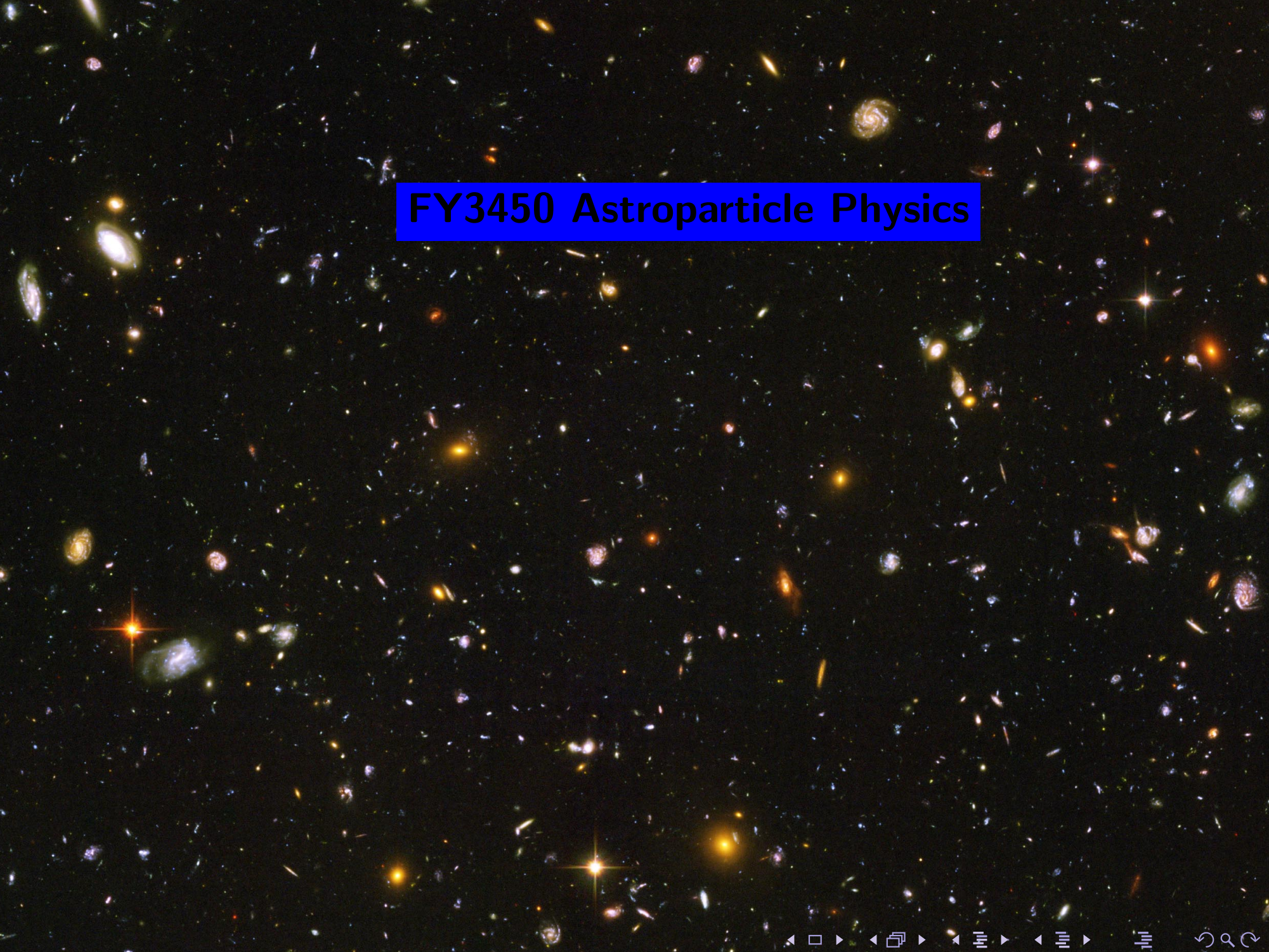

FY3450 Astroparticle Physics

Outline of the course:

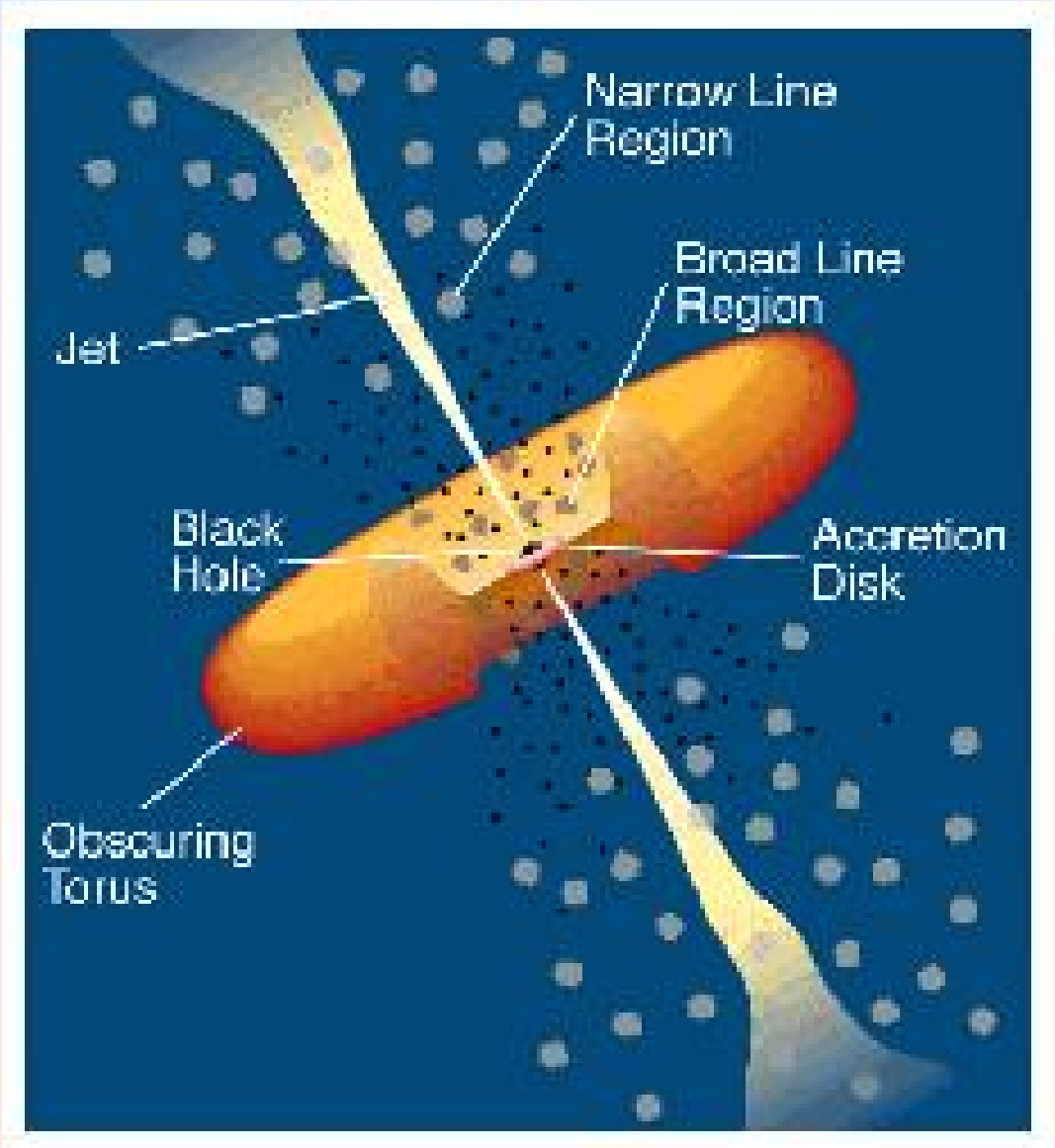
- Reviev of basic particle physics, . . .
- High-energy astrophysics:
  - non-thermal radiation, sources
  - acceleration mechanisms
  - high-energy cosmic rays
  - high-energy photons and neutrinos
- Cosmology
- Stellar astrophysics

Non-thermal radiation:

- accelerate electrons and protons:

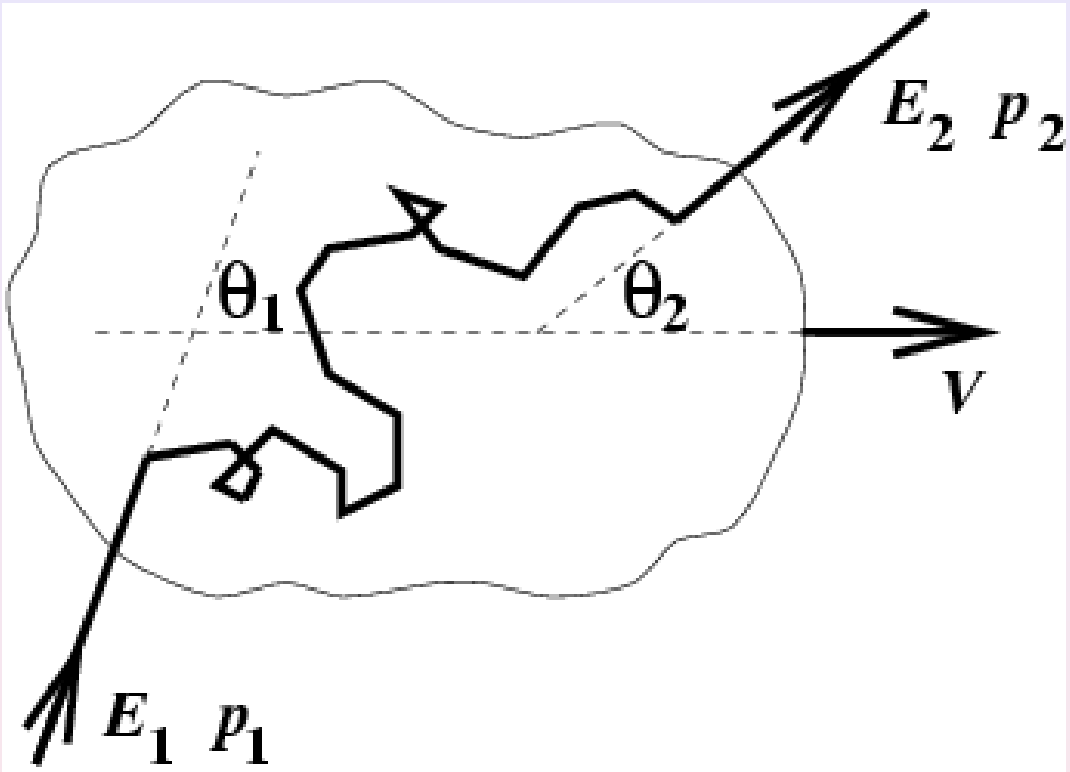
Non-thermal radiation:

- accelerate electrons and protons:



Non-thermal radiation:

- accelerate electrons and protons:



Non-thermal radiation:

- accelerate electrons and protons:
- electron: synchrotron radiation, bremsstrahlung

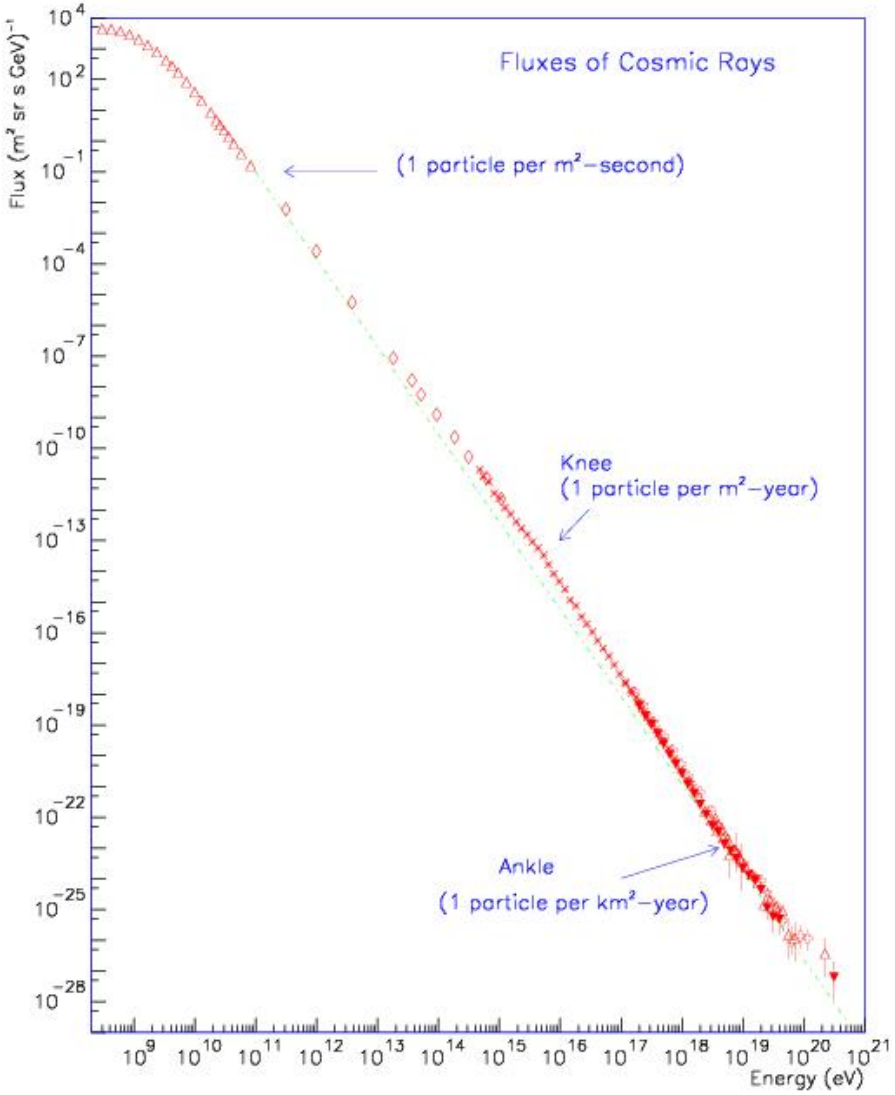
Non-thermal radiation:

- accelerate electrons and protons:
- electron: synchrotron radiation, bremsstrahlung
- $p + \gamma_{bb} \rightarrow p + \pi^0$ or $\rightarrow n + \pi^+$

Non-thermal radiation:

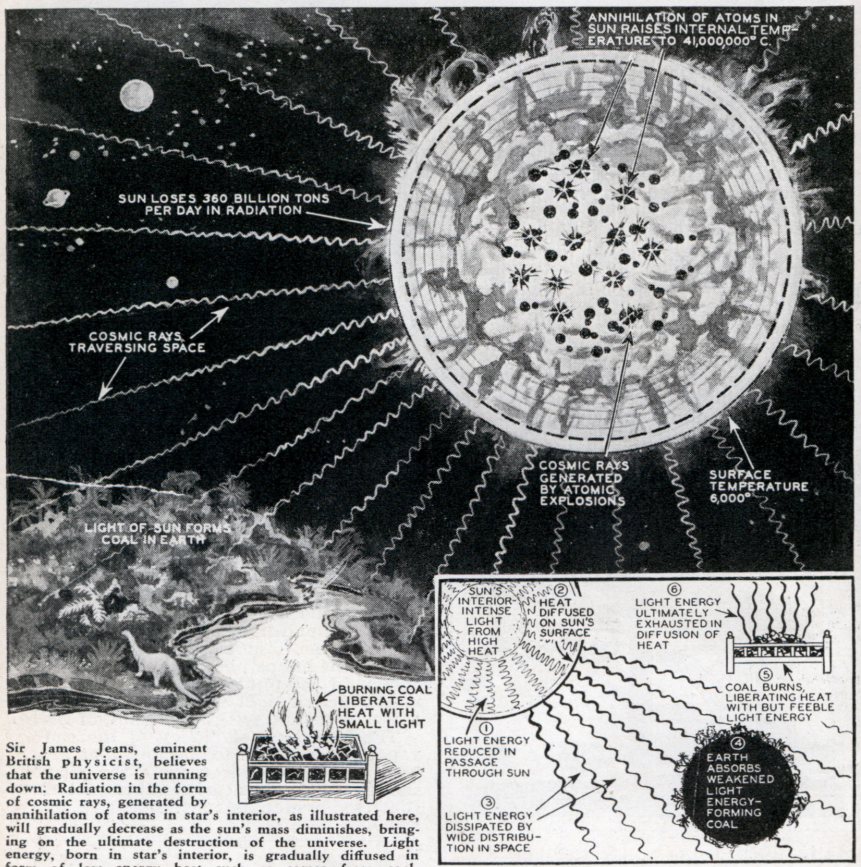
- accelerate electrons and protons:
- electron: synchrotron radiation, bremsstrahlung
- $p + \gamma_{bb} \rightarrow p + \pi^0$ or $\rightarrow n + \pi^+$
- $\pi^0 \rightarrow 2\gamma$ and $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + 2\nu_\mu$

High-energy cosmic rays:



High-energy cosmic rays:

Fate of UNIVERSE *May Be*



Sir James Jeans, eminent British physicist, believes that the universe is running down. Radiation in the form of cosmic rays, generated by annihilation of atoms in star's interior, as illustrated here, will gradually decrease as the sun's mass diminishes, bringing on the ultimate destruction of the universe. Light energy, born in star's interior, is gradually diffused in form of low energy heat such as comes from coal.

This drawing illustrates how light energy, originating at sun's interior is gradually dissipated in the universe. End of world will come when all light energy has been exhausted.

by JAY EARLE MILLER

Where in the universe does the mysterious cosmic ray originate? Science is now conducting extensive research to solve that mystery, for the answer may disclose the destiny of the earth we live on.

ON MOUNTAIN tops in Hawaii, Alaska, Peru and at other isolated points around the world—eighteen stations in all—an answer is being sought this summer to the most perplexing question in modern science—what is a cosmic ray?

press named them "Millikan's rays," the cosmic emanation continues to be the baffling enigma on which scientists throughout the world are divided.

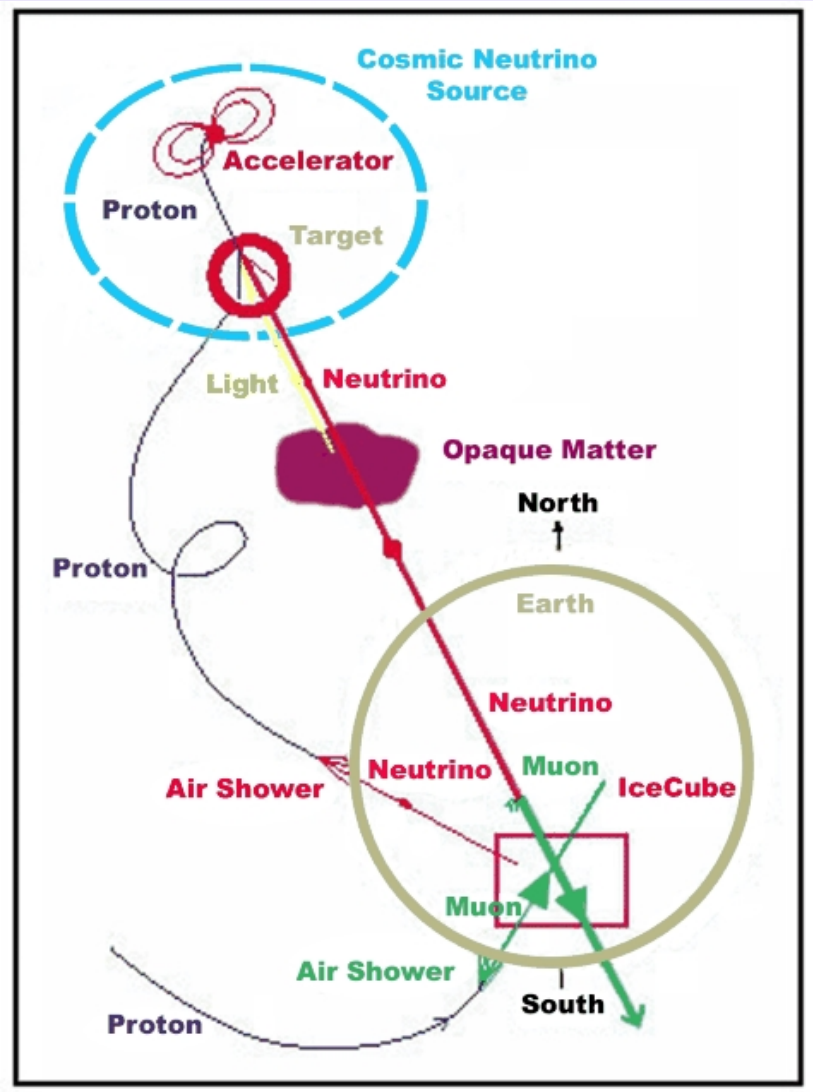
No one knows what they are, where they come from, or how they came into being,

High-energy photons and neutrinos:

- neutral, point to sources

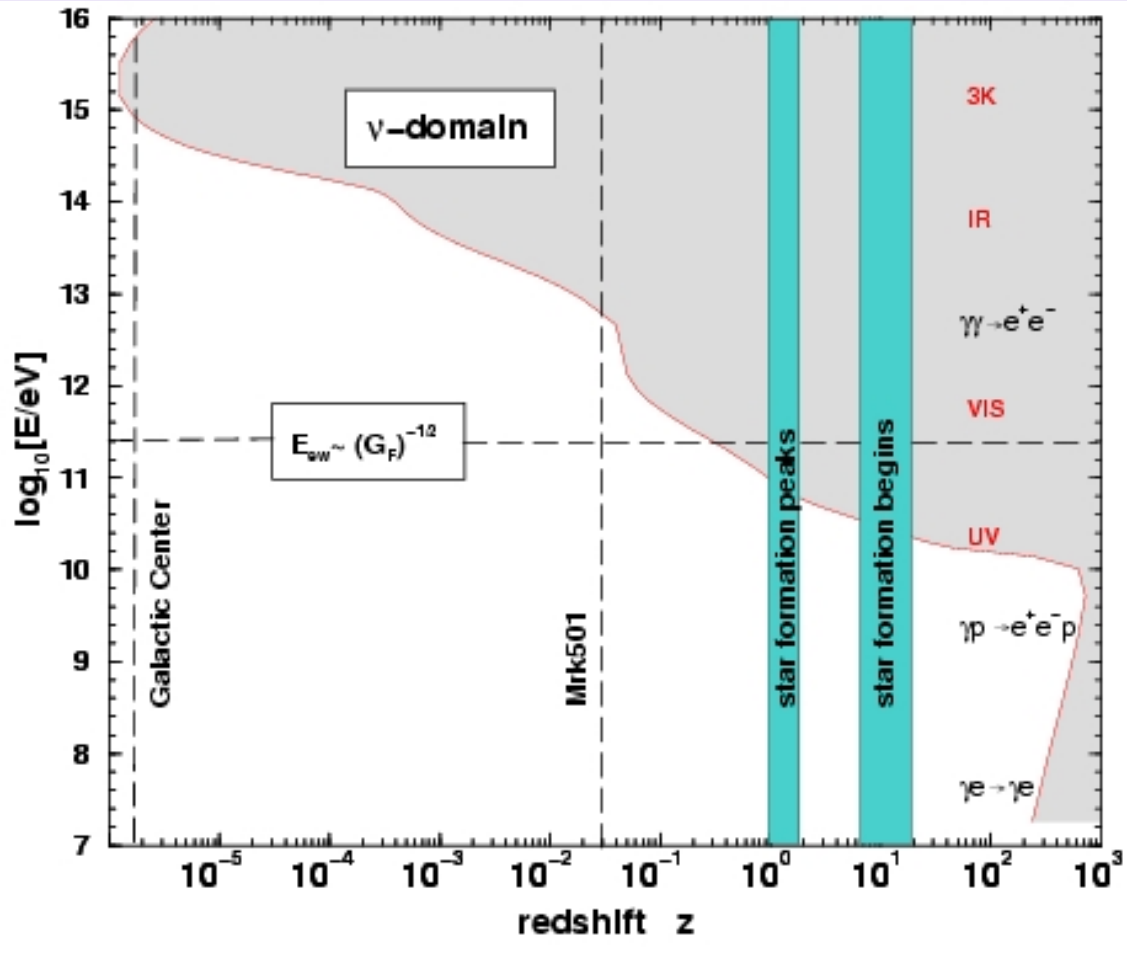
High-energy photons and neutrinos:

- neutral, point to sources
- secondaries from cosmic rays



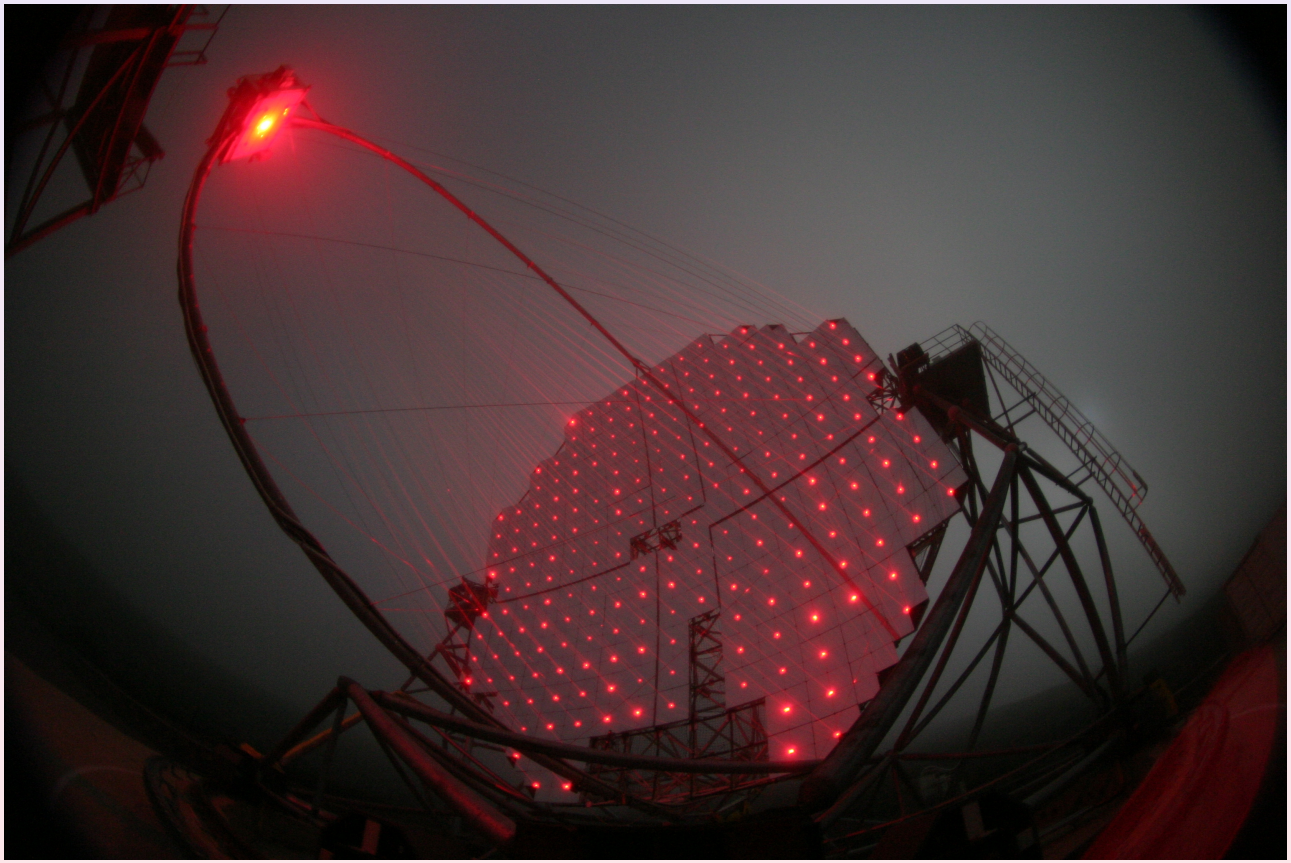
High-energy photons and neutrinos:

- neutral, point to sources
- secondaries from cosmic rays
- easy/difficult detection $\leftrightarrow$ strong/weak absorption



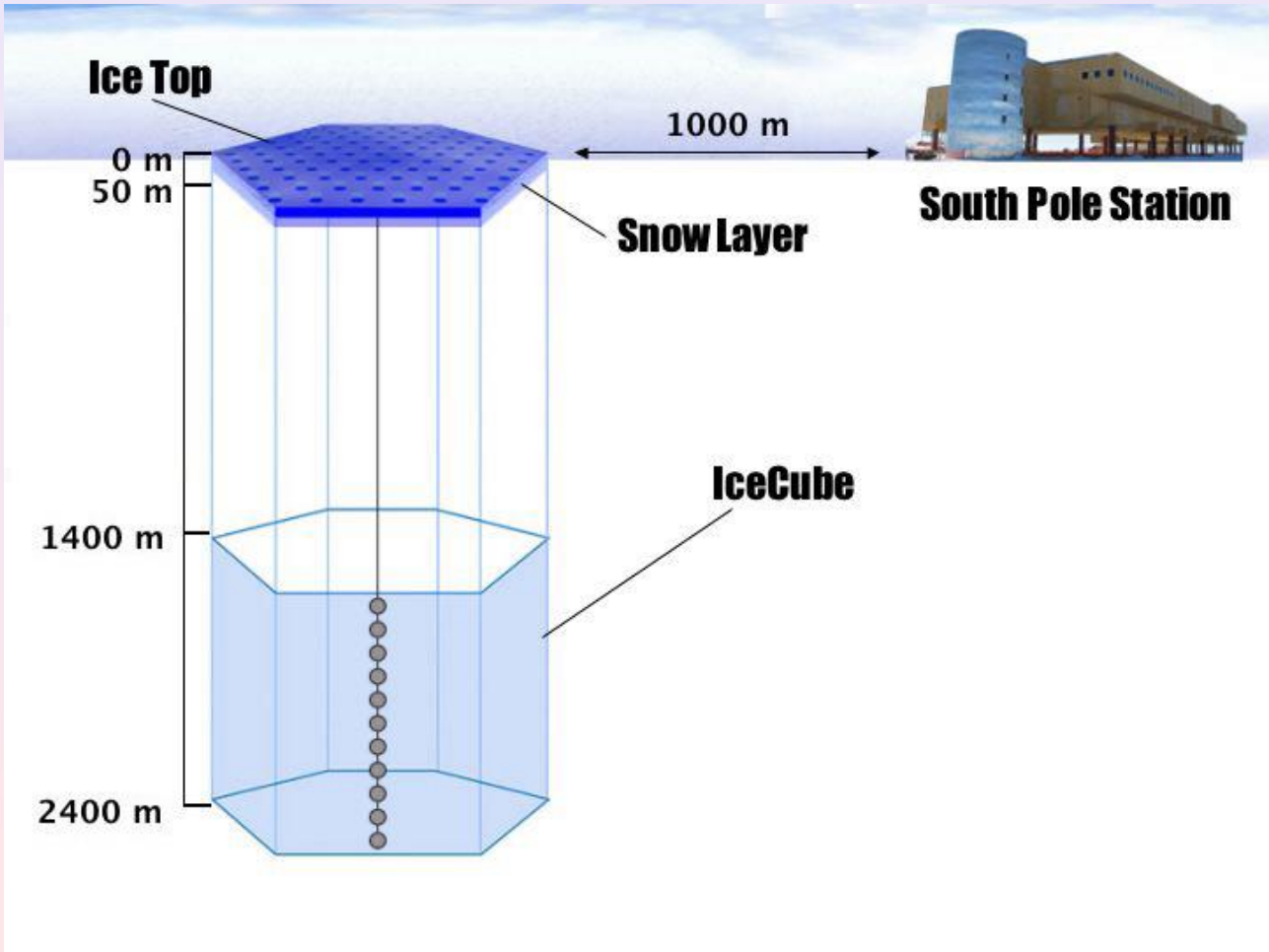
High-energy photons and neutrinos:

- neutral, point to sources
- secondaries from cosmic rays
- easy/difficult detection $\leftrightarrow$ strong/weak absorption



High-energy photons and neutrinos:

- neutral, point to sources
- secondaries from cosmic rays
- easy/difficult detection $\leftrightarrow$ strong/weak absorption



High-energy photons and neutrinos:

- neutral, point to sources
- secondaries from cosmic rays
- easy/difficult detection $\leftrightarrow$ strong/weak absorption
- indirect detection of dark matter $X\bar{X} \rightarrow \gamma\gamma, \nu\bar{\nu}$

Outline of the course:

- Reviev of basic particle physics, . . .
- High-energy astrophysics
- Cosmology:

Outline of the course:

- Reviev of basic particle physics, . . .
- High-energy astrophysics
- Cosmology:
  - Introduction: Reviev of basic particle physics, . . . Friedmann equations & FRW metric

Outline of the course:

- Reviev of basic particle physics, . . .
- High-energy astrophysics
- Cosmology:
  - Introduction: Reviev of basic particle physics, . . . Friedmann equations & FRW metric
  - Big-bang nucleosynthesis

Outline of the course:

- Reviev of basic particle physics, . . .
- High-energy astrophysics
- Cosmology:
  - Introduction: Reviev of basic particle physics, . . . Friedmann equations & FRW metric
  - Big-bang nucleosynthesis
  - Thermal relics as dark matter

Outline of the course:

- Reviev of basic particle physics, . . .
- High-energy astrophysics
- Cosmology:
  - Introduction: Reviev of basic particle physics, . . . Friedmann equations & FRW metric
  - Big-bang nucleosynthesis
  - Thermal relics as dark matter
  - Structure formation

Outline of the course:

- Reviev of basic particle physics, . . .
- High-energy astrophysics
- Cosmology:
  - Introduction: Reviev of basic particle physics, . . . Friedmann equations & FRW metric
  - Big-bang nucleosynthesis
  - Thermal relics as dark matter
  - Structure formation
  - Cosmic microwave background and its anisotropies

Outline of the course:

- Reviev of basic particle physics, . . .
- High-energy astrophysics
- Cosmology:
  - Introduction: Reviev of basic particle physics, . . . Friedmann equations & FRW metric
  - Big-bang nucleosynthesis
  - Thermal relics as dark matter
  - Structure formation
  - Cosmic microwave background and its anisotropies
  - Baryogenesis

Outline of the course:

- Reviev of basic particle physics, . . .
- High-energy astrophysics
- Cosmology:
  - Introduction: Reviev of basic particle physics, . . . Friedmann equations & FRW metric
  - Big-bang nucleosynthesis
  - Thermal relics as dark matter
  - Structure formation
  - Cosmic microwave background and its anisotropies
  - Baryogenesis
  - Inflation
- Stellar astrophysics

Expansion of the Universe:

- Milky Way $\neq$ Universe:
  Hubble discovered 1924 a Cepheid variable in Andromeda $\Rightarrow$ able to measure its distance

Expansion of the Universe:

- Milky Way $\neq$ Universe:
- Hubble's law: $v(r) = Hr \Rightarrow$ expanding Universe

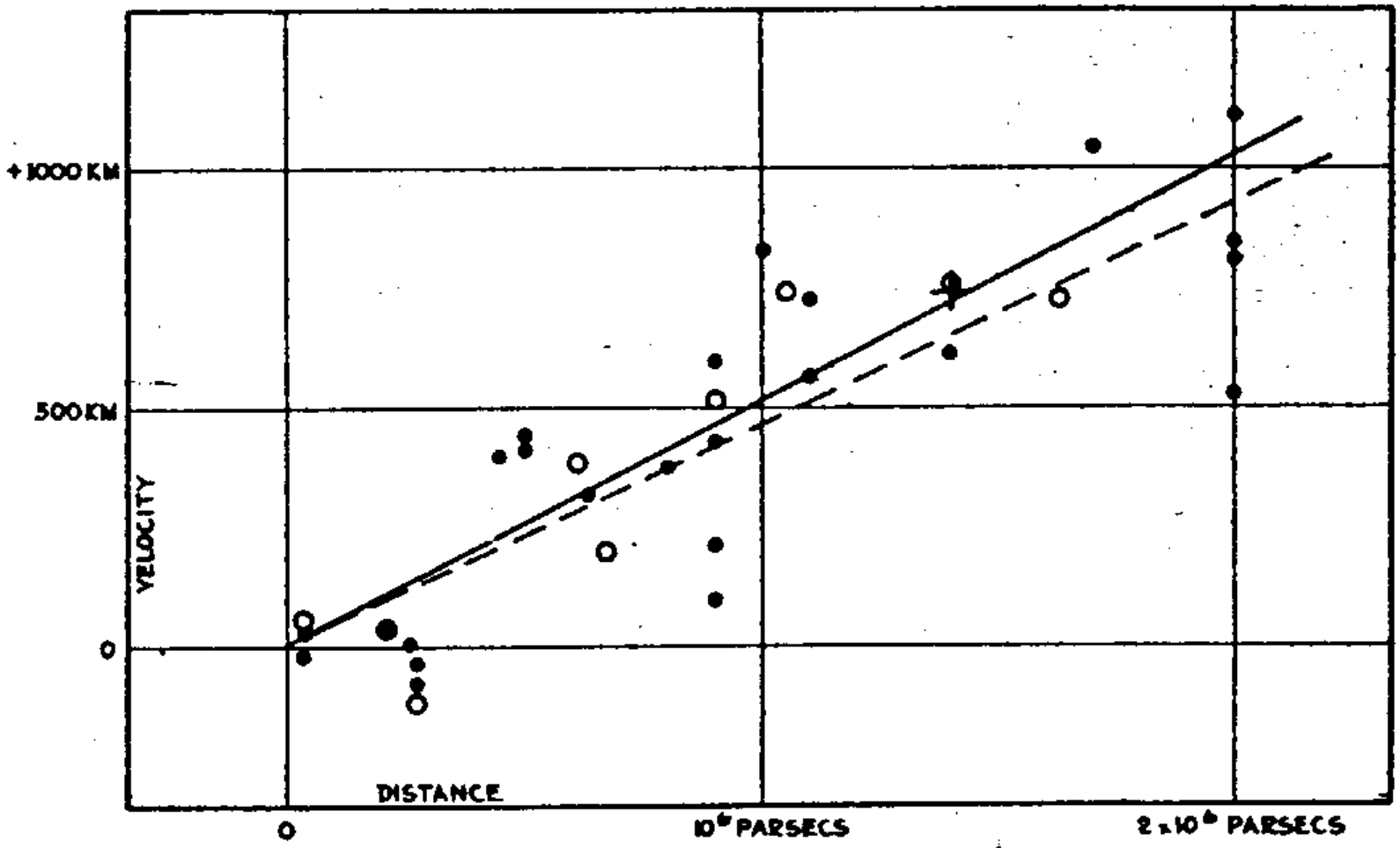
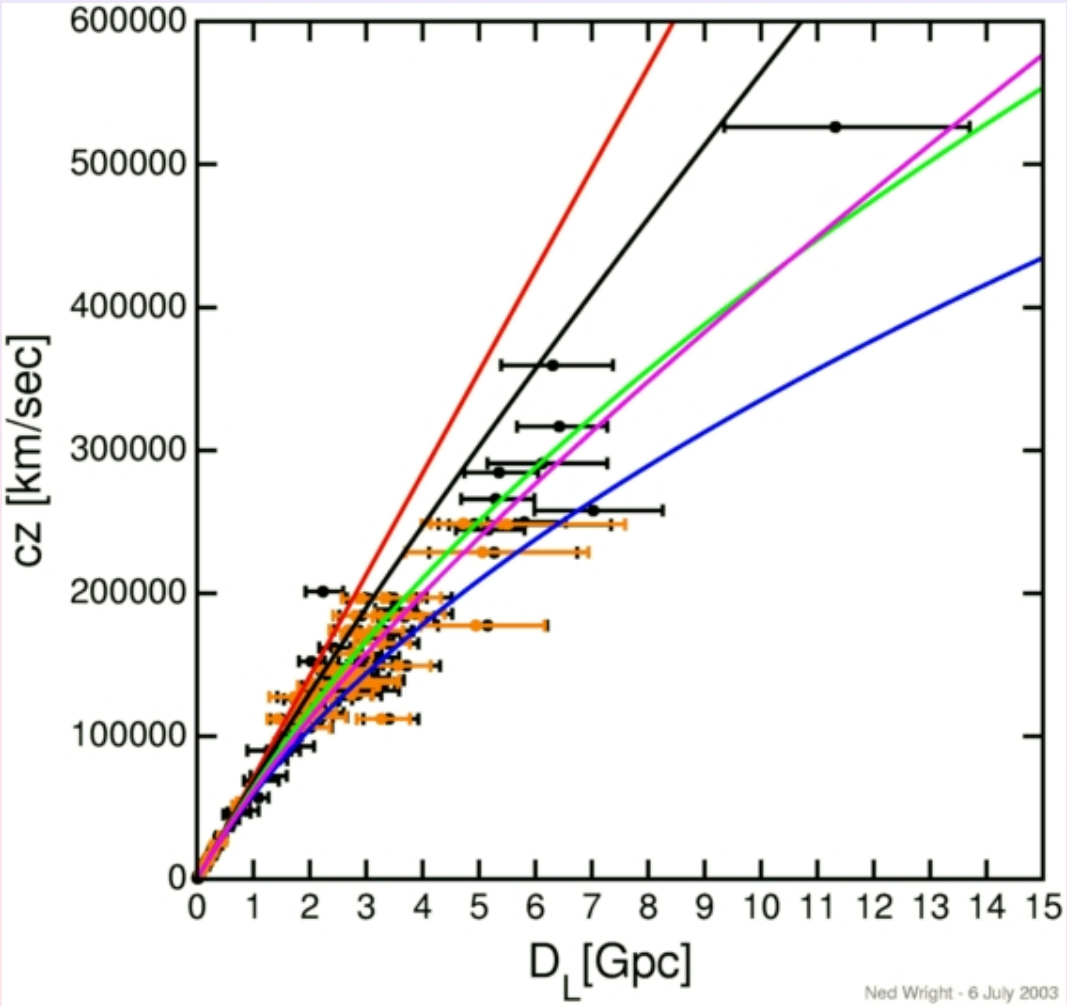


FIGURE 1

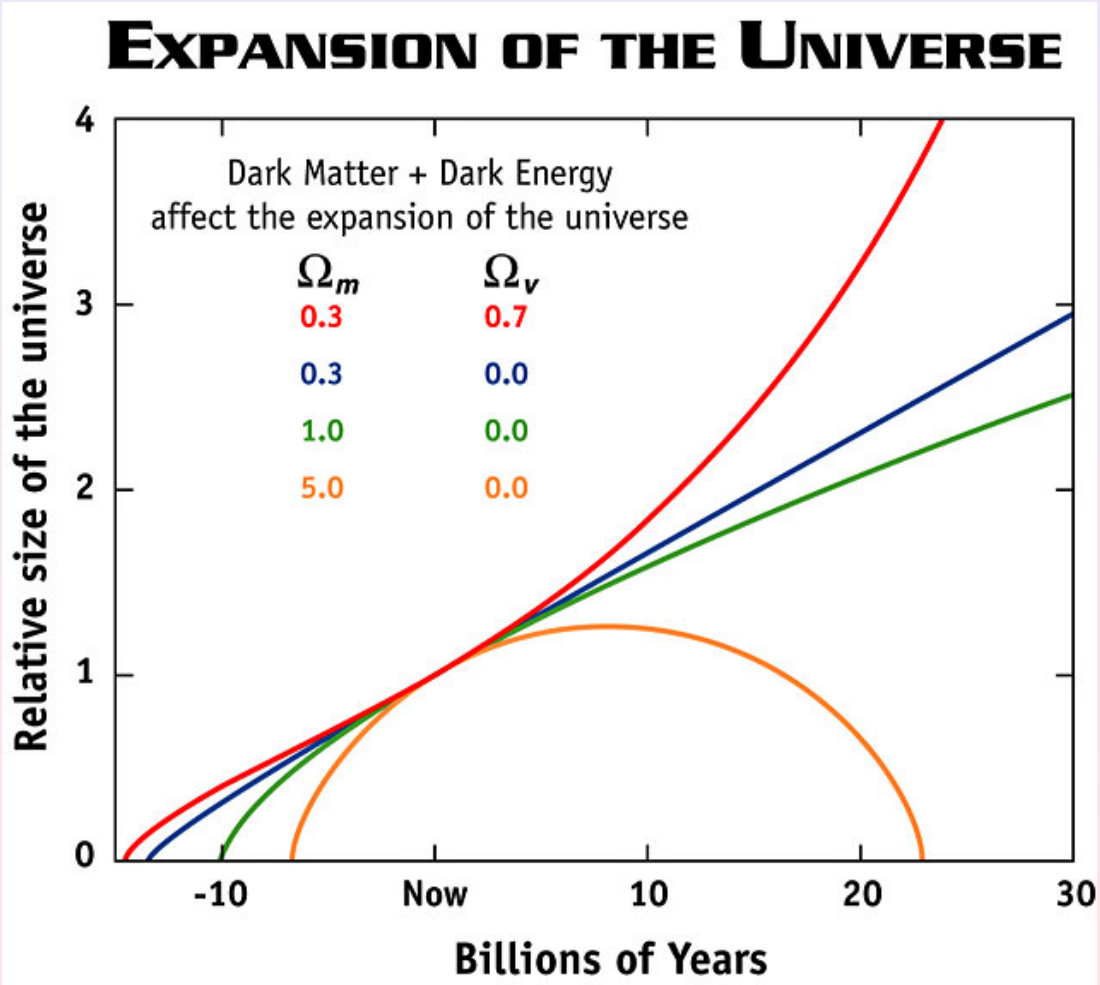
Expansion of the Universe:

- Milky Way $\neq$ Universe:
- Hubble's law: $v(r) = Hr \Rightarrow$ expanding Universe
- for larger distances: $z = H_0 d_L + \frac{1}{2}(q_0 - 1)(H_0 d_L)^2 + \ldots$



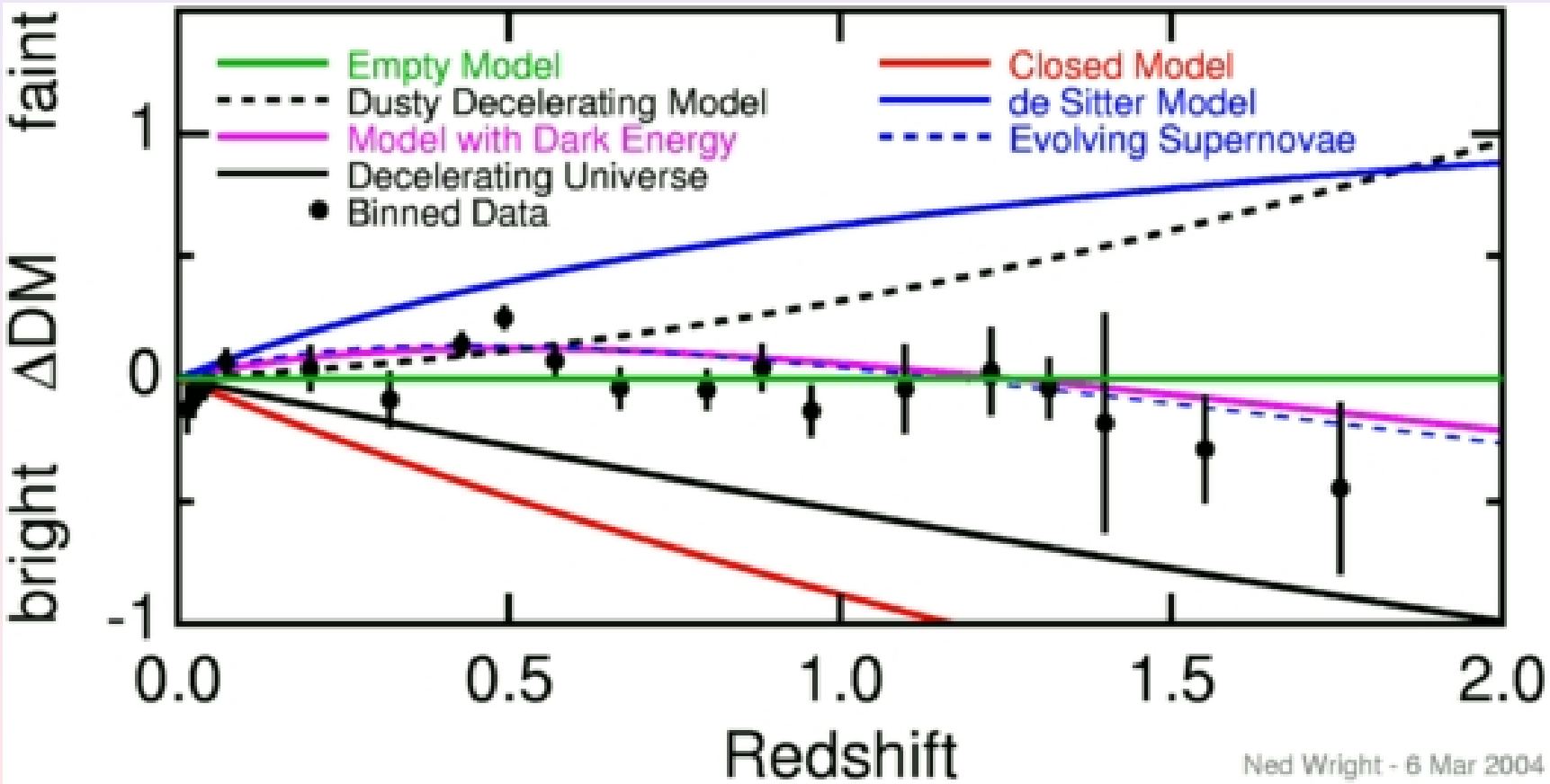
Expansion of the Universe:

- Milky Way $\neq$ Universe:
- Hubble's law: $v(r) = Hr \Rightarrow$ expanding Universe
- for larger distances: $z = H_0 d_L + \frac{1}{2}(q_0 - 1)(H_0 d_L)^2 + \ldots$



Expansion of the Universe:

- Milky Way $\neq$ Universe:
- Hubble's law: $v(r) = Hr \Rightarrow$ expanding Universe
- for larger distances: $z = H_0 d_L + \frac{1}{2}(q_0 - 1)(H_0 d_L)^2 + \ldots$

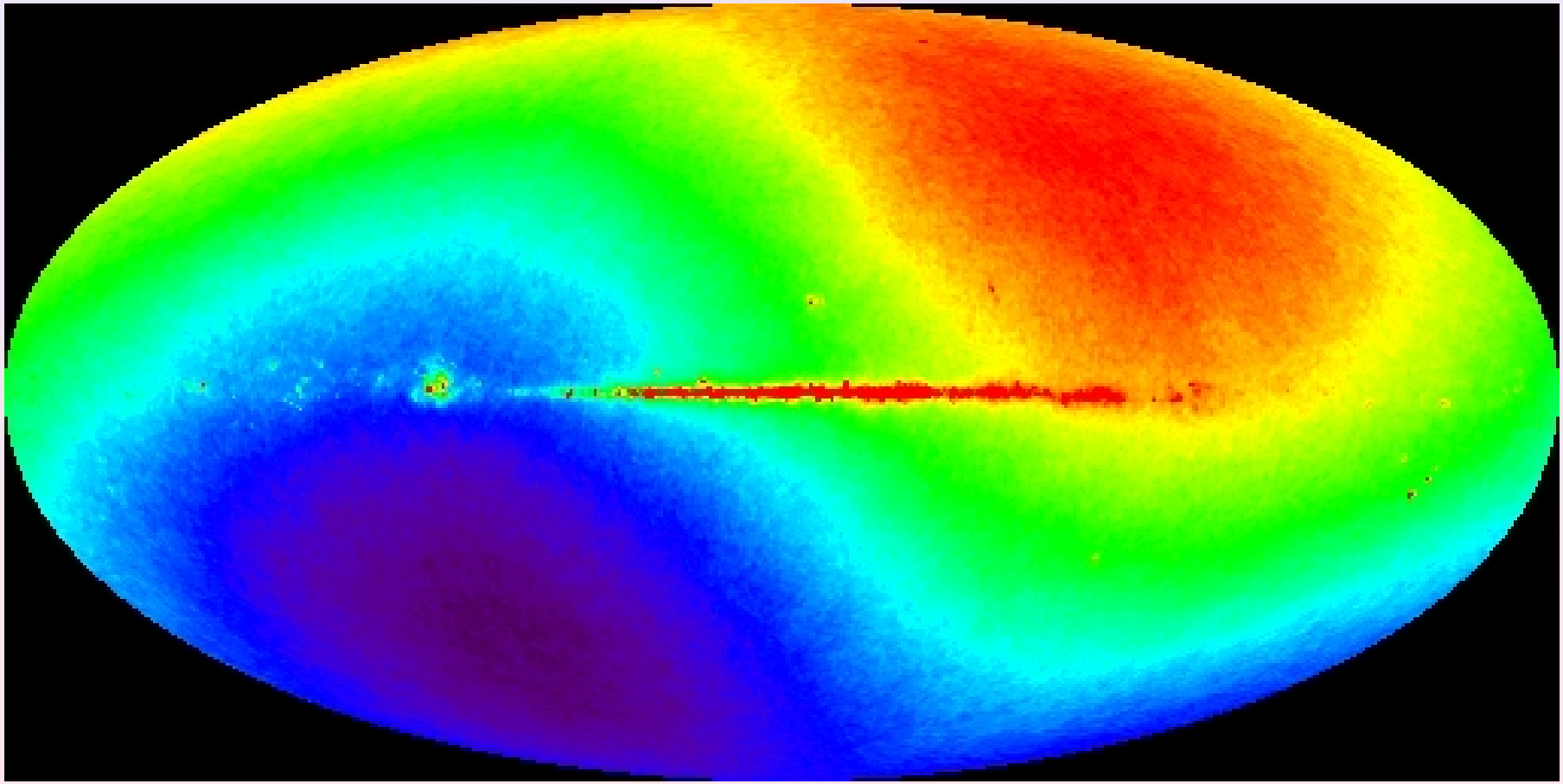


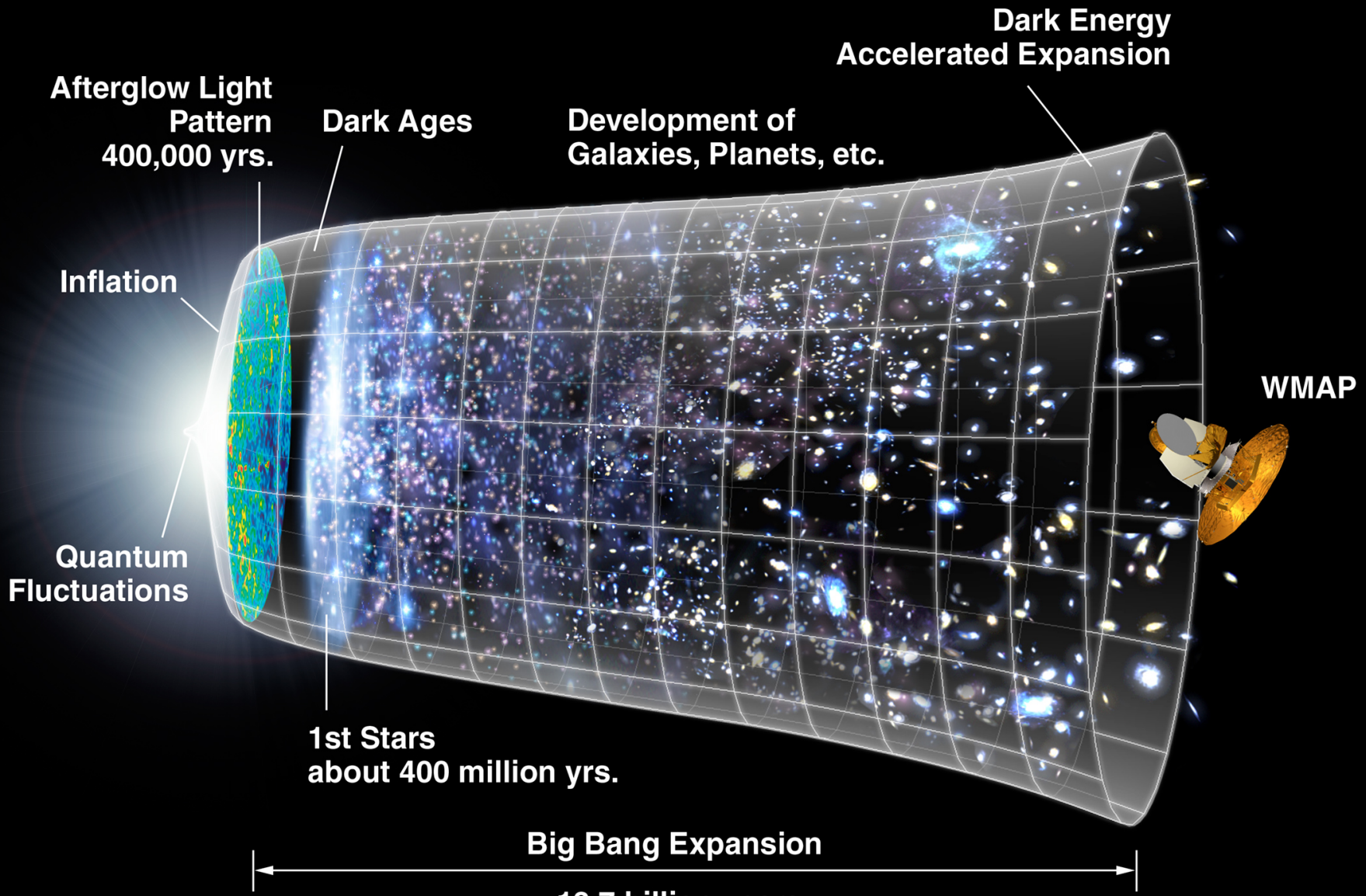
Isotropy and homogenity on large scales:

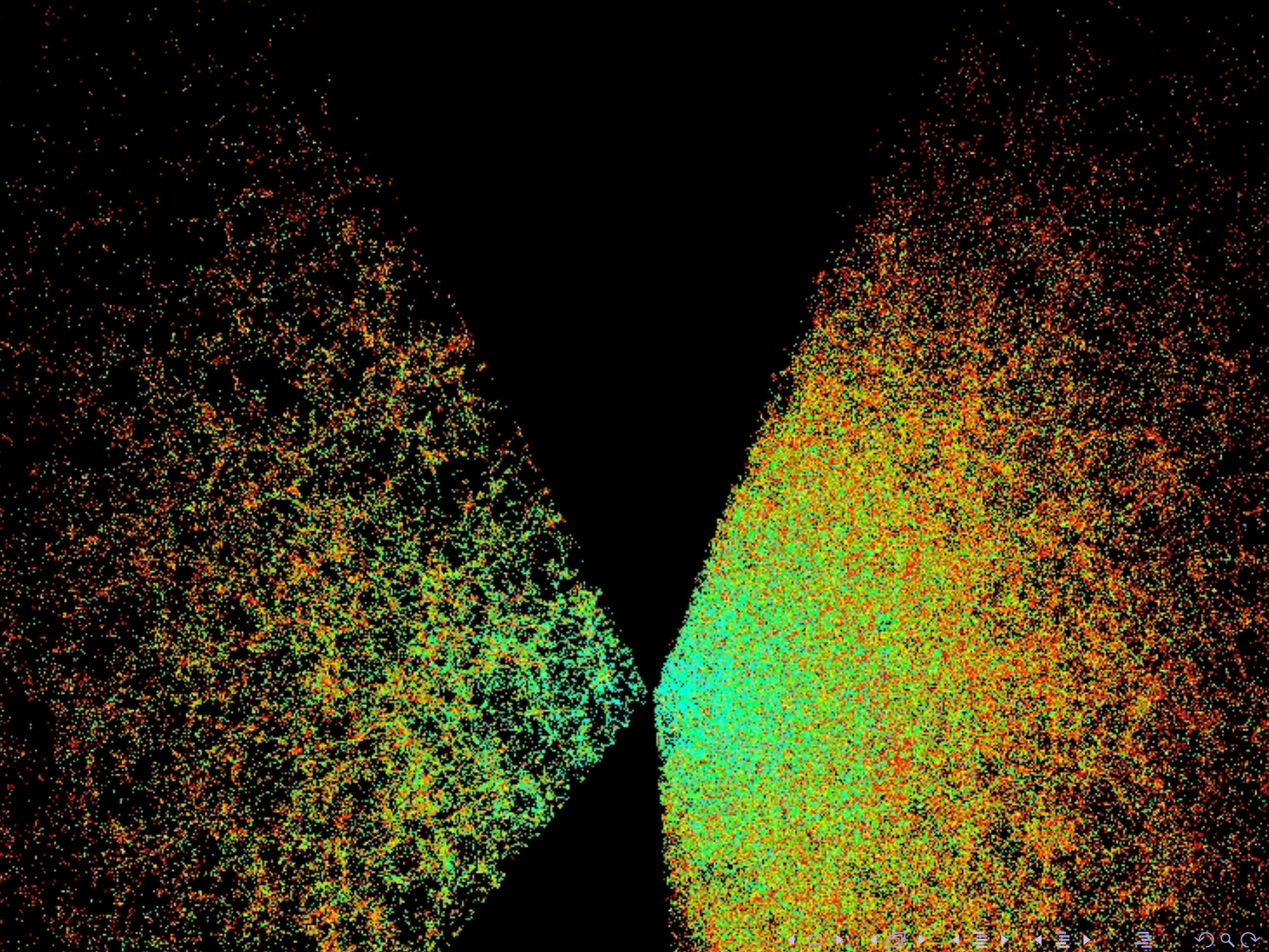
- simplifies theoretical analysis: one variable $R(t)$

Isotropy and homogenity on large scales:

- simplifies theoretical analysis: one variable $R(t)$
- best evidence: small $\Delta T/T \sim 10^{-4}$ 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



Age of the Universe:

- glubular cluster ages: 13 Gyr

Age of the Universe:

- glubular cluster ages: 13 Gyr
- cooling of WD: 10 ± 2 Gyr

Age of the Universe:

- glubular cluster ages: 13 Gyr
- cooling of WD: 10 ± 2 Gyr
- compared to

$$\frac{1}{H_0} \approx 70\,\mathrm{km/s/Mpc} \approx 13\,\mathrm{Gyr}$$

Age of the Universe:

- glubular cluster ages: 13 Gyr
- cooling of WD: 10 ± 2 Gyr
- compared to

$$\frac{1}{H_0} \approx 70\,\mathrm{km/s/Mpc} \approx 13\,\mathrm{Gyr}$$

- but for $\Omega_m = 1$:

$$t_0 = \frac{2}{3H_0}$$

Light element abundances and BBN:

- $Y(^4\mathrm{He}) \approx 24\%$, but only 1% build-up in stars

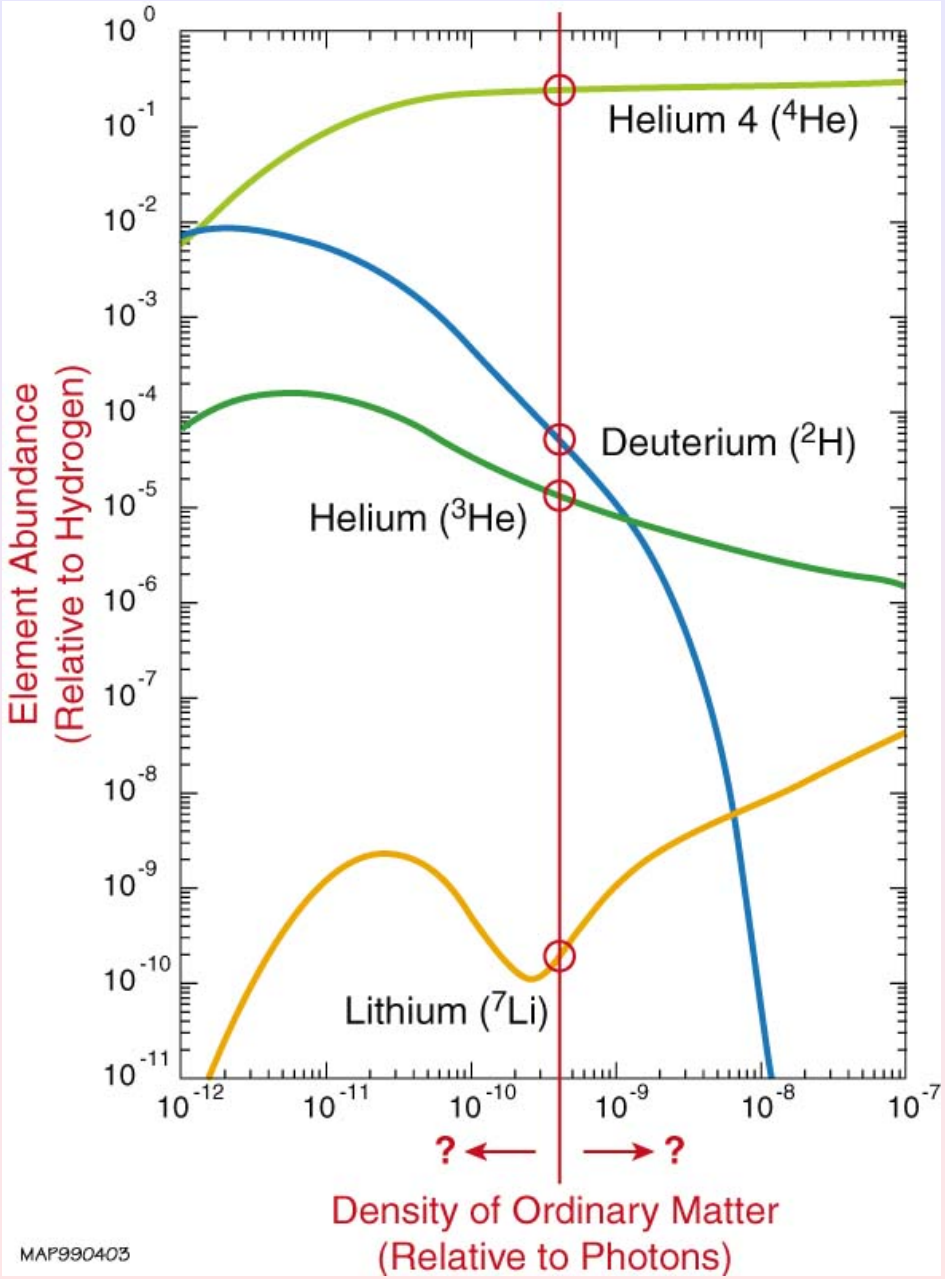
Light element abundances and BBN:

- $Y(^4\mathrm{He}) \approx 24\%$, but only 1% build-up in stars
- ^{7}Li small bindings energy, should not be produced at all in stars

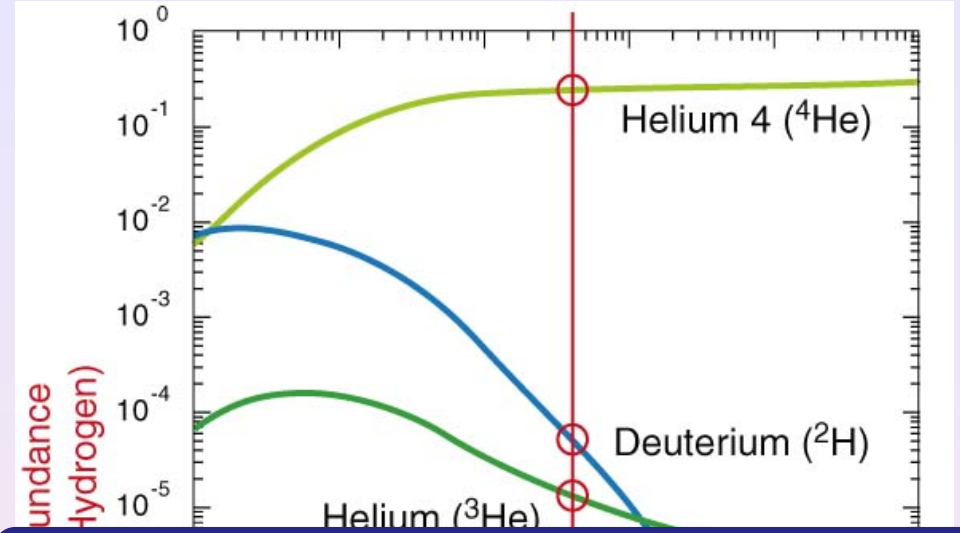
Light element abundances and BBN:

- $Y(^4\mathrm{He}) \approx 24\%$, but only 1% build-up in stars
- ^{7}Li small bindings energy, should not be produced at all in stars
- BBN predicts the correct abundance of D, ^{4}He, and ^{7}Li as function of the fraction of baryons, $\Omega_b h^2$

Light element abundances and BBN:

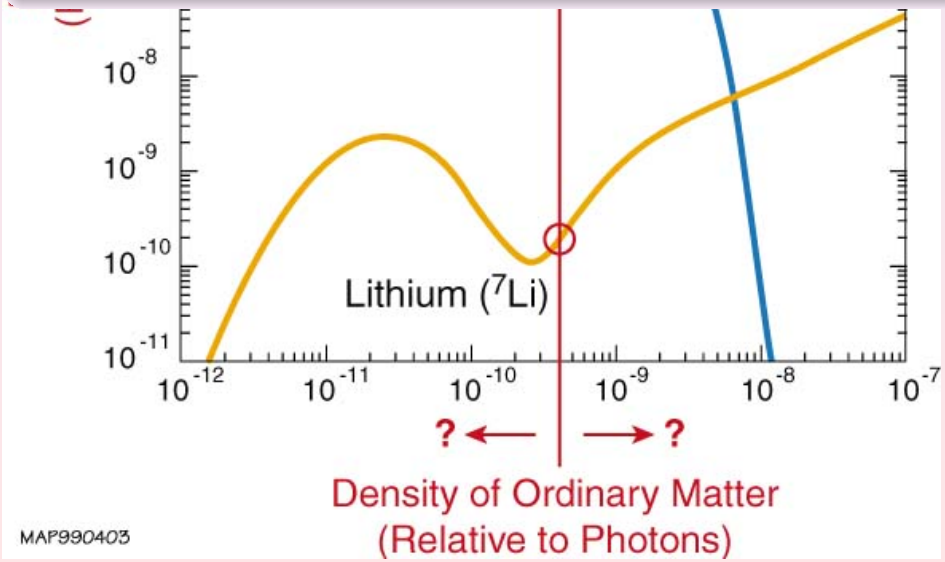


Light element abundances and BBN:



$\Omega_b \approx 0.05 \ll 1$ for realistic value of h

is there something else than baryons?



(Dark) matter:

- a flat universe requires

$$\rho = \rho_{\rm cr} = \frac{3H_0^2}{8\pi G}$$

(Dark) matter:

- a flat universe requires

$$\rho = \rho_{\rm cr} = \frac{3H_0^2}{8\pi G}$$

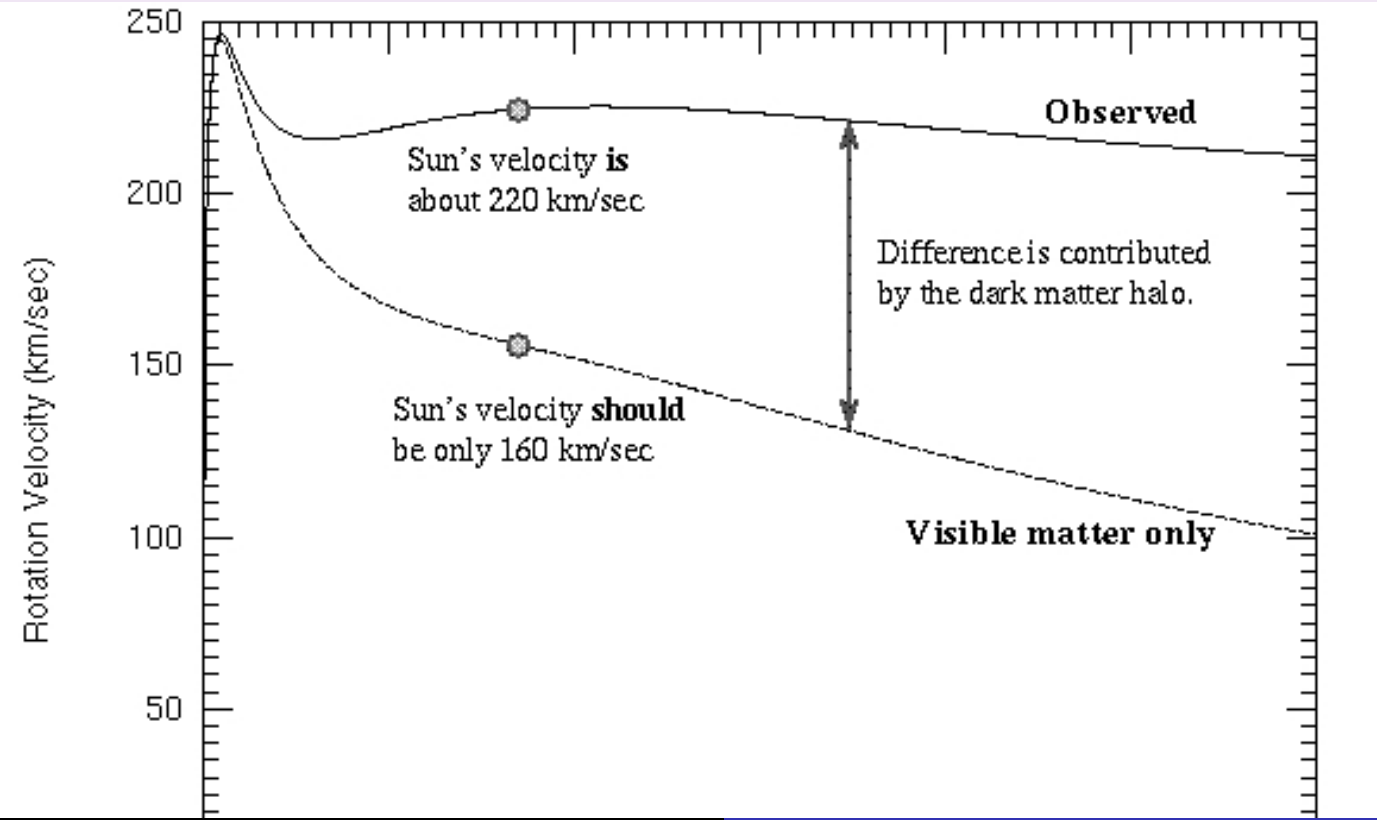
- luminous matter $\Omega_{\rm lum} = \rho_{\rm lum}/\rho_{\rm cr} \approx 0.01$

(Dark) matter:

- a flat universe requires

$$\rho = \rho_{\rm cr} = \frac{3H_0^2}{8\pi G}$$

- luminous matter $\Omega_{\rm lum} = \rho_{\rm lum}/\rho_{\rm cr} \approx 0.01$
- rotation curves in galaxies:



(Dark) matter:

- a flat universe requires

$$\rho = \rho_{\rm cr} = \frac{3H_0^2}{8\pi G}$$

- luminous matter $\Omega_{\rm lum} = \rho_{\rm lum}/\rho_{\rm cr} \approx 0.01$
- rotation curves in galaxies:
- virial mass of cluster of galaxies: $\langle GM/r \rangle = 2\langle v^2 \rangle$

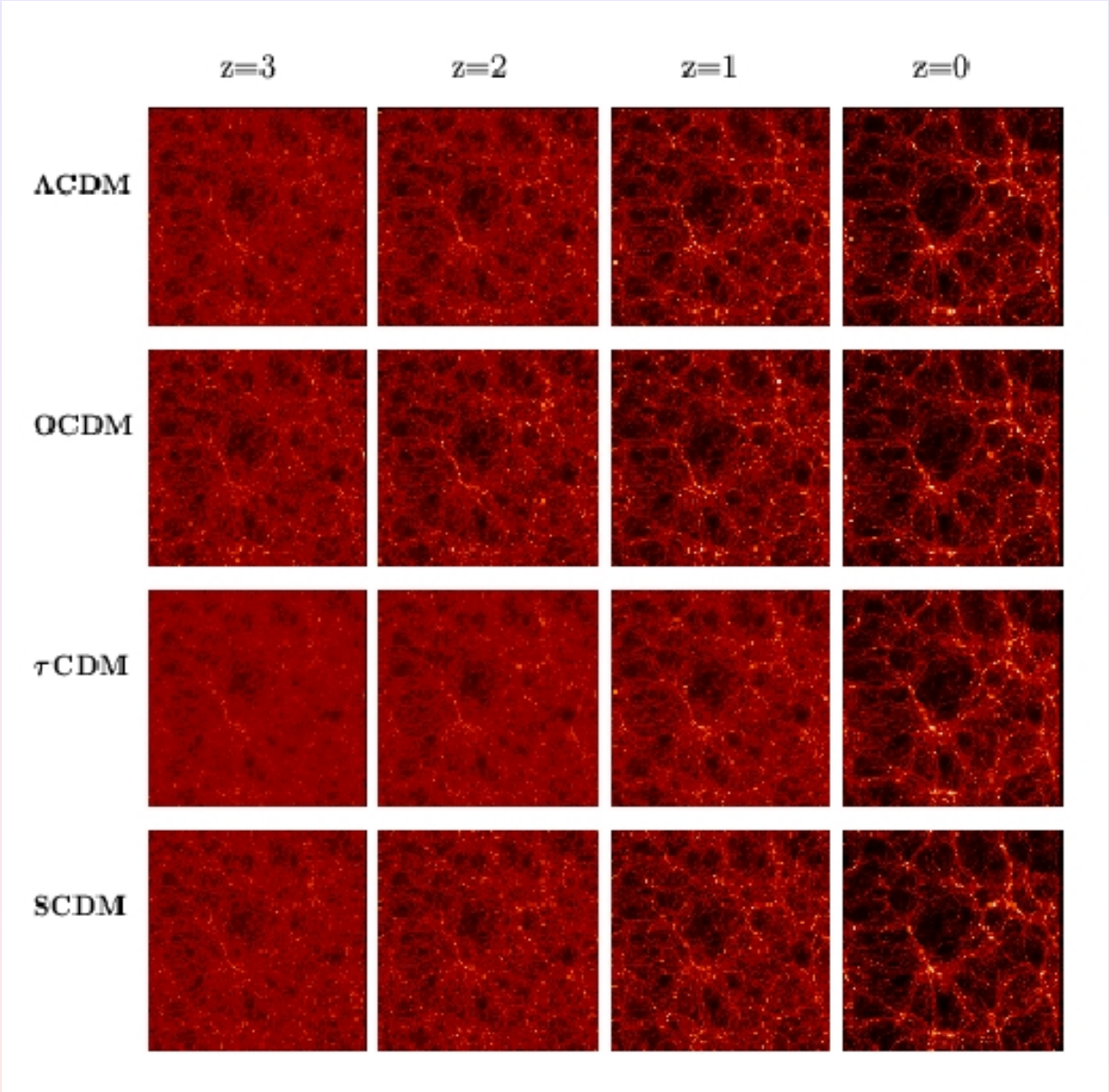
(Dark) matter:

- a flat universe requires

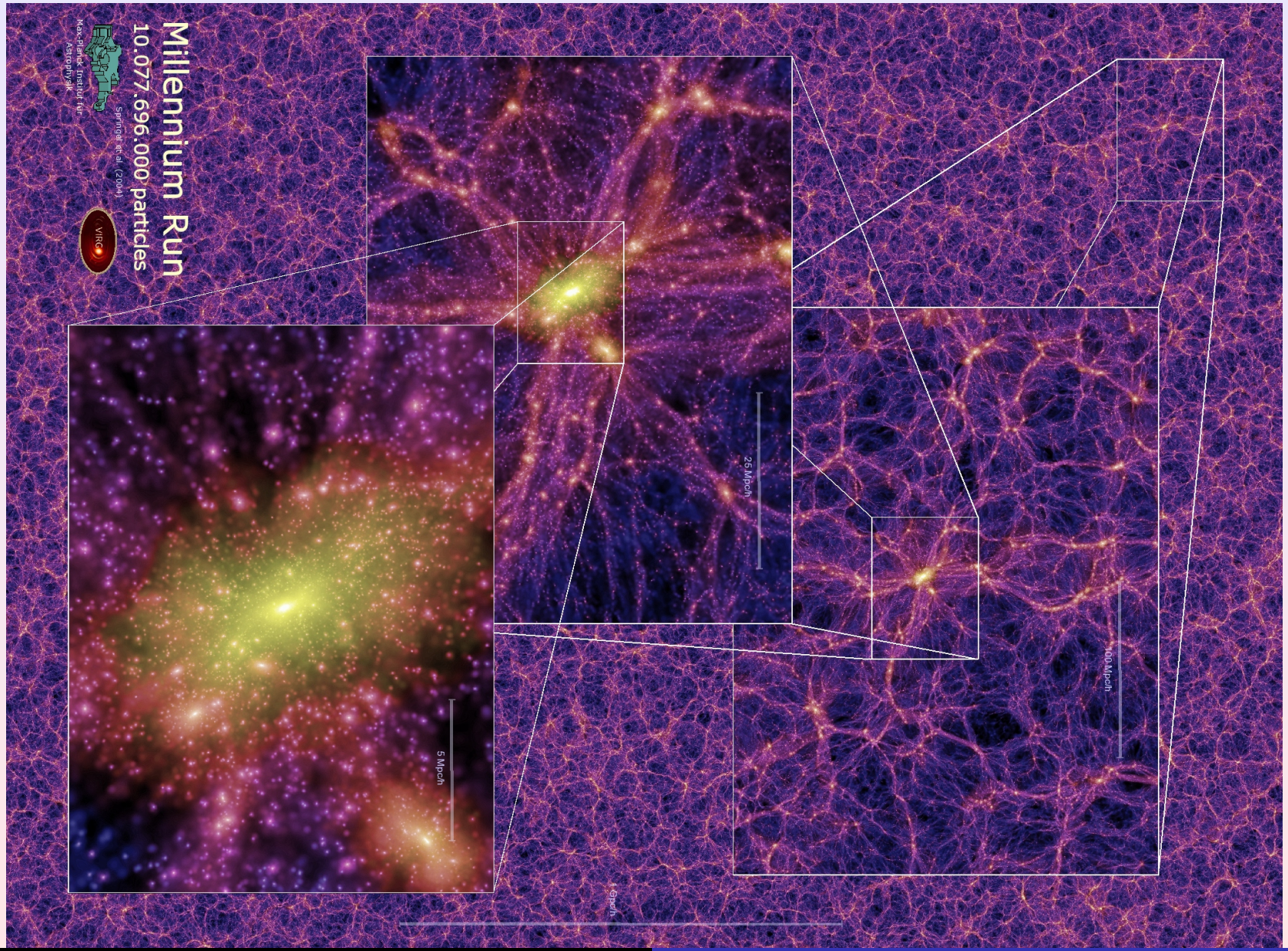
$$\rho = \rho_{\rm cr} = \frac{3H_0^2}{8\pi G}$$

- luminous matter $\Omega_{\rm lum} = \rho_{\rm lum}/\rho_{\rm cr} \approx 0.01$
- rotation curves in galaxies:
- virial mass of cluster of galaxies: $\langle GM/r \rangle = 2\langle v^2 \rangle$
- successful structure formation requires cold dark matter

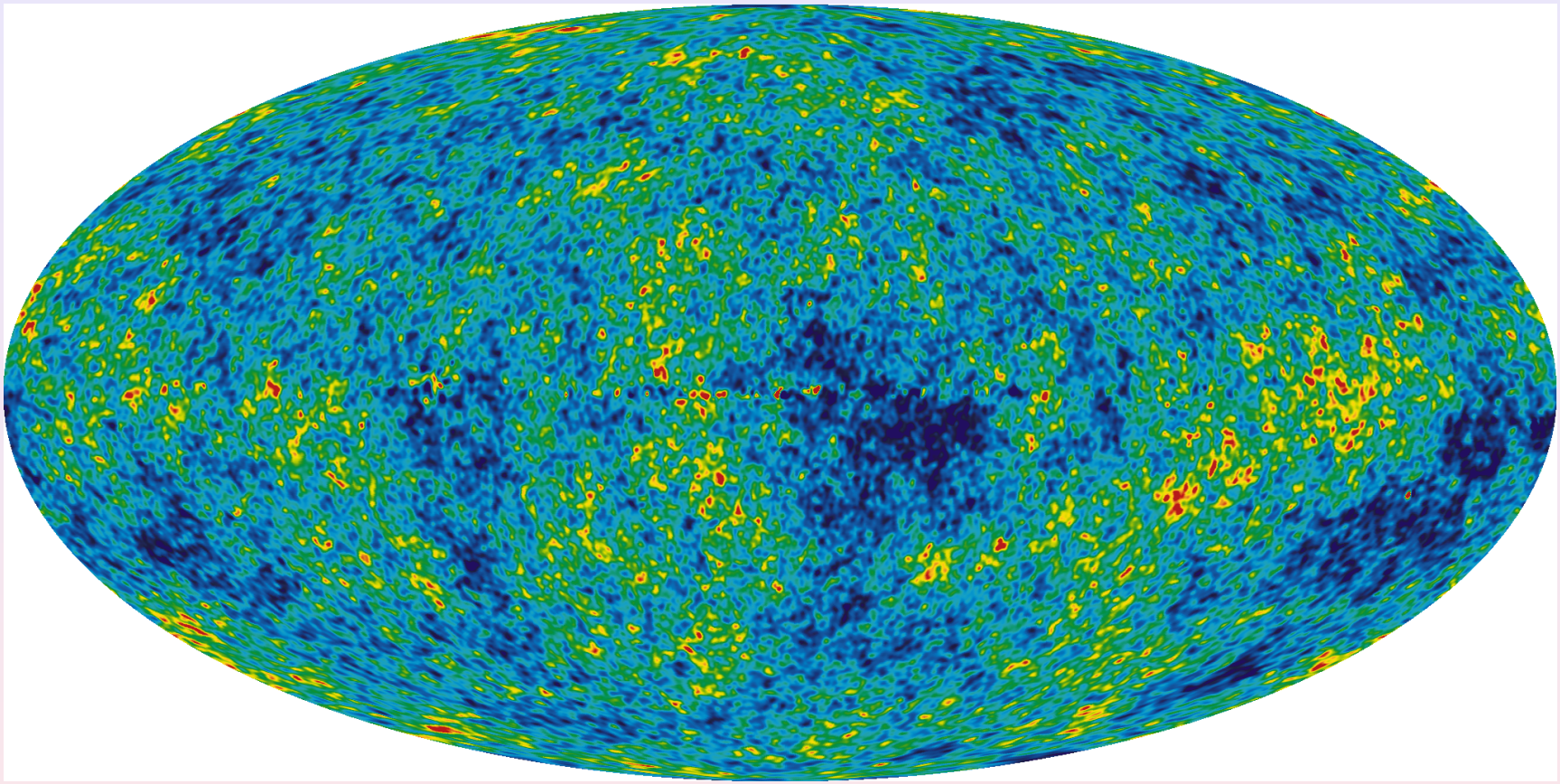
LSS:

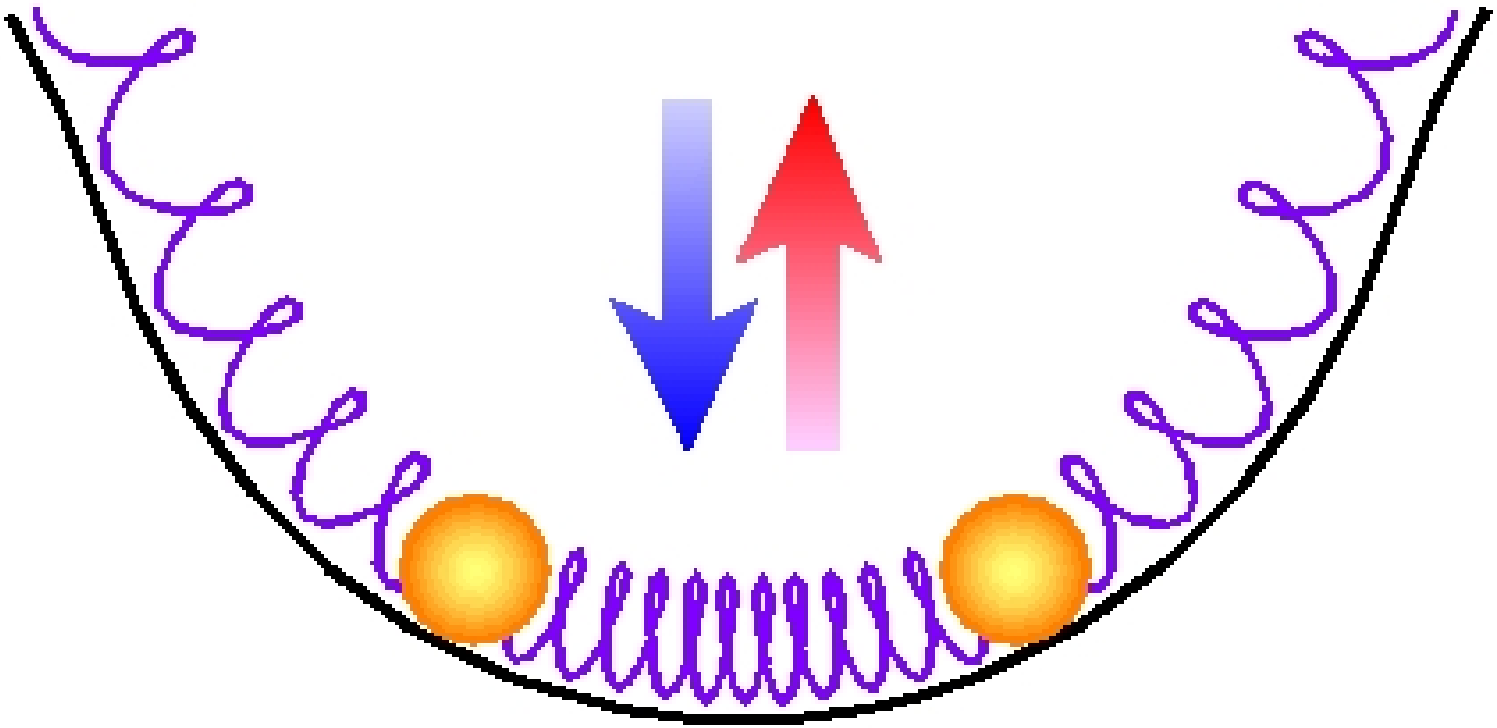


LSS:

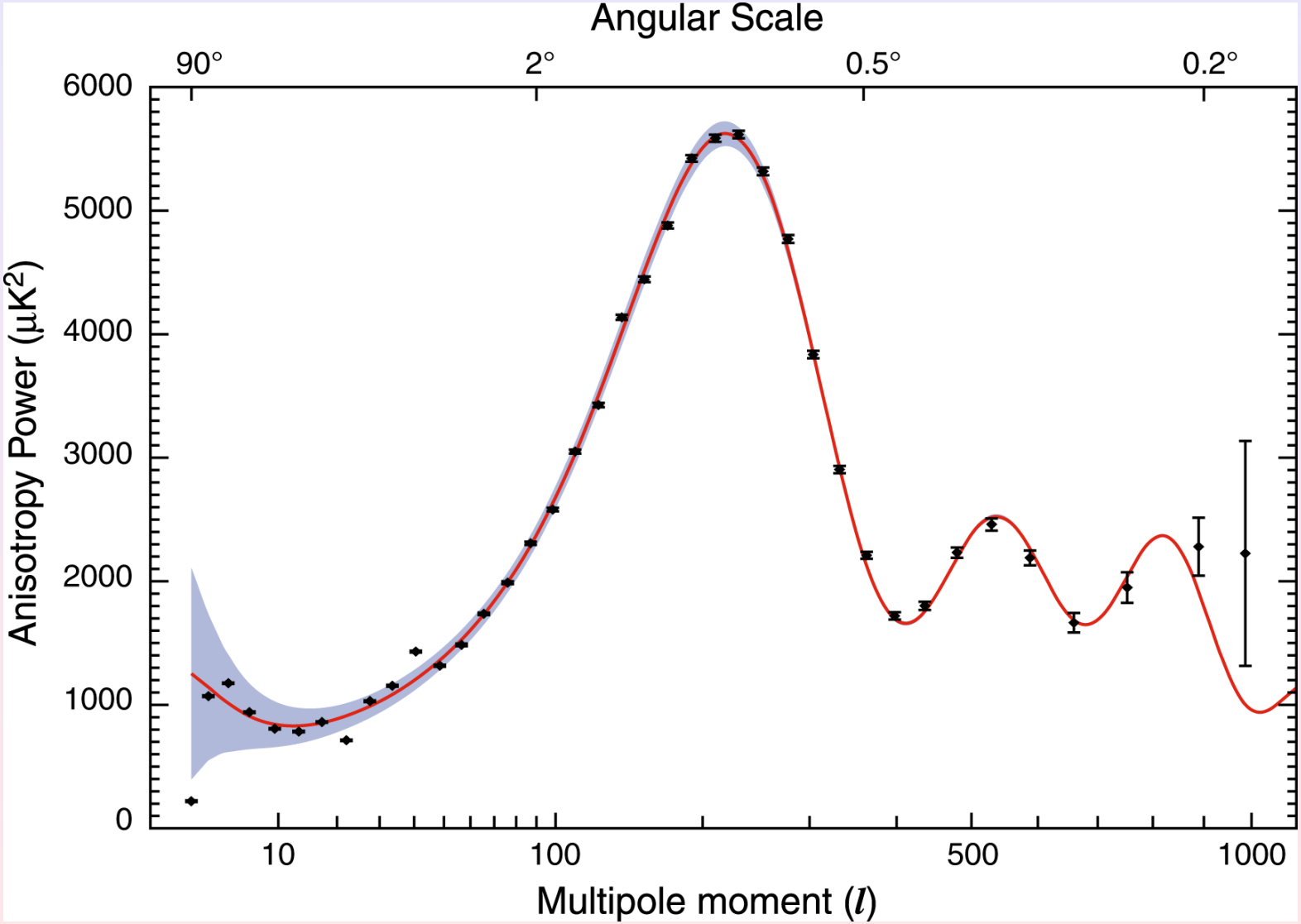

Millennium Run
10.077.696.000 particles
Springel et al. (2004)
Max-Planck-Institut für Astrophysik
VIRGO
5 Mpc/h
25 Mpc/h
100 Mpc/h
1 Gpc/h

Cosmic microwave background:




Seeing Sound

Cosmic microwave background:



Inflation and dark energy:

- standard hot big-bang picture has many problems

Inflation and dark energy:

- standard hot big-bang picture has many problems
- what is the source of inhomogenities?

Inflation and dark energy:

- standard hot big-bang picture has many problems
- what is the source of inhomogenities?
- solution: periode of exp. accelerated expansion at "$t = 0$"

Inflation and dark energy:

- standard hot big-bang picture has many problems
- what is the source of inhomogenities?
- solution: periode of exp. accelerated expansion at "$t = 0$"
- at present: again accelerated expansion!?

Outline of the course:

- Reviev of basic particle physics, . . .

Outline of the course:

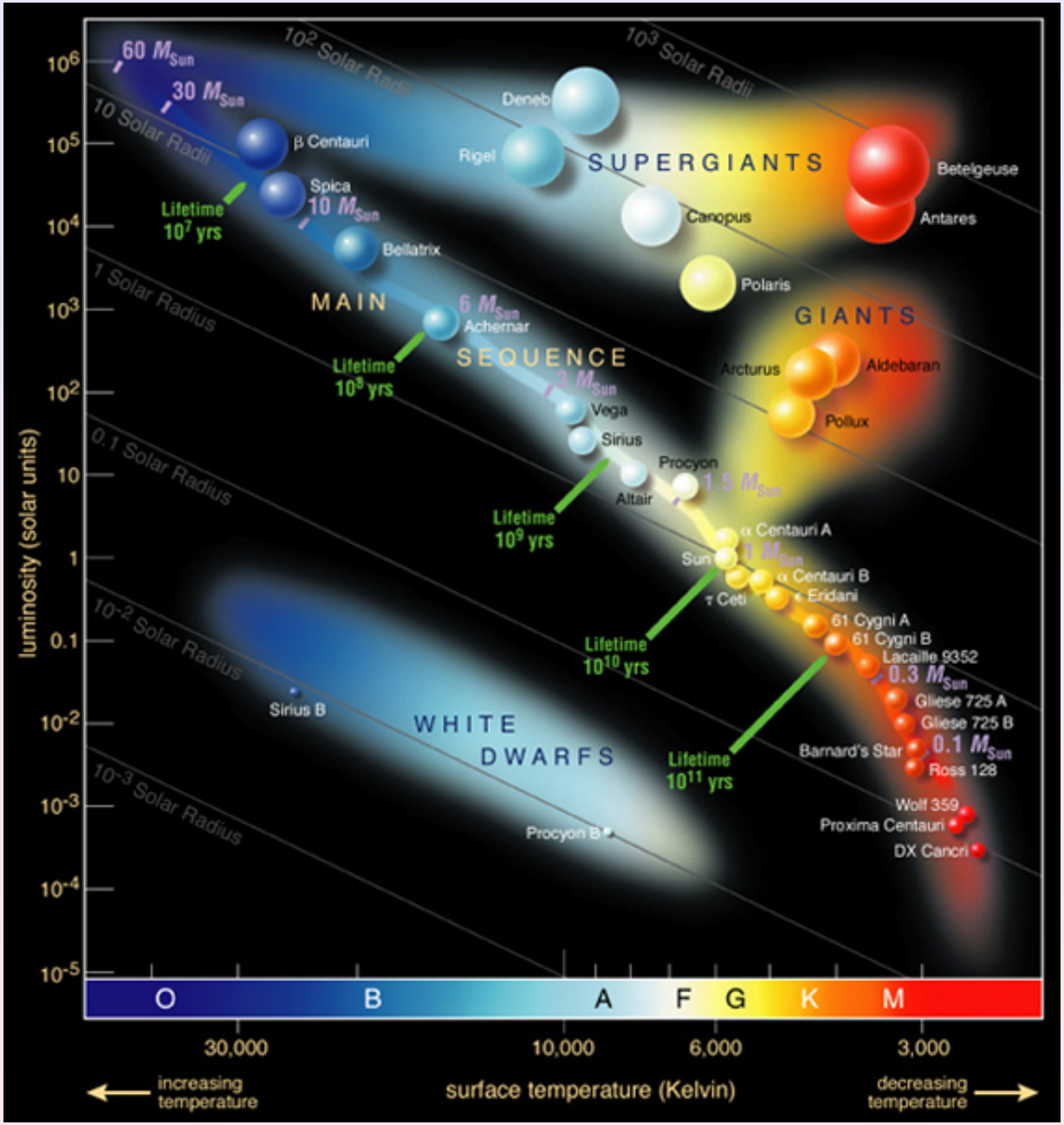
- Reviev of basic particle physics, . . .
- High-energy astrophysics
- Cosmology

Outline of the course:

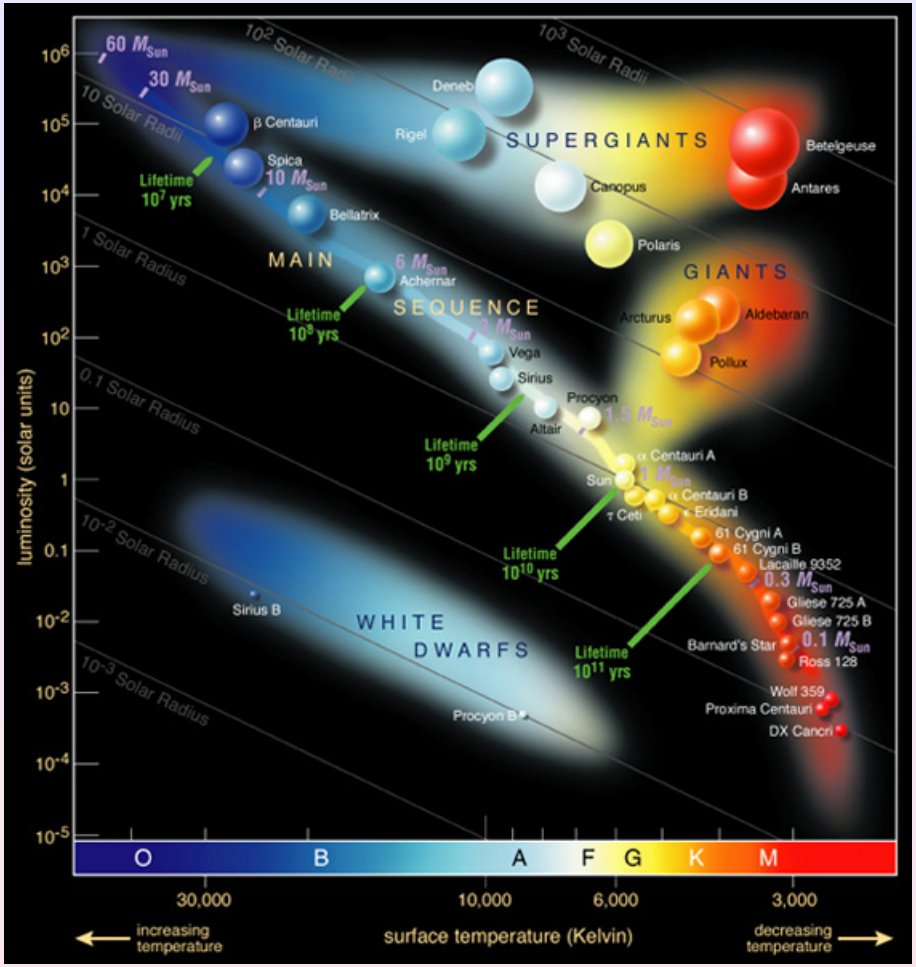
- Reviev of basic particle physics, . . .

- Stellar astrophysics
  - Equations of stellar evolution
  - Simple models for MS stars
  - Nuclear processes and neutrinos, neutrino oscillations
  - stars as tool for particle physics

Stars:

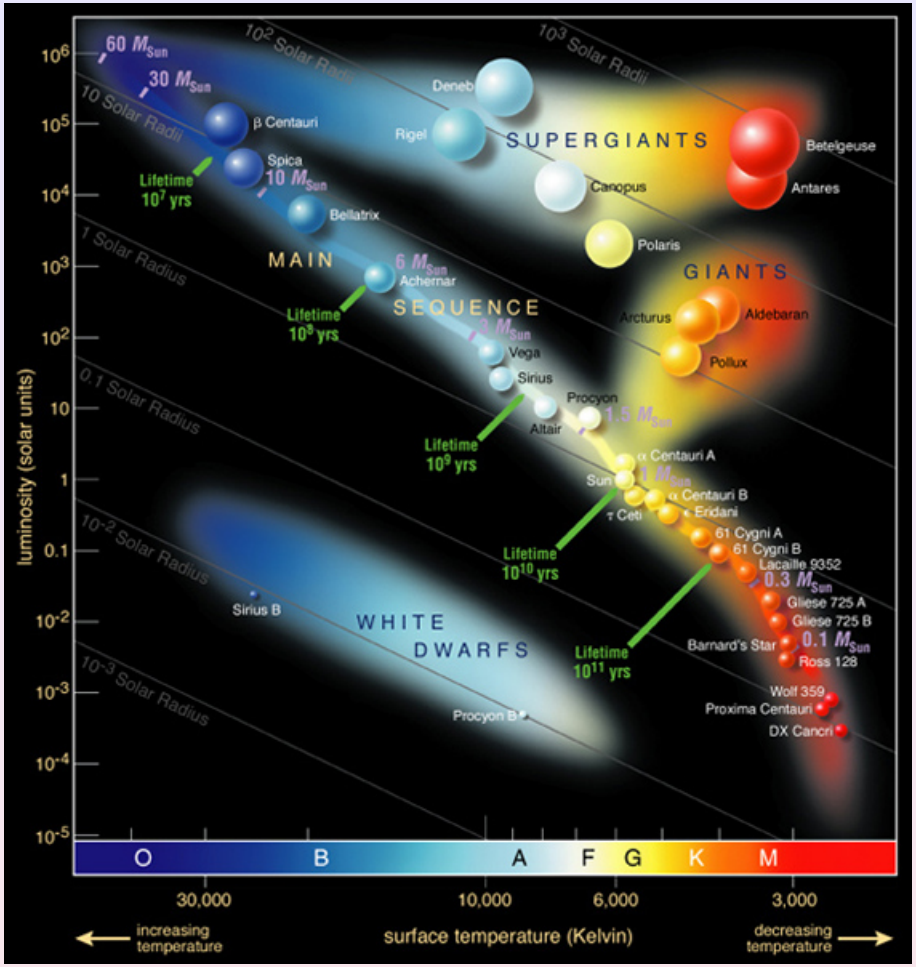

luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
3 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Deneb
Rigel
SUPERGIANTS
Betelgeuse
Antares
Canopus
β Centauri
Spica
Bellatrix
Polaris
Lifetime 10^7 yrs
MAIN
SEQUENCE
Achernar
Lifetime 10^8 yrs
GIANTS
Arcturus
Aldebaran
Pollux
Vega
Sirius
Procyon
Altair
Lifetime 10^9 yrs
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
Lifetime 10^{10} yrs
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Lifetime 10^{11} yrs
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
WHITE
DWARFS
Procyon B
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Stars:



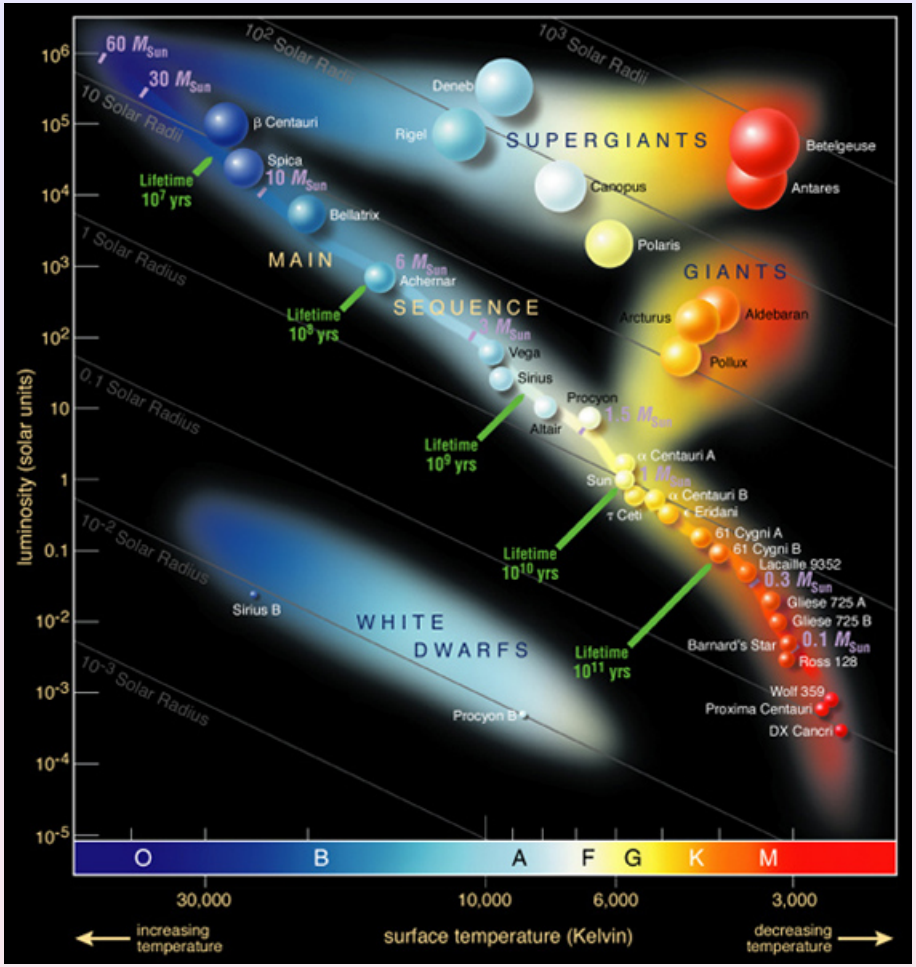
- Why are most stars on main-sequence?

Stars:



- Why are most stars on main-sequence?
- How do they produce energy? Evolution? Neutrinos?

Stars:



- Why are most stars on main-sequence?
- How do they produce energy? Evolution? Neutrinos?
- if standard picture is correct, constrain new physics