21-yr measurements of solar meridional circulation from SOHO/MDI and SDO/HMI: Anomalous northern hemisphere during cycle 24

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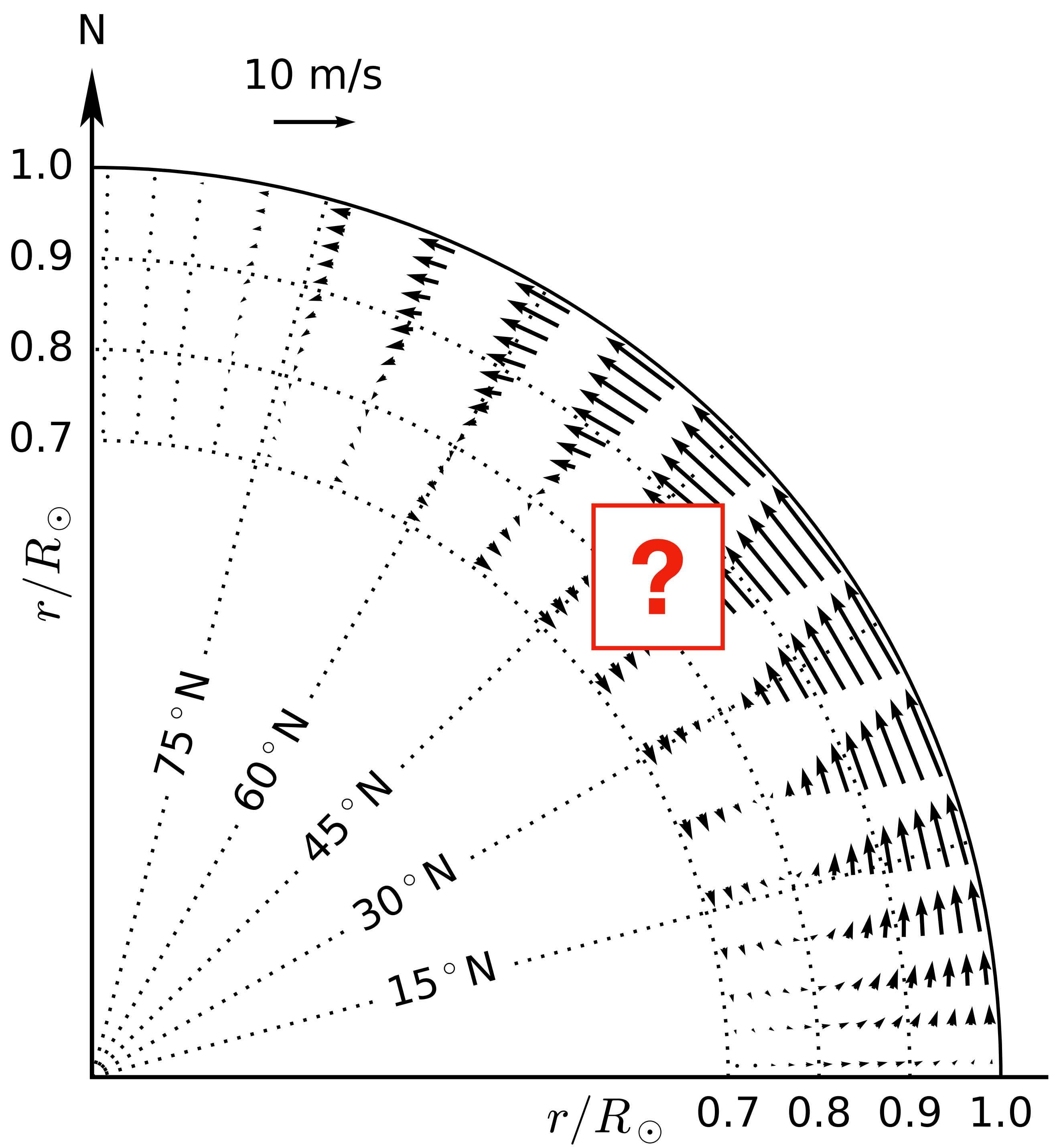
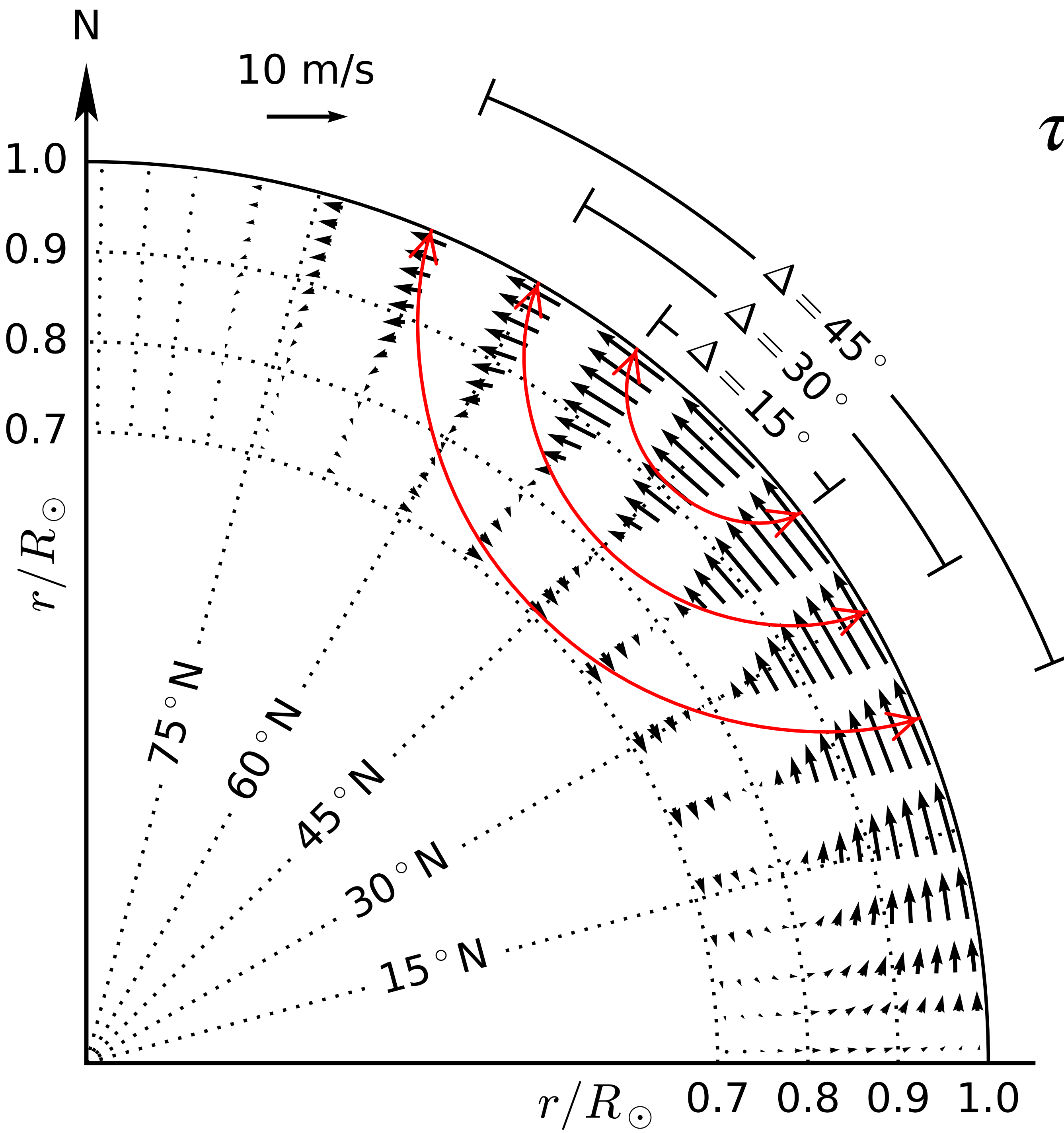
Solar meridional circulation



- surface observations: poleward, 10-20 m/s
- mass conservation implies return flows in deeper layers
- importance: flux transport dynamo models

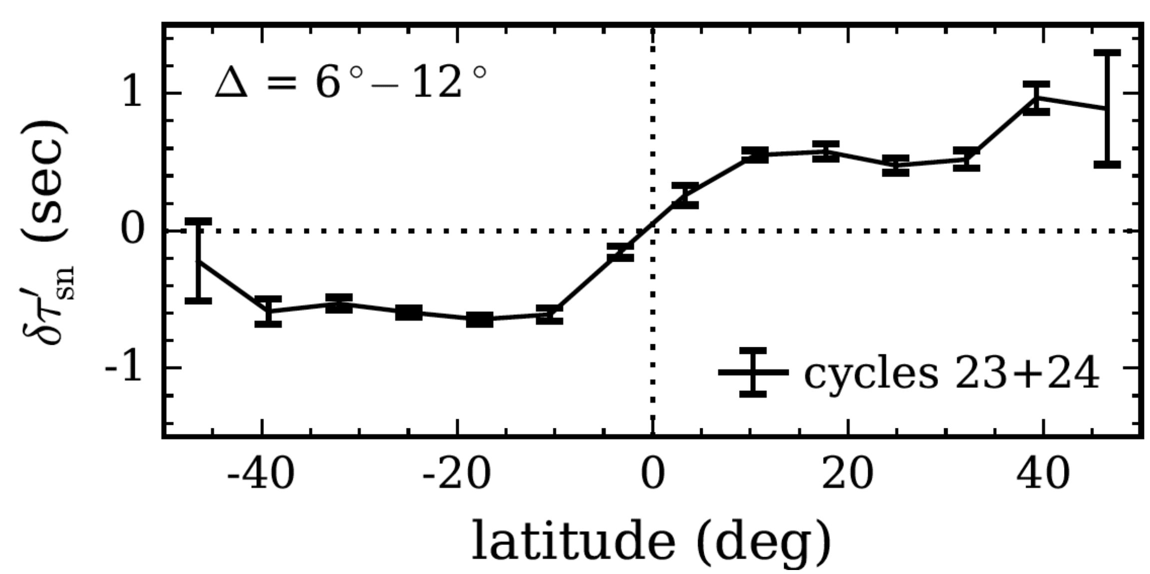
Time-distance helioseismology and the ray approximation



$$\tau_s - \tau_n \equiv \delta\tau_{sn} = -2\int_{\Gamma_{sn}} \frac{\mathbf{u}\cdot d\mathbf{l}}{c^2}$$

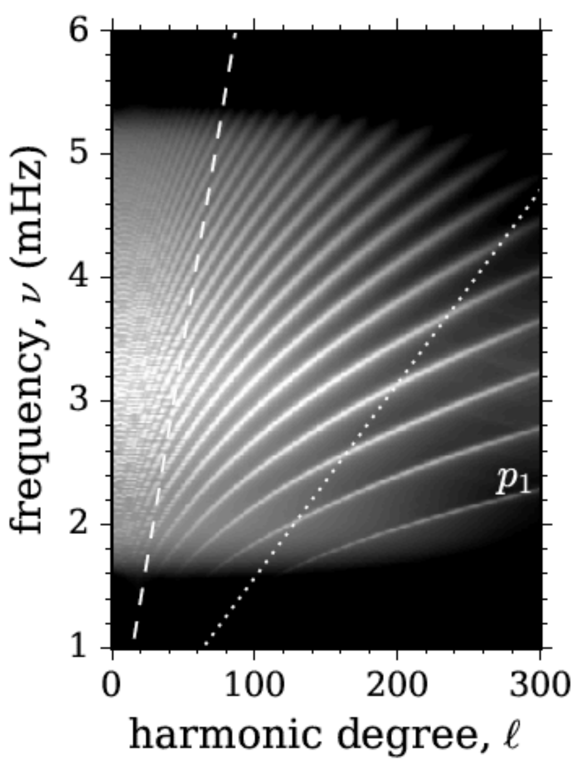
- The north-south travel-time shifts are sensitive to the subsurface meridional flows along the ray paths

typical measurement

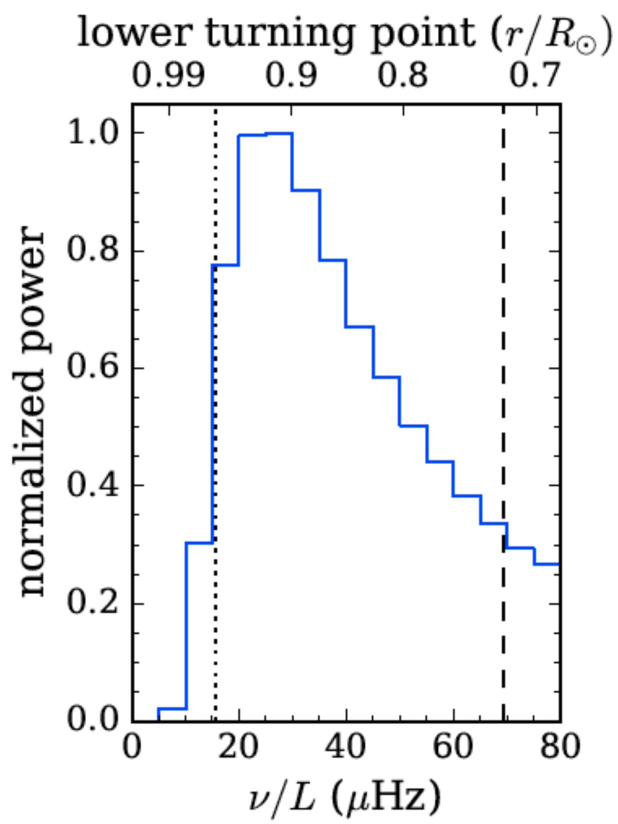


21-yr Dopplergrams from MDI and HMI

power spectrum from medium-degree Dopplergrams



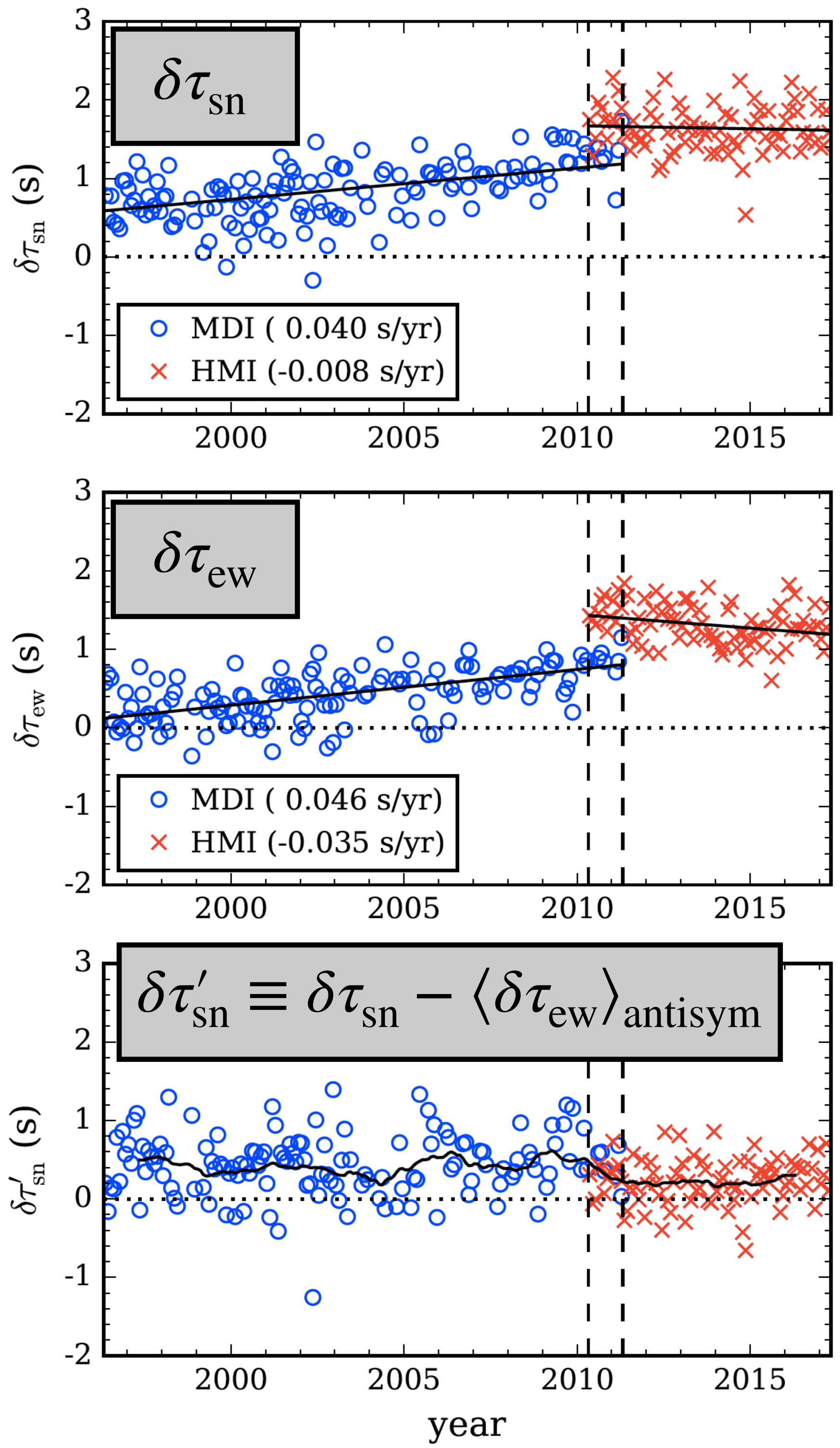
histogram of mode power



- medium-degree Dopplergrams
  - from smoothed and subsampled full-resolution Dopplergrams
  - contain little information of p-modes in the near-surface layers
- period: 1996.05-2017.04
  - from 14-yr MDI and 7-yr HMI data
  - covering 12-yr of cycle 23 and 9-yr of cycle 24
- unwanted signals such as supergranulation and solar rotation are removed.

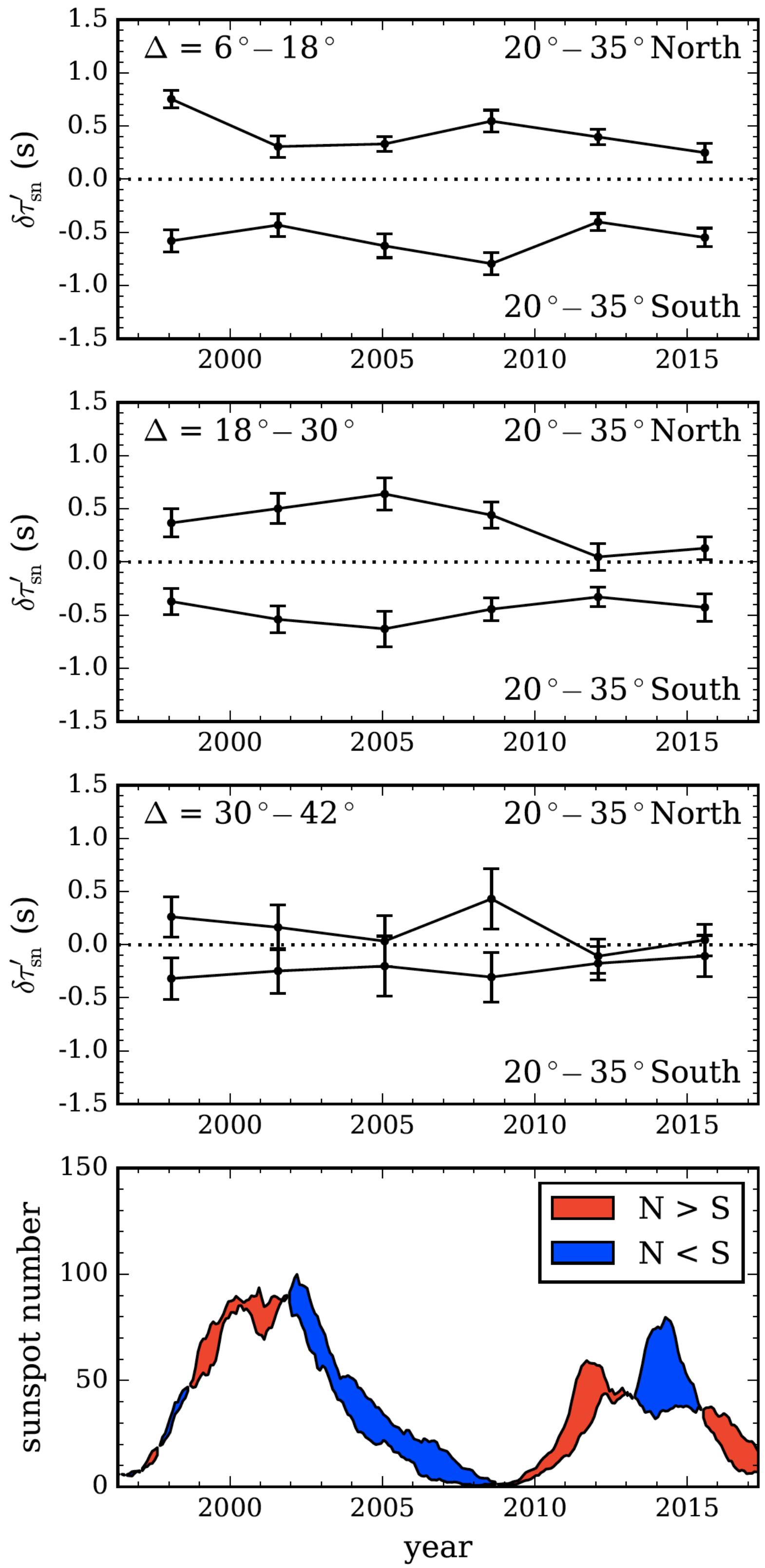
Systematic effects: Center-to-limb variations (Zhao et al. 2012)

average over 6°≤Δ≤42° and the two hemispheres at mid-latitudes



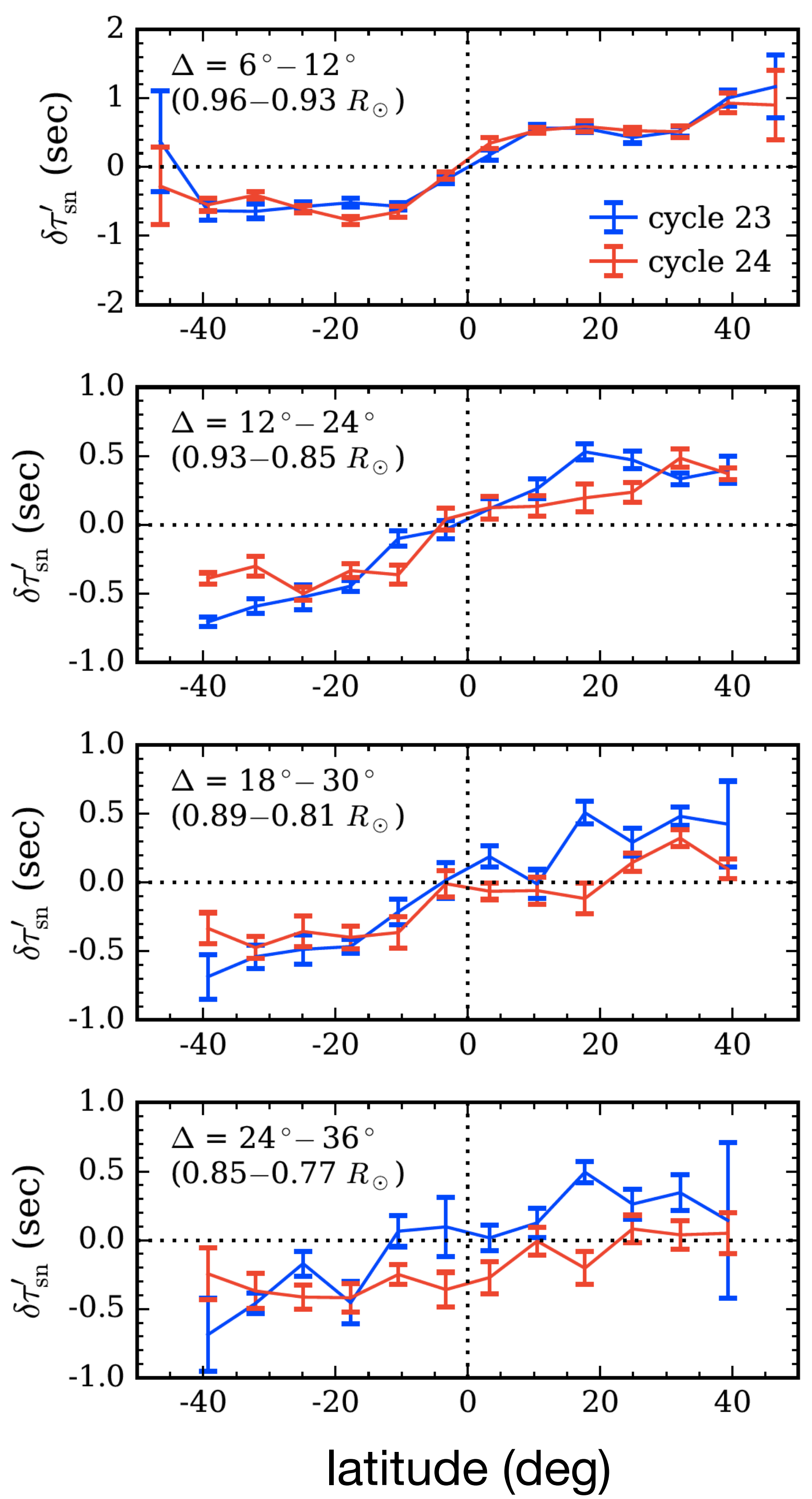
- antisymmetric part of $\delta\tau_{ew}$ is expected to represent the C-to-L variations (Zhao et al. 2012)
- C-to-L variations of MDI and HMI are different and vary over time
- after removing the C-to-L variations, the $\delta\tau'_{sn}$ from MDI and HMI are generally consistent; however, the amplitude during the rising and maximum phases of cycle 24 is slightly smaller.

Anomalous northern hemisphere during cycle 24

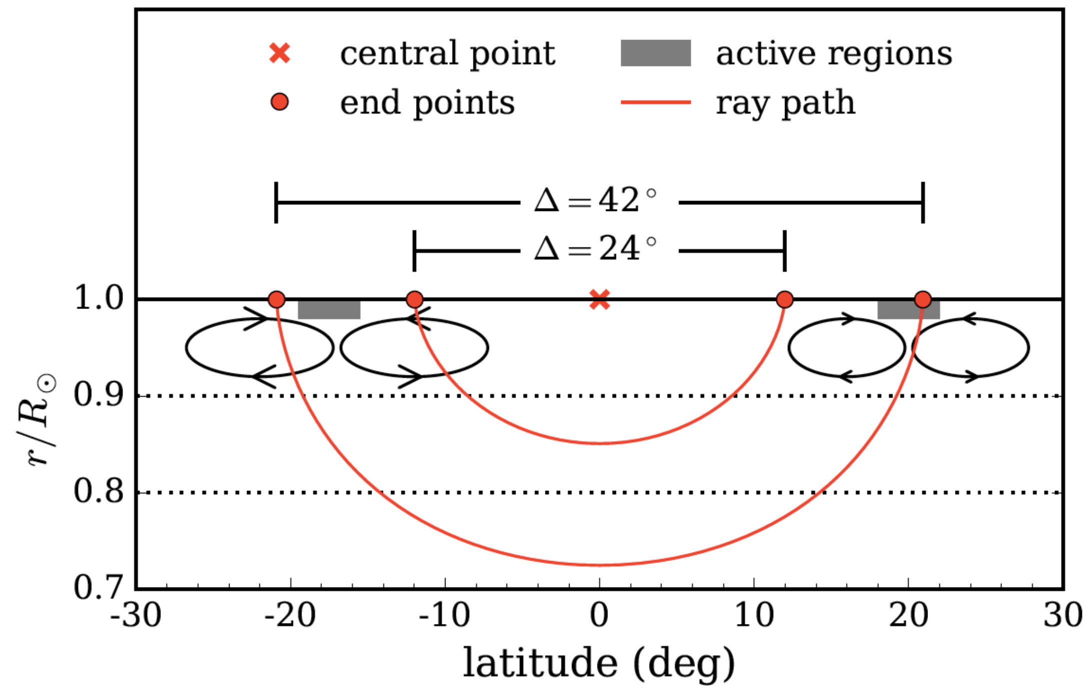


- 6°<Δ<18°: $\delta\tau'_{sn}$ decreases during solar maximum
  - consistent with observations in the past
  - mostly due to the inflows toward active regions
- 18°<Δ<30°: $\delta\tau'_{sn}$ decreases during rising phase
  - we shall see that travel-time shifts caused by the near-surface inflow toward the active latitudes might partly explain the different solar cycle variations for different distance ranges
  - northern hemisphere during cycle 24 is anomalous for large-distance cases
- 30°<Δ<42°: low S/N

Anomalous northern hemisphere during cycle 24

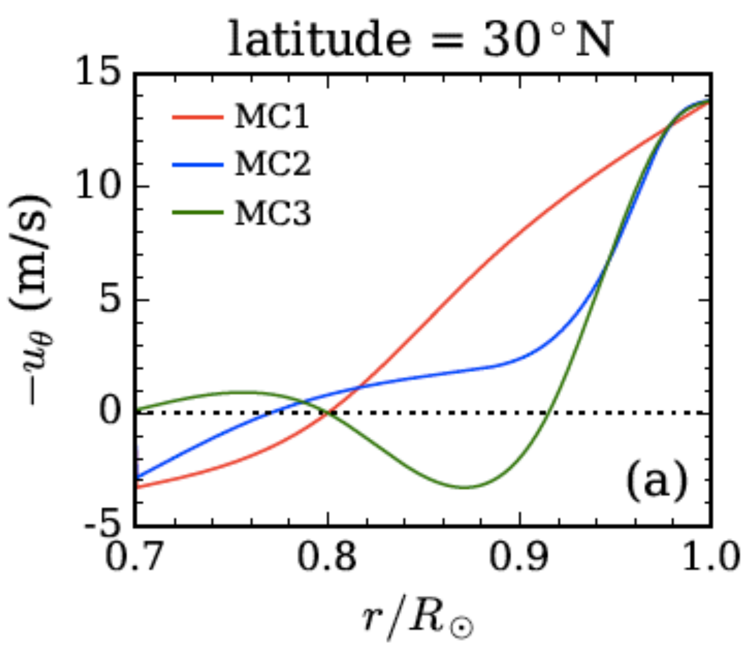


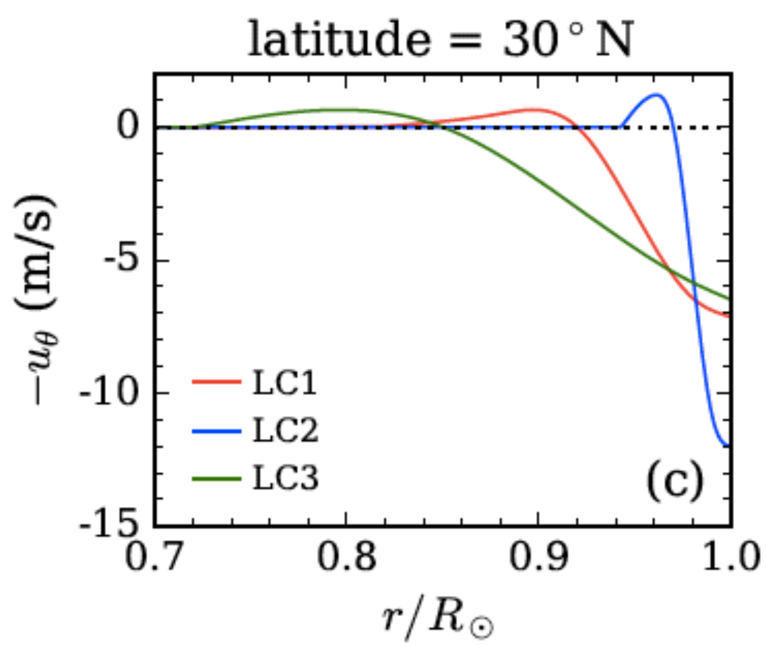
- small Δ:
  - cycle 23 agrees with cycle 24
  - zero at the equator
- large Δ:
  - cycle 24's northern hemisphere is anomalous
  - non-zero at the equator: P-angle error? equator-crossing flow?

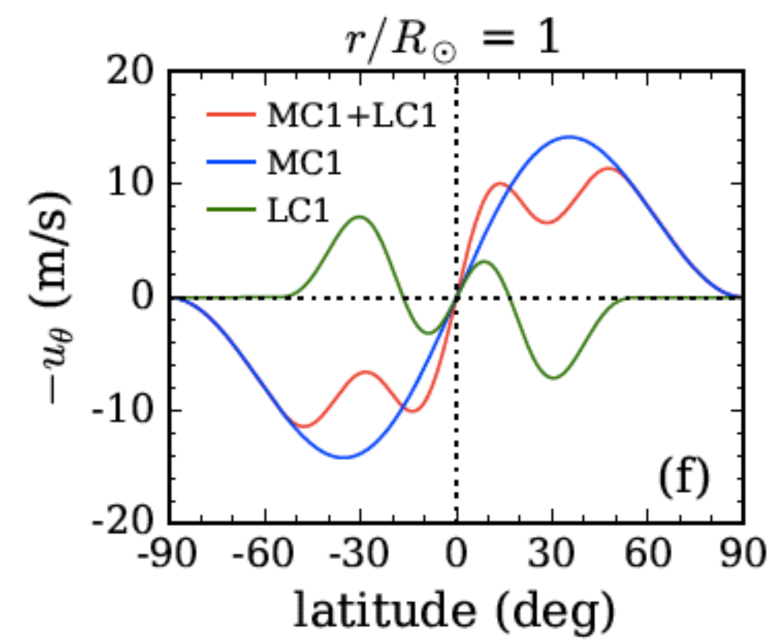


➡ asymmetry between the near-surface flows in the two hemispheres may cause the non-zero values at the equator for large Δ

Flow models





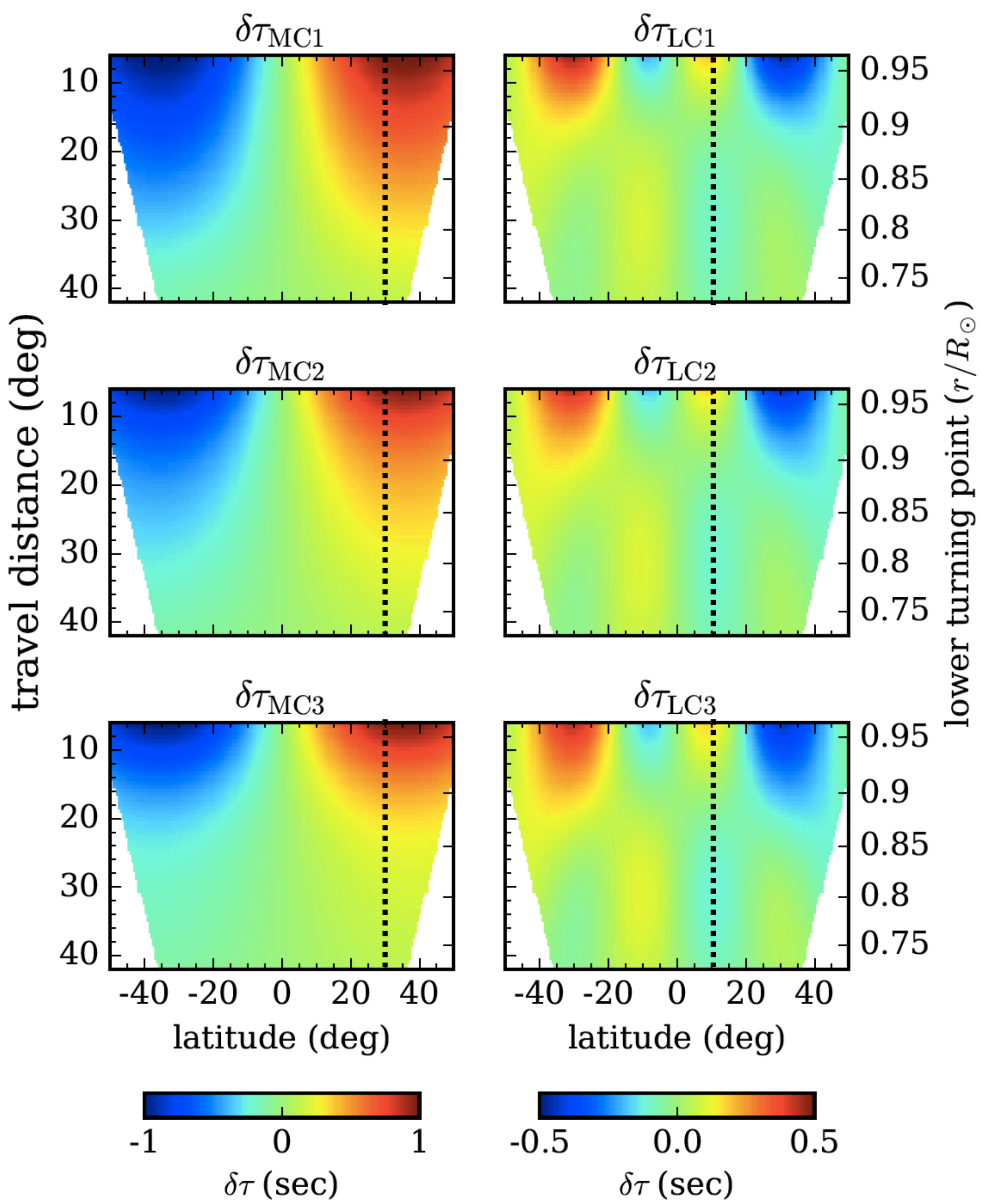


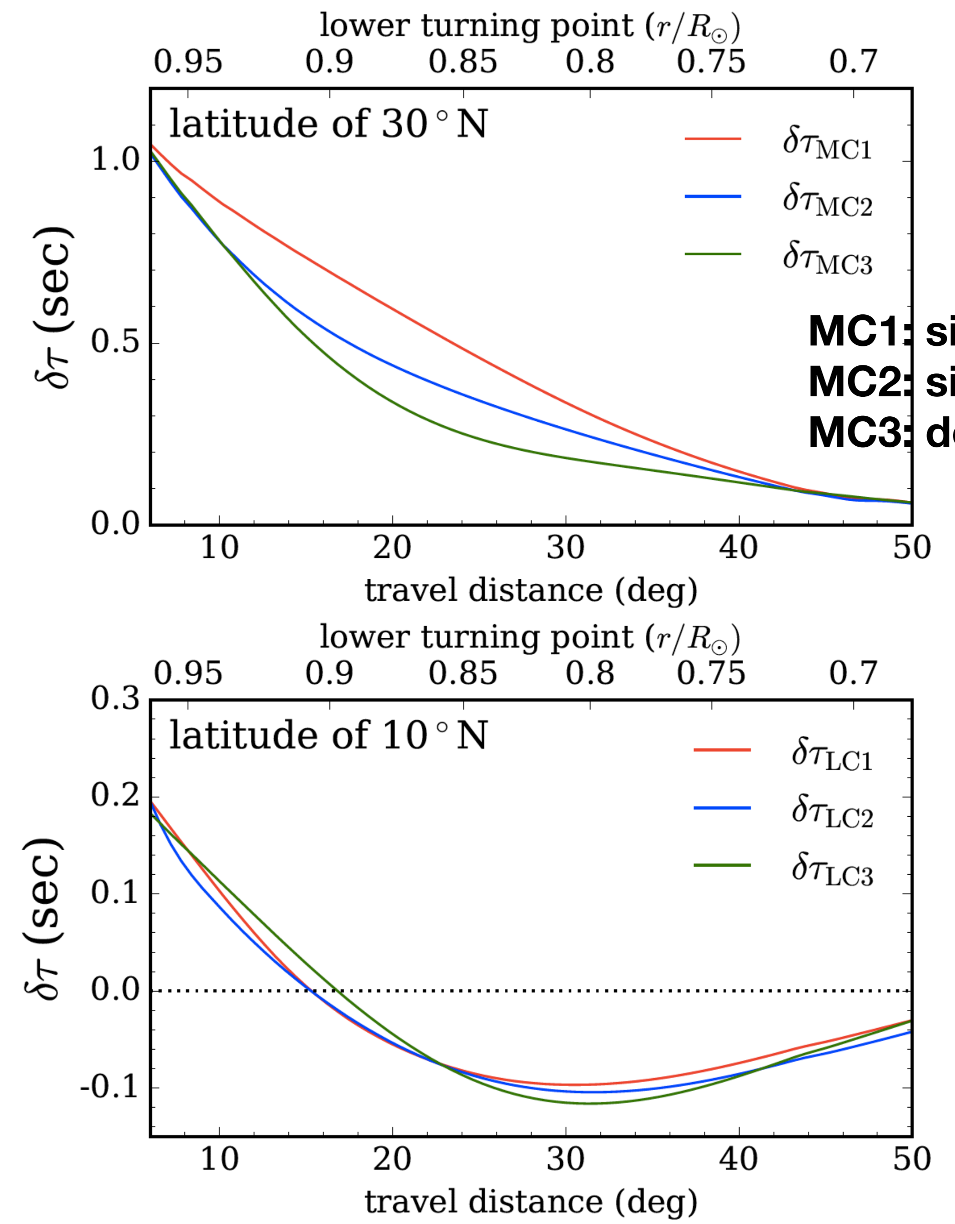
➡ **Meridional Circulation**
- **MC1: single-cell model (strong)**
- **MC2: single-cell model (weak)**
- **MC3: double-cell (3-layer) model**

➡ **Local Cellular flows**
- **LC1: returns at 0.9 $R_\odot$**
- **LC2: returns at 0.96 $R_\odot$**
- **LC3: returns at 0.8 $R_\odot$**

➡ **MC + LC**

Forward-modeled travel-time shifts



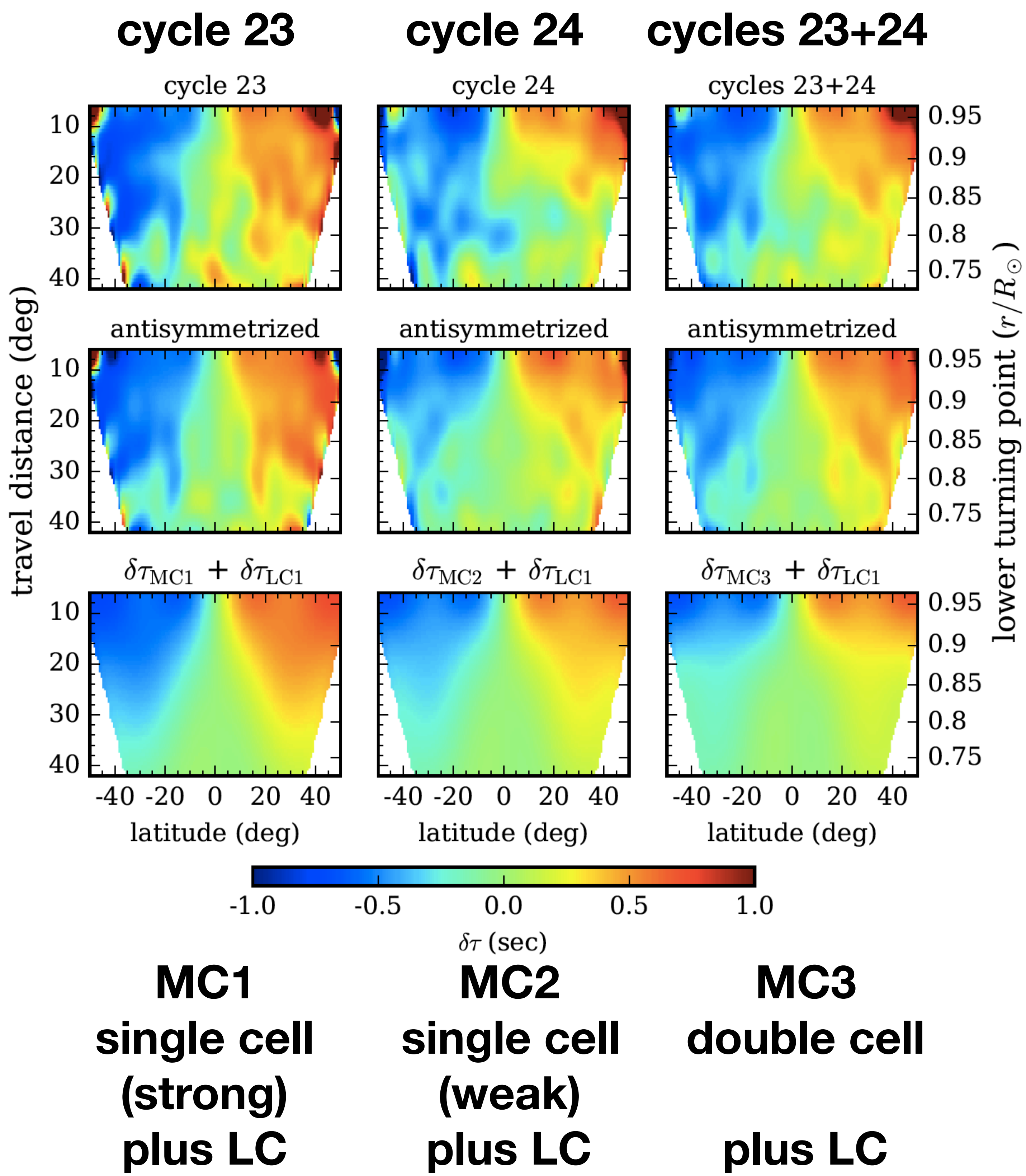


MC1: single-cell model (strong)
MC2: single-cell model (weak)
MC3: double-cell model

LC1: returns at 0.9 $R_\odot$
LC2: returns at 0.96 $R_\odot$
LC3: returns at 0.8 $R_\odot$

- the weaker the poleward flows in the convection zone, the faster the $\delta\tau_{MC}$ decreases
- $\delta\tau_{LC}$ has different sign for $\Delta<18°$ and $\Delta>18°$, which explains to some extent the different solar cycle variations for different distance ranges
- the depth of return flows do not determine where $\delta\tau_{MC}$ or $\delta\tau_{MC}$ change their signs
- contribution from the upper convection zone is significant
- contribution from the lower convection zone is on the order of 0.01 sec

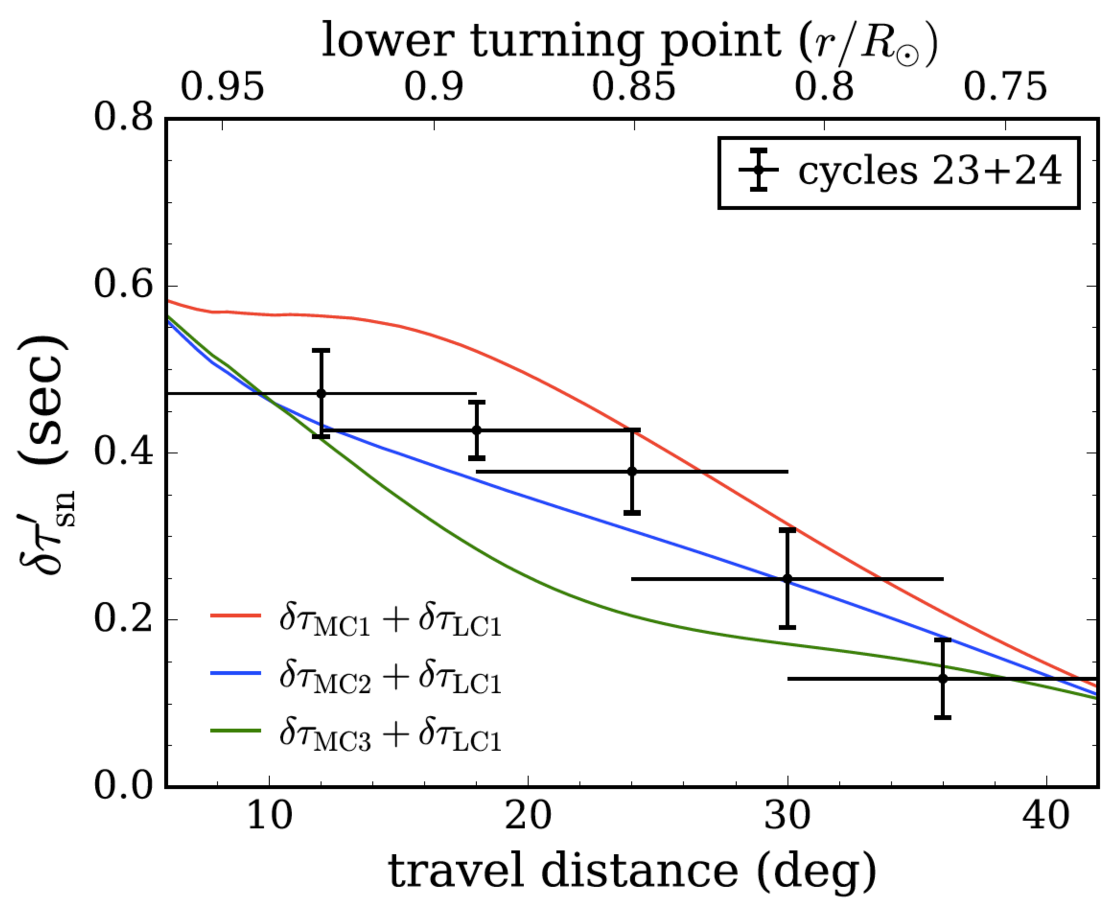
Measured vs. forward-modeled results



- cycle 23 favors one-cell model
- cycle 24's southern hemisphere generally agrees with cycle 23
- cycle 24's northern hemisphere is anomalous for large Δ

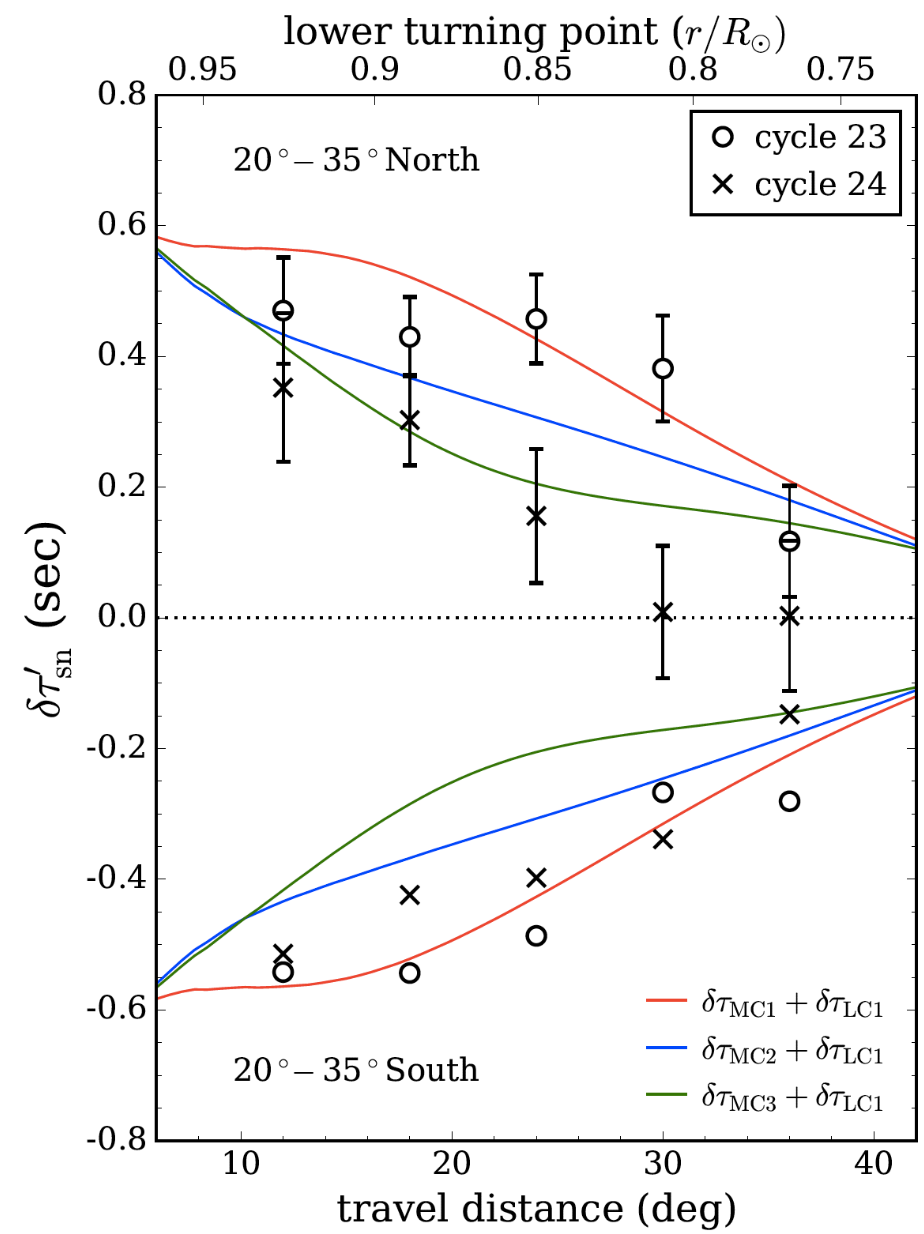
Measured vs. forward-modeled results

average over 21 yr and two hemispheres



MC1: single-cell model (strong)
MC2: single-cell model (weak)
MC3: double-cell model

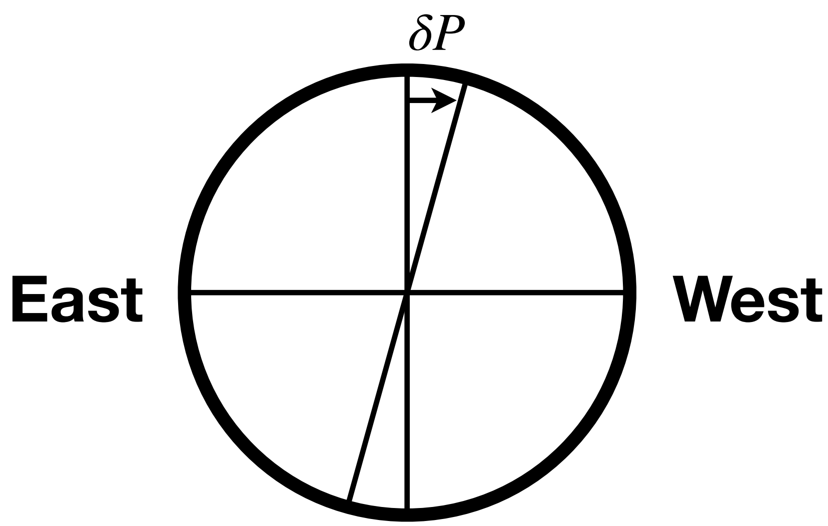
comparison between two cycles and two hemispheres



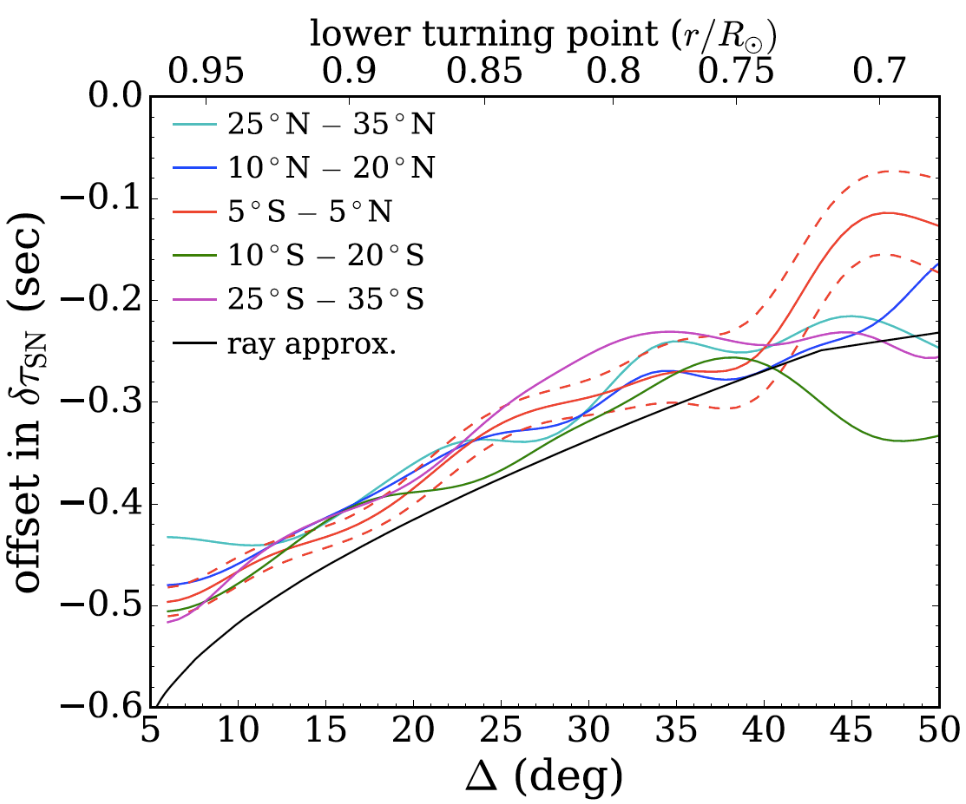
Thank you for your attention!

Supplementary material

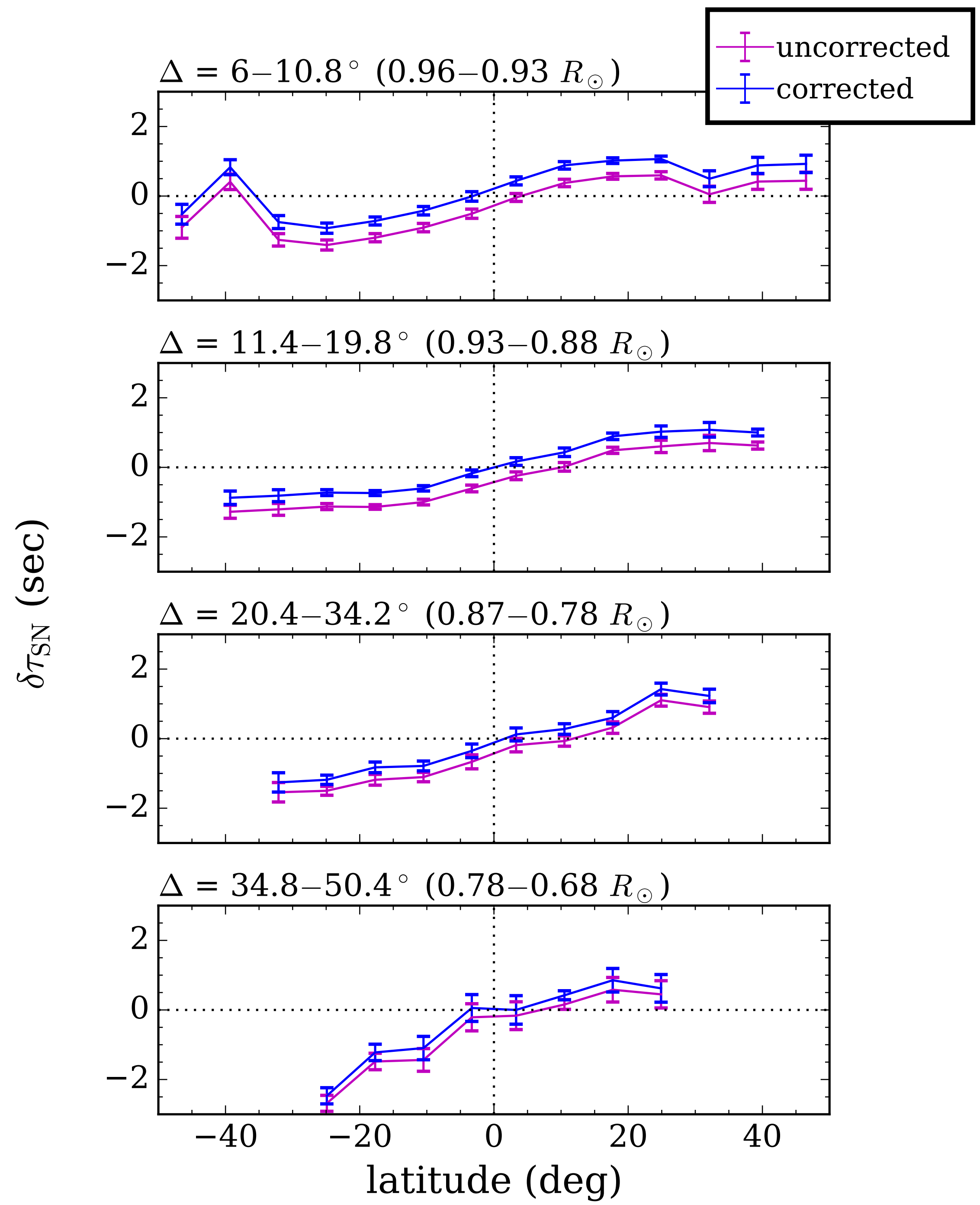
Systematic effects: P-angle uncertainty (Giles 2000)



- The P-angle error has its largest effect for short-distance measurements.



south-north travel-time measurements from MDI data

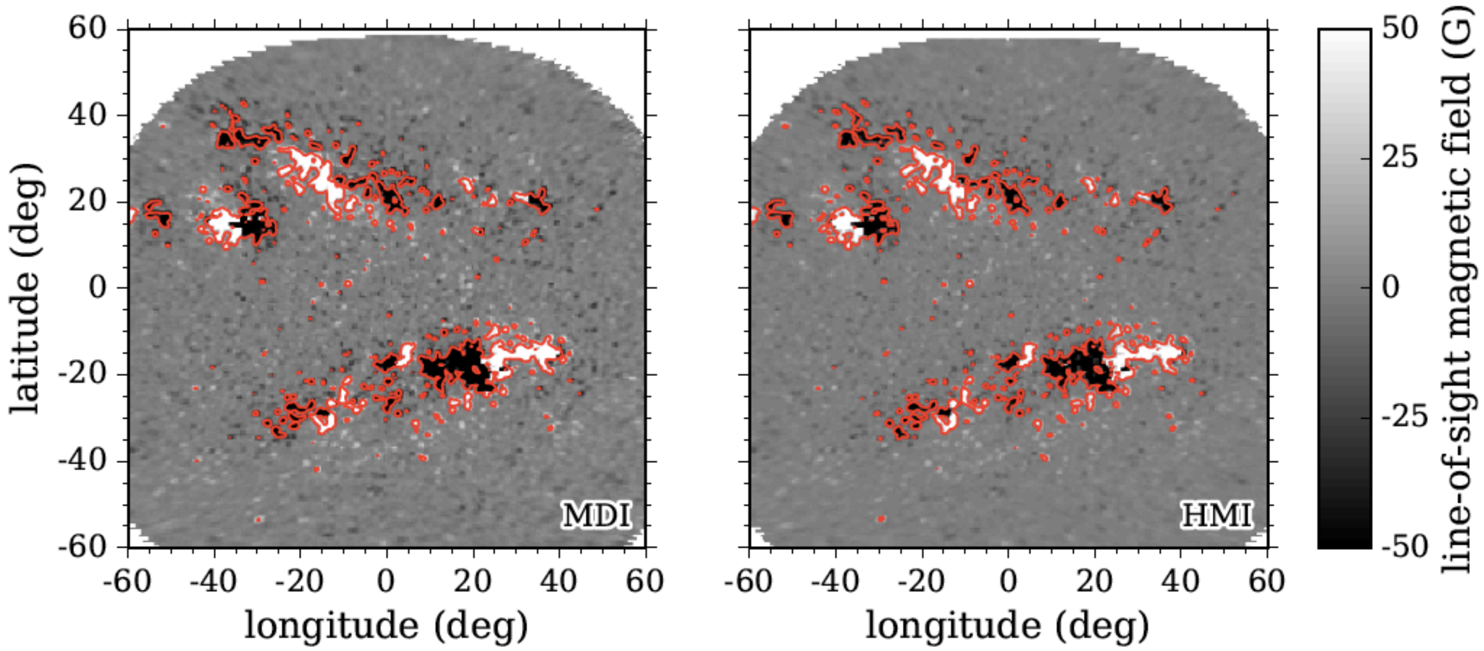


Supplementary material

Systematic effects: surface magnetic field (Liang & Chou 2015)

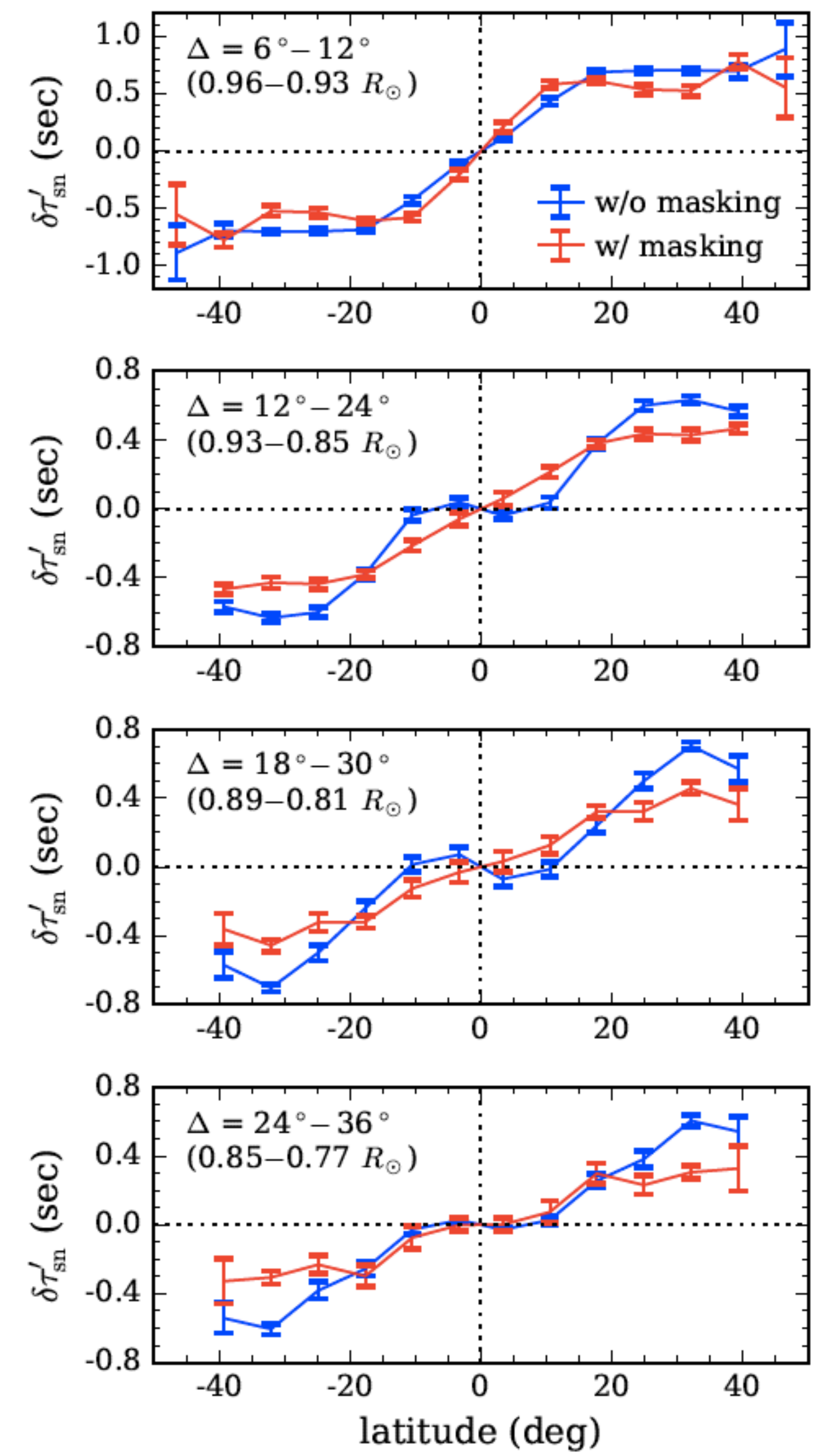
An example of the masked areas

MDI: |B| > 30 G HMI: |B| > 20 G



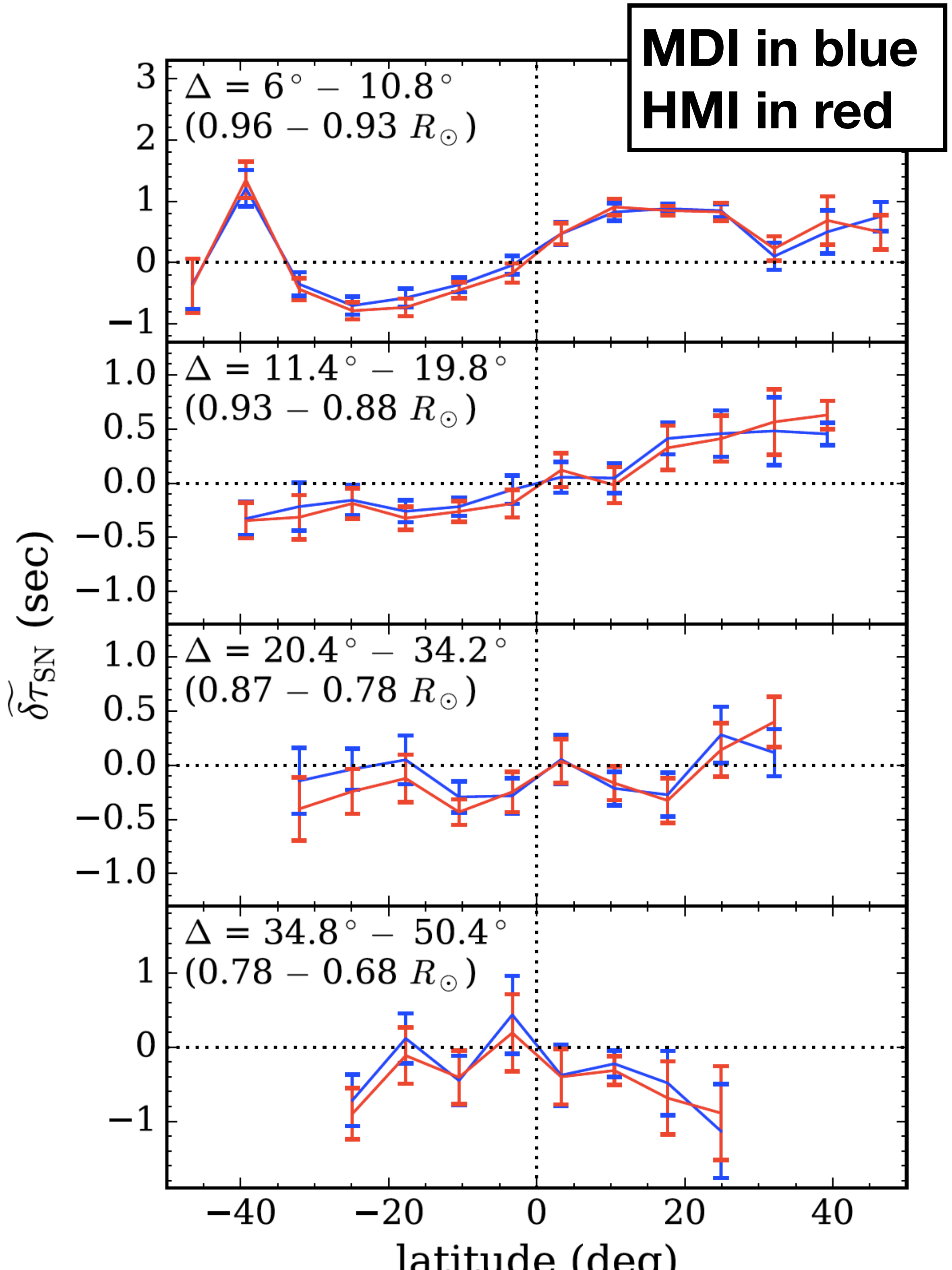
Different thresholds for different instruments (which have different sensitivities to the magnetic field) to make the masked areas the same.

how the surface magnetic field affects the travel-time measurements



Supplementary material

MDI vs. HMI in the concurrent period 2010.05-2011.04 (rising phase of cycle 24)



- results from MDI and HMI both show significant reduction in the northern hemisphere for $\Delta > 20°$ in the rising phase of cycle 24

Supplementary material

Measured vs. forward-modeled results: antisymmetric part of the travel-time shifts