# Solar Total and Spectral Irradiance Measurements and Models: A Users Guide

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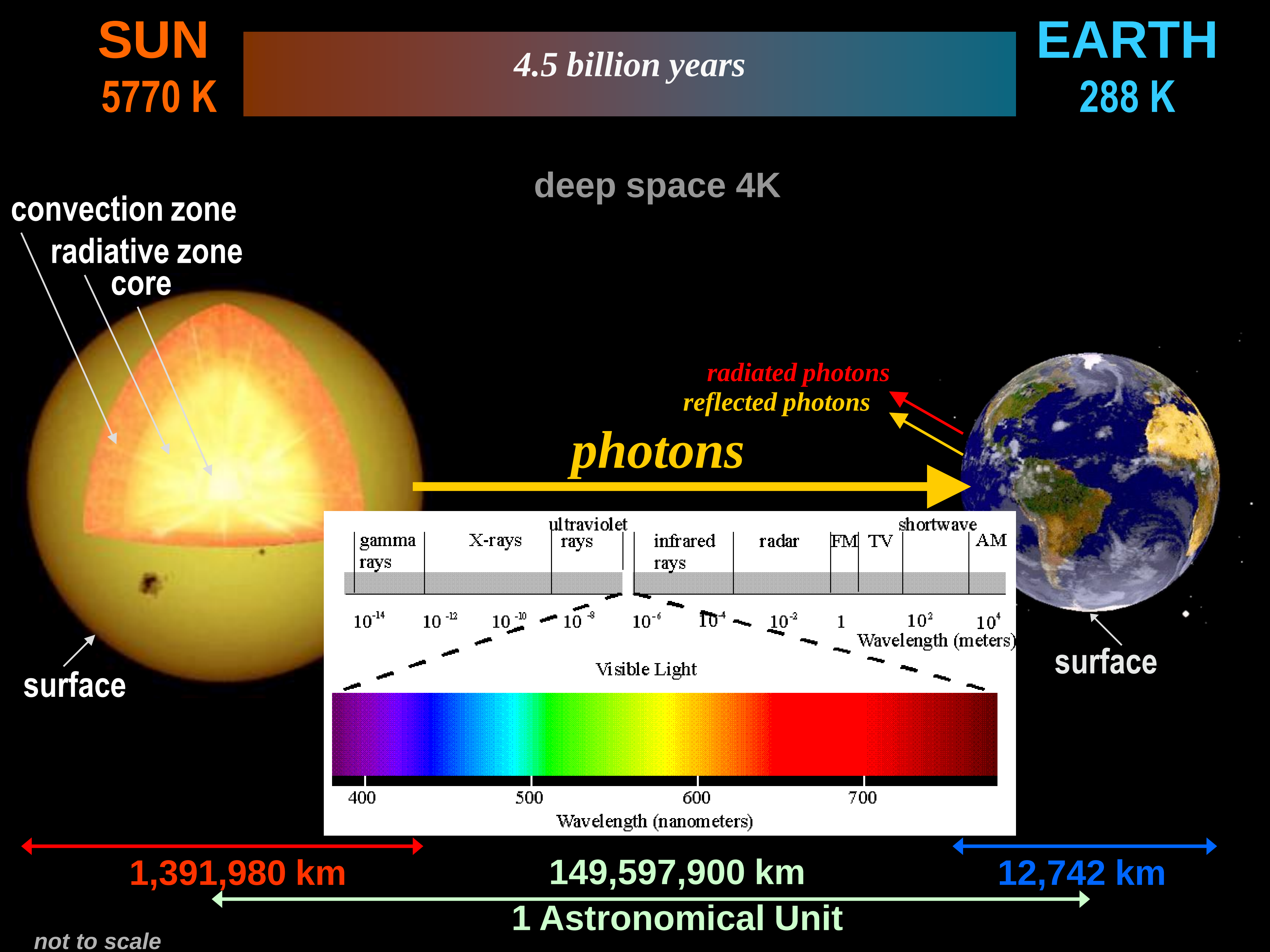
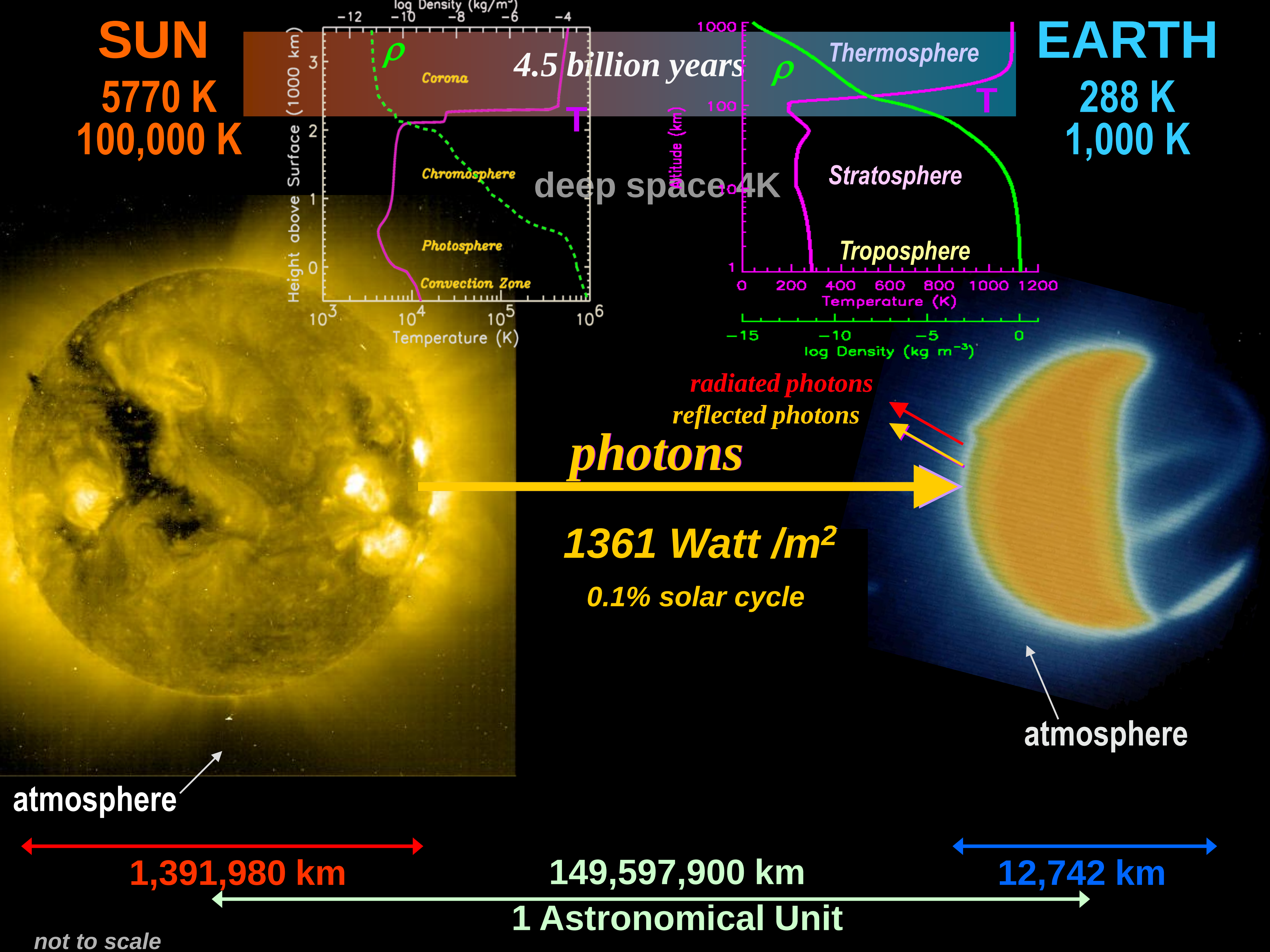
- **Sun-Earth System**
- **Solar Irradiance Measurements**
  - *total, spectral*
- **Space-Era Irradiance Variability**
  - *amplitude, sources*
  - *variability models*
- **Reconstructing Historical Changes**
  - *since the Maunder Minimum*
  - *during past millennia*

Earth

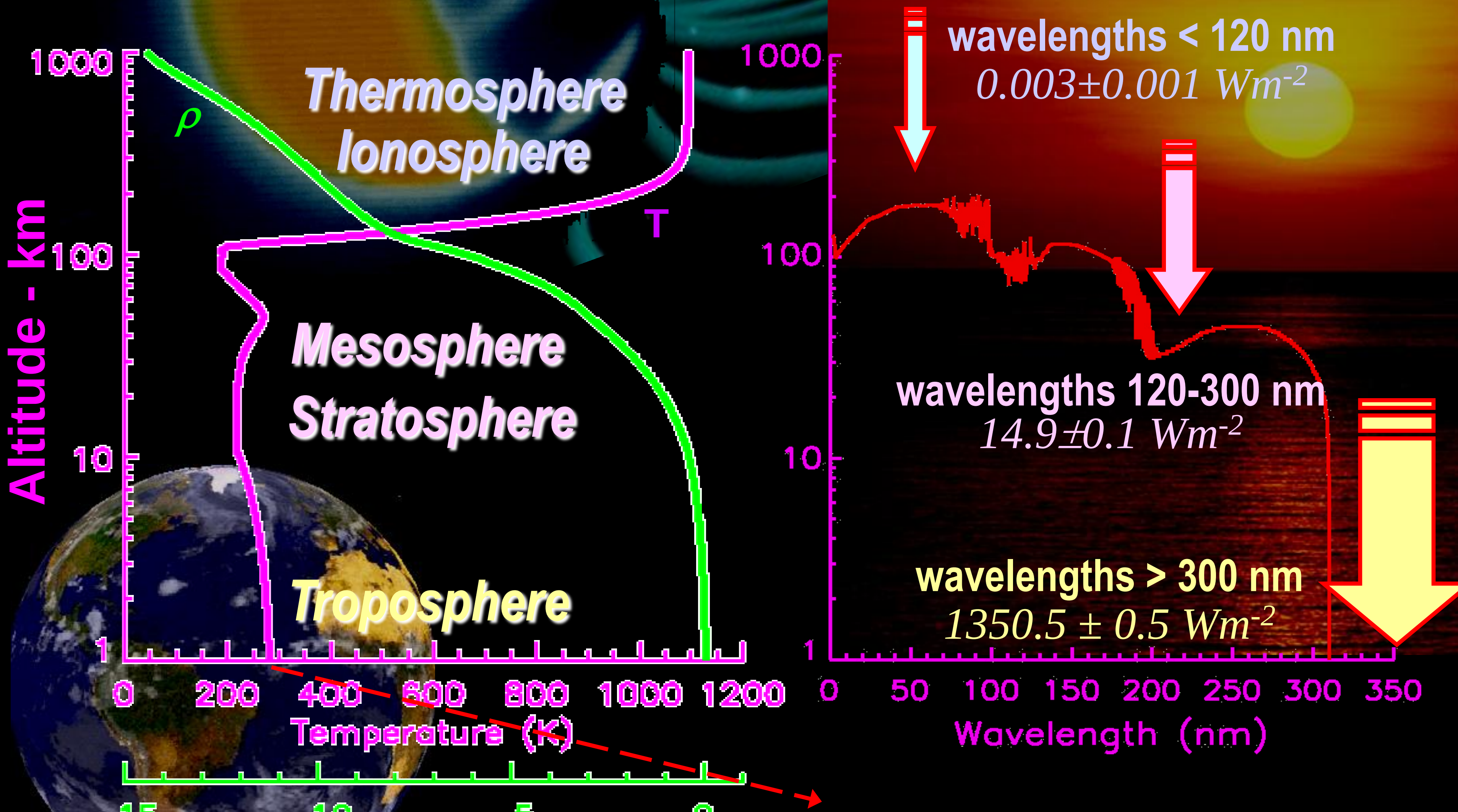
Heliophysics Summer School,
Boulder, CO, Jul09


SUN
5770 K
4.5 billion years
EARTH
288 K
deep space 4K
convection zone
radiative zone
core
radiated photons
reflected photons
photons
surface
surface
gamma rays
X-rays
ultraviolet rays
infrared rays
radar
FM
TV
shortwave
AM
10-14 10-12 10-10 10-8 10-6 10-4 10-2 1 102 104
Wavelength (meters)
Visible Light
400 500 600 700
Wavelength (nanometers)
1,391,980 km
149,597,900 km
12,742 km
1 Astronomical Unit
not to scale

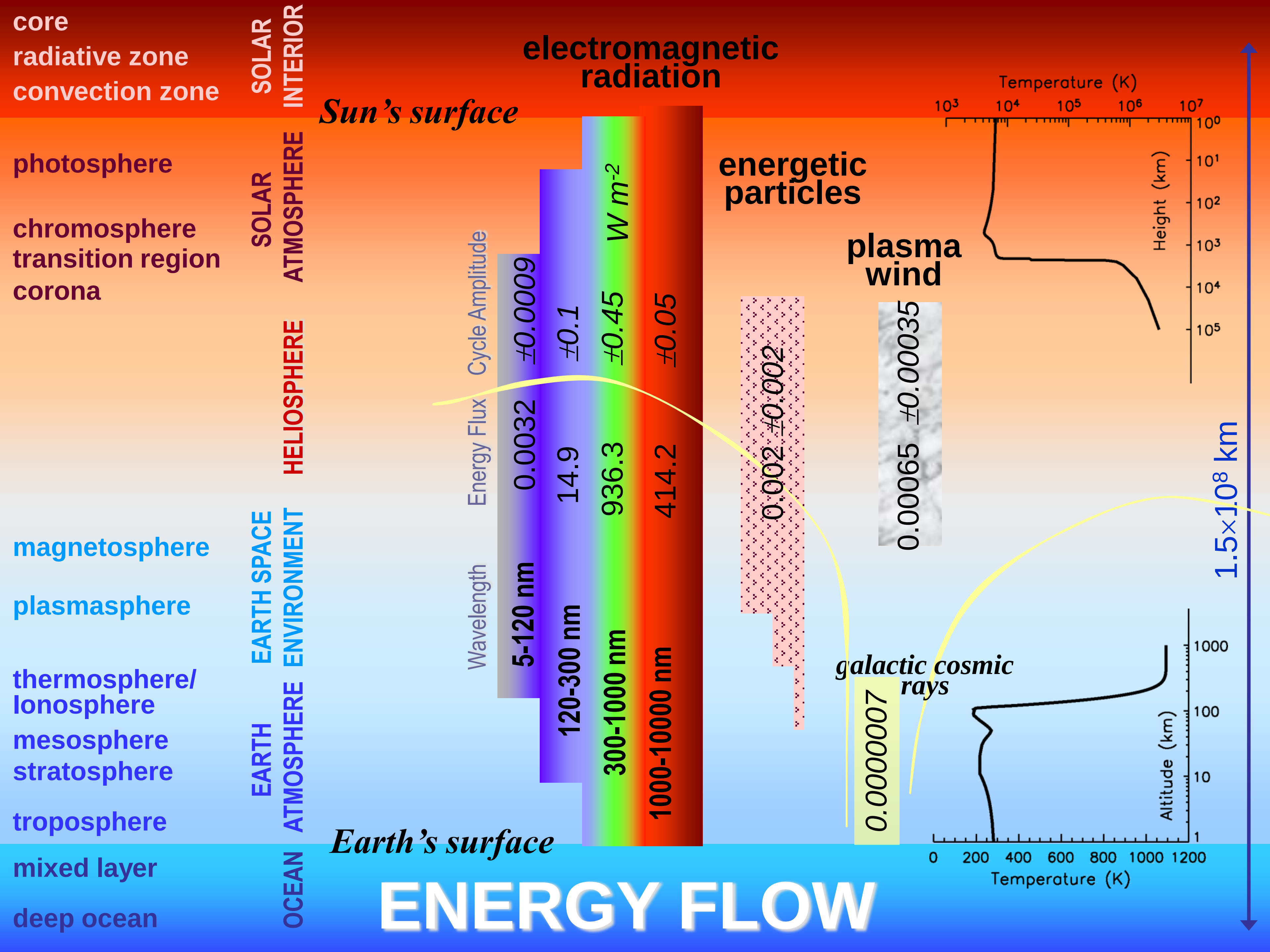


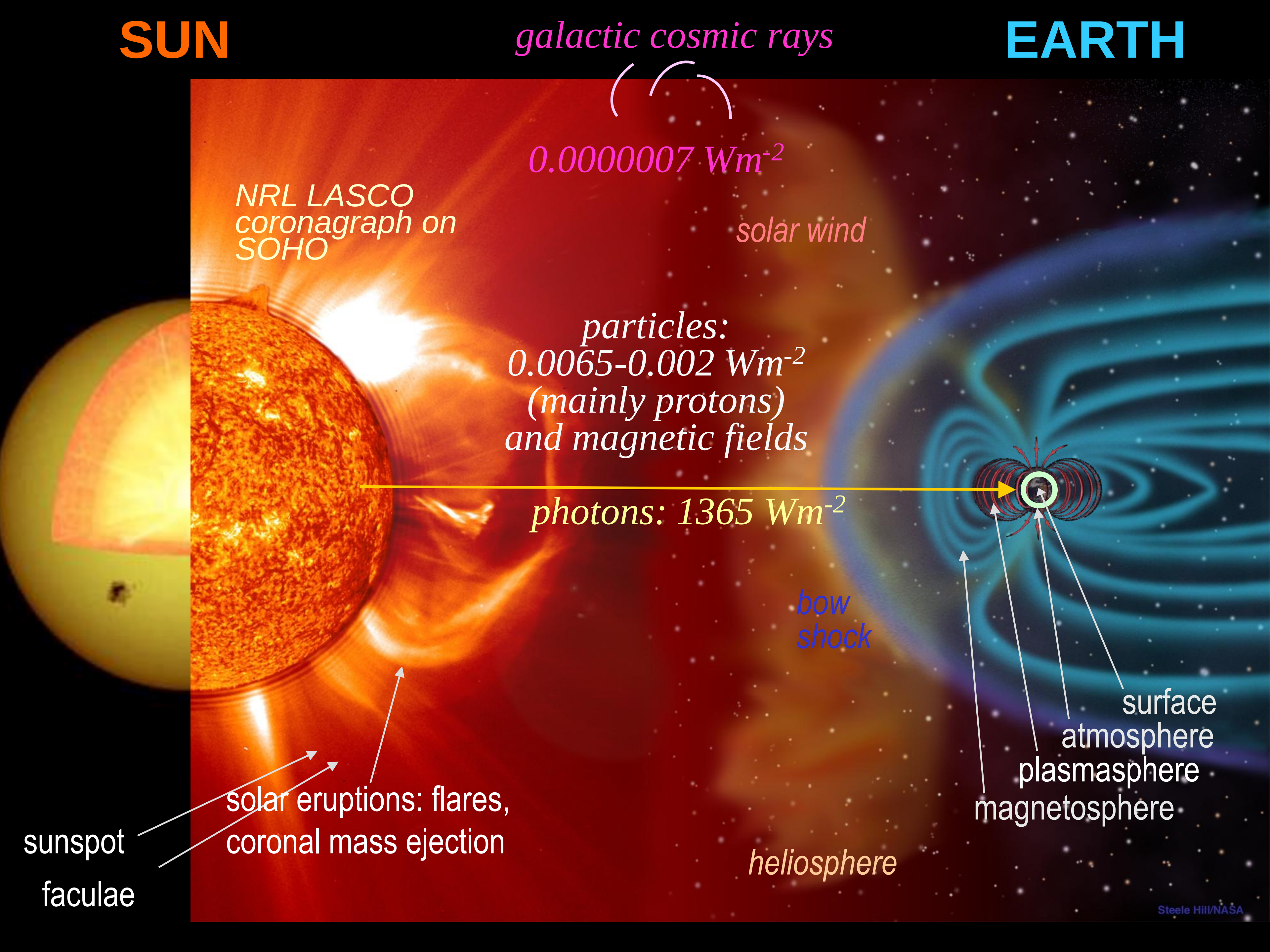
SUN
5770 K
100,000 K
EARTH
288 K
1,000 K
4.5 billion years
deep space 4K
log Density (kg/m-3)
Height above Surface (1000 km)
Temperature (K)
ρ
T
Corona
Chromosphere
Photosphere
Convection Zone
Thermosphere
Stratosphere
Troposphere
Altitude (km)
Temperature (K)
log Density (kg m-3)
radiated photons
reflected photons
photons
1361 Watt /m2
0.1% solar cycle
atmosphere
atmosphere
1,391,980 km
149,597,900 km
12,742 km
1 Astronomical Unit
not to scale

# Solar Radiation Establishes the Thermal Structure of the Earth and its Atmosphere

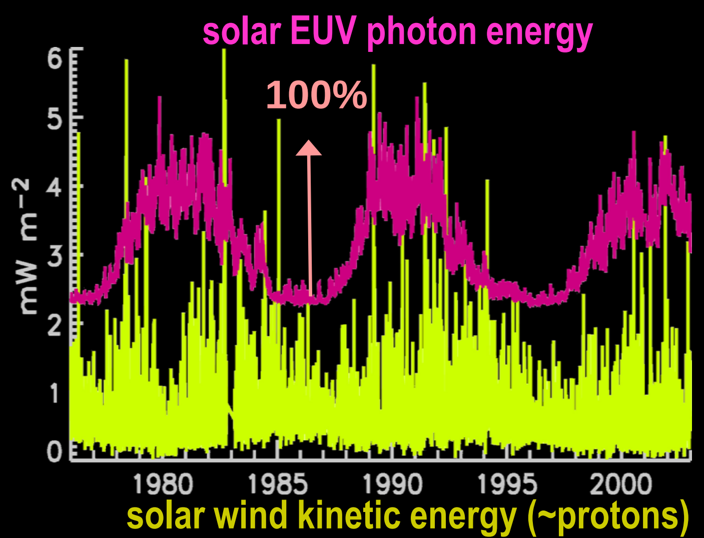


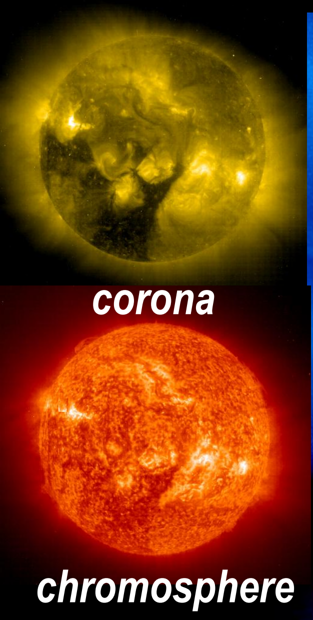

**SUN (255 K) + GHG (33 K) = 288 K**

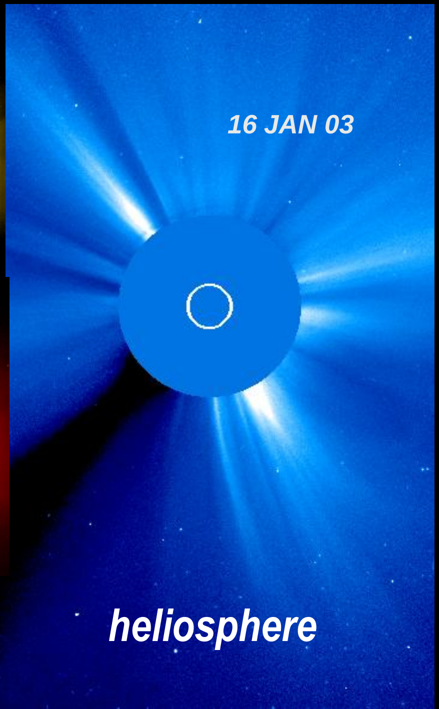

core
radiative zone
convection zone
SOLAR INTERIOR
electromagnetic radiation
Sun's surface
photosphere
chromosphere
transition region
corona
SOLAR ATMOSPHERE
HELIOSPHERE
magnetosphere
plasmasphere
EARTH SPACE ENVIRONMENT
thermosphere/ Ionosphere
mesosphere
stratosphere
troposphere
EARTH ATMOSPHERE
mixed layer
deep ocean
OCEAN
Earth's surface
ENERGY FLOW
W m-2
Cycle Amplitude
Energy Flux
Wavelength
±0.0009
0.0032
5-120 nm
±0.1
14.9
120-300 nm
±0.45
936.3
300-1000 nm
±0.05
414.2
1000-10000 nm
energetic particles
0.002 ±0.002
plasma wind
0.00065 ±0.00035
galactic cosmic rays
0.0000007
Temperature (K)
Height (km)
Altitude (km)
1.5×10^8 km

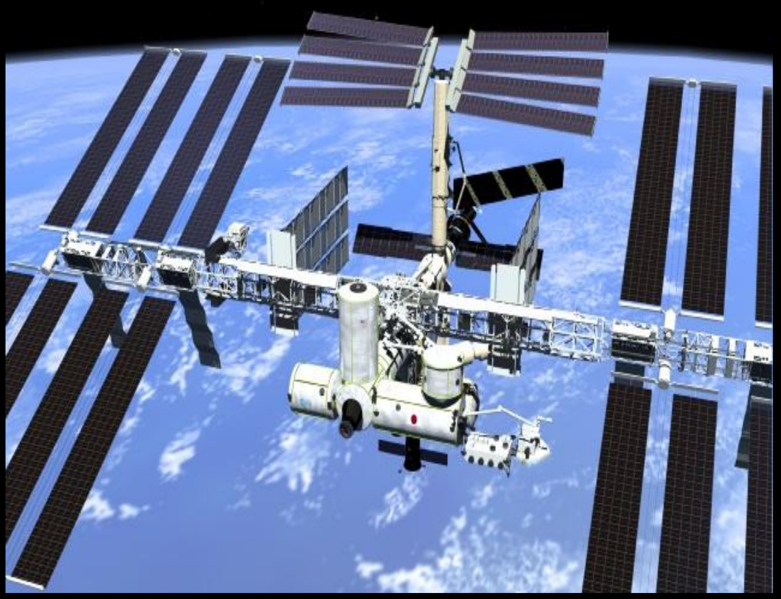

SUN
galactic cosmic rays
EARTH
0.0000007 Wm-2
NRL LASCO coronagraph on SOHO
solar wind
particles: 0.0065-0.002 Wm-2 (mainly protons) and magnetic fields
photons: 1365 Wm-2
bow shock
surface
atmosphere
plasmasphere
magnetosphere
solar eruptions: flares, coronal mass ejection
sunspot
faculae
heliosphere
Steele Hill/NASA

# Solar Photons, Particles and Plasma

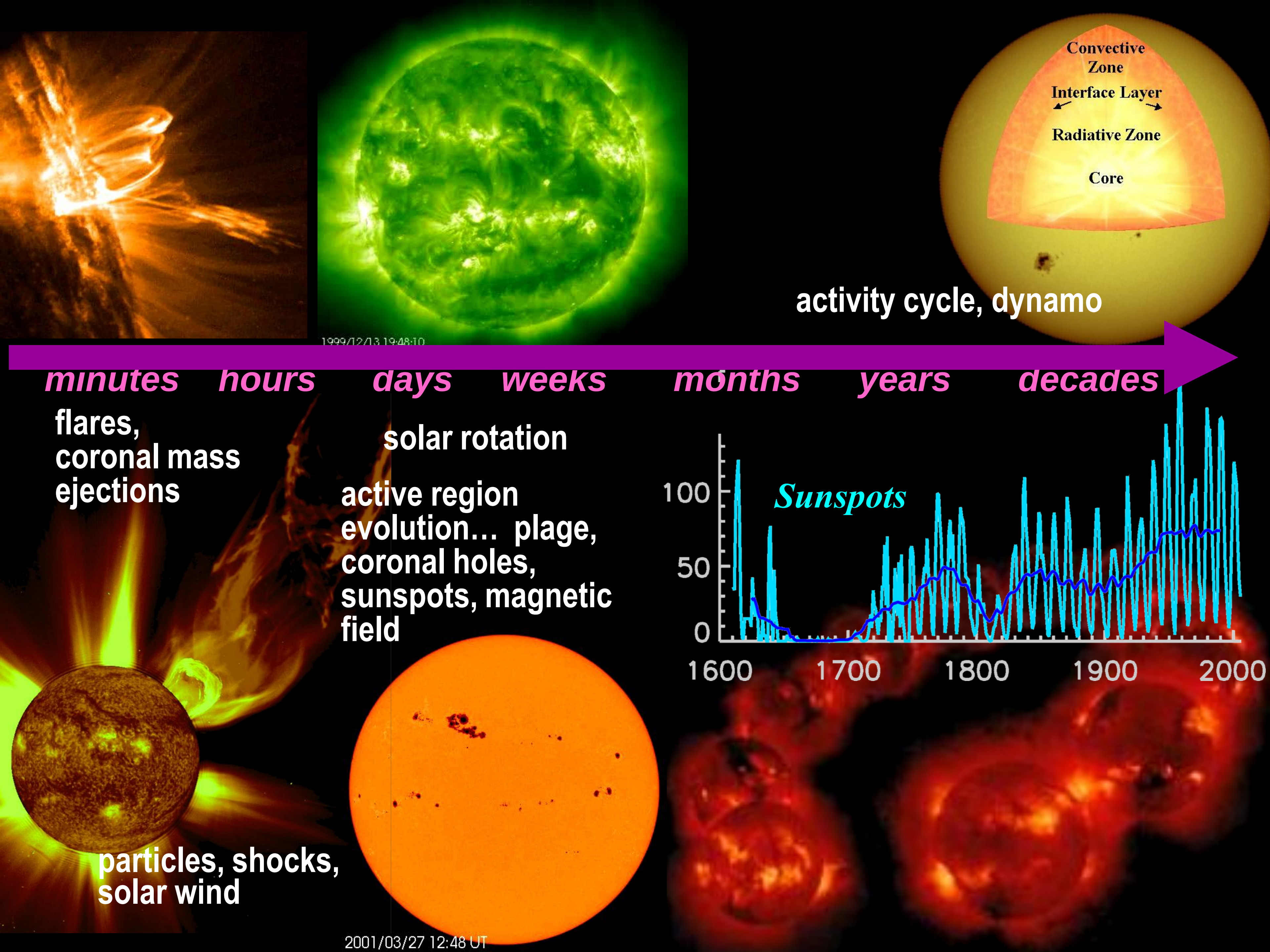


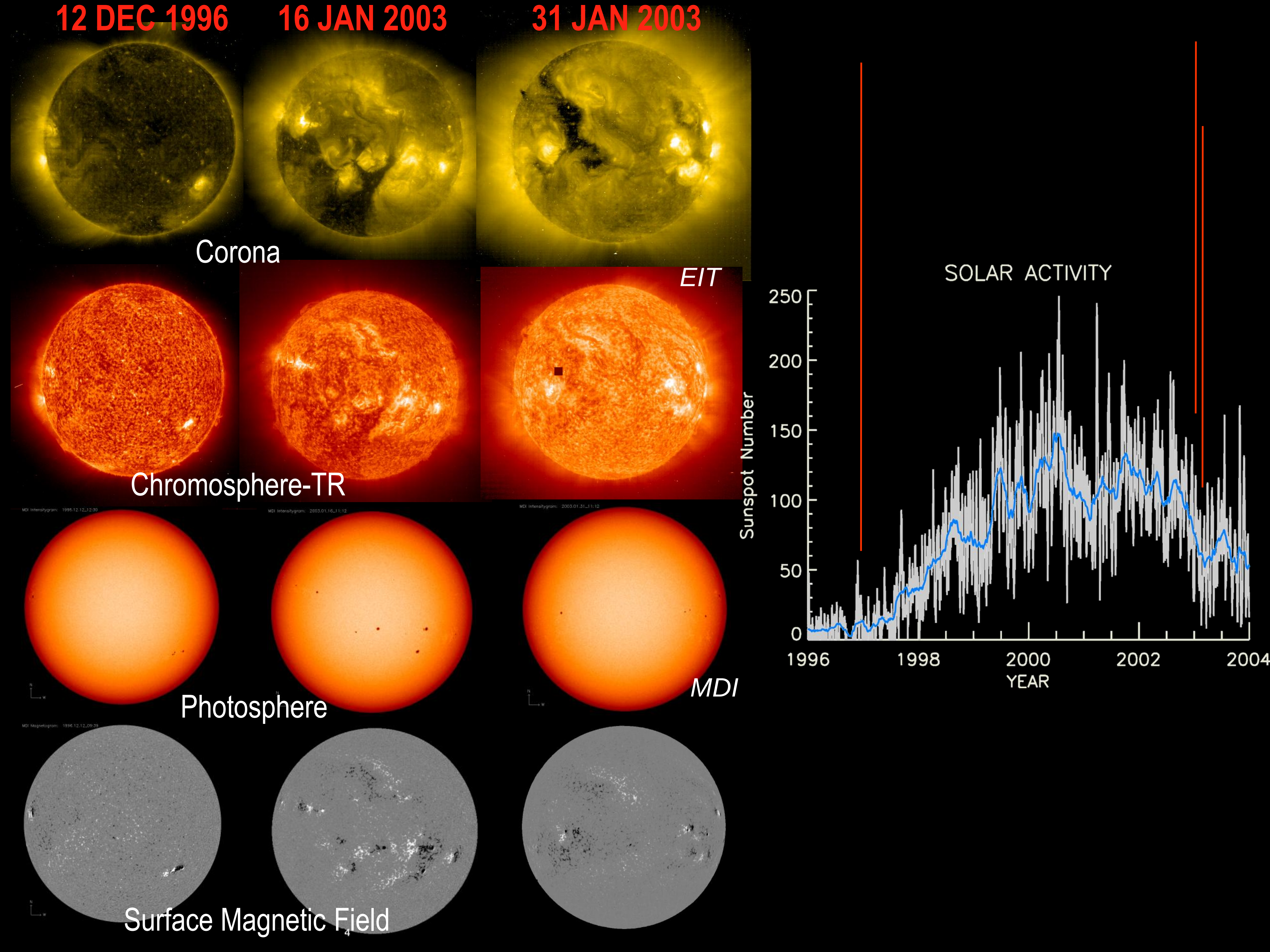



*International Space Station: 400 km*


1999/12/13 19:48:10
Convective Zone
Interface Layer
Radiative Zone
Core
activity cycle, dynamo
minutes
hours
days
weeks
months
years
decades
flares, coronal mass ejections
solar rotation
active region evolution… plage, coronal holes, sunspots, magnetic field
Sunspots
100
50
0
1600
1700
1800
1900
2000
particles, shocks, solar wind
2001/03/27 12:48 UT


12 DEC 1996
16 JAN 2003
31 JAN 2003
Corona
EIT
Chromosphere-TR
Photosphere
MDI
Surface Magnetic Field
SOLAR ACTIVITY
Sunspot Number
250
200
150
100
50
0
1996
1998
2000
2002
2004
YEAR

# How Bright is the Sun?… *A Century of Enquiry*

**Ground….**
**1837: Herschel**
**1880: Langley**

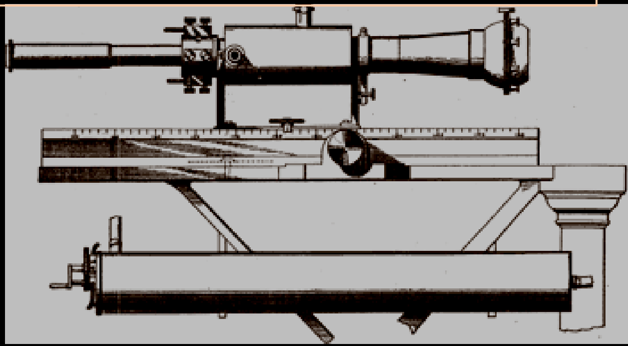
***"… the observation of the amount of heat the sun sends the earth is among the most important and difficult in astronomical physics, it may be termed the fundamental problem of meteorology"***

**1902-1955: Abbot**

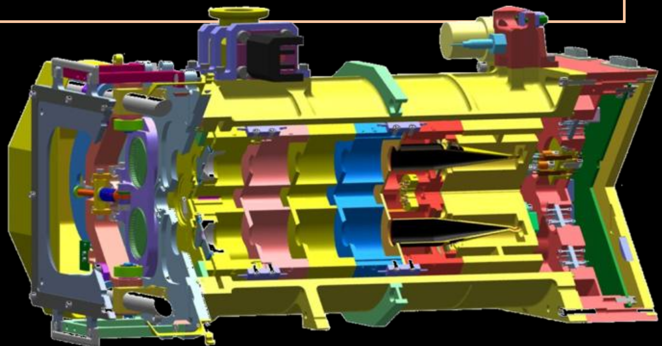
**Aircraft and Balloons**
**1967: 1359±13 W m$^{-2}$**
**1977: 1373±20 W m$^{-2}$**

**Space**
**1980: 1371±10 W m$^{-2}$**
**1990: 1365±10 W m$^{-2}$**
**2003: 1361±4 W m$^{-2}$**

***From Langley's bolometer…***
**"An instrument that measures radiant energy by correlating the radiation-induced change in electrical resistance of a blackened metal foil with the amount of radiation absorbed"**

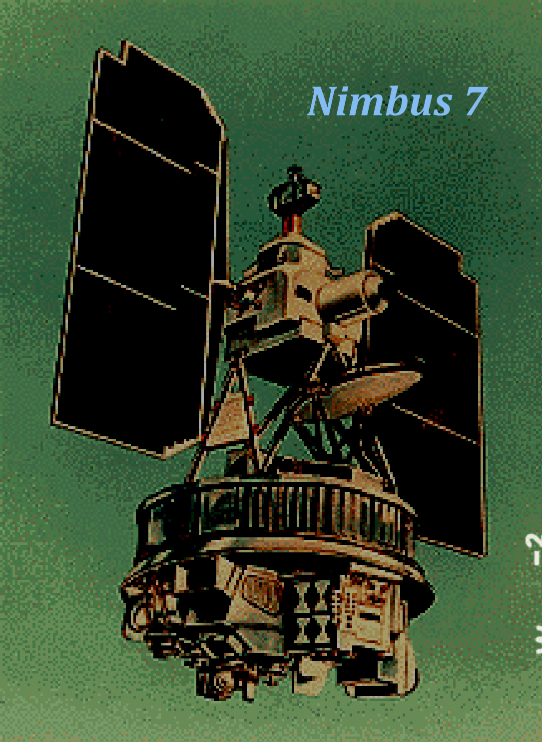


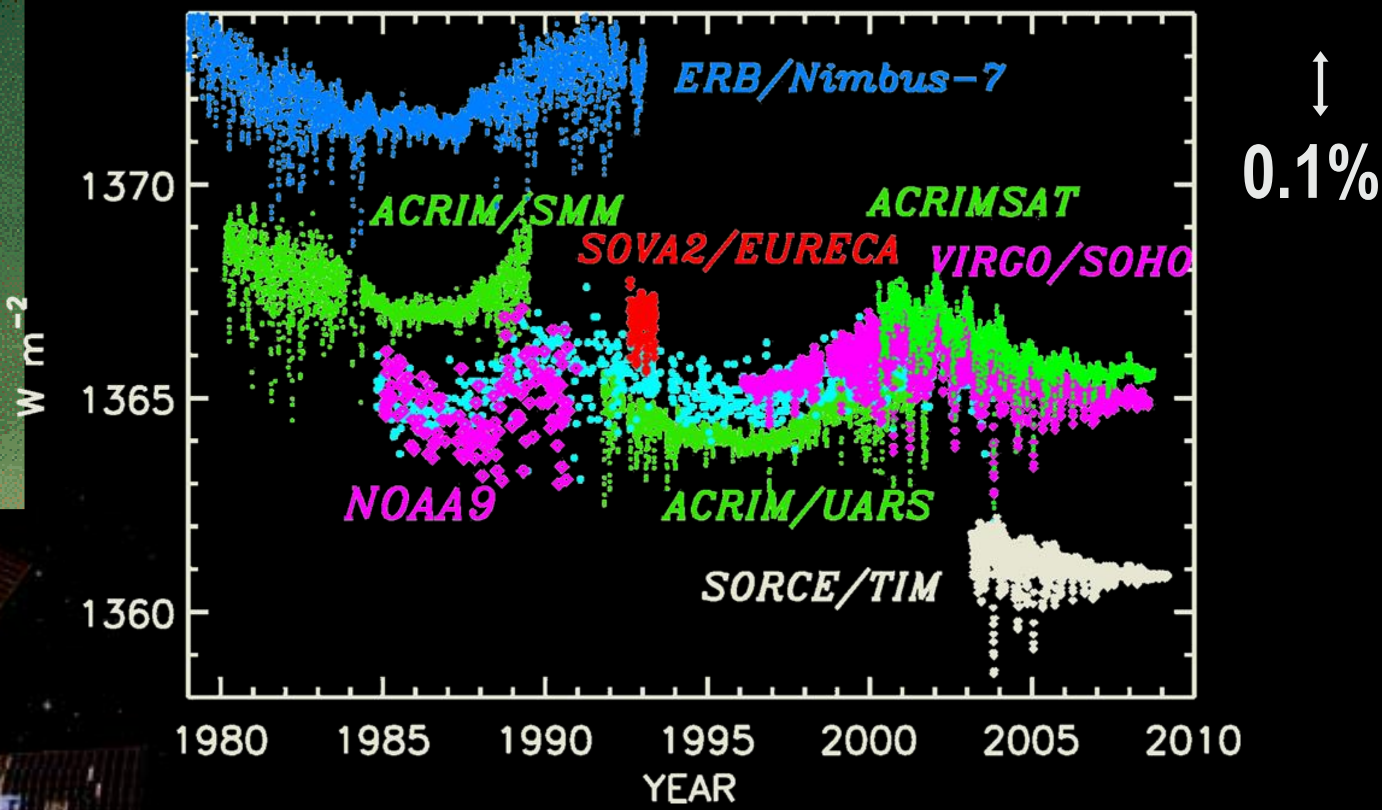
***… to the Total Irradiance Monitor (TIM) on NASA's Solar Radiation and Climate Experiment (SORCE)***
**a state-of-the-art, active cavity electrical substitution radiometer with phase-sensitive detection, NiP black surf*aces,* redundant cavities, NIST calibration….**



*http://lasp.colorado.edu/sorce/*

# Total Solar Irradiance Measurements from Space





***GLORY/TIM: 2010 ?→***

***... the first "benchmark" irradiance measurement***

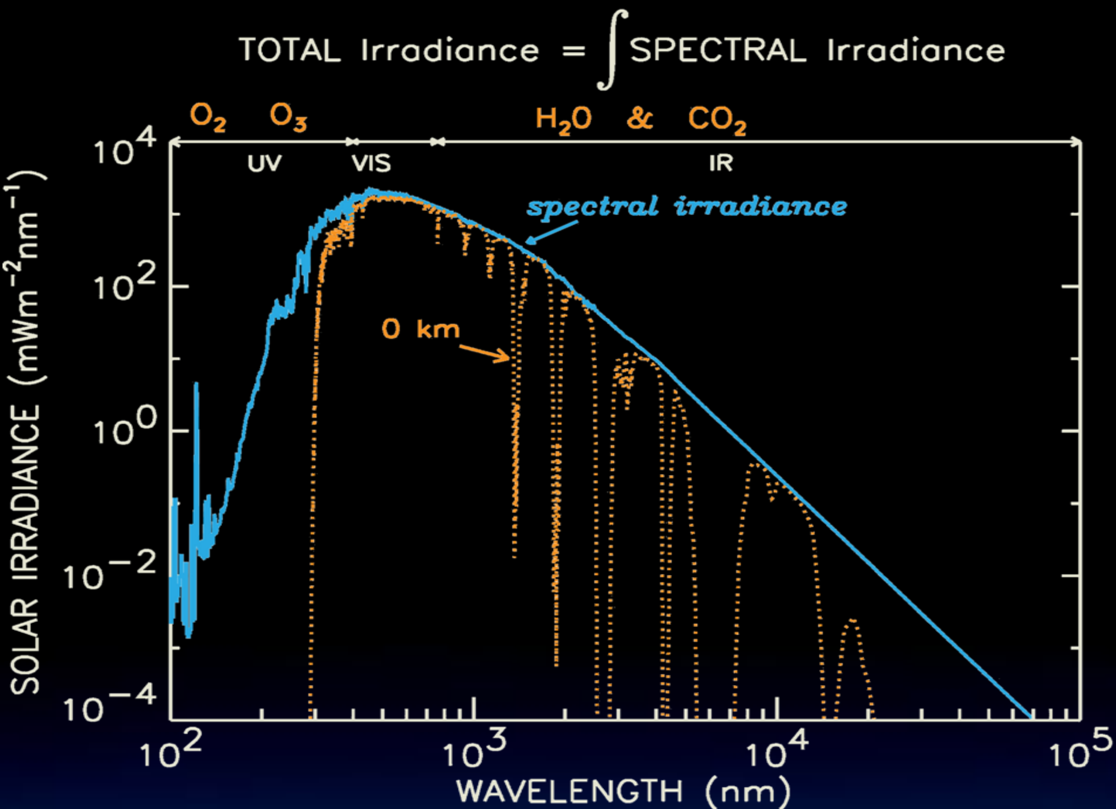
***… end-to-end calibration with NIST cryogenic radiometer***

***NPOESS/TSIS: 2013 ?→***

***... operational solar monitoring***

# Solar Spectral Irradiance:

***separating photon fluxes into wavelength bands***




**wavelengths < 120 nm**

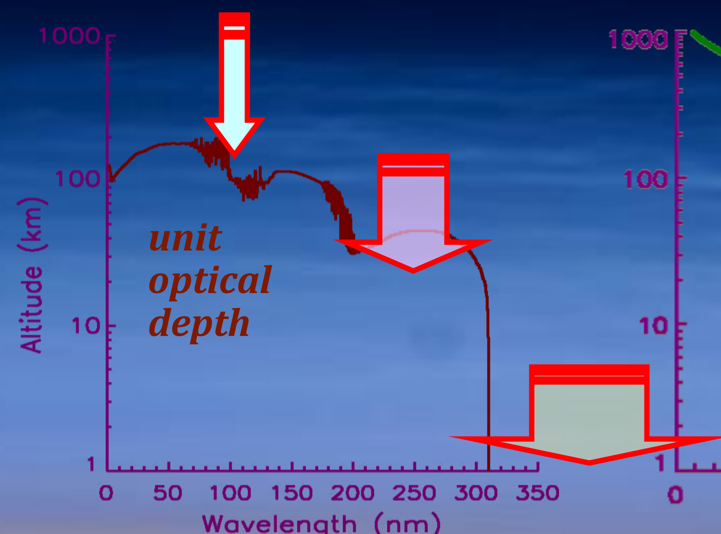
***0.003±0.001 Wm$^{-2}$***

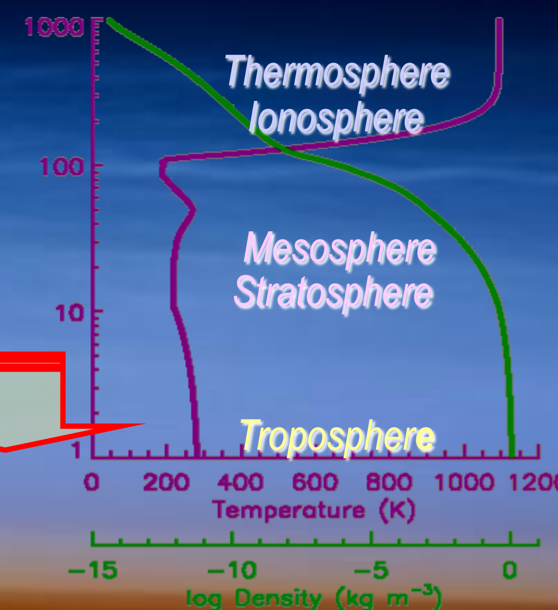
wavelengths 120-300 nm

*14.9±0.1 Wm$^{-2}$*

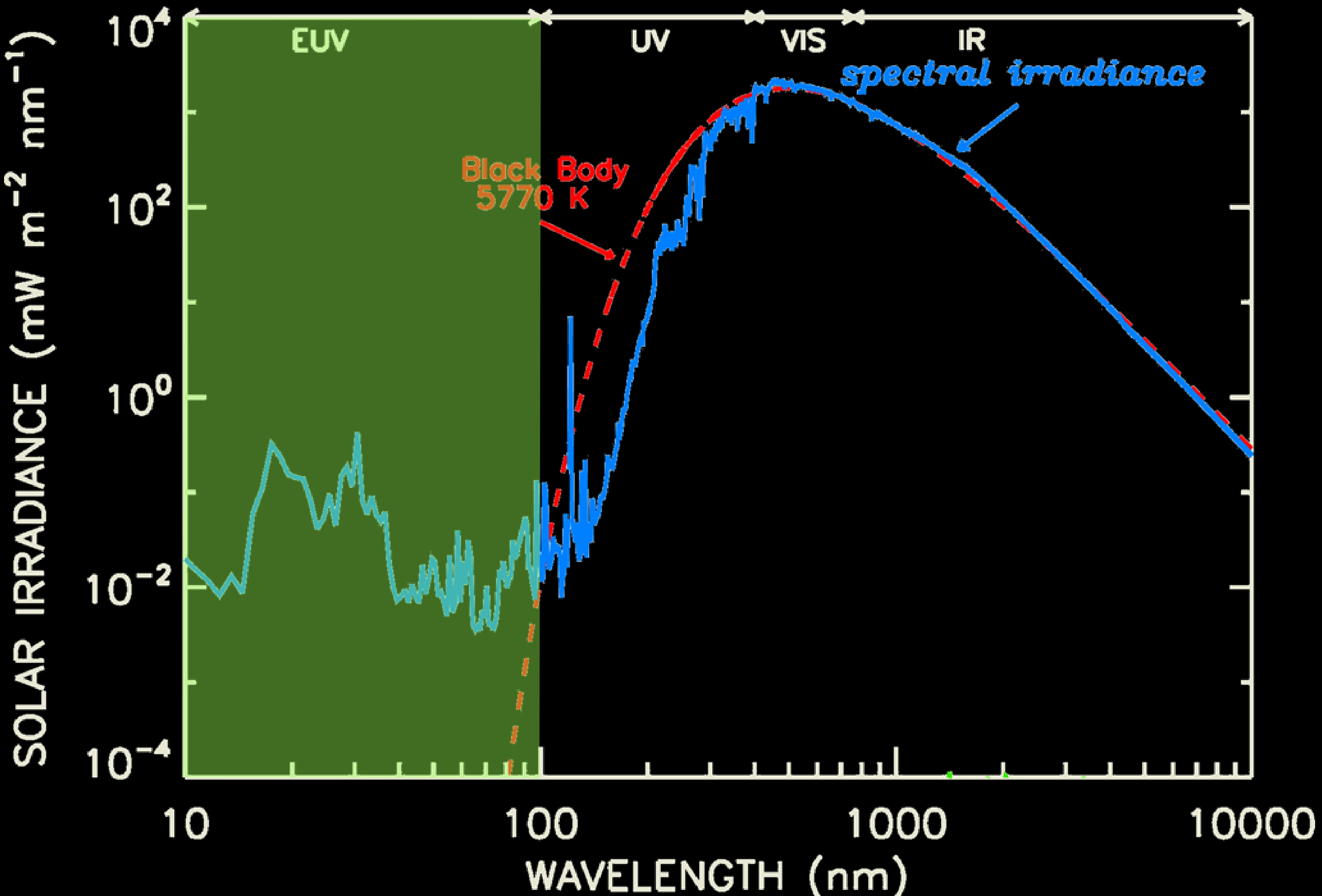
**wavelengths > 300 nm**

***1350.5 ± 0.5 Wm$^{-2}$***

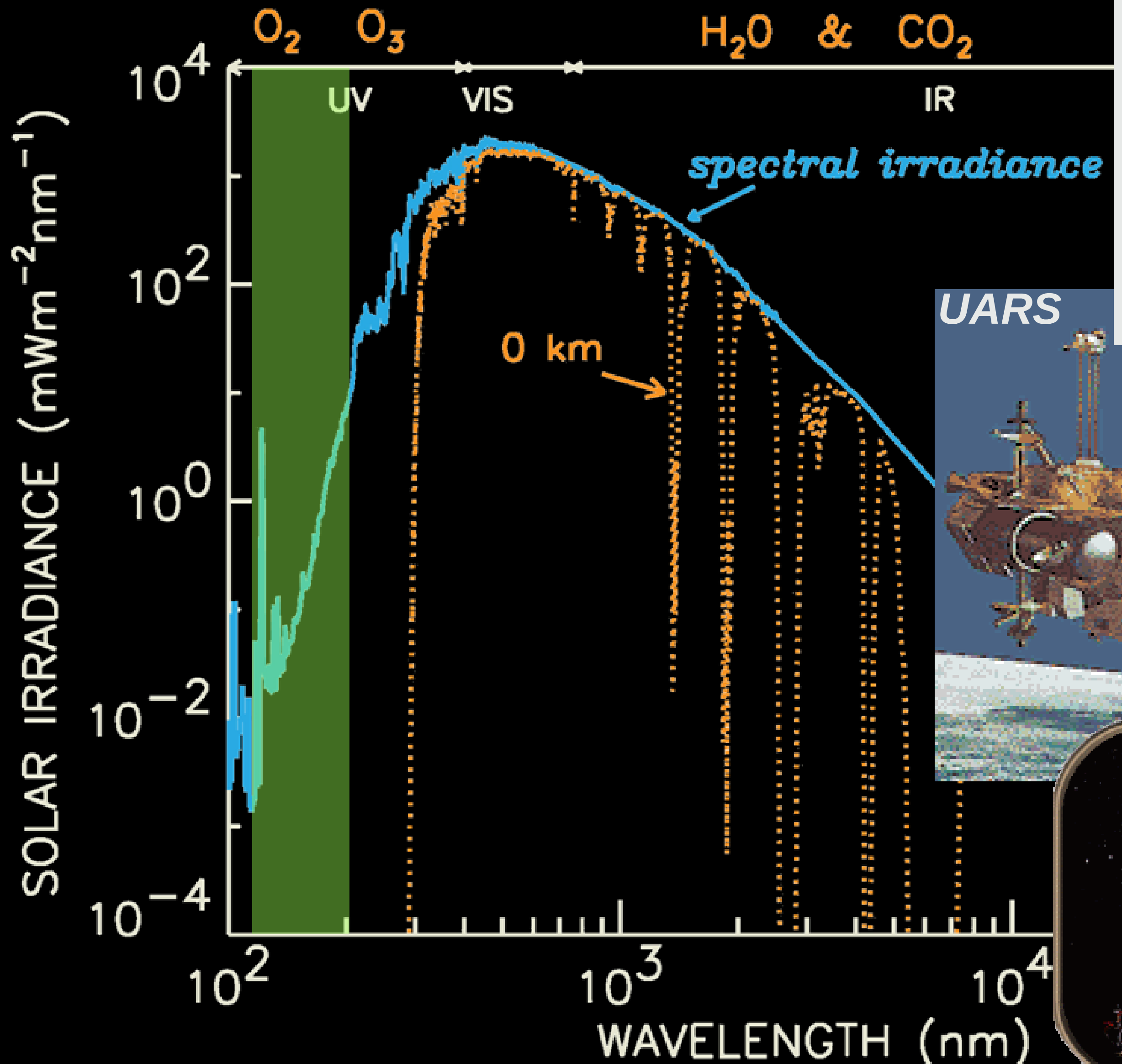


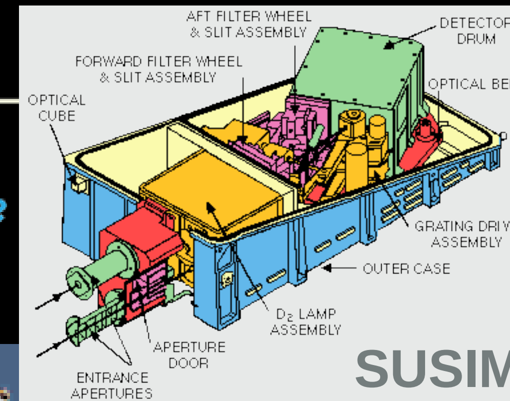



# Solar Spectral Irradiance Observations: Extreme Ultraviolet (0-100 nm)



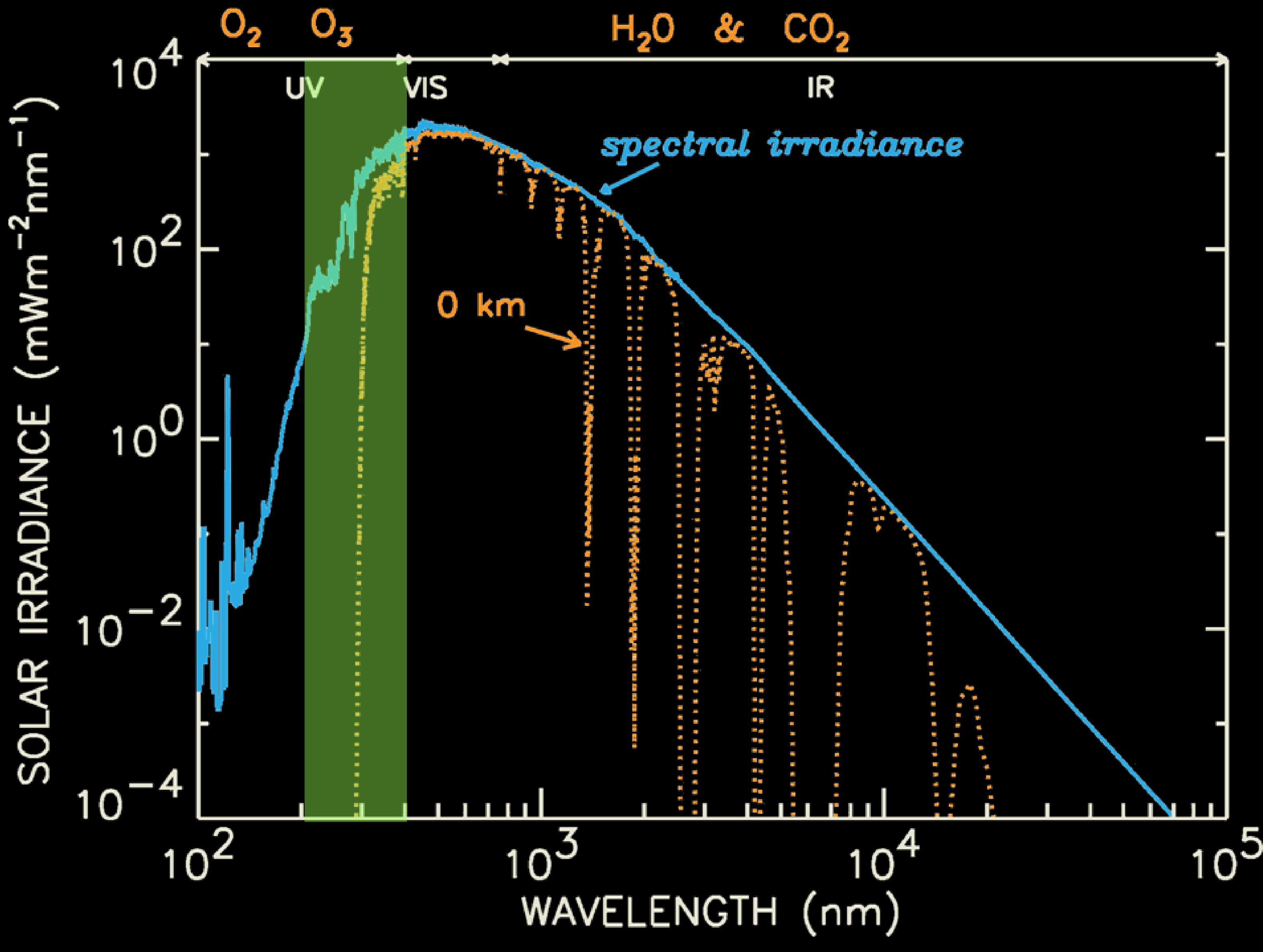
# Solar Spectral Irradiance Observations: Far Ultraviolet (120-200 nm)



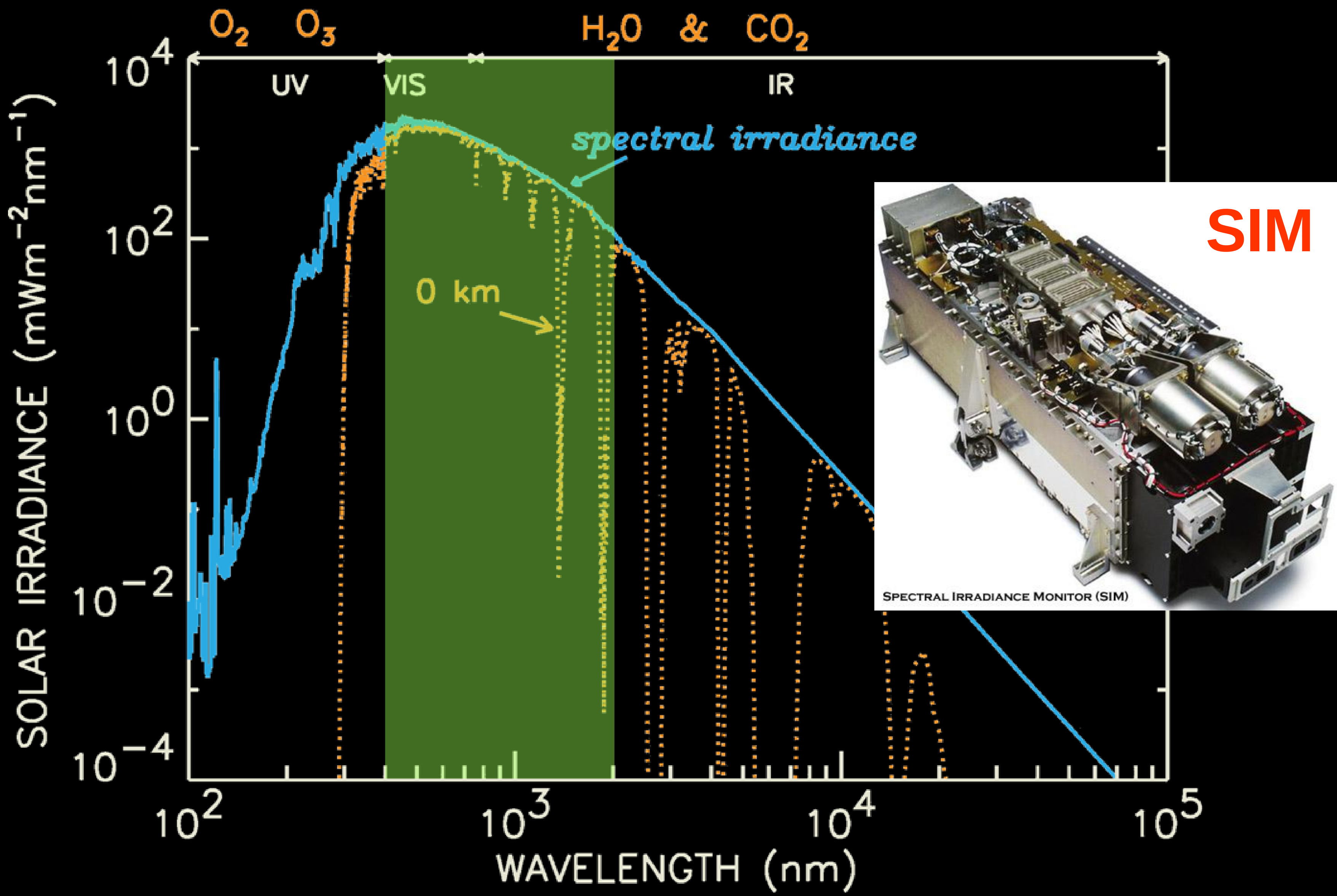





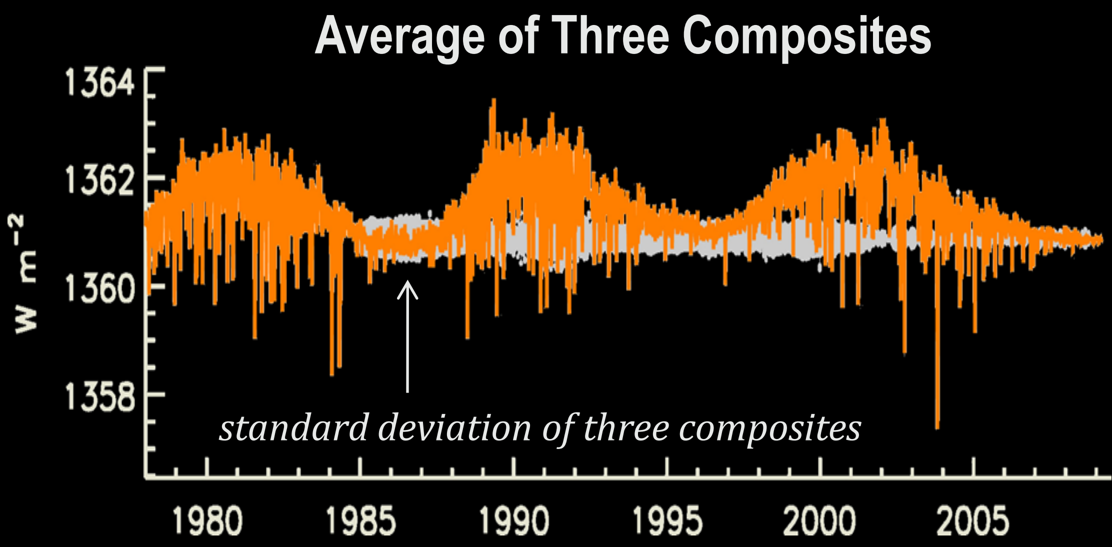
# Solar Spectral Irradiance Observations: Middle and Near UV (200-400 nm)



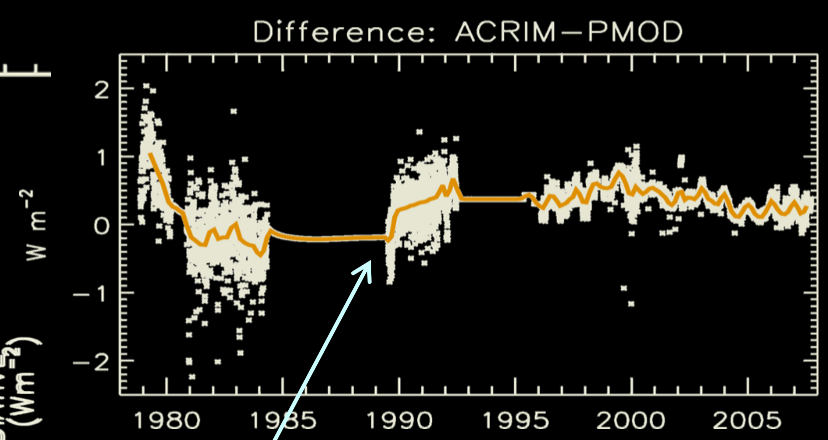
# Solar Spectral Irradiance Observations: Visible and Near IR (400-2000 nm)

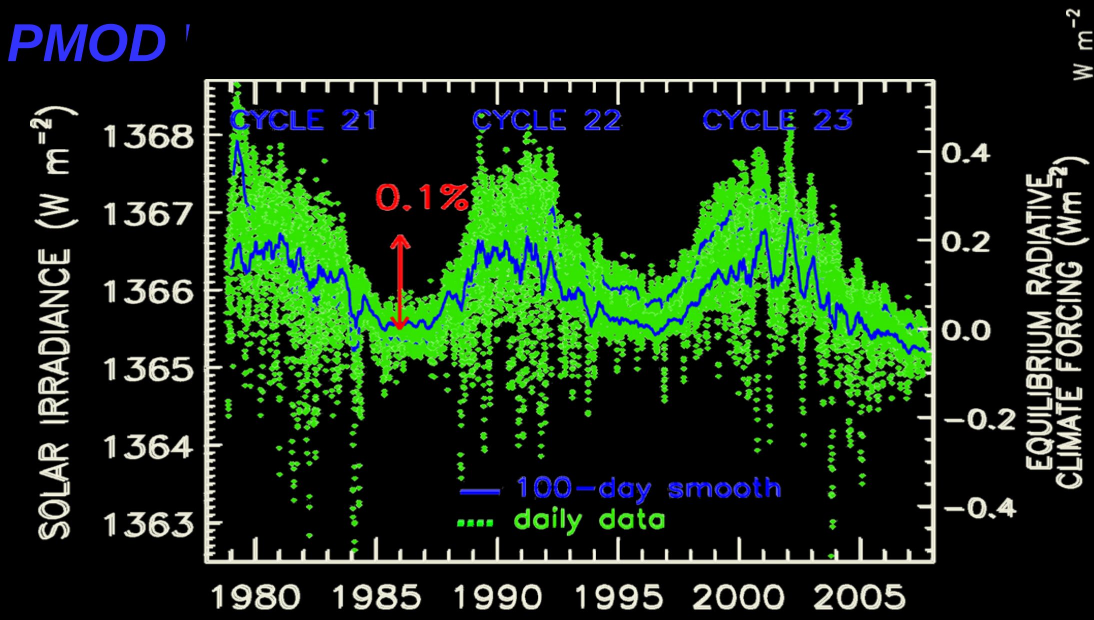


# How Does Solar Irradiance Vary?



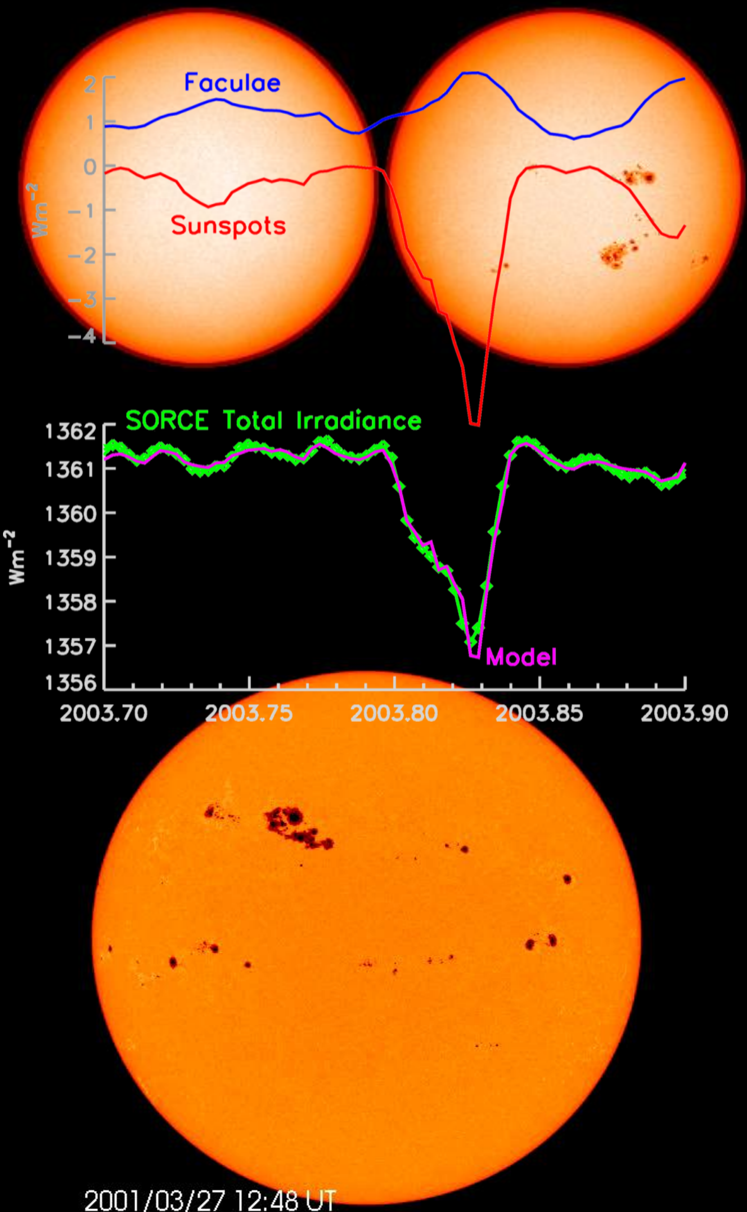

- ✧ 5-min oscillation ~ 0.003%
- ✧ 27-day solar rotation ~ 0.2%
- ✧ 11-year solar cycle ~ 0.1%
- ✧ longer-term variations not yet detectable – *……do they occur?*

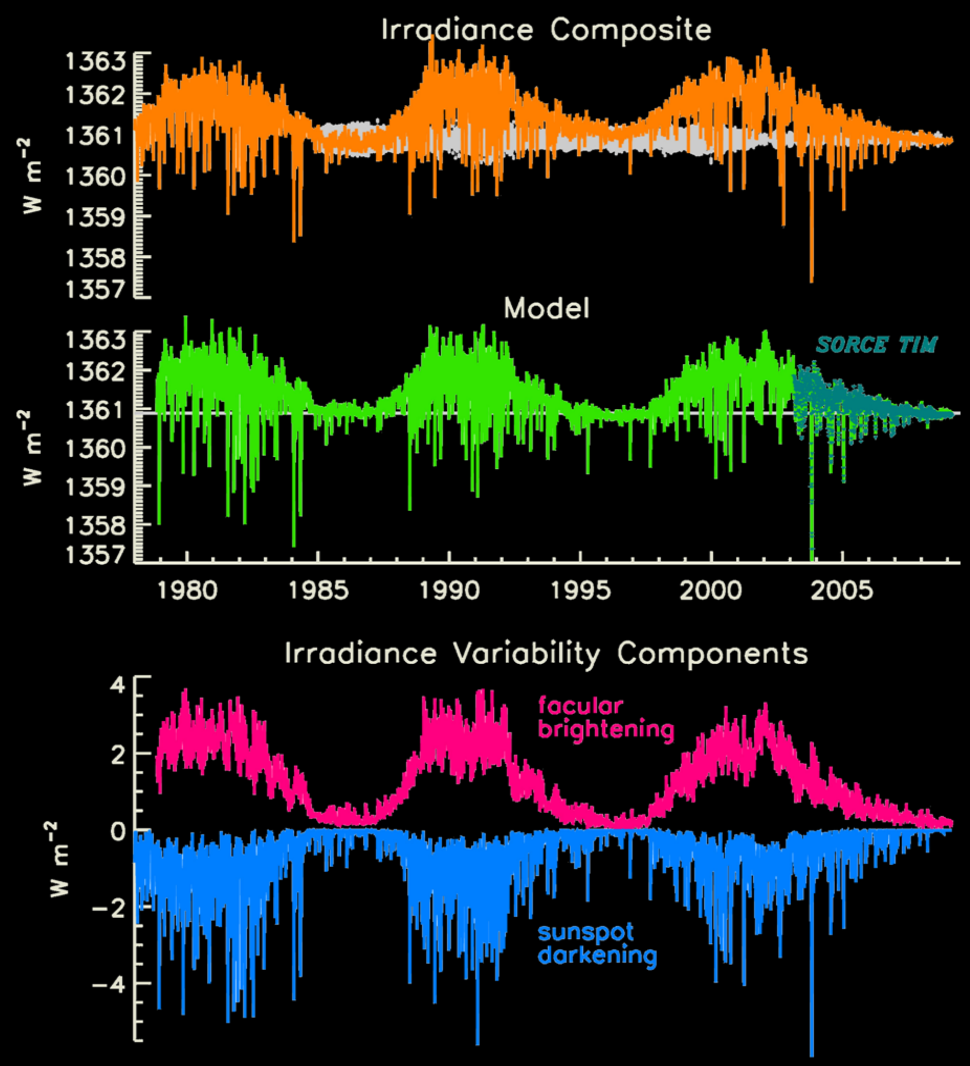


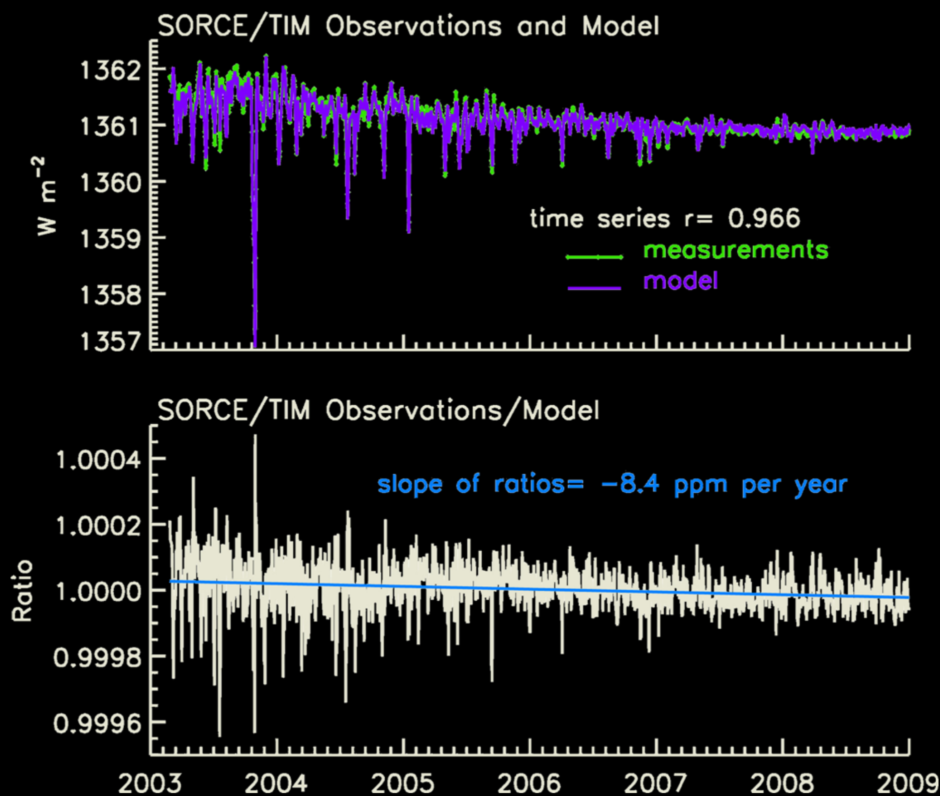

*- upward trend in ACRIM composite occurs primarily from an increase in 1989-1992*
*- attributable to ERB instrument sensitivity drifts near end of Nimbus 7 mission*

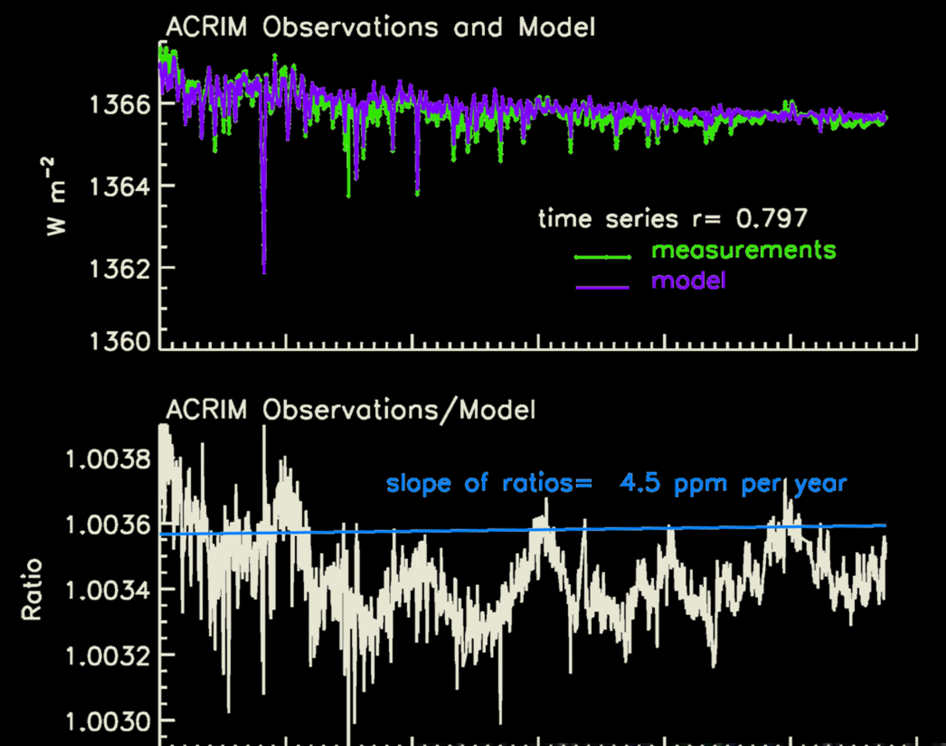
# Why Does Solar Irradiance Vary?

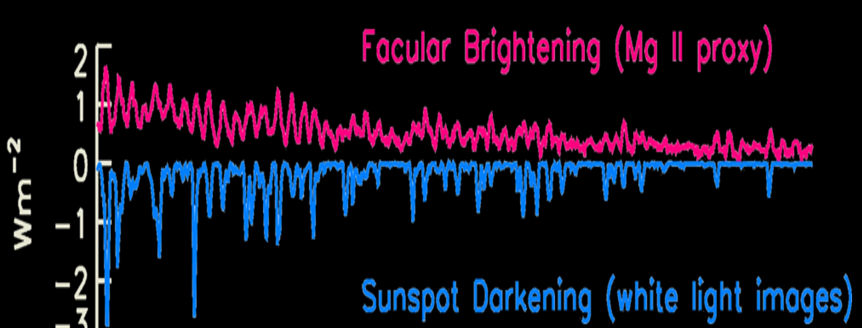


# TSI Observations vs. Model



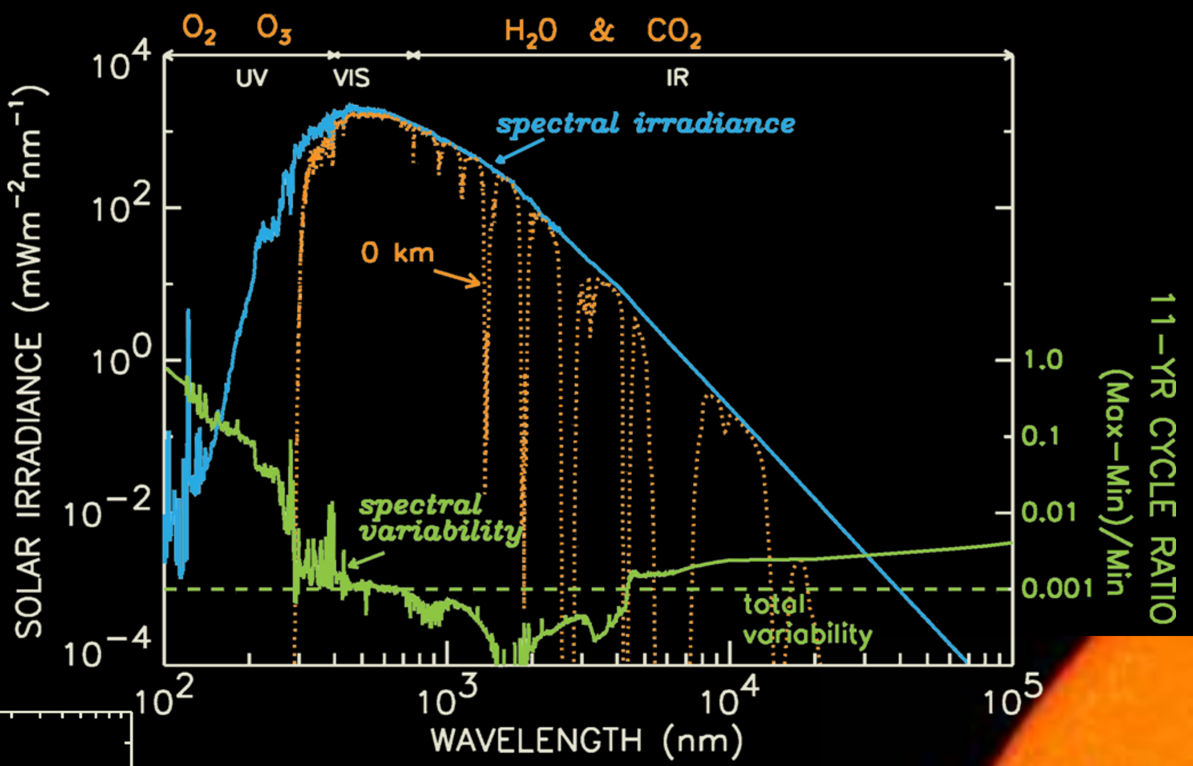



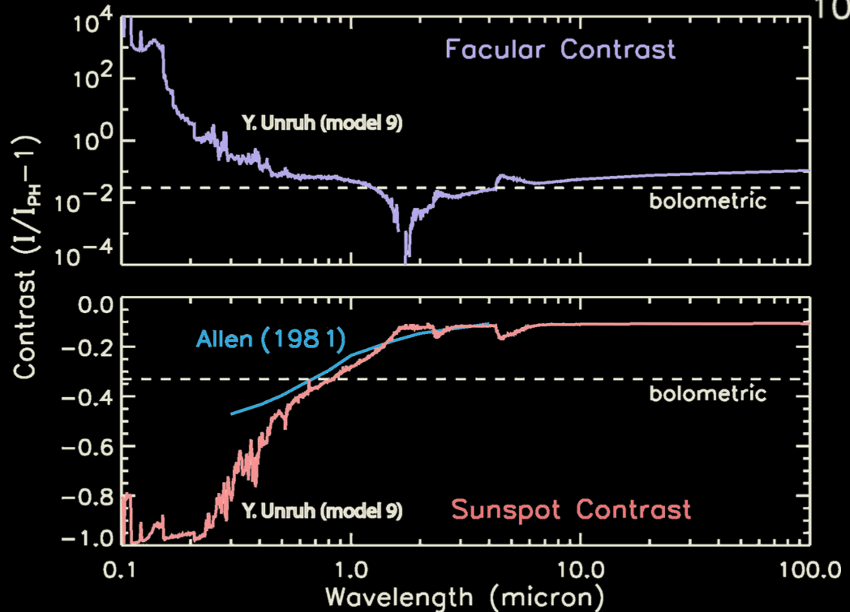


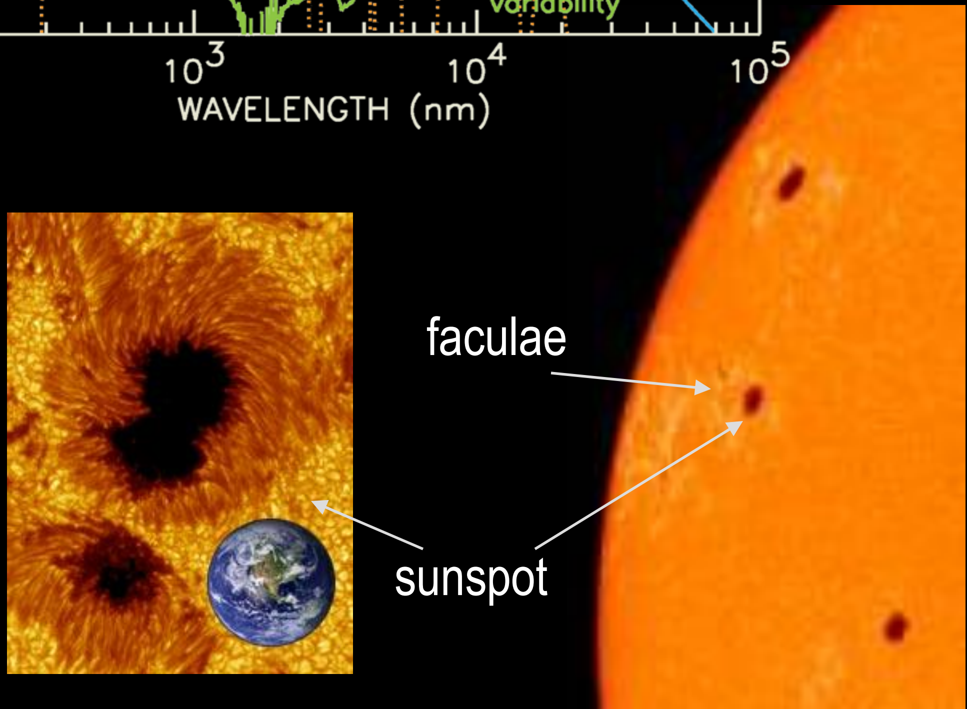
# How Does Spectral Irradiance Vary?
# (and Why)

*sources of solar irradiance variability are wavelength-dependent…*

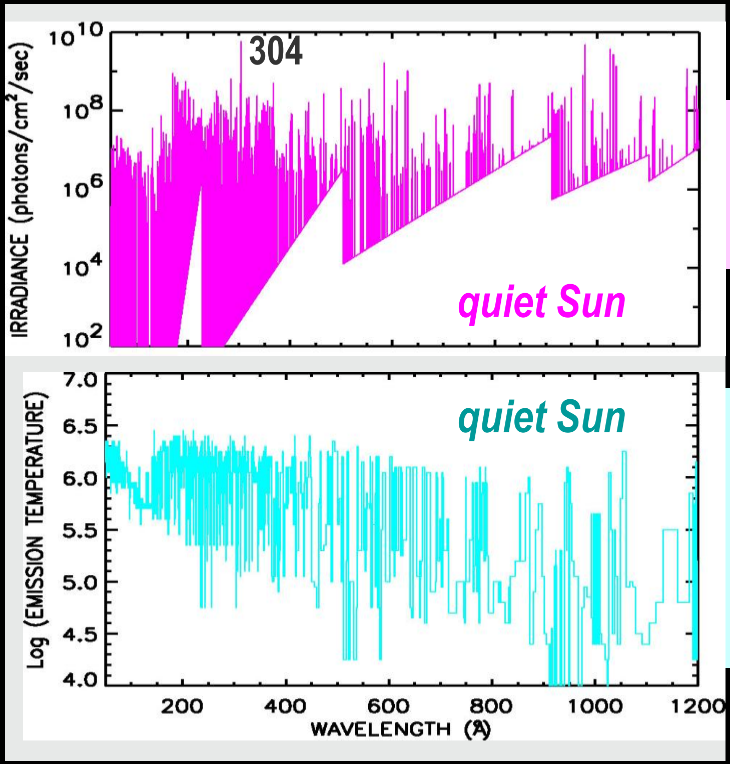
*THUS, spectral irradiance variations depend on wavelength*



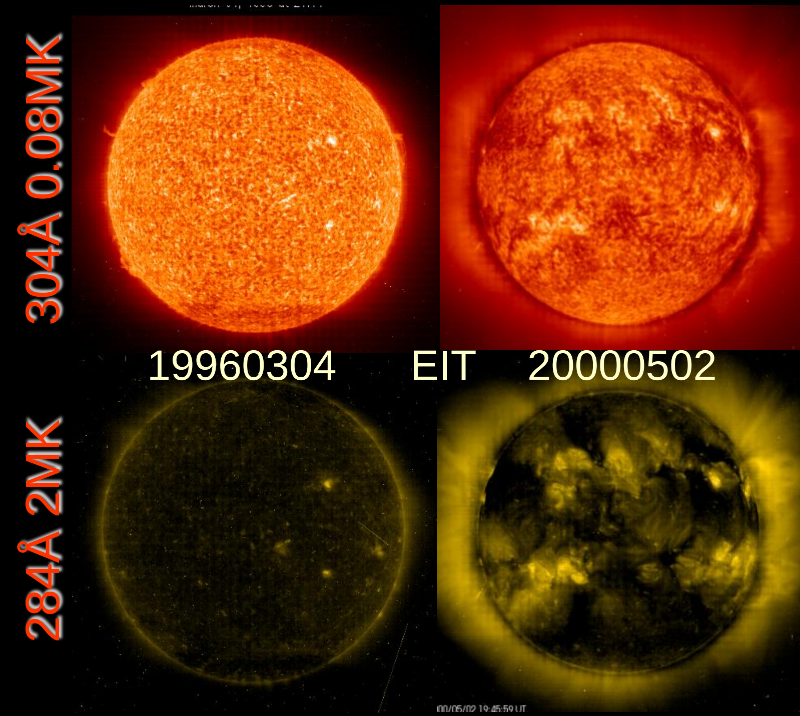



# Chromospheric and Coronal EUV Sources



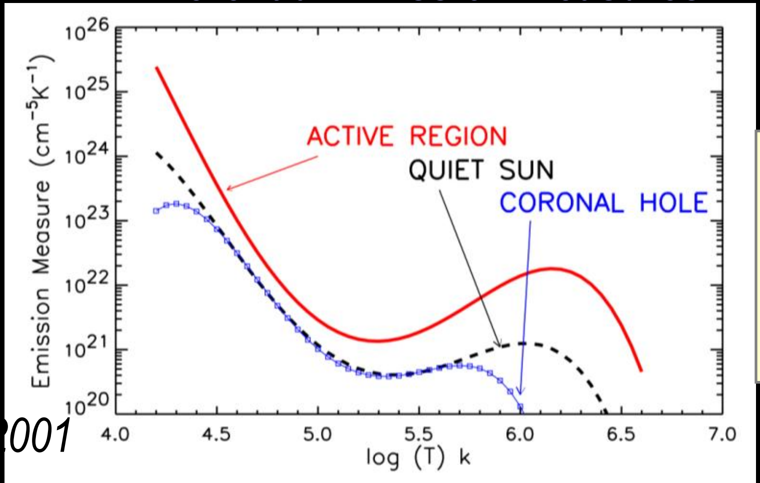

*EUV spectrum:*
*>1500 lines*
*5 continua*

*emission line temperatures vary over 2 orders of magnitude*




## Differential Emission Measures

*different plasma temperatures and densities*




2001

*For an optically thin emission line:*

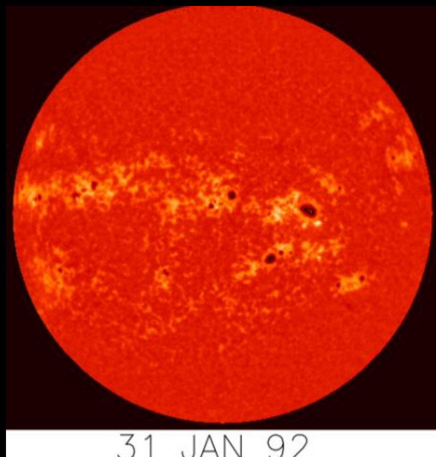
**radiance: $I(\lambda) = \int G(T) EM(T) dT$**

**T - electron temperature**

**G(T) - emissivity of atomic transition ÷ $n_e^2$**

**EM(T)= $n_e^2$ ds/dT - differential emission measure**

# Quantifying the Bright Plage/Facular Signal

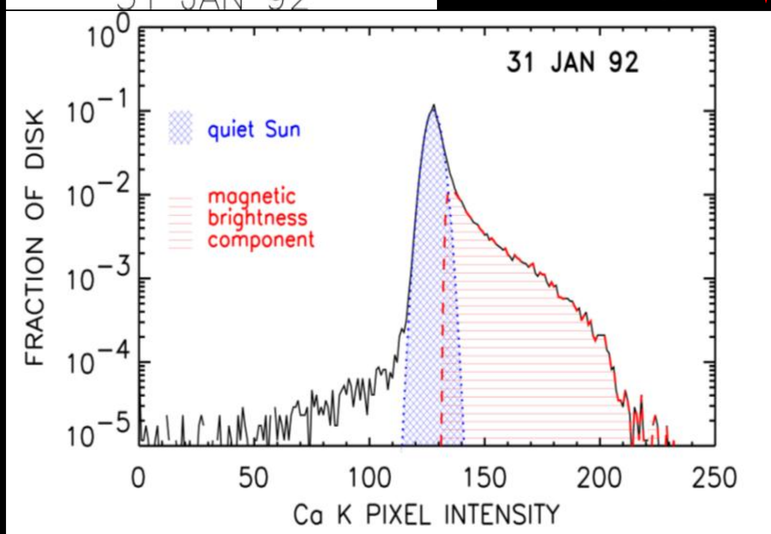


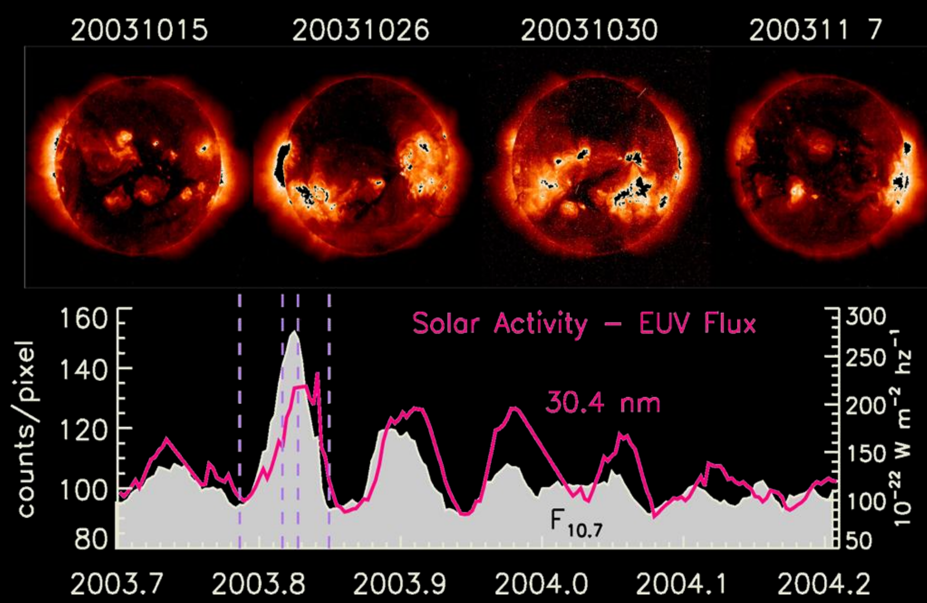

***Image***

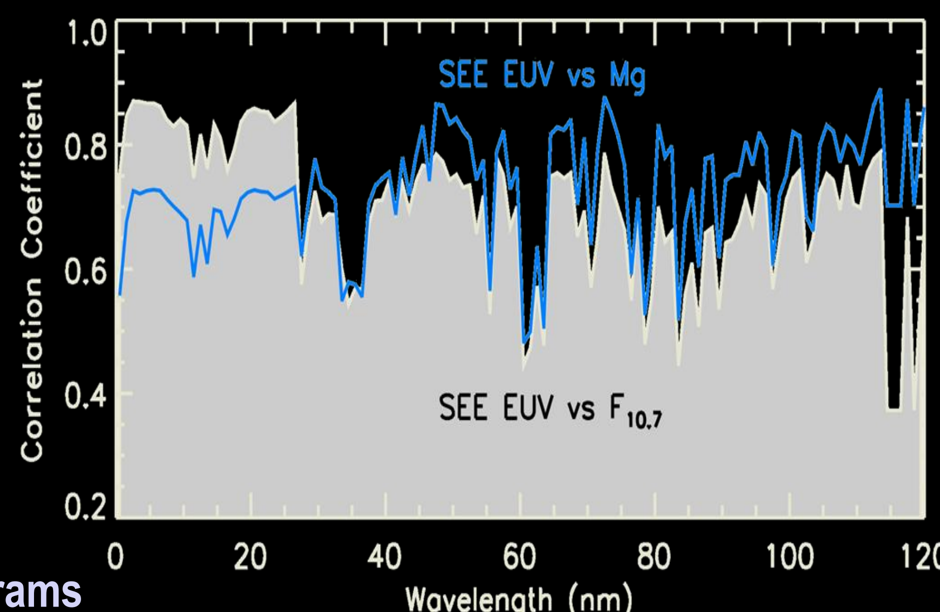
***Histogram***

***Active Components***

***Irradiance Variability***



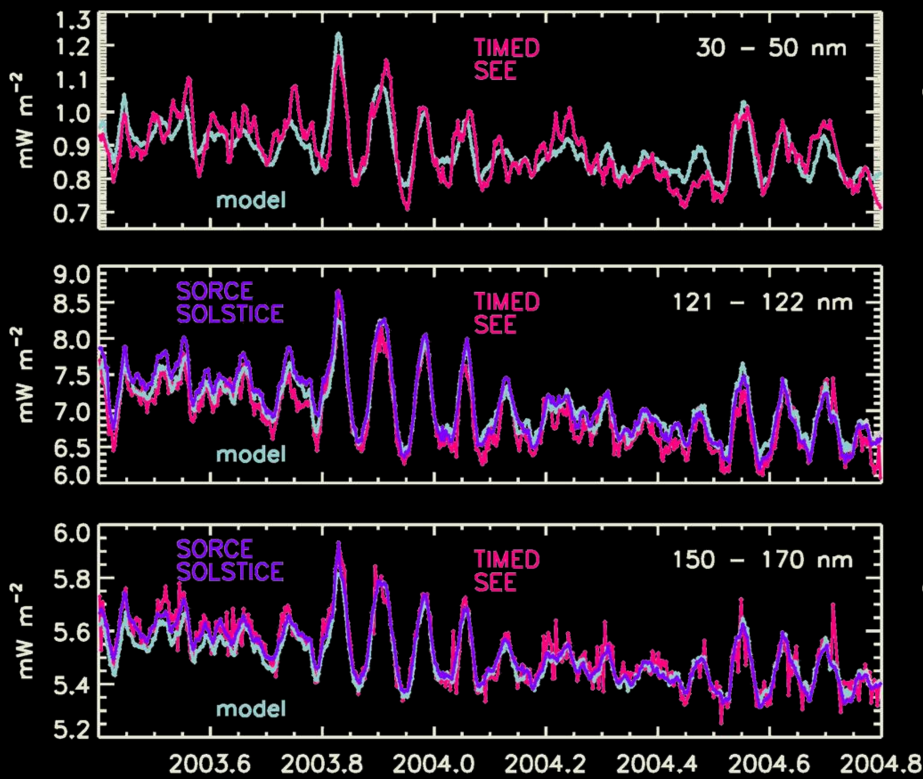



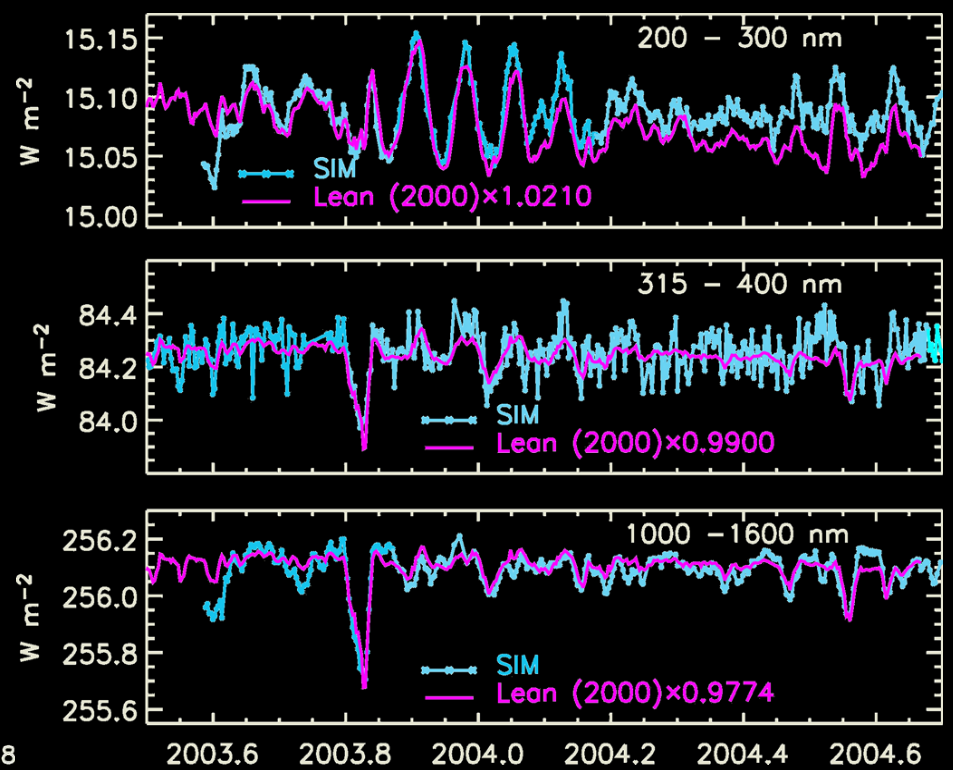



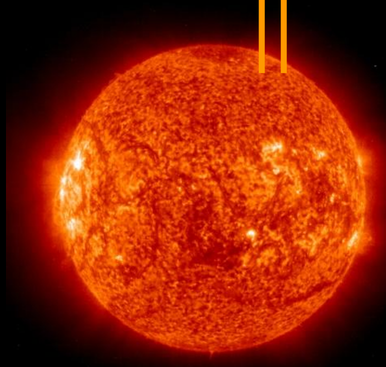

- plausible facular contrast
- plausible center-to-limb contrast variation
- center-to-limb variation of radiance
- area of enhanced emission from Ca K histograms

*Lean, Cook, Marquette & Johannesson, Ap. J., 1998*

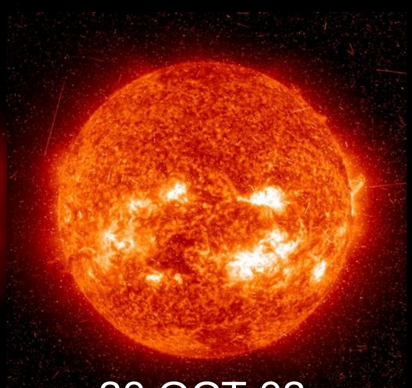
# Spectrum Changes During Solar Rotation



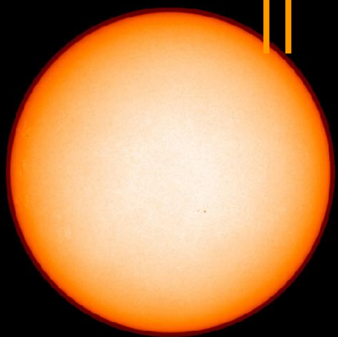



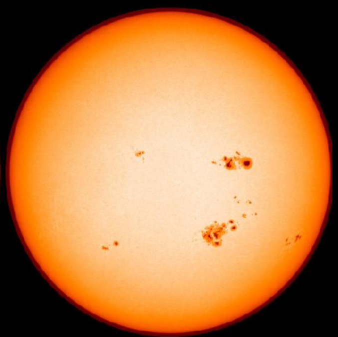
17 OCT 03



30 OCT 03

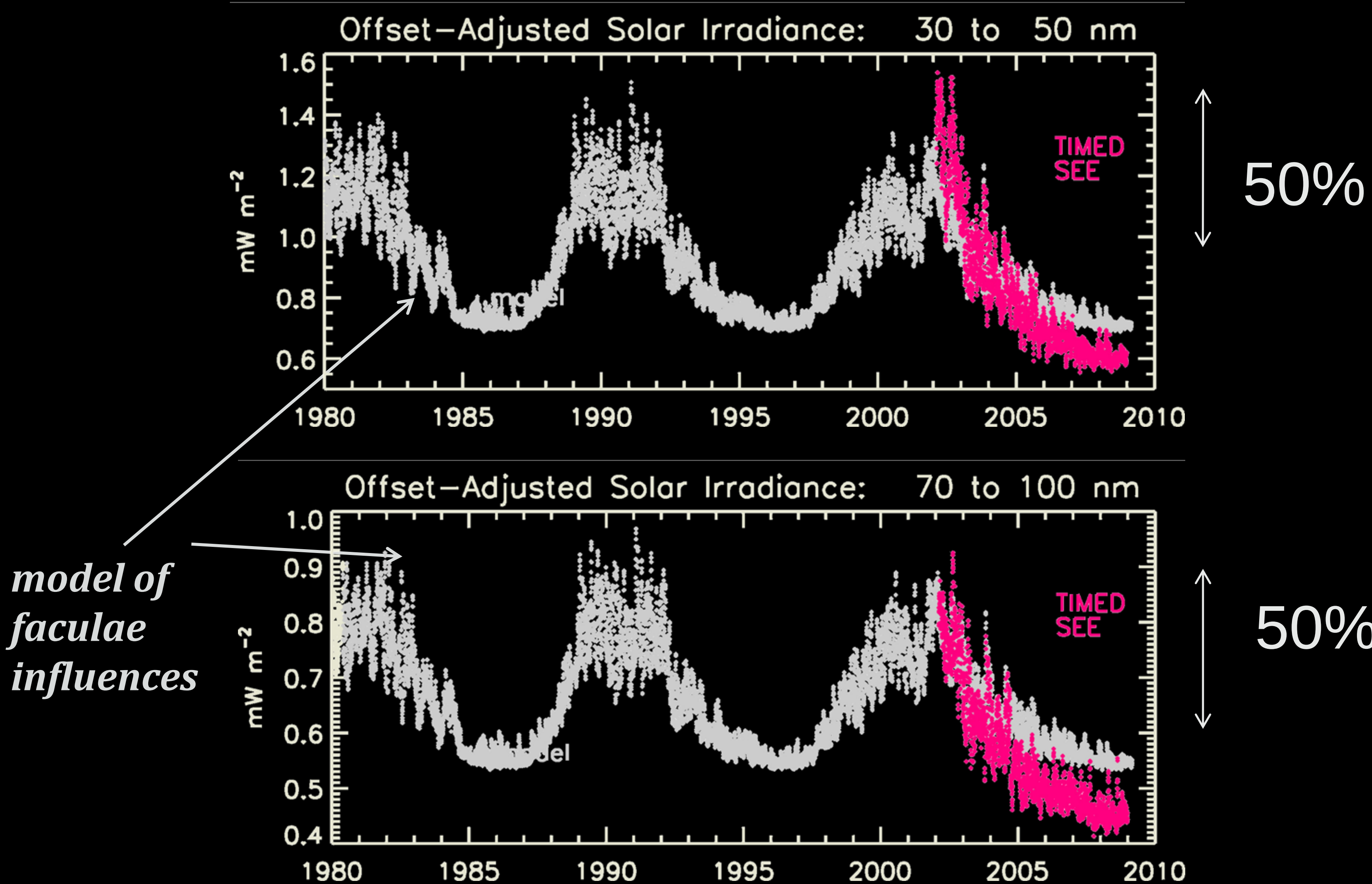


17 OCT 03

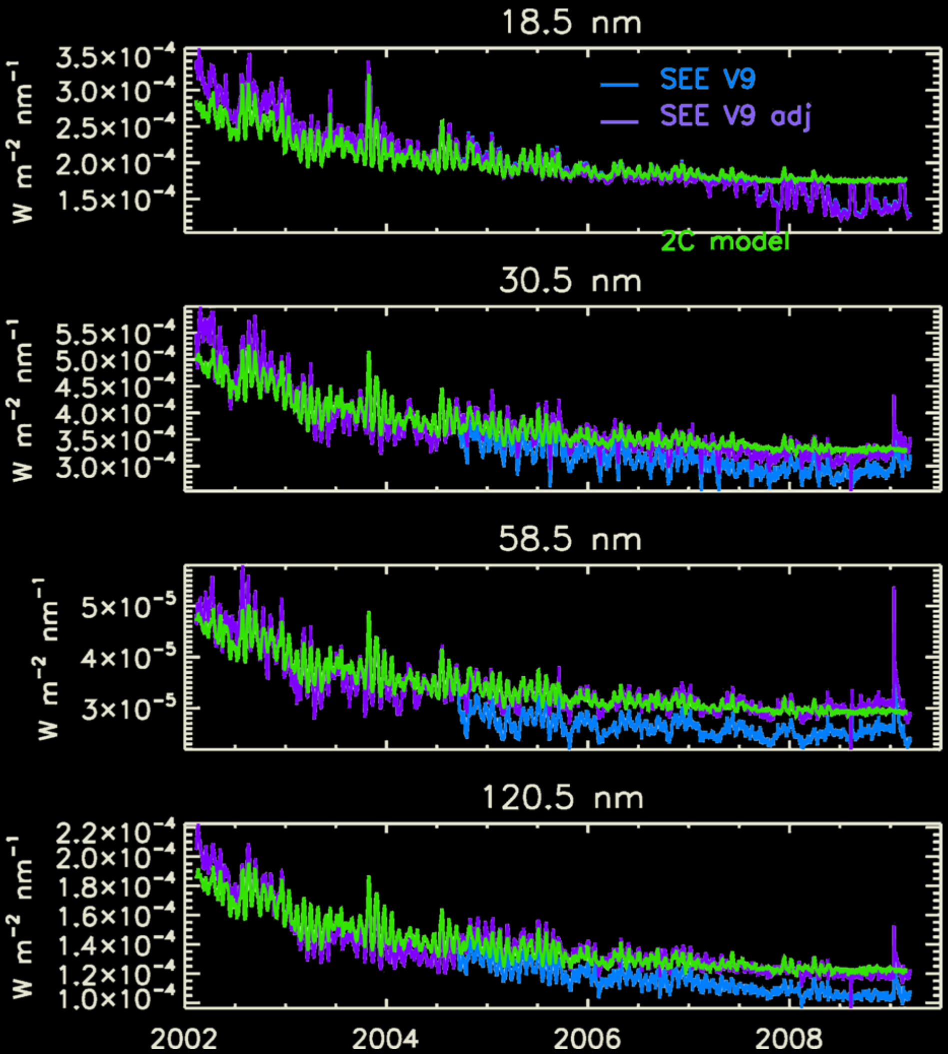


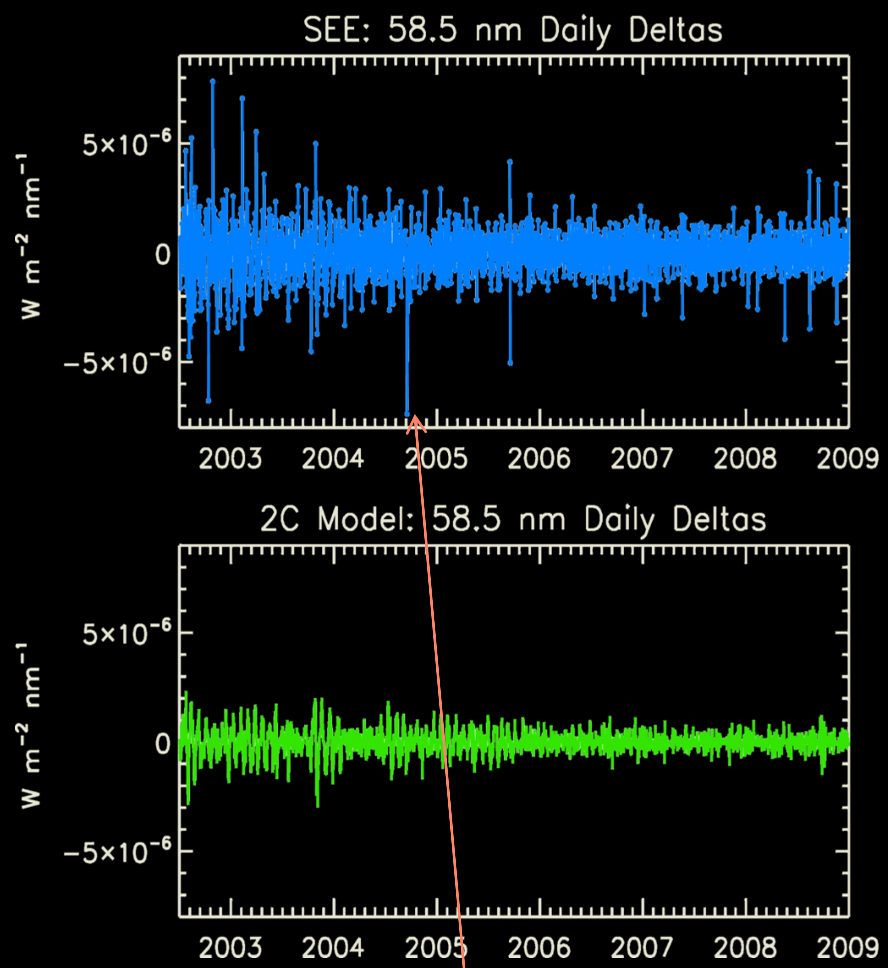
30 OCT 03

# Solar Spectral Irradiance Variations: Extreme Ultraviolet (0-100 nm)



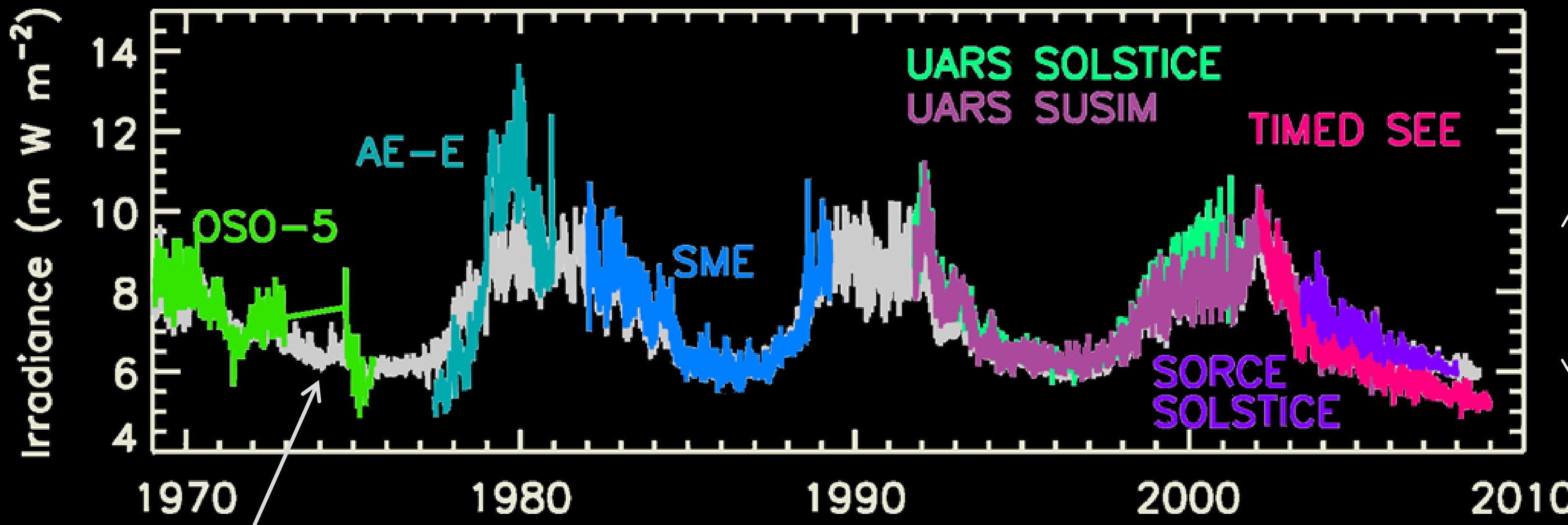
# EUV Observations vs. Model



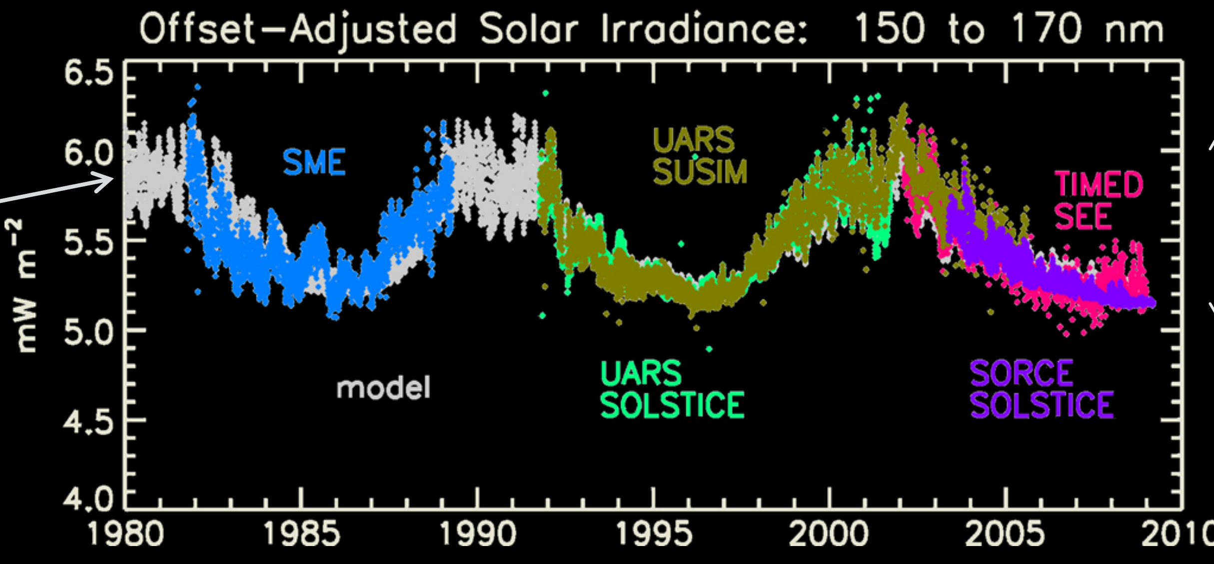




***SEE V10 corrects for instrument sensitivity jump between 16-21 Sept 2004***

# Solar Spectral Irradiance Variations: Far Ultraviolet (120-200 nm)



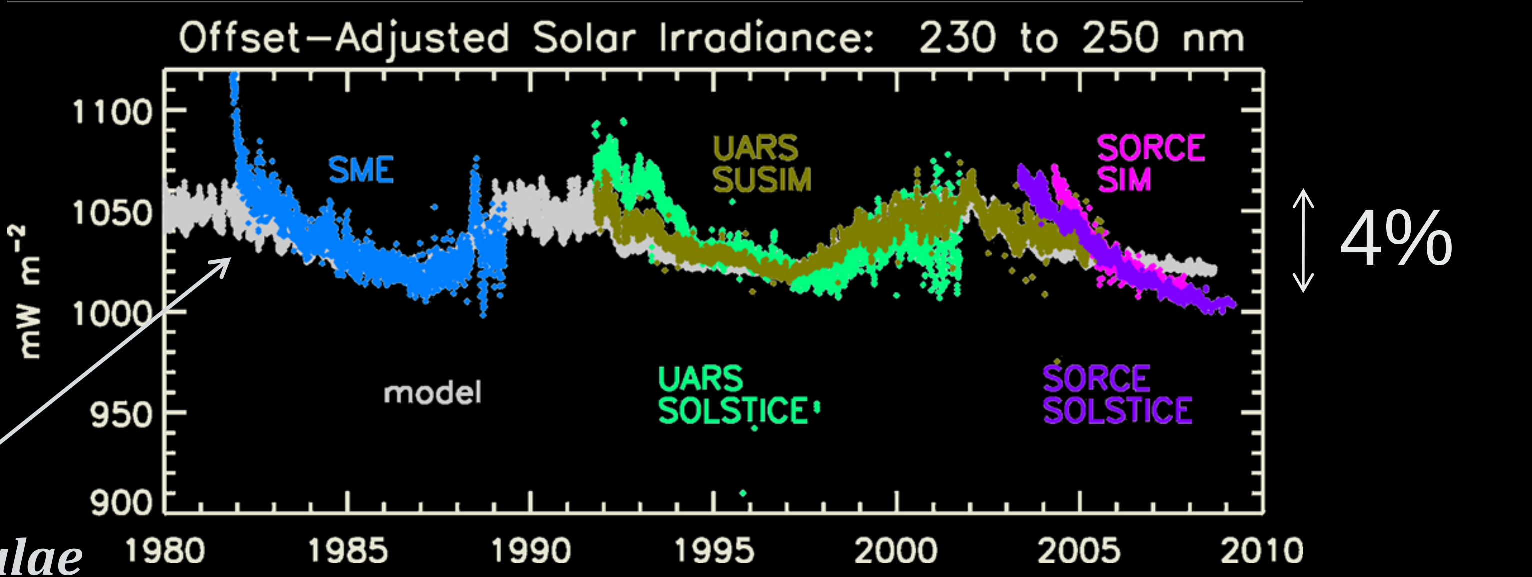

50%



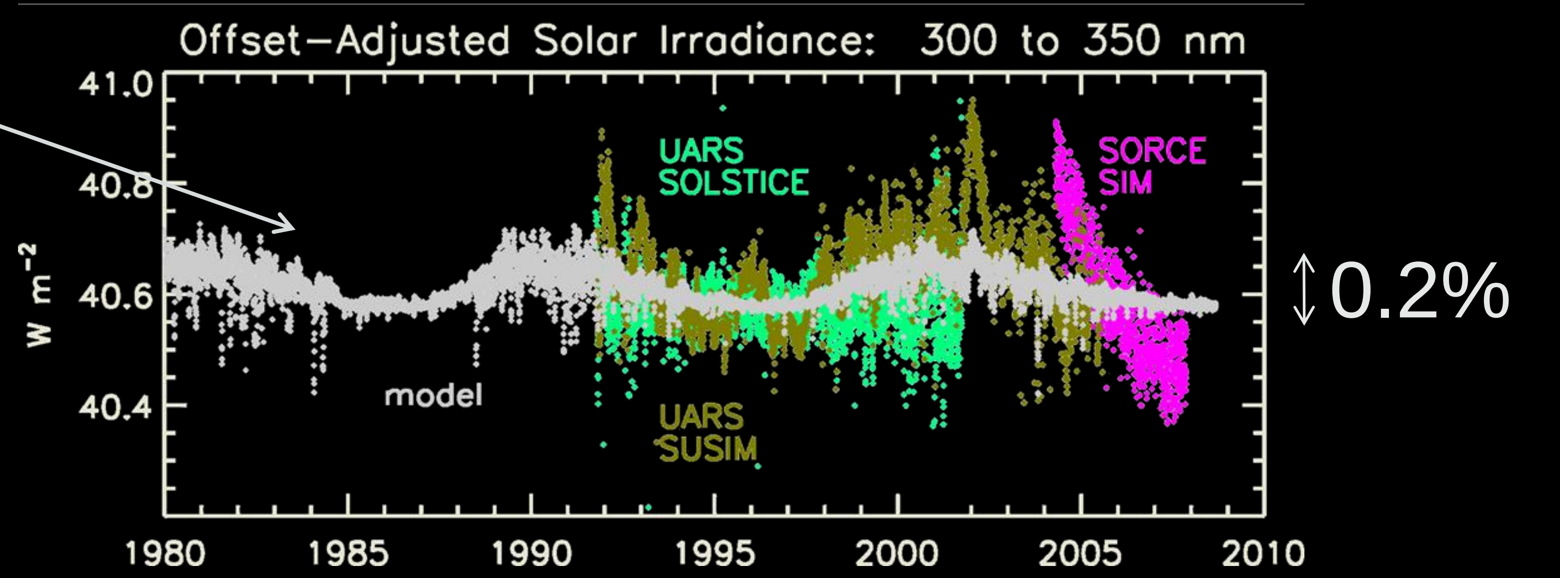

20%

*model of faculae influences*

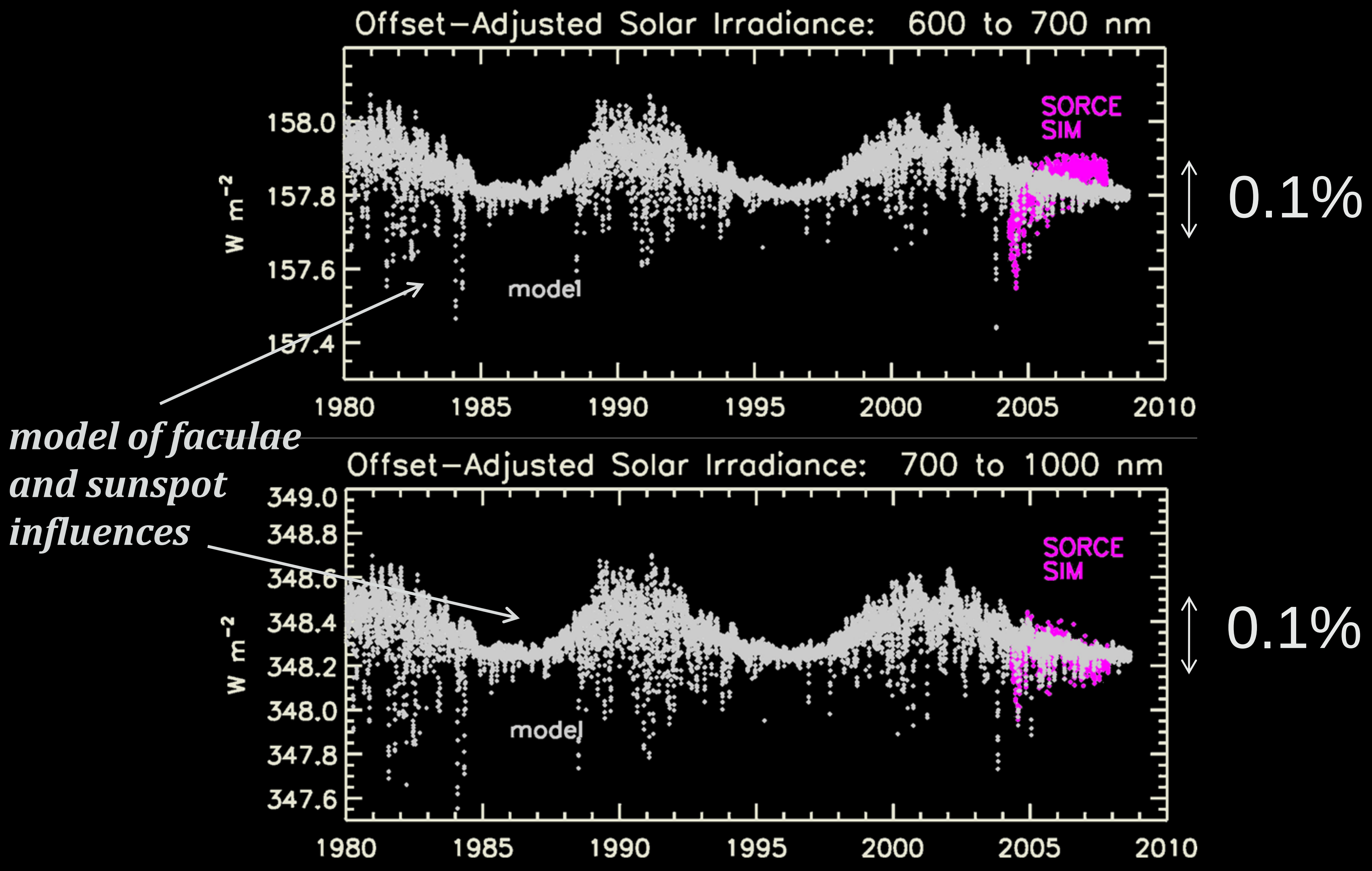
# Solar Spectral Irradiance Variations: Middle and Near Ultraviolet (200-400 nm)




*model of faculae and sunspot influences*

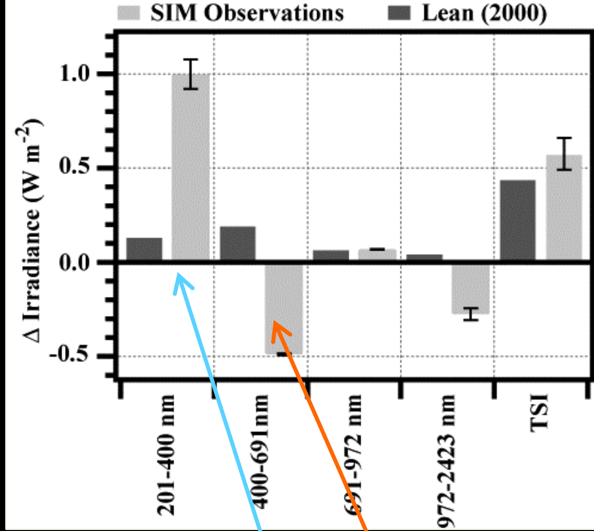


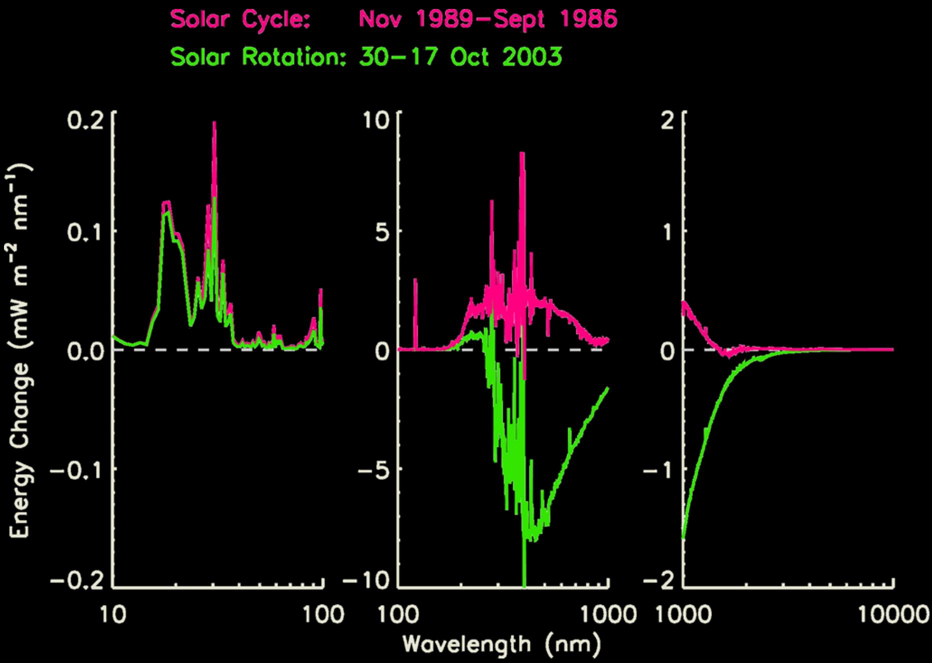
# Solar Spectral Irradiance Variations: Visible and Near IR (400 – 2000 nm)



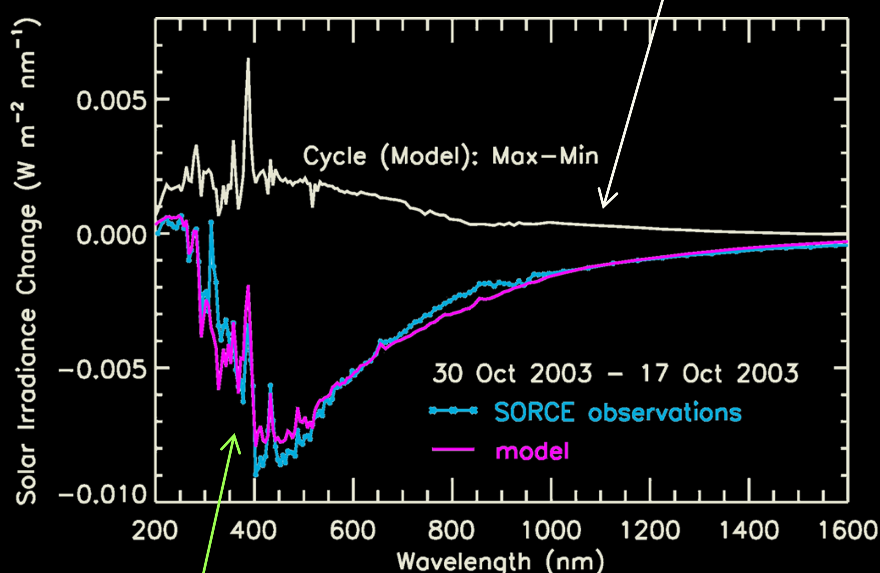
# Solar Spectrum Energy Change: Solar Cycle, Solar Rotation

*Harder et al., GRL, 2009*



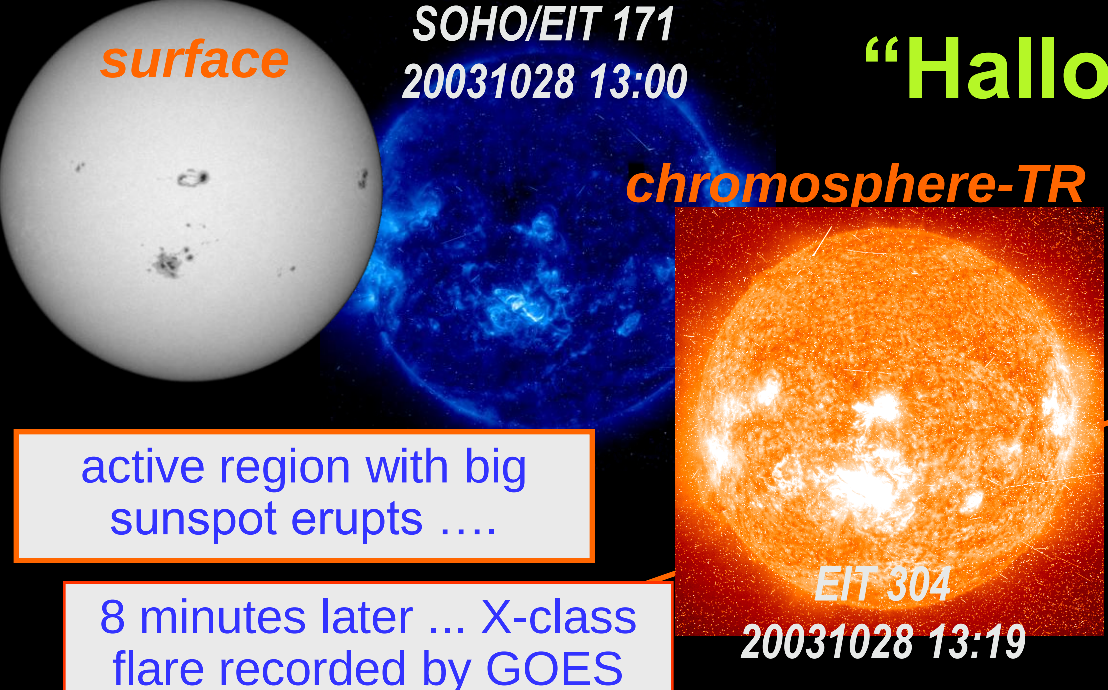




***SIM solar cycle variations are out-of-phase at visible wavelengths and larger at UV wavelengths. compared with model***



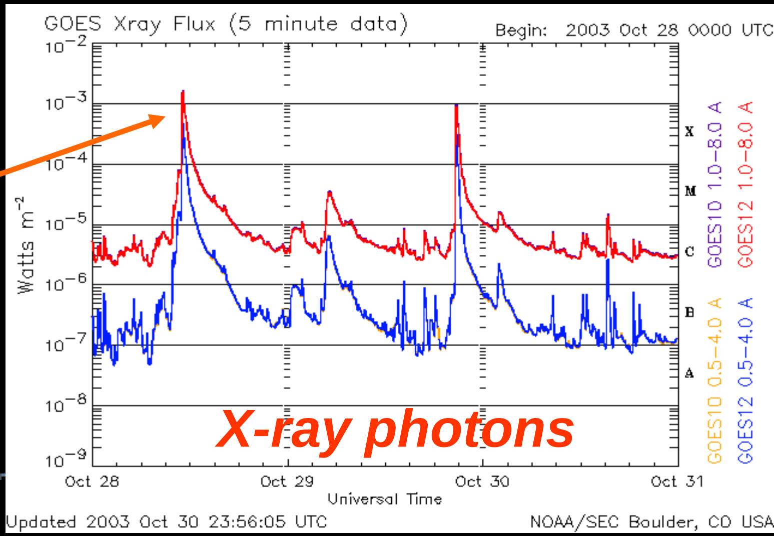

***good agreement at all wavelengths for 27-day rotational modulation***

# "Halloween" Solar Storm
## October 28th, 2003

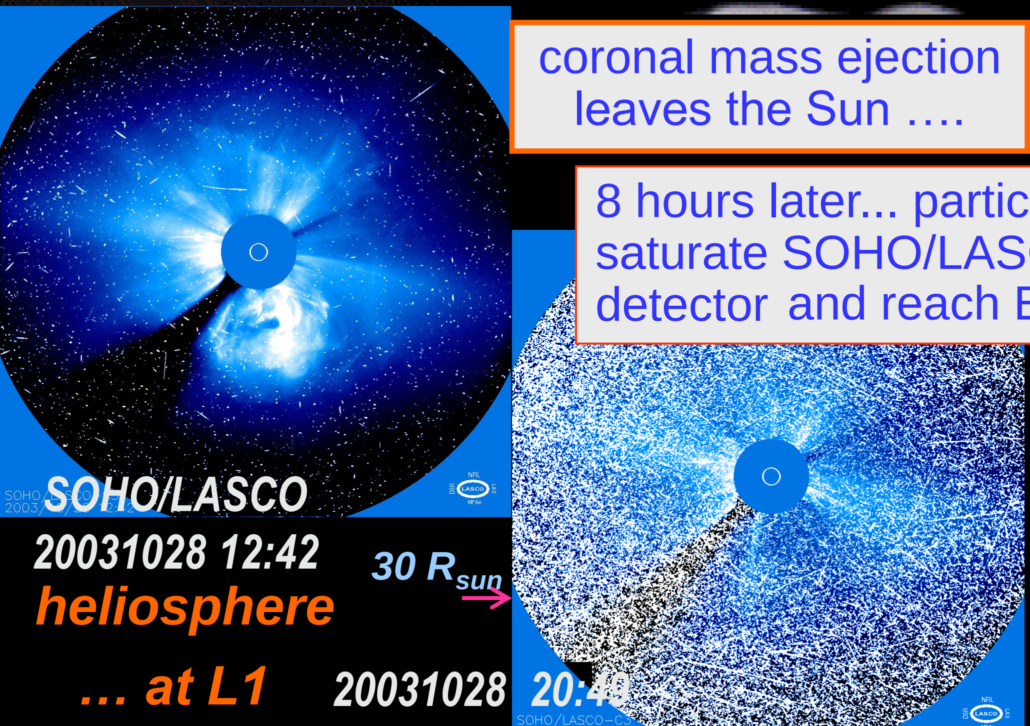



active region with big sunspot erupts ….

8 minutes later ... X-class flare recorded by GOES

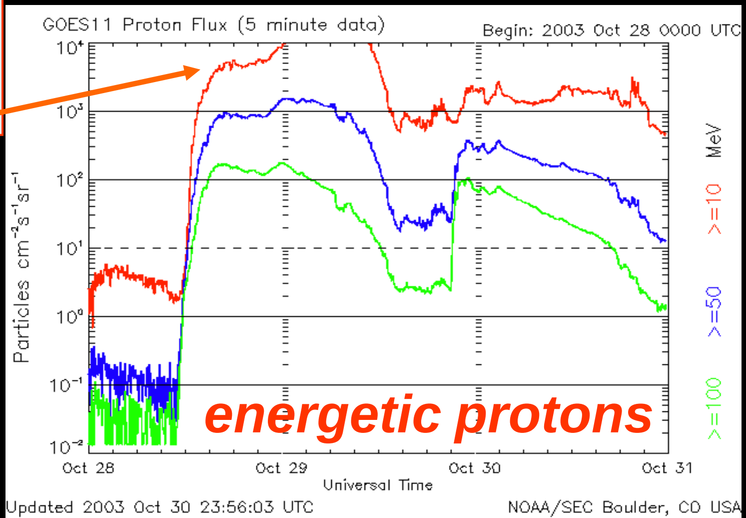



coronal mass ejection leaves the Sun ….

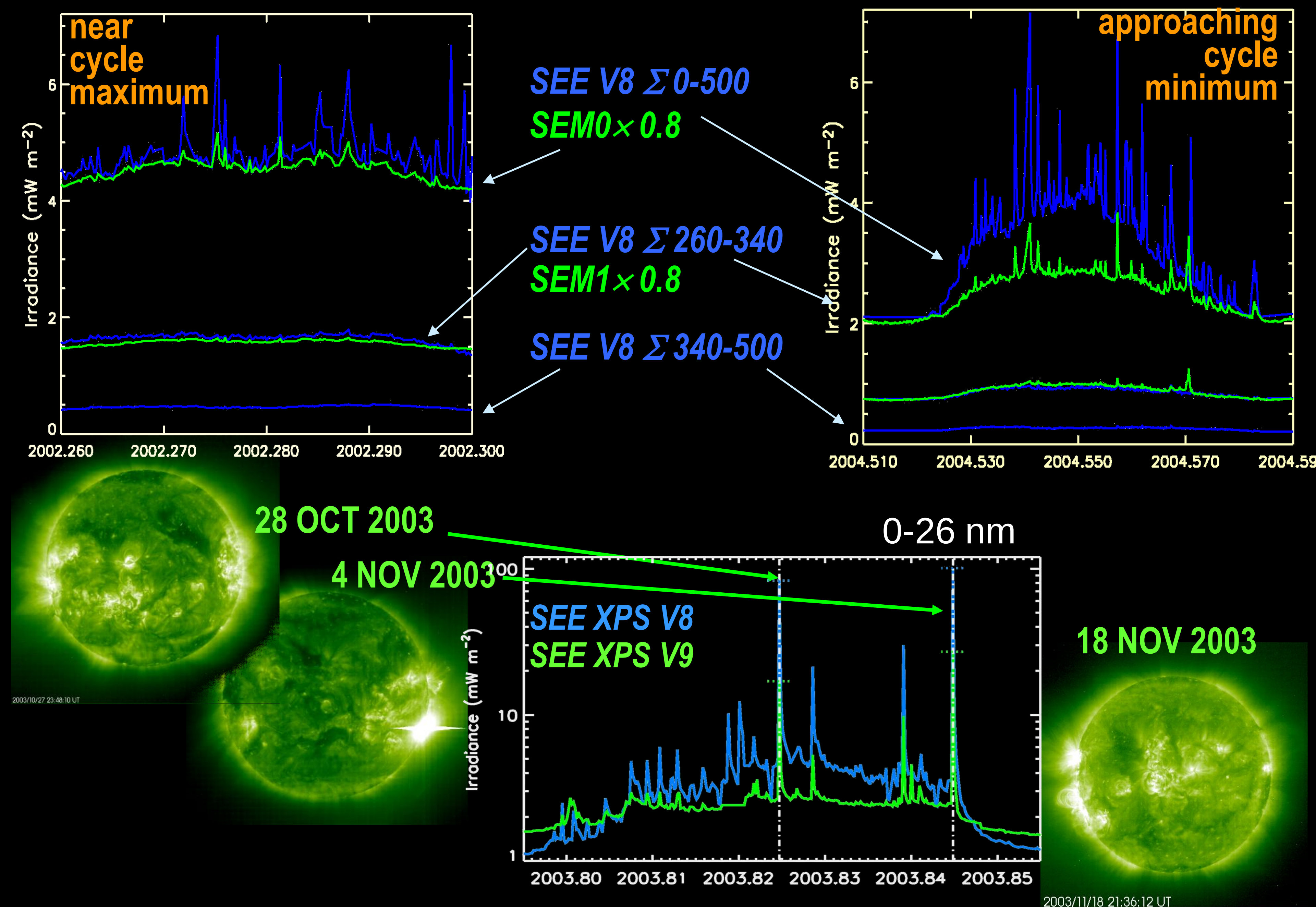



8 hours later... particles saturate SOHO/LASCO detector and reach Earth

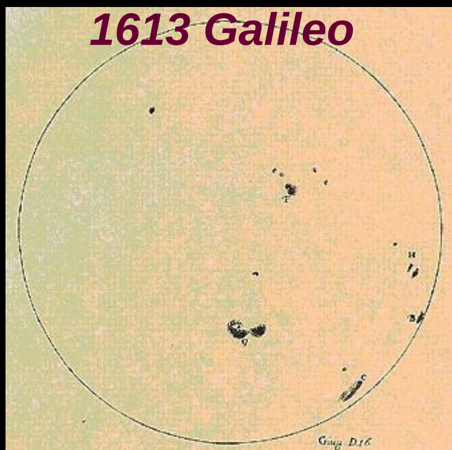
*NOAA National Weather Service*
*http://www.sec.noaa.gov/*

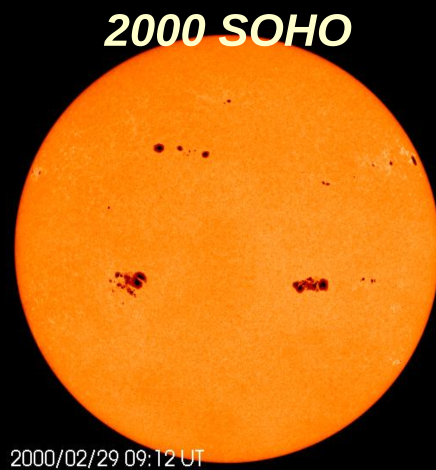


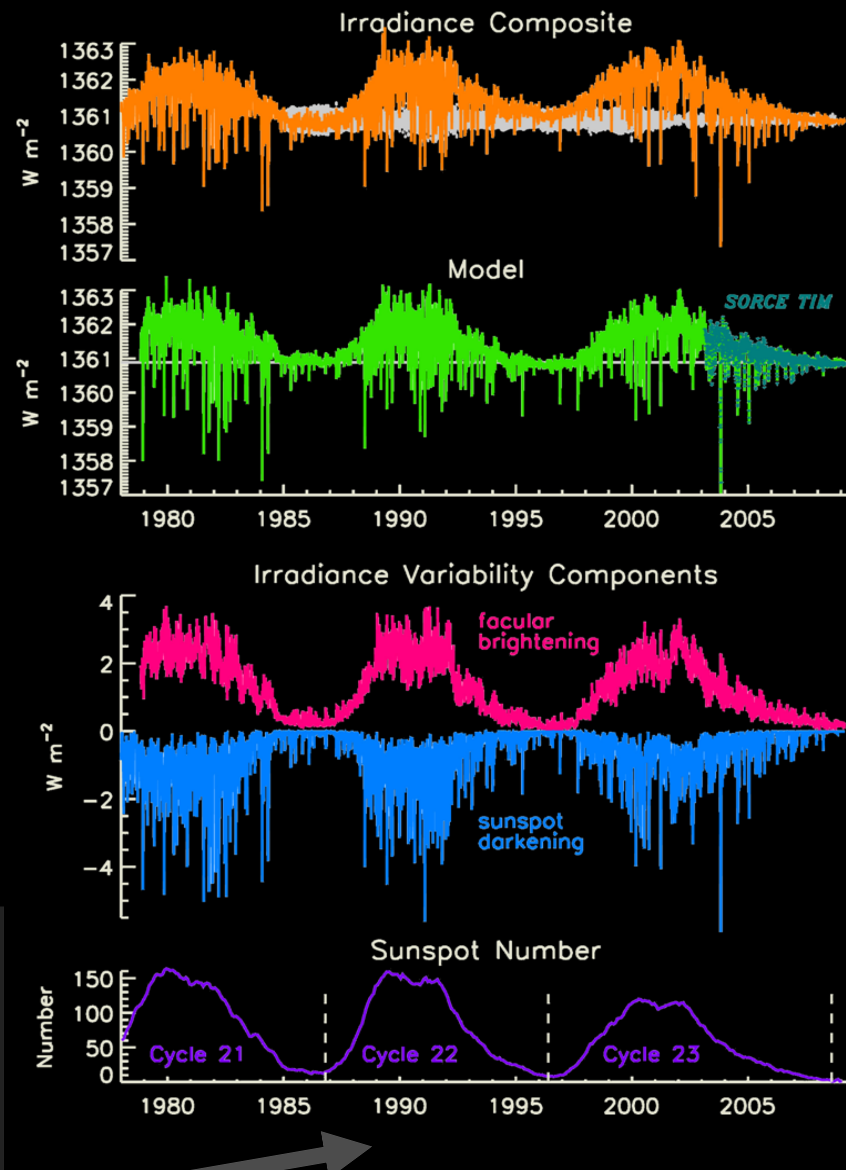
# Irradiance Changes in Flares



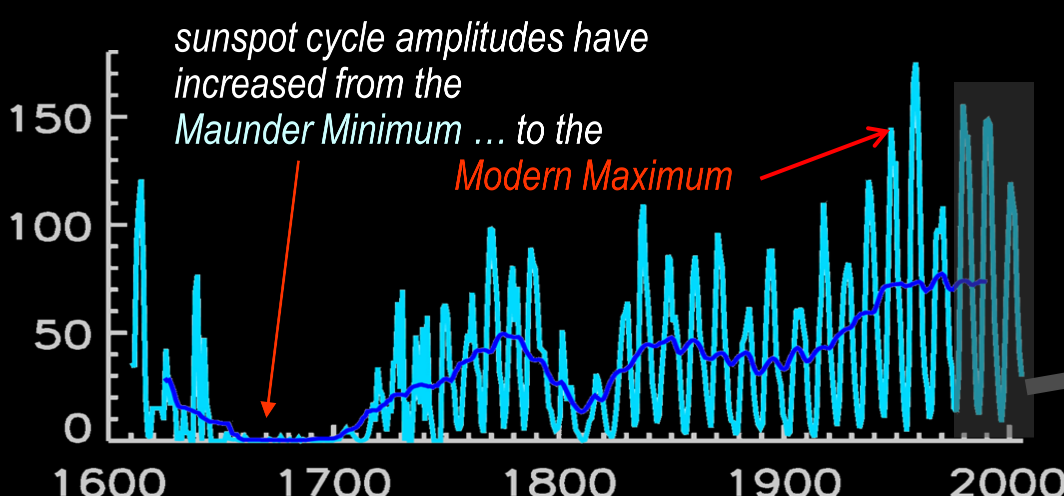
# Reconstructing Past Solar Irradiance Variations



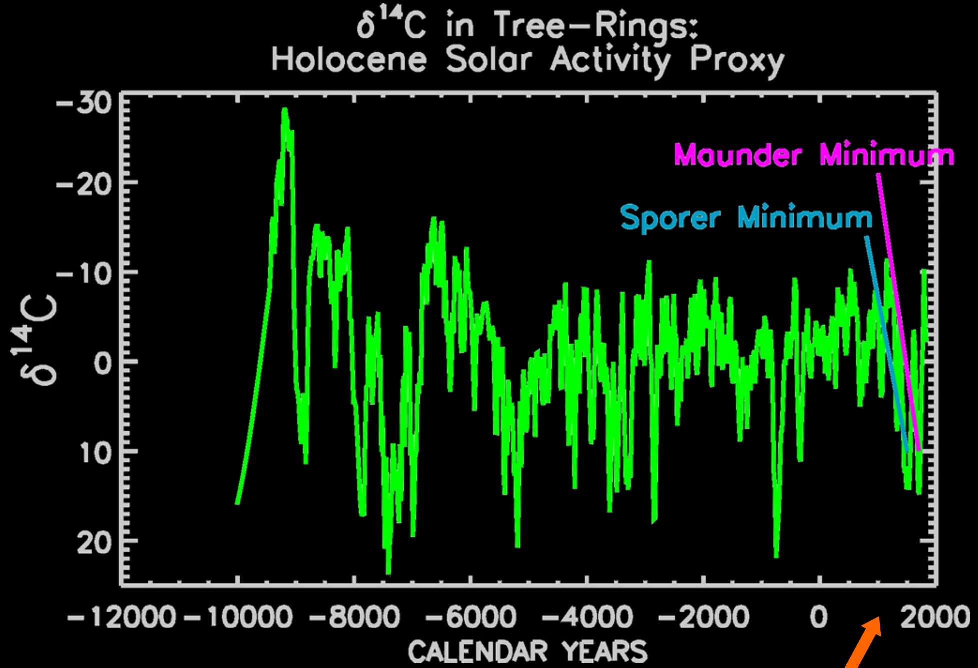




*Past Solar Activity*

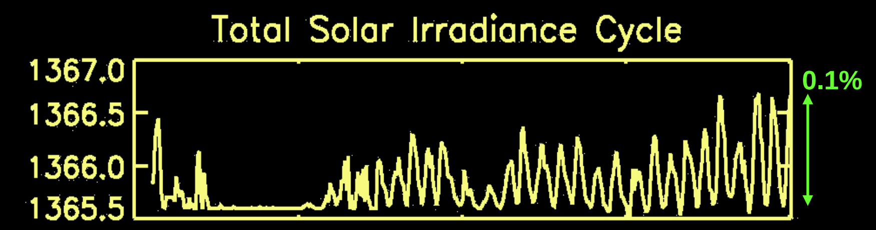


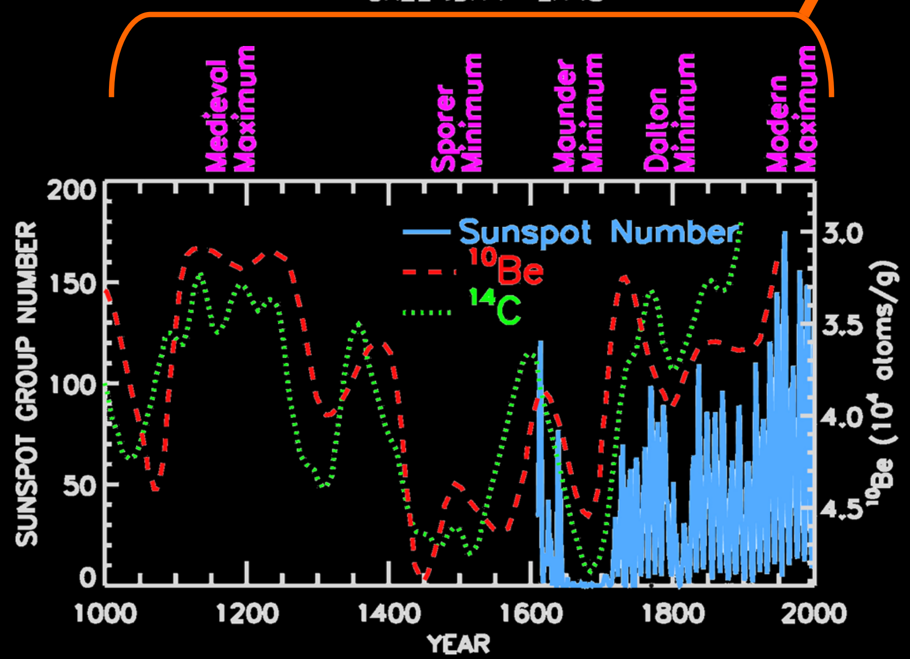
# Centennial-Millennial Solar Variability

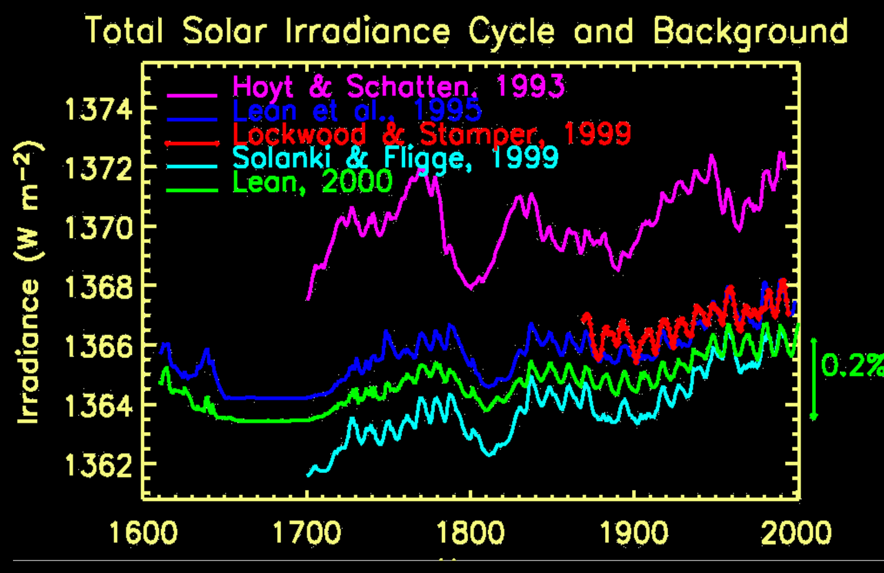



***cosmogenic isotope changes***
***- $^{14}C$ in tree-rings, $^{10}Be$ in icecores -***
***imply long-term solar activity***

***… do they also imply long-term solar irradiance variations?***



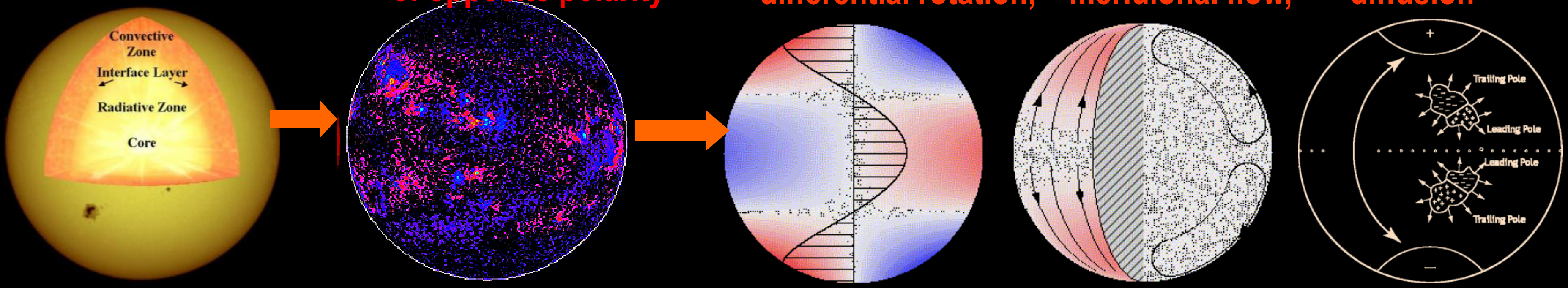



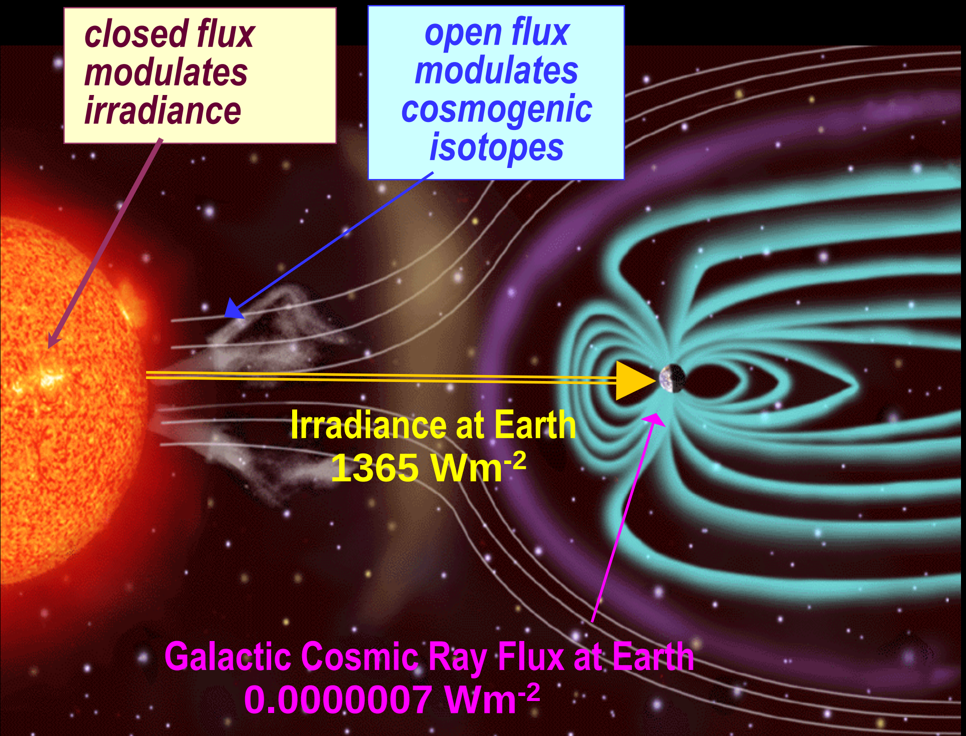
# Estimating Long-Term Solar Variability

sub-surface dynamo

surface magnetic fields of opposite polarity

transported by… differential rotation, meridional flow, diffusion

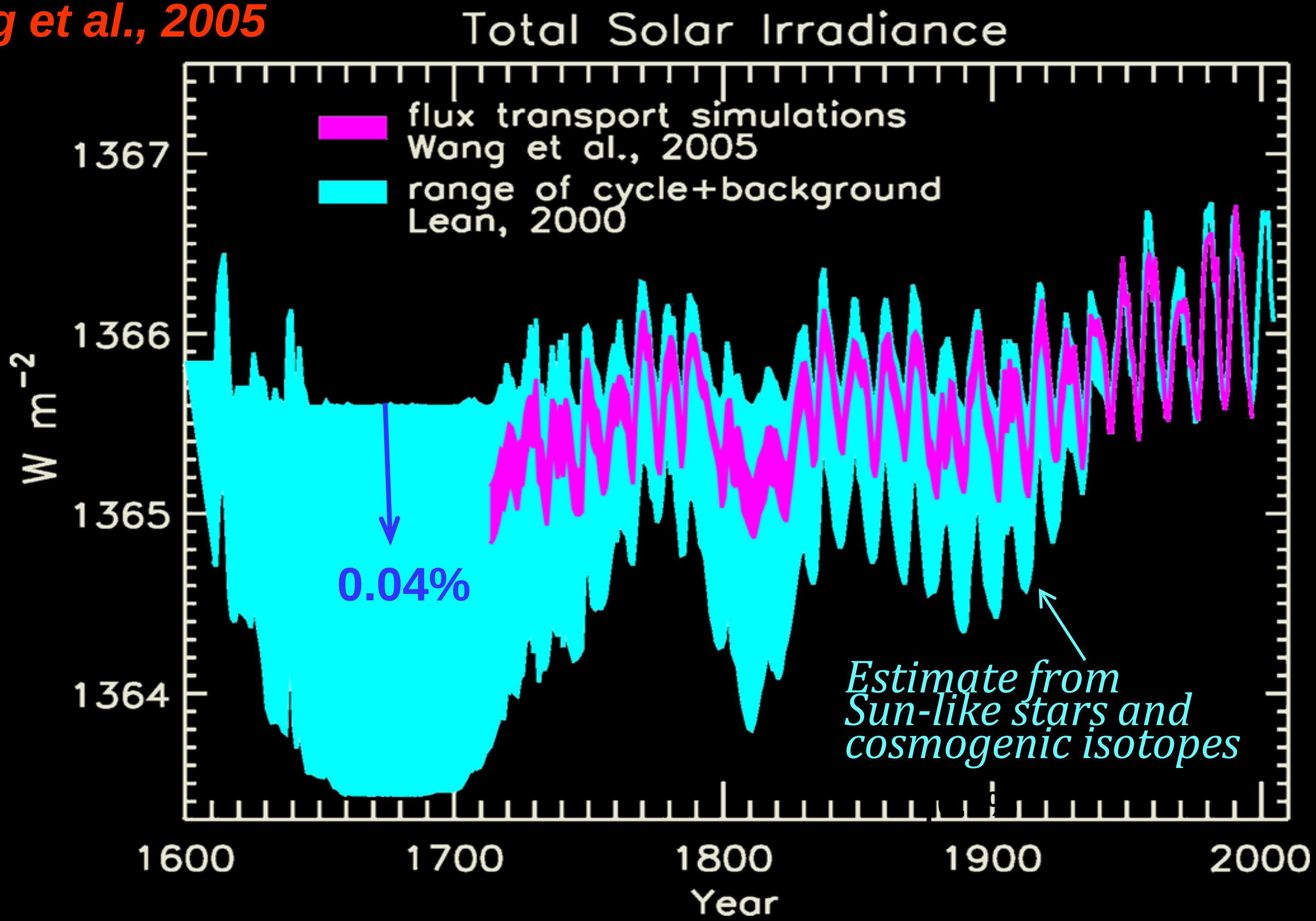


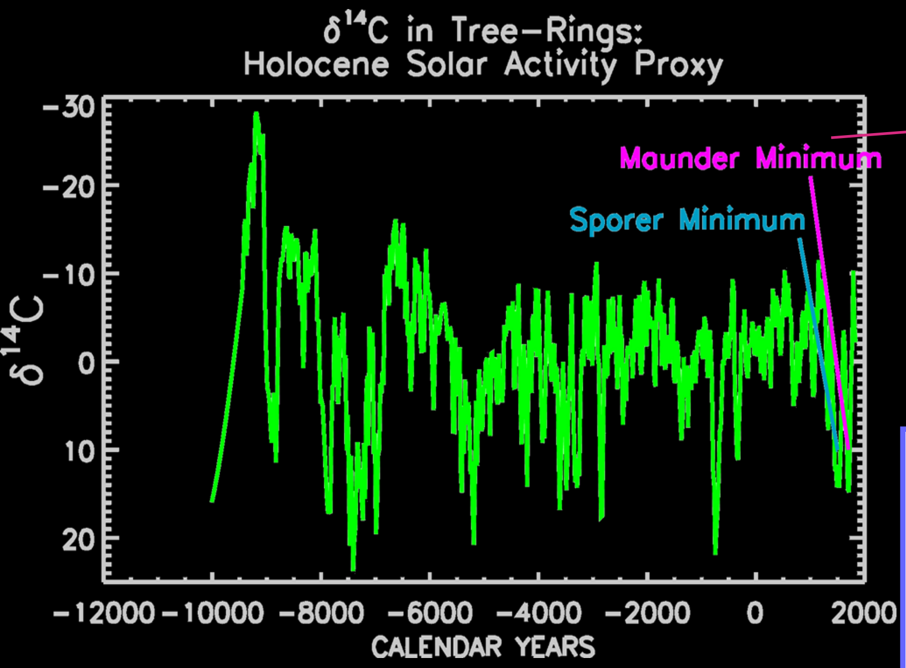

# Reconstructing Solar Irradiance since the Maunder Minimum

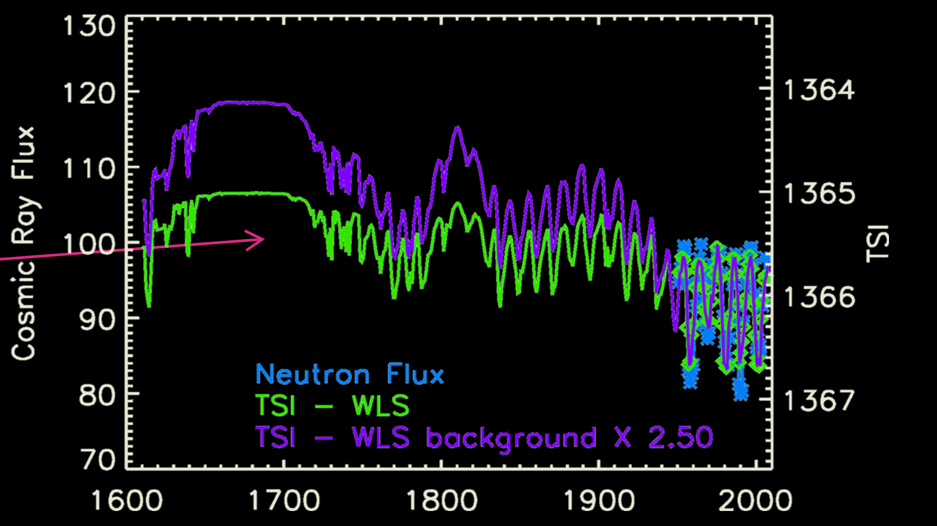
**NRL Flux Transport Model**

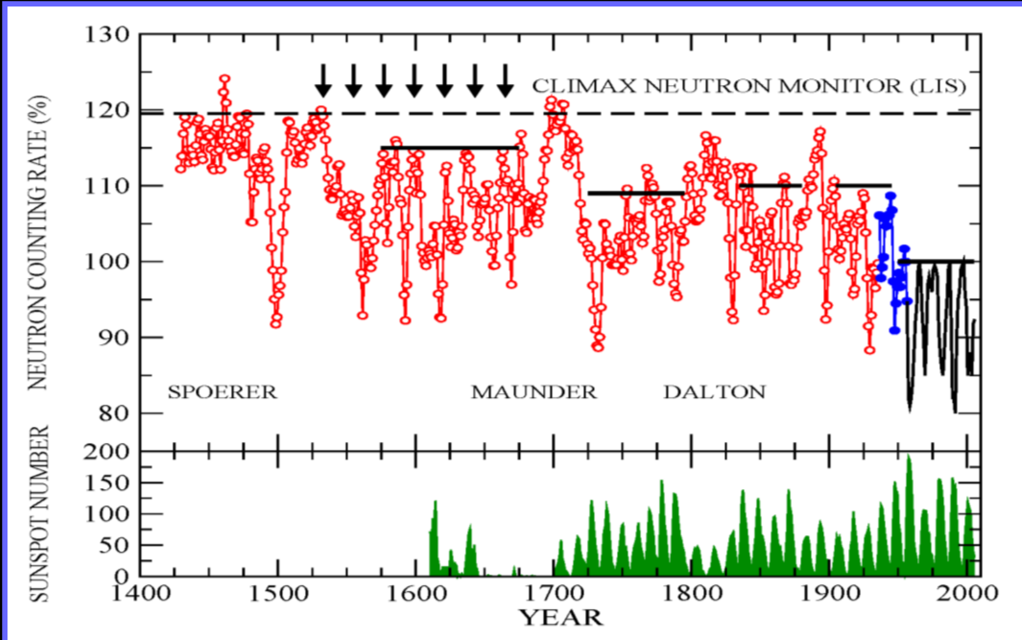
***Wang et al., 2005***



# Reconstructing Solar Irradiance during Past Millennia from Cosmogenic Isotpoes



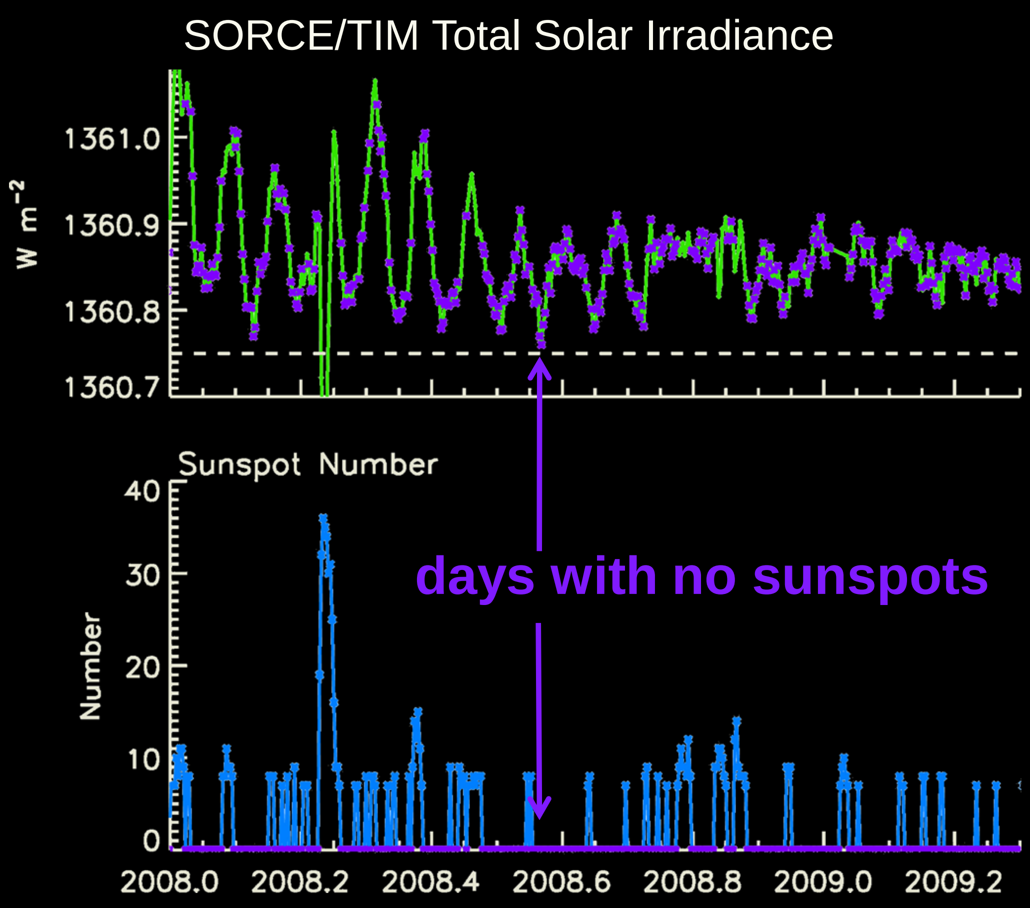




**Ken McCracken, 2007 ICRC**

***Courtesy of Frank McDonald, 2009***

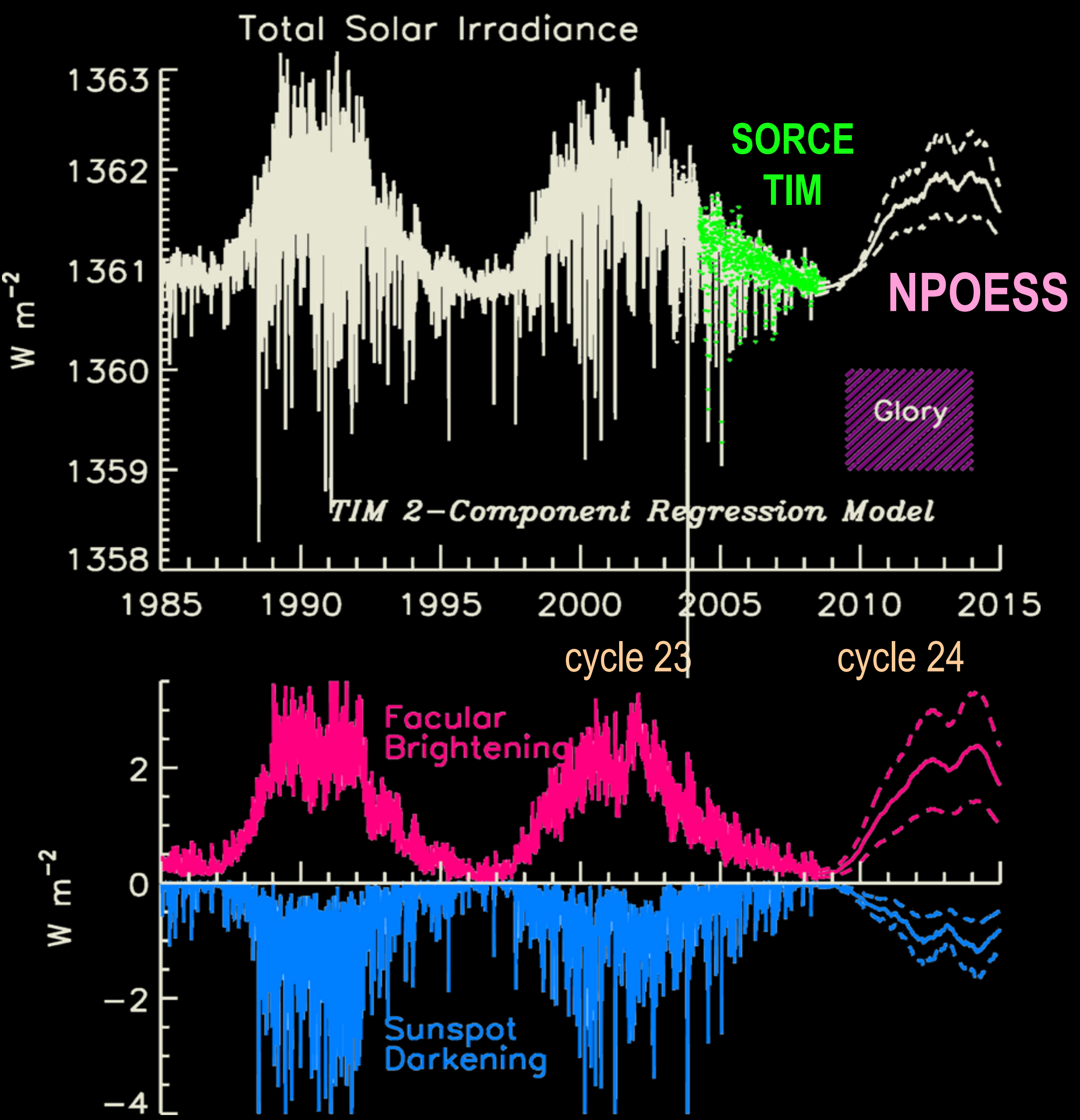
# Are we entering a protracted solar minimum?




- *TIM total solar irradiance has varied continuously throughout the current quiet period, even when sunspots were absent*
- *Bright faculae have been present on the disk throughout the minimum period, producing rotational modulation*
- *Lowest levels reached in mid 2008….. solar cycle minimum?*
- *Hinode EUV (coronal) signal also minimum in mid 2008*

***An accurate, precise, long solar irradiance record is crucial to constrain solar-driven climate change.***

# How – and Why - will Solar Irradiance Change in the Next Decade?




**Solar Cycle 24:**

- 40% higher than cycle *23*
  *(Dikpati et al, 2005)*
- less active than cycle 23
  *(Wang and Sheeley, 2009)*

***GLORY/TIM: 2010 →***

***... the first "benchmark" irradiance measurement***

***… end-to-end calibration with NIST cryogenic radiometer***

***NPOESS/TSIS: 2013 →***

***... operational solar monitoring***

***… total and spectral irradiance***

***… SORCE, TIM and SIM heritage***

LISIRD: Lasp Interactive Solar IRradiance Datacenter

http://lasp.colorado.edu/lisird/

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LISI
LASP INTERACT
IRRADIANCE DA

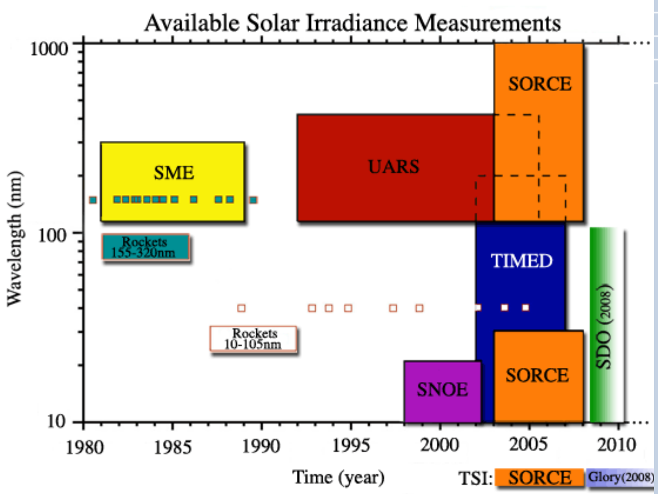
## WHAT IS LISIRD?

Welcome to the Lasp Interactive Solar IRradiance Datacenter or LISIR website. This data center is currently in its early stages of development. LAS plans to have LISIRD provide convenient interactive access to a comprehensiv set of solar irradiance measurements, models, and composite solar irradianc spectra and time series. Click here to begin querying data.

Currently, we have a Data Access Interface that queries data from several LAS missions: SORCE, TIMED SEE, SME, UARS SOLSTICE, and soon SNOE (se graphic below).

We encourage community input to help us make this the most useful site possibl You can help LASP by taking our on-line survey. We also welcome an comments you might have concerning the features, capabilities, and data sets yo would like to see provided at this data center. We will endeavor to take int account the comments and requests we receive in order to make this data cent as useful as possible.

Below is a quick-look graphic of current available measurements (by clicking o different regions of the graphic, you will be taken to that dataset):




In order to maximize the accessibility and usability of solar irradiance data an information from multiple missions, LASP has initiated the process of developin

Institute of Meteorology: Input Data

http://www.geo.fu-berlin.de/en/met/ag/strat/forschung/SOLARIS/Input_data/index.html

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### Input Data:

Recommendations for CMIP5

**I) Solar Irradiance Data**

Variations in the total solar irradiance (TSI), the so-called "solar constant", over a solar cycle are small (0.08%) (e.g., Fröhlich, 2000). However, variations in the ultraviolet (UV) part of the solar spectrum, which is important for ozone production and middle atmosphere heating, range from 8% at 200nm to about 5% from 220nm to 260nm, 0.5% around 300nm, and 0.1% above 400nm (e.g., Lean et al., 1997; Woods and Rottman, 2002). Much larger variations are observed at shorter wavelengths (over 50% at 120nm, 10-15% from 140-200nm), which are mainly absorbed in the higher atmosphere (mesosphere and thermosphere).

To account for the highly variable and wavelength-dependent changes in solar irradiance, daily spectrally resolved solar irradiance data from 1 Jan 1950 to 31 Dec 2006 (in mW/m$^2$/nm) are provided by Judith Lean for different time periods, different time resolution (daily or monthly) and different wavelength regions. The data were derived with the method described in Lean et al. (1997), Lean (2001), and Lean et al. (2005). A short description of how the data were (re)constructed can be found here.

Each modelling group is required to integrate these data over the individual wavelength intervals in their

- radiation scheme (to adjust the shortwave heating rates) and

he photolysis rates).

rovided solar flux data directly (integrated over the respective emistry schemes), rather than a parameterization with the sed.

t and zipped. To unzip use "gunzip file.gz".

ed as follows:

header ...

wavelength grid centers ...

wavelength bands width (1 nm bins from 0 to 750 nm, 5 nm bins from 750 to 5000 nm, 10 nm bins from 5000 to 10000 nm, 50 nm bins from 10000 to 100000 nm) ...

Spectral irradiance (mW/m2/nm) daily for years indicated in the file name

YEAR MONTH DAY TSI in W/m2

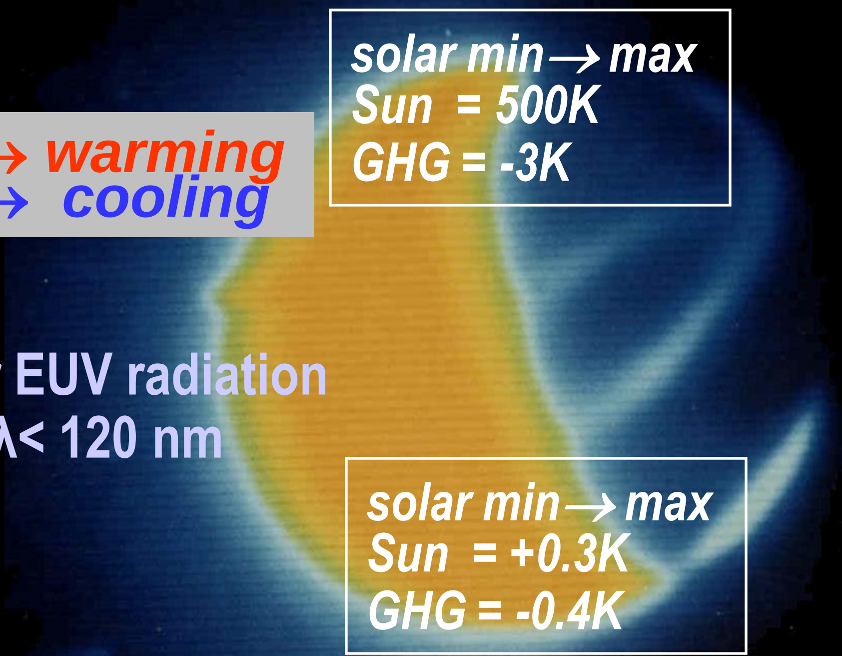
solar flux data ...

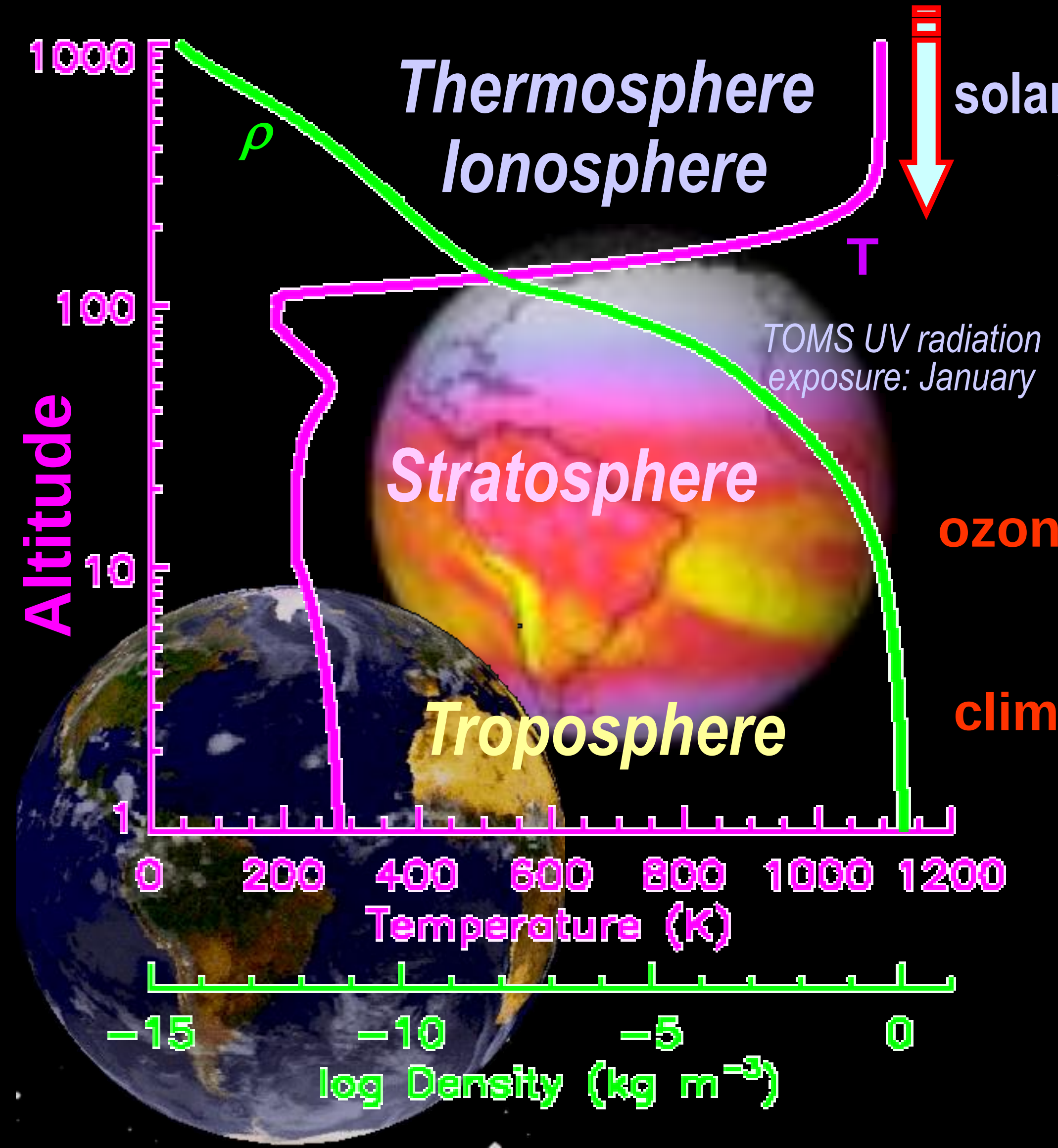
model: 1 nm bins
0-100,000 nm
daily since 1947
monthly since 1882
yearly since 1610

**SPACE WEATHER**

solar increase → *warming*
$CO_2$ increase → *cooling*

*solar min → max*
*Sun = 500K*
*GHG = -3K*






*solar min → max*
*Sun = +0.3K*
*GHG = -0.4K*

solar increase → *warming*
$CO_2$ increase → *cooling*

ozone depletion

**GLOBAL CHANGE**

climate change

solar increase → *warming*
$CO_2$ increase → *warming*

*solar min → max*
*Sun = +0.1K*
*GHG = +0.2K*

# SUMMARY

## *How Bright is the Sun?*

- **Total Irradiance – 1361 $Wm^{-2}$ (SORCE/TIM) or 1365 $Wm^{-2}$ (ACRIM)?**
- **Spectral Irradiance – percentage uncertainties**

  *… absolute offsets among independent instruments exceed variability*

## *How Does it Vary?*

- **Total Irradiance – 0.1% during recent activity cycles, 0.3% in strong rotational modulation, <0.1% since Maunder Minimum?**
- **Spectral Irradiance – 1% to 40% in UV, 0.1% in visible**

  *… SORCE observations have larger UV changes than model or prior observations*

  *…variations in visible and near-IR spectrum are out-of-phase with solar activity*
- **Past and future solar Irradiance changes are uncertain**

  *… continuous, high precision monitoring will advance understanding*

## *Why do we Care?*

- **Natural climate change occurs simultaneously with anthropogenic influences**

  *… solar & volcanic influences, internal modes (ENSO, QBO), greenhouse gases, aerosols*

  *… solar influence may both accelerate and mitigate global warming in the next two decades*