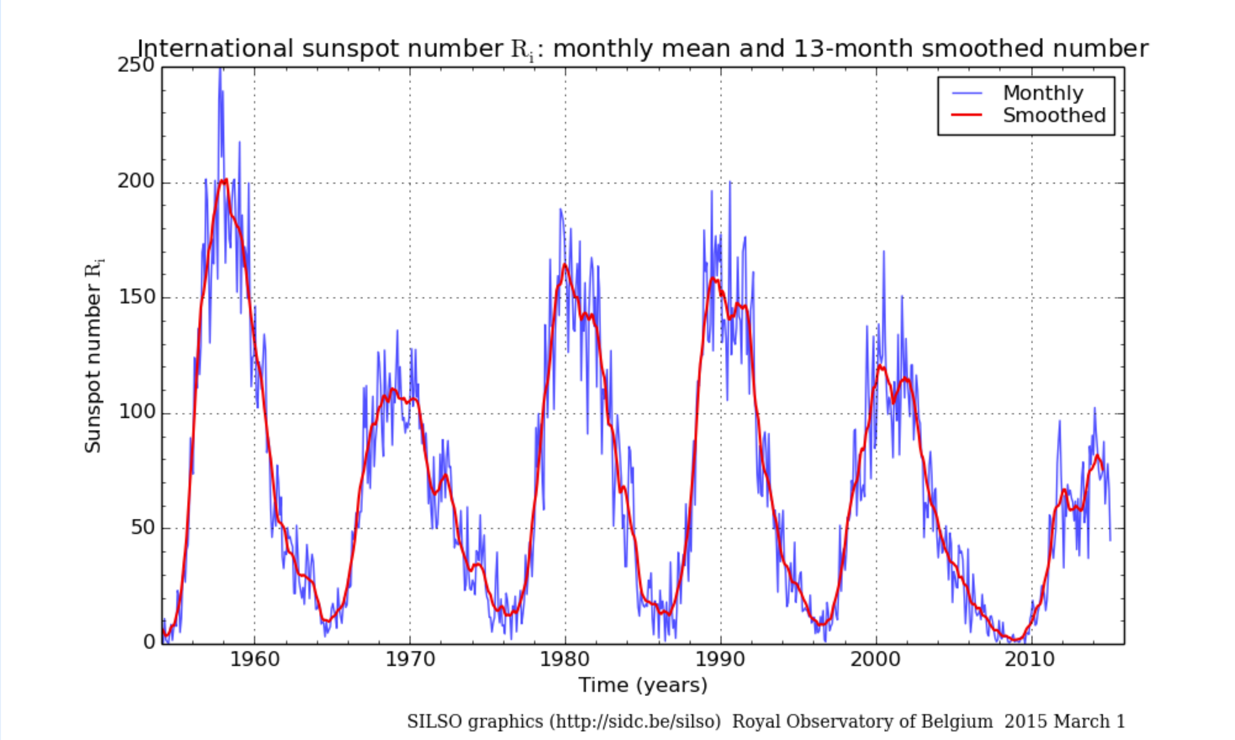
Solarnet III/HELAS VII/SpaceInn Conference
Freiburg, August 31-September 4, 2015

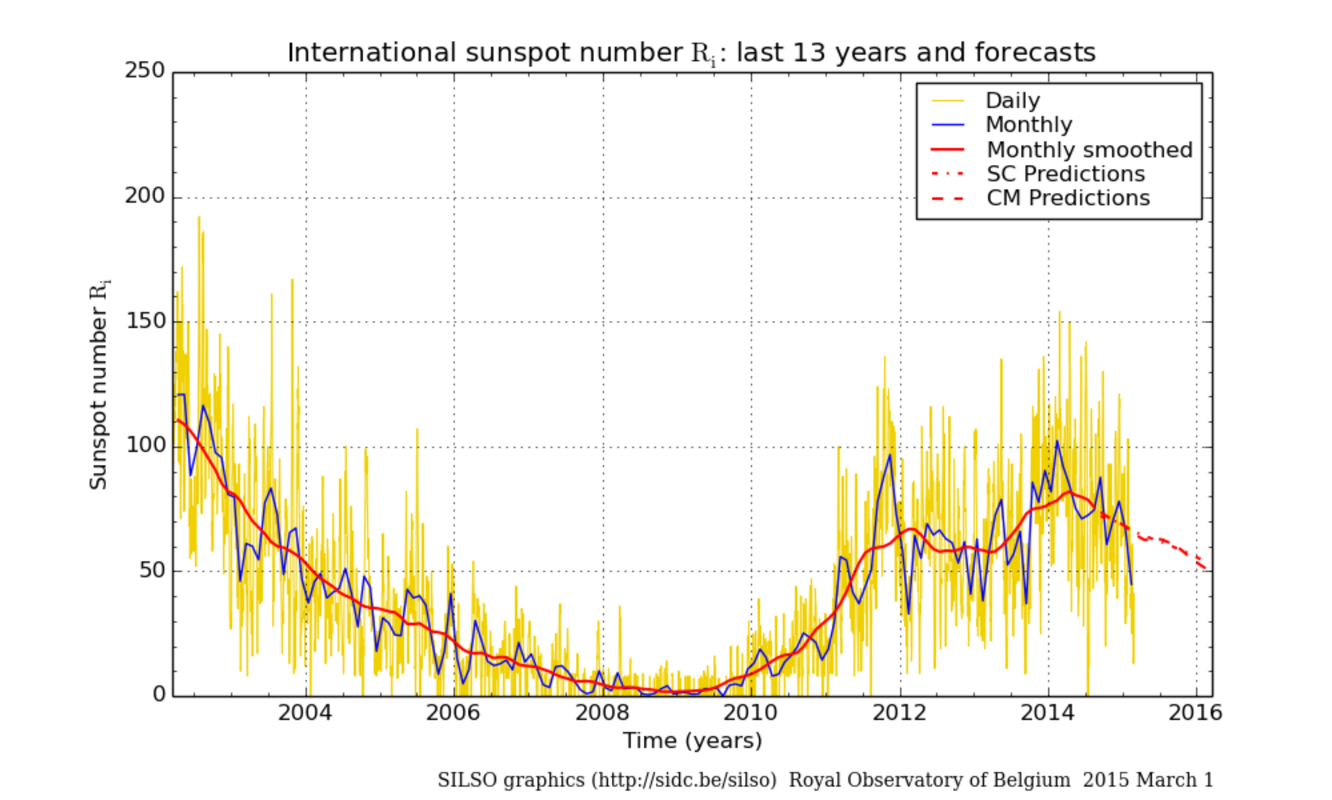


The cause of the weak solar cycle 24

J. Jiang[1], R. Cameron[2], & M. Schüssler[2]

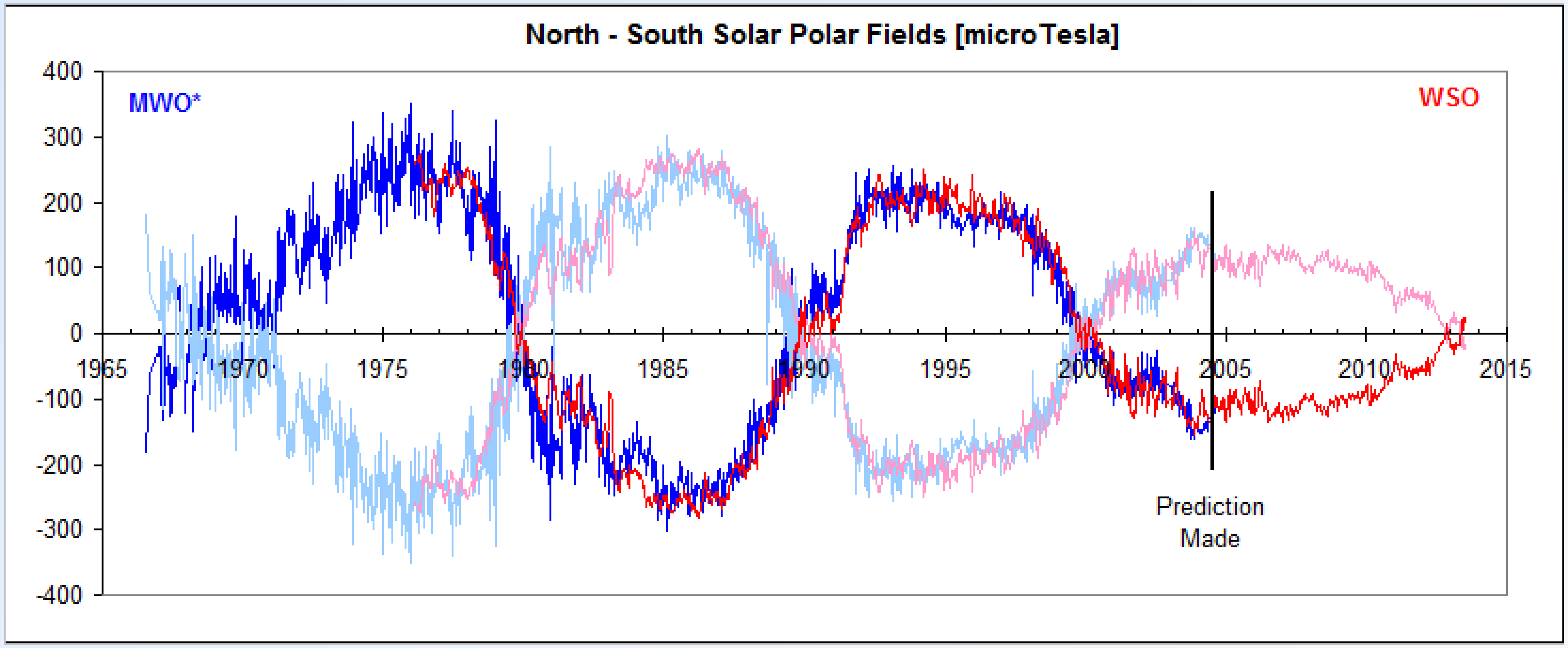
[1] National Astronomical Observatories, Chin. Acad. Sci., Beijing, China
[2] Max Planck Institute for Solar System Research, Göttingen, Germany

The extended and deep minimum of cycle 23



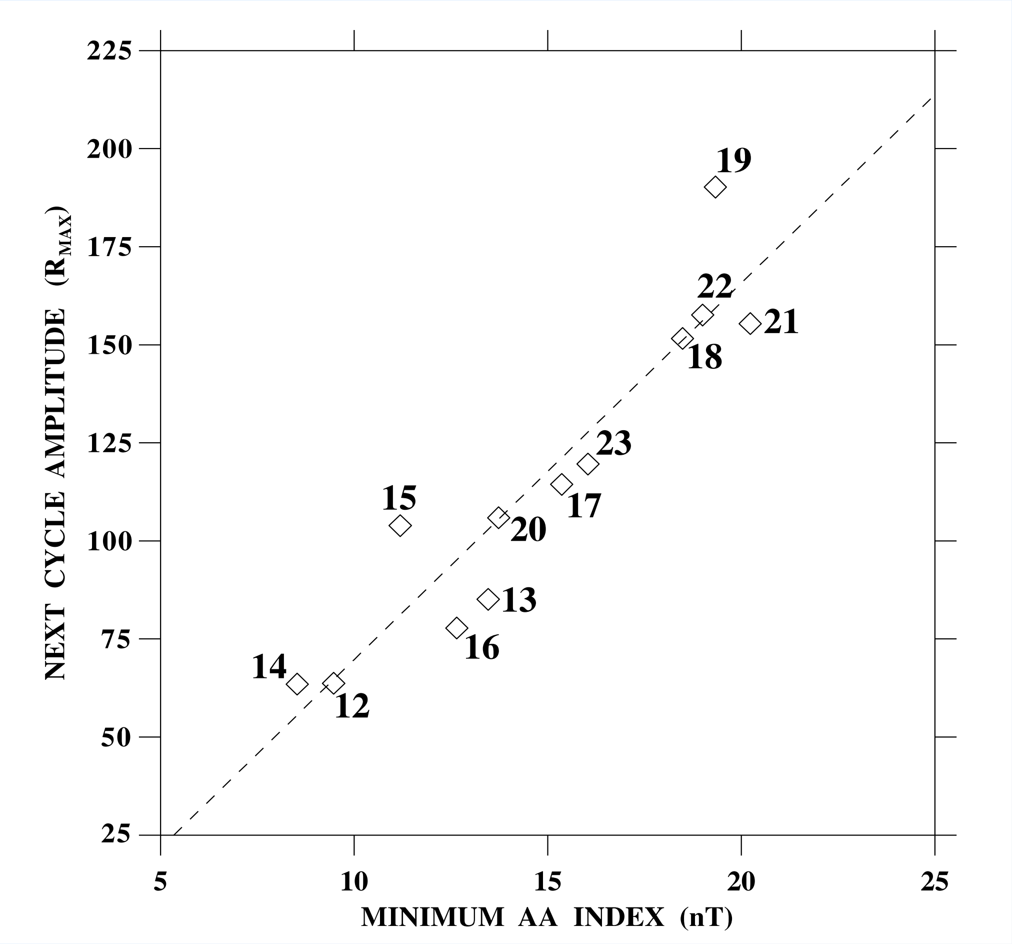
- Low sunspot number, many spotless days
- Early warning of a weak following cycle 24?

Weak polar fields built up during cycle 23



- Polar fields ~40% lower compared to cycle 22
- Precursor of a weak subsequent cycle?

Weak polar fields built up during cycle 23



Wang & Sheeley (2009)

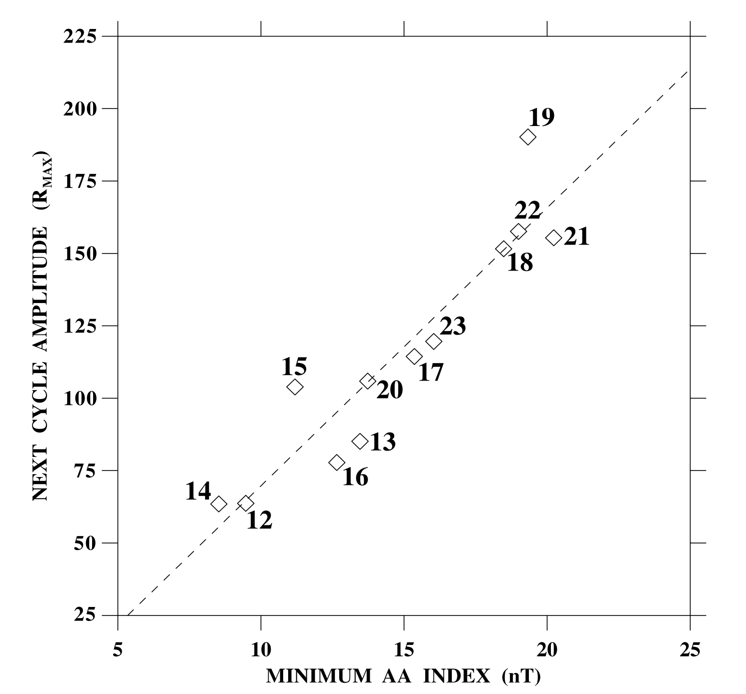
Geomagnetic aa-Index @ solar minima

(→ proxy for open heliospheric flux, dipole moment & polar fields)

is correlated with the strength of the subsequent cycle

Weak polar fields built up during cycle 23

Wang & Sheeley (2009)



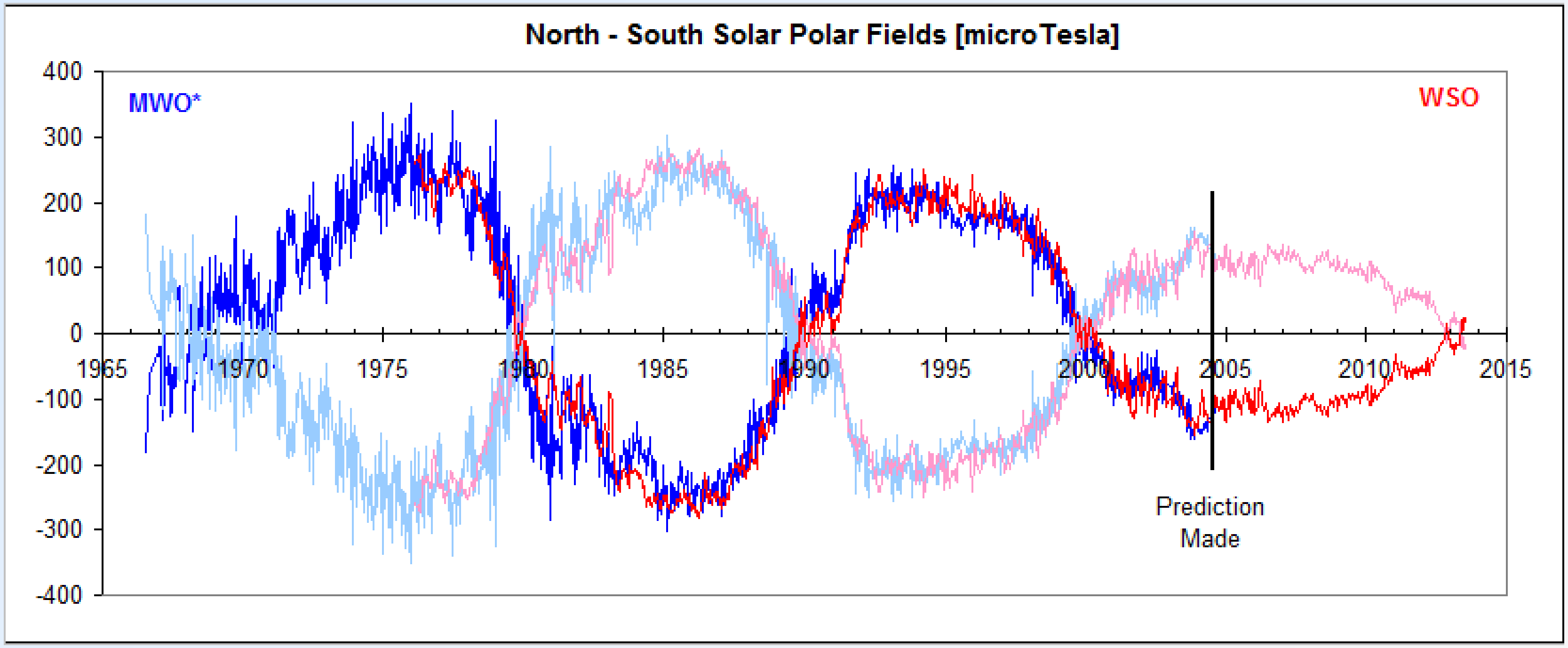
Cameron & S. (2015):
the correlation reflects
a causal relationship

↓

The poloidal magnetic flux connected to the polar fields is by far the dominant source of the toroidal flux that emerges during the subsequent activity cycle.

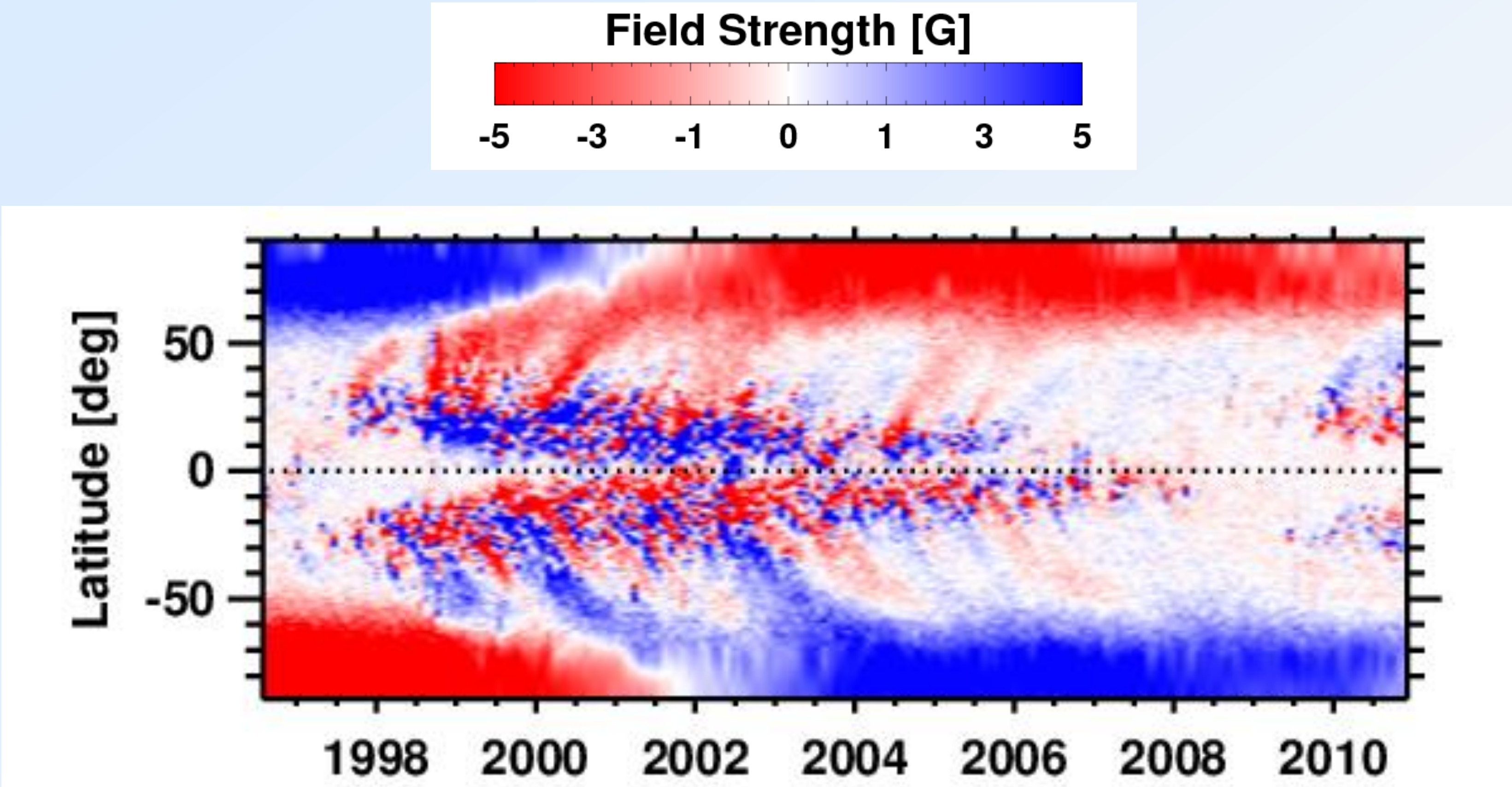
→ talk on Tuesday morning

Why such unusually weak polar fields?



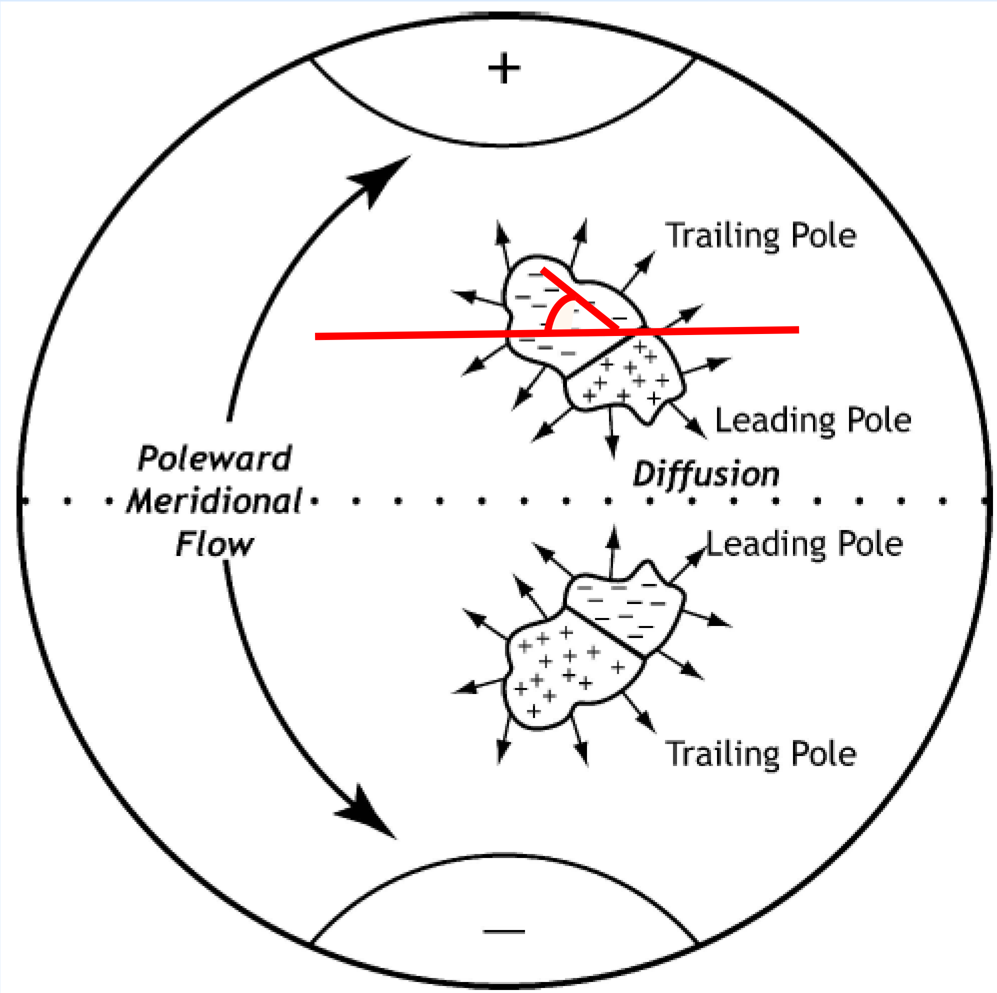
courtesy L. Svalgaard

Built-up of the polar fields during cycle 23



Based on SOHO/MDI synoptic magnetograms
(Sun et al., 2011)

How are the polar fields built up?



Wang (2005)

Surface flux transport model:

- flux emergence in tilted bipolar magnetic regions (BMRs)
- cancellation & flux advection by diff. rotation, convection, and meridional flow
- polar fields eventually determined by flux transport over the equator

BMR parameters:

- area
- latitude
- tilt

Transport parameters:

- diffusivity
- meridional flow

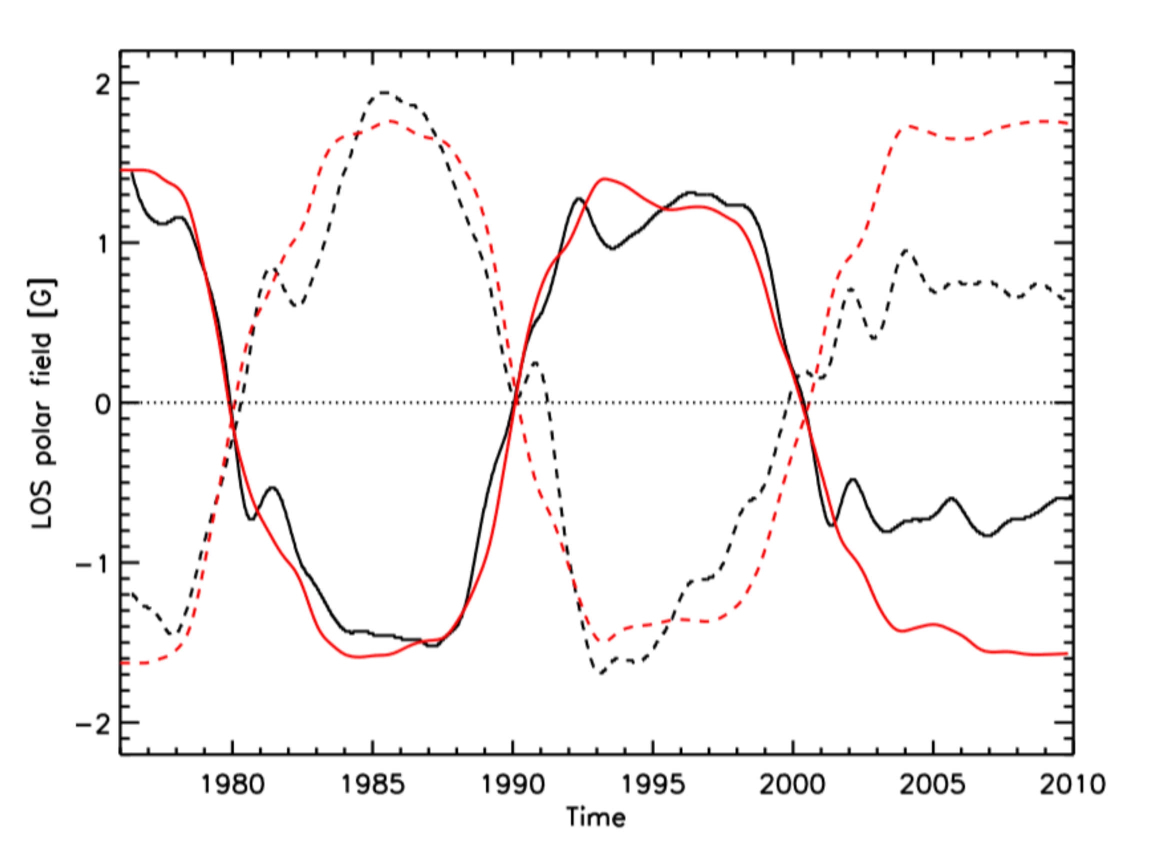
Surface flux transport (SFT) simulations…

$$\frac{\partial B}{\partial t} = -\Omega(\lambda)\frac{\partial B}{\partial \phi} - \frac{1}{R_\odot \cos\lambda}\frac{\partial}{\partial \lambda}[v(\lambda)B\cos\lambda]$$
$$+ \eta_H \left[\frac{1}{R_\odot^2 \cos\lambda}\frac{\partial}{\partial\lambda}\left(\cos\lambda \frac{\partial B}{\partial \lambda}\right) + \frac{1}{R_\odot^2\cos^2\lambda}\frac{\partial^2 B}{\partial \phi^2}\right]$$
$$+ D(\eta_r) + S(\lambda, \phi, t), \qquad (1)$$

… were rather successful in reproducing the observed (or reconstructed) evolution of polar fields in cycles 15-22, but…

Surface flux transport (SFT) simulations…

… failed rather miserably for the polar fields in cycle 23:



WSO obs.

SFT sim.

solid: north pole
dashed: south pole

BMR tilt vs. latitude:

$$\alpha = 1.32\ \lambda^{1/2}$$

Jiang et al. (2013)

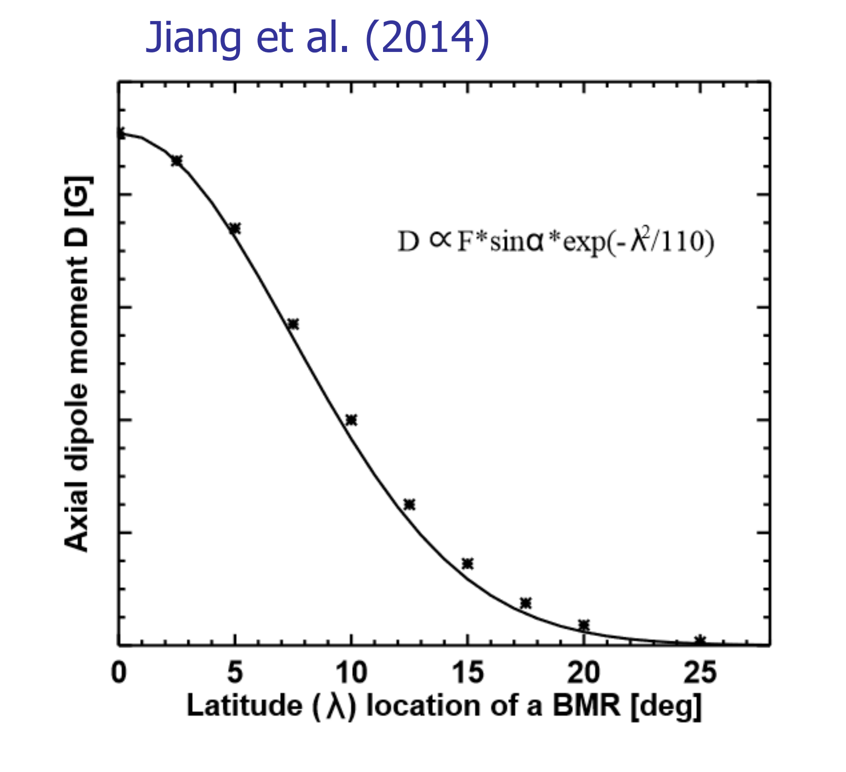
Cycle 23 was rather normal in many respects…

- cycle strength
- latitude distribution of sunspot groups
- area distribution
- tilt angle distribution

… so people resorted to assuming arbitrary (in fact, not observed) variations of the meridional flow to „explain" the weak polar fields

(e.g., Schrijver & Liu 2008, Wang et al. 2009, Nandy et al. 2011, Yeates 2014)

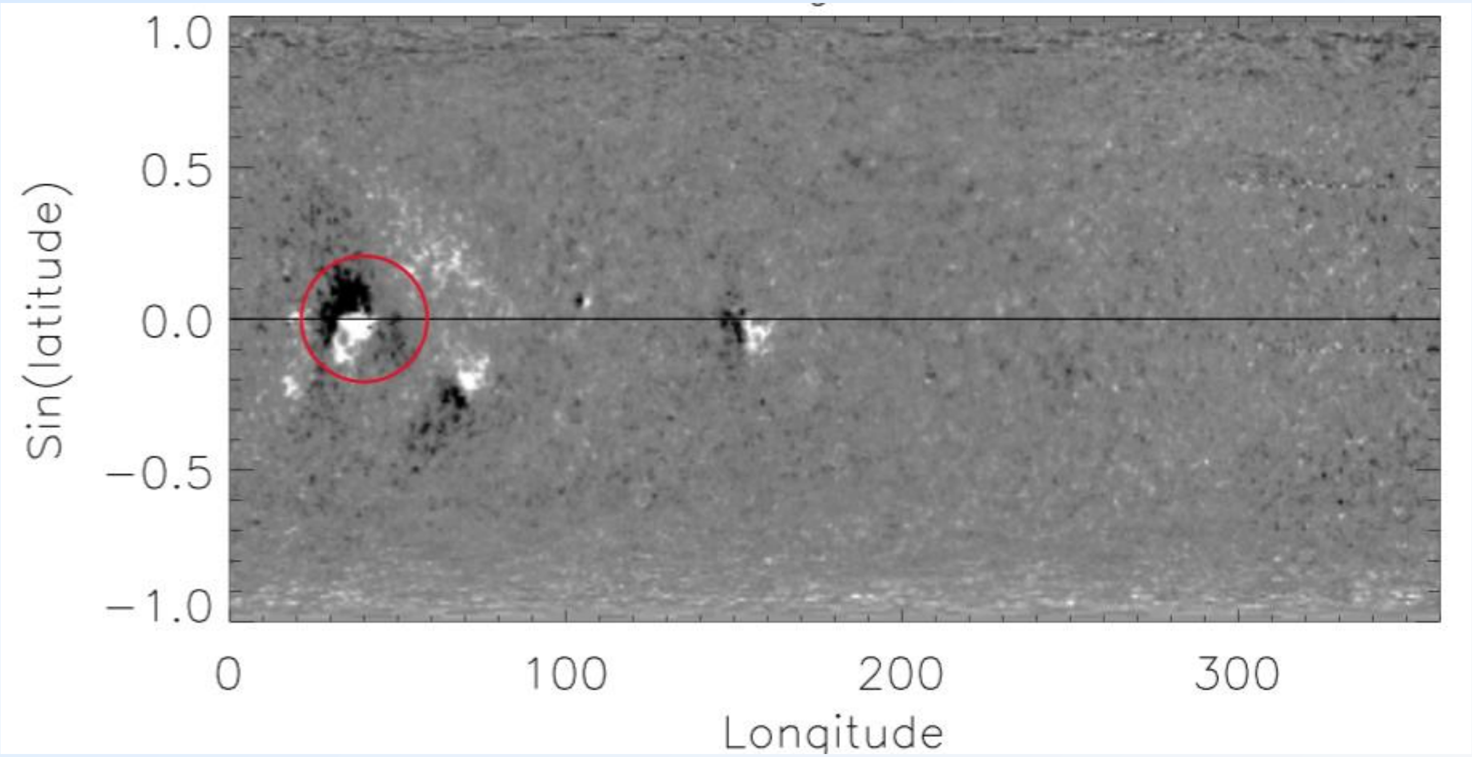
… but randomness can make a difference.



Contribution of 6×10^{21} Mx BMRs to the axial dipole moment around solar minimum as a function of emergence latitude

Bipolar regions emerging above ~20 deg latitude contribute only temporarily to the axial dipole moment.
The dipole moment around solar minimum is strongly affected by the relatively small number of near-equator BMRs.

… but randomness can make a difference.



Cameron et al. (2012)

Kitt Peak synoptic magnetogram for CR 1772 (February 1986)

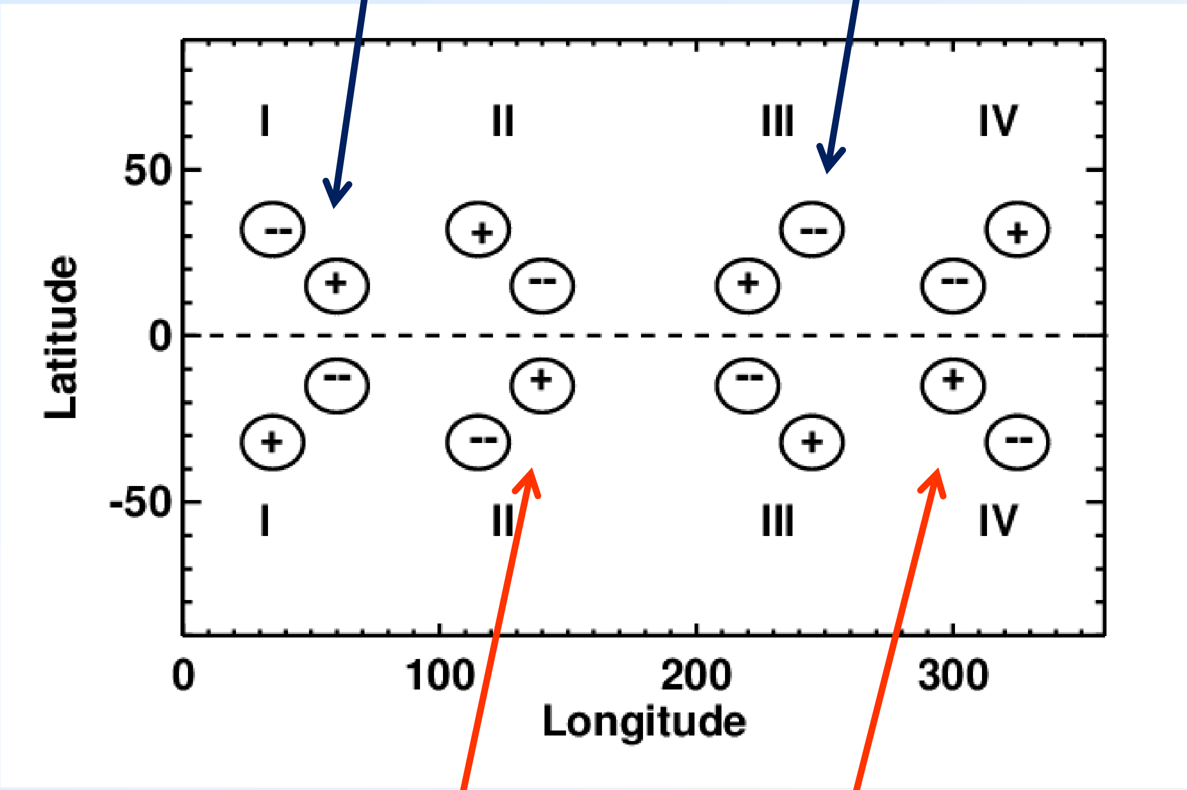
Single bipolar regions emerging near or across the equator can have a significant impact on the built-up of the polar flux.

Effect of BMR polarity orientation on B_{polar}

regular

anti-Hale,
negative tilt

→ increases polar fields@minimum



anti-Hale,
regular tilt

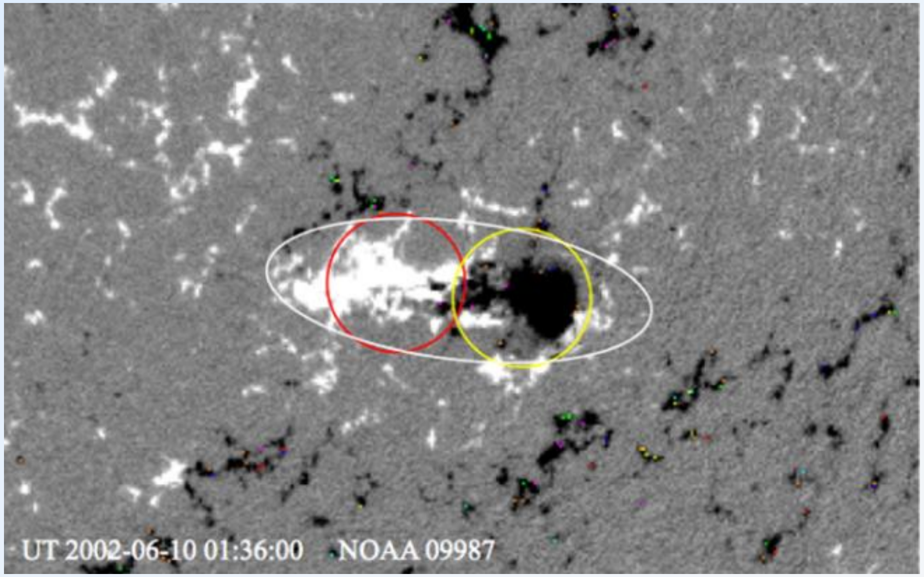
negative tilt

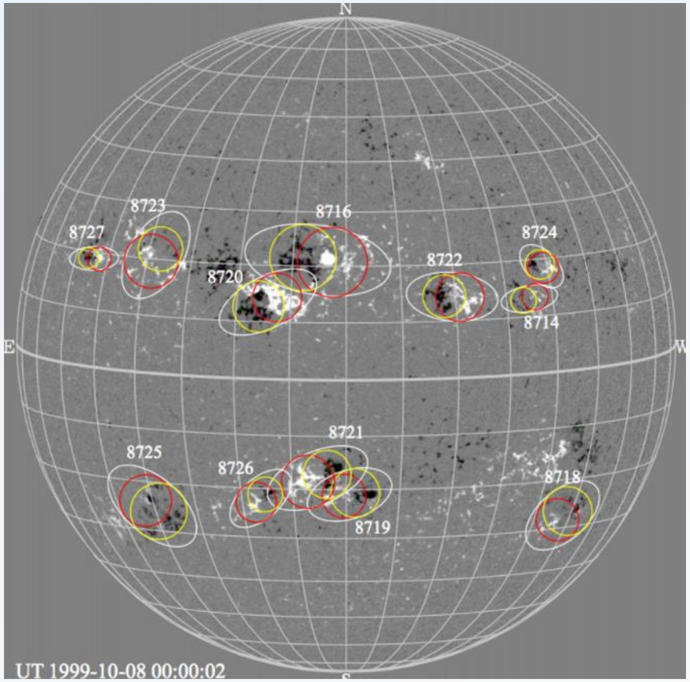
→ decreases polar fields@minimum

Complete tilt angle & polarity information for cycle 23

J. Li & R.K. Ulrich (ApJ 758, 115; 2012)

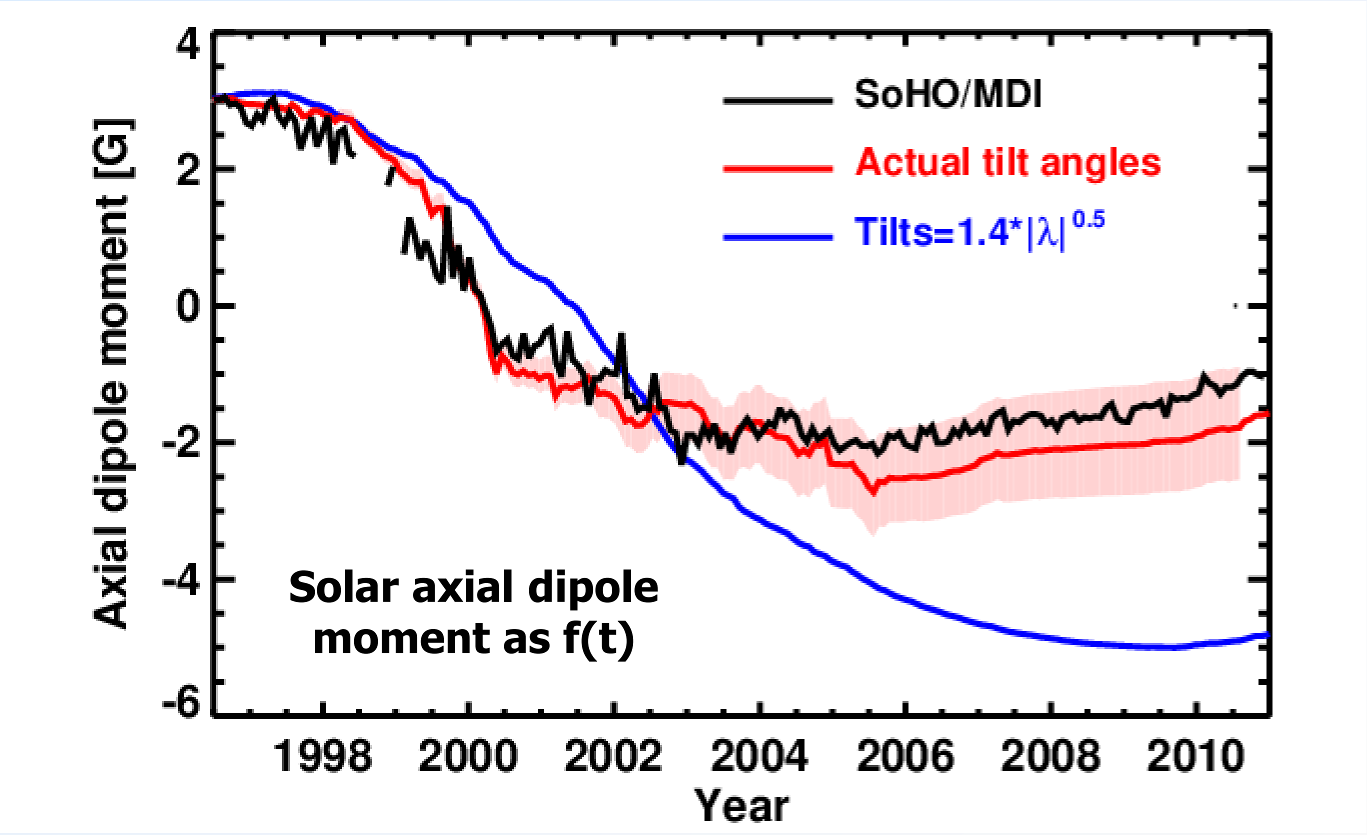
- 2775 bipolar magnetic regions identified in MDI magnetograms from May 1996 until April 2011
- Tilt angles measured when central meridional angle ≤ 45°
- Averages for multiple measurements





New SFT simulations for cycle 23

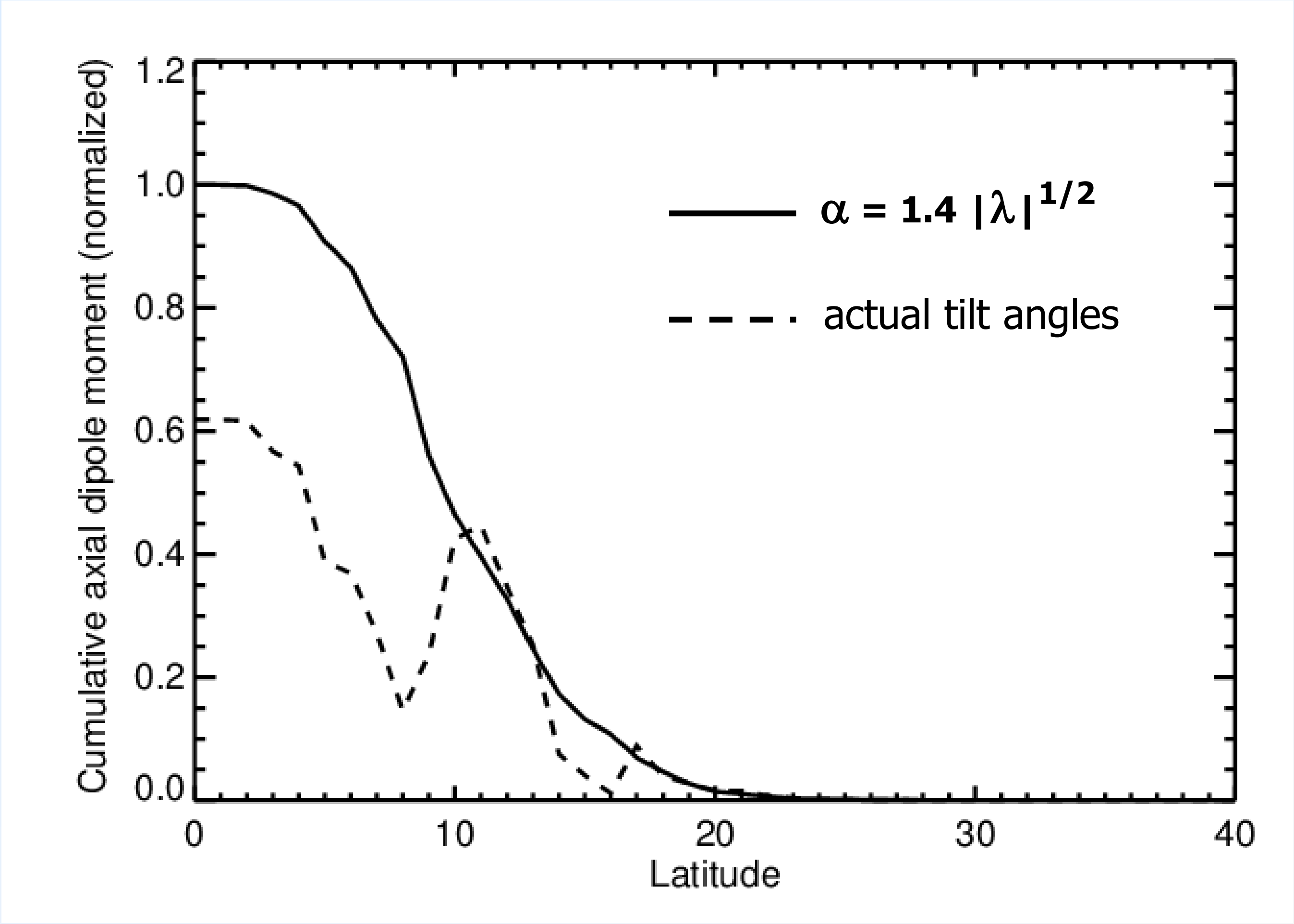
- using standard procedures & parameters
  (turb. diffusivity, diff.rotation, meridional circulation,
  treatment of active regions as BMR sources)
- Initial condition: MDI synoptic map für CR 1911 (June 1996)
- new: Li & Ulrich tilt angle & polarity data used



pink shading:
error estimate

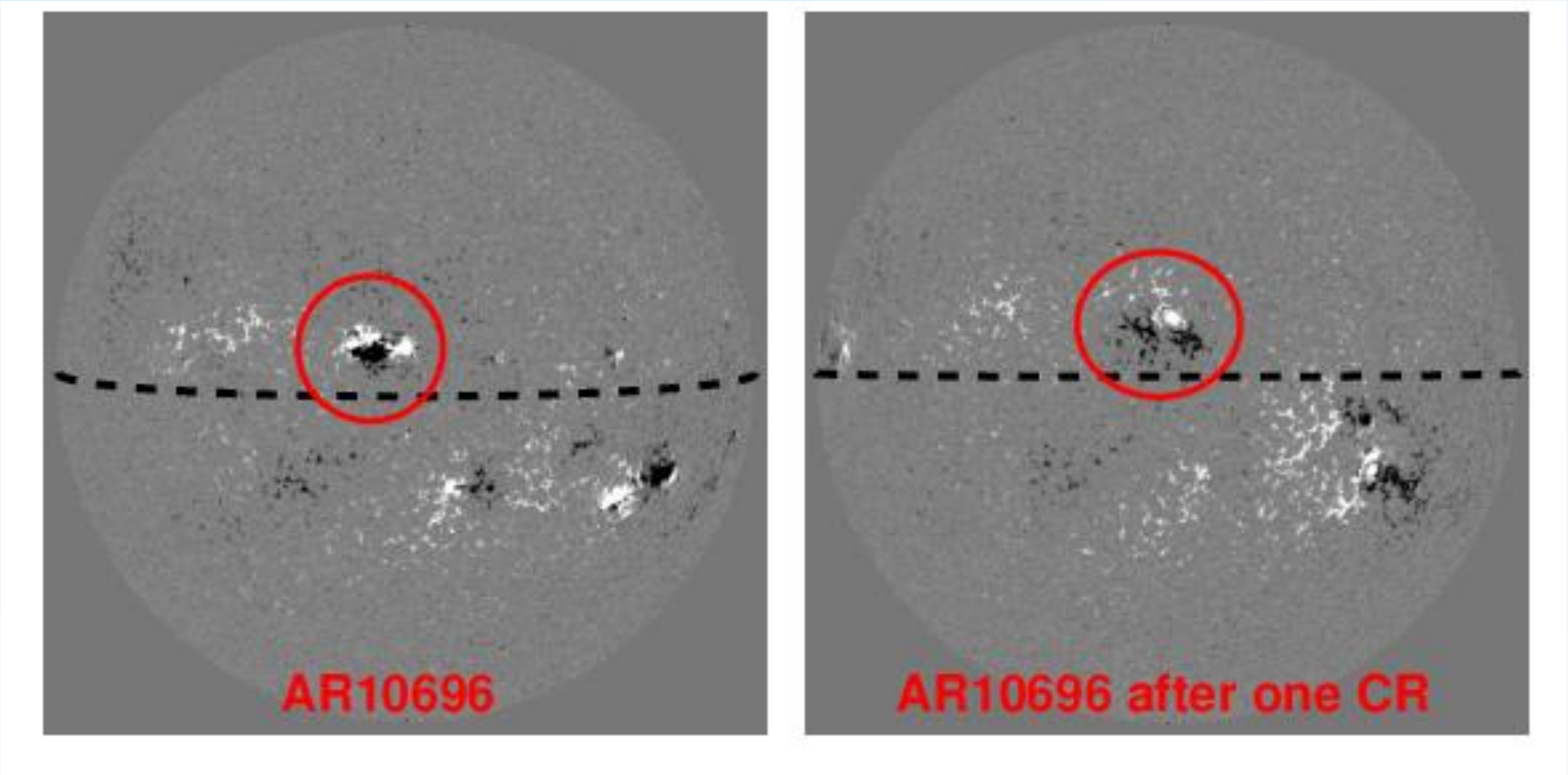
Jiang et al. (2015)

Low-latitude BMRs are responsible…



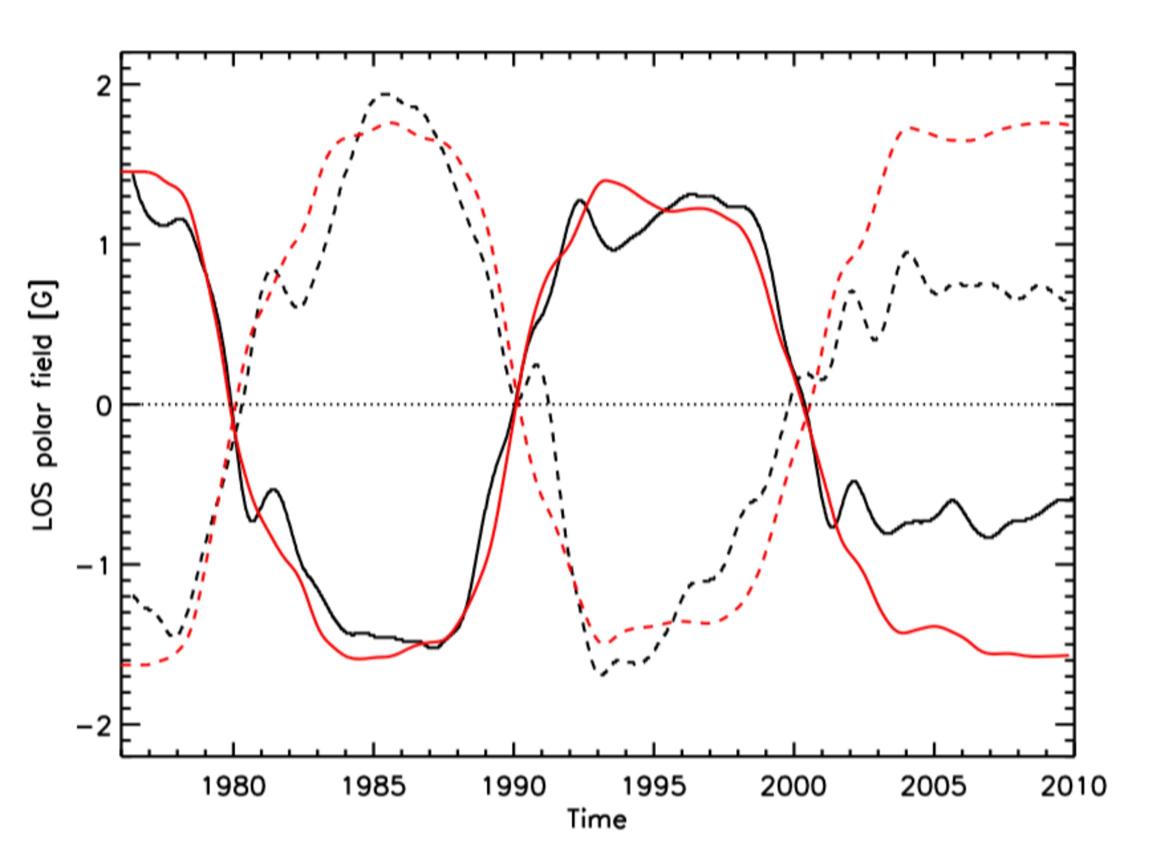
Cumulative contributions (in latitude) of cycle 23 BMRs to the axial dipole moment at activity minimum

AR 10696 (Nov/Dec 2004)



Near-equator emergence and „wrong" North-South polarity orientation
→ transport of negative magnetic flux (black) over the equator
→ weakened the buildup of the polar fields

Were cycles 21 and 22 different?



WSO obs.

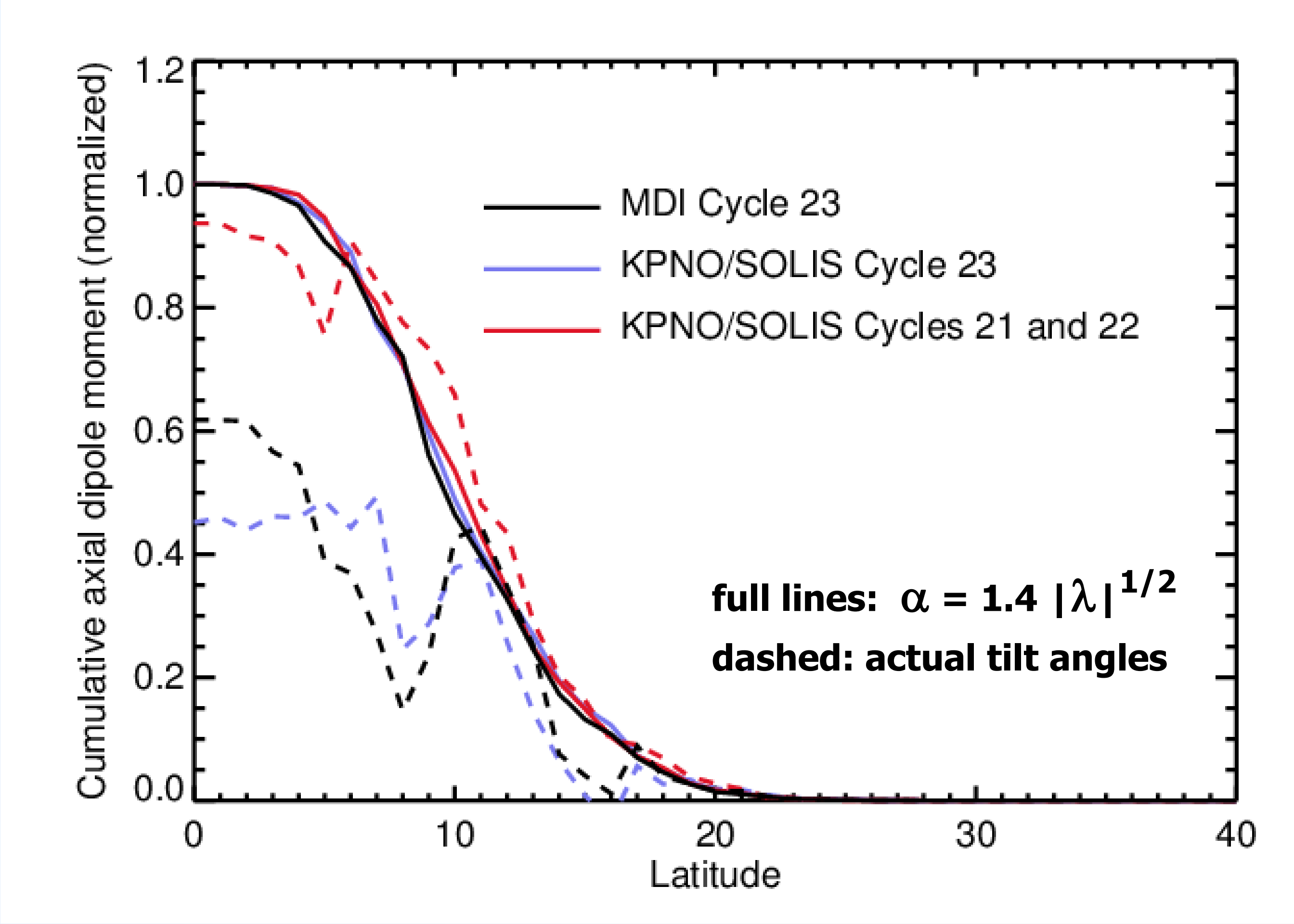
SFT sim.

Jiang et al. (2013)

tilt vs. latitude:

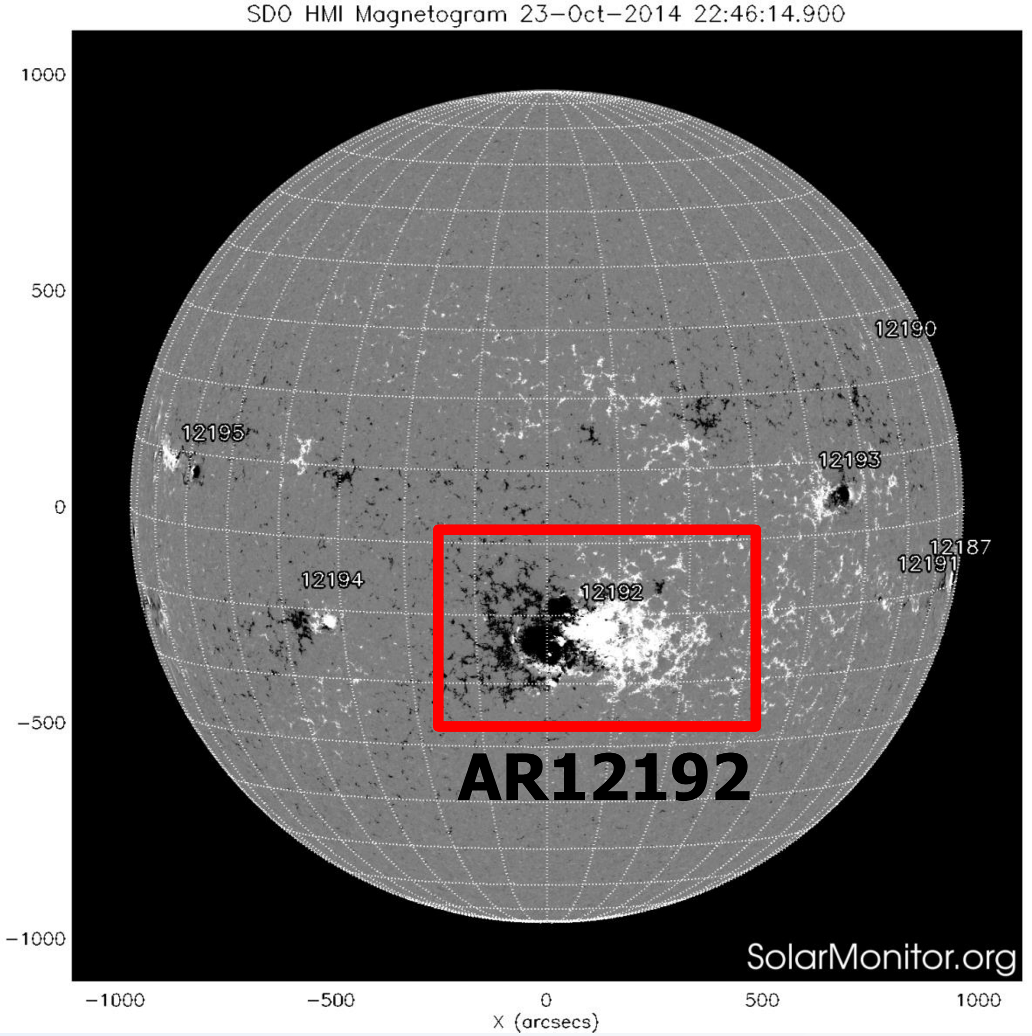
$\alpha = 1.32\ \lambda^{1/2}$

Were cycles 21 and 22 different?



Cumulative contributions (in latitude) to the axial dipole moment at activity minimum

Occasionally there are really big ones…

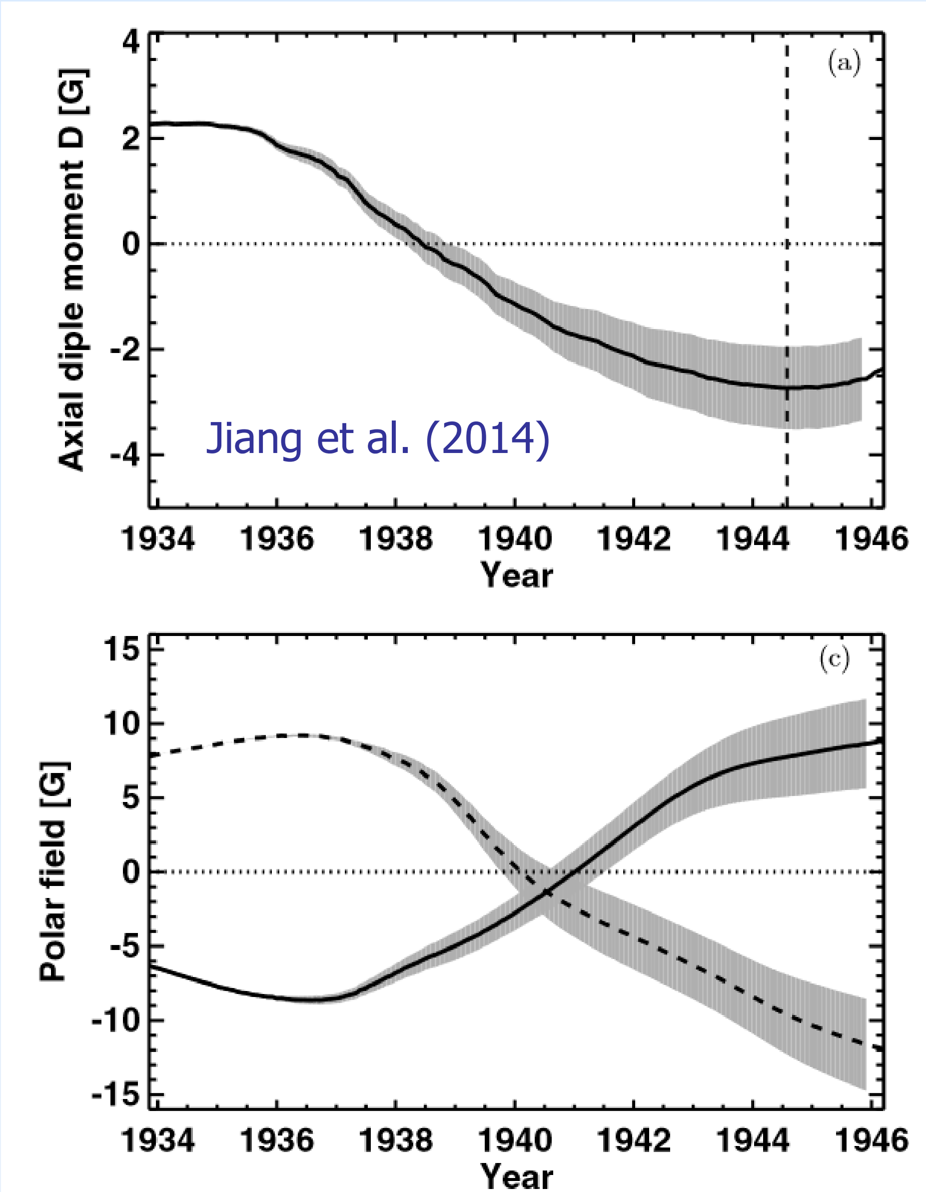


October 2014

Conclusions

- The polar field (axial dipole moment) during the declining phase and minimum and solar cycle 23 is reproduced by SFT simulations using the actual tilts and polarities of BMRs emerging during the cycle.
- The weakness of the polar fields results from the scatter of the tilt angles and small-number statistics of low-latitude big BMRs.
- This caused the low amplitude of cycle 24.
- Cycle strength prediction is not possible earlier than a few years before activity minimum. Long-term predictions (covering more than one cycle) are meaningless.
- A few „rogue BMRs" may throw the Sun into a grand-minimum state…

Effect of tilt angle scatter on the polar field



Effect of the tilt angle scatter on the axial dipole moment and the polar fields in SFT simulations (example: cycle 17)

→

The weak axial dipole moment during the minimum phase of cycle 23 was a 2σ-effect

shaded: 1σ uncertainty

Error estimate

- **Main source of error:** determination of the tilt angle
  $\rightarrow$ independent measurement of a subset of ARs

- **Procedure:**
  - ❖ use different data source: Kitt Peak synoptic magnetograms
  - ❖ identify ~700 bigger BMRs from the SOON list of ARs (~30% of Li & Ulrich)
  - ❖ define BMR by threshold in |B|
  - ❖ determine COG of the two polarities $\rightarrow$ tilt angle
  - ❖ calculate rms deviation from the Li & Ulrich data

- **Result:** overall rms error: ≈12 deg, AR area dependent: 50 biggest ARs: ≈5 deg

- **Run 50 SFT simulations** with random scatter of the tilt angles according to the area-dependent tilt angle error
  $\rightarrow$ determine standard deviation of axial dipole moment, polar field at f(t)