

Title: What is the Universe Made Of? The Case for Dark Matter and Dark Energy

Date: Jul 13, 2012 07:30 PM

URL: <http://pirsa.org/12070004>

Abstract: For the first time in human thought it is now possible to observationally determine how much matter is in the Universe as a whole. These observations strongly support the Λ CDM Concordance Model of Hot Big Bang Cosmology, and reinforce earlier indications that ordinary matter (atoms, nuclei and electrons) make up at present at most 4% of the total of the Universal energy density. The big surprise was that the rest consists of two kinds of unknown forms of matter: the so-called Dark Matter and Dark Energy. This talk summarizes for non-specialists the various lines of evidence for their existence, and some of the theoretical ideas which have been proposed to account for their properties

What is the Universe Made of?

*The Case for Dark Energy
and Dark Matter*

Cliff Burgess



1905 – A Big Year for Einstein

- Photo-electric Effect
 - “On a Heuristic Point of View concerning the Production and Transformation of Light.” *rd* Mar 18, *pub* Jun 9
- Brownian Motion
 - “On the Movement of Small Particles Suspended in Stationary Liquids Required by the Molecular-Kinetic Theory of Heat.” *rd* May 11, *pub* Jul 18
- Special Relativity
 - “On the Electrodynamics of Moving Bodies.” *rd* Jun 30, *pub* 26 Sep
- Size of Molecules*
 - “A New Determination of Molecular Dimensions.” *rd* Aug 19, *pub* Feb 8
- Mass-Energy Equivalence
 - “Does the Inertia of a Body Depend upon Its Energy Content?” *rd* Sep 27, *pub* Nov 21



Albert Einstein

* *PhD Thesis and most cited*

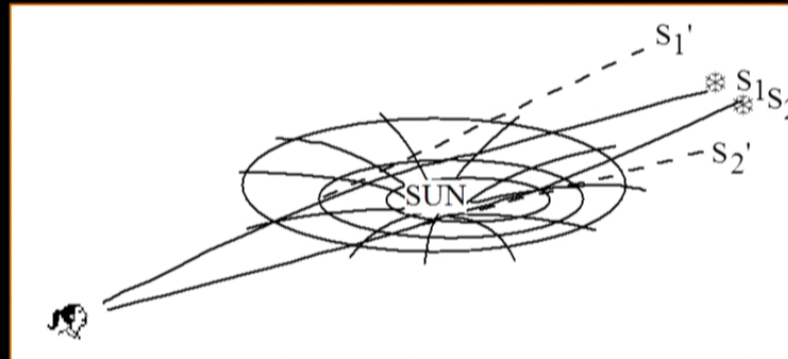
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Outline

- **The Hot Big Bang**
 - *Evidence for an Expanding Universe*
 - *Evidence for a Hot Big Bang*
 - *Evidence for Dark Matter and Dark Energy*
- **Contact With Fundamental Physics**
 - *Dark Matter*
 - *Why Dark Energy is Harder*
- **Outlook**

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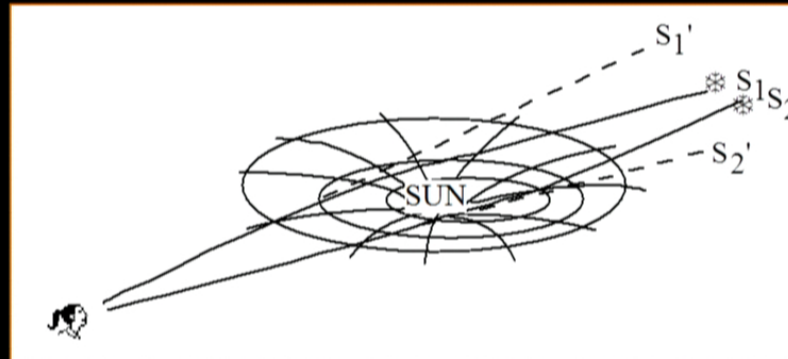
Gravity, Matter & Geometry



- According to Einstein gravity is really the response of space and time to the presence of matter.
 - The presence of energy curves space and time.
 - The curvature of space changes how objects move.

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Gravity, Matter & Geometry



- According to Einstein gravity is really the response of space and time to the presence of matter.
 - The presence of energy curves space and time.
 - The curvature of space changes how objects move.
- *Knowing how matter is distributed over large scales tells us the shape and evolution of the Universe.*

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Distribution of Visible Matter

Courtesy: Jason Ware

- Visible matter is found in space as stars, dust and gas.
- Most stars are found inside galaxies.
- Most galaxies are found inside clusters of galaxies.



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A 3D View

*Courtesy: Sloan Digital Sky Survey
WMAP*



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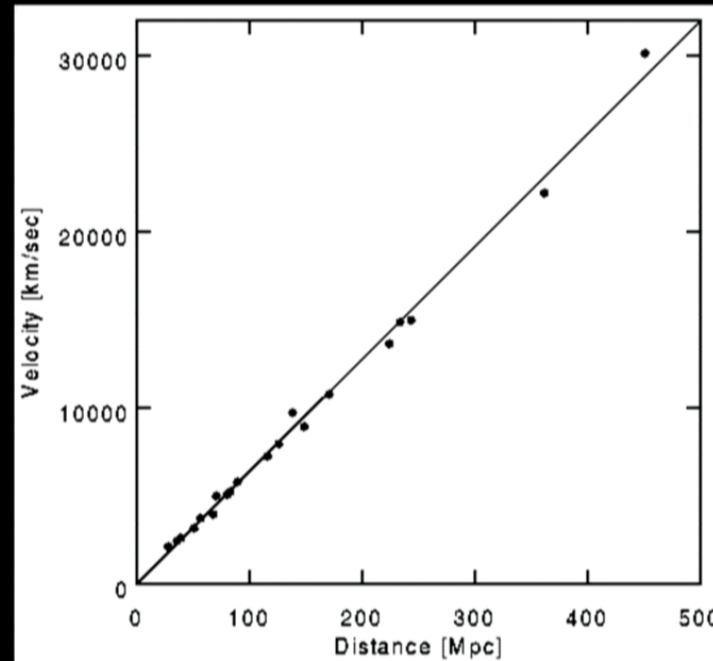
Evidence for an Expanding Universe

- The sky is dark
- The Hubble Law
- The homogeneity and isotropy of the universe
- The slower decay of more distant supernovae

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$$v = H_0 d$$

Courtesy: Ned Wright's Cosmology Page

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In all directions galaxies recede from us with a speed proportional to their distance from us:

Implies all observers see the same law.

As expected if all started at the same point simultaneously.

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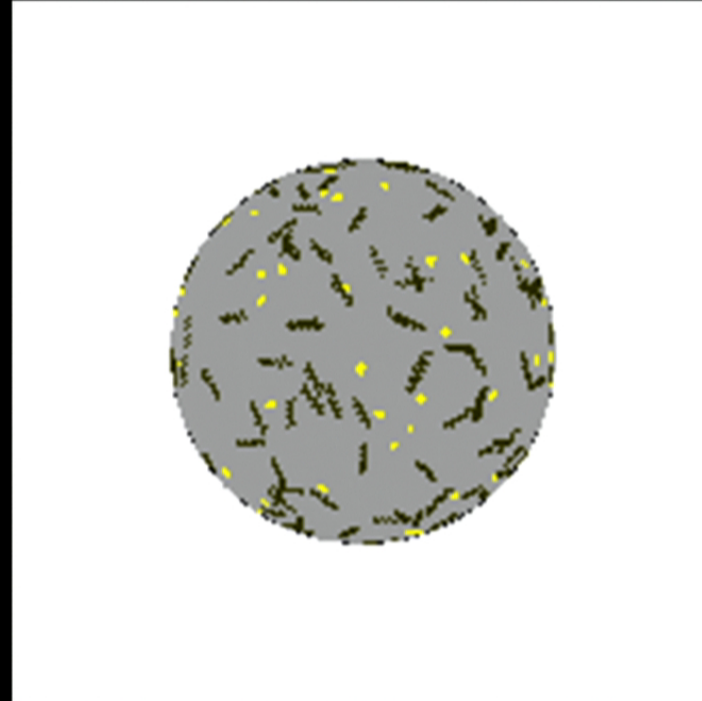
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The Hot Big Bang

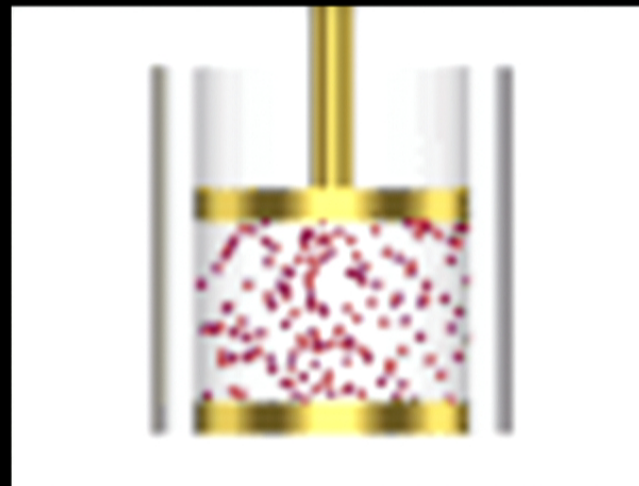
- Matter in an expanding container cools.
 - Extrapolating back in time suggests the Universe was once very small and very hot.
- The Hot Big Bang theory assumes the Universe was initially a small, hot soup of elementary particles.



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How Would We Know?

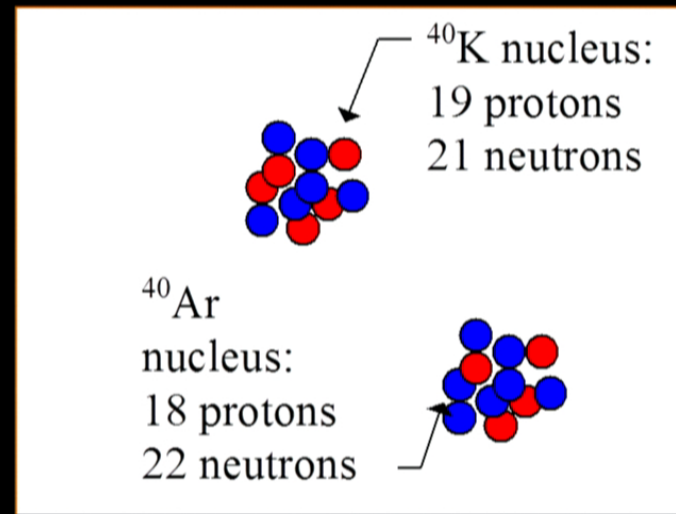
- The Universe being hot *means* that the particles within it are randomly moving with higher speeds.
- At high enough temperatures particles get knocked apart into their constituents.



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How Would We Know?

- Atoms can survive once the Universe cools below 1000 degrees.
 - Charged electrons and nuclei combine to form neutral atoms.
- Nuclei can survive below 10 billion degrees.
 - Protons and neutrons combine to form nuclei.



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Evidence for a Hot Big Bang

- Primordial element abundances
- The cosmic microwave background
- T_{CMB} vs distance

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Evidence for a Hot Big Bang

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When the universe cools to the point where nuclei can form (around 10^{10} K) then the relative abundances of the light elements can be calculated.

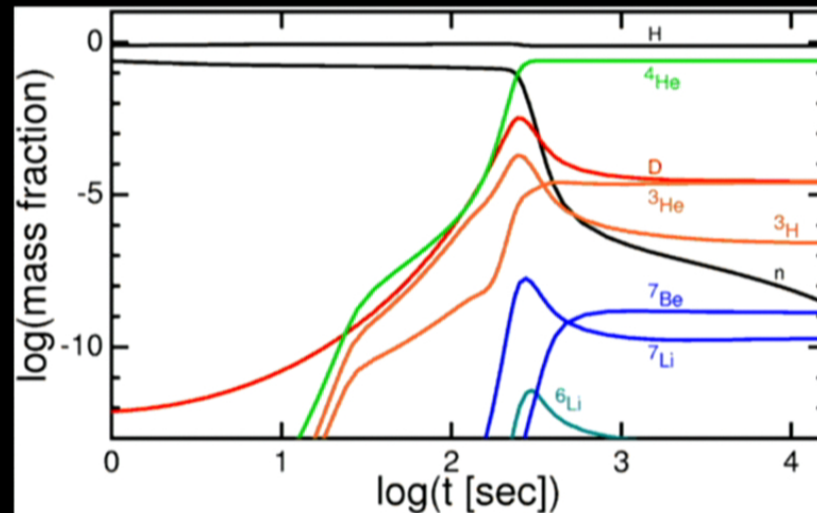
The predictions for the isotopes of H, He, Li and Be agree with the measured abundances.

Agreement is very sensitive to the total number of atoms present.

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Evidence for a Hot Big Bang

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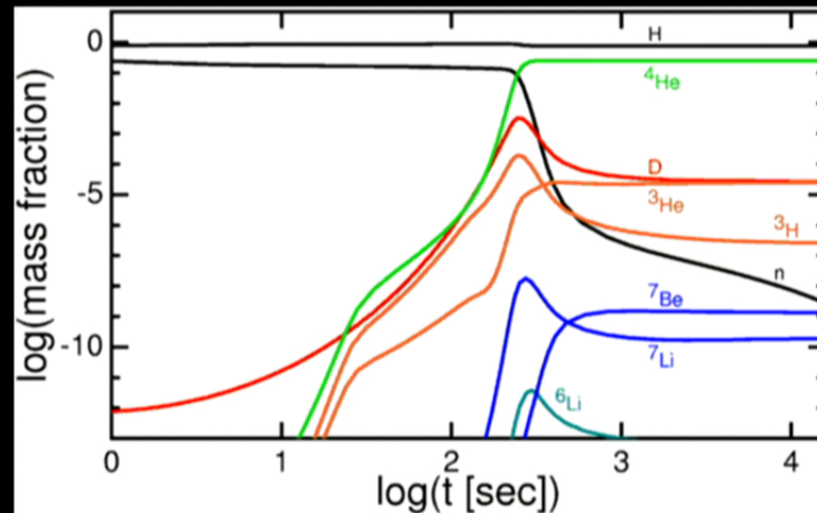
Burles, Nolette & Turner, 1999

Courtesy: Ned Wright's Cosmology Page

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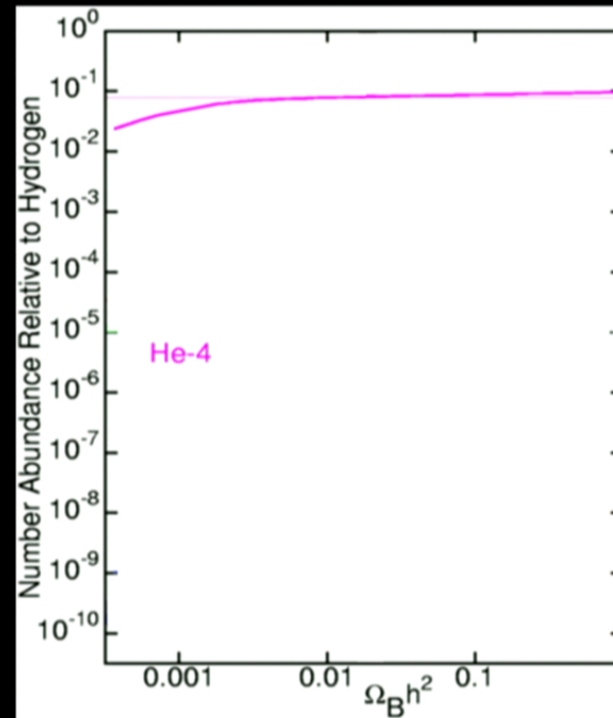
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Total Mass Density of Atoms

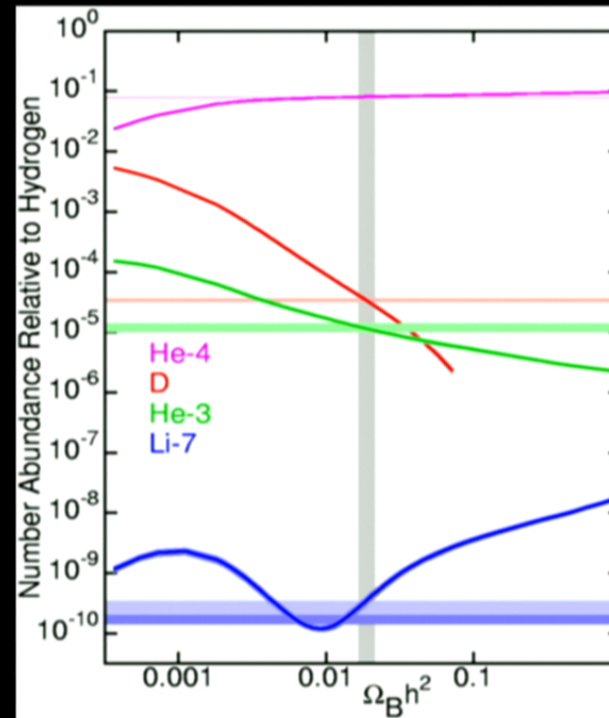
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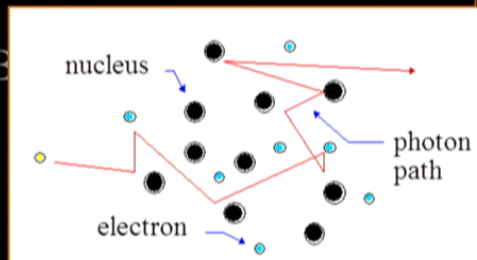
Burles, Nolette & Turner, 1999

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Courtesy: Ned Wright's Cosmology Page

Evidence for a Hot Big Bang

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When the universe cools enough for atoms to form (around 10^3 K) it becomes transparent to light.

Above 1000 degrees atoms break up into electrons and nuclei.

Unlike atoms, electrons and nuclei carry electric charge and so scatter light very efficiently.

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Evidence for a Hot Big Bang

- Primordial element abundances
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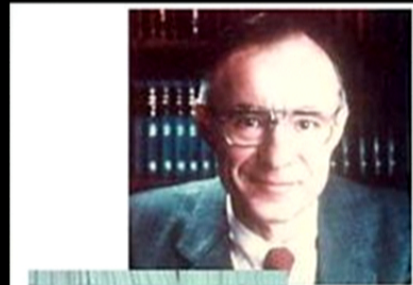
The light present at this time is still running around the universe.

This light is now seen as microwaves due to the intervening expansion of the universe.

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Evidence for a Hot Big Bang

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Arno Penzias



Robert Wilson

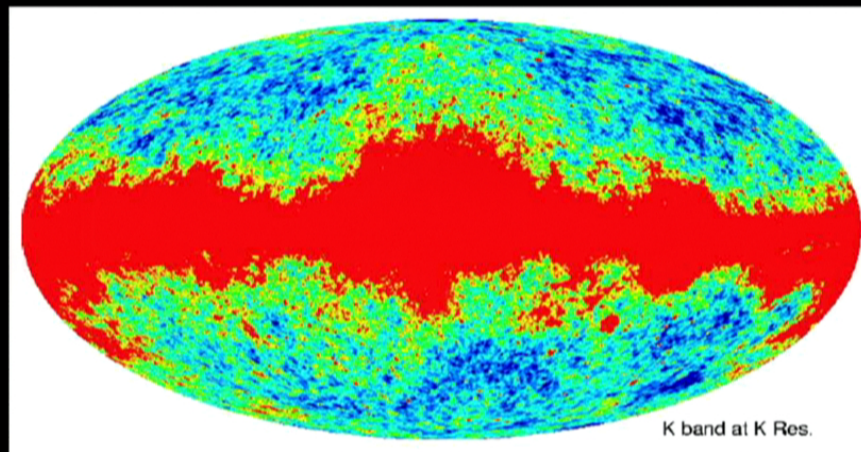


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Evidence for a Hot Big Bang

WMAP

- Primordial element abundances
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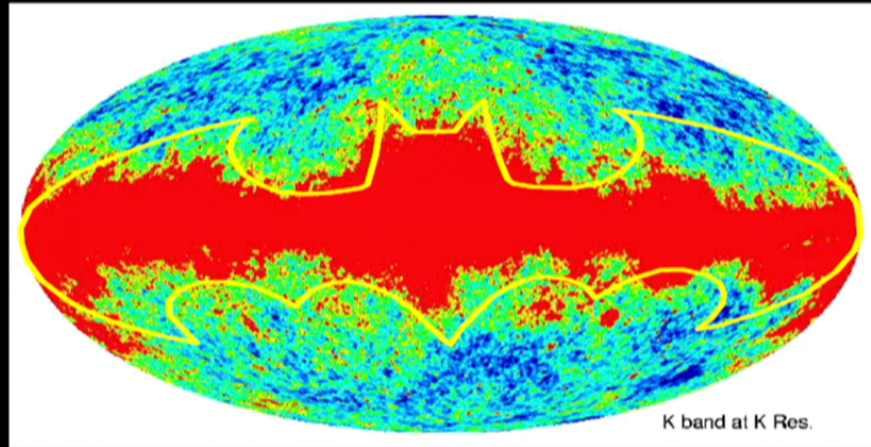
The temperature of the CMB has been measured as a function of direction.

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Evidence for a Hot Big Bang

Batfit courtesy of Stephane Coutu

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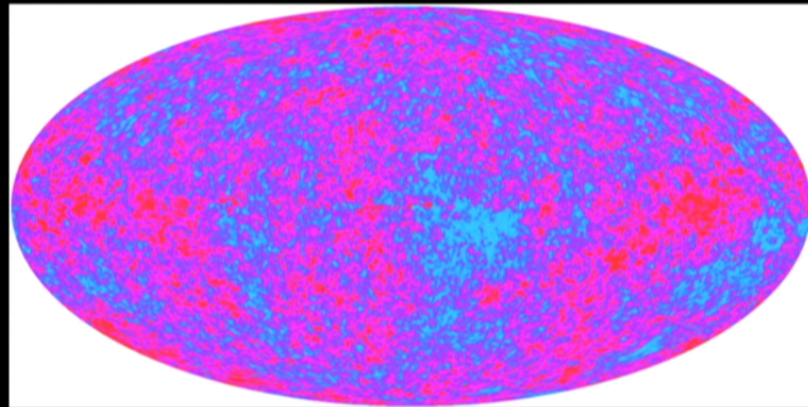
What is it telling us?

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Evidence for a Hot Big Bang

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CMB Temperature vs Direction



WMAP collaboration

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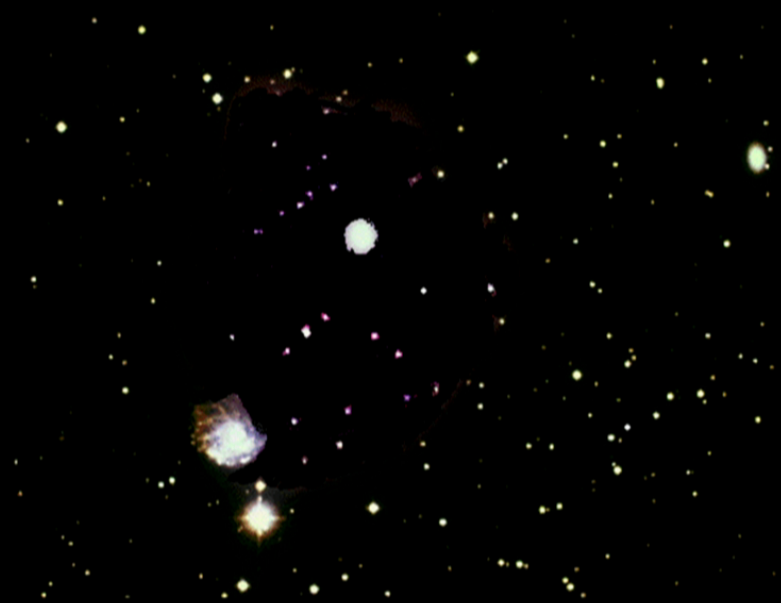
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Evidence for Dark Matter

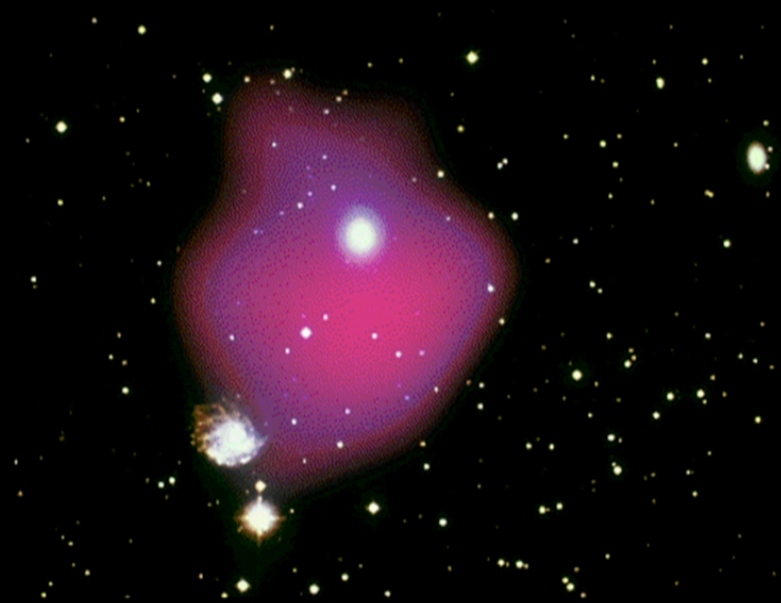
- Mass in galaxies
- *Mass in clusters of galaxies*
- Temperature fluctuations in the CMB
- Start of galaxy formation



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Evidence for Dark Matter

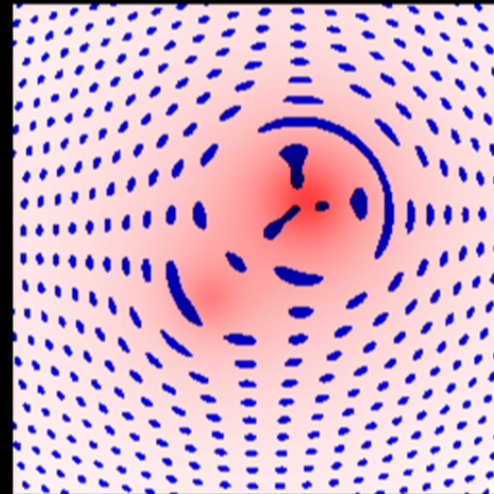
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Courtesy: Ned Wright's Cosmology Page

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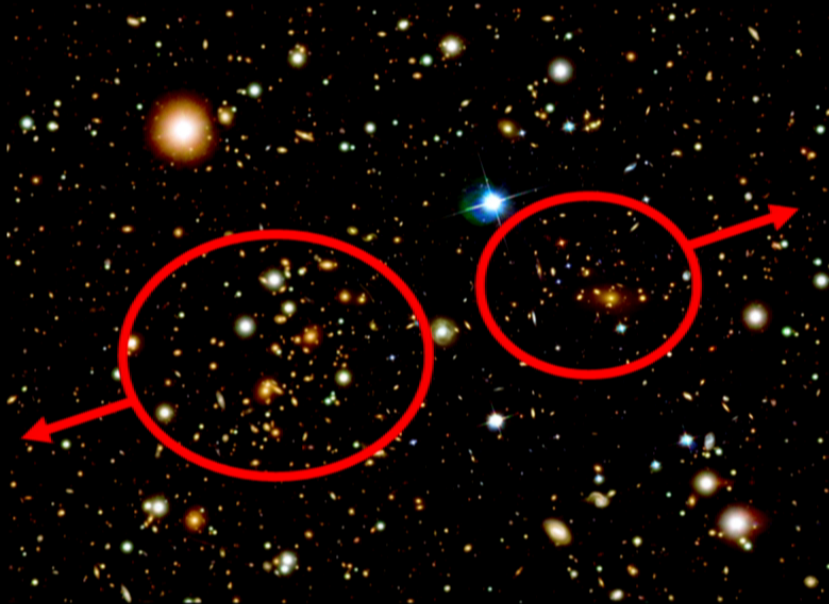
The Bullet Cluster: Separating Dark and Visible Matter

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Evidence for Dark Matter

Colliding galaxy clusters

- Mass in galaxies
- *Mass in clusters of galaxies*
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The Bullet Cluster: Separating Dark and Visible Matter

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Evidence for Dark Matter

- Mass in galaxies
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- Start of galaxy formation

Hot intra-cluster gas



The Bullet Cluster: Separating Dark and Visible Matter

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Evidence for Dark Matter

Mass measured by lensing

- Mass in galaxies
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The Bullet Cluster: Separating Dark and Visible Matter

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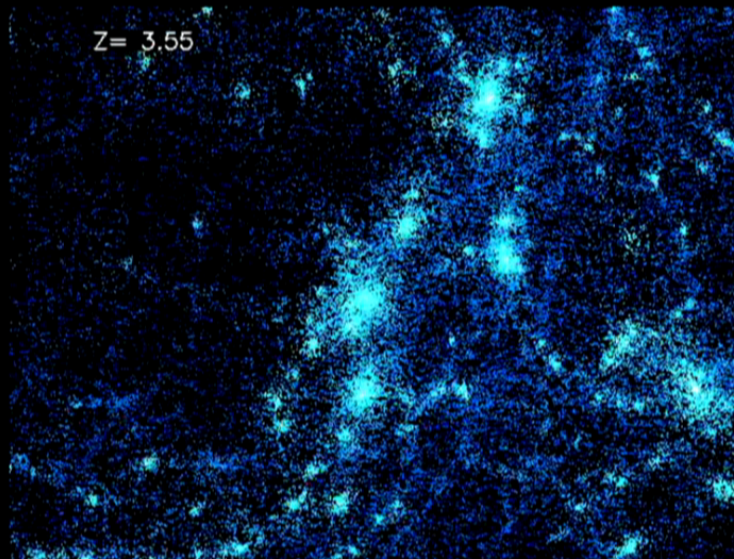


*The Bullet Cluster: Separating
Dark and Visible Matter*

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Evidence for Dark Matter

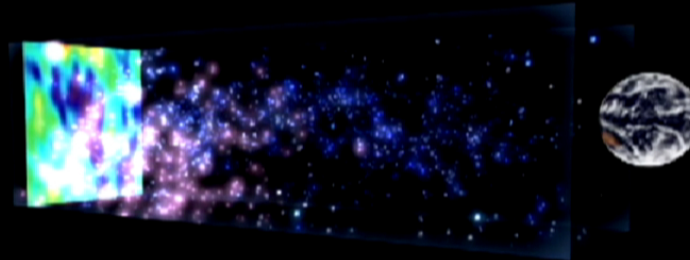
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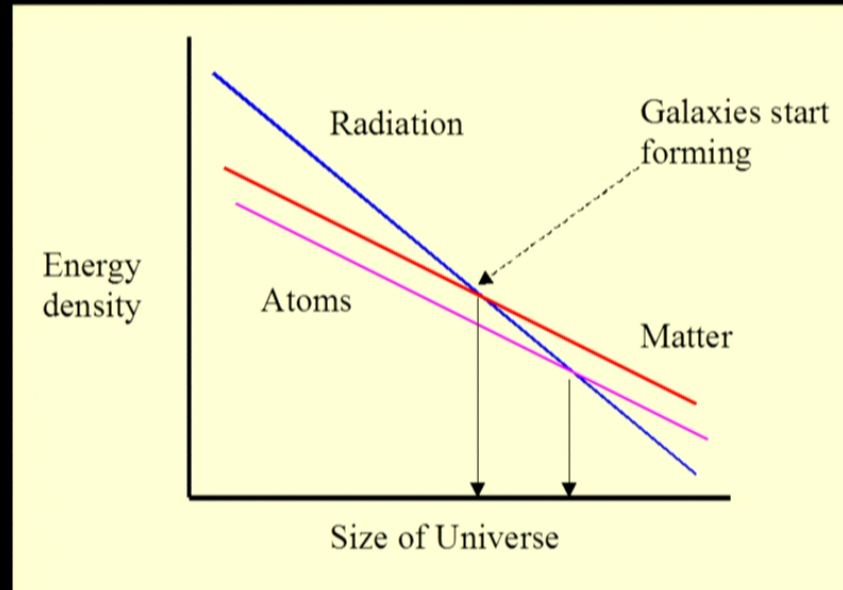
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Evidence for Dark Matter

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Evidence for Dark Energy

- *Brightness of very distant supernovae*
- Flatness of the universe as a whole

Very distant objects should not precisely follow Hubble's Law because gravitational attraction should decelerate the universal expansion.

This can be tested by looking for deviations from Hubble's Law for very distant supernovae.

Evidence for Dark Energy

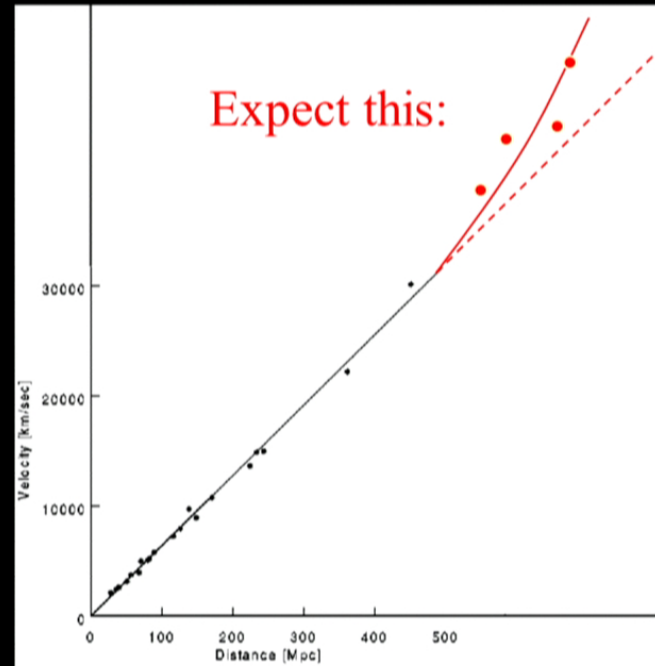
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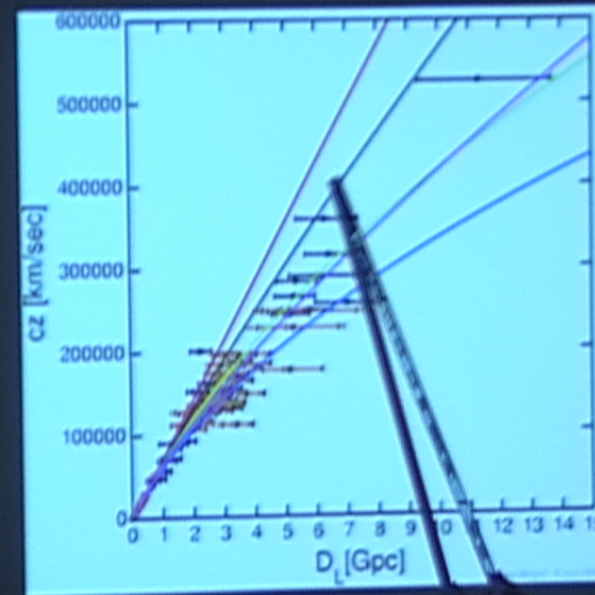
The universal expansion should be decelerating due to gravitational attraction

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Evidence for Dark Energy

Tonrey et.al., 2003

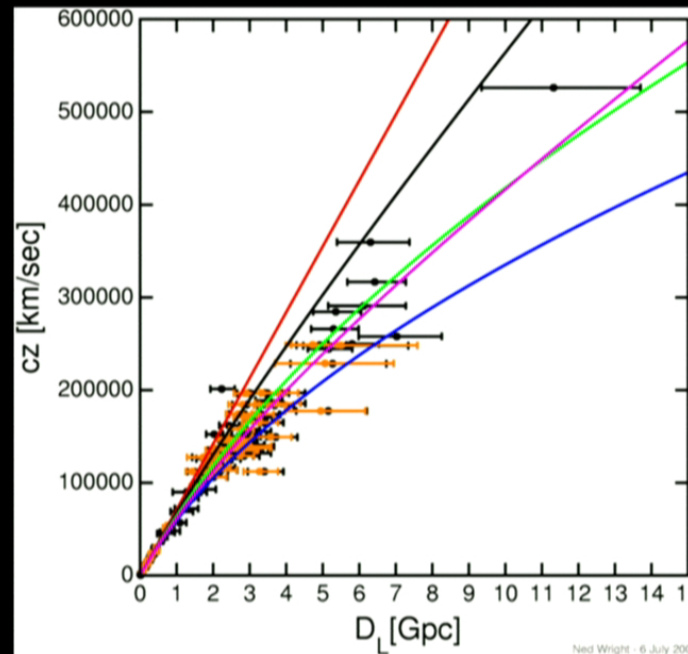
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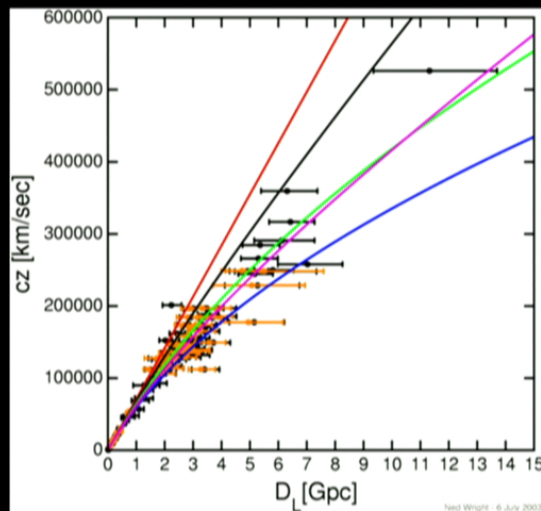


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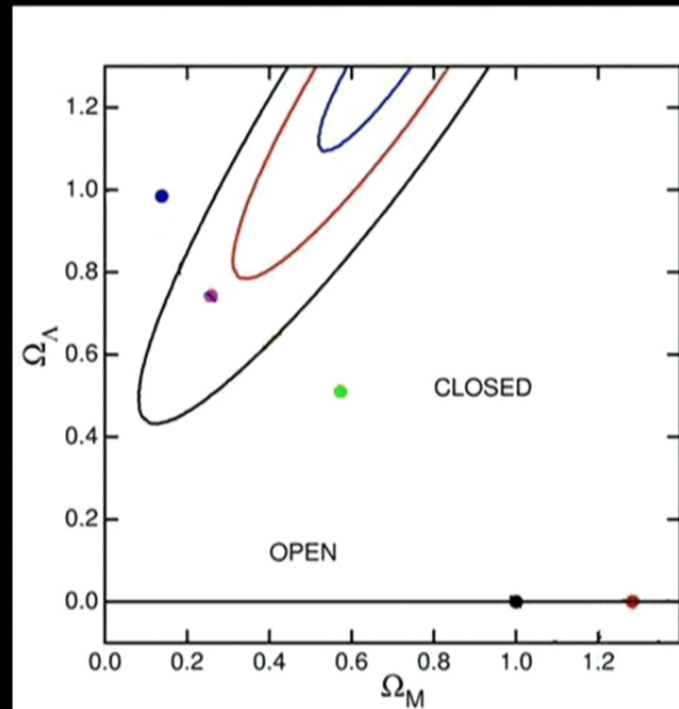
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Amount of Dark Energy



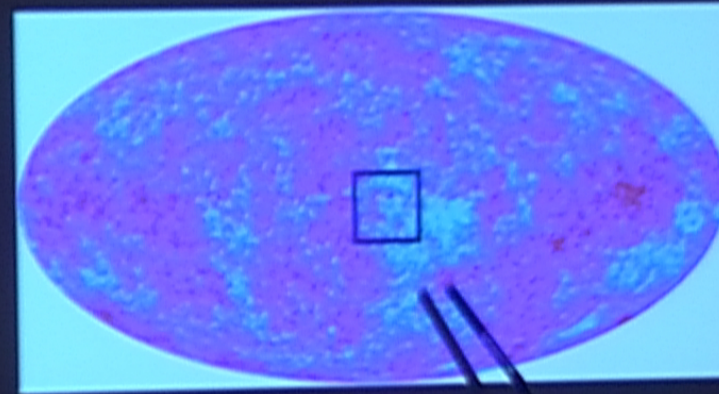
Amount of Dark Matter

Courtesy: Ned Wright's Cosmology Page

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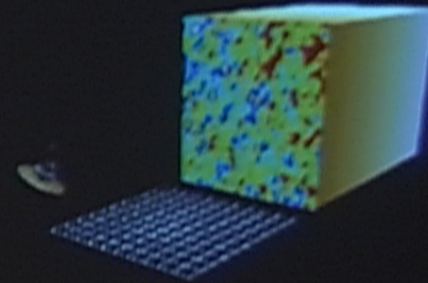
WMAP collaboration

These are due to sound waves in the primordial gas which emitted this light.

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Evidence for Dark Energy

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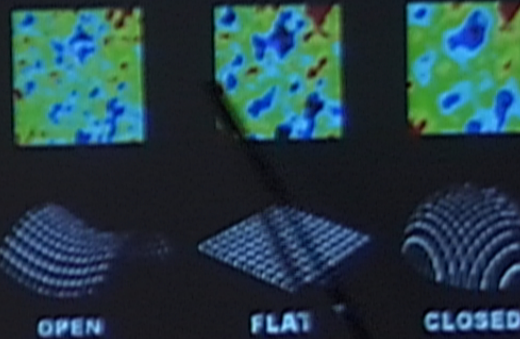
The CMB allows the inference of the properties of the later universe through which these photons pass.

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Evidence for Dark Energy

- Brightness of very distant supernovae
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GEOMETRY OF THE UNIVERSE

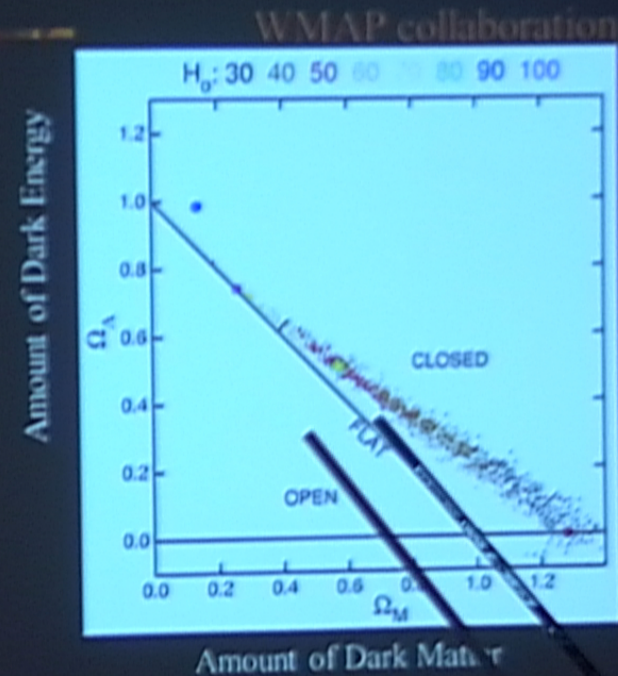


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Evidence for Dark Energy

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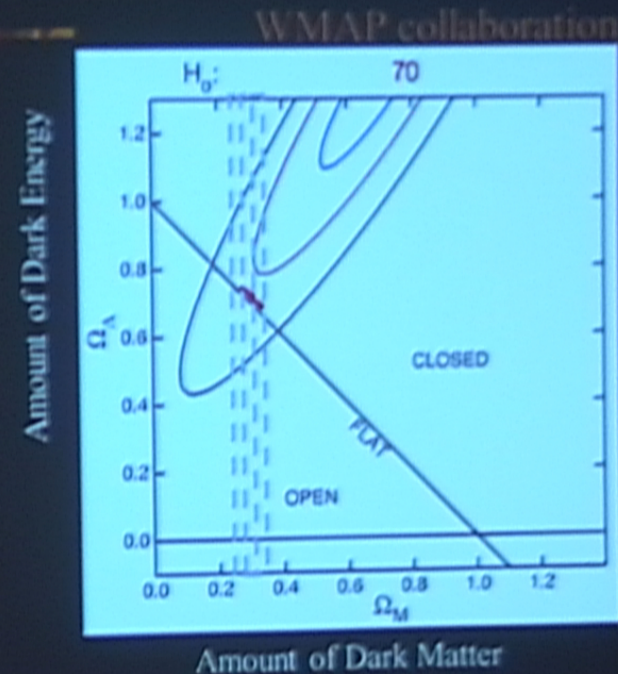


Measurement of CMB fluctuations correlates flatness with the universal expansion rate, H_0 .

Evidence for Dark Energy

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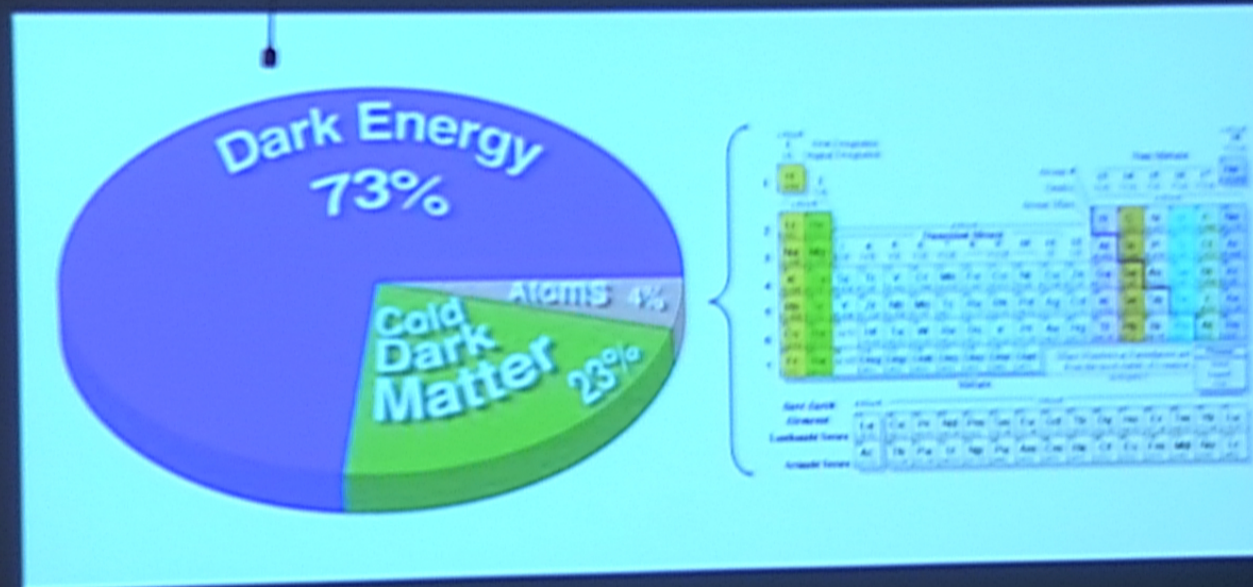
Customized: Neil Dirlikov's Cosmology Primer



Dark Energy required to explain CMB is consistent with the measured amount of Dark Matter

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Concordance Cosmology



From best fits to the 'Concordance Cosmology'

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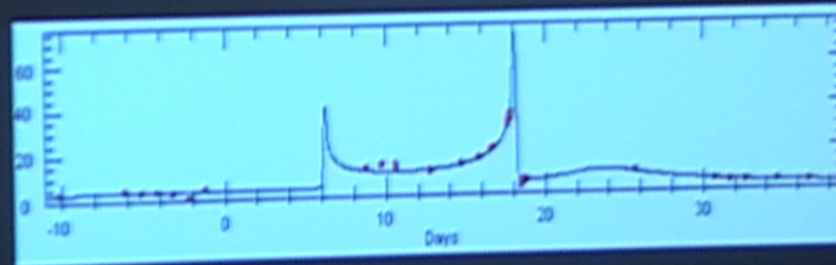
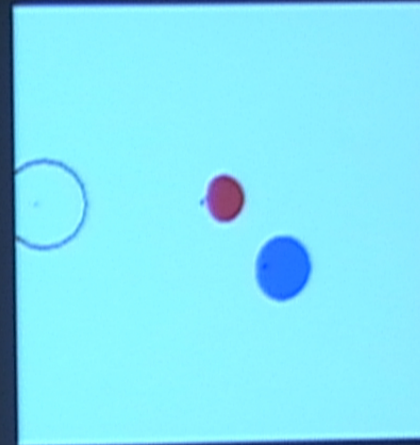
What is the Dark Matter?

- Ordinary atoms?
- Modifications to the Law of Gravity?
- New kind of particles?

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What is the Dark Matter?

- *Ordinary atoms?* ✗
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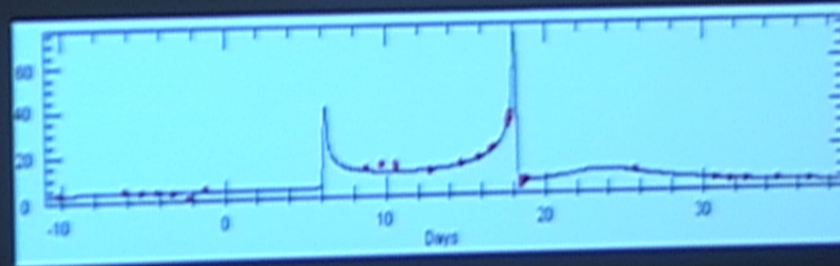
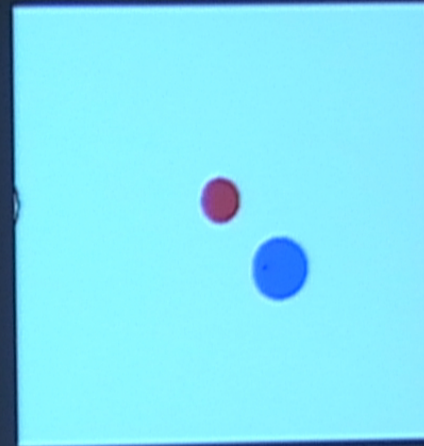


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What is the Dark Matter?

- Ordinary atoms?
- *Modifications to the Law of Gravity?*
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The devil is in the details:



No proposals yet succeed for galaxies and clusters and the CMB.

Very difficult to modify gravity at long distances without having problems with fundamental principles.

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What is the Dark Matter?

- Ordinary atoms?
- Modifications to the Law of Gravity?
- *New kind of particles?*



Weakly Interacting Massive Particles arise in most theories of microscopic physics.



Their residual cosmic abundance is naturally the right size to agree with the observed amount of Dark Matter.

Outlook

- Cosmological observations are now redundantly testing the Hot Big Bang model.
 - Observations support the ‘Concordance Cosmology’.

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Outlook

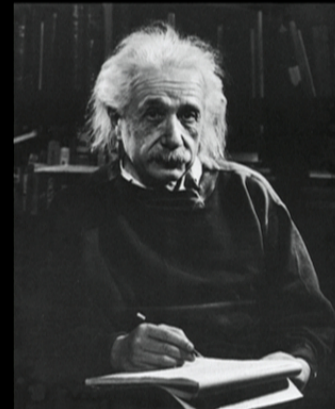
- Cosmological observations are now redundantly testing the Hot Big Bang model.
 - Observations support the ‘Concordance Cosmology’.
- The concordance involves several lines of independent evidence for both Dark Matter and Dark Energy.
 - Neither can be dark forms of ordinary atoms.
- Dark Matter may be new kinds of elementary particles, but Dark Energy is more difficult to embed into a fundamental theory (although a few proposals do exist).
 - If so we’ll know from a variety of observational tests.

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Outlook

“If I had only known, I’d have become a locksmith.”

Albert Einstein



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$\frac{V}{\ell}$ T $y = 2x$ (0.01) **DROPBOX**
 $T = 2\sqrt{\ell}$ $T = 2\pi\sqrt{\frac{\ell}{g}}$
 $2 = \frac{2\pi}{\sqrt{g}}$

Monster of the Milky Way
 Nov A

