Advancements in Solar Irradiance Measurements and Long-term Data Continuity

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"As there is only one object in the sky on whom we utterly depend, there can be no astronomical question of more practical significance to mankind than that of the Sun's variability"

- John A. Eddy

1931 -2009

Historical Perspective on Solar Variability

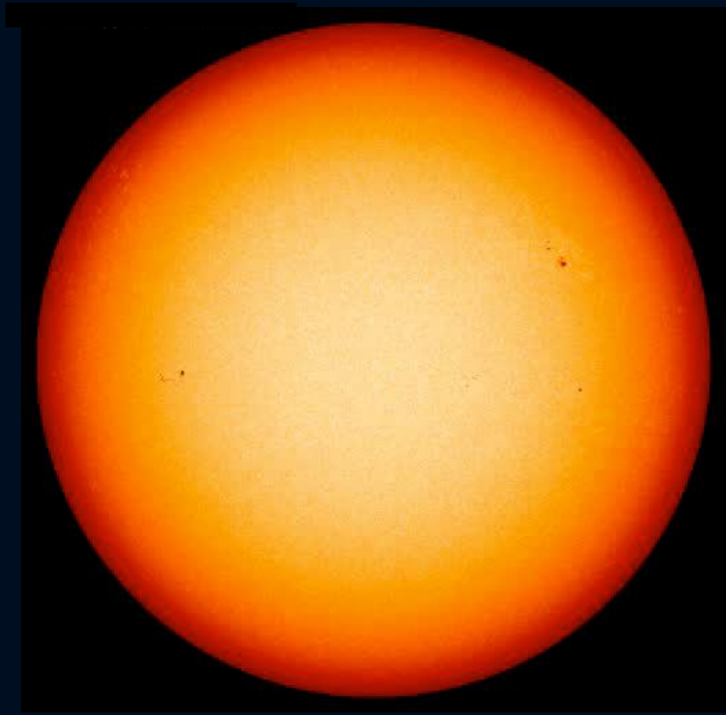
XIII. *Observations tending to investigate the Nature of the Sun, in order to find the Causes or Symptoms of its variable Emission of Light and Heat; with Remarks on the Use that may possibly be drawn from Solar Observations.* By William Herschel, L.L.D. F.R.S.

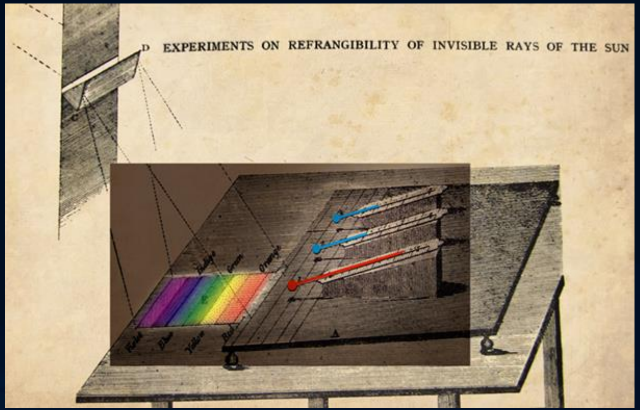
Read April 16, 1801.

On a former occasion I have shewn, that we have great reason to look upon the sun as a most magnificent habitable globe; and, from the observations which will be related in this Paper, it will now be seen, that all the arguments we have used before are not only confirmed, but that we are encouraged to go a considerable step farther, in the investigation of the physical and planetary construction of the sun. The influence of this eminent body, on the globe we inhabit, is so great, and so widely diffused, that it becomes almost a duty for us to study the operations which are carried on upon the solar surface. Since light and heat are so essential to our well-being, it must certainly be right for us to look into the source from whence they are derived, in order to see whether some material advantage may not be drawn from a thorough acquaintance with the causes from which they originate.

Herschel, W., *Philos. Trans. R. Soc. London*, **91**, 265-318, 1801

Frederick William Herschel
(1738 – 1822)





Discovered the infrared solar radiation, a spectral region that still receives considerable attention in terms of the solar irradiance reference spectrum absolute scale some 220 years later.

TSI & SSI focused missions & opportunities moving forward

Over 4 decades of LASP solar irradiance measurement continuity…

1981-1989

1991-2005

FUV & MUV SSI

2003-2020

2013-2017 (TSI)

2017-present

New Tech Demo (ESTO)

2018-2022

2022 -

2024-

Long-term strategies

2028-

- What can we learn from past and present solar missions?
- Are the methods of observation adequate and are the results accurate enough?
- What are the observations to be continued? What are the missing ones?
- New directions? - new instrumental concepts or novel technologies, new observation strategies
- What is the best strategy for ensuring the proper observation of essential observables (dedicated missions, hosted payloads, CubeSats)?

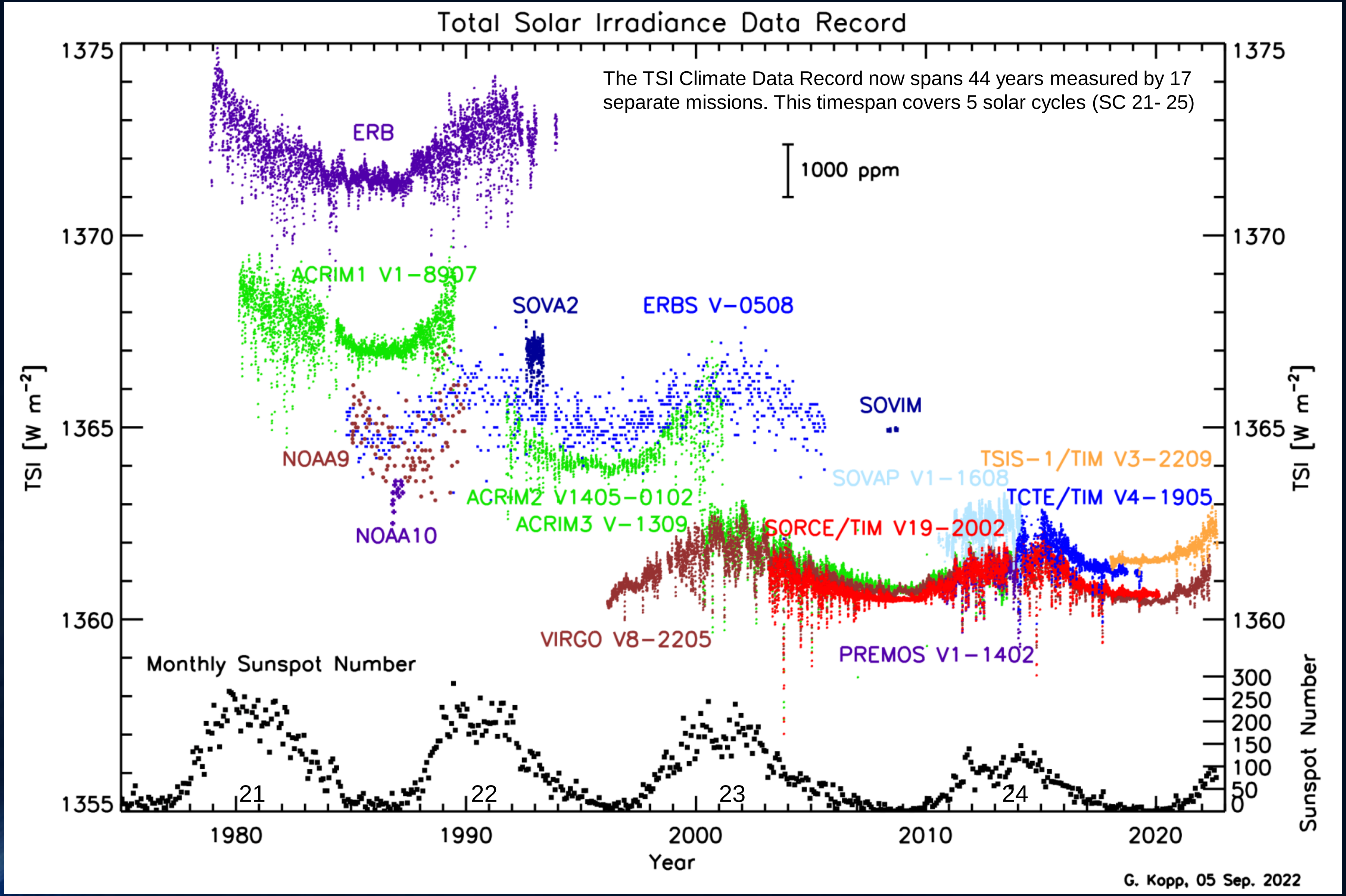
Total Solar Irradiance (TSI)

"It is ridiculous to try to measure variations in a constant"

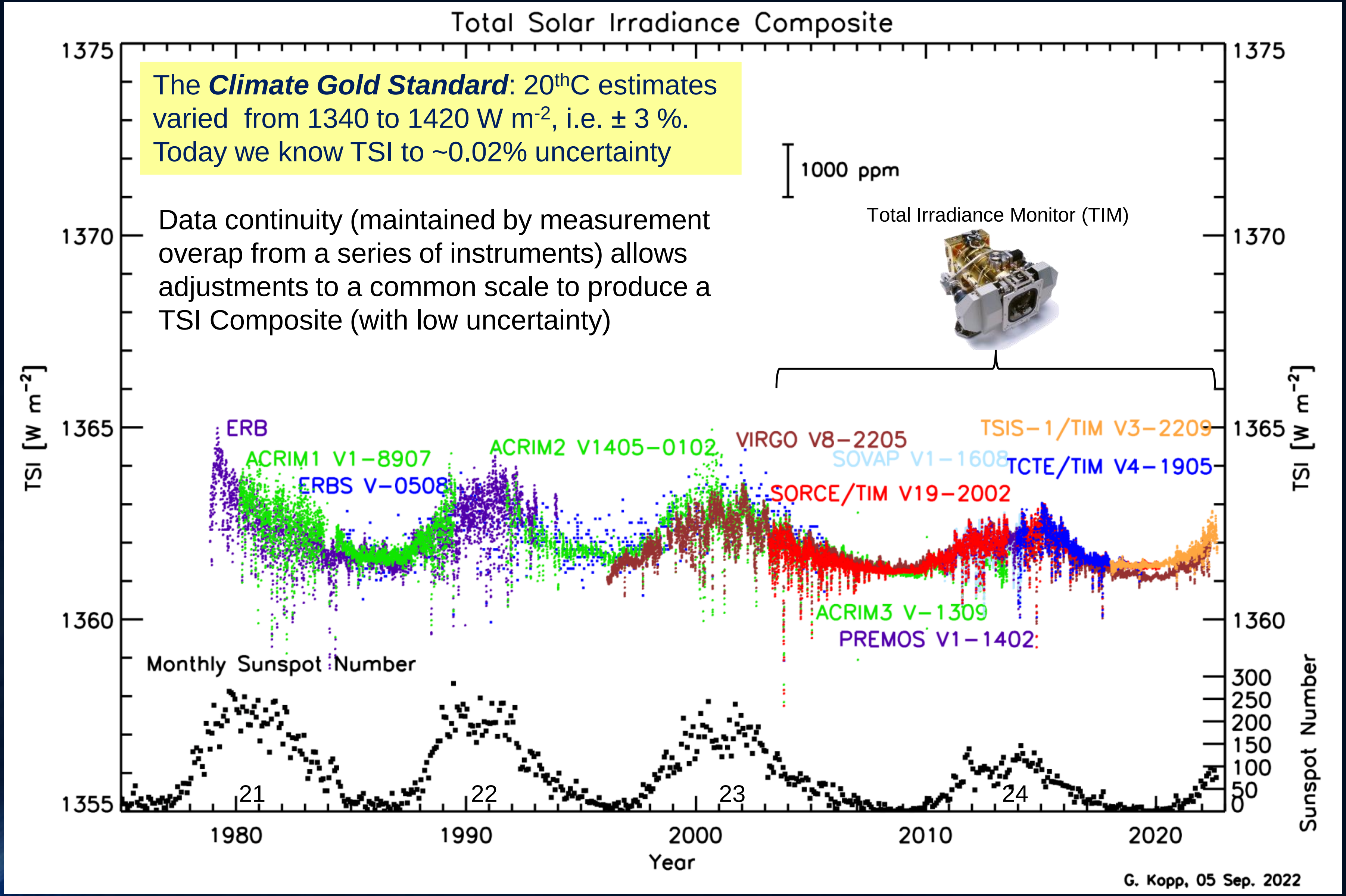
- Heinrich Wilhelm Dove (1806-1879)
famous meteorologist & climatologist

b. Liegnitz, Prussia
(now Legnica, Poland)

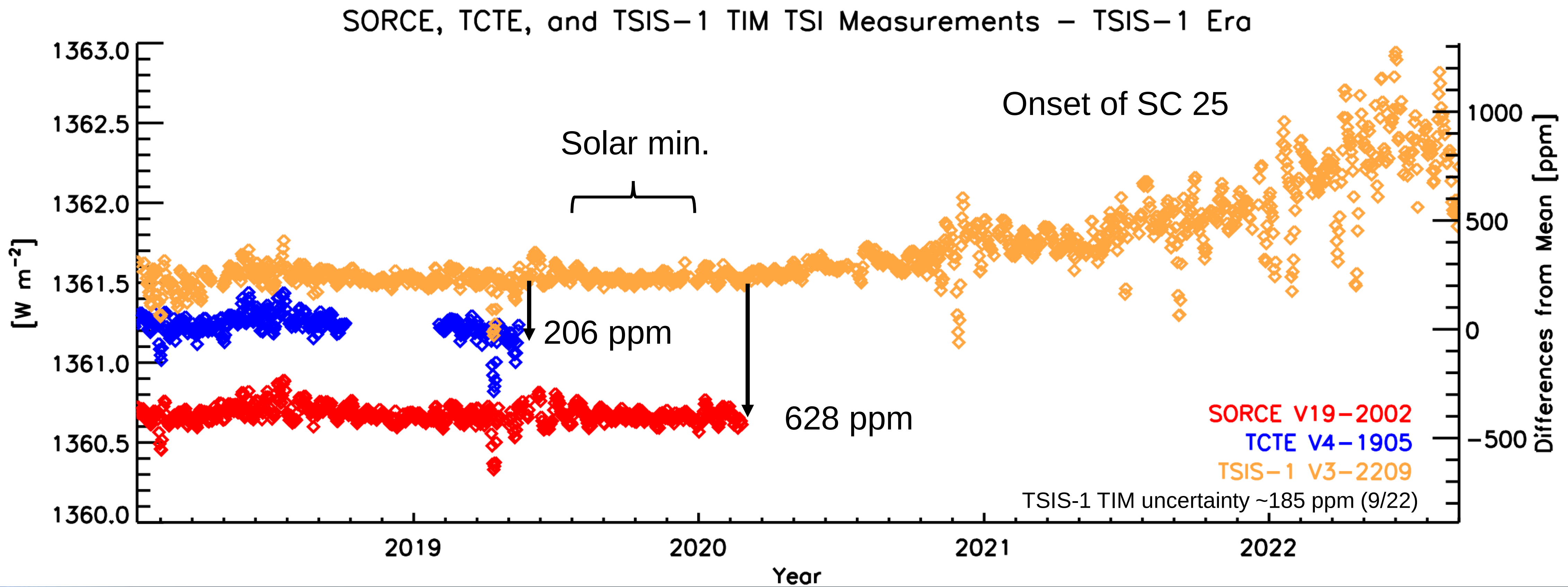
Total Solar Irradiance Data Record



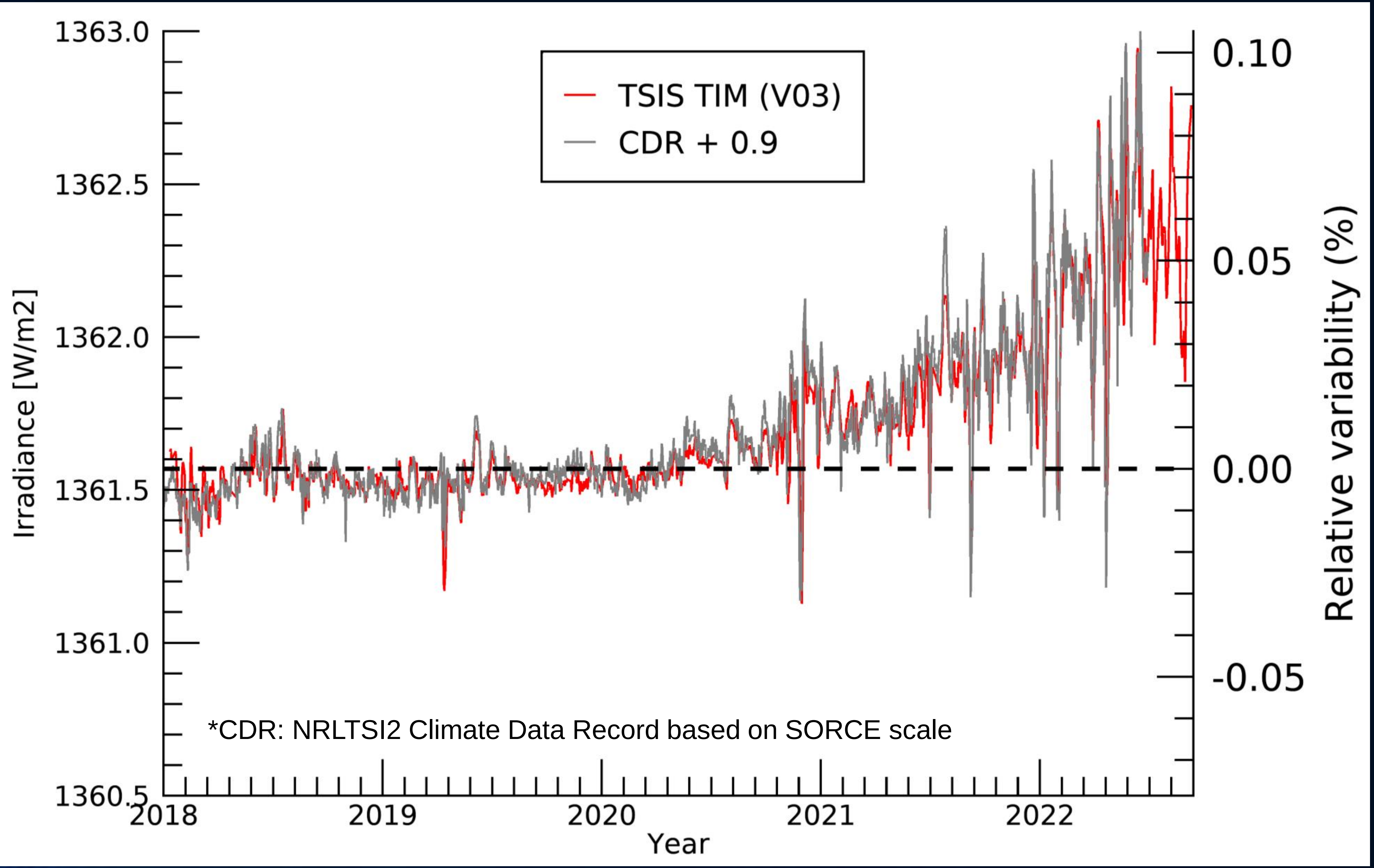
Total Solar Irradiance Composite



Overlapping TIM Total Solar Irradiance Measurements



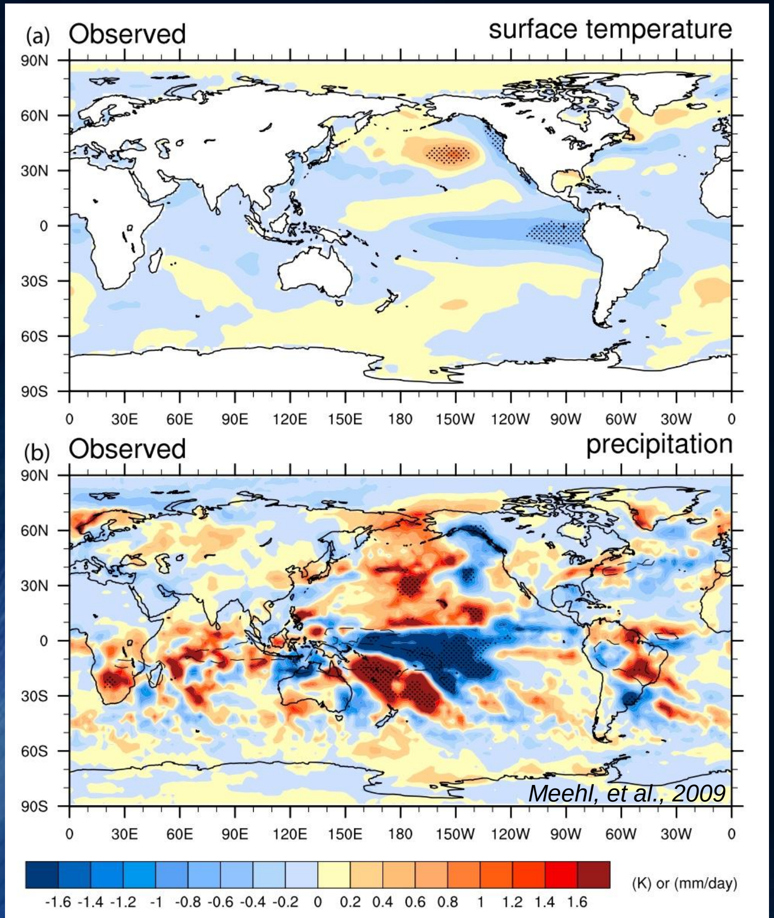
TSIS-1 TIM TSI Measurements vs. Model



TSI Influence on Climate

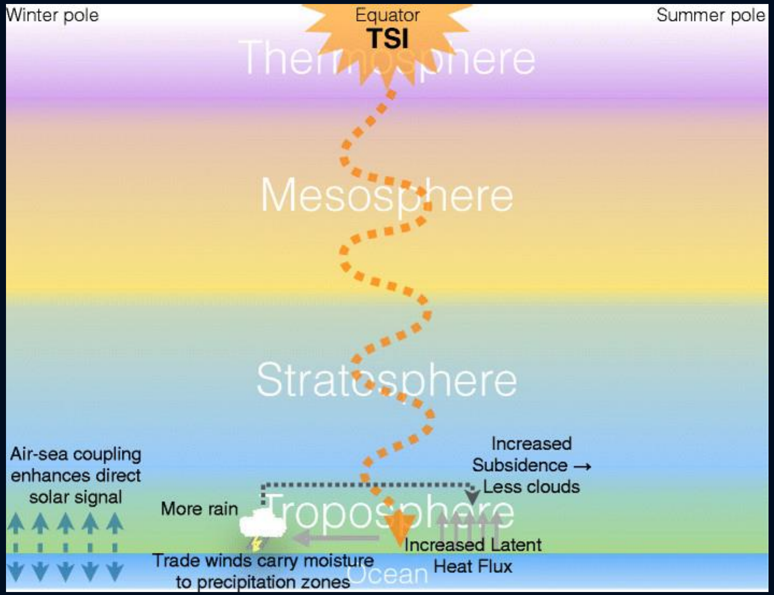
Variations in the direct absorption of TSI by oceans likely to be significant because

- *Large oceanic heat capacity*
- *Integrates long-term, small variations in heat input*



"Bottom up" mechanism

(Vis-IR SSI "TSI" Influence : Meehl et al. 2009)



Figures: A. Seppälä, et al., Progress in Earth and Planetary Science, 2014

Involves solar radiation being absorbed over the oceans

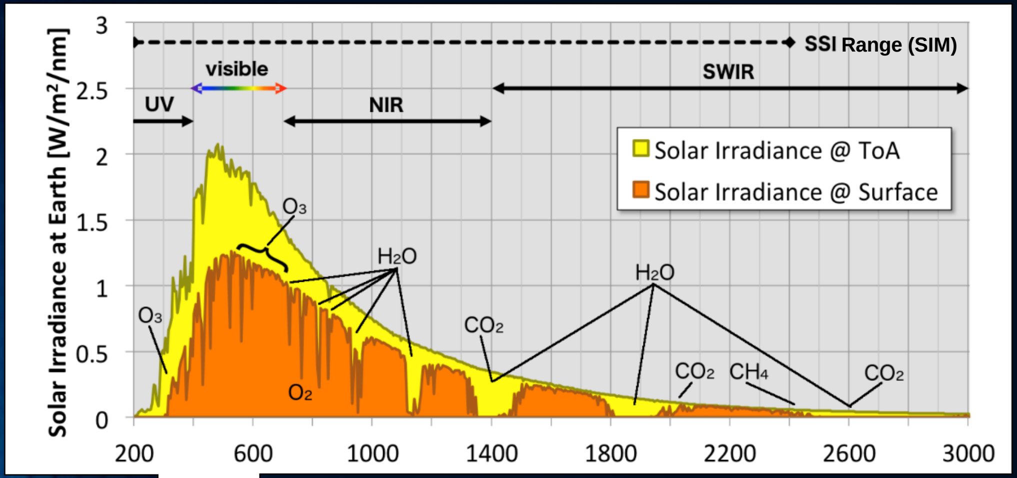
- *Produces increases in evaporation*
- *Increased moisture converging in the precipitation zones.*

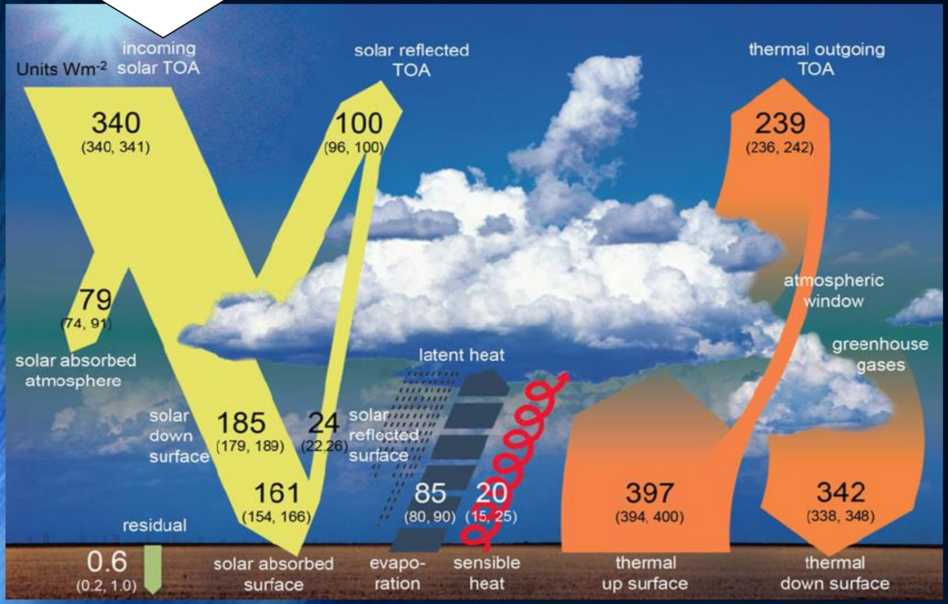
This further leads to changes in precipitation patterns and vertical motions, influencing the trade winds and ocean upwelling.

- *Produces stronger Hadley and Walker circulations and associated colder sea surface temperatures for solar maximum.*

SSI Influence on Climate

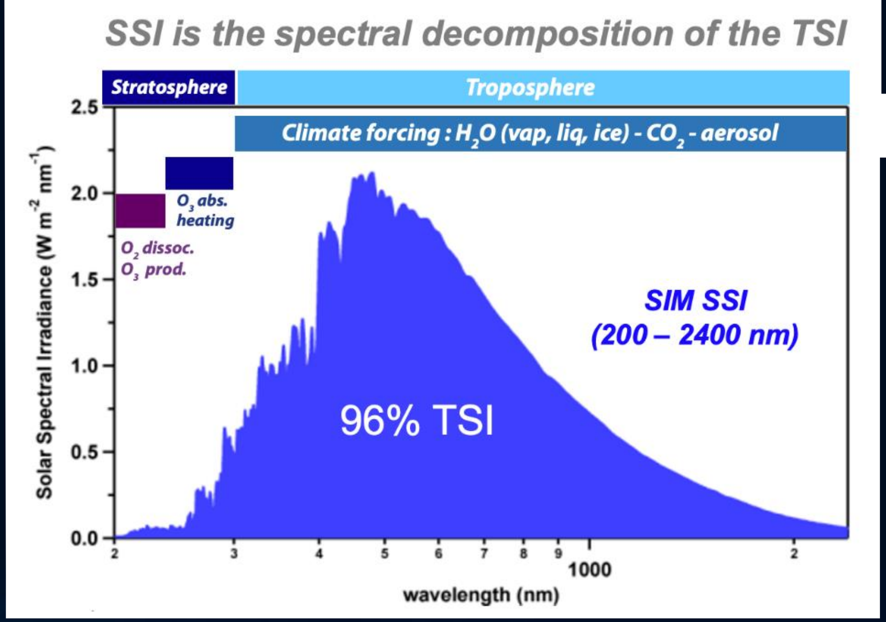
Solar Influence on Global Energy Budget

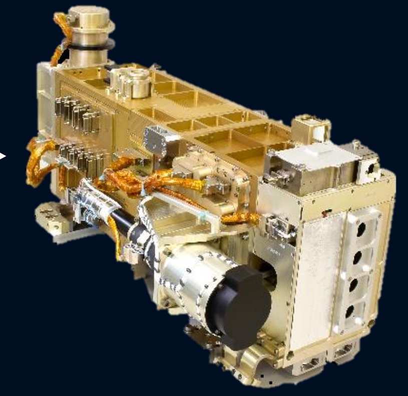




Science Justification: extending the important long-term data record of SSI

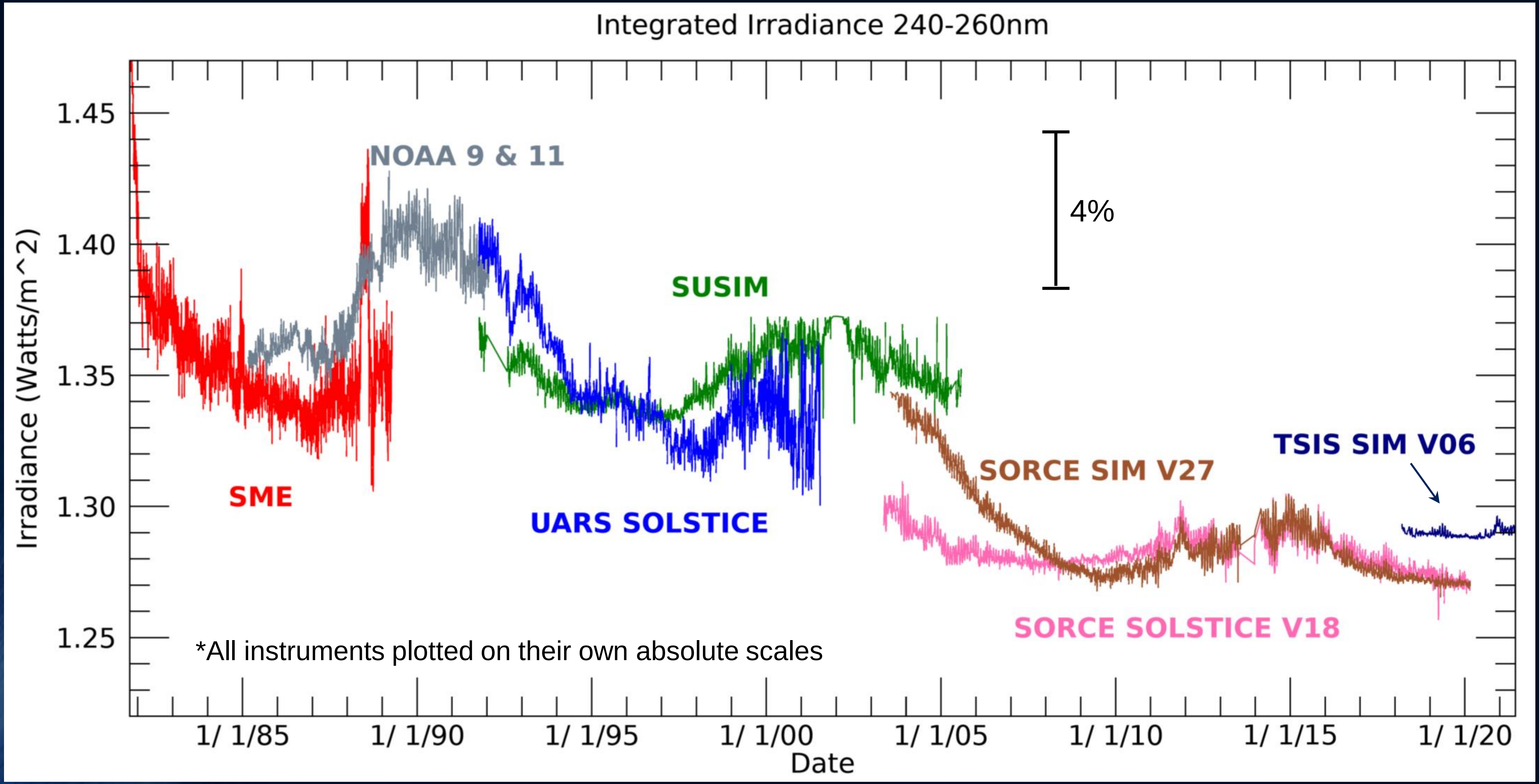
- The SSI climate record extends back to 2003 (SORCE) and is critical for NASA's Sun-climate science as highlighted in the 2018 Earth Science Decadal Survey. **New, advanced climate models require solar spectral inputs**
- SSI measurements enable in-depth research of the Sun's influence on Earth's ozone layer & atmospheric circulation – "Top-Down" Mechanism, Haigh, (1996).
- The SSI climate record provides the temporal spectral variability that is important for detailed understanding on how the Earth's atmosphere and surface absorb the solar energy.





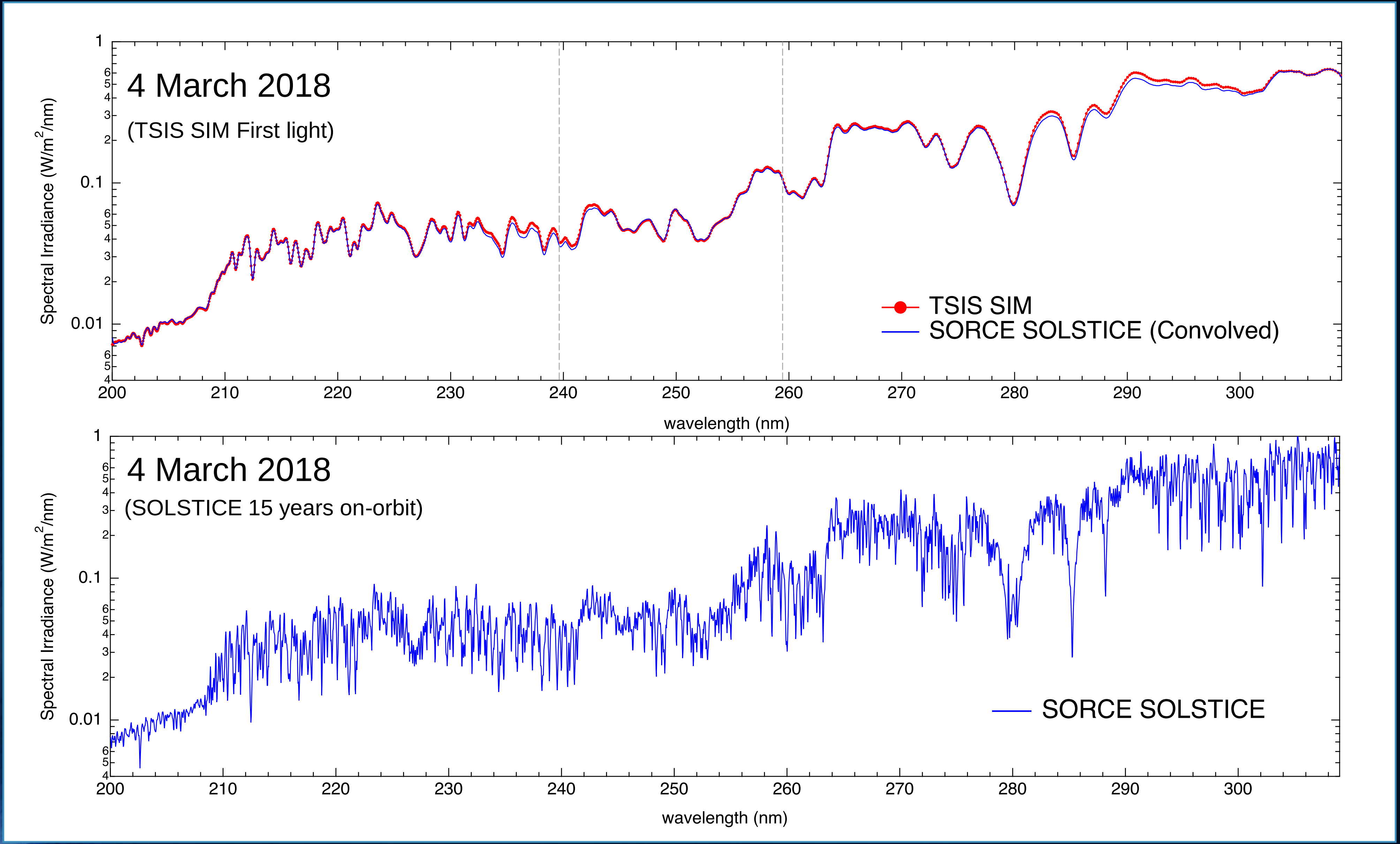
Spectral Irradiance Monitor

UV SSI Data Record*

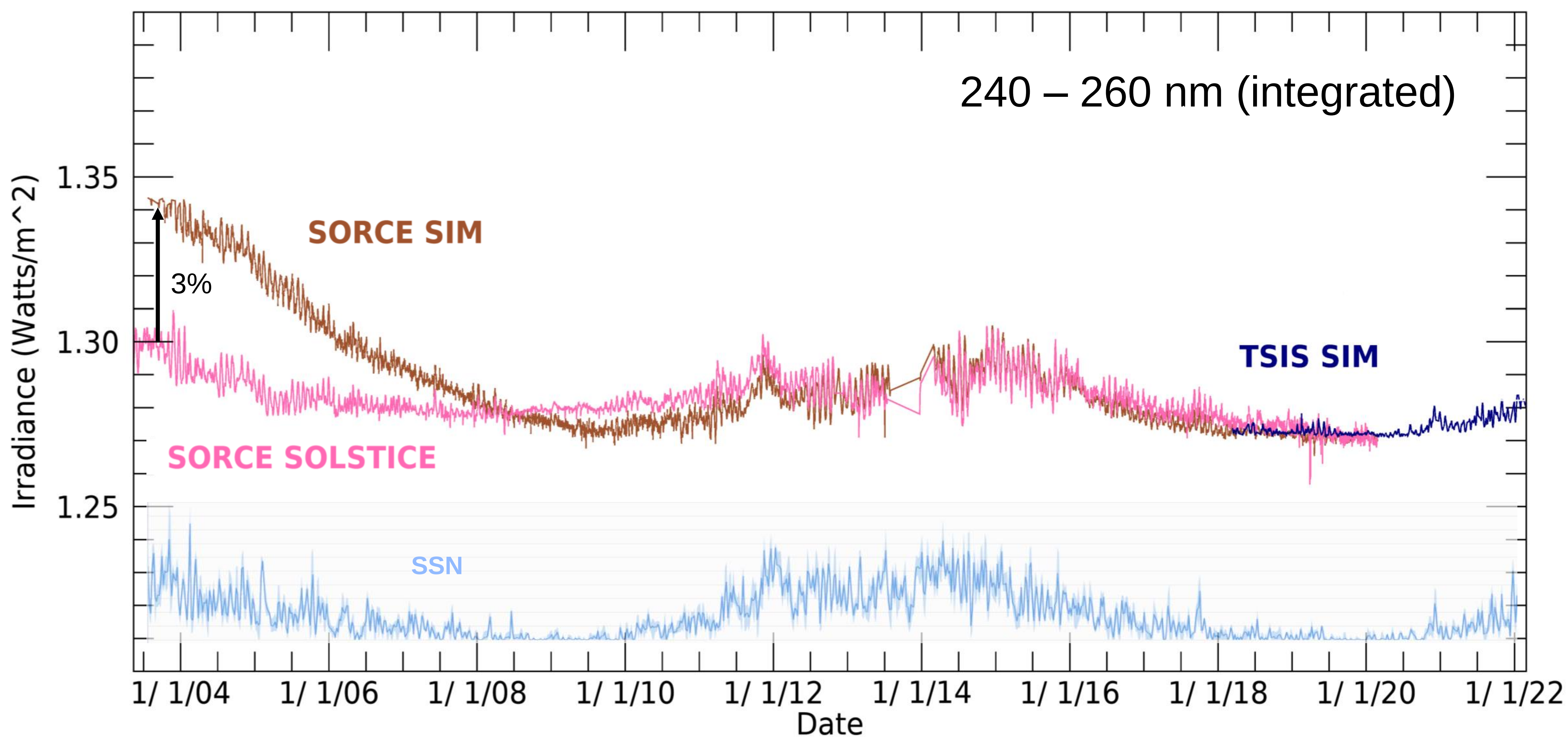


*Comprehensive discussion in Marty Snow's talk later in this session…and with more cats!

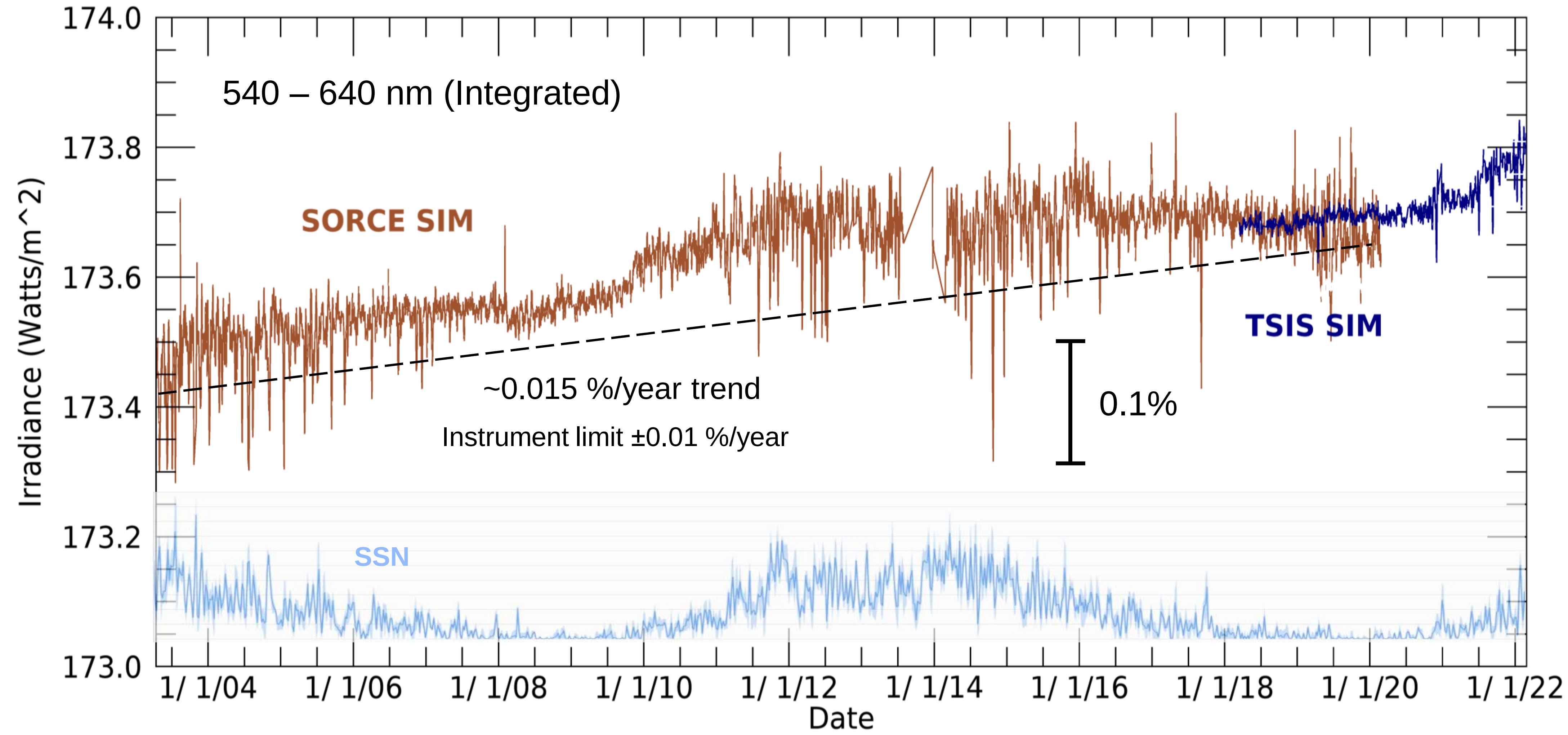
Comparison TSIS SIM – SORCE SOLSTICE SSI spectrum (200 – 310 nm)



UV SSI Data Record



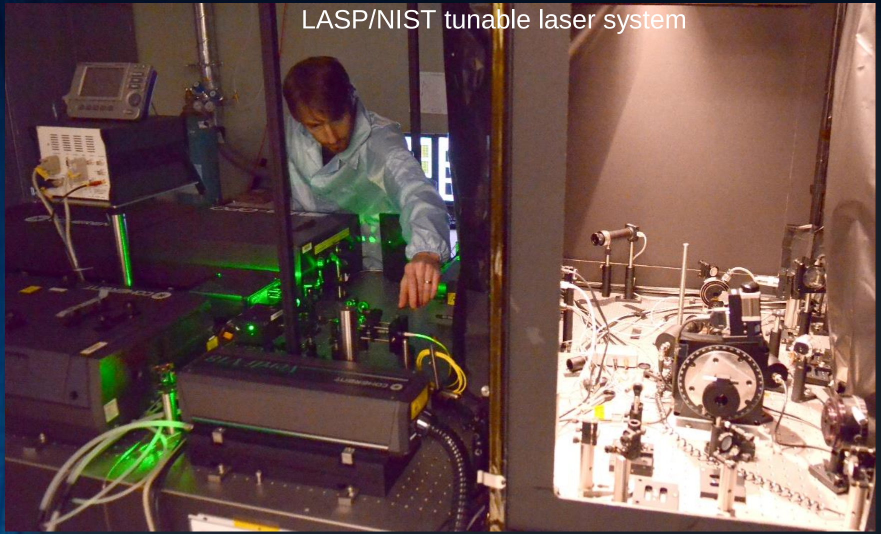
Visible SSI Data Record

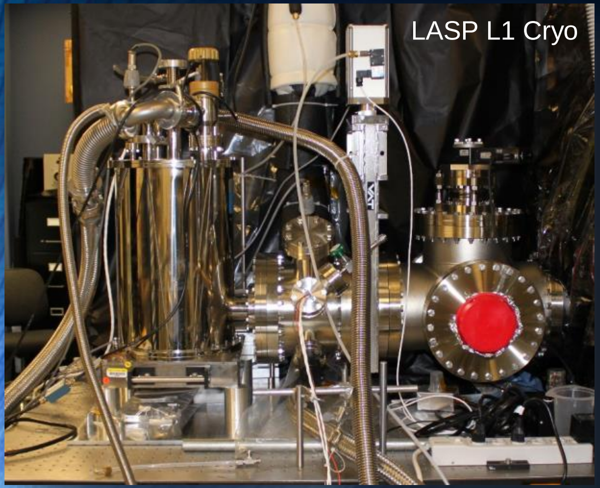


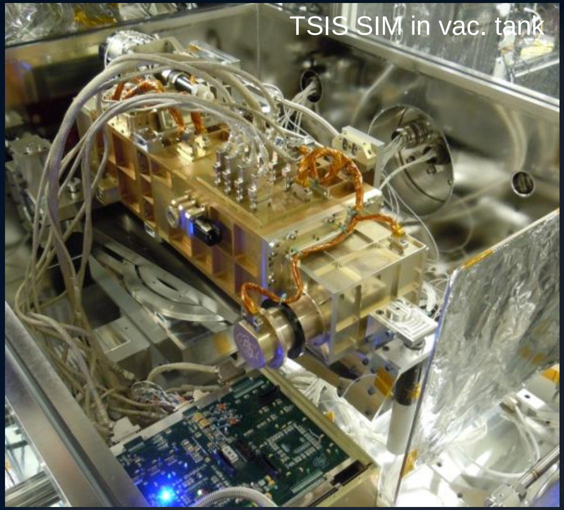
TSIS-1 SSI Scientific Impacts

TSIS SIM Absolute Accuracy in Irradiance

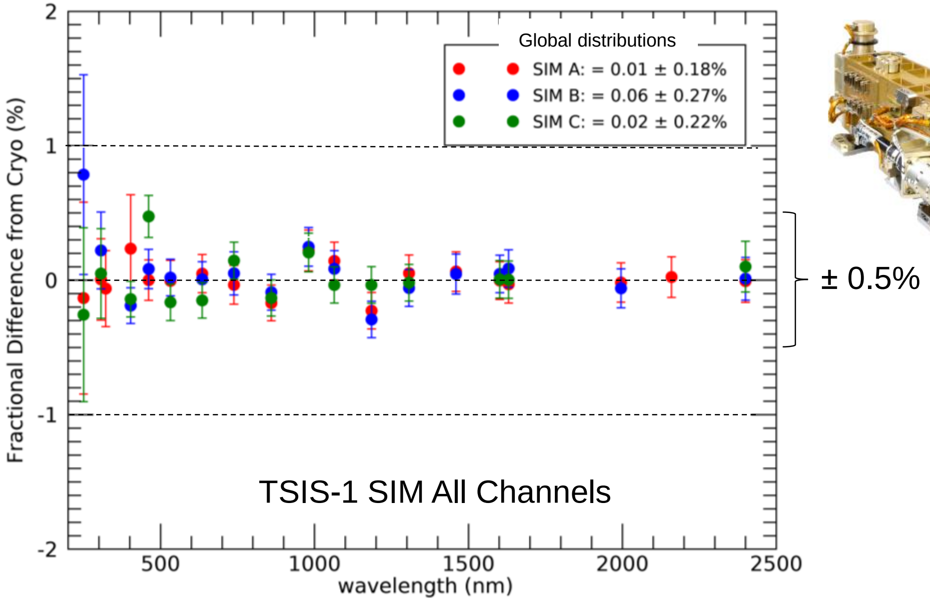
Final full spectrum calibration in irradiance tied to NIST-traceable cryogenic radiometer







TSIS SIM Ch. A, B, C ESR Irradiance Calibration to Cryogenic Radiometer



$$s_{SIM}^2 = s_{offset}^2 + s_{dist.}^2 + s_{SRF}^2$$

Vis-IR Distribution

$$s_{VIR} = \sqrt{(0.03)^2 + (0.19)^2 + (0.14)^2}$$

$$s_{VIR} = 0.24\ \%$$

UV Distribution (≤ 400 nm)

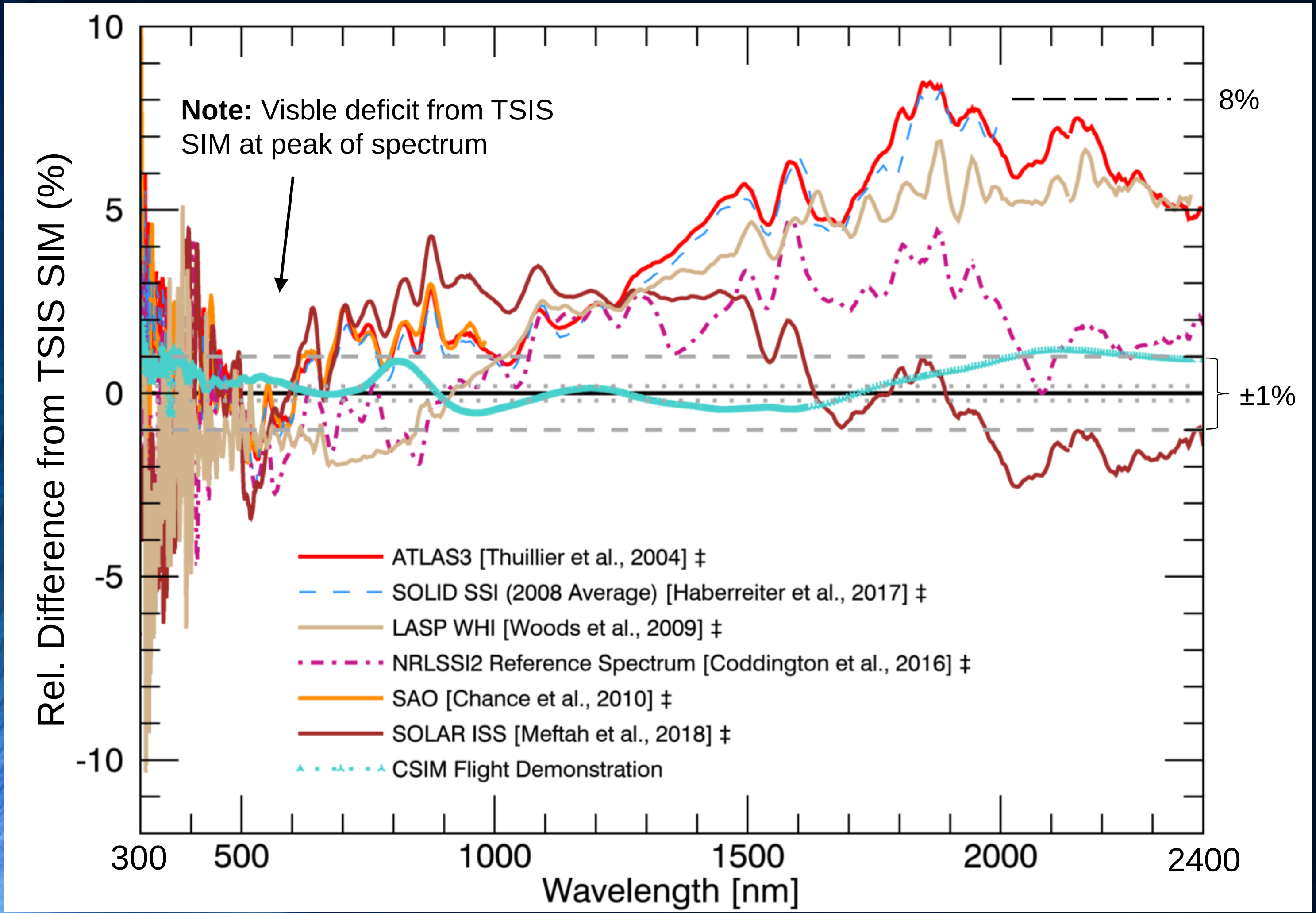
$$s_{UV} = \sqrt{(0.31)^2 + (0.23)^2 + (0.14)^2}$$

$$s_{UV} = 0.41\ \%$$

E. Richard, *et al*., *Remote Sens.*, *12*(11), 1818; doi.org/10.3390/rs12111818, (2020).
E. Richard, *et al., Proc. SPIE 11131*, doi:10.1117/12.2531268. (2019)

Solar Reference Spectra Comparison

Reference Solar Irradiance Spectra and CSIM Compared to TSIS SIM

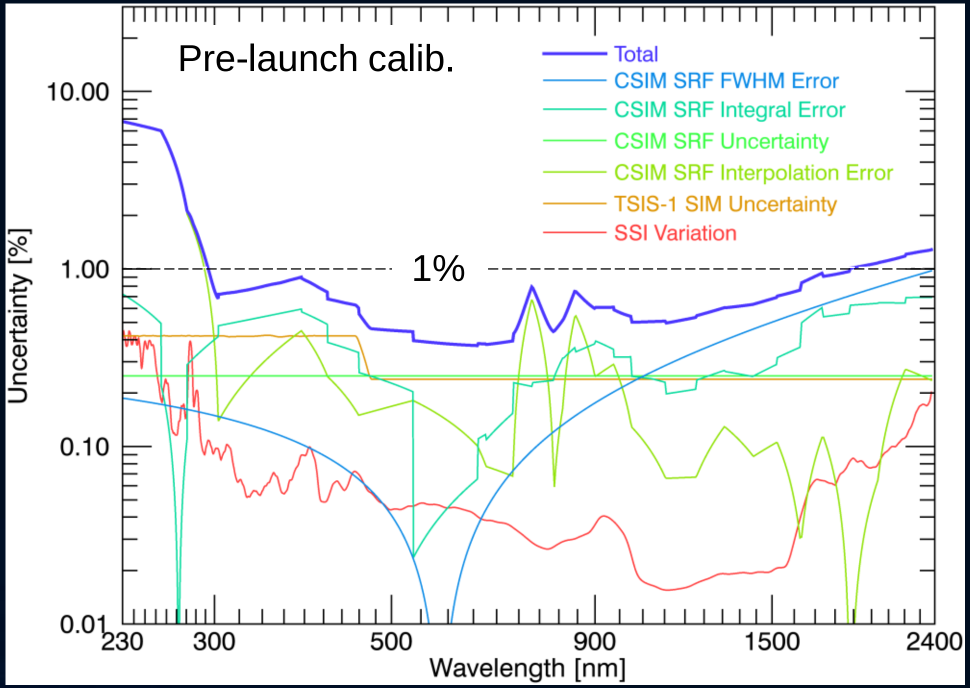


TSIS-1 SIM ($$$)

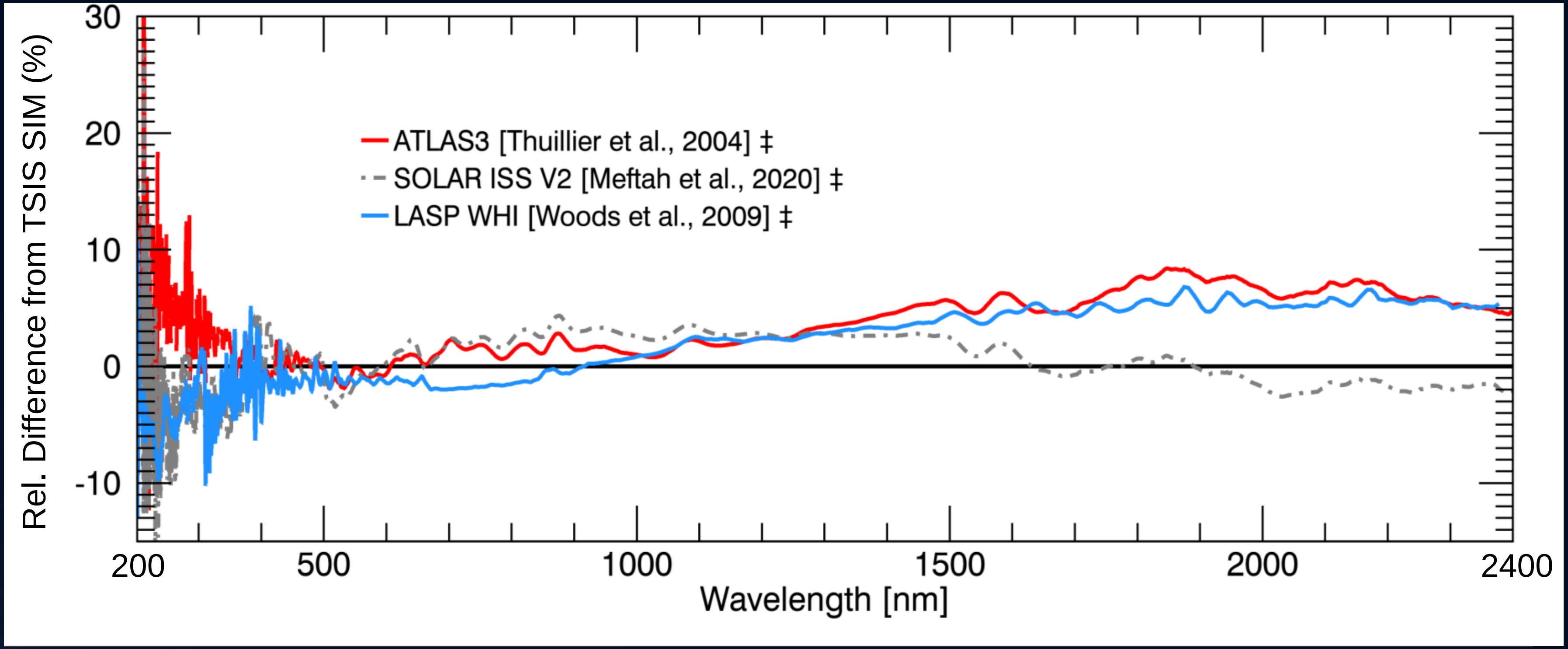
CSIM 6U CubeSat ($)

Equal relative scale

CSIM total uncertainty tied to NIST cryogenic radiometer



TSIS-1 SIM Comparison to other Solar Reference Spectra

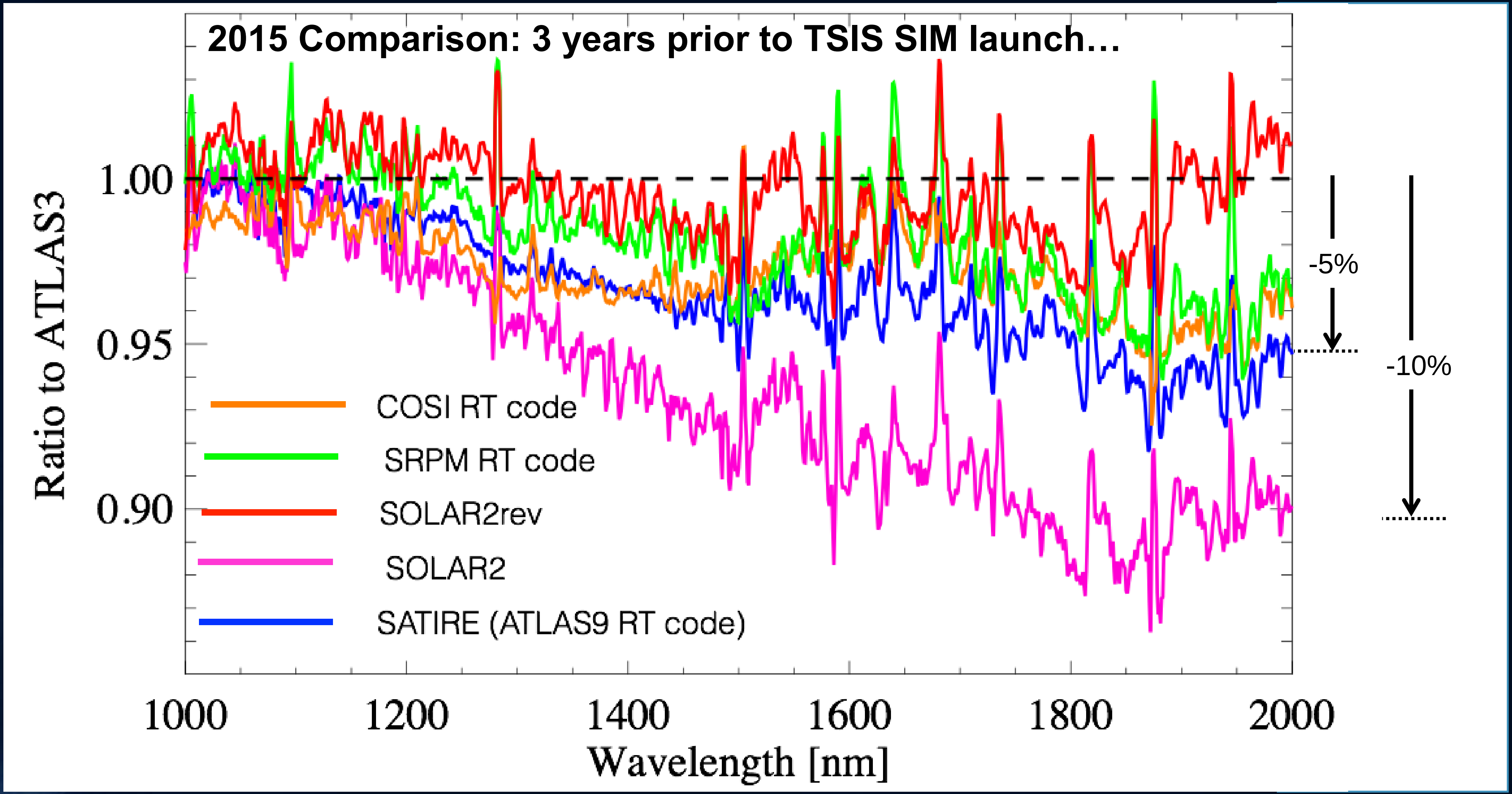


Spectrum	205-2390 (W/m^2)	+ 52 (W/m^2)*	Adopted TSI value (W/m^2)	Diff from TSI (W/m^2)	% Diff.
ATLAS3 ‡	1333.6	1385.6	1361	+ 24.6	+ 1.8
LASP-WHI ‡	1321.0	1373	1361	+ 12.0	+ 0.9
SOLAR-ISS	1320.8	1372.8	1361	+ 11.8	+ 0.9
TSIS-1 SIM	**1309**	**1361.0**	**1361.5**	**- 0.5**	**- 0.04**

‡ Excludes normalization to TSI (ATLAS3, LASP-WHI)

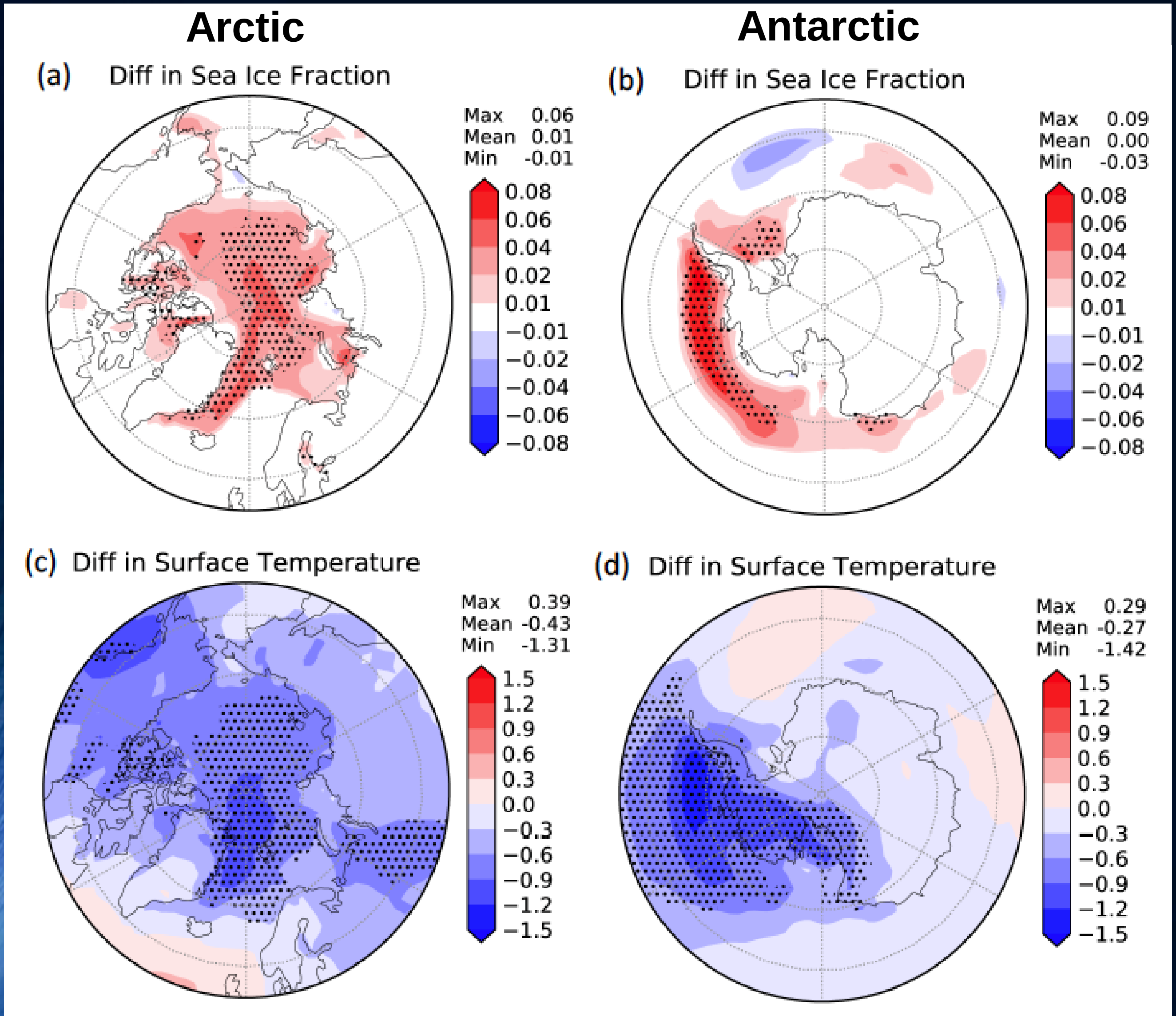
*Scalar offset: i.e., the unmeasured part of spectrum (mostly >2390 nm)

Models lower than ATLAS-3 in near IR



Gerard Thuillier et al., "*SOLSPEC onboard the International Space Station: Absolute Solar Spectral Irradiance in the Infrared Domain and Comparison with Recent Solar Models*", 2015 Sun-Climate Symposium, Savannah, Georgia, USA

Solar Irradiance Spectrum Difference has Significant Impacts on Arctic Sea Ice Fraction and Surface Temperature



NCAR CESM2 Simulations

Method:

The recent TSIS-1 mission has provided more accurate SSI observations than before. The SSI difference in a given VIS or NIR band can be as large as 4 W m^{-2}.

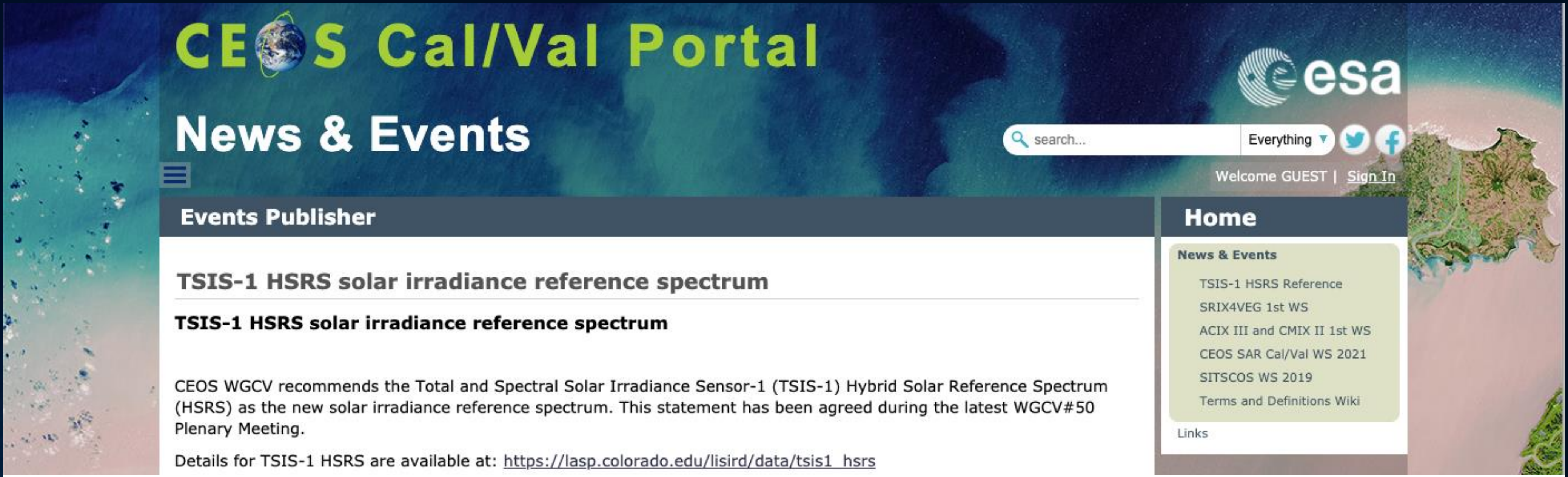
Impact:

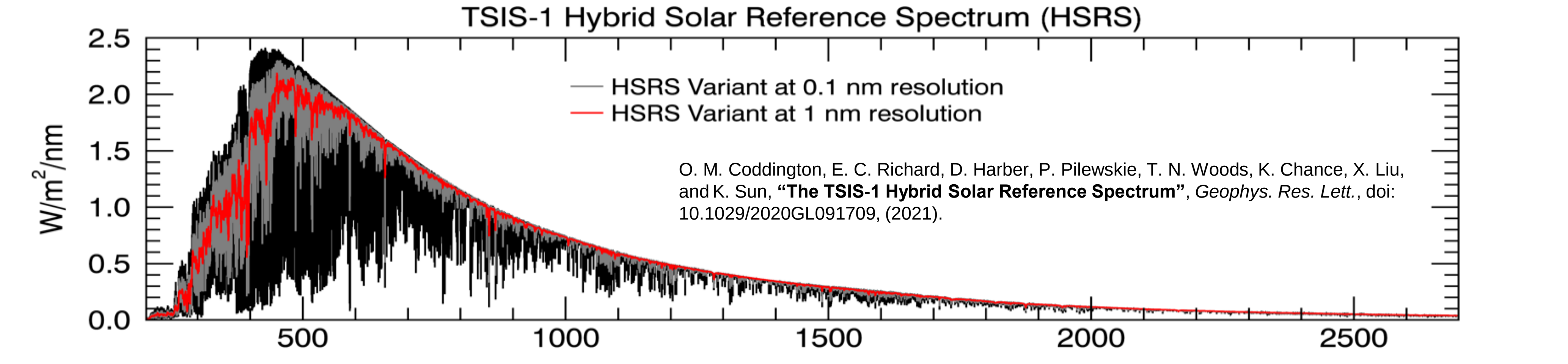
The results show that, due to different spectral reflectance of sea ice and water surfaces in the VIS and NIR, the set of simulation with more SSI in the VIS has less solar absorption by the high-latitude surfaces, ending up with colder polar surface temperature and larger sea ice coverage.

(Jing, et al., *Journal of Climate*, 2021)

TSIS-1 HSRS Formally Recognized

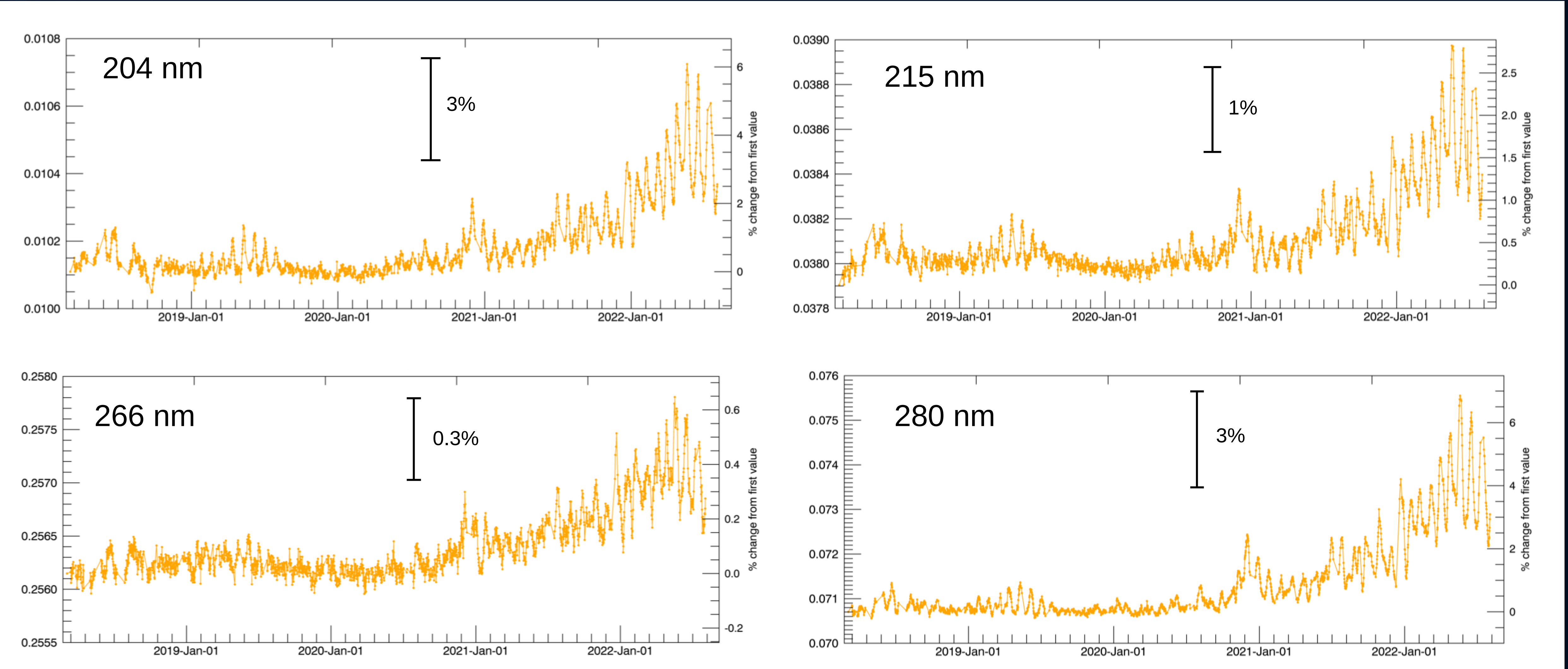
March 2022: The Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) recommended the TSIS-1 HSRS as the new solar irradiance reference spectrum [https://calvalportal.ceos.org/events/].



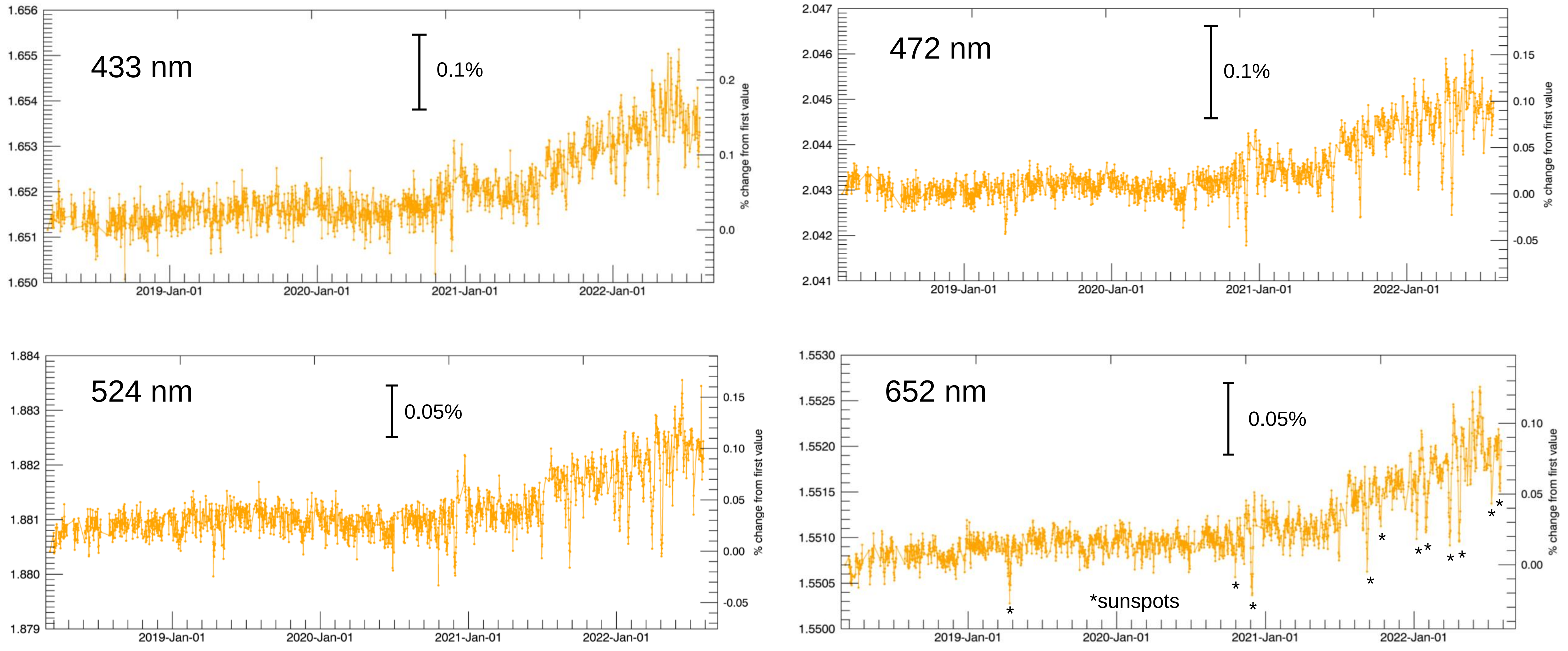


TSIS-1 Long-term SSI (from Solar Minimum into SC 25)

TSIS-1 SIM Ultraviolet Time Series (4.5 years)

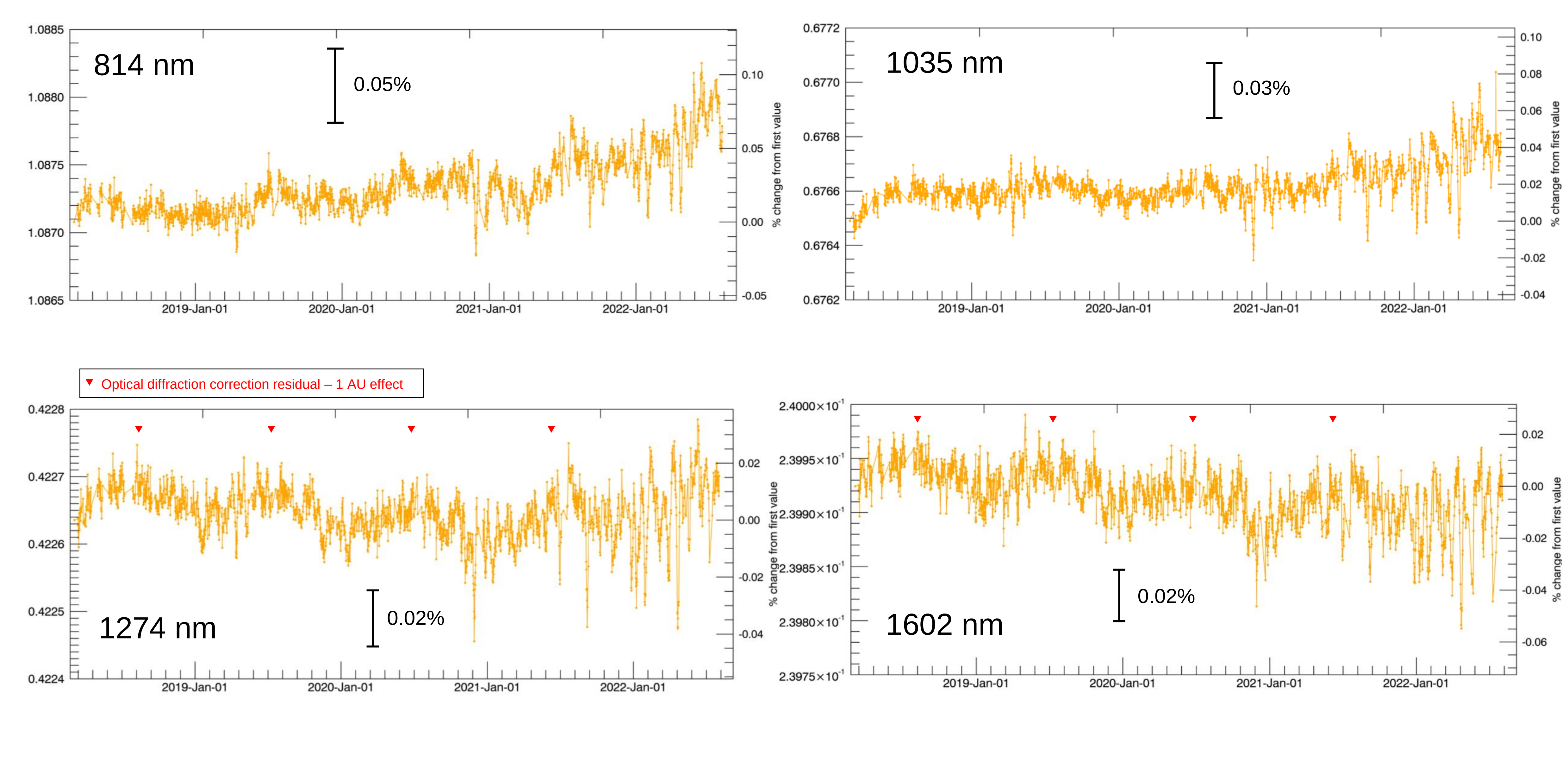


TSIS-1 SIM Visible Time Series (4.5 years)

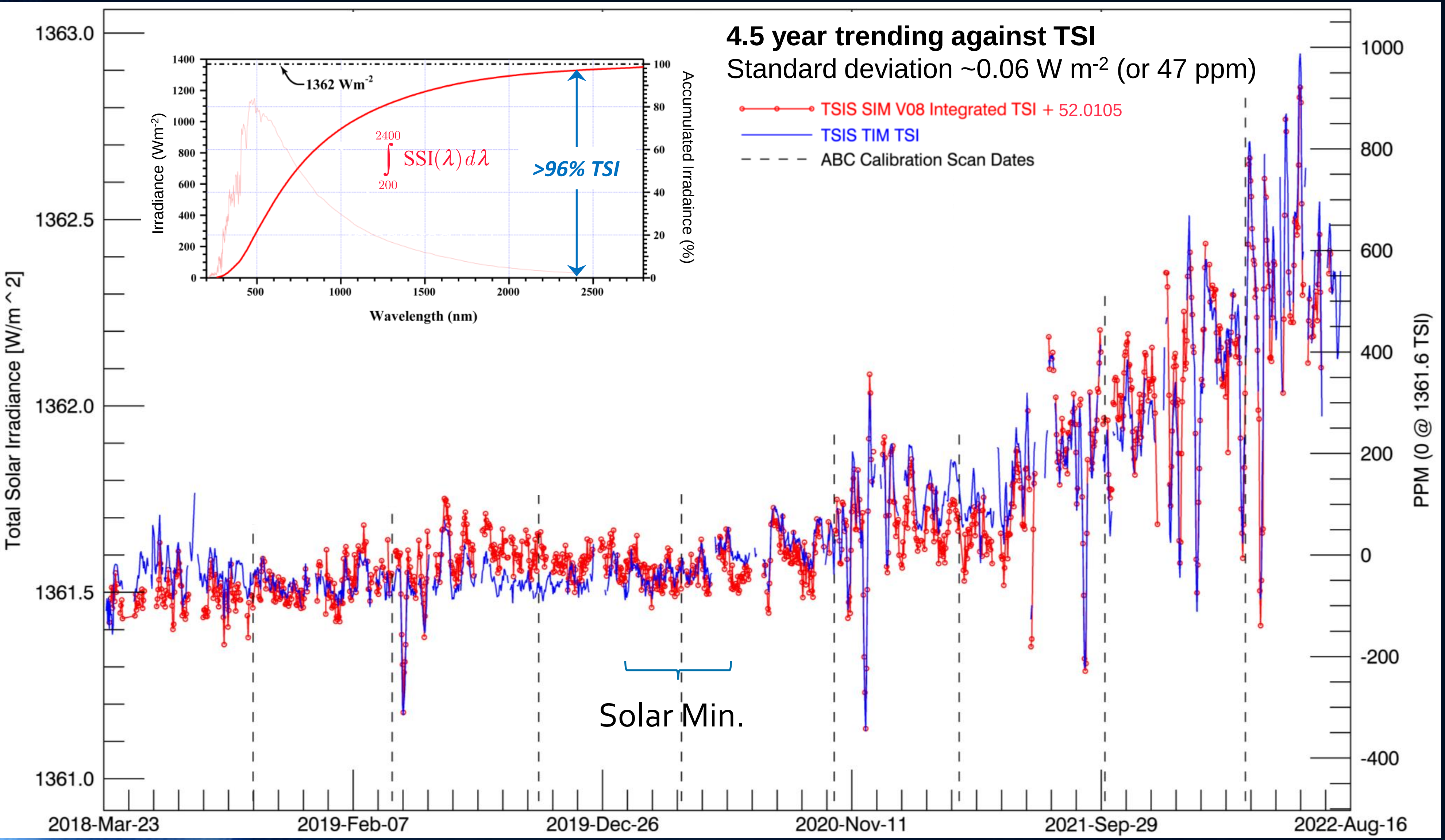


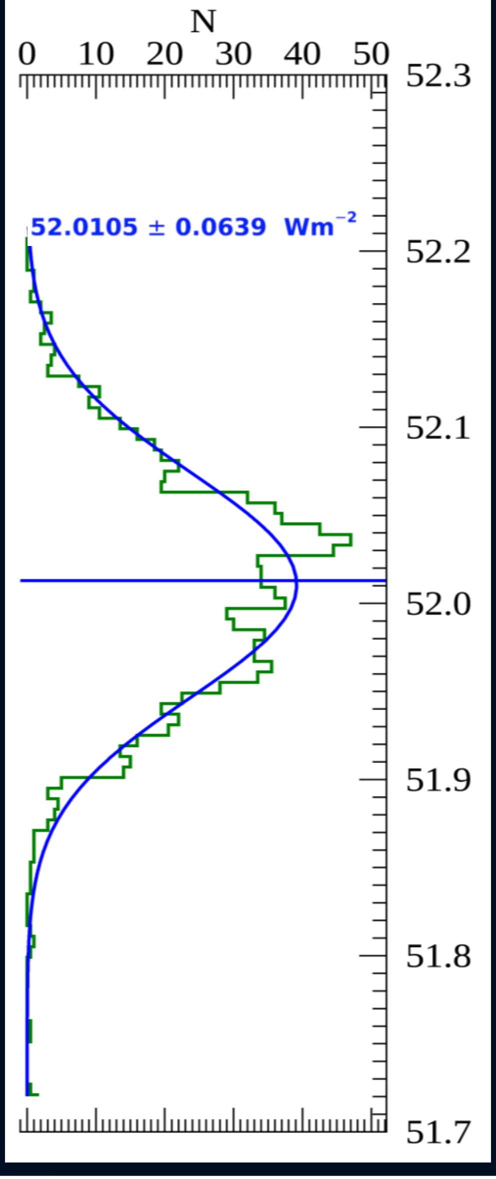
All variability consistent with TSI – No out-of-phase SC behavior in Visible shown in SORCE SIM

TSIS-1 SIM Infrared Time Series (4.5 years)



Integrated SIM SSI vs. TIM TSI Comparison



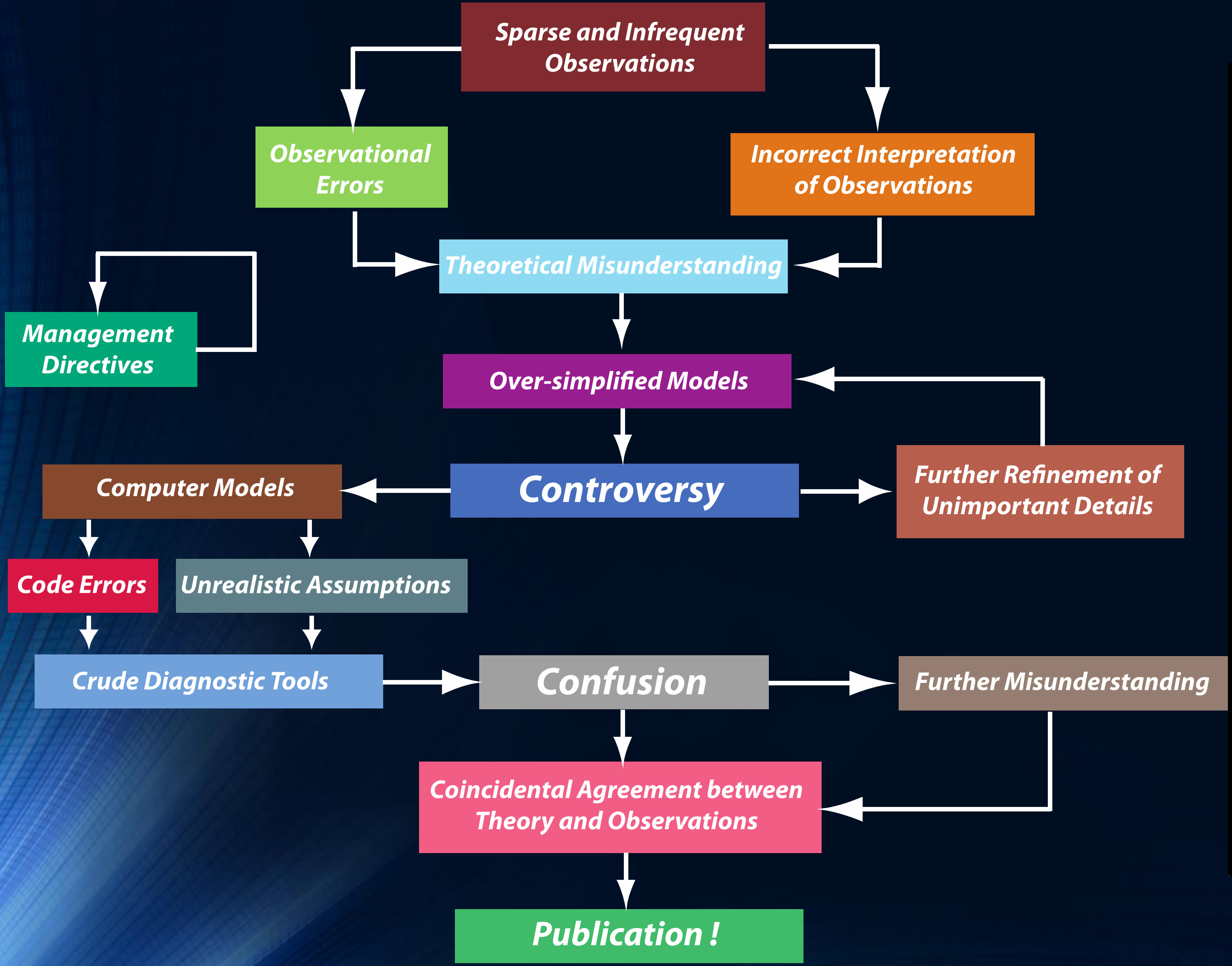


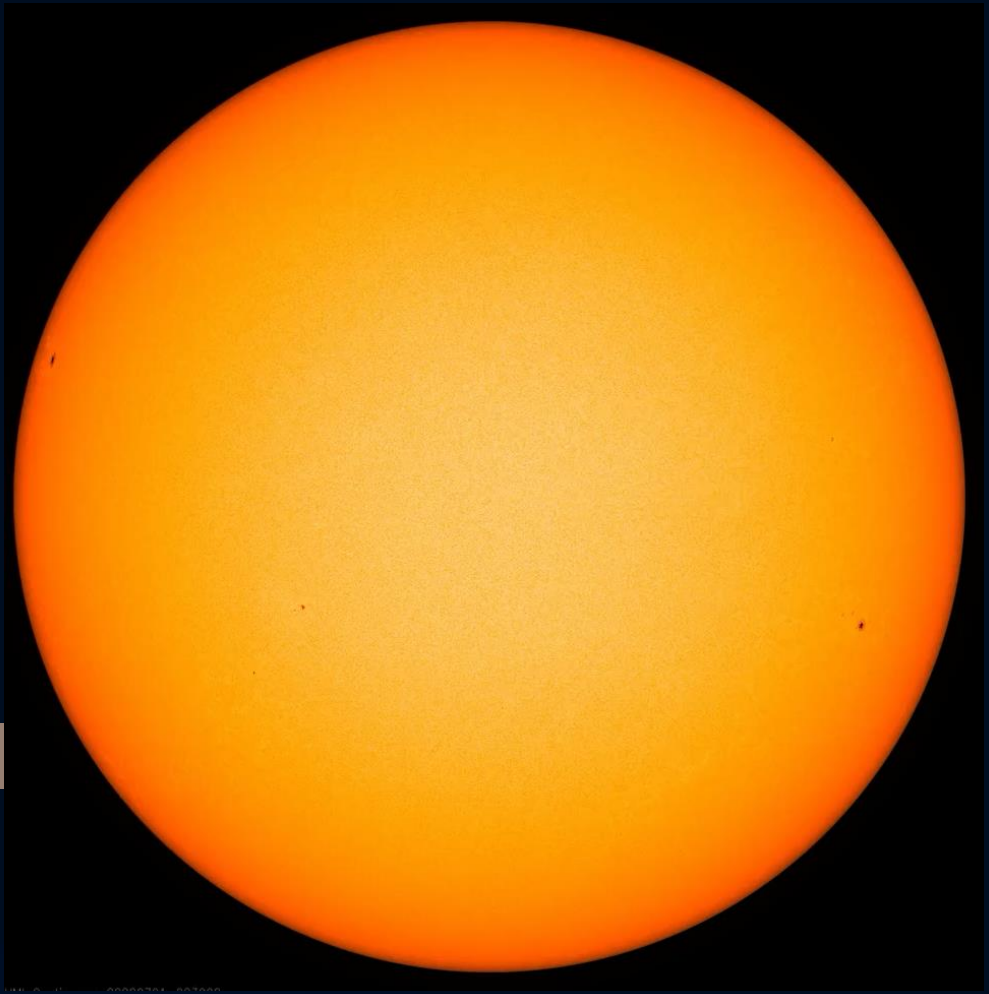
Measured vs. Model SSI Comparisons

“I’m sorry…if you were right, I’d agree with you”

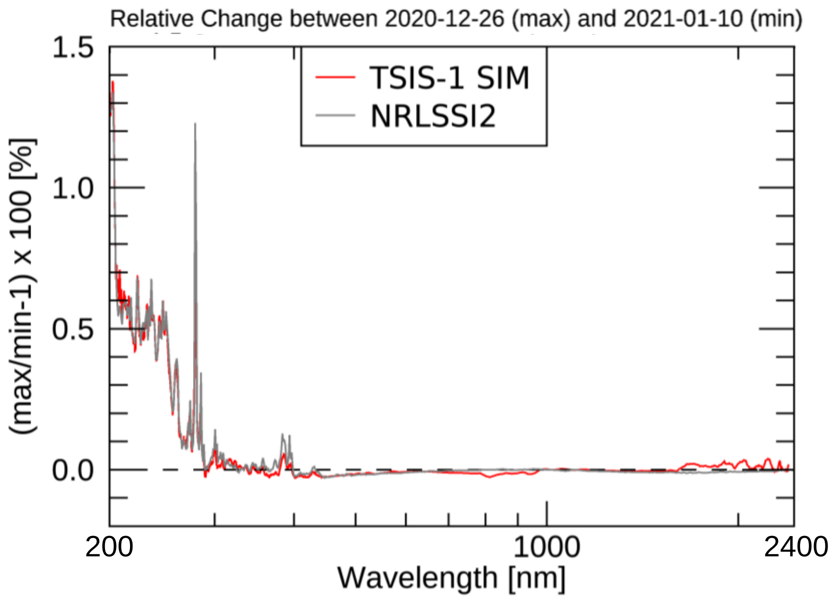
- Robin Williams

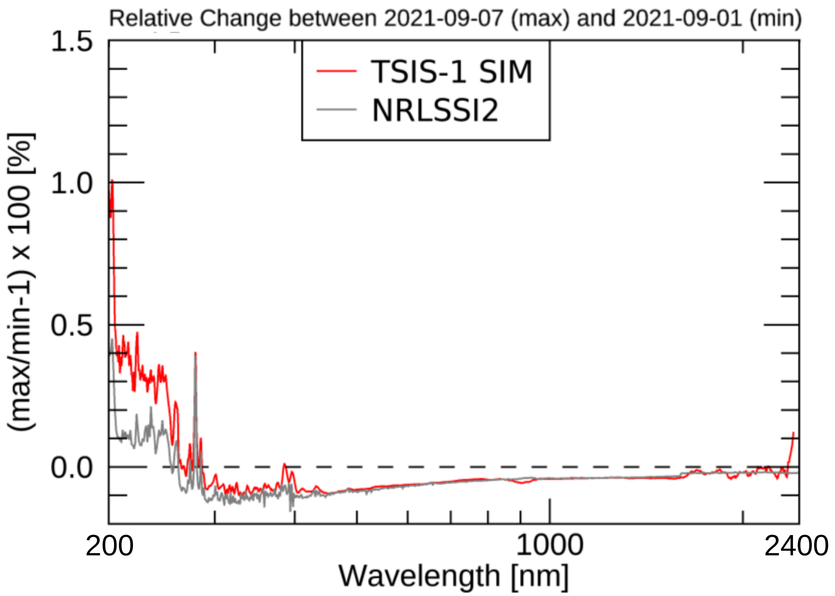
The prior state of SSI Measurements and Models



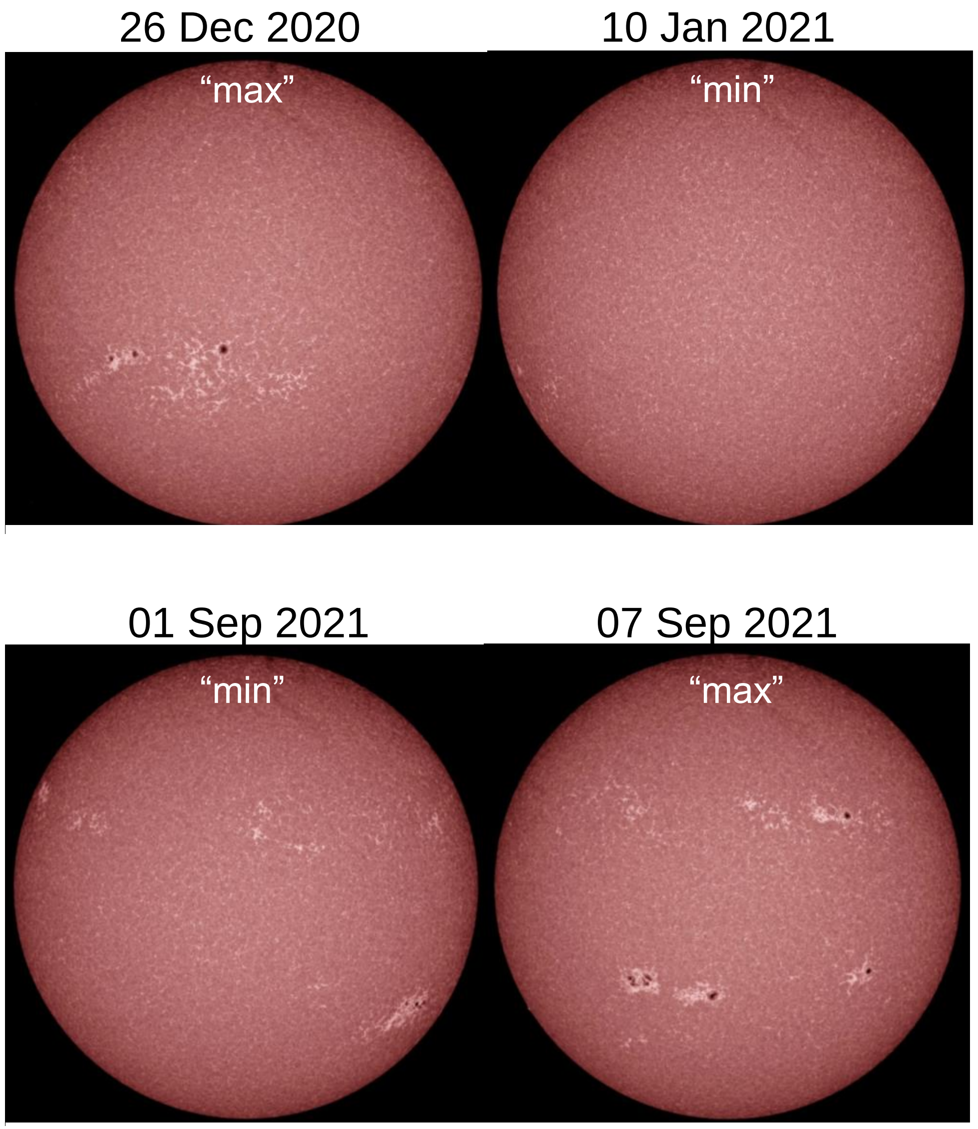


Short-term spectral variability: Measured vs. Modeled





Onset of Solar Cycle 25

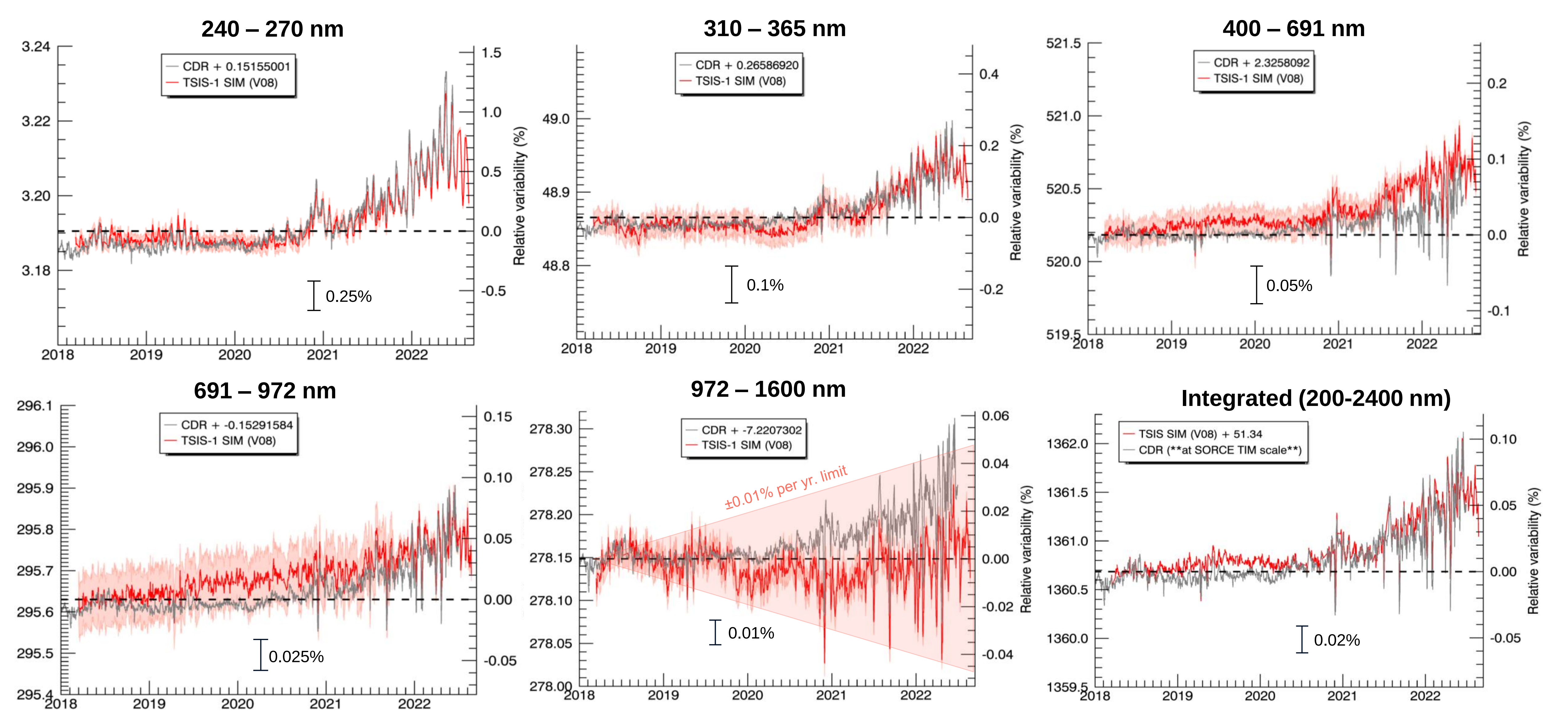


NASA SDO AIA 1700 (https://sdo.gsfc.nasa.gov/data/aiahmi)

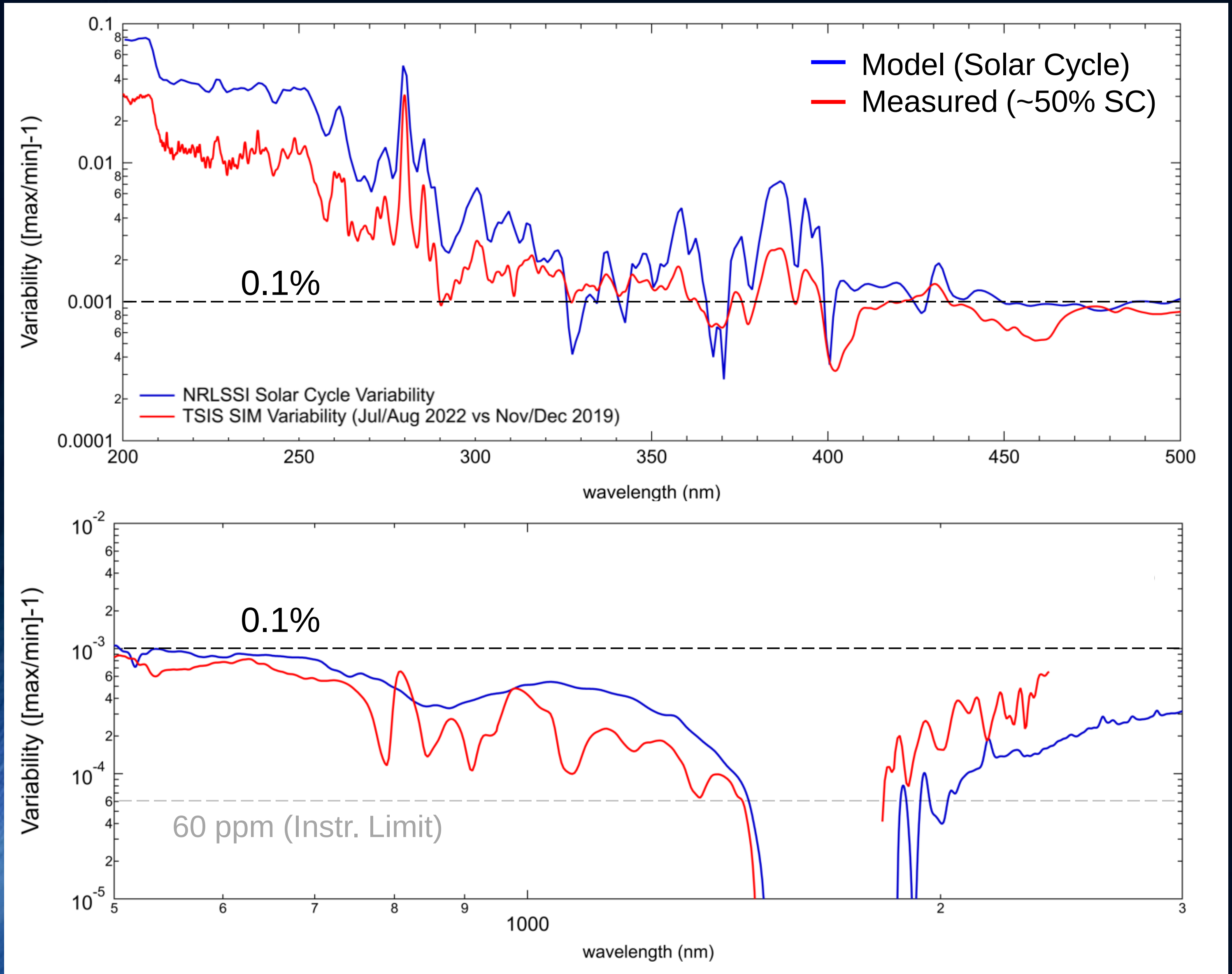
Long-term spectral variability (4.5 years): Measured vs. CDR

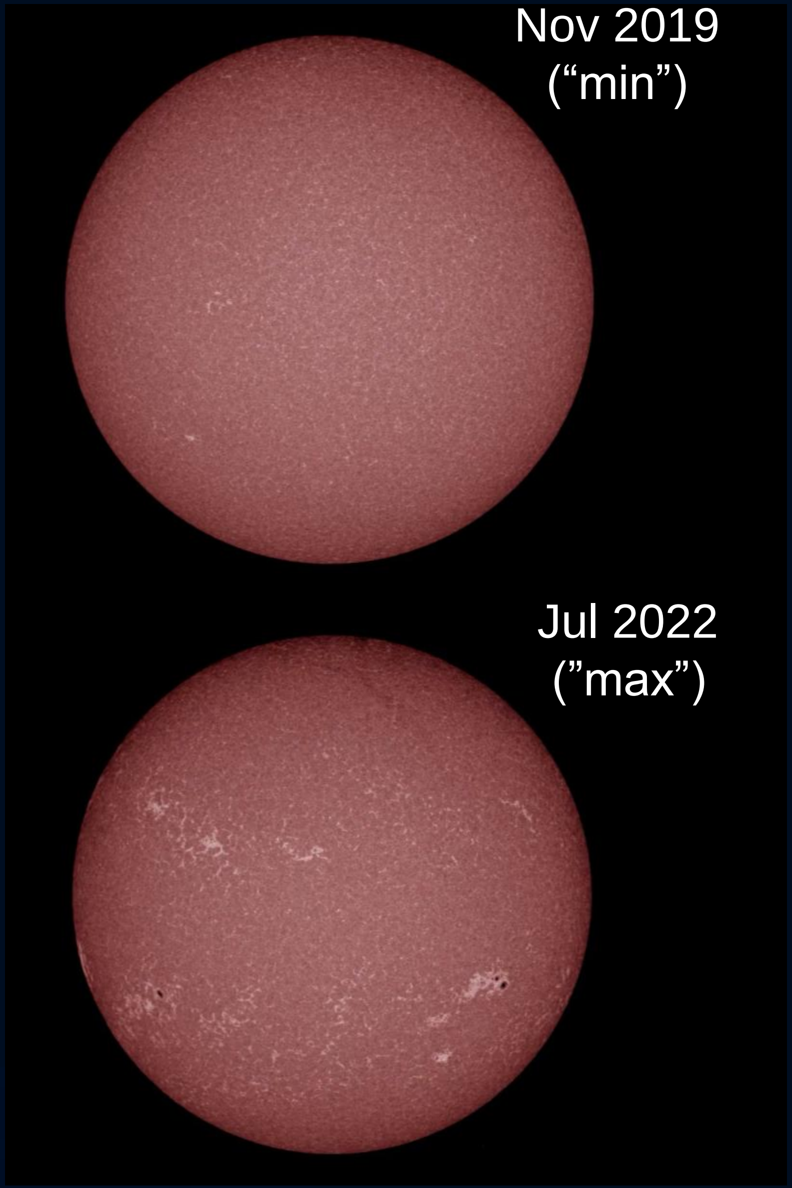
Note: CDR (Climate Data Record) is NRLSSI2 model based on SORCE scales

TSIS-1 SIM V08 is latest SSI data release



TSIS-1 SIM Long-term Spectral Variablity





NASA SDO AIA 1700 (https://sdo.gsfc.nasa.gov/data/aiahmi)

New Technology Infusion

"Even if you're on the right track, you'll get run over if you just sit there"

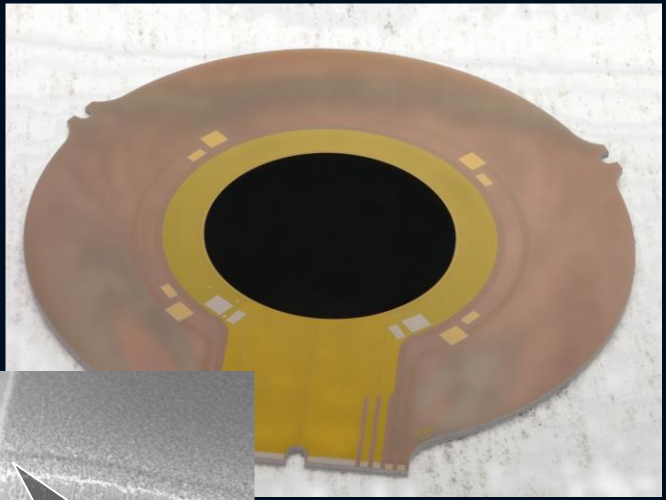
- Will Rogers

LASP-NIST Advanced Component Technologies Developments

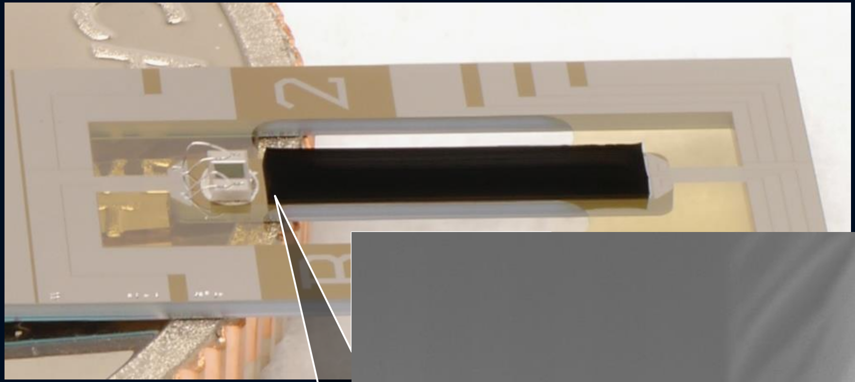
"Key Next-Generation Technologies"

- **Silicon-Based Bolometers**
  - Developed/fabricated by NIST Boulder
  - Vertically aligned carbon nanotubes (Typical absorptance >99.9%)
  - Integrated heater
- **Deep Reactive-Ion Etched Apertures**
  - Fabricated by NIST Boulder
  - Fabricated to extremely high tolerances (very low area uncertainties, 10's ppm)
  - Very small CTE, High thermal stability

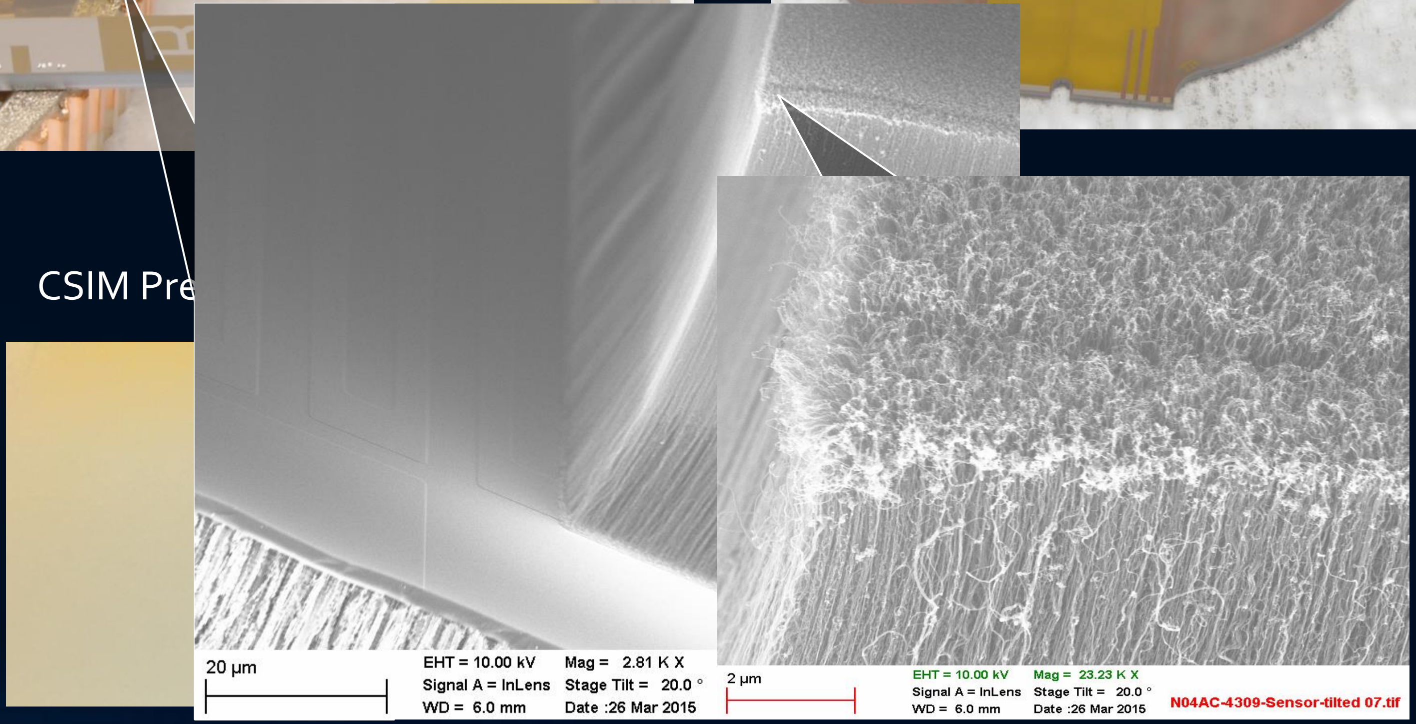
CTIM Bolometer



CSIM Bolometer



CSIM Pre

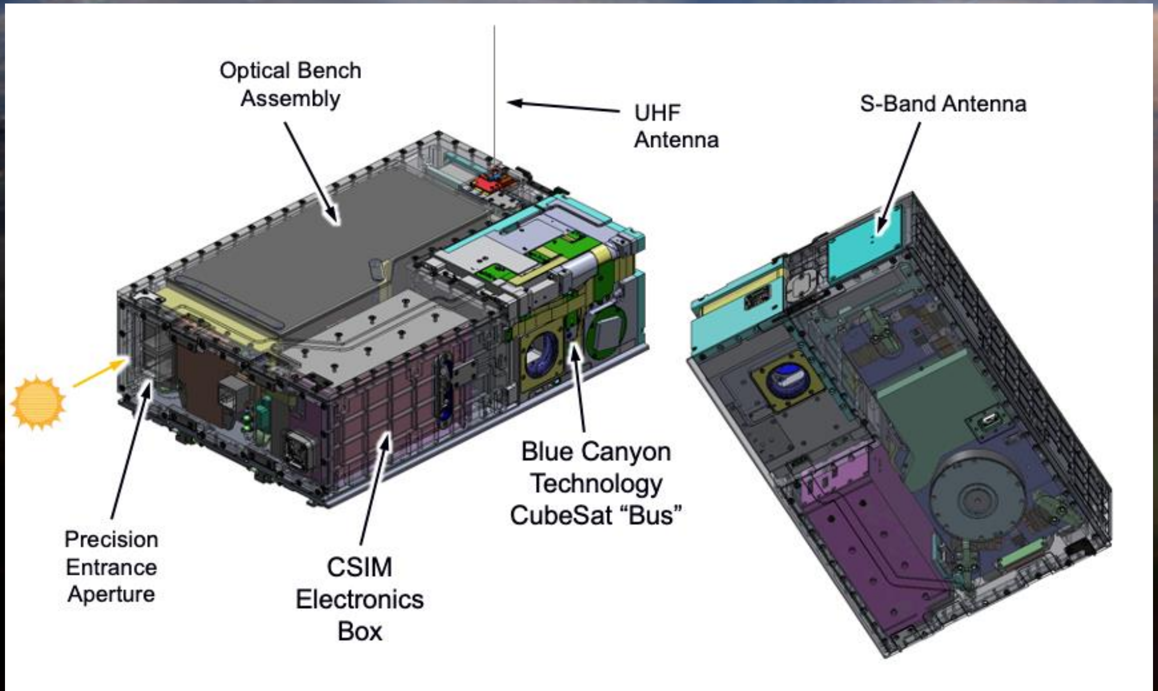


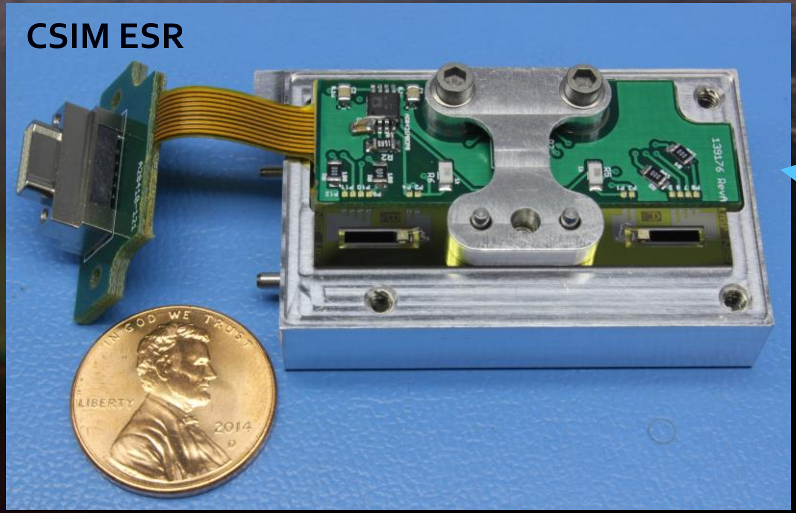
CSIM-FD IIP & InVEST: Compact Spectral Irradiance Monitor

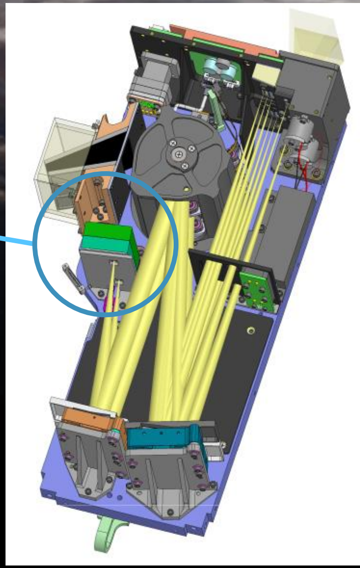
"Next Generation" SSI Measurement

CSIM is a compact solar spectral irradiance monitor that is a cost-effective and low risk alternative instrument designed for considerable implementation flexibility, high calibration accuracy and performance stability for obtaining high-priority Earth Science measurements.

Goal: Achieve **flight-qualified instrument** for LEO operational demonstration and TSIS validation. (Launched Dec 2018, EOM Feb 2022)

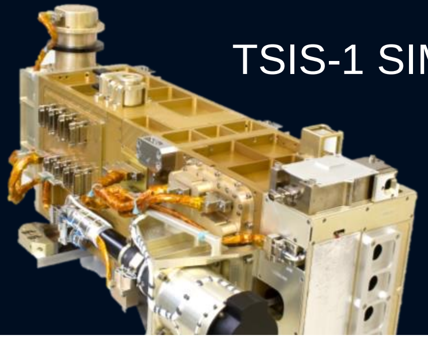




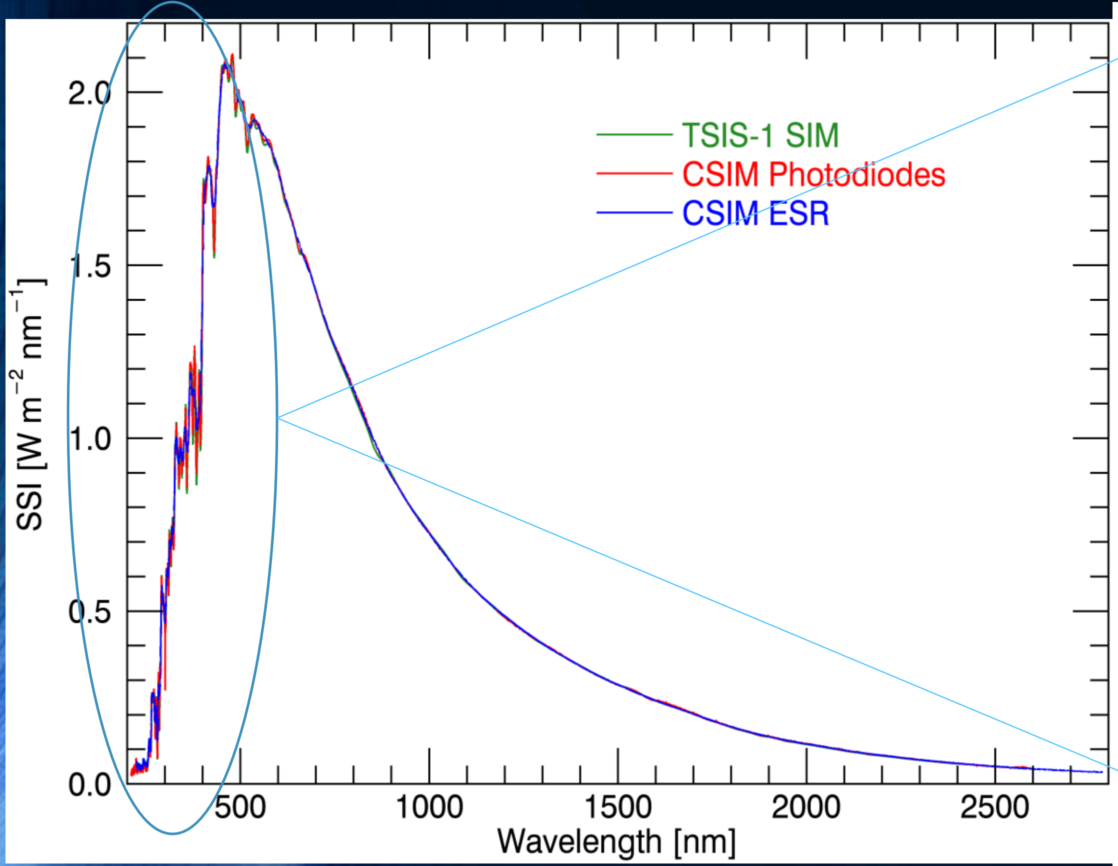


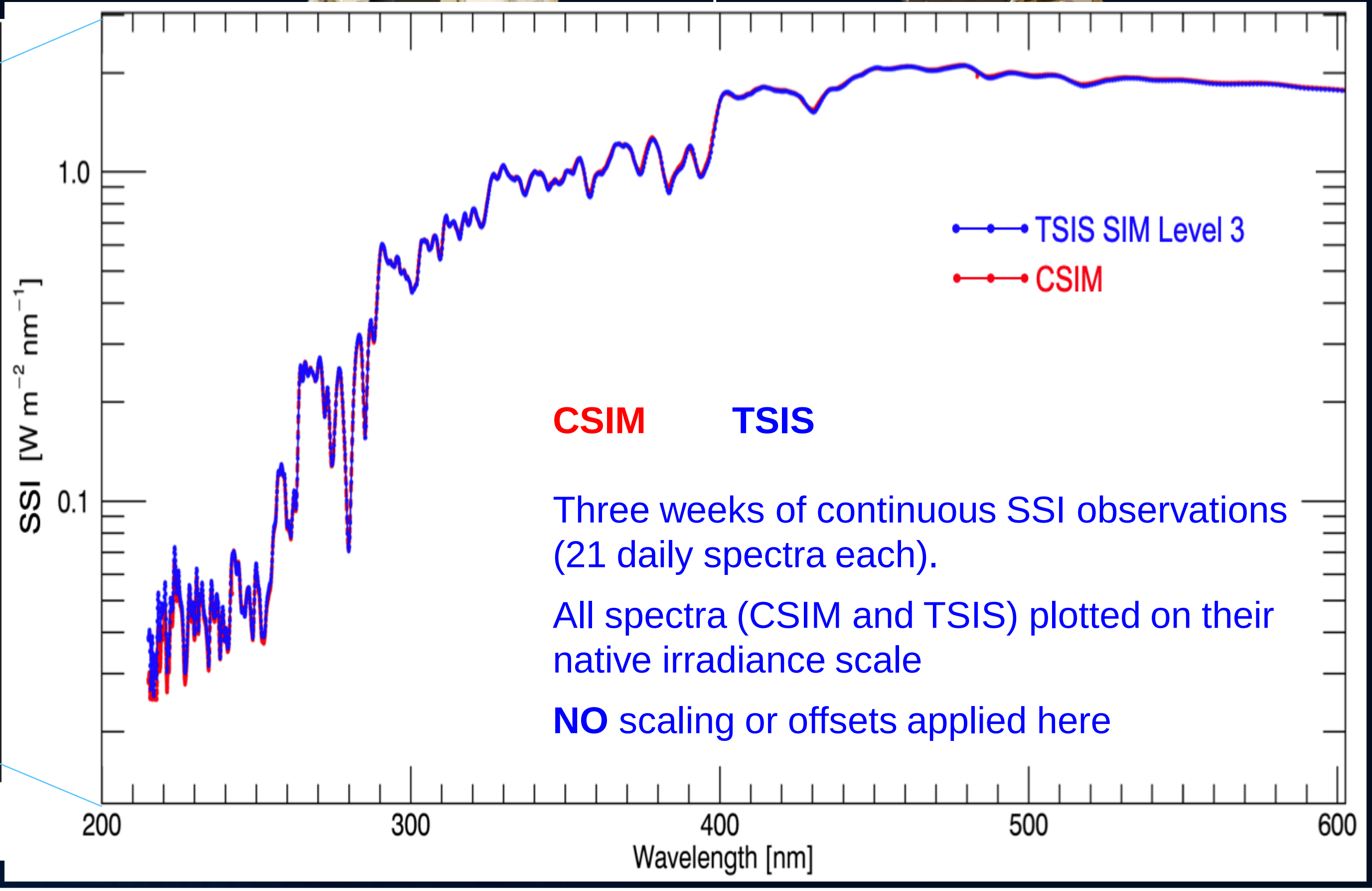
TSIS – CSIM Absolute Solar Spectrum

Solar Spectral Irradiance (SSI) measurements by TSIS-1 SIM and CSIM during solar minimum period resulted in a newly established SSI reference spectrum for Earth Science applications



Equal



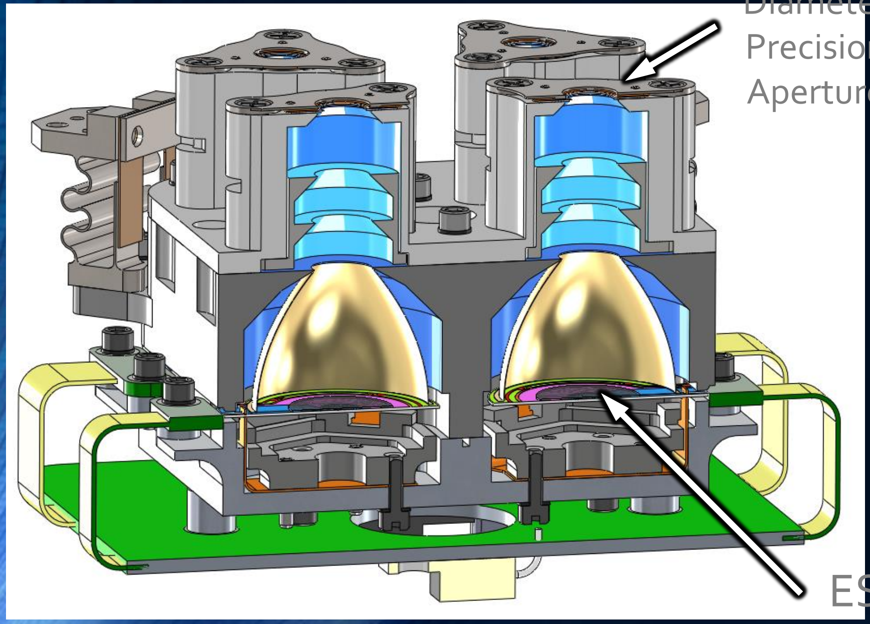


PI: Dave Harber

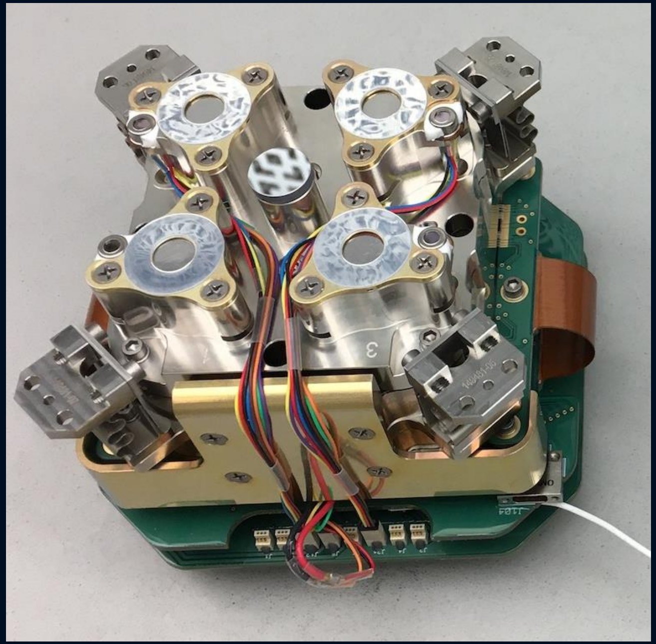
CTIM-FD IIP: Compact Total Irradiance Monitor
"Next Generation TIM"

CTIM Detector Head

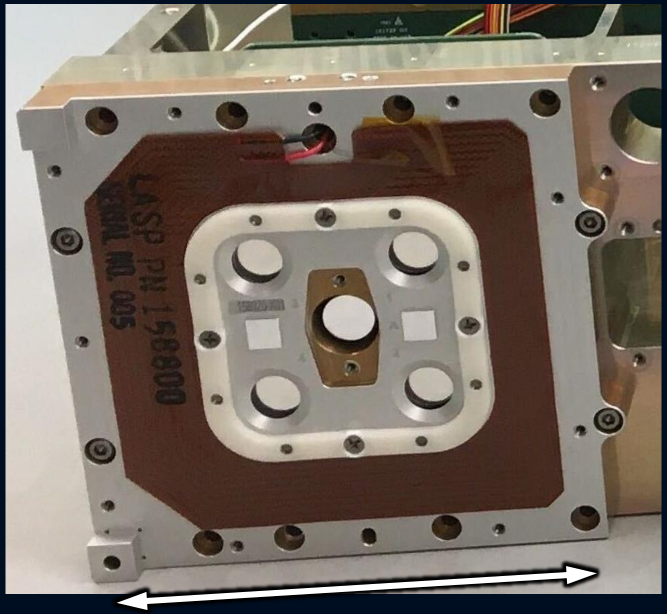
- Each detector head has four channels
  - Redundant channel degradation tracking
- Shutter for each channel



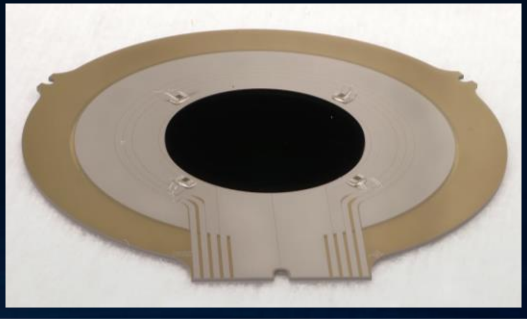
Integrated Detector Head



CTIM Detector Head

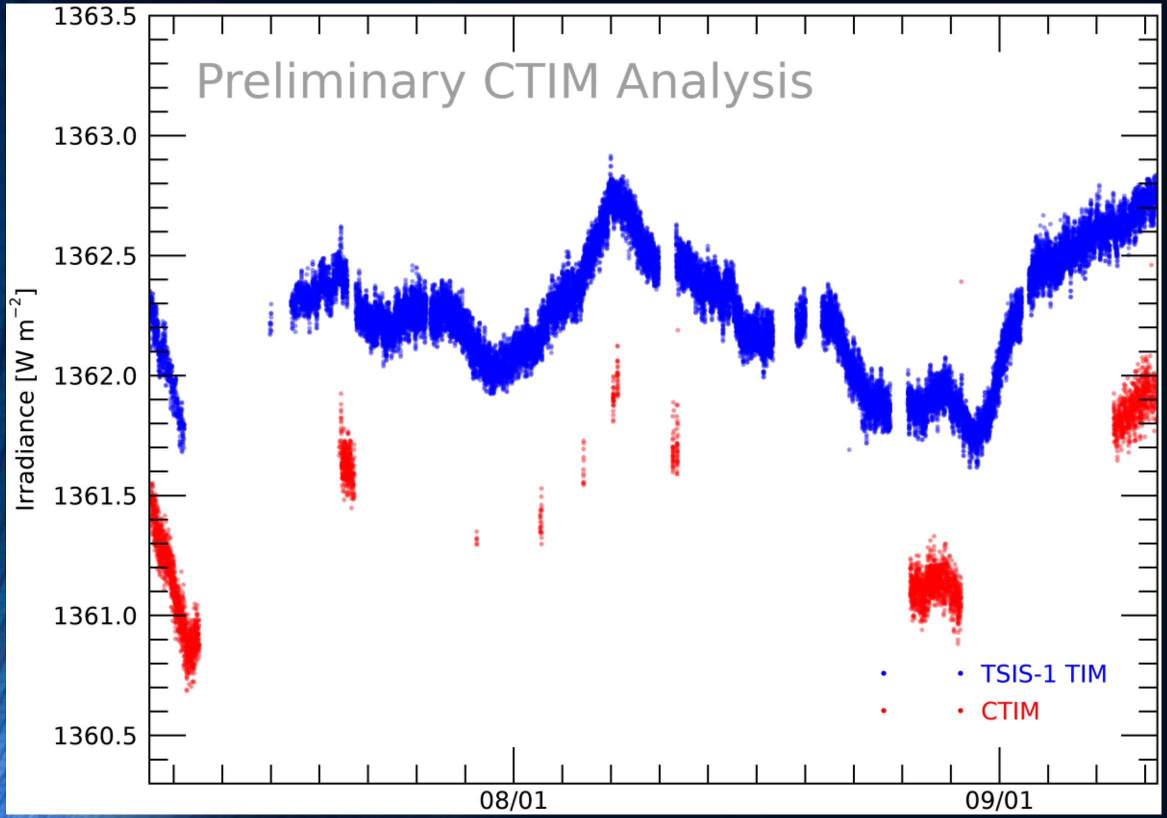


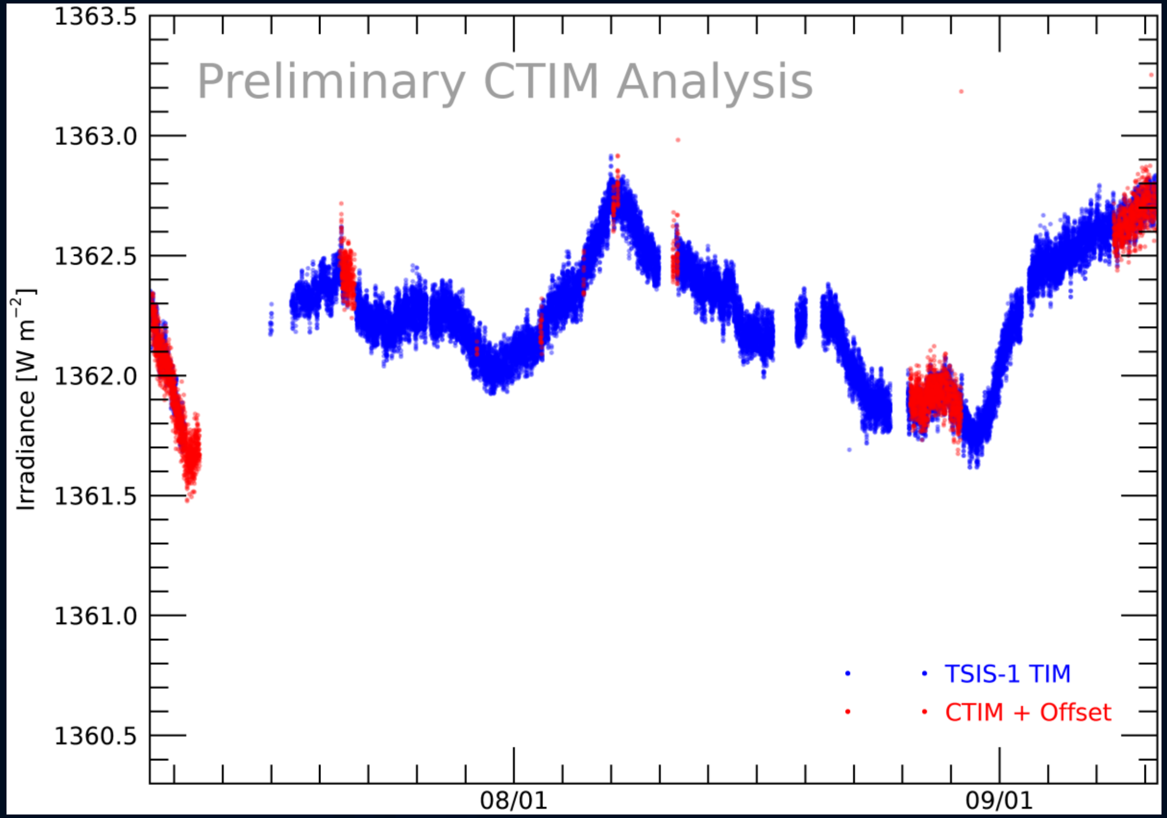
Key new technology: Silicon + Vertically Aligned Carbon Nanotubes

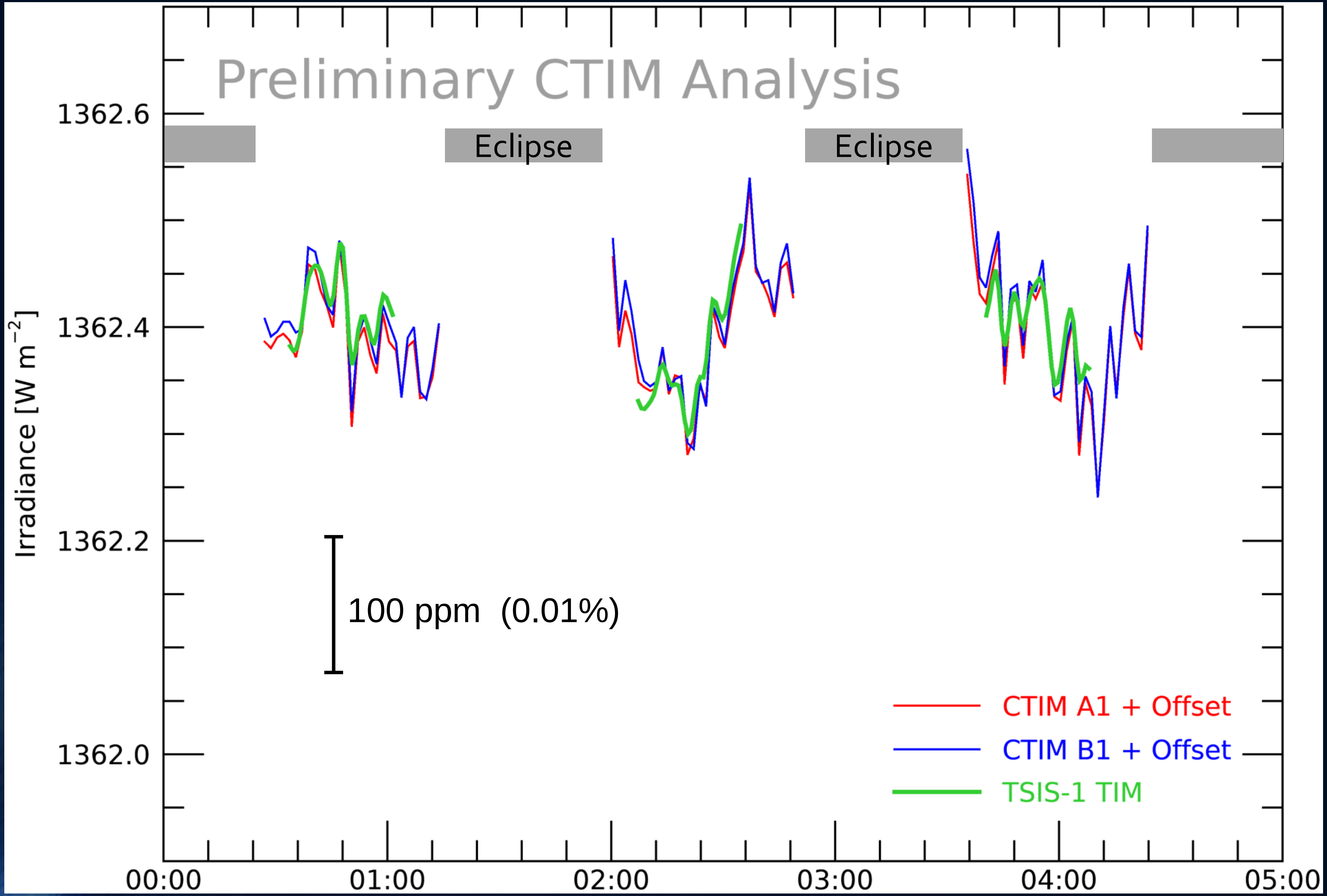


- Microfabrication allows 2D fabrication with micron-level precision
- Typical absorptance 99.9%
- Developed with NIST Boulder Sources and Detectors Group

TSI Comparison: TSIS-1 TIM vs. CTIM Preliminary






Preliminary CTIM Analysis
Eclipse
Eclipse
1362.6
1362.4
1362.2
1362.0
Irradiance [W m^{-2}]
100 ppm (0.01%)
CTIM A1 + Offset
CTIM B1 + Offset
TSIS-1 TIM
00:00
01:00
02:00
03:00
04:00
05:00