The Universe
and
the Making of the Chemical Elements

Jan-Olov Liljenzin

Professior emeritus

Chalmers University of Technology

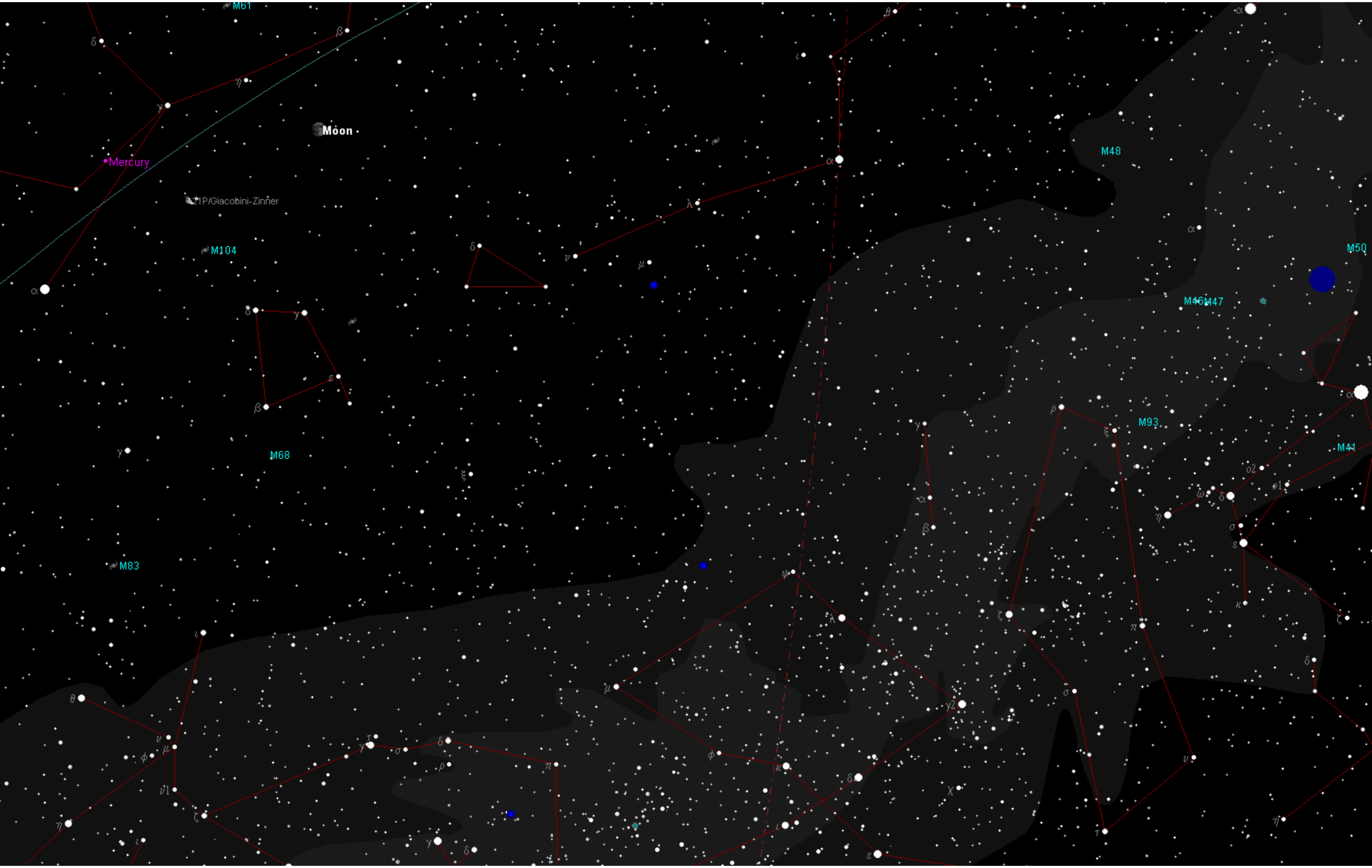
My presentation will mainly treat:

- stars and galaxies
- development of the Universe
- energy producktion in stars
- formation of the chemical elements

There is no ”renewable” energy in the Universe (only a green slogan)

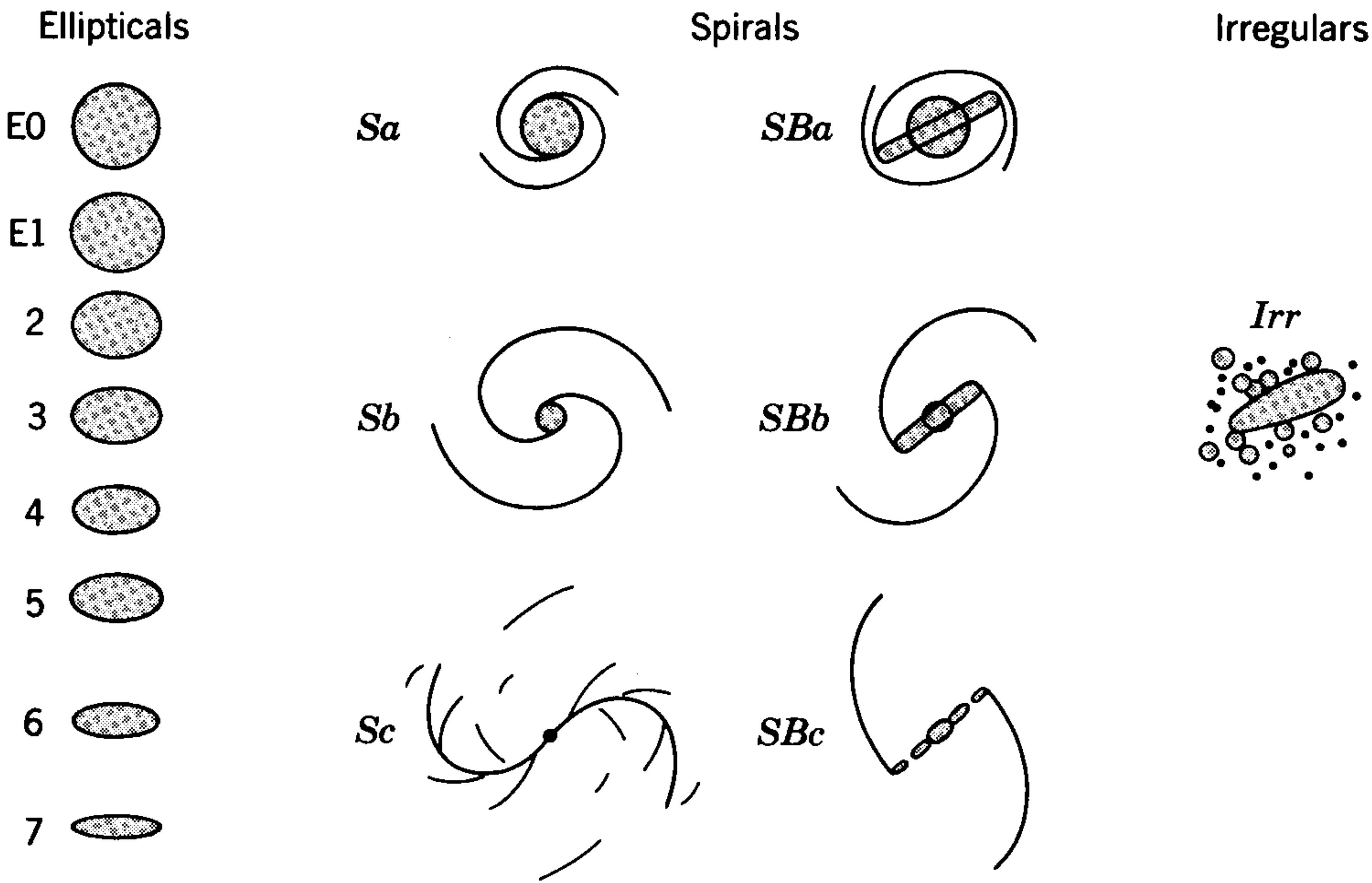
All energy in the Universe is generated by one of the following processes:

- Free fall in a gravity field (potential to kinetic energy conversion)
- Fusion of light nuclei to heavier nuclei, e.g. 4 ^{1}H to 1 ^{4}He
- Fission of a heavy nucleus into two lighter nuclei, e.g. ^{235}U fission
- Loss of matter into ”black holes”, i.e. matter is partly converted into radiation energy when it disappears
- General repulsion in the Universe by the action of quintessence (poorly understood phenomenon which counteracts gravity)

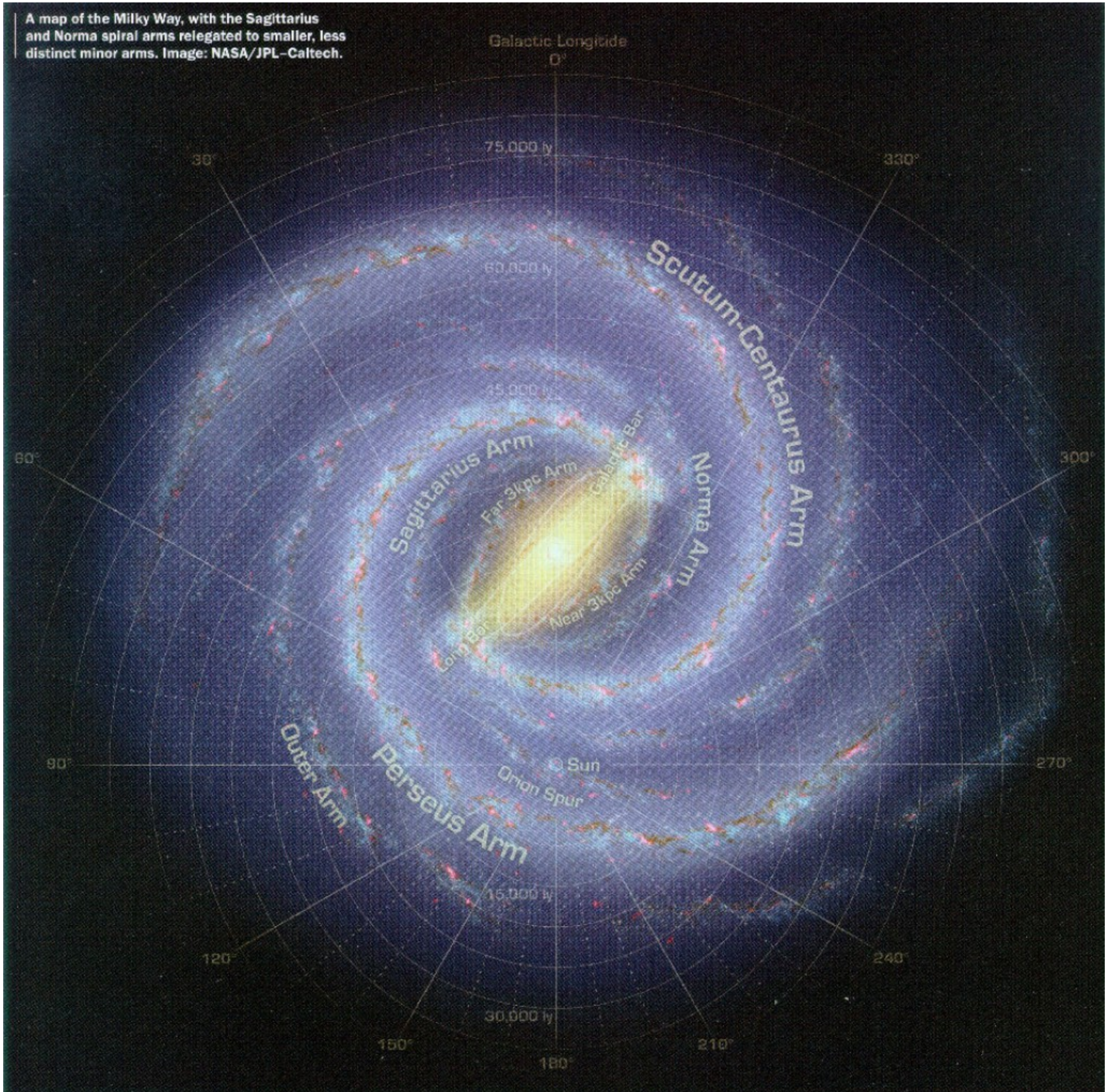


Example of the night sky

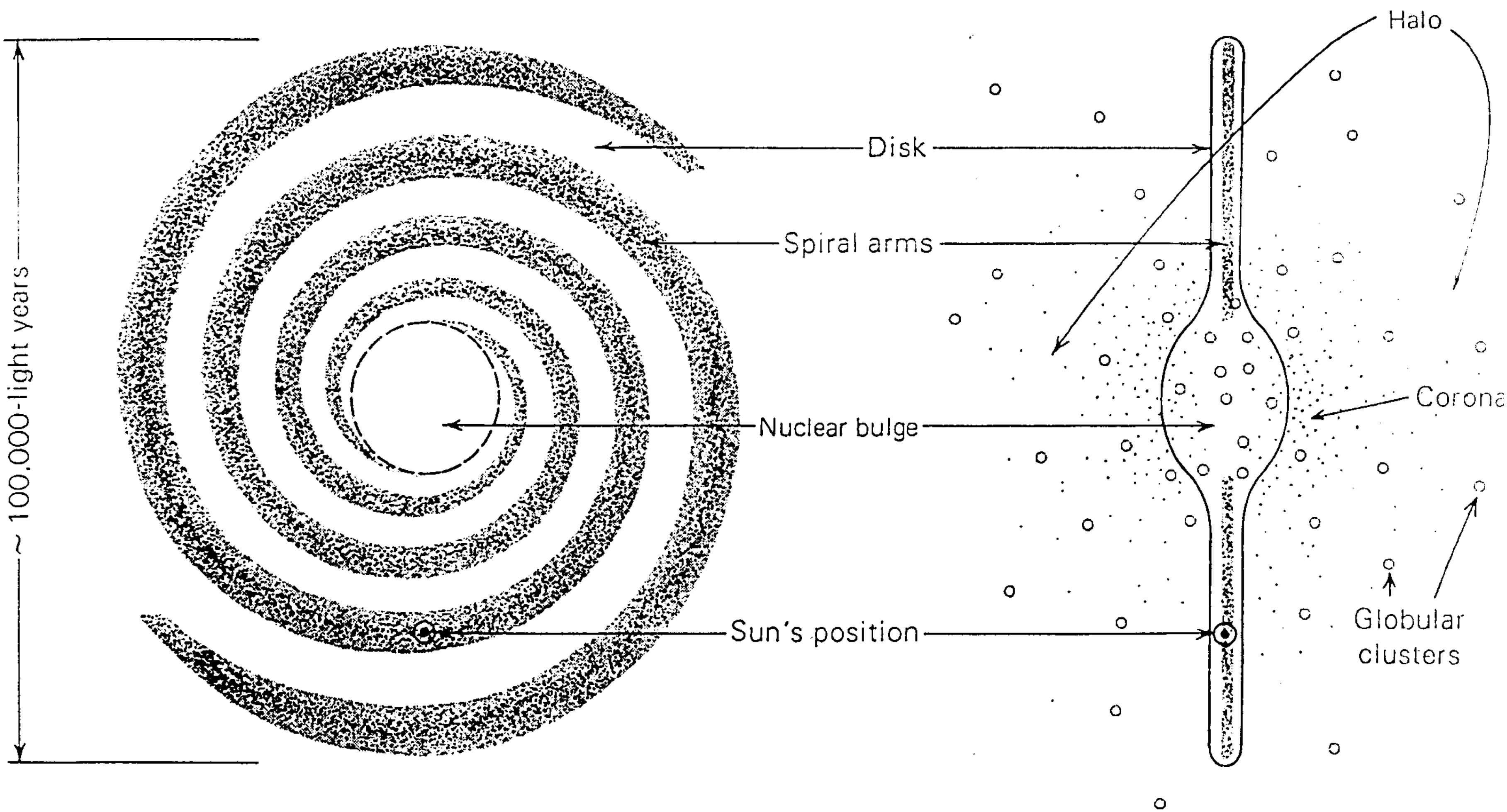
The spiral galaxy M31



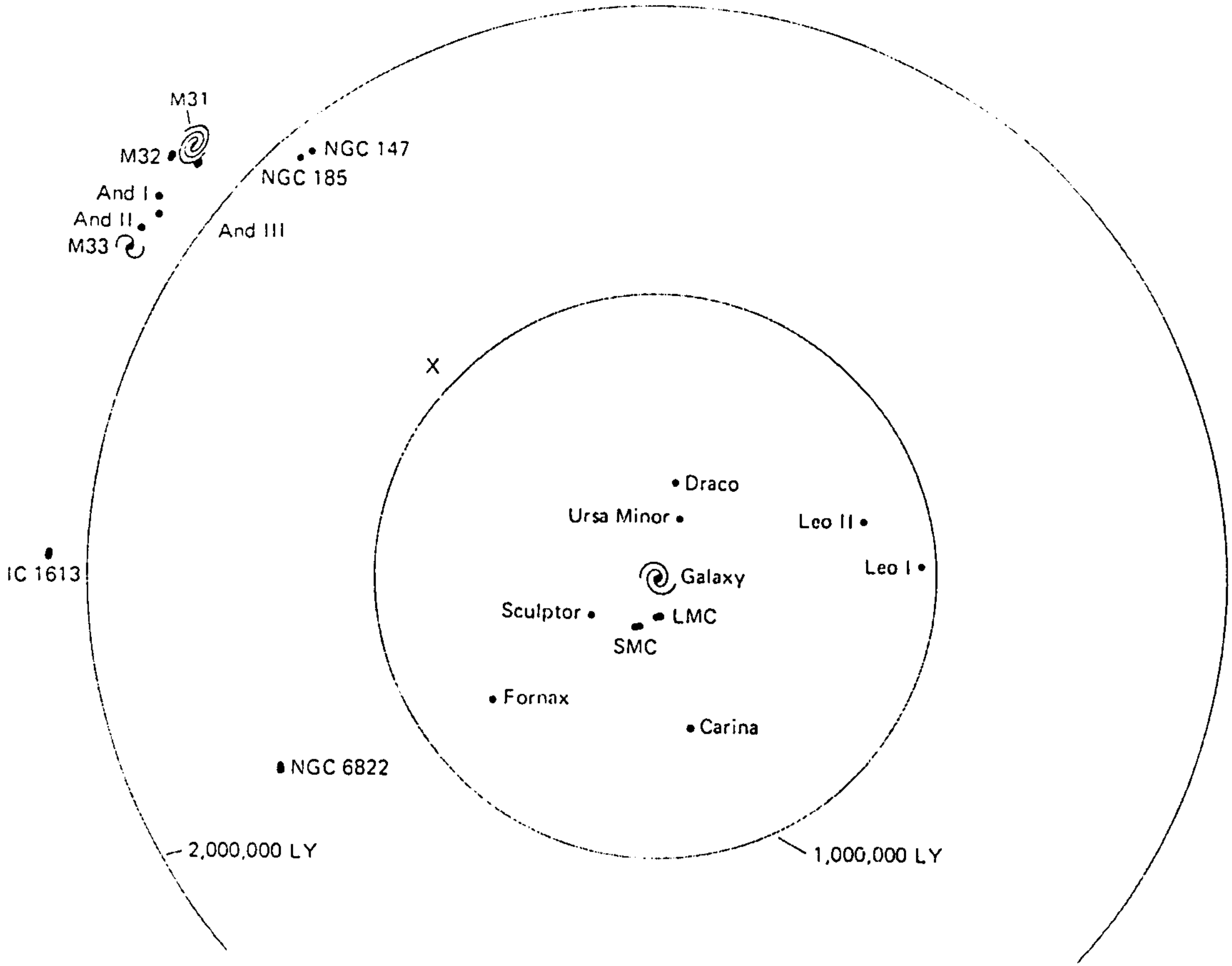
Types of galaxies according to the Hubble classification system.



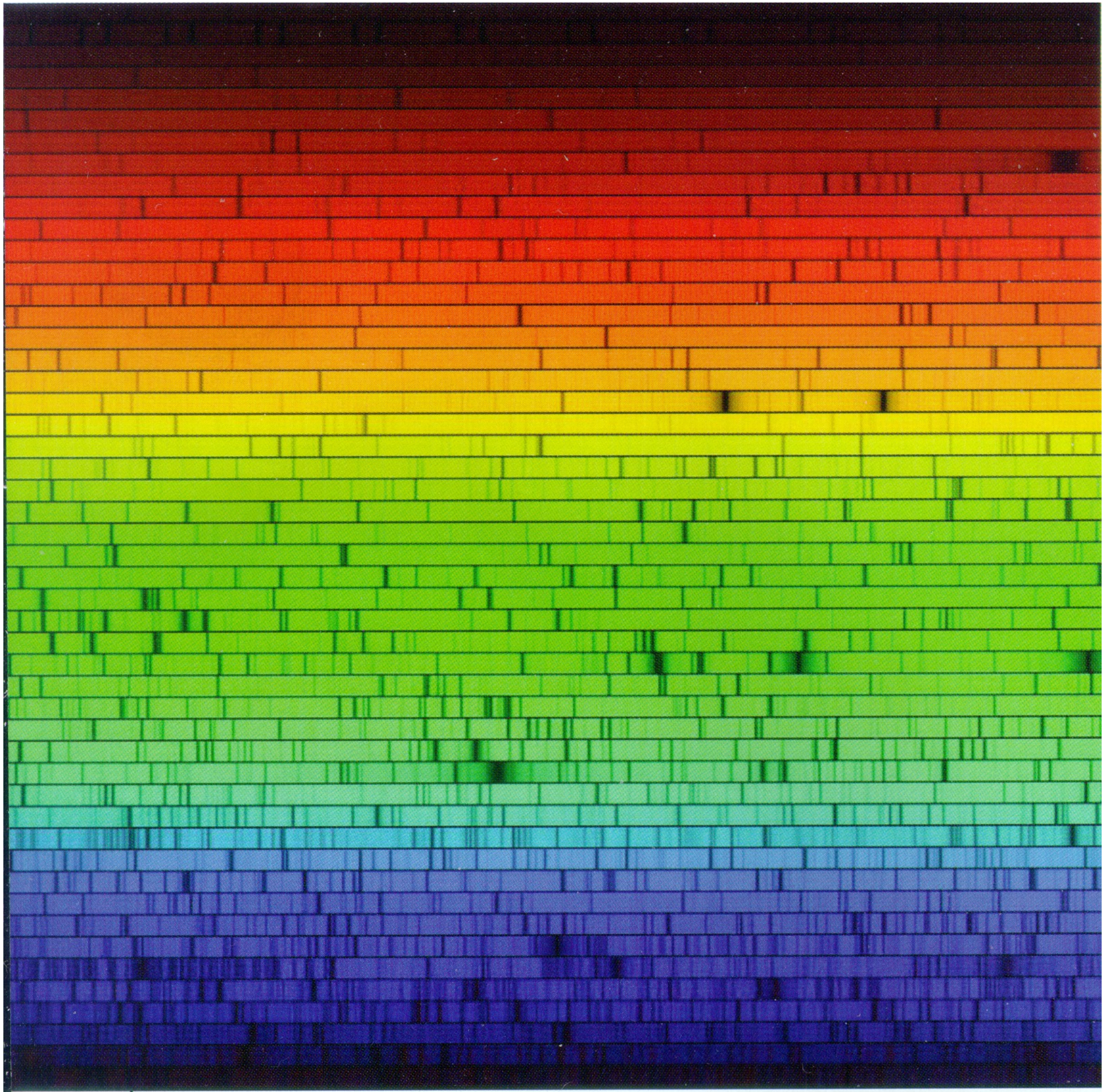
A map of the Milky Way, with the Sagittarius and Norma spiral arms relegated to smaller, less distinct minor arms. Image: NASA/JPL–Caltech.



Schematic drawing of our galaxy. In the projection on the left (seen from the south side of the galactic plane), the sun rotates counter clockwise around the center



The Local Group of galaxies. The X marks the center of gravity



Splitting starlight into a spectrum shows many dark bands from absorption by elements in stellar atmospheres. This one shows the Sun's spectrum. Image: W M Keck Observatory.

The Big Bang theory
(Alpher – Bethe – Gamow 1946)

Observations:

- All stars at large distances show a measurable shift of the spectral lines from various elements towards the red (lower energy).
  This is called *redshift* (E. Hubble1929)
- The redshift increses with the distance to the star

Assumption:

The properties of the four (five?) forces of nature are constant in time

Conclusions:

- The spectral lines of an element have always the same wavelengths, constant in time
- The redshift is a Doppler effect caused by the velocity away from us
- The velocity increases with distance in all directions, i.e. The Universe behaves like an adiabatically expanding gas
- The Hubble constant, H, can be calculated from the redshifts of today (velocity, v, m/s) and distance (d, m) as follows

  $H = v/d$ which yields

  $H = (2.26 \pm 0.23) \times 10^{-18}\ s^{-1}$ (NASA 2007) (does it vary with time?)

Hence, the Universe was a probably point a long time ago, T_0, which is less than $1/H$ (in reality the age of the Universe might be different due to a sinking expansion velocity in the collective gravitational field or an increased expansion velocity due the action of the fifth force of nature – the variable quintessence

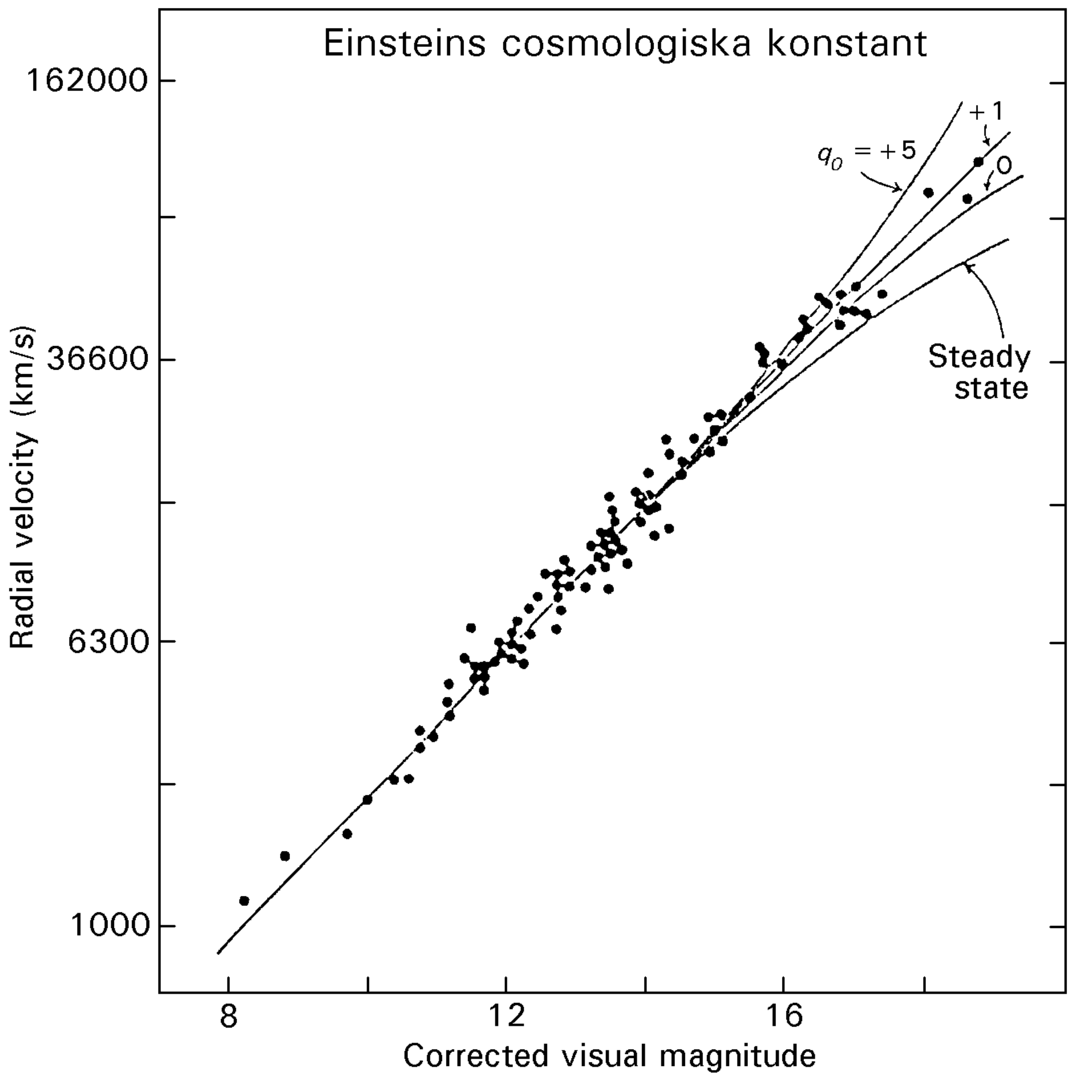
At present, the velocity of expansion increases with time!

$T_0 \approx 1/H = (14.0 \pm 1.4) \times 10^9$ years

The oldest stars in the globular star clusters M13 and M92 are about 15×10^9 years old (VandenBerg, U. of Victoria, 1996, from star models)

Other investigated globular star clusters seems to be between 12 and 16 billion years old.

(using mechanics for gravitating multi-body systems in computer simulations and assuming that all the stars in the cluster were born at the same time)



Hubblediagram for clusters of galaxies. The dots represent observations and the curves correspond to predictions made using different assumptions about the future development of the Universe

Problem:

- No stars in our galaxy (the Milky Way) can be older than the Universe (problem seems to lessen with new measurements)

Possible explanations:

- Distance determinations are wrong (e.g. optical lines of the elements change their wavelength with time)
- Measured nuclear reaction data are wrong, or change with time
- The laws of mechanics does not apply in empty space
- The four forces of nature change their properties with time, e.g. gravity.
- Quanta of light ”tires” with time (Hoyle and others)
- Empty space has anti-gravitational properties (Einstein’s cosmological constant)
- Quintessence works sometimes and counteracts gravity at long distances (at present this seems to be the case)

Origin and development of the Universe

(what can nuclear chemists do in this area?)

- Determine the age of materials on Earth using the natural production of e.g. ^{3}H and ^{14}C
- Determine the chemical composition by activation analysis, e.g. dust and rocks from the Moon and on Mars (Sejourner 1997, Spirit and Opportunity since 2005)
- Determine mineral types and oxidation states by Mössbauer spectroscopy, e.g. dust and rocks on Mars (Spirit and Opportunity since 2005)
- Determine isotopic composition of materials from e.g. Earth, meteorites, Moon, mars in order to find their age and the age of the elements
- Measure the neutrino fux on Earth
- Study nucear reactions and their products to get information on the state equation for matter (equilibrium matter – quark gluon plasma)
- Study the nuclear reactions involved in the energy production in stars
- Produce and study the decay of nuclei involved in the r-, p-, and s-processes

The work is usuallt done in groups containing both nuclear physicists and nuclear chemists, and sometimes scientists from many other fields

The beginning of time or ”the Big Bang”

Time, t, = 0 – 10^{-55} s

The Universe is small 10^{-62} m

The content consists of extremely high energy photons (?)

The small size yield rapidly a homogeneous state

Time 10^{-55} – 10^{-35} s

The radius of the Universe expands to about 10^{-47} m

Time 10^{-35} – 10^{-30} s

The radius increases extremely rapidly to about 100 m (”inflation”)

(hypothesis: the force of gravity is repulsive, or quintessence dominates over gravity, during a short time)

At the end the Universe consists of photons, gluons and quarks

Time $10^{-30} - 10^{-3}$ s

The general theory of relativity, thermodynamics, and normal particle physics can be applied (with some difficulty)

Temperature: $T = 1.52 \times 10^{10}(K \times s^{1/2}) \times t^{-1/2}$ (K)

Density: $\rho_m = 4.48(kg \times m^{-3} \times s^{3/2}) \times t^{-3/2}$ (kg/m^3)

The amount (mass) of photons dominates enormously over the amount (mass) of matter

The force of gravity prevents photons to leave the Universe (behaves like a black hole)

Time $10^{-3} - 10^{-1}$ s

Quarks and gluons disappear

Ends with about equal amounts (mass) of electrons, positrons, neutrinos, and photons

Very small amount of protons and neutrons (p^+ about 10^{-9} of γ in number)

The density is so high that neutrinos are absorbed immediately again

Time 0.1 – 14 s

Equilibria: $p^+ + n \leftrightarrow n + e^+$ $\quad Q = -1.80$ MeV

$n + n \leftrightarrow p^+ + e^-$ $\quad Q = 0.78$ MeV

Ends with: $e^- + e^+ \rightarrow 2\gamma + \nu_e$ $\quad Q = 1.02$ MeV

The density is low enough to permit neurinos to escape from the Universe

Final result: *62 % protons and 38 % neutrons*

Time 14 s – 35 min

Reactions: $p^+ + n \rightarrow d^+$ $\quad Q = 0.41$ MeV

$d^+ + \gamma \rightarrow p^+ + n$ $\quad Q = -0.41$ MeV

$d^+ + d^+ \rightarrow \alpha$ $\quad Q = 23.85$ MeV

$n \rightarrow p^+ + e^- + \nu_e$ $\quad Q = 0.78$ MeV; $t_{1/2} = 10.4$ min

The Universe finally consists of 69 % photons, 31 % neutrinos and 10^{-7} % of various kinds of matter (why was some matter left at all?)

Density: 0.0001 kg/m3

Result: *72-78 % protons, 28-22 % helium nuclei*, + corresponding number of free electrons

Time 35 min – 700 000 years

The temperature is still so high that the Universe is a plasma which is non-transparent to light (behaves similarly to the plasma formed in a nuclar explosion)

At the end: $T \sim 3000$ K

Atoms can form and the photons escape

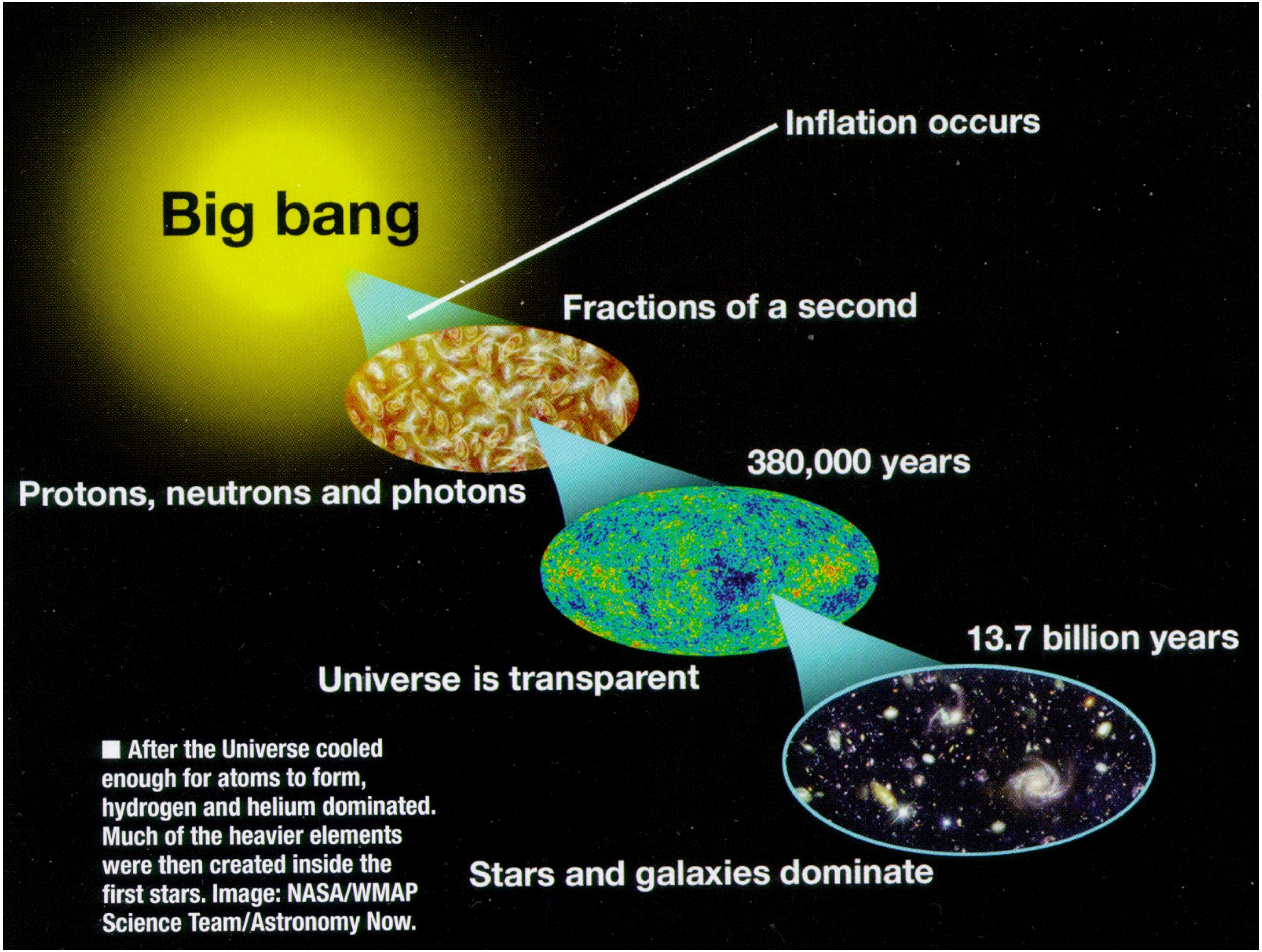
Time 700 000 years – now

Temperature is given by: $T = T_0(s^{2/3})\times t^{-2/3}$ (K)

T_0 is the temperature at the time when the density of photons has decreased to the density of matter

The predicted value of T is now about 4 K; Measured T is 2.7 K (temperature of the the micro wave background)

This agreement between prediction and experiment is one of the strongest arguments that support the Big Bang theory



■ After the Universe cooled enough for atoms to form, hydrogen and helium dominated. Much of the heavier elements were then created inside the first stars. Image: NASA/WMAP Science Team/Astronomy Now.

Thermonuclear reactions:

Thermal kinetic energy, E:

$dn/dE \propto e^{-E/kT}$ Boltzmann distribution

The electrostatic repulsion between atomic nuclei leads to limited reaction surface (cross section), $\sigma(E)$

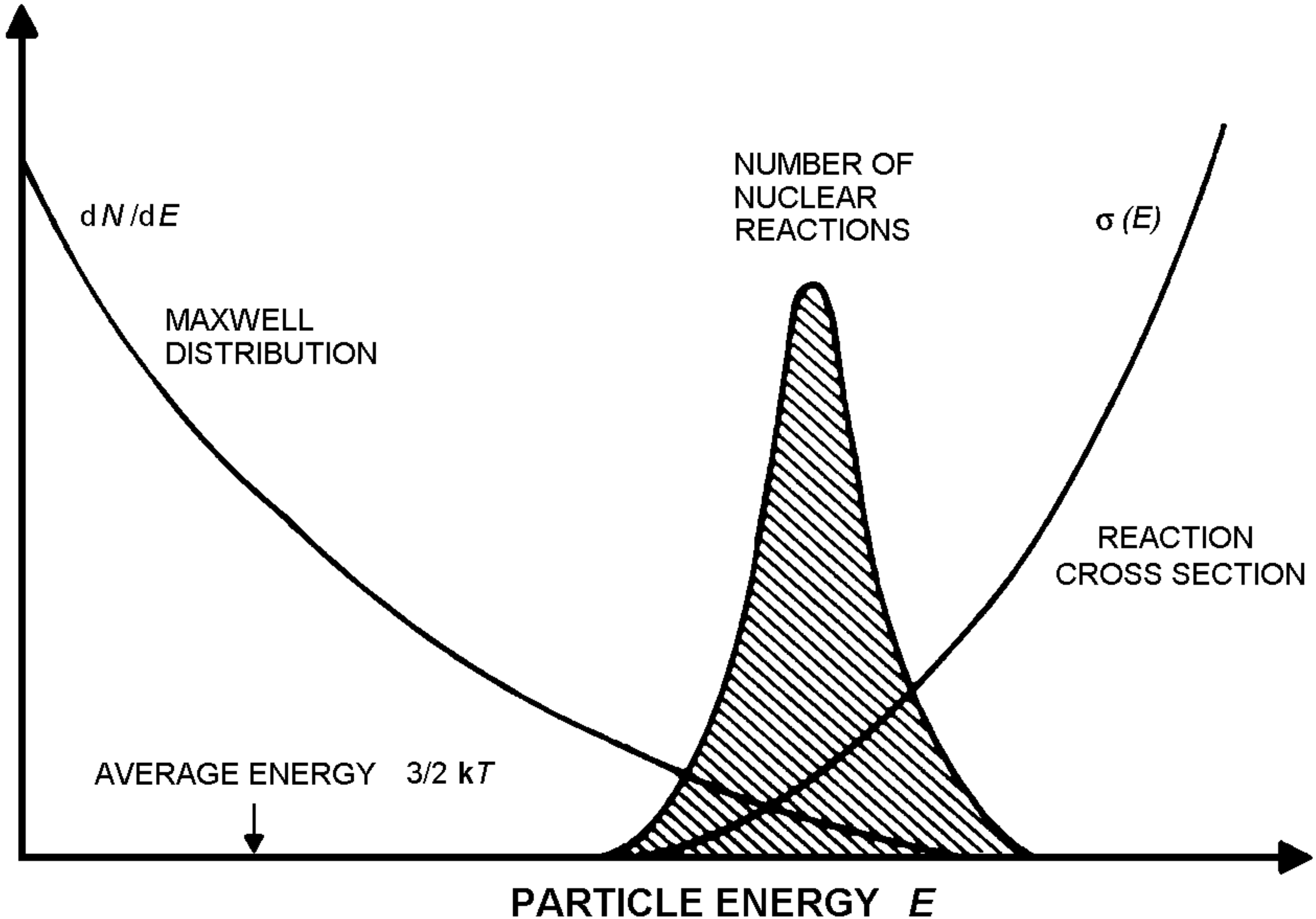
Below the coulomb barrier, the cross section is due to the tunnel effect, thus

$\sigma(E) \propto e^{-b/\sqrt{E}}$ below the barrier

The reaction velocity, R

$R \propto \sigma(E) \times dn/dE \propto e^{-b/\sqrt{E}} \times e^{-E/kT}$

Leads to a low reaction rate which is strongly temperature dependent (particle energy) and dependent on the number of atoms per unit of volume.



dN/dE
MAXWELL DISTRIBUTION
NUMBER OF NUCLEAR REACTIONS
σ (E)
REACTION CROSS SECTION
AVERAGE ENERGY 3/2 kT
PARTICLE ENERGY E

Thermonuclear energy production in hydrogen-rich stars

The proton-proton chains

Important at $T < 15\times10^6$ K

$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu$

$^2H + {}^1H \rightarrow {}^3He + \gamma$

$^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H$

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

$^7Be + e^- \rightarrow {}^7Li + \nu$

$^7Li + {}^1H \rightarrow 2\,{}^4He$

$^7Be + {}^1H \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be + e^+ + \nu$

$^8Be \rightarrow 2\,{}^4He$

Energy production 26.7 MeV/^{4}He

The Carbon – Nitrogen cycle

Important at T > 15 × 10^6 K

$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$

$^{13}N \rightarrow {}^{13}C + e^+ + \nu$

$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$

$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$

$^{15}O \rightarrow {}^{15}N + e^+ + \nu$

$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$

Energy production 26.7 MeV/^{4}He

Energy production in stars with little hydrogen

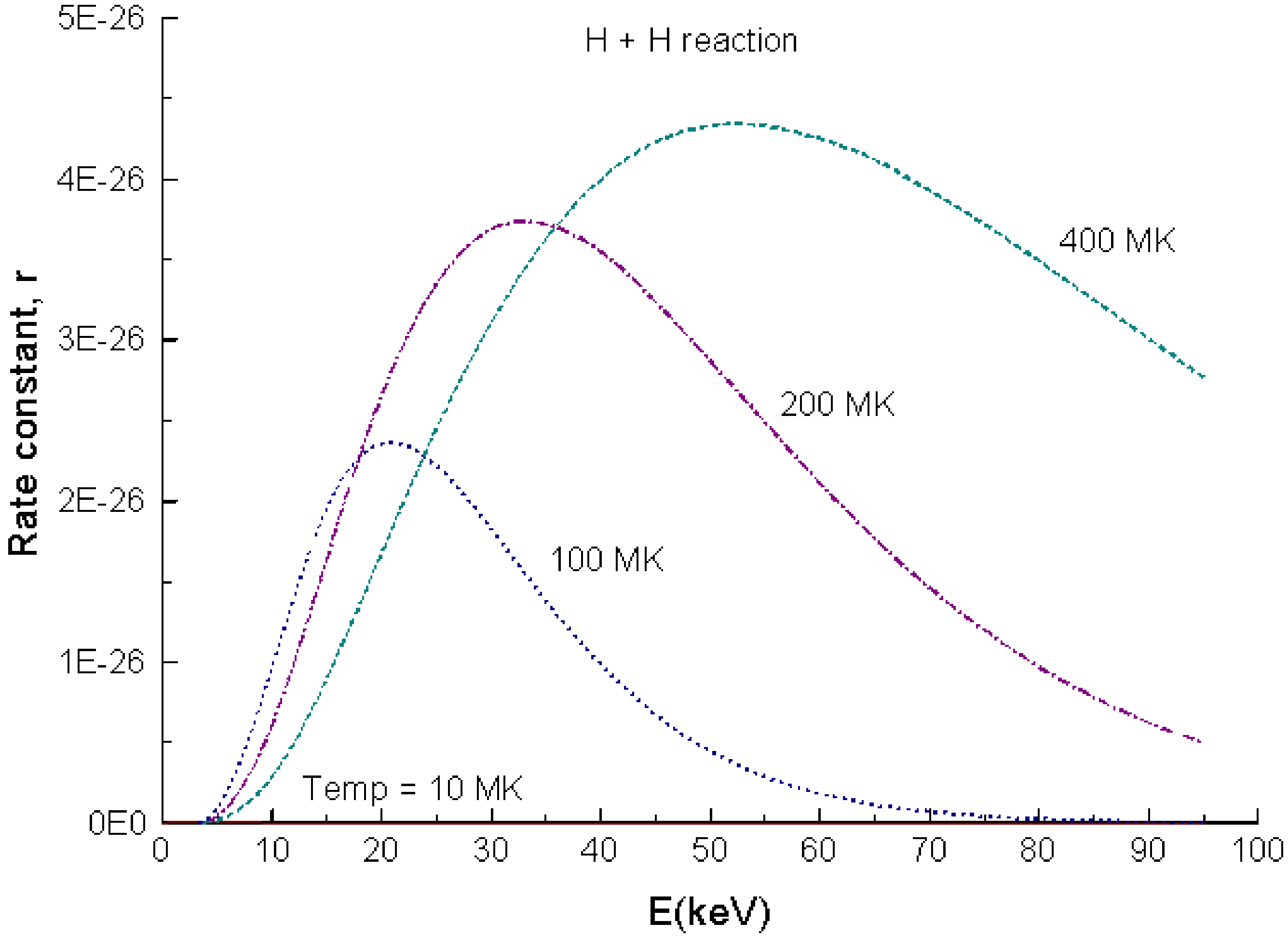
The triple - alfa process

Important at T > 10^8 K

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

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

Energy production 7.27 MeV/^{12}C



$$\left(\frac{dN}{dt}\right)_{^2H} = \frac{1}{2} \times N_{^1H}^2 \times \int_0^\infty r(E) \times dE$$

How can we calculate what is happening inside a star?

Known facts:

- Total mass (from orbit transit times)
- Total energy emission (corrected for distance, etc)
- Spectrum of emitted light - ”surface” temperature
  - ”surface” composition (spectral lines)
  - ”surface” area (Boltzmann law)
  - the stars outer radius

In other words: m, T, r, Q, and chemical composition

In a thin shell inside the star at radius r we have:

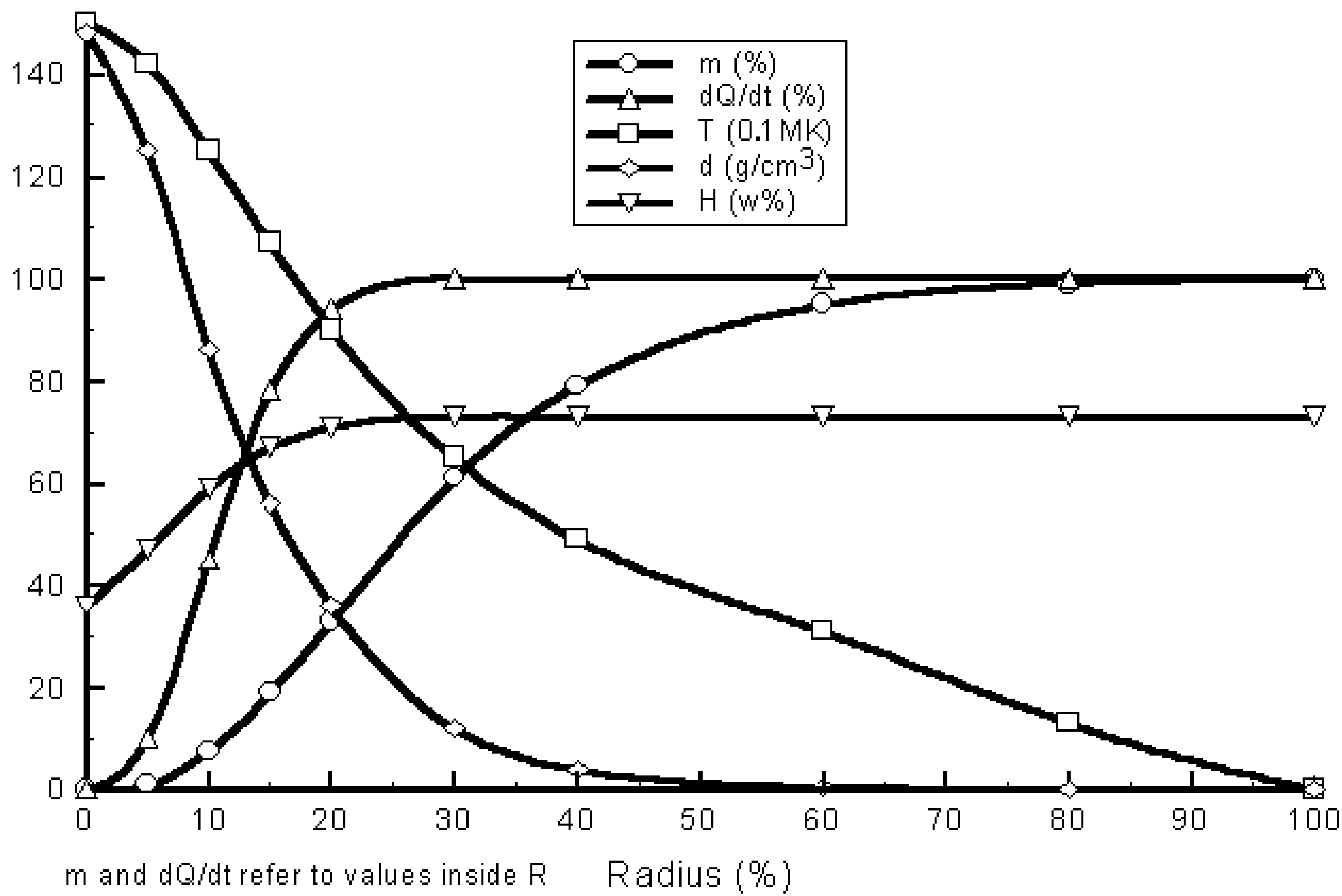
$$dm/dr = f(r)$$

$$dT/dr = g(r)$$

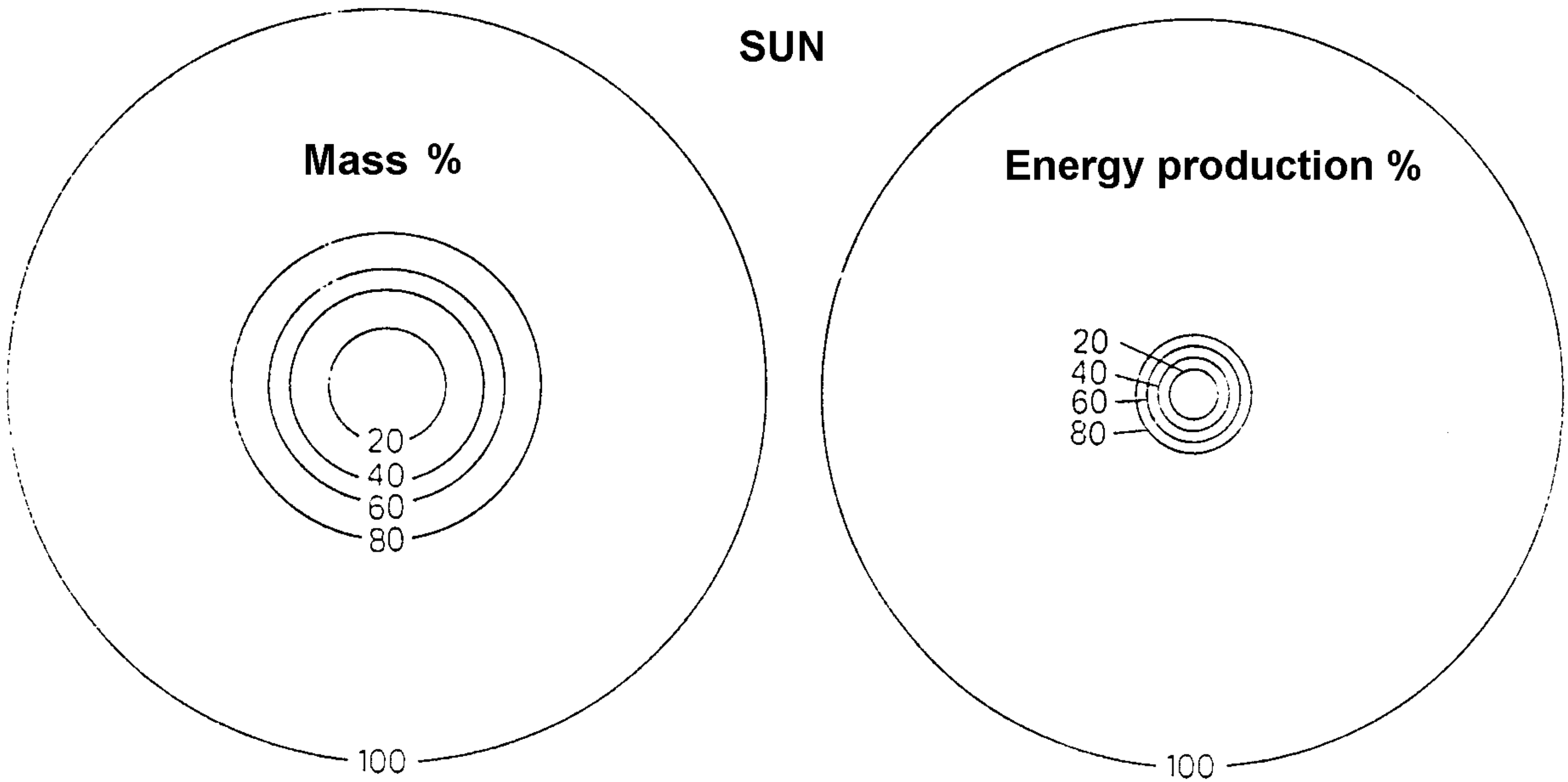
$$dQ/dr = h(r)$$

$$d(\text{composition})/dr = k(r)$$

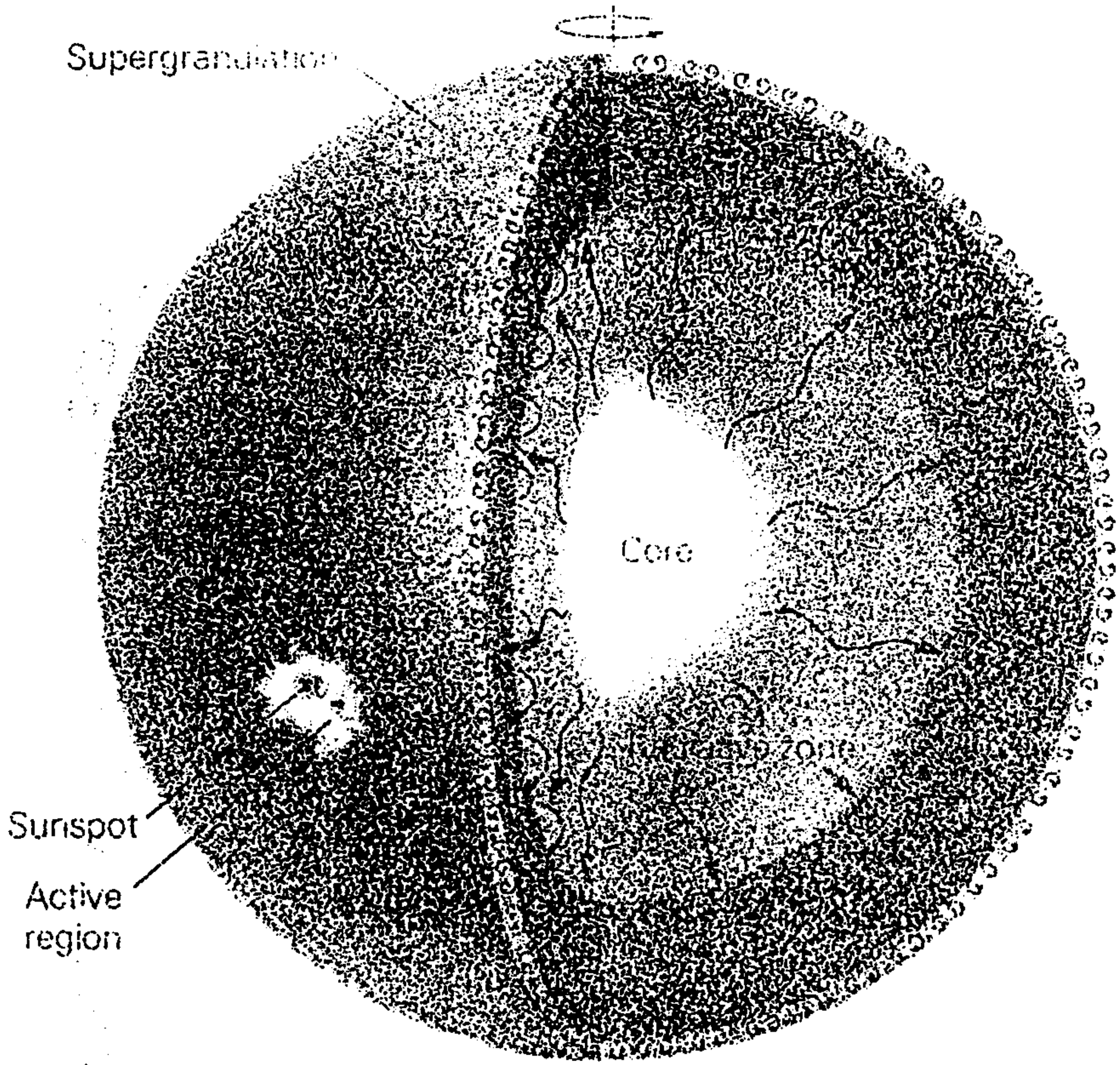
All energy produces inside a shell at r must pass through it on the way out. The pressure in the shell is given by the mass outside the shell and the law of gravity. In the center r=0, m=0, Q=0. Integration from utside in must yield these conditions at the center. In case the result deviates we must change k(r). The final model can be used to extrapolate backwards and forwards in time.



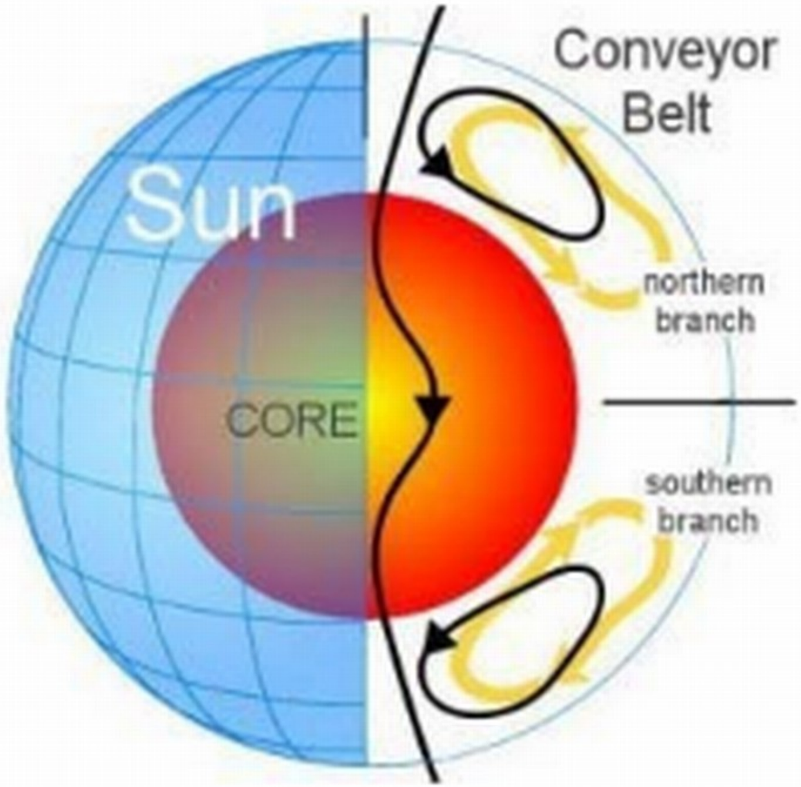
Data for present conditions obtained from a model of our sun



The numbers represent the value inside each circle

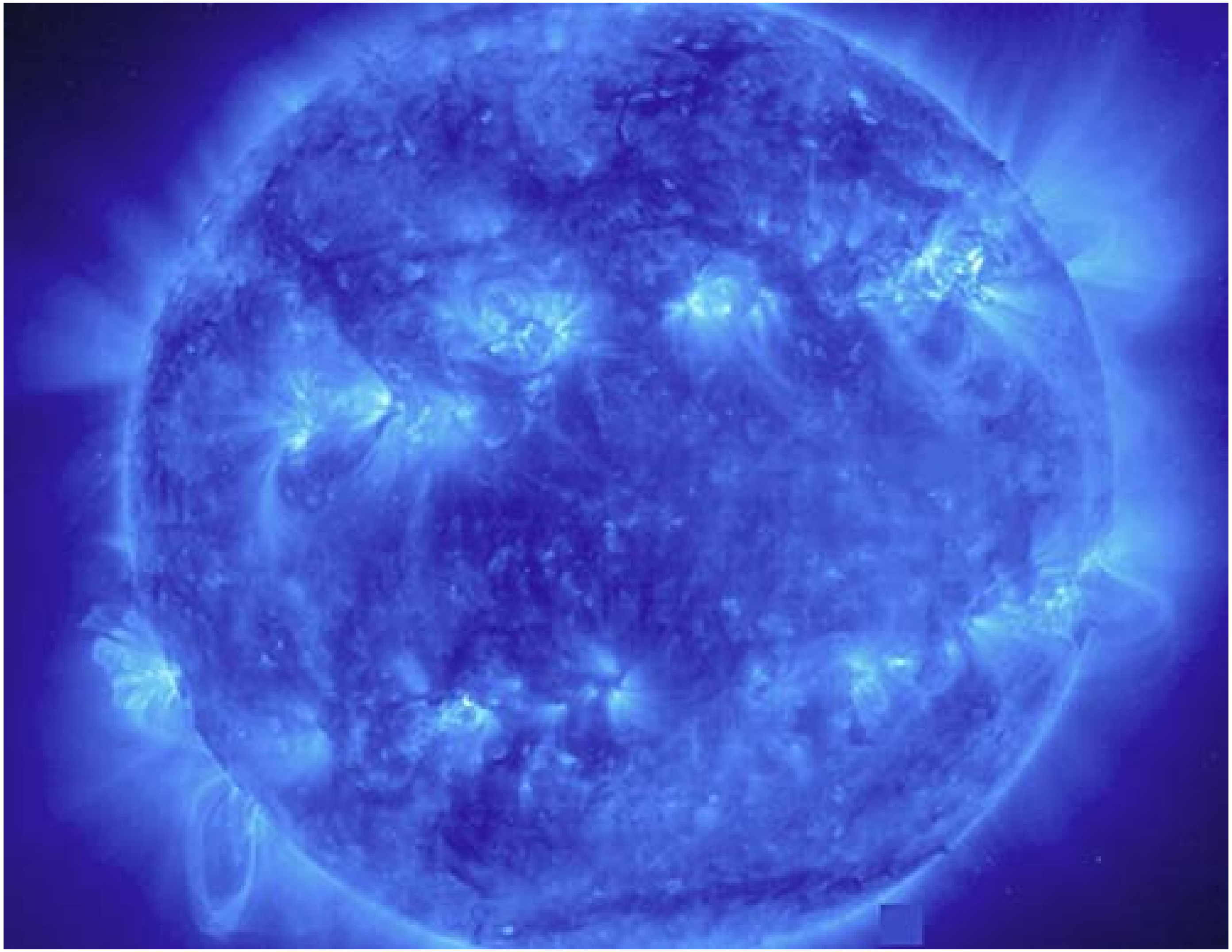

Supergranulation
Core
Sunspot
Active
region

Solar Cycle 25 peaking around 2022 could be one of the weakest in centuries

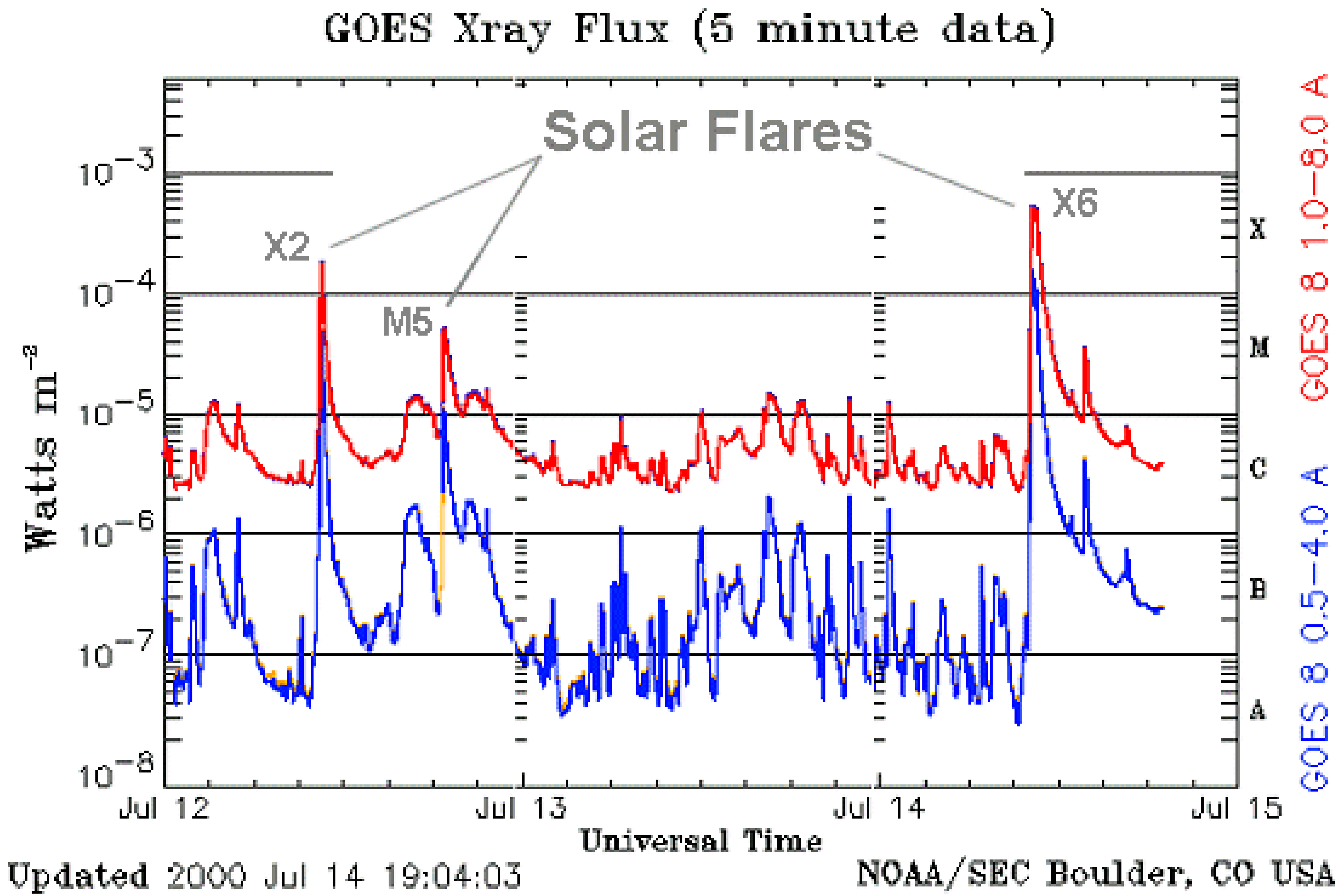


The sun's "Great Conveyor Belt" in profile.

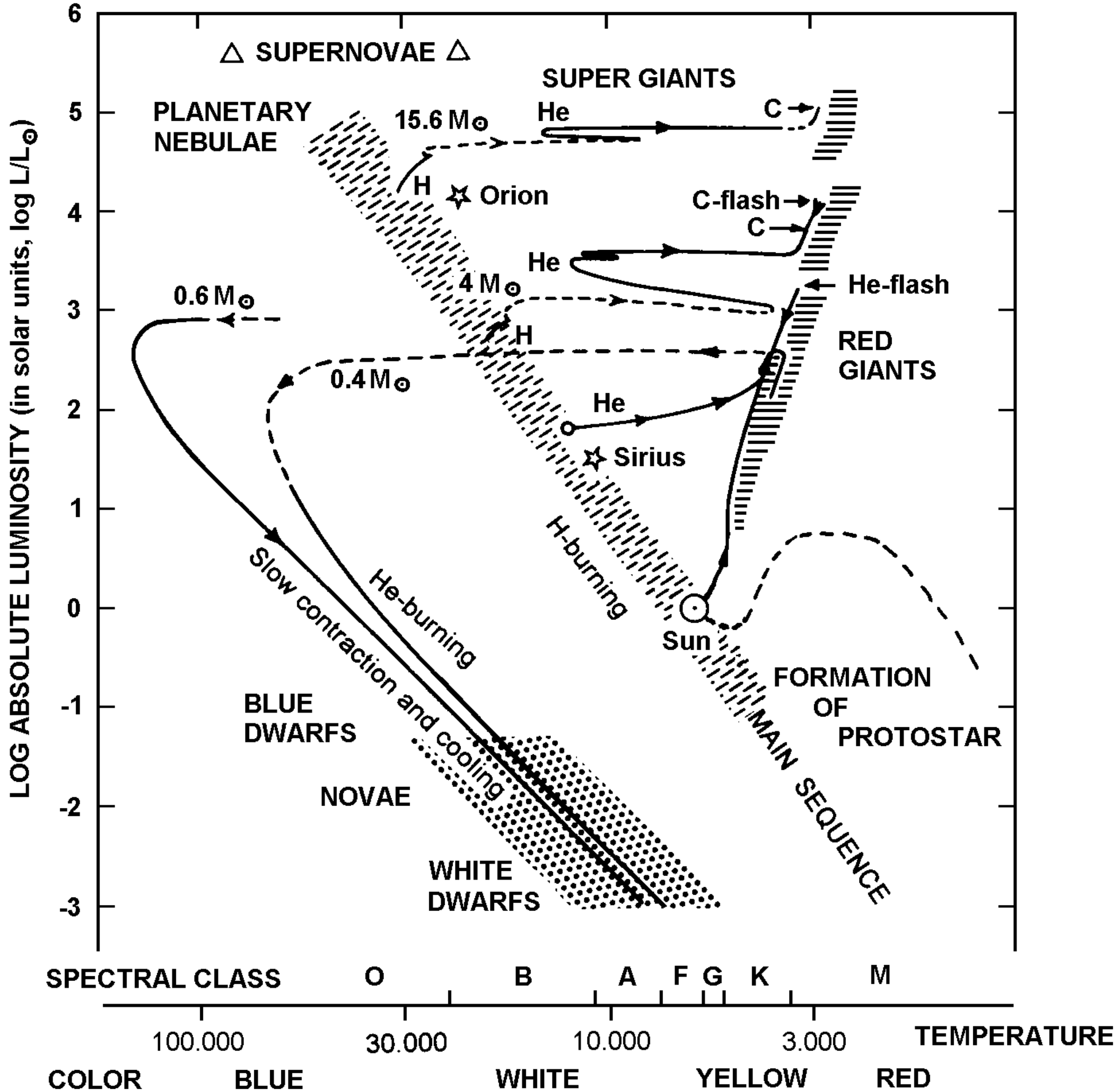
The Sun's Great Conveyor Belt has slowed to a record-low crawl, according to research by NASA solar physicist David Hathaway. "It's off the bottom of the charts," he says. "This has important repercussions for future solar activity."



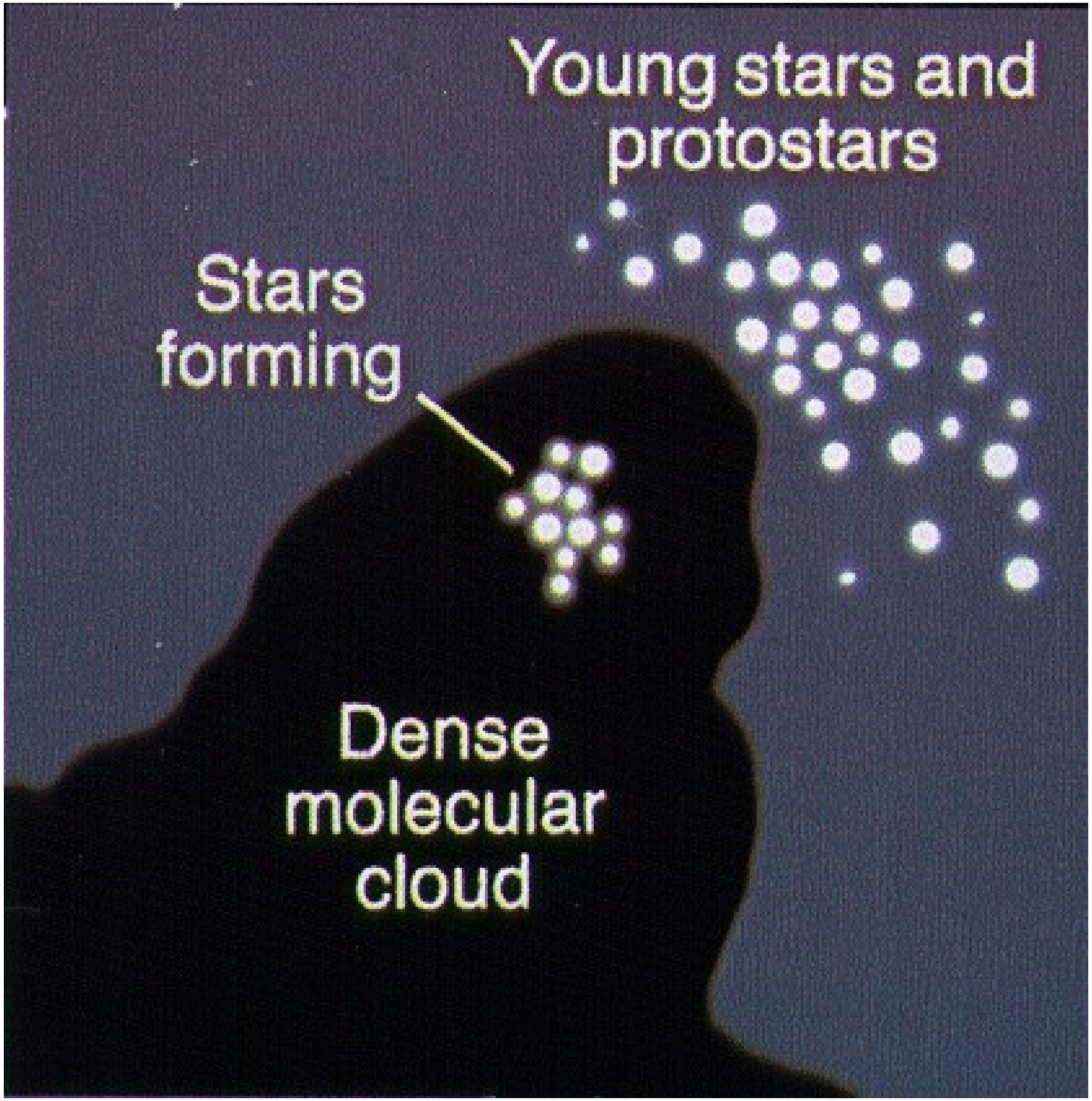
Picture from SOHO in UV-light showing surface turbulence

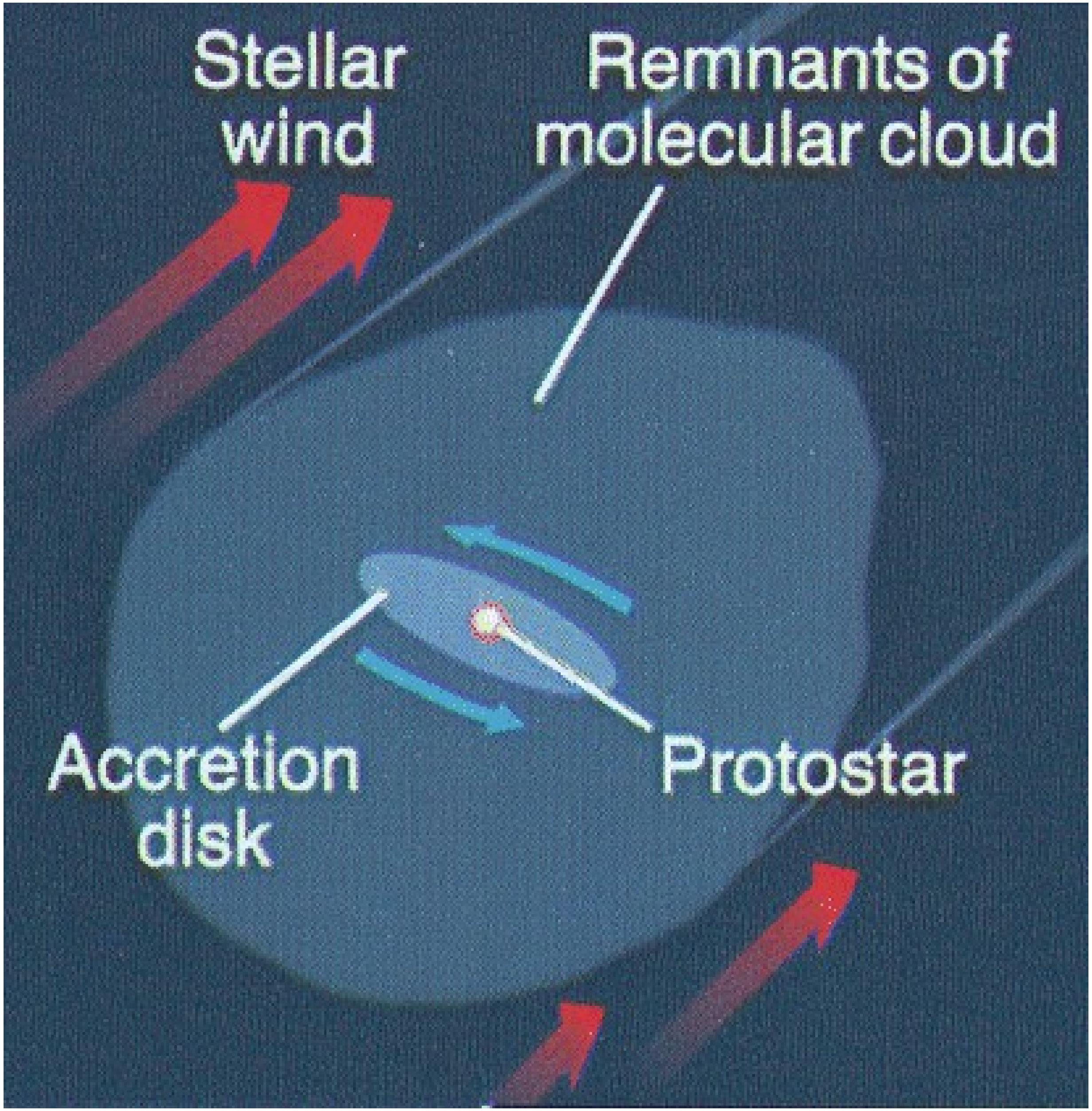


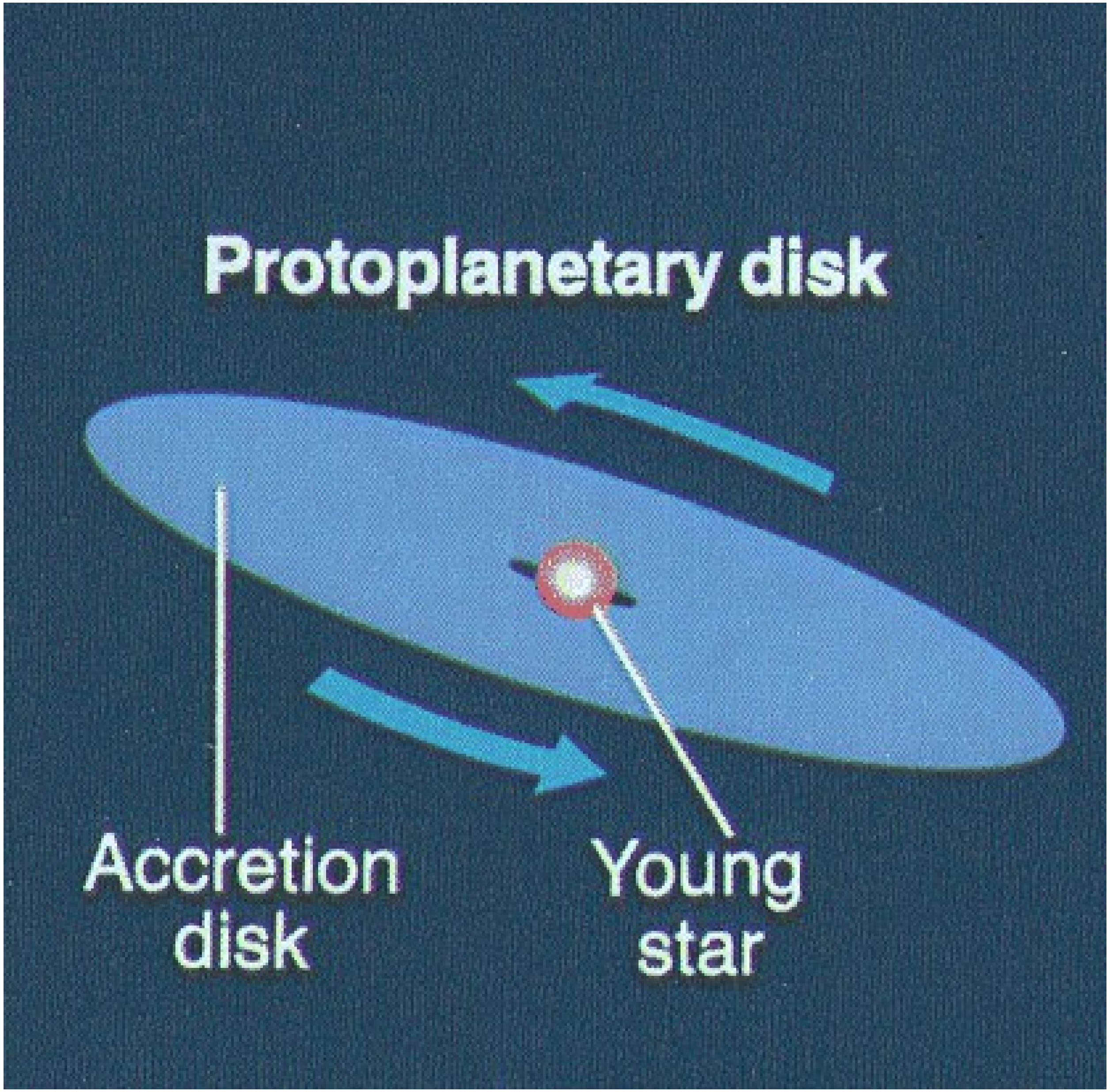
GOES Xray Flux (5 minute data)
Solar Flares
X2
M5
X6
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Watts m^{-2}
X
M
C
B
A
GOES 8 1.0–8.0 A
GOES 8 0.5–4.0 A
Jul 12
Jul 13
Jul 14
Jul 15
Universal Time
Updated 2000 Jul 14 19:04:03
NOAA/SEC Boulder, CO USA

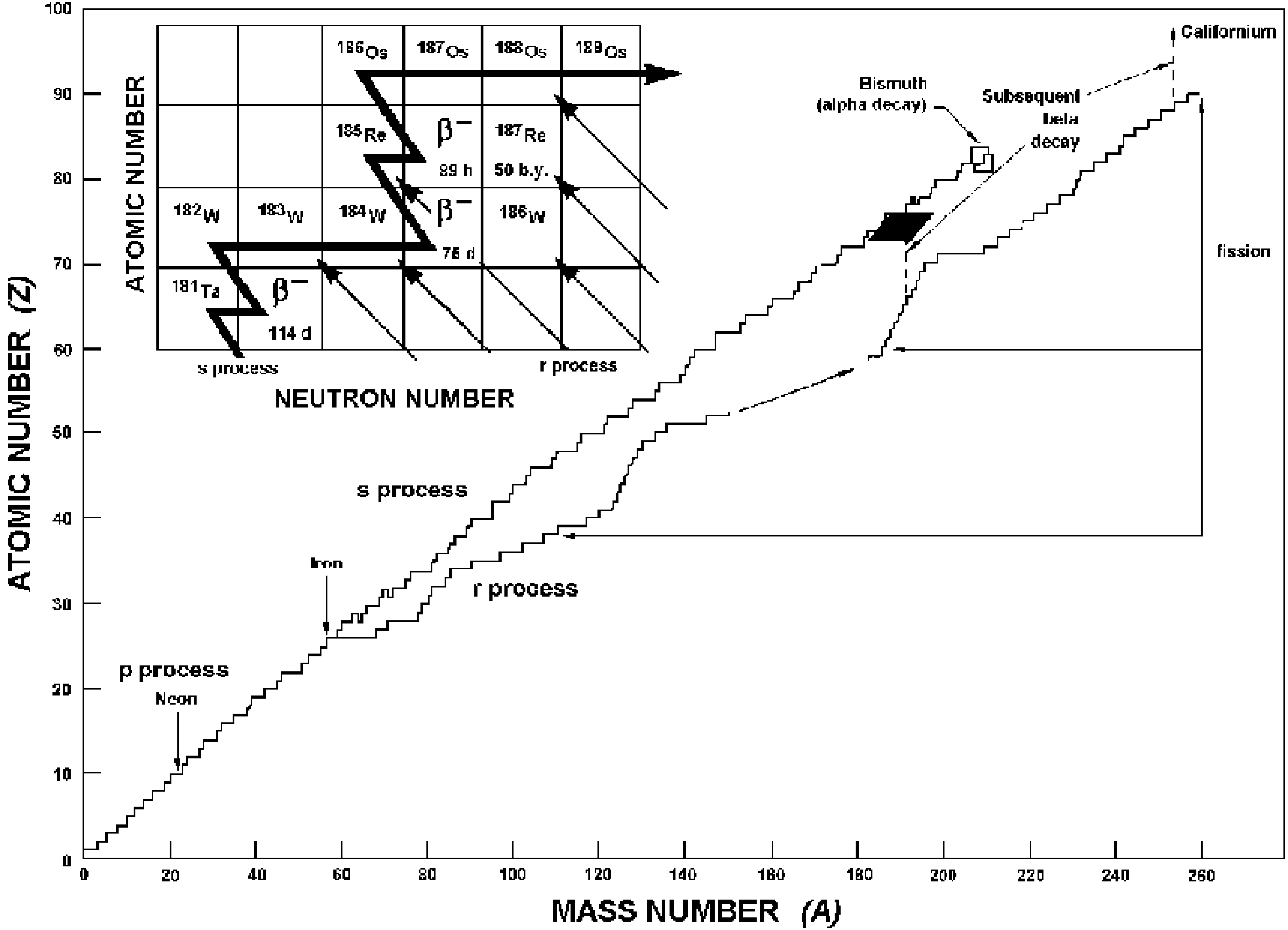


Hertzsprung-Russel diagram showing the development of stars


Young stars and protostars
Stars forming
Dense molecular cloud


Stellar wind
Remnants of molecular cloud
Accretion disk
Protostar


Protoplanetary disk
Accretion disk
Young star



ATOMIC NUMBER (Z)
MASS NUMBER (A)
p process
Neon
Iron
s process
r process
fission
Californium
Bismuth
(alpha decay)
Subsequent
beta
decay
ATOMIC NUMBER
NEUTRON NUMBER
186Os
187Os
188Os
189Os
186Re
187Re
89 h
50 b.y.
182W
183W
184W
186W
75 d
181Ta
114 d
s process
r process

The first step in the making of heavier elements is taken in the oldest stars (now mostly population II in the galactic halo). When these empties their H-supply the triple-alpha process begins. Thereby can also a small making of heavier elements proceed through the p-process.

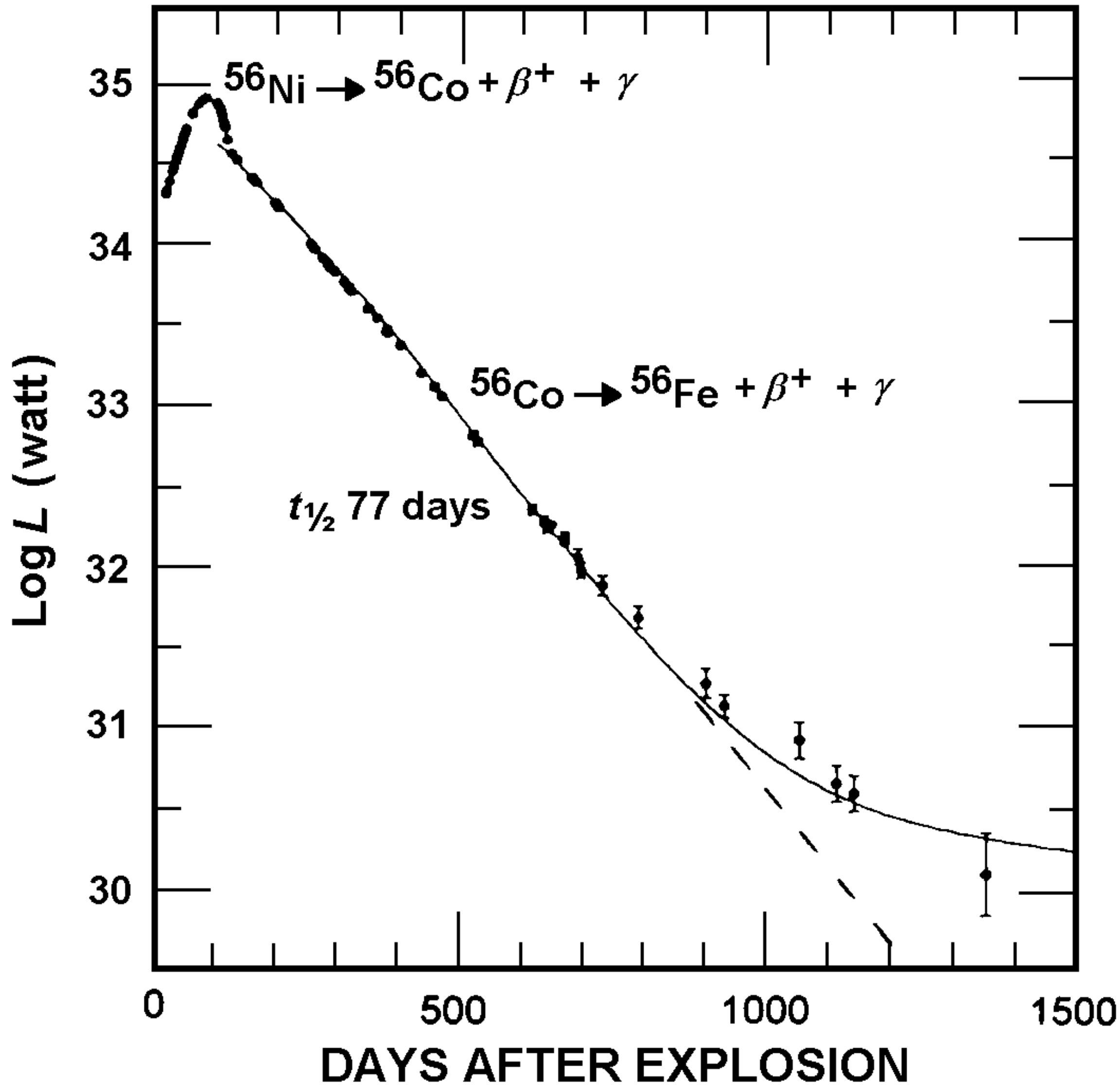
When even He becomes scarce the stars begin fusing even heavier nuclei. This yields less and less energy per mass unit until the process ends in the region Si – Fe. At the same time small amounts of neutrons are produced. These cause a slow production of heavier elements, the s-process.

At this point an unstable condition can arise for heavy stars. Their inner part is practically free of hydrogen and very hot. If a mixing occur which brings in more H from the outer layers, a violent explosion will occur. The star explodes as what is called a supernova.

The supernova explosion scatters enormous amounts of matter from the star into interstellar space at high velocity. At the same time small amounts of the heaviest element are formed by cascading n-capture in the intense n-flux caused by the explosion. These n-rich nuclei then β^--decays into more stable isotopes – the r-process.

Exploding Giant Star

Cartwheel Galaxy



Production and decay of some nuclides in supernova 1997A
(from the intensity and energy of the spectral lines)

Formation of the heaviest elements

The light from a typical supernova shows spectral lines of elements up to about cobalt. Are also heavier elements formed in typical supernova?

In the light of so called Kilonova spectral lines from gold have been seen. Thus a few such extremely high energy events may perhaps be the main source of our heaviest elements.

The age of our chemical elements

Hydrogen: Left-over from the Big Bang

Helium: Partly remaining from the Big Bang, partly formed in stars

The Re/Os clock:

^{186}Os ($t_{½}$ = 2×10^{15} år) can only be formed by fusion (s-process) and

^{187}Re ($t_{½}$ = 5×10^{10} år) is only made in the r-process (i.e. supernovas)

^{187}Re decays into ^{187}Os (stable)

^{187}Os can be made by n-capture in ^{186}Os and by the s-process

The amount of ^{187}Os made by these processes can be calculated and subtracted from the amount found today (isotopefraction).

The remaining excess of ^{187}Os must then originate from decay of ^{187}Re.

This gives us a clock which started when the last r-process ocurred. Calculated time from this r-process is about 6×10^9 years.

This value is then the probable average age of all our elements on Earth with higher atomic number than iron.

It is difficult to give an exact value because matter from more than one supernova can have been included in the formation of the solar system.

The p-, s-, and r-processes have all been studies in experiments on Earth.
The p-process has been studied using accellerators and fusion devices.

Process	Flux (n/m^2s)	Duration	Exposure (n/m^2)
s	$\approx 10^{18}$	$\approx$1000 years	$\approx 3 10^{29}$
r	$>10^{29}$	1 – 100 s	$>10^{29}$
Nuclear weapons	$>10^{33}$	$<1\mu s$	$\approx 10^{27}$
Nuclear reactors	$\approx 10^{16}$	1-6 years	$\approx 10^{23}$

The End