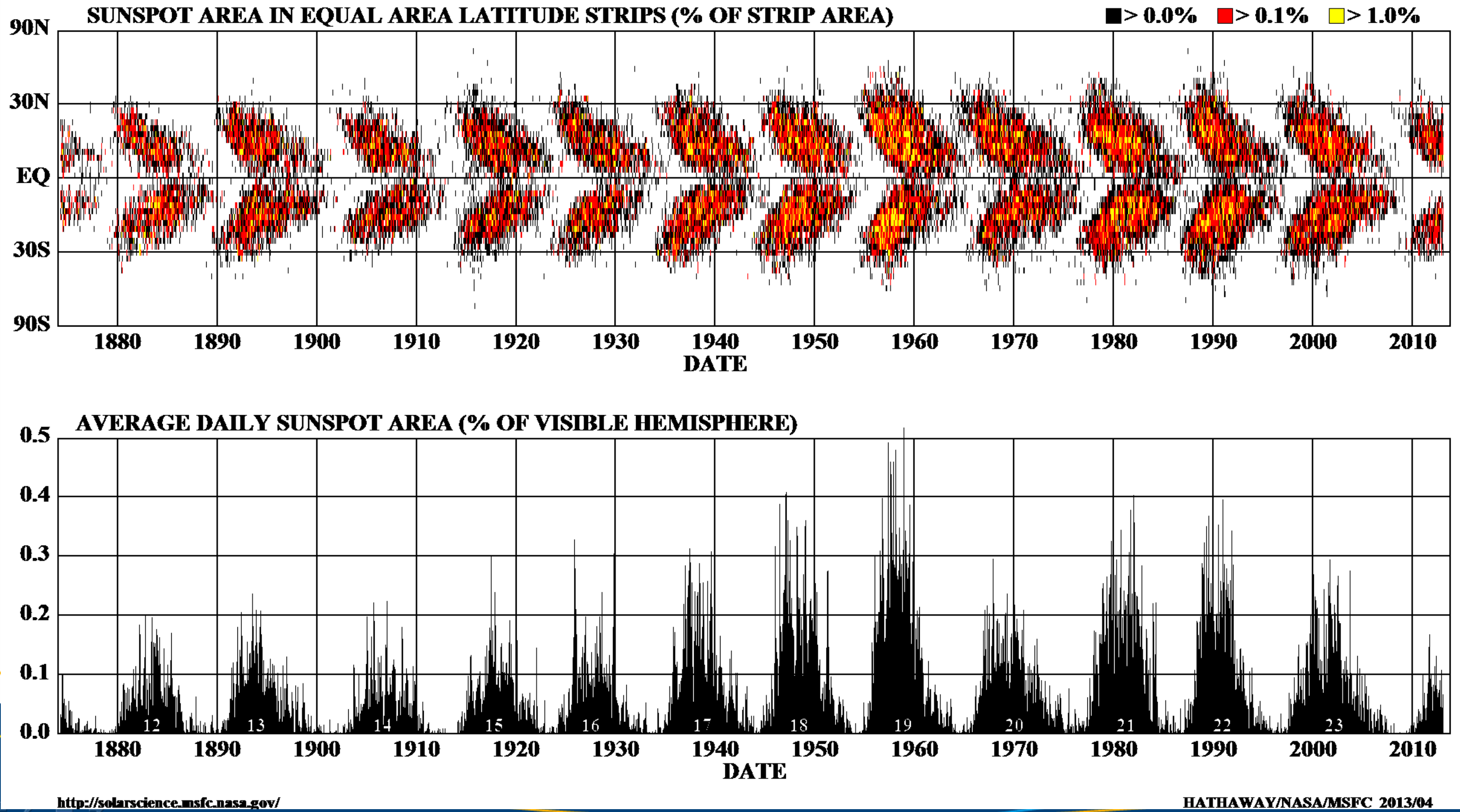
Historical sunspot data – Part I

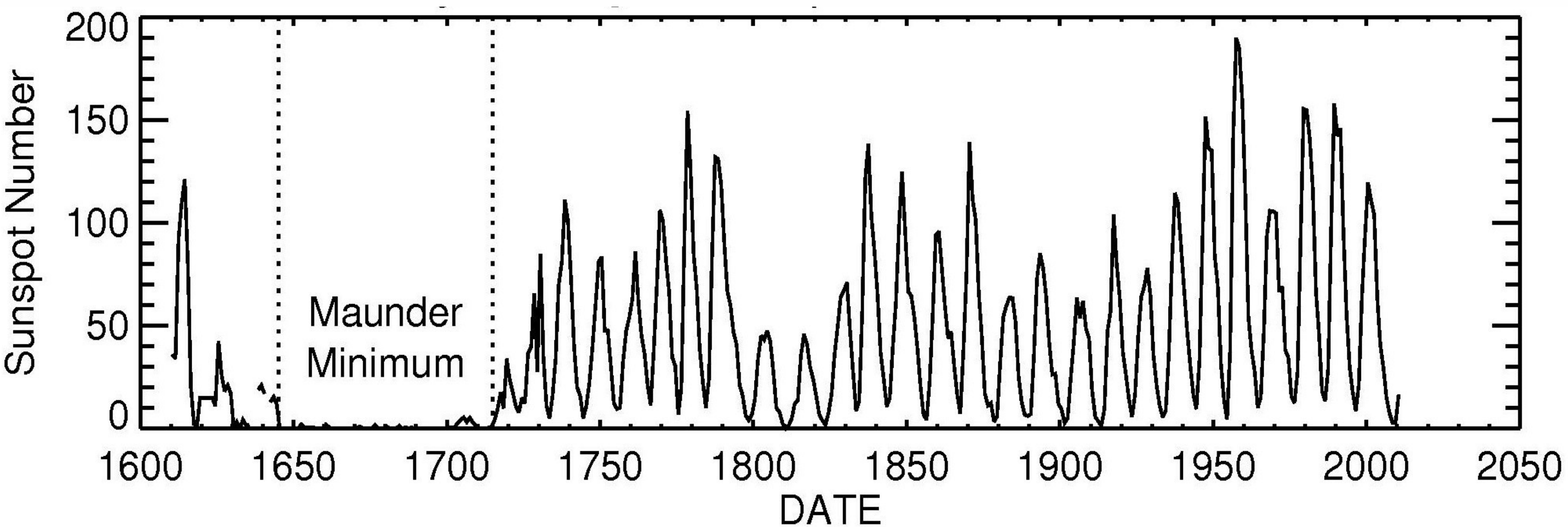
Solar cycle and “butterfly diagram”
– has it always been like this?



Why do we care?

- Modern cycle show cycle-to-cycle variability
  - They are constraining the underlying dynamo mechanism

- Period with entire absence of spots was observed
  - Even stronger constraint for dynamo process



Beyond sunspot numbers

- Sunspot positions:
  - Latitudinal variation
  - North-south asymmetry / phase lag
  - Differential rotation
- Sunspot group properties
  - Sunspot areas
  - Group tilt angles
  - Polarity separations
  - Temporal evolution

Dynamo

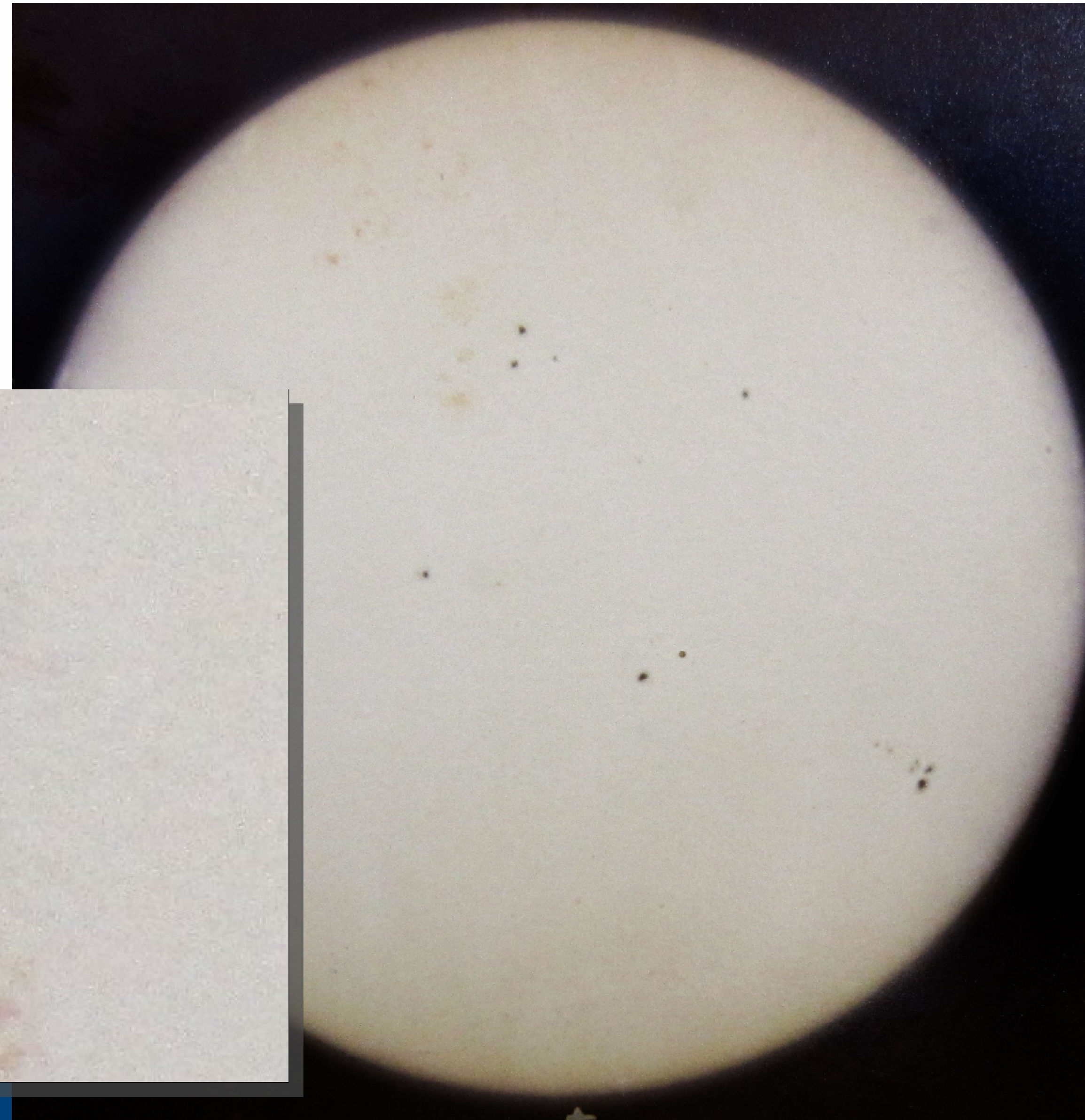
Flux emergence

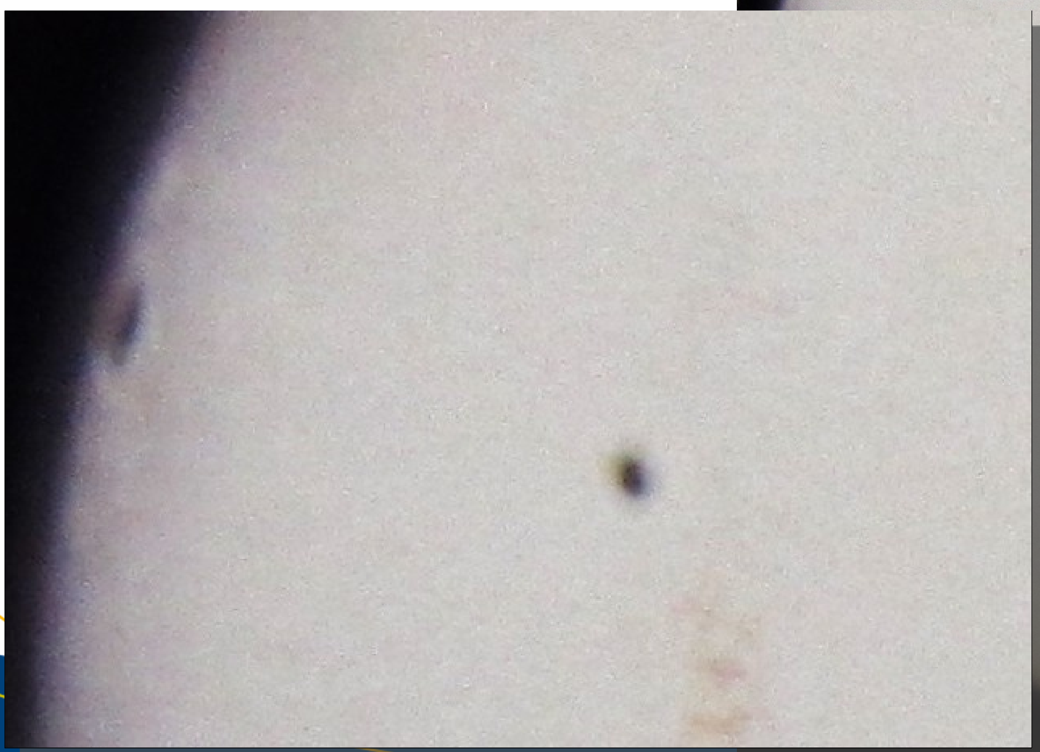
1600 1700 1800 1900 2000

AIP

Greenwich photographs

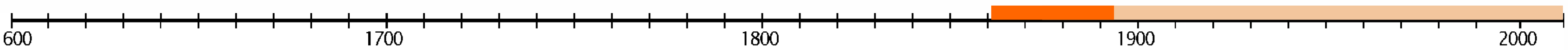
- Visual observing drawing sunspots superior to photos





Gustav Spörer 1861–1894

- 1861–1874 in Anklam, 1874–1894 in Potsdam (Germany)

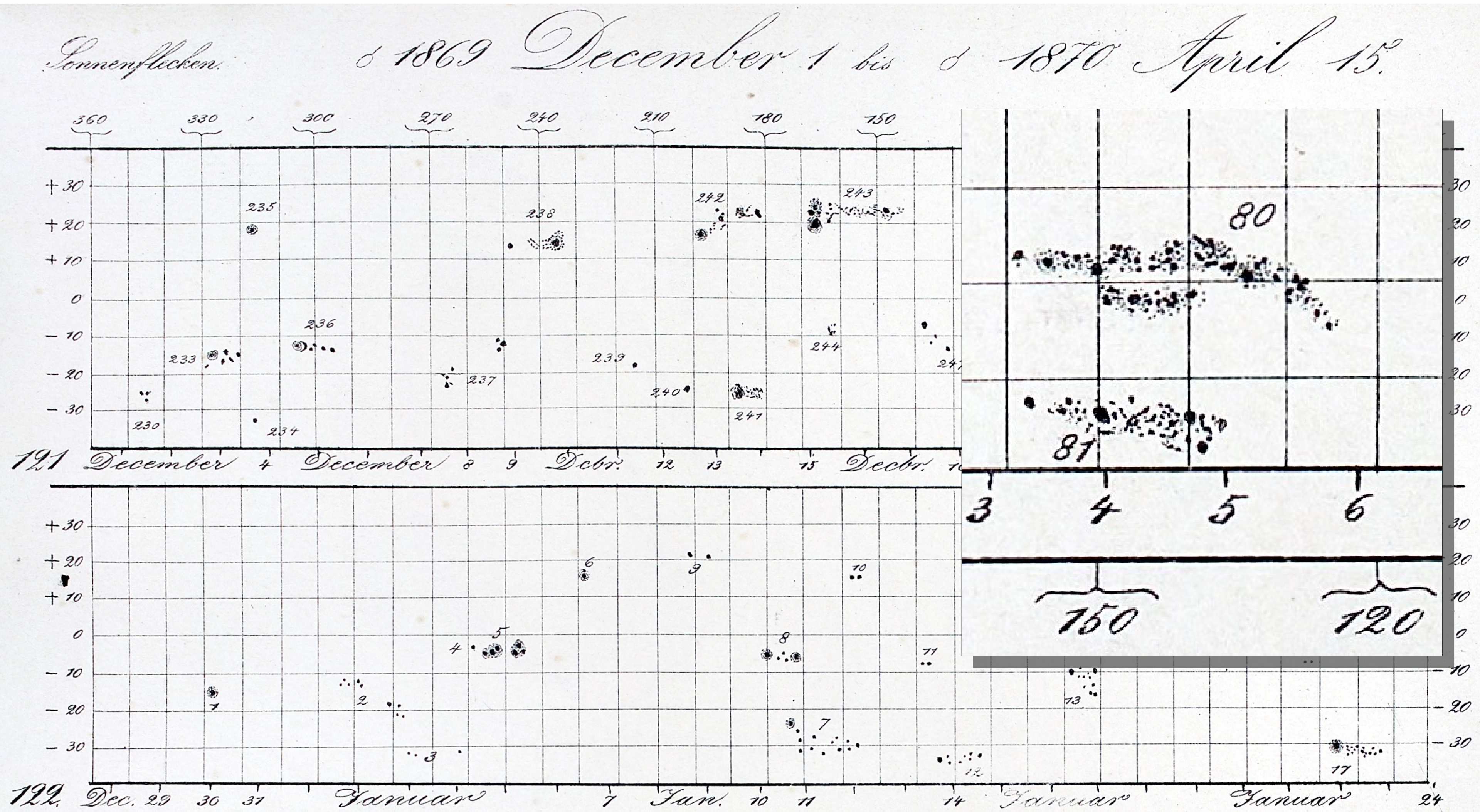


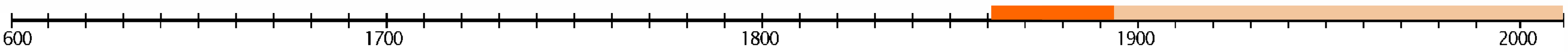
AIP

Spörer and Carrington

Diercke et al. (2015)

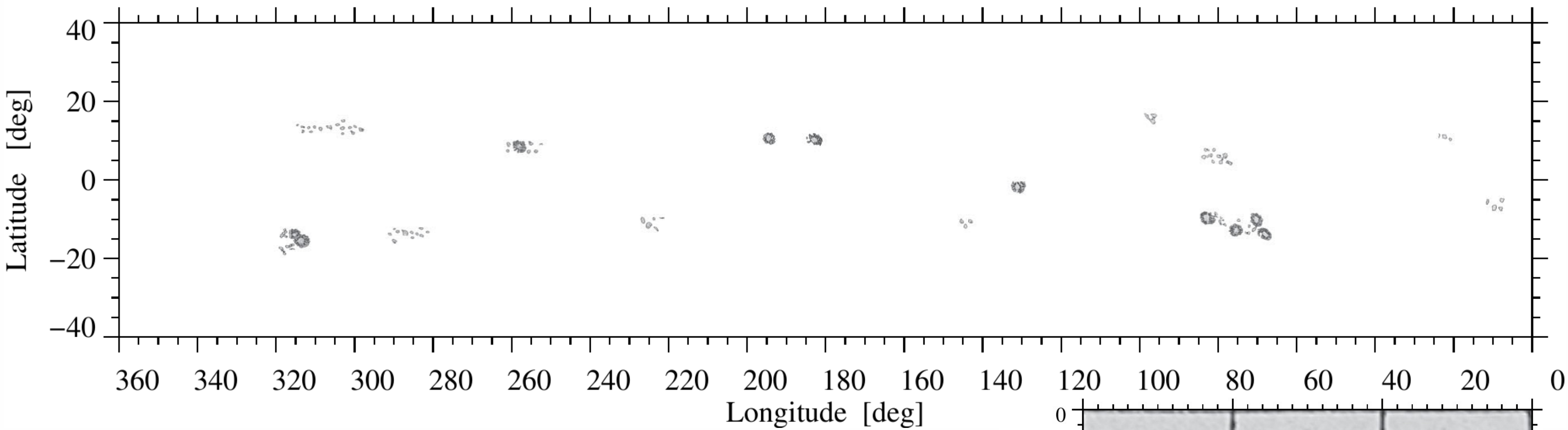
- Group drawings near passage of central meridian



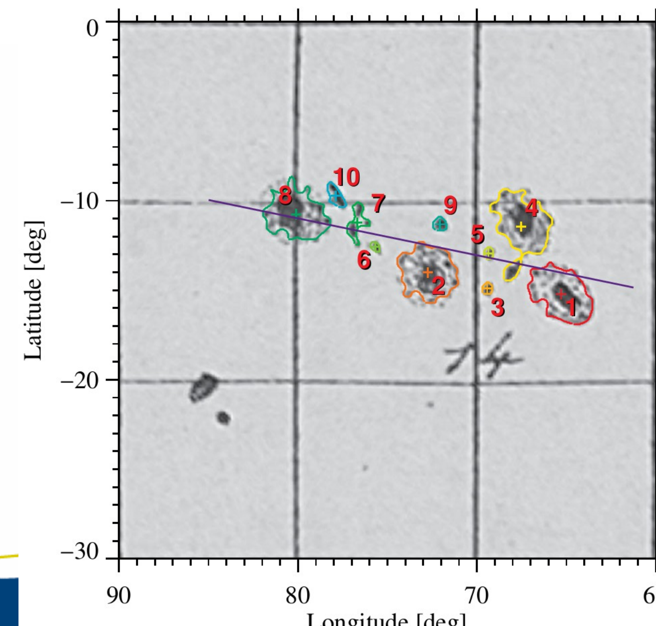


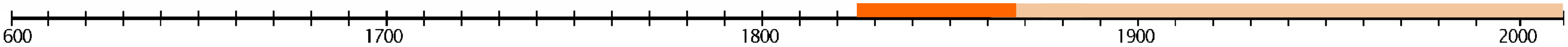
Spörer and Carrington

Diercke et al. (2015)



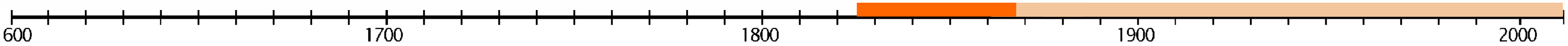
- Automated image processing / spot recognition
- Morphological operations 'dilate' / 'erode' delete features in image





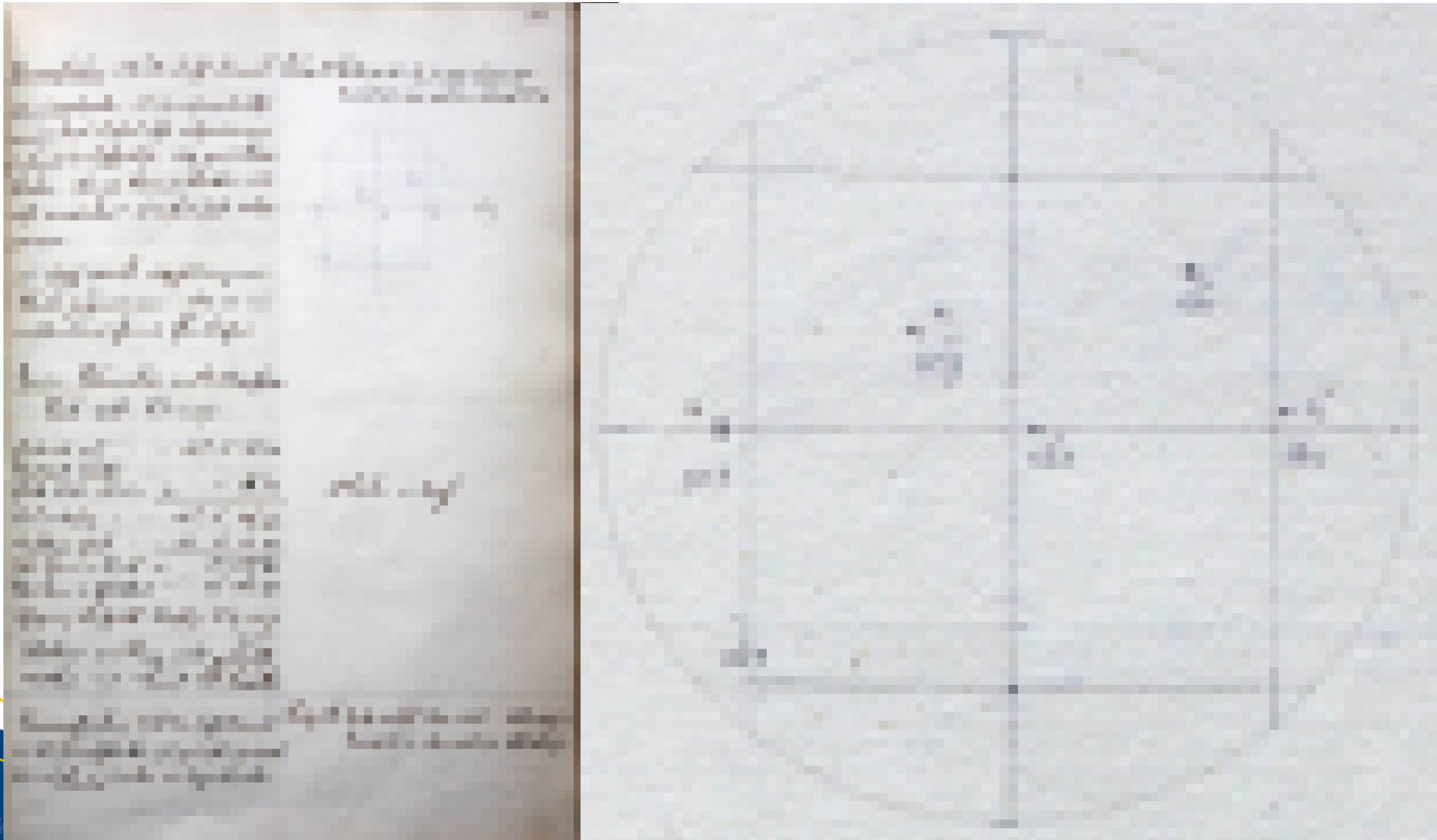
Samuel Heinrich Schwabe, 1825-1868

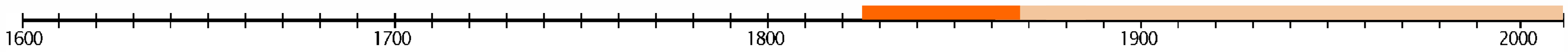
S.H. Schwabe 1789-1875, Dessau



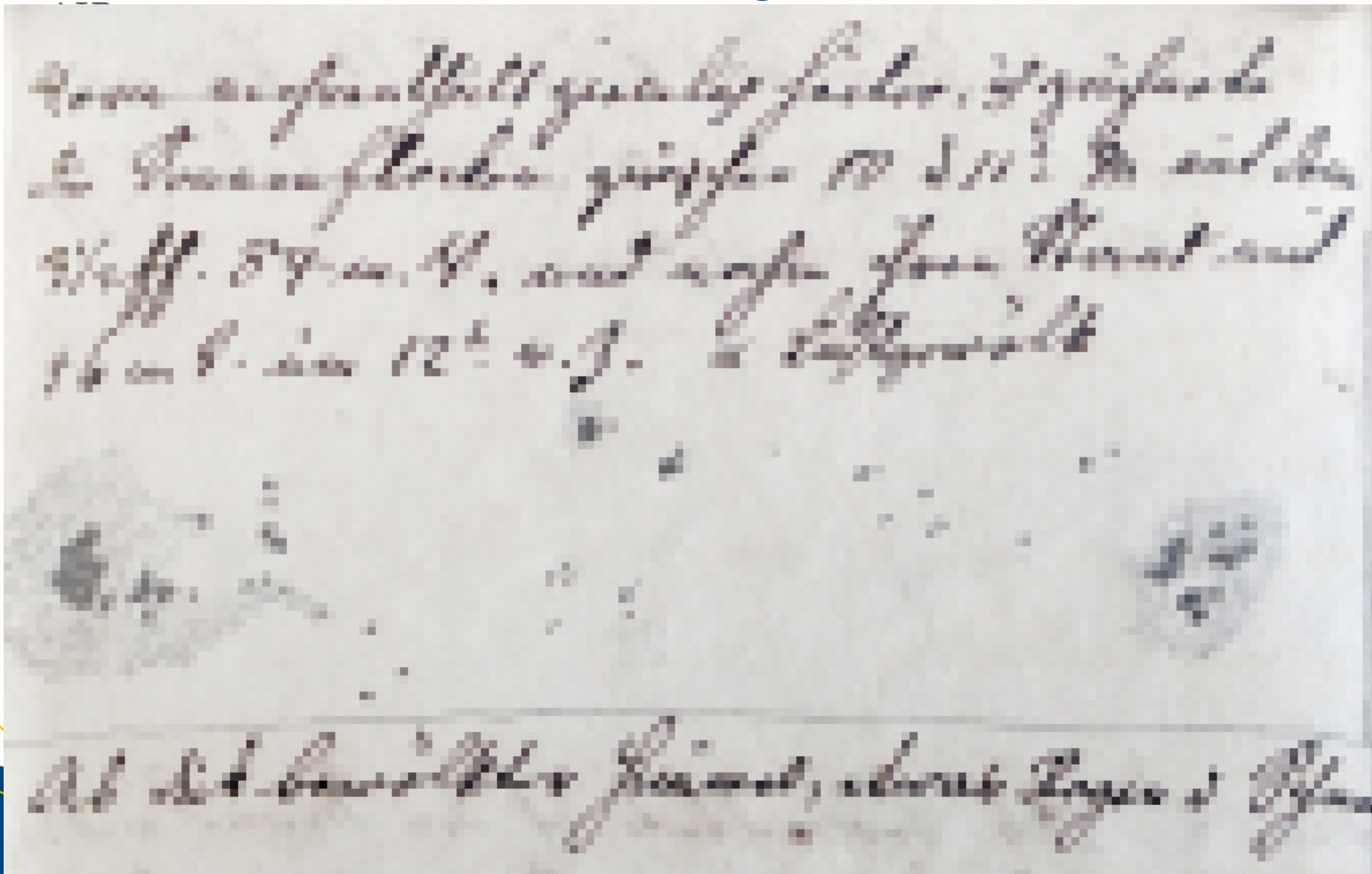
Samuel Heinrich Schwabe, 1825-1868

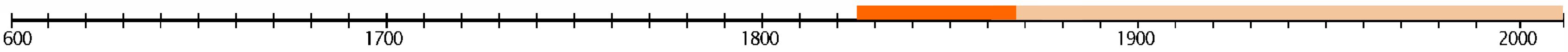
~8500 drawings





Schwabe's drawings





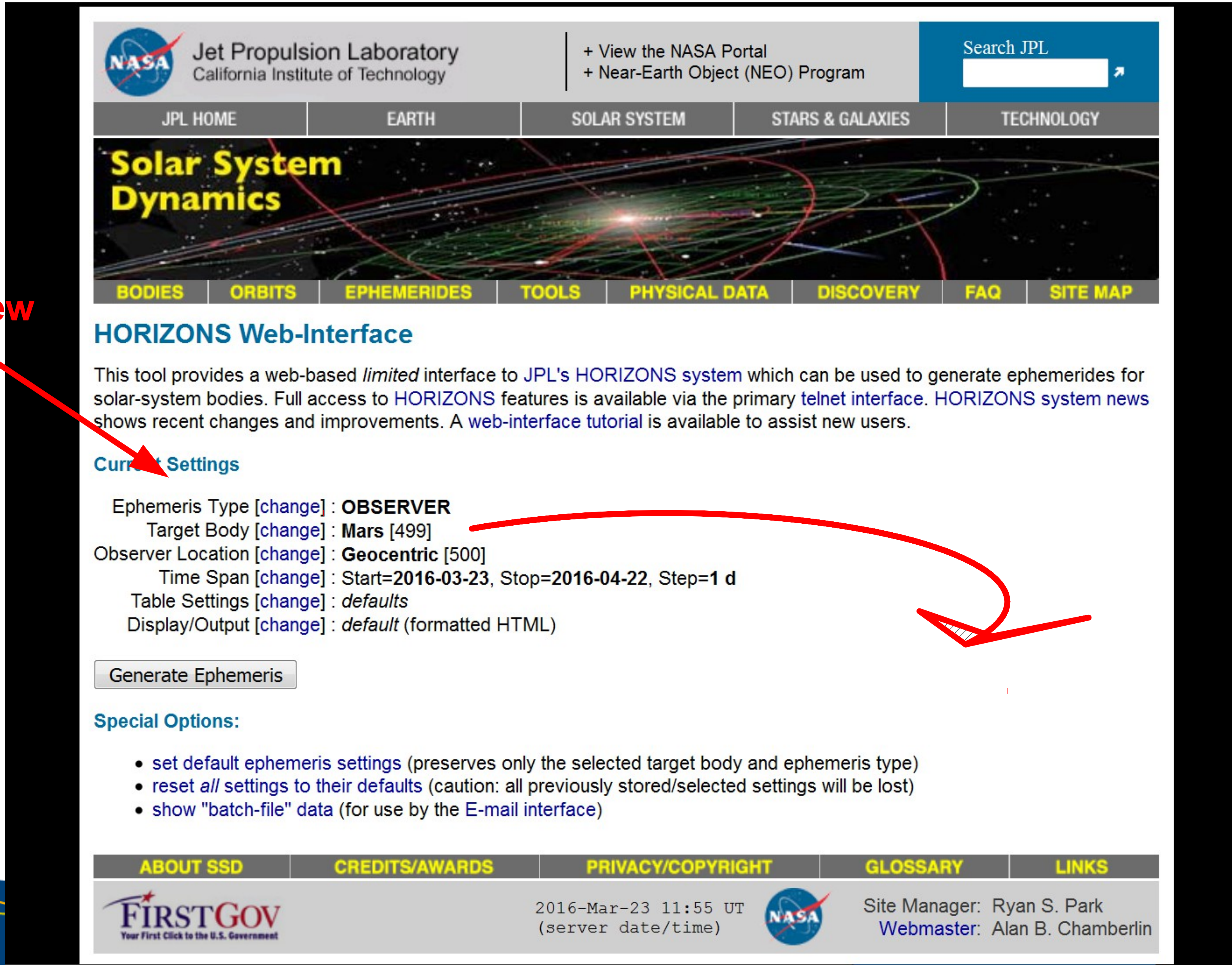
Schwabe's discovery

- Suggests solar cycle periodic with 10-year period
- Wrote his article on 31 Dec, 1843 for *Astronomische Nachrichten*

Jahr.	Gruppen.	Fleckenfreie tage.	Beobachtungstage.
1826	118	22	277
1827	161	2	273
1828	225	0	282
1829	199	0	244
1830	190	1	217
1831	149	3	239
1832	84	49	270
1833	33	139	267
1834	51	120	273
1835	173	18	244
1836	272	0	200
1837	333	0	168
1838	282	0	202
1839	162	0	205
1640	152	3	263
1841	102	15	283
1842	68	64	307
1843	34	149	324

Using JPL Horizons http://ssd.jpl.nasa.gov/horizons.cgi

Default view



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+ Near-Earth Object (NEO) Program

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HORIZONS Web-Interface

This tool provides a web-based *limited* interface to JPL's HORIZONS system which can be used to generate ephemerides for solar-system bodies. Full access to HORIZONS features is available via the primary telnet interface. HORIZONS system news shows recent changes and improvements. A web-interface tutorial is available to assist new users.

Current Settings

Ephemeris Type [change] : **OBSERVER**
Target Body [change] : **Mars** [499]
Observer Location [change] : **Geocentric** [500]
Time Span [change] : Start=**2016-03-23**, Stop=**2016-04-22**, Step=**1 d**
Table Settings [change] : *defaults*
Display/Output [change] : *default* (formatted HTML)

Generate Ephemeris

Special Options:

- set default ephemeris settings (preserves only the selected target body and ephemeris type)
- reset *all* settings to their defaults (caution: all previously stored/selected settings will be lost)
- show "batch-file" data (for use by the E-mail interface)

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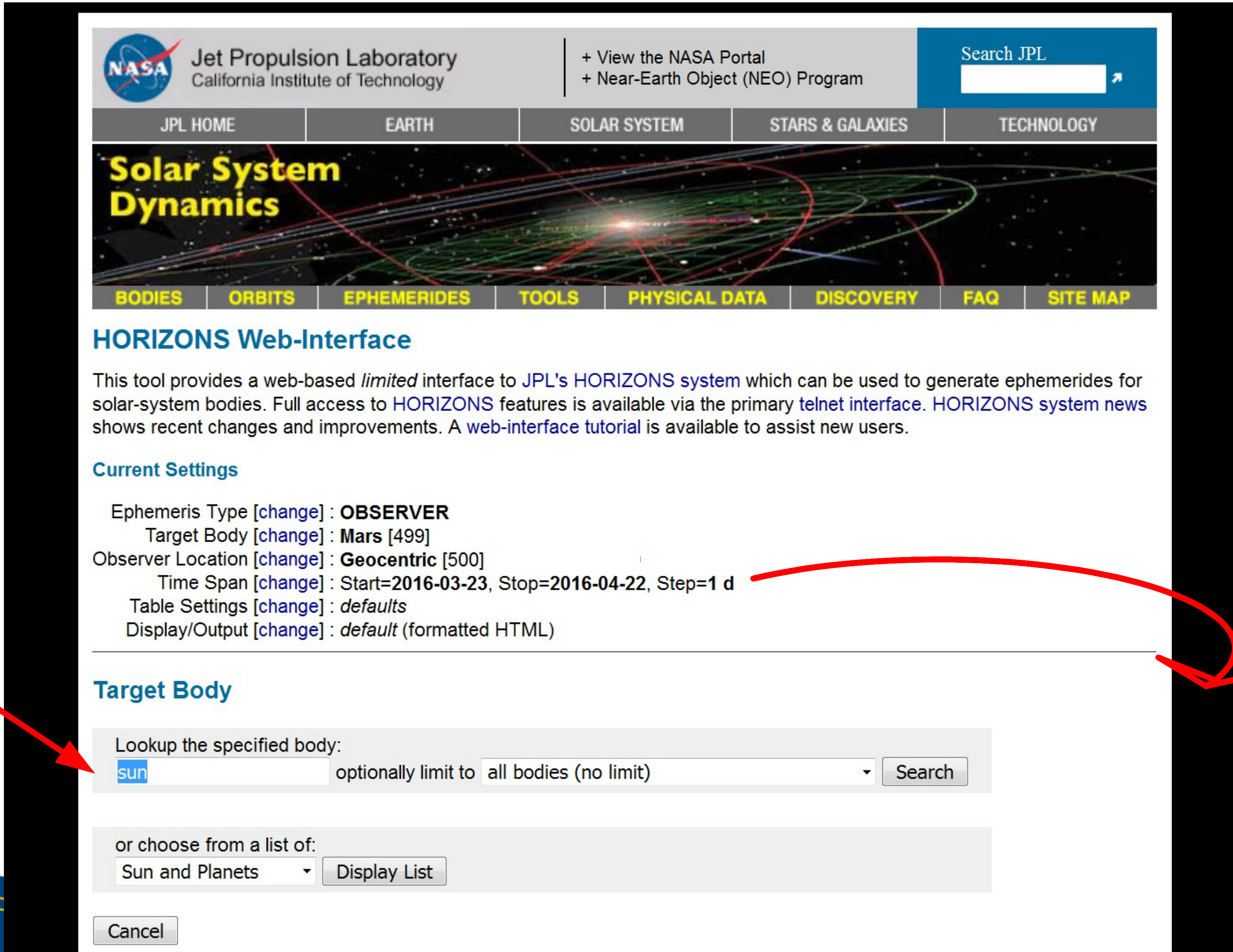
FIRSTGOV Your First Click to the U.S. Government

2016-Mar-23 11:55 UT
(server date/time)

Site Manager: Ryan S. Park
Webmaster: Alan B. Chamberlin

Using JPL Horizons http://ssd.jpl.nasa.gov/horizons.cgi



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Time Span [change] : Start=**2016-03-23**, Stop=**2016-04-22**, Step=**1 d**
Table Settings [change] : *defaults*
Display/Output [change] : *default* (formatted HTML)

Target Body

Lookup the specified body:
sun optionally limit to all bodies (no limit) Search

or choose from a list of:
Sun and Planets Display List

Cancel

AIP

Using JPL Hor

Sun/Planets

ID	Name	Available Time Span	Ephemeris File
10	Sun	B.C. 9998-Mar-20 to A.D. 9999-Dec-31	DE431MX
199	Mercury	B.C. 9998-Mar-20 to A.D. 9999-Dec-31	DE431MX
299	Venus	B.C. 9998-Mar-20 to A.D. 9999-Dec-31	DE431MX
399	Earth	B.C. 9998-Mar-20 to A.D. 9999-Dec-31	DE431MX
499	Mars	1900-Jan-04 to 2500-Jan-04	MAR097.DE424
599	Jupiter	1799-Dec-18 to 2200-Jan-14	JUP310.DE430.MERGED
699	Saturn	1800-Jan-07 to 2200-Jan-16	SAT375L.MERGED.DE430
799	Uranus	1899-Dec-18 to 2100-Jan-06	URA111.DE430
899	Neptune	B.C. 3000-Jun-04 to A.D. 3000-Jan-04	NEP081.MERGED.DE421
999	Pluto	1900-Jan-08 to 2100-Jan-03	PLU055L_MERGED.DE433

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Solar System Dynamics

BODIES | ORBITS | EPHEMERIDES

HORIZONS Web-Interface

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Current Settings

Ephemeris Type [change] : **OBSERVER**
Target Body [change] : **Sun [Sol]** [10]
Observer Location [change] : **Geocentric** [500]
Time Span [change] : Start=**2016-03-23**, Stop=**2016-04-22**, Step=**1 d**
Table Settings [change] : *defaults*
Display/Output [change] : *default* (formatted HTML)

Time Span

switch to discrete-times form

Preset: 10 day | 30 day | 60 day

Start Time: 1825-01-01

Stop Time: 1867-12-31

Step Size: 6 hours

Use Specified Times | Cancel

Available time span for currently selected target body:
BC 9998-Mar-20 to **AD 9999-Dec-31** TT.

Times may be specified as calendar dates and optionally times (e.g. "YYYY{BC|AD}-MMM-DD {hh:mm} {UT|TT}", or Julian dates (e.g. "{JD }DDDDDDD.DDDD") where items in curly braces {} are optional. For years earlier than 1000, be sure to append 'AD' (or 'BC' as appropriate). Unless otherwise specified, UT is assumed for OBSERVER tables.

See the HORIZONS documentation for accepted formats and advanced capabilities. Allowable time-spans for all bodies are available on a separate page.

Using JPL Horizons – Table settings

Table Settings

Select observer quantities from table below:
[switch to manual-entry list-of-numbers form]

Use Settings Below | Cancel

Optionally preset observer quantities selection using one of the following:
planets | satellites | small-bodies | default | all | none

1. [x] Astrometric RA & DEC	16. [ ] Sub-Sun position angle & distance	* 31. [ ] Observer ecliptic lon. & lat.
* 2. [ ] Apparent RA & DEC	17. [x] North Pole position angle & distance	32. [ ] North pole RA & DEC
3. [ ] Rates; RA & DEC	18. [ ] Heliocentric ecliptic lon. & lat.	33. [ ] Galactic longitude & latitude
* 4. [ ] Apparent AZ & EL	19. [ ] Heliocentric range & range-rate	34. [ ] Local apparent SOLAR time
5. [ ] Rates; AZ & EL	20. [ ] Observer range & range-rate	35. [ ] Earth->obs. site light-time
6. [ ] Satellite X & Y, pos. angle	21. [ ] One-way (down-leg) light-time	> 36. [ ] RA & DEC uncertainty
7. [ ] Local apparent sidereal time	22. [ ] Speed wrt Sun & observer	> 37. [ ] Plane-of-sky error ellipse
8. [ ] Airmass & extinction	23. [ ] Sun-Observer-Target ELONG angle	> 38. [ ] POS uncertainty (RSS)
9. [ ] Visual mag. & Surface Brght	24. [ ] Sun-Target-Observer ~PHASE angle	> 39. [ ] Range & range-rate 3-sigmas
10. [ ] Illuminated fraction	25. [ ] Target-Observer-Moon angle/ Illum%	> 40. [ ] Doppler & delay 3-sigmas
11. [ ] Defect of illumination	26. [ ] Observer-Primary-Target angle	41. [ ] True anomaly angle
12. [ ] Satellite anglular separ/vis.	27. [ ] Sun-Target radial & -vel pos. angle	42. [ ] Local apparent hour angle
13. [ ] Target angular diameter	28. [ ] Orbit plane angle	43. [ ] PHASE angle & bisector
14. [x] Observer sub-lon & sub-lat	29. [ ] Constellation ID	
15. [ ] Sun sub-longitude & sub-latitude	30. [ ] Delta-T (CT - UT)	

Notes:
* affected by optional atmospheric refraction setting (below)
> statistical value that uses orbit covariance if available

Observer quantities are described in the HORIZONS documentation.

Use Selected Settings | Cancel

Using JPL Horizons – Table settings

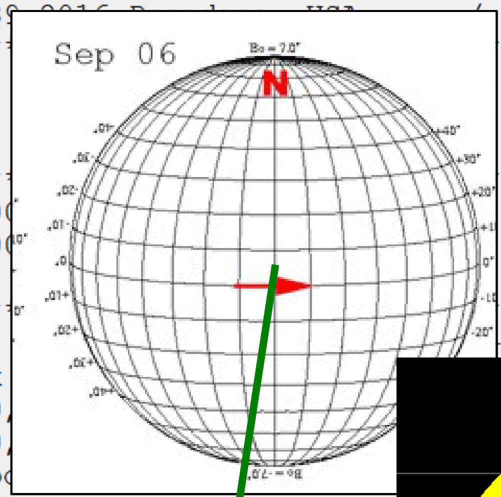
Optional observer-table settings:

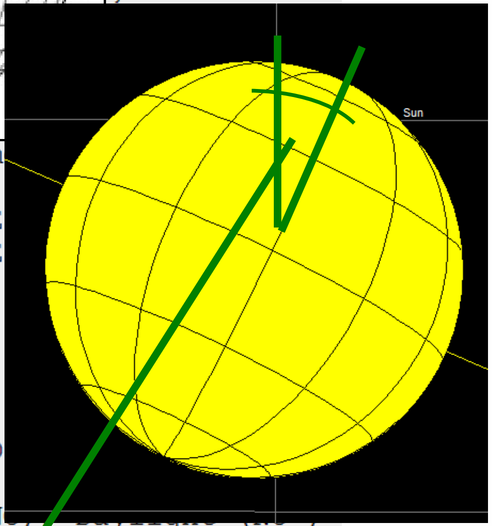
date/time format :	Julian Day -- display date/time in year-month-day and/or Julian-day format
time digits :	minutes (HH:MM) -- controls output precision of time
angle format :	decimal degrees -- select RA/Dec output format
output units :	km & km/s -- units for most output quantities
range units :	Astronomical Units -- units for range-type quantities
refraction model :	airless model (no refraction) -- select atmospheric refraction model
airmass limit :	-- suppress output when airmass is greater than this limit [1,38]
elevation cutoff :	(deg) -- suppress output when object elevation is less than this limit [-90,90]
solar elong. limits :	0 - 180 (deg) -- suppress output when solar elongation is outside this range
hour angle cutoff :	(h) -- suppress output when the local hour angle exceeds this value [0,12]
suppress range-rate :	☐ -- suppress range-rate for range/range-rate output
skip daylight :	☐ -- suppress output during daylight
extra precision :	☐ -- output addition digits for RA/Dec quantities
RTS flag :	disable -- output data only at target rise/transit/set (RTS)
reference system :	ICRF/J2000.0 -- reference frame for geometric and astrometric quantities
CSV format :	☐ -- output data in Comma-Separated-Values (CSV) format
object page :	☑ -- include object information/data page on output

Use Settings Above | Default Optional Settings | Cancel

AIP

```
*****************************************************************************
Ephemeris / WWW_USER Wed Mar 23 05:39:3                        Horizons
*****************************************************************************
Target body name: Sun (10)
Center body name: Earth (399)
Center-site name: GEOCENTRIC
*****************************************************************************
Start time      : A.D. 1825-Jan-01 00:0
Stop  time      : A.D. 1867-Dec-31 00:0
Step-size       : 360 minutes
*****************************************************************************
Target pole/equ : IAU_SUN                                              }
Target radii    : 696000.0 x 696000.0 x
Center geodetic : 0.00000000,0.00000000,
Center cylindric: 0.00000000,0.00000000,
Center pole/equ : High-precision EOP mo
Center radii    : 6378.1 x 6378.1 x 6356.8 km     {Equator, m
Target primary  : Sun
Vis. interferer : MOON (R_eq= 1737.400) km        {source: DE
Rel. light bend : Sun, EARTH                      {source: DE
Rel. lght bnd GM: 1.3271E+11, 3.9860E+05 km^3/s^2
Atmos refraction: NO (AIRLESS)
RA format       : DEG
Time format     : JD
EOP file        : eop.160322.p160613
EOP coverage    : DATA-BASED 1962-JAN-20 TO 2016-MAR-22. PRED
Units conversion: 1 au= 149597870.700 km, c= 299792.458 km/s,
Table cut-offs 1: Elevation (-90.0deg=NO ),Airmass (>38.000=N
Table cut-offs 2: Solar Elongation (  0.0,180.0=NO ),Local Hour Angle( 0.0=NO )
*****************************************************************************
```

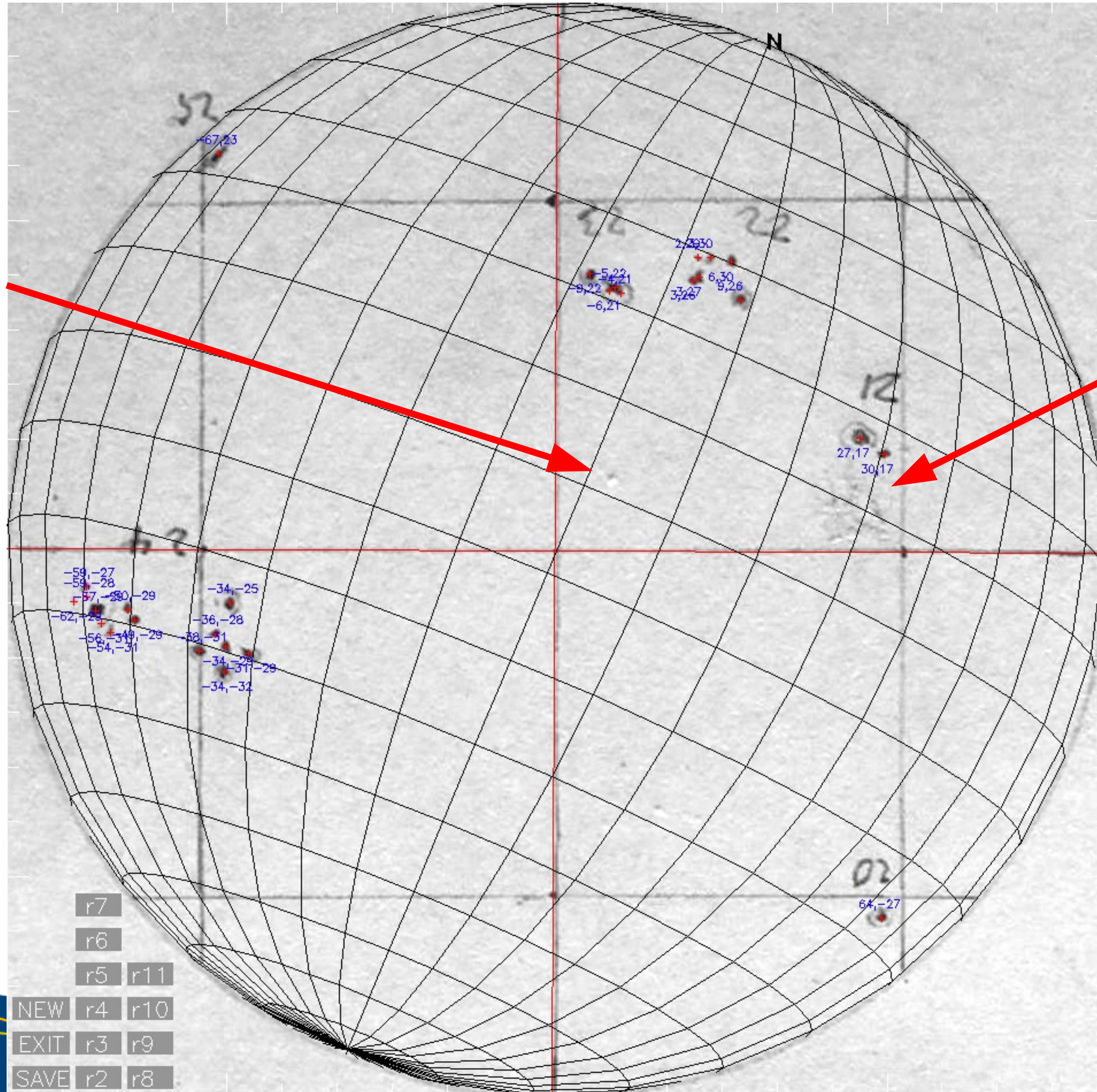




Date__________JDUT	R.A._(J2000.0)_DEC.		Ob-lon	Ob-lat	NP.ang	NP.dist
$$SOE						
2387627.500000000	283.92010	-22.84413	155.25	-3.27	2.0083	-974.46
2387627.750000000	284.19526	-22.81949	151.96	-3.30	1.8857	-974.44
2387628.000000000	284.47030	-22.79438	148.66	-3.33	1.7631	-974.41
2387628.250000000	284.74524	-22.76879	145.37	-3.35	1.6406	-974.38
2387628.500000000	285.02007	-22.74274	142.08	-3.38	1.5180	-974.35
2387628.750000000	285.29480	-22.71622	138.79	-3.41	1.3954	-974.32
2387629.000000000	285.56940	-22.68923	135.49	-3.44	1.2728	-974.29
2387629.250000000	285.84390	-22.66177	132.20	-3.47	1.1503	-974.26
2387629.500000000	286.11828	-22.63385	128.91	-3.50	1.0277	-974.23
2387629.750000000	286.39255	-22.60546	125.62	-3.52	0.9052	-974.20
2387630.000000000	286.66669	-22.57660	122.33	-3.55	0.7827	-974.16

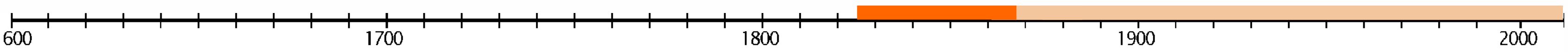
Schwabe 1825-1867

Pinholes from other circles



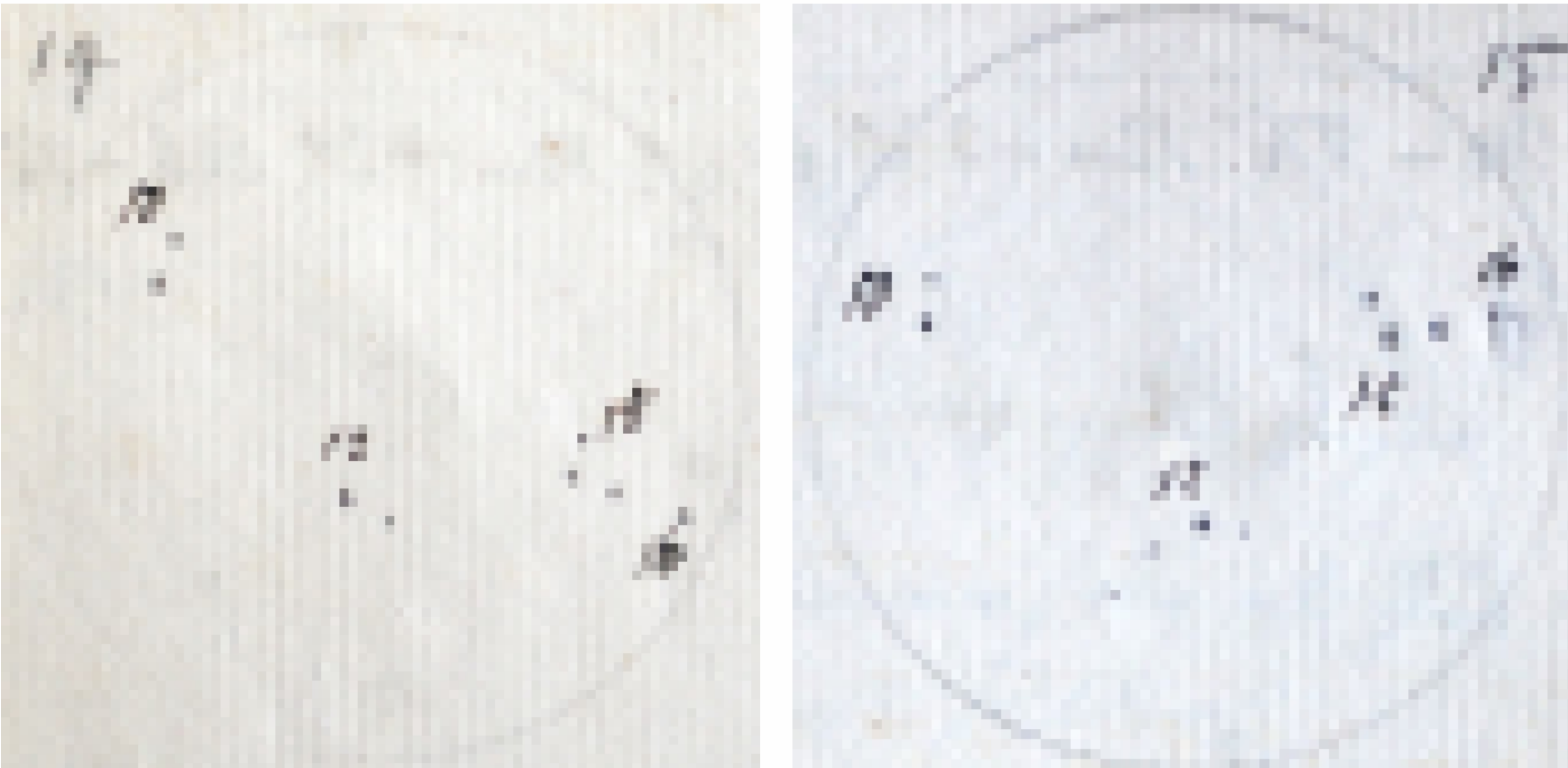
Erased spots

1858 Mar 03



Schwabe 1825-1867

- For 1100 drawings: rotational matching



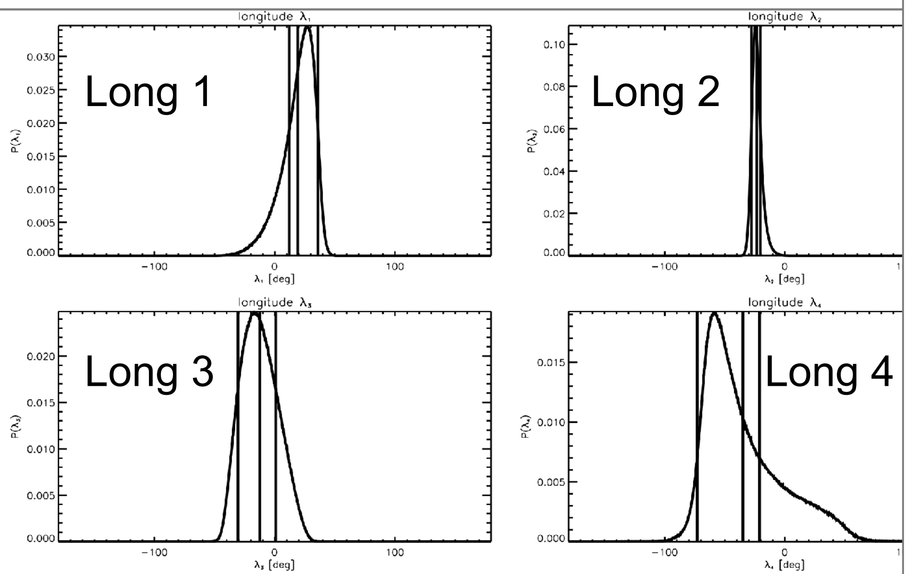
1829 Feb 01 and 02

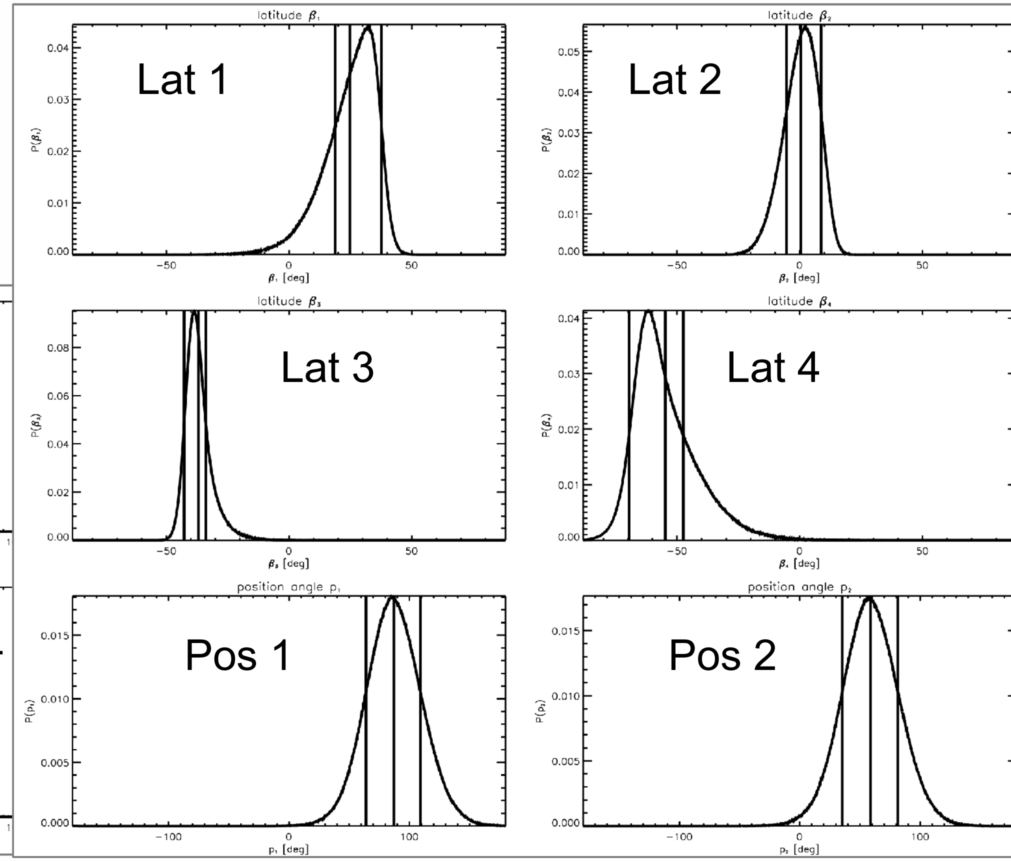
Rotational matching

- Adopt given differential rotation of Sun (from spots)
- Say 2 drawings with *n* spots gives model with:
  - 2 unknown position angles of drawings
  - *n* unknown latitudes
  - *n* unknown longitudes
  - Neglects proper motion of spots (typically < 0.1°)
- Use Bayesian inference for obtaining plausibility of model
- Advantage: full probability distribution of unknowns available → decide whether parameters/model are useful

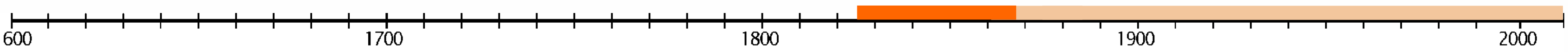
Rotational matching

- Resulting probability density distributions





→ match rejected



Schwabe 1825-1867

- Result:

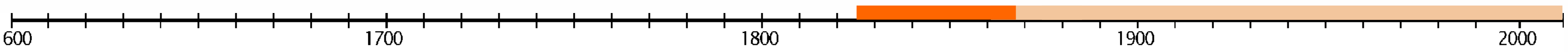
Positions discarded

Positions from different method

Heliocentric distance from center

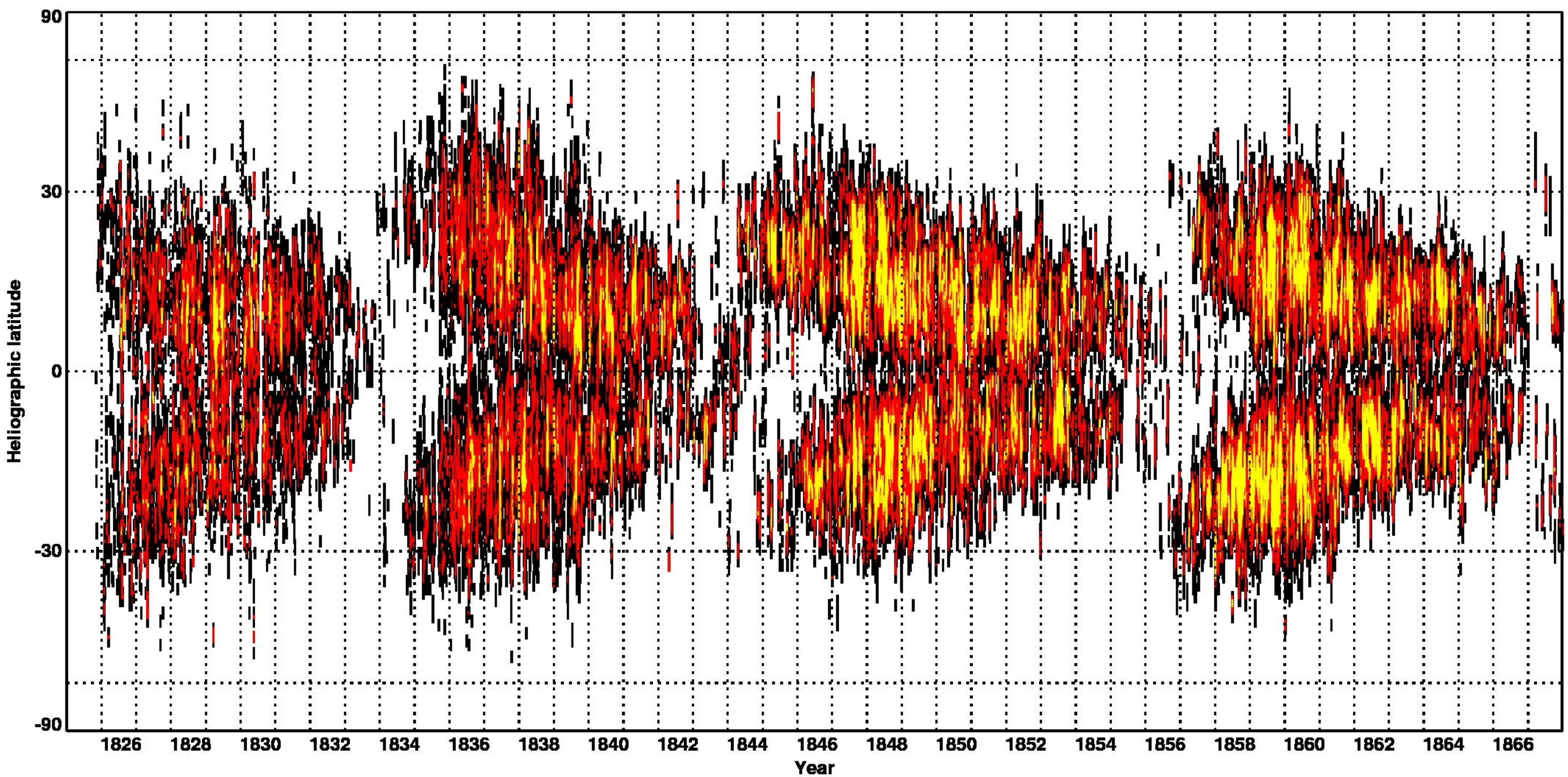
Umbral area in millionths of solar hemisphere (MSD)

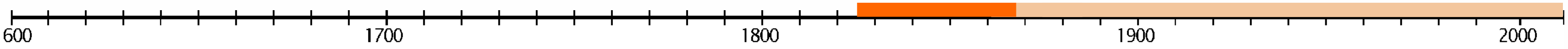
YYYY	MM	DD	HH	MI	T	L0	B0	CMD	LONG	LAT	M	Q	S	GROUP	MEASURER				DELTA	UMB	P
1829	02	01	14	00	1	255.9	-6.2	NaN	NaN	NaN	-	4	10	10-0	dathe	-.-	-.-	-.-	NaN	-	
1829	02	01	14	00	1	255.9	-6.2	NaN	NaN	NaN	-	4	7	10-1	dathe	-.-	-.-	-.-	NaN	-	
1829	02	01	14	00	1	255.9	-6.2	NaN	NaN	NaN	-	4	8	12	dathe	-.-	-.-	-.-	NaN	-	
1829	02	01	14	00	1	255.9	-6.2	NaN	NaN	NaN	-	4	6	12	dathe	-.-	-.-	-.-	NaN	-	
1829	02	01	14	00	1	255.9	-6.2	NaN	NaN	NaN	-	4	7	15	dathe	-.-	-.-	-.-	NaN	-	
1829	02	01	14	00	1	255.9	-6.2	NaN	NaN	NaN	-	4	7	15	dathe	-.-	-.-	-.-	NaN	-	
1829	02	01	14	00	1	255.9	-6.2	NaN	NaN	NaN	-	4	7	15	dathe	-.-	-.-	-.-	NaN	-	
1829	02	01	14	00	1	255.9	-6.2	NaN	NaN	NaN	-	4	8	16	dathe	-.-	-.-	-.-	NaN	-	
1829	02	02	12	00	1	243.9	-6.3	46.0	289.9	-5.1	H	3	7	10-0	dathe	-.-	-.-	-.-	45.8	15	!
1829	02	02	12	00	1	243.9	-6.3	48.5	292.4	-11.7	H	3	5	10-1	dathe	-.-	-.-	-.-	48.2	5	!
1829	02	02	12	00	1	243.9	-6.3	-7.0	236.9	13.5	H	3	7	12	dathe	-.-	-.-	-.-	21.0	14	!
1829	02	02	12	00	1	243.9	-6.3	-0.4	243.5	18.8	H	3	5	12	dathe	-.-	-.-	-.-	25.1	5	!
1829	02	02	12	00	1	243.9	-6.3	-13.3	230.6	12.9	H	3	2	12	dathe	-.-	-.-	-.-	23.3	1	!
1829	02	02	12	00	1	243.9	-6.3	-27.8	216.1	-26.1	H	3	7	15	dathe	-.-	-.-	-.-	33.1	14	!
1829	02	02	12	00	1	243.9	-6.3	-31.4	212.5	-19.9	H	3	8	15	dathe	-.-	-.-	-.-	33.4	22	!
1829	02	02	12	00	1	243.9	-6.3	-41.4	202.5	-22.1	H	3	8	15	dathe	-.-	-.-	-.-	43.0	23	!
1829	02	02	12	00	1	243.9	-6.3	-55.9	188.0	-26.1	H	3	7	16	dathe	-.-	-.-	-.-	56.7	16	!
1829	02	02	12	00	1	243.9	-6.3	-63.7	180.2	-26.3	H	3	4	16	dathe	-.-	-.-	-.-	63.7	4	!
1829	02	02	12	00	1	243.9	-6.3	-31.6	212.3	-21.4	H	3	3	15	dathe	-.-	-.-	-.-	34.1	2	!
1829	02	02	12	00	1	243.9	-6.3	-30.6	213.3	-21.2	H	3	3	15	dathe	-.-	-.-	-.-	33.2	2	!



Schwabe 1825-1867

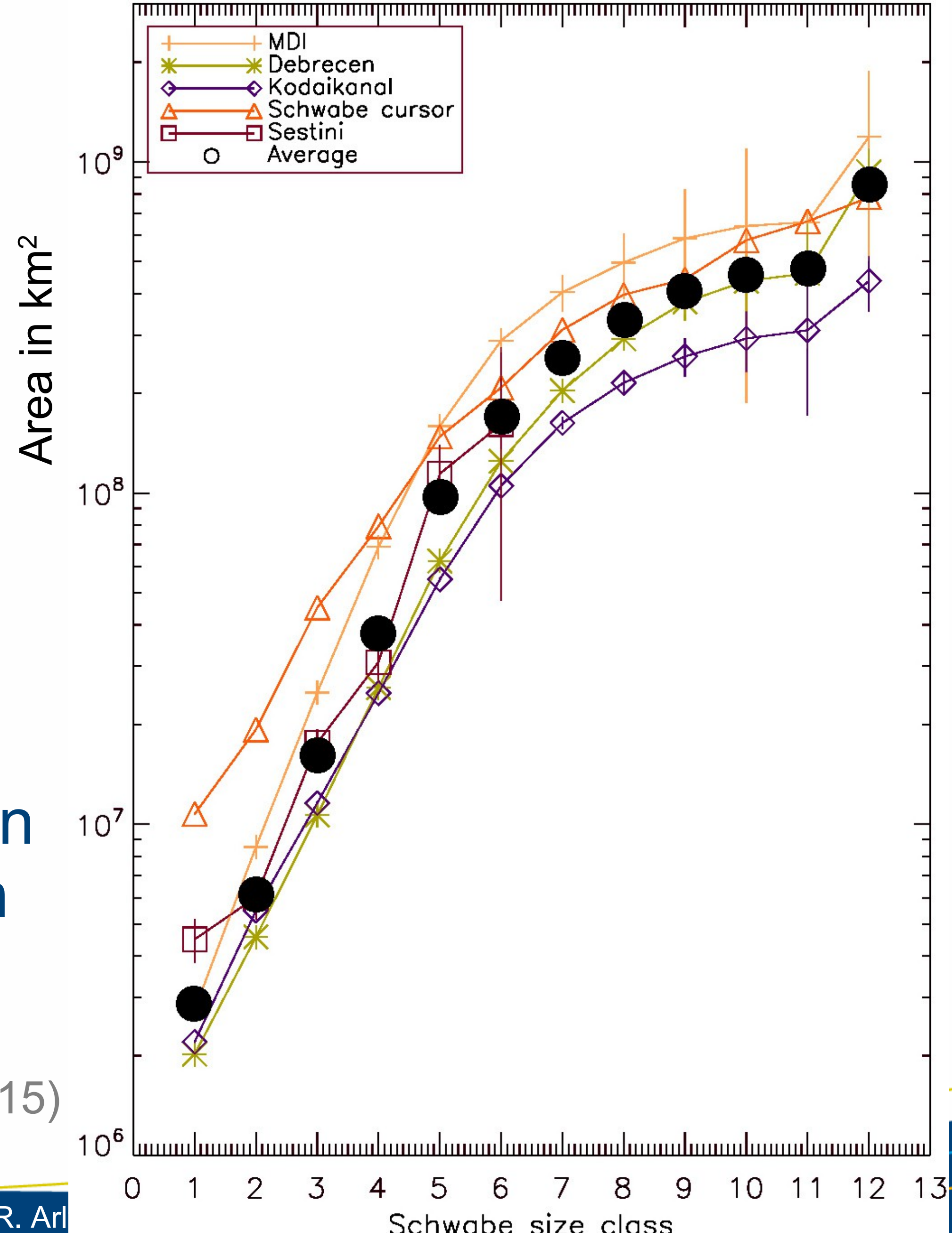
- 134,000 positions (Arlt et al. 2013), ~ 95,000 by Raisa Leussu, Oulu





Schwabe

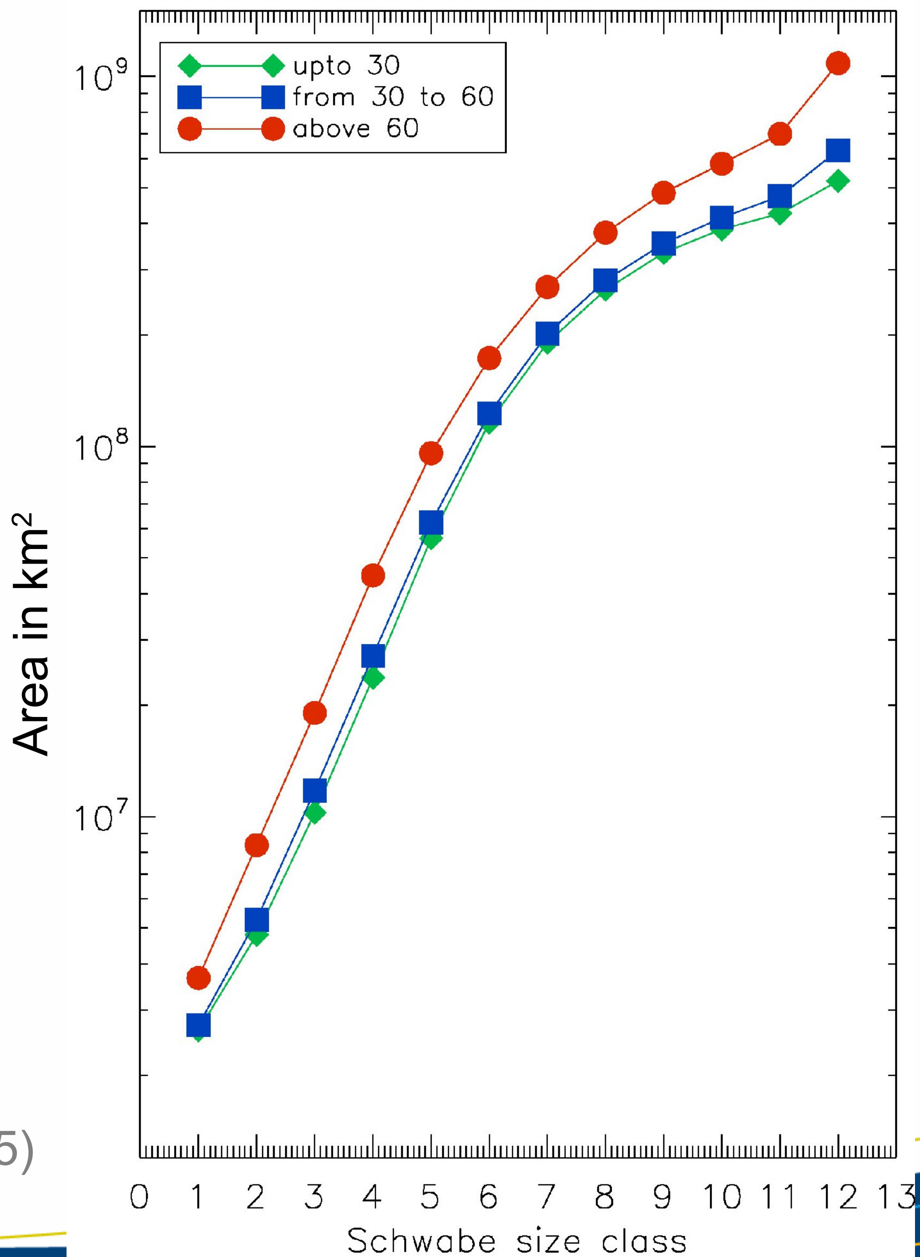
- Convert *12 size classes* into physical size
- Statistical approach matching size distribution of modern data sets
- + direct comparison with 2 months of high-precision observations by Sestini in 1850



Senthamizh Pavai et al. (2015)

Schwabe

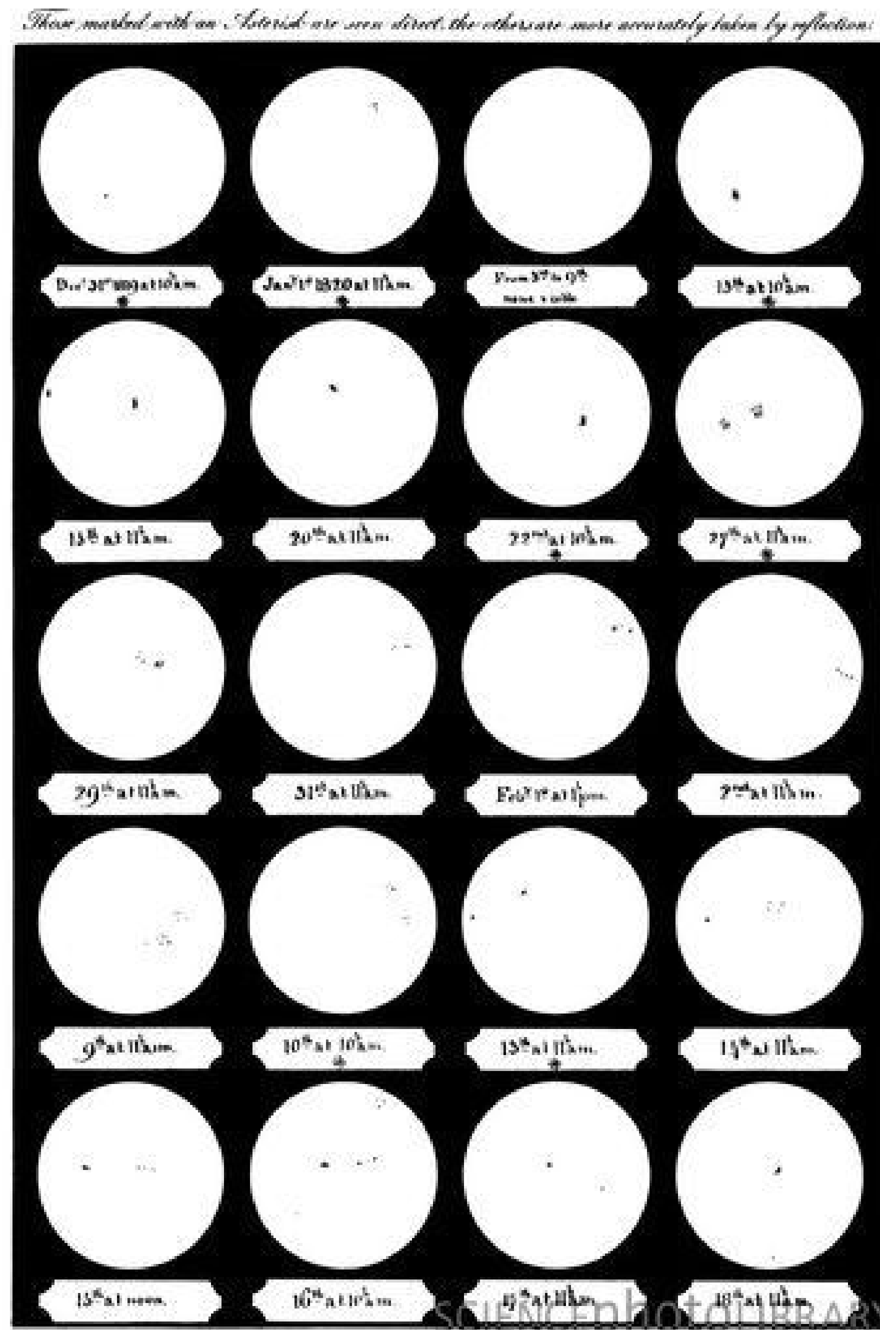
- Set lower limit for histogram to 10^6 km^2, because
  - typical size of pores
  - smallest spots corresponding to Sestini
  - Schwabe's detection ability very high
- Study disk-centre distances <30º, 30º-60º, 60º-75º

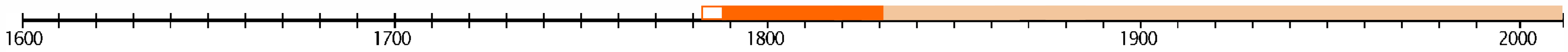


Senthamizh Pavai et al. (2015)

Adams

- Stored at Royal Astronomical Society library
- Still on to-do list





AIP

Honoré Flaugergues, ~1788-1830

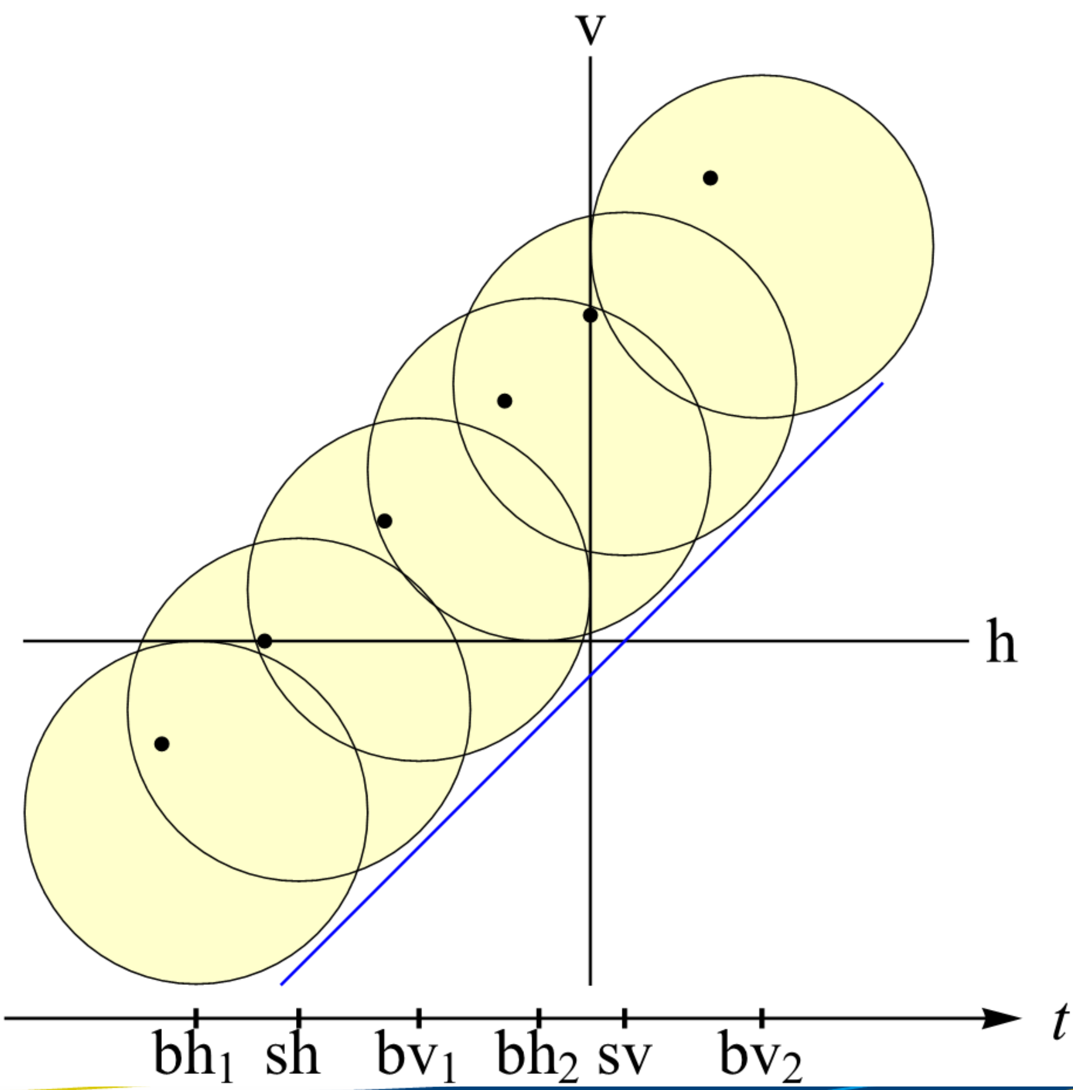
- Several hundred sunspot observations
- Wolf’s interpretation of *sunspot numbers* correct
- Today in archives of the Paris Observatory library
- Mostly contact times:

"le bord du ⊙ al horaire	12 39 58
la grande tache a l'oblique	12 40 22.5
la petite tache a l'oblique	12 40 46
la grande tache al horiare	12 41 21
la petite tache al horaire	12 41 31
le bord du soleil al horaire	12 42 09
le letite tache al oblique	12 42 18
le grande tache al oblique	12 42 22"

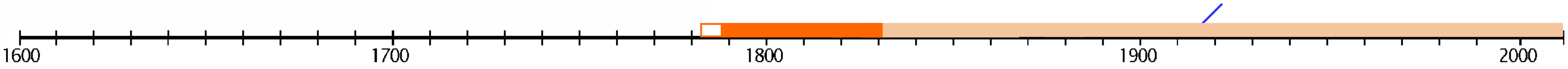
...yet to be analysed

Honoré Flaugergues, ~1788-1830

- Reconstruct spot position from transit times
- Example: horizontal alignment of cross-hairs, oblique motion of Sun



Provided by Egor Illarionov



Honoré Flaugergues

- Reconstruct spot position from transit times
- Example: equatorial alignment if “hour” (vertical) line and oblique line
- But …

Provided by Egor Illarionov

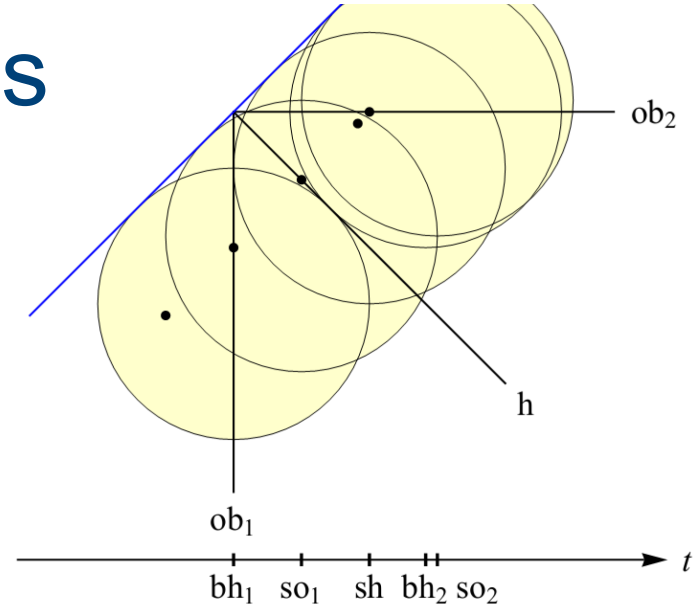


Fig. 6 Motion of the solar disk and sunspot through hour wire h and oblique wires ob_1 and ob_2. On the time axis t there are marked corresponding transition times. Blue line is a line of daily motion of the sun.

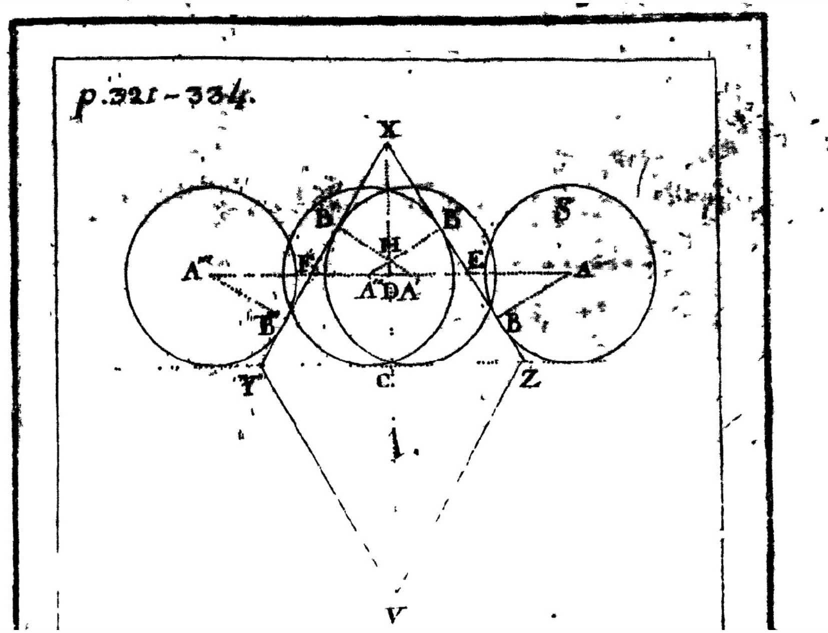
Table 10 Sequence of transition times of solar disk and sunspot as observed on 1795 March 4. Firstly wires originate at the line of motion of the ”north” pole of the solar disk, then at the line of motion of the ”south” pole.

le bord du ☉ al horiare	12:39:58	13:01:58
le grande tache al oblique	12:40:22	13:02:07
la grande tache al horiare	12:41:21	13:03:21 (+1)
le bord du ☉ al horiare	12:42:09	13:04:09 (+1)
le grande tache al oblique	12:42:22	13:04:30

AIP

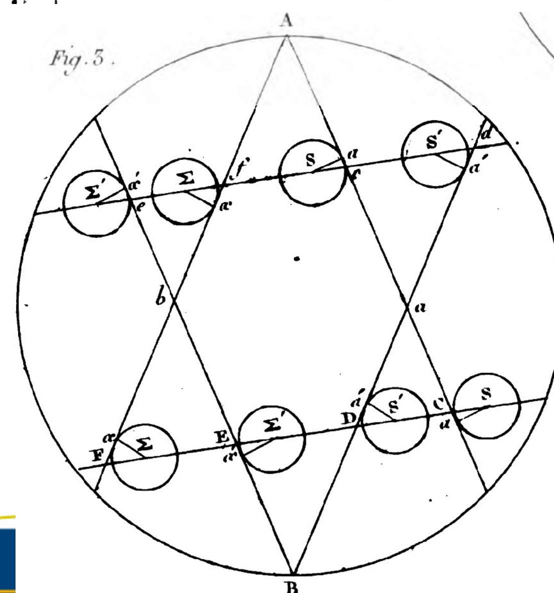
Honoré Flaugergues, ~1788-1830

- … description indicates rhomb-shaped cross-hairs,
  unclear when used.



Flaugergues (1813)

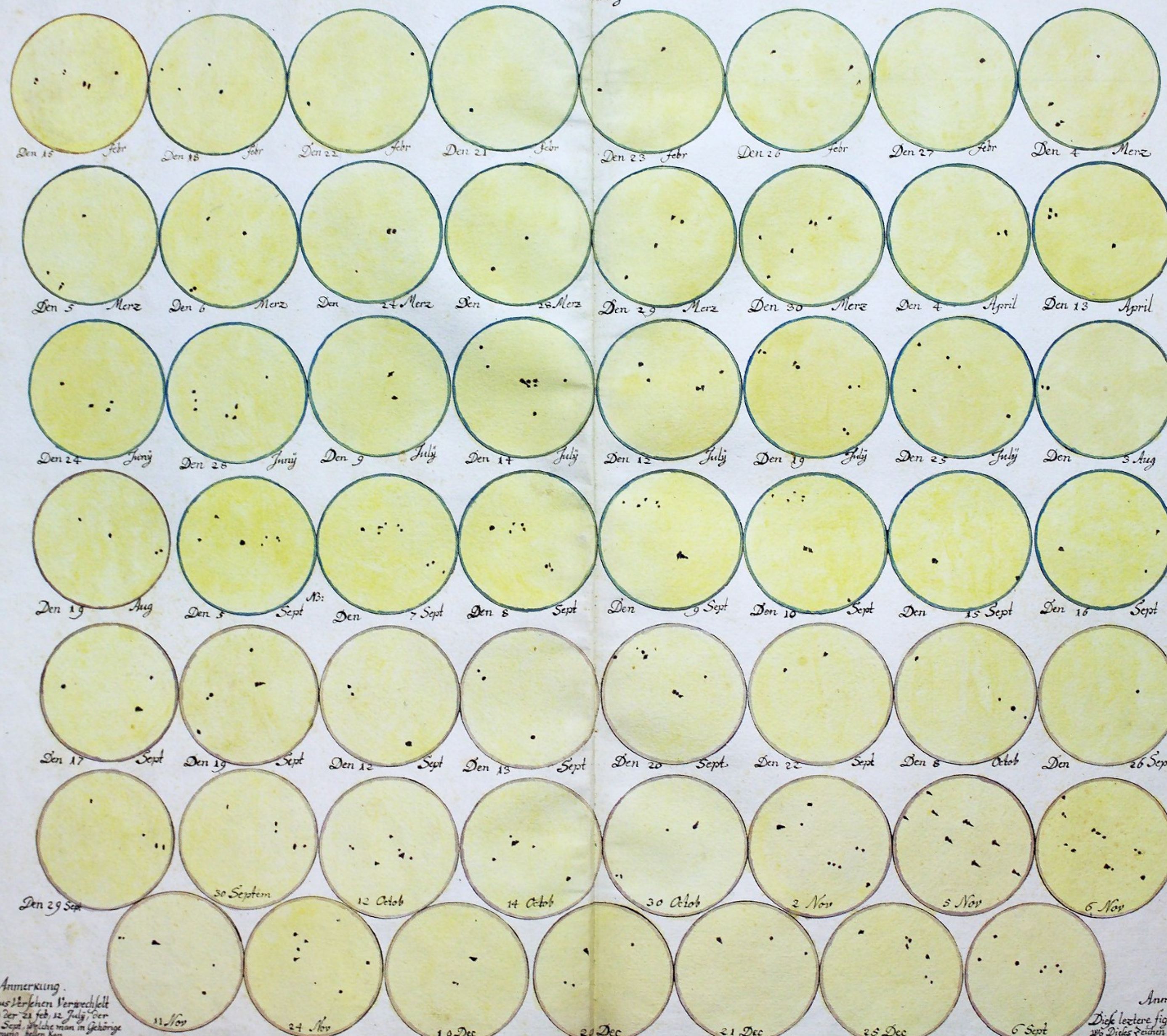
- Also described by others



Monteiro da Rocha (1808)

Vorstellung, und Abzeichnungen der Sonnen Maculn A:1749

Observirt und Verzeichnet von J: C: Staudach in Nürnberg

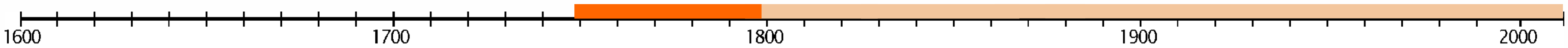


Anmerkung.

Diese so aus Versehen Verwechselt worden, sind der 21 feb, 12 July, der 12. 13. 26 Sept. welche man in Gehörige Ordnung stellen kan

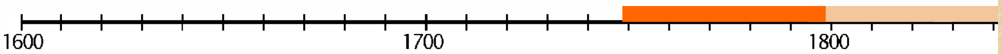
Anmerkung

Diese leztere figur gehört dahin wo Dieses Zeichen steht NB. es stet aber auch noch mehr Verwechselt

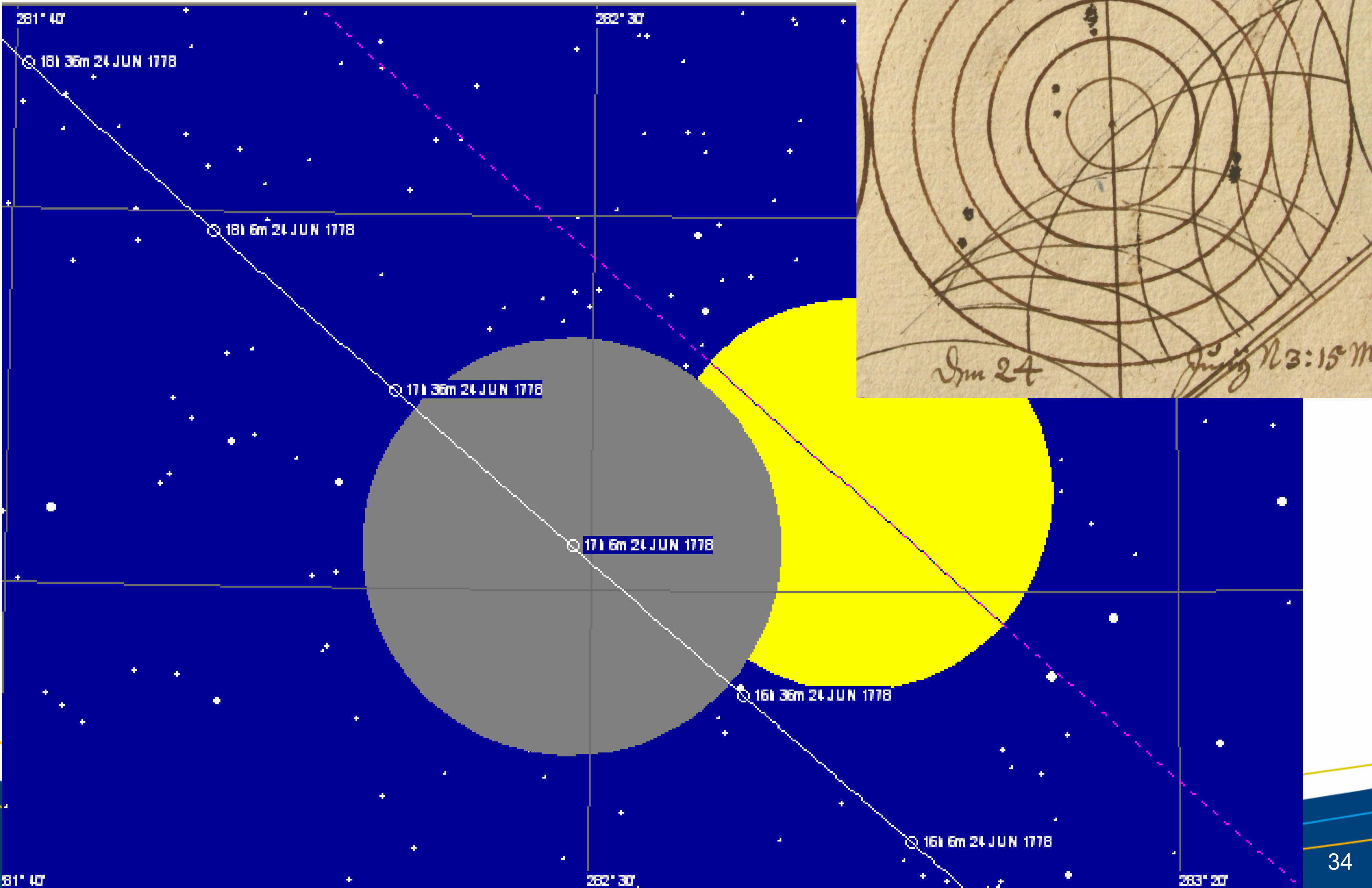


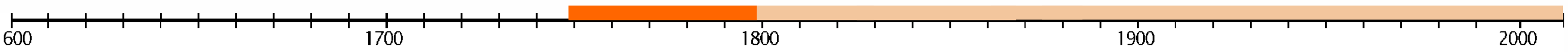
Johan Caspar Staudacher, 1749-1799

- About 1000 drawings
- Apparently the only continuous observer in the 18th century
- Original stored in library of AIP



Staudacher: Jun 24, 1778

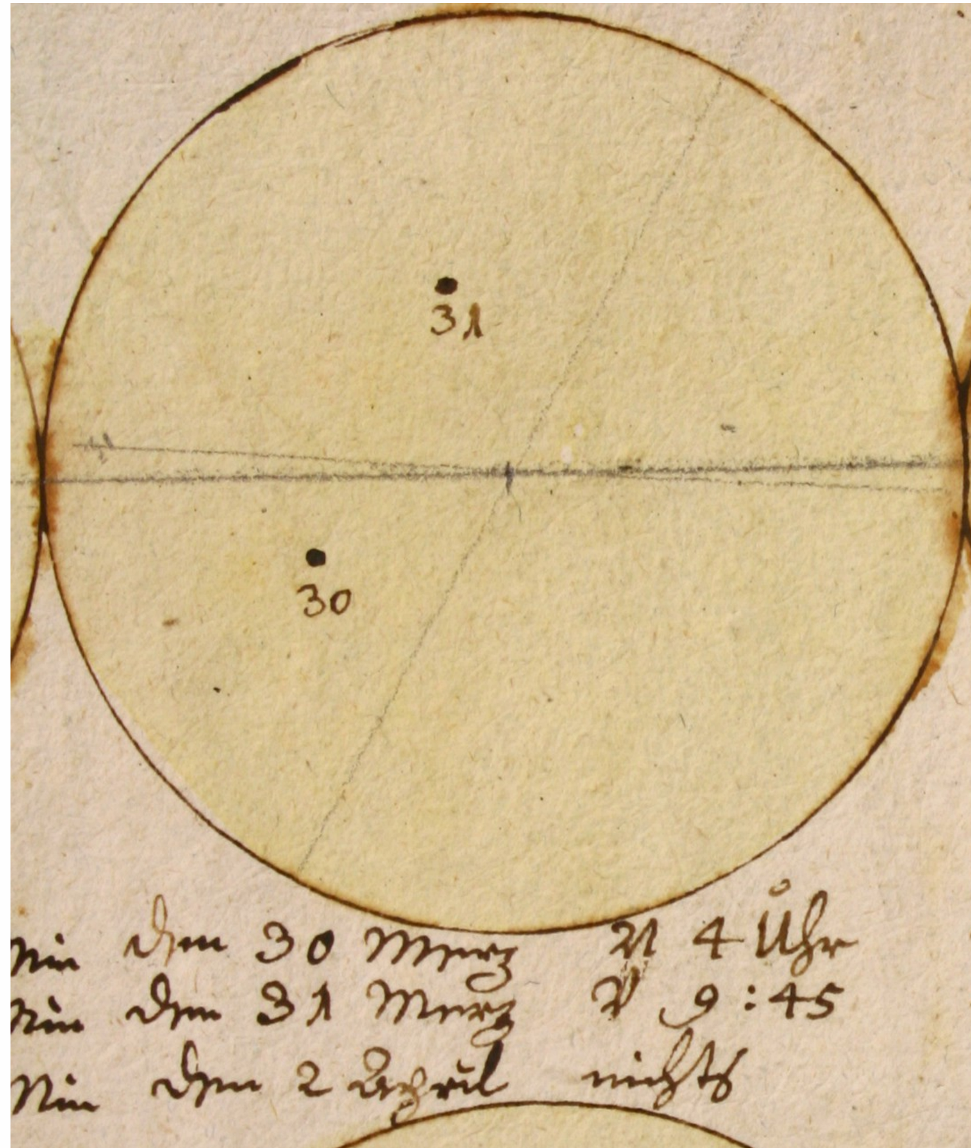


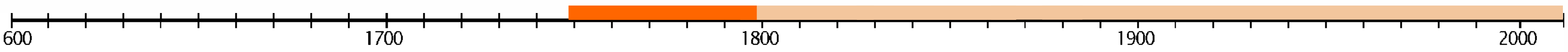


Staudacher

- Many positions were found by rotational matching
- Here: equator looks like parallel to 30-31
- But time difference less than 18 hours!

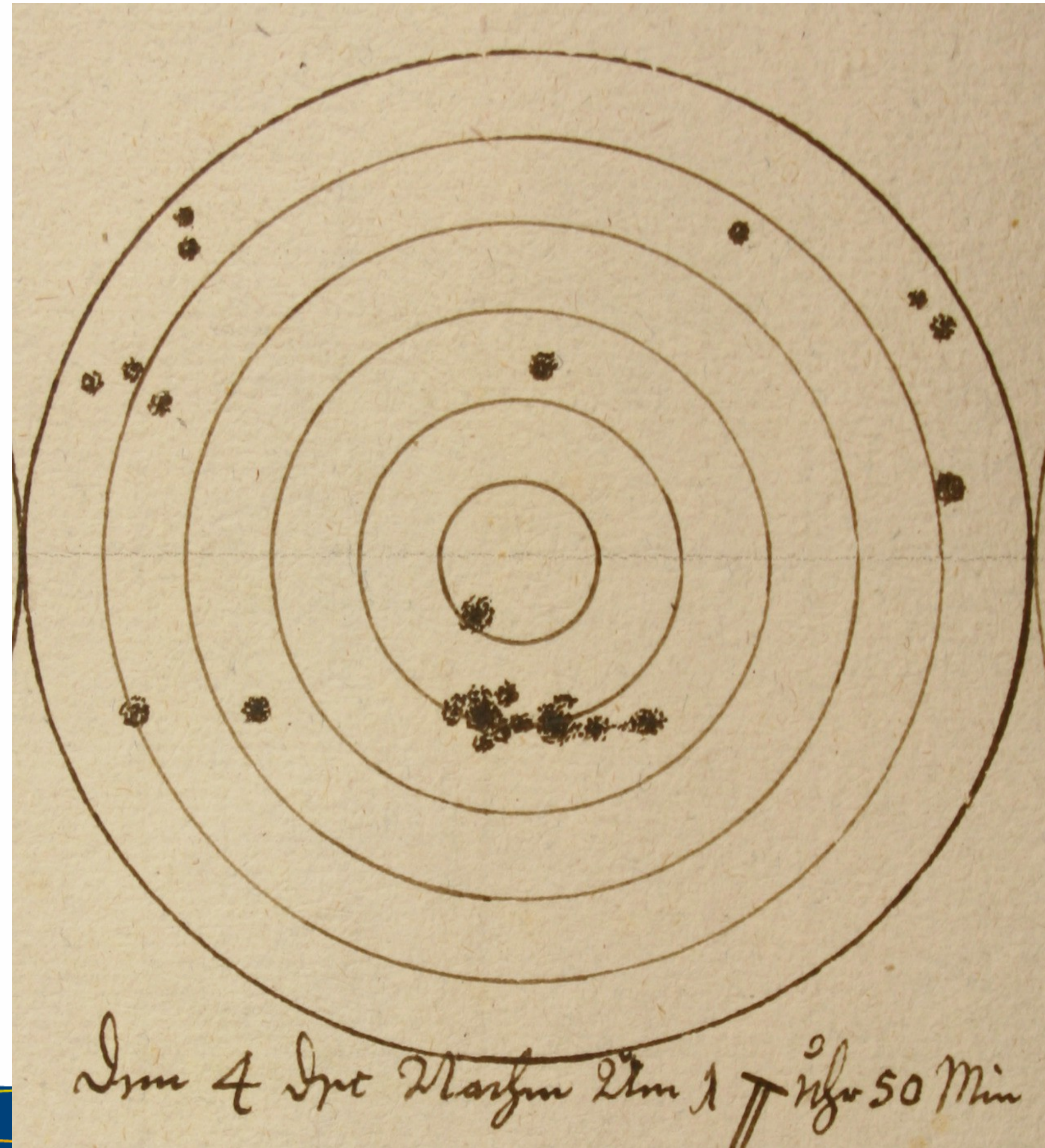
➔ Orientations of drawings different

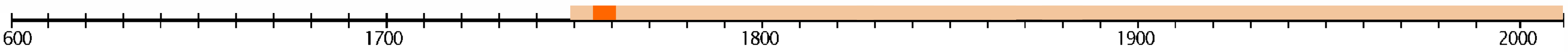




Staudacher

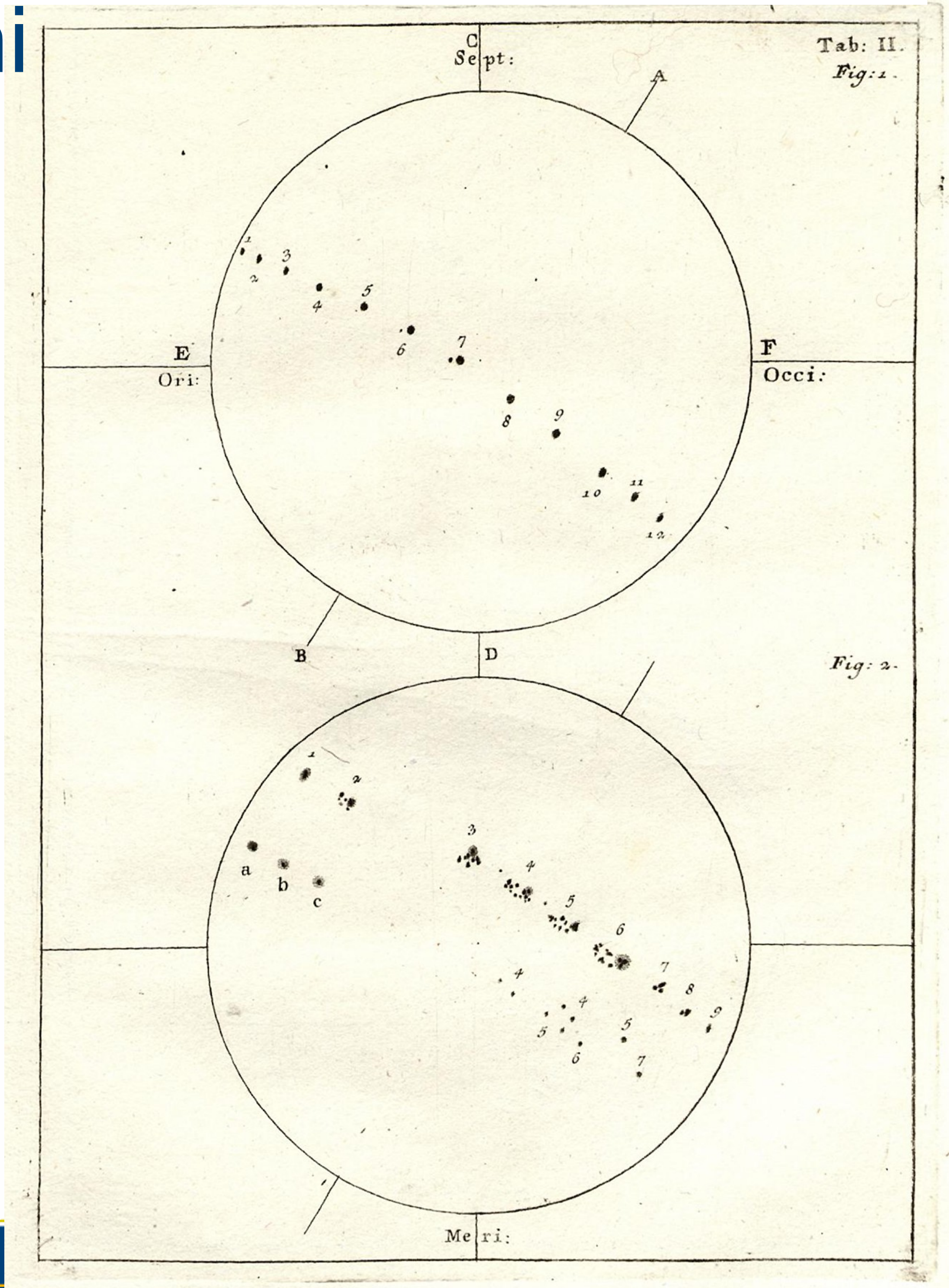
- Different drawing style starting in the end of 1768
- Here: 1768 Dec 04

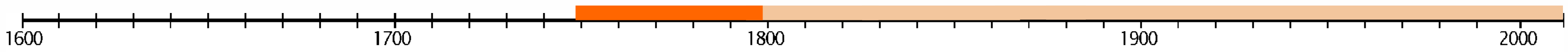




Ludovico Zucconi 1754-1760

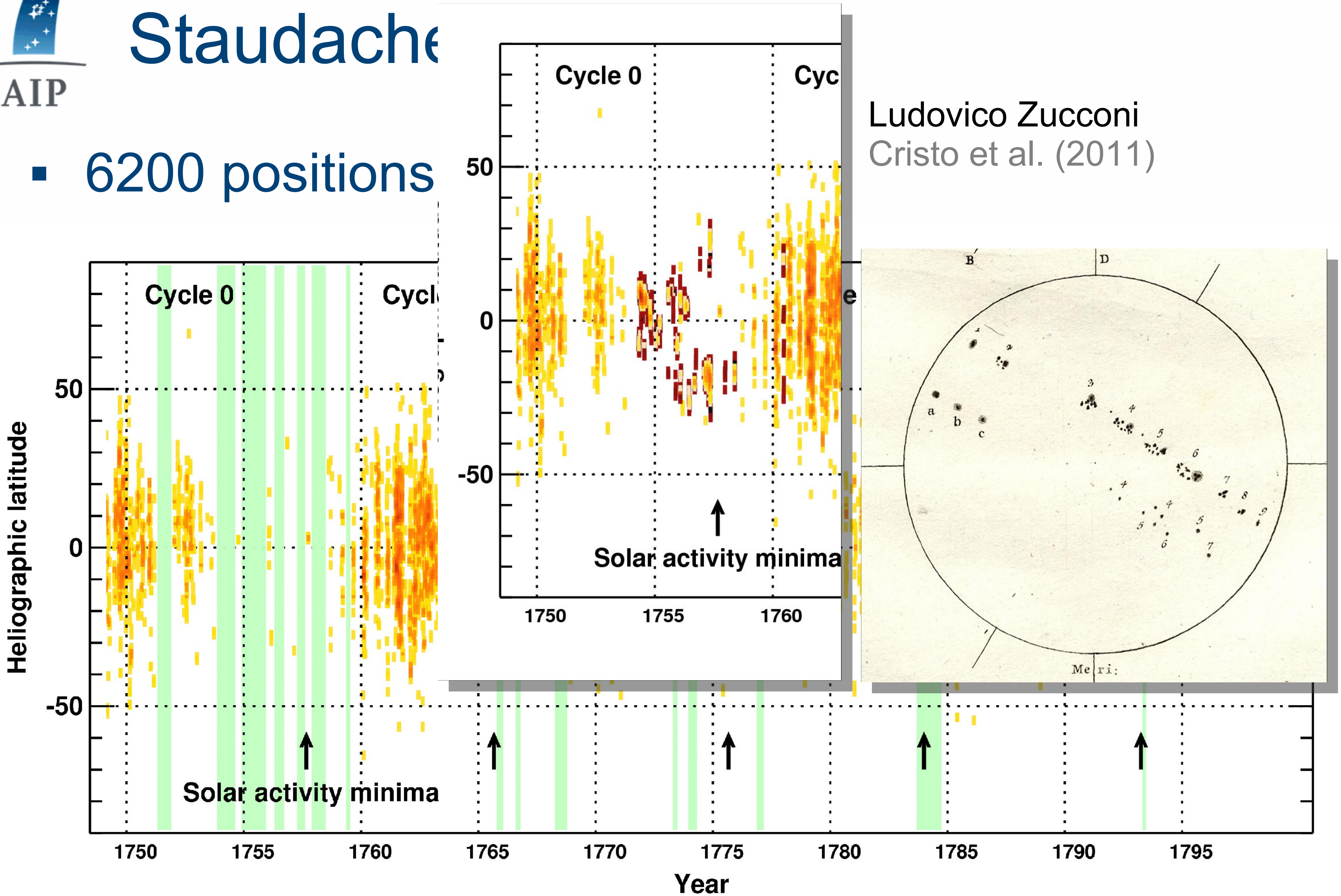
- Much more precise than Staudacher
- Only a few years
- Analysis by Cristo, Vaquero & Sanchez-Bajo (2011)





Staudache

- 6200 positions

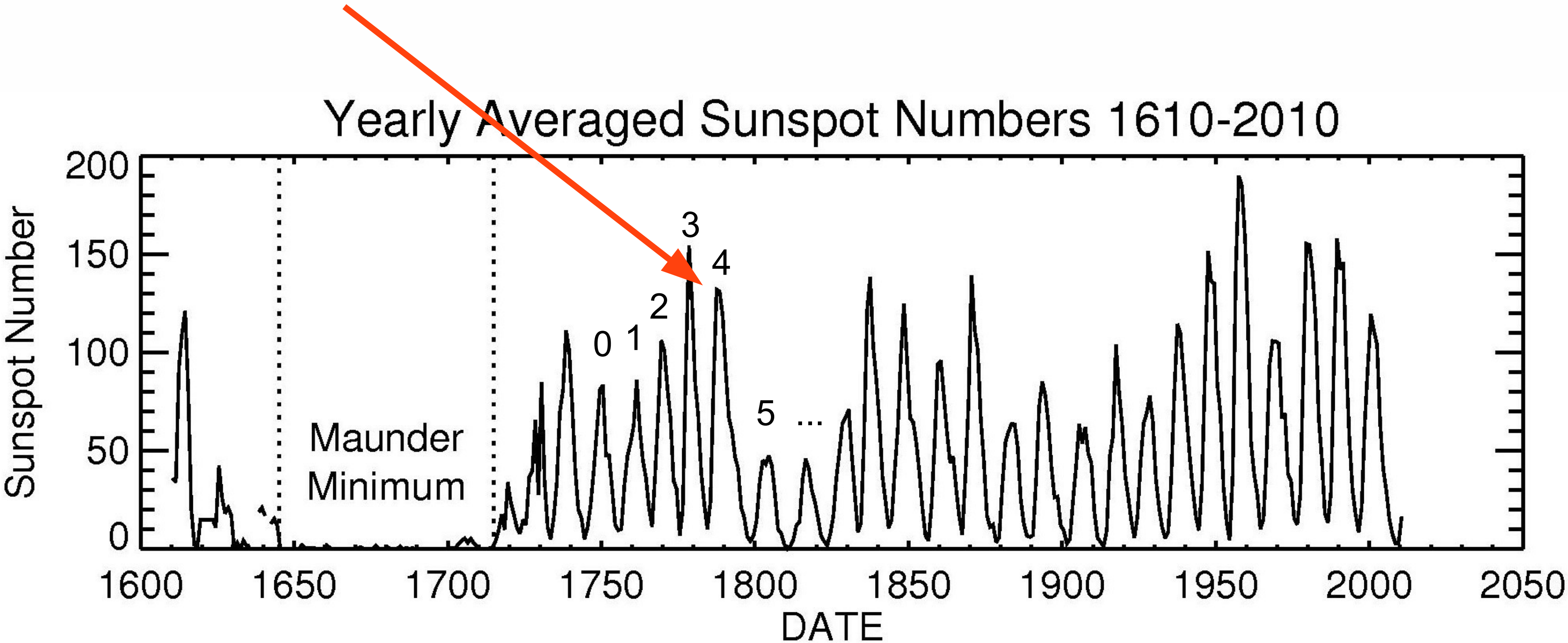


Ludovico Zucconi

Cristo et al. (2011)

Cycle 4: Long cycle or lost cycle?

- Cycle 4 unusually long, indications for hidden cycle

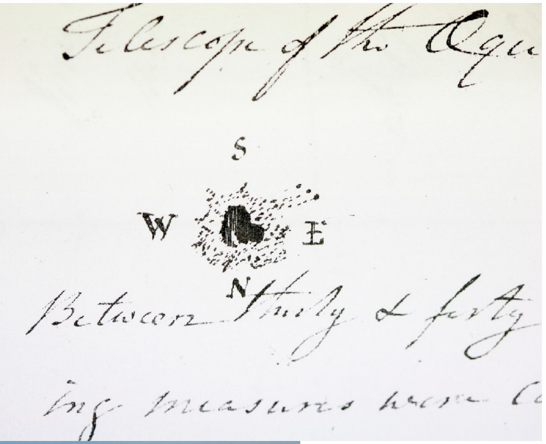


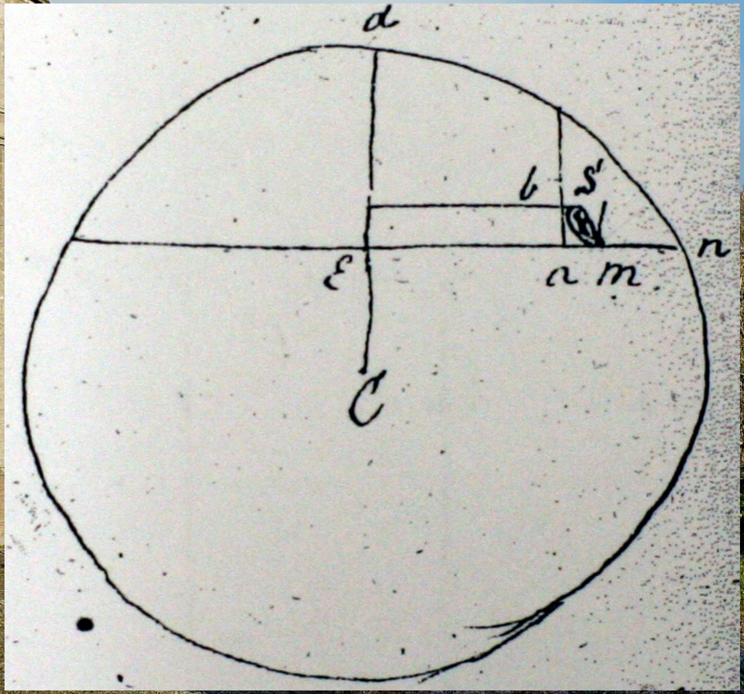
Based on Hoyt & Schatten (1998)

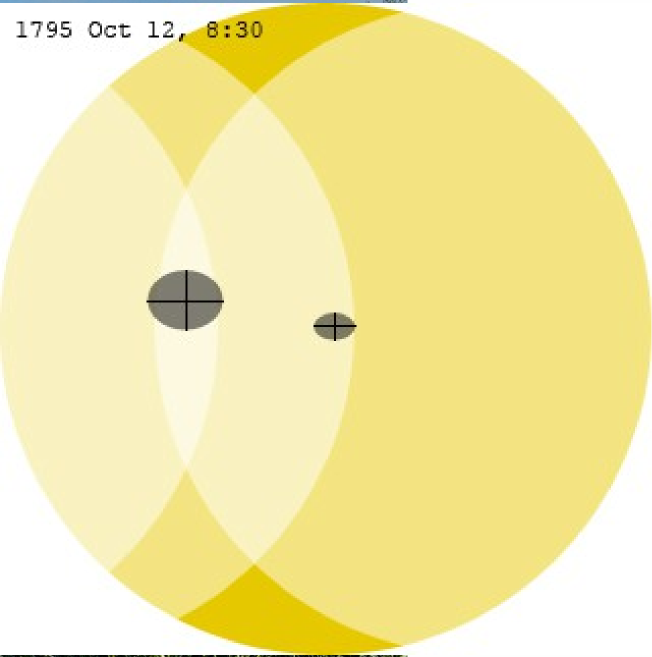
1600 1700 1800 1900 2000

Hamilton and Gimingham

- Armagh Observatory 1795–1797

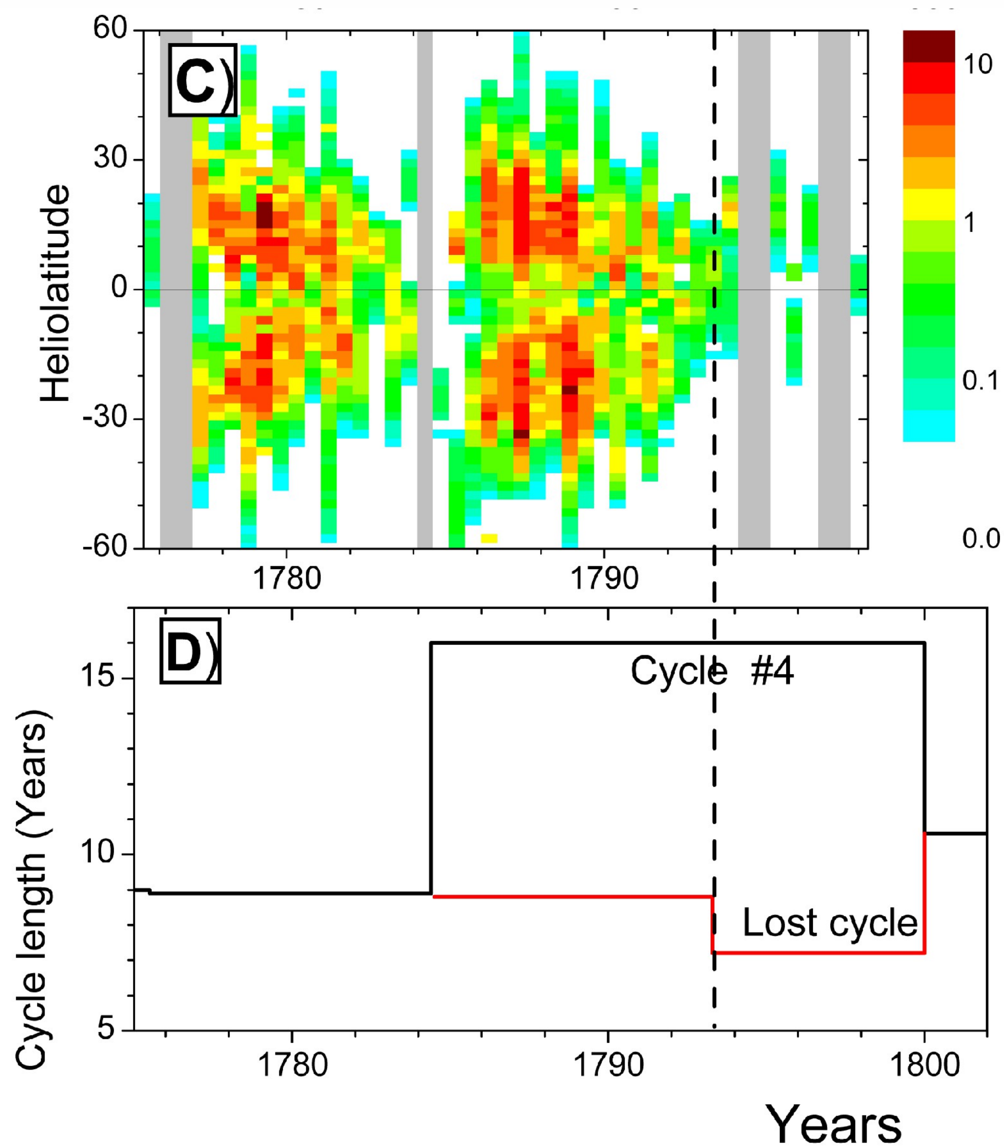






Staudacher + observations at Armagh

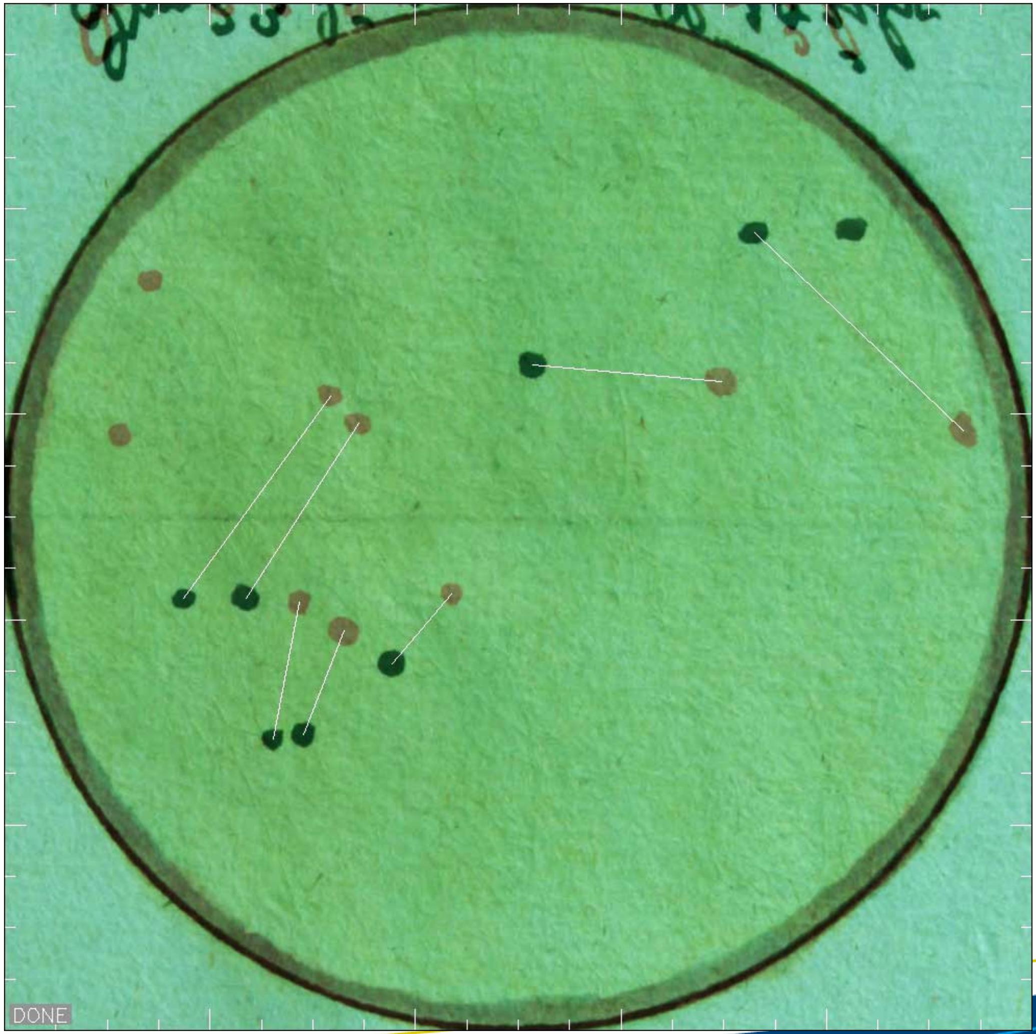
- Indication in sunspot number very subtle
- But visible through latitude distributions
- Data by Flaugergues will be extremely valuable
- Project proposal for the summer 2014



Usoskin et al (2009)

Staudacher – differential rotation

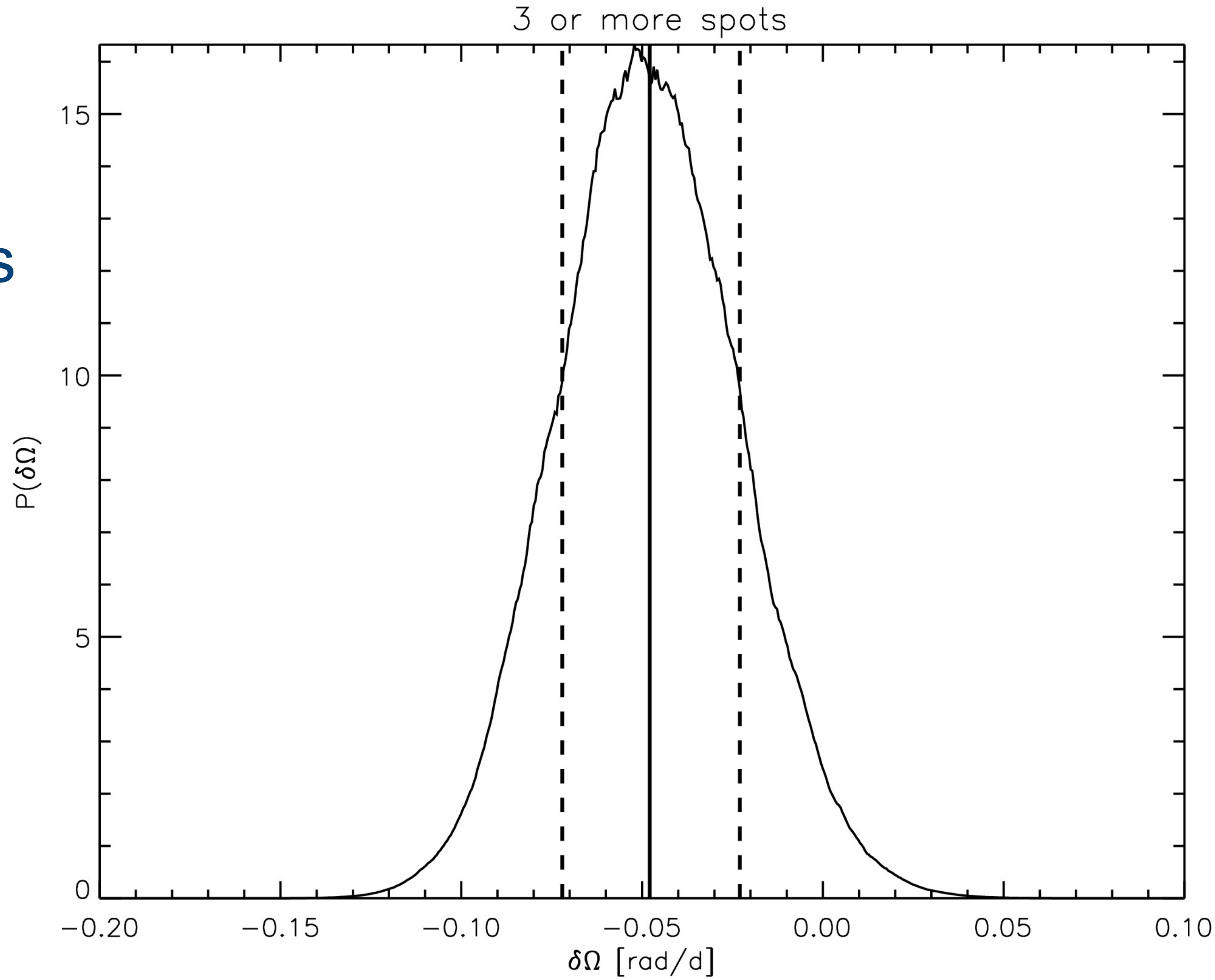
- Pairs of drawings
- Again Bayesian
- Free parameters now:
  - Sunspot positions
  - Orientation of disks
  - Time offset
  - Differential rotation
- Recall: full knowledge of error margins



AIP

Staudacher – differential rotation

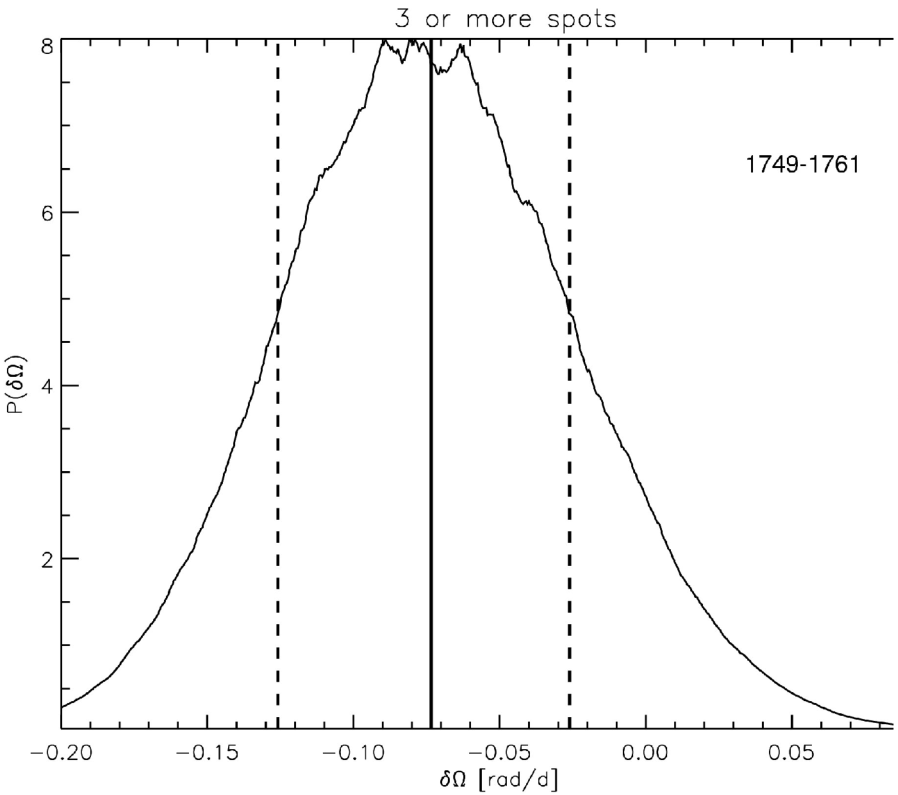
- Full probability distribution for all combinations of parameters
- Integrated distribution gives “marginal distribution” for desired parameter
- Sun: -0.0501 /d
(Balthasar et al. 1986)

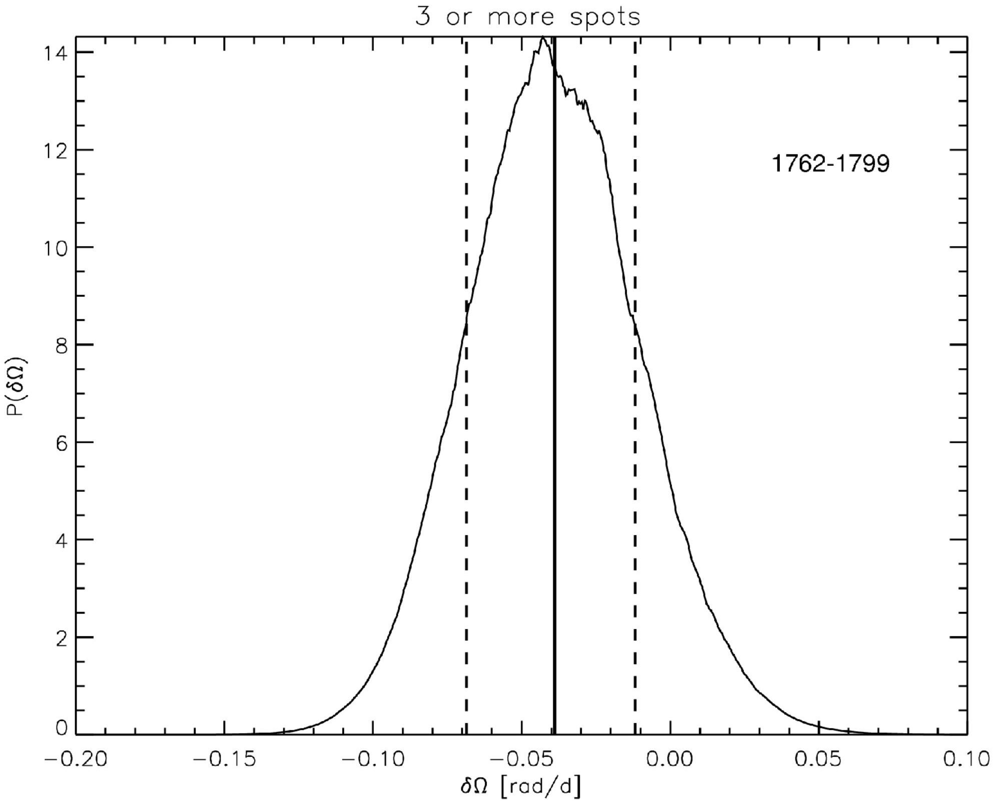


Arlt & Fröhlich (2012)

Staudacher – differential rotation

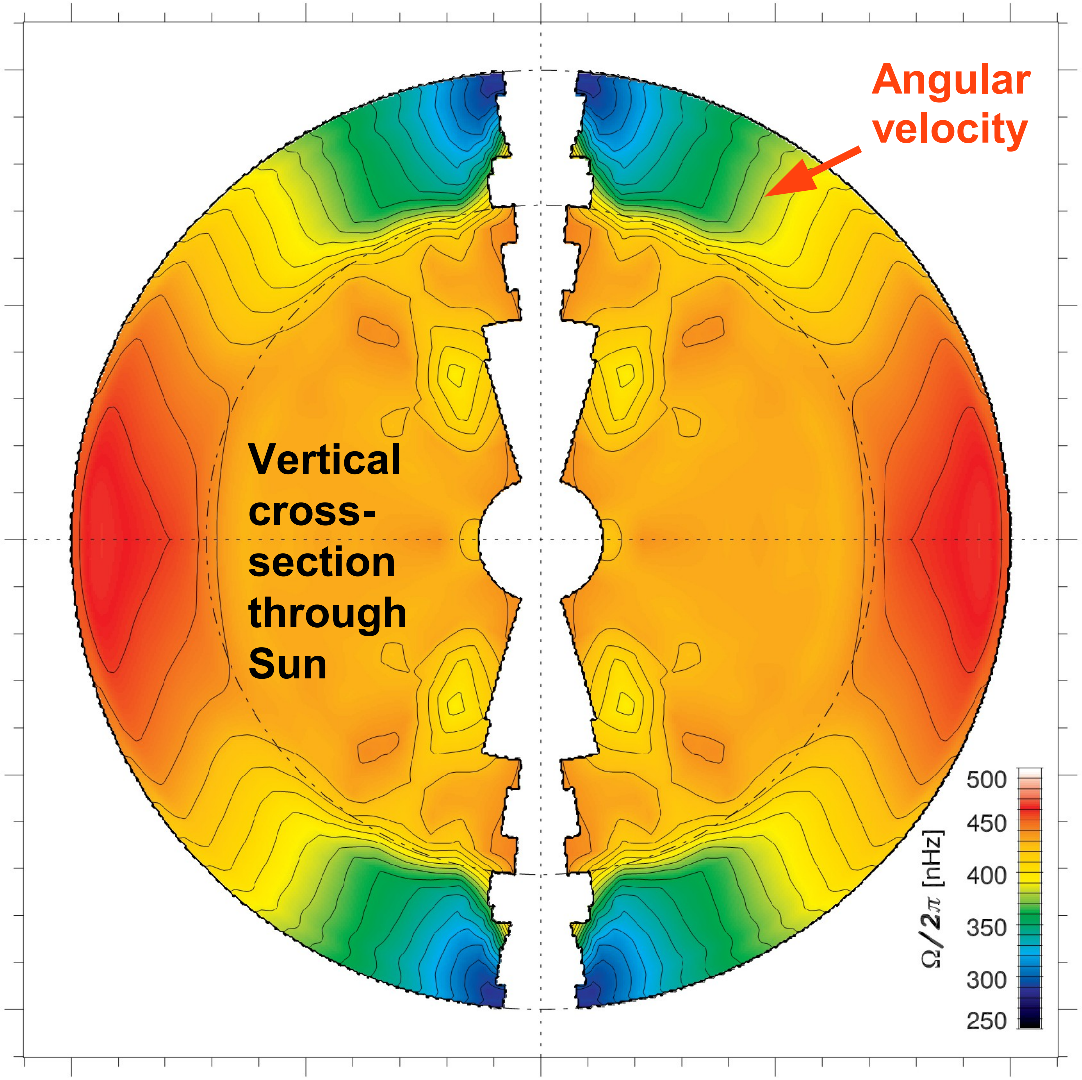
- Split the period into two and see what happens
  (Arlt & Fröhlich 2012)





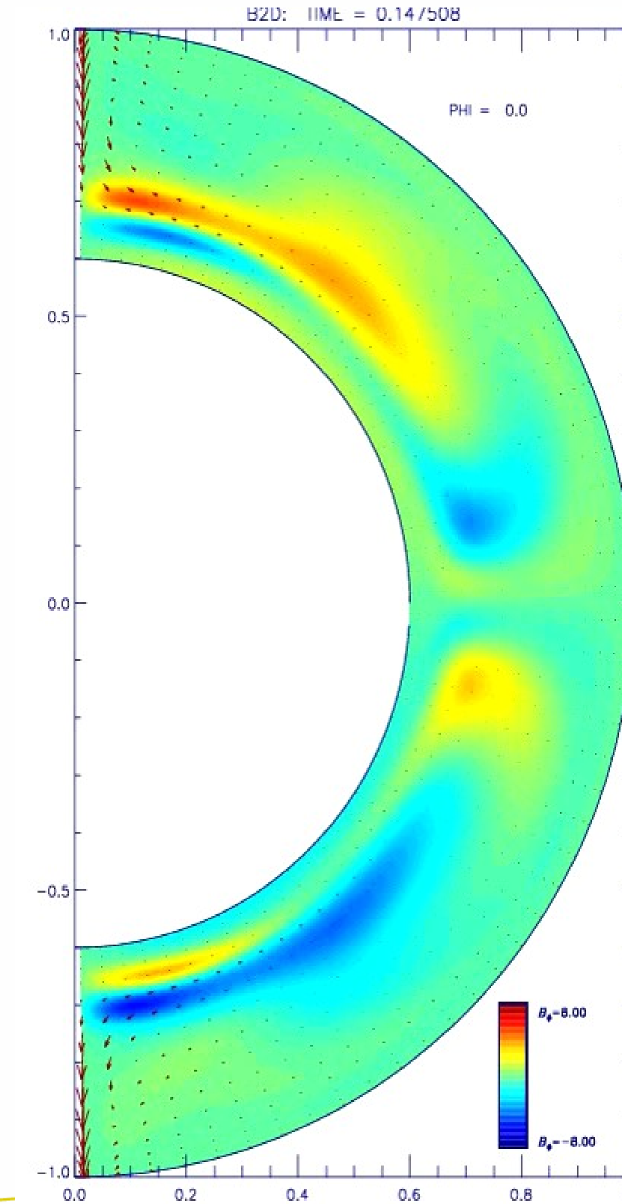
Grand minima in the computer

- Differential rotation generated by convection zone
- Λ-effect theory based on rotating, stratified turbulence
- See papers by Rüdiger, Kitchatinov, Küker



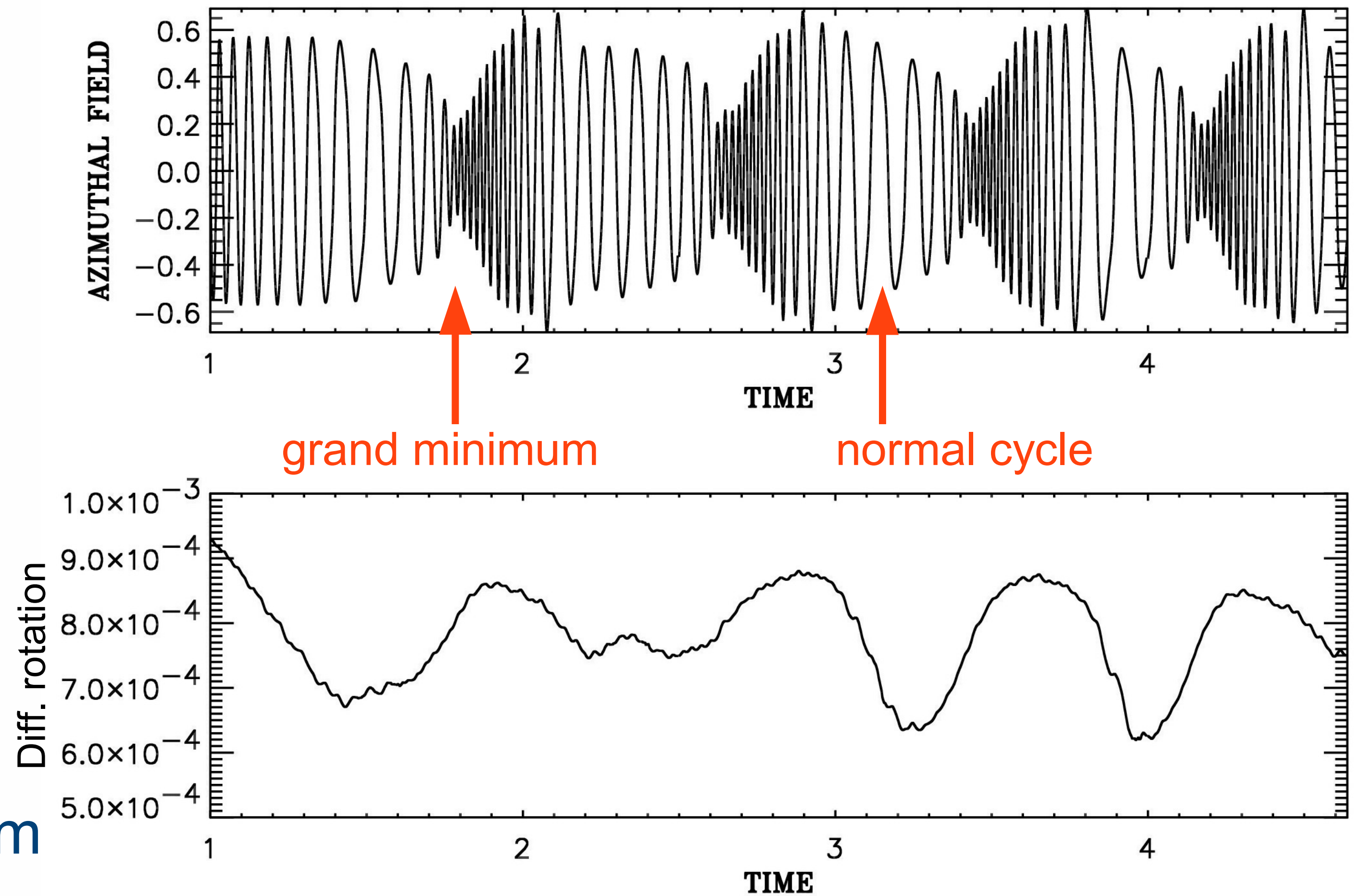
Dynamo sketch

- Strong azimuthal fields at bottom of convection zone
- Taken as a measure for surface activity
- Flux rise to the surface not modelled
- Here: kinematic (no magnetic effect on flows)



Differential rotation in dynamo

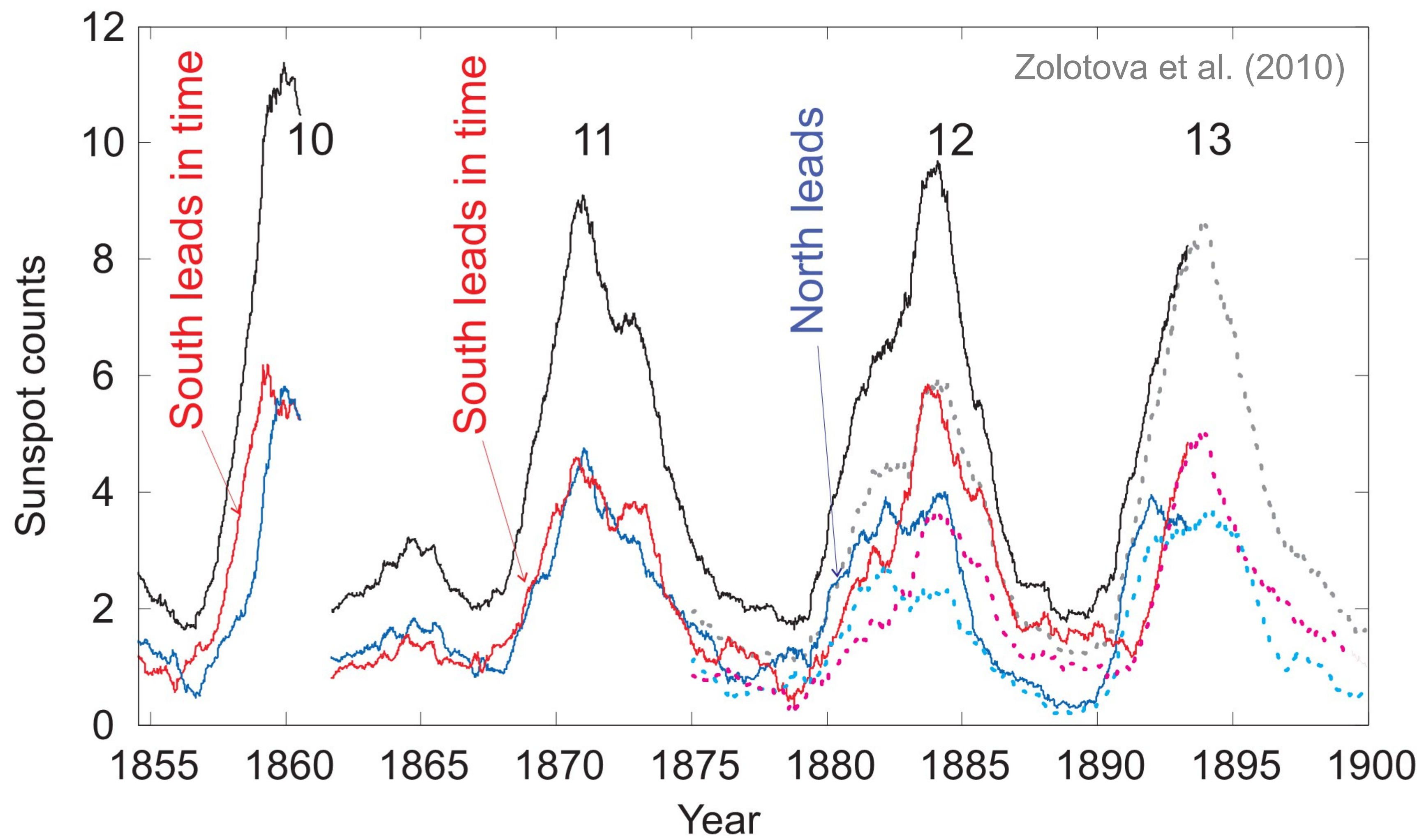
- Solve mean-field eq. for ***B*** *and* $\Omega(r,\theta)$
- Include back-reaction on generation of diff. rotation
- Get maximum diff. rot after grand minimum



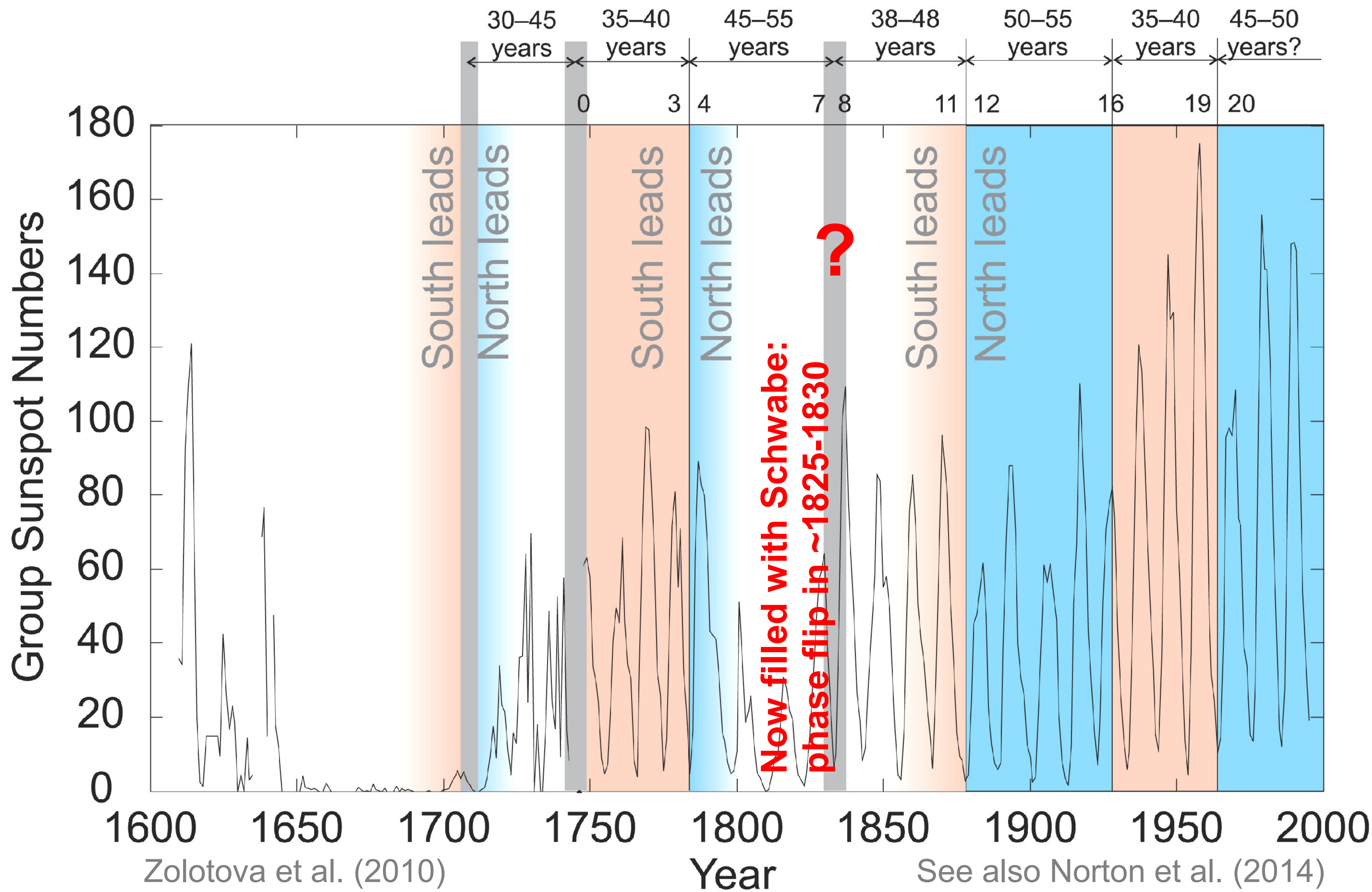
Küker, Arlt, Rüdiger (1999),
but also e.g. Tobias (1997), Bushby (2006)

Hemispheric cycle phase

- Cycle of northern and southern hemisphere not in phase



Hemispheric coupling important for dynamo



Zolotova et al. (2010)

See also Norton et al. (2014)