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Solar cycle forecasting,

Using a data-driven 2×2D Babcock-Leighton model

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A Dynamo-based Forecast of Solar Cycle 25

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Abstract We present a data-driven version of the solar cycle model of Lemerle and Charbonneau (*Astrophys. J.* **834**, 133; 2017), which we use to forecast properties of the upcoming sunspot Cycle 25. The two free parameters of the model are fixed by requiring the model to reproduce Cycle 24 upon being driven by active region data for Cycle 23. Our forecasting model incorporates self-consistently the expected fluctuations associated with stochastic variations in properties of emerging active regions, most notably the scatter in the tilt angle of the line segment joining the opposite polarity focii of bipolar magnetic regions, as embodied in Joy's law. By carrying out ensemble forecasts with statistically independent realizations of active region parameters, we can produce error bars that capture the impact of this physical source of fluctuations. We forecast a smoothed monthly international sunspot number (version 2.0) peaking at 89^{+29}_{-14} in year $2025.3^{+0.89}_{-1.05}$, with a 6 month onset delay in the northern hemisphere, but a peak amplitude 20% higher than in the southern hemisphere.

Keywords Solar cycle, models · Solar cycle, observations · Magnetic fields, photosphere

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Collège de Bois-de-Boulogne

Fonds de recherche sur la nature et les technologies Québec

CRAQ Comprendre l'Univers Understanding the Universe

GRPS Université de Montréal

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- <u>2×2D Babcock-Leighton model design and calibration</u>
- Data driving
- Predictability and calibration
- Forecasting

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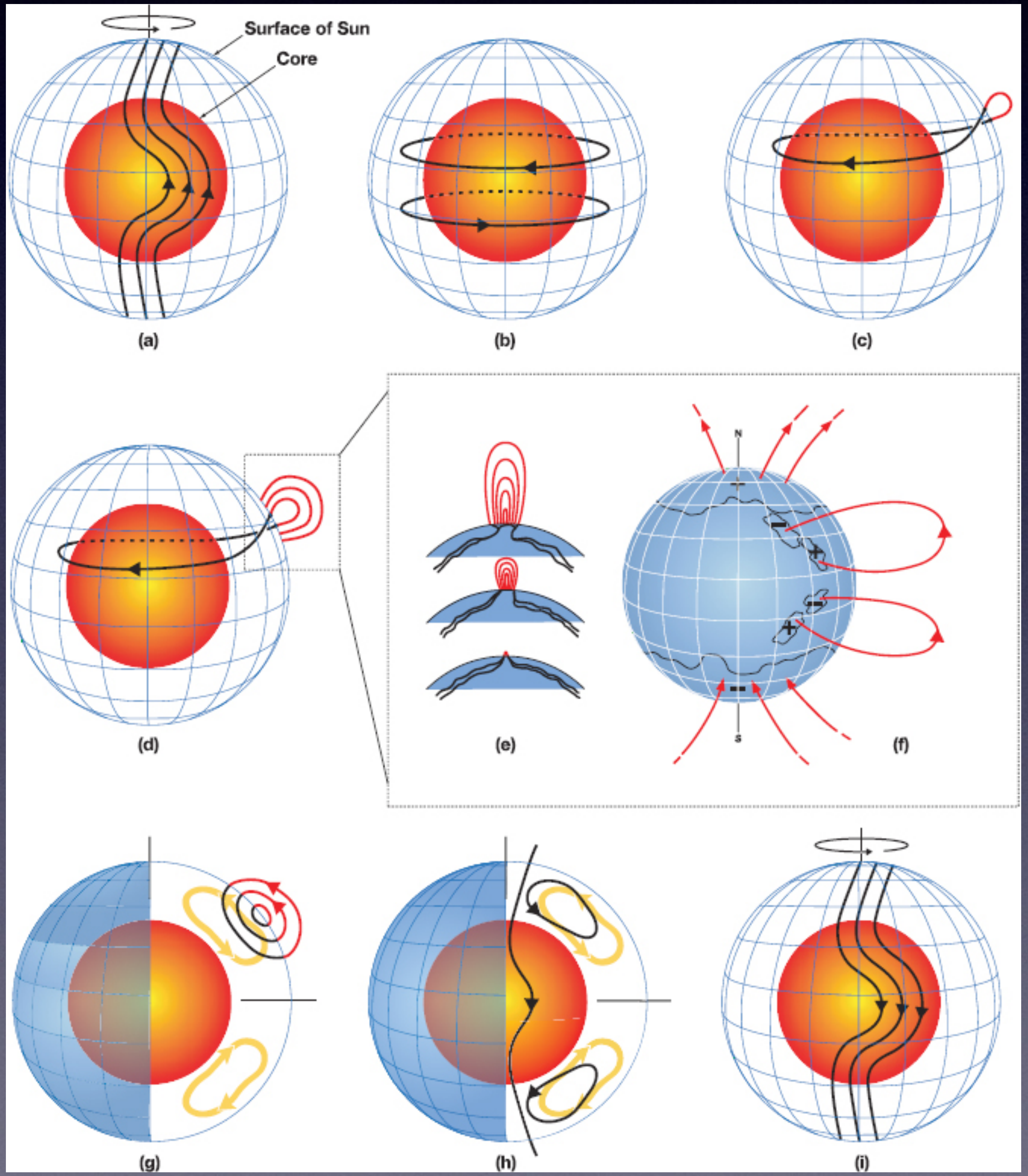
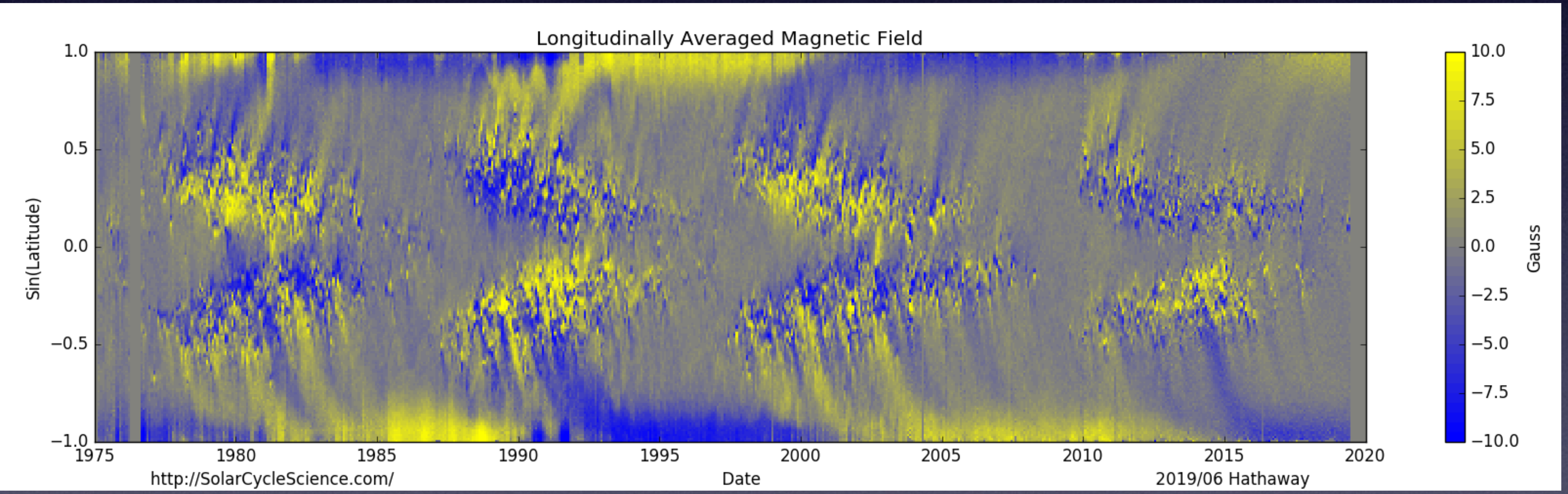
Babcock-Leighton dynamo models

- Phenomenological approach: « as simple as possible, but not simpler »
- Directly based on observed solar surface features



Dikpati & Gilman 2007



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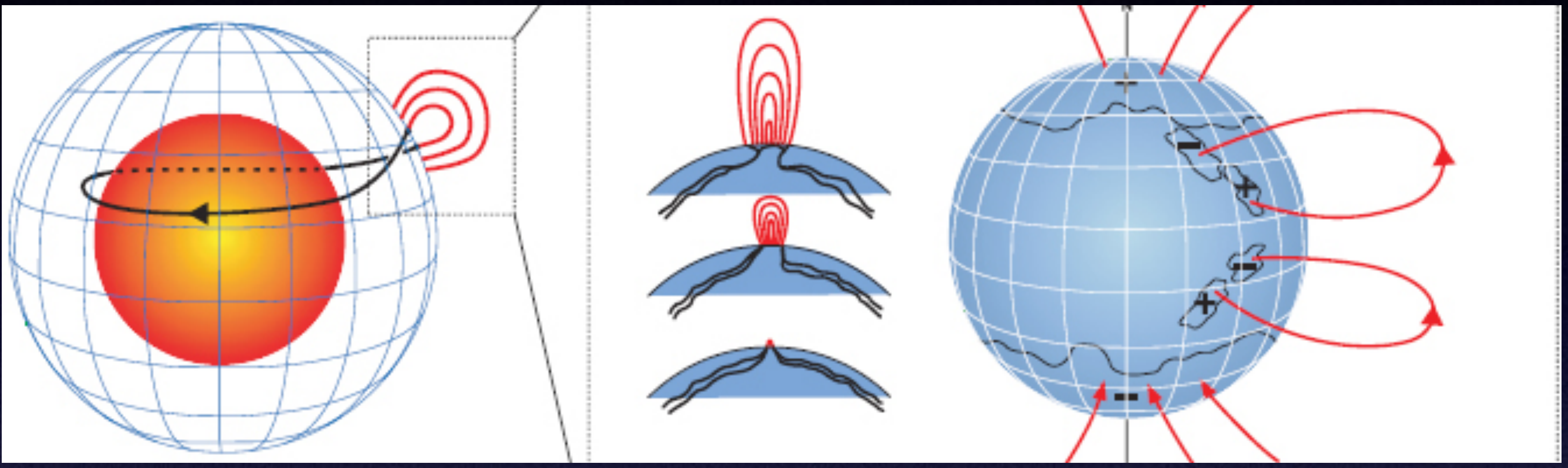
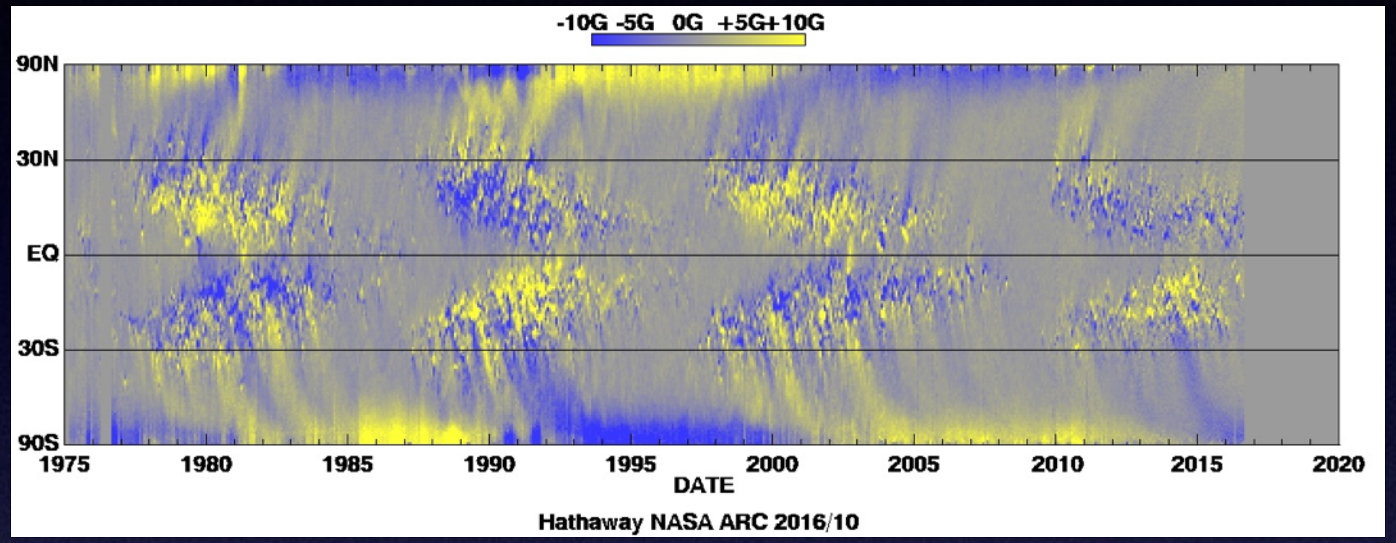
2×2D hybrid Babcock-Leighton dynamo model

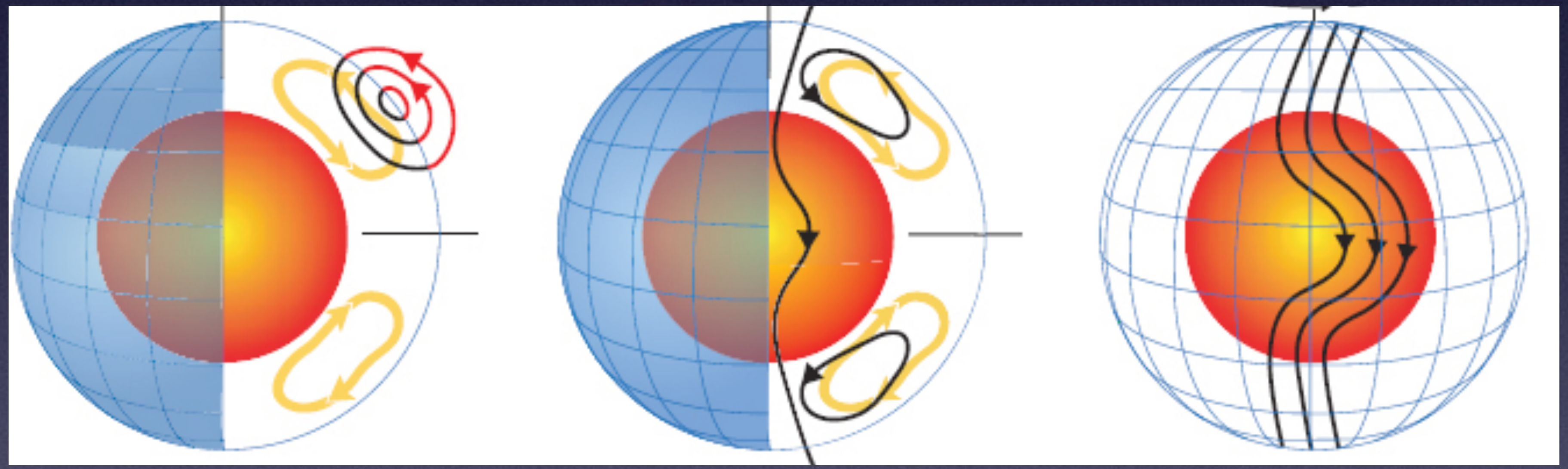
- 3 ~distinct mechanisms treated separately, with steady flows :

1. SFT module: MHD induction (magnetic flux "transport") at the surface (2D, non-axisymmetric)

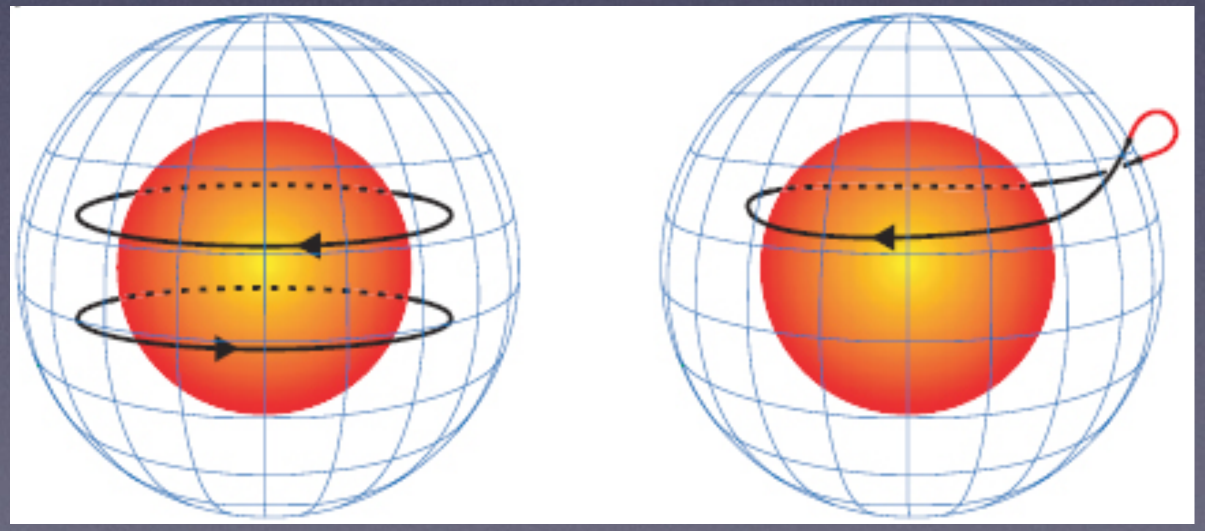




2. FTD module: MHD induction (flux "transport") in the meridional plane (2D, axisymmetric)



3. Destabilization / ascent / emergence of magnetic flux tubes (non axisymmetric)



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$$\frac{\partial B_R}{\partial t} = -\frac{1}{\varpi}\frac{\partial}{\partial \theta}\left[\sin\theta\, u_\theta(R,\theta) B_R\right] - \Omega(R,\theta)\frac{\partial B_R}{\partial \phi} + \frac{\eta_R}{\varpi^2}\left[\sin\theta \frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial B_R}{\partial\theta}\right) + \frac{\partial^2 B_R}{\partial\phi^2}\right] - \frac{B_R}{\tau_R} + S_{\mathrm{BMR}}(\theta,\phi,t)$$

2. FTD module: MHD induction (flux "transport") in the meridional plane (2D, axisymmetric)

$$\frac{\partial B_\phi}{\partial t} = -\varpi(\boldsymbol{u}_{\mathrm{P}}(r,\theta)\cdot\boldsymbol{\nabla})\left(\frac{B_\phi}{\varpi}\right) + \eta(r)\left(\nabla^2 - \frac{1}{\varpi^2}\right)B_\phi - (\boldsymbol{\nabla}\cdot\boldsymbol{u}_{\mathrm{P}}(r,\theta))B_\phi + \frac{1}{\varpi}\frac{\partial\eta(r)}{\partial r}\frac{\partial(\varpi B_\phi)}{\partial r} + \varpi\boldsymbol{B}_{\mathrm{P}}\cdot\boldsymbol{\nabla}\Omega(r,\theta)$$

$$\frac{\partial A_\phi}{\partial t} = -\frac{1}{\varpi}(\boldsymbol{u}_{\mathrm{P}}(r,\theta)\cdot\boldsymbol{\nabla})(\varpi A_\phi) + \eta(r)\left(\nabla^2 - \frac{1}{\varpi^2}\right)A_\phi + S_A(R,\theta,t)$$

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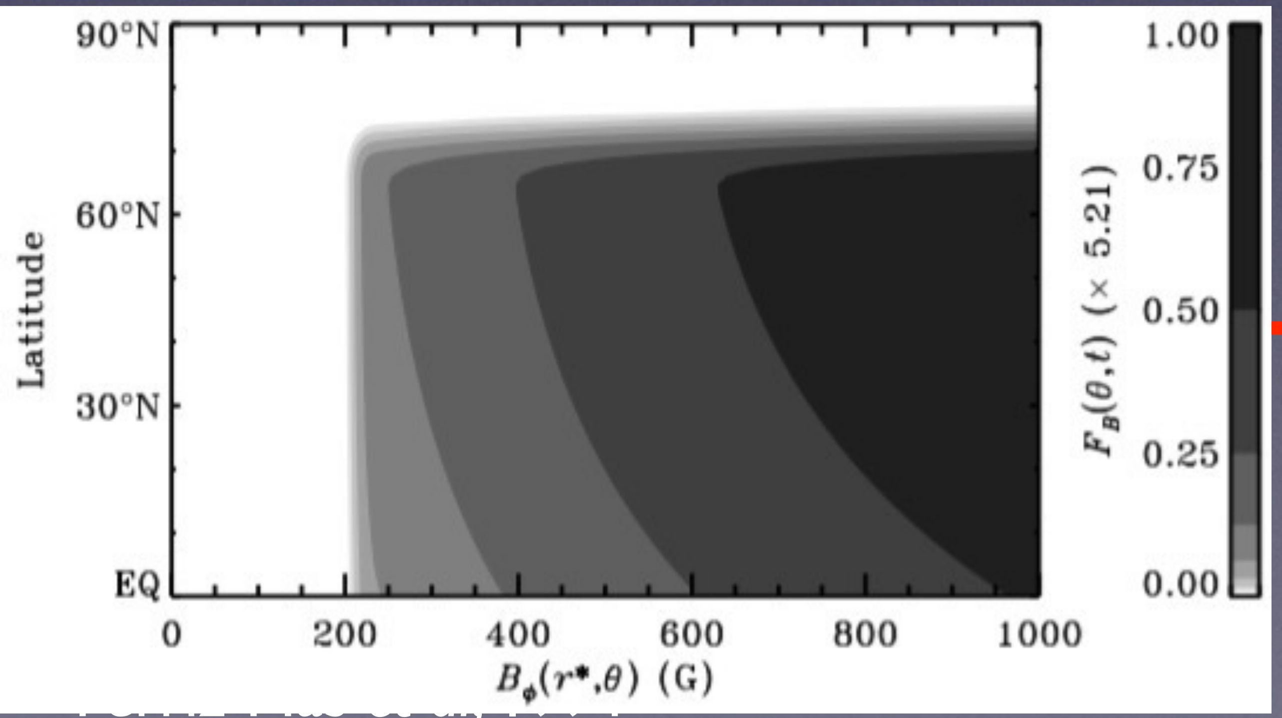

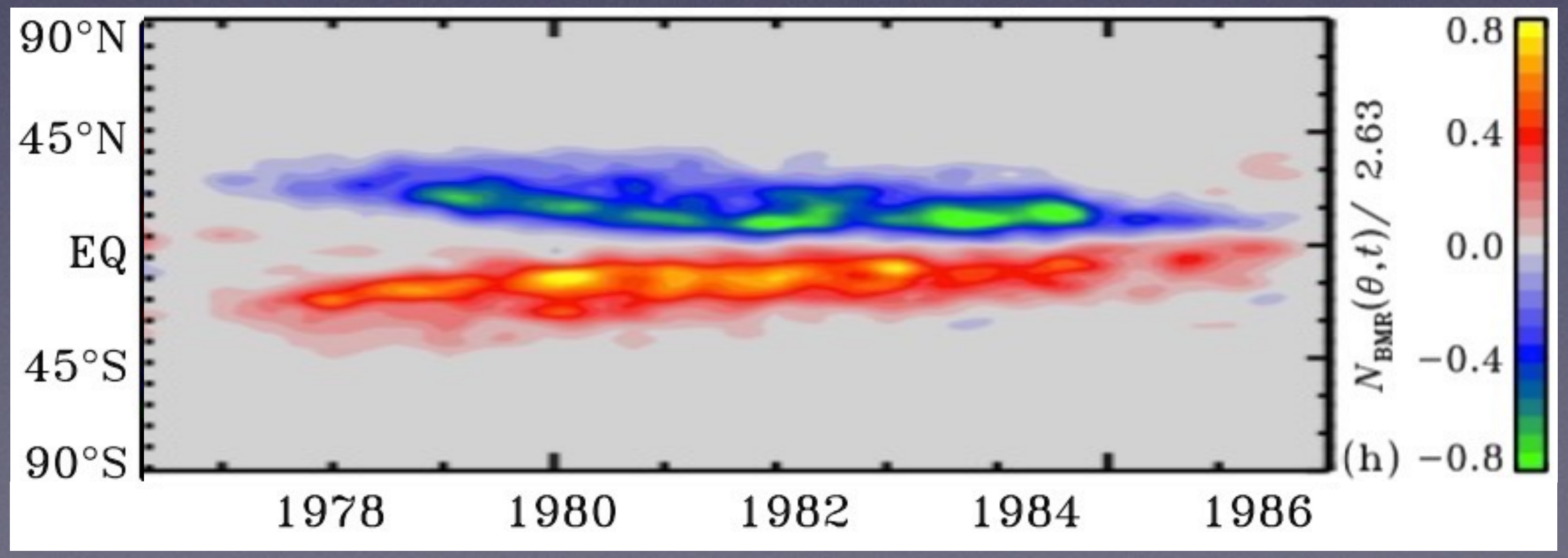

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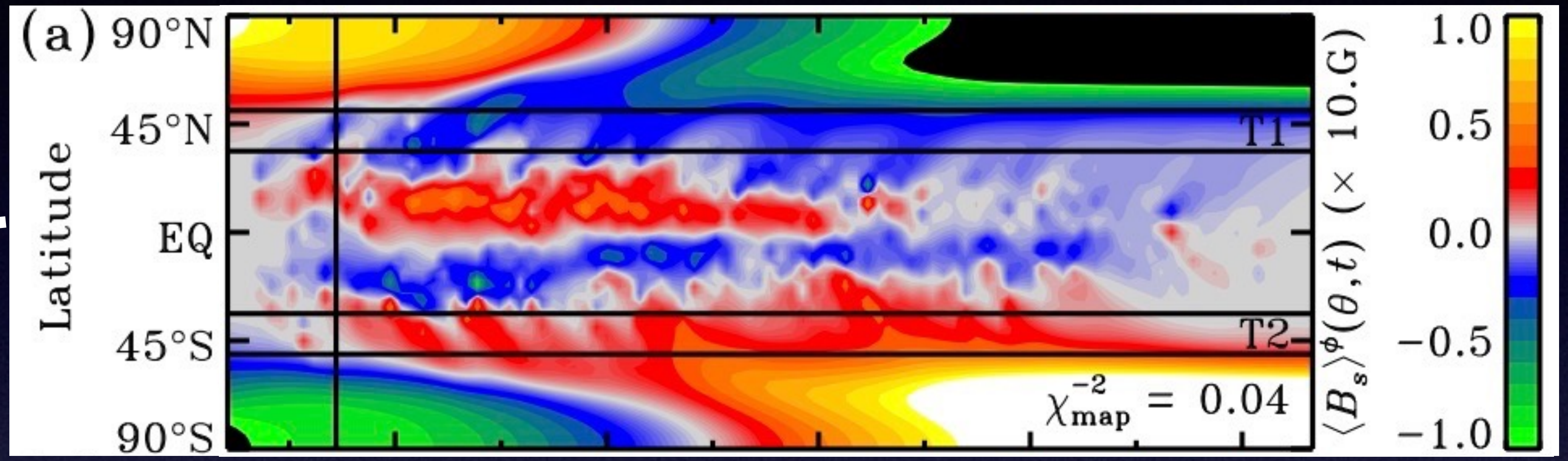

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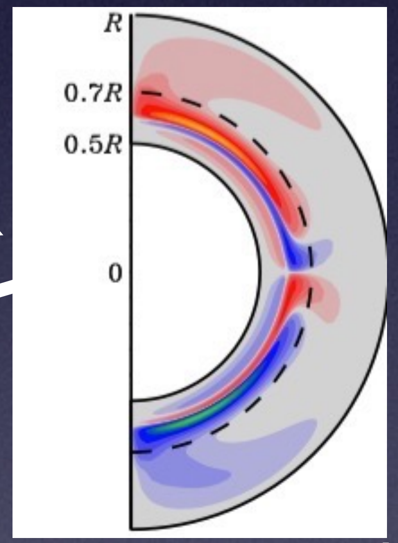

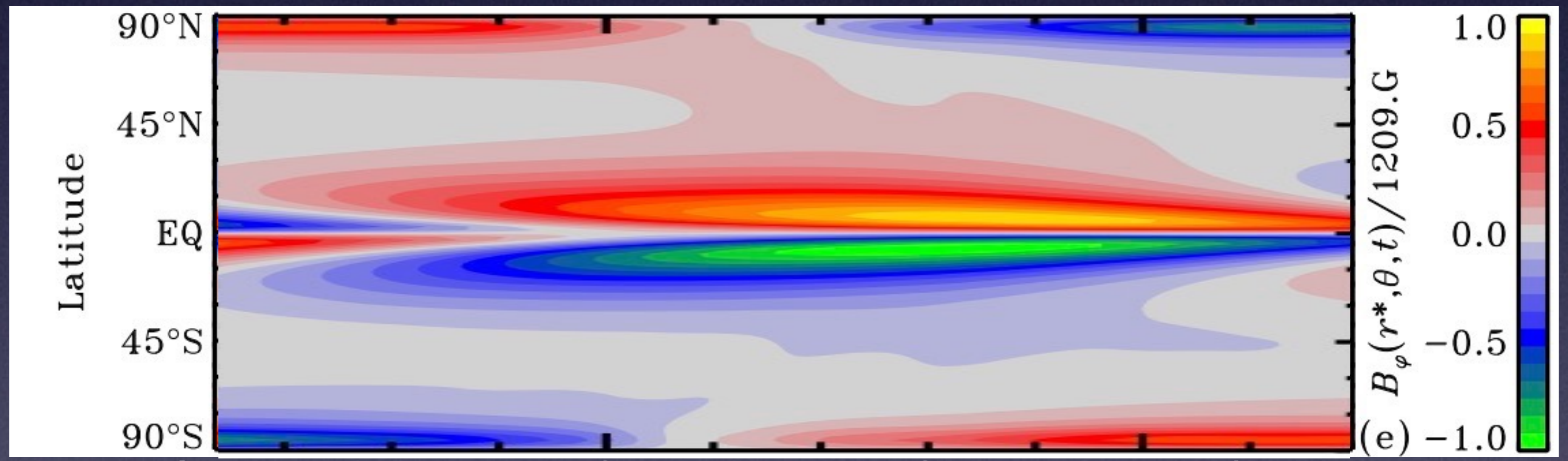

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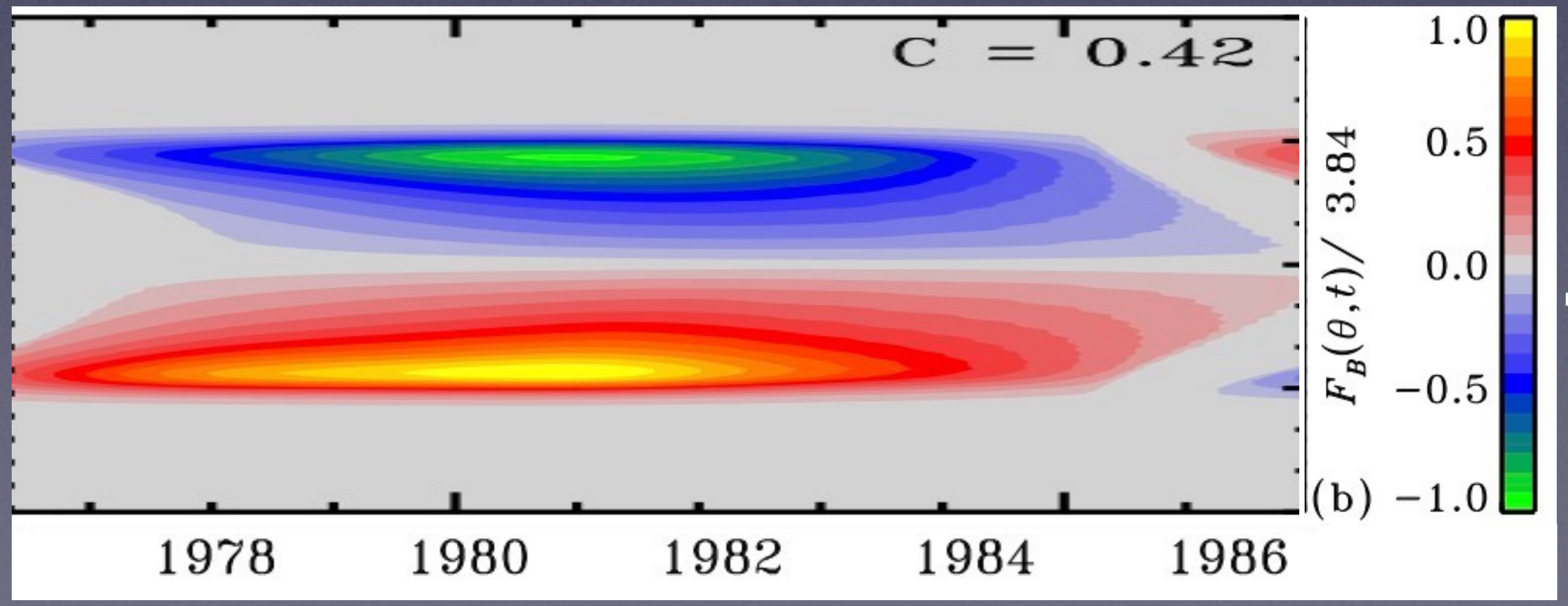

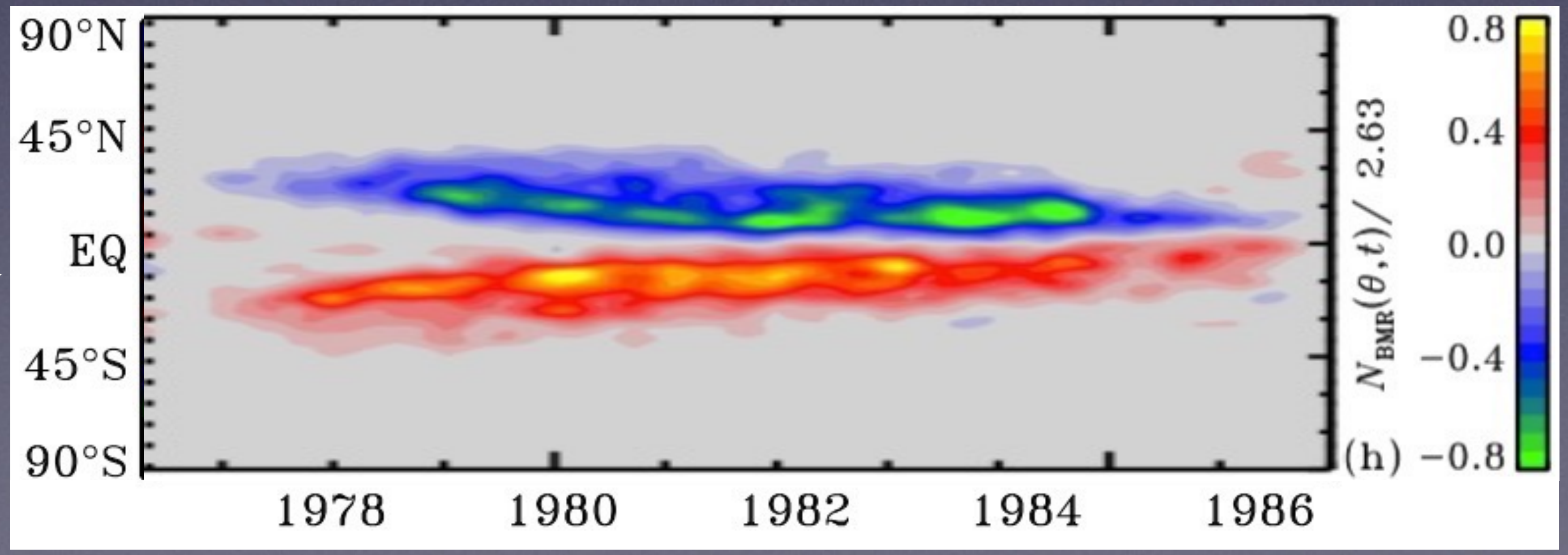

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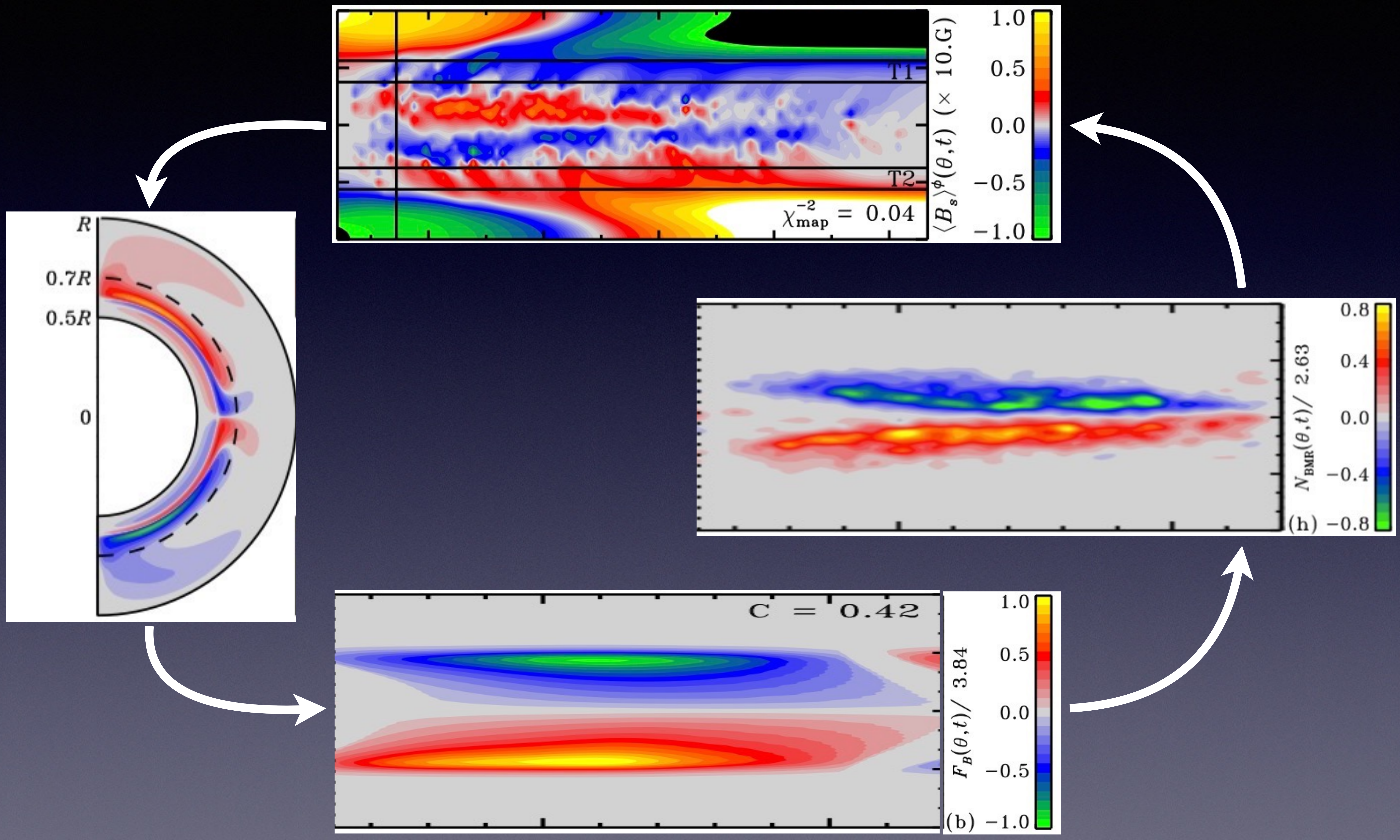

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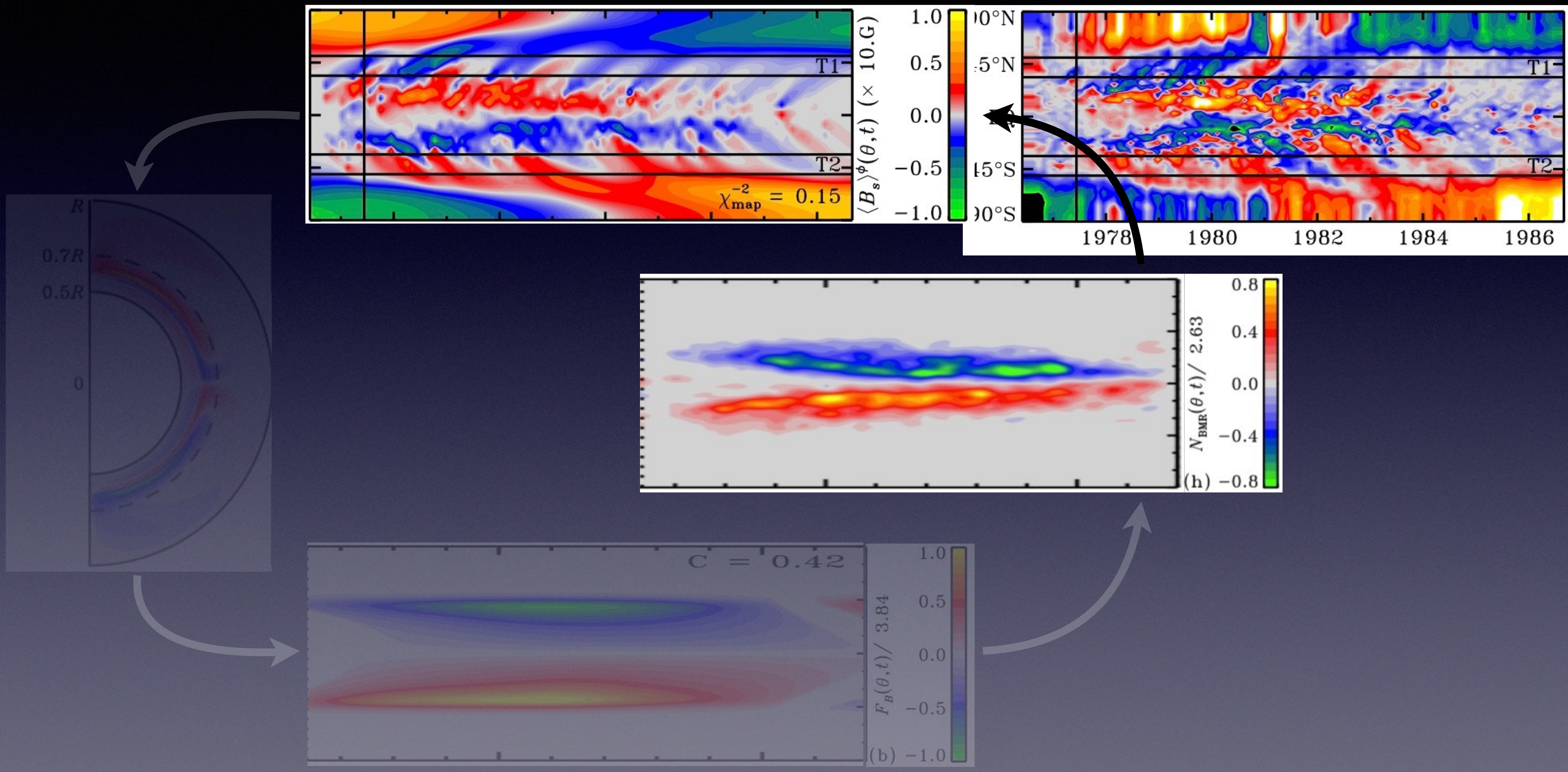
Model calibration / optimization



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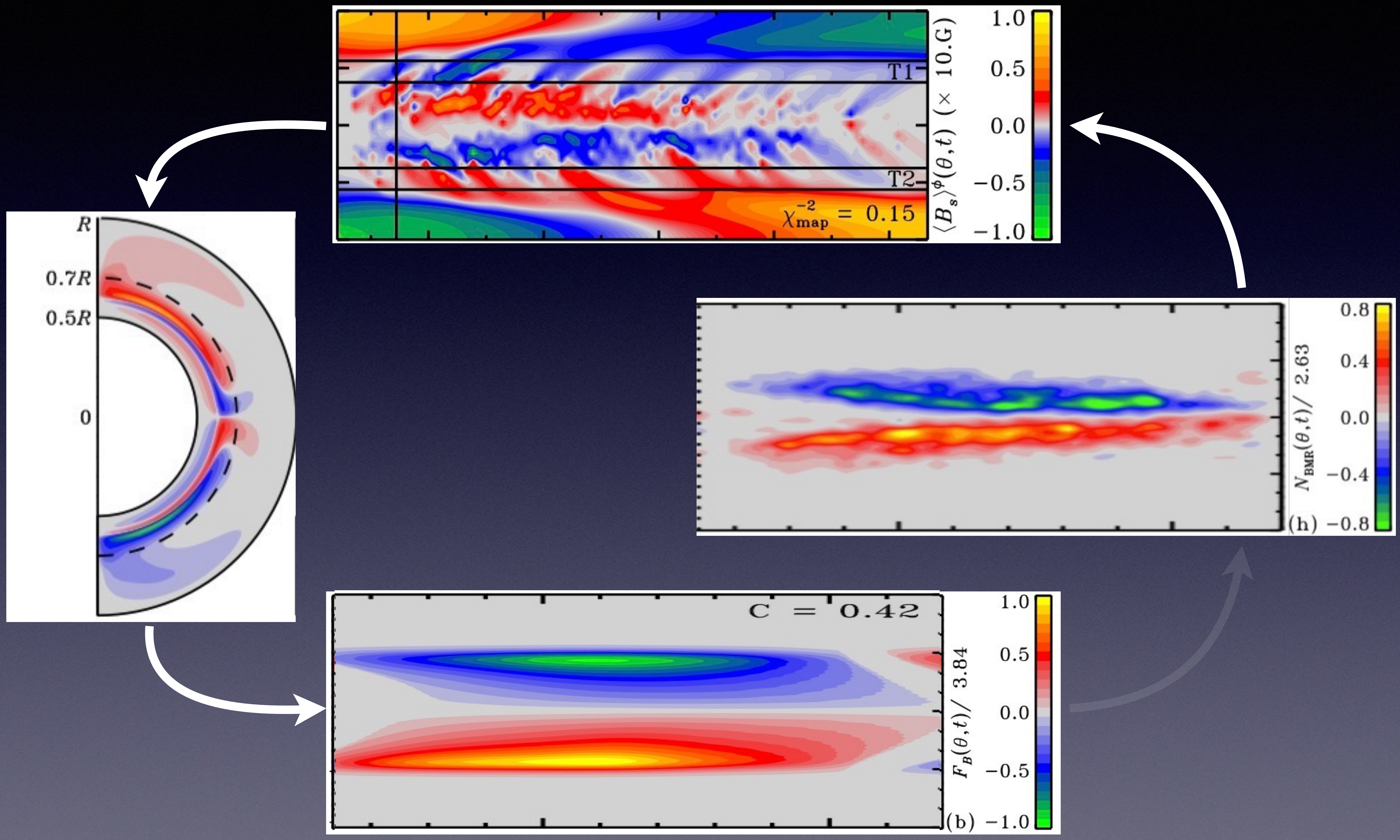

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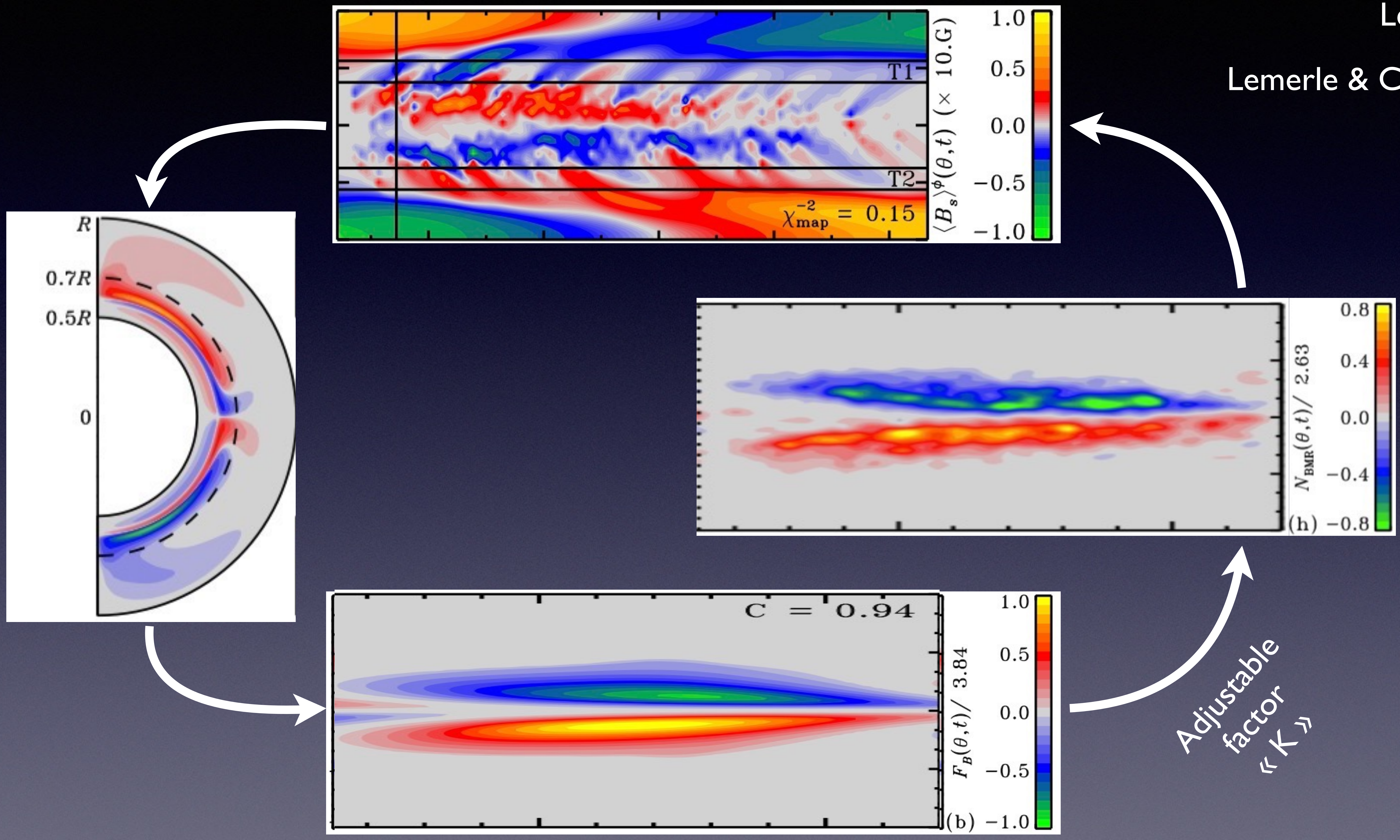
2×2D hybrid Babcock-Leighton dynamo model

Lemerle et al, 2015

Lemerle & Charbonneau 2017



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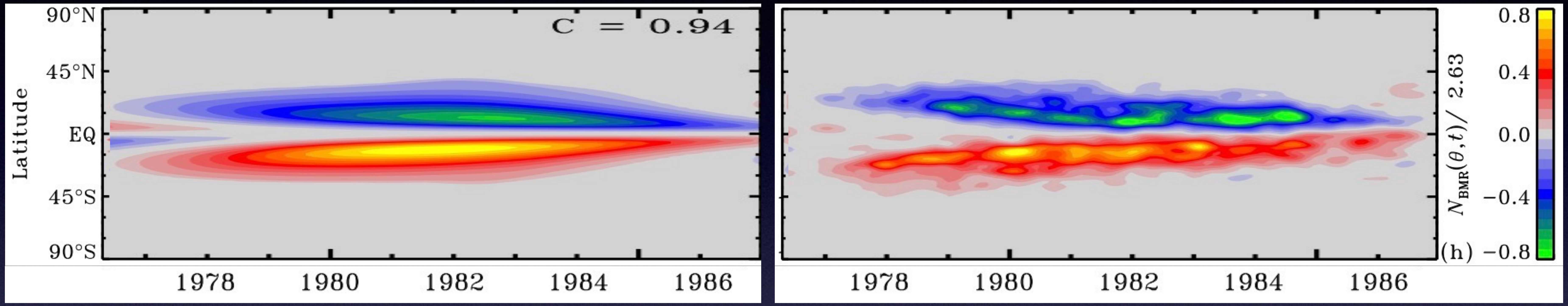
2 modes of BMR emergence

FTD emergence function = ? ? ? => BMRs deposited in SFT



1. Data <u>driven</u> mode: deposit active regions taken from <u>dataset</u> on the solar surface while letting the internal field evolve correspondingly

   OR

2. <u>Self-emergence</u> mode: the <u>model</u> emerges its <u>own population</u> of active regions.

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1. Datasets used for data-driving

AVERAGE PROPERTIES OF BIPOLAR MAGNETIC REGIONS DURING SUNSPOT CYCLE 21

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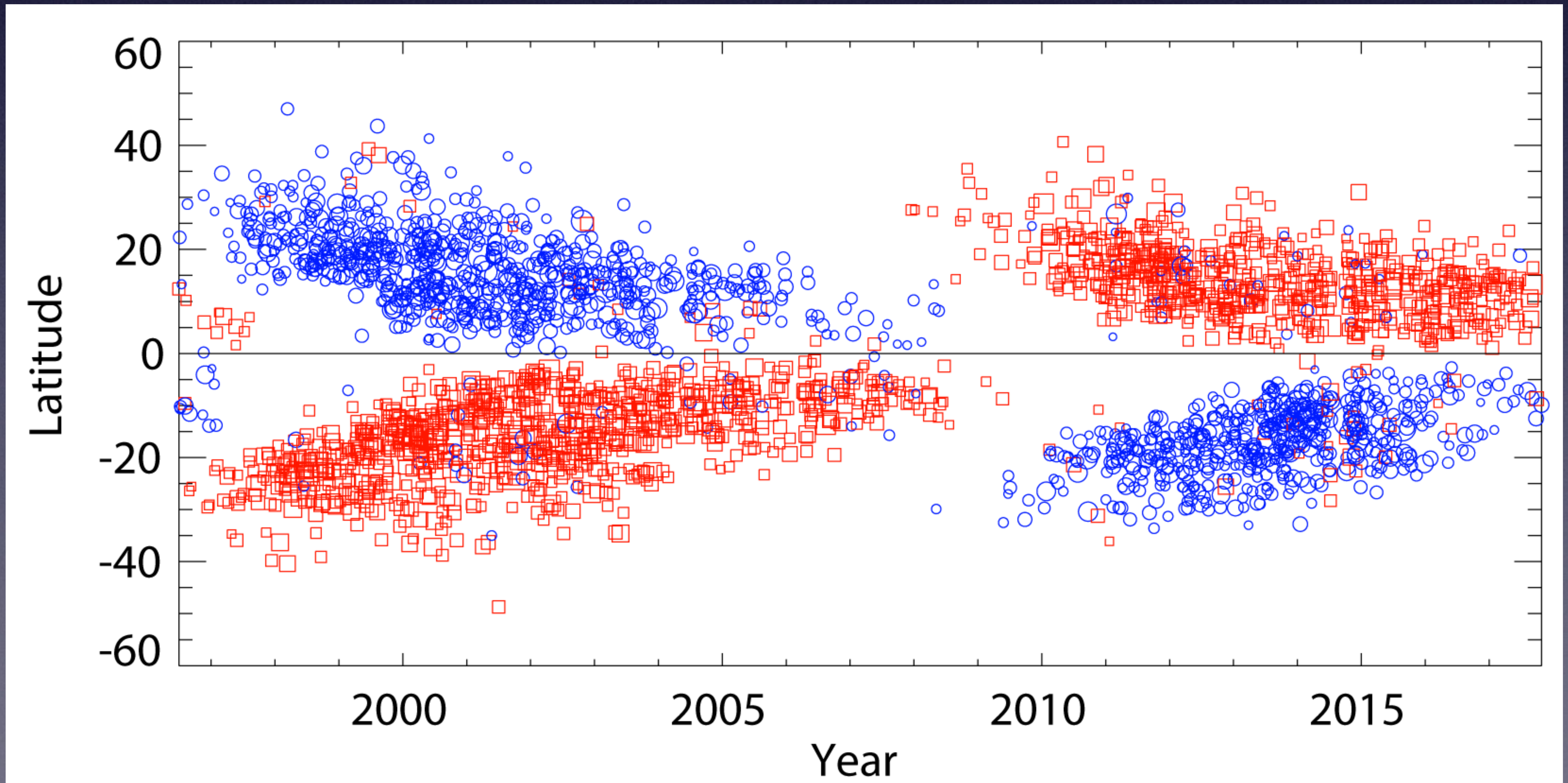
E.O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375–5000, U.S.A.

(Received 25 April, 1989)

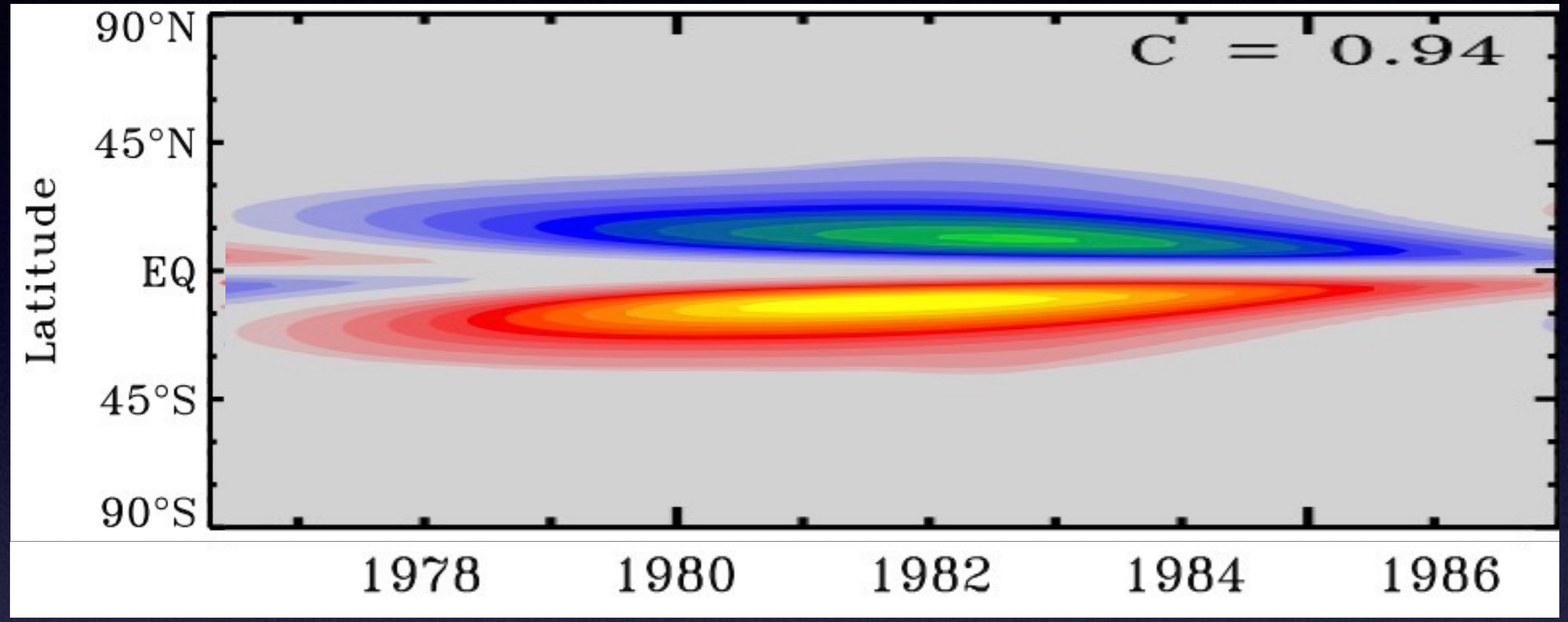


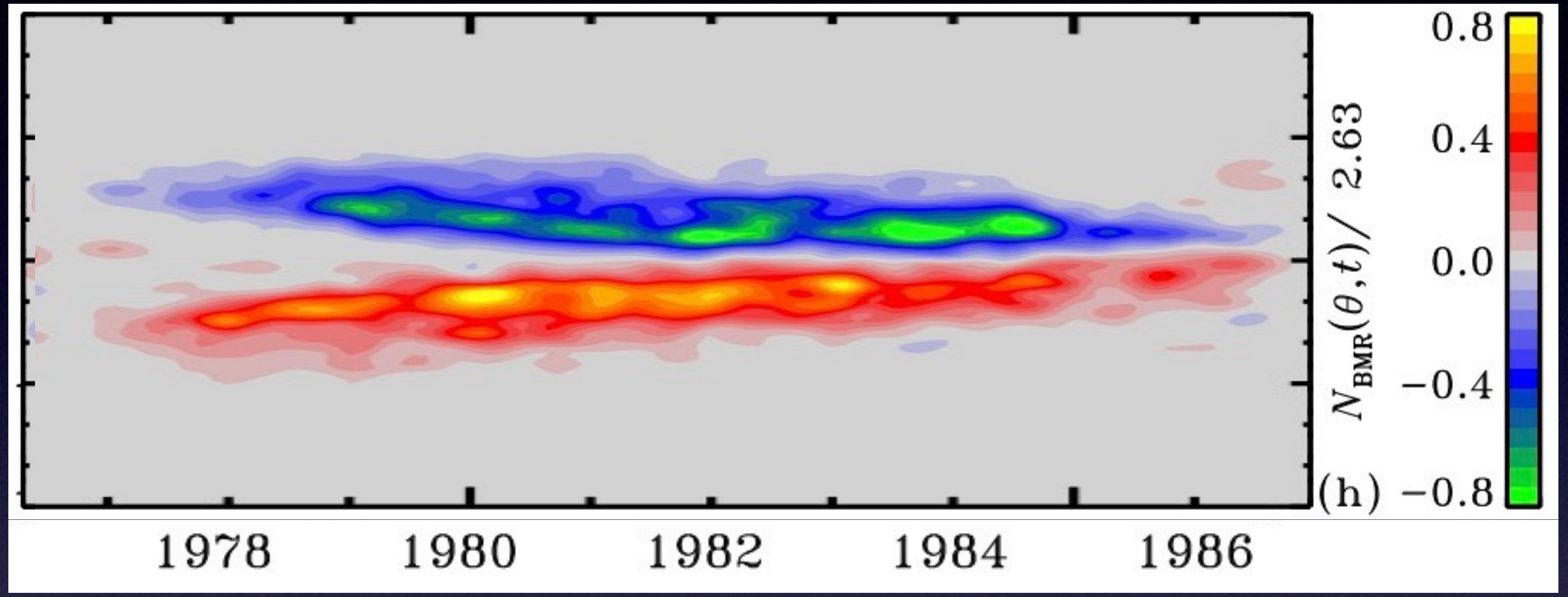
Yeates, 2016
dataverse.harvard.edu/dataverse/solardynamo (maintained by Muñoz)

Yeates et al, 2007

2. Self-emergence mode: BMR statistics

FTD emergence function ==> BMRs deposited in SFT





- probability of emergence <u>proportional</u> to B_φ strength, etc
  => 2 ajustable parameters: B_φ threshold & absolute number of emergences
- at <u>time</u> & <u>latitude</u>, directly above the source B_φ
- <u>tilt</u> angle, bipole <u>separation</u>, magnetic <u>flux</u> extracted from probabilistic distributions…

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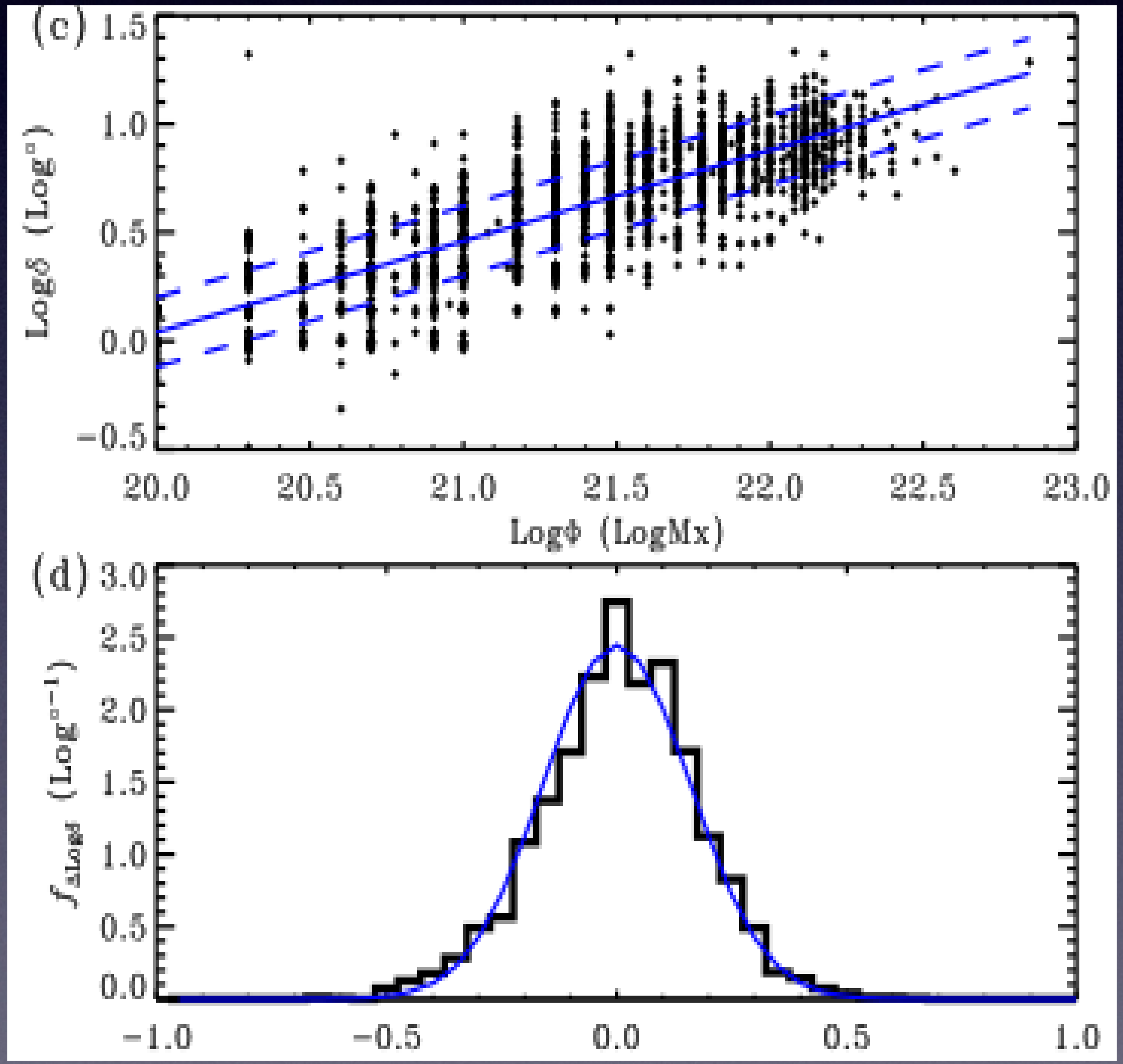
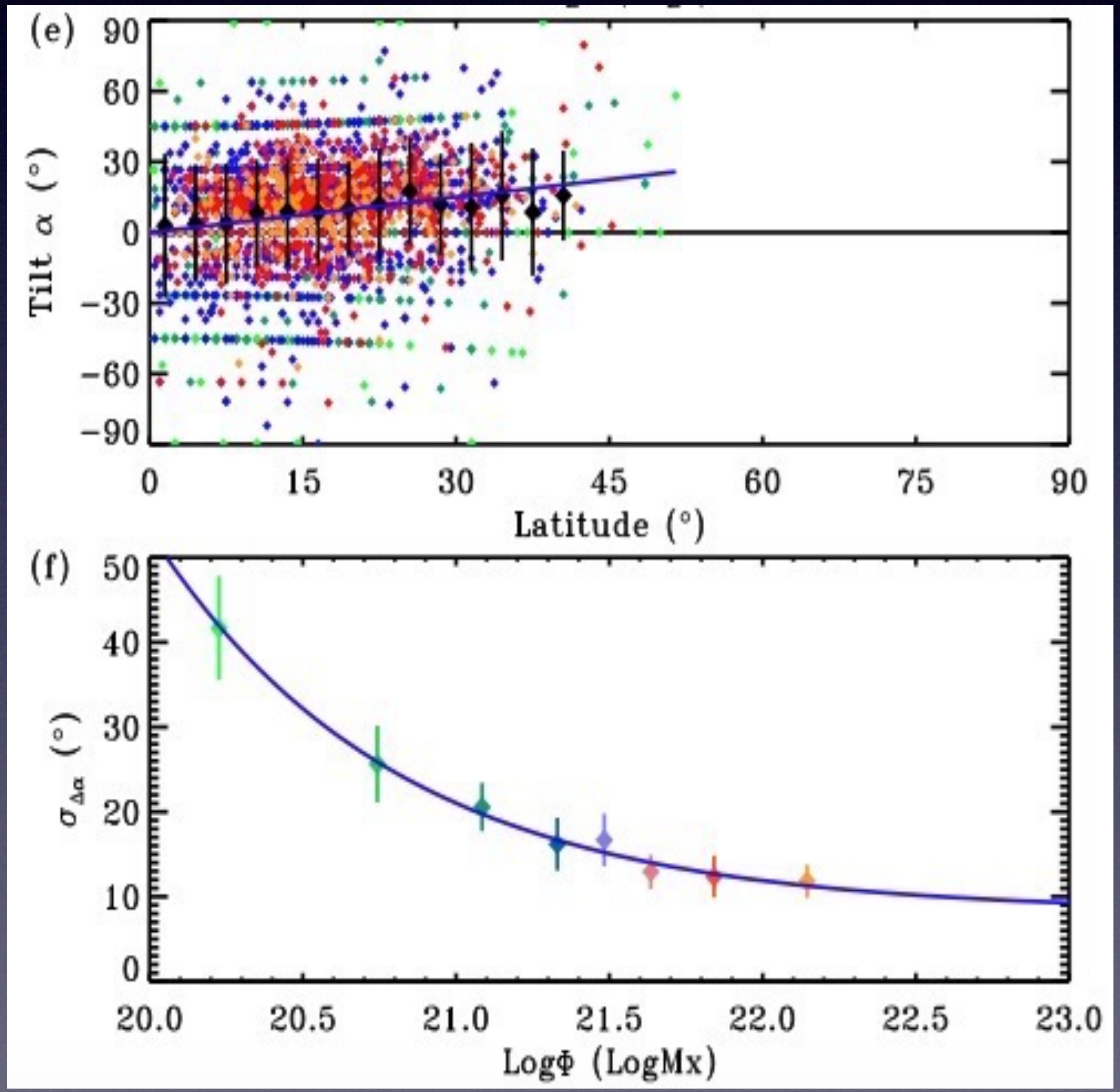
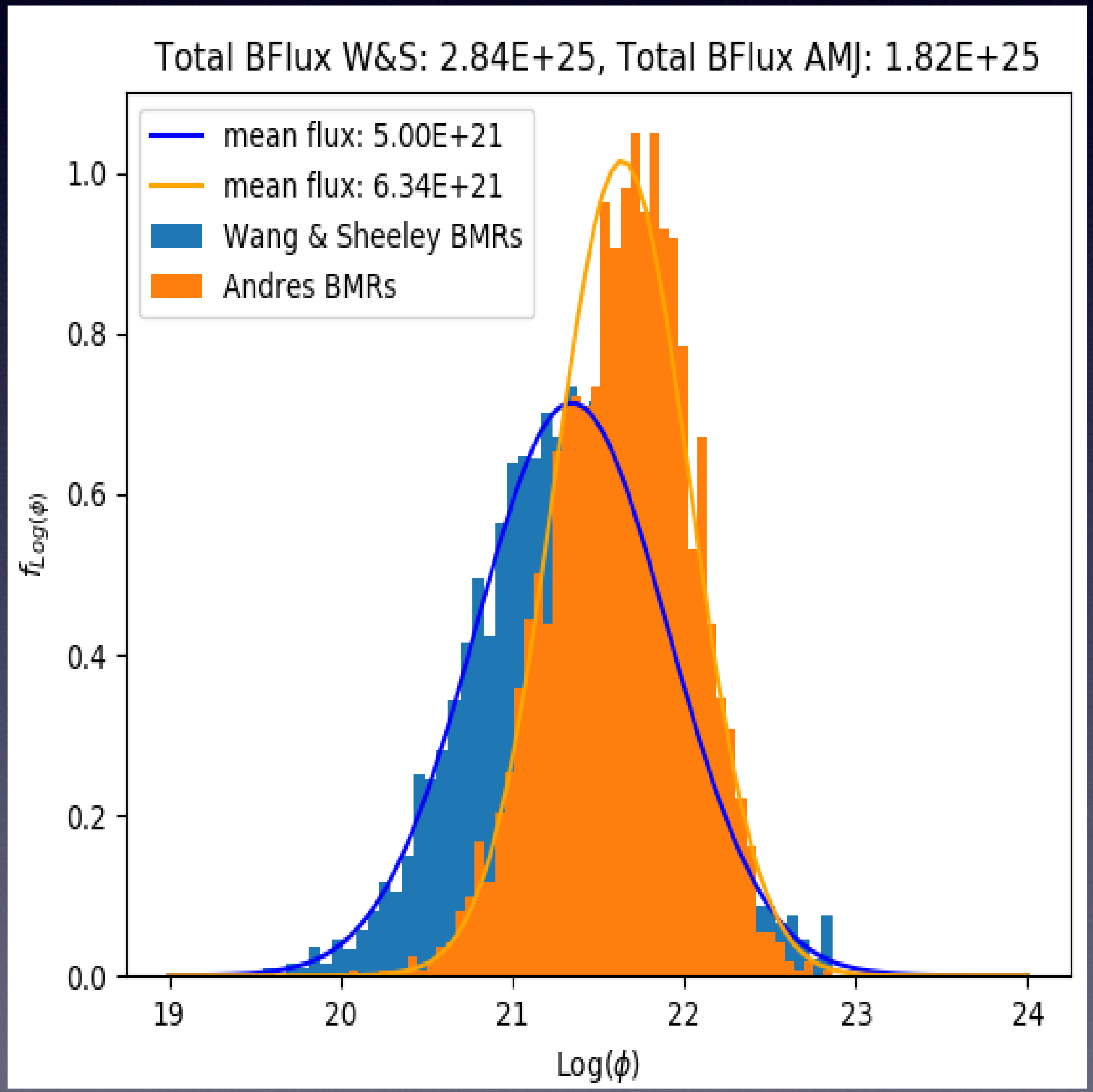
2. Self-emerging mode: BMR statistics

- inherent fluctuations associated with stochastic variations in BMR properties:
  => tilt angle, bipole separation and magnetic flux from probabilistic distributions…

scatter = primary source of stochasticity in the regeneration of the surface dipole







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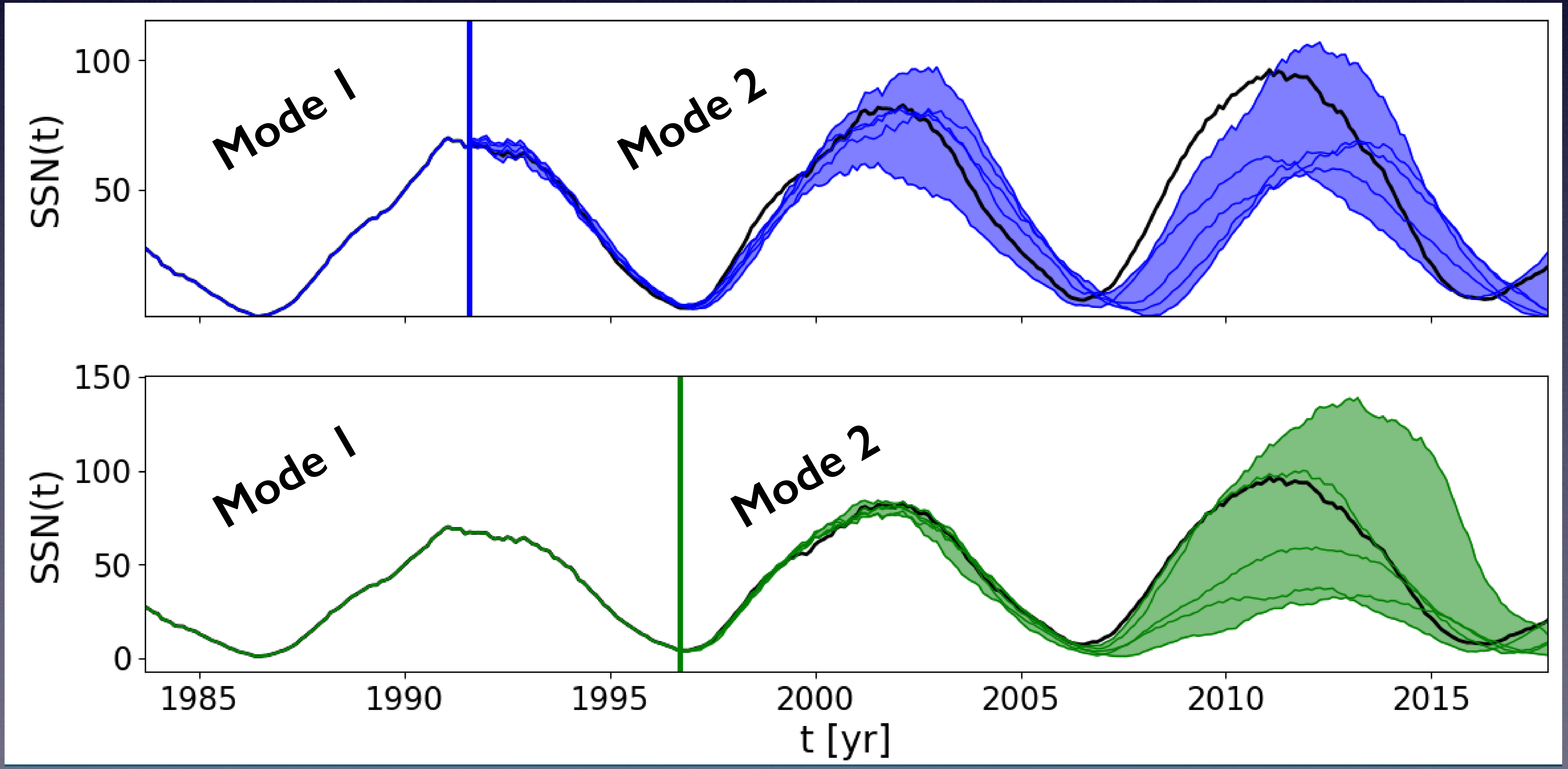
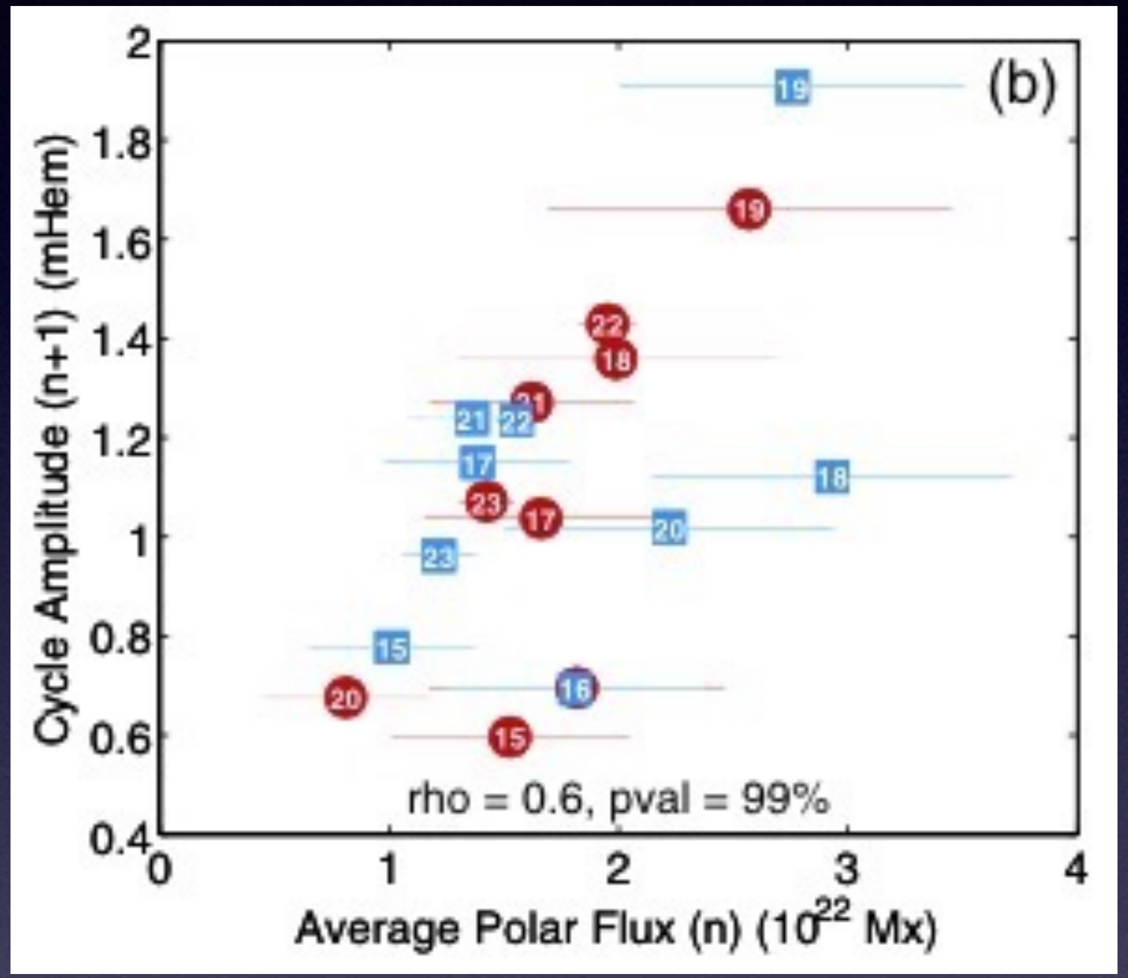
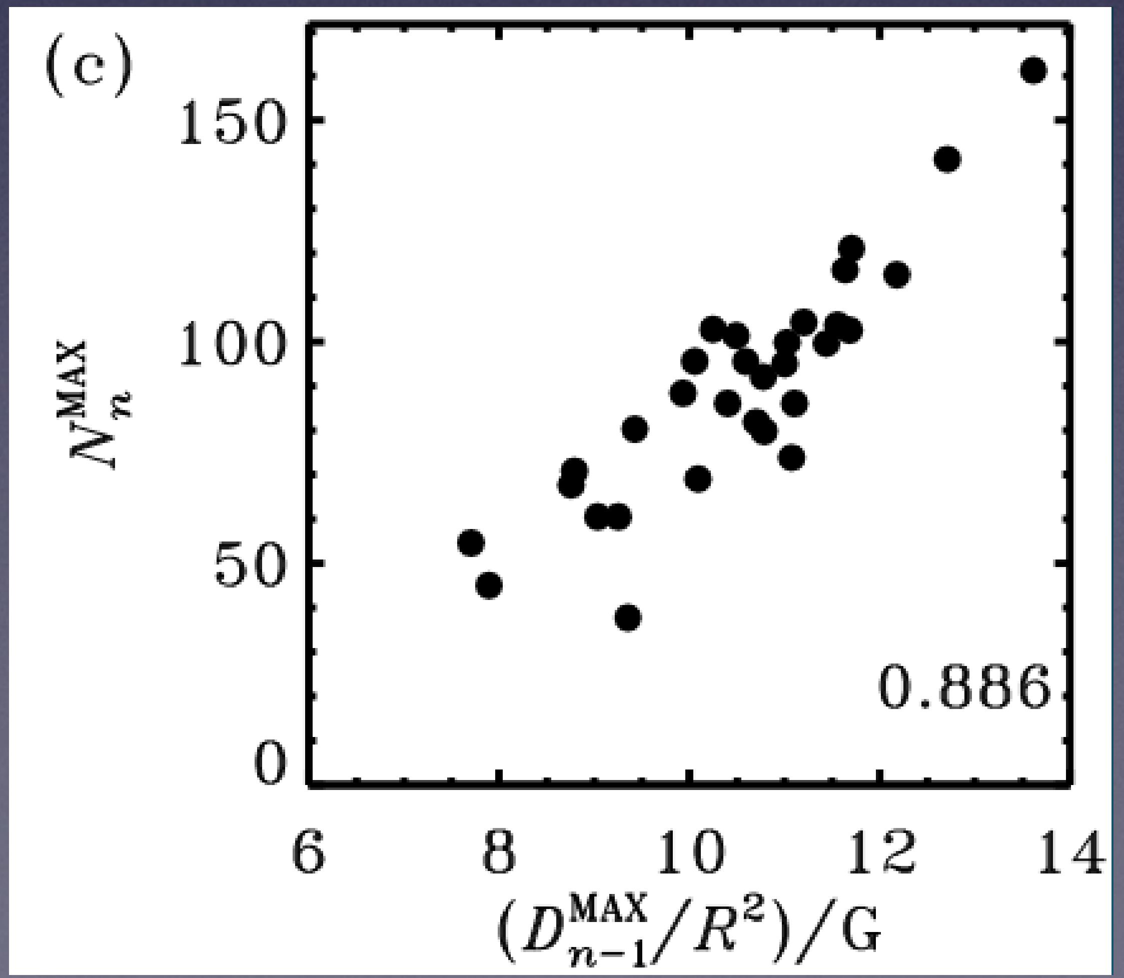
Predictability of solar activity

- Procedure :
  - Start in mode 1: deposit active regions taken from databases
  - Switch to mode 2 : the model emerge its own population of active regions
- Forecasting window:
  - ~one cycle, when the emergence mode is switched at cycle minimum







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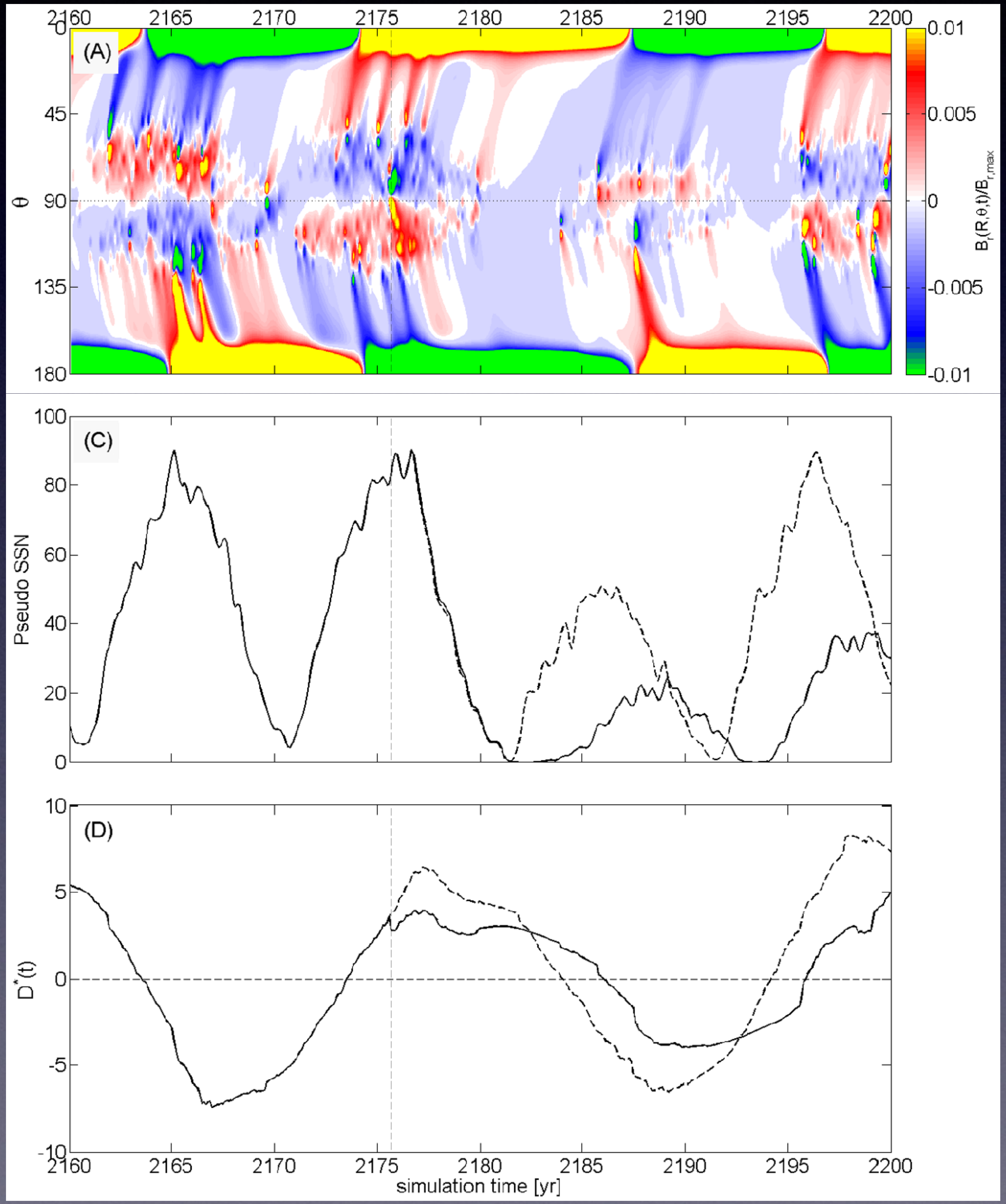
Predictability of solar activity

- But : effect of single <u>extreme</u> emergences (BMR) :



Nagy et al, 2017

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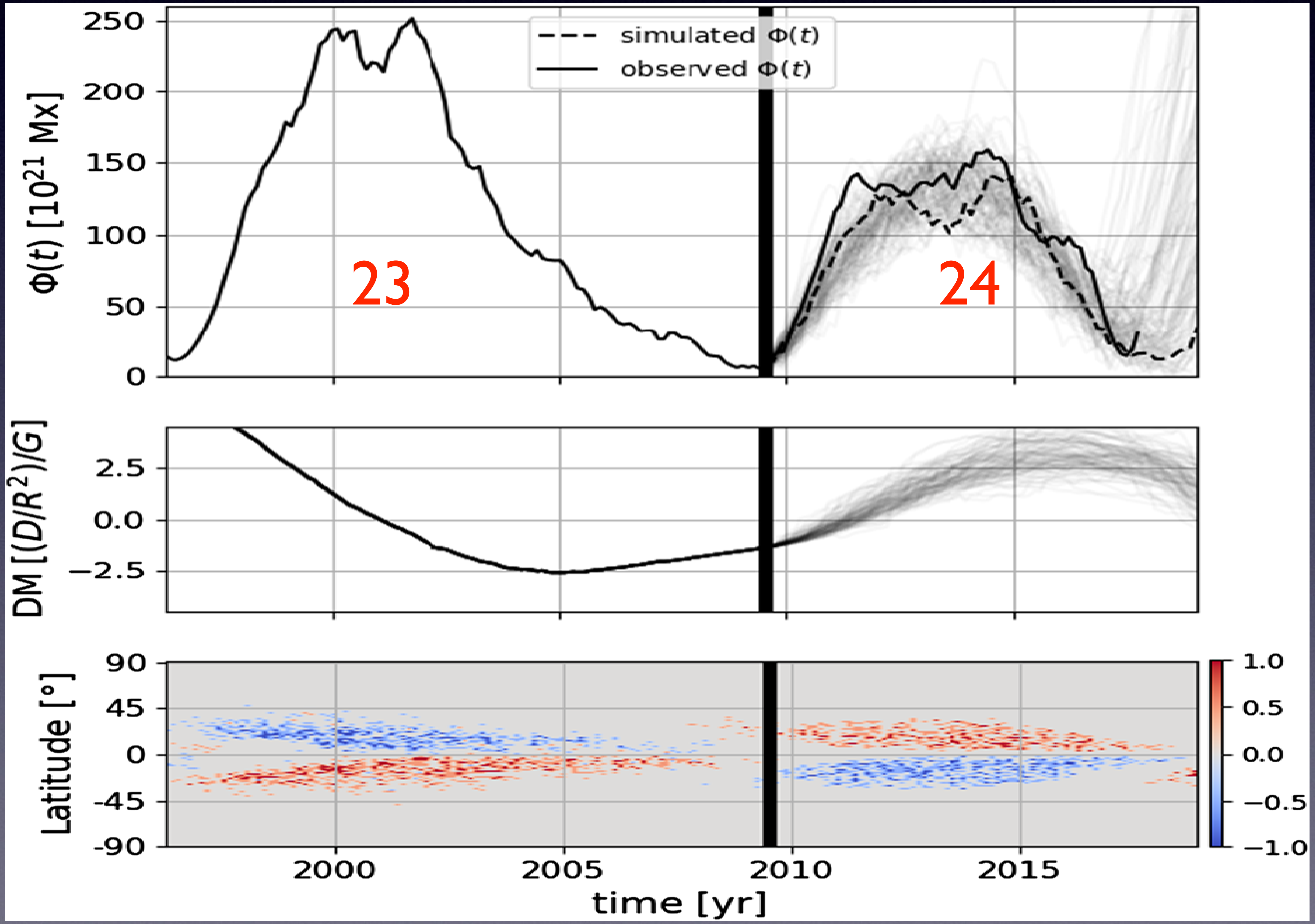
Data assimilation / calibration over cycle 24

- Adjust <u>strength of initial condition</u> (dipole) to reproduce end of cycle 23
- Adjust last model parameter (<u>*dynamo number*</u> « K ») to reproduce cycle 24



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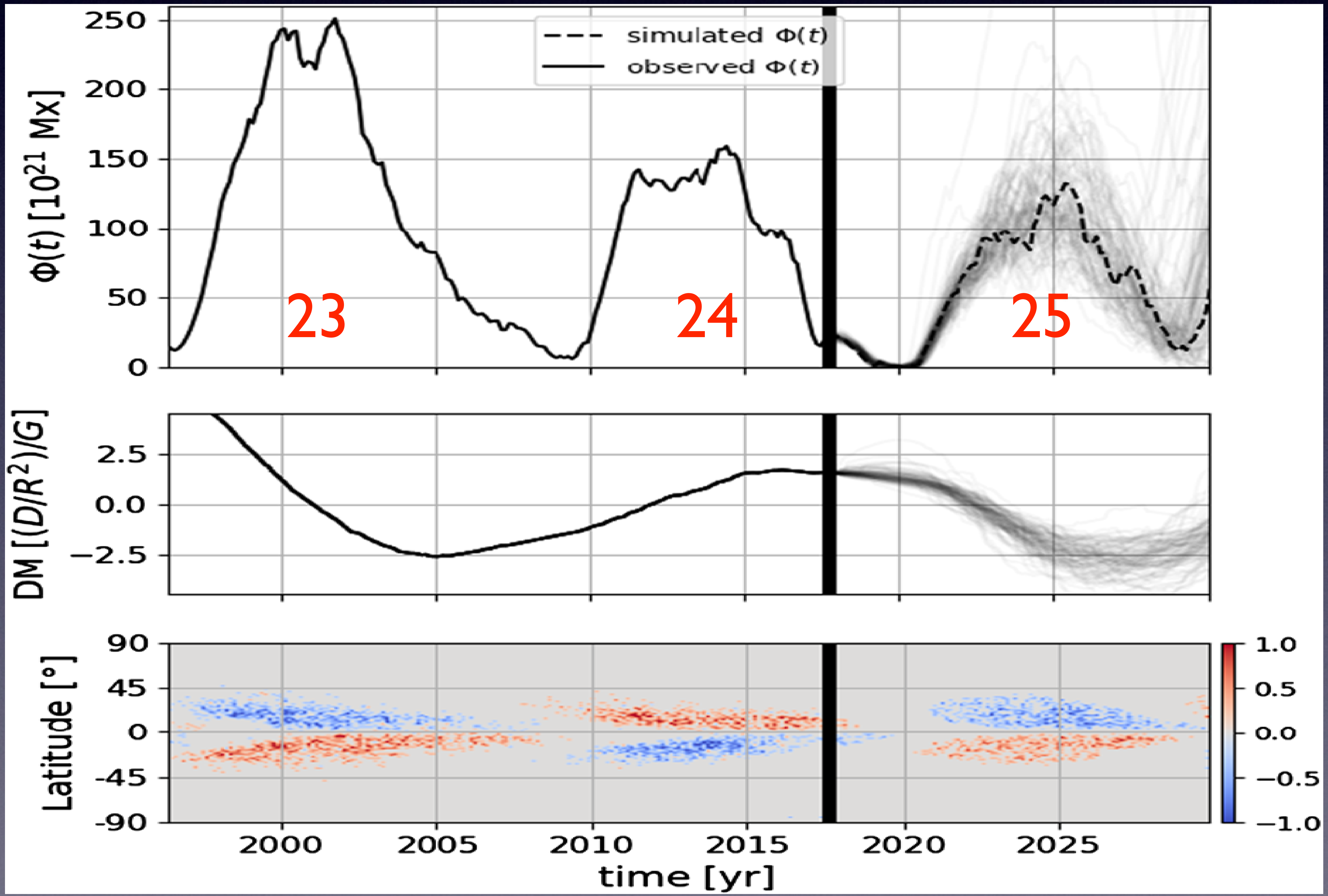
Forecasting cycle 25

- Ensemble forecast, with statistically independent realizations of active region parameters :
  - 1D+time: Sunspot number (SSN)
  - 1D+time: Axial dipole moment
  - 2D+time: Sunspot emergence lat-time map

$$\mathrm{ISSN} = 0.67 \times \frac{\Phi}{10^{21}\,\mathrm{Mx}} \quad [\text{Cycles } 23+24]$$



Metric	Global
Onset date	$2020.49^{+0.13}_{-0.12}$
Peak ISSN	89^{+29}_{-14}
Date of peak ISSN	$2025.27^{+0.89}_{-1.05}$
Cycle duration	10.0 ± 0.74

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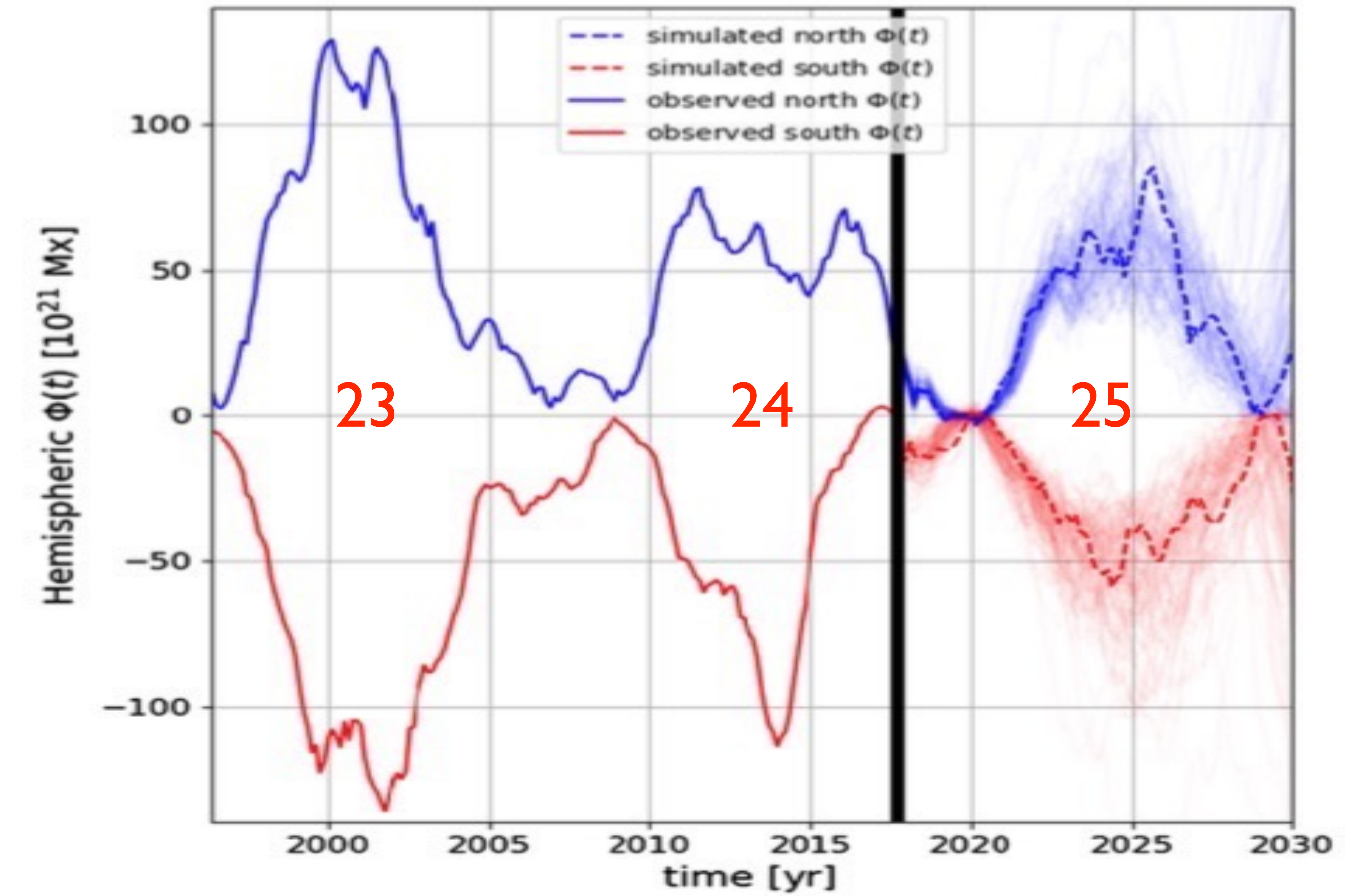
Forecasting cycle 25

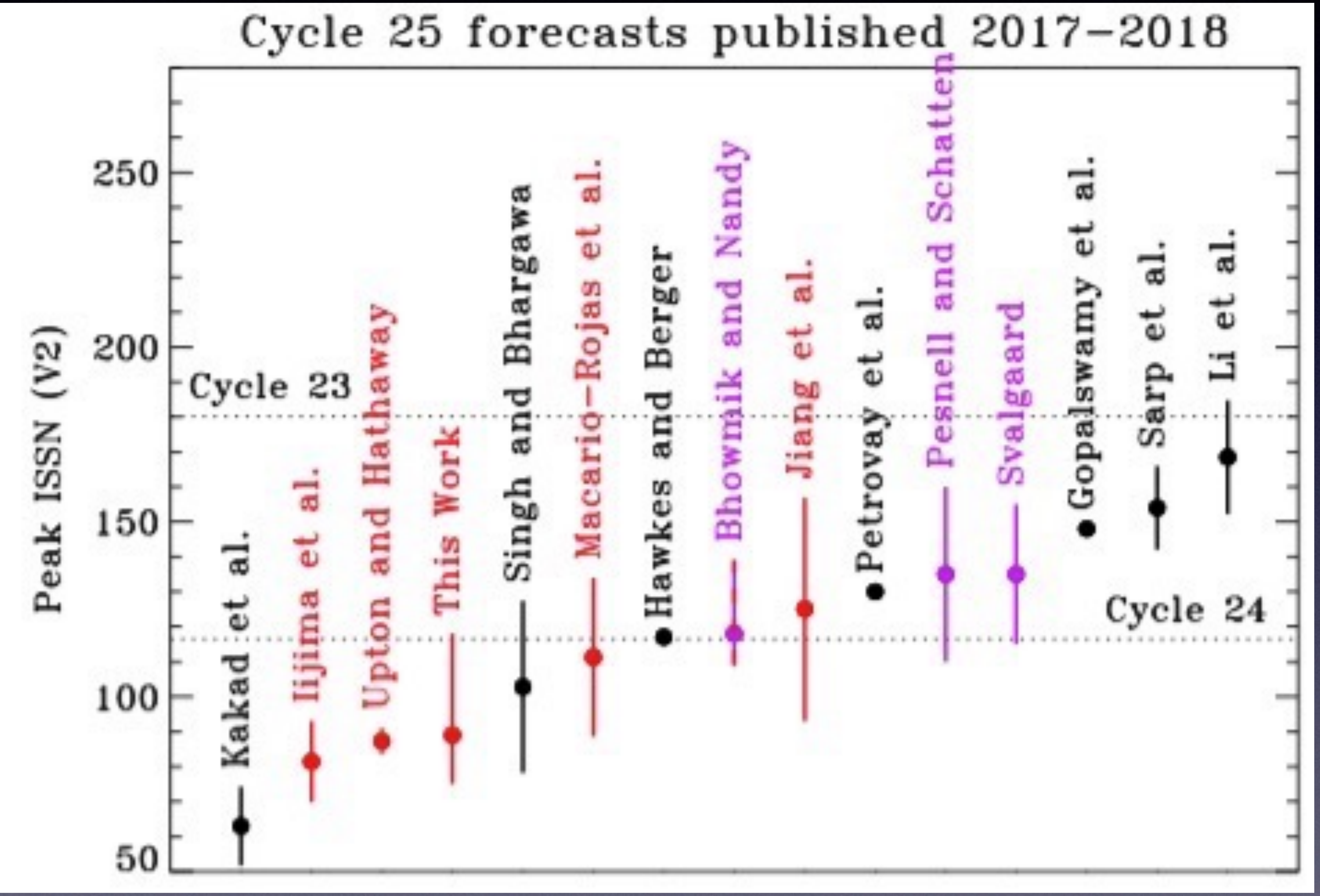
- Ensemble forecast, with statistically independent realizations of active region parameters :
  - 1D+time: Sunspot number (SSN)
  - 1D+time: Axial dipole moment
  - 2D+time: Hemispheric asymmetries

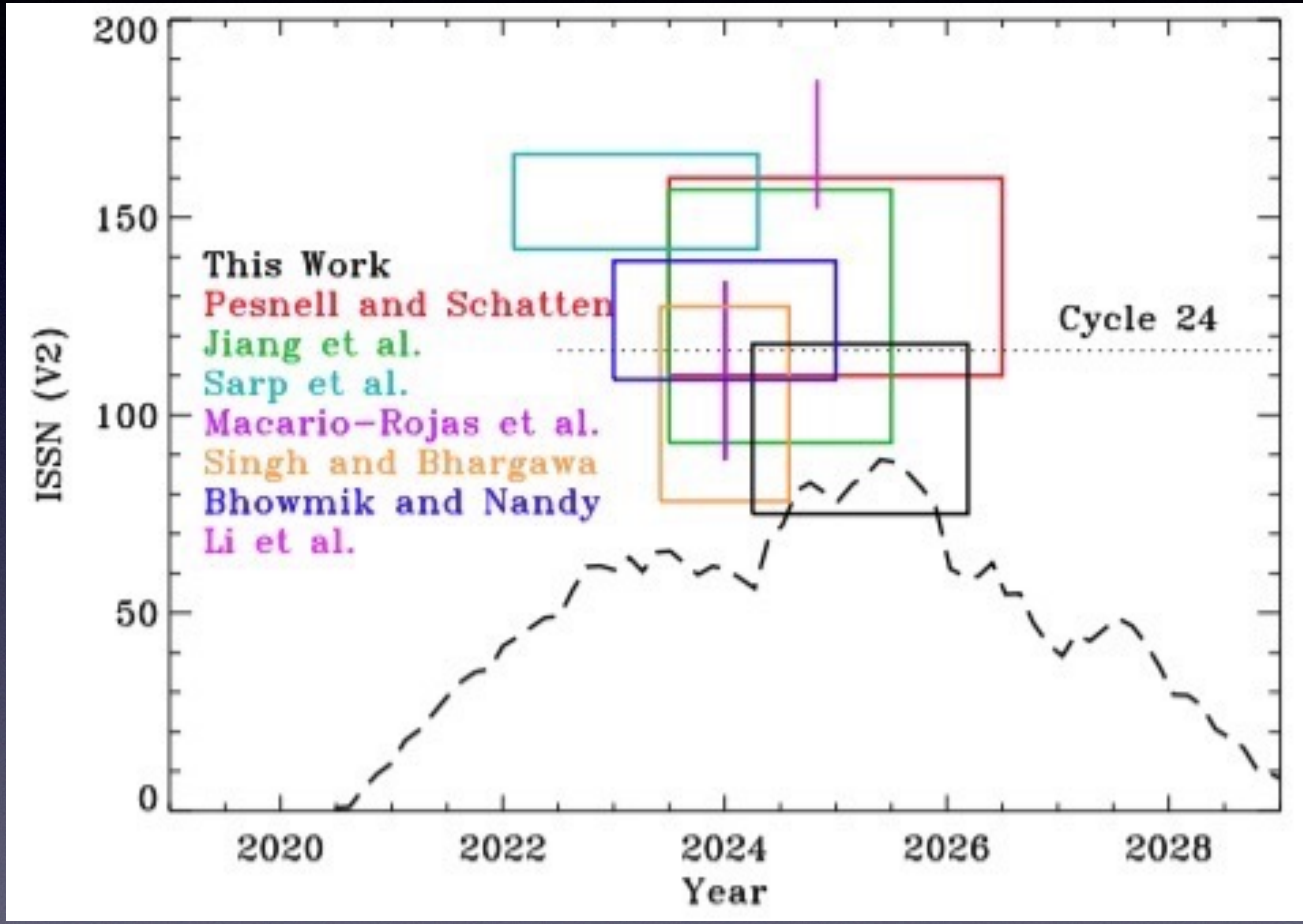


Metric	Global
Onset date	$2020.49^{+0.13}_{-0.12}$
Peak ISSN	89^{+29}_{-14}
Date of peak ISSN	$2025.27^{+0.89}_{-1.05}$
Cycle duration	10.0 ± 0.74

N-hemisphere	S-hemisphere
$2021.00^{+1.14}_{-0.13}$	$2020.49^{+0.13}_{-0.75}$
50^{+20}_{-10}	42^{+16}_{-9}
$2025.02^{+1.14}_{-0.93}$	$2025.15^{+1.13}_{-1.39}$
10.2 ± 1.22	10.3 ± 1.44

Forecasting cycle 25





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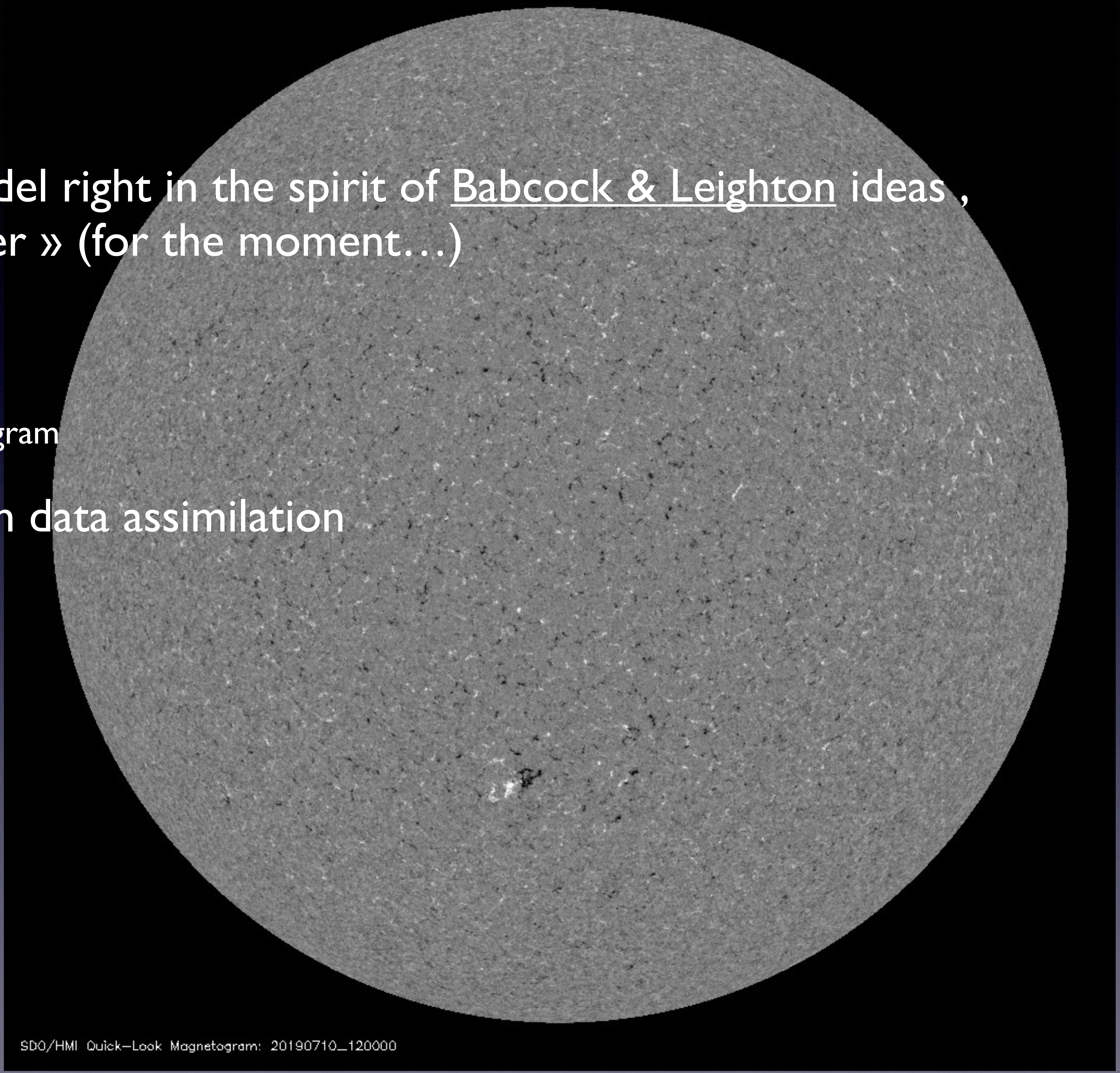
Summary

- A 2×2D hybrid SFT-FTD dynamo model right in the spirit of Babcock & Leighton ideas , « as simple as possible, but not simpler » (for the moment…)
- Doubly-calibrated on the Sun:
  - surface flux transport vs magnetograms
  - emergence function vs observed butterfly diagram
- Ready for *real-time* calibration through data assimilation
- A forecasted cycle 25 :
  - rather short (~10 years)
  - slightly weaker than cycle 24
- long rising phase
- weaker Southern hemisphere
- delayed Northern hemisphere
- room for a *strong* cycle 26



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