

# Solar Cycle Dependence of the Deep Meridional flow

Zhi-Chao Liang

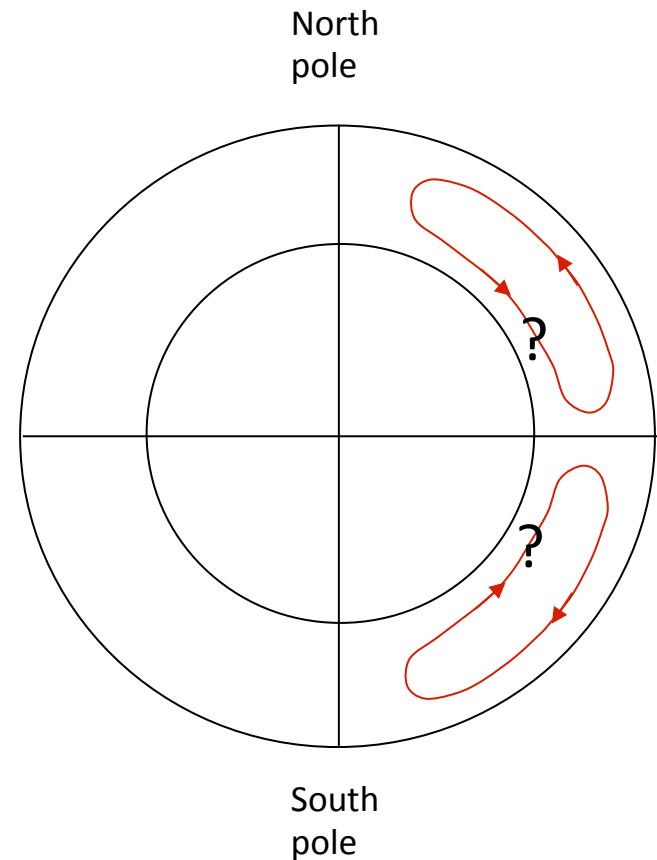
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Max-Planck-Institut für Sonnensystemforschung

(July 2016, SPACEINN & HELAS8)

# Meridional flow observation in the past

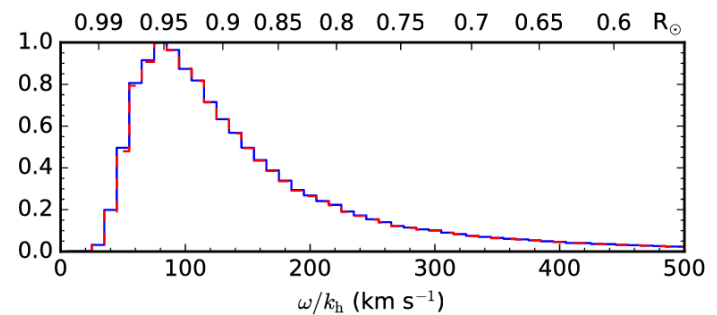
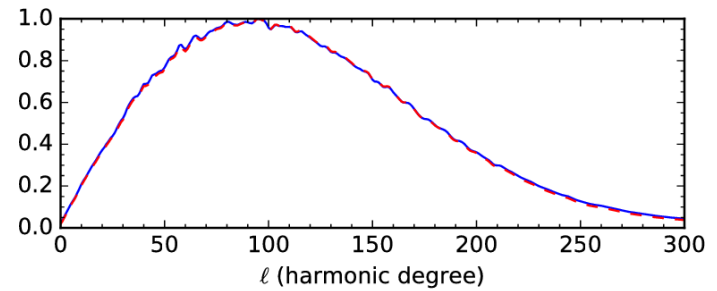
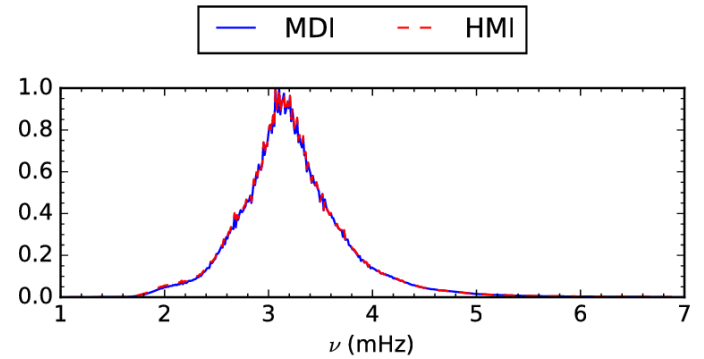
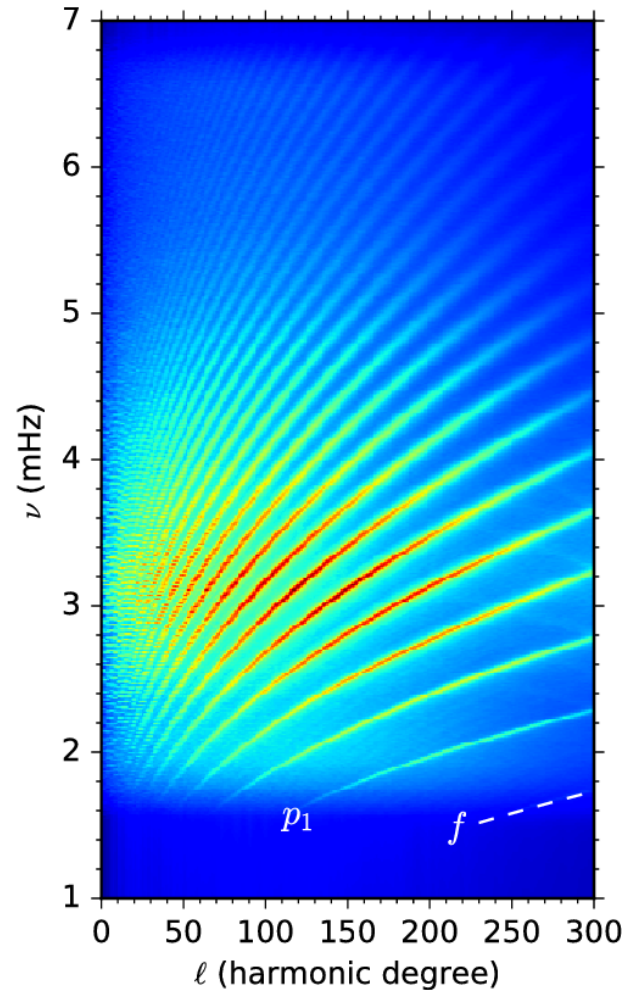
- Surface observations (tracers, Doppler shifts, ...)
  - Pole-ward motion
  - Peak velocity about 10 ~ 20 m/s
- Subsurface measurements (time-distance, ring diagram, mode frequency,...)
  - Extend to the entire convection zone
  - Suffer from systematic errors



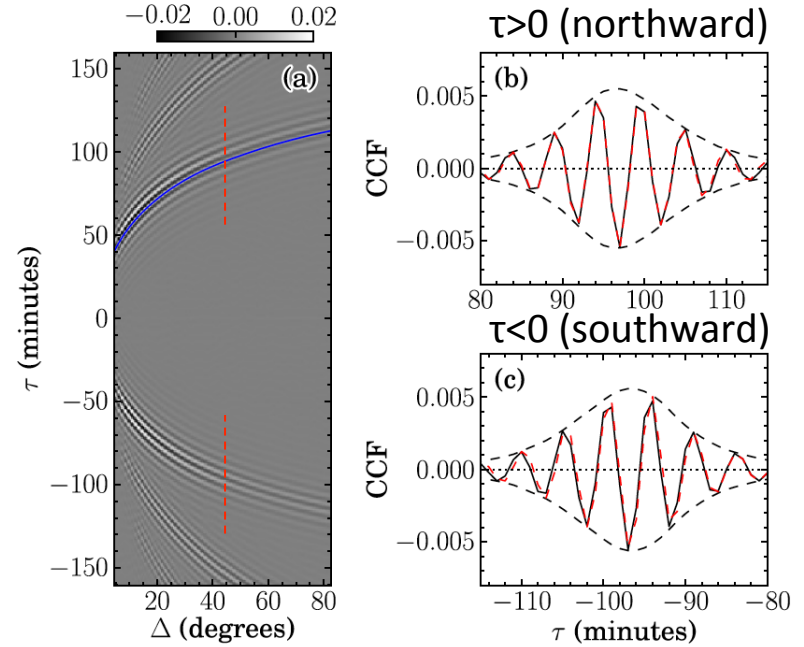
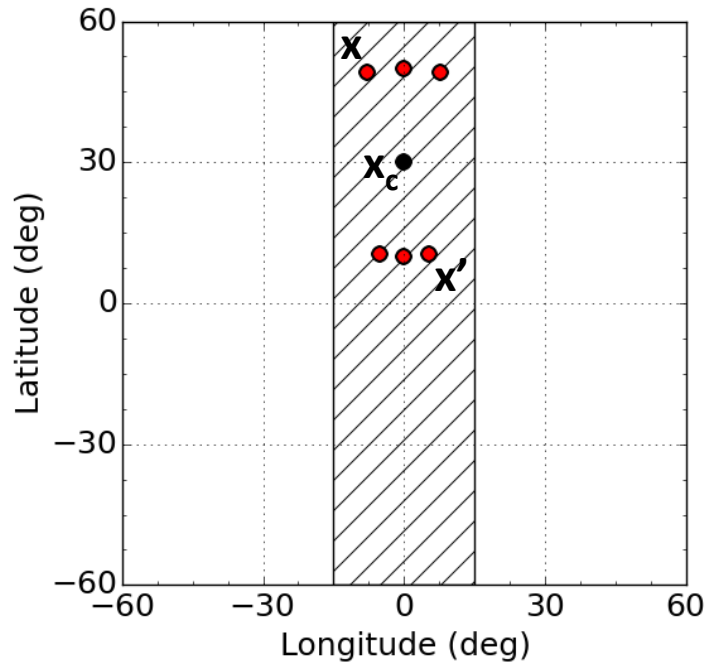


# Medium- $\ell$ dopplergrams taken by MDI and HMI

$|m|$ -summed power spectrum



# Travel time measurement



$$C(\mathbf{x}_c, \Delta, \tau) = \int \psi(\mathbf{x}, t) \psi(\mathbf{x}', t + \tau) dt$$

$$\Delta = |\mathbf{x} - \mathbf{x}'|$$

$\mathbf{x}_c$  is the central point  
between  $\mathbf{x}$  and  $\mathbf{x}'$

$$G(\tau) = a_0^2 \cos(a_1^2 (\tau - a_2)) \exp\left(-\frac{(\tau - a_3)^2}{2a_4^2}\right)$$

Phase travel time

$$\delta\tau^{NS} = \tau^S - \tau^N$$

# Major systematic errors

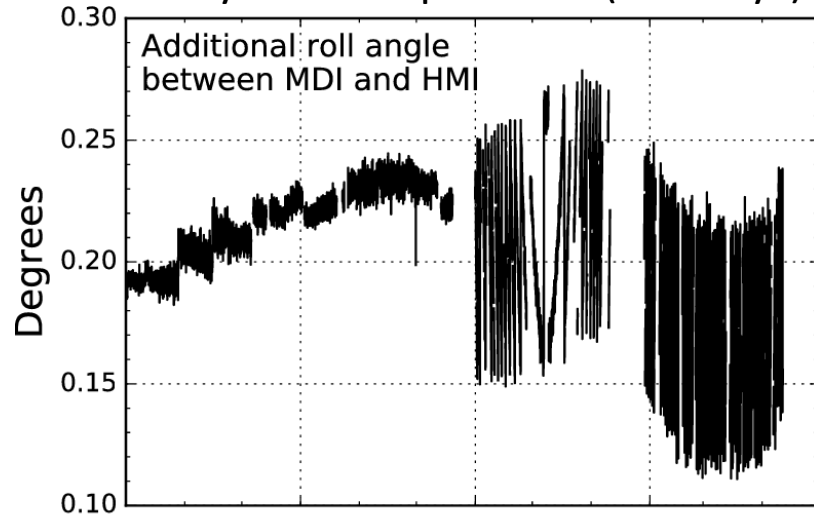
- **Center-to-limb variation**  
**(Zhao et al. 2012; Balder & Schou 2012)**
- Roll angle (P angle) misalignment in MDI instrument  
(Giles et al. 2000; Beck & Giles 2005)
- Contamination from active regions  
(Liang & Chou 2015)

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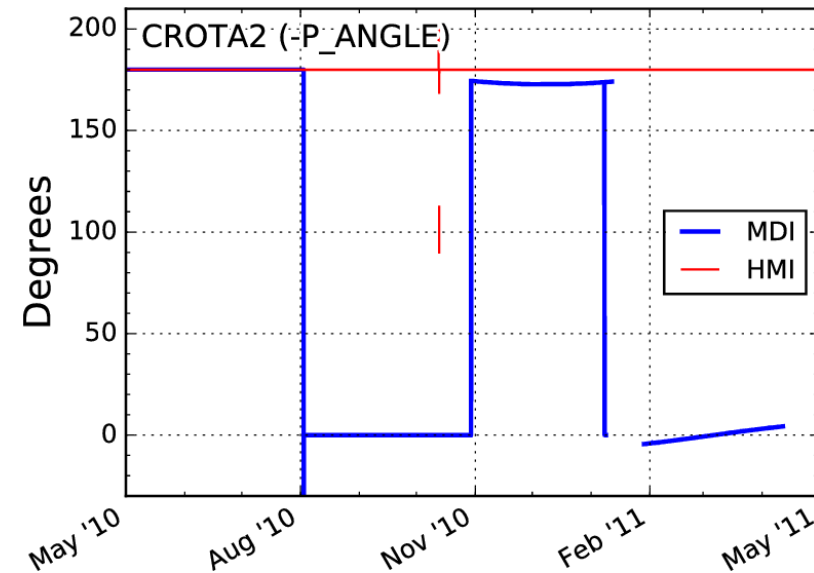
# MDI roll angle registers w.r.t. HMI

May 2010 – April 2011 (280 days)

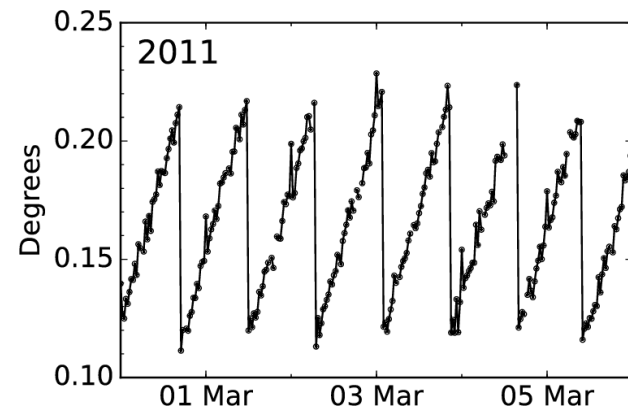
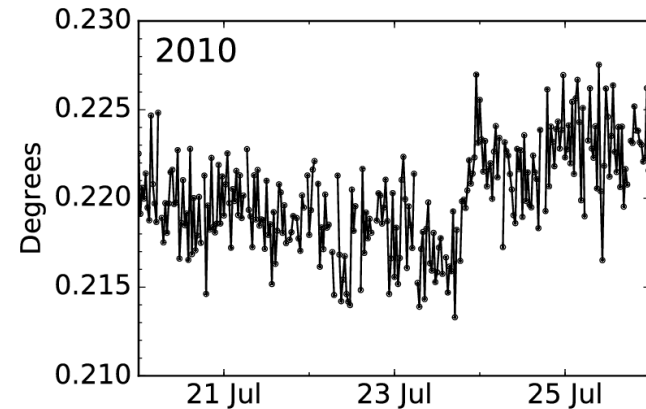


2010.05 – 2010.10

- Median = 0.219456155712 ~ 0.22 (agree with Liu et al. 2012)

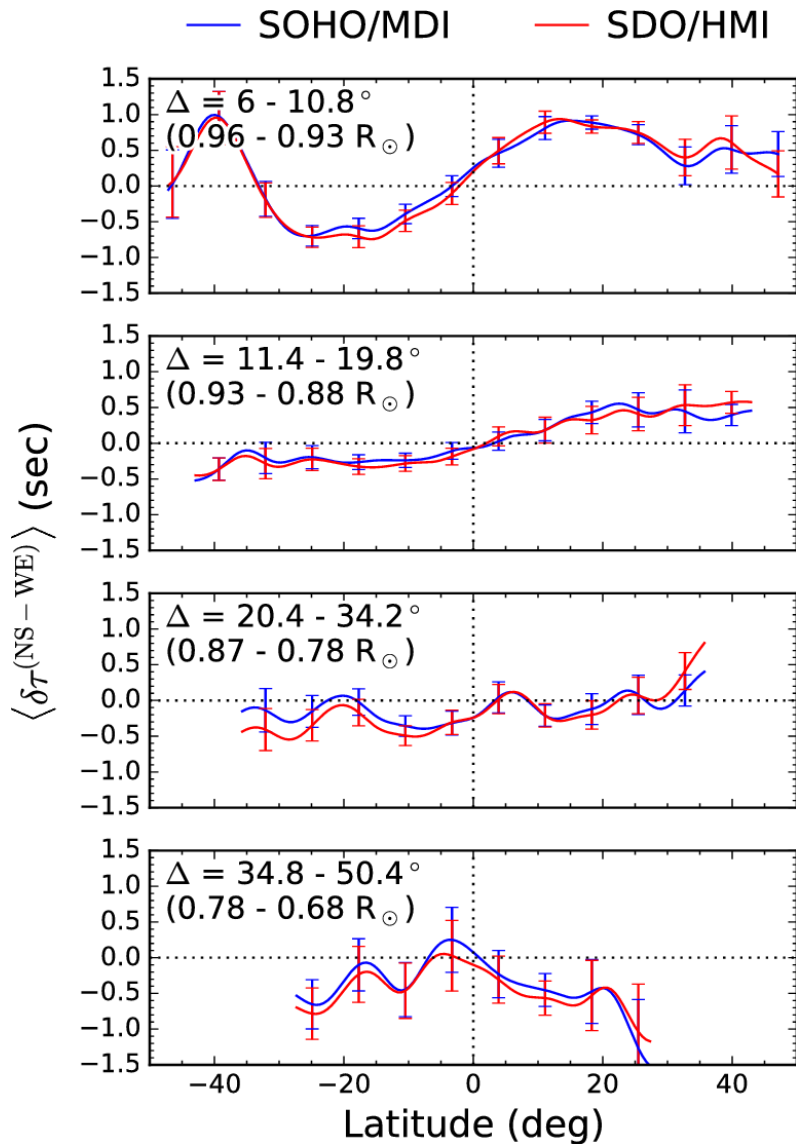


Zoom in



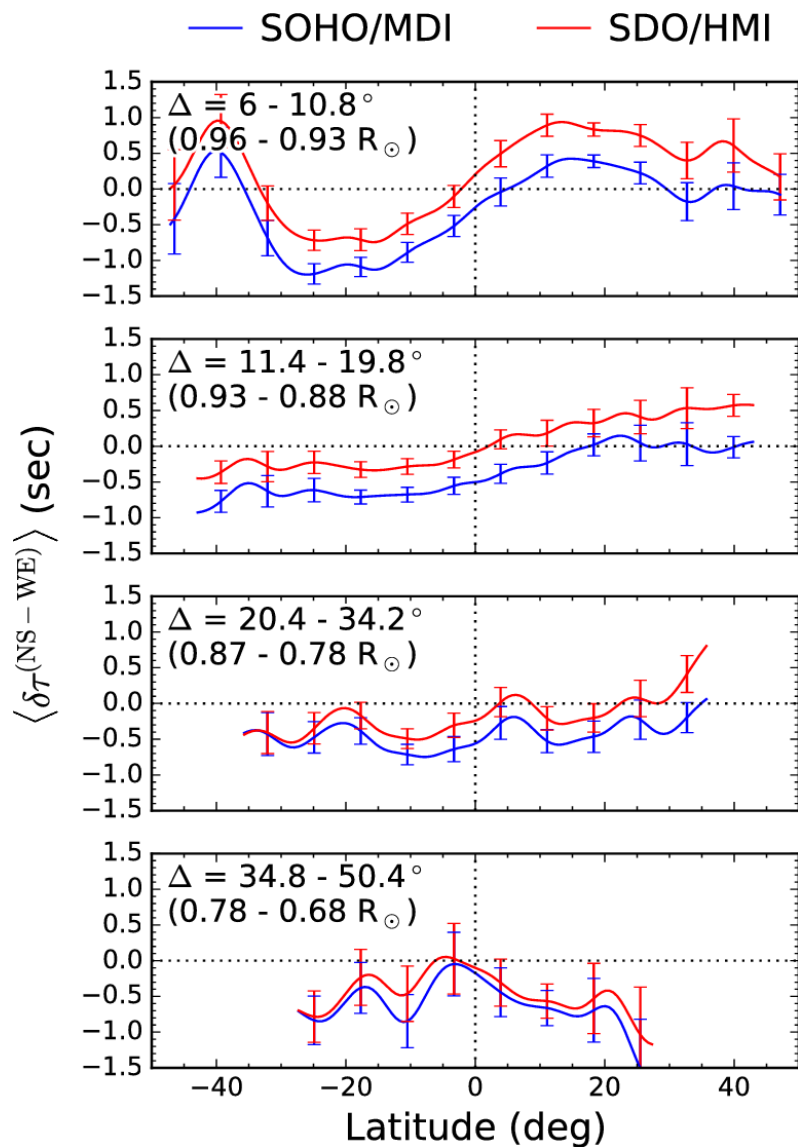


# MDI vs. HMI

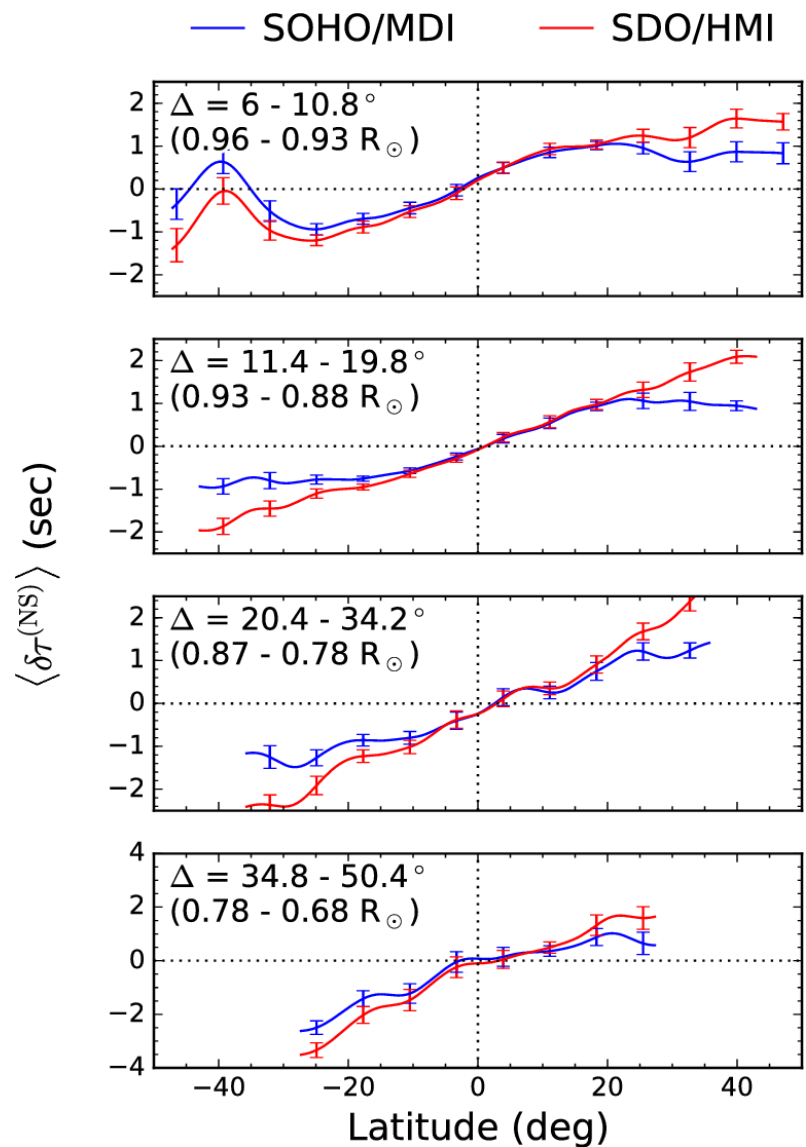


- Data:  
medium- $\ell$  Dopplergrams
- Period:  
2010.05 -- 2011.04 (280 days)
- Corrected systematics:
  - MDI P angle uncertainty
  - Center-to-limb variation

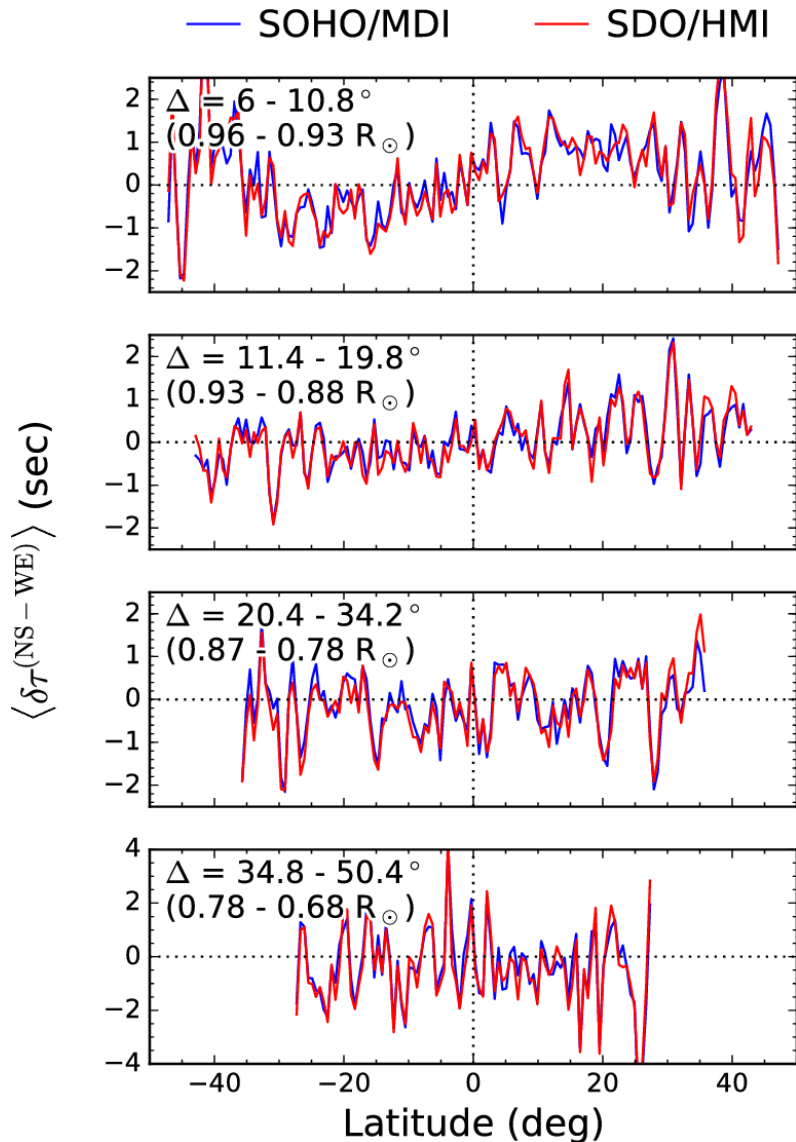
# Without P angle correction to MDI data



# Without center-to-limb correction



# MDI vs. HMI (without smoothing)



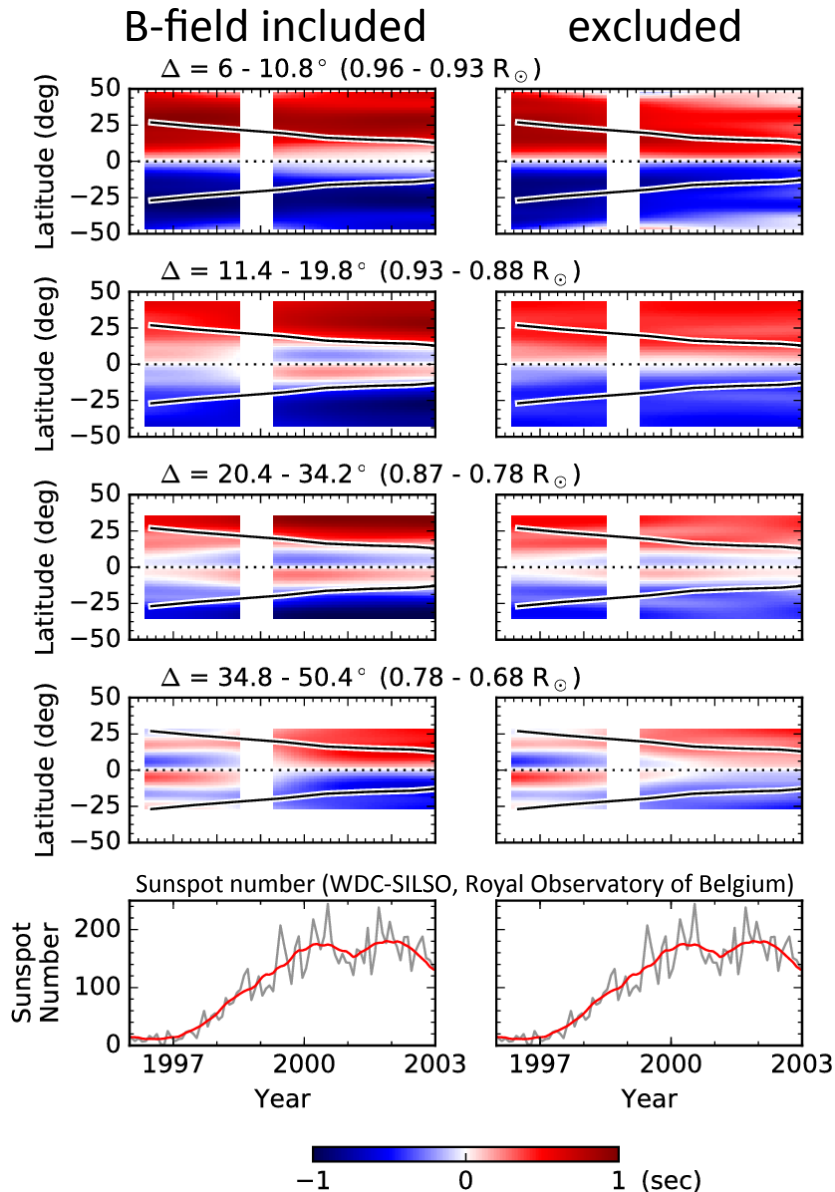
- Most of the fluctuations come from the Sun (e.g., realization noise) rather than the instruments.

# Major systematic errors

- Roll angle (P angle) misalignment in MDI instrument (Giles et al. 2000; Beck & Giles 2005)
- Center-to-limb variation (Zhao et al. 2012; Balder & Schou 2012)
- **Contamination from active regions (Liang & Chou 2015)**

# Contamination from active regions

MDI

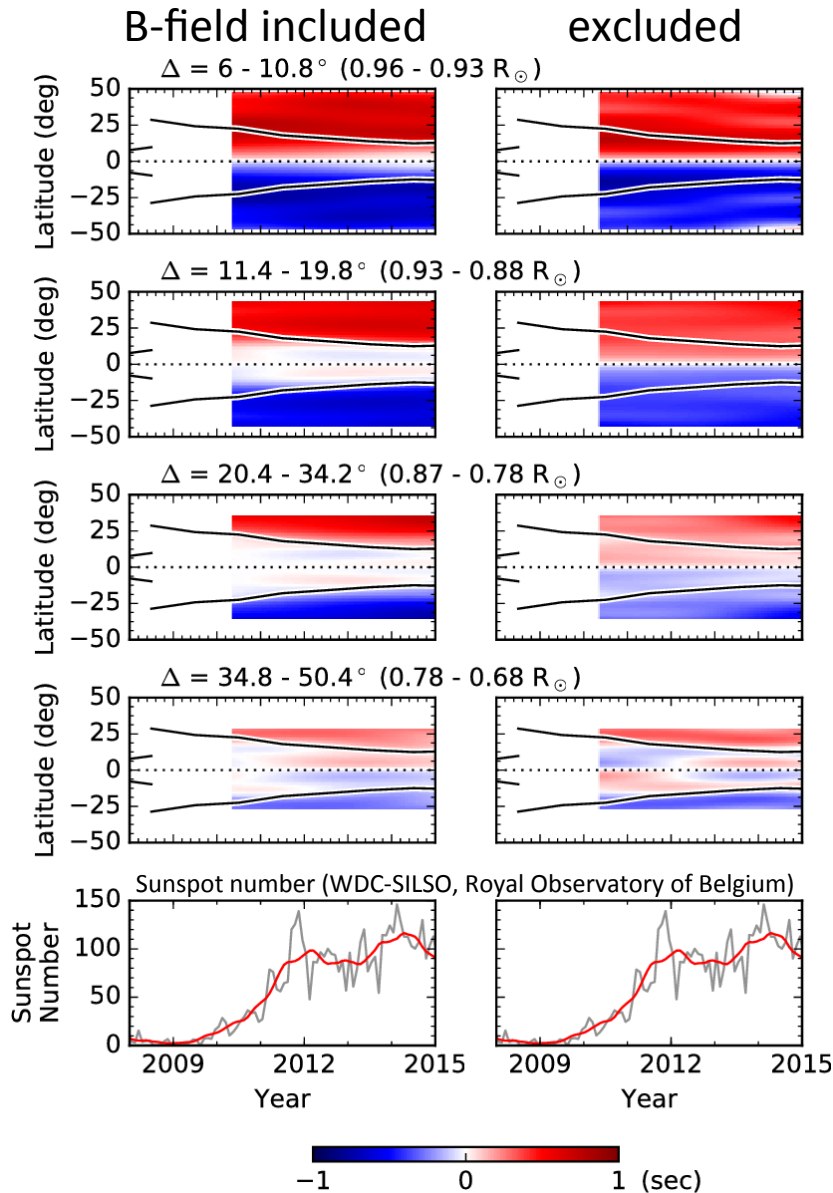


- Using data points inside active regions will introduce an “effective” downward flow centered at active latitude
- It is a local effect and unrelated to the large-scale meridional flow.
- Perturbations in lower panels become more prominent after the removal of active regions

Liang & Chou (2015a,b)

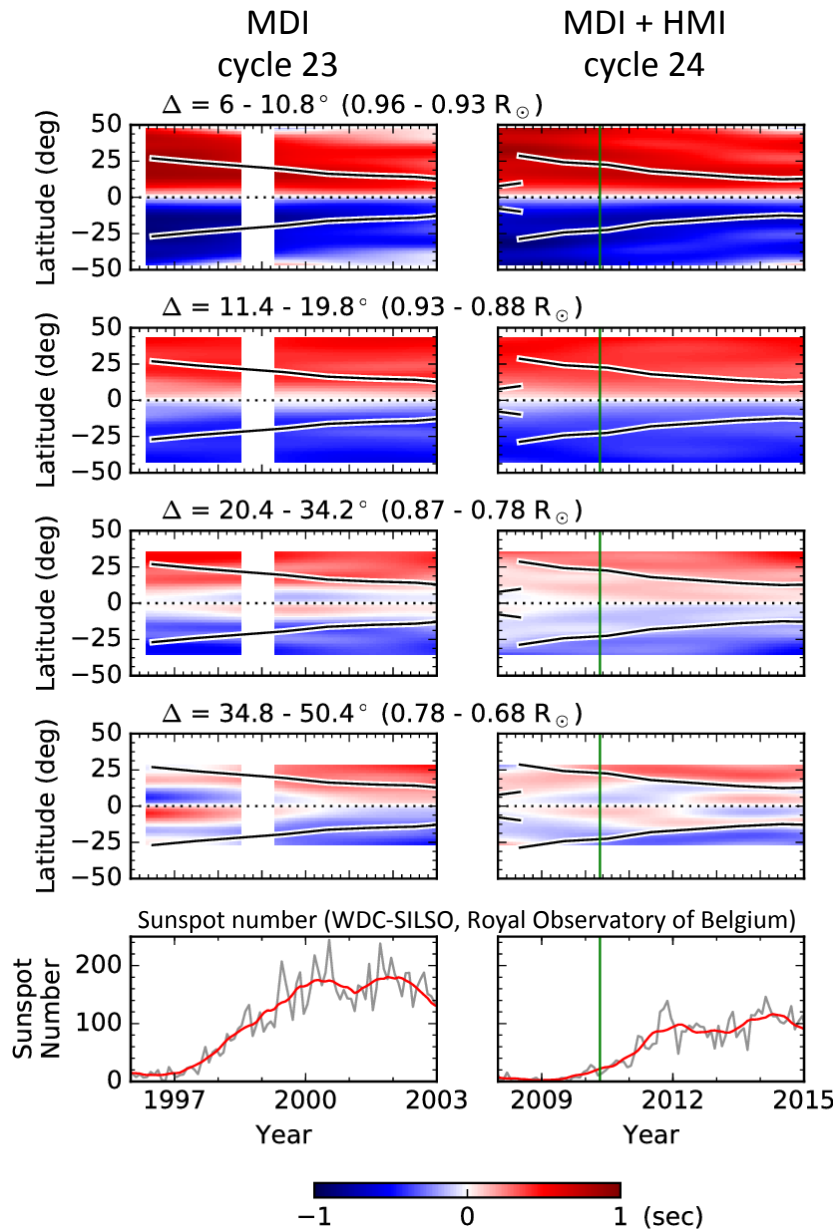
# Contamination from active regions

HMI

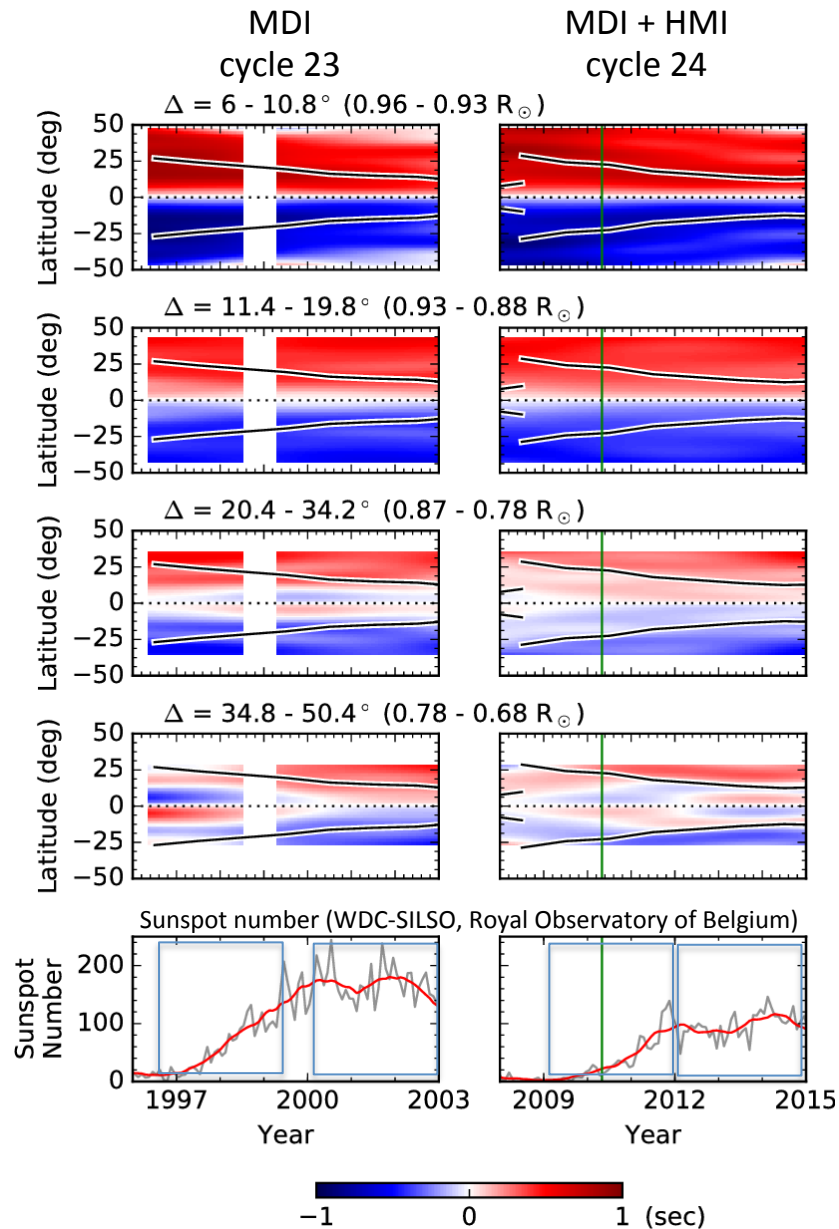


- The contamination in cycle 24 is less than that in cycle 23.
- A similar pattern to MDI at the base, albeit weaker.

# MDI vs. HMI

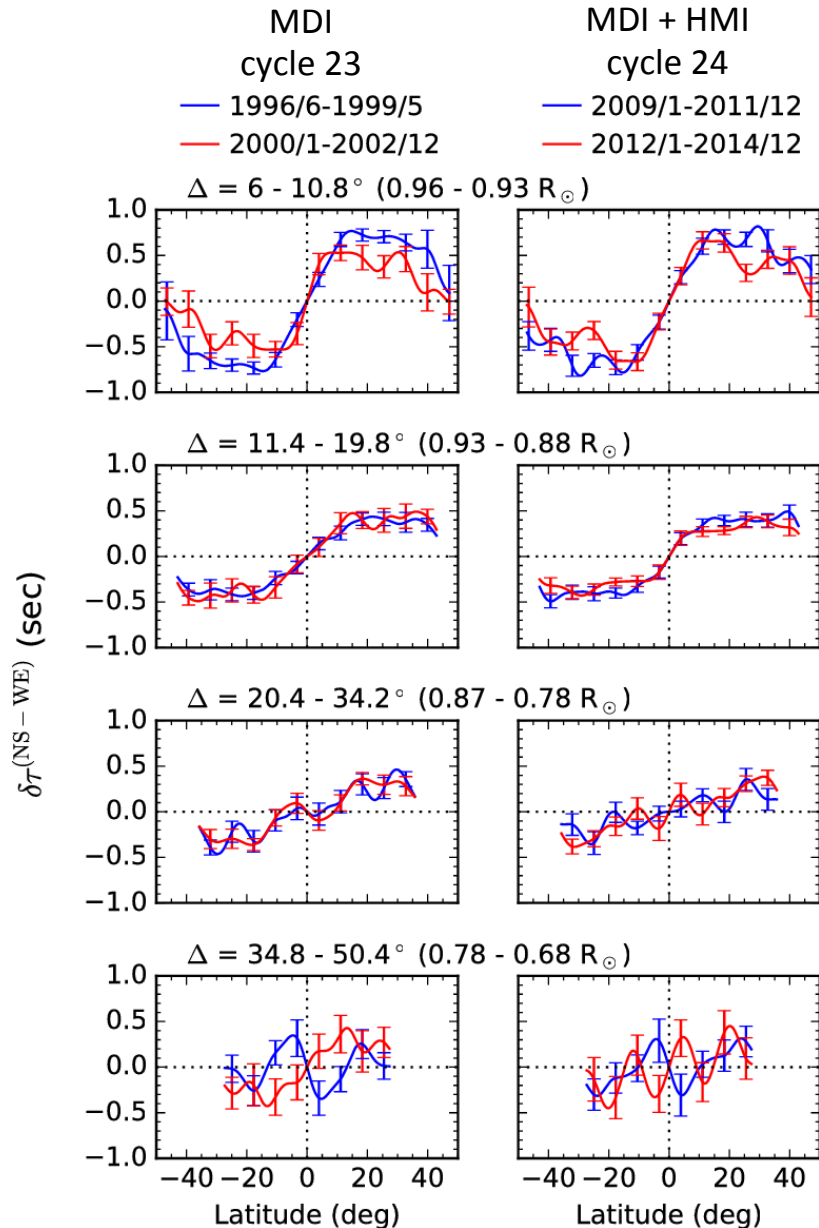


# MDI vs. HMI





# MDI vs. HMI



- Top panels  
Slower meridional flow in solar maximum
- Bottom panels  
Sign changes in rising phase

# Summary

- Major systematic errors
  - Center-to-Limb variation
  - P angle uncertainty
  - Contamination from active regions
- MDI vs. HMI (overlap period)
  - Consistent in the overlap period
  - Most of the fluctuations come from the Sun rather than the instruments
- MDI vs. HMI (solar cycle)
  - Near surface: Slower meridional flow in solar maximum
  - Near the base: A change of sign in rising phase
  - Solar cycle dependence in convection zone

Thank you