Lecture 20
Cosmology, Inflation, dark matter

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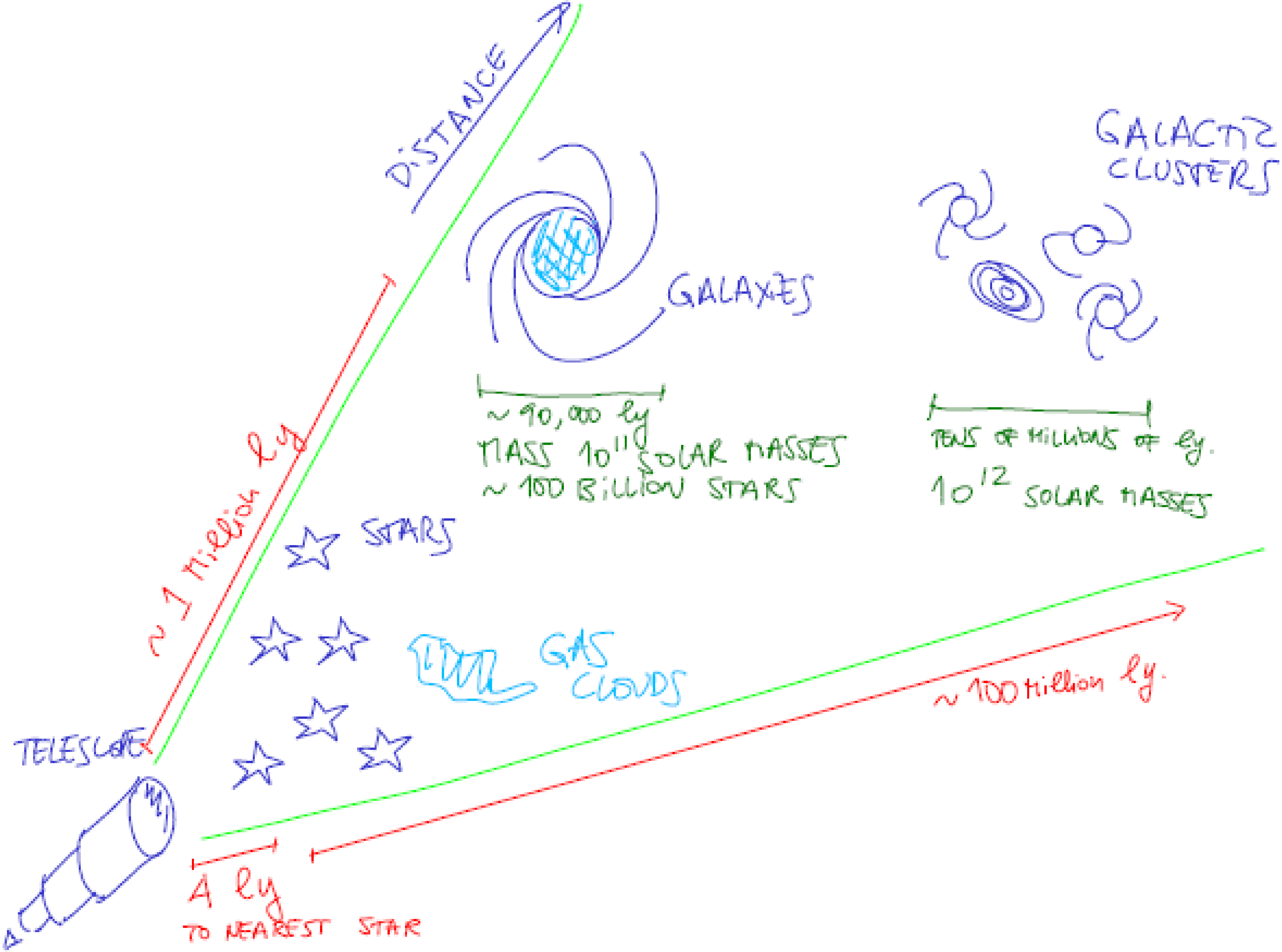
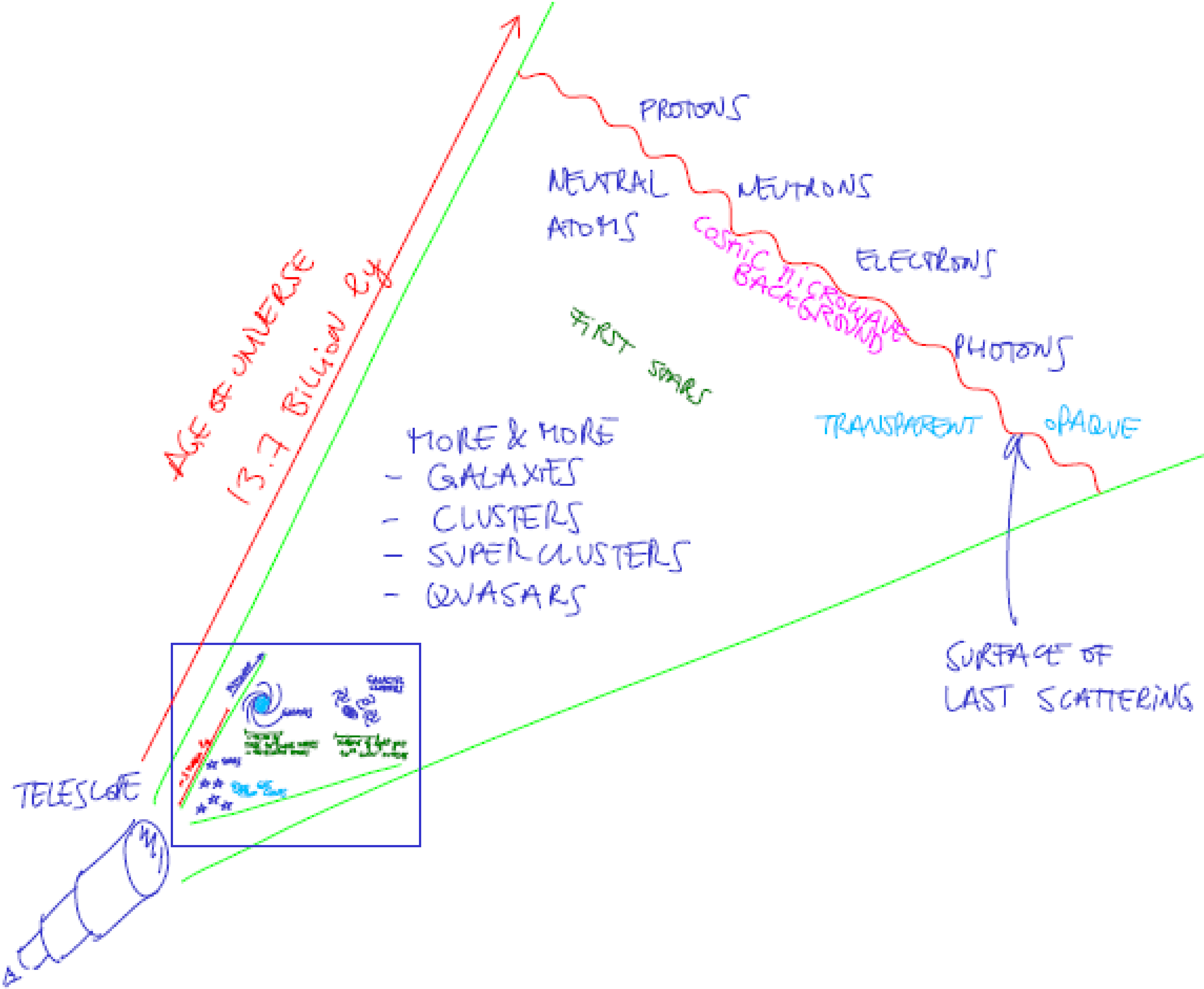
News

Presentations:

- One speaker only (20 minute talks)
- You can do demonstrations, videos, etc...
- Test the equipment in Hoyt beforehand
- Emphasize scientific aspects, link to topics seen in course
- You will be evaluated by the rest of the class
- You have to make it interesting and explain the physics well
- Everyone should learn something from the talks
- You will give me:
  - The file of your talk
  - A one page summary of the main points
  - Three possible exam questions

Light from distant sources emitted long ago: look back in time



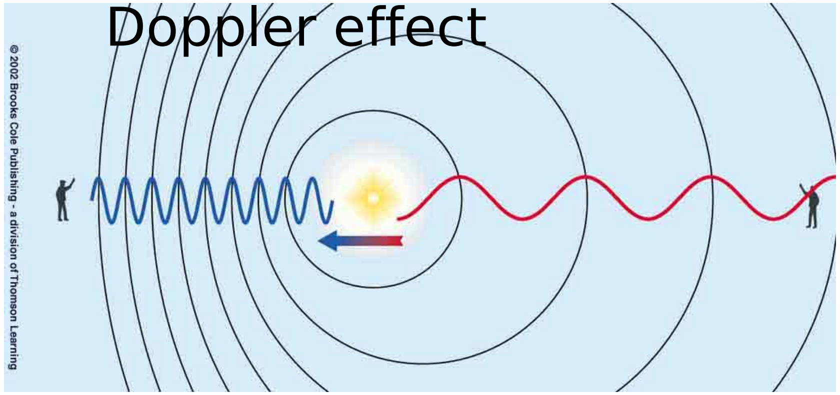

AGE OF UNIVERSE
13.7 BILLION LY
PROTONS
NEUTRAL
ATOMS
NEUTRONS
COSMIC MICROWAVE
BACKGROUND
ELECTRONS
FIRST
STARS
PHOTONS
TRANSPARENT
OPAQUE
MORE & MORE
- GALAXIES
- CLUSTERS
- SUPERCLUSTERS
- QUASARS
SURFACE OF
LAST SCATTERING
TELESCOPE

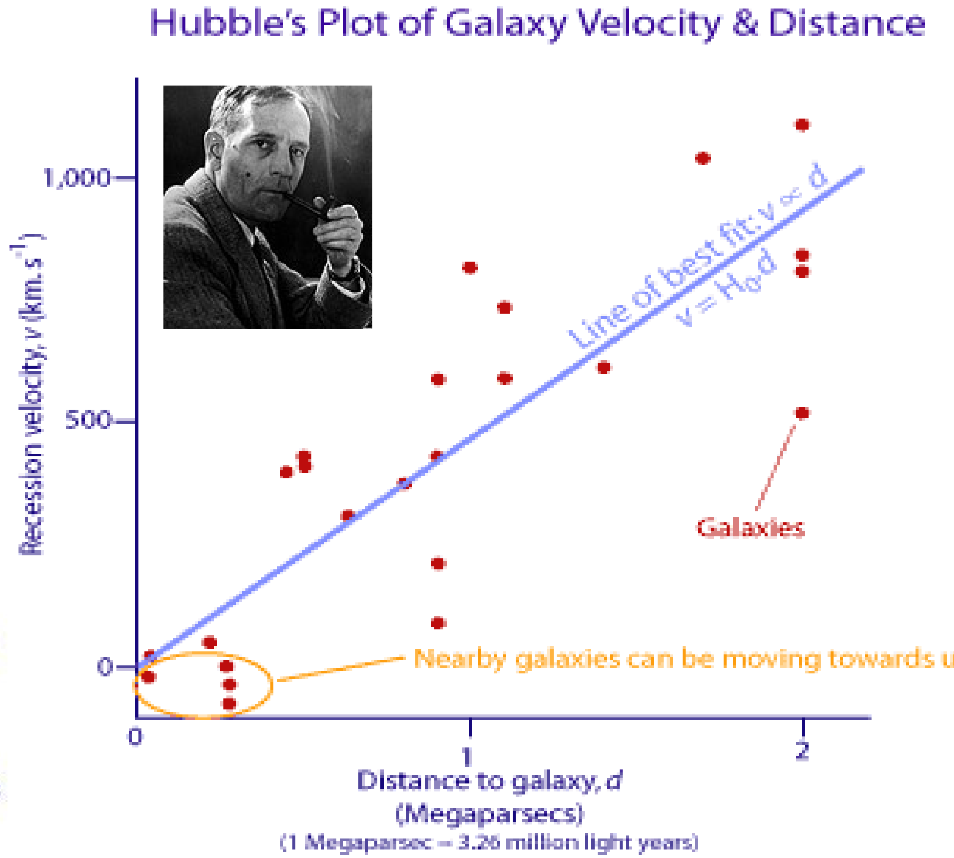
Cosmology

- We assume the following:
  - **Homogeneity**: matter and energy are evenly distributed on the largest scales
  - **Isotropy**: the universe looks the same in all directions
  - **Universality**: the physical laws that govern the universe are the same everywhere (and everywhen)
- **Cosmological Principle**: An observer anywhere in the universe sees approximately the same thing
  - No place is special, no edge or center

- Big Bang theory
  - Hubble: the universe is expanding
  - Observation: all galaxies are receding from us due to this expansion (their recession is NOT due to their own motion)
  - If the universe expanding now, it's logical to assume it was smaller before... all galaxies and stars come from a hot, high-density plasma (soup of fundamental particles+energy)

Galaxies are being carried away





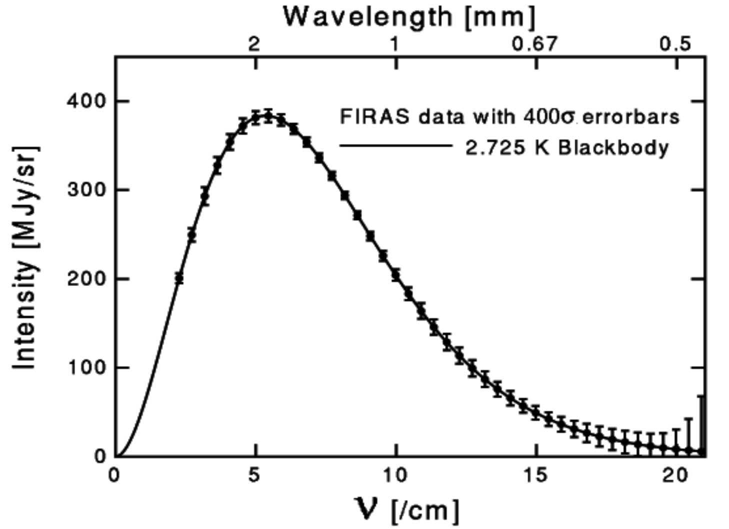
- Measure distance from Earth to galaxy by measuring how bright the galaxy is: supernova explosions have known brightness
- Measure the recession velocity by redshift of atomic spectral lines
  - The same pattern of lines appears moved towards red part of the spectrum: the larger the shift, the higher the velocity
- It's not that the galaxies fly apart on their own: the Universe is expanding

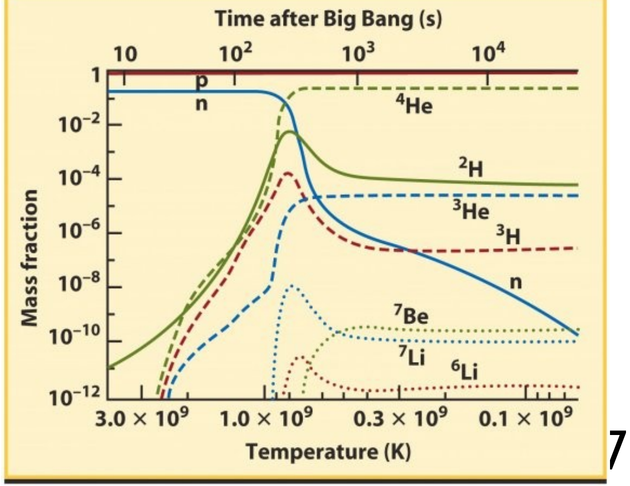
Big Bang

- Big Bang is probably a very bad name: there is NO explosion into space
- It is space itself who is expanding! ← IMPORTANT!
- We cannot know what it is expanding into: all our measurements and what we know of the world is limited to THIS space!

Observational tests:

- Galaxies receding
- Detect cosmic microwave background
  - Pervasive radiation: the same in all directions in sky
  - When the universe became transparent
  - Perfect blackbody radiation at T=2.7 K
- Amount of light nuclei in intergalactic space
  - Observations match expectations from Big Bang nucleosynthesis (t~3 min)
- Distribution, form, evolution of stars/galaxies
  - Young stars less rich in heavy metals

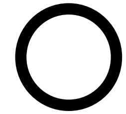




Geometry of space

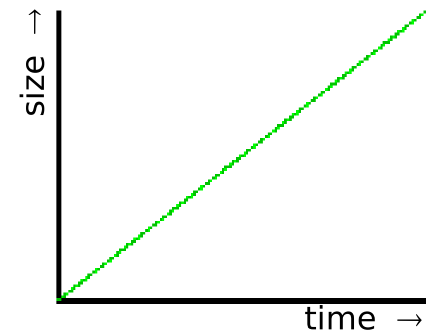
- Universe has no boundary or edge
  - Either it is infinite or curved through a 5th dimension

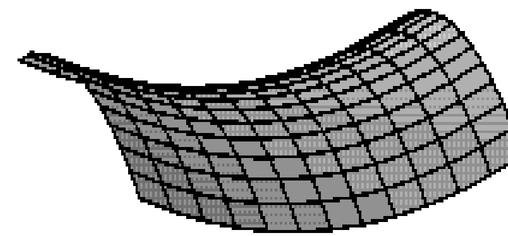
Infinite 1D object



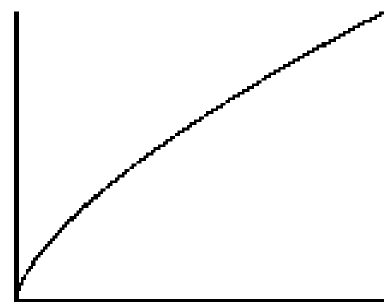
1D object curved through a second dimension to meet itself

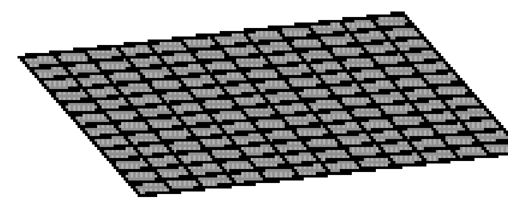
- **OPEN**: Total energy* is positive
  - Space is not curved into itself
  - Sum of angles in triangle < 180°
  - Universe will expand forever



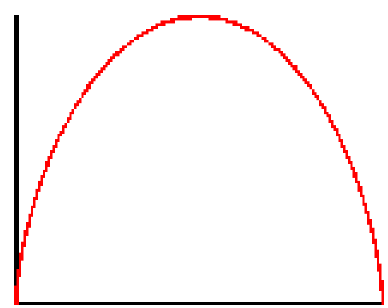


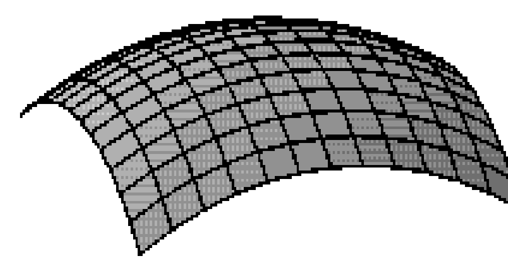
- **FLAT**: Total energy is exactly zero
  - Space is flat
  - Sum of angles in triangle = 180°
  - Universe will just barely expand to a stop: **very special case!**





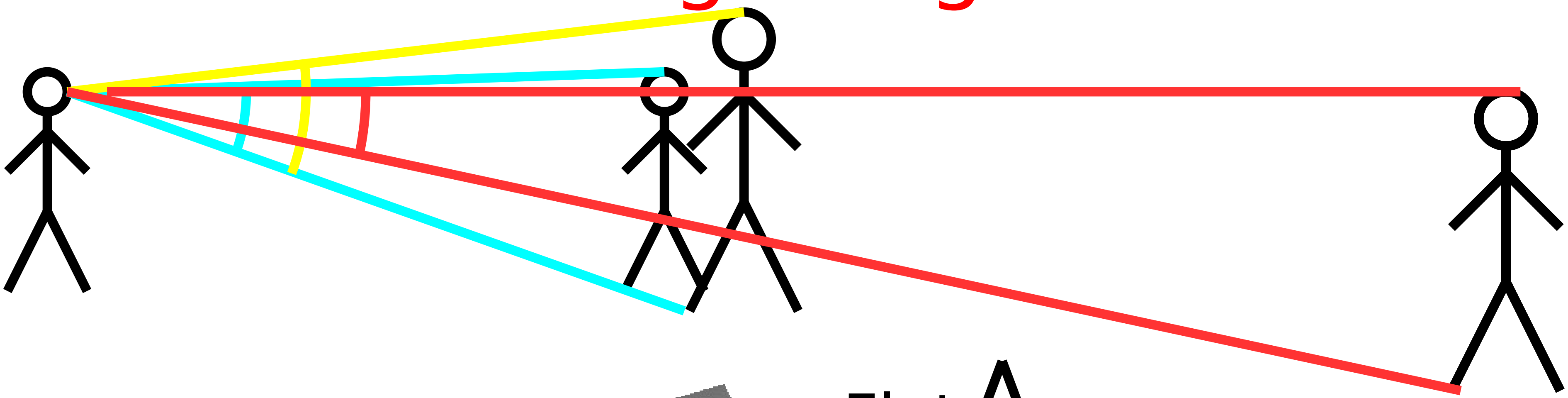
- **CLOSED**: Total energy is negative
  - Space is curved back into itself
  - Sum of angles in triangle > 180°
  - Universe will stop expanding and collapse into itself: Big Crunch

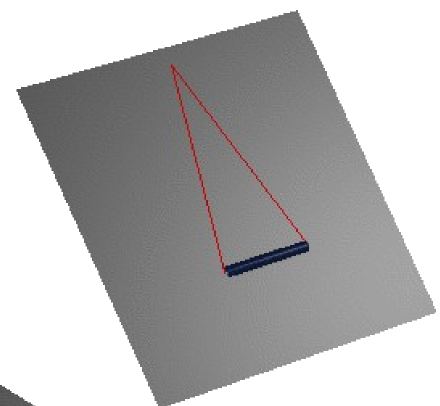




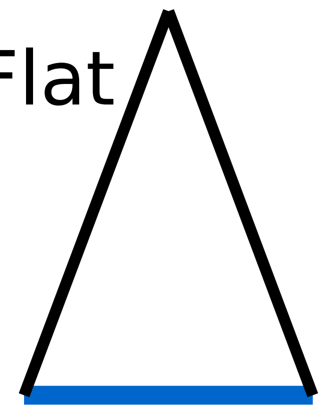
* Total energy: matter contributes positive energy, gravity contributes as negative energy

How big things look

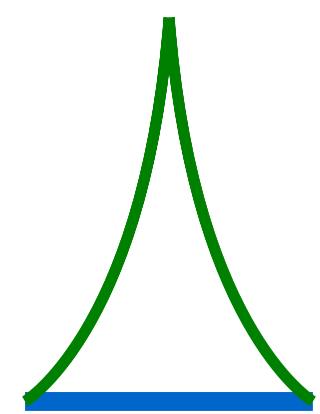


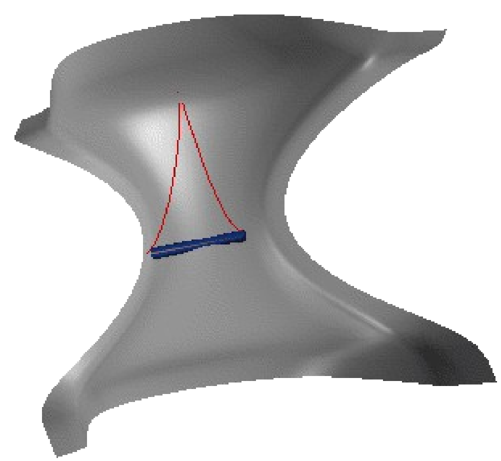


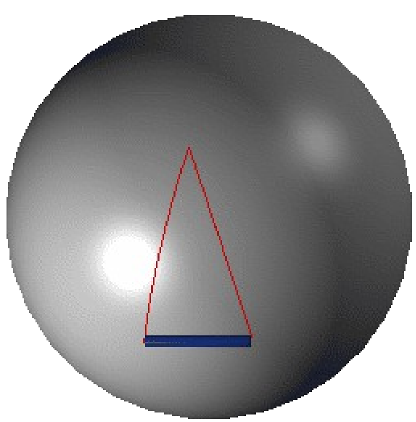
Flat

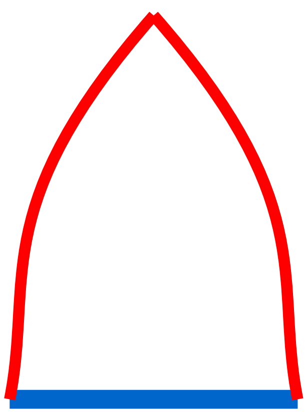


Open:
Looks Smaller





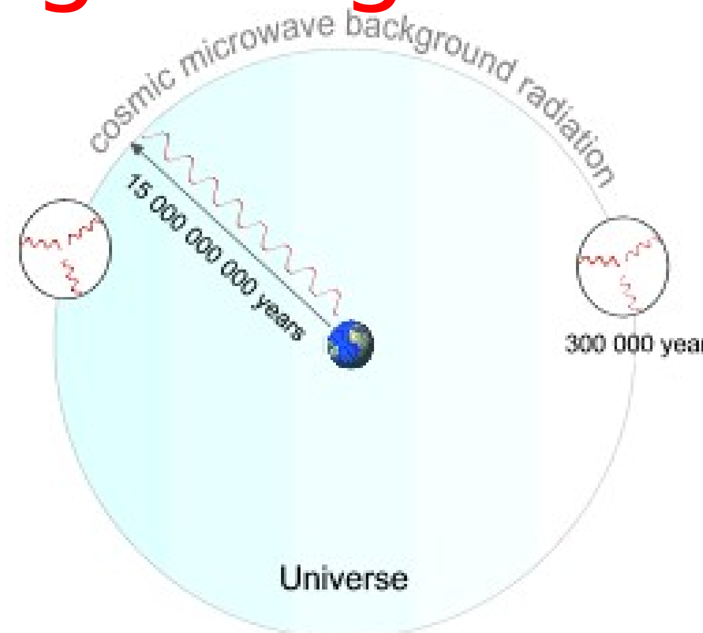


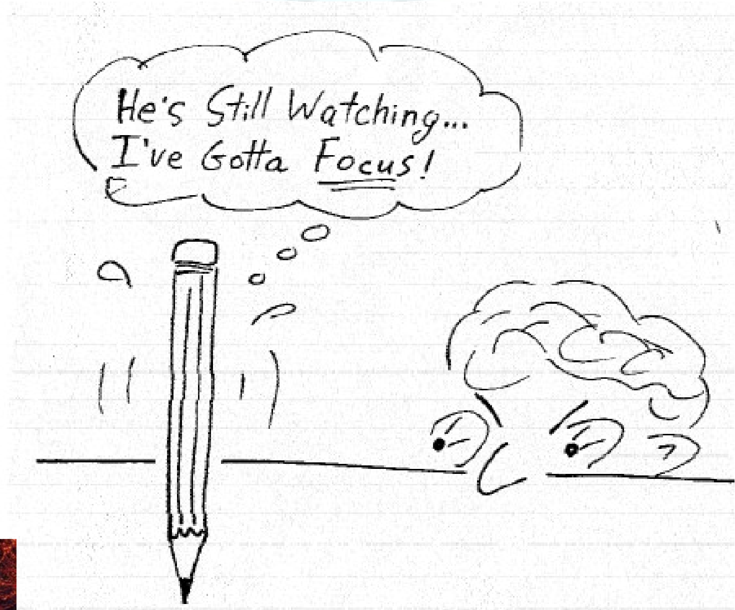


Closed:
Looks Bigger

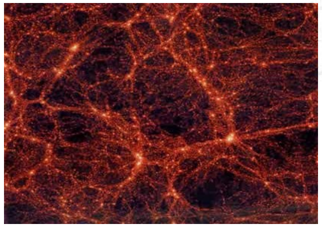
Problems with the Big Bang

- **Singularity problem**
  - All of the Universe at a point? yikes!
- **Horizon problem**
  - Why is universe (CMB in particular) so smooth and isotropic on large scales?
  - At t=400,000 years, only parts of the universe as large as 400,000 ly (around 1˚ in today's sky) could be causally connected, yet all have very similar Temperature: 2.7K?
  - A million causally disconnected regions (no info/light can reach the others): how come they all agreed to have the same Temperature (to 1 part in 100,000)?

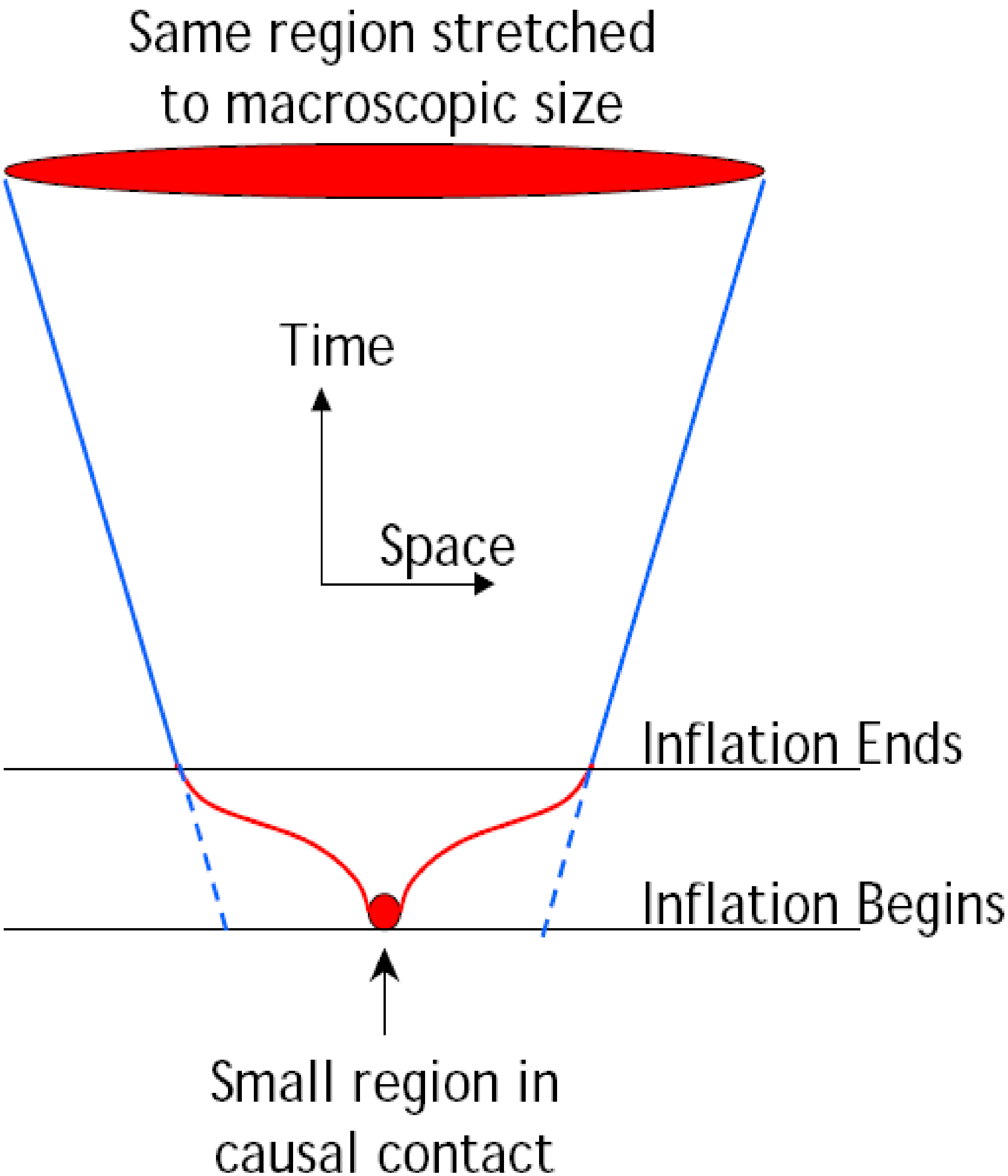




- **Flatness problem**
  - Universe appears to be very close to "flat"
  - $\Omega_{now} \sim 1 \pm 0.01 \rightarrow \Omega_{1sec} = 1 \pm 10^{-16} \rightarrow \Omega_{inflation} = 1 \pm 10^{-60}$
  - Requires fine tuning of basic model
- **Large scale structure problem**
  - How do galactic structures form in a perfectly homogeneous universe?



Solution: Cosmic Inflation (1979)

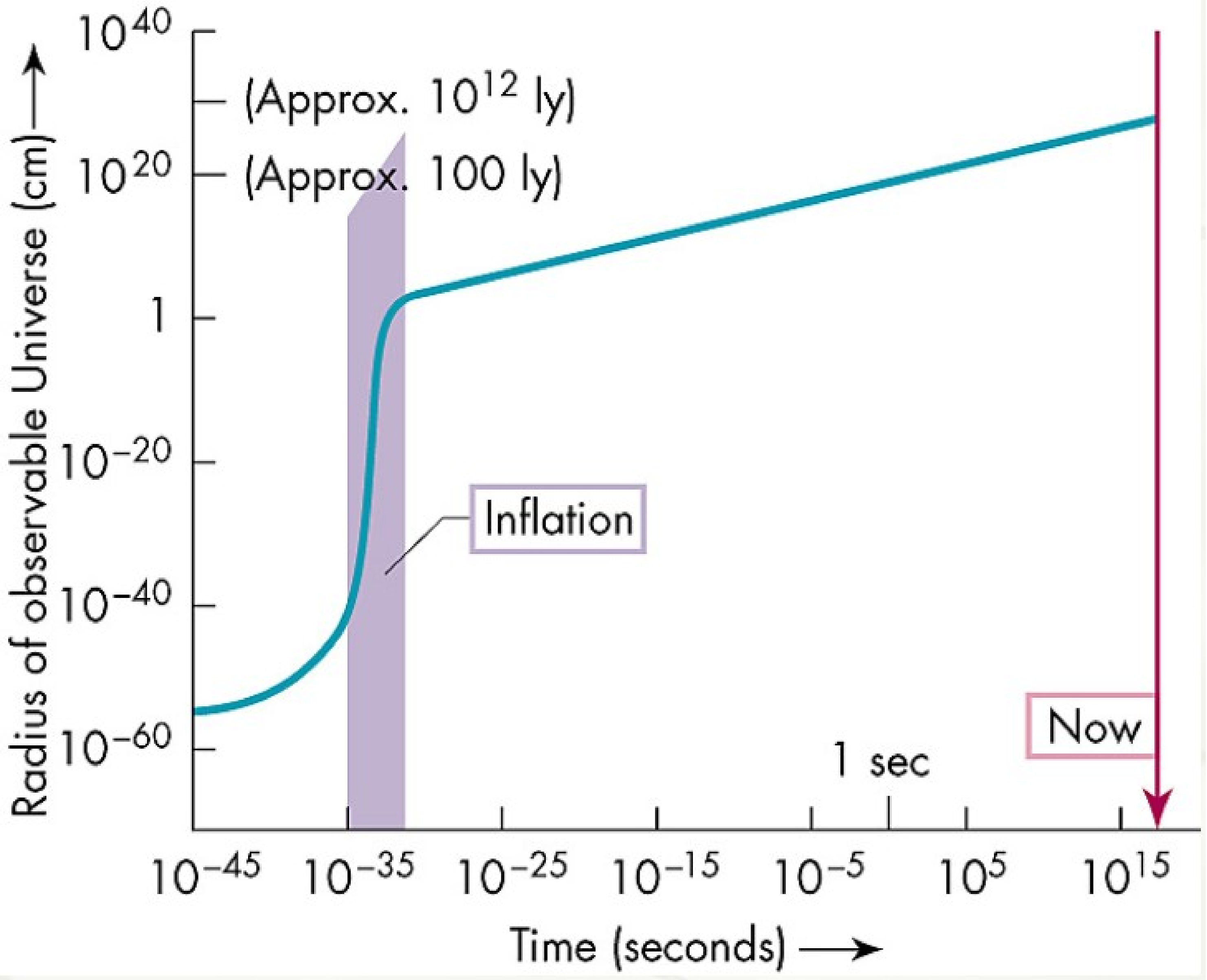


Very-rapid, exponential expansion of the universe

Occurs during interval $t=10^{-37}$-10^{-32} s

Universe expanded by a factor of 10^{40}-10^{100} during this time!

Radius of universe as function of time



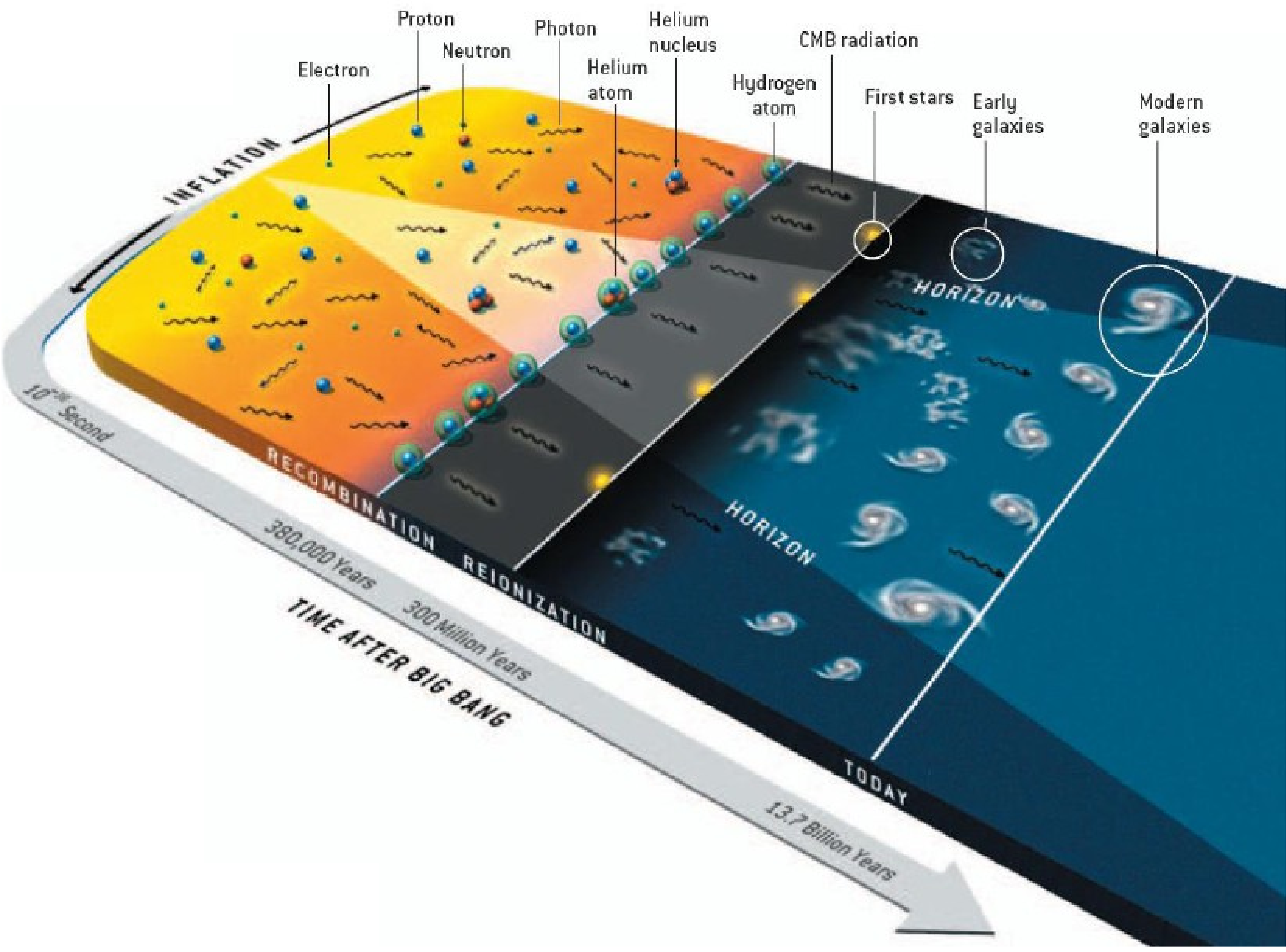
Arny, *Explorations*, McGrawHill

Does this rapid expansion imply a violation of relativity (speed greater than c)?

NO! It is space itself that is expanding, rather than material particles moving apart at high speed in a fixed stationary space

Inflation in one minute

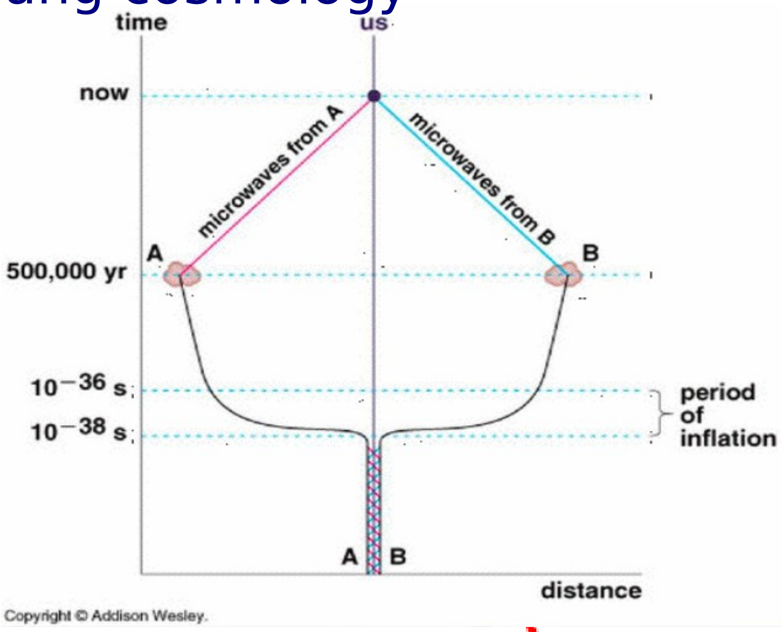
- Universe starts very small ... perhaps as a tiny fluctuation in a spacetime foam: a billion times smaller than a single proton!
- An unstable field or “particle” (inflaton) fills the space of the fluctuation
- It is a very particular field: it consists of **gravitational repulsion!**
- This repulsion was the **driving force behind the Big Bang**: drove it into **exponential** expansion, doubling in size every 10^{-37} second or so!
- This field was unstable and it decayed (like a radioactive substance), ending inflation after about 10^{-35} second
- The **decay released energy** which produced **ordinary particles**, forming a hot, dense “**primordial soup**”
- At the end of inflation, the region destined to become the presently observed universe was about the size of a **marble**
- The “primordial soup” matches the assumed starting point of the standard Big Bang — the standard Big Bang description takes over
- The universe continues to expand and cool to the present day



Proton
Photon
Helium
nucleus
Neutron
CMB radiation
Electron
Helium
atom
Hydrogen
atom
First stars
Early
galaxies
Modern
galaxies
INFLATION
HORIZON
RECOMBINATION
REIONIZATION
HORIZON
TODAY
Second
380,000 Years
300 Million Years
13.7 Billion Years
TIME AFTER BIG BANG

Inflation to the rescue

Inflation solves the major problems with Big Bang cosmology



Singularity problem

Quantum fluctuation possibly in endless fractal-like stream of universes (still unsolved)

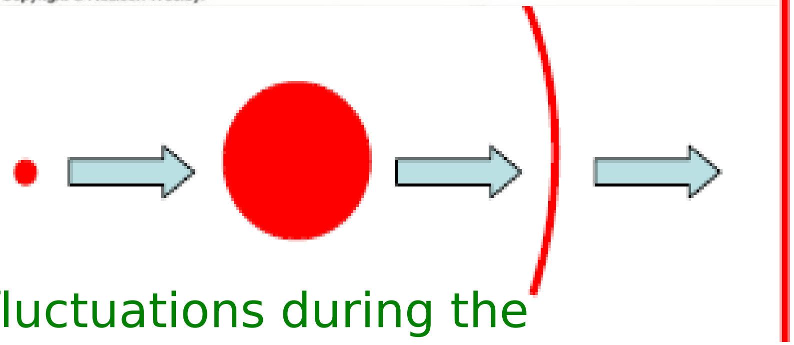
Horizon problem

Universe starts out very small and causally connected: that's how it ends up with similar Temperature

Flatness problem

No matter how curved space is originally, blow it up large enough and it will look flat

Inflation predicts a universe that is indistinguishable from flat

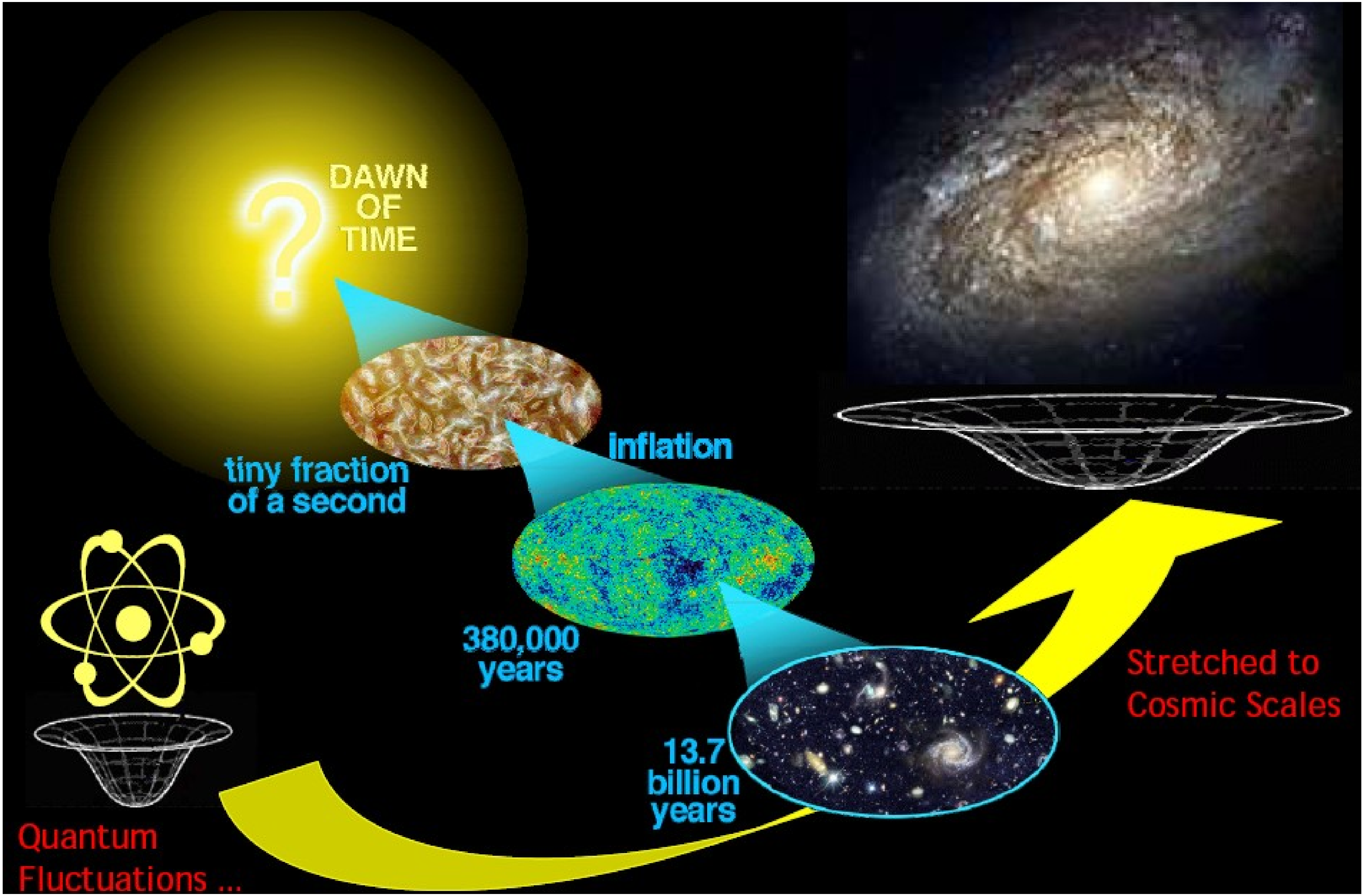


Large scale structure problem

The initial inhomogeneities are due to quantum fluctuations during the inflationary epoch: virtual particle pairs that formed would be separated by inflationary expansion before they could annihilate, creating uneven densities

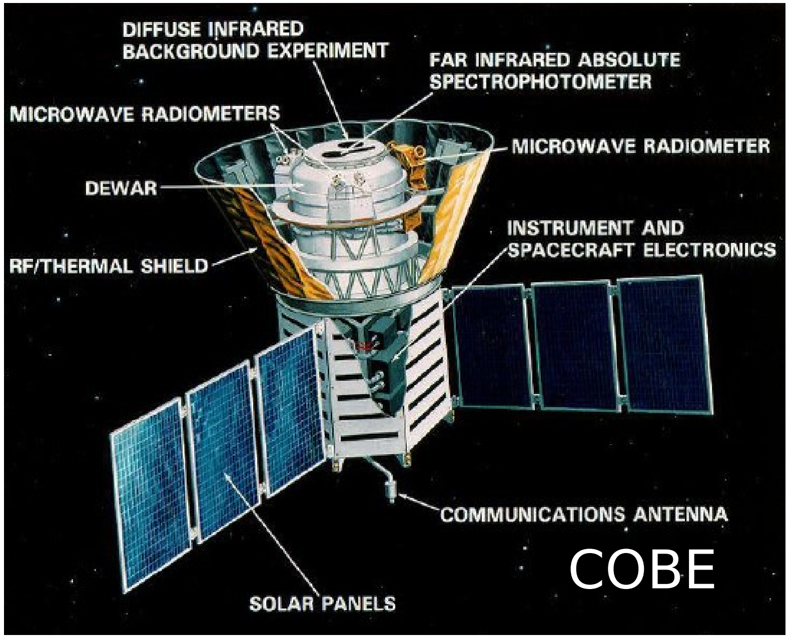
Inhomogeneities were continually created, and then stretched to much larger scales: largest present-day structures (superclusters, voids, filaments) are the result of quantum fluctuations that occurred on submicroscopic scales!

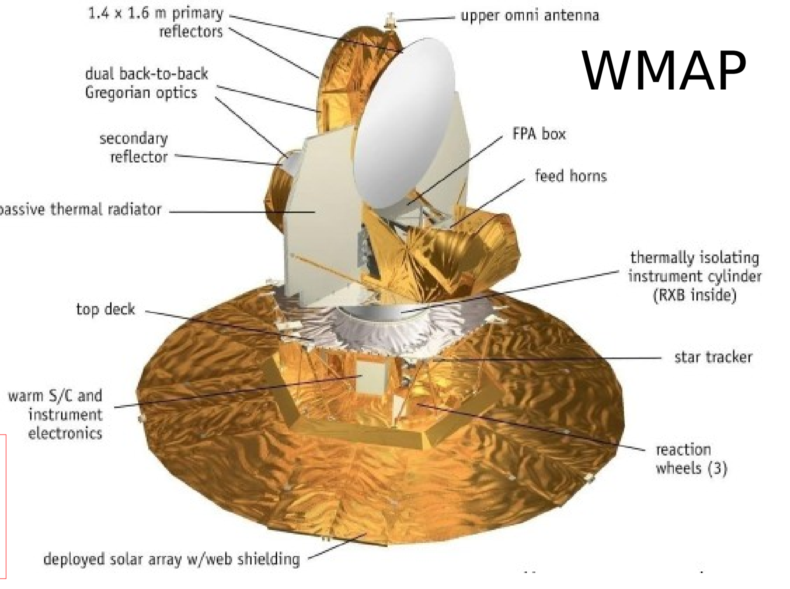
Quantum physics on a cosmic scale!



Incredible new data in last 10 years

- Fluctuations in Temperature/color of the CMB (1 part in 100,000)
  - **COBE** (1989-1993)
  - Angular resolution: 7°
  - Temperature sensitivity: 10^{-5}
  - J.Matter & G. Smoot: Nobel prize 2006
  - **WMAP** (2001-present)
  - Angular resolution: 15'
  - Temperature sensitivity: $3x10^{-6}$
- Observations of supernovae in distant galaxies
  - Supernova Cosmology Project
  - High-z

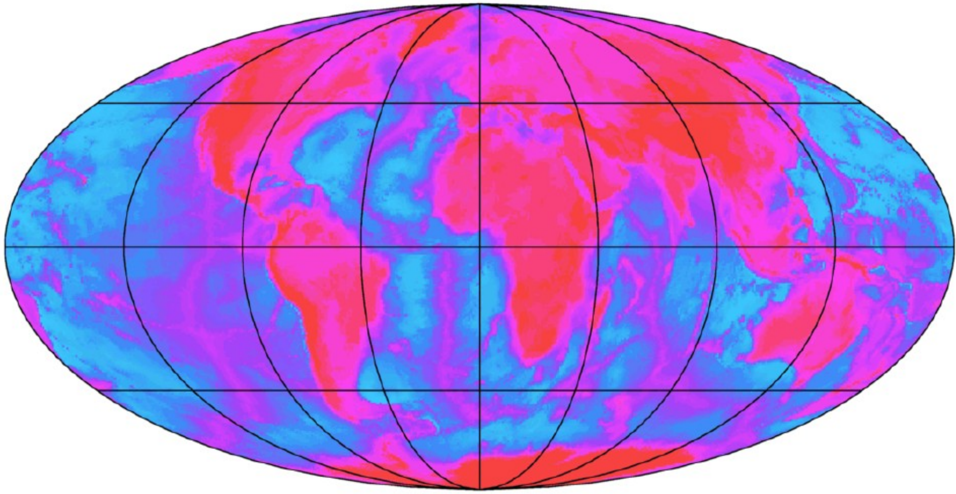




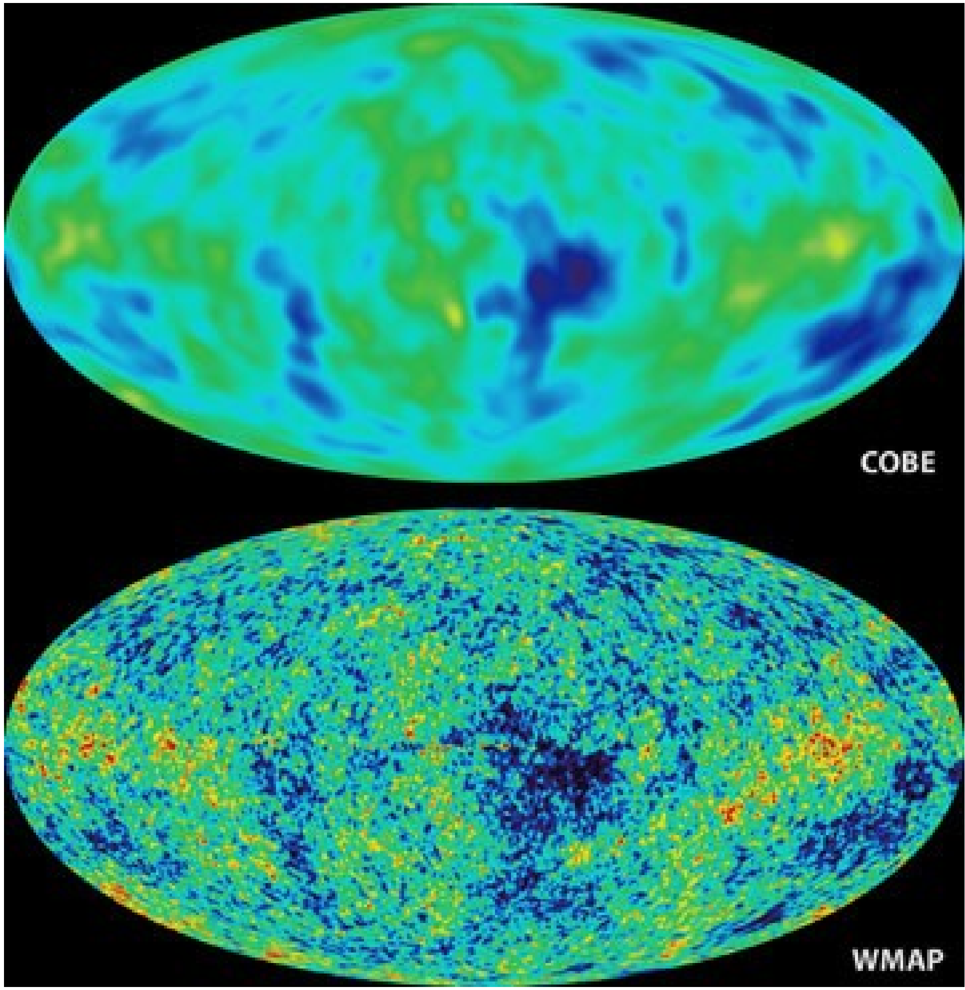
Universe is "flat"

Expansion of the universe is accelerating

CMB anisotropies

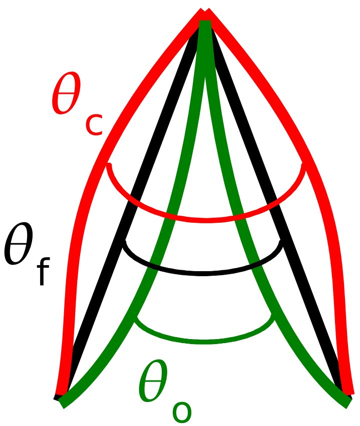


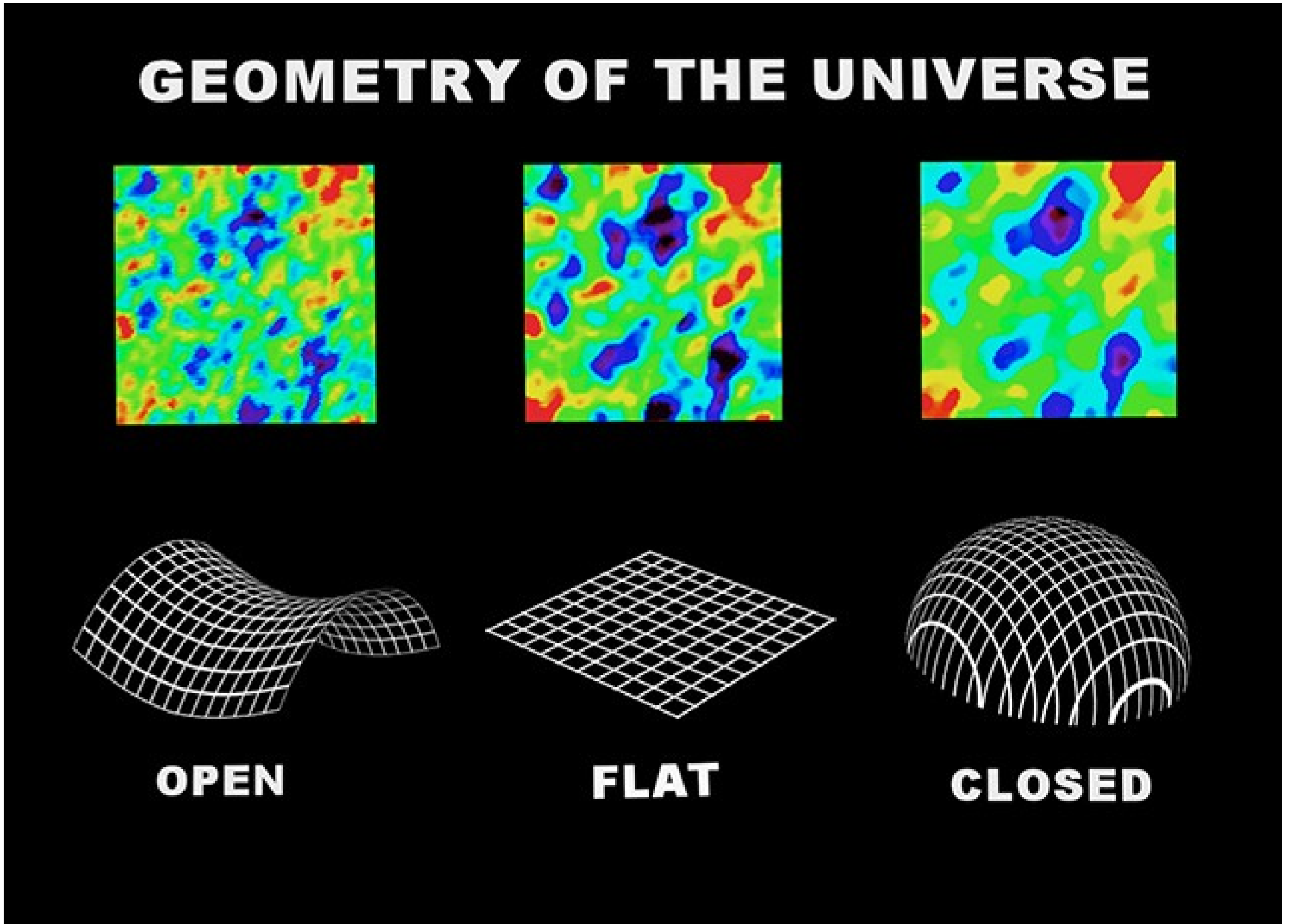
- CMB: A picture of the universe when it was 400,000 years old
- The CMB spectrum is uniform at 2.7K, wherever you look in the sky
- If you look with more sensitive devices, you begin to see tiny differences of the order of 1 part in 100,000 in the Temperature/color
- They are the fluctuations that would give rise to the large scale structure we see today, as predicted by inflation!



Size of fluctuations → geometry

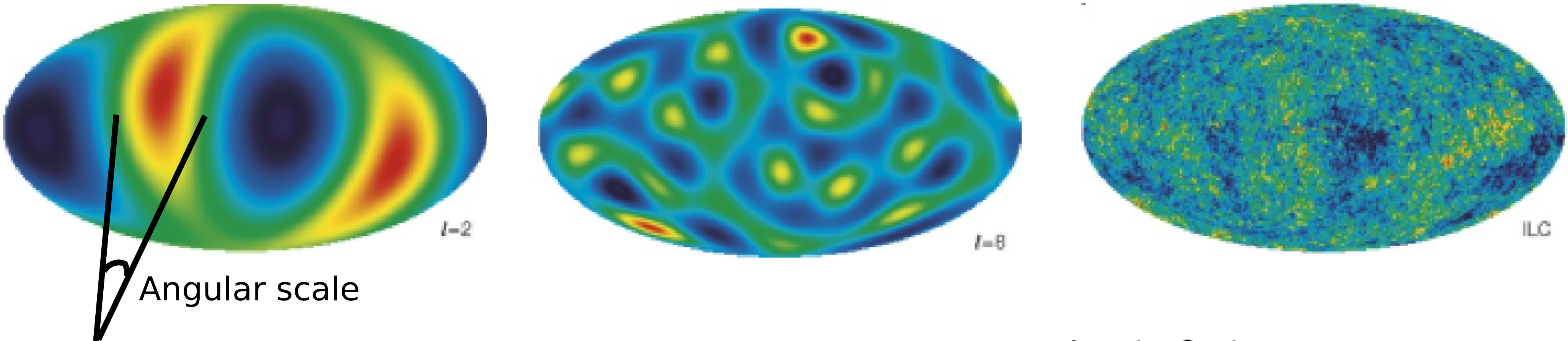
- Size of fluctuations/structure in CMB is sensitive to the geometry of the universe
- Light comes to us from distance ~13.3 billion years, but the path of light depends on how spacetime is curved
- Look at angular size of fluctuations



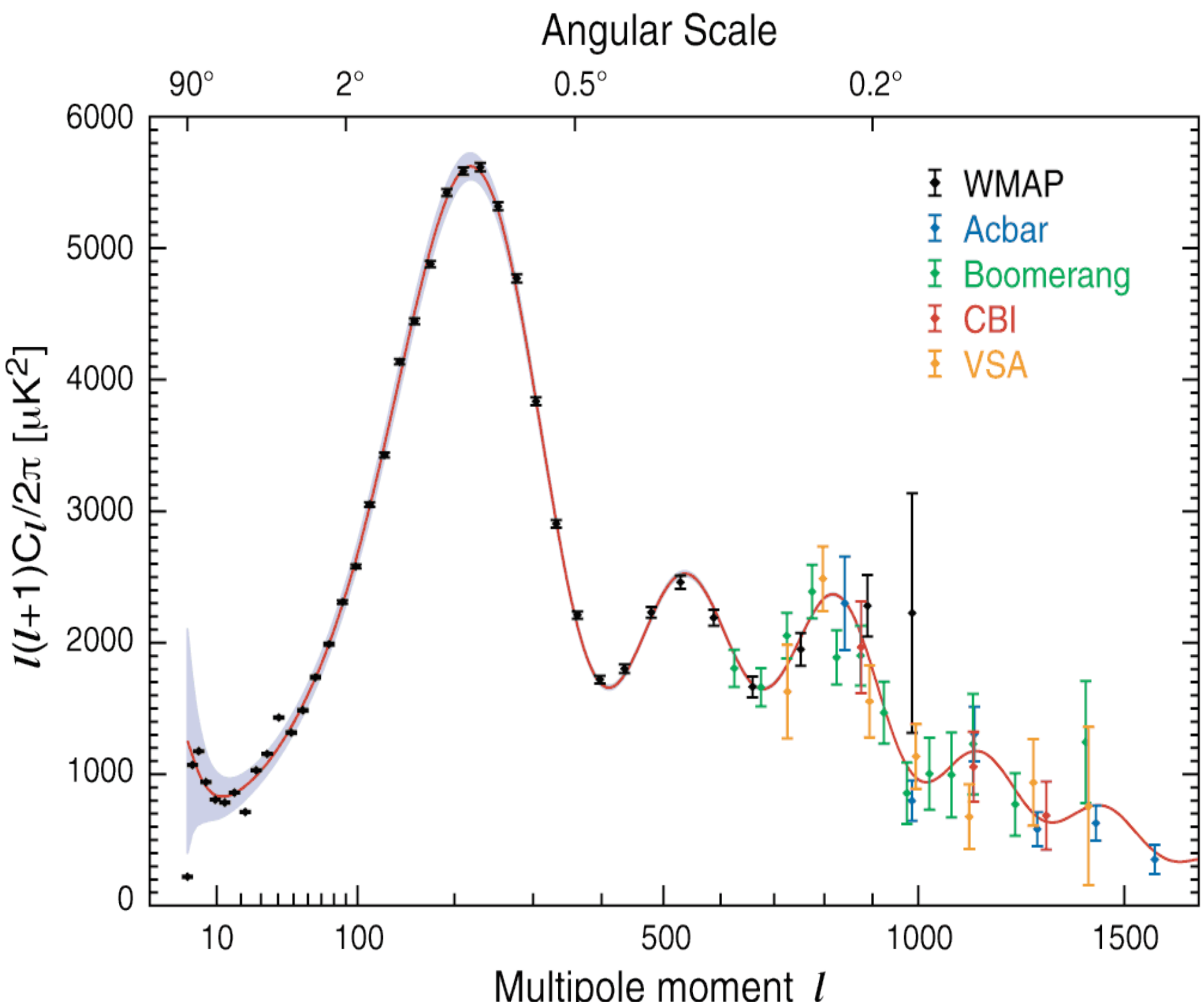


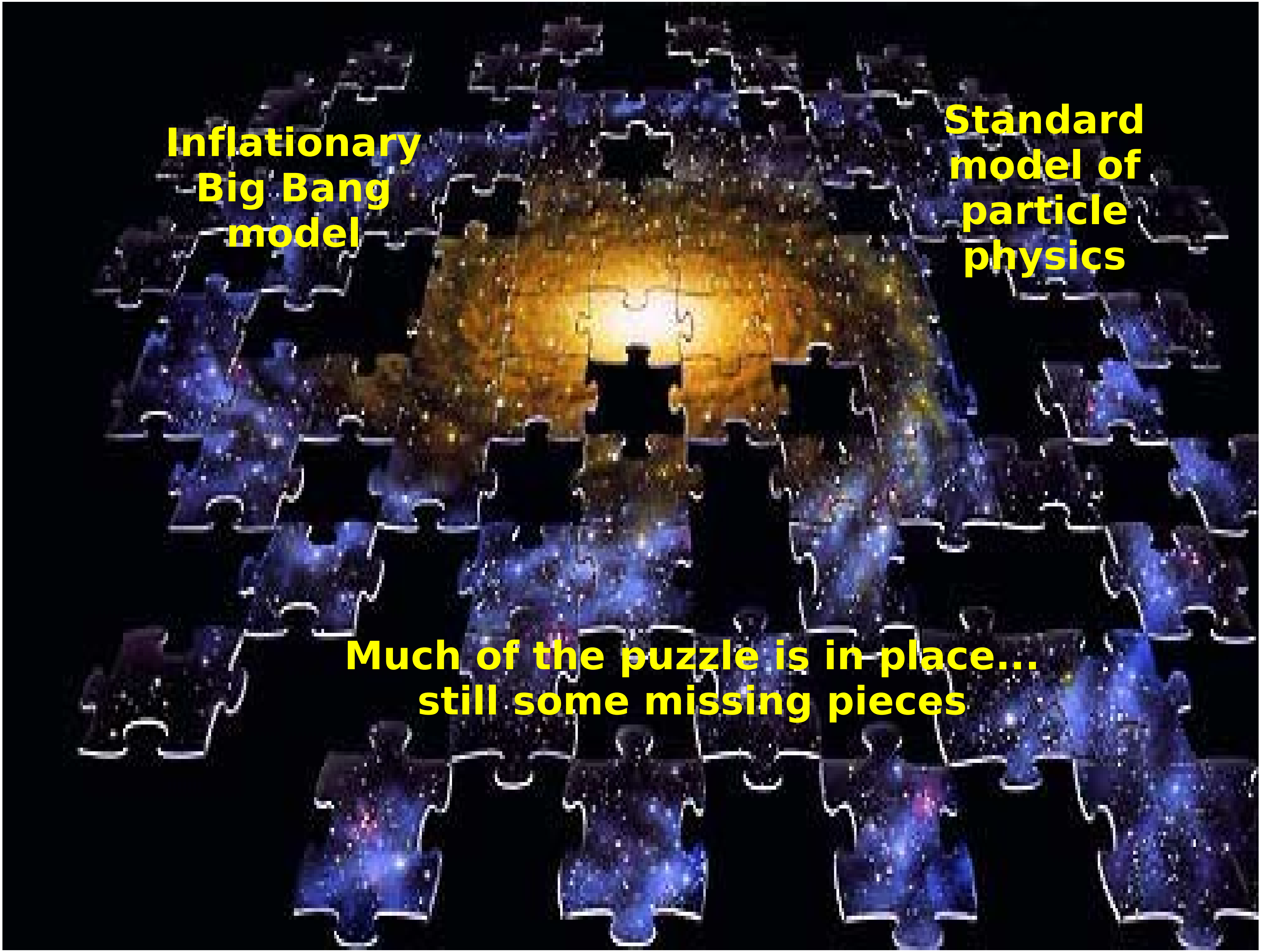
Measure:

- θ_f if space is flat
- θ_o if space is open
- θ_c if space is closed



- "Power spectrum" (size) of Temperature fluctuations is sensitive to different matter/energy components
- We can tell the density and rate of expansion in the early universe
- The exact mixture of material in the early Universe (baryons, neutrinos, dark matter), cosmological parameters (H_0, vacuum energy) and initial perturbation spectrum, control the position and amplitude of these peaks and troughs



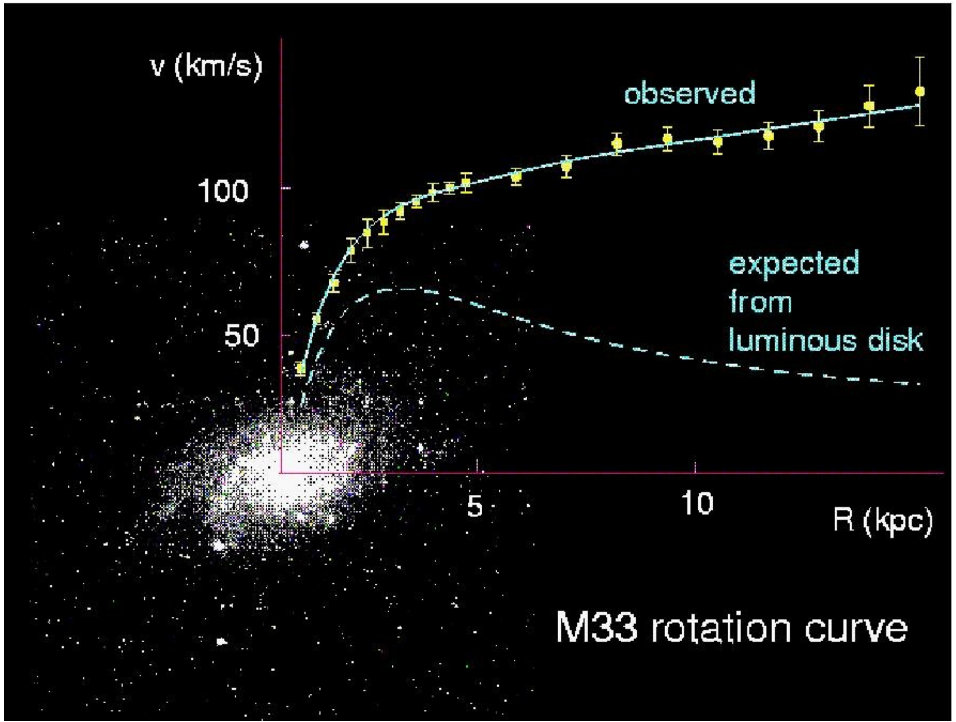

Inflationary Big Bang model
Standard model of particle physics
Much of the puzzle is in place...
still some missing pieces

Dark matter

- Relate velocity in radial direction and force in orbits of stars around galaxies:

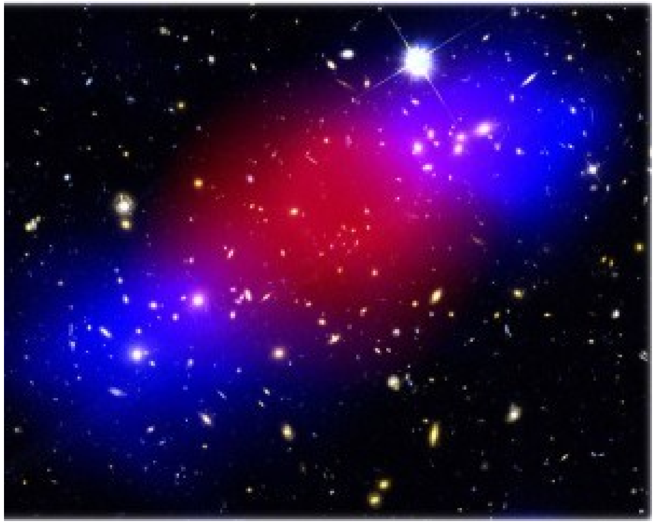
$$F = \frac{mv^2}{R} \; ; \; F = \frac{GMm}{R^2} \quad \rightarrow \quad \frac{mv^2}{R} = \frac{GMm}{R^2}$$

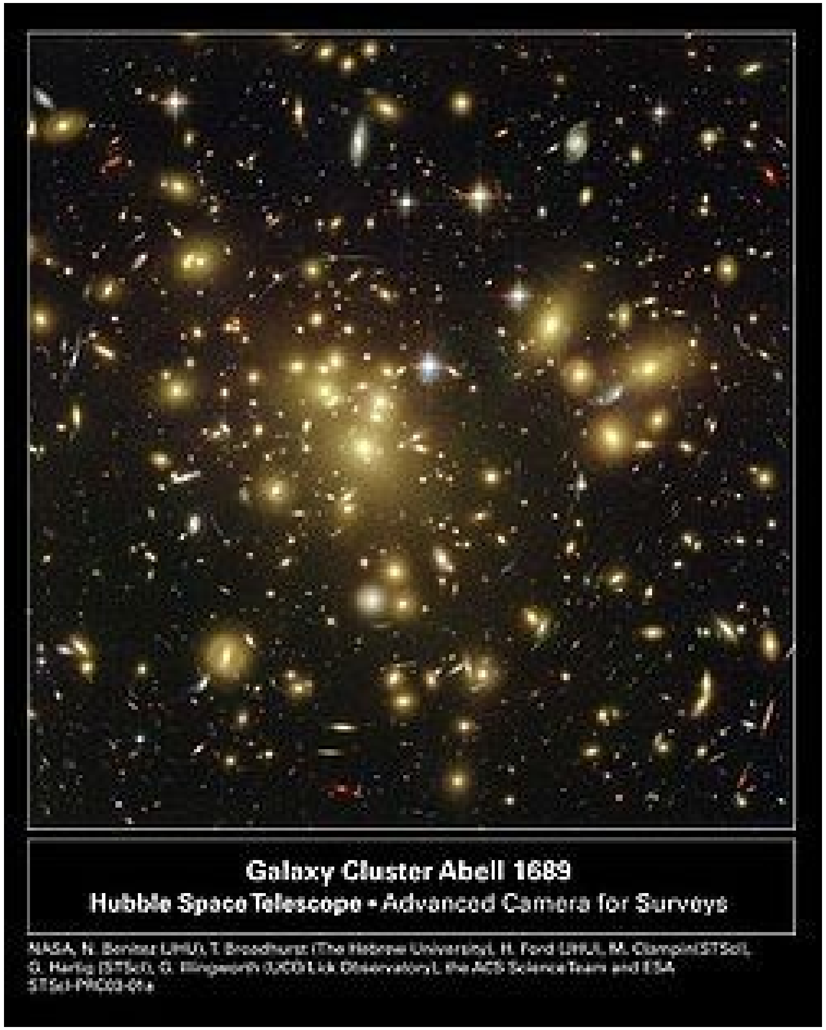
- Find that outer stars rotate **too quickly** for observed central mass
- Same finding in galactic clusters: galaxies are attracted to others far more than accounted for by the visible matter in the galaxies
- Require stronger gravitational force?
- Evidence for a new form of matter in the universe that interacts gravitationally but not via the other forces
- Does not emit or absorb light, for example!



More evidence for dark matter

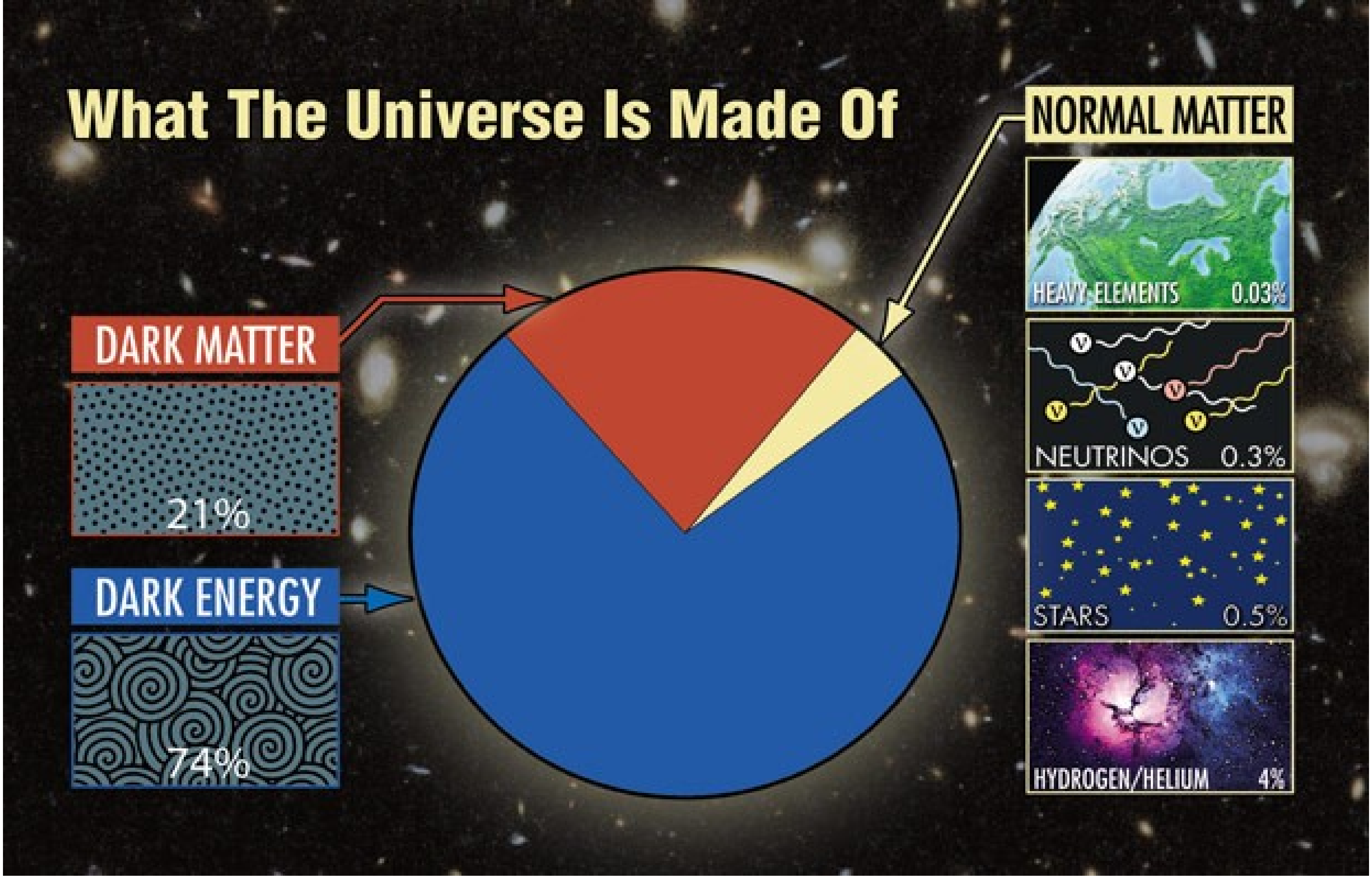
- Gravitational lensing
  - Visible matter is not enough
- Collisions of clusters
  - Visible matter slows down because it interacts with visible matter (red)
  - Dark matter sails through (blue)





We just don't know what it is!

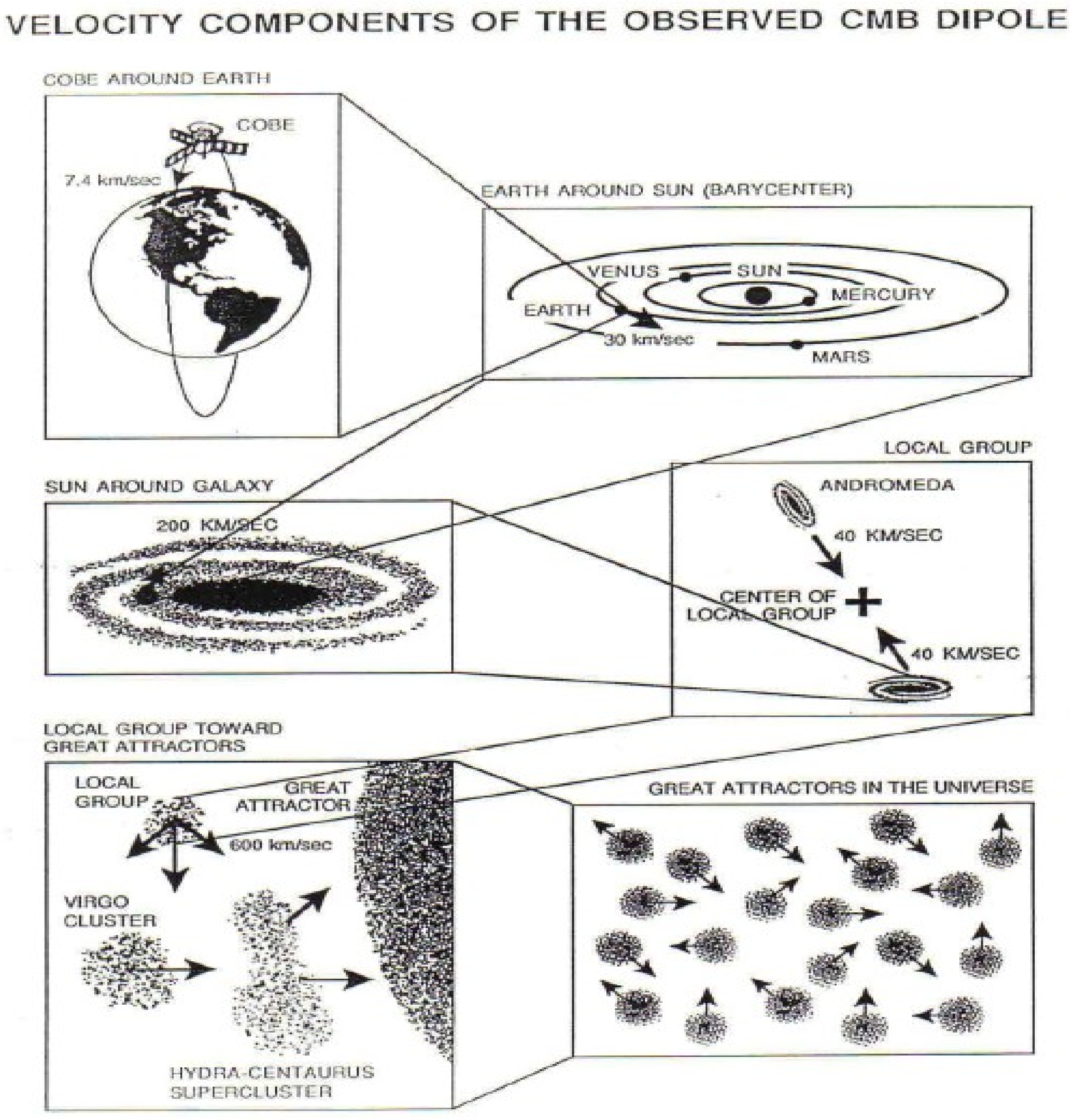
May make up up to 80% of the mass of the Universe!



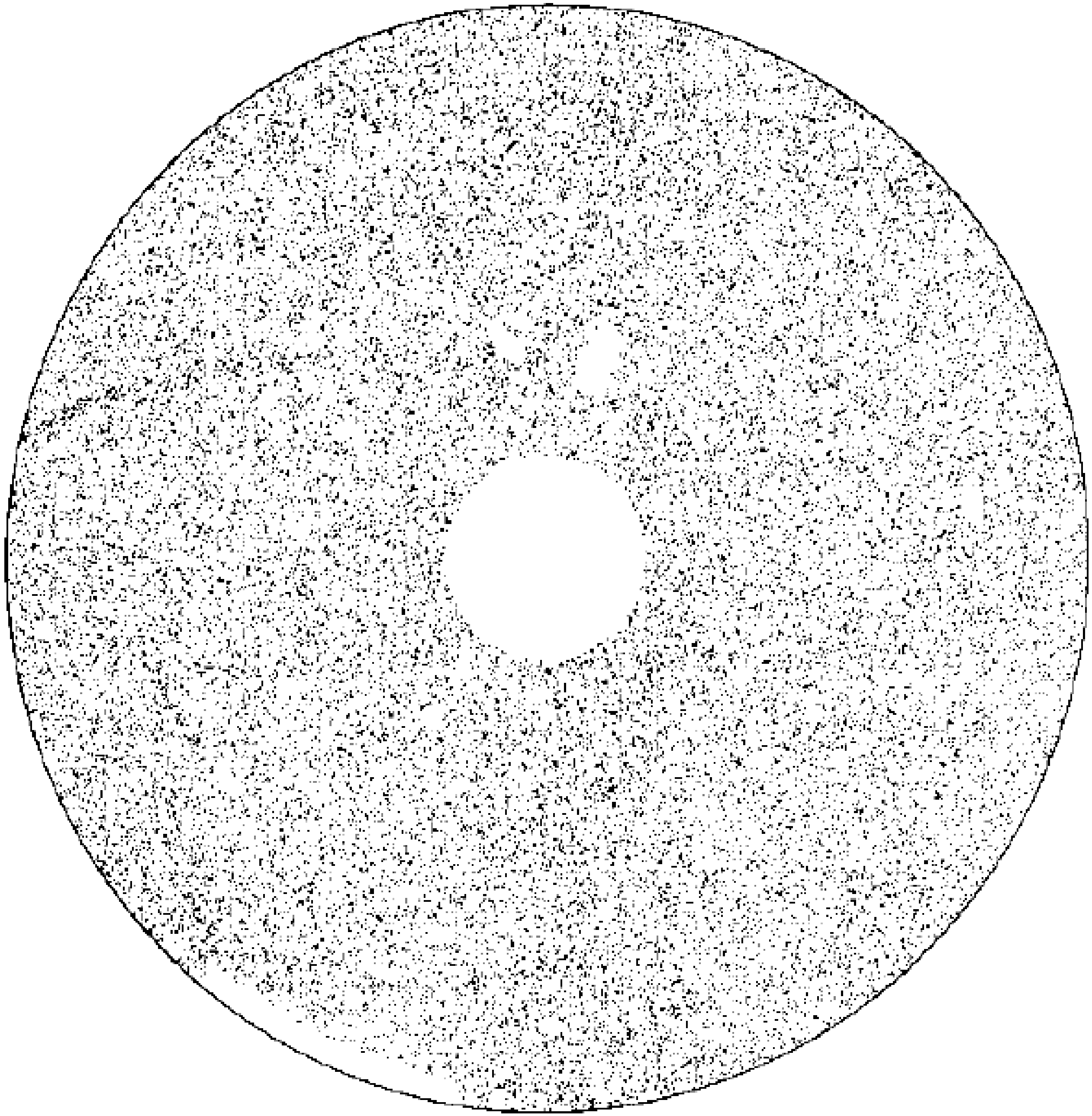
- Us: ~5%
- Dark matter ~20%
- Dark energy ~75%

95% of the universe is unknown!

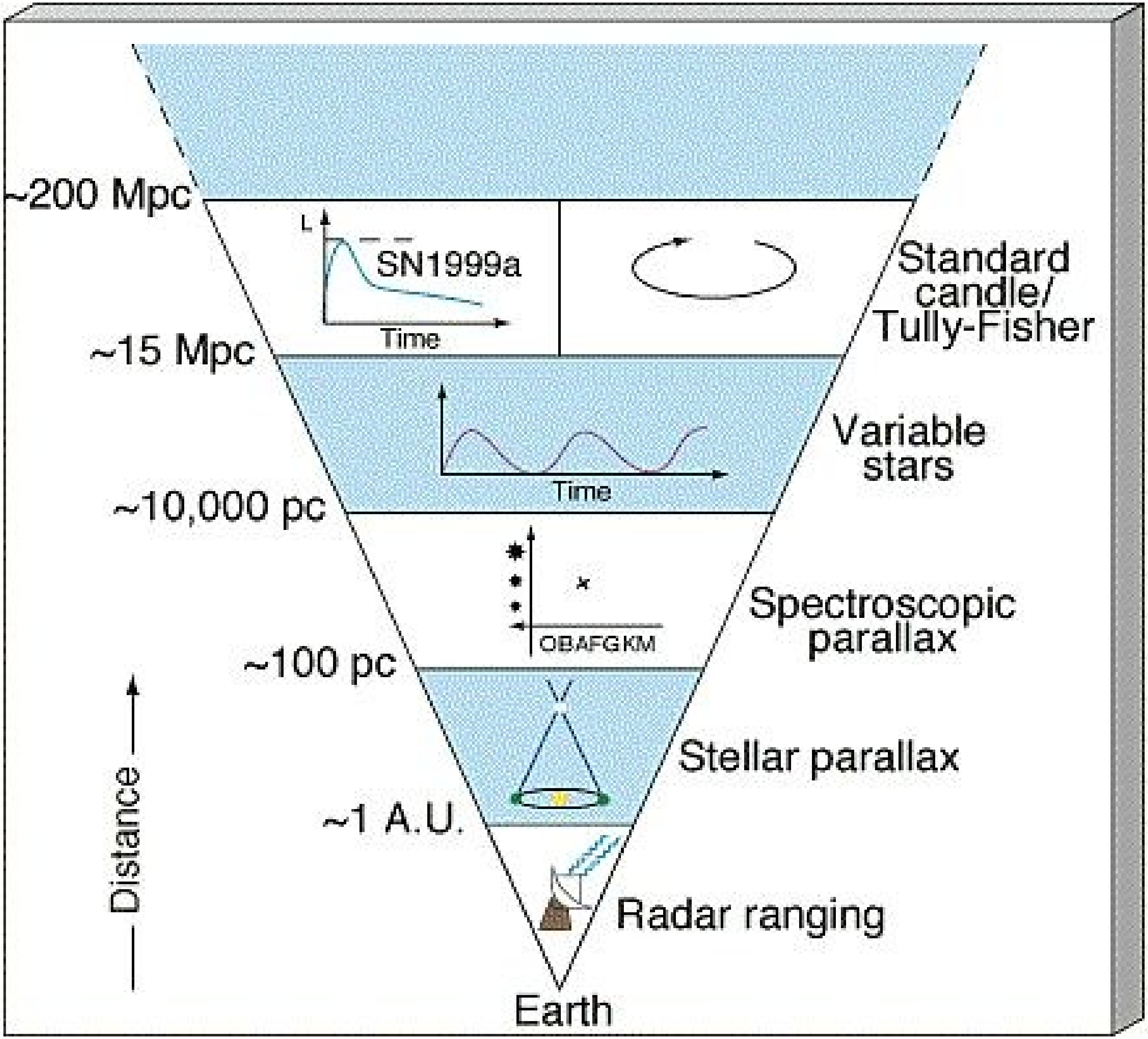
Extras


VELOCITY COMPONENTS OF THE OBSERVED CMB DIPOLE
COBE AROUND EARTH
COBE
7.4 km/sec
EARTH AROUND SUN (BARYCENTER)
VENUS
SUN
MERCURY
EARTH
30 km/sec
MARS
LOCAL GROUP
ANDROMEDA
40 KM/SEC
CENTER OF LOCAL GROUP
40 KM/SEC
SUN AROUND GALAXY
200 KM/SEC
LOCAL GROUP TOWARD GREAT ATTRACTORS
LOCAL GROUP
GREAT ATTRACTOR
600 km/sec
VIRGO CLUSTER
HYDRA-CENTAURUS SUPERCLUSTER
GREAT ATTRACTORS IN THE UNIVERSE

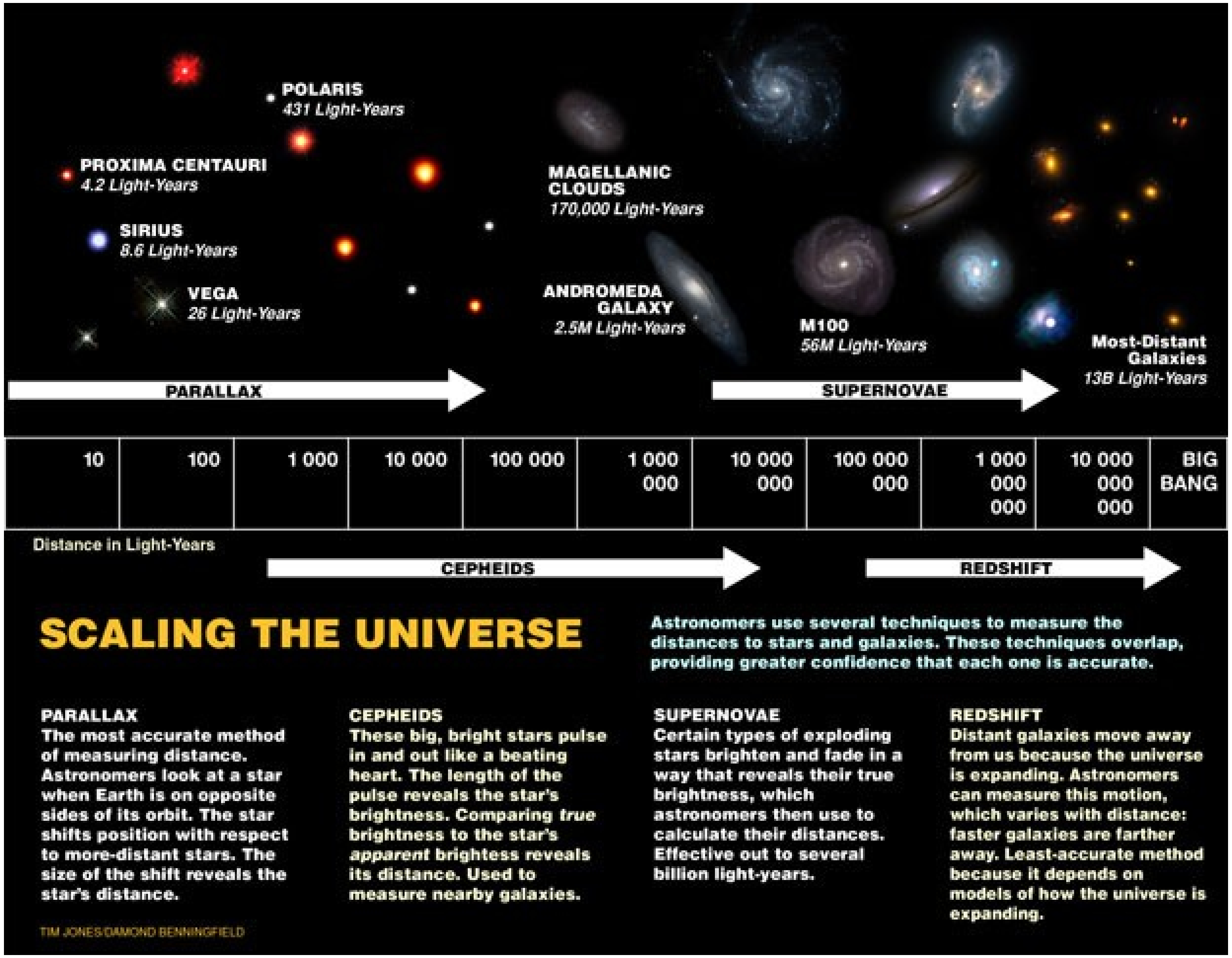
Isotropy of Radio Source Counts



How to measure distance to objects

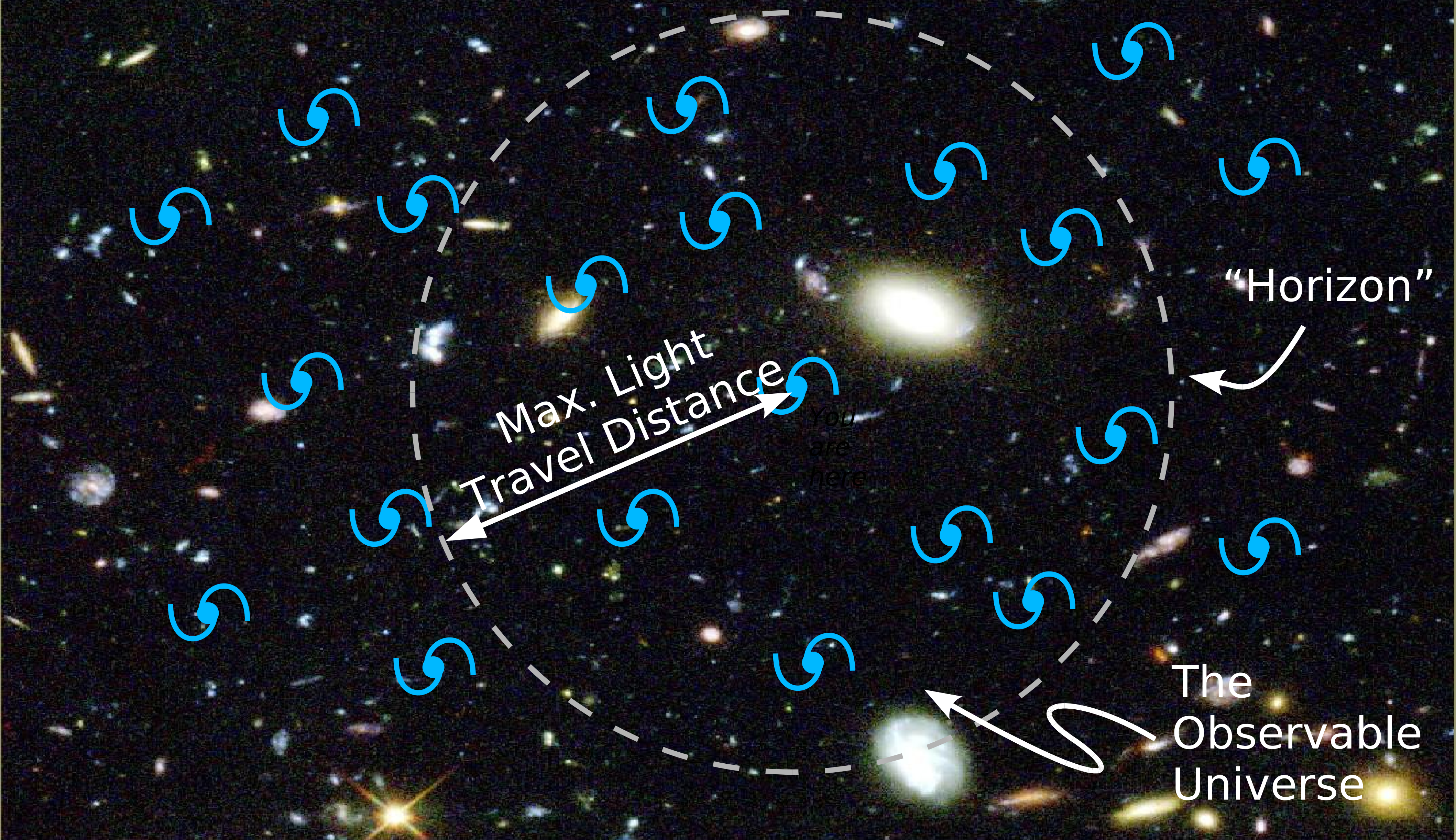


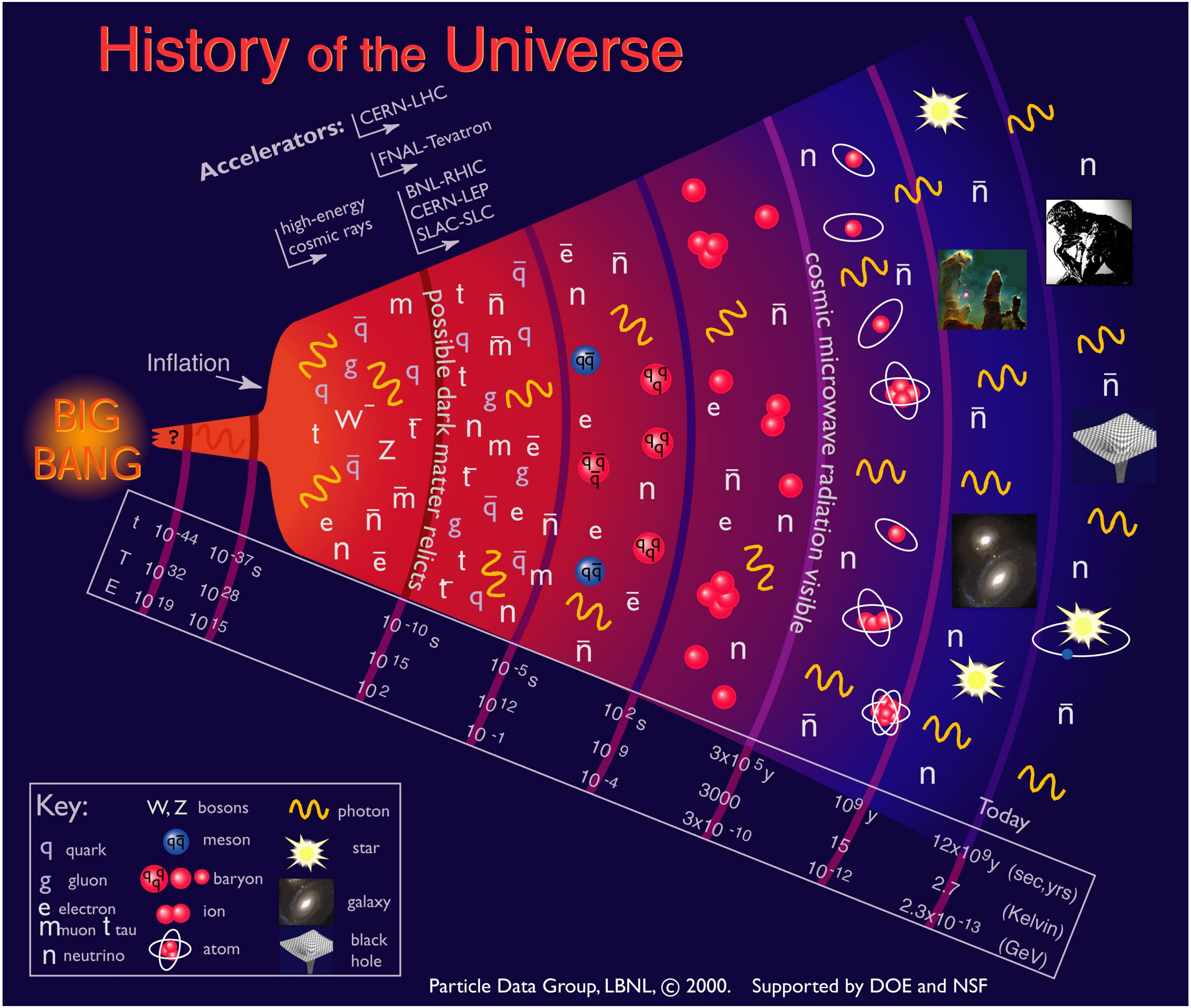
Measuring distances



Even if the Universe is infinite, the *Observable Universe* is finite

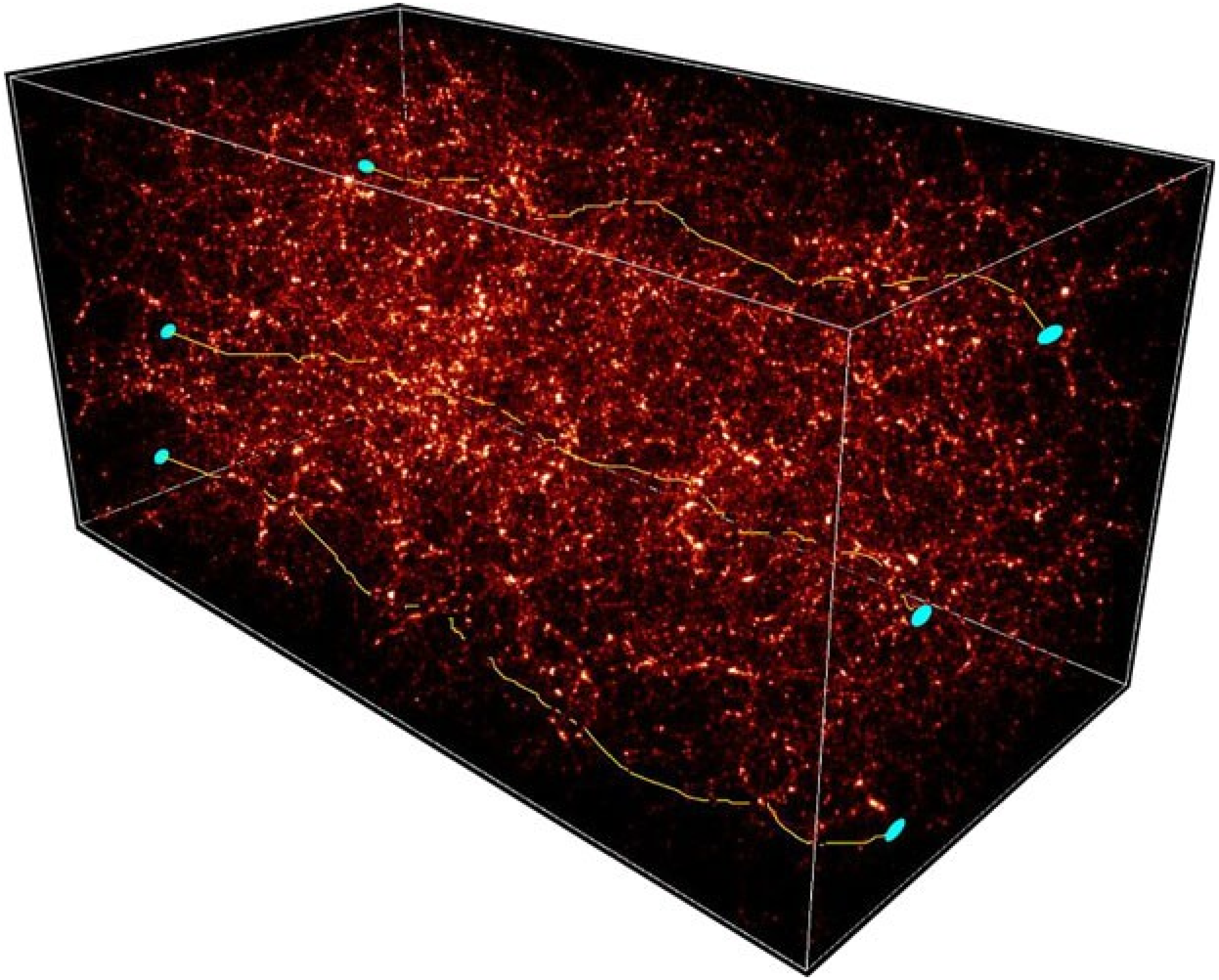
Size=14 billion pc = 46 billion ly

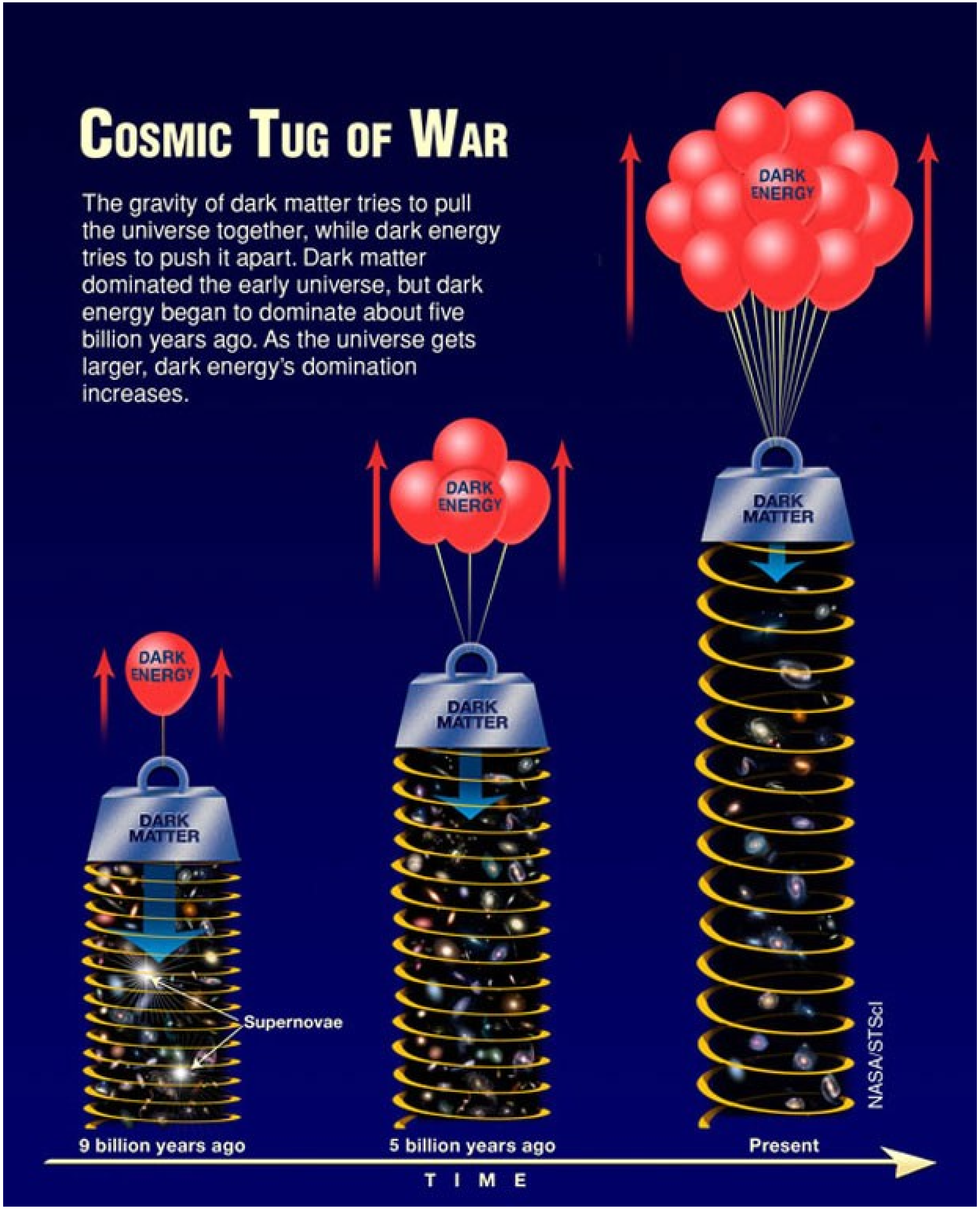




History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y Today 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 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

- Dark matter path, weak lensing




COSMIC TUG OF WAR
The gravity of dark matter tries to pull the universe together, while dark energy tries to push it apart. Dark matter dominated the early universe, but dark energy began to dominate about five billion years ago. As the universe gets larger, dark energy's domination increases.
DARK ENERGY
DARK MATTER
Supernovae
DARK ENERGY
DARK MATTER
DARK ENERGY
DARK MATTER
NASA/STScI
9 billion years ago
5 billion years ago
Present
TIME