Correcting $F_{10.7}$ for use in Ionospheric Models

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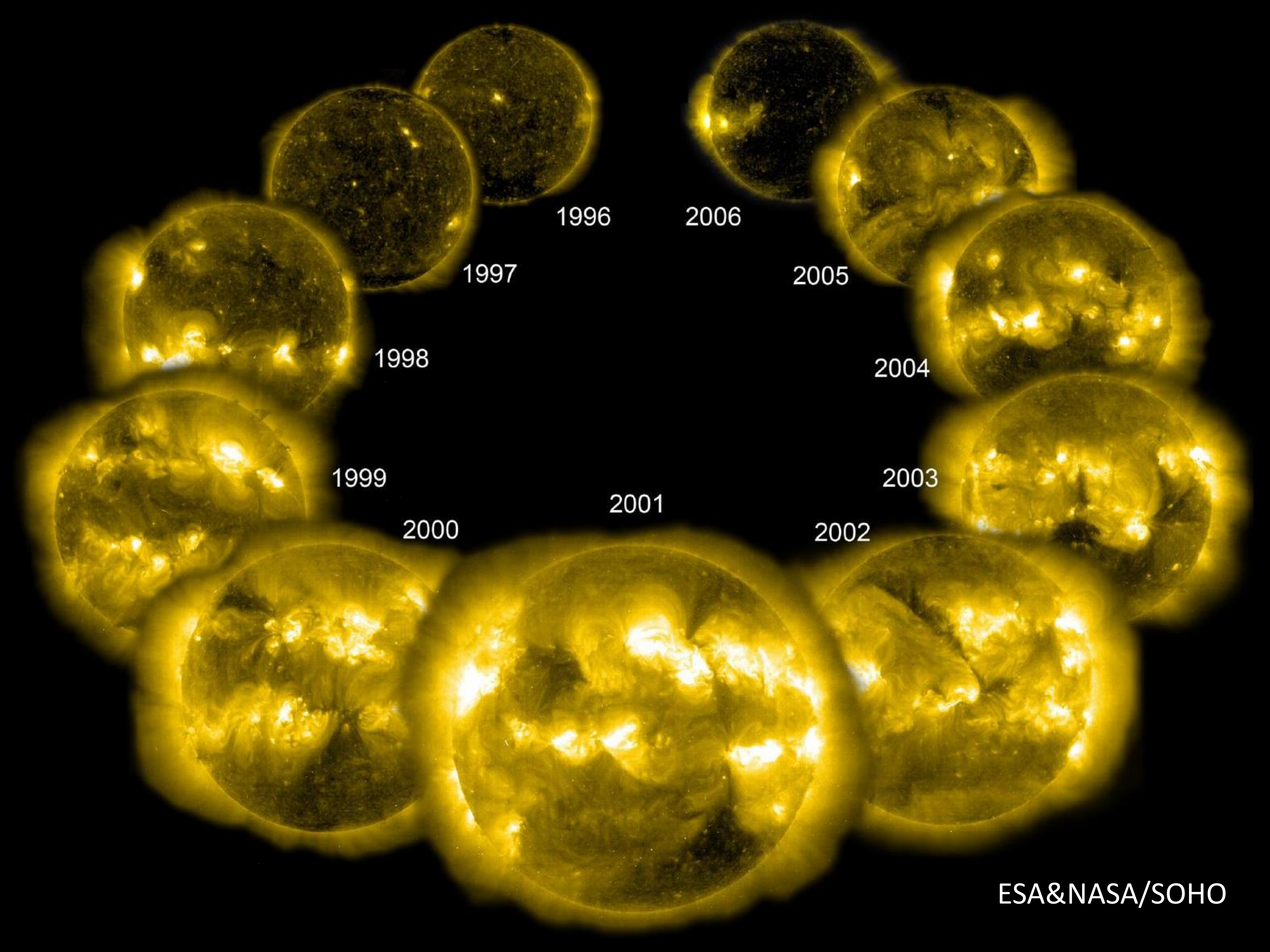
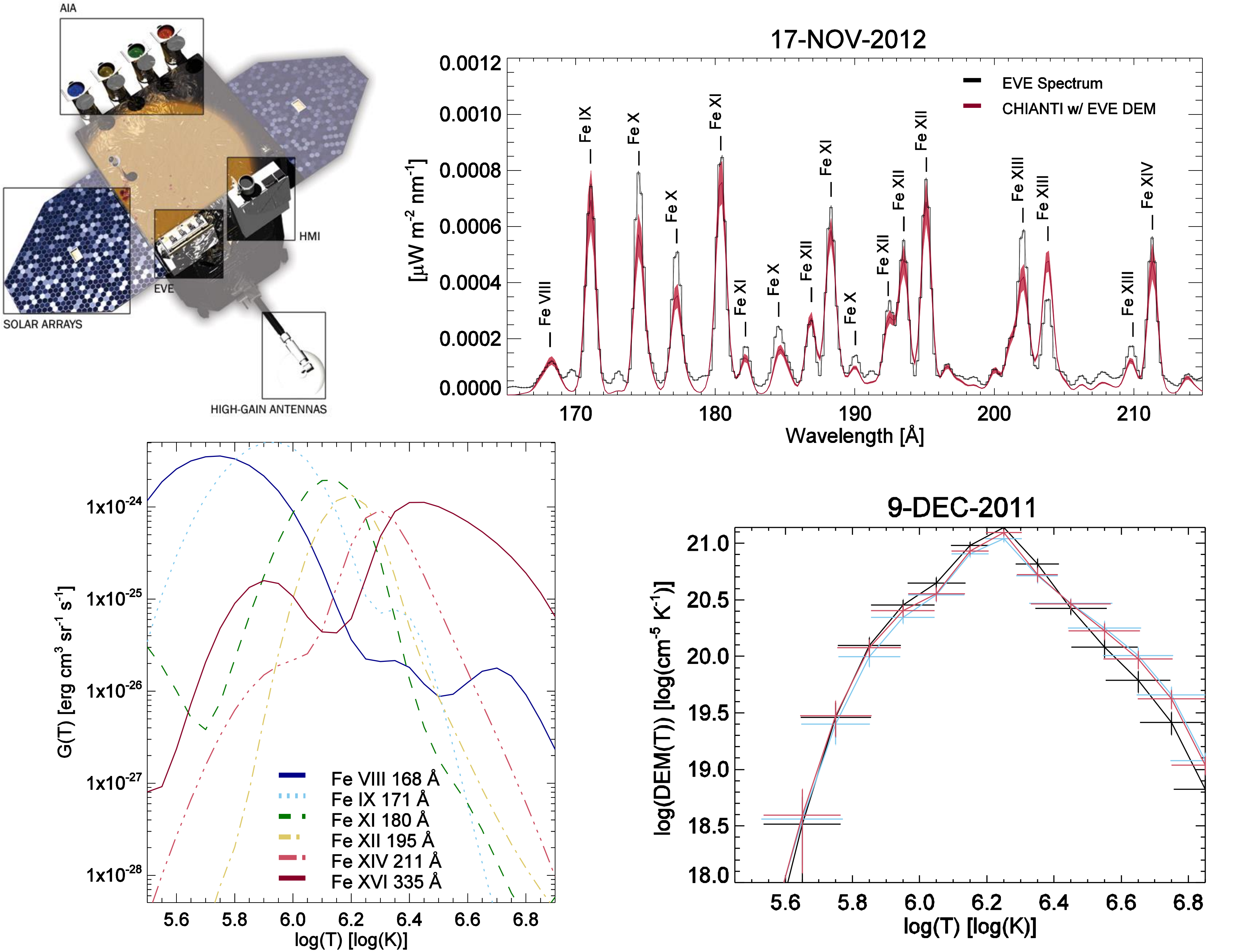
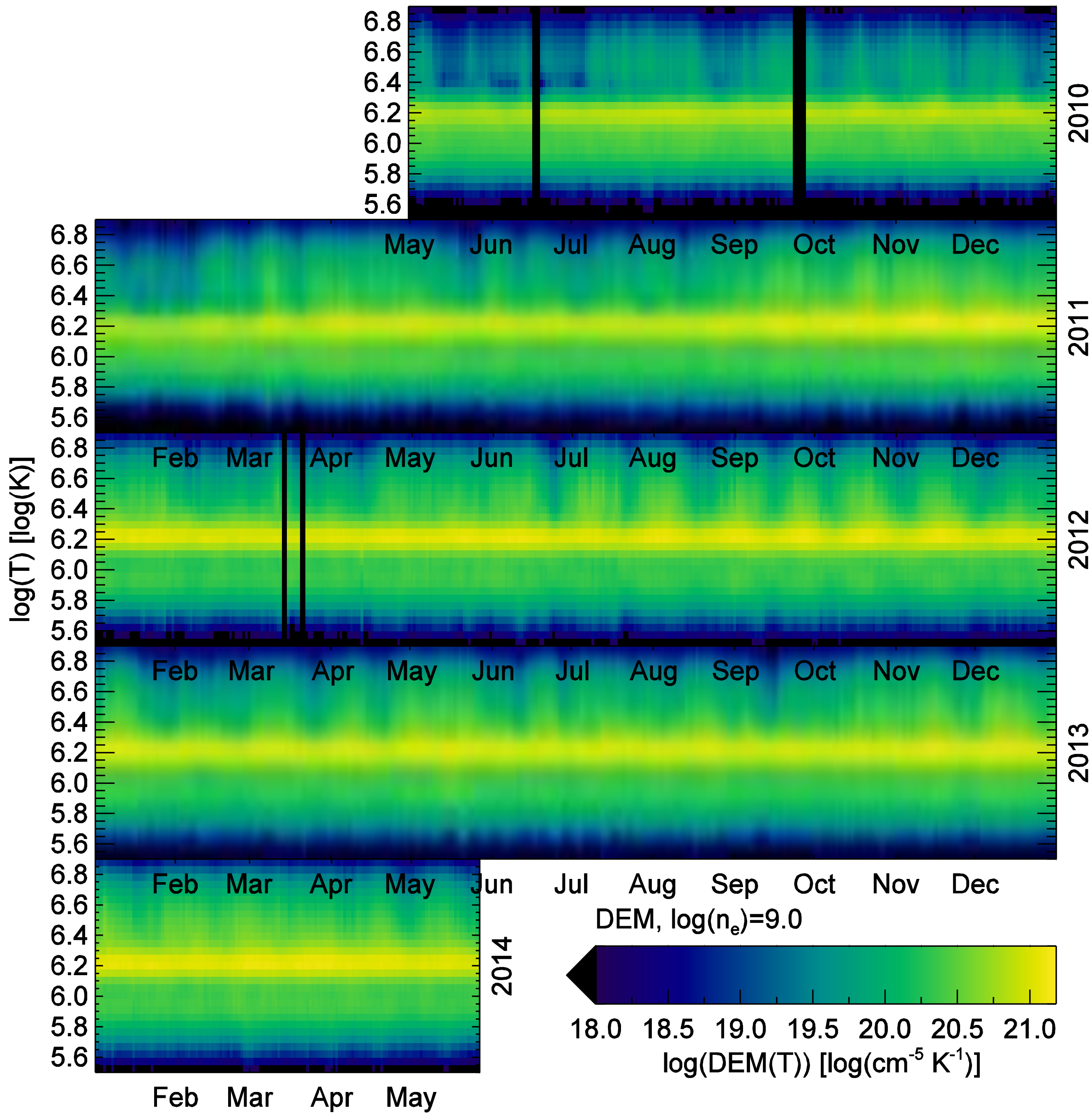
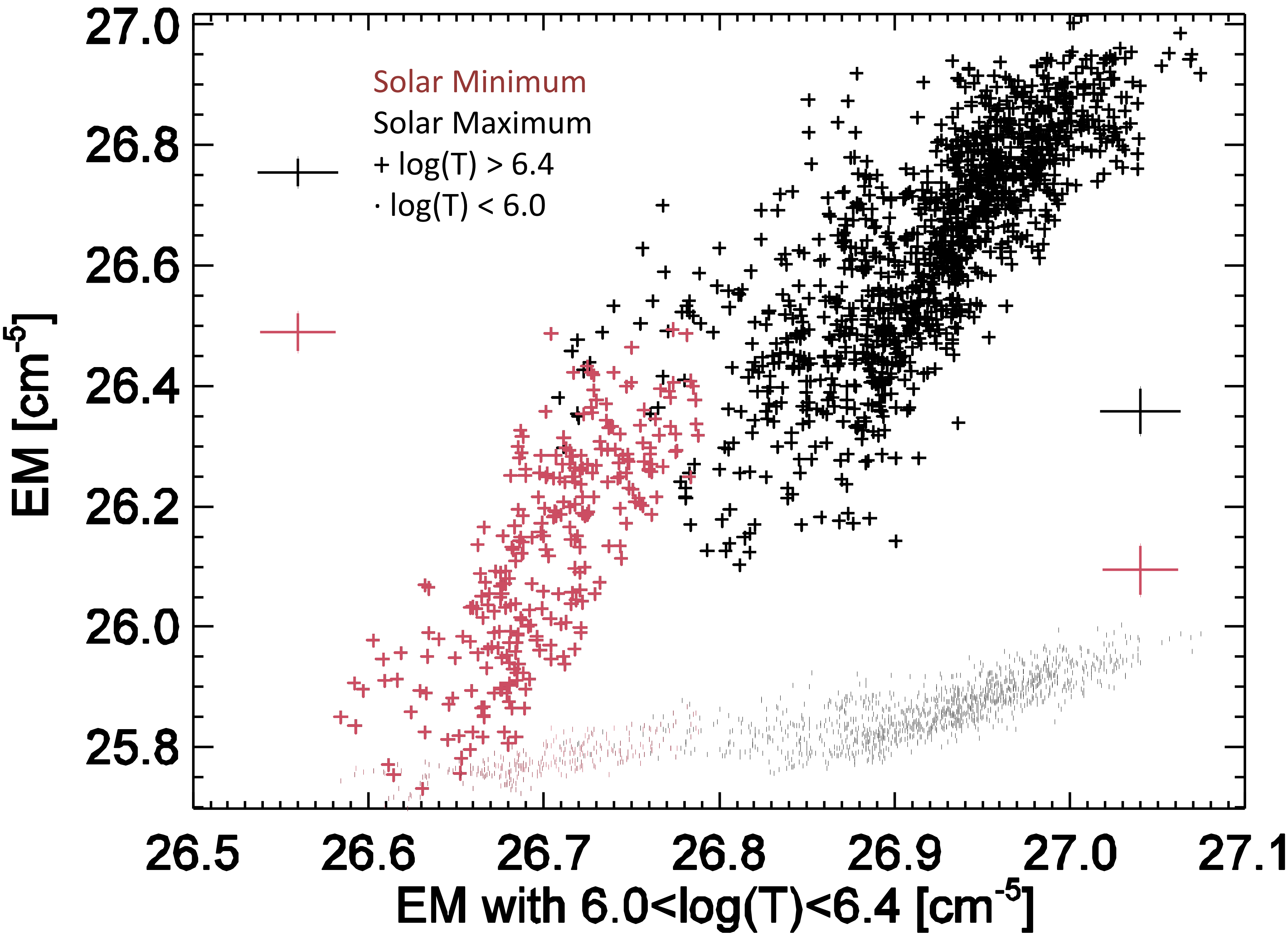
4th November, 2016


1996
2006
1997
2005
1998
2004
1999
2003
2001
2000
2002
ESA&NASA/SOHO

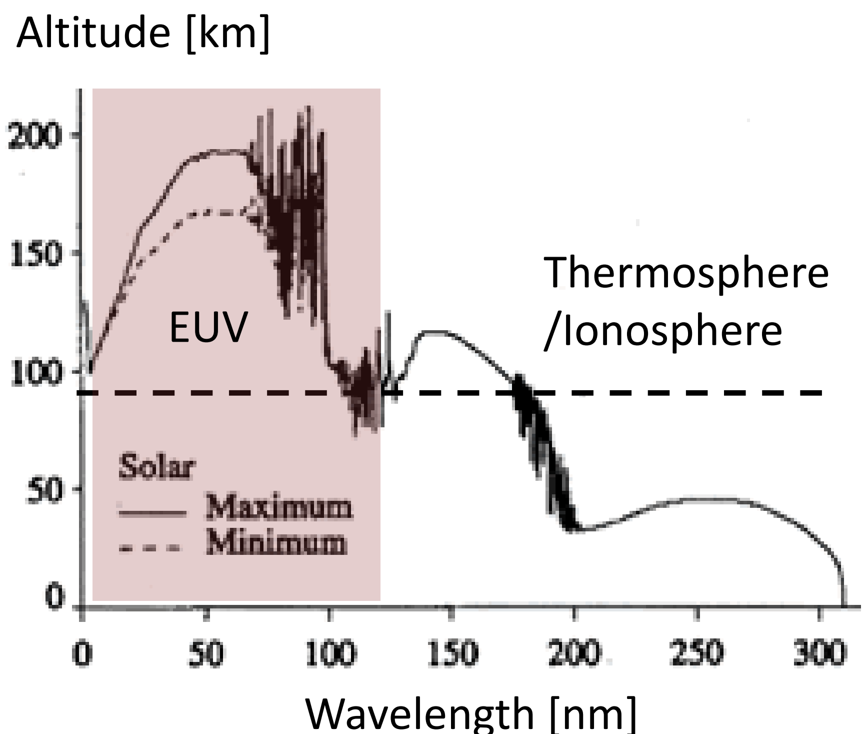

AIA
SOLAR ARRAYS
EVE
HMI
HIGH-GAIN ANTENNAS
17-NOV-2012
EVE Spectrum
CHIANTI w/ EVE DEM
[μW m^{-2} nm^{-1}]
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
Fe VIII
Fe IX
Fe X
Fe X
Fe XI
Fe XI
Fe X
Fe XII
Fe XI
Fe X
Fe XII
Fe XII
Fe XII
Fe XIII
Fe XIII
Fe XIII
Fe XIV
170
180
190
200
210
Wavelength [Å]
G(T) [erg cm^3 sr^{-1} s^{-1}]
1x10^{-24}
1x10^{-25}
1x10^{-26}
1x10^{-27}
1x10^{-28}
Fe VIII 168 Å
Fe IX 171 Å
Fe XI 180 Å
Fe XII 195 Å
Fe XIV 211 Å
Fe XVI 335 Å
5.6
5.8
6.0
6.2
6.4
6.6
6.8
log(T) [log(K)]
9-DEC-2011
log(DEM(T)) [log(cm^{-5} K^{-1})]
21.0
20.5
20.0
19.5
19.0
18.5
18.0
5.6
5.8
6.0
6.2
6.4
6.6
6.8
log(T) [log(K)]



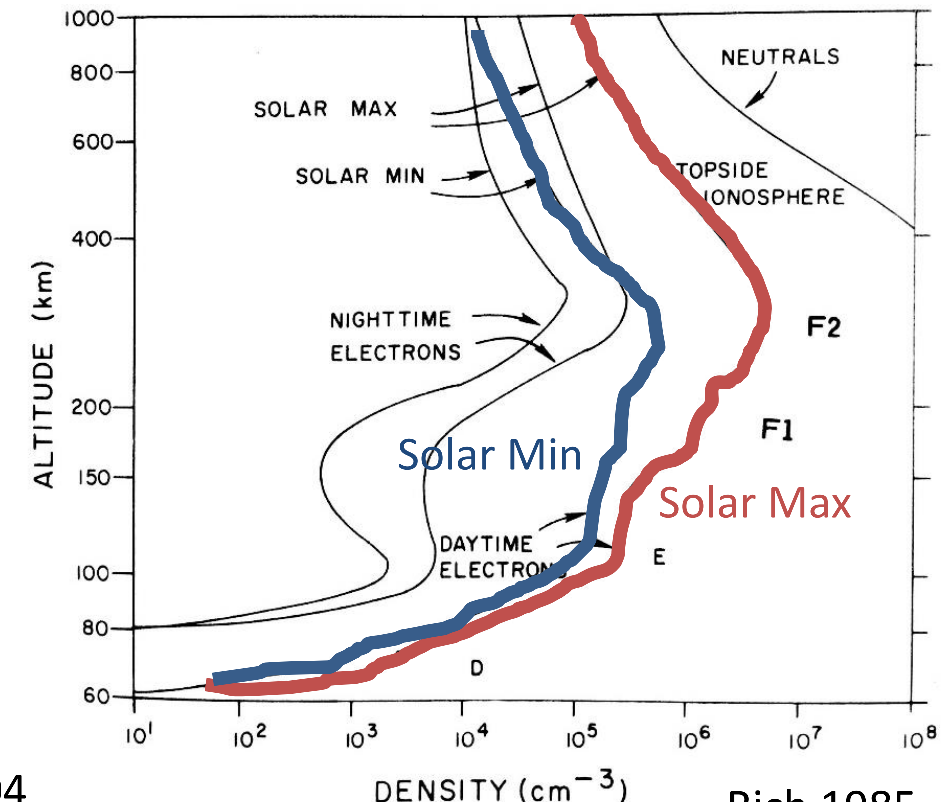
log(T) [log(K)]
6.8
6.6
6.4
6.2
6.0
5.8
5.6
2010
2011
2012
2013
2014
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
DEM, log(n_e)=9.0
18.0
18.5
19.0
19.5
20.0
20.5
21.0
log(DEM(T)) [log(cm^-5 K^-1)]



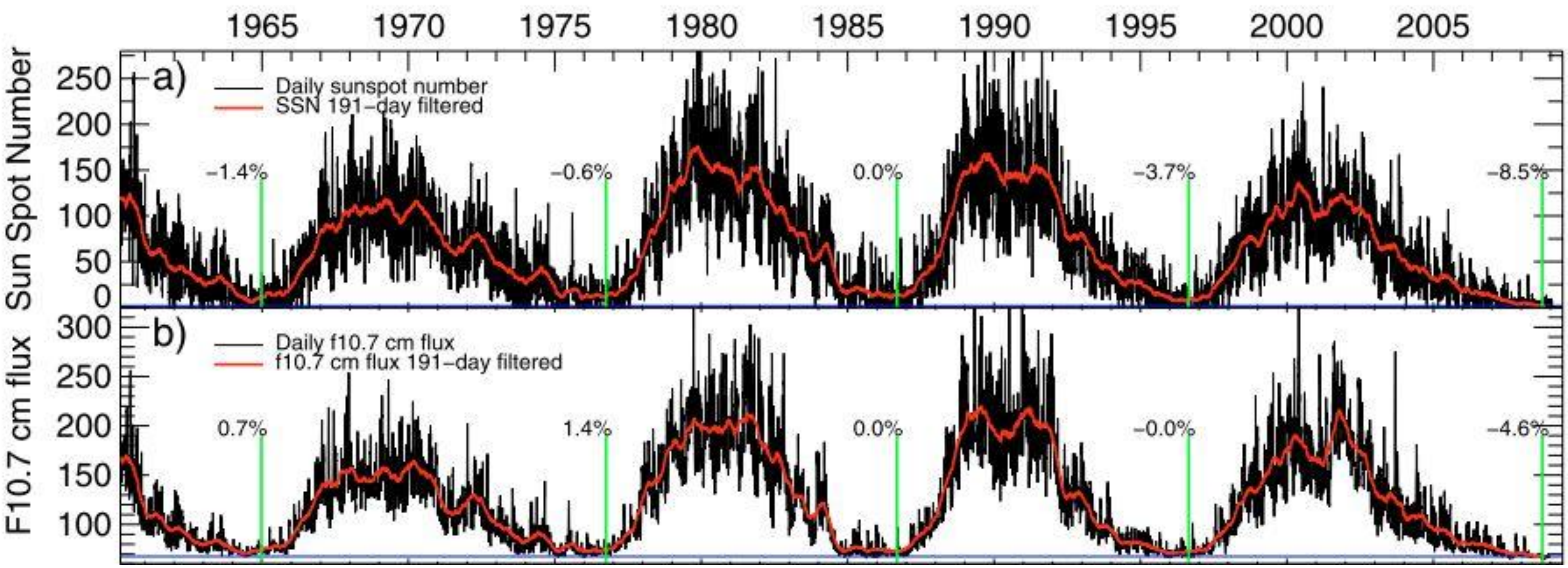
Solar Minimum
Solar Maximum
+ log(T) > 6.4
· log(T) < 6.0
EM [cm-5]
EM with 6.0<log(T)<6.4 [cm-5]
27.0
26.8
26.6
26.4
26.2
26.0
25.8
26.5
26.6
26.7
26.8
26.9
27.0
27.1



Haigh 2004

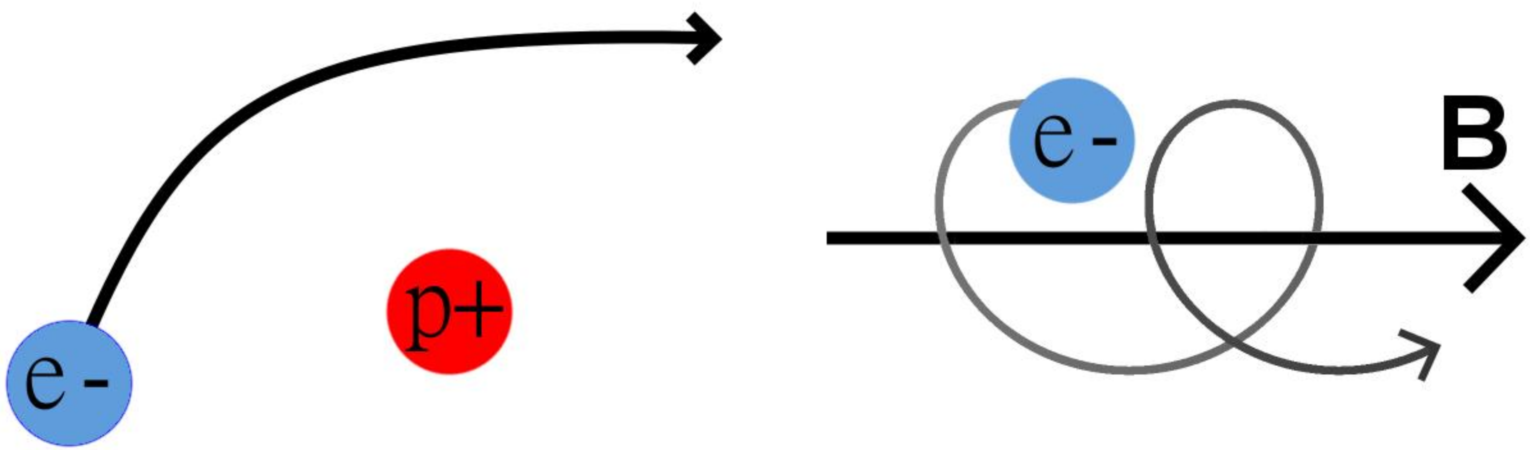


Rich 1985



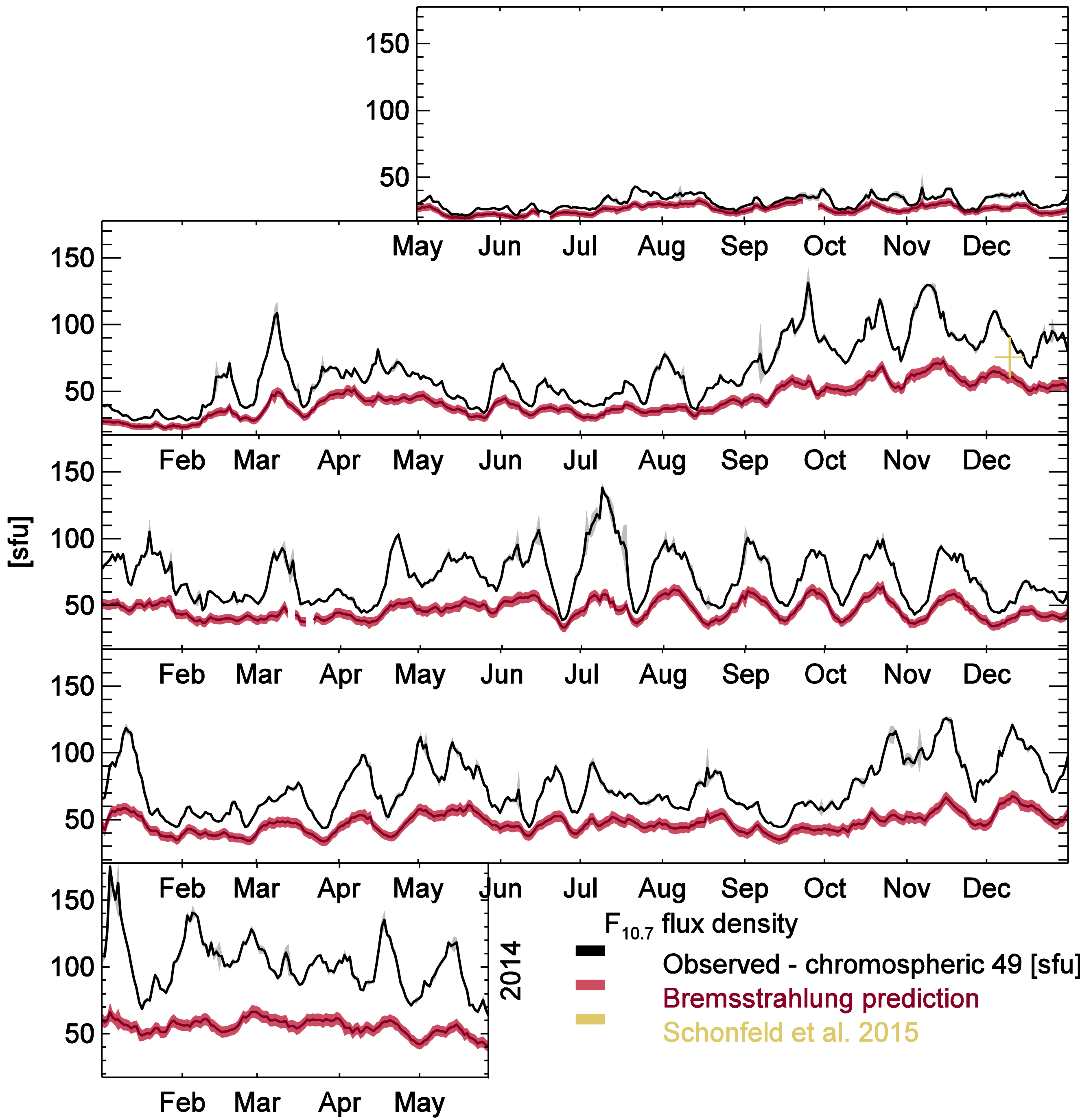
1 sfu = 10^4 Jy = 10^{-19} erg cm^{-2} s^{-1} Hz^{-1}

Fröhlich 2009

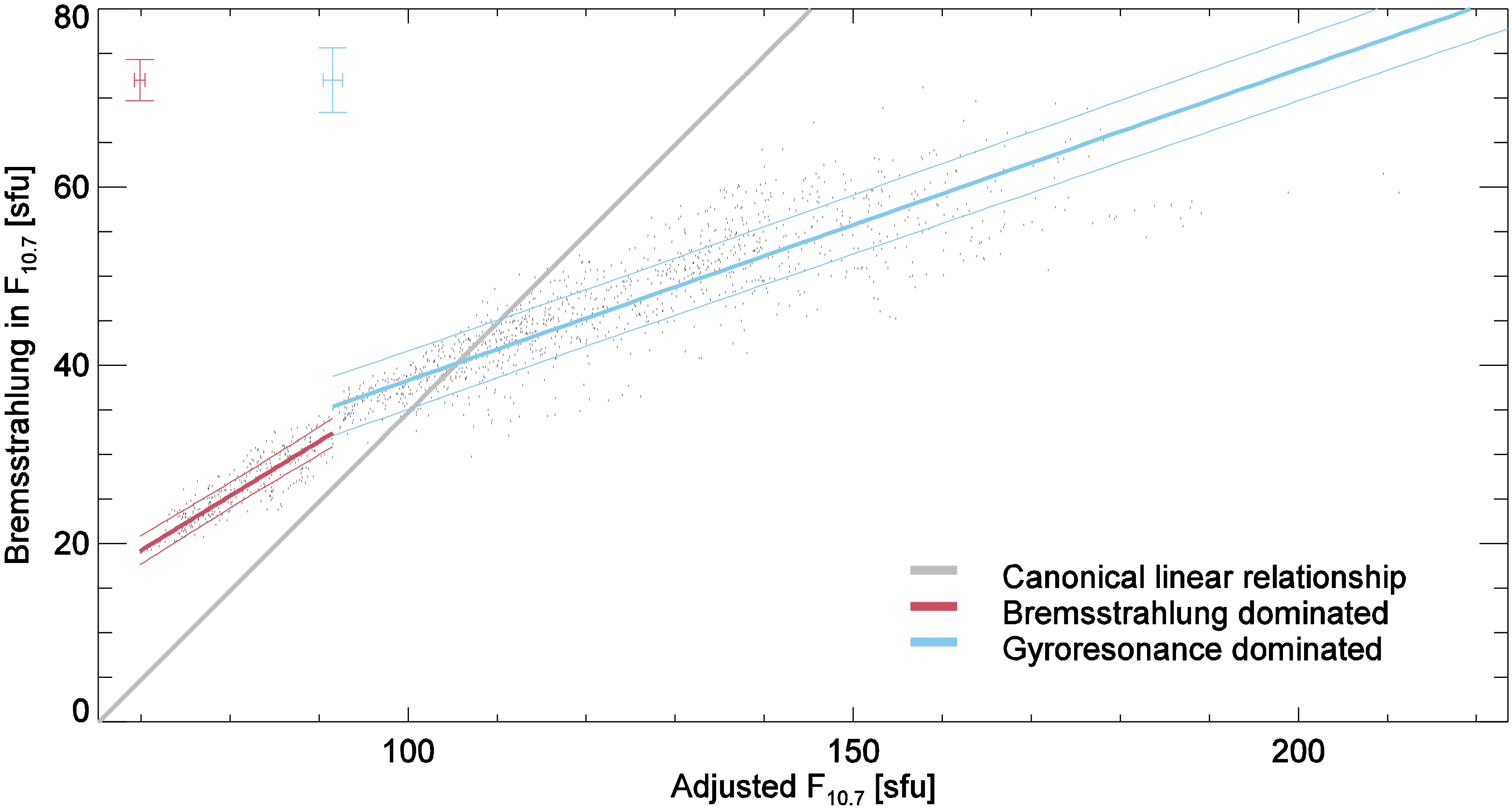


Bremsstrahlung

Gyroresonance



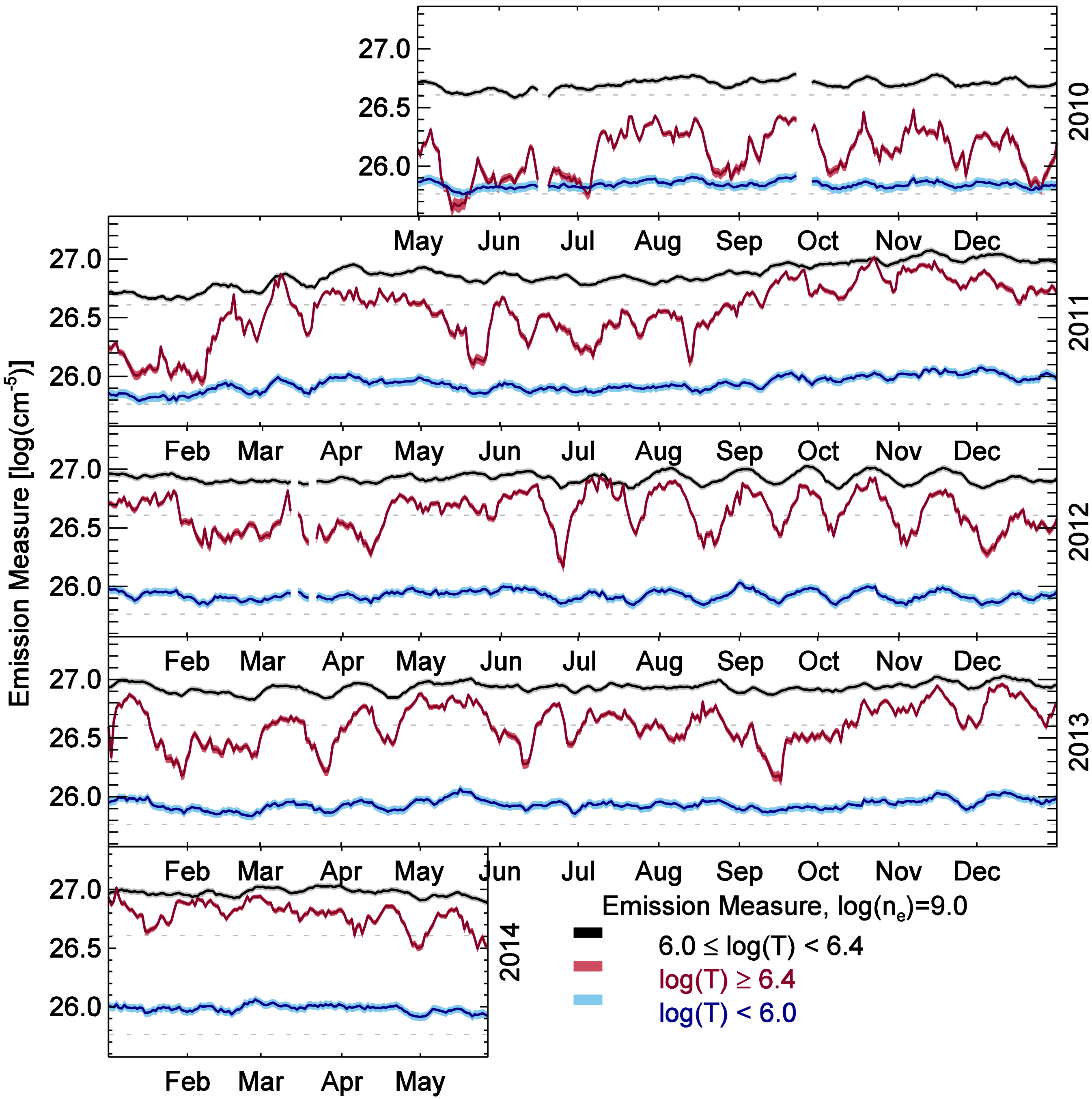
150
100
50
2010
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2011
Feb
Mar
Apr
2012
2013
2014
[sfu]
F10.7 flux density
Observed - chromospheric 49 [sfu]
Bremsstrahlung prediction
Schonfeld et al. 2015


80
60
40
20
0
100
150
200
Bremsstrahlung in F10.7 [sfu]
Adjusted F10.7 [sfu]
Canonical linear relationship
Bremsstrahlung dominated
Gyroresonance dominated

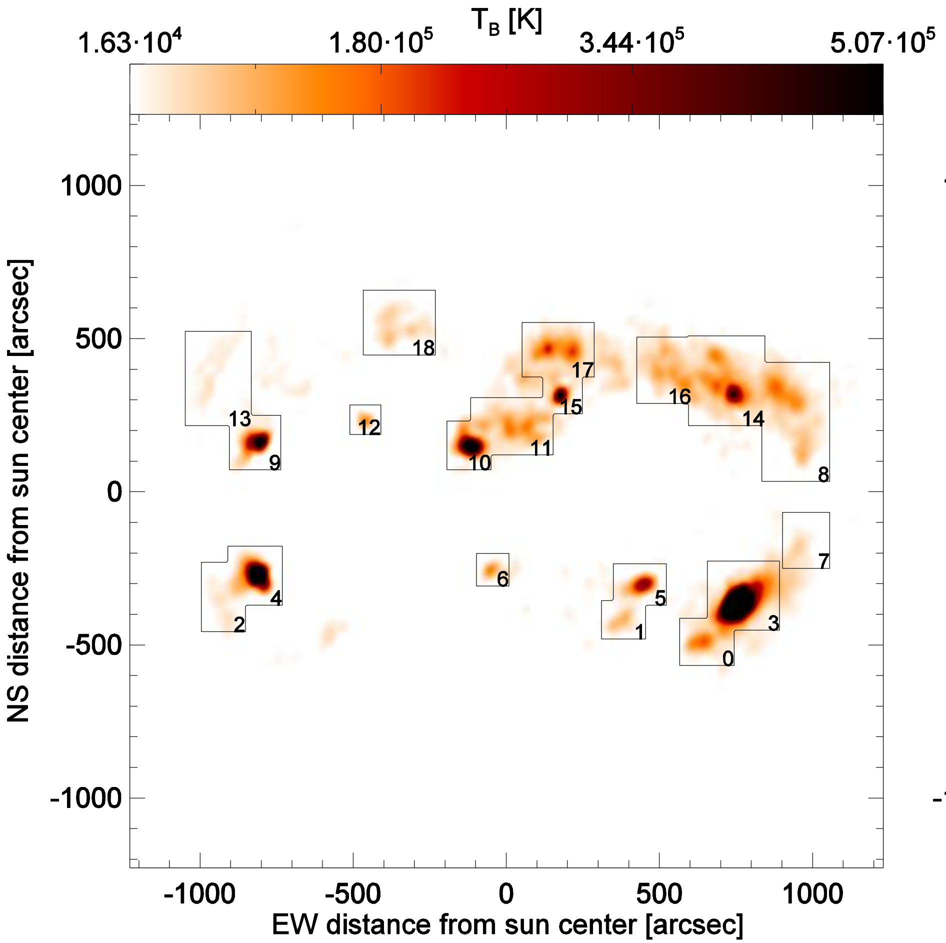
Conclusion

- Coronal plasma variation over the solar cycle
  - Discontinuity between solar minimum and maximum
- $F_{10.7}$ reproduction
  - Time variable contribution from gyroresonance and bremsstrahlung emission
  - Non-linear relationship between EUV and $F_{10.7}$
- Future
  - Compare with and correct ionospheric model input

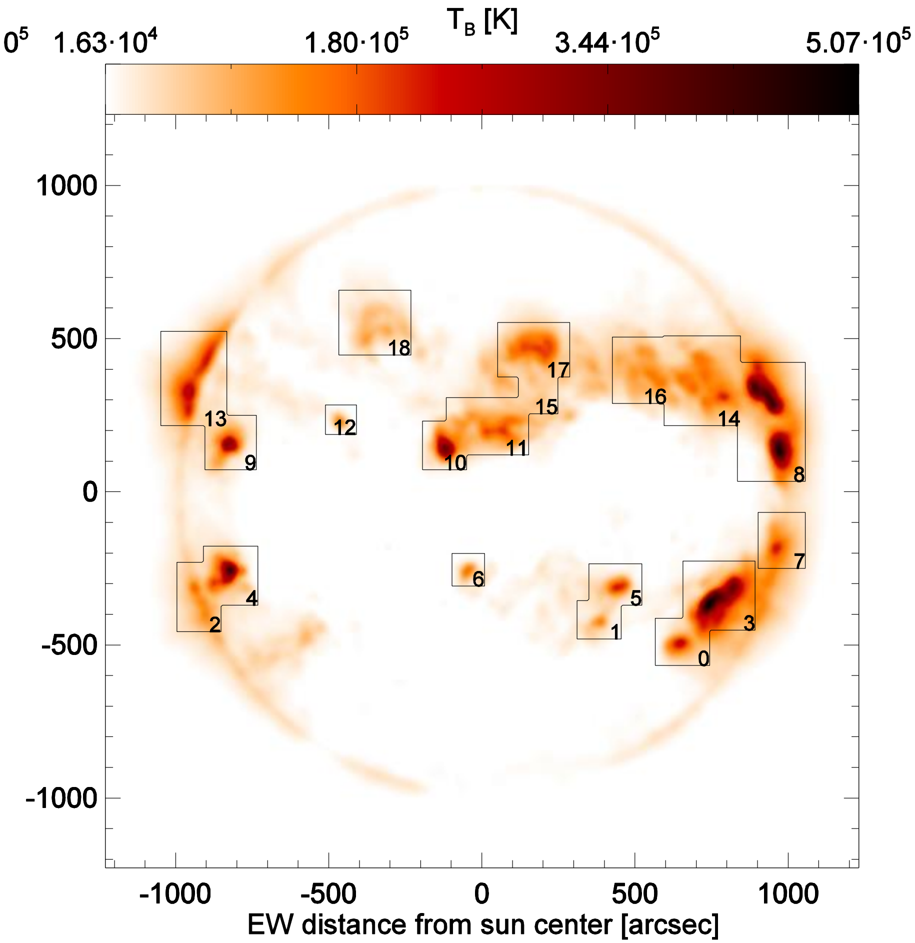

Thank You


Emission Measure [log(cm^{-5})]
27.0
26.5
26.0
May Jun Jul Aug Sep Oct Nov Dec
Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2010
2011
2012
2013
2014
Emission Measure, log(n_e)=9.0
$6.0 \leq \log(T) < 6.4$
$\log(T) \geq 6.4$
$\log(T) < 6.0$

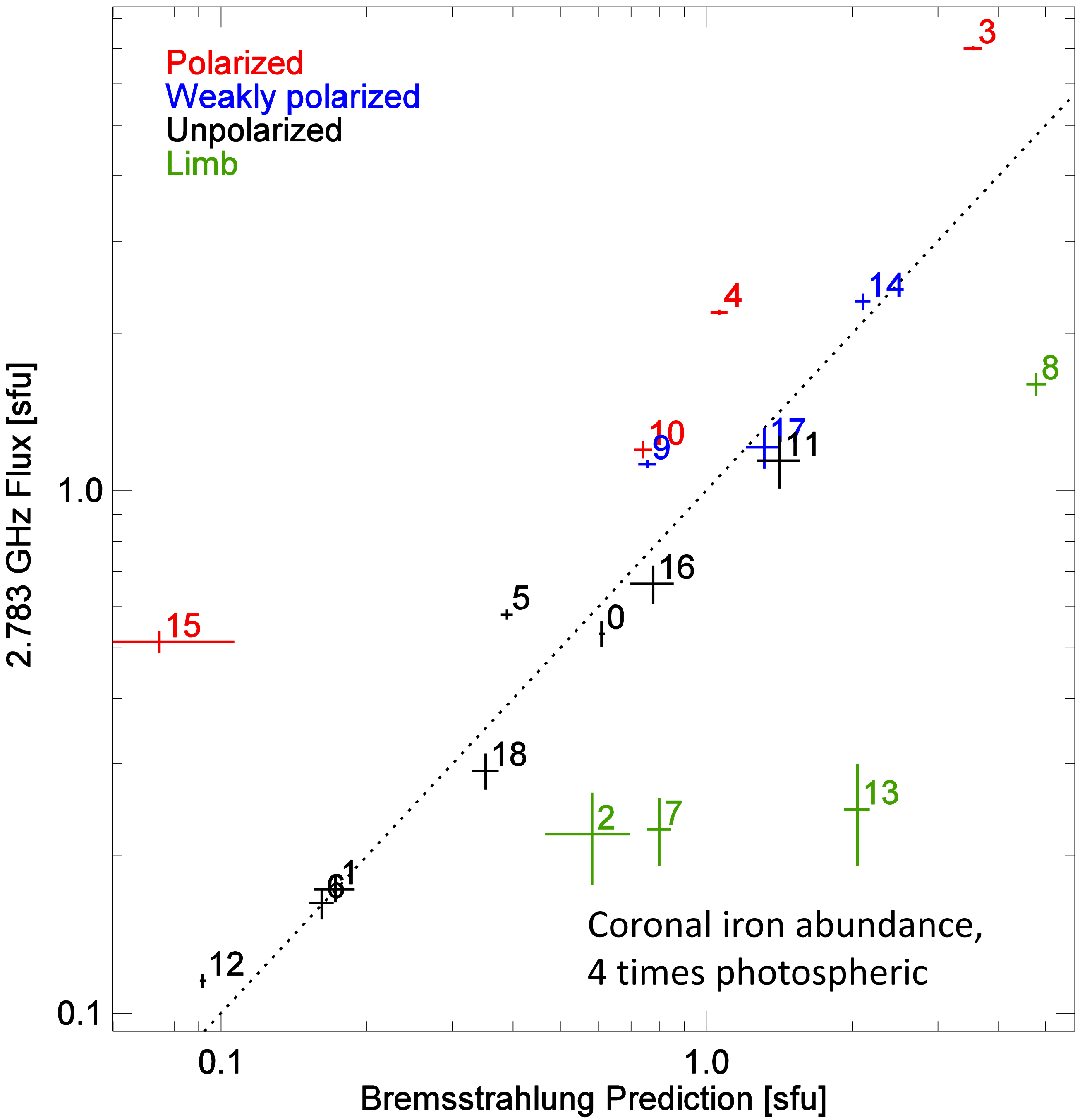
Predicted Radio Bremsstrahlung

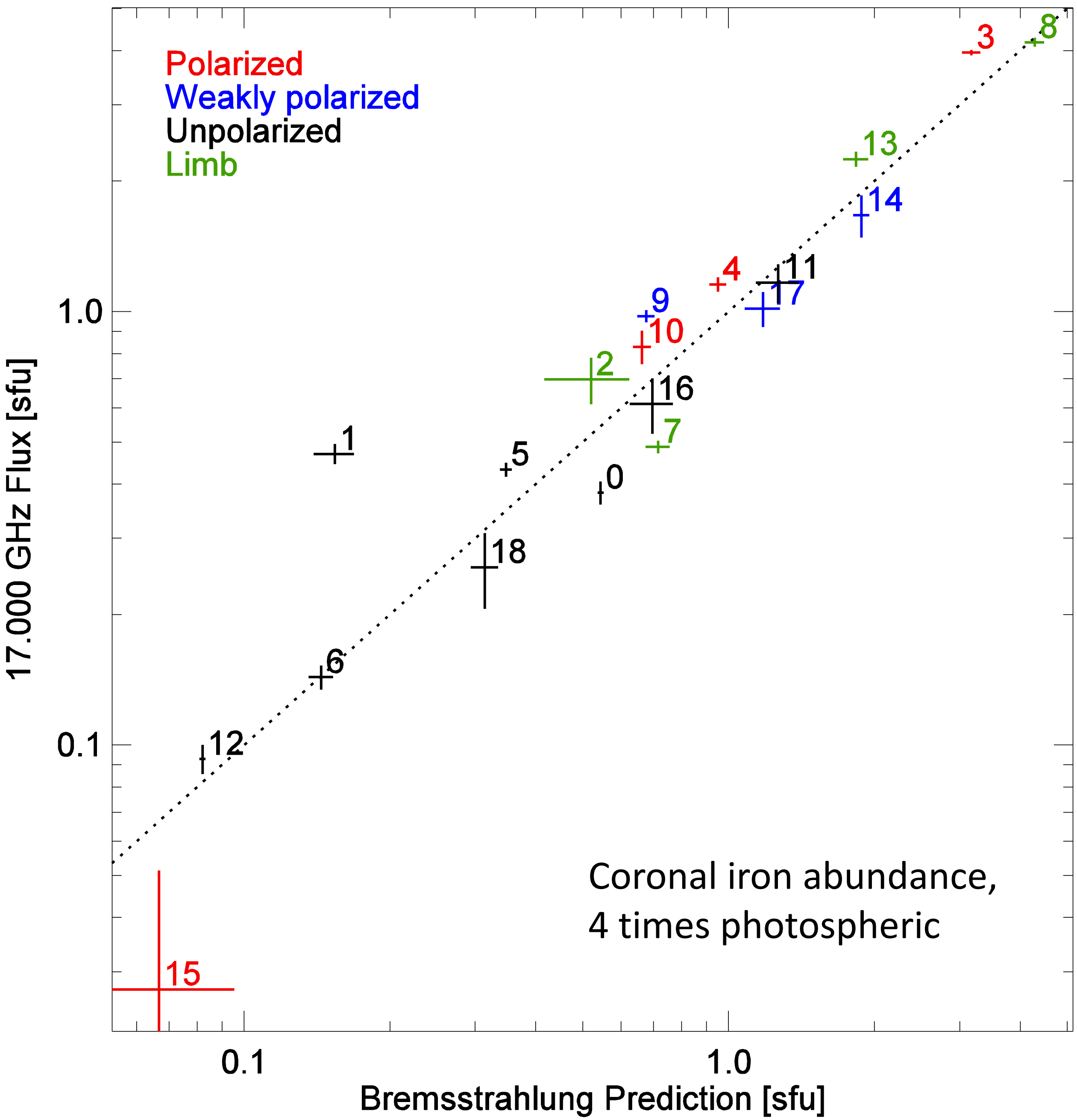


10.7 cm observation

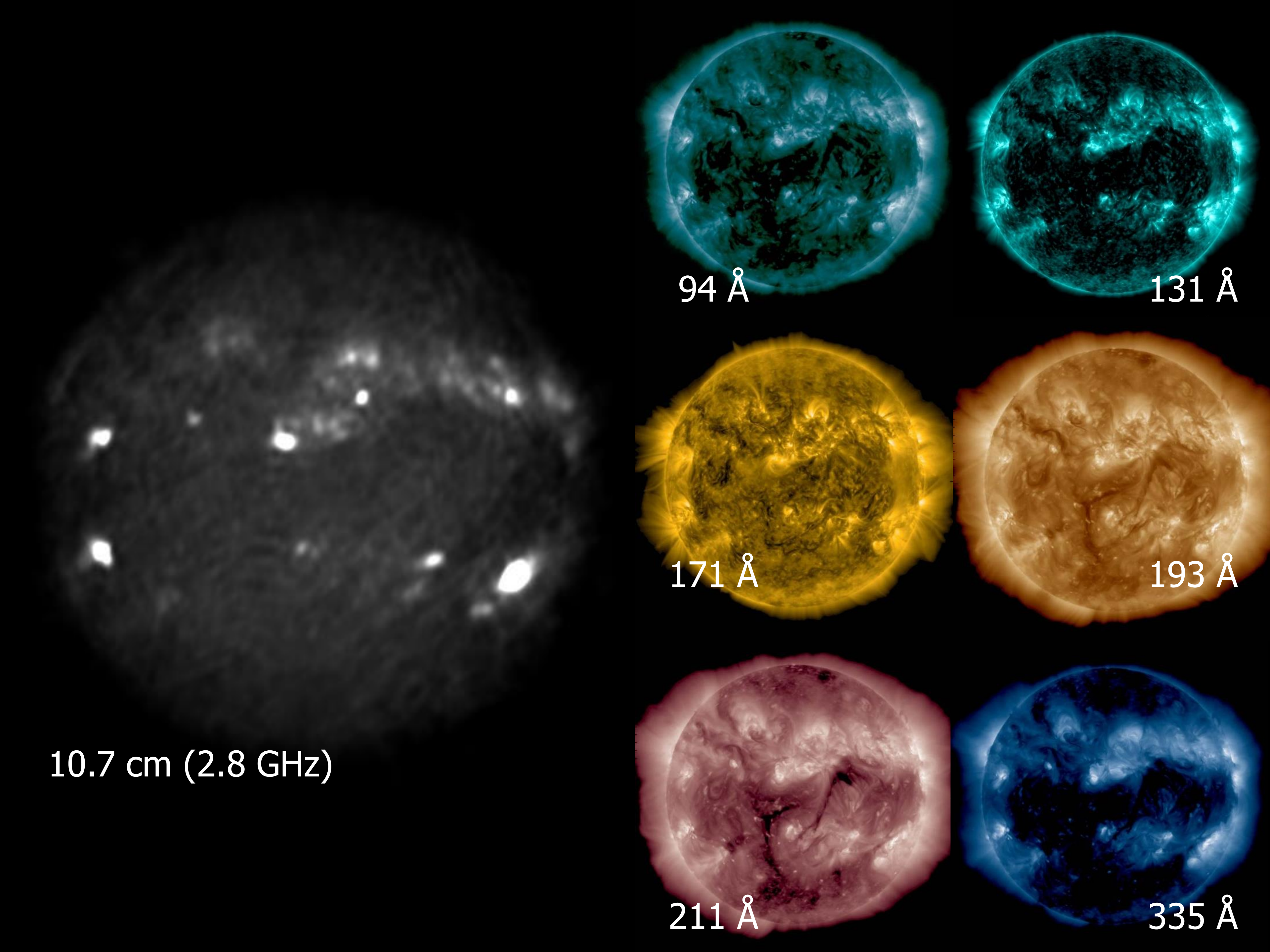


Bremsstrahlung prediction


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

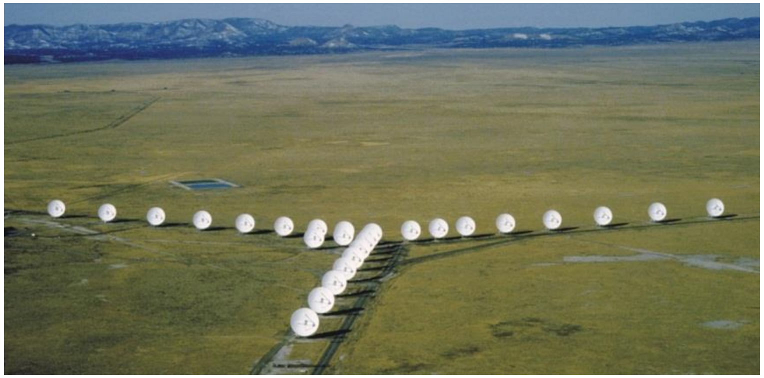


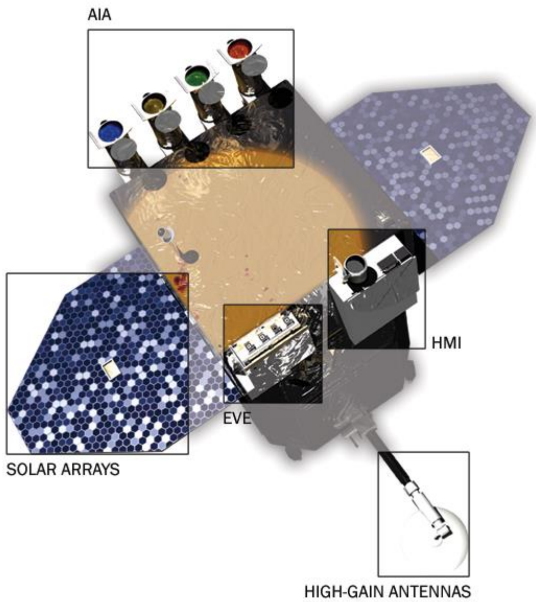
Polarized
Weakly polarized
Unpolarized
Limb
Coronal iron abundance,
4 times photospheric
17.000 GHz Flux [sfu]
Bremsstrahlung Prediction [sfu]
1.0
0.1
0.1
1.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18


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

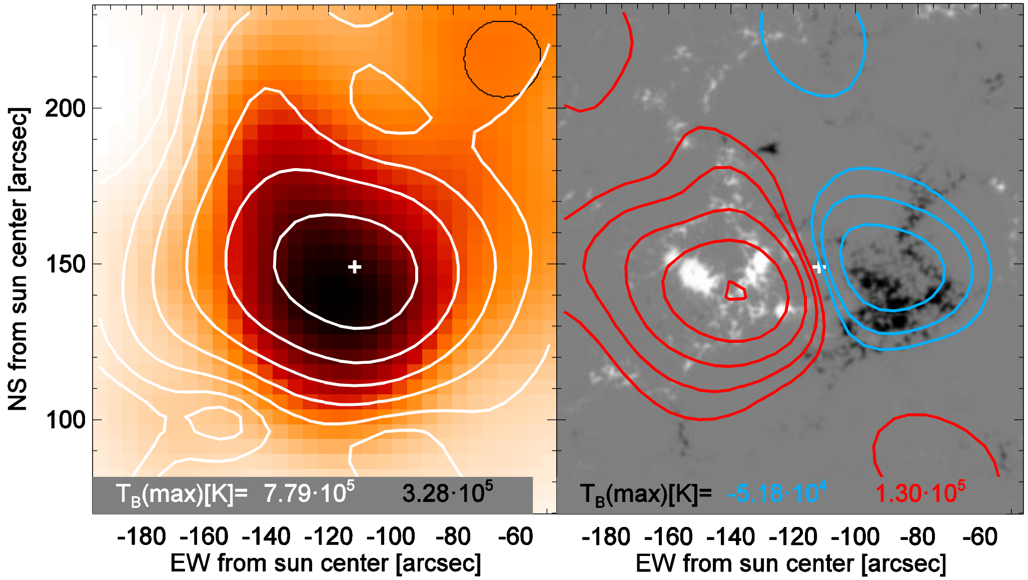
Observations

- 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





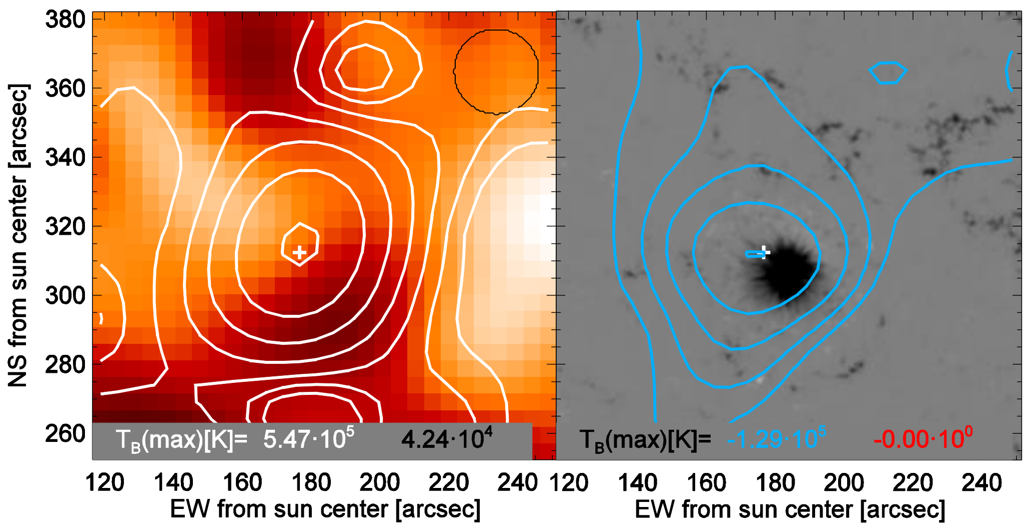
Strongly Polarized Regions



Region 10

Left:
Image = bremsstrahlung
Contours = radio intensity

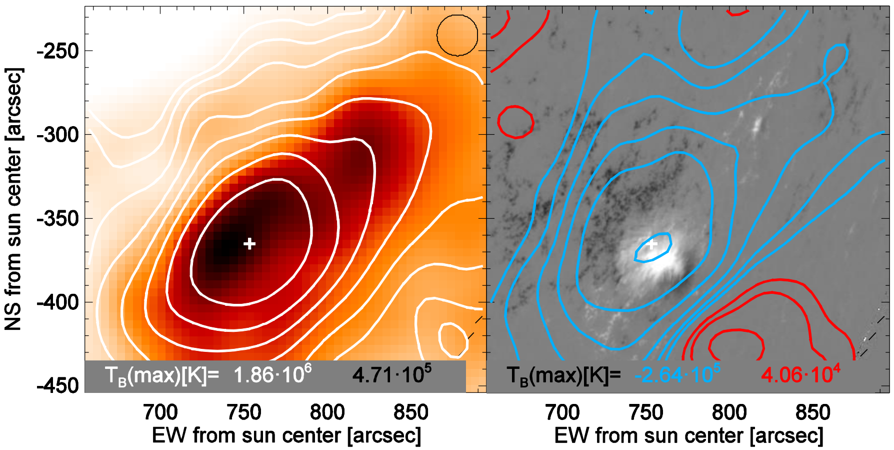
Right:
Grayscale = photospheric magnetic field
Contours = radio circular polarization



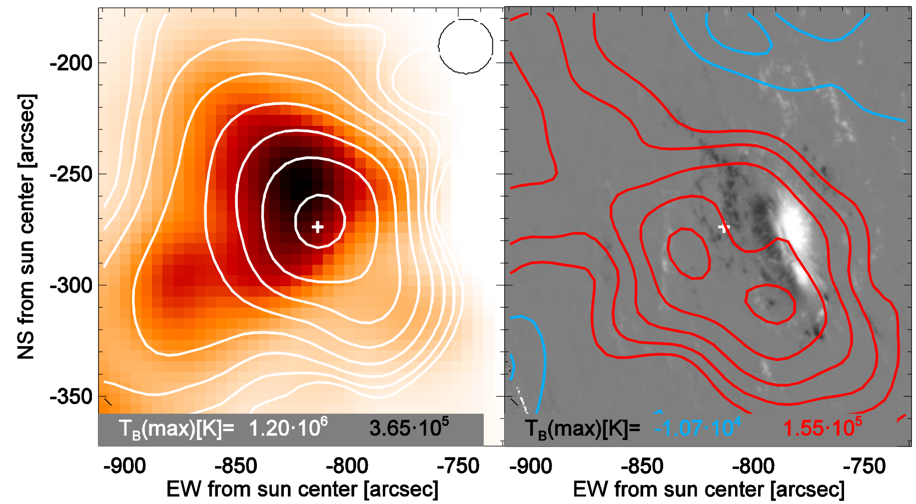
Region 15

Strong Polarization Examples

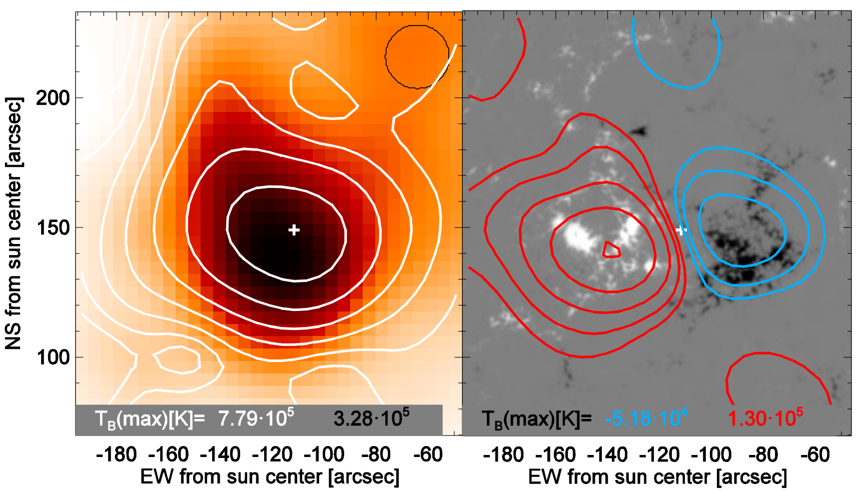
Region 3



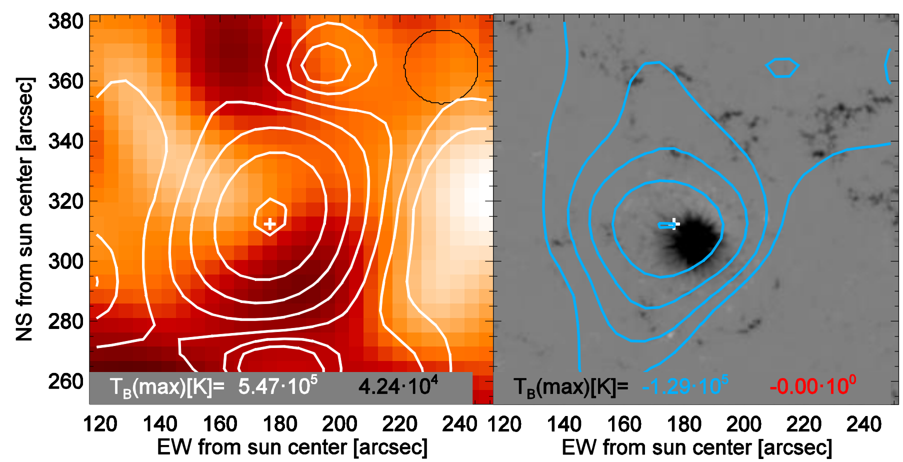
Region 4



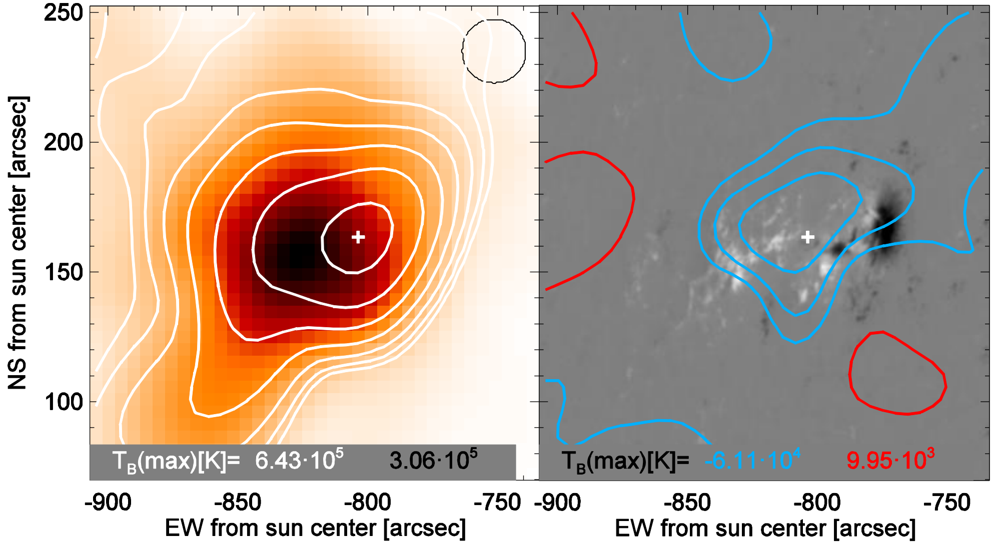
Region 10



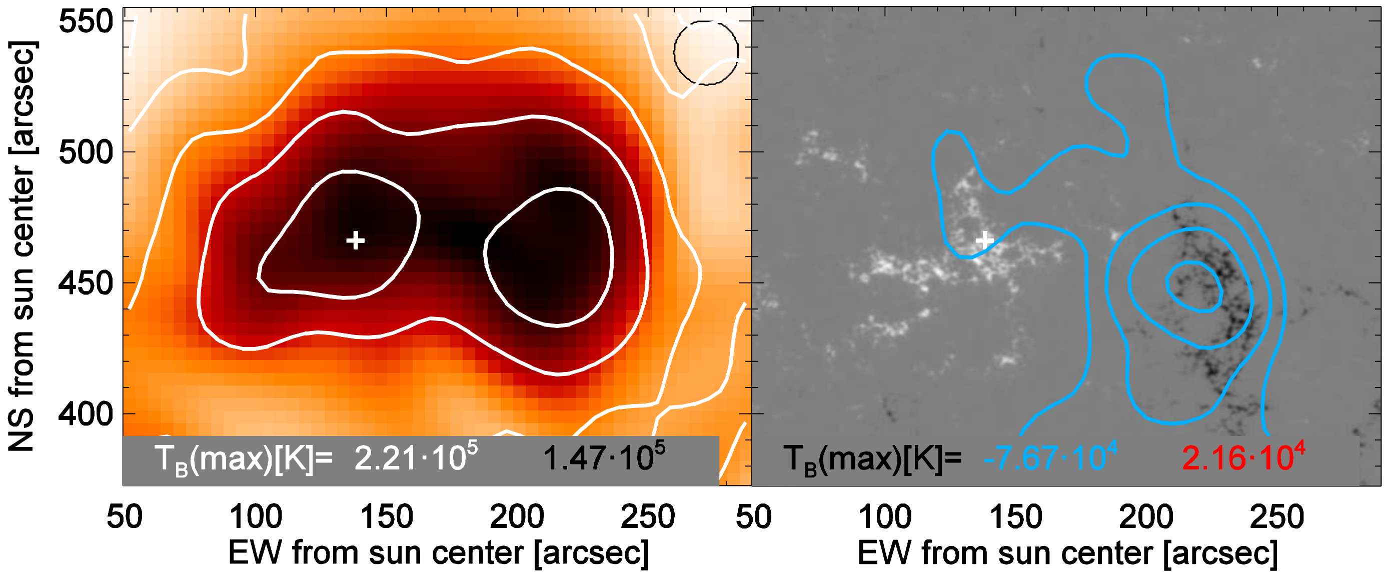
Region 15



Weak Polarization Examples



Region 9

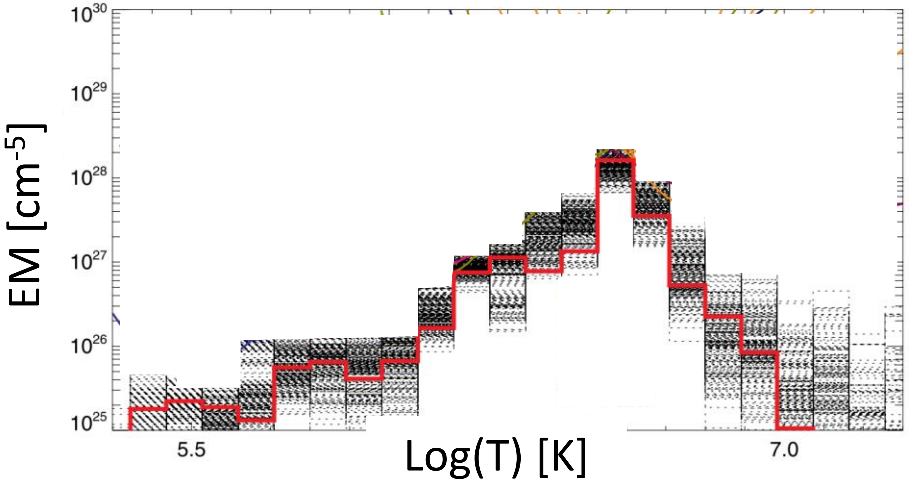


Region 17

Differential Emission Measure

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

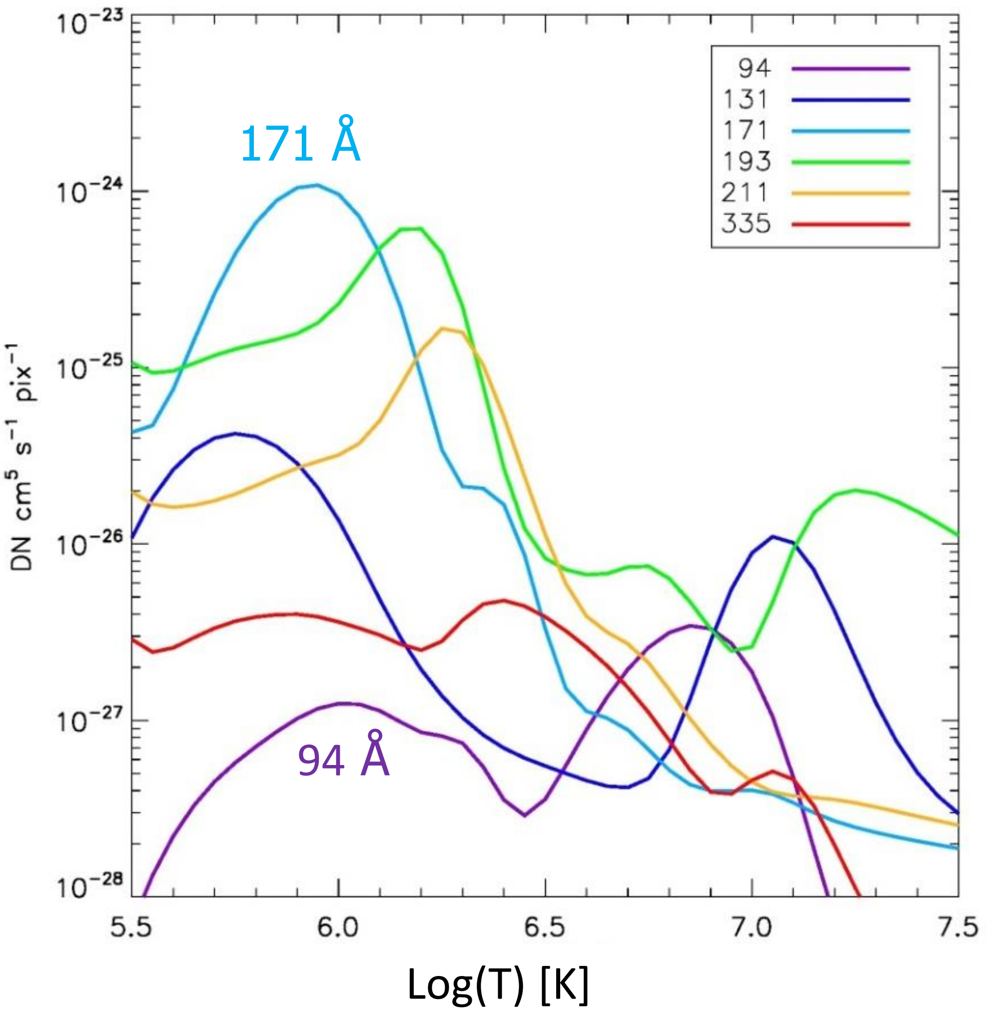
Warren, Brooks, and Winebarger 2011



1: Calculating the DEM

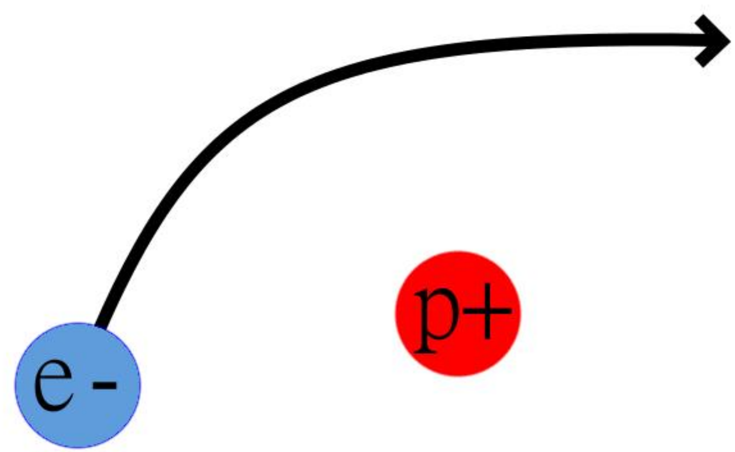
$$Flux_i = \sum Resp_i(T) \times DEM(T) \times \Delta T$$

- 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

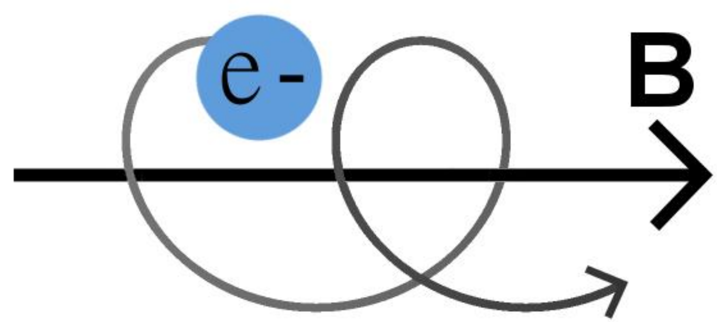


$F_{10.7}$ Generation Mechanisms

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



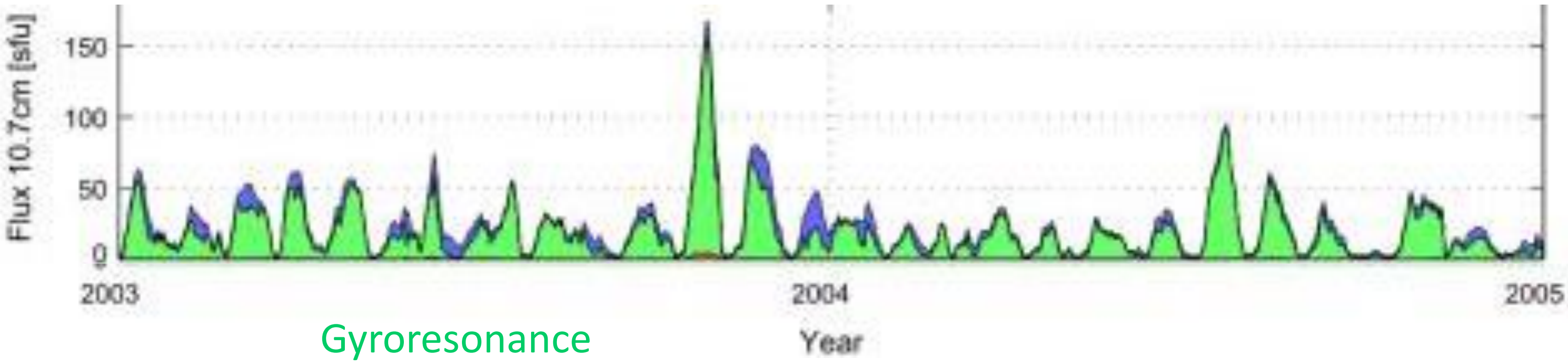
- Gyroresonance
  - Active region cores
  - Electrons spiraling around magnetic fields
  - Circularly polarized
  - Traces magnetic field



The Mechanism Matters

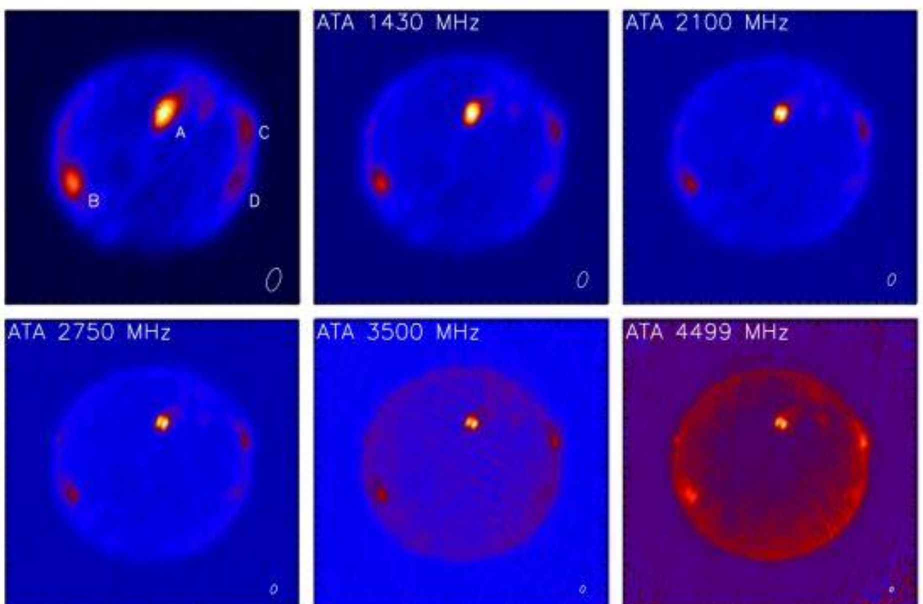
- Bremsstrahlung is generated by collisions
  - Collisionally excited atomic emission lines emit EUV
- Gyroresonance results from magnetic fields
  - No magnetically driven emission in EUV
- **Gyroresonance is a contaminant when $F_{10.7}$ is used as an EUV proxy**
  - $F_{10.7}$ is a direct input to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

Recent Studies



Gyroresonance
Bremsstrahlung

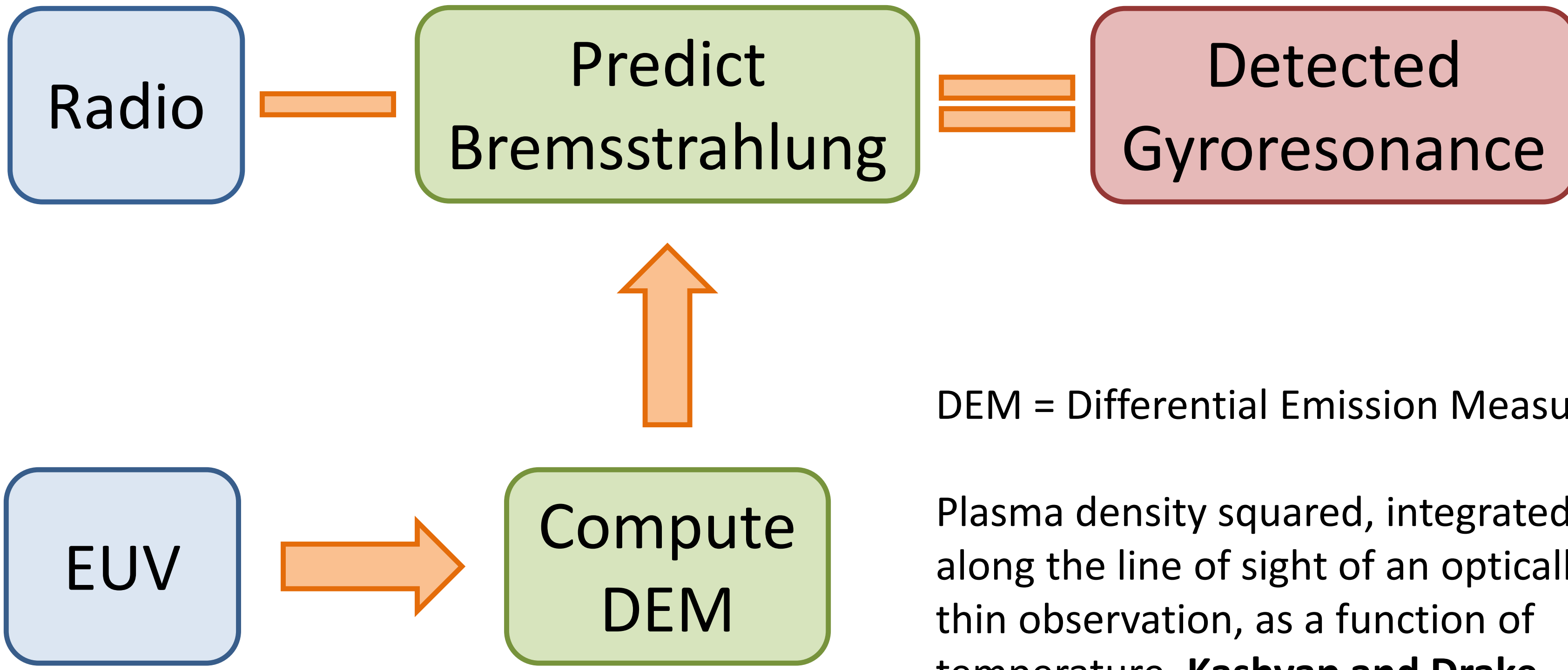
Dudok de Wit, Bruinsma, Shibasaki 2014



- 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.