The expanding universe and the big bang

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kmn

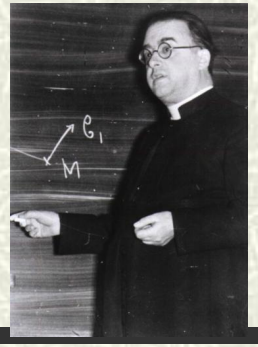
Plus: New results from PLANCK

Overview

- **The runaway galaxies**
  Slipher's redshifts and Hubble's law
- **The expanding universe**
  Einstein vs Friedmann and Lemaitre
- **The big bang model**
  Lemaitre's fireworks universe
- **A cosmic fossil (1965-)**
  The cosmic microwave background







I The runaway galaxies

- Nebulae observed by Marius, Halley, Messier (1614)

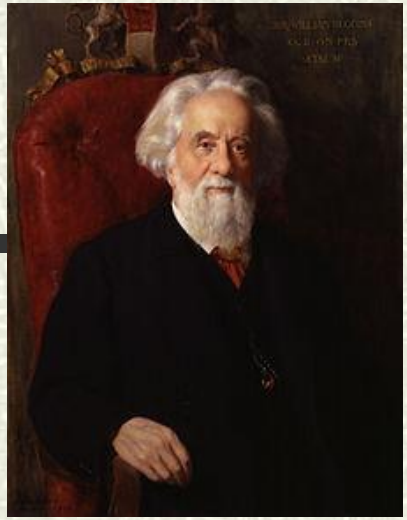
- 'Island universes'? Kant (1755-96)
  Galaxies of stars at immense distance?
  Or faint stars quite close?

- Wilhem Herschel
  Catalogue of a thousand (1786)
  36-inch reflecting telescope

- Earl of Rosse
  72-inch reflecting telescope (1845)
  Some nebulae have spiral structure, stars

Problem of resolution, distance

Spectroscopy



Sir **William Huggins** (1824 – 1910)

- Spectroscopy and photography (19th cent)
  Emission and absorption lines of celestial objects
- Composition of the stars
  William Huggins and spectroscopy
- Motion of the stars
  William Campbell and the Doppler Effect
- Composition of the spiral nebulae?
  Difficult to resolve

William Campbell (1862 – 1938)

The Lowell observatory

Percival Lowell (1855 – 1916)

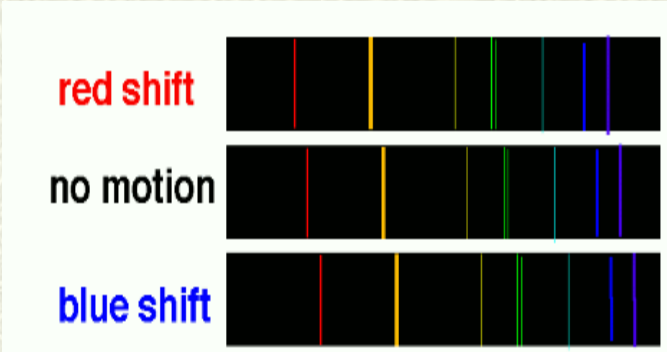
- Modest refracting telescope (24-inch)
  Flagstaff, Arizona
- Founded by Percival Lowell (1894)
  Eccentric astronomer
- Controversial
  Canals on Mars
- Employed Vesto Slipher (1901)
  Brashear spectrograph
- Spectroscopy of the nebulae?

Spectra of the nebulae

- Analyse light of the spiral nebulae? (1909)
  Evolving solar system? Lowell
- Slipher reluctant
  Larger telescopes failed
- Experiments with spectrograph camera
  Good results with fast camera lens
- Clear spectrum for Andromeda nebula (1912)
  Significantly blue-shifted
  Approaching at 300 km/s

Vesto Slipher

$\Delta\lambda/\lambda = v/c$

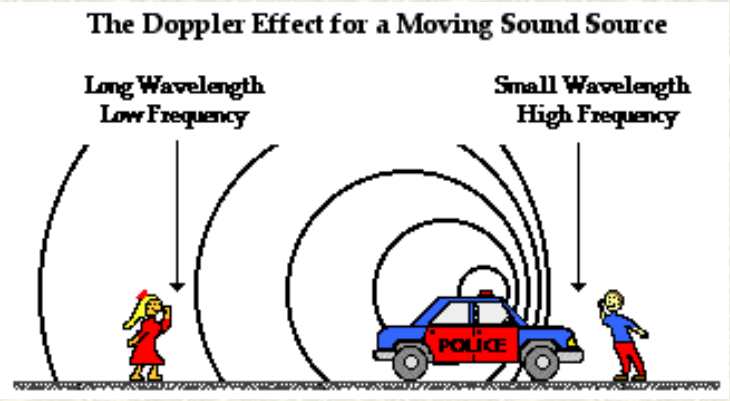


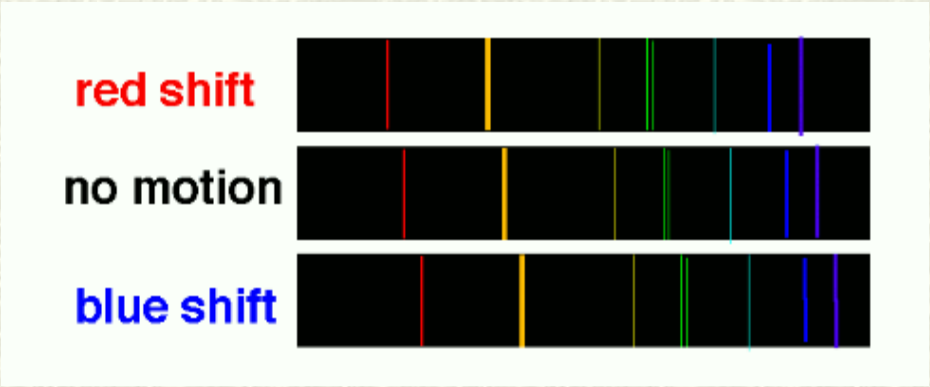
The Doppler effect

Frequency of light depends on relative motion of observers

Doppler Effect

measure motion of object from frequency of light emitted





Slipher's redshifts

- **25 nebulae redshifted (1917)**
  Large outward velocities
  Some receding at 1000 km/s

- **Much faster than stars**
  Not gravitationally bound by MW?

- **Island universe debate**

"Island universe hypothesis gains favour"

- **More measurements**
  More redshifts

RADIAL VELOCITIES OF TWENTY-FIVE SPIRAL NEBULÆ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

The Great Debate (1920)

Distinct galaxies

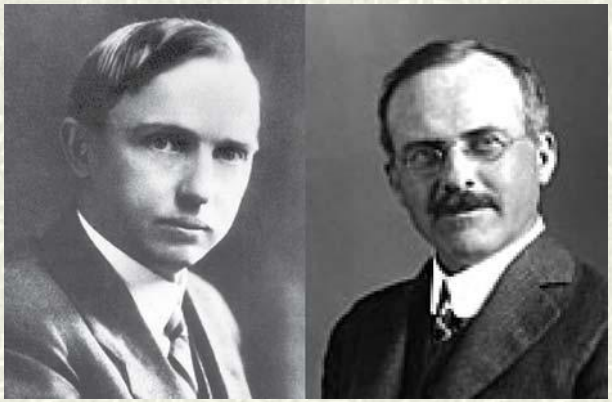
- Redshifts – not gravitationally bound?
- Stellar structure of spiral nebulae
- Many faint novae – great distance?

OR

One galaxy

- Size of Milky Way (*300,000 Lyr)*
- Rotation data *(Van Maanen)*
- Andromeda nova (supernova)

Harlow Shapley vs Heber Curtis



Hubble's answer (1925)

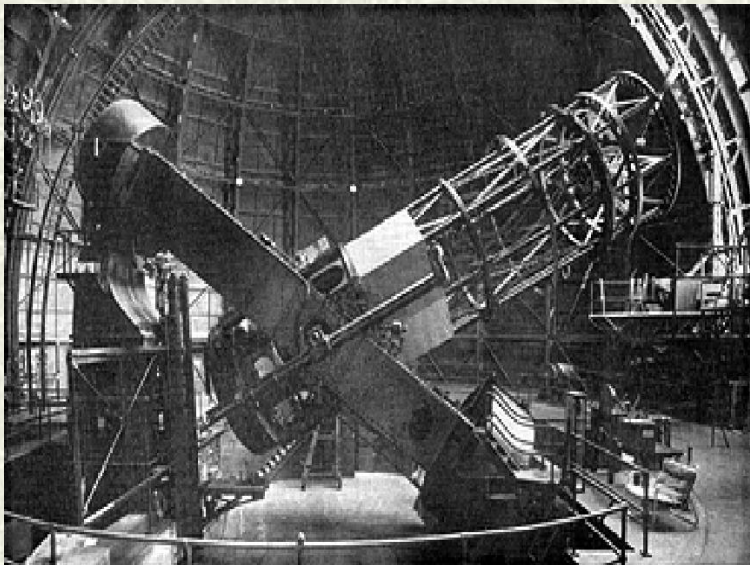
- Edwin Hubble (1921)
- Ambitious astronomer

- Hooker telescope (Mt Wilson, 1917)
- 100-inch reflector

- Resolved Cepheid stars in nebulae
- Known luminosity and distance
- Far beyond Milky Way! (1925)

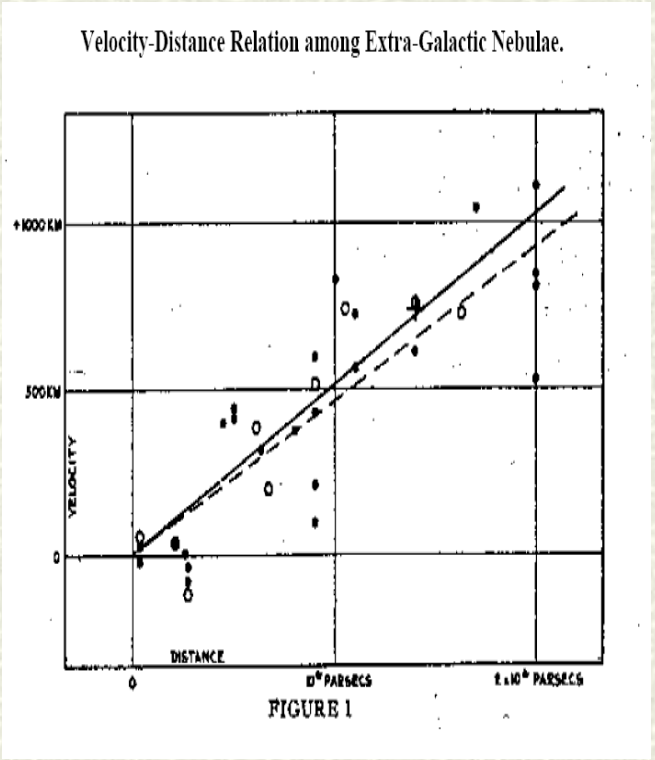
Nebulae are distinct galaxies

Edwin Hubble (1889-1953)



A velocity/distance relation (1929)

- What do the velocities of the galaxies mean?
- Is there a relation between distance and velocity ?
- Combine 24 distances with Slipher redshifts
- Approx linear relation: **Hubble's law**



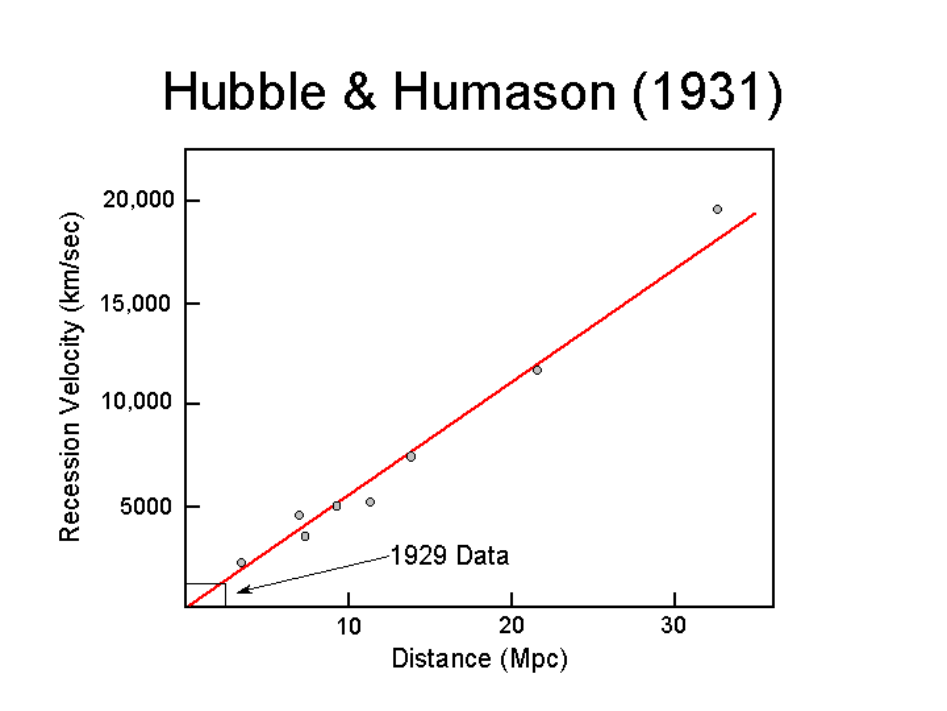
Furthest galaxies receding fastest

Slipher not acknowledged

m = 585 km/s/Mpc

Justification (1931)

- Distances for 40 galaxies
- Redshifts for 40 galaxies
- Reduced scatter – linear relation
- Justification



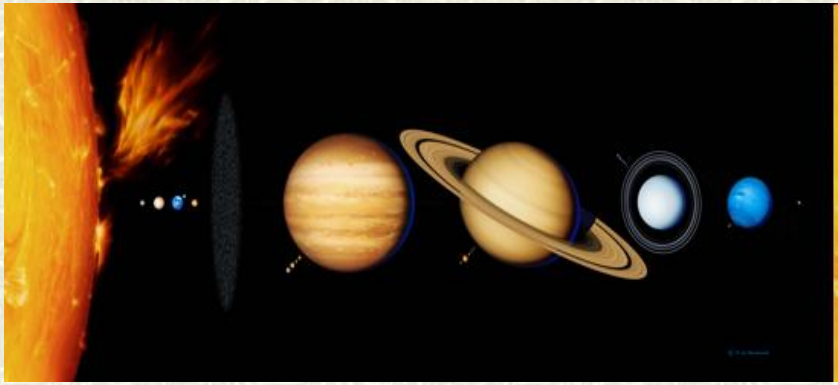
Explanation?
Not the expanding universe

II The expanding universe

Isaac Newton

- What do the redshifts represent?
- Recession velocities for distant galaxies?
- If so, why?
- Newtonian gravity pulls in $F = GMm/r^2$
- What is pushing out?

Space, time fixed

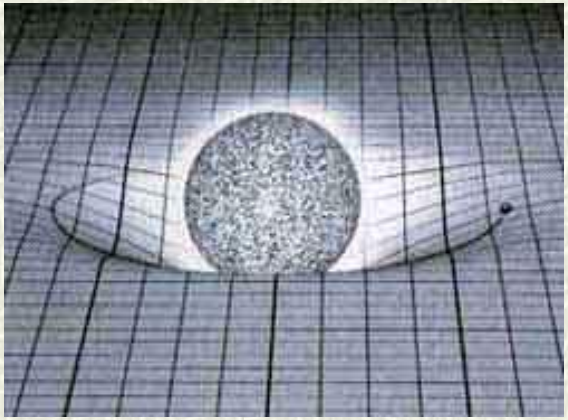


General relativity (1915)

- Space+time = space-time
- Space-time dynamic
- Distorted by motion, mass
- Causes other mass to move

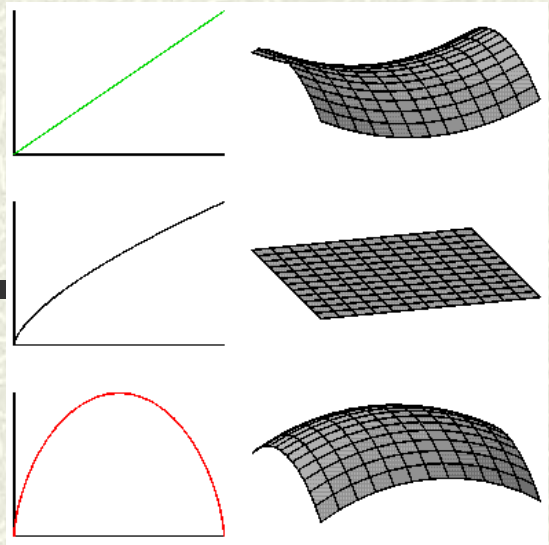
Gravity = curvature of space-time

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



- Eddington experiment (1919)

The evolving universe



Apply Einstein's gravity to the cosmos

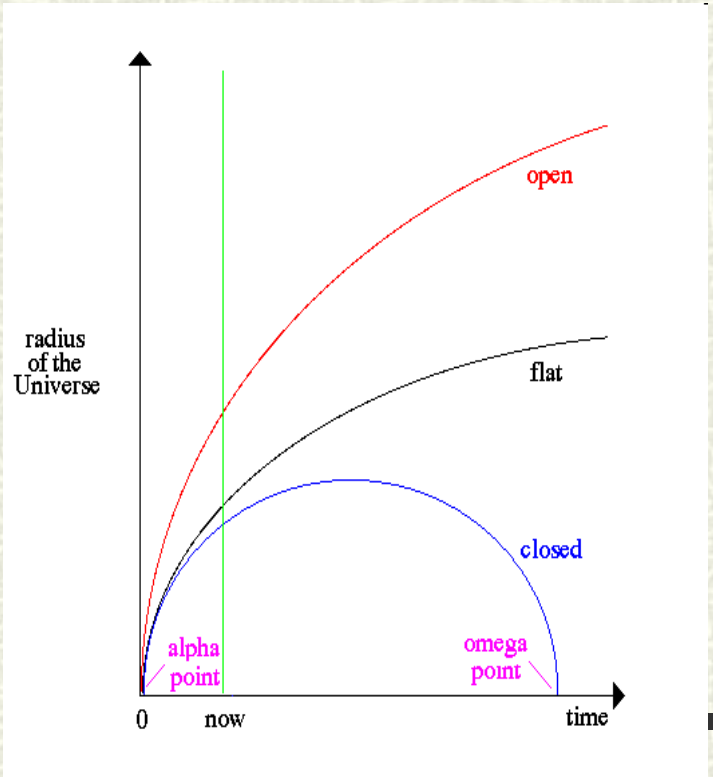
- Predicts time-varying radius
- Space expanding or contracting

  Gravity vs expansion
- Depends on matter $\Omega = d/d_c$
- Positive or negative curvature

Friedman: 3 possibilities (1924)

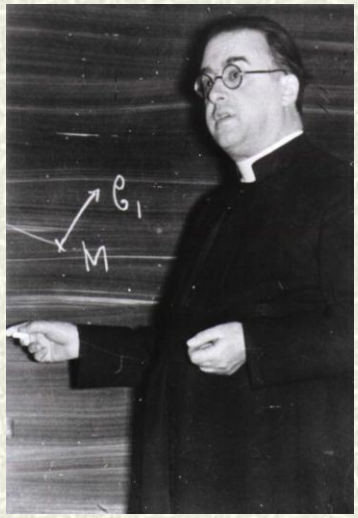
Rejected by Einstein: static universe

$$G_{\mu\nu} + \lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



Lemaitre's expanding universe (1927)

- Aware of Slipher redshifts
- Redshifts = expansion of space ?
- New solution of Einstein's equations
- Expanding universe
- Rate of expansion = *585 km/s/Mpc*

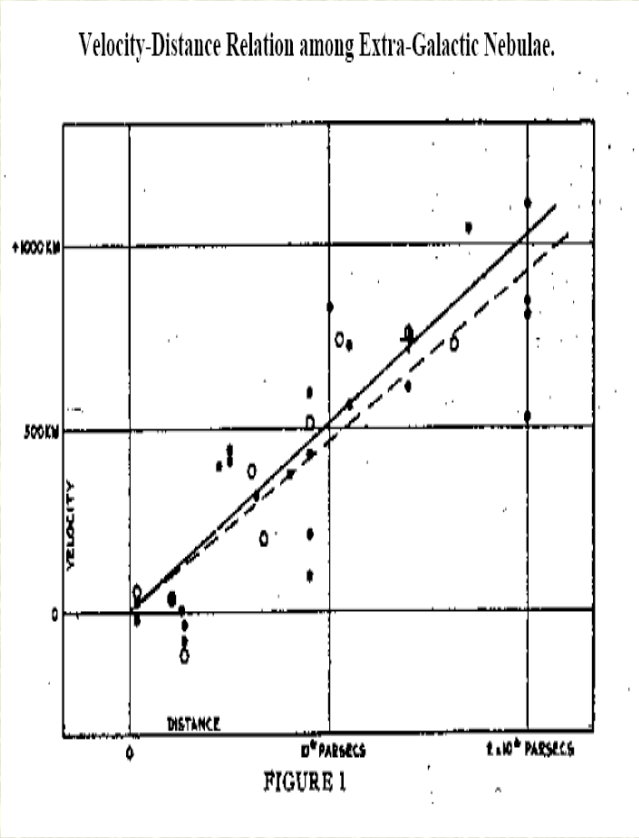


Fr Georges Lemaitre

Obscure journal
Rejected by Einstein

The expanding universe (1931)

- Hubble-Slipher graph (1929)
- Einstein, de Sitter static models don't fit
- Lemaitre paper translated (MNAS, 1931)
- Satisfactory explanation
- Space is expanding (relativists)
- More evidence from Hubble/Humason (1931)



Expansion of space

Who discovered the expanding universe?

- Einstein *Framework*
- Friedman *Evolving universe*
- Hubble, Slipher *Observational evidence*
- Lemaitre *Expanding universe + experiment*

'Hubble graph' should be Hubble-Slipher graph

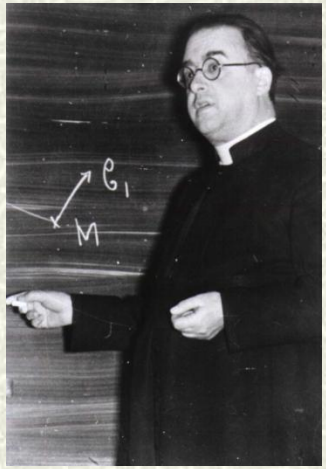
'Hubble expansion 'should be Hubble-Lemaitre expansion

Astronomers sceptical (Hubble)

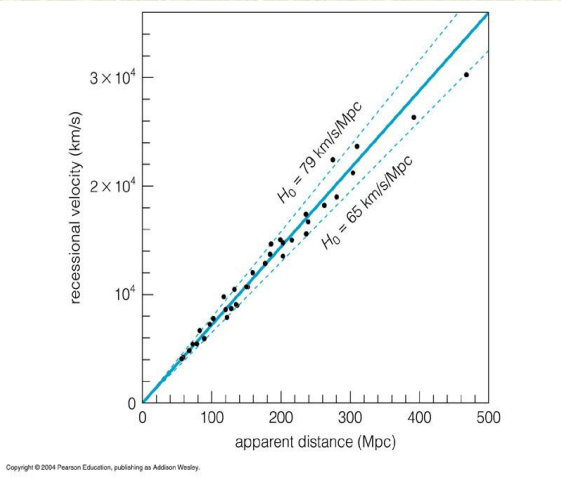
III The big bang model

- Lemaitre: rewind Hubble graph
- *U* smaller in the past
- Tiny volume originally
- Extremely dense, extremely hot
- Expanding and cooling since

Density = clock



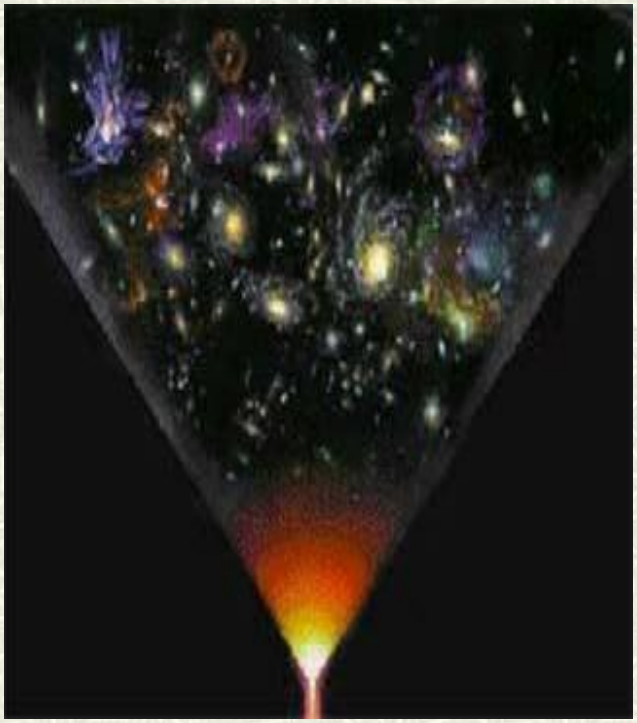
Fr Georges Lemaitre



Lemaitre's 'primeval atom' (1931)

Problems

- Wrong age (from expansion)
- Singularity problem $Lim_{x \to 0} (1/x)$
- Where do the laws of physics come from?
- Where does spacetime come from ?
- Smacks of religion (Einstein)



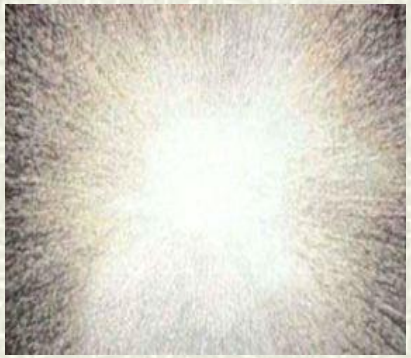
∞ *density,* ∞ *temp at* $t = 0$ *?*

New evidence

- Nuclear physics (1940s)
- Did the chemical elements form in the stars?
- Not all of them

Georges Gamow

- In Lemaitre's primeval furnace ?
- ***H***, ***He*** nuclei (*1 s*)



- Predicts *U* = 75% ***H***, 25% ***He***
- Agrees with observation

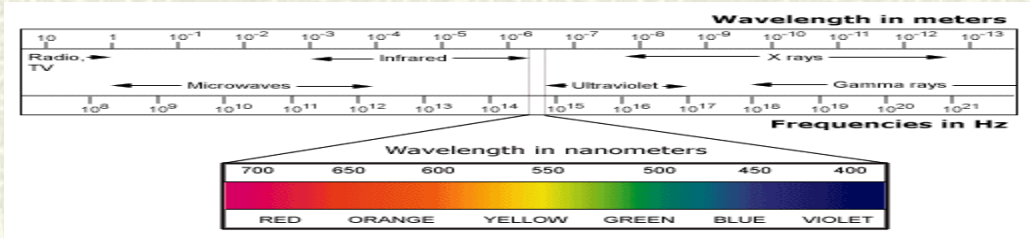
Heavier atoms formed in stars

More evidence: cosmic radiation?

- Infant universe very hot indeed
- Full of radiation
- Released when atoms formed
  (300,000 yr)
- Still observable today?

  Low temp, microwave frequency

Alpher, Gamow and Herman



No-one looked (1940s)

Cosmic microwave background (1965)

CMB discovered accidentally

- Universal signal
- Low frequency (microwave)
- Low temperature (3K)

Penzias and Wilson

Echo of Big Bang!

BB model goes mainstream

The big bang – evidence

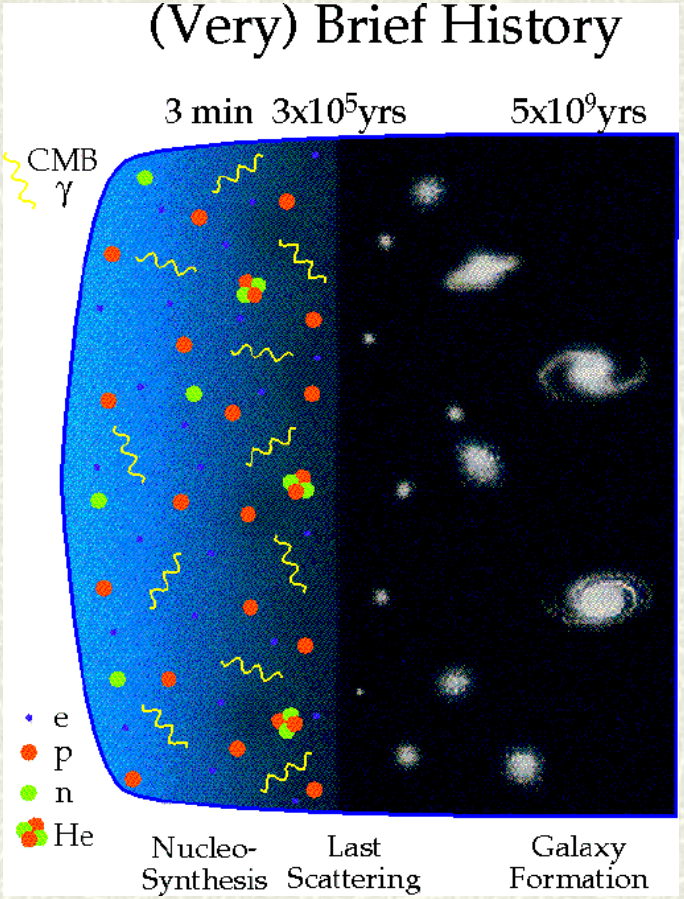
√ ***1.*** The expansion of the *U*

√ ***2.*** The abundance of H and He

√ ***3.*** The cosmic background radiation

√ ***4***. The distribution of galaxies

Expanding and cooling

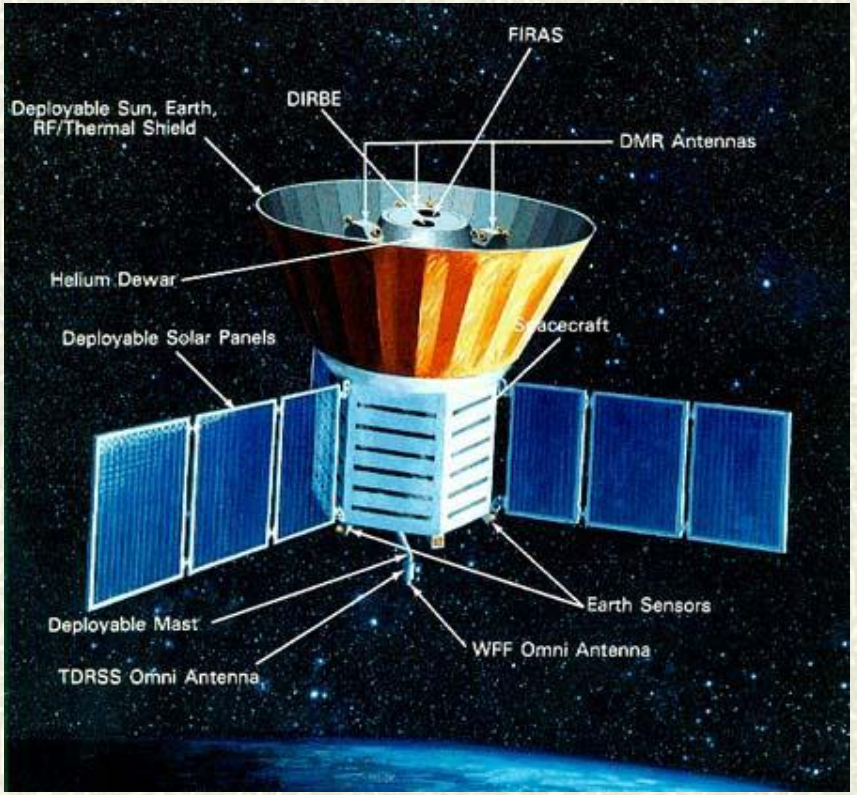


How did it start?

IV Modern measurements of the CMB

- Details of background radiation
- Full spectrum
- Comparison with theory
- Perturbations?

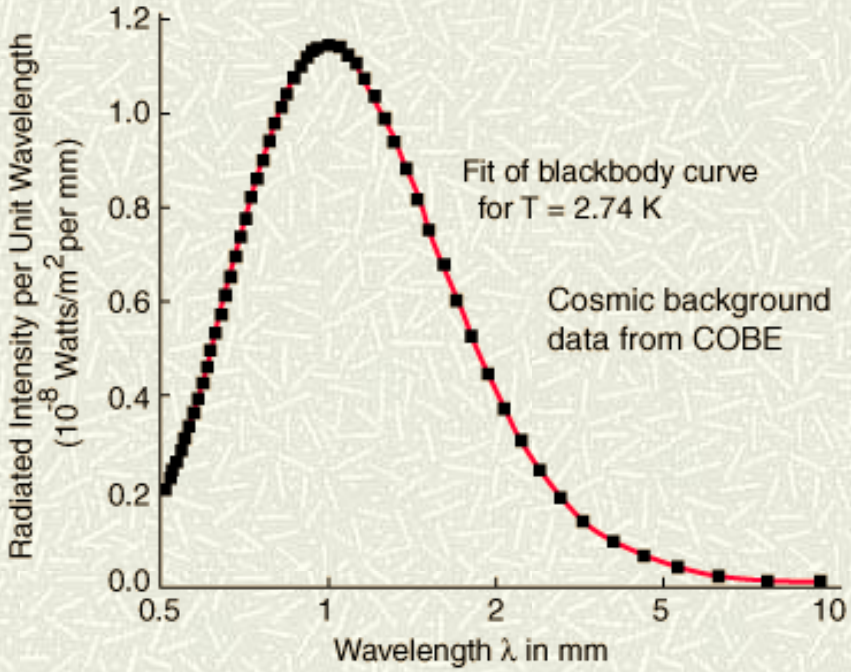
- ***Balloon experiments***
- ***Satellite experiments***



COBE satellite (1992)

COBE measurements of CMB

- Expected temperature
- Expected frequency
- Perfect blackbody spectrum



- *Radiation very uniform*
- *Variation of 1 in* 10^5
- *Seeds of galaxies ?*

COBE (1992)

Nobel Prize

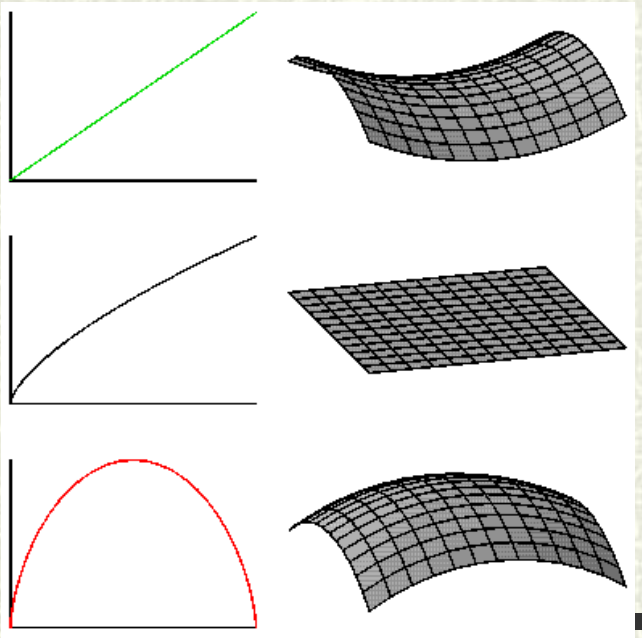
Problems

Robert Dicke

Background radiation raised new questions

- Horizon problem *why so uniform?*
- Galaxy problem *how did galaxies form?*
- Flatness problem *fine balance?*

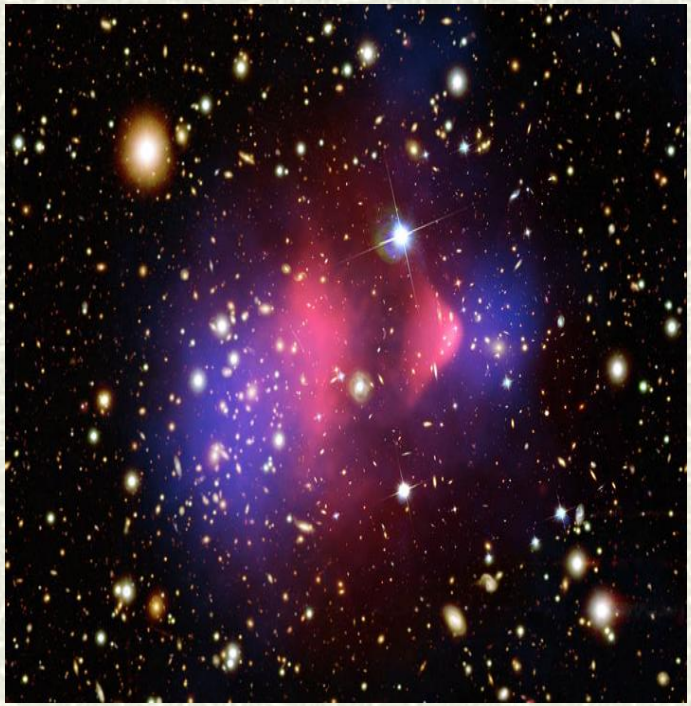
Conflict between theory and experiment
Astrophysics: $\Omega = 0.3$



Dark Matter

- First suggested in 1930s
- Stellar motion

normal gravitational effect but cannot be seen directly



- Explains motion of stars
- Explains motion of galaxies
- Explains gravitational lensing

Matter = OM (20%) + DM (80%)

$\Omega = 0.3$?

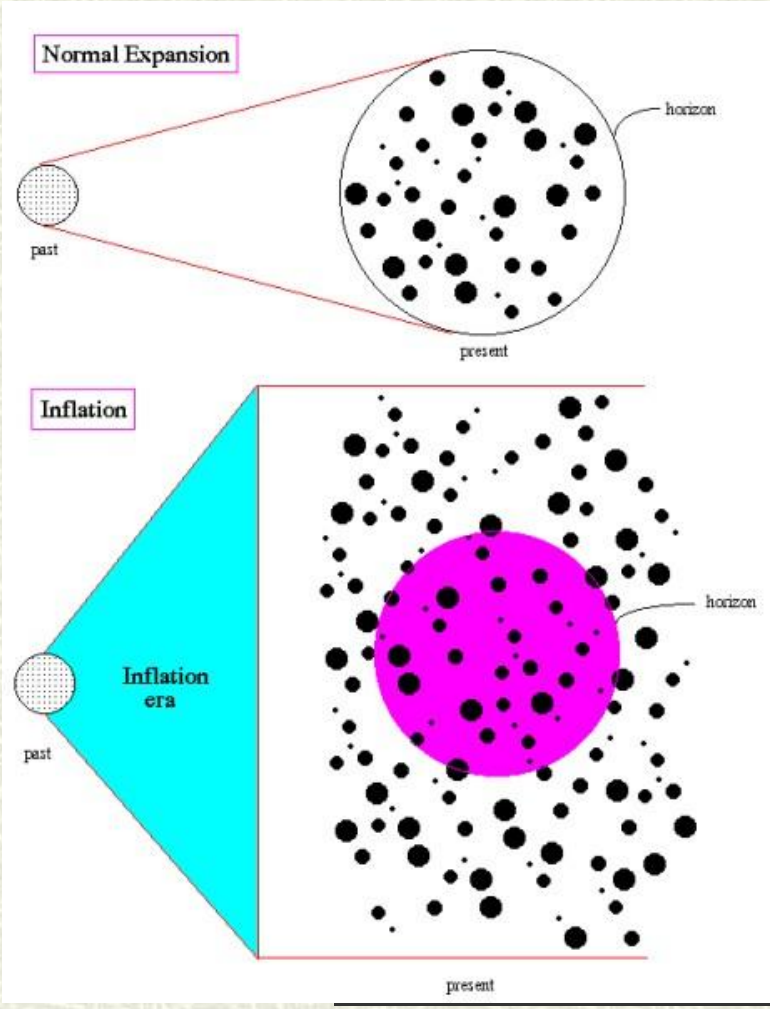
The Theory of Inflation

- Initial **exponential expansion**
- Driven by *phase transition*

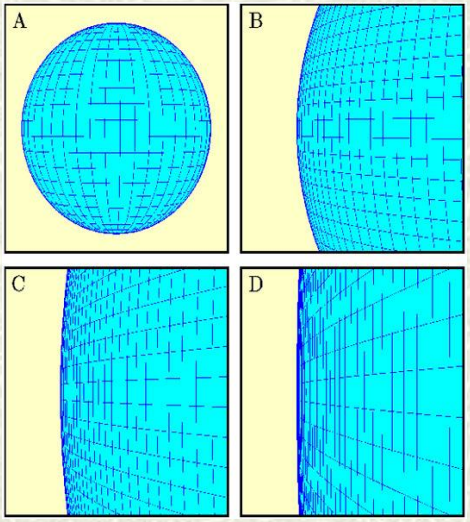
Repulsive force

- Expansion of 10^{35} in 10^{-32} s
- Smooths out inhomogeneities
- Smooths out curvature

'No hair' universe

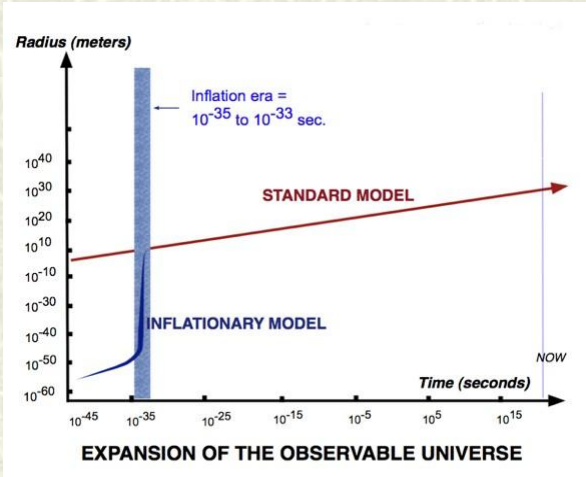


The inflationary universe (1981)



- Solves horizon problem
  Early U incredibly small
- Solves flatness problem
  Geometry driven towards flatness
- Mechanism for galaxy formation
  Quantum fluctuations inflated

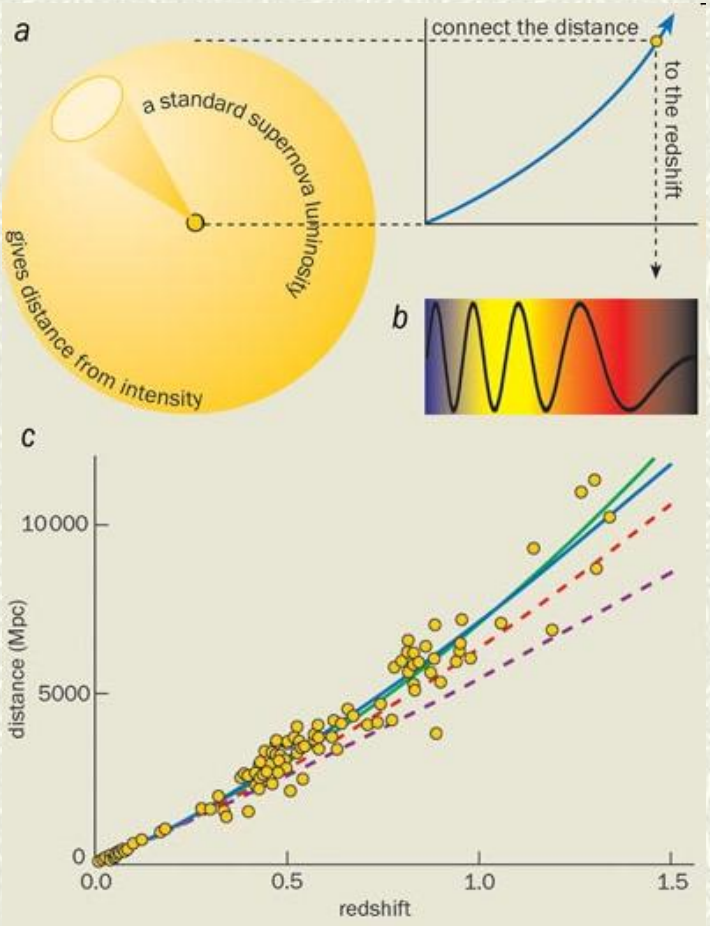
$\Omega = 1$?



Conflict between theorists and experimentalists

Supernova astronomy (1998)

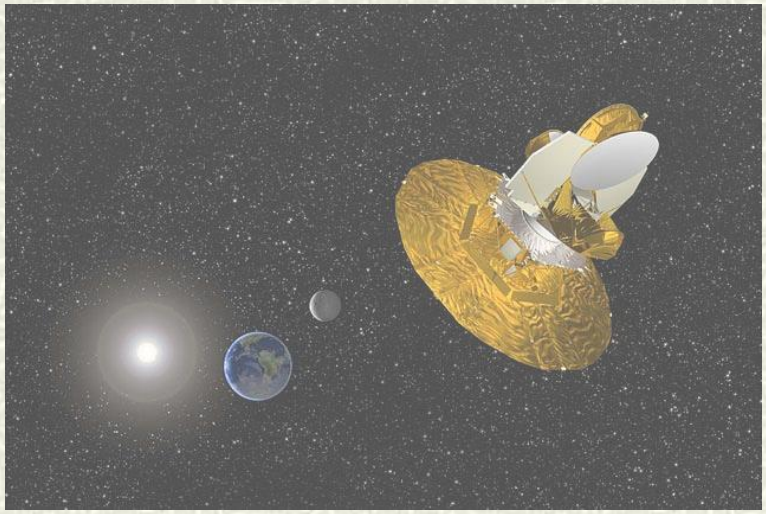
- Supernovae as standard candles (1998)
- Furthest galaxies too far away
- Expansion speeding up
- Geometry of *U* flat ($\Omega = 1$)
- Support for inflation

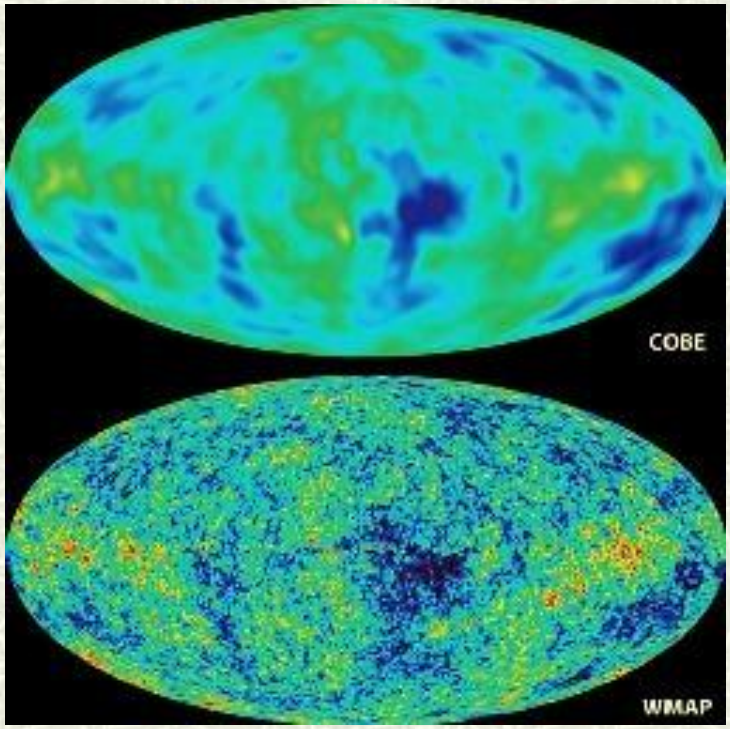


Dark Energy

WMAP Satellite (2002)

- Details of *CMB* spectrum
- Details of galaxy formation
- Details of flatness of *U*
- Dark energy?





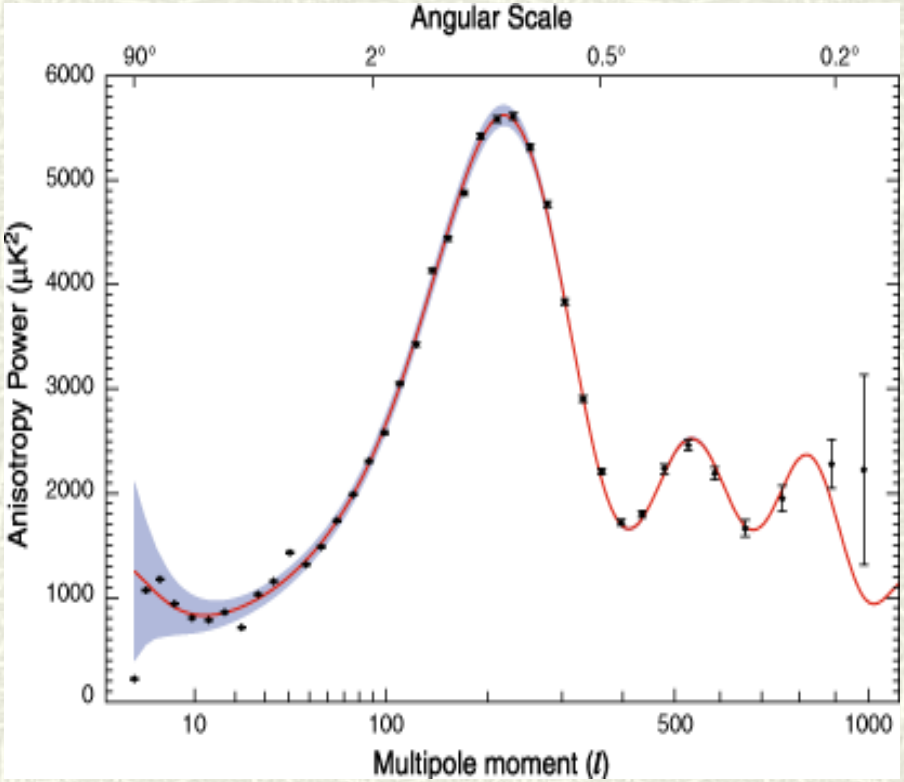
Cosmic microwave background

WMAP measurements of CMB (2005)

- Spectrum of *T* variations
- Geometry is flat (to 1%)
- Dark energy 74%

Strong support for inflation

Strong support for dark energy

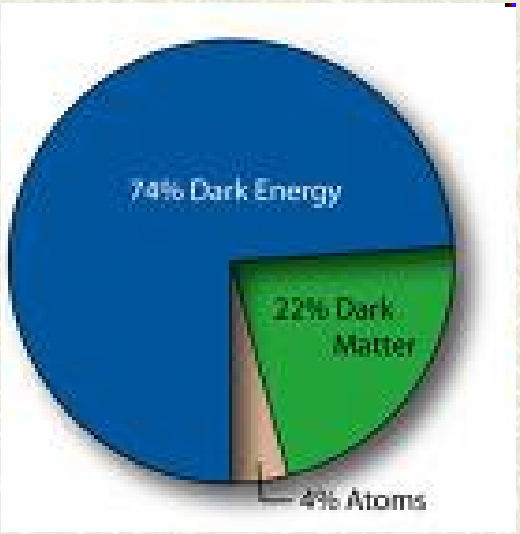


Fit to theory

Modern big bang model: *Λ-CDM*

A flat, accelerating universe containing matter, dark matter and dark energy

1. Ordinary matter: 4% (astrophysics)
2. Dark matter: 22% (astrophysics)
3. Dark energy : 74% (supernova, CMB)



ΛCDM

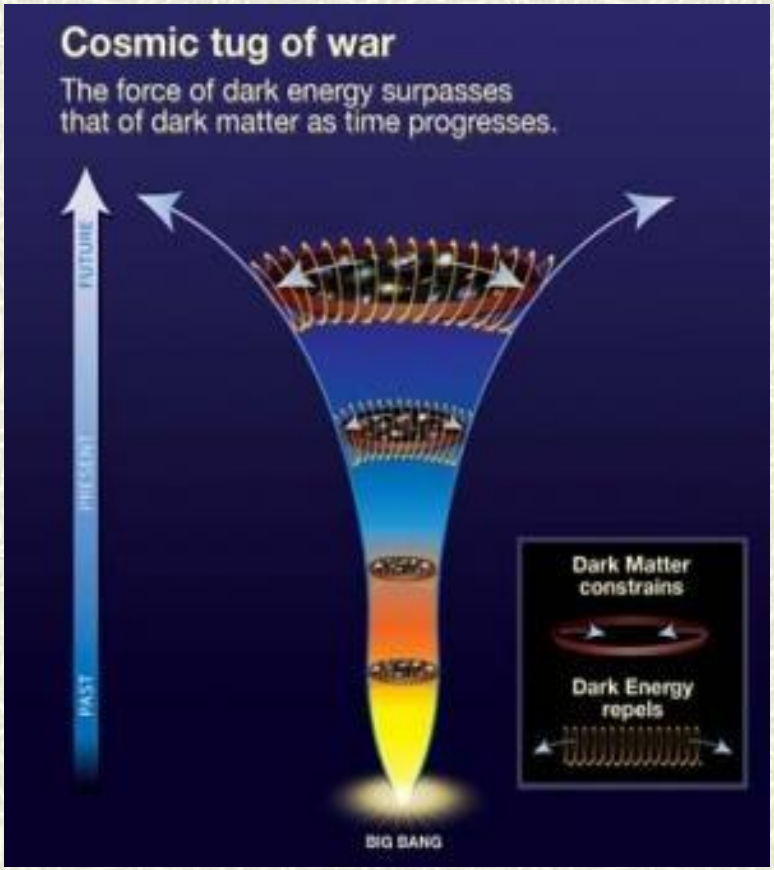
Ω = 1

Cause of acceleration: dark energy

- Predicted by relativity
- Cosmological constant
- Natural tendency of space to expand

- Energy of vacuum?
- Why so small?
- Why of similar density to matter?

- Not well understood
- Fate of universe?



New results: Planck Satellite (ESA, 2013)

1. Improved sensitivity

$$\Delta T/T \approx 1x10^{-6}$$

2. Full spectrum of *T* anisotropy

New acoustic peaks :scale invariance?

Accurate values for Ω_Λ , Ω_M

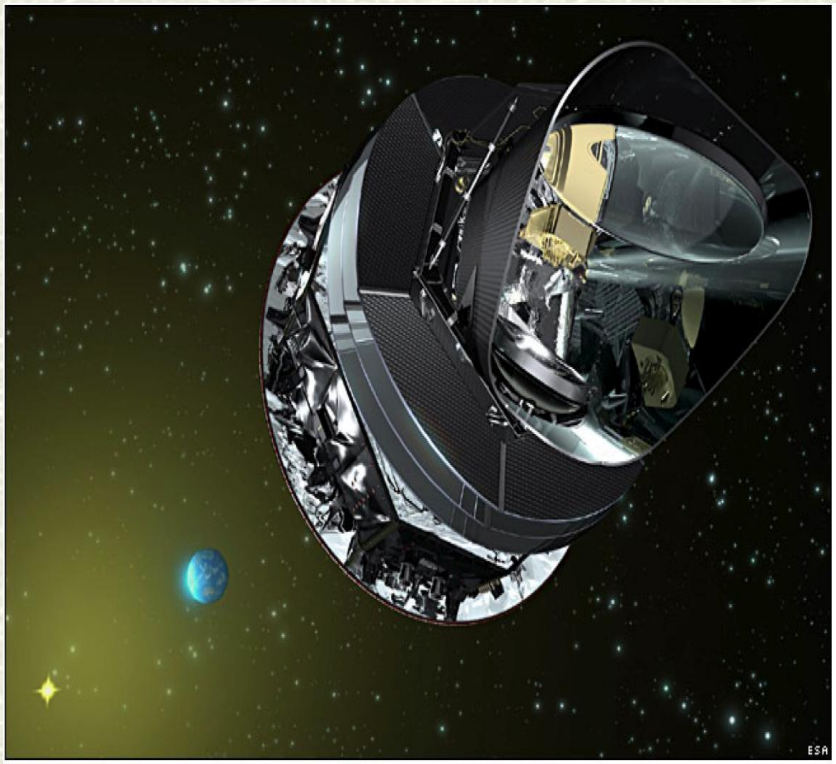
3. Gravitational lensing

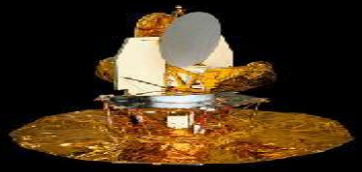
Remove degeneracies

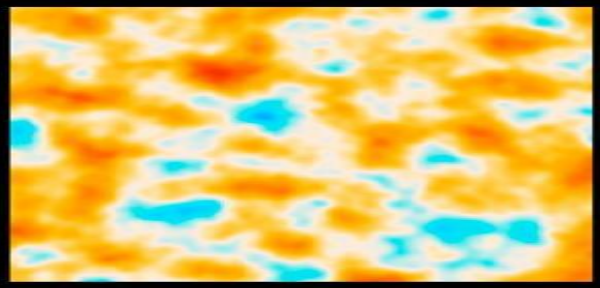
4. Polarization measurements

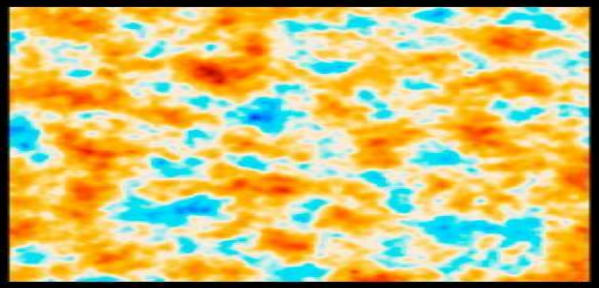
E-modes: fluctuations

B-modes: gravity waves?





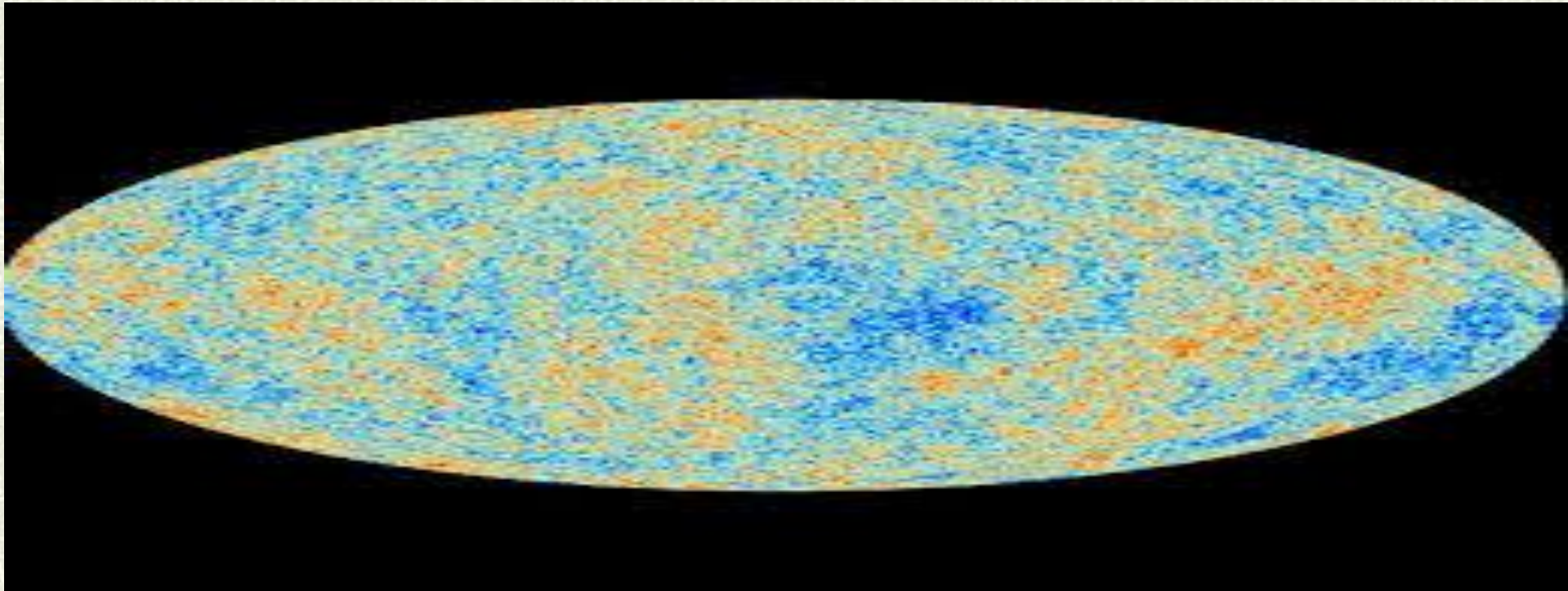




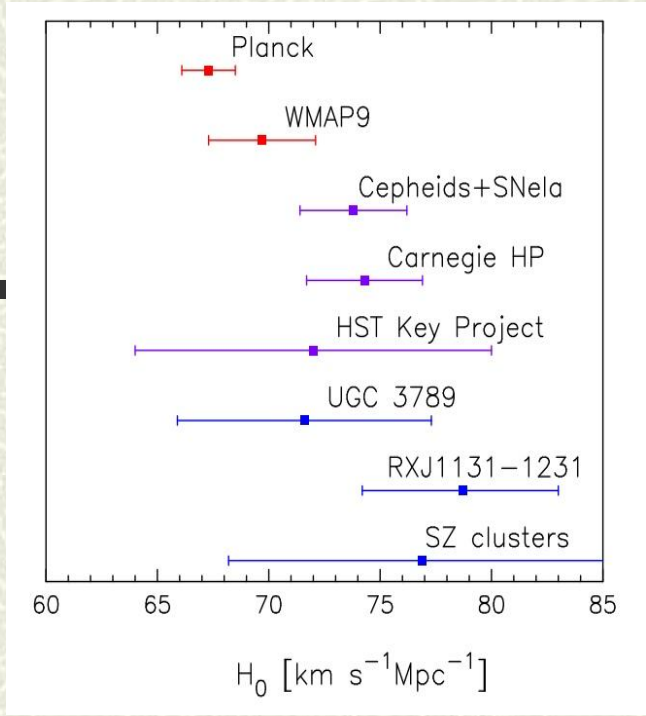
COBE

WMAP

Planck



Planck results (2013)



1. New Hubble constant

67.3 +- 1.2 km/s/MPC

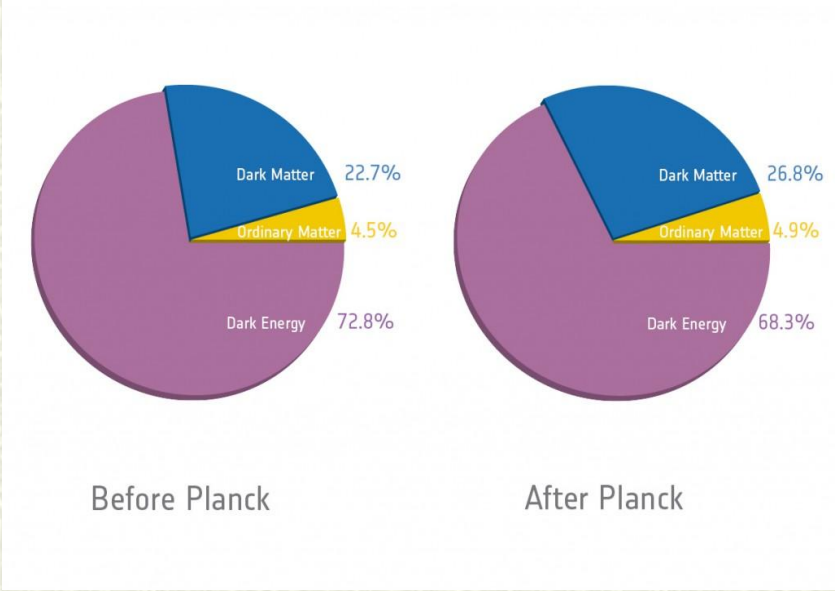
Age = 13.8 billion yr

2. Curvature ; flat

$\Omega_k = -0.0005 +- .07$

3. New mass/energy parameters

$\Omega_\Lambda = 68,\ \Omega_{DM} = 27, \Omega_{OM} = 4.9\ \%$

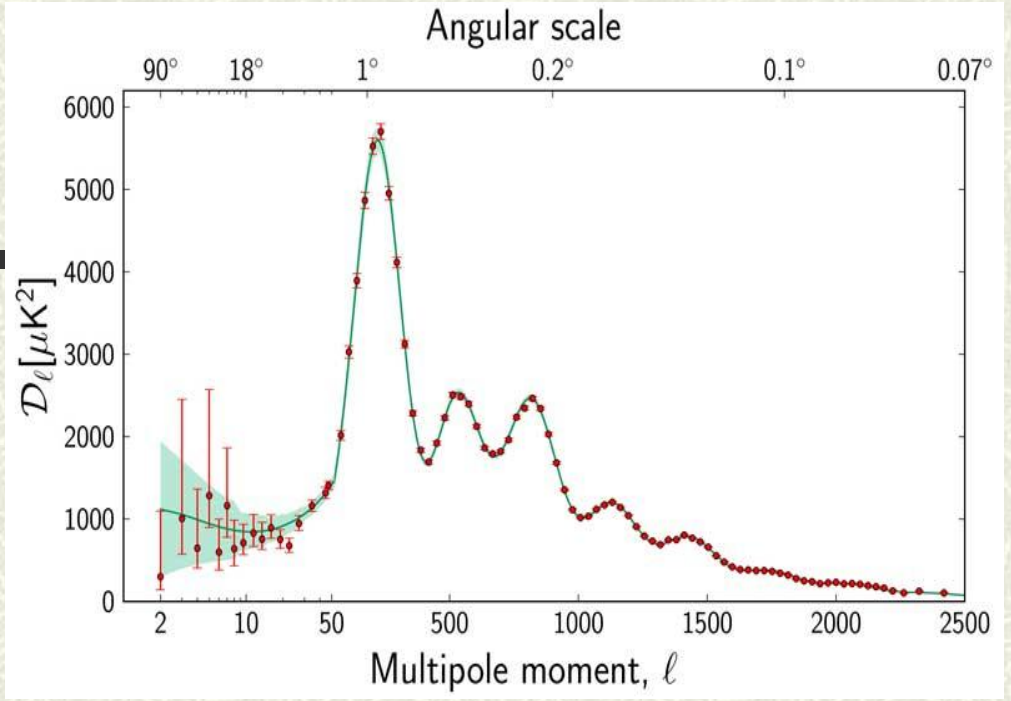


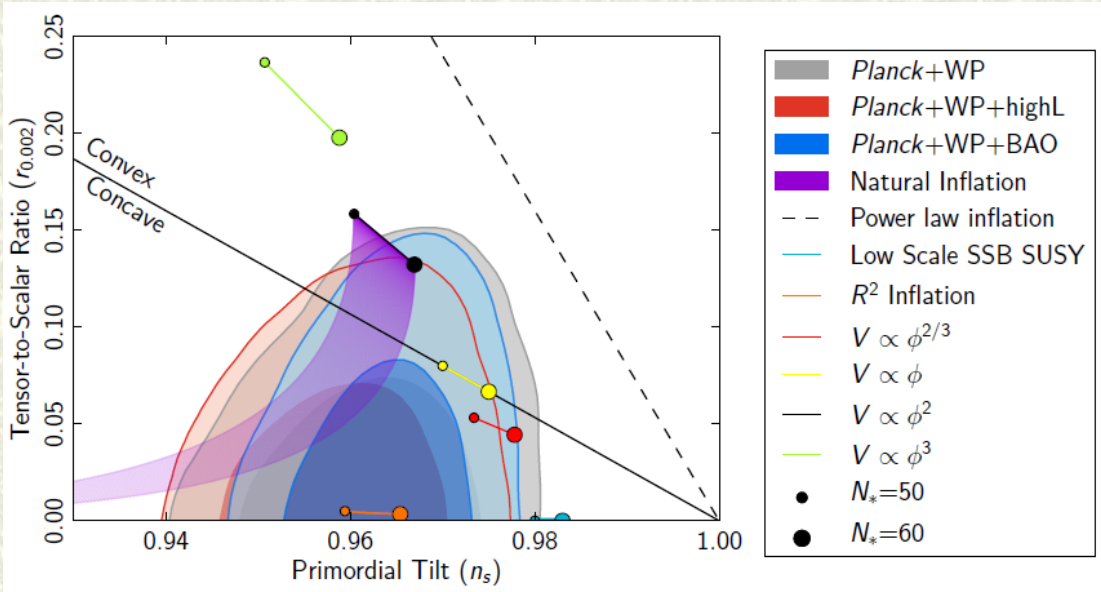
Planck Results

1. **Power spectrum**
   Not scale invariant $n_s = 0.96$

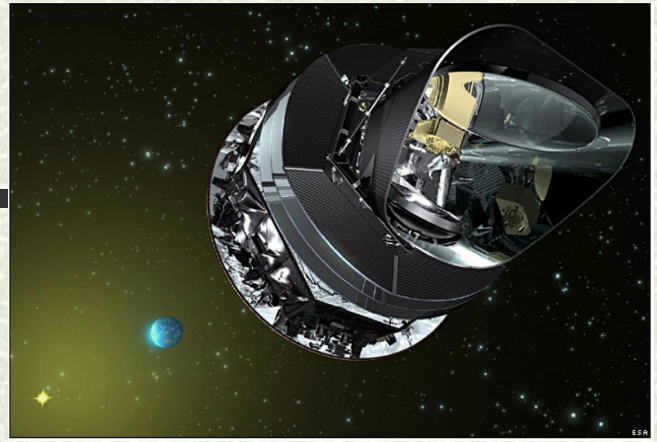
2. **Compatible with inflation**
   Simple 'slow-roll' models
   Higgs-type field?

3. **Complex inflation out**
   Double field out
   Hybrid models out
   Cyclic models out





Next: Planck 2014



1. **More on inflation models?**
   Higgs-types field?

2. **More on dark energy**
   Echo of inflation?

3. **Polarization measurements**
   E-modes and B-modes

4. **Gravity waves**
   Support for inflation
   Unified field theory

The big bang - problems

- Nature of dark energy?

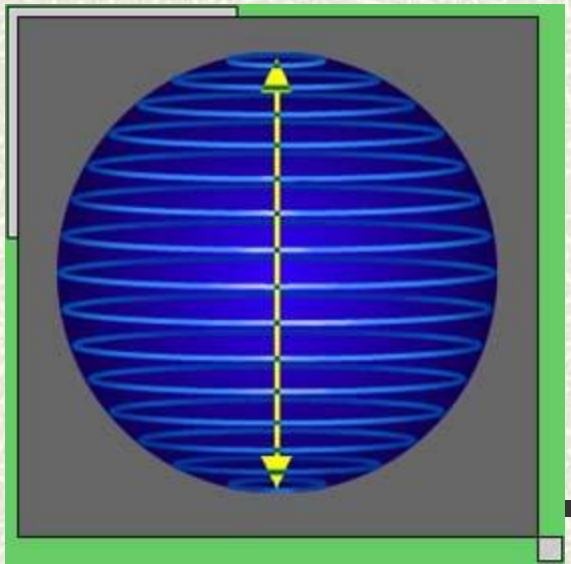
  Role in BB?

- Which model of inflation?

  The multiverse?

- The singularity problem

  What banged?
  What does time zero mean?
  No-boundary universe



The singularity: a cyclic universe?

- Breakdown at time zero
- No model of bang itself

- Multiple bangs?
- Colliding branes
- Prediction of string theory

- Cyclic universe
- Eternal universe

Cyclic universe

Tests? Non-Gaussianities in CMB