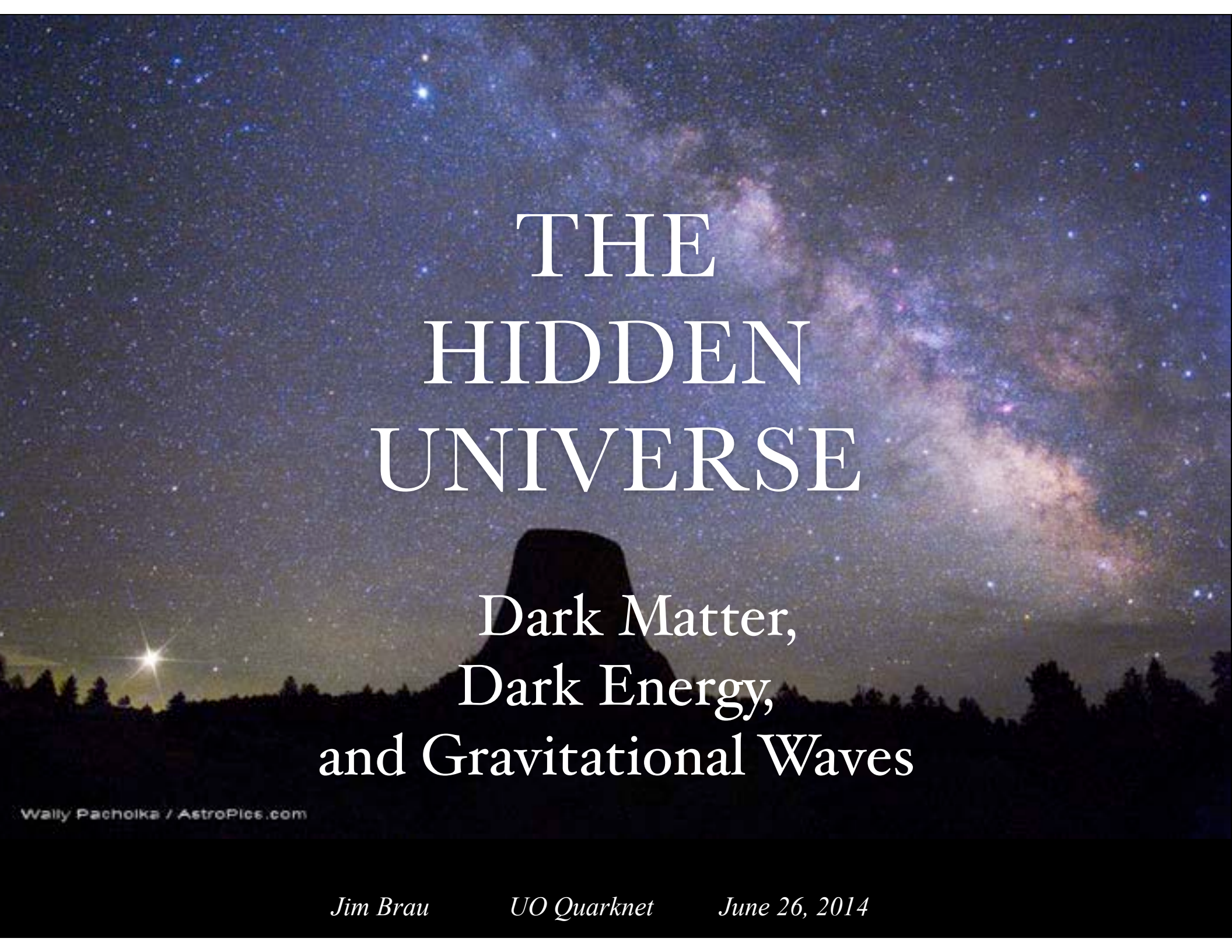




THE HIDDEN UNIVERSE

Dark Matter,
Dark Energy,
and Gravitational Waves

Wally Pacholka / AstroPics.com



Wally Pacholka / AstroPics.com

Jim Brau

UO Quarknet

June 26, 2014



Virgo Cluster

Hubble Space Telescope

Ultra Deep Field Image

Hubble Space Telescope



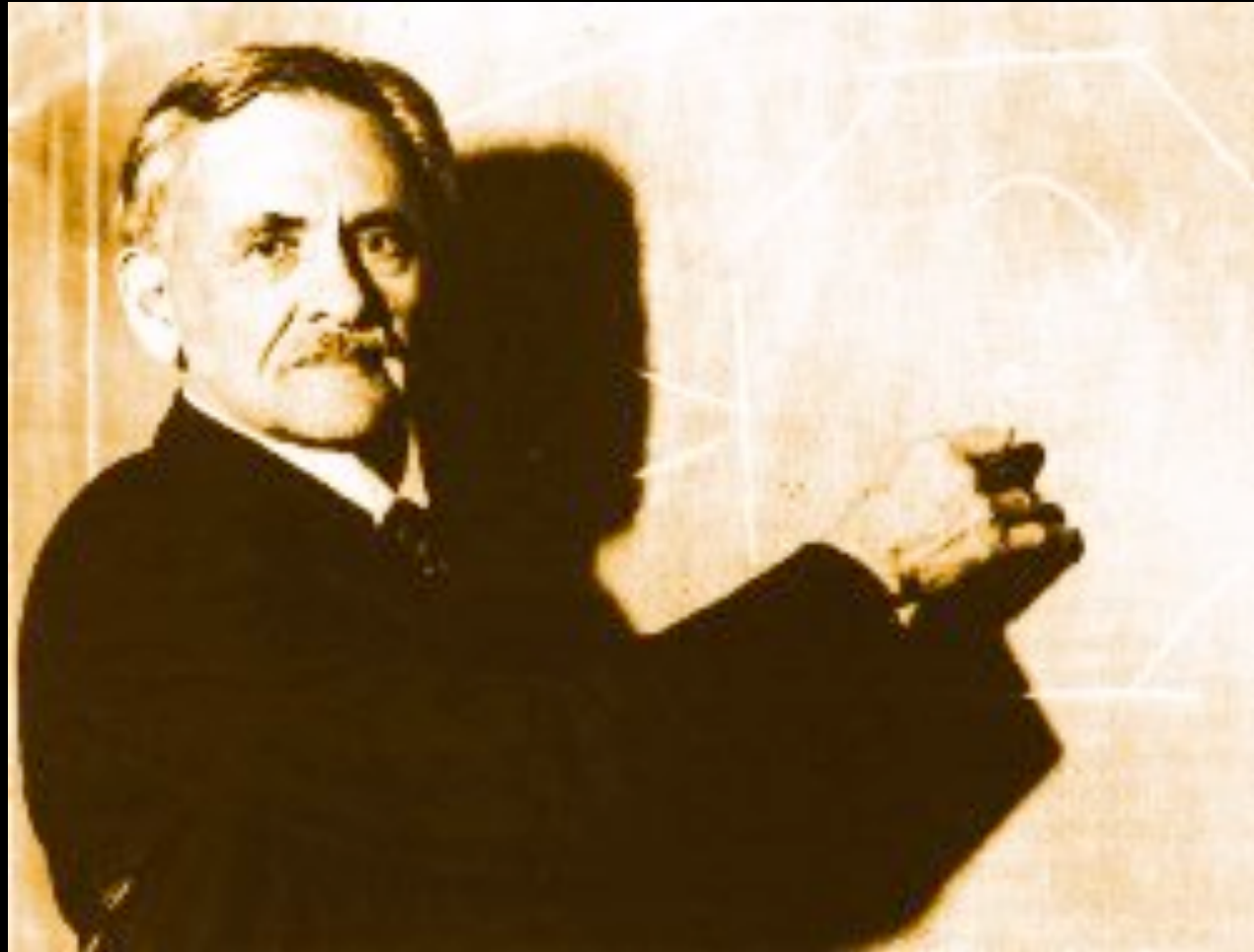
The End of Physics ?

"The more important fundamental laws and facts of physical science have all been discovered,

and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote."

The End of Physics ?

Nobel Laureate
Albert A. Michelson,
at the dedication of
Ryerson Physics Lab,
U. of Chicago, 1894



What is the universe made of?

- Atomic ("ordinary") matter
 - mostly protons, neutrons and electronsexplains visible universe
- But the visible universe is only a fraction of the entire universe that we have discovered

Dark Matter
Dark Energy
Gravitational Waves

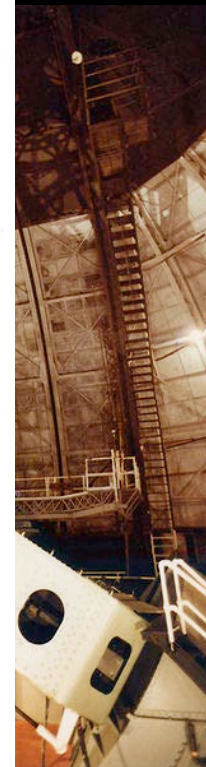
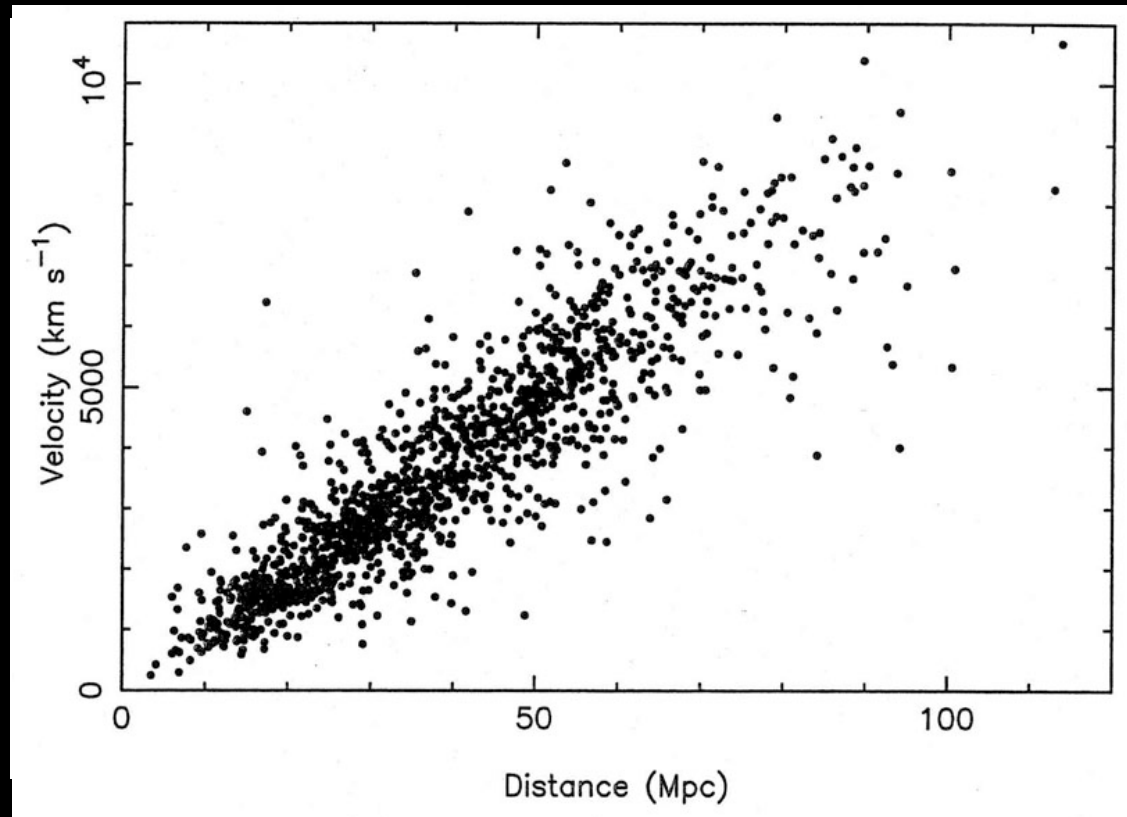
1929 - Hubble Discovered Universe is Expanding



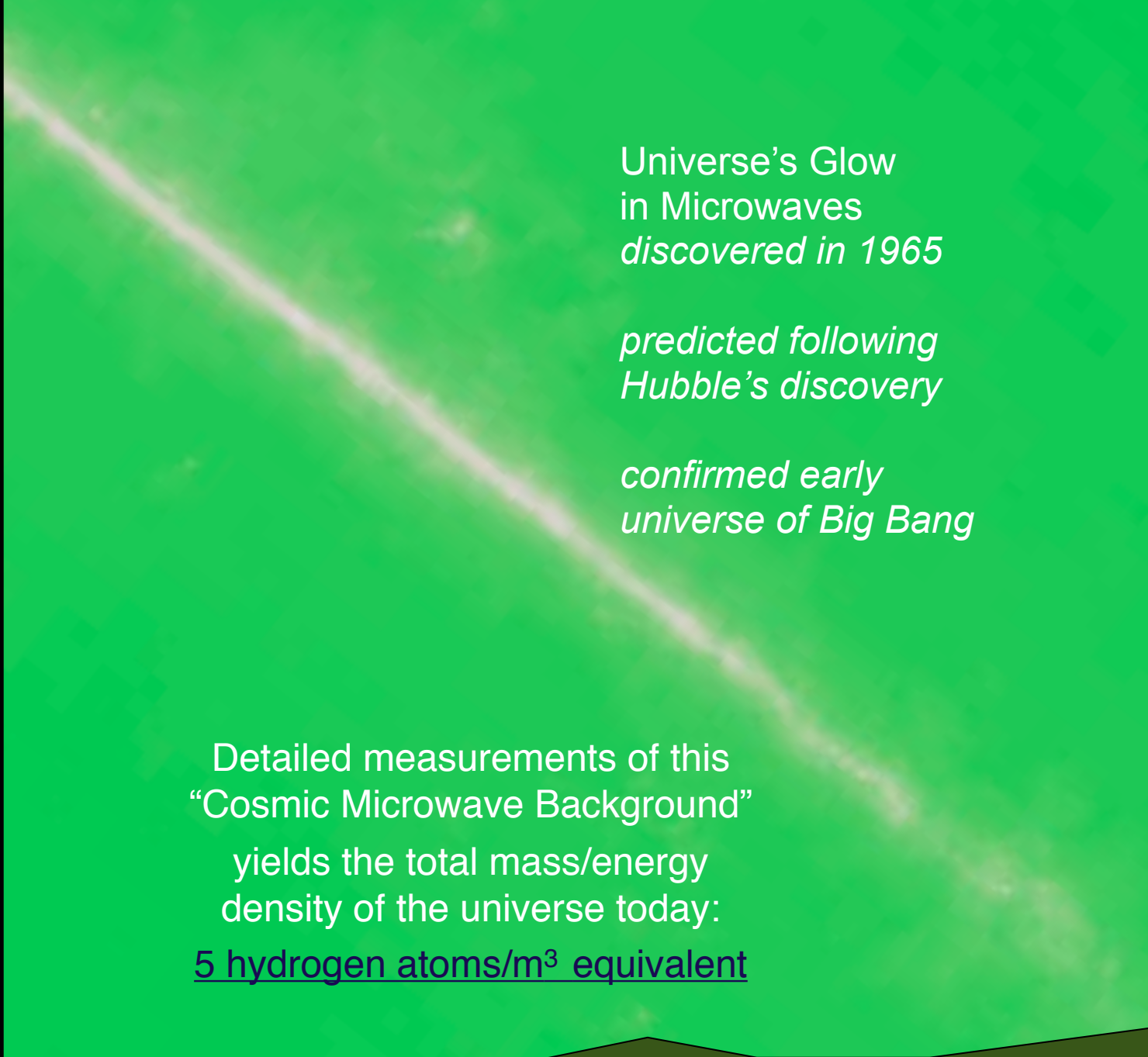
First evidence that Universe began with a Big Bang



Edwin Powell Hubble
(1889-1953)



1929

A map of the Cosmic Microwave Background (CMB) radiation, showing a blue background with a prominent diagonal band of higher intensity (yellow/orange) and various smaller fluctuations. The map is set against a black background with a dark blue, jagged horizon line at the bottom.

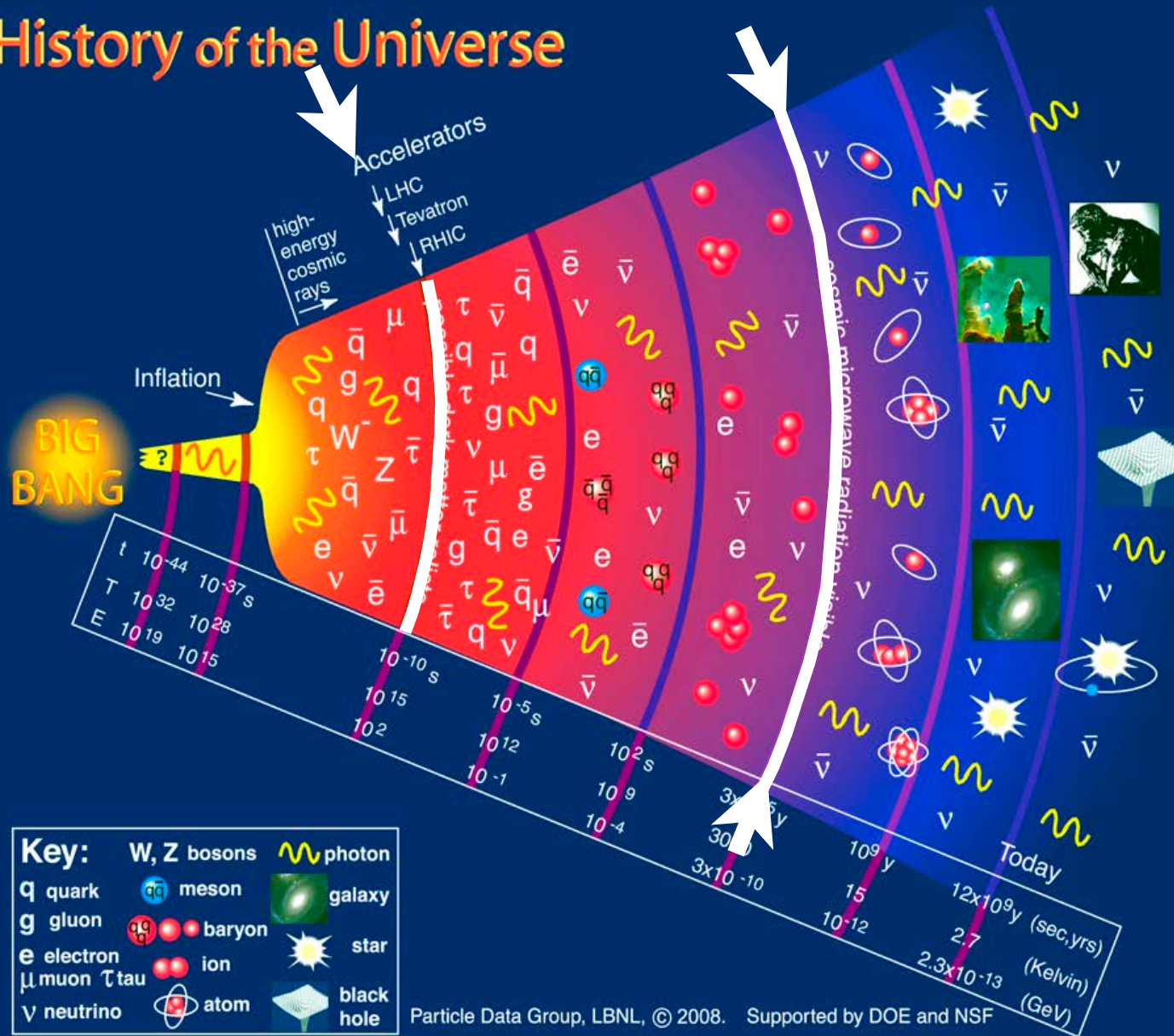
Universe's Glow
in Microwaves
discovered in 1965

*predicted following
Hubble's discovery*

*confirmed early
universe of Big Bang*

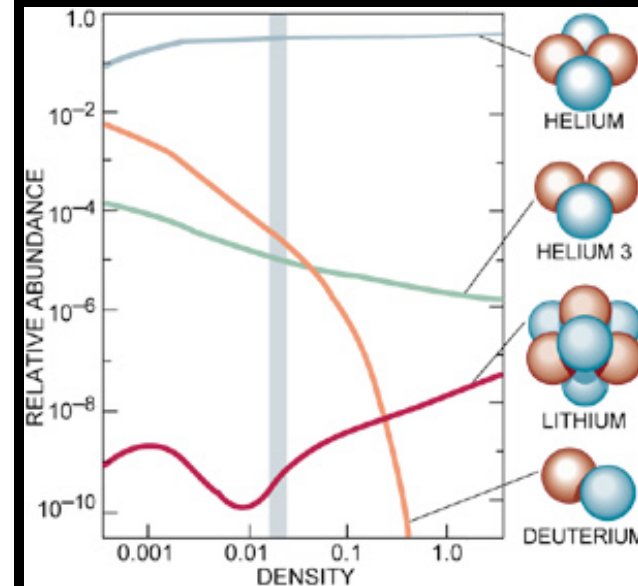
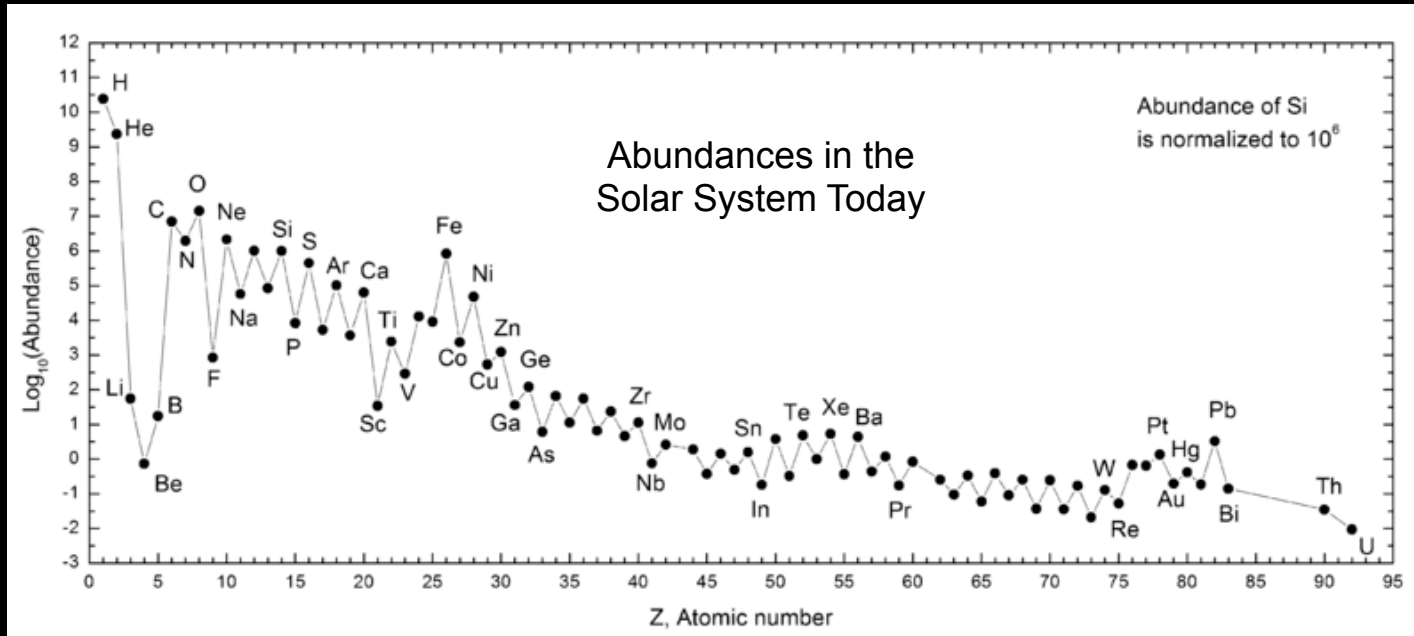
Detailed measurements of this
“Cosmic Microwave Background”
yields the total mass/energy
density of the universe today:
5 hydrogen atoms/m³ equivalent

History of the Universe



Nuclear Physics in the Early Universe

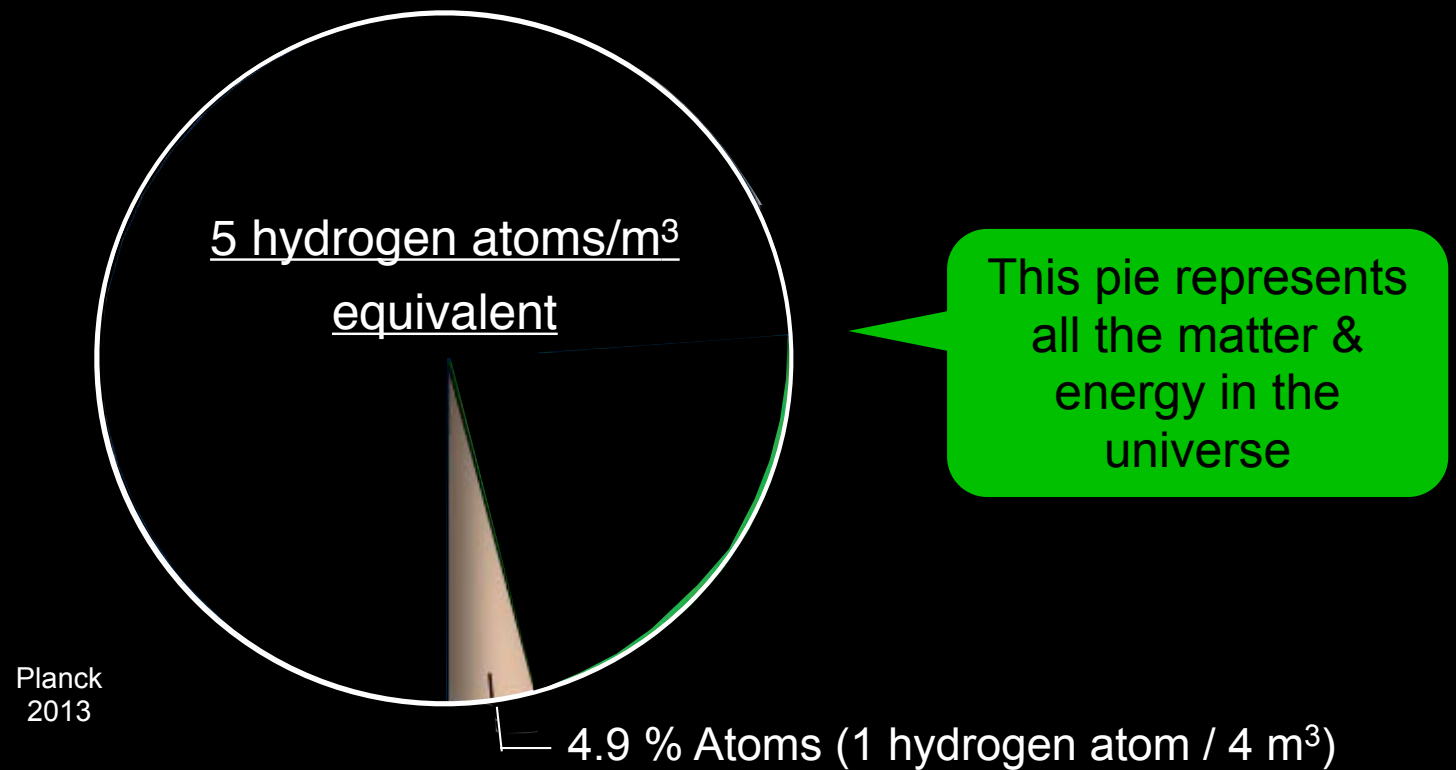
- Early universe produced atomic abundances



- Nicely explained in Big Bang Theory
- Establishes density of nuclear/atomic matter
 - today (after expansion) 1 hydrogen atom/ 4 m³
 - 1/20 of total mass/energy of universe

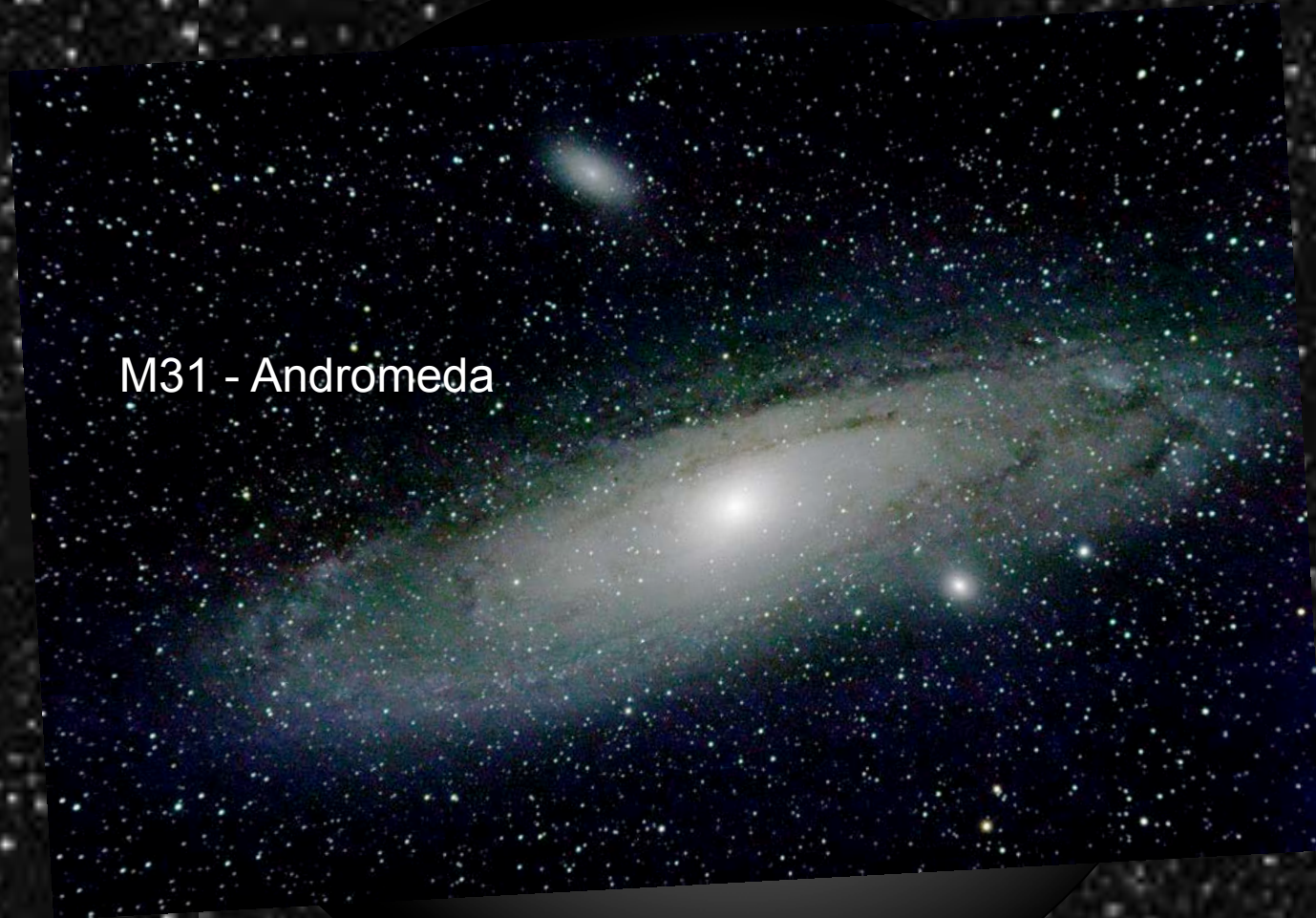
The Matter Crisis

- not enough matter to “make-up” known matter & energy of the Universe

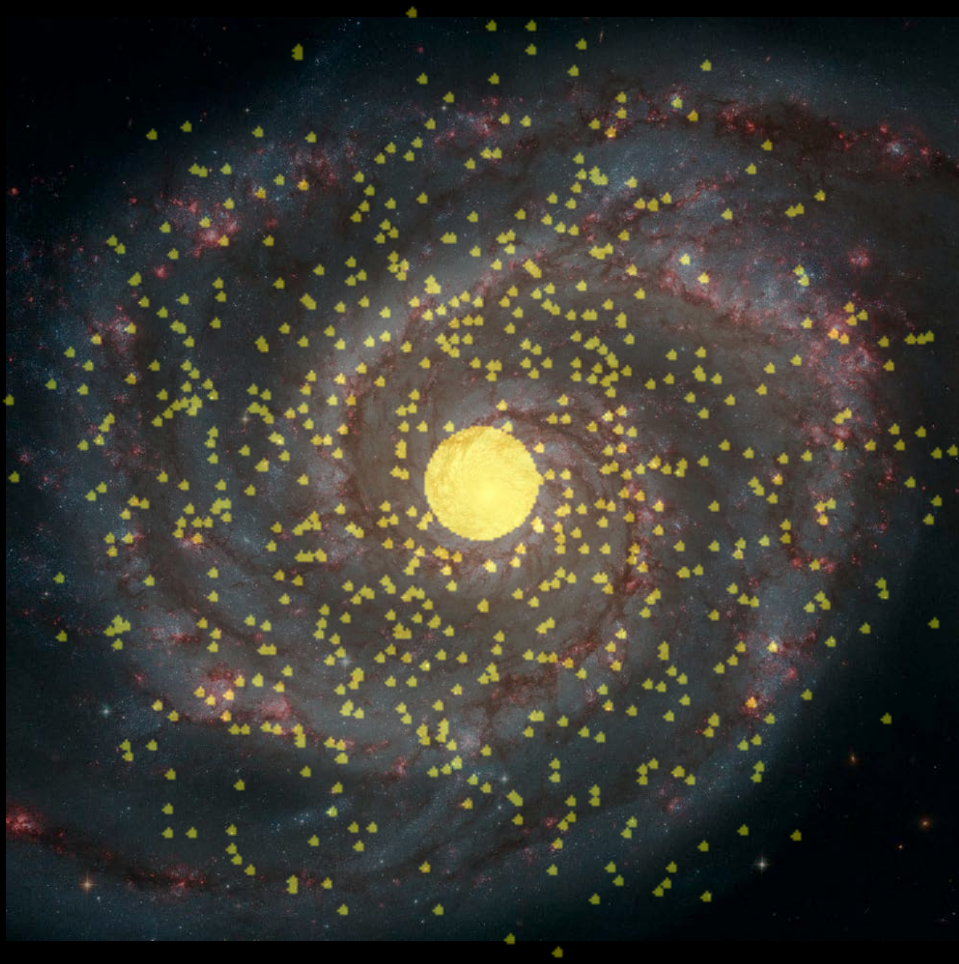


Halo of Dark Matter

M31 - Andromeda



How we know dark halos surround galaxies?



Expected-
based on visible stellar mass

Observed-
reveals invisible (“dark”) mass

Vera Rubin
1950s

Early Dark Matter Evidence

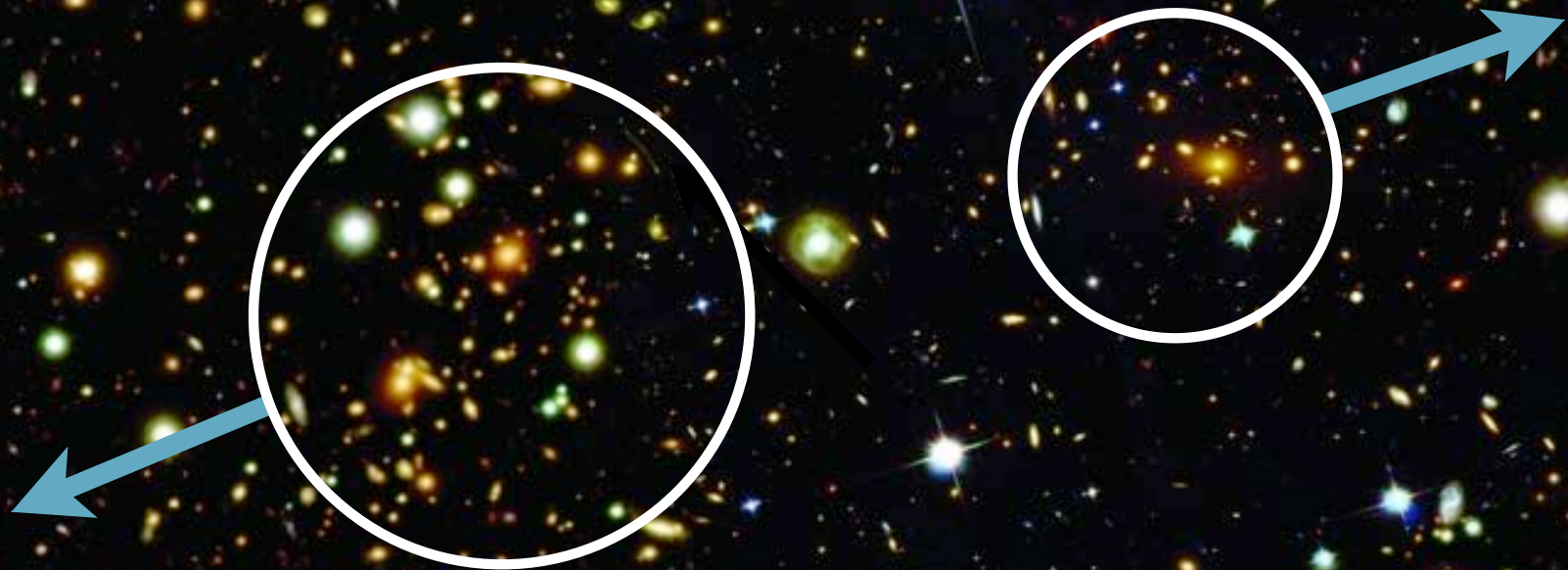


Fritz Zwicky

- 1930s motions of clusters of galaxies cannot be understood – Fritz Zwicky

Coma
Cluster

Bullet Cluster



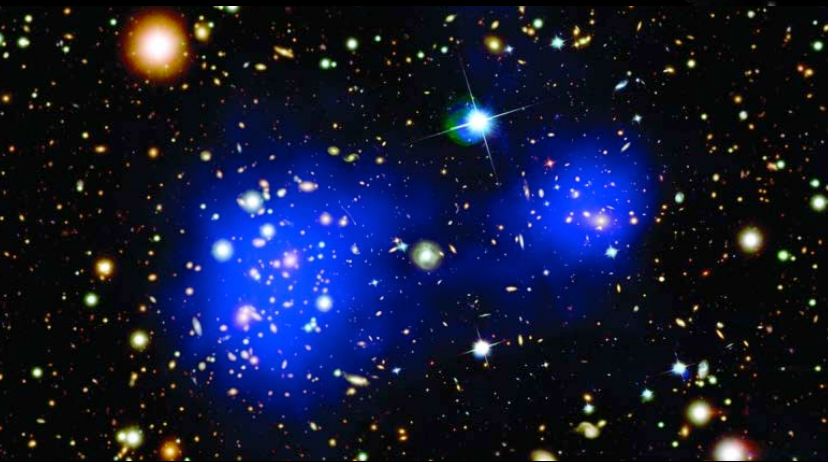
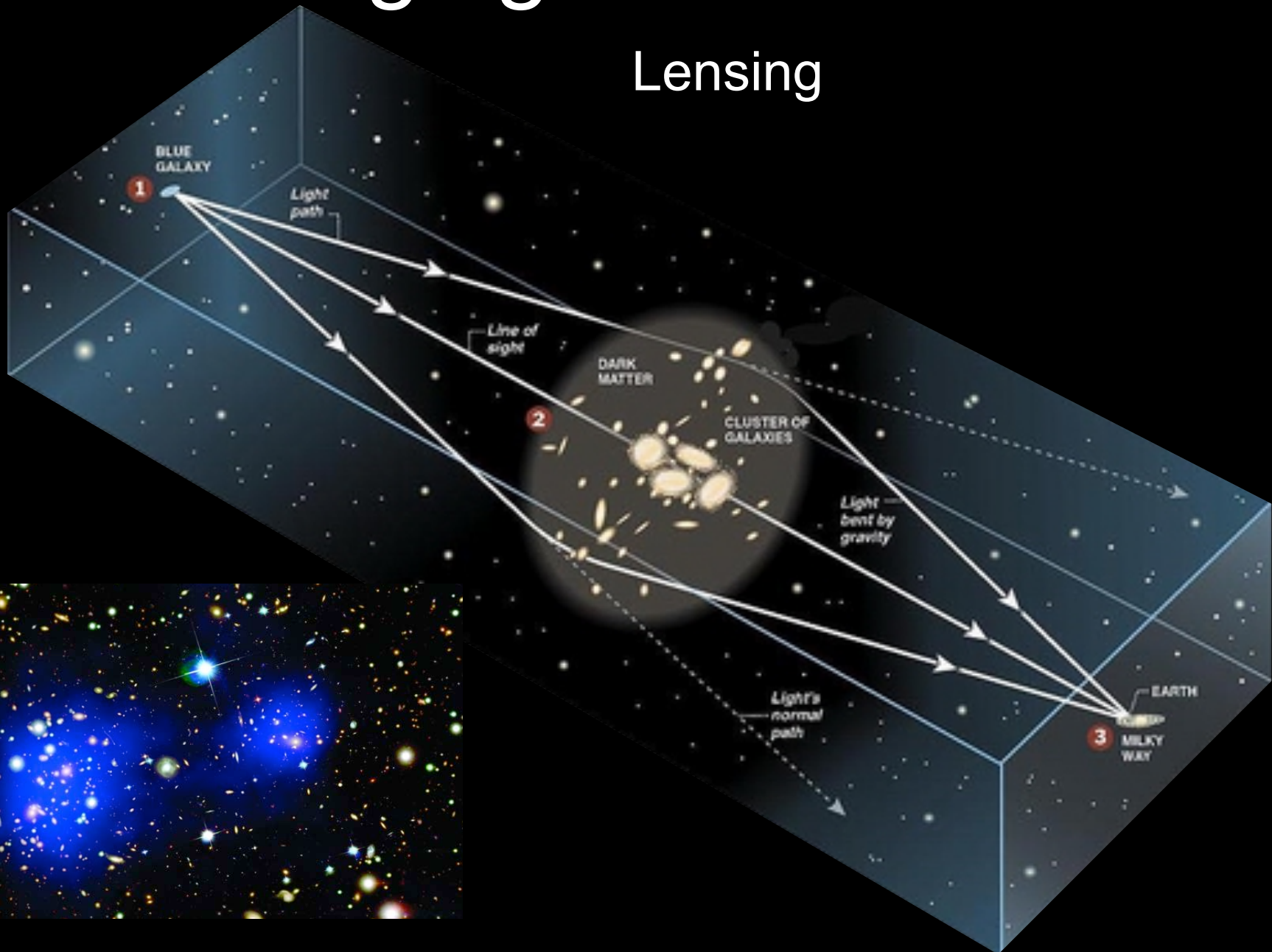
Bullet Cluster



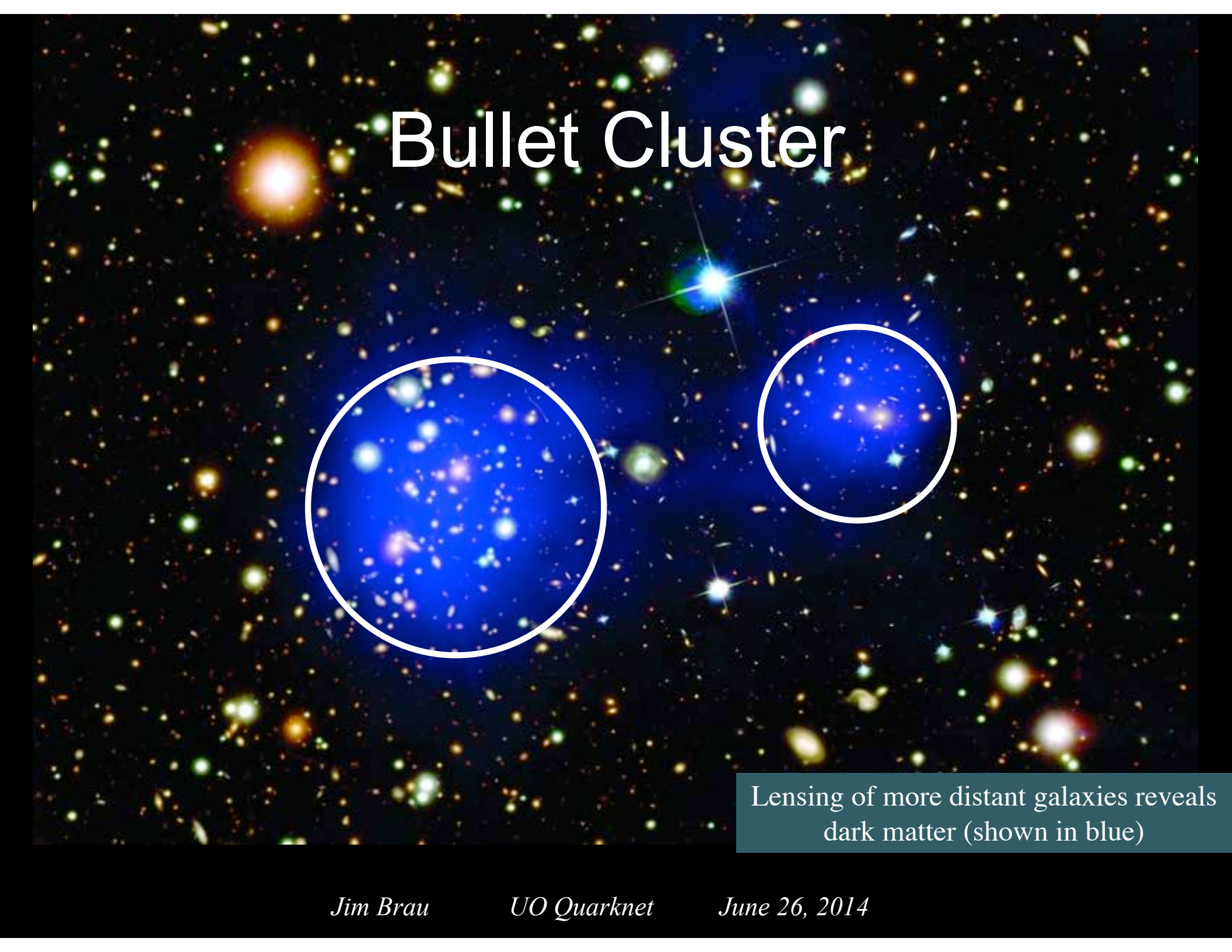
X-Ray emissions (red) -
Hot gas produced during pass through,.

Imaging Dark Matter

Lensing

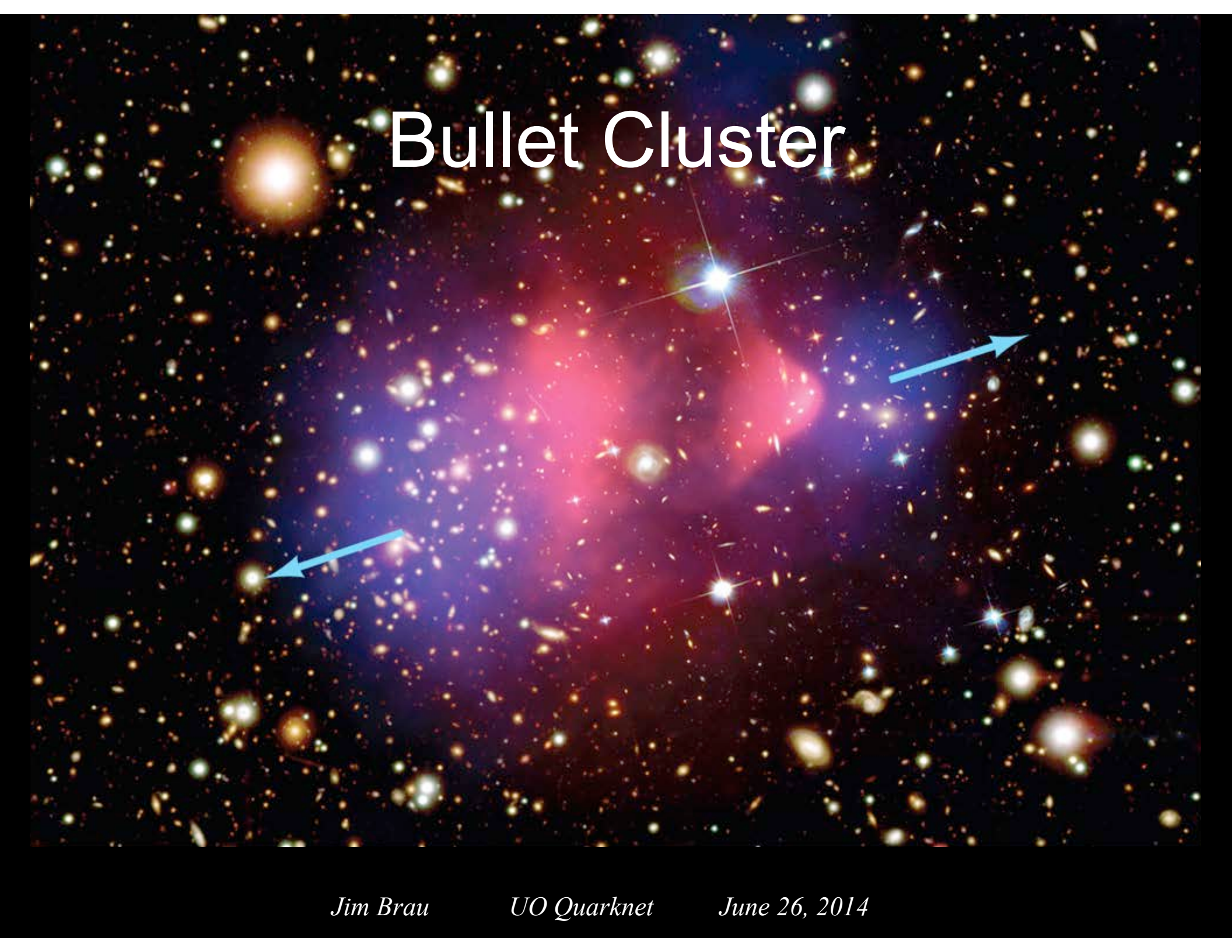


Bullet Cluster

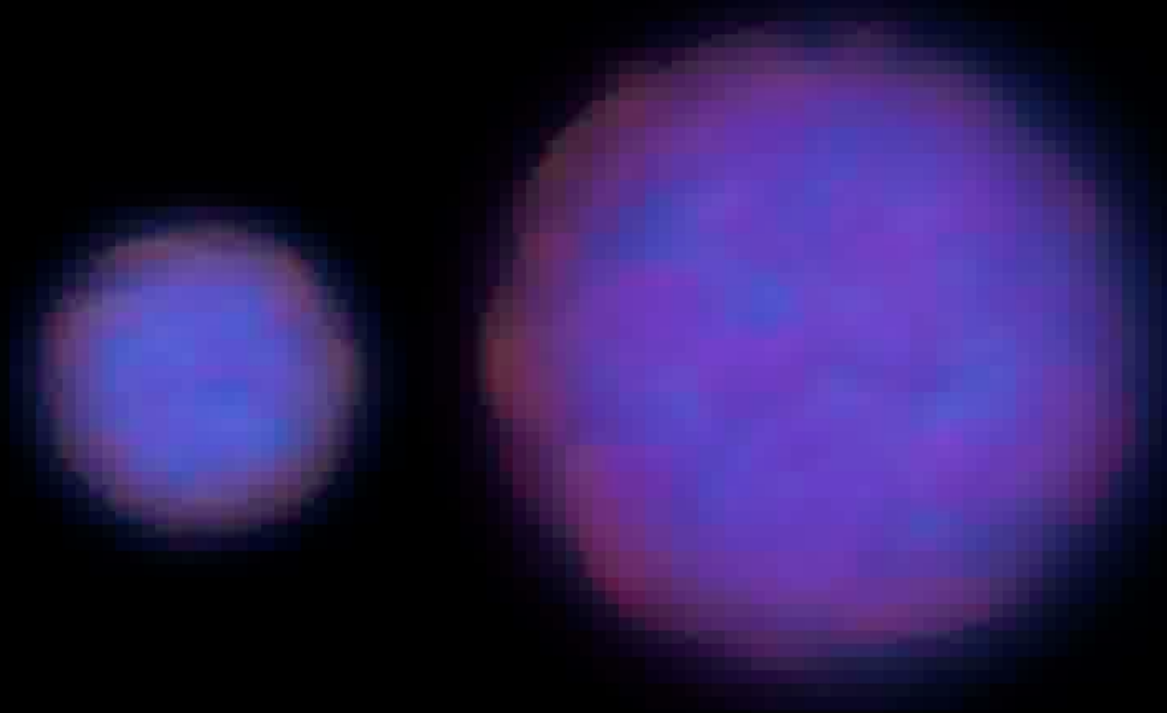


Lensing of more distant galaxies reveals
dark matter (shown in blue)

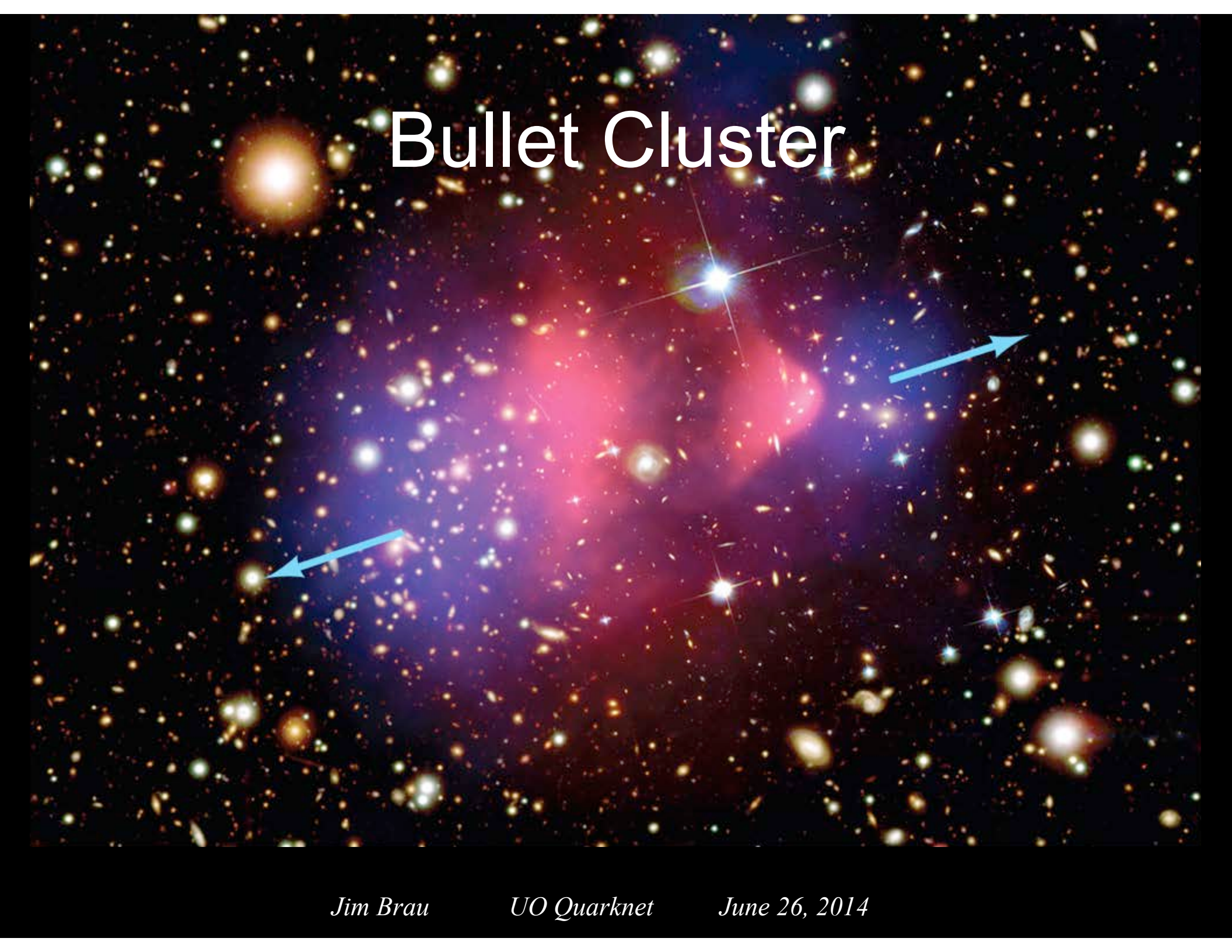
Bullet Cluster



Animation of Bullet Cluster collision

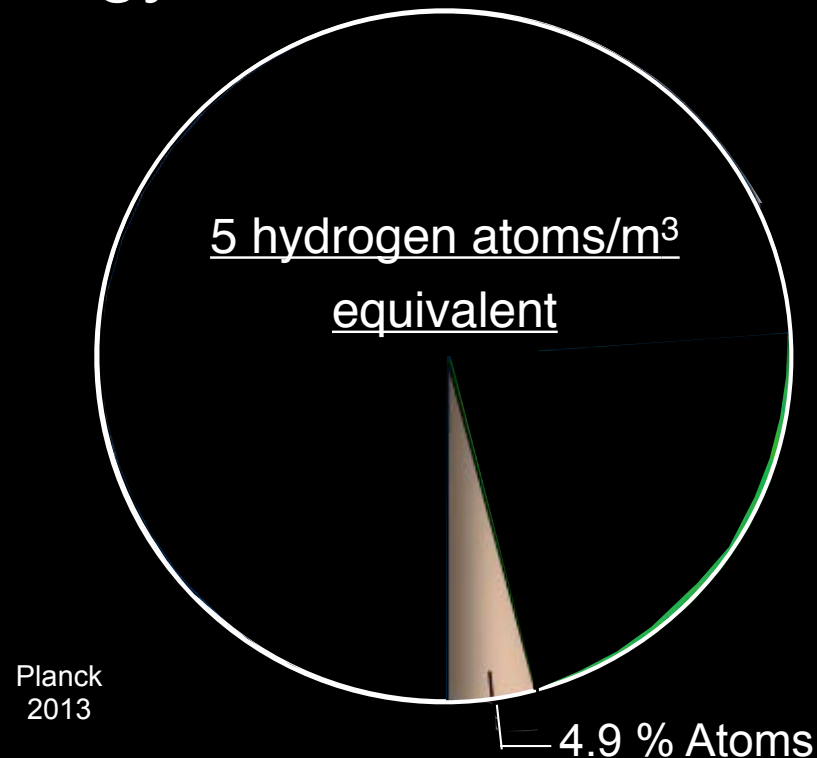


Bullet Cluster



The Matter Crisis

- better
- still not enough matter to “make-up” known matter & energy of the Universe



This pie represents all the matter & energy in the universe

What is the Dark Matter that Dominates Atomic Matter by 5/1?

- We have motivated ideas, but only direct evidence will be definitive
 - ~~Neutrinos?~~ WIMPs? Neutralinos?
 - Axions? ~~MACHOs~~ Exotics?
- Accelerator, satellite, or underground experiments may discover Dark Matter particles

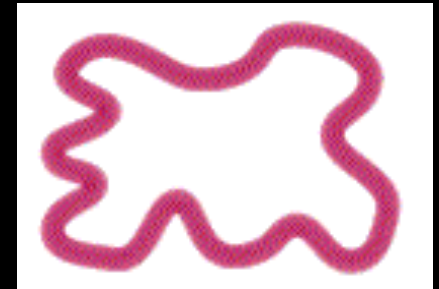
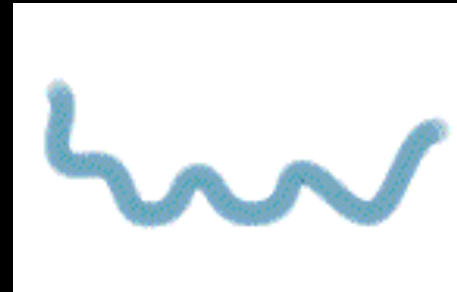


Candidate Theory Explains Dark Matter

SuperString Theory



- Unifies all particles and all forces
 - gravity with quantum mechanics
- Fundamental particles are represented as vibrations on string



- Strings are miniscule

- Atom is 10,000,000,000,000,000,000,000,000 x bigger
Dimension of String = 10^{-25} atomic size = 10^{-35} meters

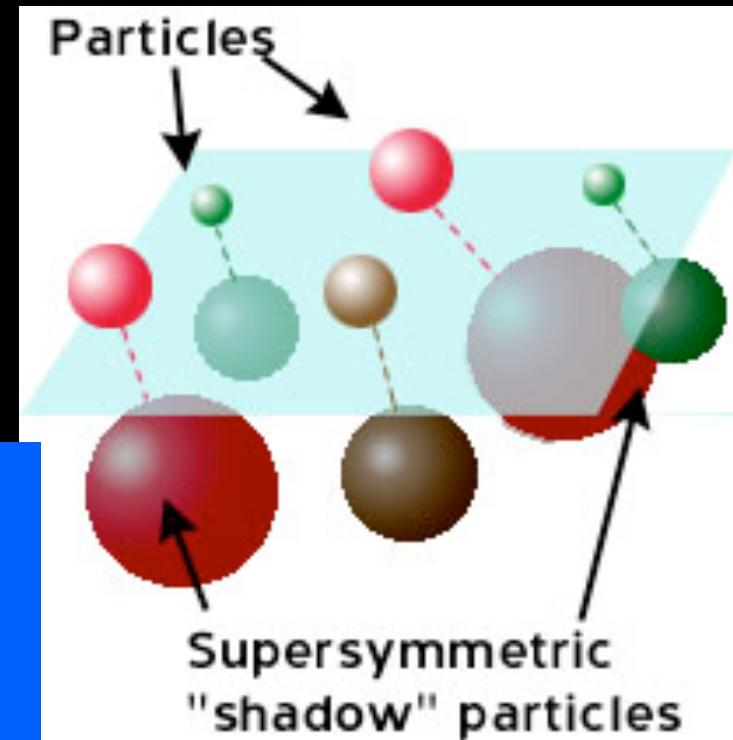
- Requires another set of matching particles

- the super-partners of ordinary particles

Supersymmetry, Strings, and Dark Matter

- The supersymmetric particles have just the properties expected of Dark Matter

But the dark matter particles may arise from even more fascinating New Physics. We just don't know - the search goes on!



Searching for Dark Matter Particles

many approaches

Particle Collider



Large Hadron Collider (LHC)
ATLAS Collaboration
w/ U. Oregon

Signals from Space



Fermi/GLAST Satellite

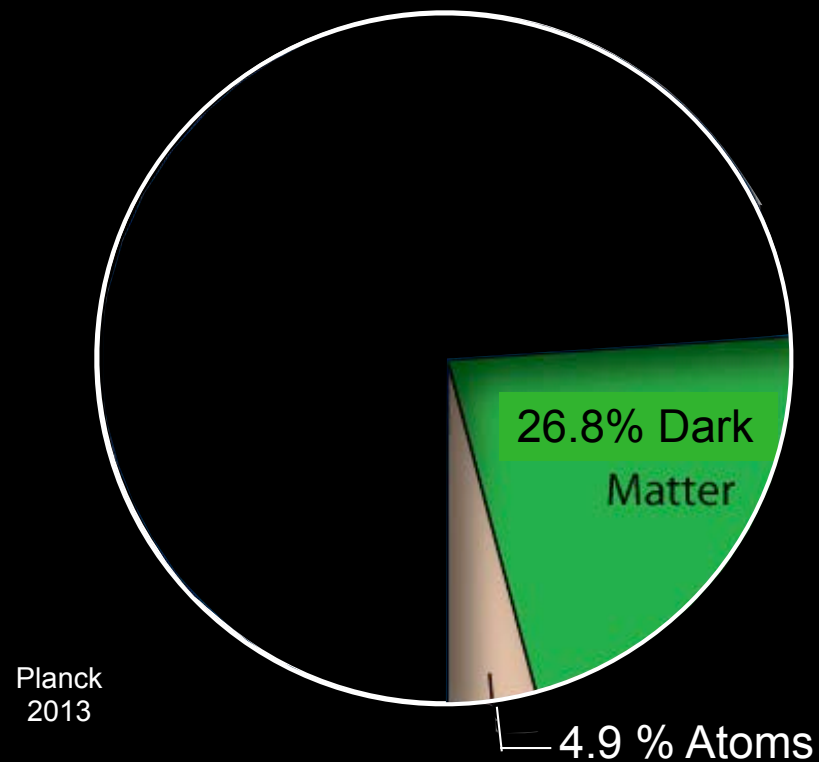
Underground Detectors



CDMS Underground

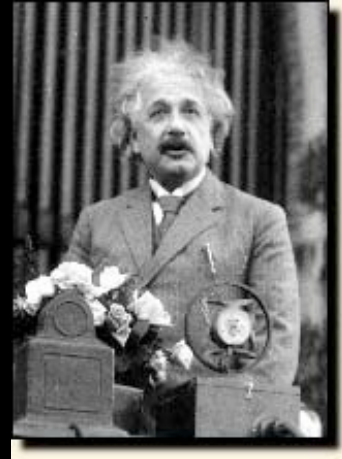
Matter/Energy Budget Crisis

- What could account for the missing matter/energy of the Universe?



This pie represents all the matter & energy in the universe

Mass & Energy



It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing -- a somewhat unfamiliar conception for the average mind.

Furthermore, the equation E is equal to $m c^2$, in which energy is put equal to mass, multiplied by the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa.

The mass and energy were in fact equivalent, according to the formula mentioned above.

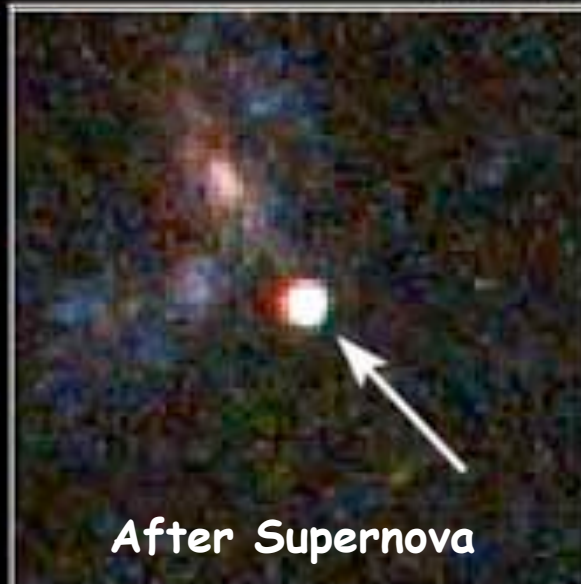
Center for the
History of Physics

Measuring Expansion of Universe

Distant Supernovae



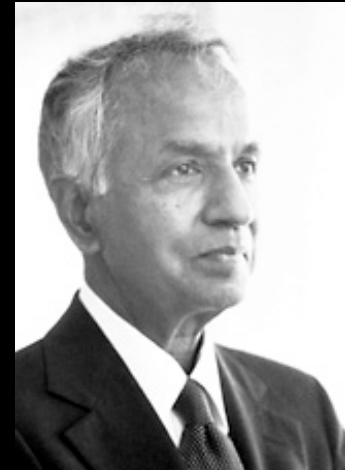
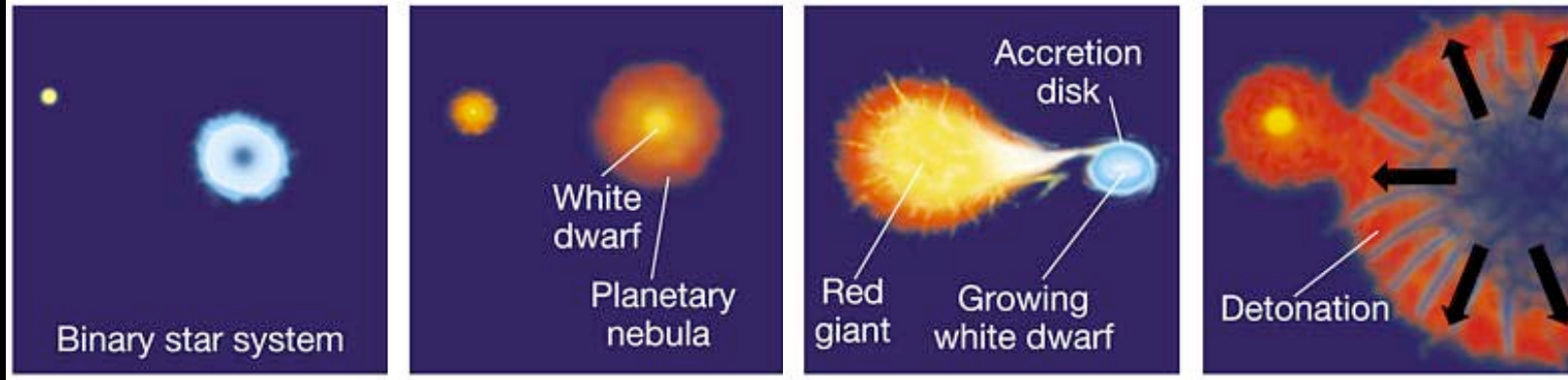
Hubble Space Telescope - ACS



Type Ia Supernovae are “Standard Candles”

Standard Candle = known luminosity

(a) Type I Supernova



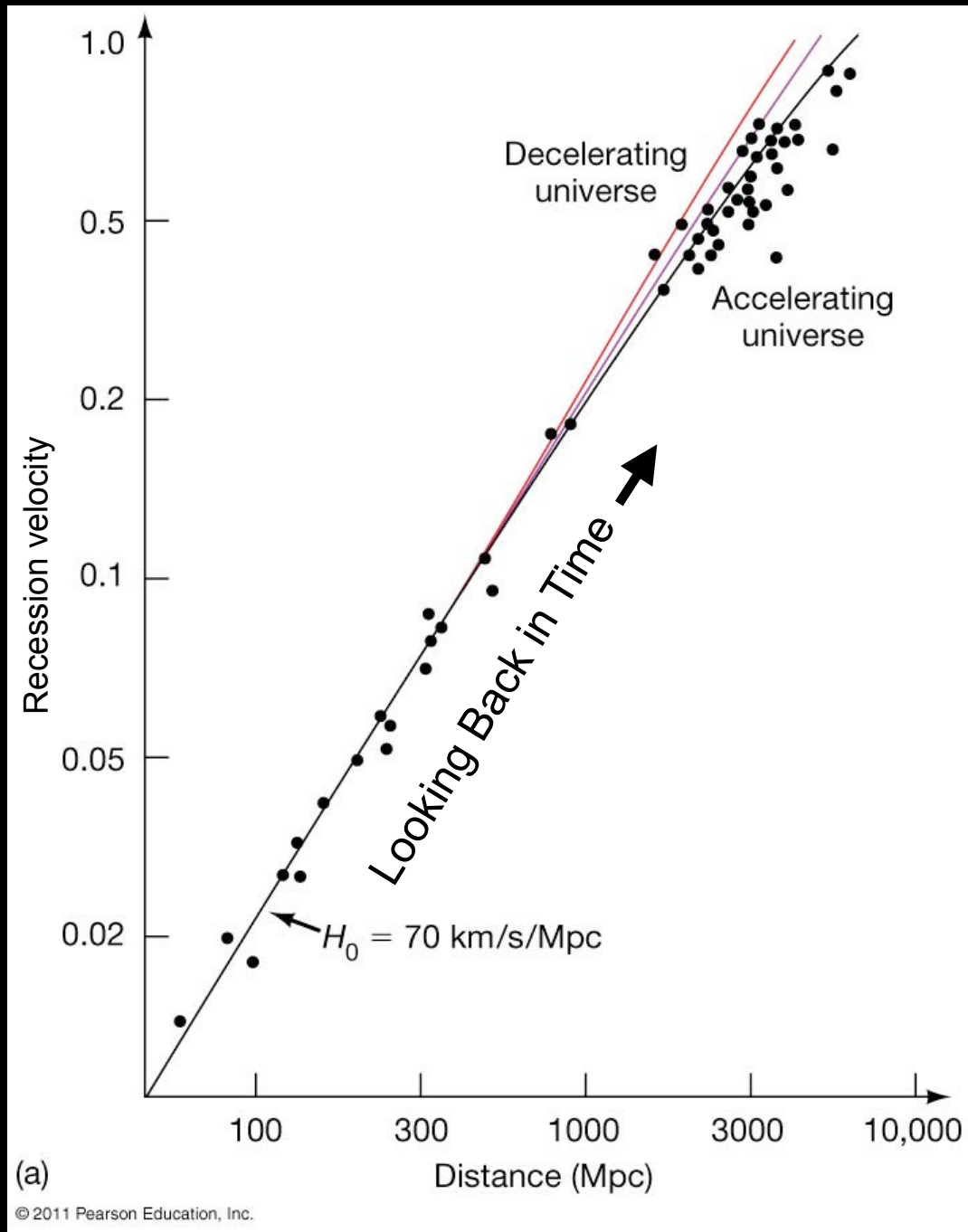
Chandrasekhar



Pauli

Chandrasekhar Limit

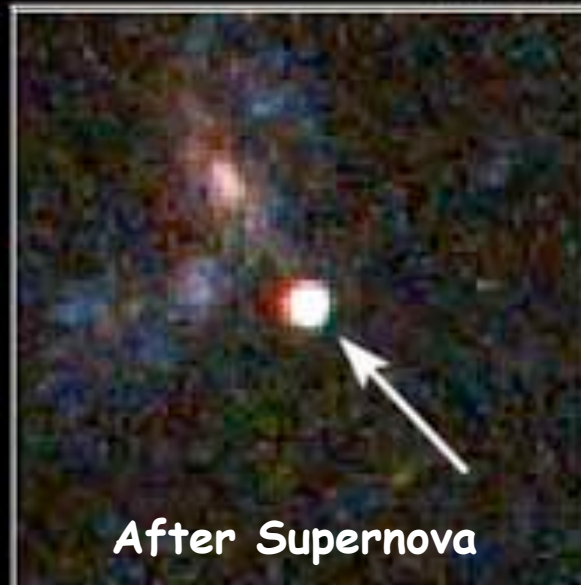
- $1.4 \times M_{\text{SUN}}$ (density = 1000 kg/cm^3)
- over this mass white dwarf collapses and explodes
- luminosity determined by mass = $1.4 \times M_{\text{SUN}}$



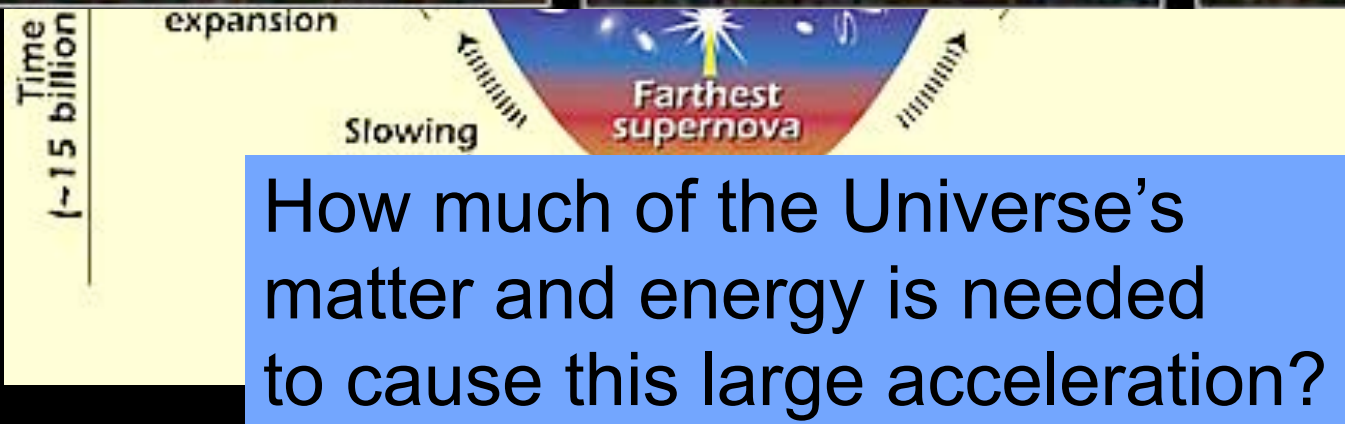
Measuring Expansion of Universe

Distant Supernovae

Hubble Space Telescope - ACS



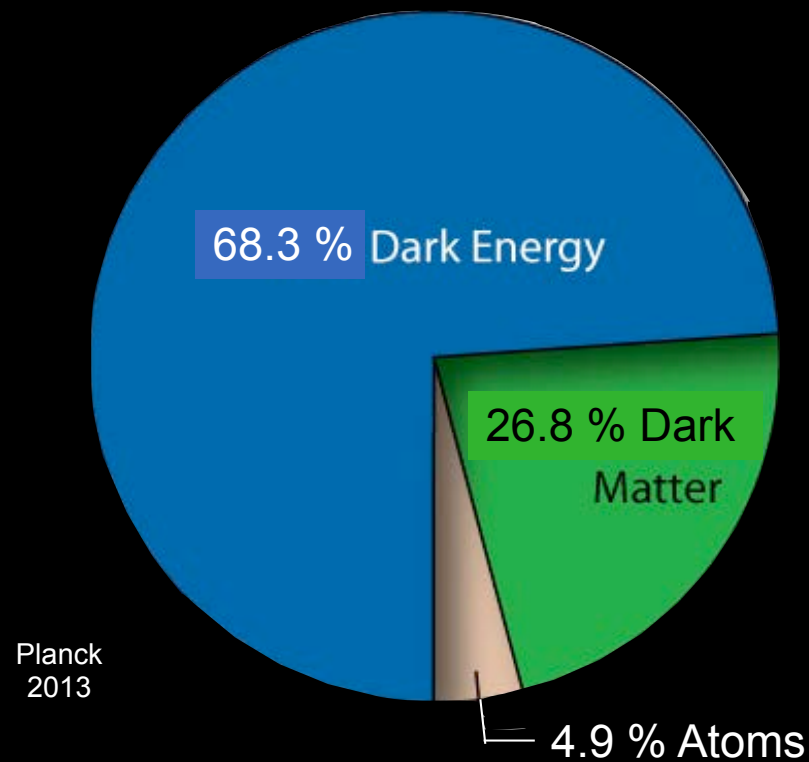
of
se
ng



Driven by
Dark Energy

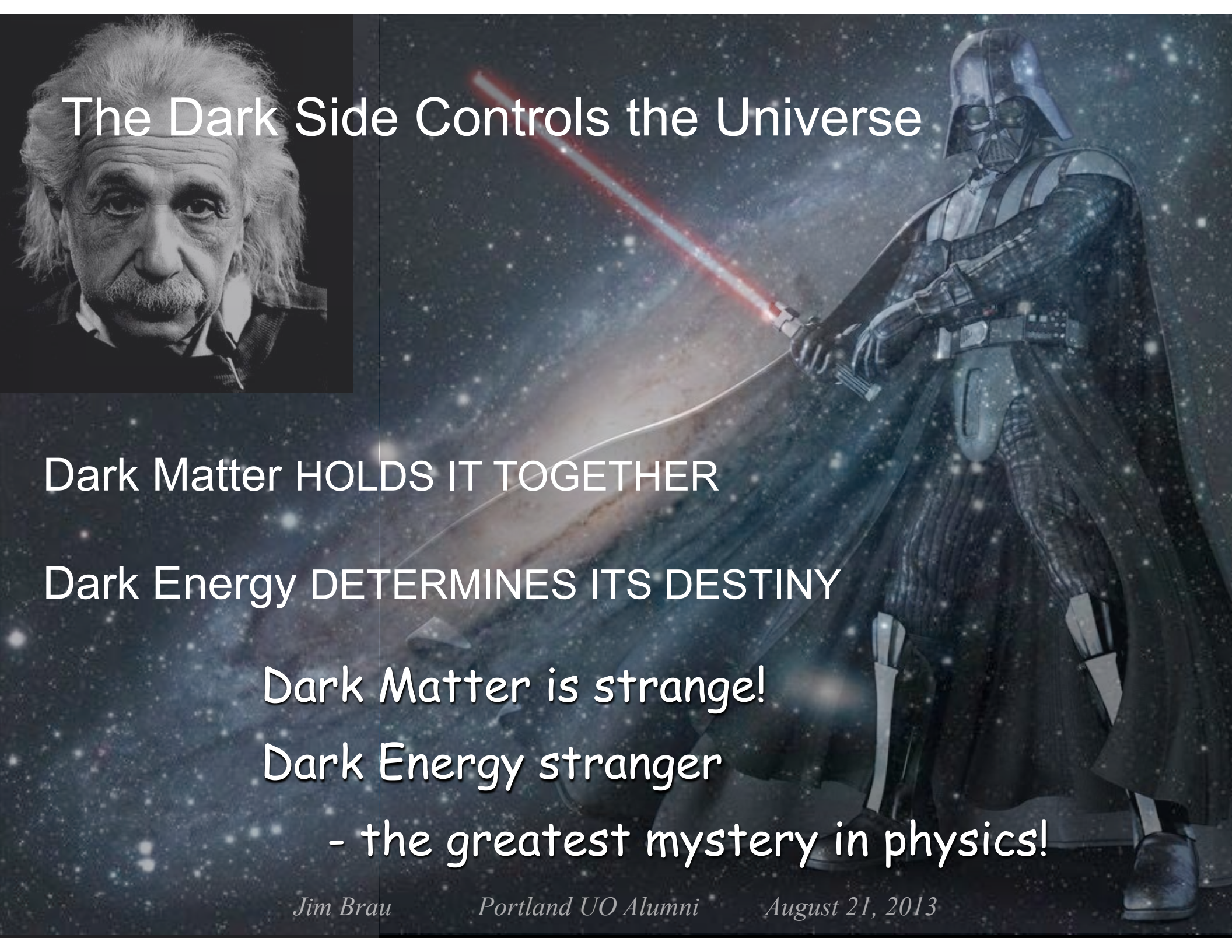
Acceleration Component called “Dark Energy”

- The dominant “stuff” of the universe is **dark matter** and **dark energy**



This pie represents
all the matter &
energy in the
universe

5 hydrogen atoms/m³
equivalent



The Dark Side Controls the Universe

Dark Matter HOLDS IT TOGETHER

Dark Energy DETERMINES ITS DESTINY

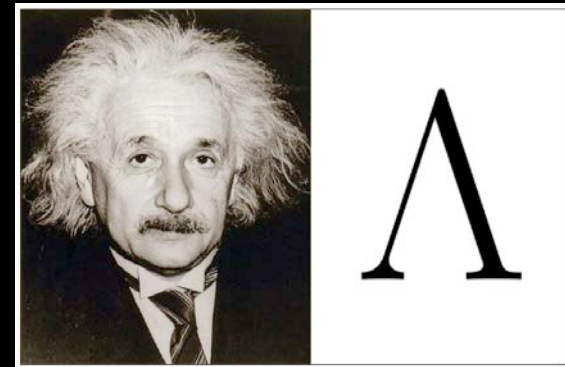
Dark Matter is strange!

Dark Energy stranger

- the greatest mystery in physics!



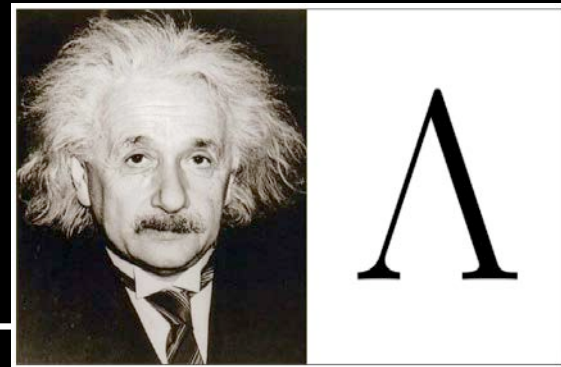
What is Dark Energy?



- Cosmological constant?
 - Einstein's addition (1917) to General Theory of Relativity.
 - Designed to overcome natural pull of gravity, producing a "static universe".
 - 1929 - Edwin Hubble's discovered universe was expanding
 - Einstein called cosmological constant his "greatest blunder." He retracted the constant.

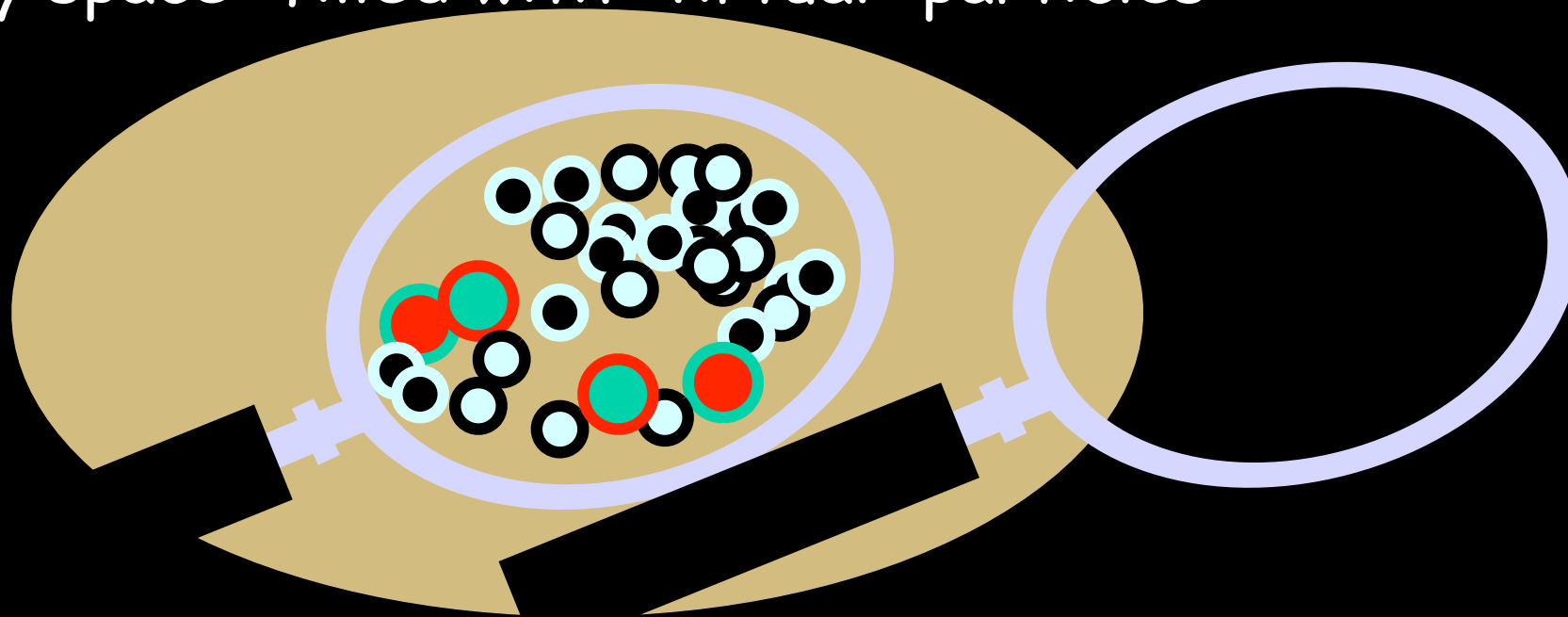


What is Dark Energy?



Cosmological Constant could result from quantum vacuum fluctuations

- Quantum physics $\rightarrow$ no truly empty space
- "Empty space" filled with "virtual" particles



Vacuum Fluctuations

- The effect of these virtual particles can be calculated using Quantum Field Theory
 - But this theoretical result is far too big
 - By a factor of
1,000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000 = 10^{120}
 - This is a BIG-time mystery
 - we know how the universe might make Dark Energy,
but we don't know how to make so little
 - There is no fundamental understanding of Dark Energy

$$E_o = \frac{1}{4\pi} \hbar \omega$$

vacuum energy is the sum of all the simple harmonic

$$E_0 = \sum_j \frac{1}{4\pi} \hbar \omega_j$$

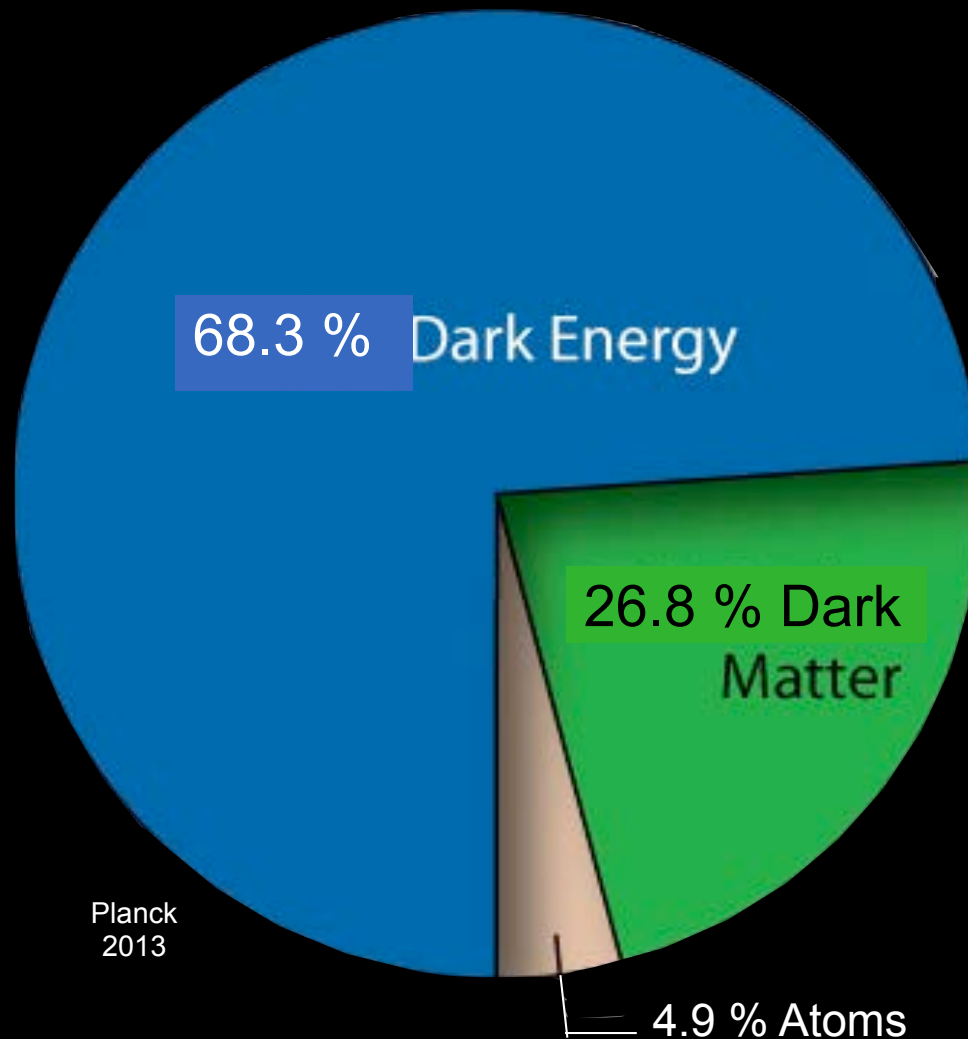
λ_n) for the scalar field. This sum may be evaluated for large n and L and λ_n goes to infinity. The periodic boundary conditions are satisfied for integer values of n . There are then $Ldk/2\pi$ discrete values of k and the sum becomes an integral:

$$E_o = \frac{1}{4\pi} \hbar L^3 \int \frac{\omega}{(2\pi)^3} d^3k$$

pose a cutoff at a maximum wavevector k_{max} :

$$\rho_{vac} = \lim_{L \rightarrow \infty} \frac{E_0}{L^3} = \frac{\hbar k_{max}^4}{32\pi^3}$$

Substance of the Universe



Future Studies of Dark Energy

Four Techniques

- distant supernovae
- frozen sound waves in early universe
- gravitational lensing
- galaxy clusters

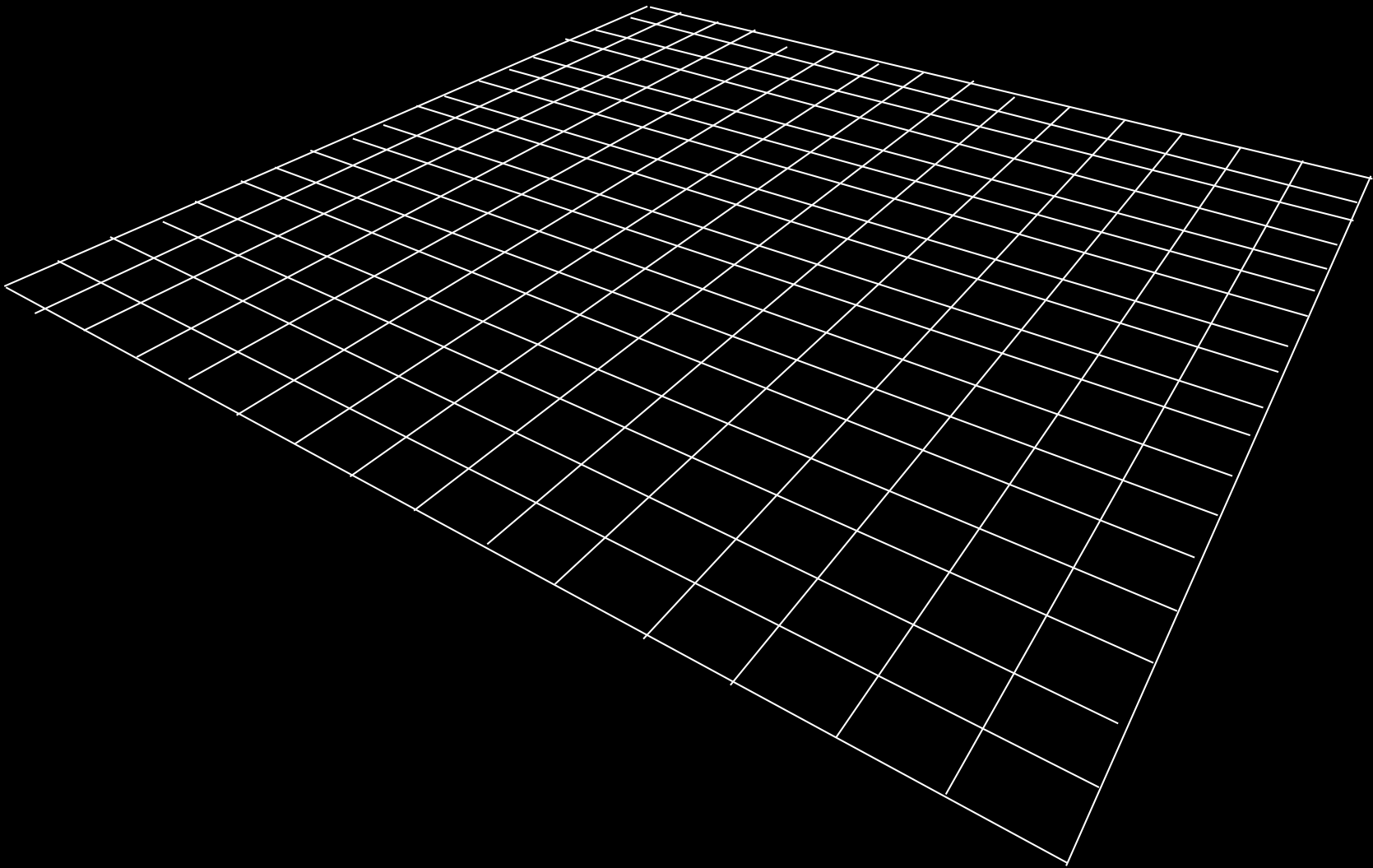
Blanco 4-meter telescope at Cerro Tololo Inter-American Observatory high in the Chilean Andes.

Search for Gravitational Waves

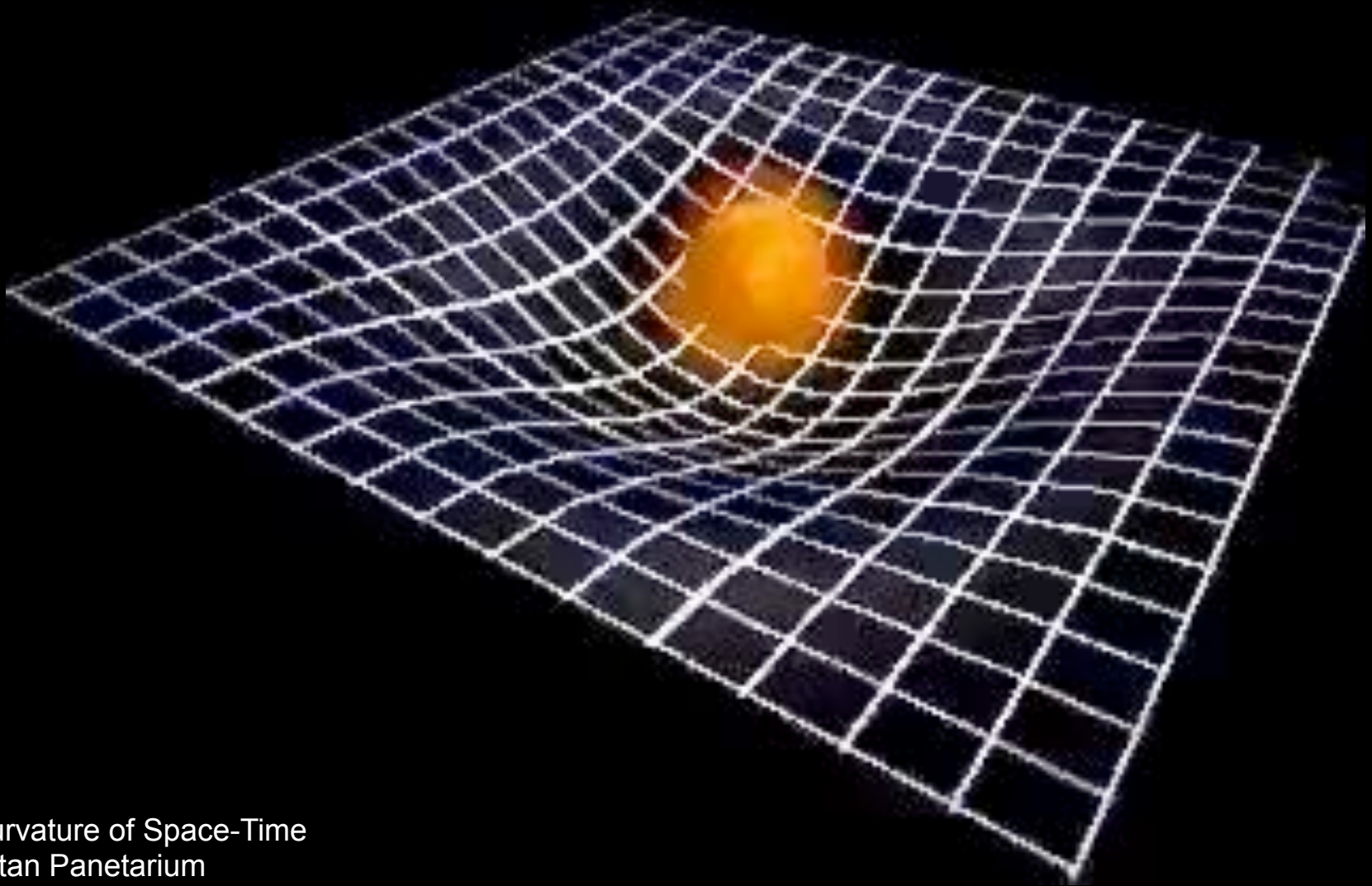
LIGO Scientific Collaboration
w/ U. Oregon

Laser Interferometer Gravitational-wave
Observatory (LIGO)
Hanford, WA

Mass-free “flat” Space-time



Mass “warps” Space-time

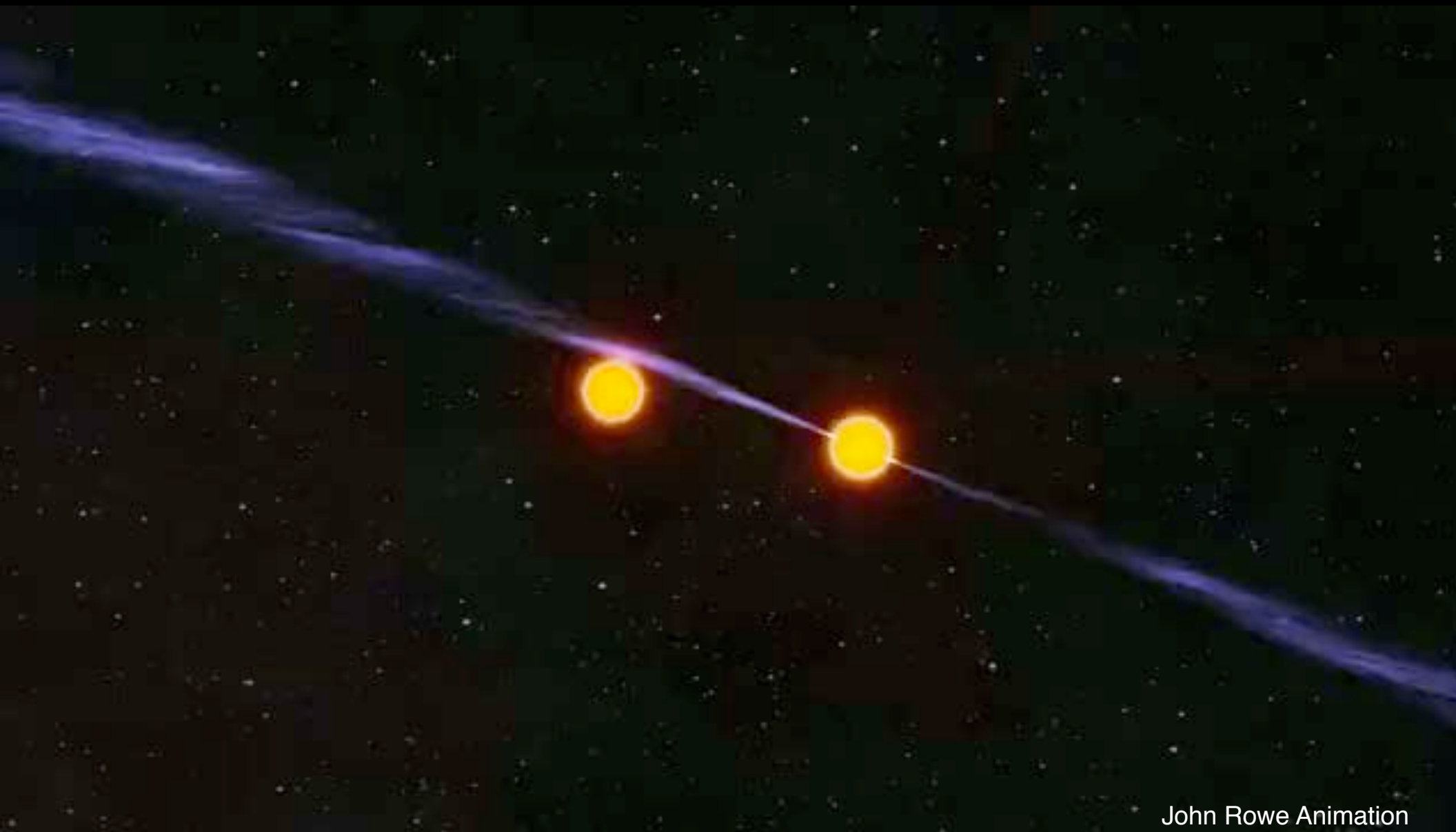


The curvature of Space-Time
Kurdistan Planetarium

Gravity & Gravitational Waves

- The curvature of Space-time changes as masses within the spatial fabric move
- Large masses (black holes, neutron stars,...) will produce observable changes:

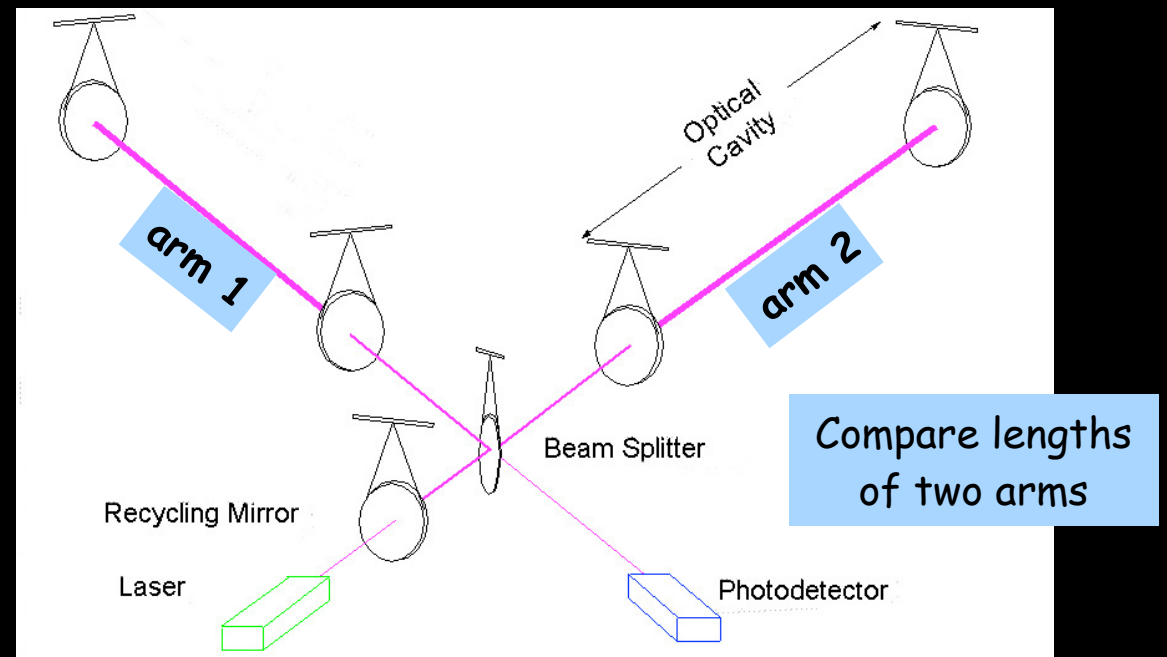
producing ripples in space
gravitational waves



John Rowe Animation
www.JohnRowe.org

Detecting Gravitational Waves

- Disturbances in space very small - space is STIFF!
 - small fraction of atomic nucleus over a kilometer
- Small disturbance can be measured by large laser interferometer (LIGO)



Global Network of Gravitational Wave Interferometers

LIGO

4 km



GEO 600m



Virgo 3 km



**LSC:
LIGO+GEO**



**LIGO
4 km**

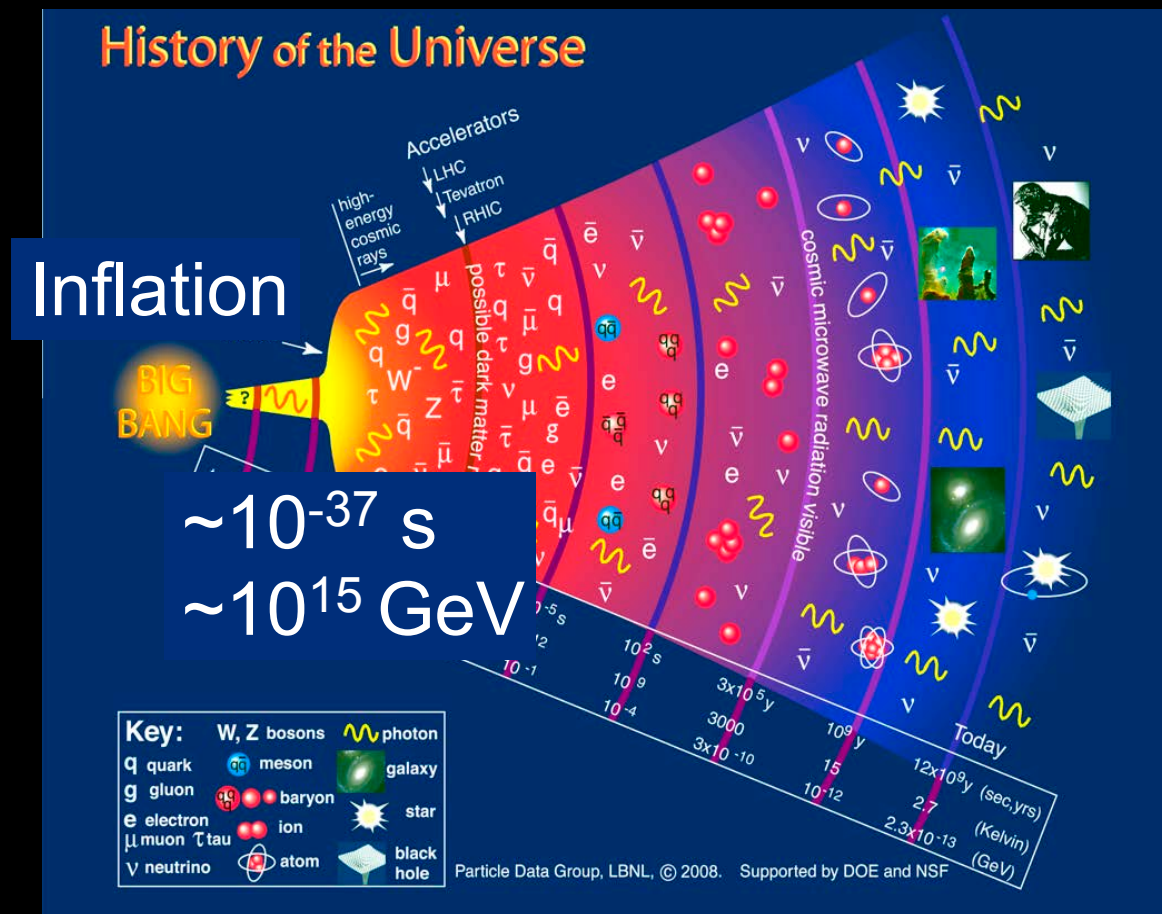


The next astronomy - Gravitational waves

- Many discoveries resulted from expanding astronomy for electromagnetic radiation
radio waves, infrared, ultraviolet,
X-rays, gamma-rays
- Revolutionary discoveries such as
 - neutron stars, black holes, gamma ray bursts, dark matter, dark energy, etc.
- We anticipate unexpected discoveries from gravitational wave astronomy

BICEP2

- Have gravitational waves from the VERY EARLY Universe been observed?



The End of Physics ?

What is Dark Matter?

What is Dark Energy?

What can gravitational waves tell us
about the universe?

What is the Higgs boson?

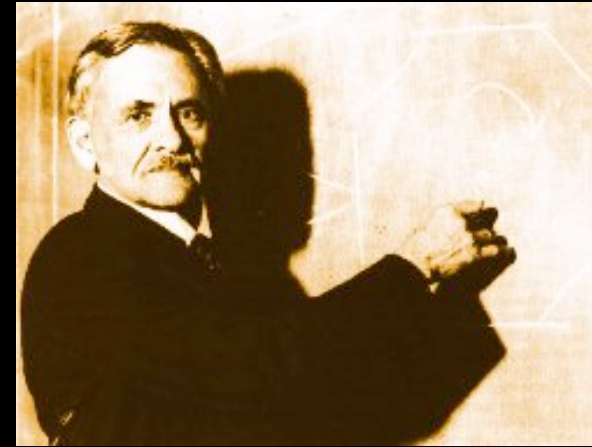
How are electrons related to quarks?

How can gravity and quantum
mechanics be reconciled?

Why are neutrinos so light?

....

....

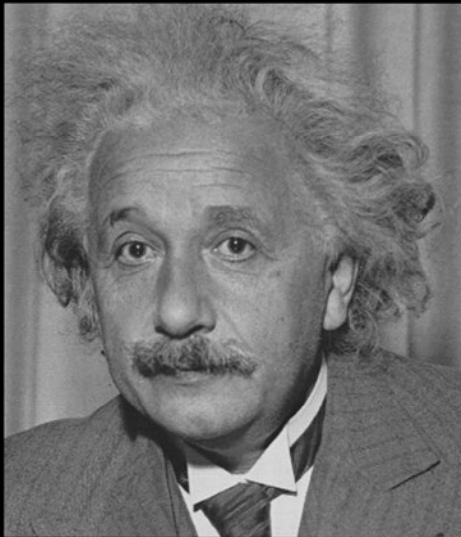


Albert A. Michelson, 1894

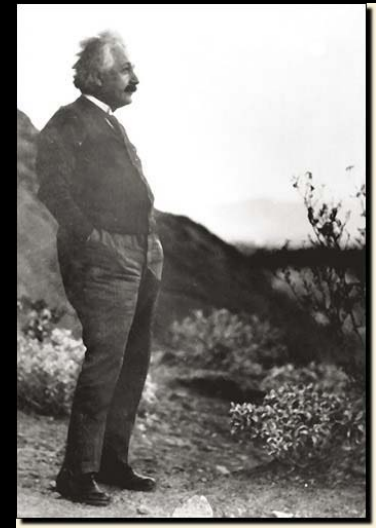
The Hidden Universe: Dark Matter, Dark Energy, & Gravitational Waves

- The Universe is dominated by mysterious components:
 - 5% “ordinary”, atomic matter
 - 27% dark matter - what is it?
 - 68% dark energy - what is it?
- Many upcoming scientific projects will advance our knowledge of these mysterious components of the HIDDEN UNIVERSE
- Advanced LIGO may soon open the gravitational wave window on the Universe

*One thing I have
learned in a long life:
that all our science,
measured against
reality, is primitive
and childlike
—and yet it is the
most precious thing
we have.*



Jim Brau



The most beautiful
experience we can
have is the
mysterious.

It is the fundamental
emotion which
stands at the
cradle of true art
and true science.

Acknowledgements

RESEARCH SUPPORTED BY

Department of Energy
OFFICE OF SCIENCE



NATIONAL SCIENCE FOUNDATION



Philip H. Knight

Acknowledgement: images from <http://www.AstroPics.com>