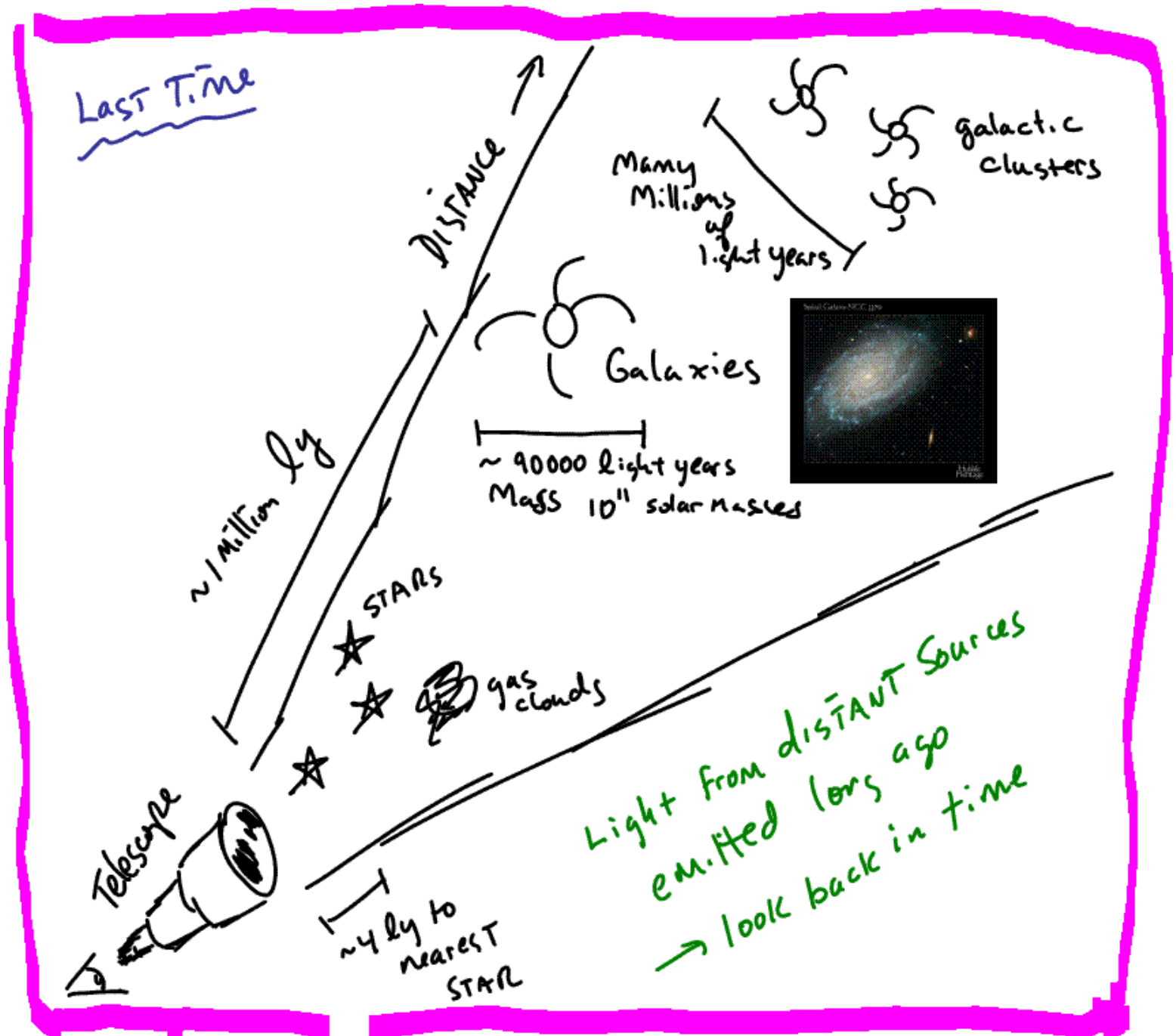
Physics 100 – November 26, 2007

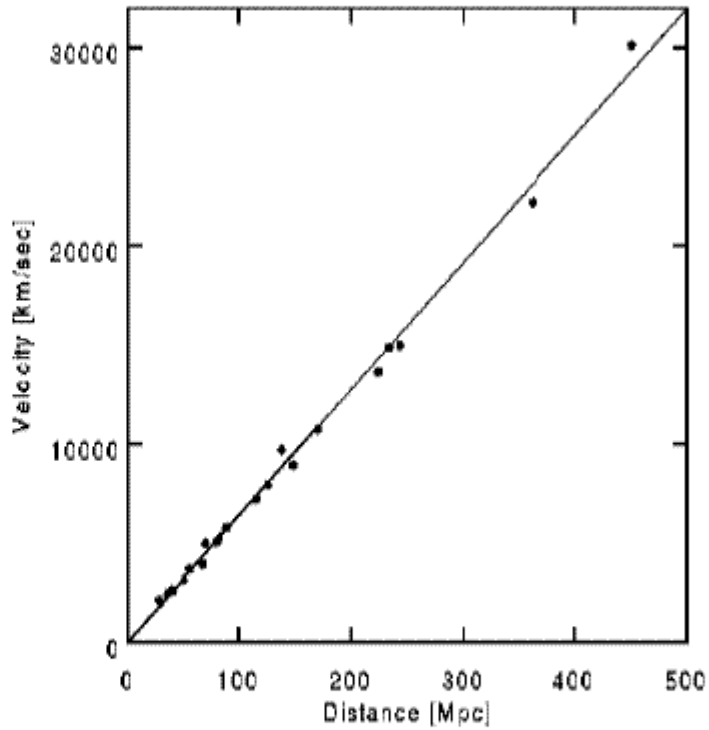
- Exam 2
- Presentations
  - Dec. 3 GPS
  - Dec. 5 Nucl. Terrorism
    Asteroids
  - Dec. 10 History
    CMB
  - Dec. 12 Music
    Nucl. Bombs
- Additional reading on cosmology (not required)
  → See class website


Last Time
Distance
Many Millions of light years
galactic clusters
Galaxies
~ 90000 light years
Mass 10^11 solar masses
~1 Million ly
STARS
gas clouds
Telescope
~4 ly to nearest STAR
Light from distant sources emitted long ago
→ look back in time

We live in an expanding universe

Edwin Hubble
(1929)

Recession Velocity →



Slipher early 20's

Also Milton Humason

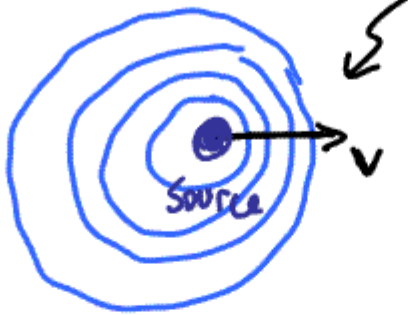
Distance to galaxy

Determined by redshift of atomic spectral lines

Determined by brightness (supernova in distant galaxy)

"Redshifted light"

Frequency Appears lower to objects in direction away from direction of Motion



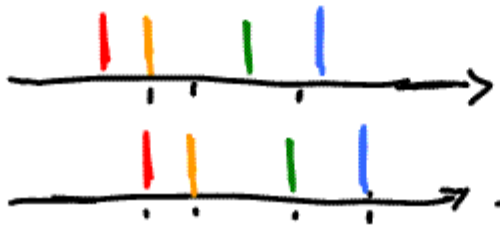
Frequency Appears higher to observers in direction of Motion

observer

"Blueshifted" light

larger v — larger the red and blue shifts.

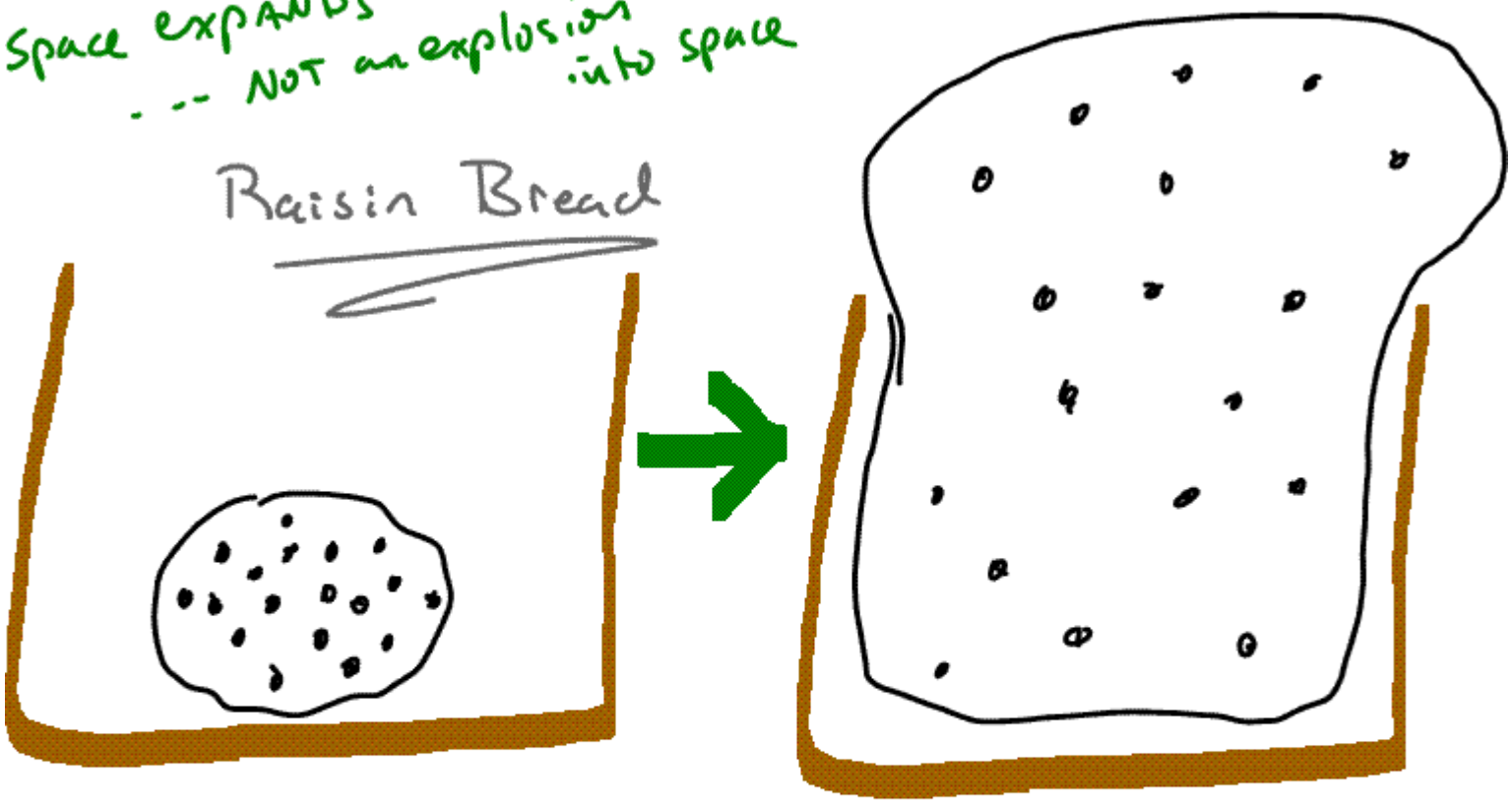
spectrum line positions shifted in color/frequency for source moving away from observer



Atomic Spectrum

(Color also changes — not shown)

Space expands
... NOT an explosion into space

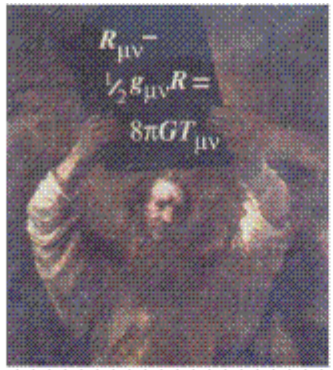


The expanding universe

NOT so crazy - General Relativity predicts it ...

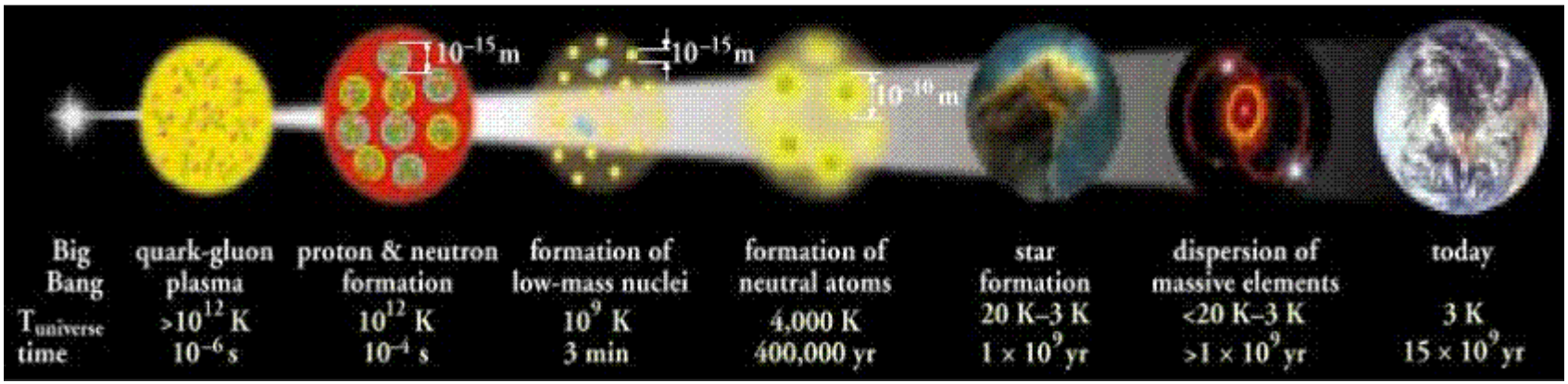
Einstein added a CONSTANT to remove
The non-STATIC aspect of eqns

Why Believe ? ...



- R. Kolb

... in the Hot Big Bang ?



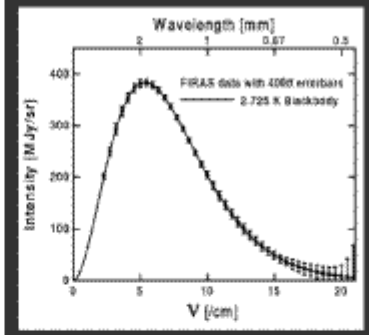
- Observe light from Time universe became transparent
  T ~ 400,000 years

- Perfect blackbody all directions in sky

- Amount of light nuclei in interstellar / intergalactic space agrees w/ expectation from Big Bang Nucleosynthesis
  T ~ 3 minutes

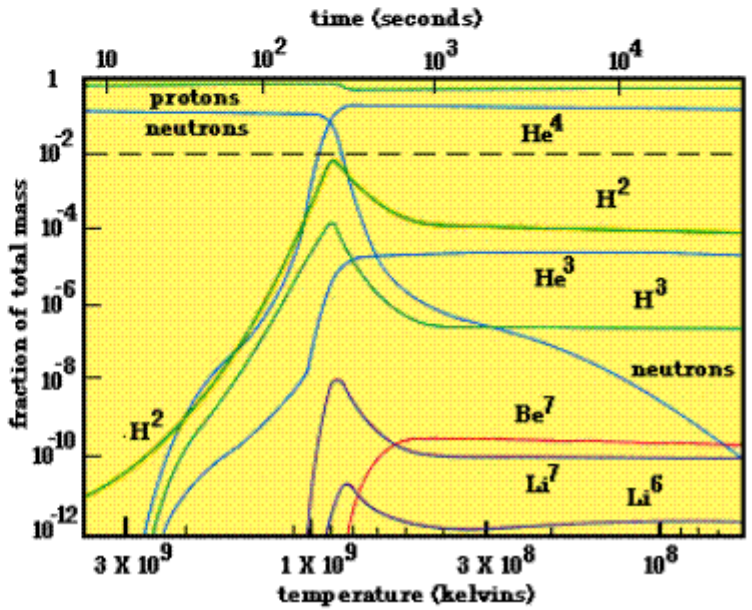
Cosmic Microwave Background

Penzias and Wilson - 1964



Uniform and isotropic

– in as far as they could measure



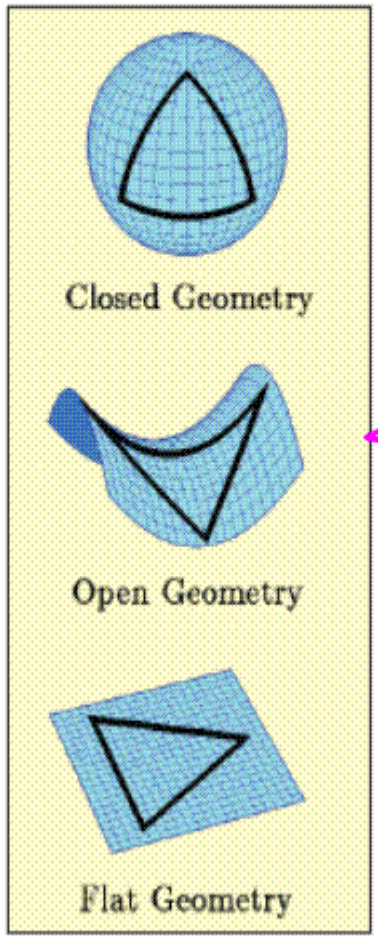
Problems w/ Big Bang

nonstatic universe expected from Relativity

Relativity allows space to have different curved geometries ?

Which is our universe?

Flat space is A very special case!



Sum of angles in triangle

$> 180°$

← universe expands... slows down + collapses

$< 180°$

← universe expands forever

$= 180°$

← universe expands to a stop

Very special case

- **Singularity Problem** – Yikes!! All of the universe at a Point?

- **Horizon Problem** – Why is universe so smooth and isotropic on large scales?

  Why CMB so smooth and isotropic

  at T = 400,000 yrs

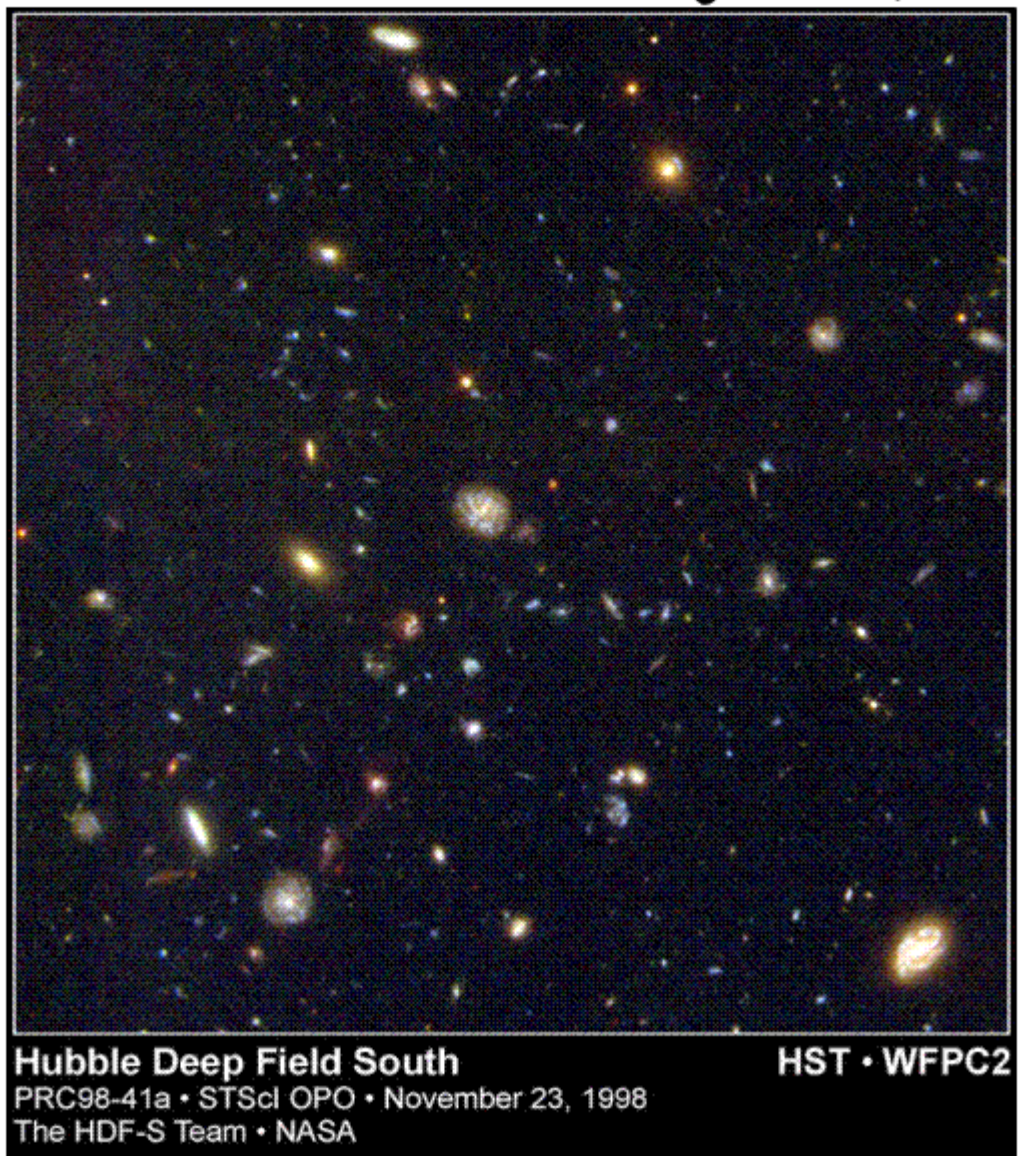
  only parts of universe as large as 400,000 light years could be causally connected

  yet all at same temperature??

- **Flatness problem** – universe appears to be very close to "flat" ... very Special Case.

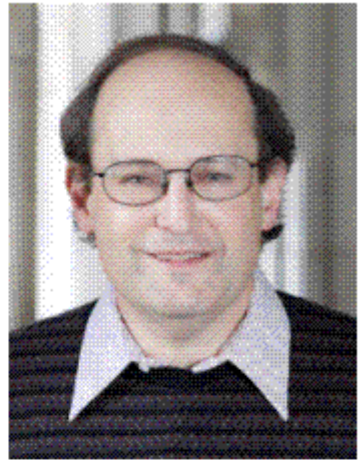
  Requires fine tuning of basic Model

- large scale structure problem – how do galactic structures form in a perfectly homogenous universe?



Andrei Linde
(Stanford)

Cosmic Inflation
~1979



Paul Steinhardt
(Princeton)

Andy
Albrecht
(UC Davis)

Idea used by
many cosmological theories
to solve Basic
Problems w/
Big Bang Model

Inflationary
Big Bang
Models

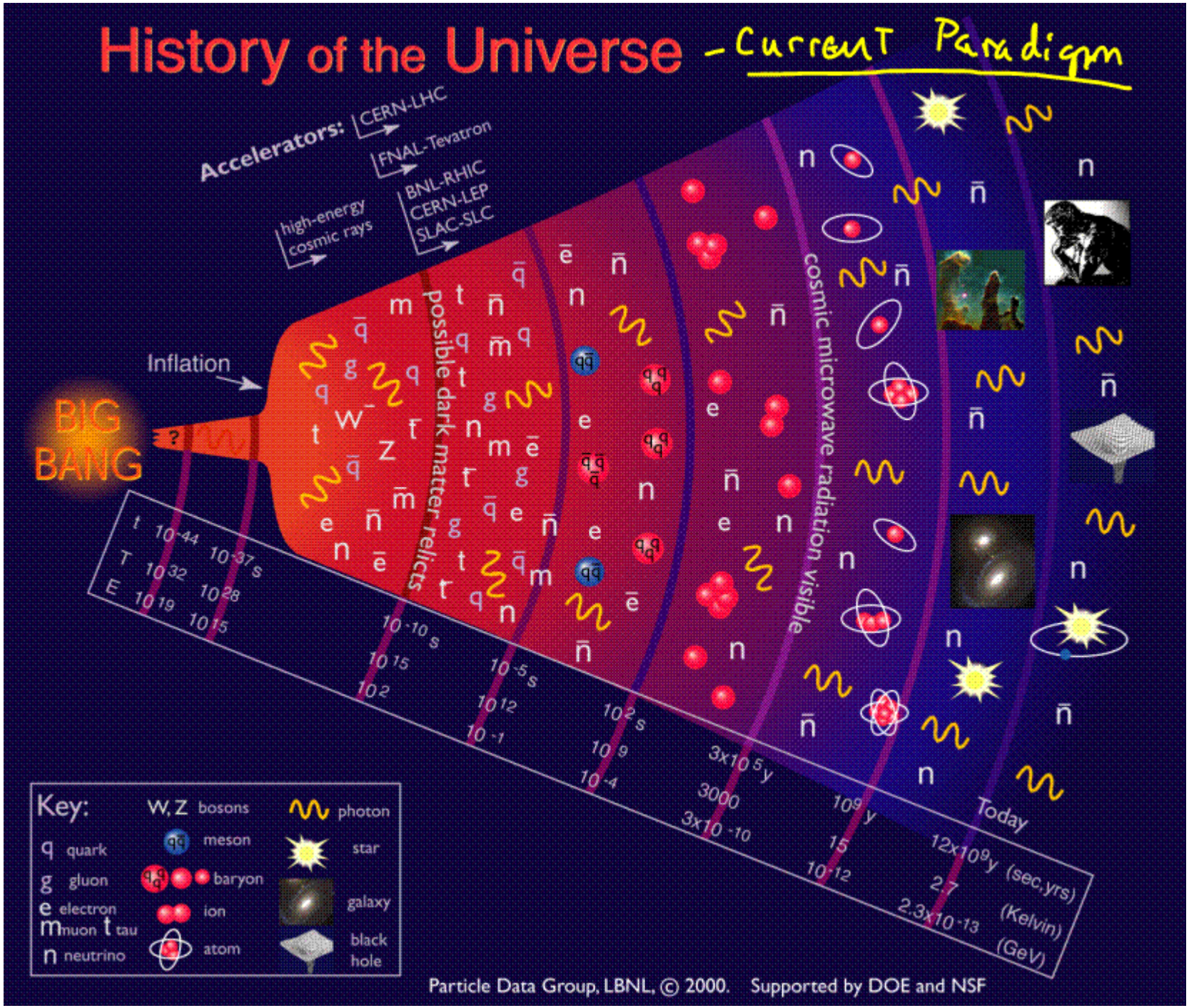
Alan Guth (MIT)

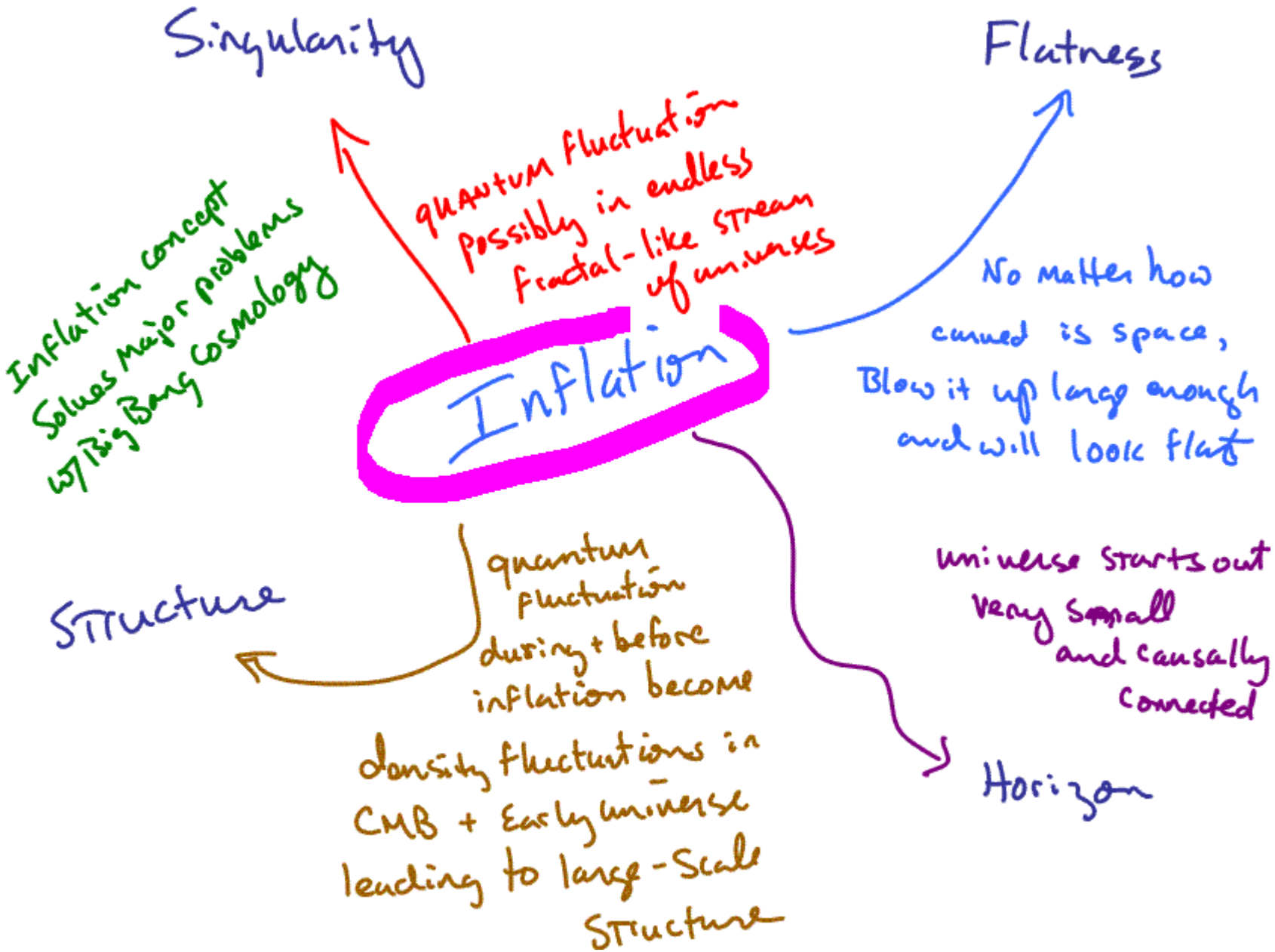
Inflation

- Universe starts very small
- Perhaps as a tiny fluctuation in a spacetime foam of tiny fluctuations
  maybe $\sim 10^{-26}$ m in size

- Properties of such a fluctuation can be constructed so as to create an unstable repulsion filling the space of the fluctuation — some "field" of particle is created in a quasi-stable excited state → inflaton What was it exactly?
- Leads to inflation — The ultimate understatement!

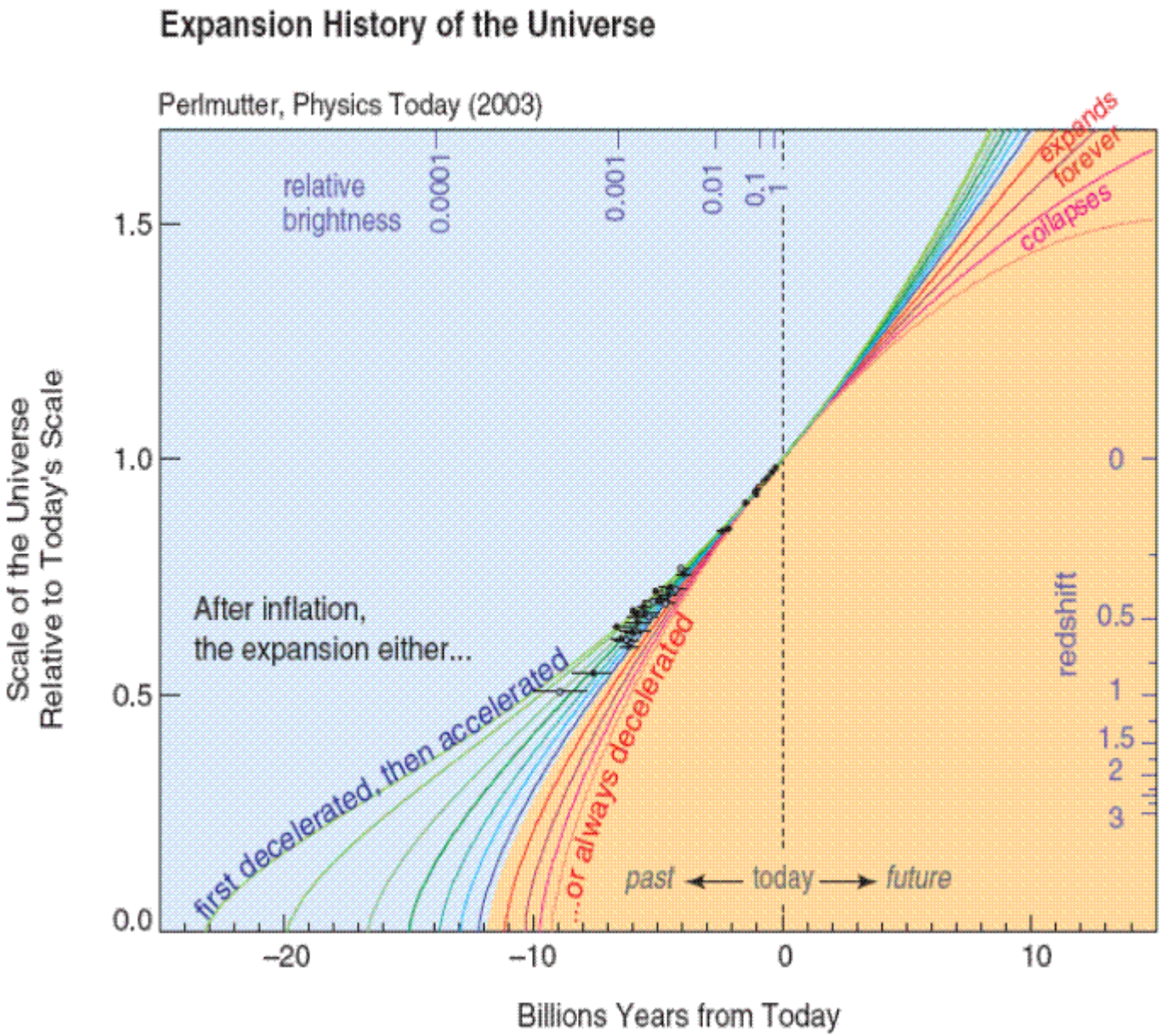
  Vast exponential superluminal expansion of the universe as inflaton "relaxes" expansion slows. Energy Driving inflation Dumped into matter + radiation and we have initial conditions for Big Bang Model as we know it

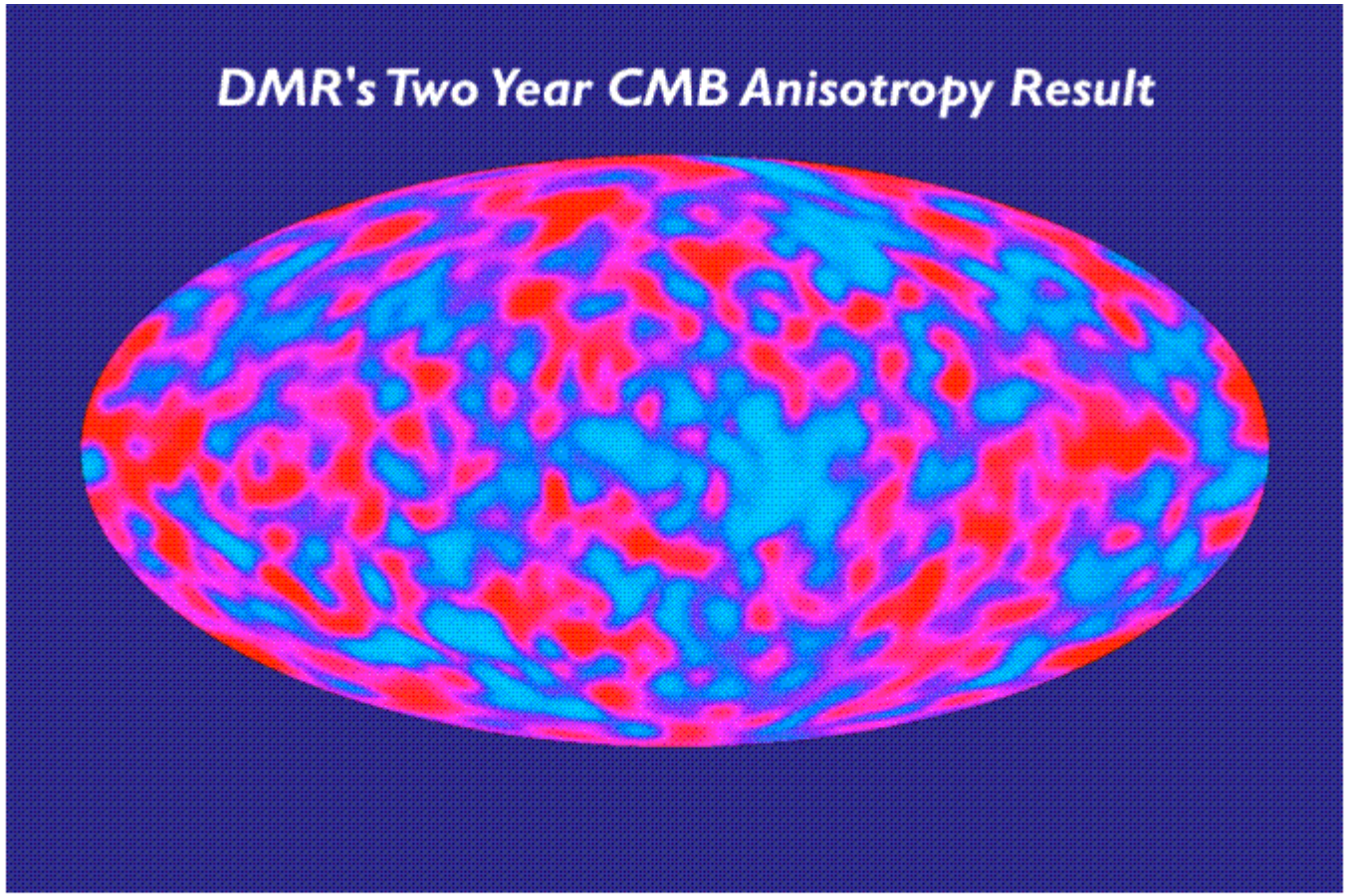

History of the Universe - Current Paradigm
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
10 15
10 2
10-5 s
10 12
10 -1
102 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
109 y
15
10-12
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


Singularity
Flatness
Inflation concept
Solves major problems
w/ Big Bang cosmology
quantum fluctuations
possibly in endless
fractal-like stream
of universes
Inflation
No matter how
curved is space,
Blow it up large enough
and will look flat
Structure
quantum
fluctuations
during + before
inflation become
density fluctuations in
CMB + Early universe
leading to large-scale
structure
universe starts out
very small
and causally
connected
Horizon

Incredible new data in the last 10 years

- Fluctuations in the Temperature/color of the CMB (1 part in 10^5)
  - Cobe, WMAP — satellites
- universe is "flat"
- Expansion of the universe is Accelerating
  - observations of supernovae in distant galaxies
    - Two groups of scientists: Supernova Cosmology Project — Perlmutter at UC Berkeley; High-Z Team


Expansion History of the Universe
Perlmutter, Physics Today (2003)
relative brightness
0.0001
0.001
0.01
0.1
1
expands forever
collapses
After inflation, the expansion either...
first decelerated, then accelerated
...or always decelerated
redshift
0
0.5
1
1.5
2
3
past
today
future
Scale of the Universe Relative to Today's Scale
0.0
0.5
1.0
1.5
–20
–10
0
10
Billions Years from Today



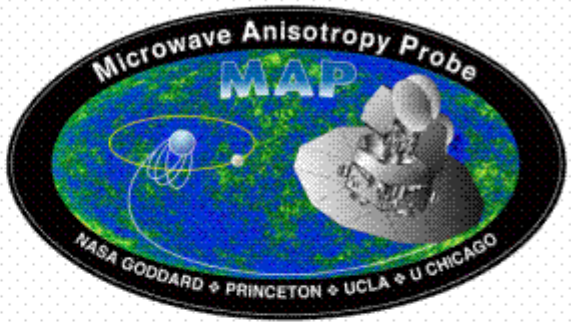
CMB "color" or Temperature seen to vary by 1 part in 100,000

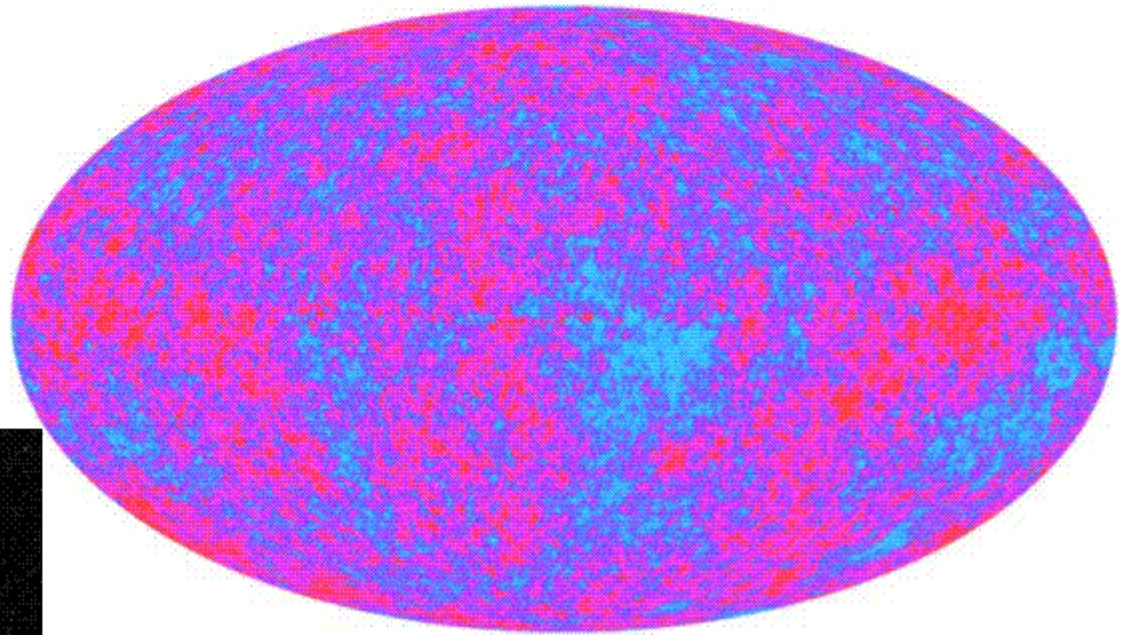
1992 COBE Satellite observation of CMB over all Sky

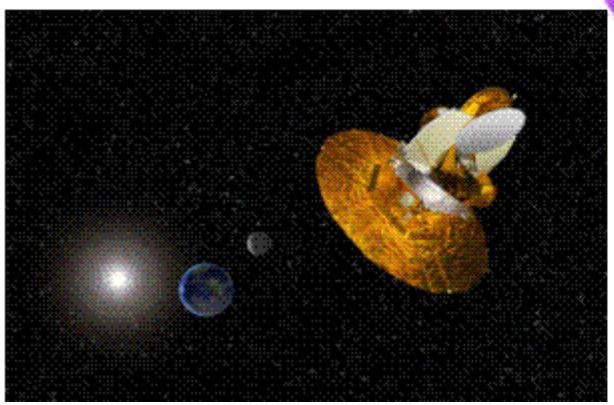
Cosmic Background Explorer

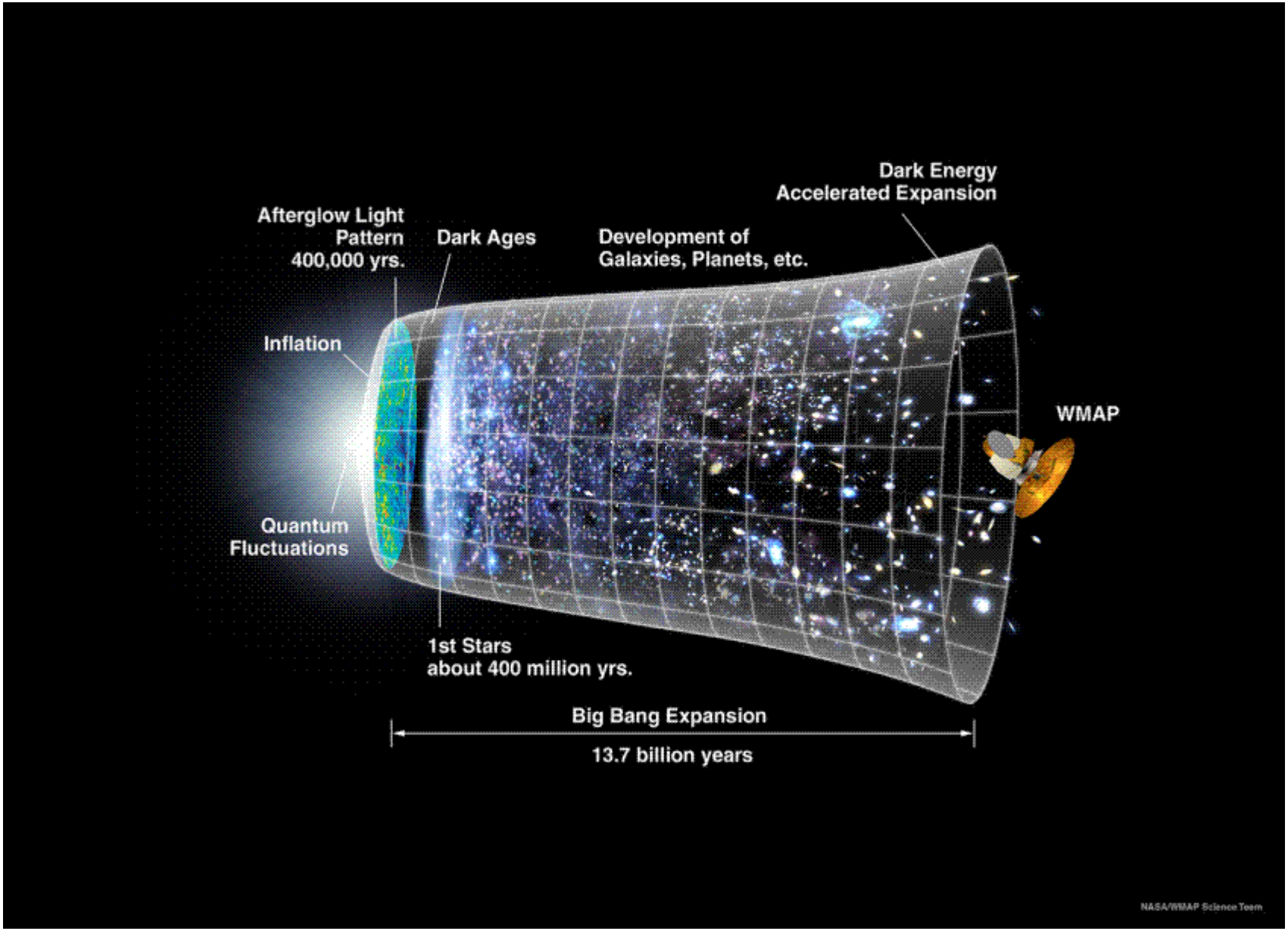
WMAP - Wilkinson Microwave Anisotropy Probe

(2003 High Resolution Study of CMB





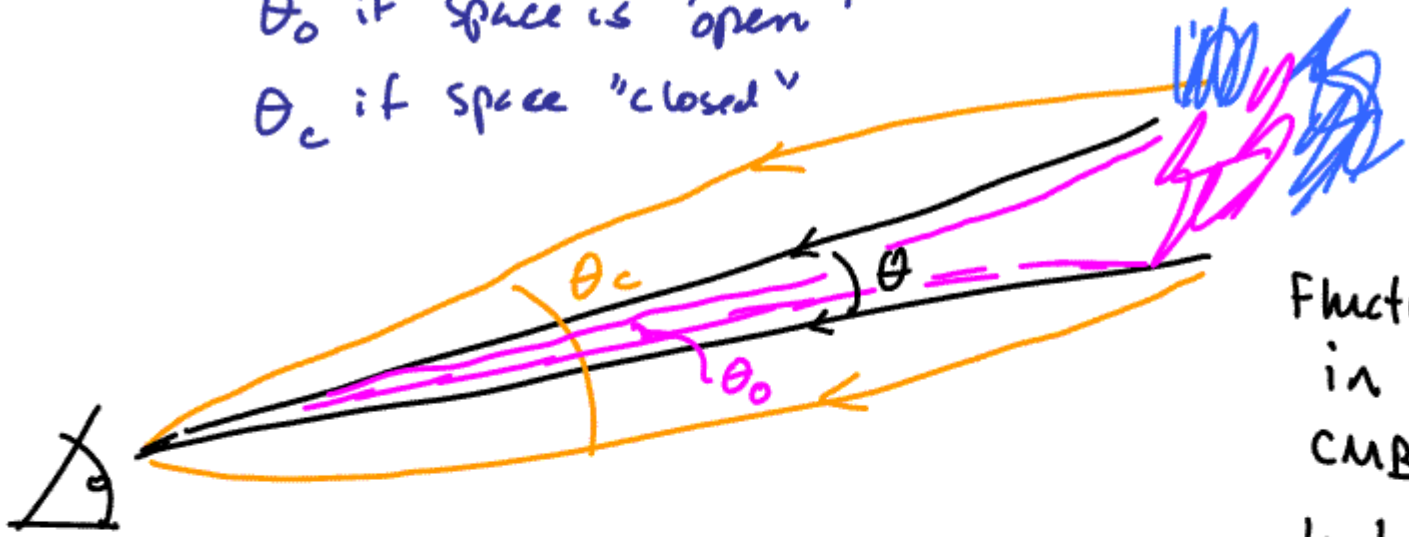



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Measure θ_f if space is flat

θ_o if space is "open"

θ_c if space "closed"

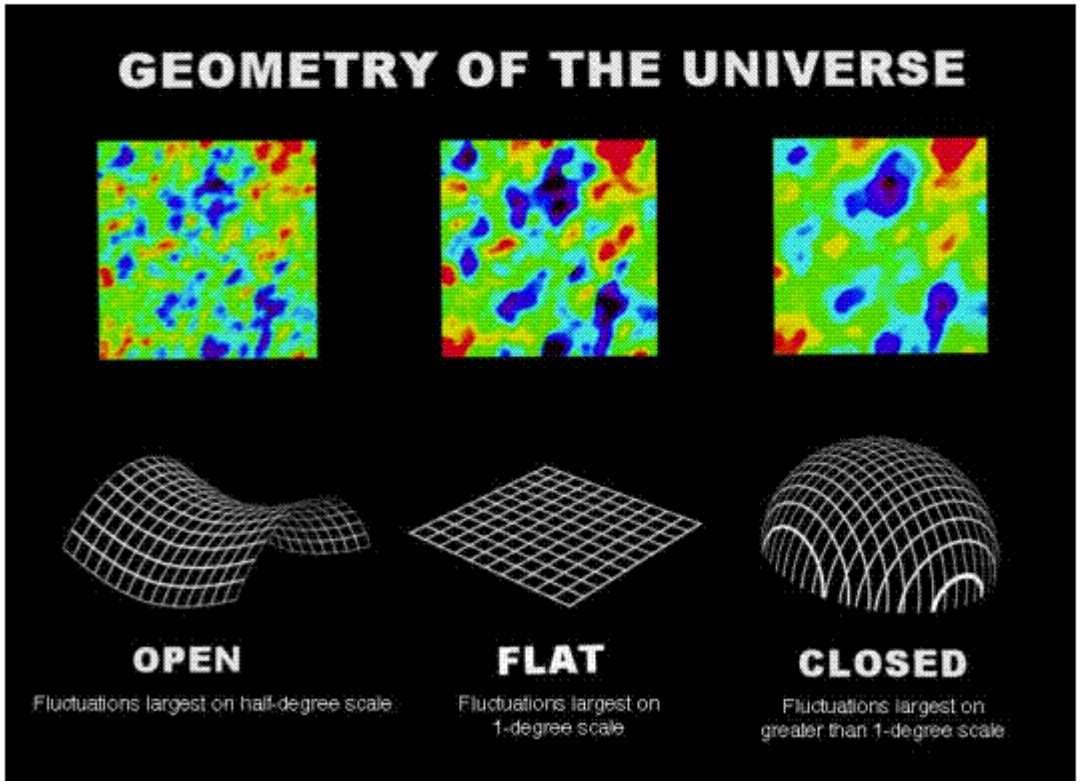


Fluctuations in CMB - light comes to us from DISTANCE of (Age of universe - 100,000) light years

Look at Angular Size of fluctuations in CMB

PATH light takes depends on geometry of universe. We measure different Angular Sizes depending on geometry of space between

Size of fluctuations/structure in the CMB is sensitive to the geometry of the universe




Inflationary Big Bang Model
STANDard Model of Particle Physics
Much of the Puzzle is in place
Still some Missing Pieces ...

Dark Matter

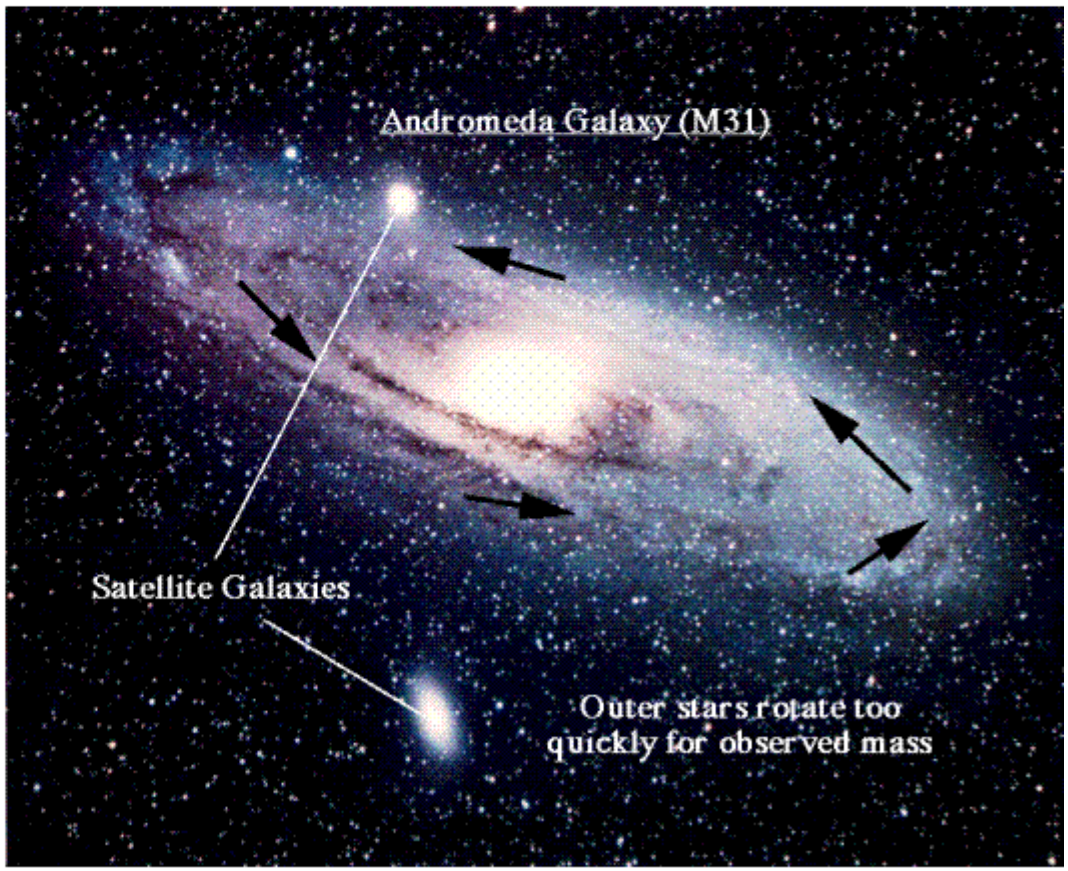
Orbits $F = \frac{mv^2}{r}$ $F = \frac{GMm}{r^2}$

Circular Motion

$\frac{mv^2}{r} = \frac{GMm}{r^2}$

Can relate velocity radius and force in orbits.

Have seen that orbits in stars and galactic clusters require stronger Gravitational force than can be explained by conventional Observable "visible" matter



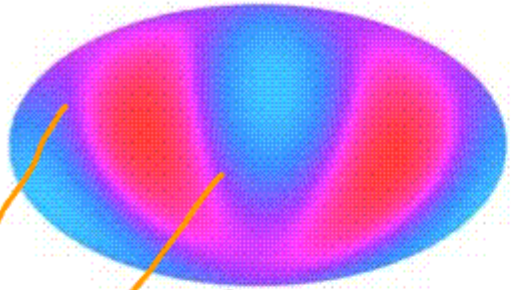
-P. Cushman

This is evidence for a new form of Matter in the universe that interacts gravitationally but Not via the other forces.

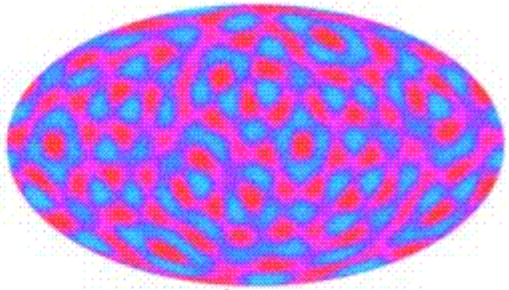
Does Not emit or absorb light, for example.

And we don't know what it is!

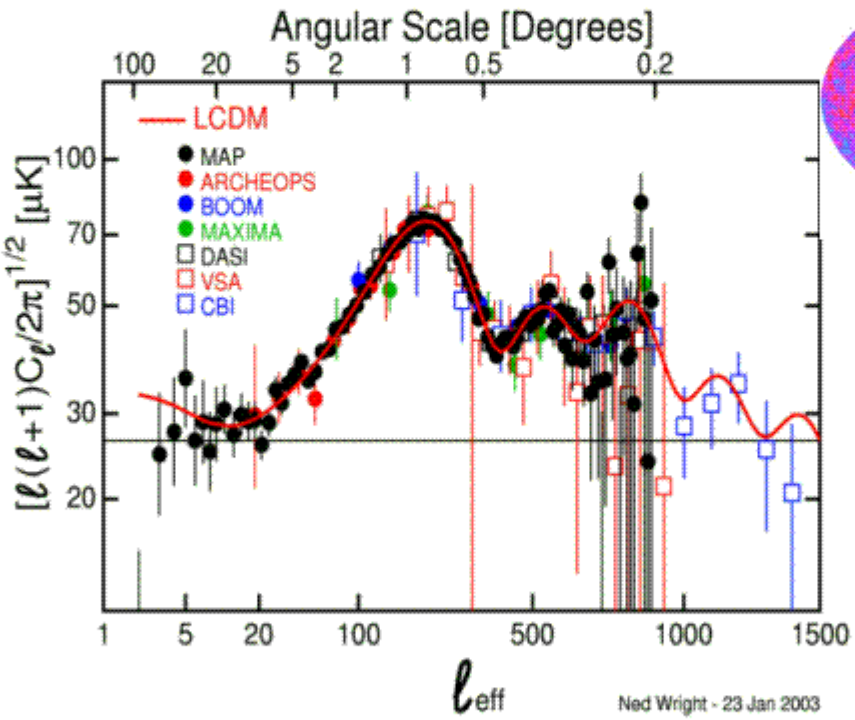
May make up 80% of the Mass in the universe!!

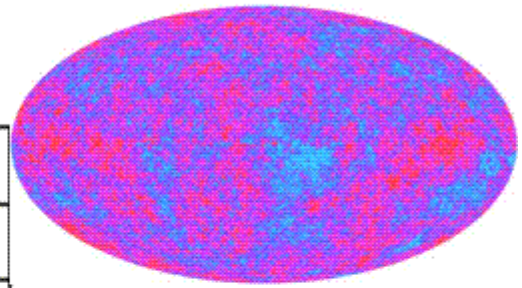


$\ell = 2$



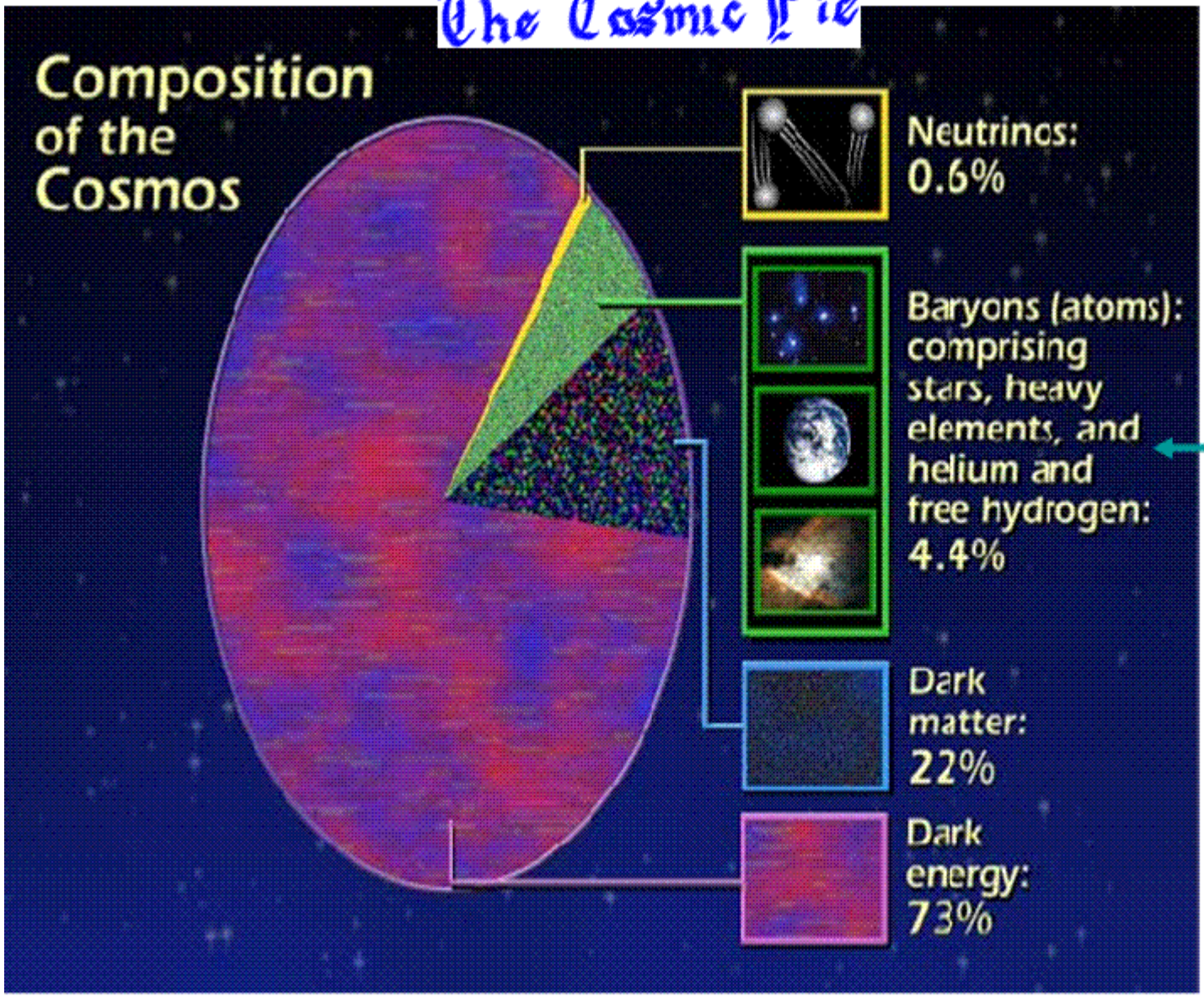
$\ell = 16$





"Power spectrum" (size) of temperature fluctuations sensitive to different matter/energy components of the universe

The Cosmic Pie



95% of the universe is unknown!

figure from E. Linder LBL