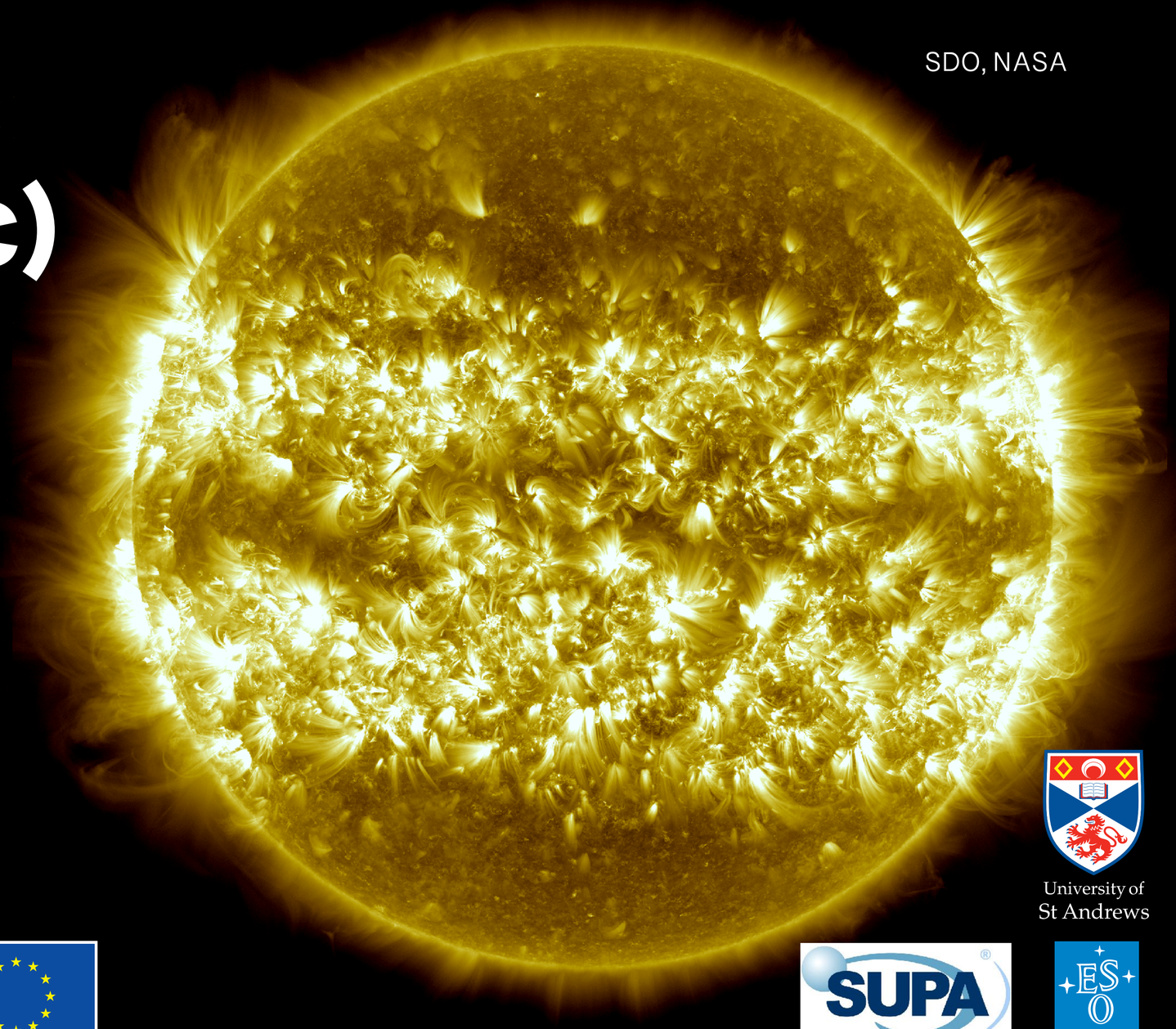
The (magnetic) Sun-as-a-star

Lisa Theres Lehmann

Gaitee A. J. Hussain, Moira M. Jardine,
Duncan H. Mackay, Aline Vidotto,
Jean-François Donati

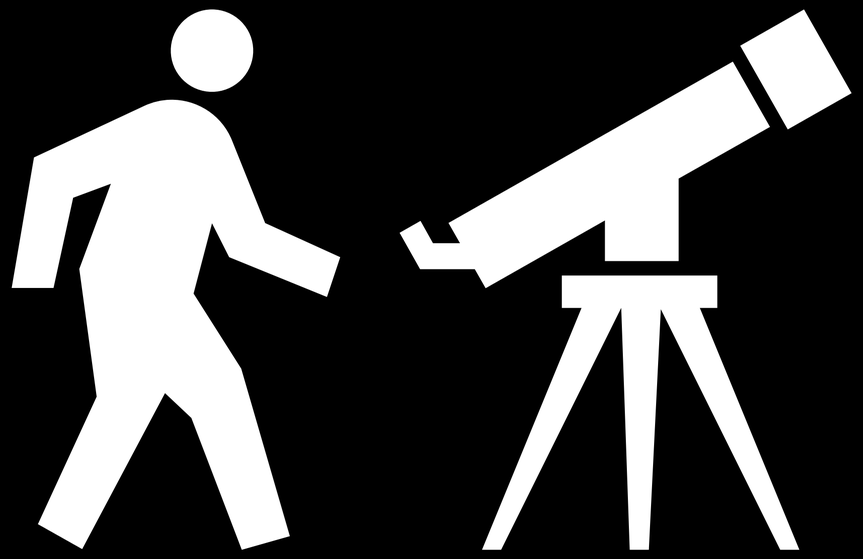
Besançon - 9 Jun 2022



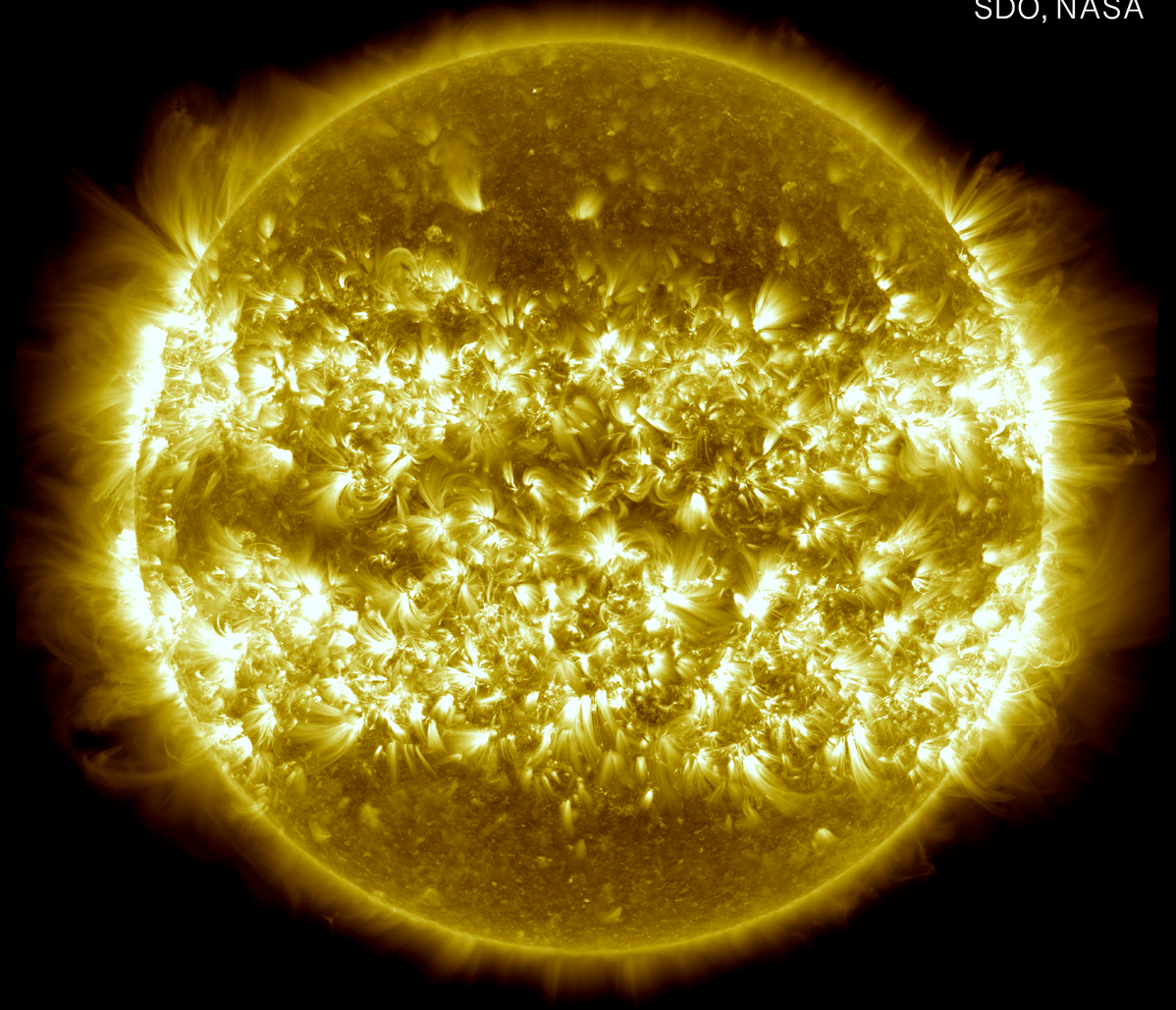
SDO, NASA

University of St Andrews

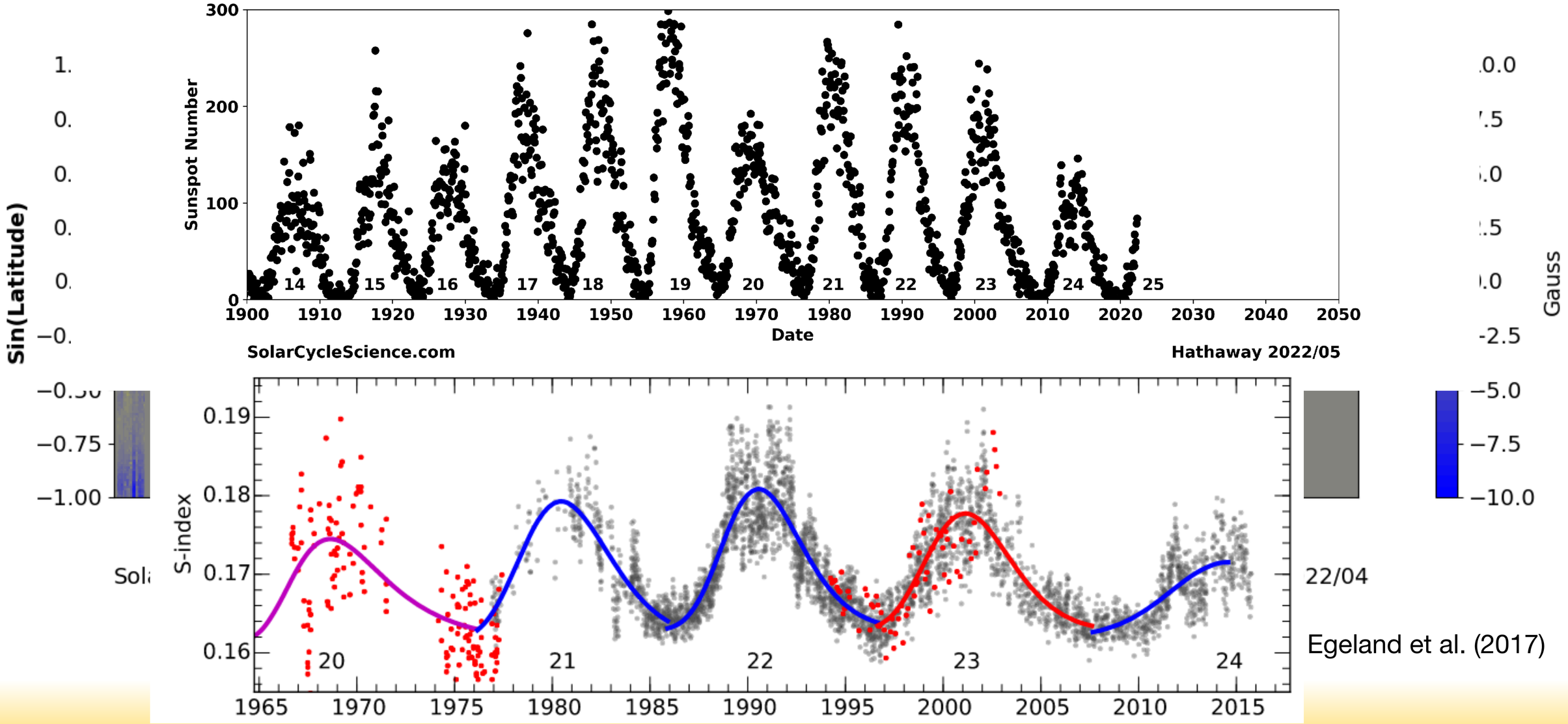
How does the Sun look like as a distant star?



SDO, NASA

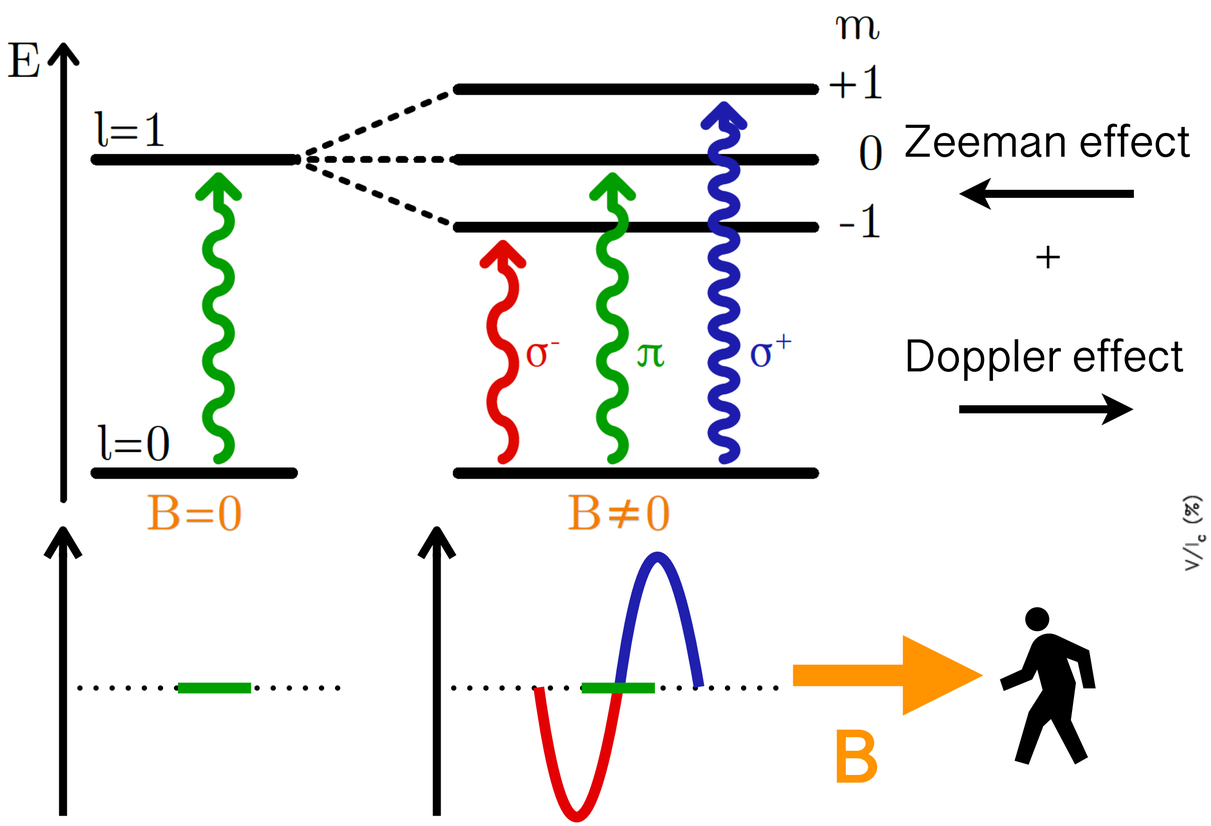


The Sun shows cyclic variation of the small- and large-scale fields



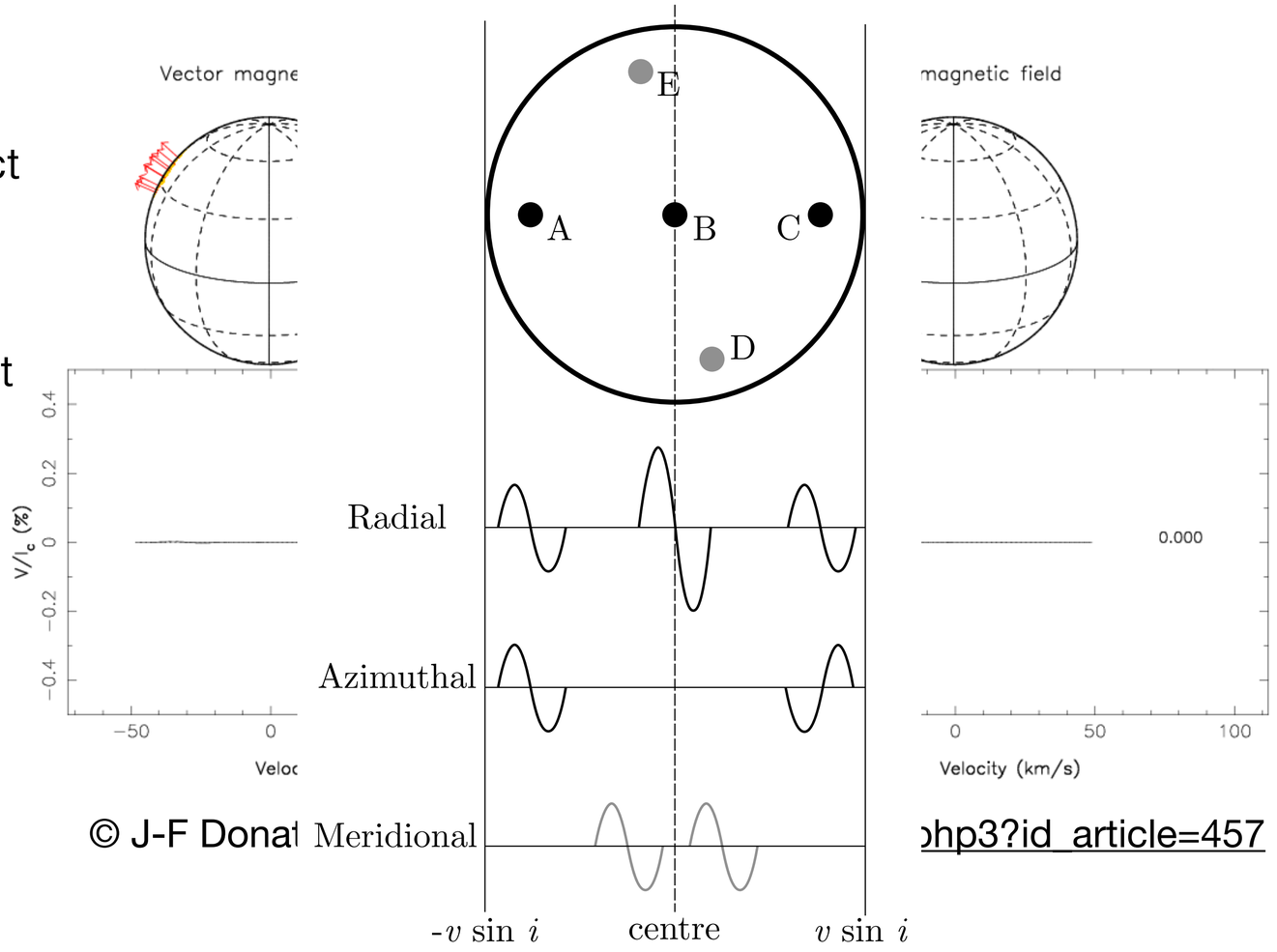
Egeland et al. (2017)

Observing stellar magnetic fields



Circularly polarised spectral lines (Stokes V)

$$V \propto \lambda^2 g_{\text{eff}} B_{||}$$



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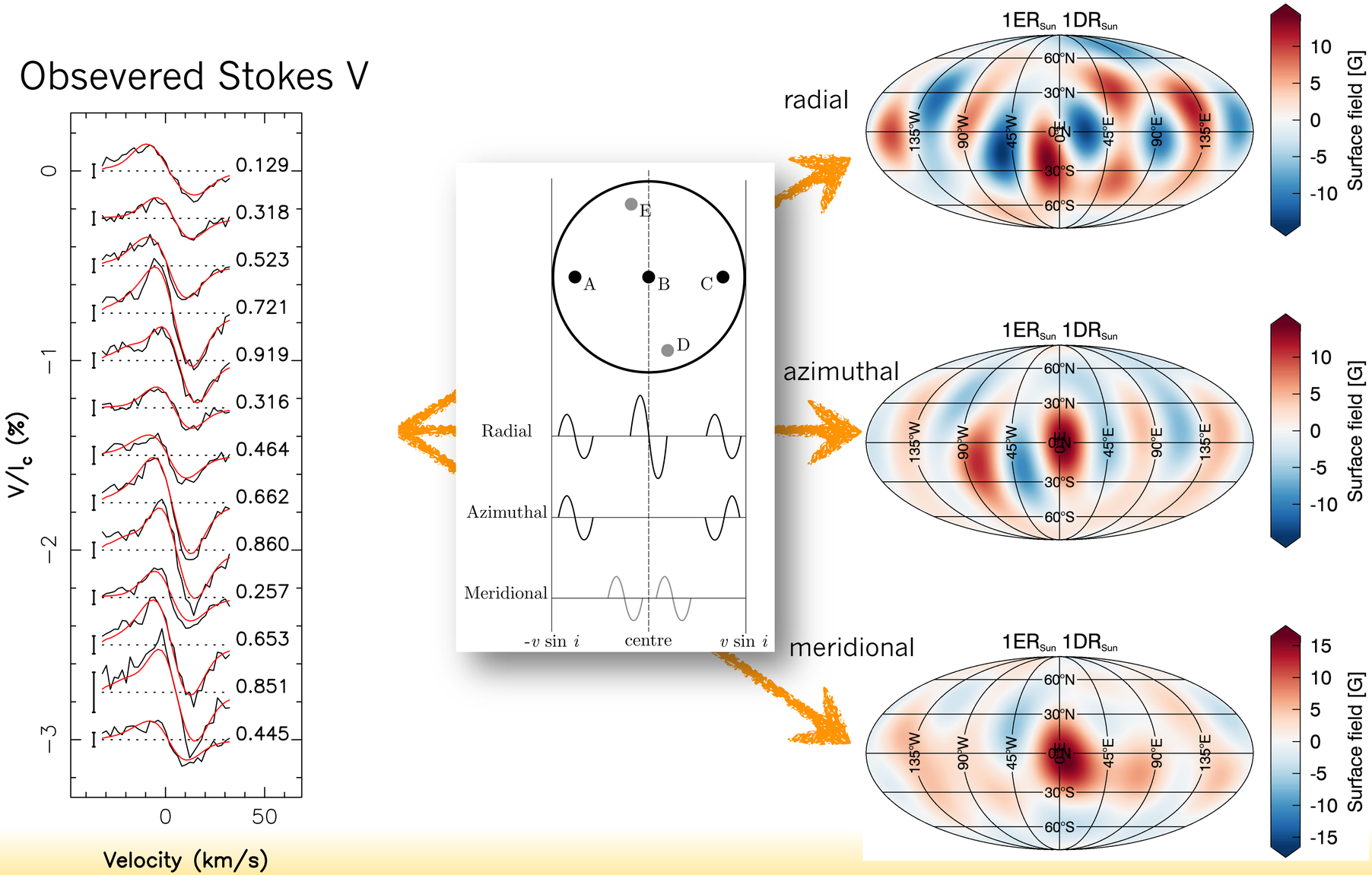
ZDI - Zeeman-Doppler Imaging

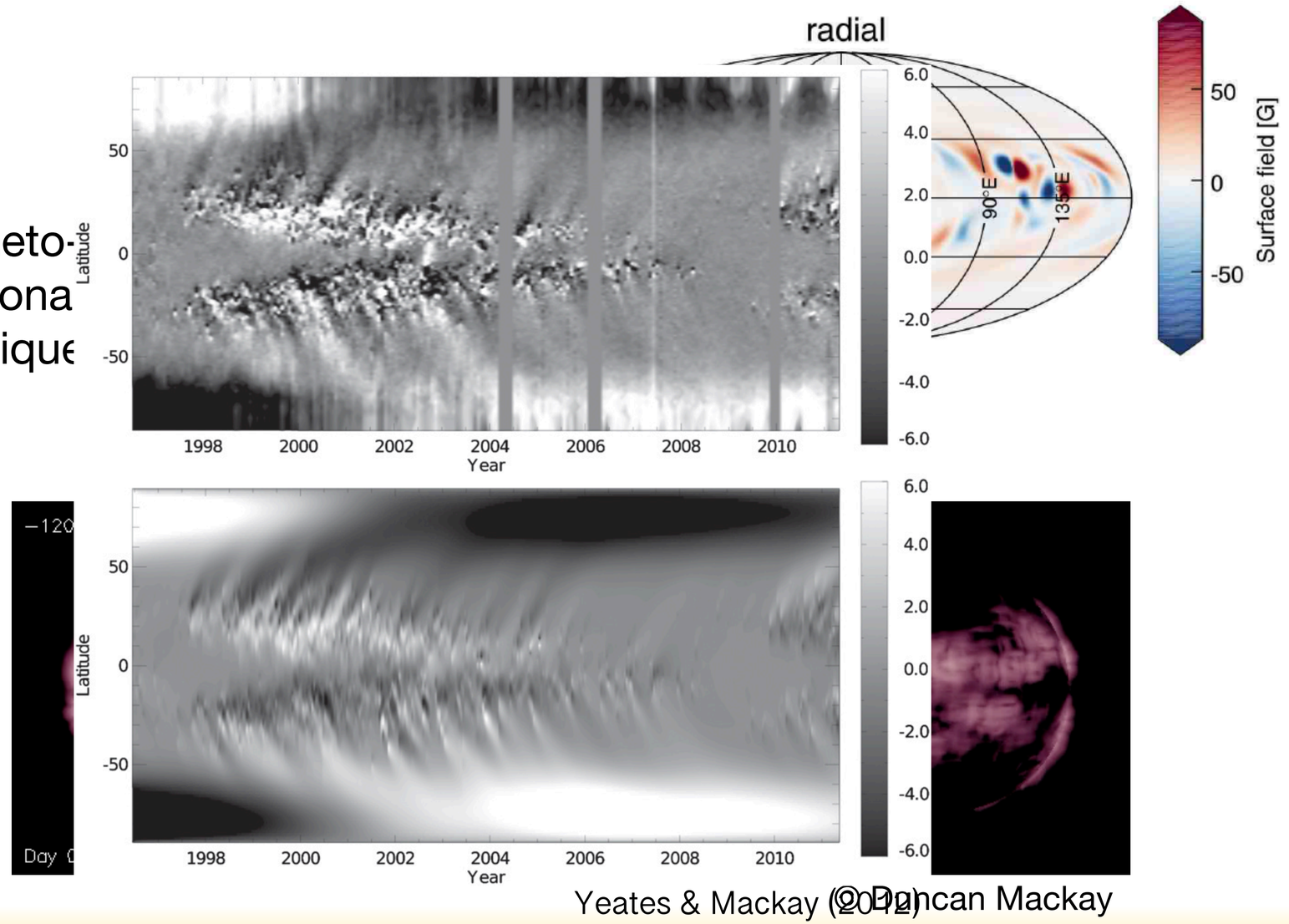
Zeeman Doppler Imaging (ZDI)



3D non-potential flux transport simulations

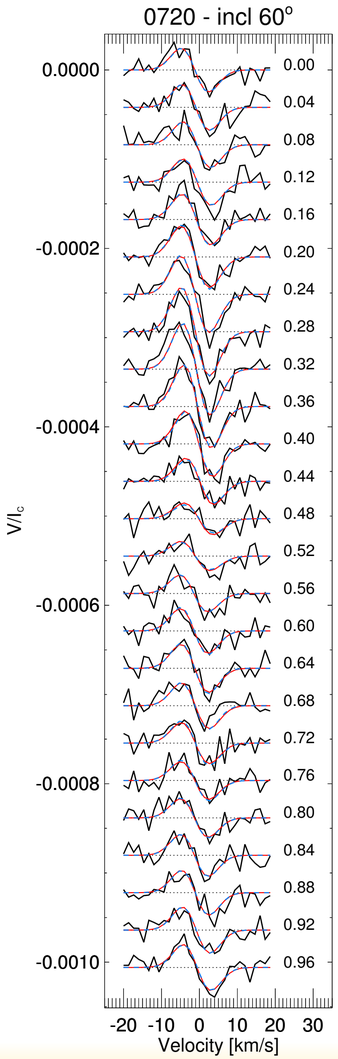
- Magnetic flux transport model based on Gibb et al. (2016) and Yeates & Mackay (2012)
- Photosphere flux emergence of bipolar spots and surface flux transport
- Flux advected from photosphere to corona using the magnetofrictional technique
- Non-potential corona evolution up to 2.5 R_{Sun}
- Flux emergence properties based on solar synoptic maps covering 15 yr (1996/06 – 2011/01)

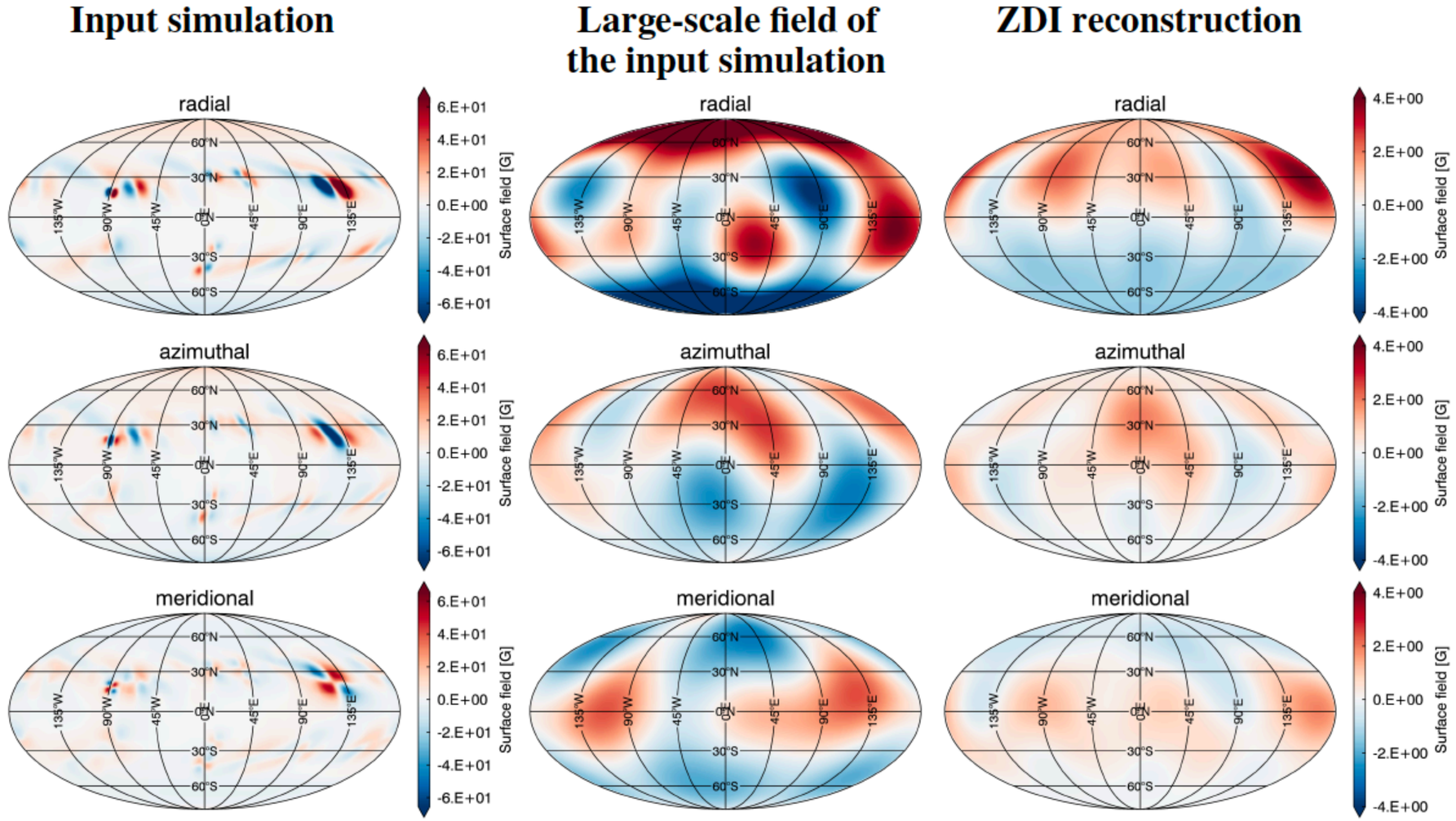
Magneto-
fricationa
technique



Yeates & Mackay (2012) © Duncan Mackay

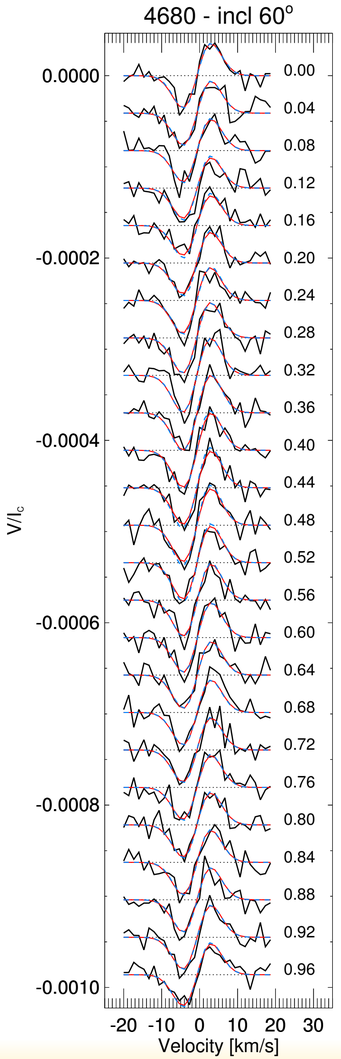
The Sun-as-a-star seen with ZDI

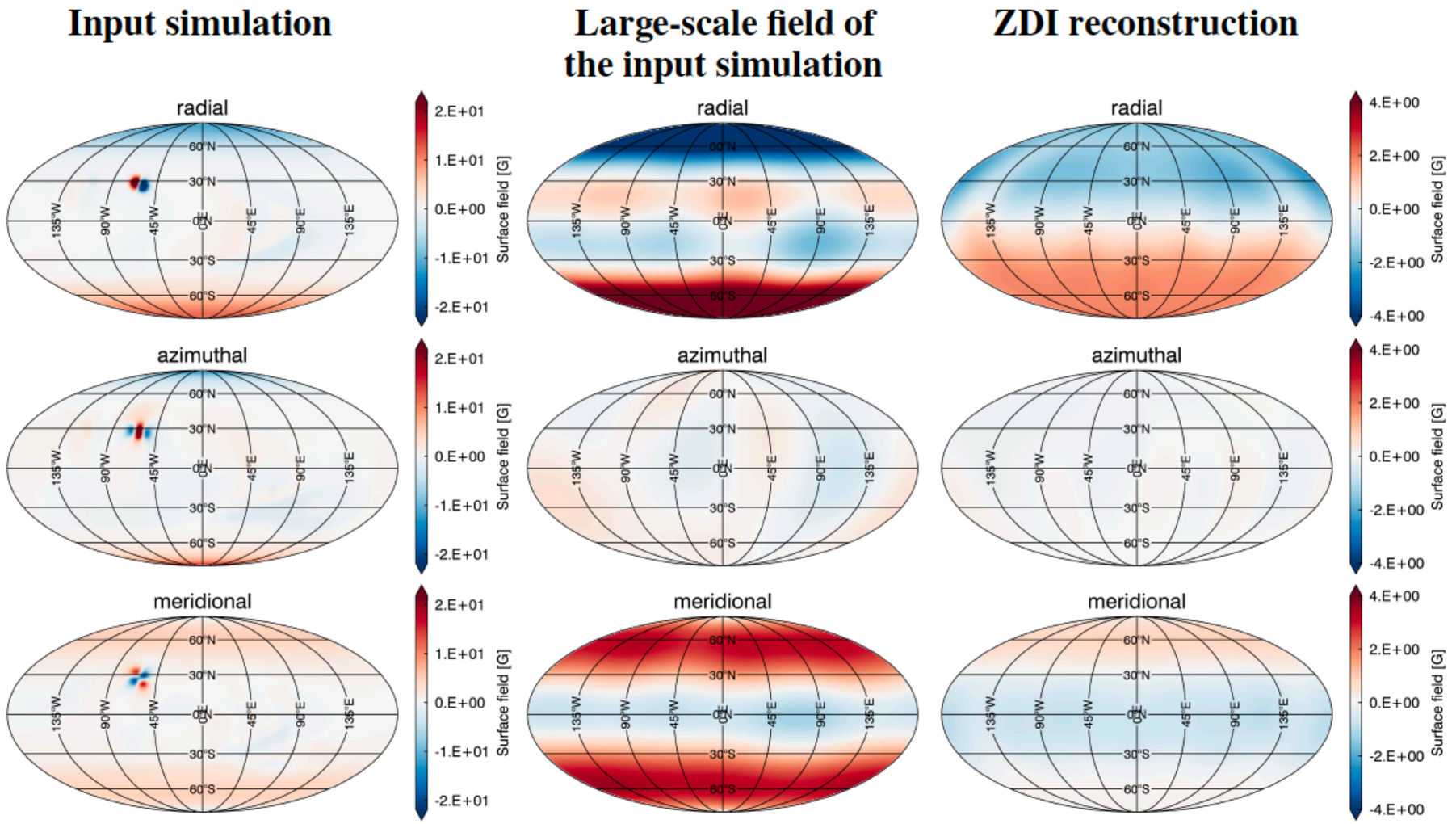




Lehmann et al. (2021)

ZDI is blind for small-scale sunspots

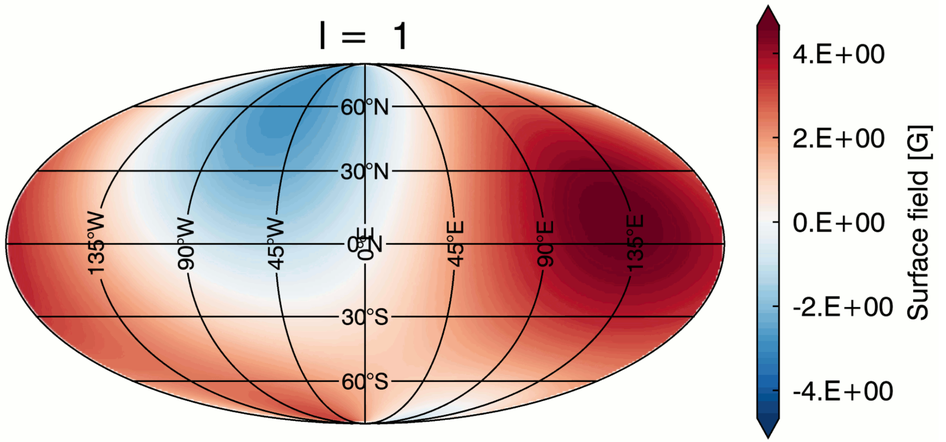


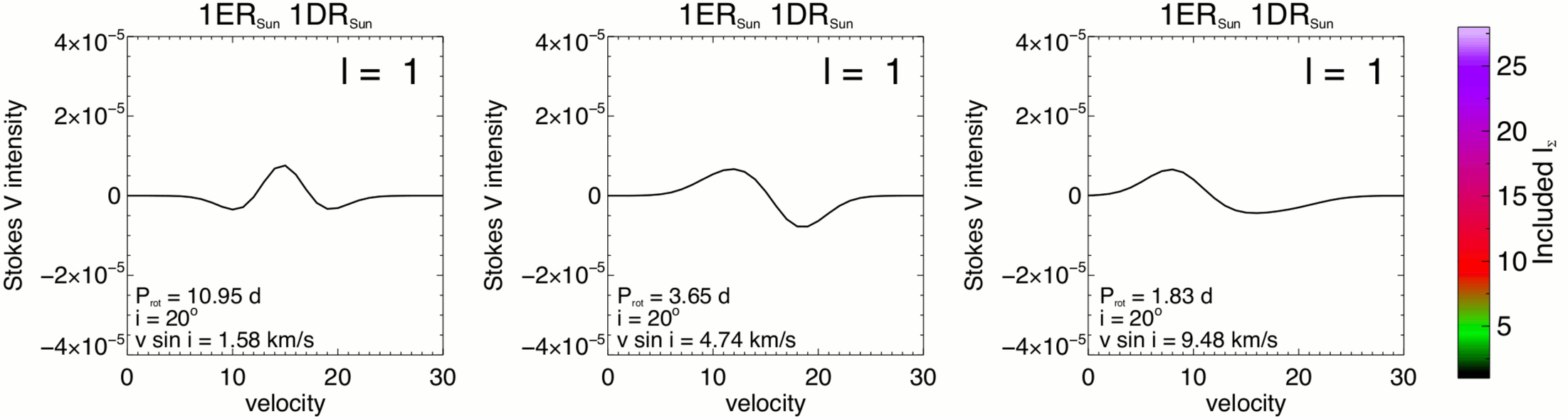


Lehmann et al. (2021)

Stokes V captures the large-scale field only (depending on $v_e \sin i$)

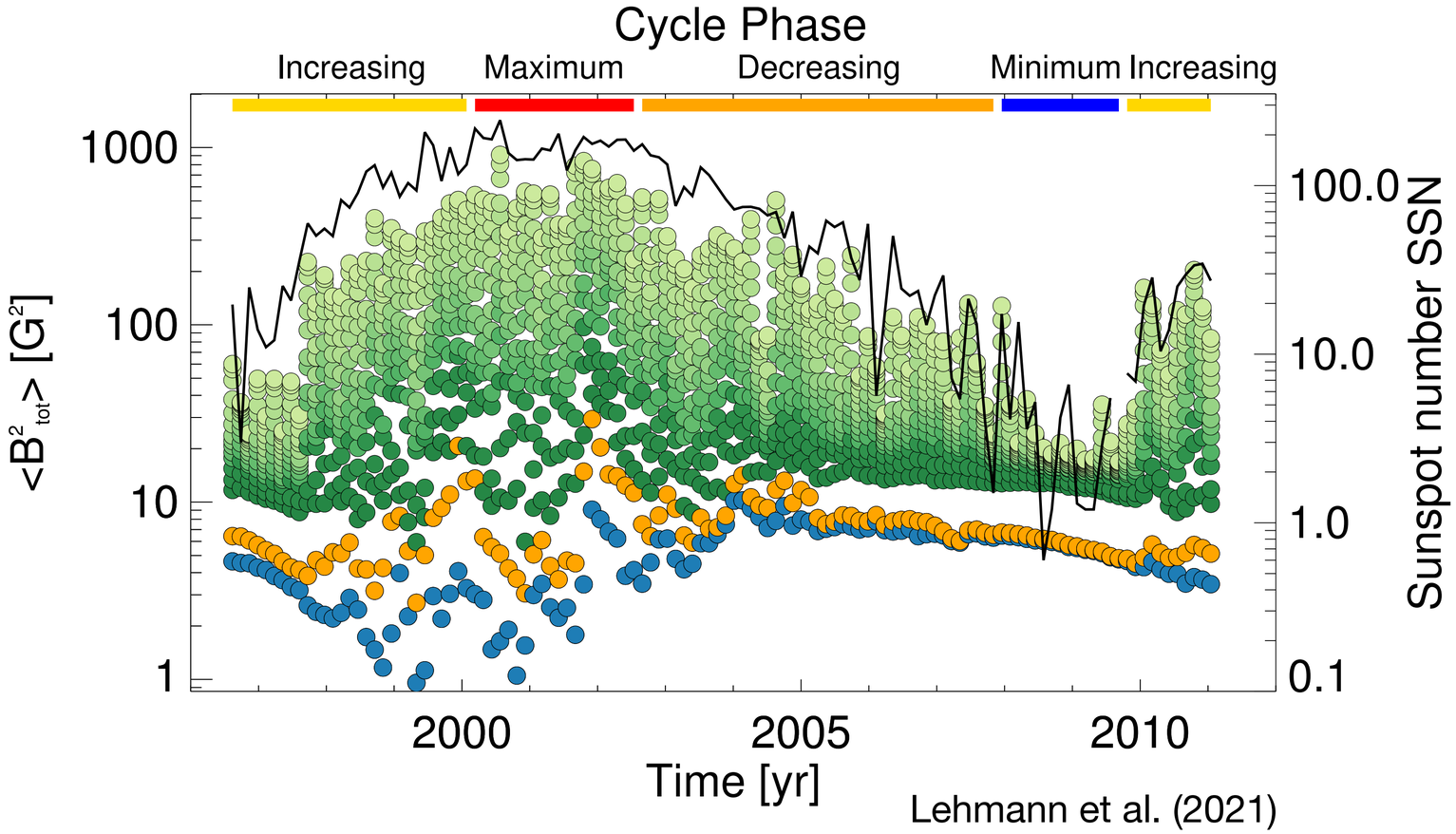
Solar-like star:





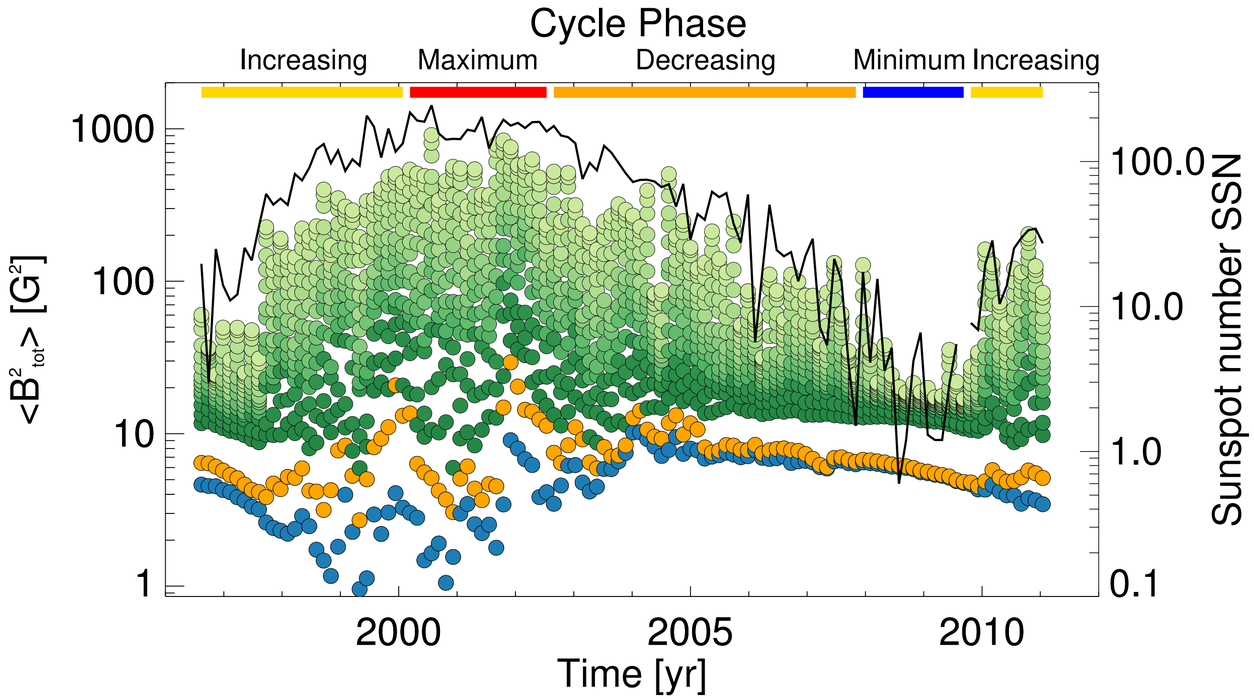
The simulations are in agreement with the solar observations

- The total field (small + large-scale field) follow the trend with sunspot number (SSN)
- Large-scale field show different behaviour:
  - Dipolar mode: anti-phase trend to SSN
  - Quadrupolar mode: in phase with SSN and recovers double-peak at maximum

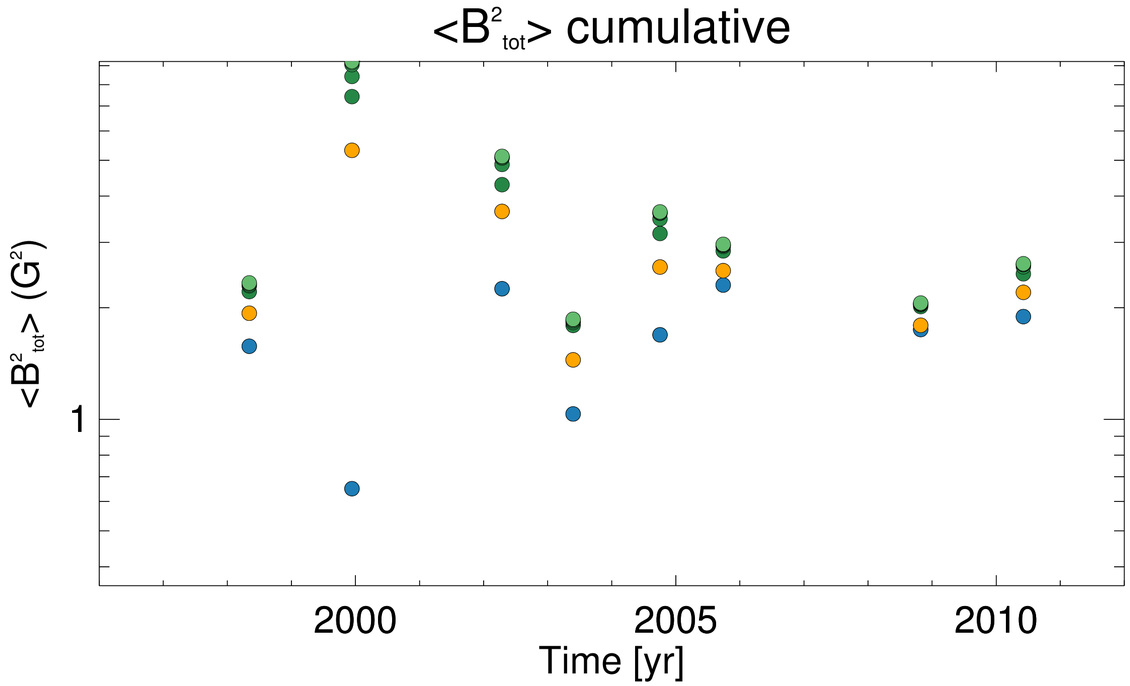


Lehmann et al. (2021)

The total magnetic field energy recovered by ZDI

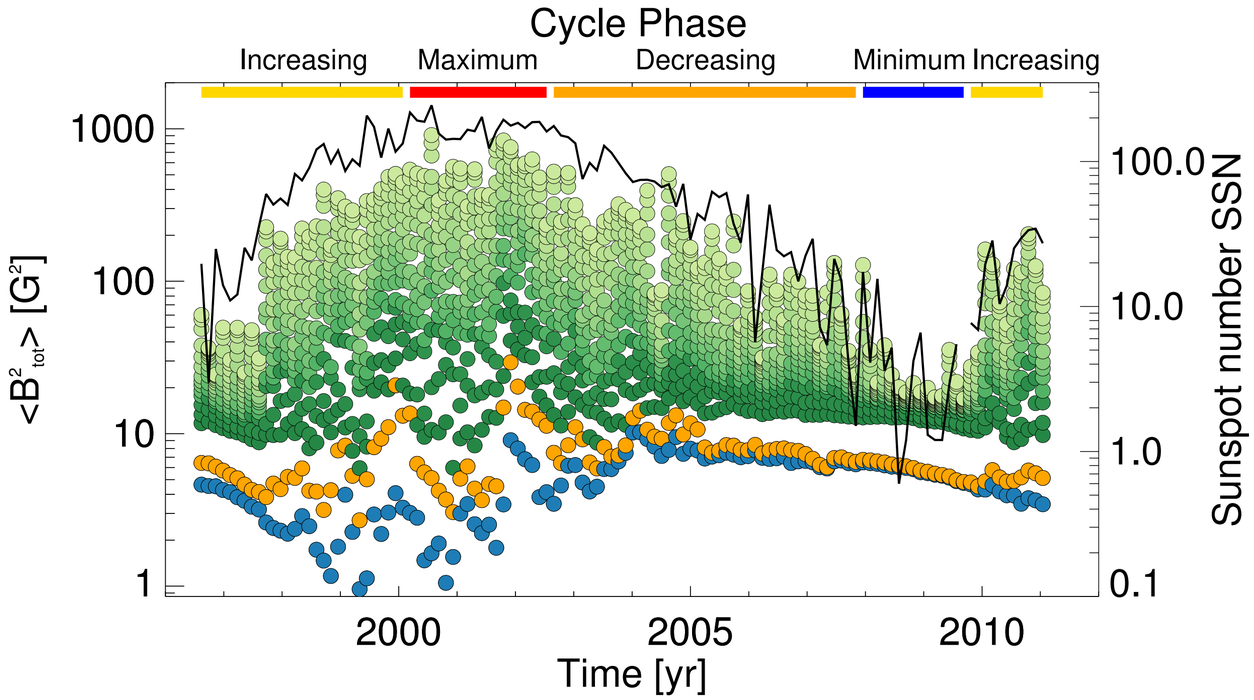


Input simulations

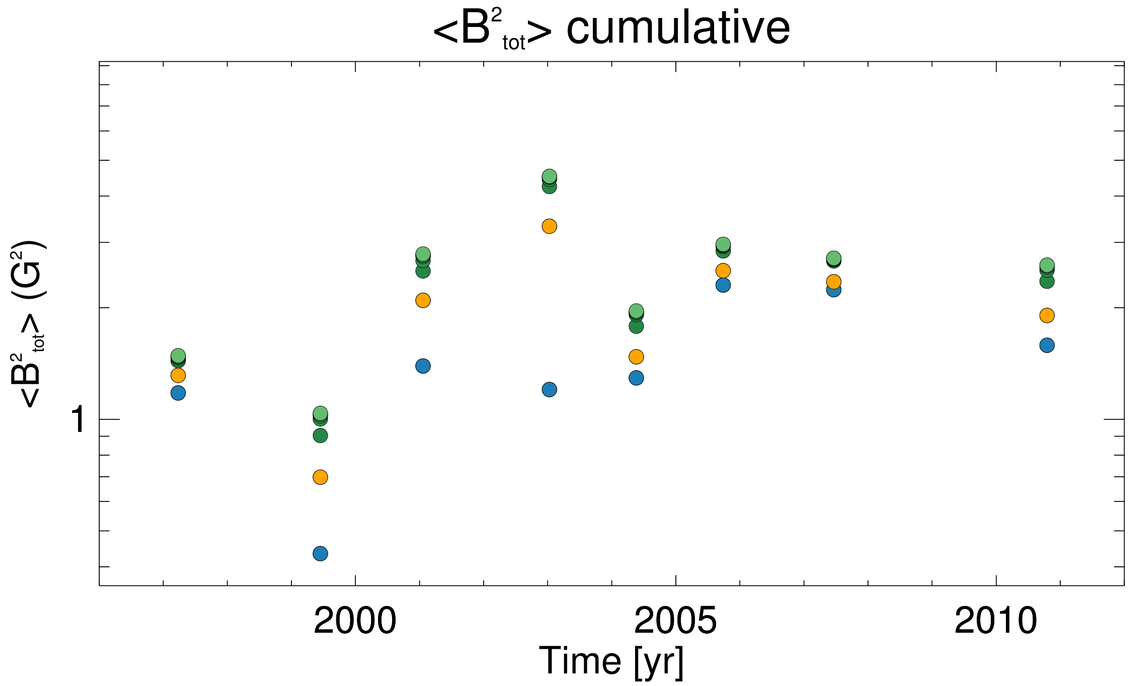


ZDI reconstructions

The total magnetic field energy recovered by ZDI



Input simulations



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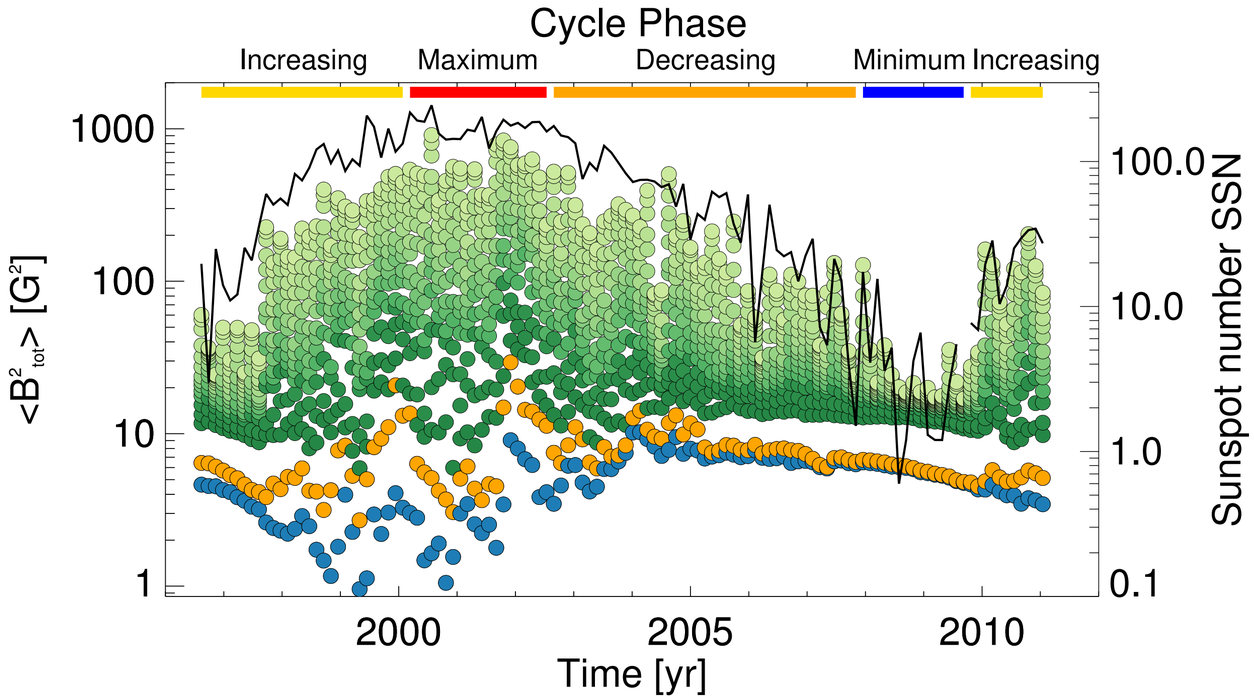

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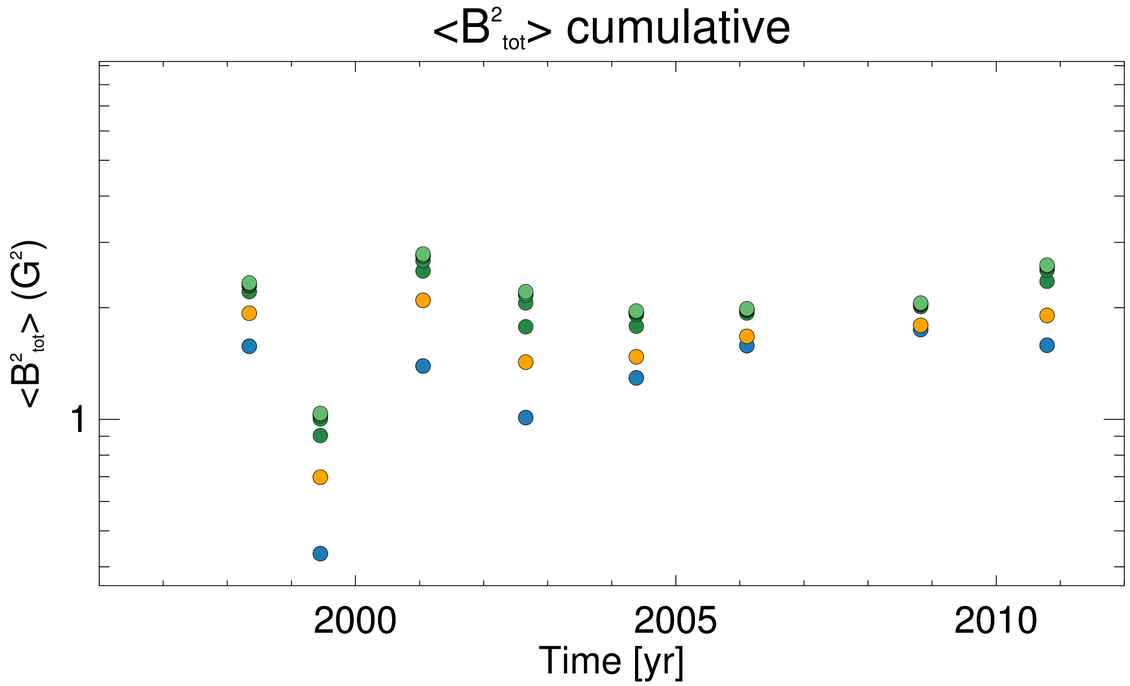
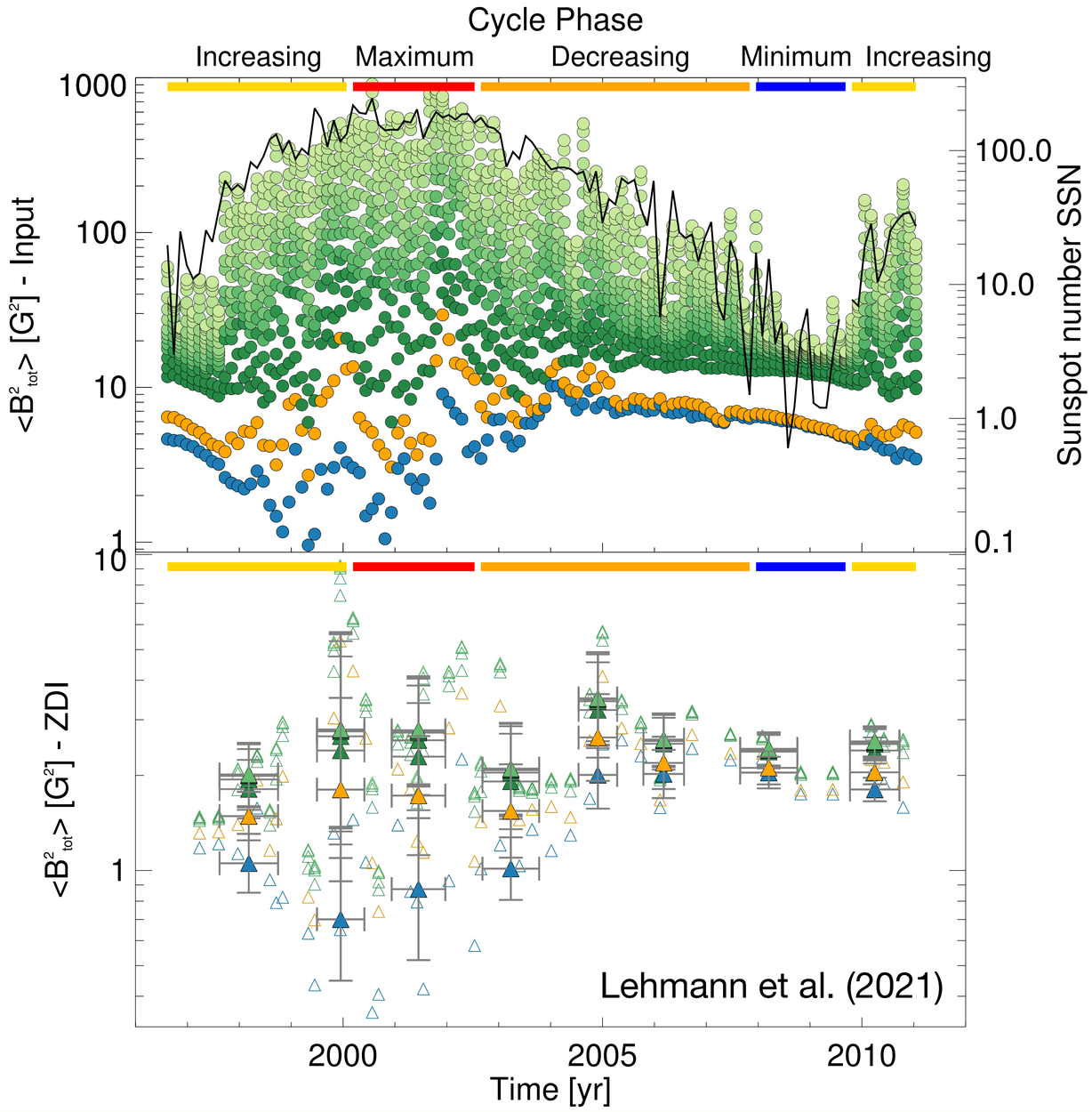


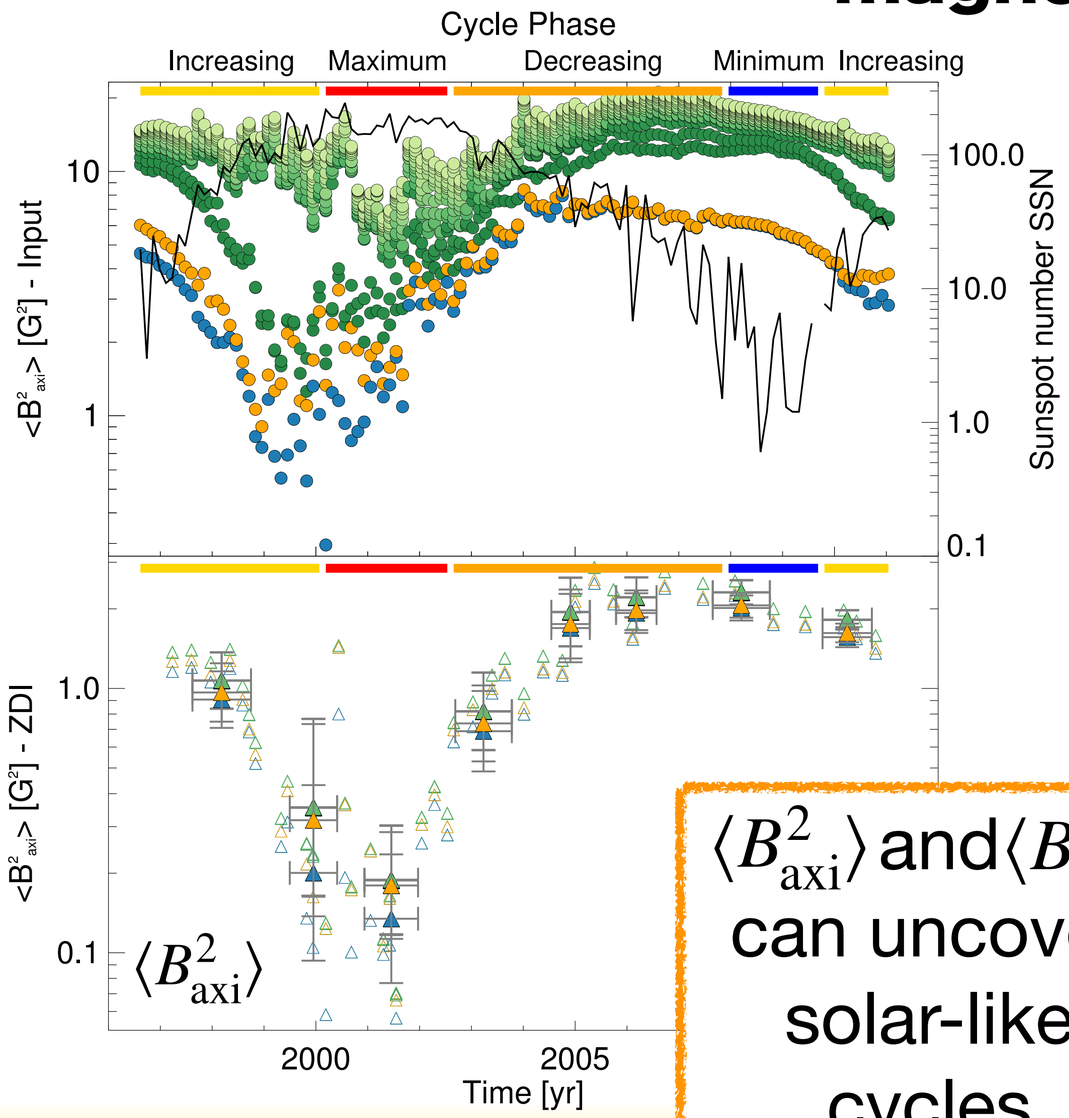
ZDI reconstructions

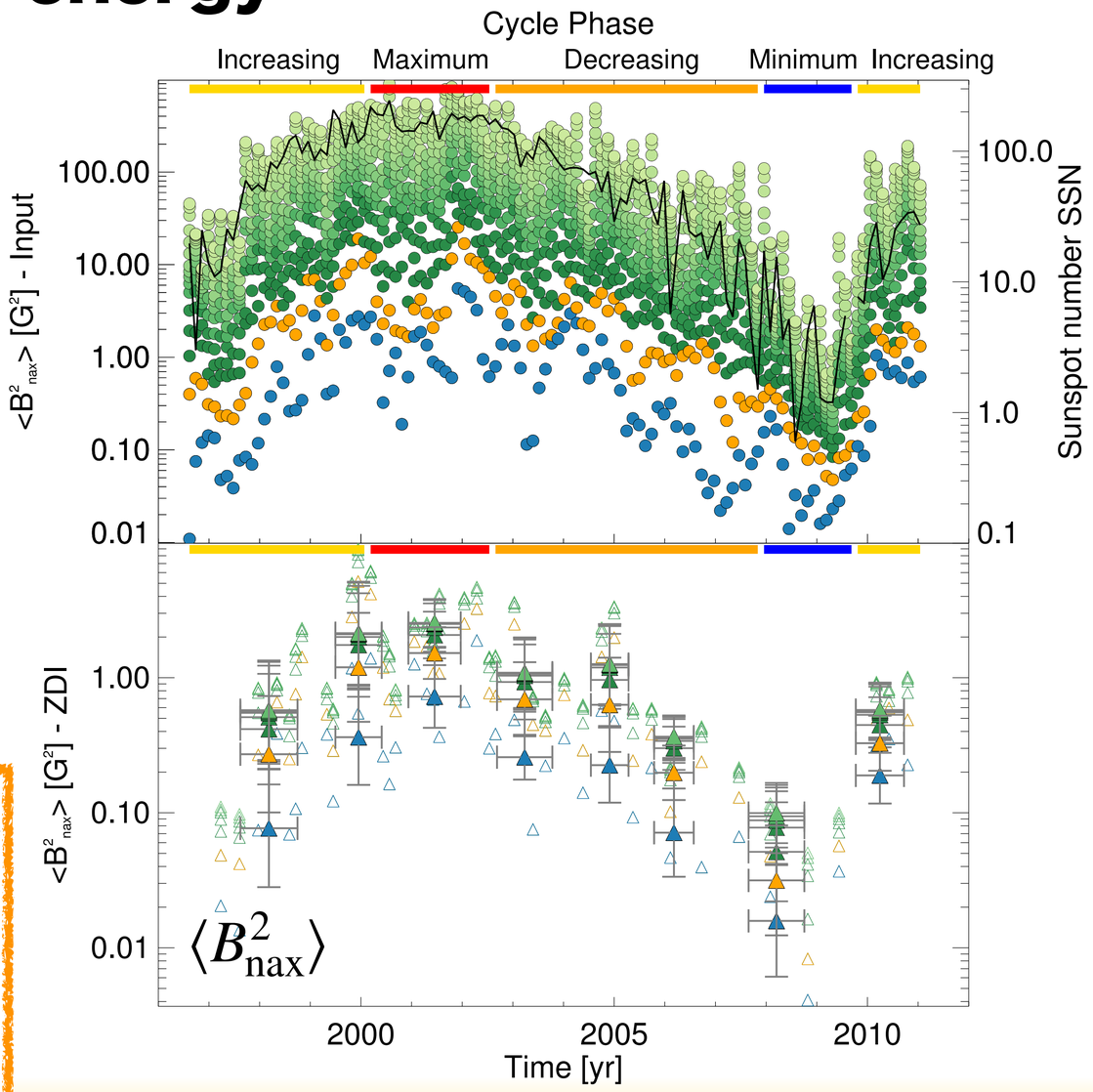
Total magnetic energy recovered by ZDI

- Statistical analysis:
  - Determining mean and standard derivation after drawing 100 times 8 maps of the 8 bins (equally spaced in time)
- $\langle B^2_{\rm tot} \rangle$ is not the best measure to track solar-like activity cycles !!!



The axisymmetric and non-axisymmetric magnetic energy



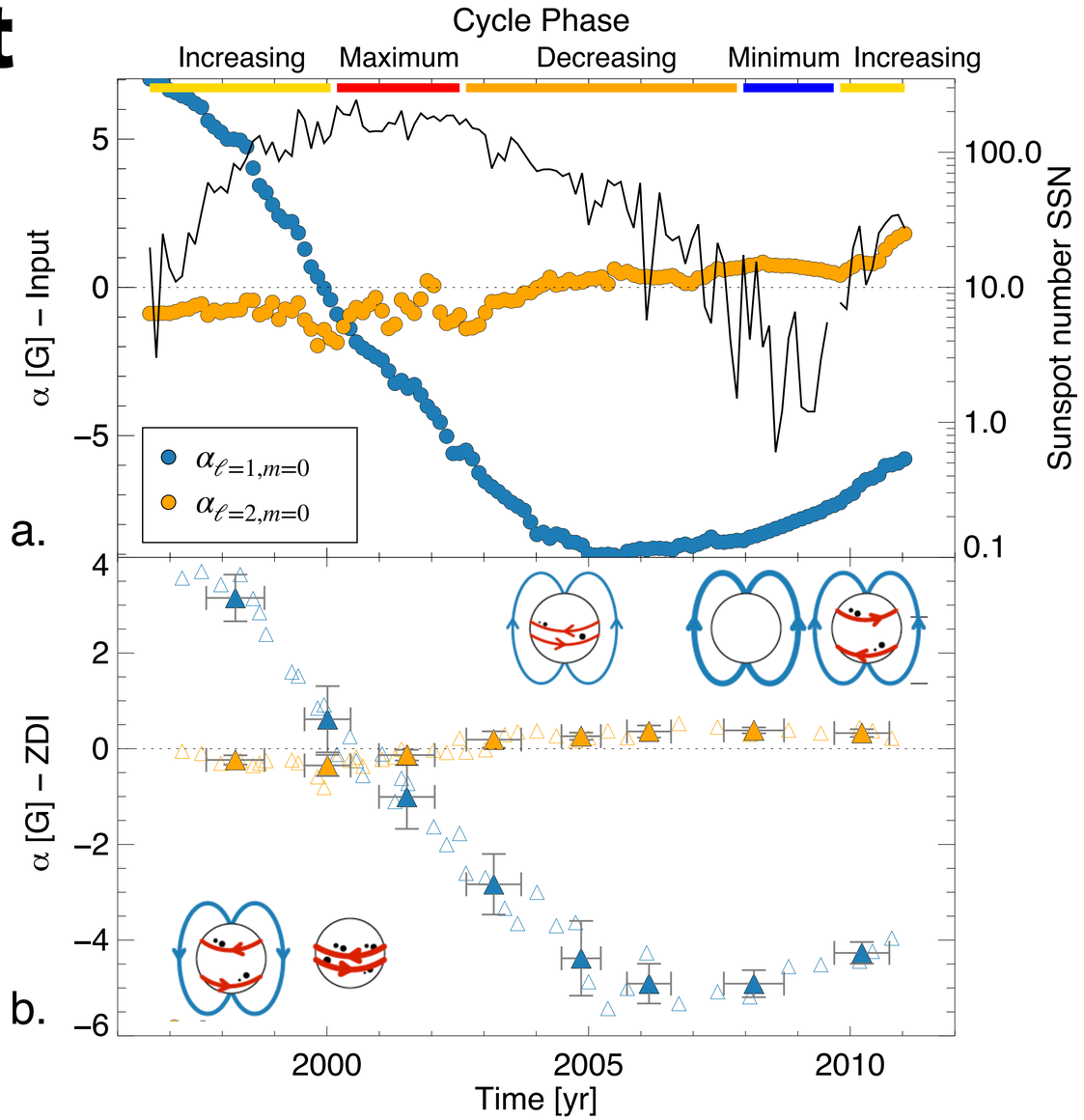


$\langle B^2_{\rm axi} \rangle$ and $\langle B^2_{\rm nax} \rangle$ can uncover solar-like cycles

Lehmann et al. (2021)

ZDI recovers important dynamo modes

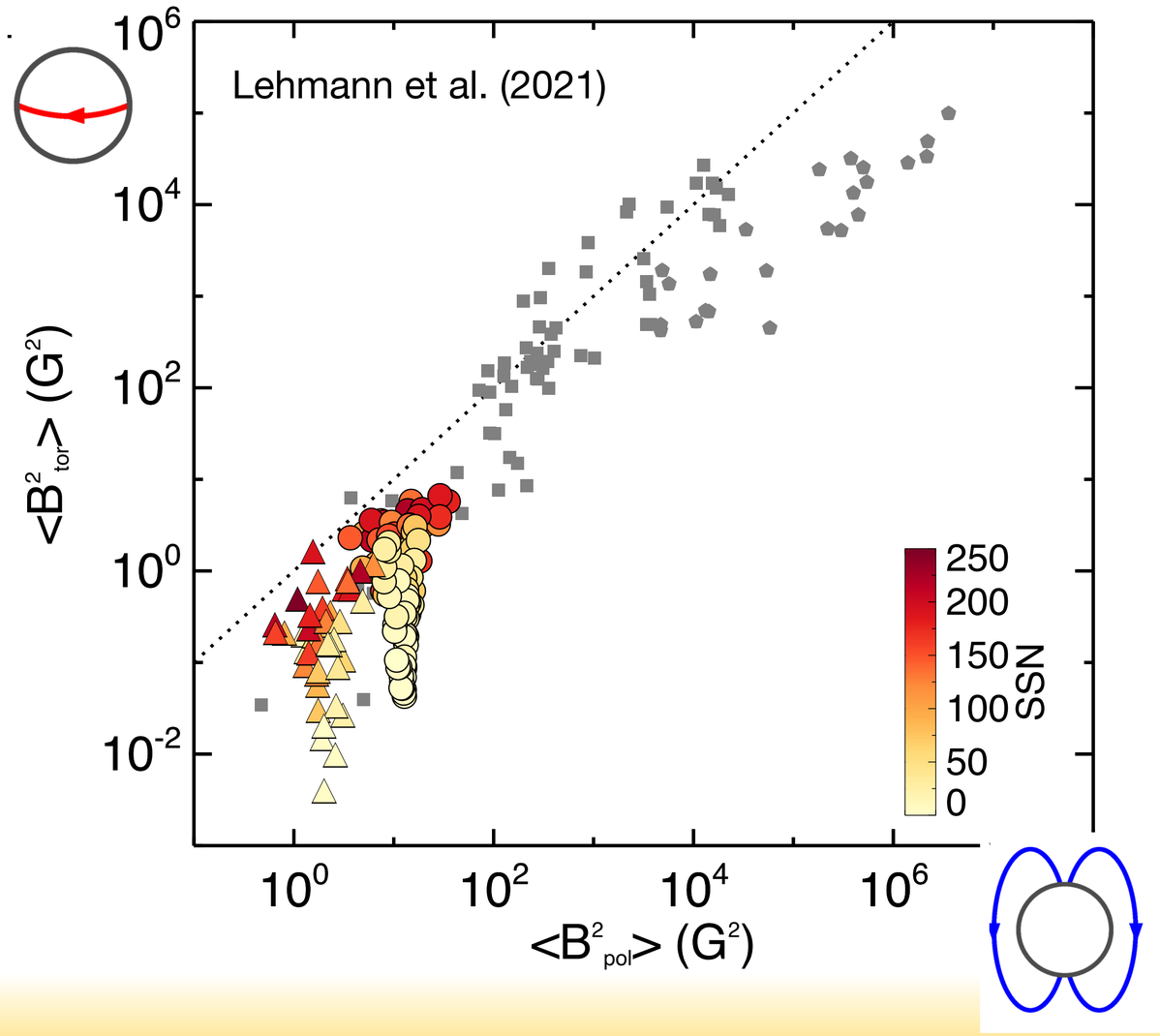
- ZDI recovers very well the radial poloidal axisymmetric dipole (blue)
  - important information about the internal dynamo can be recovered
- Also the trend of the radial poloidal quadrupolar mode is recovered but effected by larger variations



Lehmann et al. (2021)

The Sun shows specific trends with time and sun spot number (SSN) likely recoverable with ZDI

- For low sunspot numbers (SSN) the poloidal energy reaches a lower limit, while the toroidal energy decreases strongly
- Global dipolar field seems to define minimum poloidal field
- Toroidal energy increases with SSN and S-index (Ca II H&K)
  - Toroidal field likely to trace small-scale field emergences



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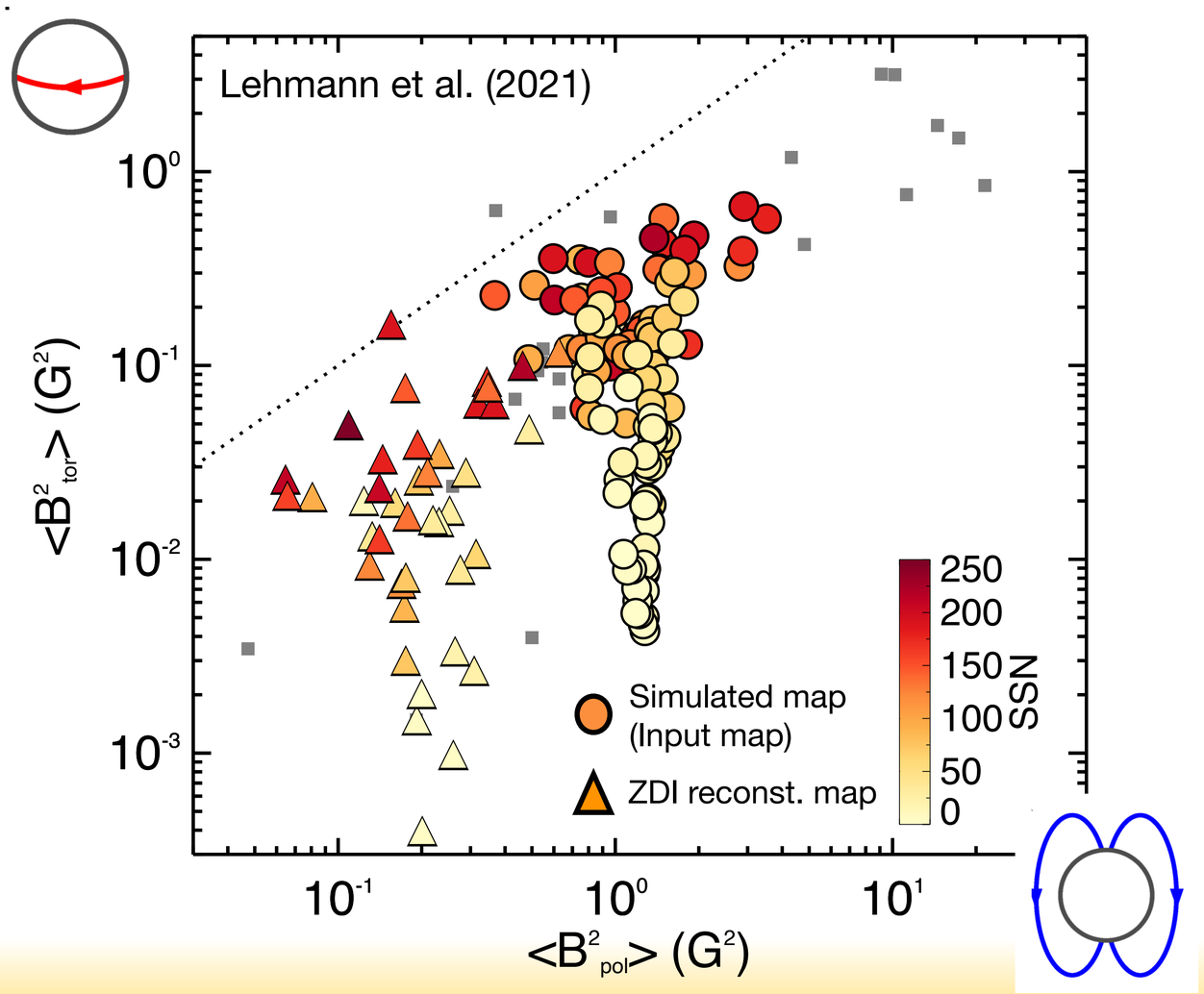

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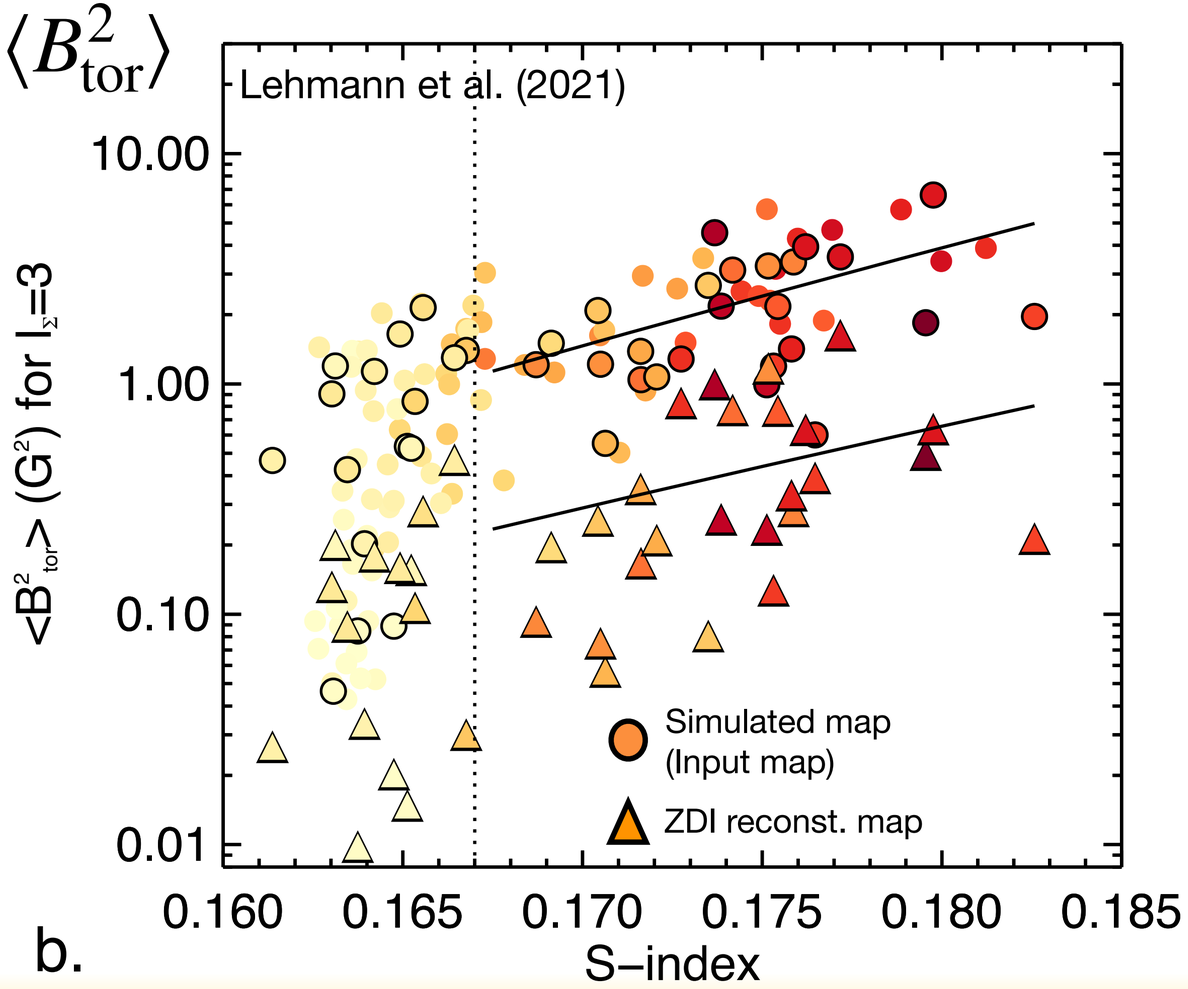
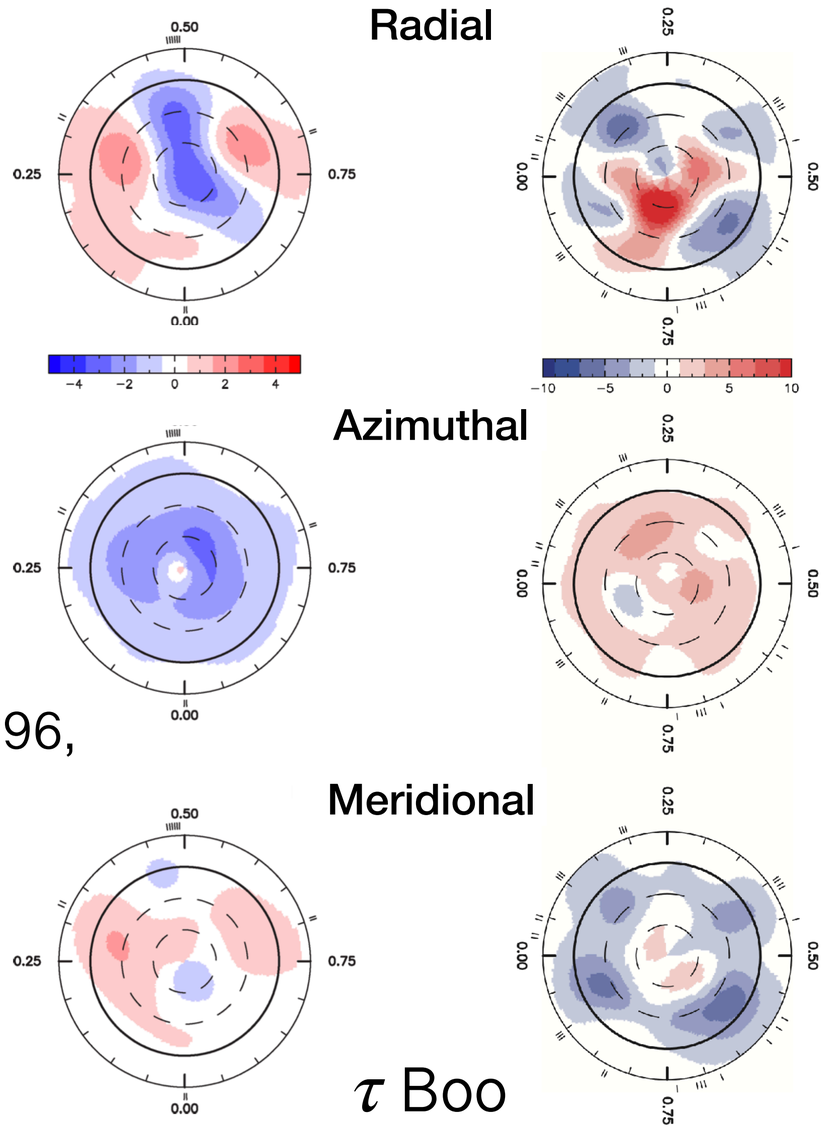


Stellar Cycles: first discoveries

- Polarity reversals (**cycles**) observed for ~15 stars (spectral class K5-F8):
  - τ **Boo** (Catala+07, Donati+08, Fares+09,13, Mengel+16, Jeffers+18)
  - HD190771 (Petit+09)
  - HD78366, HD190771, ξ Boo A (Morgenthaler+11)
  - ε **Eri** (Jeffers+14,17)
  - HD29615 (Waite+15, Hackman+16)
  - χ^1Ori (Rosén+16, Willamo+21)
  - **61 Cyg A** (Boro Saikia+16,18)
  - LQ Hya (Lehtinen+20)
  - κ **Ceti** (Boro Saikia+21)
  - BE Cet, HD29615, HD35296, V1358 Ori (Willamo+21)
  - **HD75332** (Brown+21)
- First stellar cycle: τ Boo (F8V, P_{rot}=3.1d, vsini=14.27) (Donati+08)



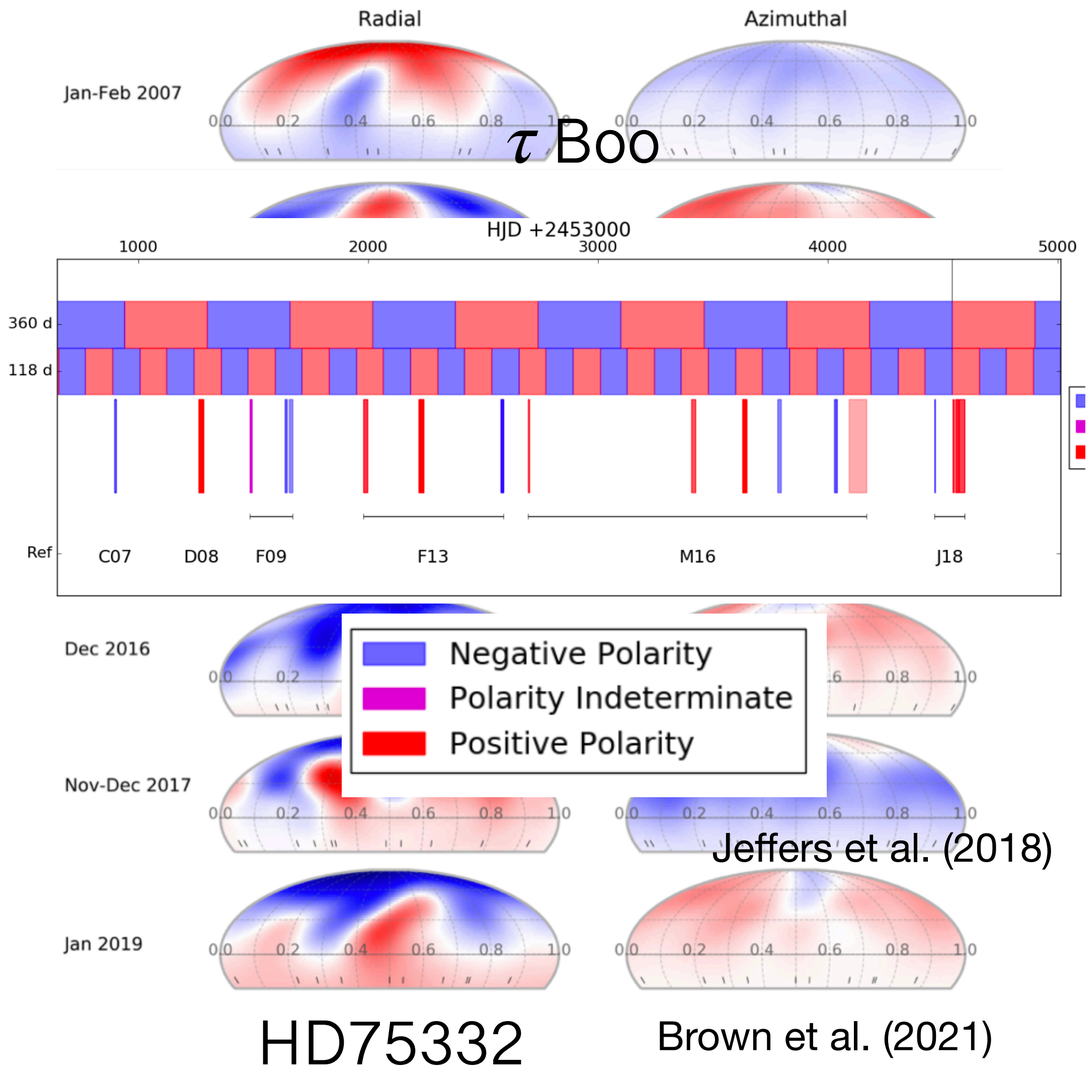
τ Boo

Catala et al. (2007) Donati et al. (2008)

Stellar Cycles: different appearances

- τ Boo (F8V, P_{rot}=3.1d, vsini=14.27km/s)
  - 240d magnetic cycle in phase with chromospheric cycle (e.g. Catala+07, Donati+08, Fares+09,13, Mengel+16, Jeffers+18)
- HD75332 (F7V, P_{rot}=3.6d, vsini=9.0km/s, no hot Jupiter)
  - Shows 1.06yr magnetic cycle in phase with chromospheric (Brown+20)
    - **Thiner convection zone**

      => shorter magnetic cycles
- HN Peg (G0V, P_{rot}=4.6d, vsini=9.0km/s, 200Myr)
  - No radial field reversal but azimuthal band vanishes and re-appears (Boro Saikia+15)
    - **Magnetic cycle depend on stellar age (?)**



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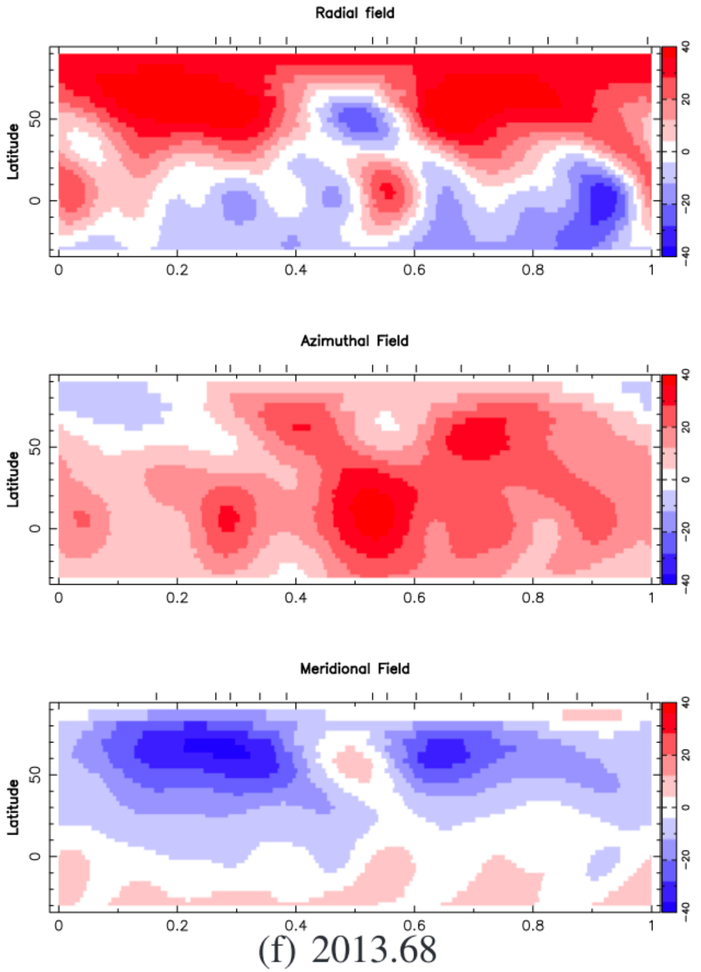
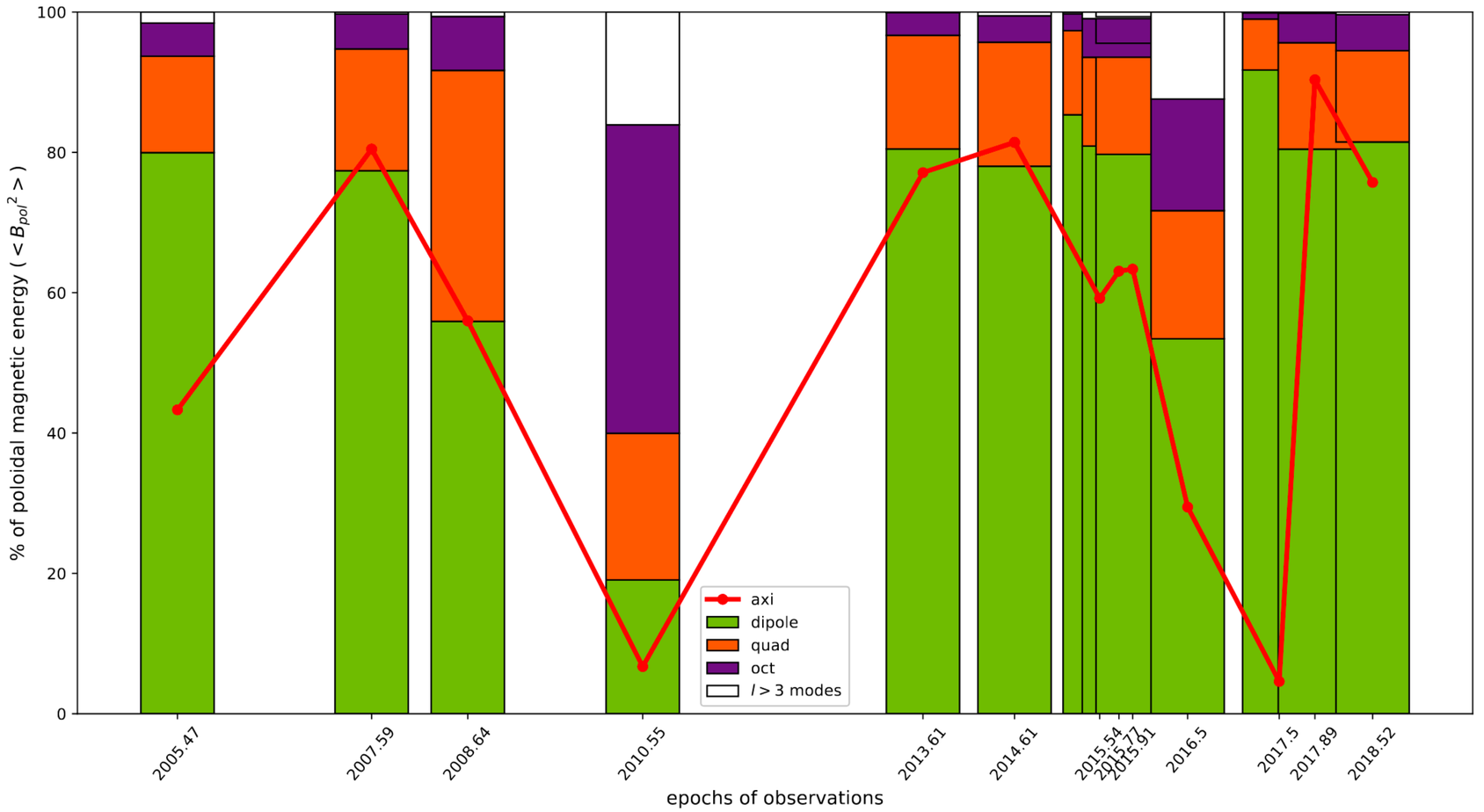


HN Peg Boro Saikia et al. (2015)

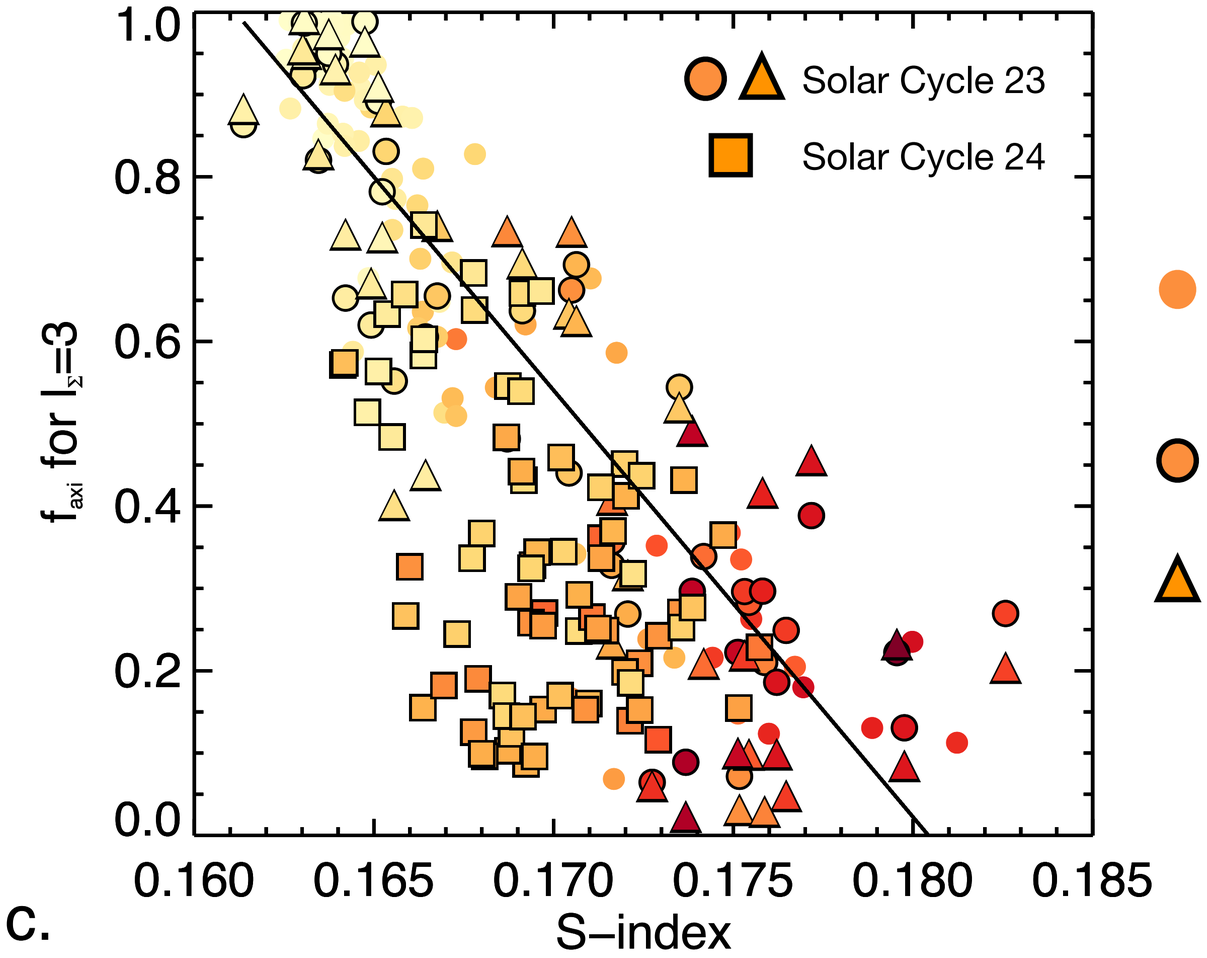
The most solar-like magnetic cycle: 61 Cyg A

- 61 Cyg A (K5V, P_{rot}=34.2d, vsini=0.92km/s) (Boro Saikia+16,18)
  - Strongest dipolar field and simplest large-scale field at activity minimum
  - Dipole axis wandered from high latitude at activity minimum to mid latitude at activity maximum



Boro Saikia et al. (2018)

61 Cyg A f_{axi} shows clear linear decrease similar to the Sun: its slope can indicate the cycle strength



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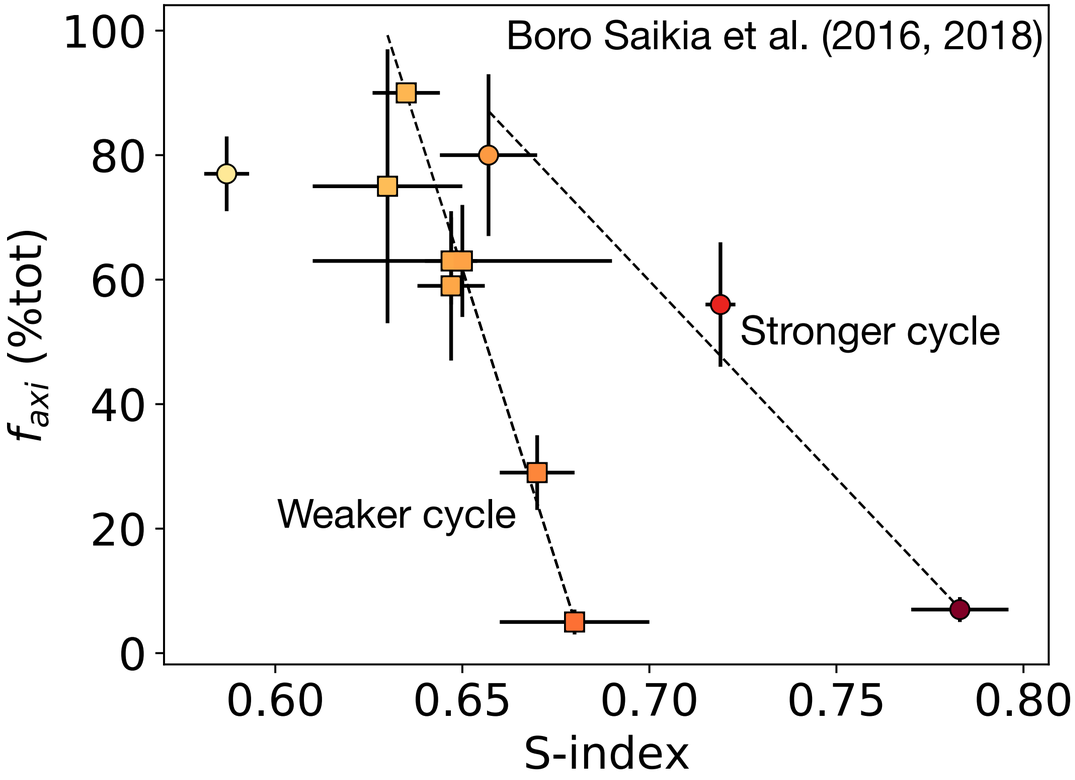
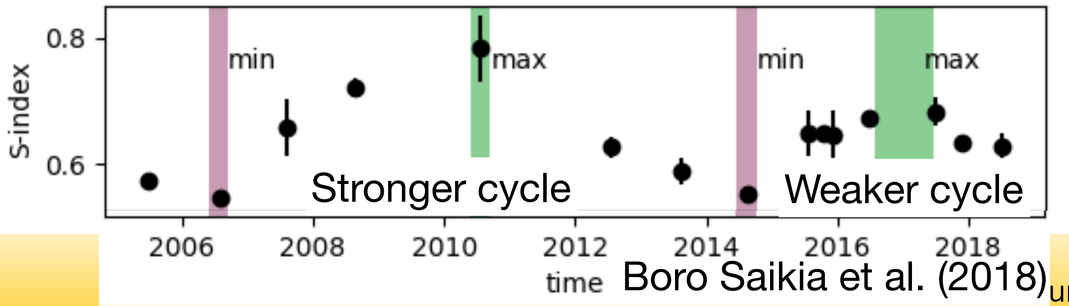
Lehmann et al. (2021)



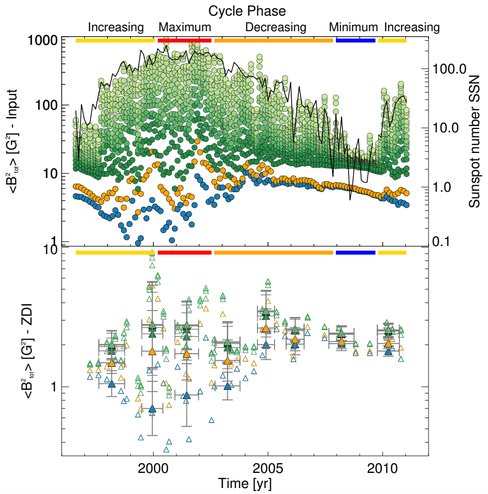


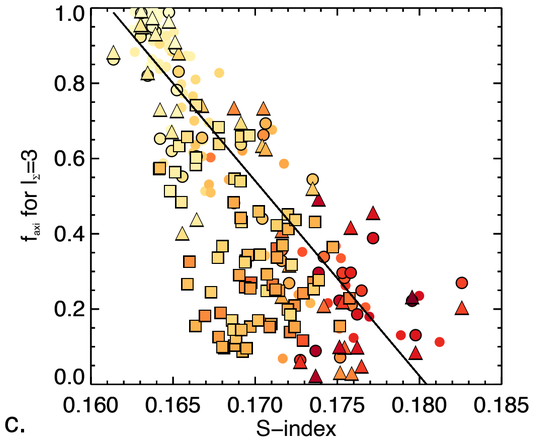
Boro Saikia et al. (2018)

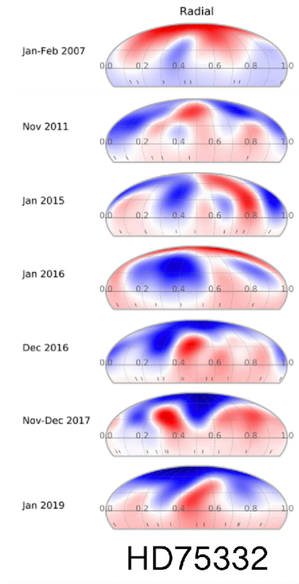
Summary

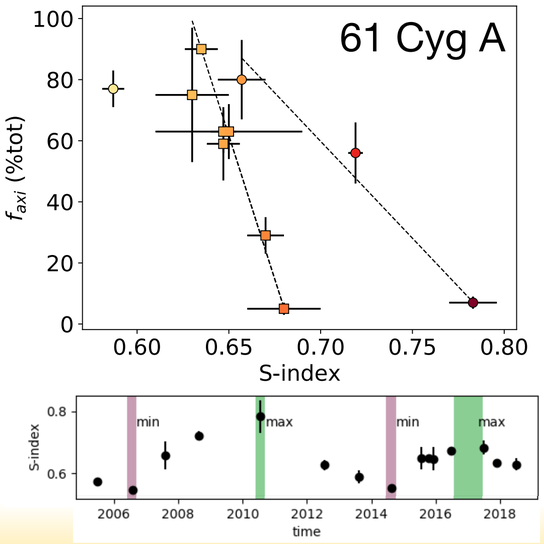
To observe solar-like cycles:

-  $\langle B^2_{\rm tot}\rangle$ or $\langle B_{\ell_\Sigma=3}\rangle$
-  $f_{\rm axi}$, $\langle B^2_{\rm axi}\rangle$ or $\langle B^2_{\rm nax}\rangle$









Is the solar cycle typical?

- Need more (and longer) spectropolarimetric surveys in the optical to answer !!!

So far we found:

- ~15 stars with polarity reversals
- τ Boo, HD75332 and 61 Cyg A show magnetic cycles in phase with chromospheric cycles
  - Thiner convection zone => shorter cycles
  - Dependency of magnetic cycles on the stellar age (?)

Thank you!

Lisa T. Lehmann

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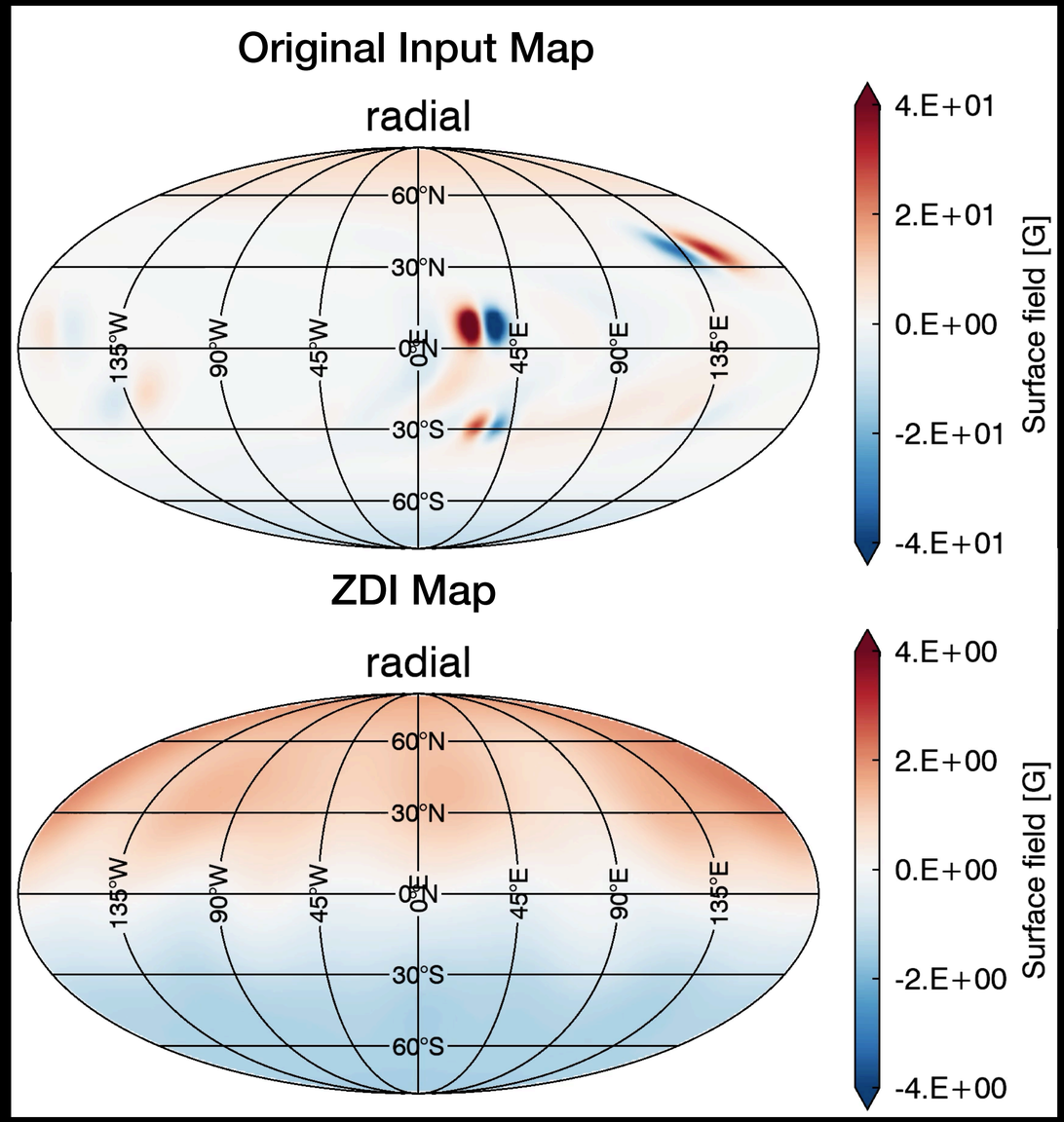
Main paper of the presented work

- Lehmann et al., 2021, MNRAS, 500, 1243
  or on http://arxiv.org/abs/2010.10214



Lehmann et al. (2021)

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