The Dark Side of the Universe

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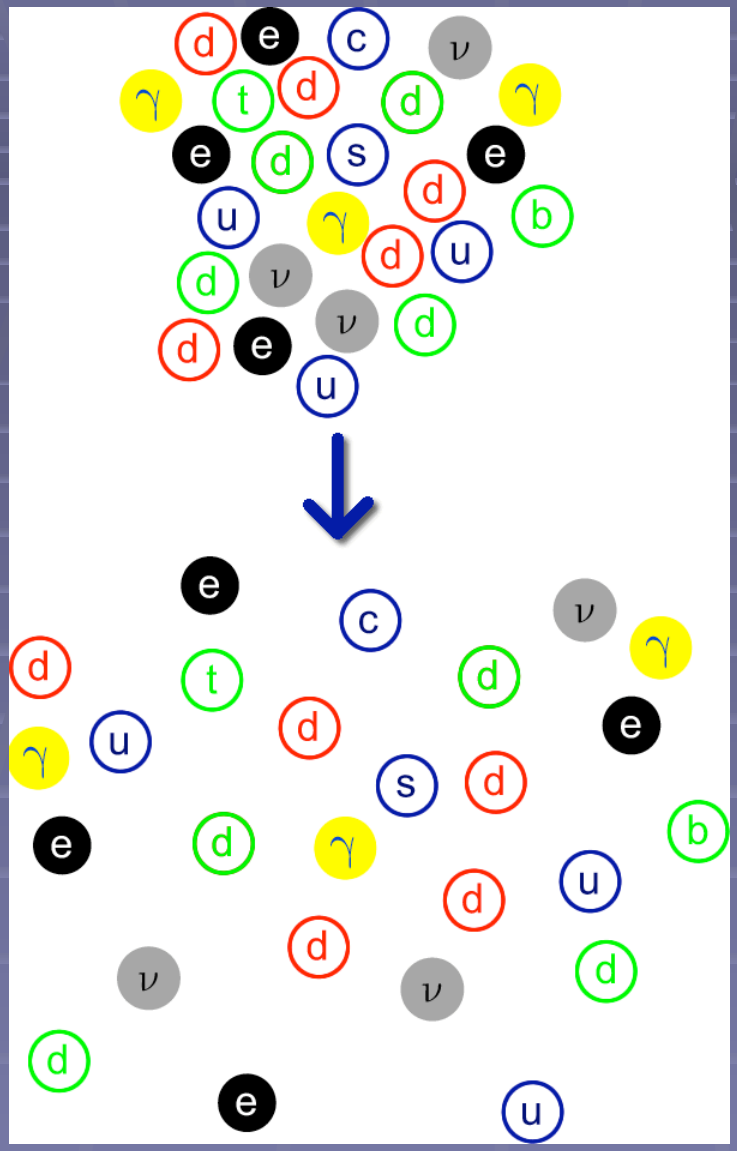
BIG BANG

14 BILLION YEARS AGO

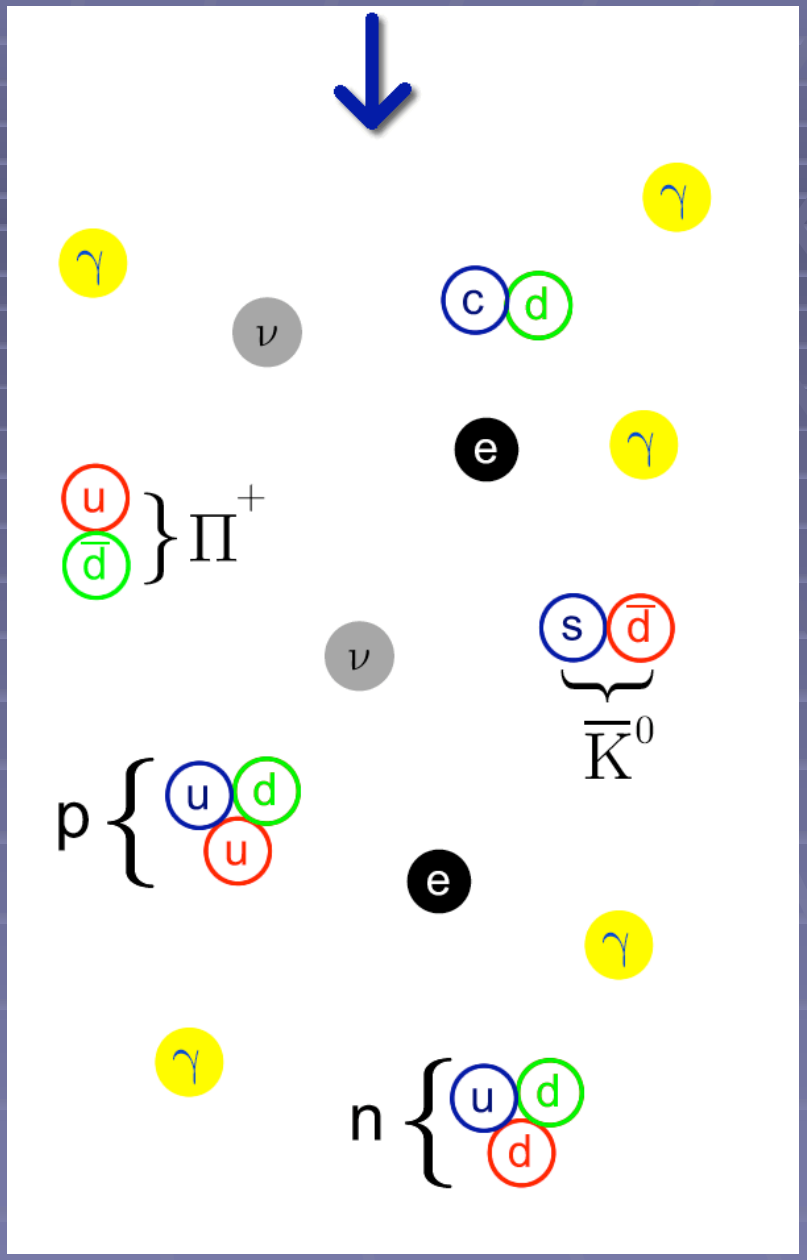


Hot primordial soup

Universe is Cooling and Expanding

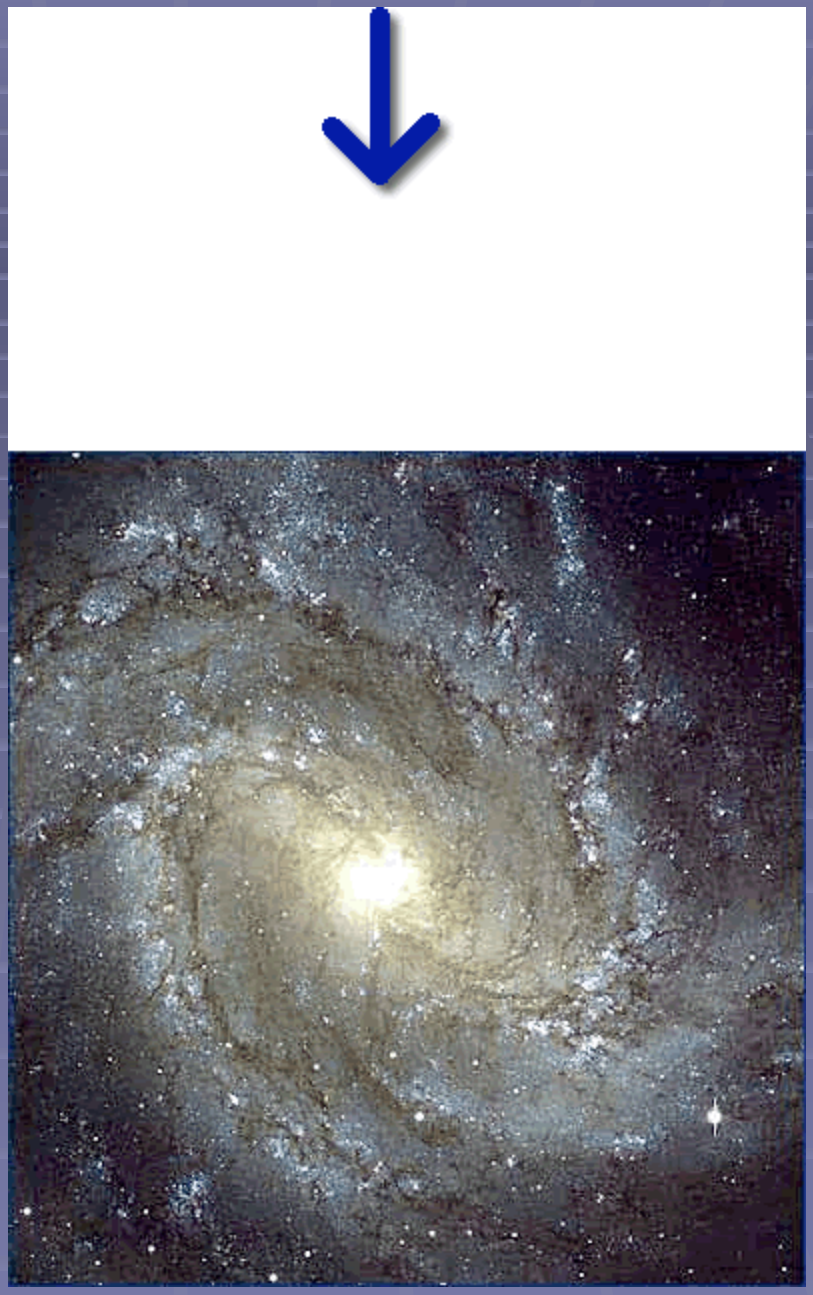
QUARK/HADRON TRANSITION

t = 0.01 sec



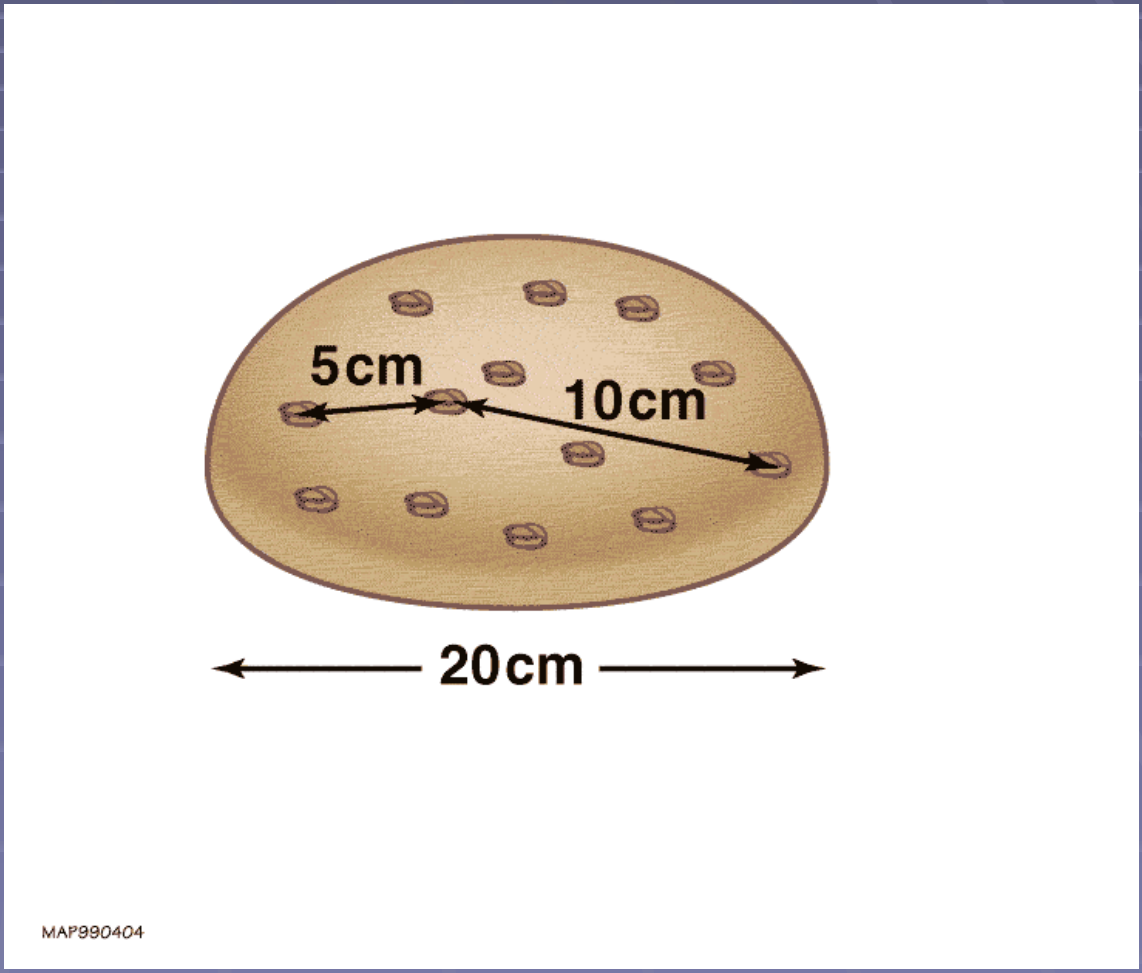
Galaxy formation

t =1 million years



Raisin Bread Model of the Universe

- As the loaf rises, raisins move steadily apart from one another, with the loaf maintaining the same configuration.



Cosmological Principles

- Universe is homogeneous:

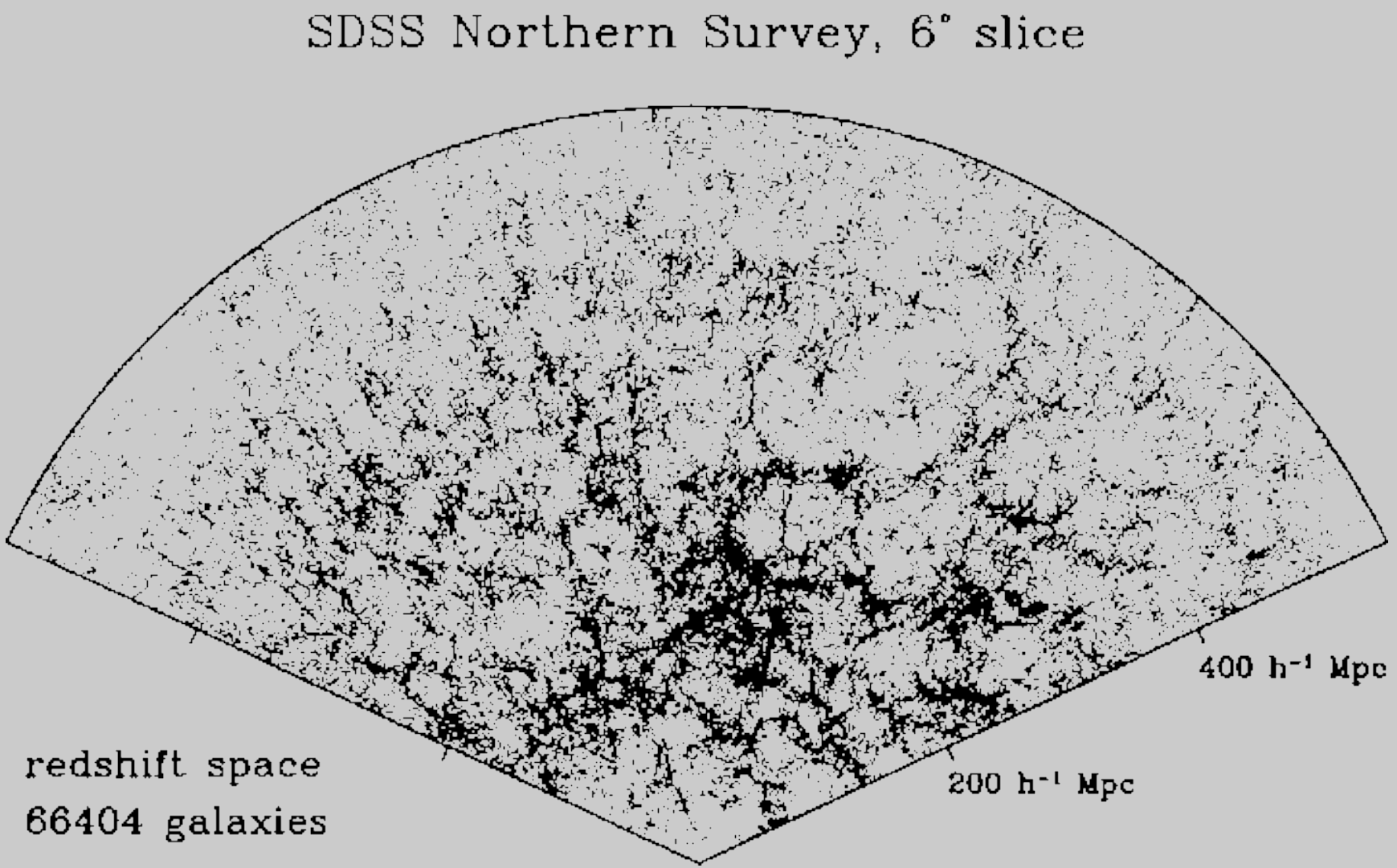
  looks the same at every point

  (on average)

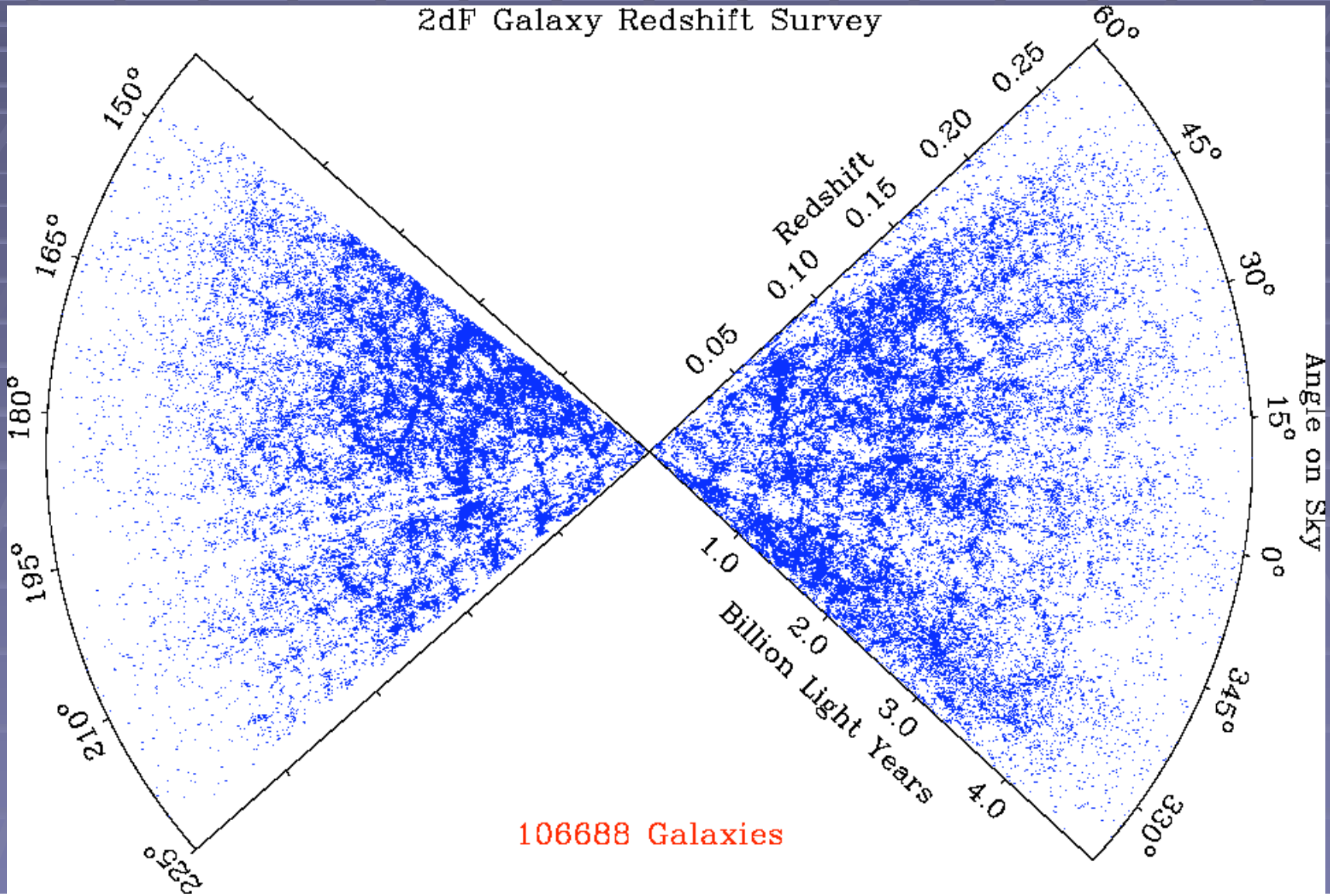
- Universe is isotropic:

  looks the same in every direction

The Great Wall



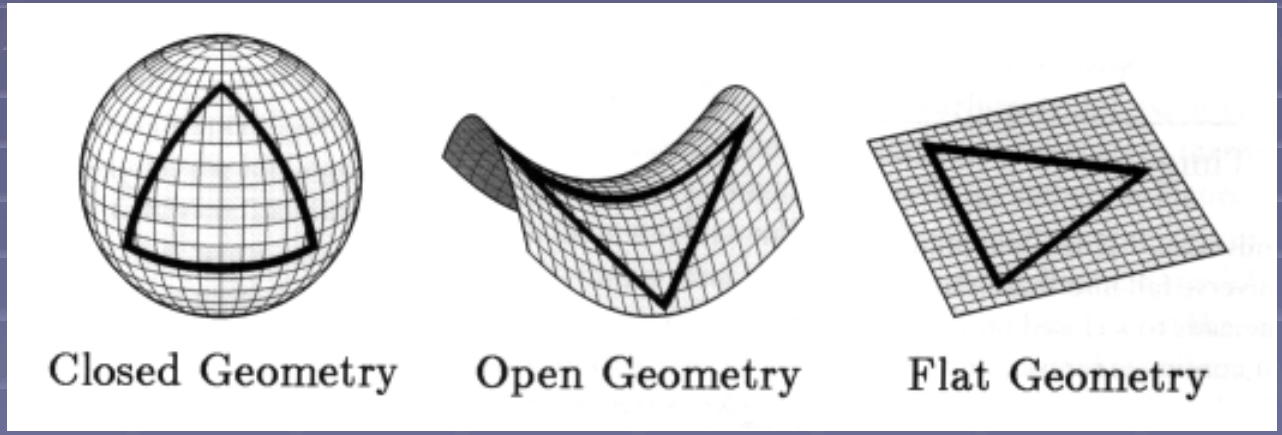
Homogeneous Universe



At the turn of the Millenium, recent experiments answered some of the BIG QUESTIONS:

- What is the geometry of the universe?
- What is the mass of the observable universe?
- How big is the universe?
- BUT many questions remain: what is the universe made of?

Geometry of the Universe



1930: Three possible geometries for the universe

2000: The geometry of the universe is FLAT!!!!!!

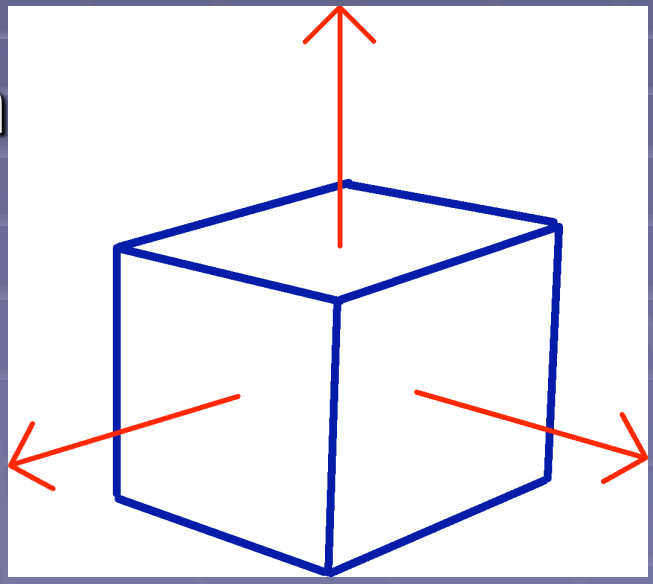
Universe has Flat Geometry

- Universe is NOT two-dimensional.
- Goes out to infinity in all three directions:

$$x, y, z$$

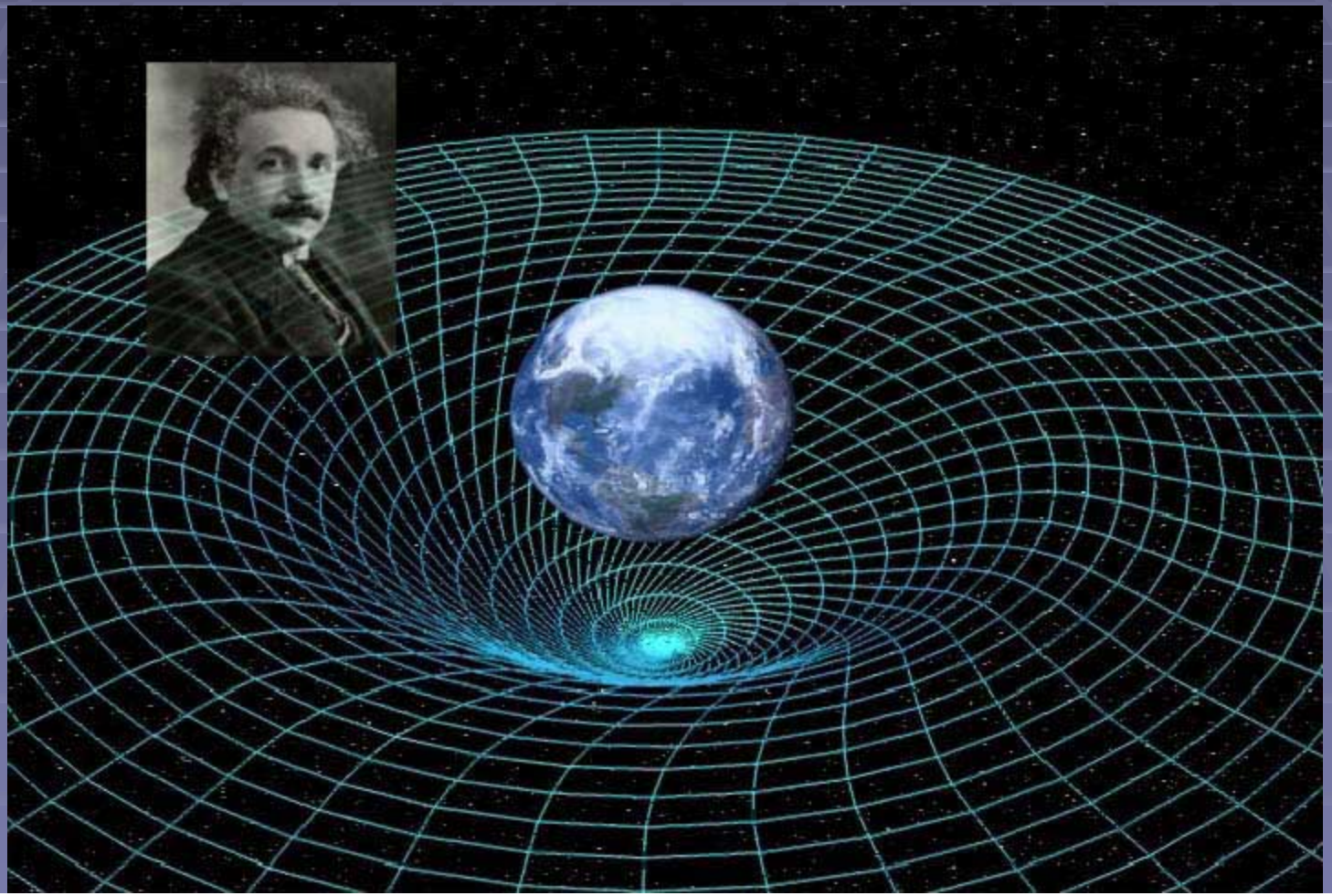
Shortest distance between points is a straight line.

No curvature required, no weird geometry.

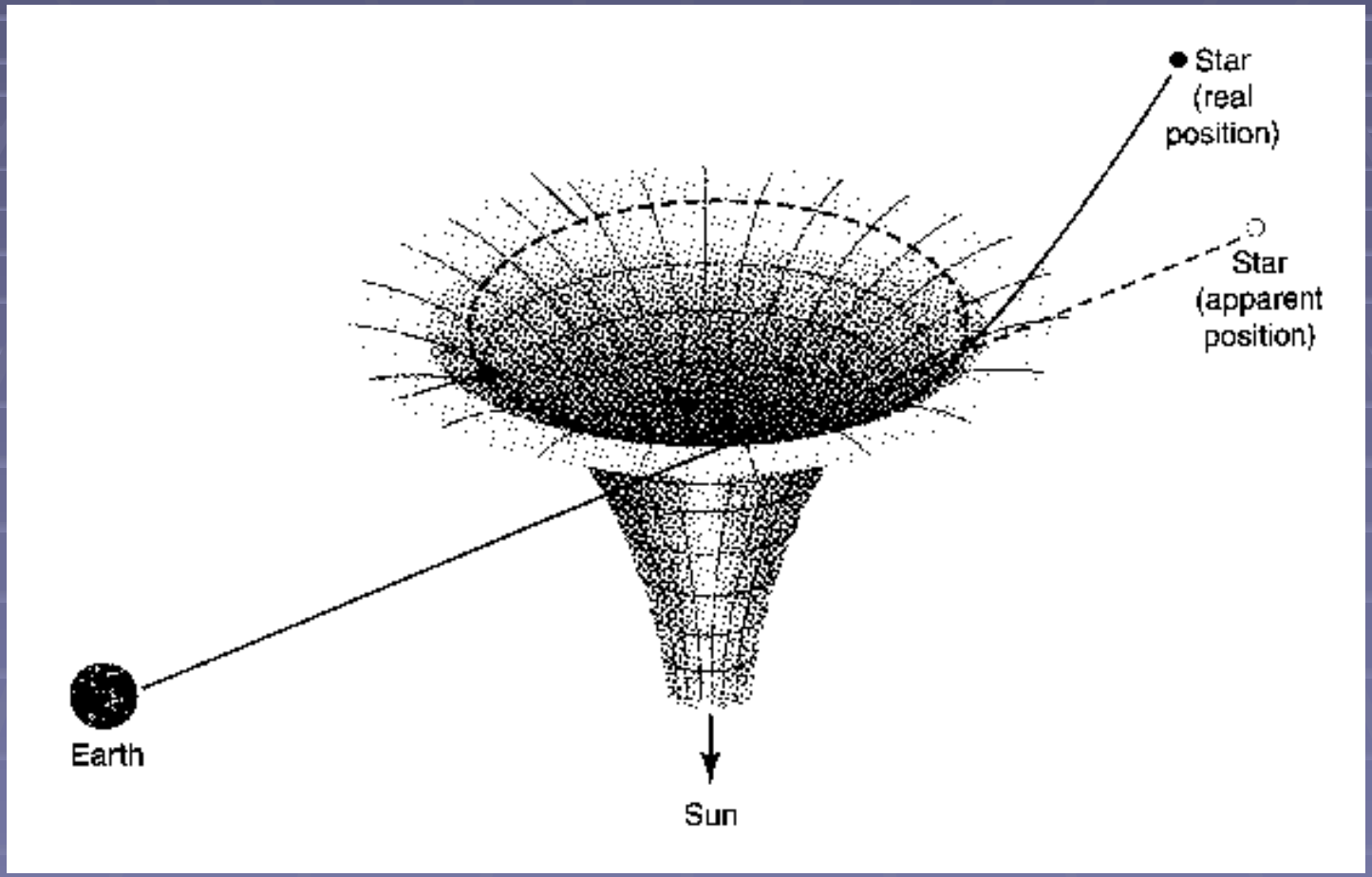


Geometry is Determined by Matter Content

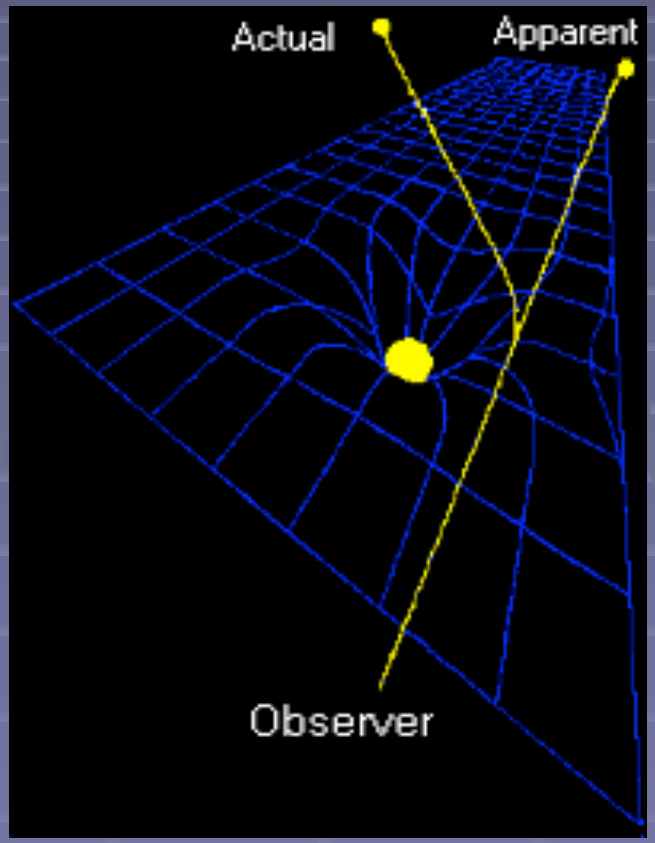
Warping of Spacetime:



Matter Bends Light



Objects appear to be in different positions



As we look backwards in time:

- All points in infinite universe getting closer and closer

  --- yet universe can still be infinite all the way back!

Eventually, the density at each point is so great we lose description (maybe string theory?)

Big Bang at every point in the universe.

Big Bang happens everywhere at once (not at a single point)







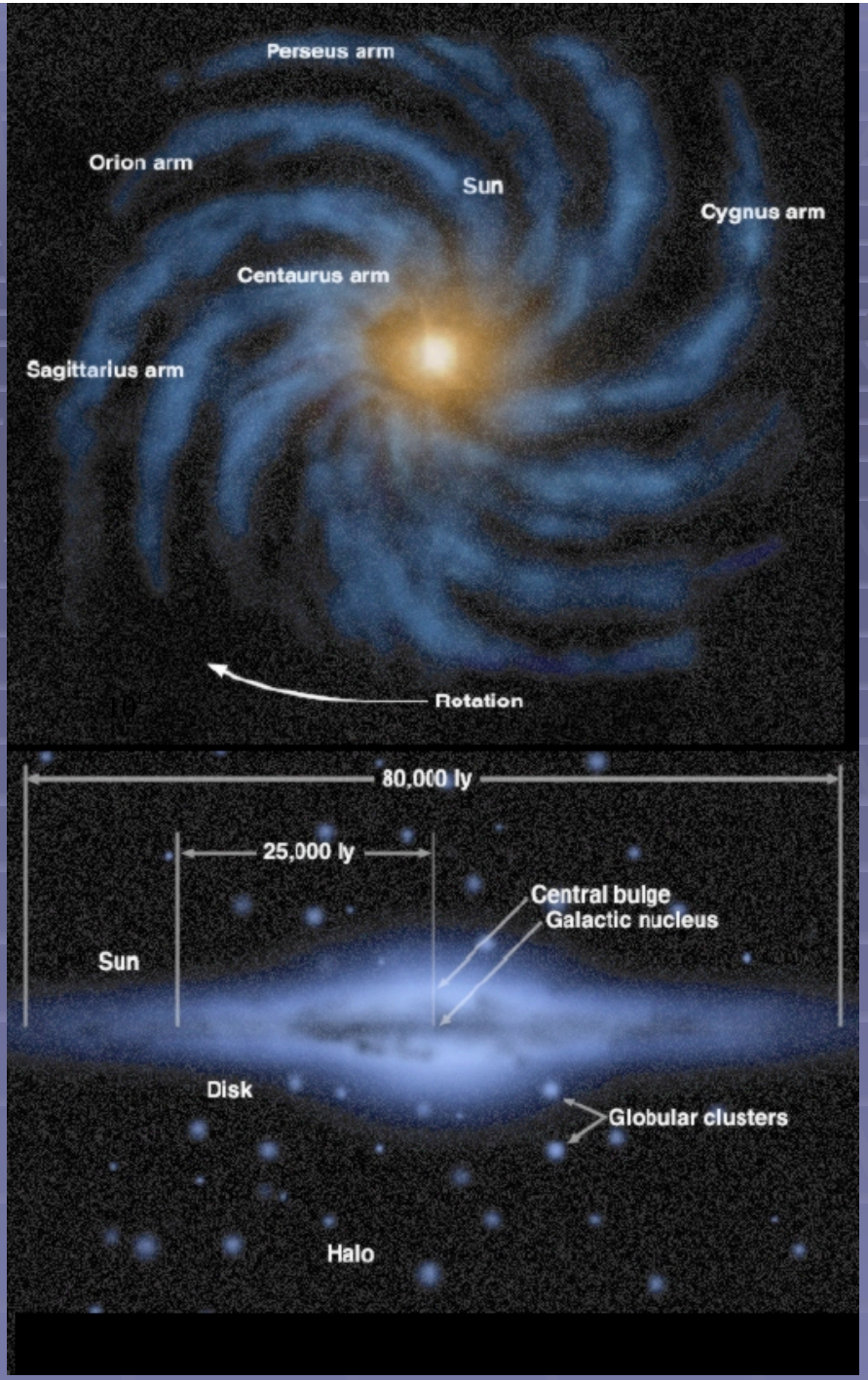
Dark Matter in Galaxies

- What do galaxies look like?
- Rotation Curves and galactic dark matter
- Evidence for dark matter in clusters of galaxies
- What can the Dark Matter be?

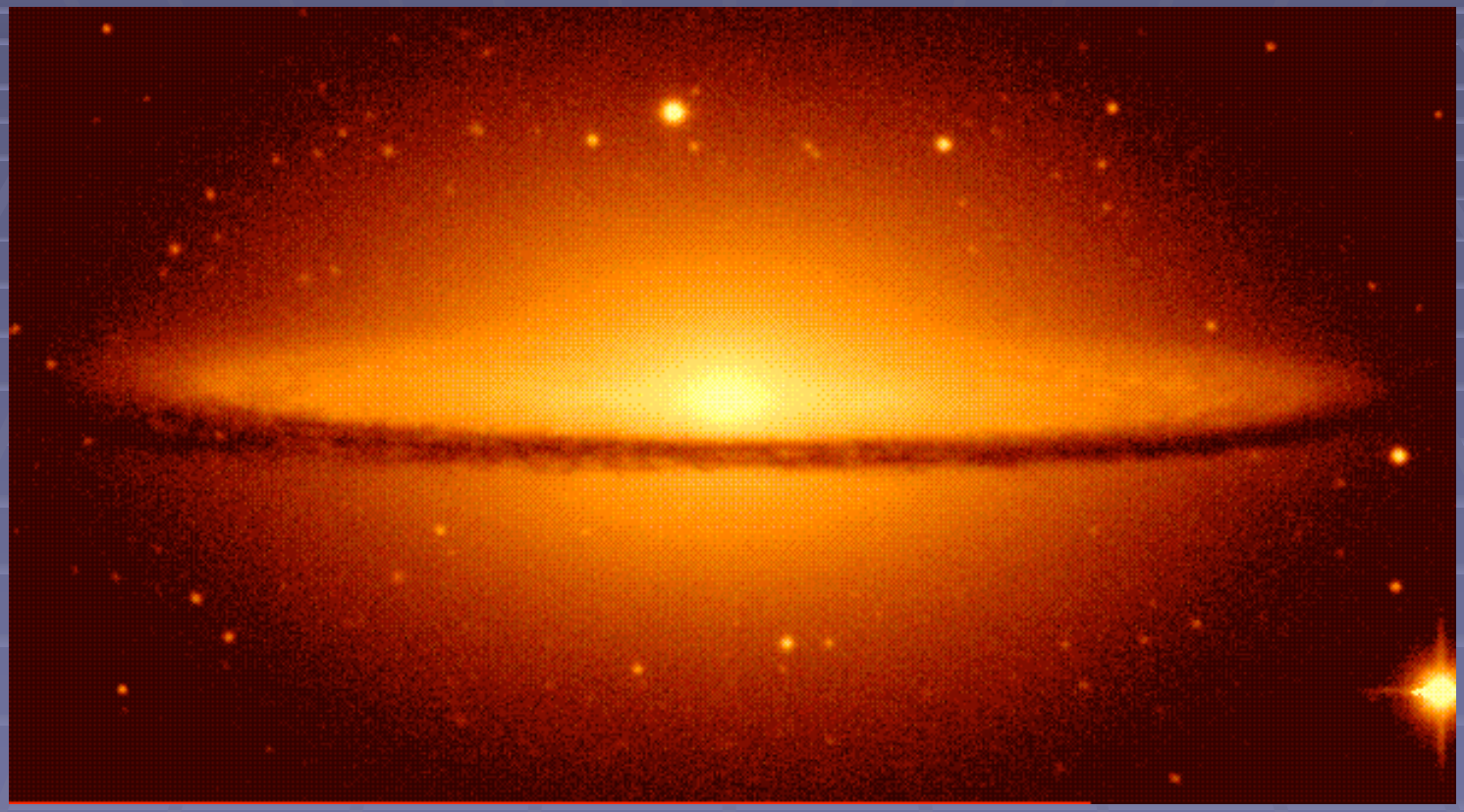
Our Galaxy: The Milky Way

The mass of the galaxy:

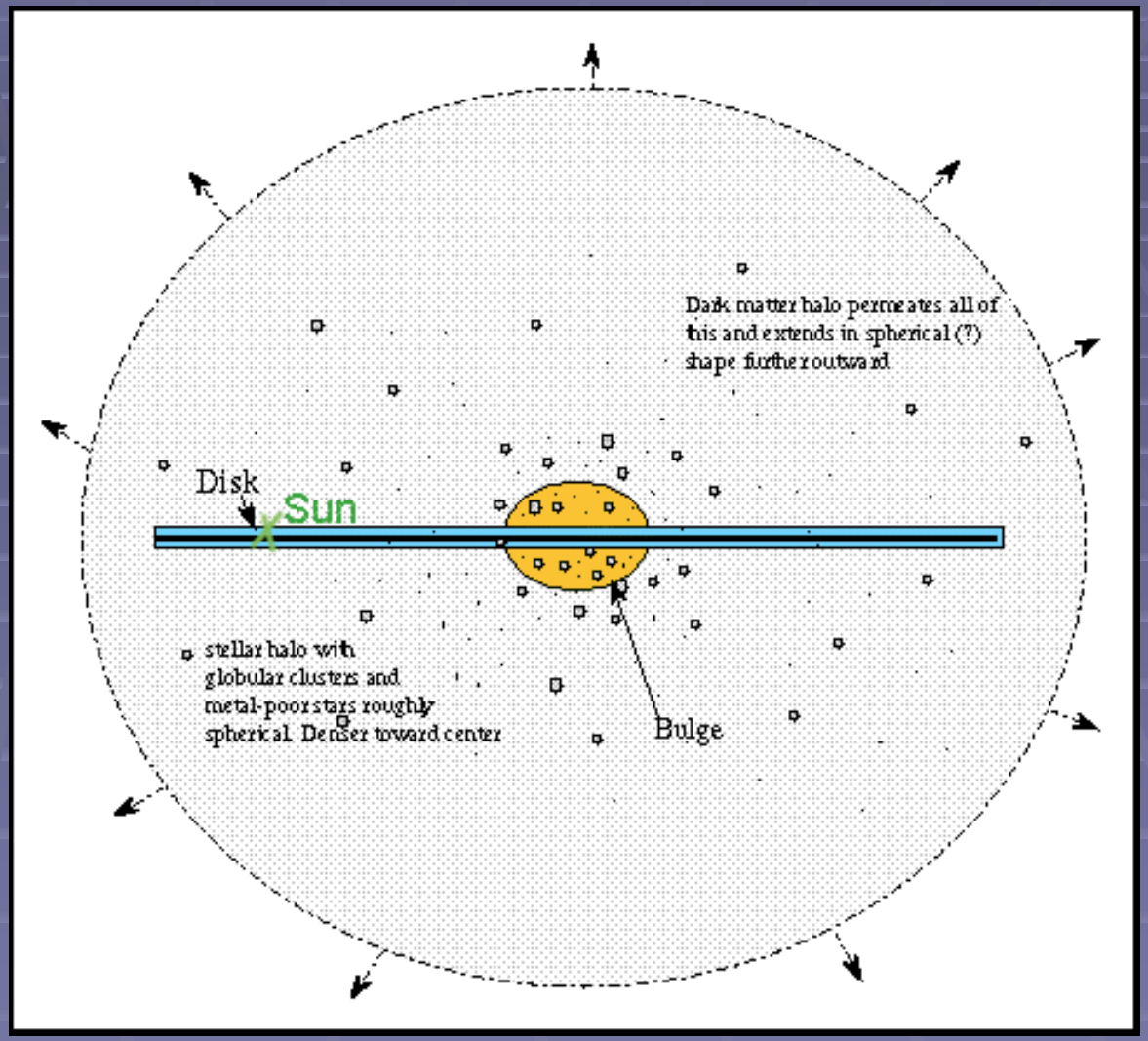
10^{12} solar masses



Galaxies



Scematic of typical galaxy



Galaxies have Dark Matter Haloes

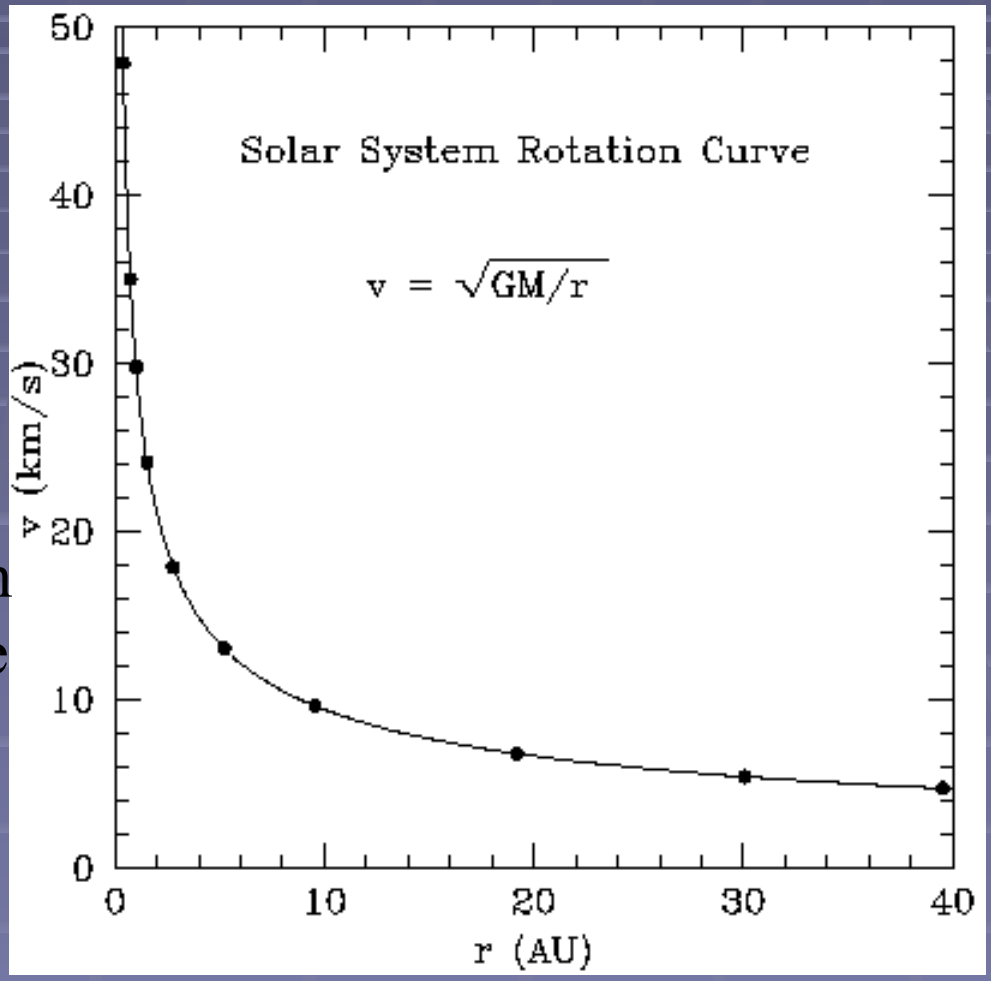
Rotation Curves

- How do we know that galaxies have dark matter haloes? Rotation Curves.
- Example: Solar System Rotation Curve
- 95% of the mass of galaxies is made of an unknown component!!!

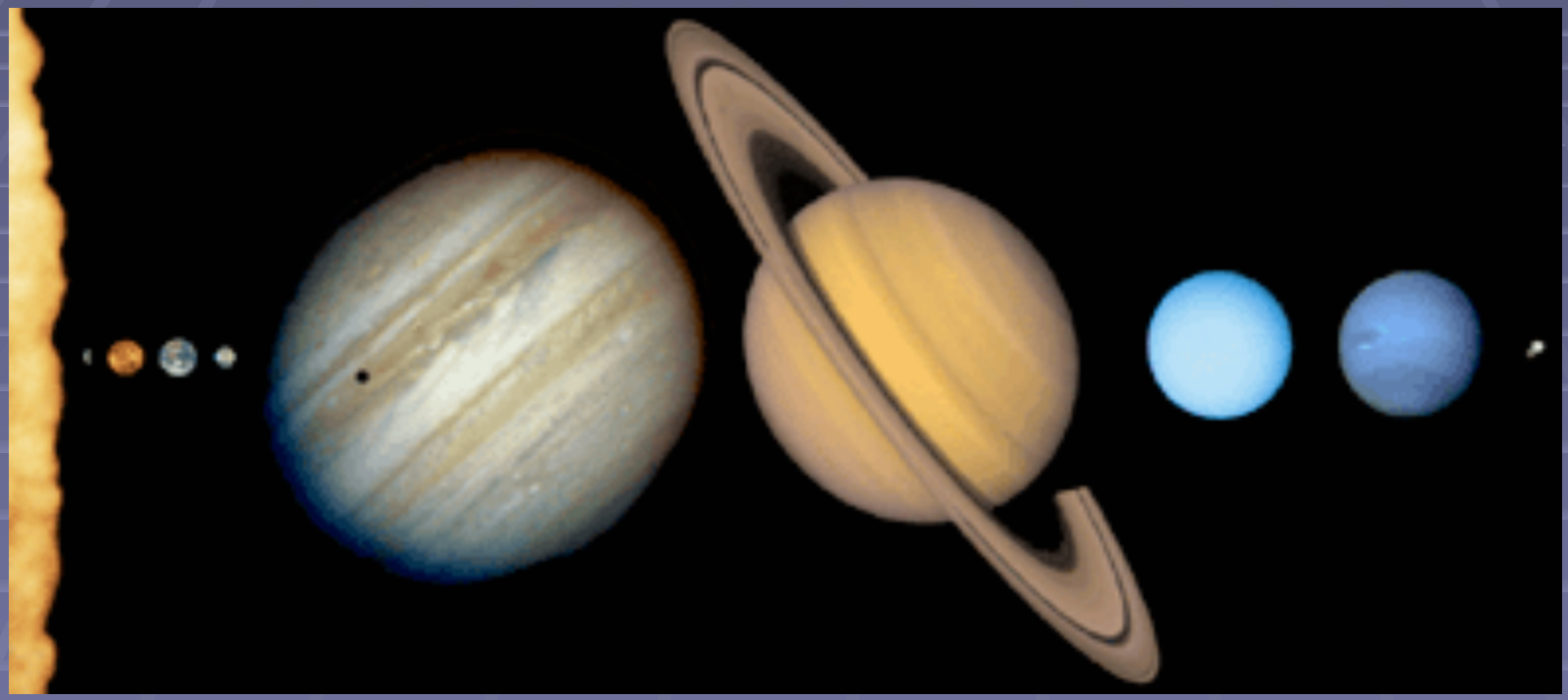
Solar System Rotation Curve

Average Speeds of the Planets

As you move out from the Sun, speeds of the planets drop.



Solar System



Tyco Brahe (1546-1601)

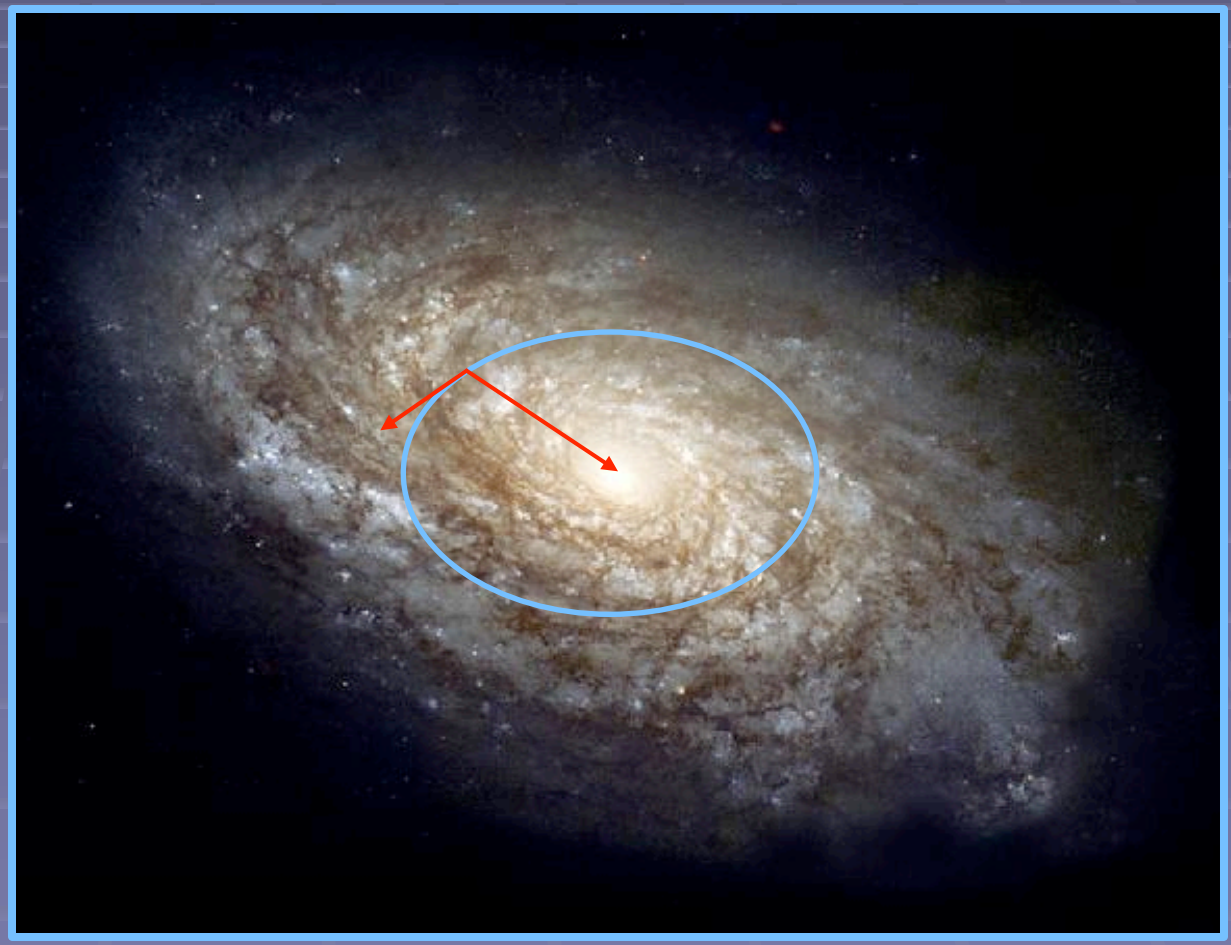
Lost his nose in a duel, and wore a gold and silver replacement.

Studied planetary orbits.

Died of a burst bladder at a dinner with the king.

Rotation Curves of Galaxies

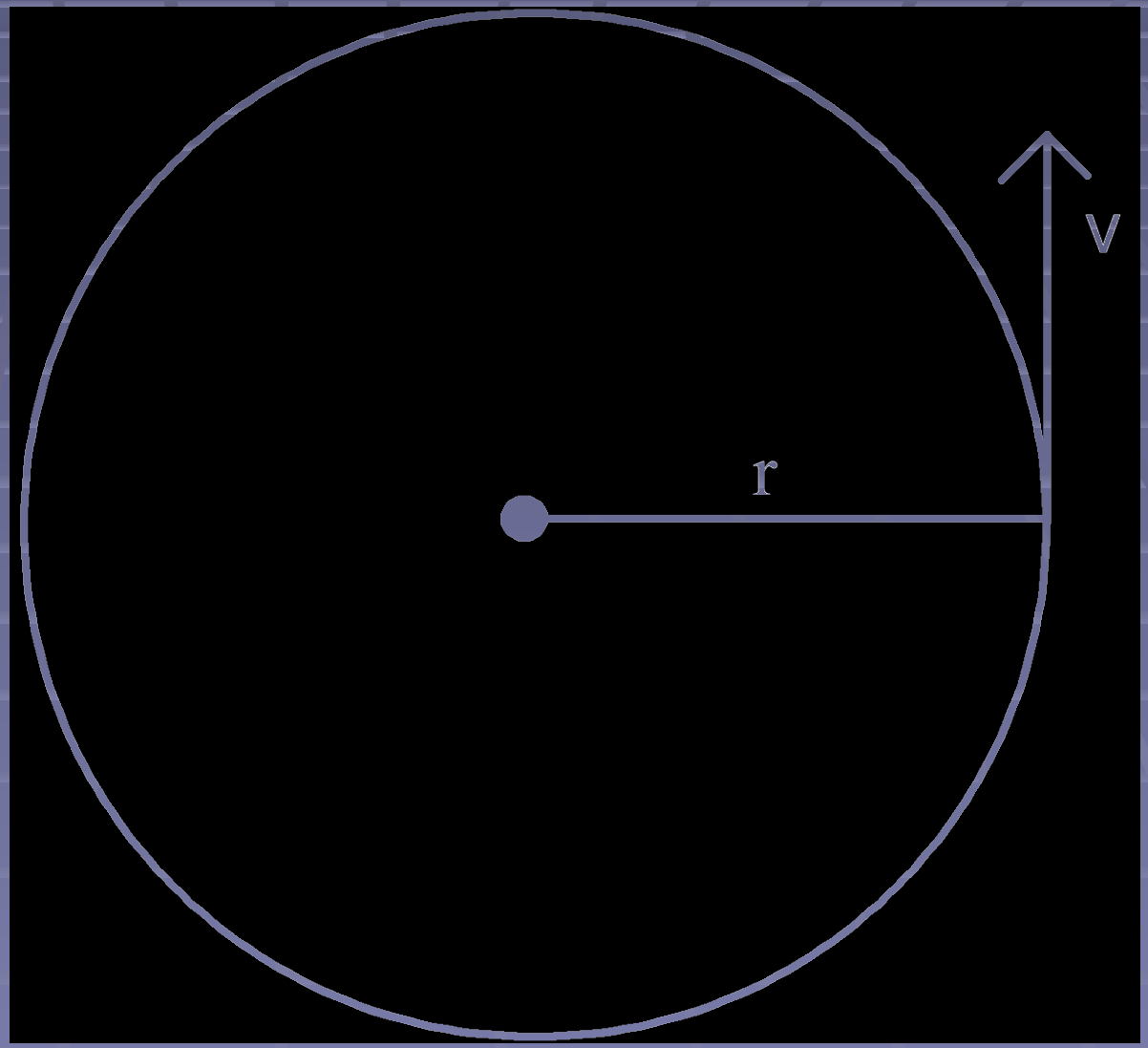
Orbit of a star in a Galaxy: speed is Determined by Mass



Speed is determined by Mass

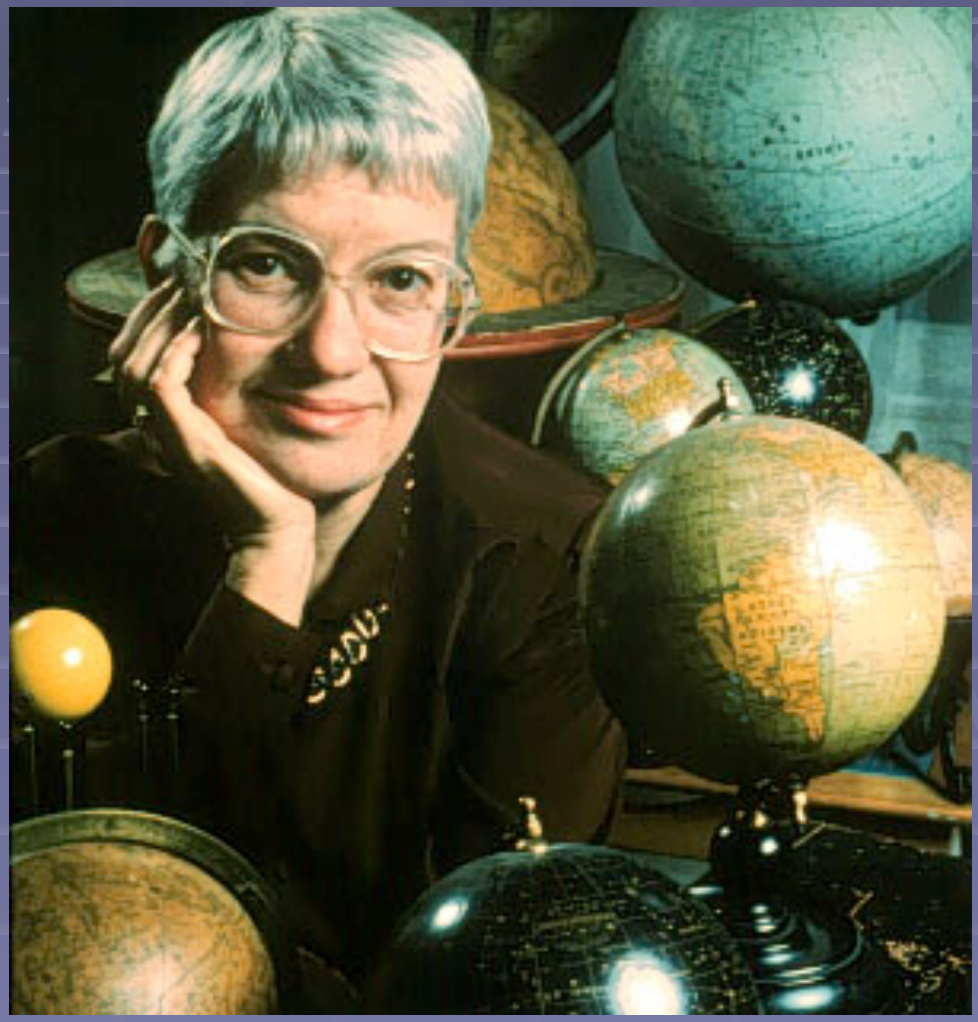
$$\frac{GM(r)m}{r^2} \qquad \frac{mv^2}{r}$$

The speed at distance r from the center of the galaxy is determined by the mass interior to that radius. Larger mass causes faster orbits.



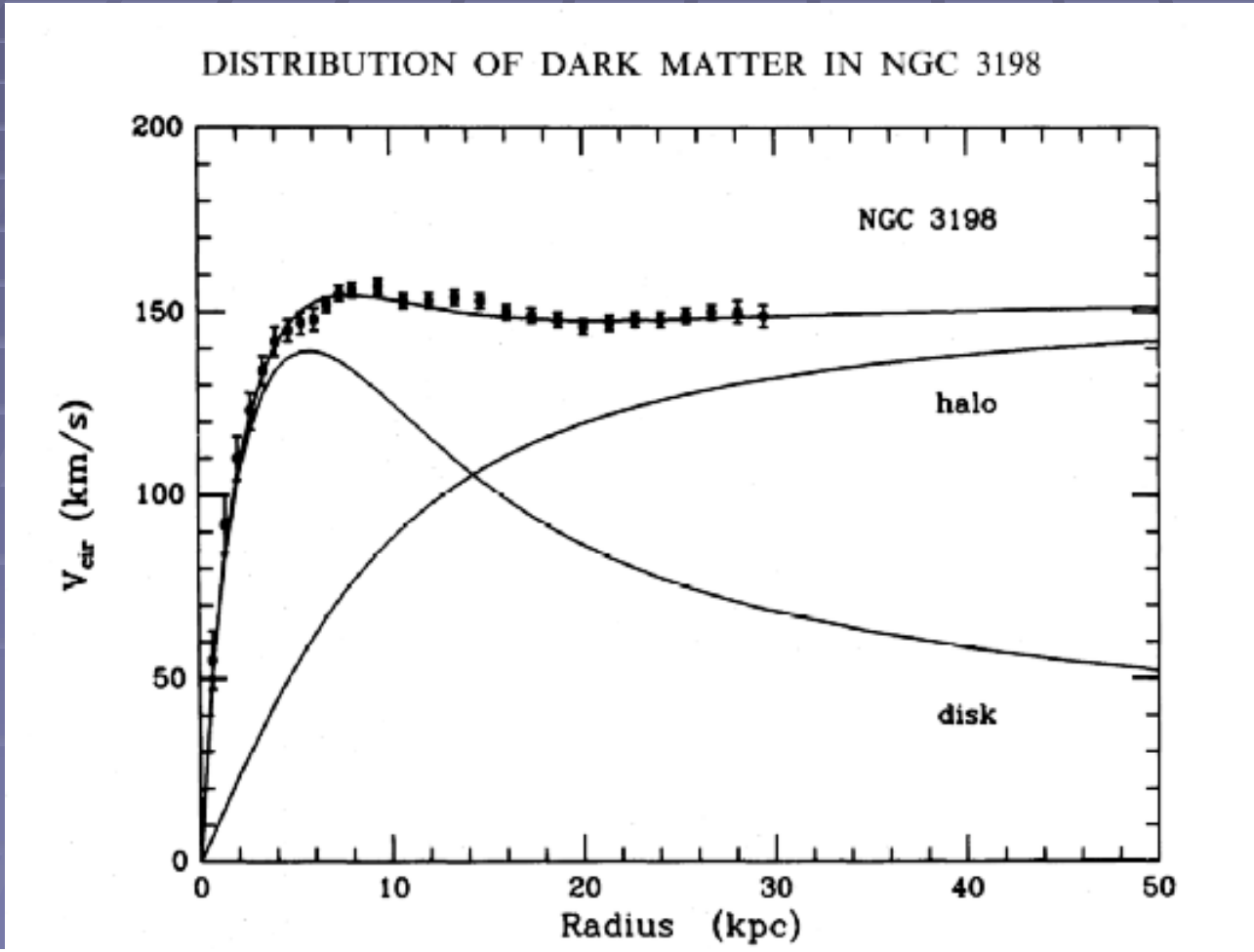
Vera Rubin

Studied rotation curves of galaxies, and found that they are FLAT!



95% of the matter in galaxies is unknown dark matter!

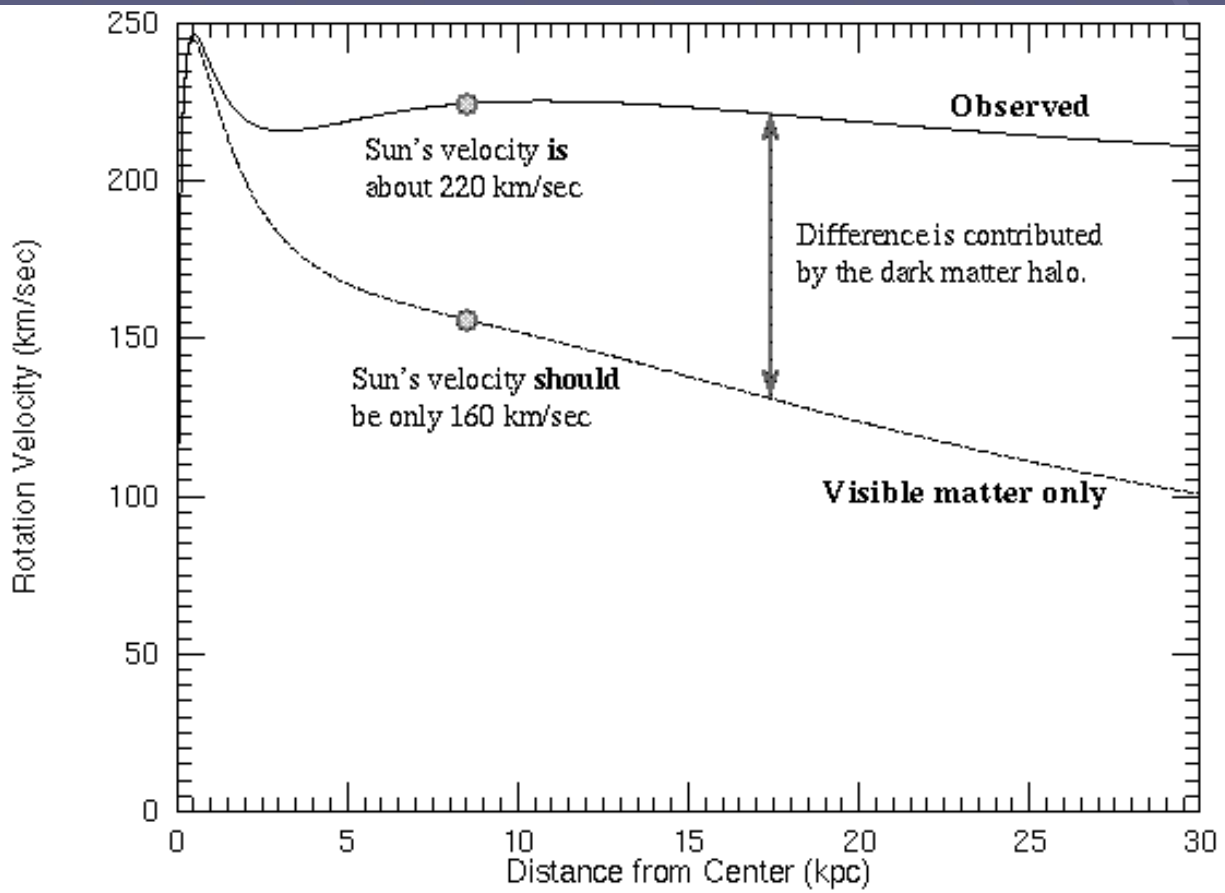
- Rotation Curves of Galaxies:



OBSERVED: FLAT ROTATION CURVE

EXPECTED FROM STARS

Sun's orbit is sped up by dark matter in the Milky Way

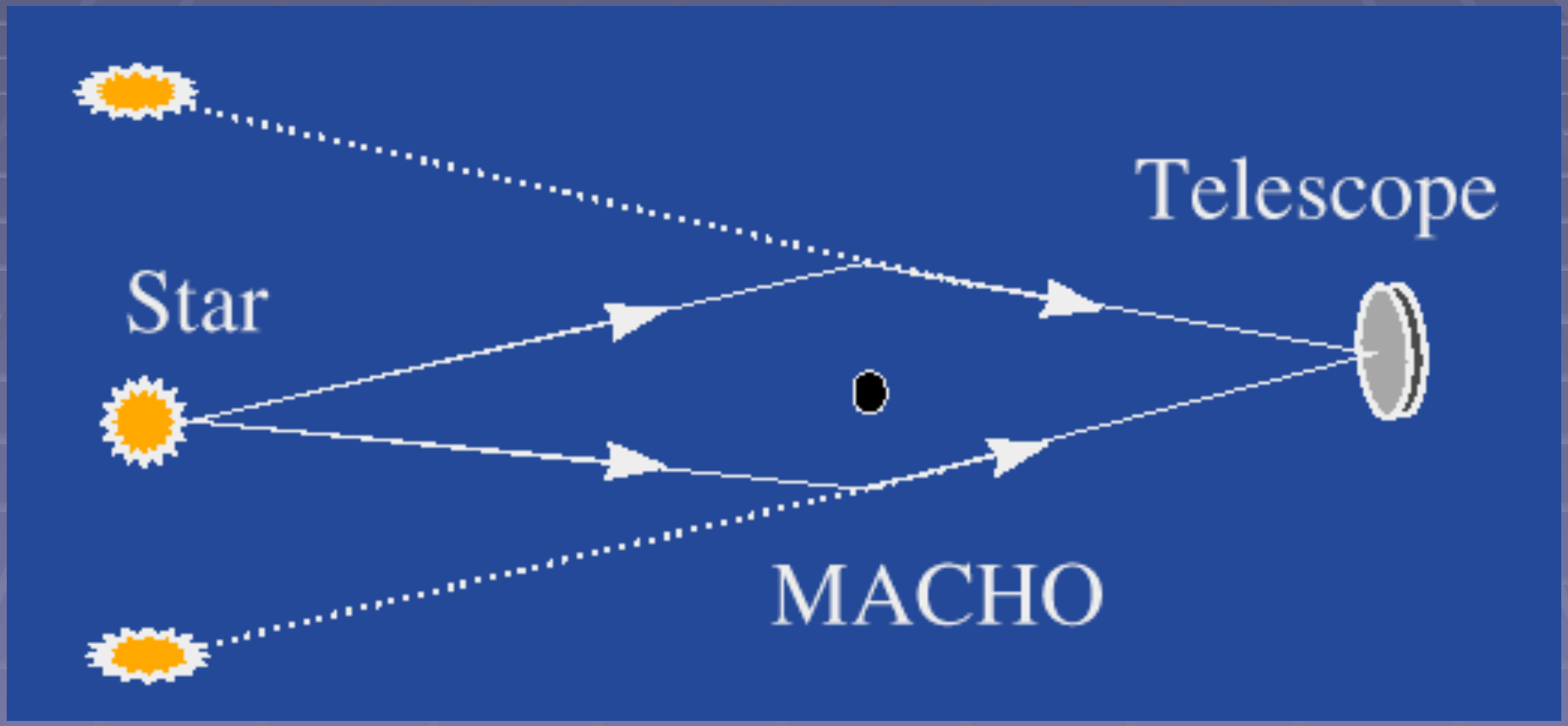


The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

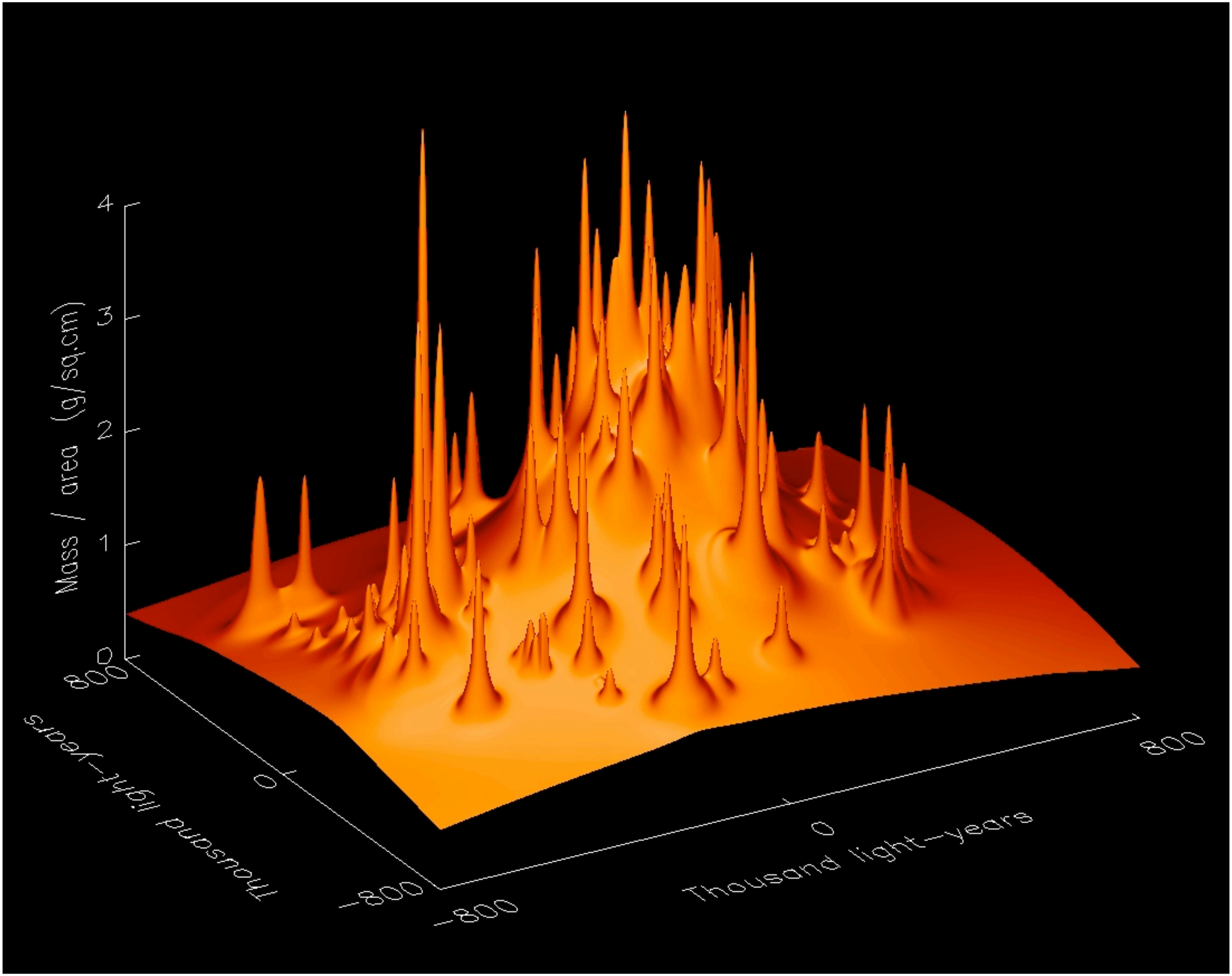
Dark Matter in Clusters of Galaxies

- Rotation Curves of Galaxies in the Cluster
- Lensing
- Gravitationally Confined Hot Gas in Clusters

Lensing: Another way to detect dark matter: it makes light bend

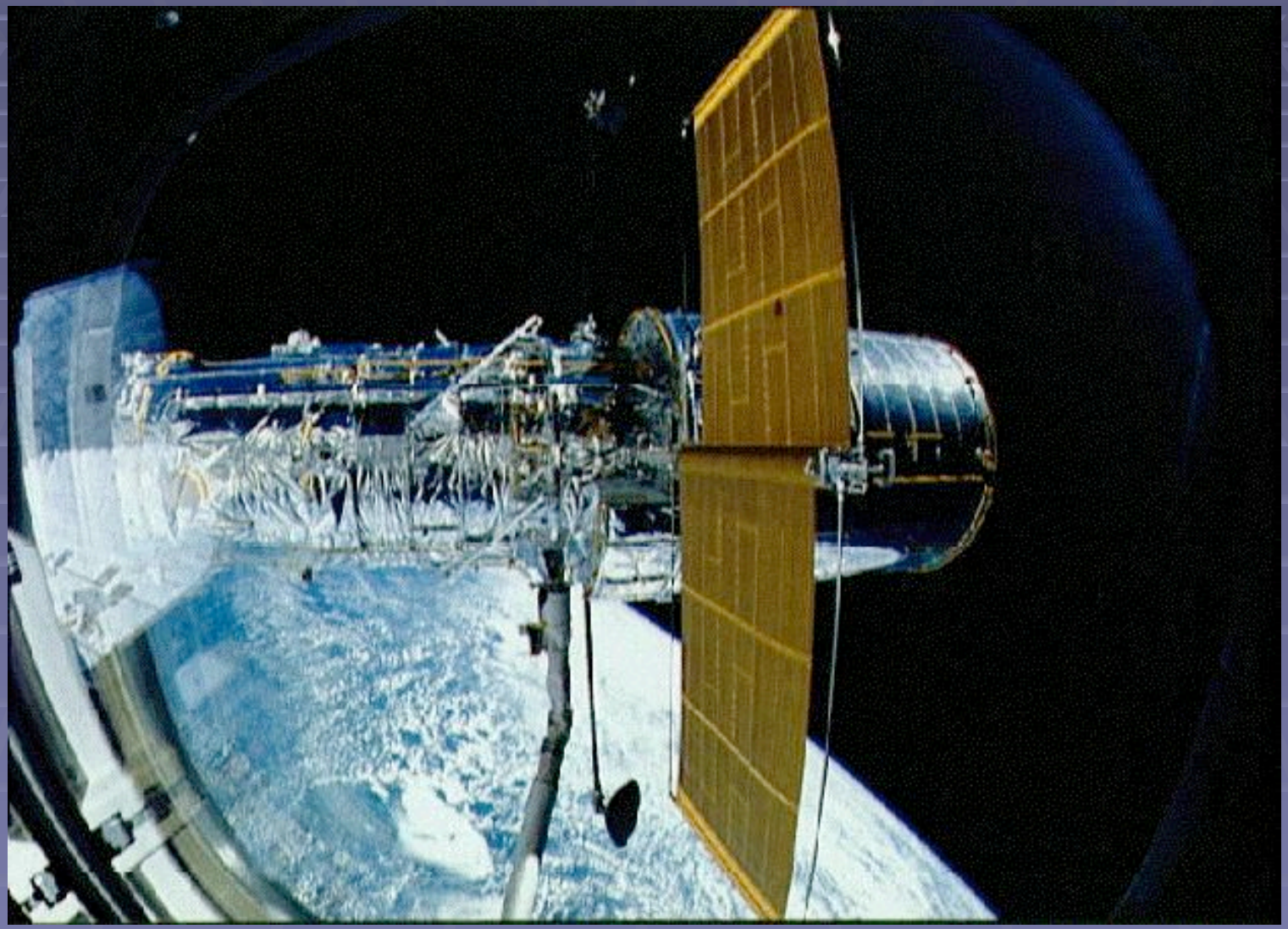


Lensing by dark matter



Mass / area (g/sq.cm)
0
1
2
3
4
800
0
-800
Thousand light-years
-800
0
800
Thousand light-years

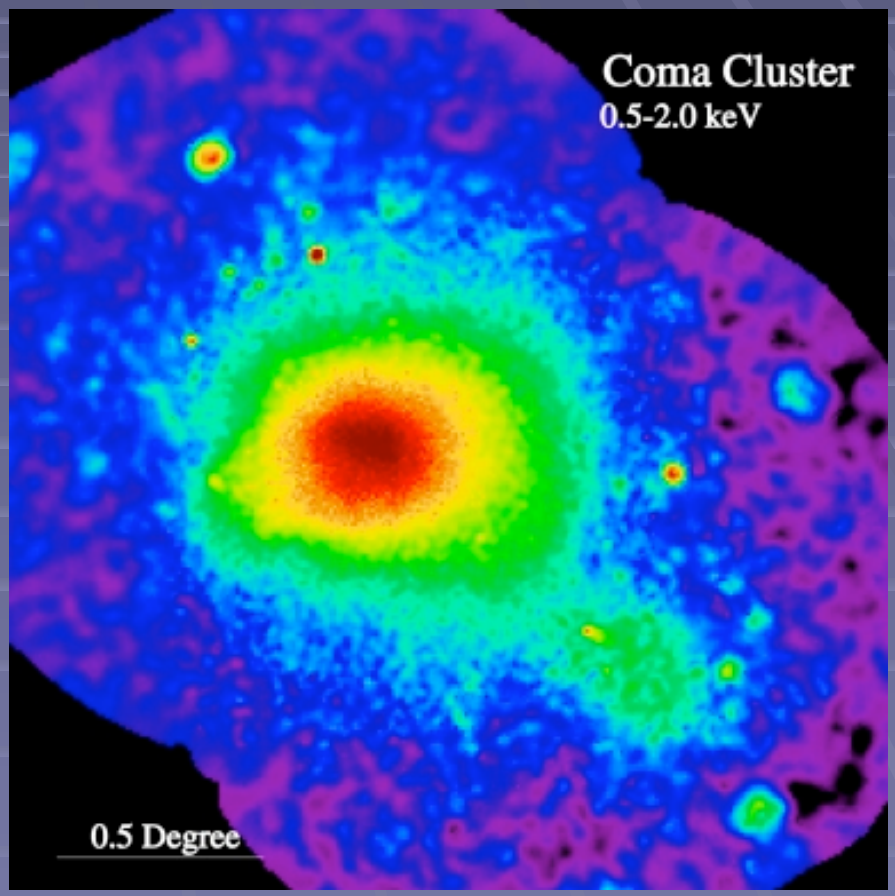
Hubble Space Telescope



Hot Gas in Clusters: The Coma Cluster

Without dark matter, the hot gas would evaporate.

Optical Image



X-ray Image from the ROSAT satellite

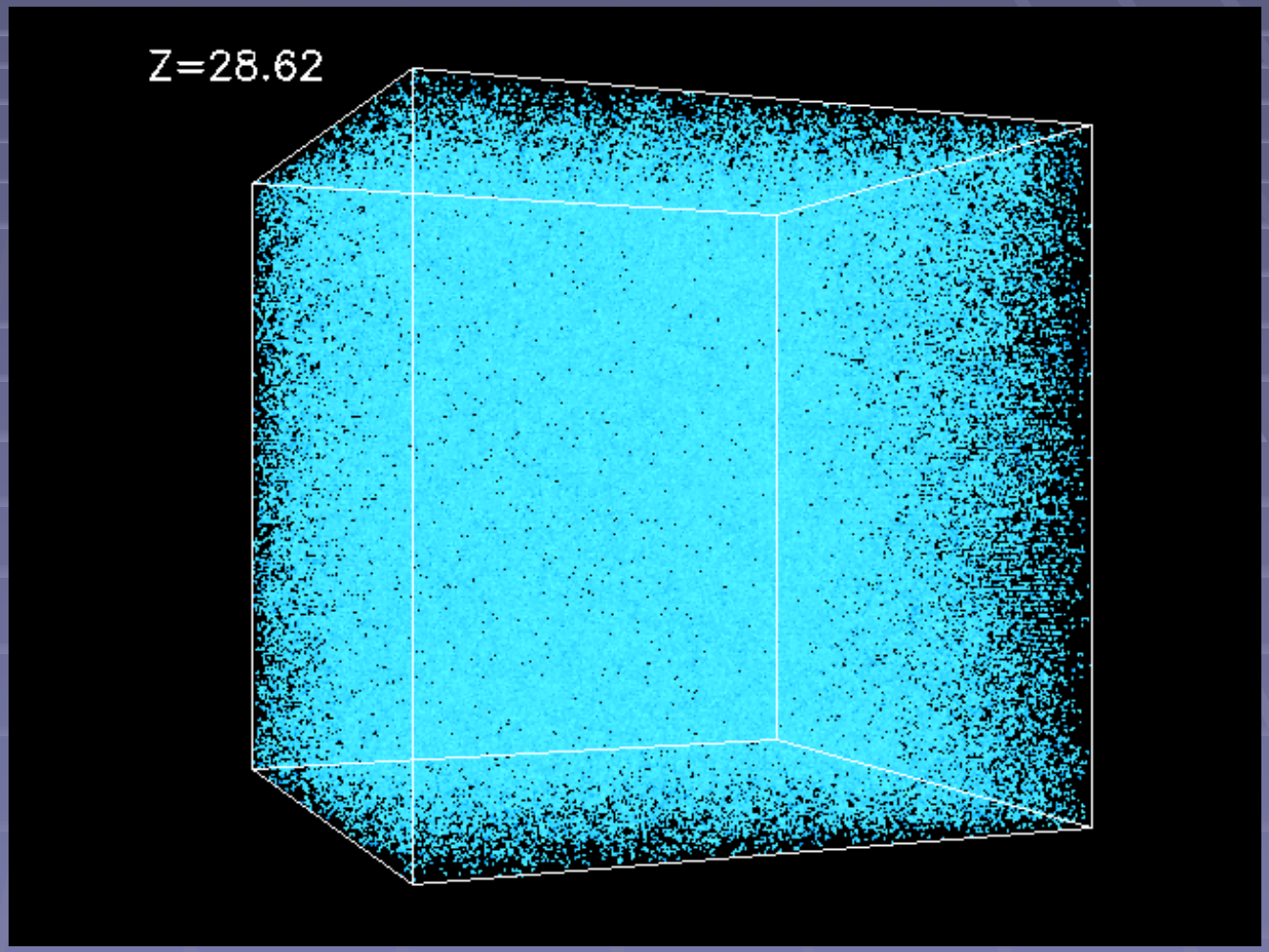
The Dark Matter Problem:

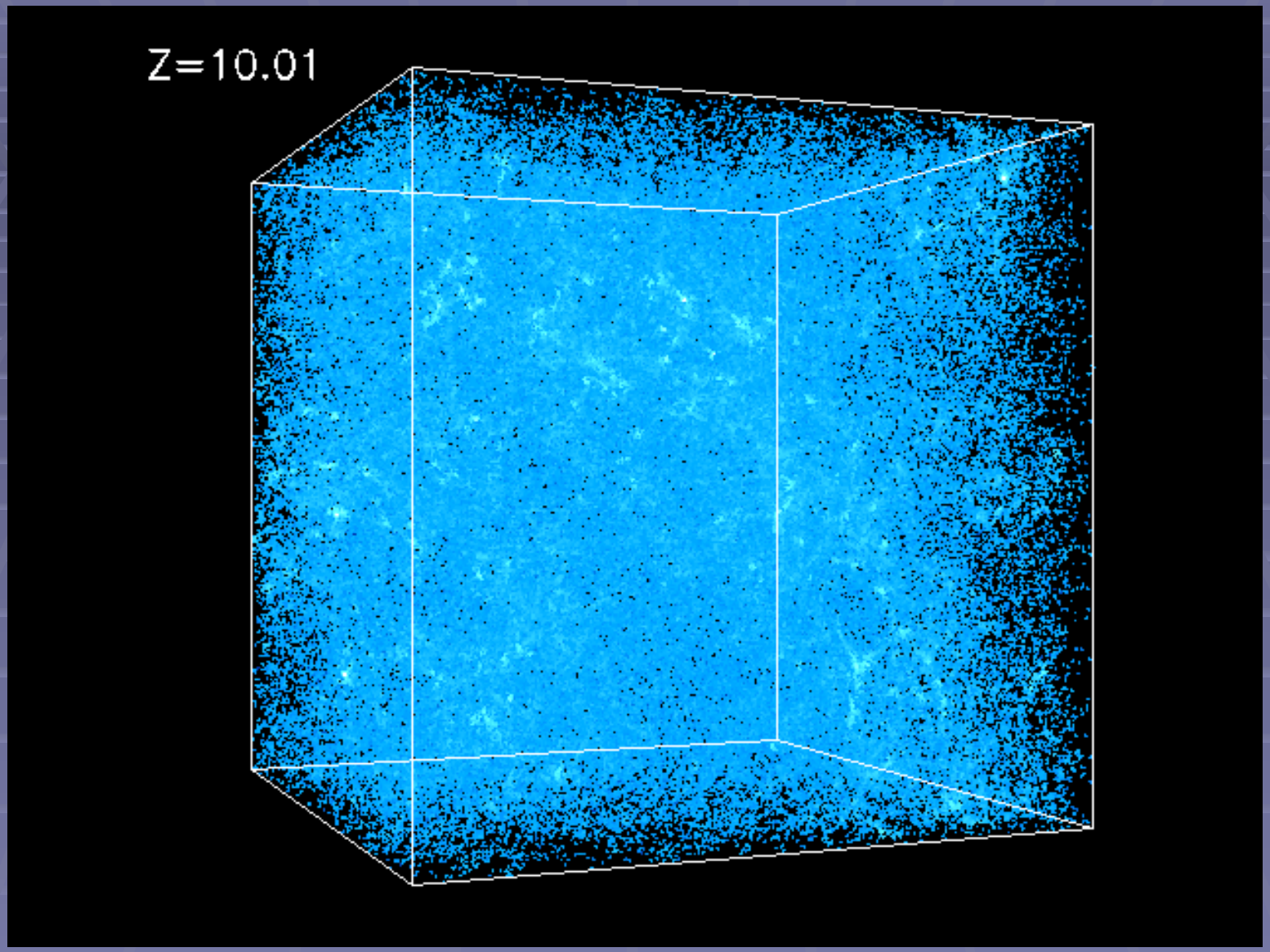
- 95% of the mass in galaxies and clusters of galaxies are made of an unknown dark matter component

Known from: rotation curves,
gravitational lensing,
hot gas in clusters.

Formation of Structure: Numerical Simulations

Dark Matter particles come together to make galaxies, clusters, and larger scale structures

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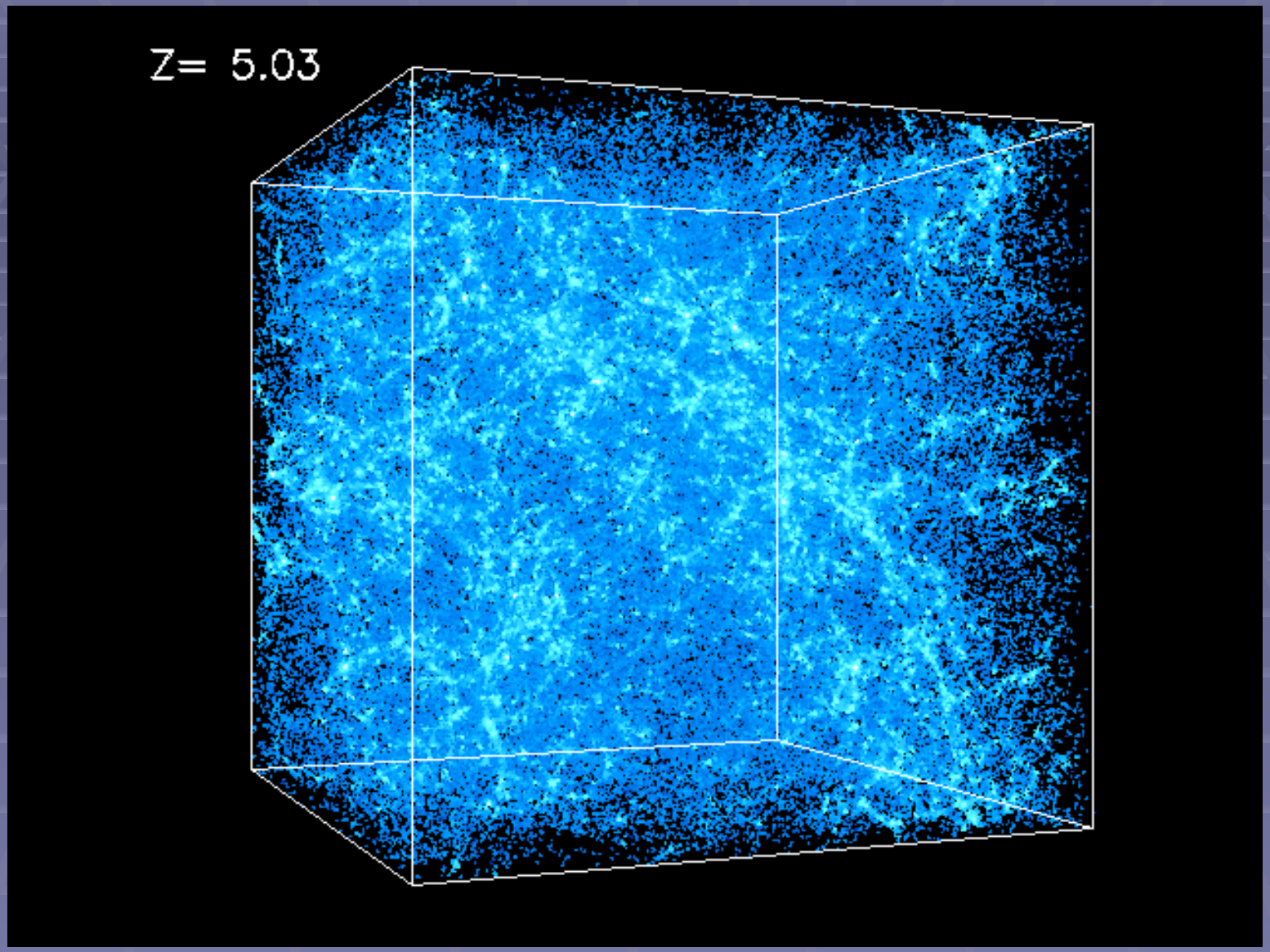
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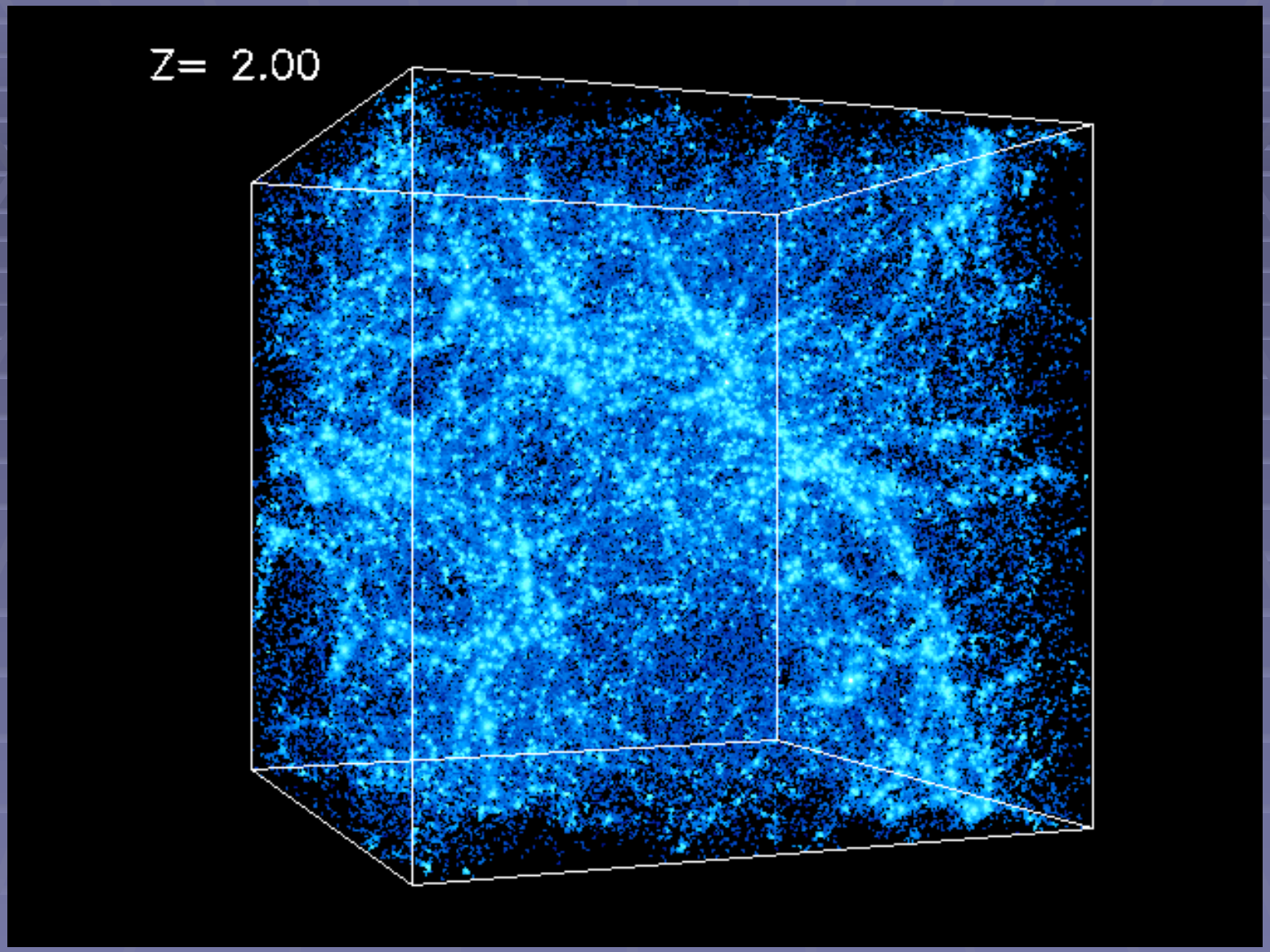
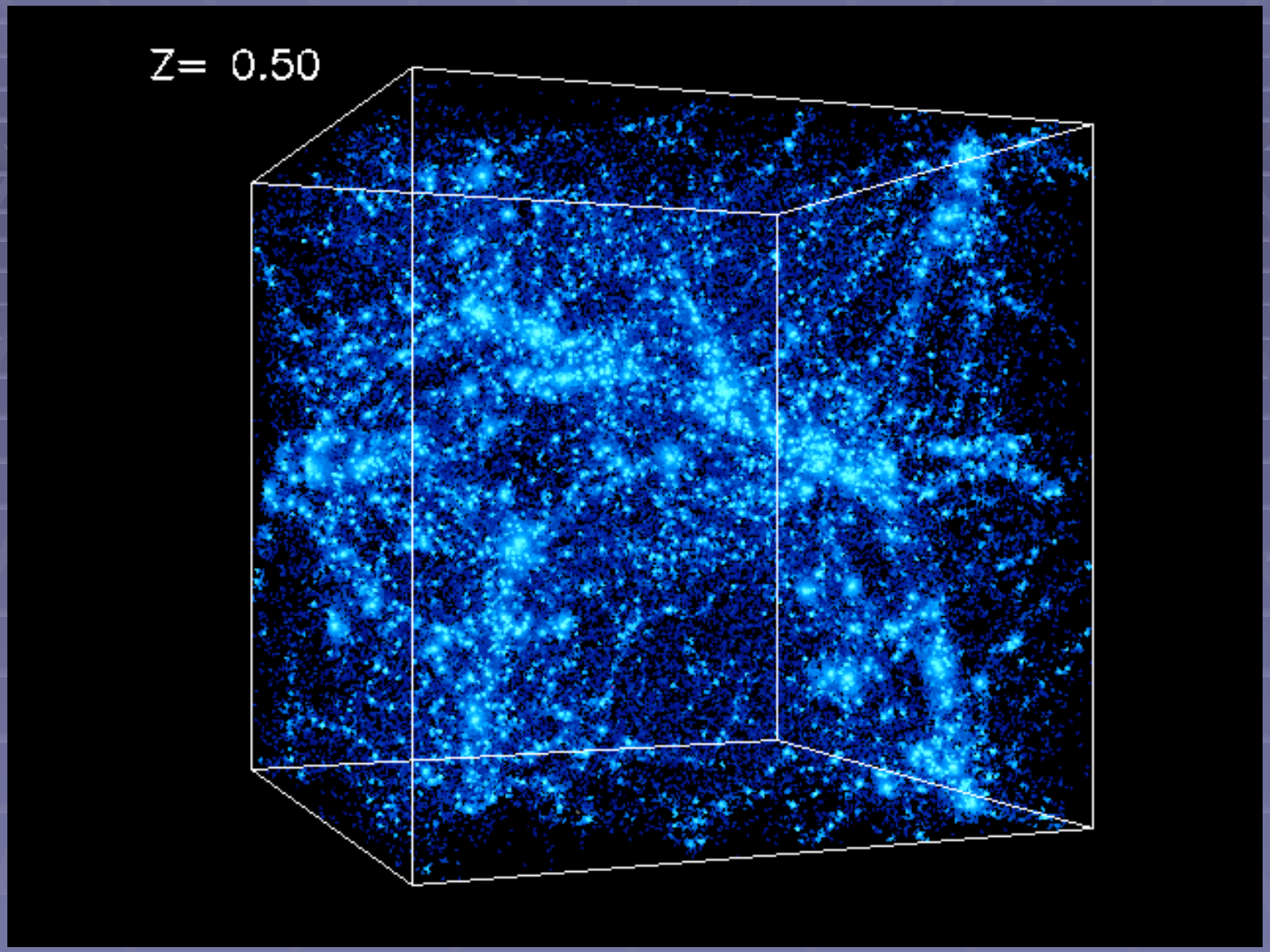

Z= 2.00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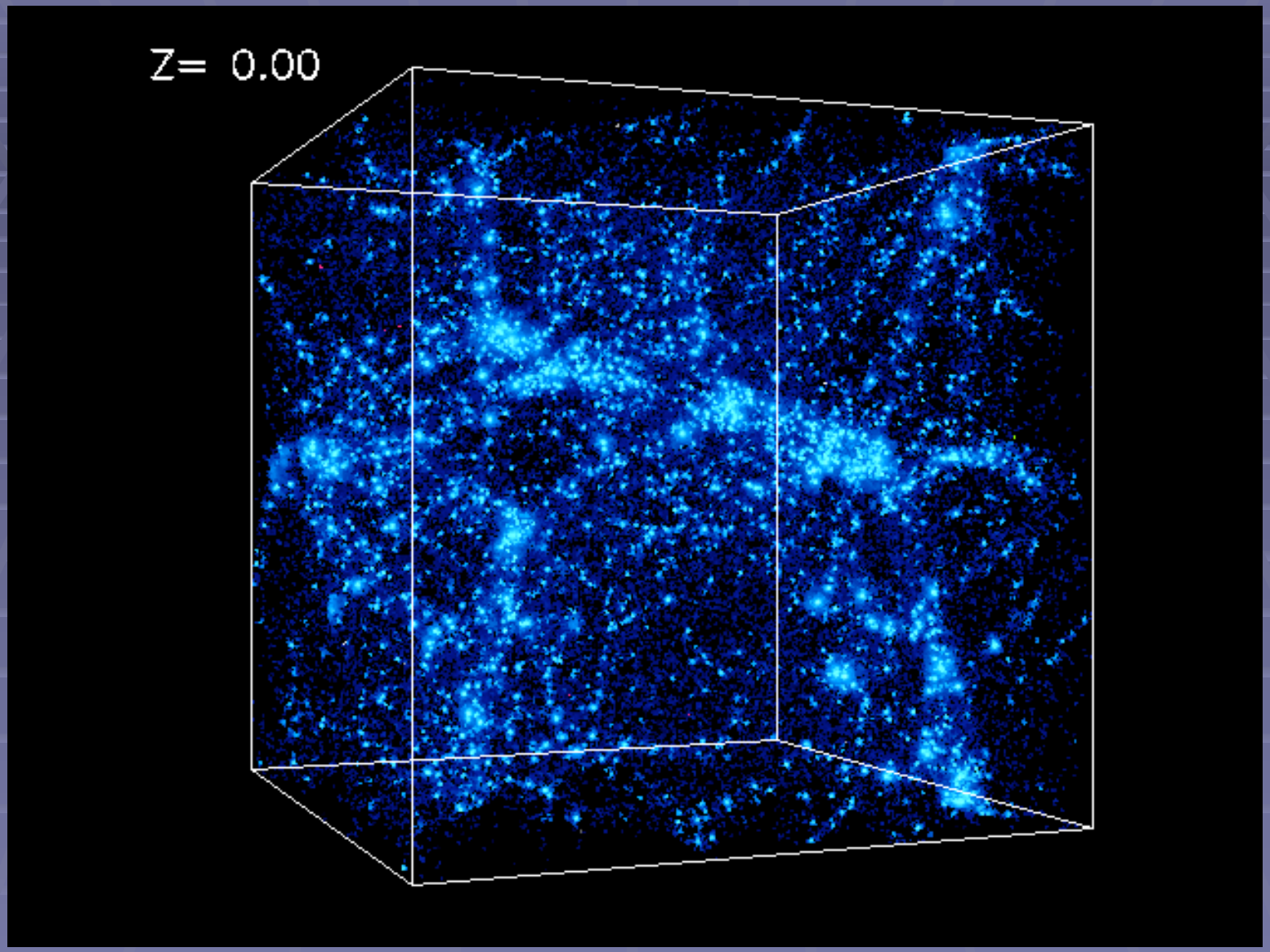

Z= 0.00

The Dark Matter is NOT:

- Diffuse Hot Gas (would produce x-rays)
- Cool Neutral Hydrogen (see in quasar absorption lines)
- Small lumps or snowballs of hydrogen (would evaporate)
- Rocks or Dust (high metallicity)

(Hegyi and Olive)

What Can the Dark Matter Be?

- MACHOs: Massive Compact Halo Objects

  made of ordinary matter

  OR

- WIMPs: Weakly Interacting Massive Particles

  made of exotic matter

MACHOs

- Faint stars
- Planetary Objects (Brown Dwarfs)
- Stellar Remnants:
- White Dwarfs
- Neutron Stars
- Black Holes

Is Dark Matter Made of Stars? NO!

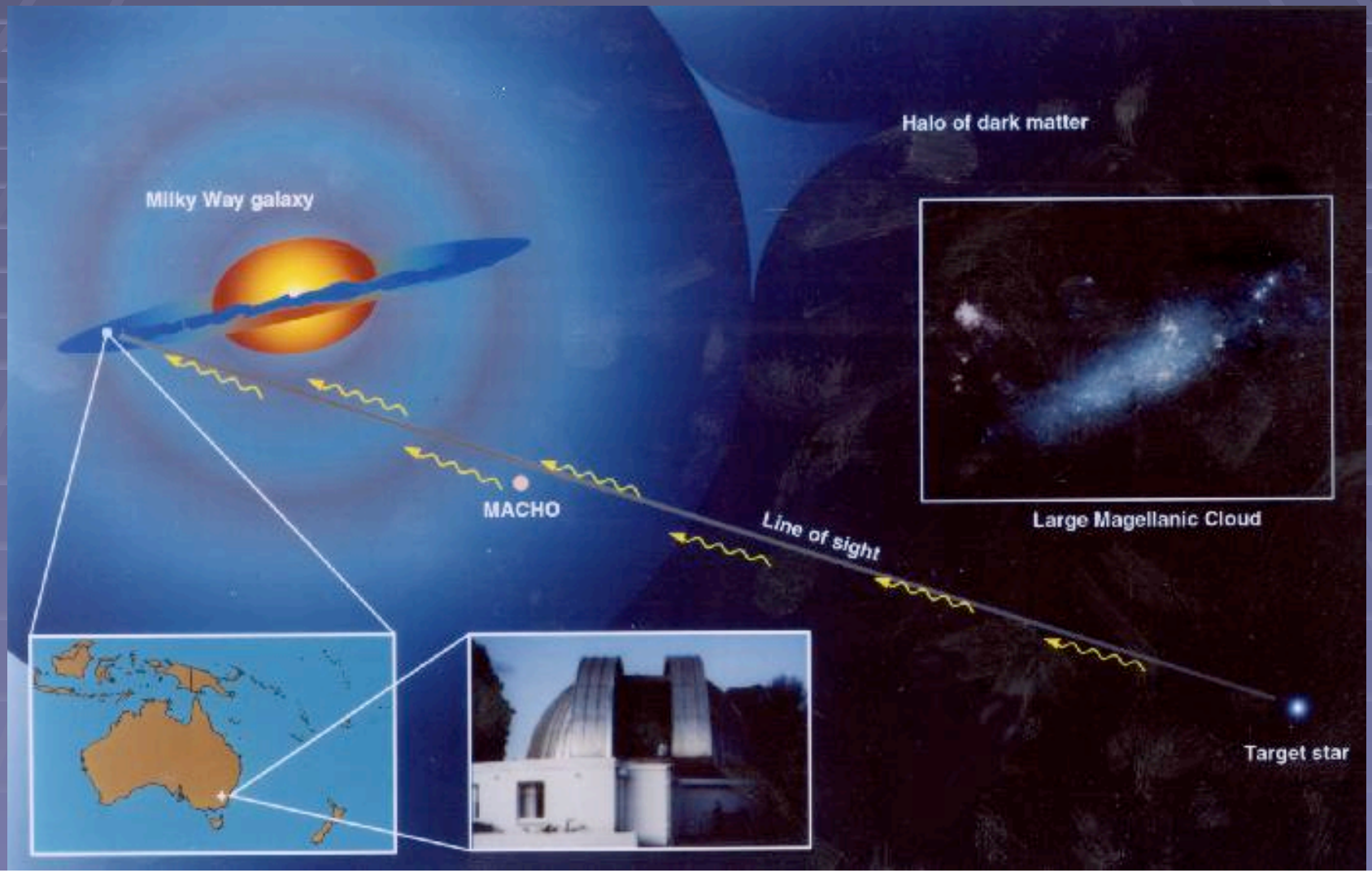
- Faint Stars: Hubble Space Telescope
- Planetary Objects:

  parallax data

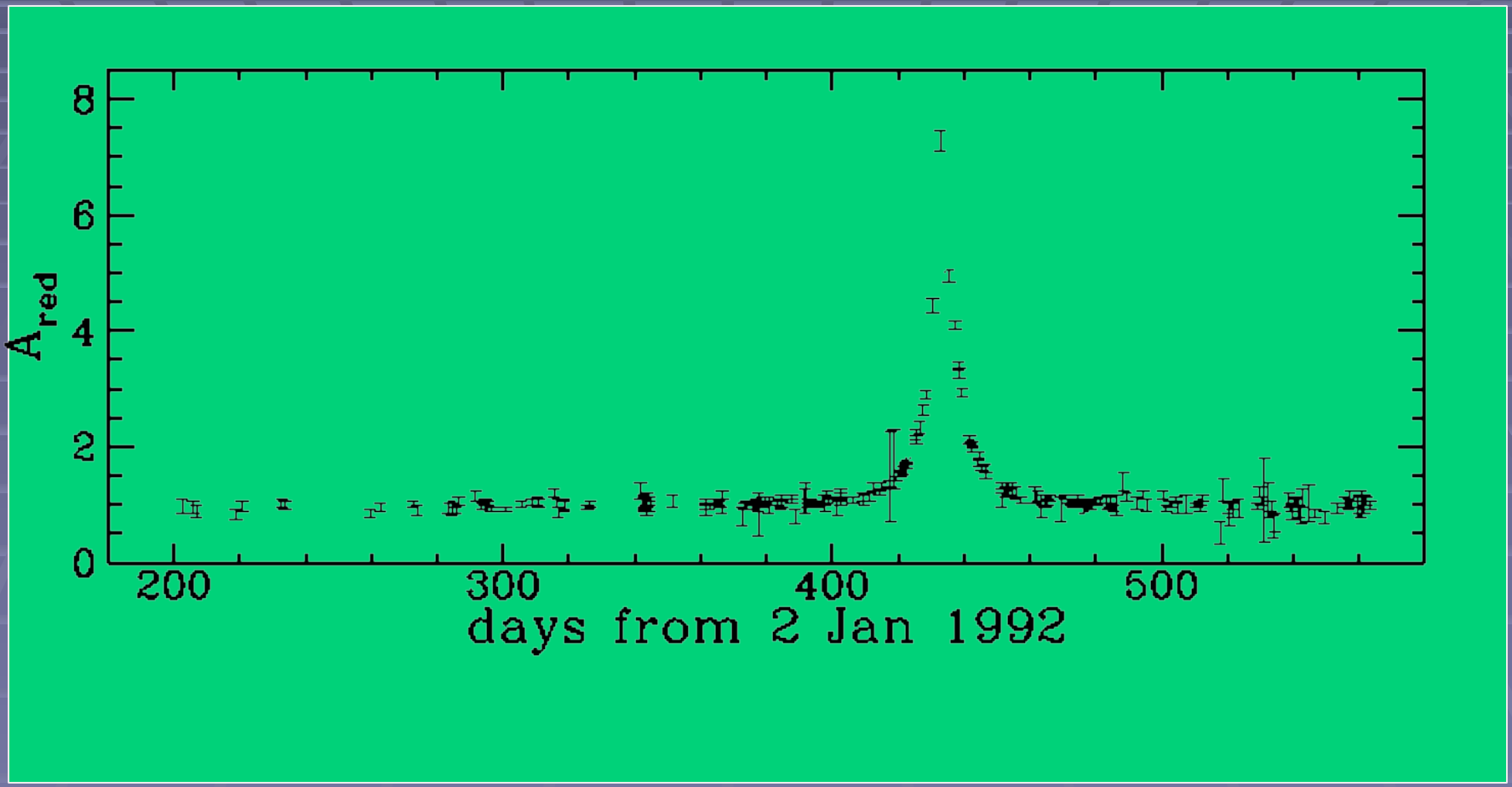
  microlensing experiments

Together, these objects make up less than 3% of the mass of the Milky Way.

Microlensing experiments



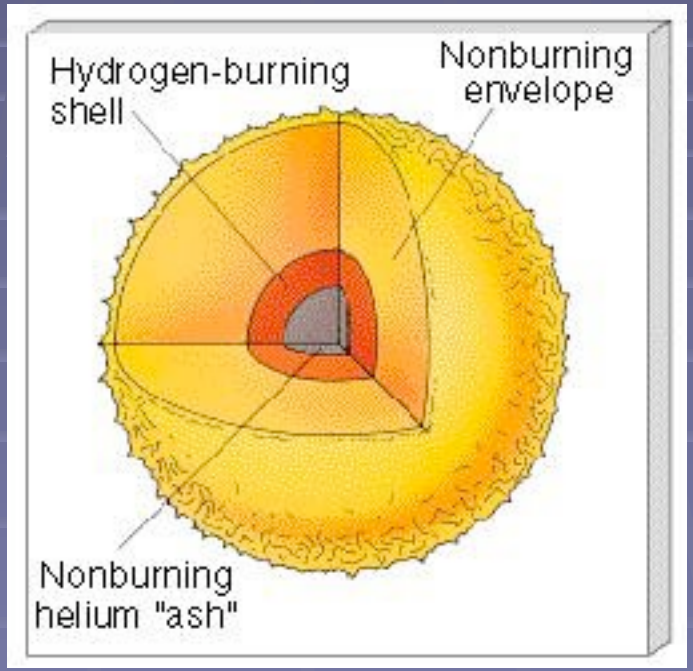
Microlensing Event



Only three percent of the Halo can be made of faint stars or brown dwarfs.

Stellar Evolution

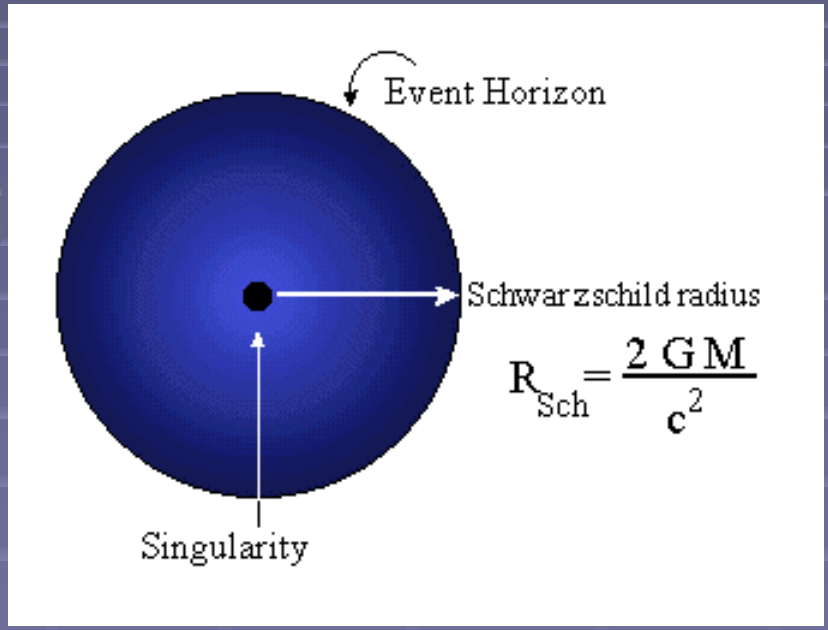
- Currently, the Sun is undergoing fusion:
  4 Hydrogen burning to Helium



Stellar Remnants

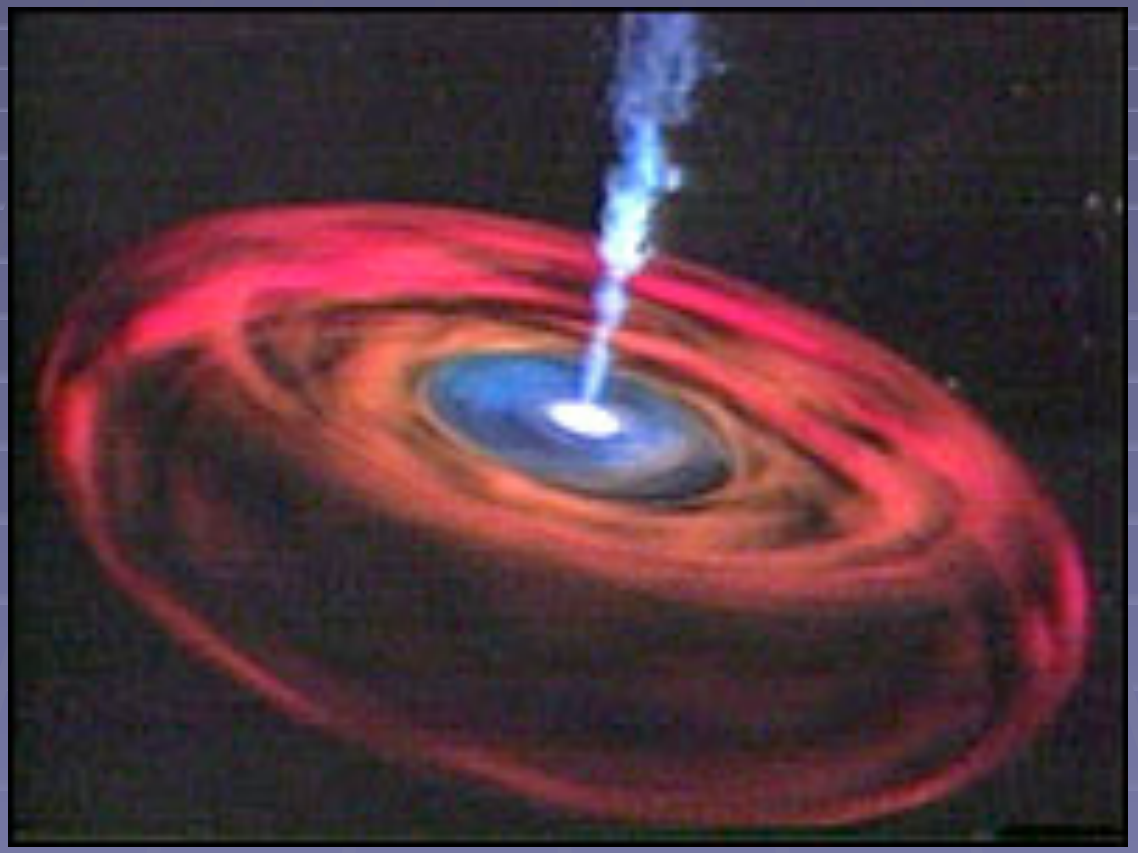
- Three possible outcomes:
- **White Dwarf**: Once the Sun runs out of nuclear fuel, it will collapse to a white dwarf (electron degeneracy pressure)
- **Neutron Star**: Stars three times as heavy as the Sun collapse to neutron stars (neutron degeneracy pressure)
- **Black Hole**: Stars twenty times as heavy as the Sun collapse to black holes.
- These three dark matter candidates are all about as massive as our Sun.

Black Hole Structure



The gravity of the black hole is so strong that anything entering inside the event horizon can never escape, not even light!

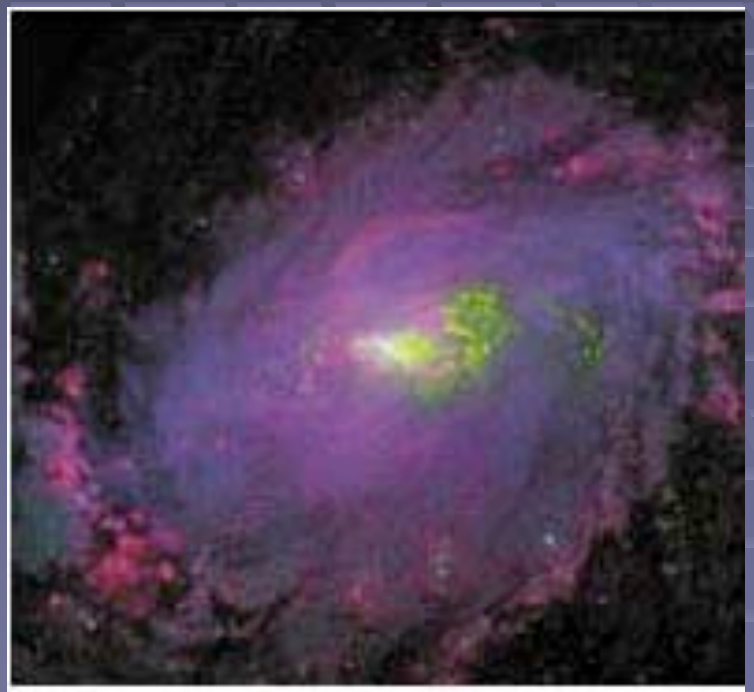
Artist's Impression of a Black Hole



Black Hole at Center of Galaxy

At the center of every galaxy
is a very massive black hole,
as massive as a million suns.

These massive black holes
form from mergers
and are NOT the dark matter.



This image from Hubble shows gas and dust swirling around a massive black hole in the center of the galaxy M77 (NGC 1068).

Is Dark Matter made of Stellar Remants? NO

- Their progenitors overproduce infrared radiation.
- Their progenitors overproduce element abundances (C, N, He)
- Enormous mass budget.
- Requires extreme properties to make them.
- NONE of the expected signatures of a stellar remnant population is found.

At most 20% of the dark matter can be white dwarfs, neutron stars, or remnant blackholes.

I HATE MACHOS!

DESPERATELY LOOKING FOR **WIMPS**!

WIMPs

Weakly Interacting Massive Particles

- About 100 times as heavy as protons
- Go right through us:

  The Death Theory: one interacts in a human roughly every 70 years
- Motivated by supersymmetry from particle theory

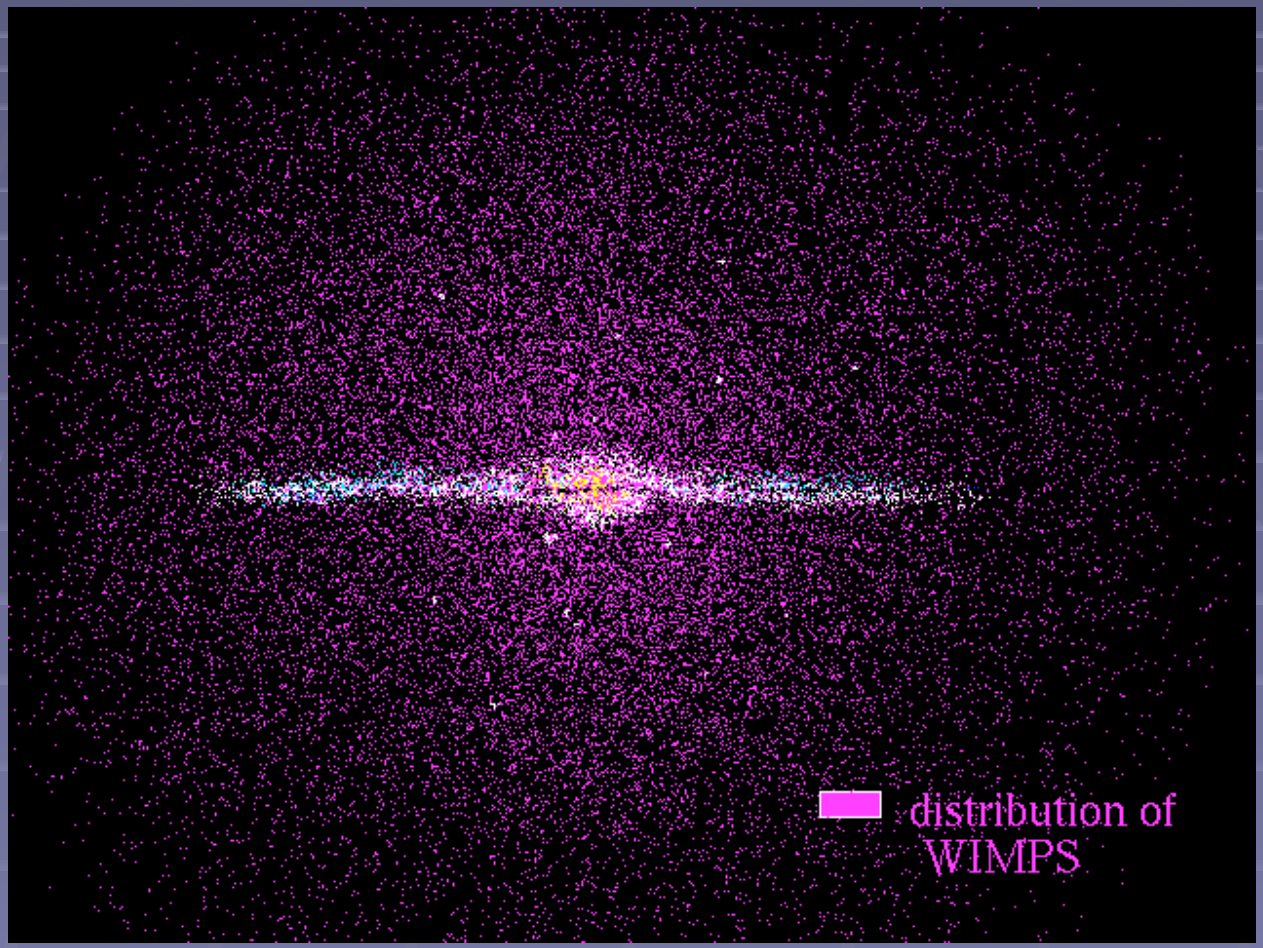
Supersymmetry

- Particle theory designed to keep particle masses at the right values
- Every particle we know has a partner:

photon	photino
quark	squark
electron	selectron

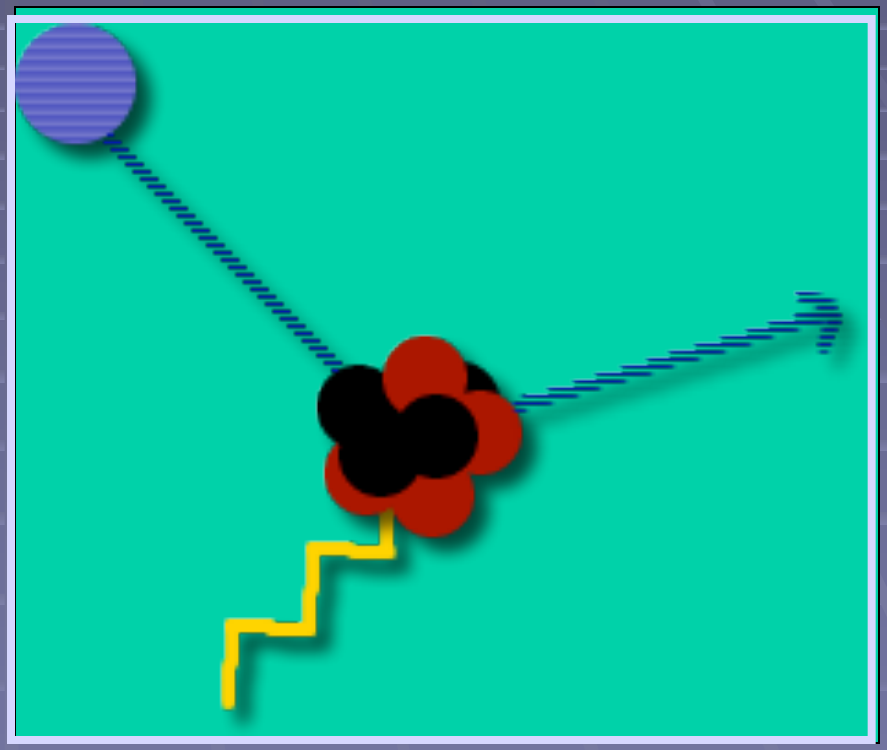
- The lightest supersymmetric partner is a dark matter candidate.

WIMP dark matter halo



Detection of WIMP dark matter

A WIMP in the Galaxy travels through our detectors. It hits a nucleus, and deposits a tiny amount of energy. The nucleus recoils, and we detect this energy deposit.



Expected Rate: less than one count/kg/day!

Ongoing experiments

- Heidelberg/Moscow
- IGEX Collaboration (Canfranc)
- MIBETA
- LiF/Tokyo
- Rosebud
- CRESST (Germany)
- CMDS (U.S.)
- Edelweiss (France)
- UKDMC (UK)
- DAMA (Italy)
- Saclay (France)

The Dark Matter of the Galaxy is still Unknown!

What is the universe made of?

- 5% ordinary atoms
- 30% dark matter
- 65% dark energy

Galaxies are made of dark matter.

Best candidate: WIMPs, not MACHOs!

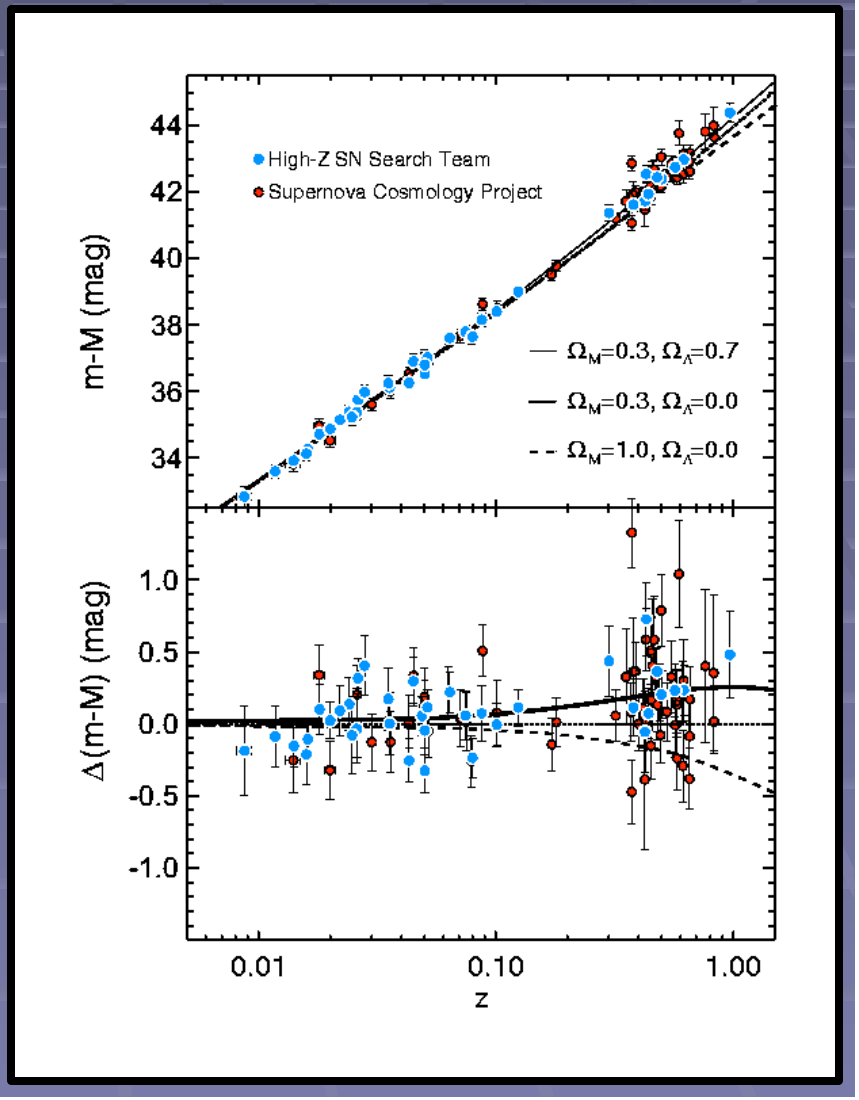
Next week, dark energy.

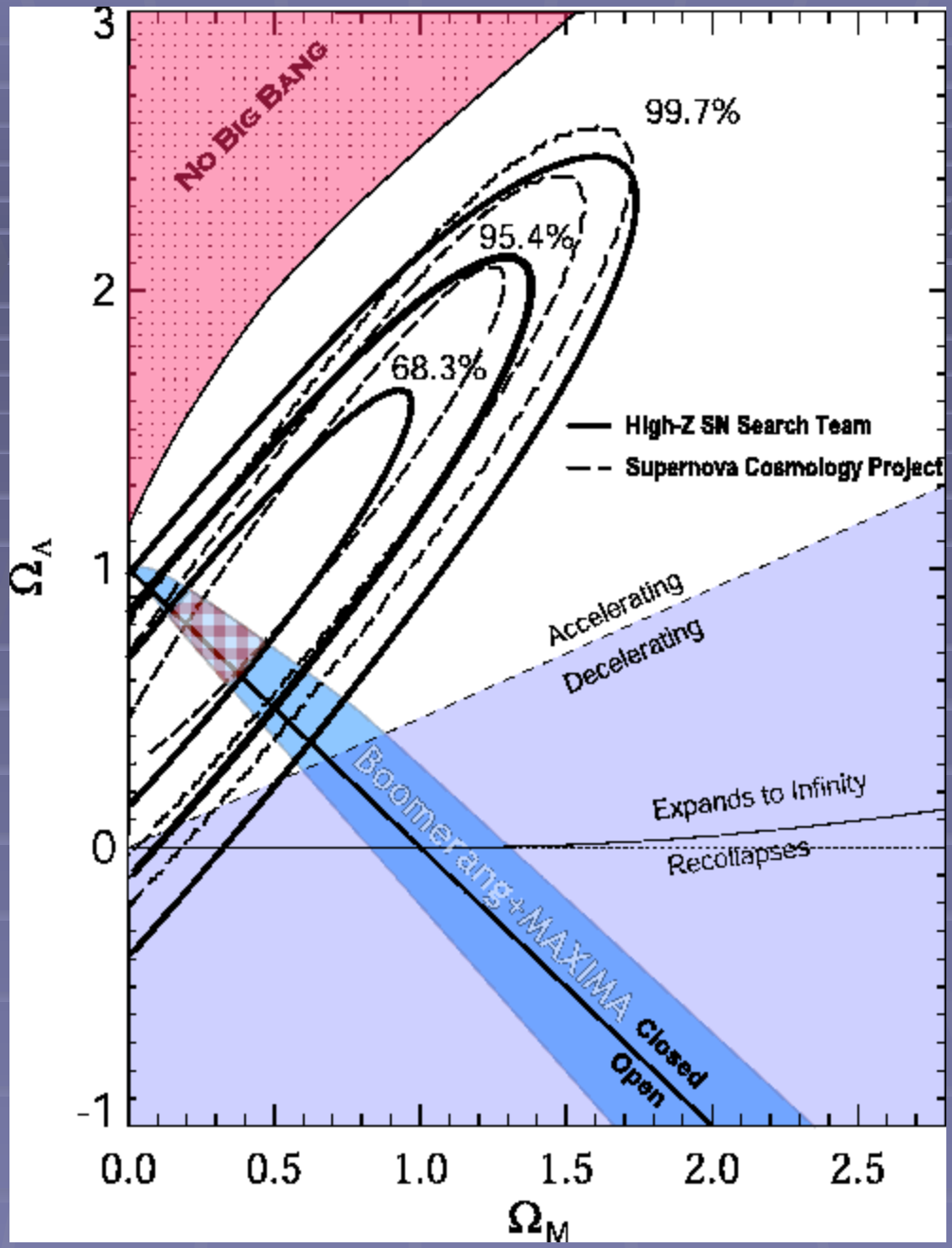
Our Universe is Accelerating

Observations of Type IA Supernovae suggest that the Universe is accelerating.

- Possible explanations:
  - I. Dark Energy
    - Cosmological constant
    - Decaying vacuum energy (Freese, Adams, Frieman, and Mottola 1987
    - Quintessence (Ratra and Peebles, Steinhardt, Wang, et al.)
  - II. Modification to the Einstein Equations

    Cardassian cosmology (Freese and Lewis 2002)




No Big Bang
99.7%
95.4%
68.3%
High-Z SN Search Team
Supernova Cosmology Project
Accelerating
Decelerating
Expands to Infinity
Recollapses
Boomerang+MAXIMA
Closed
Open
Ω_Λ
Ω_M
3
2
1
0
-1
0.0
0.5
1.0
1.5
2.0
2.5

Pie Chart of The Universe