The Martian Ionosphere over a full Solar Cycle as Observed by the Mars Express Radio Science Experiment MaRS

Martin Pätzold, Kerstin Peter, Michael K. Bird, Silvia Tellmann
RIU-Planetary Research at Universität zu Köln, Cologne, Germany

Bernd Häusler
Institute for Spaceflight Engineering and Space Applications
University of the German Armed Forces Munich
Neubiberg, Germany

Introduction

- Mars Express Radio Science MaRS:
  - operational since early 2004 (declining phase of solar cycle 23)
  - occultation experiment for the radio sounding of the neutral atmosphere (see poster by Tellmann et al.) and the ionosphere
  - occultations occur in „seasons“; not all seasons can be observed because of s/c power constraints (eclipses) or because of coinciding with solar conjunctions
  - radio sounding of the ionosphere at two frequencies (S-band and X-band); of HIGH ADVANTAGE for the derivation of the TRUE vertical electron density profile
  - about 900 electron density profiles were observed from 2004 to 2017 at SZA > 50°

Introduction; solar cycles

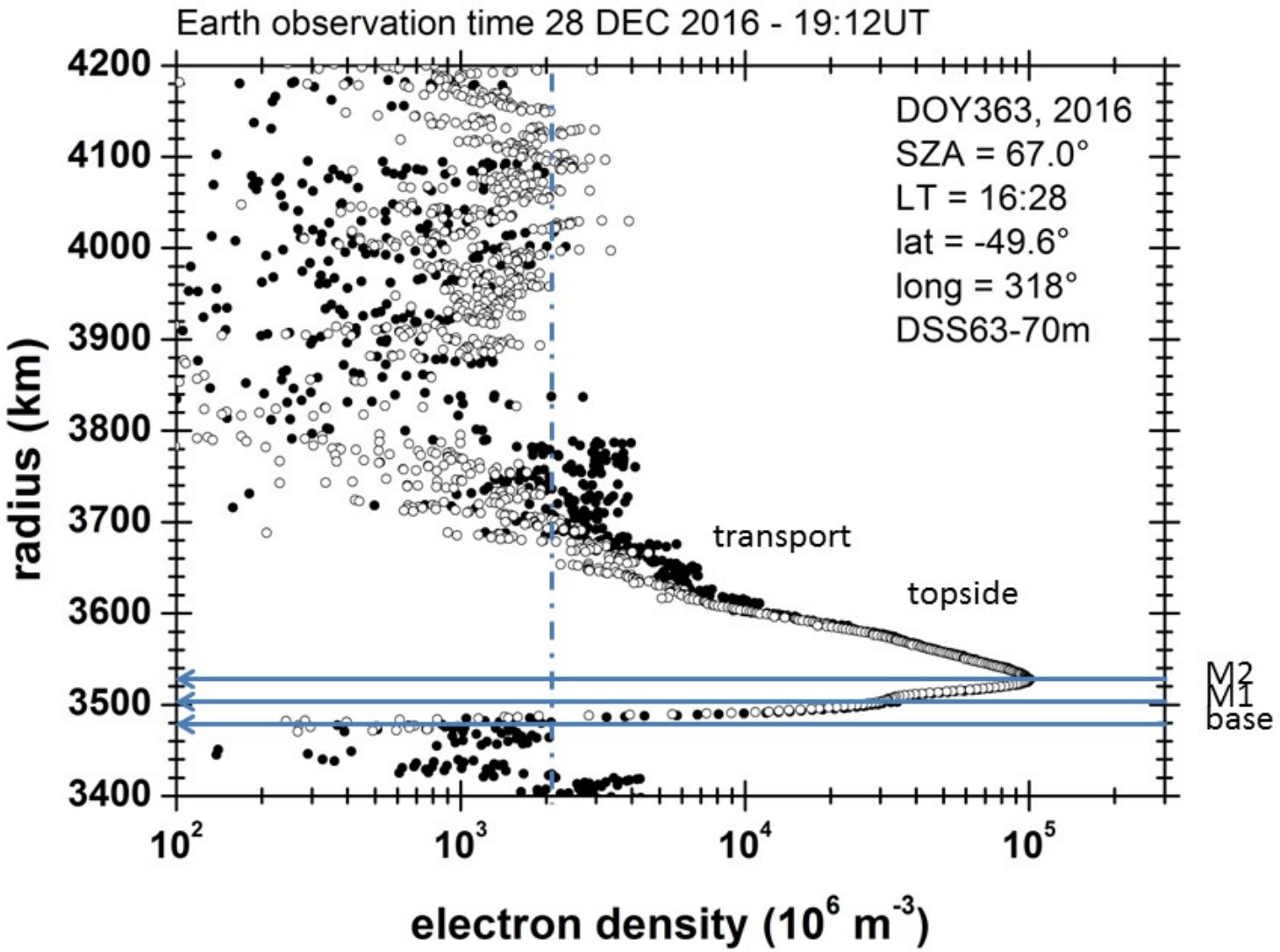
- solar cycle 23: average activity
  - start August 1996
  - end December 2008
  - duration 12.3 years
  - maximum sunspot count November 2001

- solar cycle 24: weak activity and probably short duration (10 years?)
  - start December 2008
  - end… today? ☺ March 2018 lowest sunspot number since 2008

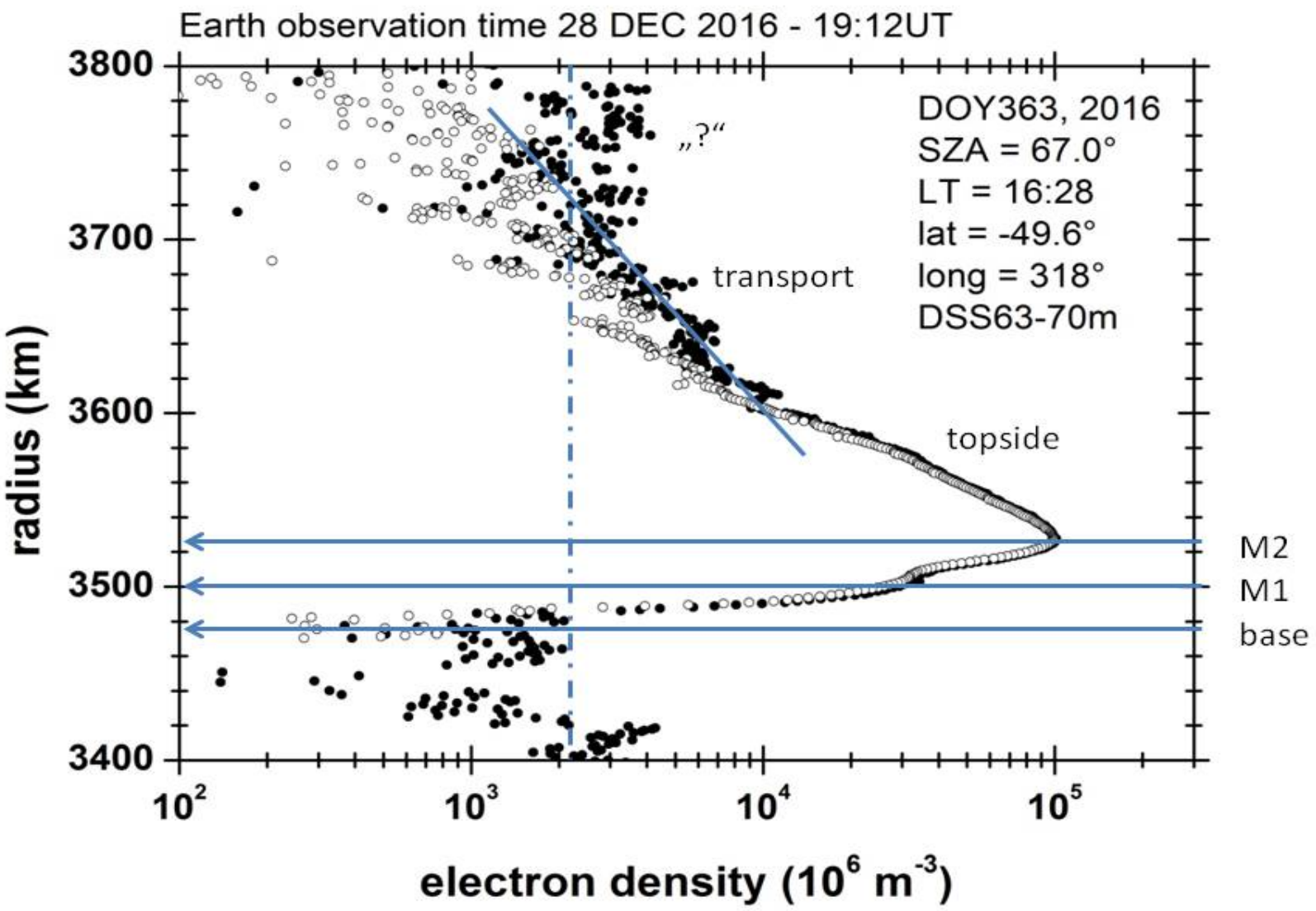
Introduction; solar flux

- two-layer daytime structure of the lower ionosphere
- formation of the day-time ionosphere by photoionisation
  - controlled by the solar flux
  - main layer M2 formed almost exclusively by solar EUV
  - lower layer M1 formed by solar X-ray and secondary ionisation
  - additional electron density below M1 (merged layers; ex meteor layers…) probably caused by enhanced X-ray photoionisation of NO2 (see talk by Peter et al.)
  - ionopause not always identified because of noise level

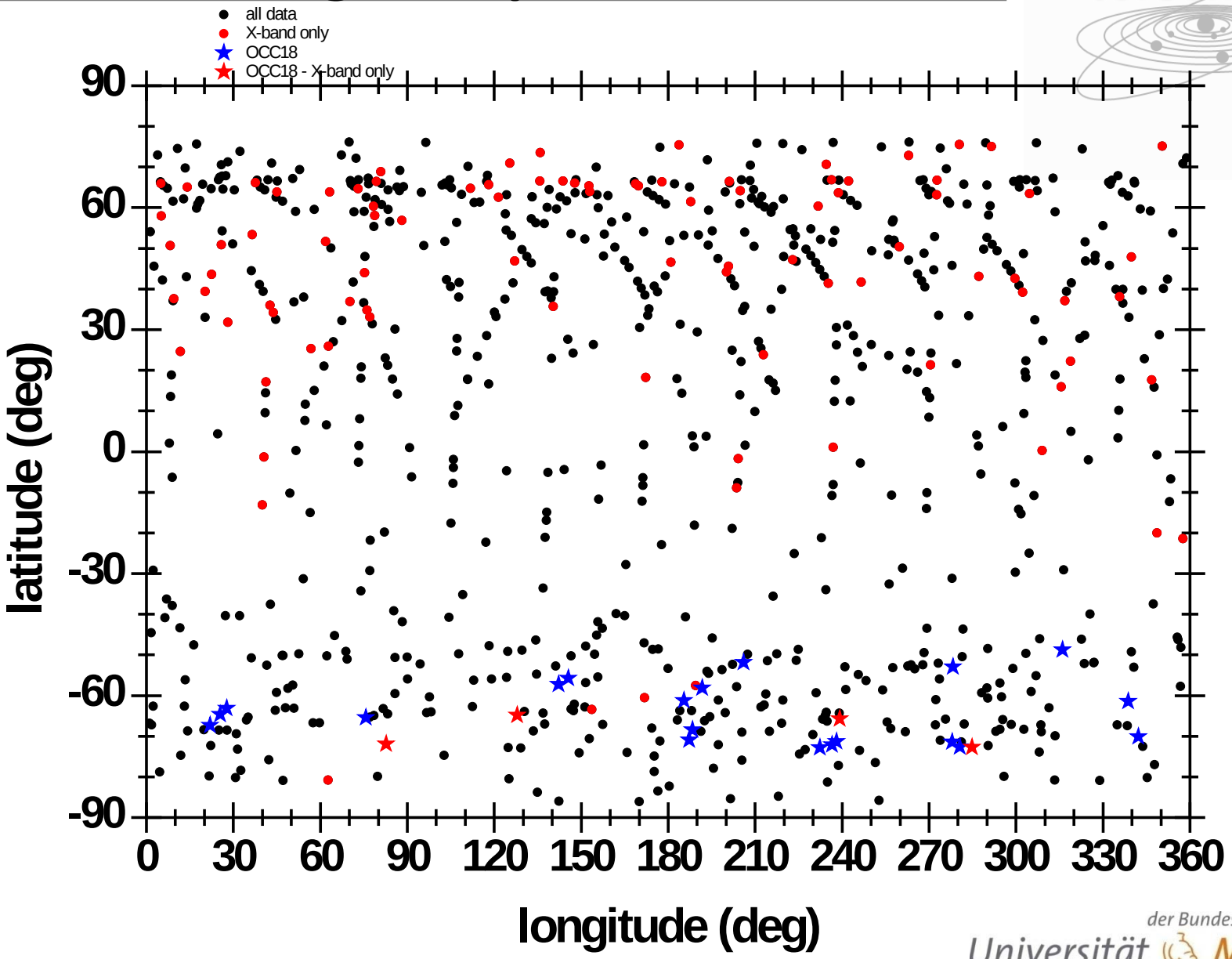
Ionospheric structure



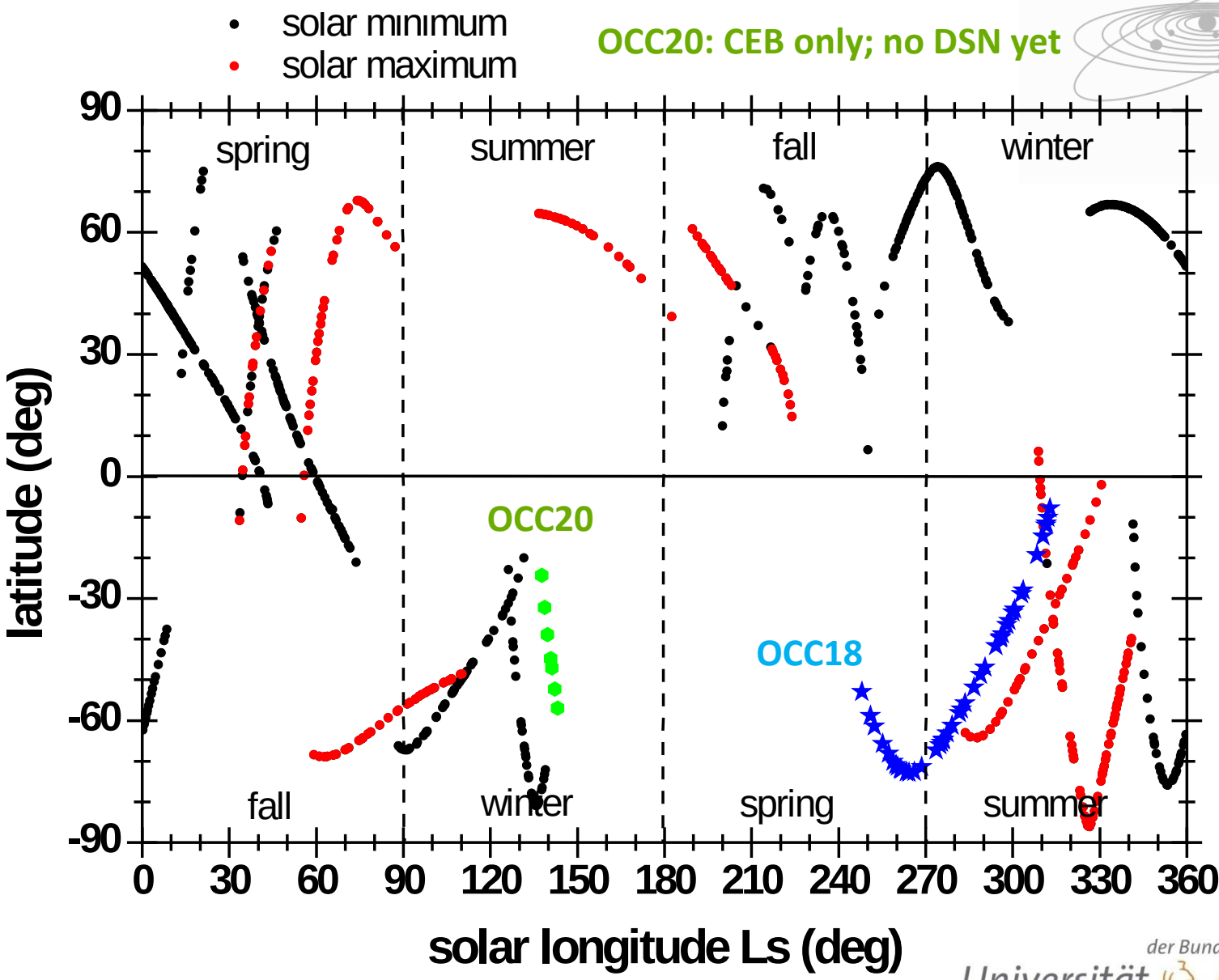
Ionospheric structure



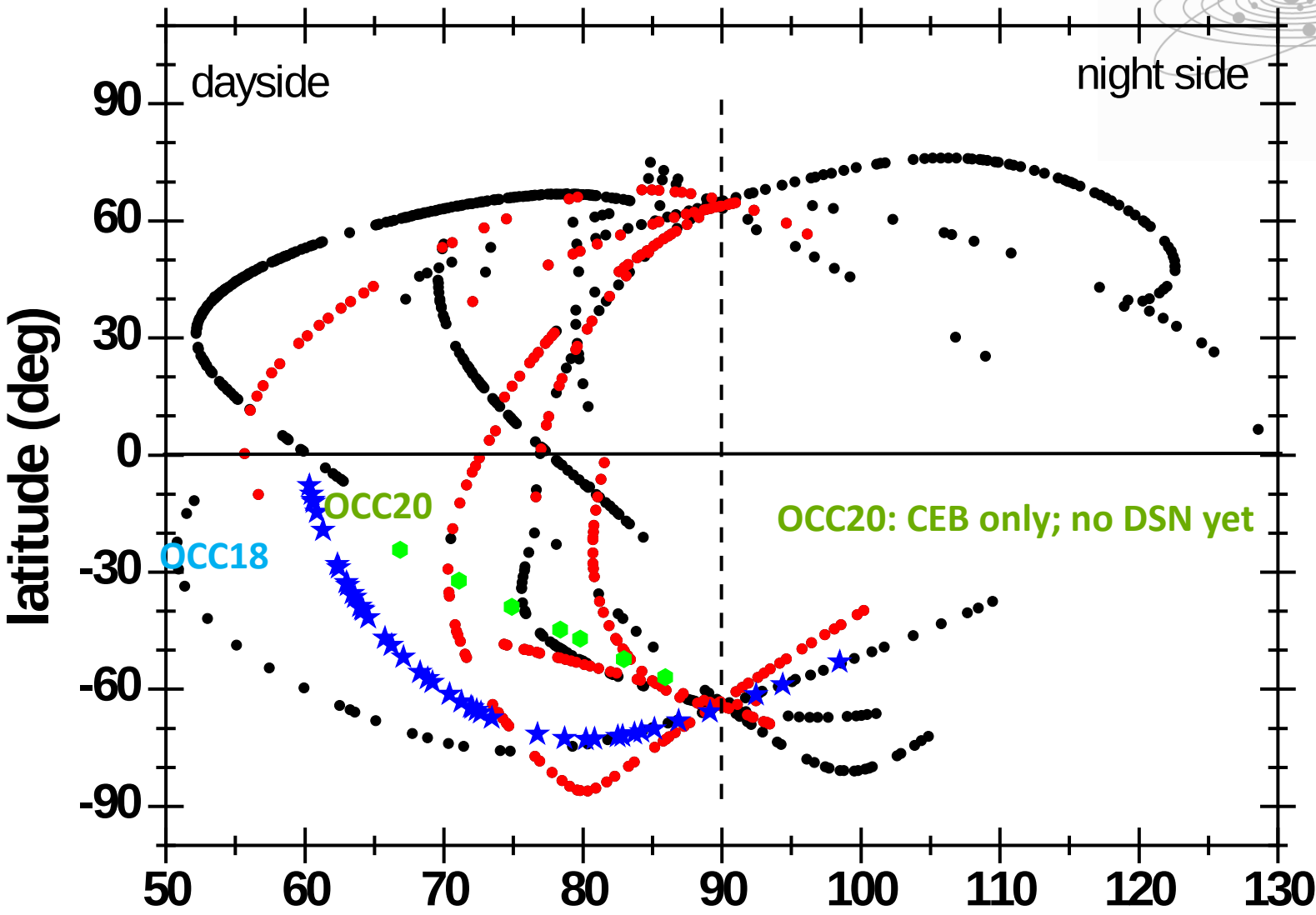
MaRS coverage: map



MaRS coverage: seasons



MaRS coverage: solar zenith angle

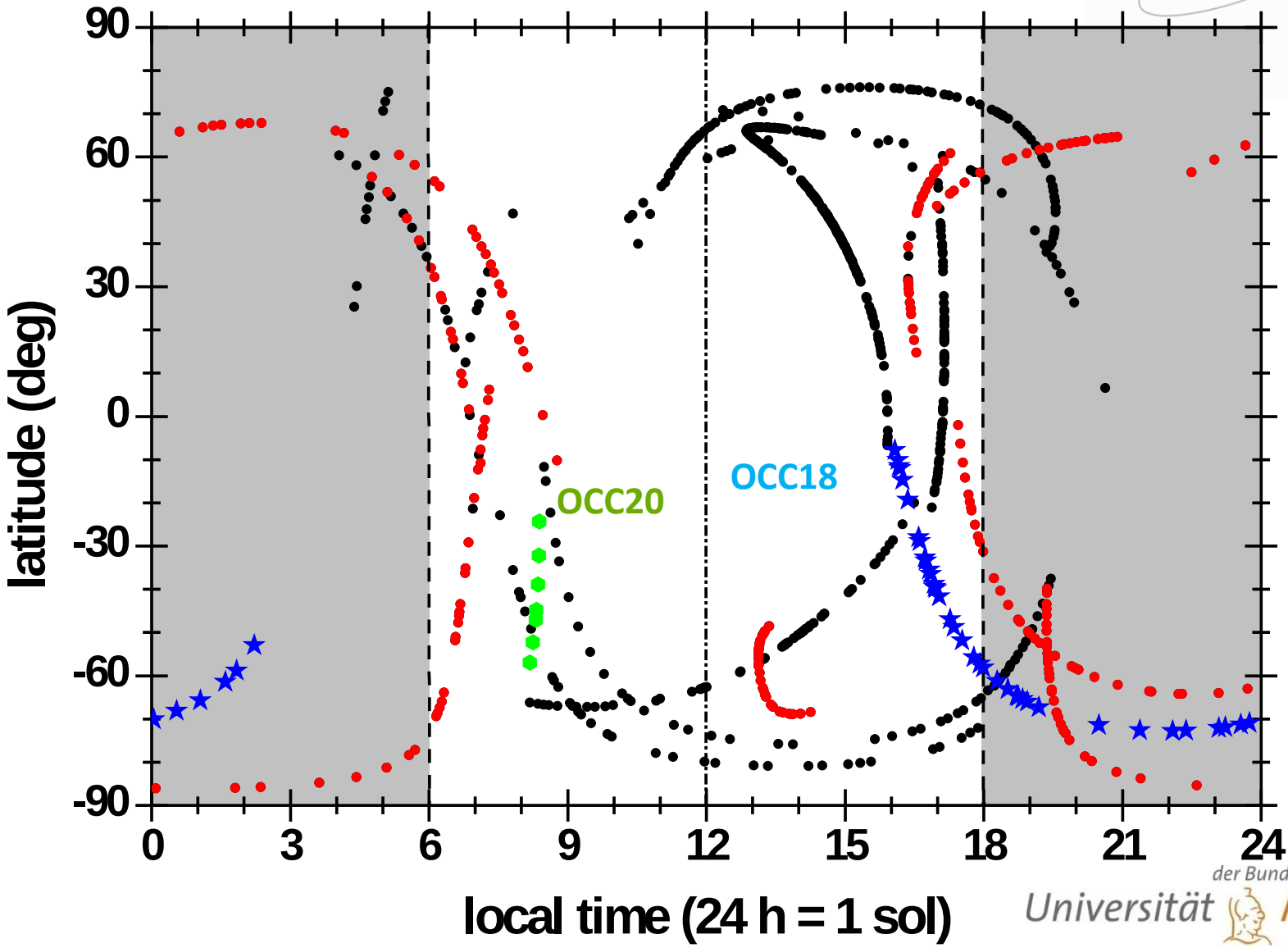


Planetenforschung RIU

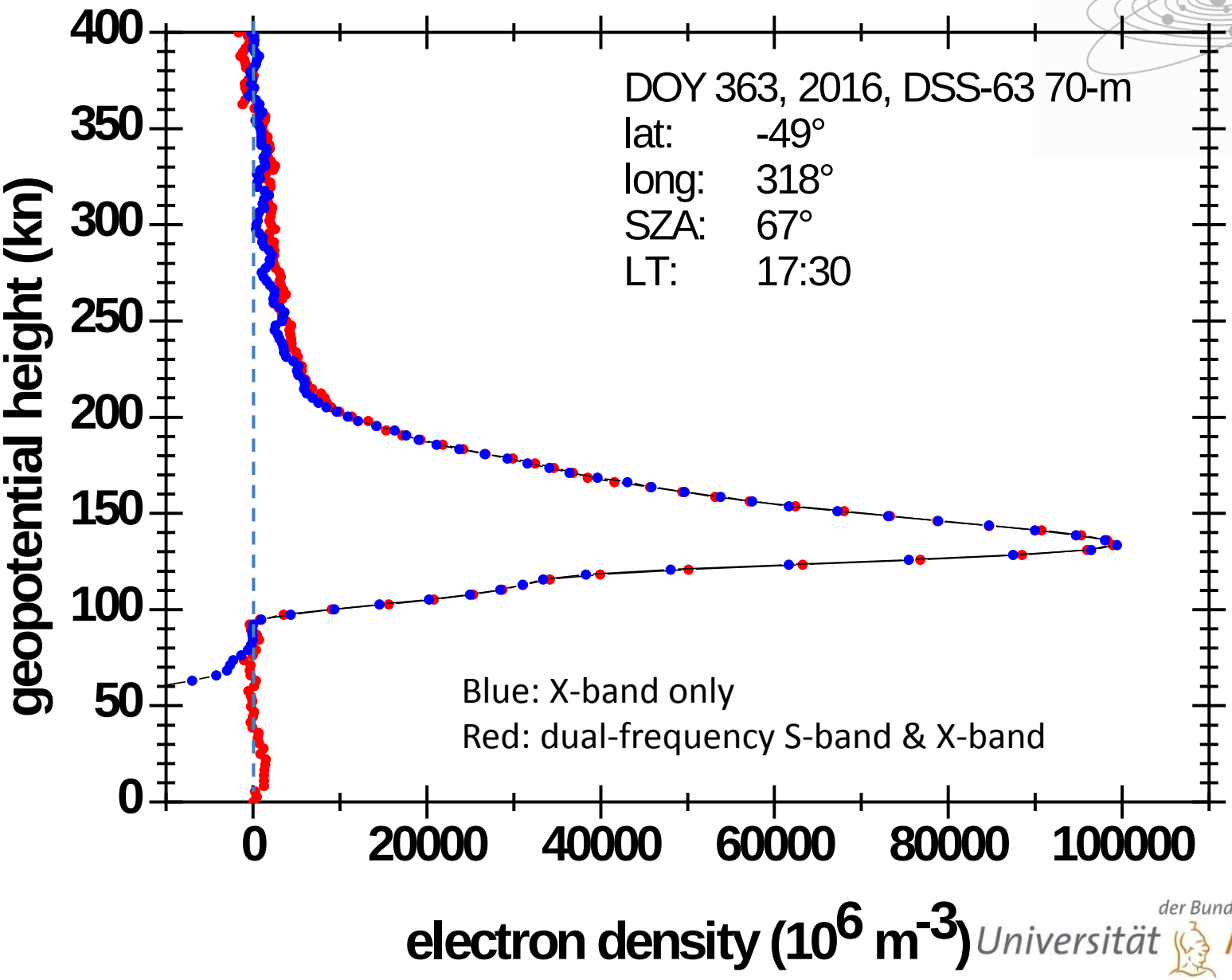
der Bundeswehr Universität München

MaRS coverage: local time

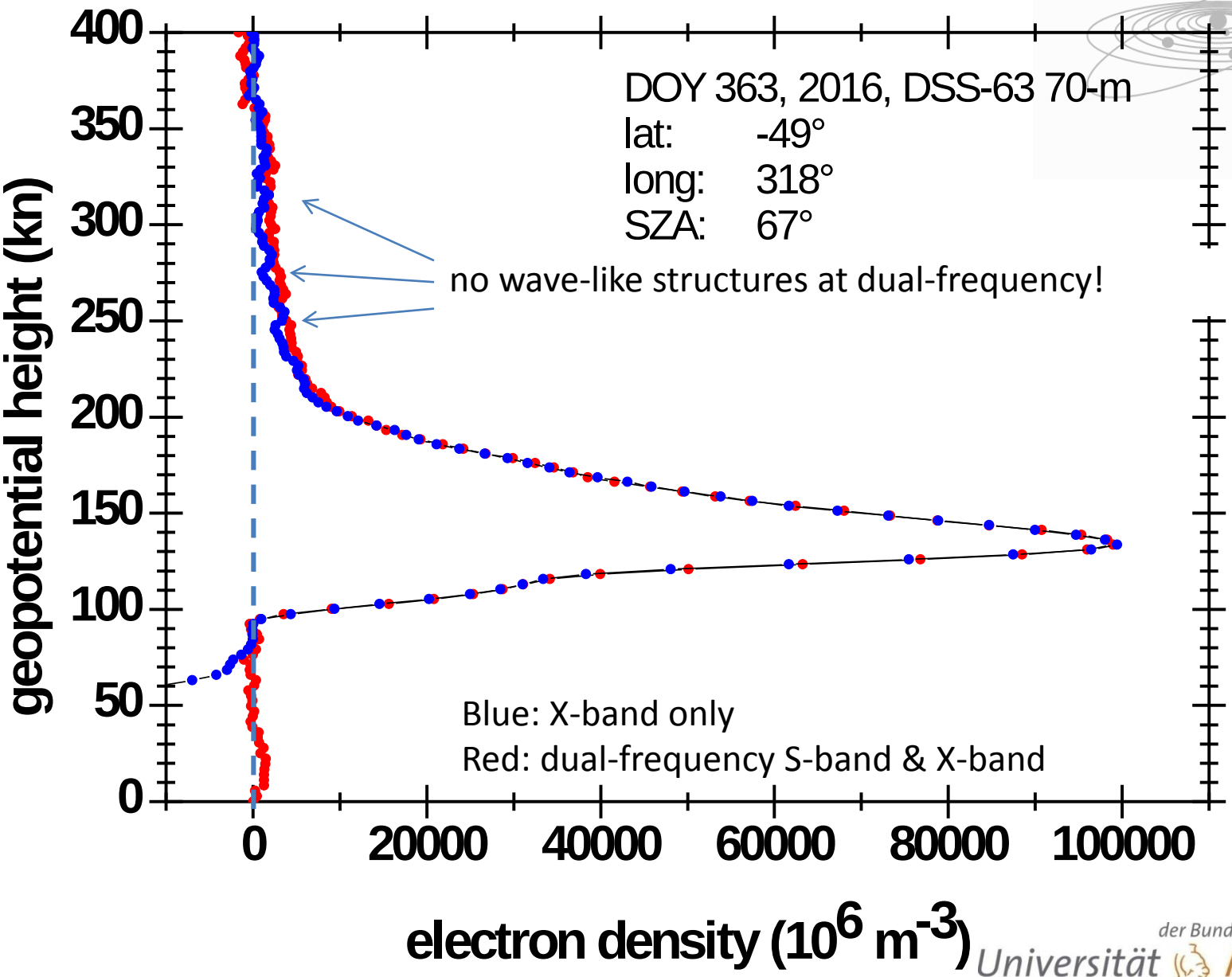
OCC20: CEB only; no DSN yet



MaRS operations: ionosphere



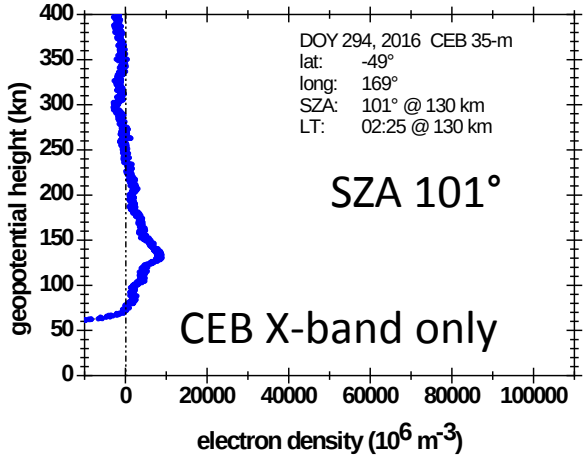
MaRS operations: ionosphere

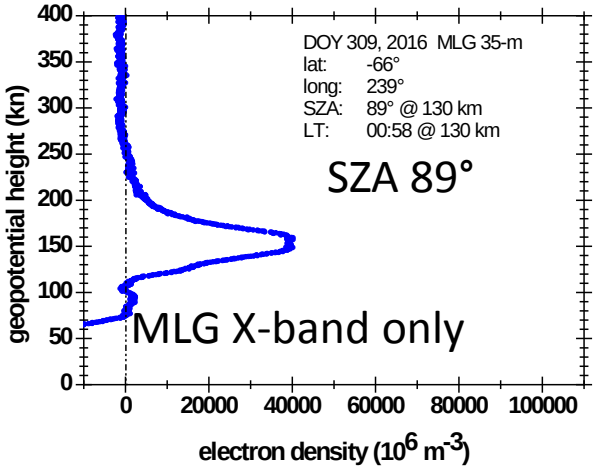


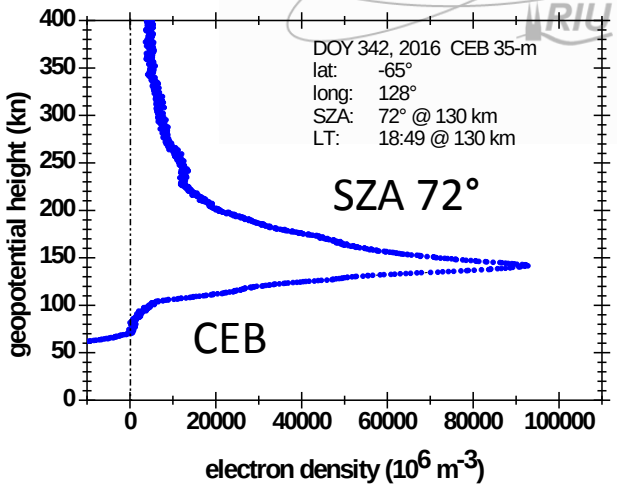
Planetenforschung RIU

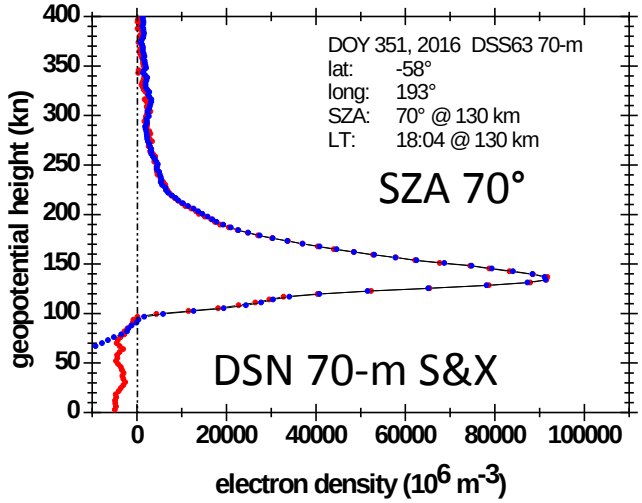
der Bundeswehr Universität München

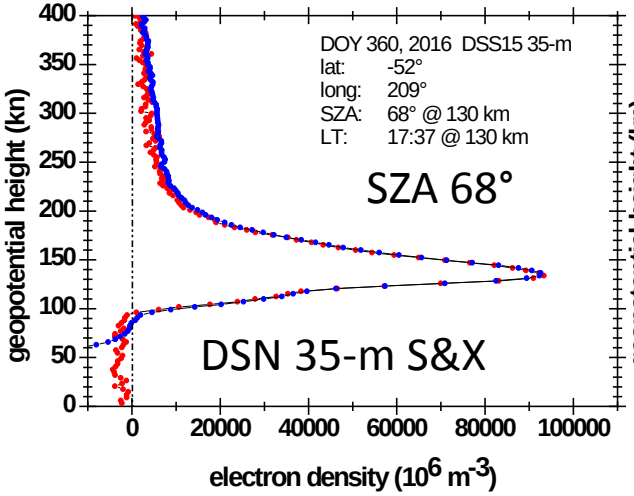
MaRS operations: neutral atmosphere

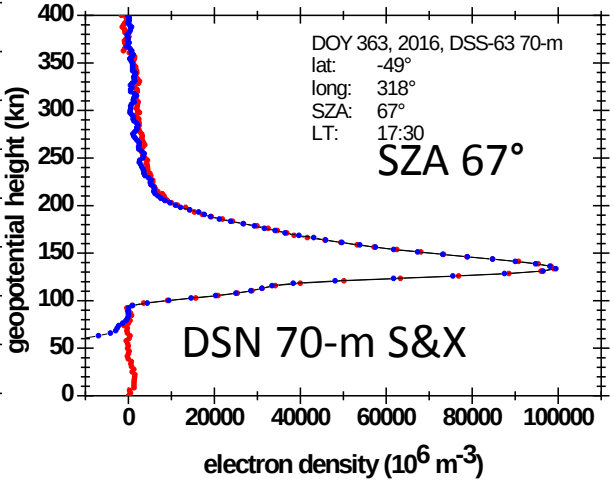




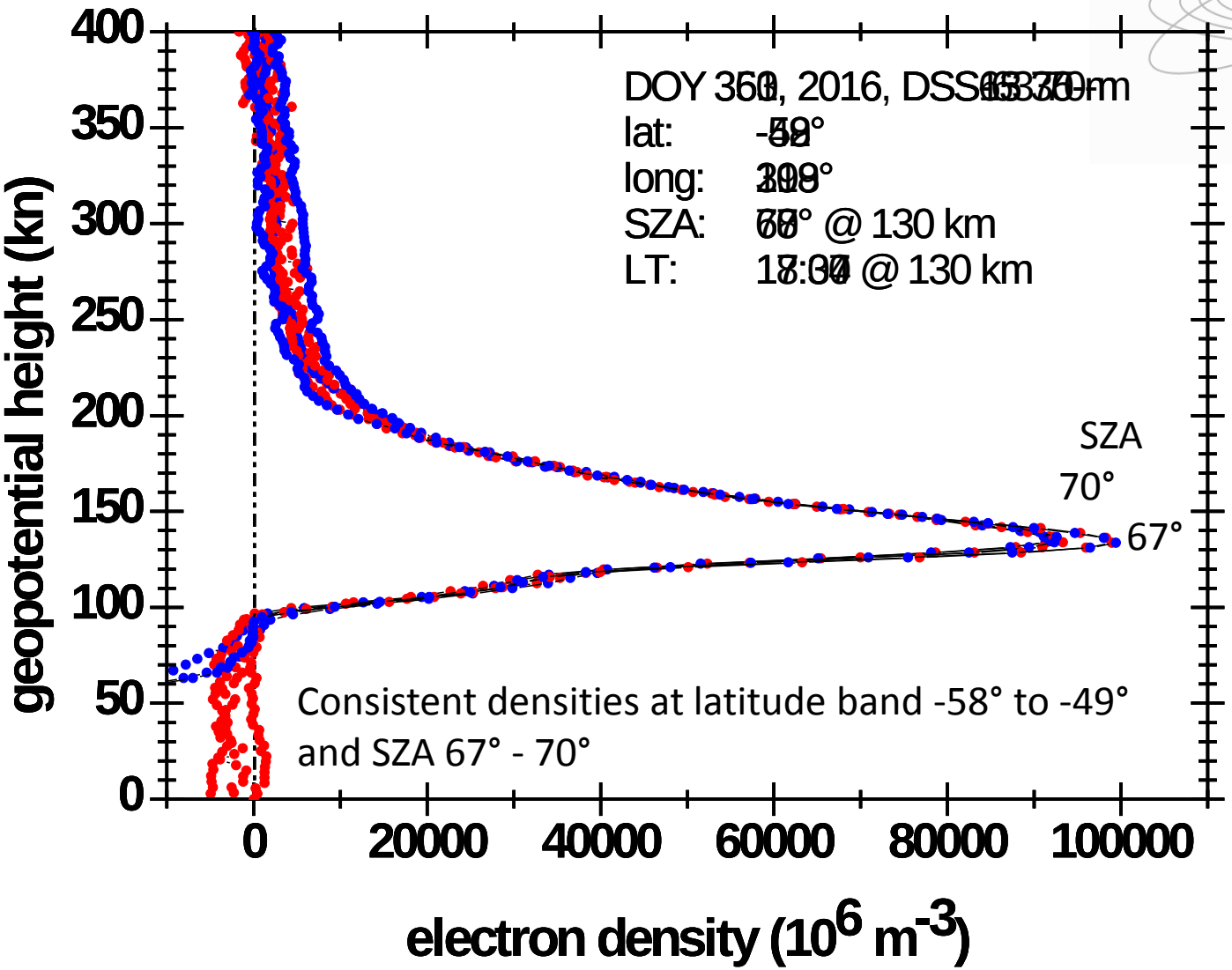


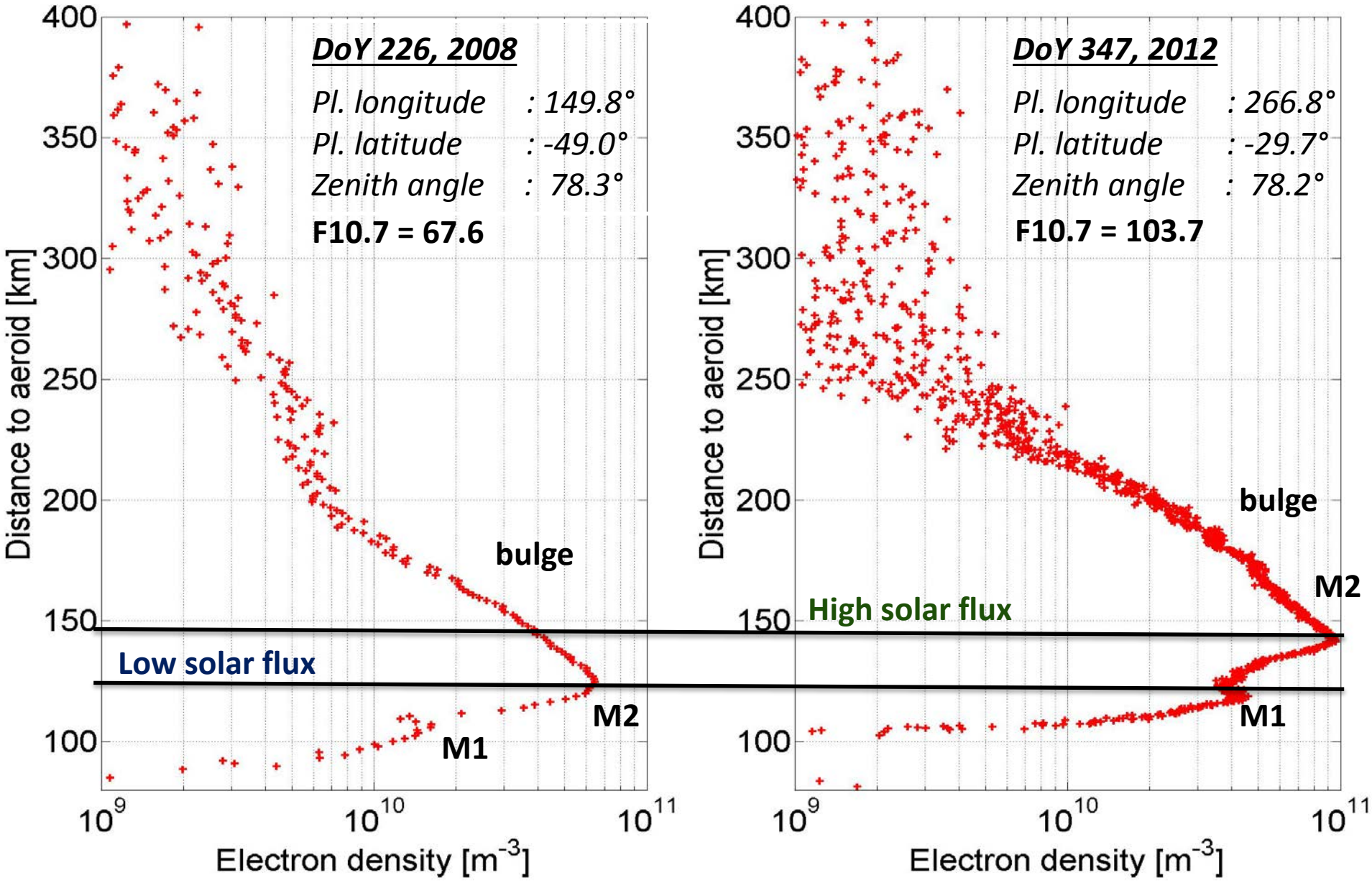


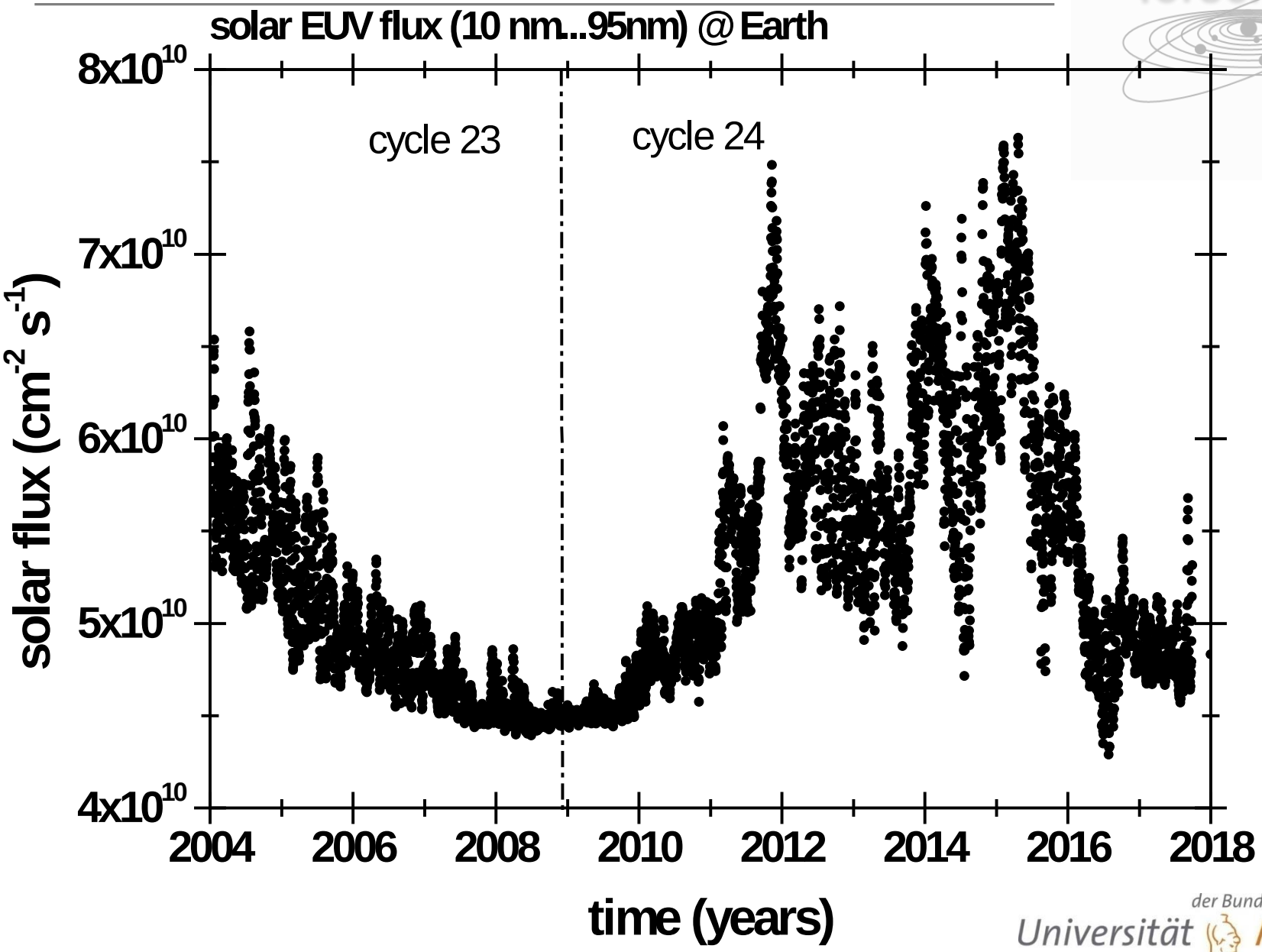


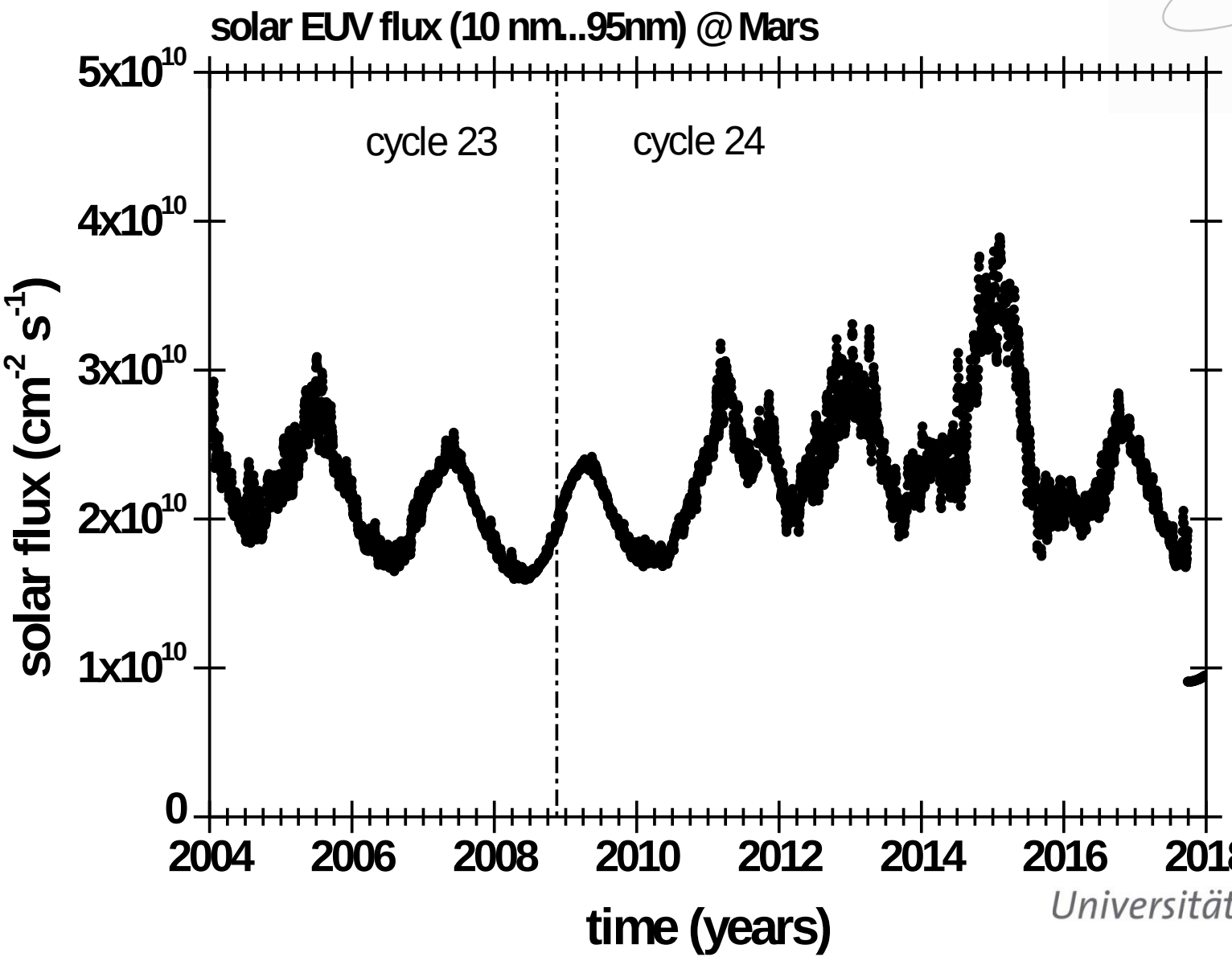


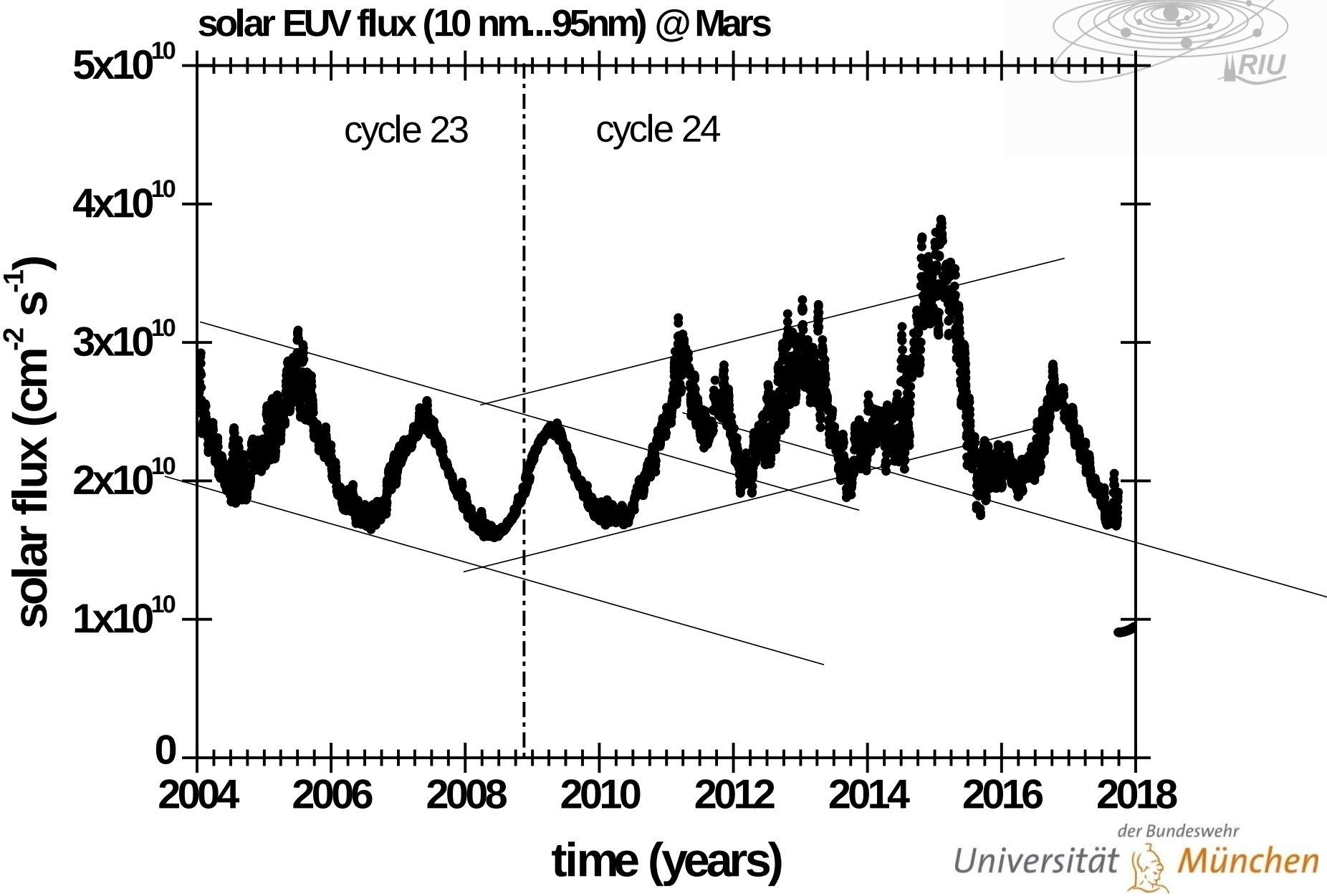
MaRS operations: neutral atmosphere

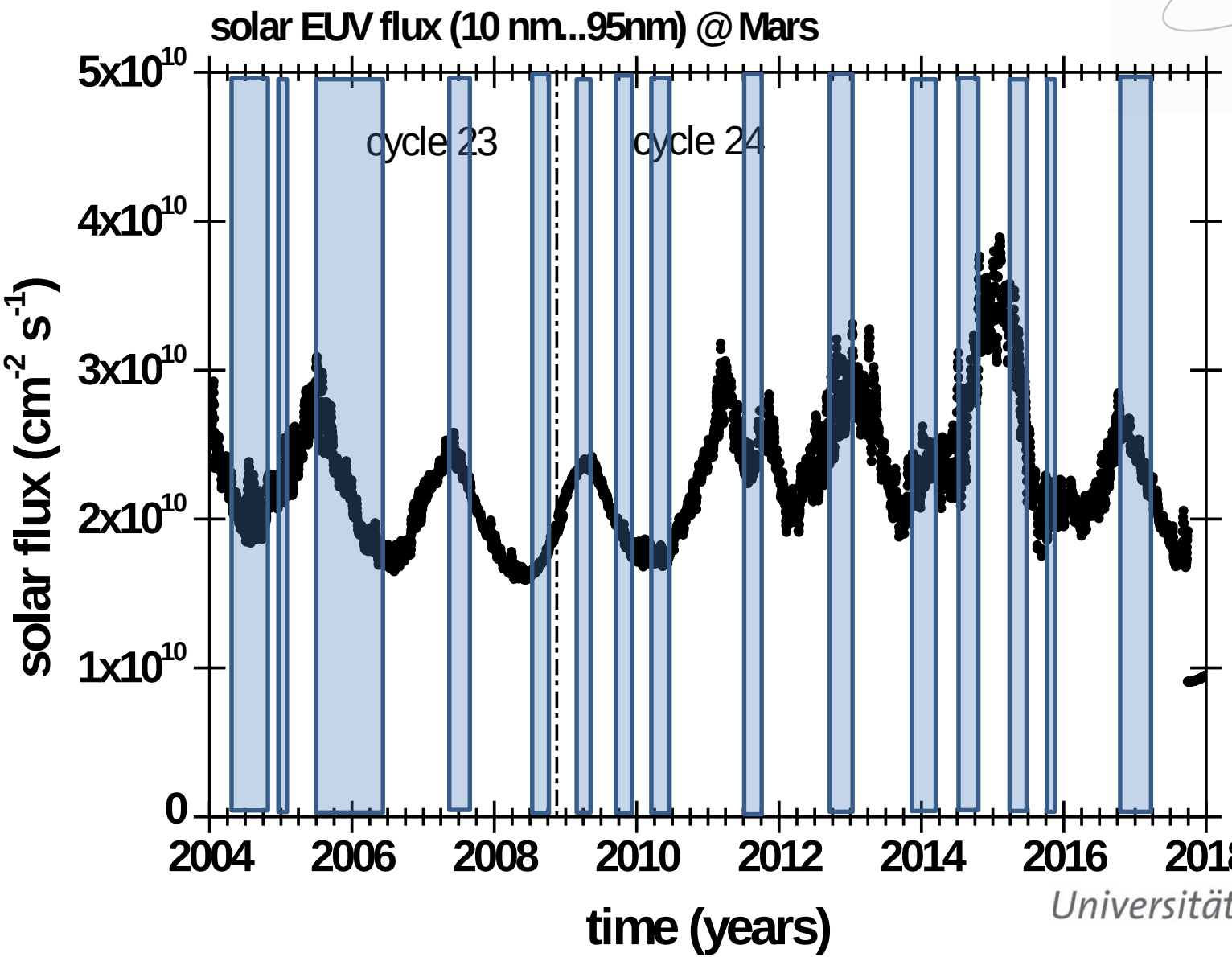


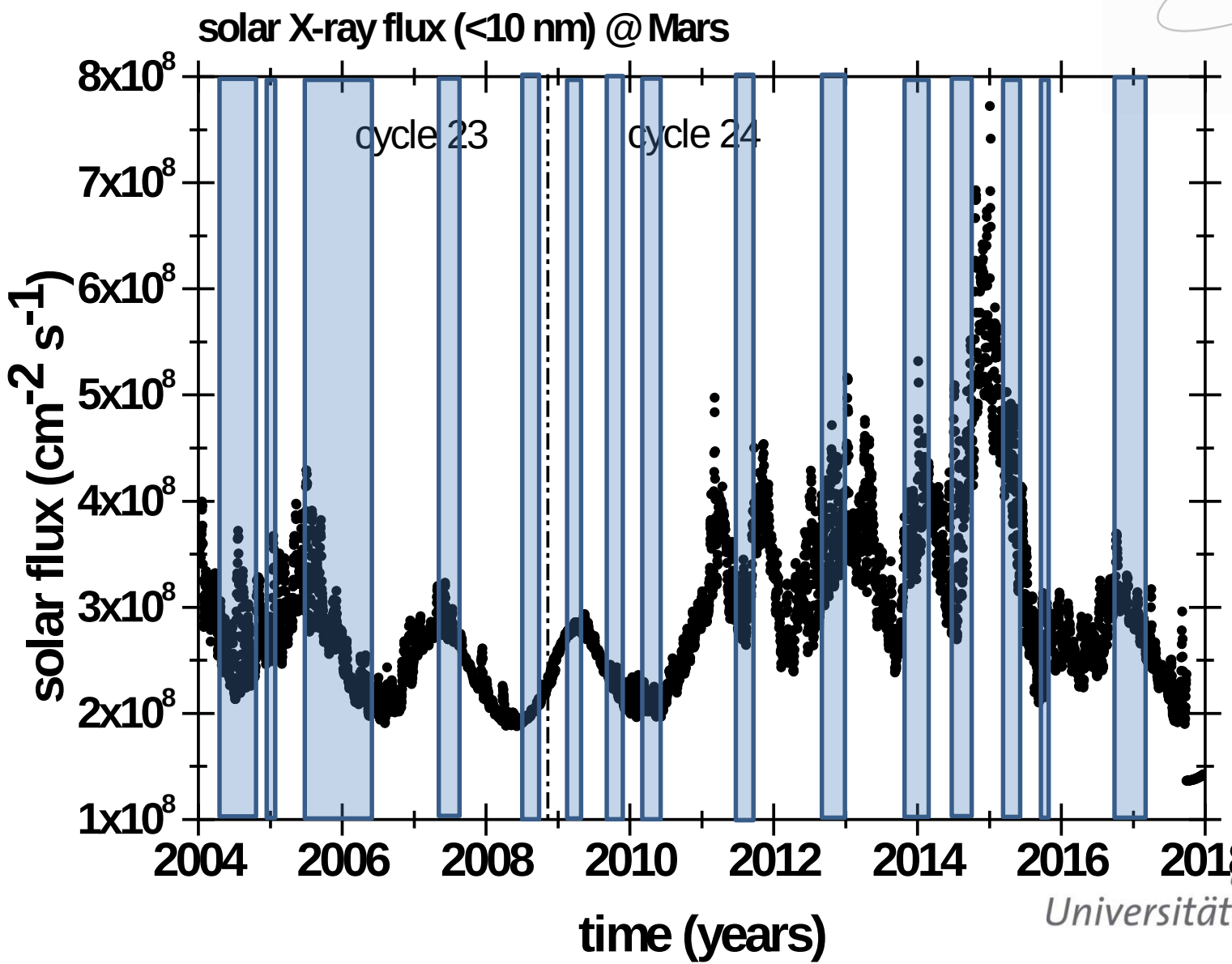

DoY 226, 2008
Pl. longitude : 149.8°
Pl. latitude : -49.0°
Zenith angle : 78.3°
F10.7 = 67.6
DoY 347, 2012
Pl. longitude : 266.8°
Pl. latitude : -29.7°
Zenith angle : 78.2°
F10.7 = 103.7
Distance to aeroid [km]
Electron density [m-3]
bulge
M2
M1
Low solar flux
High solar flux

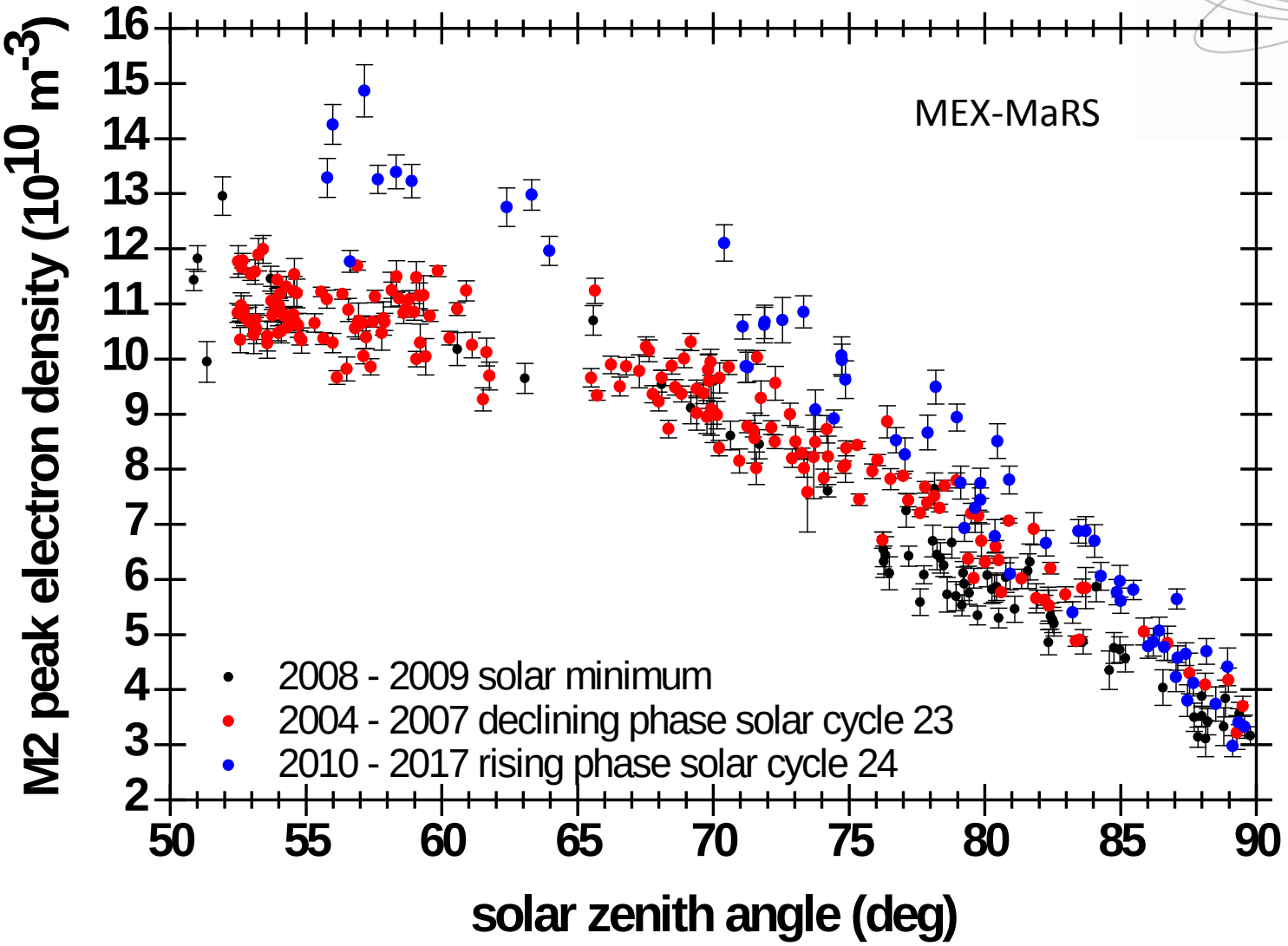


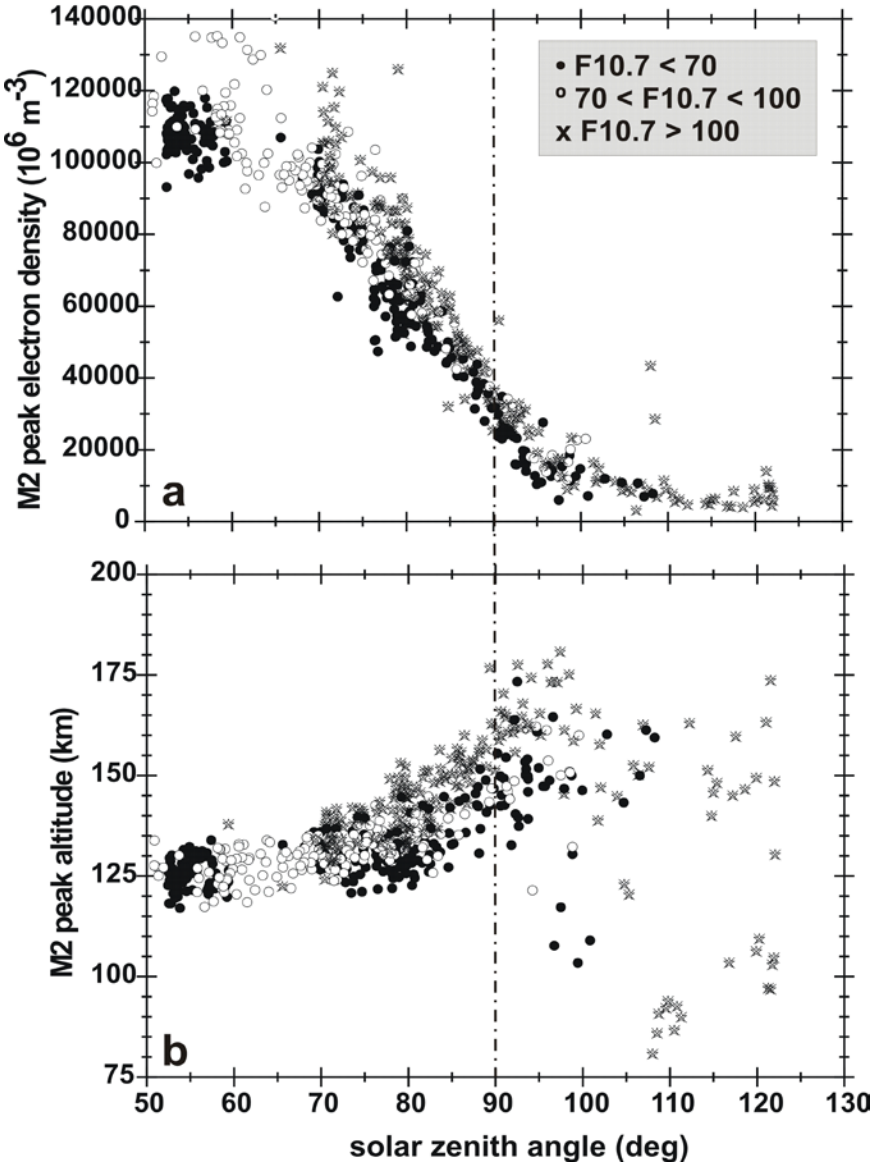

solar EUV flux (10 nm...95nm) @ Mars
5x10^10
4x10^10
3x10^10
2x10^10
1x10^10
0
cycle 23
cycle 24
solar flux (cm^-2 s^-1)
2004
2006
2008
2010
2012
2014
2016
2018
time (years)


solar EUV flux (10 nm...95nm) @ Mars
cycle 23
cycle 24
5x10^10
4x10^10
3x10^10
2x10^10
1x10^10
0
solar flux (cm^-2 s^-1)
2004
2006
2008
2010
2012
2014
2016
2018
time (years)

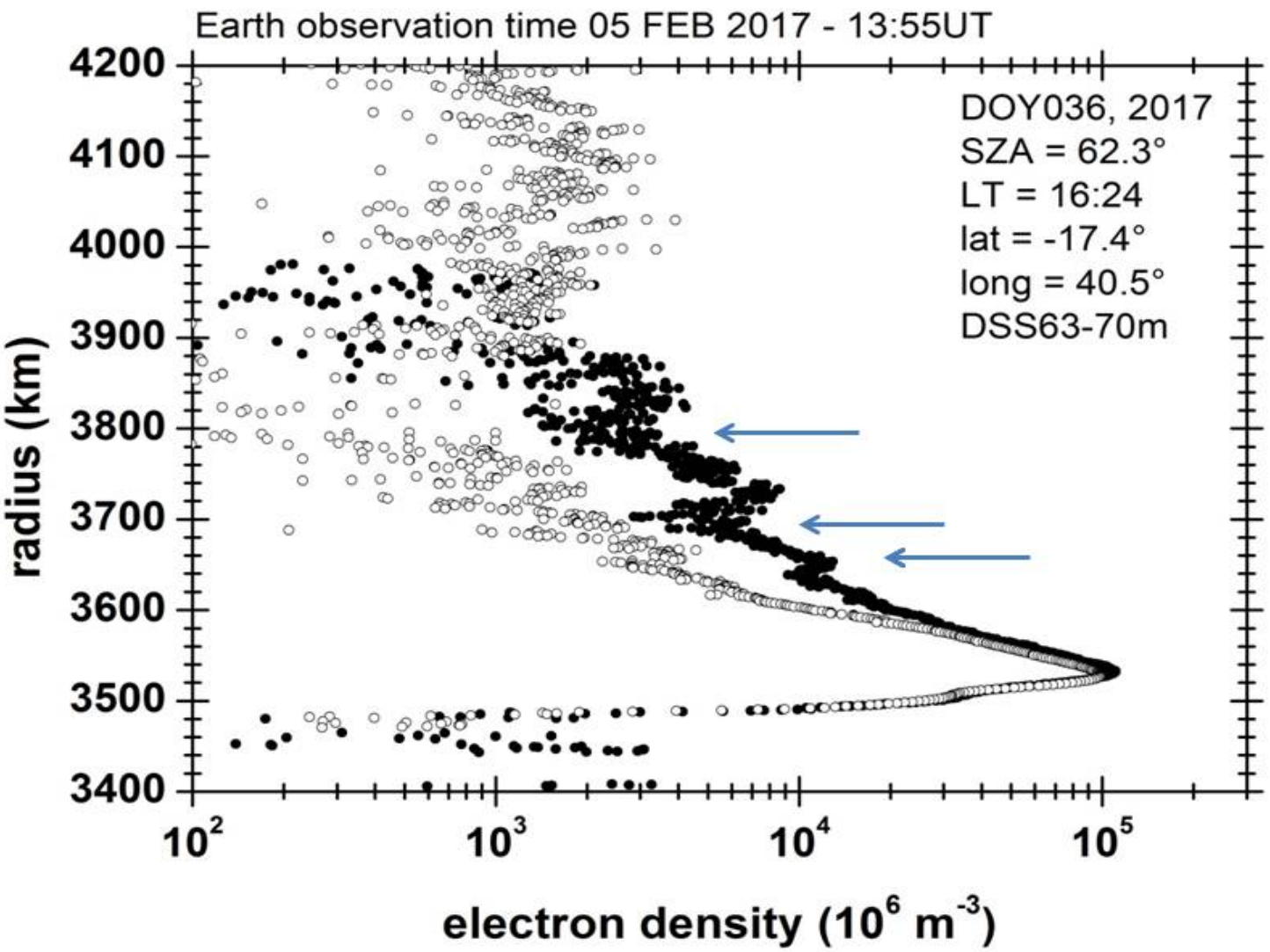

solar EUV flux (10 nm...95nm) @ Mars
cycle 23
cycle 24
5x10^10
4x10^10
3x10^10
2x10^10
1x10^10
0
solar flux (cm^-2 s^-1)
2004
2006
2008
2010
2012
2014
2016
2018
time (years)


solar X-ray flux (<10 nm) @ Mars
cycle 23
cycle 24
solar flux (cm-2 s-1)
8x10^8
7x10^8
6x10^8
5x10^8
4x10^8
3x10^8
2x10^8
1x10^8
2004
2006
2008
2010
2012
2014
2016
2018
time (years)

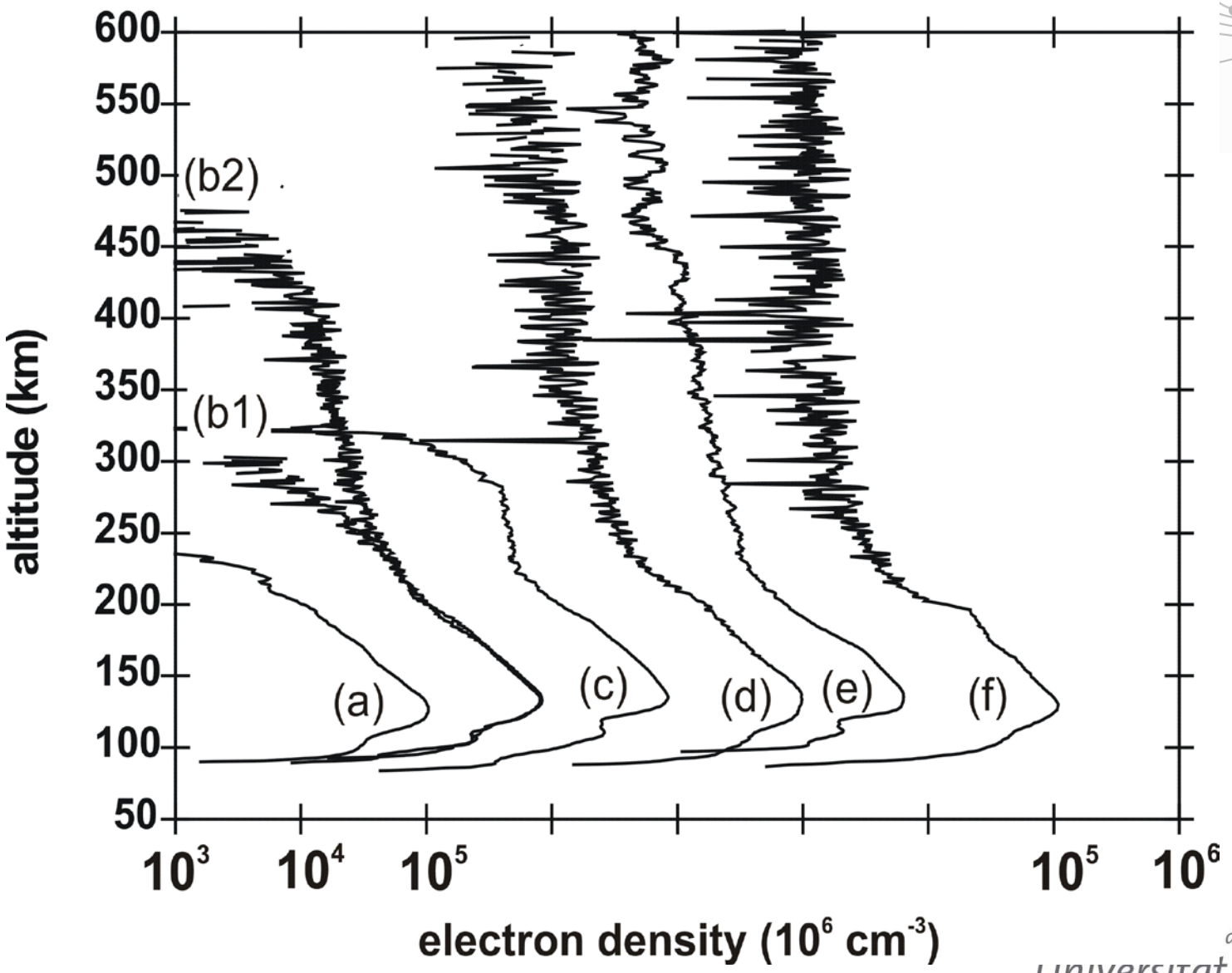

MEX-MaRS
M2 peak electron density (10^{10} m^{-3})
solar zenith angle (deg)
2008 - 2009 solar minimum
2004 - 2007 declining phase solar cycle 23
2010 - 2017 rising phase solar cycle 24
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
50
55
60
65
70
75
80
85
90


• F10.7 < 70
° 70 < F10.7 < 100
x F10.7 > 100
M2 peak electron density (10^6 m^{-3})
140000
120000
100000
80000
60000
40000
20000
0
a
M2 peak altitude (km)
200
175
150
125
100
75
b
50
60
70
80
90
100
110
120
130
solar zenith angle (deg)

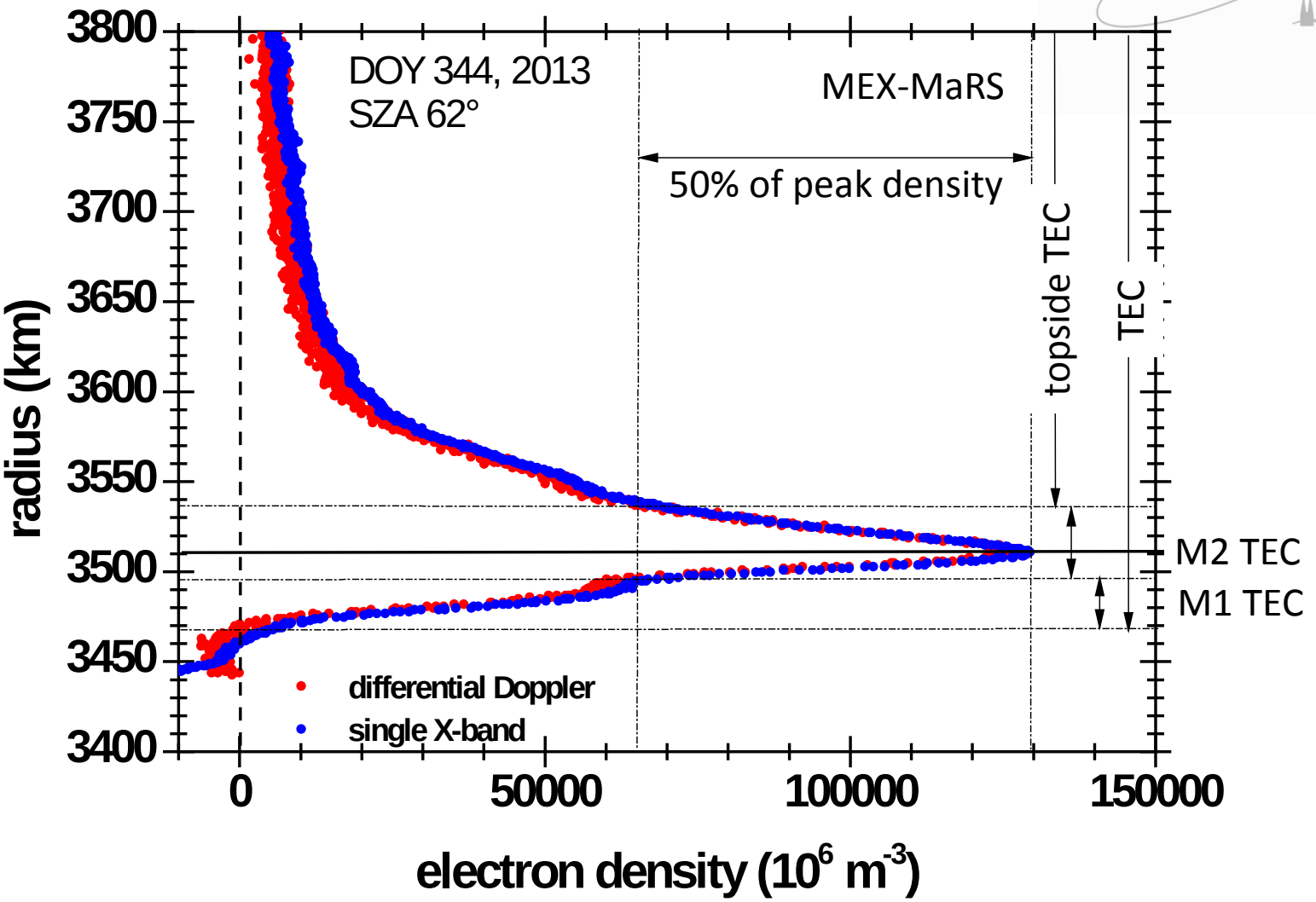
Topside variations

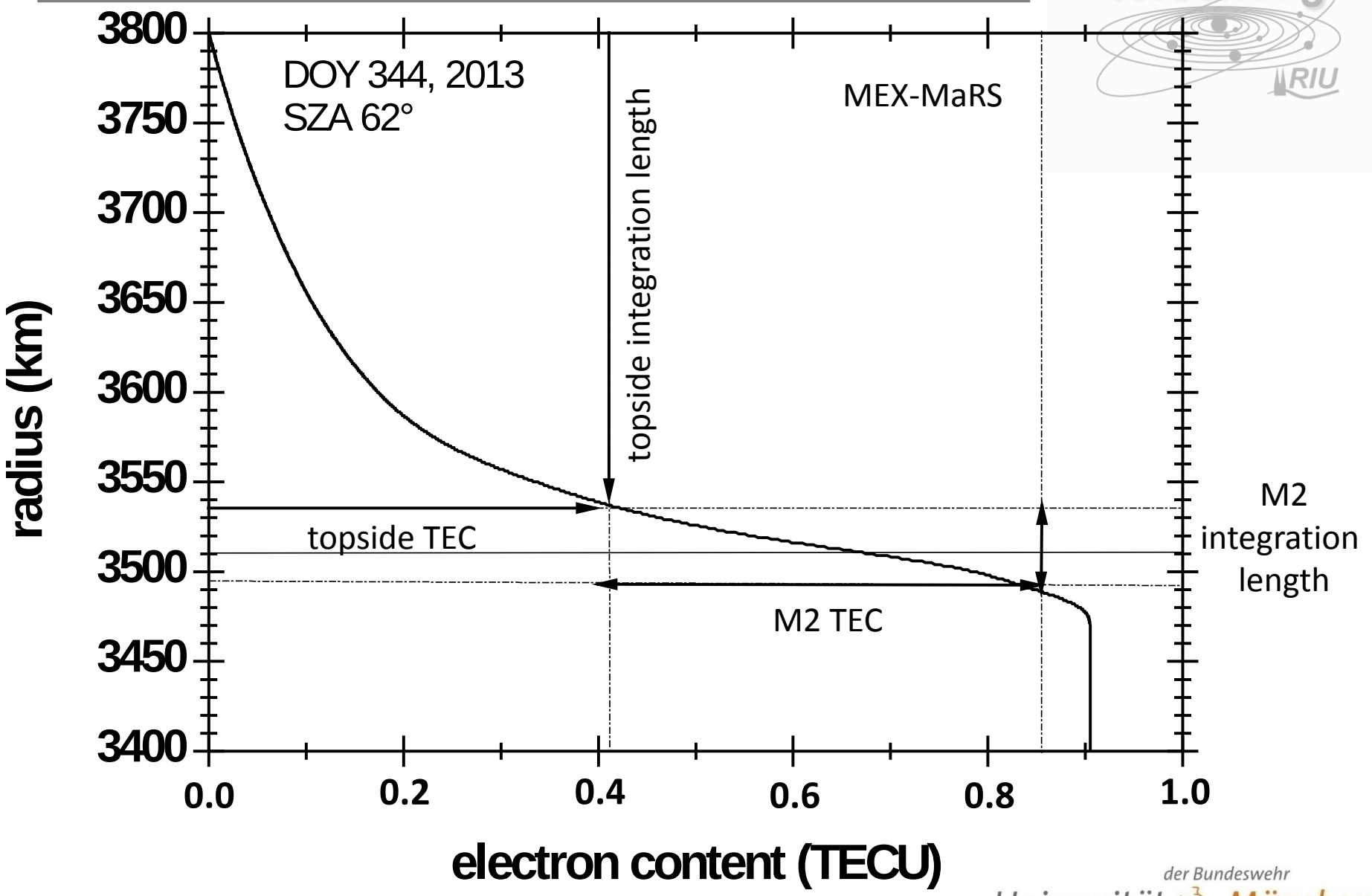


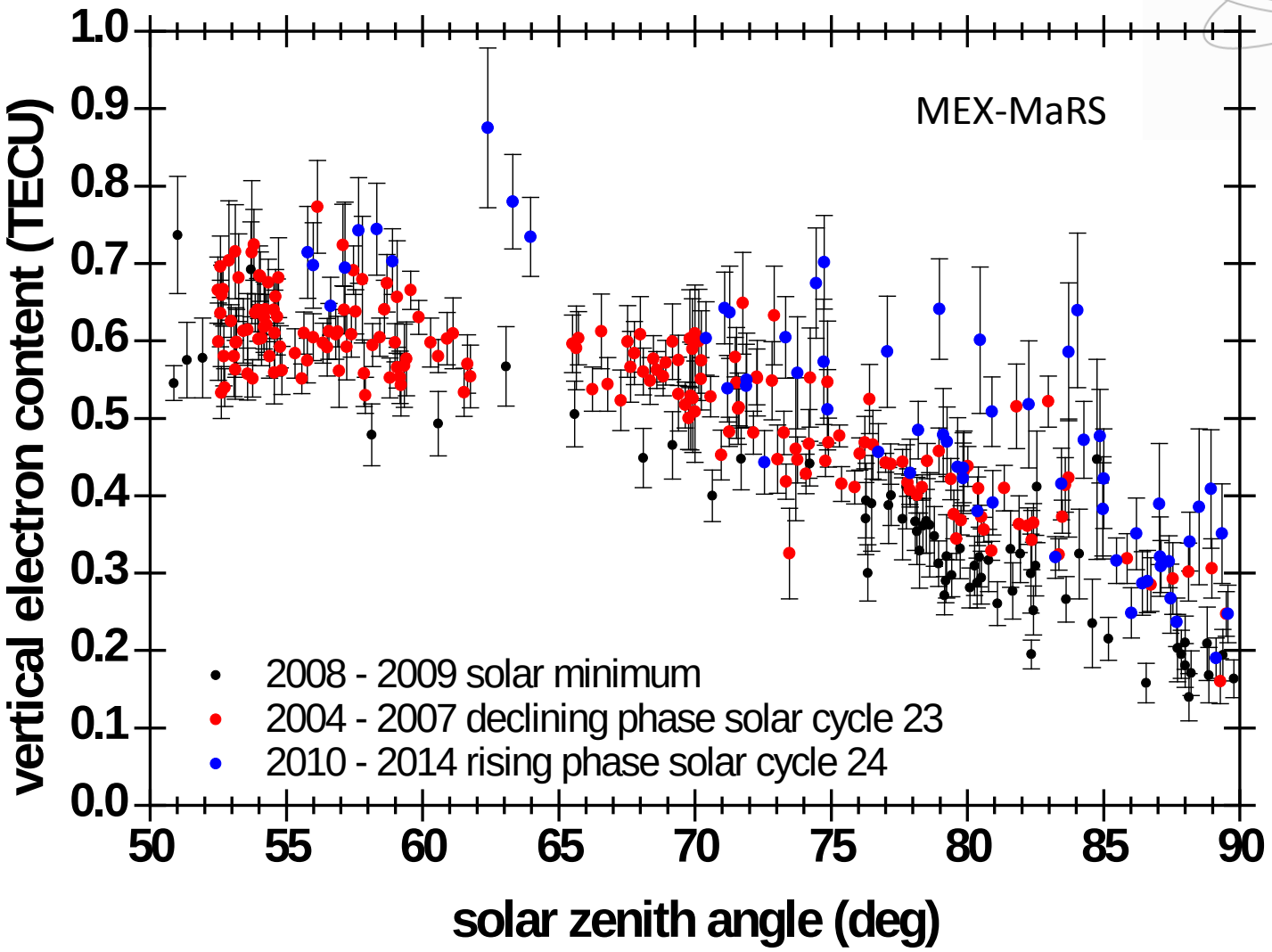
Topside variations



Vertical electron content




DOY 344, 2013
SZA 62°
MEX-MaRS
topside integration length
topside TEC
M2 TEC
M2
integration
length
radius (km)
electron content (TECU)
3800
3750
3700
3650
3600
3550
3500
3450
3400
0.0
0.2
0.4
0.6
0.8
1.0

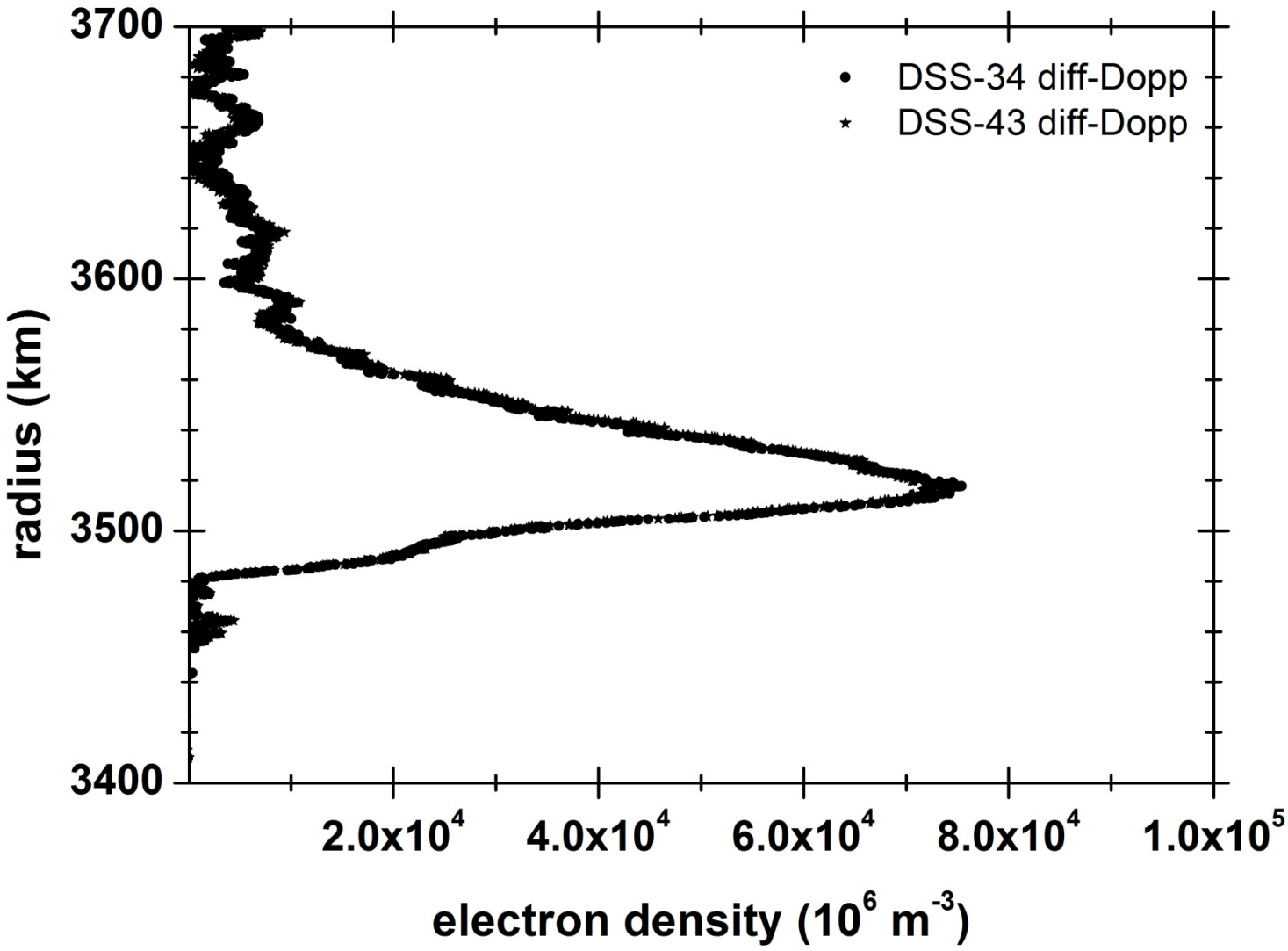

MEX-MaRS
vertical electron content (TECU)
solar zenith angle (deg)
2008 - 2009 solar minimum
2004 - 2007 declining phase solar cycle 23
2010 - 2014 rising phase solar cycle 24
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
50
55
60
65
70
75
80
85
90

conclusion

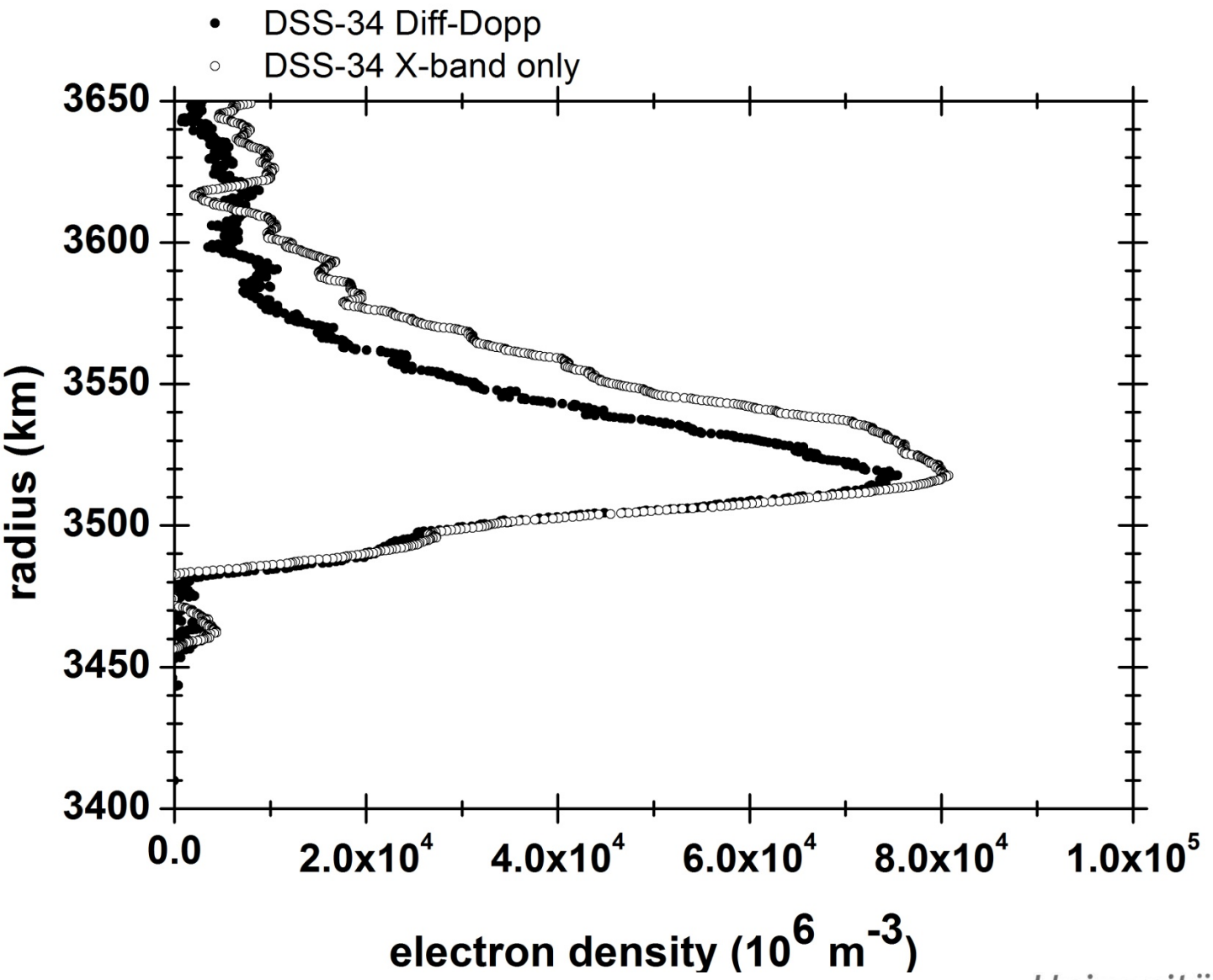
- About 900 electron density profiles observed in the Martian ionosphere for SZA > 50°, all local times and almost all seasons for solar min and max
- Formation of the large-scale low-altitude ionosphere is under solar control; solar flux is modulated by the orbit and varies by 50% during a Martian year; solar cycle contributes +/-10%...20%
- M1 & M2 peak densities and altitudes follow the solar zenith angle but not exactly the Chapman theory
- Topside and transport region highly variable
- Vertical total electron content can be computed; electron content dominated by the M2 layer (high electron density over a short integration path); follows SZA like the peak density
- Dual-frequency radio sounding reveils the true plasma distribution within the ionosphere; electron density profiles from single frequency (X-band) radio sounding alone need to be analysed very very carefully….

NASA Deep Space Complex 40, Tidbinbilla, Australia

DSS-34 & 43 diff-Dopp electron density profile



DSS-34 electron density profile



DSS-34 & 43 electron density profile