Quantum Mechanics of Macroscopic Objects

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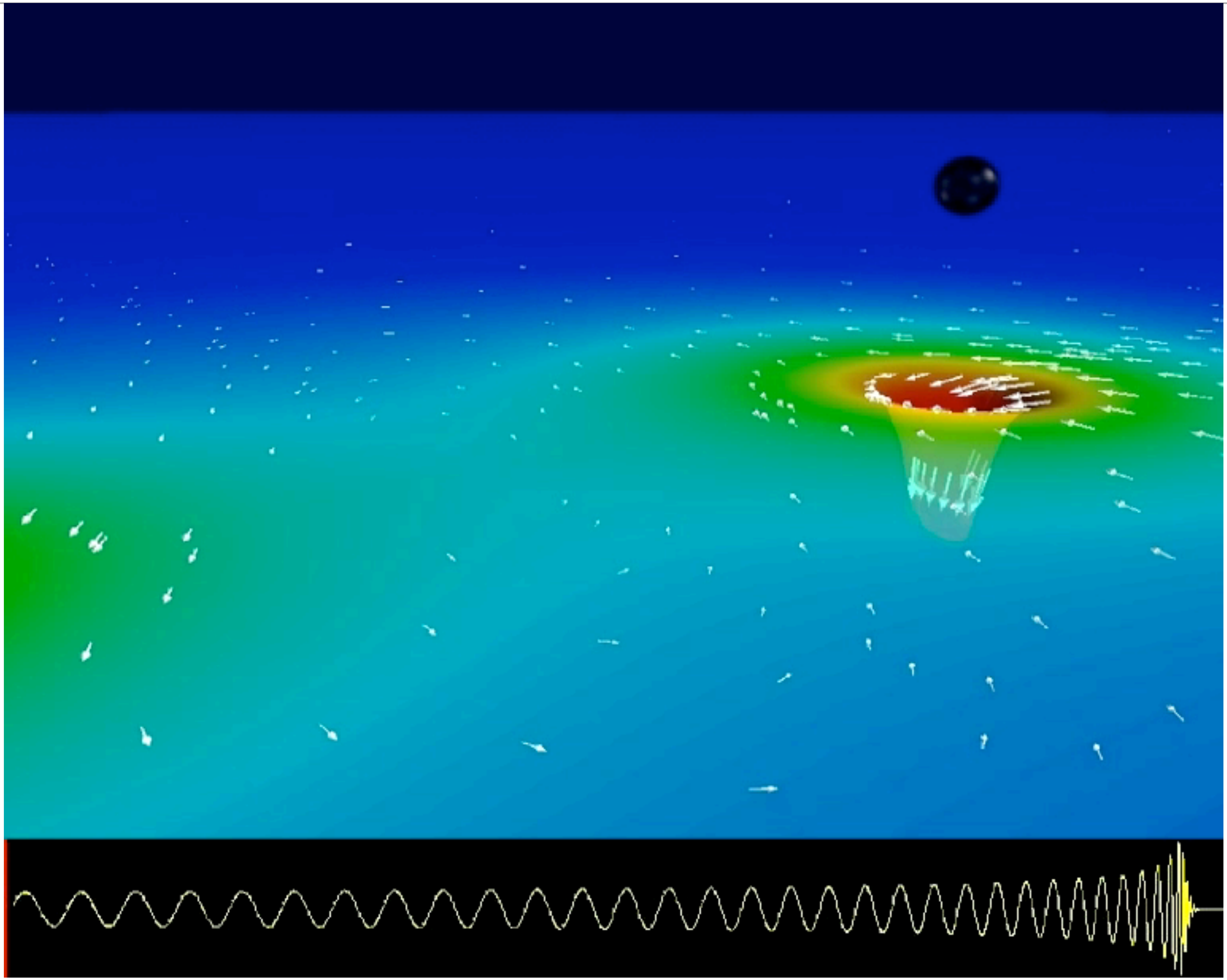
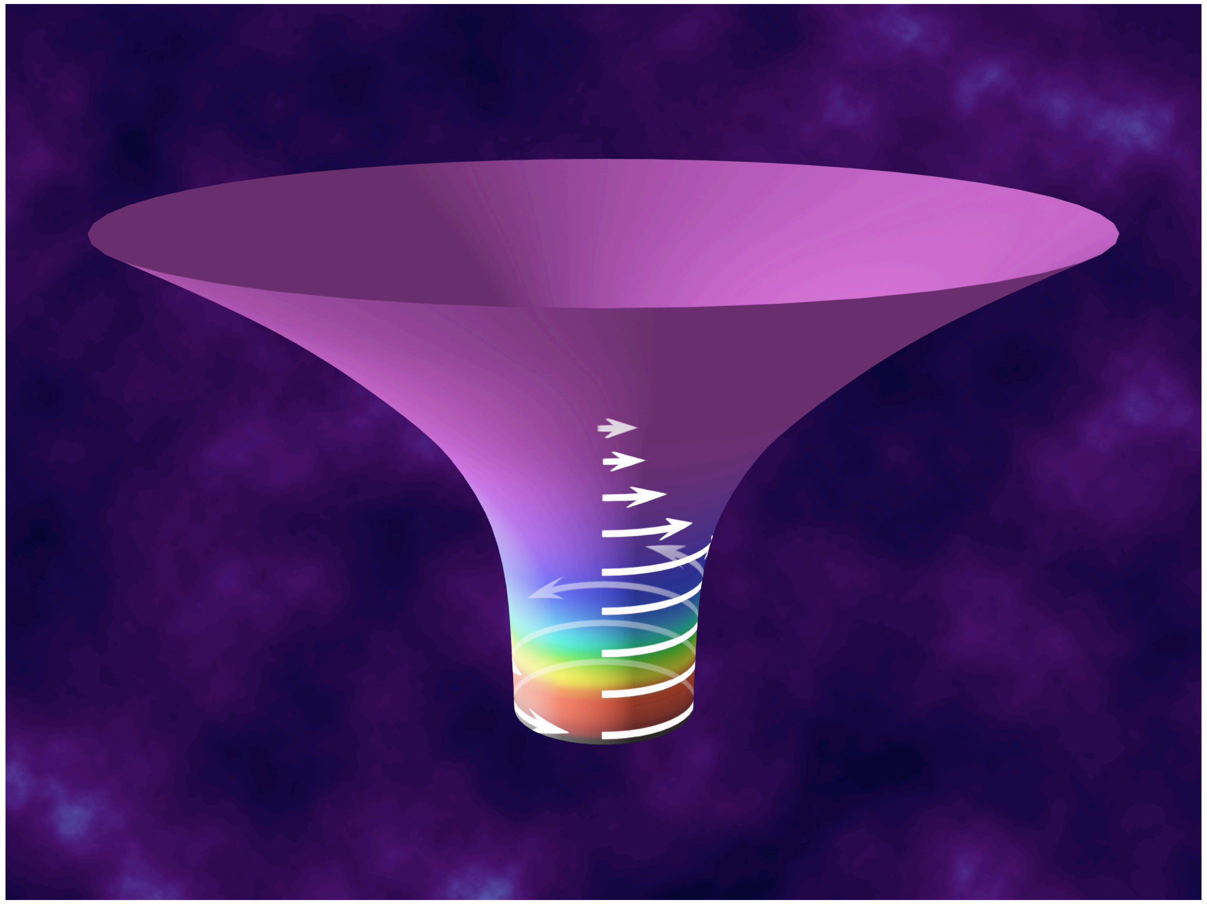
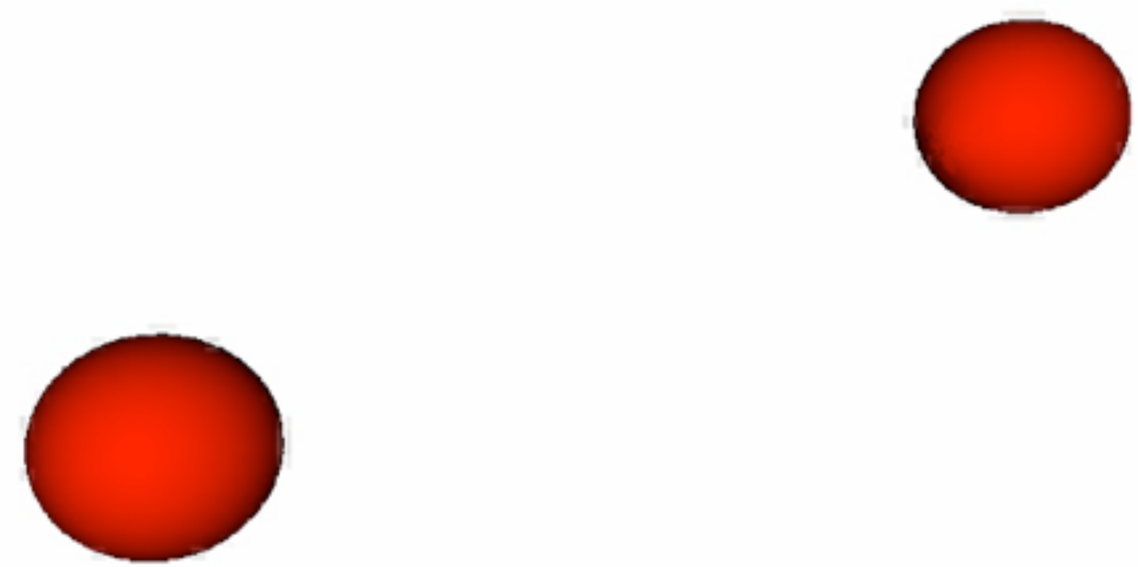
Black Holes Collide



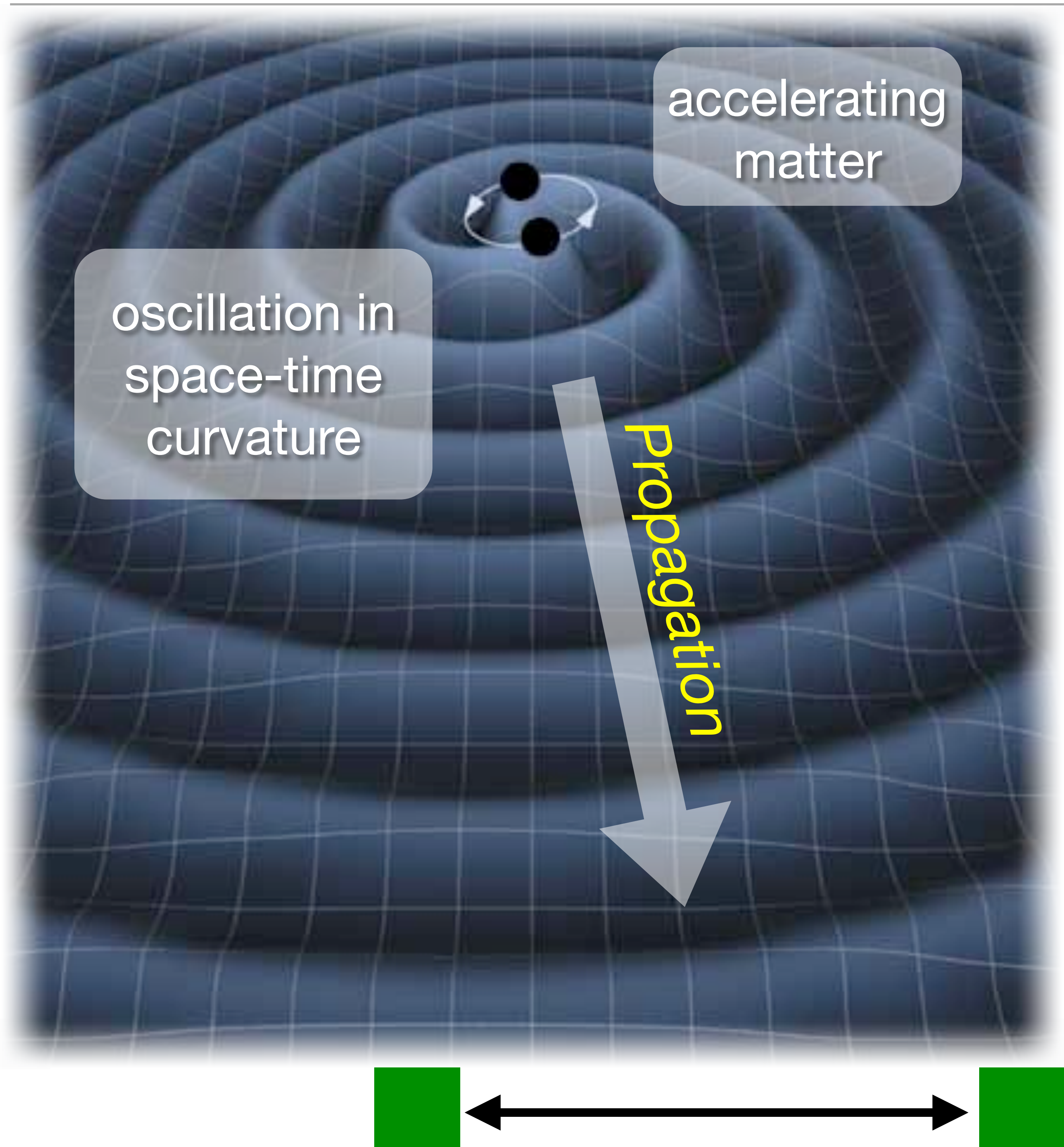
Black Holes





- Black Holes form after very heavy stars run out of fuel, they collapse from millions of km to several km
- Time stops at the surface of black holes. Space is highly curved.
- They get distorted when they collide with each other.
- The best way to learn about black holes is to detect gravitational waves.

Gravitational Waves are Ripples of Spacetime



$\Delta L \sim L \cdot h$

- Relative change in distance is

$$\frac{\Delta L}{L} = (\sim 0.1)\frac{\text{size of system}}{\text{distance to earth}}$$

- Black-hole collision events not frequent enough in our own galaxy. Andromeda is 3 Million Light Years away

$$\frac{\Delta L}{L} = (\sim 0.1)\frac{10\text{ km}}{3\text{ Mly}} \sim 4 \times 10^{-20}$$

- If we separate objects by 4 km

$$\Delta L = 10^{-16}\text{ meter}$$

(still an over estimate)

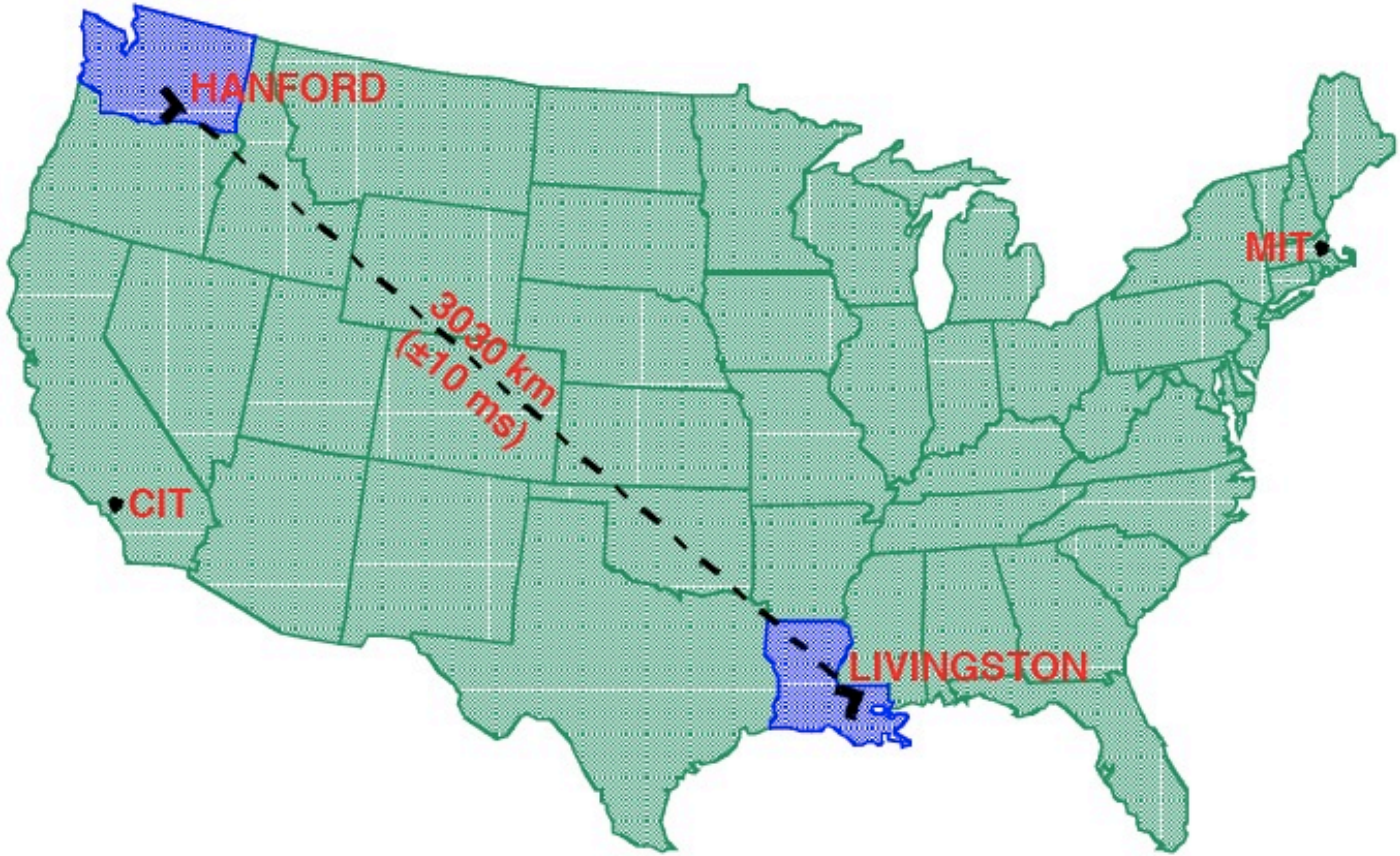
relative distance between free objects oscillates

Laser Interferometer Gravitational-wave Observatory (LIGO)

Hanford, Washington

Laser Interferometer Gravitational-wave Observatory (LIGO)

Livingston, Louisiana


HANFORD
3030 km
(±10 ms)
CIT
MIT
LIVINGSTON

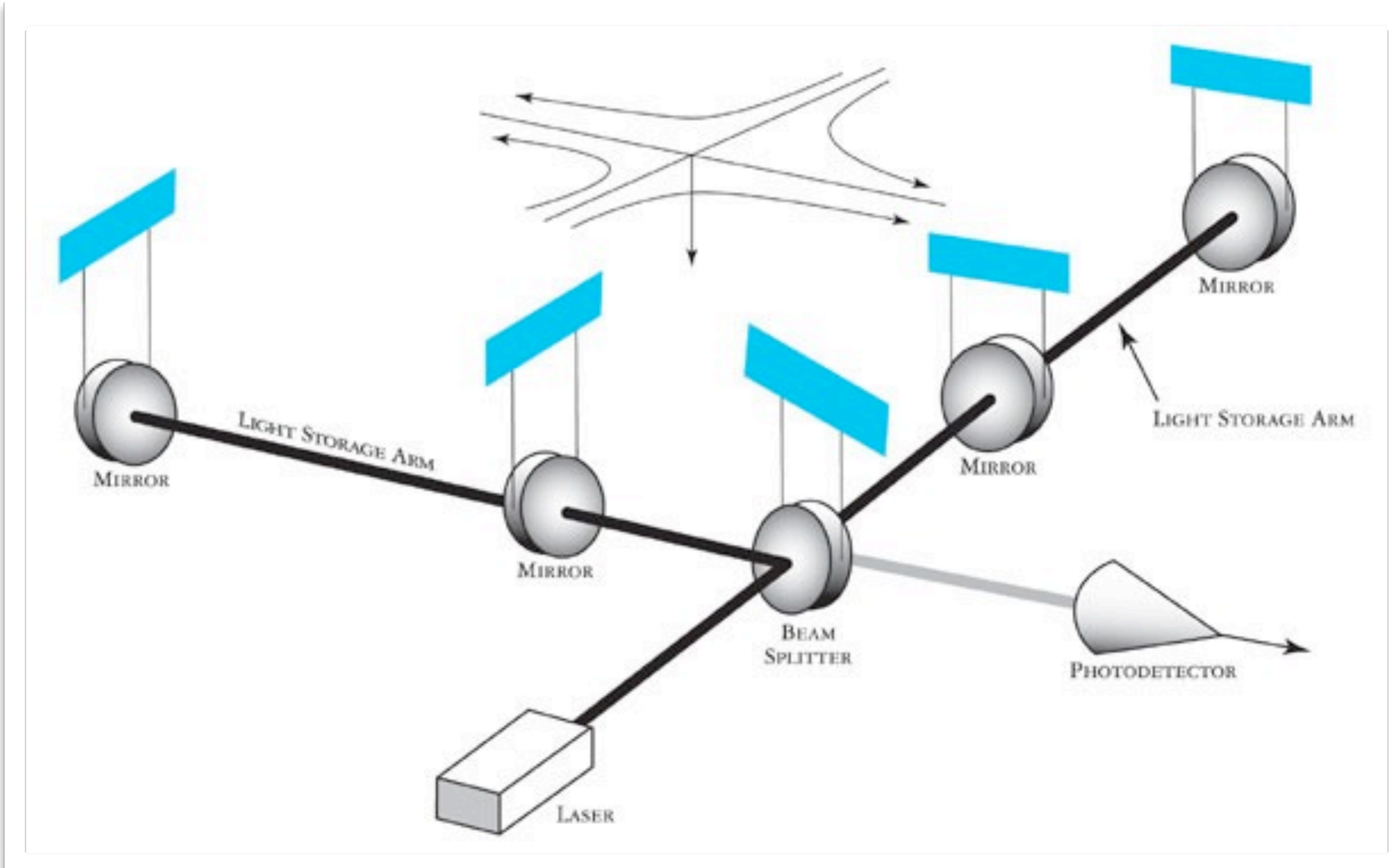
International Partners

VIRGO: near Pisa, Italy
French-Italian

GEO600, near Hannover, Germany
British-German

TAMA 300, near Tokyo
Japanese

Michelson Interferometry



Current position sensitivity: 10^{-18} meter = 1 attometer

waves from 40 Hz to 10 kHz

LIGO Sensitivity

	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)

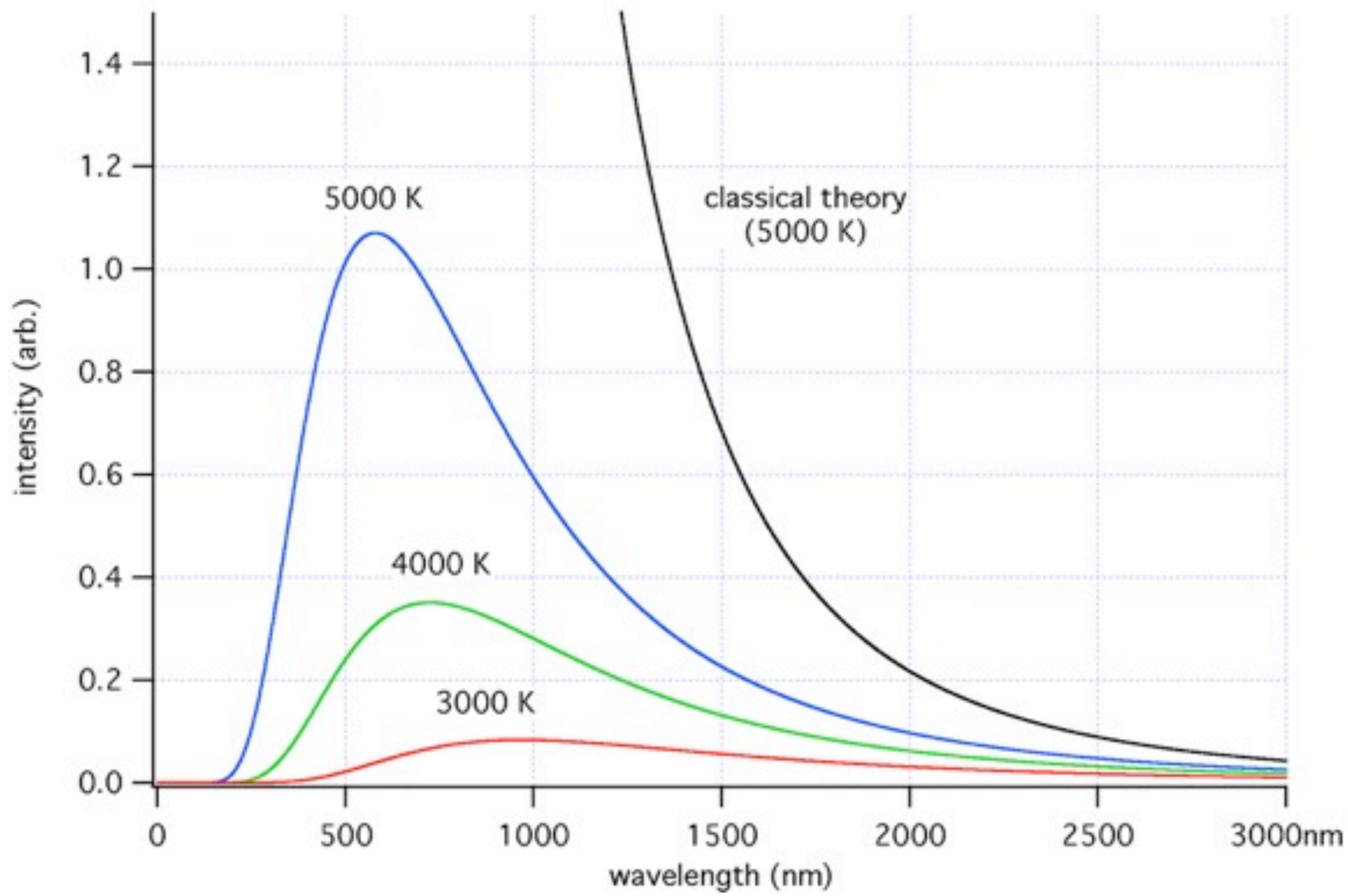
average over many atoms (wide beam)

Photons: Black-Body Radiation

- Light energy is *quantized (broken into pieces, or photons)*

$$E = h\nu = \frac{hc}{\lambda}$$

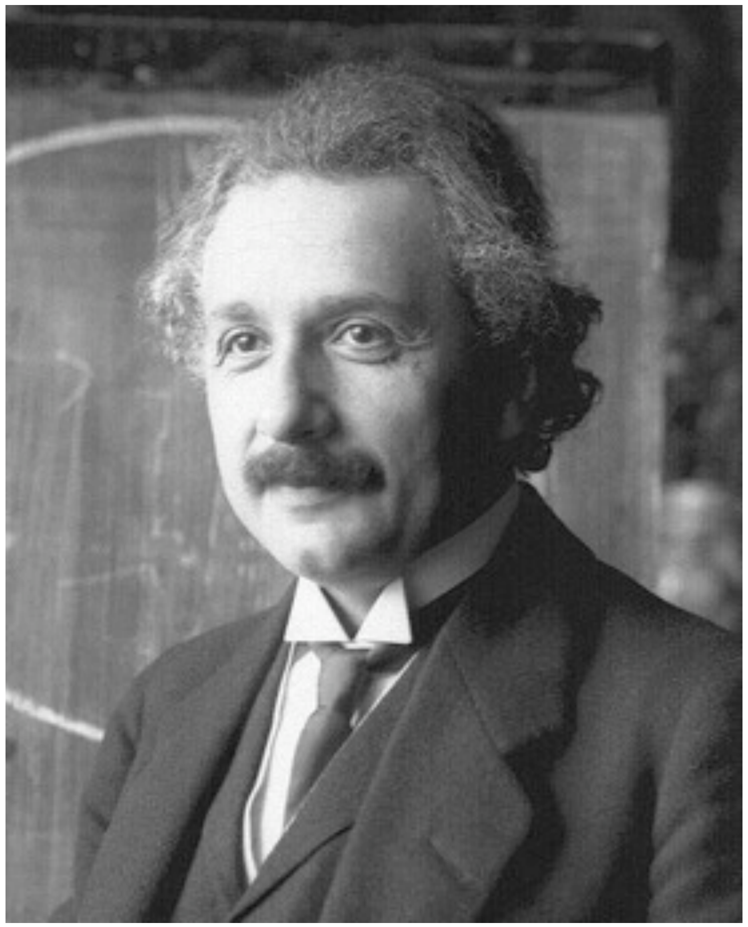
Max Planck
1858-1947



Planck's black-body radiation spectrum (1900)

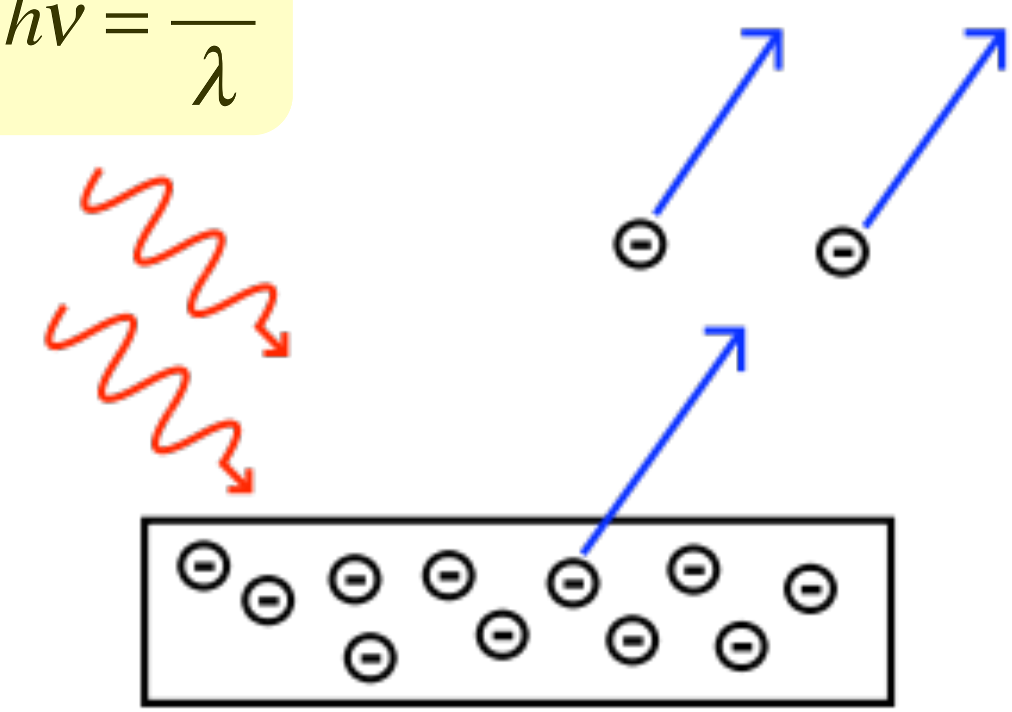
Short-wavelength light not radiated: thermal energy not enough to "excite" photons

Photoelectric Effect



Albert Einstein
1879-1955

$$E = h\nu = \frac{hc}{\lambda}$$

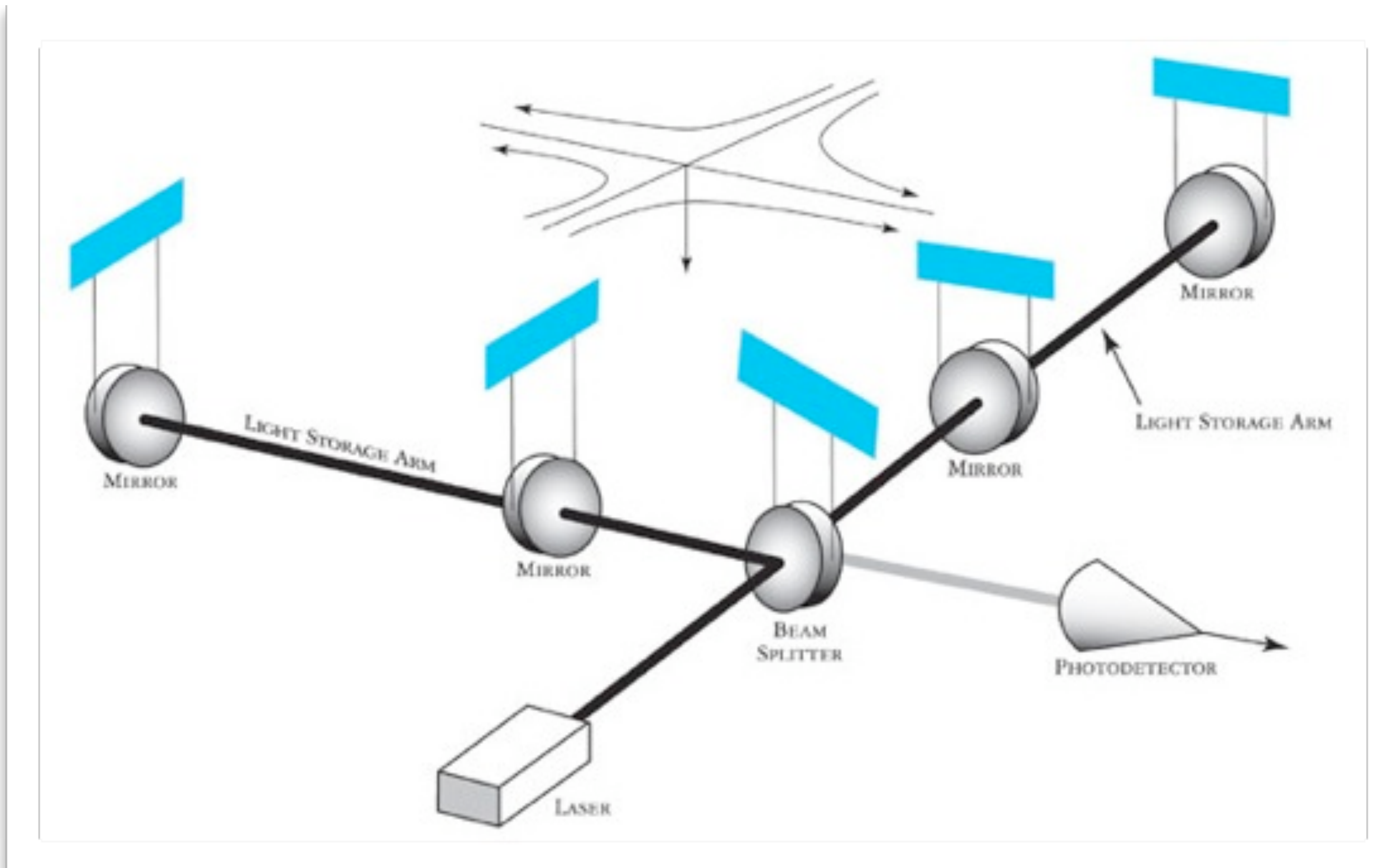


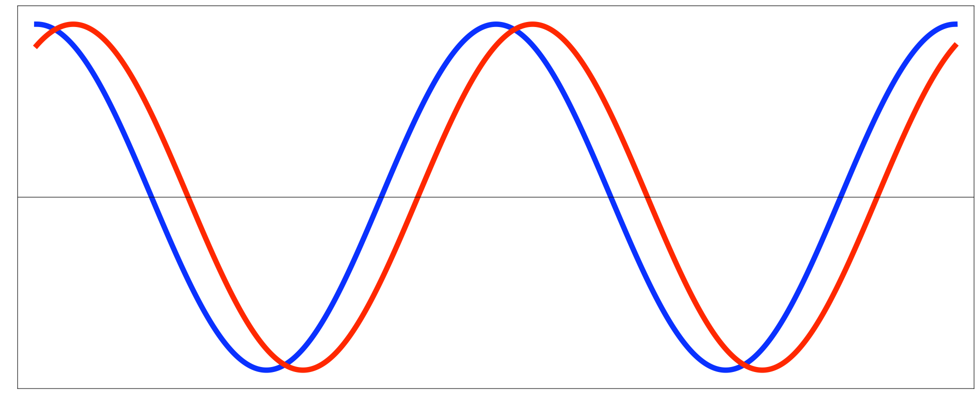
- Only light with short enough wavelength can "knock" electrons out of metal: because energy delivered *discretely*. (1905)

$$h\nu = \phi + E_{kinetic}$$

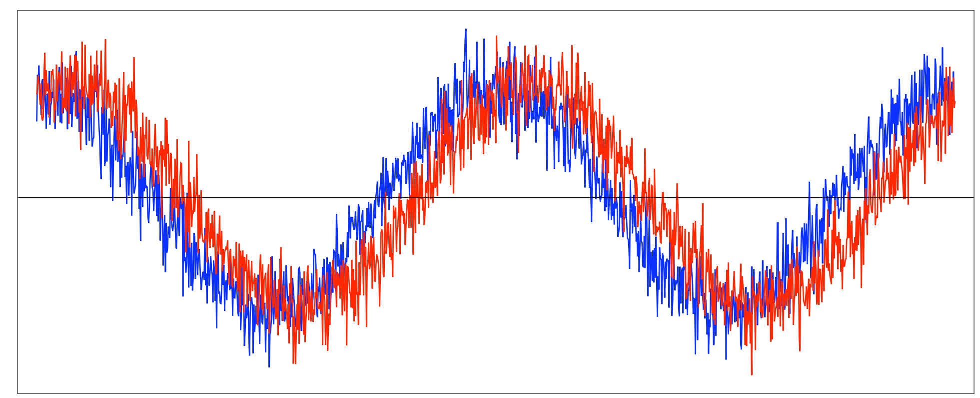
Photon "shot noise"

- Quantization of light limits measurement accuracy.





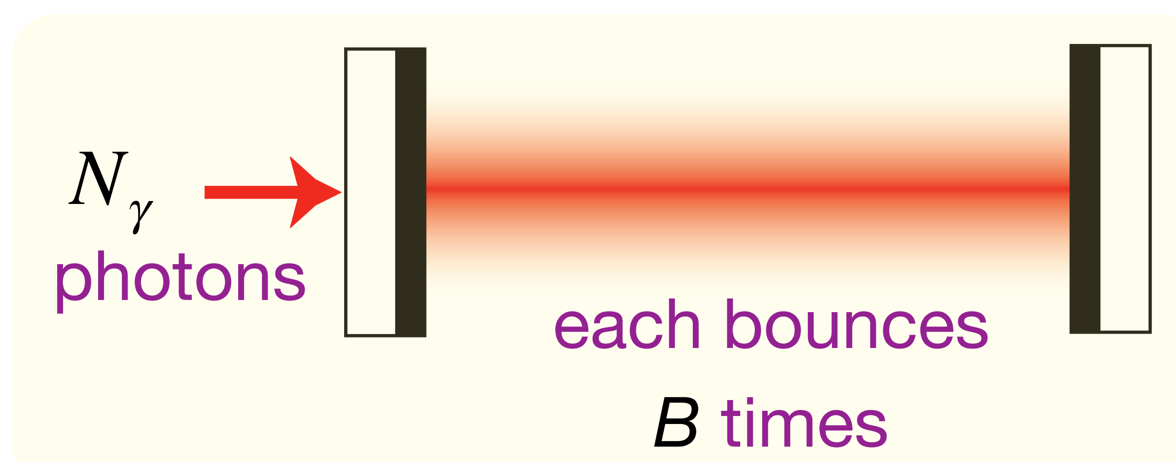
classical electromagnetic wave



now with quantum fluctuations

- For LIGO, which has Fabry-Perot cavities

$$\delta x \sim \frac{\lambda}{2\pi} \frac{1}{B} \frac{1}{\sqrt{N_\gamma}}$$

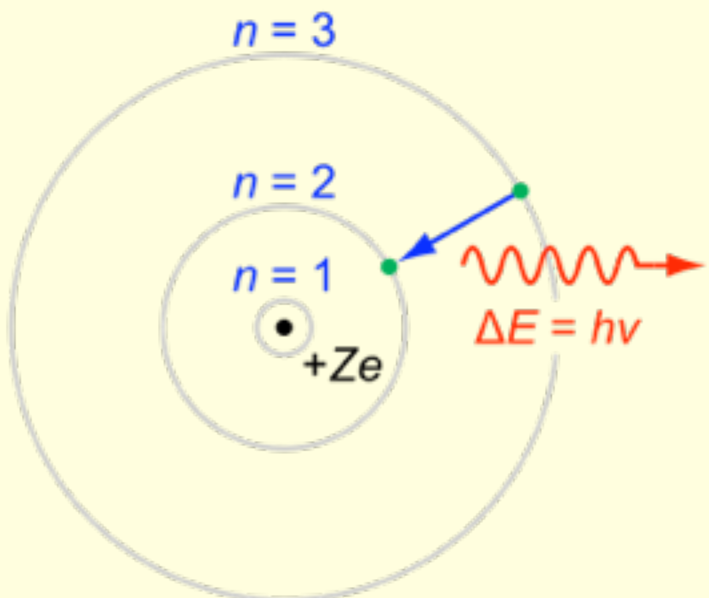


- Need to increase # of photons
- *... but this is not yet the whole story*

Wave/Particle Duality

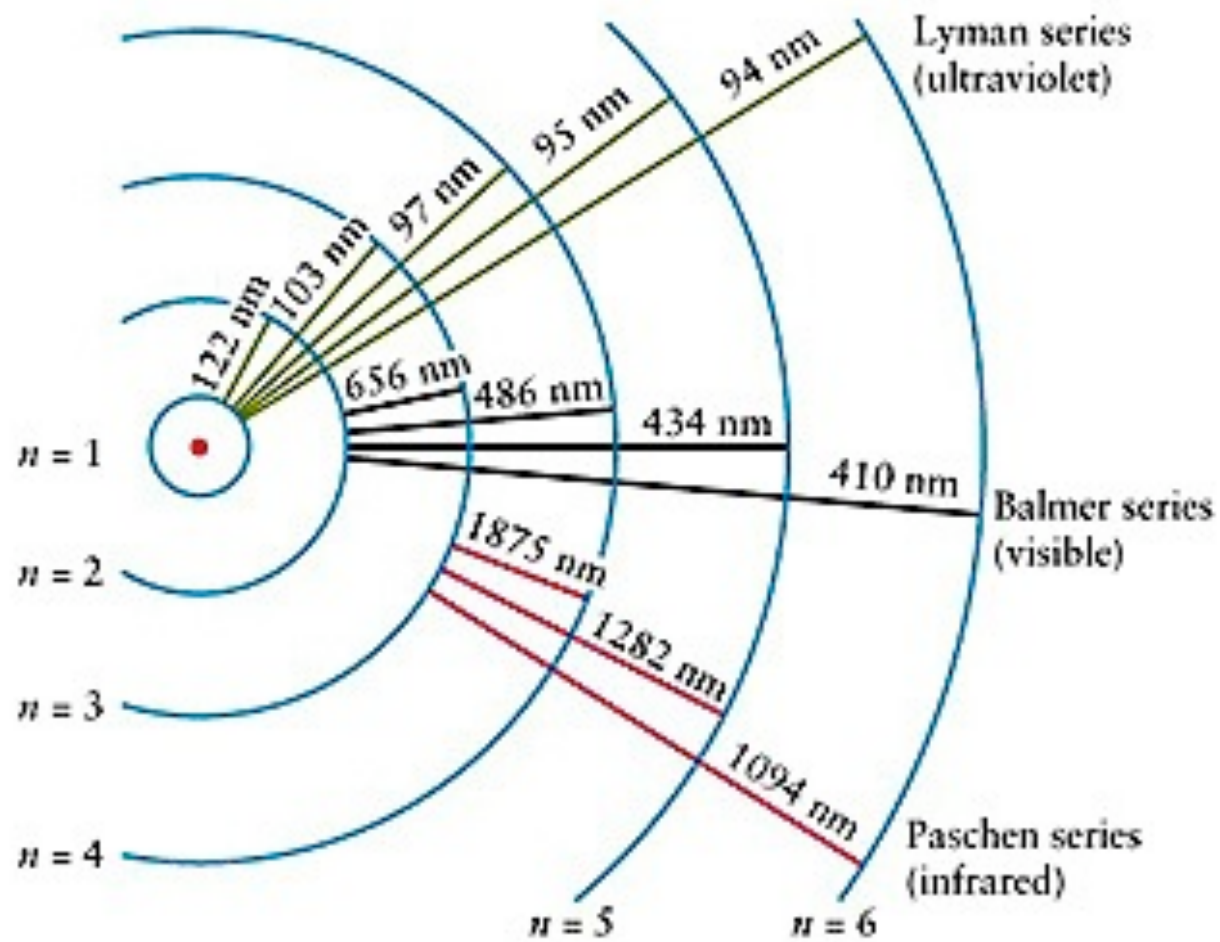
- Quantization of light: light is wave --- but also particles
- Electrons are particles --- but they are also waves

Niels Bohr



Bohr's model of atom

1913



de Broglie

Electrons are also waves

Bohr's orbits are standing waves

1924

de Broglie wave length

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

Wave/Particle Duality

- Quantization of light: light is wave --- but also particles
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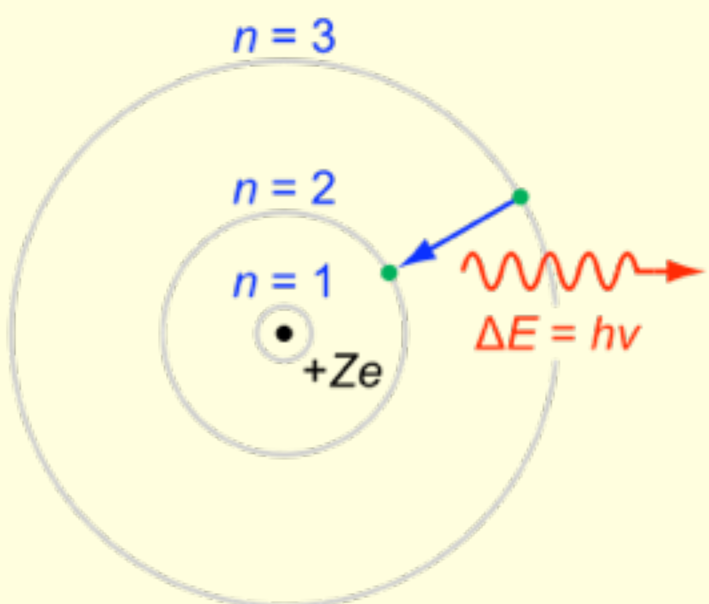
Niels Bohr



Bohr's model of atom

1913

de Broglie

Electrons are also waves

Bohr's orbits are standing waves

1924

modern quantum mechanics

Werner Heisenberg

Erwin Schrödinger

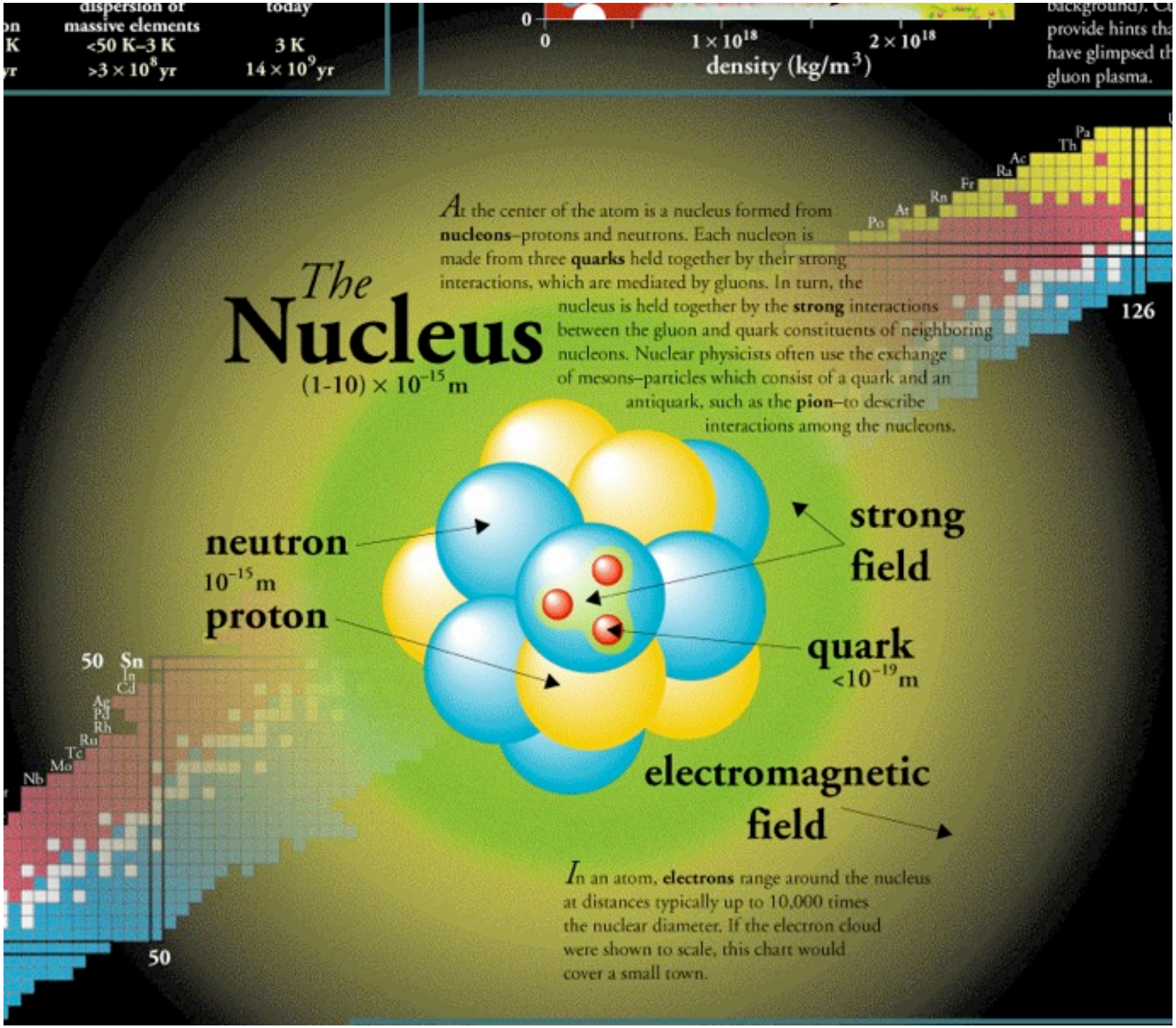
The Schrödinger Equation

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = -\frac{\hbar^2}{2m}\nabla^2\Psi(\mathbf{r},t) + V(\mathbf{r})\Psi(\mathbf{r},t)$$

Ψ **: wavefunction**

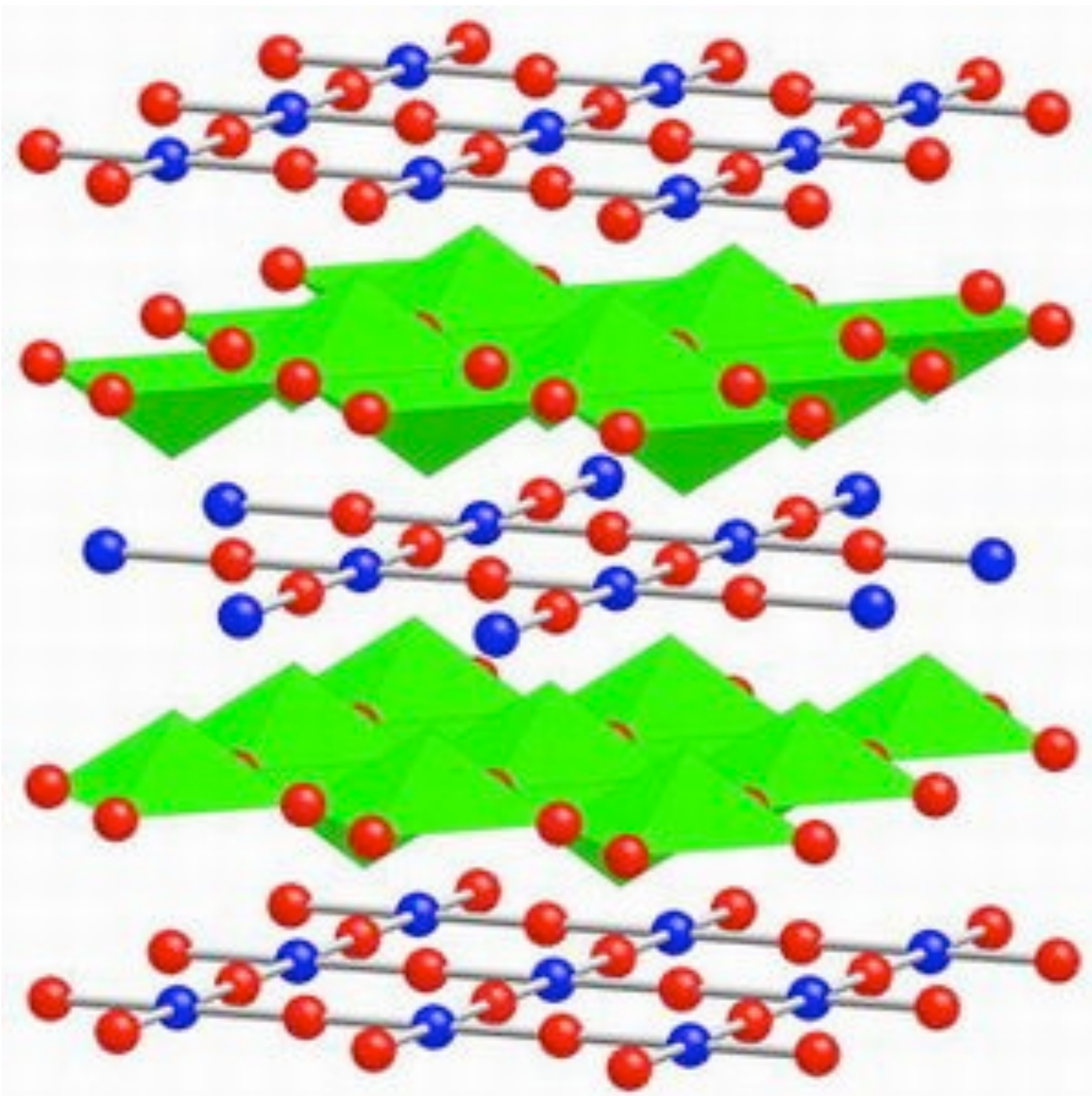
$|\Psi|^2$: probability density

Quantum Mechanics as Foundation of Modern Physics

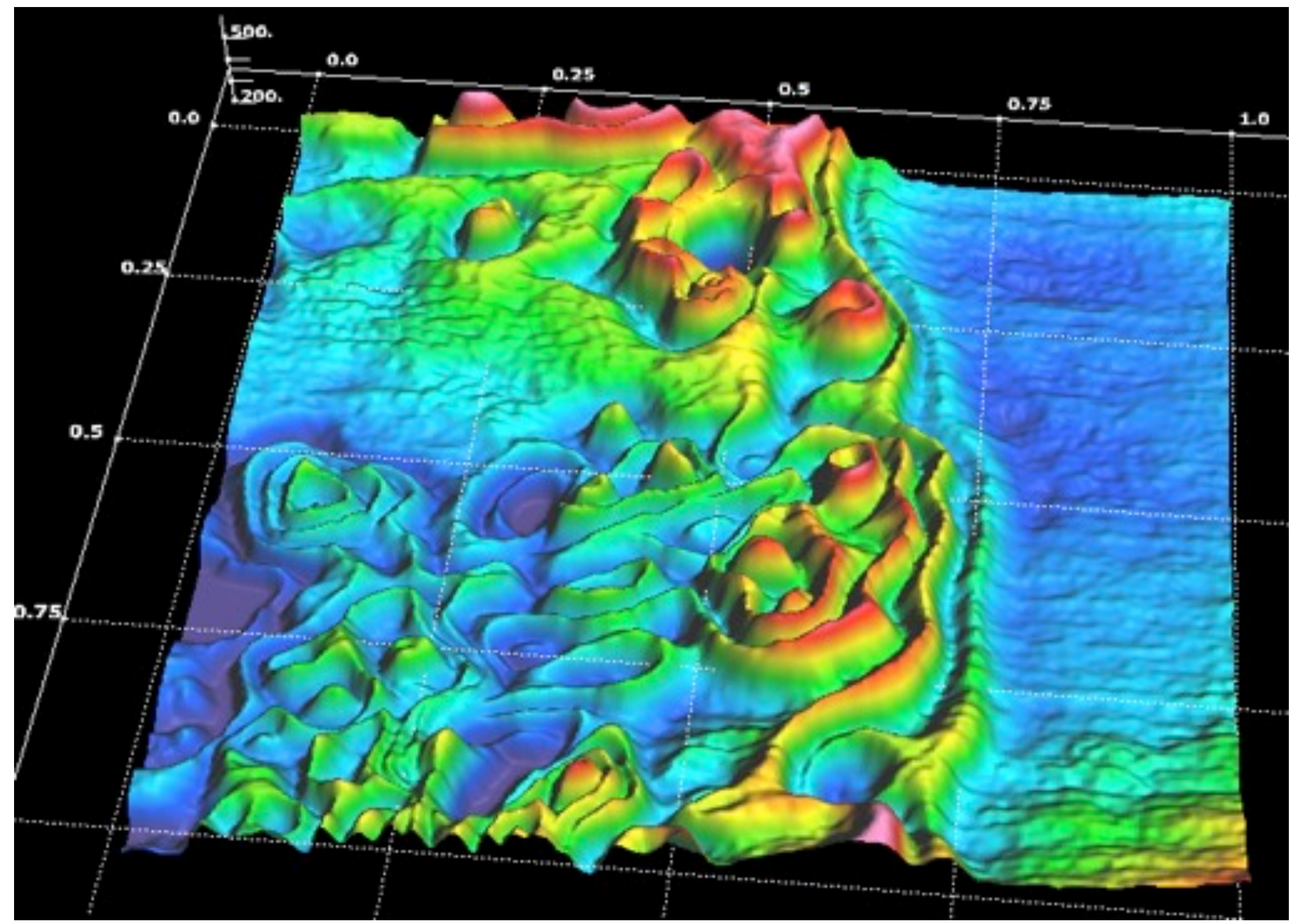


Nuclear & Particle Physics: Revealing Deeper Structures of Matter

Quantum Mechanics as Foundation of Modern Physics



Structure of superconducting material YBCO
(Argonne National Lab)

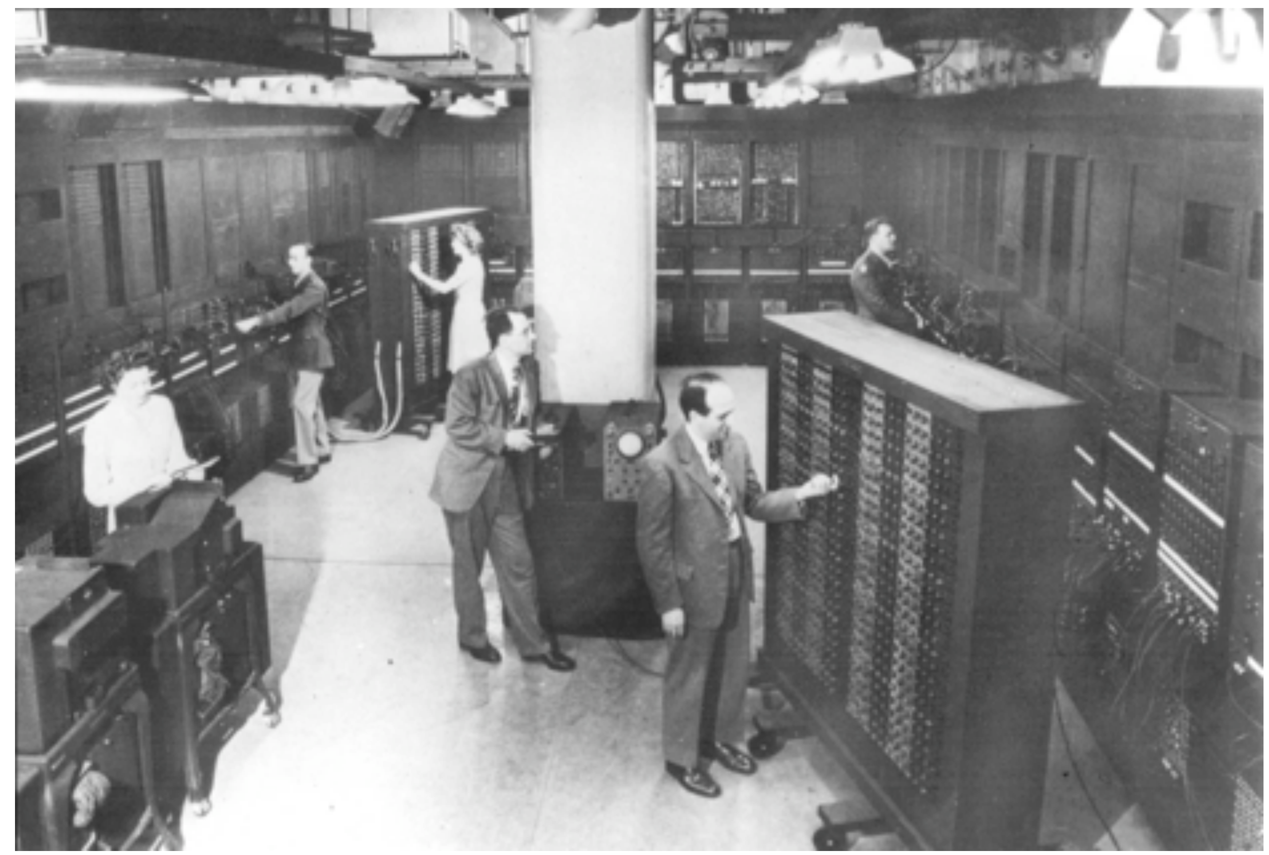


Electron density map in a 2-D electron gas
(G. Finkelstein, Duke University)

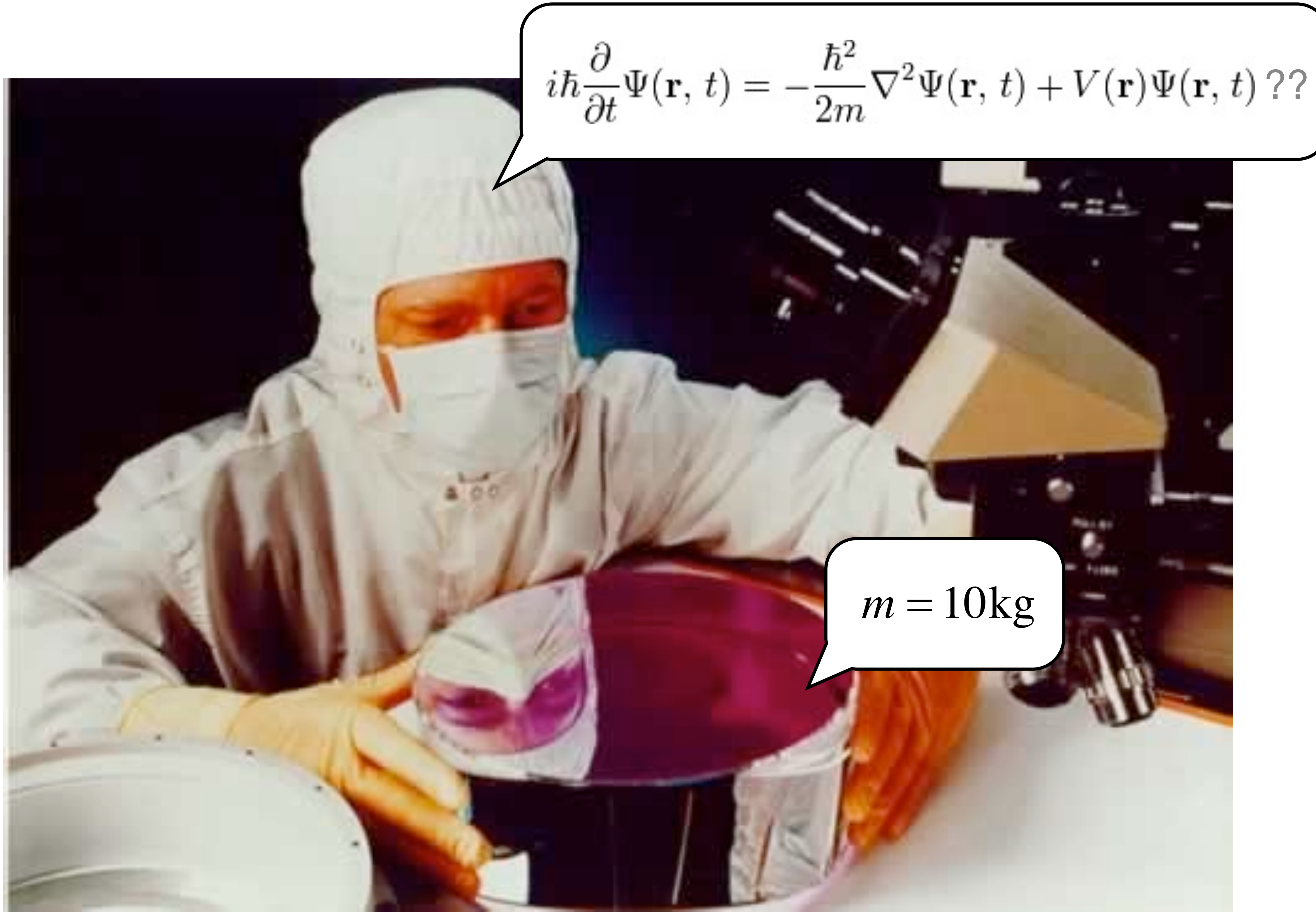
Condensed Matter Physics: Exotic Properties of Matter

Quantum Mechanics in Modern Technology

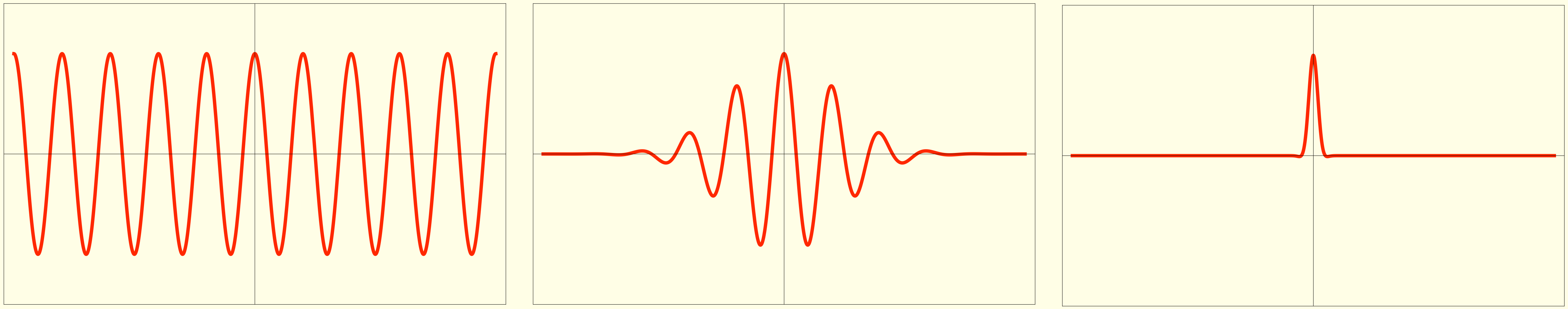
= 40,000 X



ENIAC: picture from the U of Penn


$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},\,t) = -\frac{\hbar^2}{2m}\nabla^2\Psi(\mathbf{r},\,t) + V(\mathbf{r})\Psi(\mathbf{r},\,t)$??
$m = 10\text{kg}$

The Heisenberg Uncertainty Principle



a "pure" wave has unique wavelength
cannot be localized at all

a wavy burst contains multiple wavelengths
somewhat localizable

a sharp burst contains many wavelengths
very localizable

Fourier Analysis: $\delta x \times \delta\left(\frac{1}{\lambda}\right) \geq \frac{1}{2\pi}$

- De Broglie Wavelength

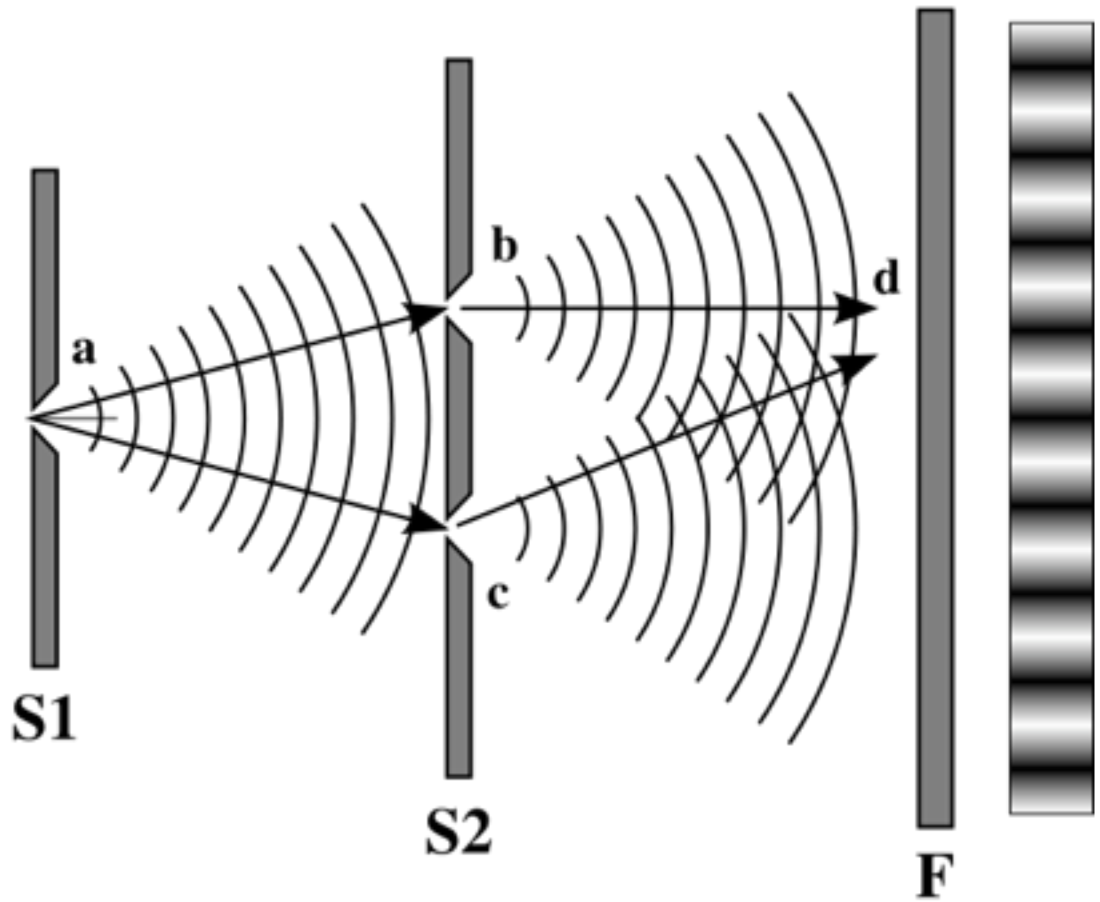
$$\lambda = \frac{h}{p} = \frac{h}{mv} \Rightarrow p = \frac{h}{\lambda} \Rightarrow \delta p \times \delta x \geq \frac{h}{2\pi} \equiv \hbar$$

Position & Momentum (speed) of Particle Cannot be Simultaneously Specified!

Heisenberg Uncertainty Principle

Quantum Superposition

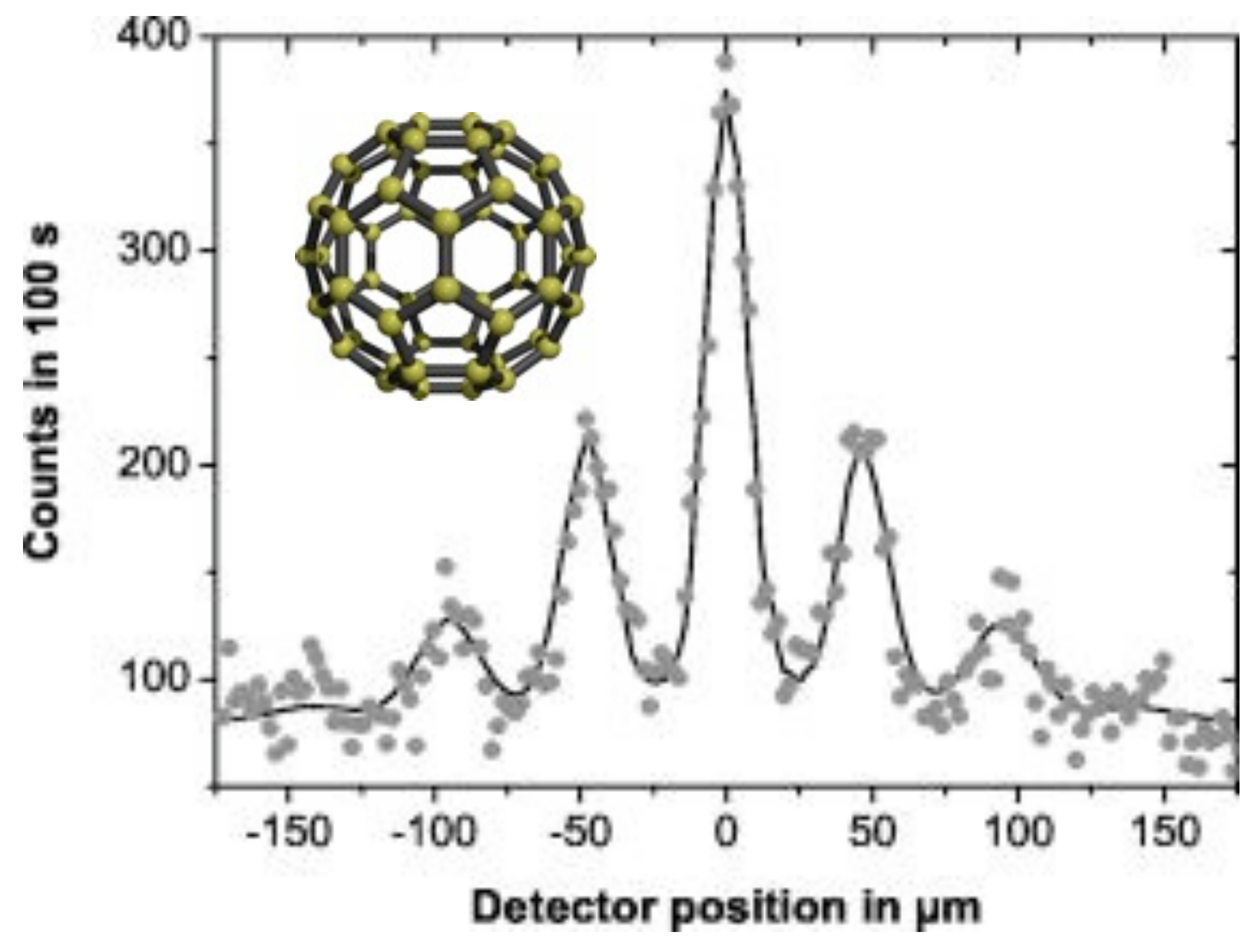
- Waves Interfere: Quantum Superposition



Double Slit for Matter Wave

particle at a superposition state

$$|\Psi(S2)\rangle = |b\rangle + |c\rangle$$

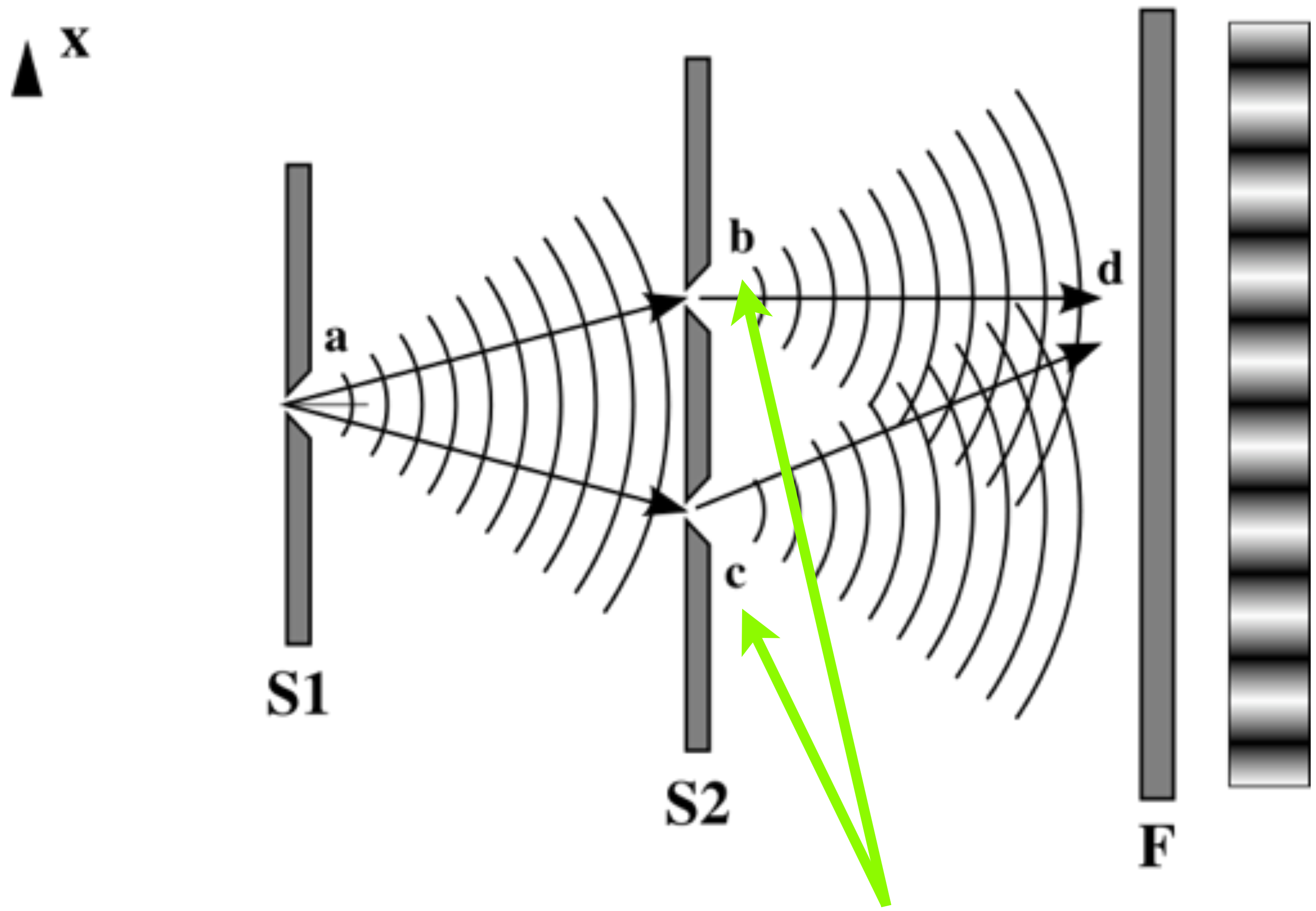


Data Using Fullerene Molecule C_{60}

Research Group of A. Zeilinger in Vienna

Collapse of Wave Function due to Measurement

- Measurement Collapses Wave Function
- Can destroy interference pattern (*loss of quantum coherence, or **decoherence***)



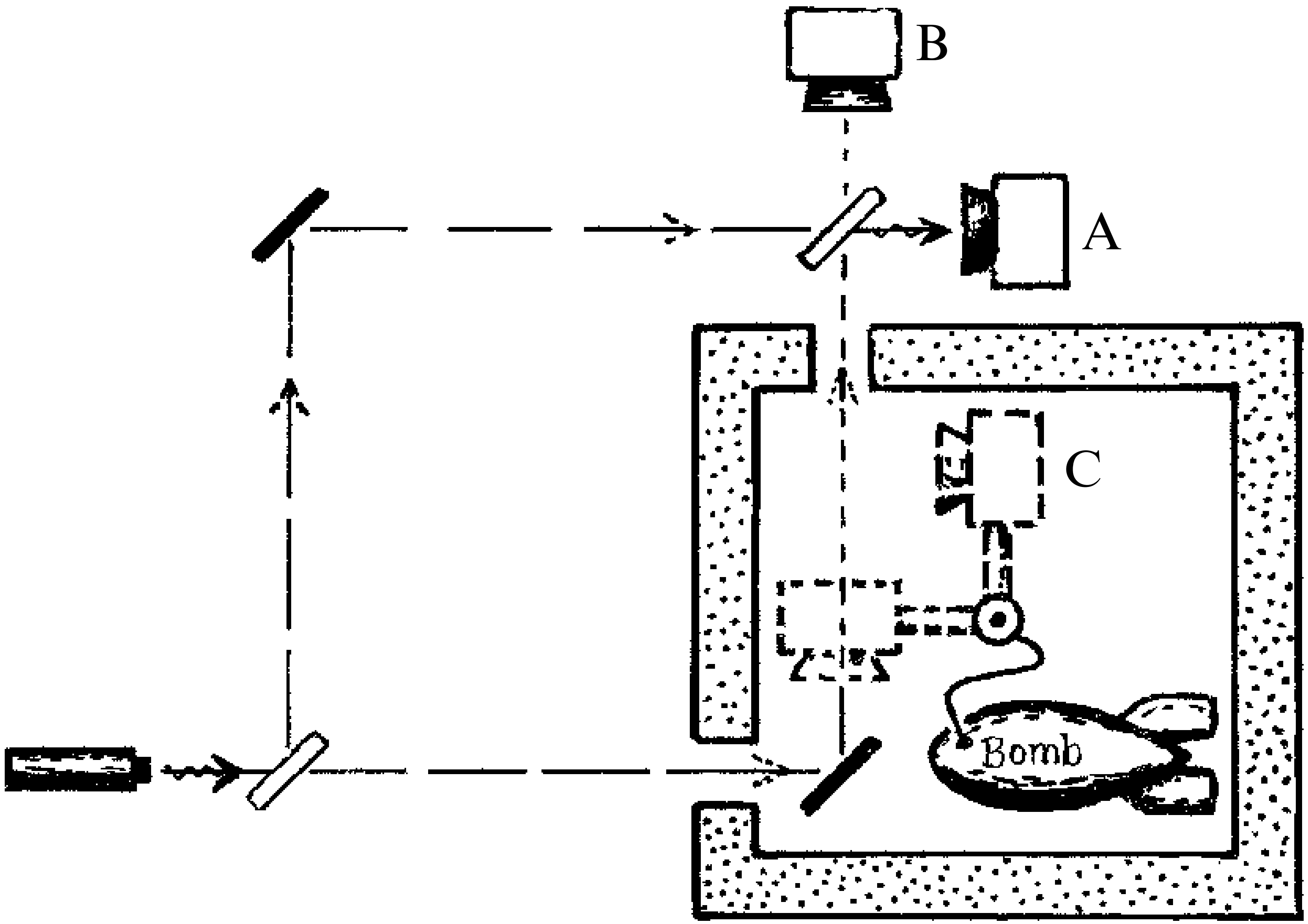
Interference Pattern would Disappear

If Detectors Placed Here

$$|\Psi(S2)\rangle = |b\rangle + |c\rangle \quad \xrightarrow{\text{measurement}} \quad |b\rangle \text{ or } |c\rangle$$

quantum superposition — measurement — classical choice

Bomb Testing "Experiment"



Elitzur-Vaidman Bomb Test (Drawing by Roger Penrose)

How do we make sure a bomb is good without detonation

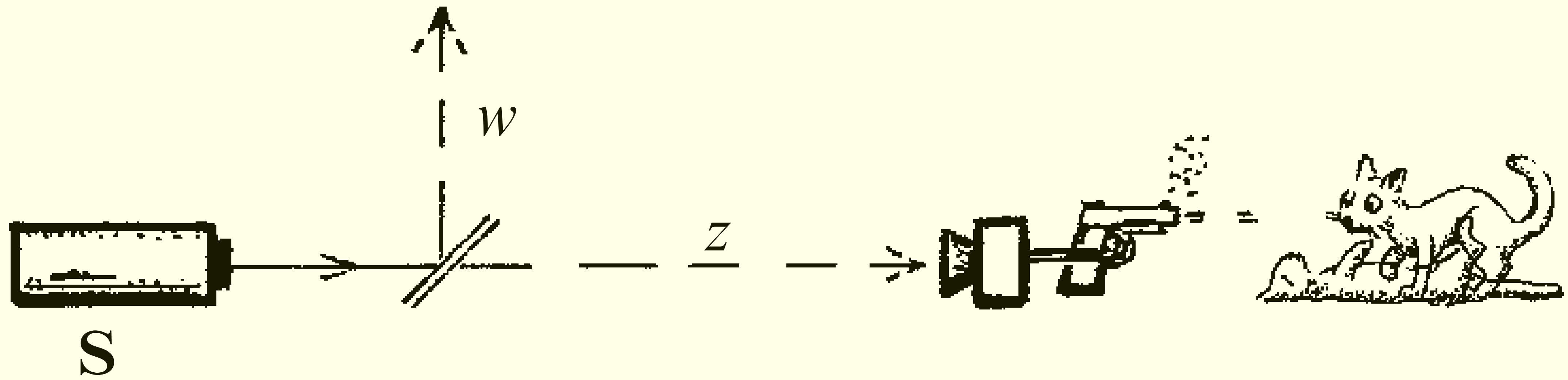
Bad bomb: mirror fixed, photon always appear in A port

Good bomb: mirror movable, *measures* photon, so 50% chance for photon to appear in B

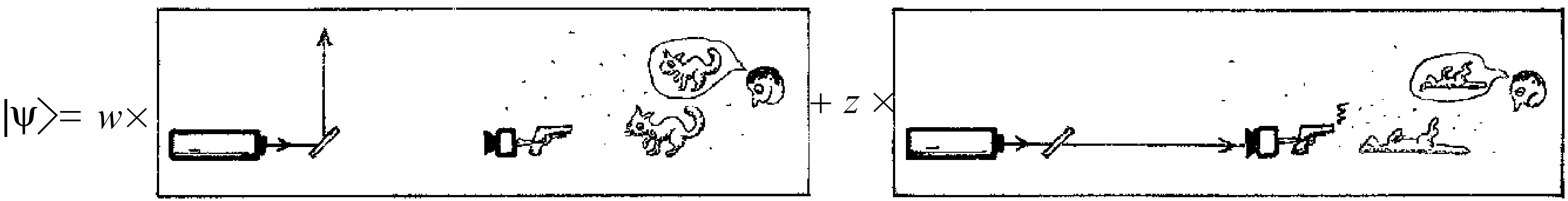
Yet: photon appearing in B doesn't mean it has gone through the path with bomb

Tested by Zeilinger et al. (not with bombs)

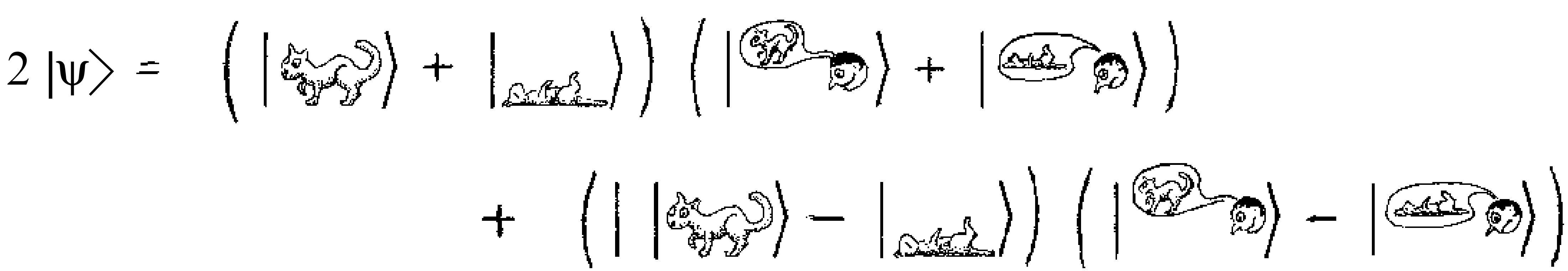
Macroscopic quantum superpositions?



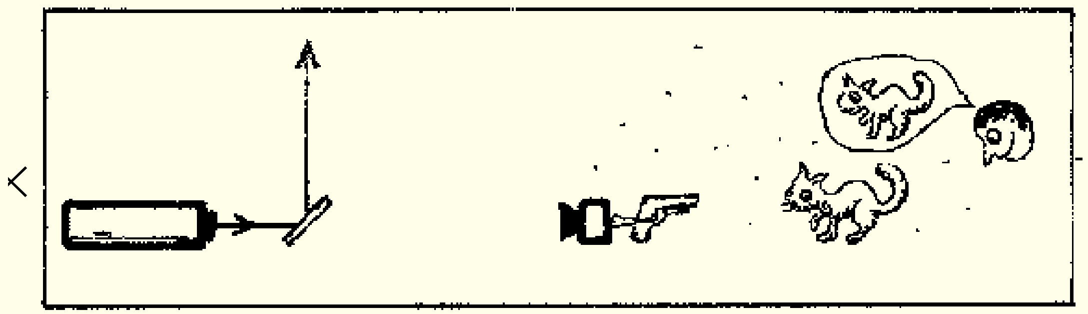
Schrödinger's cat thought experiment (picture by Roger Penrose)



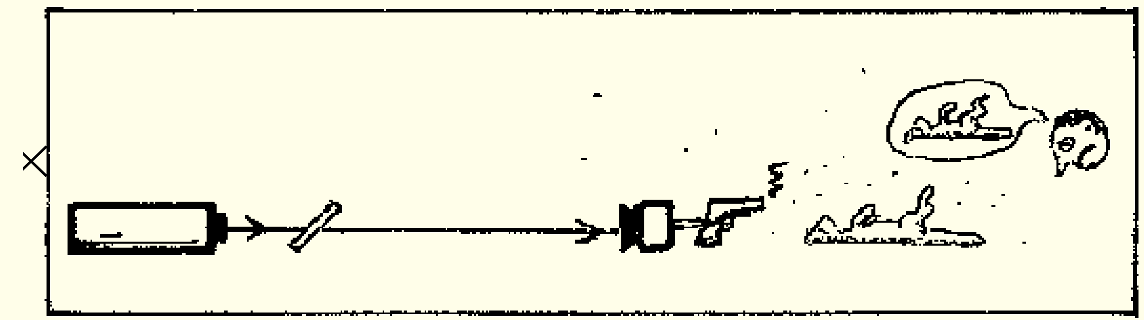
Mathematically Equivalent to



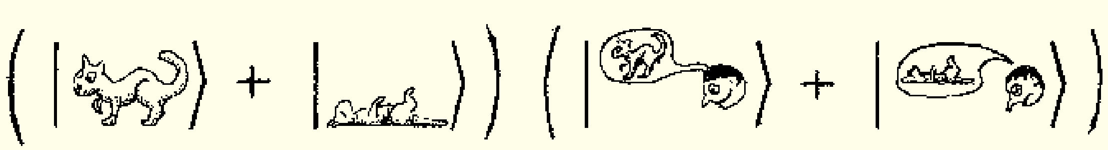
How does Quantum transition into Classical?



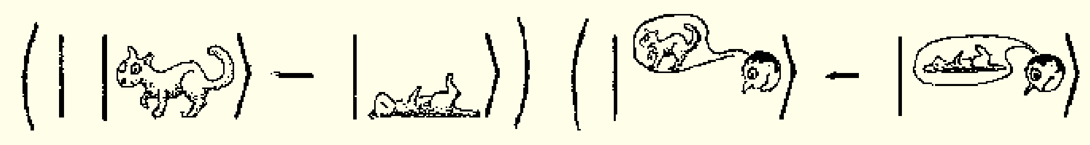
or



this is the way things work classically



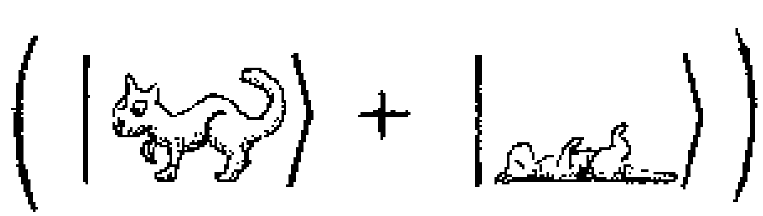
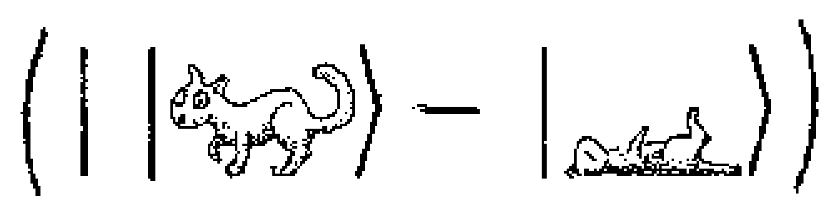
or



this is NOT the way things work classically

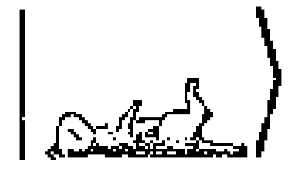
Question:

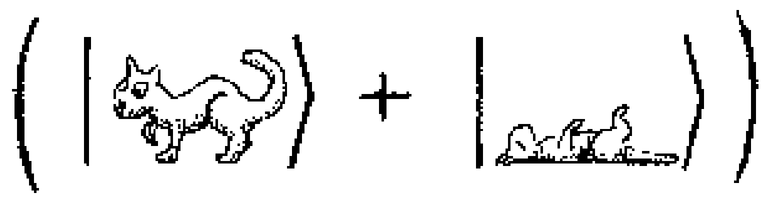
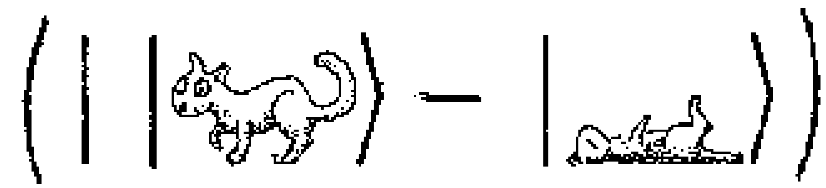
Why is  **vs.**  **classical ?**

instead of  **vs.**  **?**

What determines the choice? How is it implemented?

Different Thoughts on Quantum Classical Transition

Why is  **vs.**  **classical ?**

instead of  **vs.**  **?**

What determines the choice? How is it implemented?

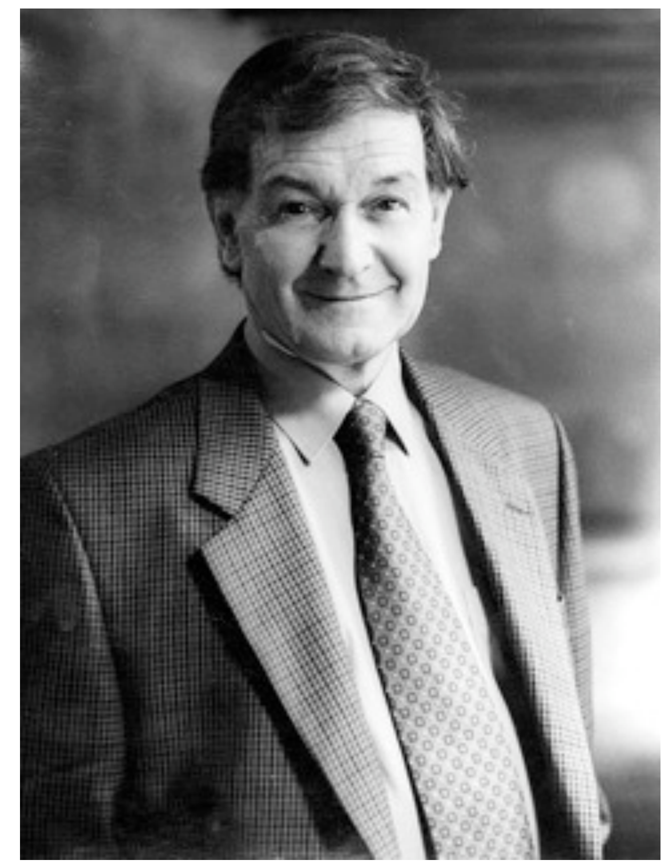
Prevalent answer:

macroscopic systems are in constant contact with the "environment"

environment measures the system, and collapses it into classical states. **(Environmental Decoherence)**

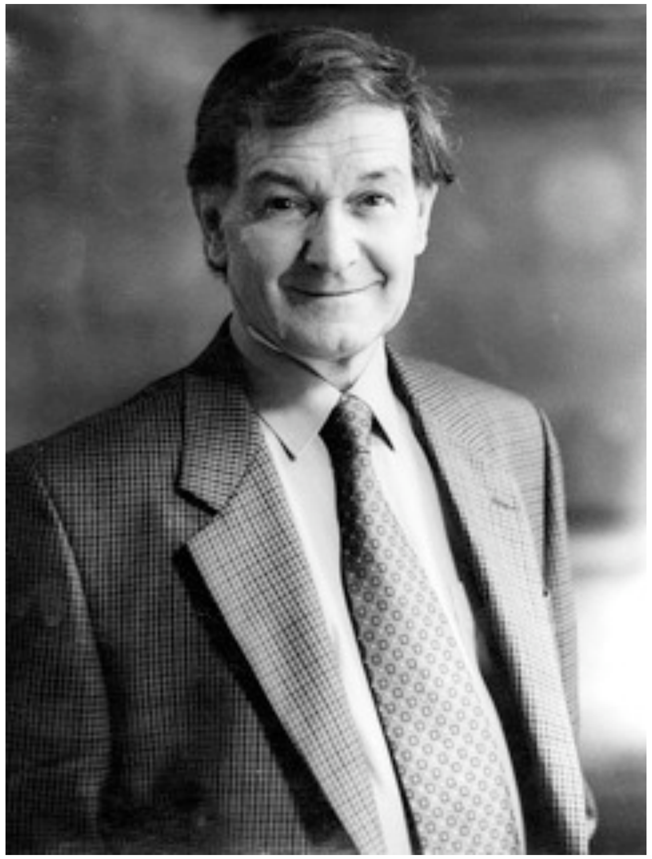
Environment influences the decision of which states are classical

Enough isolation with environment prevents classical physics from emerging



- Roger Penrose: quantum superposition will be destroyed by gravity. "Gravity Decoherence"

Gravity Decoherence



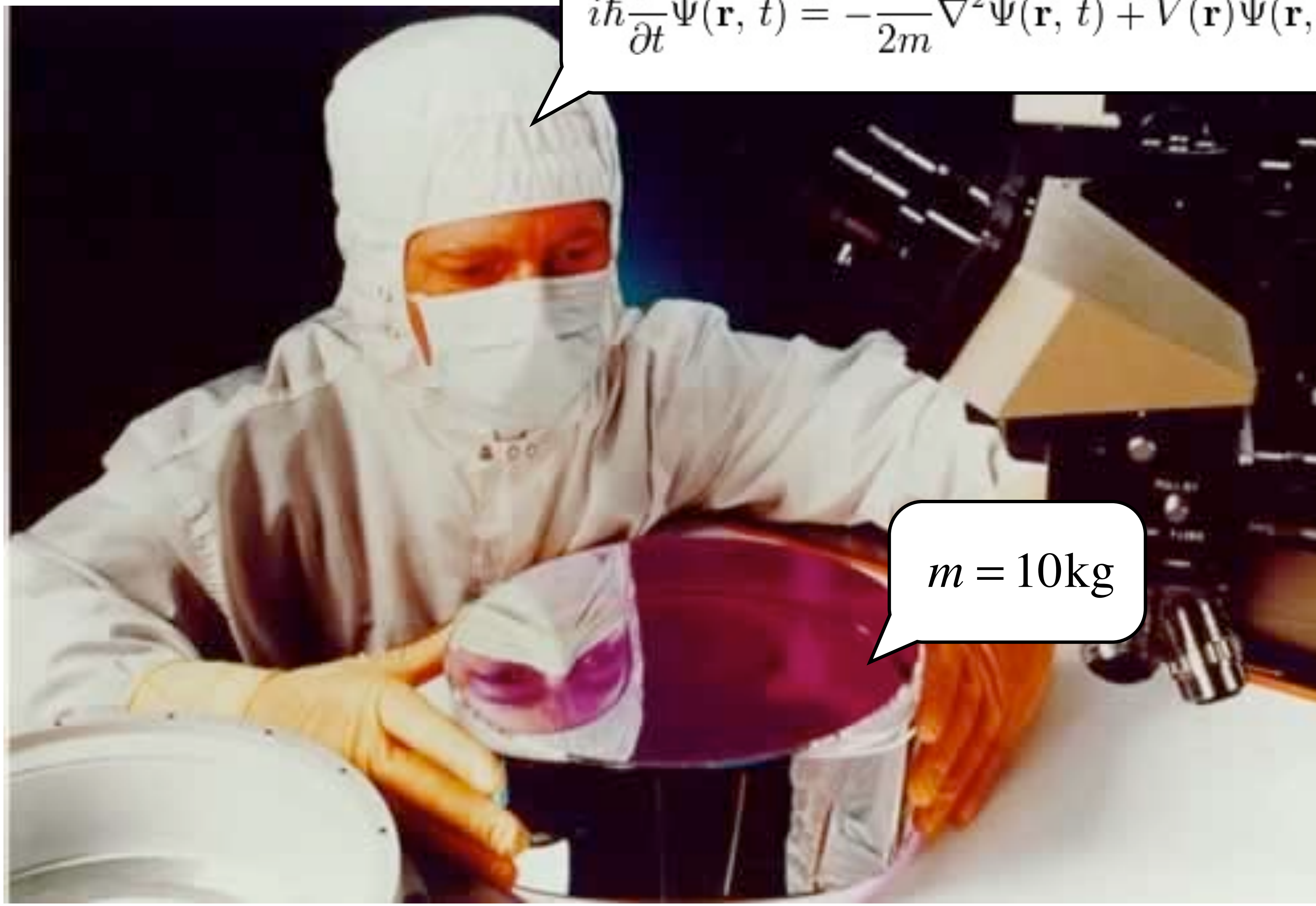
Sir Roger Penrose

- Roger Penrose: "Gravity Decoherence"
- Motivation:
  - quantum superposition, through gravity, cause superposition in space-time structure, which must disappear quickly

timescale for "decoherence"

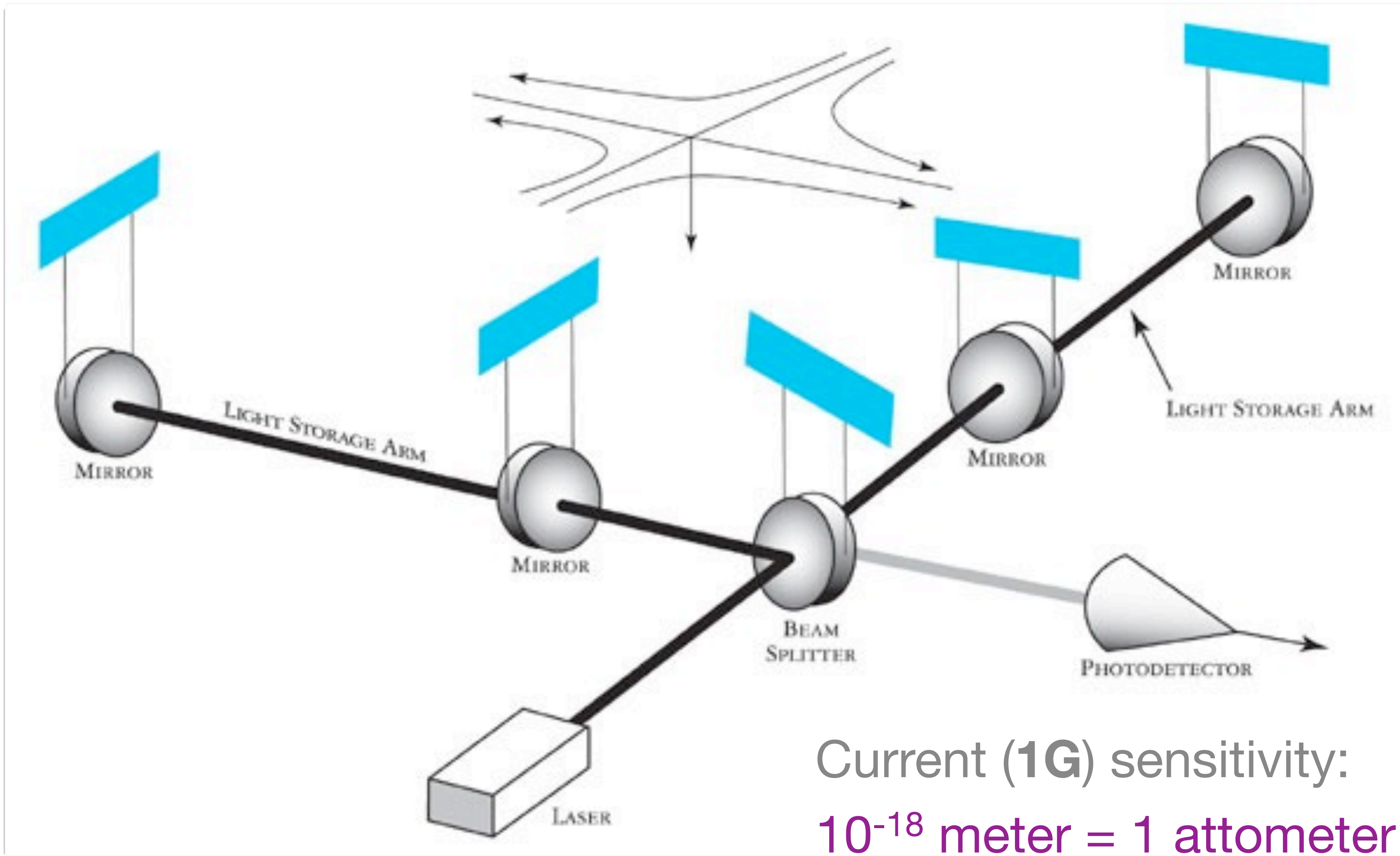
$$\tau \sim \frac{\hbar}{E_G}$$

- Further conjectured that **consciousness must be quantum**


$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},\,t) = -\frac{\hbar^2}{2m}\nabla^2\Psi(\mathbf{r},\,t) + V(\mathbf{r})\Psi(\mathbf{r},\,t)$??
$m = 10\text{kg}$

How does Quantum Mechanics Affect LIGO

- If Quantum Mechanics works in LIGO, then 10 kg test masses are also like waves



Current (**1G**) sensitivity:

10^{-18} meter = 1 attometer

$$\delta x \cdot \delta p \sim \hbar \sim 10^{-34} \qquad \delta p \sim m \cdot \delta v \sim m\omega \cdot \delta x$$

$$\delta x \sim \sqrt{\frac{\hbar}{m\omega}} \sim 10^{-19}\,\text{m, at 100Hz}$$

Only 10 from Heisenberg Uncertainty!!

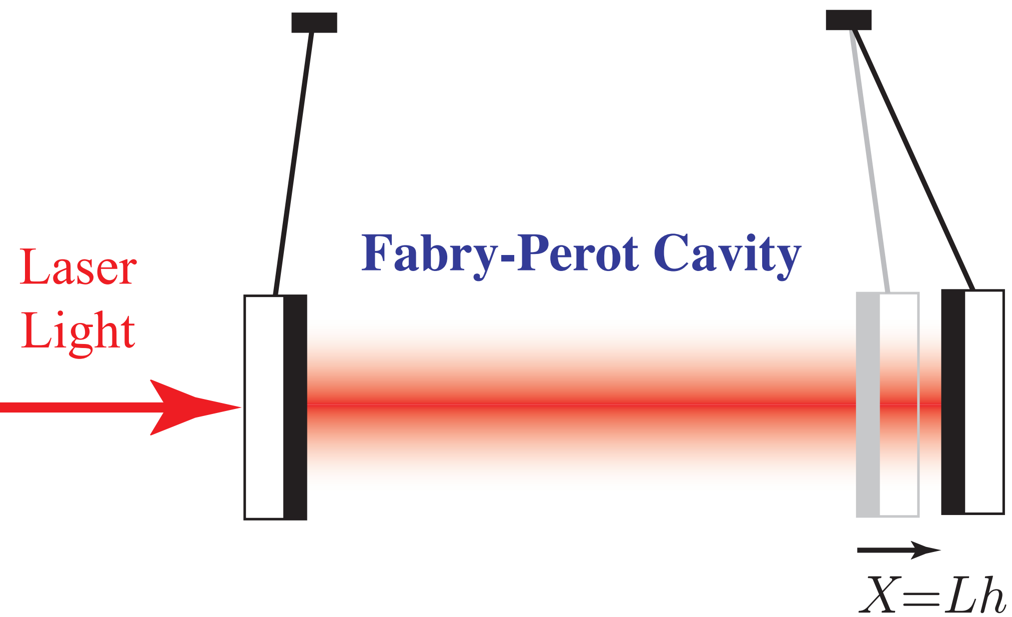
Advanced LIGO **(2G)**

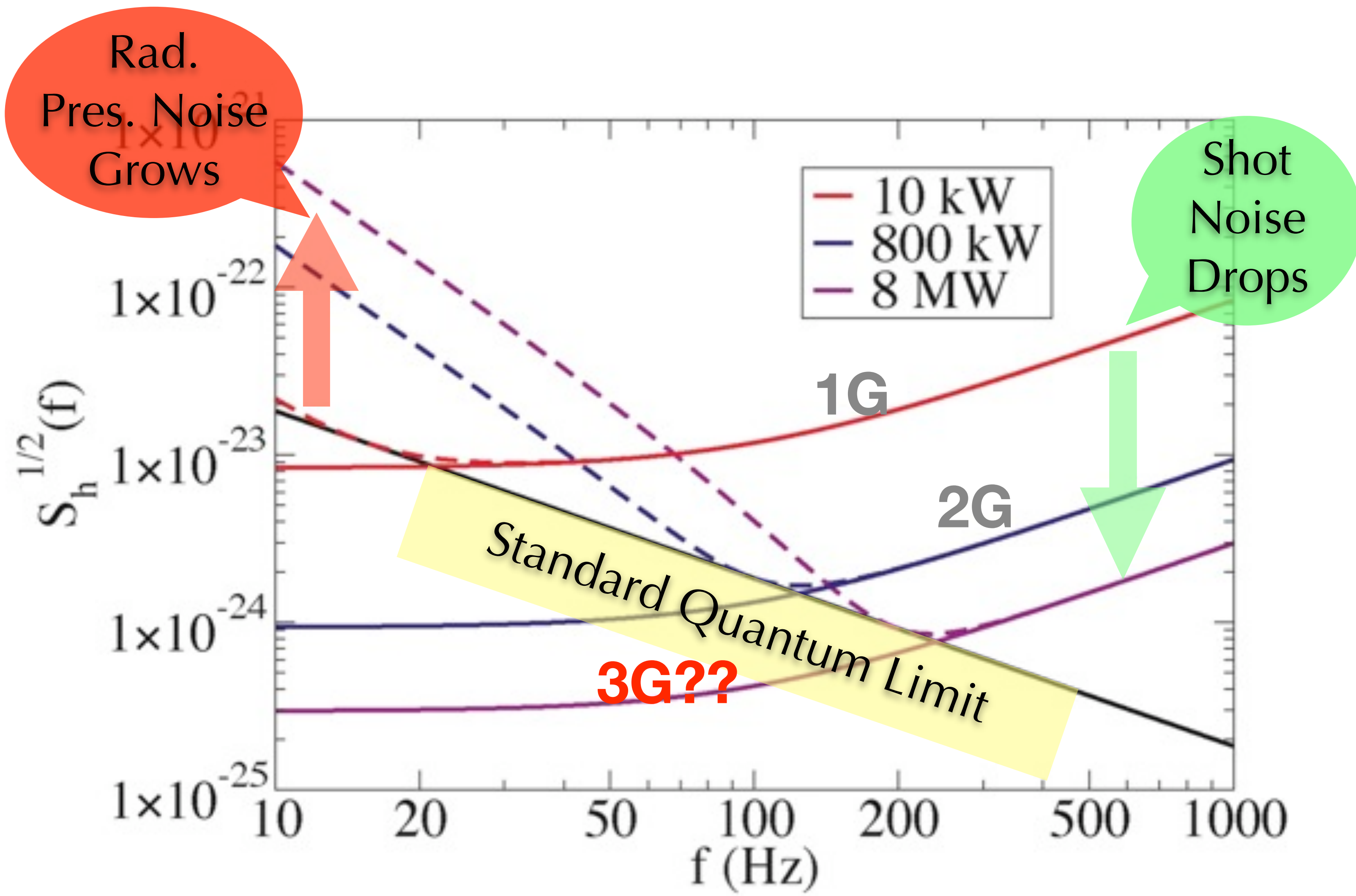
(already started construction)

has 10x sensitivity!!

Symptom of Heisenberg Uncertainty

- Shot noise decrease when we increase photon number.
- But photons also kick the mirrors randomly. This effect increase with photon number





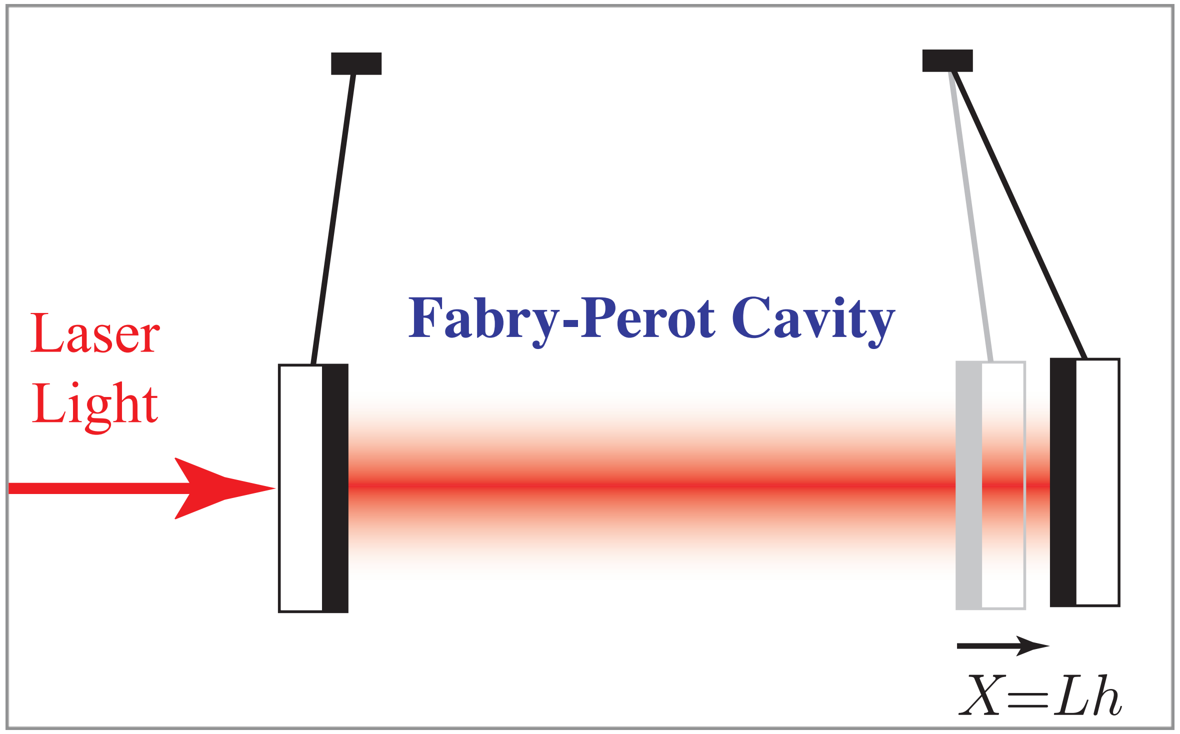
The Standard Quantum Limit poses challenge toward further improvement

$$\delta x \sim \sqrt{\frac{\hbar}{m\omega}}$$

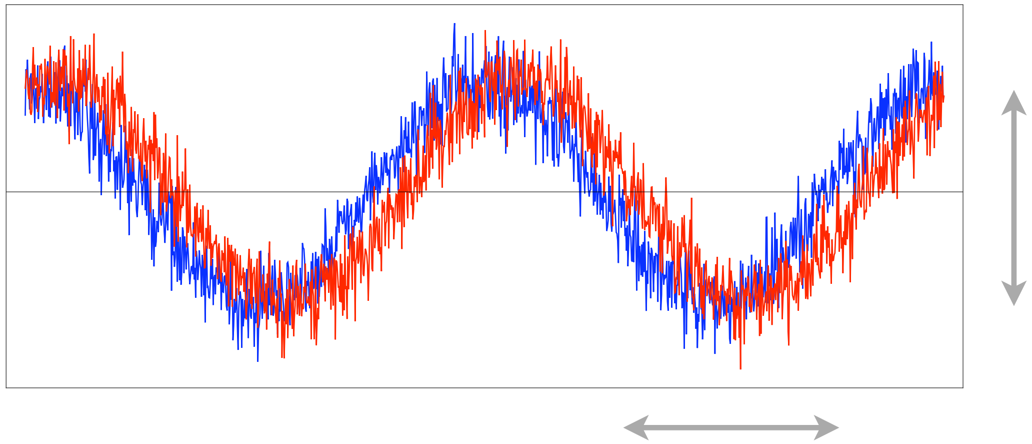
could use heavy mirrors, but not very efficient

How may we circumvent the Quantum Limit?

- Coherent removal of radiation-pressure noise



out-going light
from cavity



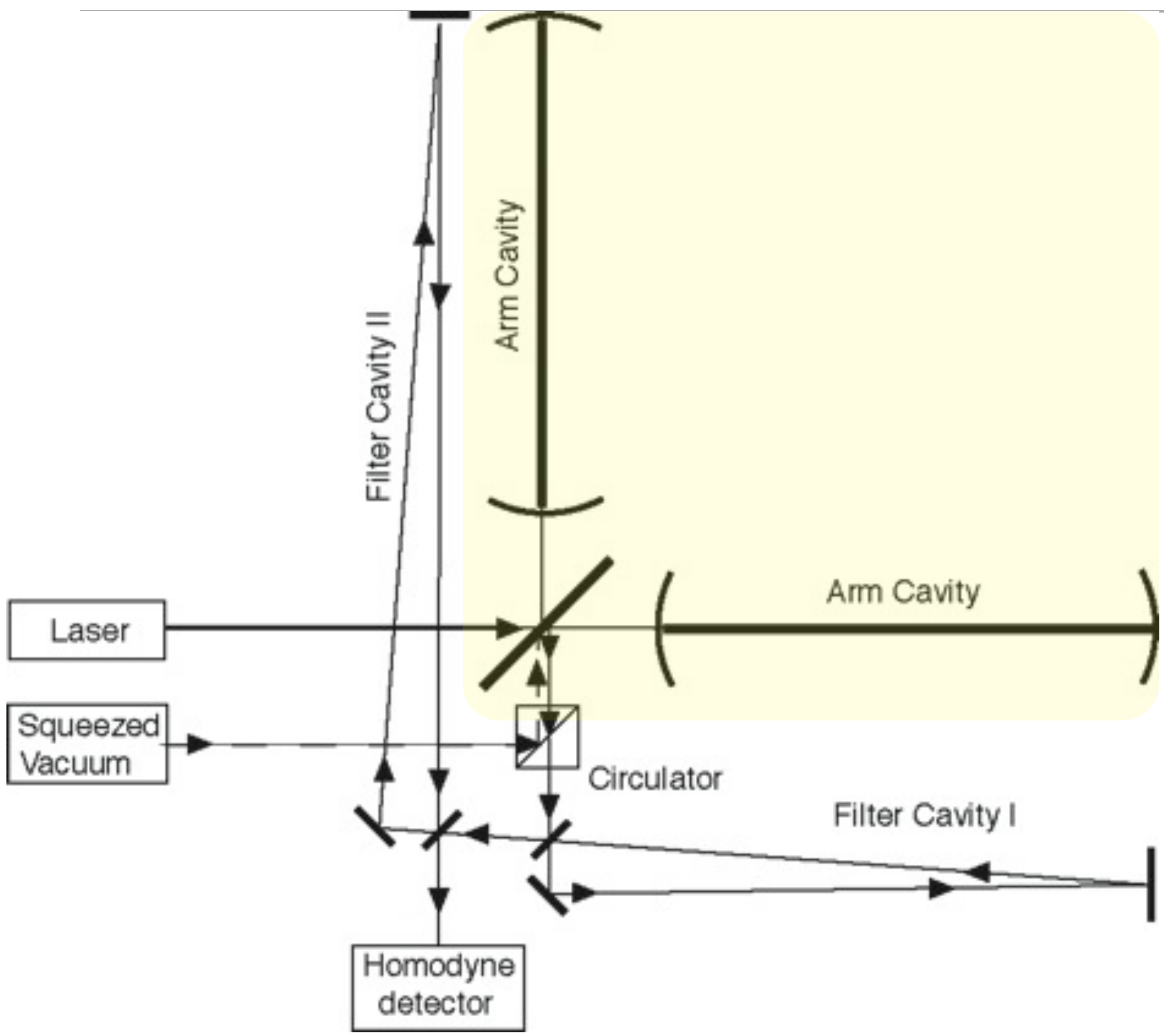
amplitude modulation
(photon kicks to mirrors)

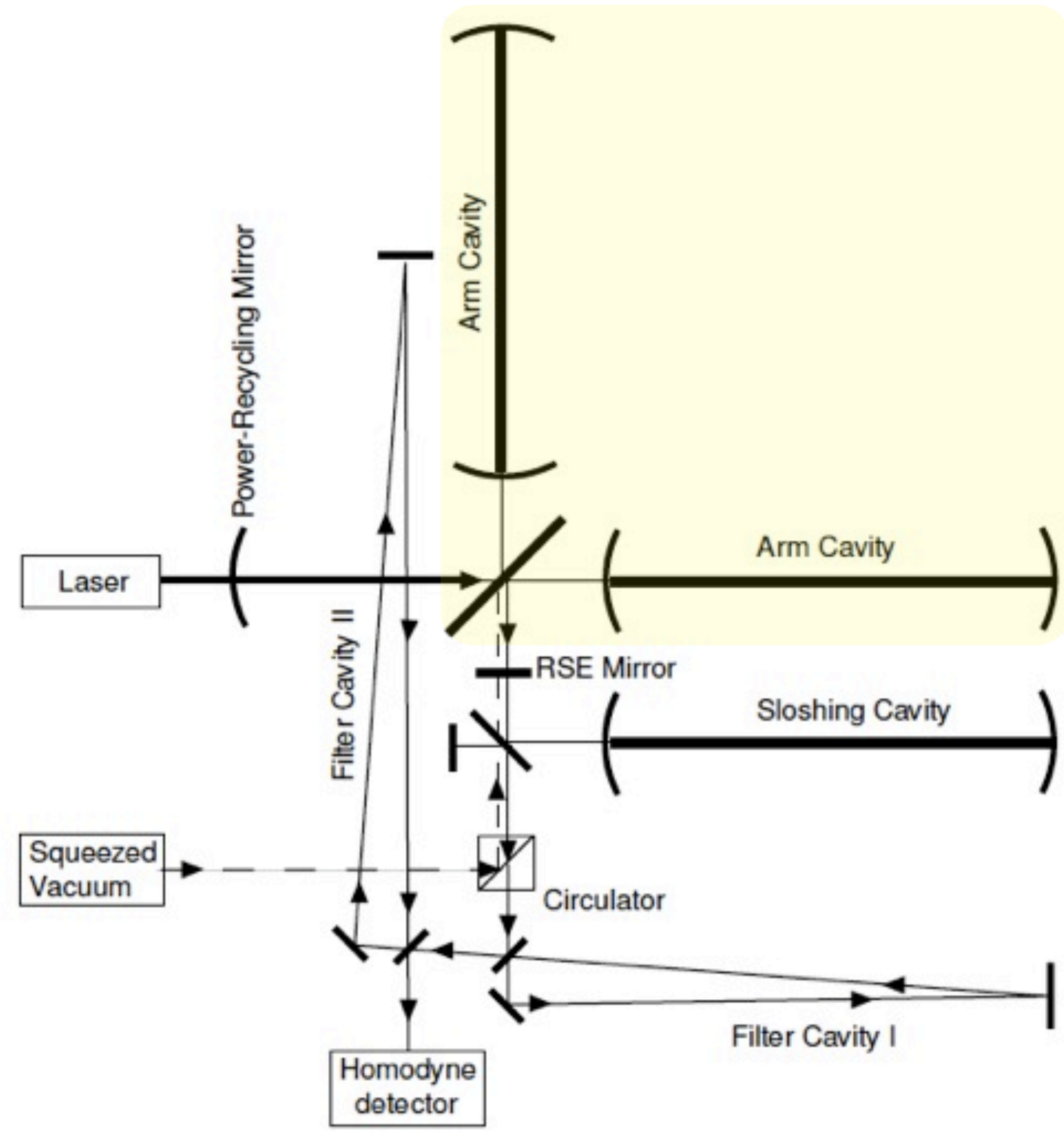
phase modulation
(mirror motion plus shot noise)

mirror motion: GW-induced & kick induced

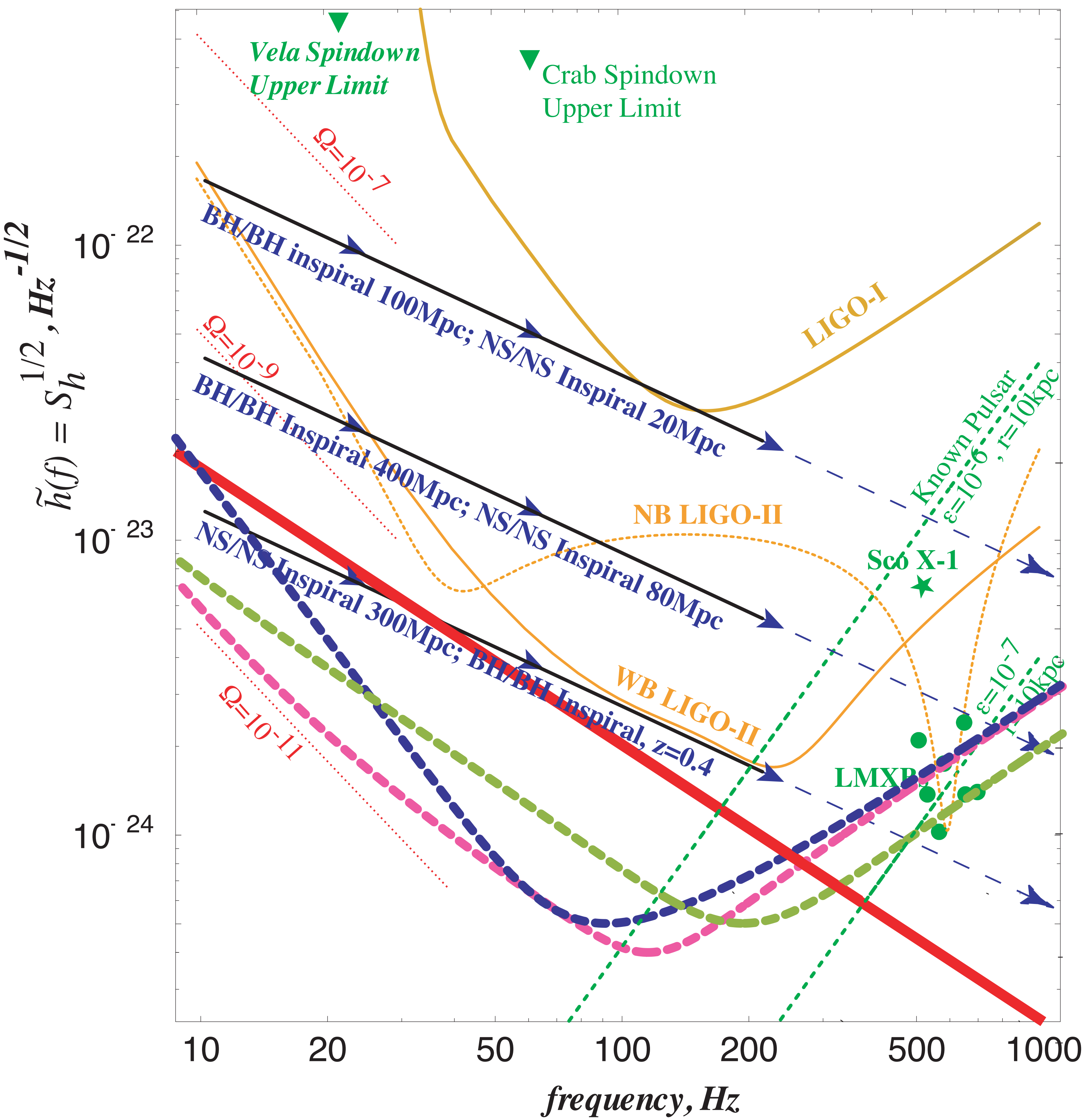
Radiation-Pressure Noise canceled when ***combination*** between amplitude and phase is measured

Designs become more complicated

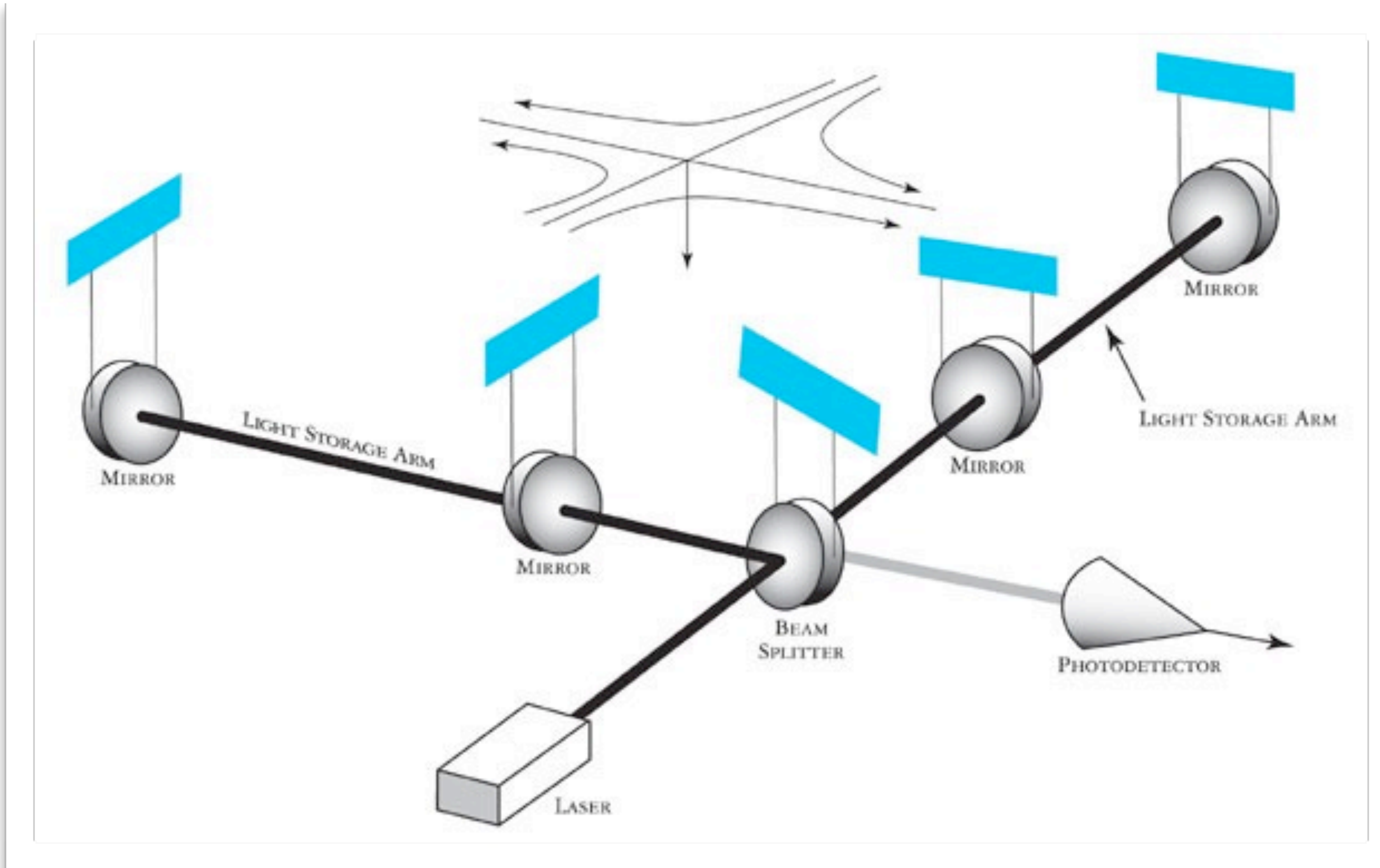




Noise spectra of 1, 2 and 3G detectors



LIGO exploration of gravity decoherence

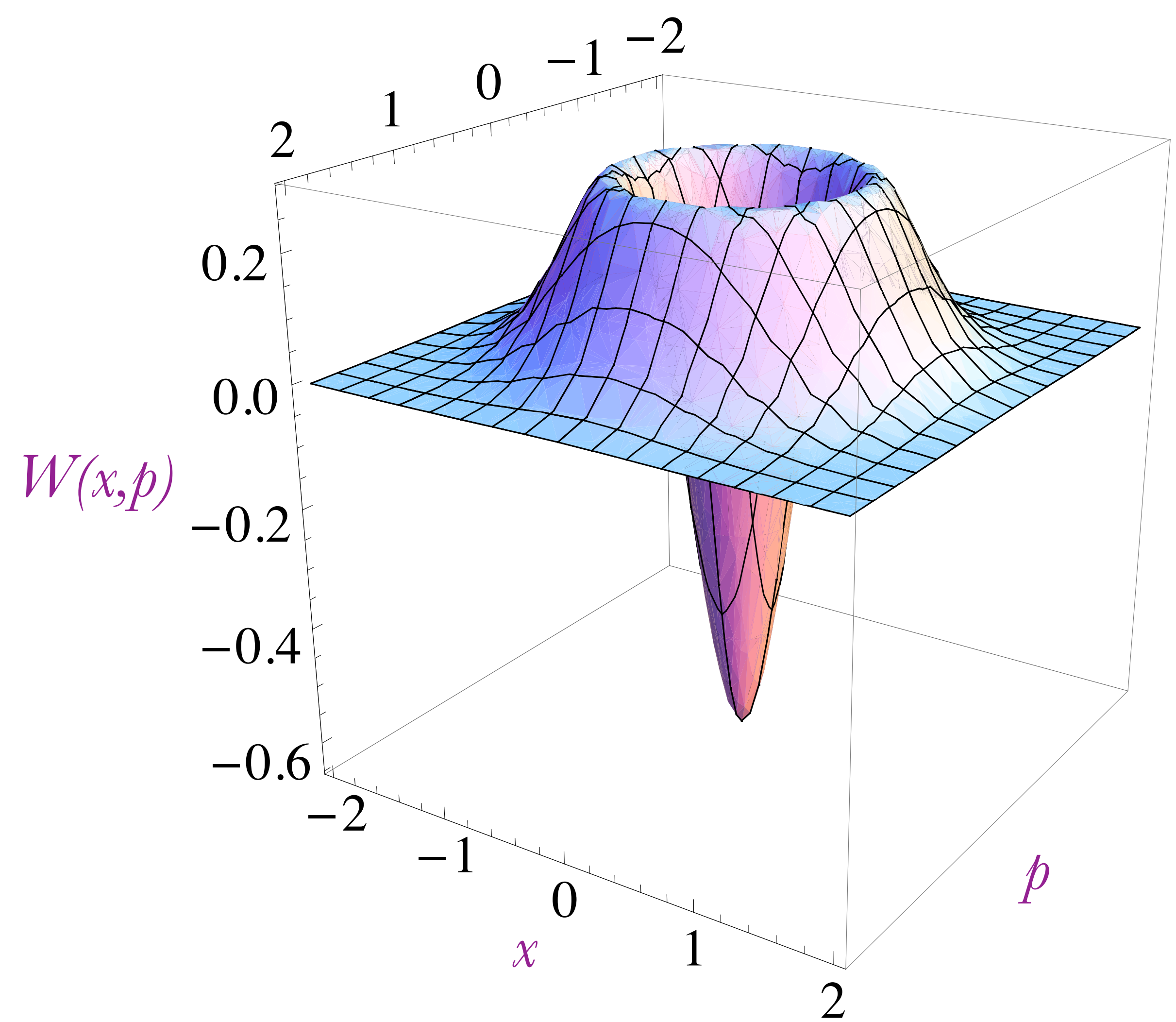


- Prepare quantum superposition state & observe how fast it becomes classical
  - survival time due to standard quantum mechanics & environmental decoherence: ~ 100 ms
  - gravity decoherence time: could be far less than 1 ms because mirrors are heavy

Preparation of non-classical quantum states

- We can also prepare exotic mirror quantum state without classical counterparts.
- Wigner function: *best analogy* to classical probability distribution of (x,p)
- Obtainable through measurements of ($a\ x+b\ p$)

CT image of a brain



Mirror state with non-positive *Wigner Function*

Summary

- Quantum Mechanics has been successful in the microscopic world, do they influence the macroscopic world?
- Yes! Although LIGO mirrors are heavy (10 kg), their quantum uncertainties will seriously affect sensitivity in the near future.
- Ways can be designed to circumvent those uncertainties.
- We can use LIGO to explore quantum mechanics of macroscopic objects