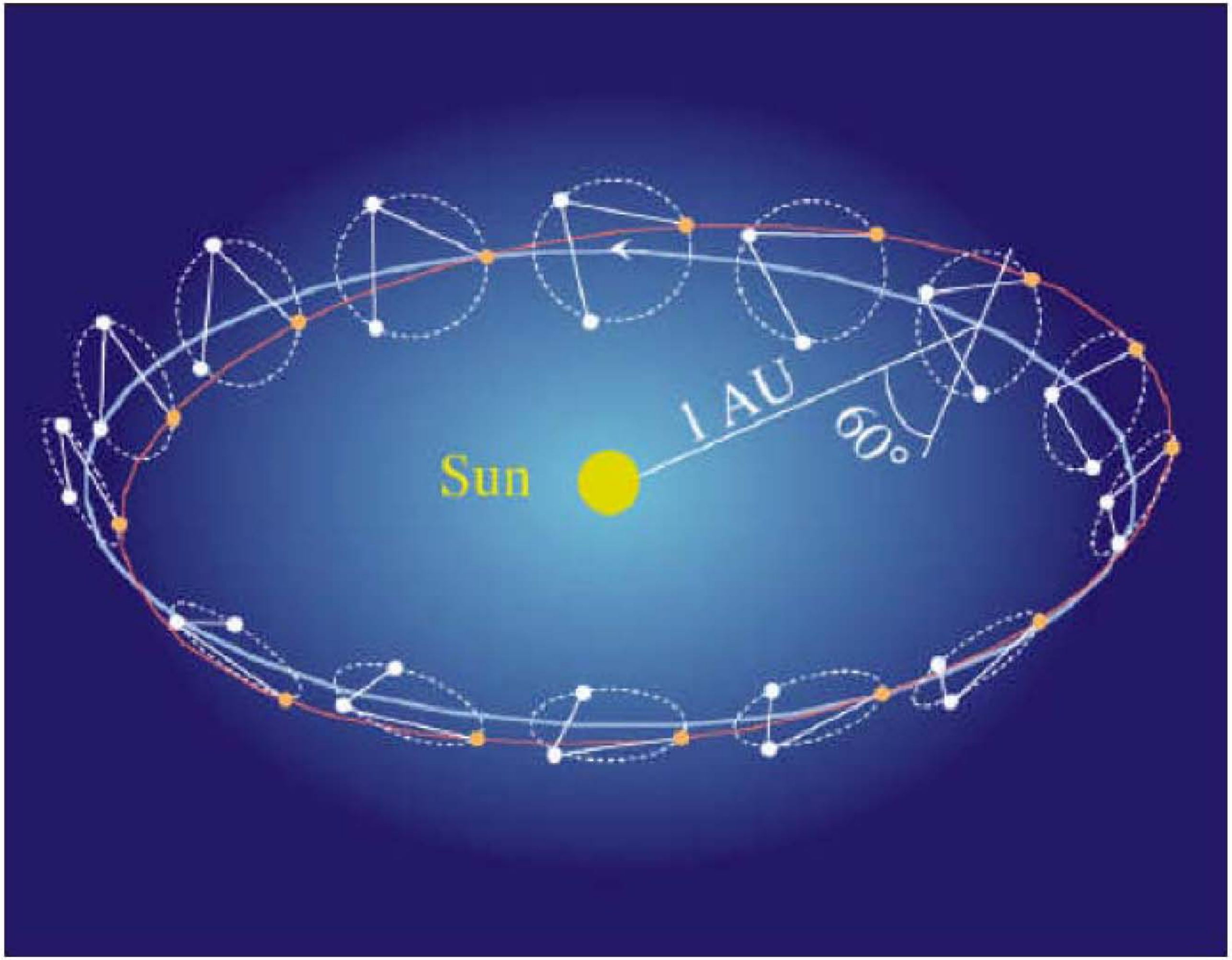


Mission Concept

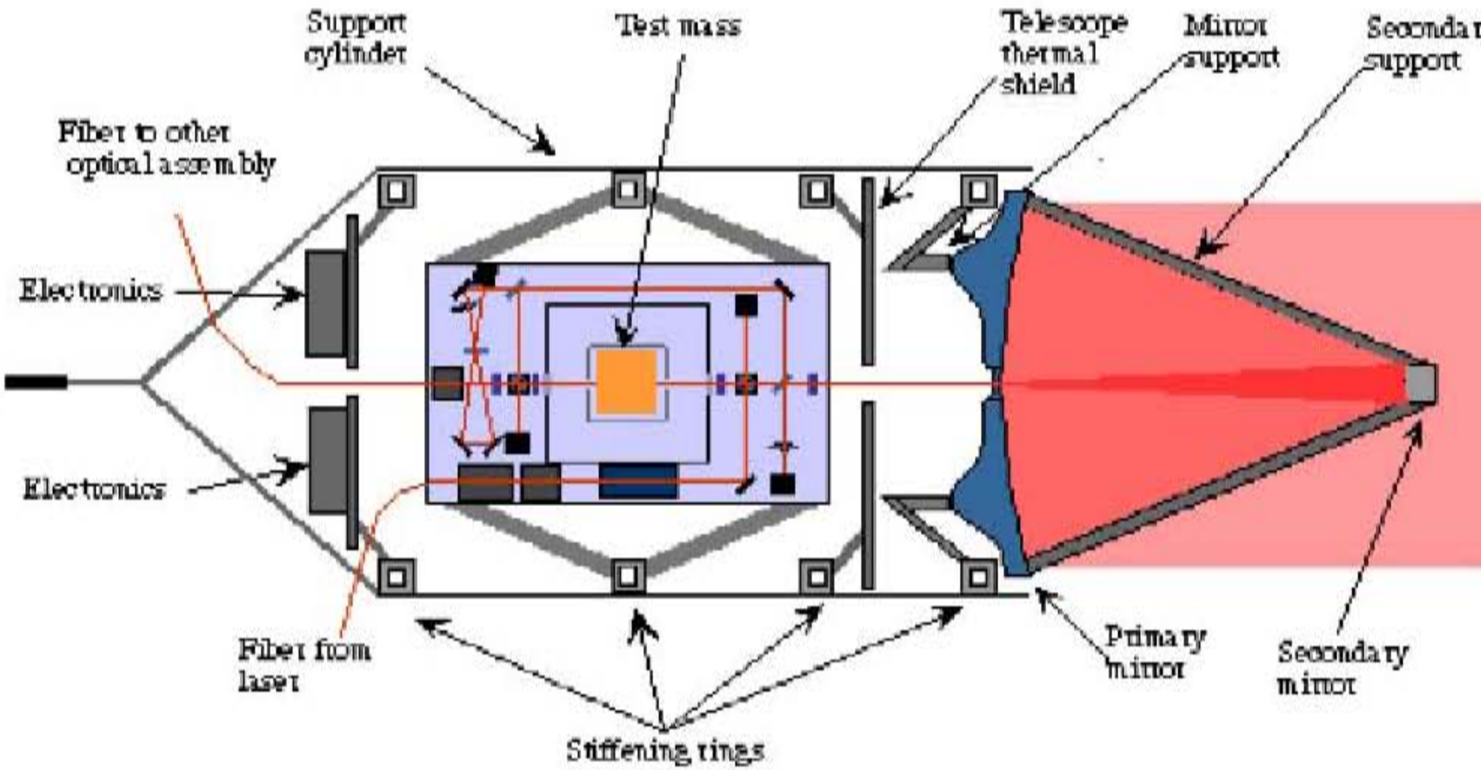


Spacecraft Orbits

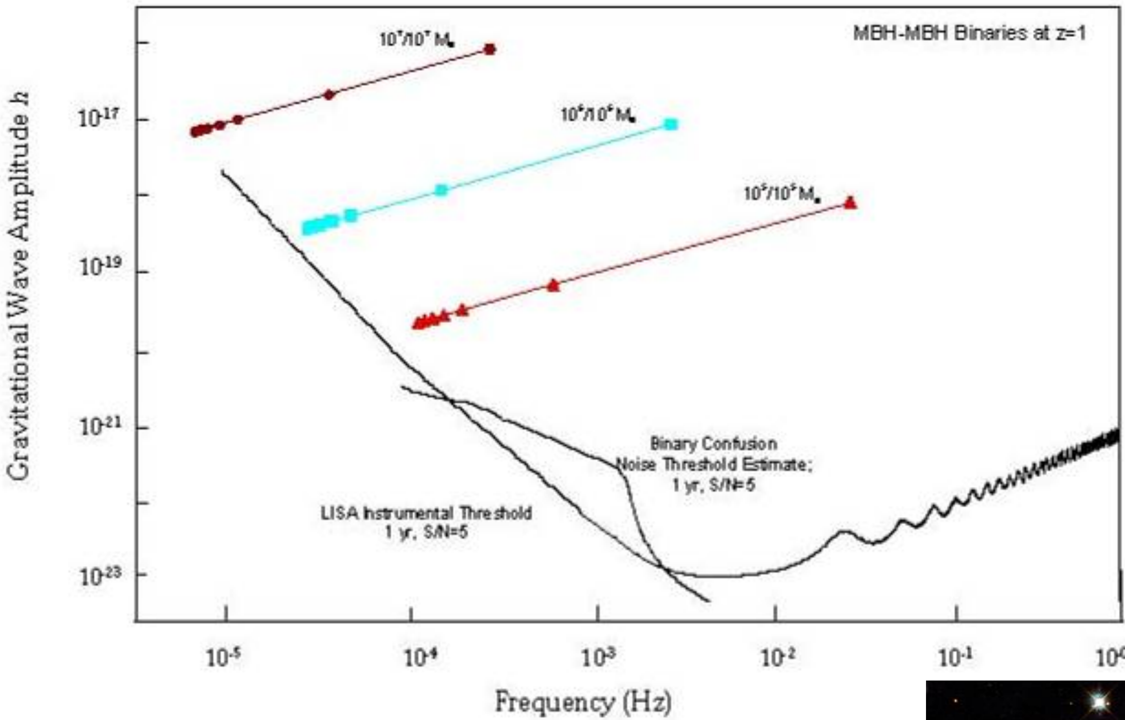
- Spacecraft orbits evolve under gravitational forces only
- Spacecraft fly "drag-free" to shield proof masses from non-gravitational forces

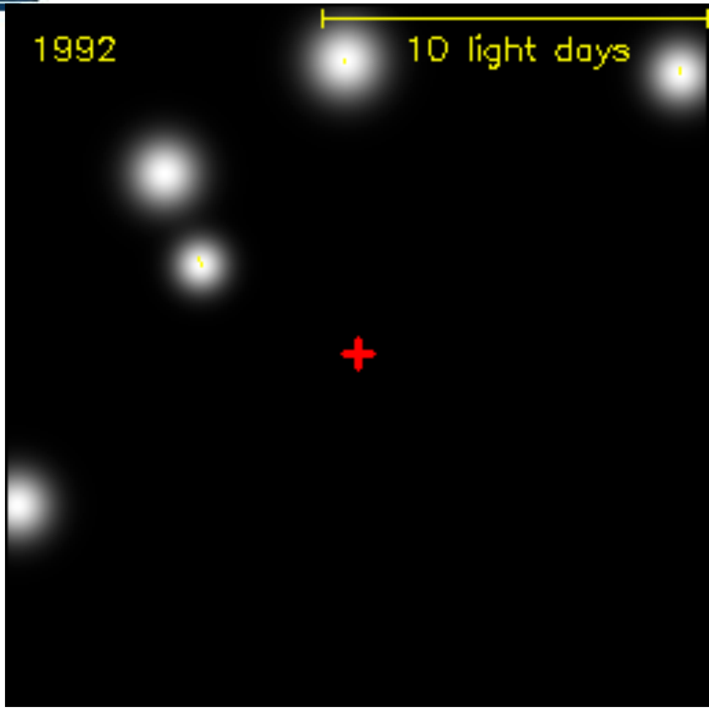


Optical System



Massive Black Holes in Merging Galaxies





R. Genzel

Hubble Space Telescope