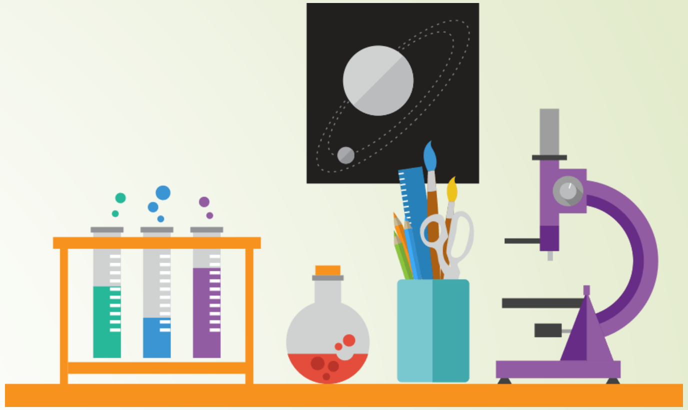

# Modern Scientific Method

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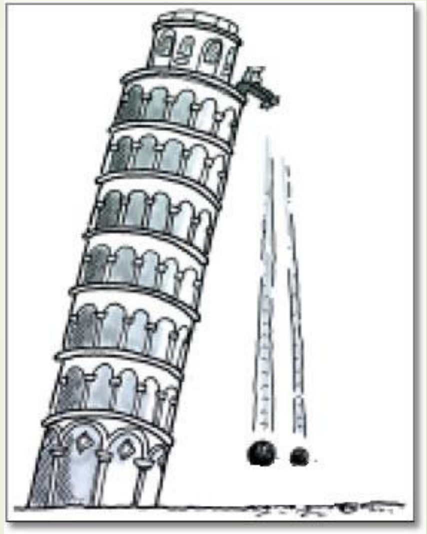
# Modern Science

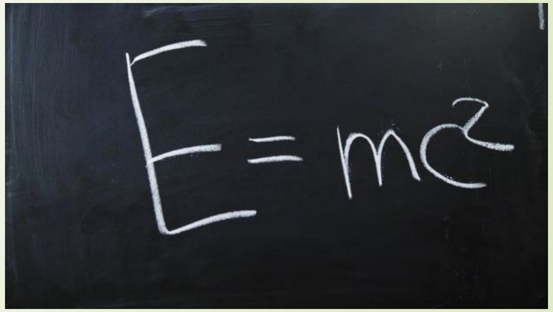
- Why do we do science? Man's curiosity about nature, desire to understand how the universe works
- Modern scientific knowledge derived from facts arrived at by observations and experiments
  - Not personal opinions, speculation, imagination, authority
- Ancient science vs. modern science:
  - Aristotle said heavier object falls faster to earth as more material attracted to earth more
  - Galileo took two objects of different weights to the top of leaning tower of Pisa, dropped them at same time, they reached ground at same time



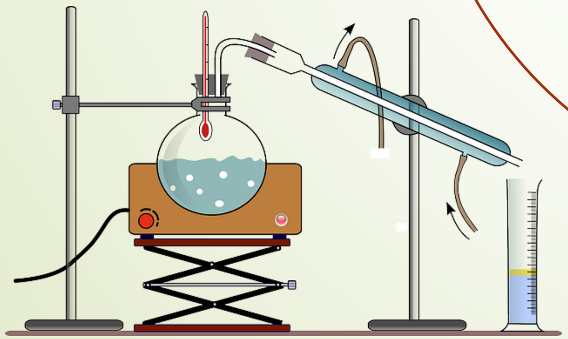
# Modern scientific method


Observations
Experiments

Generalize: new theory, or refine existing theory



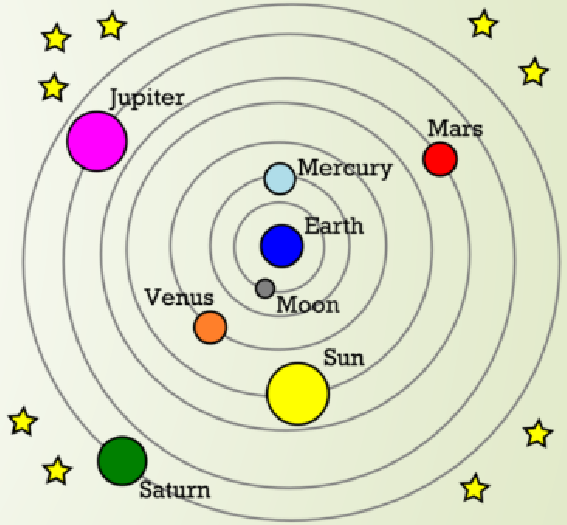

Make predictions, run experiments to test theory



Confirm or falsify existing theory

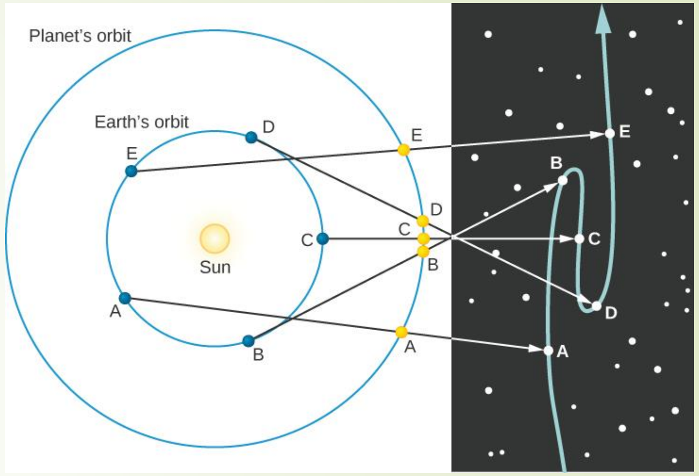
# Example: Science of the solar system Geocentric theory

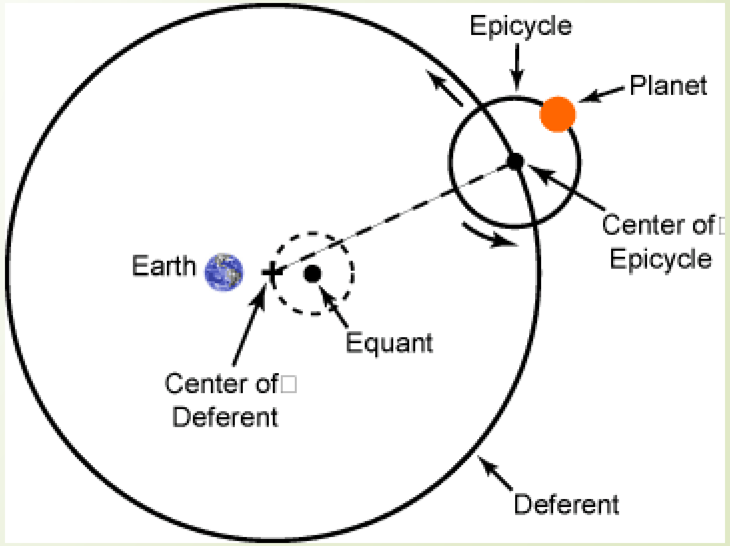
- Pre-modern science: geocentric theory
  - Based on observation that earth is stationary and heavenly bodies appear to be moving
  - All heavenly bodies are perfect spheres, moving around earth in perfect circles
- Aristarchus proposed sun centric model, but failed to convince
  - Could not explain why we don't perceive motion



# Ptolemy and epicycles

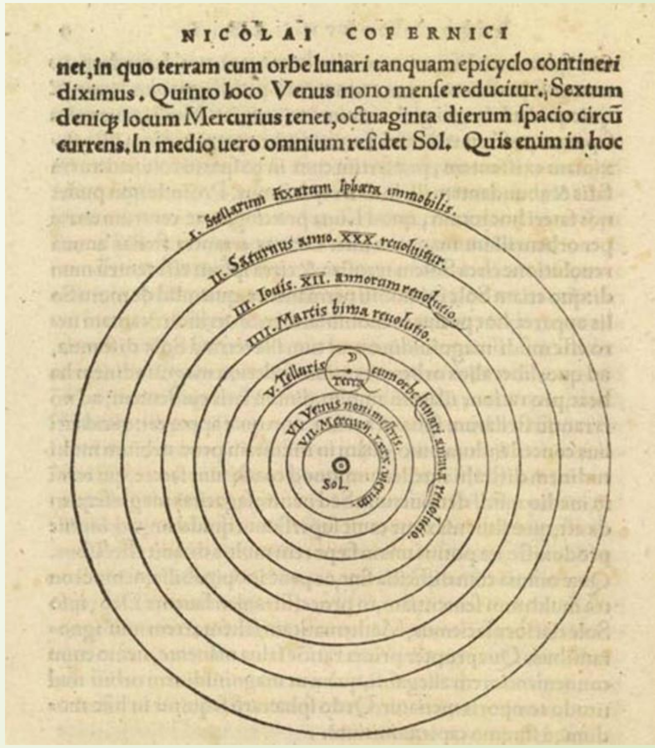
- Fairly accurate measurements of stars and planets in ancient times
- Some observations did not fit geocentric model, for example, retrograde motion of planets
- Ptolemy refined geocentric theory to explain observations
  - Each planet moves in a circular path (epicycle)
  - Center of epicycle moves around earth in a circular path (deferent)
- Church also encouraged geocentric model as it was consistent with Bible



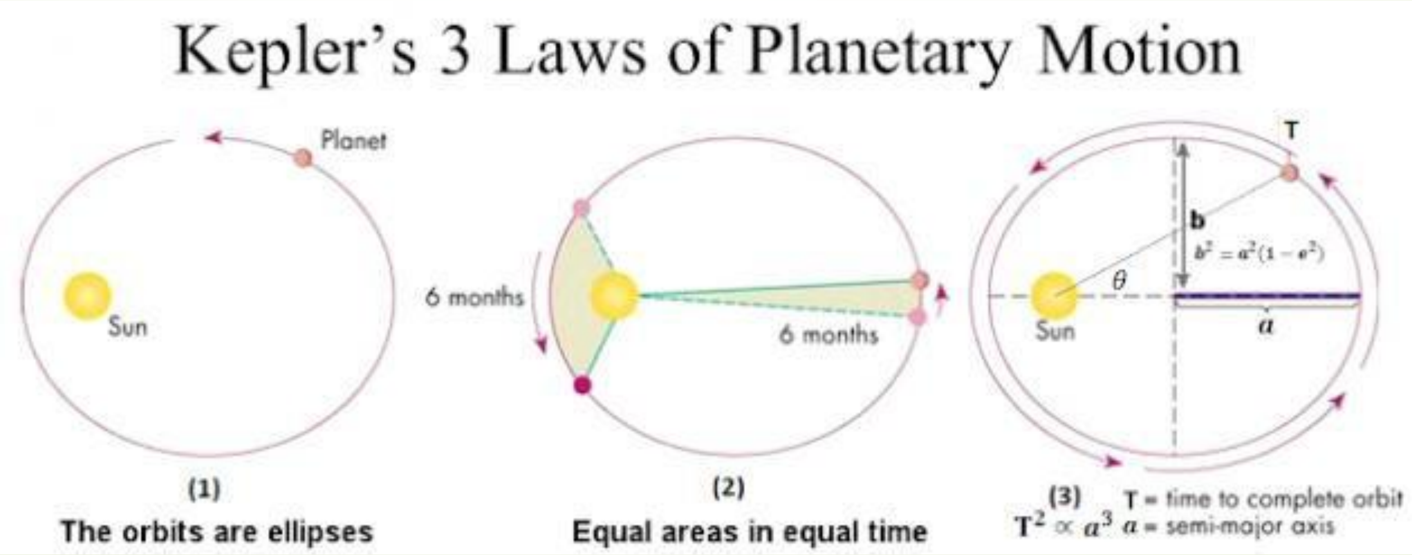
# Copernicus and heliocentric theory

- Work on astronomy continued in the middle ages in the Islamic world, India, China
  - Precise measurements for religious purposes
  - Analysis and criticism of Ptolemy's theory
  - Suggestion that something other than earth could be the center of the solar system
- Europe rediscovers translations, Islamic science via Byzantine scholars moving West (fall of Constantinople)
- Copernicus (16$^{th}$ century) proposed heliocentric theory
  - Sun, not earth, is center of the solar system
  - Still needed epicycles to match observations (wrong circular orbits), not immediately better than Ptolemy



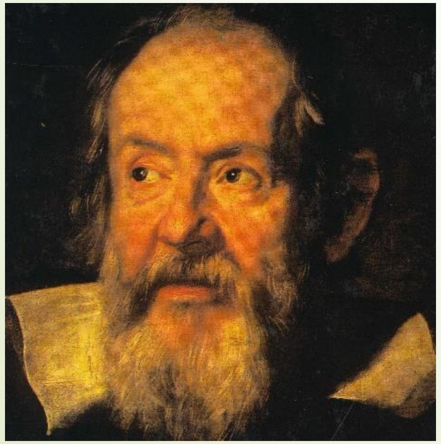
# Brahe and Kepler's laws

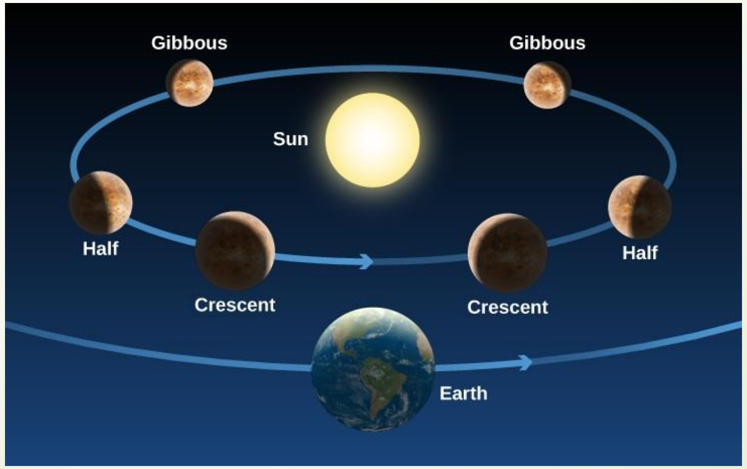
- Further refinements to Copernicus model in 16th -17th century
  - Brahe made careful observations
  - Brahe's assistant Kepler proposed laws of planetary motion to fit the new observations
- Heliocentric model became simpler and more accurate than geocentric model, starting to become more acceptable



# Galileo and the telescope

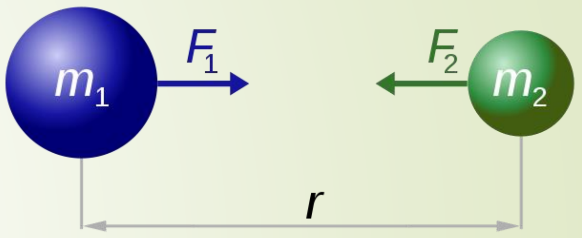
- Galileo (17th century) used the telescope to make observations in support of the heliocentric model
  - Observed phases of Venus which were not noticeable to naked eye
  - Proved that Jupiter has moons, nothing special about Earth's moon (moon goes around Earth was an argument for geocentric theory)
- Church initially opposed, made Galileo recant (who is said to have muttered "And yet it moves"), but later became more tolerant



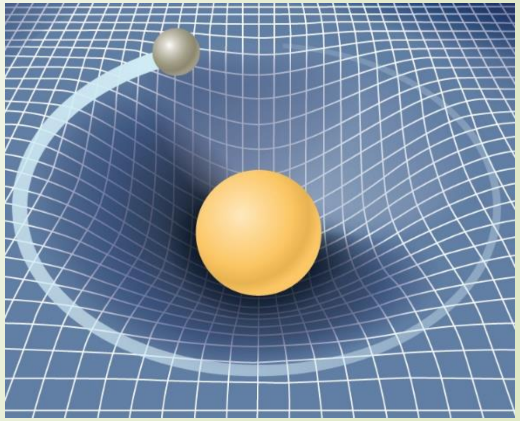



# Newton, Einstein, gravity

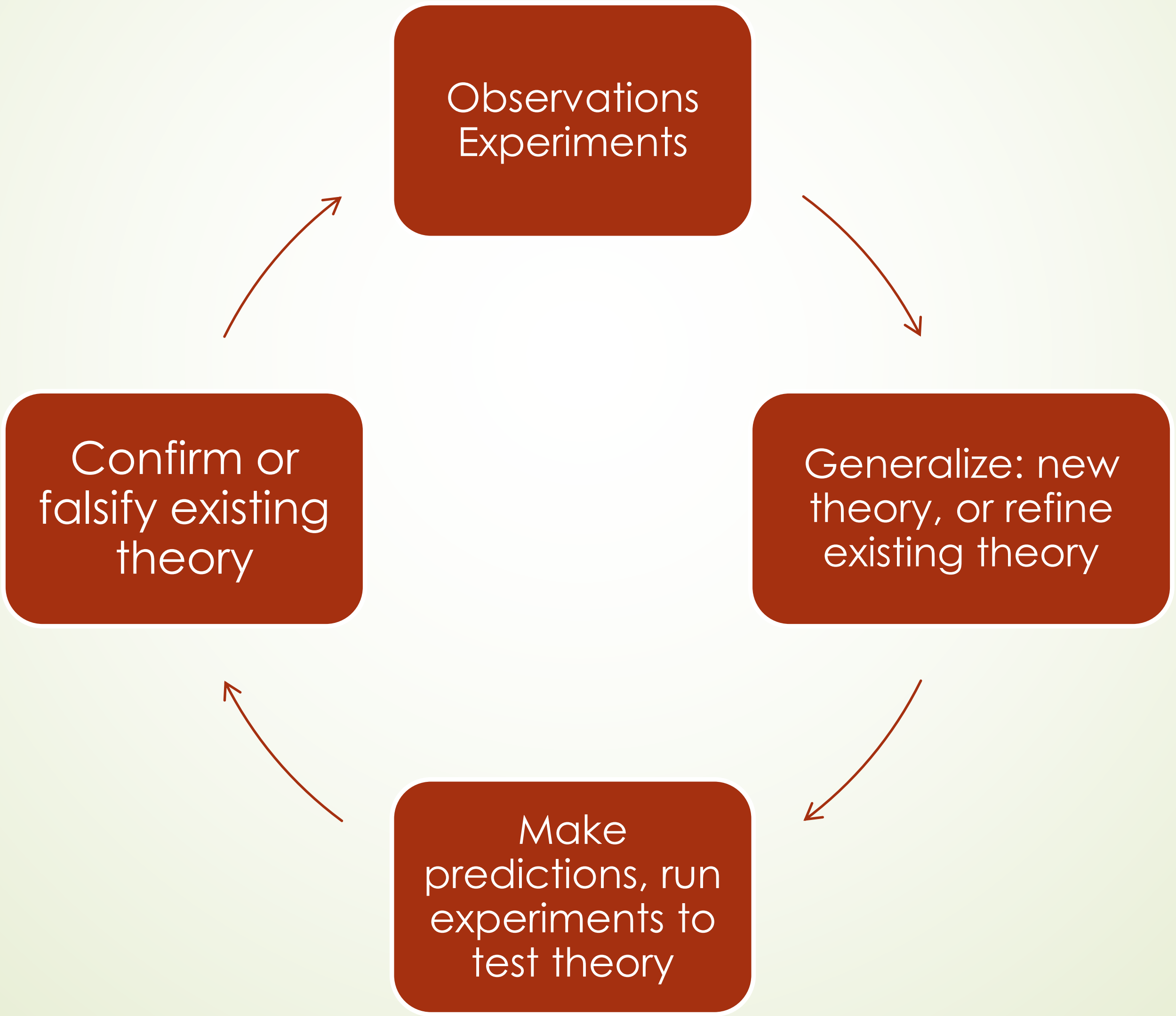
- Newton's law of gravitation (17th – 18th century) could explain astronomical observations, Kepler's laws and elliptical orbits
  - Contributions by Robert Hooke and others
  - Does not explain the origin of gravity
- Heliocentric theory fully accepted after almost two centuries of being worked upon
  - Paradigm shift between theories is a long process
- Einstein's theory of general relativity (20th century) further explained gravity in terms of space-time
  - Better matches astronomical observations under high gravity scenarios




$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$



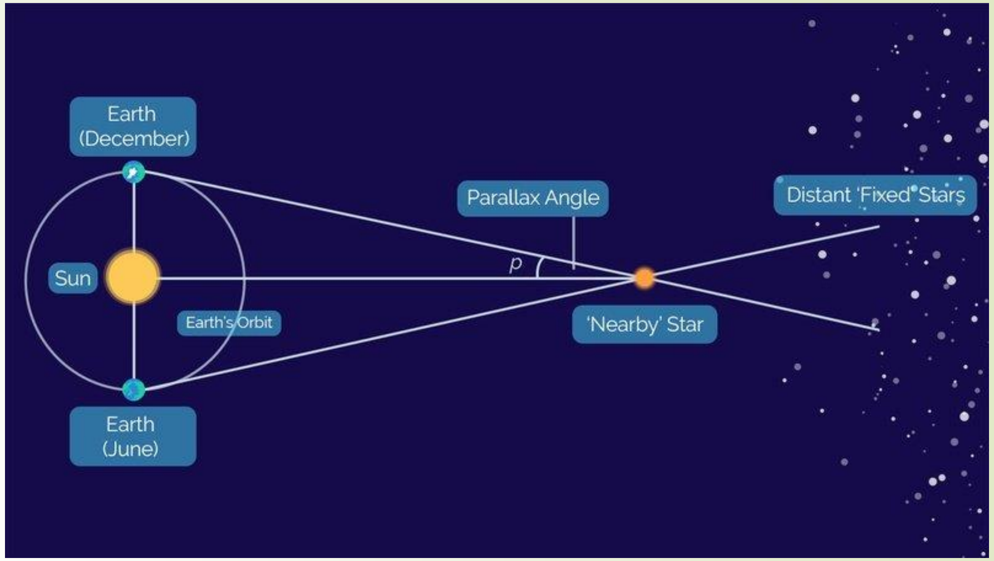
# Let's revisit the scientific method



# Scientific Observations

- Observations with our senses, but there is more to it
- Observations depend on what technology is available
  - Robert Hooke's Micrographia (17th century): one of the earliest microscope illustrations, opened up a new world
  - Galileo's telescope helped prove heliocentric theory
- Observations depend on experience and skill of observer
  - New medical student seeing X-ray may not "see" many things
- Not always actively done, can happen by chance, luck and serendipity sometimes
  - Alexander Fleming and the discovery of penicillin (1928): On returning from vacation, Fleming found fungus on agar plate, and bacteria did not grow around the fungus

# Fallible observations




- Observations can be fallible (prone to errors)
  - Observation of stationary earth led to geocentric theory
- Preconceived notions, biases, expectations can cloud observations
  - Religious beliefs biased ancient scientists towards geocentric theory
- If background knowledge wrong, observations can be defective, missed, or misinterpreted
  - Heliocentric theory of Aristarchus disproved initially, because expected to see changing alignment of stars due to parallax, but none was found
  - Stars too far away to notice parallax with naked eye, noticeable with telescopes

# Observations and background knowledge

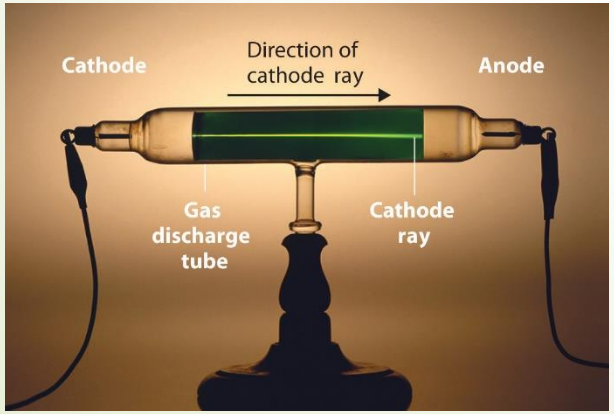
- Background knowledge decides what observations to make
  - You have to know what you are looking for, else may be missed
- Example: interpreting fossils much better after Darwin’s theory of evolution
- Tiktaalik is an extinct transitional animal between fish and four legged vertebrates
  - Fins more like limbs, with wrist bones, has a neck
  - Discovered in 2004, lived 375 million years ago
  - Could have been misinterpreted if not for knowledge of evolution of animals

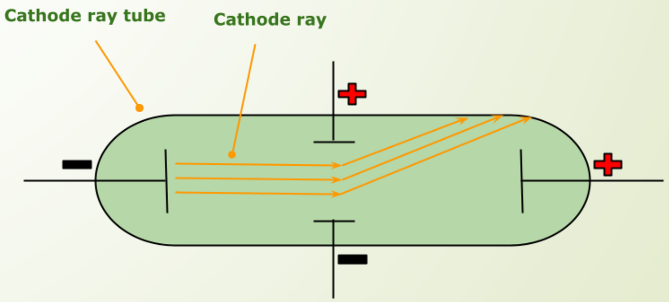
# Experiments: controlled observations

- Real life observations: many processes superimposed on, and interact with, each other in complicated ways
  - Aristotle's theory of heavier object falling faster based on stone falling slower than leaf (due to air resistance)
  - In perfect vacuum, a leaf and stone would fall at same speed
- Experiments are controlled observations
  - Careful setup to eliminate confounding factors
  - Blinding to remove expectations on outcome
  - Controlled initial conditions, clearer conclusions
  - Objective procedures, no subjective judgement
  - Reproducible by others, multiple observers and sources
- Experiments can be fallible too

# Example: Wrong experimental setup

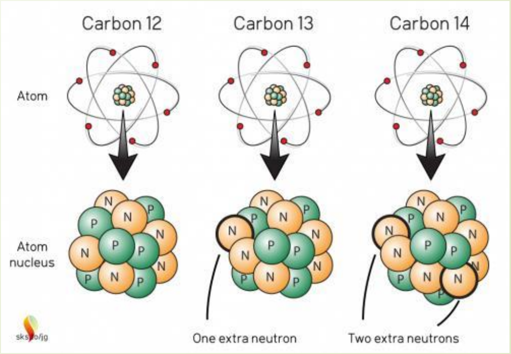
- Cathode rays: when high voltage across metals plates on either end of glass tube, electric discharge occurs, glowing inside tube
- 1880s: Heinrich Hertz conducted experiments to see if cathode rays are charged. Applied electric field perpendicular to direction of motion, no deflection was noticed
  - Why? Imperfect vacuum, gas particles get ionized and disrupt results
- Later, J. J. Thomson improved vacuum technology and found deflection, calculated charge to mass ratio of electron



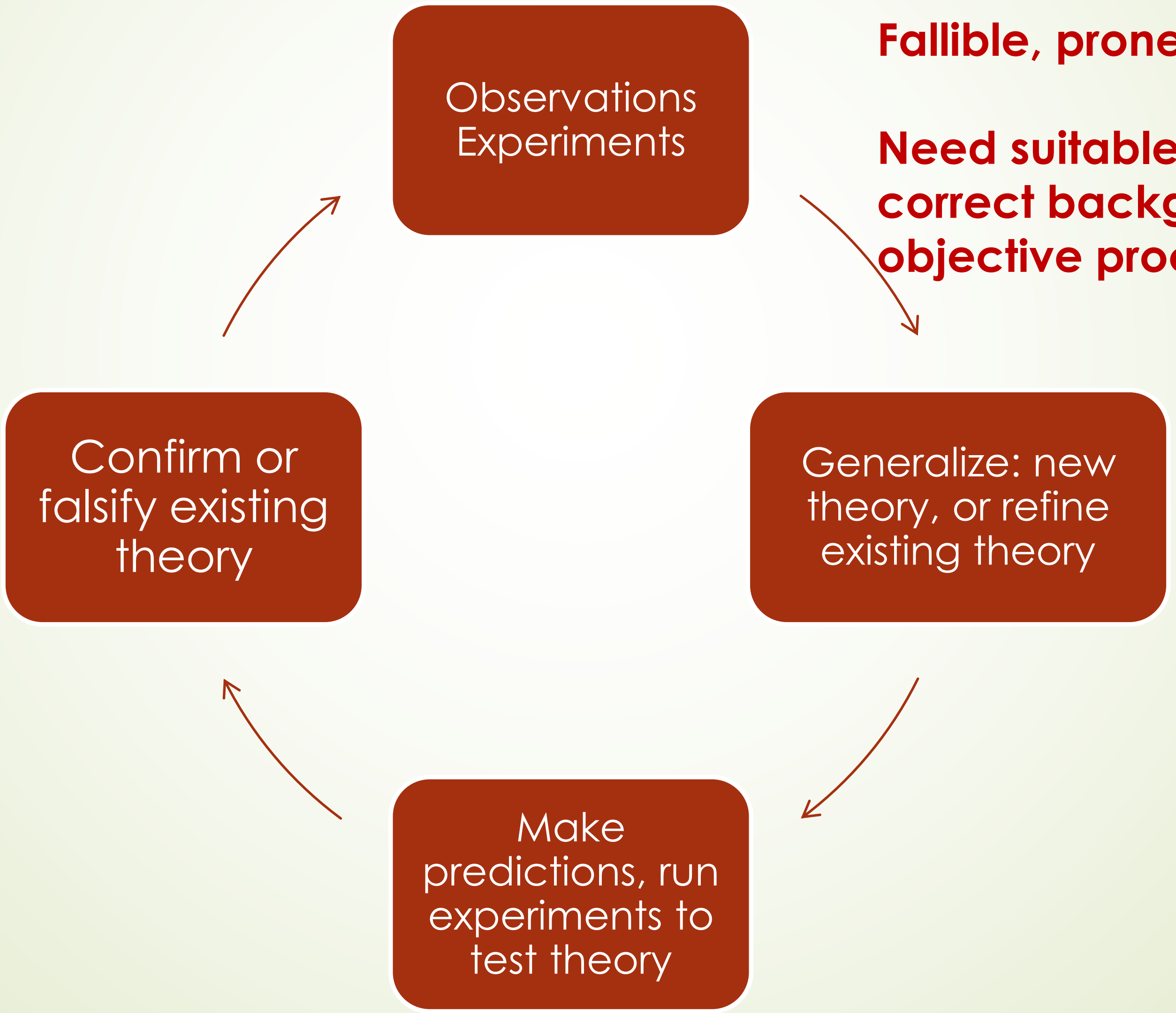



# Example: Wrong background knowledge

- Late half of 19th century: experiments to measure molecular weight
  - Scientists expected molecular weight of natural elements and compounds to be multiples of hydrogen weight, but experiments did not give this result
  - Why? Naturally occurring isotopes in different ratios led to different results
- Experiment setup and interpretation of results depends on background knowledge and available technology
  - Experimental results can be revised with better assumptions and technology
  - Science needs an open mind, ability to accept flaws in observations and experimental results and revise theories



# Let's revisit the scientific method

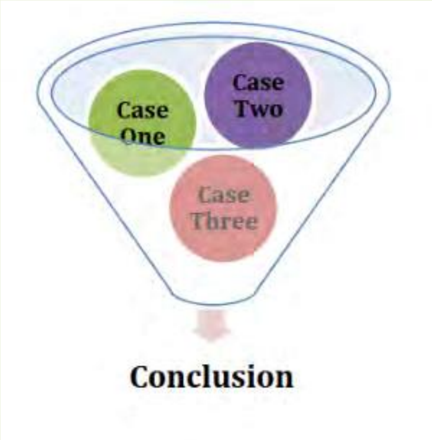



**Fallible, prone to errors**

**Need suitable technology, equipment, correct background knowledge, objective procedures**

# Generalizing facts via induction

- Induction or inductive argument: proceed from a finite number of observations to a generalized theory
  - Observe: many metals expand when heated
  - Generalize: metals expand when heated
- Must consider a large number of samples collected in a variety of conditions to avoid incorrect generalizations
  - Background knowledge used to decide how many samples is enough
  - To observe different types of metals, must know what are the various types of metals



# Enumerative induction

- Enumerative induction: enumerate many instances and generalize
- Strong inductive argument: generalization about relevant property based on a sample that is large enough and representative of the target group
  - Target group: a group of entities about which generalization is being made
  - Sample: observed members of the group (simple random sampling is one way)
  - Relevant property: the property about which generalization is being made
- Wrong generalizations from induction
  - Hasty generalizations based on a small sample
  - Biased sample, not representative of a group

# Analogical induction

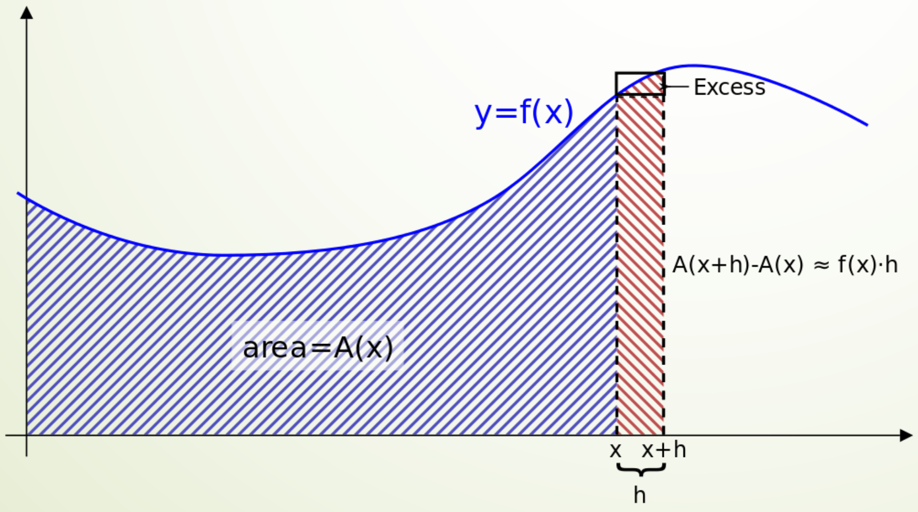
- Use of analogy in inductive reasoning
  - Observe: Drug X is used to treat disease Y in mice, dogs, and other mammals
  - Analogy: Humans are also mammals and biologically similar to mice, dogs
  - Generalize: Drug X will treat disease Y in humans also
- Need to ensure that similarities used in analogy are relevant to the property about which generalization is being made
  - Birds can fly but humans cannot, because of different body structure
- Helpful to have a large number of analogies from diverse cases
  - Test Drug X on different types of mammals
- May lead to incorrect generalizations
  - Aristotle concluded men have more teeth than women because it is so in horses

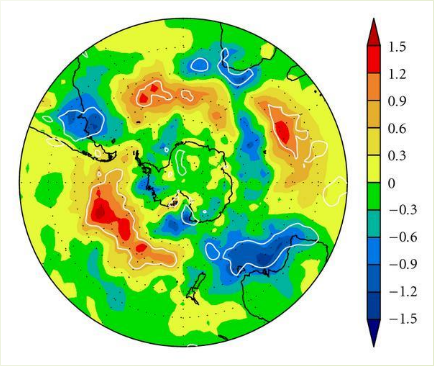
# Statistical induction

- Statistical induction can be used to draw probabilistic conclusions as well
  - Some scientific theories may not be exact but only probabilistic
- Example: Smoking causes lung cancer (probabilistically)
  - Not all smokers get lung cancer, not all lung cancer patients are smokers, smoking only increases the probability of developing lung cancer
  - Sampling and induction can be used to estimate probability of cancer if smoking
- Formulating such theories involves techniques from probability and statistics
  - Statistical models measure relative risk, increase in probability of developing lung cancer if you smoke (as compared to when you don’t smoke)
  - Statistical methods to calculate right size of sample, margin of error and confidence interval of the generalization

# Role of mathematics and computation

- Math is the language in which science is written
- Need enough mathematical tools before good theories can be formulated
  - Newton developed calculus to formulate his laws of motion
- Computational tools when closed form equations are difficult to obtain
  - Closed form equations not possible for complex systems like weather
  - Analysis of such models done via numerical methods, computer simulations



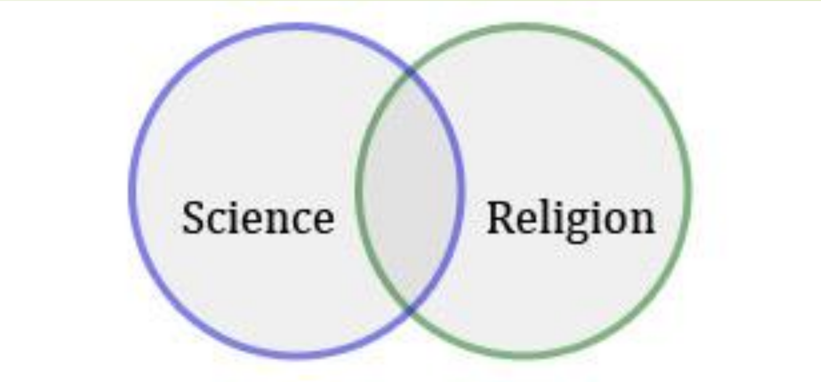
# What makes a good theory?

- Many possible ways to generalize: which theory to pick?
  - What if multiple theories can explain observations?
- Characteristics of a good scientific theory
  - Consistent internally (no contradictions) and with all observations (present, future)
  - Testable or falsifiable, i.e., there exists some tests or observations that can prove the theory false, but the theory hasn't been proven false yet
  - Able to provide a causal explanation for the observations (not always needed)
  - Simplicity (icing on the cake)

# Falsifiability

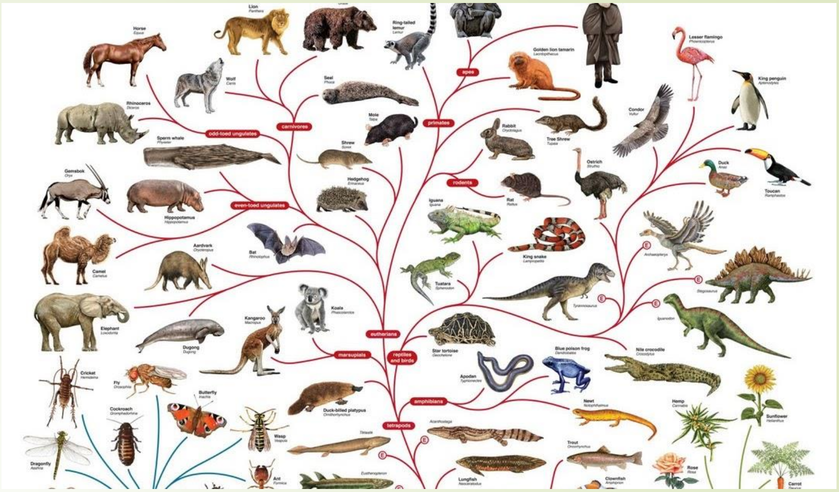
- A good scientific theory is falsifiable (term by Karl Popper), but is not falsified yet
  - Note that falsifiability not same as theory being true or useful
- Examples of falsifiable theories
  - A stone released near the surface of earth will fall down (falsified by finding a stone that goes up when released)
  - It rains on every Monday (not true but falsifiable, falsified by finding a dry Monday)
  - It rains on Mondays with 30% probability (falsified by finding probability of rain on Mondays to be greater than 30%)
- Examples of non-falsifiable theories
  - Earth is only 5000 years old but God placed much older fossils inside it to trick humans into believing it is older
  - Luck influences outcomes of sporting events (maybe true but not testable)

# Falsifiability and faith



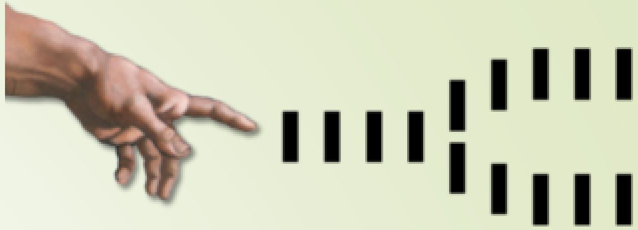

- Some theories are built on faith and not on falsifiability
  - Example: whatever happens, happens for your good
- Faith, religion with non-falsifiable theories may be important to some (not necessarily all) people for happiness and mental peace
  - Falsifiability is required for matters of science, not matters of faith
- Can science and faith co-exist?
  - Important to keep the domains of science (knowable, falsifiable) and faith (unknowable, non-falsifiable) separate
  - As what is knowable keeps increasing with progress in science, must keep updating the boundaries between faith and science
  - Must guard against faith encroaching on science: pseudoscience (non-falsifiable or debunked theories pretending to be science)

# Falsifiability and scope



- Extent of falsifiability is a measure of quality of theory
  - Theory with broader scope yields many more falsifiable predictions
  - More falsifiable claims in diverse scenarios → broader scope, better theory
- Example: evolution vs. creationism for origin of life
- Evolution explains many more diverse phenomenon besides origin of life
  - Diverse fossil records in different geological layers, from simpler organisms in older layers to more complex ones in newer layers
  - Similarities between humans and other primates, other species of animals
  - Emergence of infectious diseases, antibiotic resistance
  - Composition of earth's atmosphere and biosphere

# Causality and explanations



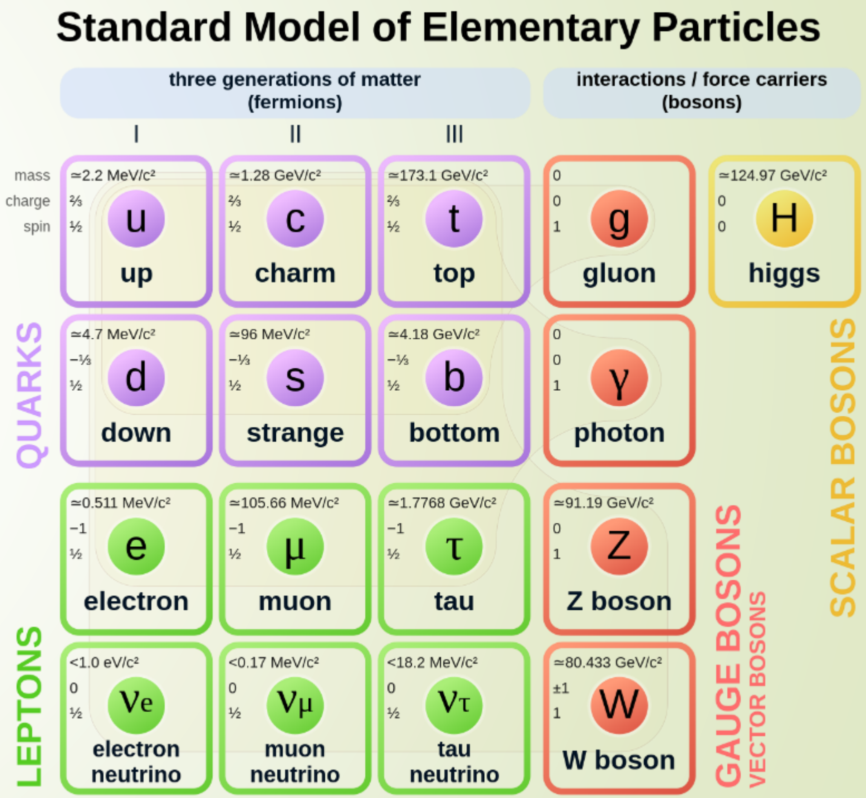
- Theories that provide a causal explanation are better than those that don't
  - Heating causes atoms to take up more space, hence metals expand when heated
  - Newton's theory of gravity did not provide a cause for gravity, but Einstein's theory did via warping of space-time
- How to identify causal factors in scientific observations?
  - Method of agreement: multiple occurrences of a phenomenon have a common factor, which may be the cause
  - Method of difference: phenomenon occurs when factor present, does not occur when factor absent
  - Varying causal factor in an experiment reliably changes the outcome or response
- Not easy to identify causality, especially when multiple, interdependent causal factors present, and causality is probabilistic
  - Cancer caused by multiple things going wrong, hard to pin blame on one

# Confusions with causality

- Correlation is not causation, maybe due to a hidden causal variable
  - Correlation found between baldness and heart attacks, but one doesn't cause the other (both observations may be due to some hormones?)
- Irrelevant factors may be present, needs background knowledge to judge
  - Most lung cancer patients in a group are smokers and have black hair, which factor is relevant and which is irrelevant?
- "Post hoc, ergo propter hoc" (after that, therefore because of that)
  - Taking a placebo pill and resting cures a headache
- Correctly identifying cause and effect
  - Does exercise cause good health or do healthy people exercise more?
- Can infer causality only when a clear explanation exists as to why changing an explanatory variable changes the outcome or response

# Limitations of causality

- Not all theories that provide causal explanations are correct
  - Boyle's law (pressure on gas inversely proportional to volume) explained by Newton incorrectly with a theory of motionless gas particles that repel with force inversely proportional to distance (proved false later with observations of particle motion)
- Not all theories without causal explanations are invalid or wrong
  - Standard model of particle physics has many elementary particles for matter and forces, generates testable predictions, useful
  - But cannot provide causal explanations for many phenomenon for now (why is there more matter than anti-matter?)



# Simplicity: Occam's Razor


- Occam's razor (law of parsimony): between competing theories, simpler explanation is preferred
  - Nature does nothing in vain (Newton), so simpler one is probably correct
  - Why does apple fall to earth? Earth attracts the apple or an invisible alien moves the apple to earth?
- Caveat: Occam's razor is just a guideline, not mandatory requirement
  - Sometimes, complex theories may in fact be correct (classical mechanics much simpler than quantum mechanics)
  - What is simple or complex can be subjective (which is simpler: geocentric or heliocentric theory?)

# Let's revisit the scientific method

Observations
Experiments

Generalize: new theory, or refine existing theory

Make predictions, run experiments to test theory

Confirm or falsify existing theory

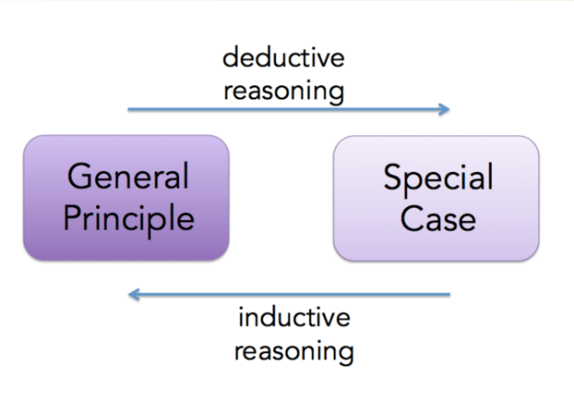
**Inductive argument**

**Math and stats tools**

**What makes a good theory? (consistent with observations, falsifiable, causal explanation, simplicity)**

# Predictions using deduction

- Theory formulated to fit existing observations. What next?
  - Multiple alternate theories can simultaneously coexist as well
- Generate predictions using deduction in variety of conditions
  - Premise/theory: Metals expand when heated
  - Observation/initial condition: X is a metal
  - Prediction based on deduction: X will expand when heated
  - Test: Heat X and check if it expands



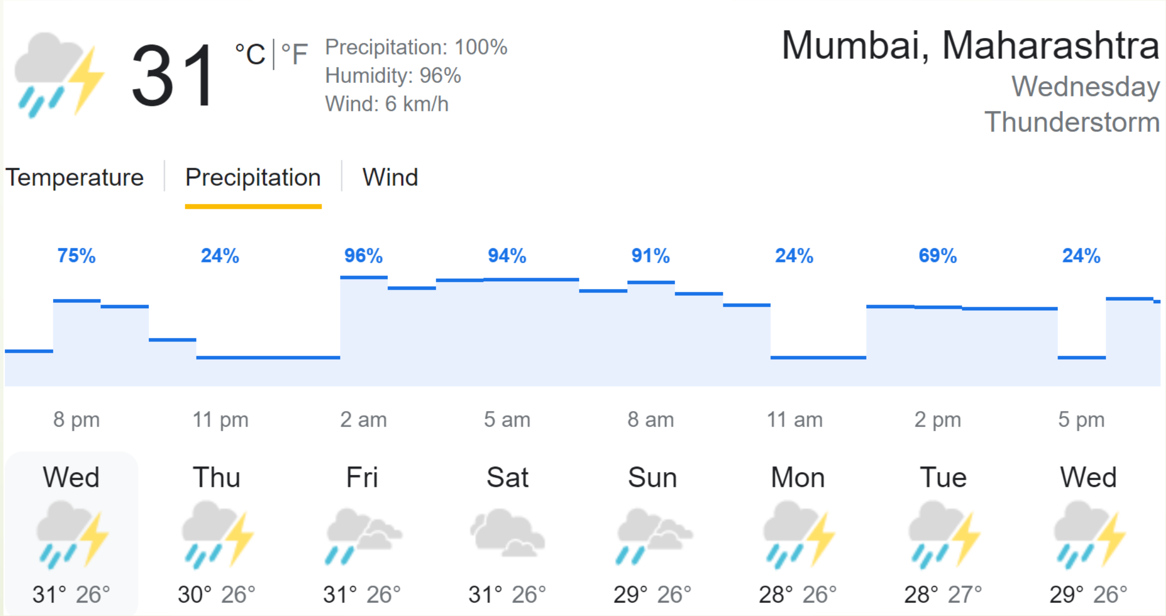

- Run experiments to test predictions
  - If experimental results match predictions, theory is correct for now
  - Else, theory proved false, refine existing theory or propose new theory
- Experimental results matching predictions increases confidence in theory, but future prediction may not match, theory may be proved false later

# Noisy initial conditions

- How to generate prediction if initial conditions are not known exactly?
  - Noise in measurement of mass can lead to error in predicted gravitational force
- Some theories are not very sensitive to initial conditions
  - Slight variation in initial conditions results in slight variation in predictions
- For some dynamic systems, slight change in initial conditions will lead to large deviations in final result (chaos theory)
  - Example: weather systems
  - Butterfly effect: small changes like adding a butterfly flapping wings can cause appearance of a tornado in a weather system calculation
- Generating predictions for such scientific models is very tricky

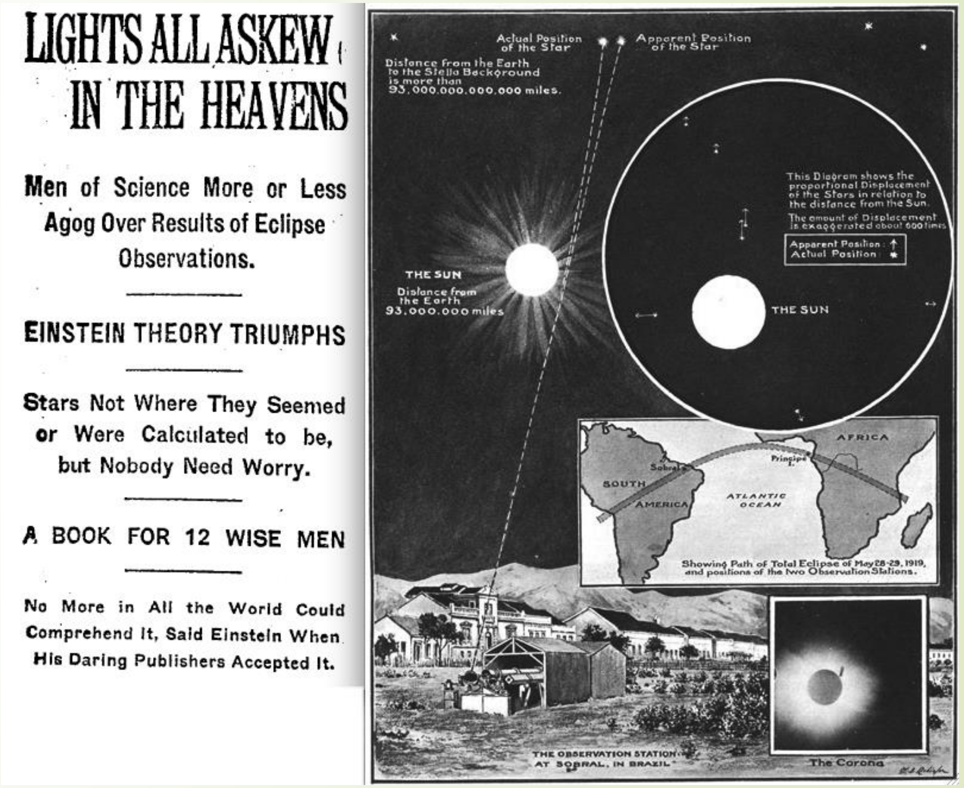
# Predictions using simulations

- Weather predictions using climate science models via simulations
- Example: calculating probability of rain using a weather model
  - Simulate weather for many different possible initial conditions
  - Calculate the fraction of the output scenarios that predict rain



# Experiments to test predictions

- Predictions from theories can be verified only if suitable technology, experimental equipment, resources exist
  - Hi-tech expensive particle accelerators, space telescopes ("big science")
- Collaboration between experimental and theoretical scientists: Eddington made observations that proved Einstein's theory
  - Prediction: bending of starlight by Sun but needs eclipse of sun to see stars near sun
  - Expedition to solar eclipse (1919) undertaken amidst war, clouds, lots of complications



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

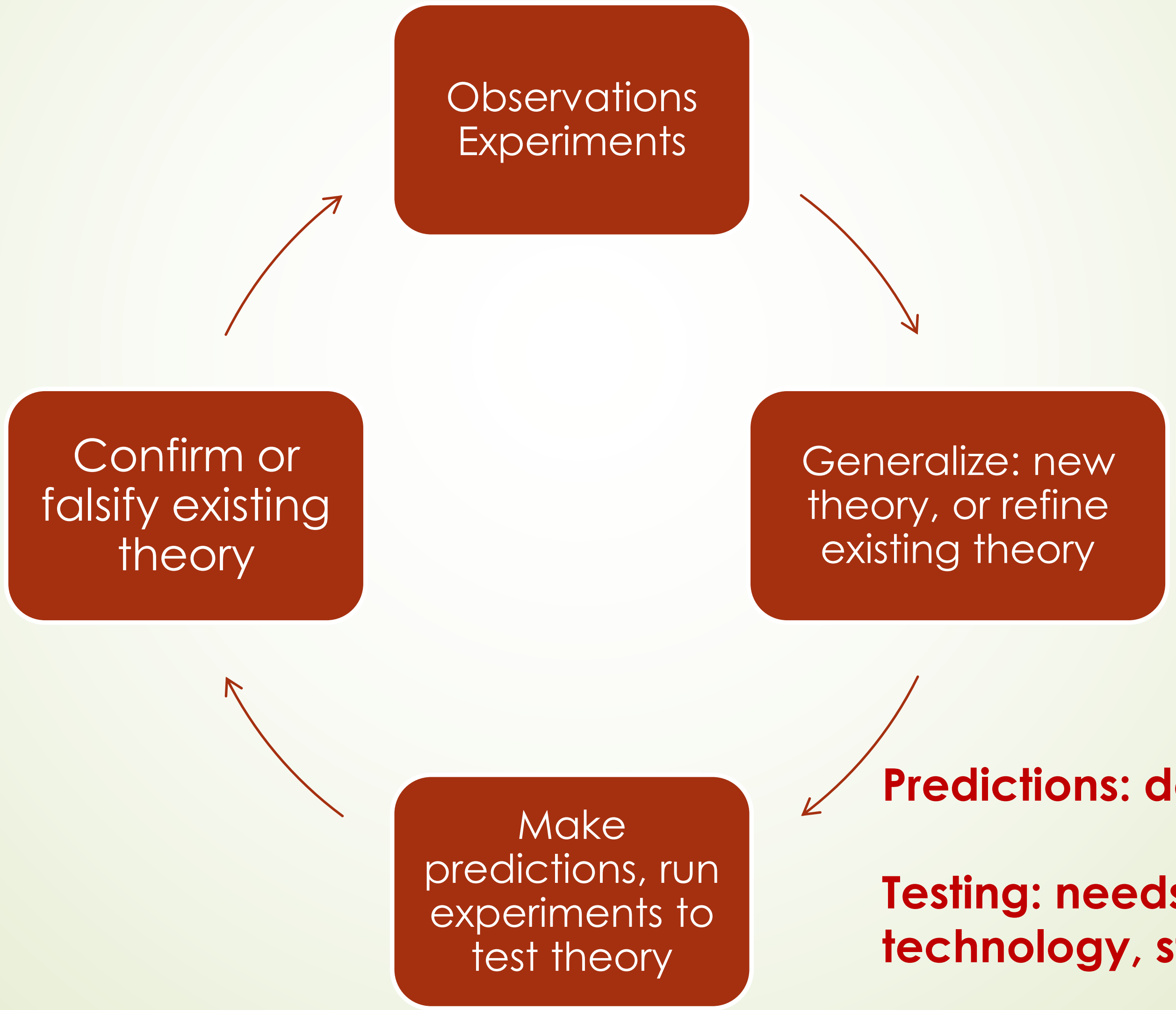
# Statistical methods to test predictions

- How do you test a theory that makes only statistical predictions?
  - Example: Smokers have a higher risk of developing lung cancer
  - Example: COVID-19 vaccines reduce risk of serious infection
- Collect samples using research study to statistically test hypothesis
  - Active experimental study: administer vaccines and measure disease outcome
  - Passive observational study: observe cancer incidence in smokers and non-smokers (un-ethical to ask people to smoke and see if cancer occurs)
- Use statistical techniques to decide if the observed samples confirm or reject the theory
  - Is the incidence of cancer higher in smokers than non-smokers? Do the observations increase the likelihood of the theory that smoking causes cancer?
  - Statistical tools to compute sample size, margin of error, confidence interval, …

# Statistical testing protocols

- How to test theory that vaccine/drug X prevents disease Y?
  - Collect a large and representative sample of people willing to take X
  - Randomly assign people to experimental group or control group
  - Administer X to experimental group but not to control group
  - Give placebo to control group (what if experimental group feels better simply by knowing they are getting a drug?)
  - Double blind study (information about drug or placebo is kept hidden from all participants, to avoid biases)
  - Make both groups similar to each other in all other aspects (age, health, socio-economic profile, gender, ..) to avoid impact of confounding variables
  - Run study, collect samples, compute statistics, draw conclusions
  - Compute confidence intervals, statistical significance (high statistical significance → unlikely that results have occurred due to chance alone)
  - Have other researchers reproduce the results in other scenarios

# Let's revisit the scientific method




**Predictions: deduction, simulation**

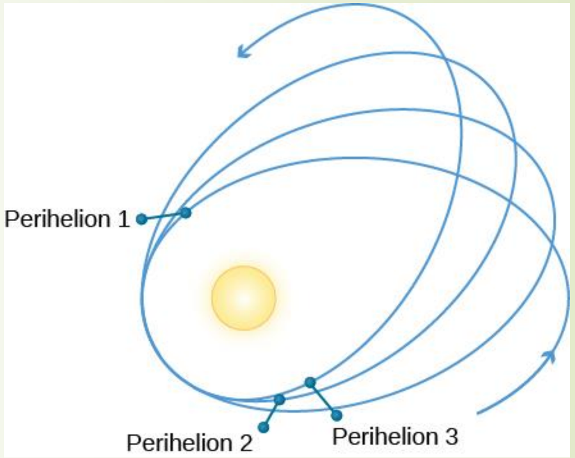
**Testing: needs suitable equipment, technology, statistical techniques**

# Science and an open mind

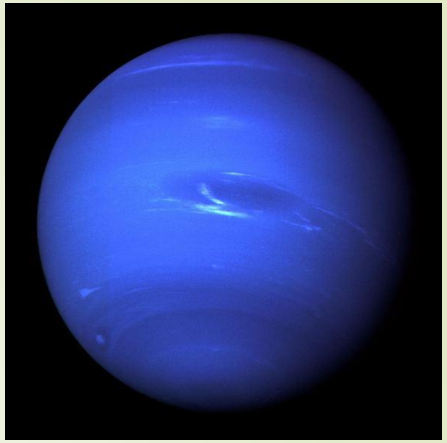
- Science discovers truth iteratively: observe facts, frame hypothesis, test, confirm, or falsify and frame new hypothesis again
  - When a theory is falsified, it provides insights to frame new theory
  - If theory not falsified, we cannot be certain it wont be falsified in future
- Confirming or falsifying much harder in case of probabilistic theories
  - Need large number of samples, can only confirm or falsify probabilistically
- Science demands an open mind, must be prepared to be wrong
  - Scientific theories must be testable, falsifiable
  - Observations, experimental results can be updated with time
  - Must be ready to accept falsifying evidence and start over again

# Example: Theory of solar system

- Theory of solar system and gravity has undergone multiple refinements whenever predictions did not match new observations and experimental results
  - Example: adding epicycles, elliptical orbits
- Predictions from Newton's theory of gravity mostly matched observations, but small discrepancies noticed
- Example: Mercury's orbit twist not explainable by Newton's theory
  - Newton's theory breaks down in high gravity scenarios
- Later, Einstein's theory of gravity (general theory of relativity) could accurately predict Mercury's orbit, accepted as a better theory for now

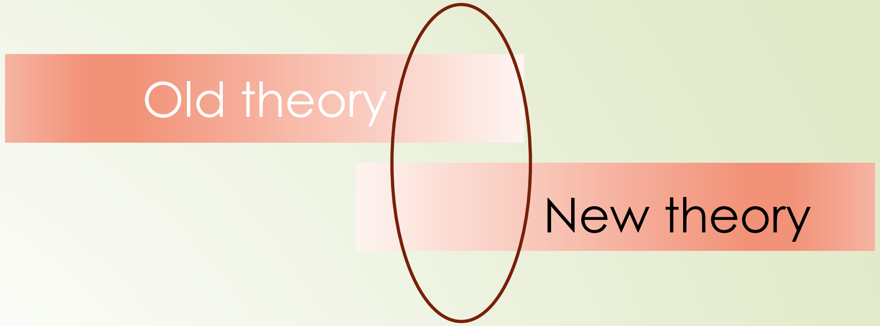


# When to accept falsification?



- Sometimes, apparent falsifications of a theory may be false alarms, and theory can still turn out to be true
  - Orbit of Uranus did not match predictions from Newton's theory of gravitation. Explained by presence of another planet which was causing the distortions. Eventually led to the discovery of Neptune
  - Another planet Vulcan predicted similarly to explain Mercury's orbit discrepancies, searched extensively, but turned out to be wrong
- Scientists must have an open mind and accepting falsifying data, but need not ditch theory at first hint of falsification
  - Dogmatism (within limits) has a positive role to play too
  - Eventually, enough evidence will accumulate to clarify truth

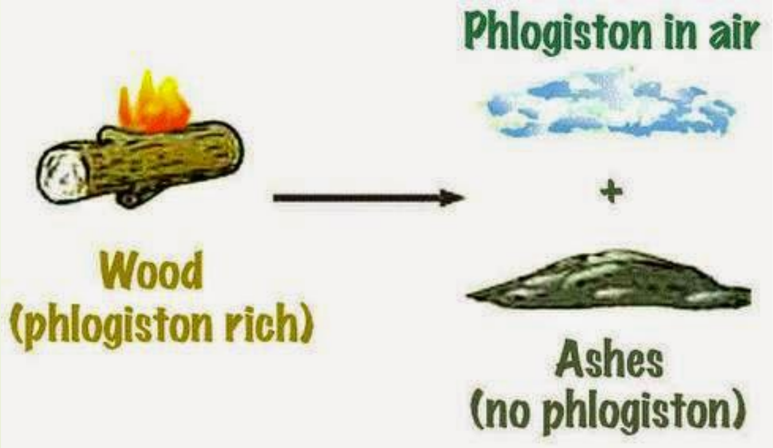
# Paradigm shifts

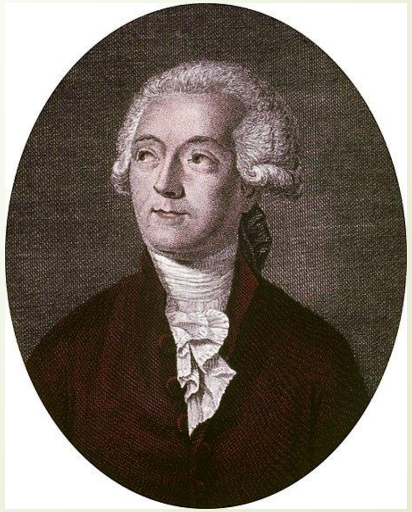



- When old theory falsified, transition to new theory is not immediate
  - Multiple alternate theories may exist and be debated at same time
  - How transitions happen explained by Kuhn ("Structure of Scientific Revolutions")
- Normal science happens within a paradigm, e.g., Newtonian physics
  - Develops a paradigm with new mathematical theories, experimental results
- When falsifications emerge, normal science may fail to see early signs
  - Those doing normal science and those proposing new rival paradigms will be "living in different worlds" and may not be convinced by each other
  - There may not be a rational argument for choosing one paradigm over the other during the transition period, due to insufficient data
- Eventually, enough evidence accumulates, scientific revolution happens
  - Not just new laws but new way of looking at things: a paradigm shift

# Examples of paradigm shifts

- Example: Copernicus vs. Ptolemy was debated for a long time, took 2 centuries for heliocentric theory to be fully accepted
- Example: the theory of phlogiston (fire-like element responsible for combustion) disproved when Lavoisier and others showed that some substances increase in weight after burning. But work on phlogiston continued for some more time, with tricks like negative weight for phlogiston



# Scientific debates

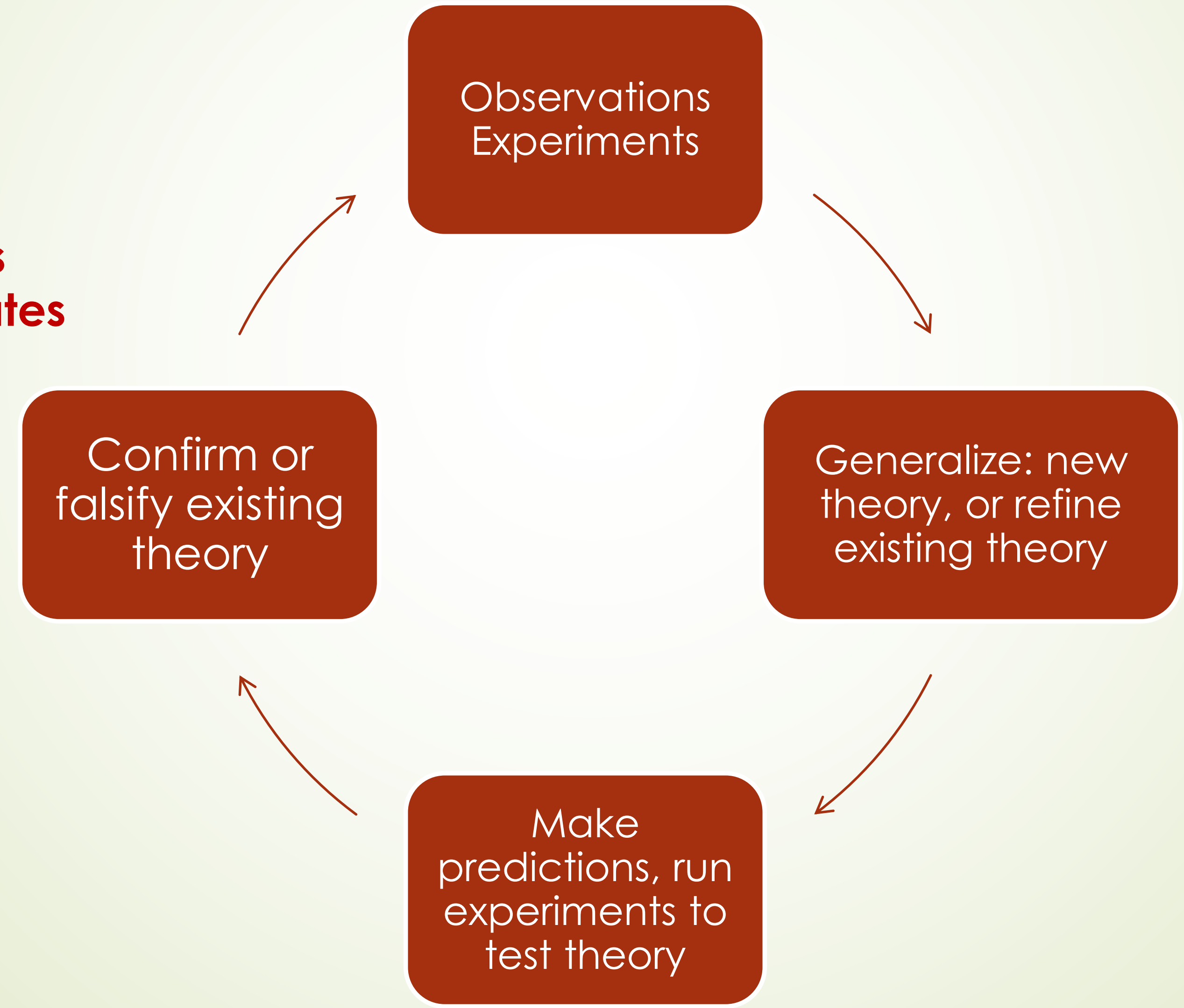

- It is possible to have multiple conflicting theories to explain the same scientific observations, especially during a paradigm shift
  - Insufficient data, inadequate experimental setup
  - Science does not “converge” to a correct theory immediately
- Debate is healthy: science progresses by arguments and debates
- Identify good scientific debates from bad ones
  - All contending theories must be falsifiable
  - Each side must be willing to engage with and examine evidence from others
  - All sides must have an open mind to accept falsifying evidence

# Science vs. pseudoscience

- Multiple conflicting points of view are all normal and welcome in science
- But beware of misinformation, pseudo-science. How to distinguish?
- Pseudoscience: non-scientific beliefs claiming to be scientific
  - Pseudoscience theories not testable or falsifiable by modern scientific method
  - Even if possible to test, unable to evaluate and accept falsifying evidence objectively (due to bias, ignorance, religious faith, vested interests)
- Superstitions: non-scientific beliefs, but not claiming to be science
  - May start as coping mechanisms for things science cannot yet explain
  - Ideally, society moves away from superstitions as science progresses

# Let's revisit the scientific method

**Paradigm shifts**
**Scientific debates**



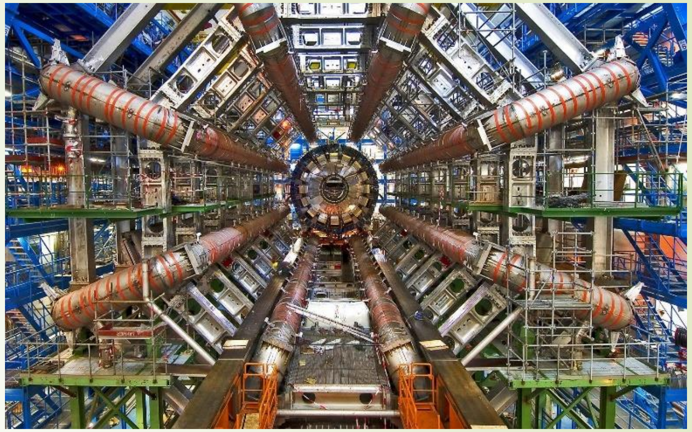
# Factors impacting progress of science

- How does science develop?
  - Curiosity about nature → Observe → generalize → predict and test → confirm or falsify → iterate
- Assuming everyone is equally curious, why does science develop rapidly in some places and in some times, not in others?
- Besides the scientific method, science needs:
  - Appropriate technology
  - Money
  - People
  - An "ecosystem"
- Science is not just a function of individual genius alone

# Human resources

- Ancient science developed in large civilizations with agricultural surplus, wealth
  - Enough free time to stop worrying about survival and think of other things
- Robust mechanisms to propagate knowledge to future generations
  - Oral traditions (India), writing systems (China, Mesopotamia, Egypt)
  - Printing press made transmission of knowledge very easy in modern times
- Events that promote skepticism, critical thinking, literacy in common man
  - Protestant reformation and questioning the authority of the Church
- Circumstances that bring scientists together to one place
  - Fall of Constantinople, scholars move West from Byzantine empire
  - Jews flee Europe to US during World War 2

# Funding



- Funding allows scientists to work on “pure” science,  where no immediate commercial gains are visible
- Funding more important today, with expensive equipment required for experiments
  - From few intellectuals in small labs to “big science”
  - Large Hadron Collider, space exploration
- Who funds science?
  - Patronage from kings in olden days (some kings patronized science more than others)
  - Government and military funding to win wars (huge burst in funding due to World War 2 and subsequent Cold War between US and USSR)
  - Industry, traders (when economy is wealthy)

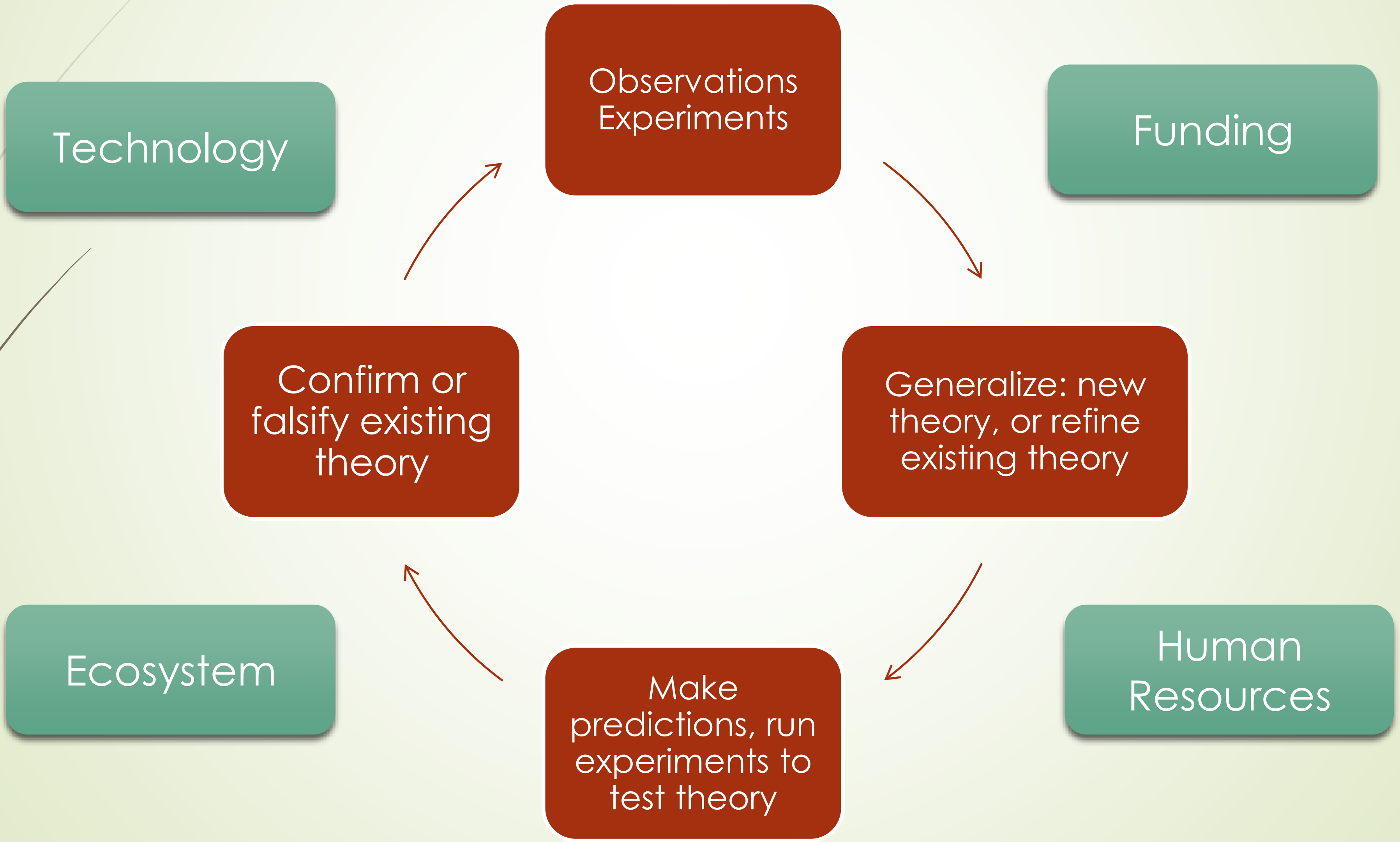
# Funding and objectivity


- Is the money impacting the objectivity of scientists?
  - Tobacco lobby blocked research linking smoking and cancer for several decades
  - Will labs funded by oil companies truthfully report impact of fossil fuels on climate change?
- What kind of questions must science investigate? Anything for which funding is available? Is there a right and wrong?
  - Gene editing to create designer babies?
  - Gain of function research: what genes increase virulence of a virus?
  - Destructive weapons, nuclear bombs?
  - Research that can be misused?

# Ecosystem

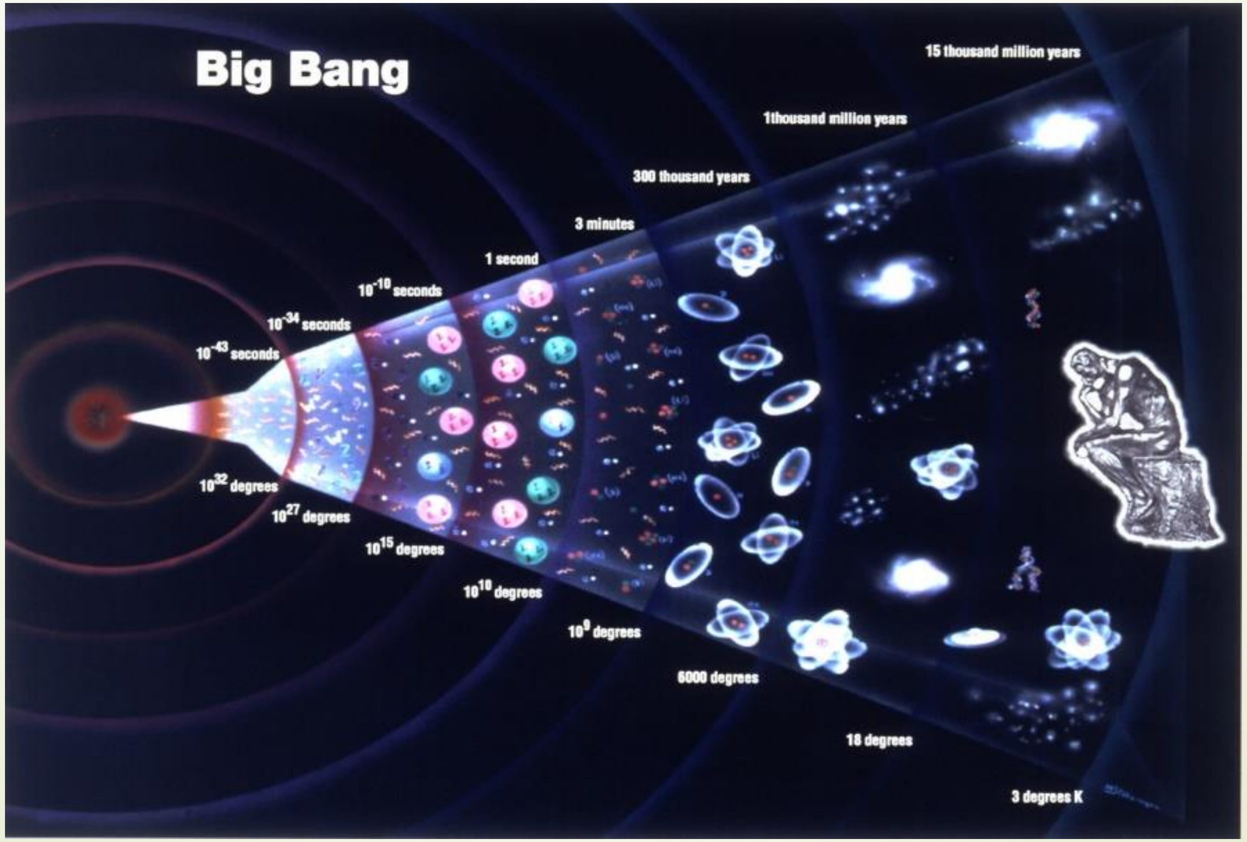
- Political and social stability, scientific temper in population
- Institutional support, vibrant scientific community
  - Royal society in London during $17^{th}$-$18^{th}$ century
  - Edison's research lab, Bell labs in $20^{th}$ century
  - Universities and research labs in modern days
  - Newton's comment of "standing on the shoulders of giants"
- Cross pollination of ideas, locally and globally
  - Interactions between scientists and craftsmen during Age of Reason
  - Golden age of Islam due to confluence of scholars from many places
  - Age of discovery resulted in exchange of ideas with indigenous cultures, led to advances in natural history

# How does science progress?



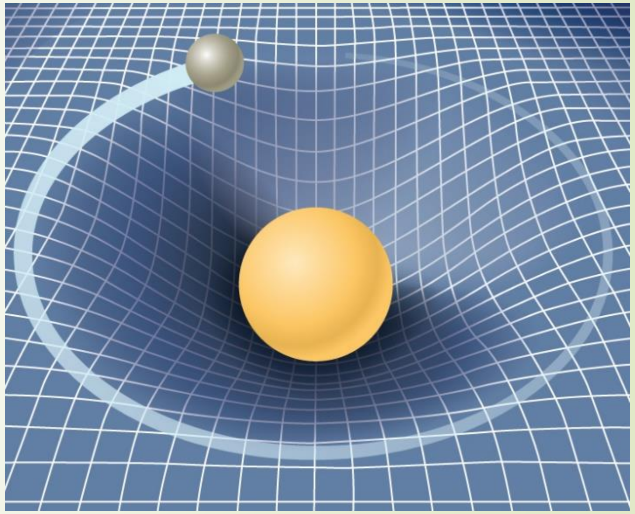
# Case study: Big Bang Theory

- We know today that the universe started with a "Big Bang"
- How did this science develop? A case study of the scientific method studied so far



# How was the universe created?

- Einstein's theory of gravity explains how the universe and gravity work, but doesn't explain its origin or its structure
  - How many stars and galaxies? Why did it start?
- Different civilizations had their own creation myths
  - Bible says universe created ~4000BC (computed by reconstructing timeline from stories)
- After Darwin's evolution and carbon dating of rocks, it was understood that the universe is very old
- Two theories: creation (religious) or eternal universe which always existed (scientists)



# Milky way

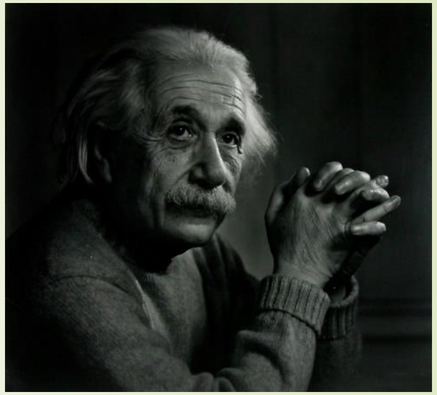
- William Herschel (discovered Uranus in 18th century) observed milky way
  - Proposed milky way was a pancake shaped collection of stars including the Sun
- Others measured parallax of stars due to Earth's revolution around Sun, used this measurement to estimate distances to stars and size of milky way
  - About 10% of the size we know today
- Is the milky way the only galaxy or are there more?

# How many galaxies are there?

- Messier catalogued a bunch of non-star objects in the sky, including nebulae
  - Nebulae = clouds (smudges, unlike stars which are points of light)
  - M31 is the Andromeda nebula
- Are these nebulae in the milky way itself or are they other galaxies?
  - Herschel thought they were just baby stars in our galaxy
  - Many thought they were other galaxies (including religious arguments: God is infinite, so universe is infinite)
- No way to decide for a long time: what is nature of universe? How many galaxies? Eternal or created?
  - Not enough technology to answer these questions

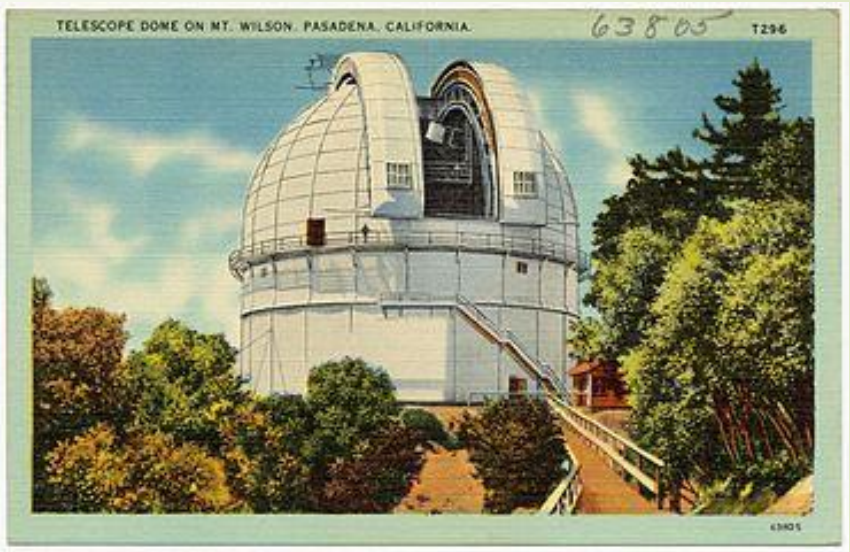
# Theoretical ideas

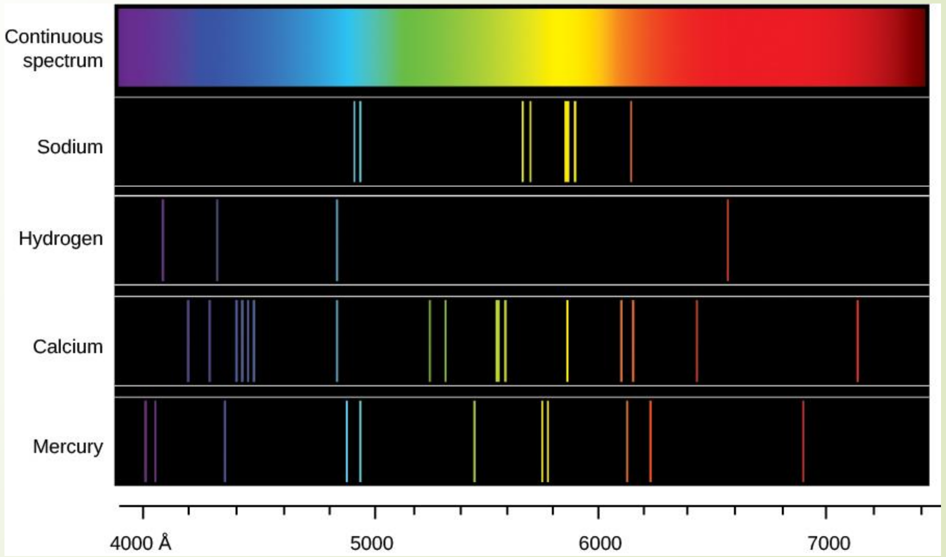
- Einstein's theory of gravity predicts that universe should have collapsed under gravitational attraction
- Why does it not? Einstein added a cosmological constant (a fudge factor) for anti-gravitational effect, to stop universe from collapsing
  - Made his theory fit with the general view of static eternal universe
- Other theorists ditched cosmological constant
  - Lemaitre, a pastor scientist, proposed that universe started from a primeval atom which exploded, and explosion is counteracting gravity, which explains why universe is not collapsing
- This "big bang model" ignored by Einstein and other scientists
  - No easy way to test this theory
  - Big bang supported by church (similar to creation theory) and Lemaitre was a pastor, so his science was suspected



# New technologies

- $20^{th}$ century: 3 new technologies, and a lot more funding for science
  - More powerful telescopes, large observatories
  - Photographic plates to capture images over long exposure, better than just human observations
  - Spectroscopy: infer what wavelengths present in light from stars, infer which elements are present based on which wavelengths emitted/absorbed



# A way to measure distances to stars

- Stars with variable brightness observed using photographic plates and measurements across days
- Early 1900s: Henrietta Leavitt and her team finds a way to measure distance of stars (better than parallax method)
  - Some stars have variable brightness, and period of variability was correlated with brightness of stars (longer period had more brightness)
  - One can measure period of variable star, deduce actual brightness
  - Measure apparent brightness, calculate actual brightness from above, put both together to infer distance

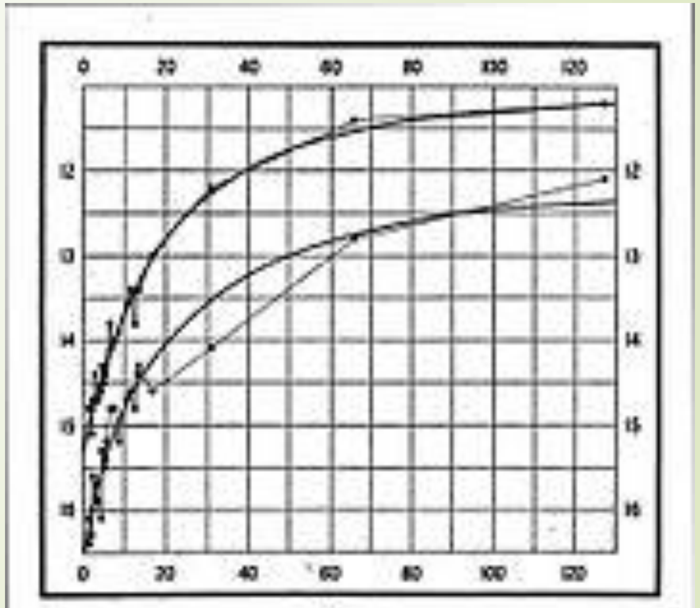


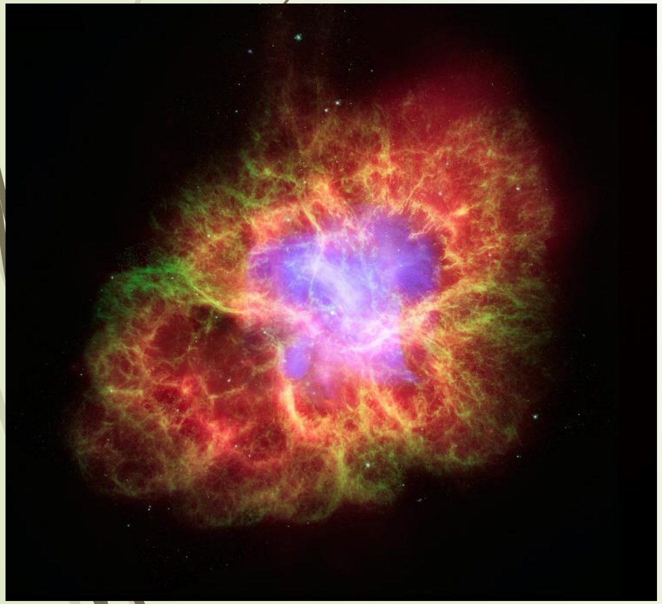

Fig. 1.

# Hubble's rise to fame

- Edwin Hubble: one of the greatest astronomers of his generation
  - Hubble space telescope named after him
- 1920s: Hubble discovered that the universe is made up of many galaxies, not just milky way
  - Found a variable star in Andromeda nebula. Used Leavitt's method to measure distance, and found it was 900K light years, while milky way is only 100K light years
  - Concluded that Andromeda is another galaxy
- Today nebulae are just clouds of dust and young stars
  - Many former nebulae have been identified as galaxies, and Andromeda is our closest

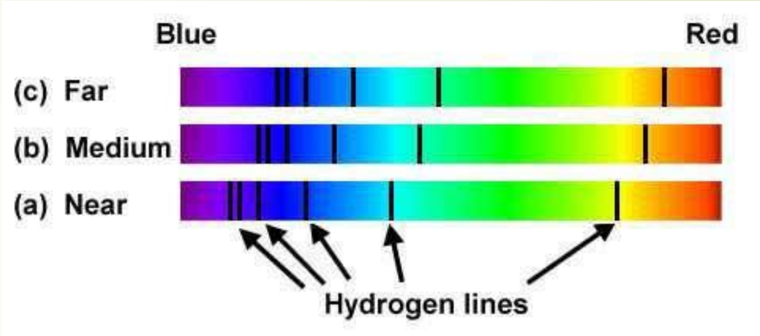
# Hubble Space Telescope

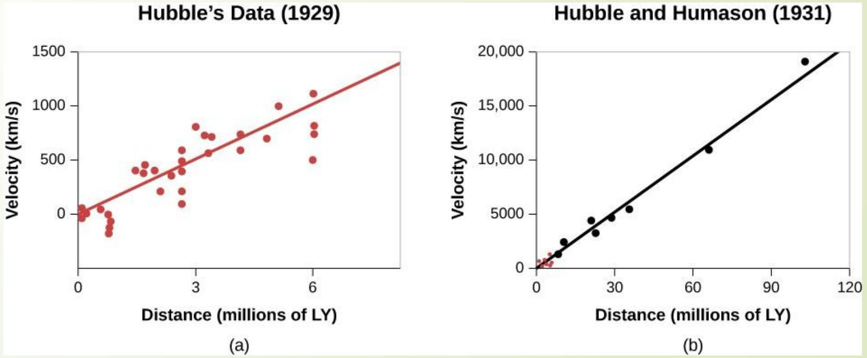
- Many beautiful images of the universe from Hubble space telescope
  - Above earth's atmosphere and its distortions
  - Example: Crab nebula, butterfly nebula, Hubble deep field image of galaxies
- More powerful James Webb Space Telescope launched Dec 2021
  - Infrared space telescopes to observe early universe



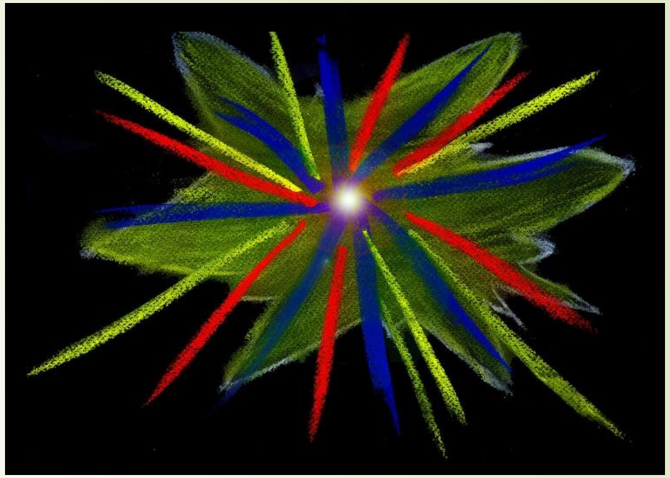
# Expanding universe

- More contributions by Hubble to prove that universe is expanding
  - Not expansion *in* space, but expansion *of* space
- Spectroscopy: know which elements present in stars by observing which wavelengths absorbed or emitted in the light spectrum of the star
- The spectrum of a star moving away is shifted to longer wavelengths: red shift
- Hubble found proof for expanding universe
  - Galaxies moving away (red shift observed for most)
  - Velocity of galaxy proportional to distance, called "Hubble's Law"



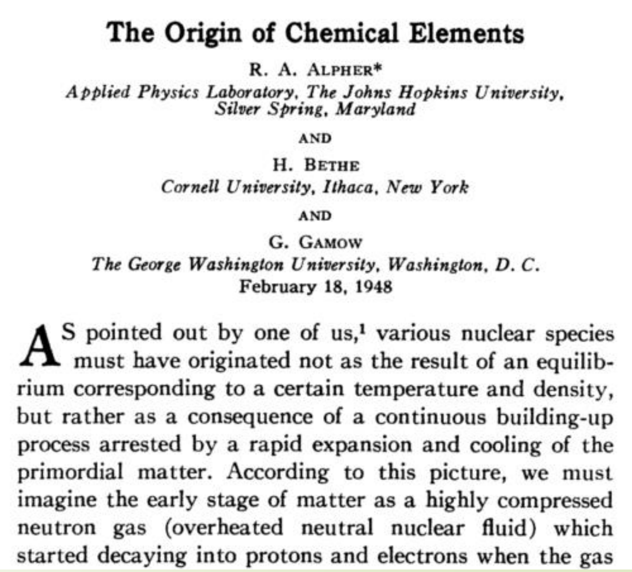
# Hubble's Law Implications



- Hubble's law supports Big Bang theory (but Hubble didn't get into debate)
  - If galaxy twice as far is moving at twice the speed, at some point all galaxies would have started from the same point
- Lemaitre took Hubble's law as proof of his theory being correct
  - Einstein also supported "Big Bang" theory now
- But still, many unexplained observations
  - How are various elements formed? Did primeval atom have all elements? Why is the universe mostly composed of light atoms (H, He), instead of heavier, more stable atoms like iron?

# Nucleosynthesis in the Big Bang

- 1940s: Scientists Alpher, Gamow wrote a paper explaining nucleosynthesis of Big Bang (author Bethe added for fun to call it the Alpha-Beta-Gamma paper)
  - Theoretically turned back clock to beginning periods of Big Bang
  - Matter is compressed, very hot, primeval soup of protons, electrons, neutrons
  - Their theory could explain how various reactions will result in H and He formation in about 300 seconds
  - Used computers of WW2 to perform complex calculations
  - Could explain abundance of H, He but could not explain how heavier elements were formed (atomic weight 5 not stable enough to form in these conditions)



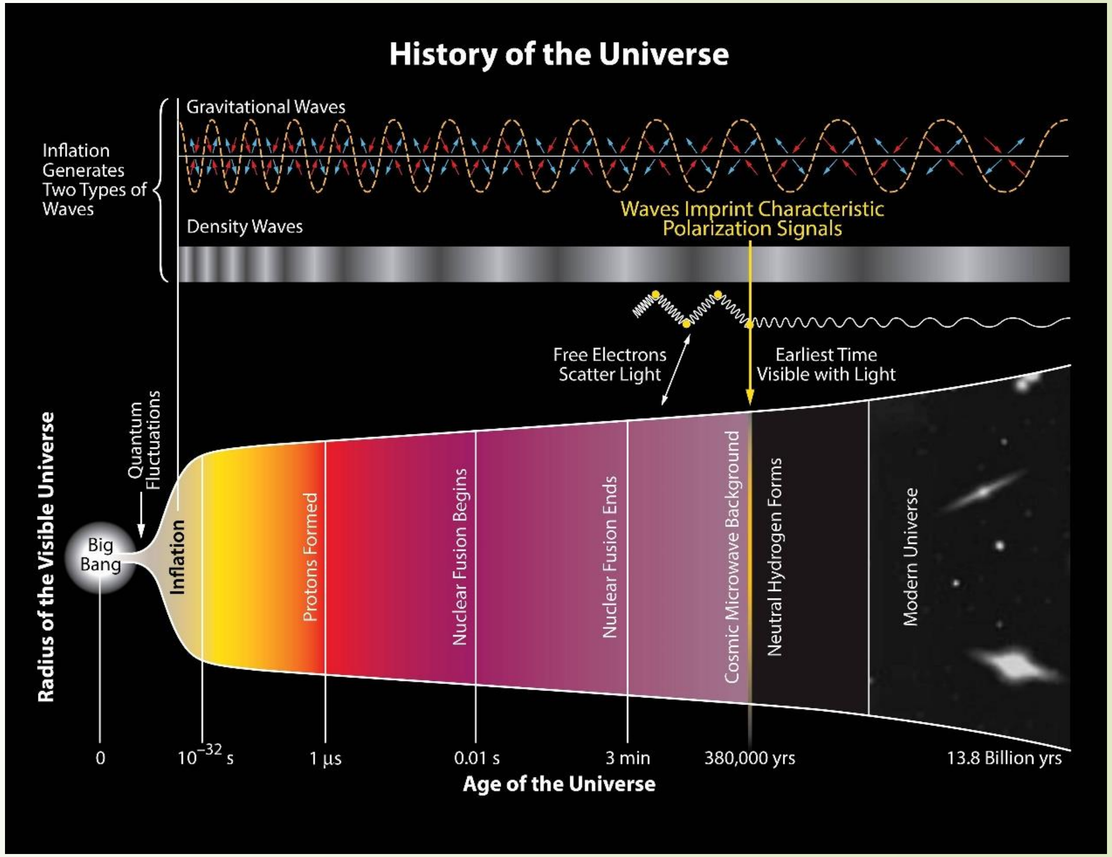
**The Origin of Chemical Elements**

R. A. ALPHER*
*Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland*
AND
H. BETHE
*Cornell University, Ithaca, New York*
AND
G. GAMOW
*The George Washington University, Washington, D. C.*
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas

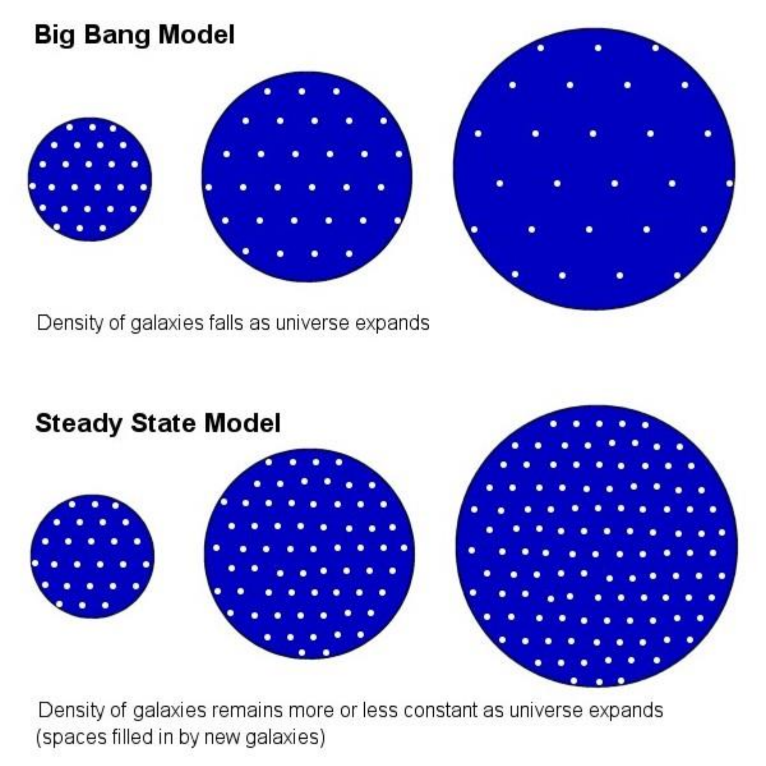
# Cosmic Microwave Background (CMB) Radiation

- After 300,000 years of Big Bang, all charged particles are bound into atoms, light can finally escape
- Alpher, Gamow, Herman predicted that this light radiation can still be detected in the universe today
  - Due to red shift, wavelength predicted about 1mm, called cosmic microwave background (CMB) radiation
  - No experimental techniques to detect, no one looked for it, forgotten



# Steady State theory vs. Big Bang

- Also in 1940s, Fred Hoyle, along with Gold and Bondi, proposed steady state theory of universe
  - Universe was expanding, new matter being created to fill gaps (too little to notice)
  - Universe evolves but remains the same
  - Compatible with red shift of Hubble, replaces eternal static model as competition for Big Bang
  - Fred Hoyle coined the term “Big Bang” mockingly for other model



# More nucleosynthesis

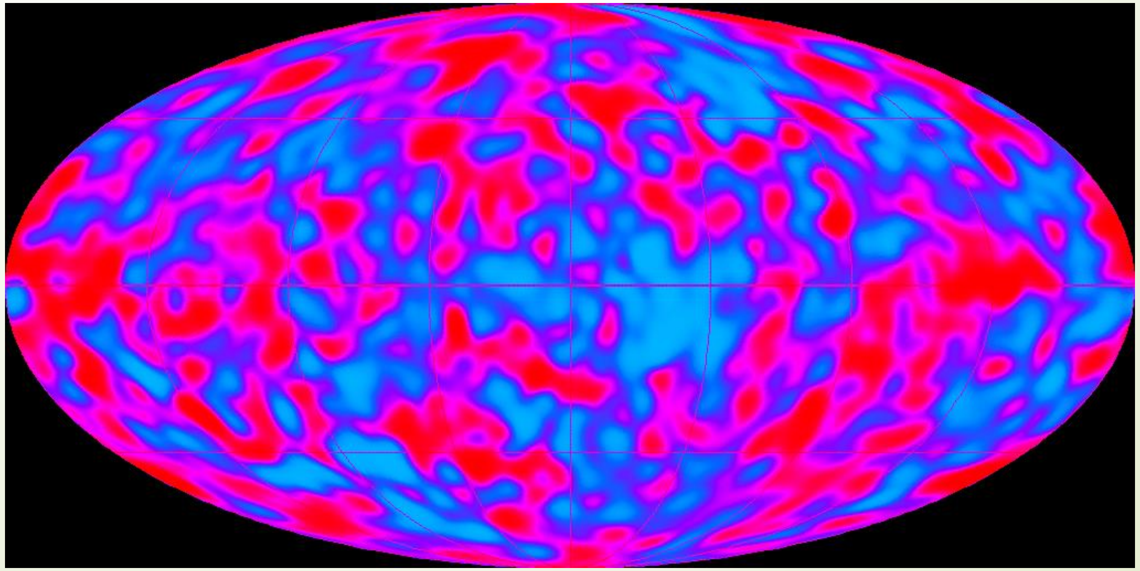
- Fred Hoyle developed a nucleosynthesis model to explain formation of heavy elements in the correct ratios
  - Regular stars: gravity pulls matter in, outward pressure due to nuclear fusion
  - Dying star runs out of fuel, contracts, heats up, more nuclear fusion, expands, and so on
  - Spasms of dying stars have high temperature, pressure to synthesize heavier elements
  - Some heavy stars contract rapidly and then explode as supernovas, spilling star dust with heavier elements, which seed new stars elsewhere
- Hoyle's nucleosynthesis solved puzzle for both Big Bang and Steady State theories
- First use of anthropic principle: theories of universe constrained to allow for the development of humans (otherwise, we wouldn't be here)
  - Predicted unknown energy state of carbon atom, later observed experimentally

# Radio astronomy

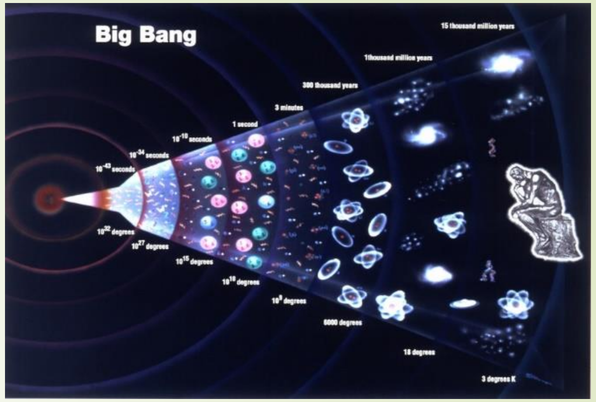
- Mid 1960s, radio telescopes by AT&T Bell Labs for satellite communication
- Scientists discovered that they could collect and analyze radio waves from space
- Penzias and Wilson were engineers who found some hissing background noise in their radio telescope
  - Initially attributed it to faulty equipment or "white dielectric material" from pigeons (pigeon poop!)
- After eliminating all causes, and discussing with theoretical astrophysicists, they discovered that it was CMB radiation predicted by Alpher, Gamow, Herman (forgotten and recently rediscovered by other physicists)
- Penzias and Wilson win Nobel prize in 1978

# Clinching evidence for Big Bang

- If constant CMB everywhere, then how are galaxies formed? Need variation in density to seed galaxies
- Alan Guth's theory of inflation proposed sudden expansion of universe that could have caused non-uniformity
- 1992: COBE satellite discovered tiny variations in CMB from different parts of sky which would have seeded early galaxies
- Paradigm shift completed, everyone shifted to Big Bang model



# Big Bang Theory: Summary




- How was the universe created? Many creation myths
- Einstein's cosmological constant blunder biased towards eternal universe and theoretical models of Big Bang initially ignored
- Evidence slowly accumulating on universe expansion (red shift, Hubble's laws)
- Theories proposed both for big bang and steady state universe that fit observations
- Scientists work in their own paradigms, fleshing out details like nucleosynthesis
- Clinching evidence (CMB, COBE) caused paradigm shift
- What we know: lots of detail on how universe was created after big bang
- What we do not know: what happened before big bang, what is dark matter+dark energy (>95% of universe), many details about the early universe, …
- Newer theories of gravity and origins of universe could emerge in the future