# UCOR-125:

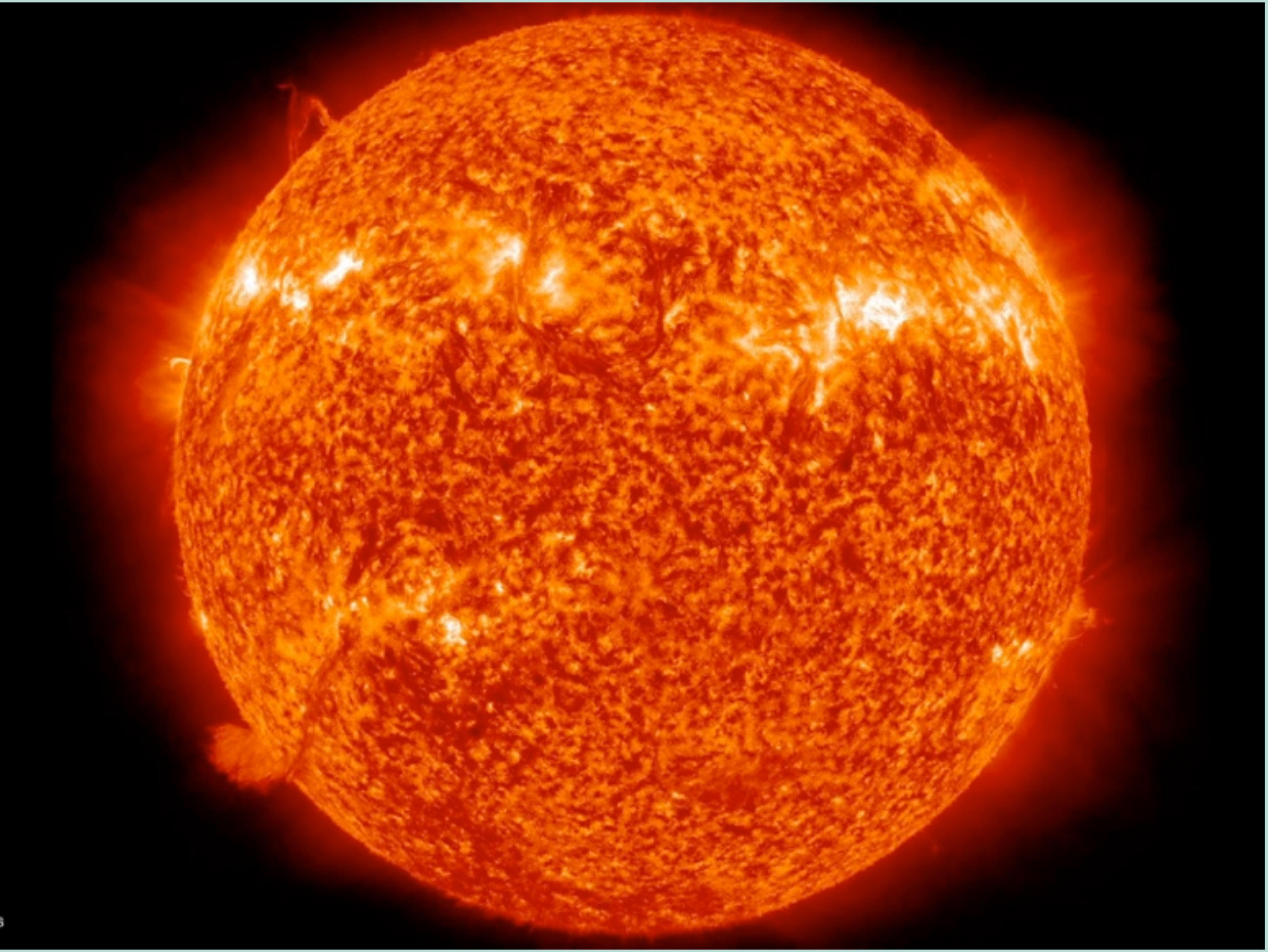
# Astronomy


with your host:

**Lecture 14:**
**The Sun**

Coop

# The Sun



m ~ 2e30 kg
~ 300,000 m_e

r ~ 7e5 km
~ 110 r_e

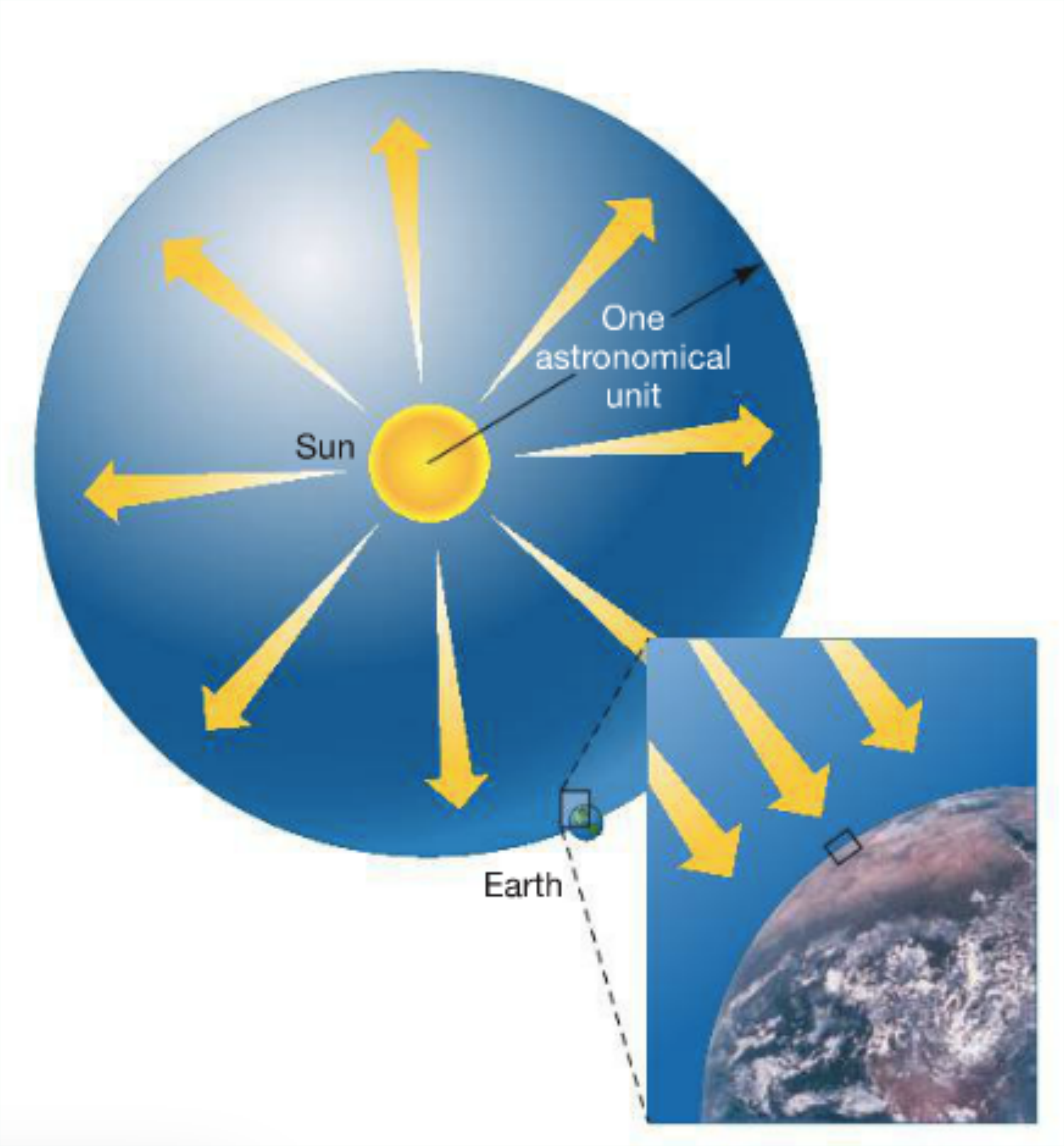
d ~ 28,000
years

density ~
1400 kg/m^3

# The Sun: Ch 16

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

# The Sun: Ch 16



The Sun: Ch 16

## Just how bright is the sun?

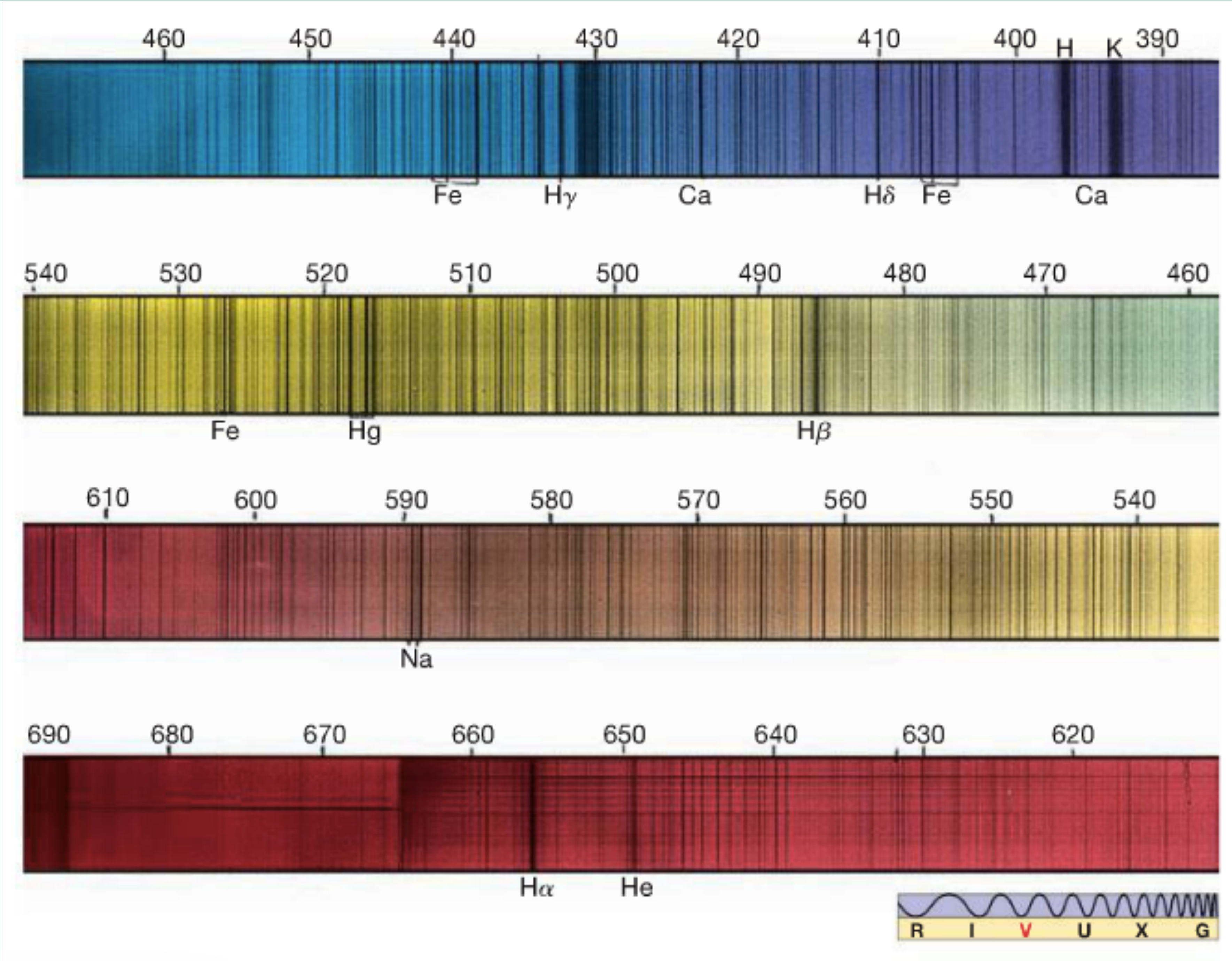
- Solar constant: 1400 W/m^2
- 50% reaches earth, 30% goes to the atmosphere, 20% reflected away
- About a mol of square meters in an AU sphere around the sun
- Result: 4 X 10^26 W
- 10 billion 1 megaton bombs/second
- Could evaporate the world's oceans in 6 seconds, melt the crust in 3 minutes

The Sun: Ch 16

**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 |

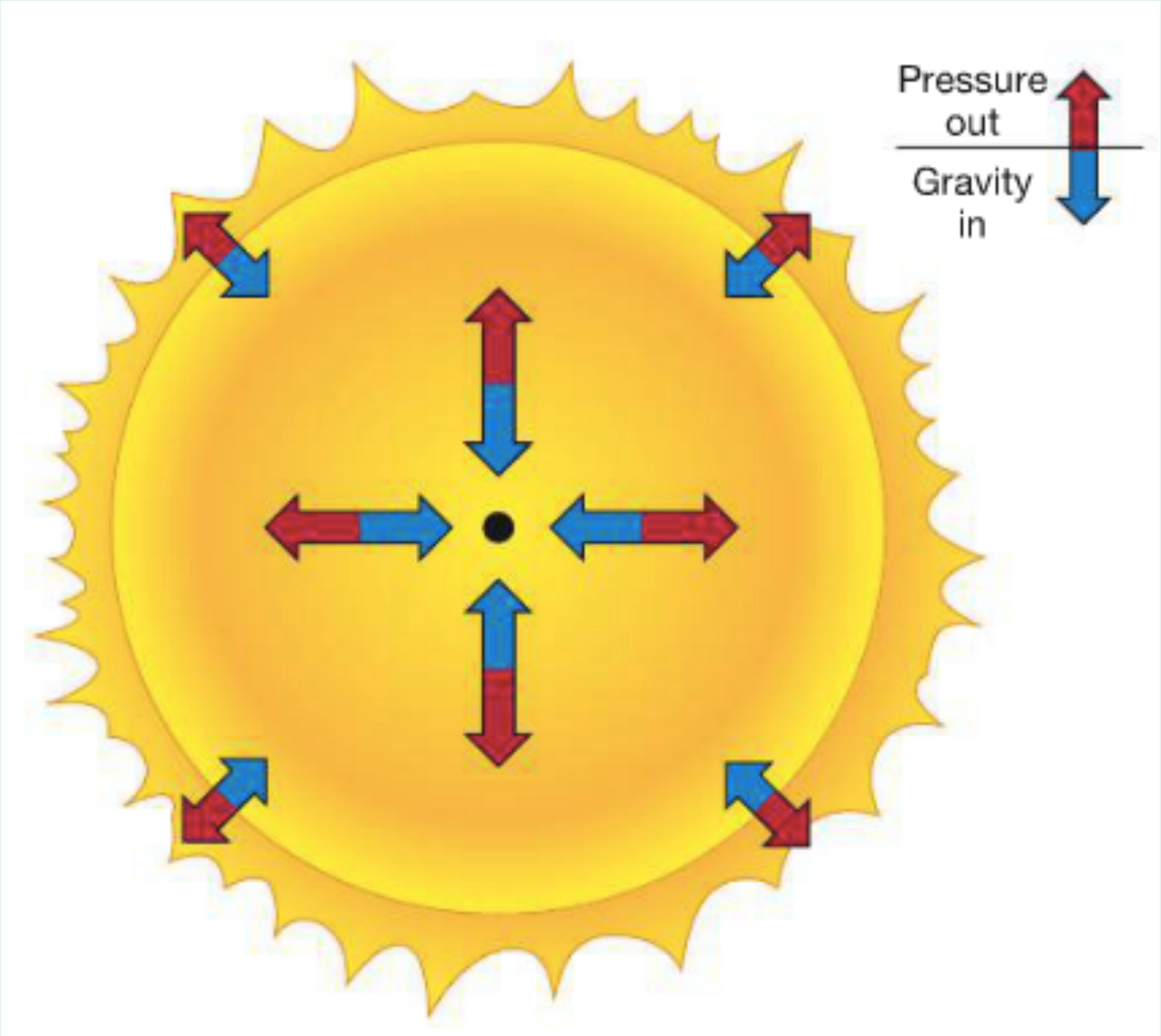
# Solar Spectrum



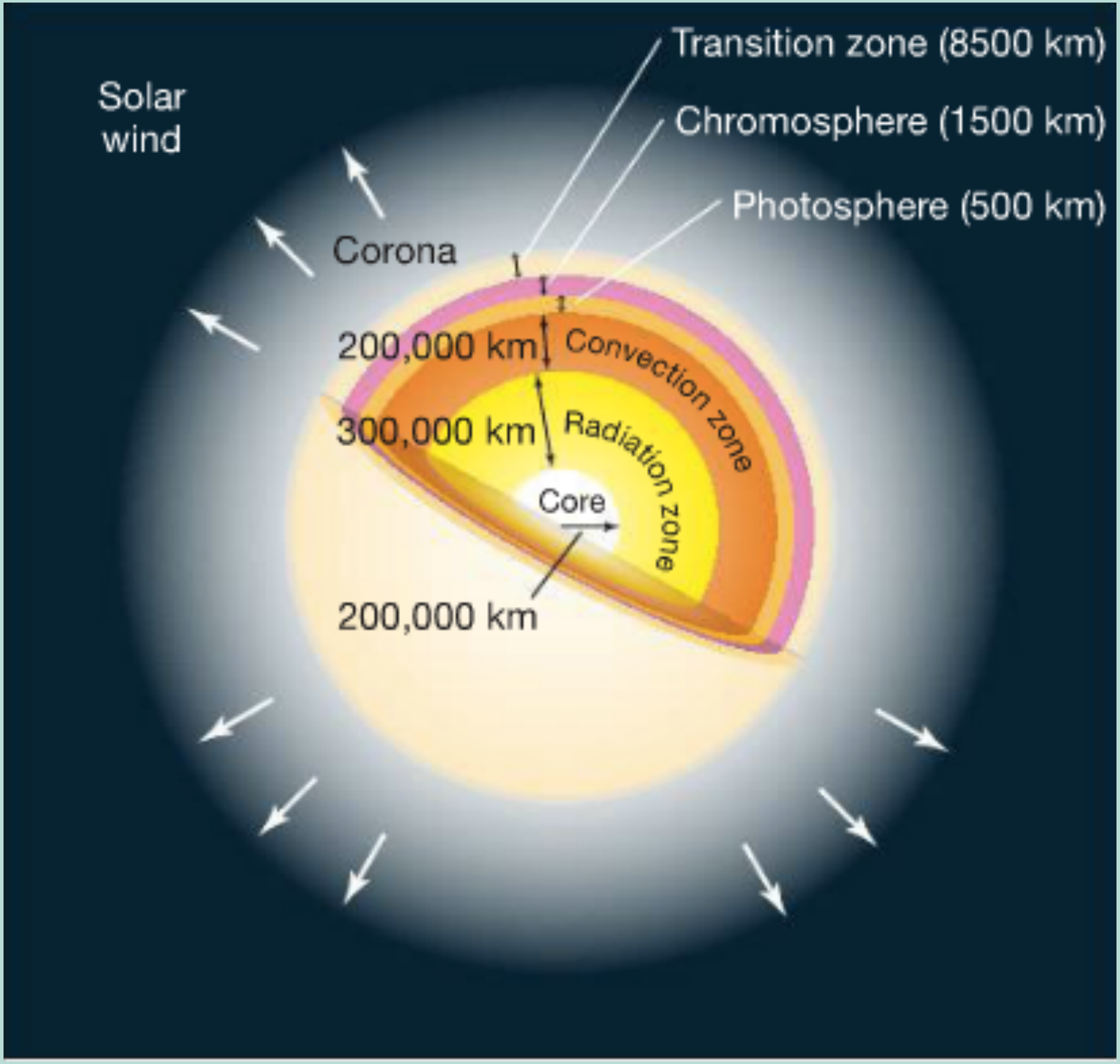
- Recall, we learn not just about the emitted radiation (emission lines), but also the intermediate atmosphere of the sun (absorption lines)

The Sun: Ch 16

# Hydrostatic Equilibrium



# Standard Solar Model



# The Sun: Ch 16

- 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

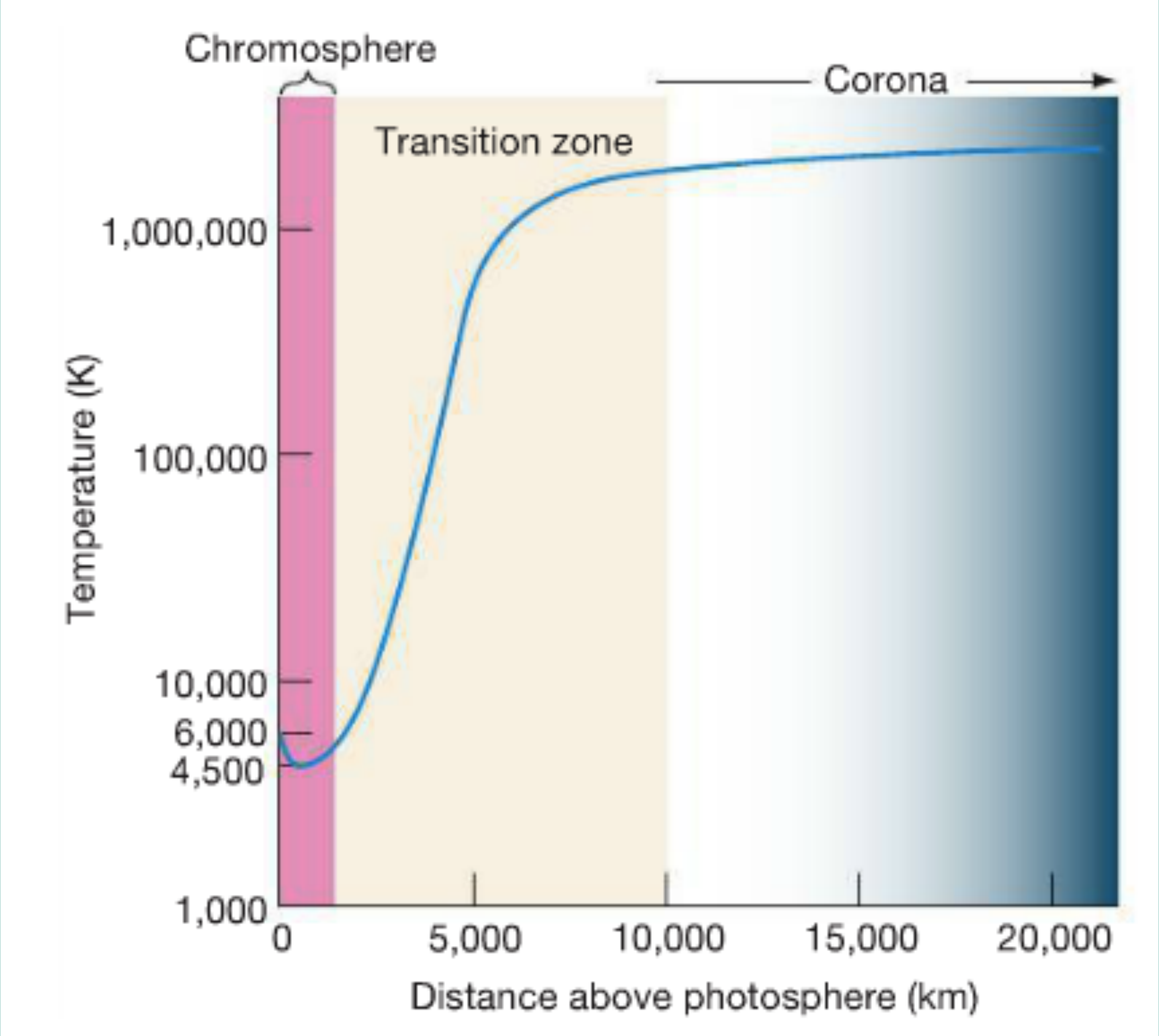
- This heat CONVECTS to the surface which glows like a black body (photosphere)

# The Sun: Ch 16

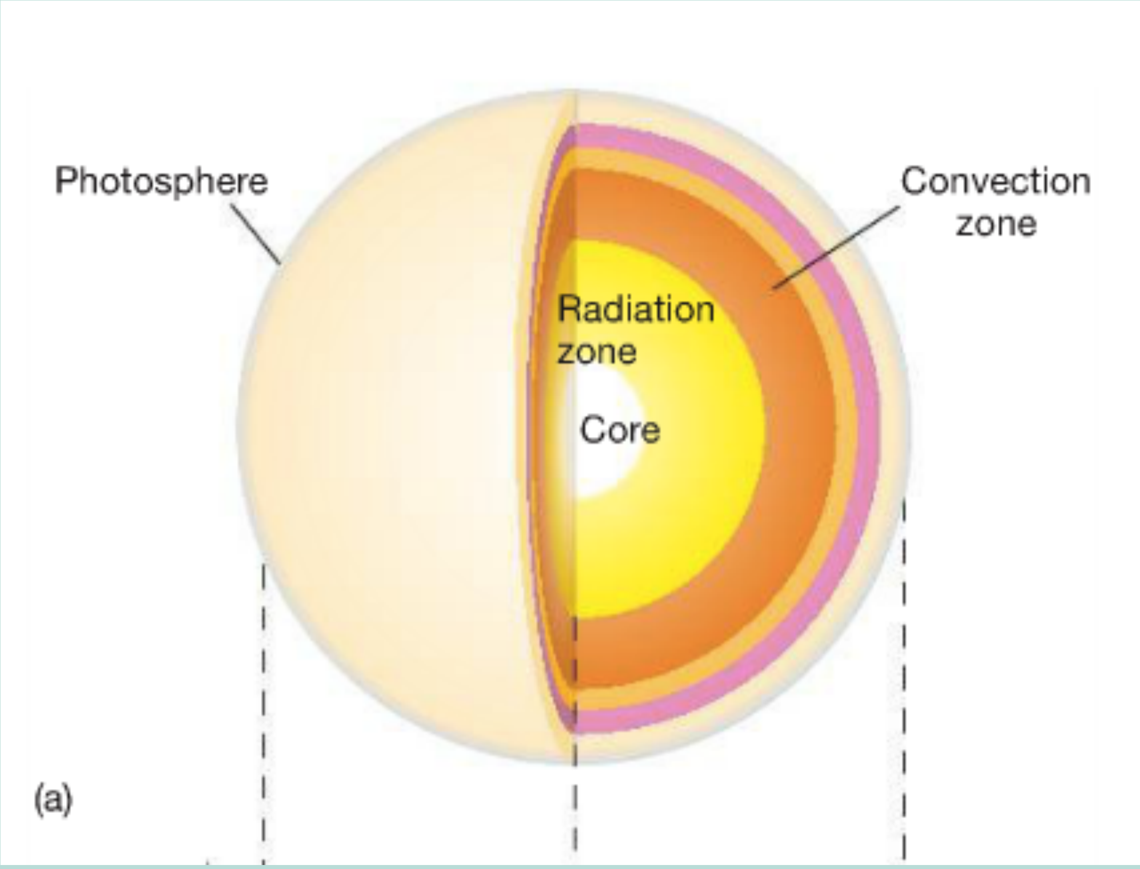
**TABLE 16.1 The Standard Solar Model**

| 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 | $2 \times 10^{-4}$ | Electromagnetic radiation can escape—the part of the Sun we see |
| Chromosphere | 696,500* | 4500 | $5 \times 10^{-6}$ | Cool lower atmosphere |
| Transition zone | 698,000* | 8000 | $2 \times 10^{-10}$ | 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 |

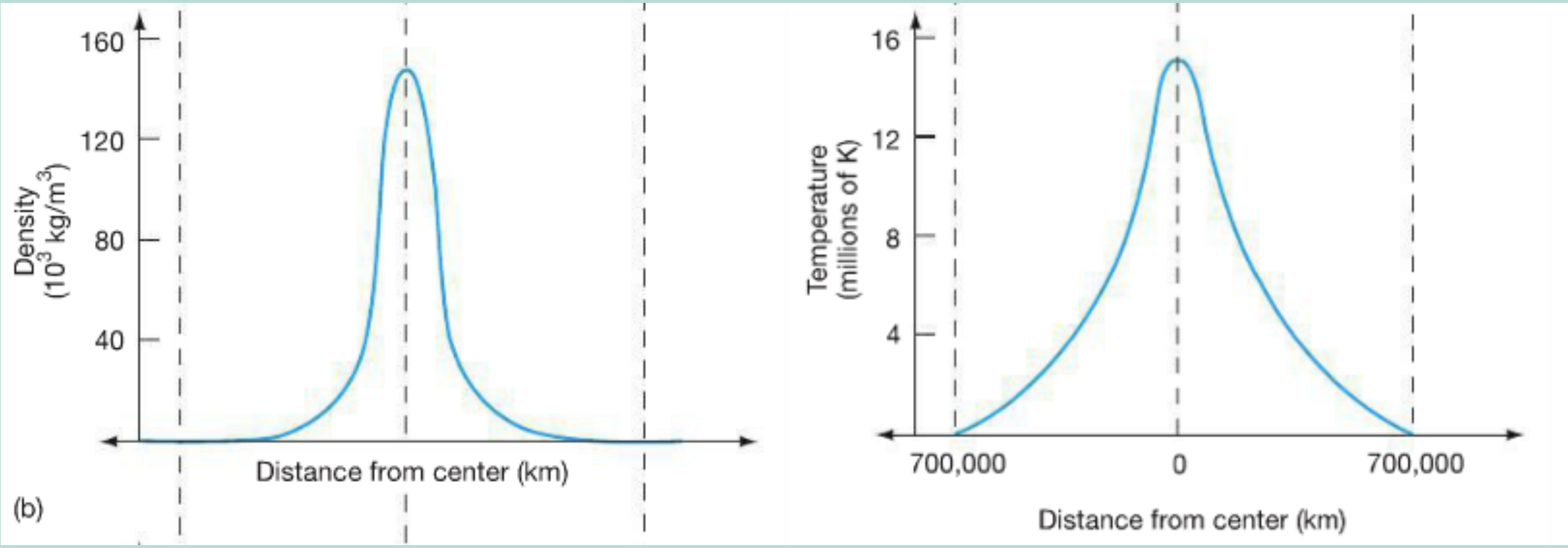
# Atmospheric Physics is Hard



# The Sun: Ch 16

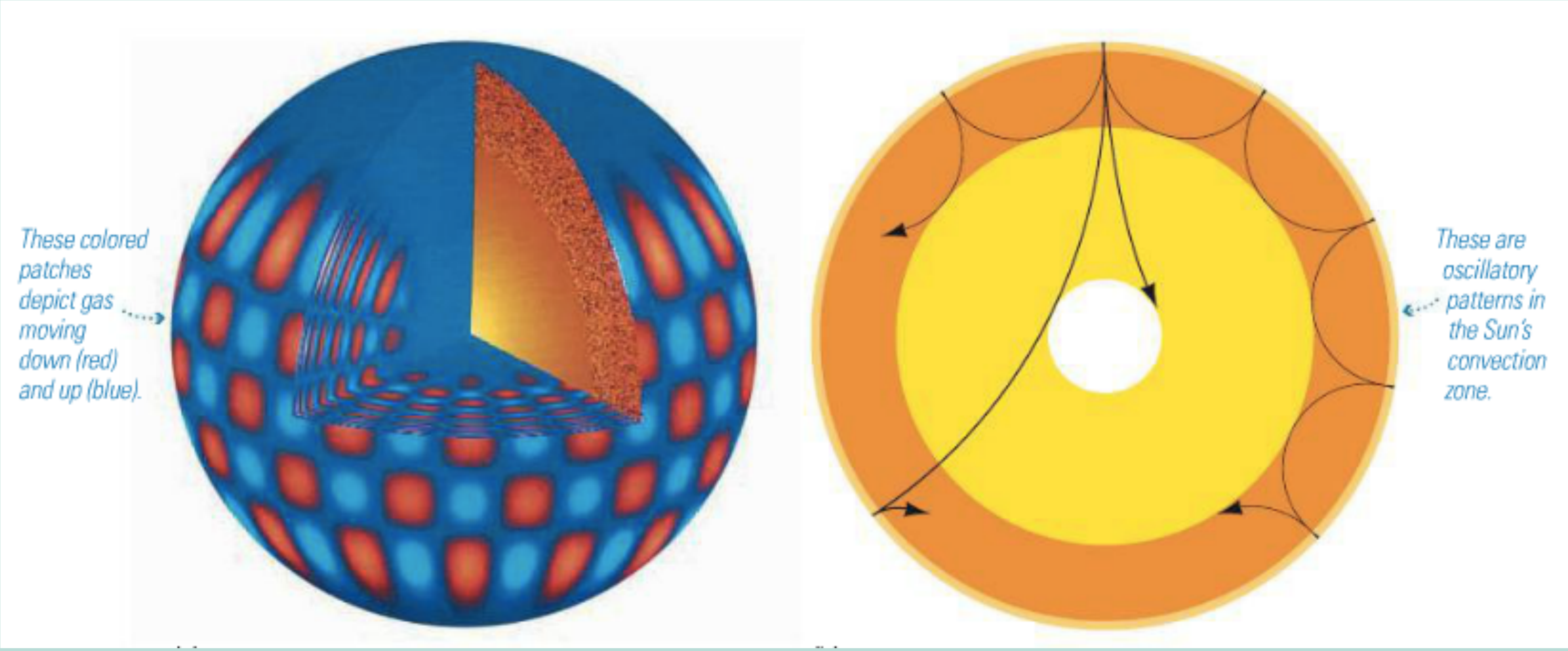


Photosphere
Convection zone
Radiation zone
Core
(a)

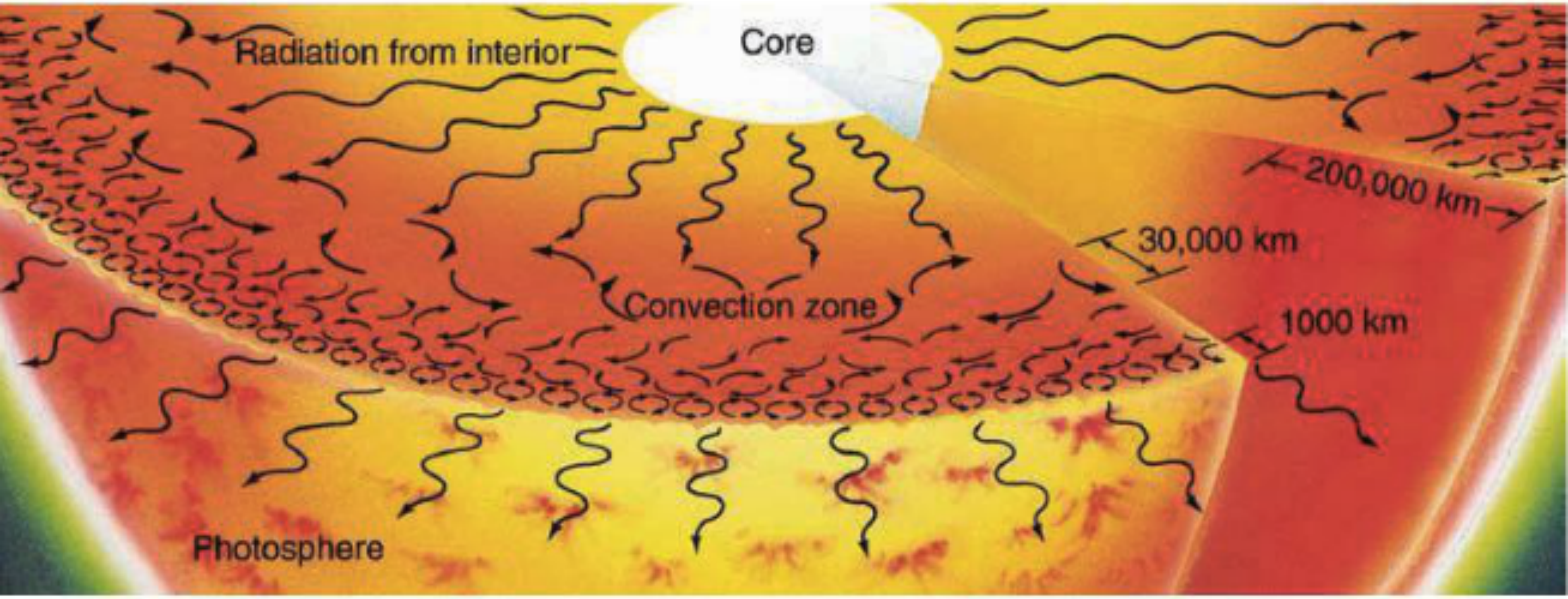
160
120
80
40
Density ($10^3$ kg/m$^3$)
Distance from center (km)
(b)
16
12
8
4
Temperature (millions of K)
700,000
0
700,000
Distance from center (km)

# Helioseismology



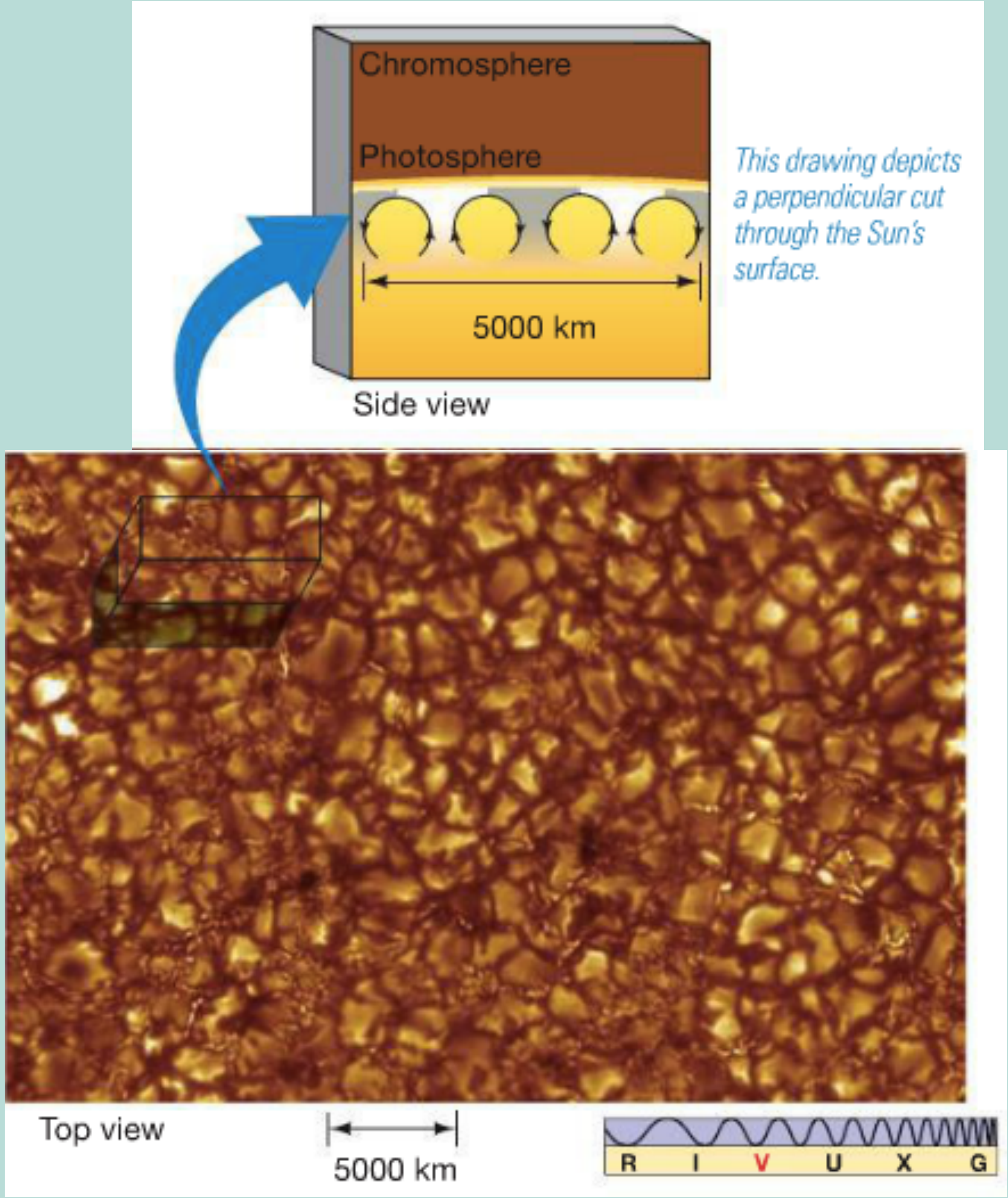

Global Oscillations Network Group (GONG)

# Convection Cells



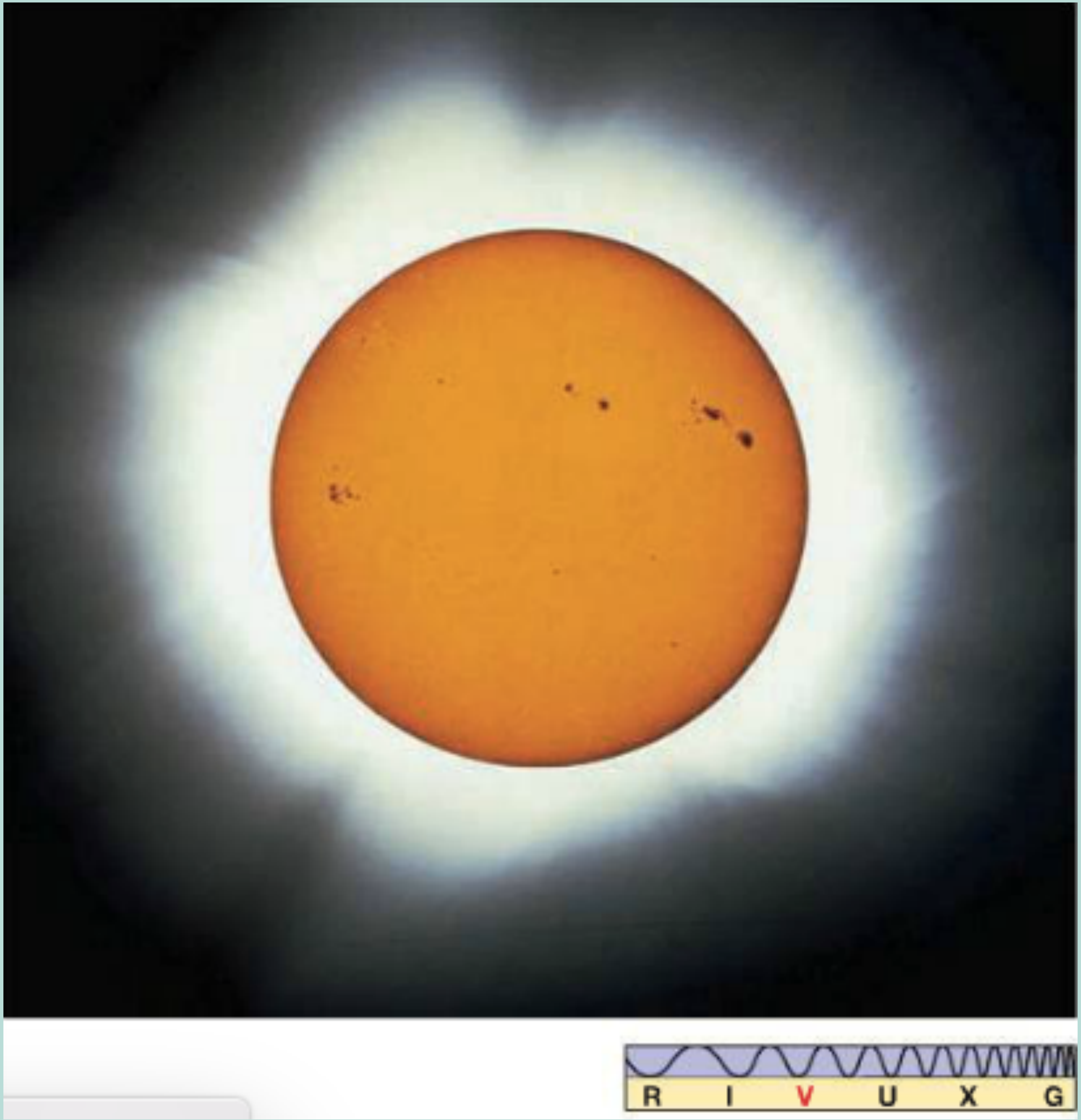

Hierarchy of cells

# Solar Granules

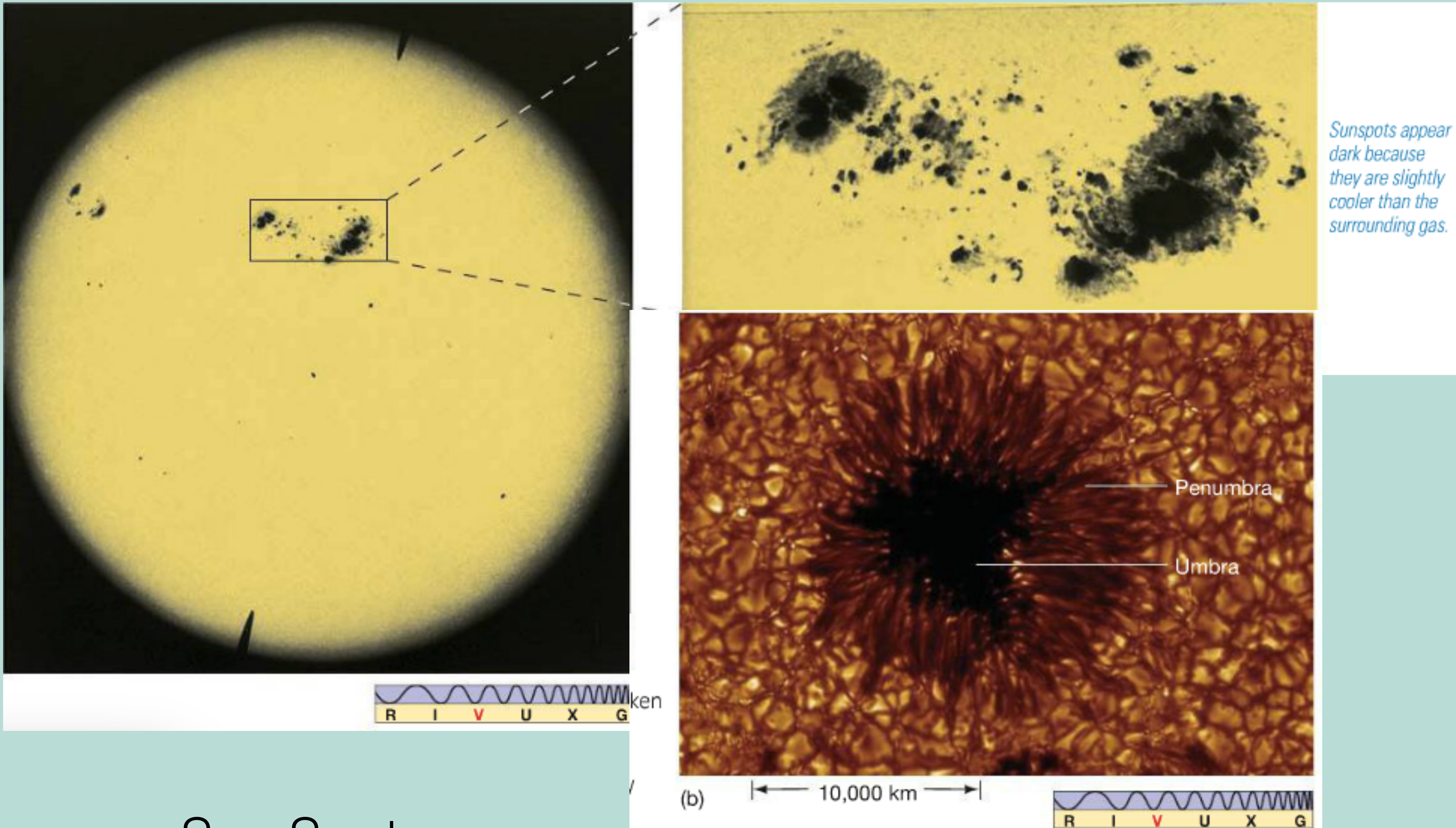



- Each granule is approximately the size of the Earth!

# Sun Spots from Earth



# The Sun: Ch 16




Sun Spots

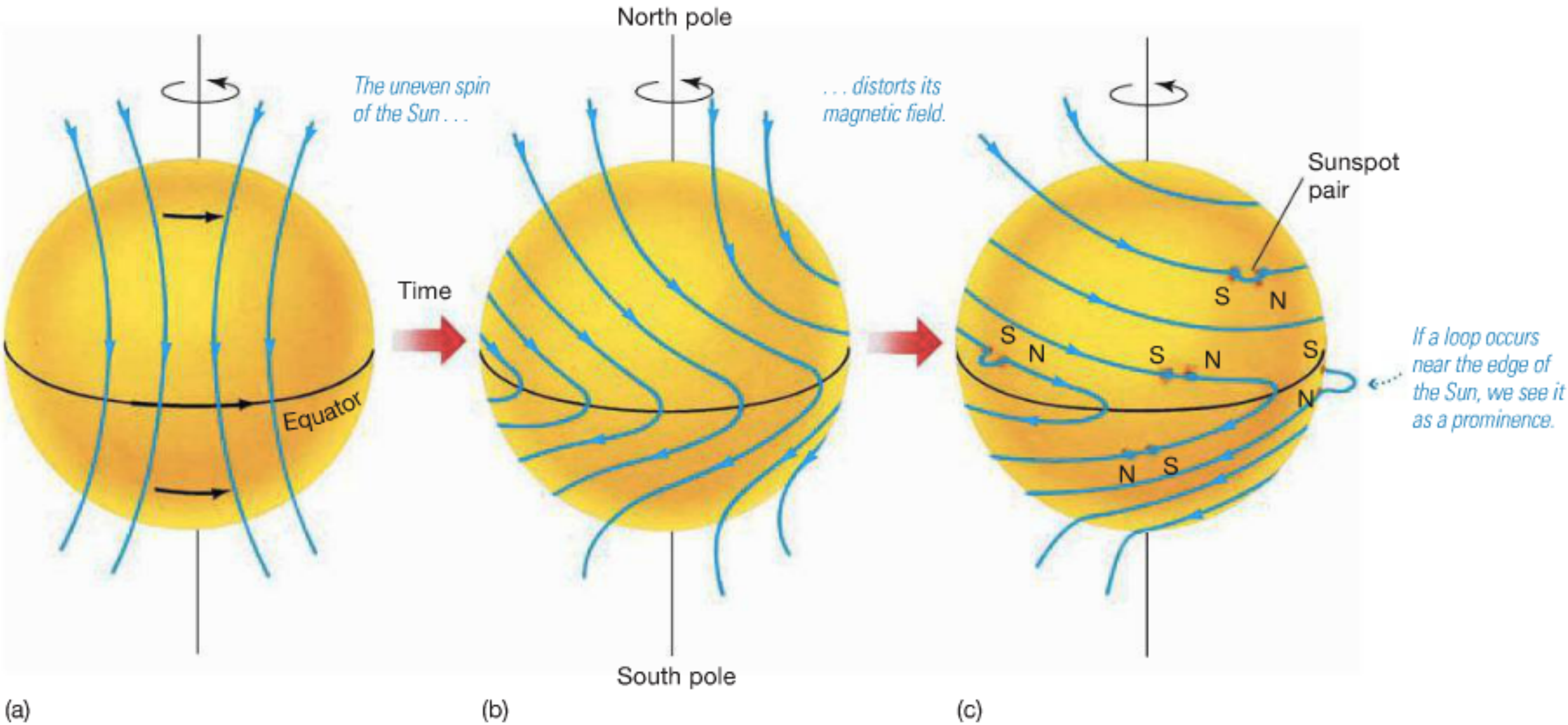
- Umbra is 1000K cooler than the rest of the sun (still bright!)

The Sun: Ch 16

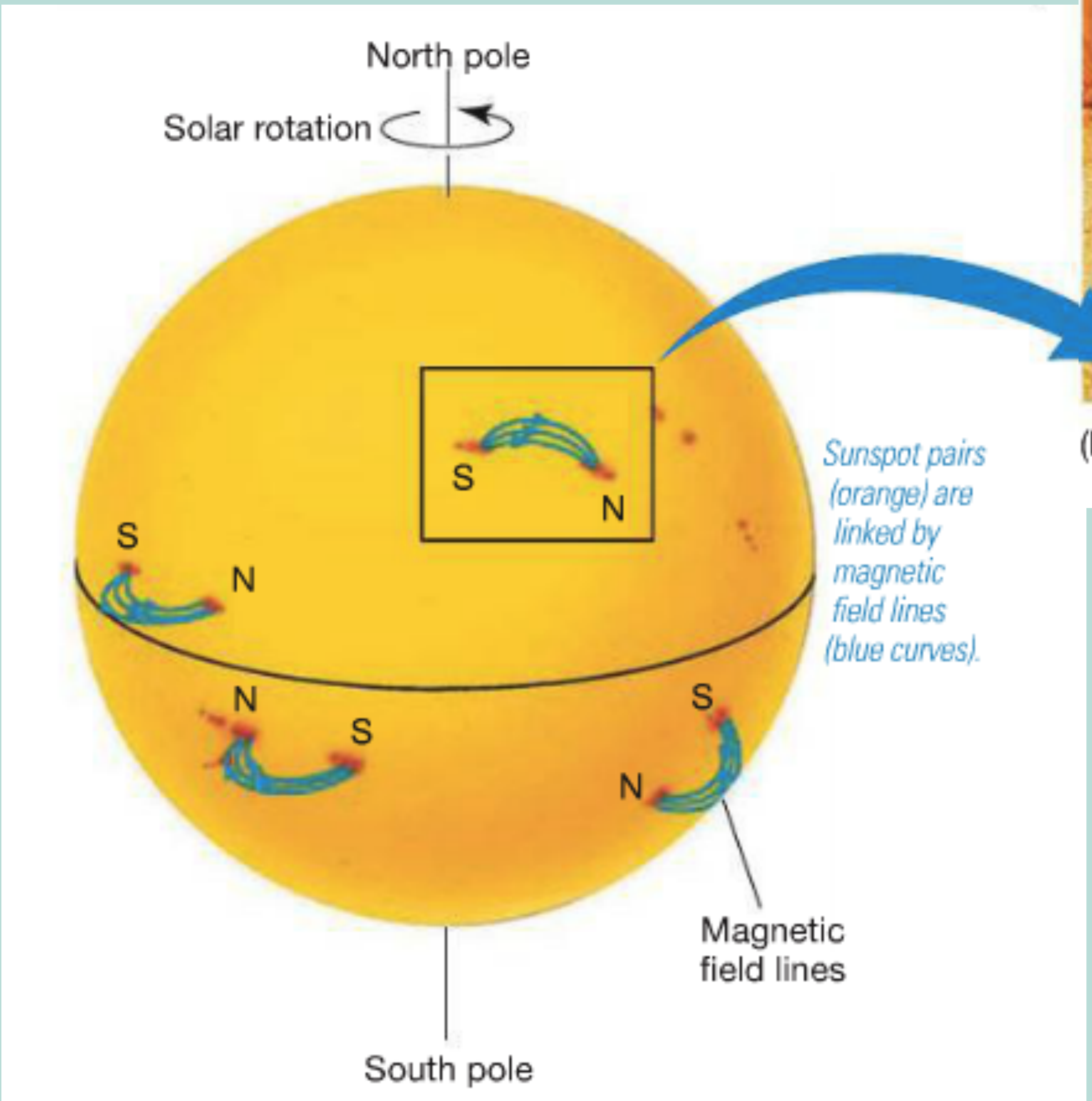

DISCUSSION

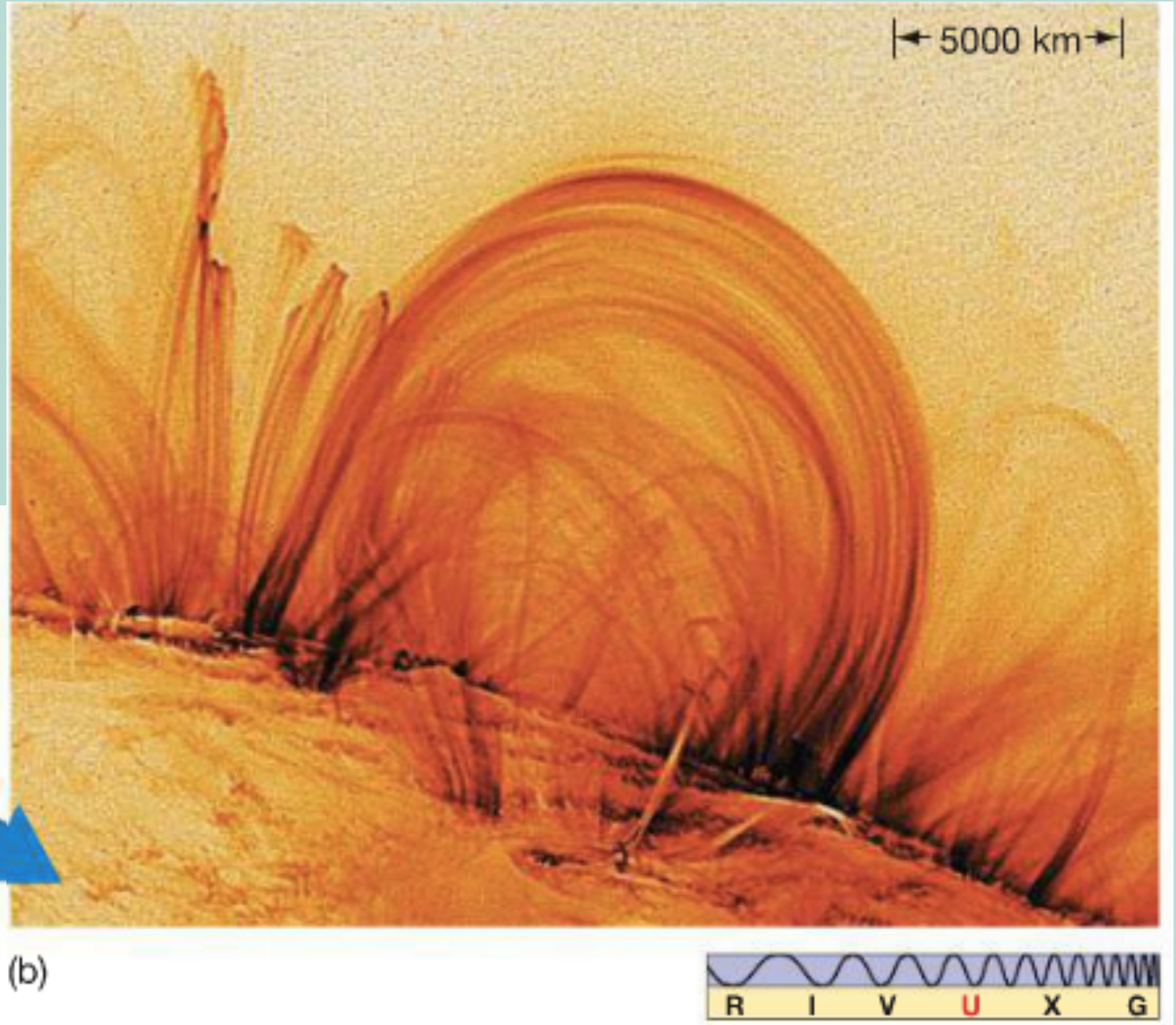
The Sun: Ch 16

# Origin of Sun Spots



# Sun Spots and Magnetism

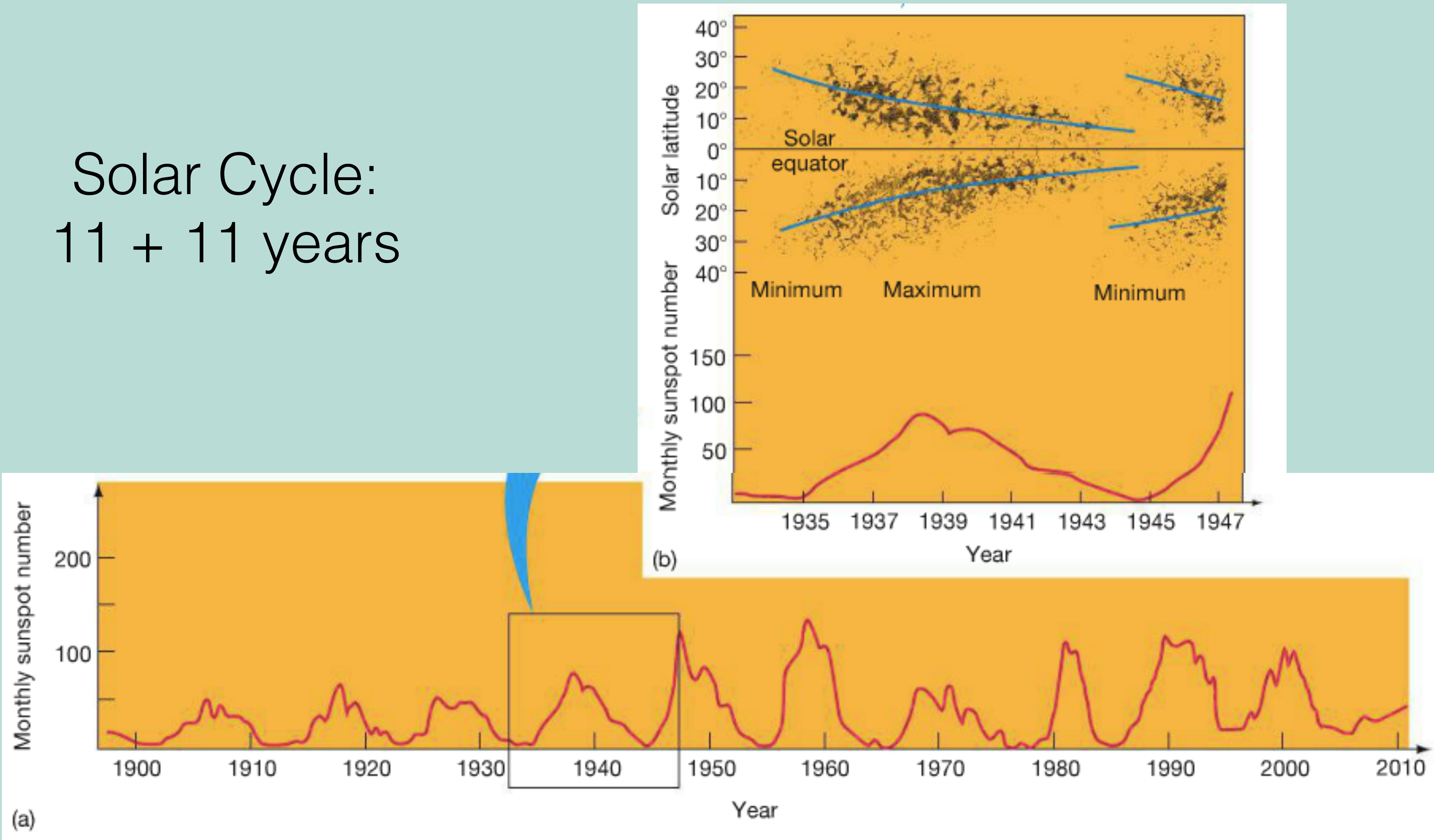


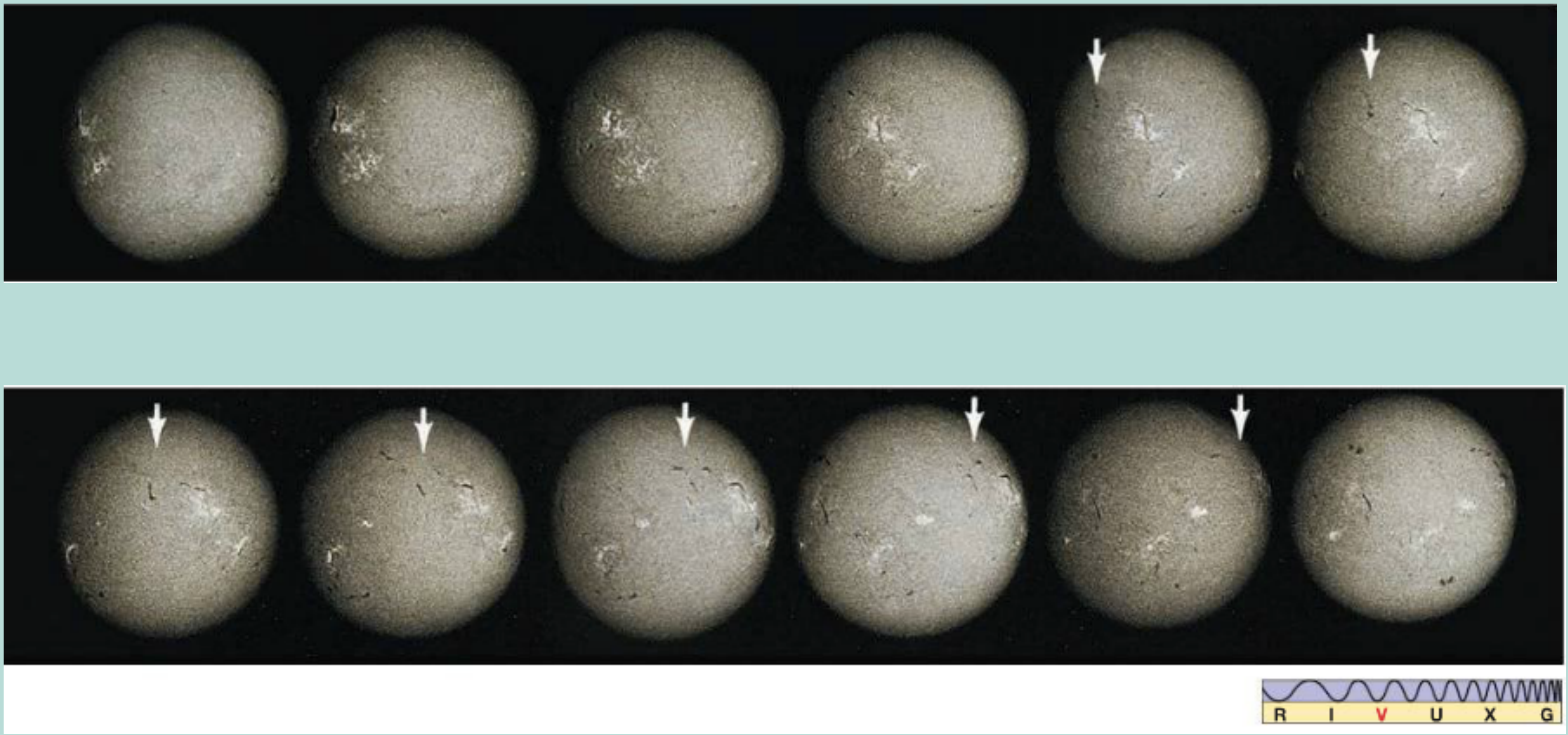




(b)

# The Sun: Ch 16

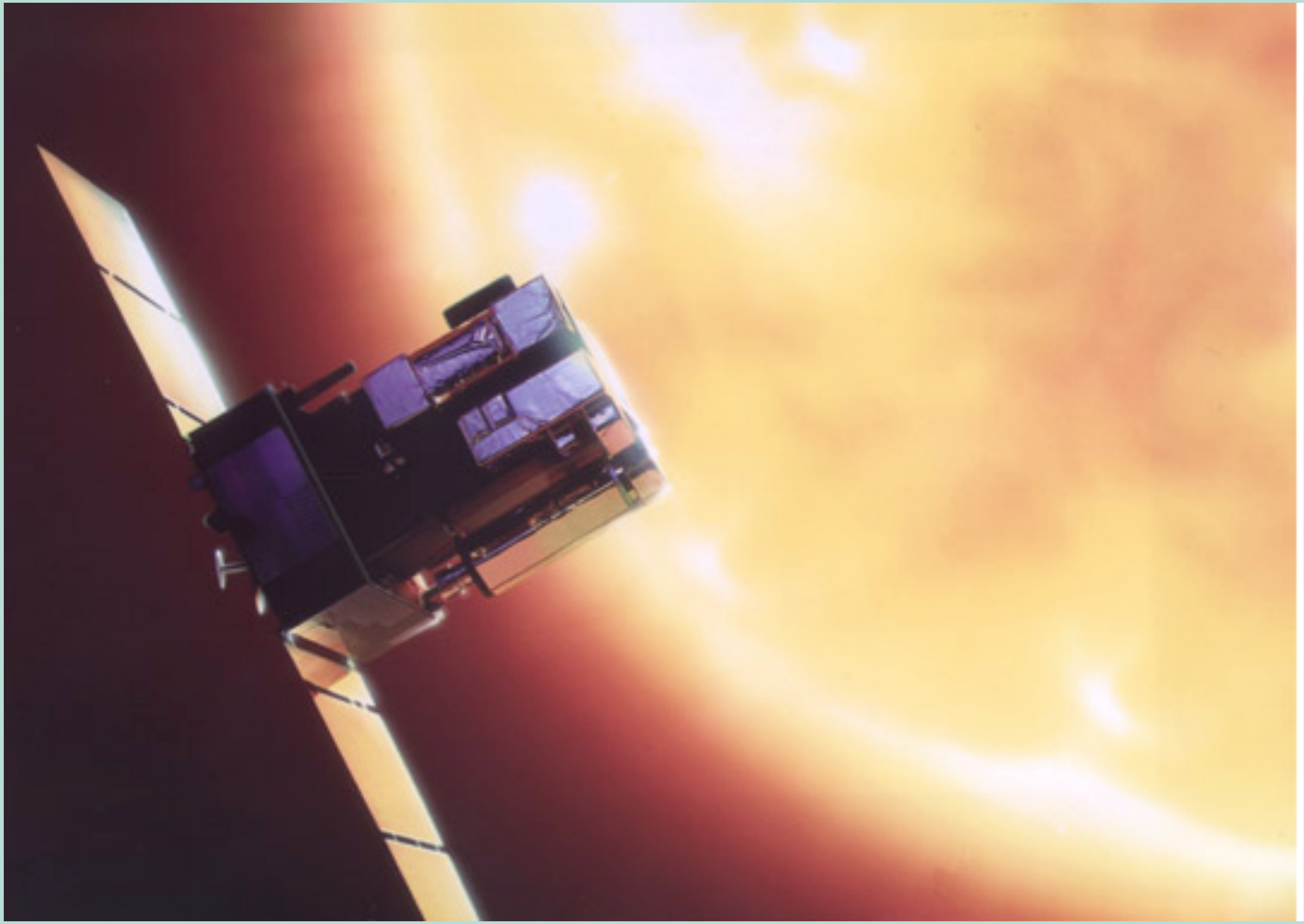
Solar Cycle:
11 + 11 years






Sun Spots in Motion

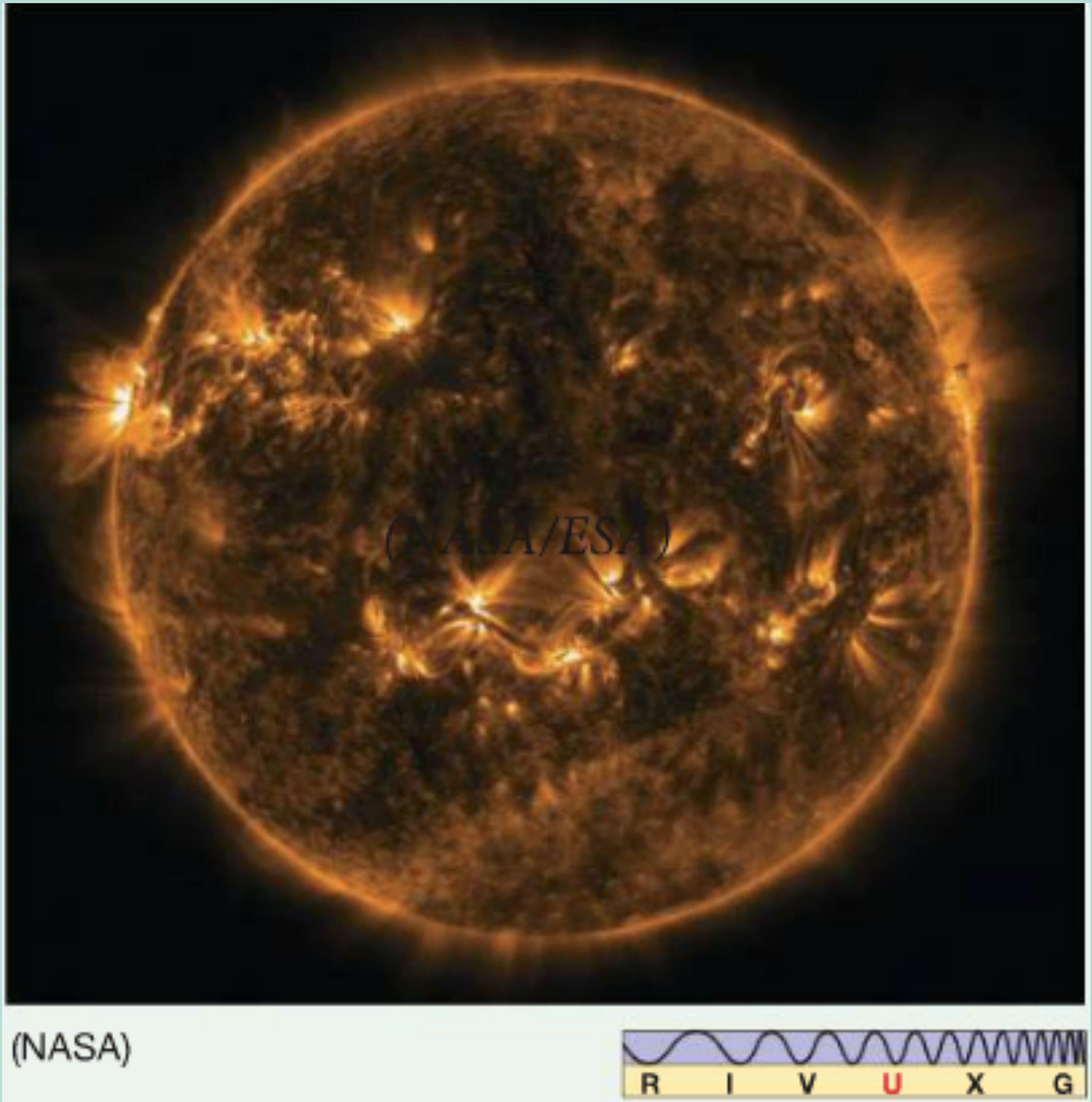
SOHO (SOlar Heliospheric Observatory)



(L1 point)

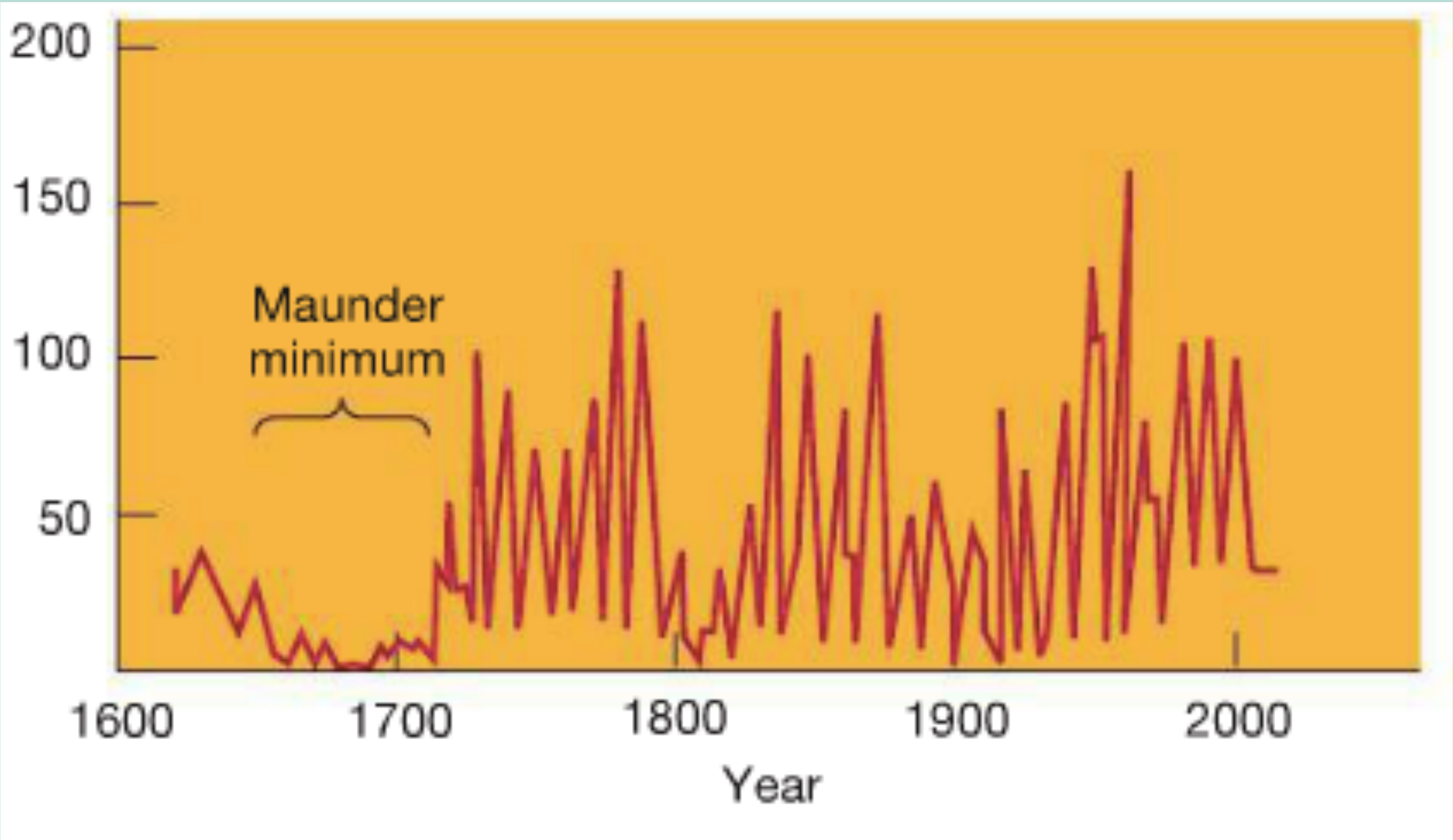
https://sohowww.nascom.nasa.gov/

# SDO (Solar Dynamics Observatory)




(NASA)

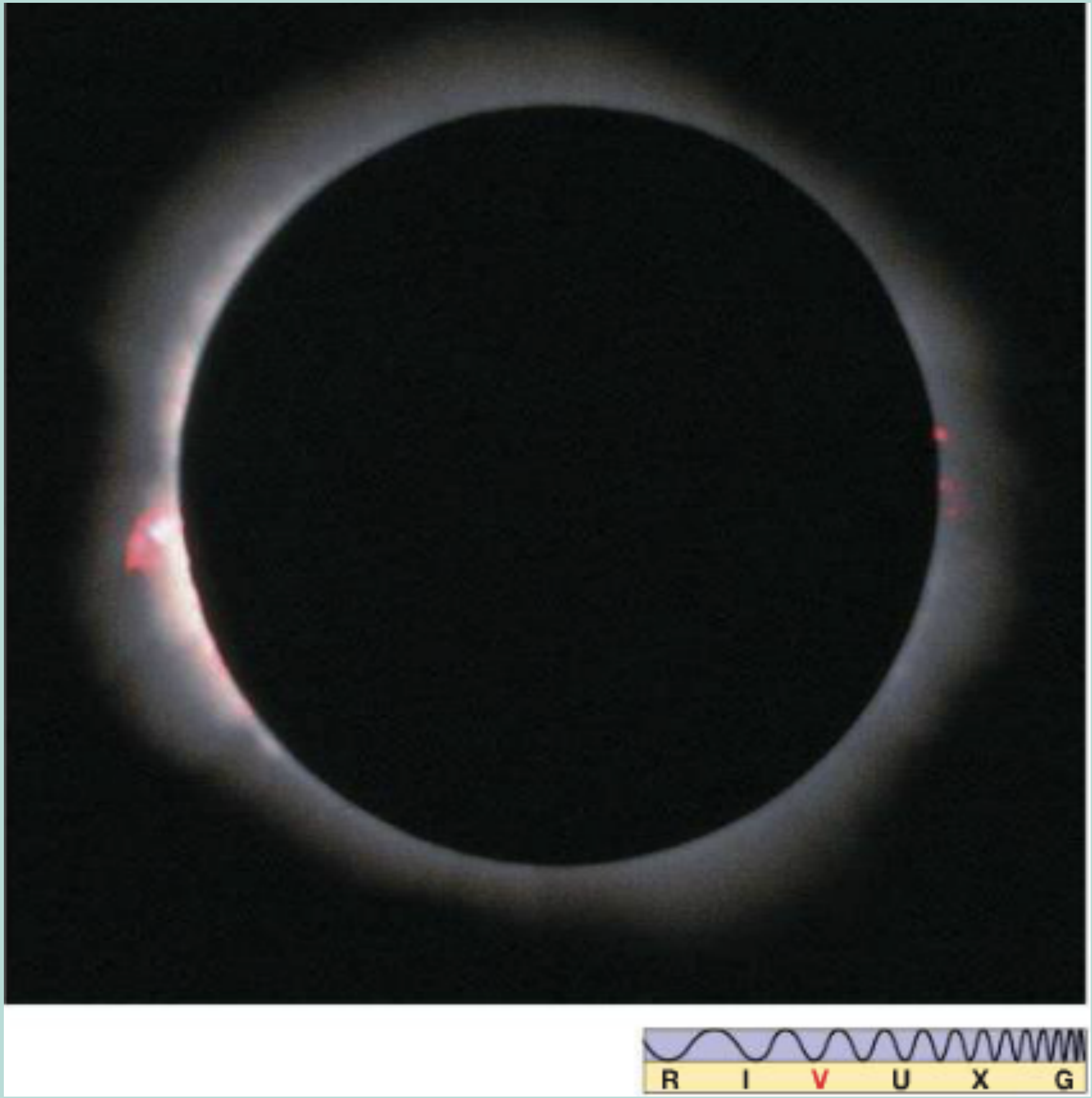
# Maunder Minimum



A beautiful summer day in the Netherlands…

No real evidence of weather ⟷ Solar Activity

# Chromosphere




(red hue due to Hα lines)

# Corona

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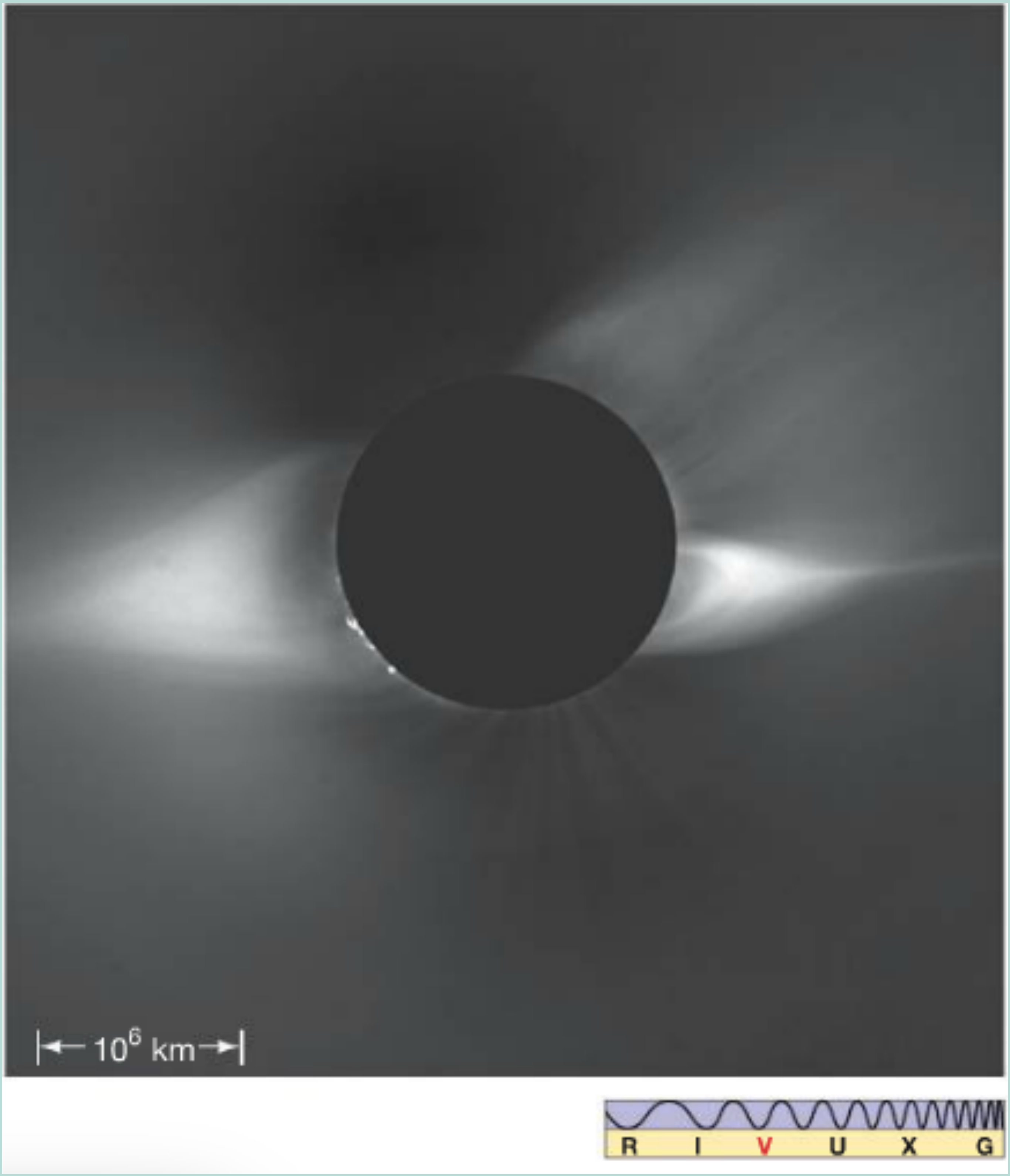
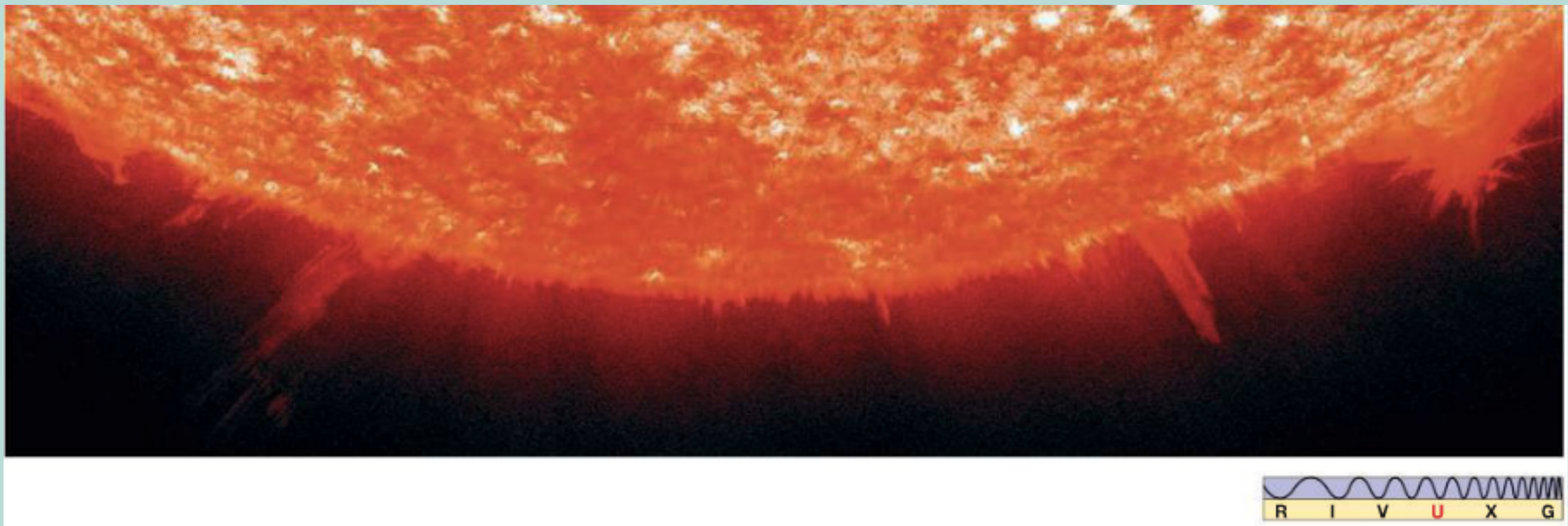
- Solar wind blasts out towards earth at 500 km/s
- Thus the sun is “evaporating” at a rate of 2 million tons of solar matter per second
- Sounds big, but amounts to 0.1% of its mass over the last 4.6 billion years

# Corona during solar cycle peak



# Solar Spicules



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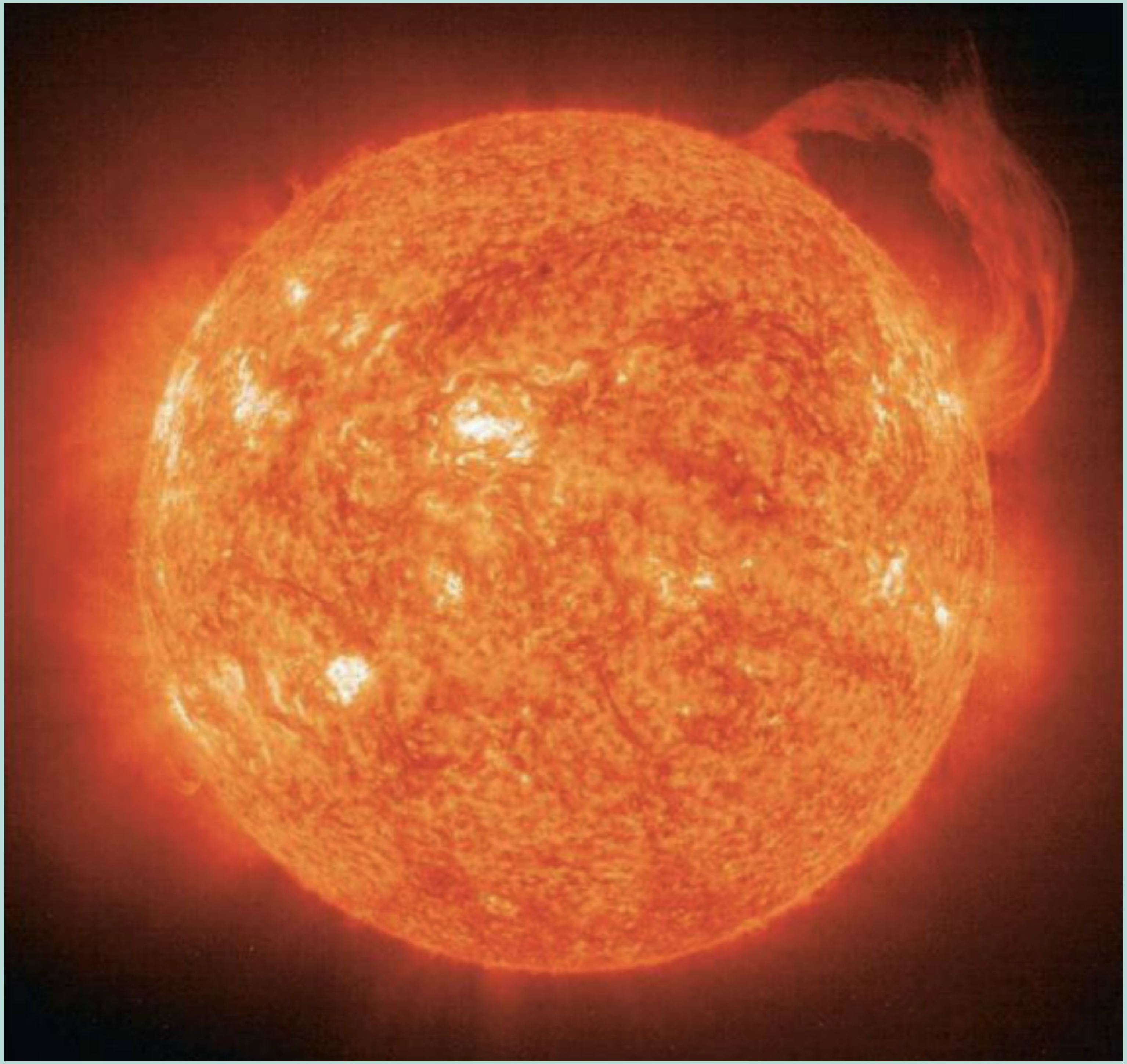
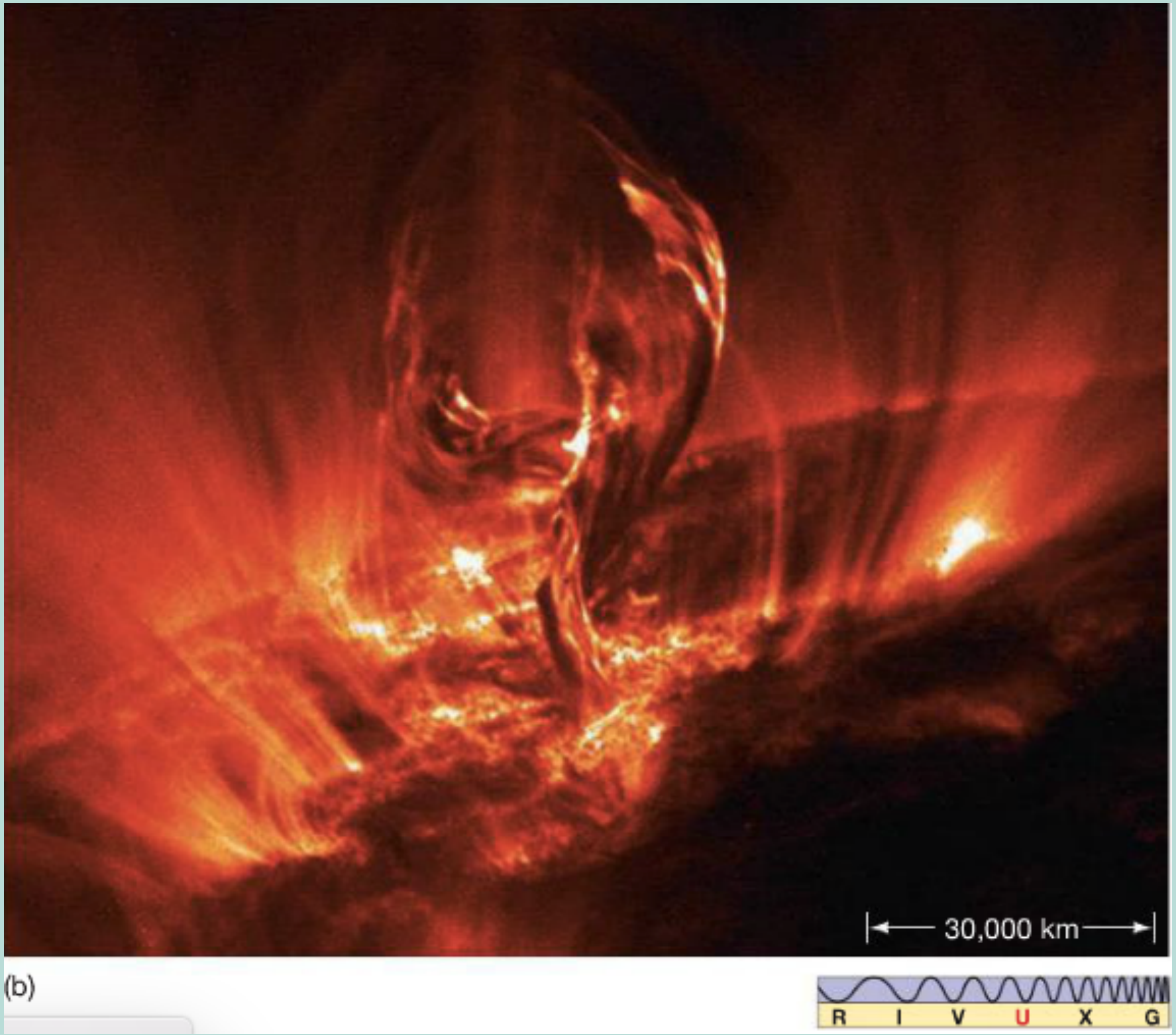
# Serious Solar Prominence



# Solar Prominence



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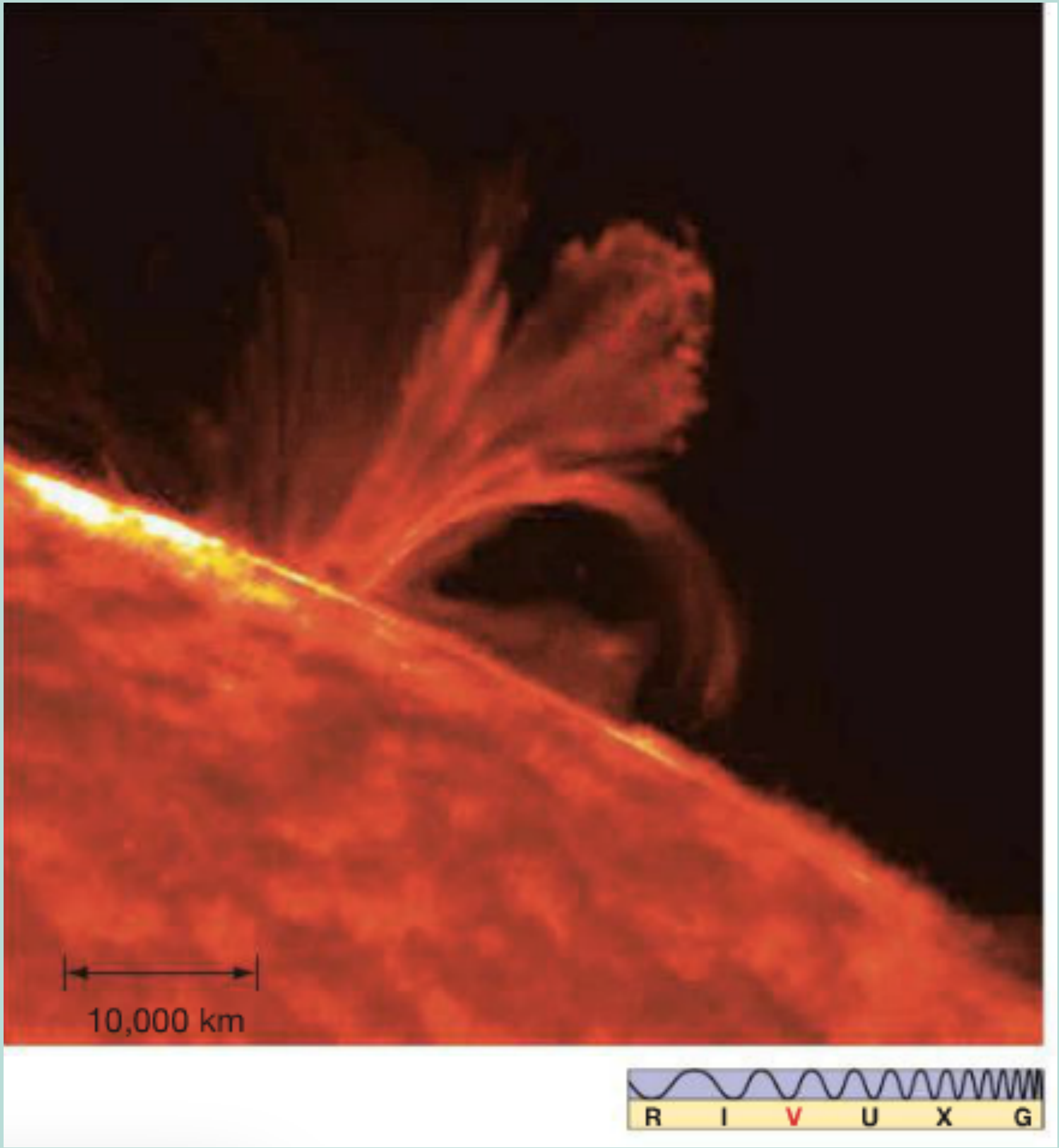
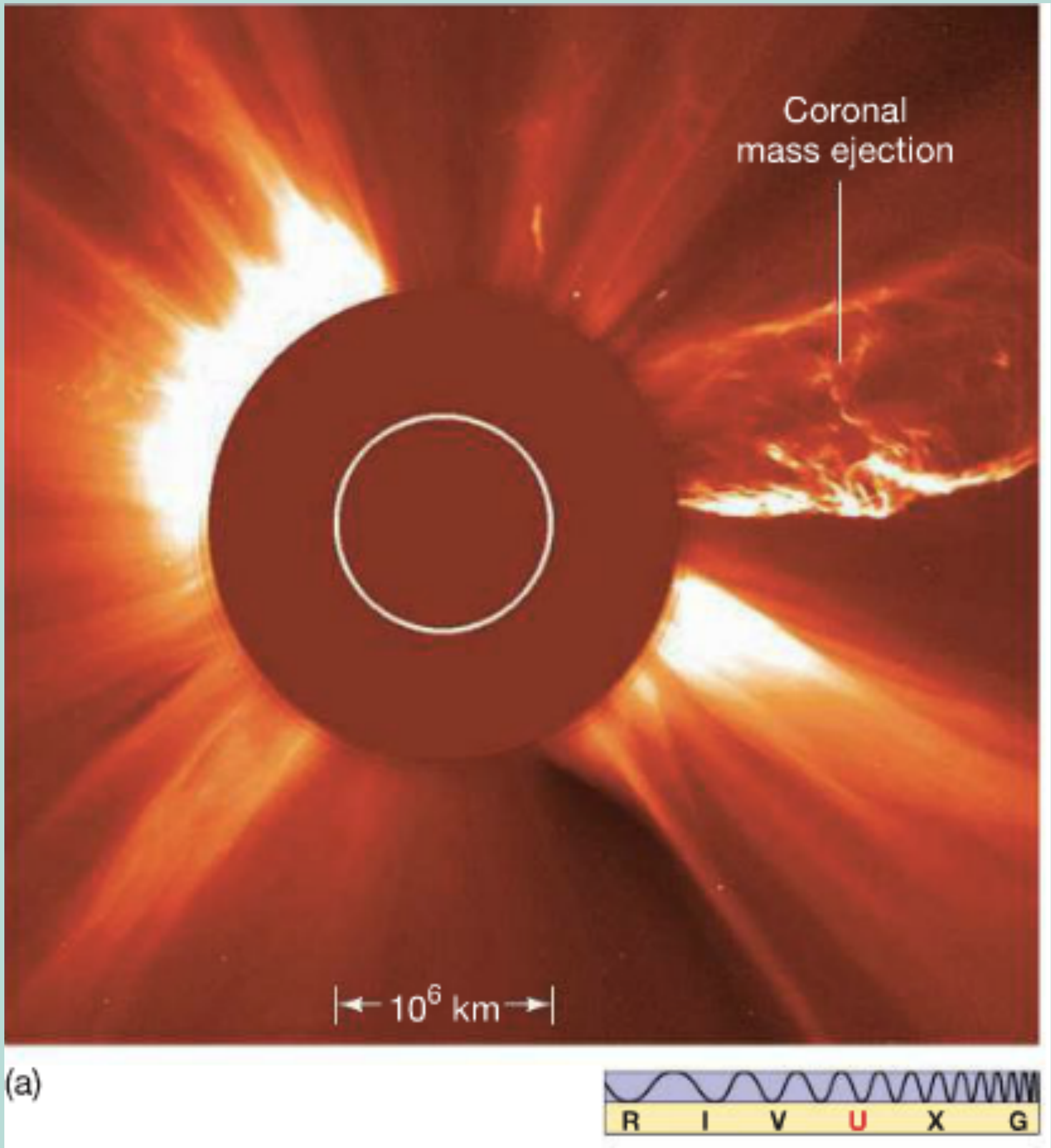
# Solar Flare



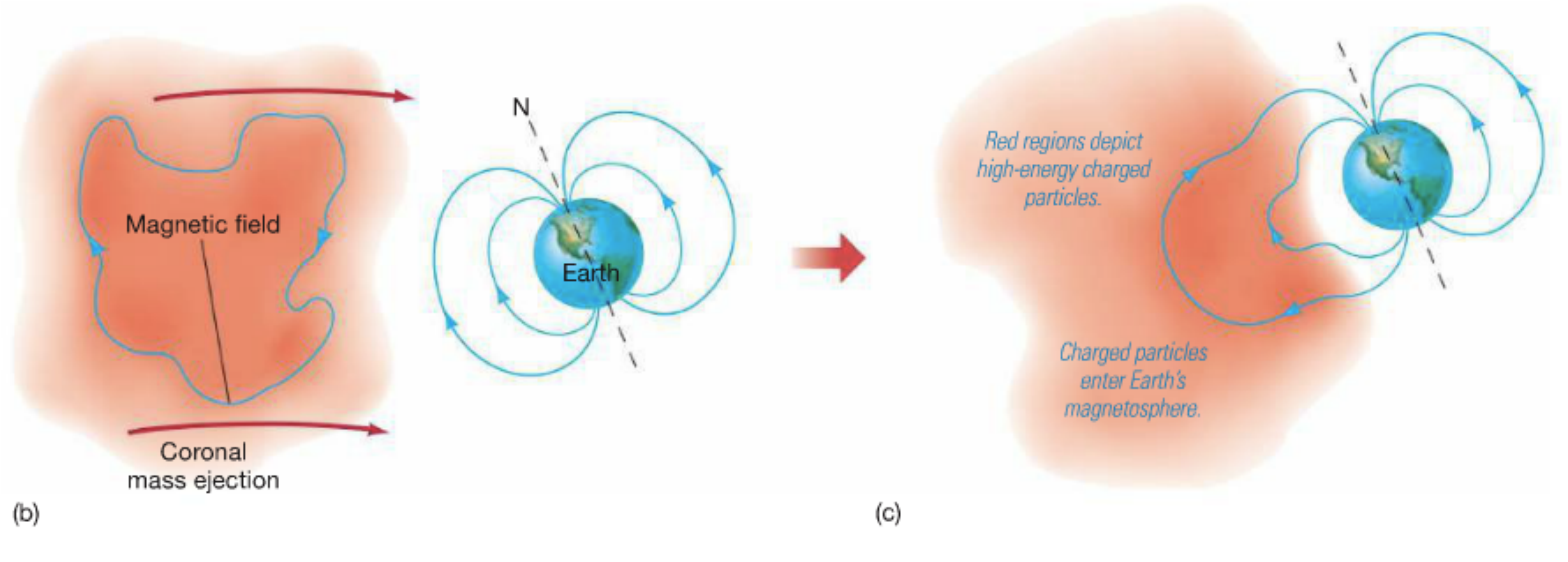
# The “Carrington" Event

- 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

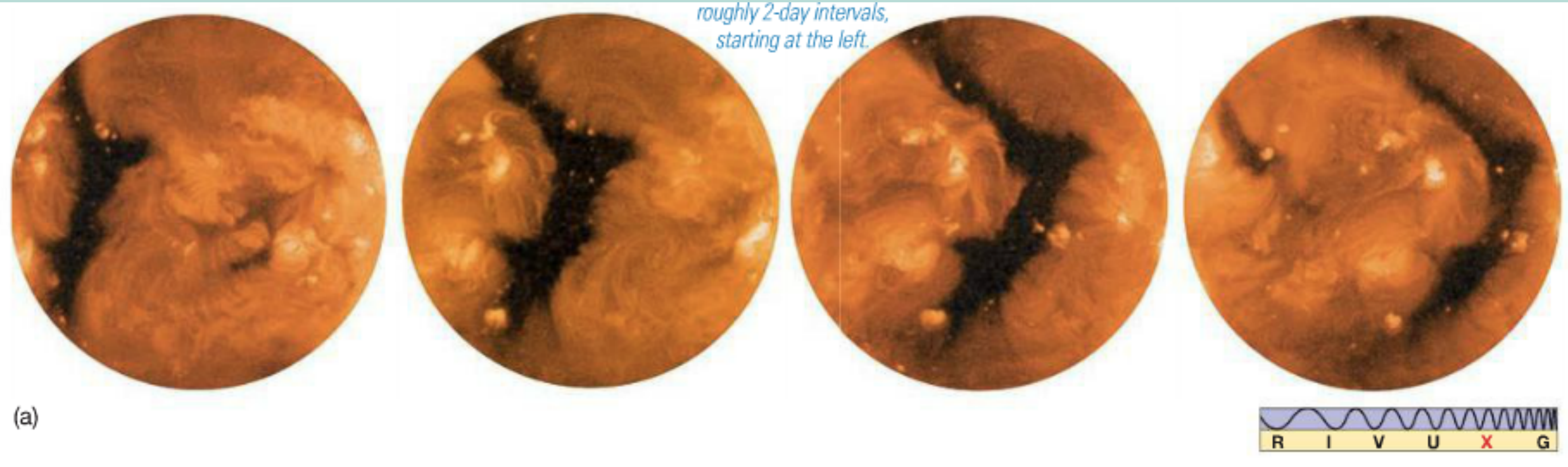
# Coronal Mass Ejection (CME)



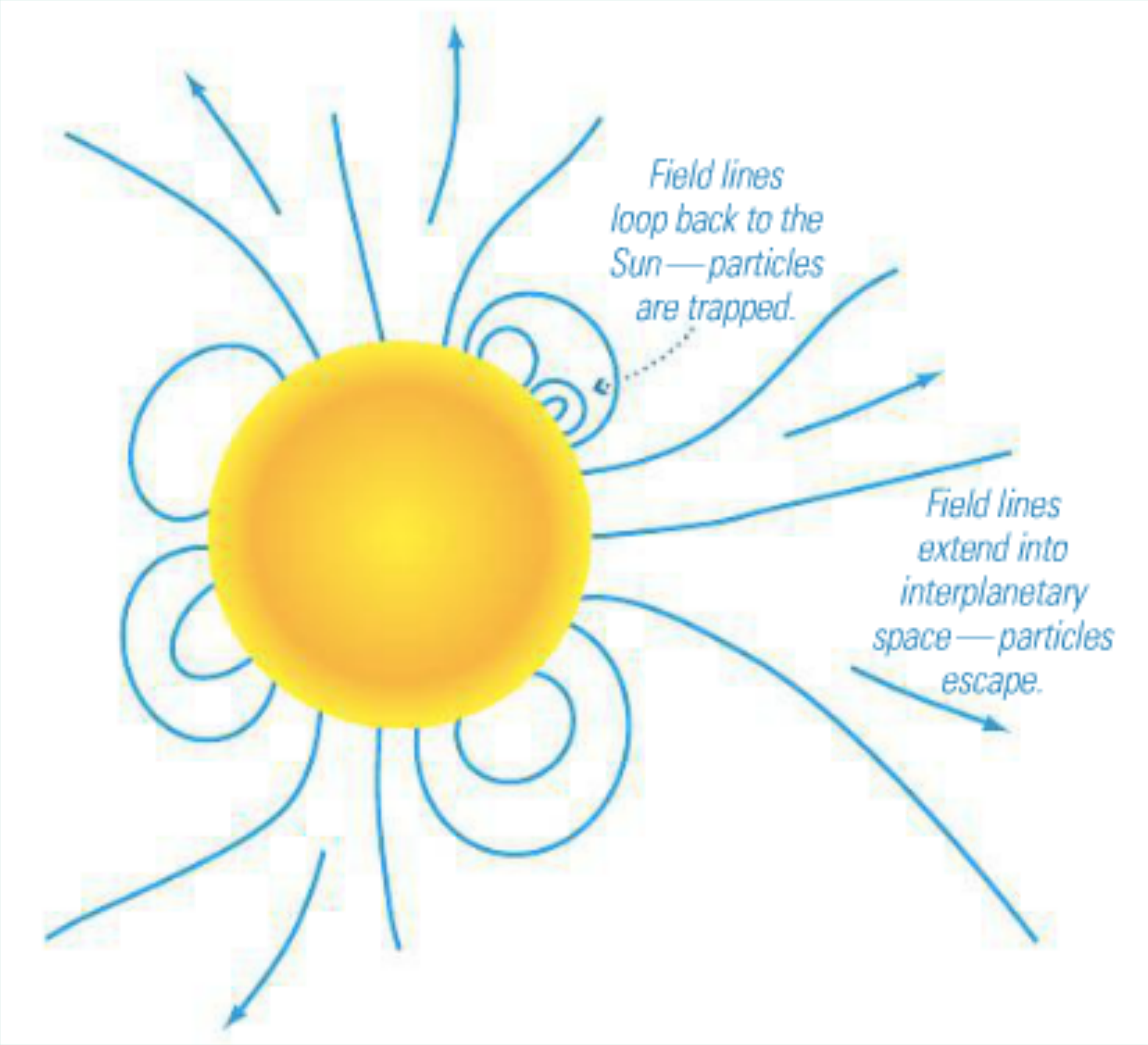
# Reconnection



# Coronal Holes



# “Coronal Holes” are escaping field lines



# Sir Arthur Eddington

1882 - 1944 UK

# Fusion Vs Wood

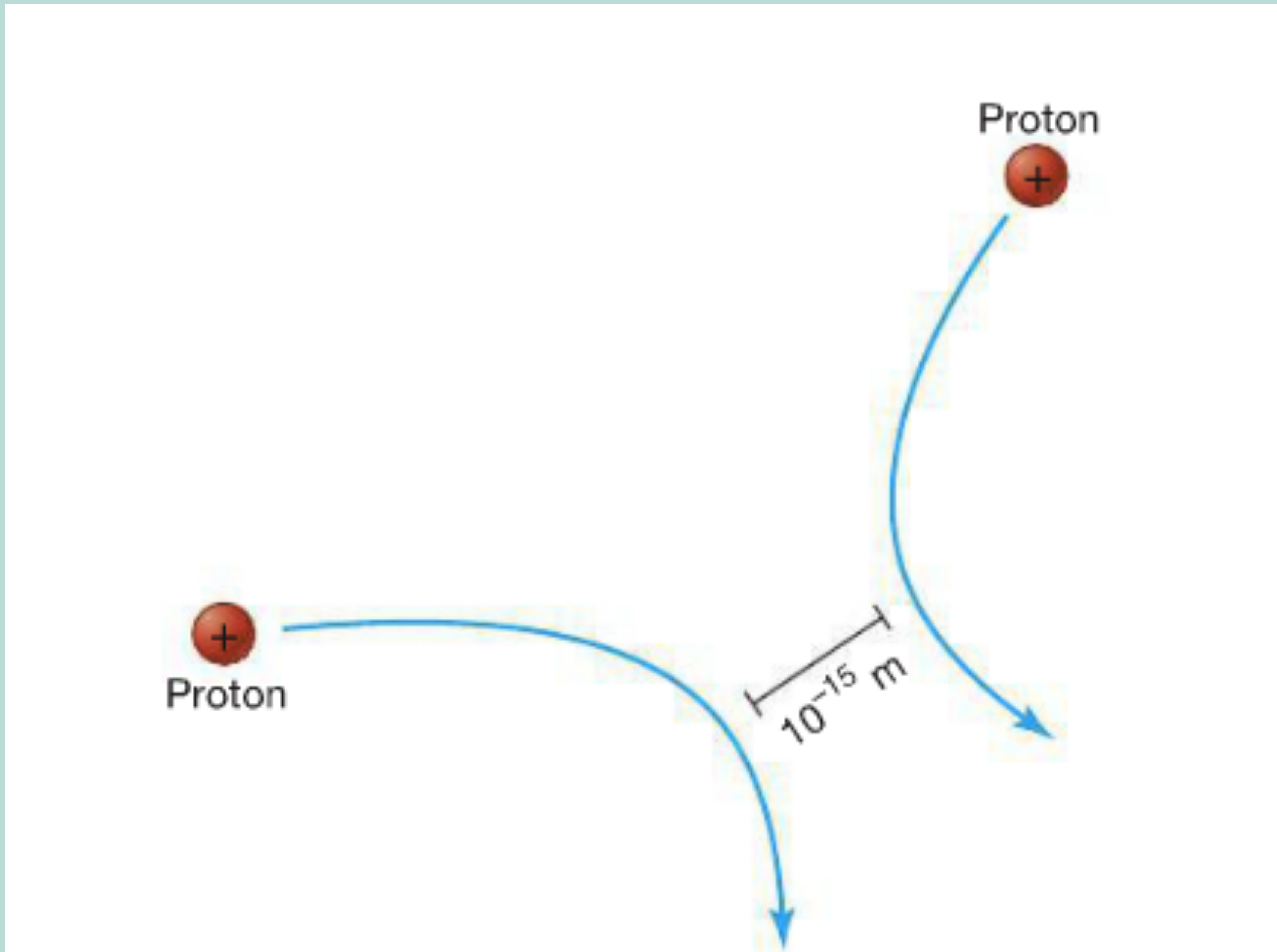
- If you divide the solar luminosity by the solar mass you get 2 mW / kilogram
- Wood generates 1,000,000 times more than that. A bon fire, merely the size of the pitiful earth would burn as bright as the sun
- How long would that fire burn though? Ans: not 5 billion years.
- Consider over 5 billion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

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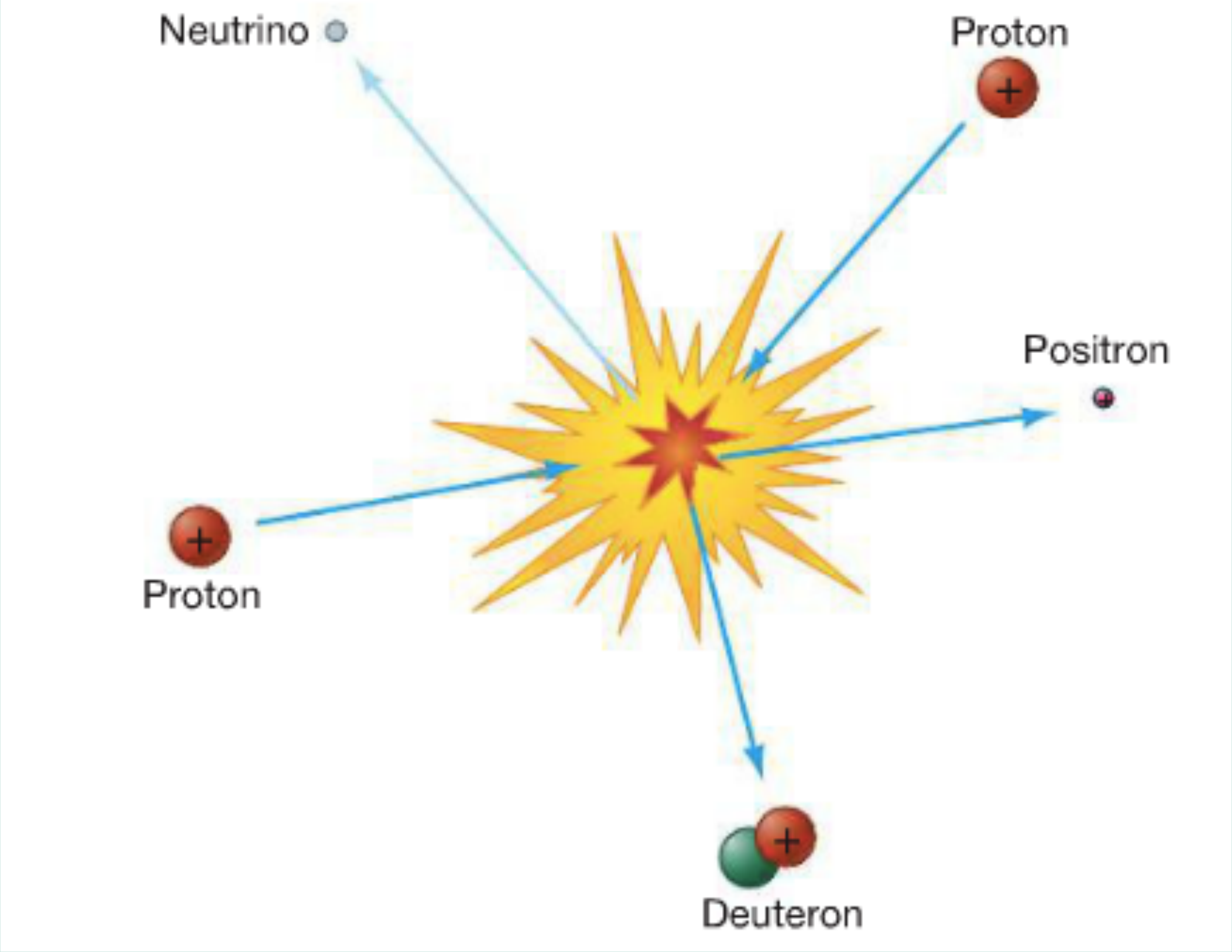
T > 10 million Kelvin

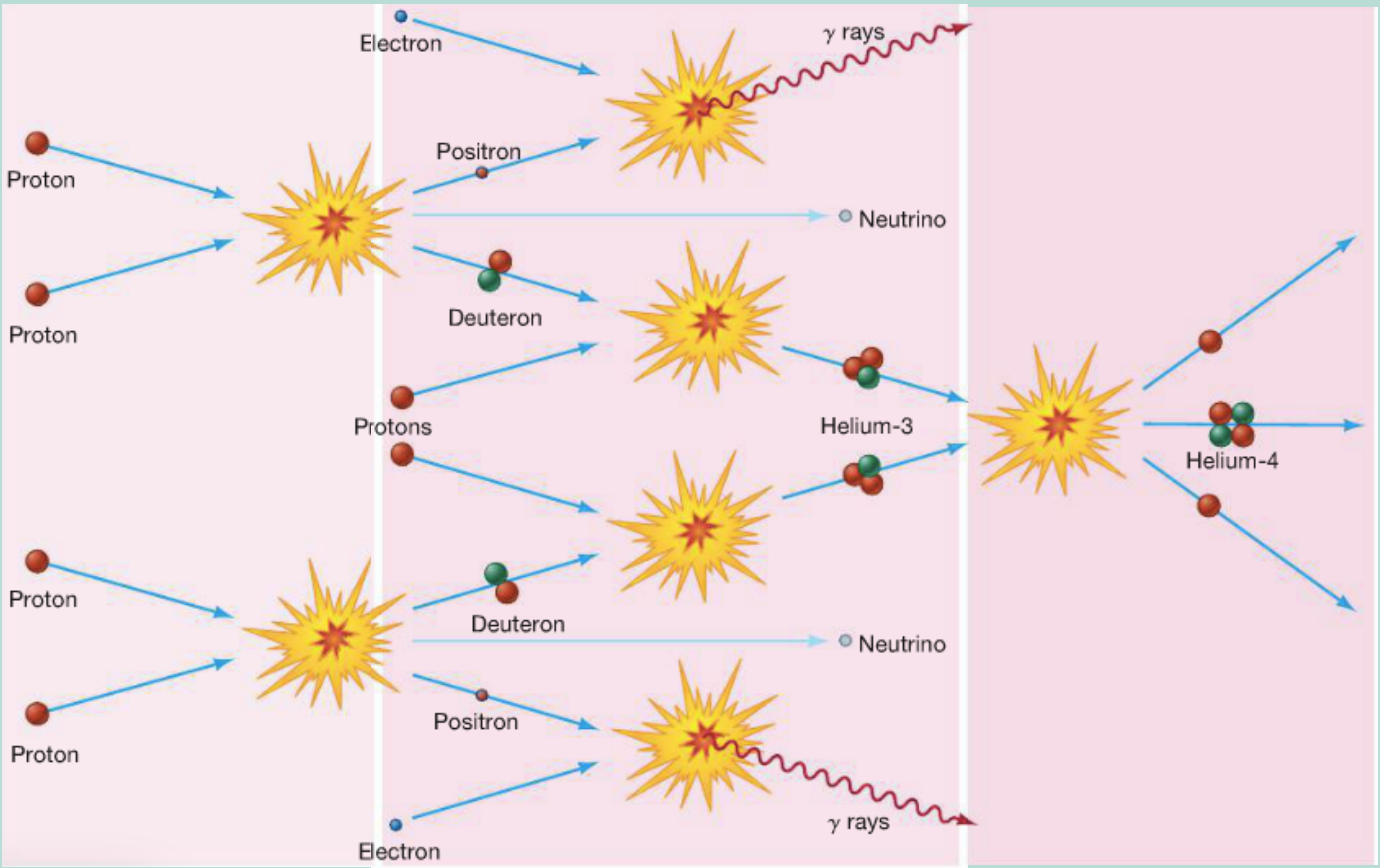
(we'll talk about these later)




(anti-matter)

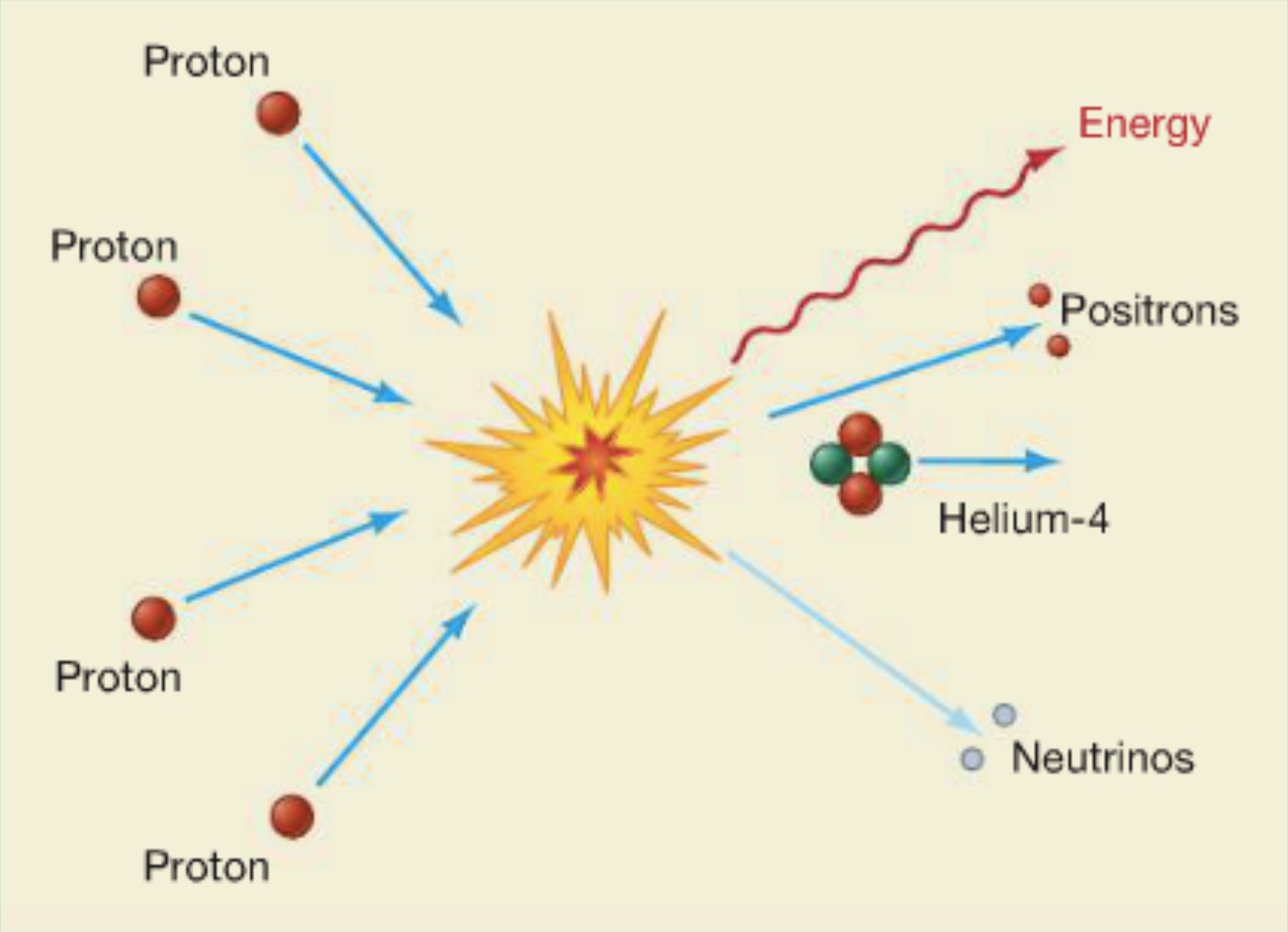
(isotopes)

# How to burn 4 hydrogen nuclei



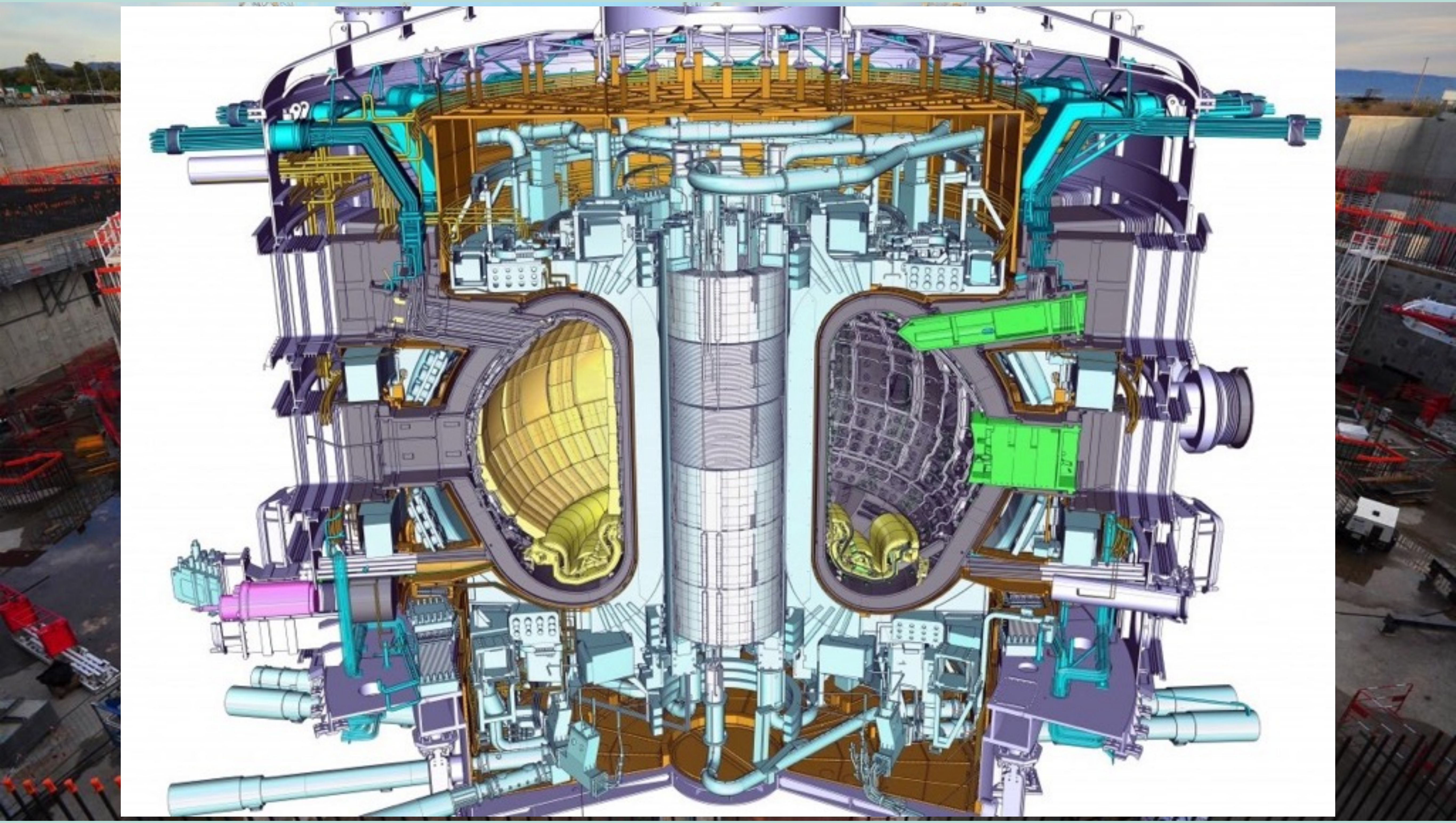
The Sun: Ch 16

# 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

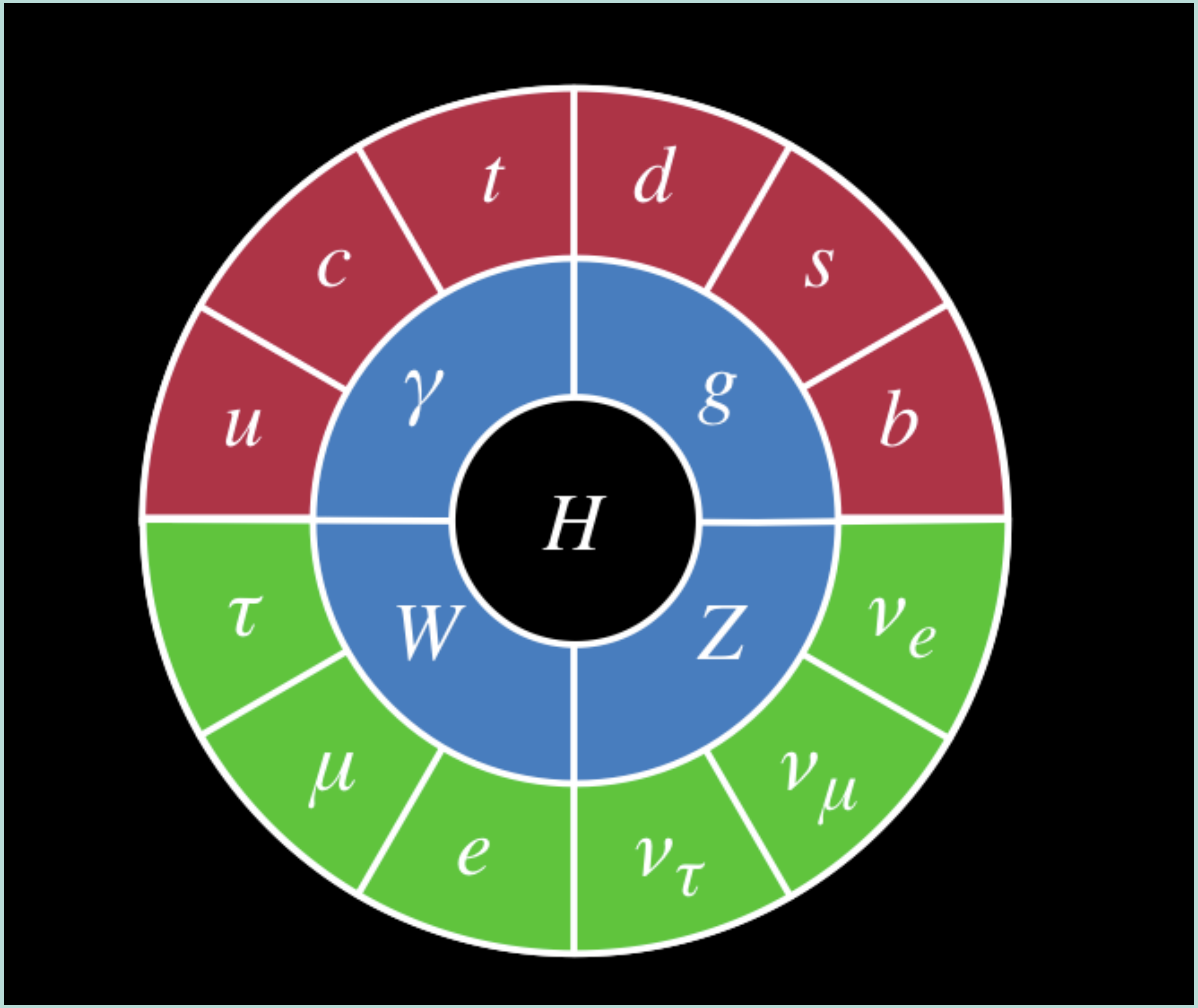


International ThermoNuclear Reactor (2027)

The Sun: Ch 16


DISCUSSION

# Behold…



The Sun: Ch 16

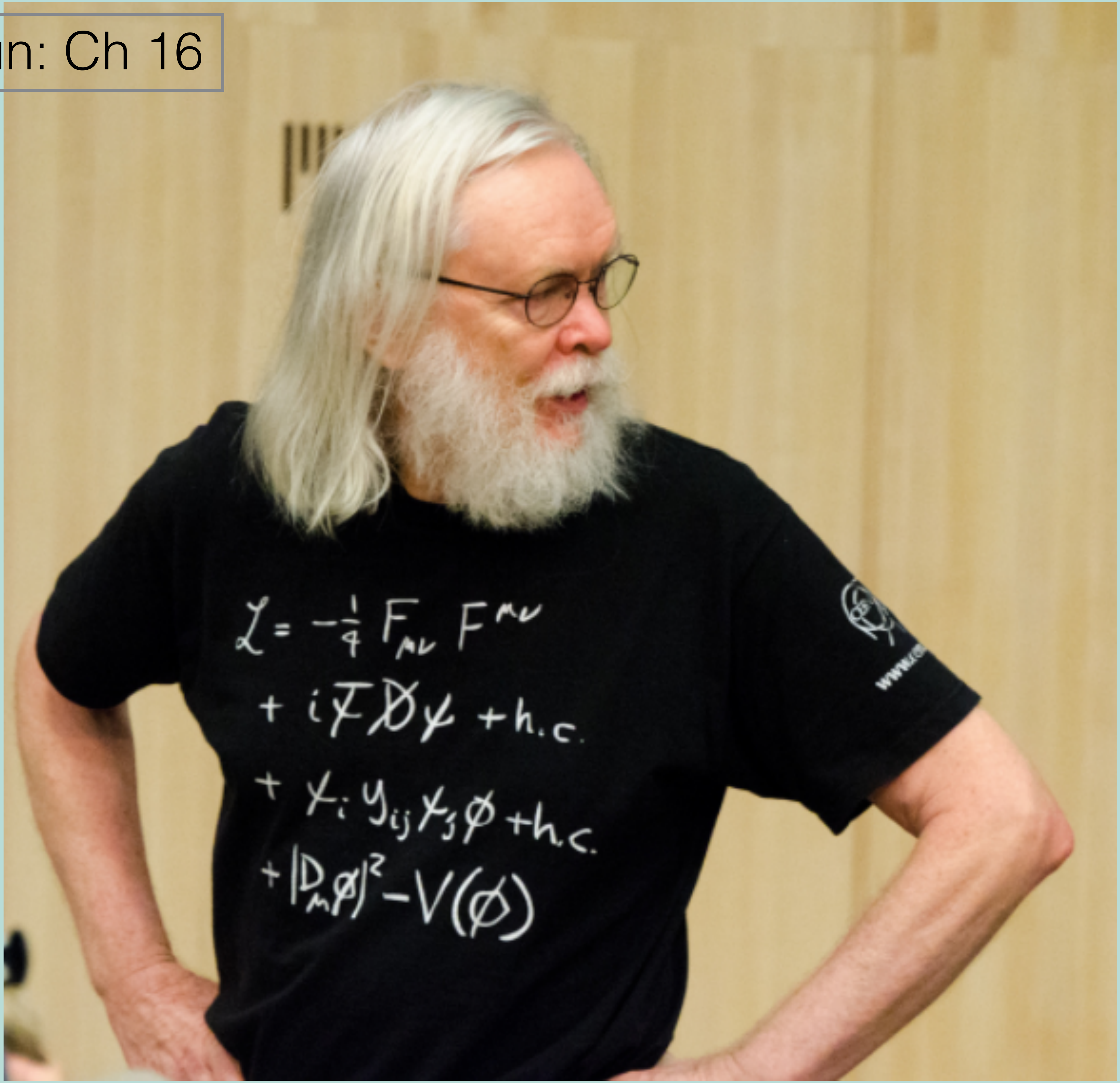
# Gotta catch'em all

# The Sun: Ch 16

75% of Physics.

$$
\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_e^\lambda)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m_\nu^\lambda)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
& m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)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_e^\kappa(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m_\nu^\lambda(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
& \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m_e^\lambda(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m_\nu^\kappa(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m_\nu^\lambda}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
& \tfrac{g}{2}\tfrac{m_e^\lambda}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m_\nu^\lambda}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m_e^\lambda}{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}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
& \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
& \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\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{Y}X^- - \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{Y}X^+) + 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}
$$

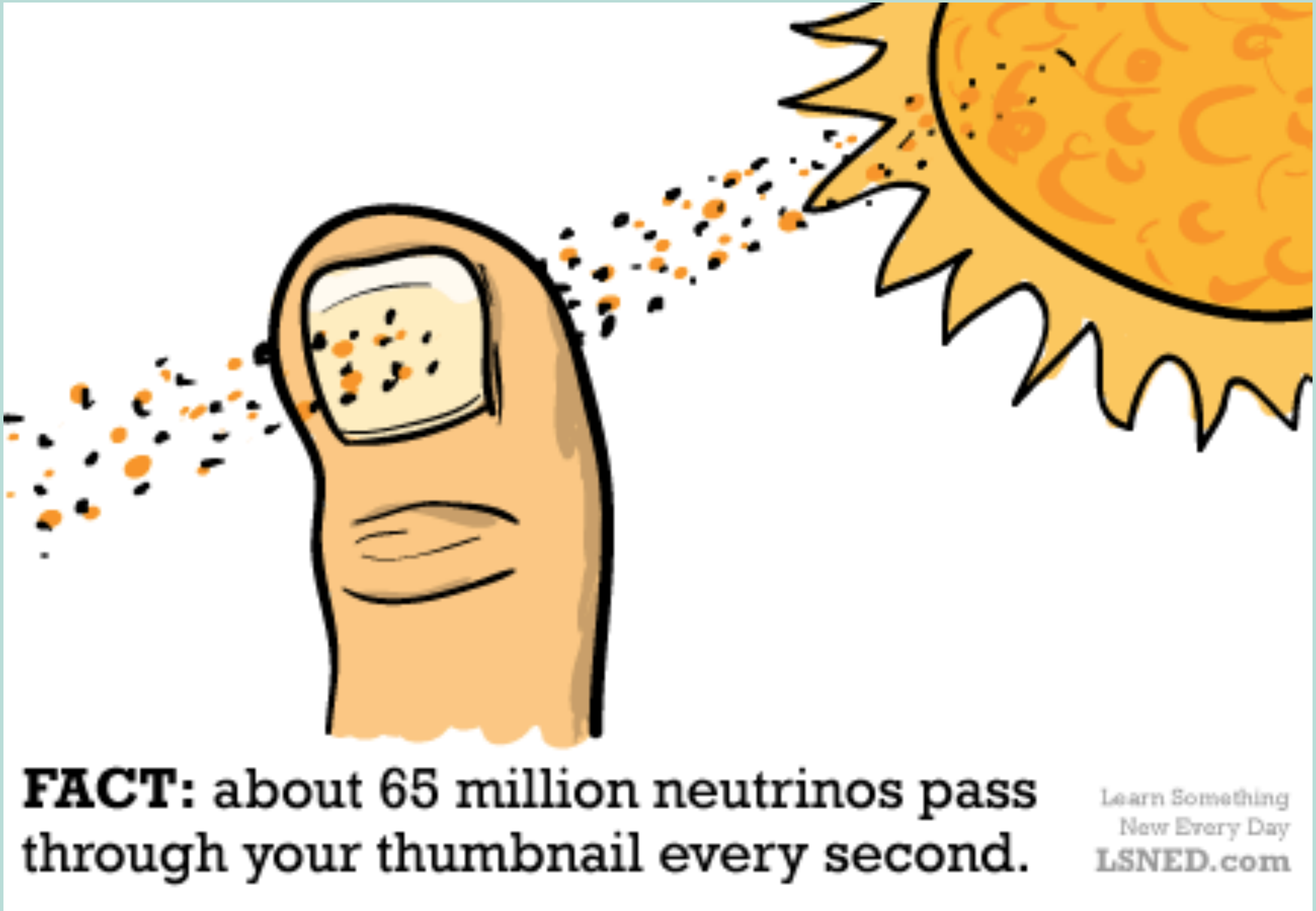
# The Sun: Ch 16


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

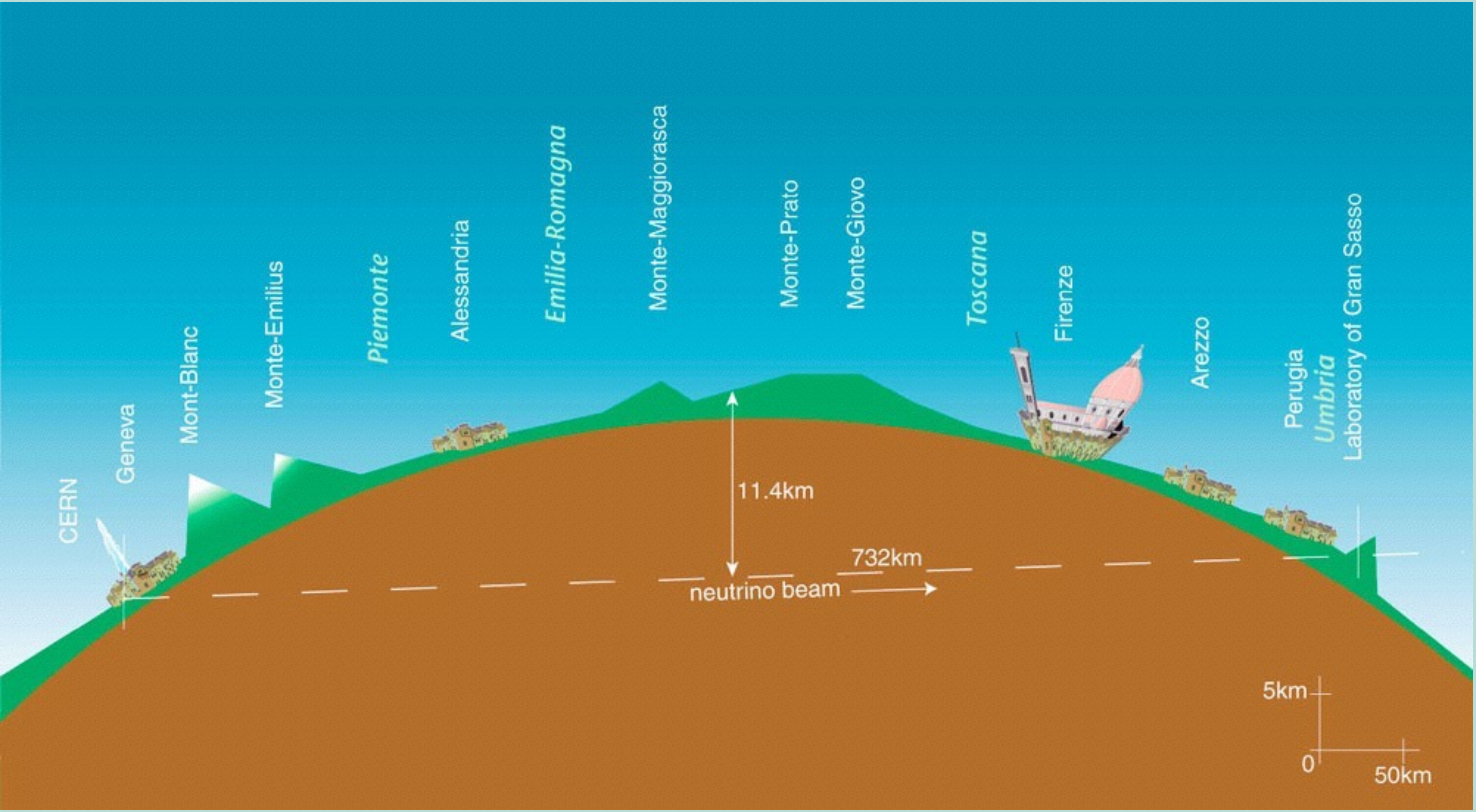
# Solar Neutrino Problem

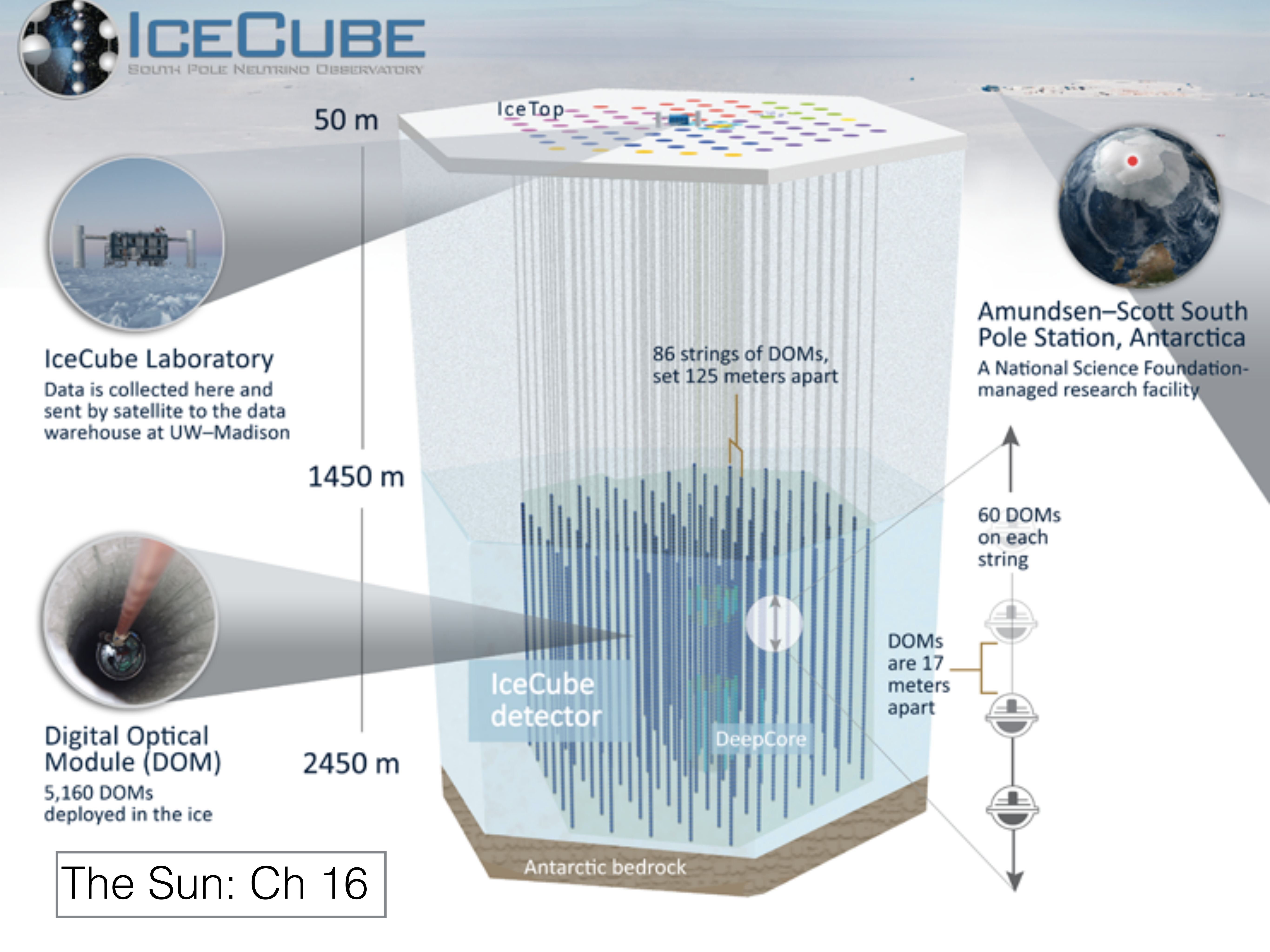
- With the amount of data that we have on the sun, we know exactly how many neutrinos are created in the core
- We also know how likely those neutrinos are to interact with our detectors
- We see a mismatch. This was explained by “neutrino oscillations”, experimentally verified in 2002

# The Sun: Ch 16


FACT: about 65 million neutrinos pass through your thumbnail every second.
Learn Something
New Every Day
LSNED.com

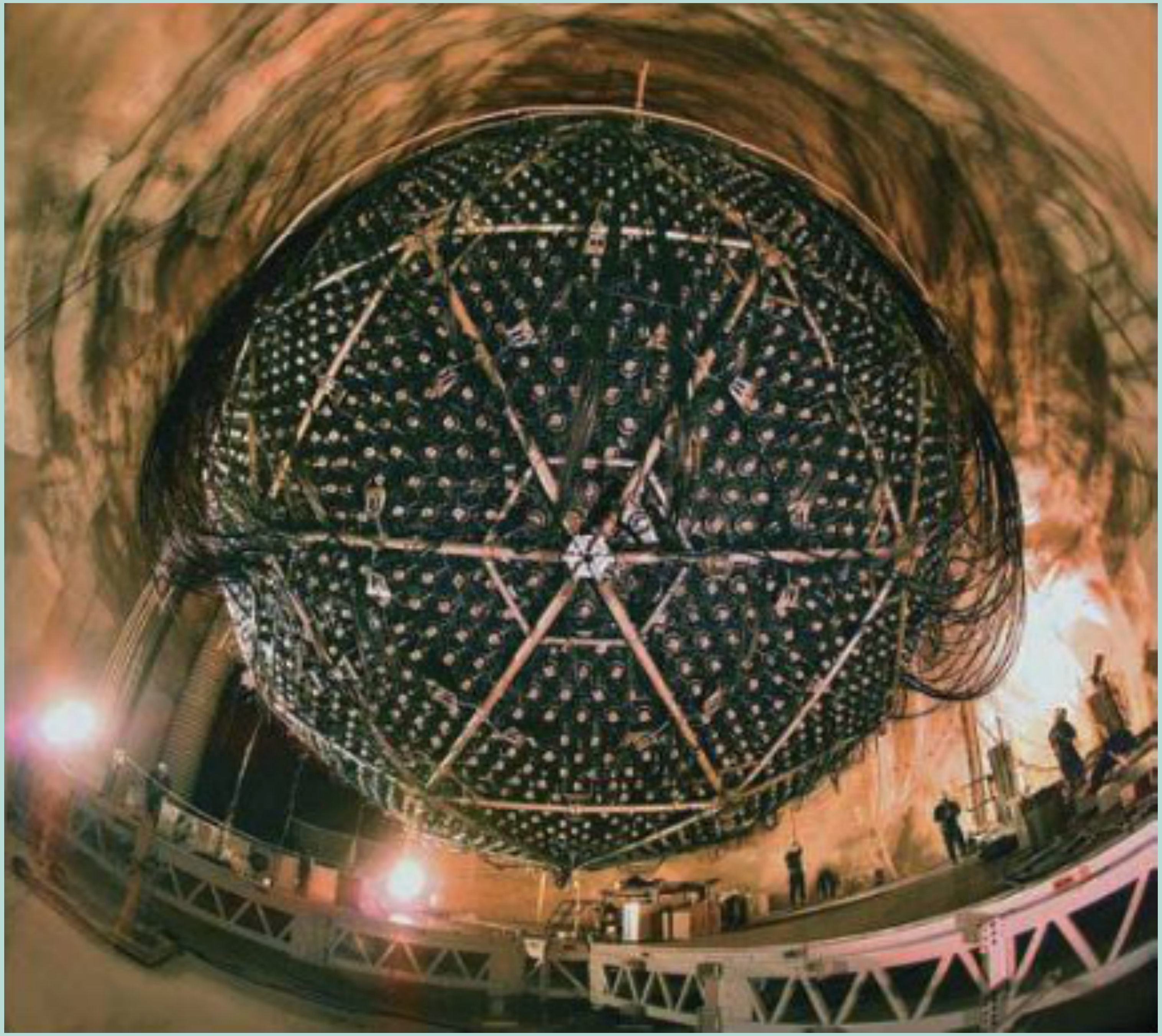
The Earth is transparent to neutrinos.




ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
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
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
Antarctic bedrock

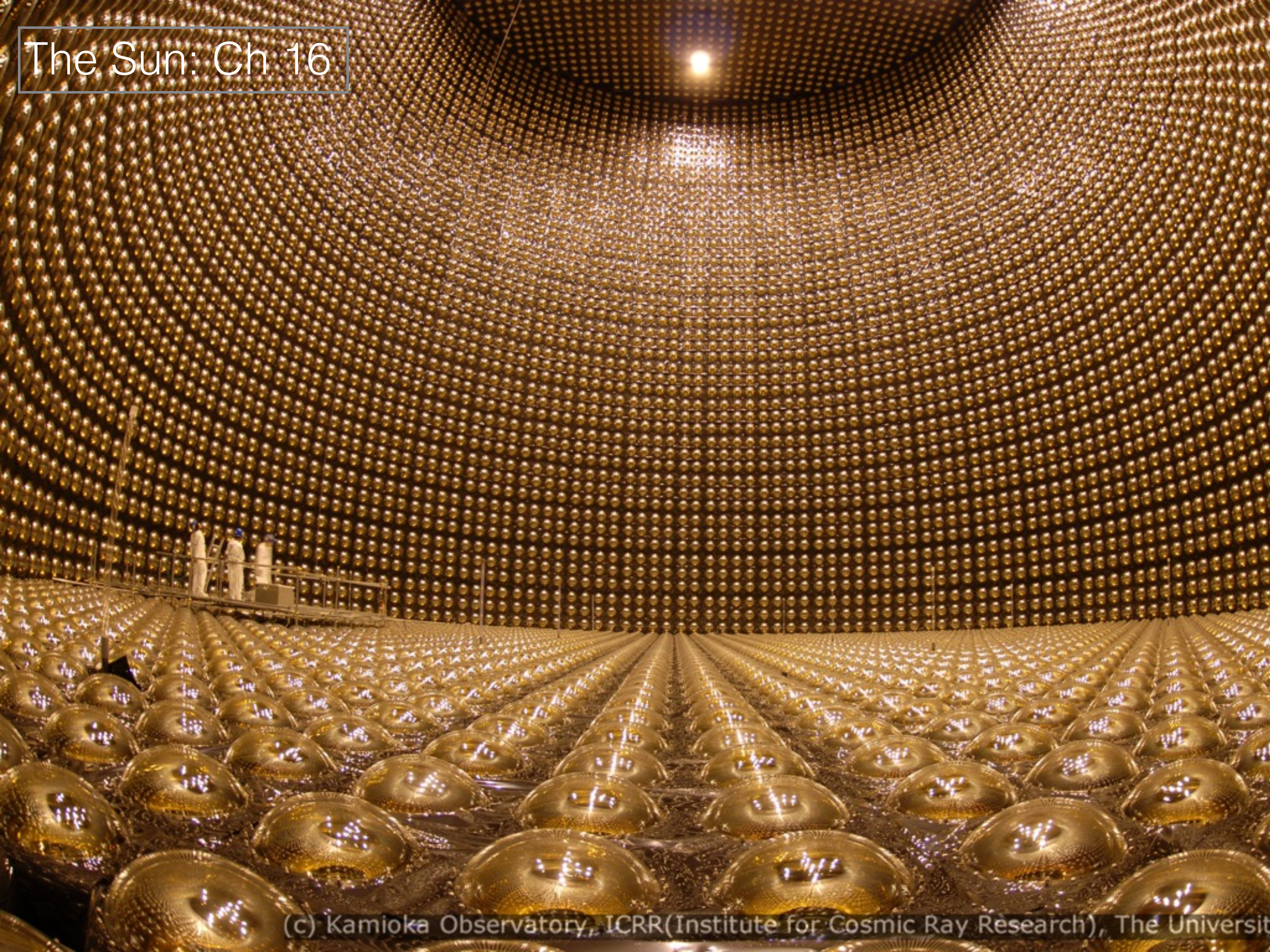
The Sun: Ch 16

# Ontario, CA



Sudbury Neutrino Solar Laboratory

# The Sun: Ch 16


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