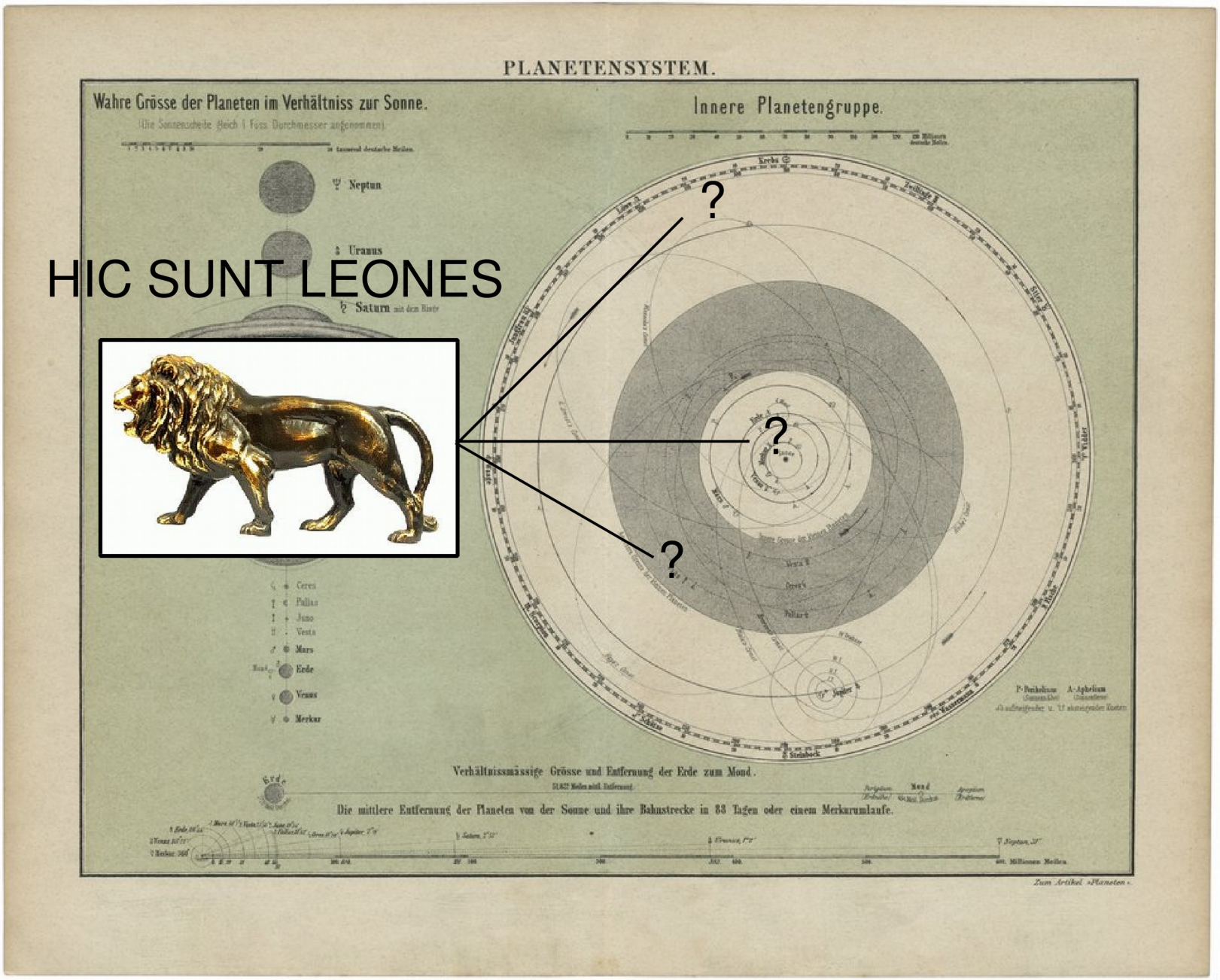
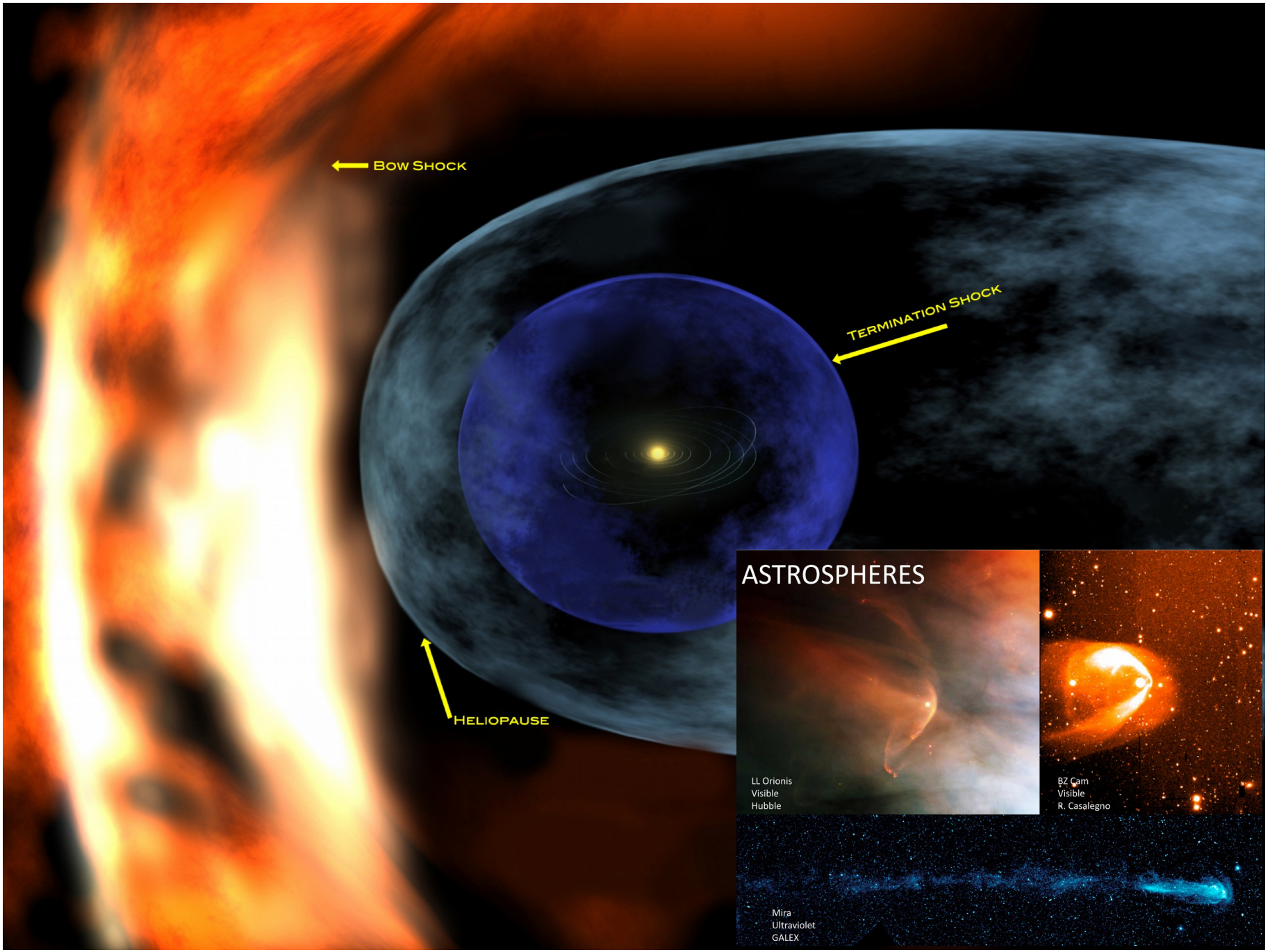
# The Solar Wind

L. Berger
Extraterrestrial Physics, Institute for Experimental and Applied Physics, Christian-Albrechts-University Kiel, Germany


PLANETENSYSTEM.
Wahre Grösse der Planeten im Verhältniss zur Sonne.
Innere Planetengruppe.
Neptun
Uranus
Saturn
Ceres
Pallas
Juno
Vesta
Mars
Erde
Venus
Merkur
HIC SUNT LEONES
?
?
?
Verhältnissmässige Grösse und Entfernung der Erde zum Mond.
Die mittlere Entfernung der Planeten von der Sonne und ihre Bahnstrecke in 83 Tagen oder einem Merkurumlaufe.

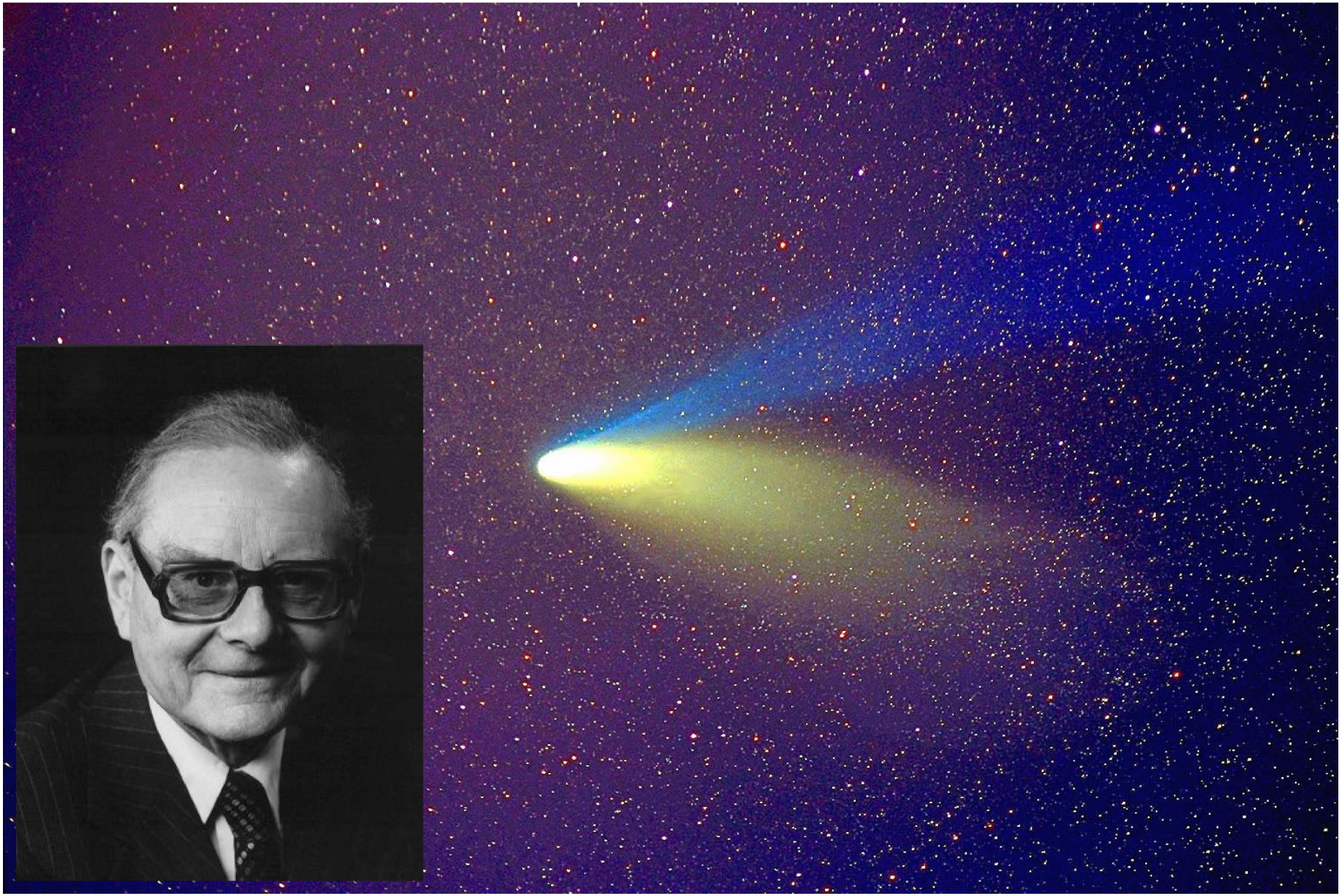
# Today : Heliosphere is formed by the Solar Wind



1859 : Richard Carrington – Related observed flare to geomagnetic storm
~1895 : Kristian Birkeland – Transient Solar ions and electrons


Lars Berger
berger@physik.uni-kiel.de

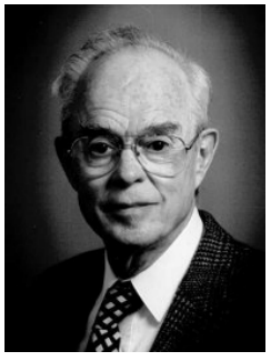
# 1951 : Ludwig Biermann – Suggests continuous Solar Wind



Lars Berger
berger@physik.uni-kiel.de

# 04.10.1957 : Soviet Sputnik 1 – Beginning of Space Age
# 1958 : Eugene Parker – Suggests Solar Wind model
# Predicts Parker Spiral

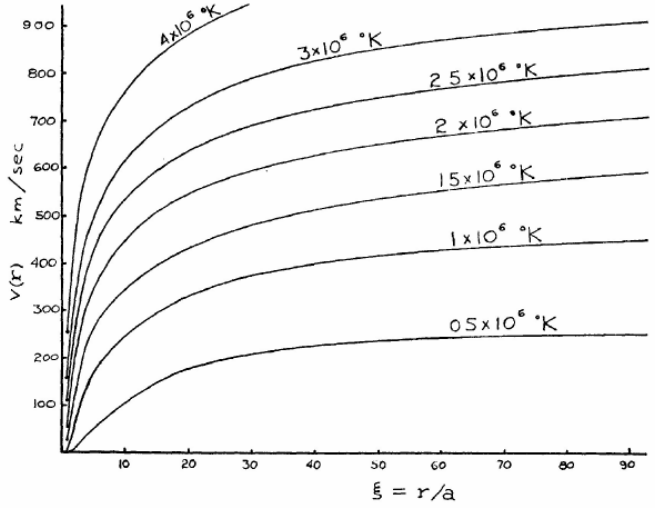
## DYNAMICS OF THE INTERPLANETARY GAS AND MAGNETIC FIELDS*

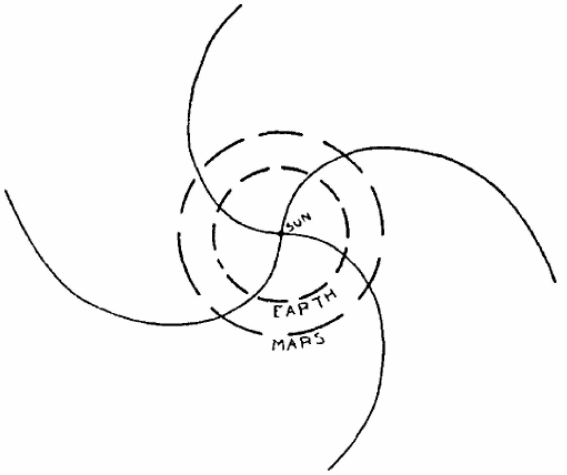


E. N. PARKER
Enrico Fermi Institute for Nuclear Studies, University of Chicago
*Received January 2, 1958*

ABSTRACT

We consider the dynamical consequences of Biermann's suggestion that gas is often streaming outward in all directions from the sun with velocities of the order of 500–1500 km/sec. These velocities of 500 km/sec and more and the interplanetary densities of 500 ions/cm³ ($10^{14}$ gm/sec mass loss from the sun) follow from the hydrodynamic equations for a $3 \times 10^6$ ° K solar corona. It is suggested that the outward-streaming gas draws out the lines of force of the solar magnetic fields so that near the sun the field is very nearly in a radial direction. Plasma instabilities are expected to result in the thick shell of disordered field ($10^{-5}$ gauss) inclosing the inner solar system, whose presence has already been inferred from cosmic-ray observations.



# 1959 : Soviet Lunar2 rocket confirmed stream of ions

## THE STUDY OF INTERPLANETARY IONIZED GAS, HIGH-ENERGY ELECTRONS AND CORPUSCULAR RADIATION OF THE SUN, EMPLOYING THREE-ELECTRODE CHARGED PARTICLE TRAPS ON THE SECOND SOVIET SPACE ROCKET*

K. I. GRINGAUZ, V. V. BEZRUKIKH, V. D. OZEROV and R. E. RYBCHINSKII

Translated by R. MATTHEWS from *Iskusstvennye Sputniki Zemli*, 6, 101, (1961).

. . . . . .

3. Starting from 9.30 hr Moscow time on 13 September 1959 up to the moment of the container of the second space rocket reaching the moon the container was recorded as passing through a positive ion flux (in all probability protons) with energies exceeding 15 eV; $N \sim 2 \times 10^8$ cm$^{-2}$/s. This follows from the fact that during this time approximately identical positive collector currents were recorded in all four traps (see the last section of Fig. 4.)

The existence at a different time of a proton flux with energies exceeding 25 eV was observed employing similar instrumentation at different distances from the earth (in particular with $R \sim 125{,}000$ km) during a number of radiotelemetering data transmission sessions during the flight of the automatic interplanetary station in October 1959.

The proton fluxes recorded refer evidently to solar corpuscular radiation observed for the first time in this manner in interplanetary space outside the earth's magnetic field.

# 1962 : American Mariner2 measures speed and temperature

Science 7 December 1962:
Vol. 138 no. 3545 pp. 1095-1097
Solar Plasma Experiment
Marcia Neugebauer and Conway W. Snyder
Jet Propulsion Laboratory, California Institute of Technology, Pasadena

## Solar Plasma Experiment

*Abstract*. A preliminary summary of the data received from the Mariner II solar plasma experiment for the period 29 August through 31 October 1962 is presented. During this period there was always a measurable flow of plasma from the direction of the sun. The velocity of this ion motion was generally in the range 400 to 700 km/sec. Time variations, plasma density, and ion temperatures are also discussed.

The Mariner II solar plasma experiment is made with a single electrostatic spectrometer which always points to within less than ½ degree of the center of the sun. Positively

. . . . . .

. . . . . .

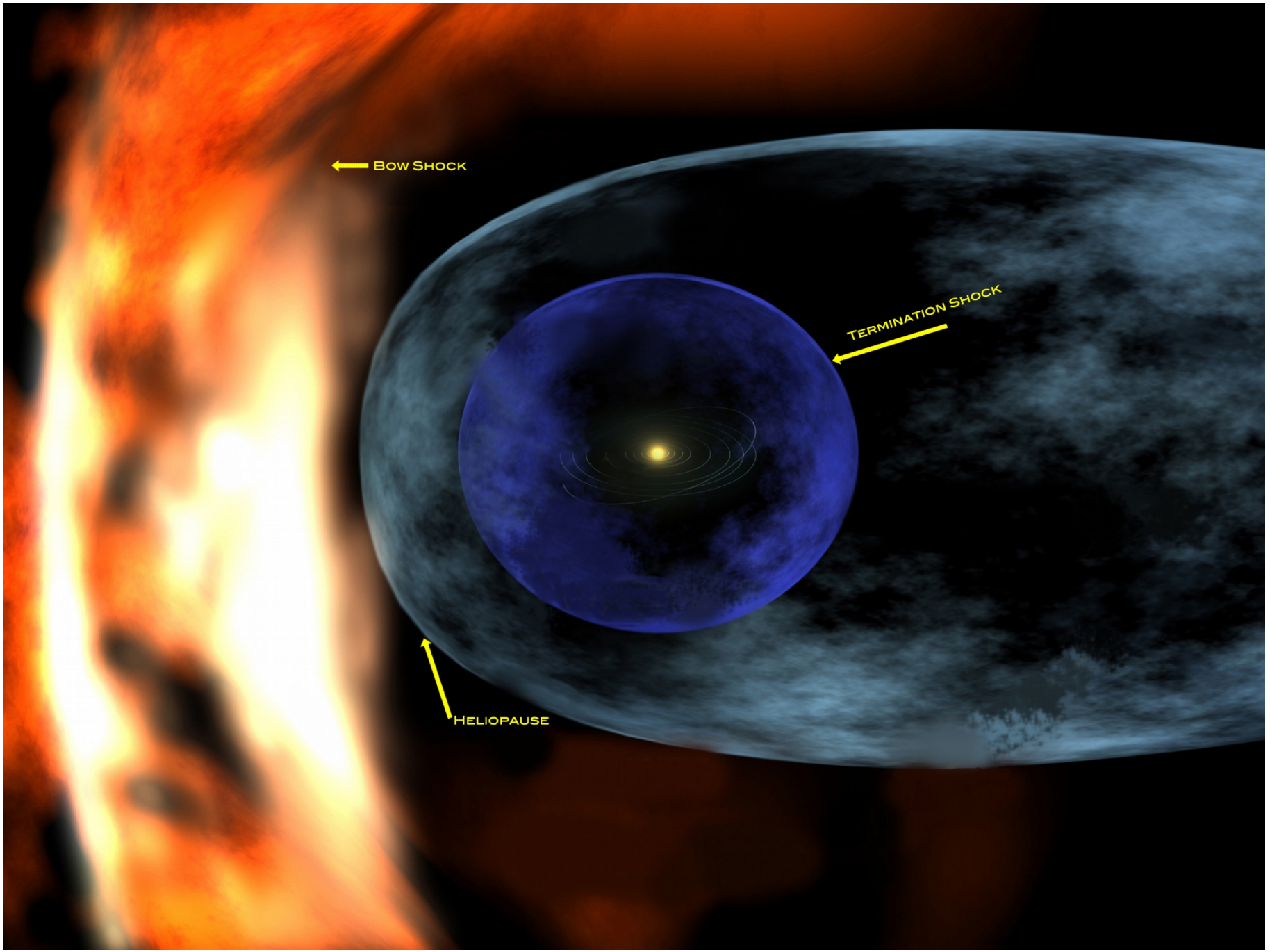
X. The measured velocity agrees fairly well with the value predicted from Parker's "solar wind" theory (*4*) but is higher than the value predicted from the observation of comet tail orientations (*5*) and much higher than the

. . . . . .

3) The plasma energy density is much greater than the energy density of the magnetic field. Thus we may conclude that the magnetic field in interplanetary space is carried along by the plasma, the field giving little or no hindrance to the plasma flow.

. . . . . .

# What can we learn from the Solar Wind ?



Mean Plasma Parameter

$V_{sw} = 441 \pm 111 km/s$

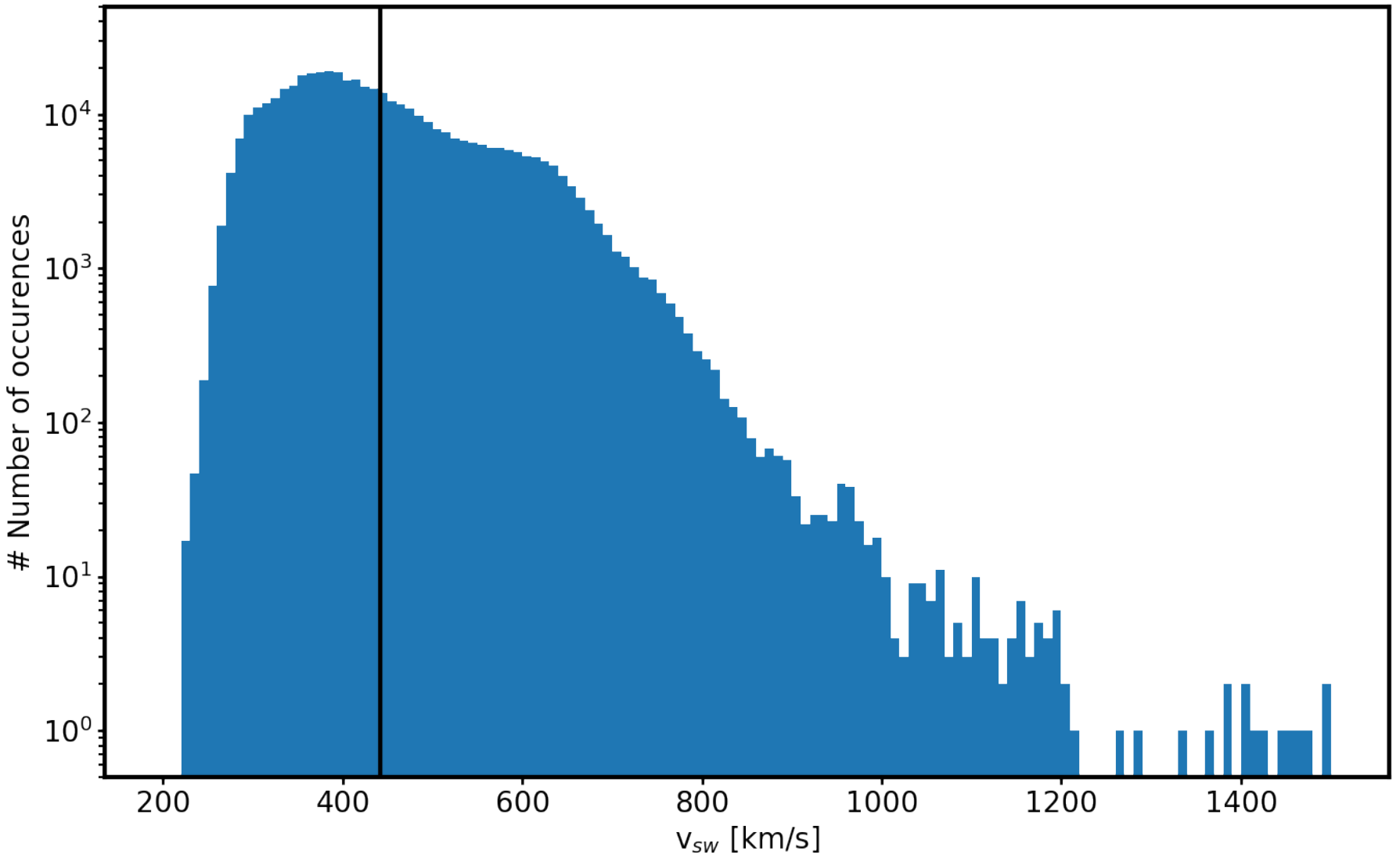
$D_{sw} = 6.2 \pm 5.6 cm^{-3}$

$T_{sw} = 89*10^3 \pm 84*10^3 K$

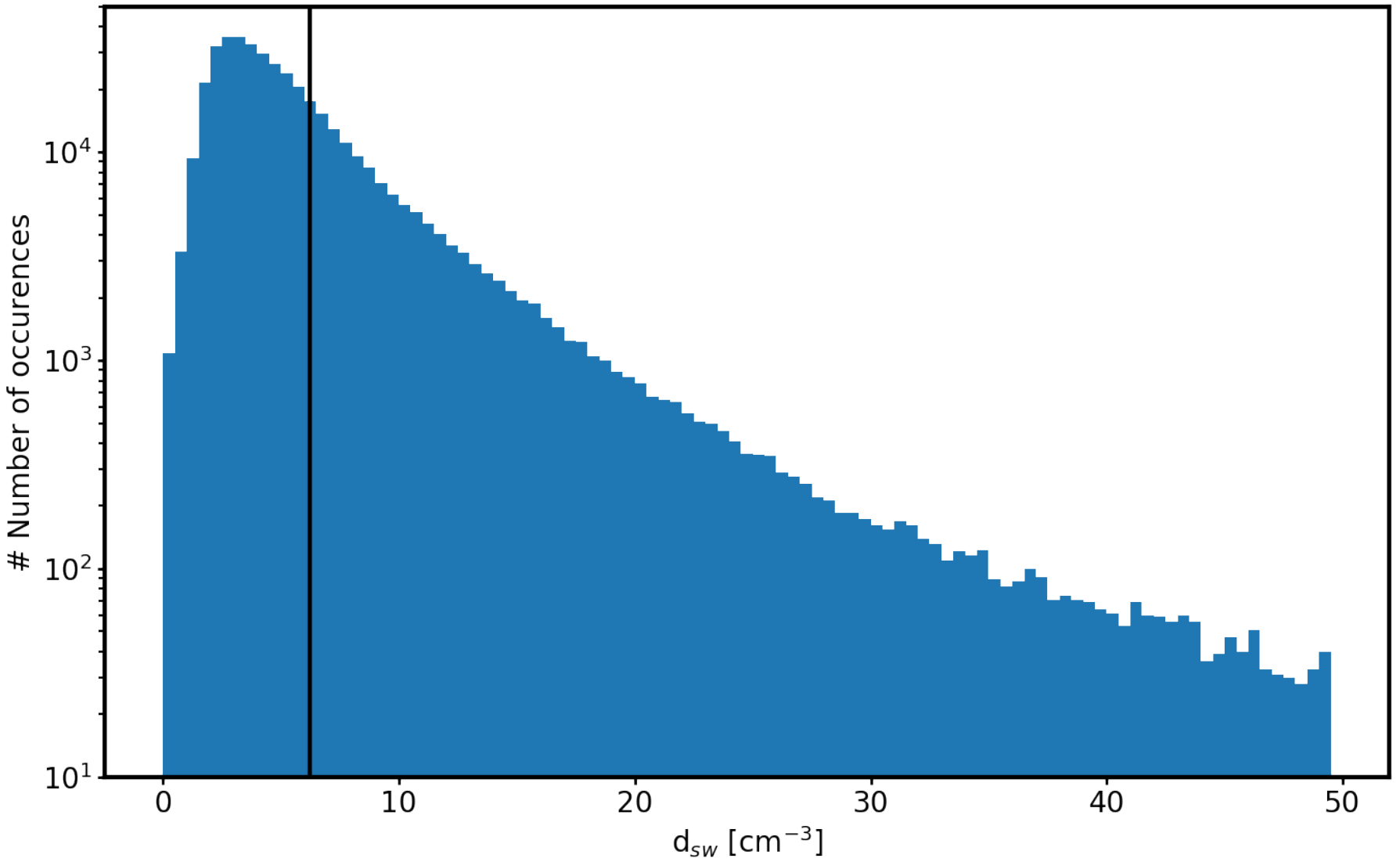
$v_{th,sw} = 25 km/s \pm 11 km/s$

$B = 5.45 \pm 3.2 nT$

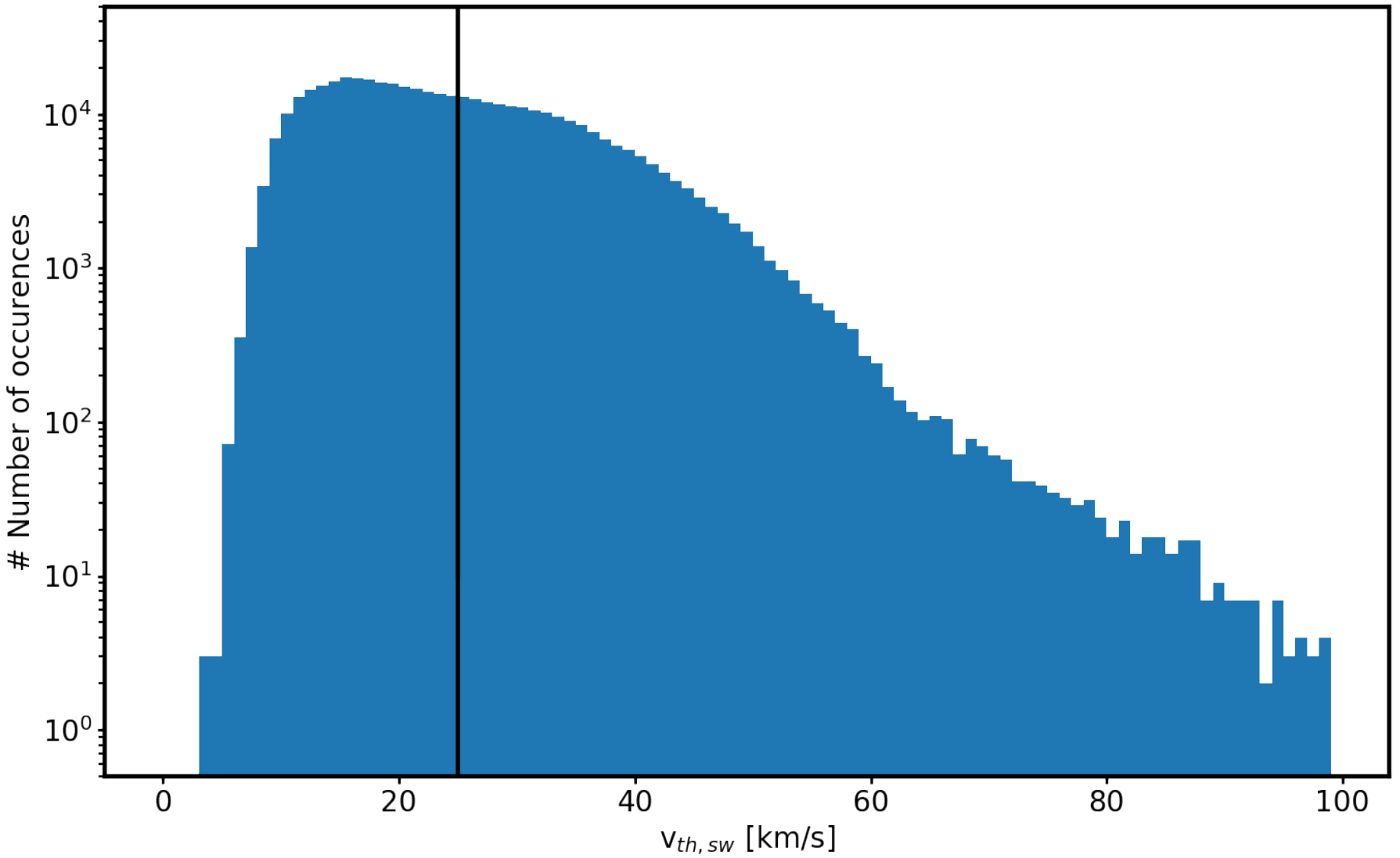
Lars Berger
berger@physik.uni-kiel.de




Lars Berger
berger@physik.uni-kiel.de

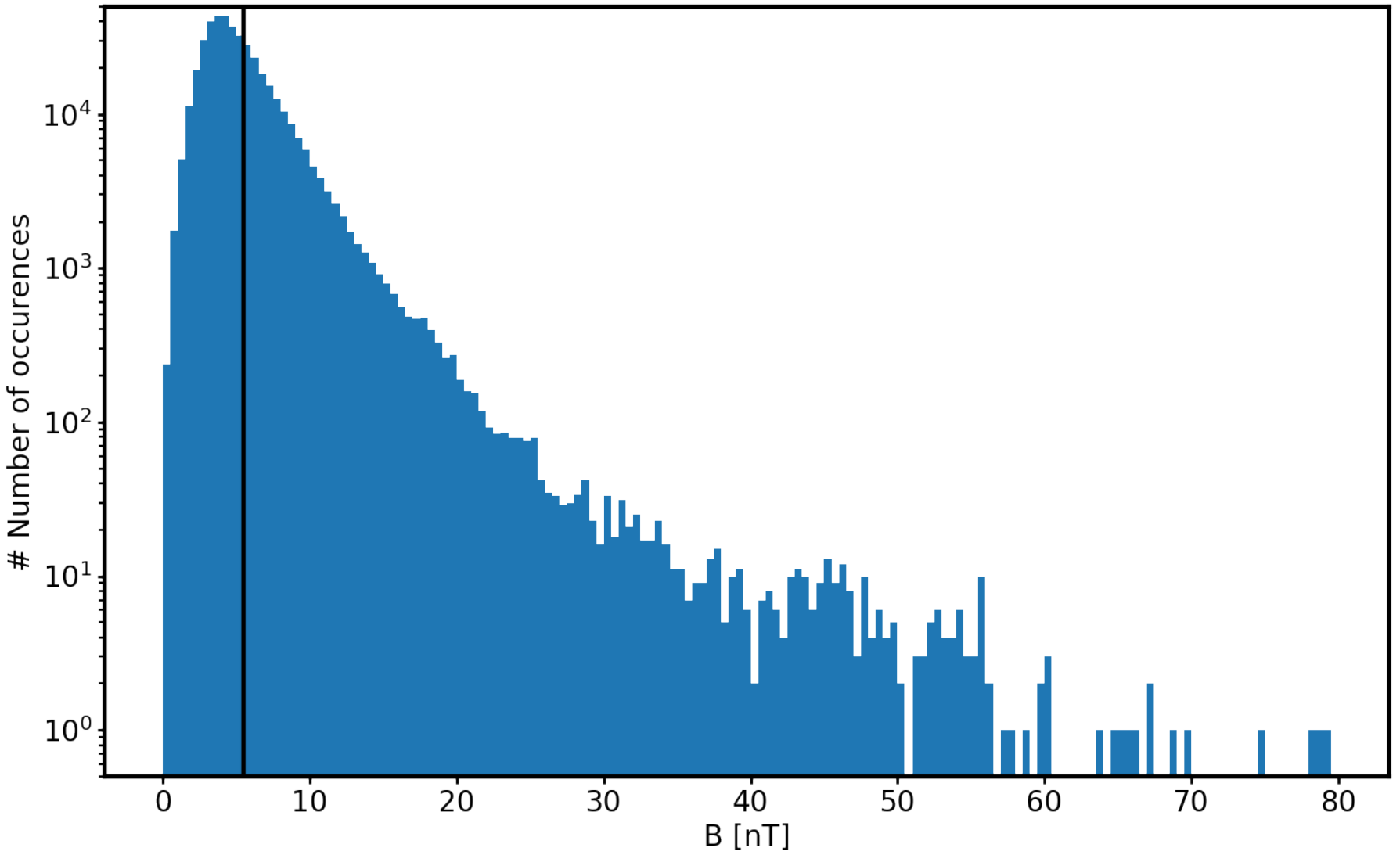



Lars Berger
berger@physik.uni-kiel.de



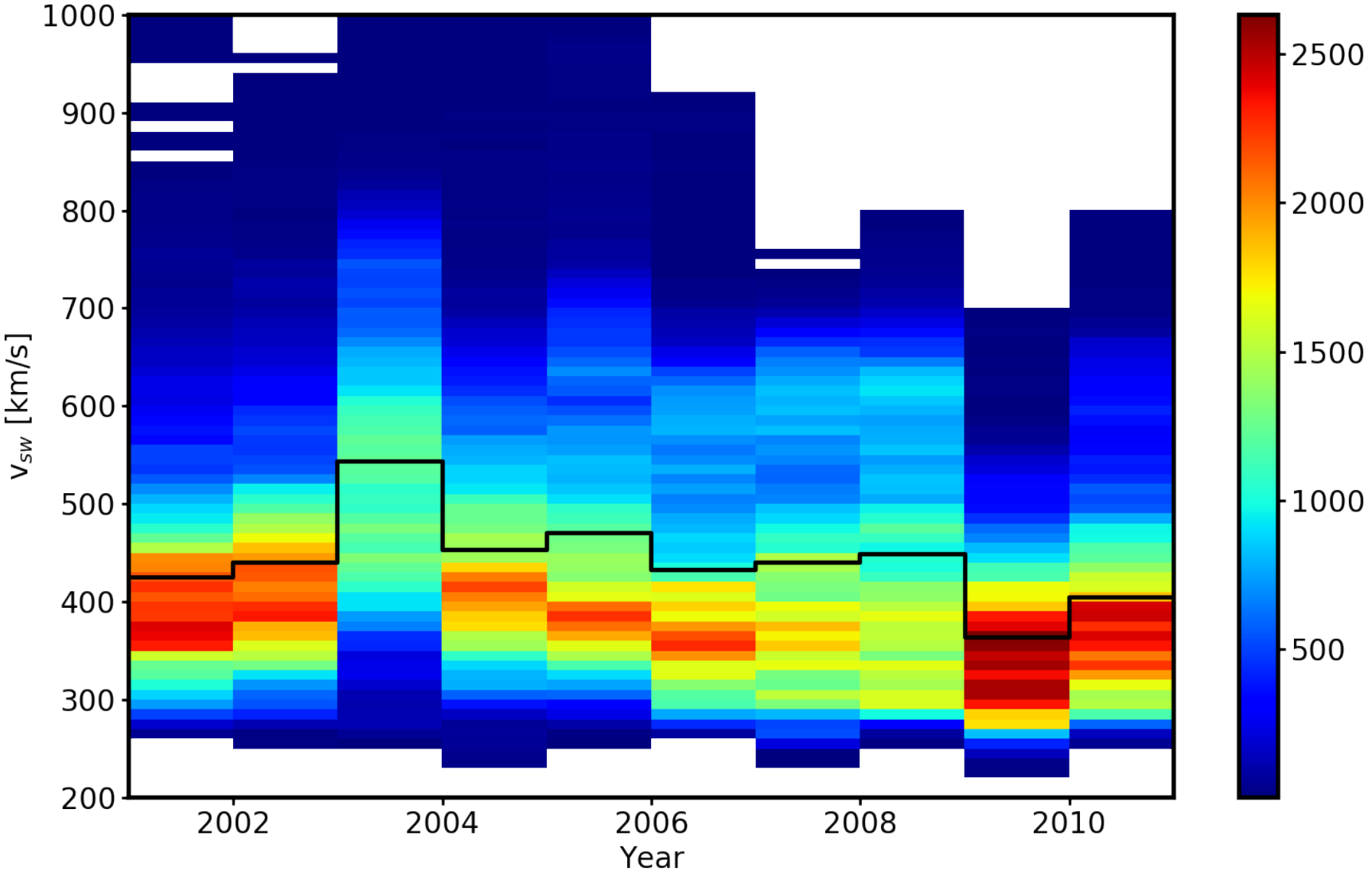

Lars Berger
berger@physik.uni-kiel.de

# Observations : 10 Years ACE 2001-2010

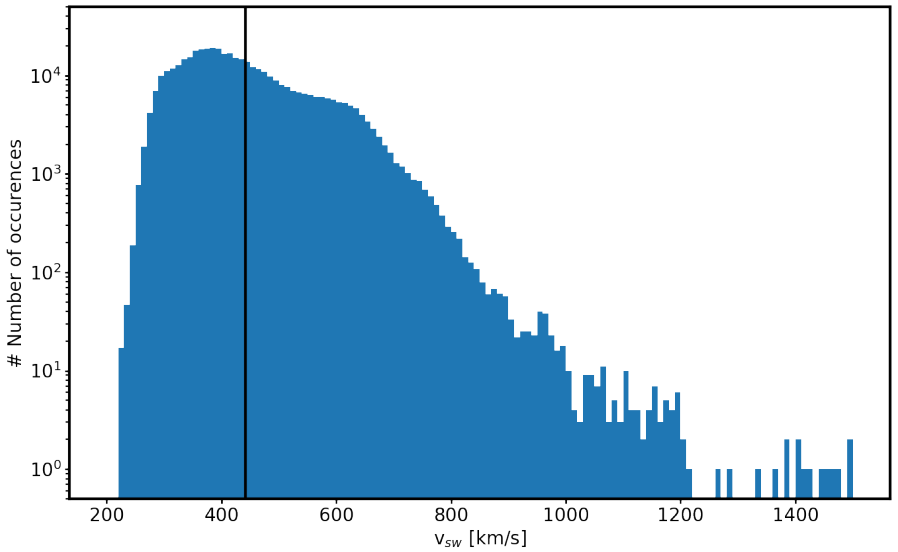


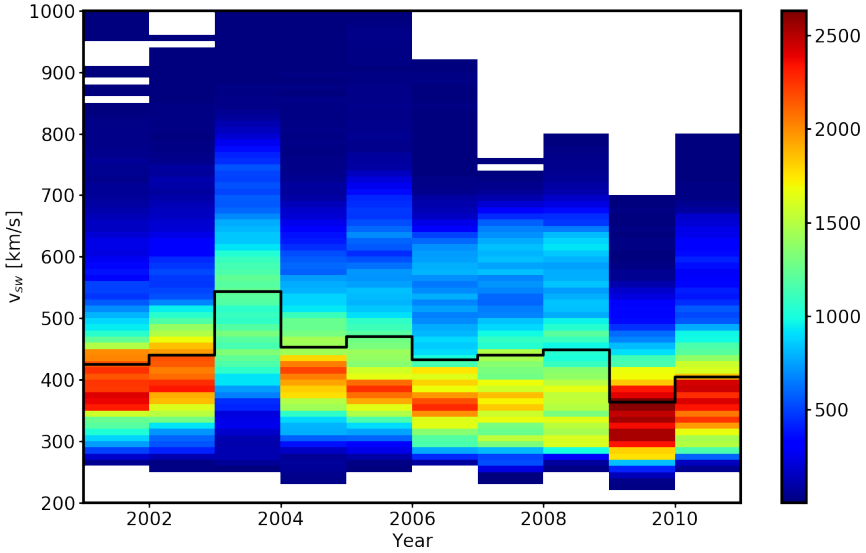

Lars Berger
berger@physik.uni-kiel.de

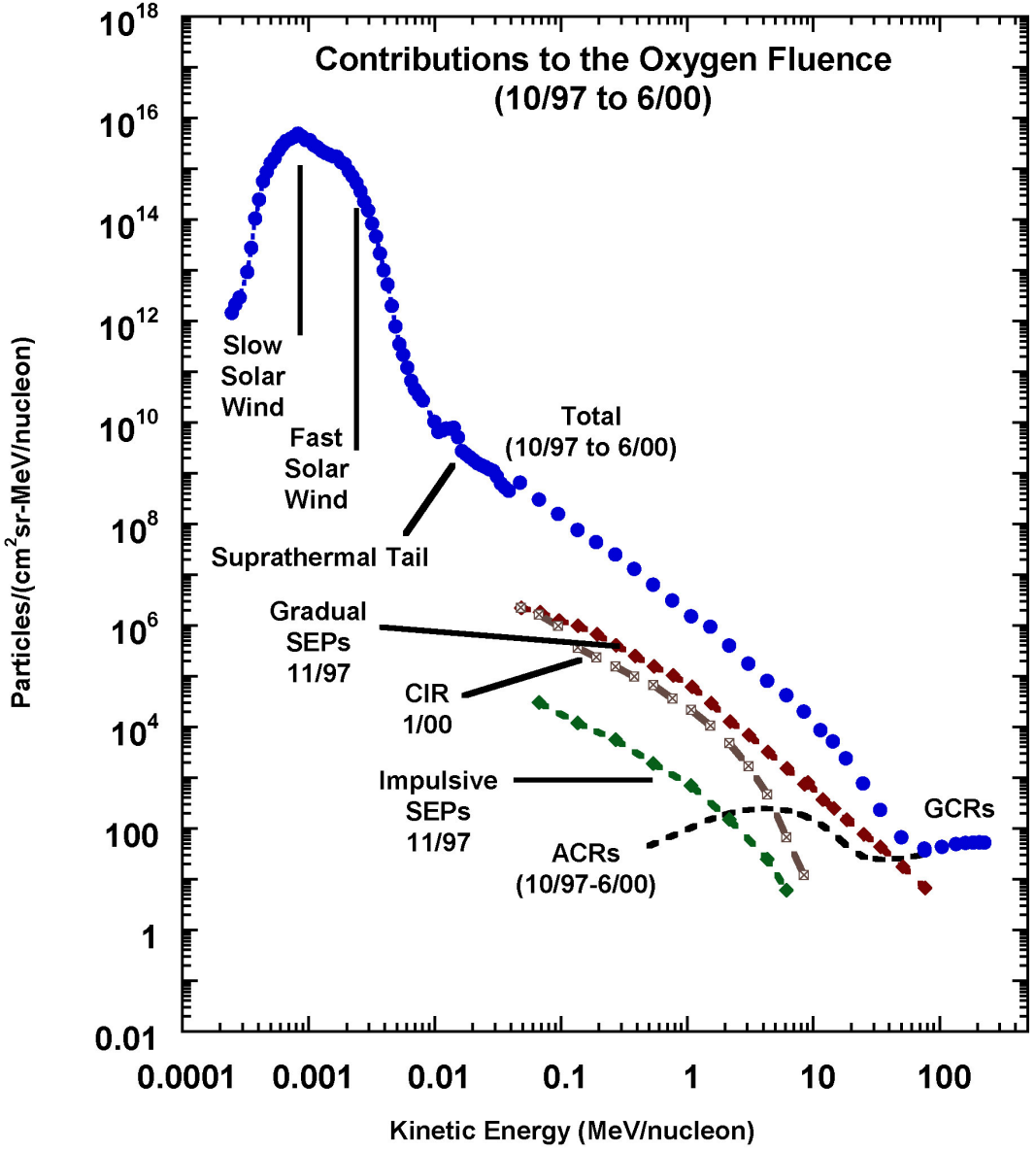
# Observations : 10 Years ACE 2001-2010 – Solar Cycle Variation




Lars Berger
berger@physik.uni-kiel.de

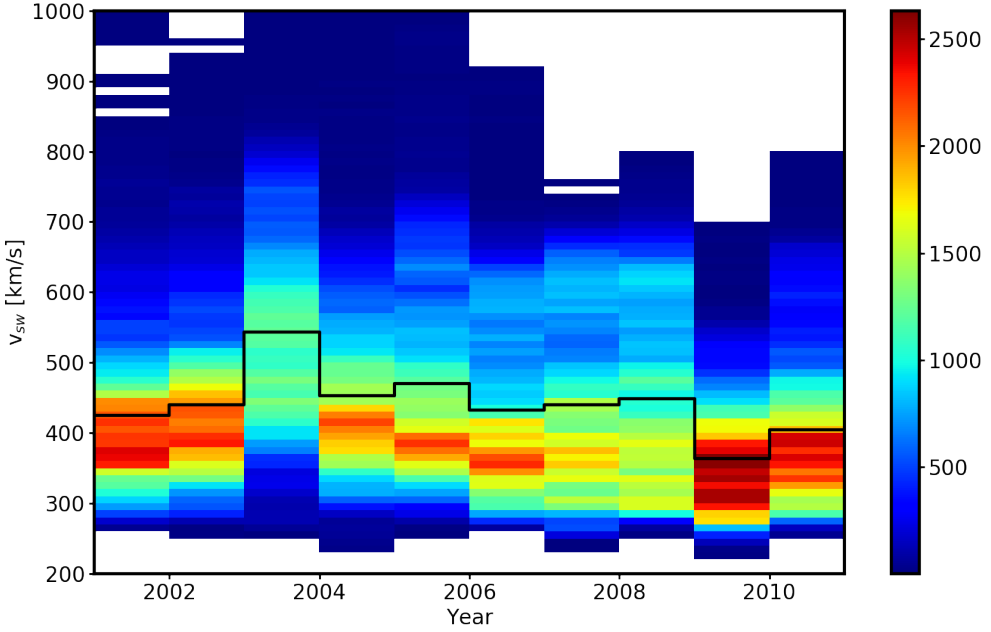


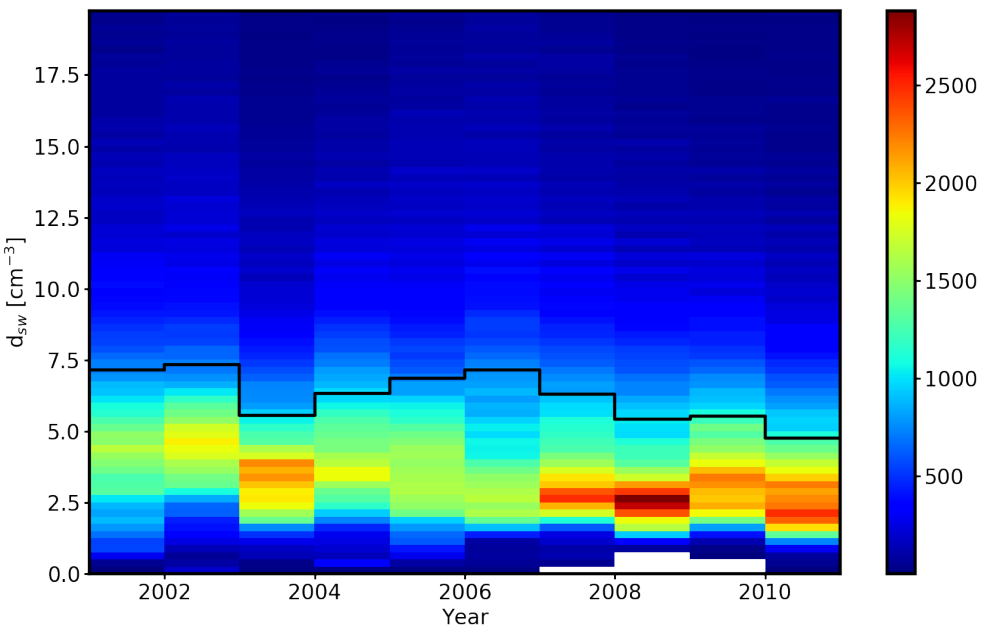



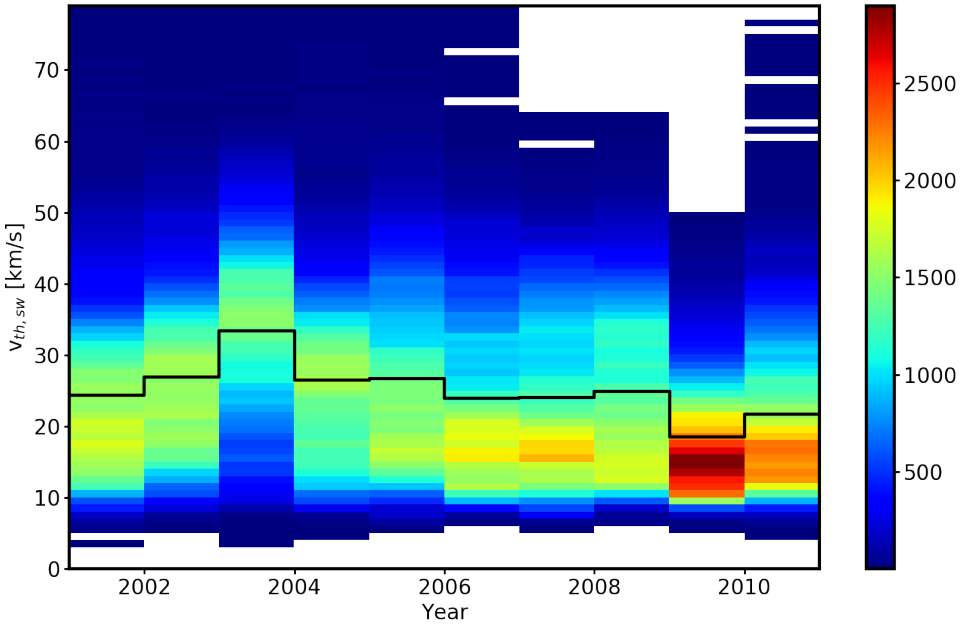



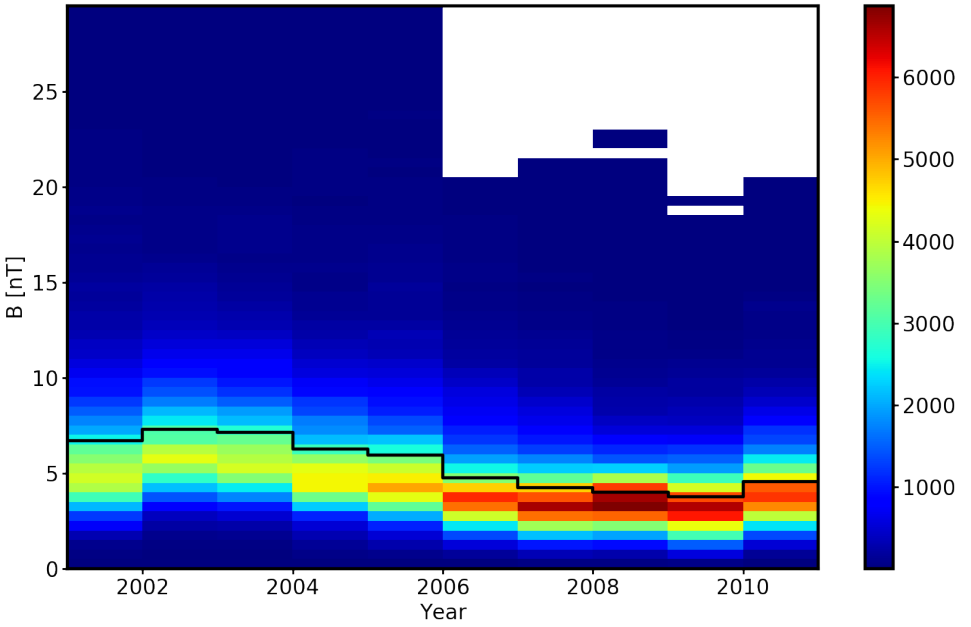

From http://www.srl.caltech.edu

# Observations : 10 Years ACE 2001-2010 – Solar Cycle Variation



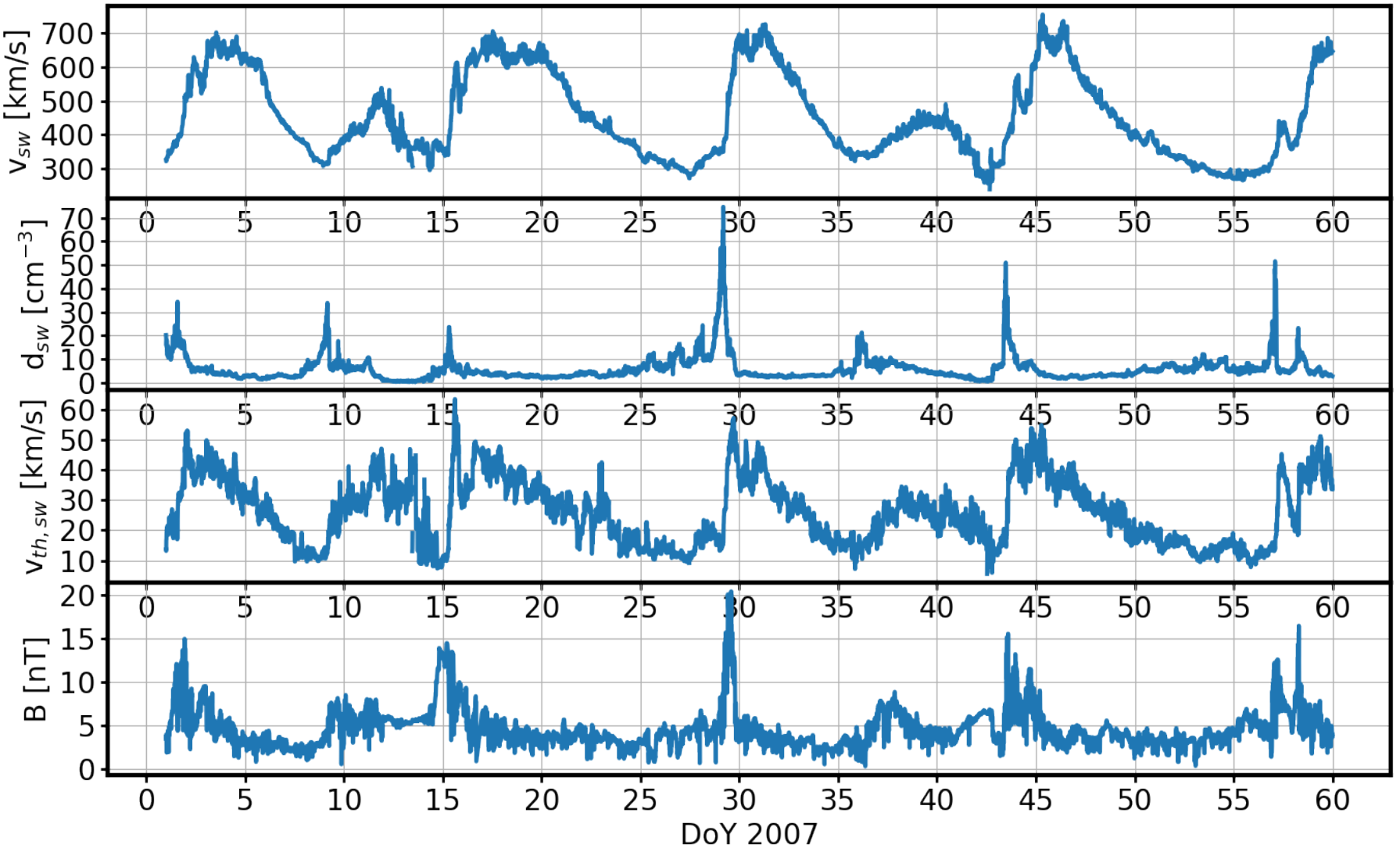



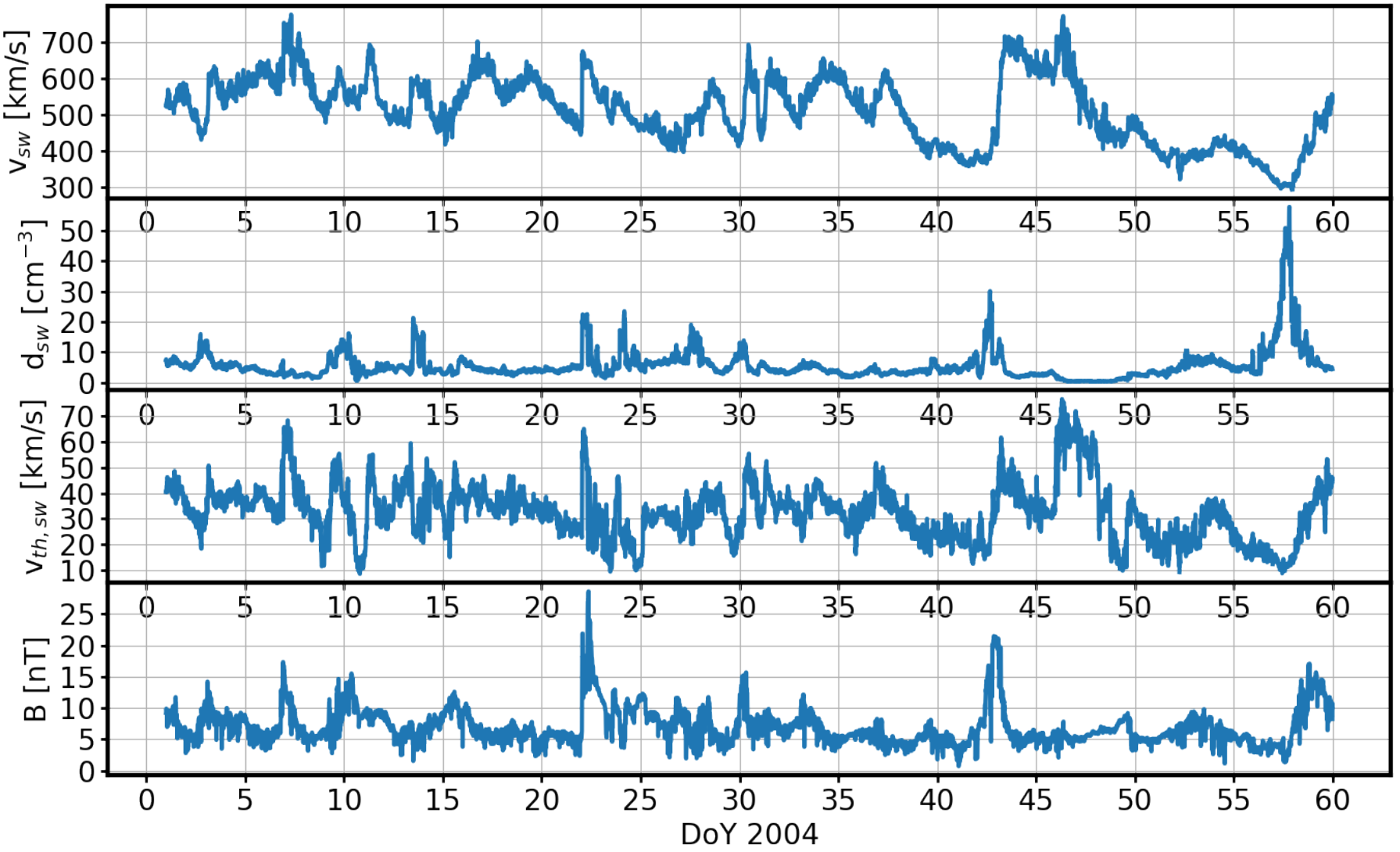



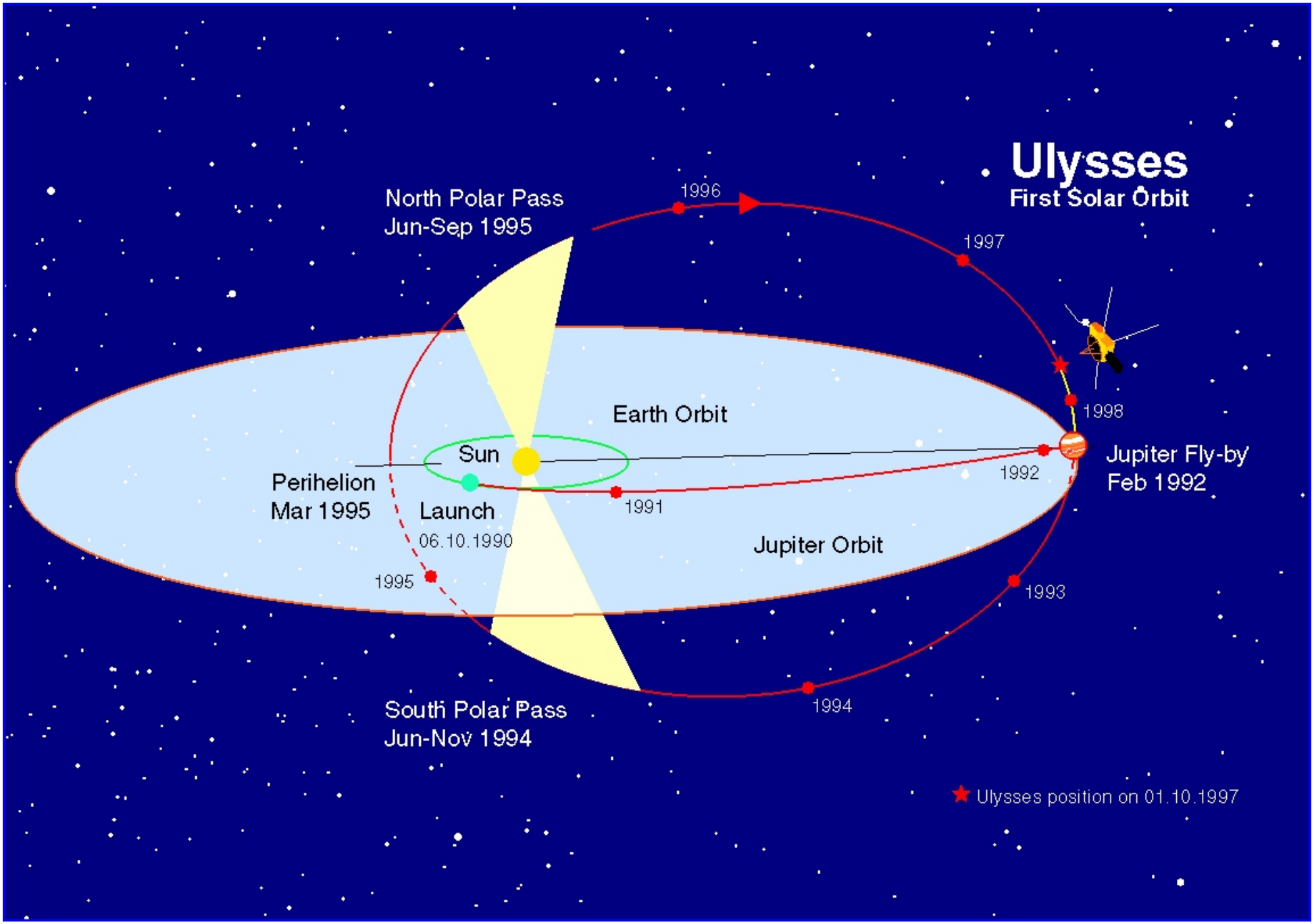




Lars Berger
berger@physik.uni-kiel.de

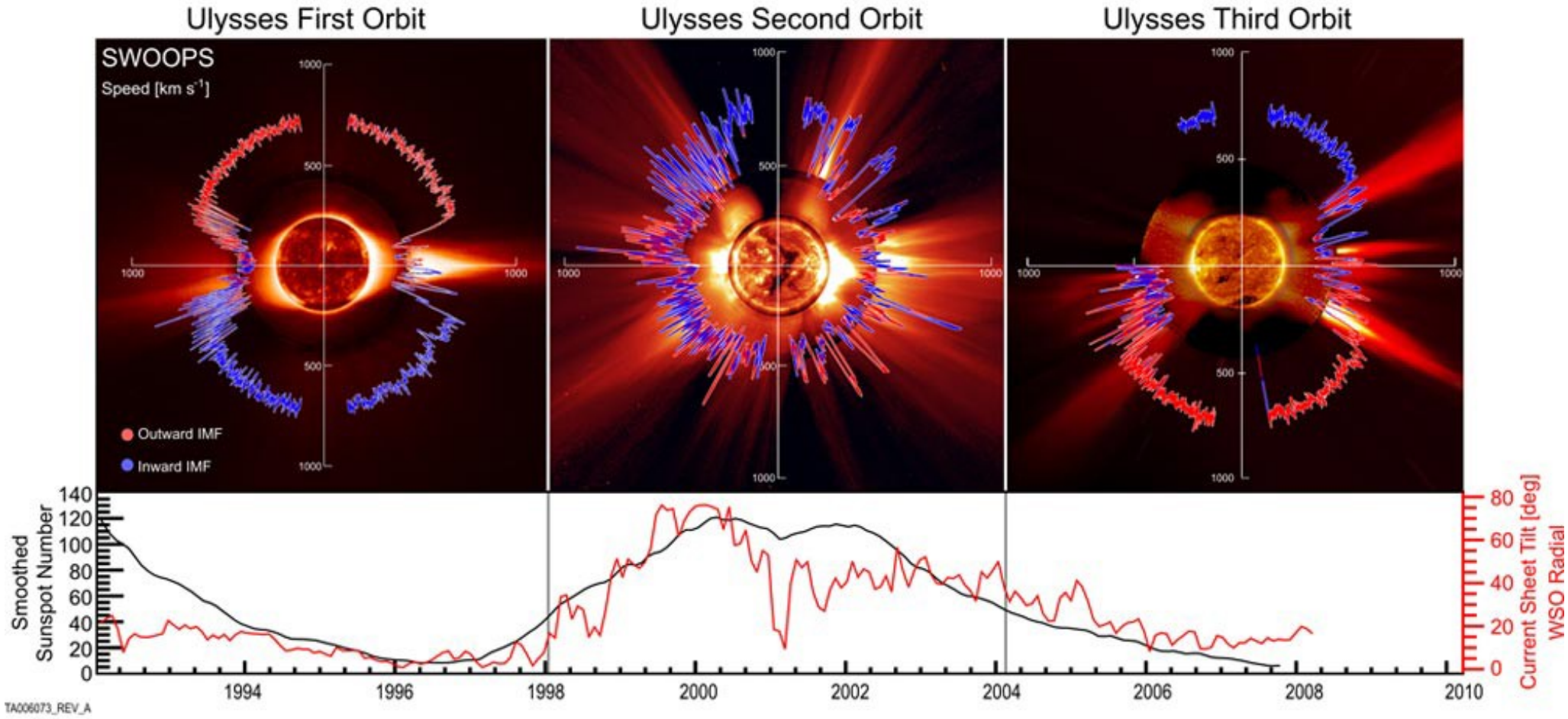
# Observations : 10 Years ACE 2001-2010 – Solar Minimum

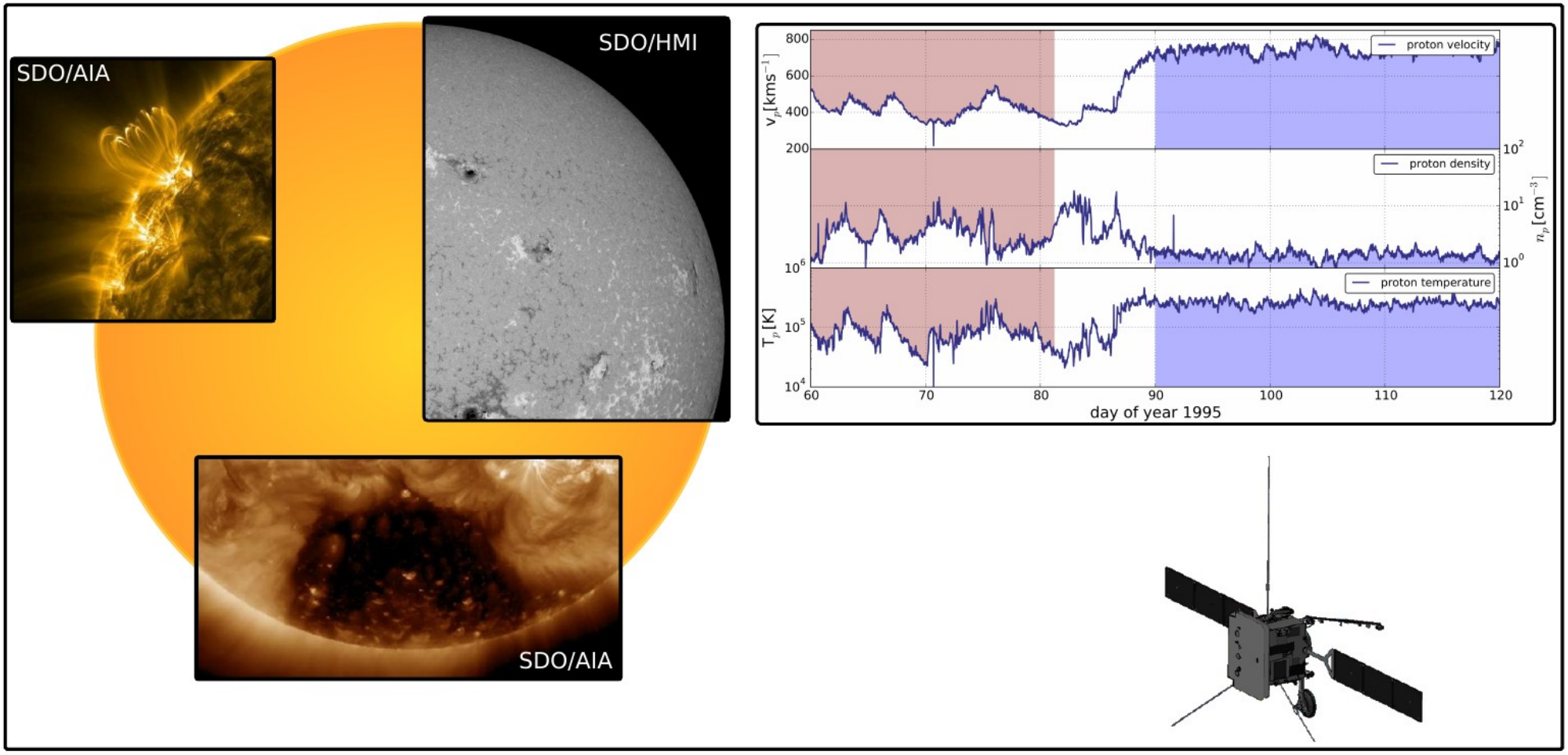



$v_{sw}$ [km/s]
700
600
500
400
300
$d_{sw}$ [$cm^{-3}$]
50
40
30
20
10
0
$v_{th,sw}$ [km/s]
70
60
50
40
30
20
10
B [nT]
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40
45
50
55
60
DoY 2004


Ulysses
First Solar Orbit
North Polar Pass
Jun-Sep 1995
South Polar Pass
Jun-Nov 1994
1996
1997
1998
1992
1991
1995
1994
1993
Earth Orbit
Sun
Perihelion
Mar 1995
Launch
06.10.1990
Jupiter Orbit
Jupiter Fly-by
Feb 1992
Ulysses position on 01.10.1997

# Origin of the Solar Wind : Ulysses 1990

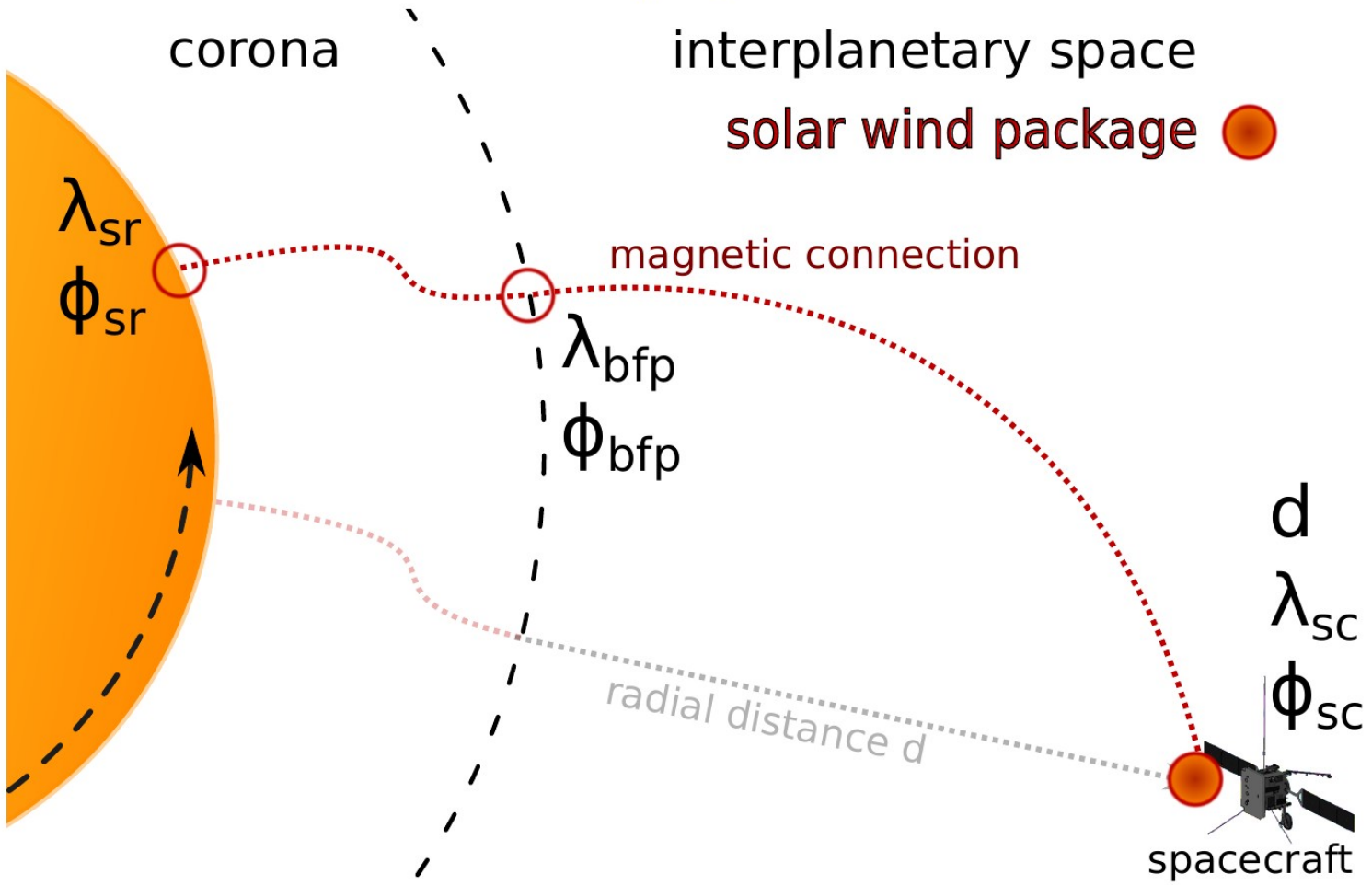





Source small pictures: Courtesy of NASA/SDO and the AIA and HMI science teams.

# Linking in-situ Data to its Source

## Back Mapping - Ballistic




$$\lambda_{sr}(d, v_{sw}) = \lambda_{sc} + \frac{\omega d}{v_{sw}} + \Delta\lambda_{mag}$$
$$\phi_{sr} = \phi_{sc} + \Delta\phi_{mag}$$

# Linking in-situ Data to its Source

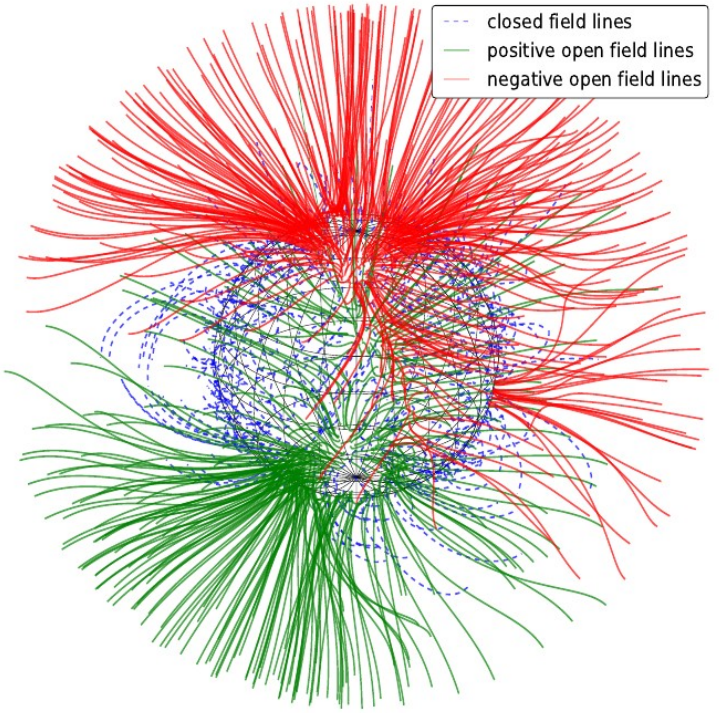
## Back Mapping - Magnetic

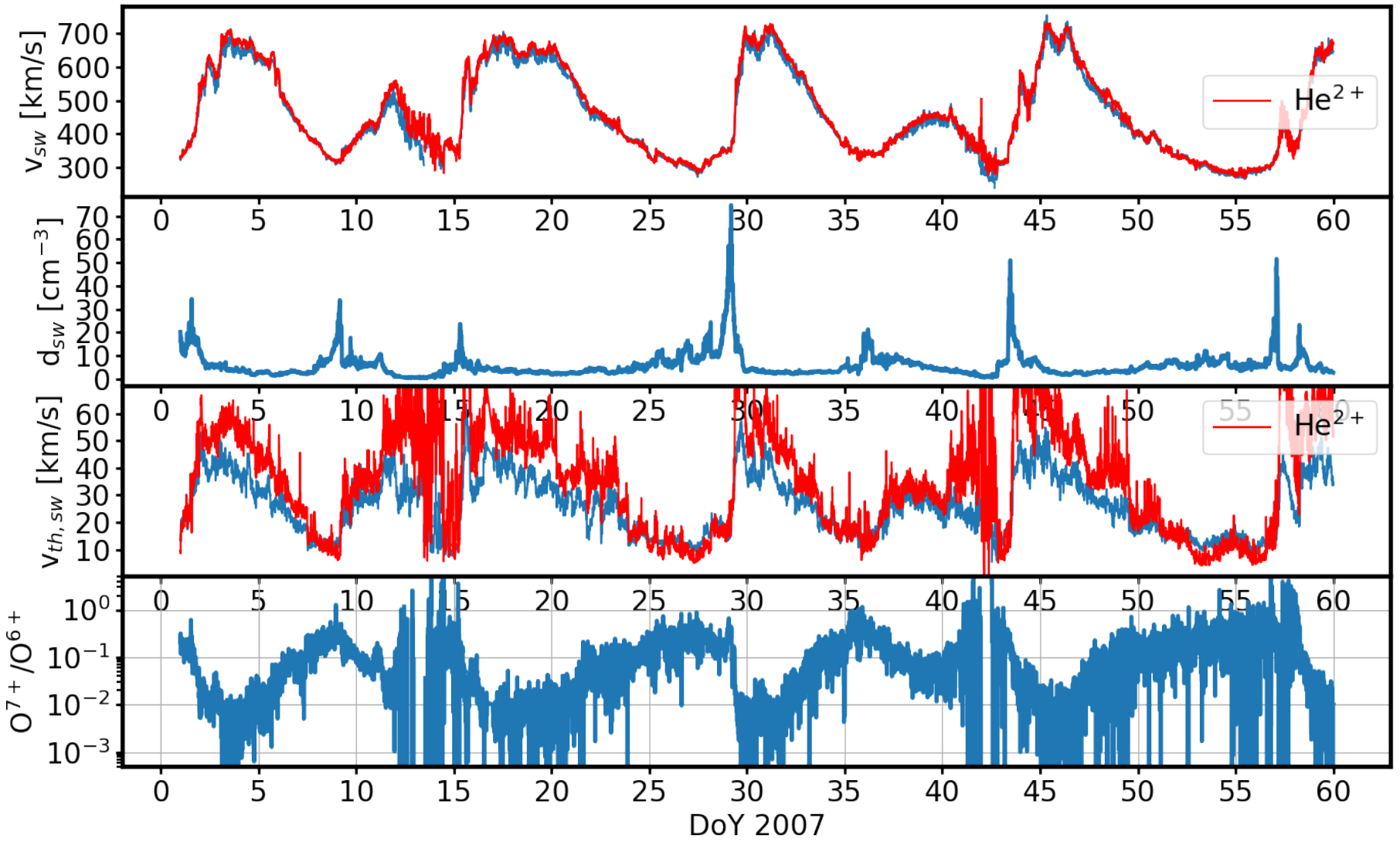
$\Delta\lambda_{mag}$ and $\Delta\phi_{mag}$ must be determined by using a model of the coronal magnetic field: The Potential Field Source Surface (PFSS) model (Altschuler & Newkirk (1969), here Kruse (2018)).

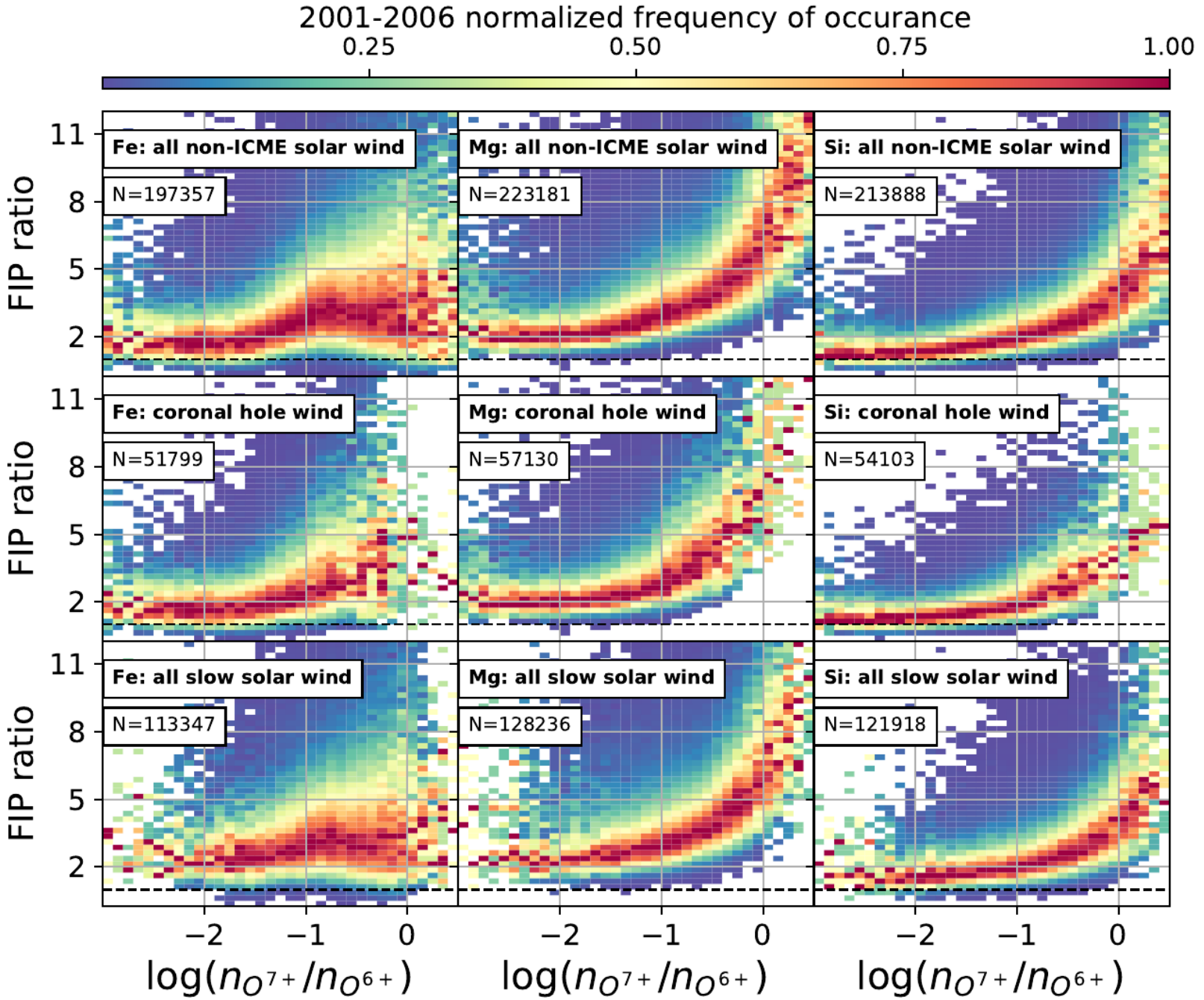
Assumption: a current-free corona

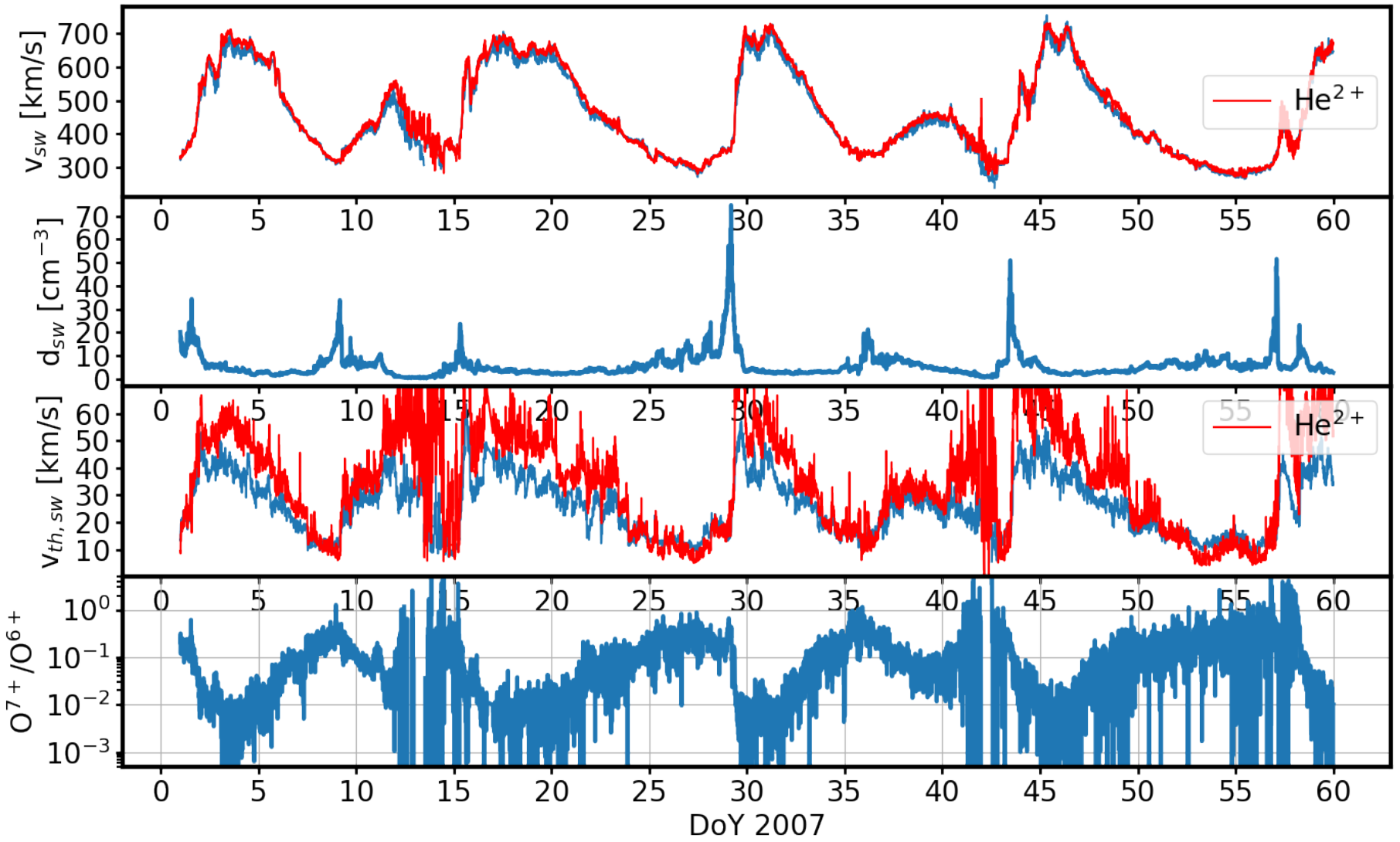
Inner boundary: photospheric magnetic field, taken from synoptic maps (MDI on SOHO)

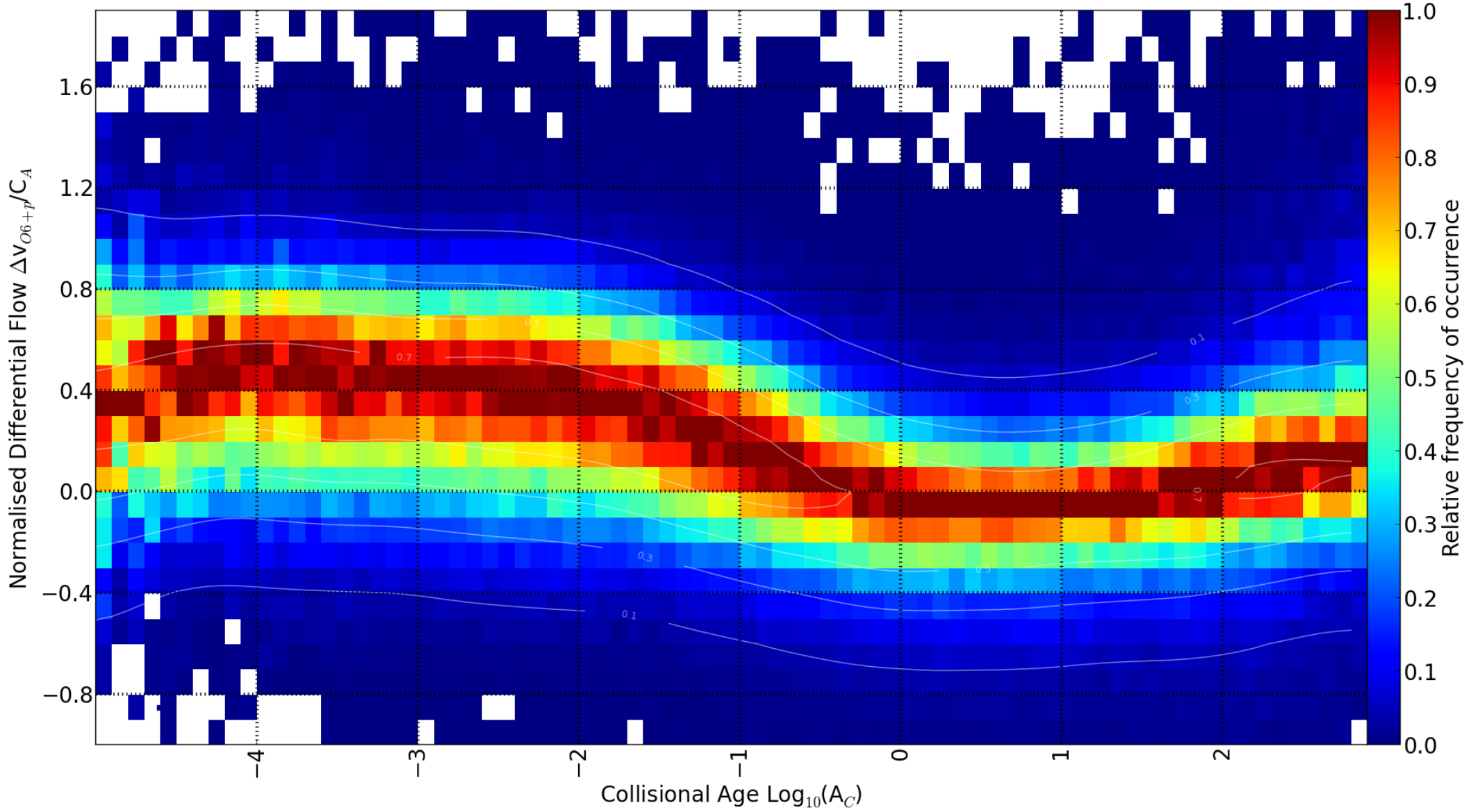
Outer boundary: the source surface at 2.5 $R_\odot$, here field lines must be strictly radial



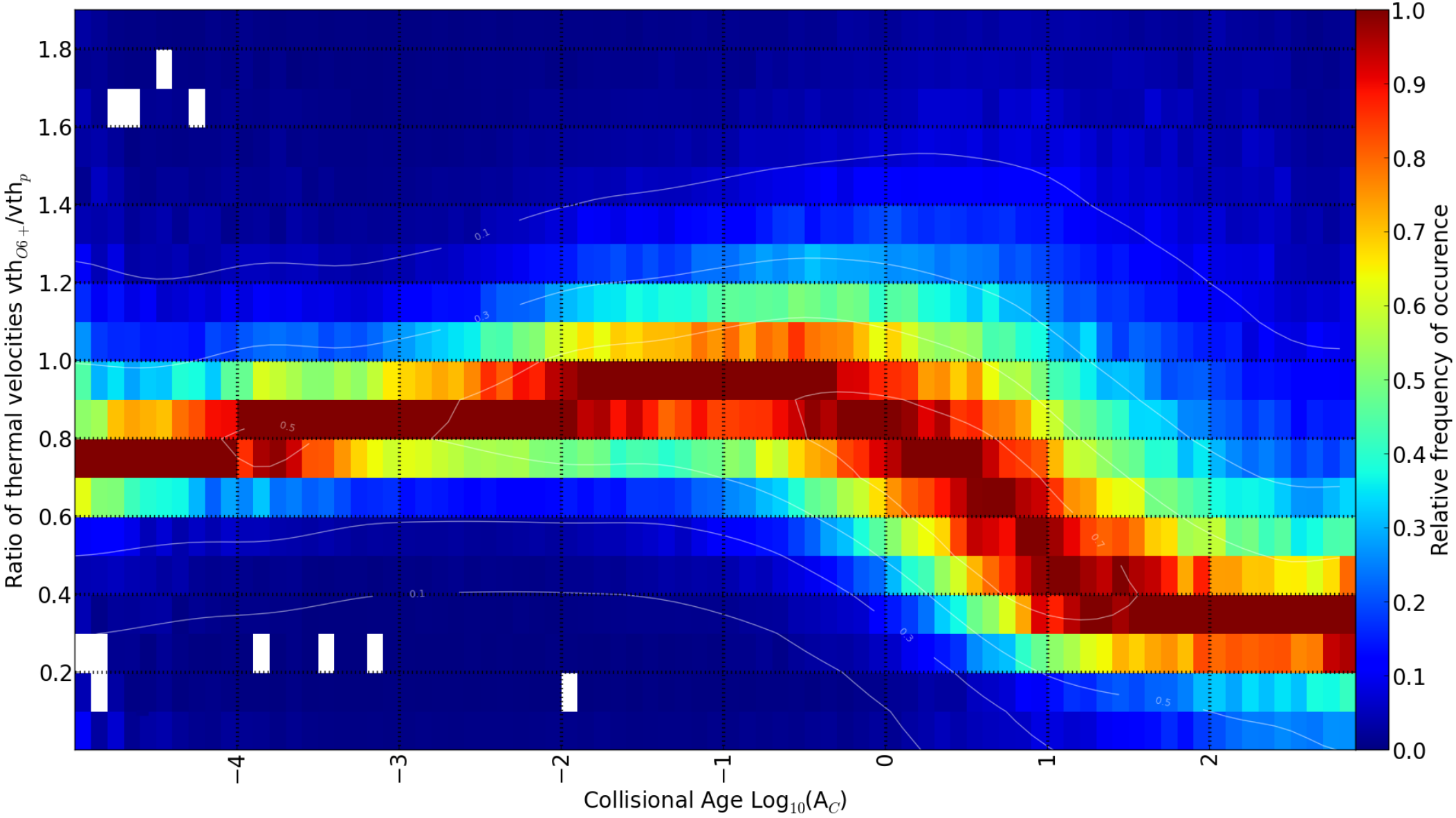

$v_{sw}$ [km/s]
700
600
500
400
300
$He^{2+}$
$d_{sw}$ [$cm^{-3}$]
70
60
50
40
30
20
10
0
$v_{th,sw}$ [km/s]
60
50
40
30
20
10
$He^{2+}$
$O^{7+}/O^{6+}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
0
5
10
15
20
25
30
35
40
45
50
55
60
DoY 2007

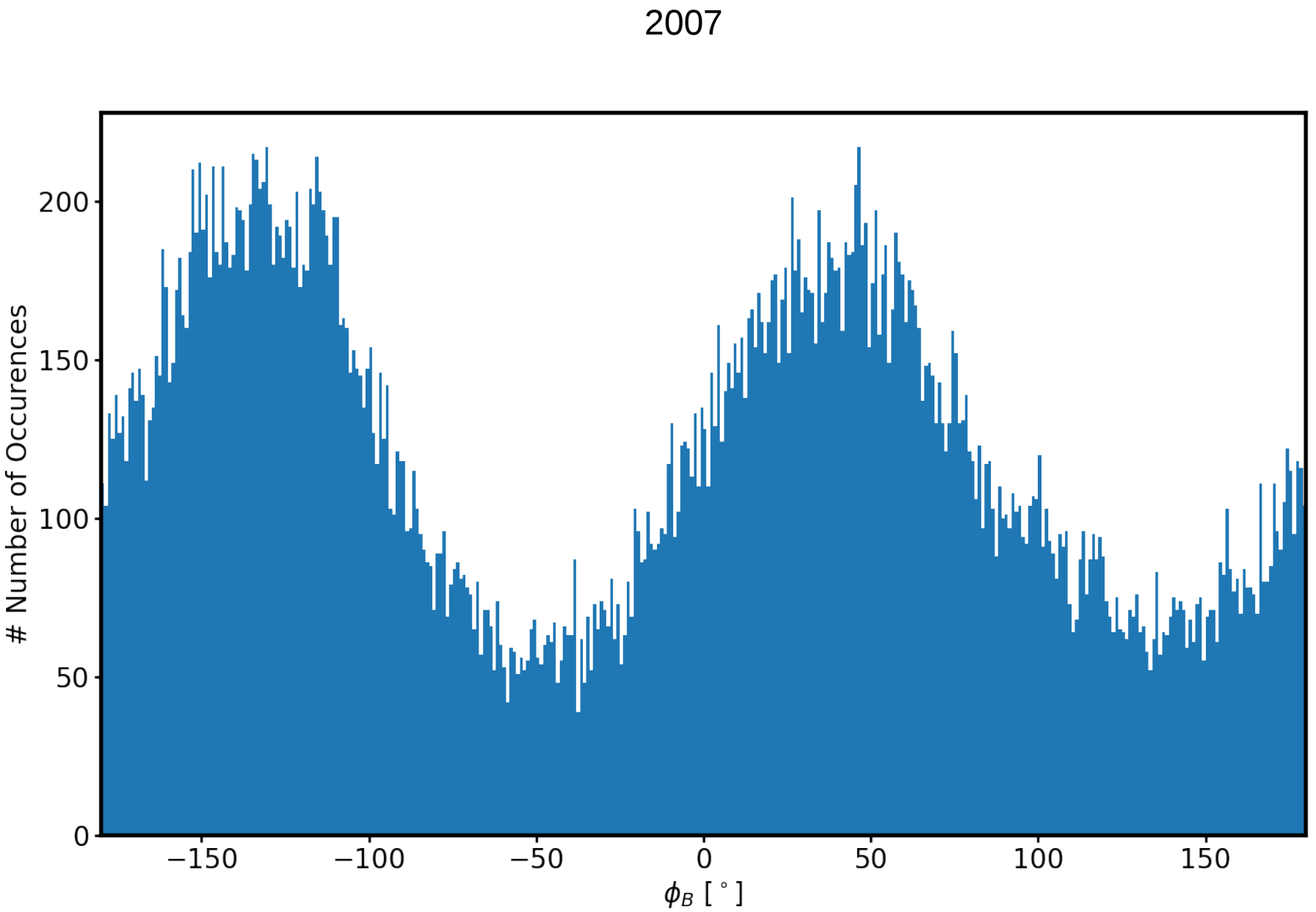

2001-2006 normalized frequency of occurance
0.25
0.50
0.75
1.00
Fe: all non-ICME solar wind
N=197357
Mg: all non-ICME solar wind
N=223181
Si: all non-ICME solar wind
N=213888
Fe: coronal hole wind
N=51799
Mg: coronal hole wind
N=57130
Si: coronal hole wind
N=54103
Fe: all slow solar wind
N=113347
Mg: all slow solar wind
N=128236
Si: all slow solar wind
N=121918
FIP ratio
11
8
5
2
−2
−1
0
log(n_O7+/n_O6+)

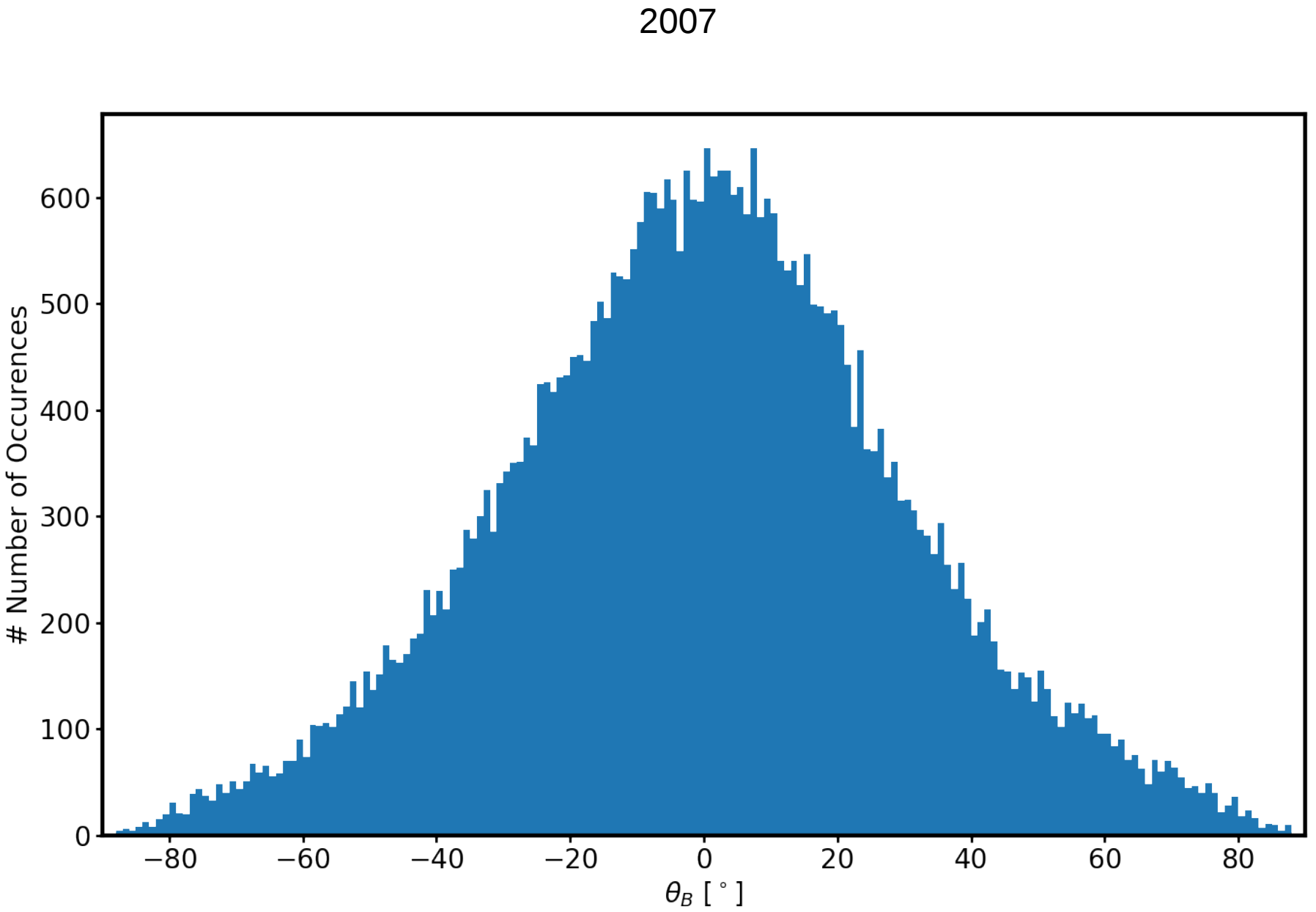

$v_{sw}$ [km/s]
700
600
500
400
300
He$^{2+}$
$d_{sw}$ [cm$^{-3}$]
70
60
50
40
30
20
10
0
$v_{th,sw}$ [km/s]
60
50
40
30
20
10
He$^{2+}$
$O^{7+}/O^{6+}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
0
5
10
15
20
25
30
35
40
45
50
55
60
DoY 2007


Normalised Differential Flow $\Delta v_{O6+p}/C_A$
1.6
1.2
0.8
0.4
0.0
−0.4
−0.8
−4
−3
−2
−1
0
1
2
Collisional Age $\mathrm{Log}_{10}(A_C)$
Relative frequency of occurrence
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

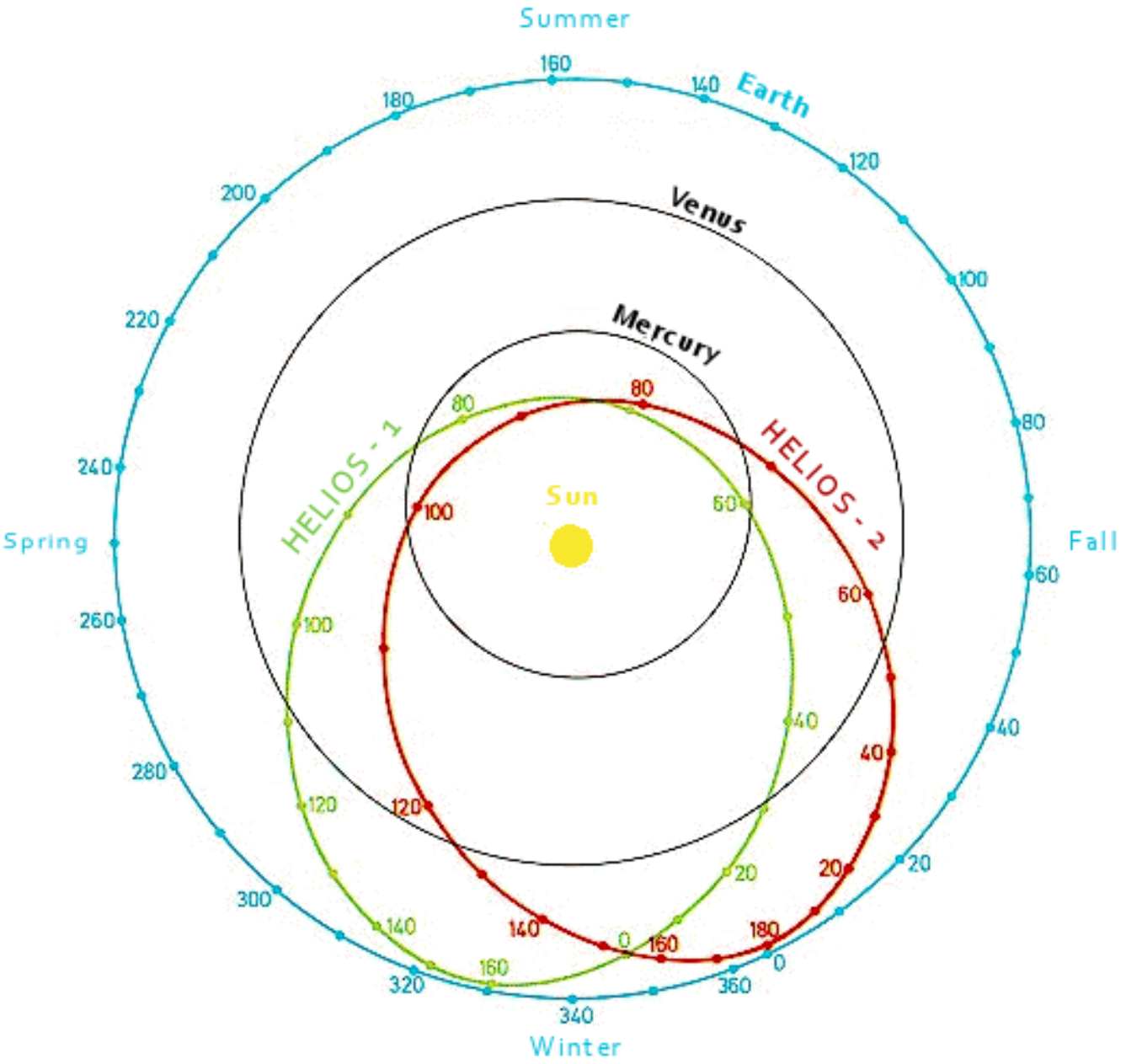
# Non thermal features – Equal thermal speed vs. Equal Temperature (Nils Janitzek)

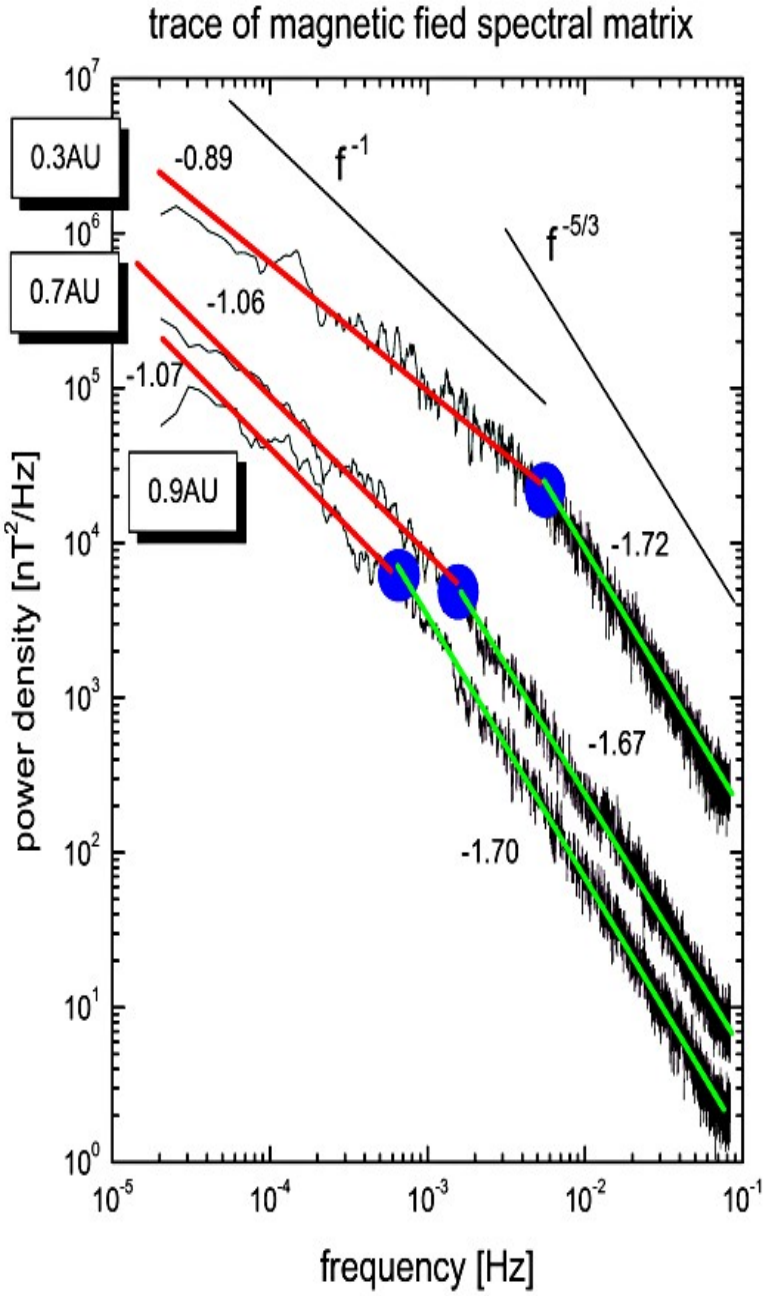


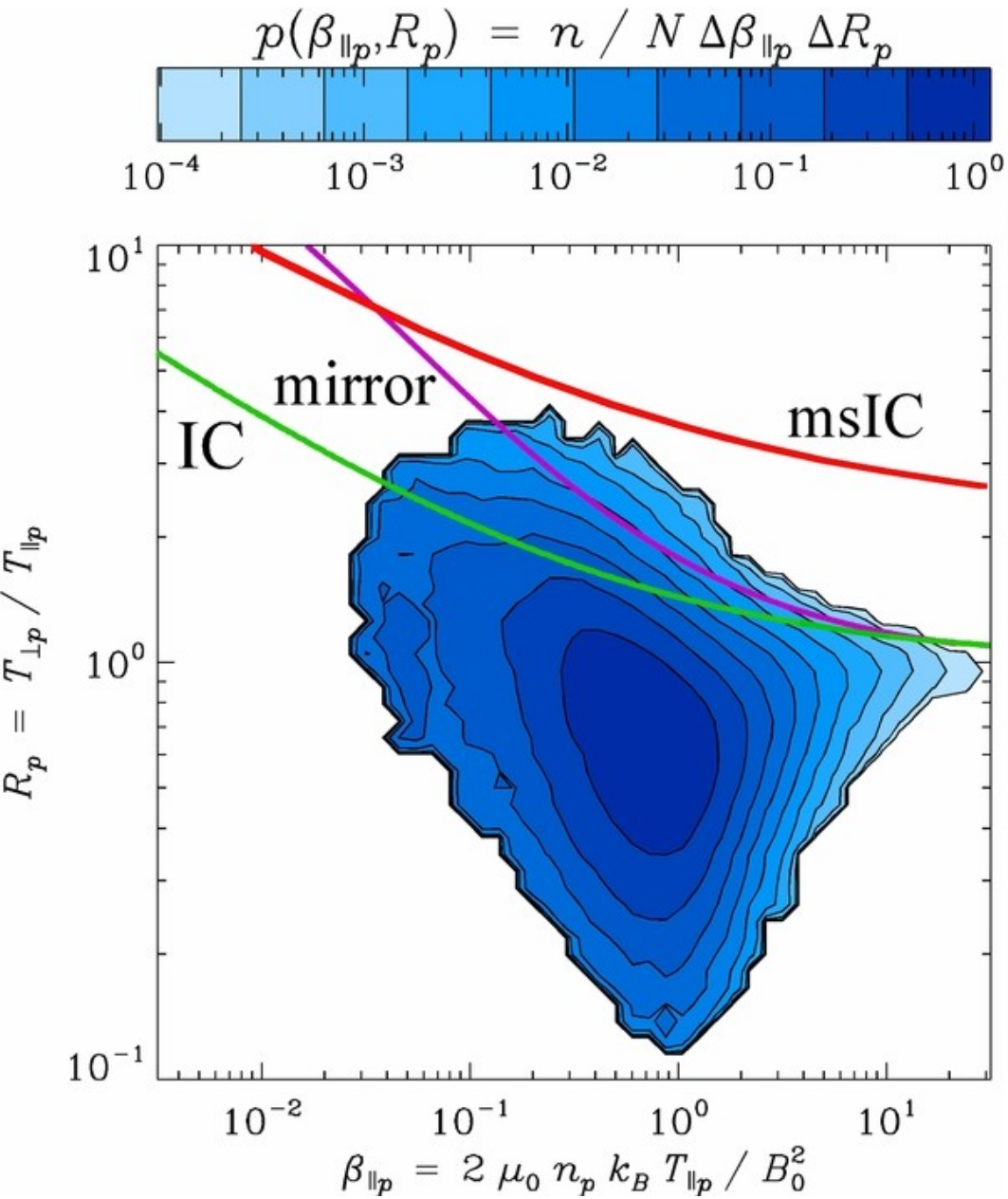

2007
# Number of Occurences
0
50
100
150
200
−150
−100
−50
0
50
100
150
$\phi_B$ [°]

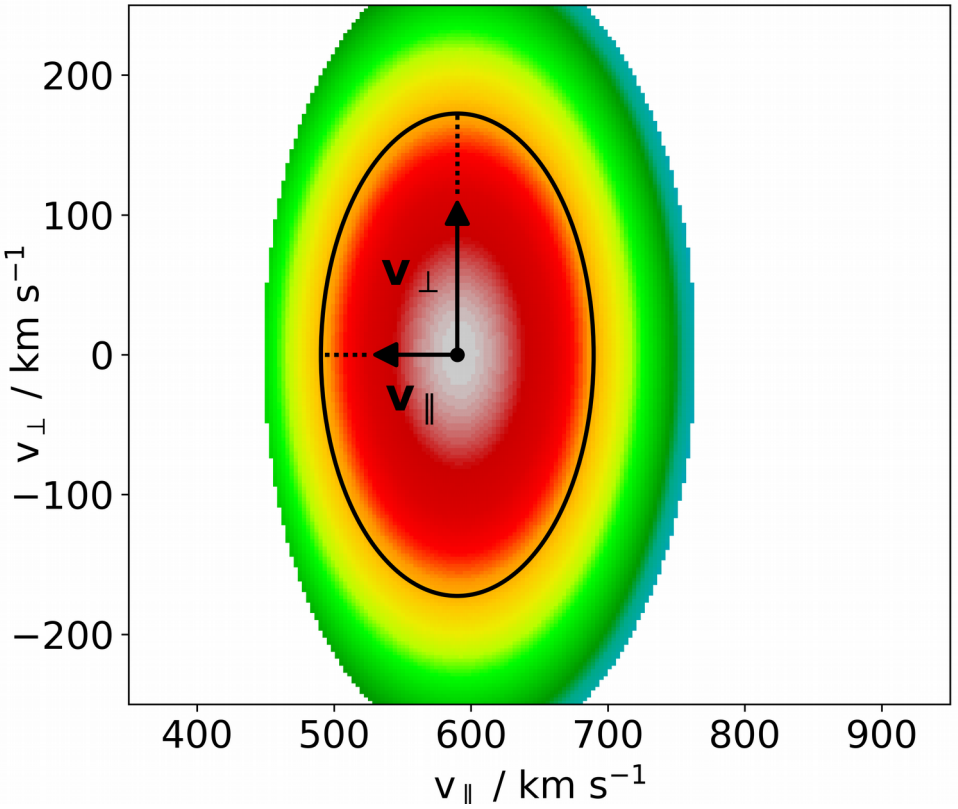

2007
# Number of Occurences
0
100
200
300
400
500
600
−80
−60
−40
−20
0
20
40
60
80
$\theta_B$ [ ° ]

# Parker Spiral globally – Helios 1974 / 1976



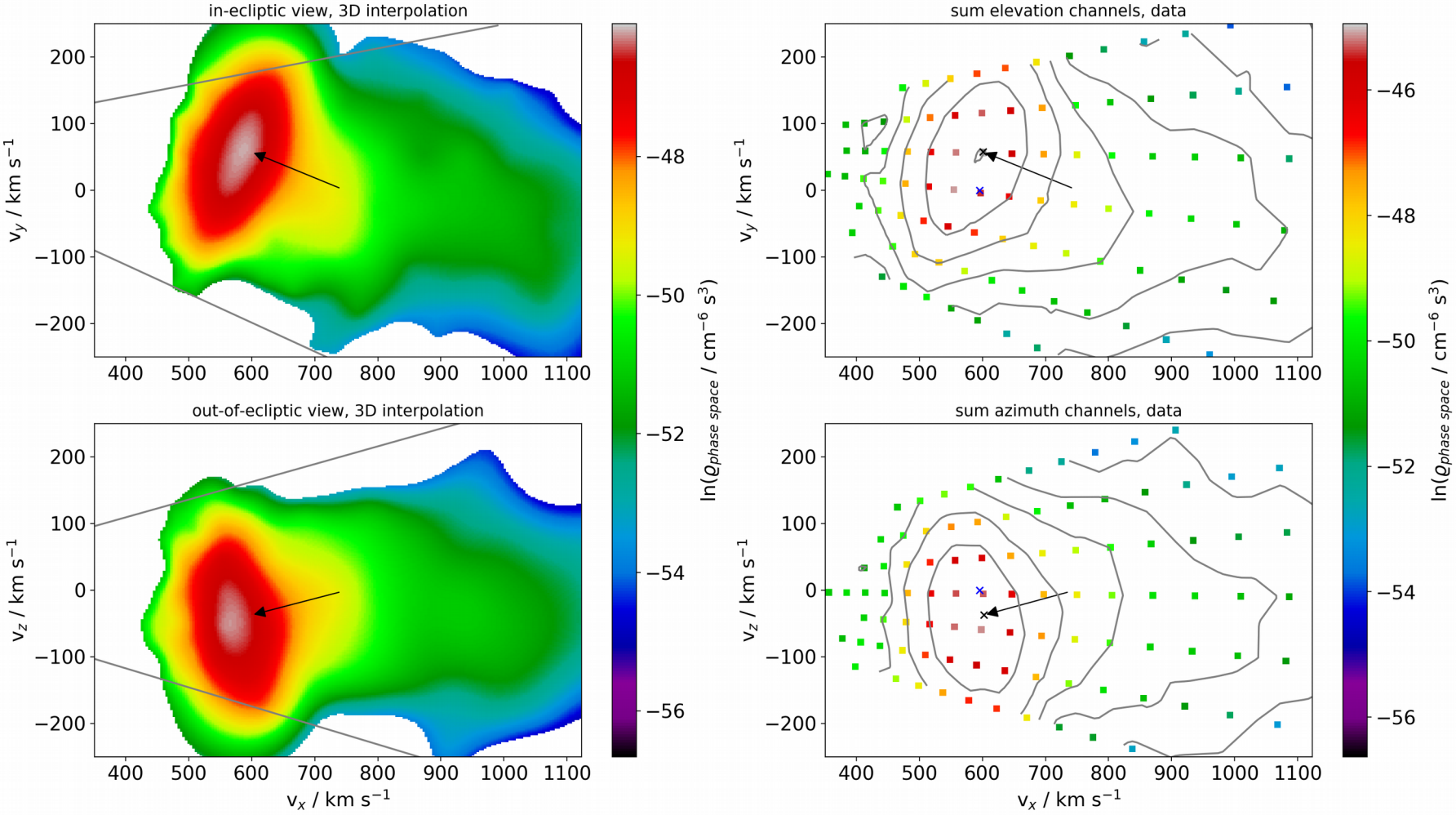

trace of magnetic fied spectral matrix
0.3AU
0.7AU
0.9AU
-0.89
-1.06
-1.07
-1.72
-1.67
-1.70
f^-1
f^-5/3
power density [nT^2/Hz]
frequency [Hz]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-5
10^-4
10^-3
10^-2
10^-1



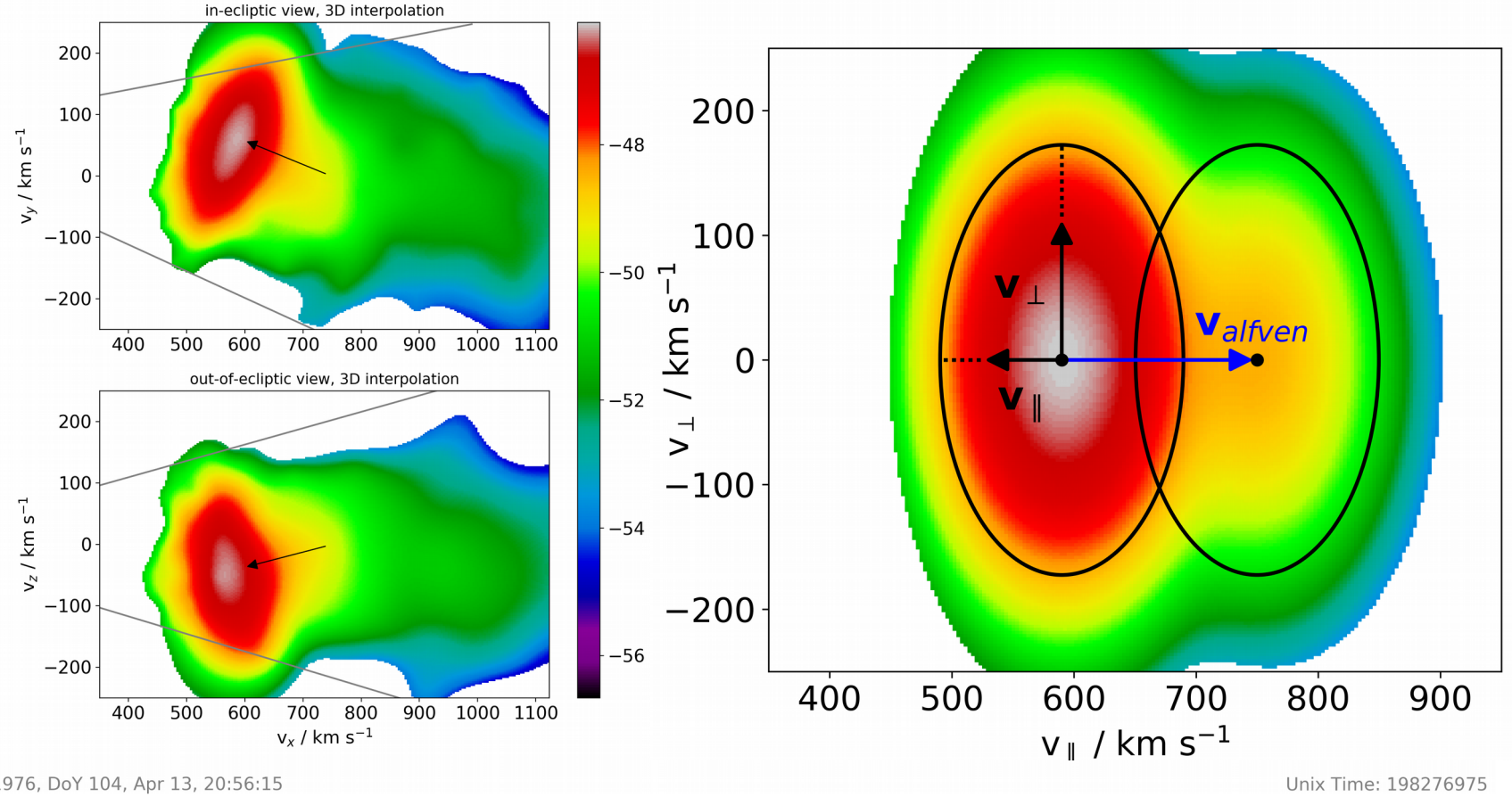

Isenberg et al. 2013

# What is the micro-state of the Solar Wind ? (Jan Steinhagen)



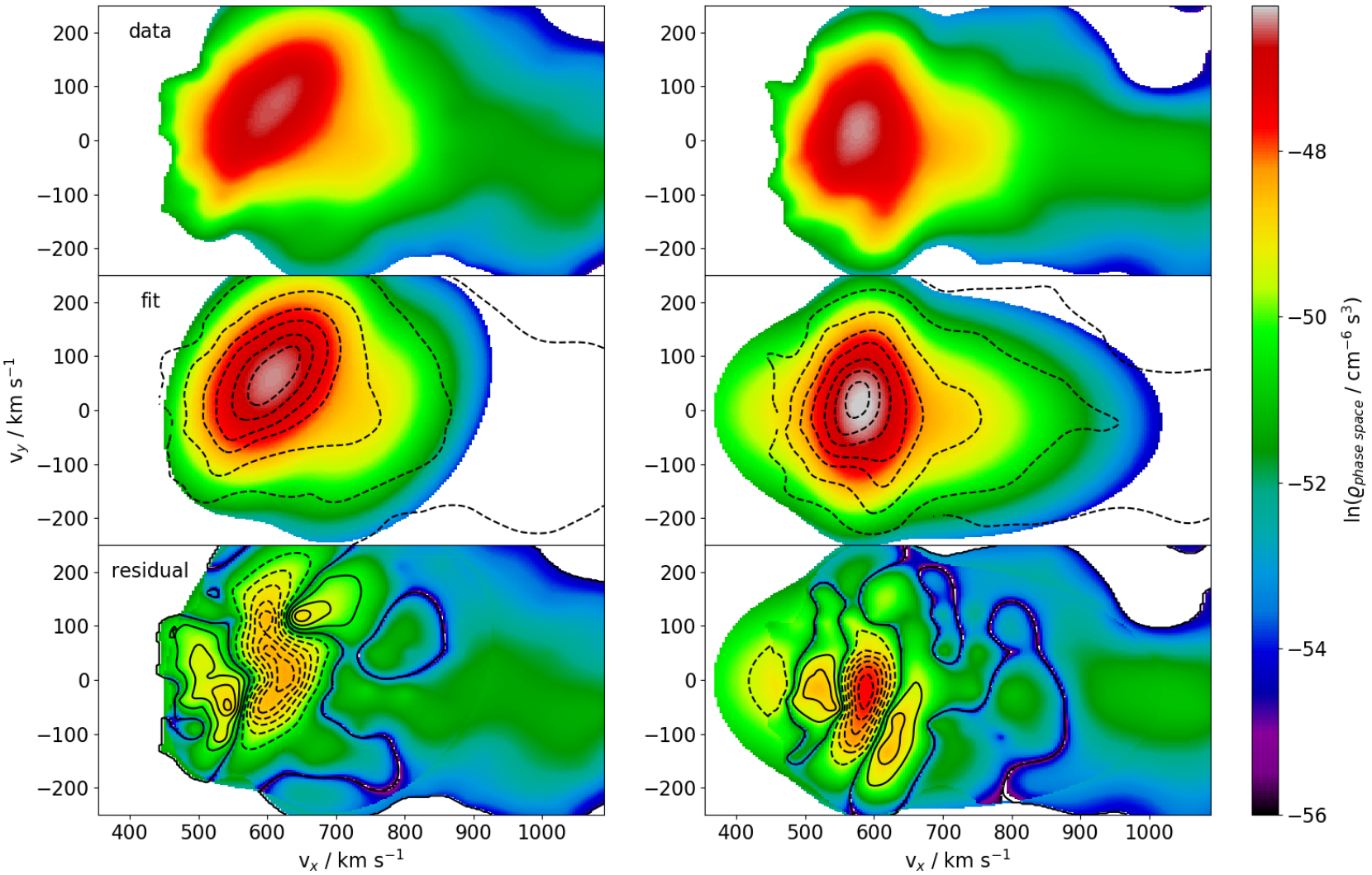

Helios 2: 1976, DoY 104, Apr 13, 20:56:15

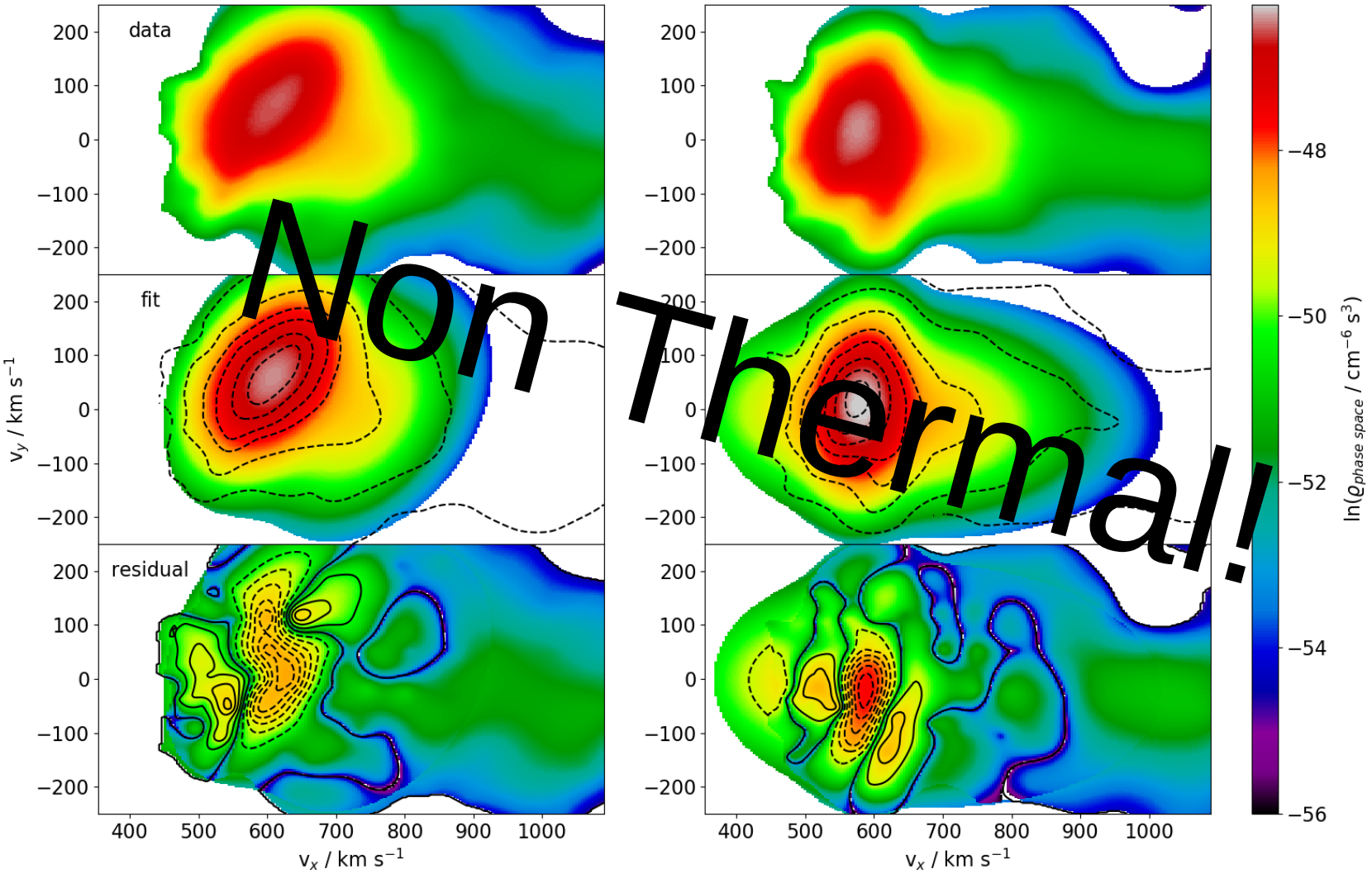
Unix Time: 198276975



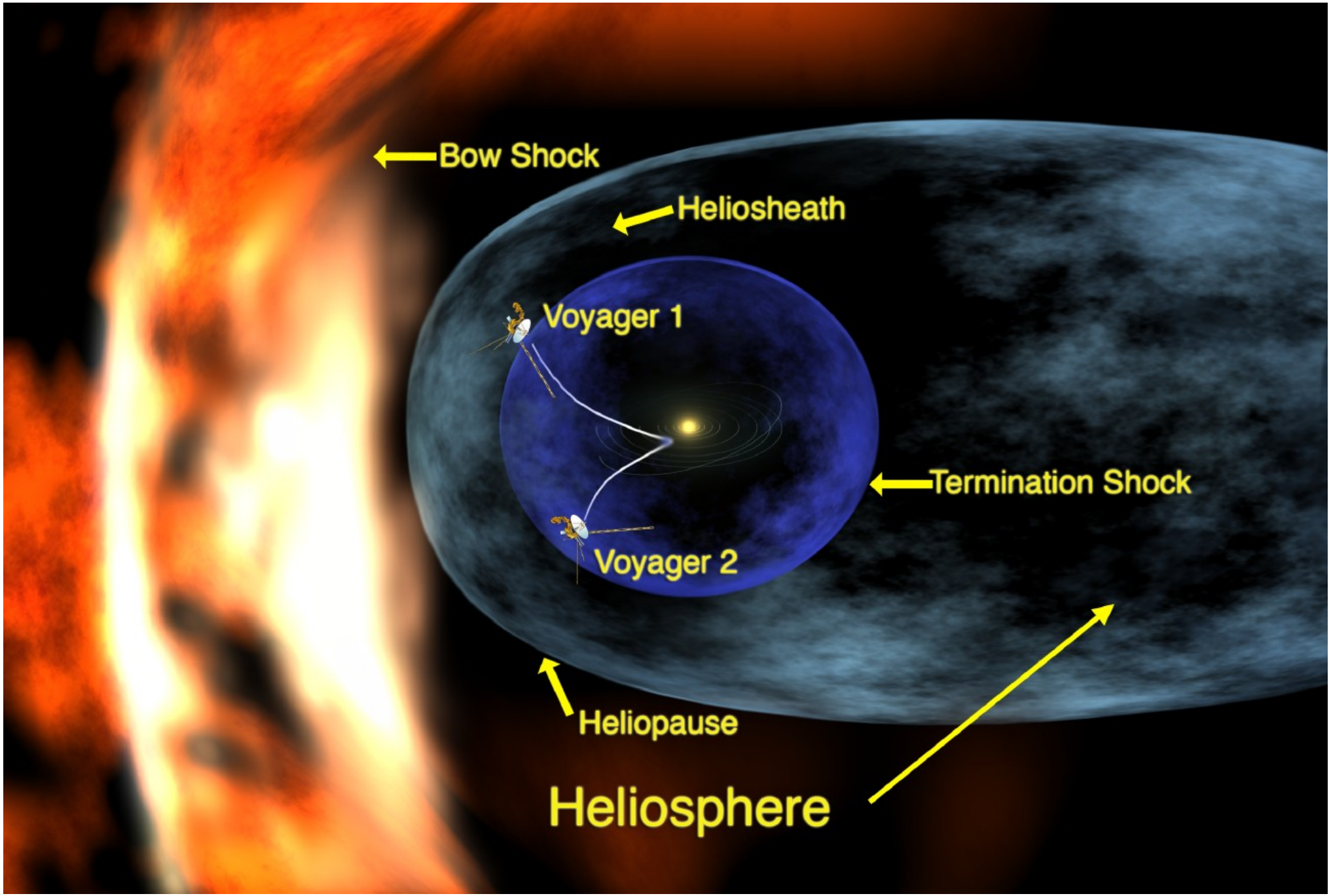

Helios 2: 1976, DoY 104, Apr 13, 20:56:15

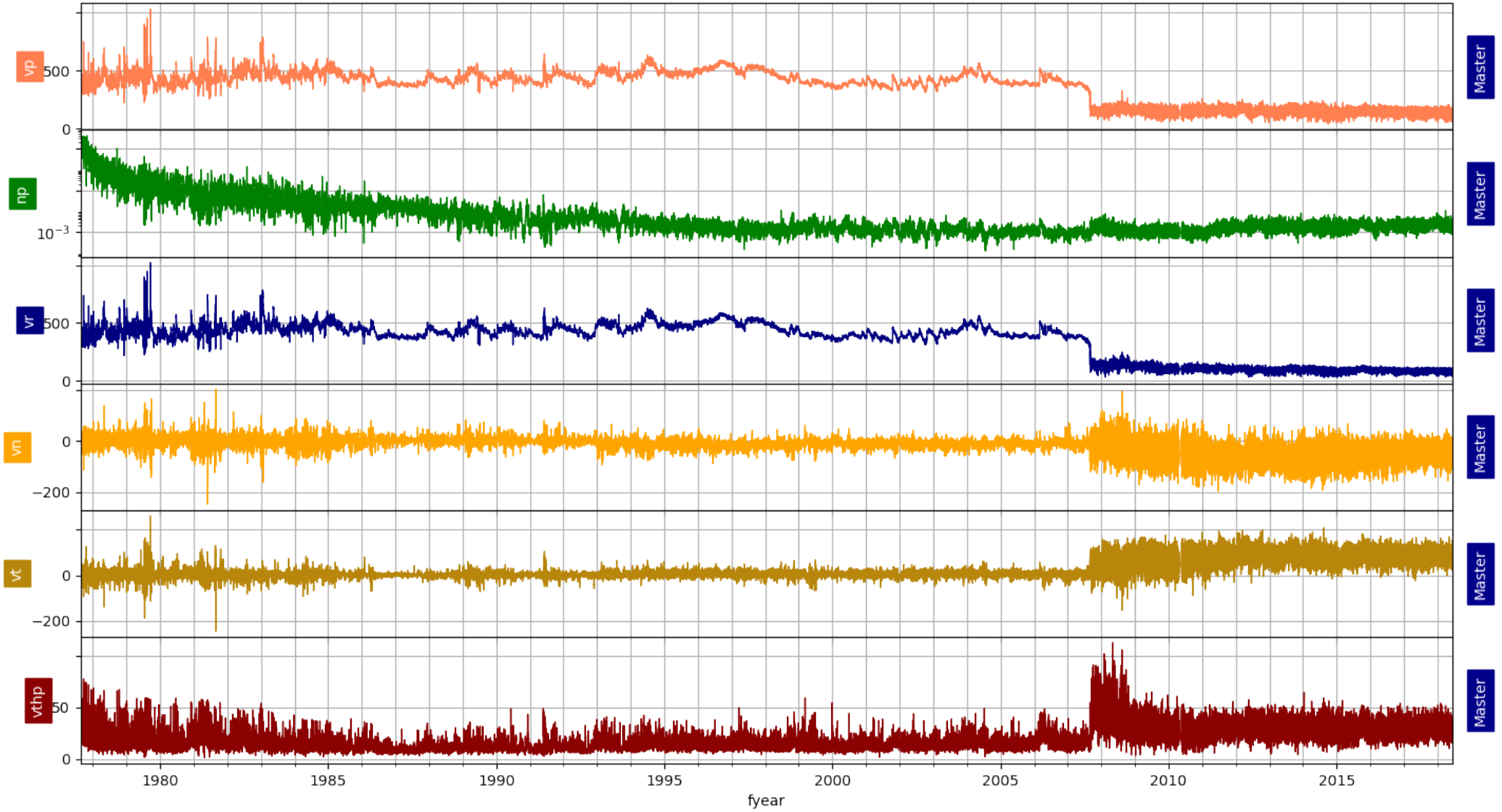
Unix Time: 198276975

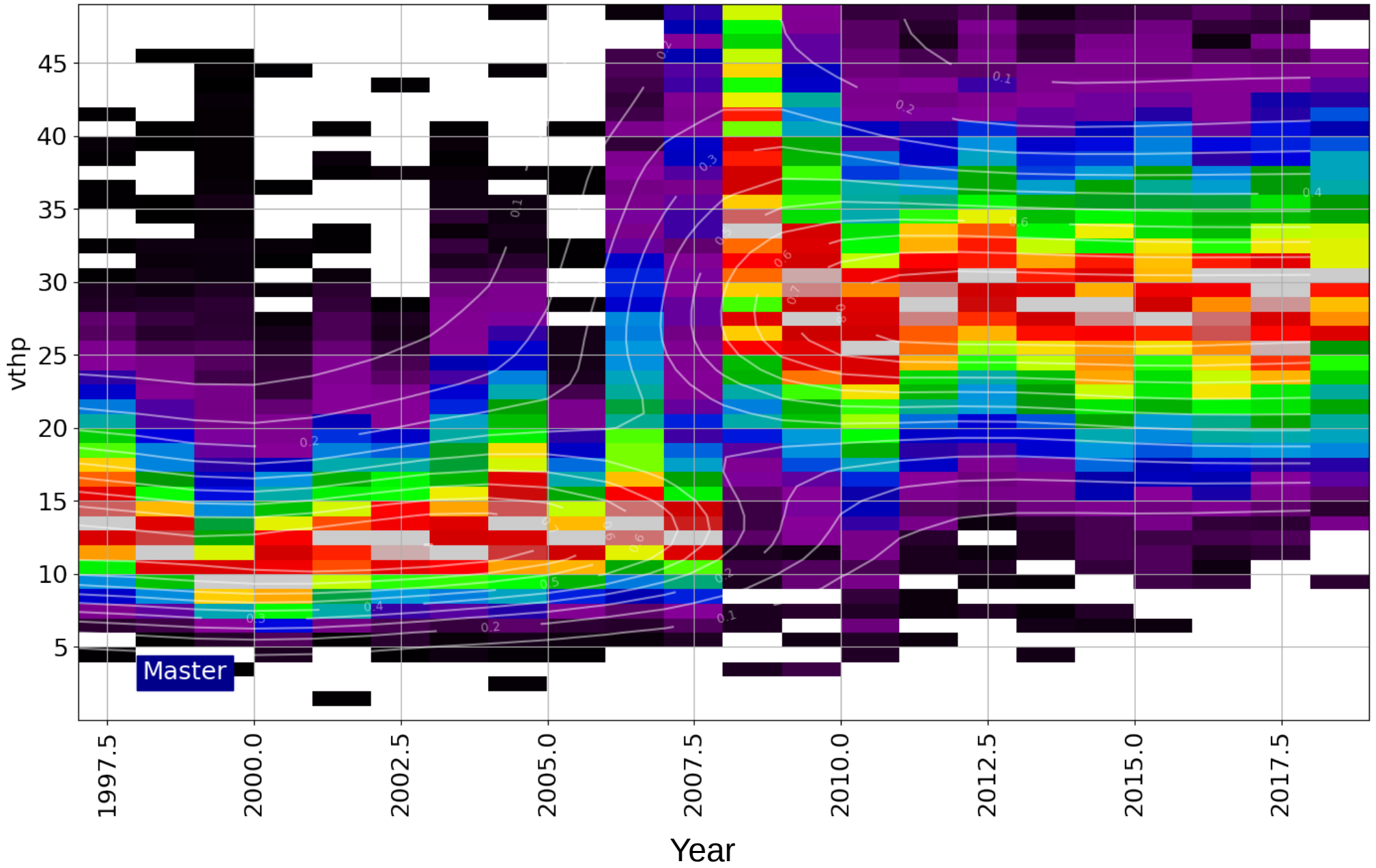

data
fit
residual
200
100
0
−100
−200
400
500
600
700
800
900
1000
$v_x$ / km s$^{-1}$
$v_y$ / km s$^{-1}$
−48
−50
−52
−54
−56
ln($\varrho_{phase\ space}$ / cm$^{-6}$ s$^3$)

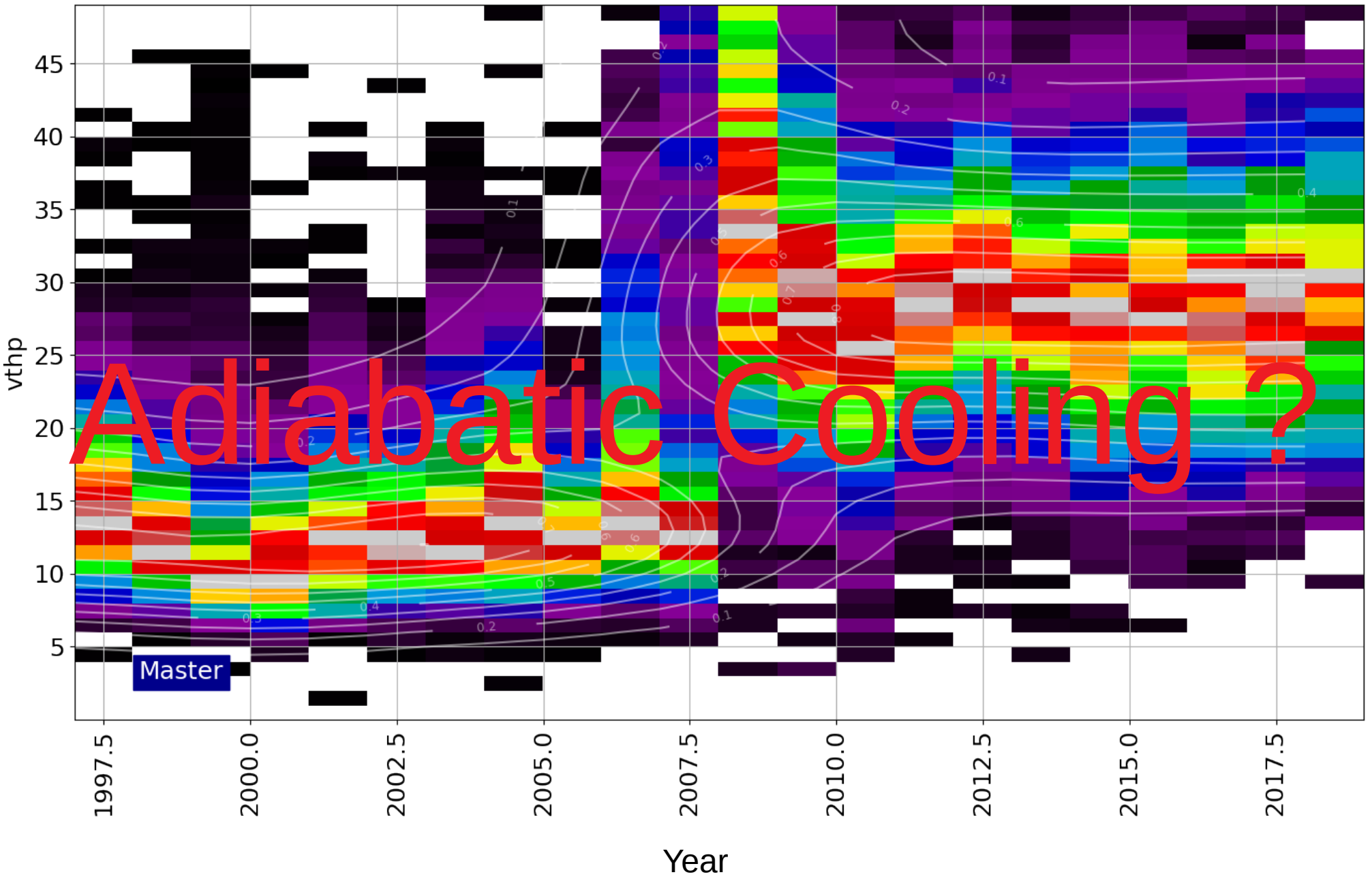

data
fit
residual
Non Thermal!
$v_y$ / km s$^{-1}$
$v_x$ / km s$^{-1}$
$v_x$ / km s$^{-1}$
ln($\varrho_{phase\ space}$ / cm$^{-6}$ s$^3$)
200
100
0
−100
−200
400
500
600
700
800
900
1000
−48
−50
−52
−54
−56


THE
SOUNDS
OF
EARTH


Bow Shock
Heliosheath
Voyager 1
Termination Shock
Voyager 2
Heliopause
Heliosphere


vp
500
0
np
$10^{-3}$
vr
500
0
vn
0
−200
vt
0
−200
vthp
50
0
Master
Master
Master
Master
Master
Master
1980
1985
1990
1995
2000
2005
2010
2015
fyear


vthp
45
40
35
30
25
20
15
10
5
Master
1997.5
2000.0
2002.5
2005.0
2007.5
2010.0
2012.5
2015.0
2017.5
Year




Lars Berger
berger@physik.uni-kiel.de