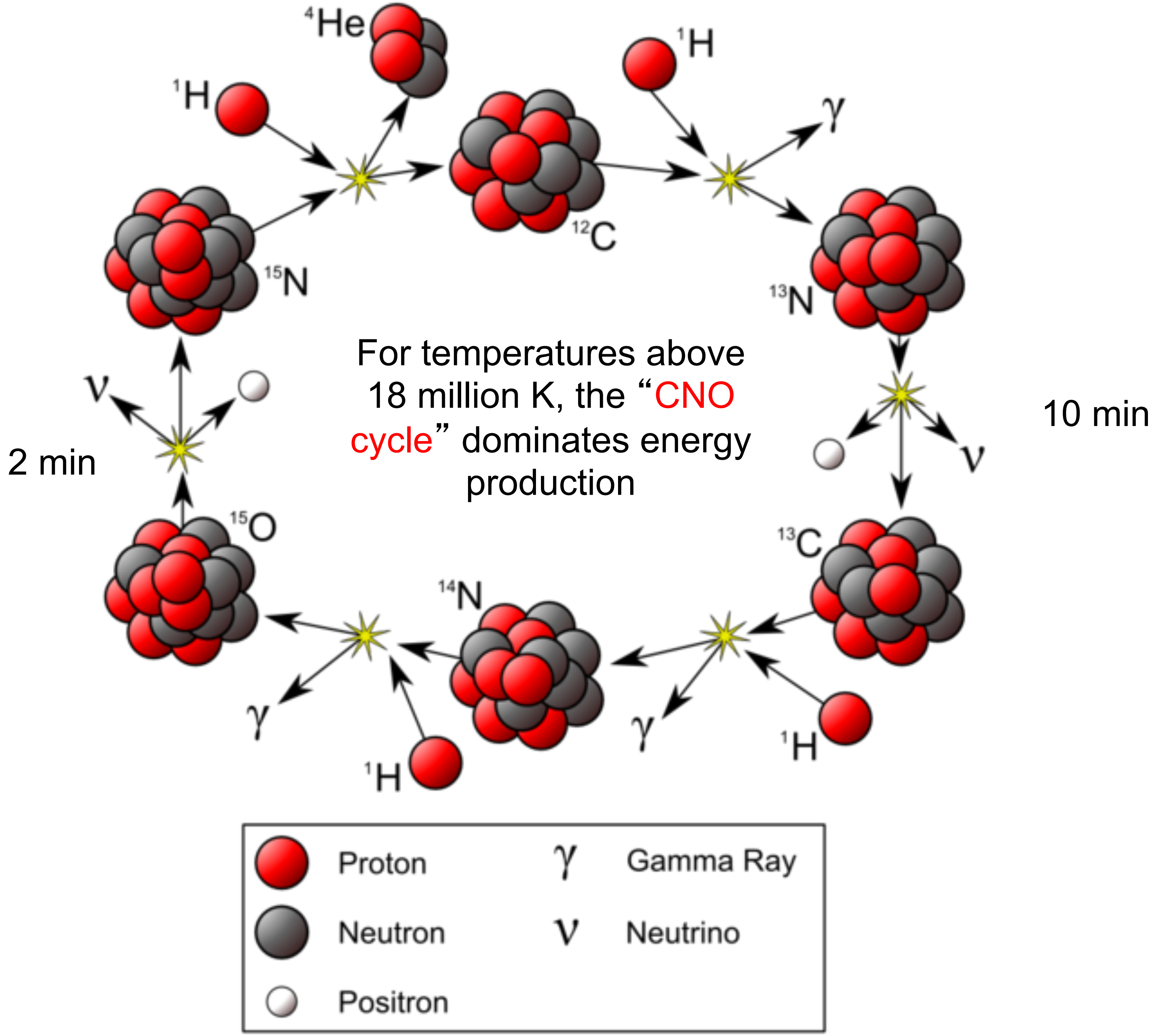
Hydrogen Burning in More Massive Stars and The Sun

http://apod.nasa.gov/apod/astropix.html



For temperatures above 18 million K, the "CNO cycle" dominates energy production
10 min
2 min
^{4}He
^{1}H
^{12}C
^{13}N
^{13}C
^{14}N
^{15}O
^{15}N
γ
ν
Proton
Neutron
Positron
γ Gamma Ray
ν Neutrino

THE CNO CYCLE

$$^{12}C + p \rightarrow {}^{13}N + \gamma + 1.94\,\text{MeV}$$
$$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e + 1.20\,\text{MeV}$$
$$^{13}C + p \rightarrow {}^{14}N + \gamma + 7.55\,\text{MeV}$$
$$^{14}N + p \rightarrow {}^{15}O + \gamma + 7.29\,\text{MeV}$$ * slowest
$$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e + 1.74\,\text{MeV}$$
$$^{15}N + p \rightarrow {}^{12}C + {}^{4}He + 4.97\,\text{MeV}$$

Putting it all together, subtracting off the 1.71 MeV carried away by the neutrinos and adding the 2.04 MeV from positron annihilation

$$4p + {}^{12}C \rightarrow {}^{4}He + {}^{12}C + 25.02\,\text{MeV}$$

(Again $\sim 6 \times 10^{18}$ erg/gm)

The ^{12}C is a catalyst. It is not used up but makes the series of reactions possible. Note however, nucleosynthetic aspects.

CNO $\rightarrow$ ^{14}N

CNO CYCLE (Shorthand)

$$^{12}C(p,\gamma)^{13}N(e^{+}\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(e^{+}\nu)^{15}N\,(p,\alpha)^{12}C$$

nb. $\alpha \equiv {}^{4}He$

CNO CYCLE vs PP 1

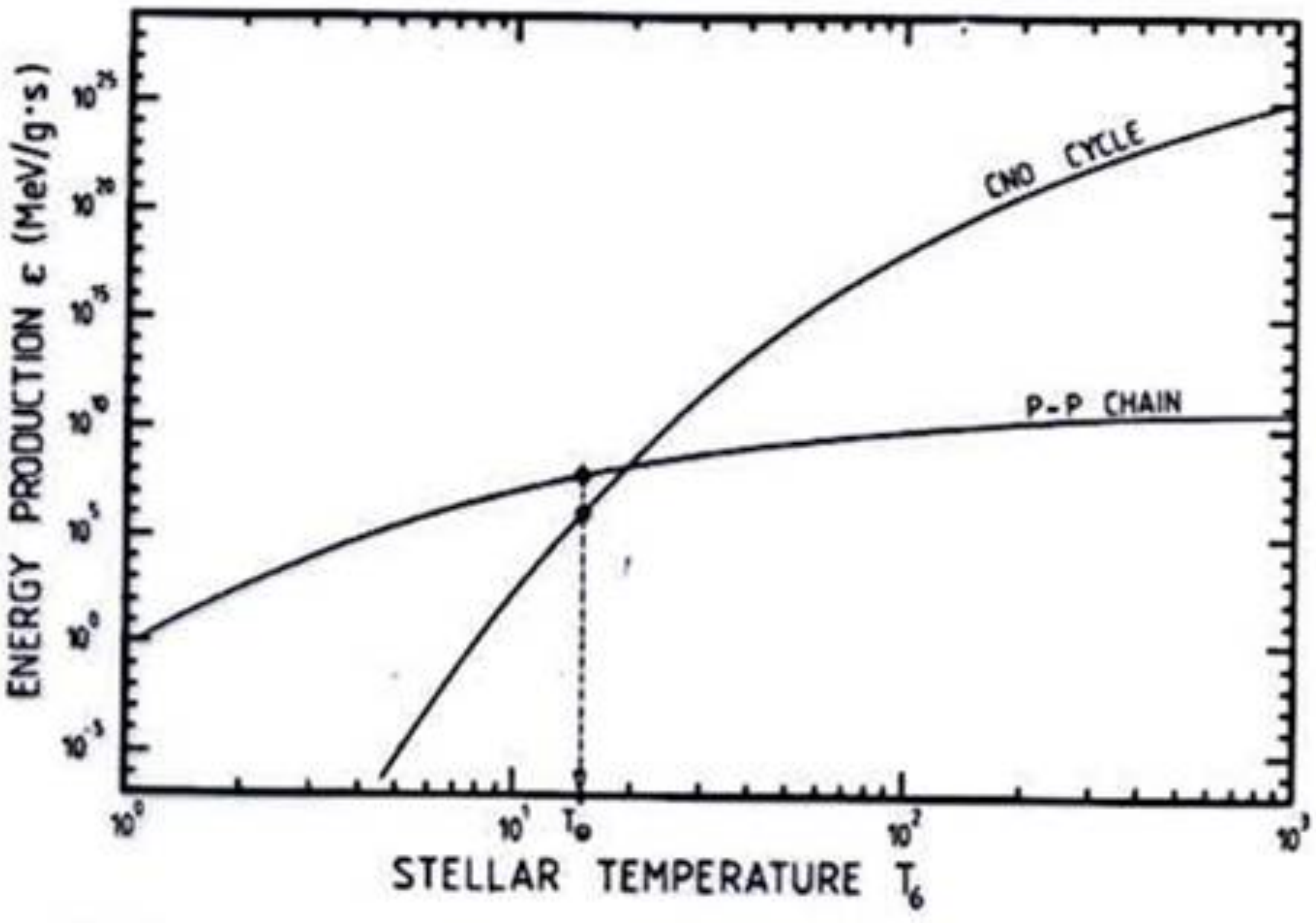
$$\epsilon_{CNO} \approx 3.4 \times 10^{-4} \rho X_{CNO} X_H (T/10^7)^{20} \text{ erg g}^{-1} \text{ s}^{-1}$$

where X_{CNO} is the mass fraction of carbon, nitrogen, and oxygen combined. This is based on the slowest reaction, $^{14}N(p,\gamma)^{15}O$.

$$\begin{aligned}\frac{\epsilon_{CNO}}{\epsilon_{pp}} &= \frac{3.4 \times 10^{-4}}{0.076}\left(\frac{X_{CNO}}{X_H}\right)(T/10^7)^{20-4} \\ &= (4.5 \times 10^{-3}(0.01/0.70)(T/10^7)^{16} \\ &= 6.4 \times 10^{-5}(T/10^7)^{16}\end{aligned}$$

which is greater than unity for T greater than 18 million K.

This turns out to mean that the CNO cycle dominates in (Population I) stars of over 2 $M_\odot$.



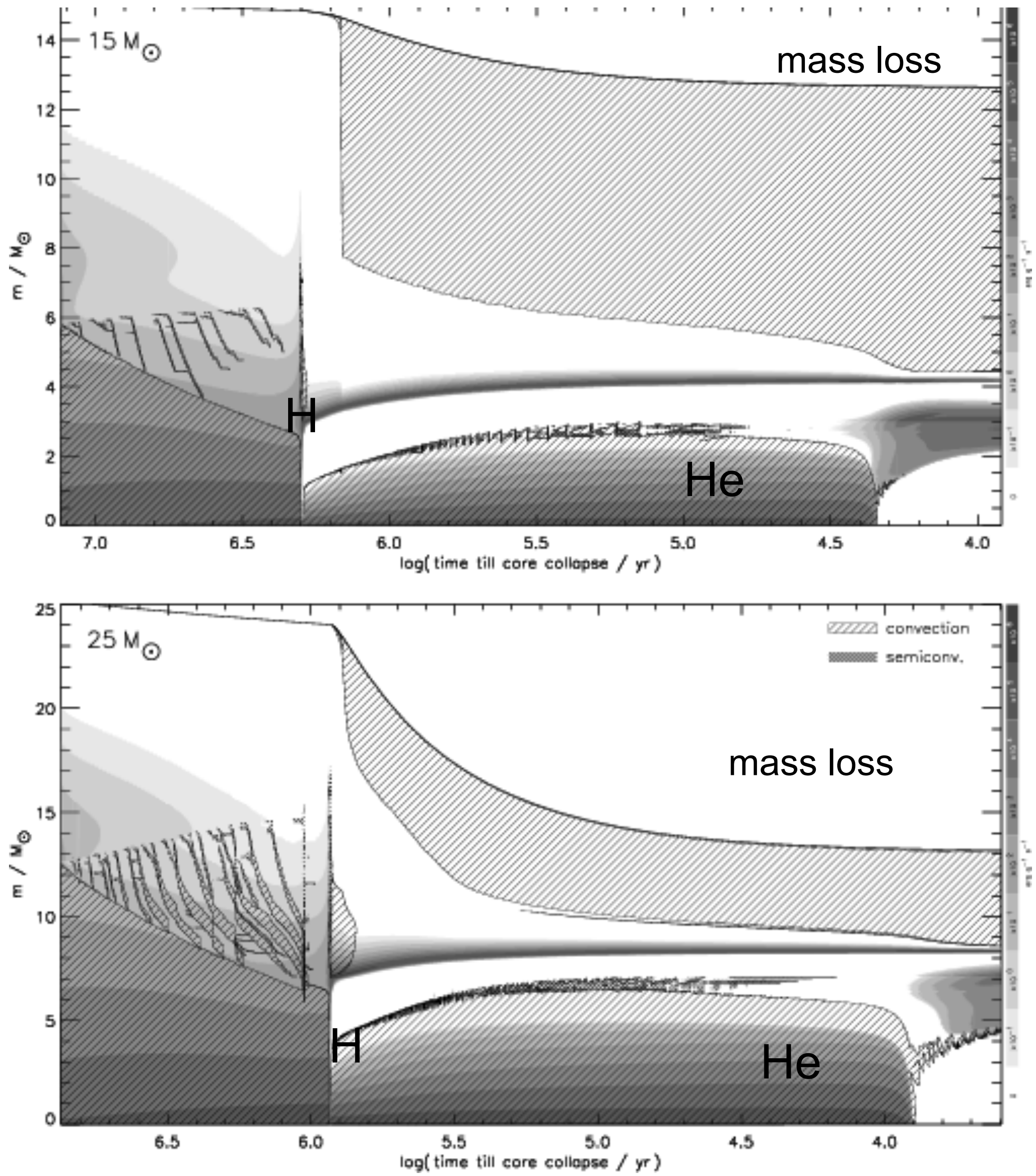
ENERGY PRODUCTION ε (MeV/g·s)
CNO CYCLE
P-P CHAIN
10^{-5}
10^{0}
10^{5}
10^{10}
10^{15}
10^{20}
10^{25}
10^{0}
10^{1}
$T_{\odot}$
10^{2}
10^{3}
STELLAR TEMPERATURE T_6

More Massive Main Sequence Stars

	$10\,M_\odot$	$25\,M_\odot$
X_H	0.32	0.35
L	$3.74\,x10^{37}$ erg s^{-1}	$4.8\,x10^{38}$ erg s^{-1}
T_{eff}	24,800 (B)	36,400 (O)
Age	16 My	4.7 My
T_{center}	$33.3\,x10^{6}$ K	$38.2\,x10^{6}$ K
ρ_{center}	8.81 g cm^{-3}	3.67 g cm^{-3}
τ_{MS}	23 My	7.4 My
R	$2.73\,x10^{11}$ cm	$6.19\,x\,10^{11}$ cm
P_{center}	$3.13\,x10^{16}$ dyne cm^{-2}	$1.92\,x10^{16}$ dyne cm^{-2}
$\%\,P_{radiation}$	10%	33%

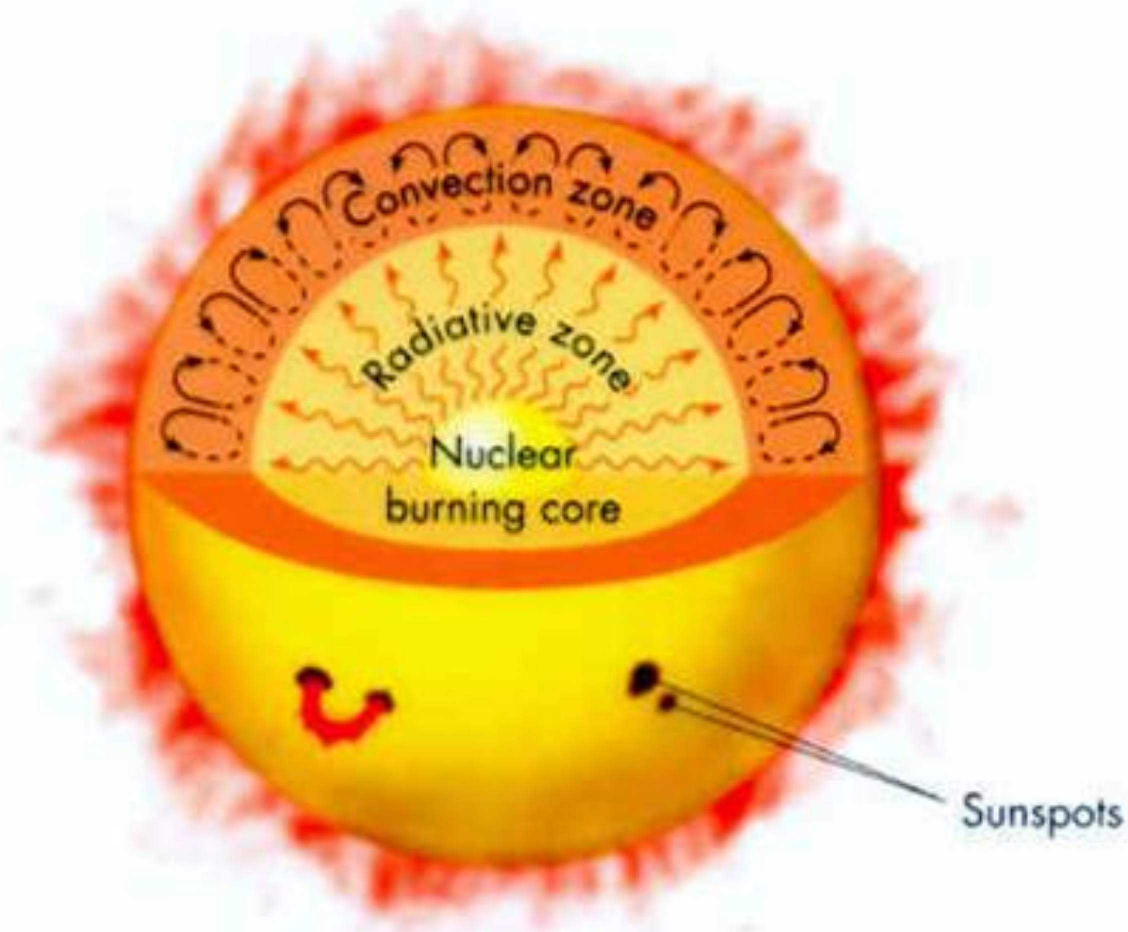
Surfaces stable (radiative, not convective); inner roughly 1/3 of mass is convective.

Convective history 15 $M_\odot$ and 25 $M_\odot$ stars

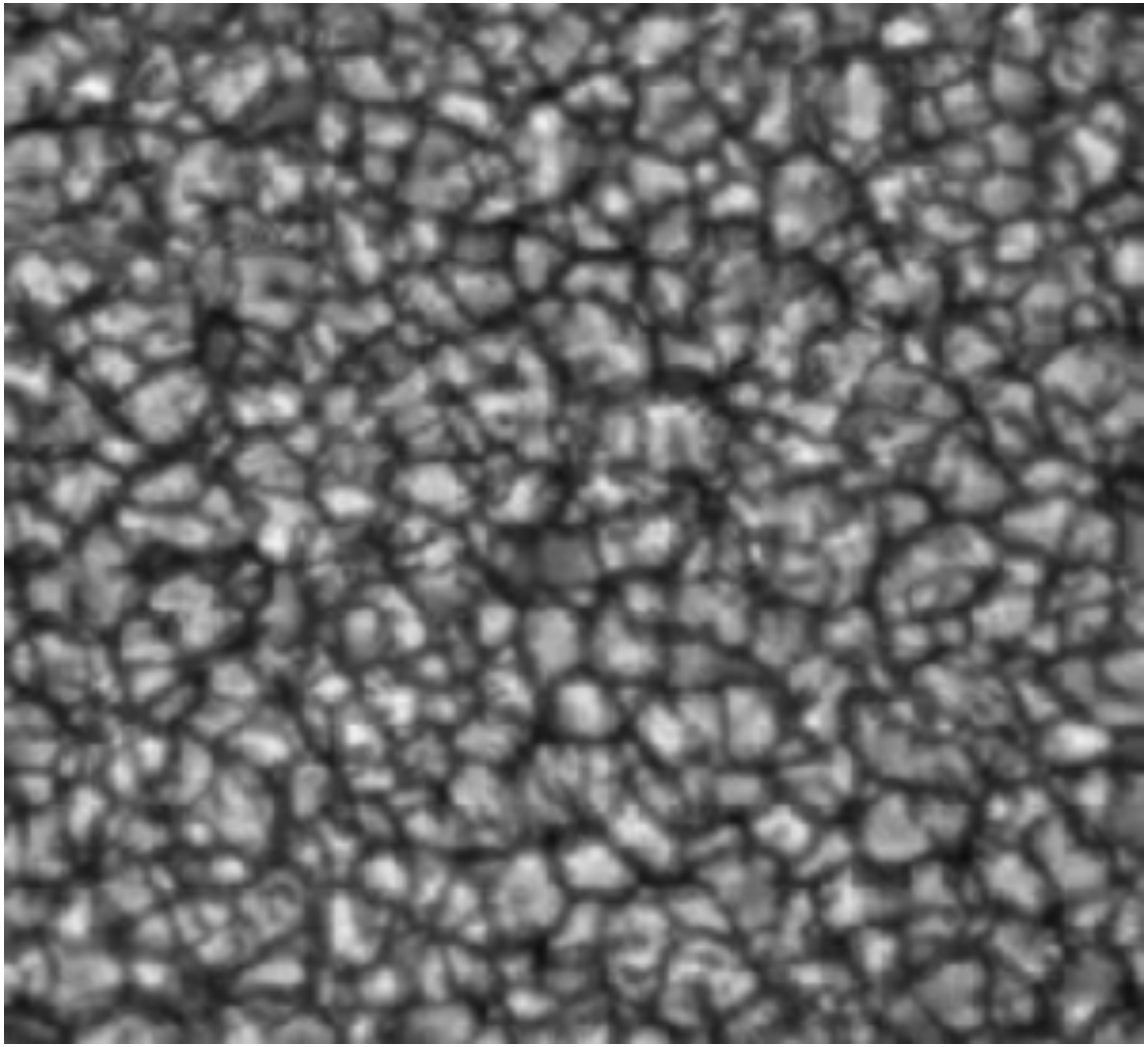


The 15 solar mass star is bigger than the 25 solar mass star when it dies

The Sun

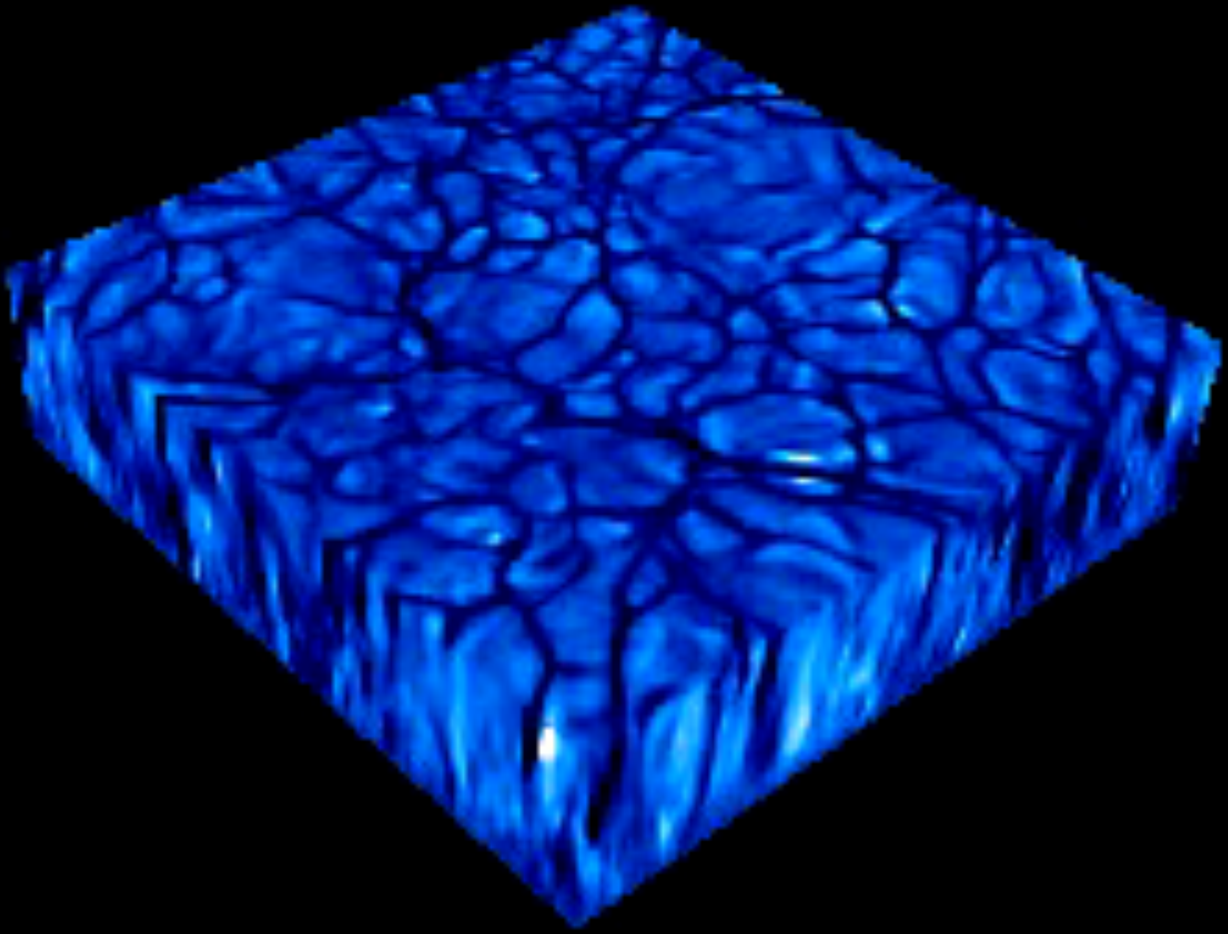


Convection zone ~2% of mass; ~25% of radius http://www3.kis.uni-freiburg.de/~pnb/granmovtext1.html

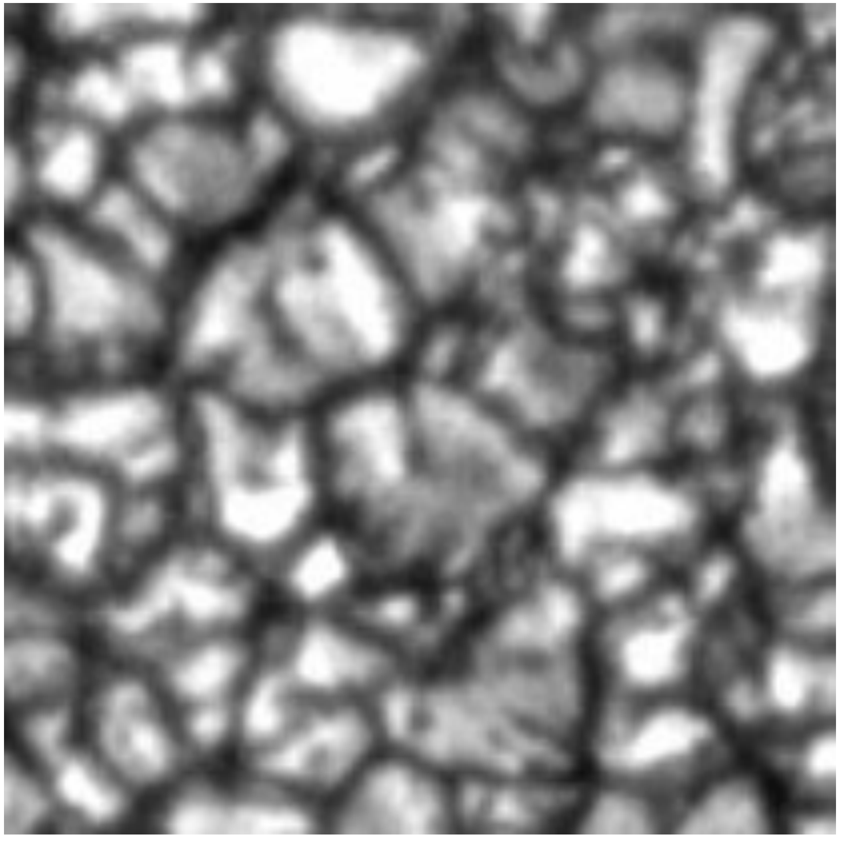


June 5, 1993

Matter rises in the centers of the granules, cools then falls down. Typical granule size is 1300 km. Lifetimes are 8-15 minutes. Horizontal velocities are 1 – 2 km s^{-1}. The movie is 35 minutes in the life of the sun



Andrea Malagoli



35 minutes 4680 +- 50 A filter

size of granules 250 - 2000 km

smallest size set by transmission
through the earth's atmosphere

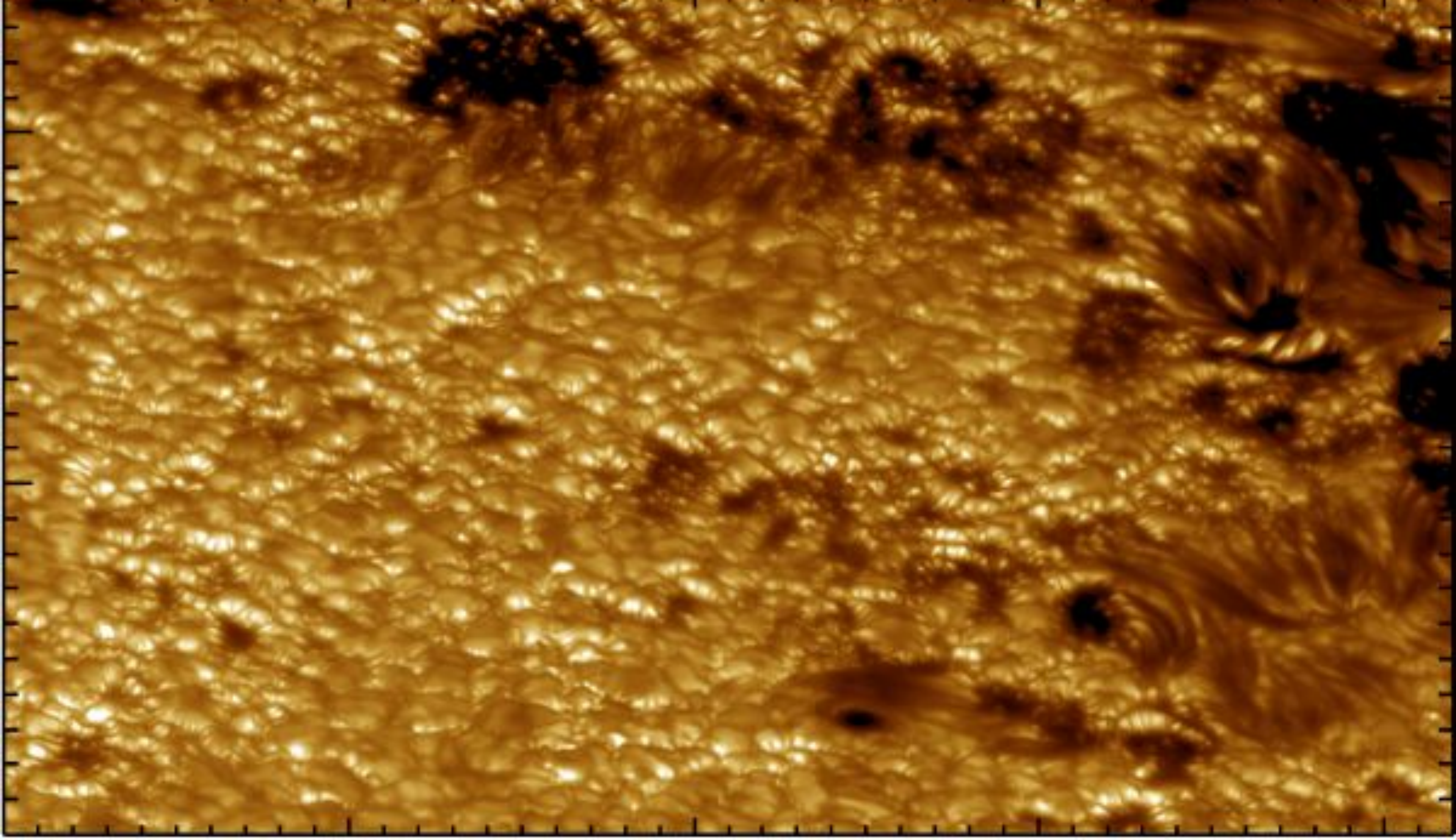
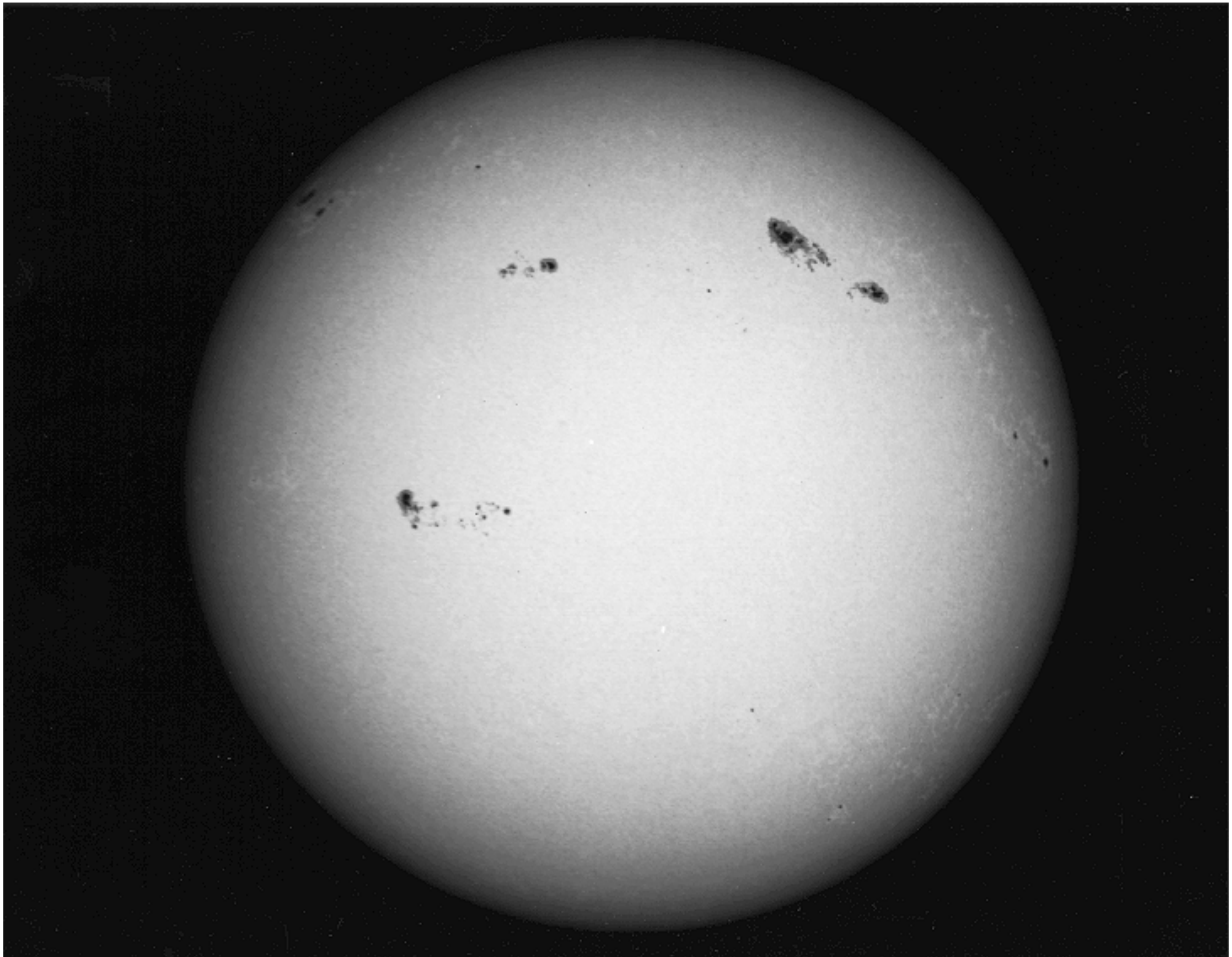


Image of an active solar region taken on July 24, 2002 near the eastern limb of the Sun.

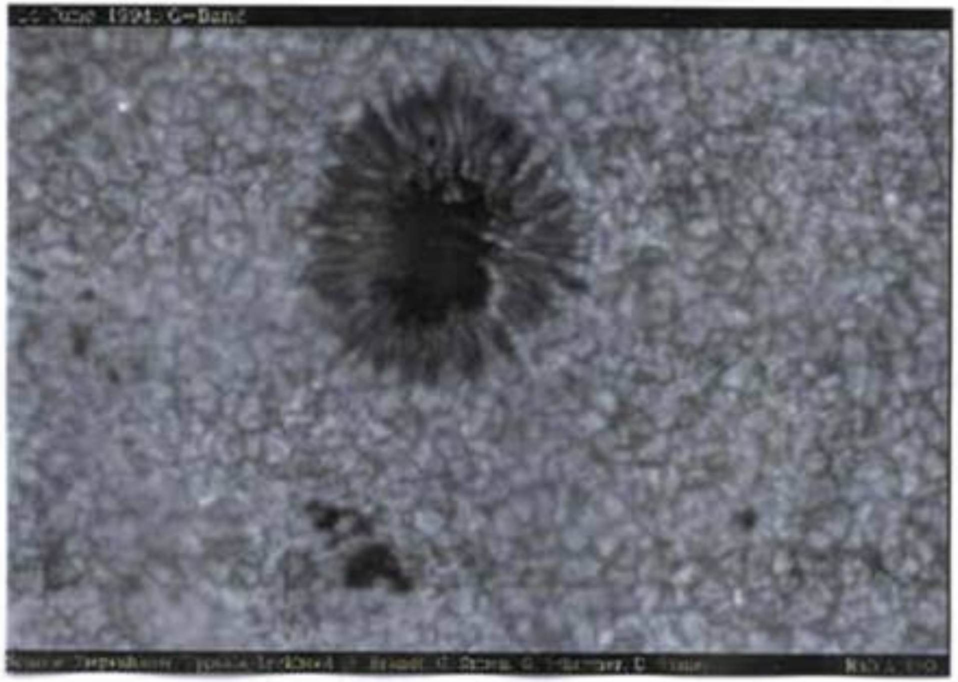
Looking more towards edge of the sun
to see 3D structure

http://www.boston.com/bigpicture/2008/10/the_sun.html

http://www.uwgb.edu/dutchs/planets/sun.htm

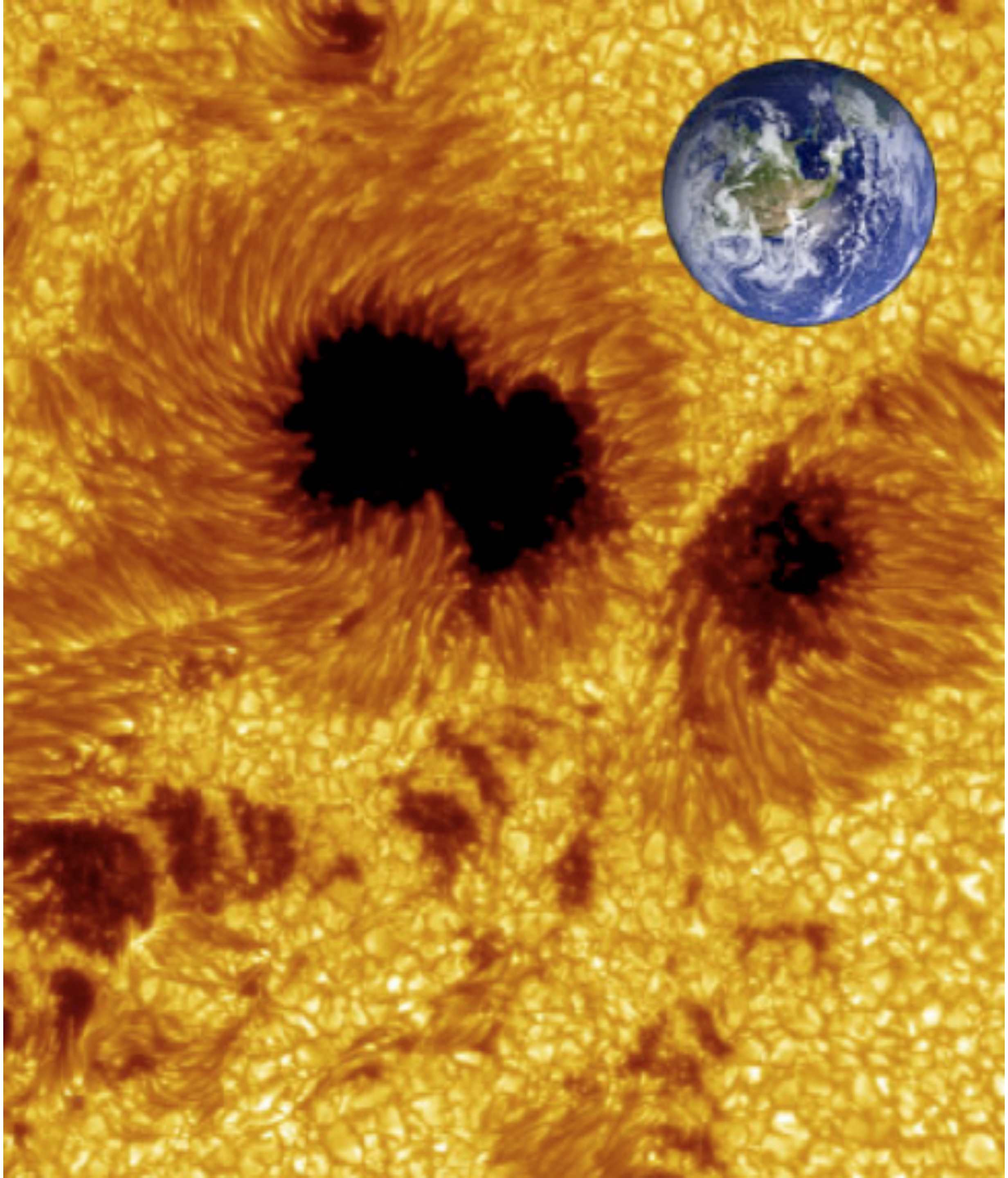


sunspots discovered by Galileo and Harriot 1610

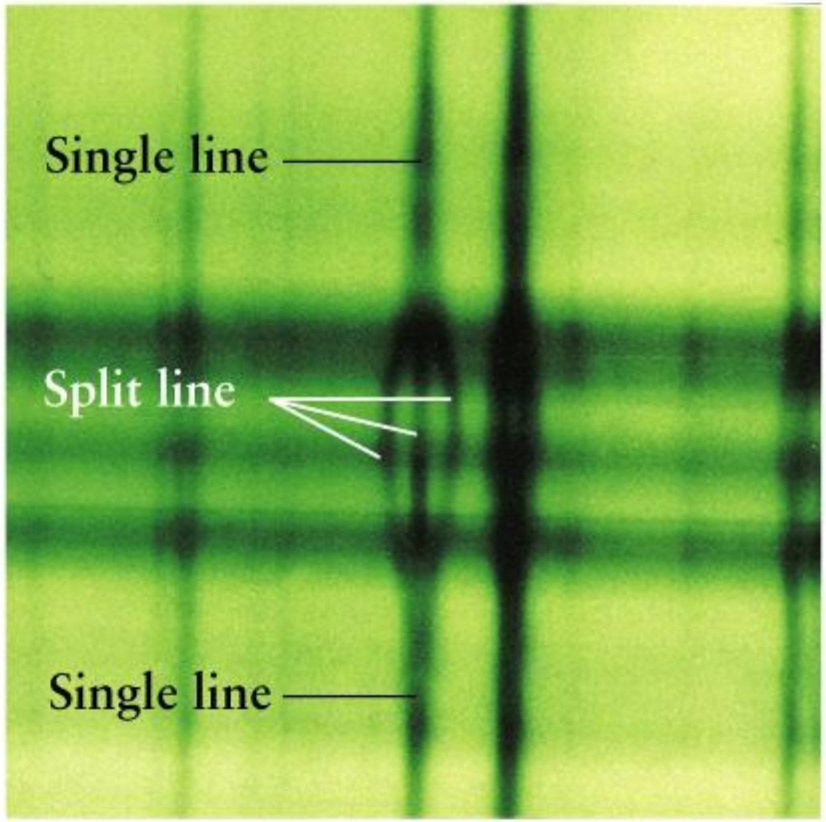


A moderately large sunspot. The Earth would just cover the darkest area. The darkest area is called the "umbra". The surrounding radial darkness the "penumbra".

The umbra is cooler by about 1000 K than the surrounding star (note granulation). The magnetic field in the sunspot is typically 1000 - 4000 Gauss. (The Earth's magnetic field is about 1 Gauss; the sun, on the average < 100 Gauss).



Zeeman Effect

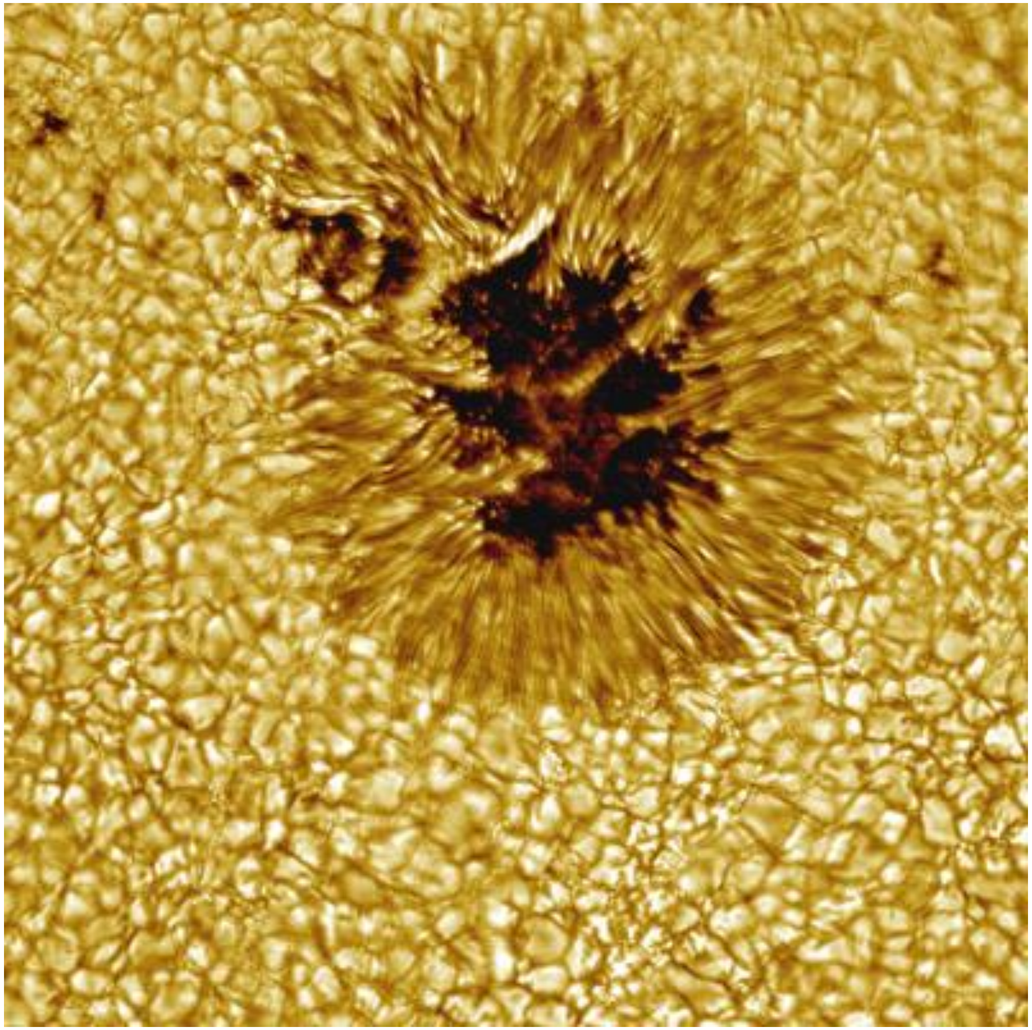


outside sunspot

inside sunspot

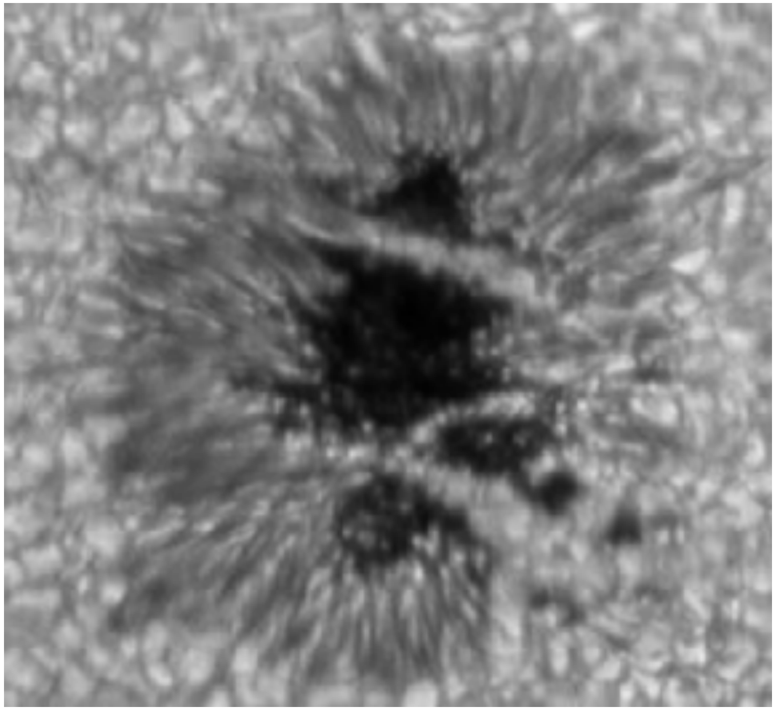
Breaks "degeneracy" in energy of states with different "spins"

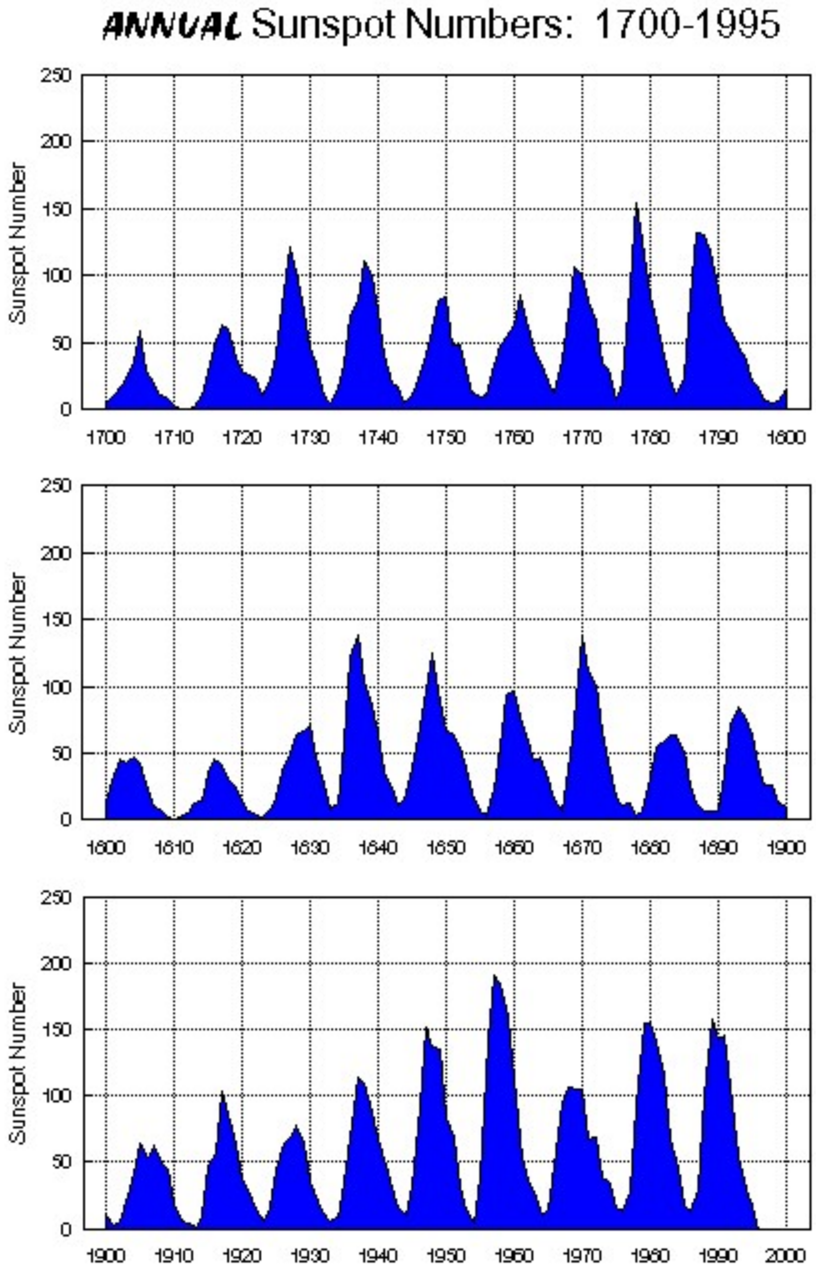
Strength of the field can be measured by the degree of splitting



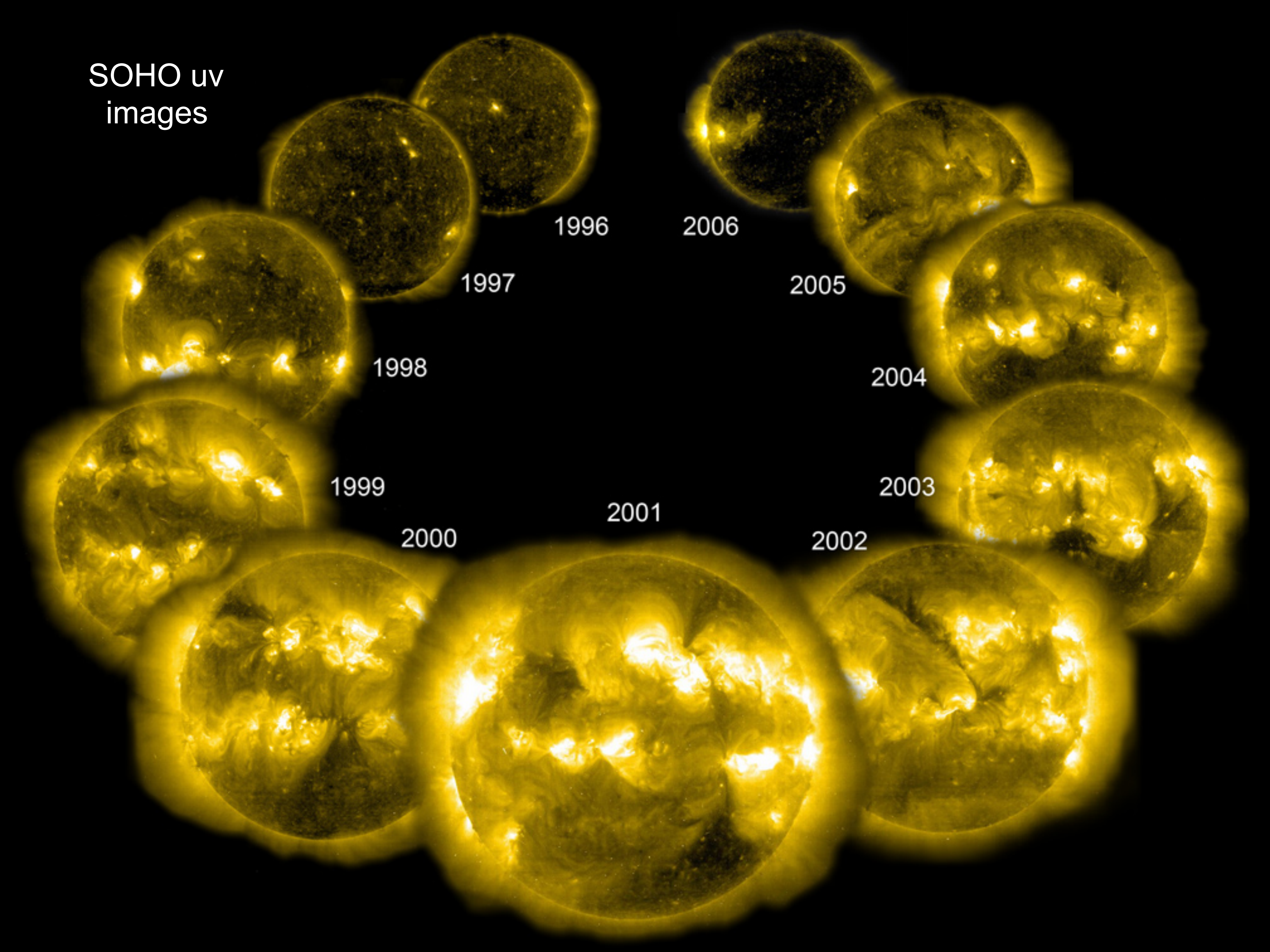
about 25,000 km across

1.1 hours



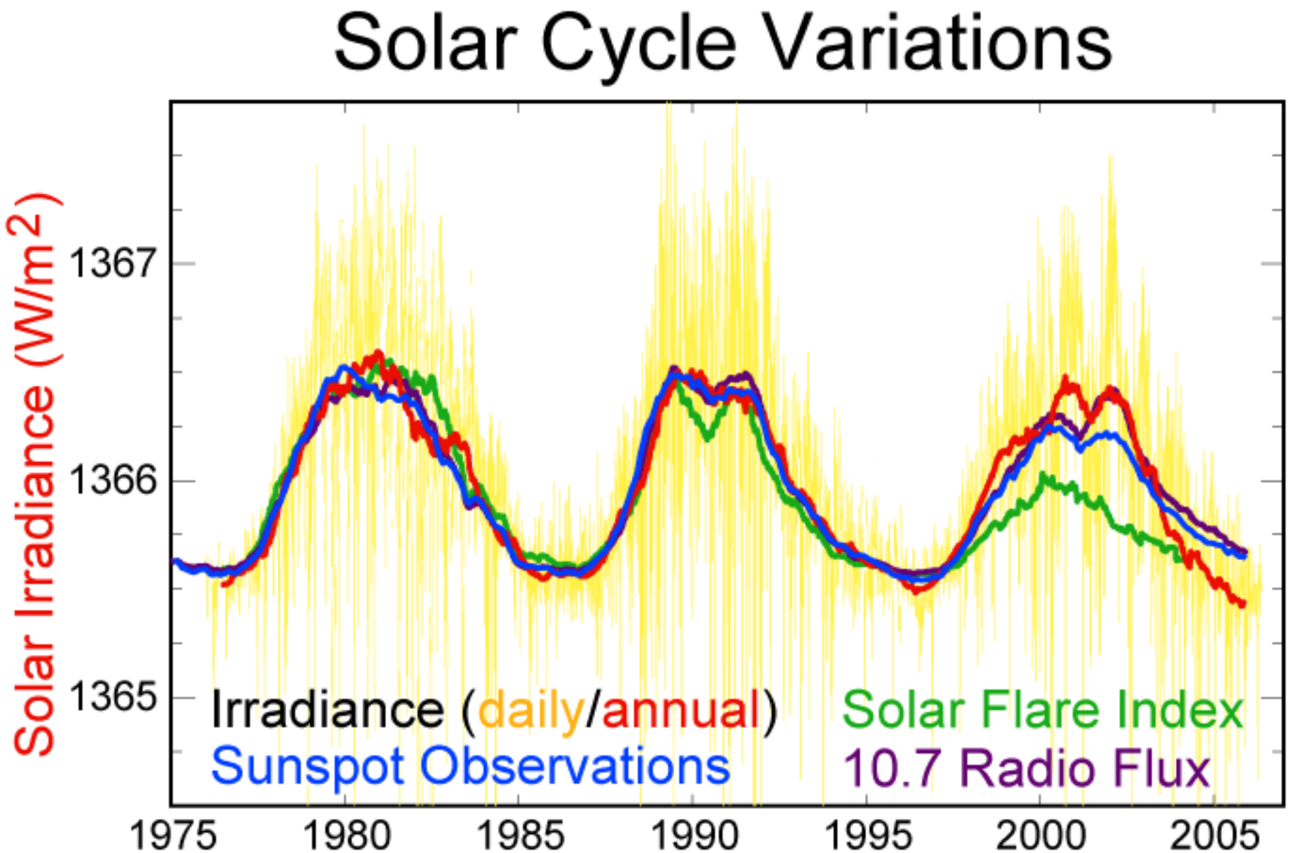


11 year cycle



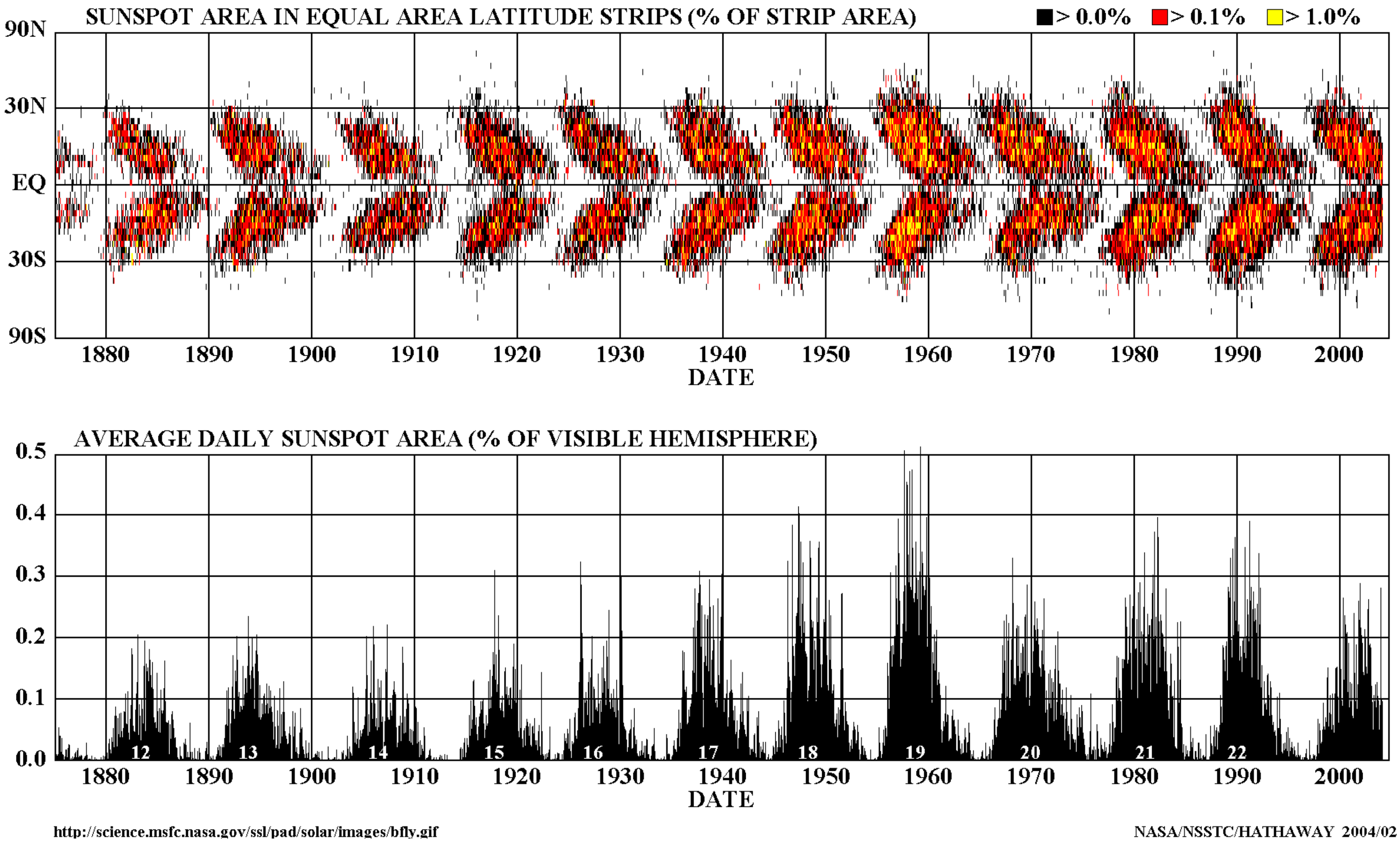
SOHO uv
images
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006

The sun actually changes its luminosity a little …



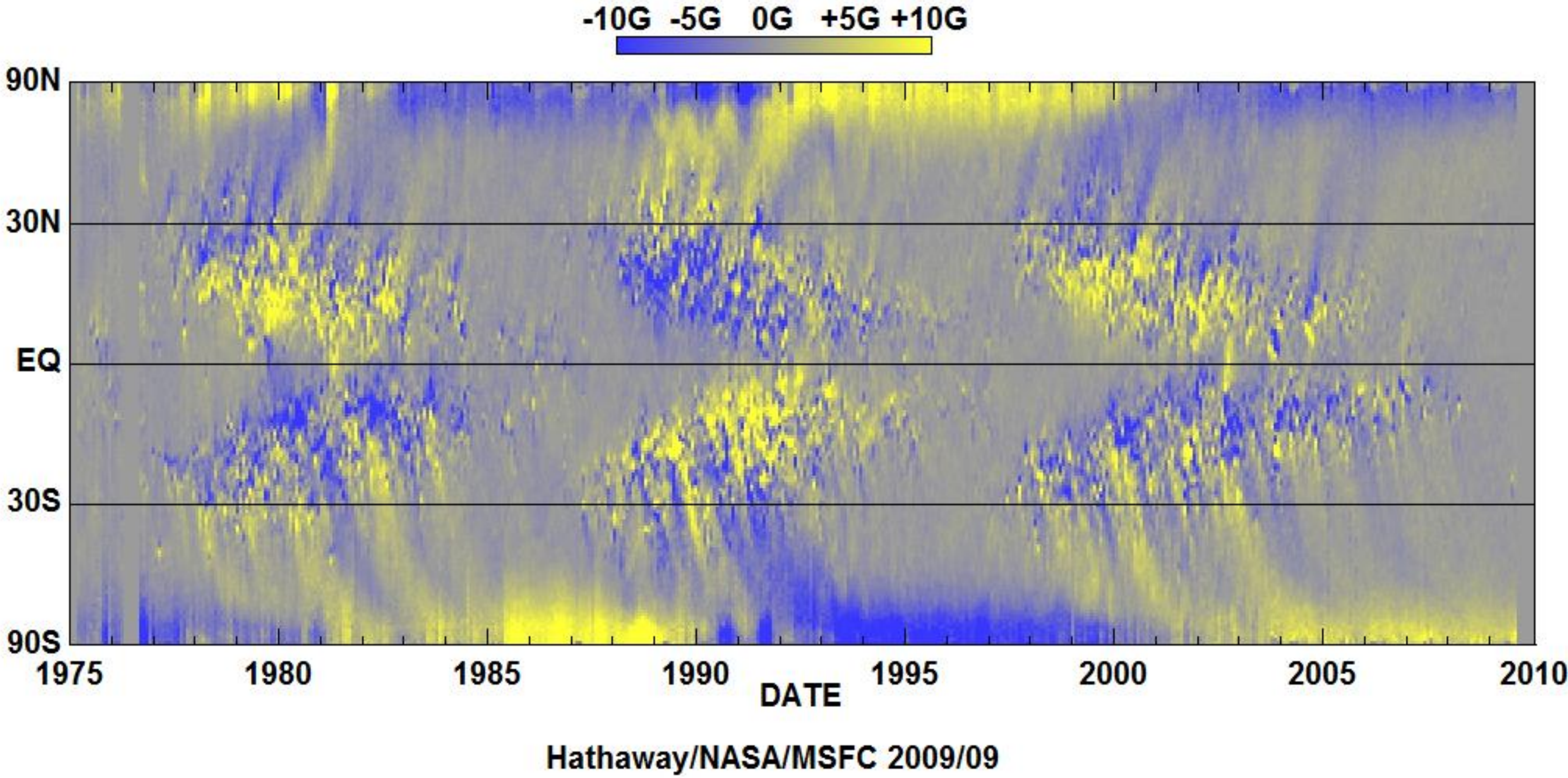
Variability in solar irradiance was undetectable prior to satellite observations starting in 1978

Sunspot activity as a function of latitude

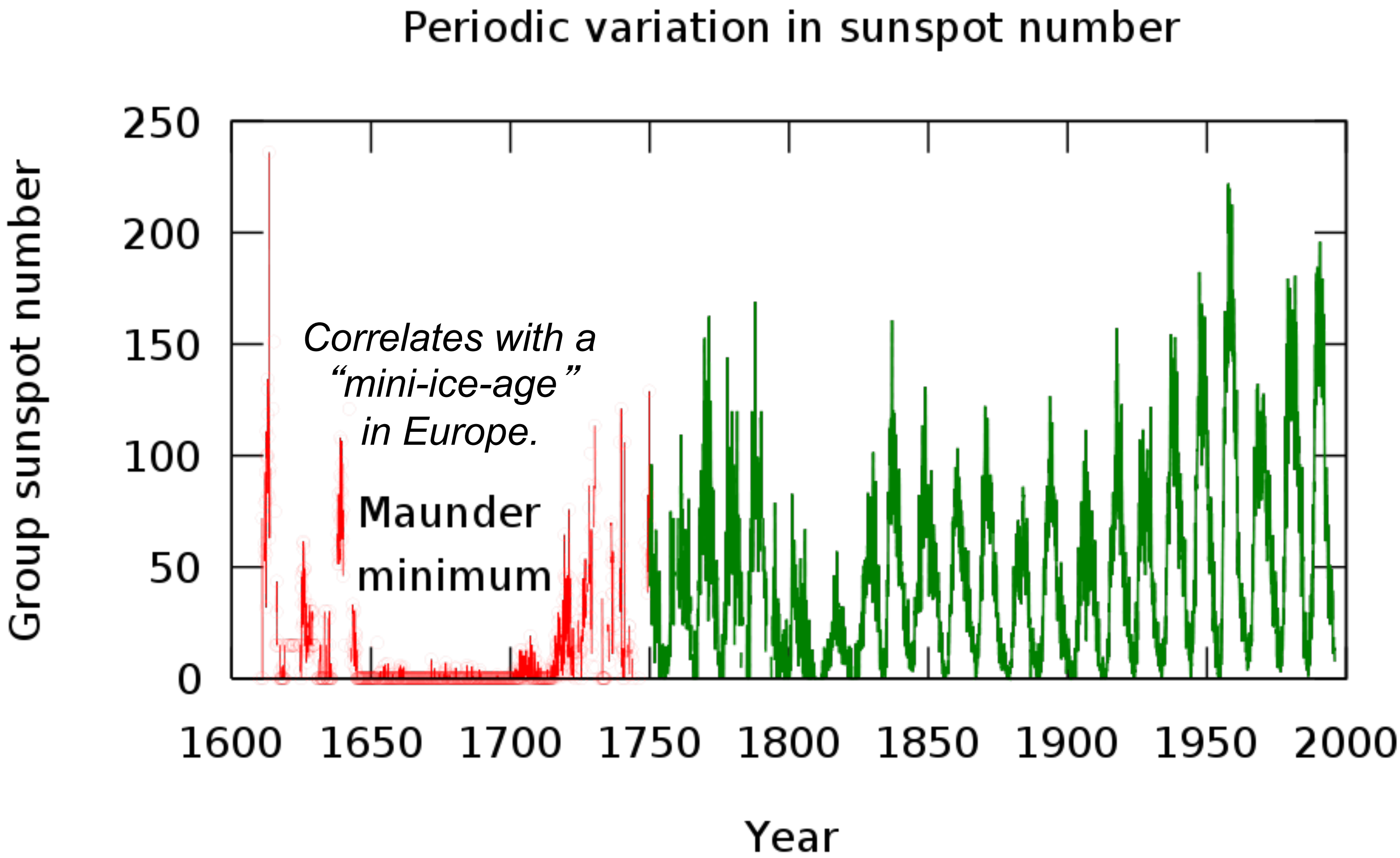


Spots start to happen at high and low latitude and then migrate towards the equator

Radial magnetic field



Complete cycle takes 22 years and the suns magnetic field reverses every 11 years



Cause - Multipolar field variation (quadrupole instead of dipole)?
Fluctuations at tacyocline?

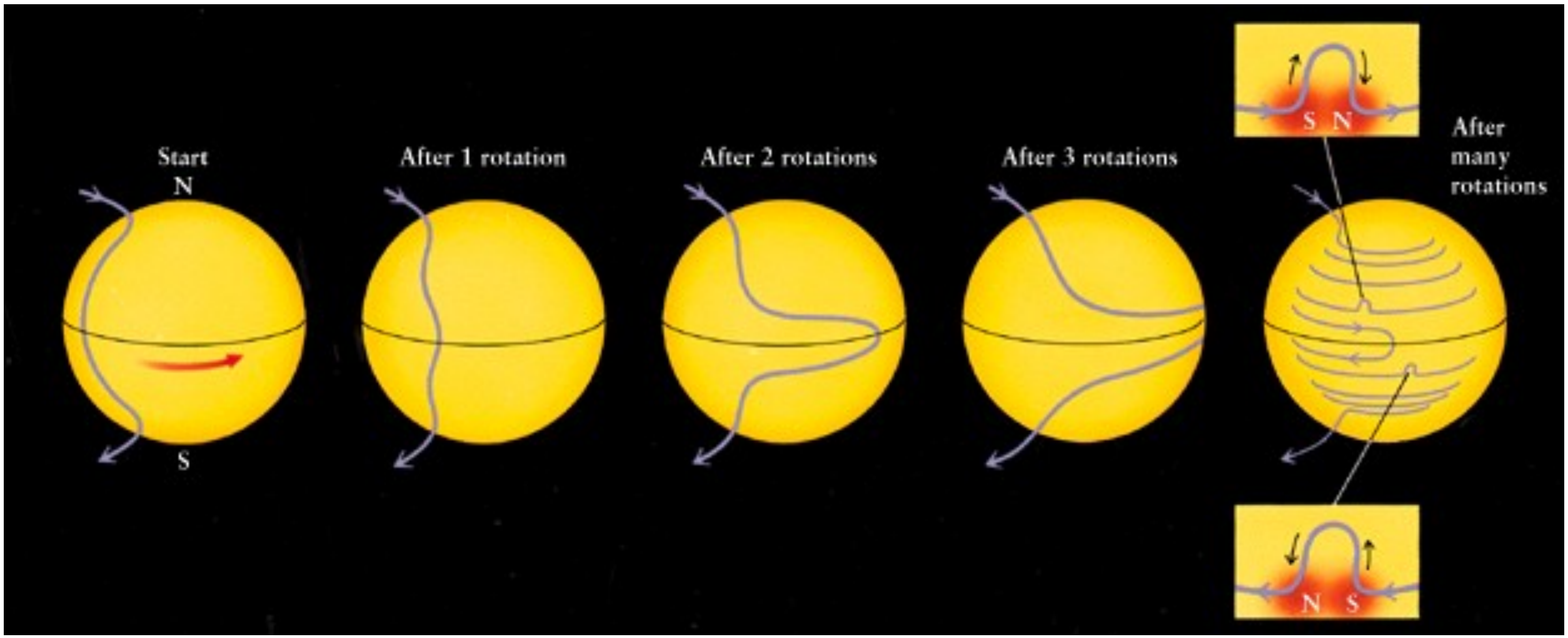
Little Ice Age

The exact cause of the solar cycle is not well understood, but It is known that the magnetic field of the sun (or at least its surface field) goes through reversals every ~11 years. The whole cycle takes 22 years.

In the “Babcock model”, the cycle is caused by the *differential rotation of the sun*. In three years the equatorial regions go round 5 additional revolutions compared with the polar ones. This winds up the field and creates stress that is released in part by surface activity (flares, sunspots, etc).

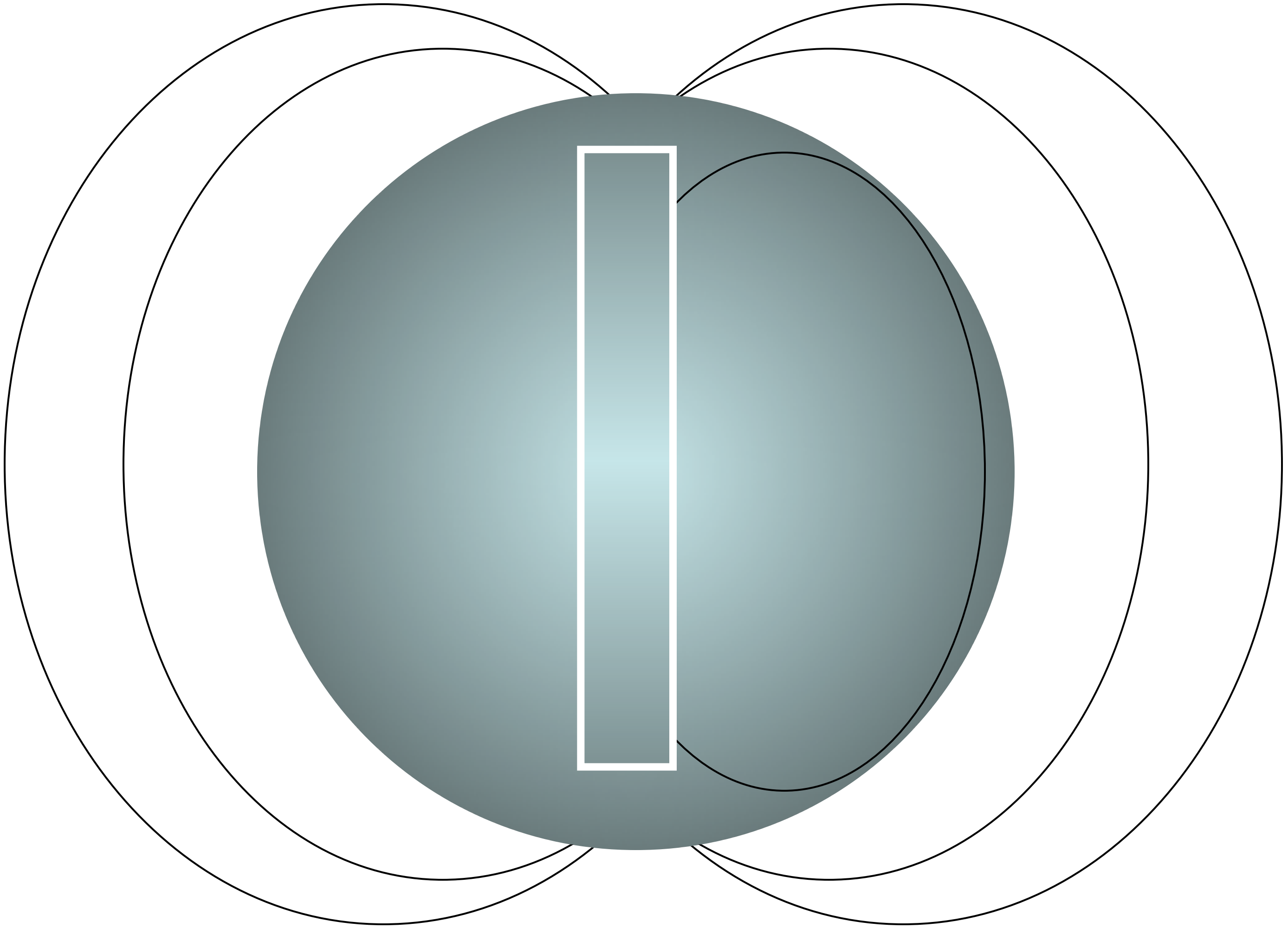
Rotation:
26.8 d at equator
31.8 d at 75^o latitude

This differential rotation exists only in the convection zone. The radiative core rotates rigidly.



Babcock Model

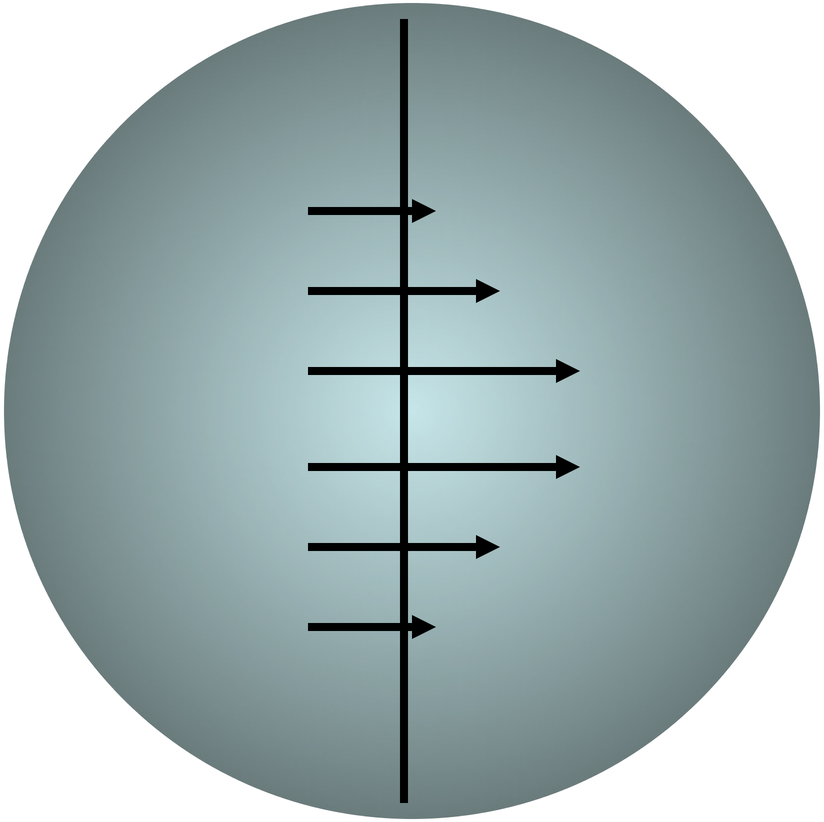
Magnetic
Field



Babcock Model

Magnetic Field

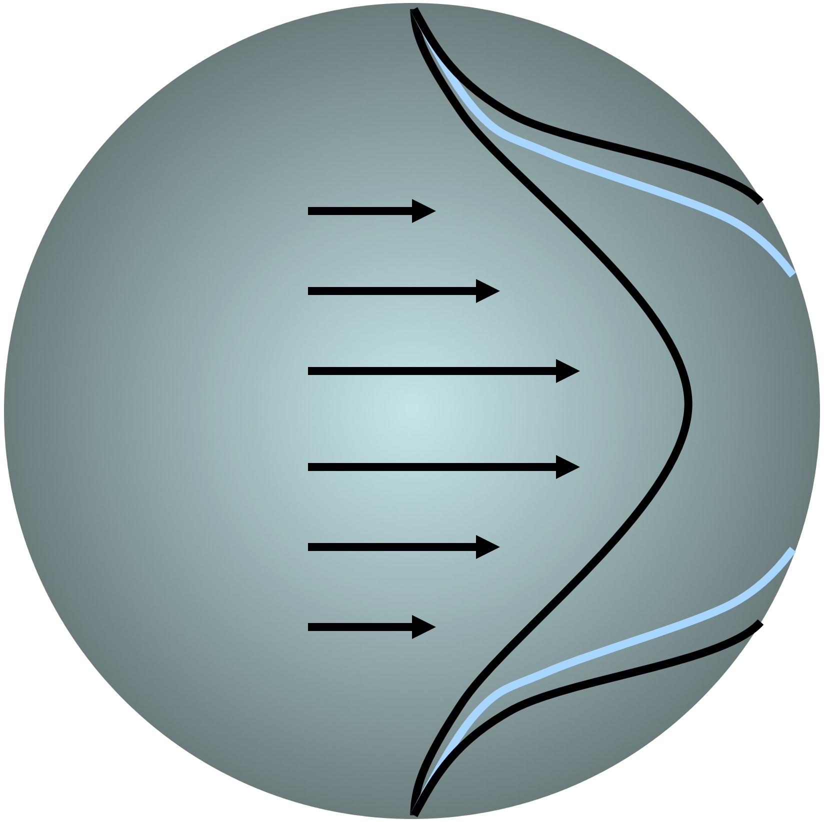
Differential Rotation



Babcock Model

Magnetic Field

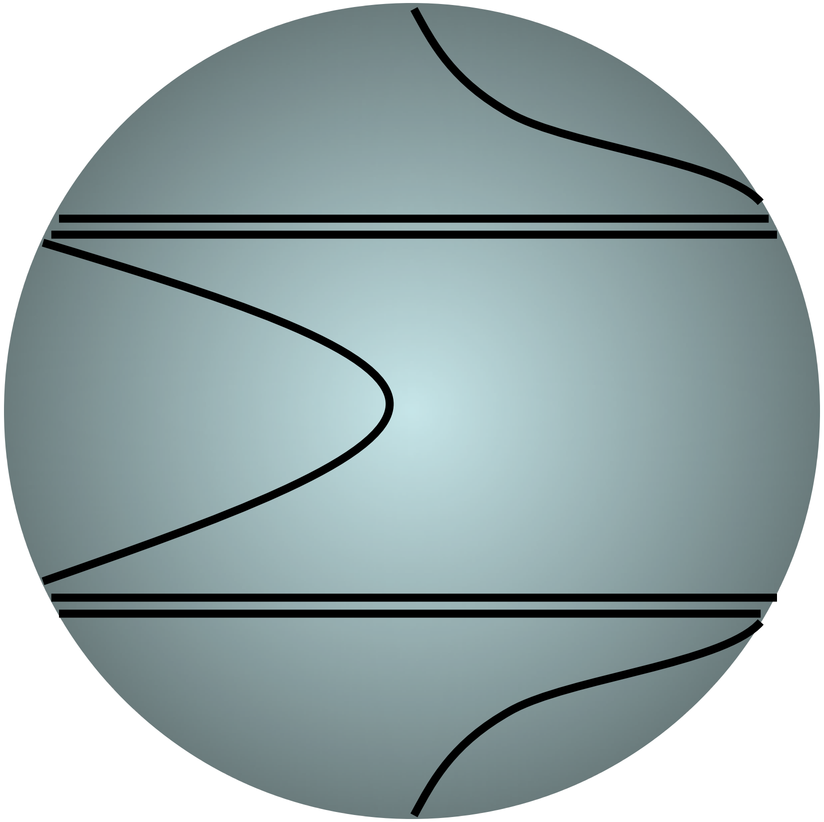
Differential Rotation

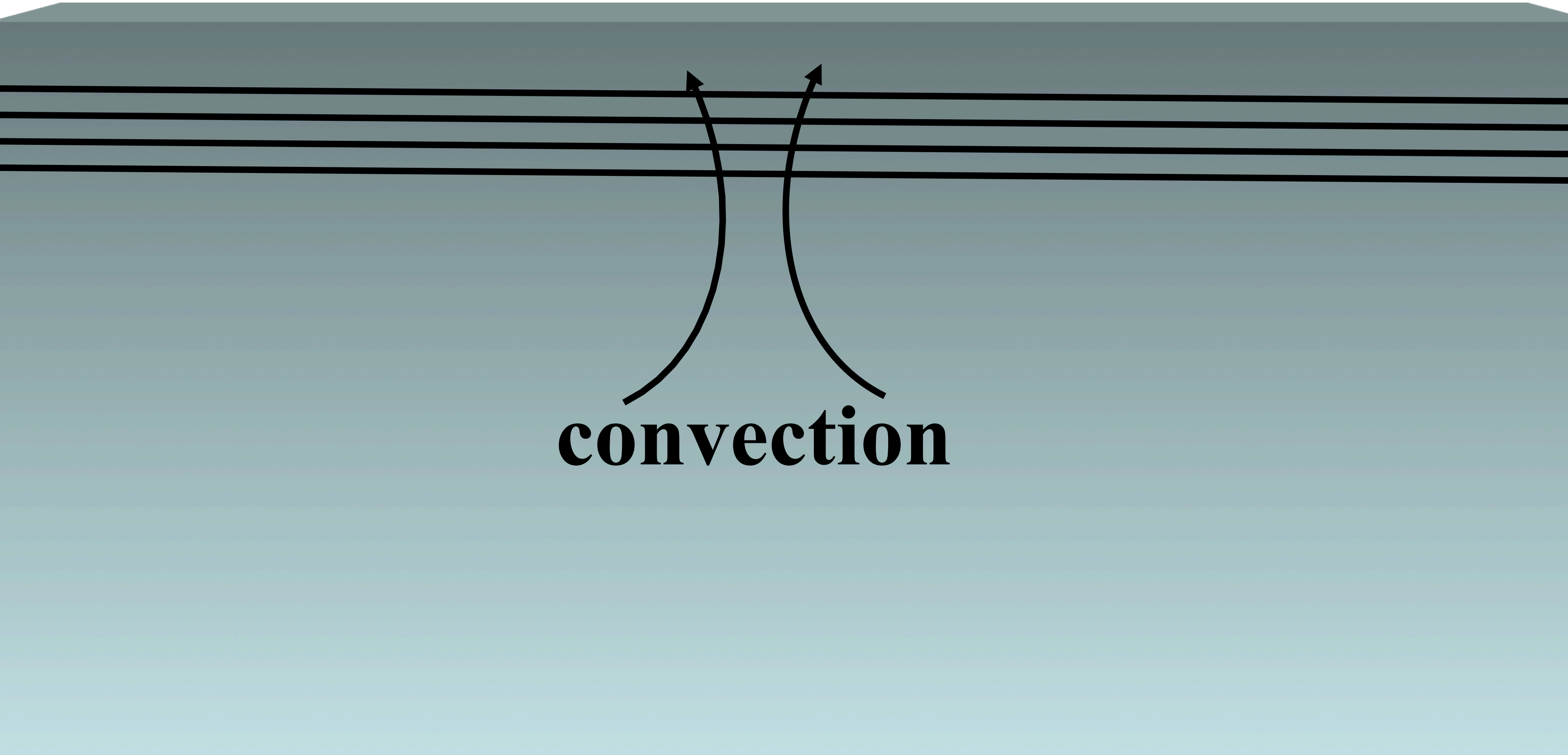


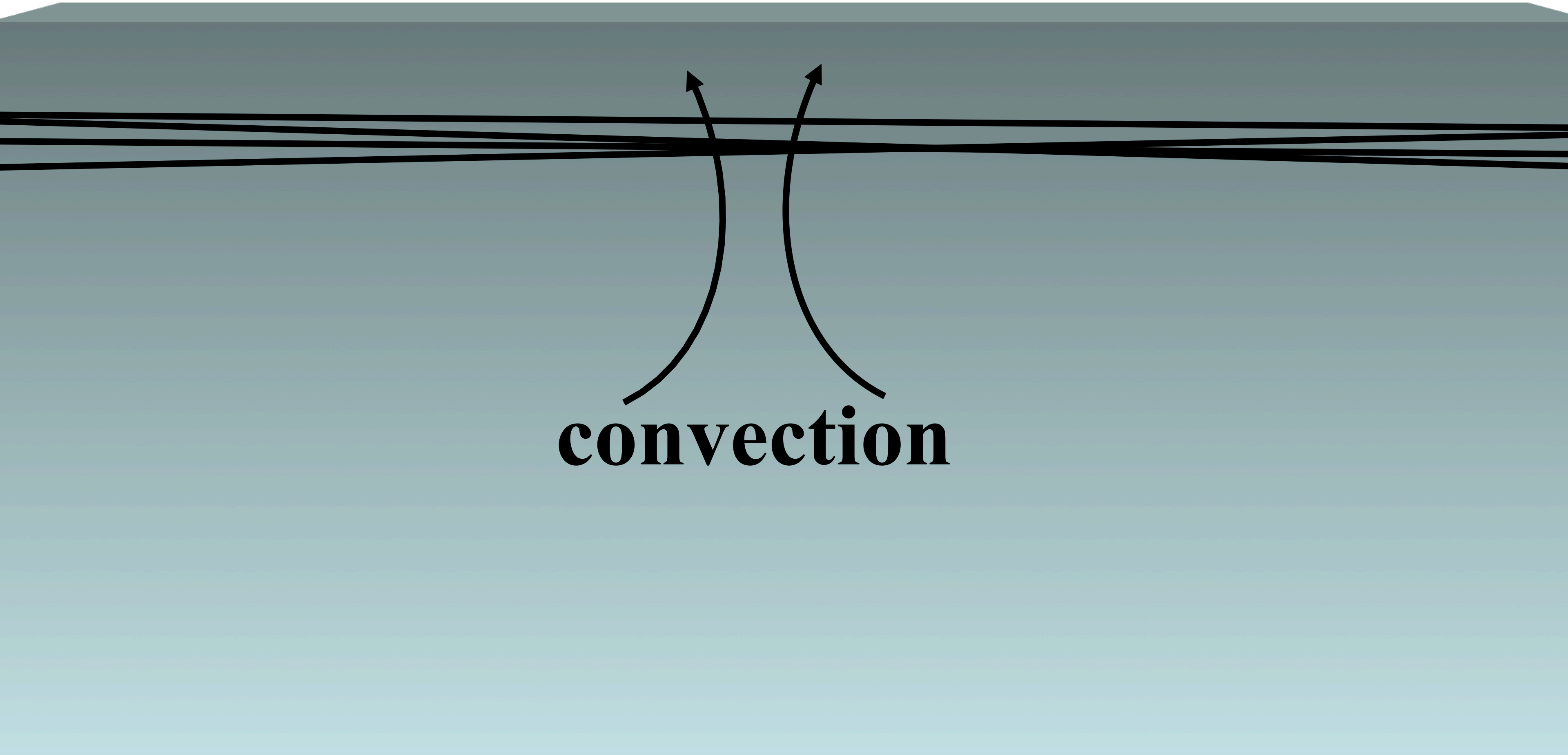
Babcock Model

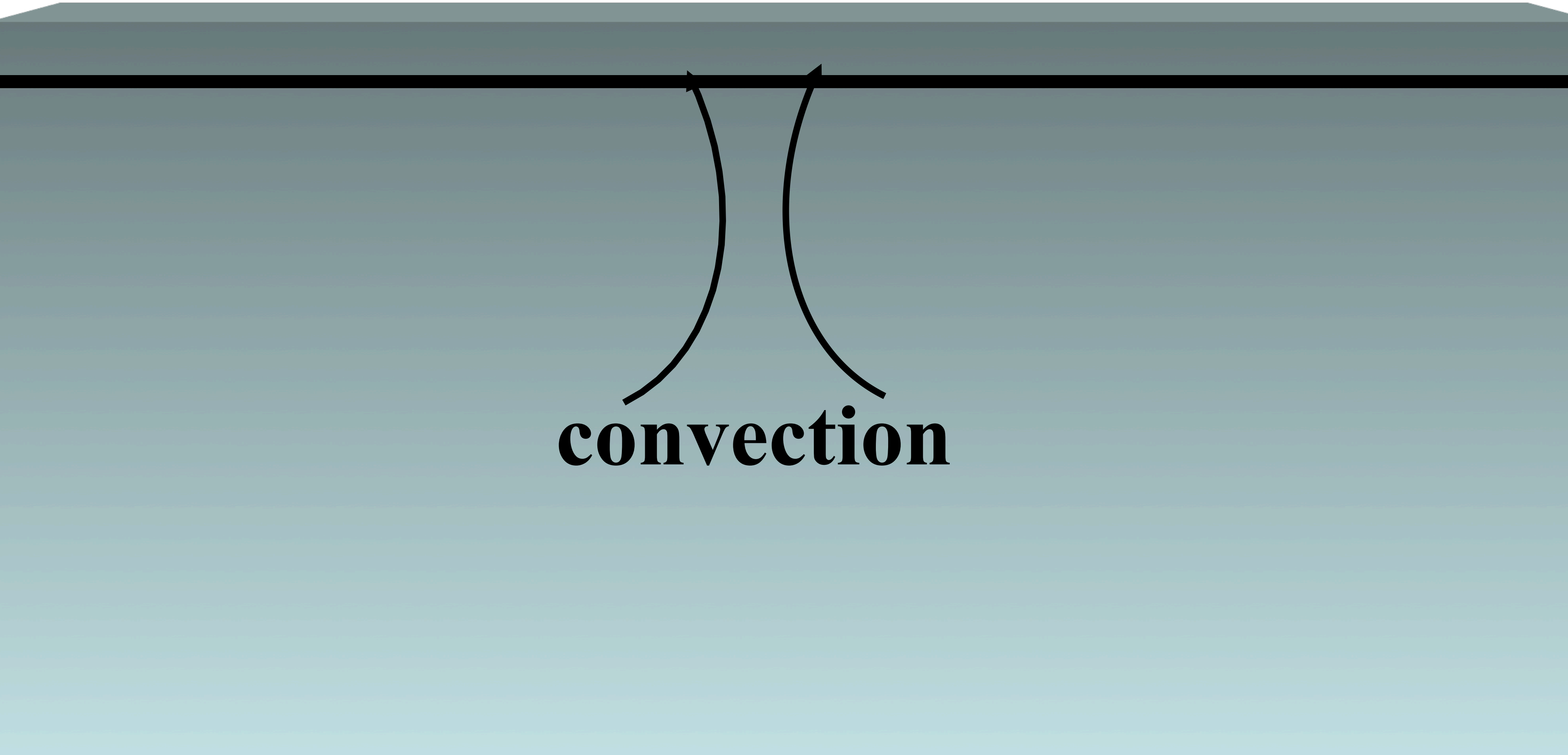
Magnetic Field

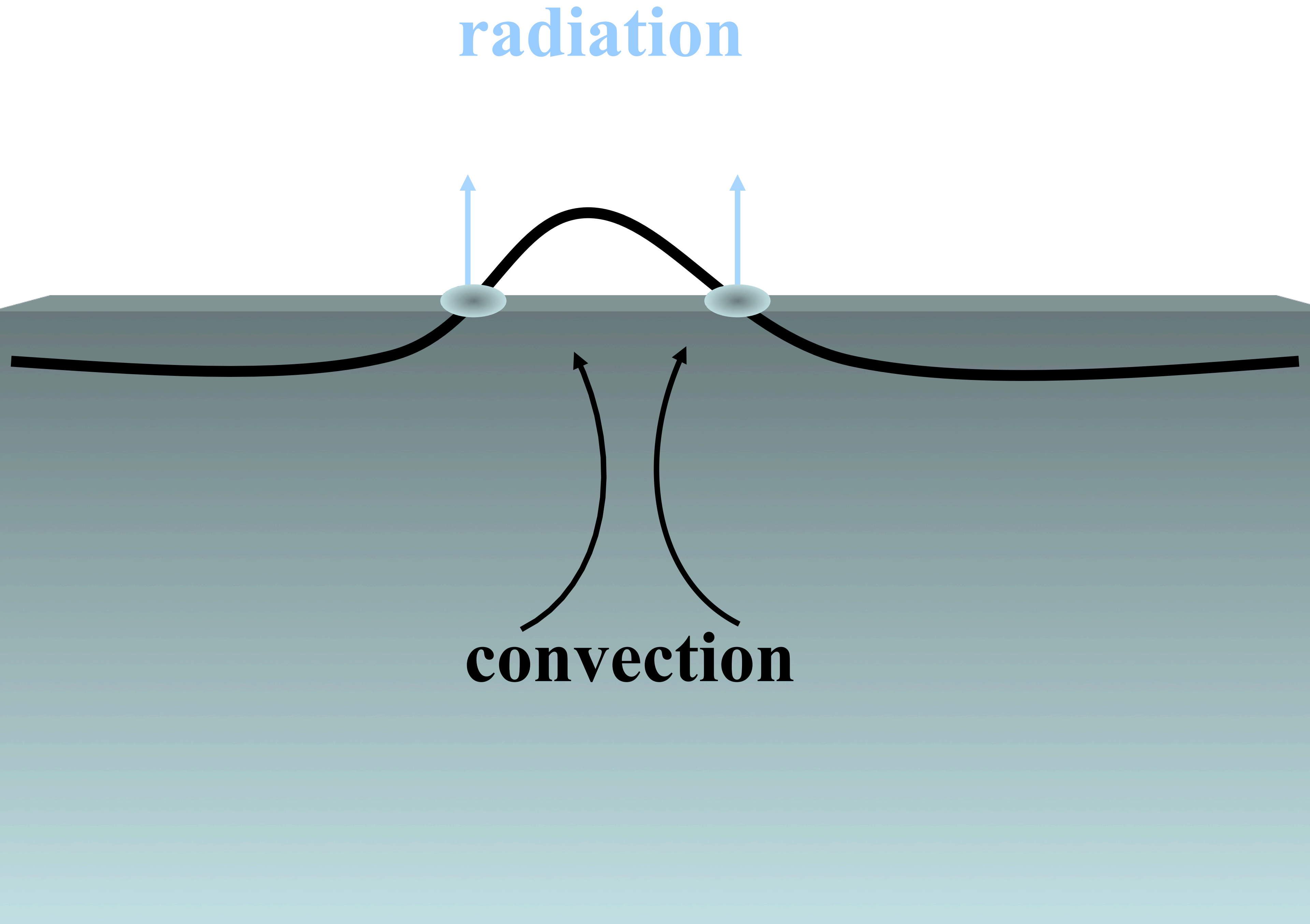
Differential Rotation

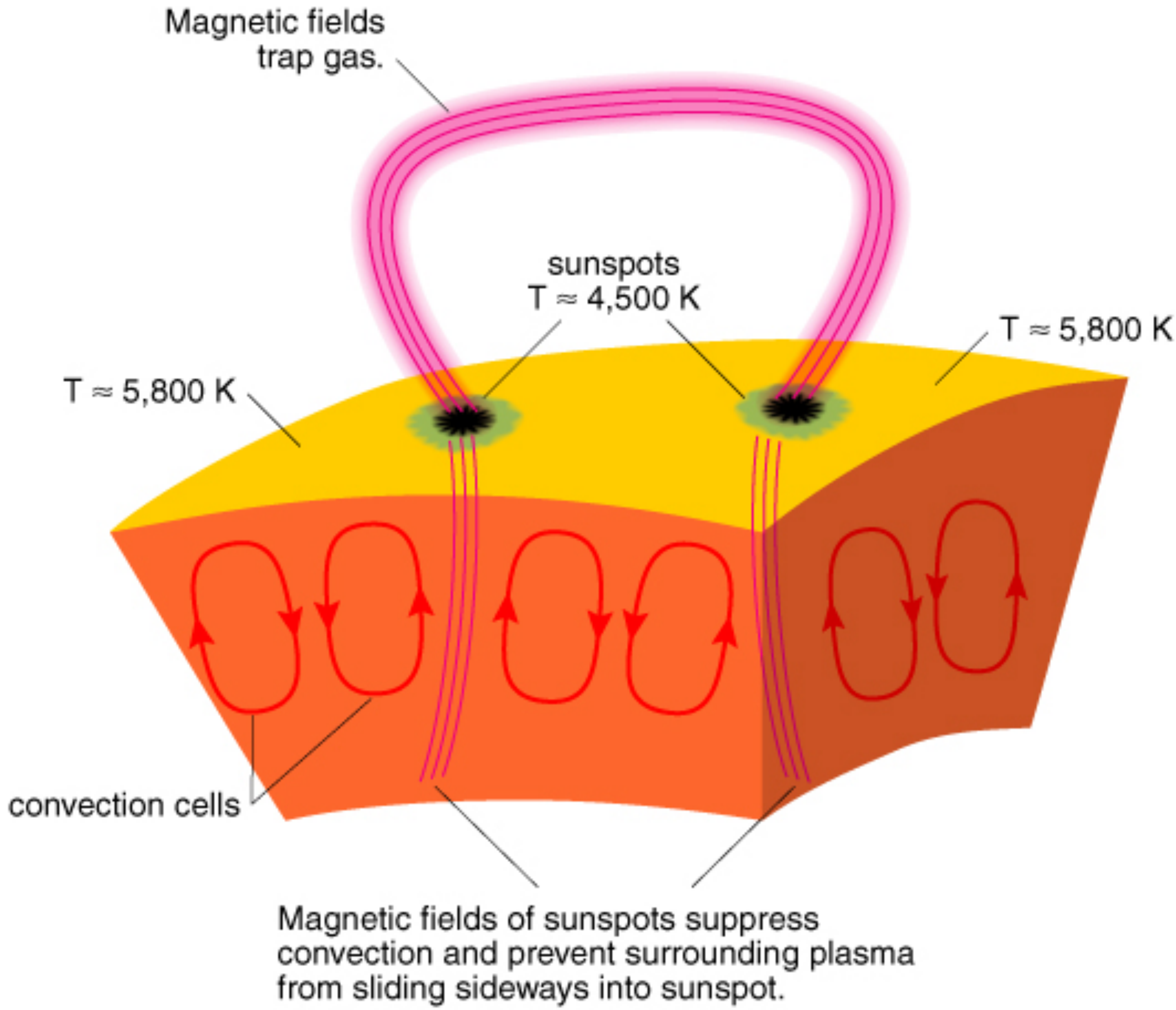



convection


convection


convection


radiation
convection

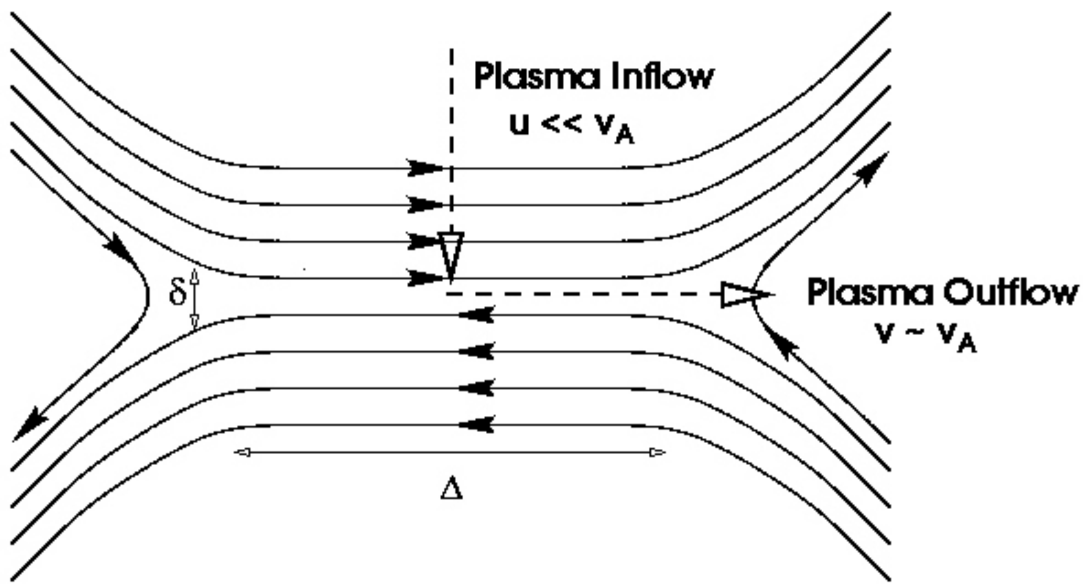

Magnetic fields
trap gas.
sunspots
T ≈ 4,500 K
T ≈ 5,800 K
T ≈ 5,800 K
convection cells
Magnetic fields of sunspots suppress convection and prevent surrounding plasma from sliding sideways into sunspot.

The smallest loop is 3 times the size of the Earth

Energy stored in magnetic field

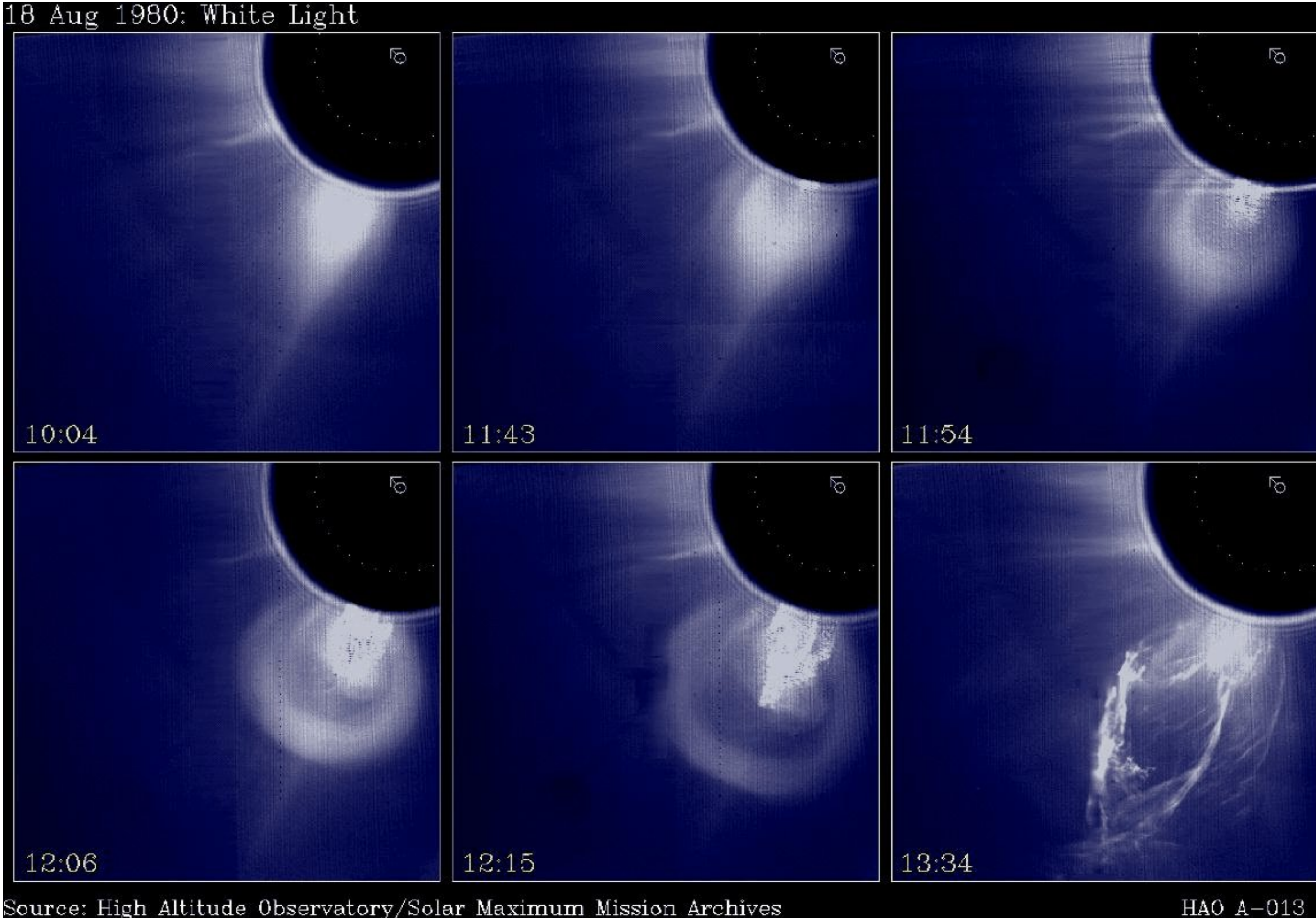
$$E = B^2 / 8\pi \quad \text{erg cm}^{-3}$$

Can be released by "reconnection"

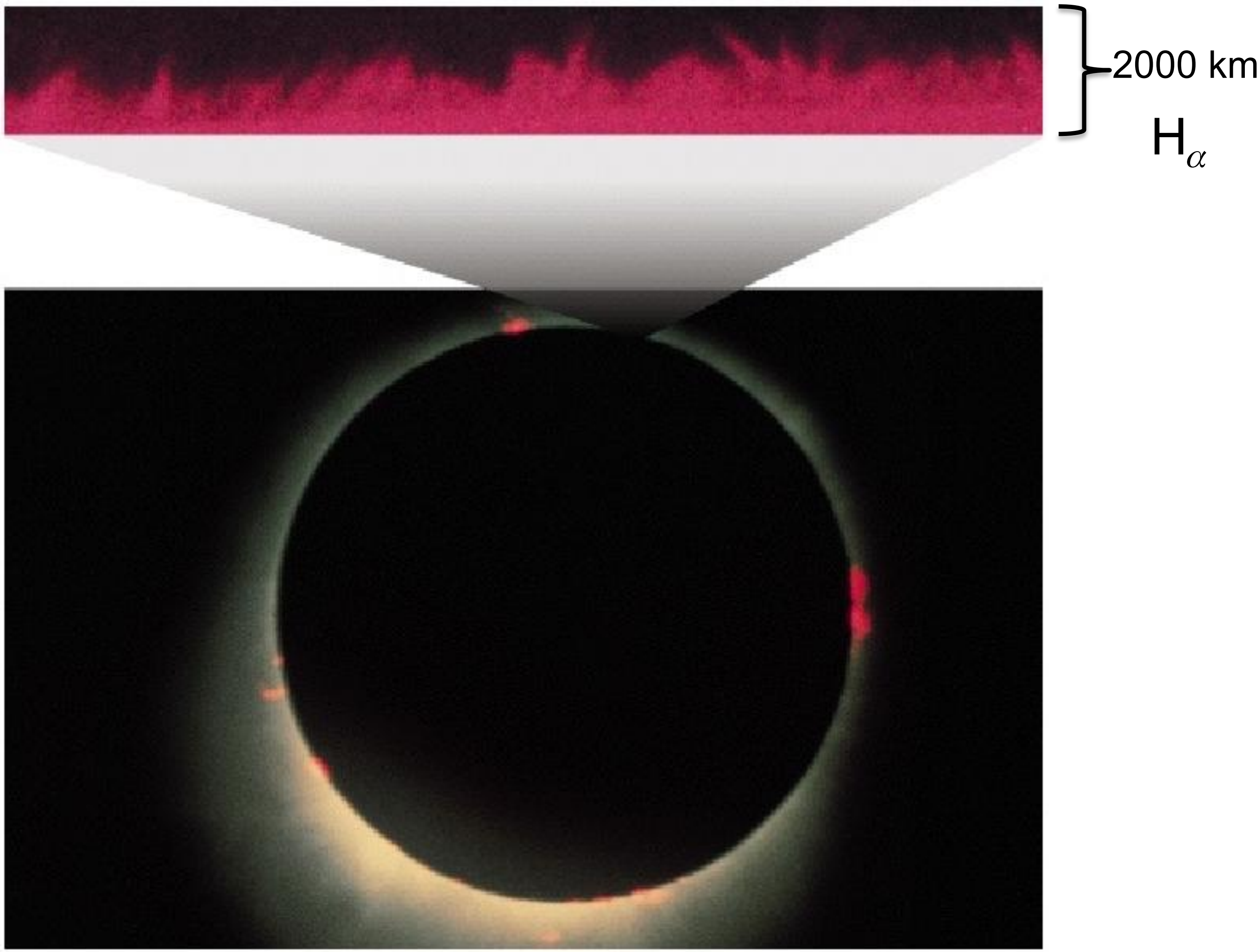


http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article&article_id=14

Coronal Mass Ejection



Chromosphere

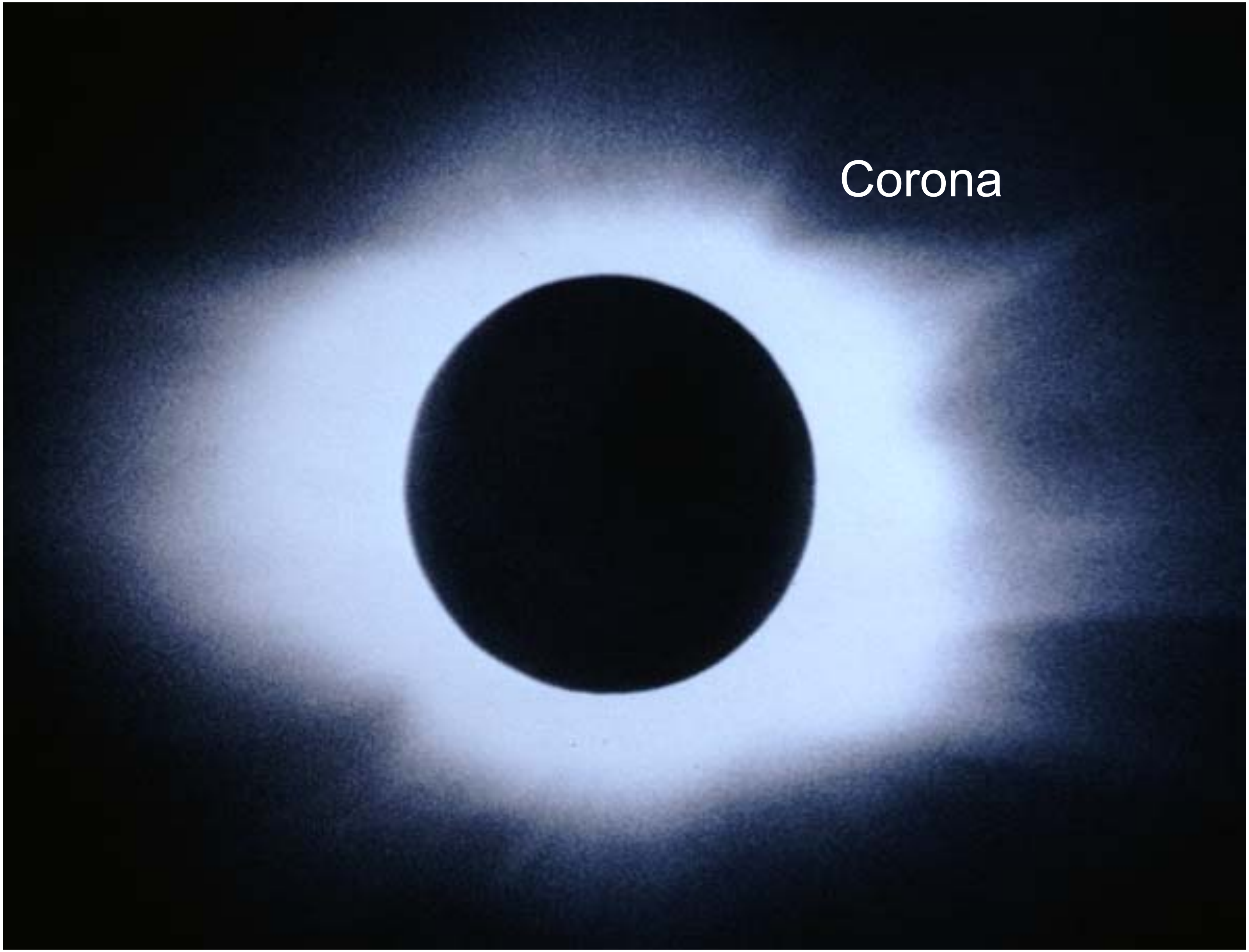


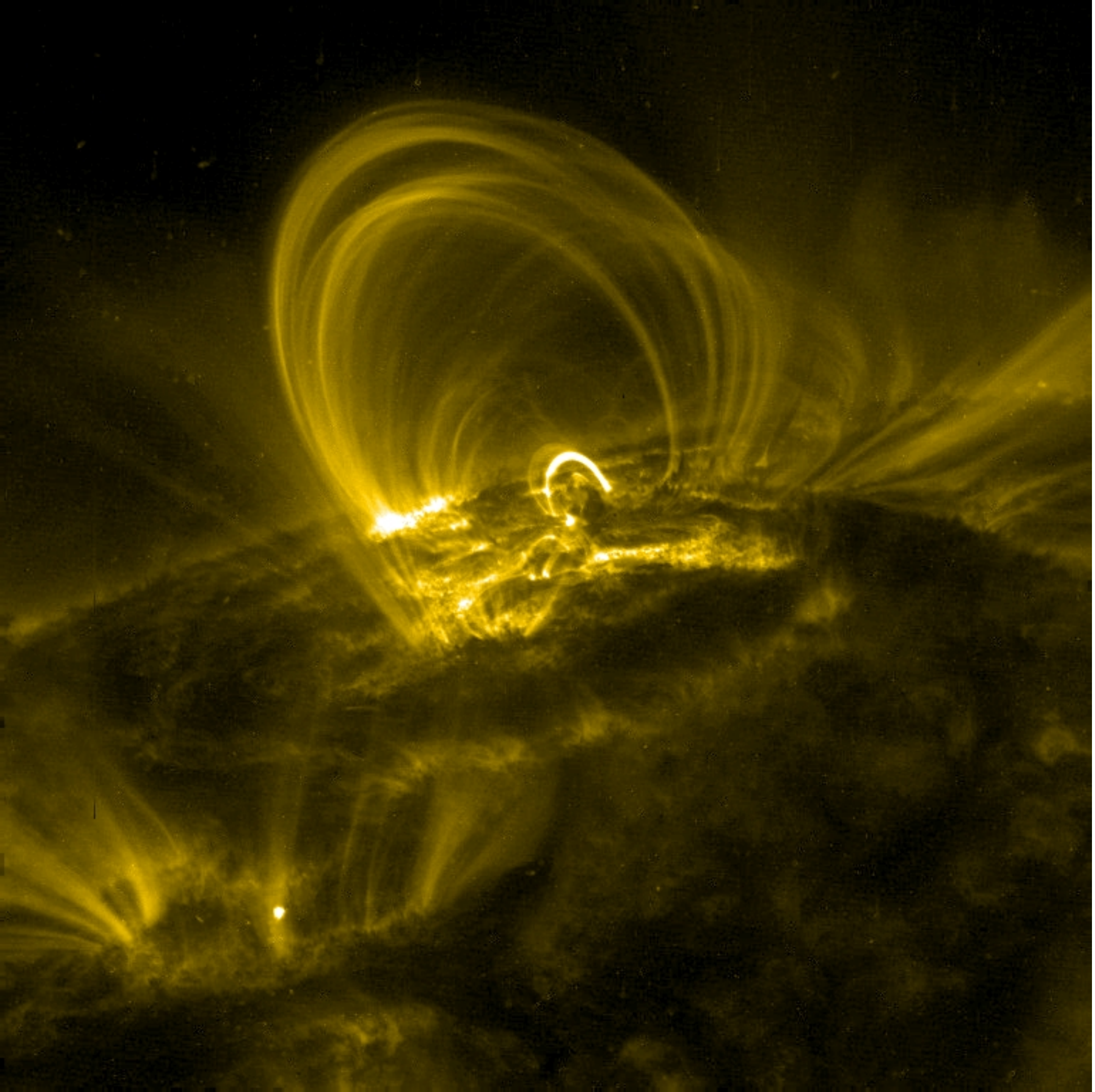
The chromosphere is a narrow layer above the photosphere. It has low density ~0.01% that of the photosphere.

Initially the temperature and density both decline above the photosphere, but once 3000 K is reached the temperature rises again to 35,000 K It is heated by magnetic reconnection.

The chromsphere is a transition region from the photosphere to the corona.

Chromosphere	Corona
~Hydrostatic equilibrium	Dynamic
Helium neutral	Helium ionized
Radiates energy effectively	Inefficient radiator
Emission lines	Emission lines
~10,000 K	~1,000,000 K
Reddish due to H_α	Highly ionized, uv, x-rays

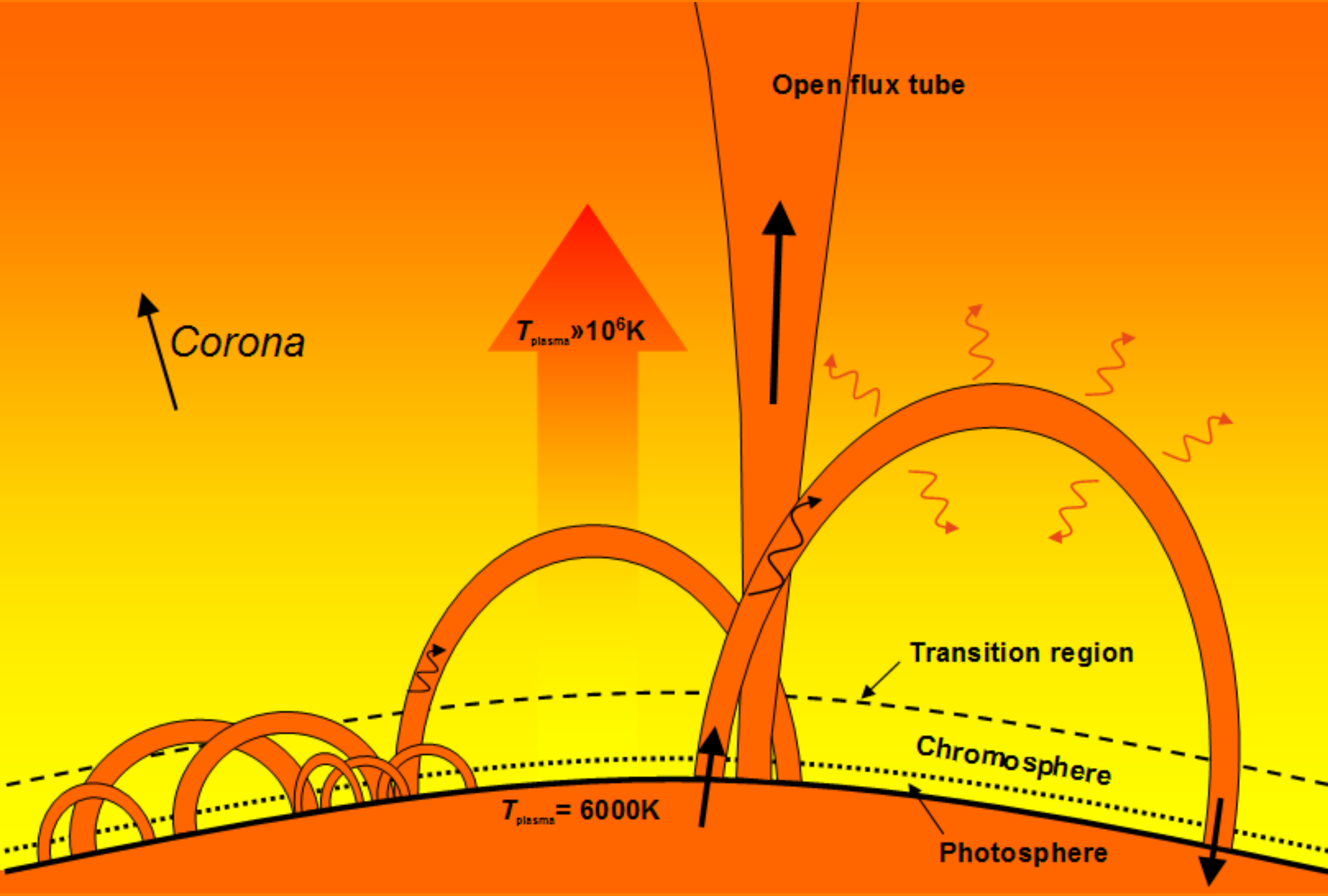

Corona



Coronal Loop

Picture at 141 Angstroms

Temperature About 10^6 K


Open flux tube
Corona
T_{plasma}»10^6K
Transition region
Chromosphere
T_{plasma}= 6000K
Photosphere

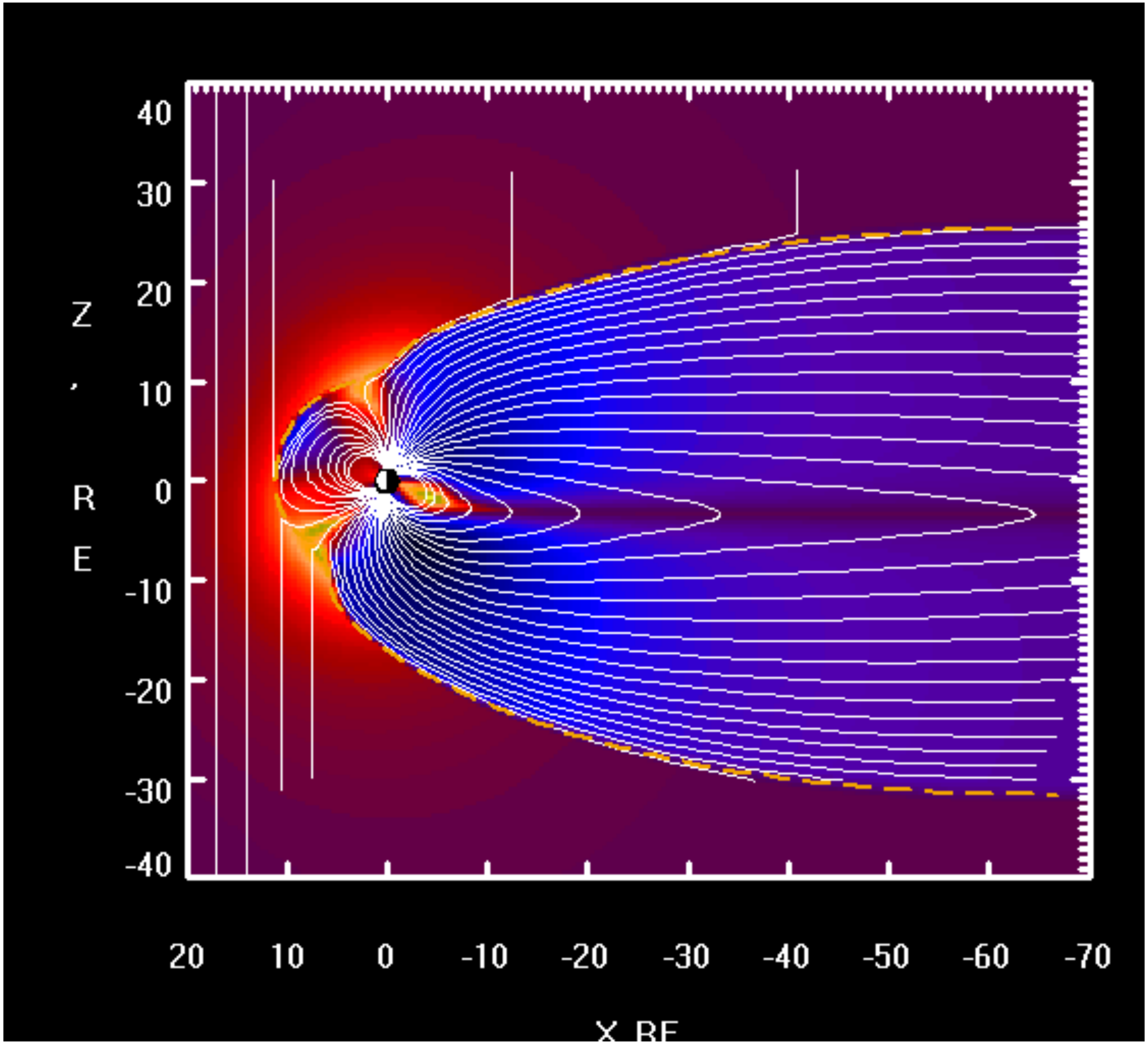
Temperature

Center	15.7 million K
Photosphere	5800 K
Sunspot (umbra)	4240 K
Penumbra	5680 K
Chromosphere	5000 – 20000 K
Corona	0.5 to 3 million K

Density

Mean density entire sun	1.41 g cm^{-3}
Central density	150 g cm^{-3}
Photosphere	10^{-9} g cm^{-3}
Chromosphere	10^{-12} g cm^{-3}
Corona	10^{-16} g cm^{-3}
Air (earth)	10^{-3} g cm^{-3}

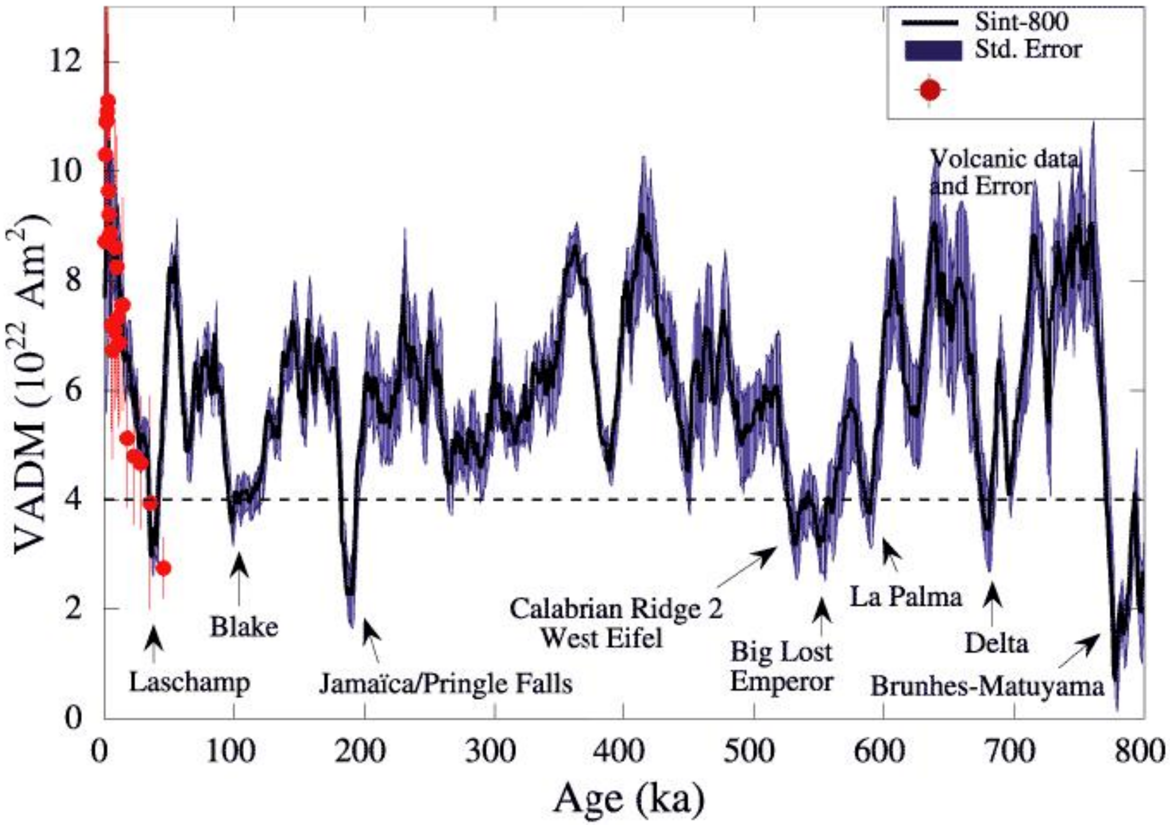
Mass loss rate ~ 10^{-13} solar masses/yr



40
30
20
10
0
-10
-20
-30
-40
Z, RE
20
10
0
-10
-20
-30
-40
-50
-60
-70
X, RE

Effects on earth of solar cycle

- Radio communications and satellite health
- Ozone production and hence uv flux at earth
- Cosmic ray flux
- Aurorae

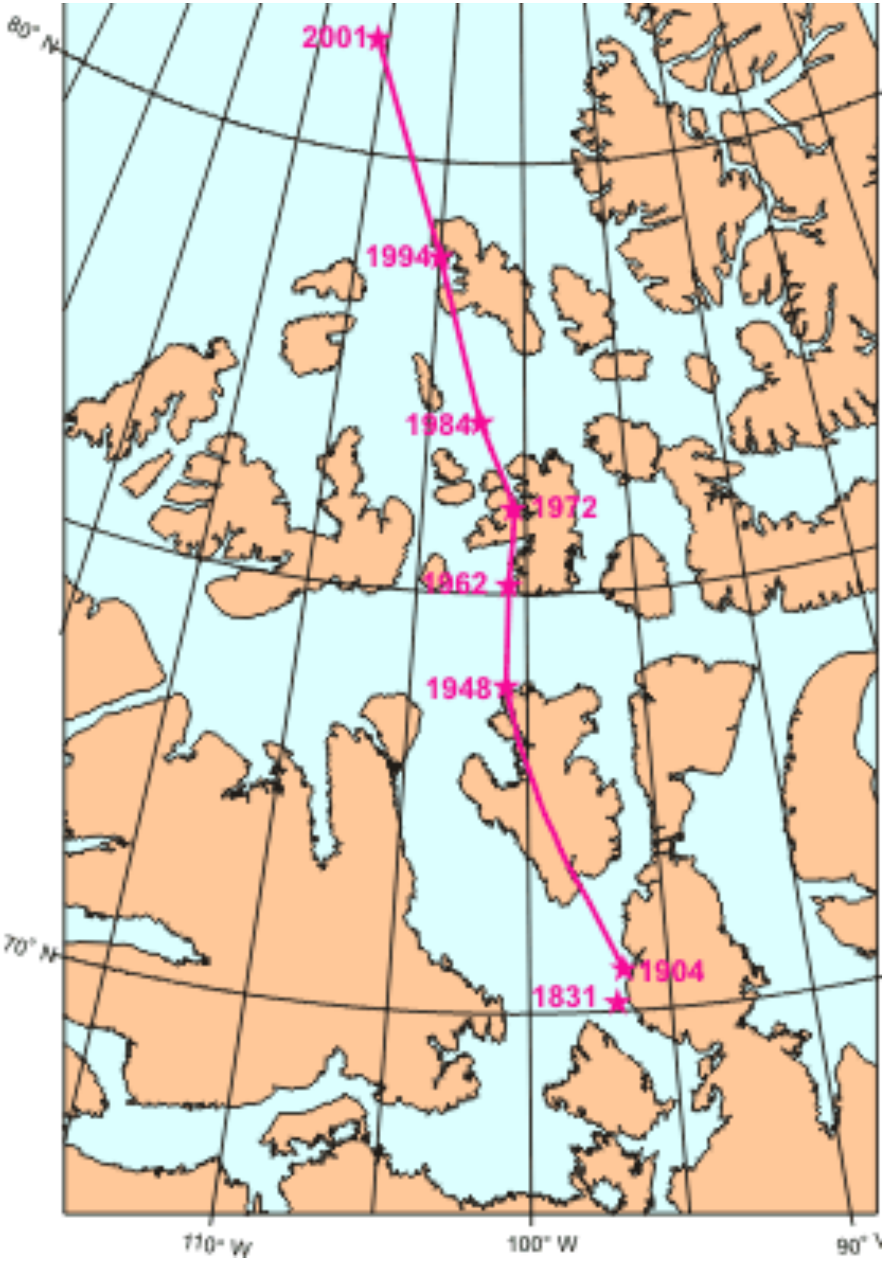


The last reversal was 800,000 yrs ago, but the average time between reversals is 300,000 yrs

Names are the rock strata where the field is measured

http://www.astronomycafe.net/qadir/q816.html

The current magnetic field strength at the Earth's surface of 0.6 Gauss. But long term observations show that it is DECREASING at a rate of about 0.07 percent PER YEAR. This means that in 1500 years from now, it will only be about 35 percent as strong as it is today, and in 4000 years it will have a strength of practically zero.



Magnetic north is currently in northern Canada moving at 10 to 50 km/yr.

In a few decades it will reach Siberia

http://science.nasa.gov/science-news/science-at-nasa/2003/29dec_magneticfield/

Solar flares vs solar prominences
(the latter are bigger)

http://science.howstuffworks.com/sun5.htm

The Solar Neutrino "Problem"

Hydrogen Burning on the Main Sequence

In all cases

$4p \rightarrow {}^4He + 2\,e^+ + 2\nu_e$

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

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

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

(*pp*1)

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

$\tau_{1/2}$ = 53 d

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

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

(*pp*2)

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

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

$^8Be \rightarrow {}^4He + {}^4He$ 7 x 10^{-17} s

(*pp*3)

Averaged over the sun

- pp1 85%
- pp2 15%
- pp3 0.02%

$T_{central}$ = 15.7 Million K

Hydrogen Burning on the Main Sequence

In all cases $4p \rightarrow {}^4He + 2\,\nu_e + 2\,e^+$

pp1

$$p(p,e^+\nu_e)^2H(p,\gamma)^3He(^3He,2p)^4He$$

$$p(p,e^+\nu_e)^2H(p,\gamma)^3He$$

pp2

$$p(p,e^+\nu_e)^2H(p,\gamma)^3He(\alpha,\gamma)^7Be(e^-,\nu_e)^7Li(p,\alpha)^4He$$

pp3

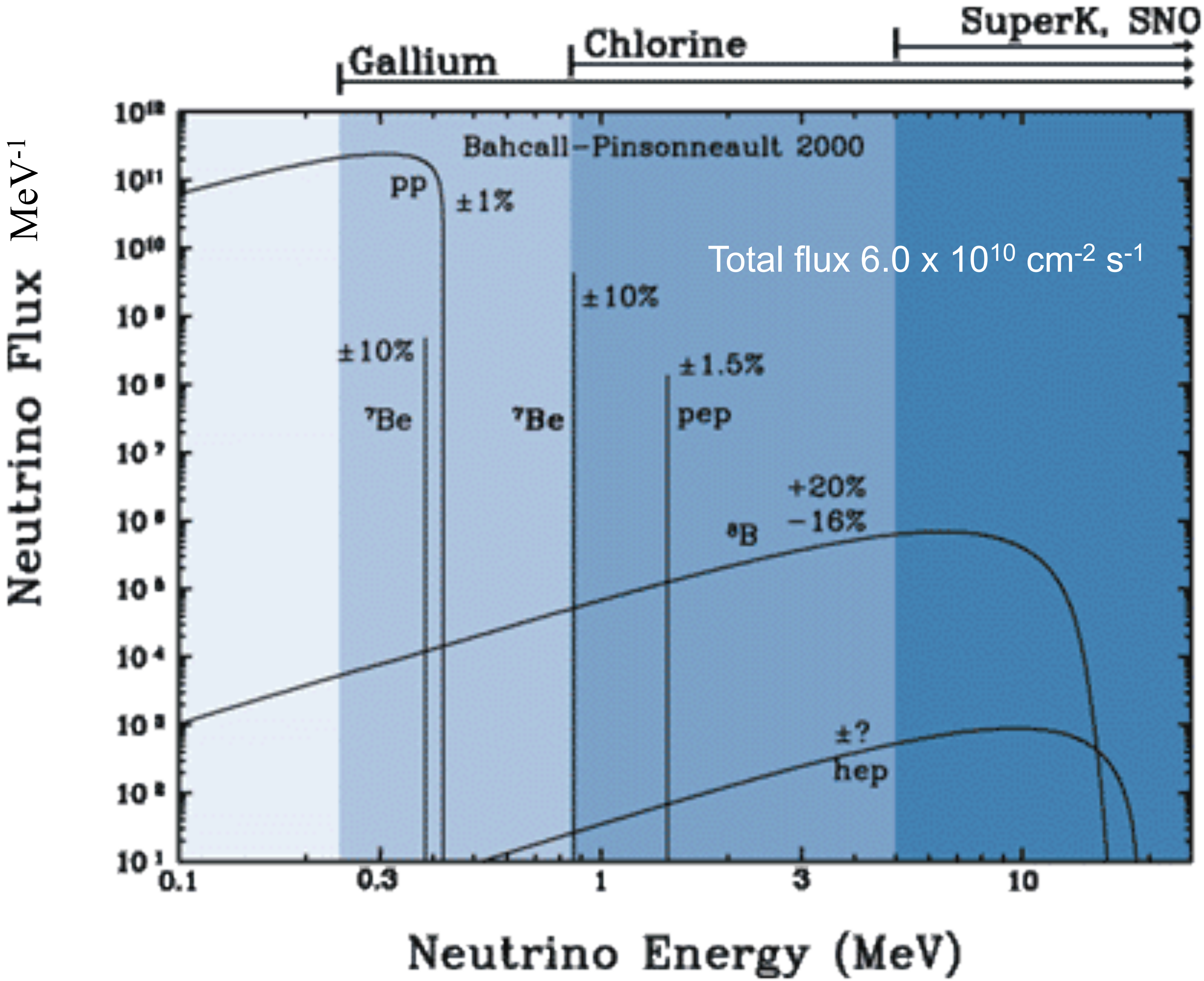
$$p(p,e^+\nu_e)^2H(p,\gamma)^3He(\alpha,\gamma)^7Be(p,\gamma)^8B(e^+\nu_e)^8Be^*$$

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

Neutrino Energies

Species	Average energy	Maximum energy	
p+p	0.267 MeV	0.420 MeV	
^{7}Be	0.383 MeV	0.383 MeV	10%
	0.861	0.861	90%
^{8}B	6.735 MeV	15 MeV	

In the case of ^{8}B and p+p, the energy is shared with a positron hence there is a spread. For ^{7}Be the electron capture goes to two particular states in ^{7}Li and the neutrino has only two energies



SuperK, SNO
Chlorine
Gallium
Bahcall-Pinsonneault 2000
Total flux 6.0 x 10^{10} cm^{-2} s^{-1}
pp
±1%
±10%
±10%
±1.5%
^{7}Be
^{7}Be
pep
+20%
−16%
^{8}B
±?
hep
10^{12}
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.1
0.3
1
3
10
Neutrino Flux MeV^{-1}
Neutrino Energy (MeV)

Since 1965, experiements have operated to search for and study the neutrinos produced by the sun - in order to:

- Test solar models
- Determine the central temperature of the sun

  The flux of neutrinos from ^8B is sensitive to T^{18}

- Learn new particle physics

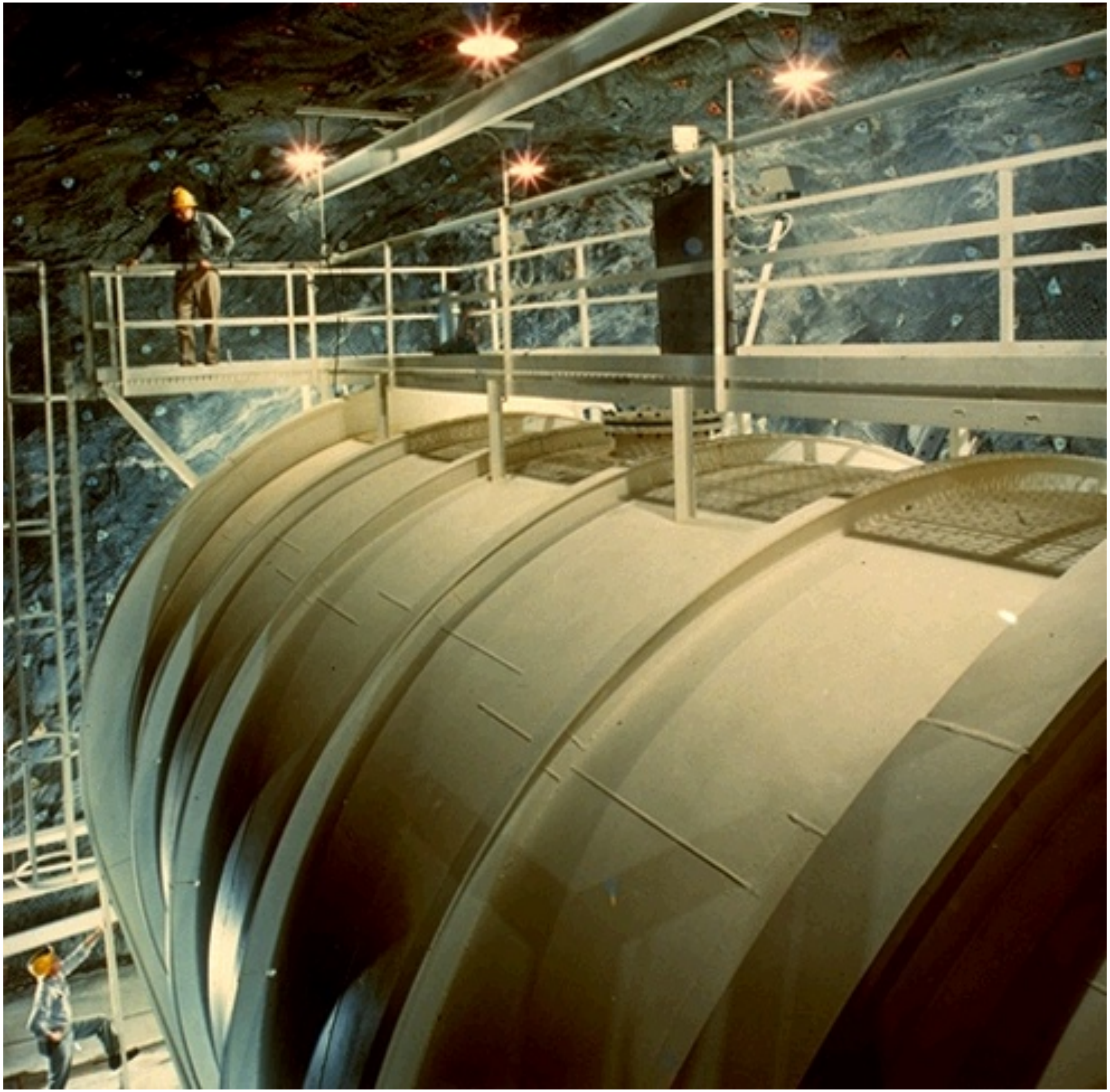
DETECTORS

The chlorine experiment – Ray Davis – 1965 - ~1999

$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^- - 0.814 \text{ MeV}$$

i.e., a neutron inside of ^{37}Cl is turned into a proton by a weak interaction involving an incident neutrino

^{37}Cl	^{37}Ar
17 p 18 n	18 p 17 n



Homestake Gold Mine
Lead, South Dakota

4850 feet down

tank 20 x 48 feet
615 tons (3.8 x 10^5 liters)
C_2Cl_4

Threshold 0.814 MeV

Half-life ^{37}Ar = 35.0 days

Neutrino sensitivity
^7Be, ^8B

8 x 10^{30} atoms of Cl

Nobel Prize 2002

DETECTORS

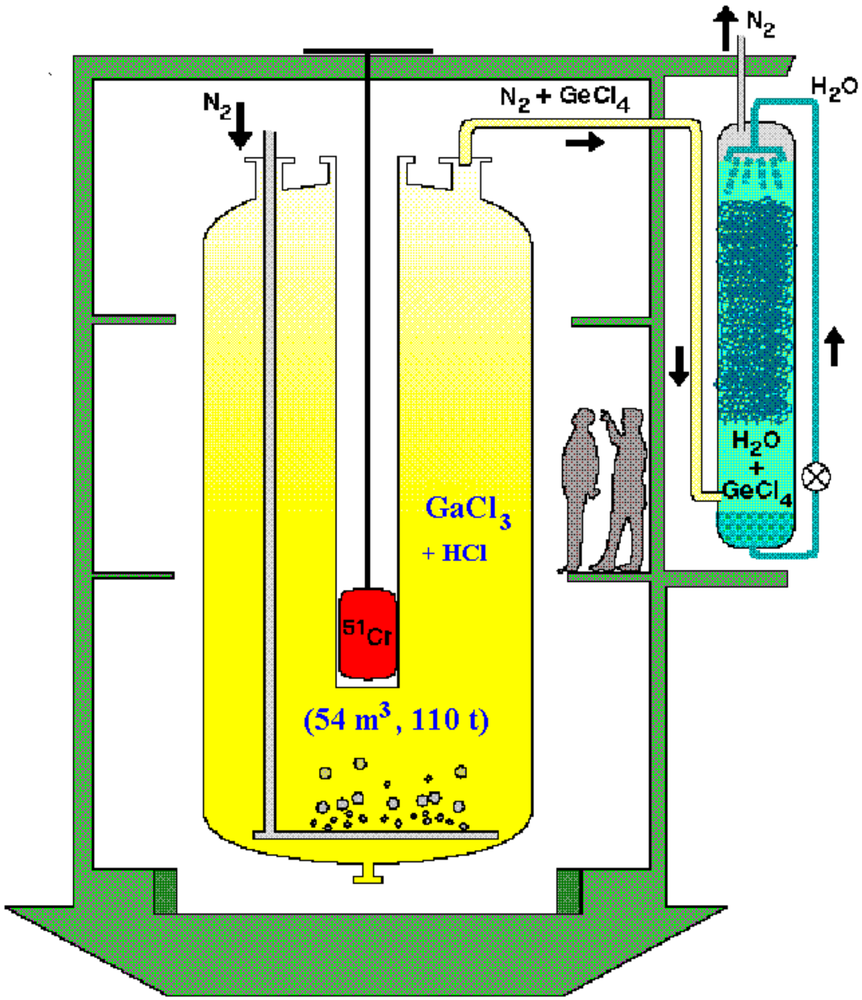
The chlorine experiment – Ray Davis – 1965 - ~1999

$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^- - 0.814 \text{ MeV}$$

The gallium experiments (GALLEX and SAGE) – 1991 – 1997 and 1990 – 2001

$$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^- - 0.233 \text{ MeV}$$

GALLEX



In Gran Sasso Tunnel – Italy

3300 m water equivalent

30.3 tons of gallium in $GaCl_3$-HCl solution

$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

Threshold 0.233 MeV

Sees pp, ^7Be, and ^8B.

Calibrated using radioactive ^{51}Cr neutrino source

DETECTORS

The chlorine experiment – Ray Davis – 1965 - ~1999

$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^- - 0.814 \text{ MeV}$$

The gallium experiments (GALLEX and SAGE) – 1991 – 1997 and 1990 – 2001

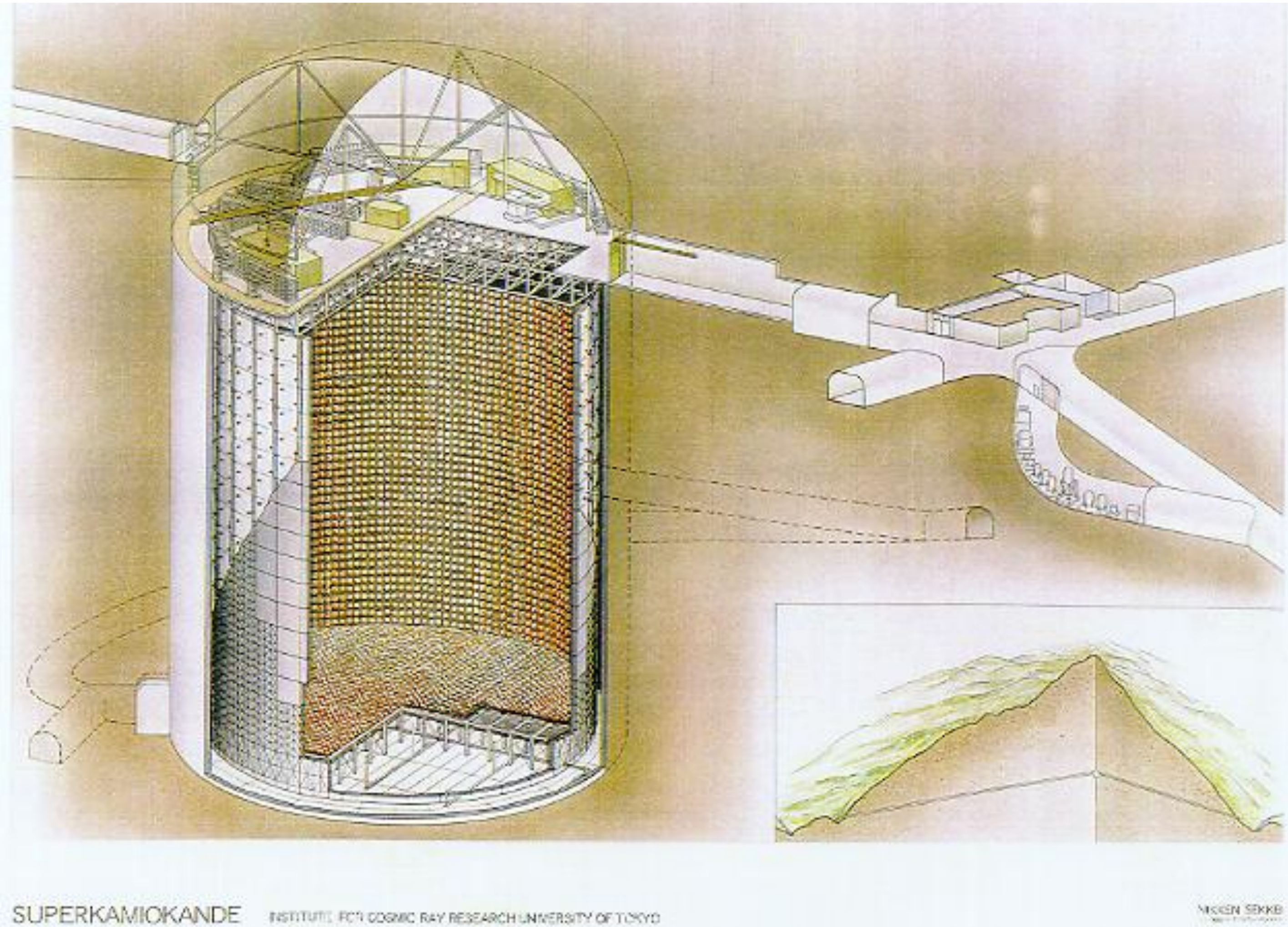
$$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^- - 0.233 \text{ MeV}$$

Kamiokande II - 1996 – 2001

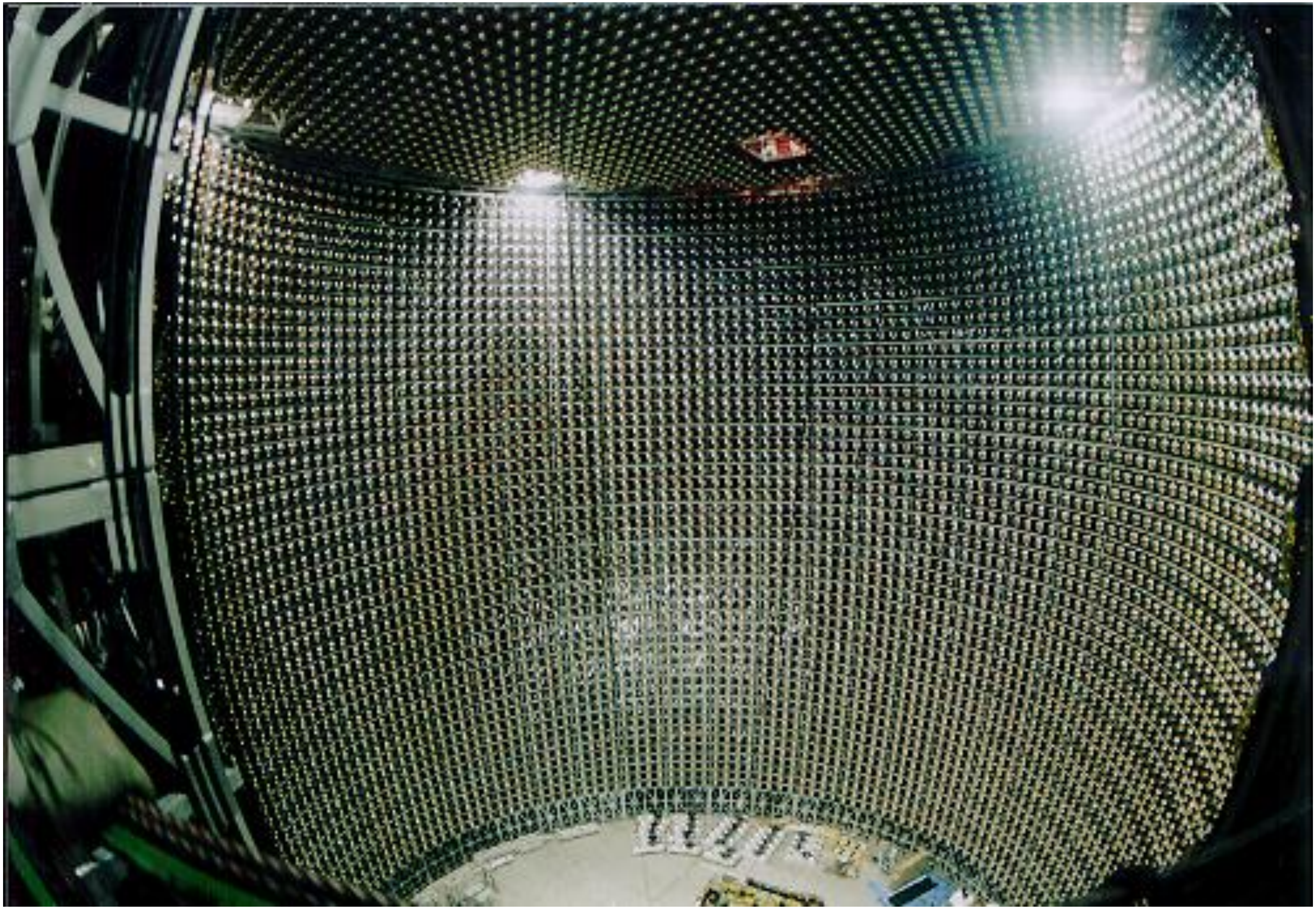
$$e^- + \nu_e \rightarrow e^- + \nu_e$$

Inelastic scattering of neutrinos on electrons in water. Threshold 9 MeV. Scattered electron emits characteristic radiation.

Kamiokande II (in Japanese Alps) 1996 - 2001

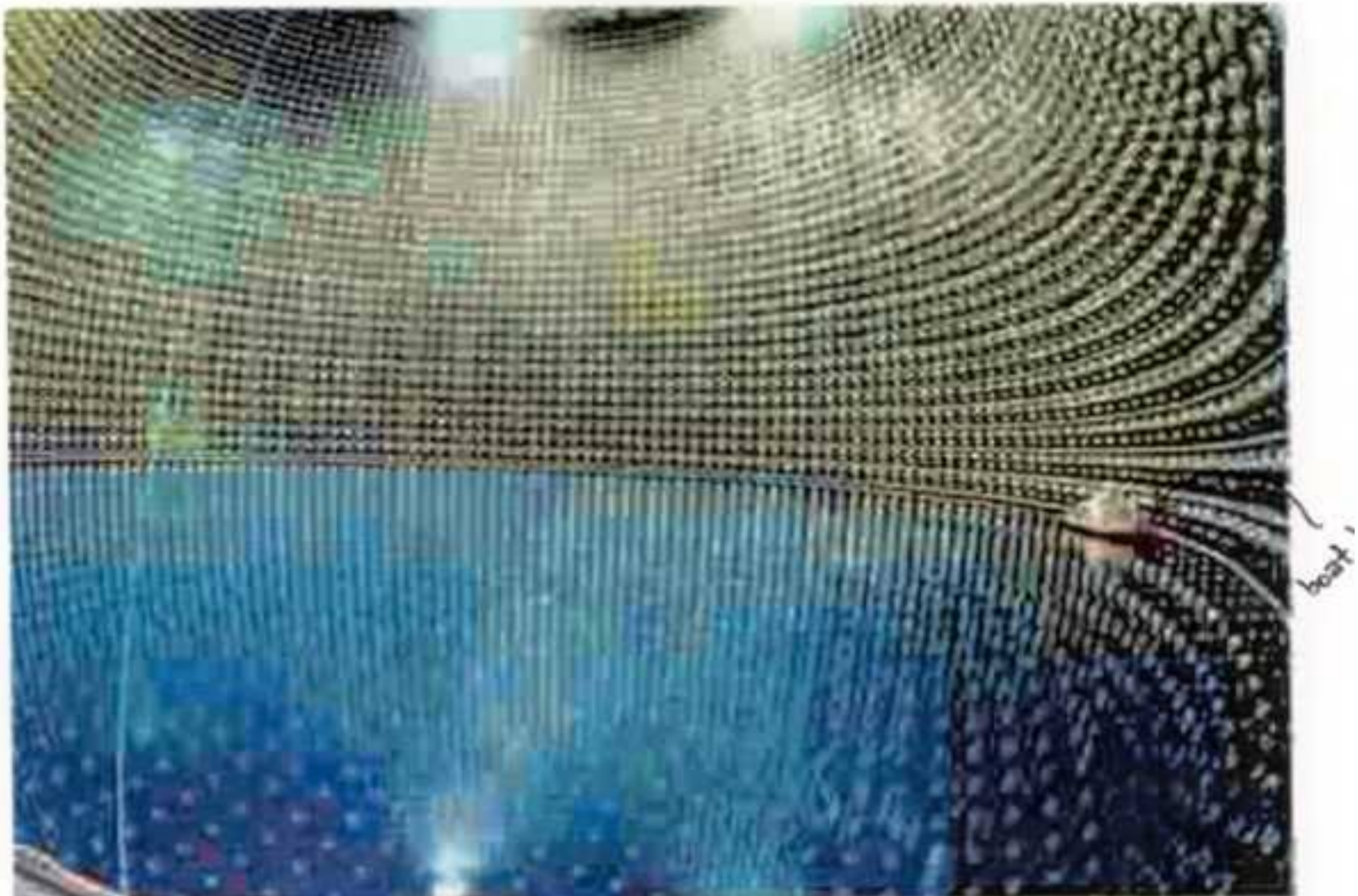


Depth 1 km
Detector H_2O
Threshold 9 MeV
Sensitive to ^{8}B
20'' photomultiplier tubes
Measure Cerenkov light
2.3 x 10^{32} electrons

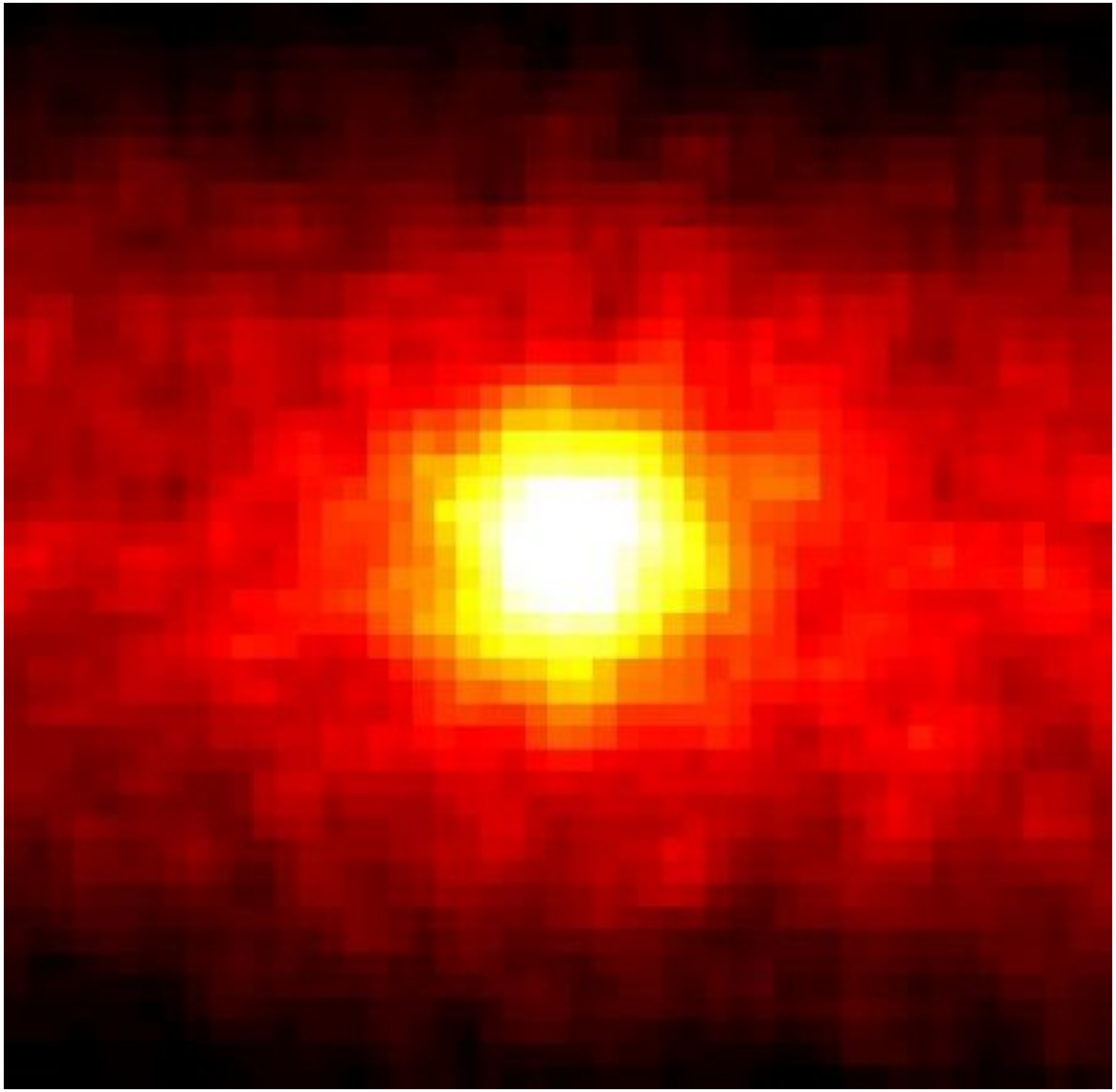


Super-KamioKande (Japan)

50,000 tons of water   0.6 mi
11,146 20" light detectors   down



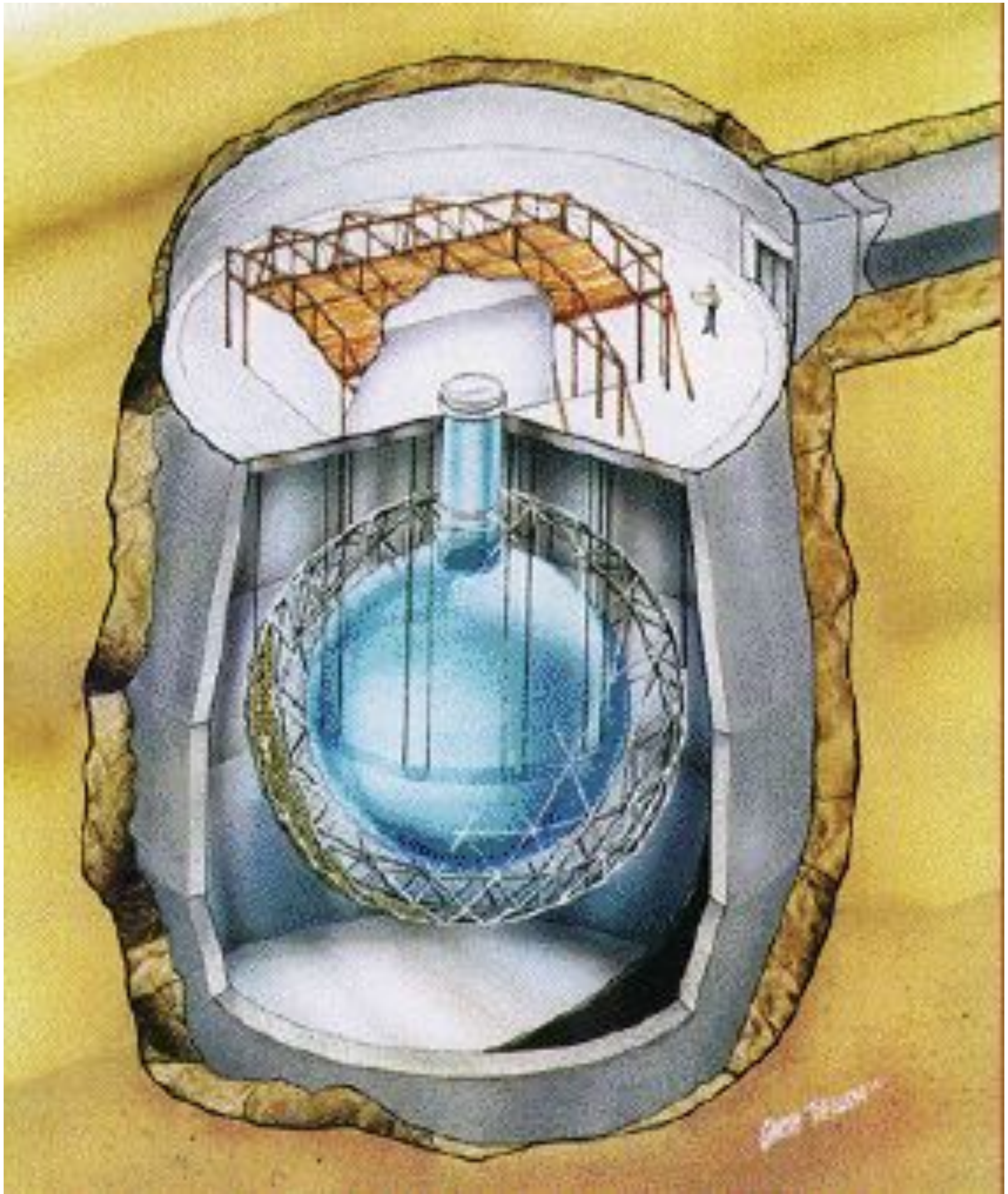
The Sun - 1999
(First picture in neutrinos)



This "picture" was taken using data from the Kamiokande 2 neutrino observatory. It contains data from 504 nights (and days) of observation. The observatory is about a mile underground.

Each pixel is about a degree and the whole frame is 90^o x 90^o.

Sudbury Neutrino Observatory



6800 ft down

1000 tons D_2O.

20 m diameter

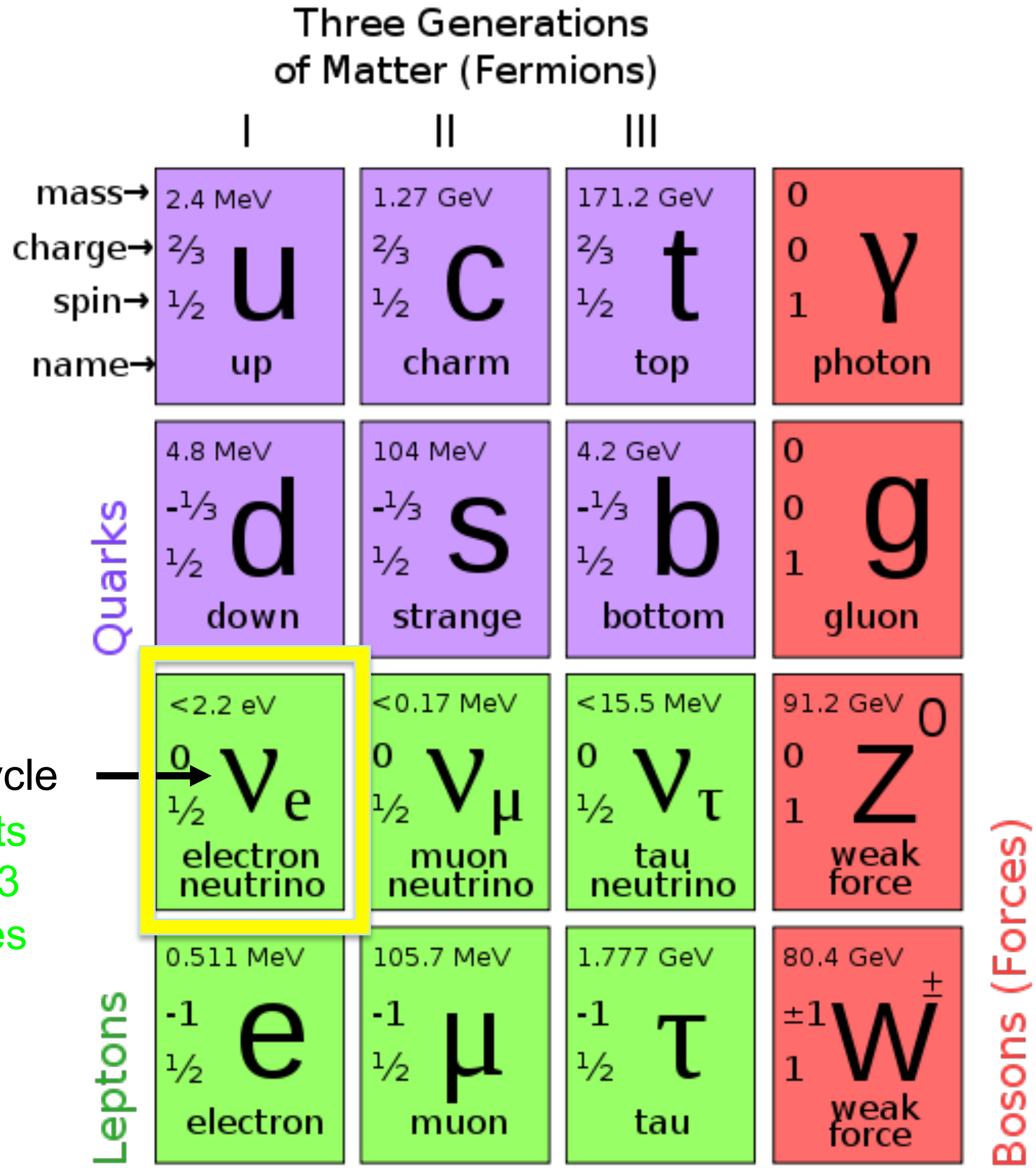
Sudbury, Canada

Threshold 5 MeV

Sees ^8B decay but can see all three kinds of neutrinos

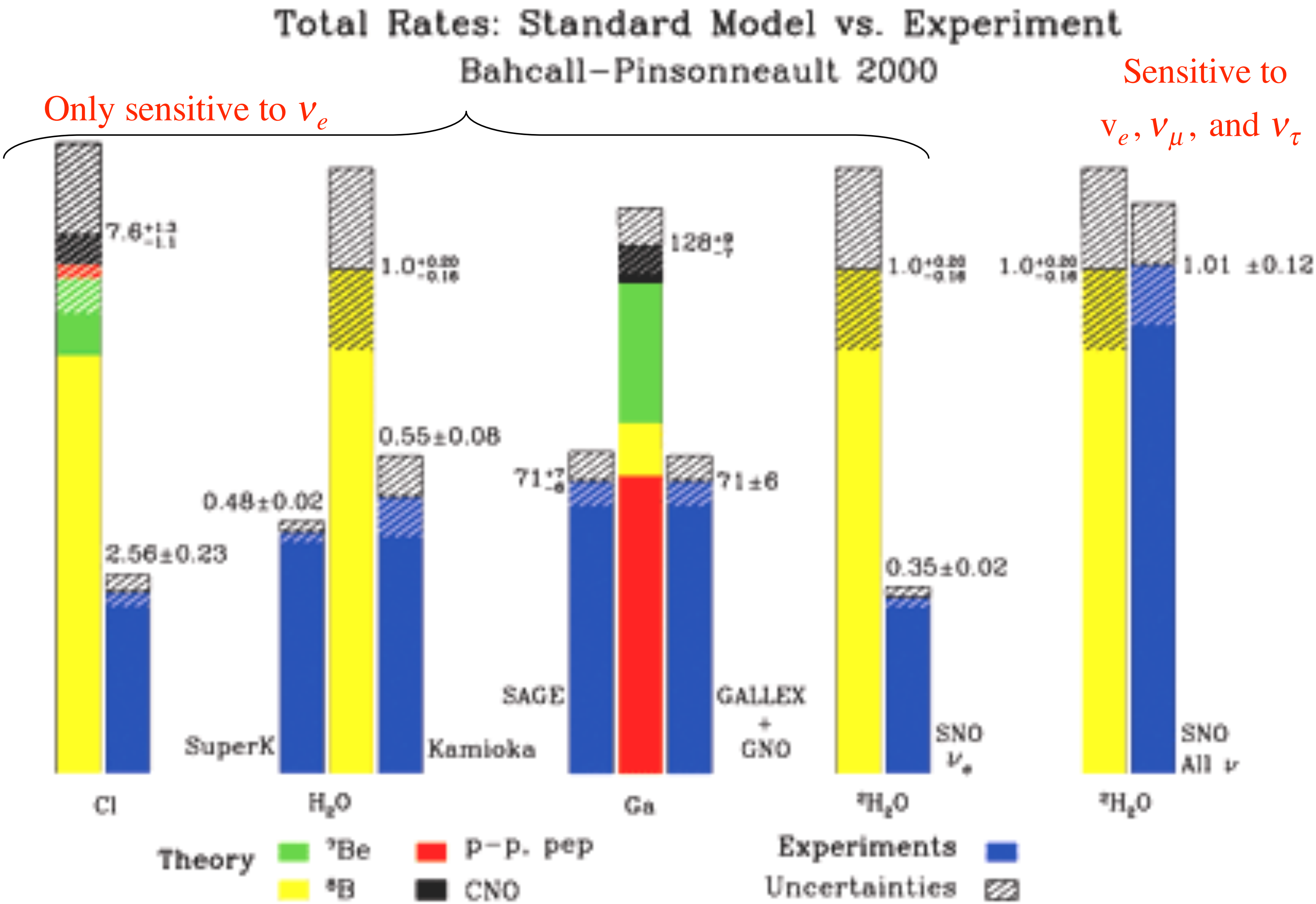
ν_e, ν_μ, ν_τ

Particle physics aside:



emitted by pp-cycle →

cosmology limits the sum of the 3 neutrino masses to < 1 eV



Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
Only sensitive to ν_e
Sensitive to
ν_e, ν_μ, and ν_τ
$7.6^{+1.3}_{-1.1}$
2.56±0.23
$1.0^{+0.20}_{-0.16}$
0.48±0.02
0.55±0.08
128^{+9}_{-7}
71^{+7}_{-6}
71±6
$1.0^{+0.20}_{-0.16}$
0.35±0.02
$1.0^{+0.20}_{-0.16}$
1.01 ±0.12
SuperK
Kamioka
SAGE
GALLEX + GNO
SNO ν_e
SNO All ν
Cl
H_2O
Ga
^2H_2O
^2H_2O
Theory
^{7}Be
^{8}B
p–p, pep
CNO
Experiments
Uncertainties

http://www.sno.phy.queensu.ca/sno/sno2.html - interactions

Neutrino interactions with heavy water $D_2O = {}^2H_2O$

Electron neutrino

$$\nu_e + {}^2\mathrm{H} \underbrace{\rightarrow}_{(np)} (pp) \rightarrow p + p + e^-$$

All neutrinos with energy above 2.2 MeV = BE$({}^2H)$

$$\nu_{e,\mu,\tau} + {}^2\mathrm{H} \rightarrow n + p + \nu_{e,\mu,\tau}$$

add salt to increase sensitivity to neutrons,

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$$

Results from SNO – 2002 (Sudbury turned off in 2006)

The flux of electron flavored neutrinos above 5 MeV (i.e., only pp3 = ^{8}B neutrinos) is

$$1.76 \pm 0.1 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

But the flux of μ and τ flavored neutrinos is

$$3.41 \pm 0.64 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

Nobel Prize in Physics - 2002

Standard Solar Model ^{8}B neutrinos

$$5.05 \, ^{+1.01}_{-0.81} \times 10^6 \text{ neutrinos cm}^{-2} \text{ s}^{-1}$$

The explanation of the solar neutrino “problem” is apparently *neutrino flavor mixing*.

http://en.wikipedia.org/wiki/Neutrino_oscillation

A flux that starts out as pure electron-”flavored” neutrinos at the middle of the sun ends up at the earth as a mixture of electron, muon, and tauon flavored neutrinos in comparable proportions.

The transformation occurs in the sun and is complete by the time the neutrinos leave the surface. The transformation affects the highest energy neutrinos the most (MSW-mixing).

Such mixing requires that the neutrino have a very small but non-zero rest mass. This is different than in the so called “standard model” where the neutrino is massless. The mass is less than about 10^{-5} times that of the electron. (Also observed in earth’s atmosphere and neutrinos from reactors).

New physics.... (plus we measure the central temperature of the sun very accurately – 15.71 million K)