The Standard Model of Cosmology

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Physics Seminar
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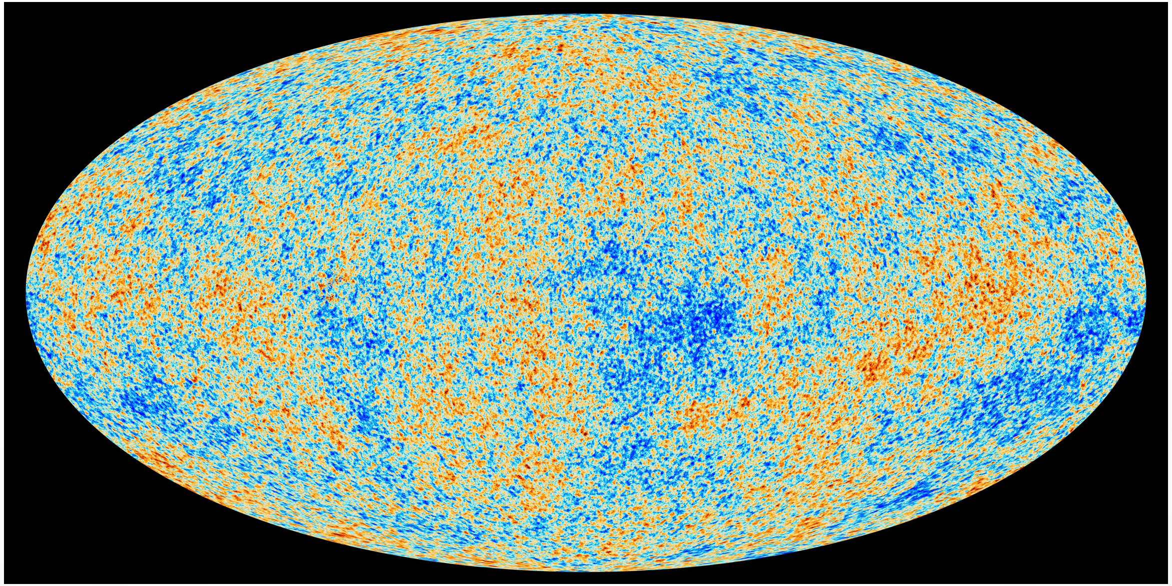
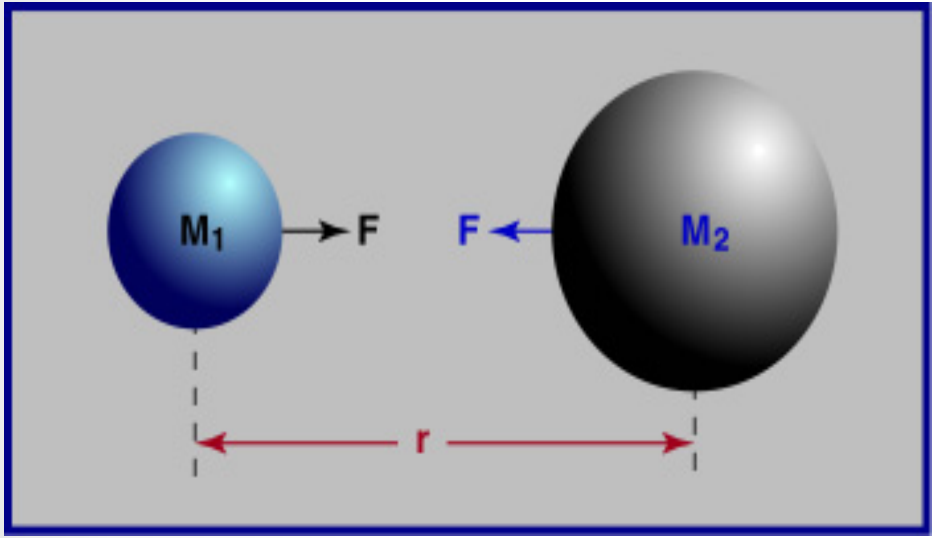


Cosmology

- is the scientific study of the large scale properties of the Universe as a whole.

- addresses questions like:
  - Is the Universe (in)finite in spatial extent?
  - Is the Universe (in)finite in temporal extent?
  - What are the possible geometries of the Universe?
  - What is the fate of the Universe?

Newton's Universal Law of Gravitation



$$F = \frac{GM_1M_2}{r^2}$$

Successes:

Described *gravitational force* on massive bodies…

- on earth
- in the sky

So what keeps the stars fixed?

Newton's view of the cosmos: *a perfect balance*?

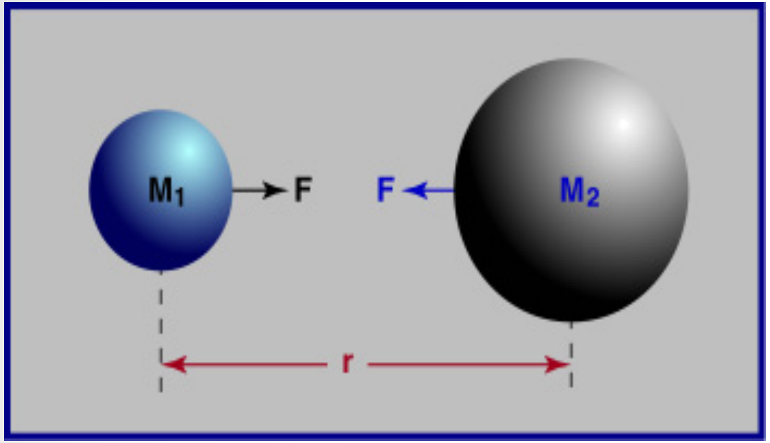
Newton envisioned…

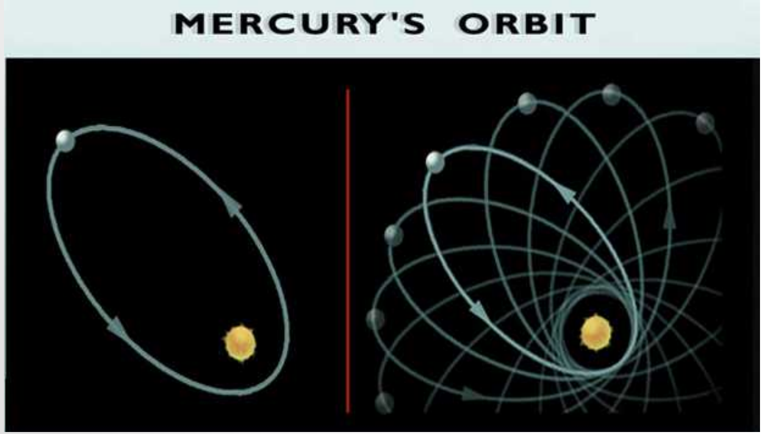
- an *infinitely* large universe
- stars were placed at just the right distances so their attractions cancelled.

Olbers' paradox

If the Universe in *infinite*, *unchanging*, and *everywhere the same*, shouldn't the entire night sky be bright?

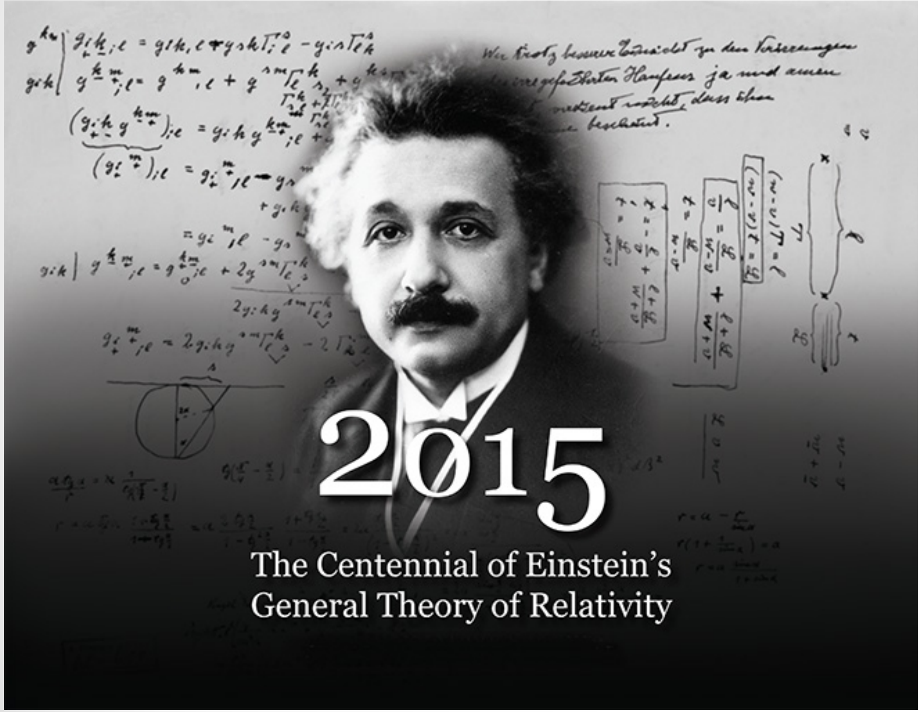
Shortcomings of the Universal Law of Gravitation…





- "Action at a distance"?
- Infinite propagation speed?
- Mercury's perihelion precession?

In 1915, Einstein gives the world his *General Theory of Relativity*



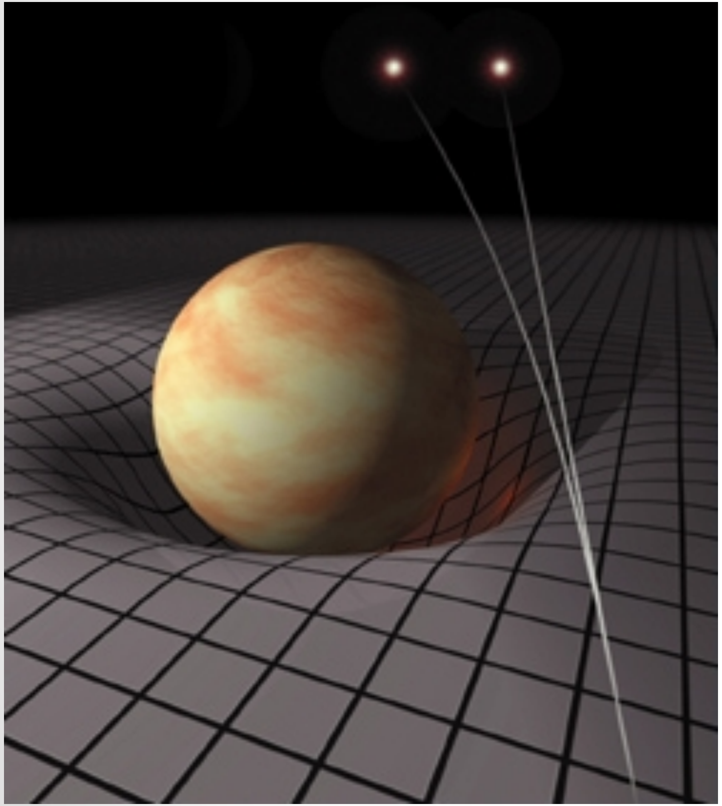
- https://www.aip.org/sites/default/files/styles/einstein_full/public/einstein_slideshow/einstein-calendar-cover2015.jpg?itok=5q5C8sNe

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

- $G_{\mu\nu}$ describes the *curvature* of spacetime
- $T_{\mu\nu}$ describes the *matter & energy* in spacetime

When forced to summarize the general theory of relativity in one sentence; *time* and *space* and *gravity* have no separate existence from *matter*.

- Albert Einstein



Sean M. Carrol, *Spacetime and Geometry: An Introduction to Einstein's General Relativity* (Addison Wesley, 2004)

Matter tells *space* how to curve,
Space tells *matter* how to move

Einstein's Static Universe

General Relativity does NOT allow for a *static cosmological model*

- Einstein introduces a *cosmological constant*

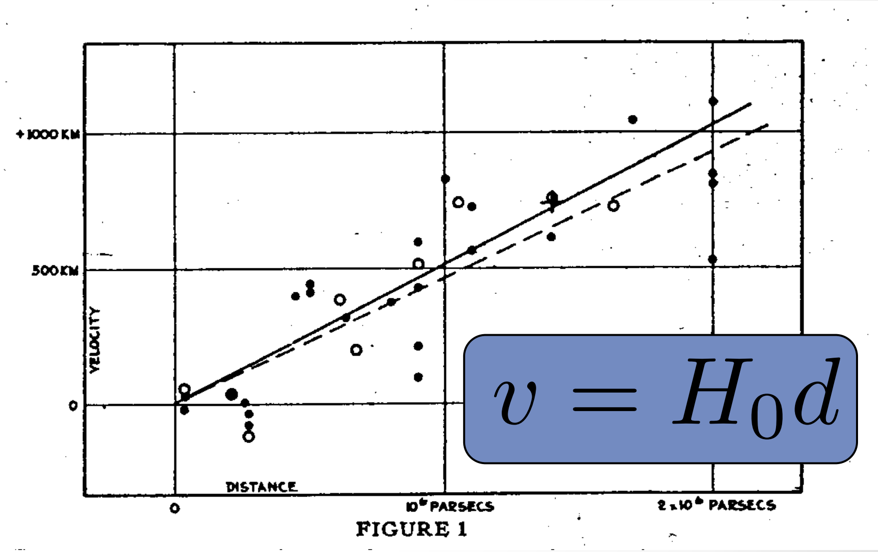
$$G_{\mu\nu} + g_{\mu\nu}\Lambda = 8\pi T_{\mu\nu}$$

- *Static Universe iff:*

$$\frac{\Lambda}{8\pi} = \frac{1}{2}\rho_m \;\; \& \;\; \kappa > 0$$

In 1929, Edwin Hubble discovers that the ***Universe is expanding**!***

http://www.astrofiles.net/bio/hubble/edwin-hubble.png



$$v = H_0 d$$

http://www.phy.mtu.edu/debate/1996/hubble_fig1_full.gif

Einstein calls Λ the "greatest blunder" of his life!

*Hubble, E. 1929, Proc. National Acad. Sci. 15, Issue 3, 168 Pub. US Nat Acad Sci, 15, 168

FRW cosmology basics:

Cosmological Principle

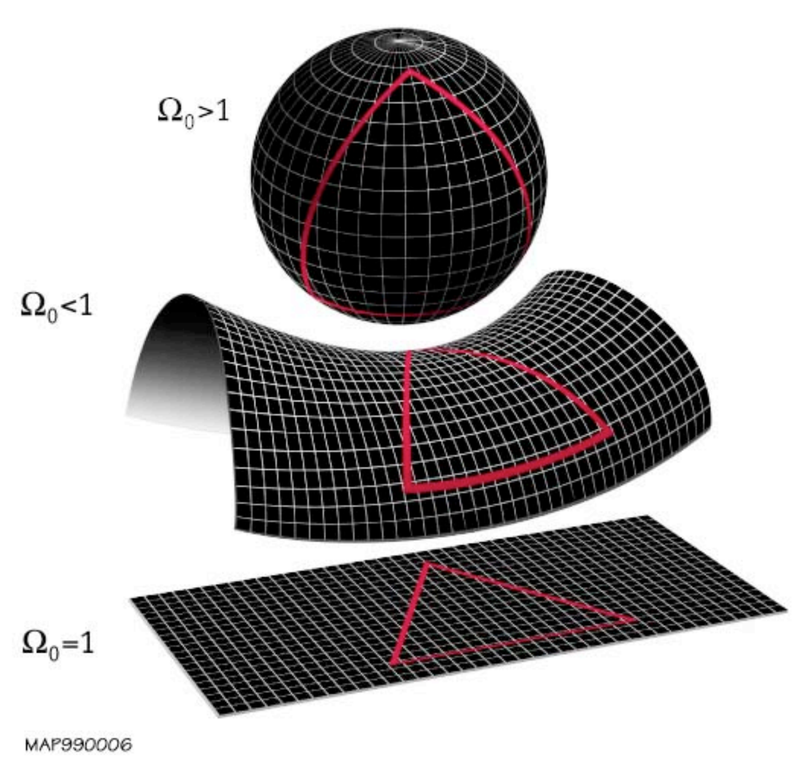
On *sufficiently large distance scales*, the Universe is

1. spatially *isotropic*
2. spatially *homogeneous*

$\Rightarrow$ *Maximally symmetric space*

For a ***Homogeneous*** & ***Isotropic*** Universe…

… 3 possible Geometries



http://wmap.gsfc.nasa.gov/media/990006/990006_2048.jpg

Recent data indicates that the Universe is *flat*

Friedmann-Robertson-Walker (FRW) Cosmology

Choose the Robertson-Walker metric*

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

3 non-interacting components:

- radiation
- *pressureless* matter
- vacuum energy (a.k.a *cosmological constant)*

* the Robertson-Walker metric describes a *spatially homogeneous, isotropic* Universe evolving in time

The Friedmann equations of FRW cosmology..

$$\rho = 3\frac{\dot{a}^2}{a^2} + 3\frac{\kappa}{a^2}$$

$$p = -\left(2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2}\right) - \frac{\kappa}{a^2}$$

$$0 = \dot{\rho} + 3(\rho + p)\frac{\dot{a}}{a}$$

- The density (ρ), pressure (p), and curvature (κ) of the Universe determine the *time evolution* of the scale factor (a).
- The matter & energy content consists of
  - *radiation*, *pressureless matter*, & *vacuum energy*.

Choose an *equation of state*

$$p = w\rho$$

- For *radiation*: $w = 1/3$
- For *pressureless matter*: $w = 0$
- For *vacuum energy*: $w = -1$

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- For *white dwarfs*: $p \propto \rho^{4/3}$

Density as a function of the scale factor

$$\rho(a) = \rho_{crit}\left(\Omega_v + \frac{\Omega_m}{a^3} + \frac{\Omega_r}{a^4}\right)$$

- Radiation dominated: $a(t) \sim t^{1/2}$
- Matter dominated: $a(t) \sim t^{2/3}$
- Vacuum dominated: $a(t) \sim e^{Ht}$

NOTICE: As $t \rightarrow 0$, $a(t) \rightarrow 0$

- Here we've set $\kappa = 0$, inline with observation

Georges Lemaître suggests the Universe had a beginning..

- Belgian Astrophysicist/Catholic Priest
- 1927 paper in *Annals of the Brussels Scientific Society**
- showed that the universe had to be either *contracting* or *expanding*.
- suggested that the Universe had a definite *beginning* in which all its matter & energy were concentrated @ *one point*.

http://www.aquinasandmore.com/resources/georges-lemaitres.jpg

* Lemaître, G. Ann. Soc. Sci. Brux. A 47, 49–59 (1927).

Did the Universe begin with a *"Big Bang"*?

http://media.graytvinc.com/images/big+bang4.jpg

The *Big Bang*…

- is ***not*** an explosion that happened @ ***one*** pt in *space*
- occurred at ***all*** pts in *space* @ ***one*** moment in *time*

***Big Bang* - a time** of *infinite* density, *infinite* temperature, and *infinite* spacetime curvature

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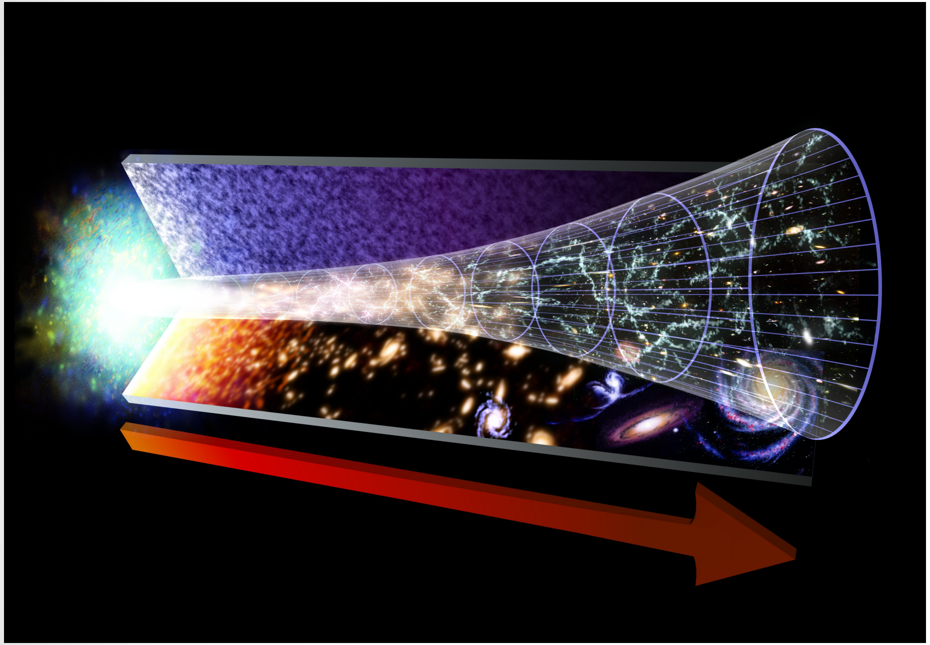

https://svs.gsfc.nasa.gov/vis/a010000/a010100/a010128/Arrow_JPG.jpg

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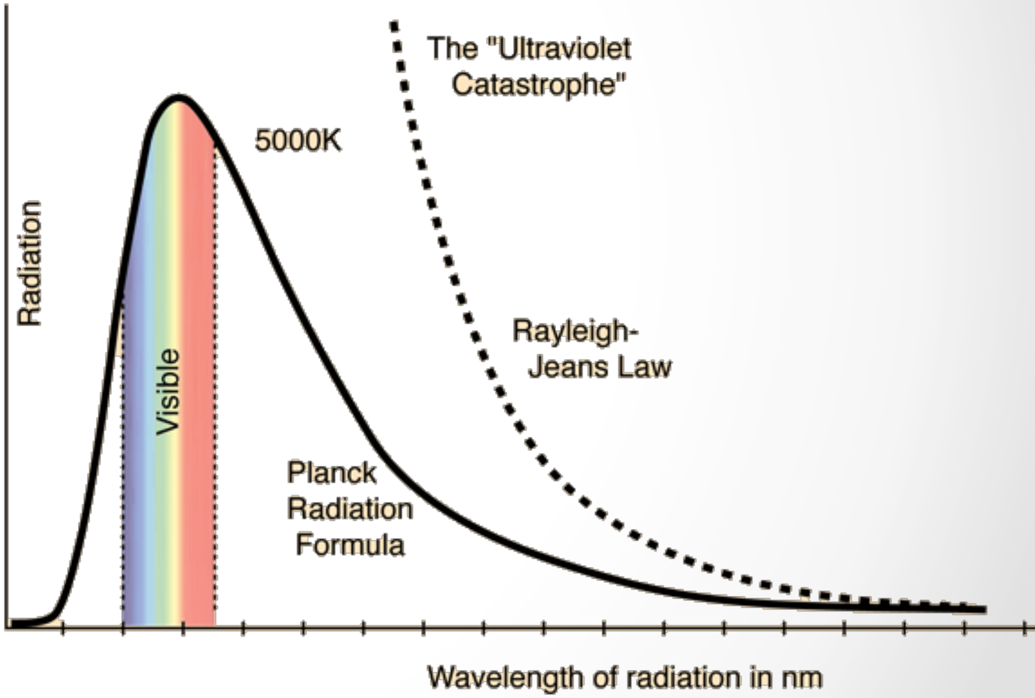
Big Bang **-** a **time** of *infinite* density, *infinite* temperature, and *infinite* spacetime curvature

In the early 1960s, the Princeton group in gravitational physics…

- finds that the Universe should be uniformly bathed in a background *microwave radiation*

- predicts a *blackbody spectrum* of the background radiation with $T \sim 10$K



http://hyperphysics.phy-astr.gsu.edu/hbase/imgmod/uvcatas.gif

In 1965, observational evidence for the Big Bang!

Arno Penzias & Robert Wilson

- Bell Lab Physicists calibrating the Bell Labs microwave antenna designed for satellite communications
  - Awarded the 1978 Nobel Prize in physics *for their discovery of the cosmic microwave background radiation.*

http://cosmictimes.gsfc.nasa.gov/online_edition/1965Cosmic/images/penzias_wilsonpgg.

Does this *background radiation* have a *Blackbody Spectrum?*

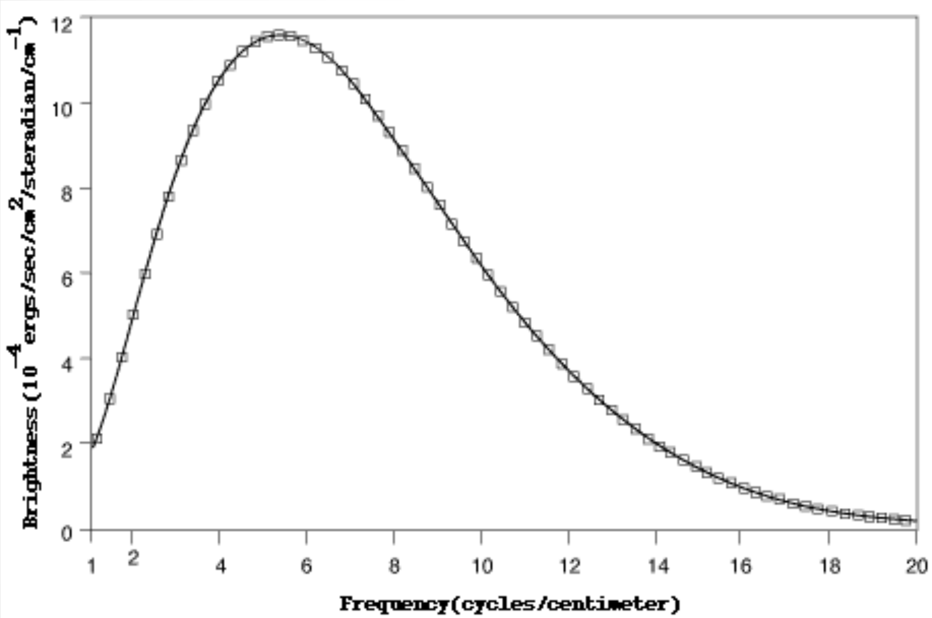
In Nov`89, NASA launches the
Cosmic Background Explorer (COBE)
to measure…

- the spectrum
- the anisotropies

http://cosmos.lbl.gov/Images/cobe_universe.jpg

of the cosmic background radiation.

Spectrum of the *Cosmic Microwave Background Radiation*



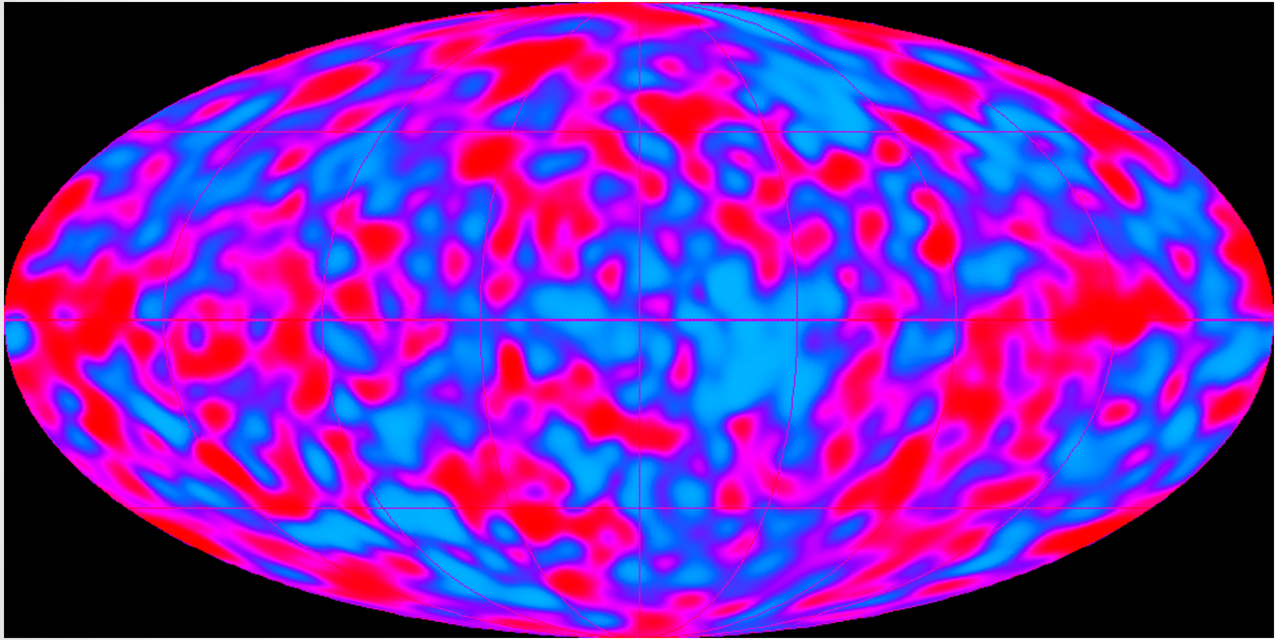
http://www.faculty.umb.edu/gary_zabel/Courses/Parallel%20Universes/Texts/Remote%20Sensing%20Tutorial%20Page%20A-9.htm

John Mather & George Smoot

Awarded the 2006 Nobel Prize in physics for their *discovery of the blackbody form and anisotropy of the cosmic microwave background radiation* measured by COBE.

- The excellent agreement with Planck's law is *the* best fit ever measured!

COBE image of the *Cosmic Microwave Background Radiation*

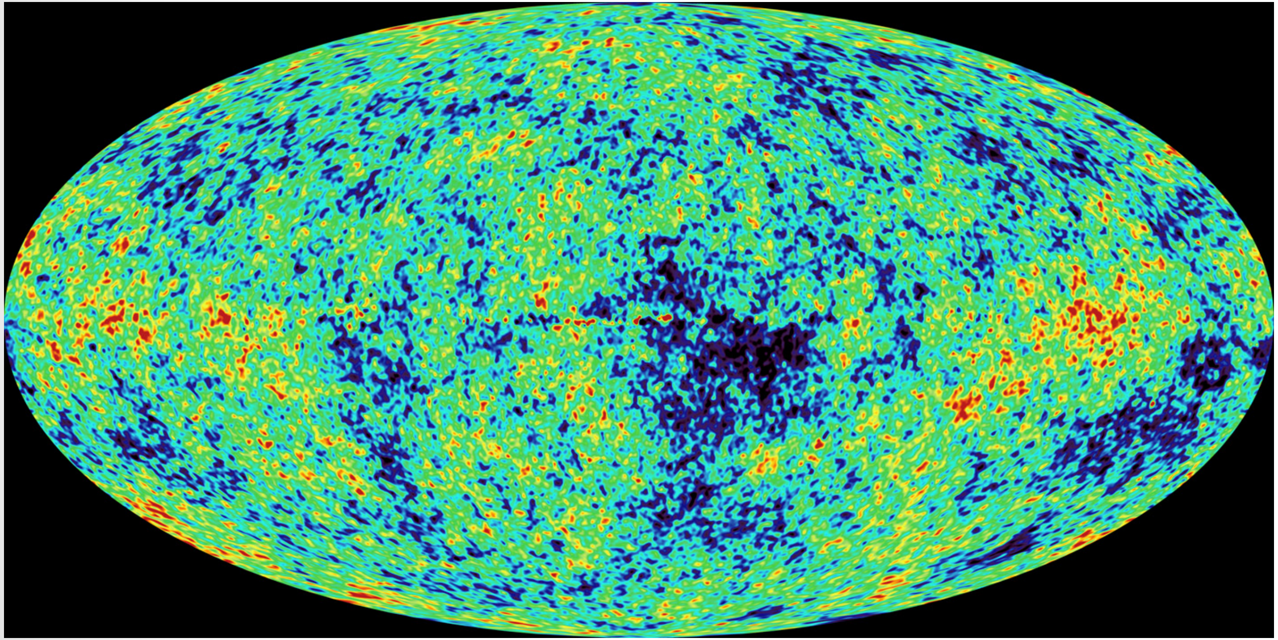


http://www.nasa.gov/images/content/403322main_COBEallsky_full.jpg

- Light from when the Universe was 380,000 years old.
- Map of μK *anisotropies*

$$T_B = 2.725\text{K} \pm 18\mu\text{K}$$

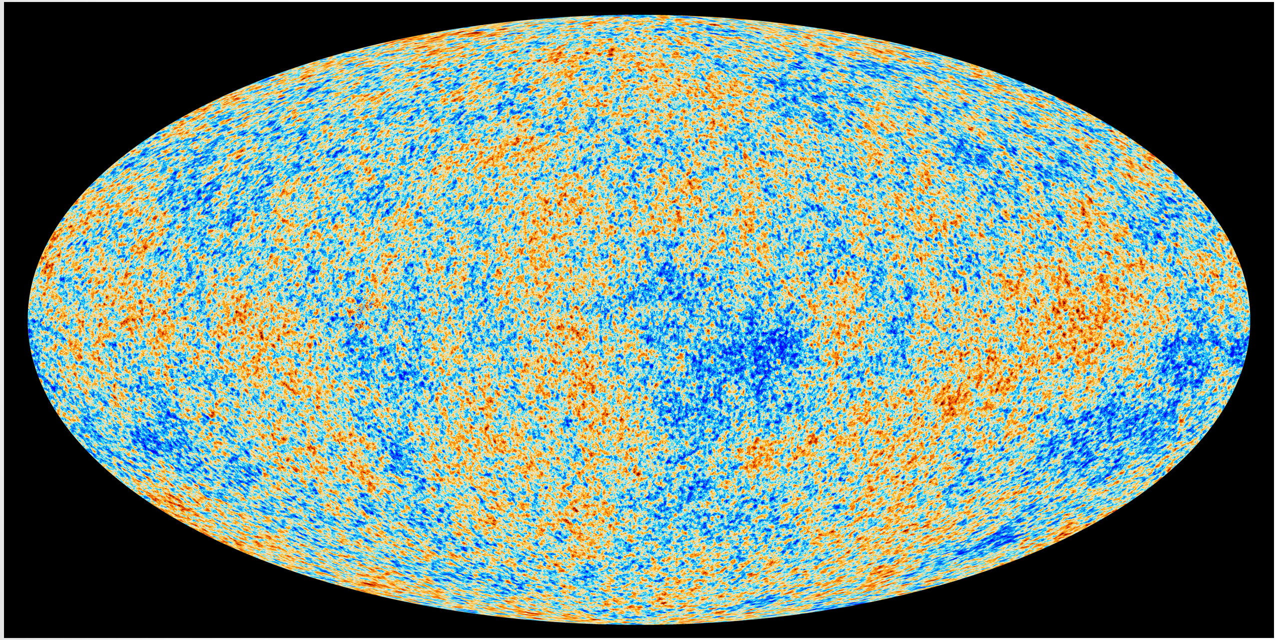
WMAP image of the *Cosmic Microwave Background Radiation*



http://www.nasa.gov/centers/goddard/images/content/96115main_Full_m.jpg

- WMAP satellite *launched* 06/01, *ended* 10/10
- WMAP image from 7 years of data!
- Data implies that universe is *flat*.

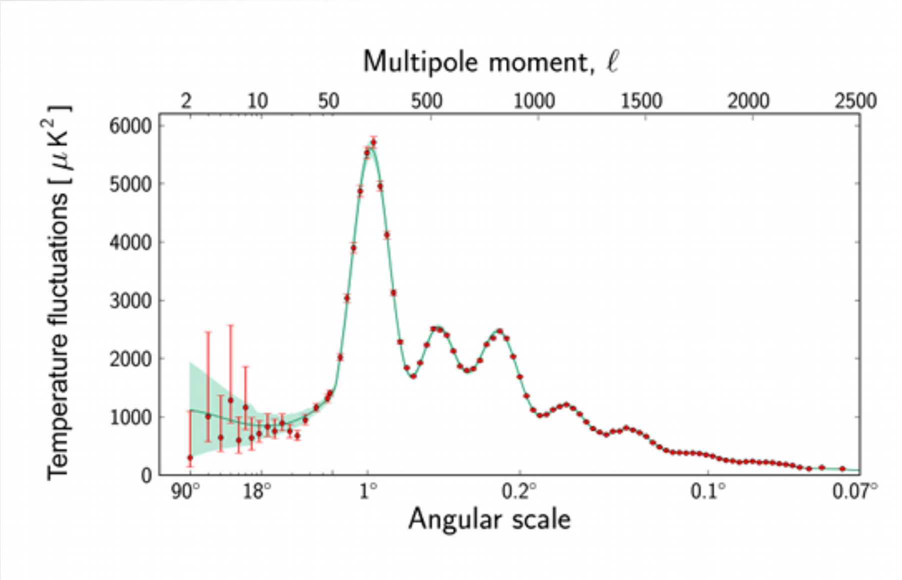
Planck image of the *Cosmic Microwave Background Radiation*



https://www.nasa.gov/mission_pages/planck/#.Vvs8mnDgI2s

- Planck satellite *launched* 05/09, *ended* 10/13
- 2.5 x *greater* resolution than WMAP (1/12°)
- Measured *polarization* of light from early universe
- Found strong evidence for *inflation*.

Detailed analysis of *temperature variations* from Planck image + WMAP data



- Green curve is line of best fit.

$$\Omega_r \sim 10^{-4}$$
$$\Omega_m = 0.309$$
$$\Omega_v = 0.691$$

$$\Omega_m \rightarrow \Omega_{baryons} = 0.049$$
$$\Omega_m \rightarrow \Omega_{dark\ matter} = 0.259$$

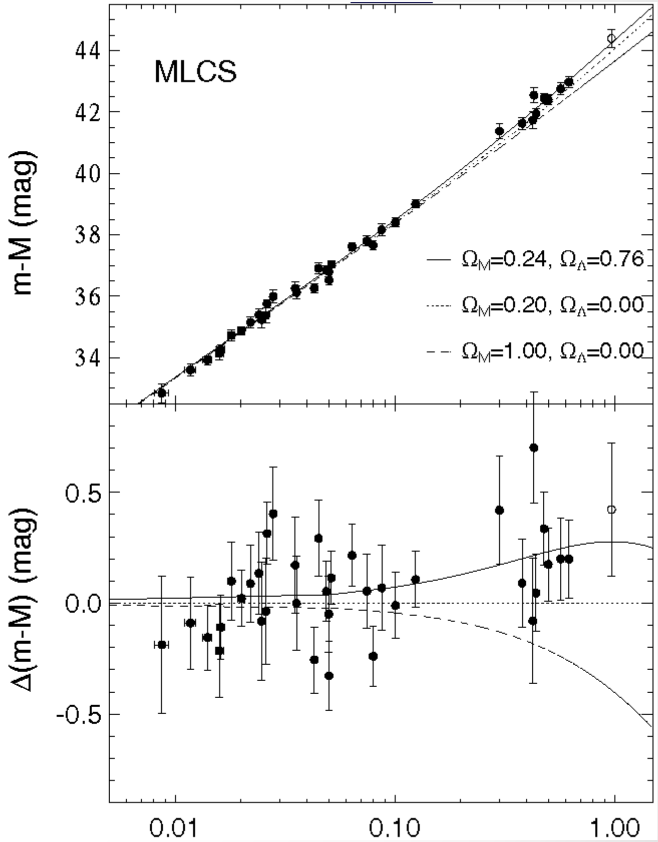
- All ordinary matter (stars, galaxies, etc..) comprises only 4.9% of the total matter/energy of the Universe!

Data from Type Ia Supernovae, WMAP and SDSS implies…

- The expansion of the Universe is *ACCELERATING!*
- *seems* to indicate a *vacuum energy*

Saul Perlmutter, Brian Schmidt, & Adam Riess

Awarded the 2011 Nobel Prize in physics *for the discovery of the accelerating expansion of the Universe through observations of distant supernovae.*



http://nedwww.ipac.caltech.edu/level5/Carroll2/Figures/figure3.jpeg
High-z Supernova Search Team: Riess et al., 1998

Puzzle 1: The Cosmological Constant Problem?

From the *zero-point energies* of vacuum fluctuations…

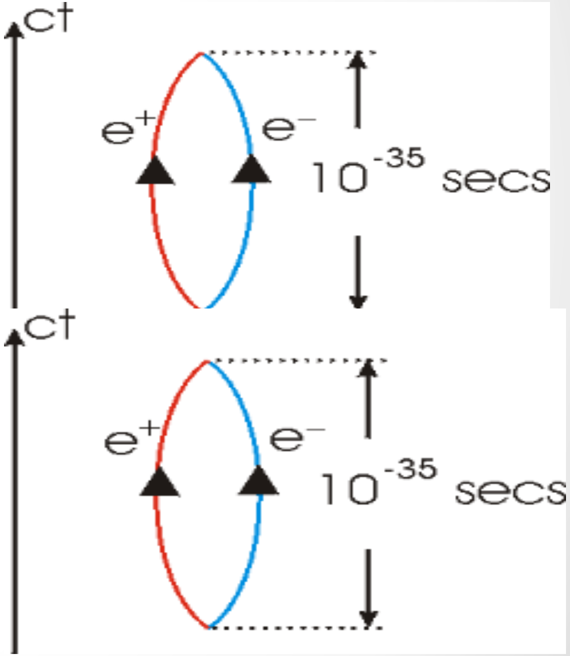
$$\rho_v^{th} \sim 2 \times 10^{110} \text{ erg/cm}^3$$

Cosmological observations imply…

$$\rho_v^{obs} \sim 2 \times 10^{-10} \text{ erg/cm}^3$$

The ratio yields..

$$\rho_v^{th} / \rho_v^{obs} \sim 10^{120}$$



http://www.upscale.utoronto.ca/GeneralInterest/Harrison/BlackHoleThermo/VirtualPair.gif

Conclusions

Theory & observational evidence imply that:

- the Universe is *flat & infinite* in spatial extent
- the Universe began w/ a “Big Bang” 13.8 billion years ago
- the Universe is undergoing an *accelerated expansion*
- the Universe will continue accelerated expansion indefinitely!

Puzzle 2: Flatness Puzzle?

Why is the Universe so *flat*?

The 1st FRW equation can be written as

$$\Omega_{total} - 1 = \frac{\kappa}{\dot{a}^2}$$

where the density parameter $\Omega(t)$ is

$$\Omega(t) = \frac{\rho(t)}{\rho_{crit}} \quad \text{with} \quad \rho_{crit} = 3\frac{\dot{a}^2}{a^2}$$

Puzzle 3: Cosmic Coincidence Problem?

Why is the vacuum energy of the same order of magnitude as the matter density?

Mathematically:

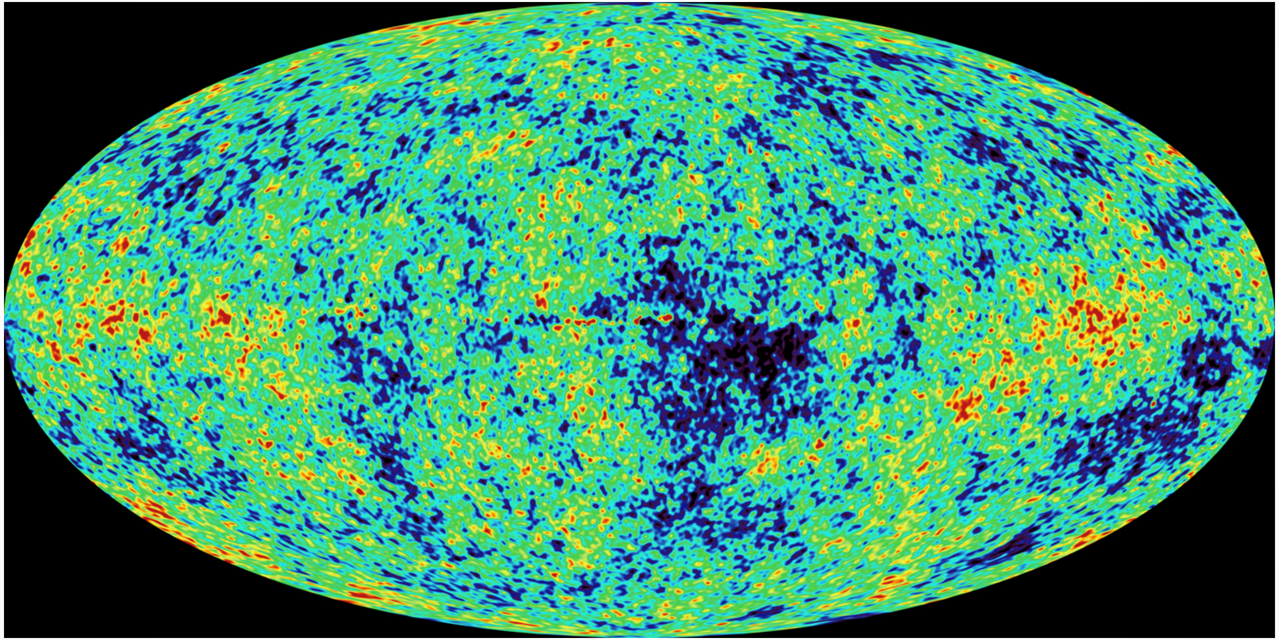
Why is $\Omega_v/\Omega_m \sim 1$?

In general:

$$\frac{\Omega_v}{\Omega_m} \propto a^3$$

Puzzle 4: Horizon Problem

Why is the CMB uniform on large scales ?



2 antipodal CMB photons are *causally disconnected*

- yet have *same temperature* to 1 part in 10^5! Why?

Puzzle 5: Initial Jump Start?

The 2nd FRW equation is

$$\frac{\ddot{a}}{a} = -\frac{1}{6}(1+3w)\rho$$

for ordinary matter, $w > -1/3$ $\quad \therefore \quad \boxed{\frac{\ddot{a}}{a} < 0}$

- So what got the Big Bang going in the 1st place?

Puzzle 6: Structure of the Universe

Where did the regions of slightly enhanced density in the early Universe originate from?