SPACE CLIMATE 7 : THE FUTURE OF SOLAR ACTIVITY
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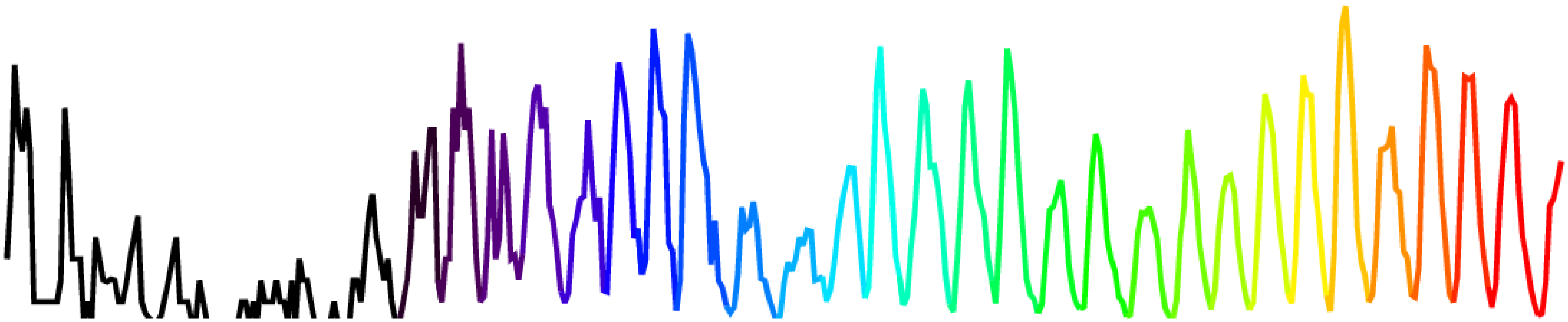
Predictability of the Solar Cycle Over One Cycle

Jie Jiang
(jiejiang@nao.cas.cn)
Beihang University, China



Key points of my talk

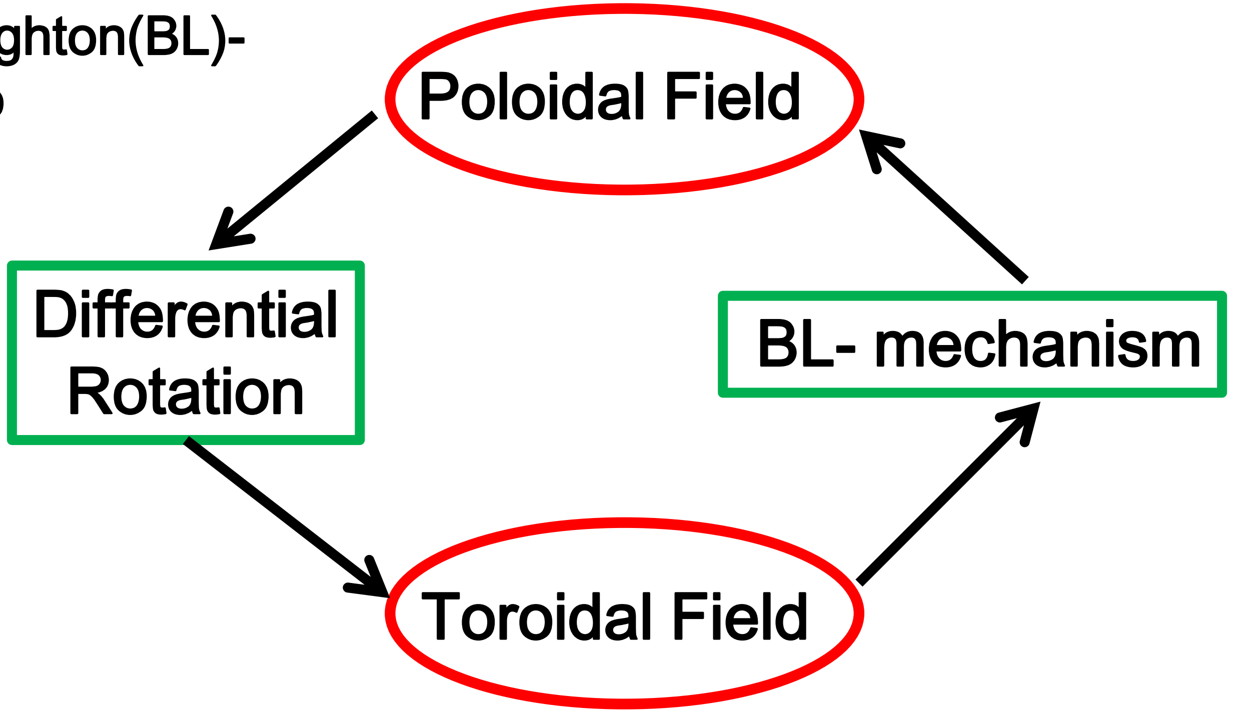
- The randomness in sunspot emergence coupled with nonlinearities determine cycle predictability.

- We proposed a method to incorporate randomness and nonlinearities into a model-based prediction for quantifying solar cycle predictability.

- Some δ-spots have significant effects on both space weather and space climate. They should be treated in surface flux transport models realistically.

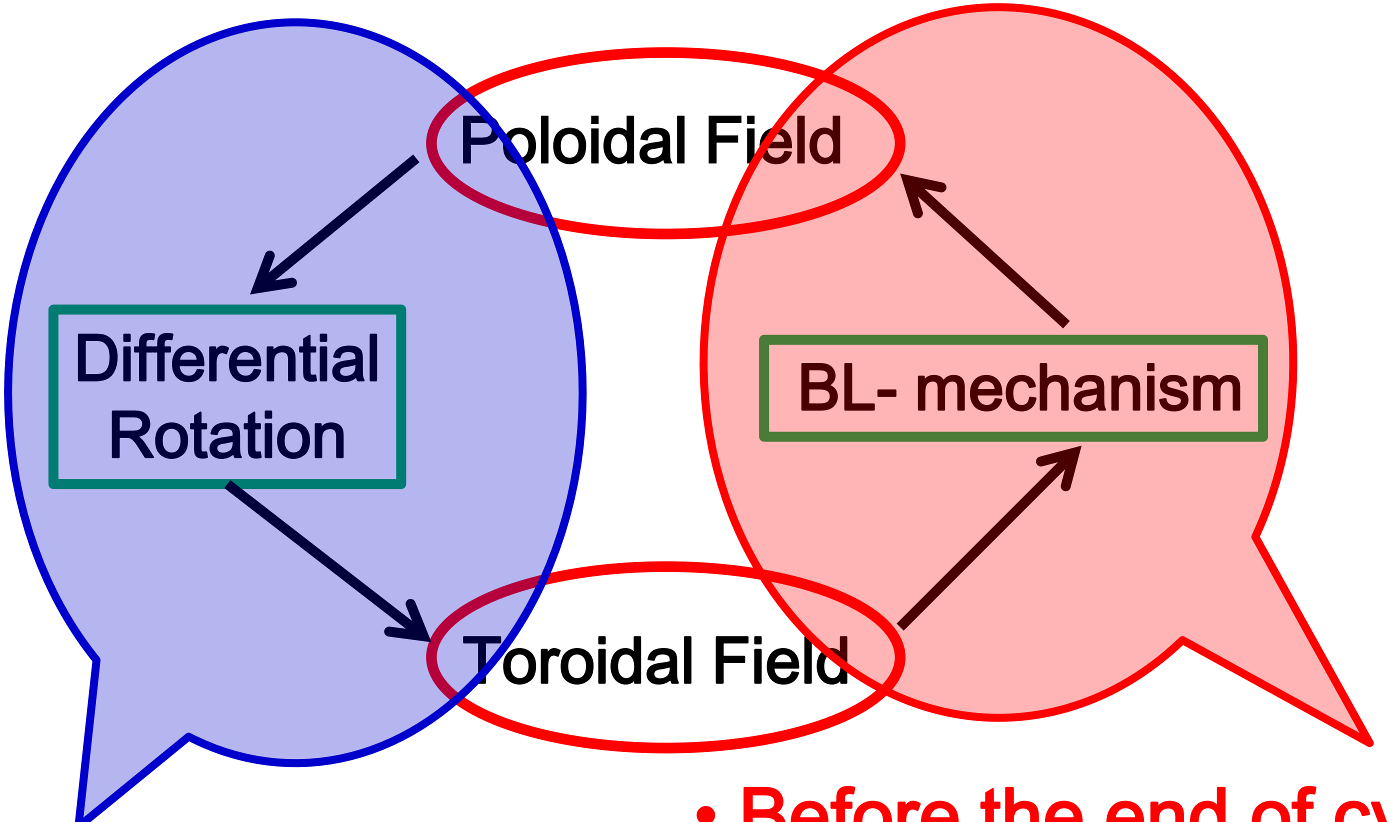
Principle of model-based predictions

Babcock-Leighton(BL)-
type dynamo



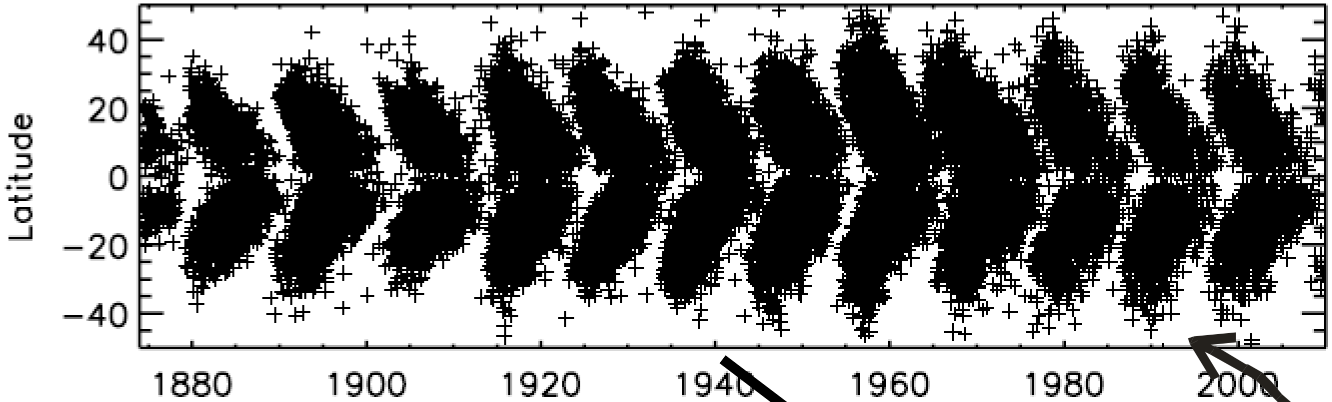
Babcock-Leighton (BL)- mechanism vs prediction:
Poloidal field is accessible to direct observation & time delay with the toroidal field

Sketch of model-based predictions



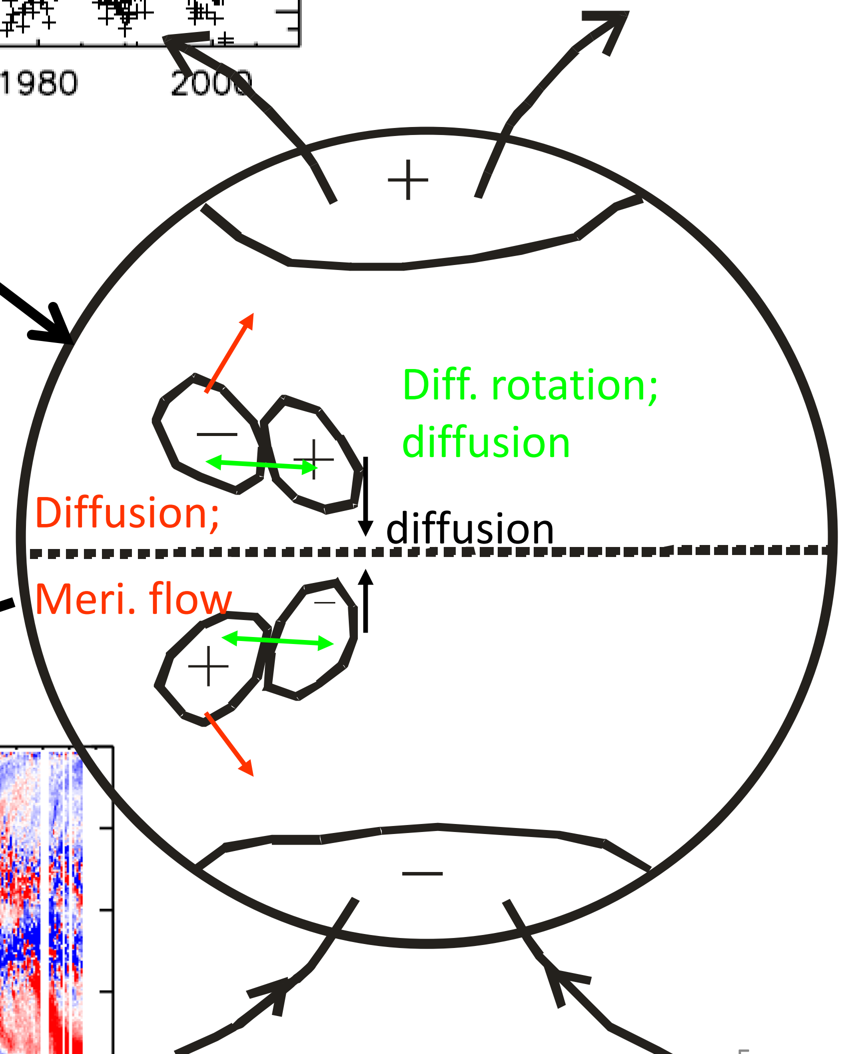
- Around the end of cy. 23
- Flux transport dynamo-based prediction
- Easy part –linear

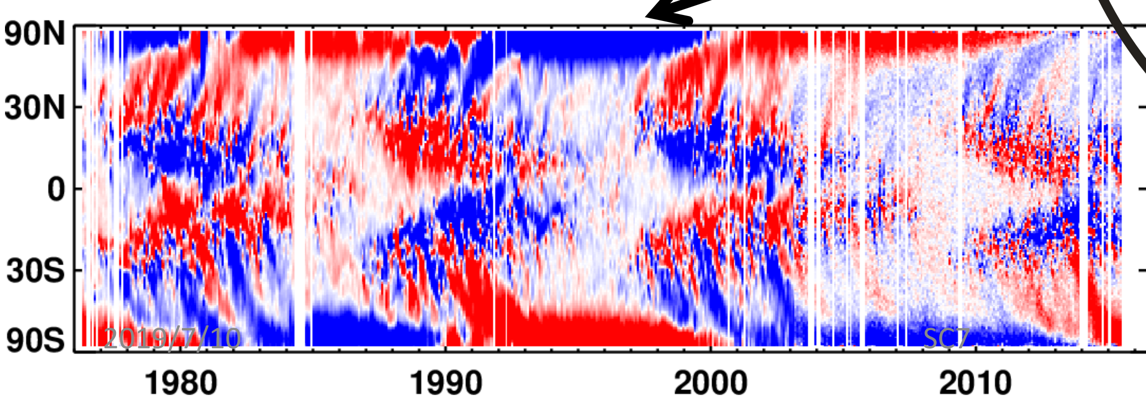
- Before the end of cy.24
- Surface flux transport model-based prediction
- Hard part –randomness & nonlinearities



The polar field is the relevant poloidal field

A powerful tool to connect the sunspot emergence to the polar field: Surface Flux Transport (SFT) Model





Misunderstanding of the polar field generation

Dipole moment of each sunspot group
in Bipolar Magnetic Region (BMR):

$$D_{\mathrm{BMR}} \propto d\,F \sin\theta \sin\alpha$$

tilt angle α, total flux F (area A), located at co-latitude θ, distance between the opposite polarities *d*

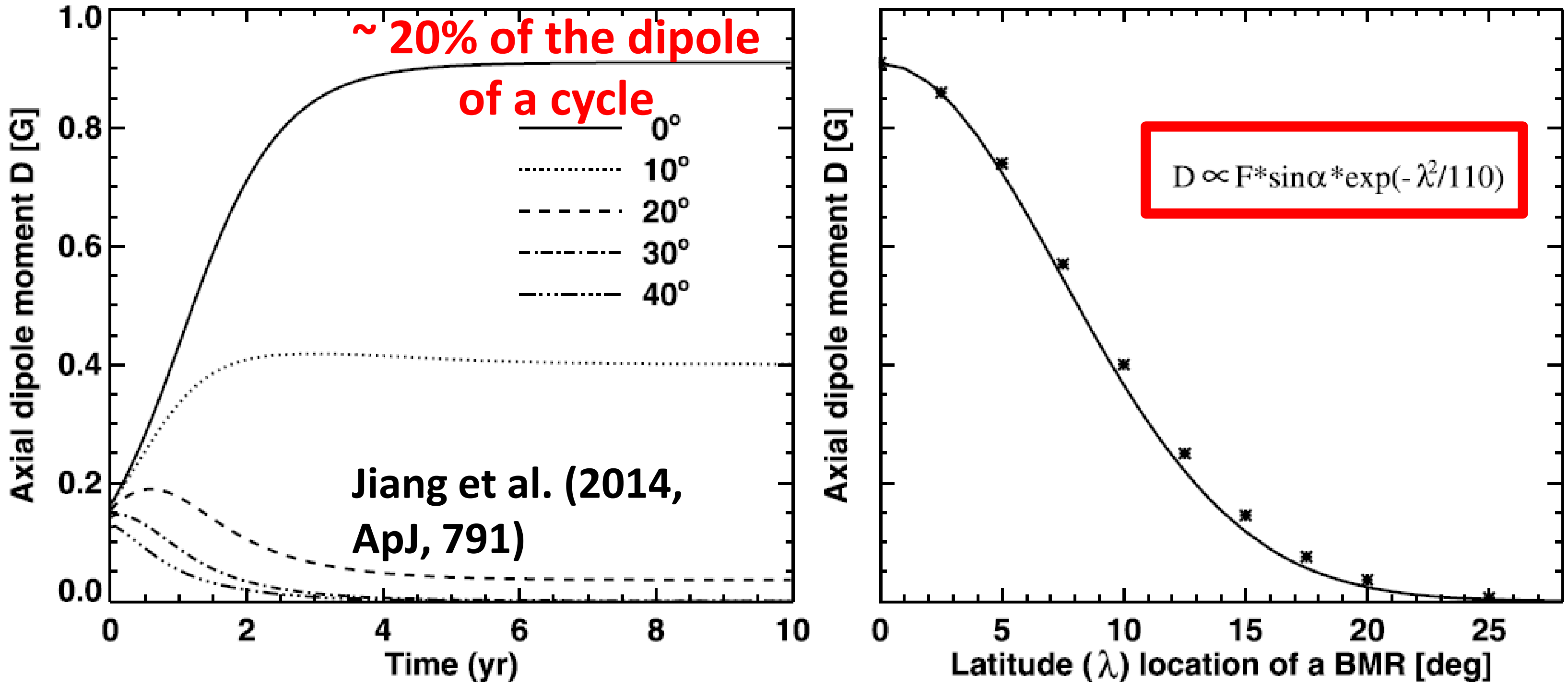
For different cycles:

- All spots obey the same Joy's law (α) and latitudinal distribution (θ).
- The only difference is the total area/flux.

→ Dipole moment (DM) at cycle minimum is proportional to the total sunspot emergence over the preceding cycle

Actually,

- For different latitudinal emergence λ, flux transport processes over the surface cause different final DMs even BMRs have the same initial DMs.



Latitudinal dependence of the DM evolution

The polar field generation is strongly affected by:

- **Nonlinear mechanisms:**
  - mean latitude of ARs:

    Stronger cycles have higher mean latitudes (Jiang et al., 2011)
  - mean tilt angle of ARs:

    Stronger cycles have weaker mean tilt angles (Dasi-Espuig et al., 2010)
  - Initial condition:

    Stronger cycles have stronger initial polar field

The polar field generation is strongly affected by:

- Stochastic mechanisms in properties of AR emergence
  - Scatter in tilt angle of ARs

    For δ-spots, the initial tilt angle α even makes no sense to the final contrition to DM (Jiang et al, 2019)

  - Scatter in latitudinal location of ARs
  - Scatter in number of ARs

- Jiang, Cameron & Schüssler (2014):

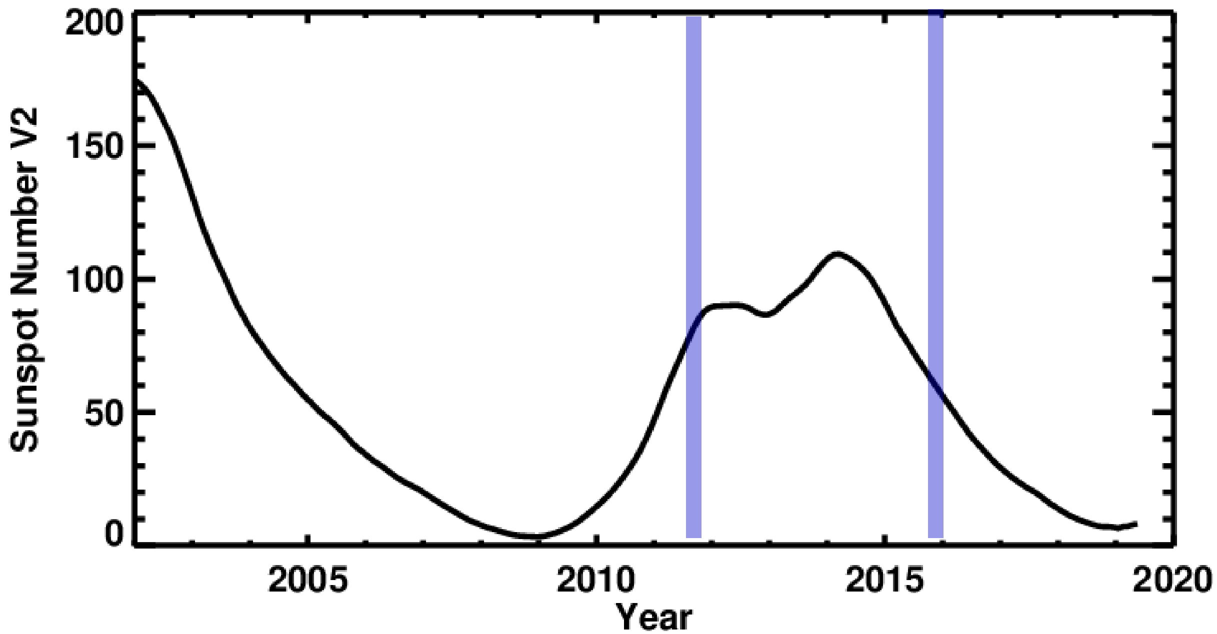
• quantified effects of the tilt scatter on the polar field (might be for the first time)

• pointed out that large ARs with high tilts emerging near the equator dominate the polar field generation – exceptional /rogue ARs

- Jiang, Cameron & Schüssler (2015):

• A number of ARs, highly tilt with “wrong” orientation and near equator emerged in cycle 23 caused the deep cycle 23 minimum.

• The random emergence of such ARs puts constraints on the scope of the solar cycle prediction.



But people want to know future cycles as early as possible ……

This motivated people to use the SFTM to predict polar field at cycle minimum

- To predict the polar field before cycle minimum, randomness and nonlinearities should be realistically incorporated into SFTMs to get the range of the polar field. Otherwise, the predicted result might be misleading.
- Furthermore, random mechanisms coupled with nonlinearities determine cycle predictability.

➡ Lead to the conception and new era:

Predictability of the Solar Cycle Over One Cycle

Jiang et al.(2018, ApJ)

Predictability of the Solar Cycle Over One Cycle

Steps:

Jiang et al.(2018, ApJ)

➢ The prediction of an ongoing cycle
- sunspot emergence using empirical relations.
- the large-scale field evolution over the solar surface using the SFT model and the sunspot emergence

↓

➢ Range of the polar field at cycle minimum

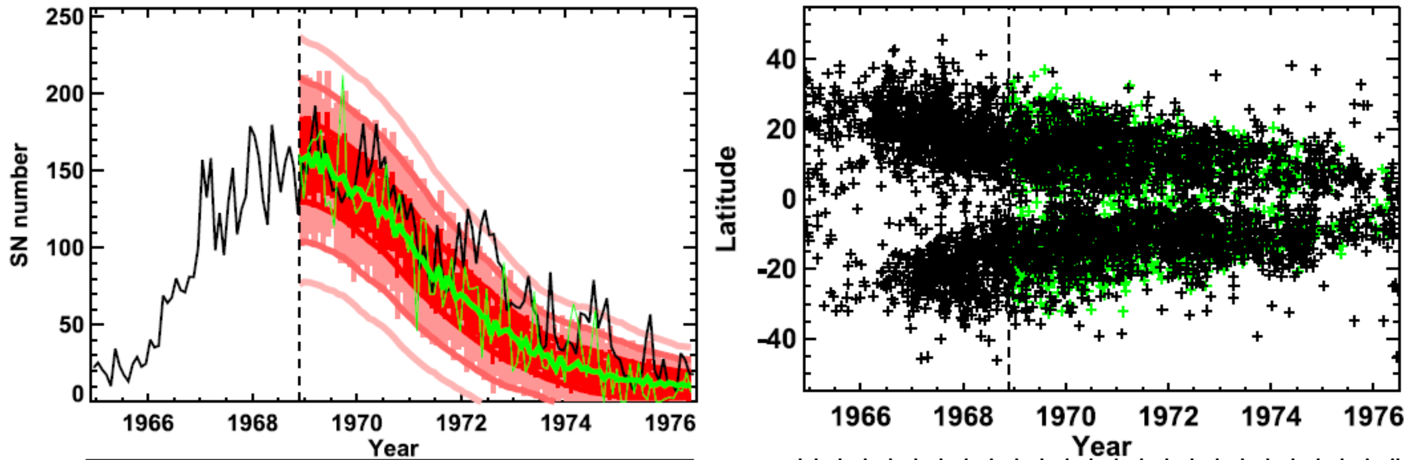
+ Carefully calibrated Linear relation with subsequent cycle

↓

➢ Prediction of the subsequent cycle (range of the amplitude and profile)

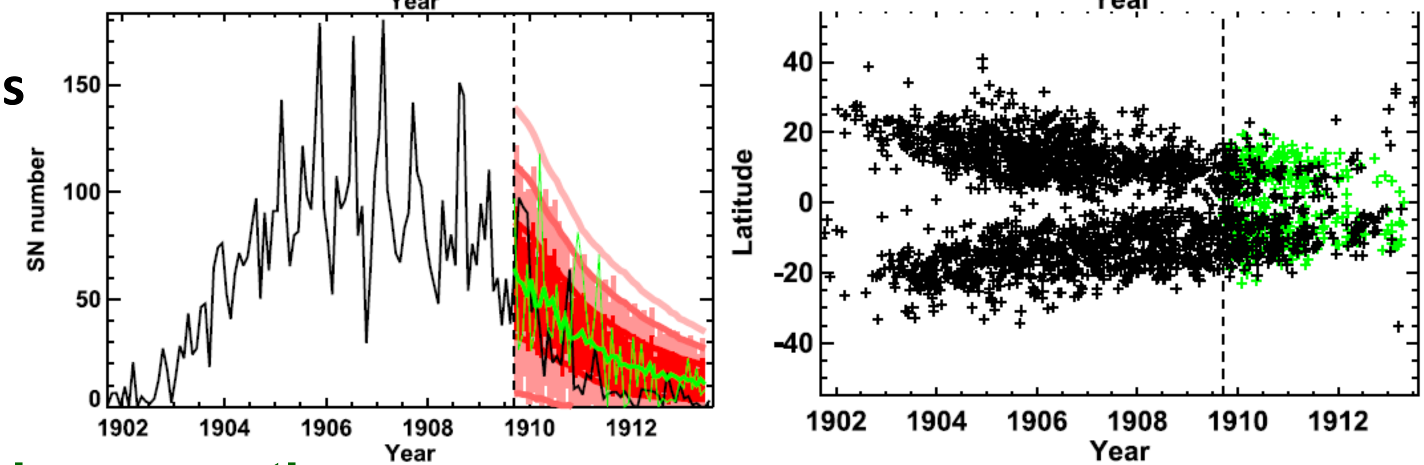
Examples: the prediction of an ongoing cycle

4 years
into cy. 20



The black curve: observed sunspot number & butterfly diagrams

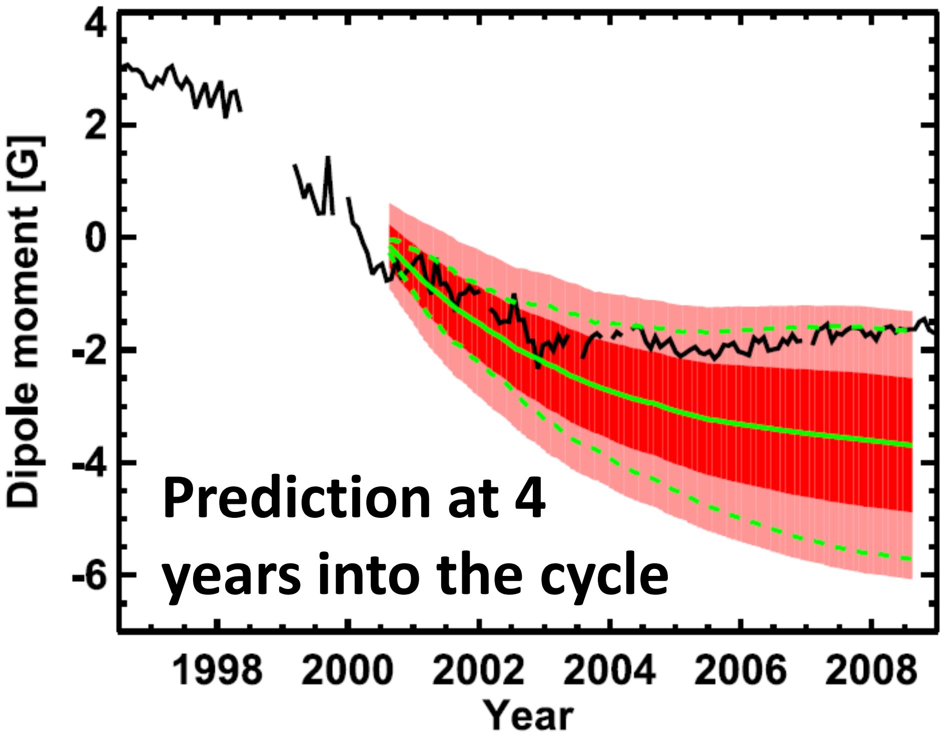
8 years
into cy.14

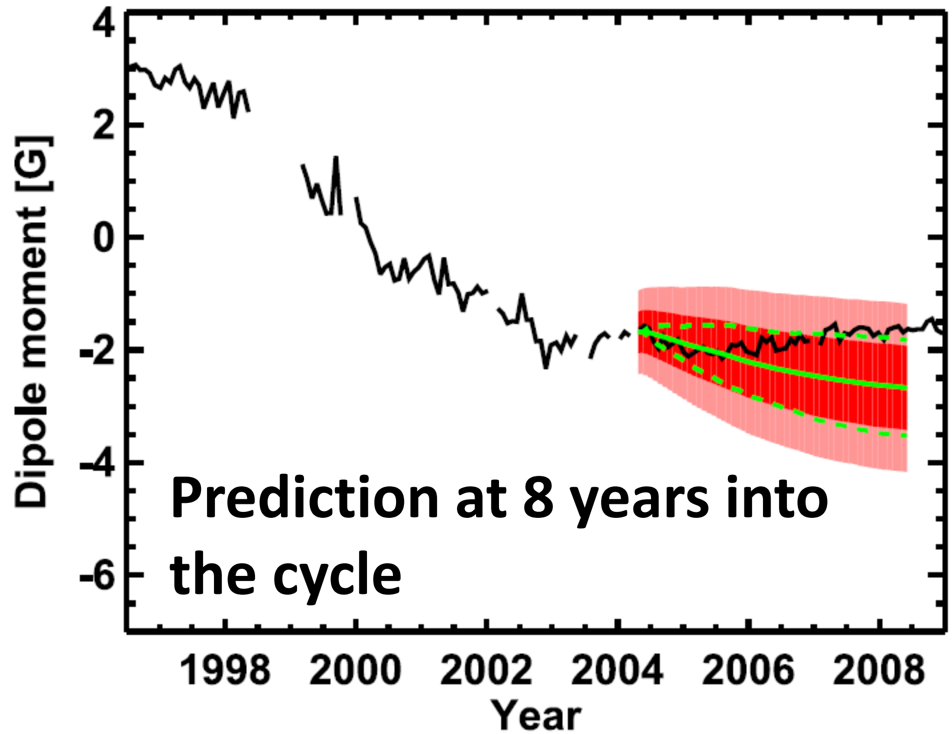


The green solid curves: the expected values from prediction and one realization from the Monte-Carlo ensemble

Dark and light red shading show the σ and 2σ uncertainties

Examples: the prediction of an ongoing cycle



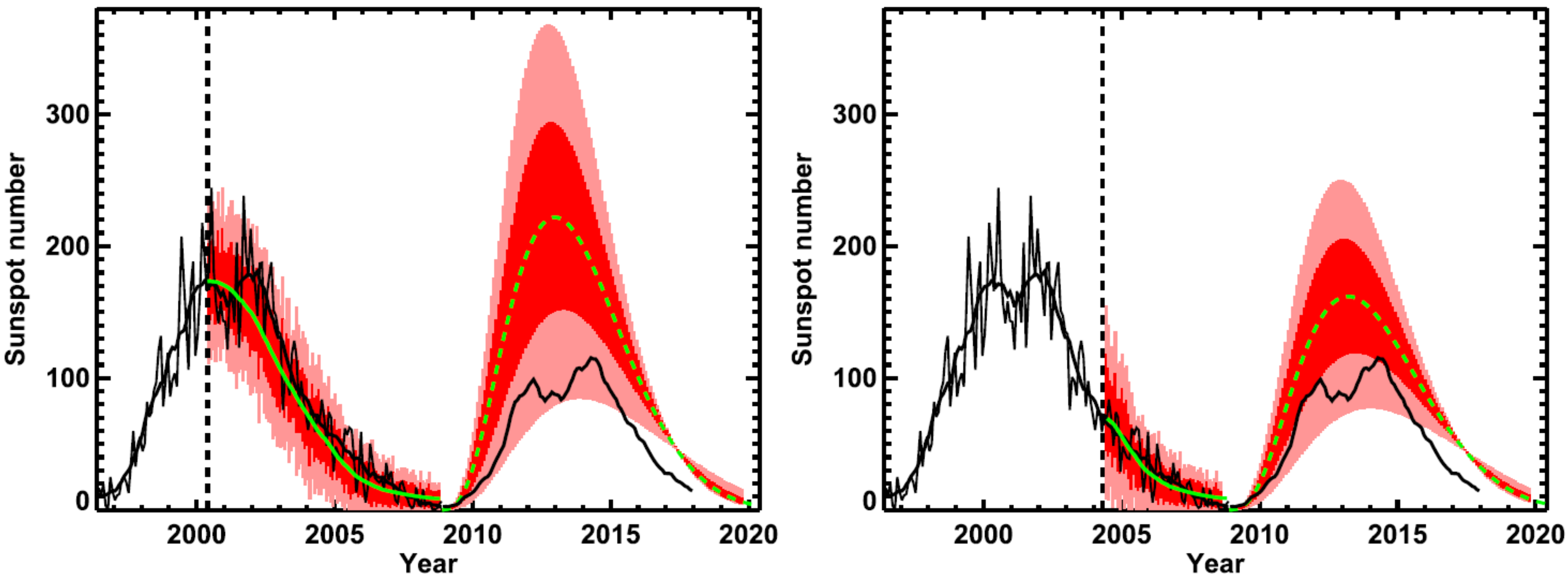


Solid green lines: the averages of 50 SFT simulations with random sources starting from the prediction timings.

Dark and light red shading: the total σ and 2σ uncertainties of the prediction

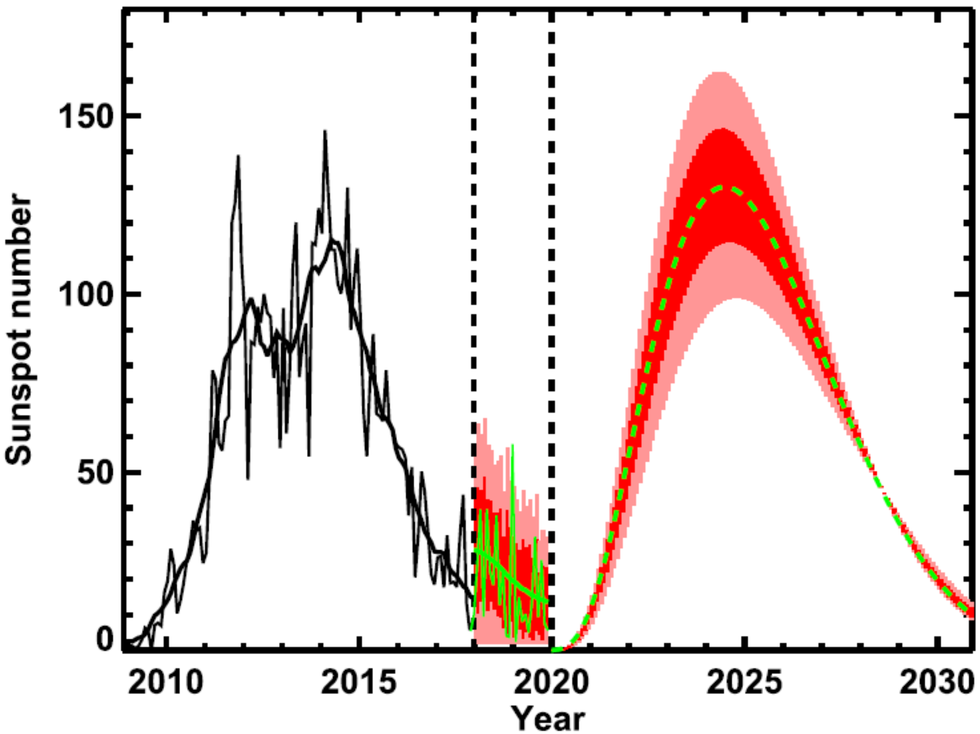
All predicted values are within ±2σ range of the predictions!!

Examples: predictability of the solar cycle over one cycle



- The observed sunspot number is within the σ to 2σ range of the predicted result, whatever the prediction time.
- The error range decreases with the prediction time.

Last updated Predictability of Cycle 25 in 2018



Jiang et al. (2018, ApJ)

- The expected amplitude of cycle 25 is 125, which is ~10% higher than current cycle 24.

- The 2σ range (light red shading) is 32, which means that the possibility that the amplitude of cycle 25 surpasses 93 is 95.4%.

Upton & Hathaway (2018, GRL):

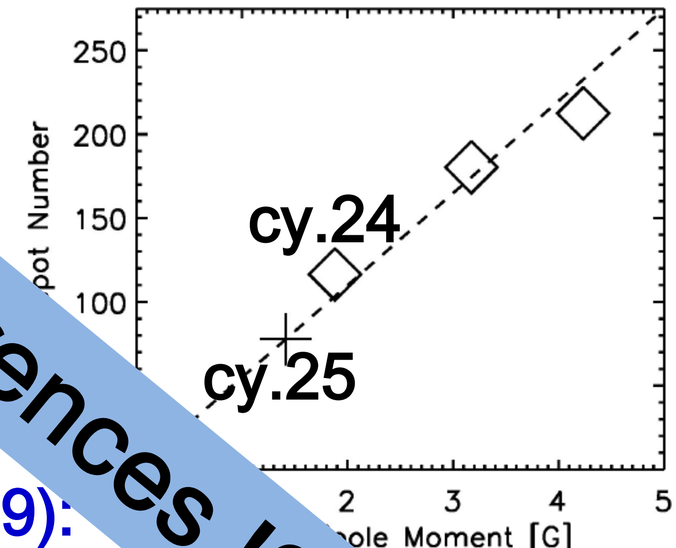
Key

- Cycle 2 … slightly weaker than Cycle 24, m … t the weakest cycle in the last hun … ars

What lead to the differences !?

Iijima et al. (2017, A&A):

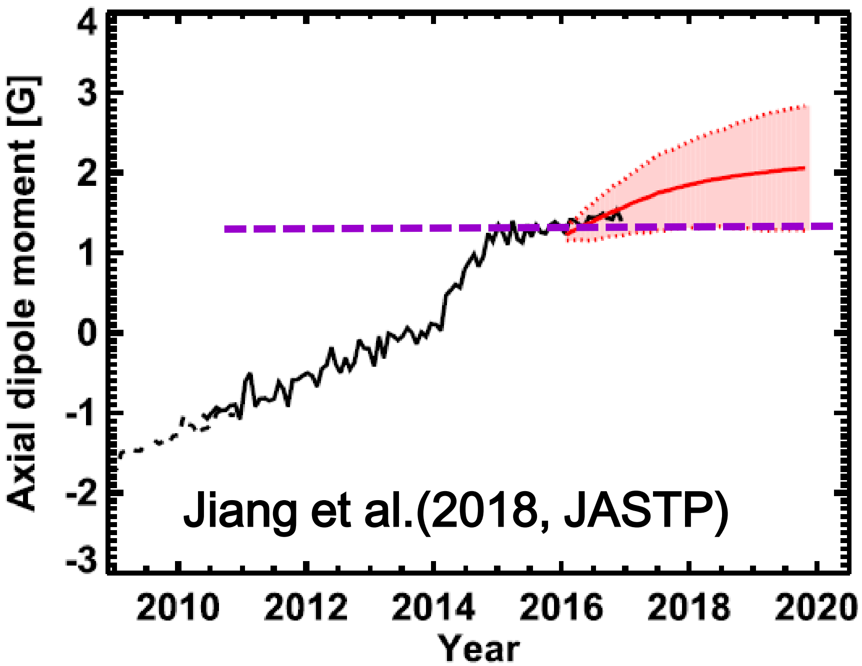
the amplitude of Cycle 25 is … weaker than the current Cycle 24.

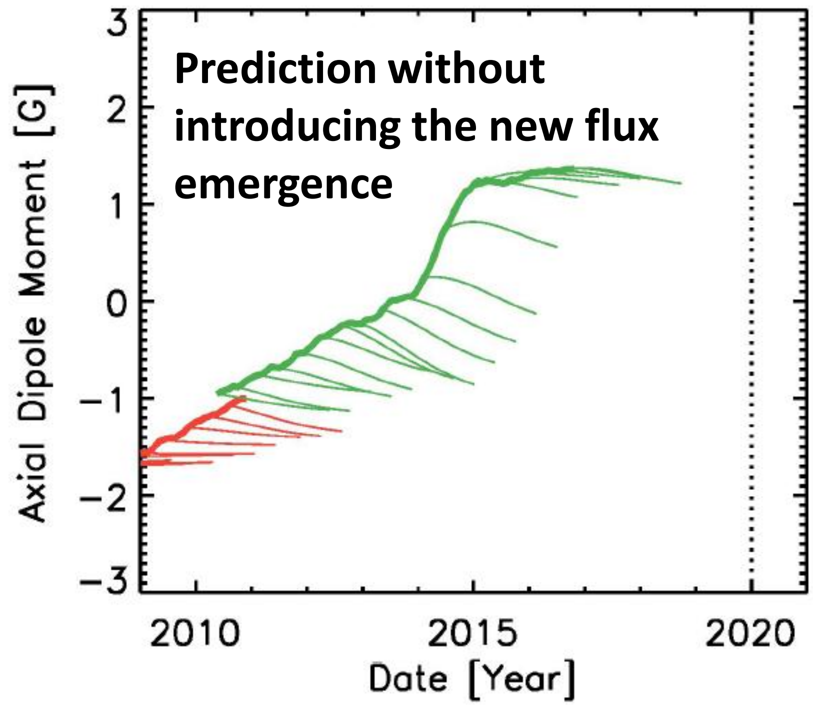


Labonville, Charbonneau, Lemerle (2019):

Our ensemble of simulated Cycle 25 points towards a cycle slightly weaker than Cycle 24

Comparison with Iijima et al. (2017)

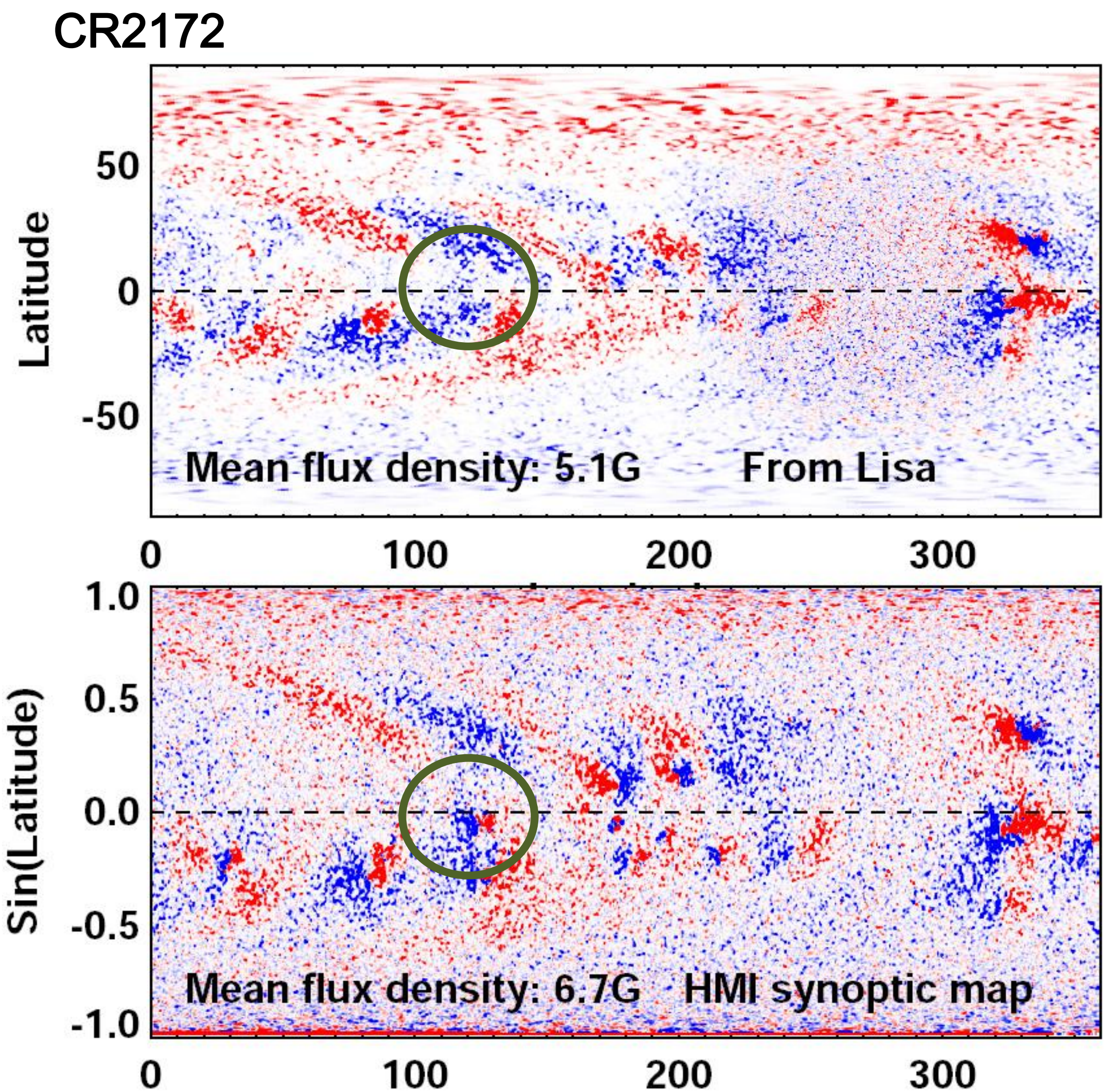




Their "plateau DM" is within our 2σ range

They claimed "Plateau of solar axial dipole moment during the period of several years before each cycle minimum"

Comparison with HU16's method

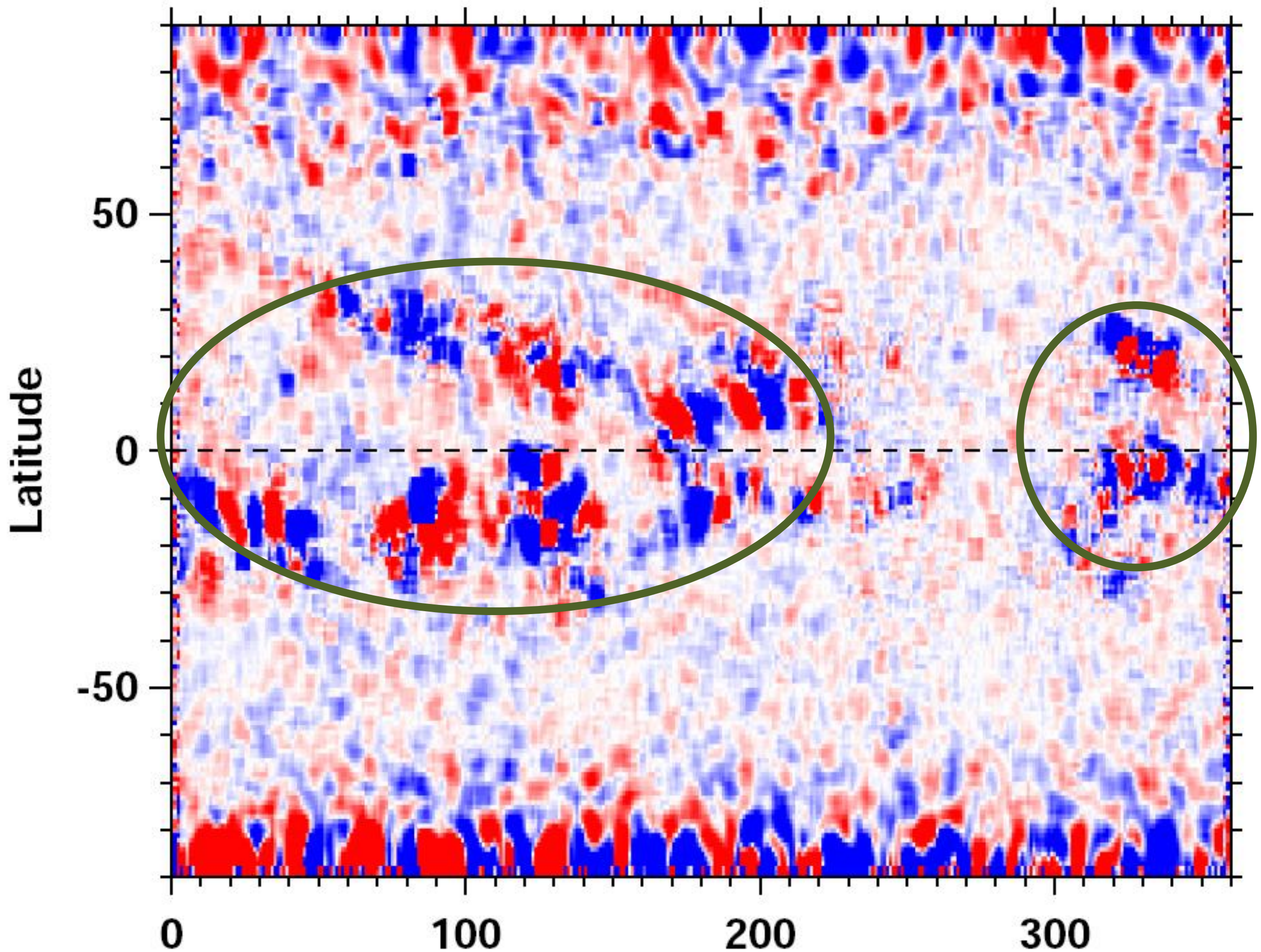


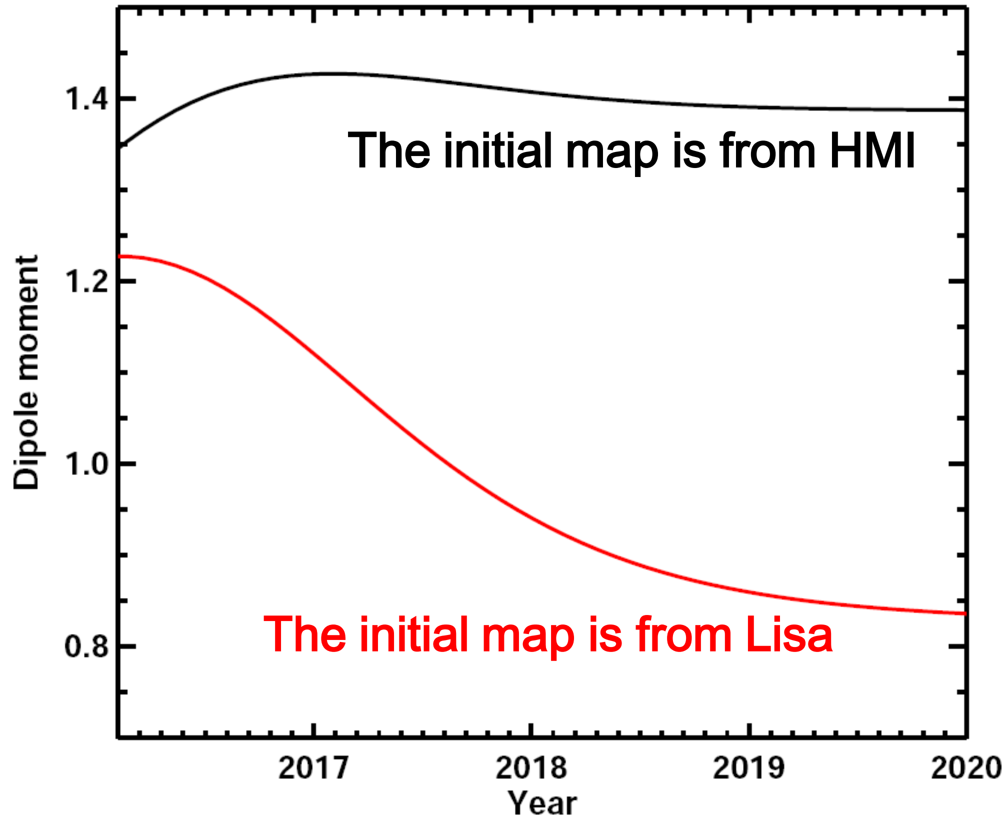
1. Initial condition for prediction:

- HU16: reconstructed synchronic Maps
- We use HMI synoptic magnetograms

I did a comparison using CR2172, Dec.25th, 2015–Jan.21th, 2016

The different flux distribution at low latitudes between the two maps/initial conditions must cause large differences in the subsequent polar field evolution.





Time evolution of the axial dipole field from SFT simulations using seemingly same synoptic magnetograms as initial conditions.

→ Different low latitude flux distributions cause large different DMs in a few years.

Comparisons with HU16’s method

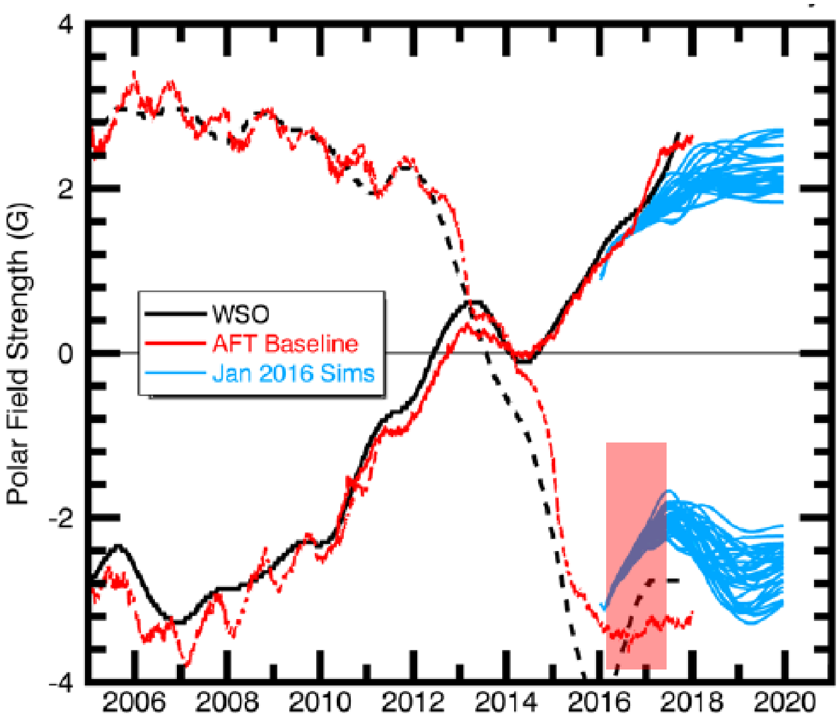
2. the properties of sunspot emergence (flux source)

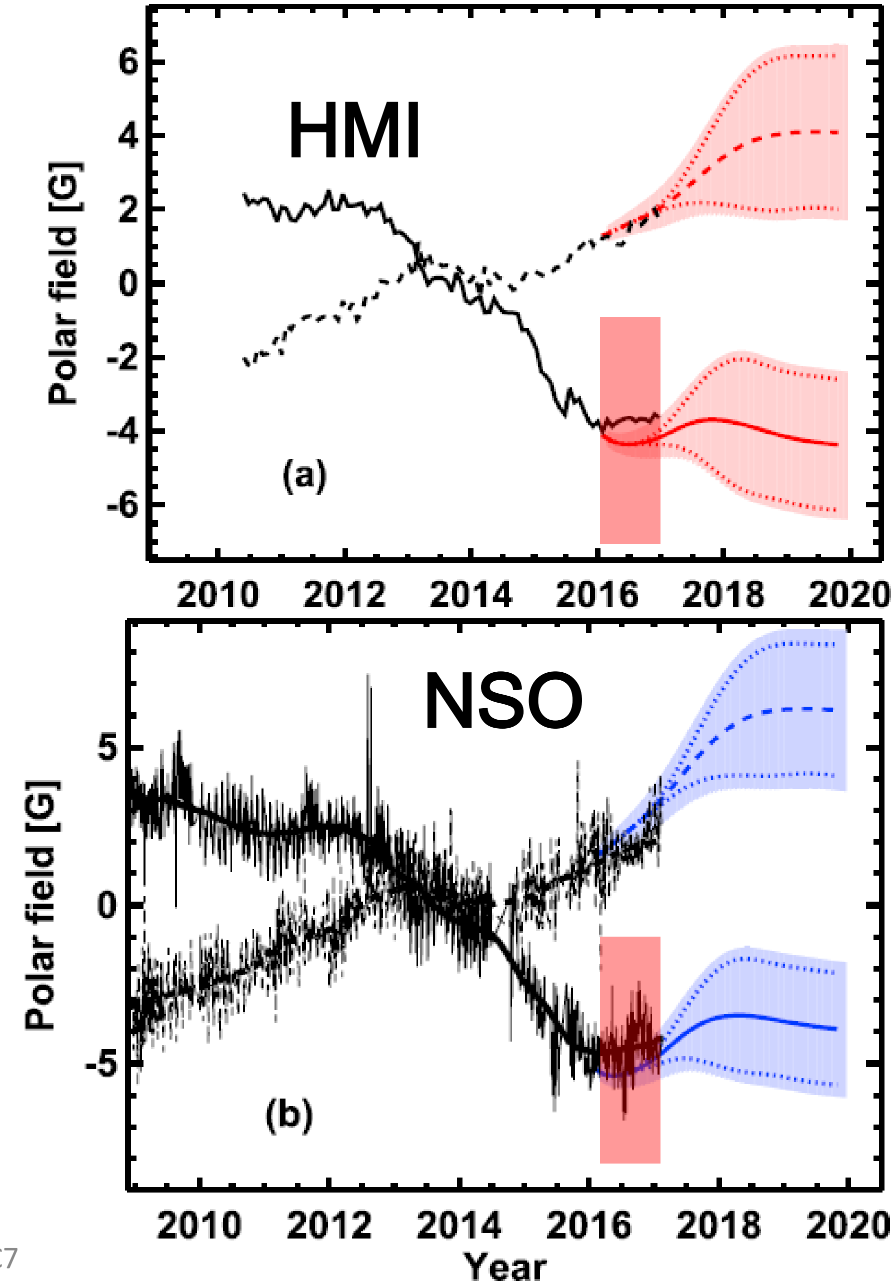
What we used is based on very careful measurements of the statistical properties of sunspot emergence, including the randomness and nonlinearities (Jiang et al., 2011, 2018).

HU16& UH18: They used ARs from cy.14 as a representation of the ARs that will appear in the next 4 years in cy.24.

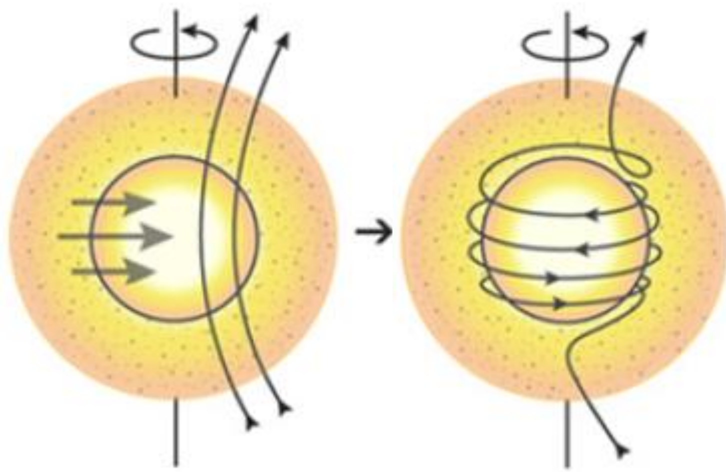
Jiang & Cao (2018, JASTP)

Comparison the polar field prediction at 2016 with
Upton & Hathaway (2018)





Comparisons with LCL19's method



(Sanchez et al. 2014)

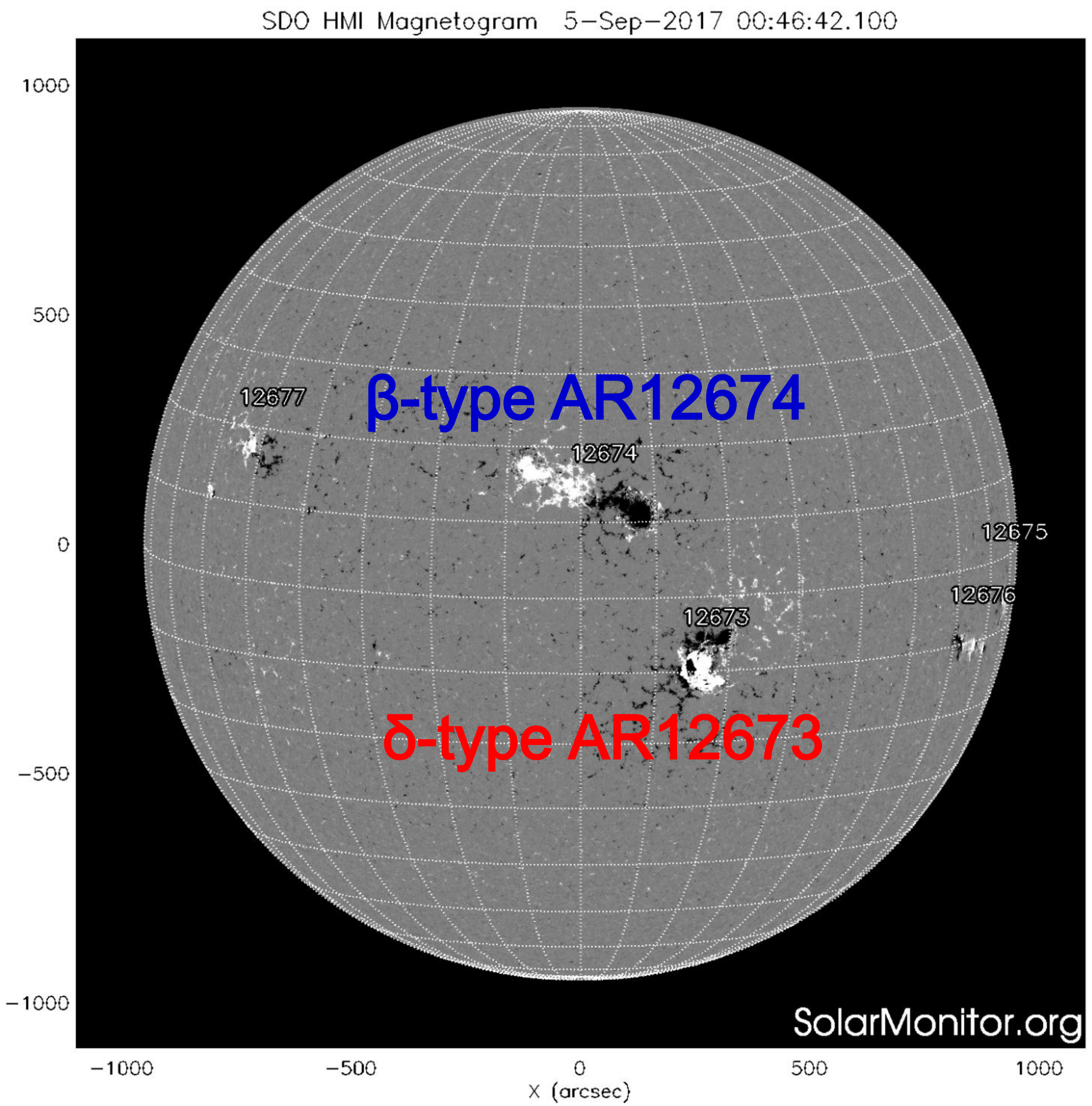
• Br does not change during the distortion to form the toroidal field ! → Polar field at mini. is correlated with the subsequent cycle

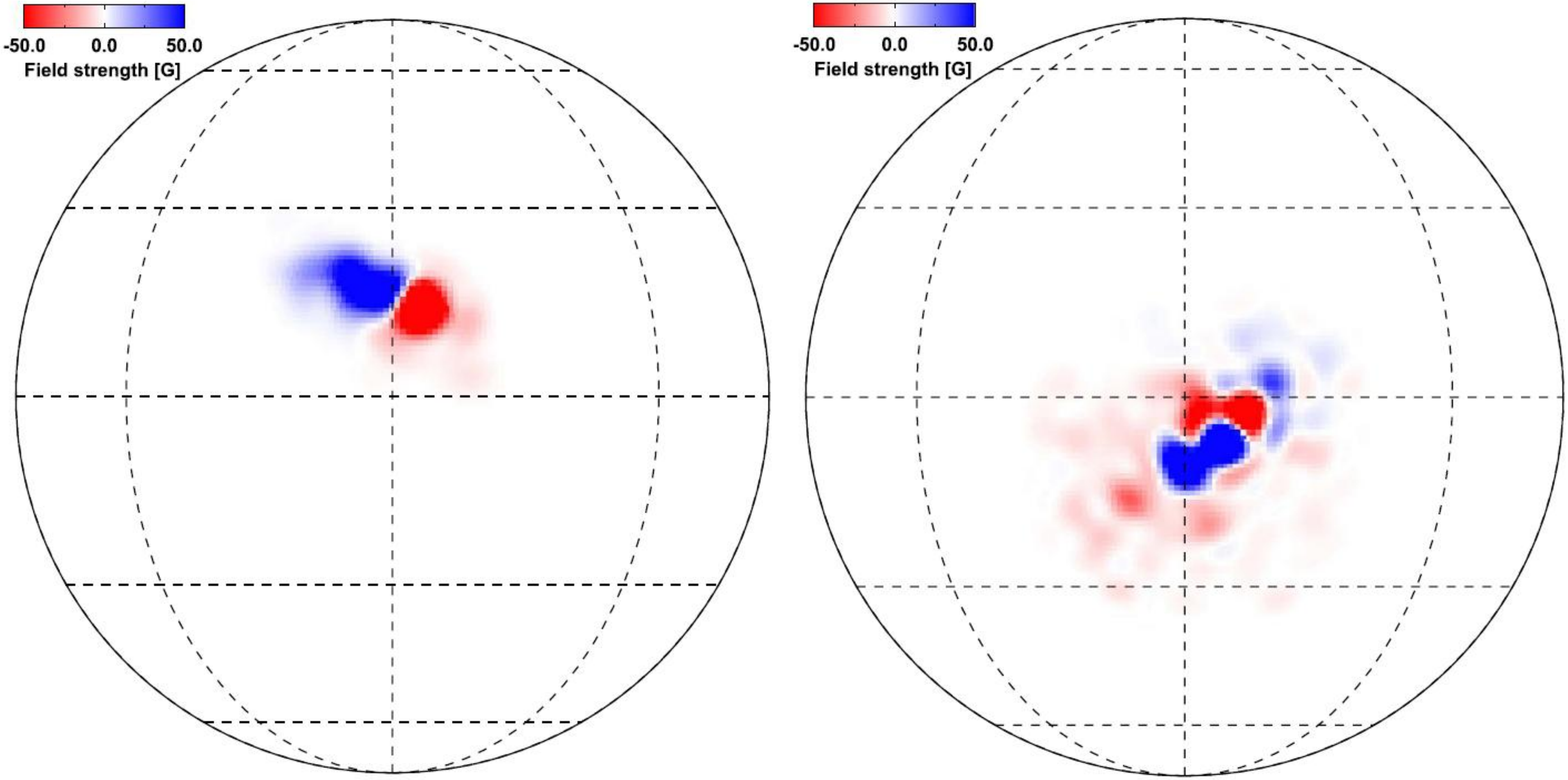
• A strong radial diffusion by LCL19 reduces the poloidal field, which generates a cycle weaker than expected.

Major point: No radial diffusion is required!

Significant effects of δ-spots on the solar cycle / space climate

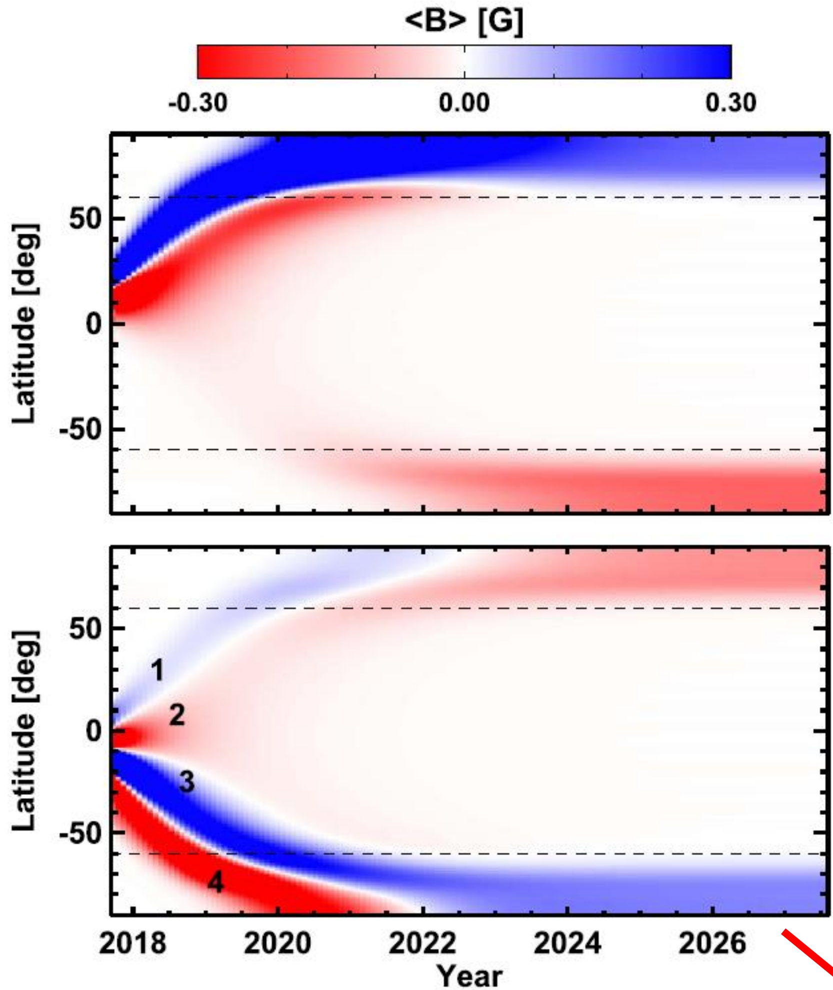
ARs are always in BMRs in SFT models.
But, there are ARs in complex structures ……

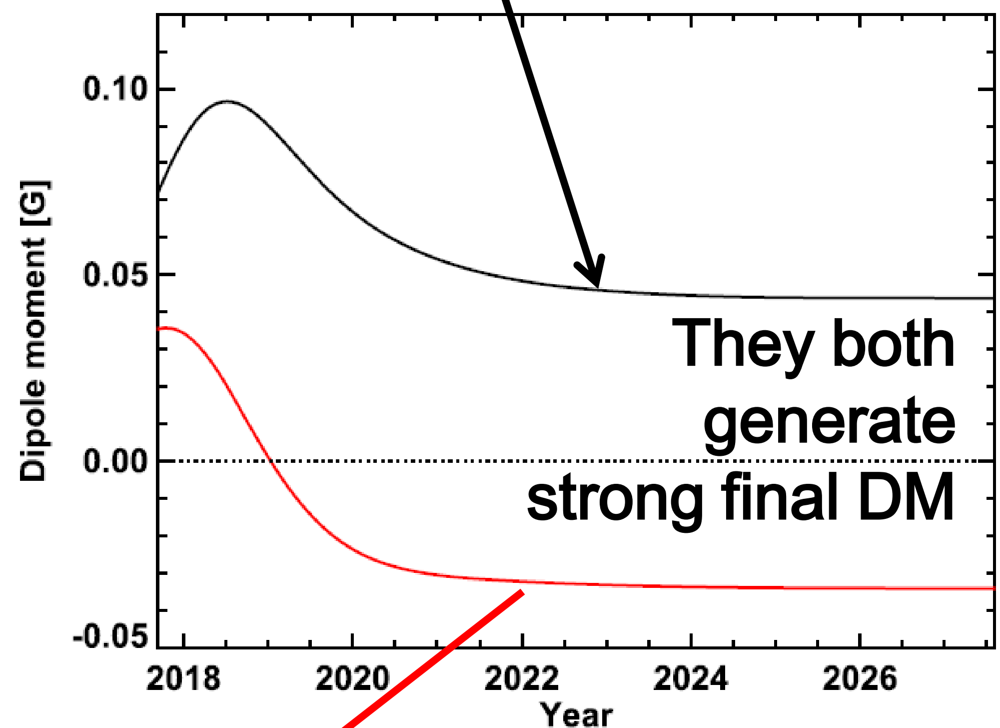




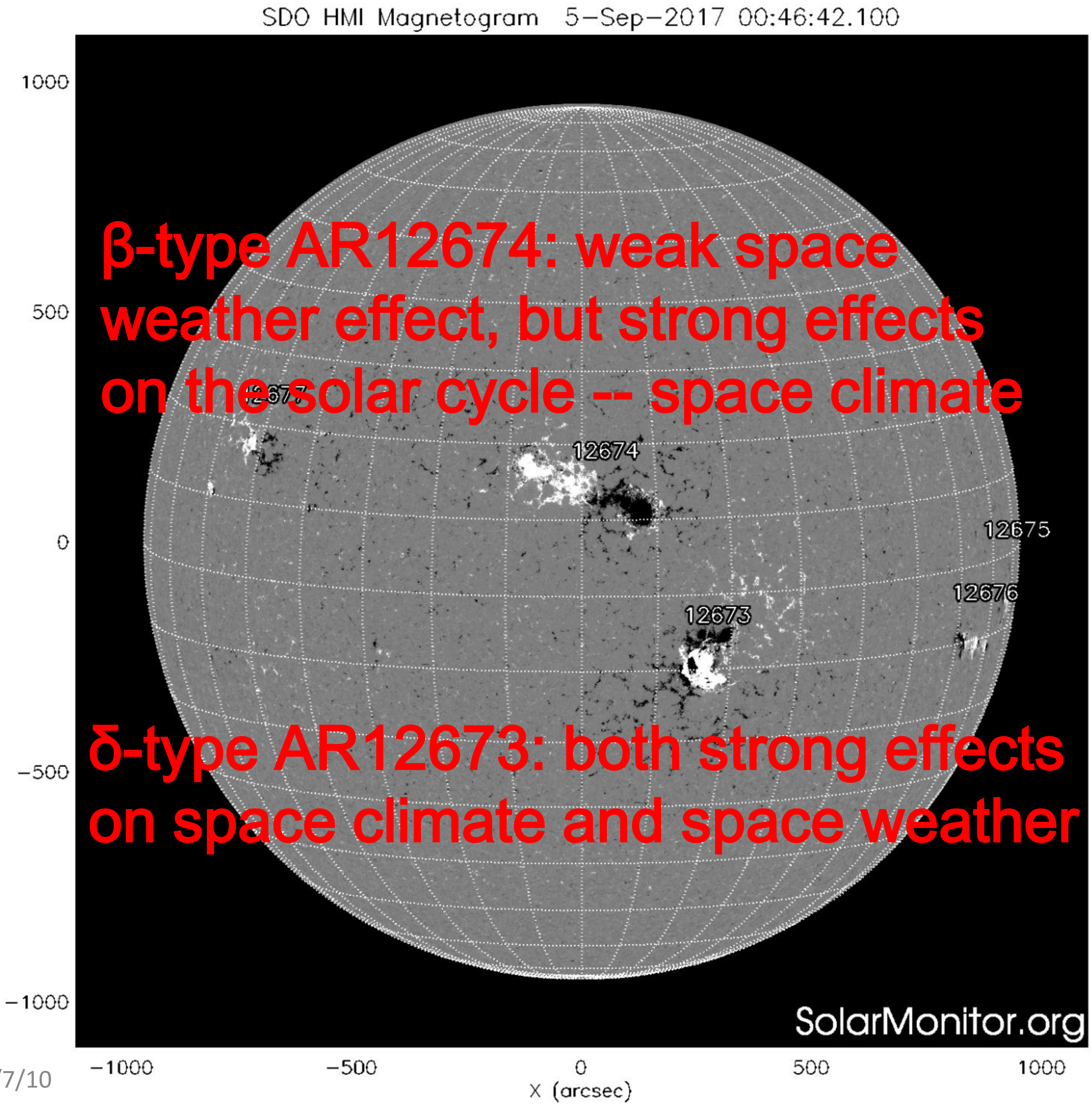
We isolated the two ARs and assimilated them into the SFT model separately (Jiang et al., 2019).

Typical BMR
DM evolution





surprising ! The δ-type AR12673: An initial positive D ends up with a negative value !



β-type AR12674: weak space weather effect, but strong effects on the solar cycle -- space climate

δ-type AR12673: both strong effects on space climate and space weather

Conclusions

- We identified and quantified randomness and nonlinearities of the solar cycle and then applied them into a scheme for quantifying solar cycle predictability.

- It is important to treat the δ-spots in surface flux transport models realistically.

Any questions are welcome ~