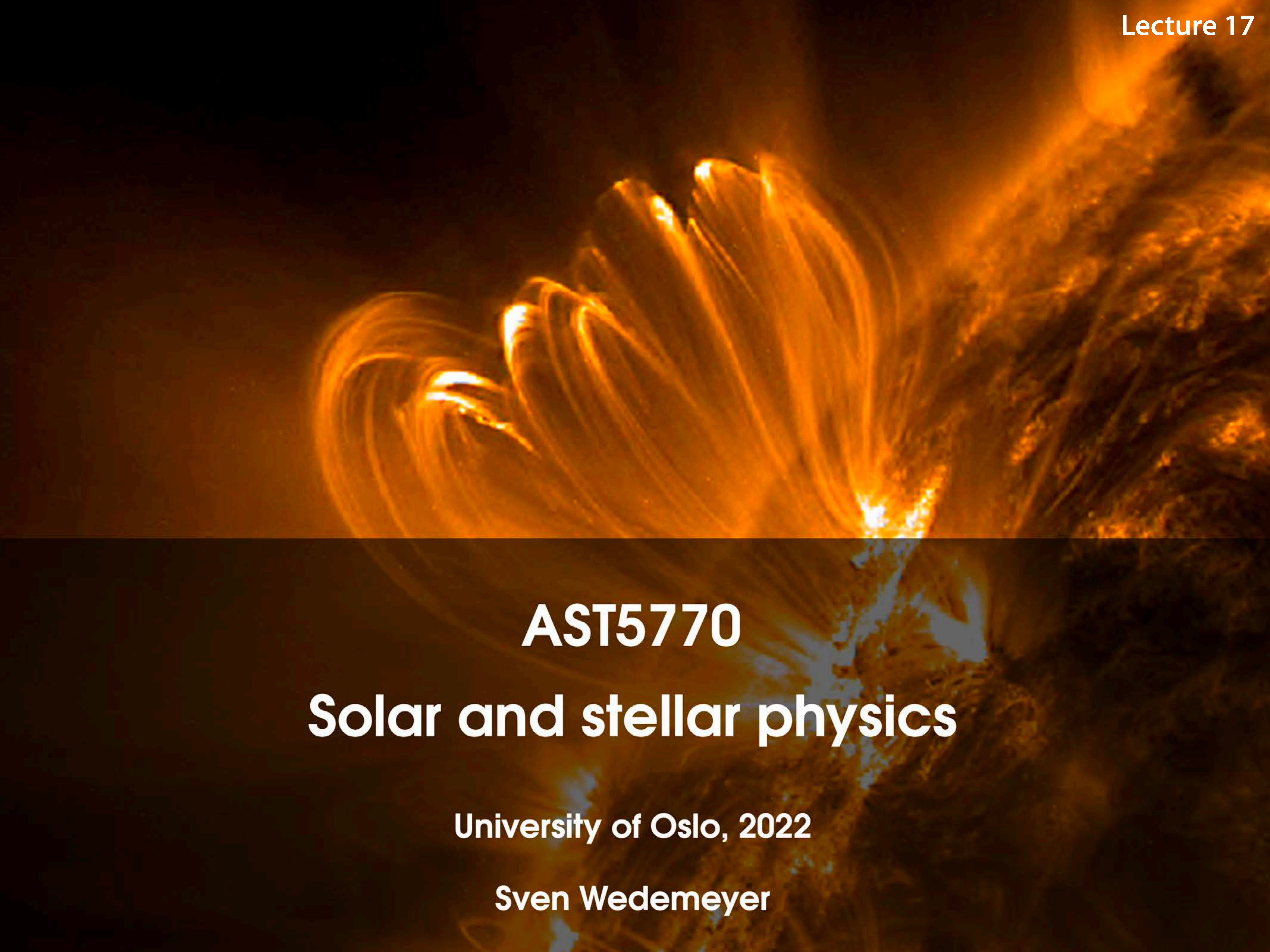


AST5770

Solar and stellar physics

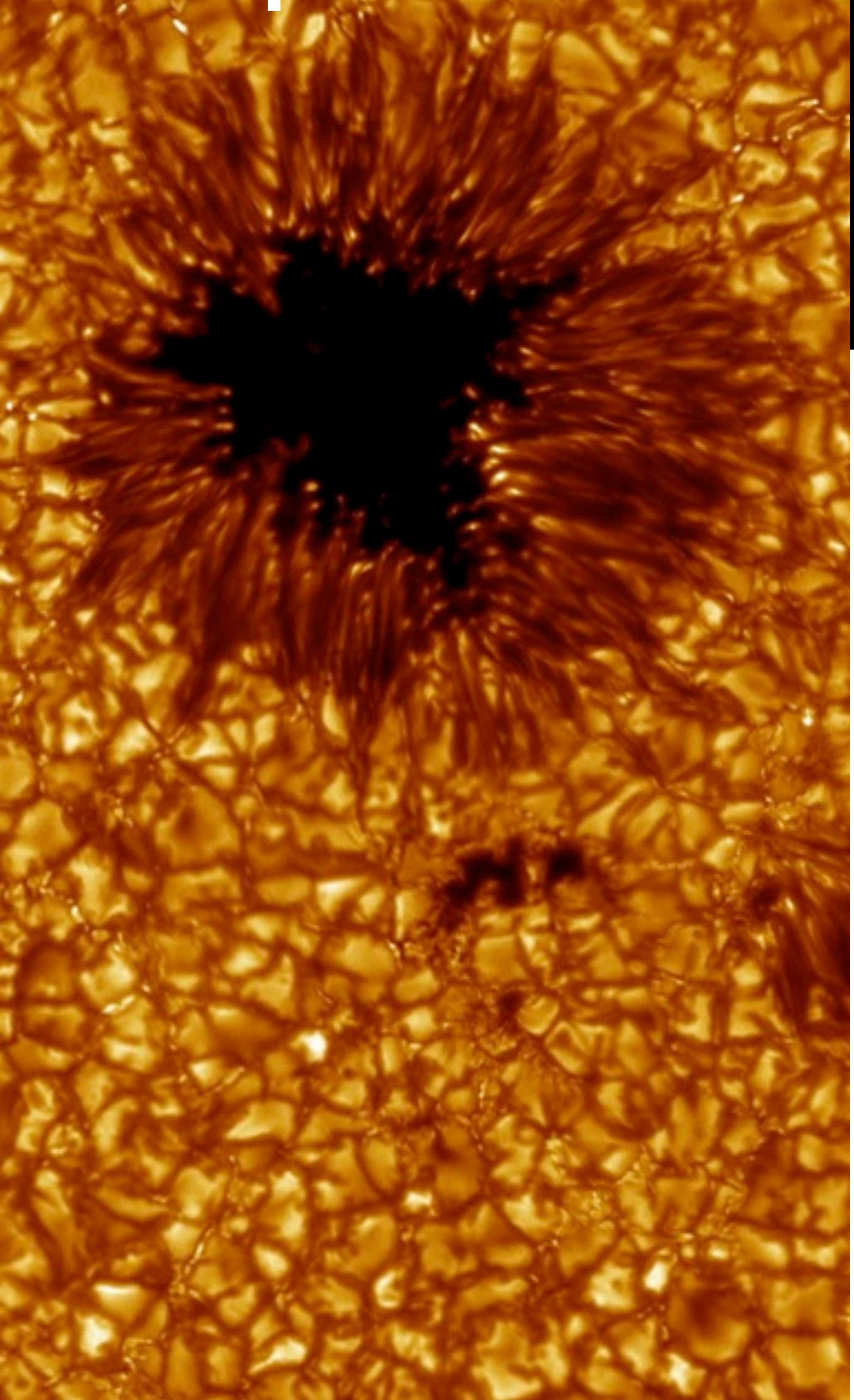
University of Oslo, 2022

Sven Wedemeyer

Sunspots

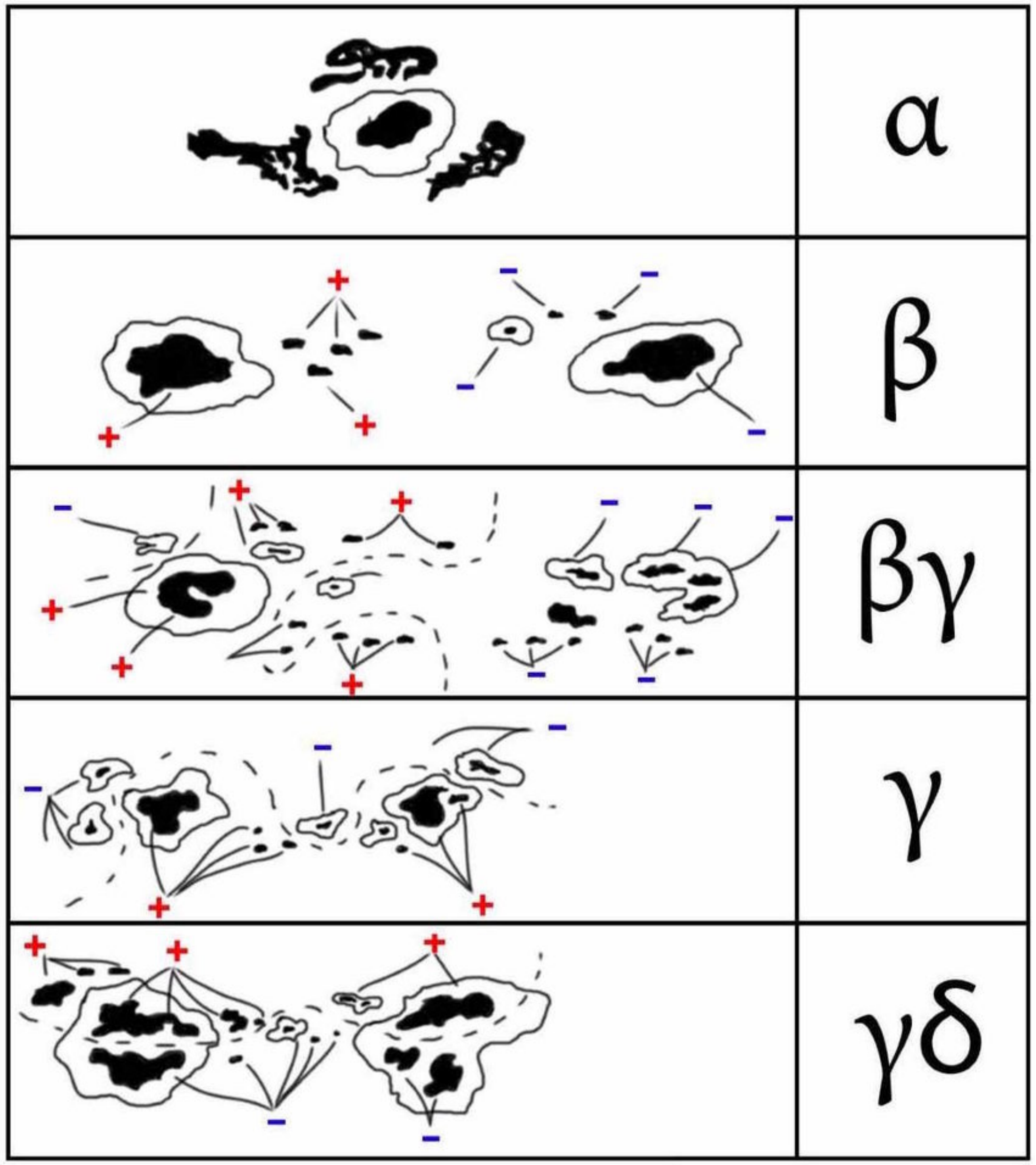
Sunspots

Recap



The Sun's magnetic field has a complicated topology.

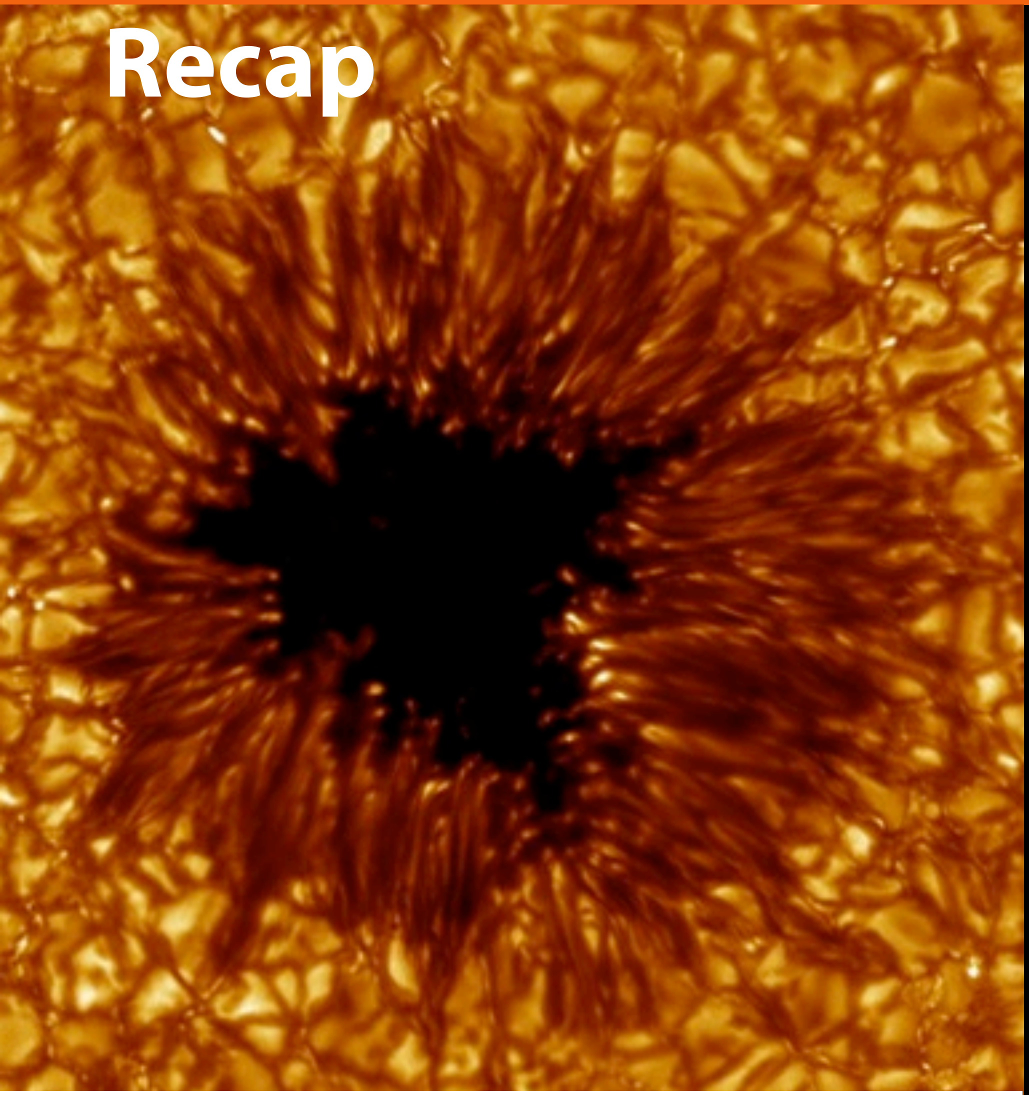
- Sunspot classification from **α to δ** (simple to complex)
- Sizes: a few 10 Mm (3Mm — 60 Mm)
- Lifetimes: hours for small sunspots to (rarely) months
- Lifetime + contained magnetic flux scale with sunspot area

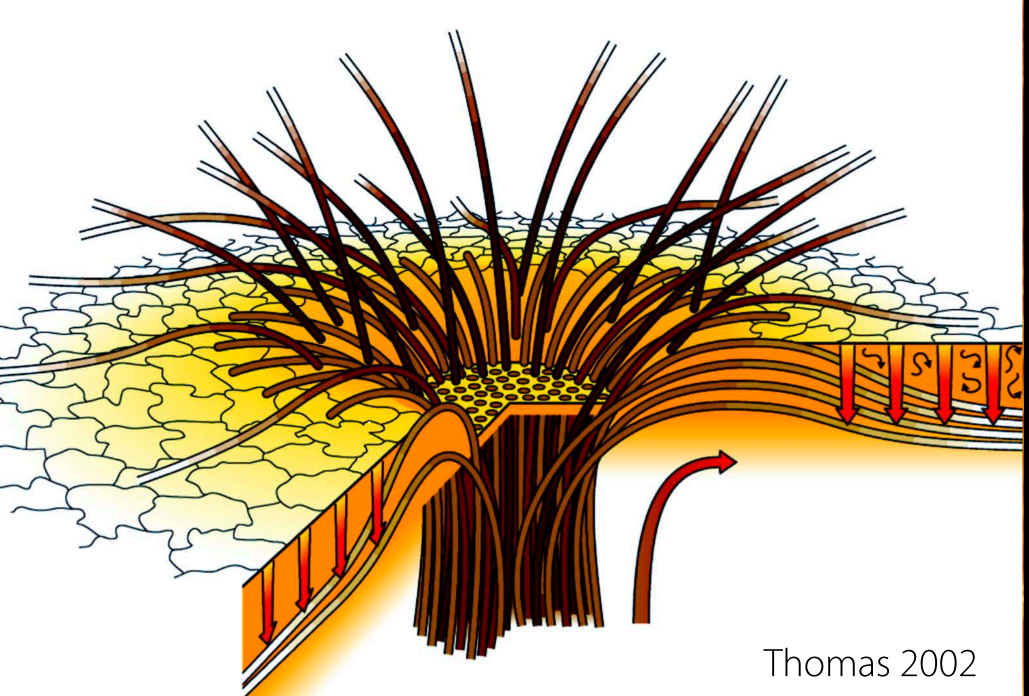


Andrus 2013

Sunspots

Recap





Thomas 2002

The Sun's magnetic field has a complicated topology.

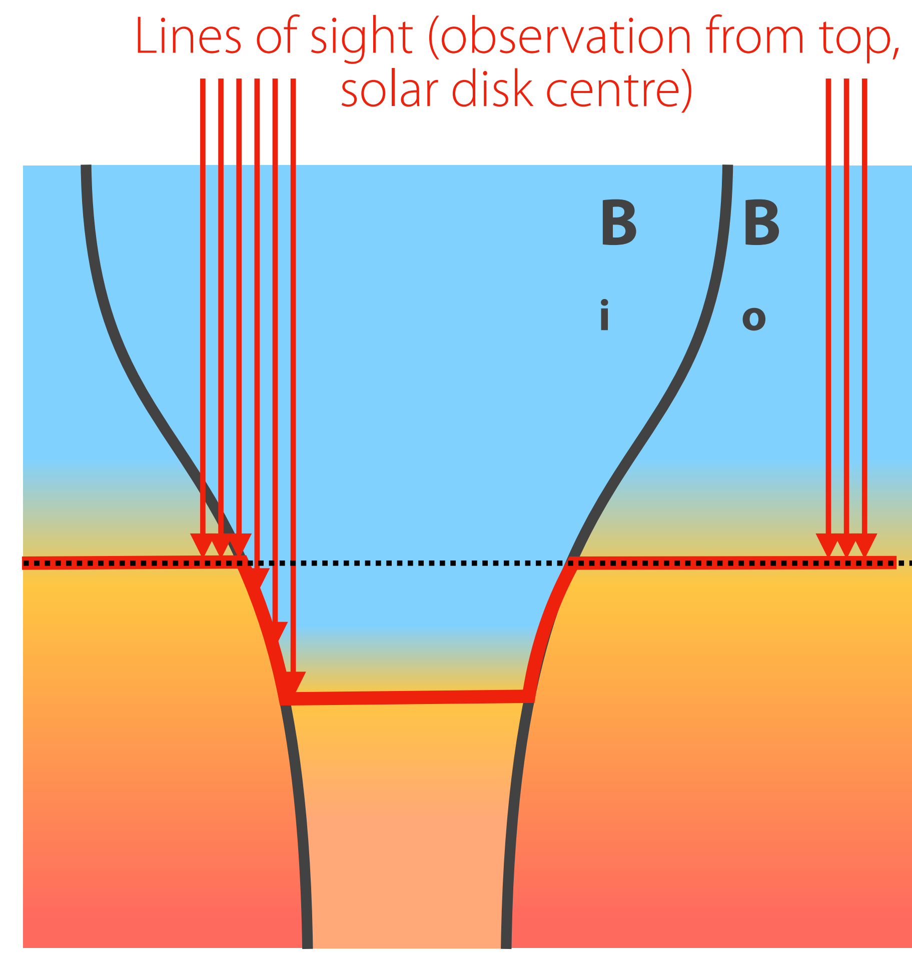
- Sunspot classification from **α to δ** (simple to complex)
- Sizes: a few 10 Mm (3Mm — 60 Mm)
- Lifetimes: hours for small sunspots to (rarely) months
- Lifetime + contained magnetic flux scale with sunspot area
- Magnetic field strength in **umbra 2-4 kG**
- Magnetic field configuration
  - Mostly vertically aligned in central umbra (photosphere)
  - "**Uncombed penumbra**": Mix of horizontally aligned and inclined magnetic field
- Strong fields inhibit convective energy transport below sunspot
  - Umbra: temperature below 4000K, brightness ~20% of Quiet Sun (appears dark)
- **Evershed flow** = outflows in penumbra along filaments with supersonic components — a result of of magneto-convection and complicated magnetic field structure of the penumbra

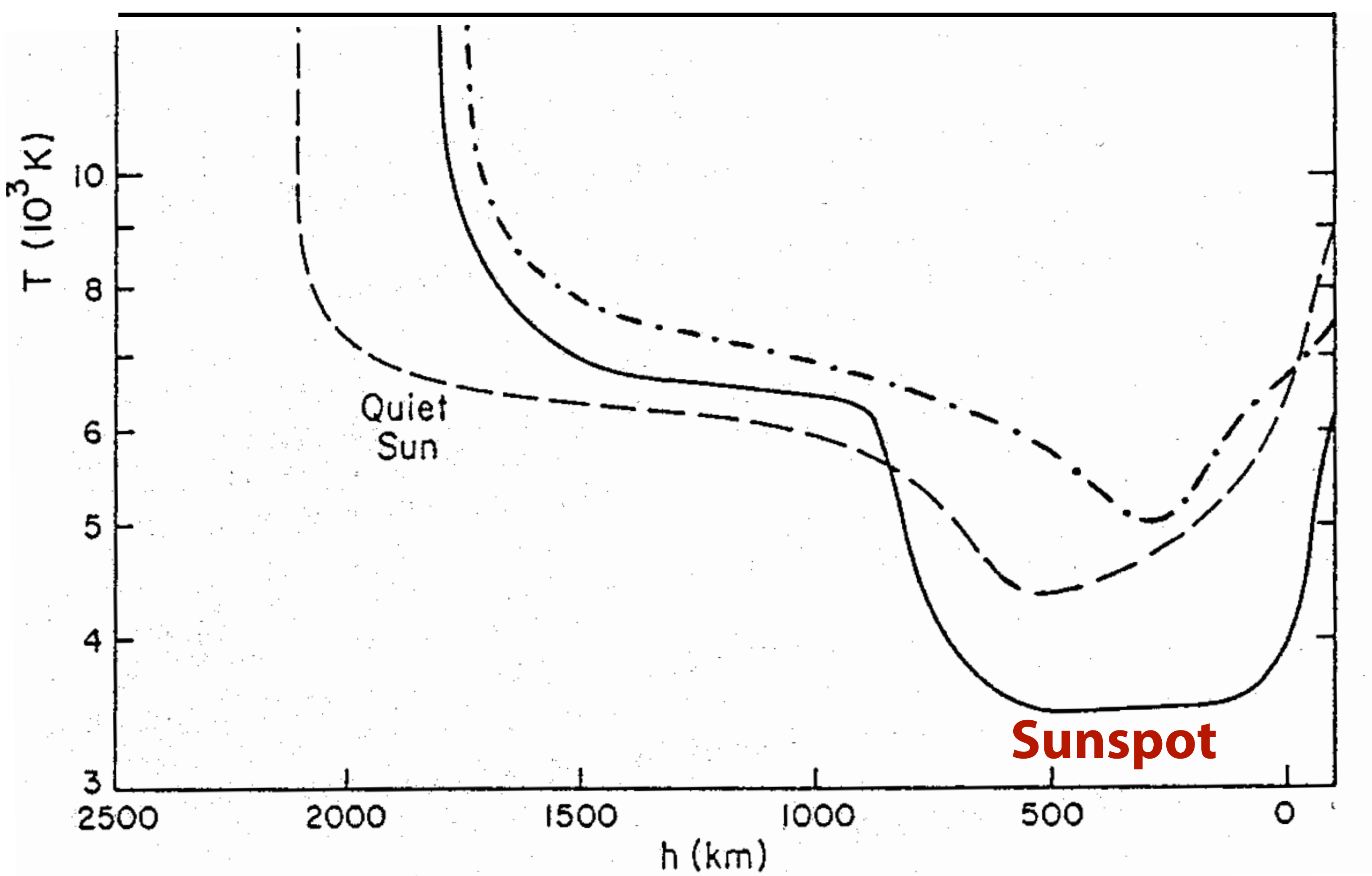
Sunspots

Recap

- Magnetic pressure due to (strong) magnetic field results in lower density and thus lower opacity

➡ **Optical depth lower** inside magnetic field structure than outside (in sunspots: **Wilson depression**)





- Temperatures in sunspot umbra much below Quiet Sun values (sunspots appear dark in the photosphere relative to surrounding)
- Sunspot temperatures rise quickly in low chromosphere, surpass Quiet Sun temperatures

Sunspots

Bridges and dots

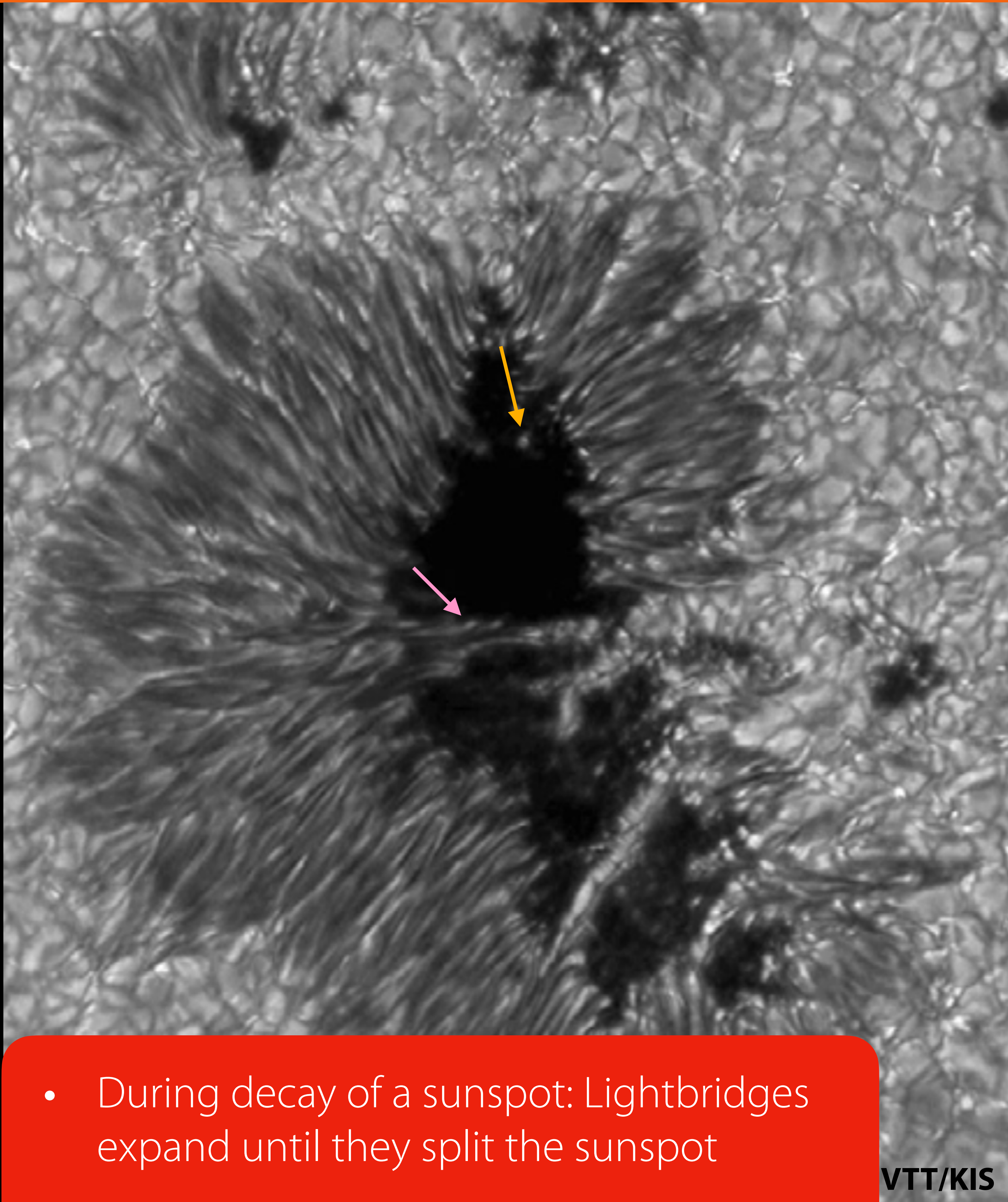
- Strong magnetic fields in umbra inhibit convection — no granulation
- **Decaying sunspots**: magnetic field strength decreases

➡ **Magneto-convection** can prevail again at some locations at first

➡ Visible consequences: **umbral dots** and **light bridges**

- Both have a central dark lane and bright edges
- Light bridges:
  - Extend across umbra, splitting it and connecting penumbra on both sides
  - Blue and redshifted velocities detected!

  ➡ Convection ongoing!



- During decay of a sunspot: Lightbridges expand until they split the sunspot

Sunspots

Bridges and dots

- Strong magnetic fields in umbra inhibit convection — no granulation
- **Forming sunspots**: magnetic field strength at surface still increases

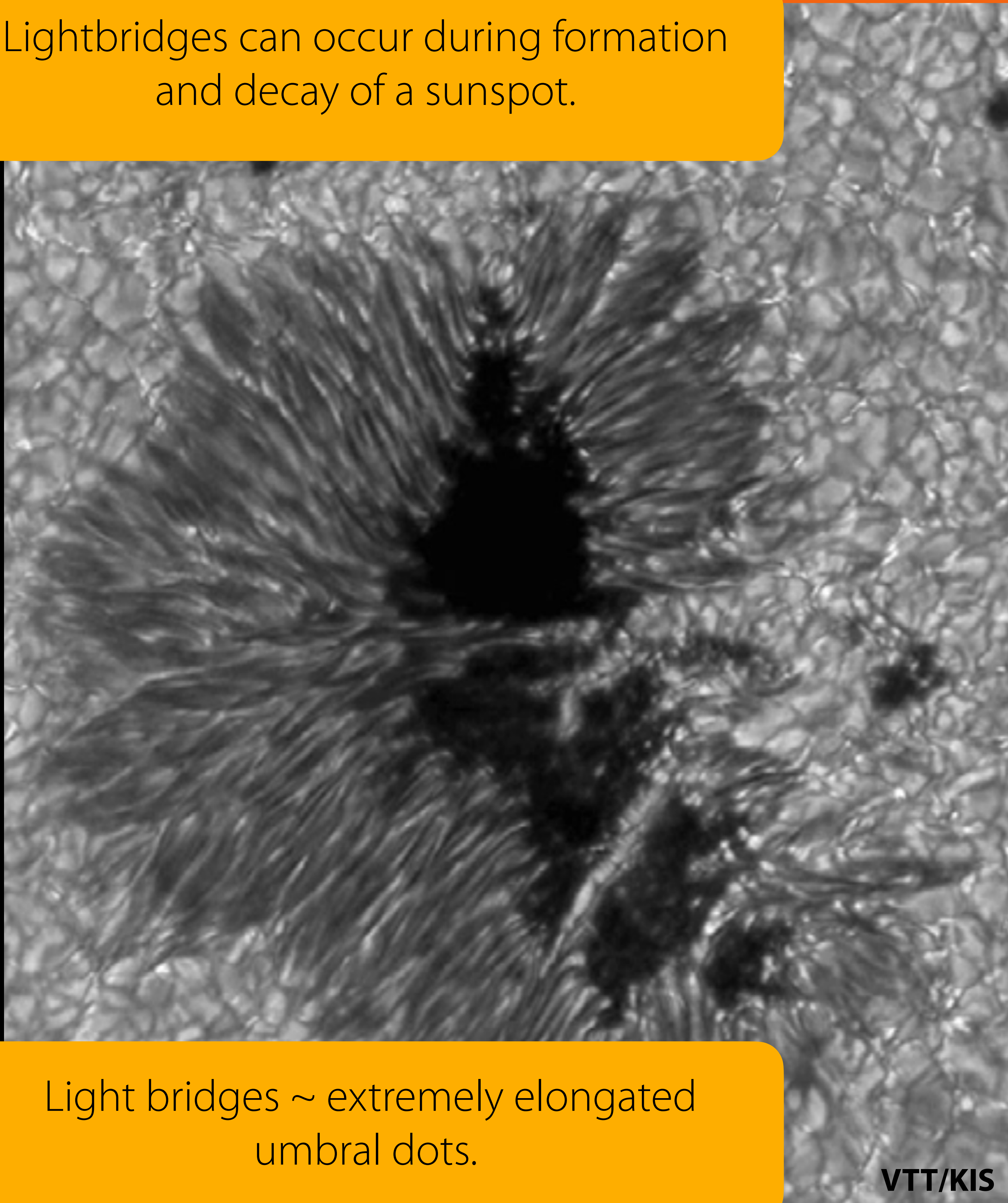
➡ **Magneto-convection** can still prevail at some locations

➡ Visible consequences:
umbral dots and light bridges

- Both have a central dark lane and bright edges
- Light bridges:
  - Extend across umbra, splitting it and connecting penumbra on both sides
  - Blue and redshifted velocities detected!

  ➡ Convection ongoing!

Lightbridges can occur during formation and decay of a sunspot.



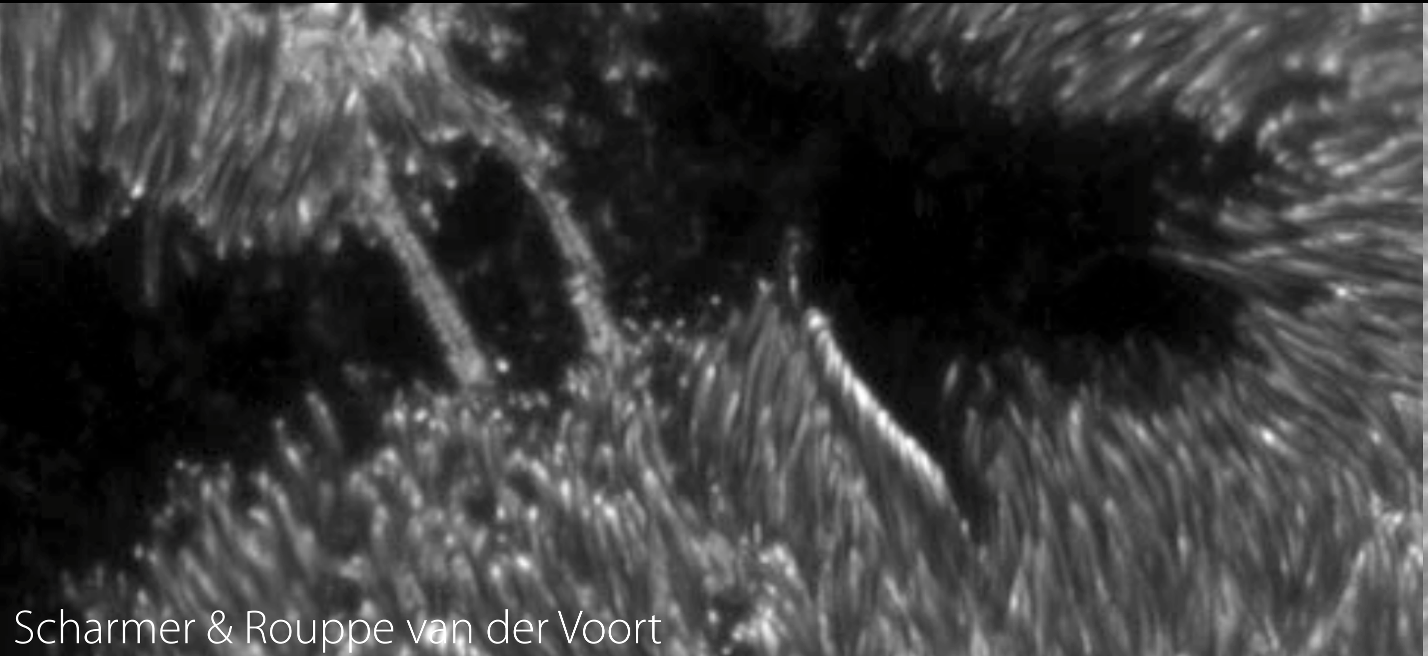
Light bridges ~ extremely elongated umbral dots.

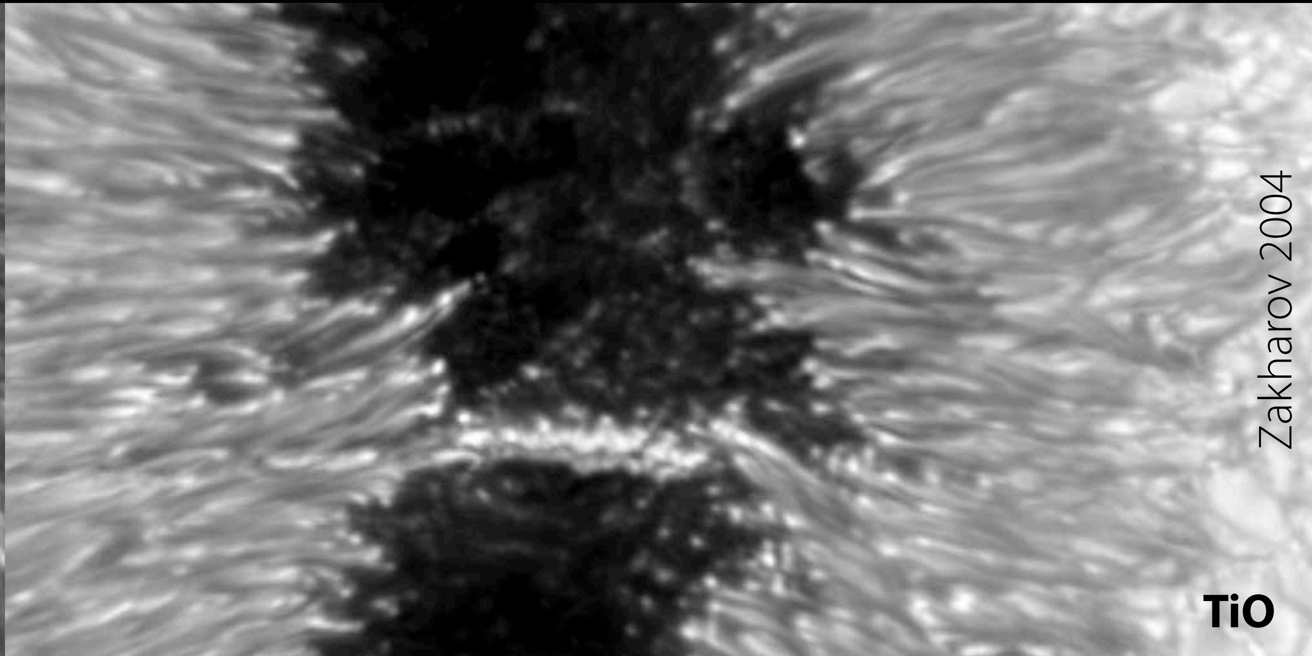
Sunspots

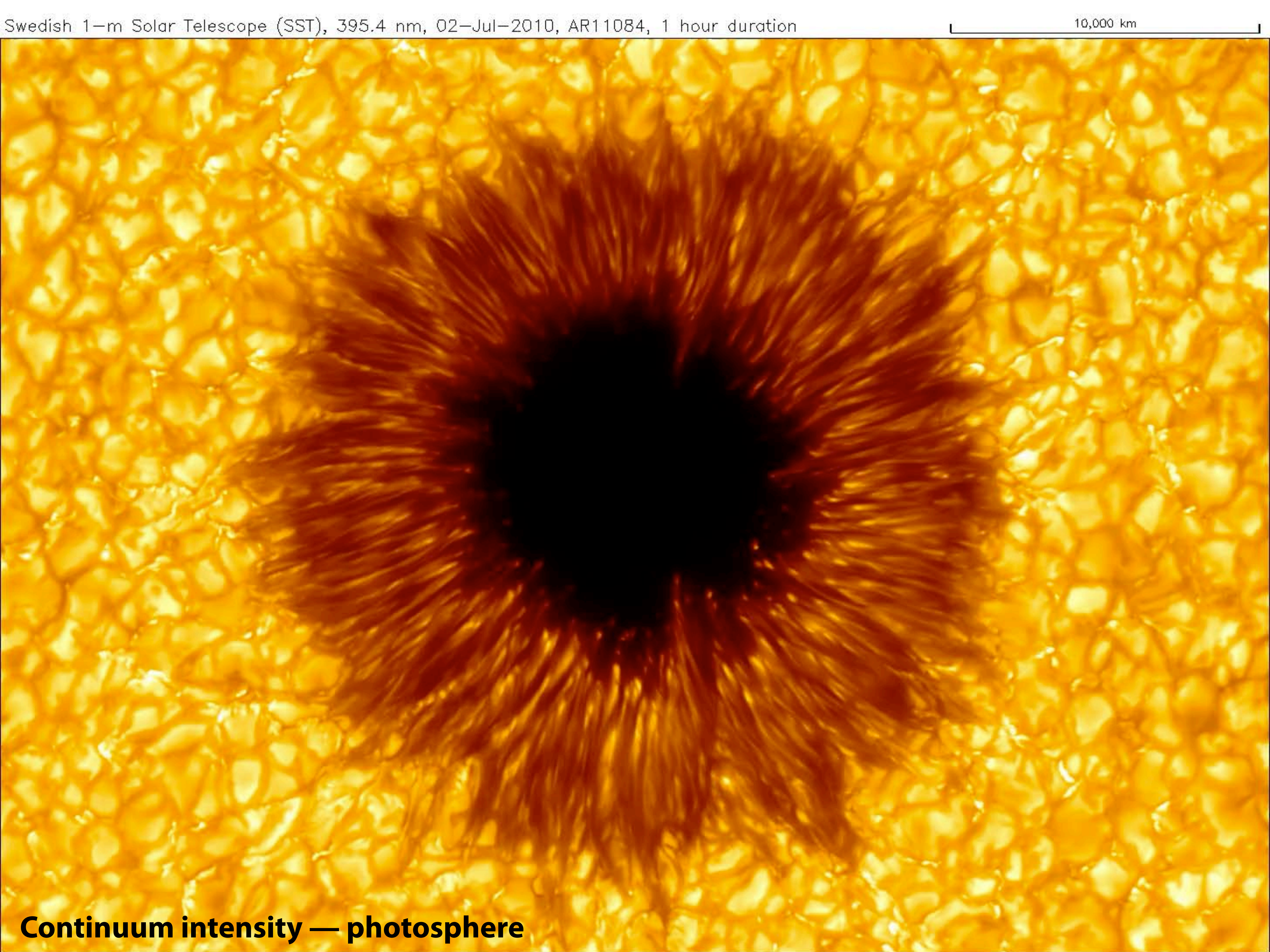
Formation of light bridges and umbral dots

- Formation and evolution of light bridges not fully understood yet.
- Observed aspects:
  - Magnetic field weaker and more inclined than in surrounding umbra
  - Umbral dots form at tip of penumbral filaments, then move into umbra
  - Typical velocities ~ a few 0.1 km/s but also supersonic downflows with up to 10 km/s
- Possible explanation (implied by observations and simulations):
  - Emerging buoyant flux tube with hot gas and weak field below/near surface in connection with sub-photospheric flows; Convective upflow continuously transports horizontal fields to surface and creates a light bridge structure.

  ➡ Uprising gas with weak field as natural consequence of magnetoconvection in a magnetic flux structure (like a sunspot)

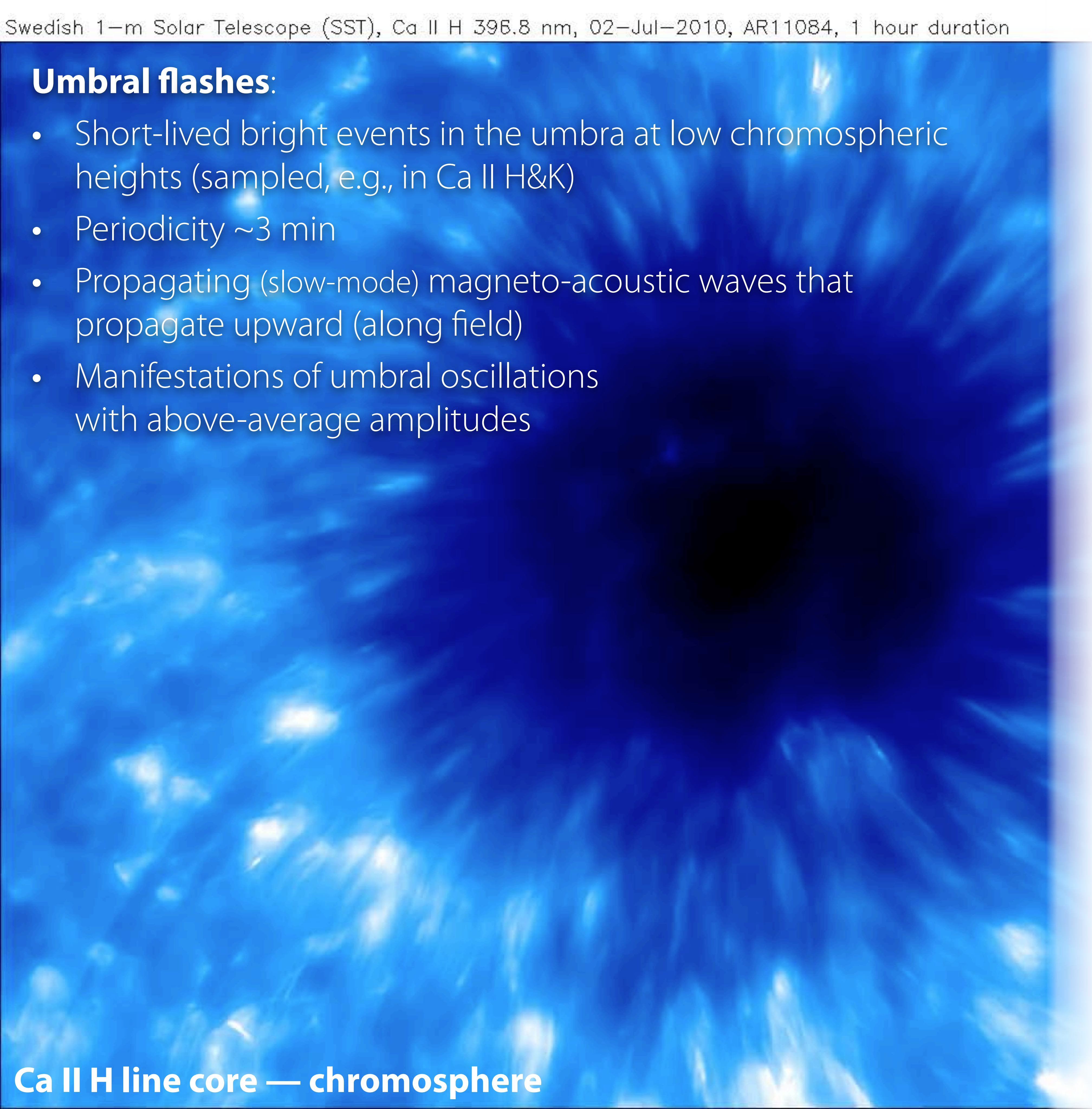


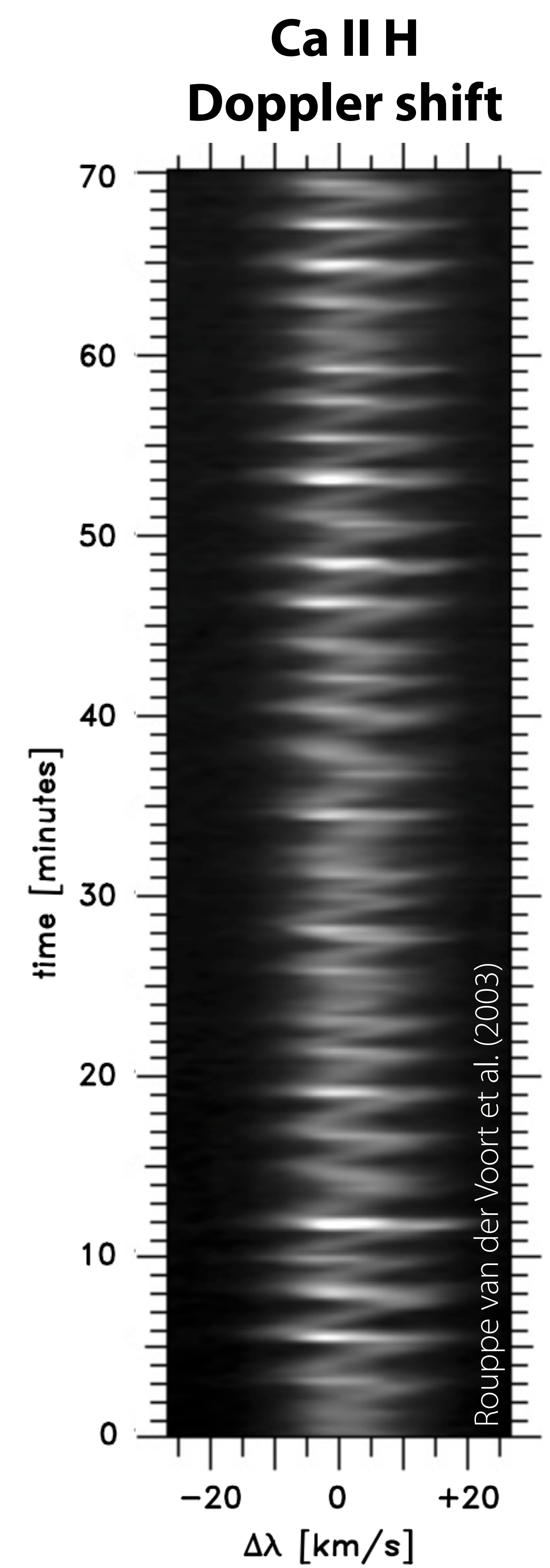



Swedish 1-m Solar Telescope (SST), 395.4 nm, 02-Jul-2010, AR11084, 1 hour duration
10,000 km
Continuum intensity — photosphere

Umbral flashes:

- Short-lived bright events in the umbra at low chromospheric heights (sampled, e.g., in Ca II H&K)
- Periodicity ~3 min
- Propagating (slow-mode) magneto-acoustic waves that propagate upward (along field)
- Manifestations of umbral oscillations with above-average amplitudes





Sunspots

Oscillations and waves

- Stratification/properties in sunspot different than in Quiet Sun (QS) plus influence of strong magnetic field
  ➡ Oscillatory behaviour different in sunspots
    - Umbra: shift towards shorter periods compared to QS

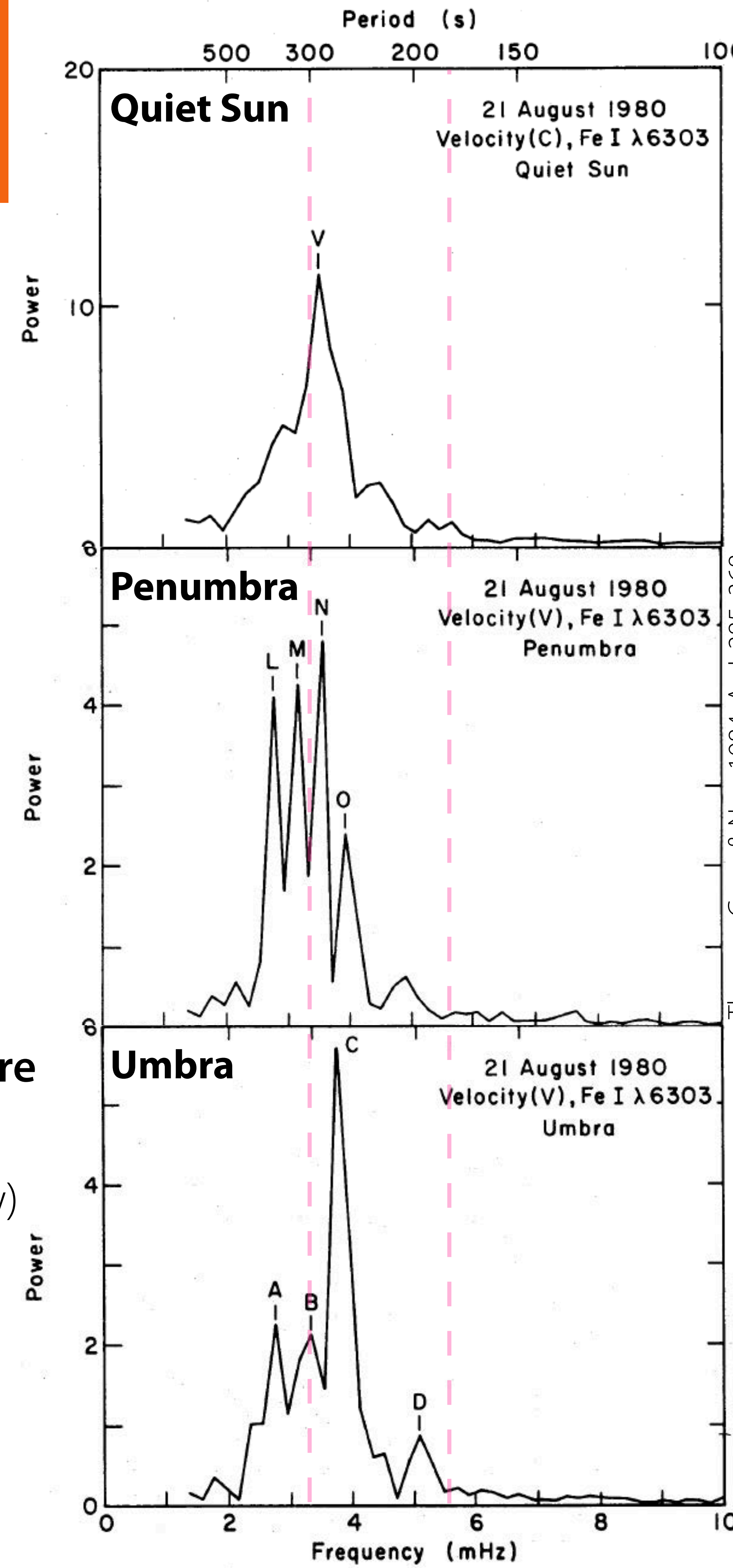
- Three major types of oscillations/waves in sunspots:

- **5-min umbral oscillations — photospheric**
  - Coherent* over a significant fraction of umbra
  - Amplitudes ~0.1km/s (or less)
  - Also in light bridges: periods ~5min period (sometimes sub-min), excited by p-mode leakage from layers below

- **3-min umbral oscillations — upper photosphere/chromosphere**
  - Coherent on smaller spatial scales.
  - Amplitudes exceed several km/s in chromosphere (lower below)
  - Vertically propagating (phase speeds ~ local sound speed)
  - Seen in chromospheric line cores as sawtooth pattern

- **Running penumbral waves**

*coherent waves: constant relative phase

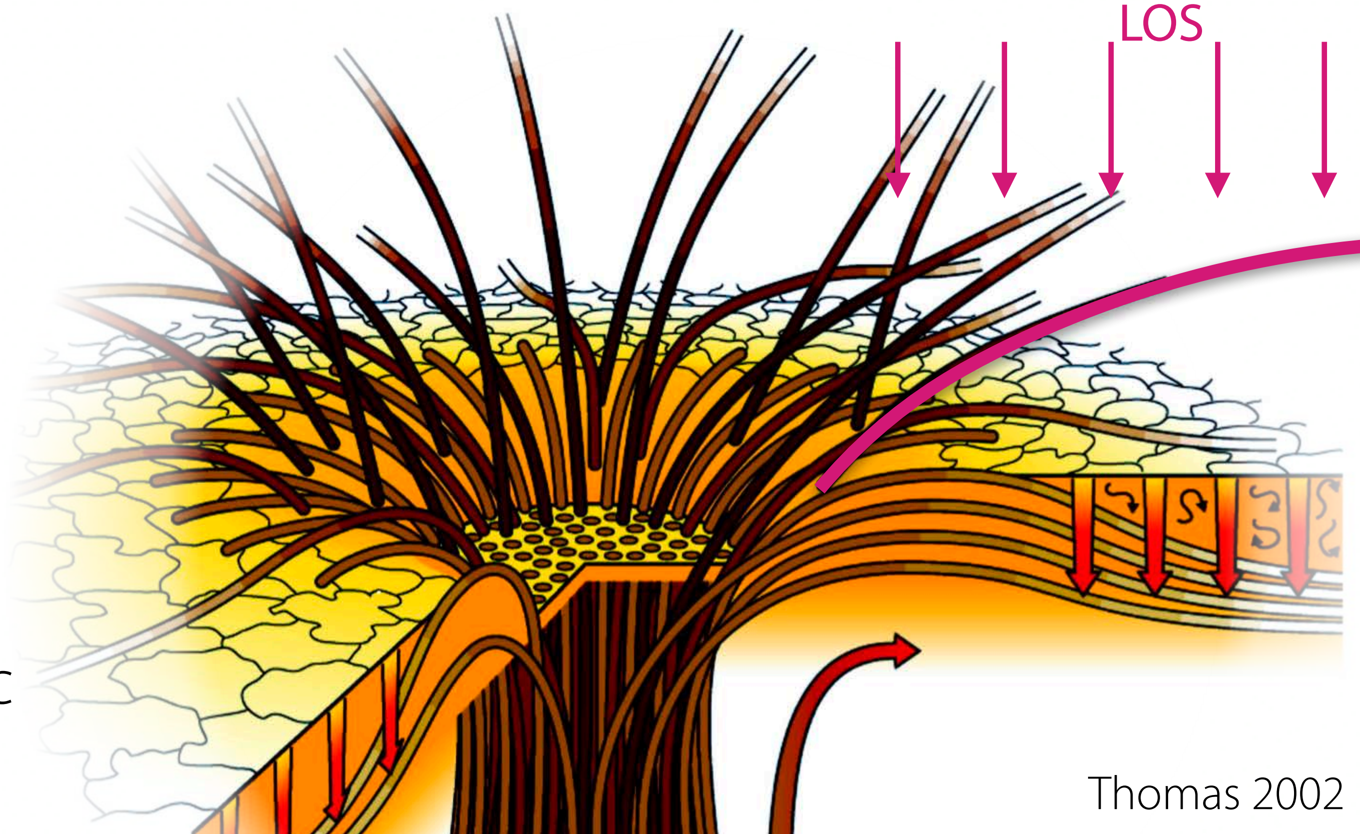


Thomas, Cram & Nye, 1984, ApJ, 285, 368

Sunspots

Oscillations and waves

- **Running penumbral waves**
  - Coherent propagating wave fronts, running radially outwards from inner to outer edge of penumbra
  - Clearly visible near the umbra-penumbra boundary (in strong chromospheric lines)
  - Chromospheric phenomenon (but (possibly?) also some photospheric parts with small amplitude)
  - Penumbral waves **guided by inclined magnetic field**
    - Magnetic field inclination increases from the inner to the outer penumbra.
    - Causes increasing apparent path length (projection!) that appears as outward propagation with decreasing velocity.
    - Radial phase speeds of 8–35 km/s, decreasing phase speed with distance.
  - Same underlying physical mechanism umbral flashes: slow-mode magneto-acoustic waves that propagate upward
  - Excited by photospheric umbral oscillations/flashes at low chromospheric levels



Thomas 2002

Sunspots

Simulating sunspots

- Magneto-convection essential for sunspots but a challenging time-dependent problem
- Consistent models needed to explain all observed phenomena
- 3D MHD simulations of two spots with opposite polarity (Rempel et al. 2009)
    - computational box ~100Mm x 50Mm x 6Mm
    - Abs. magnetic field strengths |B| ~ 3-4 kG

Continuum intensity

Rempel et al. (2009)

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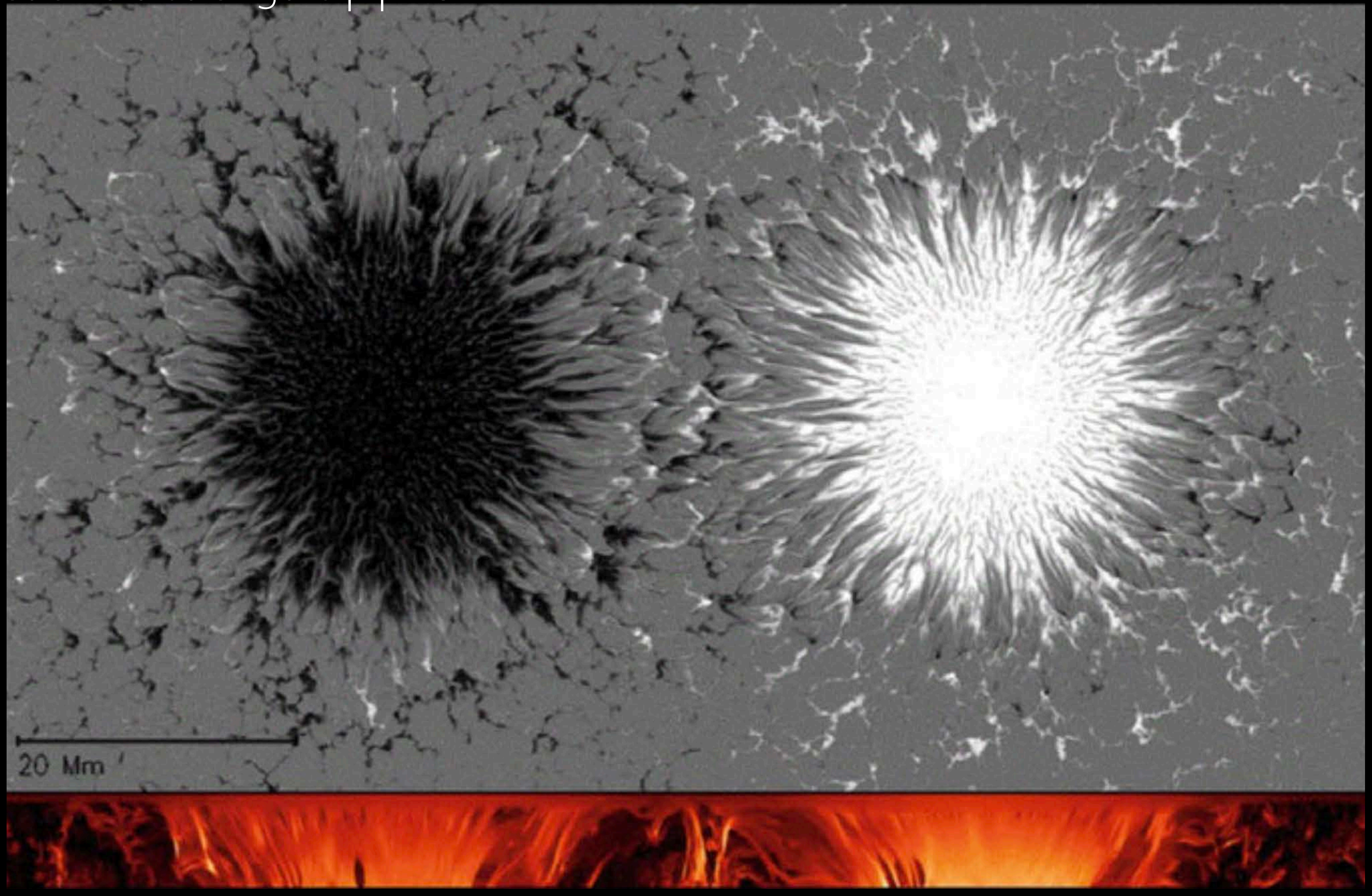
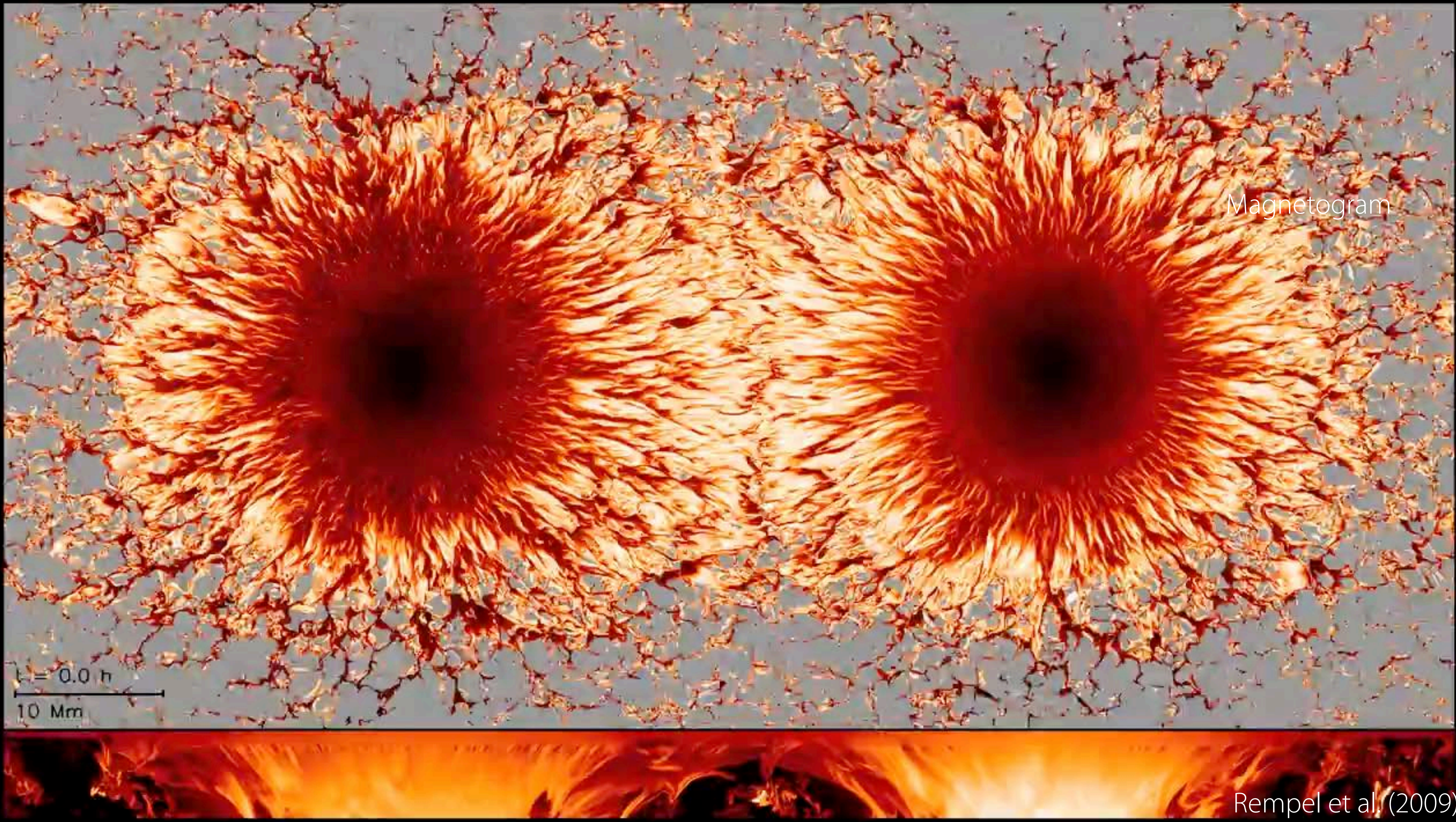


Magnetogram

Rempel et al. (2009)

Sunspots

Simulating sunspots

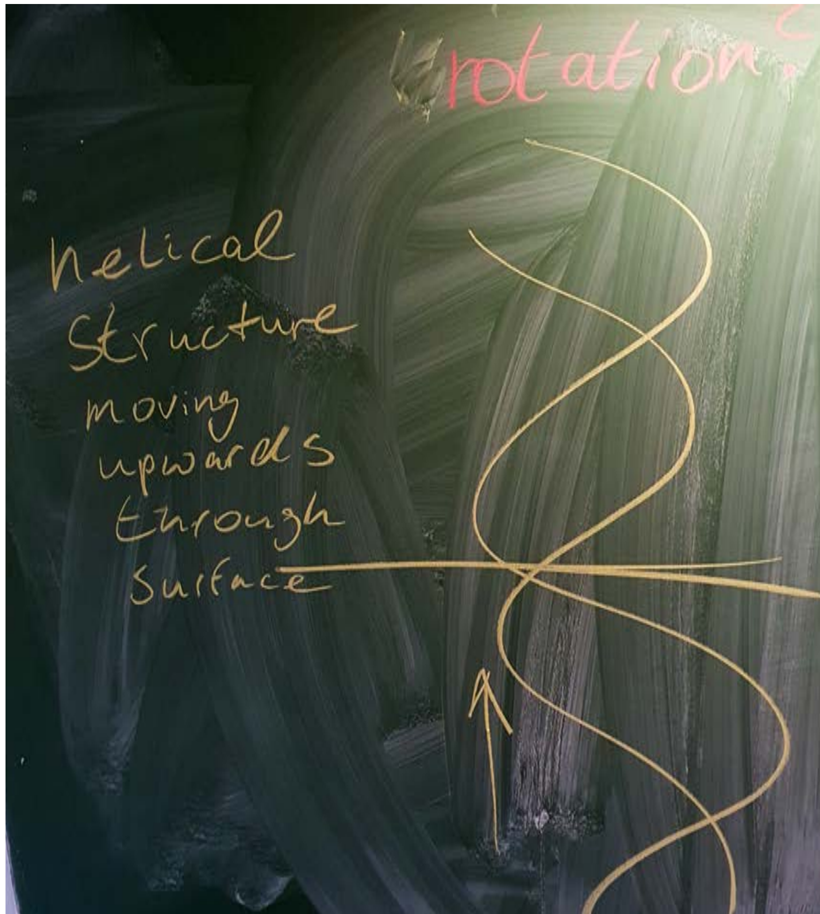


Rempel et al. (2009)

Sunspots

Rotating Sunspots

- **Observations:**
  - Detected already in 1910 (Evershed)
  - Rotation angles up to 540° were measured
  - Rotation angles about umbral center up to 200° over period of 3–5 days
  - Young sunspot groups rotate faster than old spot groups
  - Rotation rates (approx.) in line with helioseismologic measurements
  - Similar ratio of clockwise to counterclockwise rotations in both hemispheres
- **Possible explanations:**
  1. **True rotation** of a magnetic field structure due to forces that act in azimuthal direction
  2. **Apparent rotation** as helically twisted vertical magnetic field structure moves upward through the photosphere



- Rotating sunspots tend to produce more flares accompanied by eruption (more later)

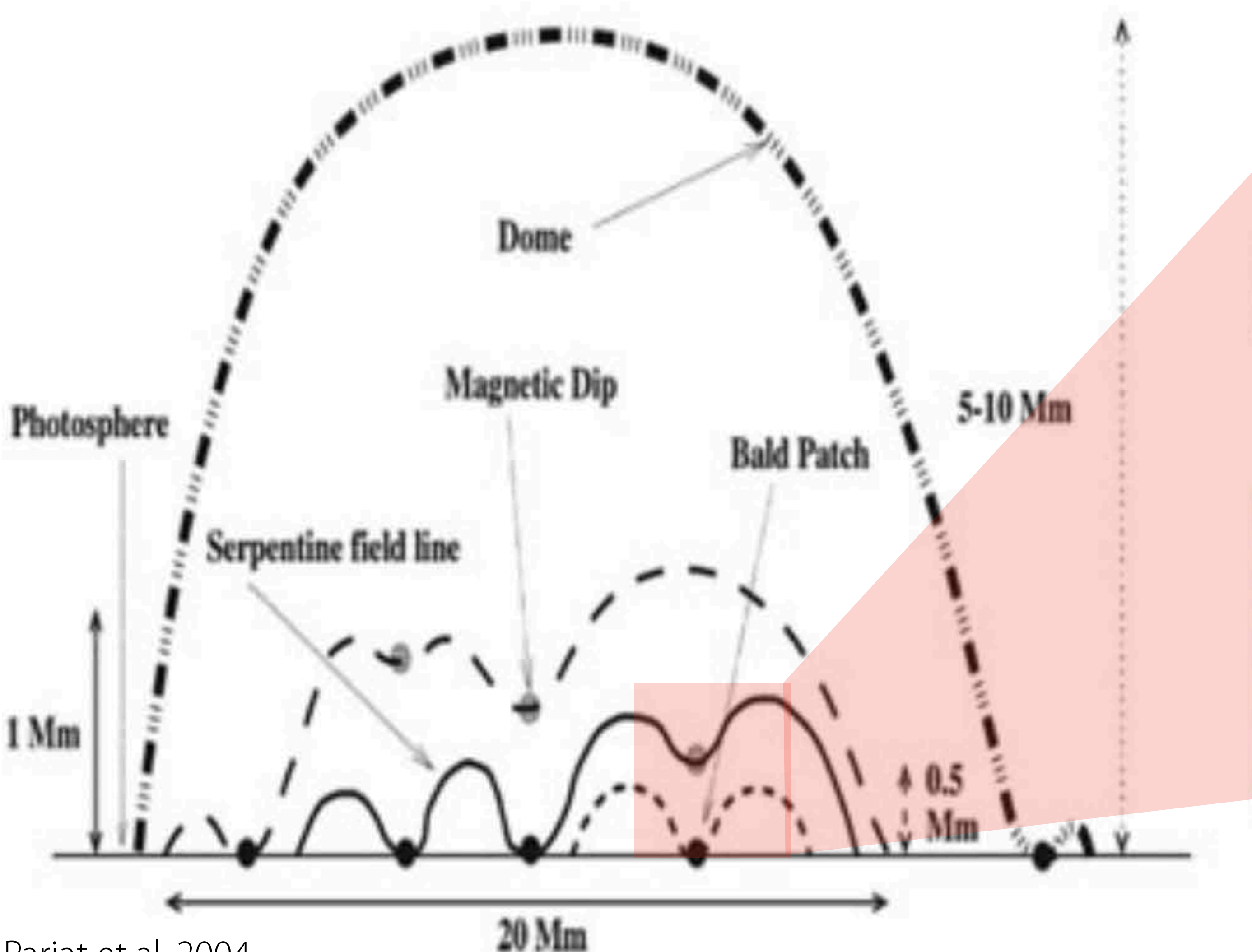
Energetic phenomena
Active Regions

Energetic phenomena in Active Regions

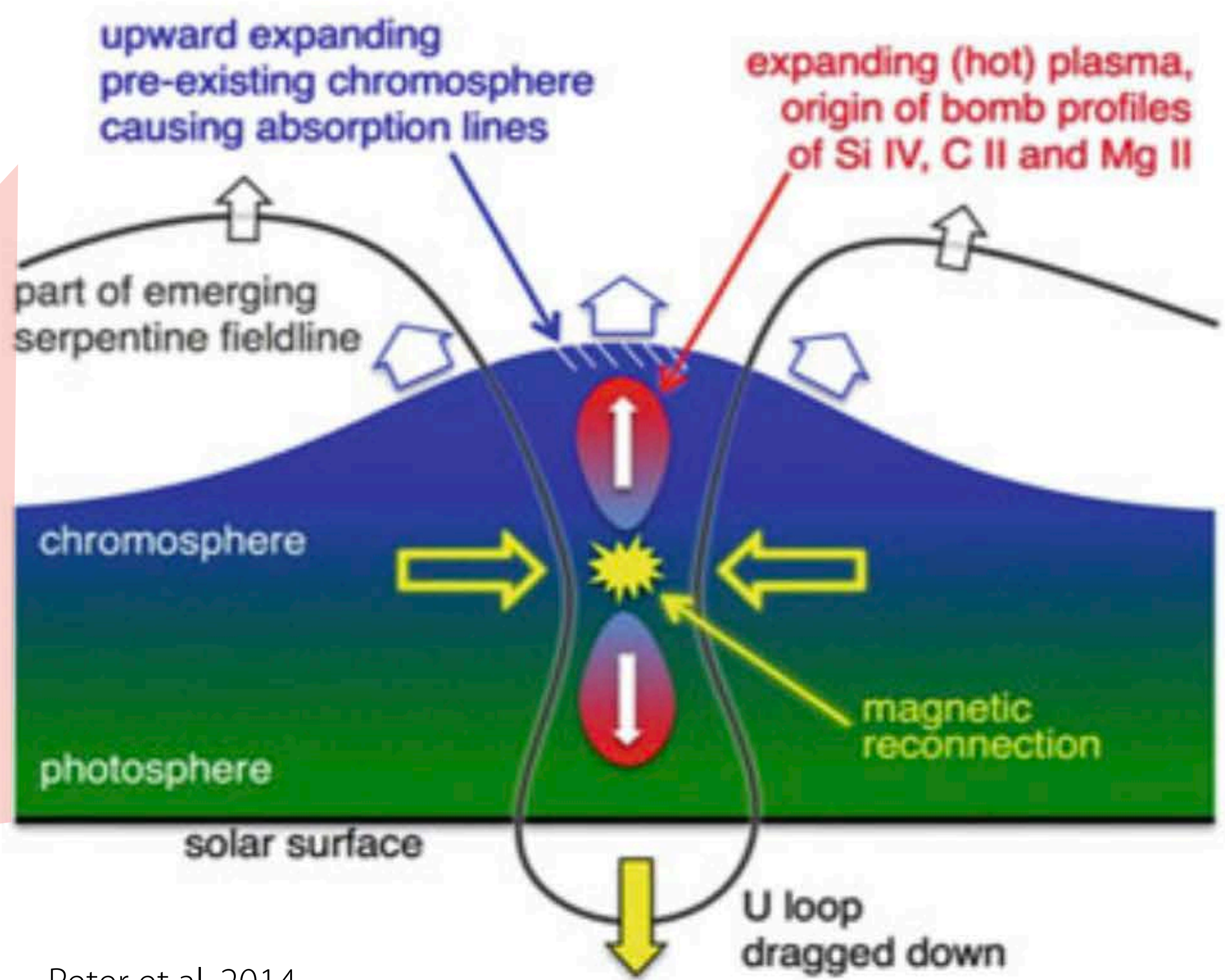
Magnetic reconnection

- Plasma motions in penumbra drag down magnetic field
- Serpentine field lines, magnetic dips, and "bald patches"
- If pushed too close, **magnetic reconnection** can occur

➡ **Reconfiguration** of magnetic field into an energetically preferable configuration and (explosive) **release of energy** (previously stored in magnetic field)



Pariat et al. 2004

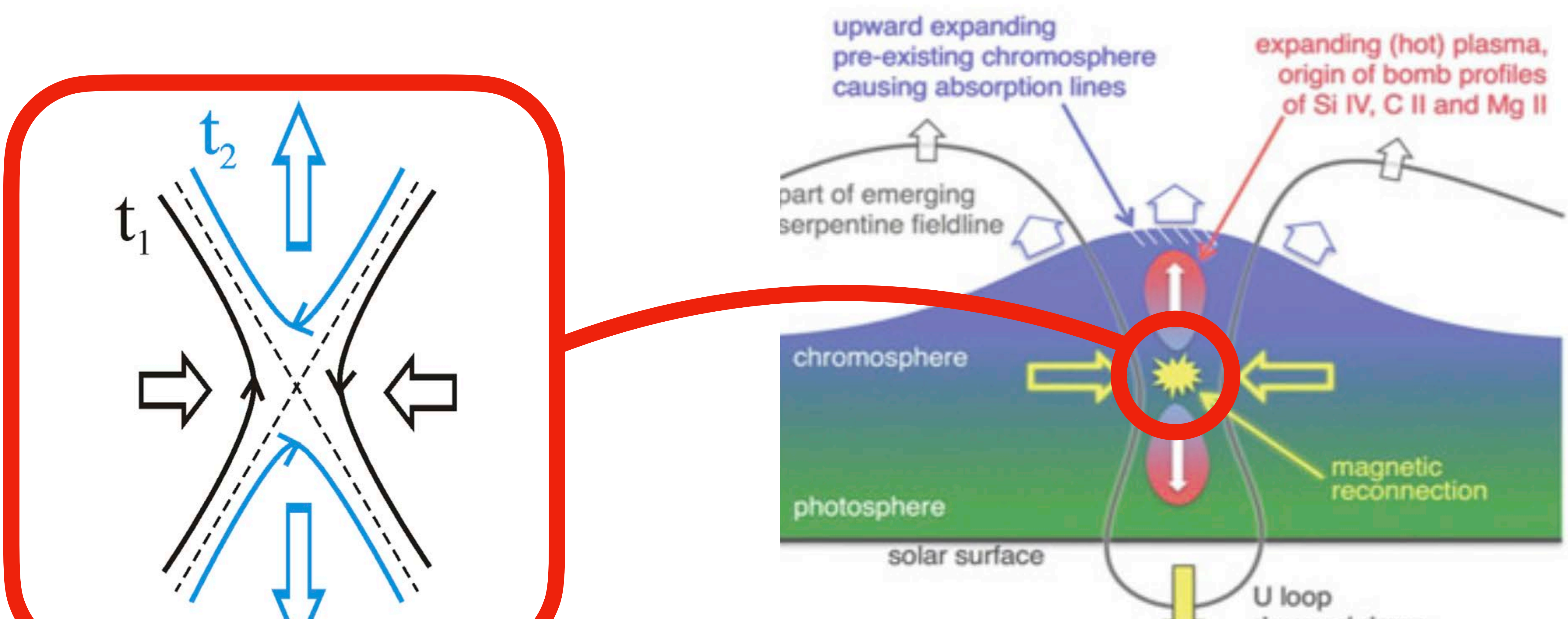


Peter et al. 2014

Energetic phenomena in Active Regions

Magnetic reconnection

- Antiparallel magnetic field lines disconnect at an X point and reconnect with other field lines
- Converts magnetic energy into kinetic energy — plasma is heated and accelerated
- Plays a critical role for a large number of phenomena on a large range of scales (e.g., solar flares, CME, geomagnetic storms at Earth…)

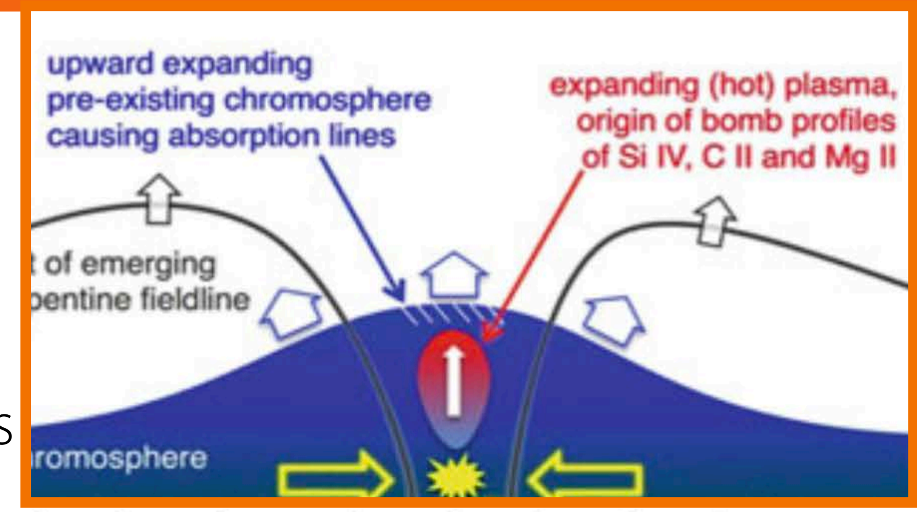


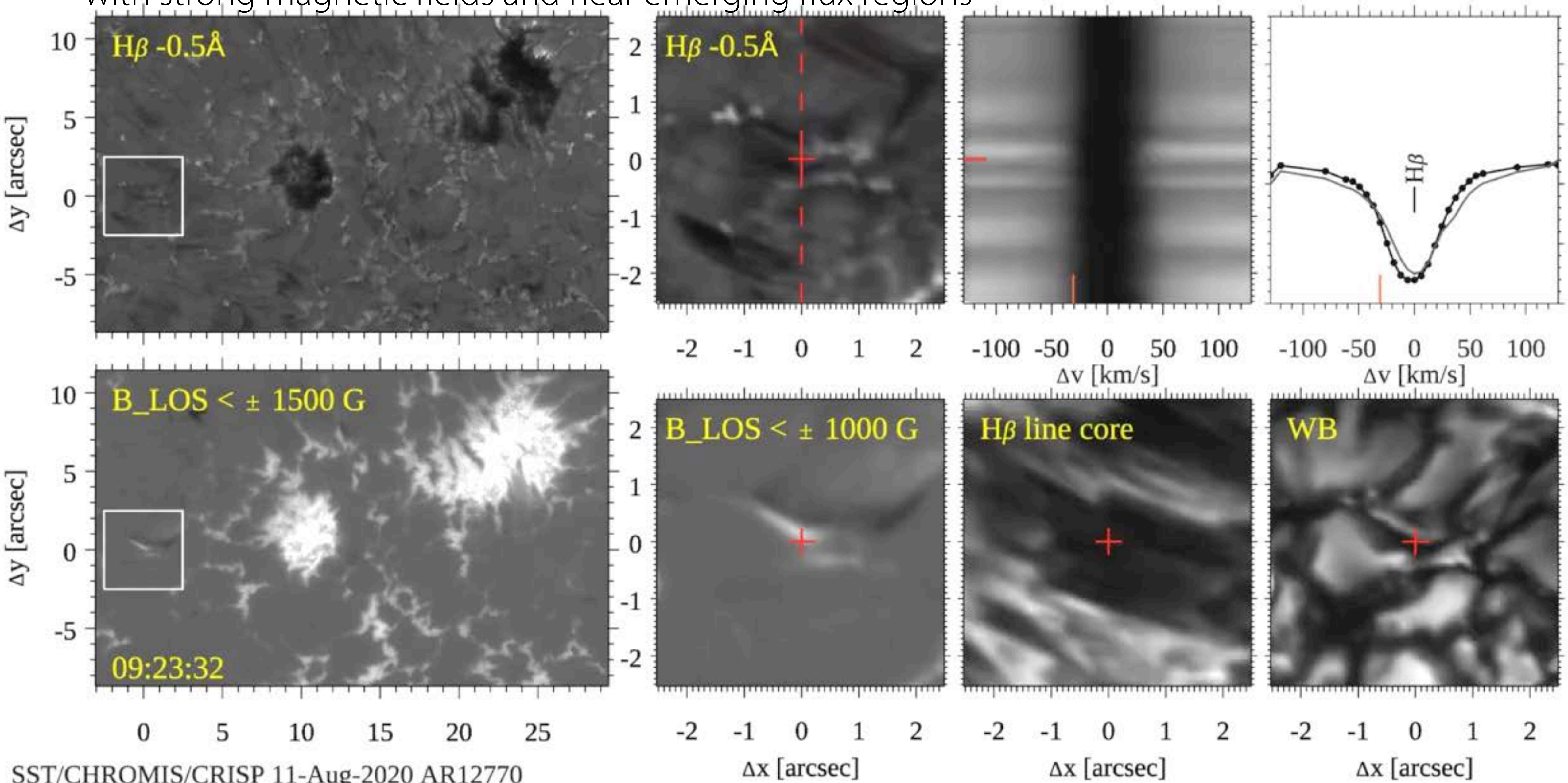
Peter et al. 2014

Energetic phenomena in Active Regions

Ellerman bombs (Discovered by Ellerman 1917)

- Bidirectional outflow from reconnection region causes a double-hump in spectral line profiles of Si IV, C II, and Mg II
- Cool material in atmosphere above causes absorption line
- Observed as <u>small-scale brightenings</u> in low chromosphere in areas with strong magnetic fields and near emerging flux regions

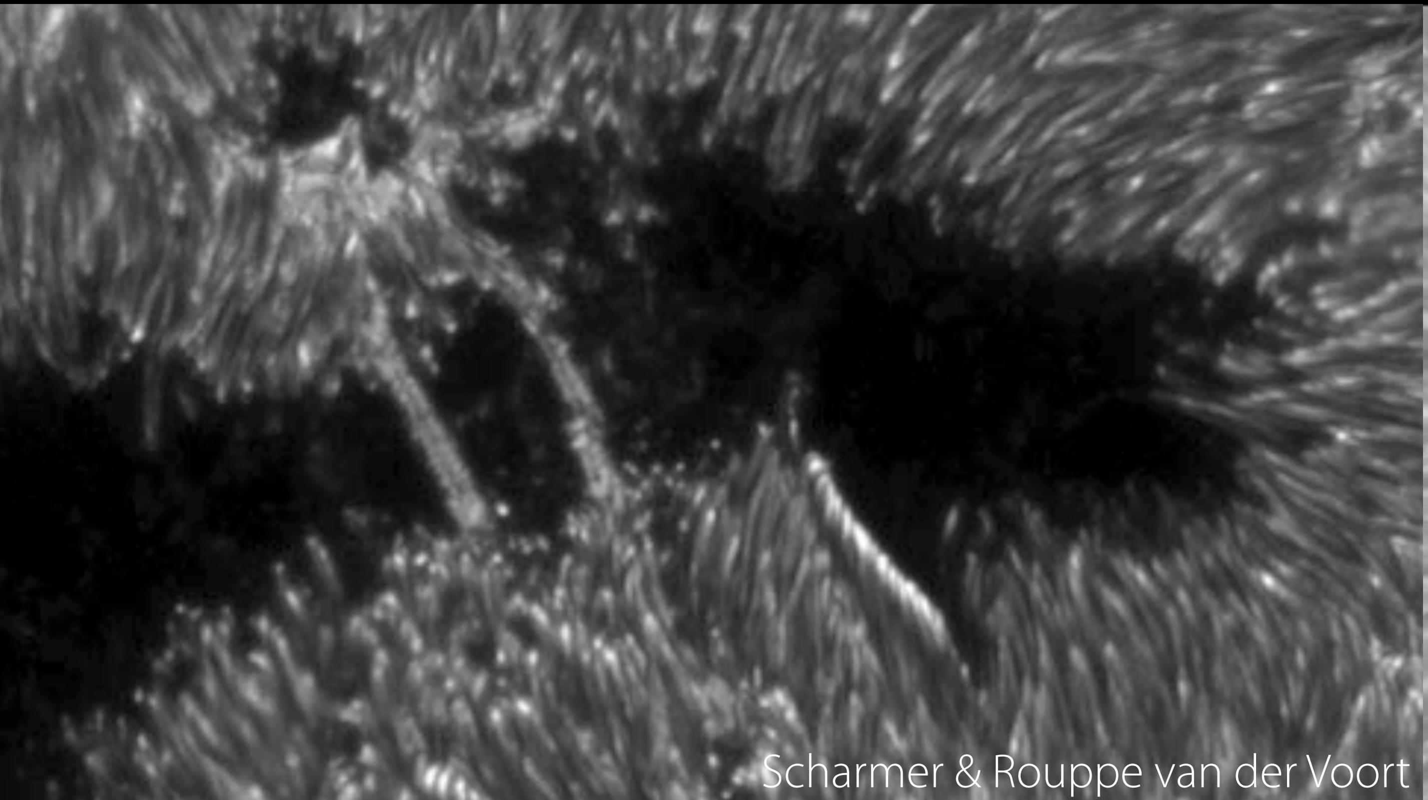


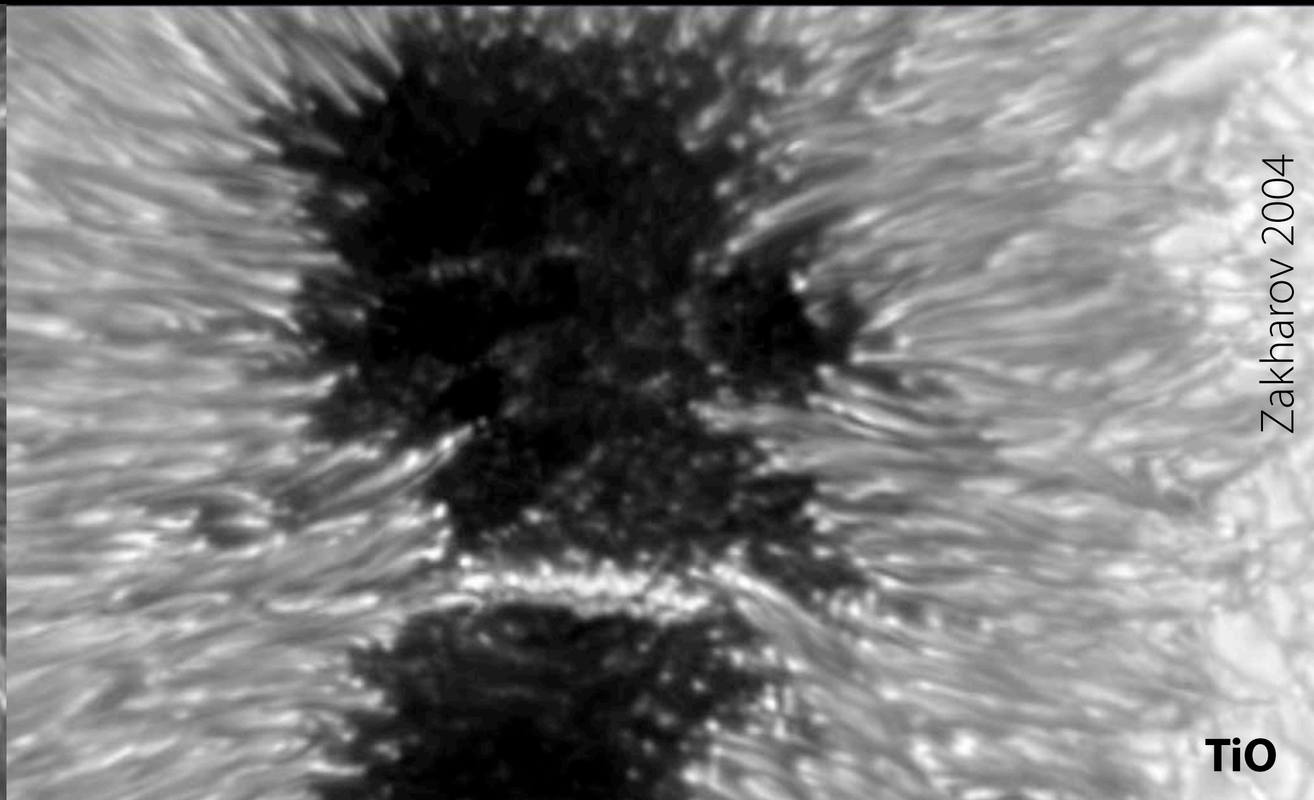


Energetic phenomena in Active Regions

Light bridges

- Observed: Plasma ejections along a light bridge of a stable and mature sunspot (e.g., in Hα surges, EUV jets at 171 Å)
  - Likely a by-product of magnetic reconnection

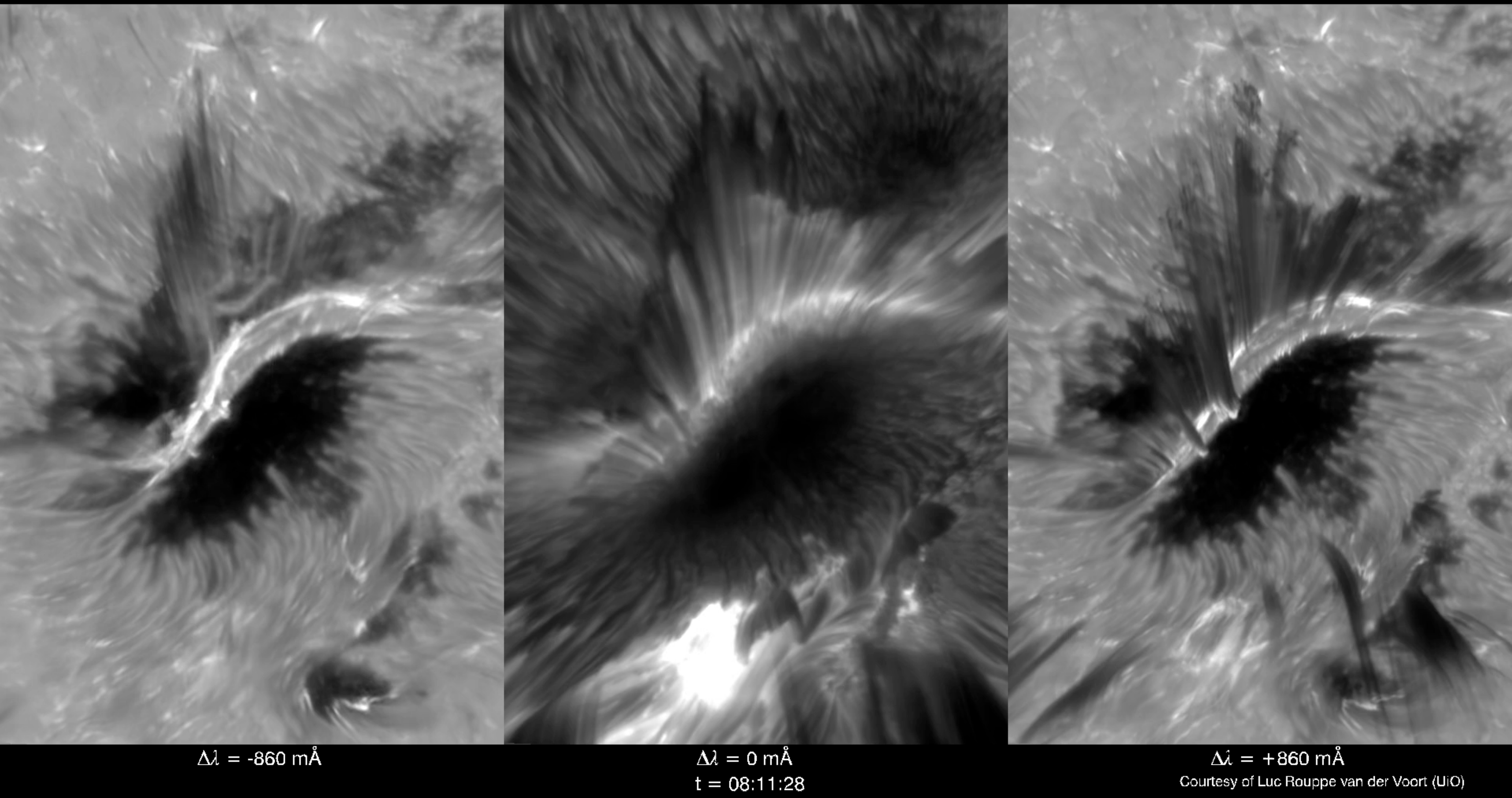




Energetic phenomena in Active Regions

Peacock jets / Fan-shaped jets

- Many dynamic phenomena in chromosphere above light bridges
- Observed above some light bridges: Fast jets in the shape of a fan / peacock tail



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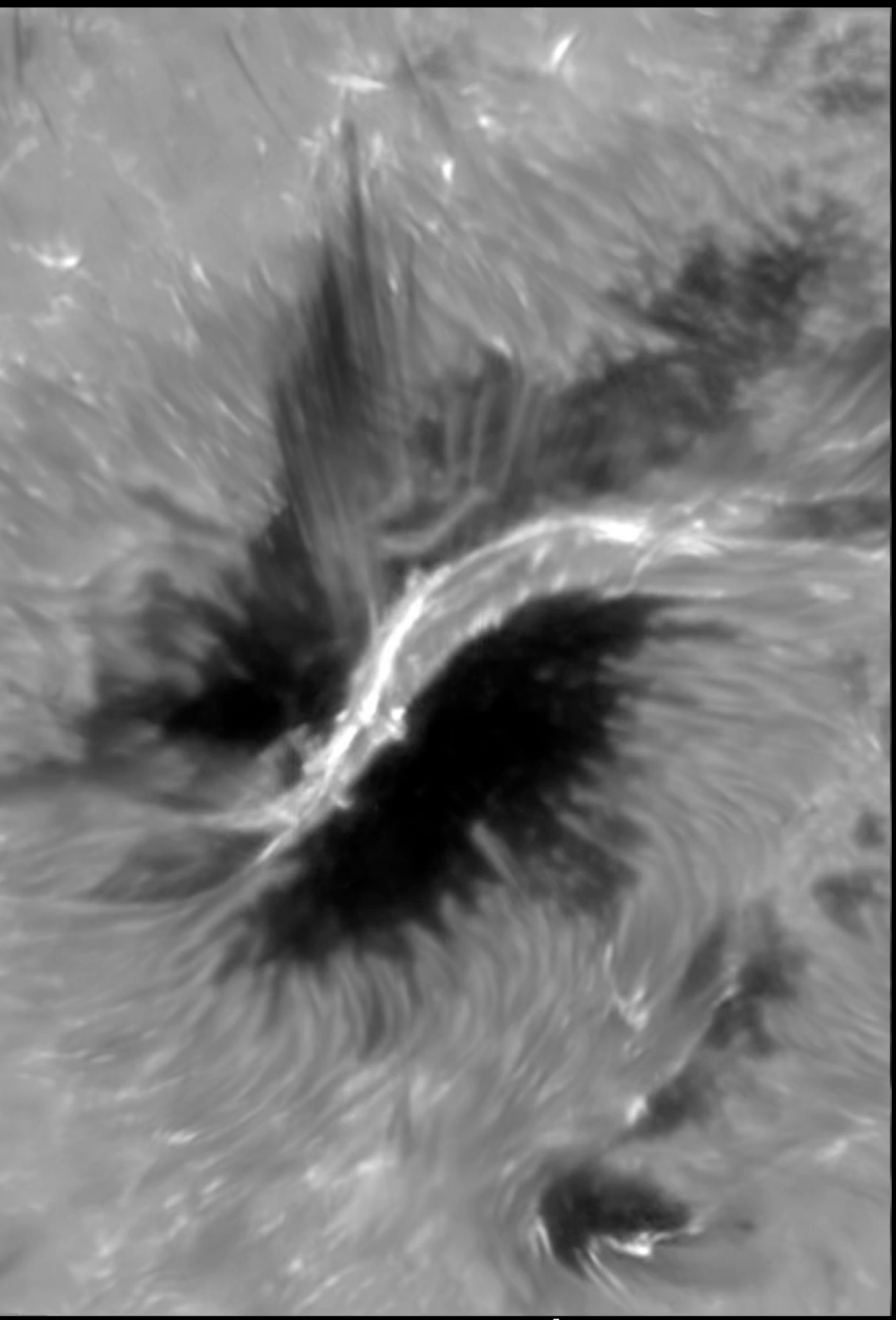


$\Delta\lambda$ = -860 mÅ

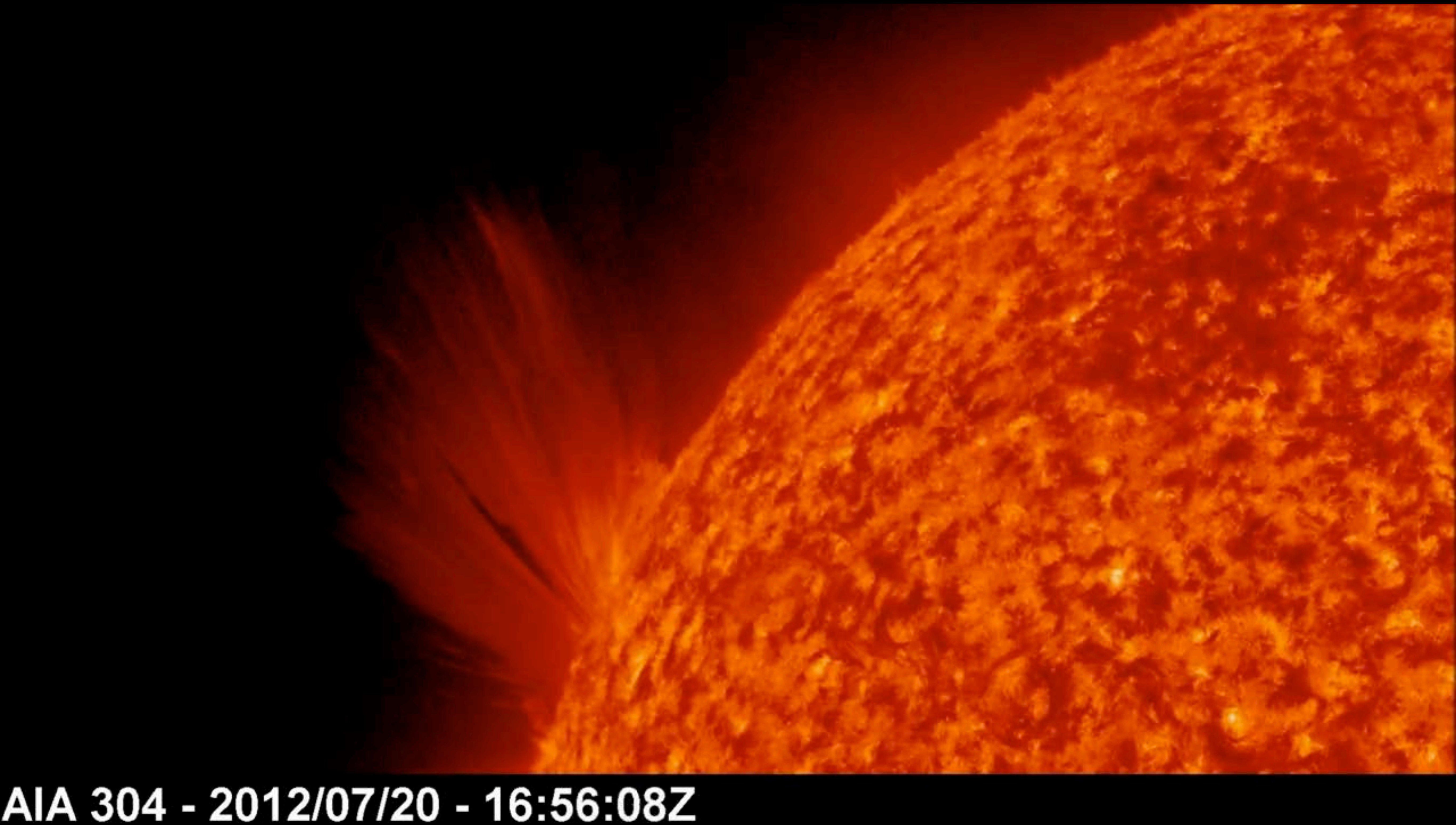
- Cool material (<15 000 K)
- Maximum speeds of up to 175 km/s !
- Extend up to 50 Mm.
- Accelerate upwards for an extended amount of time until reaching max. velocity at height between ~7 to ~50 Mm.
- Influence of the magnetic field clearly seen in the acceleration/deceleration (in contrast to gravity alone)
- Please note the length of jets (or any feature) may appear different for various diagnostics as they are sensitive to different formation height ranges / plasma properties
- **Likely explanation:** Horizontal field aligned along the light bridge shear with the pre-existing vertical field in umbra

➡ **Magnetic reconnection**

➡ Acceleration of plasma upwards along magnetic field

Energetic phenomena in Active Regions

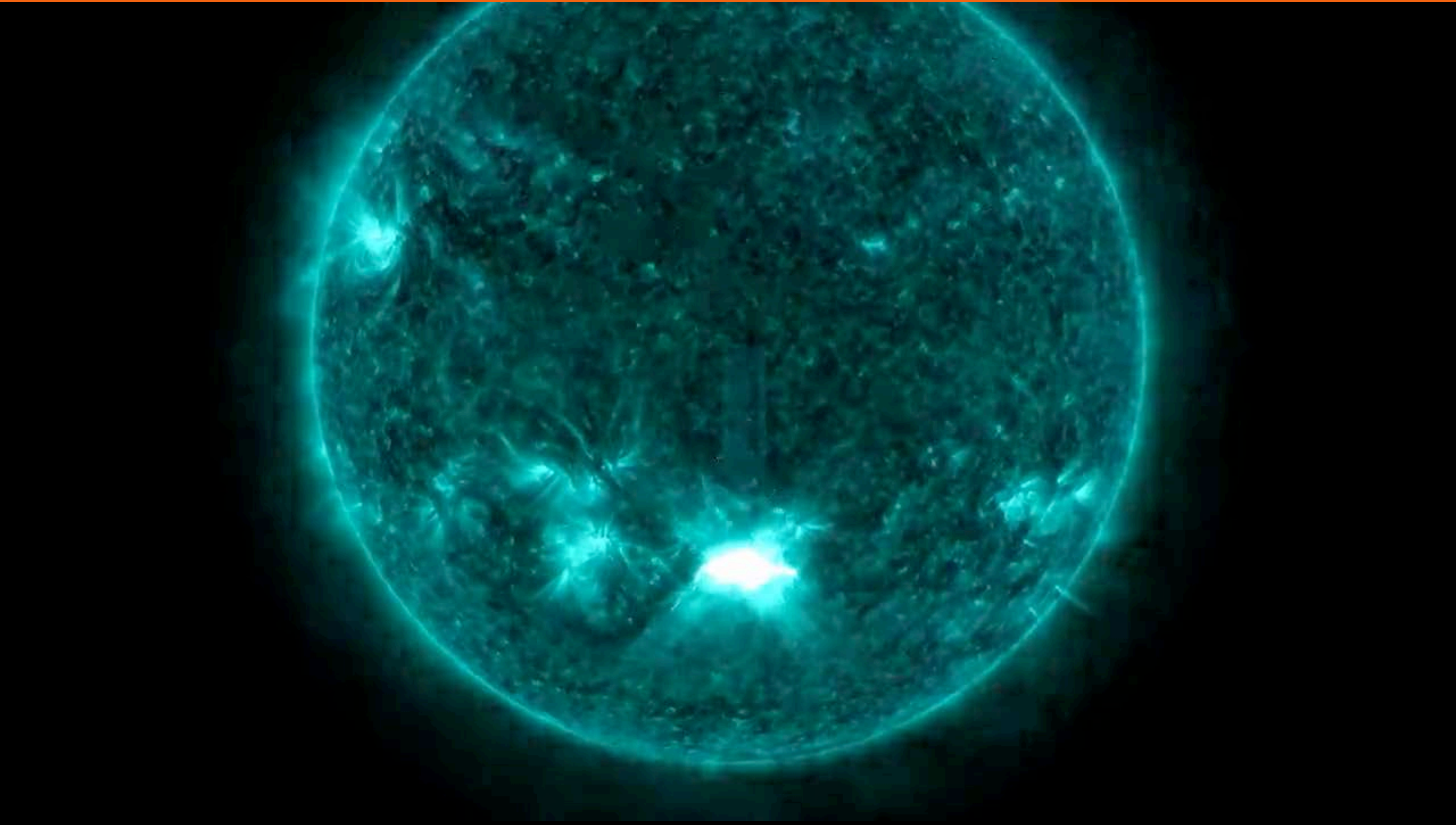
Jet Surge



NASA/SDO

Solar flares

Flares

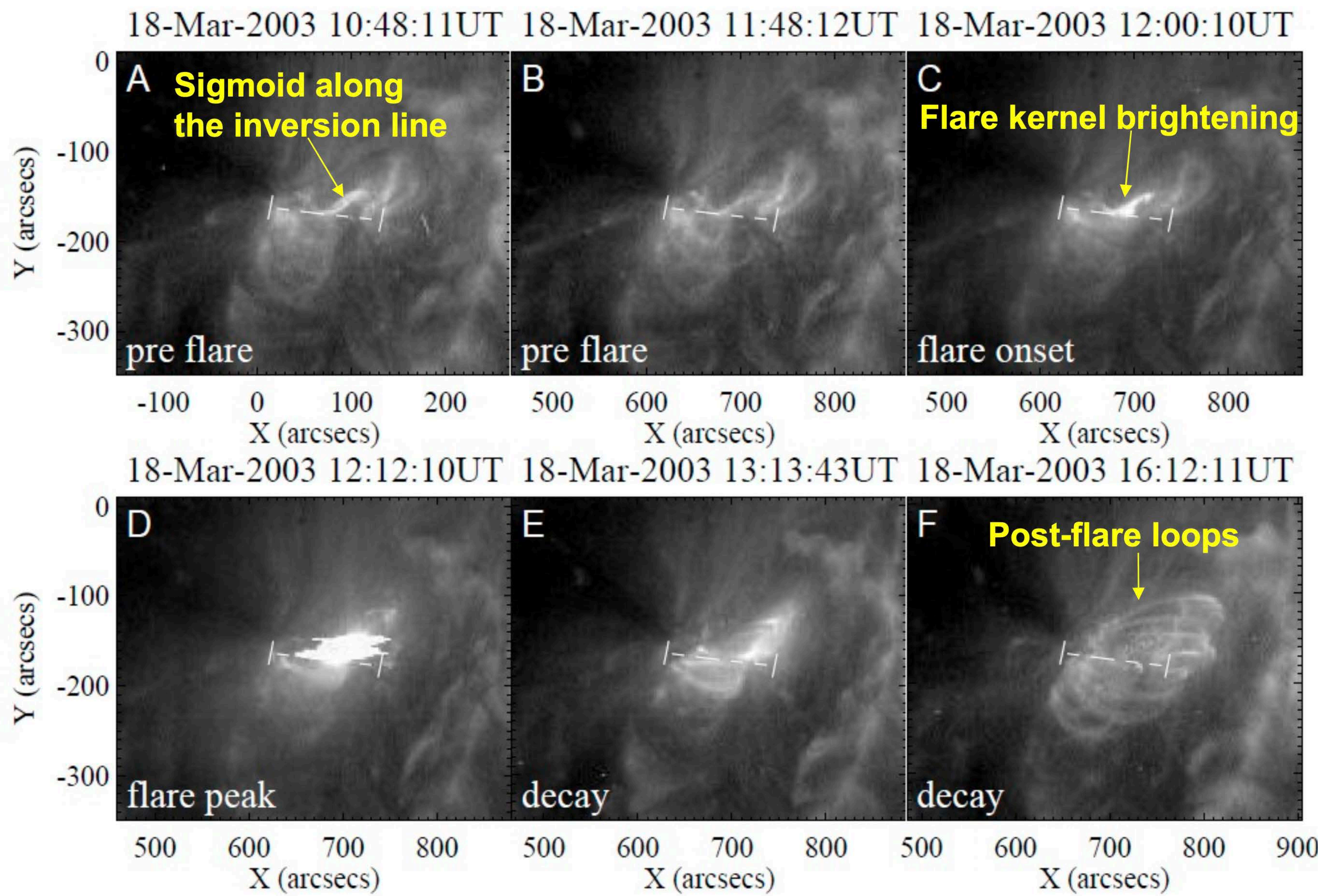


- Flares = Intense eruptions on the Sun with emission of radiation across the whole spectrum (γ- and X-rays, UV, visible / white light … radio) and energetic particles

NASA/GSFC/SDO

Flares

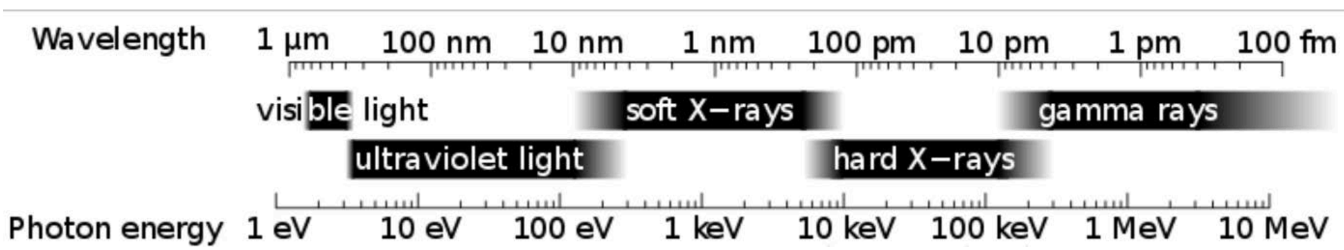
Typical evolution stages

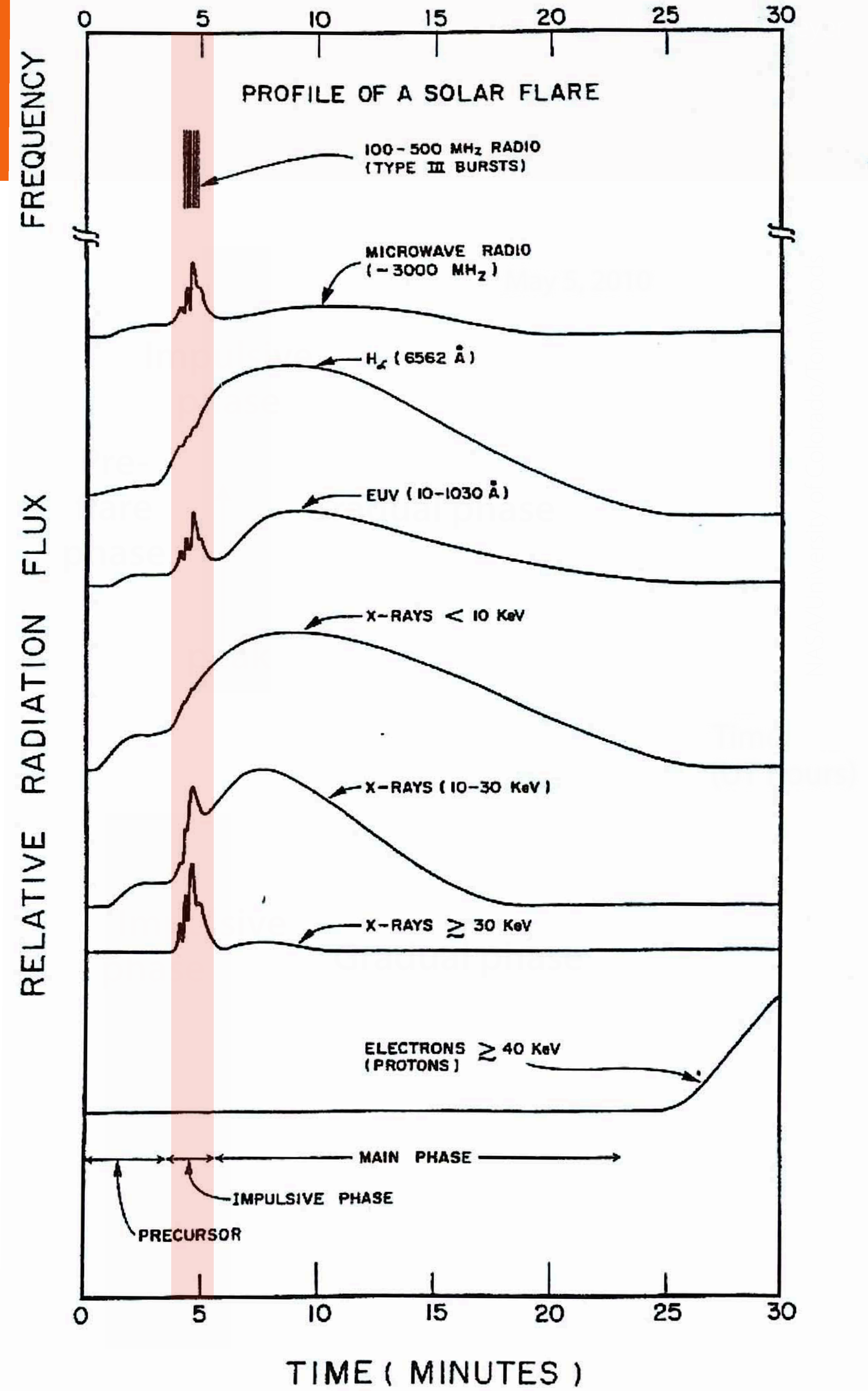


Flares

Temporal evolution

- Sudden brightening that involves all layers of the solar atmosphere
- Emission across the whole electromagnetic spectrum but different temporal variation (incl. rapid increase) depends on wavelength region
- Total energy released in flares varies from event to event
  - Range: 10^{27} - 10^{32} ergs, most of it emitted within a few 10min
  - For comparison: One H-bomb = 10 million TNT = 5 10^{23} ergs

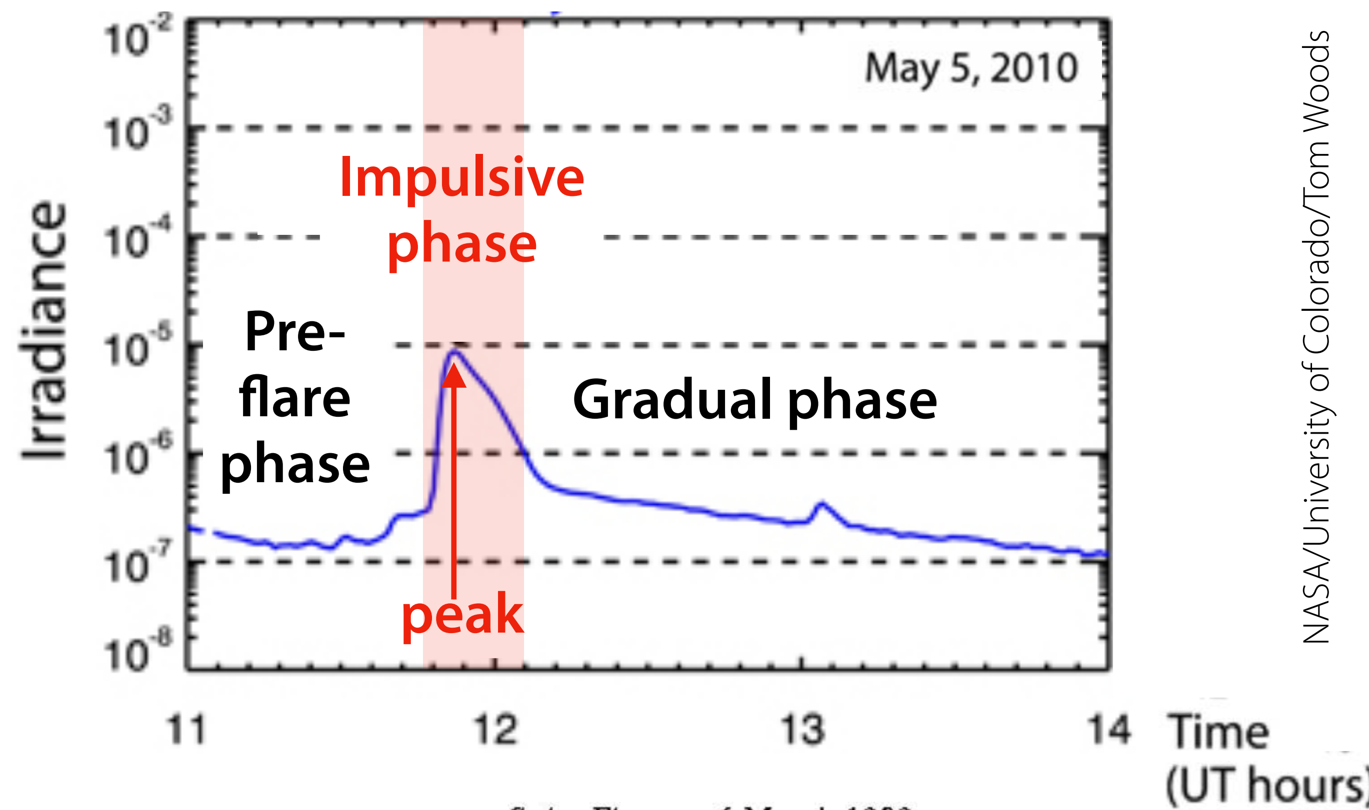




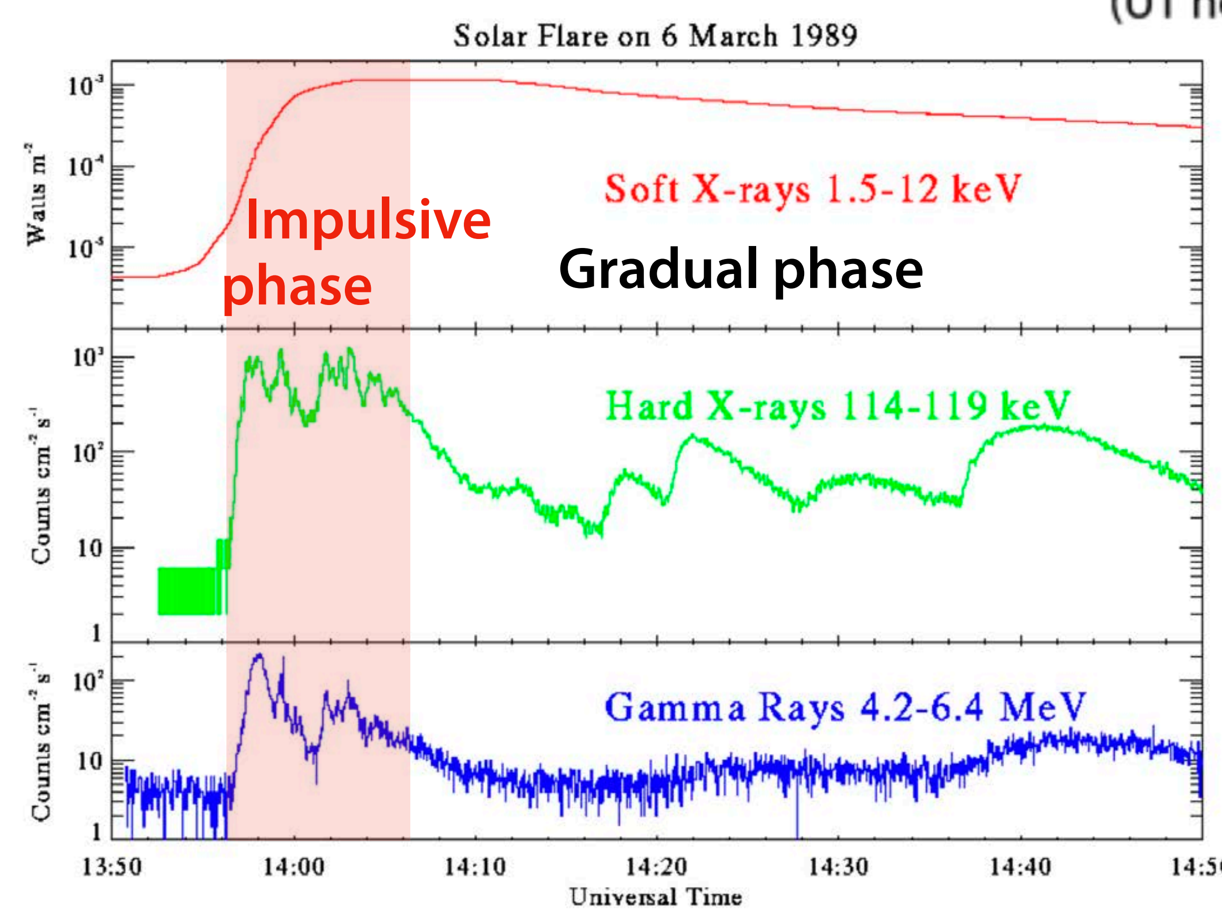
Flares

Three major phases

- **Pre-flare phase:** flare trigger phase leading to the major energy release
  - Slow increase of soft X-ray flux
- **Impulsive phase** (incl. peak): main rapid energy release phase
  - Most evident in increased hard X-ray, γ-ray, and millimetre/radio emission
  - Soft X-ray flux rises rapidly!
  - Short time-scales (1s and below), whole phase lasting for min - ~10min
- **Gradual phase** (post-flare)
  - Slow (or now) energy release / "afterglow" on longer time scales
  - No further emission in hard X-ray
  - Soft X-ray flux starts to decrease gradually.
  - Loop arcades (or arches) start to appear
  - Can last several hours



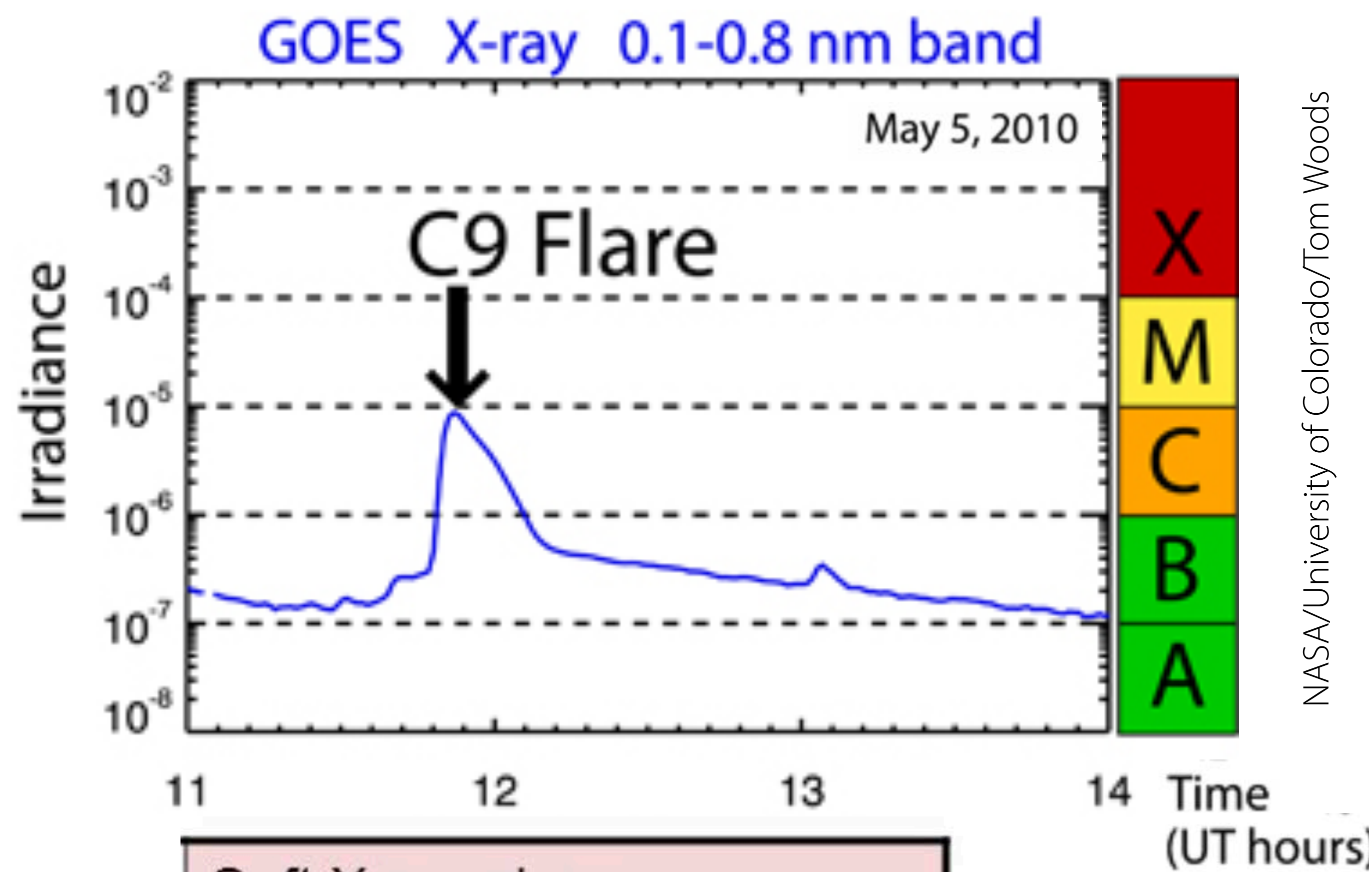
NASA/University of Colorado/Tom Woods



Flares

Classification

- **GOES** (Geostationary Operational Environmental Satellite): Several satellites
    - Measure (among many things) irradiance in several **X-ray** bands
    - Classification of a flare according to the measured peak irradiance



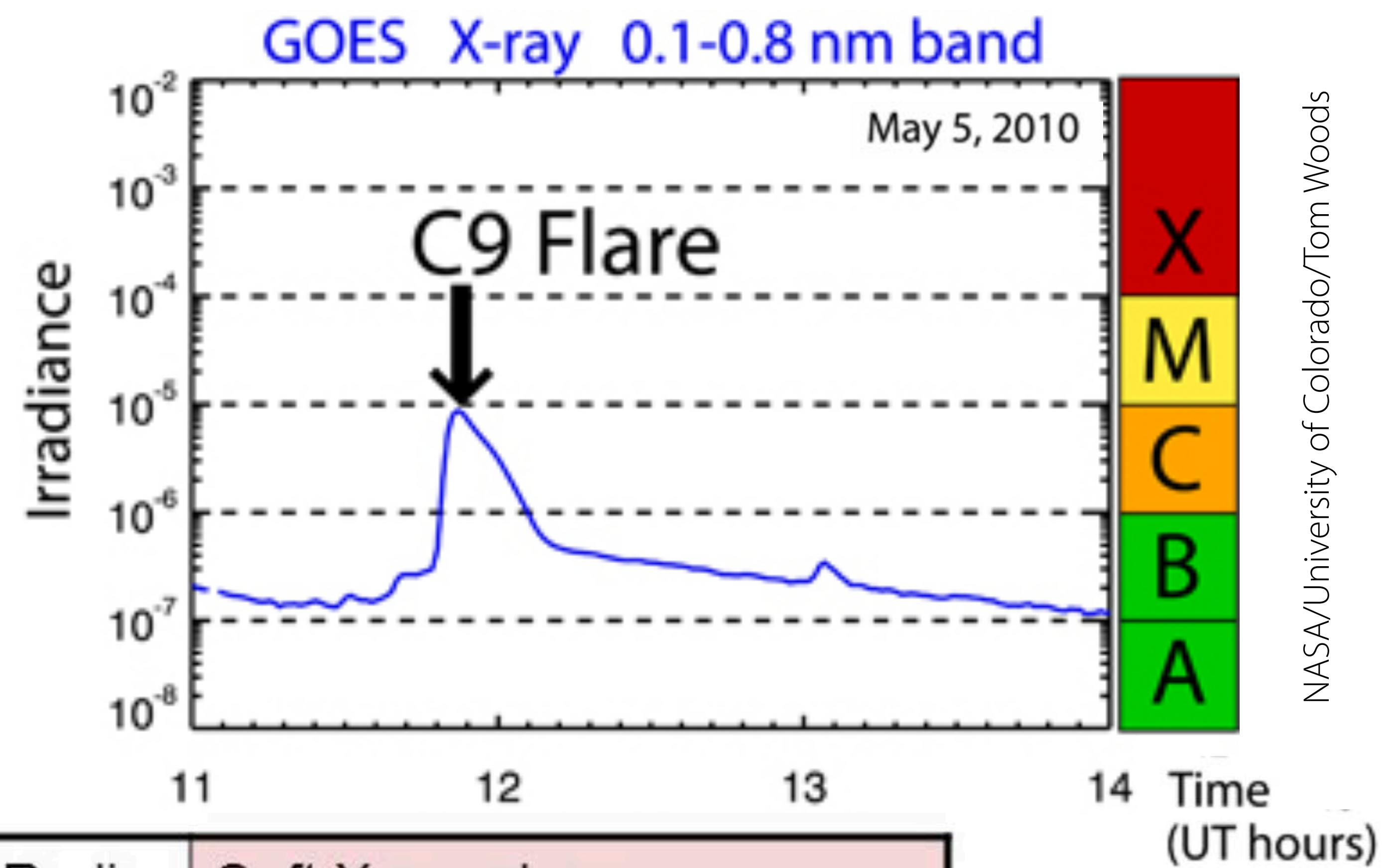
Soft X-ray class	
Importance class	Peak flux in 1-8 Å w/m^2
A	10^{-8} to 10^{-7}
B	10^{-7} to 10^{-6}
C	10^{-6} to 10^{-5}
M	10^{-5} to 10^{-4}
X	$>10^{-4}$

- Additional numbers after class letter:
    - X2 = 2 times as intense as an X1
    - X3 = 3 times as intense as an X1
    - …
- X10 (or stronger) are rare and unusually intense

Flares

Classification

- Alternative classifications schemes based on other measurable indicators, e.g.:
  - Radio flux at 5G Hz
  - Area with enhanced emission in Hα



Hα sub-classification by brightness:
F – faint, N – normal, B – bright

Hα classification			Radio flux at 5000 MHz in s.f.u.	Soft X-ray class	
Importance Class	Area (Sq. Deg.)	Area 10^{-6} solar disk		Importance class	Peak flux in 1-8 Å w/m^2
S	2.0	200	5	A	10^{-8} to 10^{-7}
1	2.0–5.1	200–500	30	B	10^{-7} to 10^{-6}
2	5.2–12.4	500–1200	300	C	10^{-6} to 10^{-5}
3	12.5–24.7	1200–2400	3000	M	10^{-5} to 10^{-4}
4	>24.7	>2400	3000	X	$>10^{-4}$

1 s.f.u. = 10^4 jansky = 10^{-2} W m^{-2} Hz^{-1}

Flares

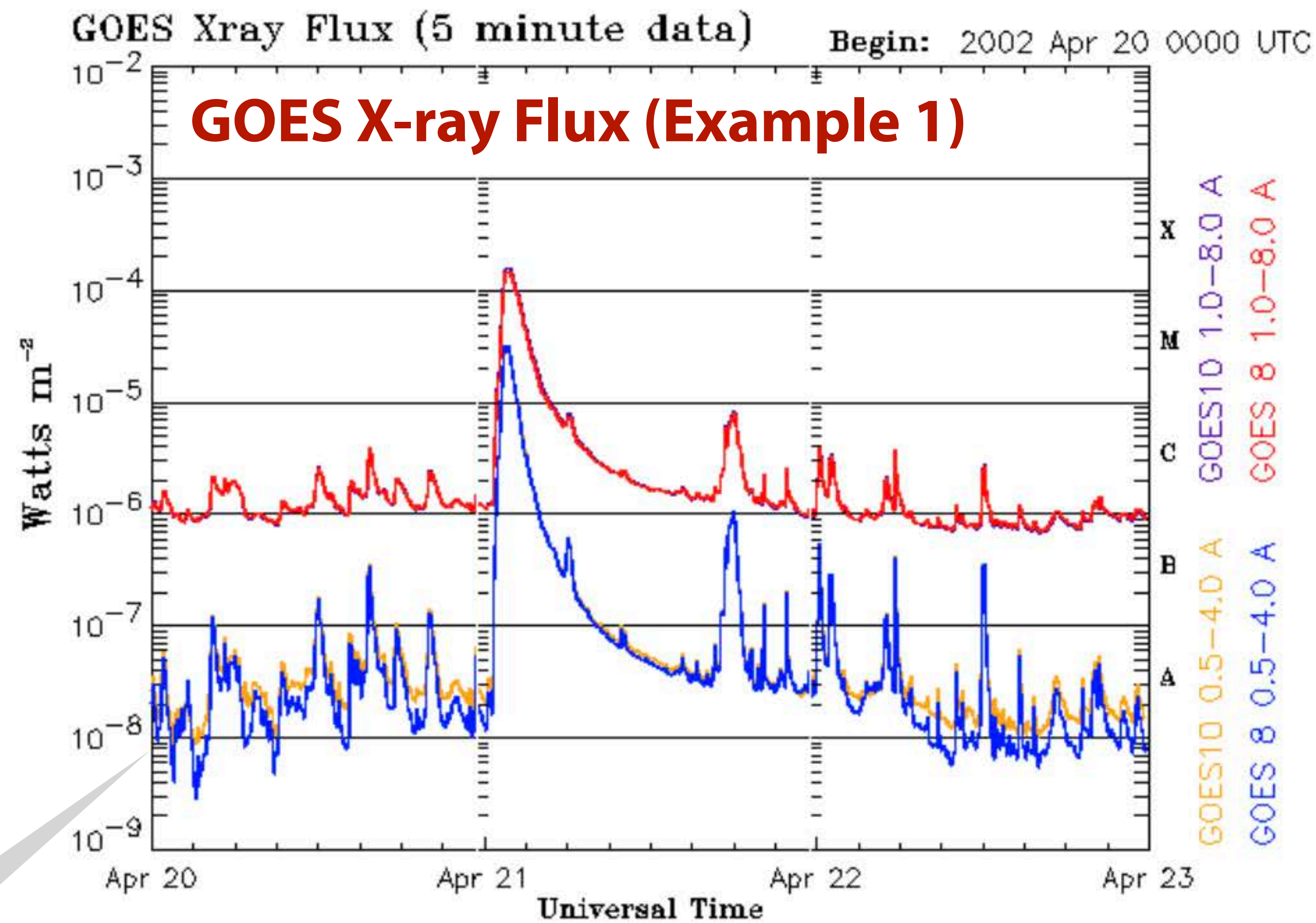
GOES observations

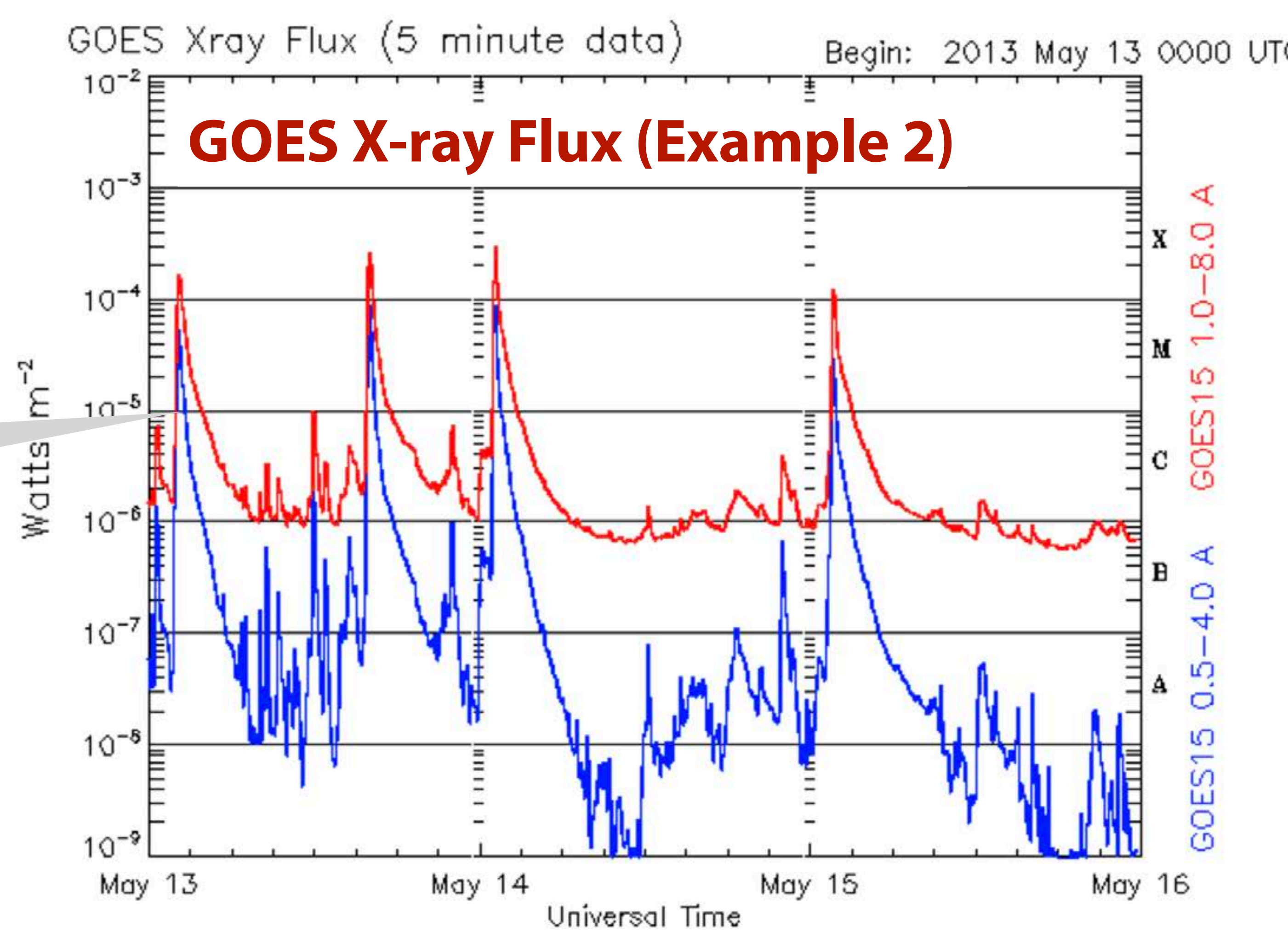
- GOES detects the X-ray irradiance of the whole Sun
- A single flare significantly varies the detected X-ray irradiance despite affecting only small region on the Sun!

Different colors = different bands

GOES class according to
0.1-0.8nm band (red)

Sequence of several flares including 4 X-class flares within 3 days





Flares

GOES observations

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- Flares also produce energetic particles, some ejected into interplanetary space
- GOES measures energetic proton flux