Variability in the Solar System

The Variable Universe – Lecture 02
Fall Semester 2021

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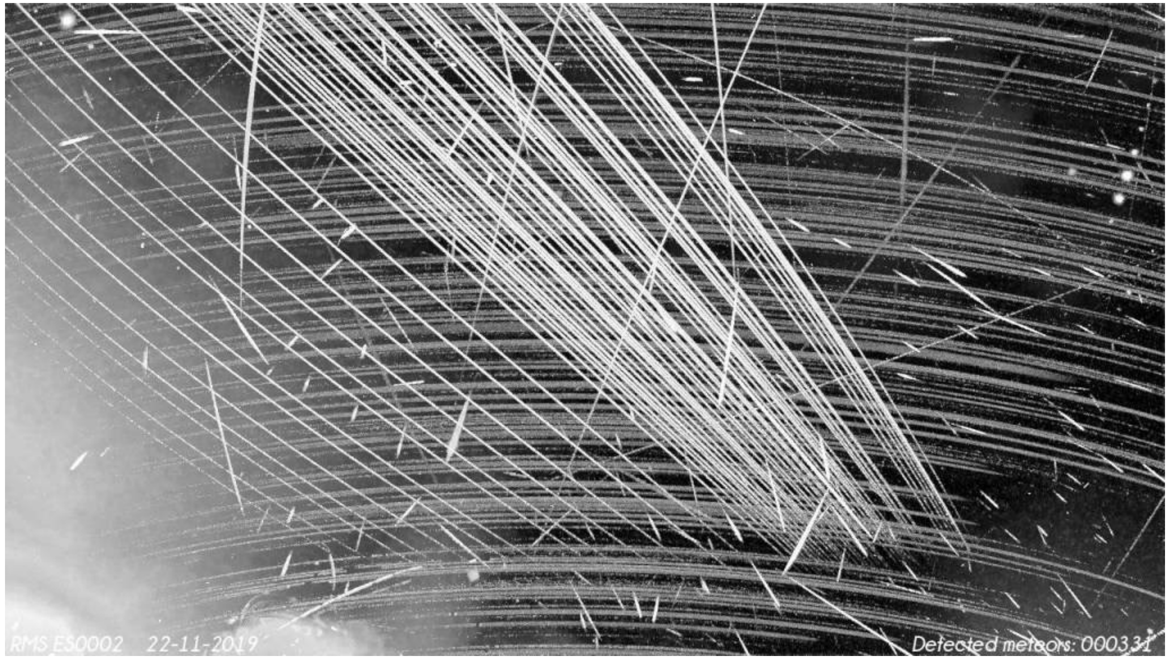
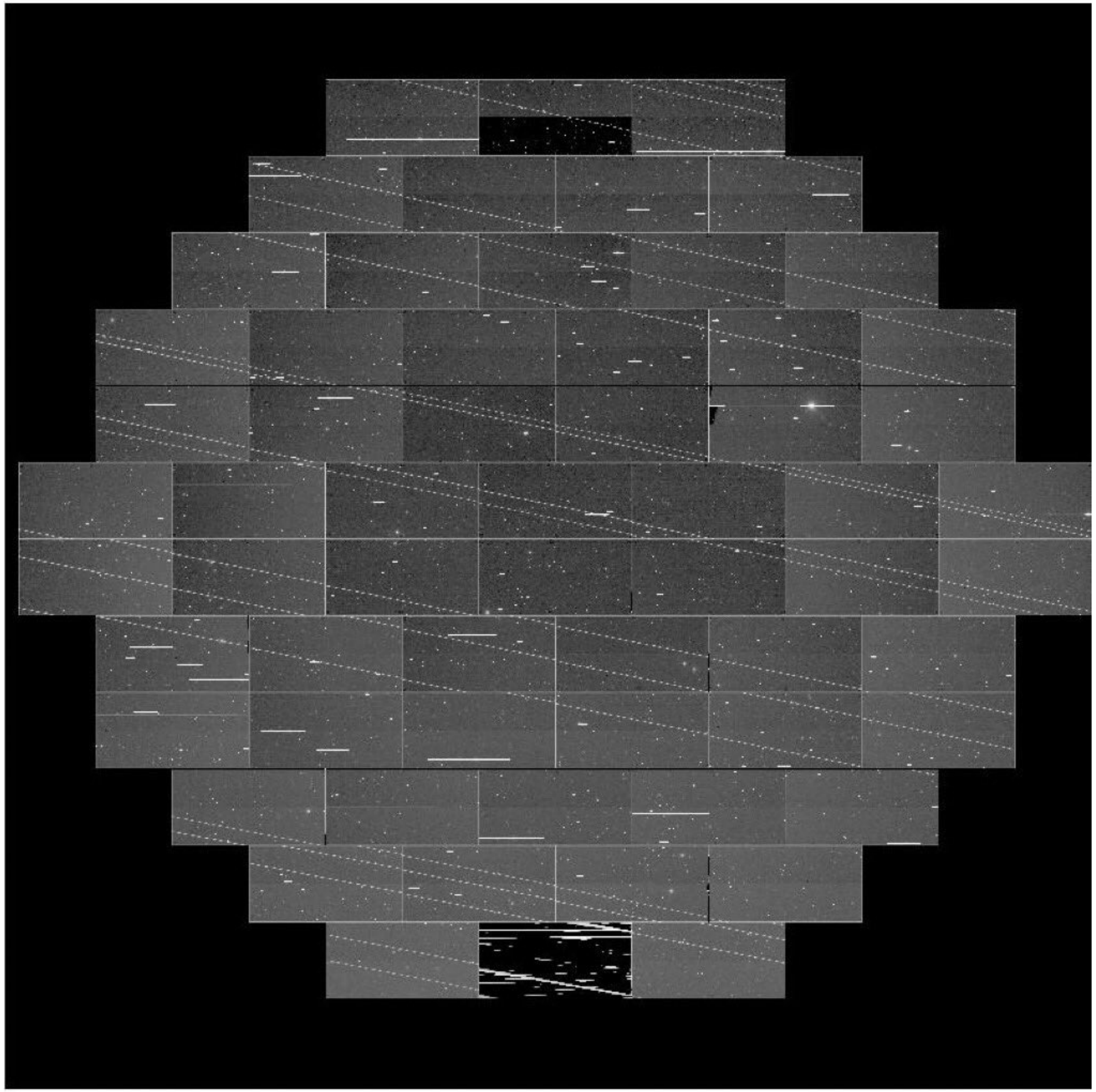
EPFL

Any questions from last week?

A human made problem for time-domain astrophysics

a human-made problem for time-domain astronomy





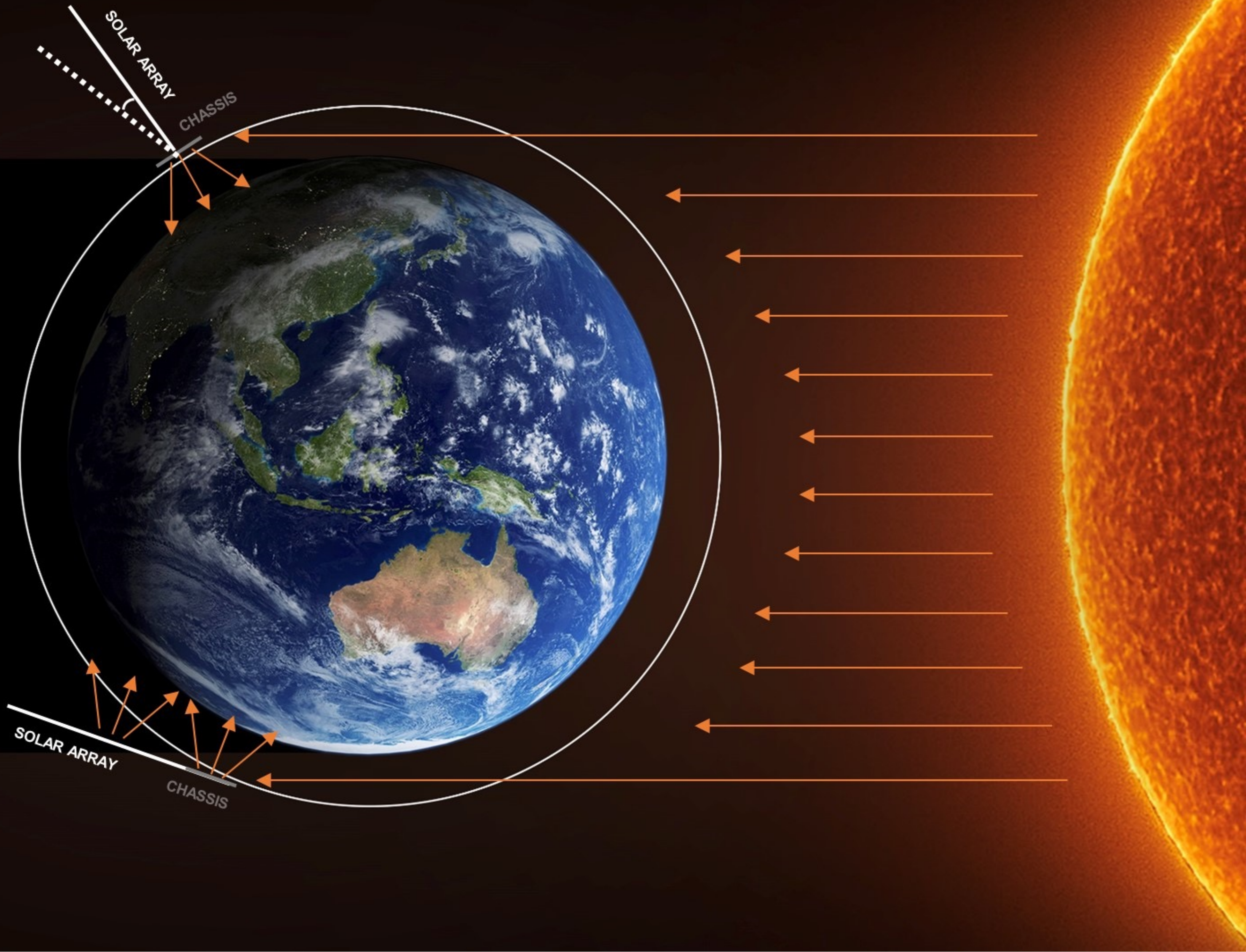
ON STATION

Add sun visor to mitigate chassis reflections

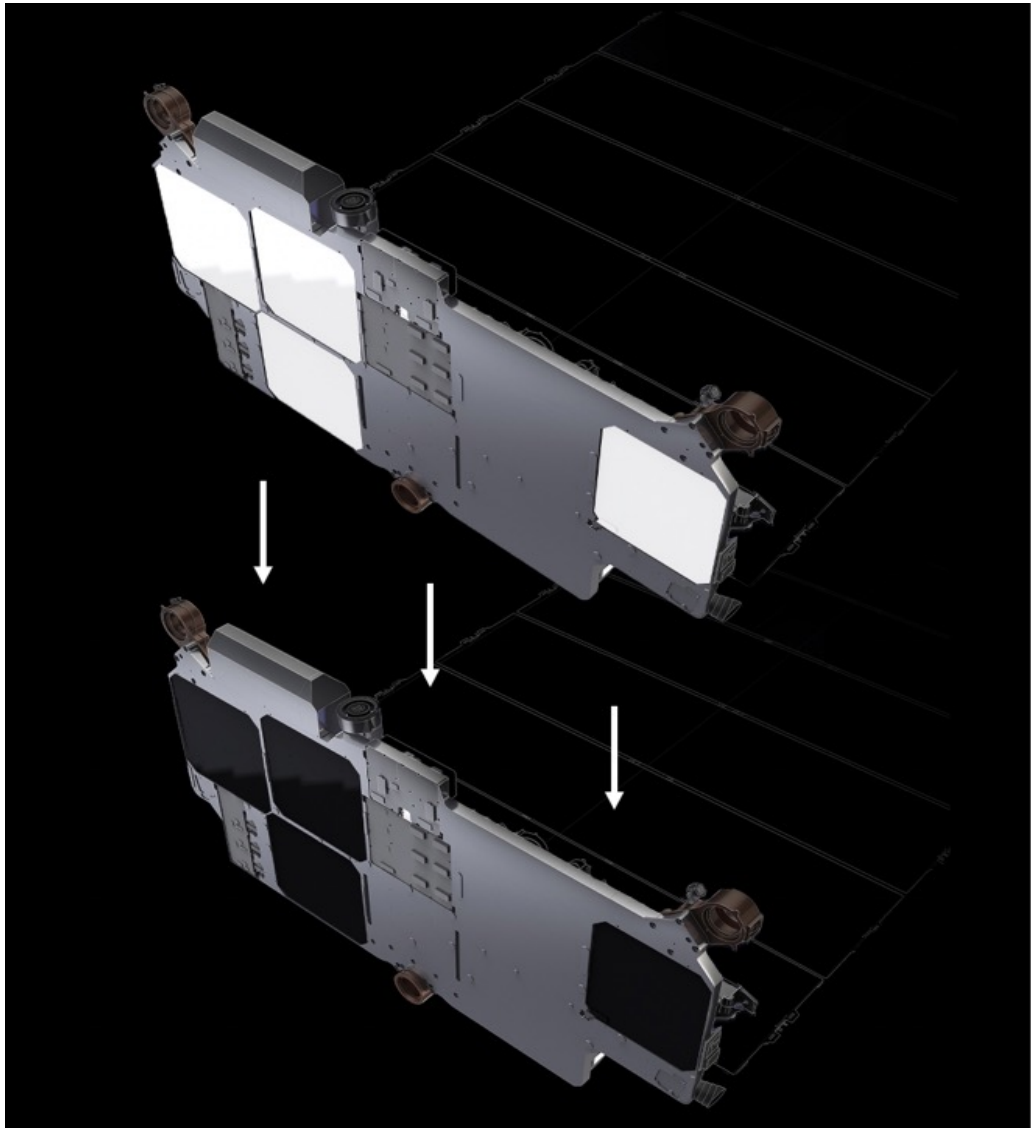
Adjust solar array angle so it is hidden behind the chassis

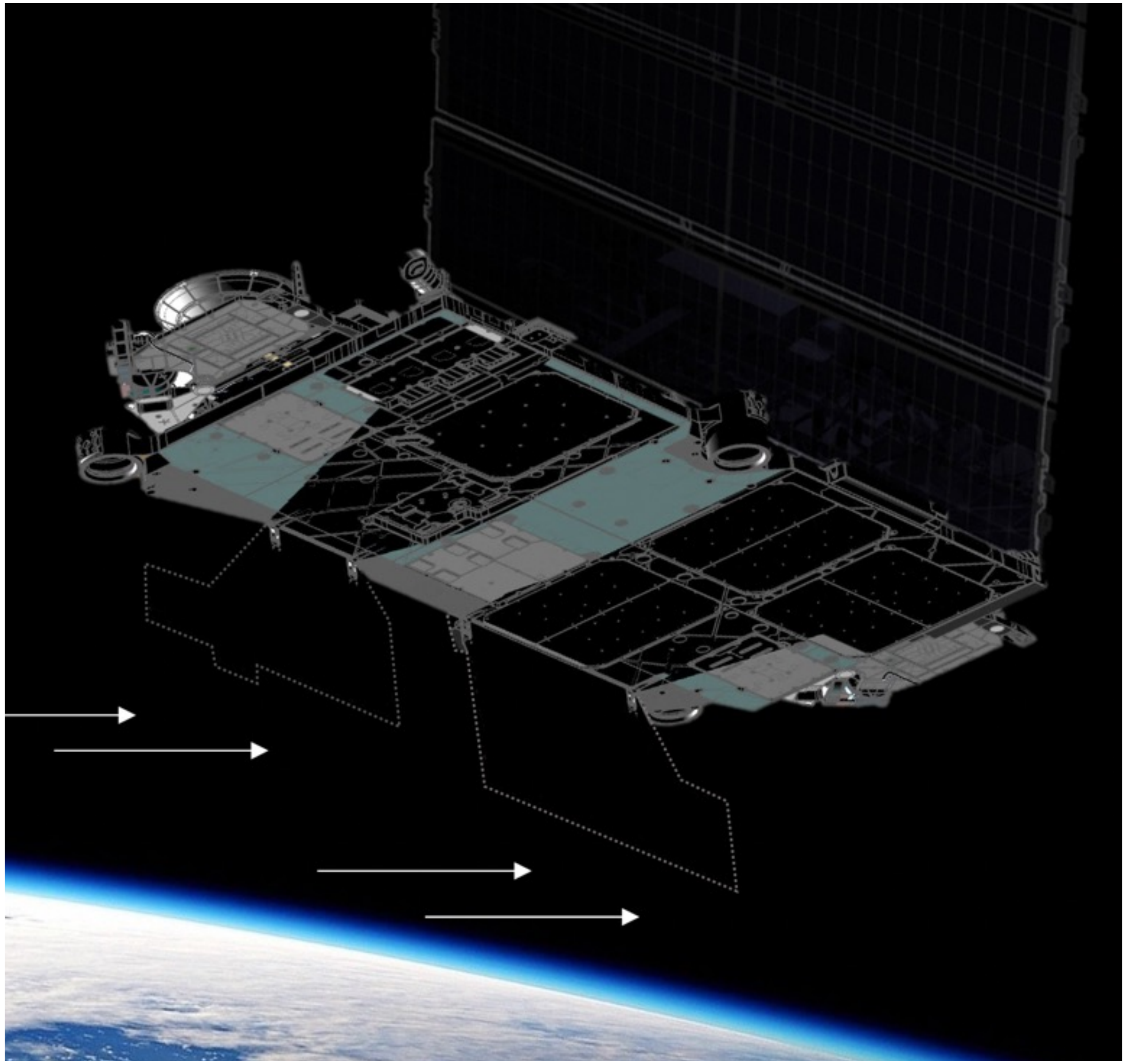
ORBIT RAISE

Roll satellite knife-edge to the sun to minimize reflect light onto the earth



Mitigations: Paint and light blockers

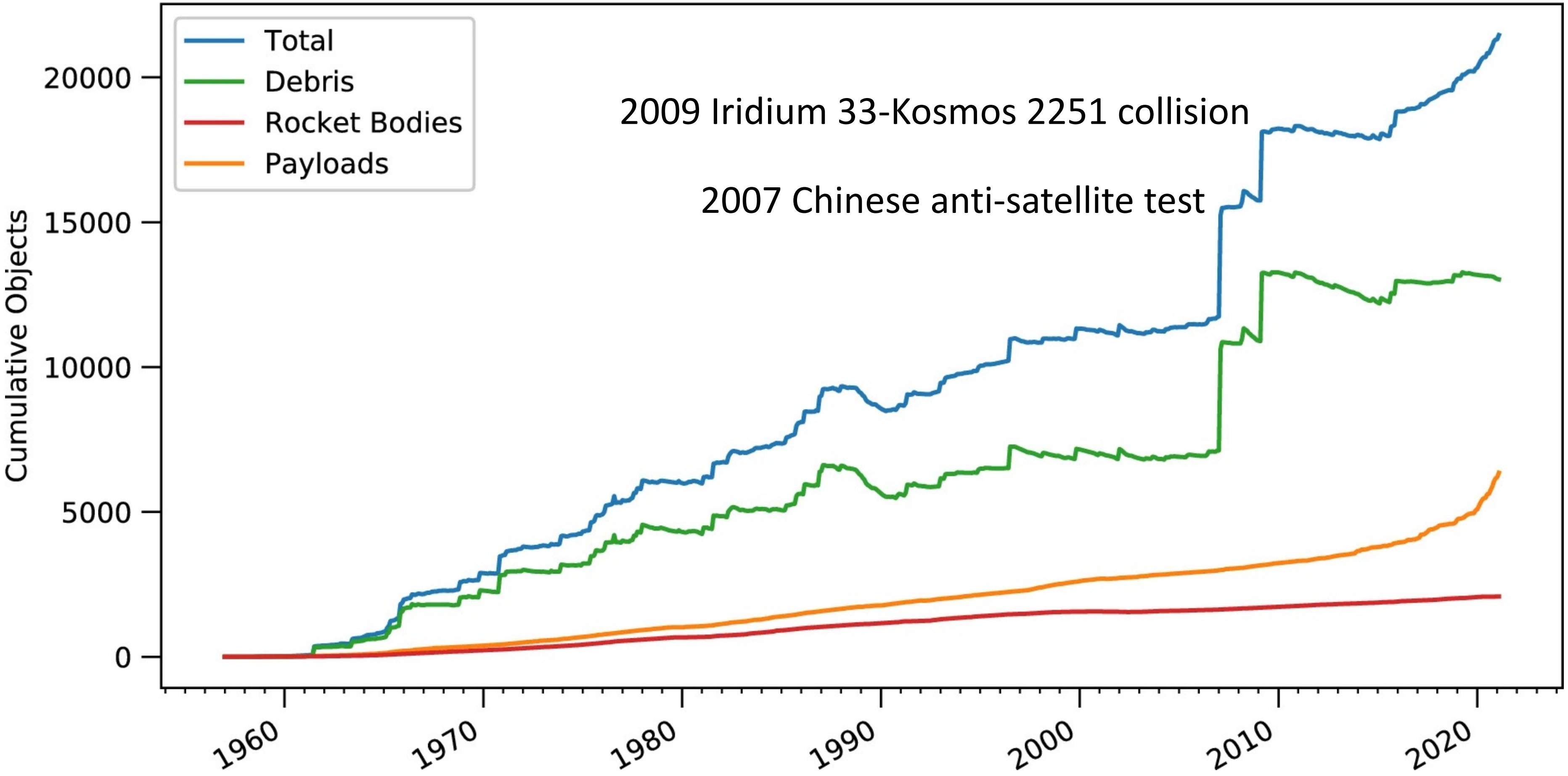




Projections

- 30 March 2021: 5000 active & defunct LEO sats
- 2019 – 2021: 50% increase, driven by SpaceX
- SpaceX: add 11000 more, requested +30000
- Total mass: 3000 tonnes (same as all current in LEO)
- 5-6 year operational time, 6 months deorbit = 10% de-orbiting at any time

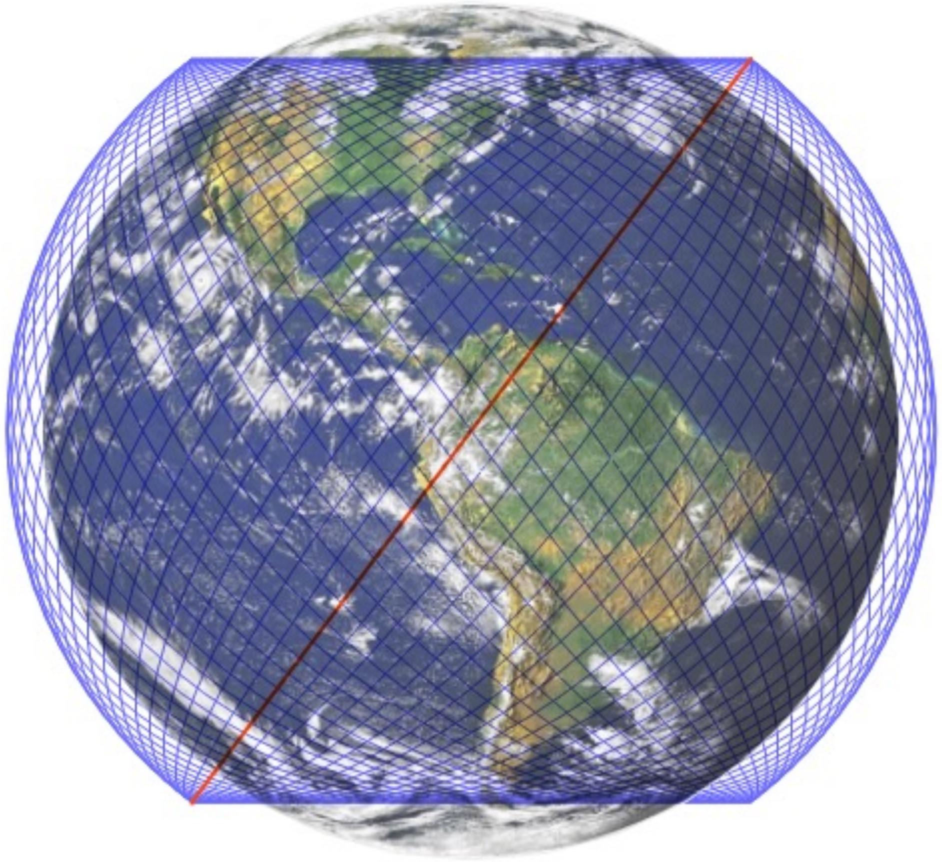
NewSpace: consumer-electronics-like space exoploitation



Boley & Byers (2021) https://www.nature.com/articles/s41598-021-89909-7

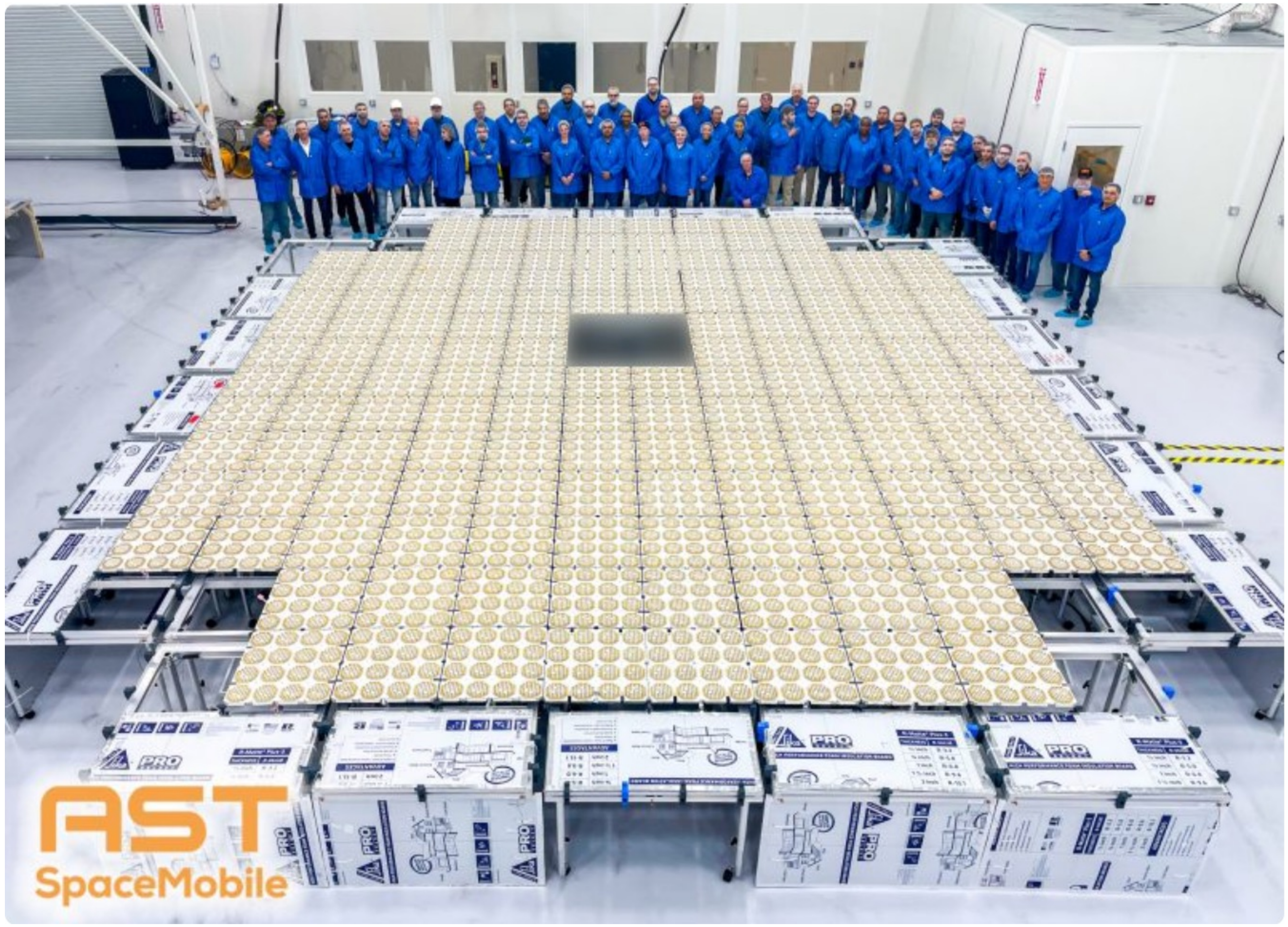
Current plans for satellite swarms

- Starlink (SpaceX): 12000 + 30000 (?) satellites, orbits 7518x340km, 4425x1200km
- OneWeb (UK+, changes ongoing): 648 satellites, ~1200km altitude
- Amazon's Project Kuiper: 3236 satellites
- Telesat (Canada): 298 satellites, all > 1000km altitude
- GW (Chinese state-owned, Guowang), 12992 satellites, orbits 500 – 1145km
- EU started study in Dec 2020



BlueWalker 3

- First one launched 10 Sep 22
- 64.4m^2 surface
- 700 km altitude
- 100 larger BlueBirds planned
- No mitigation
- Among brightest objects in night sky
- Direct connection to mobile phones = unadultered radio signals



Risks & need for coordination

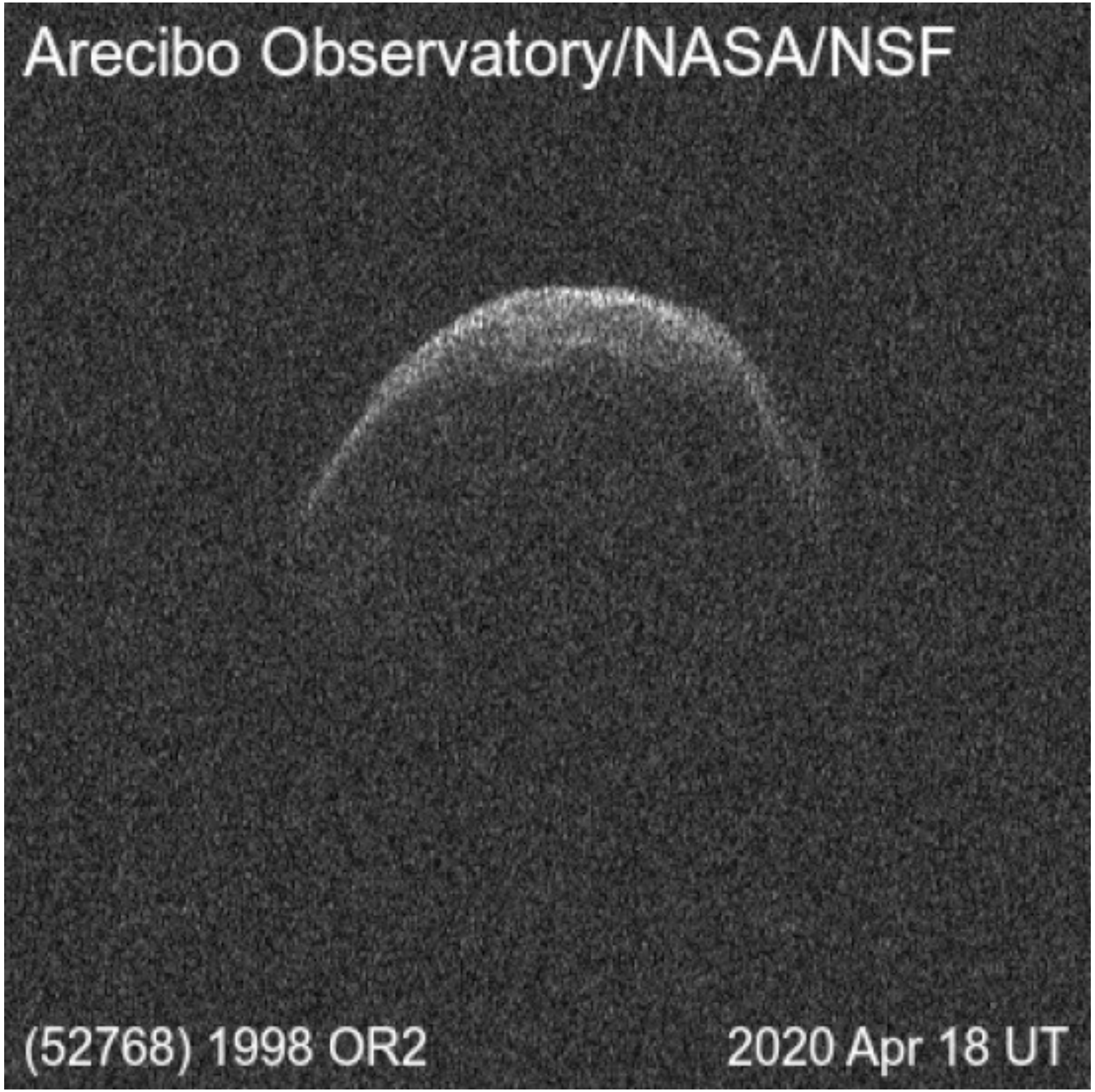
- Astronomy: light pollution, radio frequencies (overtones & interference)
- Environment: radiative forcing of 1000 launches/yr = all of sub-sonic aviation
- Orbit occupation by single actors vs 1967 Outer Space Treaty
- Kessler syndrome: on-orbit evolution dominated by debris collisions
- Currently: 12000 trackable debris pieces > 10cm in LEO, 1 million > 1cm
- Shoot-first-ask-later approach
  - human fatality risks (individual risk vs cumulative risk for 10^4 satellites)
  - Aluminum deposit as an uncontrolled geo-engineering experiment (2tonnes Al/yr)
  - Rocket trash littering the oceans
- Urgent need for international cooperation and coordination!

https://www.nature.com/articles/s41598-021-89909-7

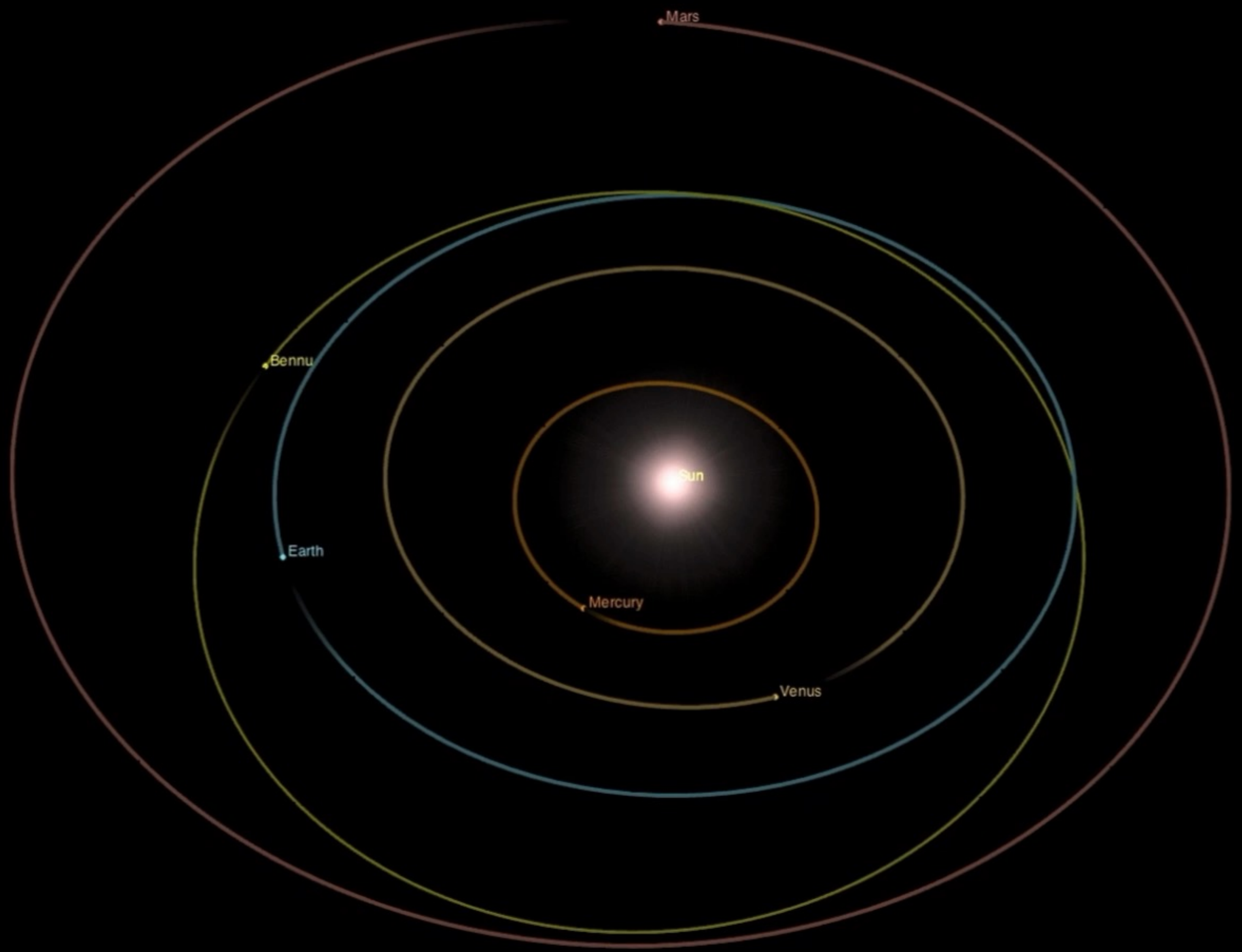
Connection to the Variable Universe

- Shortens part of night during which observations are possible: especially bad for time-resolved observations that frequently observe objects at low elevation at dusk/dawn
- Noise for search of small moving objects, such as near earth asteroids
- Radio emission together with light flashes: noise for FRB studies
- Occultations by satellites (dark): what fraction will be astrophysical events?
- Total night sky darkness changes due to reflections and laser communications
- Best-case scenario: computational power & coordination mitigate effects
- Worst-case scenario: unpredictable loss of opportunities & EM bandwidth

Asteroids



NASA GSFC video of Bennu from OSIRIS-REx https://www.youtube.com/watch?v=QunVAWABQSc https://www.asteroidmission.org/



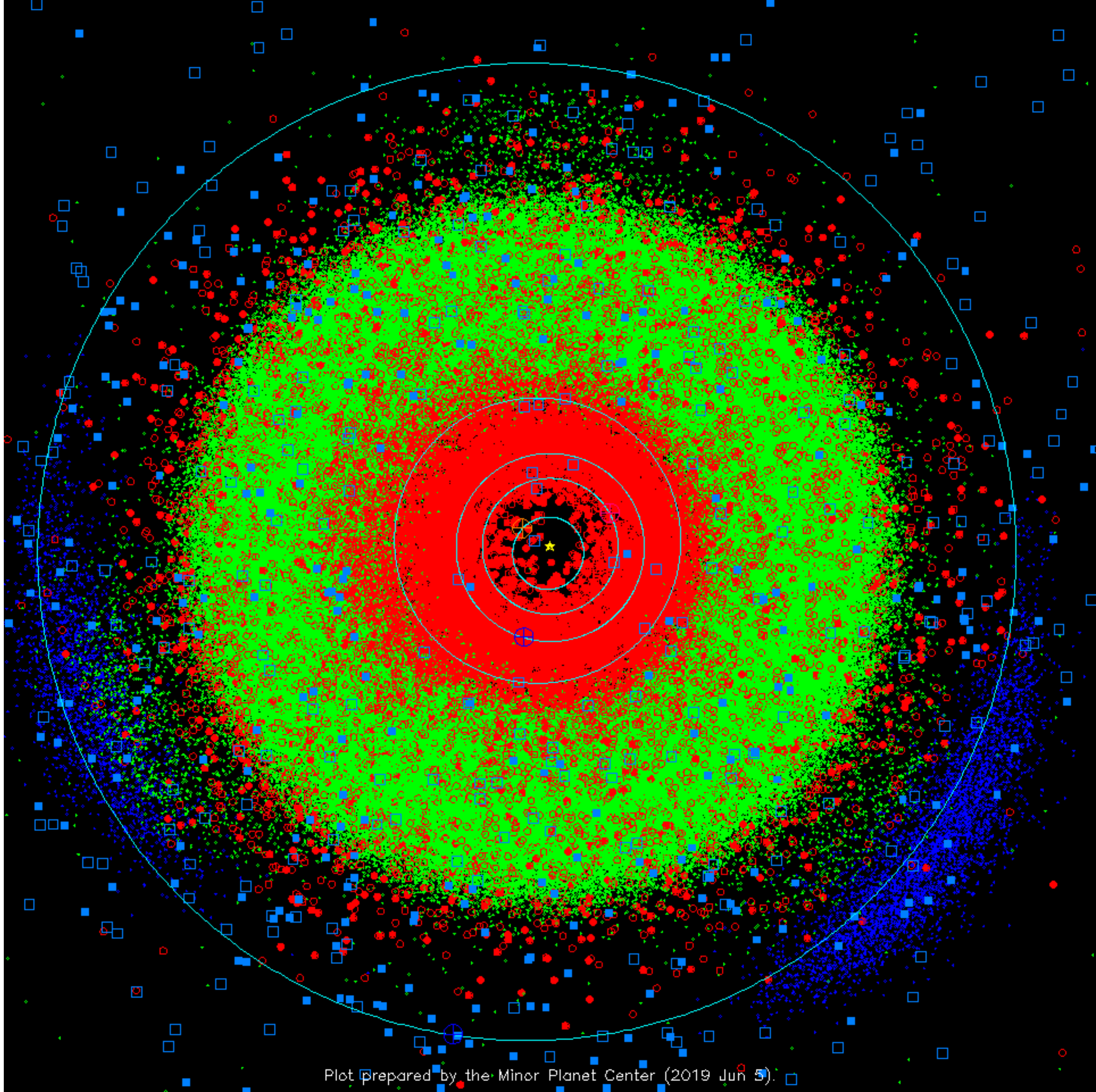
https://www.jpl.nasa.gov/images/asteroid-bennus-particle-ejection-events-animation

[Chesley et al. (2020)]

Minor planet census

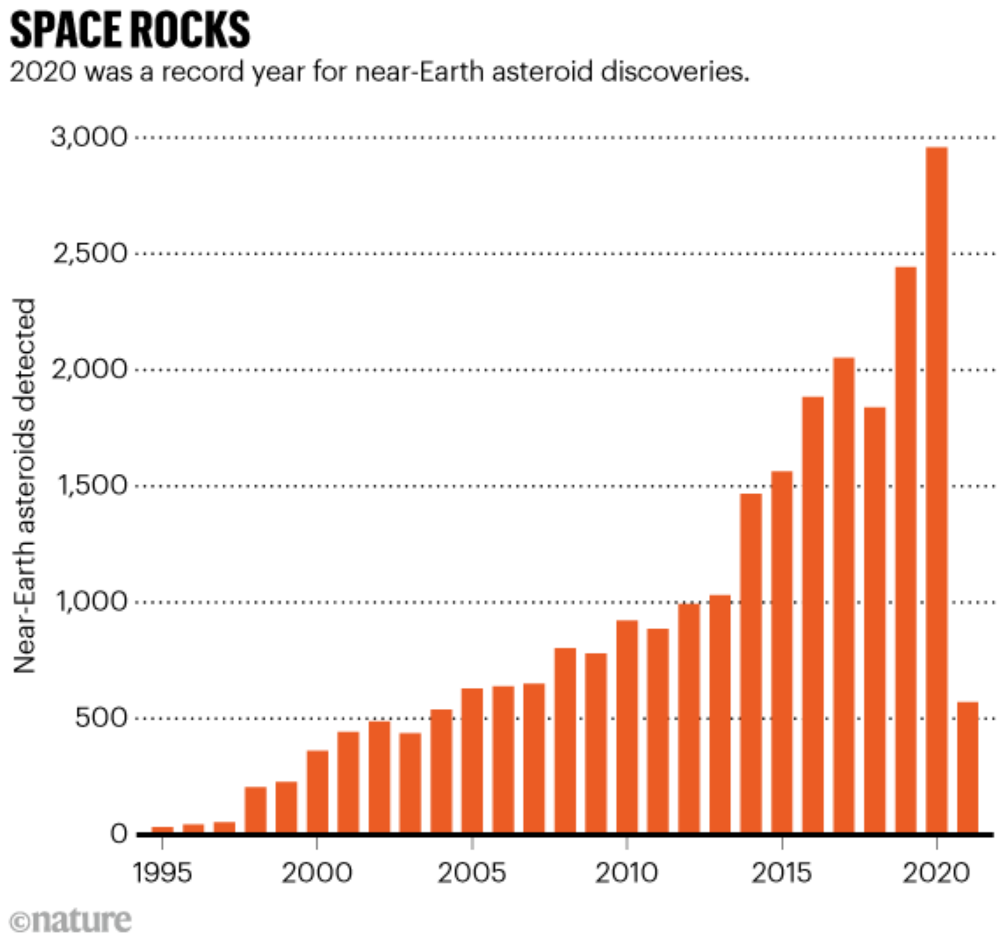
https://minorplanetcenter.net

- **1,229,357** (4 Oct 2022) +100k since last year
- Green: minor planets
- Red: perihelium < 1.3au
- Filled: > one opposition
- Open: one opposition
- Blue: Jupiter Trojans
- Filled blue squares: periodic comets
- Open blue squares: other comets



Near-Earth Asteroids (NEAs)

- 1998: NASA begins concerted search
- Currently > 25000 NEA
- 2020: almost 3000
- Oddities:
  - 2020 CD3 – 3m diameter temp minimoon (left Earth's gravity April 2020)
  - 2020 SO – leftover 1966 NASA rocket booster
- Missions / notable surveys
  - WISE / NEOWISE (NASA)
  - PanSTARRS, Catalina



https://www.nature.com/articles/d41586-021-00641-8

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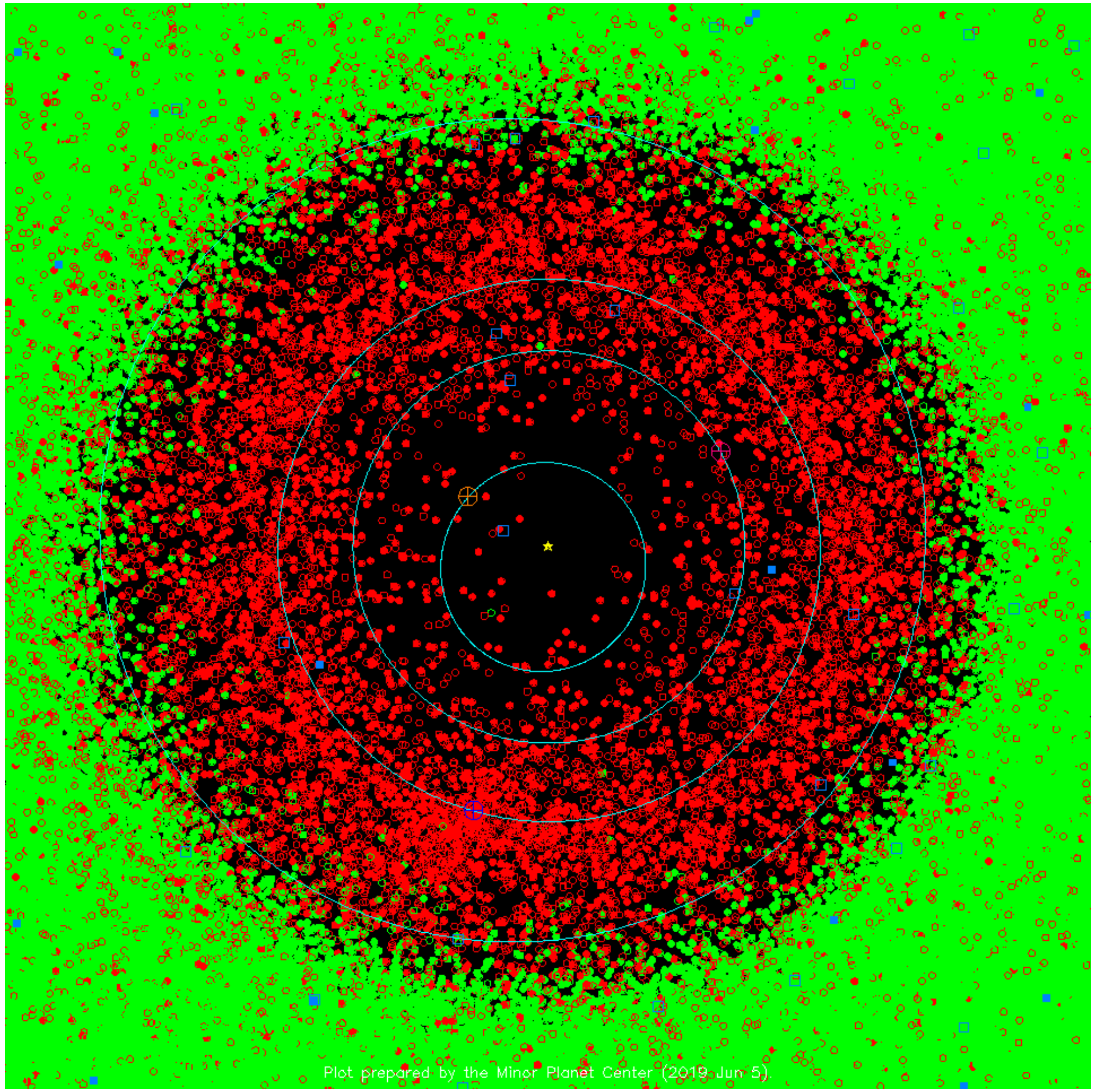


Apophis aste

apophis 2029

apophis 2029 - Go

apophis 2029 cov

apophis 2029 aste

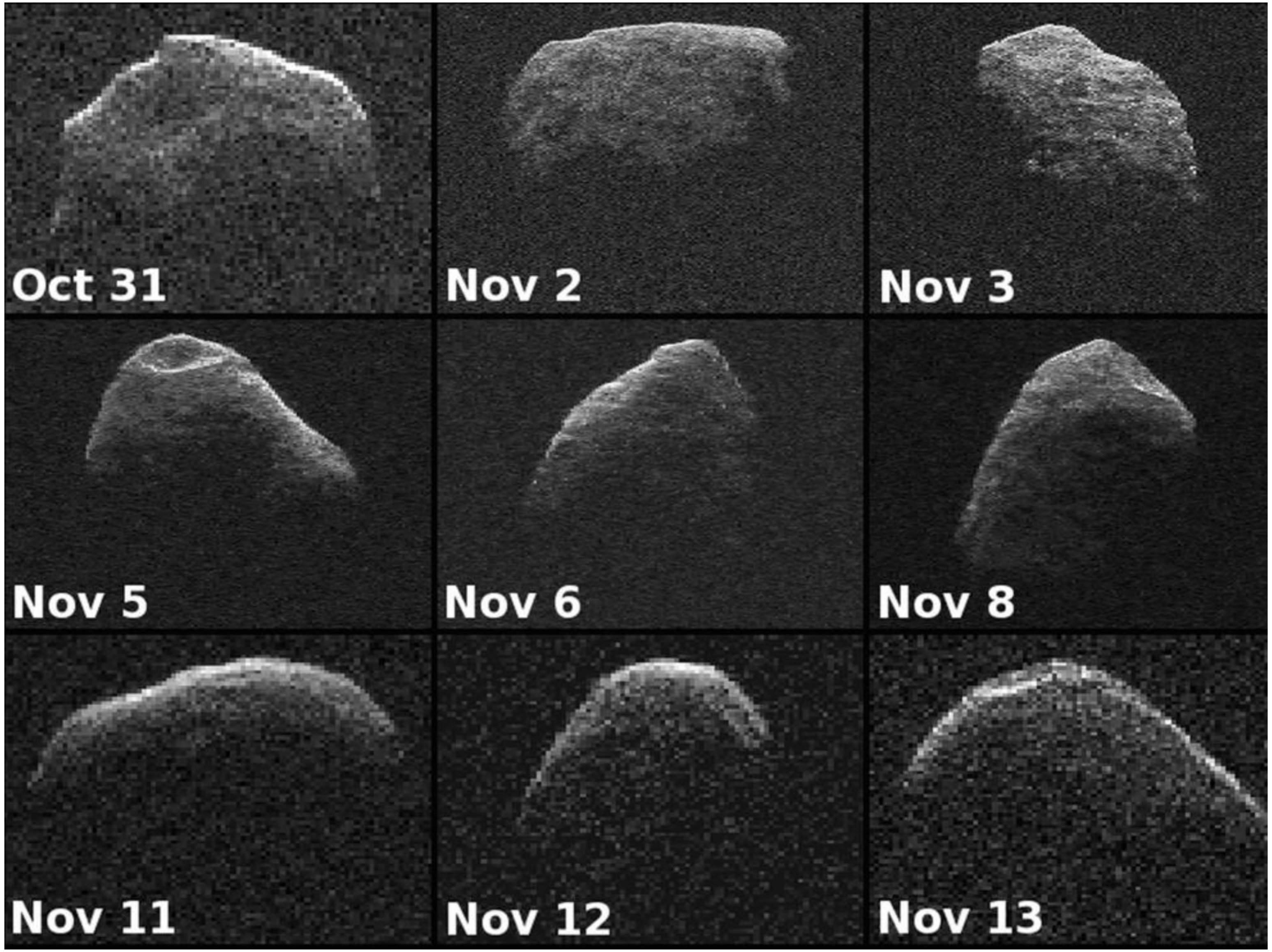
apophis 2029 pre

Asteroid W
Apophis '
could hit

ASTEROID Apophis
2029, in order to fu
shockingly claimed

Jan 10, 2013

NASA Rules Out Earth Impact in 2036 for Asteroid Apophis



Nine new radar images of near-Earth asteroid 2007 PA8 were obtained between Oct. 31 and Nov. 13, 2012.
Credits: NASA/JPL-CalTech

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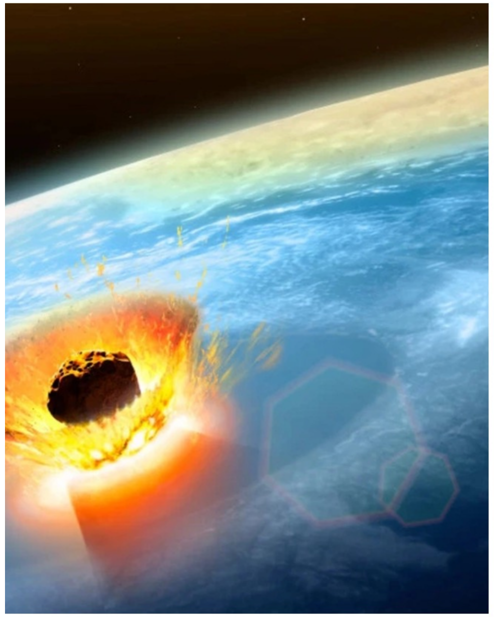
Gaming



pares for huge
t could hit Earth in our
nake 'close approach'

catastrophic asteroid strike could hit soon

019

https://www.jpl.nasa.gov/asteroid-watch

Close encounters: Apophis (340m)

- Friday 13 April 2029
- approaches to within 32,000 km
- Peak magnitude: 3.1 NAKED EYE OBJECT!
- Path: Australia to US via Atlantic Ocean
- Visible from Southern Europe (and Asia, Africa, Australia)
- Observations of 6 March 2021 flyby: no impact in next > 100 years
- Amazing opportunity to study asteroid with ground-based instruments

https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/apophis/in-depth/

https://www.nature.com/articles/d41586-021-00641-8

How do we know the orbit?

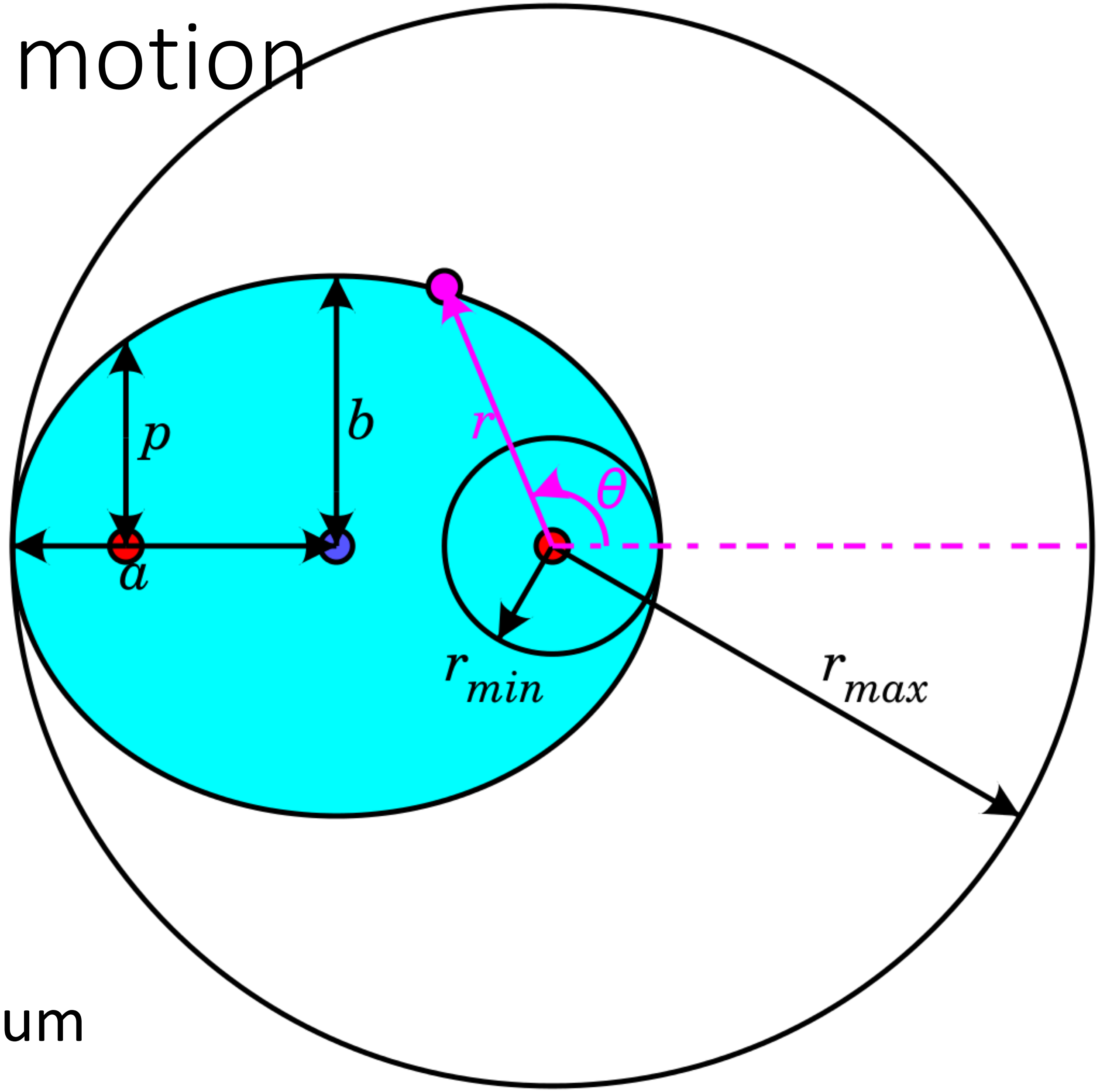
Kepler’s laws of orbital motion

I: The orbit of every planet is
an ellipse with the Sun
at one of the two foci

$$r = \frac{p}{1 + \epsilon \cos \theta} \qquad a = \frac{p}{1 - \epsilon^2}$$

$$\epsilon = \frac{r_{\max} - r_{\min}}{r_{\max} + r_{\min}} \qquad b = \frac{p}{\sqrt{1 - \epsilon^2}}$$

θ : true anomaly $\qquad$ p : semi-latus rectum

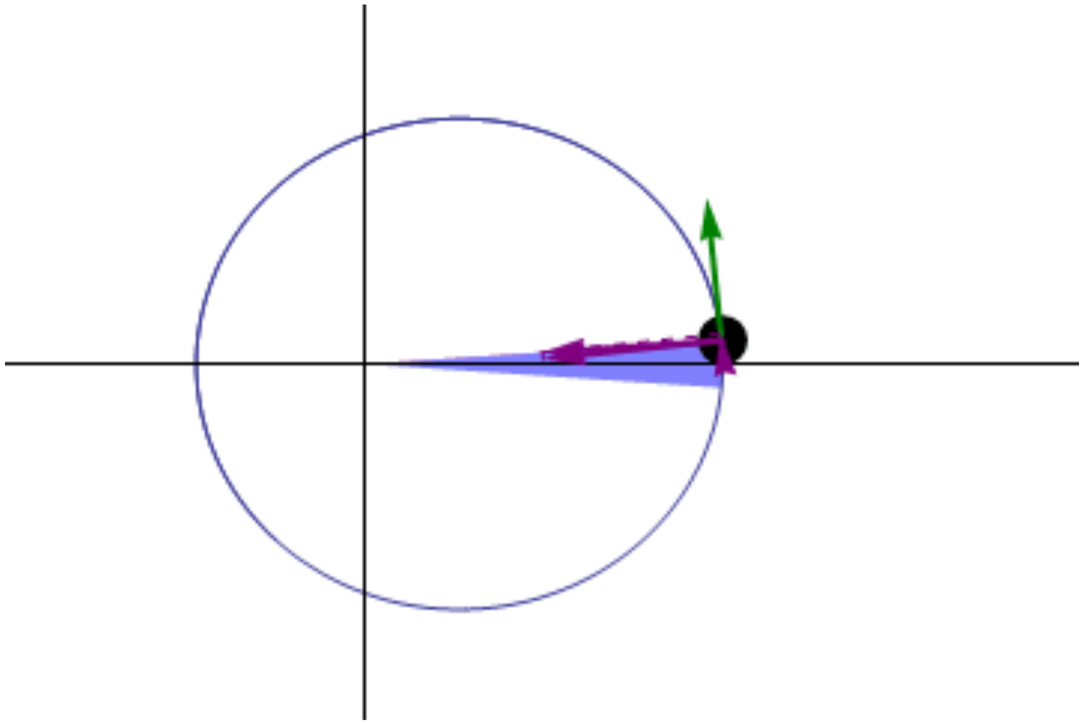


Kepler’s laws of orbital motion

II: A line joining a planet and the Sun sweeps out equal areas during equal intervals of time

$$\frac{dA}{dt} = \frac{r^2}{2}\frac{d\theta}{dt}$$

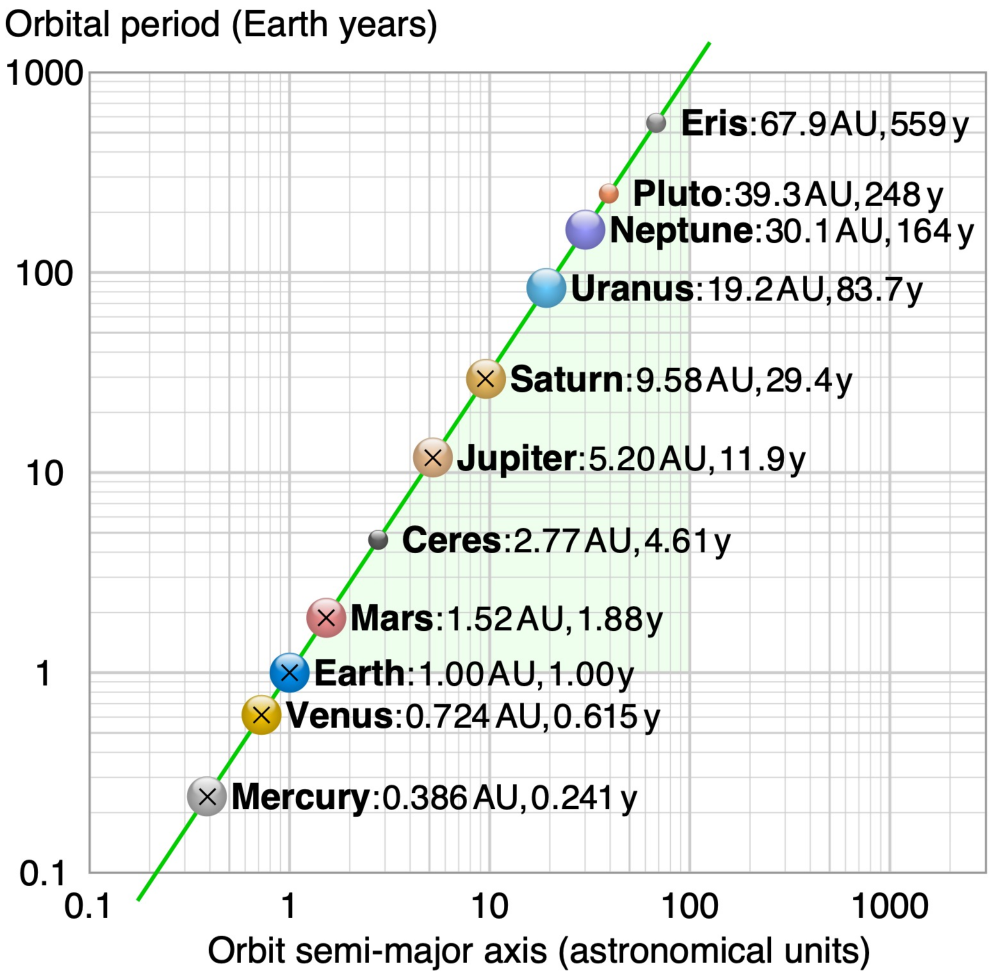
$$\mathrm{P}\,\frac{\mathrm{r}^2}{2}\,\frac{d\theta}{dt} = \pi ab$$



Kepler’s laws of orbital motion

III: The ratio of the square of an object’s orbital period with the cube of the semi-major axis of its orbit is the same for all objects orbiting the same primary

$$\frac{a^3}{P^2} = \frac{\mathrm{G(M+m)}}{4\pi^2}$$

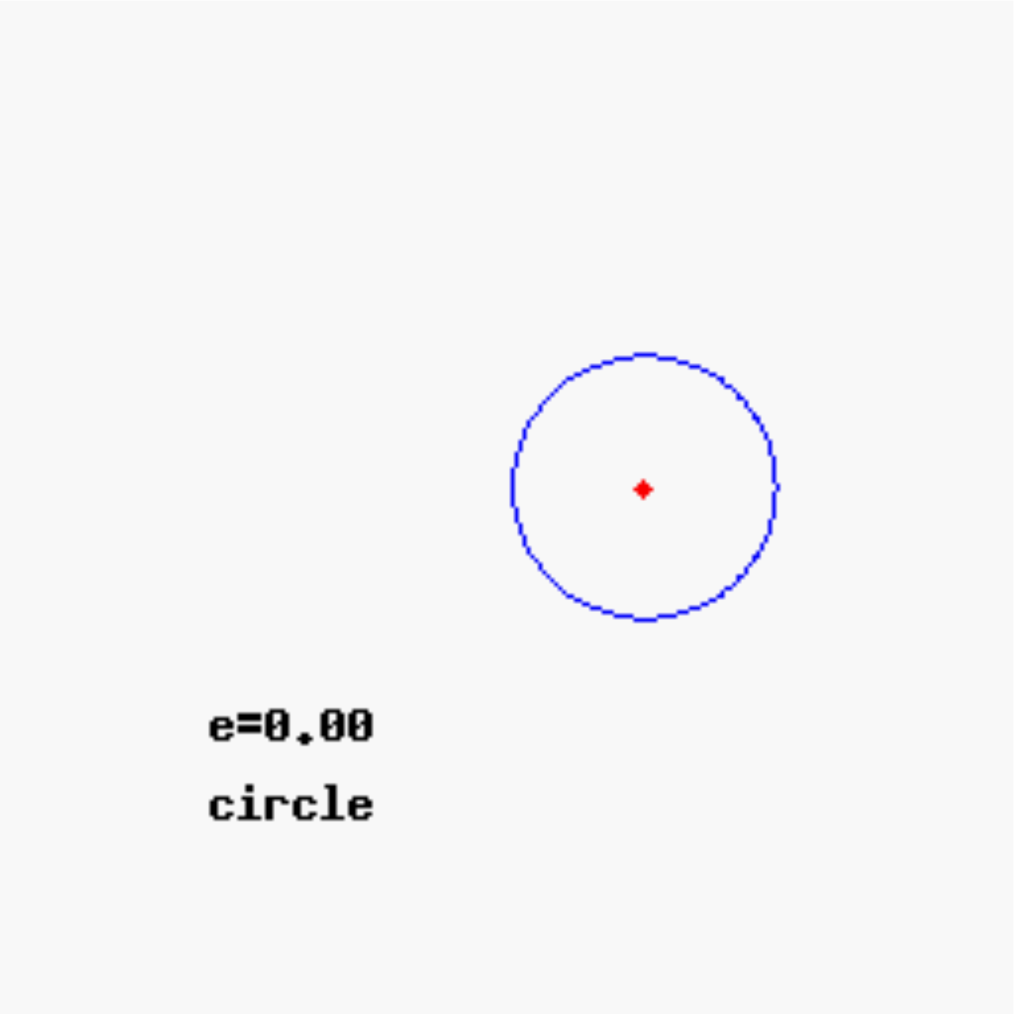


https://www.nature.com/articles/s41550-019-0816-x

'Oumuamua – the interstellar visitor

- Astrometry: hyperbolic orbit
- $\epsilon = 1.20113 \pm 0.00002$
- Cigar-shaped [98,140,440]m
- Rotation around short axis: 8.7h
- Rotation around long axis: 54.5h
- 30σ detection of non-grav acceleration
- $A_1 r^{-2} = (4.92 \pm 0.16) \times 10^{-6}\ \mathrm{m\,s^{-2}}$
- Consistent with outgassing

Oumuamua ISSI team, Nature Astronomy 3, 594, 2019

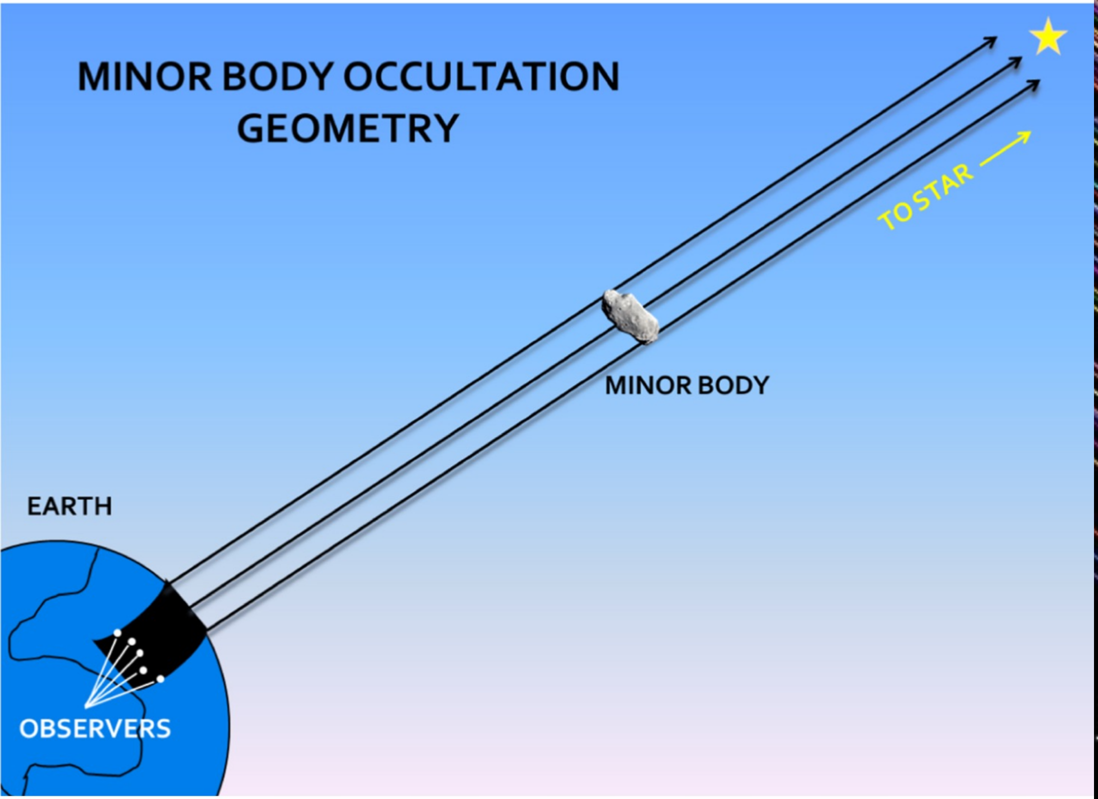


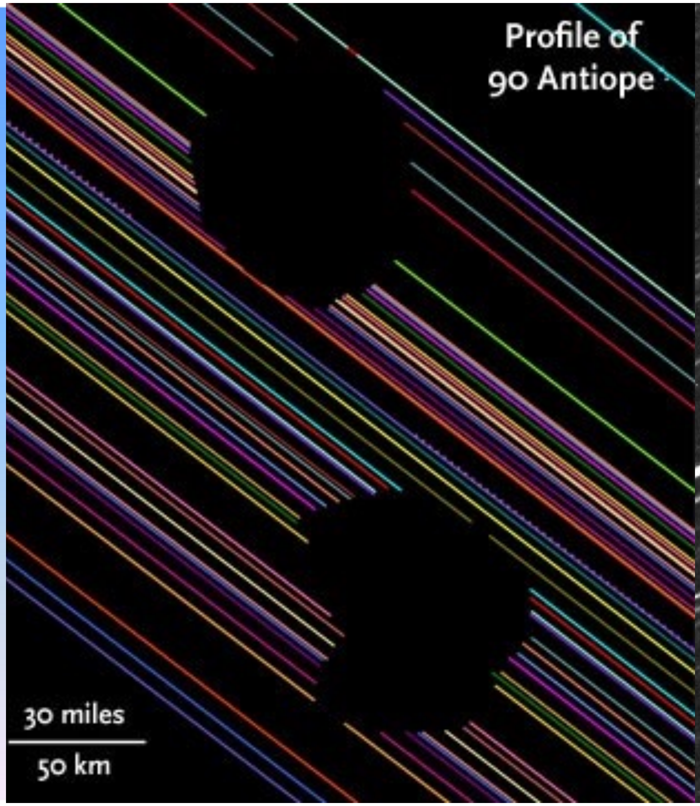
How do we know asteroid sizes?

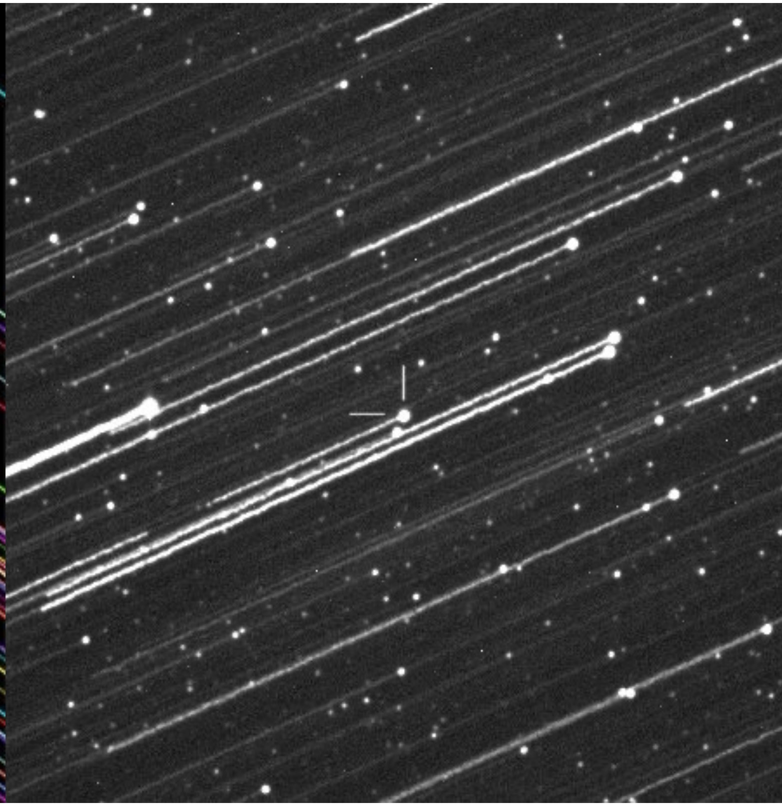
Asteroids occulting stars

Herald et al. 2020, MNRAS 499, 4570

- Placing ground-based telescopes to measure stars disappearing
- Radii more precise than from photometric modeling!



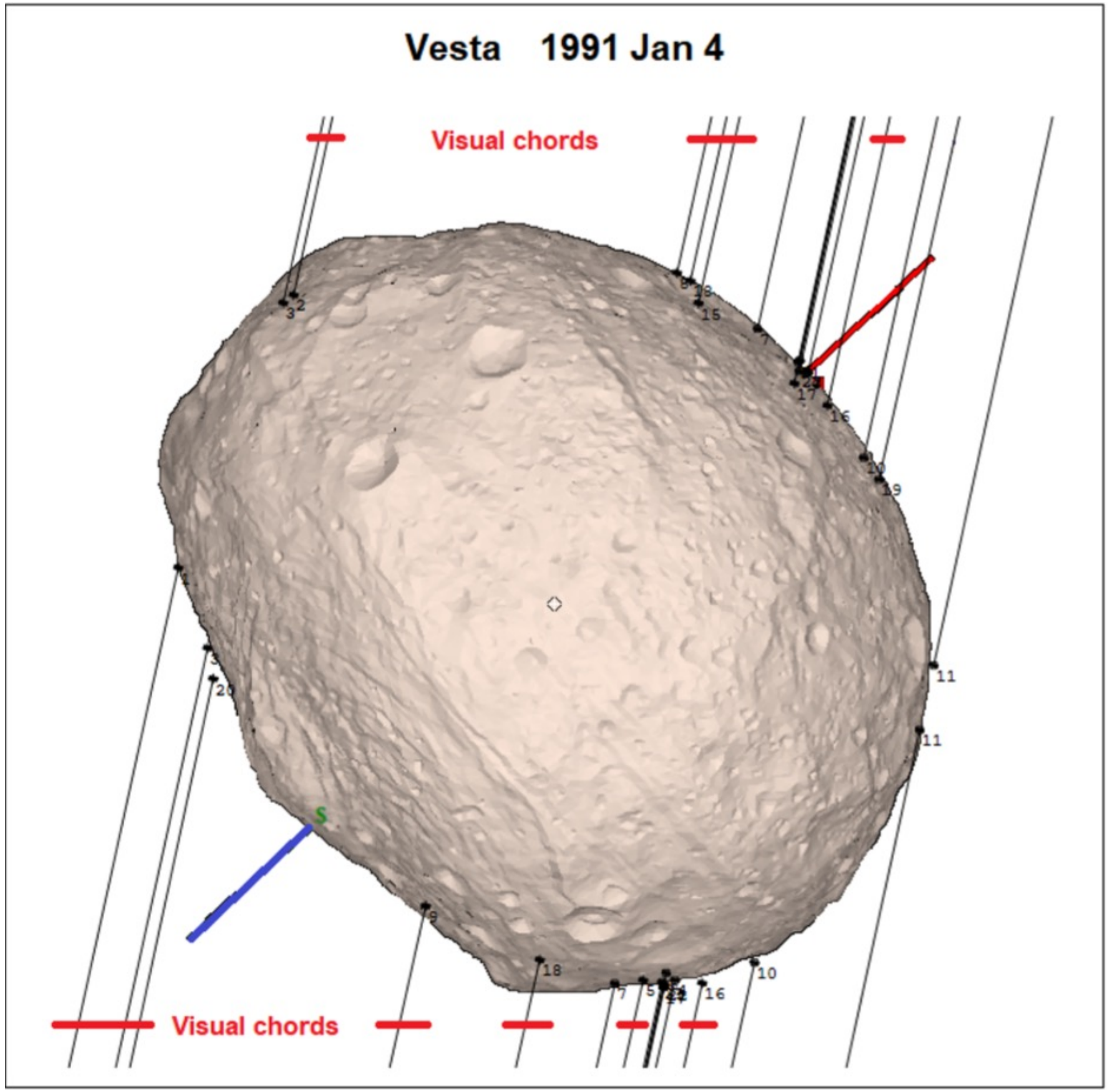




Asteroids occulting stars

Herald et al. 2020, MNRAS 499, 4570

- Chord measuring challenges:
    - Need to be where the occultation happens
    - Resolvable size directly limited by available astrometry
    - Currently: 5km minimum size
- Gaia:
    - Uses asteroids for calibration
    - DR3 astrometry likely allows 1km
    - Limitation: Gaia's own location observed from the ground

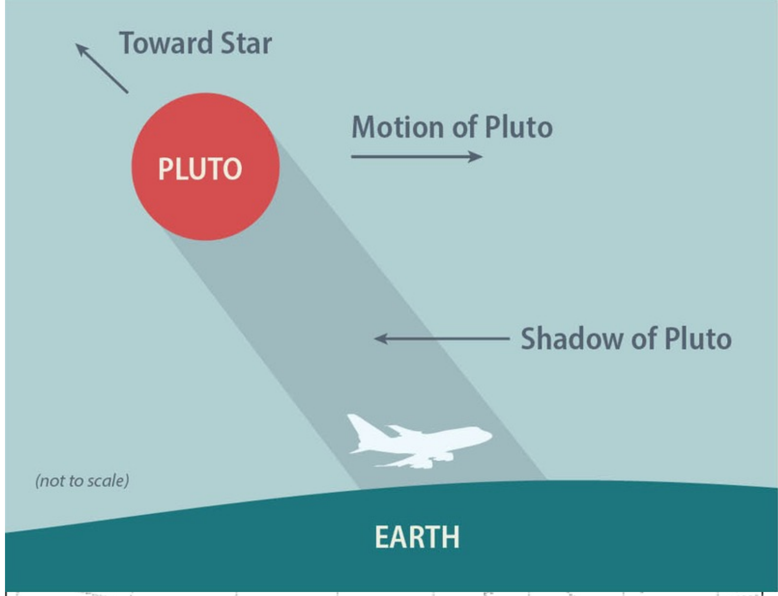


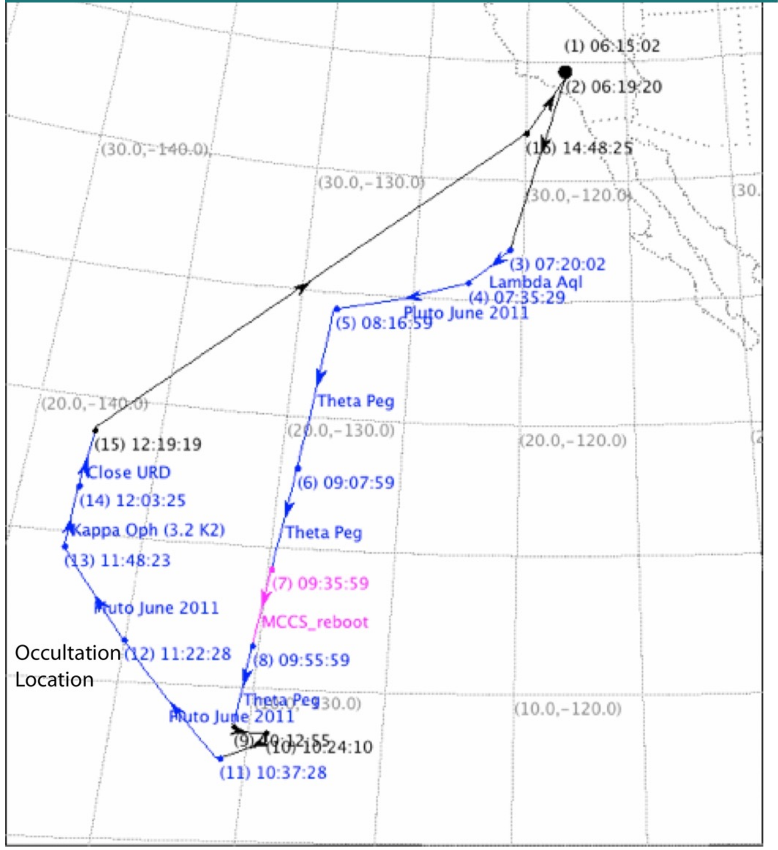
If the asteroid doesn’t come to you…

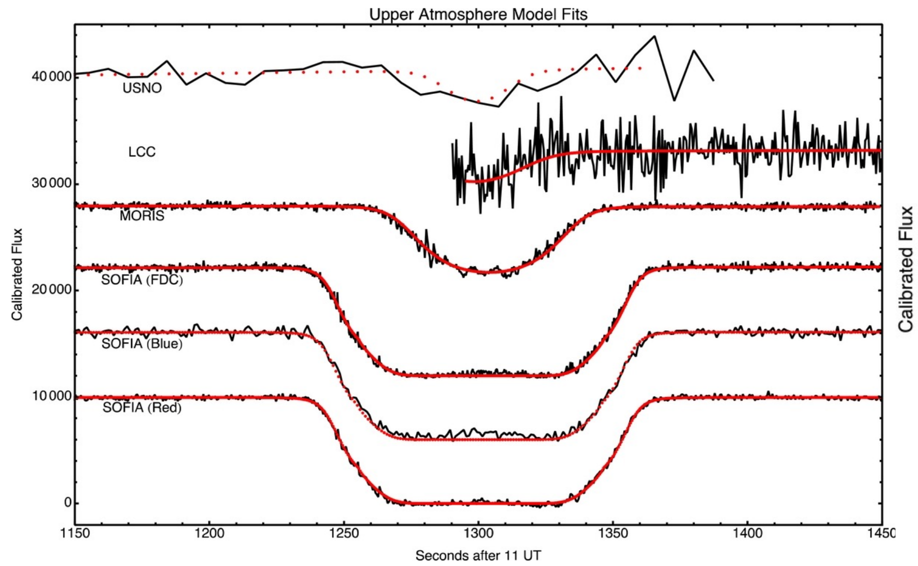
Probing Pluto’s atmosphere

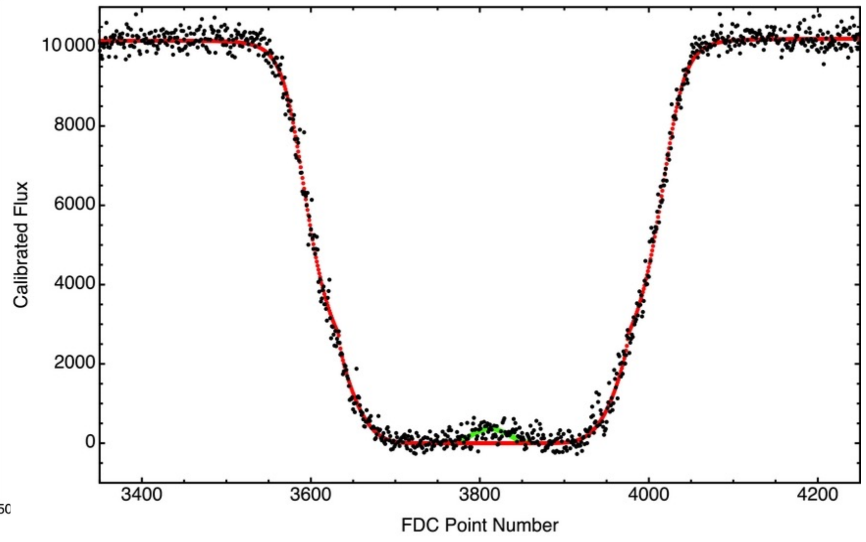
M. J. Person *et al* 2013 *AJ* **146** 83

- 1200 km diameter
- Atmospheric haze & oblateness
- Haze in lower atmosphere blocks central flash
- Time variable features: an evolving atmosphere

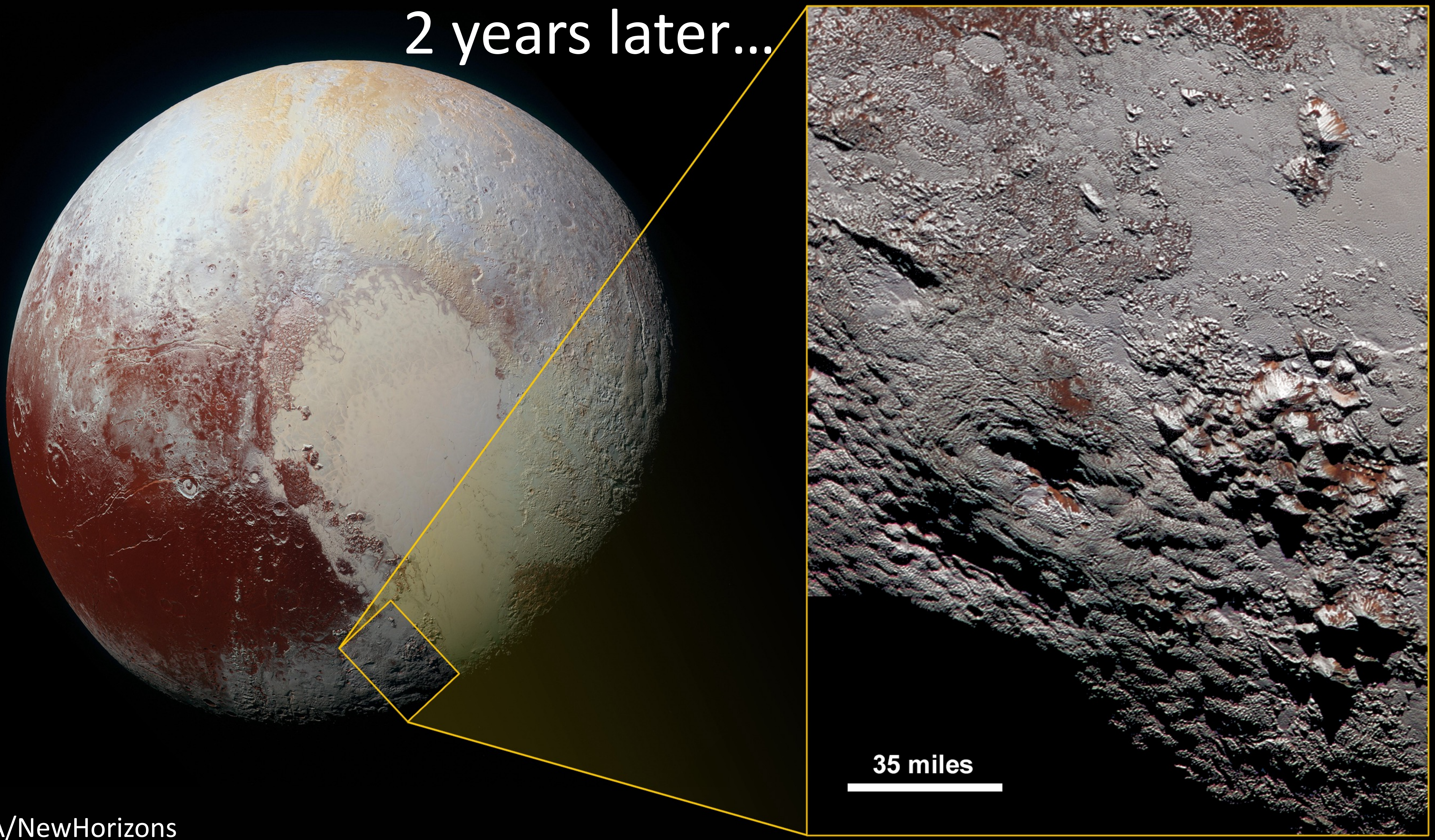




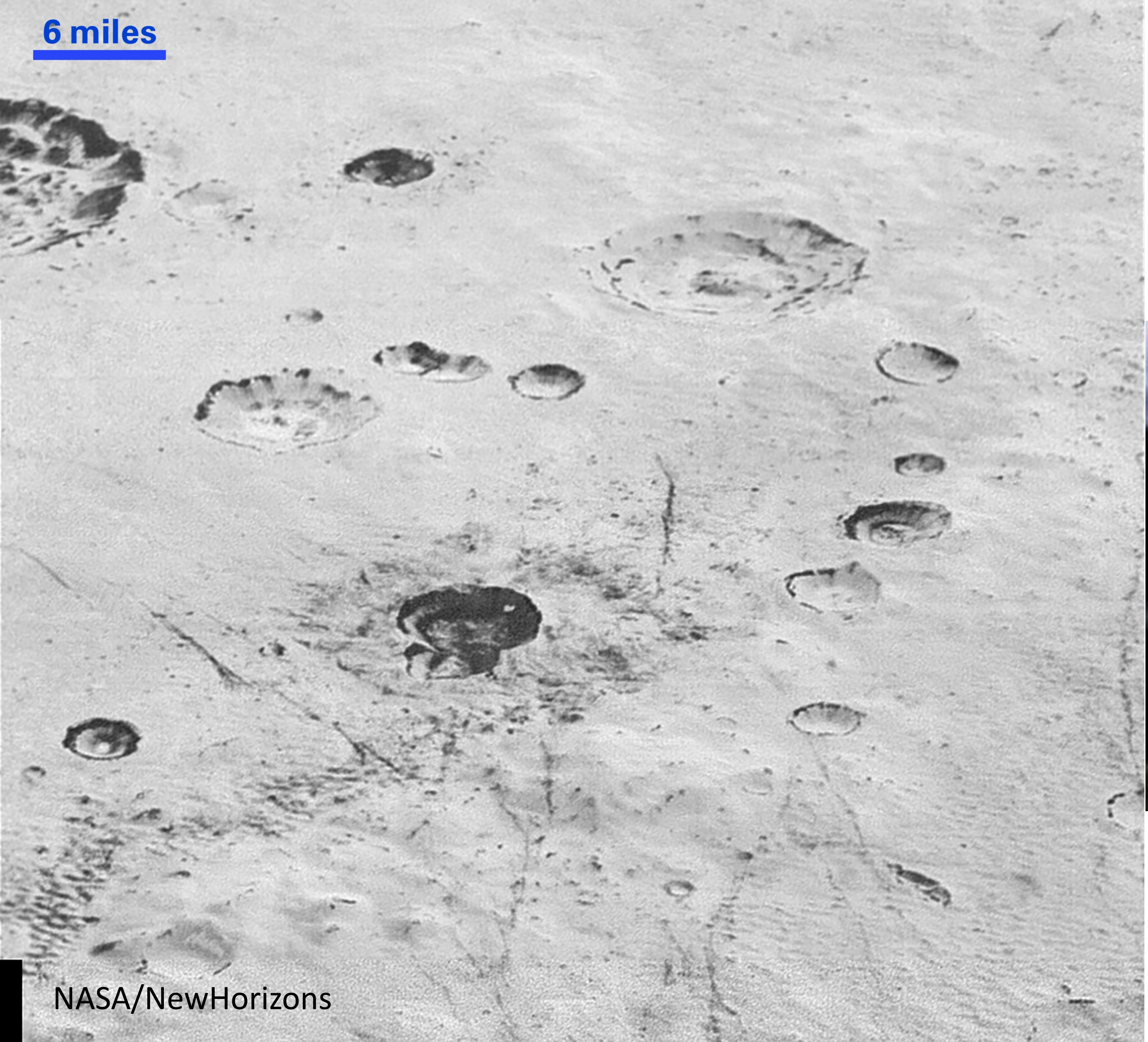




2 years later…



NASA/NewHorizons



NASA/NewHorizons

OMG!

OMG!

- All craters are big!
- Moon and other planets have lots of small craters…
- Tectonic motion can’t explain preferential sizes
- Kuiper belt devoid of small objects?

Questions?

What about our Sun?

Plumes and Plumelets

Plumes are streamers of solar material that stretch out from coronal holes – dark patches of open magnetic field – on the Sun. They appear bright in extreme ultraviolet views of the Sun, and are made up of many smaller streamers, called plumelets. Plumes play a role in creating the high-speed solar wind.

Scientists used image processing on high-resolution images from the Solar Dynamics Observatory to reveal distinct "plumelets" within structures on the Sun called solar plumes. Credit: NASA/SDO/Uritsky, et al

Solar Wind

The solar wind is a gusty stream of material that flows from the Sun in all directions, all the time, carrying the Sun's magnetic field out into space. While it is much less dense than wind on Earth, it is much faster, typically blowing at speeds of one to two million miles per hour. The solar wind is made of charged particles – electrons and ionized atoms – that interact with each other and the Sun's magnetic field.

An artist's animation of the solar wind. Credit: NASA's Goddard Space Flight Center Conceptual Image Lab/Adriana Manrique Gutierrez

Coronal Rain

Coronal, or plasma, rain is made of giant globs of plasma that drip from the Sun's outer atmosphere back to its surface. It occurs when particular conditions, such as magnetic field line configurations and local heating events in the corona, cause the plasma globs there to become cooler and denser than their surroundings, making them rain down.

NASA's SDO captures a plasma downpour on the Sun. Credit: NASA/GSFC/SDO

Sunspots

Sunspots are cooler regions on the Sun's visible surface caused by a concentration of magnetic field lines. Sunspots are the visible component of active regions, areas of intense and complex magnetic fields on the Sun that are the source of solar eruptions. Lasting from days to months, sunspots typically stretch 1,000 to 100,000 miles across. The number of sunspots goes up and down as the Sun goes through its natural 11-year cycle.

Sunspots dot the visible surface of the Sun in this image captured by SDO's HMI instrument. Credit: NASA's Goddard Space Flight Center

Coronal Mass Ejection (CME)

Coronal mass ejections, or CMEs, are large clouds of solar plasma and embedded magnetic fields released into space after a solar eruption. CMEs expand as they sweep through space, often measuring millions of miles across, and can collide with planetary magnetic fields.
When directed at Earth, a CME can produce geomagnetic disturbances that ignite bright aurora, short-circuit satellites and power grids on Earth, or at their worst, even endanger astronauts in orbit.

This image shows a coronal mass ejection released by an X.1.1 flare. Credit: NASA/SOHO

Supergranules

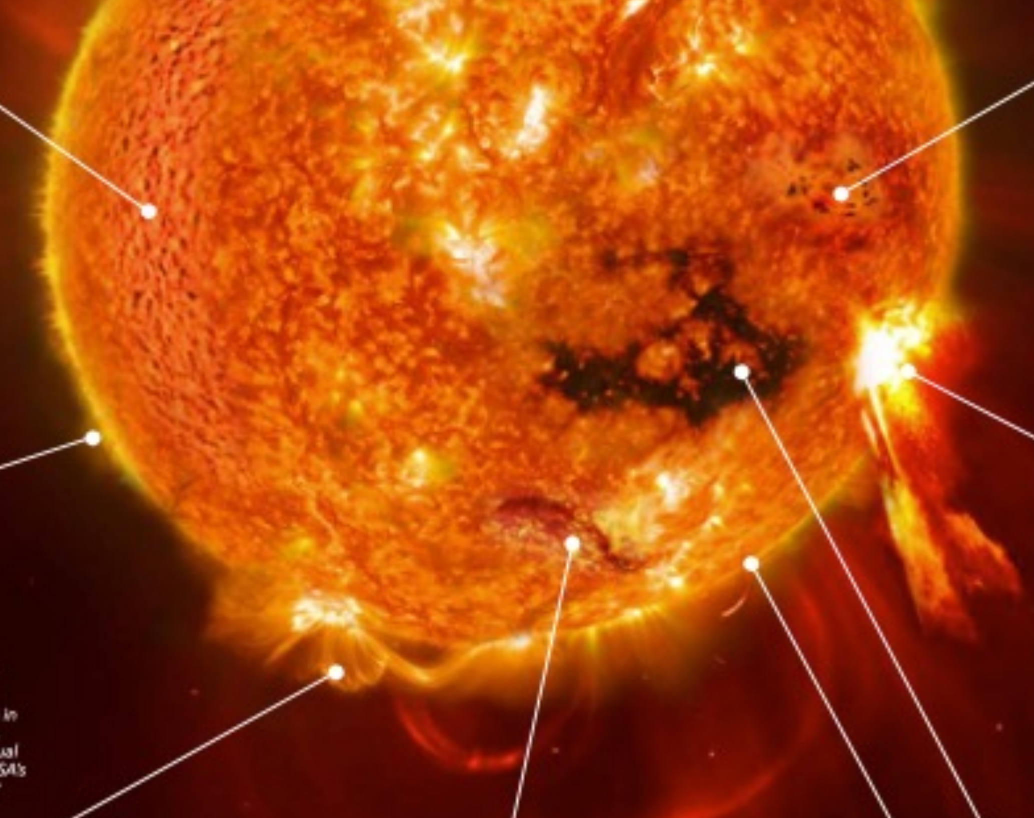
Supergranules are networks of cells covering the Sun's visible surface that stretch some 18,000 miles across – more than large enough to frame two Earths side by side. They are caused by the convection of material in the Sun.

Close-up of Active Region 12593 through the 400 nm filter of the Swedish Solar Telescope. Credit: Jaime de la Cruz Rodriguez & Jorrit

Sunquakes

Sunquakes are seismic-like activity on the Sun that ripple across the visible surface, not unlike earthquakes. They are known to accompany some solar flares, but scientists are uncertain how exactly they are triggered.

This image shows the ripples caused by a sunquake on the Sun's outlying surface. Credit: NASA's Solar Dynamics Observatory



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Spicules

At any given moment, as many as 10 million wild jets of solar material burst up from the Sun's surface. Known as spicules, these grass-like tendrils of plasma erupt as fast as 60 miles per second and can reach lengths of 6,000 miles before collapsing.

Observations of spicules from NASA's Solar Dynamics Observatory, or SDO. Over a few hours observation of the northern pole area of the Sun in extreme ultraviolet light (Aug. 3, 2010), we can see a continual frenzy of spicules. Credit: NASA's Goddard Space Flight Center

Flux Rope

A flux rope is kind of a magnetic structure that is thought to be at the heart of many of the Sun's eruptions. Flux ropes form in plasmas, such as the Sun's corona, when loops of magnetic field lines connect with each other. The resulting flux ropes are formed from bundles of magnetic fields that have a magnetic field wrapped around them, like the stripes on a candy cane. These twisted structures extend in a series of loops from the Sun's surface, and can be carried away from the Sun by a coronal mass ejection.

This image shows a series of magnetic loops called a flux rope, as captured by the Solar Dynamics Observatory. Credit: NASA's Solar Dynamics Observatory

Filament Eruption

Filaments are strands of solar material, cooler and denser than their surroundings, suspended above the Sun by magnetic forces. They appear as dark lines when seen against the bright Sun. (When a solar filament is seen at the edge of the Sun, against the blackness of space, it is called a prominence.) When solar filaments become unstable they can either fall back onto the Sun or erupt into space, sending a coronal mass ejection away from the Sun.

Filament seen with SDO's AIA instrument. Credit: NASA's Solar Dynamics Observatory

Nanojets and Nanoflares

Nanojets are bright, thin tendrils of plasma that travel perpendicular to magnetic structures in the outer solar atmosphere, reaching lengths of thousands of miles. They are spawned by nanoflares, tiny explosions on the Sun caused by a process known as magnetic reconnection, which occurs in tangled magnetic field lines.

These images showing nanojets on the Sun were captured by NASA's IRIS mission on Apr. 3, 2014. Credit: NASA's Goddard Space Flight Center

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Solar Flare

Solar flares are energetic bursts of light and particles triggered by the release of magnetic energy on the Sun. Flares are by far the most powerful explosions in the solar system, with energy releases comparable to billions of hydrogen bombs. The energetic particles accelerated by flares travel nearly at the speed of light, and can travel the 93 million miles between the Sun and Earth in less than 20 minutes.

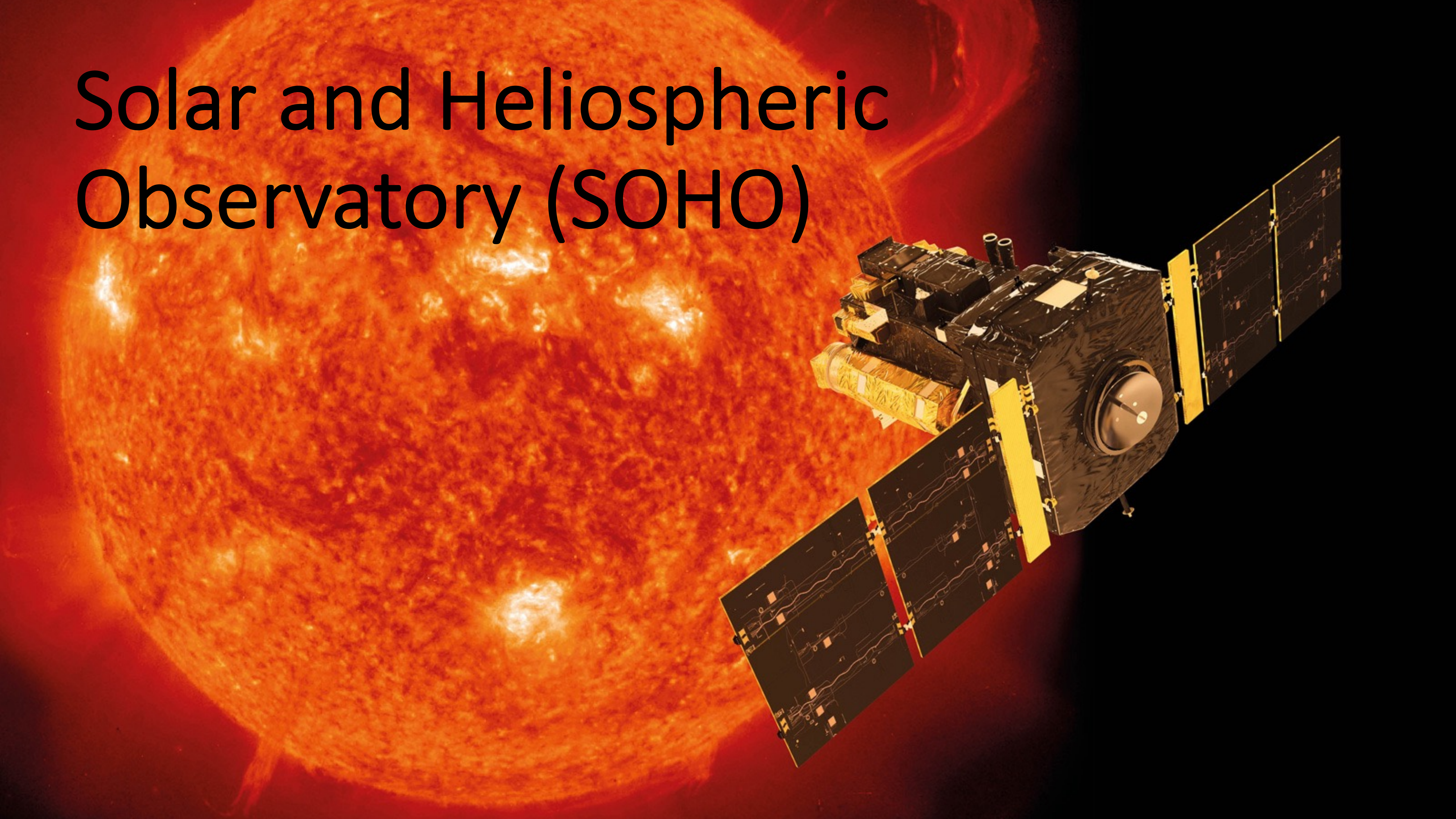
The Sun emitted a significant solar flare, peaking at 6:11 pm EDT on May 5, 2015. Credit: NASA's Solar Dynamics Observatory

Coronal Hole

A coronal hole is a patch of the Sun's atmosphere with much lower density than elsewhere. In ultraviolet views of the Sun, coronal holes appear as dark splotches. These are regions where the Sun's magnetic field lines are connected directly to interplanetary space, allowing solar material to escape out in a high-speed stream of solar wind, leaving a dark "hole" near the surface of the Sun.

The dark area across the top of the Sun in this image is a coronal hole. This image was captured on Oct. 10, 2015, by NASA's Solar Dynamics Observatory. Credit: NASA's Solar Dynamics Observatory

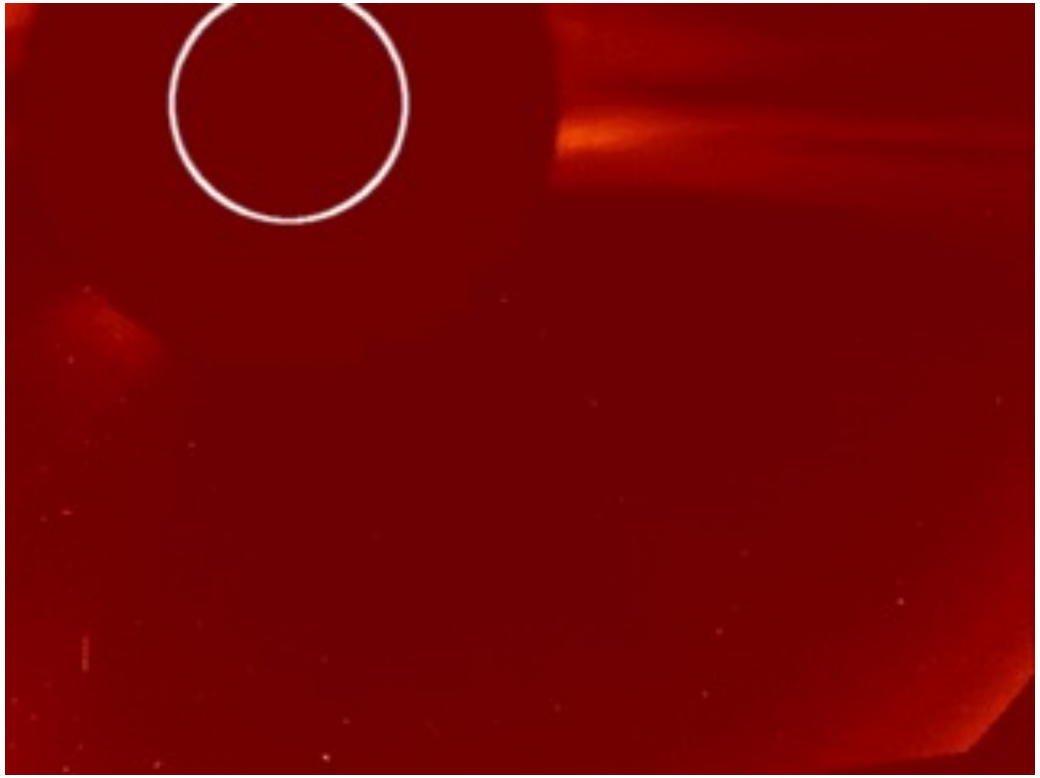
Solar and Heliospheric Observatory (SOHO)



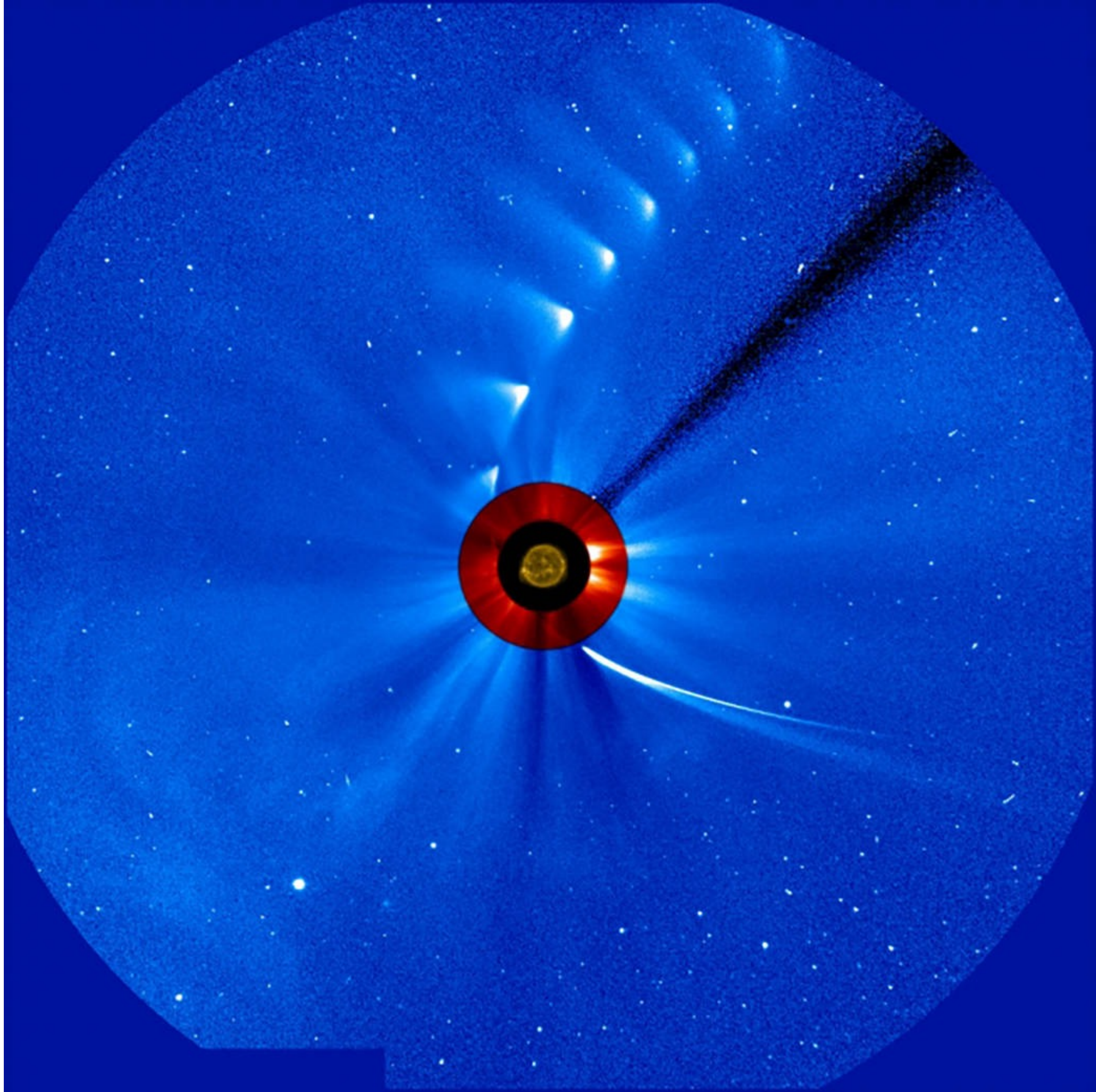
Some facts about SOHO (ESA & NASA)

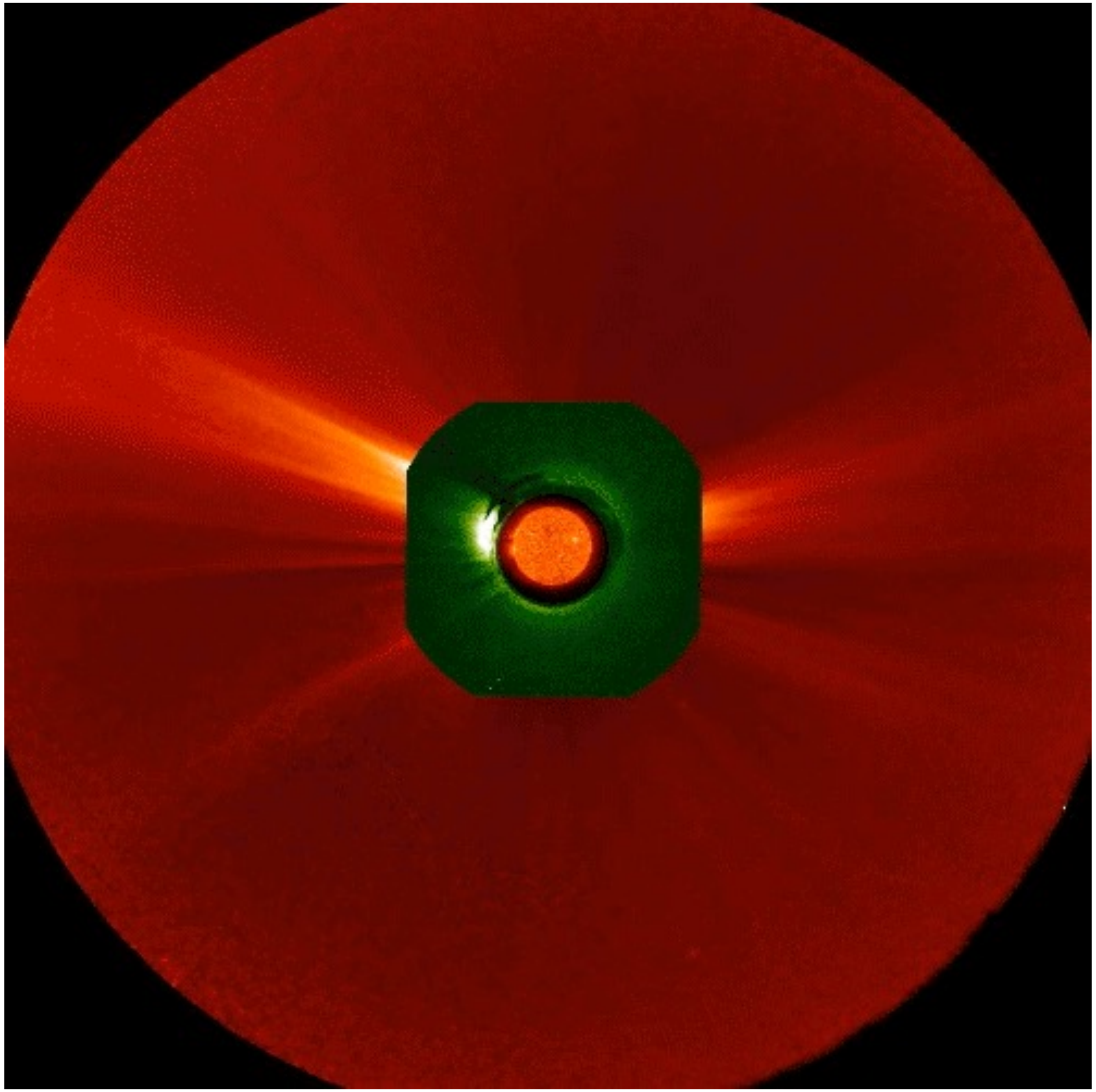
- Longest-lived Sun-watching satellite (26 yrs, 10 months) since 12/95
- Many mission extensions (initially: 4 yrs)
- ESA leads mission, NASA contributed 3/12 instruments & launch
- Transformative for Solar physics, space weather
- Changed our conception of the Sun "from a picture of a static, unchanging object in the sky to the dynamic beast it is" [Bernhard Fleck, ESA project scientist]
- 2 complete Solar cycles
- > 4000 Comets discovered (more than half of all known)

SOHO the Comet finder

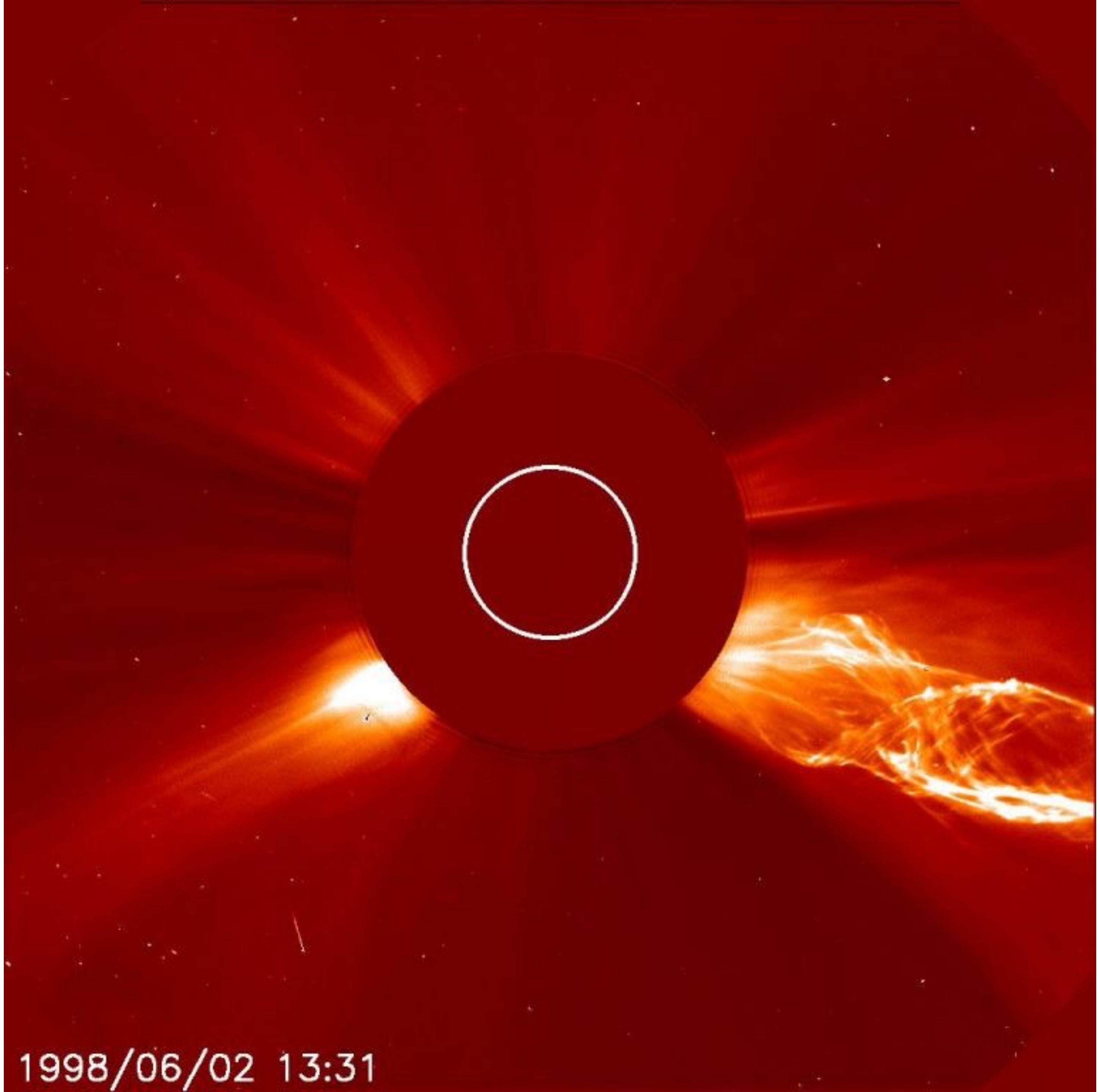


https://www.nasa.gov/feature/goddard/soho/solar-observatory-greatest-comet-hunter-of-all-time
https://www.youtube.com/watch?v=2u73bIzg5CU

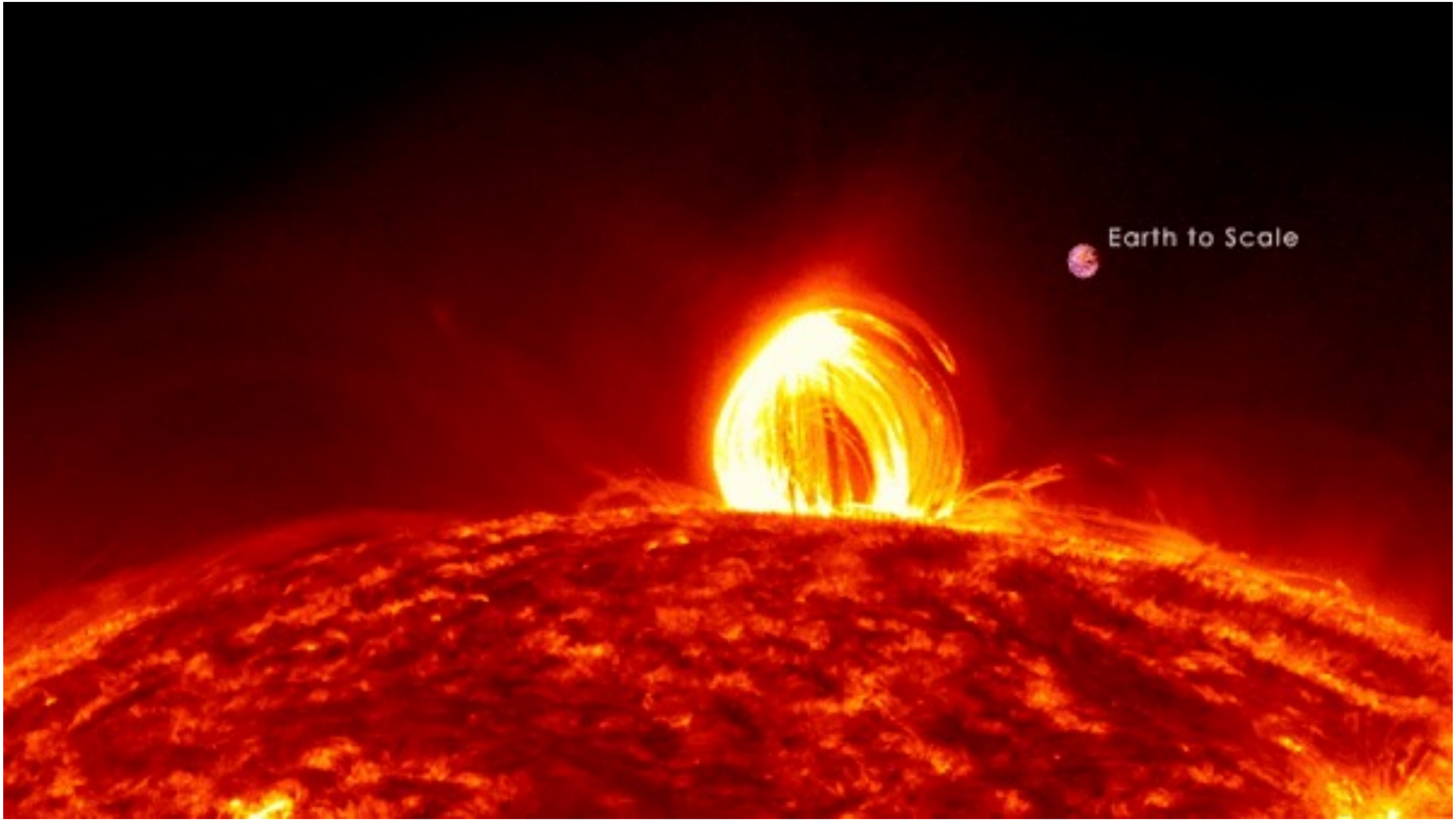




https://www.esa.int/ESA_Multimedia/Videos/2020/12/Decades_of_the_Sun_as_seen_by_SOHO [47 min video]

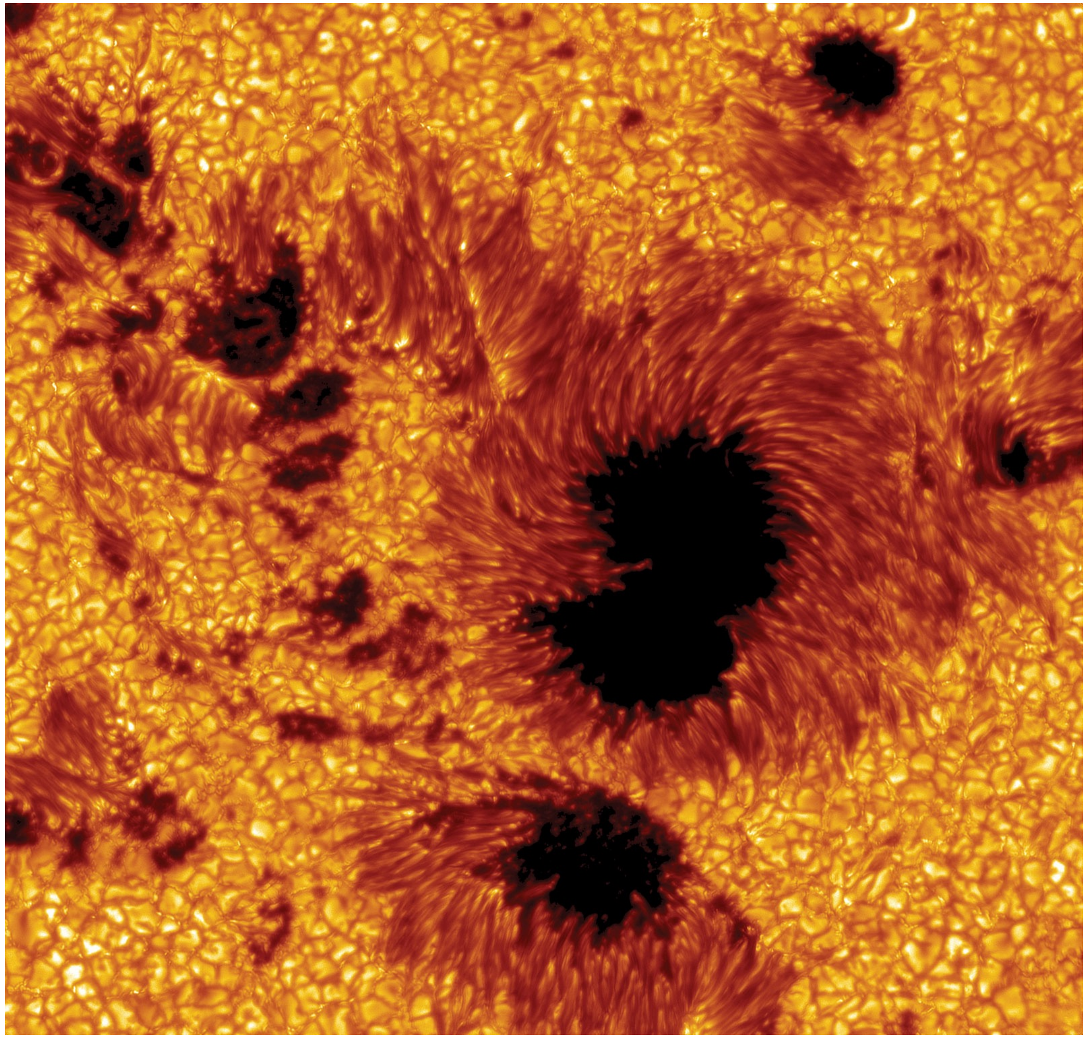


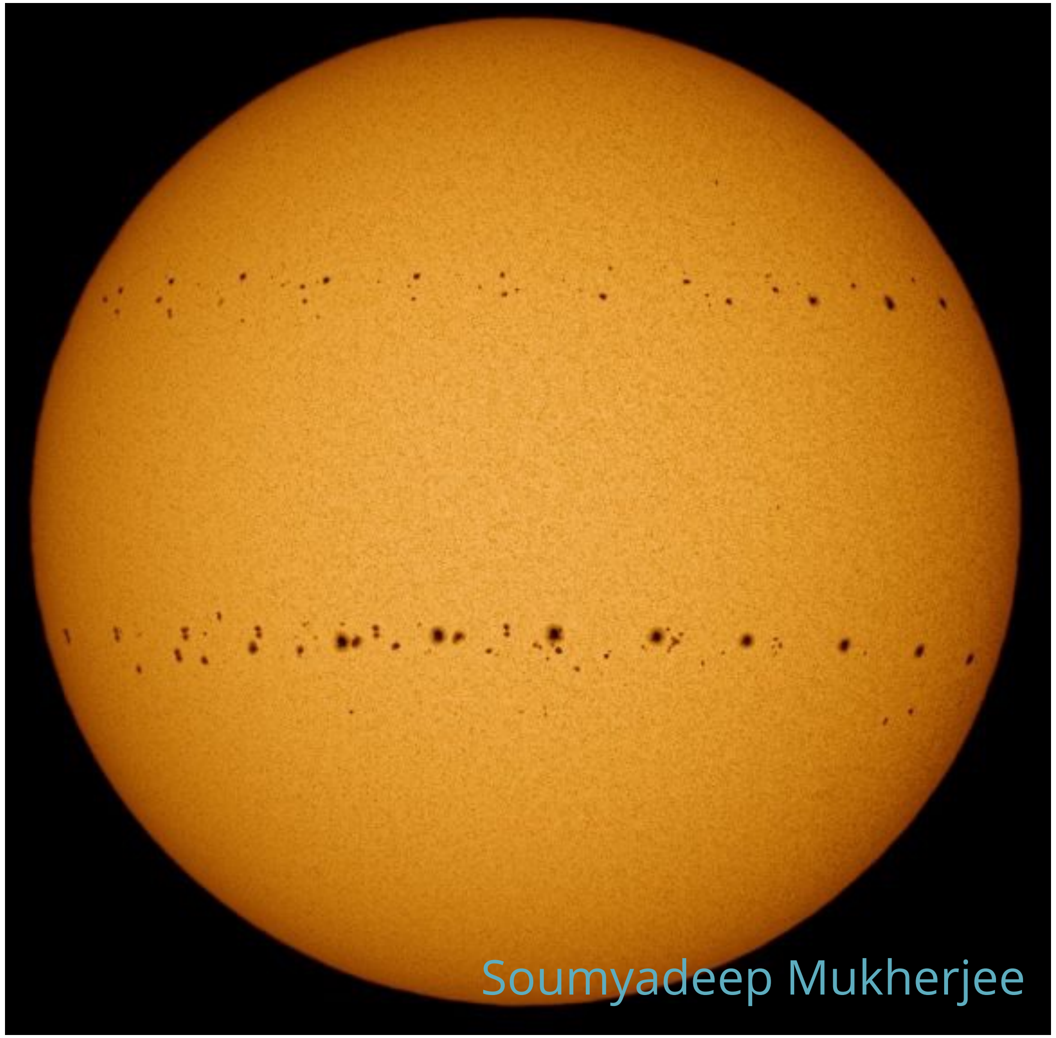
LASCO C2 coronagraph on SOHO


Earth to Scale

The Solar Cycle

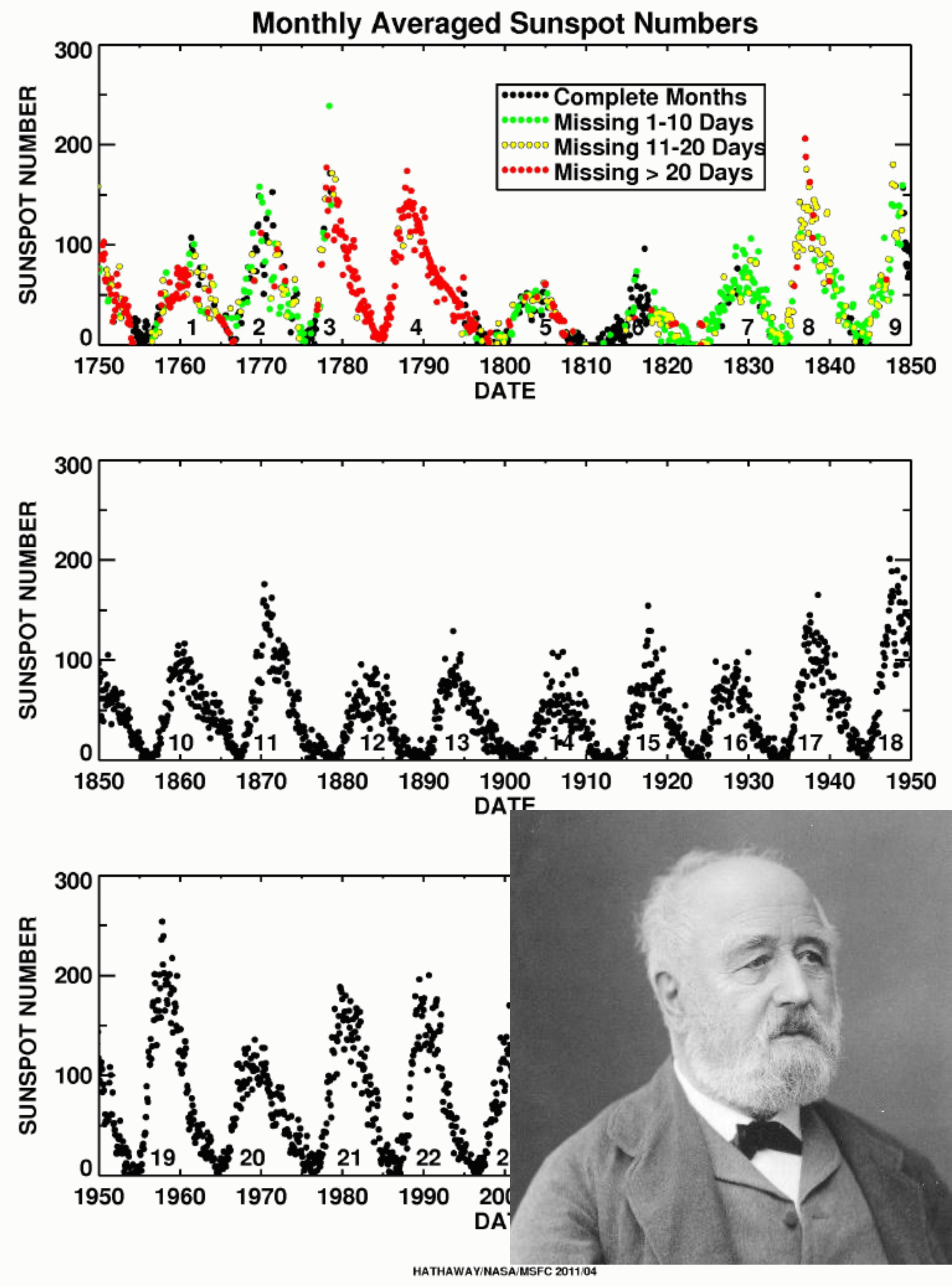
Sunspot variations over 11-year cycles



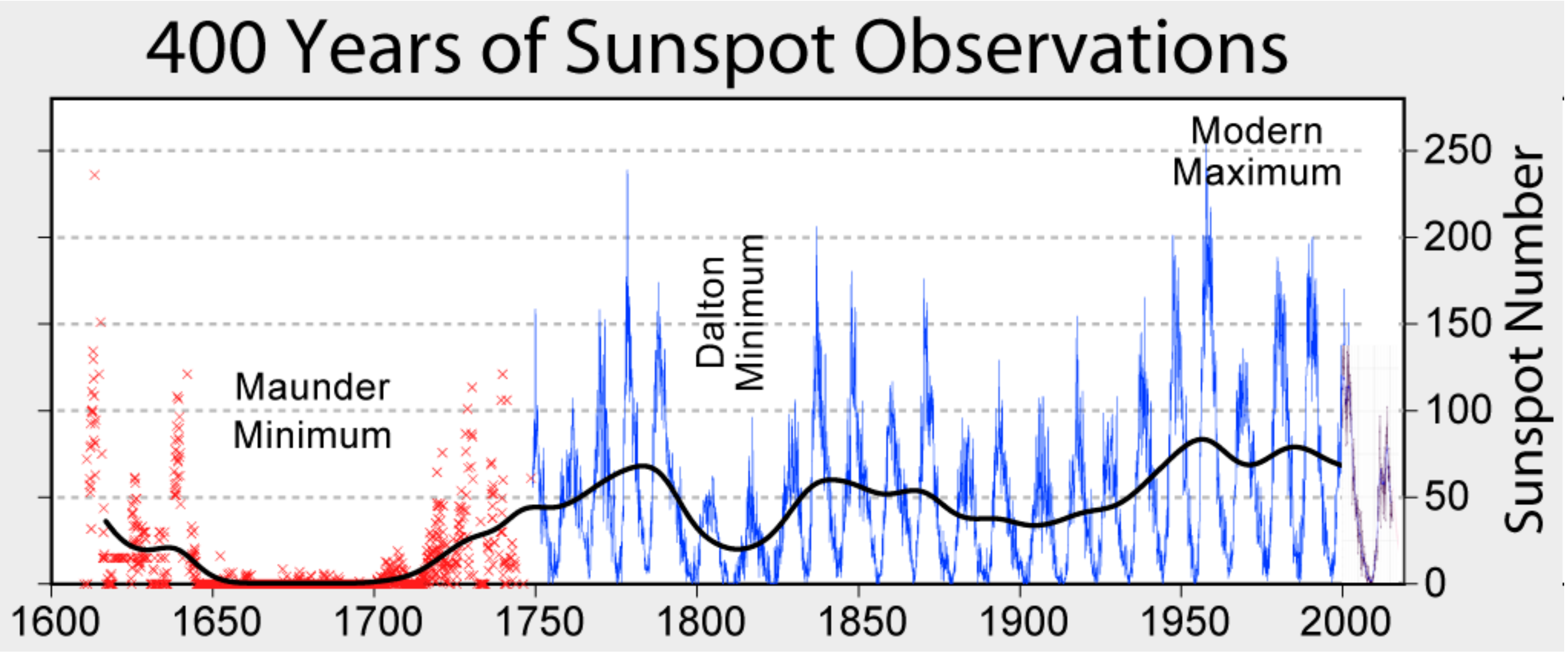


Sunspots and Solar Cycle

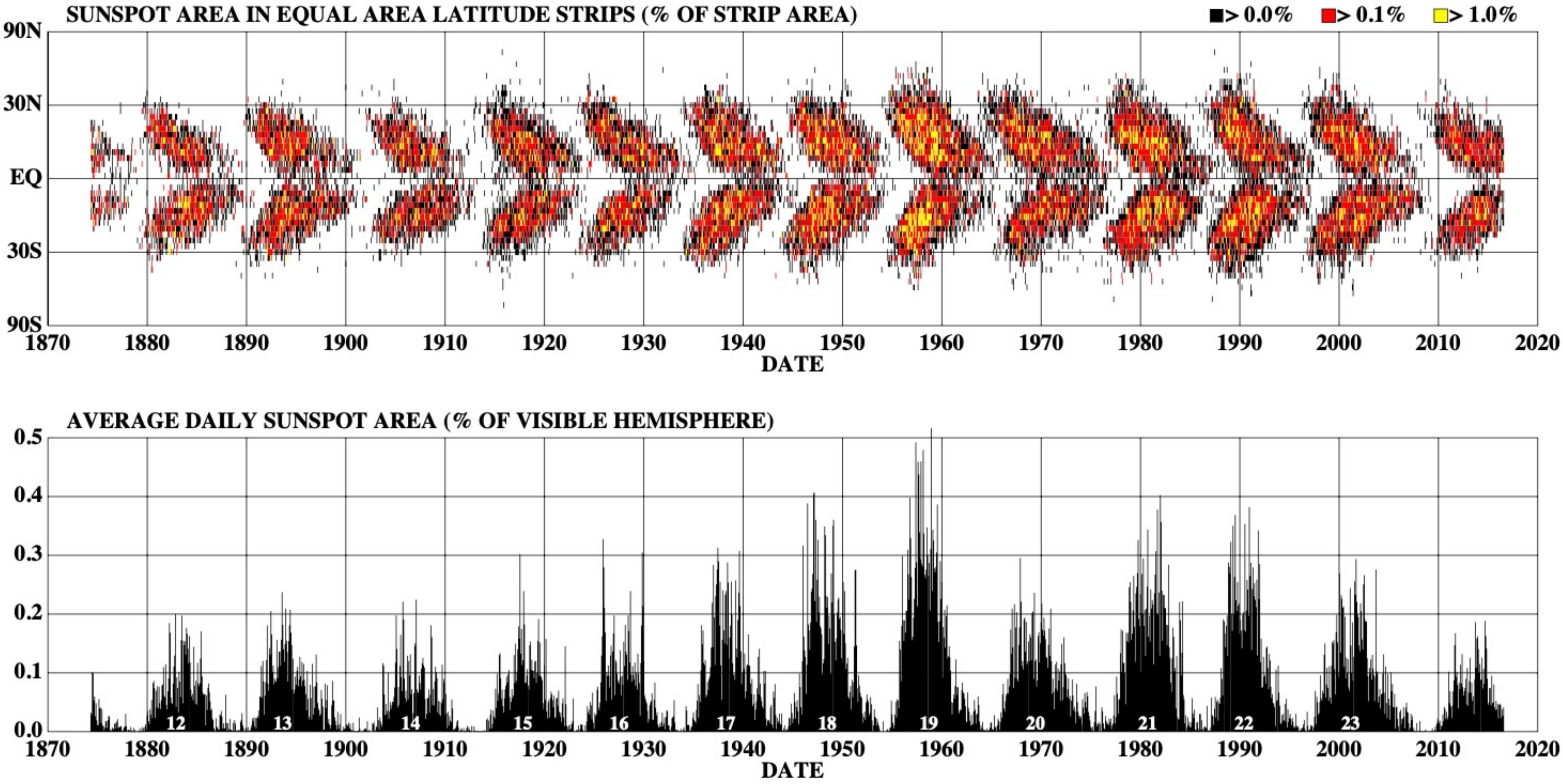
- First systematically observed by Galileo 1609
- 1775: Christian Horrebow finds variations
- 1843: Samuel Schwabe identifies Solar cycle after 17 years of observations
- 1852: Rudolf Wolf (Uni Zurich) tracked cycles back to 1745
- Wolf number = sunspot number



The Maunder minimum



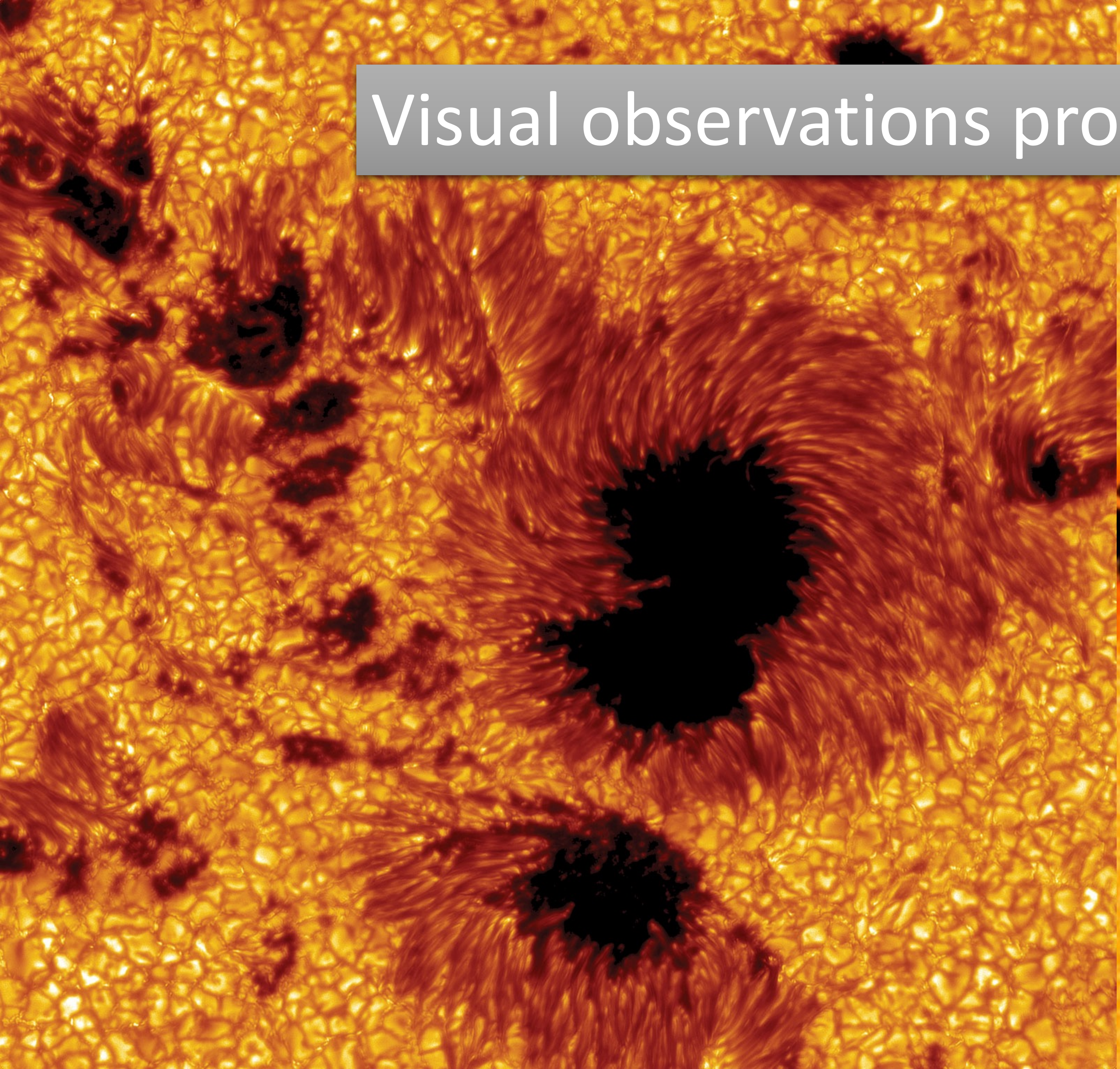
DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS

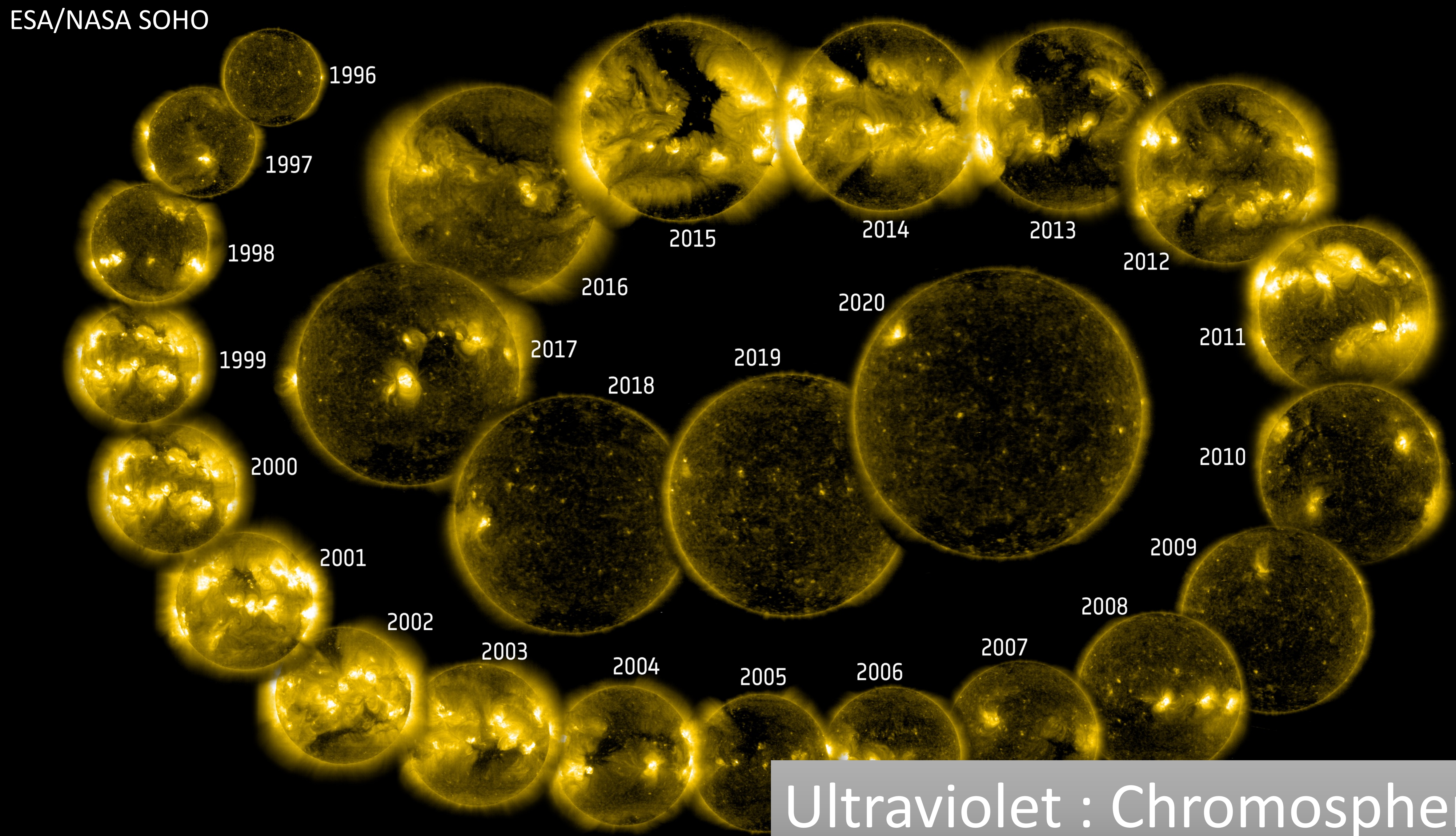


http://solarscience.msfc.nasa.gov/images/BFLY.PDF

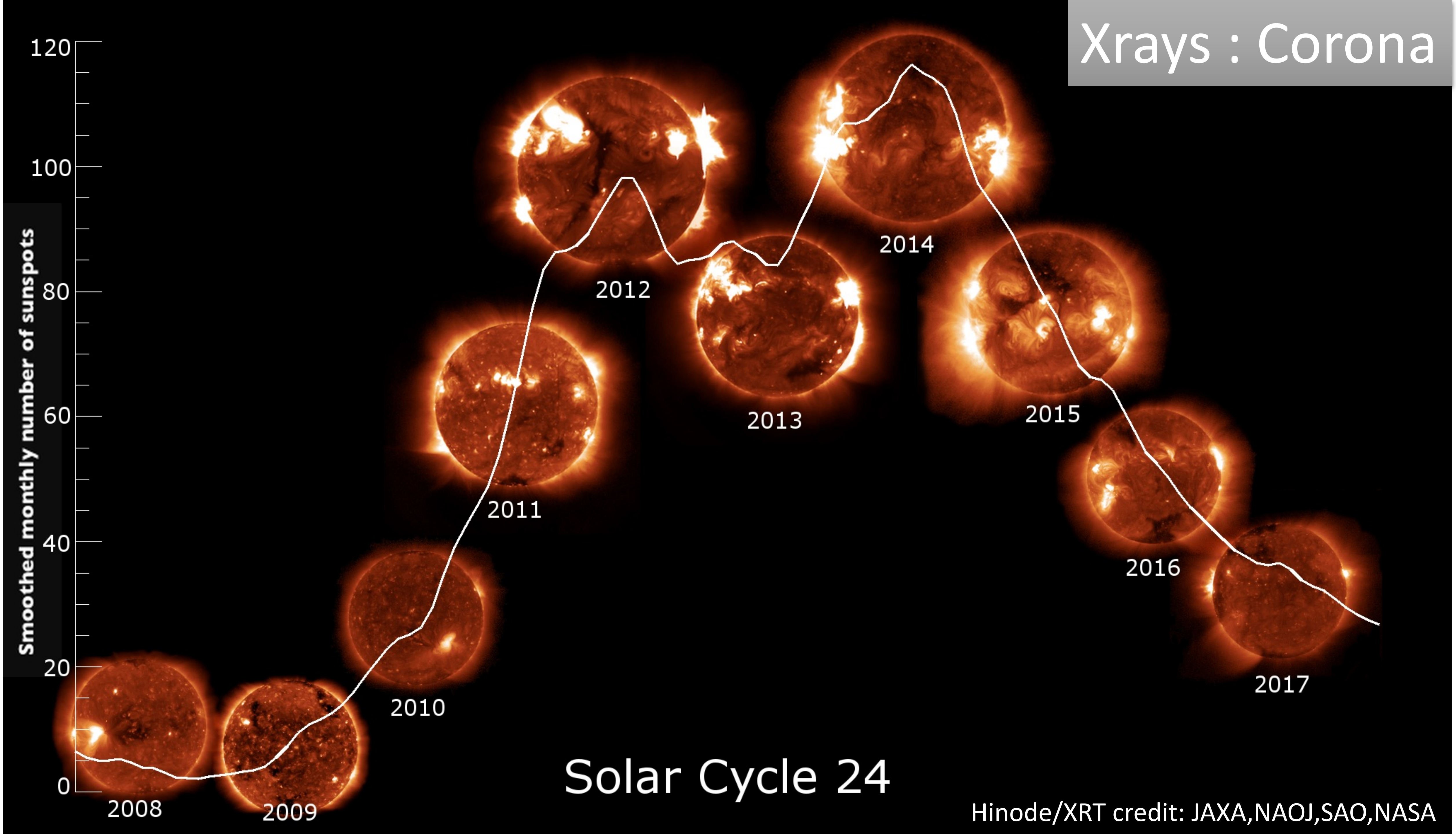
HATHAWAY NASA/ARC 2016/10

Visual observations probe Photosphere

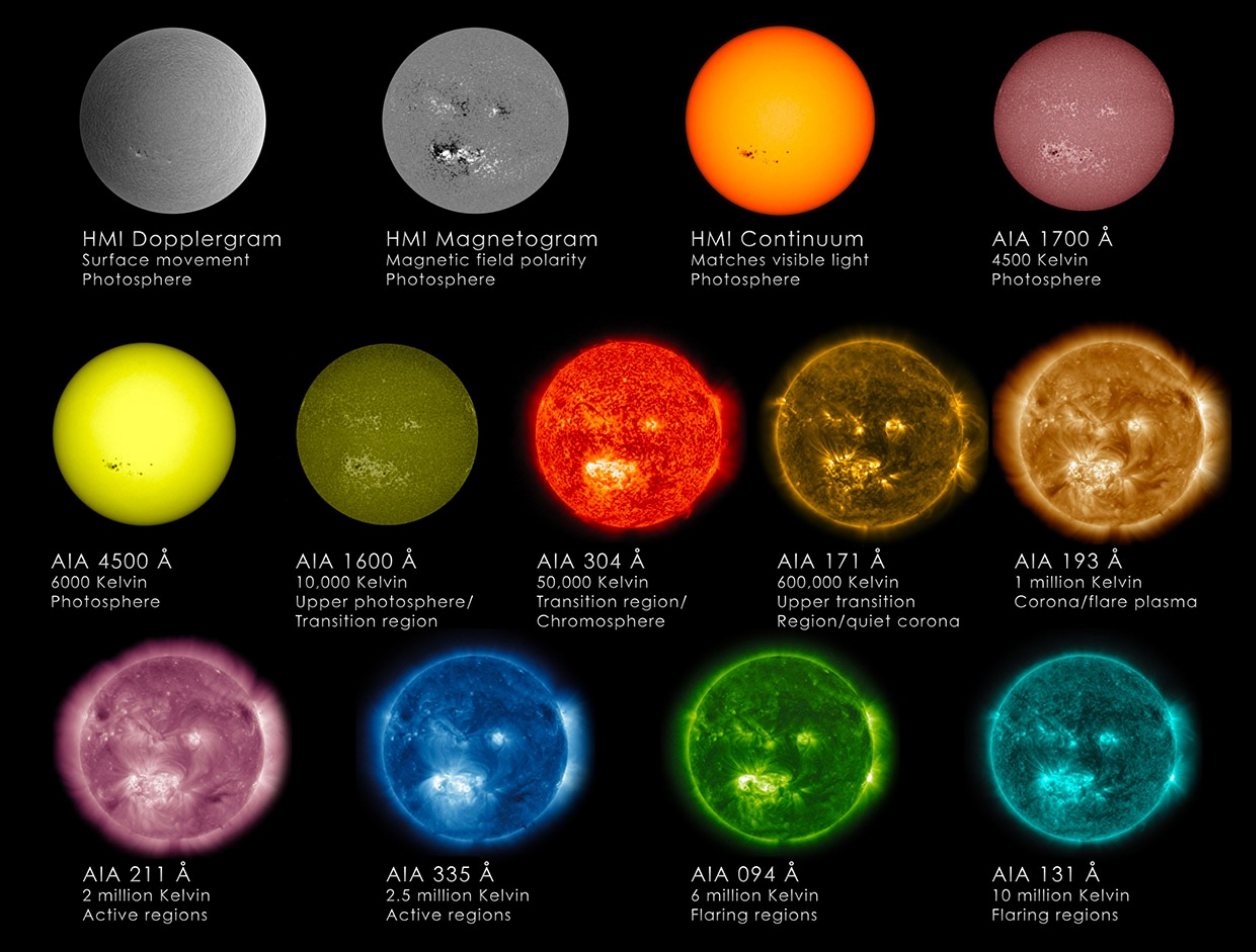




Ultraviolet : Chromosphere

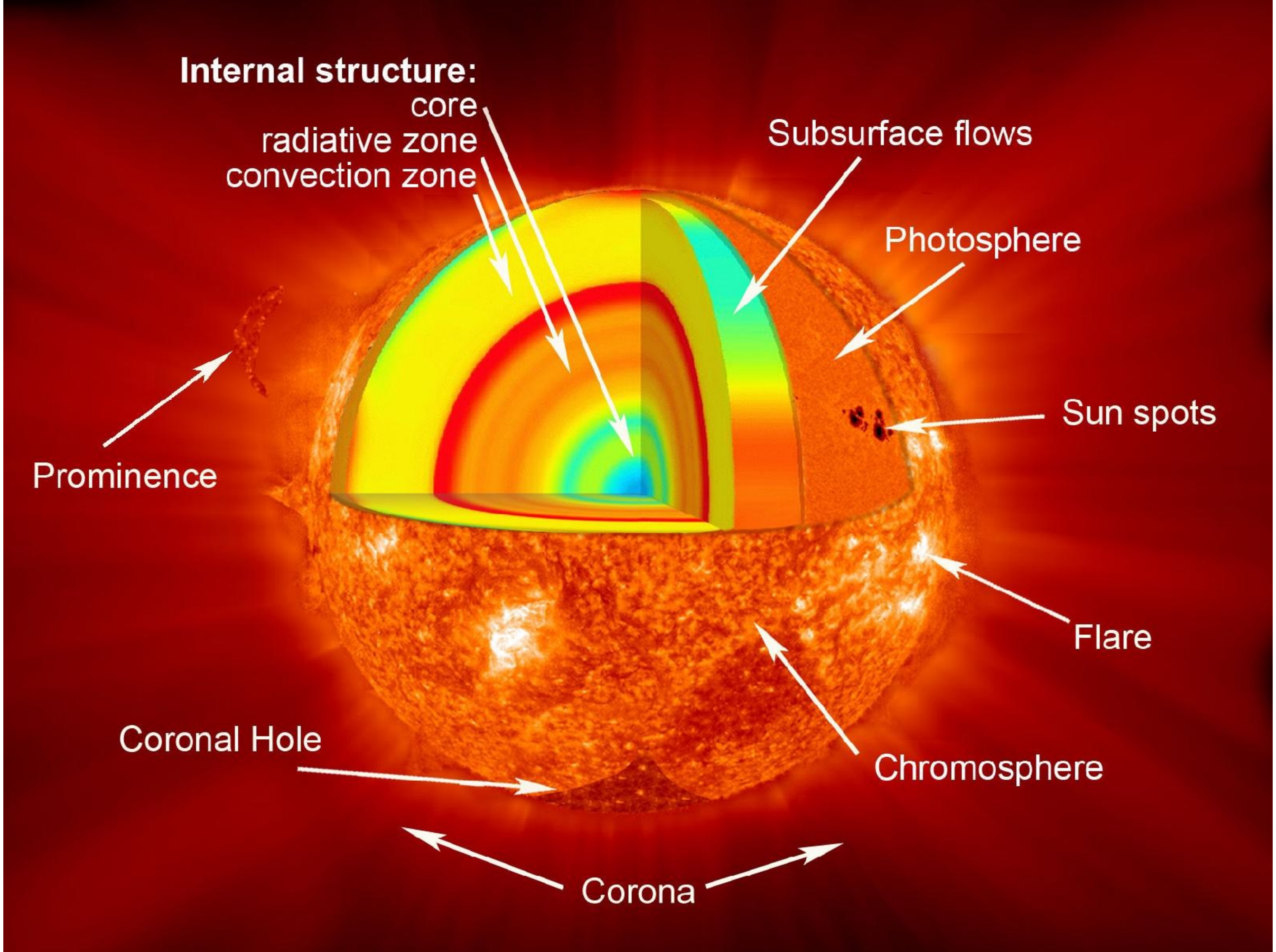


Xrays : Corona
Smoothed monthly number of sunspots
120
100
80
60
40
20
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Solar Cycle 24
Hinode/XRT credit: JAXA,NAOJ,SAO,NASA

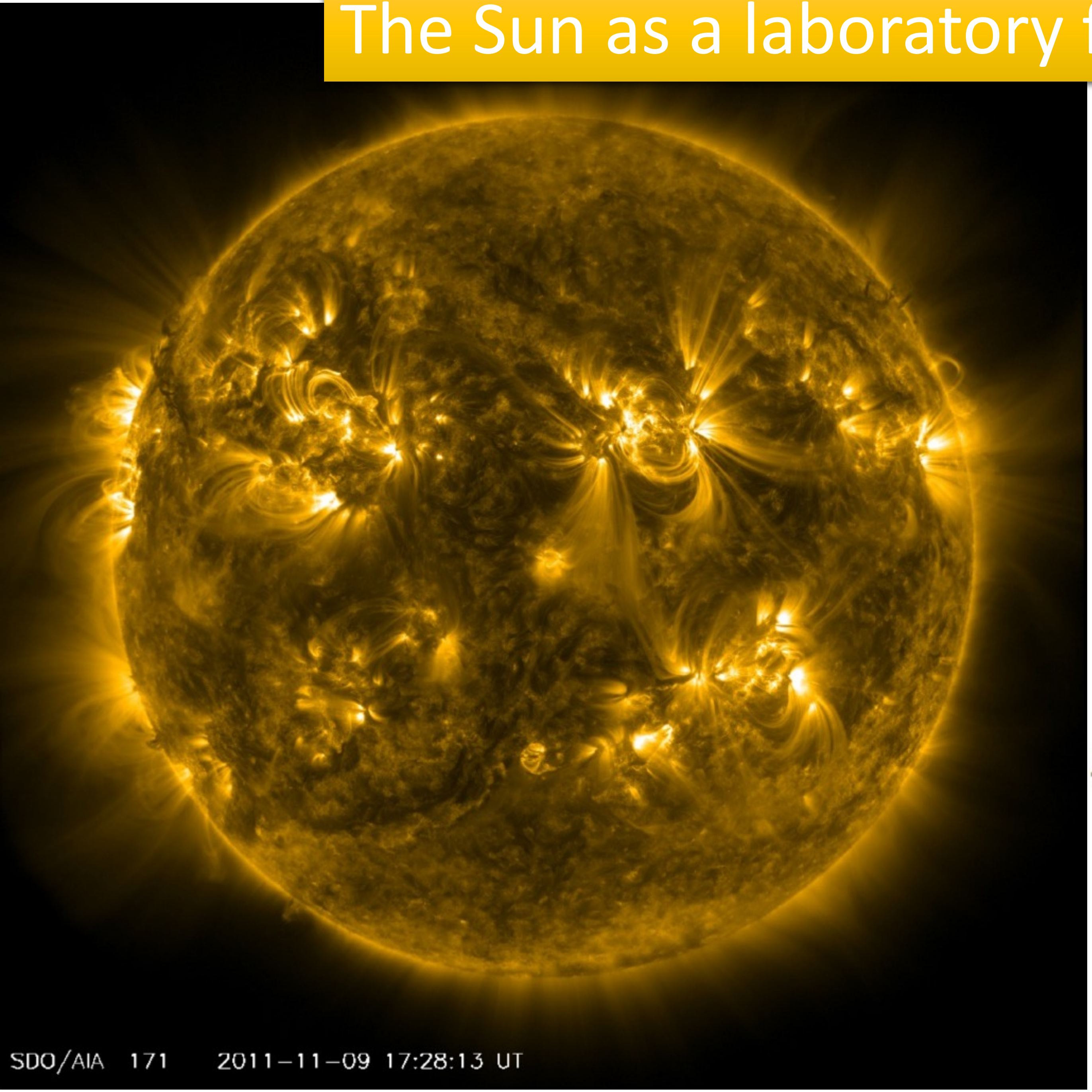


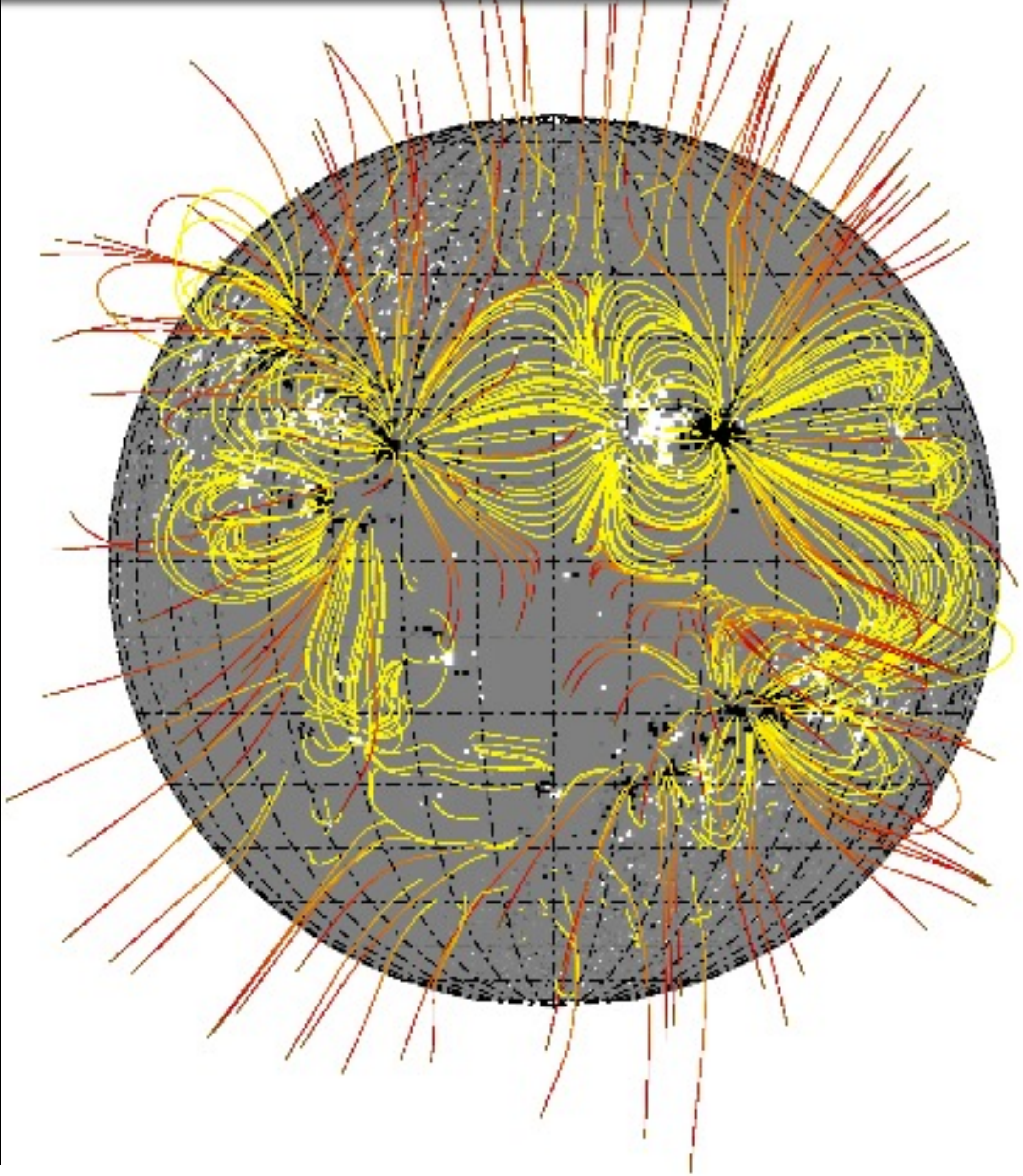
Solar Dynamics Observatory (SDO)

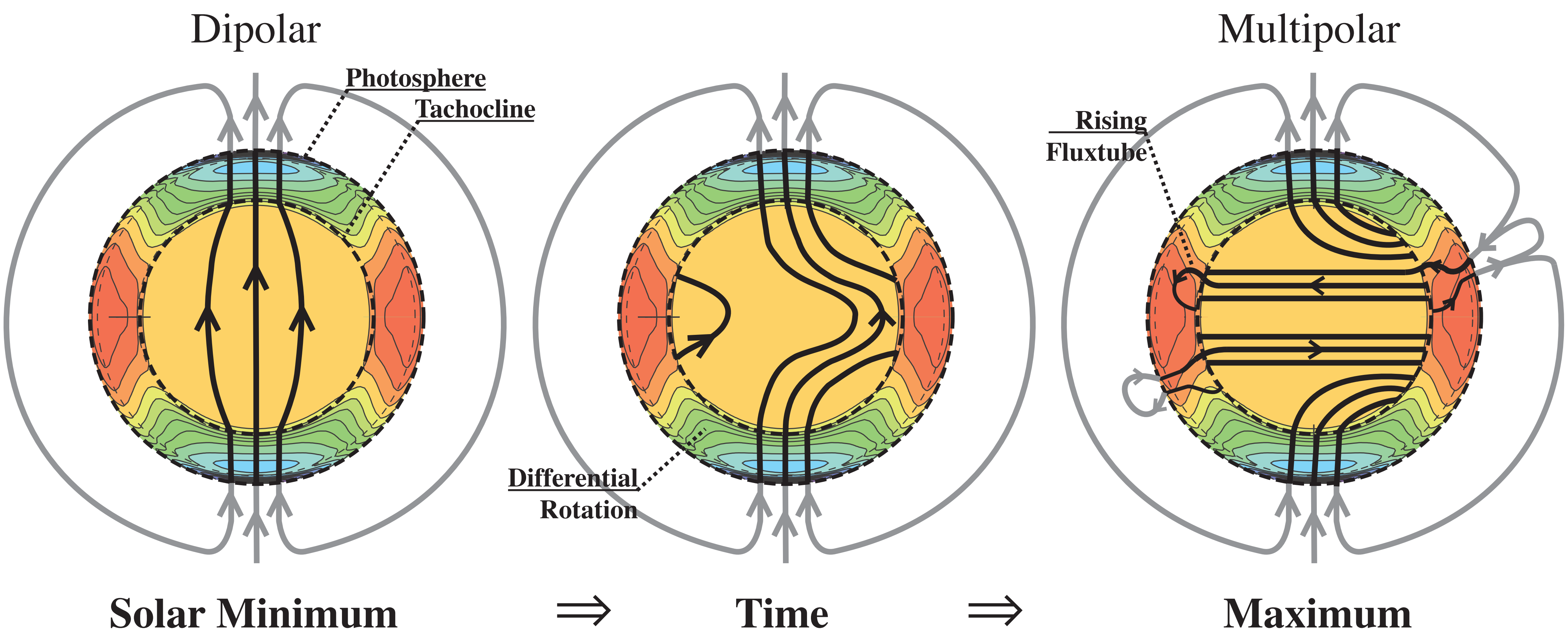
https://www.thesuntoday.org/overview/wavelengths/


Internal structure:
core
radiative zone
convection zone
Subsurface flows
Photosphere
Sun spots
Prominence
Flare
Coronal Hole
Chromosphere
Corona

The Sun as a laboratory for extreme physics







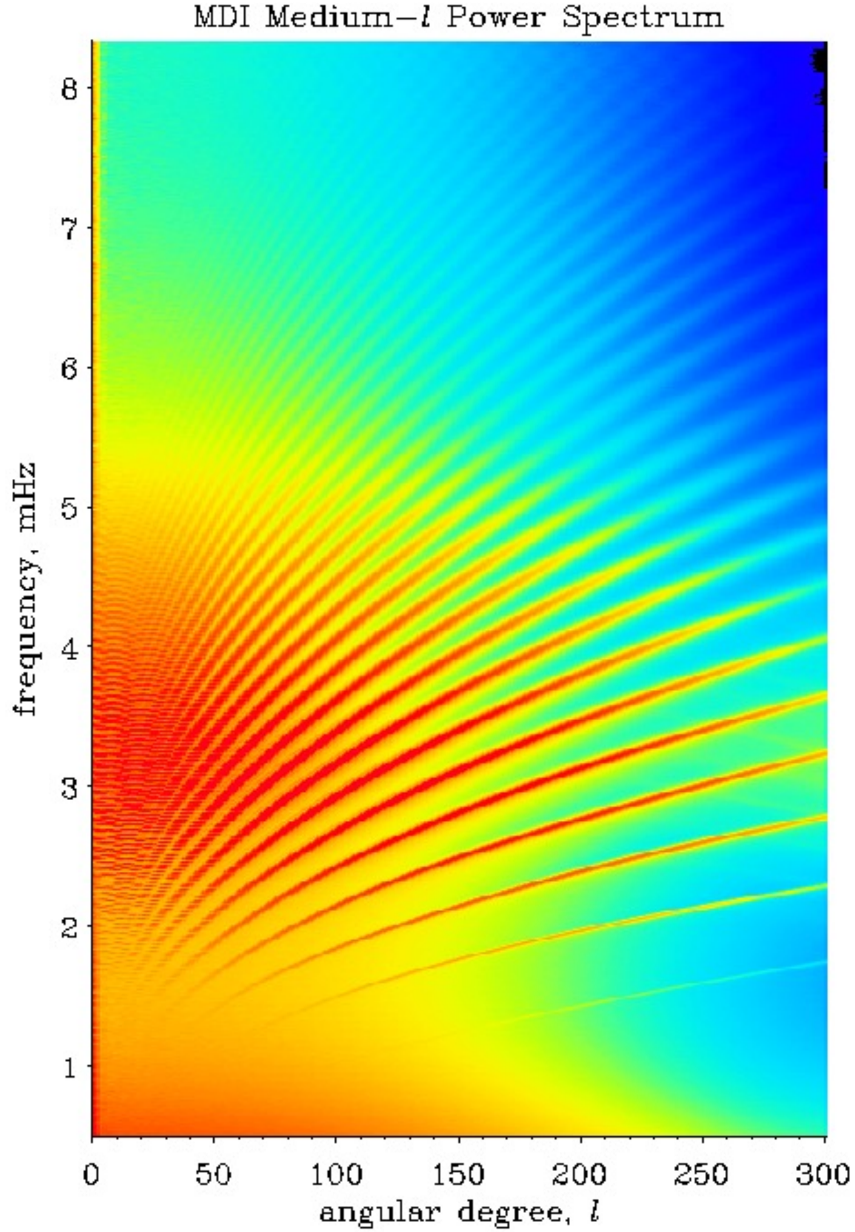
https://www2.hao.ucar.edu/hao-science/sun-dynamo-0

Helioseismology

The study of the Sun's interior by its oscillations

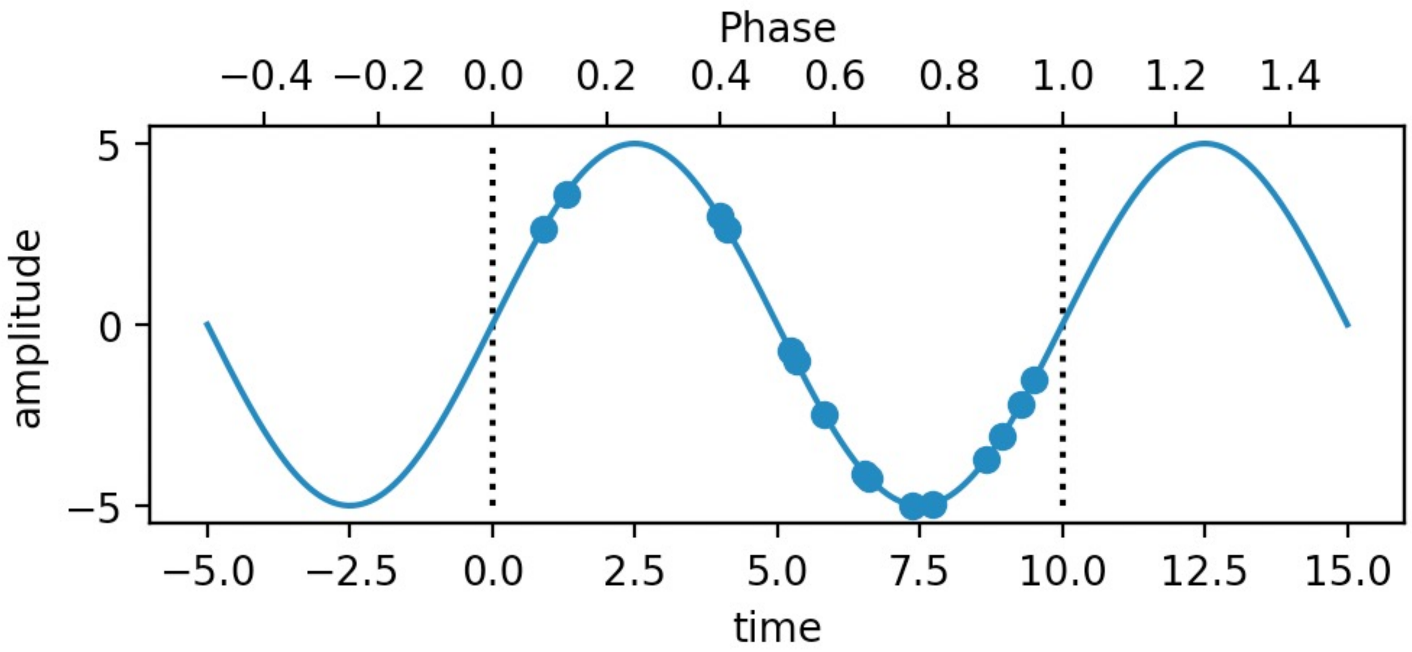
https://www.pnas.org/content/96/10/5356

https://link.springer.com/article/10.1007/s41116-016-0003-4



ESA/NASA SOHO satellite 1996

The Periodogram



- Essential for time-domain
- Assumes periodicity!
- Fourier transform of signal
- Estimator of true power spectrum

$$y = A\sin\left(\frac{2\pi t}{P} + \phi_0\right) + \epsilon$$

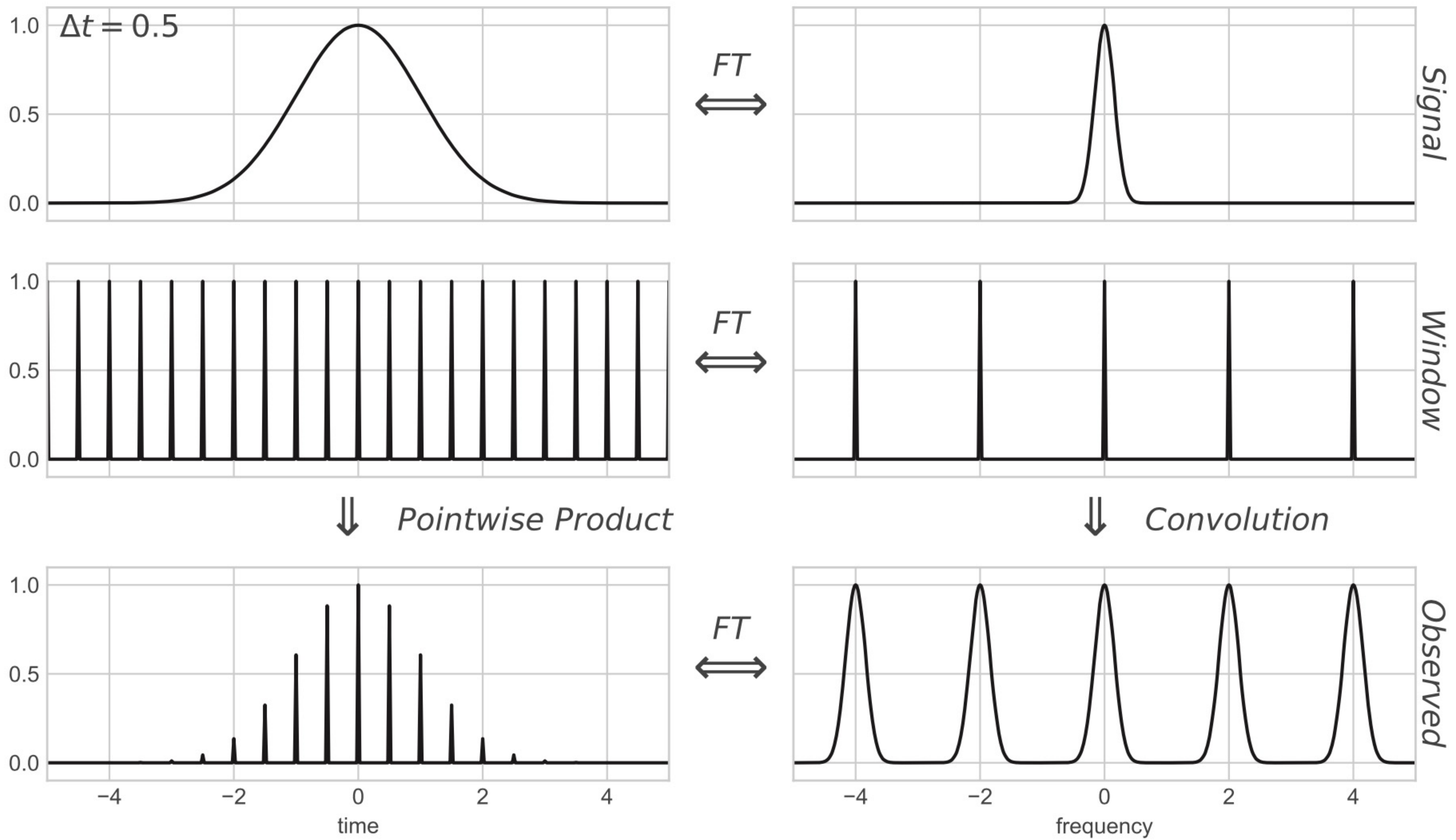
$$\phi = \frac{t}{P} - \mathrm{int}\frac{t}{P}$$

$$P_S(f) = \frac{1}{N}\left(\sum_{n=1}^{N} g_n e^{-2\pi i f t_n}\right)^2$$

$$P_S(f) = \frac{1}{N}\left[\left(\sum_{n=1}^{N} g_n \cos(2\pi\, \mathrm{f}\, \mathrm{t}_n)\right)^2 + \left(\sum_{n=1}^{N} g_n \sin(2\pi f\, t_n)\right)^2\right]$$

[VanderPlas 2018 *ApJS* **236** 16]

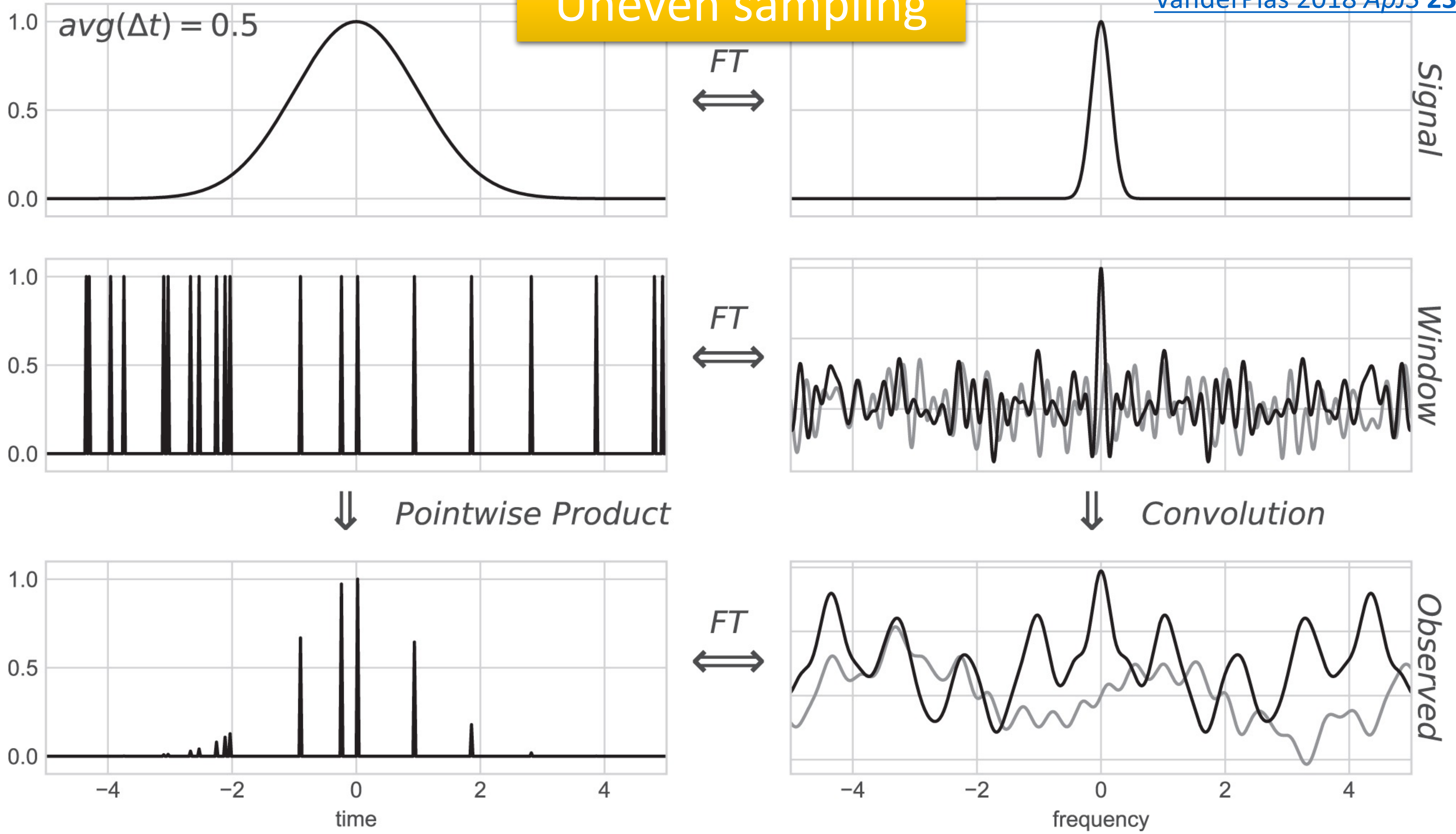
https://online.stat.psu.edu/stat510/lesson/6/6.1



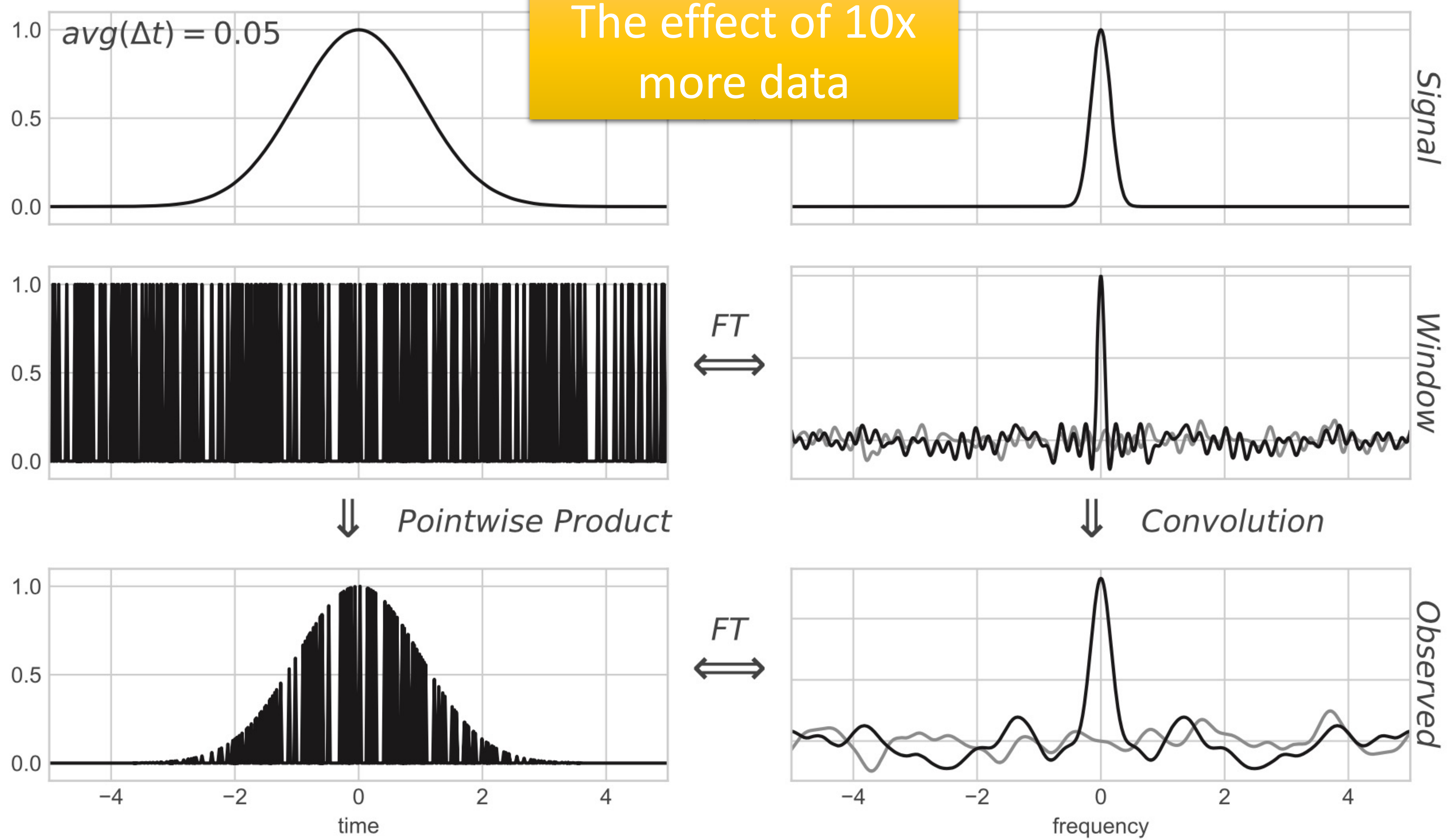
Δt = 0.5
FT
FT
FT
Signal
Window
Observed
Pointwise Product
Convolution
time
frequency

Uneven sampling

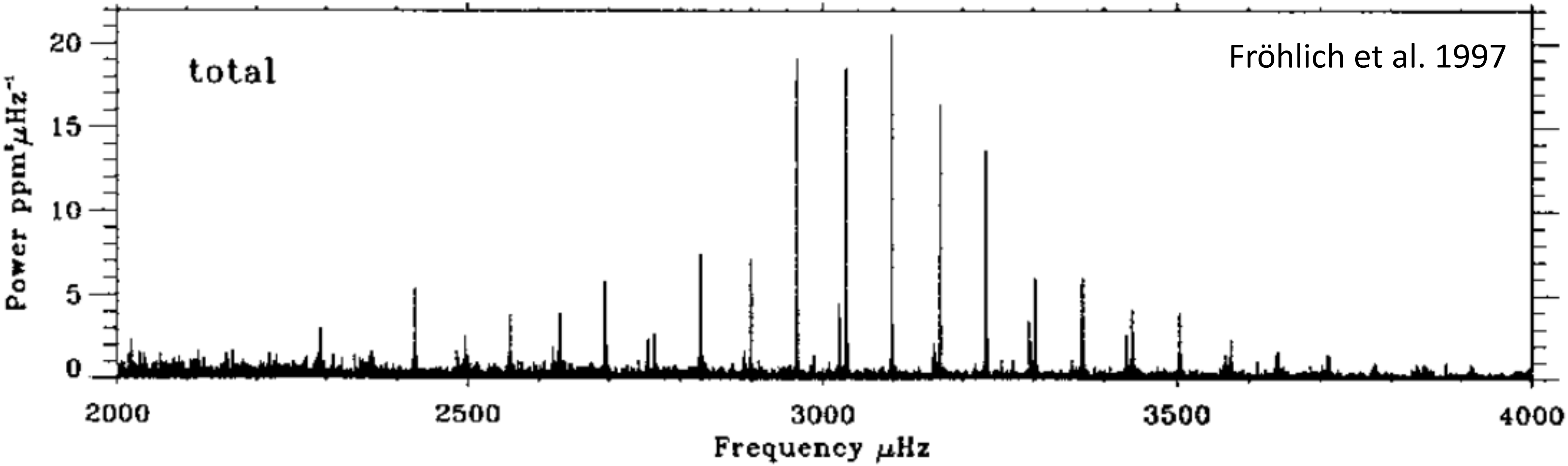
VanderPlas 2018 *ApJS* **236** 16



The effect of 10x more data

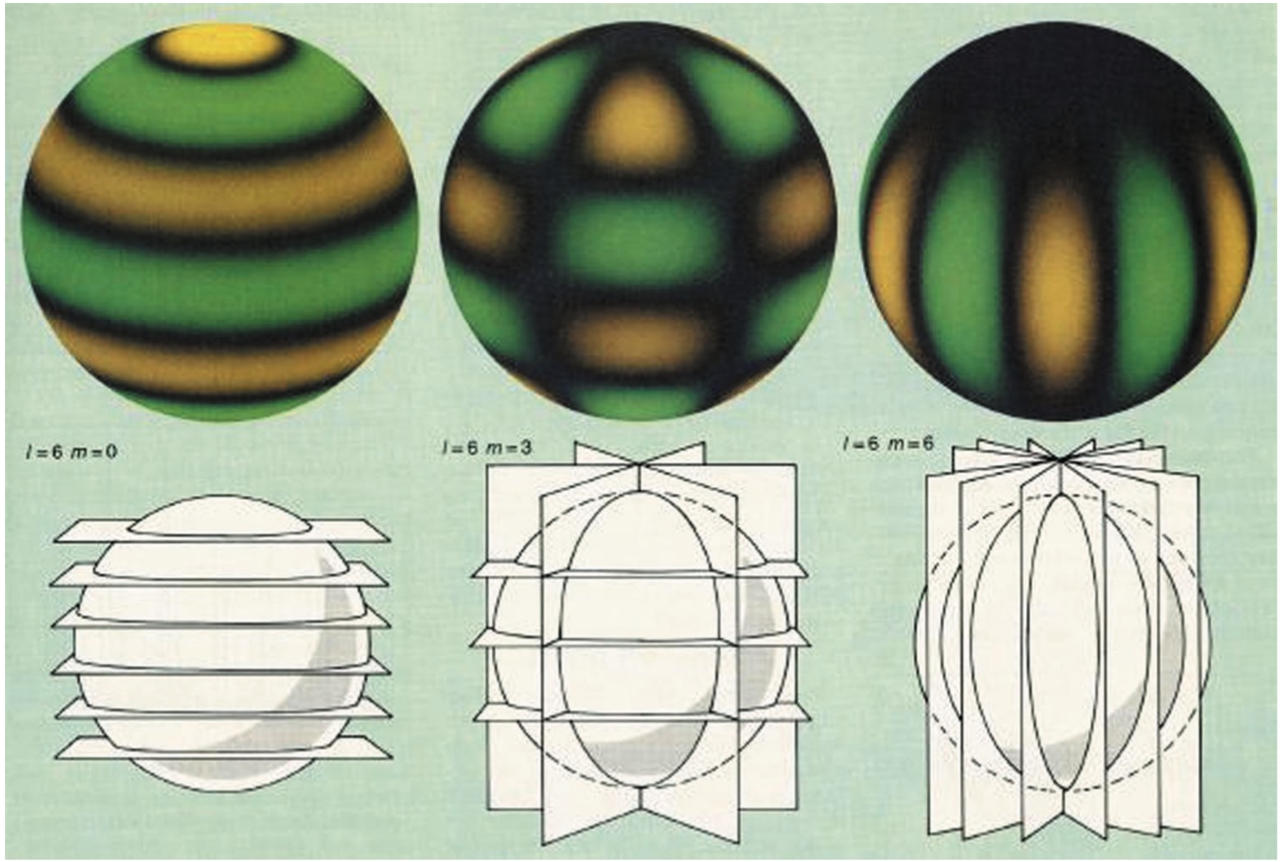


Solar oscillations



Solar oscillations: p-modes (pressure)

- 5 min oscillation discovered in 1962
- Sun has ~10 M resonant modes
- Mode eigenfunctions decomposed to spherical harmonics with radial order n, degree l, and azimuthal order m: Y_nlm
- Mostly: linear & adiabatic oscillations
- Lower l modes penetrate deeper into interior
- Use different l's to map interior!



$$\nu_{n,l} = \Delta\nu\left(n + \frac{1}{2}l + e\right) - l(l+1)D_0$$

Bedding & Kjeldsen 2003

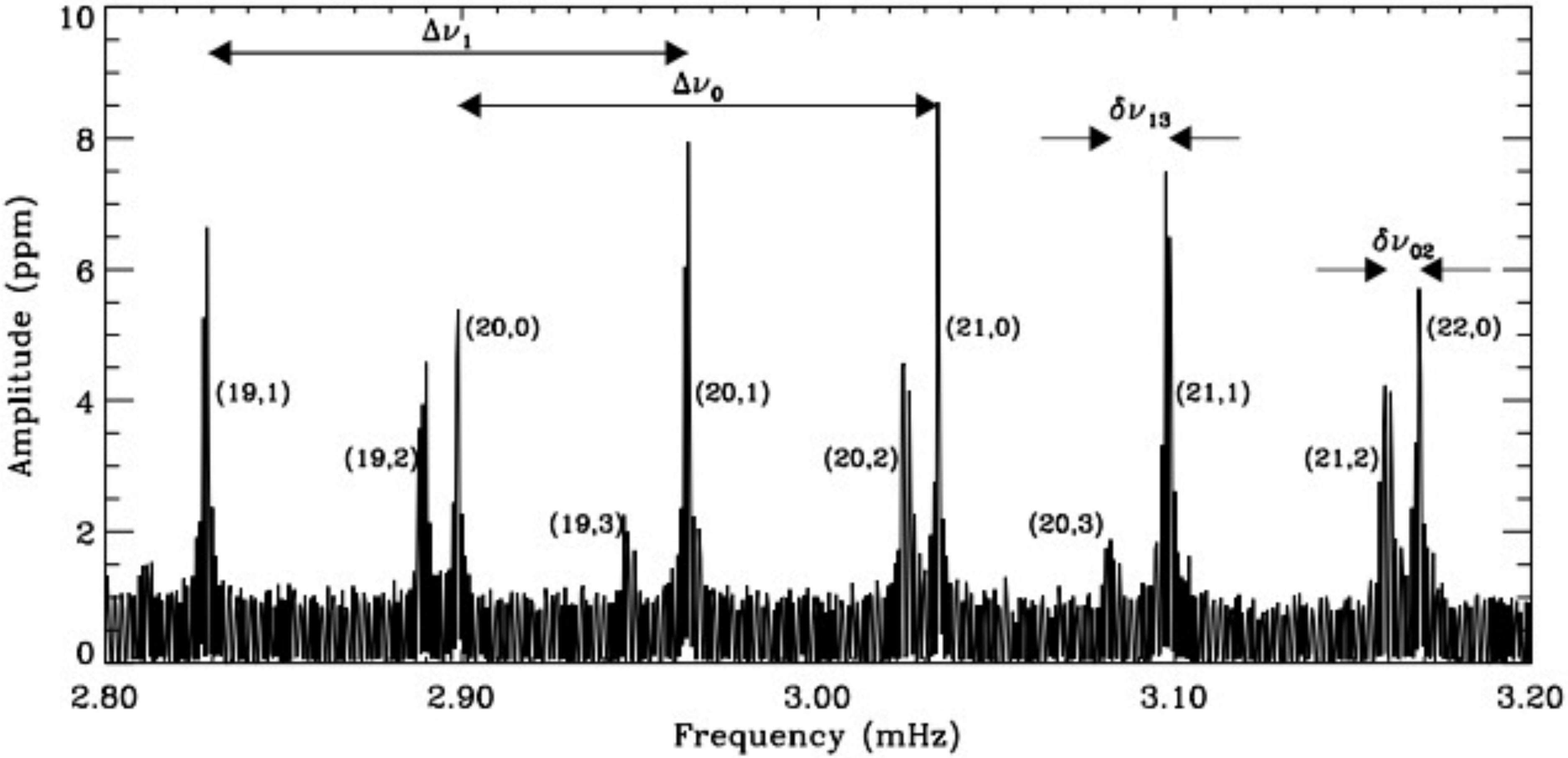
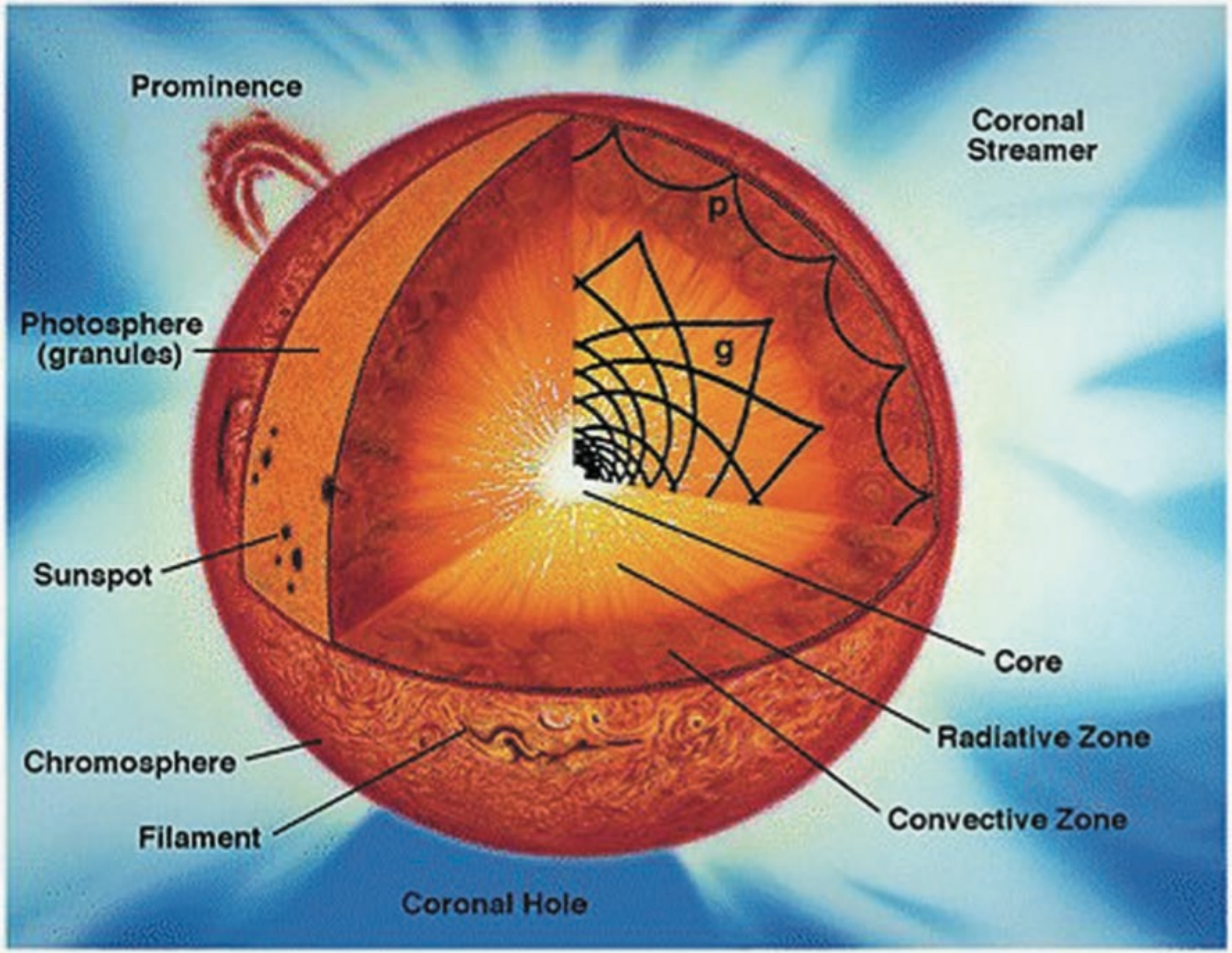
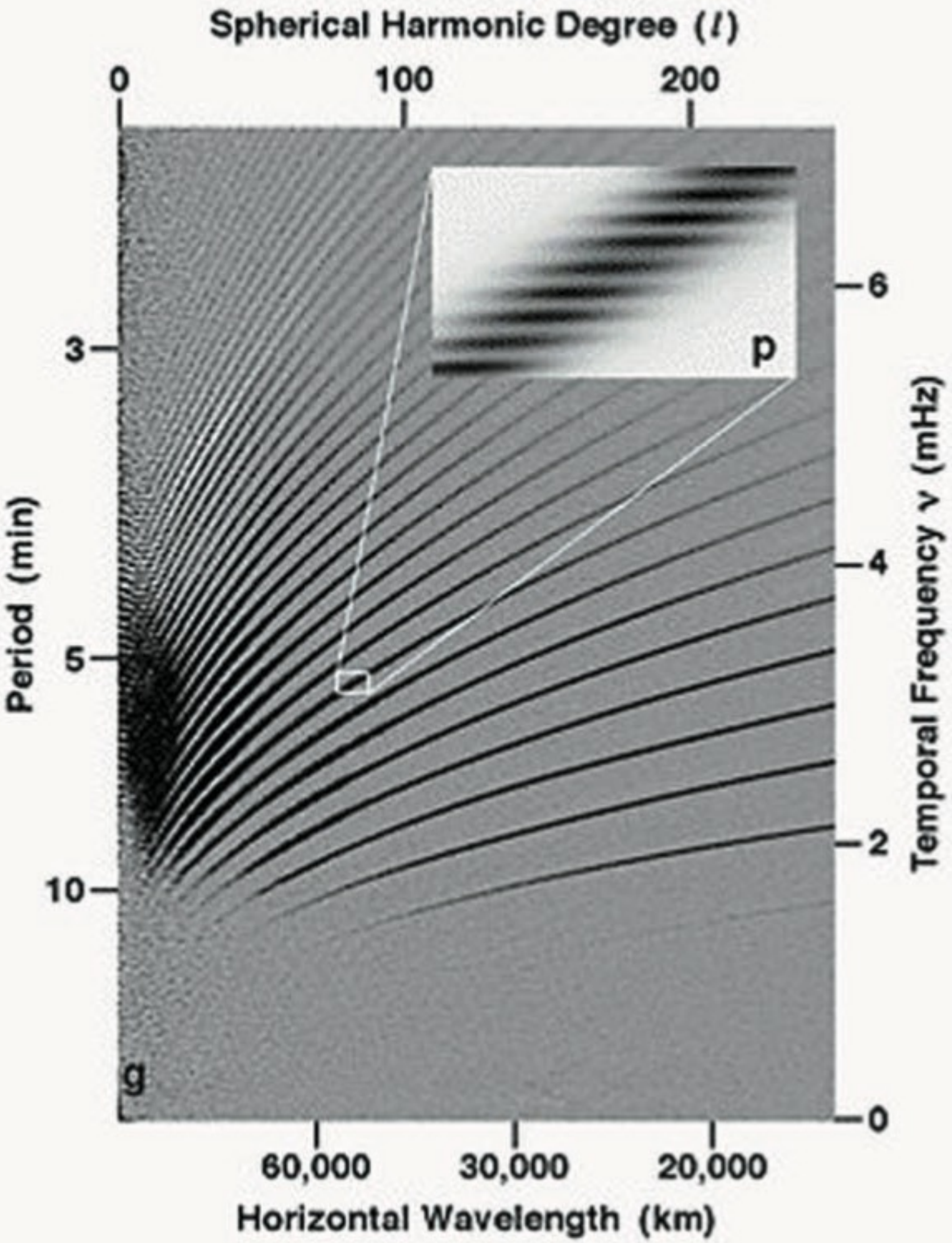
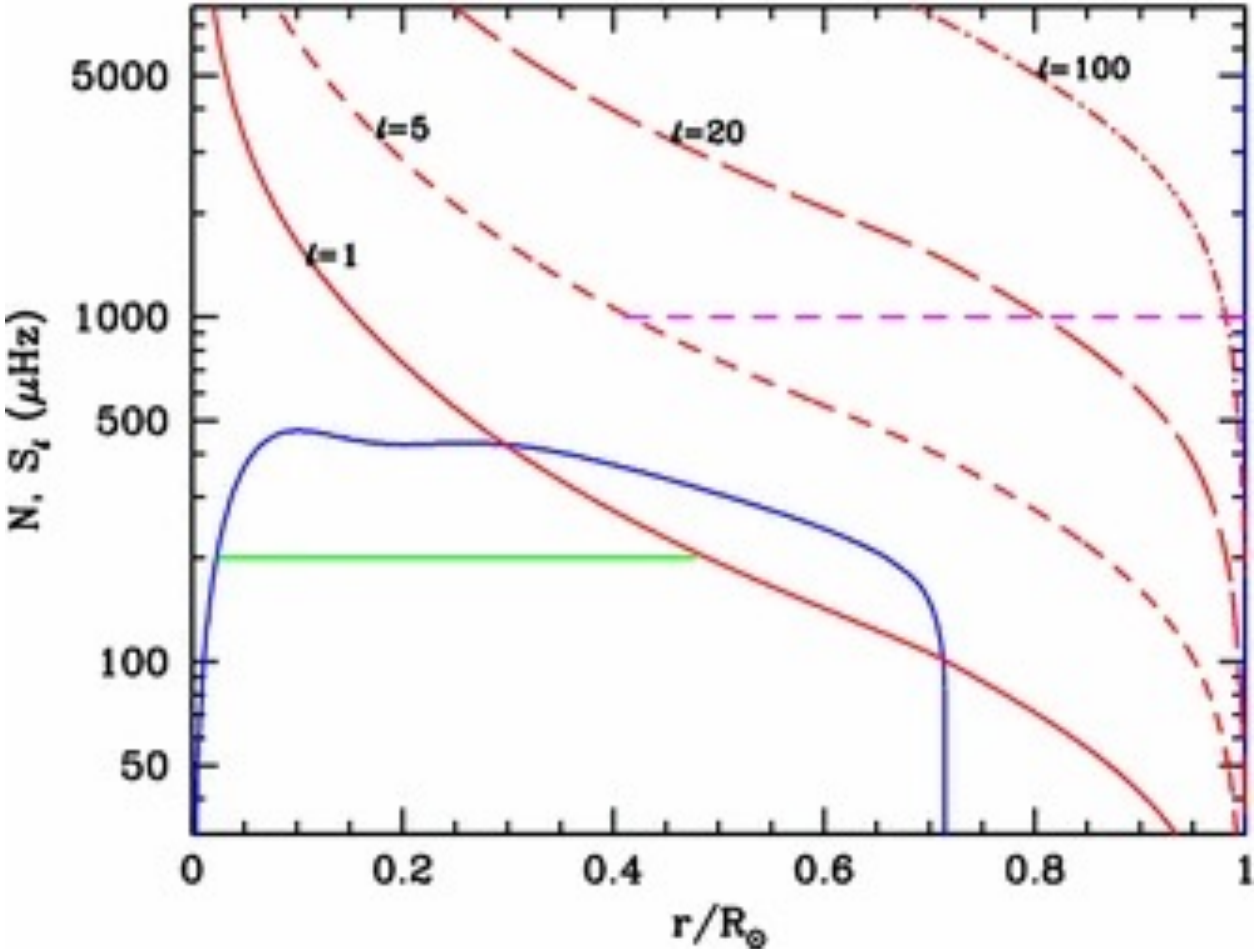


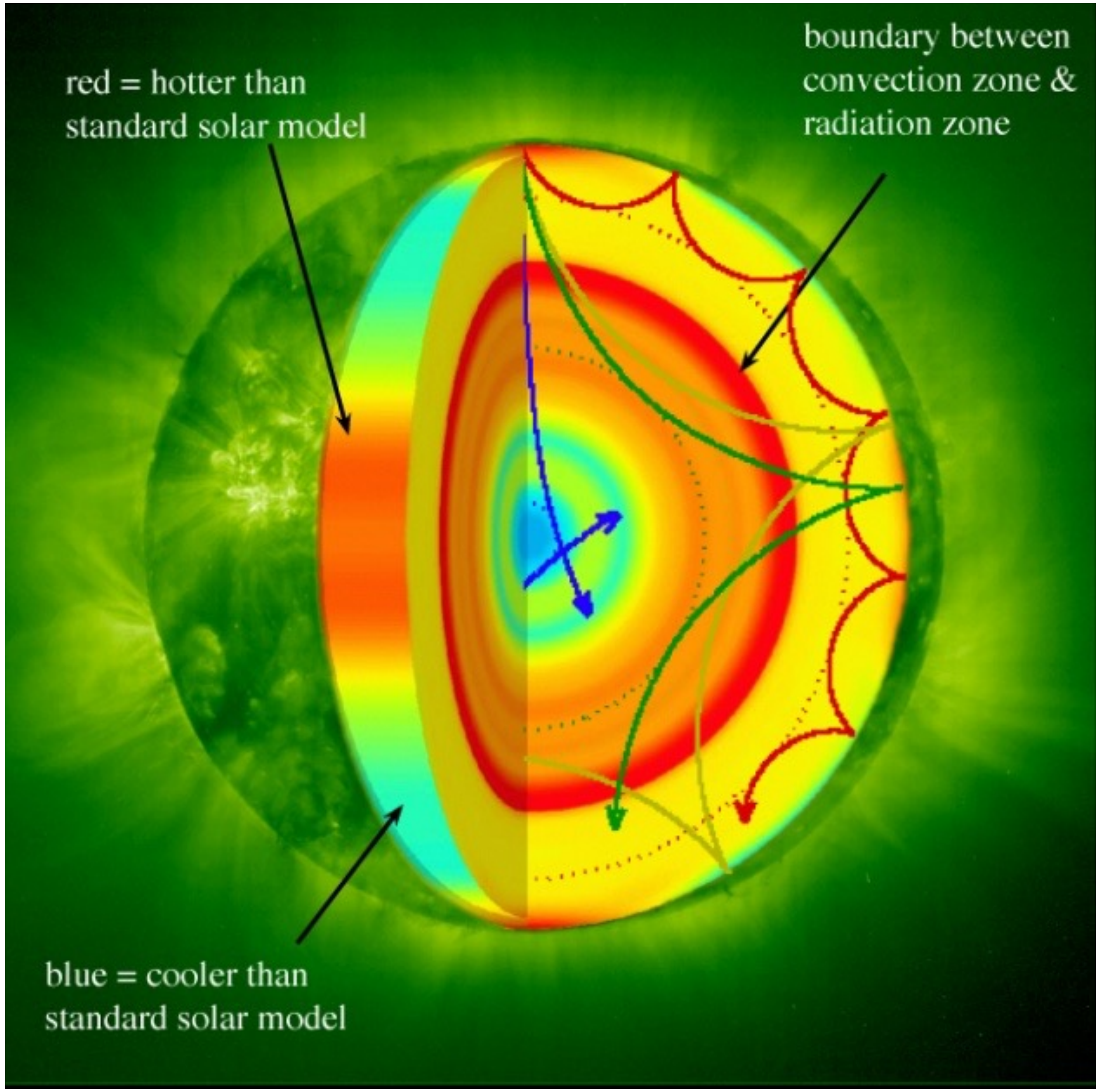
Fig. 2.— Small section of the solar amplitude spectrum (lower panel of Fig. 1), showing (n, l) values for each mode. The large and small separations are indicated. These measure the average density and core composition, respectively, and can therefore be used to infer the mass and age of a star.


Prominence
Coronal
Streamer
p
g
Photosphere
(granules)
Sunspot
Core
Radiative Zone
Chromosphere
Convective Zone
Filament
Coronal Hole


Spherical Harmonic Degree (l)
0
100
200
p
6
3
4
Period (min)
Temporal Frequency ν (mHz)
5
2
10
g
0
60,000
30,000
20,000
Horizontal Wavelength (km)



5000
1000
500
100
50
N, S_l (μHz)
0
0.2
0.4
0.6
0.8
1
r/$R_\odot$
l=1
l=5
l=20
l=100

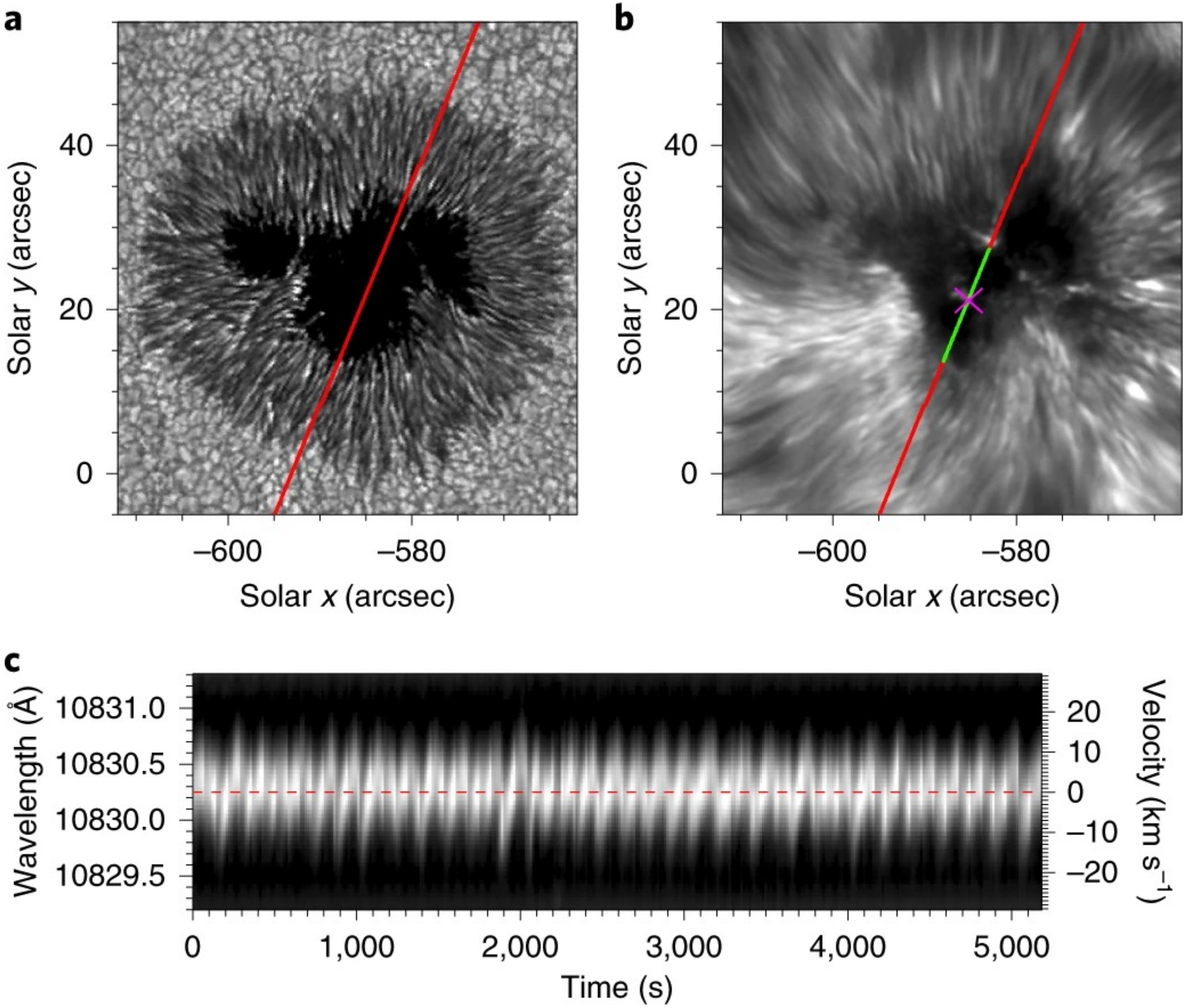


red = hotter than
standard solar model
boundary between
convection zone &
radiation zone
blue = cooler than
standard solar model

https://www.nature.com/articles/s41550-019-0945-2

Local helioseismology

- High l: spatial resolution
- High time-resolution
- Spectroscopy
- Birmingham Solar Oscillations Naetwork (BiSON): longest running helioseismology network (1976+)
- Continuous monitoring around the world



Jess et al. (2019)

Review: [Gizon & Birch (2005)]