UCOR-125:

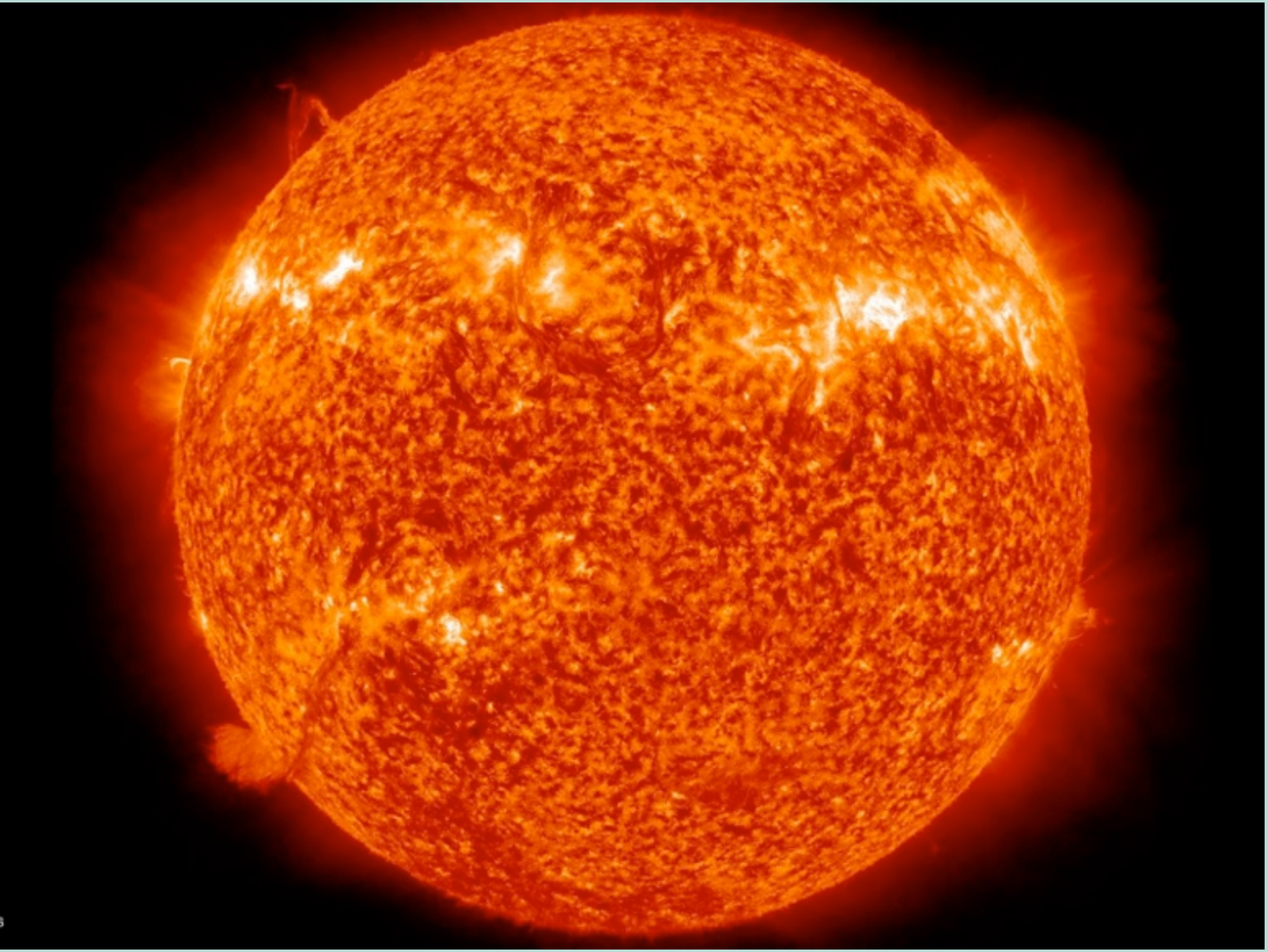
Astronomy

with your host:

Lecture 14:
The Sun

Coop

The Sun



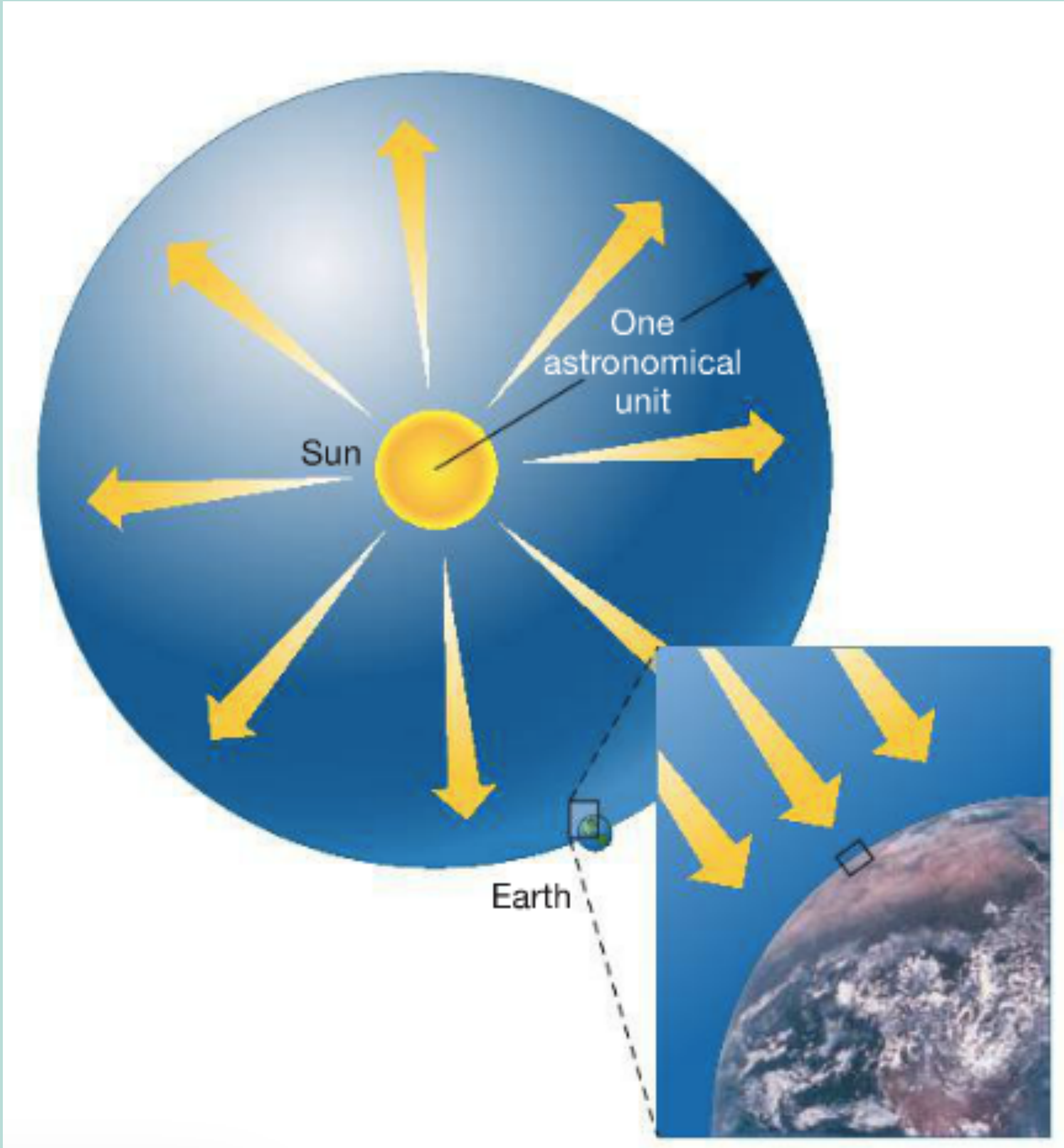
m ~ 2e30 kg
~ 300,000 m_e

r ~ 7e5 km
~ 110 r_e

d ~ 28,000
years

density ~
1400 kg/m^3

- 0.5 degrees in the sky
- Differential Rotation
- 25 day rotation period at the equator, 36 at the poles
- Effective temperature of 5800 K


One
astronomical
unit
Sun
Earth

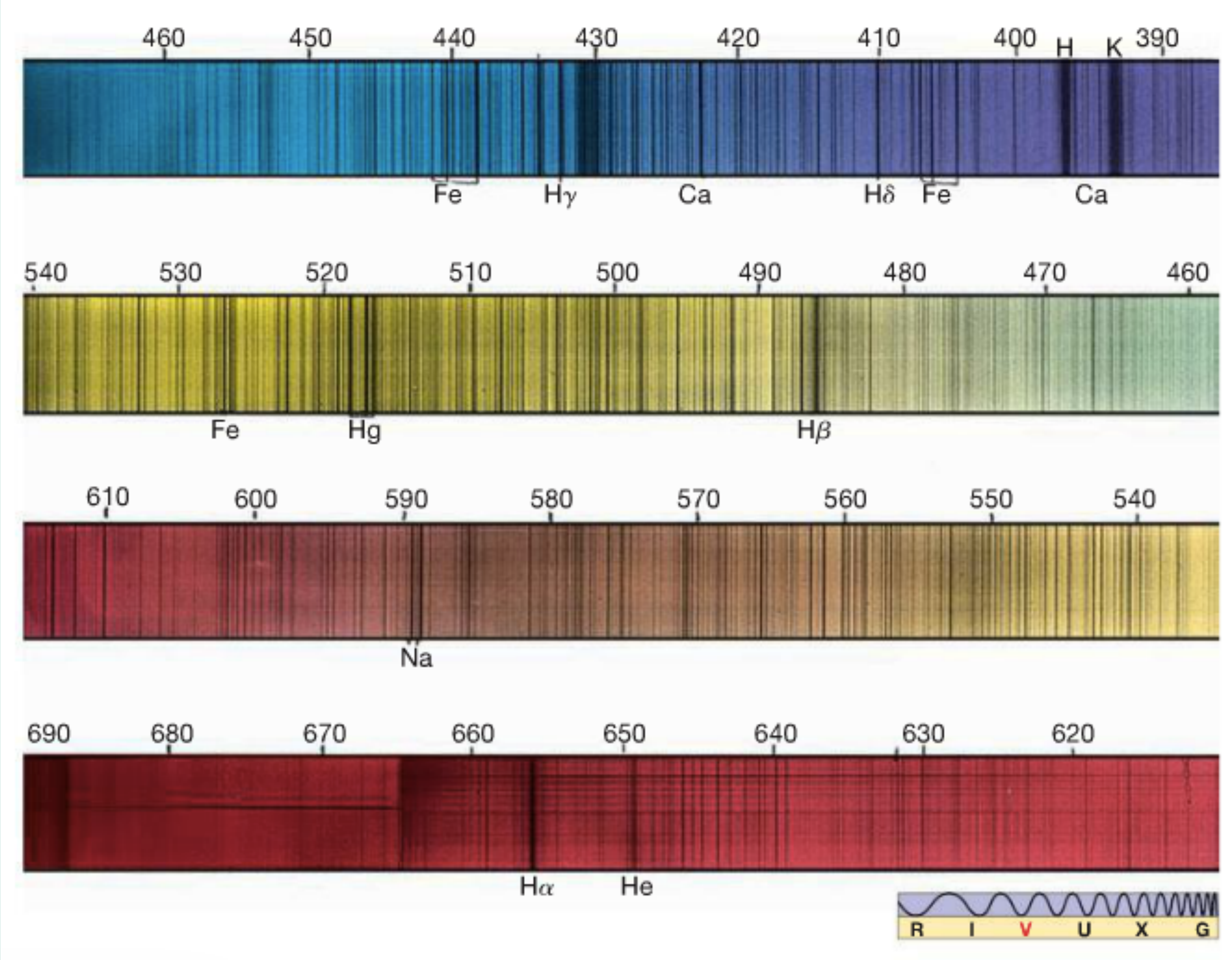
Just how bright is the sun?

- Solar constant: 1400 W/m^2
- 50% reaches earth, 30% goes to the atmosphere, 20% reflected away
- About a mol of square meters in an AU sphere around the sun
- Result: 4 X 10^26 W
- 10 billion 1 megaton bombs/second
- Could evaporate the world's oceans in 6 seconds, melt the crust in 3 minutes

TABLE 16.2 The Composition of the Sun

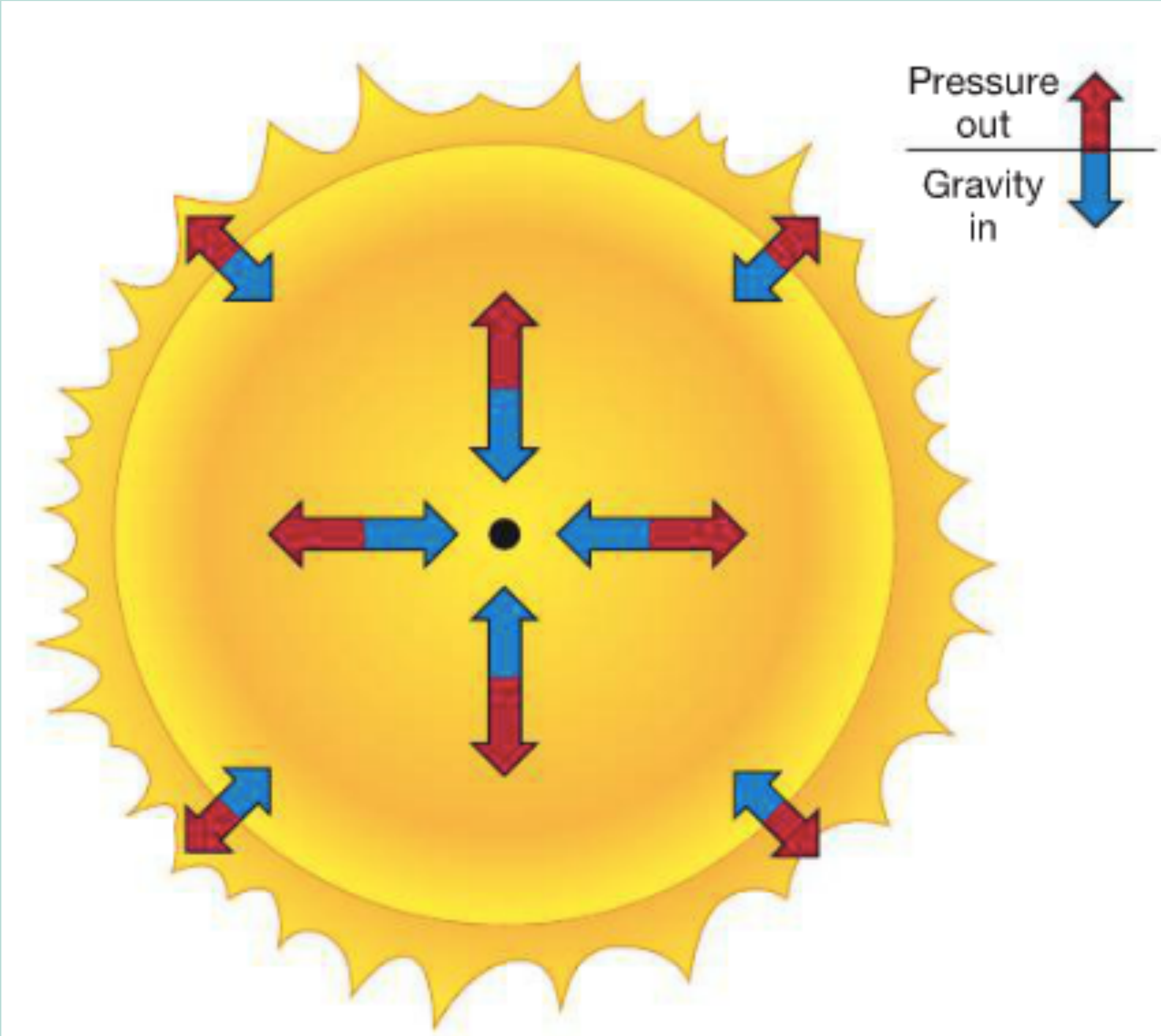
Element	Percentage of Total Number of Atoms	Percentage of Total Mass
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.0030	0.14
Sulfur	0.0015	0.040

Solar Spectrum

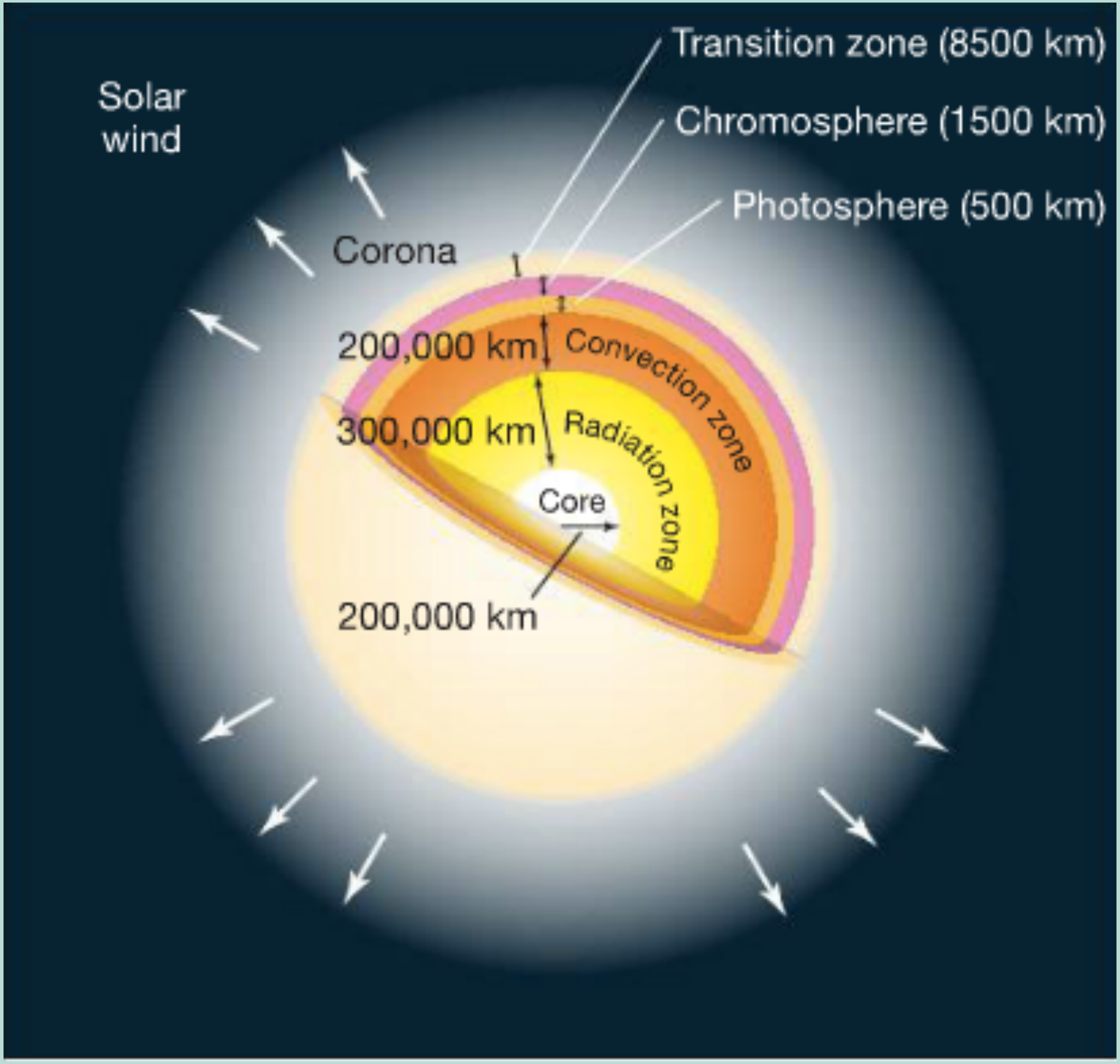


- Recall, we learn not just about the emitted radiation (emission lines), but also the intermediate atmosphere of the sun (absorption lines)

Hydrostatic Equilibrium



Standard Solar Model



- In the core it’s too hot to form atoms, so radiation doesn’t get absorbed by anything (radiation zone)

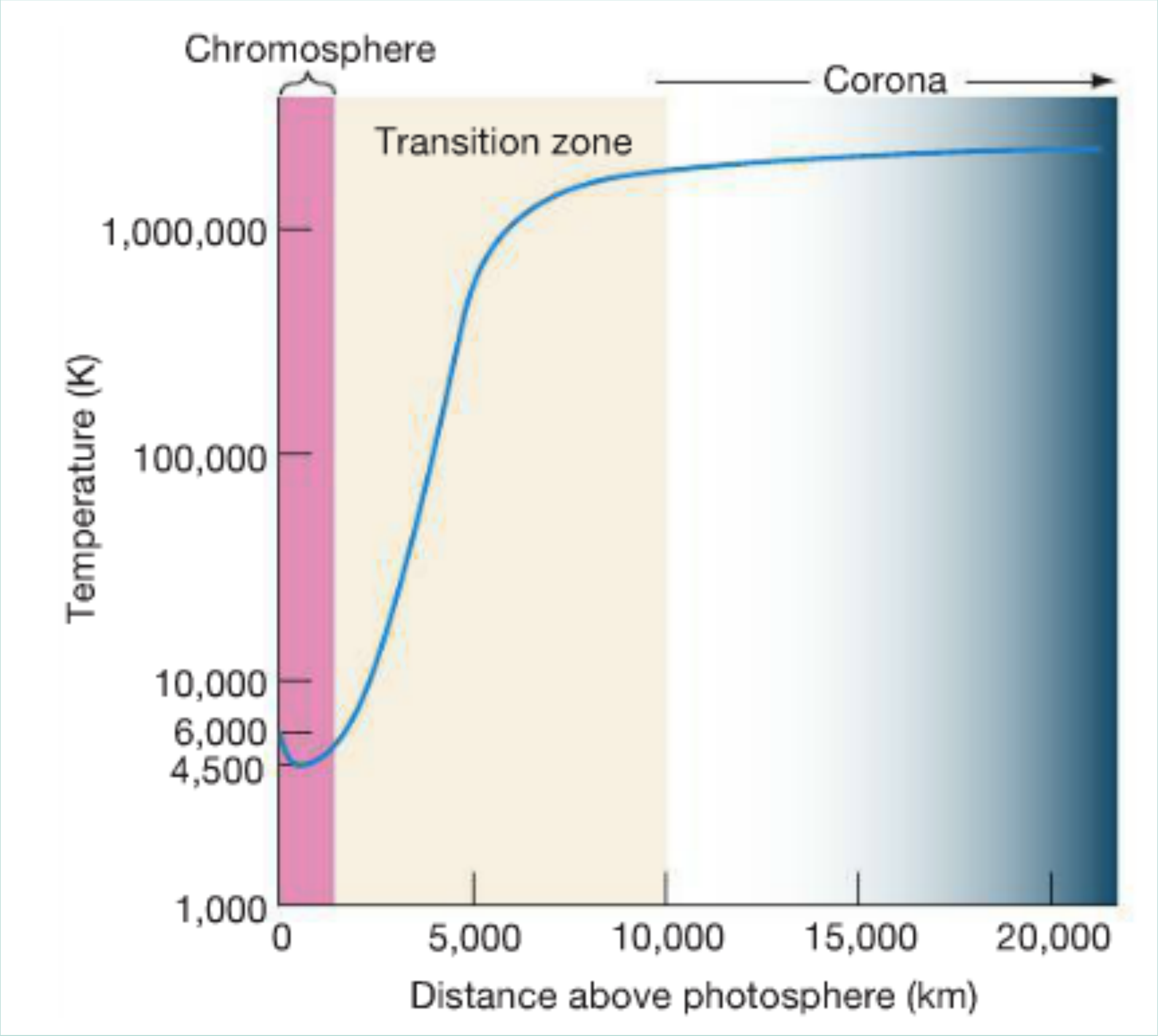
- Further out, it’s cool enough to form atoms (how cool?) and so ALL the light gets absorbed and turned into heat and reflected light

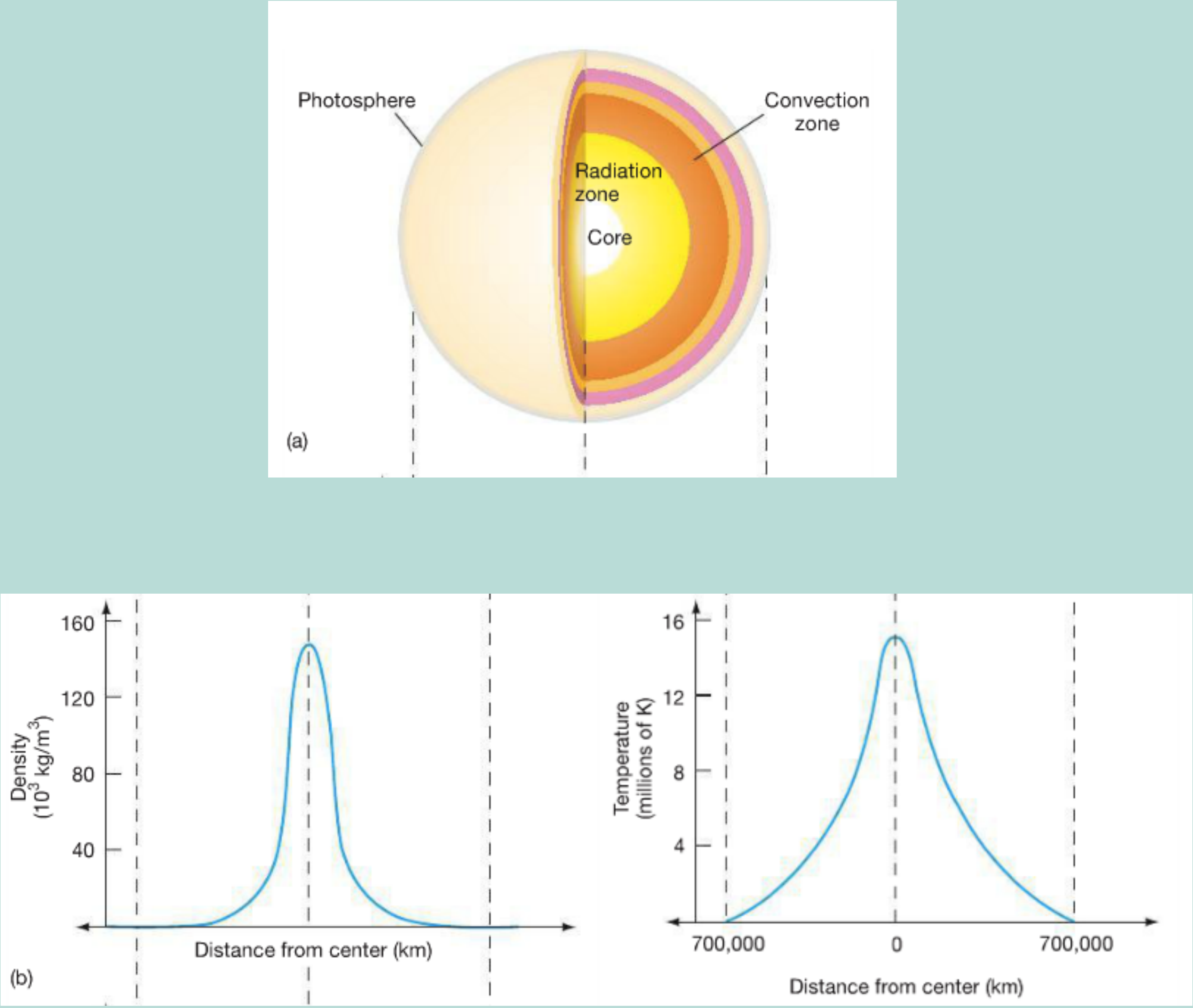
- This heat CONVECTS to the surface which glows like a black body (photosphere)

TABLE 16.1 The Standard Solar Model

Region	Inner Radius (km)	Temperature (K)	Density (kg/m^3)	Defining Properties
Core	0	15,000,000	150,000	Energy generated by nuclear fusion
Radiation zone	200,000	7,000,000	15,000	Energy transported by electromagnetic radiation
Convection zone	496,000*	2,000,000	150	Energy carried by convection
Photosphere	696,000*	5800	2×10^{-4}	Electromagnetic radiation can escape—the part of the Sun we see
Chromosphere	696,500*	4500	5×10^{-6}	Cool lower atmosphere
Transition zone	698,000*	8000	2×10^{-10}	Rapid increase in temperature
Corona	706,000*	3,000,000	10^{-12}	Hot, low-density upper atmosphere
Solar wind	10,000,000	> 1,000,000	10^{-23}	Solar material escapes into space and flows outward through the solar system

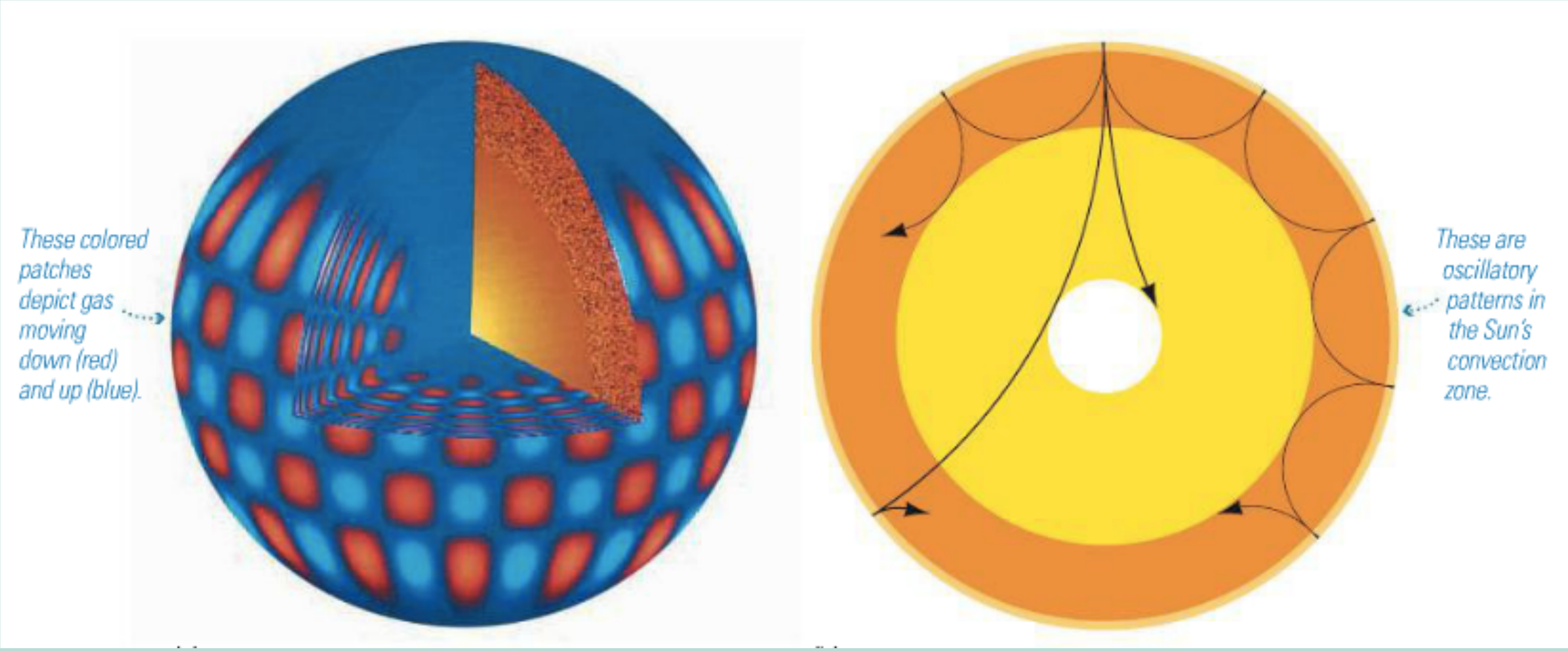
Atmospheric Physics is Hard





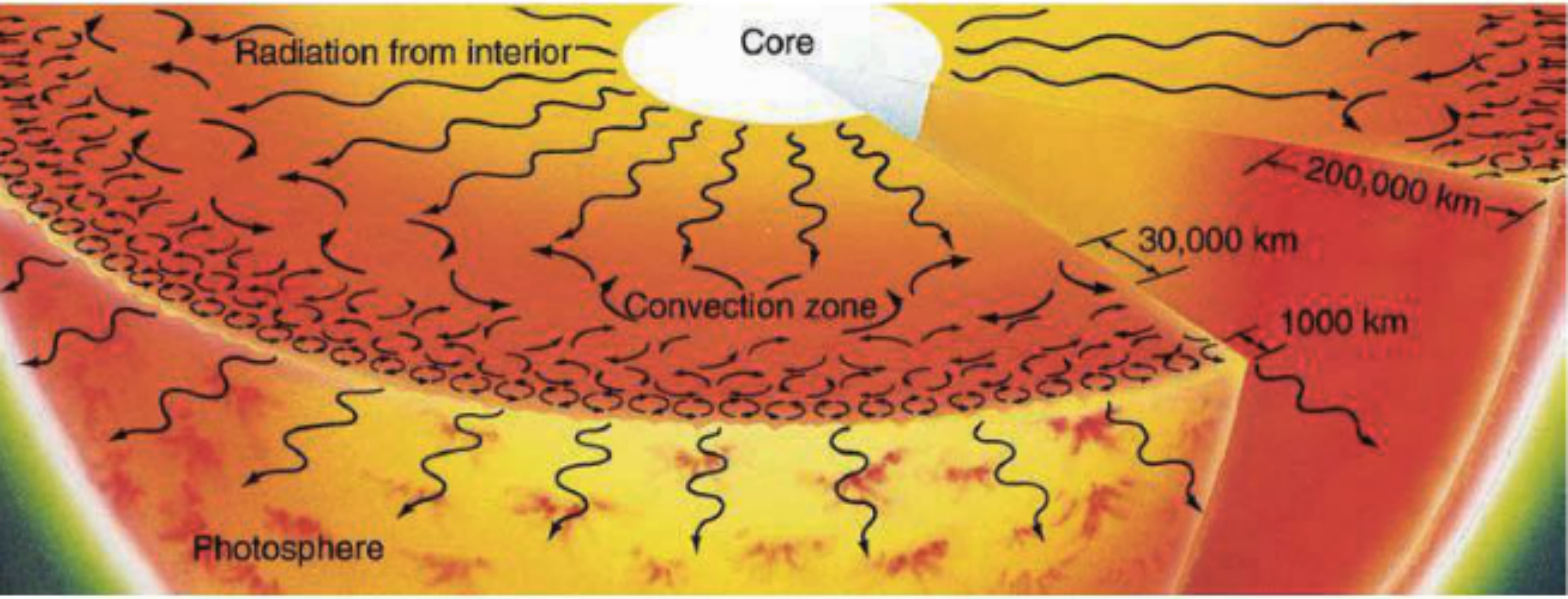
Photosphere
Convection zone
Radiation zone
Core
(a)
160
120
80
40
Density (10^3 kg/m^3)
Distance from center (km)
(b)
16
12
8
4
Temperature (millions of K)
700,000
0
700,000
Distance from center (km)

Helioseismology



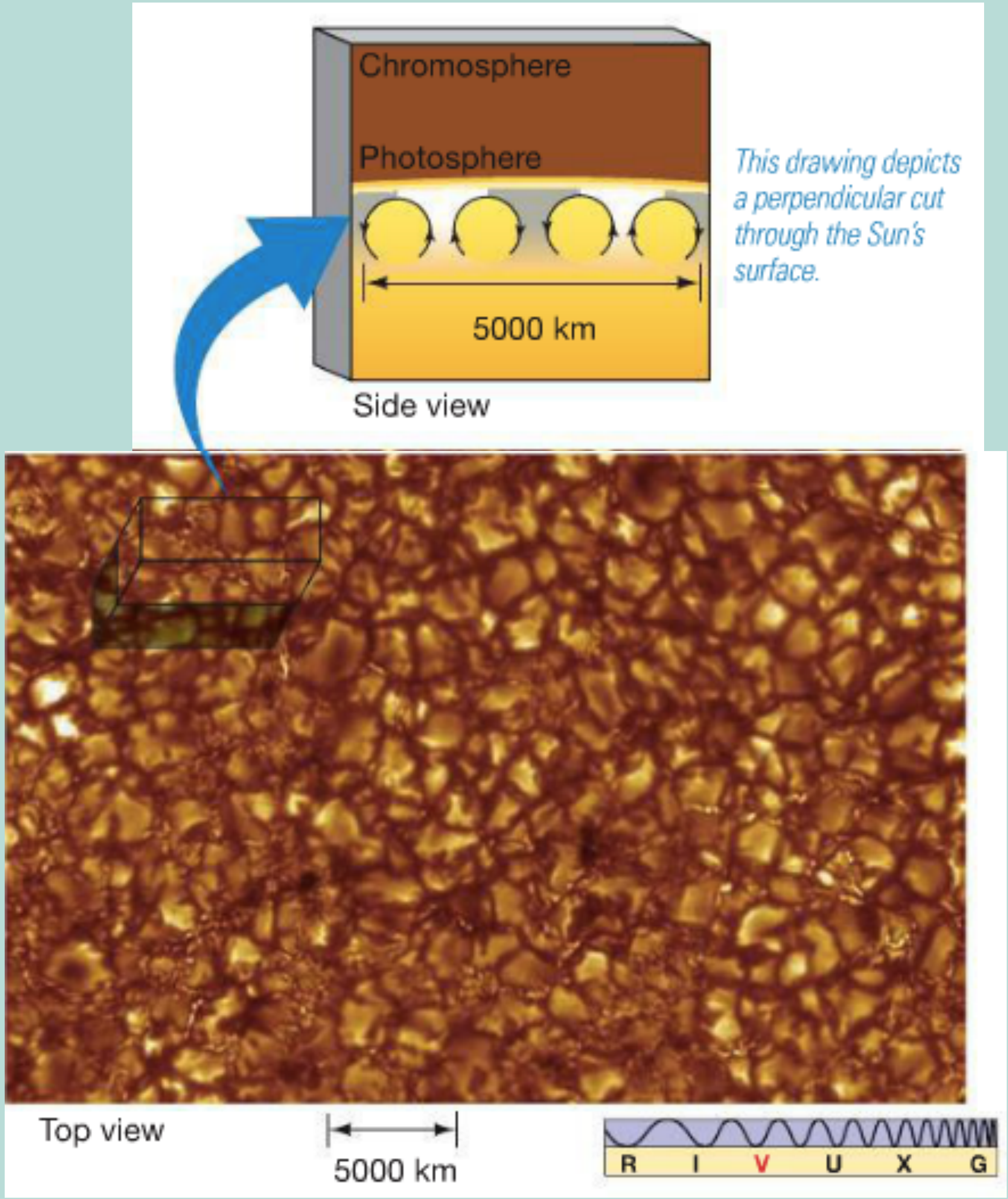
Global Oscillations Network Group (GONG)

Convection Cells



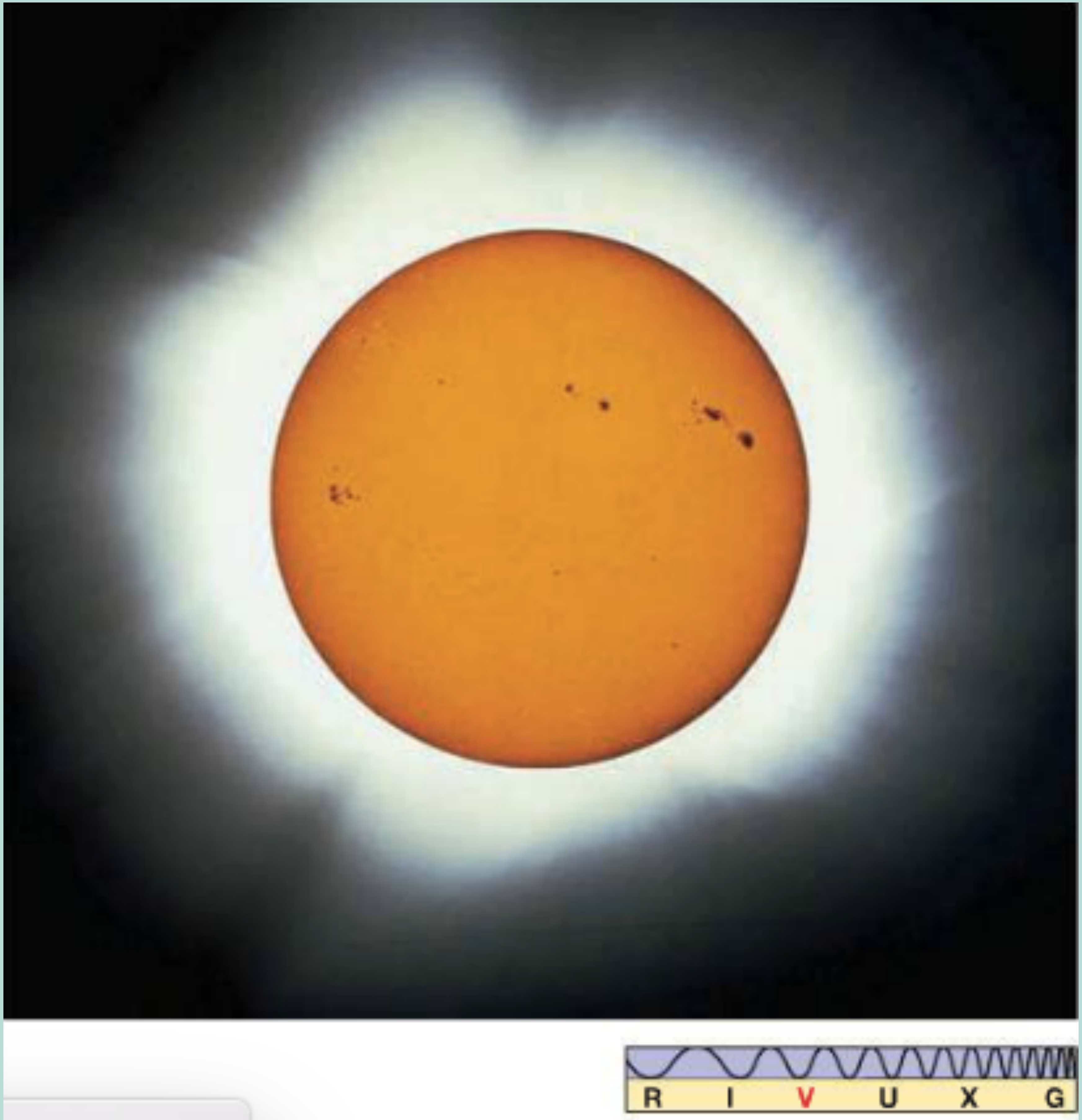
Hierarchy of cells

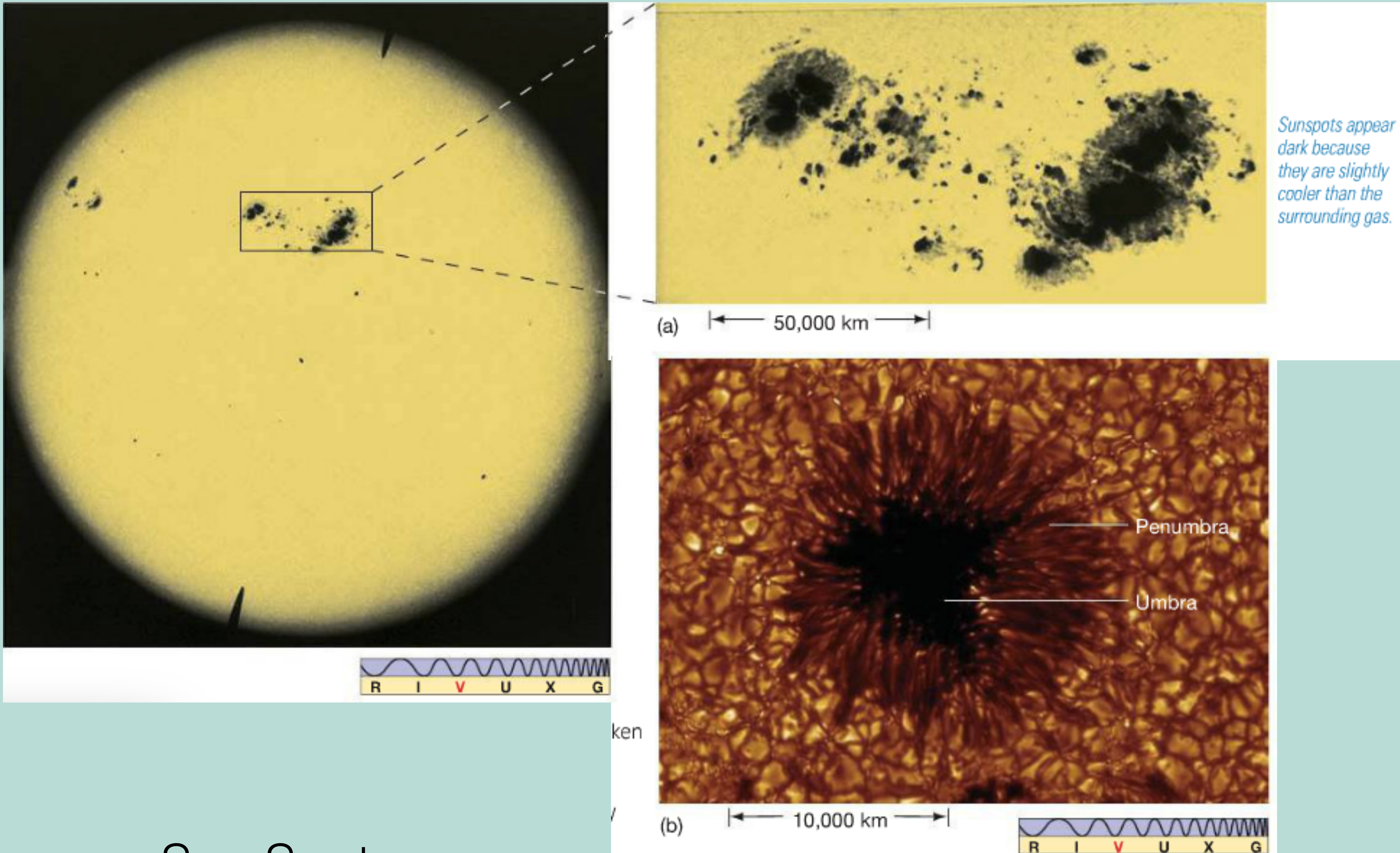
Solar Granules



- Each granule is approximately the size of the Earth!

Sun Spots from Earth

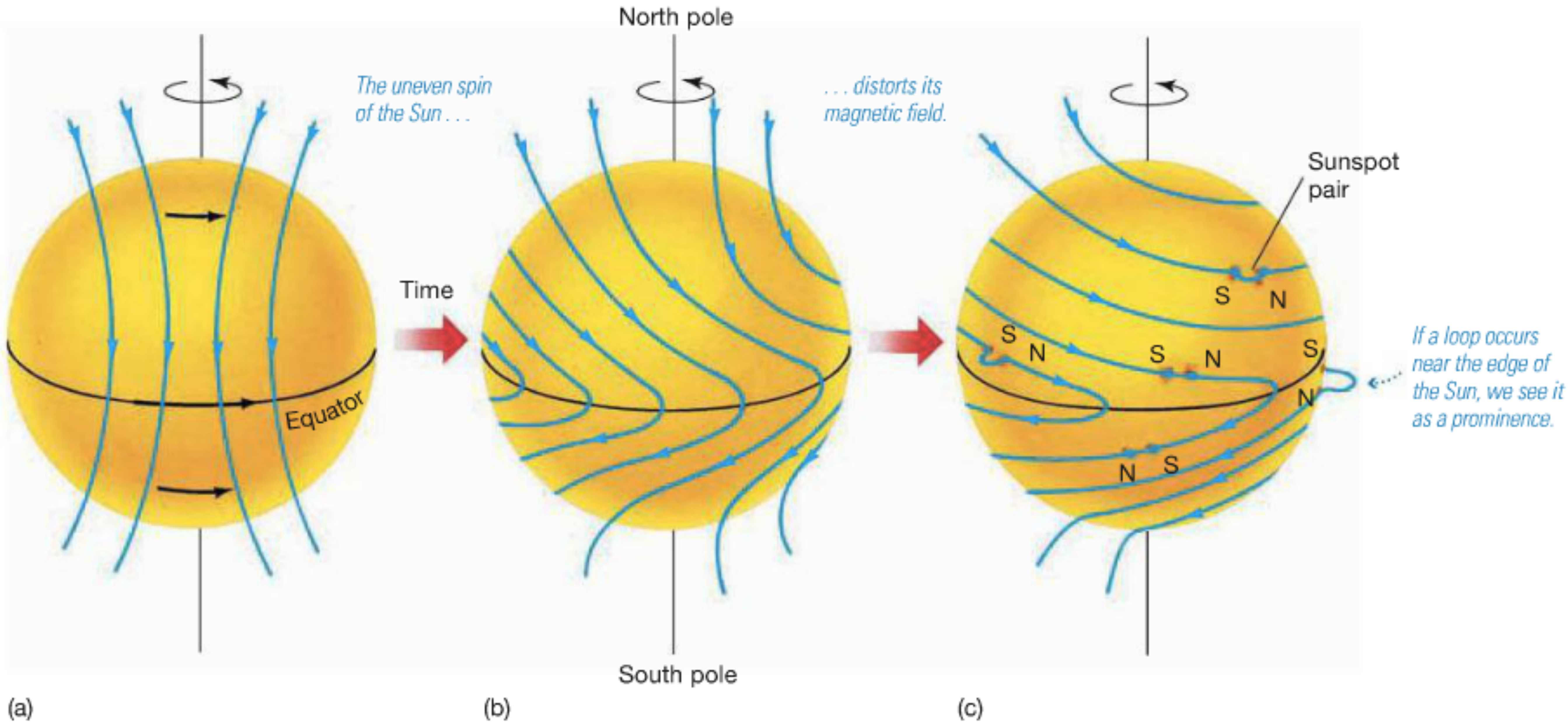




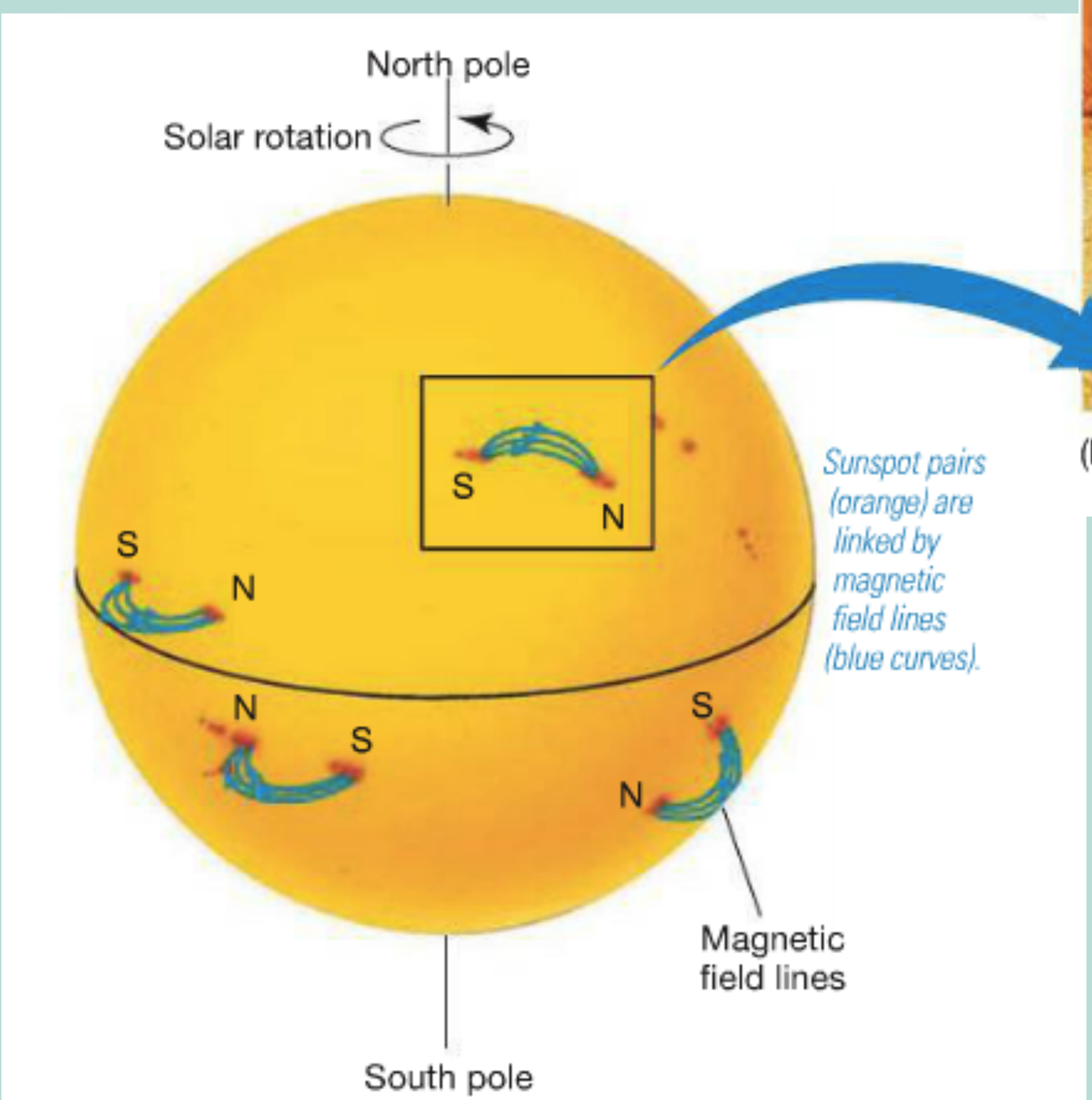
Sun Spots

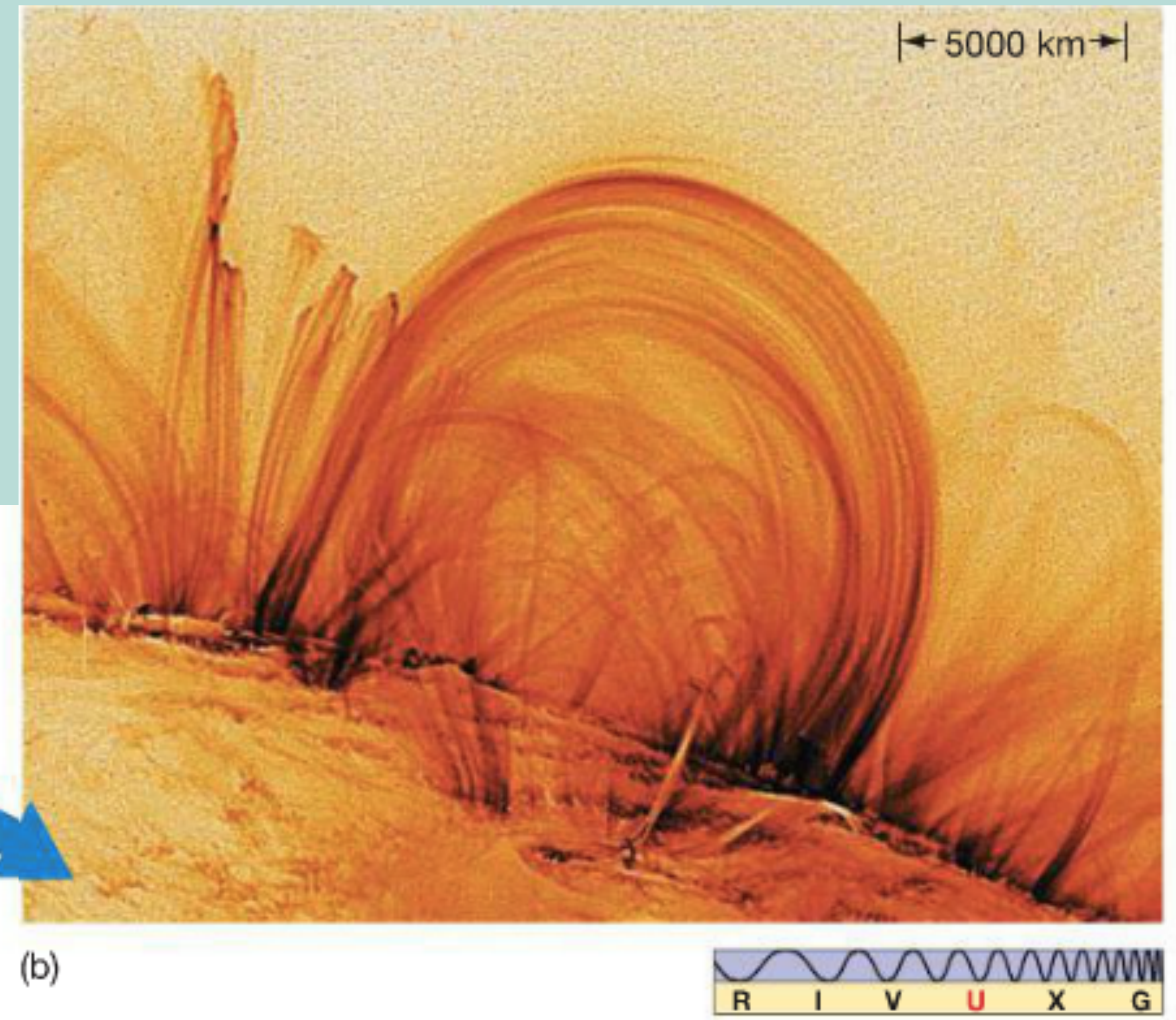
- Umbra is 1000K cooler than the rest of the sun (still bright!)

Origin of Sun Spots



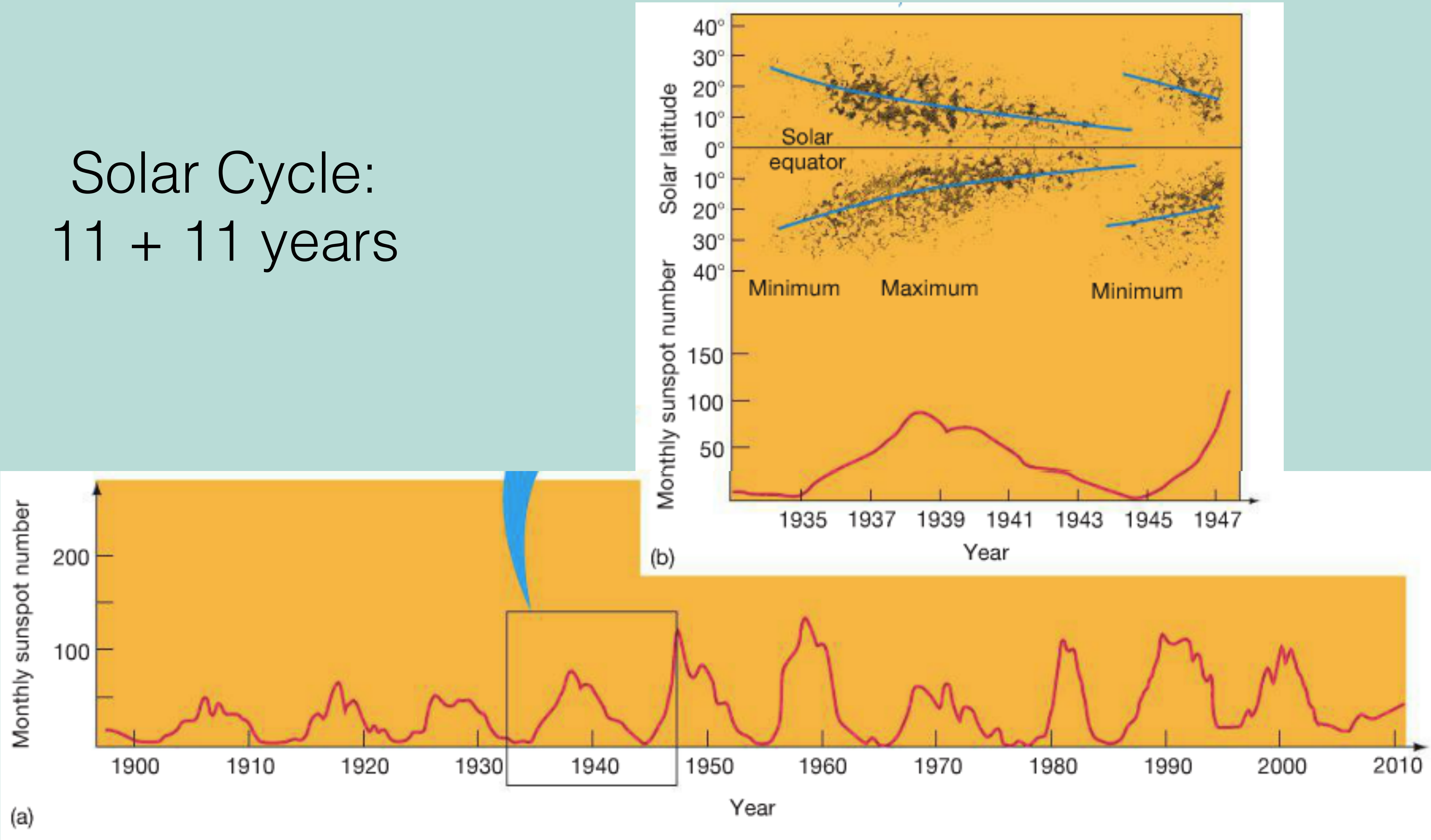
Sun Spots and Magnetism

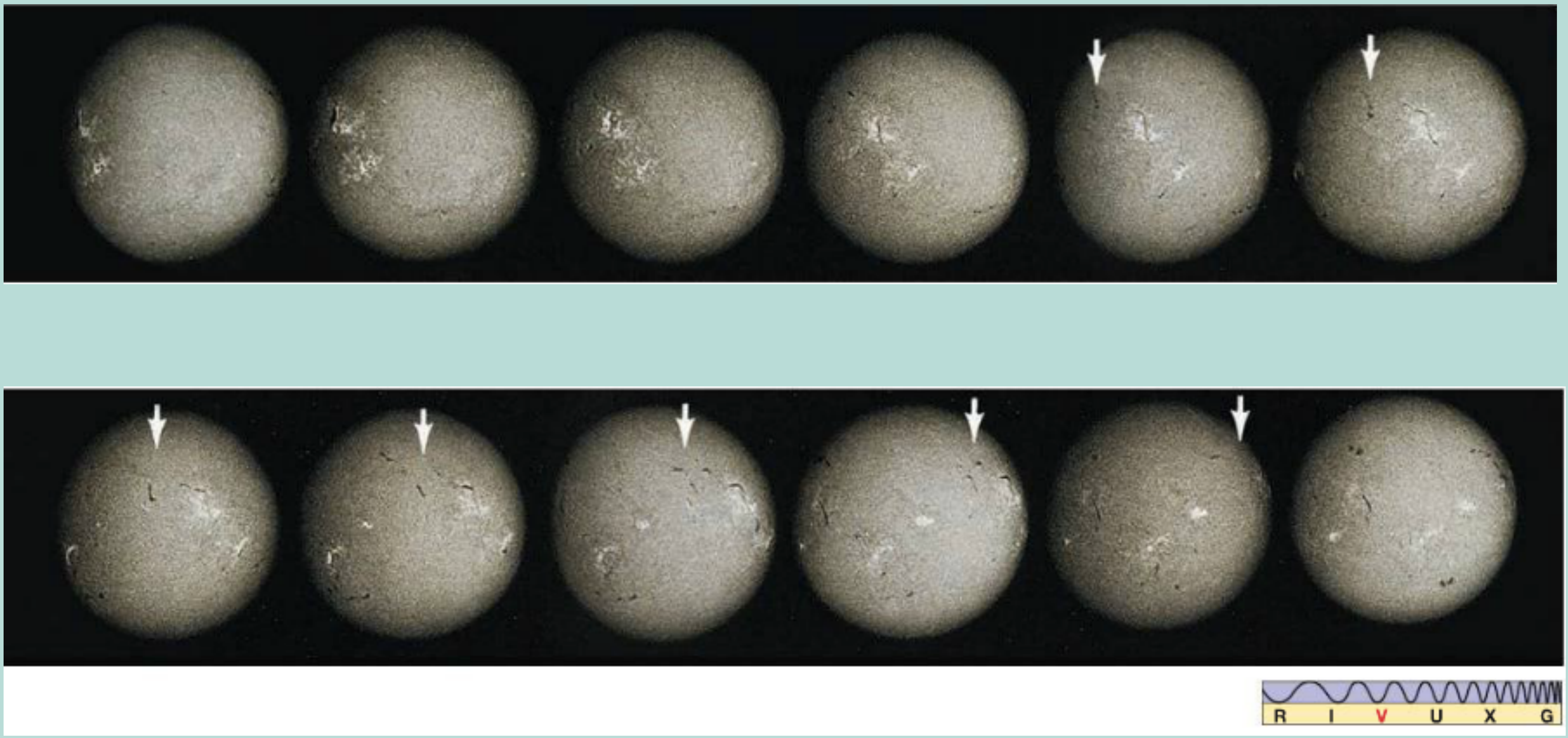




(b)

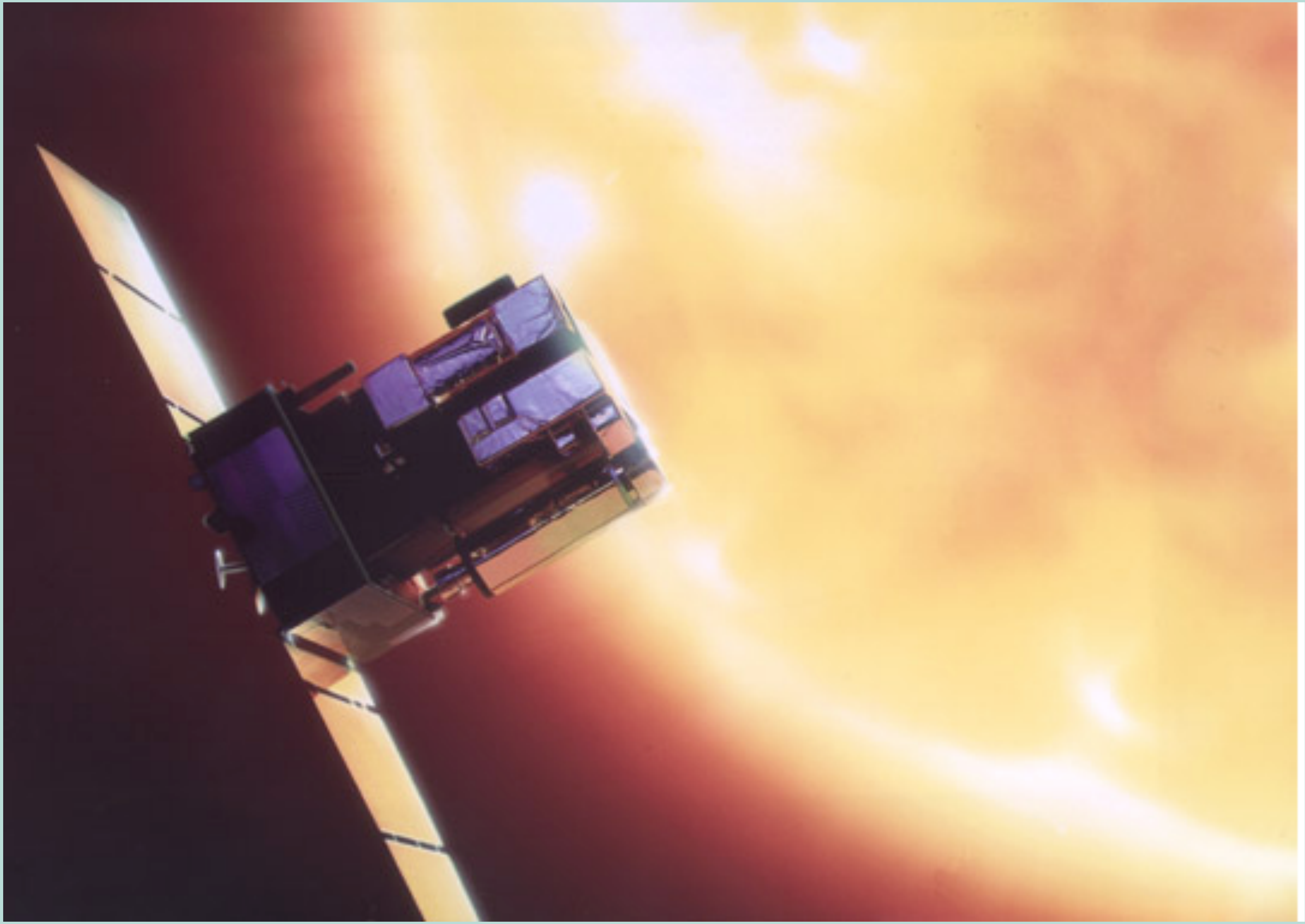
Solar Cycle:
11 + 11 years





Sun Spots in Motion

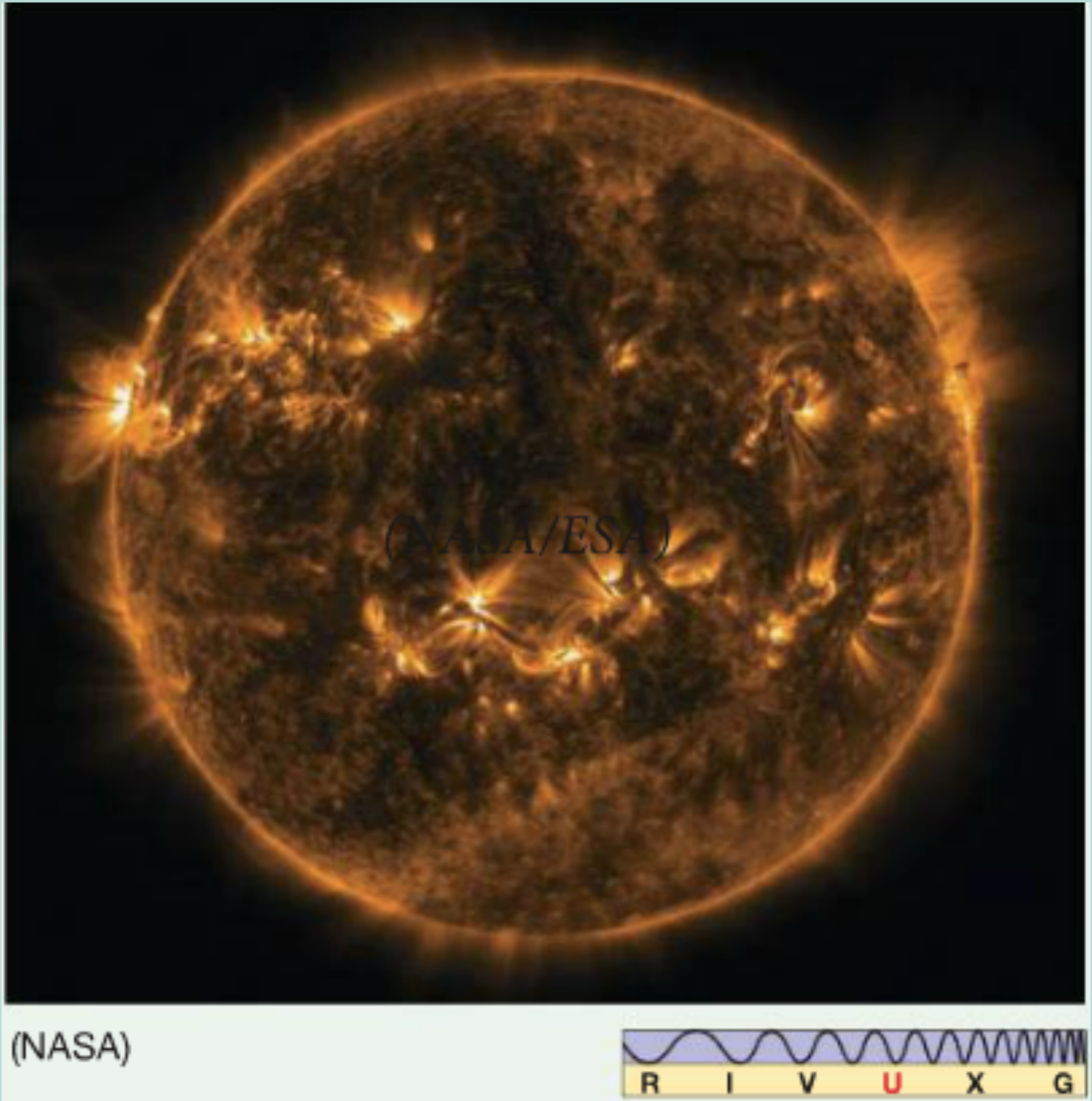
SOHO (SOlar Heliospheric Observatory)



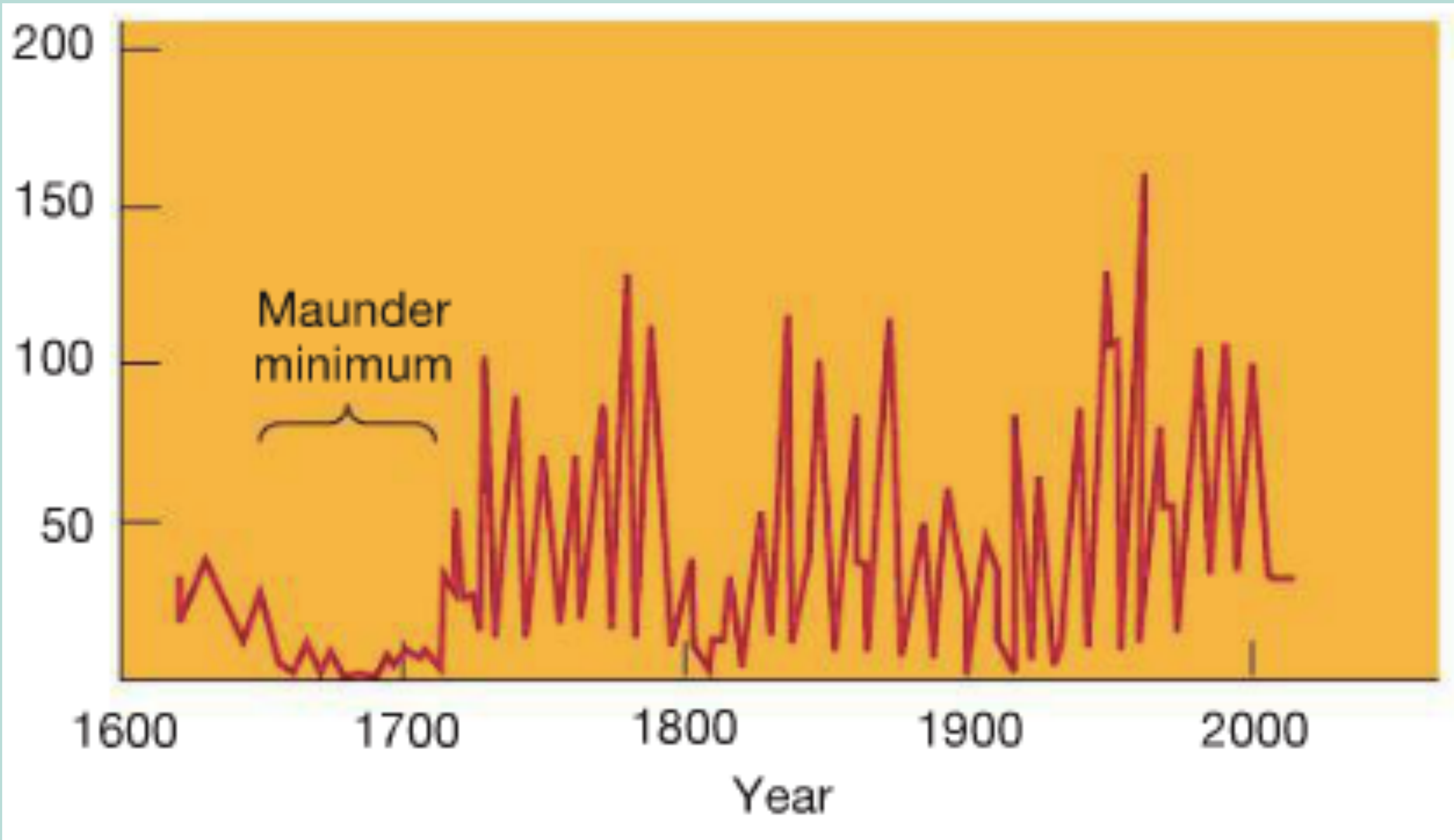
(L1 point)

LINK

SDO (Solar Dynamics Observatory)



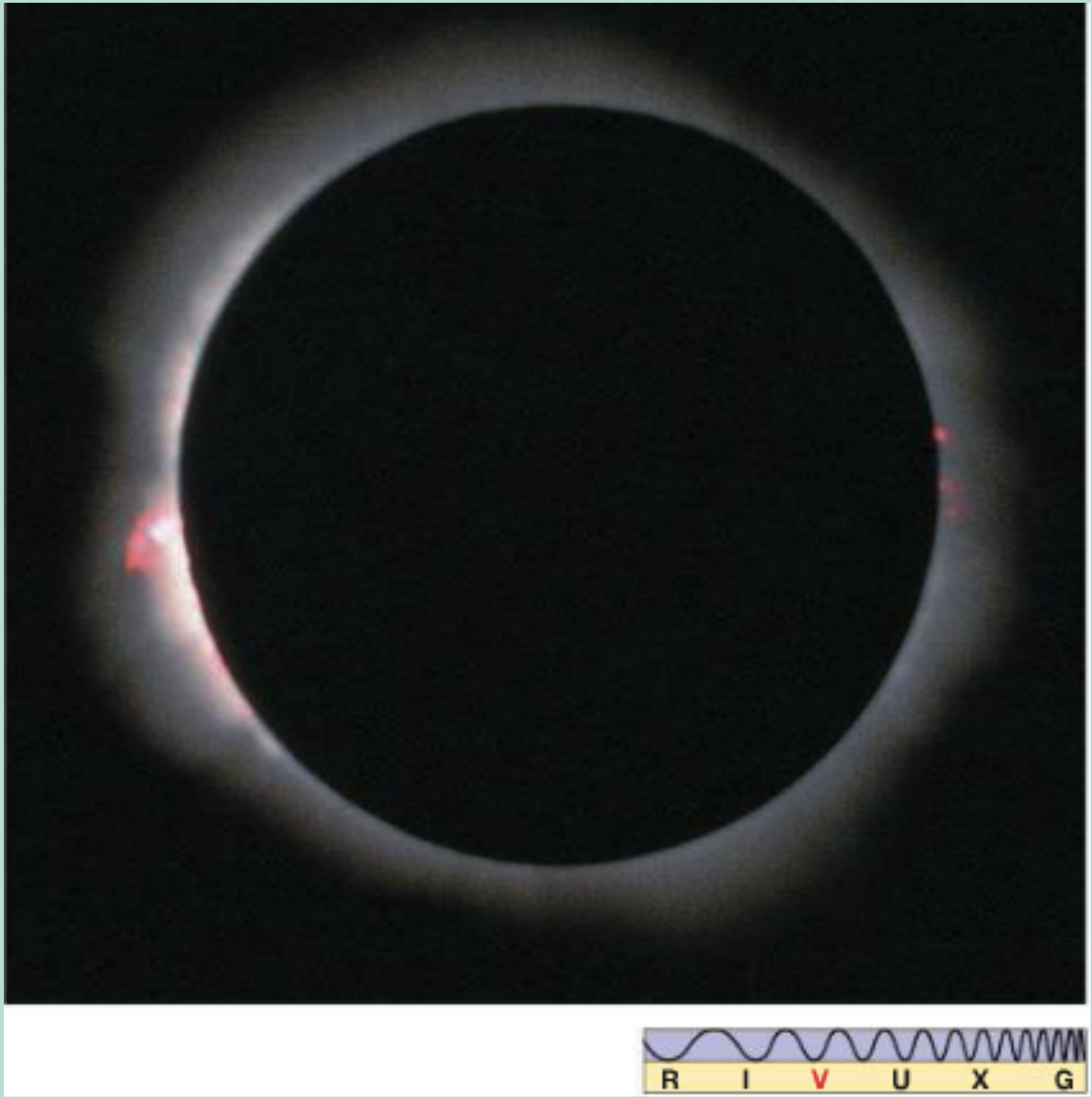
Maunder Minimum



A beautiful summer day in the Netherlands…

No real evidence of weather ⟷ Solar Activity

Chromosphere



(red hue due to Hα lines)

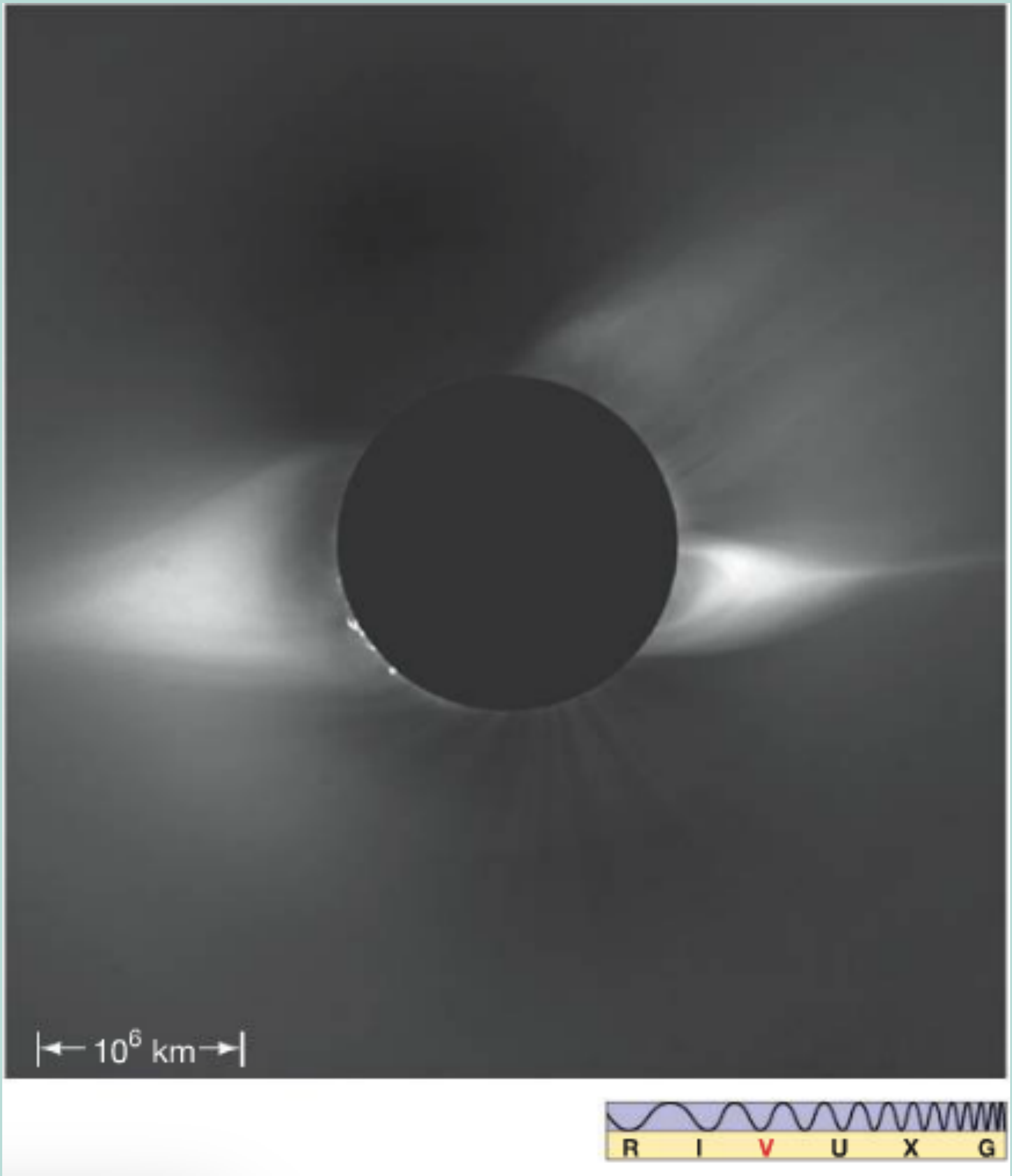
Corona

- Solar wind blasts out towards earth at 500 km/s

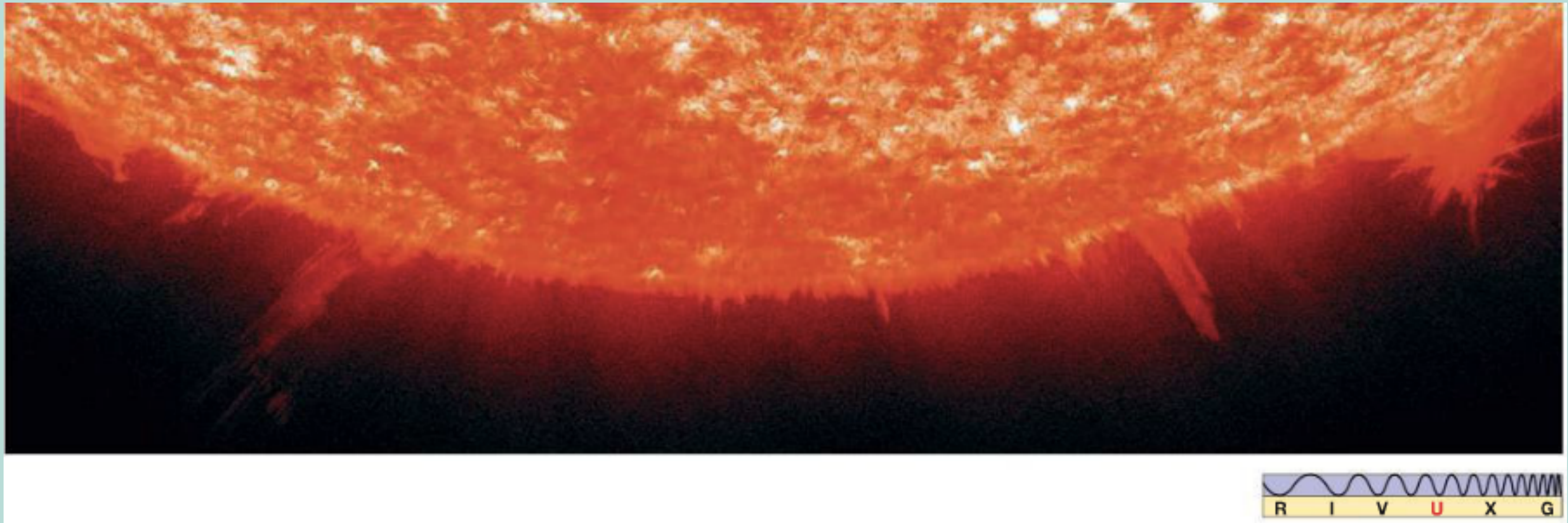
- Thus the sun is “evaporating” at a rate of 2 million tons of solar matter per second

- Sounds big, but amounts to 0.1% of its mass over the last 4.6 billion years

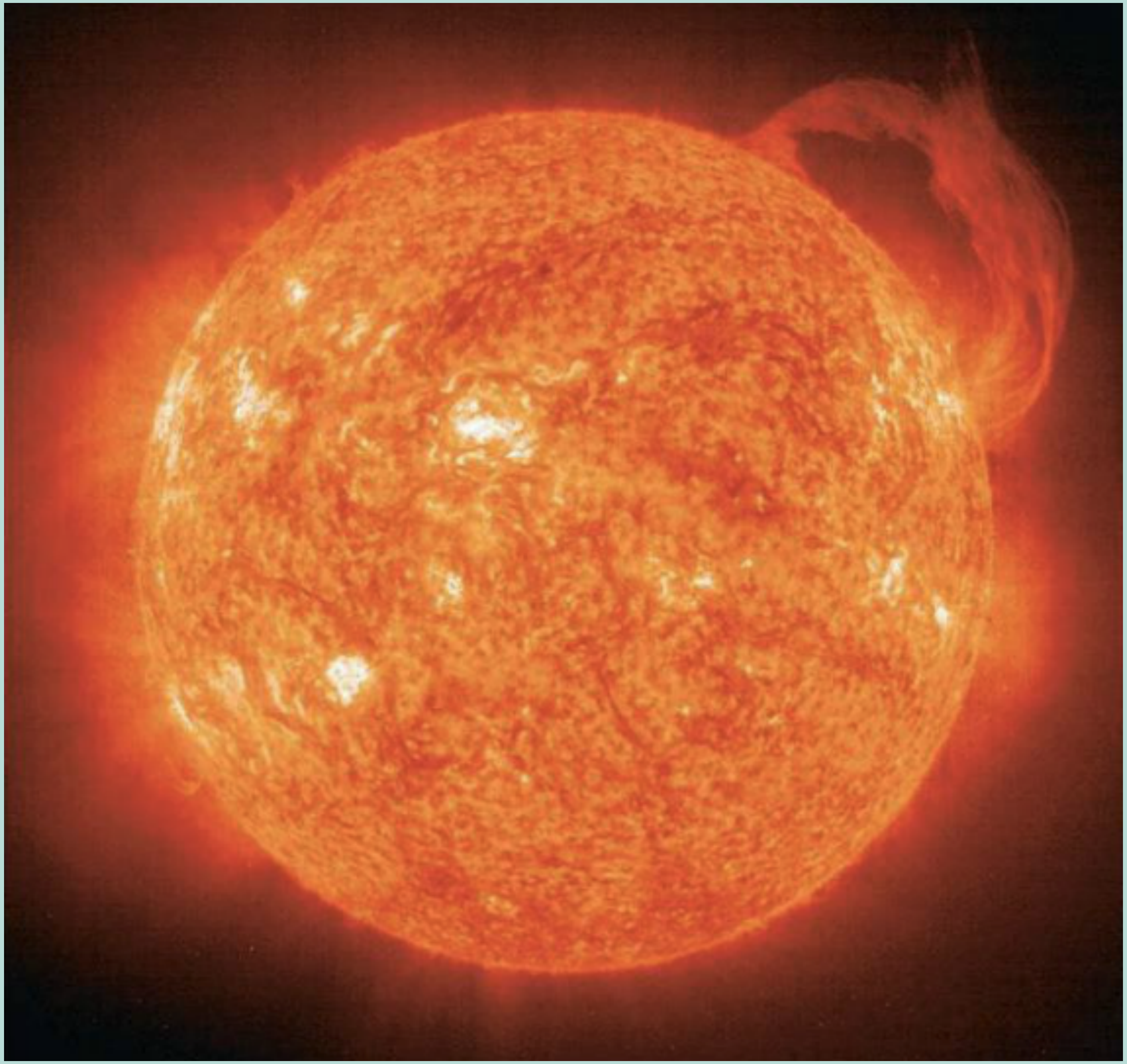
Corona during solar cycle peak



Solar Spicules



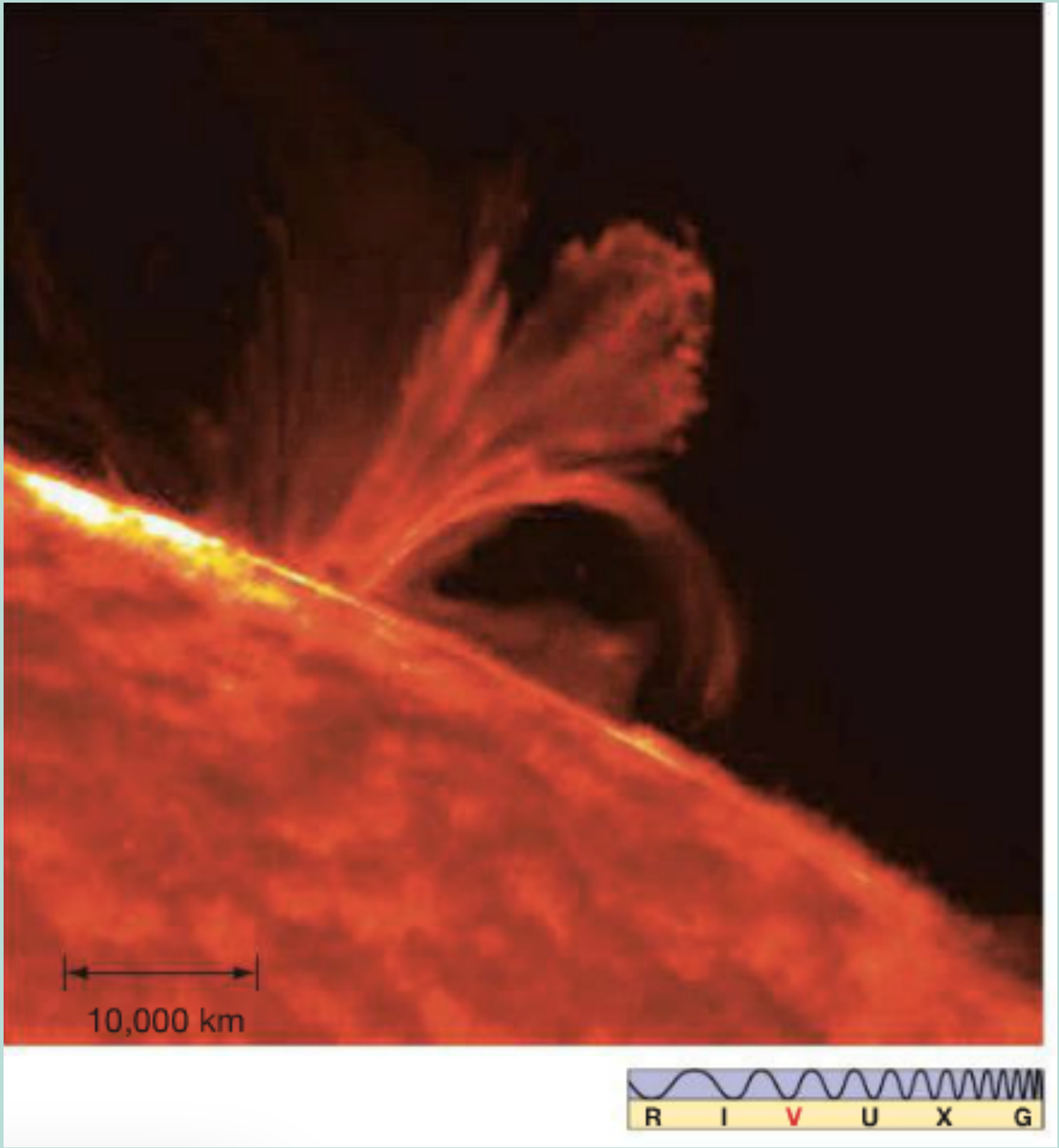
Serious Solar Prominence



Solar Prominence

(b)

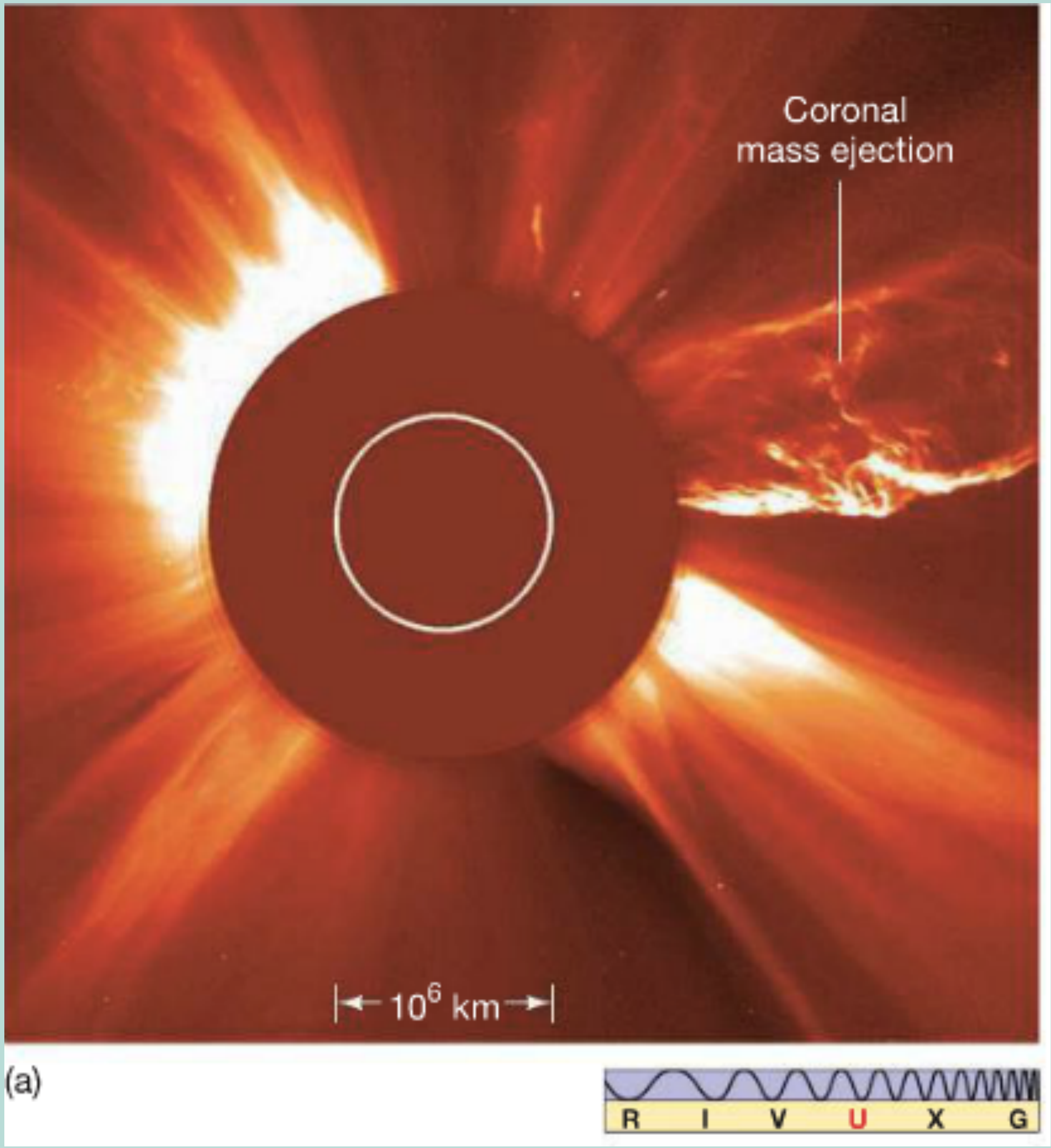
Solar Flare



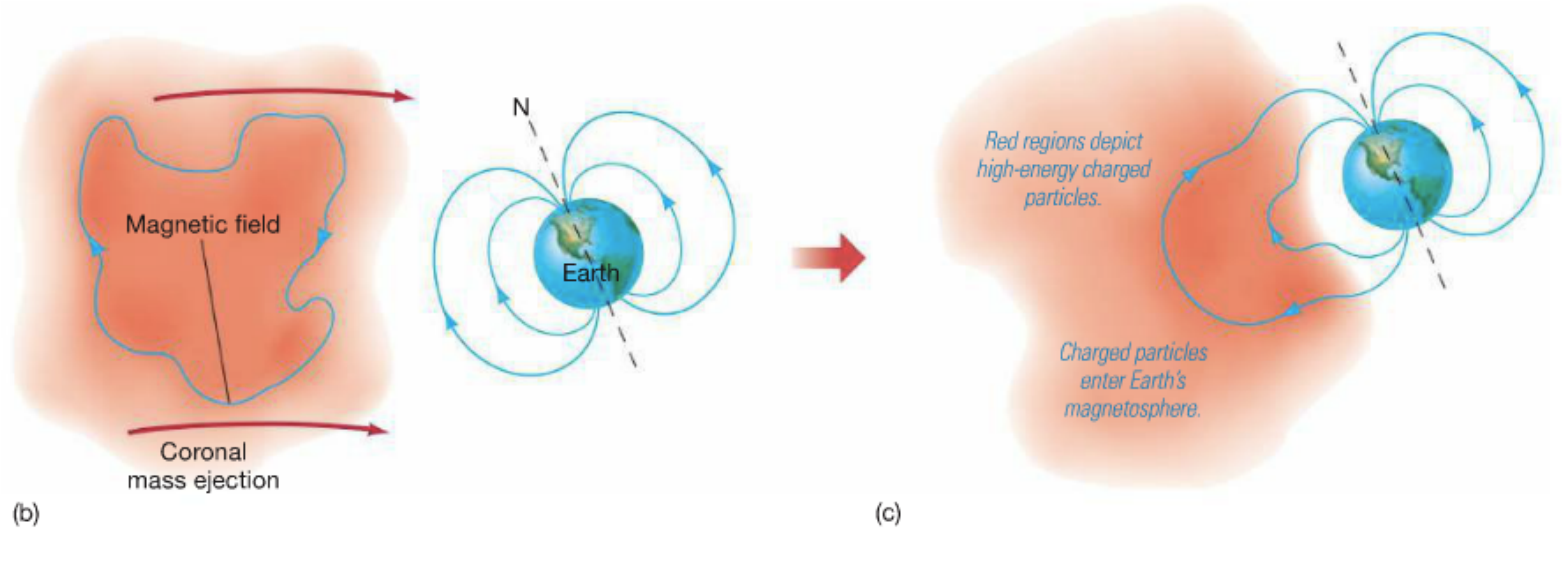
The “Carrington" Event

- September 1859
- Aurora could be seen at latitudes as far south as the Caribbean
- The Auroras in the Rockies were so bright they awoke gold miners who began preparing breakfast
- Telegraph operators could still send signals through disconnected lines!
- It has been estimated that if this happened today it would do ~ 2 trillion dollars of damage

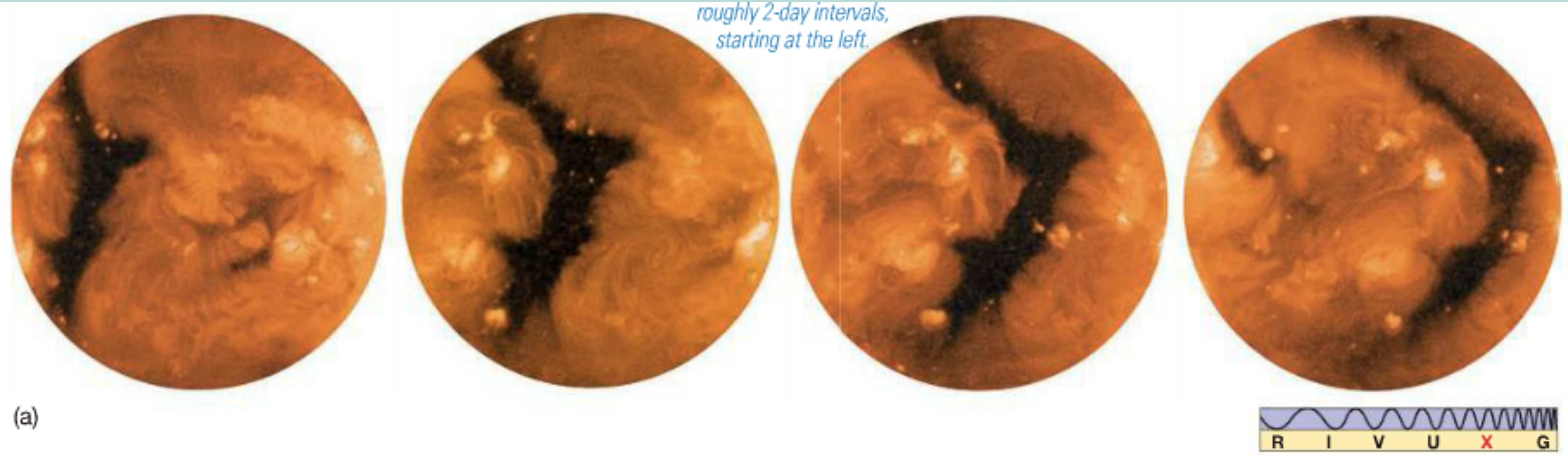
Coronal Mass Ejection (CME)



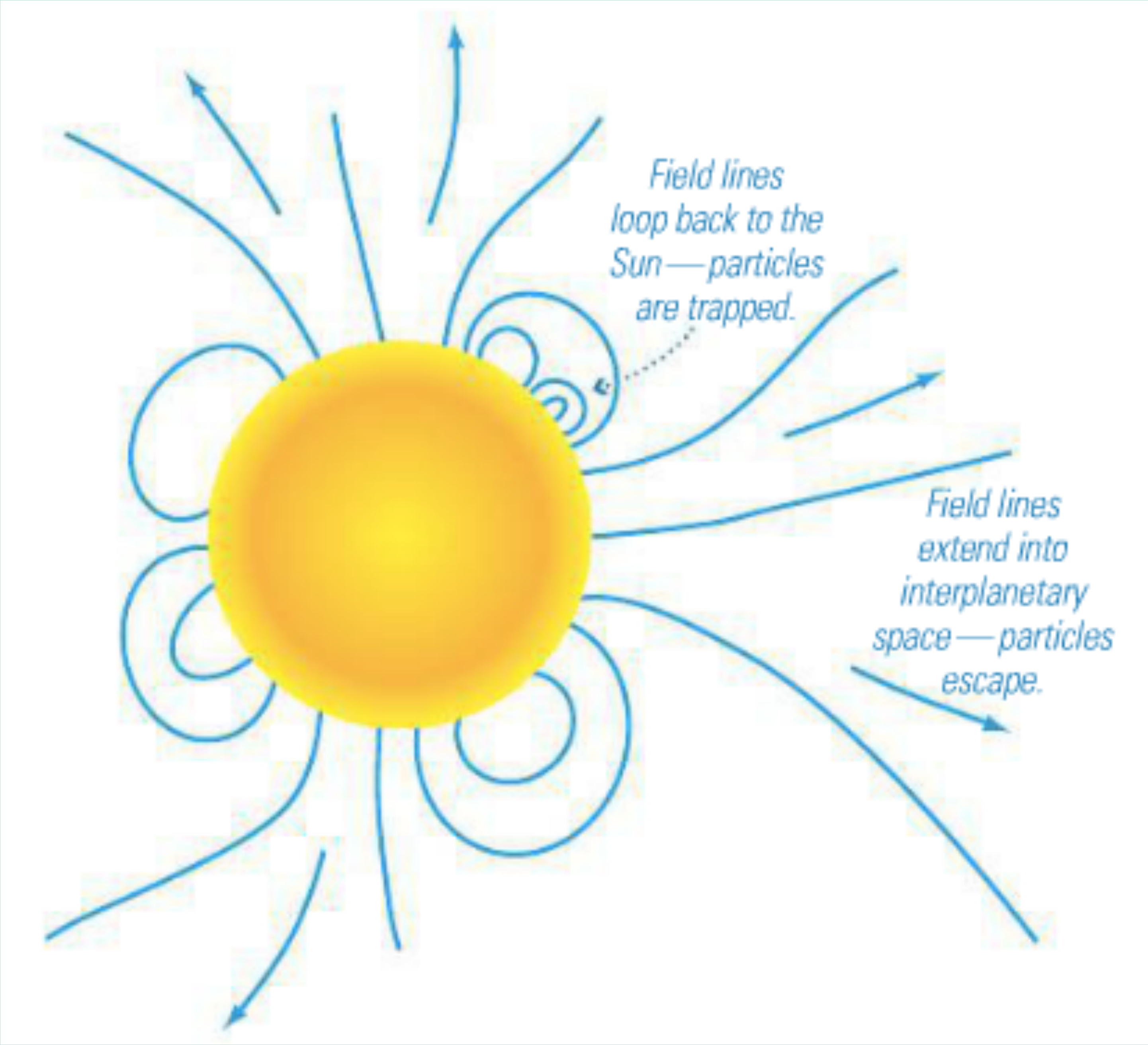
Reconnection



Coronal Holes



“Coronal Holes” are escaping field lines



Sir Arthur Eddington

1882 - 1944   UK

Fusion Vs Wood

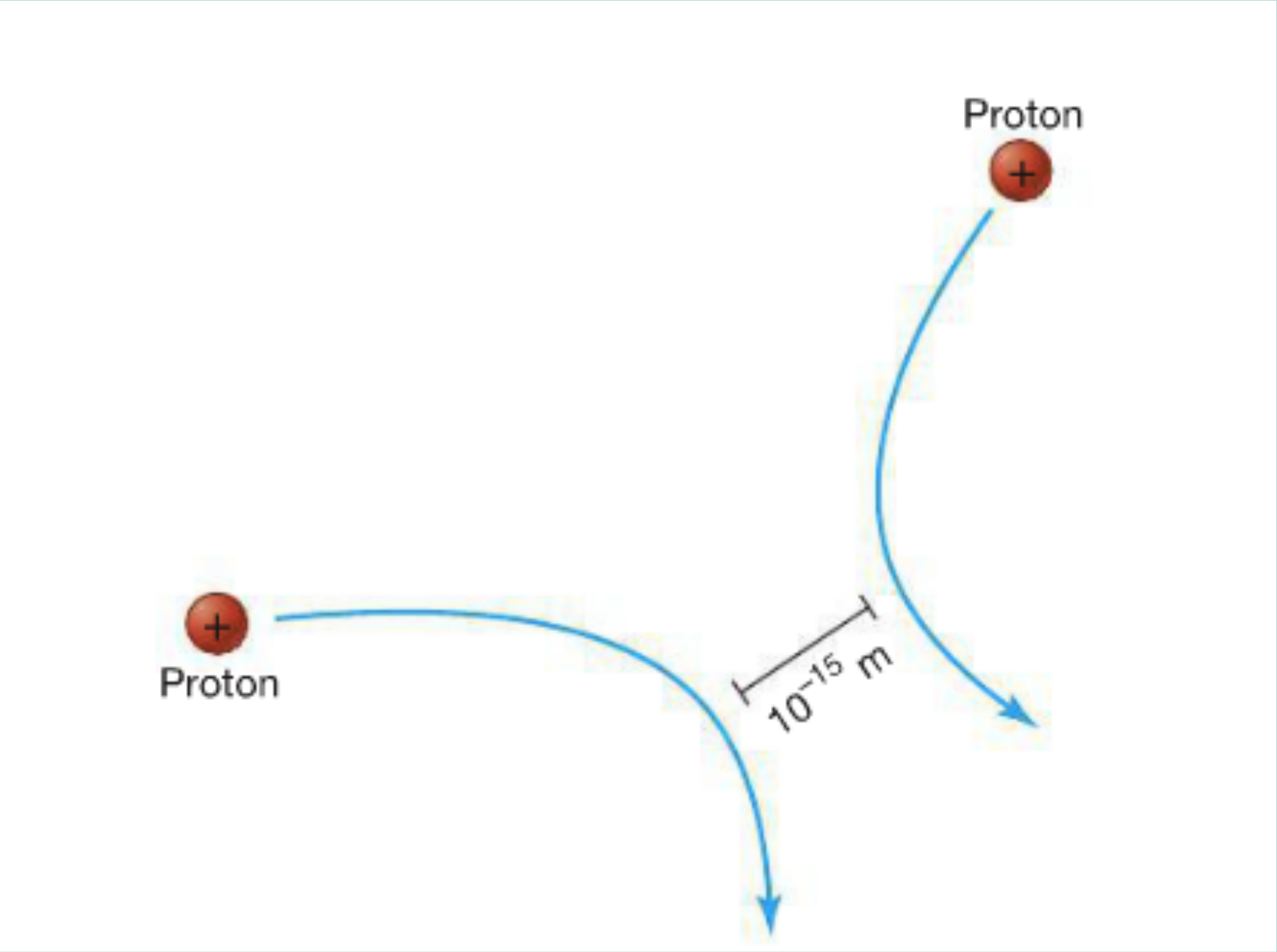
- If you divide the solar luminosity by the solar mass you get 2 mW / kilogram
- Wood generates 1,000,000 times more than that. A bon fire, merely the size of the pitiful earth would burn as bright as the sun
- How long would that fire burn though? Ans: not 5 billion years.
- Consider over 5 billion years, the amount of energy each kilogram of sun has provided so far:

10^13 Joules!!

$$E = mc^2$$

- This means 1 kg in principle could have 10^17 Joules packed inside!

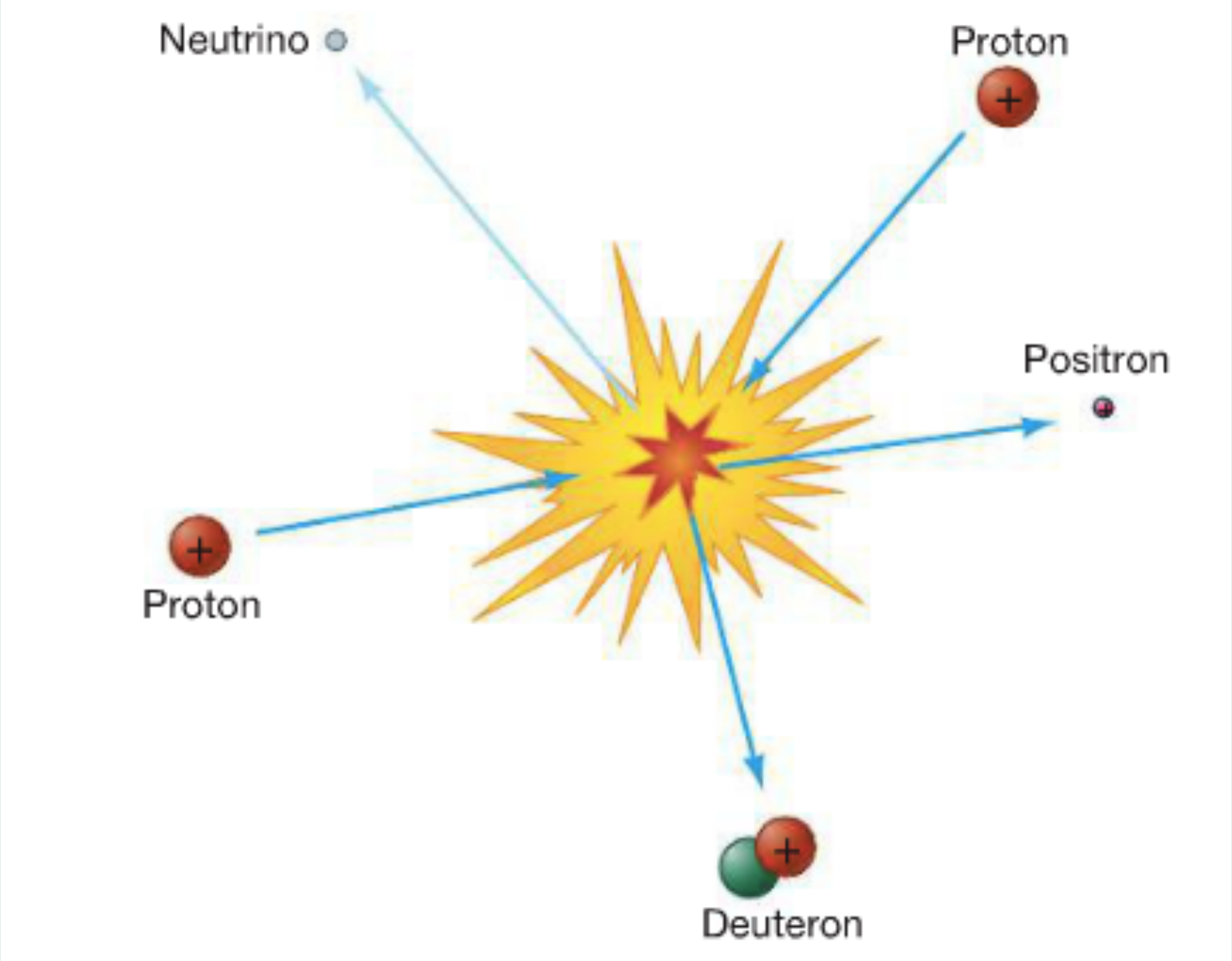
T < 10 million Kelvin



Electrostatic Repulsion

T > 10 million Kelvin

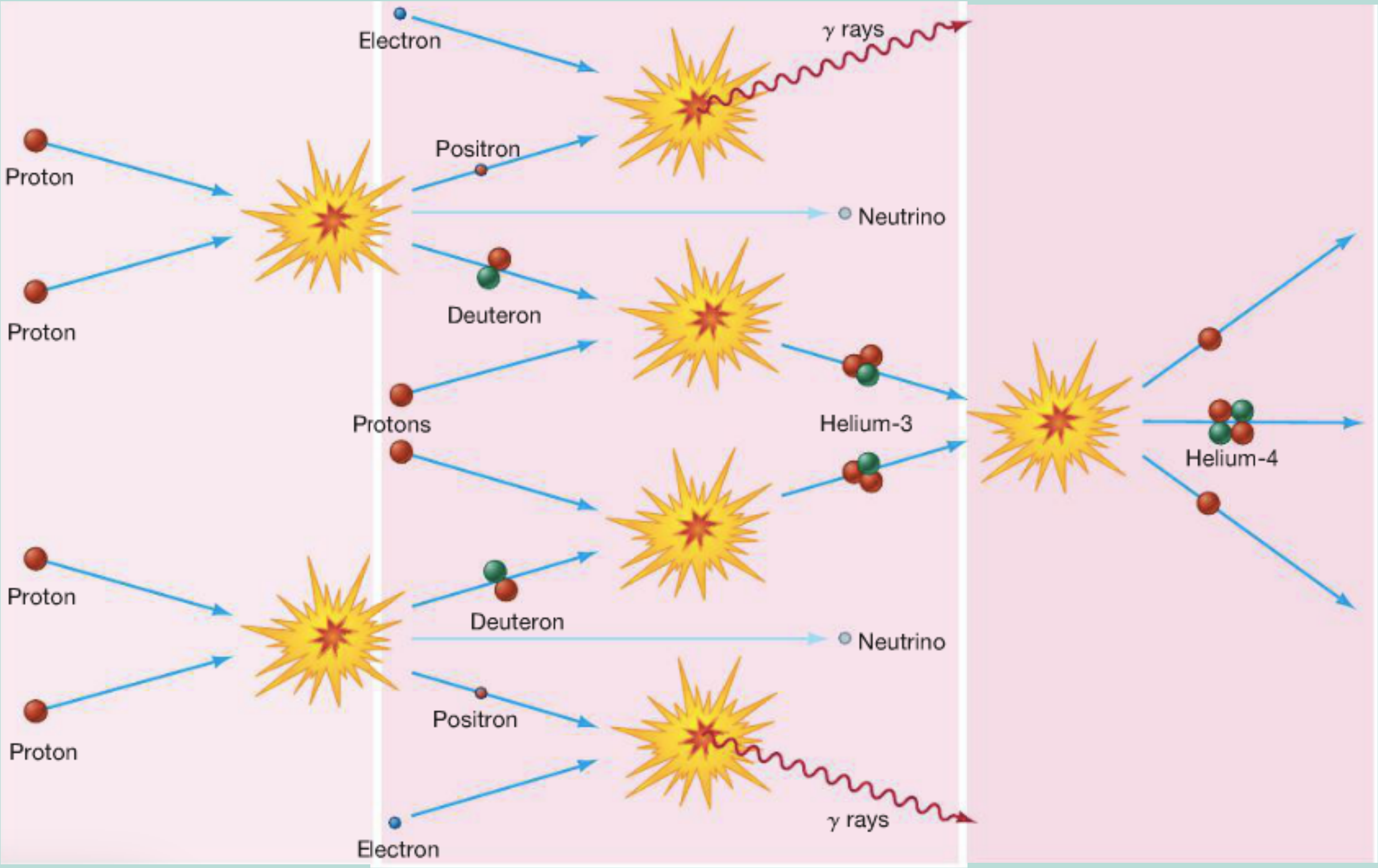
(we'll talk about these later)



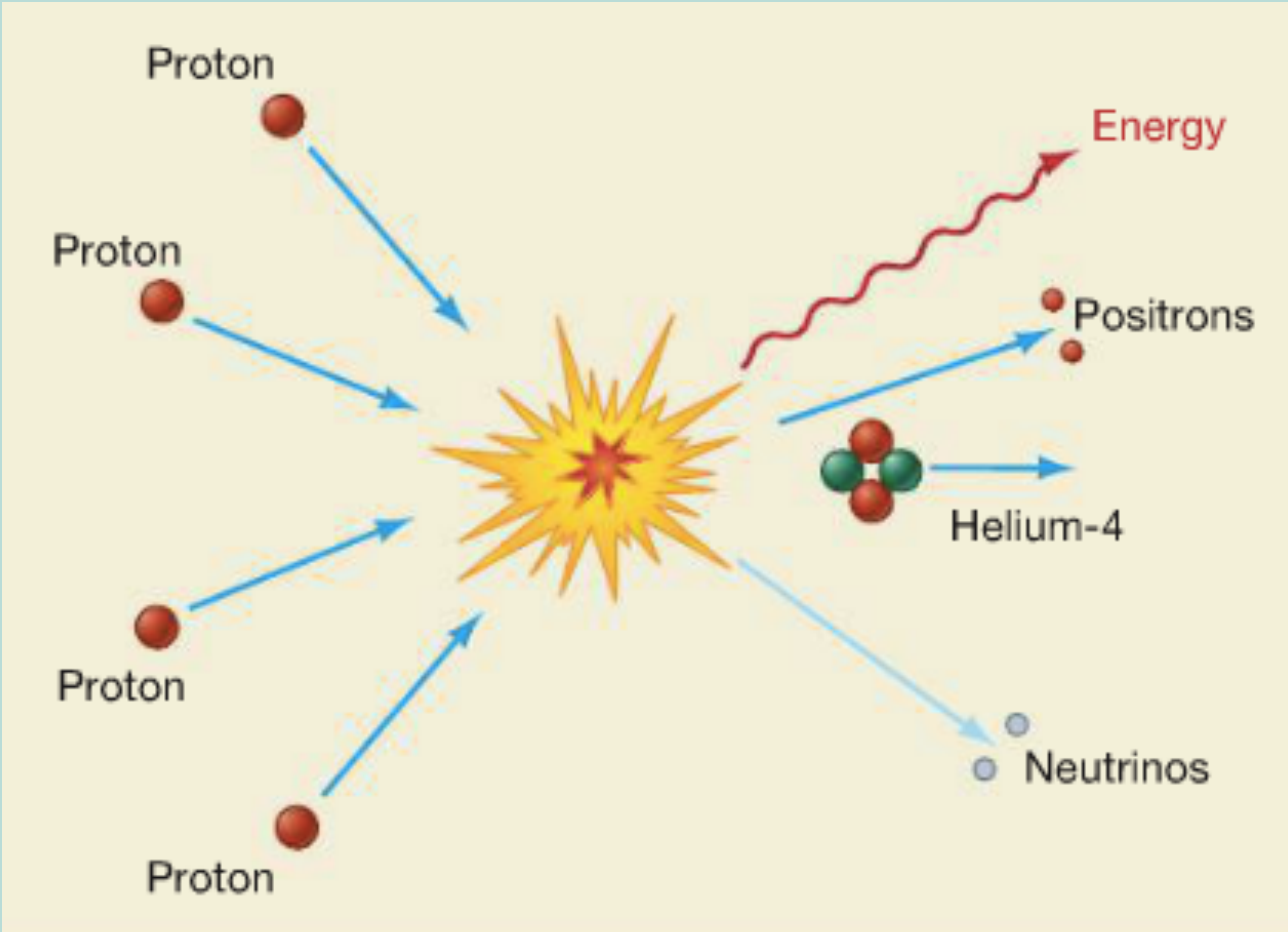
(anti-matter)

(isotopes)

How to burn 4 hydrogen nuclei

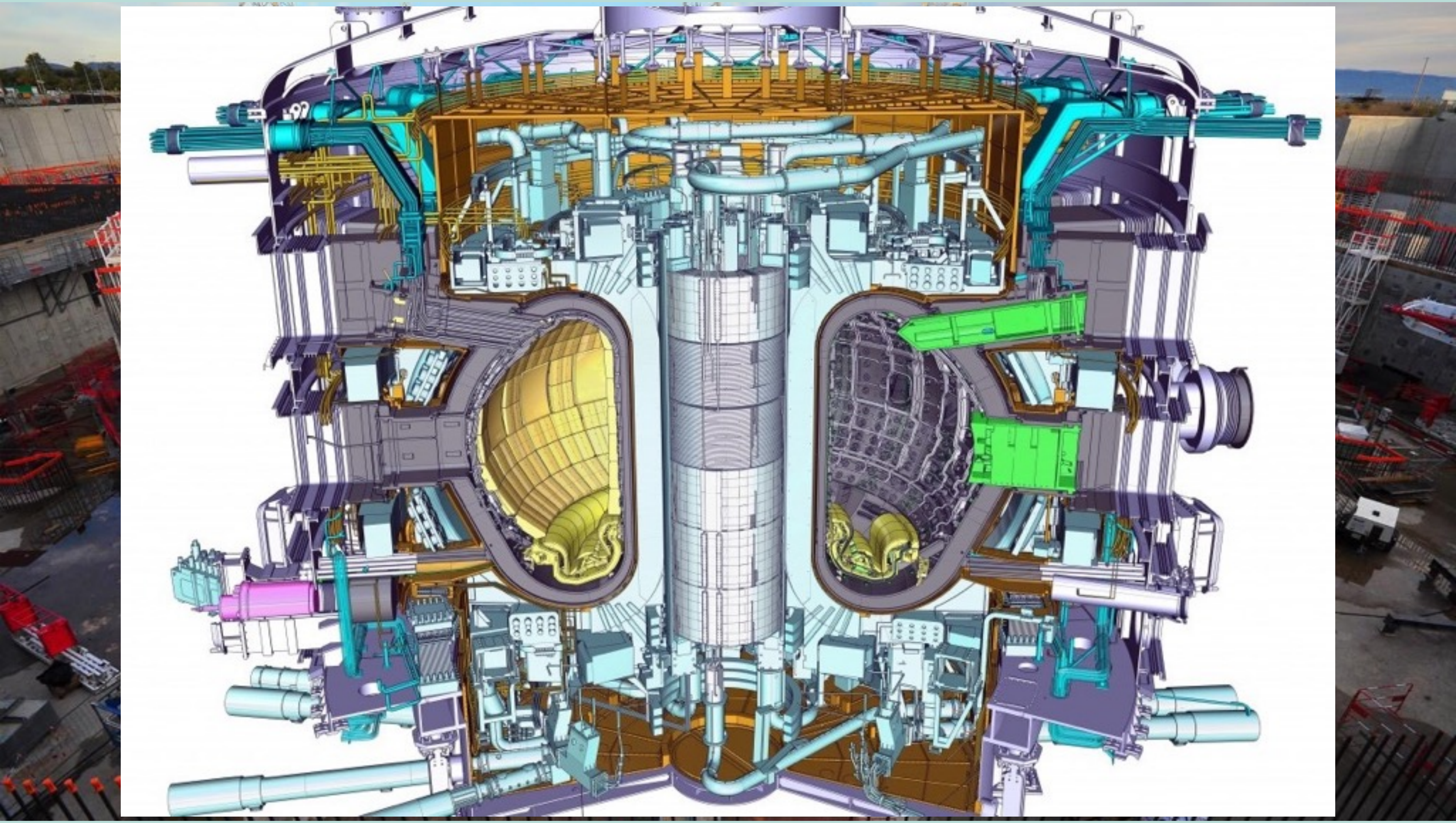


Net Fusion Reaction



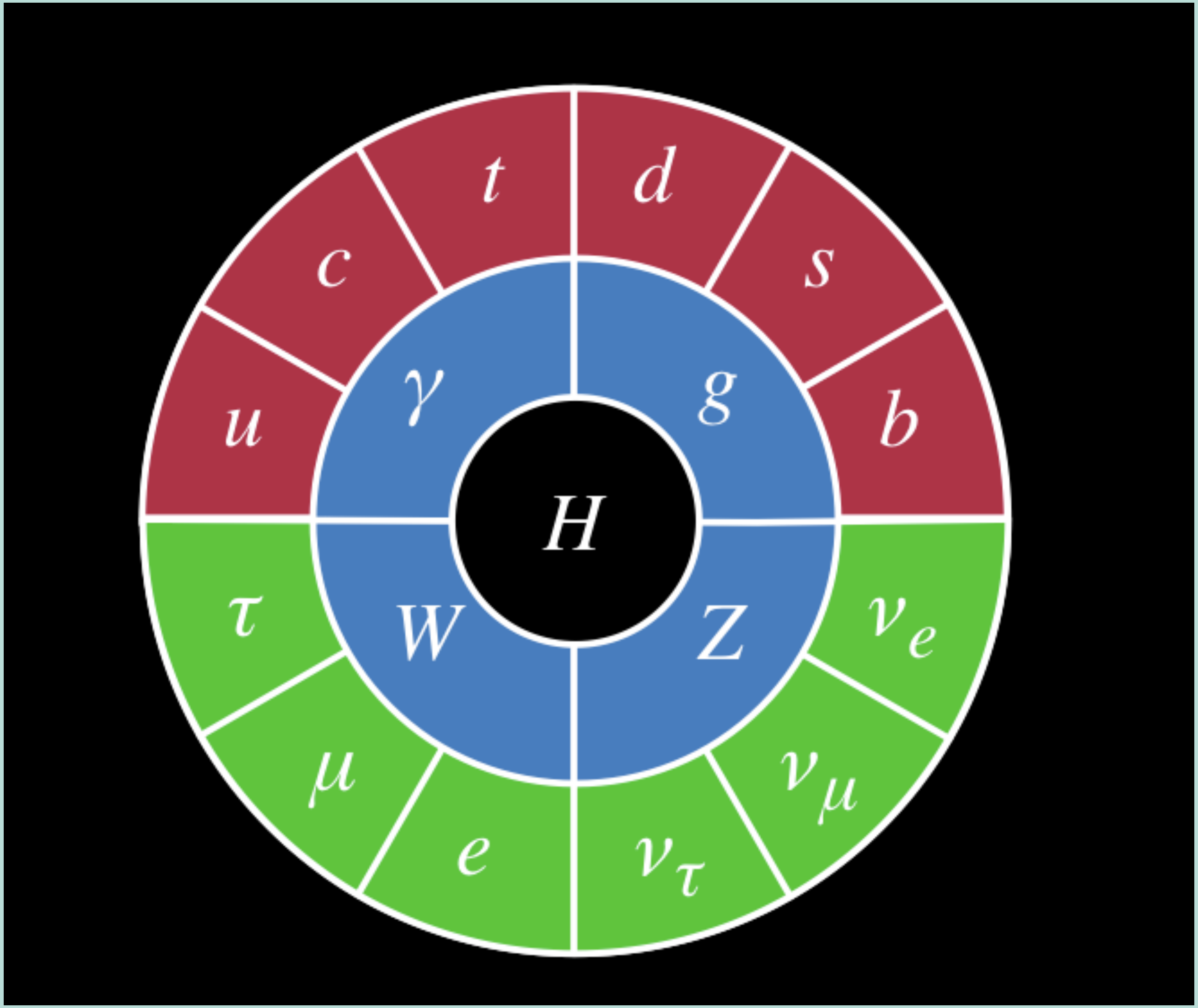
- Each fusion reaction gives you 4 X 10^(-12) J of energy.
- 1 kg gives you 10^14 J of energy, so fusion (as a fraction of the total mass energy) has an efficiency of .71%
- Side note, dropping rocks into maximally rotating black holes has an efficiency of 47%
- Thus, to keep up with 4 X 10^26 W of luminosity, 600 million tons of hydrogen must be fused into helium every second.
- Thus we lose 4.3 million tons of mass to pure energy per second (comparable to the solar wind).
- That might sound like a lot, but the sun is 10^30 kg, so we can keep doing this for 5 billion years

ITER



International ThermoNuclear Reactor (2027)

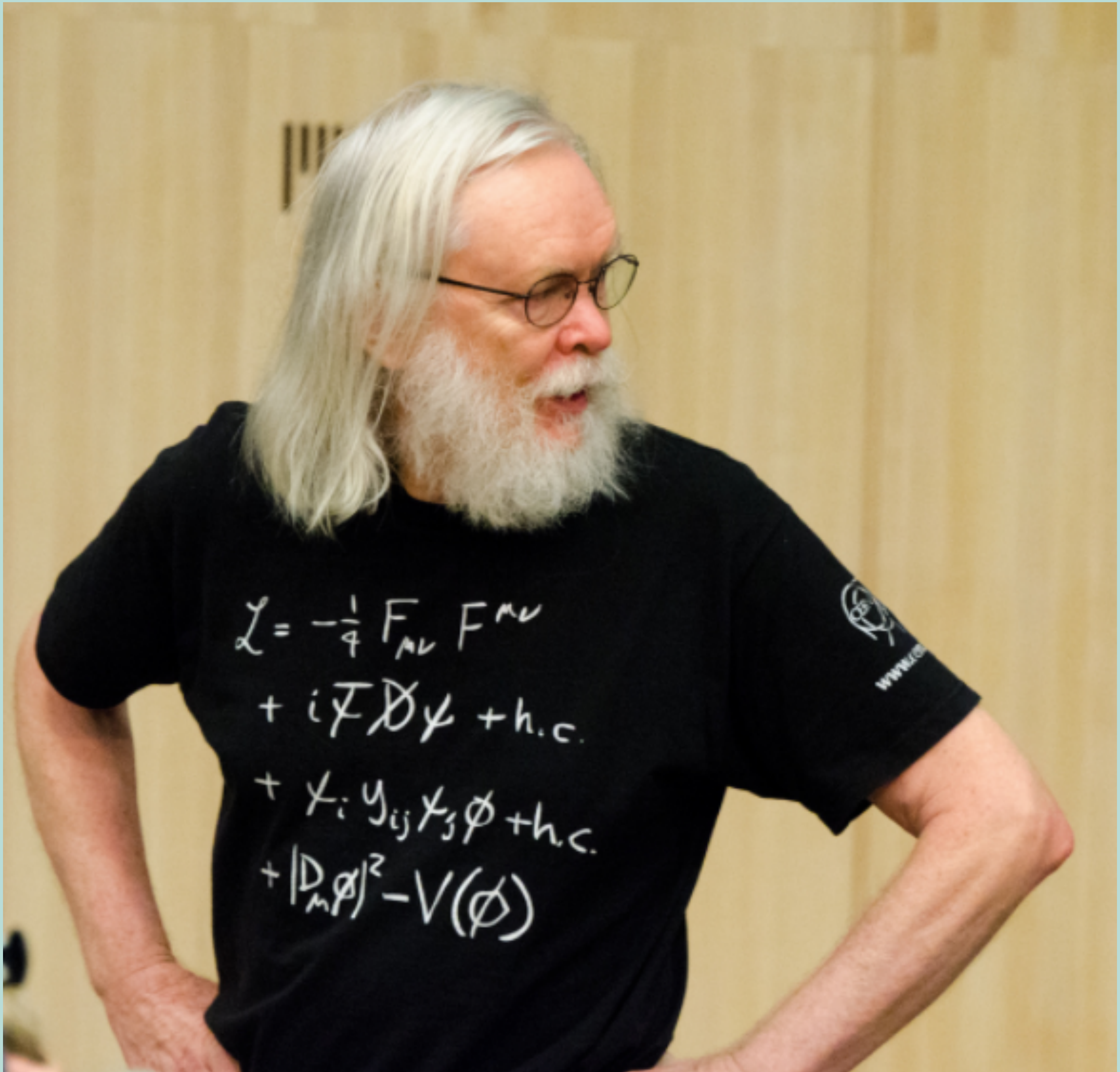
Behold…



Gotta catch’em all

$$
\begin{aligned}
\mathcal{L}_{SM} = & -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
& M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
& igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
& W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
& Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \\
& \beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
& g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
& \tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
& gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
& \tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
& \tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
& M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
& W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
& \tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2+(\phi^0)^2+2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-\right) - \\
& \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
& W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
& g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial+m^\lambda_e)e^\lambda - \bar\nu^\lambda(\gamma\partial+m^\lambda_\nu)\nu^\lambda - \bar u^\lambda_j(\gamma\partial+ \\
& m^\lambda_u)u^\lambda_j - \bar d^\lambda_j(\gamma\partial+m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
& \tfrac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2-1-\gamma^5)d^\lambda_j) + \\
& (\bar u^\lambda_j\gamma^\mu(1-\tfrac{8}{3}s_w^2+\gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
& \tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar e^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
& \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
& \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar\nu^\lambda\nu^\lambda) - \\
& \tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar e^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar\nu_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat\nu_\kappa - \\
& \tfrac{1}{4}\overline{\bar\nu_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat\nu_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
& \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) - \\
& \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5d^\lambda_j) + \bar G^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar G^aG^bg^c_\mu + \\
& \bar X^+(\partial^2-M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2-\tfrac{M^2}{c_w^2})X^0 + \bar Y\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar X^0X^- - \\
& \partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- - \partial_\mu\bar X^+Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \\
& \partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar YX^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \\
& \partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ - \\
& \partial_\mu\bar X^-X^-) - \tfrac{1}{2}gM\left(\bar X^+X^+H + \bar X^-X^-H + \tfrac{1}{c_w^2}\bar X^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-\right) + \\
& \tfrac{1}{2c_w}igM\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + igMs_w\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + \\
& \tfrac{1}{2}igM\left(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\right).
\end{aligned}
$$

75% of Physics.



$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

Solar Neutrino Problem

- With the amount of data that we have on the sun, we know exactly how many neutrinos are created in the core

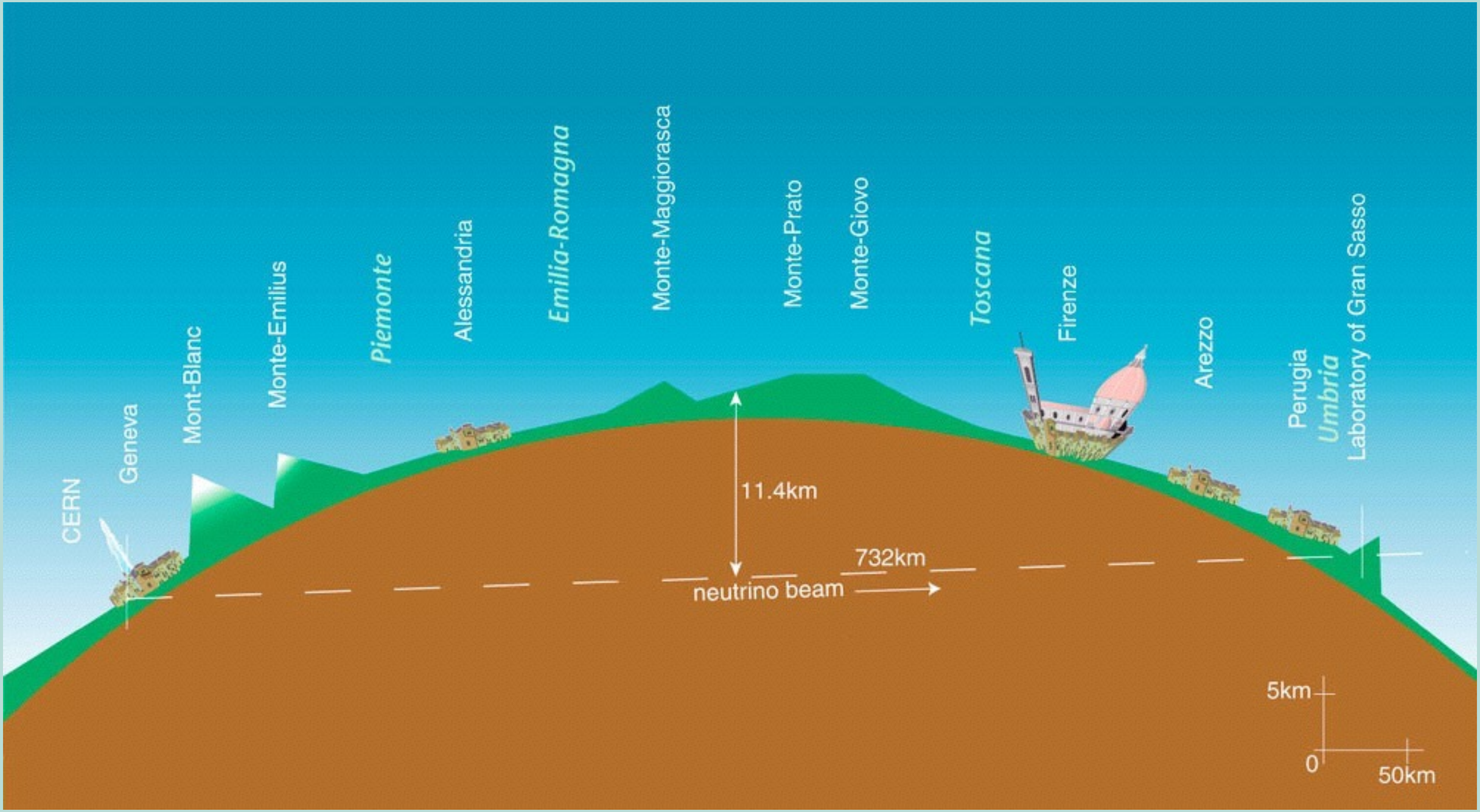
- We also know how likely those neutrinos are to interact with our detectors

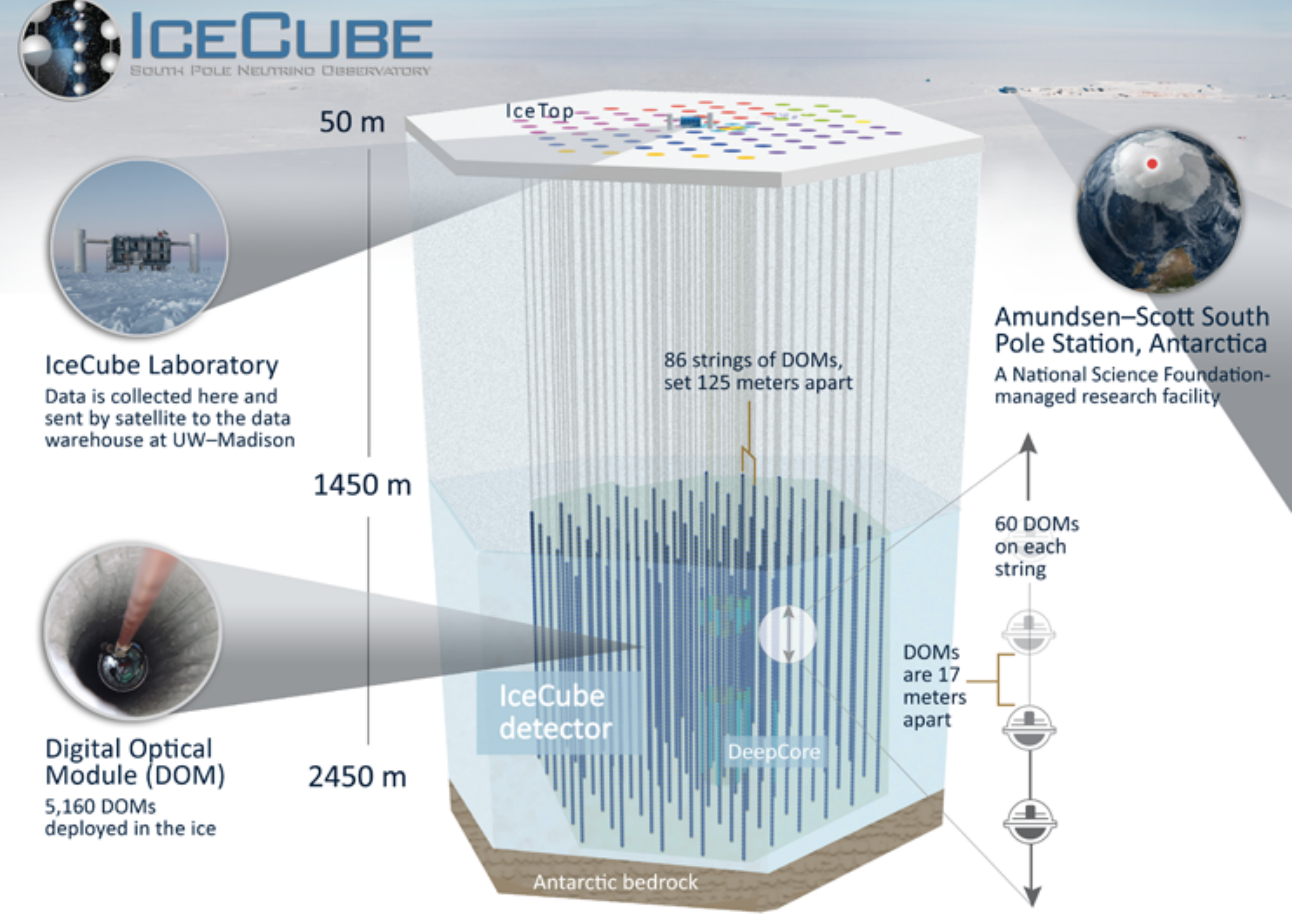
- We see a mismatch. This was explained by “neutrino oscillations”, experimentally verified in 2002

FACT: about 65 million neutrinos pass through your thumbnail every second.

Learn Something
New Every Day
LSNED.com

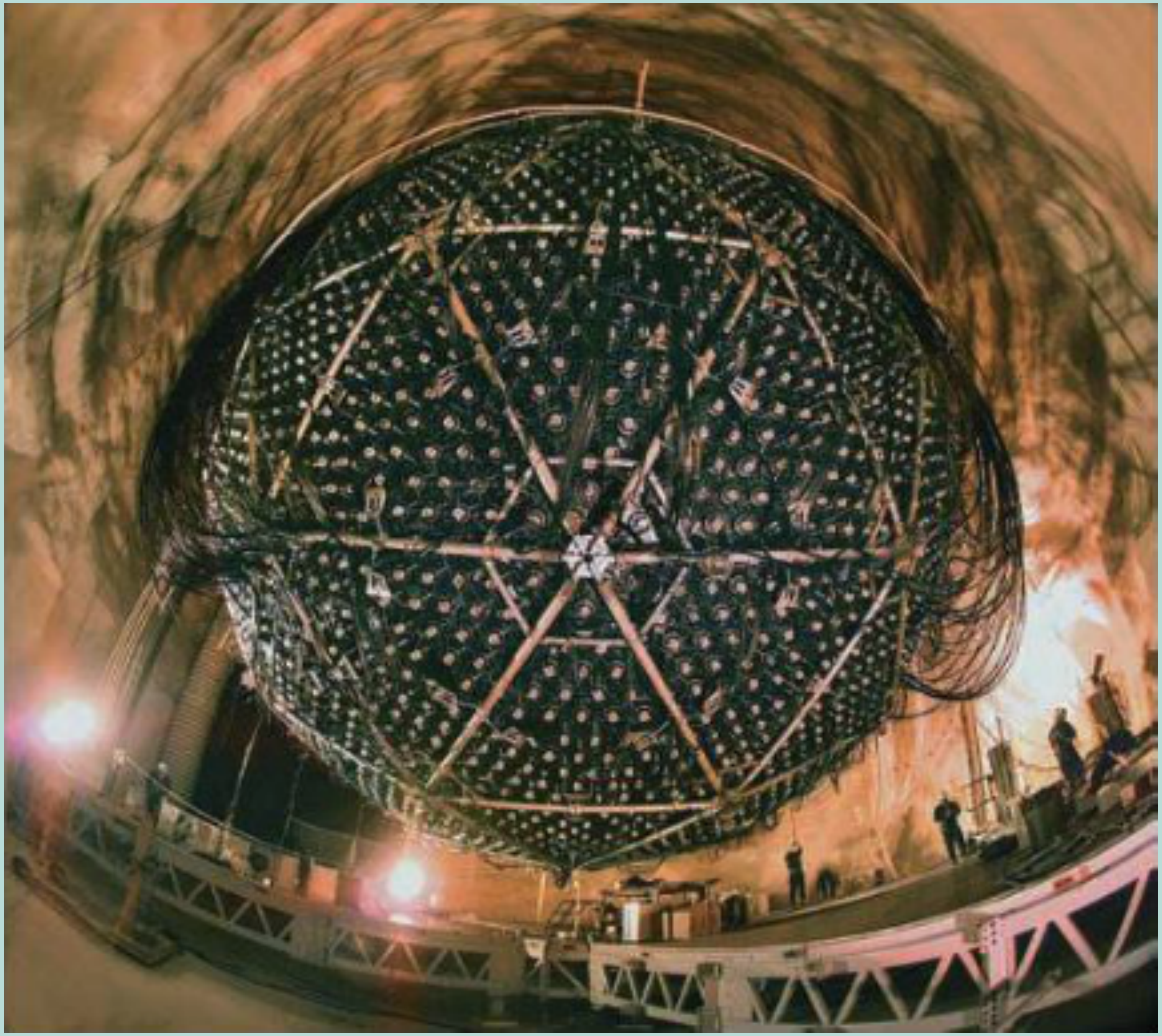
The Earth is transparent to neutrinos.



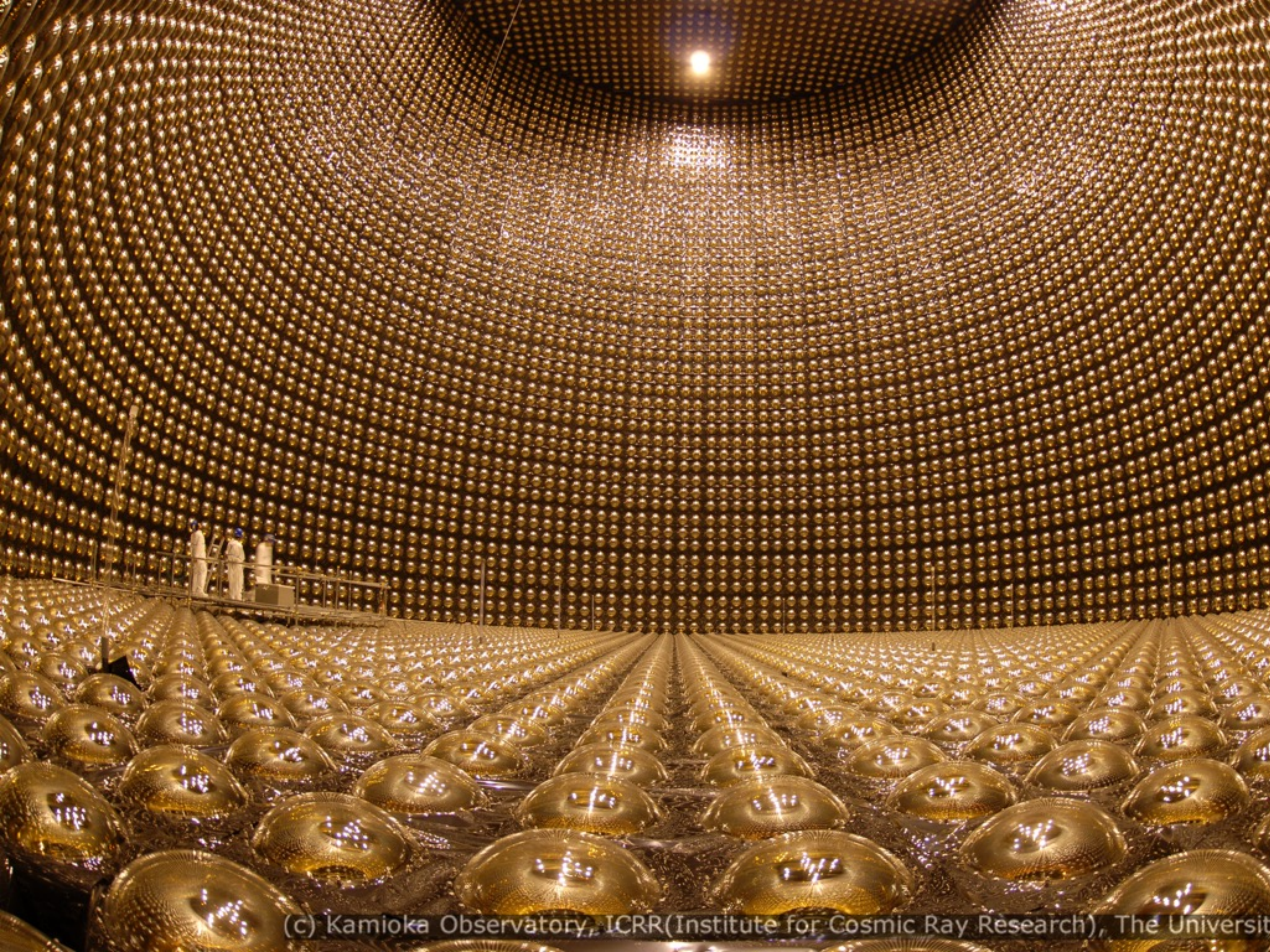


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock

Ontario, CA



Sudbury Neutrino Solar Laboratory


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The Universit