

# The Cosmic Menu of Dark Matter and Dark Energy

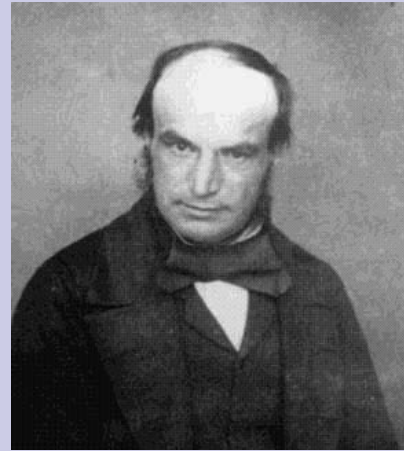
*By studying distant galaxies, supernovae, and cosmic radiation, astrophysicists have concluded that 96% of the mass-energy density in the universe is in a bizarre form unlike atomic matter or any other particles known to physicists. Why do we think it's there? Why do we care? What is it? How might we find out?*

**Edmund Bertschinger**

**MIT Department of Physics and  
Kavli Institute for Astrophysics and  
Space Research**

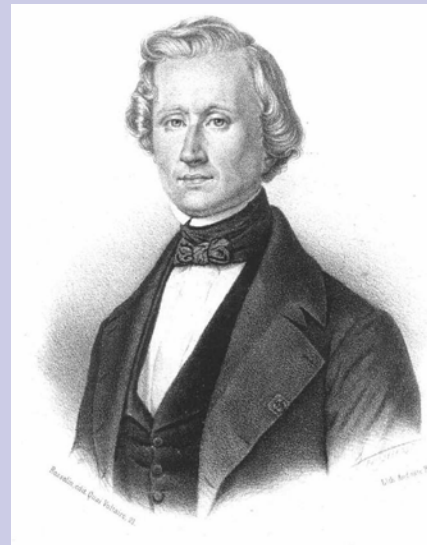
# Prologue

In 1845, only 7 planets were known.



John Crouch Adams,  
Cambridge

British and French astronomers sought to explain irregularities in the orbit of Uranus.

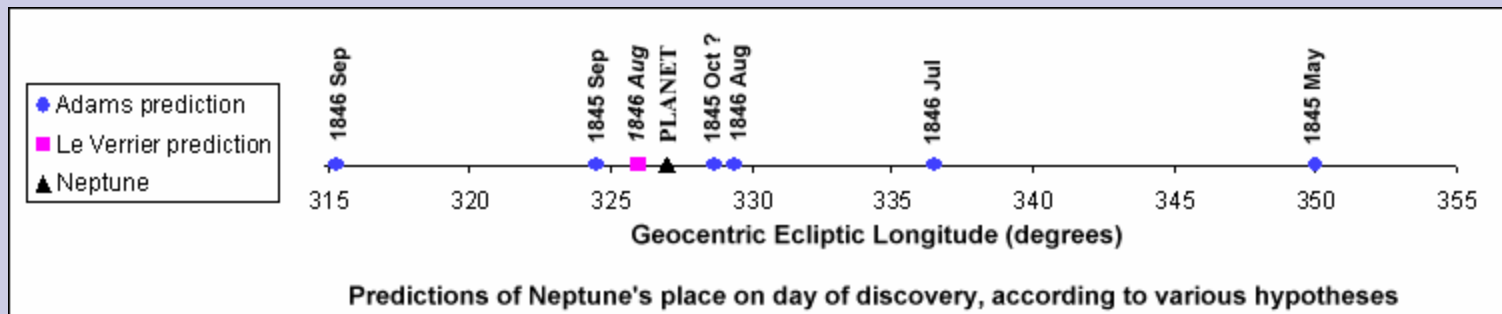


Urbain Le Verrier,  
Paris

At first, neither astronomer was listened to.

# Berlin: September 23, 1846

German astronomer Johann Galle receives a letter from Le Verrier. That night, he and his student find Neptune after only one hour of searching.



"The planet whose place you have computed *really exists.*"

# 50 years later, the end of physics? No! Radioactive decay!

1896: Henri Becquerel discovers radioactivity

1903: Becquerel, Pierre and Marie Curie win  
Nobel Prize for their studies of radioactivity

1906: Otto Hahn and Lise Meitner find  
something wrong in radioactive decay:

Radium E ( $\text{Bi}^{210}$ )  $\rightarrow$  Radium F ( $\text{Po}^{210}$ ) + electron,  
electron does not have definite energy!

*Is energy not conserved?*

Offener Brief an die Gruppe der Radioaktiven bei der  
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut  
der Eidg. Technischen Hochschule  
Zürich

Zürich, 4. Dez. 1930  
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich mildvollst  
ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich  
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie  
des kontinuierlichen beta-Spektrums auf einen verweifelten Ausweg  
verfallen um den "Wechselgats" (1) der Statistik und dem Energiegats  
zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale  
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,  
welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und  
sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie  
nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen  
müsste von derselben Grössenordnung wie die Elektronenmasse sein und  
jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche  
beta-Spektrum wäre dann verständlich unter der Annahme, dass beim  
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert  
wird, derart, dass die Summe der Energien von Neutron und Elektron  
konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die  
Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint  
mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer  
dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein  
magnetischer Dipol von einem gewissen Moment  $\mu$  ist. Die Experimente  
verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons  
nicht grösser sein kann, als die eines gamma-Strahls und darf dann  
 $\mu$  wohl nicht grösser sein als  $e \cdot (10^{-13} \text{ cm})$ .

Ich traue mich vorläufig aber nicht, etwas über diese Idee  
zu publizieren und wende mich erst vertrauensvoll an Euch, liebe  
Radioaktive, mit der Frage, wie es um den experimentellen Nachweis  
eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa  
10mal grösseres Durchdringungsvermögen besitzen würde, wie ein  
gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein  
wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn  
sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt,  
gemusst und der Ernst der Situation beim kontinuierliche beta-Spektrum  
wird durch einen Ausspruch meines verehrten Vorgängers im Amt,  
Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat:  
"O, daran soll man am besten gar nicht denken, sowie an die neuen  
Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.-  
Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht  
persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht  
vom 6. zum 7. Dez. in Zürich stattfindenden Balles hier unabkömmlich  
bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer  
untertänigster Diener

ges. W. Pauli

## How to explain the beta decay spectrum?

December 4, 1930

Dear Radioactive Ladies and  
Gentlemen,

... I have hit upon a desperate remedy  
to save ... the law of conservation of  
energy. Namely, the possibility that in  
the nuclei there could exist electrically  
neutral particles, which I will call  
neutrons, that have spin 1/2 and obey  
the exclusion principle and that further  
differ from light quanta in that they do  
not travel with the velocity of light.

...

I admit that my remedy may seem  
almost improbable because one  
probably would have seen those  
neutrons, if they exist, for a long time.  
But nothing ventured, nothing gained.

W. Pauli

Another puzzle from the golden age of physics:  
What holds galaxies together?

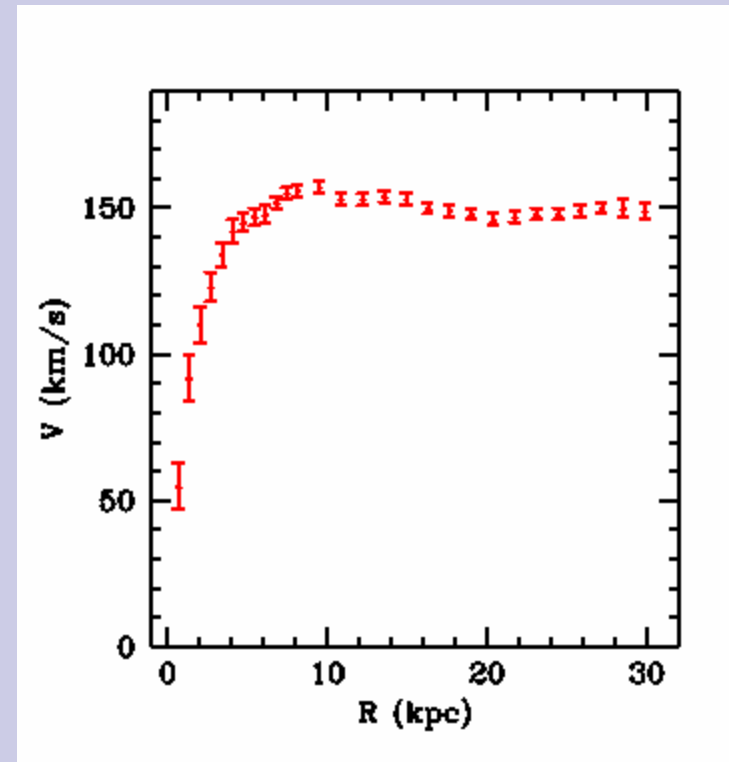
1933: Astronomer Fritz Zwicky discovers that galaxies clustered in the constellation Coma move far too quickly to be held together by gravity, unless they weigh 400 times more than their stars.



# 40 years later, Vera Rubin and galaxy rotation curves

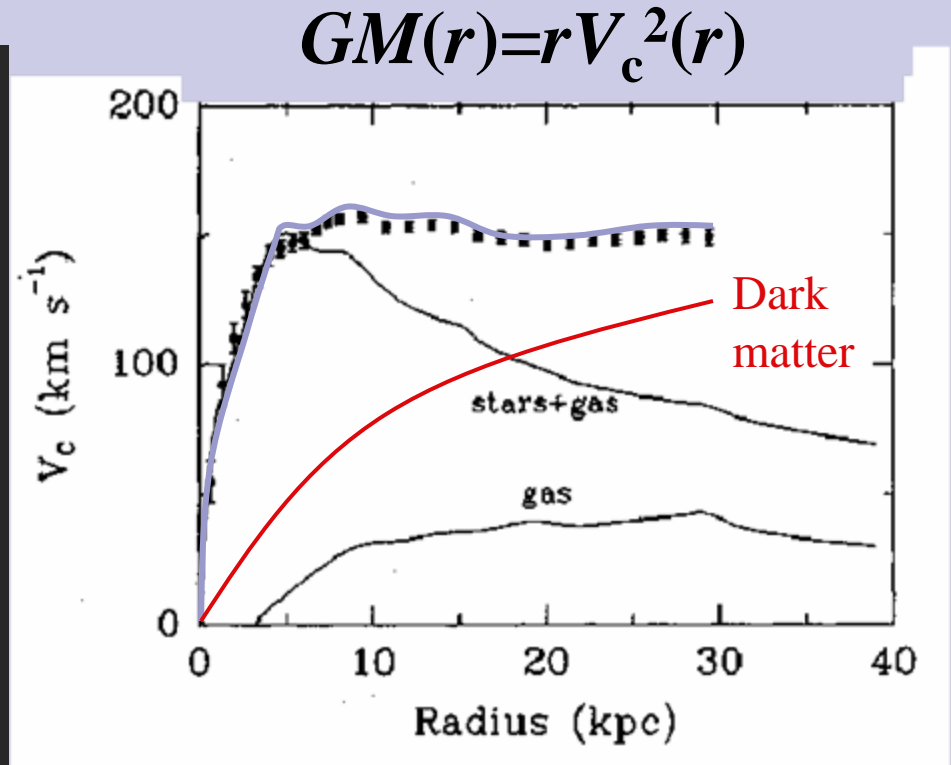
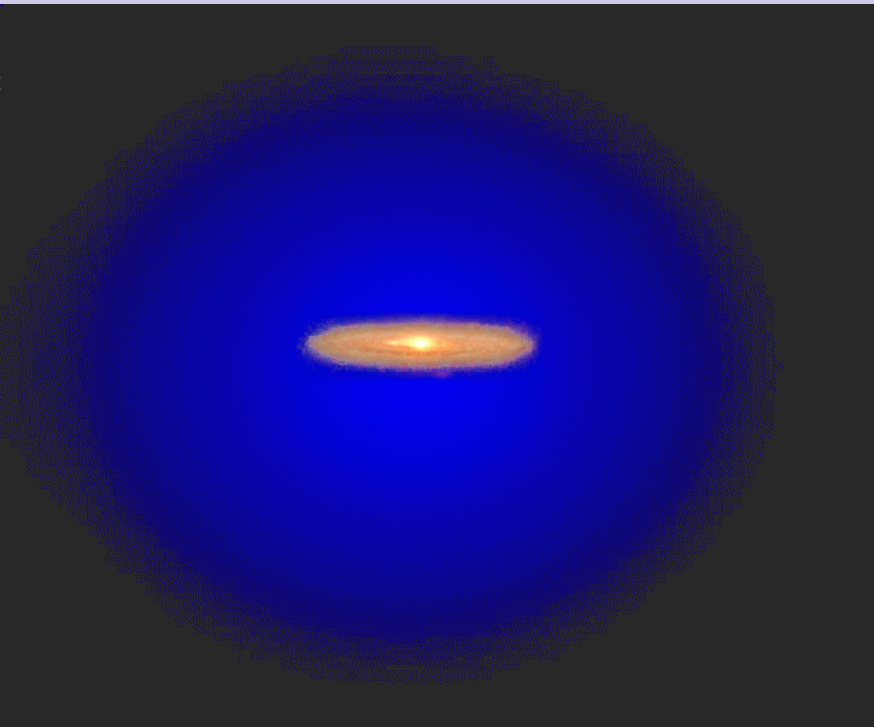


Measuring spectra of galaxies to infer velocity from Doppler shifts (c. 1970)



Stars and gas rotate with speed  $V$  around the center of NGC 3198  
(Image from Begeman 1989)

# Another desperate remedy: dark matter

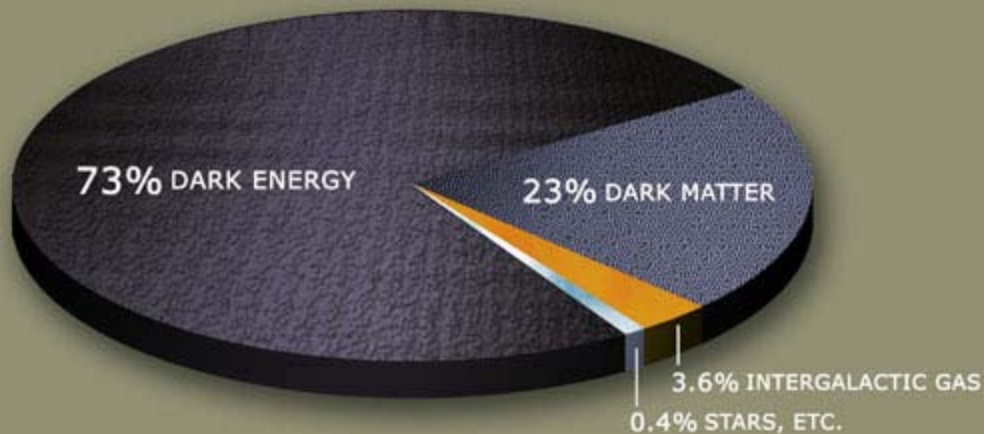


*Credits:*

*Left: J. Kormendy (NGC 4216).  
Right: K. Begeman (NGC 3198) and  
K. Freeman*

Although diffuse, dark matter is crucial for galaxy formation

# A strange menu:

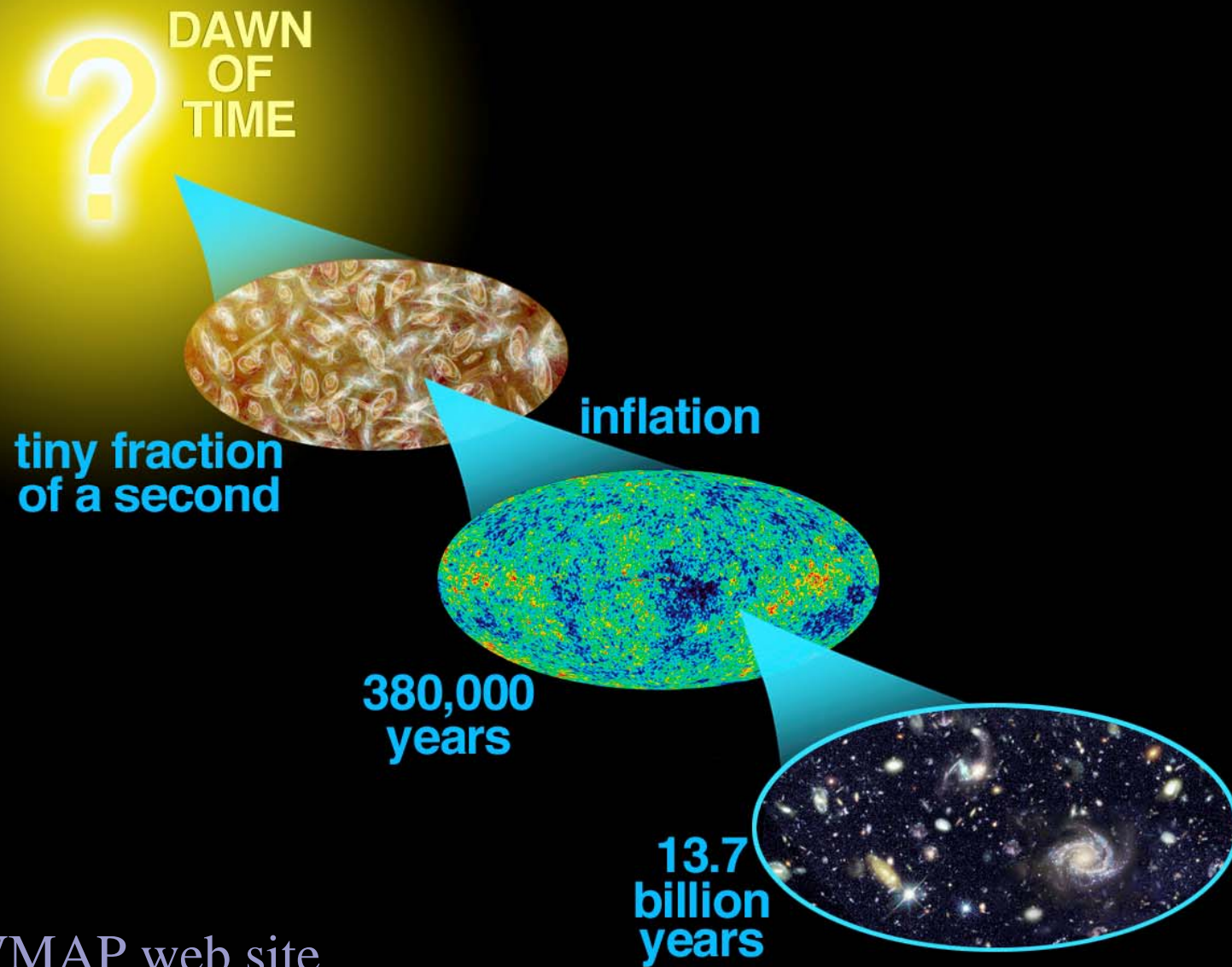


Photons: 0.03%  
Neutrinos: 0.3%  
Atoms: 4%  
Dark Matter: 23%  
Dark Energy: 73%

Credit: NASA/GSFC

# Observations of the Early Universe: Fossil Relics

- *Galaxies*
- *Cosmic Microwave Background Radiation*
- *Atoms, Dark Matter and Dark Energy*



From the WMAP web site



# The Most Distant Galaxies Observed with Hubble

# Cosmic Microwave Background Radiation

Discovery 1965

Penzias & Wilson

AT&T Bell Labs

1978 Nobel Prize

2003: Wilkinson

Microwave

Anisotropy

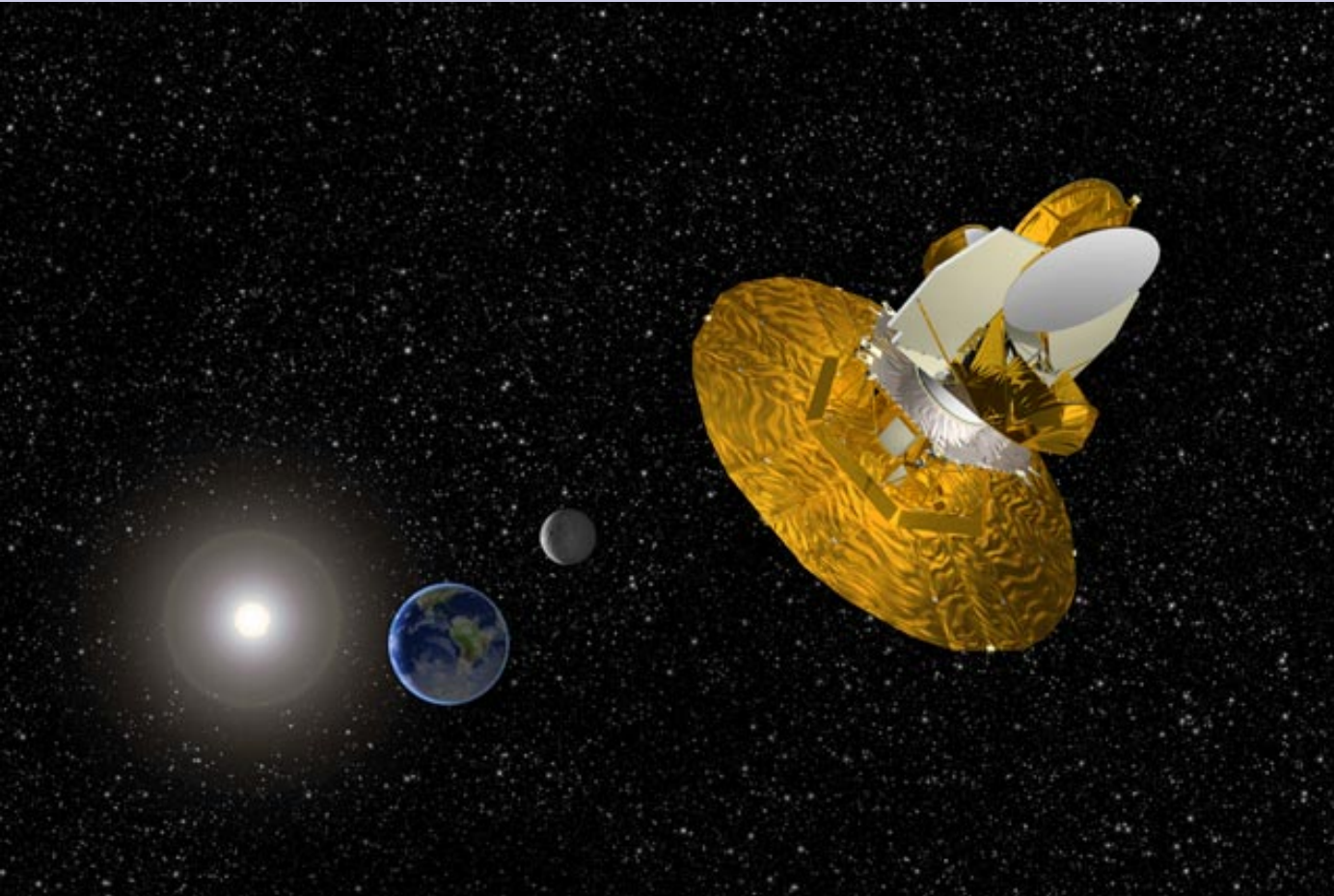
Probe (WMAP)

2006: Mather and

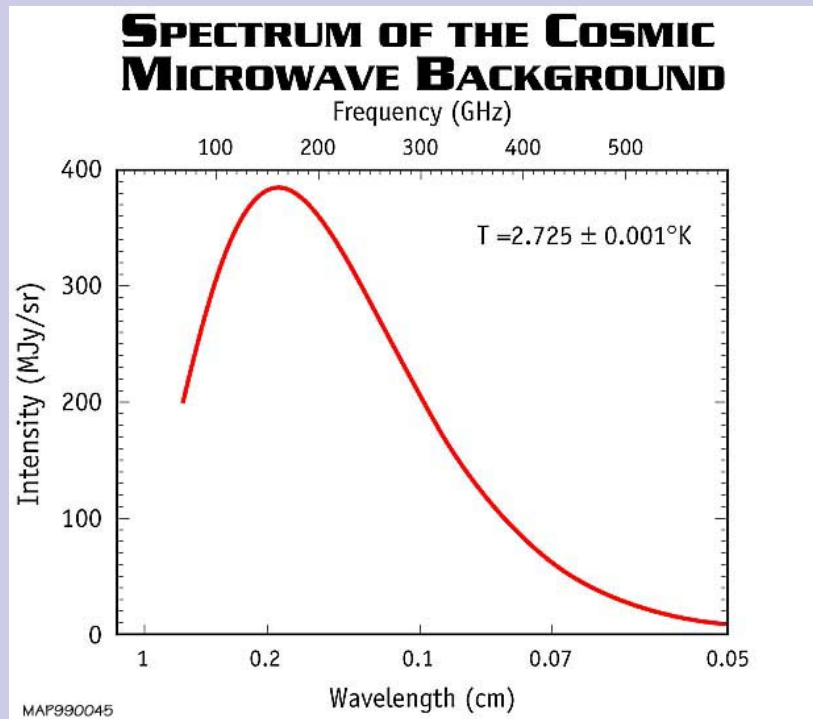
Smoot Nobel Prize

(blackbody and

anisotropy)

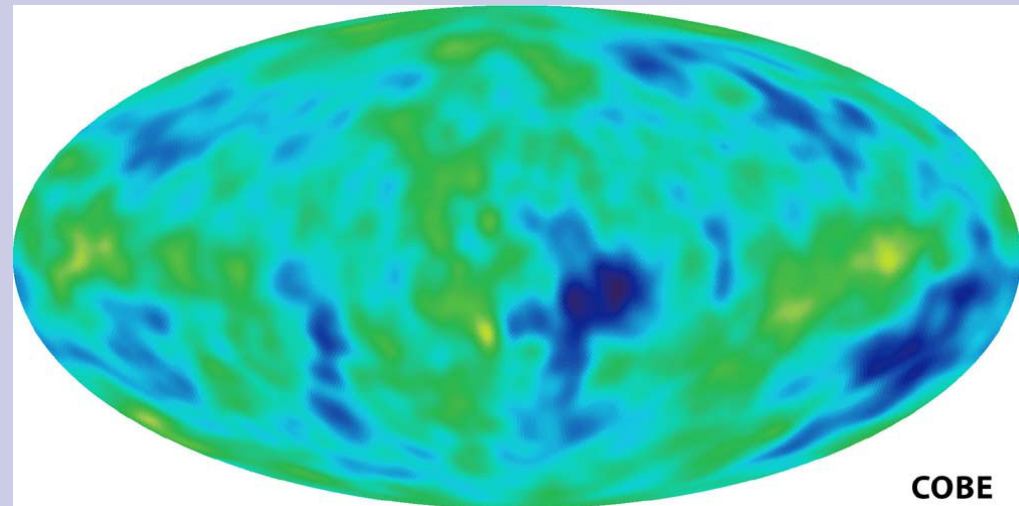


# 2006 Nobel Prize in Physics: Frequency- and spatial-dependence of cosmic microwaves from the Big Bang



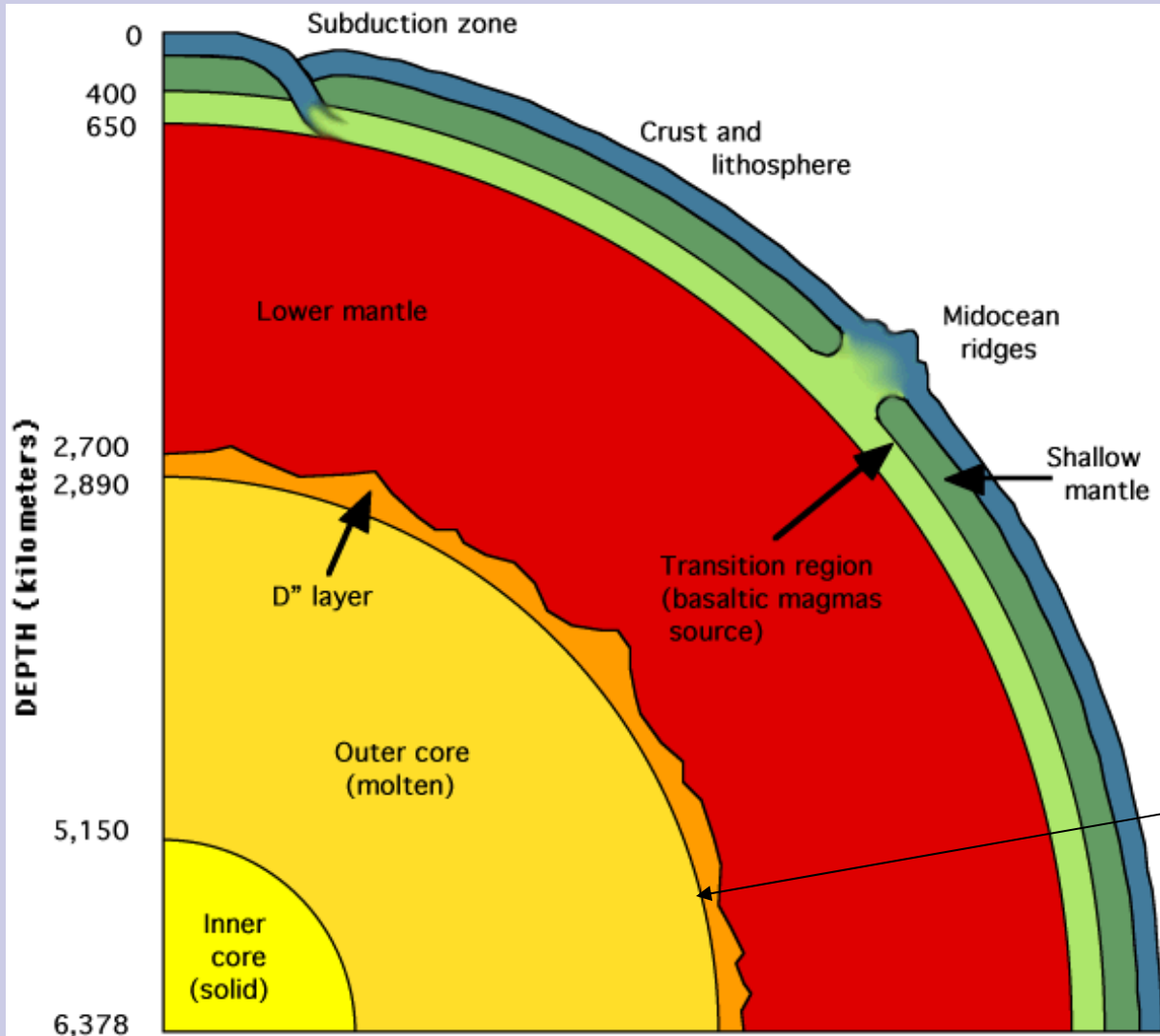
John Mather, P.I.

Microwave (1mm) map  
of the whole sky



George Smoot, P.I.

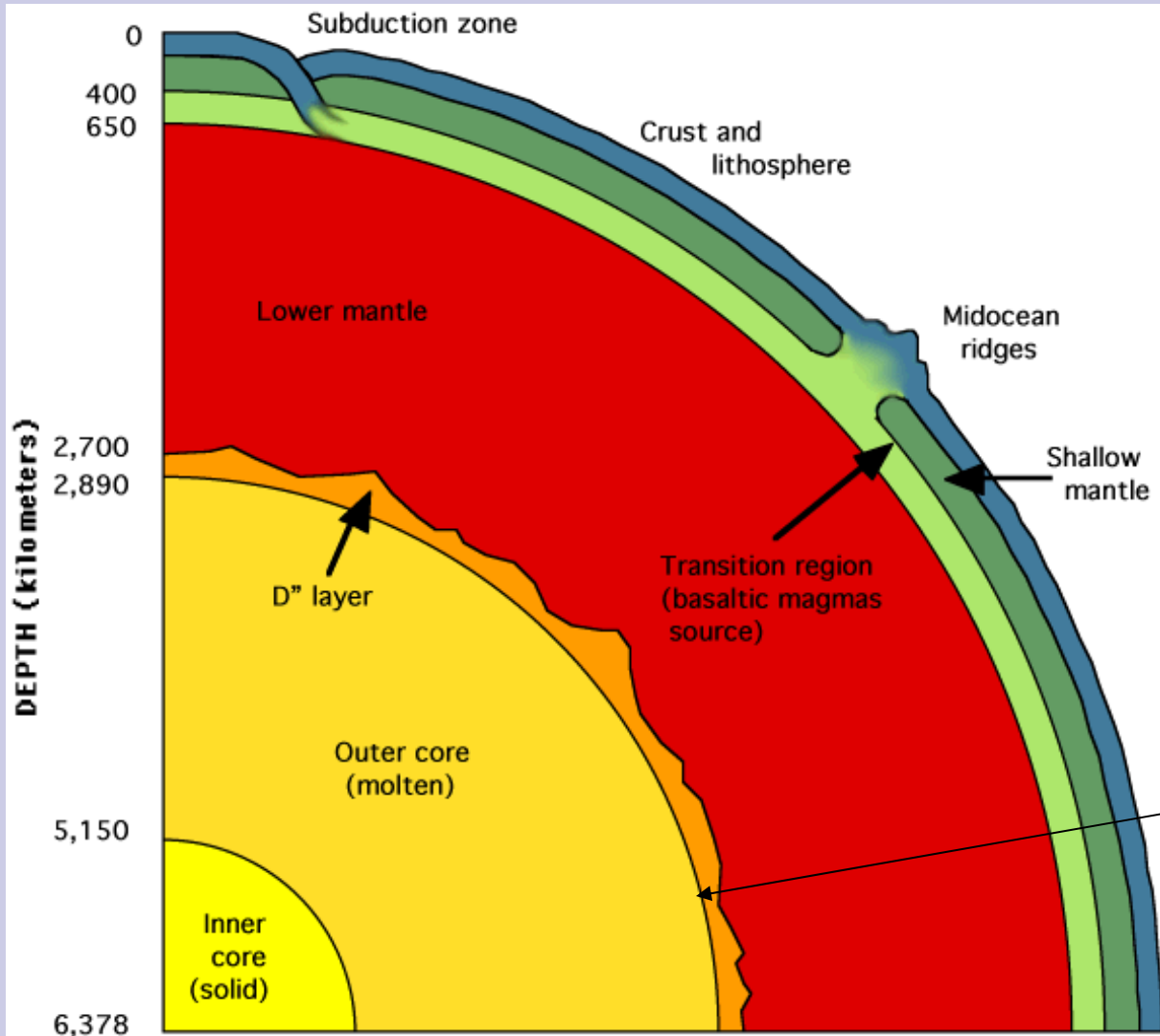
# Geography: Terrestrial Analogies



How do we know so much about the interior of the earth?

The CMB

# Geography: Terrestrial Analogies

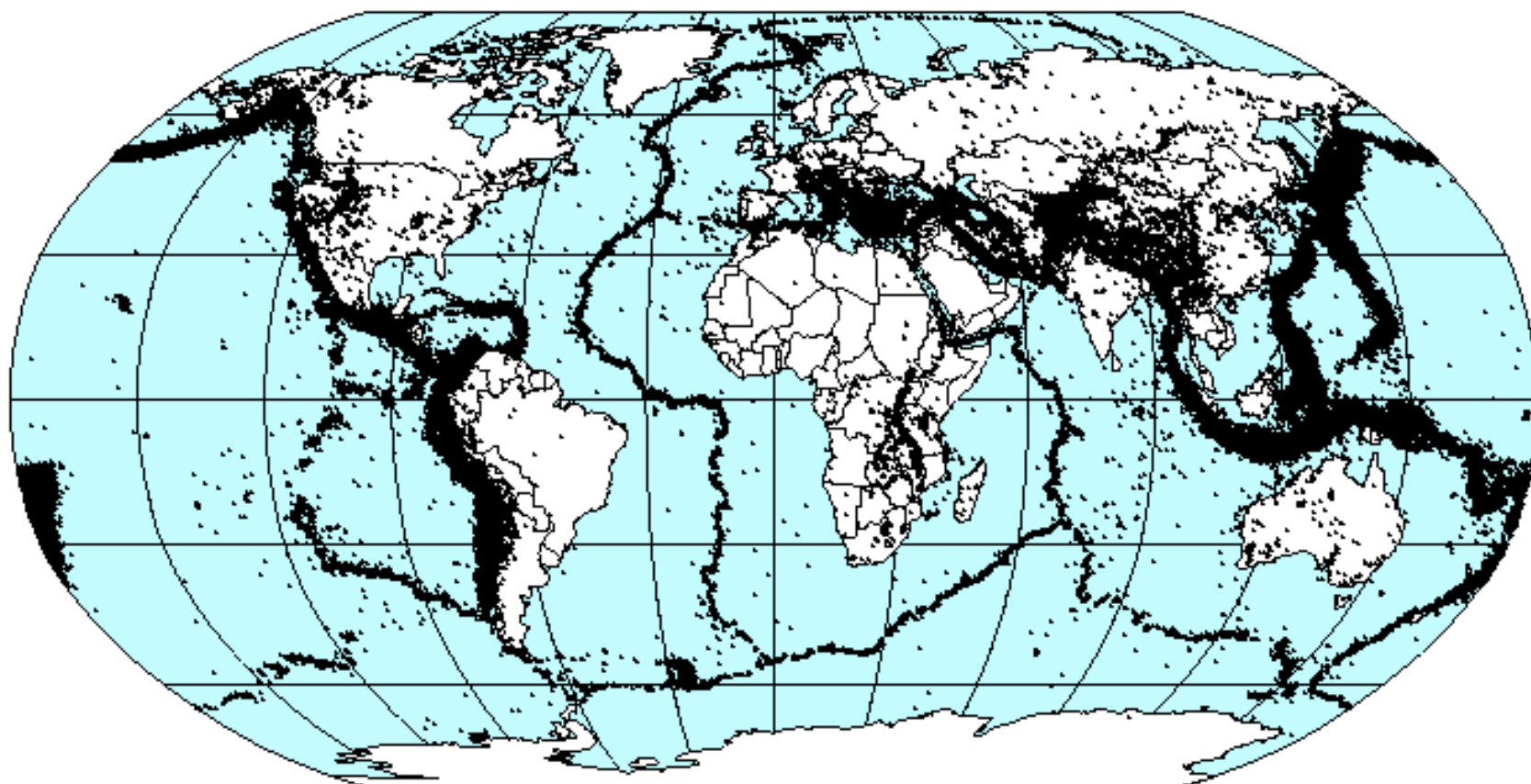


How do we know so much about the interior of the earth?

Core-Mantle Boundary

# Preliminary Determination of Epicenters

## 200,855 Events, 1963 - 1998



Paul D. Lowman, Jr.<sup>1</sup>  
Brian C. Montgomery<sup>2</sup>

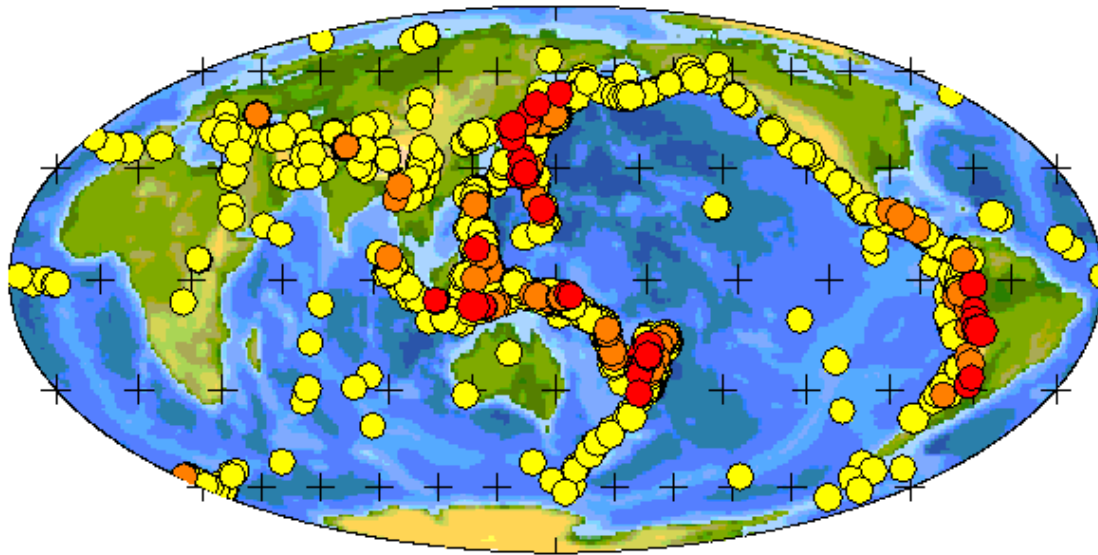
1) NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA  
2) USUHS, NASA GSFC, Greenbelt, MD 20771 USA

Data Source:  
Seismicity Catalogs  
Volume 2 Global and Regional, 2150 B. C. - 1996 A. D.  
The National Geophysical Data Center and  
The National Earthquake Information Center

Map prepared in Robinson Projection  
with magnitudes greater than 3.5.  
August 12, 1998

# Seismic Hotspots

01/01/1966 - 12/31/1996 M > 6.5



CNSS Earthquake Catalog

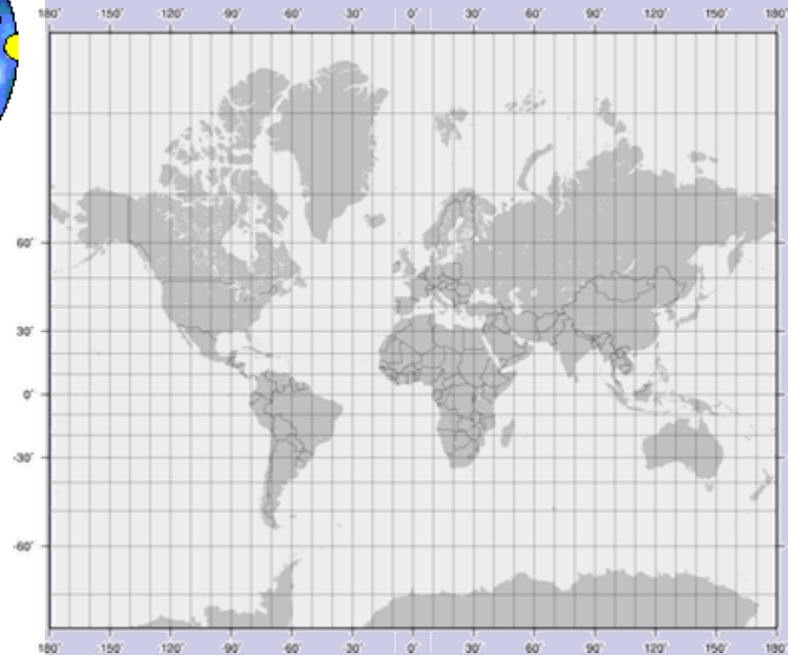


Magnitude (size)

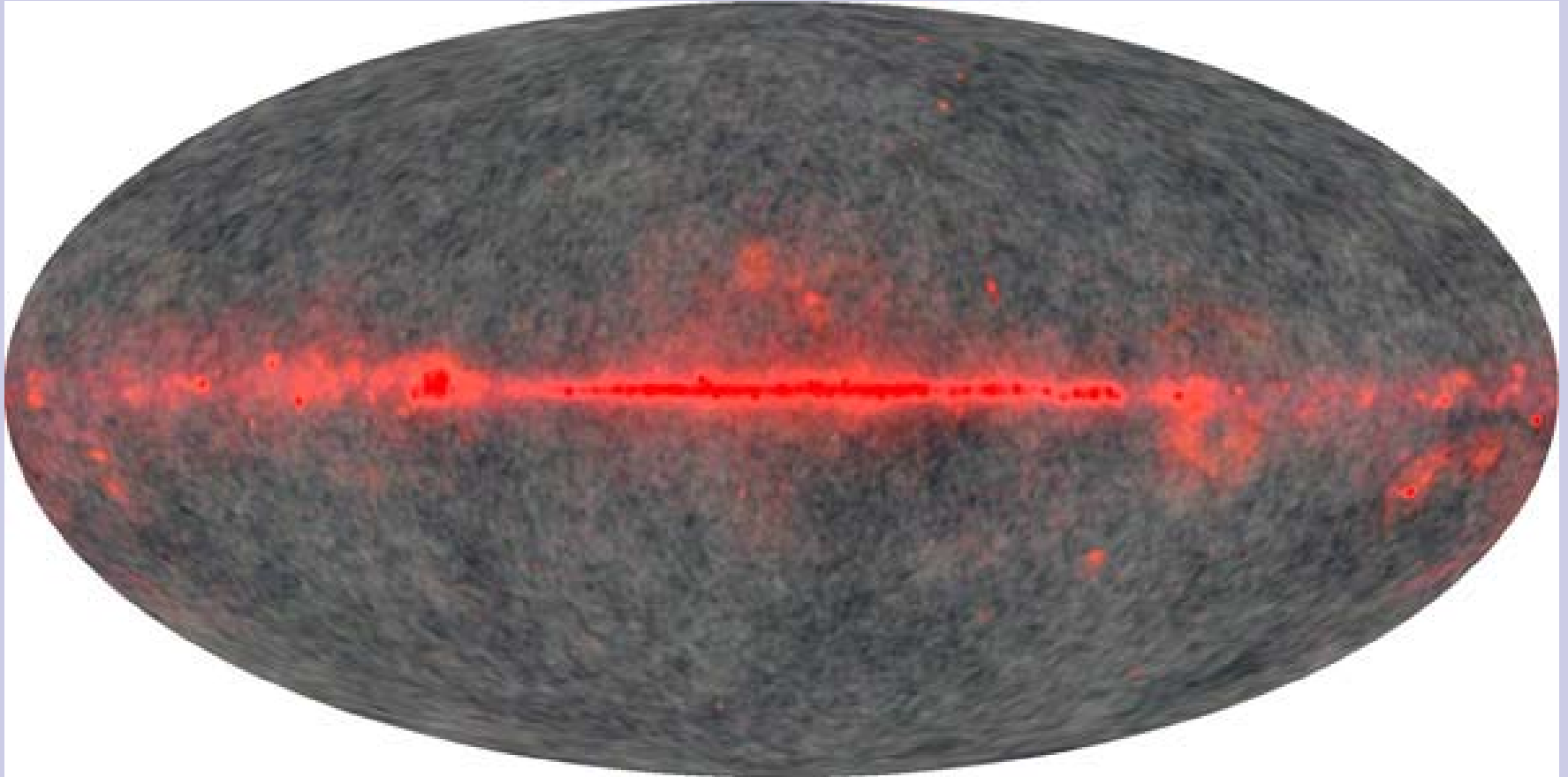


Depth in km (color)

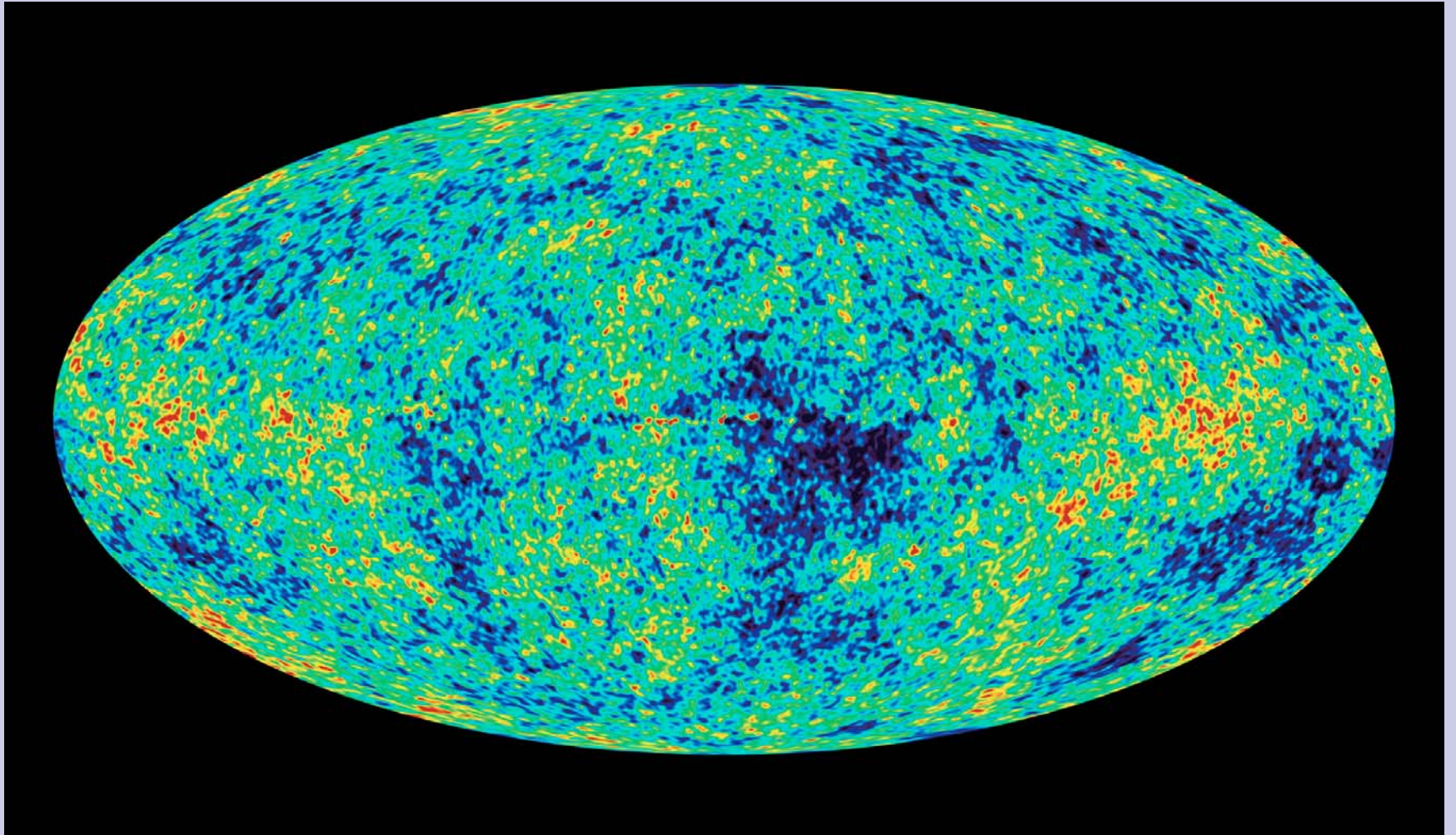
Note map projection of sphere onto flat surface



# Looking out at the celestial sphere: The Microwave universe (3-7mm)



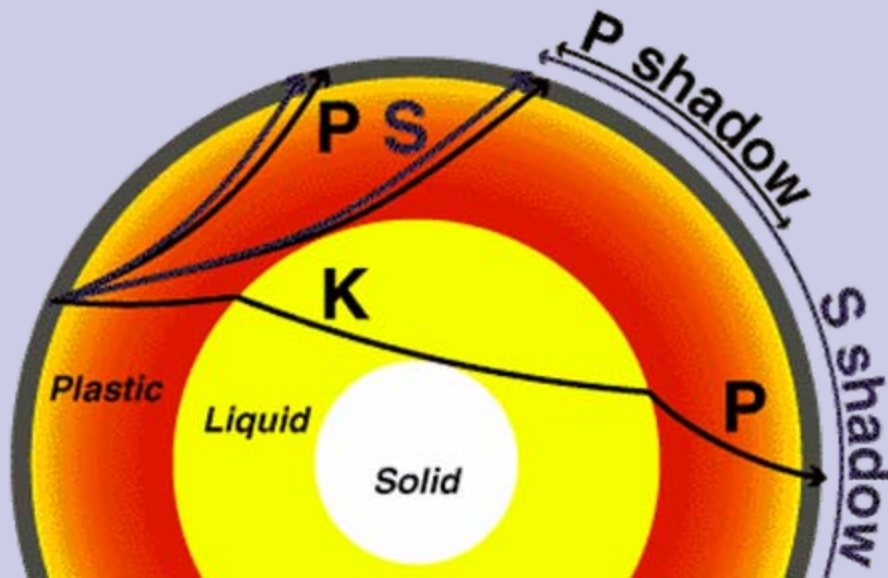
# Looking out at the celestial sphere: Cosmic Hotspots (and cold spots)



The pattern of spots reveals the structure and composition of the world.

The timing of seismic waves, or polarization of photons, add valuable information.

# Seismology: Using waves to probe structure and composition of Earth



*J. Louie, U. Nevada Reno*

P waves: longitudinal, acoustic (Primary, Pressure)

S waves: transverse, shear (Secondary, Shear)

Seismic waves revealed the liquid core in 1906 (Oldham).

# Dark Matter and Dark Energy

- **Dark Matter:** Invisible stuff that gravity draws into galaxies. Crucial element of galaxy formation.
- **Dark Energy:** Invisible stuff that gravity does not draw into galaxies. Instead, this substance accelerates the recent expansion of the Universe.
- *To date the sole evidence for these substances comes from astrophysics. Despite their similar names, they probably are completely unrelated.*

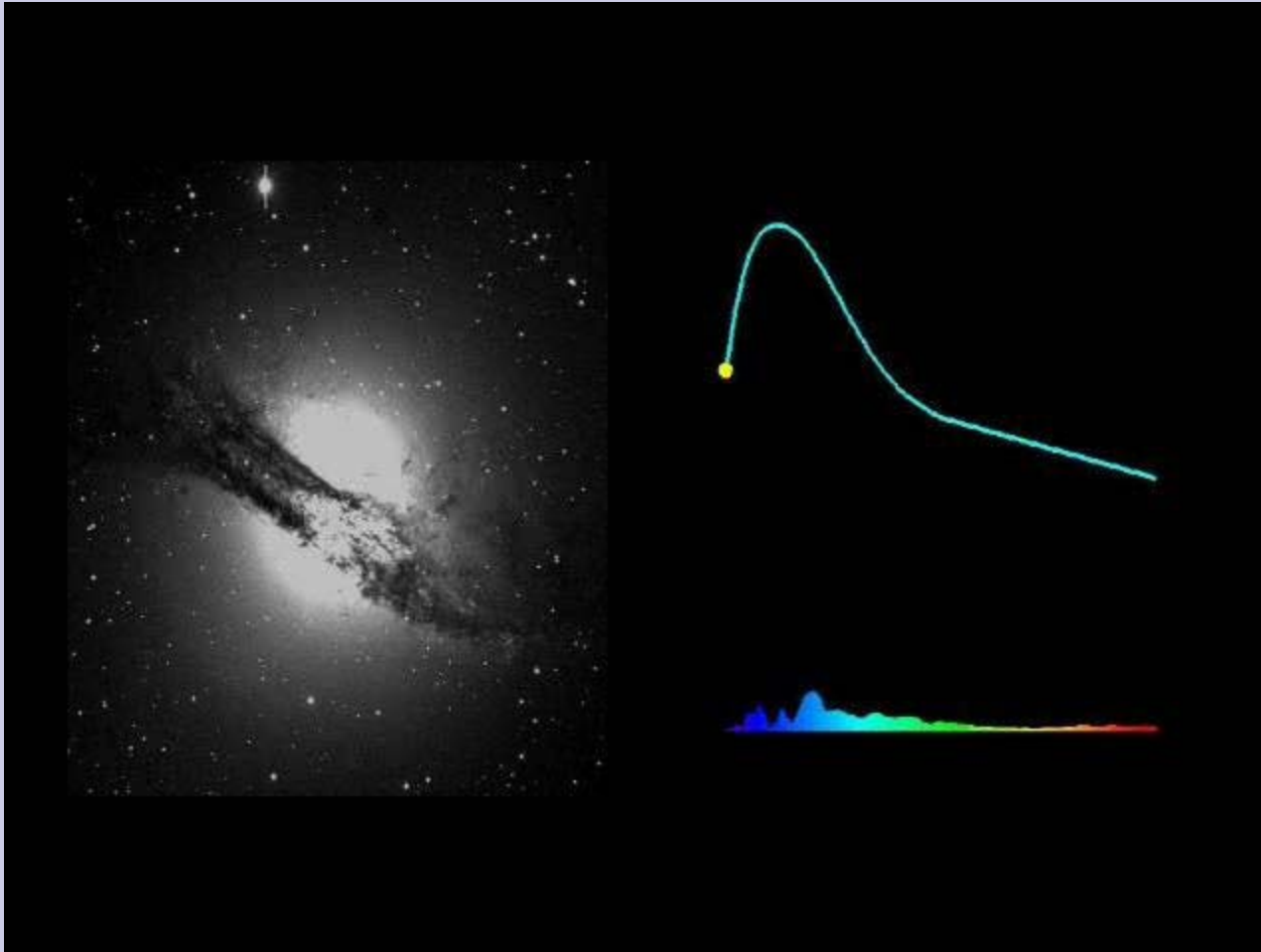
# What is the Dark Matter?

- Elementary particles with low thermal speed, otherwise could not seed galaxy formation
- Not atomic matter (primordial nucleosynthesis) or neutrinos (too light, too hot)
- **Consensus view:** Cold, very weakly interacting particles
  - A new heavy spin-1/2 particle ("neutralino")?
    - Large Hadron Collider, 2009?
  - A new ultralight spin-0 field ("axion")?
  - Searches are underway!
- Working out predictions of dark matter for cosmology is one of my research areas

# Dark Matter and Dark Energy

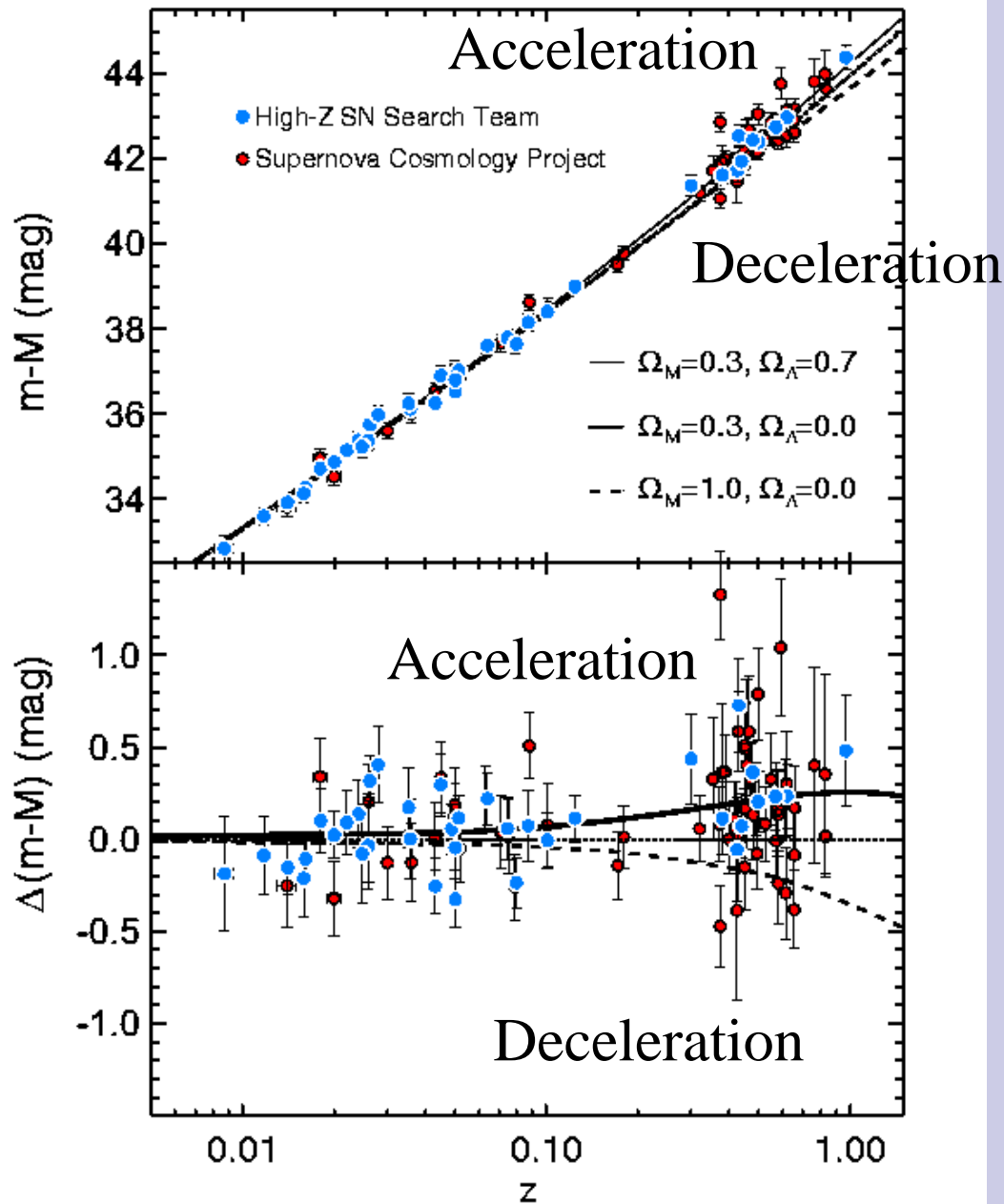
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# Supernovae halfway across the Universe!



$$\text{Apparent brightness} = \frac{\text{Power}}{4\pi r^2}$$

Credit: Supernova  
Cosmology Project



# Science Breakthrough of 1998: Dark Energy

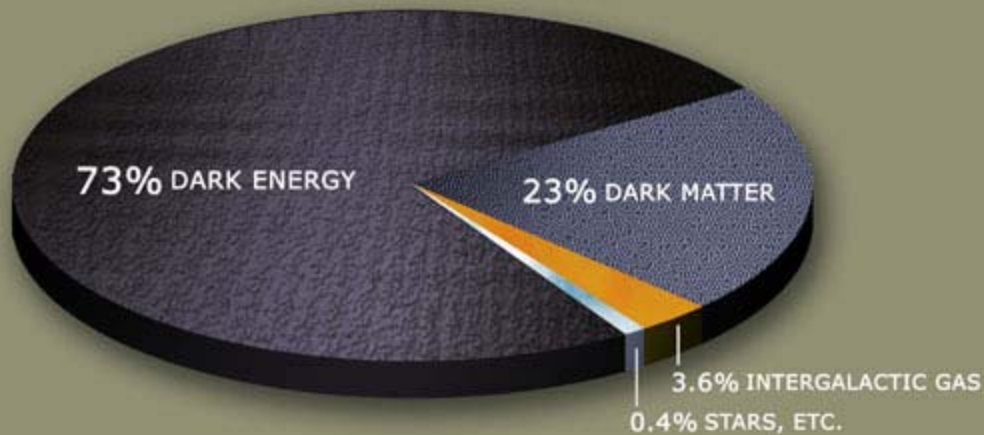
$m-M = \log(\text{Distance})$   
 $z = \text{Redshift} = \text{Velocity}$

Credit: High-z  
 Supernova Team  
 Adam Riess, VIISB

# An even more desperate remedy: Dark Energy

- A new fundamental field in the universe?
  - “Quintessence” – particles whose de Broglie wavelength is billions of light years!
- A cosmological constant?
  - Proposed by Einstein in 1917
  - Retracted as his “greatest blunder”
  - Energy density of empty space!
- Maybe General Relativity is wrong?
  - String theory might change gravity across the observable universe
  - Testing this idea is one of my research areas

# *Who ordered this?*



Photons: 0.03%  
Neutrinos: 0.3%  
Atoms: 4%  
Dark Matter: 23%  
Dark Energy: 73%

Credit: NASA/GSFC

# Additional Credits and Information

## **Credits:**

Hubble Deep Field photo courtesy Space Telescope Science Institute

WMAP (Wilkinson Microwave Anisotropy Probe) images courtesy NASA/Goddard Space Flight Center

Numerical simulation of galaxy formation (gas and dark matter) courtesy Mattias Steinmetz

## **Books:**

*Origins: Fourteen Billion Years of Cosmic Evolution*, Neil deGrasse Tyson and Donald Goldsmith

*Just Six Numbers: The Deep Forces that Shape the Universe*, Martin J. Rees

*An Introduction to Modern Cosmology*, Andrew Liddle (advanced undergraduate textbook)