# BEYOND EINSTEIN: HOW LIGHT LED THE WAY TO A DARK COSMOS

Prof. Stephen Sekula

12/6/2010

Supplementary Material for PHY1308 (General Physics - Electricity and Magnetism)

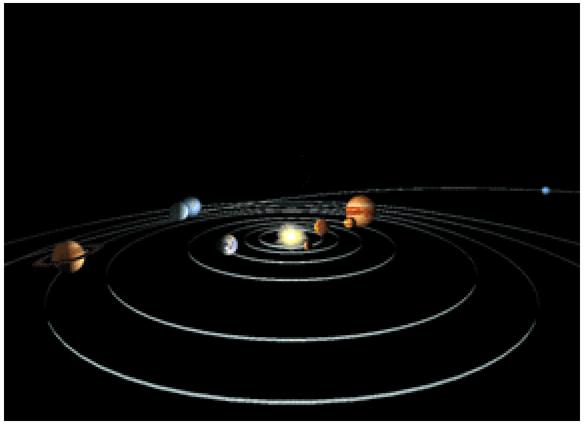
# ANNOUNCEMENTS

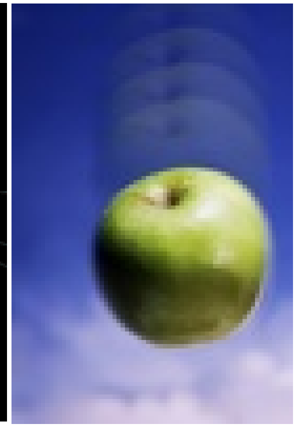
- Homework 14:
  - Due Today by 5pm

ABSTRACT

In 1905, Albert Einstein published four seminal papers. Two of those, concerning relativity and the photoelectric effect, initiated twin revolutions in our understanding of the universe. From Einstein's thinking about light, we now understand a great deal about the matter from which we are made - and how little that matter contributes to our dark cosmos.

# THE DAWN OF A CENTURY





***Mechanics*** described the universe as a perfect clockwork machine whose outcomes could be exactly predicted at all scales.

***Electromagnetism*** explained all electrical and magnetic phenomena, predicted new ones, and explained light as a wave.

***Thermodynamics*** described heat and its relationship to work and energy

# ANNOYING LITTLE PROBLEMS

- There were just some "annoying little problems" left to explain away:
  - Maxwell's Equations claimed no medium was needed for light to propagate, yet all other waves required a medium.
    - if light is a wave, it needs a medium - "the aether" - to progagate. We just had to find it!
    - ***extremely sensitive experiments failed to discover any such medium.***

# ANNOYING LITTLE PROBLEMS

- There were just some "annoying little problems" left to explain away:
  - Maxwell's Equations also had a problem with "motion"
    - "The Galilean transformation" related experiments conducted by moving observers and those conducted by stationary observed.
    - Applying the transformation to Maxwell's Equations led to conflicting predictions about what a moving and stationary observer each predict is going on in the other person's frame of reference.

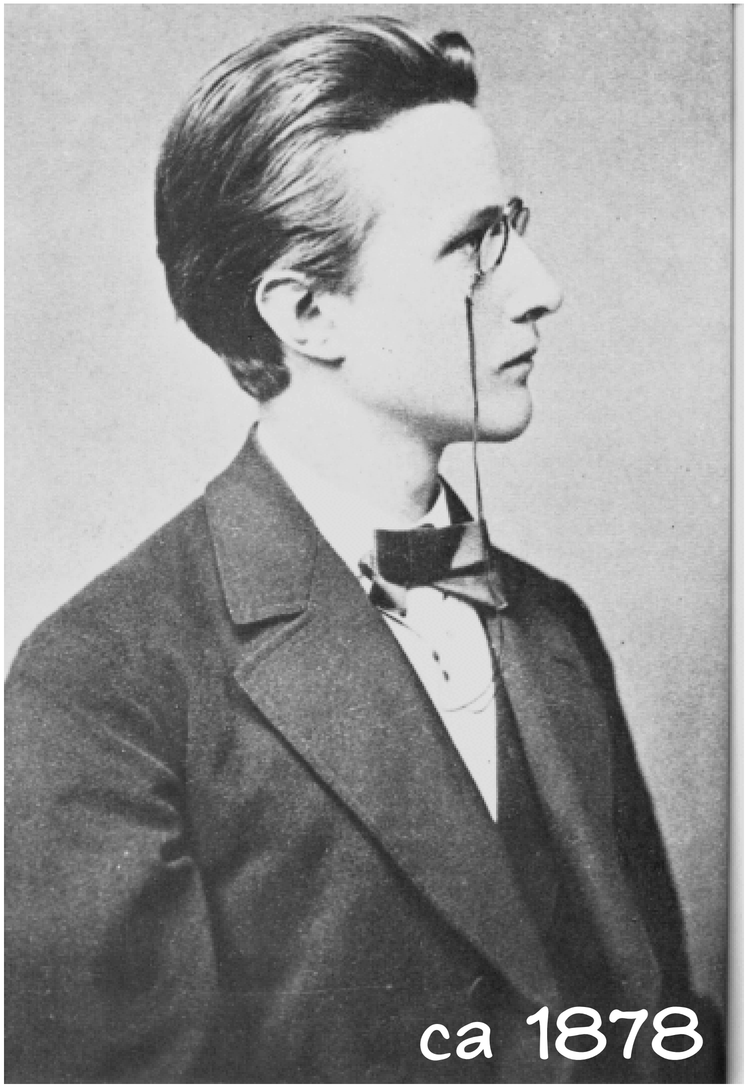
***The problem of the aether and the problem of motion led most physicists to conclude that the newly uncovered "Maxwell's Equations" were wrong. After all, how could classical physics uncovered over 200 years be wrong?***

# ANNOYING LITTLE PROBLEMS

- There were just some "annoying little problems" left to explain away:
  - Thermodynamics: a body that absorbed radiation and released it as heat - a blackbody - was predicted to emit high frequency/short wavelength light with increasingly higher and higher probability
    - "the ultraviolet catastrophe"

# THE ULTRAVIOLET CATASTROPHE

# MAX PLANCK




1858-1947

German physicist

Made central contributions to the study of heat (thermodynamics).

Turned his attention to the problem of blackbody radiation in 1894, motivated simply by wanting to understand this phenomenon.

*By 1901, he had reluctantly published an explanation based on two principles: statistics and electromagnetic energy quantization - the idea that a light wave cannot have any energy that it wants.*

# "An Act of Desperation"

" . . . a theoretical interpretation [of the blackbody spectrum] had to be found at any cost, no matter how high."

(Max Planck, in a letter to R.W. Wood)

# Electromagnetic Energy Quantization

$$E = h\,f$$

Electromagnetic
***ENERGY***

A new constant -
"Planck's Constant"

The frequency of electromagnetic radiation (light)

$$h = 6.626 \times 10^{-34}\ \text{J}\cdot\text{s}$$

# 1905

# ALBERT EINSTEIN

Albert Einstein
(1879-1955)

Fascinated by magnetism as a very early age (his father ran a company that manufactured direct current electrical equipment). Showed early talent for engineering and mathematics.

Attended the Swiss Federal Institute of Technology (ETH) in Zurich in 1896 for a teaching dipoloma; he had shown outstanding performance in mathematics and physics on an earlier entrance exam.

# ALBERT EINSTEIN


Albert Einstein
(1879-1955)

Met his first wife, Mileva, at ETH (she was the only woman in a class of 6 that entered the teaching diploma course in 1896). They were married in 1903. She failed the exam for her teaching diploma, while Einstein passed the exam.

After two frustrating years searching for a teaching post, Albert got a job at the Swiss Patent office (helped by his friends) in 1900. He worked on patent review for electromagnetic devices.

# ALBERT EINSTEIN

Albert Einstein
(1879-1955)

Einstein continued to work toward a Ph.D., which was awarded in 1905. That same year, he published four groundbreaking papers. These papers concerned:

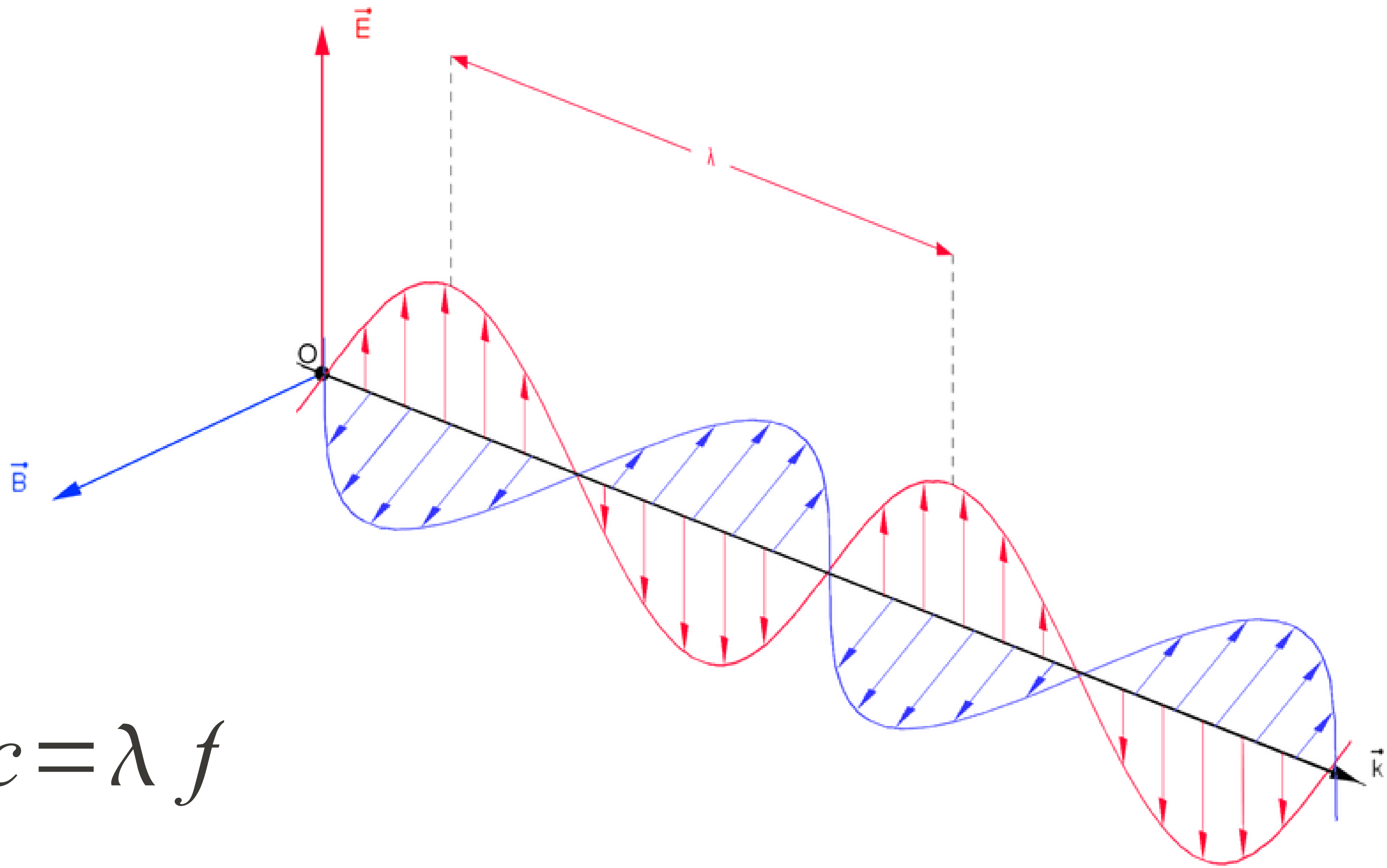
- the atomic theory of matter
- how motion affects measurement (relativity)
- the nature of light
- the equivalence of matter and energy

# THE PHOTOELECTRIC EFFECT

# What is the Photoelectric Effect?

- Light shining on a conductor will cause electric charge to move (a current!)
  - that's it. Why does this matter so much?
- Let's try to explain it using the wave theory of light

# ELECTROMAGNETIC WAVES




$$c = \lambda f$$

# BALL ON A POND

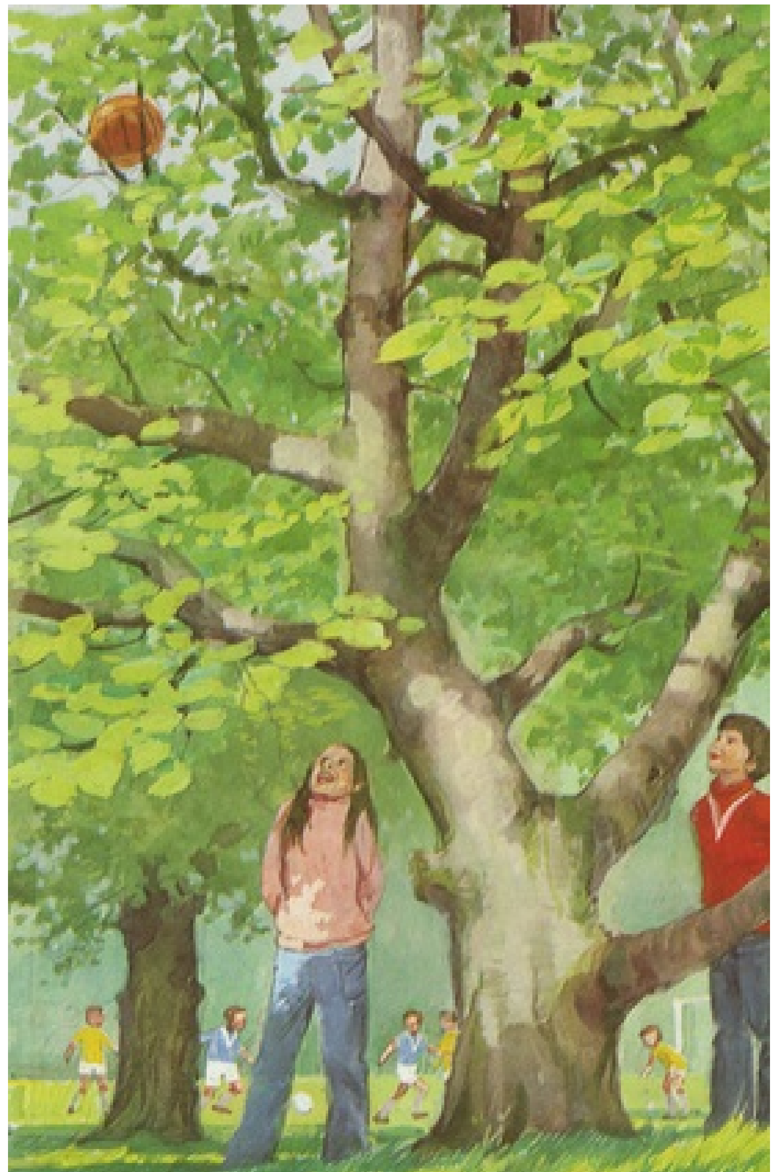
# DEMONSTRATION OF THE PHOTOELECTRIC EFFECT

- The demo uses only household items
  - a Coke can ($2)
  - sandpaper ($2)
  - a styrofoam cup ($1)
  - tinsel ($1)
  - a paperclip ($1)
  - PVC pipe ($10)
  - a paper bag ($2)
  - a sanitizing wand (UV-C light) $50

# Demonstration of the Photoelectric Effect

- Demonstrating the photoelectric effect using only household items costing less than $100
  - Priceless

# BALL STUCK IN A TREE



# EXPLANATION (ALA EINSTEIN)

- Treat light as a *particle*
  - energy related to frequency, ala Planck
- It only takes one lucky light particle - a "photon" - to knock a charge loose
- The energy of the photon must be enough to overcome the binding of the charge in the material
  - that minimum energy is called the "work function"
    - this explains why only light of certain frequencies can make charge move freely in a conductor
    - charge gets a kinetic energy that is the difference between the photon energy and the work function

# THE PHOTOELECTRIC EFFECT

$$KE_{charge} = hf - W_0$$

Kinetic energy of freed charge (e.g. electron)

photon energy (ala Planck)

Work function (property of the metal)

# Work Function of Coke Can (Aluminum)

- $W_0$ (aluminum) = 4.08 eV
- To minimally free an electron, we need:
  - $KE = 0 = hf - W_0 \rightarrow hf = W_0$
- Photon frequency needs to be at least:
  - $f = W_0/h = 9.85 \times 10^{14}$ Hz
  - $\lambda = c/f = 304$nm (shorter wavelengths mean higher frequencies)
  - UV-C is 280-200nm – more than sufficient to free electrons from Aluminum.

# REVOLUTIONS

# EINSTEIN'S LEGACY

- Light can be treated as BOTH a particle and a wave (quantum theory of radiation)
    - depends on the wavelength and how it compares to the dimensions of the target (e.g. atoms)
- What's so special about light? (quantum theory of matter)
    - if light can be BOTH a particle and a wave, is matter also actually a wave too?
    - matter (electrons, protons, etc.) was confirmed to have wave properties (confirmed in 1927 at Bell Laboratories)
- No definite state, only definite possibilities
    - if all things - radiation and matter - are waves, they they do not possess definite properties (e.g. an electron cannot be said, with absolute certainty, to be in one place and not another)
    - Probability, describing DEFINITE POSSIBILITIES, rules.

# EINSTEIN'S LEGACY

- Space and time are not fixed (relativity)
  - different observers AGREE on events, but not where or when they happen
  - All observers measure the same speed for light, REGARDLESS of their state of motion
- Energy and mass are the same thing (relativity)
  - light is pure kinetic energy (no mass)
  - nothing can travel faster than light in vacuum
  - mass can be turned into pure energy, and pure energy into mass

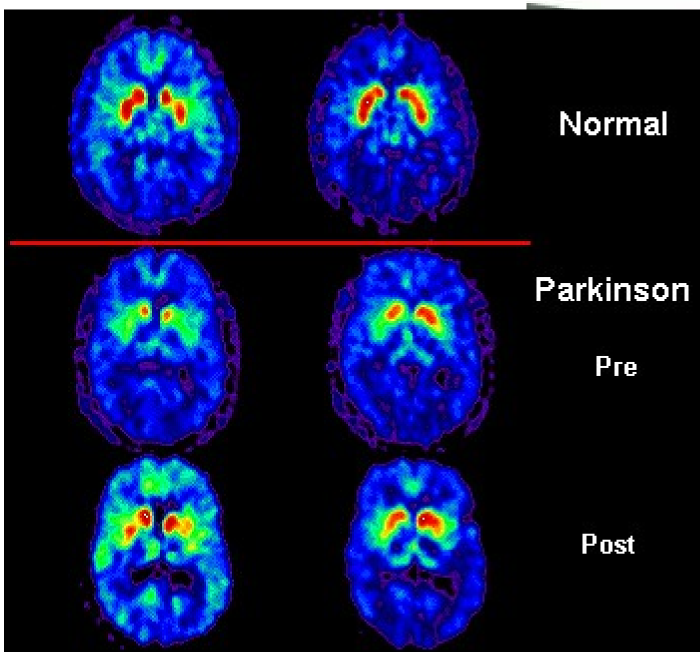
# A MOST FAMOUS EQUATION

$$E = mc^2$$

Total energy of matter when it's at rest (including heat, potential energy, etc)

The mass of the matter in question

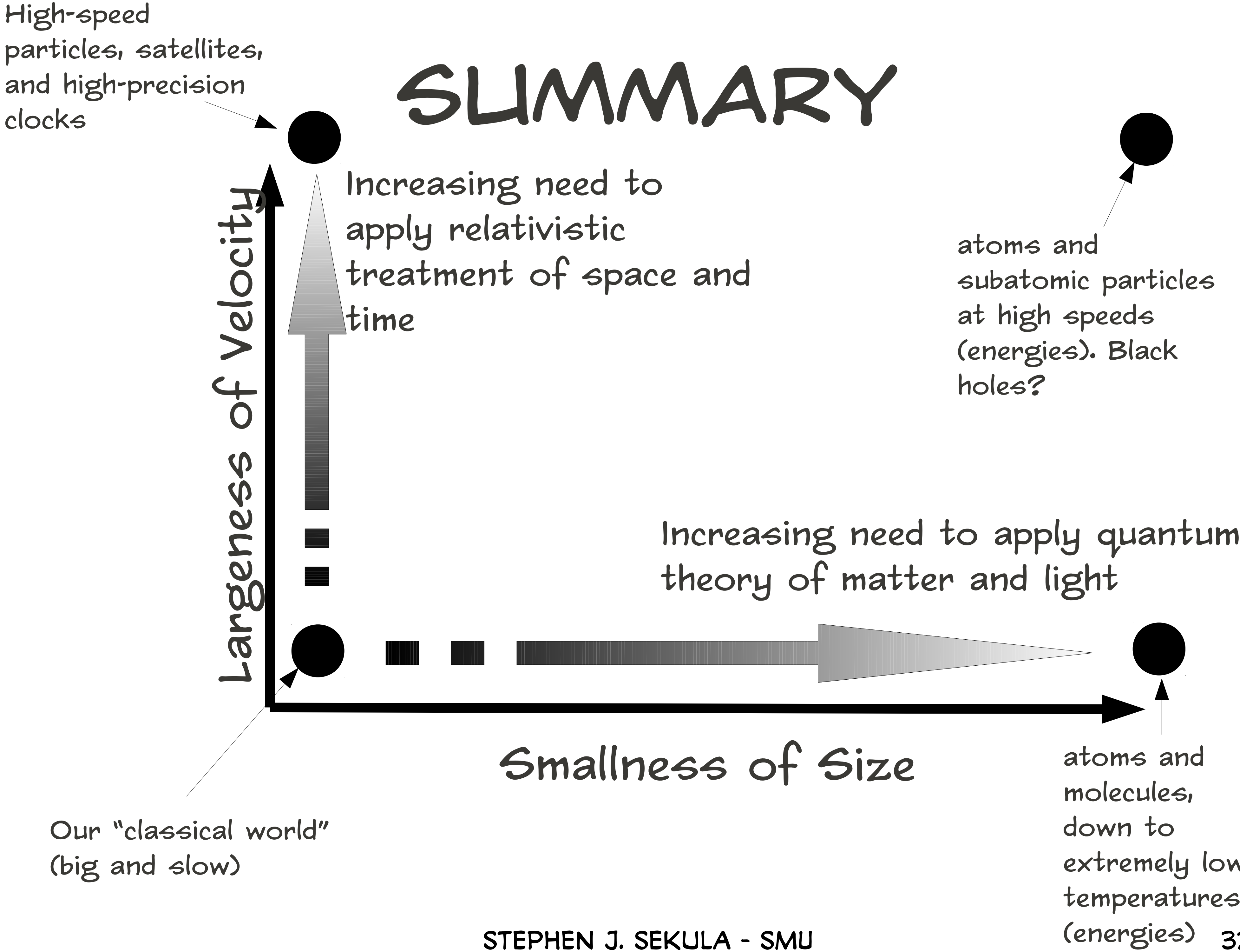
the speed of light (squared)




PET
Scanner

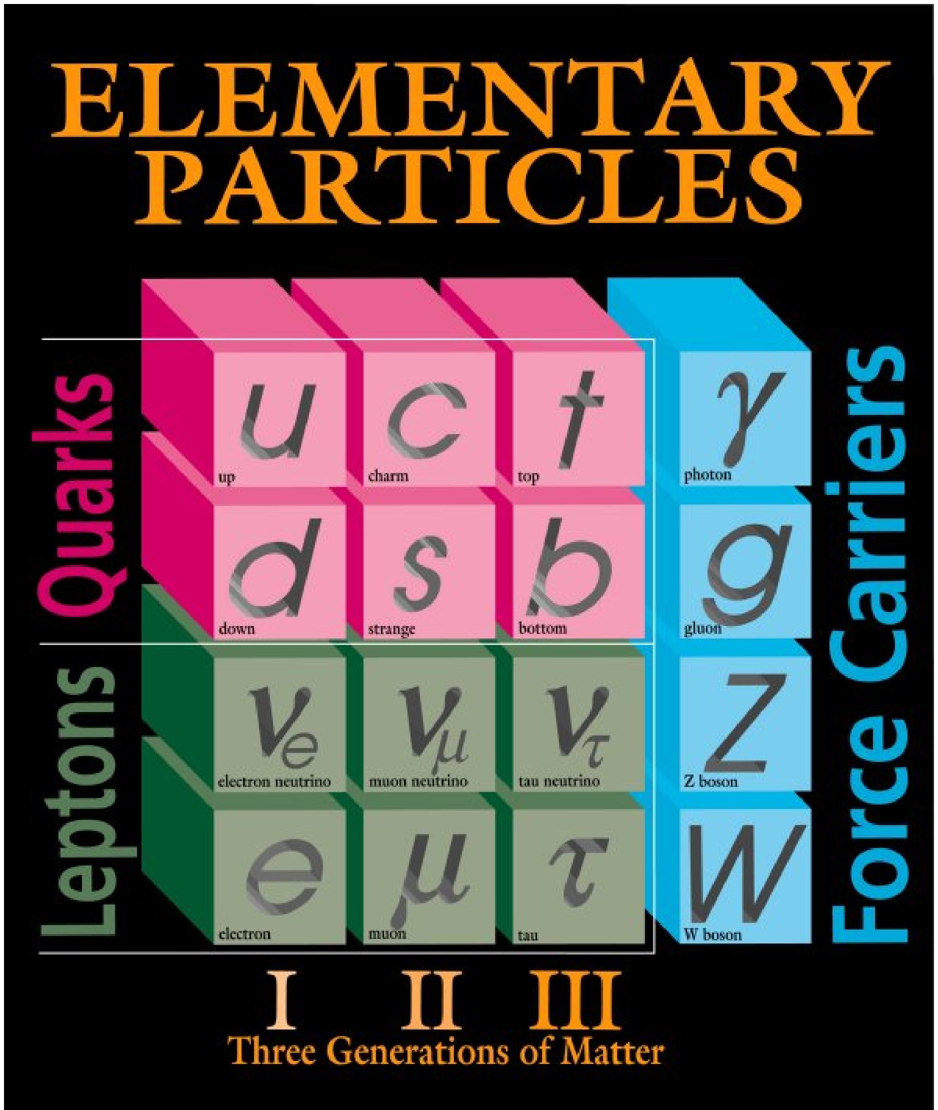
PET scans use matter and antimatter, which meet and annihilate in the body and produce radiation (light) which can be detected.

# SUMMARY


High-speed particles, satellites, and high-precision clocks
Increasing need to apply relativistic treatment of space and time
atoms and subatomic particles at high speeds (energies). Black holes?
Largeness of Velocity
Increasing need to apply quantum theory of matter and light
Smallness of Size
Our "classical world" (big and slow)
atoms and molecules, down to extremely low temperatures (energies)

# OUR DARK COSMOS
## (THE DAWN OF A NEW CENTURY)

# OUR CURRENT UNDERSTANDING OF MATTER AND FORCES

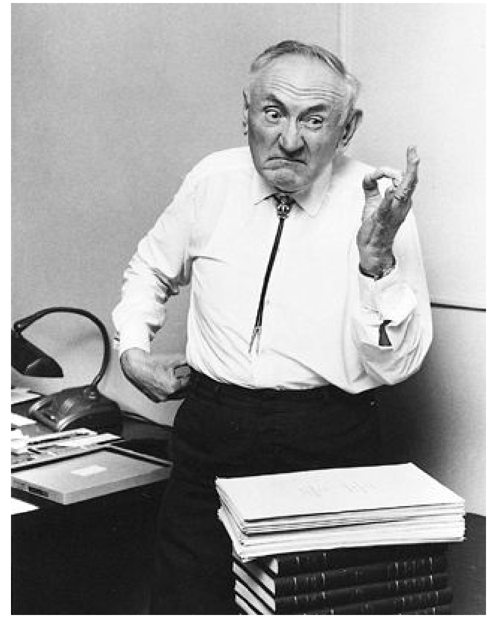



Fermilab 95-759

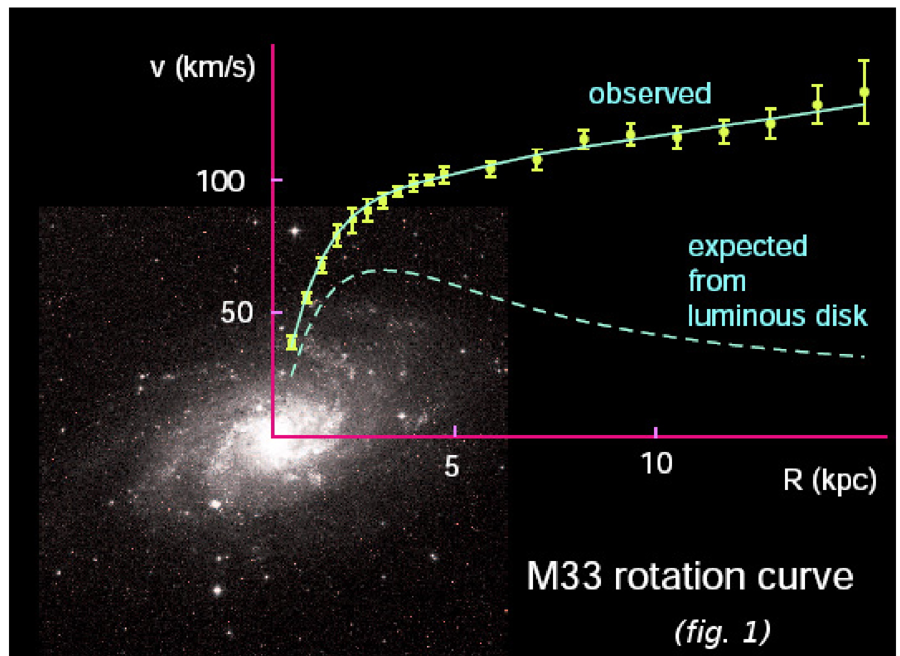
Protons and neutrons are made from quarks

- up+up+down = proton
- up+down+down = neutron

Particle colliders that have operated up until now have ONLY ever produced these particles shown here (as far as we know)

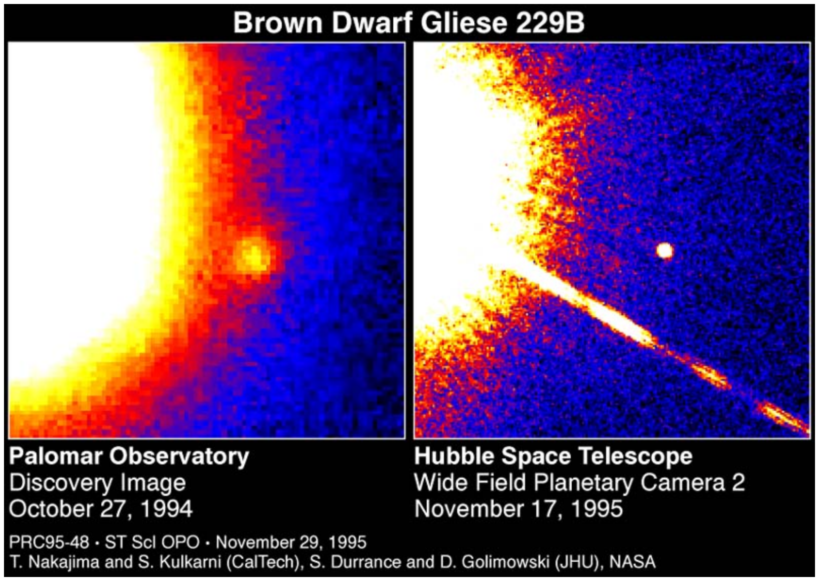


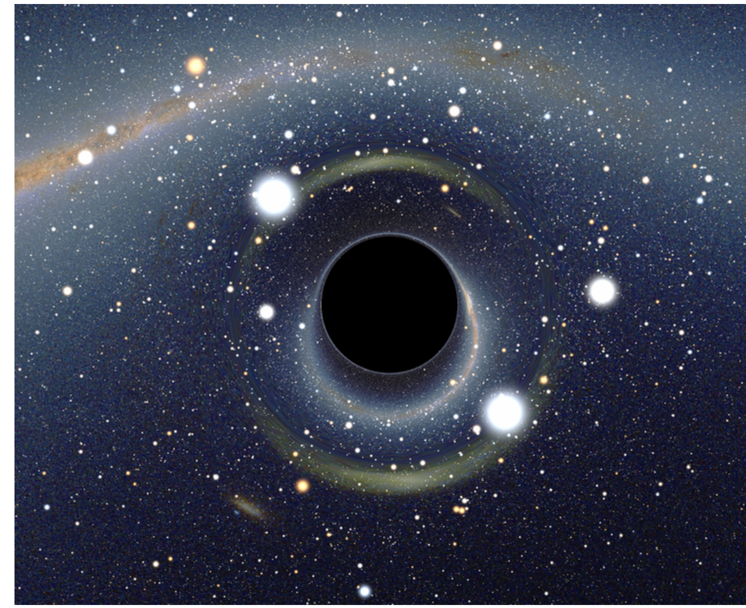
Fritz Zwicky measures the mass of the Coma Cluster using light and gravity. Finds a factor of 100 discrepancy.


Vera Rubin measures the speed of galaxy rotation for spiral galaxies, and finds the outer stars are moving too fast to be explained by the visible matter

# THINGS THAT DON'T GIVE OFF VISIBLE LIGHT



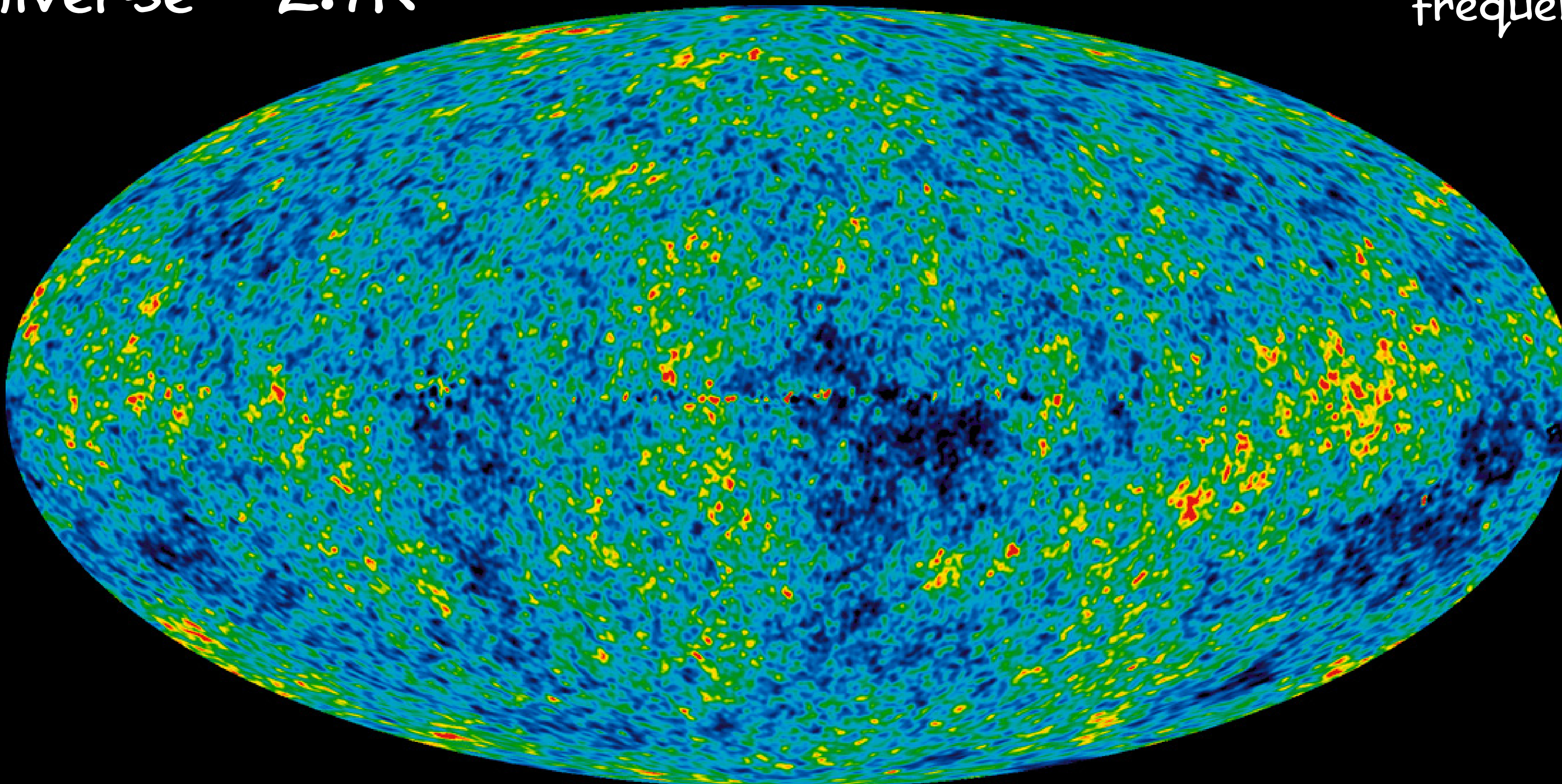



"Brown Dwarf Stars" are burned out star remnants. They do give off weak, visible light, but can be seen with x-rays and radio waves as well. Surveys don't find enough of these to explain galaxy rotation.

Black holes - the devastating remnant of a collapsed, super-massive star. Nothing - not even light - can escape its gravitational influence. A supermassive black hole is believed to reside at the center of every galaxy, including our own. Still not enough to explain dark matter.

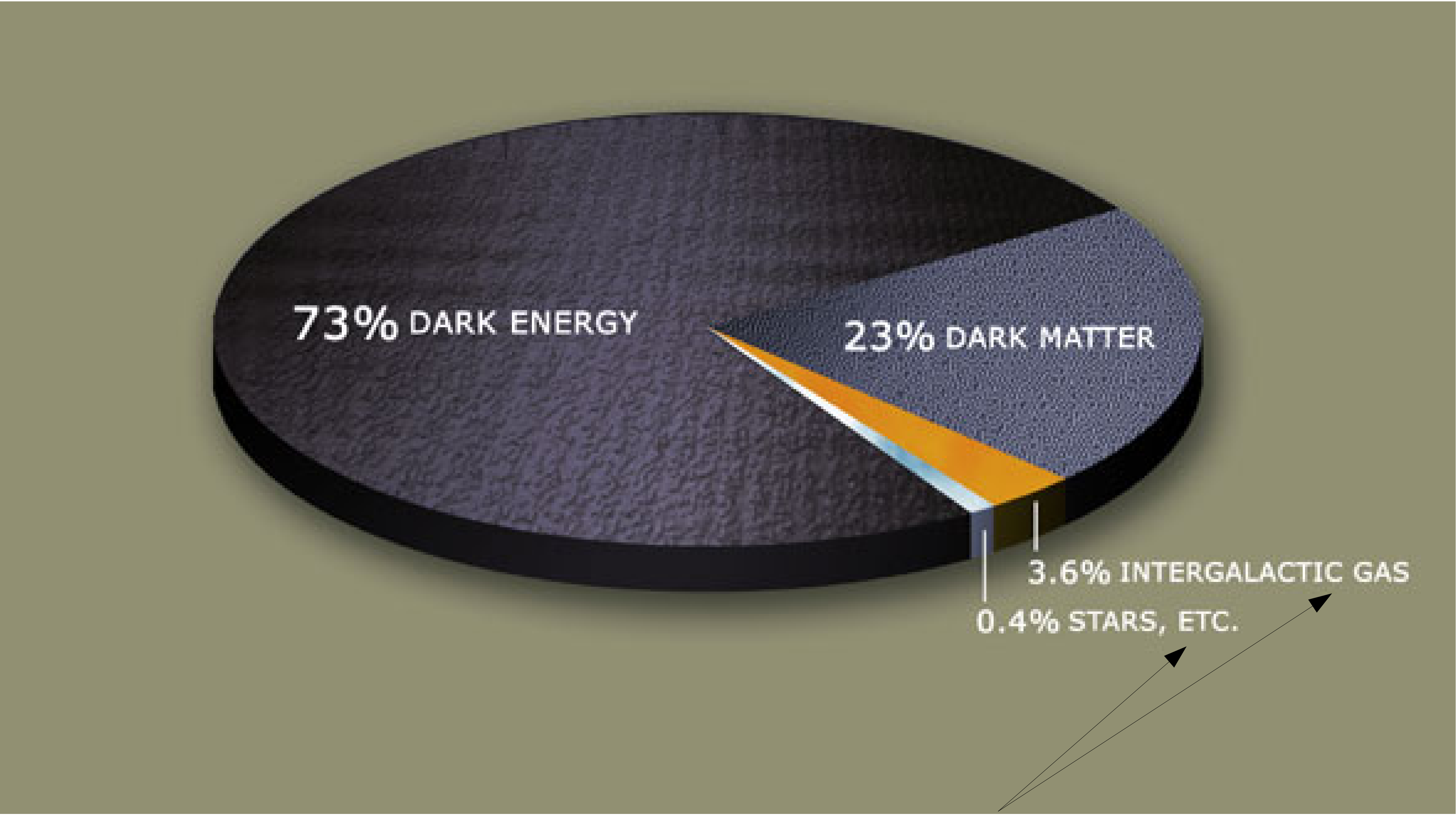
Temperature of the universe - 2.7K

Radiation (light) from big bang now has microwave frequencies



Map of the Cosmic Microwave Background (the light left over from the Big Bang) made by WMAP satellite.

"Clumpiness" is too big to be explained only by known matter acting in the early universe.




This 4% includes all atoms and all other known subatomic particles

# OUR PLACE IN THE COSMOS

# WHAT WE KNOW TODAY

- The universe is VERY OLD
  - 13.7 ± 0.13 Billion Years
    - we know this most precisely by studying the cosmic microwave background (light from the big bang)
    - Everything in the universe appears to be moving apart
    - we can make estimates of the minimum age by studying the distance of stars from earth, using optics (parallax) and the known speed of light.
- The earth is VERY OLD
  - the earth formed 4.5 Billion Years ago
    - we know this by measuring the radioactivity of very old rocks, among other things
- The universe is mostly NOT understood
  - 96% of the universe's composition is unknown
  - 15 years ago, nobody would have believed this statement

# THE BIG DIPPER

# FINAL WORDS

- Be humble before the cosmos
  - Asking the universe questions means making assumptions you can test, and knowing how to test them
  - Listen to the universe, and do not be afraid of what it has to tell you
- Question with courage and wisdom
  - Have the temerity to question
  - Have the wisdom to learn how to answer those questions
  - apply what you learn and create new knowledge

# MORE INFORMATION

# DISTANCES TO STARS

- Within a thousand light-years...
  - use optical parallax - the apparent motion of nearby stars relative to distant stars due to the Earth's motion
- Up to a few hundred thousand light-years
  - Brightness of a light source falls off as the inverse-square of the distance from the observer (us). Use the relationship between star color and temperature ("the main sequence") to match distant stars to similar nearby ones. Use the ratio of their brightness to determine distance.
- In other galaxies (more than a few hundred thousand light-years)...
  - use stars whose brightness varies with time to determine their absolute brightness, and then use the inverse-square law again by comparing their brightness to similar stars in our own galaxy.