Comparison of $F_{10.7}$ and Coronal EUV Emission using DEMs

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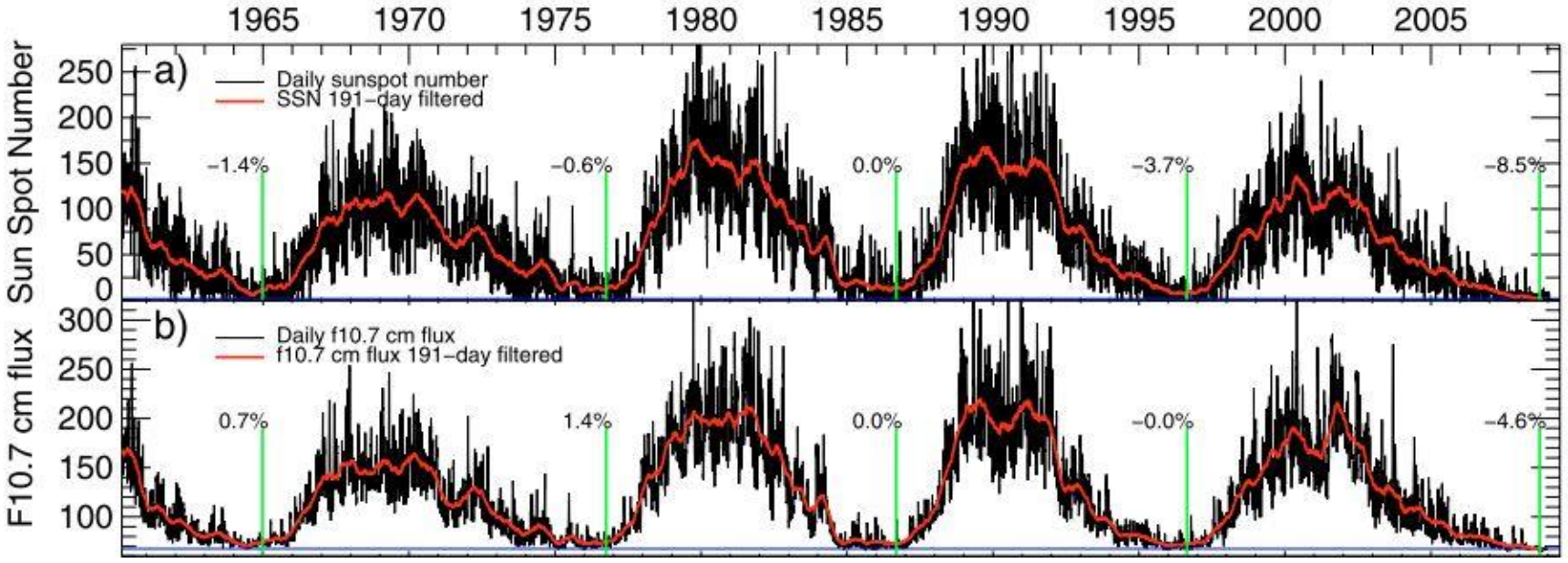
$F_{10.7}$ Index

- 10.7 cm (2.8 GHz) solar radio flux
  - 68 year observation history (Tapping 1987)
  - Used as a proxy for EUV in Ionospheric modeling

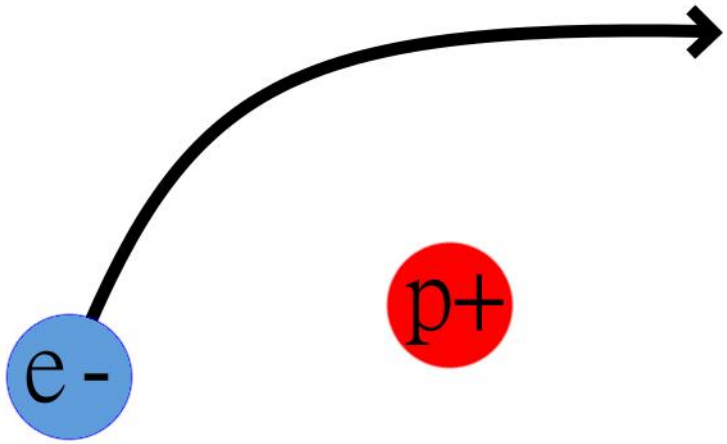


1 sfu = 10^4 Jy = 10^{-19} erg cm^{-2} s^{-1} Hz^{-1}

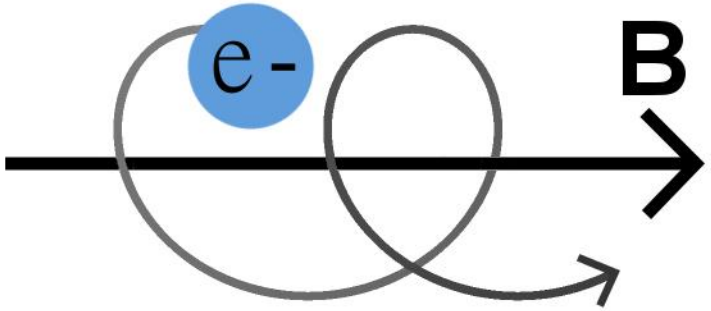
Fröhlich 2009

$F_{10.7}$ Generation Mechanisms

- Bremsstrahlung
  - Active regions and plage
  - Free-free electron-ion interactions
  - Unpolarized
  - Traces density



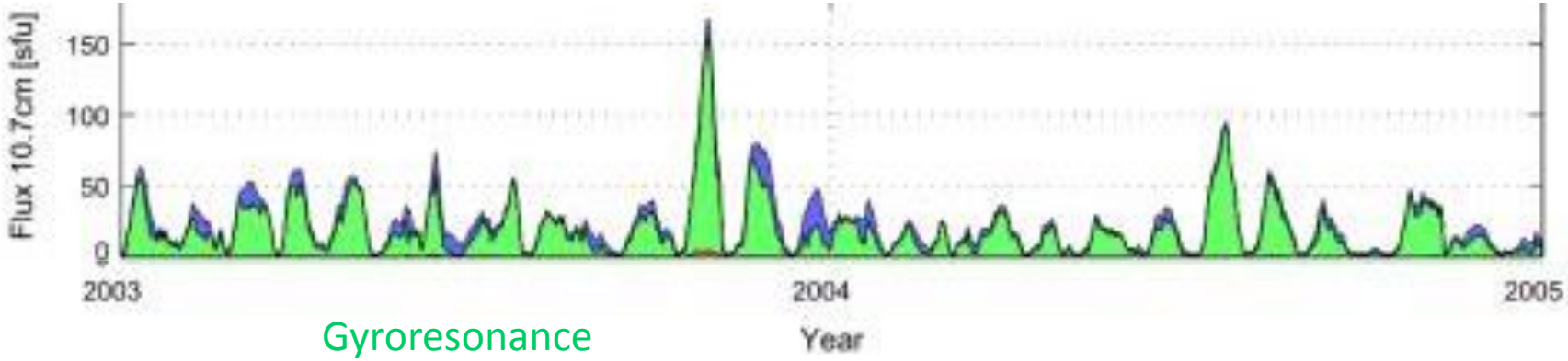
- Gyroresonance
  - Active region cores
  - Electrons spiraling around magnetic fields
  - Circularly polarized
  - Traces magnetic field



The Mechanism Matters

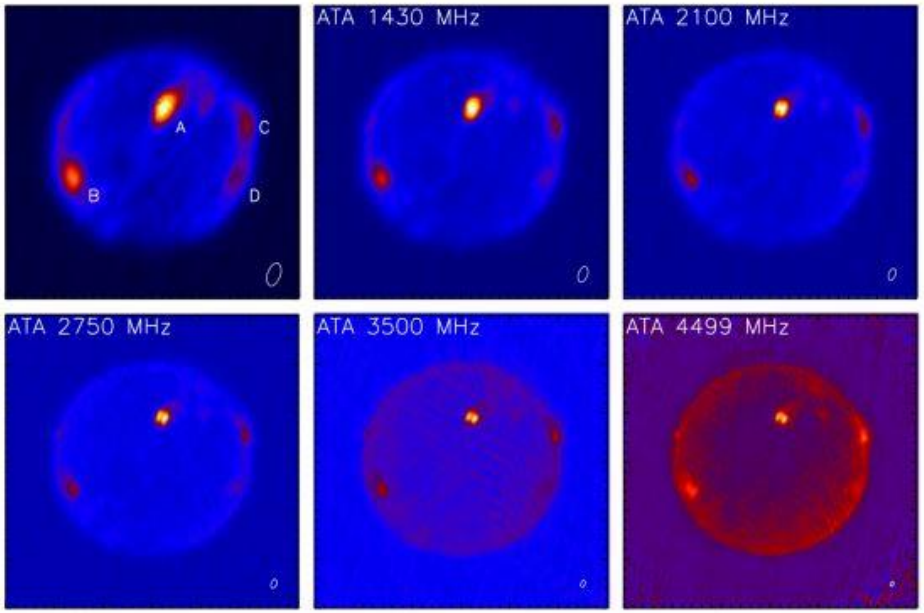
- Bremsstrahlung is generated by collisions
  - Collisionally excited atomic emission lines emit EUV
- Gyroresonance results from magnetic fields
  - No magnetically driven emission in EUV
- **Gyroresonance is a contaminant when $F_{10.7}$ is used as an EUV proxy**
  - $F_{10.7}$ is a direct input to ionosphere models
    - Typical density errors of ≈10% (Bowman et al. 2008)
- Gyroresonance fraction unclear

Recent Studies



Gyroresonance
Bremsstrahlung

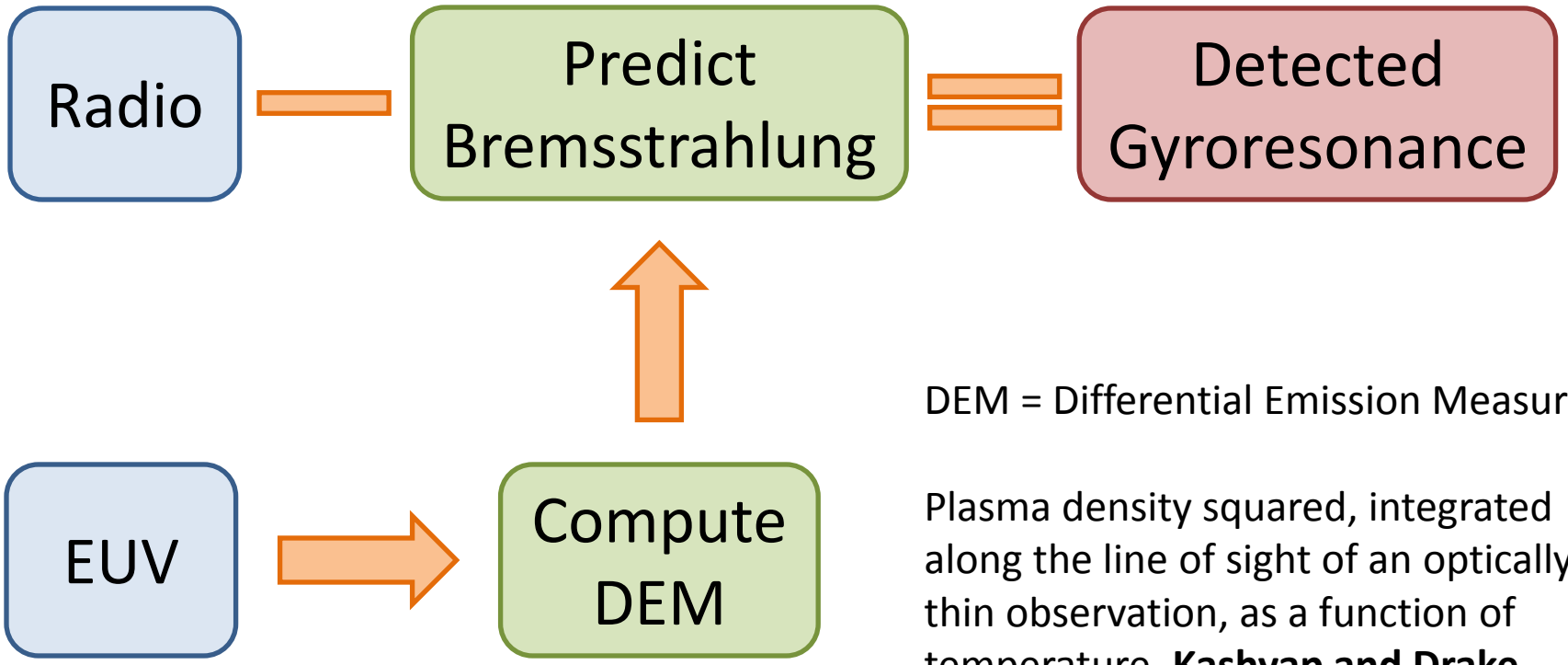
Dudok de Wit, Bruinsma, Shibasaki 2014



- Time series analysis -> gyroresonance dominated
- Imaging spectral index -> bremsstrahlung dominated

Saint-Hilaire et al 2012

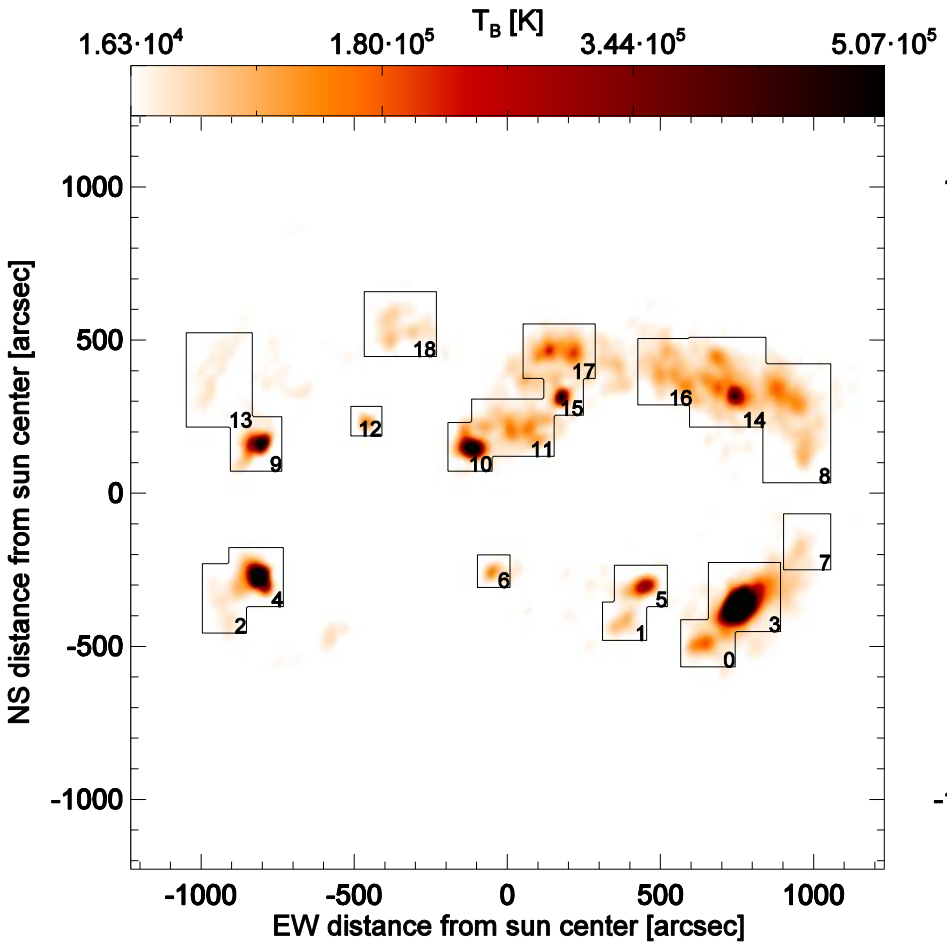
How We Separate Gyroresonance



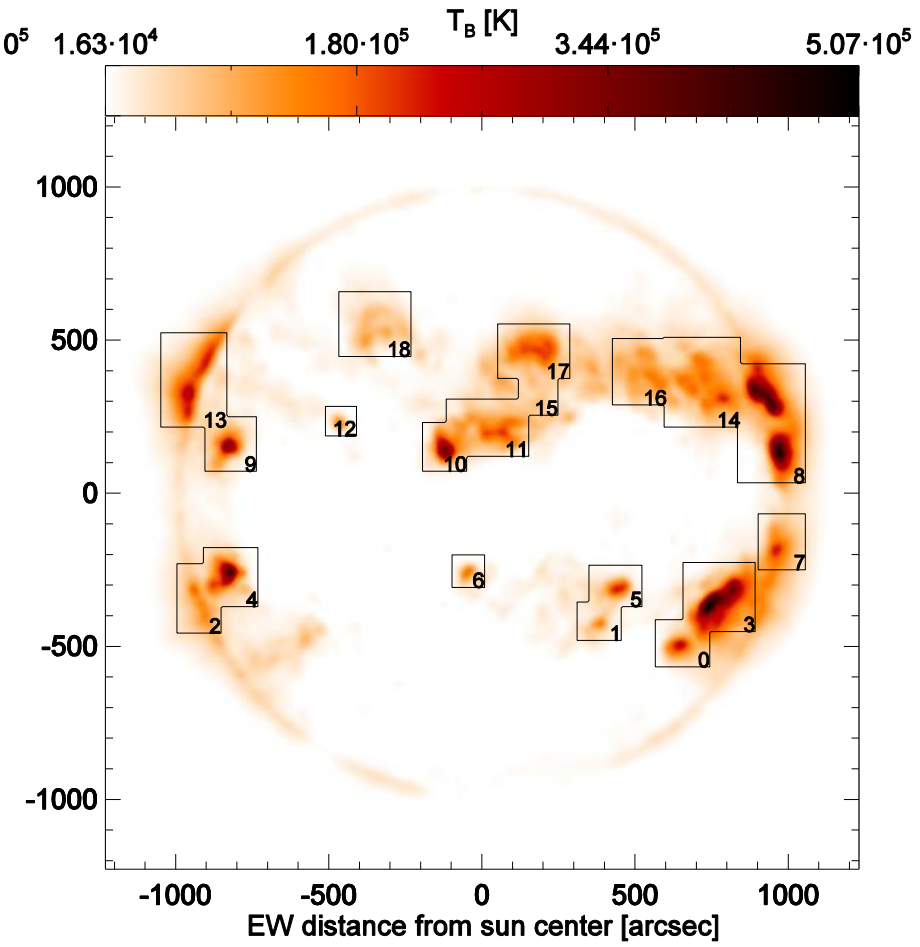
DEM = Differential Emission Measure

Plasma density squared, integrated along the line of sight of an optically thin observation, as a function of temperature. **Kashyap and Drake 1998** and **Plowman et al. 2013** methods used.

Predicted Radio Bremsstrahlung



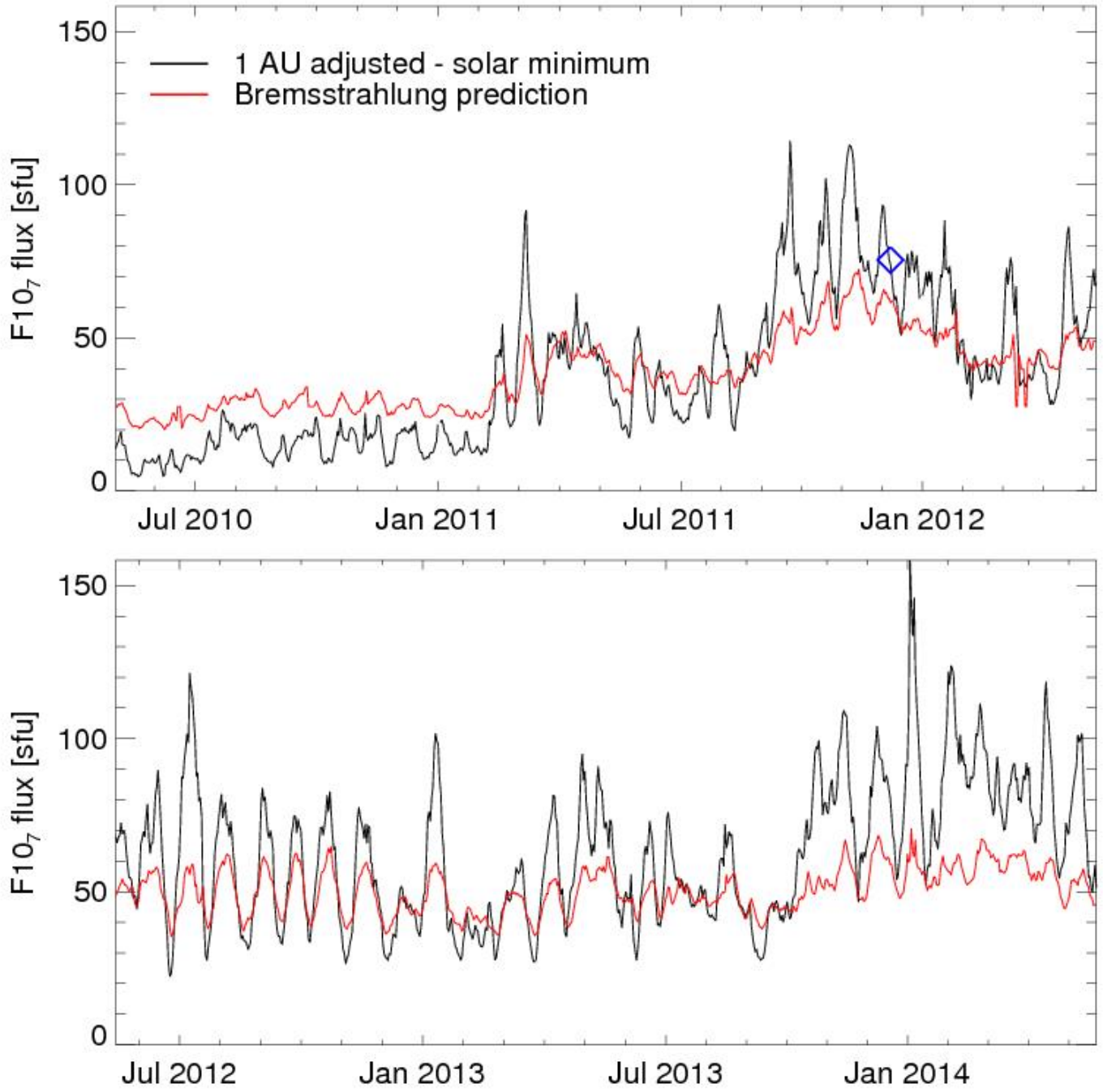
10.7 cm observation

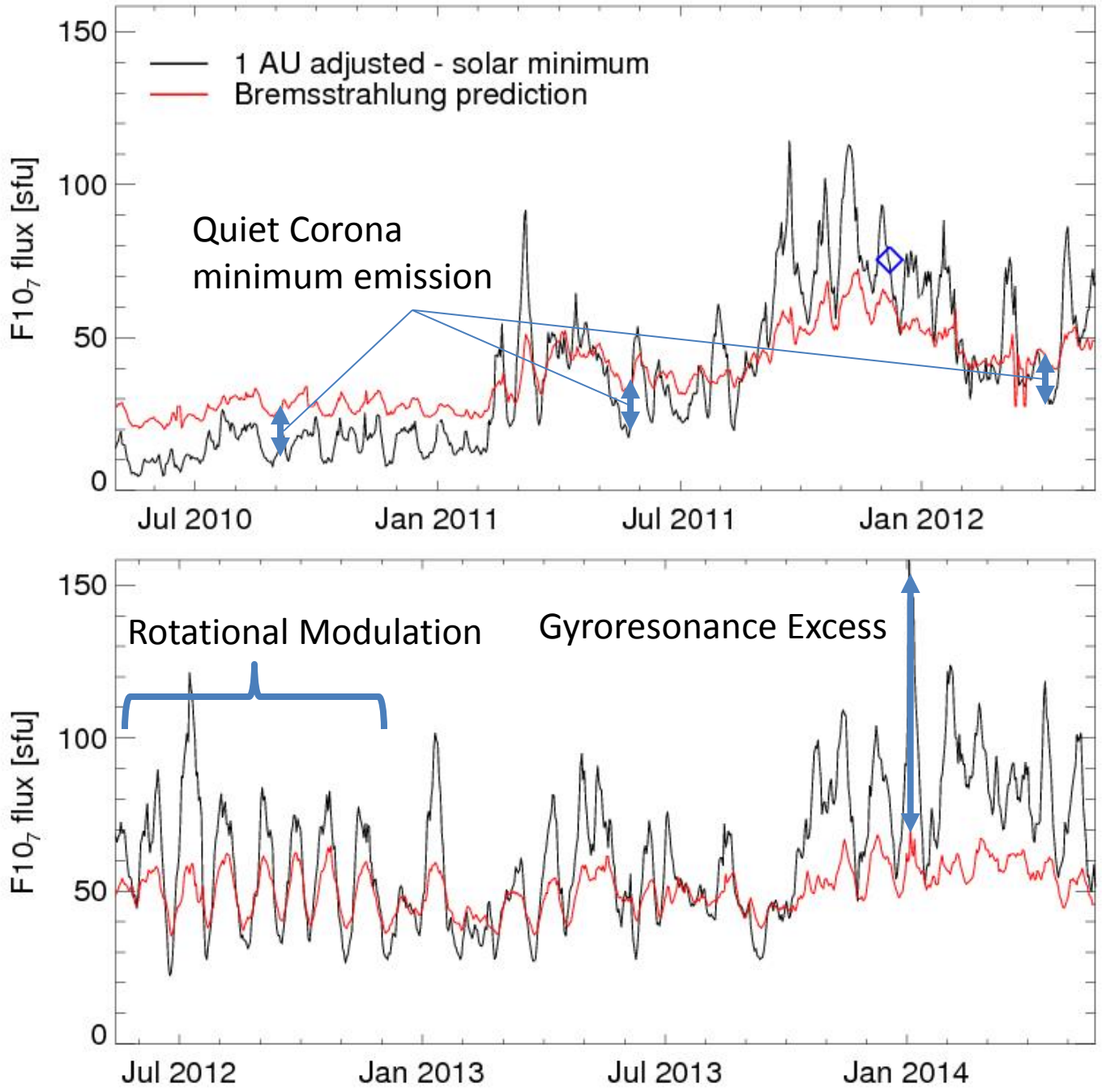


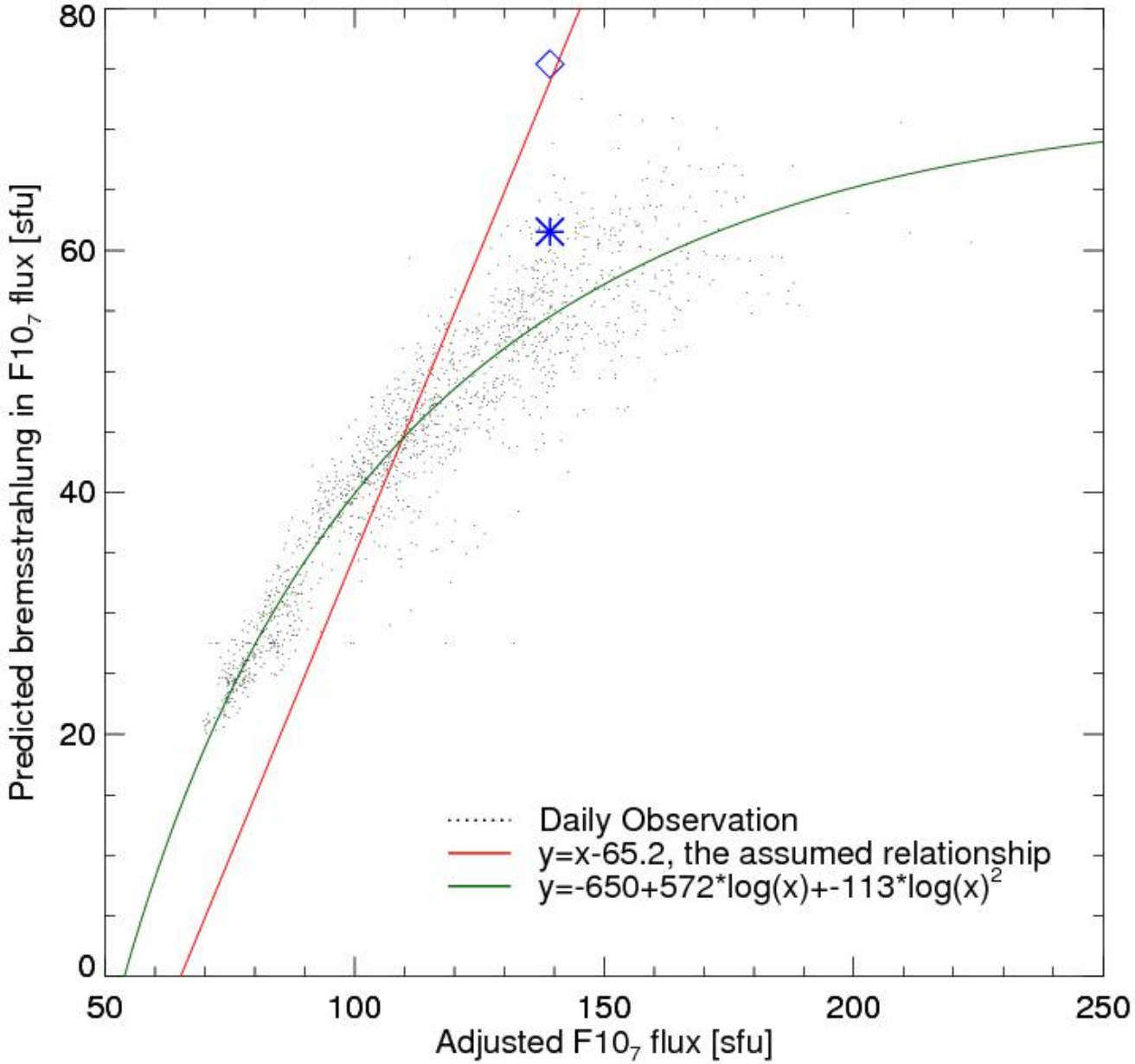
Bremsstrahlung prediction

Schonfeld et al. 2015

- Bremsstrahlung prediction successful
  - Active region morphology matches observations
  - Identified discrepancy on the limb
    - Due to height of optically thick chromospheric layer
    - Causes ≈1 day delays in $F_{10.7}$ response to solar rotation
- Gyroresonance sources identified
  - 6.2 ± 0.3 sfu, 8.1% of $F_{10.7}$
  - Same order as ionospheric modelling errors


1 AU adjusted - solar minimum
Bremsstrahlung prediction
F10$_7$ flux [sfu]
150
100
50
0
Jul 2010
Jan 2011
Jul 2011
Jan 2012
F10$_7$ flux [sfu]
150
100
50
0
Jul 2012
Jan 2013
Jul 2013
Jan 2014


150
100
50
0
F10$_7$ flux [sfu]
1 AU adjusted - solar minimum
Bremsstrahlung prediction
Quiet Corona
minimum emission
Jul 2010
Jan 2011
Jul 2011
Jan 2012
150
100
50
0
F10$_7$ flux [sfu]
Rotational Modulation
Gyroresonance Excess
Jul 2012
Jan 2013
Jul 2013
Jan 2014

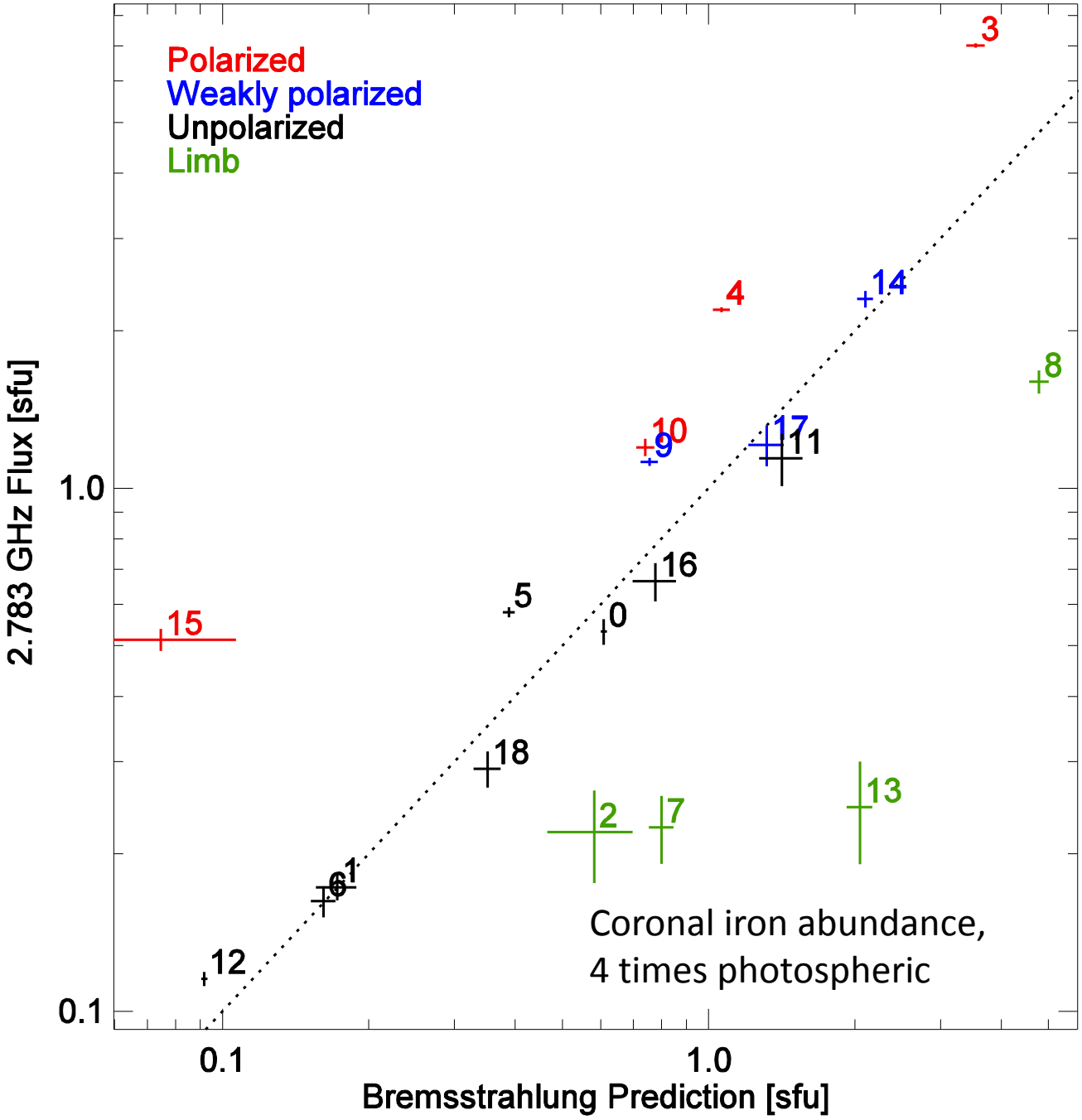

Predicted bremsstrahlung in F10$_7$ flux [sfu]
Adjusted F10$_7$ flux [sfu]
0
20
40
60
80
50
100
150
200
250
Daily Observation
y=x-65.2, the assumed relationship
y=-650+572*log(x)+-113*log(x)^2

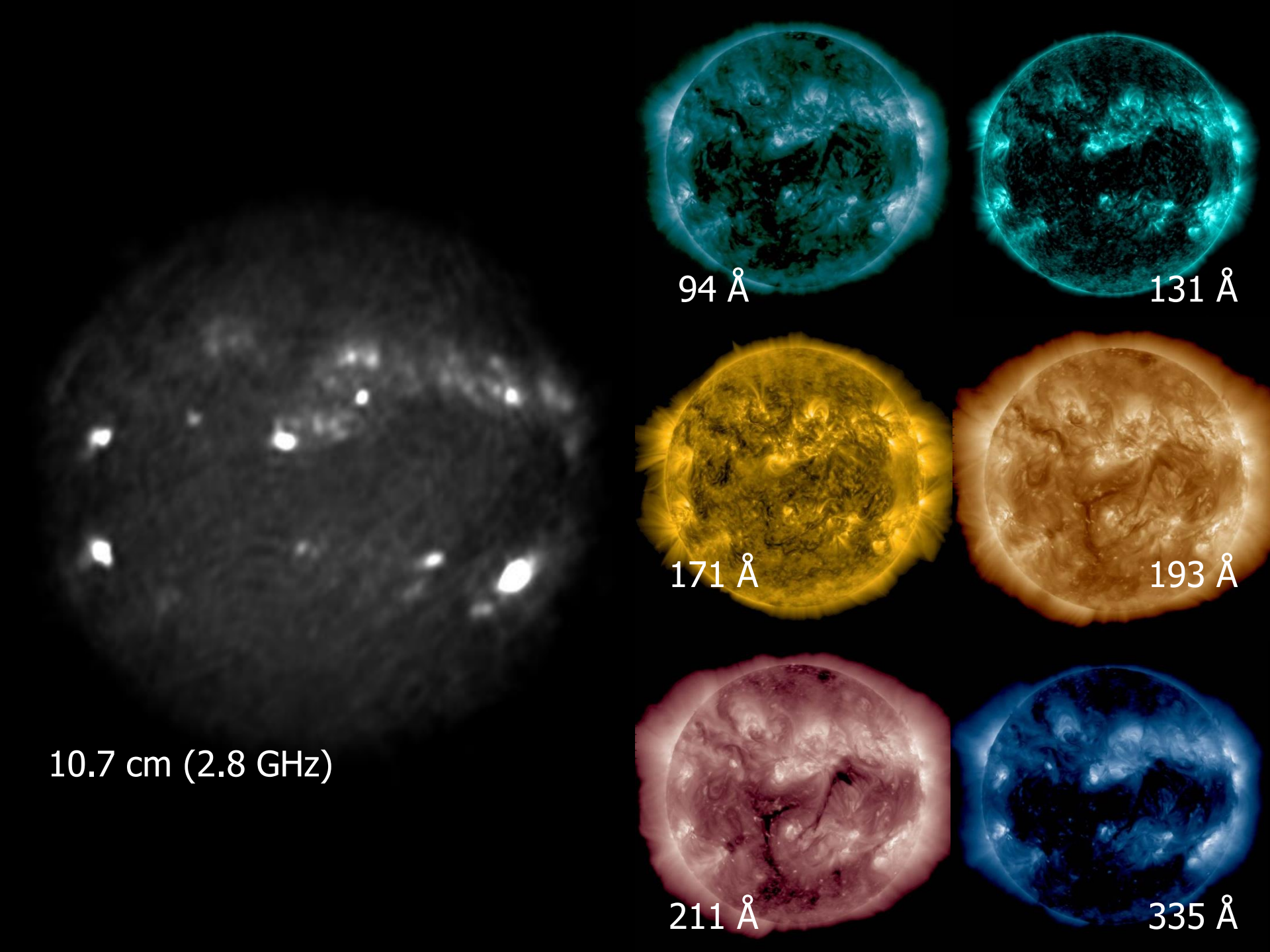
Preliminary Findings

- Successfully reproduced rotational modulation
- Quiet sun contribution to $F_{10.7}$, about 20 sfu
- Non-linear EUV and $F_{10.7}$ relationship

- Future work:
  - Finalize time series analysis
  - Coordinated single region observation
  - Repeat full disk VLA observation

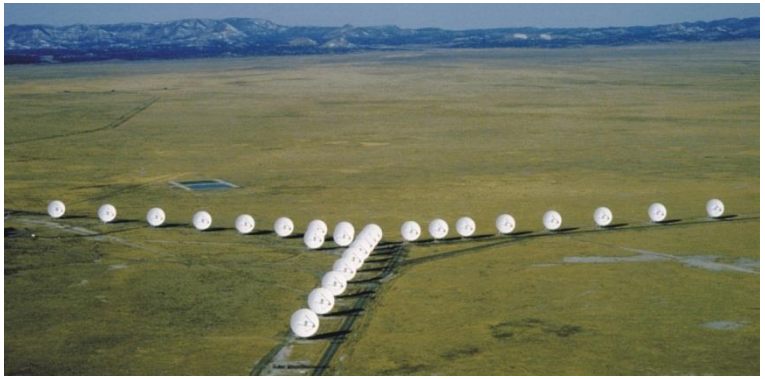

Thank You

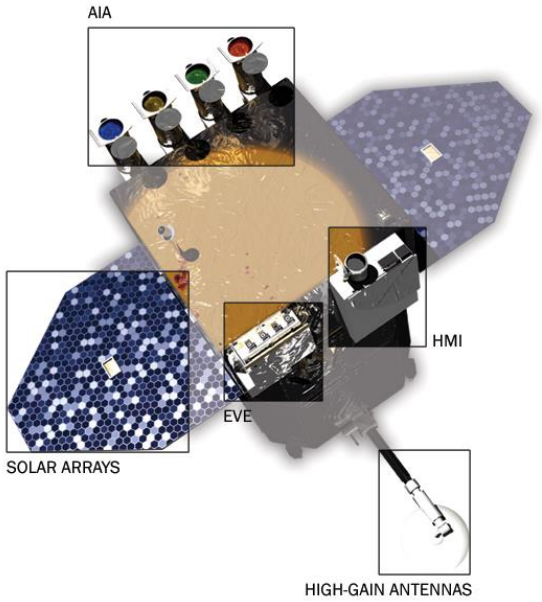

Polarized
Weakly polarized
Unpolarized
Limb
2.783 GHz Flux [sfu]
Bremsstrahlung Prediction [sfu]
0.1
1.0
0.1
1.0
Coronal iron abundance,
4 times photospheric
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

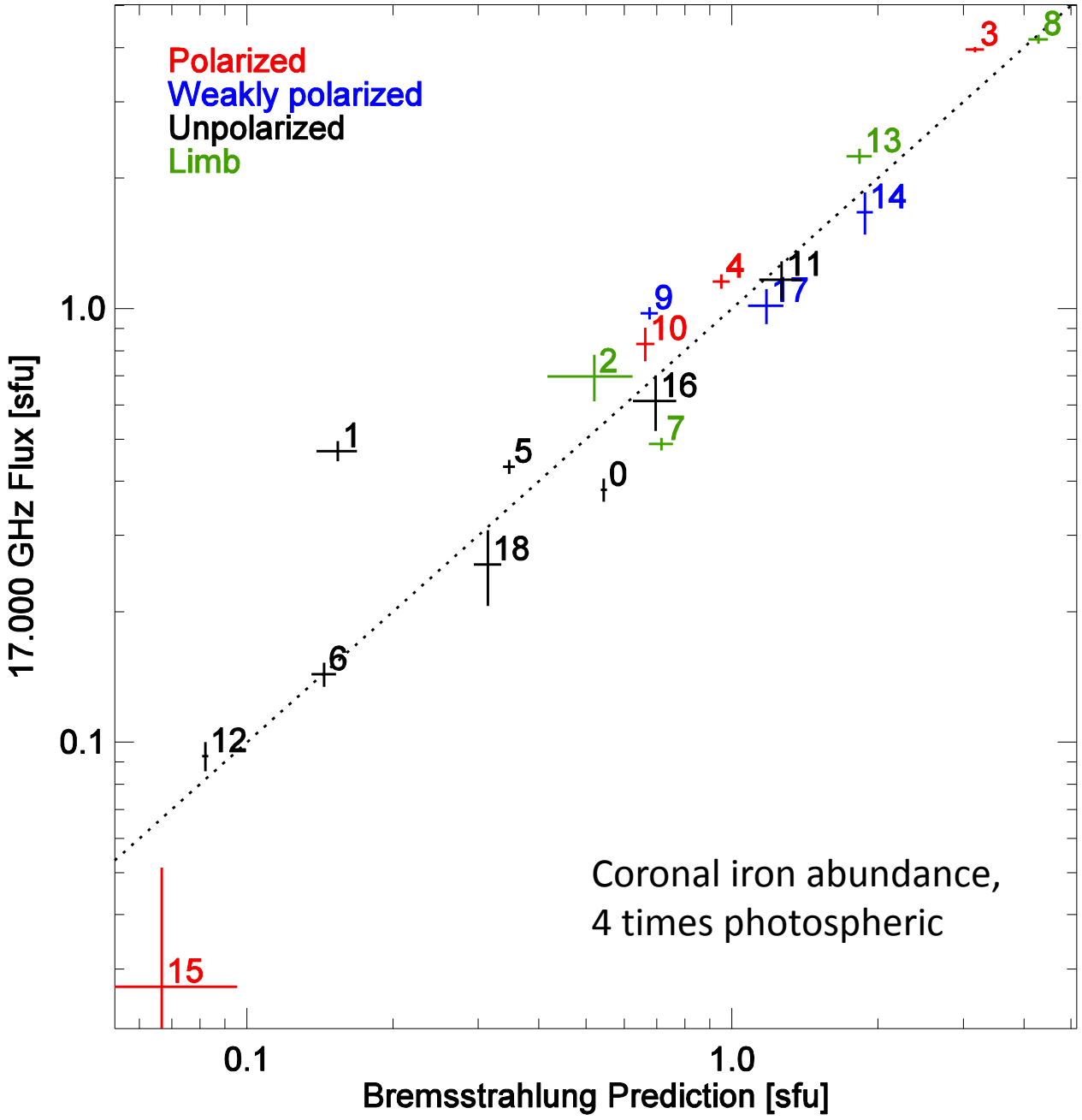

10.7 cm (2.8 GHz)
94 Å
131 Å
171 Å
193 Å
211 Å
335 Å

Observations

- Radio data
  - Karl G. Jansky Very Large Array (VLA)
    - 17 of 27 antennas
  - Eight hour integration
    - Seven pointing mosaic
  - S-band 2—4 GHz coverage
    - 10.7 cm = 2.8 GHz
- EUV data
  - Atmospheric Imaging Assembly (AIA)
  - 60 second cadence
  - Six coronal EUV bands






Polarized
Weakly polarized
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17.000 GHz Flux [sfu]
Bremsstrahlung Prediction [sfu]
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Coronal iron abundance,
4 times photospheric
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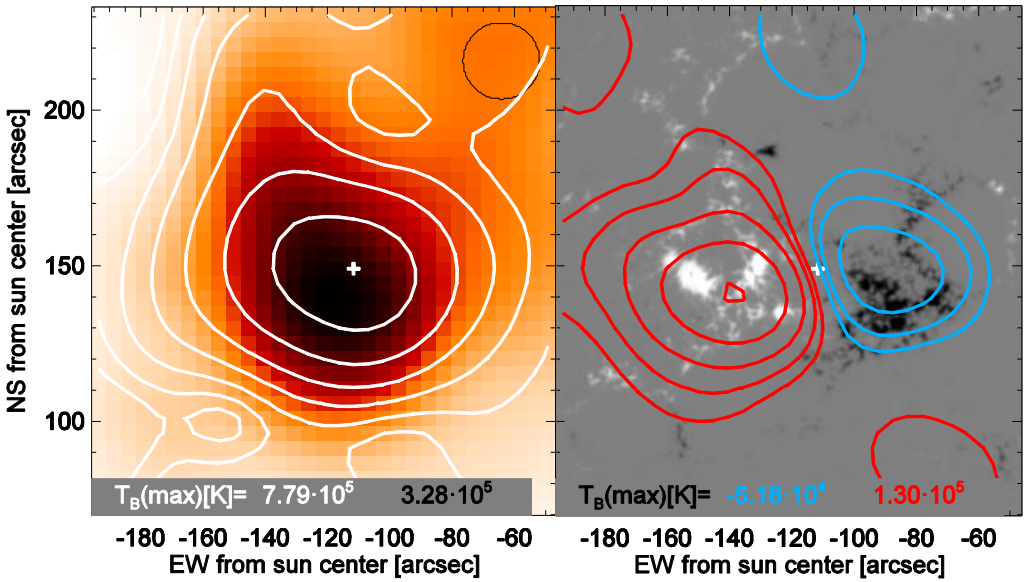
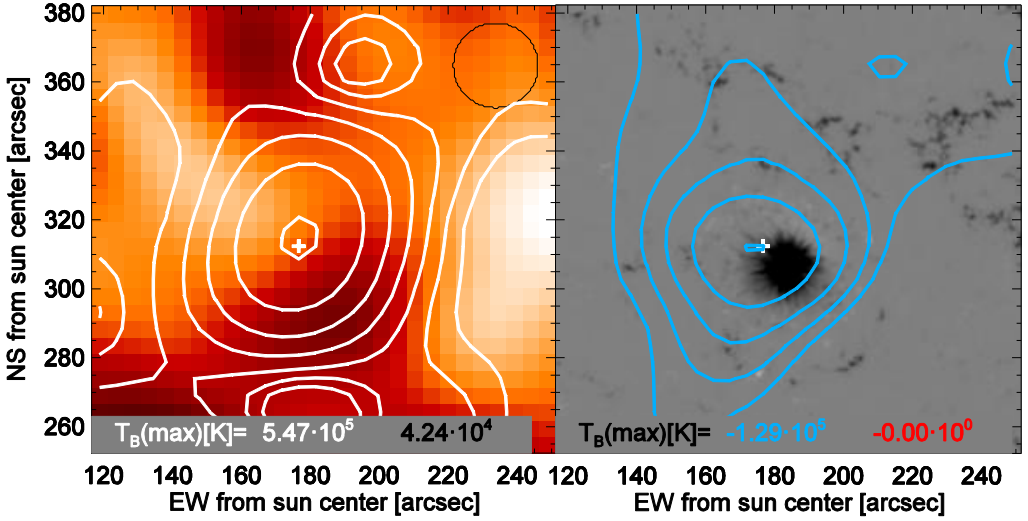
Strongly Polarized Regions



Region 10

Left:
Image = bremsstrahlung
Contours = radio intensity

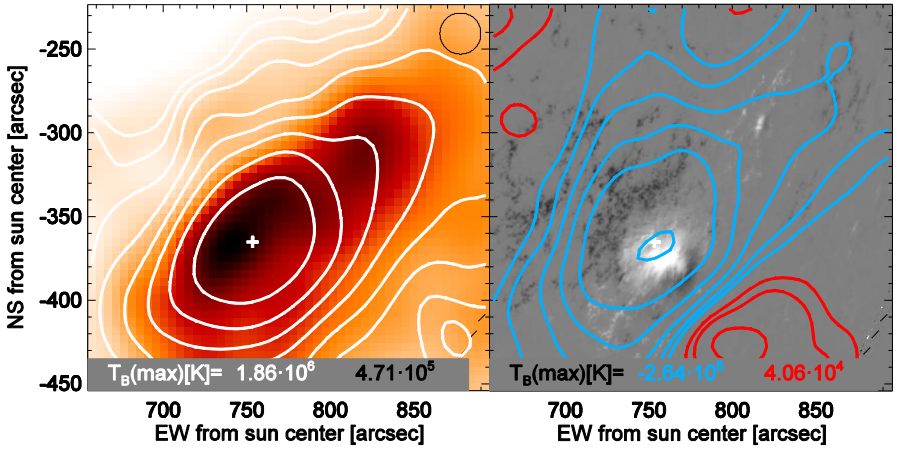
Right:
Grayscale = photospheric magnetic field
Contours = radio circular polarization



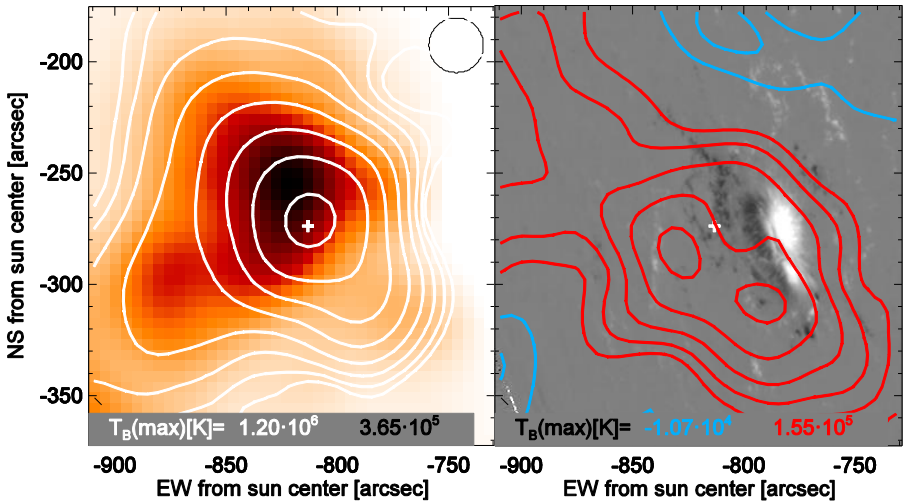
Region 15

Strong Polarization Examples

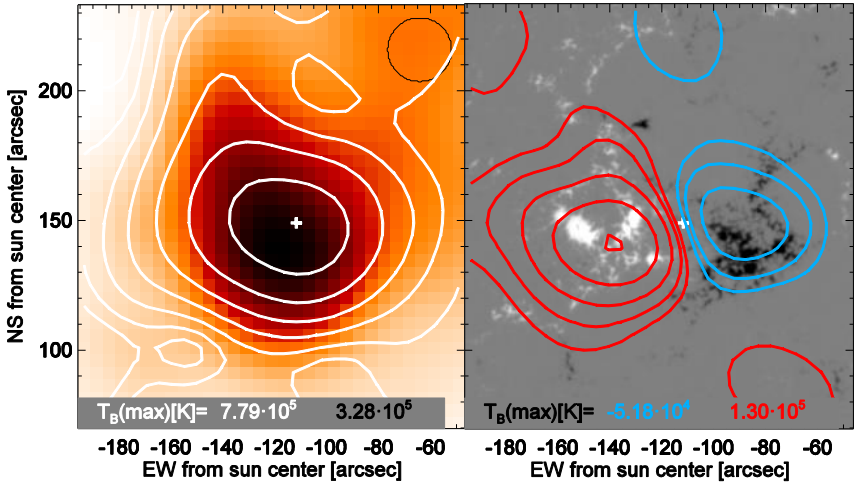
Region 3



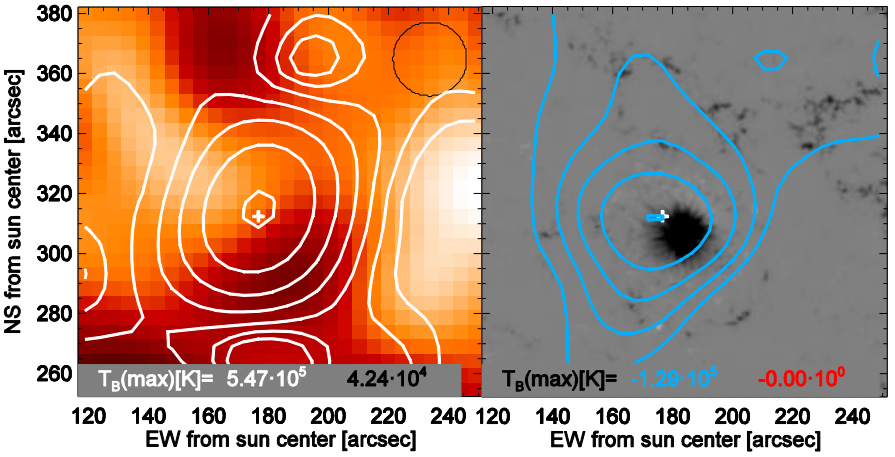
Region 4



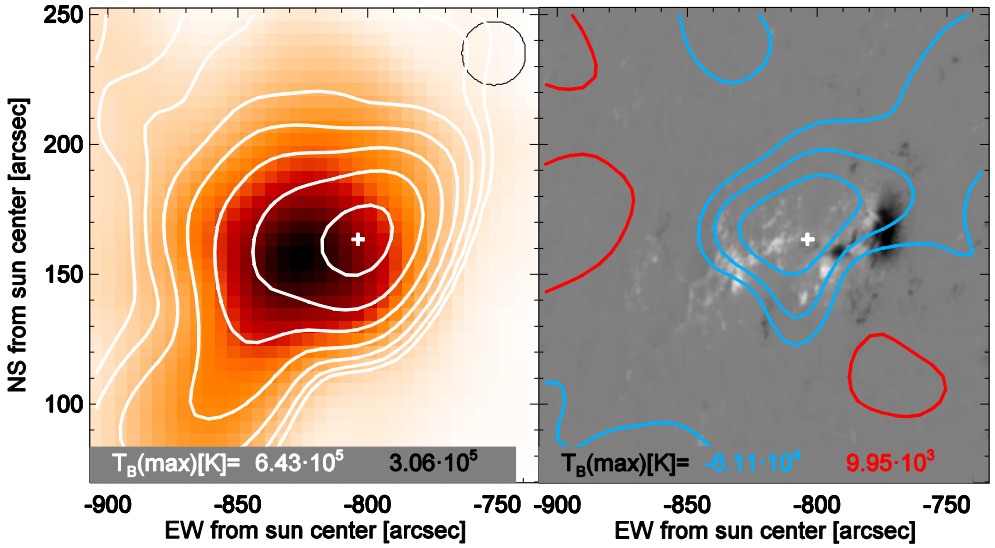
Region 10



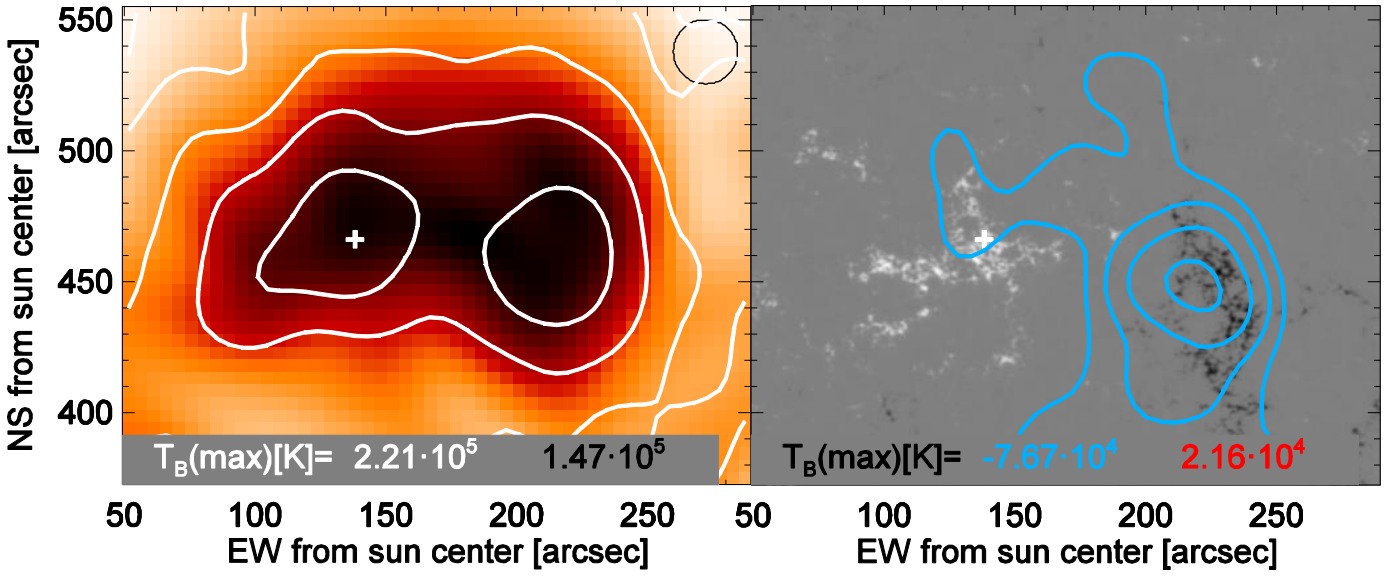
Region 15



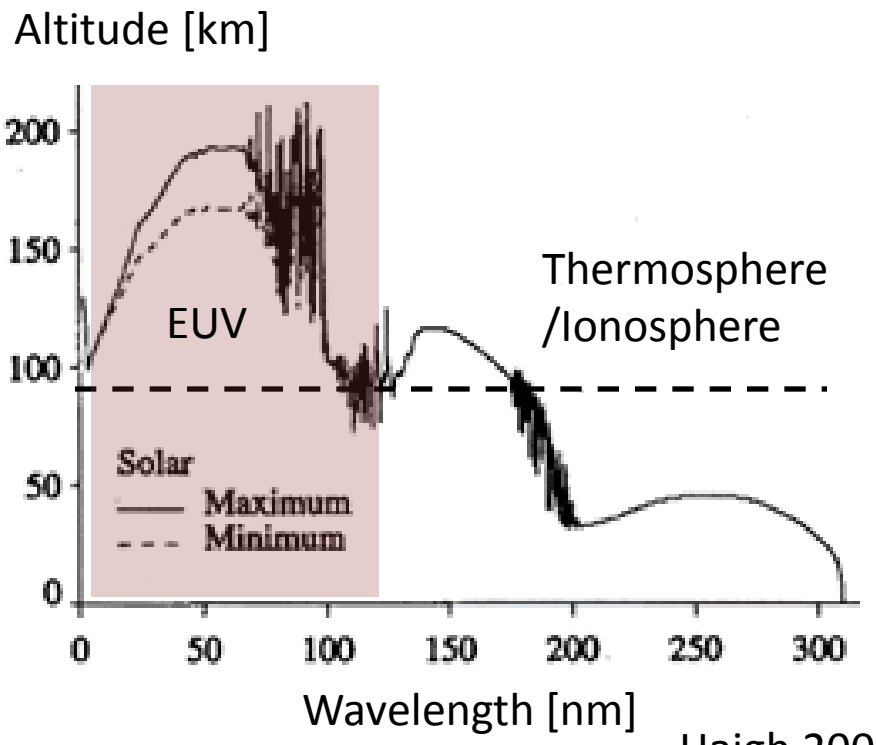
Weak Polarization Examples



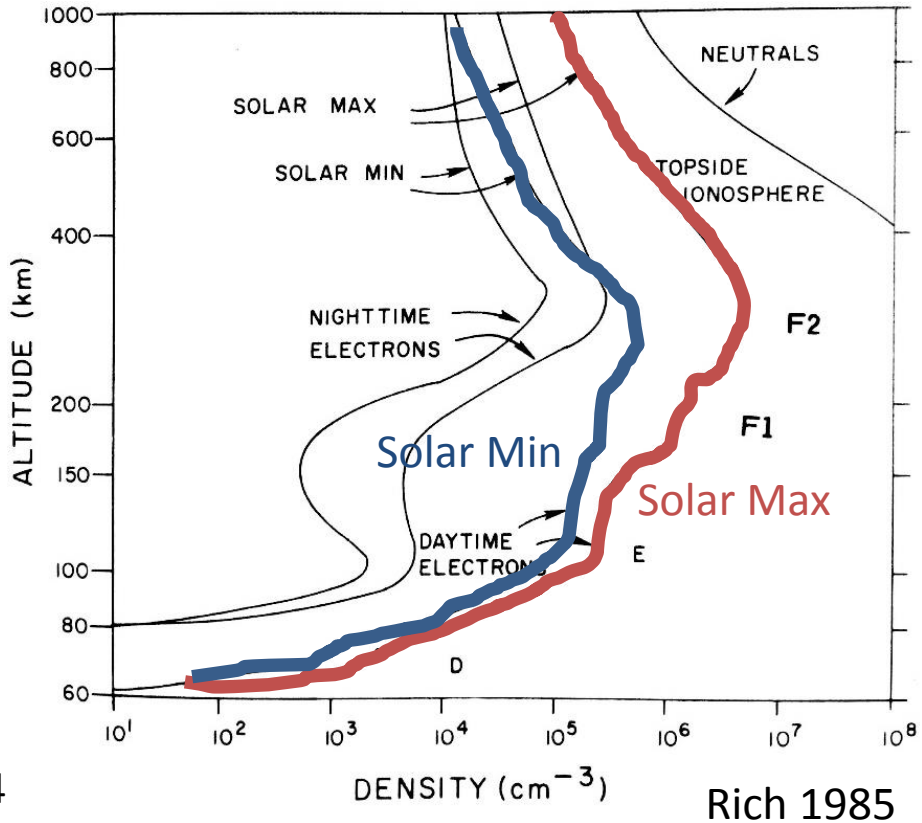
Region 9



Region 17



Haigh 2004

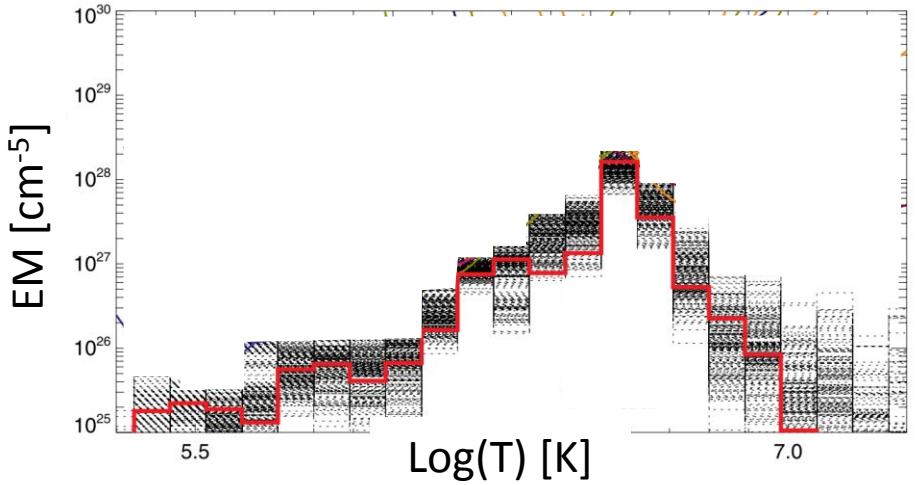


Rich 1985

Differential Emission Measure

- Emission Measure (EM)
  - EM $\propto \int {n_e}^2 \mathrm{d}s \quad [cm^{-5}]$
  - Controls strength of collisional processes
    - Bremsstrahlung emission
    - Collisionally excited atomic emission
- Differential Emission Measure (DEM)
  - Emission measure as a function of temperature
    - $\frac{\mathrm{d}EM}{d\mathrm{T}}$ $[cm^{-5}K^{-1}]$

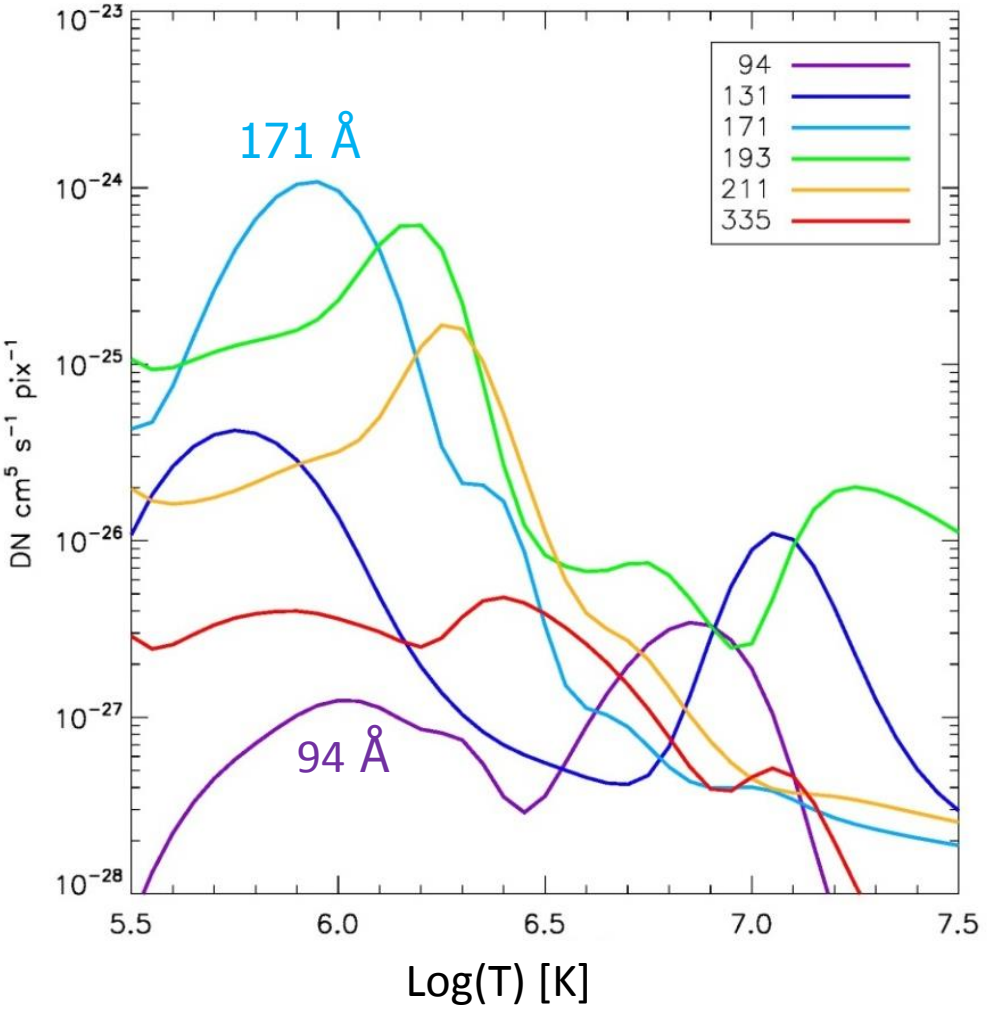
Warren, Brooks, and Winebarger 2011



1: Calculating the DEM

$$Flux_i = \sum Resp_i(T) \times DEM(T) \times \Delta T$$

- Observe optically thin medium at different temperatures
- Invert set of observations to determine necessary plasma structure
- No analytic solution
  - MCMC type forward model
  - Direct inversion



Limitations of Initial Analysis

- Only 17 of 27 antennae used
  - 37% decrease in collecting area
  - 61% reduction in u-v plane coverage
- Primary flux calibrator data unavailable
  - Assume solar attenuators were exactly 20dB
  - Estimate about 20% error in observed radio fluxes

2: Active Region Observation

- JVLA, C-configuration (7.5″ resolution at $F_{10.7}$)
  - 2—12 GHz
- EUV Imaging Spectrometer (EIS)
  - R≈4000 in 170-210 Å and 250-290 Å with 2″ spatial resolution
- Solar Optical Telescope (SOT)
  - Photospheric vector magnetograms with 0.2″ resolution

2: EVLA observation of a small active region

Merger of 5 frequency bands each 2 GHz wide