The Nature of Science

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong."

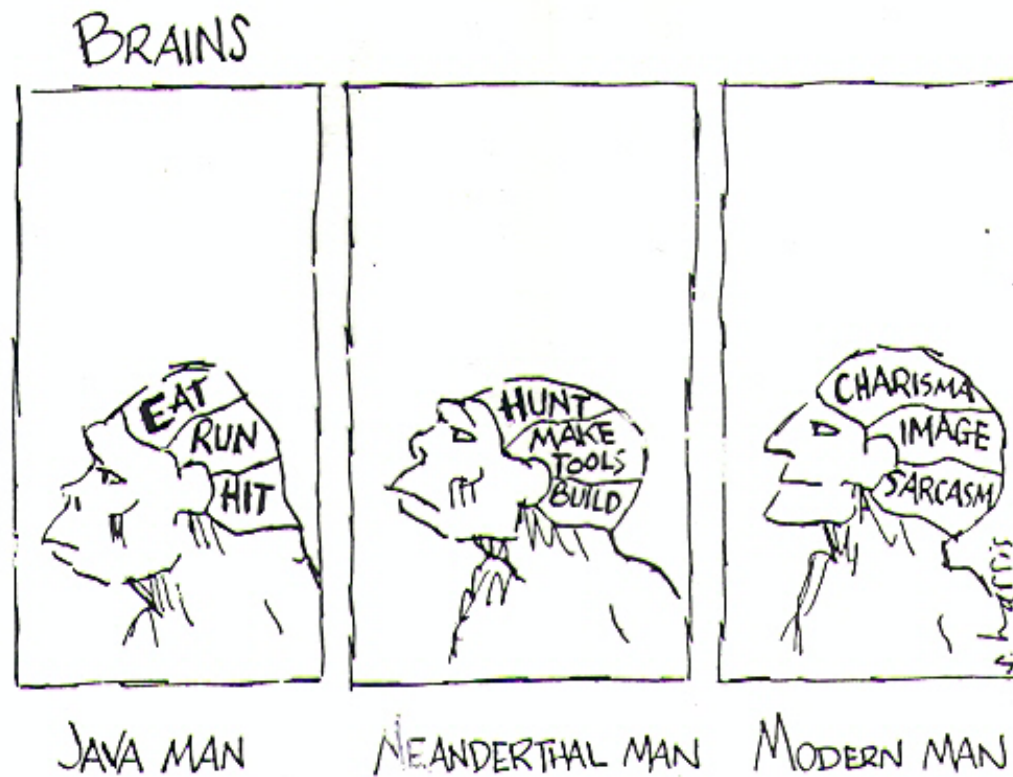*"The first principle is that you must not fool yourself and you are the easiest person to fool."*

Richard Feymann, Nobel prize winner in physics.

"It pays to keep an open mind, but not so open your brains fall out."

Carl Sagan, astronomer, creator of the Cosmos TV series.

Scientific Thinking

- It is a natural part of human behavior.
- We draw conclusions based on our experiences.
- Progress is made through "trial and error."

BRAINS

JAVA MAN — EAT RUN HIT

NEANDERTHAL MAN — HUNT MAKE TOOLS BUILD

MODERN MAN — CHARISMA IMAGE SARCASM

Science starts with curiosity ... something that is born in all of us.

The starting point is to find patterns in the natural world.

Periodic Table of the Elements

1 1IA 11A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 **H** Hydrogen 1.0079																	2 **He** Helium 4.00260
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.01218											5 **B** Boron 10.811	6 **C** Carbon 12.011	7 **N** Nitrogen 14.00674	8 **O** Oxygen 15.9994	9 **F** Fluorine 18.998403	10 **Ne** Neon 20.1797
11 **Na** Sodium 22.989768	12 **Mg** Magnesium 24.305											13 **Al** Aluminum 26.981539	14 **Si** Silicon 28.0855	15 **P** Phosphorus 30.973762	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.4527	18 **Ar** Argon 39.948
19 **K** Potassium 39.0983	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.95591	22 **Ti** Titanium 47.88	23 **V** Vanadium 50.9415	24 **Cr** Chromium 51.9961	25 **Mn** Manganese 54.938	26 **Fe** Iron 55.847	27 **Co** Cobalt 58.9332	28 **Ni** Nickel 58.6934	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.732	32 **Ge** Germanium 72.64	33 **As** Arsenic 74.92159	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.4678	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.90585	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.90638	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium 98.9072	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.9055	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.8682	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.71	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.6	53 **I** Iodine 126.90447	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.90543	56 **Ba** Barium 137.327	57-71	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.9479	74 **W** Tungsten 183.85	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.22	78 **Pt** Platinum 195.08	79 **Au** Gold 196.9665	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.3833	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98037	84 **Po** Polonium [208.9824]	85 **At** Astatine 209.9871	86 **Rn** Radon 222.0176
87 **Fr** Francium 223.0197	88 **Ra** Radium 226.0254	89-103	104 **Rf** Rutherfordium [261]	105 **Db** Dubnium [262]	106 **Sg** Seaborgium [266]	107 **Bh** Bohrium [264]	108 **Hs** Hassium [269]	109 **Mt** Meitnerium [268]	110 **Ds** Darmstadtium [269]	111 **Rg** Roentgenium [272]	112 **Cn** Copernicium [277]	113 **Uut** Ununtrium unknown	114 **Uuq** Ununquadium [289]	115 **Uup** Ununpentium unknown	116 **Uuh** Ununhexium [298]	117 **Uus** Ununseptium unknown	118 **Uuo** Ununoctium unknown

Lanthanide Series

57 **La** Lanthanum 138.9055	58 **Ce** Cerium 140.115	59 **Pr** Praseodymium 140.90765	60 **Nd** Neodymium 144.24	61 **Pm** Promethium 144.9127	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.9655	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.92534	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93032	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93421	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967

Actinide Series

89 **Ac** Actinium 227.0278	90 **Th** Thorium 232.0381	91 **Pa** Protactinium 231.03588	92 **U** Uranium 238.0289	93 **Np** Neptunium 237.0482	94 **Pu** Plutonium 244.0642	95 **Am** Americium 243.0614	96 **Cm** Curium 247.0703	97 **Bk** Berkelium 247.0703	98 **Cf** Californium 251.0796	99 **Es** Einsteinium [254]	100 **Fm** Fermium 257.0951	101 **Md** Mendelevium 258.1	102 **No** Nobelium 259.1009	103 **Lr** Lawrencium [262]

Legend: Alkali Metal · Alkaline Earth · Transition Metal · Basic Metal · Semimetals · Nonmetals · Halogens · Noble Gas · Lanthanides · Actinides

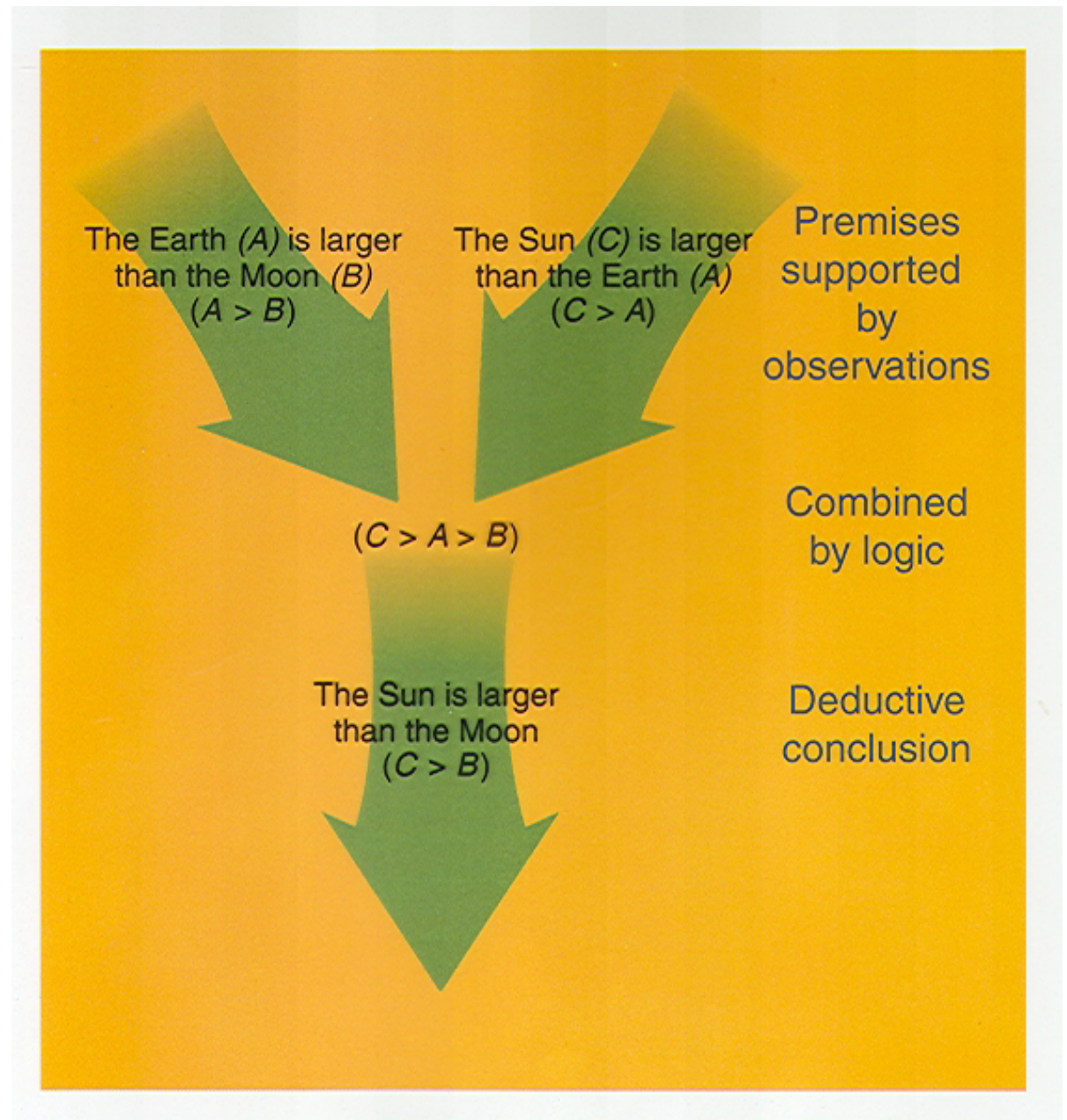Deduction combines statements or premises and combines them to reach a conclusion.

The conclusion is valid only if the premises are justified and the logical construction is correct.

Deduction preserves truth but doesn't always expand knowledge.

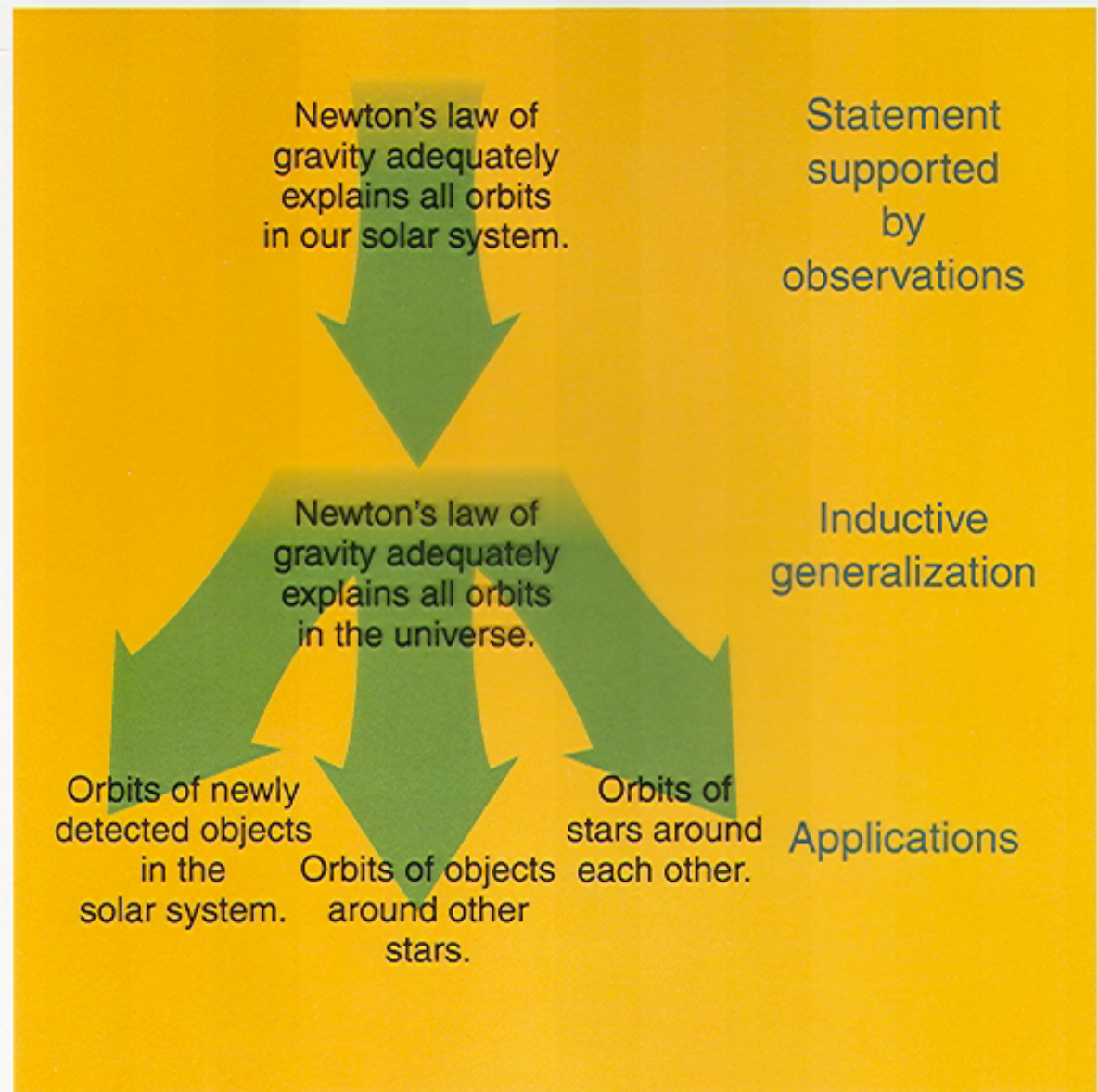*i.e. symbolic logic, arithmetic, algebra*

2 + 2 = 4

LOGIC : **DEDUCTION**

The Earth *(A)* is larger than the Moon *(B)*
(A > B)

The Sun *(C)* is larger than the Earth *(A)*
(C > A)

Premises supported by observations

(C > A > B)

Combined by logic

The Sun is larger than the Moon
(C > B)

Deductive conclusion

Induction involves a generalization from a limited amount of data to a broad conclusion.

Induction cannot yield certainty, but backed by a lot of data, gives very reliable conclusions.

Induction can expand knowledge so is a basic tool of science.

i.e. data is always finite so theories are always subject to verification.

LOGIC : *INDUCTION*

Newton's law of gravity adequately explains all orbits in our solar system.

Statement supported by observations

Newton's law of gravity adequately explains all orbits in the universe.

Inductive generalization

Orbits of newly detected objects in the solar system.

Orbits of objects around other stars.

Orbits of stars around each other.

Applications

Cause and Effect

It would be difficult to make sense of the world if we did not believe in cause and effect, that things do not happen without a reason.

Determinism

cause

variables

effect
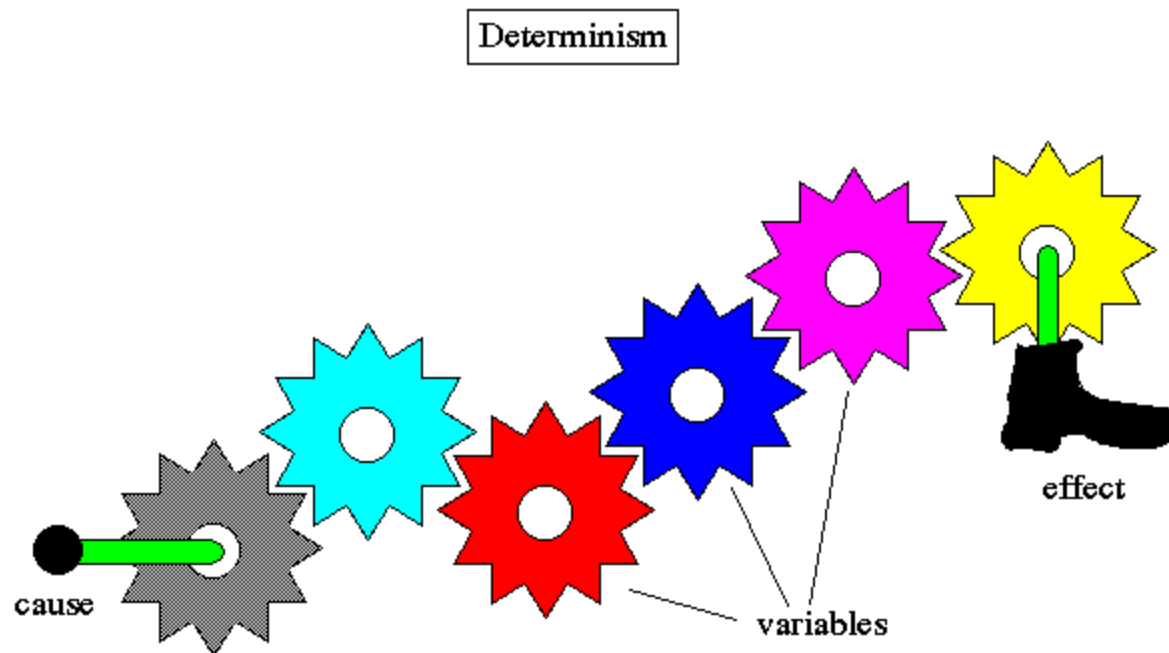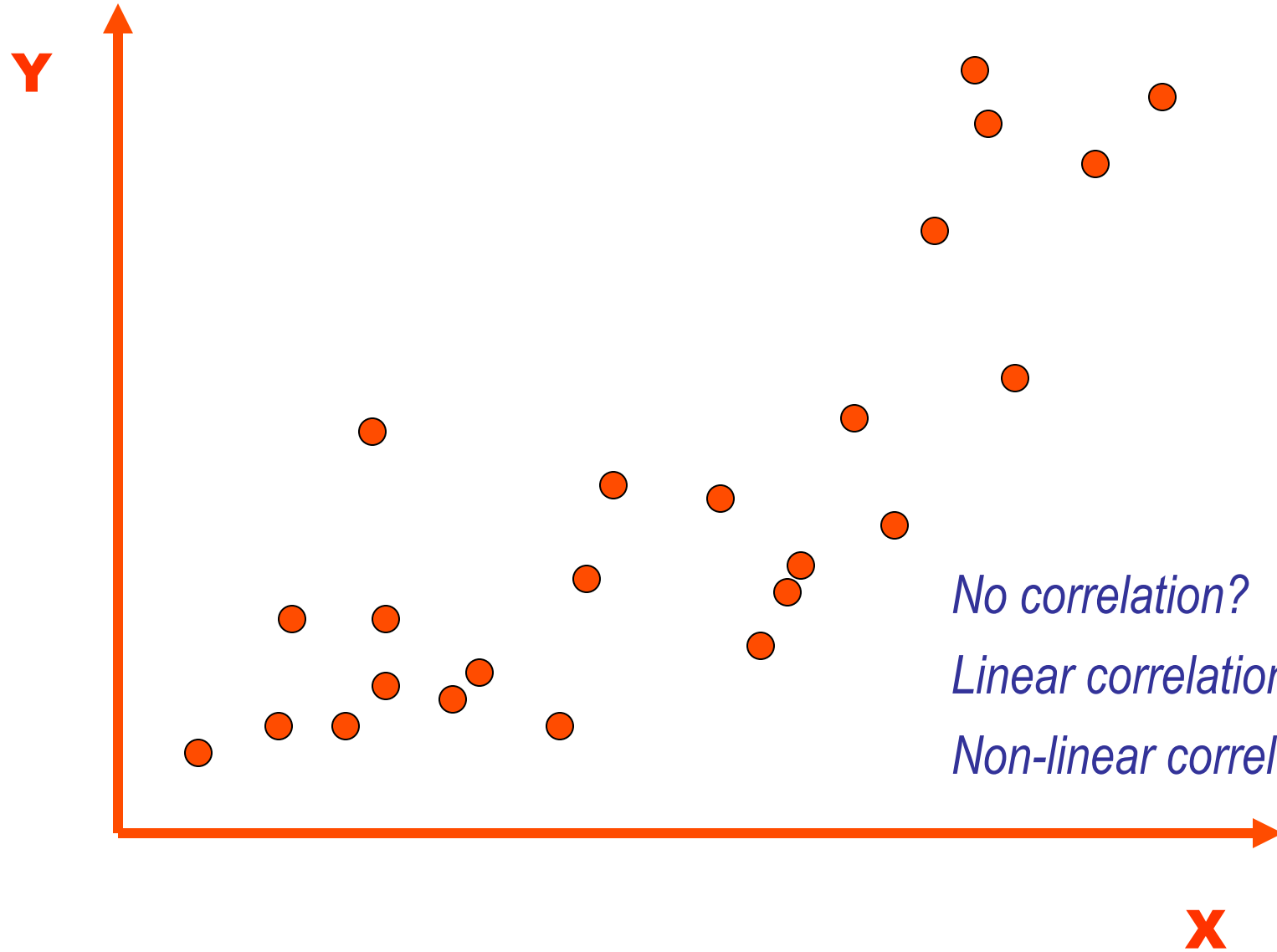
Correlation

No correlation?

Linear correlation?

Non-linear correlation?

Causation?
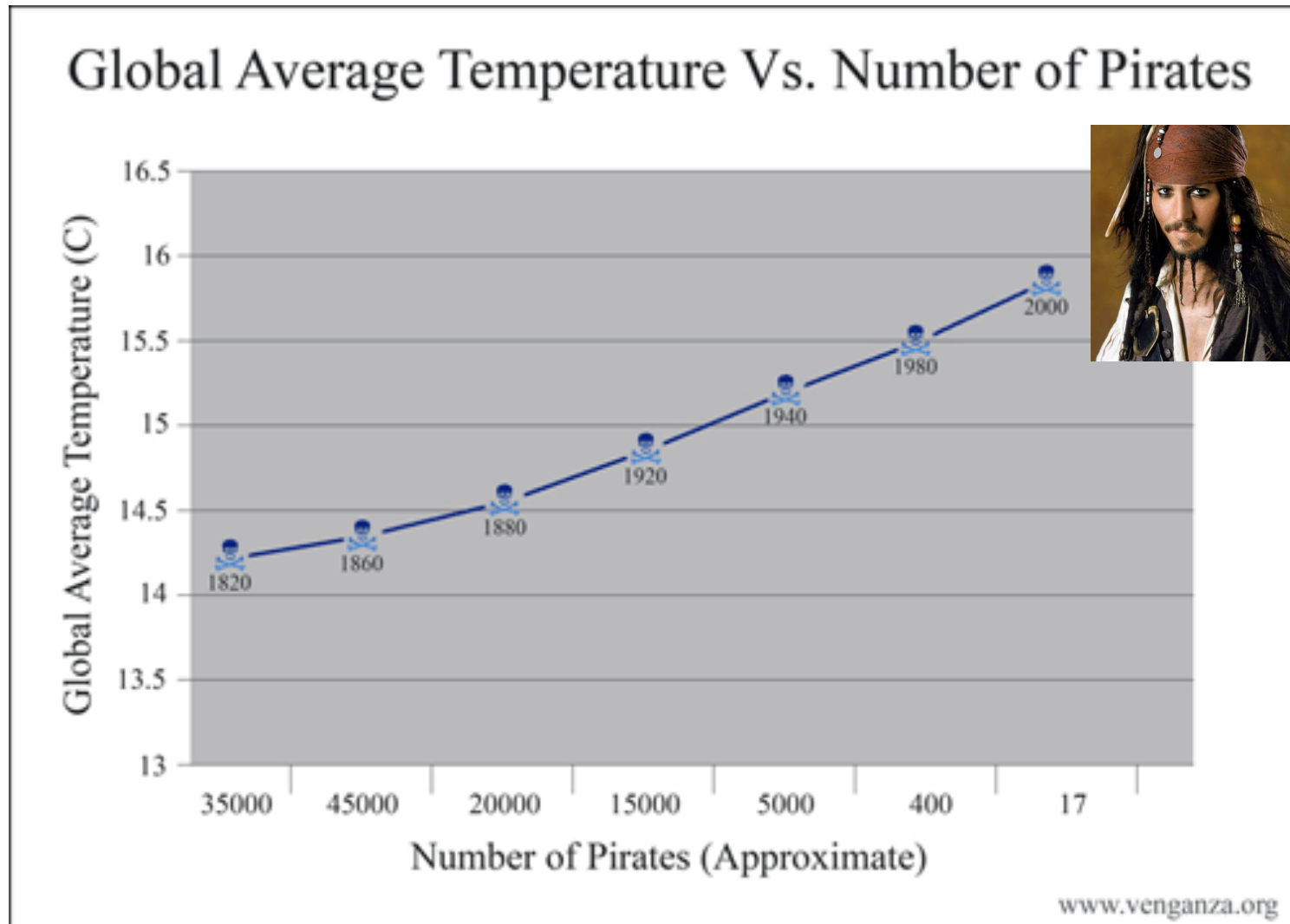
Correlation need not imply causation; underlying variable is time

Determinism

On the other hand, the universe does not work like a machine or like clockwork, where everything is perfectly and completely predictable.
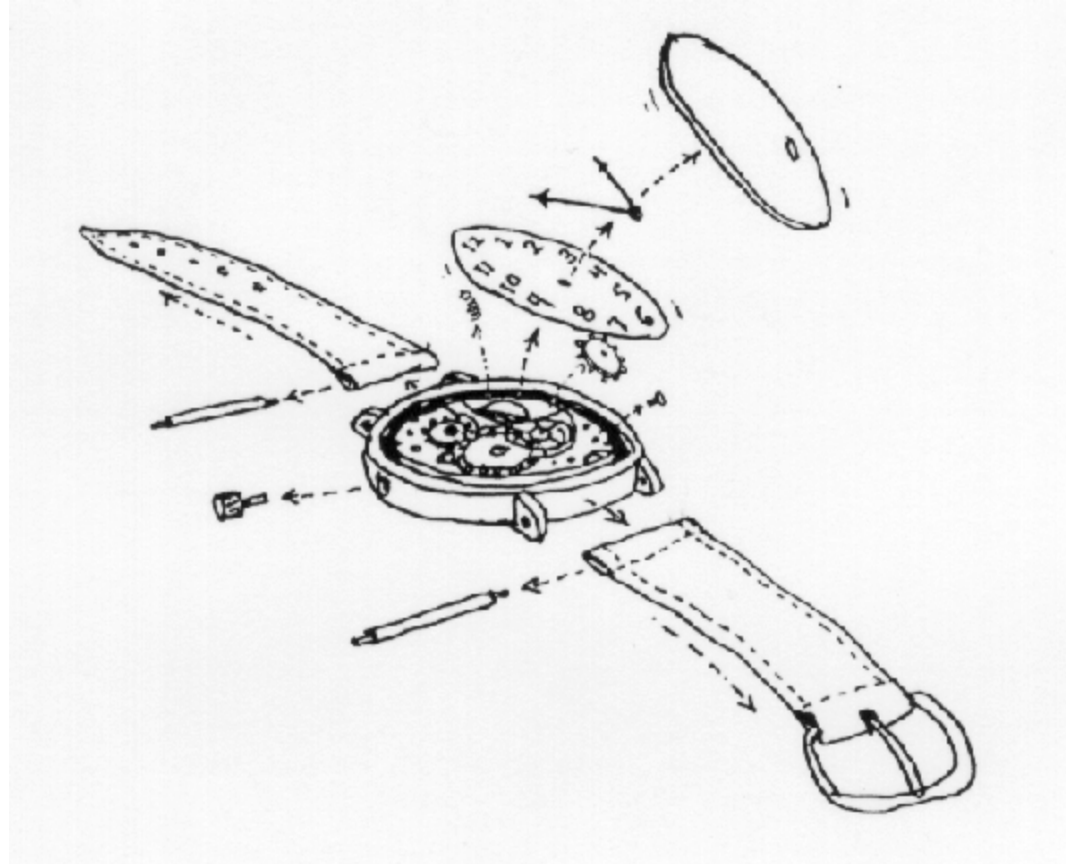
Heisenberg Uncertainty Principle

Uncertainty is a fundamental property of nature. We cannot simultaneously know the position and speed of a particle.
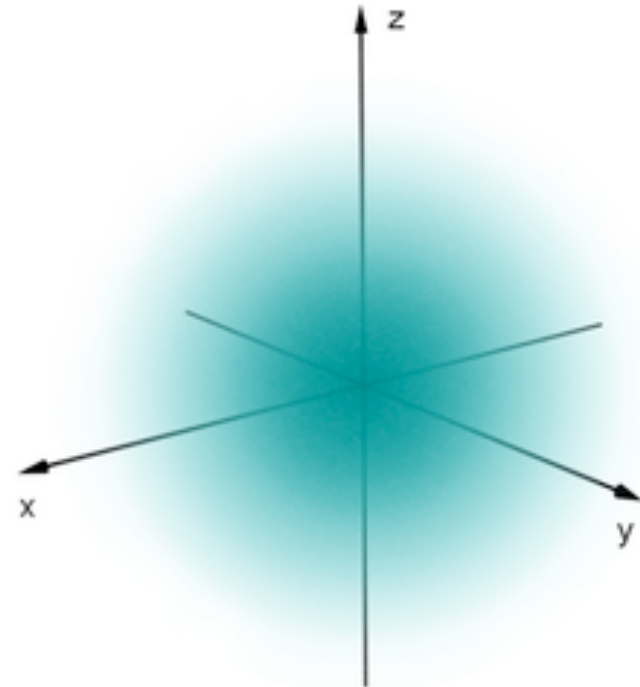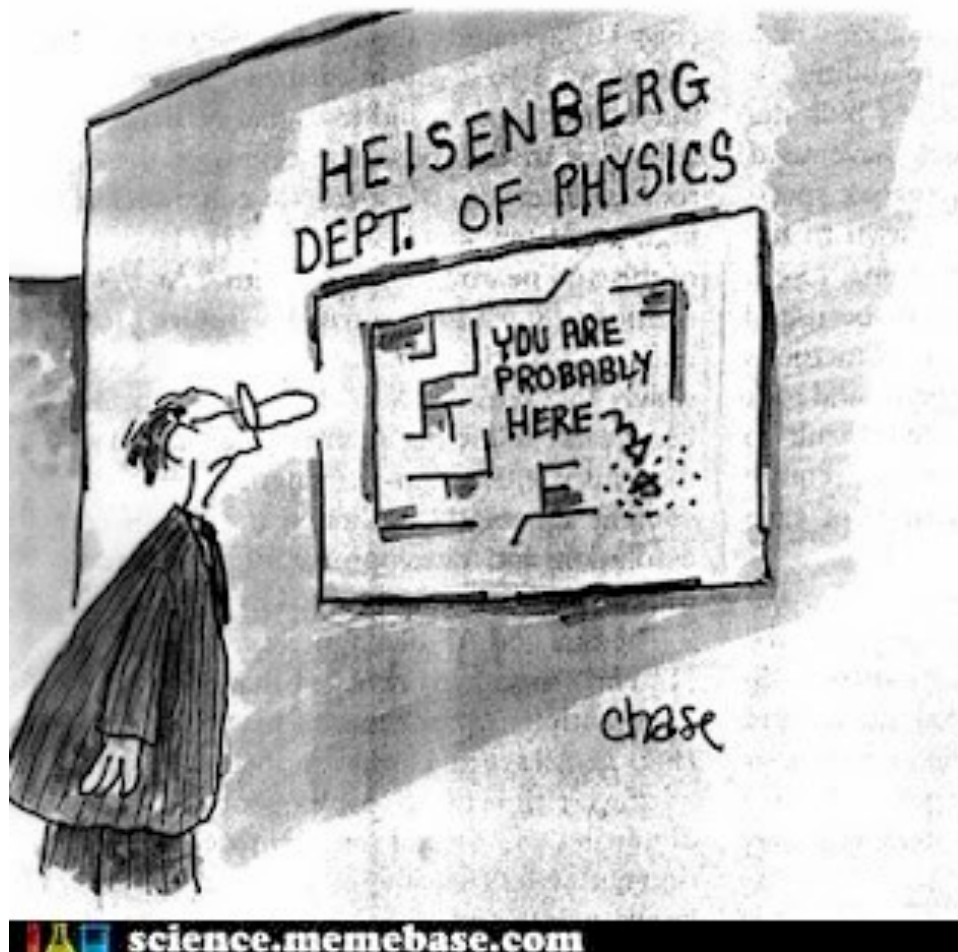
Electron probability cloud in an atom

The Importance of Evidence

- There is no science without evidence.
- All assertions must be supported by data.
- Every claim in science is subject to verification.

Science is data-driven, so progress is made by:

    1. Gathering more data   ***GOOD!***

    2. Repeating the experiment   ***BETTER!!***

    3. Someone else repeating the experiment   ***BEST!!!***

What is Evidence?

Evidence is anything that is helpful in drawing a conclusion.

Scientific evidence is:

• based on data

• reproducible

• quantitative

• not subjective

• never perfect
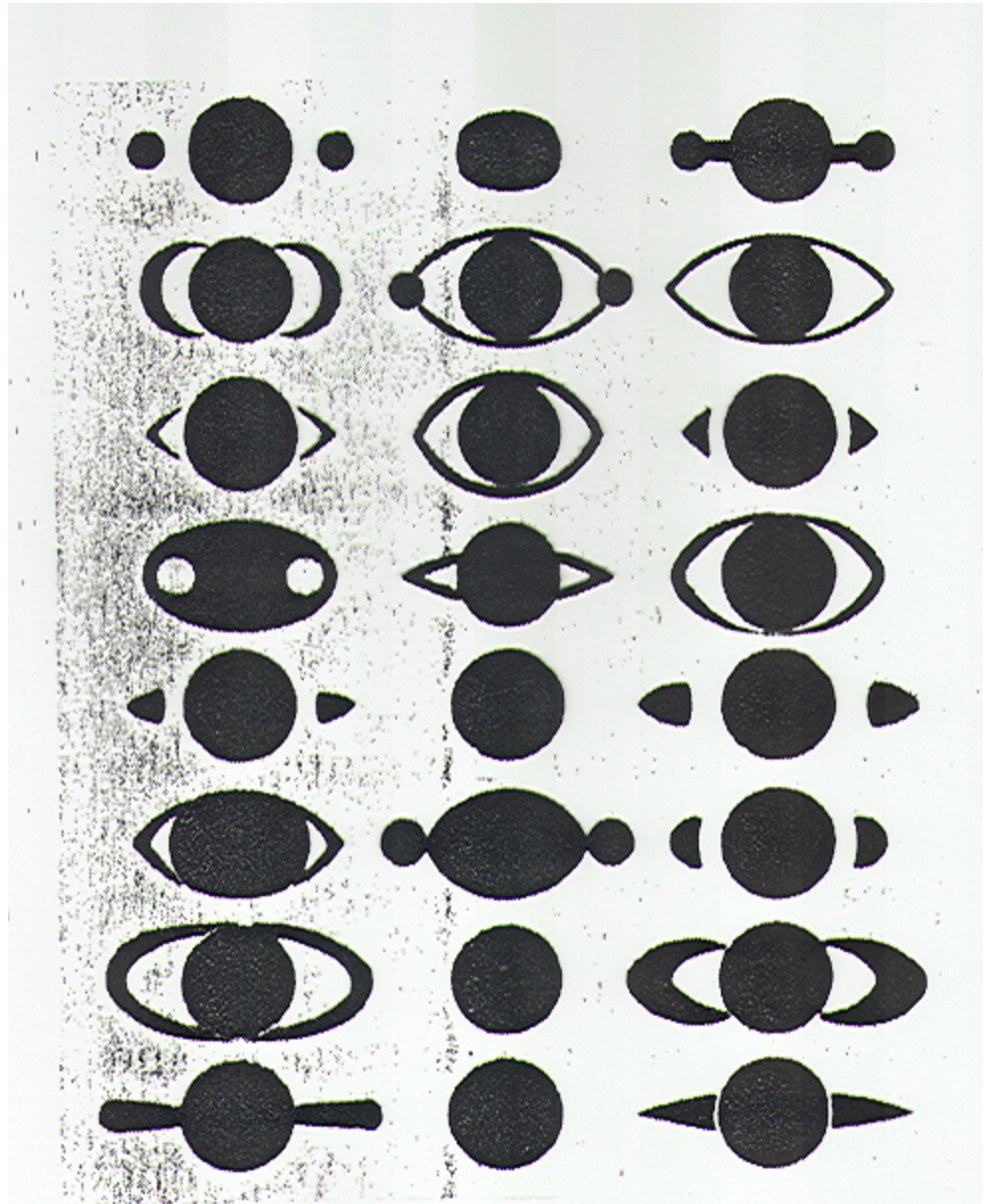
Here are observations of Saturn made in the first fifty years after the invention of the telescope (1610-1660)

Which one shows the way Saturn "really looks?"

Science progresses at the limit of observation. We always want more and better data.
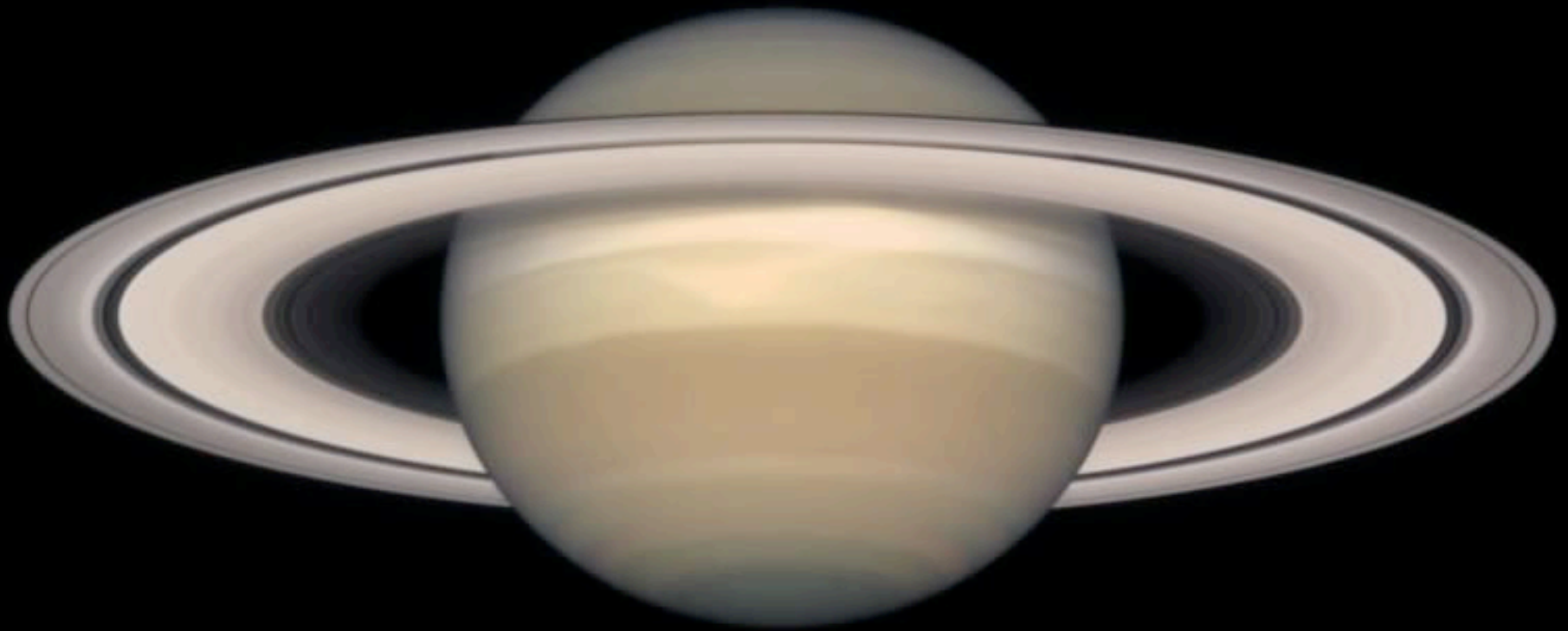
Hubble Space Telescope view of Saturn

All observations are uncertain at some level, due to limitations in the measuring apparatus. This is not really like "errors."

Where is the star really on the sky?

Multiple measurements are needed to define the uncertainty. Taking more data gives a more reliable estimate and a measure of the uncertainty.

Change in average and standard error as number of measurements increases

(a) One measurement

(b) 3 measurements

(c) 10 measurements

(d) 30 measurements
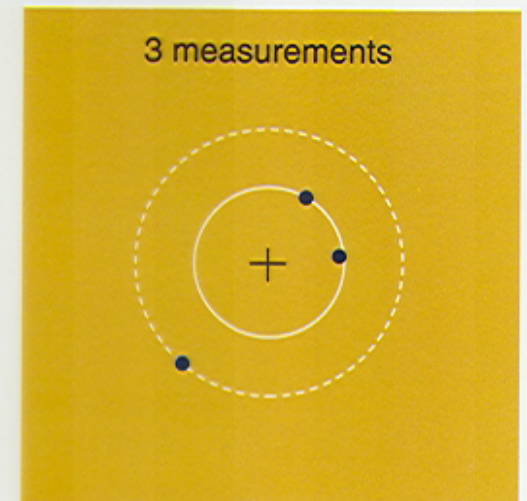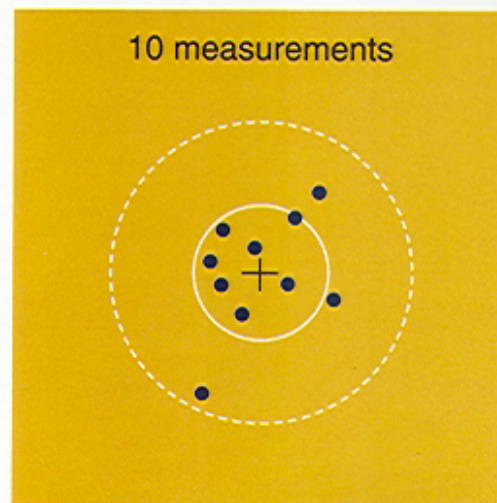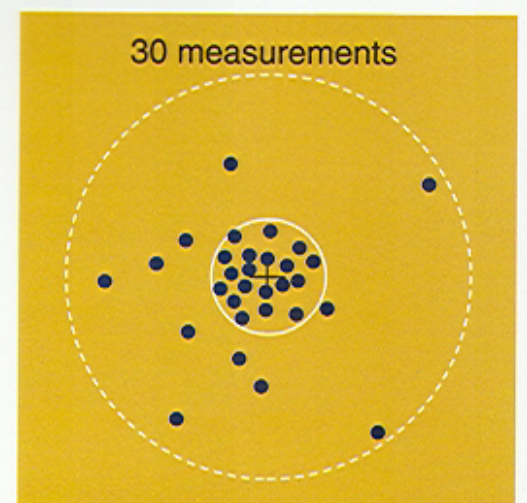
Science has Limitations

Uncertainty, imprecision, and error arise three different ways:

CONCEPTUAL   Making a false premise, confusing correlation with causation, inferring a pattern where none is present

MACROSCOPIC   There is no such thing as perfect data. Every data set is limited and every instrument has limitations

MICROSCOPIC   Heisenberg's uncertainty principle sets a fundamental limit to precision for measurement of particle position and velocity, or energy and time
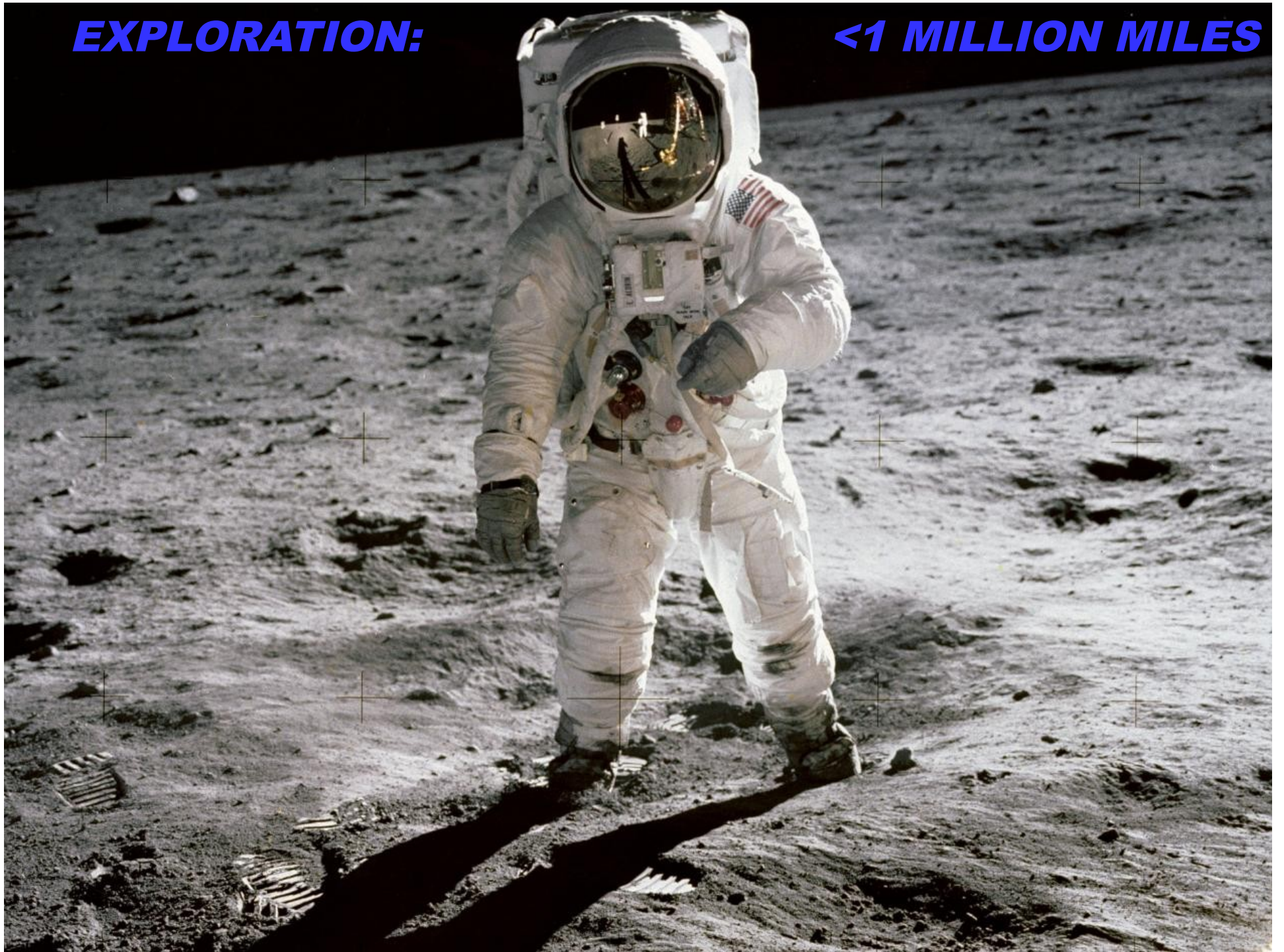
REMOTE SENSING: 1 BILLION MILES

FREE SAMPLES: 10 BILLION MILES

THE ELECTROMAGNETIC SPECTRUM

Penetrates Earth Atmosphere?

| Y | | N | | Y | N |

Wavelength (meters)

| Radio | Microwave | Infrared | Visible | Ultraviolet | X-ray | Gamma Ray |

10^3 10^{-2} 10^{-5} $.5 \times 10^{-6}$ 10^{-8} 10^{-10} 10^{-12}

About the size of...

| Buildings | Humans | Honey Bee | Pinpoint | Protozoans | Molecules | Atoms | Atomic Nuclei |

Frequency (Hz)

10^4 10^8 10^{12} 10^{15} 10^{16} 10^{18} 10^{20}

Temperature of bodies emitting the wavelength (K)

1 K   100 K   10,000 K   10 Million K

For 99.99999999999999999999999999% of the universe, including all stars and all galaxies, the evidence is indirect.

Hallmarks of Good Science

- Science seeks explanations for *observed* phenomena that rely *solely on natural causes*.

- Science progresses through the creation and testing of models of nature that explain the observations as simply as possible.

    Occam's Razor

- A scientific model must make testable predictions that could force us to revise or abandon the model.

- Plus, role of luck and persistence: A human enterprise!

Theory : *a model which survives repeated testing*

What is a Theory?

A theory is a coherent idea that explains some aspect of the natural world. It's much stronger than a hunch or a guess.

Good theories are:
- **predictive**
- **broadly applicable**
- **testable and can be refuted**
- **based on data or observations**
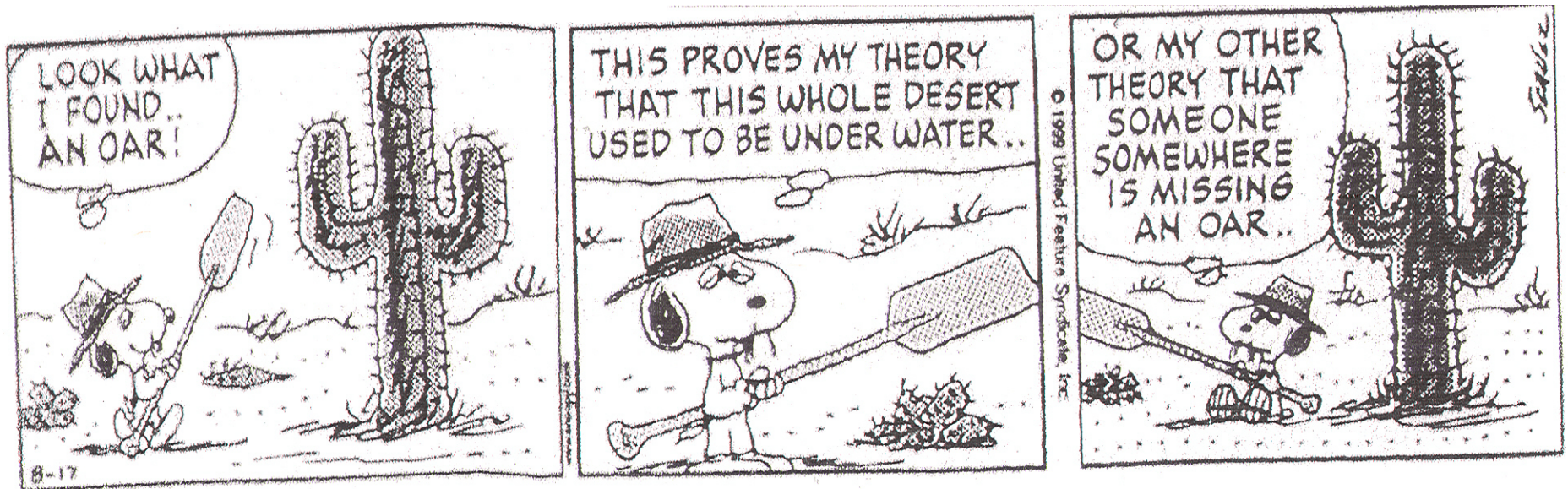
Example: Theory of Gravity

Sir Issac Newton

Newton's Theory of Gravity

M_1

$F_g = G \; \dfrac{M_1 M_2}{d^2}$

M_2

d

Newton's Orbital Cannon
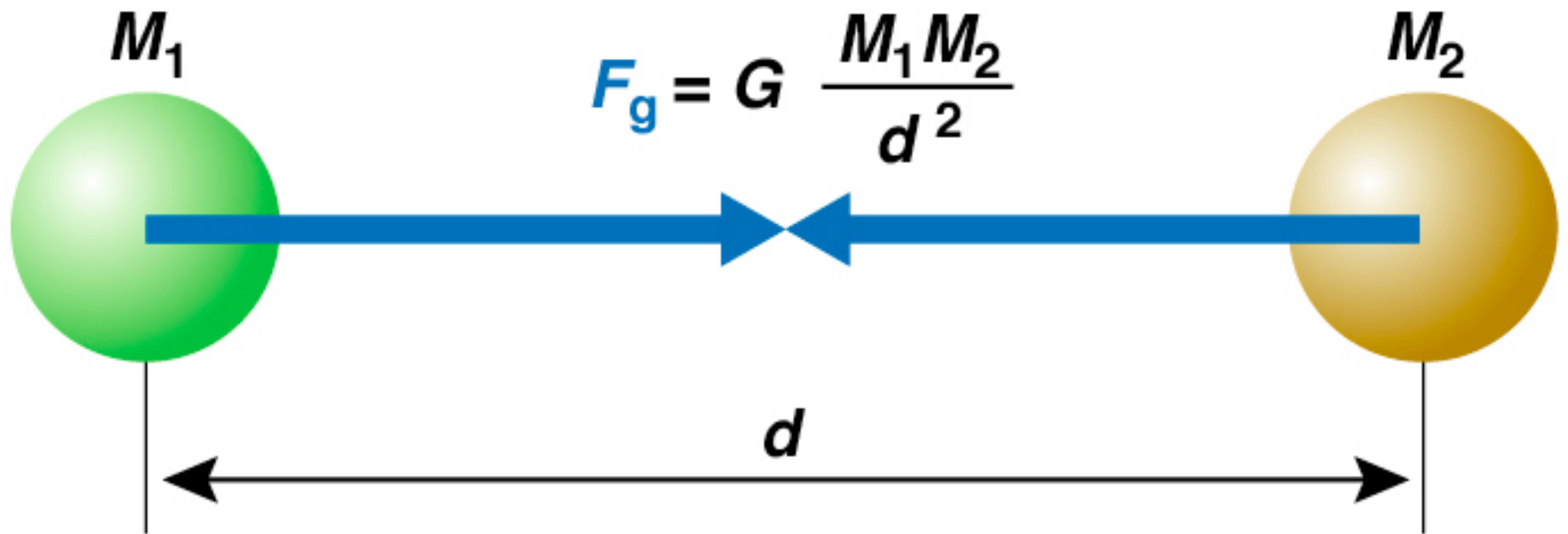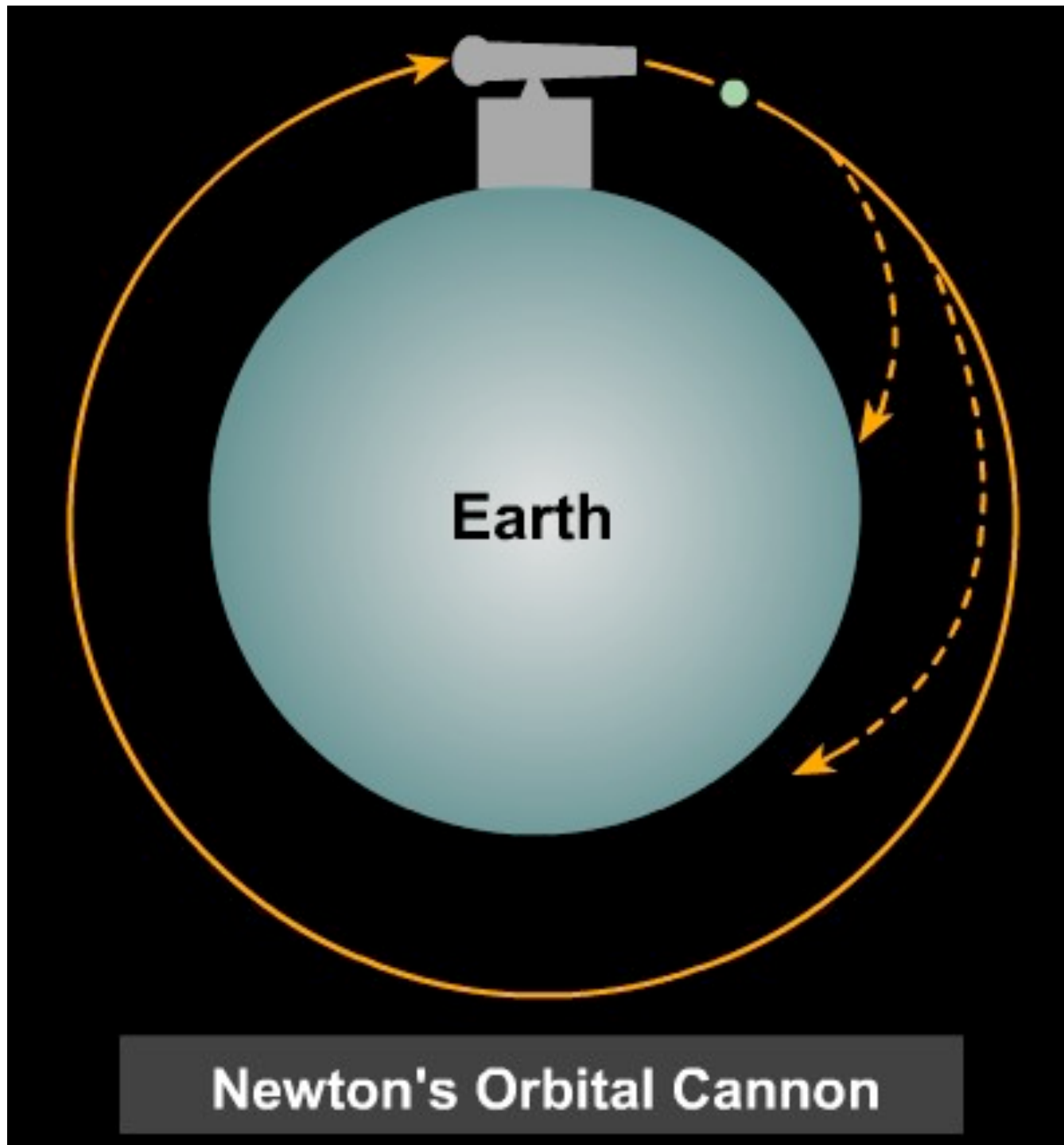
Newton's Theory of Gravity Explains Orbits of the Planets
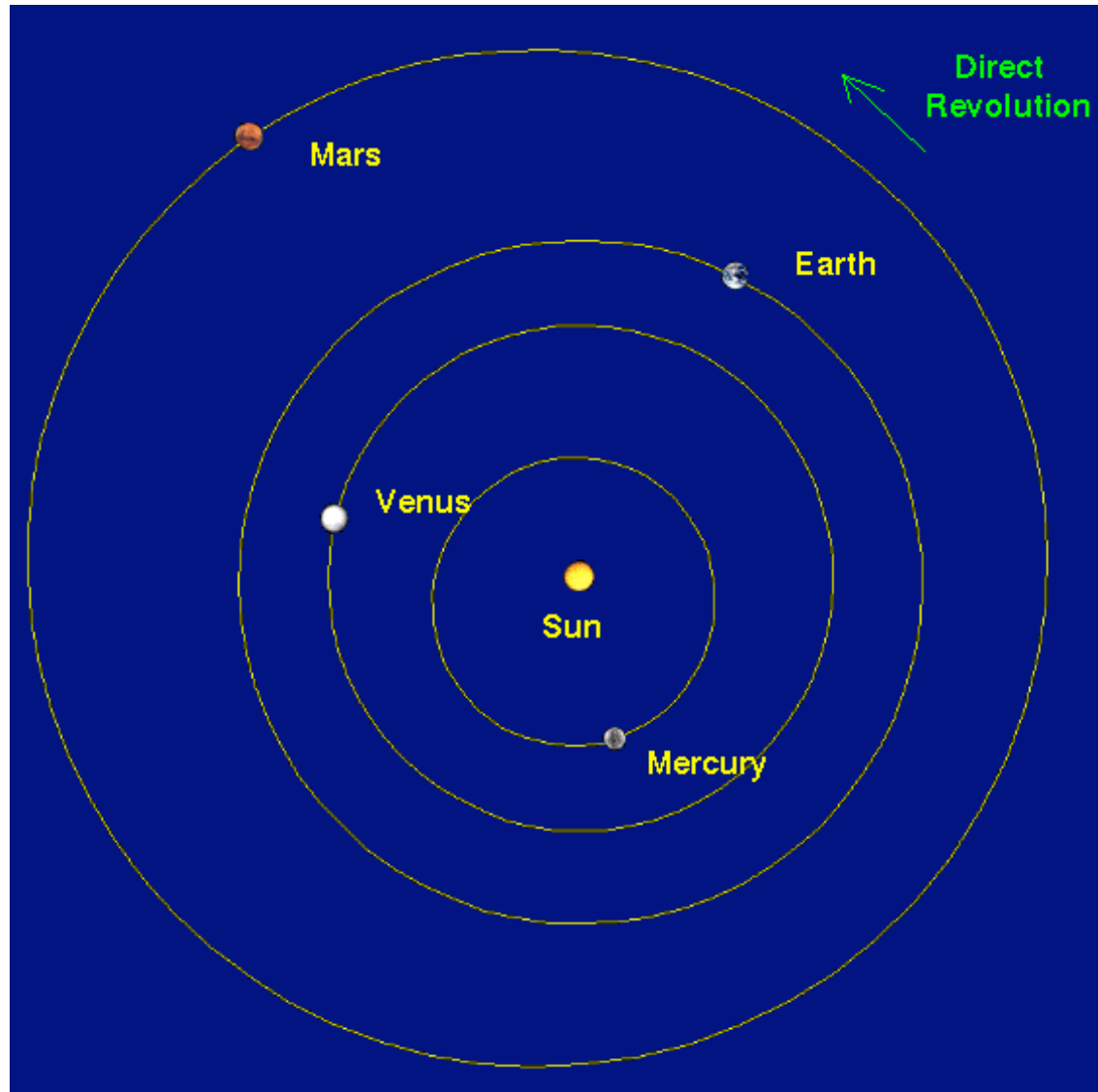
Halley's Comet – another test of Newton's theory

Halley's Comet: Orbital Period of 75 years
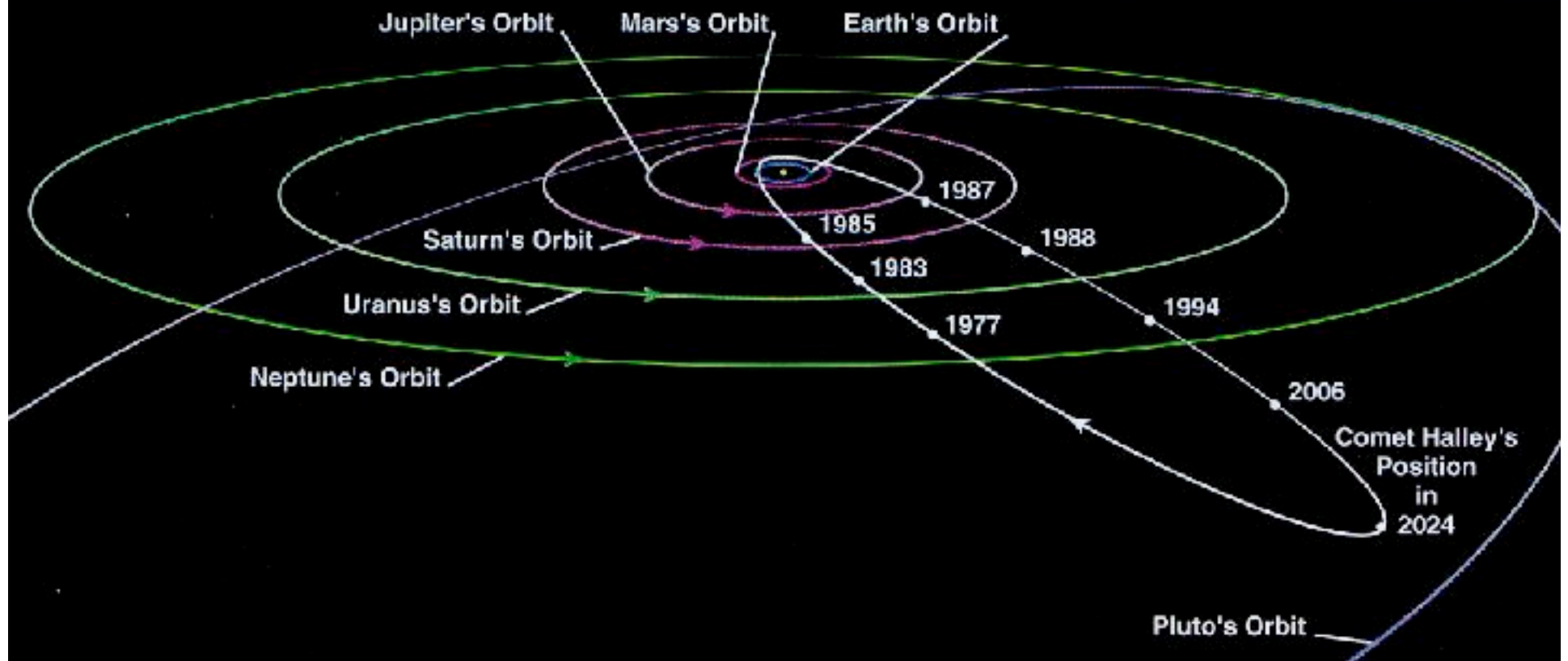
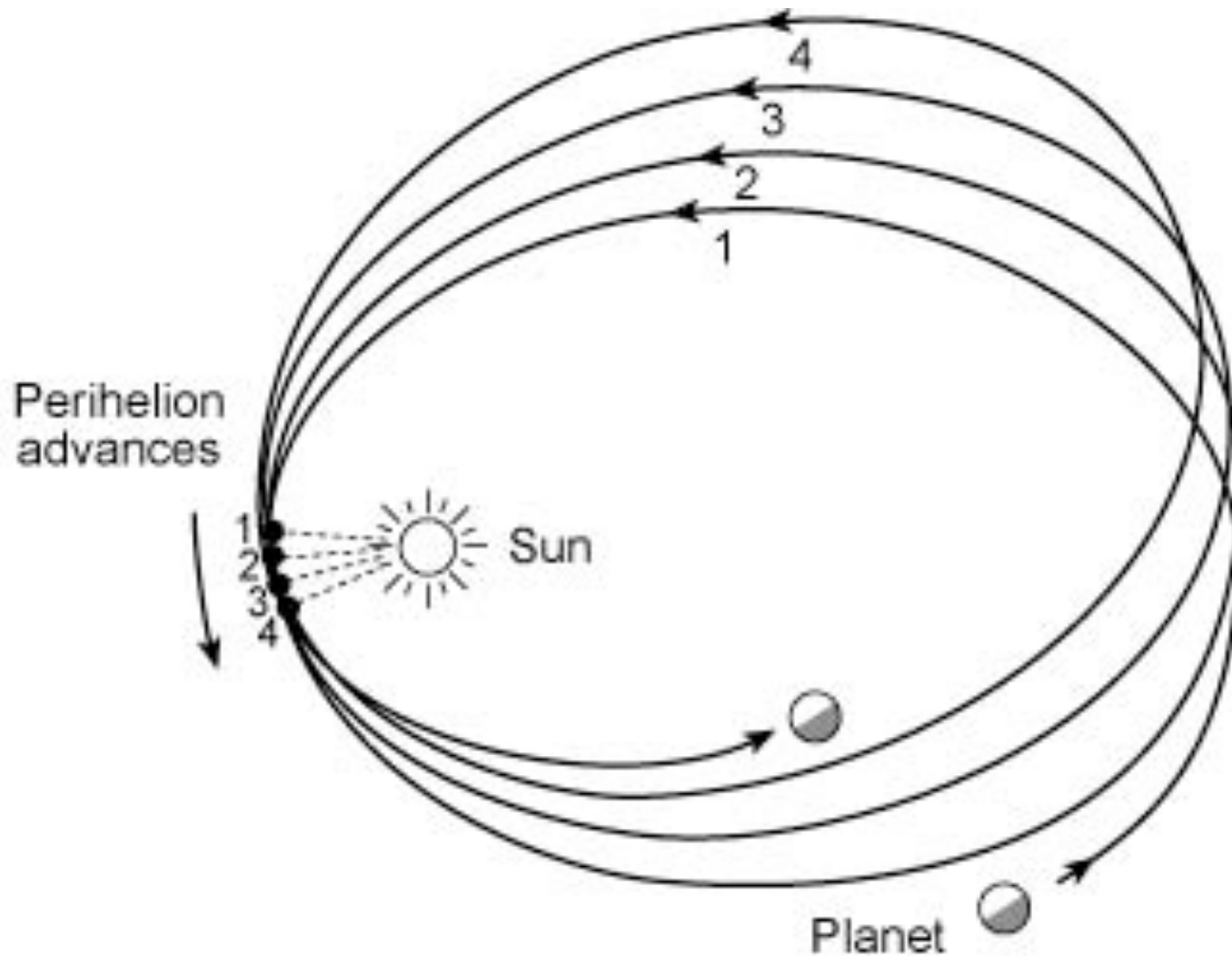# Newton's Theory of Gravity Explains Periodic Return of Halley's Comet

Prediction: Newton's Theory of Gravity – A new planet outside of Uranus
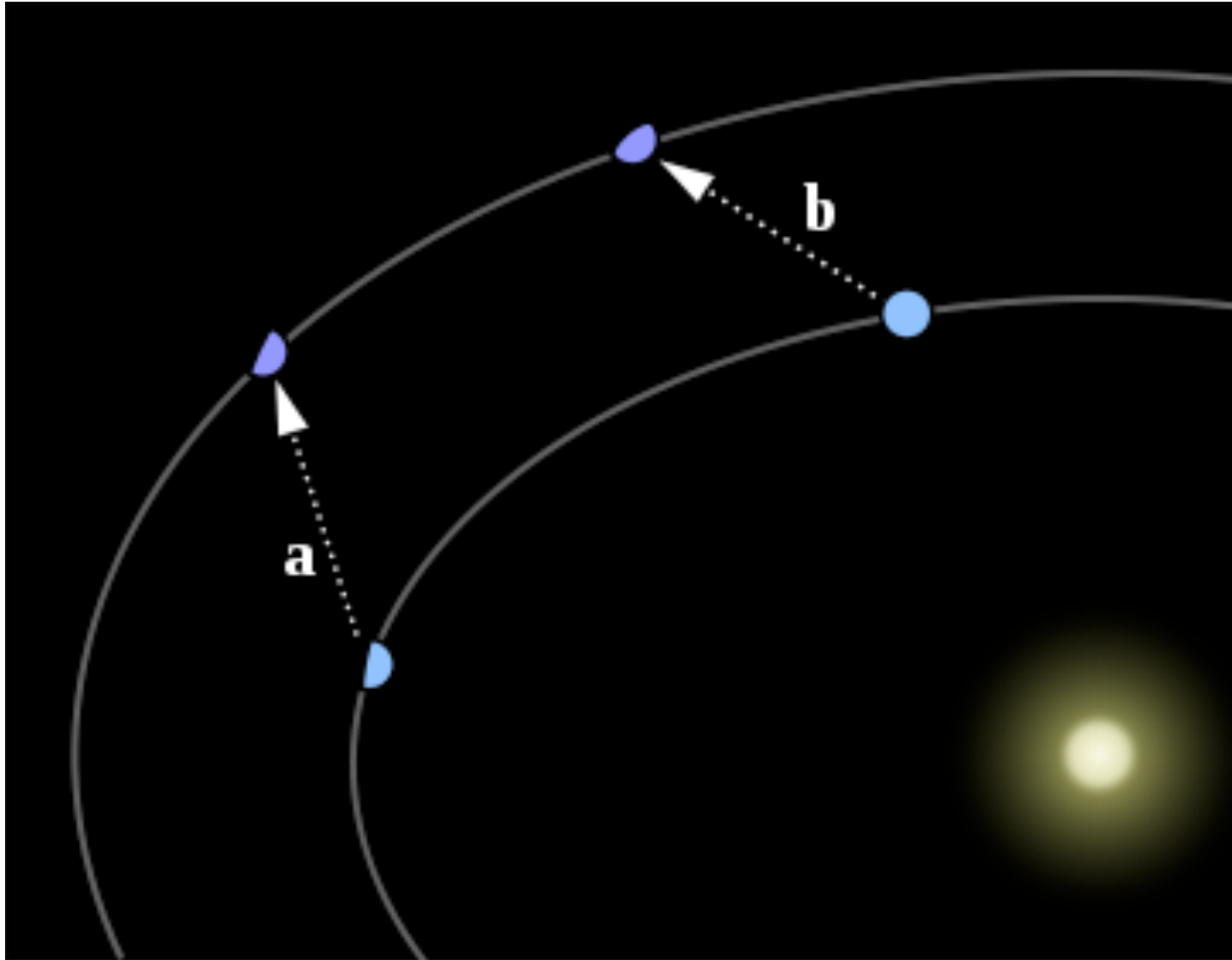
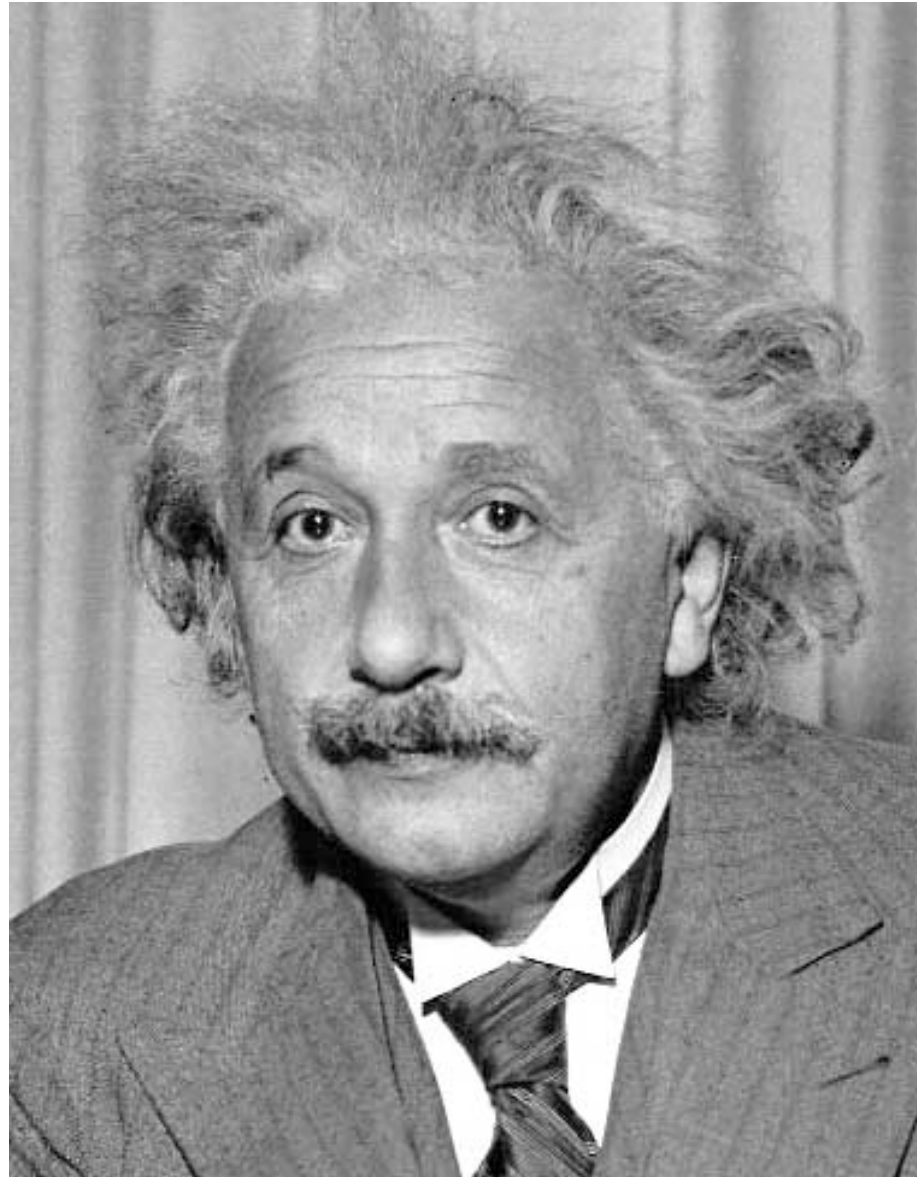# Evidence: Newton's Theory of Gravity – Discovery of Neptune
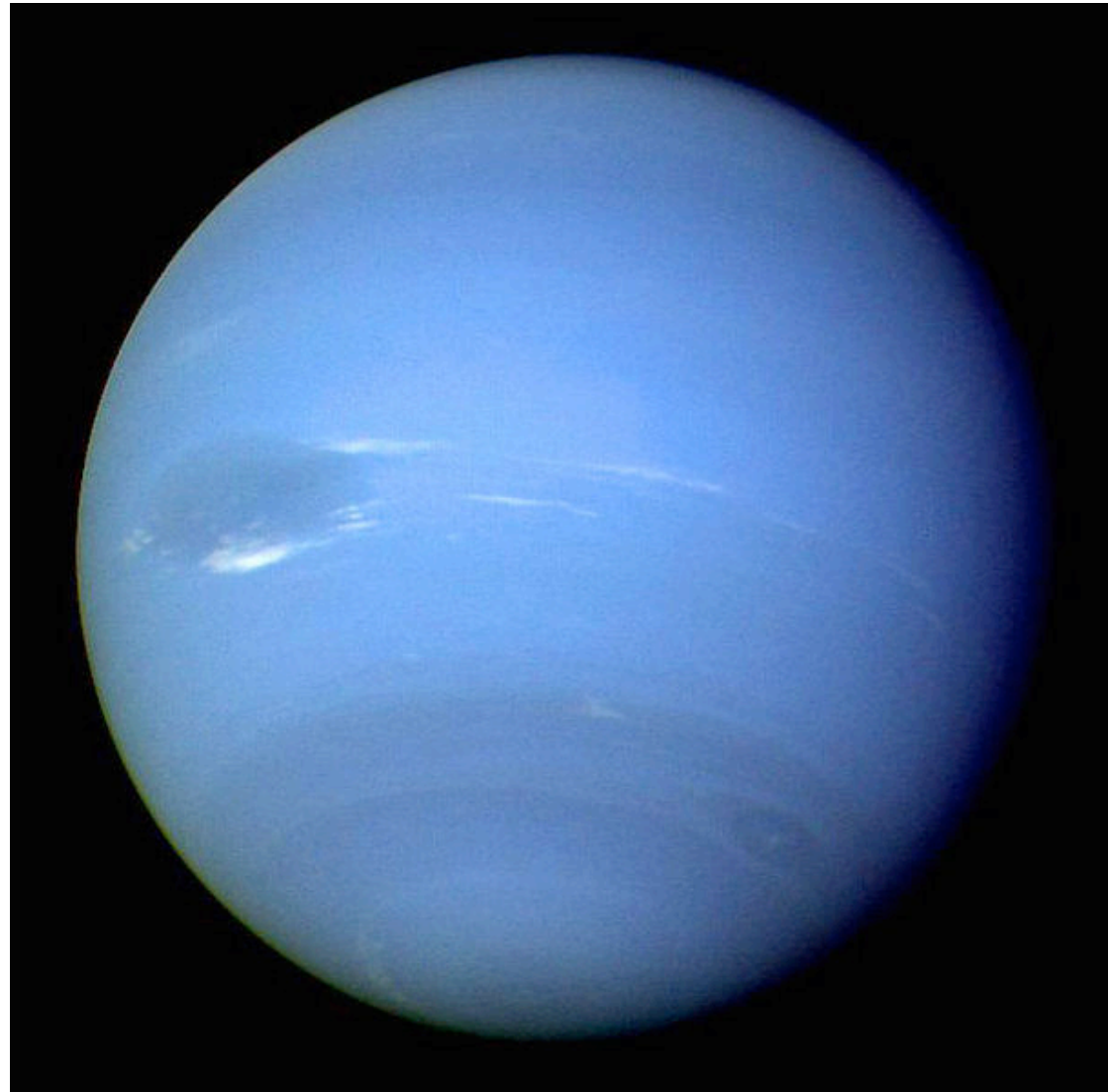
Another Problem: Mercury's Orbit Not Perfect

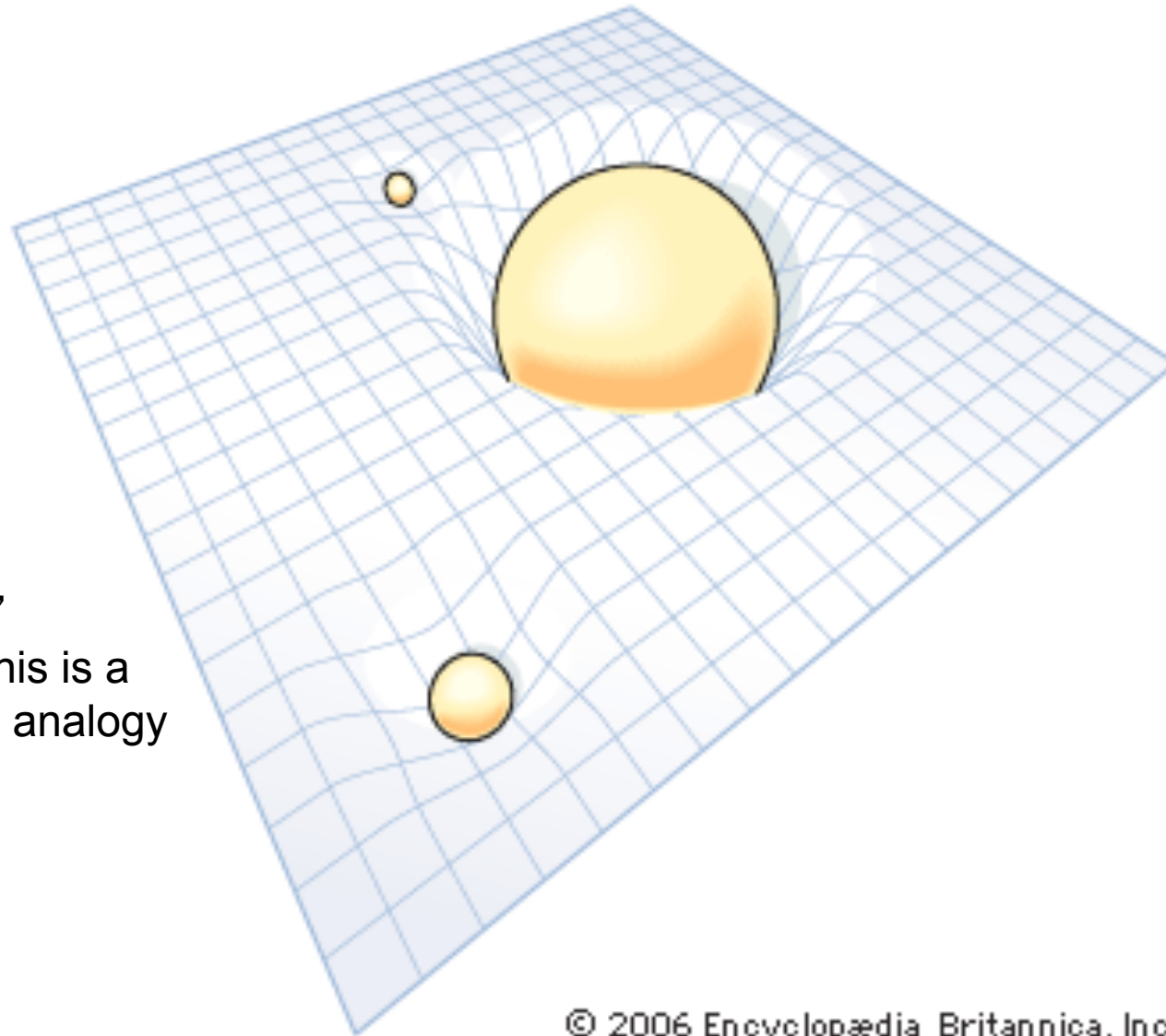# Prediction: Another Planet – "Vulcan" – inside Mercury's Orbit

NEVER OBSERVED!

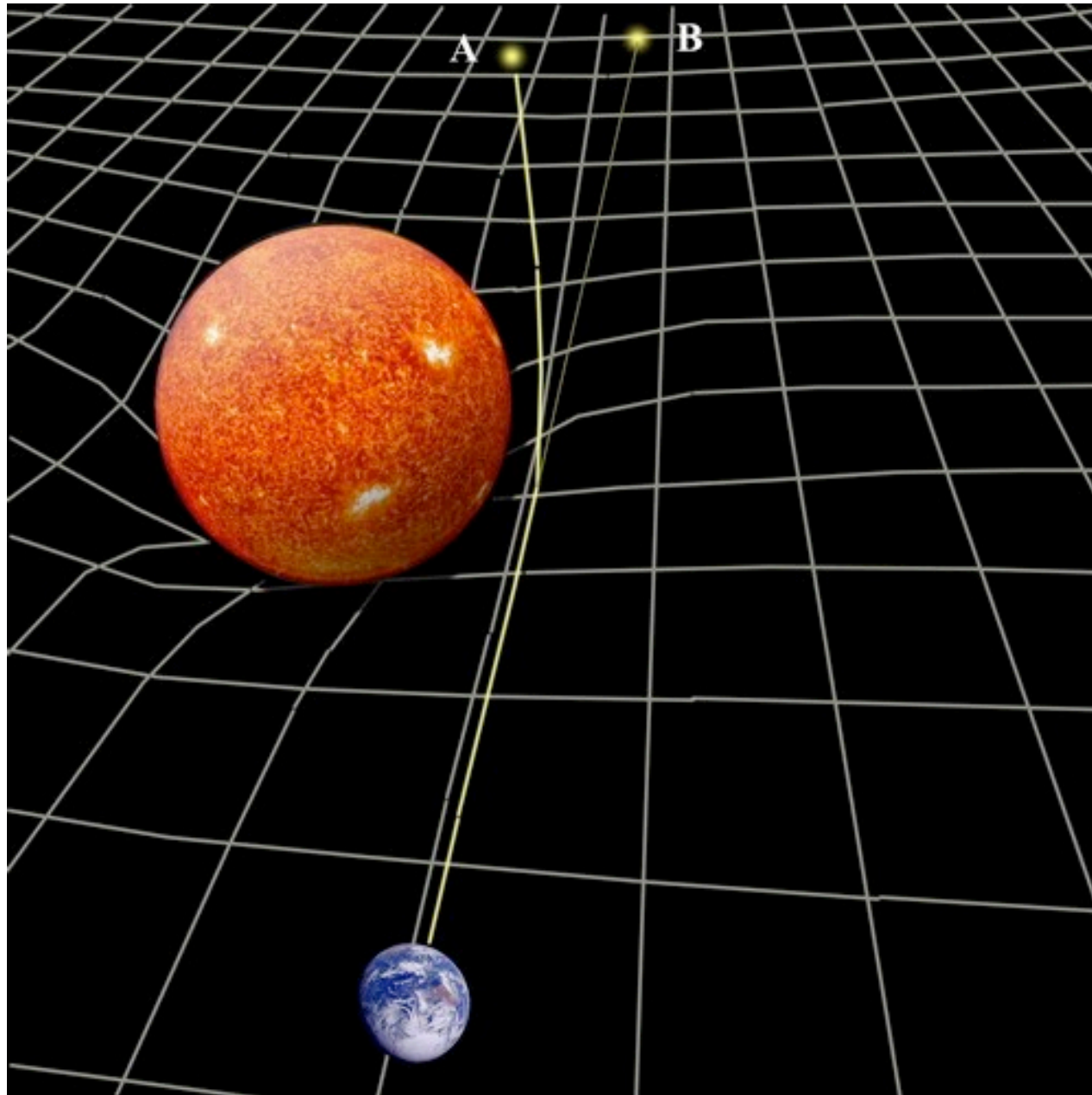# A New Theory of Gravity: General Relativity

Einstein
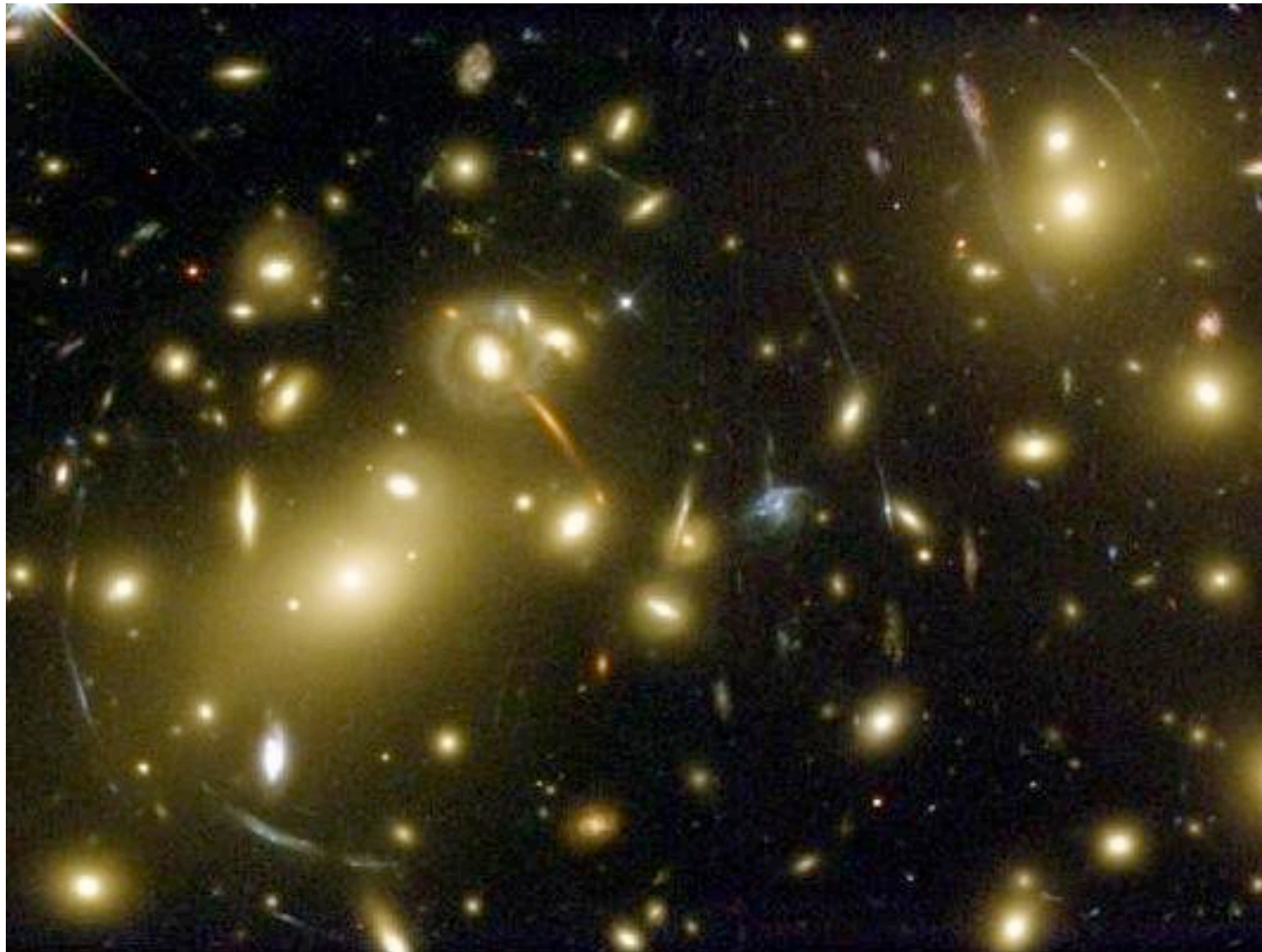
A New Theory of Gravity: General Relativity

Mass "warps" spacetime. This is a 2 dimensional analogy

Prediction: Einstein's Theory of Gravity

Evidence for General Relativity : Gravitational Lens

Is General Relativity the final Theory of Gravity?