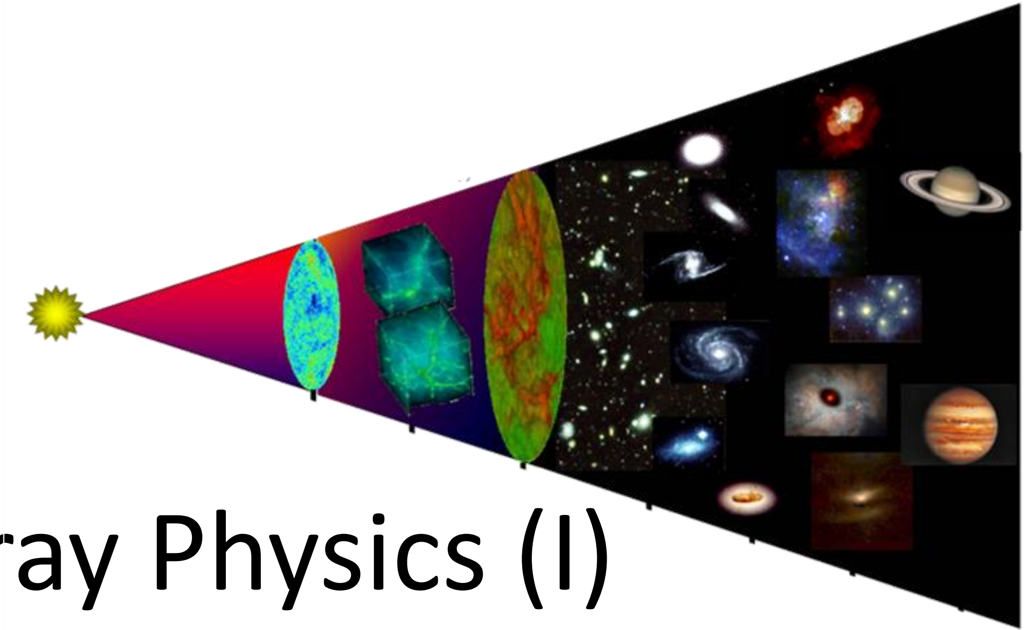

Cosmic-ray Physics (I)

- From the birth of the universe to the present -

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University of Tokyo

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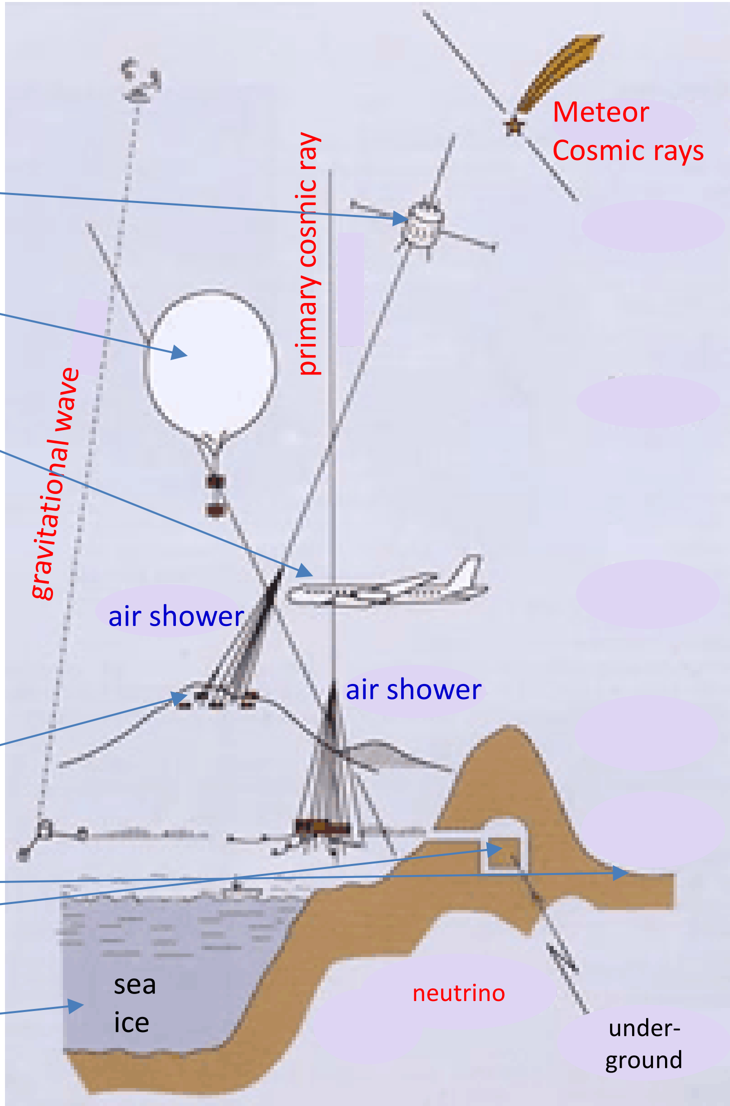
April 1, 2015

What are cosmic rays?

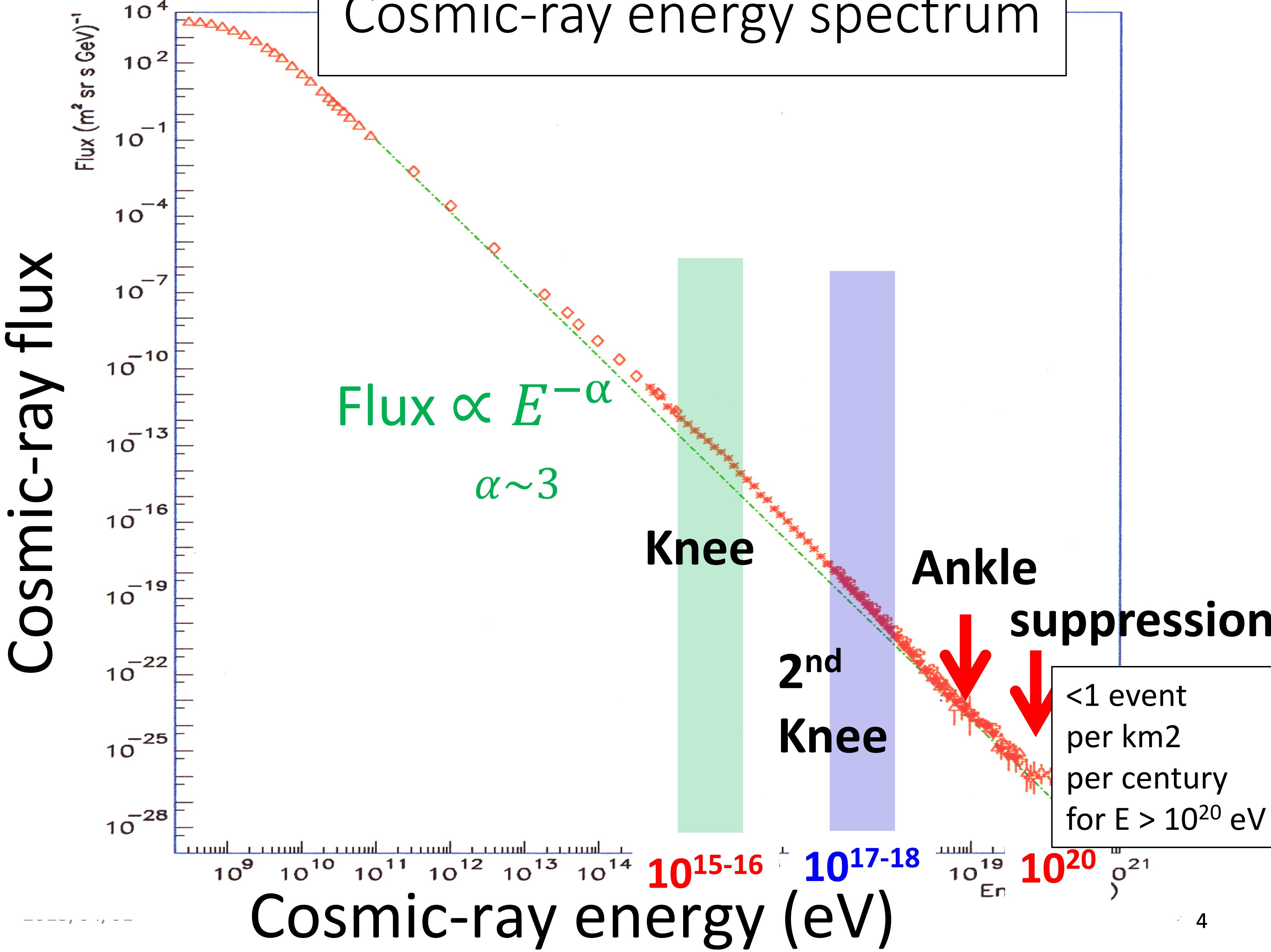
- Primary cosmic ray:
  - High-energy radiation that travels the universe and arrives at the earth
  - Mostly protons and other nuclei

Observation of cosmic rays

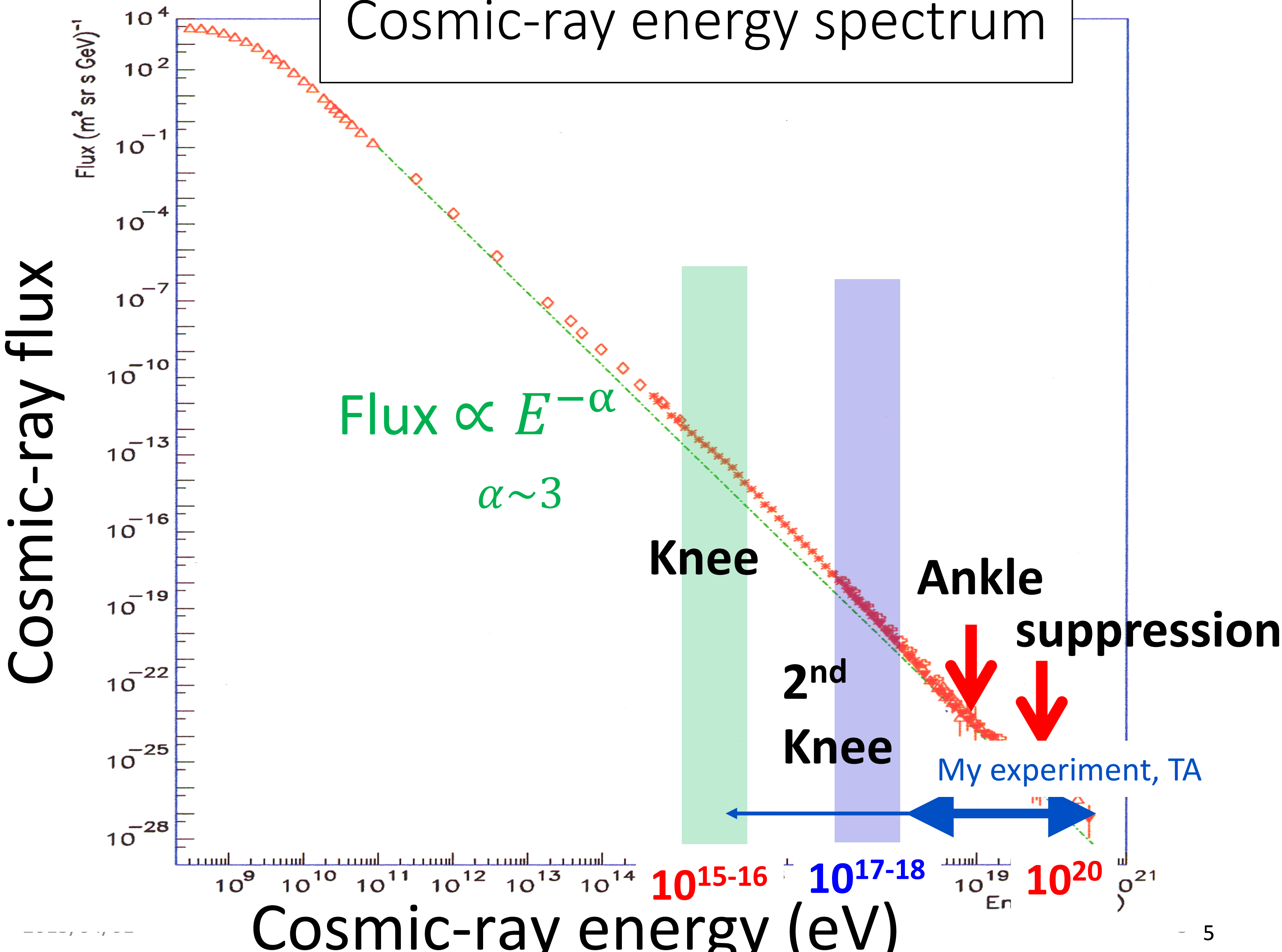
- Primary cosmic rays
  - Satellite
  - Balloon (30~40km)
  - Airplane (10~20km)
- Secondary cosmic rays
  - Radiation produced by primary cosmic rays when they enter the atmosphere
  - High mountain (3~5km)
  - Ground (~0km)
  - Underground
  - deep sea, ice



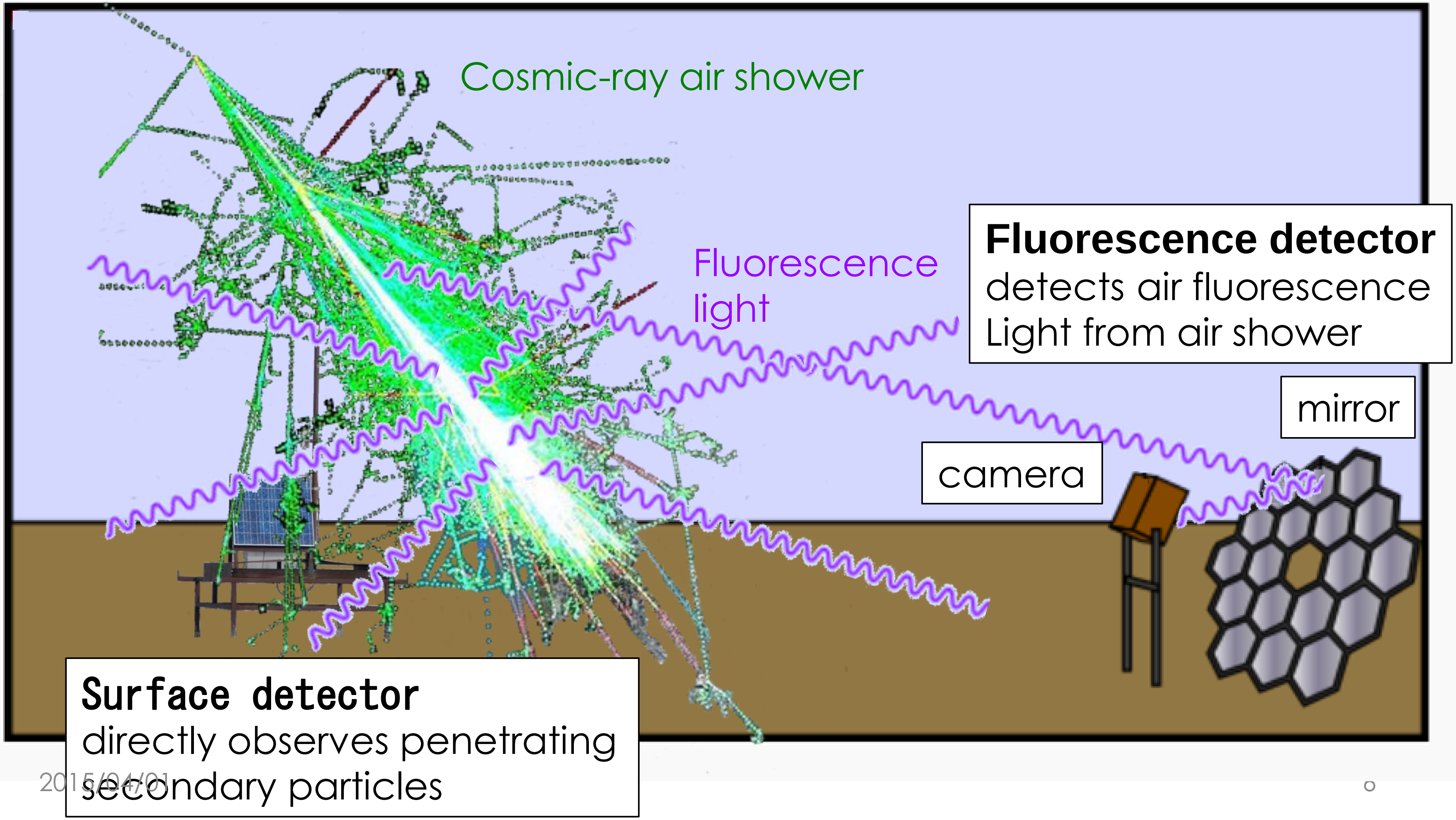
Cosmic-ray energy spectrum



Cosmic-ray energy spectrum

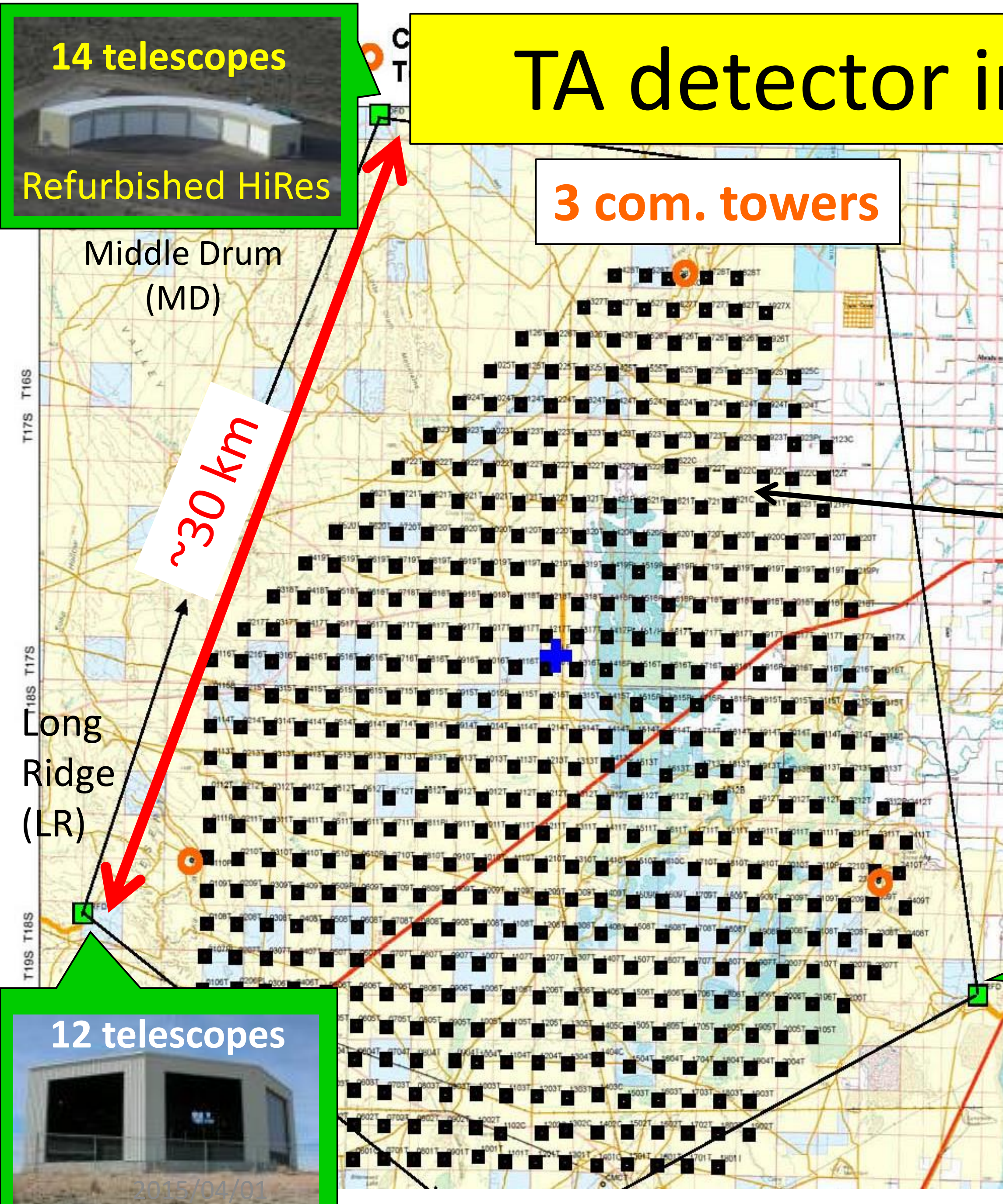


Surface detector and fluorescence detector



TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.



Surface Detector (SD)

507 plastic scintillator SDs

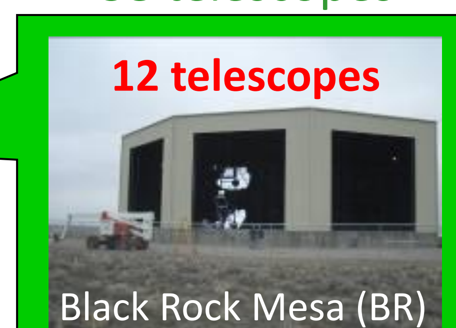
1.2 km spacing

$\sim$700 km^2

Fluorescence Detector (FD)

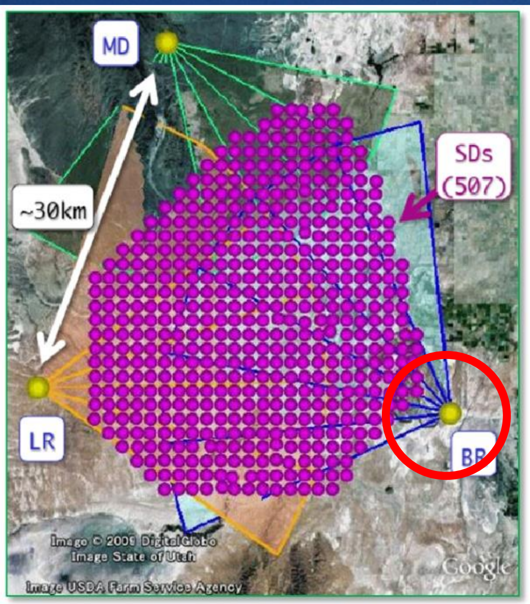
3 stations

38 telescopes



FD and SD: fully operational since 2008/May

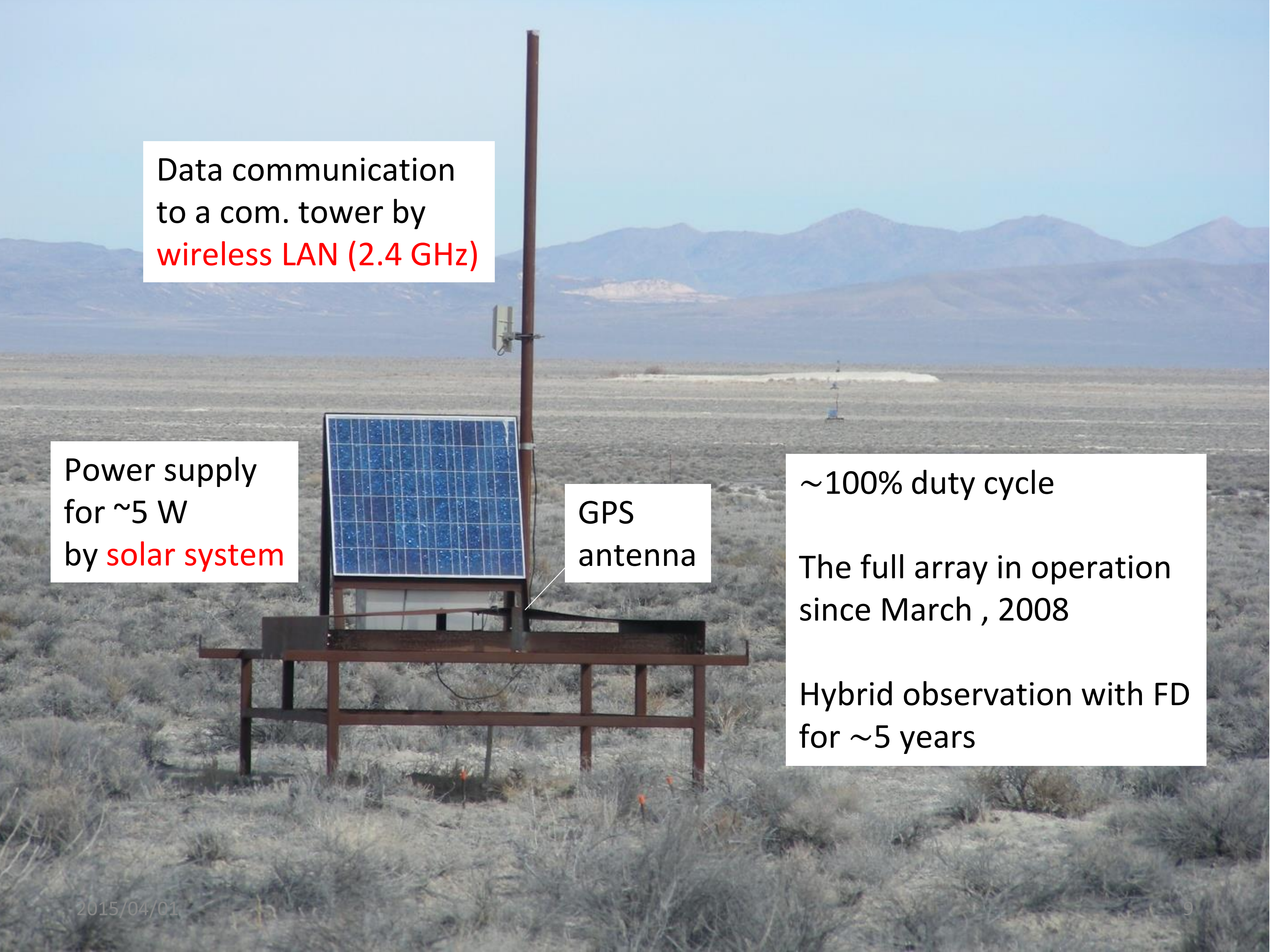
Fluorescence Detector stations



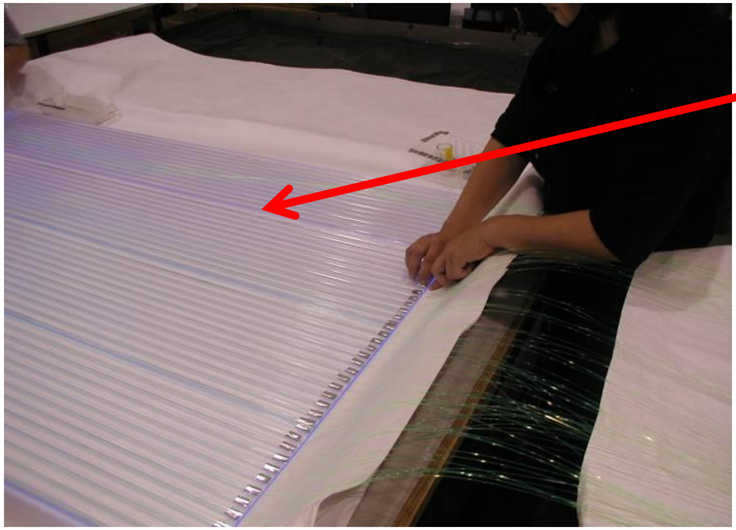
Field of View
3 – 33° in zenith
108° in azimuth

Observation
moonless, clear night
duty cycle ~10%

All three stations: observation since Nov., 2007


Data communication
to a com. tower by
wireless LAN (2.4 GHz)
Power supply
for ~5 W
by solar system
GPS
antenna
~100% duty cycle
The full array in operation
since March , 2008
Hybrid observation with FD
for ~5 years

Surface Detector (SD)

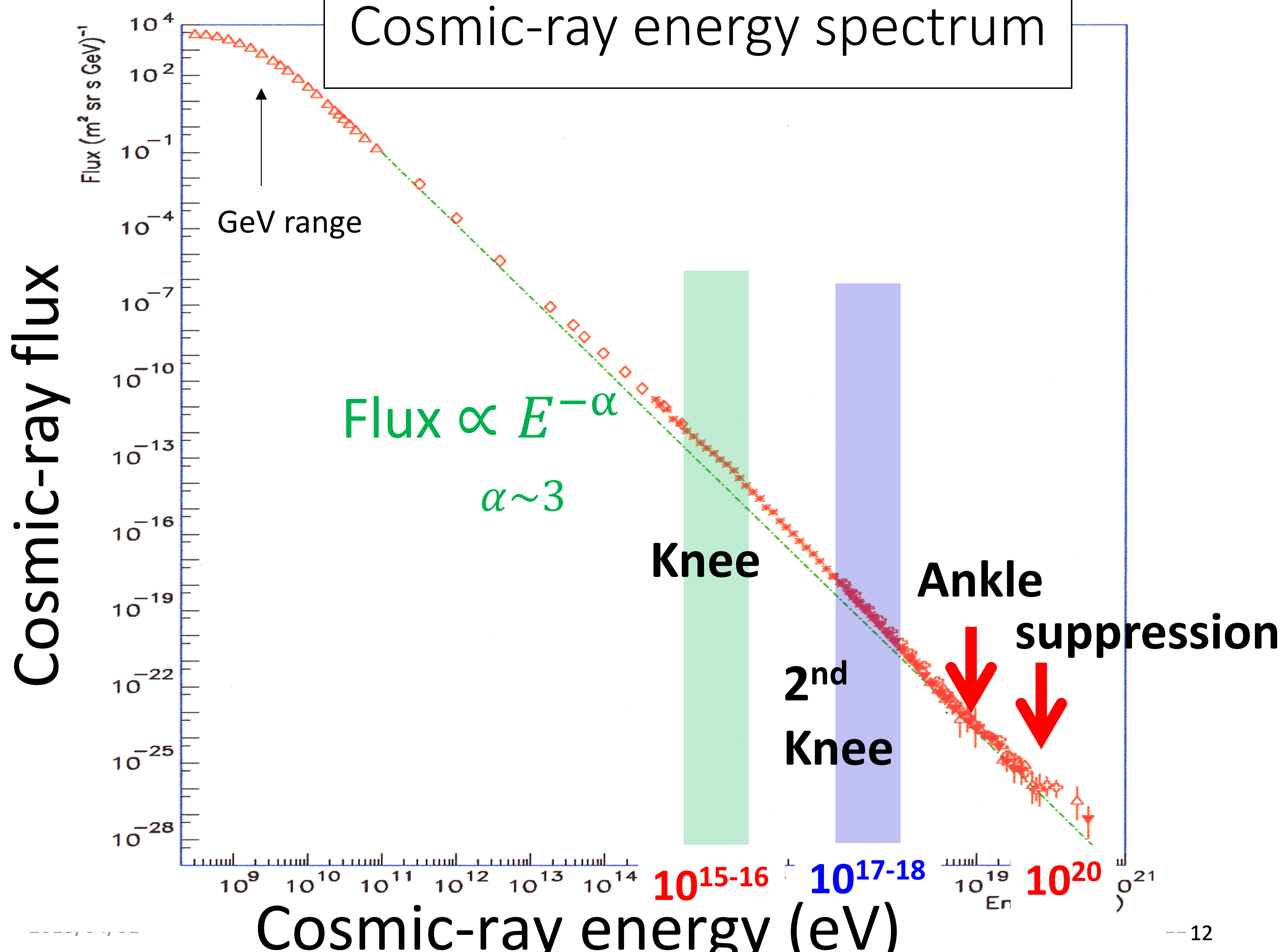


- 2 layers of plastic scintillator
  - 3 m^2 /layer
  - 1.2 cm thick/layer
- WLS fibers
  - 1 mm ϕ
  - ~100 fibers/layer
- 1 PMT for 1 layer
  - 1-inch ϕ
- 50 MHz FADC readout

Cosmic rays of around 100 MeV

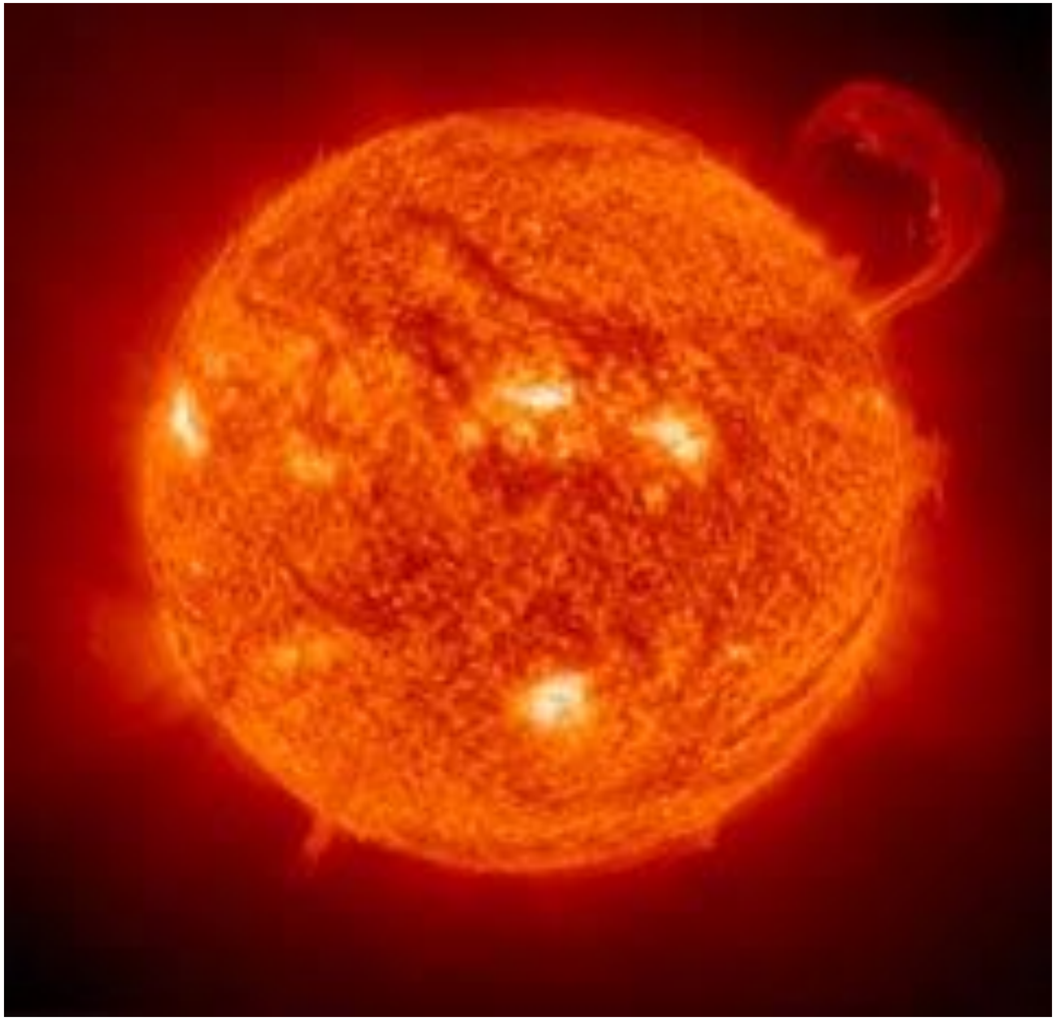
- Confied in the magnetic field between planets

Cosmic-ray energy spectrum



Sun: close cosmic-ray source

surface temperature
about 6000 degrees



Variation of CR intensity and the number of sunspots

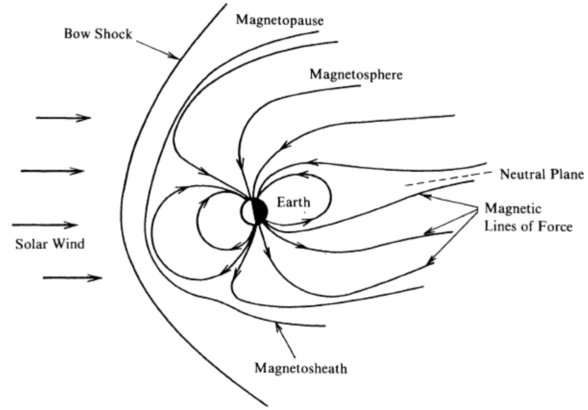
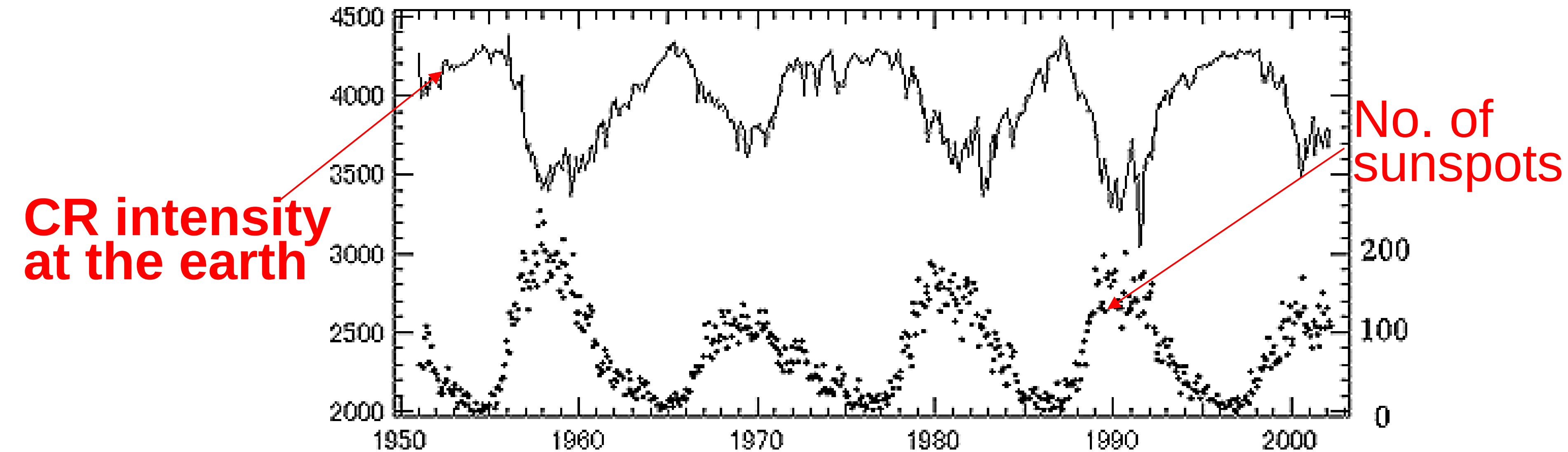
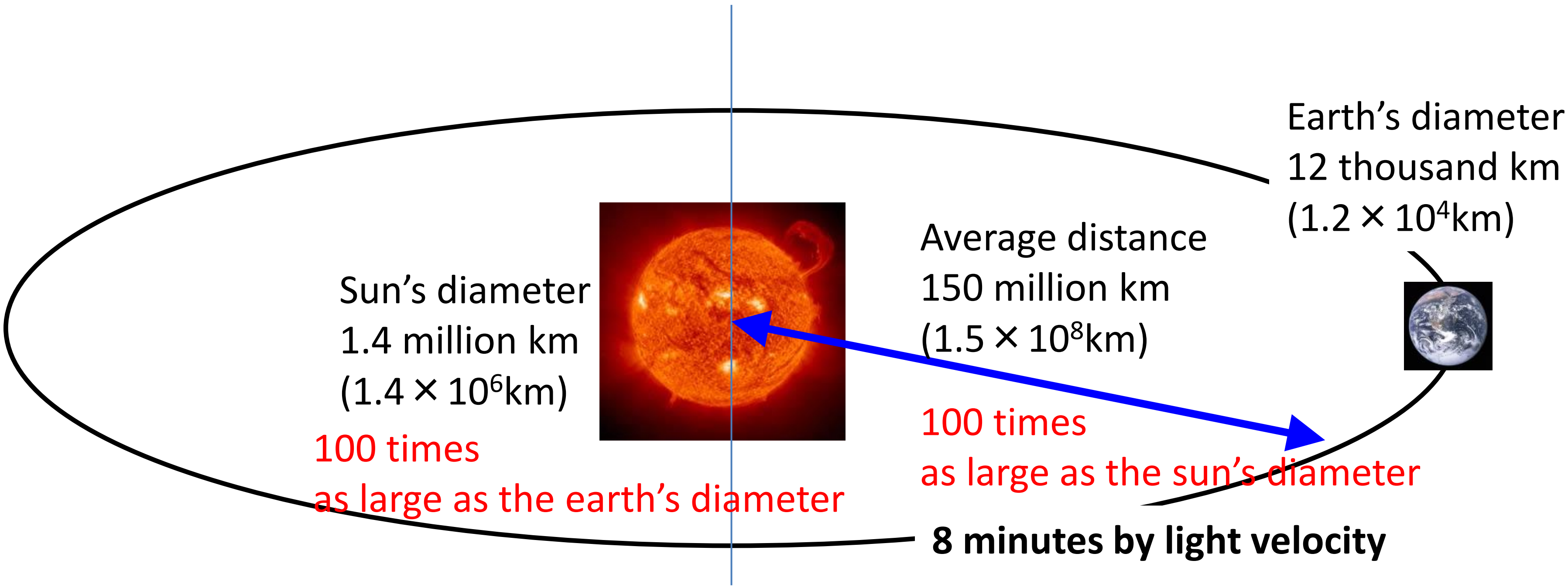


Fig. 2.5.7. The structure of the earth's magnetosphere and its vicinity.

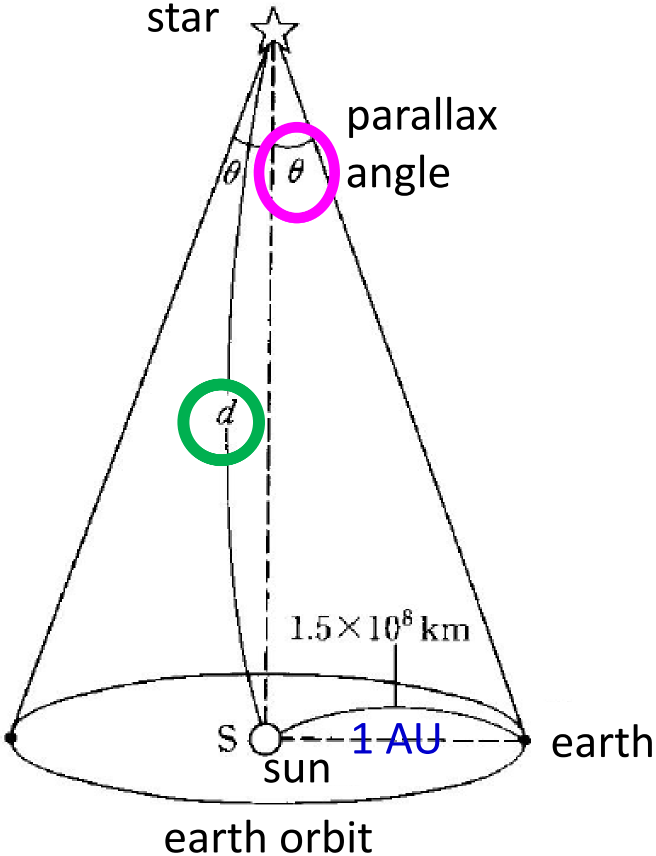


Distance between the sun and the earth



Light velocity
(3×10^5km/s)

Astronomical Unit (AU)



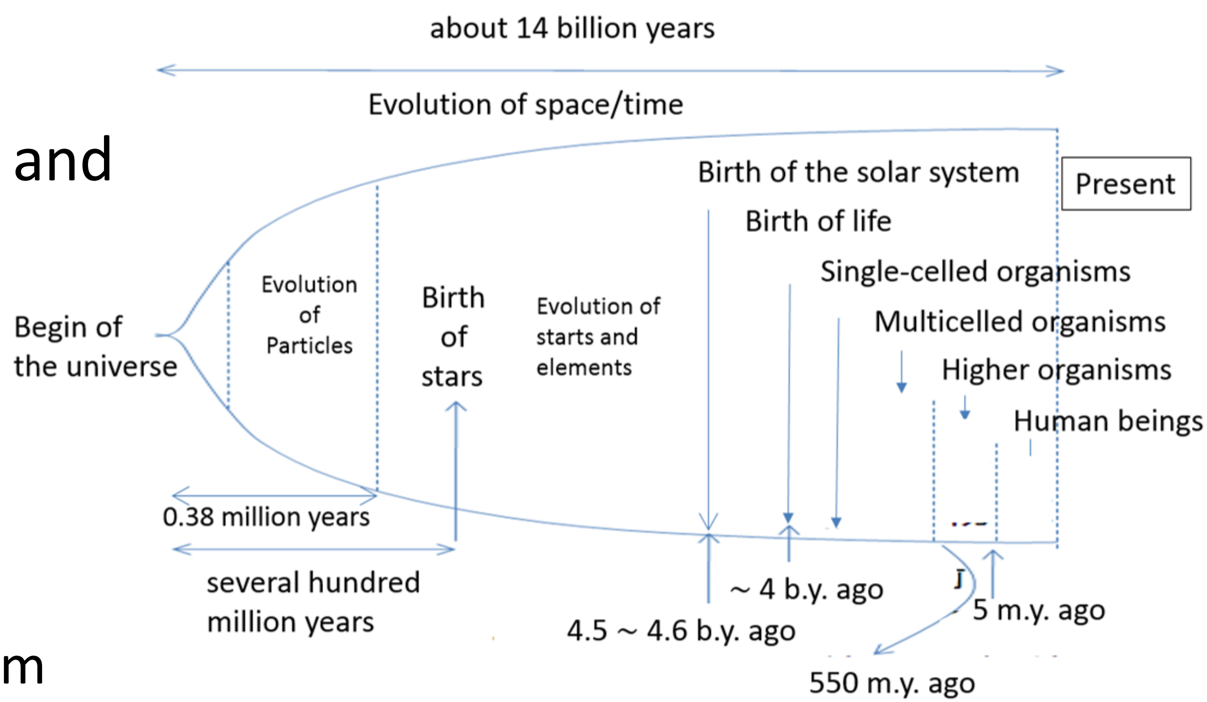
annual parallax

- 1 light year = the distance that light travels in one year = $(3.0 \times 10^{10}$cm/sec$) \times (3.16 \times 10^{7}sec)$ = 9.46×10^{12}km
- 1 AU (Astronomical Unit) = average distance between the sun and the earth = 1.50×10^{8} km
- 1 pc (parsec) : the distance for which annual parallax is 1" = 1 AU/1" = 3.09×10^{13} km
  - 1 pc = 3.26 light years

"From the birth of the universe to the present"

Evolution of the Universe for 14 billion years

- Space and time
- Particles
- Astronomical objects and elements
- The solar system
- The earth
- Organisms
  - Organic matter and the birth of life
  - Single-celled organism
  - Higher organism
  - Human beings

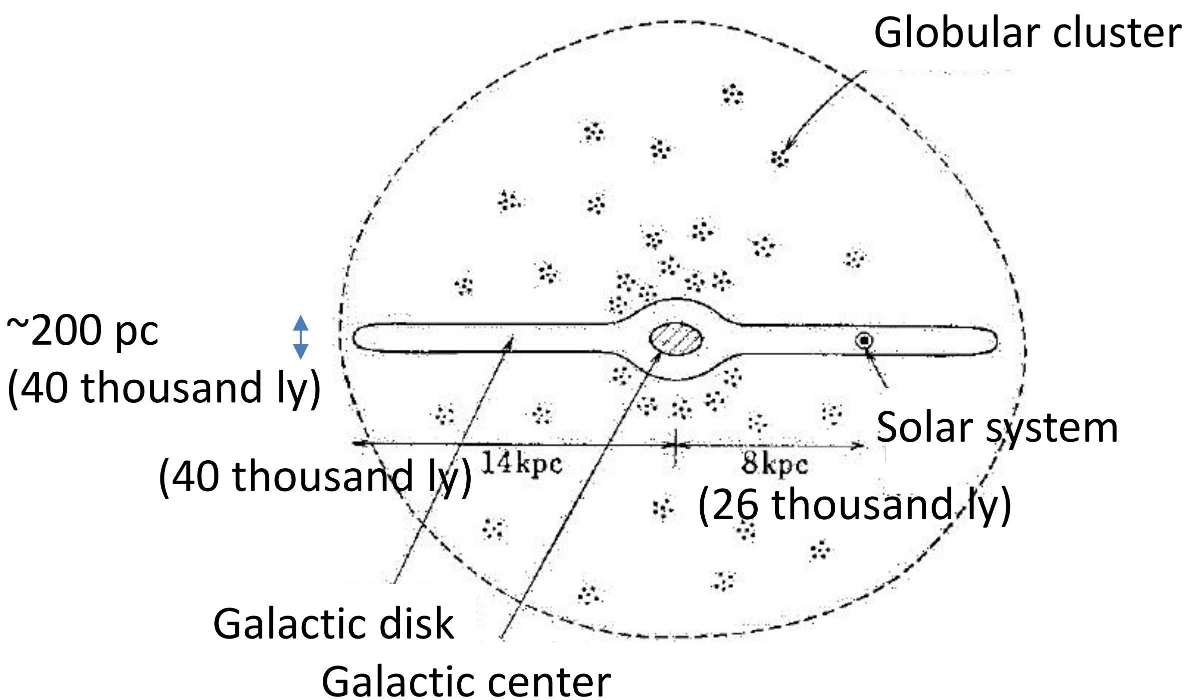


b.y. = billion years
m.y. = million years


the Milky Way

the Milky way (the Galaxy)

- Galaxy that includes our solar system



Our galaxy

1pc = 3.26 ly

ly= light year

Balance of cosmic-ray energy

- The structure of our glaxy
  - Total energy of cosmic rays in the galactic disk
    Ecr = ρcr x V $\approx 10^{54\sim55}$ erg
    - Volume V = $10^{66\sim67}$ cm^3
      - Radius of about 10 kpc
      - Thickness of about a few hundred pc
    - Galactic magnetic field of about 1 μG
  - Leakage of cosmic-ray energy from the galaxy
    Ecr/τ = ρcr x V/$\tau \approx 10^{40}$ erg/s
    - Time during which cosmic rays are confined:
      $\tau \approx 10^7$ yr $10^{14\sim15}$ s

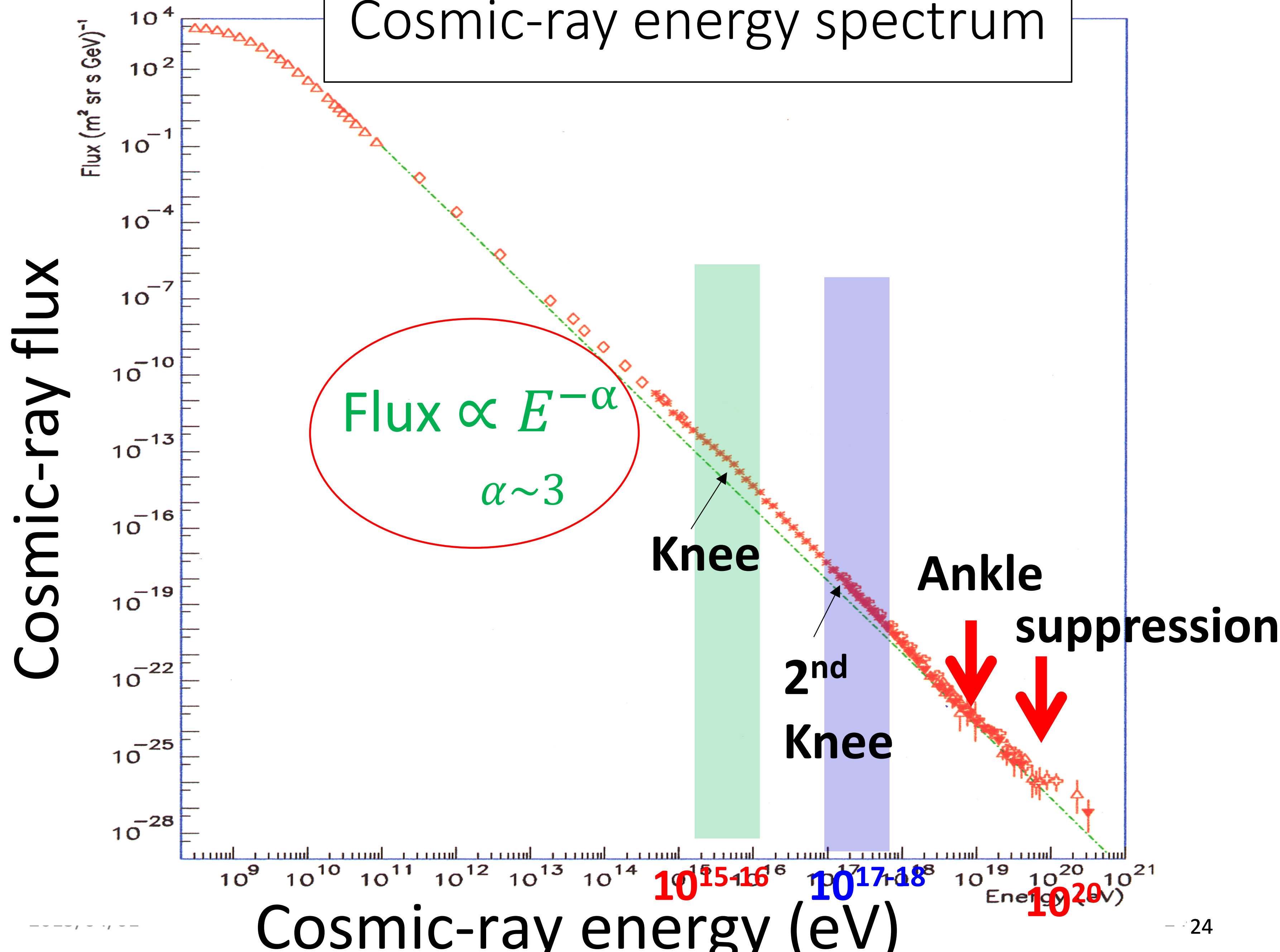
Balance of cosmic-ray energy

- The rate of energy generation by supernova $R_E \sim 10^{42}$ erg/s
  - Release of energy by a supernova explosion Esn 10^{51} erg
  - The number of supernova explosions in the galaxies 1/(30 yr)
- Supply of energy to cosmic rays by supernova explosion $E \sim 10^{40}$ erg/s $\approx Ecr/\tau$
  - Assuming that 1% of energy is used for particle acceleration

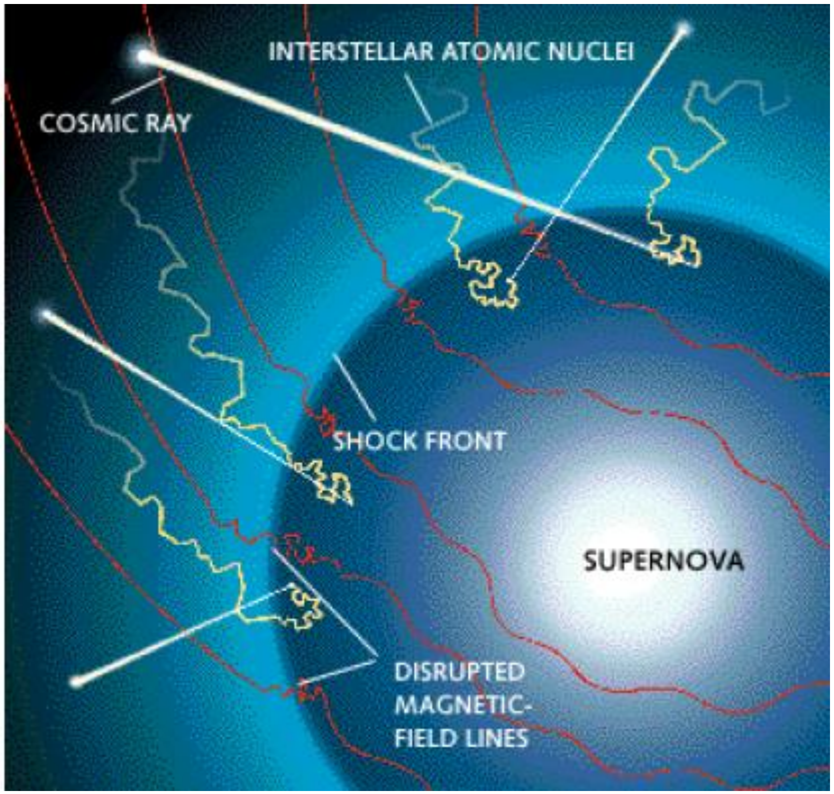
Balance of energy between supply and loss of cosmic rays in the galaxy

Intensity of cosmic rays in the galactic disk is constant

Cosmic-ray energy spectrum



Acceleration of cosmic rays shock-wave acceleration



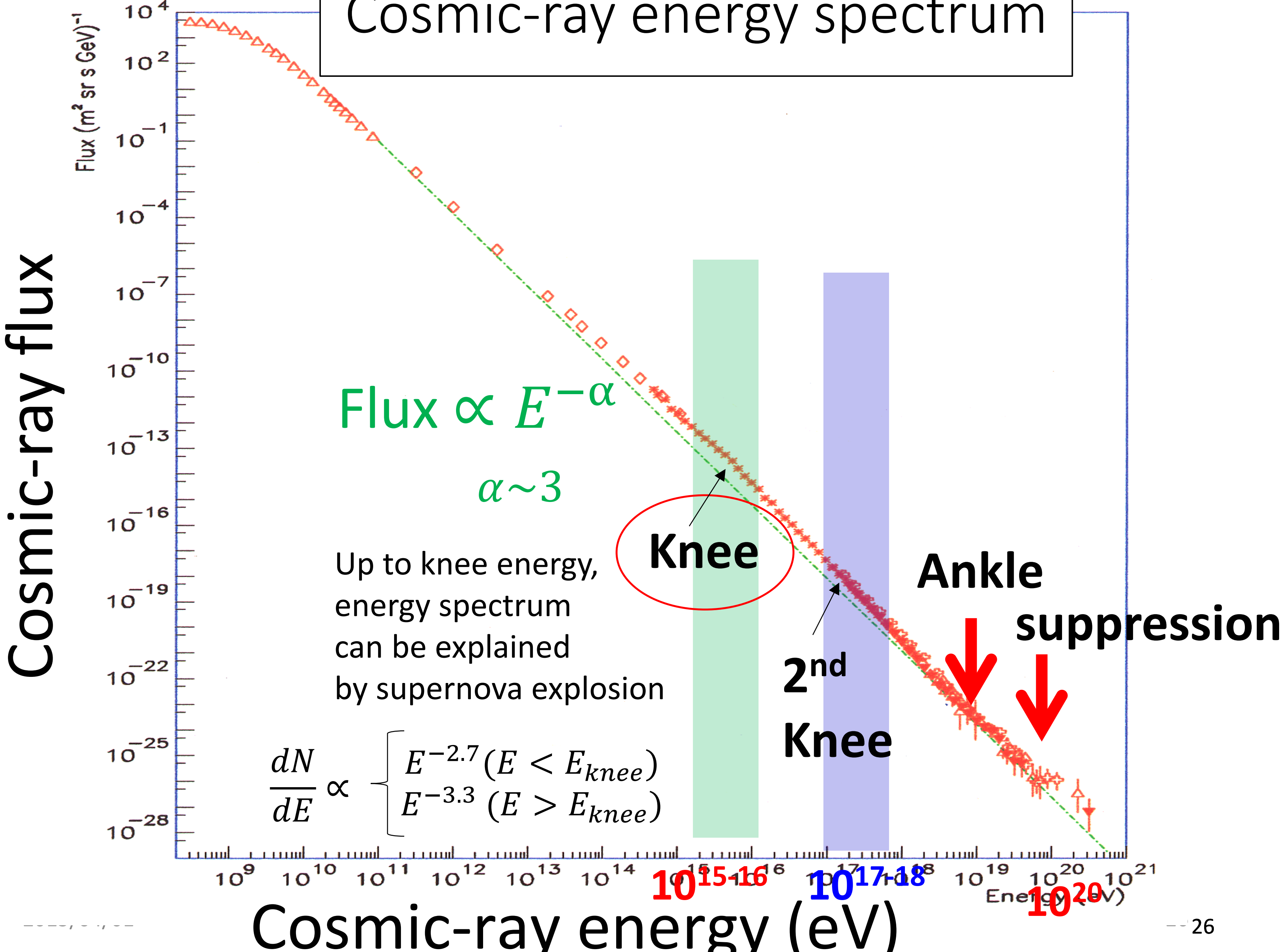
Supernova explosion
Shock wave
Cosmic ray acceleration

- Energy spectrum of cosmic rays at the source
  - $N(E) \propto E^{-2}$
    - Observed cosmic-ray spectrum may be explained
- Maximum energy for proton
  - $E_{max} \sim 10^{14}$eV

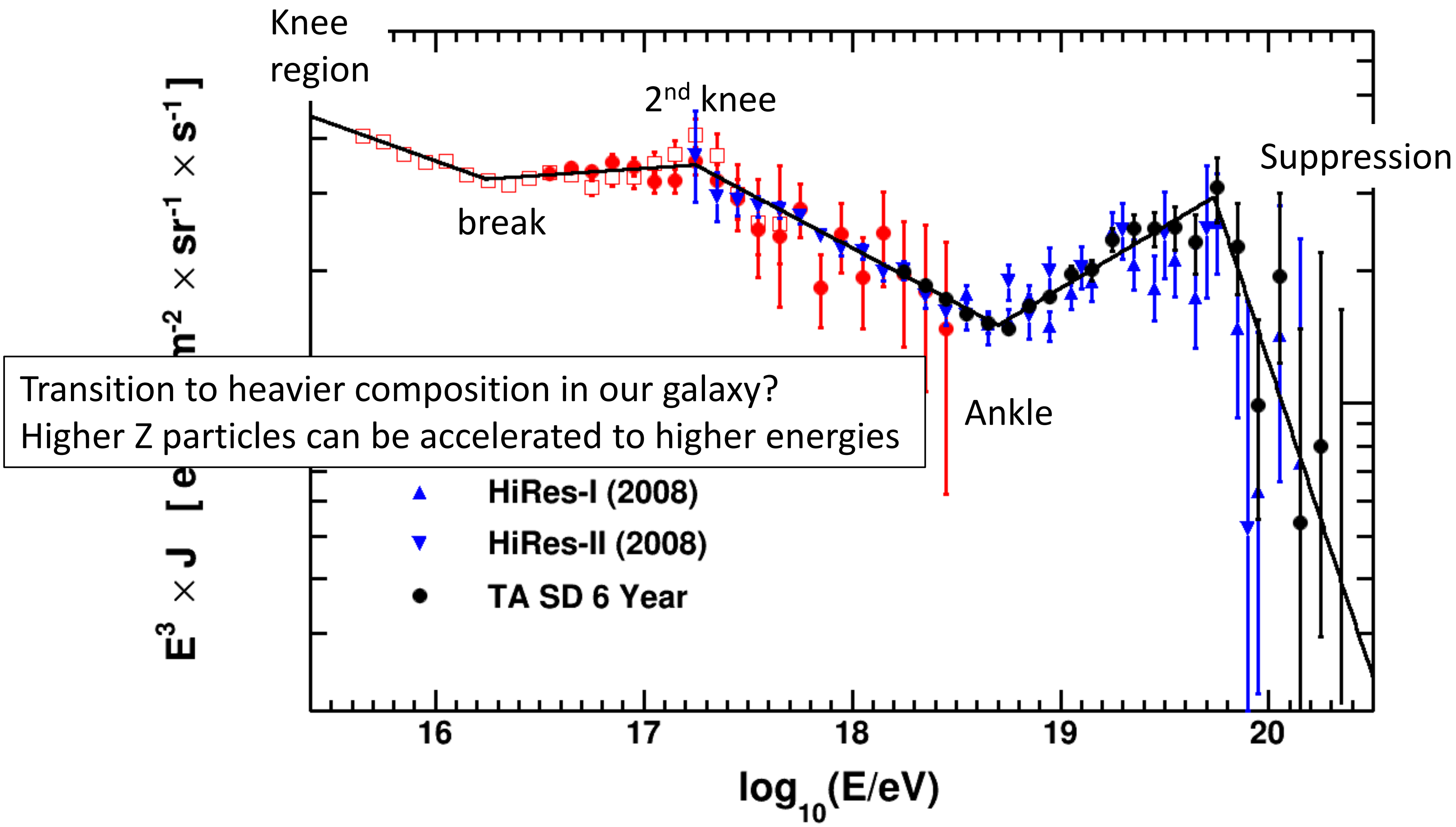
  can be possible
- Early stage of neutron stars
  - $E_{max} \sim 10^{16}$eV

  can be expected

Cosmic-ray energy spectrum



Energy spectrum at around knee and 2nd knee by my experiment (TA)

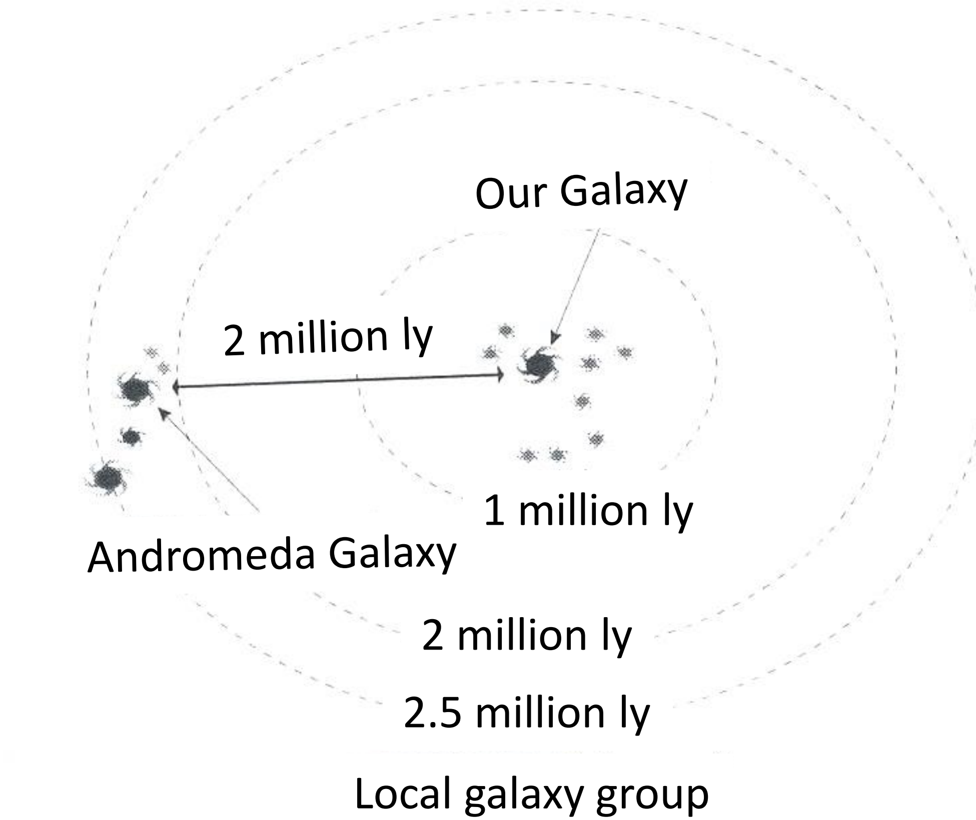


Andromeda Nebula (Galaxy)

The position of Andromeda Nebula?

- 1612: German astronomer Marius
  - He found vague spots in Andromeda constellation → It is named Andromeda Nebula because it is bright small cloud
- 1920: Heated discussion over whether Andromeda Nebula is a galaxy at far distance or not
- 1923: American astronomer Hubble
  - The distance to the Nebula was measured to be 0.75 million ly (later 2.3 million ly) using a new 100-inch telescope
  - Andromeda Nebula is a independent galaxy far beyond our galaxy

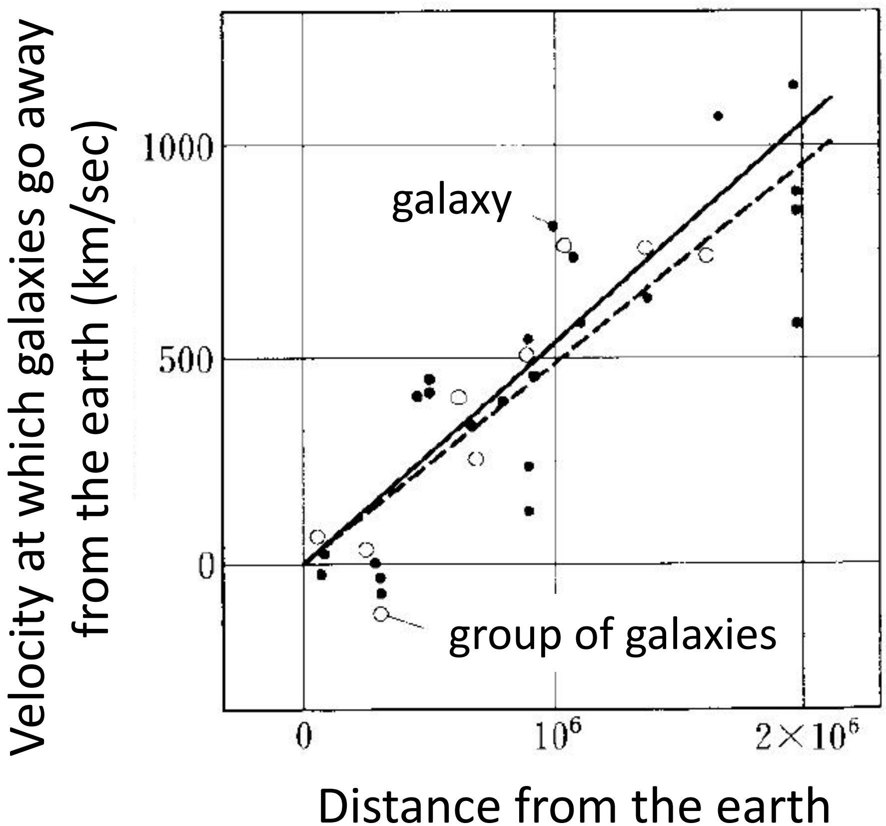
Andromeda Nebula



- Closest galaxy of which size is similar to our galaxy

Hubble plot (1929)

- Hubble measured the distances and velocities of various galaxies



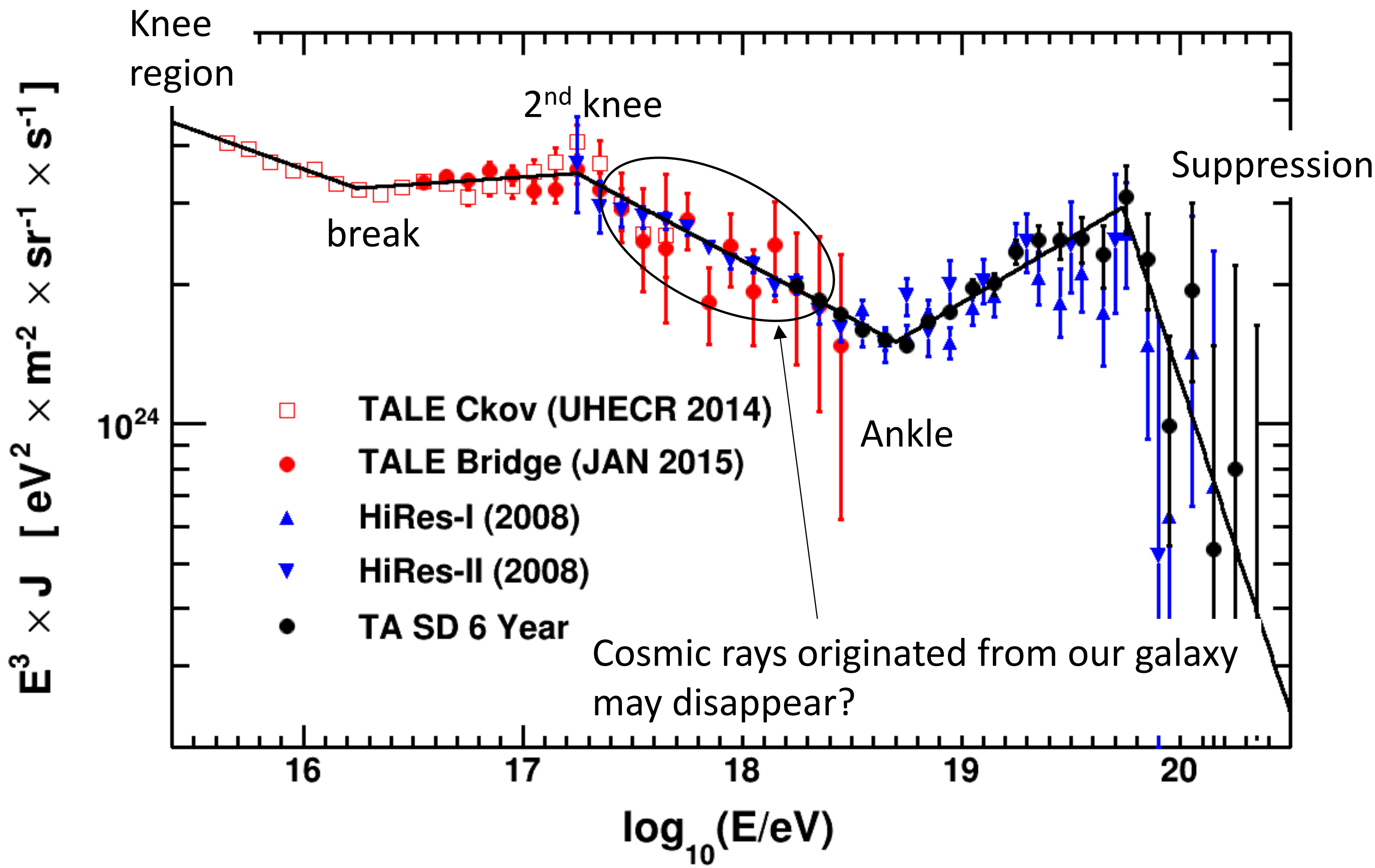
Hubble's law

- 1929: Hubble claimed that galaxies go away from the earth at the speed proportional to the distance from the earth

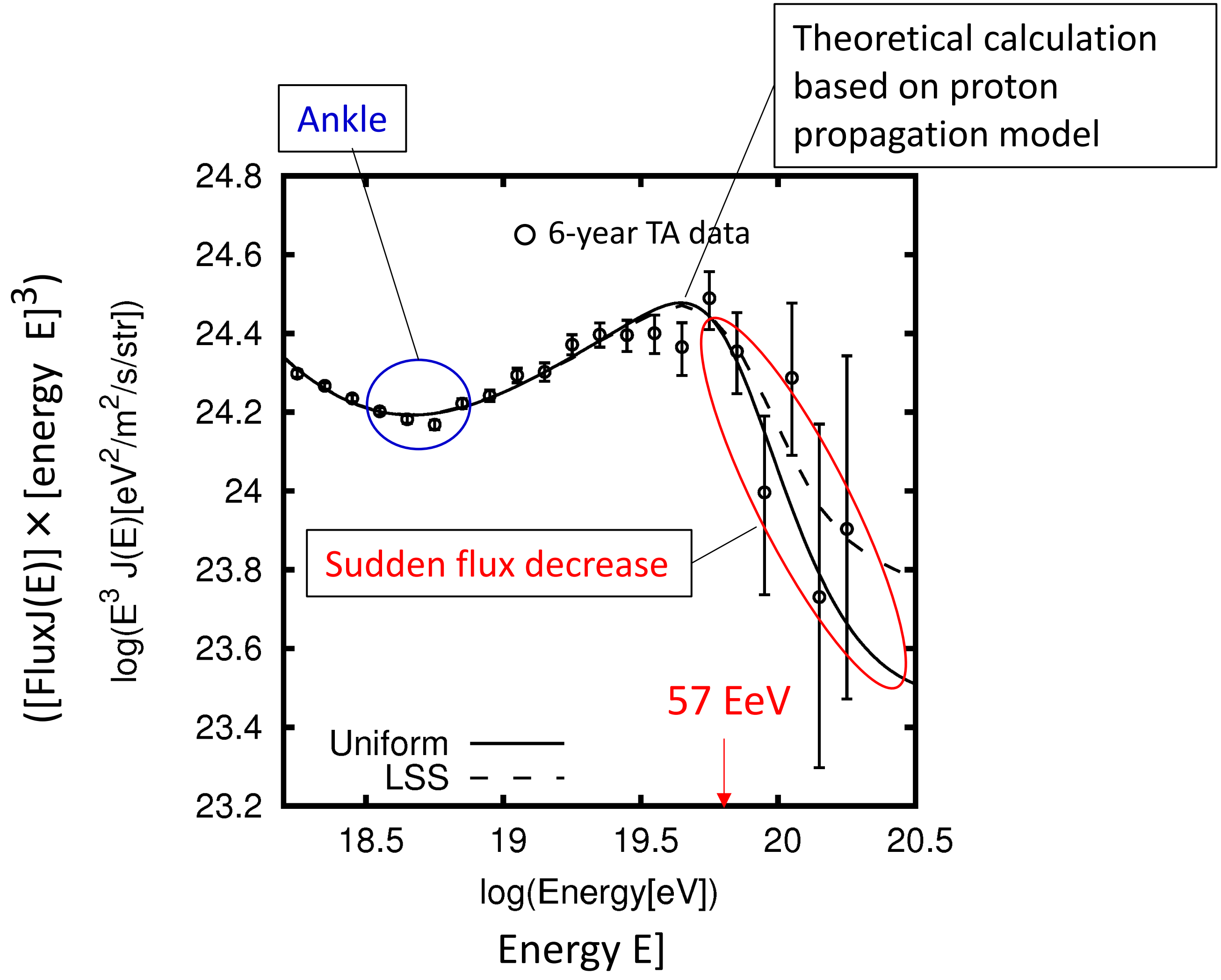
  v = H0 x r (Hubble's law)

  - v : receding velocity of a galaxy
  - r : distance from the earth
  - H_0 : Hubble constant
    - H_0=540km/sec/Mpc measured at that time
    - H_0= 71km/sec/Mpc by the recent data

Energy spectrum at around knee and 2nd knee by my experiment (TA)



TA energy spectrum at highest energy region

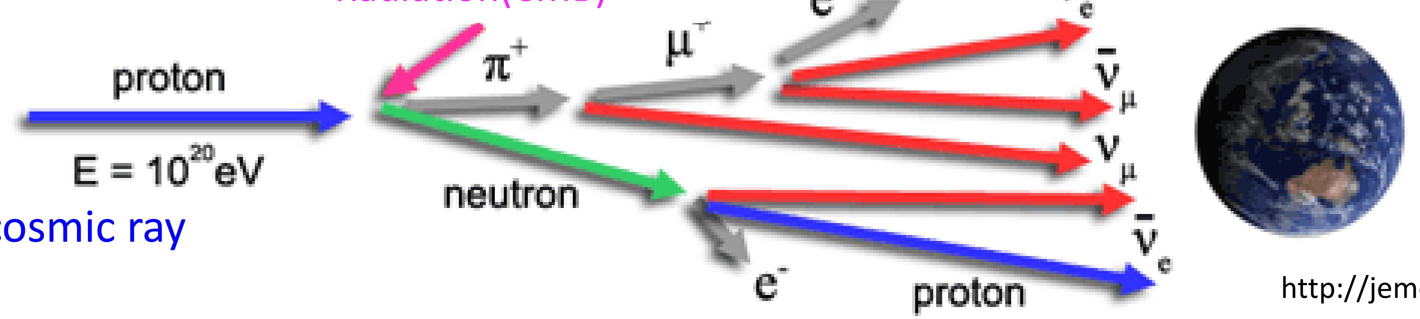


1 EeV = 10^{18}eV

GZK cutoff
(interaction of highest energy cosmic rays with cosmic microwave background photon)

- Greizen (G), Zatsepin (Z) Kuzmin (K) proposed in 1966
- According to special theory of relativity,
- (proton) cosmic rays of around 10^{20} eV, which come far beyond about 0.15 billion light years, interact with cosmic microwave background photon and lose energy rapidly, and cannot arrive at the earth

Cosmic Background Radiation(CMB)



Highest-E cosmic ray

http://jemeuso.riken.jp

(Size of Universe: ~14000 million light years)

Birth of the Universe

Big Bang

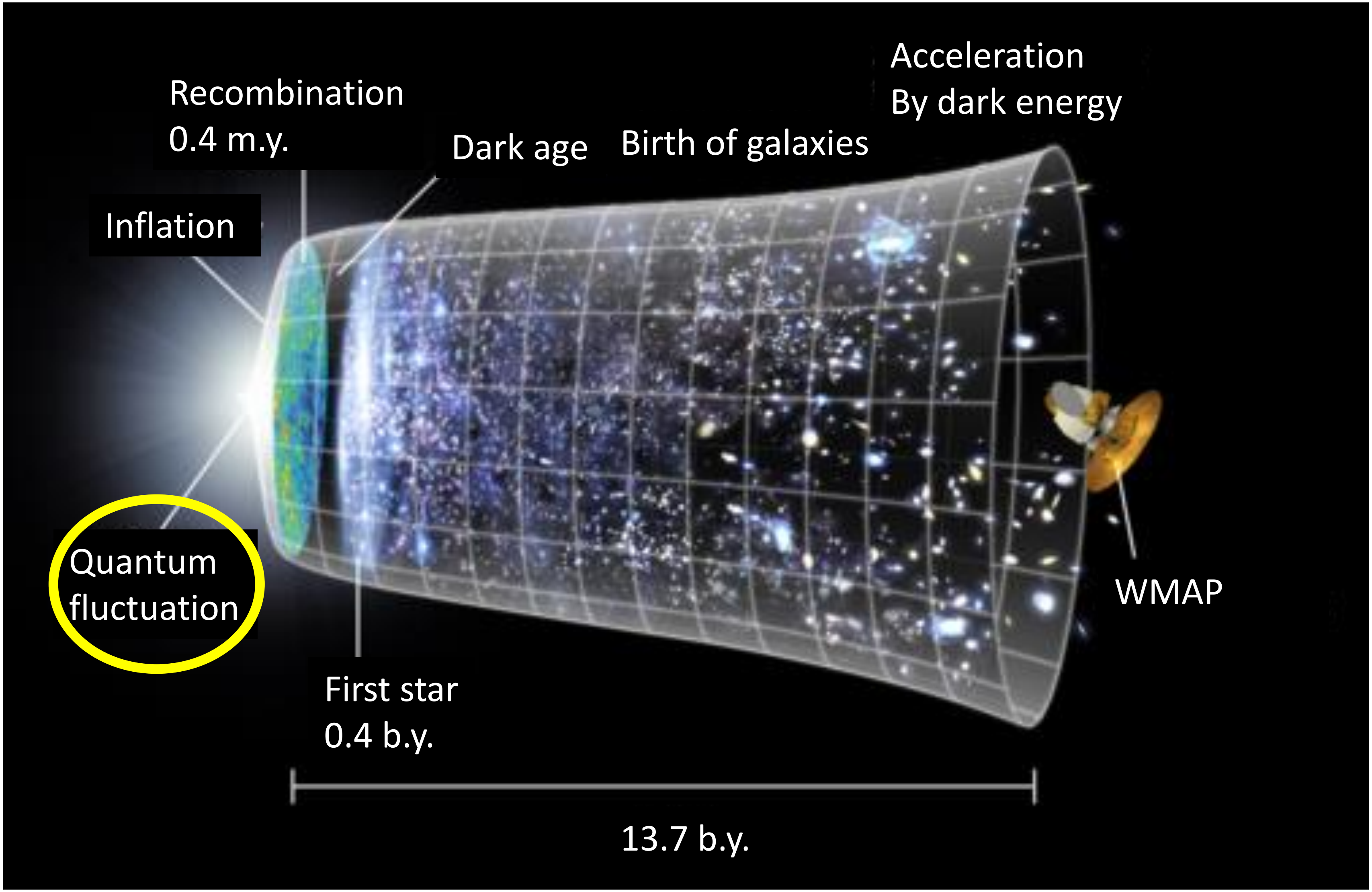
- 1948: George Gamov
  - The ancient universe was extremely denser and of higher temperature than now, and started cosmic expansion (fire-ball universe, Big bang universe)
  - The universe expanded and cooled down
    - The temperature of the universe is a few Kelvin now
  - Cosmic microwave backgrounds arrive uniformly from the sky

Inflation cosmology

- 1981: K. Sato and A.H.Guth (independently)
  - The universe performed extremely sudden expansion (inflation)
    - Phase transition from high-energy vacuum to low-energy vacuum that occurred in $10^{-36} \sim 10^{-34}$ sec after the birth of the universe
    - Emitted energy created a large amount of electromagnetic waves and particles

⇨ scorching universe

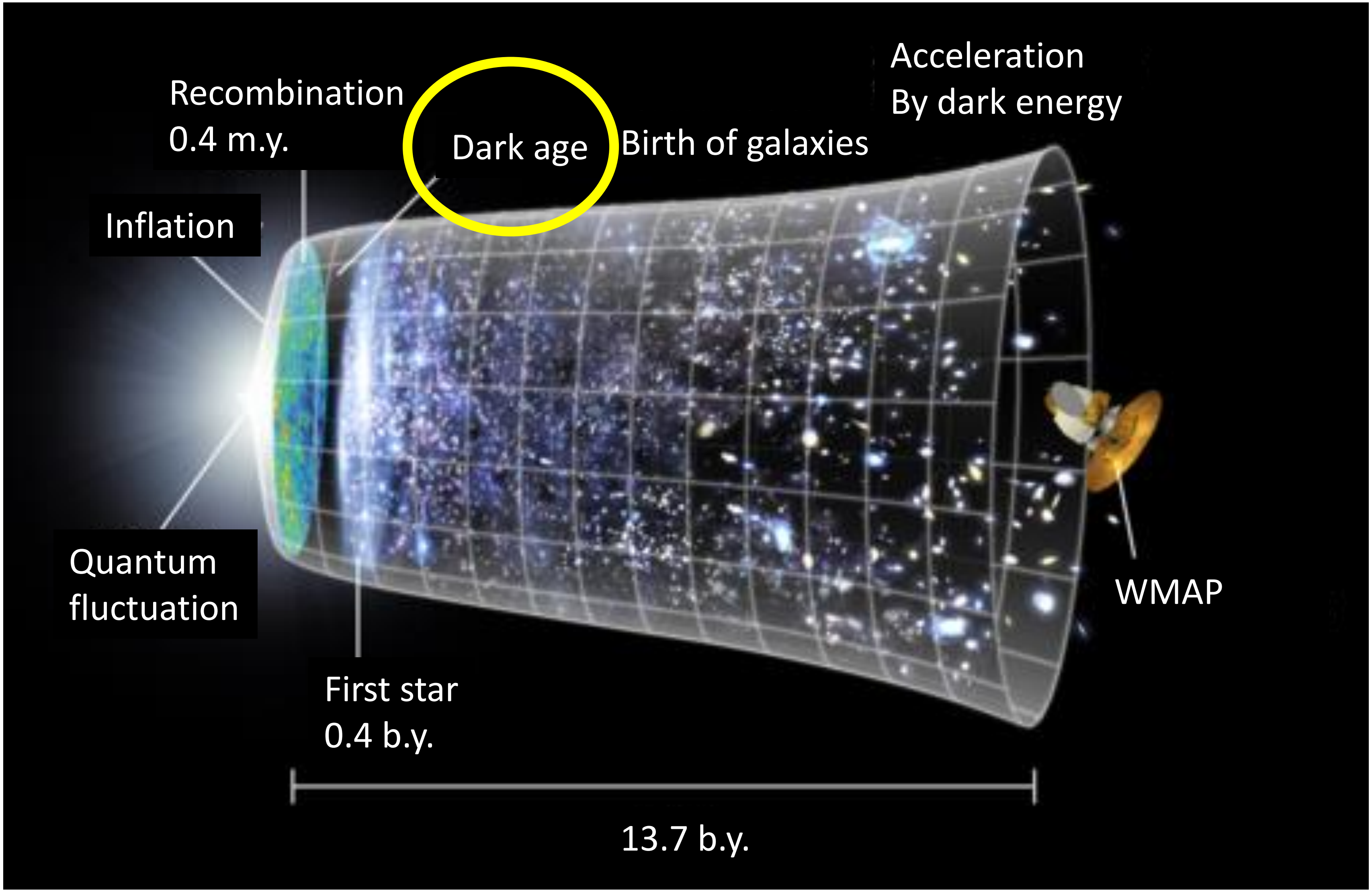
Birth and evolution of the universe



quantum fluctuation

- Quantum fluctuation in a small region at the birth of the universe
- The fluctuation was expanded by inflation
- This became the seed of large-scale structure of the universe

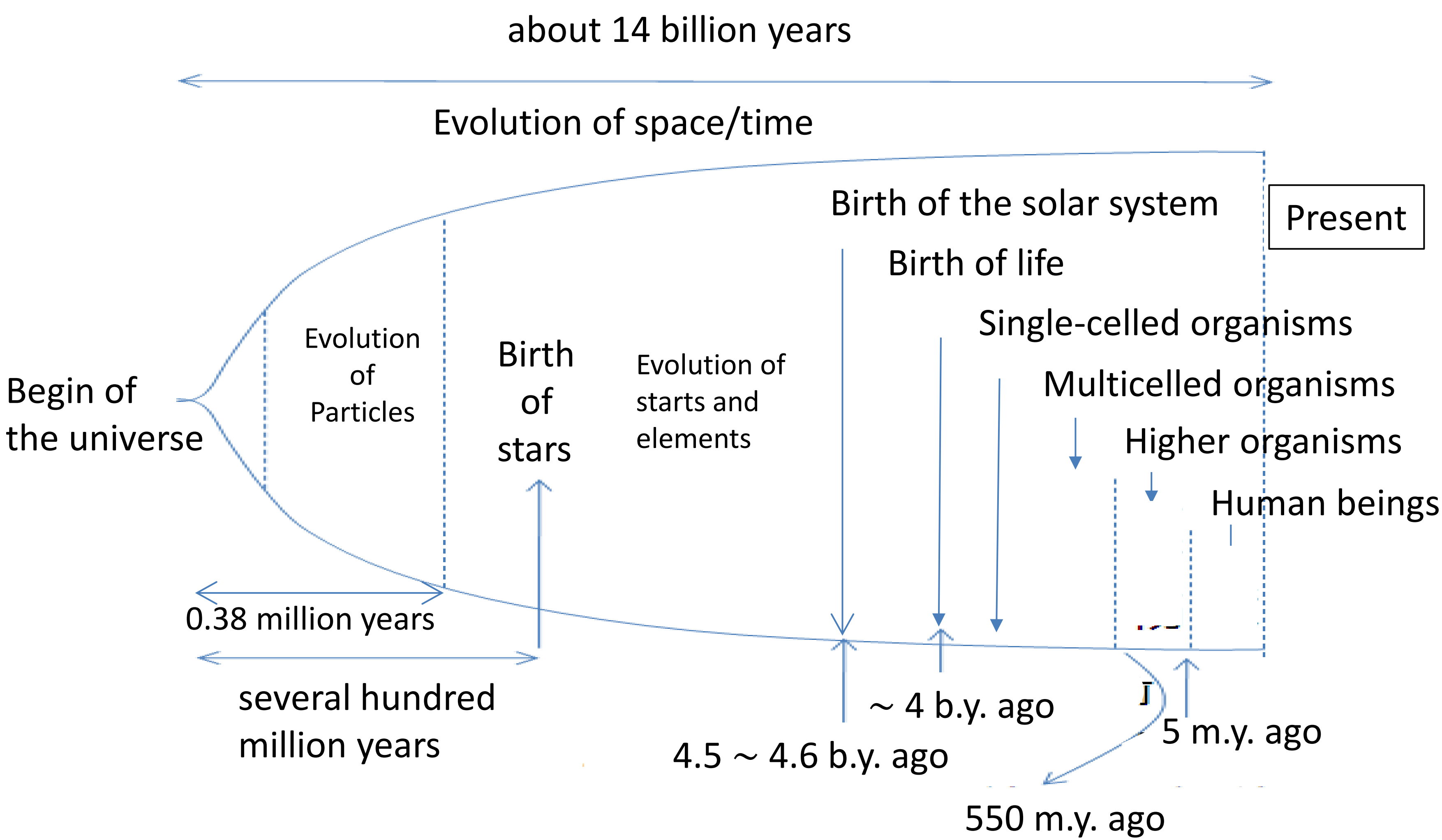
Birth and evolution of the universe



Dark age of the universe

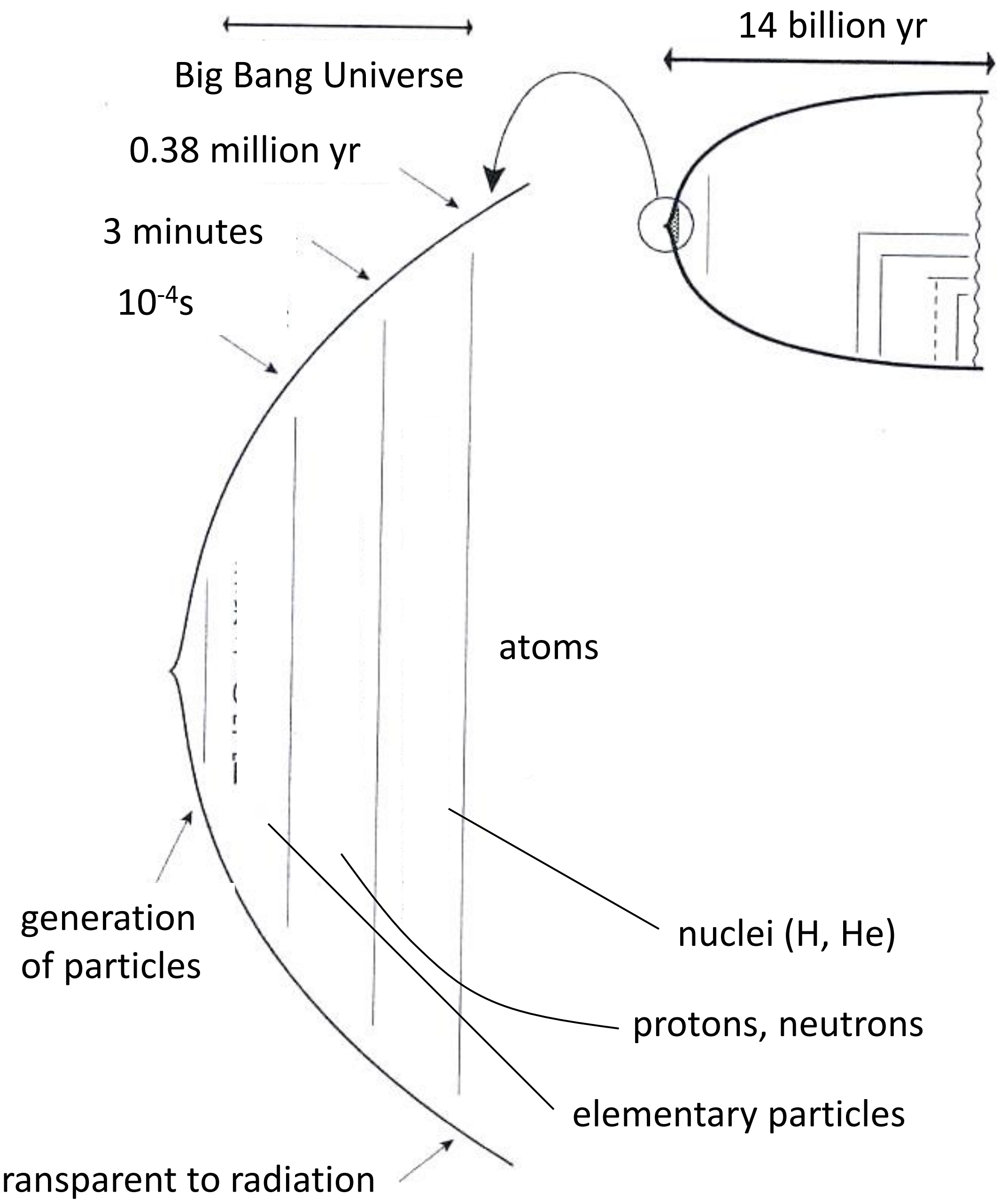
- 0.38 million years to 0.7 ~ 0.8 billion years from the birth of the universe
- Stars have not yet been formed

From the birth of the Universe to the present



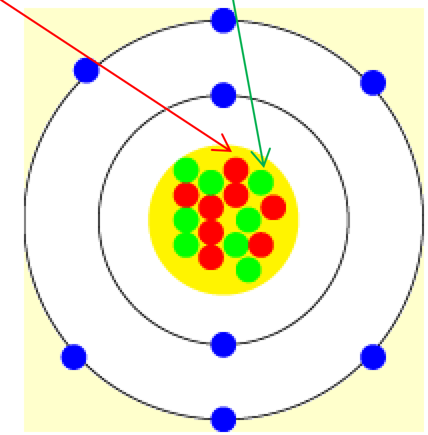
Generation of particles

Formation of particles



Elementary particles

- All of matter are broken into pieces under the condition of super-high temperature and super-high density
- An atom consists of a nucleus and electrons
- A nucleus consists of protons and neutrons



discovery

・electron (1897)

・proton (1907)

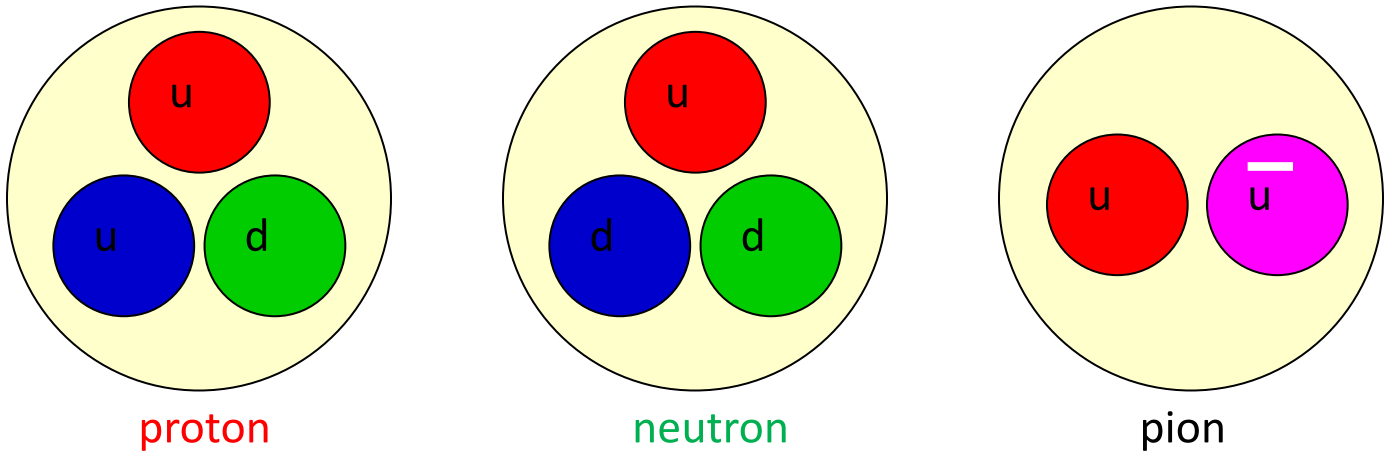
・nucleus (1908)

- Rutherford scattering

・neutron (1932)

Elementary particle – quarks

- Quarks are the elements that make hadrons such as protons, neutrons, pions



Leptons and quarks

- Electrons belong to lepton category
- Leptons are the group of elementary particles that do not undergo strong interaction
- Quarks and leptons

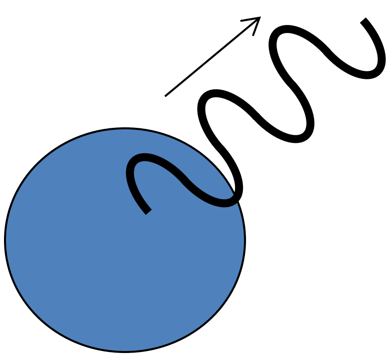
		1st generation	2nd generation	3rd generation
	quark	u, d	s, c	b, t
lepton	electron-type	e (1897)	μ (1937)	τ (1975)
	neutrino-type	ν_e (1956)	ν_μ (1962)	ν_τ (2000)

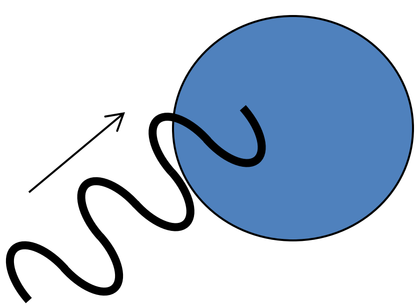
antiparticle

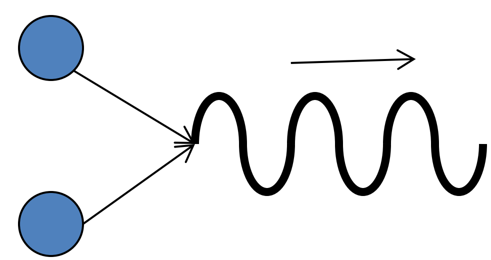
- Most of particles have antiparticles that have almost the same mass and opposite characteristics such as charge
  - 1932: discovery of positrons
  - 1955: discovery of antiprotons
- When there is enough energy, particles and antiparticles are generated

photons

- A photon is a quantum of electromagnetic interaction
  - Electromagnetic waves (radio, light, X ray)
- Light quantum was introduced by A.Einstein in 1905
  - Nobel Prize in 1921
- Important phenomena
  - Photons are generated from matter
  - Photons are absorbed in matter
  - A particle and its antiparticle are annihilated and a photon is generated







Particles

History of radiation and elementary particles

Discovery of radiation and elementary particles

- 1896: radiation
- 1897: electron
- 1907: proton
- 1912: cosmic ray
- 1932: positron
- 1932: neutron
- 1937: muon
- 1938: nuclear fission of Uranium
- 1947: pion
- 1967: quark model

- 1927: primitive atom by Lemaitre
- 1948: Big Bang theory by G. Gamov

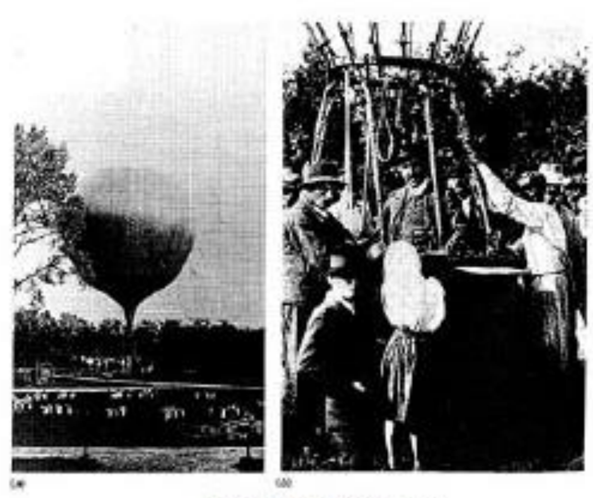
Discovery of radiation

biggest discoveries in 19 century

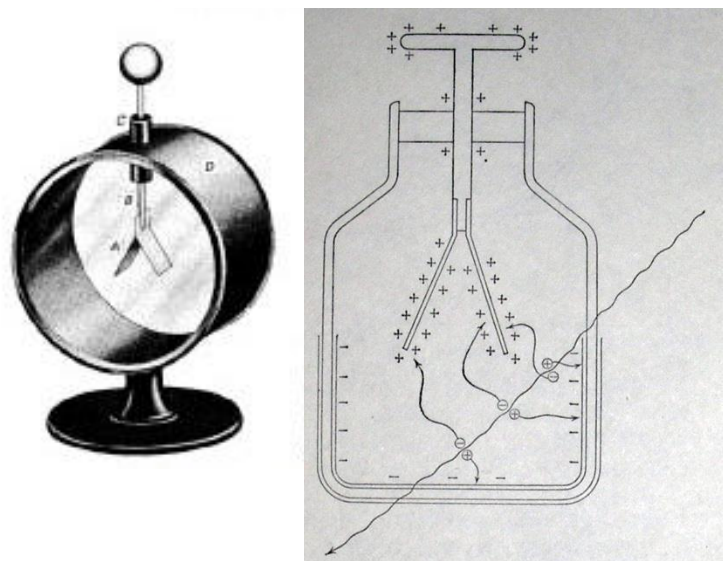
- X ray in 1895 (Nobel Prize in 1901)
- Natural radiation in 1896 (Nobel Prize in 1903)
- Radium in 1898 (Nobel Prize in 1903)

Discovery of cosmic rays by Hess

balloon



electroscope



How could Hess discover cosmic rays using the above?

Discovery of cosmic rays

- V.F.Hess repeated the measurement of radiation using a balloon and found radiation coming from outside the earth in 1912
  - First he thought that something “invisible” that neutralized an electroscope with gold-leaves was radiation from rocks
  - However, he found that its intensity increased when he went up in the sky → He found that this radiation came from outside the earth (the universe)
- Nobel Prize in 1936

Evolution of particles

Birth of the universe

Quarks & electrons

10^{-6}~10^{-5}s

Combination of 3 quarks (2 trillion K [10^{12}K]) strong interaction

protons, neutrons, electrons

3 minutes later

Nuclei from protons and neutrons (10 billion K)

mainly $^4He^{++}$

nuclei

380 thousand years later

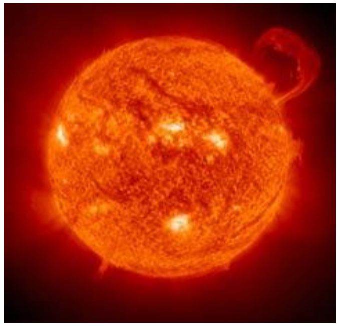
$p + e^- \rightarrow H$ (3000K) electromagnetic interaction

and $^4He^{++} + 2e^- \rightarrow {}^4He$

atoms

The universe transparent to radiation

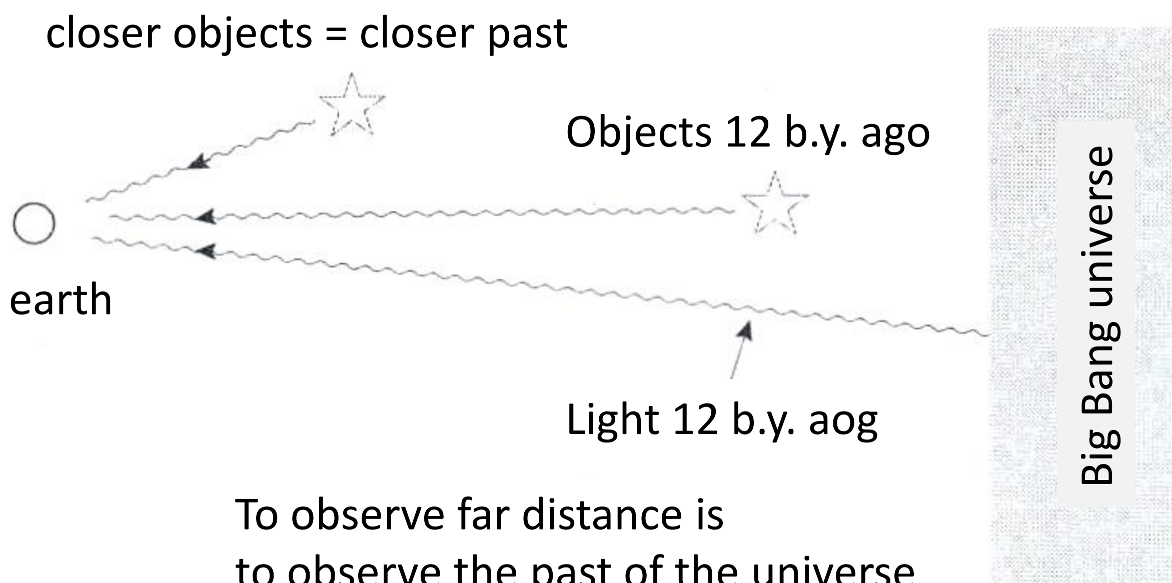
- The universe consisted of electrically neutral atoms
- Electromagnetic waves of wavelengths longer than atomic size could pass through without being disturbed by atoms
- Change in temperature of the universe
  - $(14 \text{ billion years}/380 \text{ thousand years})^{2/3} \sim 1000$
  - Change in temperature: 1/1000
  - 3000K (380 thousand years after the birth of the universe)→3K (the present, after 14 billion years)



~6000K
(Sun)

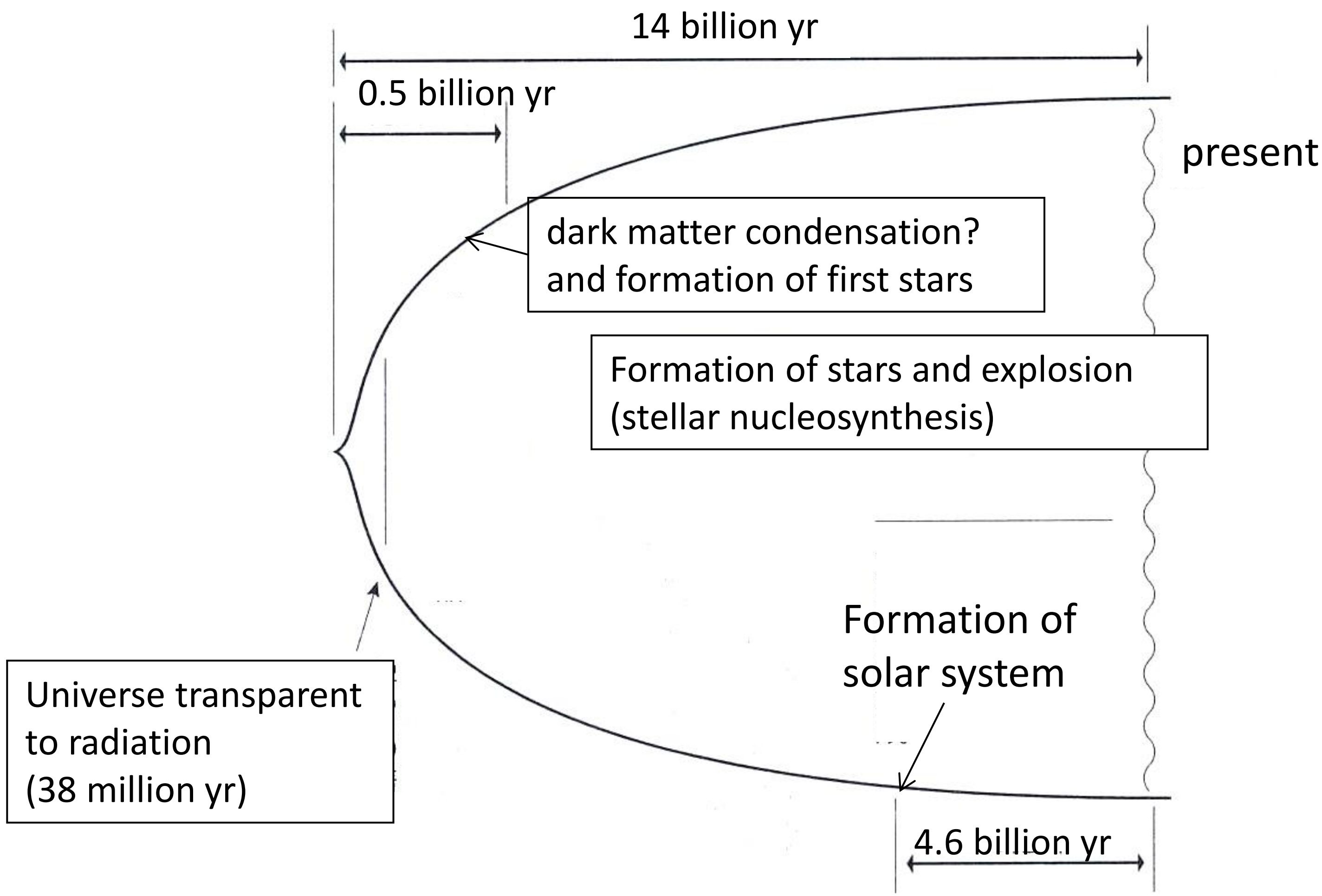
Cosmic Microwave Background (CMB) radiation

- 1965: A.Penzias and R.Wison discovered cosmic microwave background (Nobel Prize in 1978)
  - They tried to remove noise from the horn-type antenna, but failed
  - They talked to their colleagues in theoretical division
  - They found it is the discovery to prove the Big Bang model
  - The noise was CMB radiation



To observe far distance is
to observe the past of the universe

Evolution of objects and elements



The first star formation

- The first generation of starts were generated about 0.5 billion years (*) after the birth of the universe
  - It was too fast that stars were generated in about 0.5 billion years because the universe is so uniform (**)
    - If fluctuation of particle density is similar, it may take more than 14 billion years to generate stars
    - (**) fluctuation of electromagnetic wave is 10^{-5} level

⇨ Dark matter

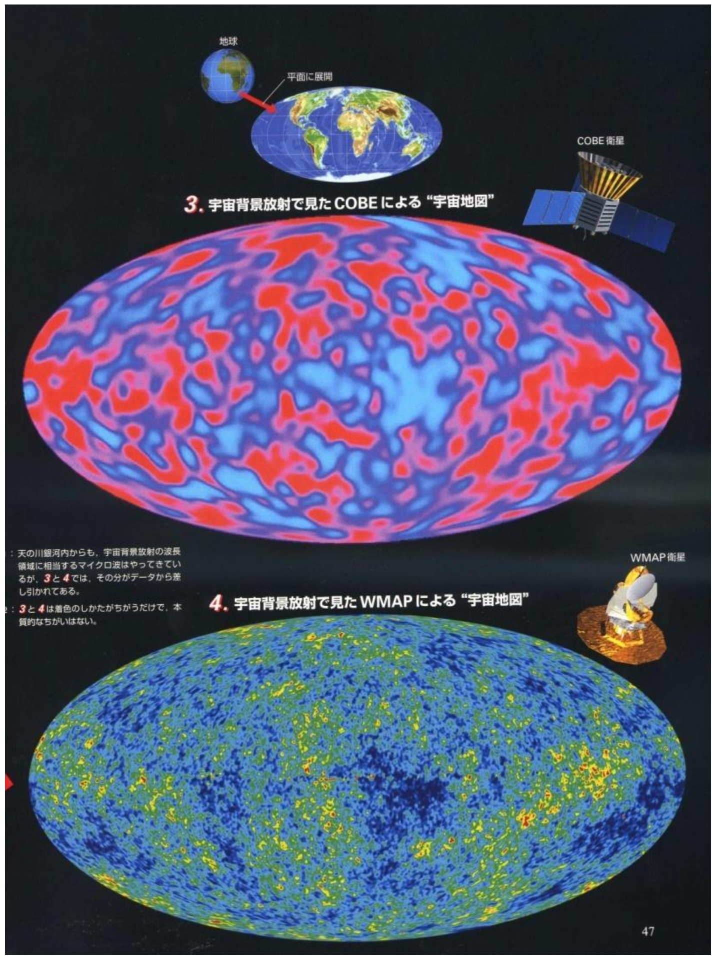
Map of the initial universe using CMB radiation

COBE

(1992)

WMAP

(2003)



Fluctuation of the intensity ~10^{-5}

Nobel Prize to G.F.Smoot in 2006

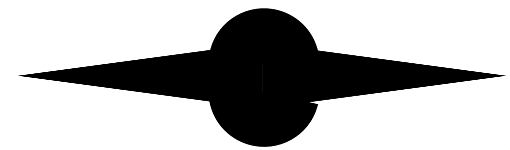
Dark matter

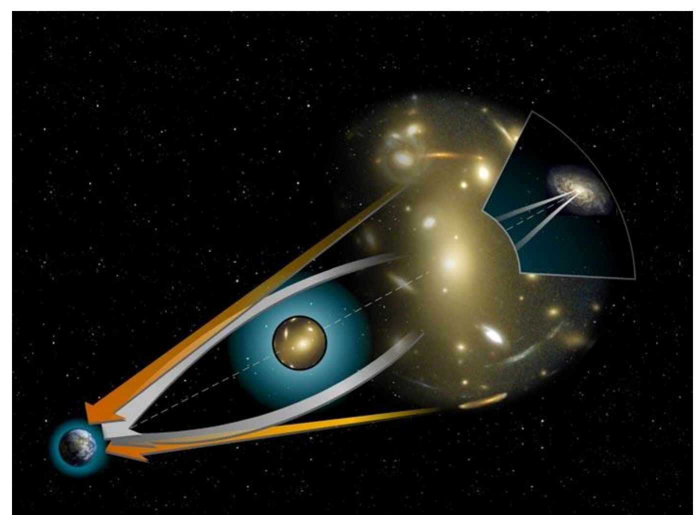
- A large amount of unidentified matter (dark matter) is necessary to explain too fast star formation
  - Invisible → matter that does not interact with light?
- Condensation of dark matter → high density
- H and He are attracted by gravity → high density
- Condensation of atoms → star formation

Dark matter

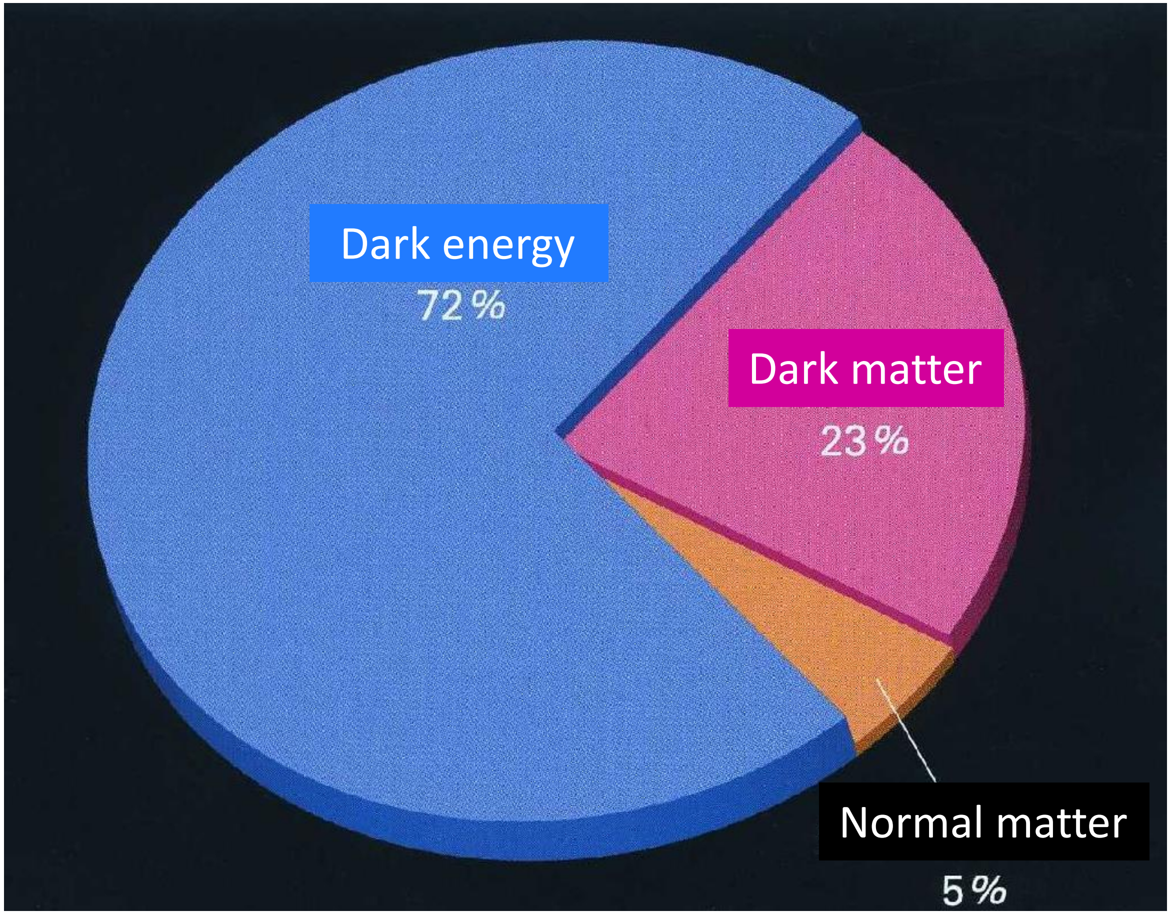
- Other supporting evidence
  - To explain fast rotation of outer edge of our galaxy
    - Matter 10 times larger than the visible amount is necessary
  - Gravitational lens effect
    - Illusion of objects
    - Deflection of objects
    - Splitting of objects

Dark matter

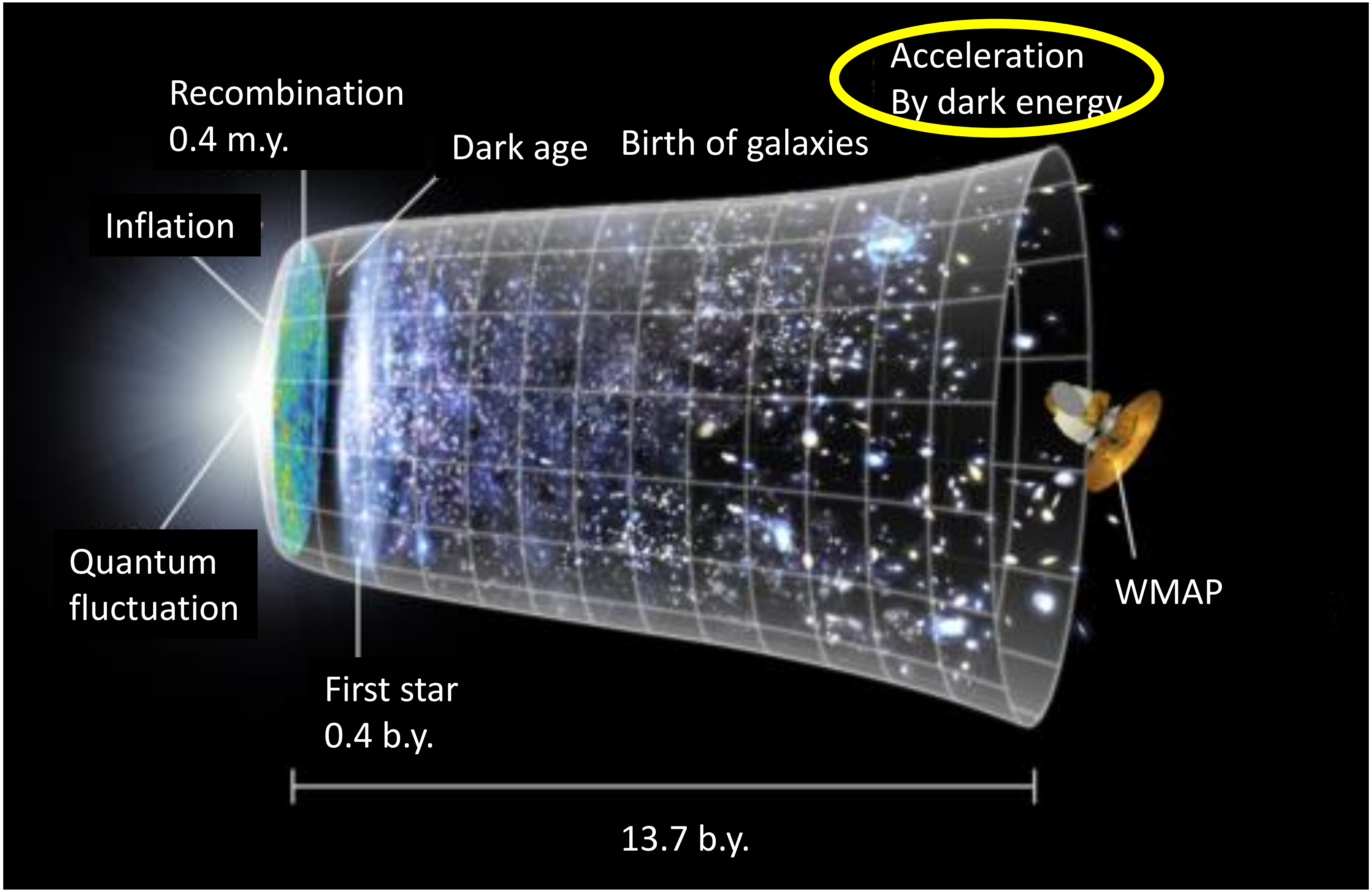




The 95% of the universe is unknown



Birth and evolution of the universe



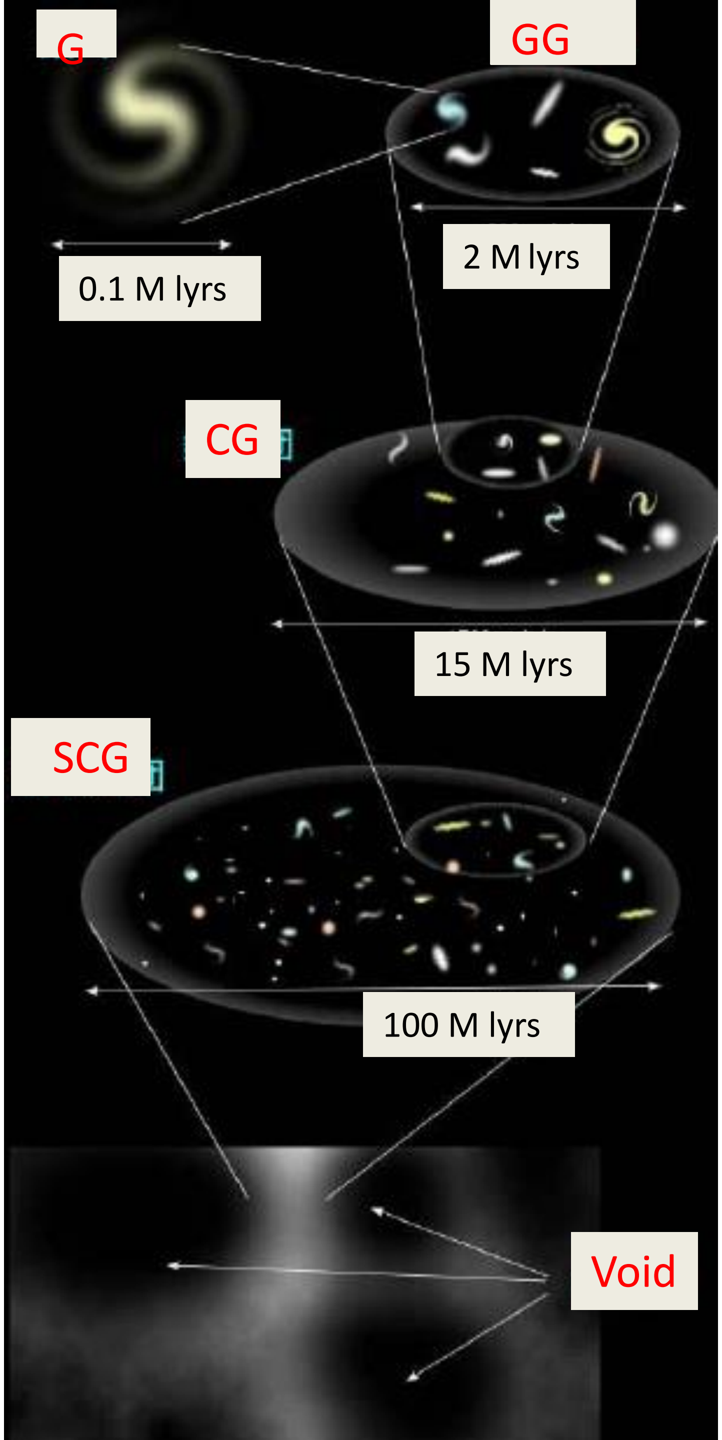
Dark energy

- It was thought that the speed of the expansion of the universe has been decreasing
- However, it was found that the speed of the expansion of the universe is accelerating
  - The measurement of the speed of galaxies using Doppler effect in 1998

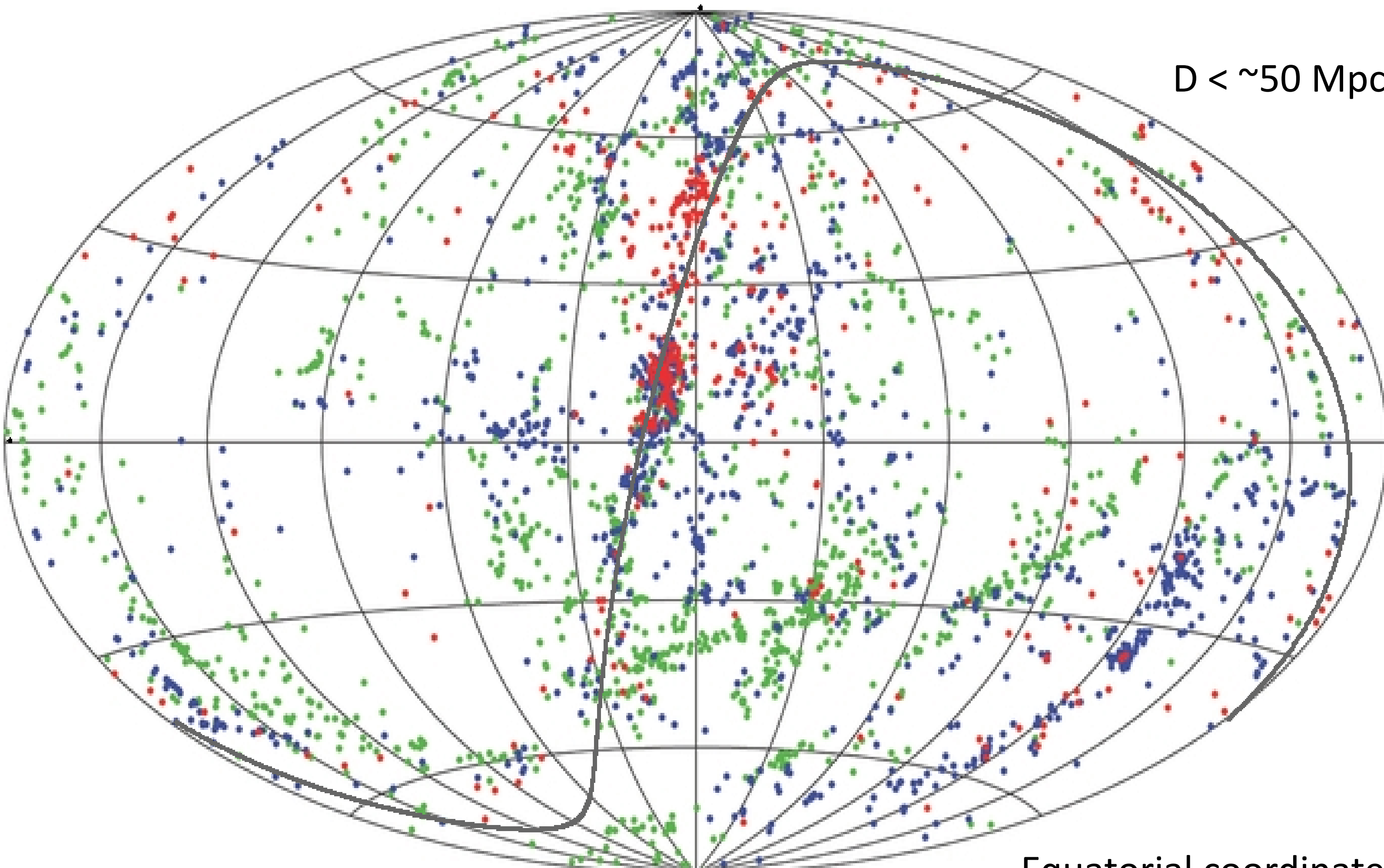
⇨ The universe is full of dark energy

Astronomical distance

- galaxy (G)
- Galaxy Group (GG)
  - 3~some ten galaxies
- Cluster of Galaxies (CG)
  - some~some ten GGs
- Super Cluster of Galaxies (SCG)
  - multiple CGs
- Large scale structure of the universe (LSS)
  - SCGs+Voids



Distribution of nearby galaxies

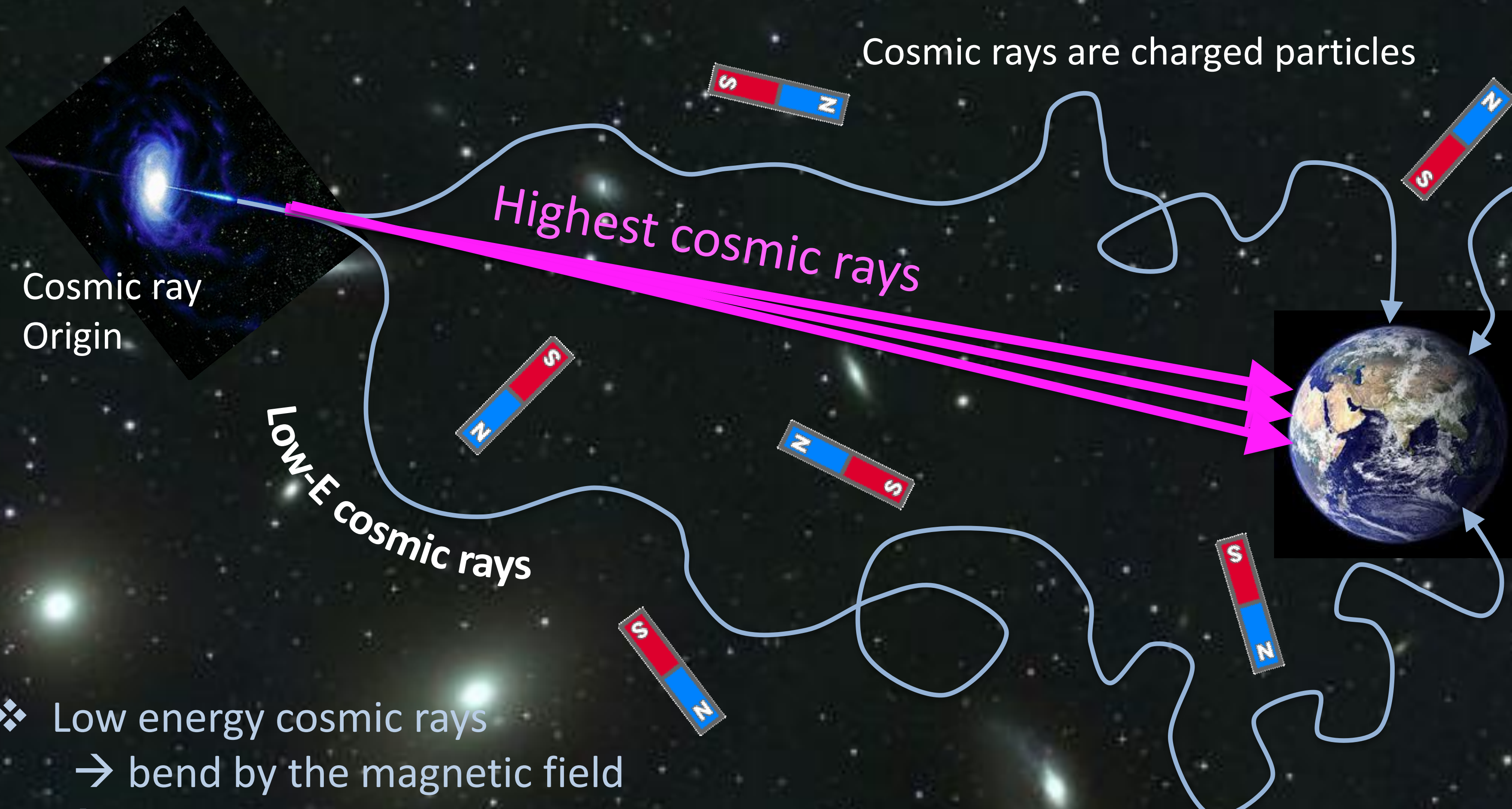


Extremely anisotropic

GZK cutoff and anisotropic matter distribution

- GZK cutoff
  - Sources of highest energy cosmic rays are restricted to nearby objects
- Anisotropic matter distribution
  - The sources can be anisotropic
- The distribution of arrival directions of highest energy cosmic rays can be anisotropic

Why highest energy cosmic rays?



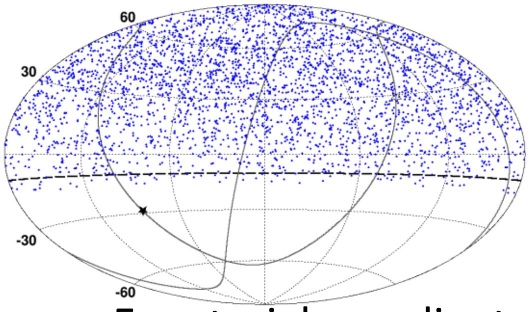
- Low energy cosmic rays
  → bend by the magnetic field
  → Isotropy at the Earth
- Highest energy cosmic rays
  → Almost go straight against magnetic field
  → Possible to find cosmic-ray hotspot

However,

- Measured anisotropy of arrival low energy (~TeV) cosmic rays was 0.1% level.
- Even for the cosmic rays of $\sim 10^{19}$ eV measured by TA (our experiment) is the distribution is isotropic

E > 10^{19}eV (10EeV)

3316 events

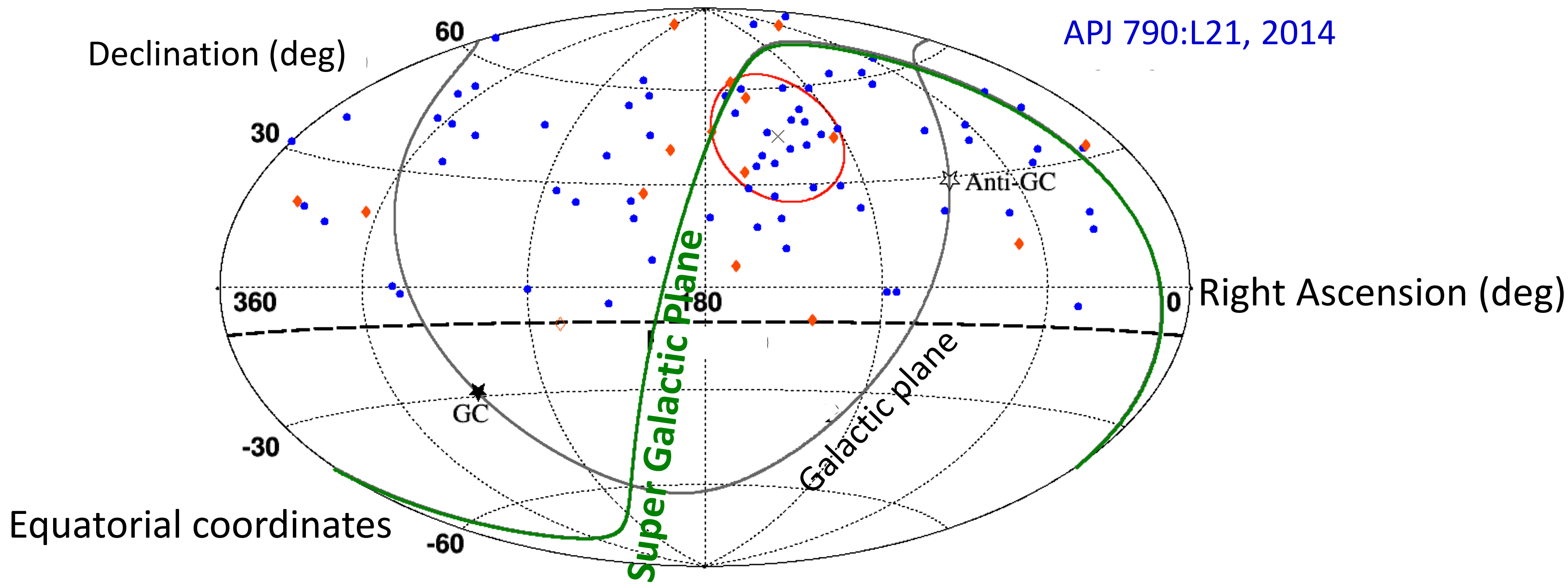


Equatorial coordinates

Distribution of arrival directions of highest energy cosmic rays

- 6-year TA data
- 87 events above 57 EeV (above cutoff)

blue : July, 2014
Press Release
APJ 790:L21, 2014

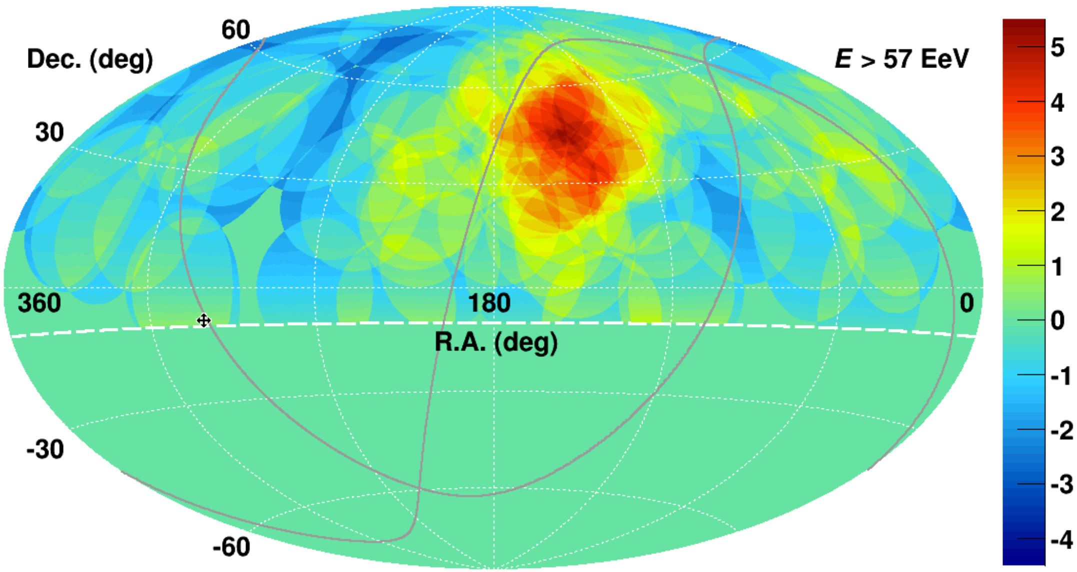


- In the red circle of 20-degree radius
  - Expectation of isotropy : 5.5 events
  - Observation : 23

23/5.5 ~400% flux excess

Anisotropy of arrival direction of highest energy cosmic rays
Hotspot

20-degree radius oversampling



Significance

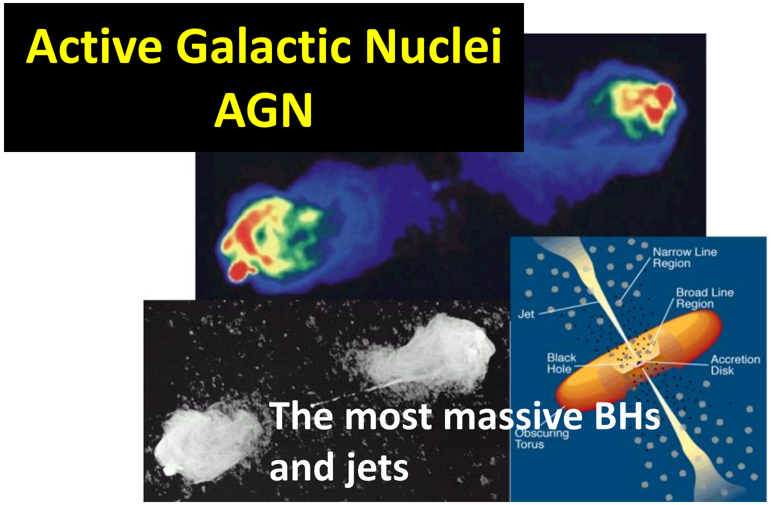
5.55σ

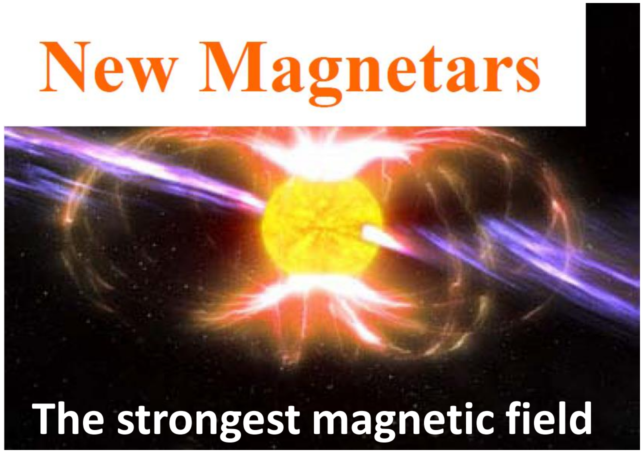
We found first highest Significance for anisotropy

- The probability to obtain maximum significance which exceeds 5.55σ is 10^{-5} (4σ)

Frontier of anisotropy using highest-energy cosmic rays

UHE accelerators in the universe
(Candidates of highest-energy CR origin)

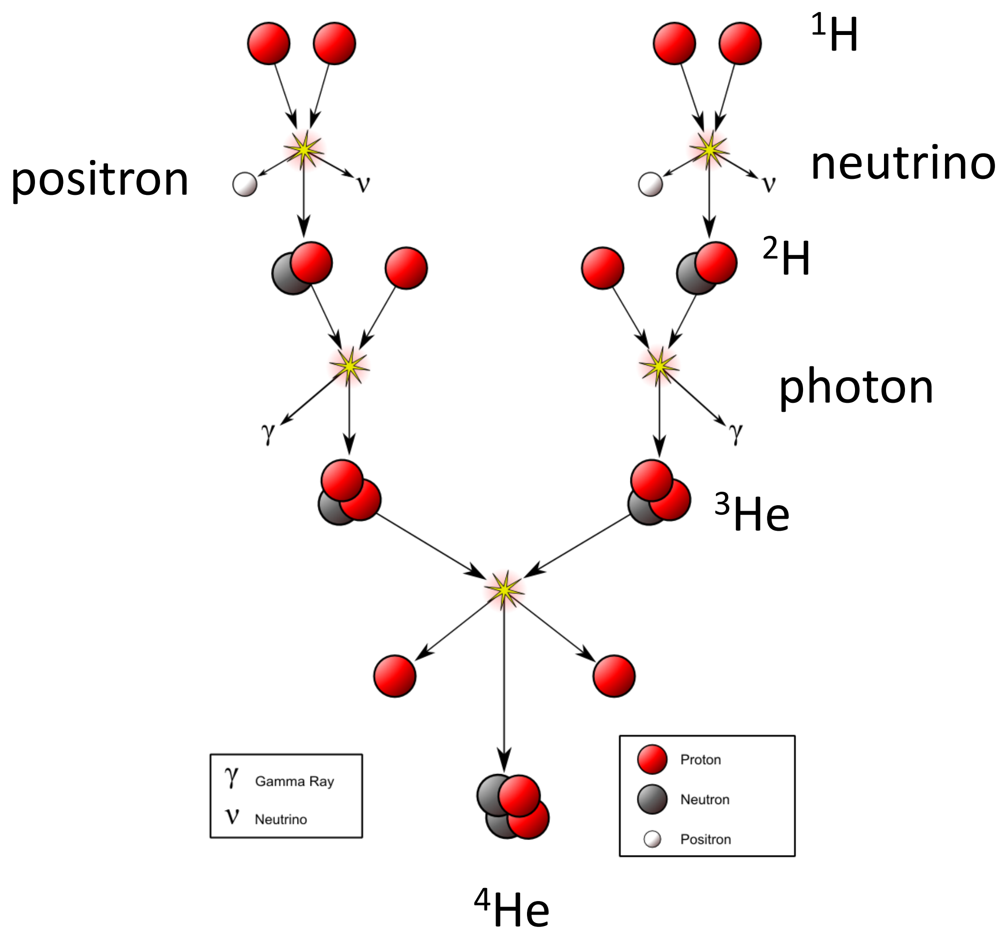




Birth of stars

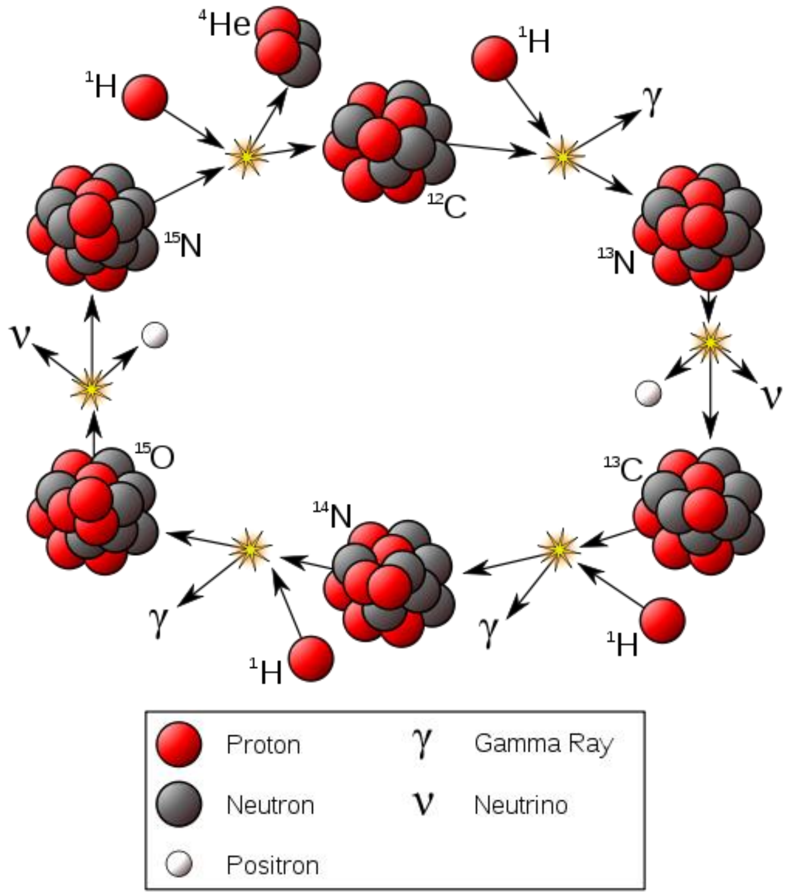
Star burning (I)

- Nuclear interaction
  - pp chain



Star burning (II)

- CNO cycle
  (20 million Kelvin)
  - One of nuclear interactions by which hydrogens are converted to helium



Star burning (III)

- ^{4}He is heavy → ^{4}He are condensed in the center → triple-alpha reaction

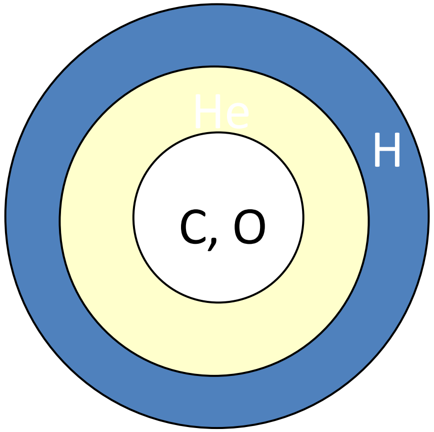
$$^{4}He + ^{4}He \rightarrow ^{8}Be$$
$$^{8}Be + ^{4}He \rightarrow ^{12}C + \gamma$$

(about 0.1 billion Kelvin)

- Then

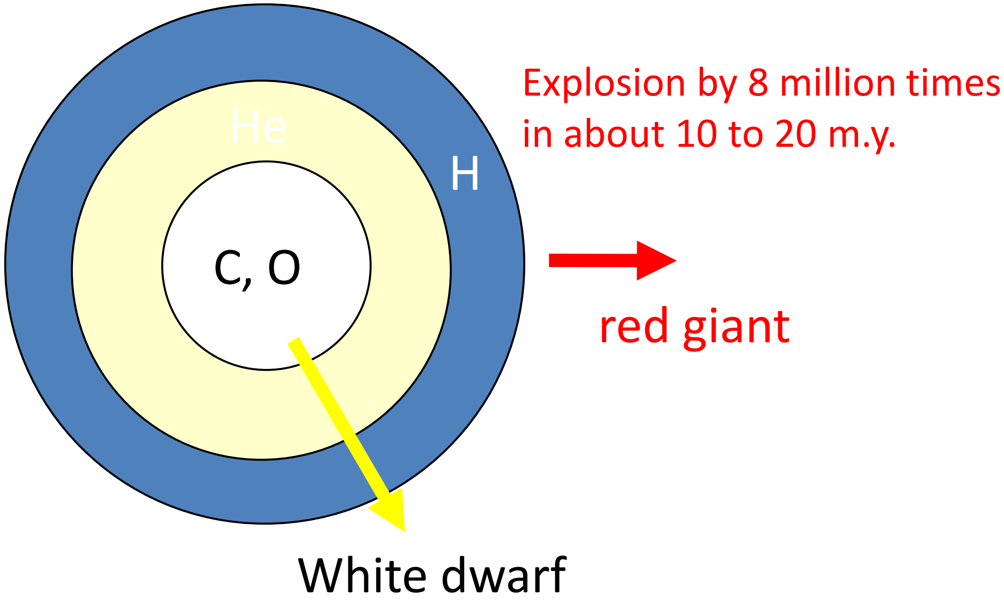
$$^{12}C + ^{4}He \rightarrow ^{16}O + \gamma$$

- Finally irons (Fe) are generated
  - Iron is a nucleus that has the strongest combination



Life of a star is decided by its weight (I)

- Light star
  - $M < 0.1M_{sun}$
    - do not burn
  - $M < 0.8M_{sun}$
    - Slow pp chain (14 b.y.)
- M ~ Msun
  - pp chain (10 b.y.)
  - Triple-alpha interaction
  - C and O generation



Life of a star is decided by its weight (II)

- $M > M_{sun}$
  - $M >$ some times of M_{sun}
    - CNO cycle
      - He synthesis end (50 m.y.)
    - Triple-alpha reaction
    - C, O generation
    - Red giant star
    - White dwarf

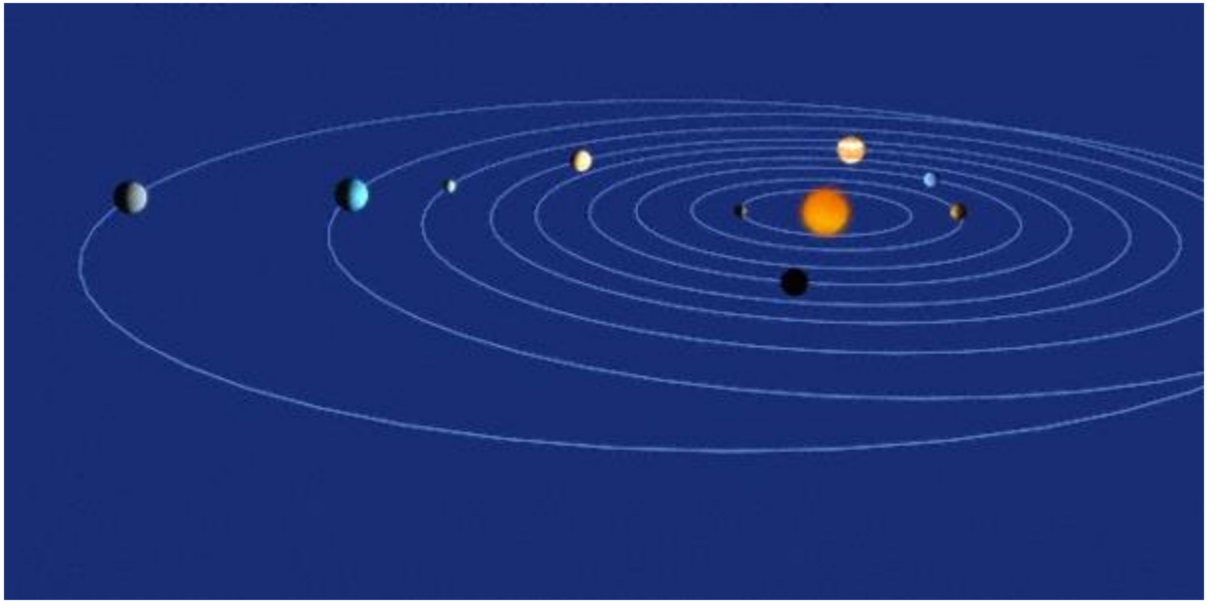
- $M > 10 \times M_{sun}$
  - C, O core size is large enough
  - Synthesis of heavier elements
    - Up to Ni, Co, Fe
  - Shrinkage by gravity
    - 10 billion Kelvin in the center

explosion

Ejection of elements

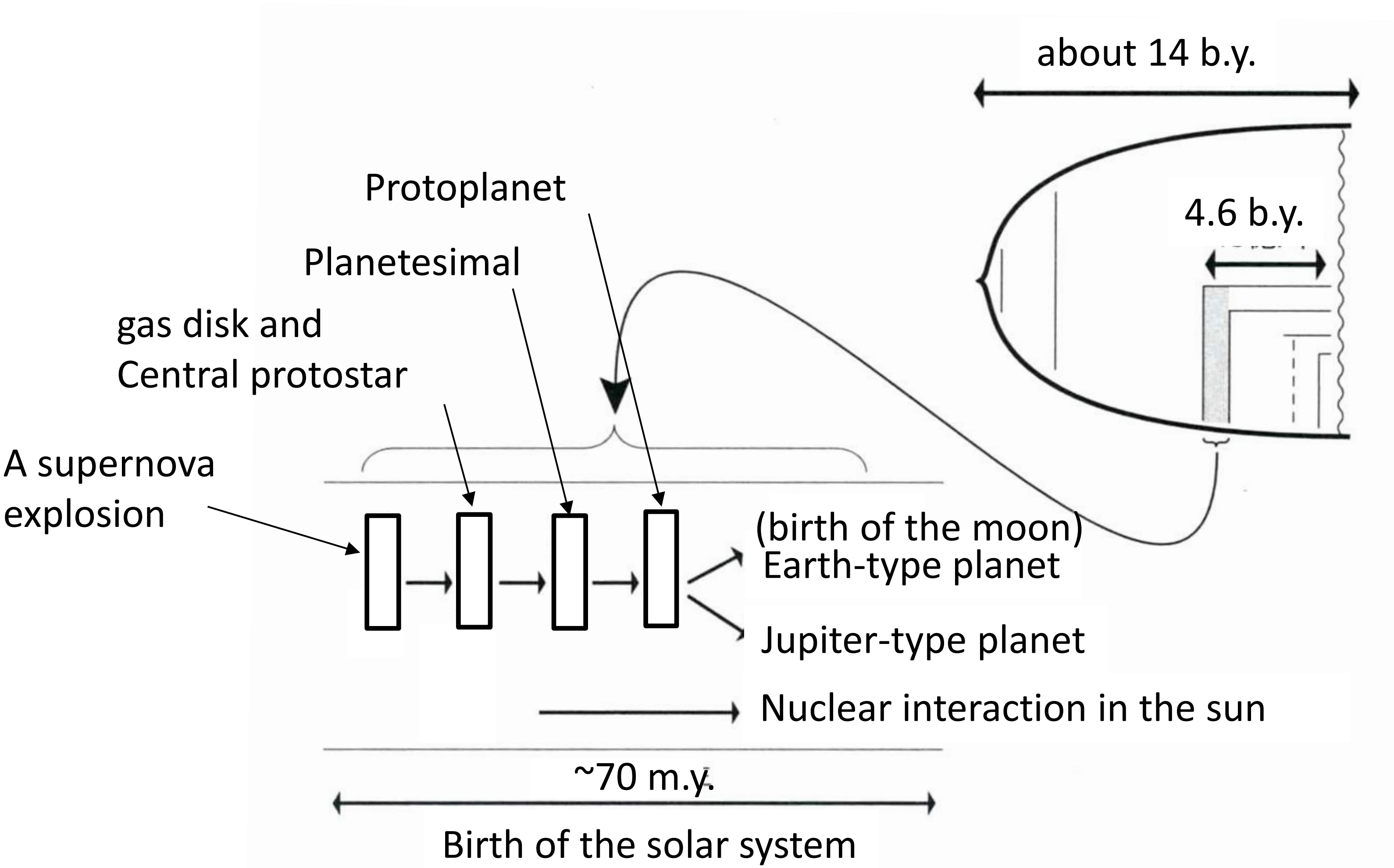
- Red giant
  - Carbon generated in helium layer → convection → unverse
  - In the gas layer
    - Neutrons＋heavy nuclei → heavier nuclei
      - Generation of elements heavier than iron?
- Supernova
  - Generation of a large amount of neutrons during explosion
    - Elements heavier than iron (gold, silver, uranium)

Birth of the solar system



Birth of the solar system

- A supernova caused an explosion 4.6 billion years ago?

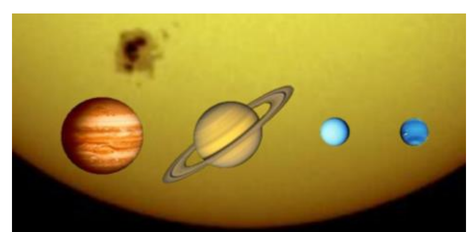


Towards the birth of the solar system

- The solar system consists of hydrogen, helium and heavier elements (about 2% of all)
  - Main composition was hydrogen and a small fraction of helium after the Big Bang
  - The following processes
    - Birth of a star
    - Star burning
    - Creation of heavier elements
    - Explosion of a star
    - Scattering of elements

Towards the birth of the solar system

- A supernova explosion
- Shrinkage of interstellar clouds
- Gas disk
  - A protostar in the center
  - The thickness of the disk shrinked
    - Planetesimal
    - Protoplanet ← planetesimas gathered
      - Earth-type planet
        - » rock
      - Jupiter-type planet
        - » Gas, ice

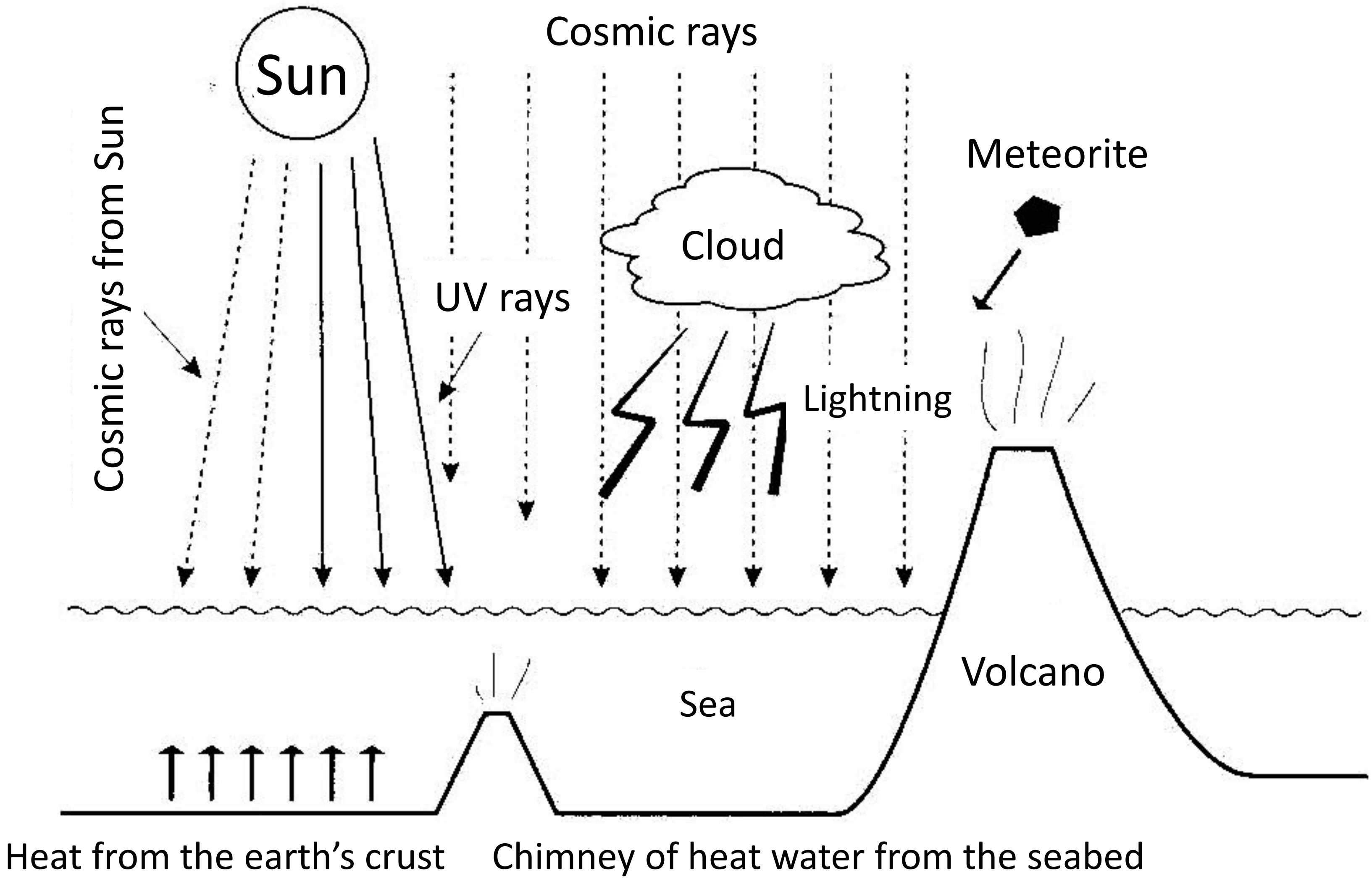


Sun

- It took about 100 million years to start nuclear reaction
  - The star shrank by gravitational force
  - Nuclear reaction started when the temperature in the center became 10 million K
- The planets have been formed in parallel

Birth and evolution of the Earth

Surface of the primitive earth



Birth of the earth and life

- Birth of the earth
  (4.55 billion years [b.y.] ago)
- Magma ocean (4.3 b.y. ago)
- Primitive sea (4 b.y. ago)
- The first land*
- Active volcano activity (2.7 b.y. ago)
- Geomagnetic field increase (2.7 b.y. ago)
- Supercontinents
  - The first (1.9 b.y. ago)
  - Rodinia (1 b.y. ago)
  - Gondwana (0.5-0.6 b.y. ago)
  - Pangaea (0.2 b.y. ago)
- present

- Birth of life (3.8 b.y. ago)
- Emergence of bacteria carrying out strong photosynthesis that generate oxygen (2.7 b.y. ago)
- Multicellular organism (1 b.y. ago)

Higher organism
evolution and extinction

- Paradise of Ediacara fauna (650 million years [m.y.] ago)
- Mass extinction at Precambrian end (570 m.y. ago)
  - The whole earth freezed?
- Explosive evolution in Cambrian Era (530 m.y. ago)
  - related to the formation of Gondwana supercontinent?
- Mass extinction at Ordovician Period end (460 m.y. ago)
  - Increase of water level due to warming?
- Mass extinction at Paleozoic Era end (incl. trilobites) (247 m.y. ago)
  - Lack of oxygen due to big volcano activity?

- Mass extinction at Mesozoic Era end (65 m.y. ago)
  - Extinction of dinosaurs
    - Due to the collision of a huge meteorite with the earth?

To the evolution of humans

- Diffusion of mammals
- Hominid (30 million years ago)
- Anthropoid ape
- Australopithecus (3～4 million years ago)
- Homogenus (2 million years ago)
  - Homo erectus
  - Homo sapiens (1 million years ago)
- Civilization   (5000 years ago)

End