ASTRONOMICAL INSTITUTE OF THE ROMANIAN ACADEMY, 26 MAY 2021

THE SUNSPOT CYCLE

FROM UNDERSTANDING TO FORECASTING

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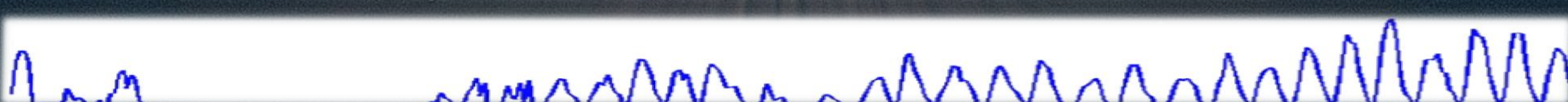
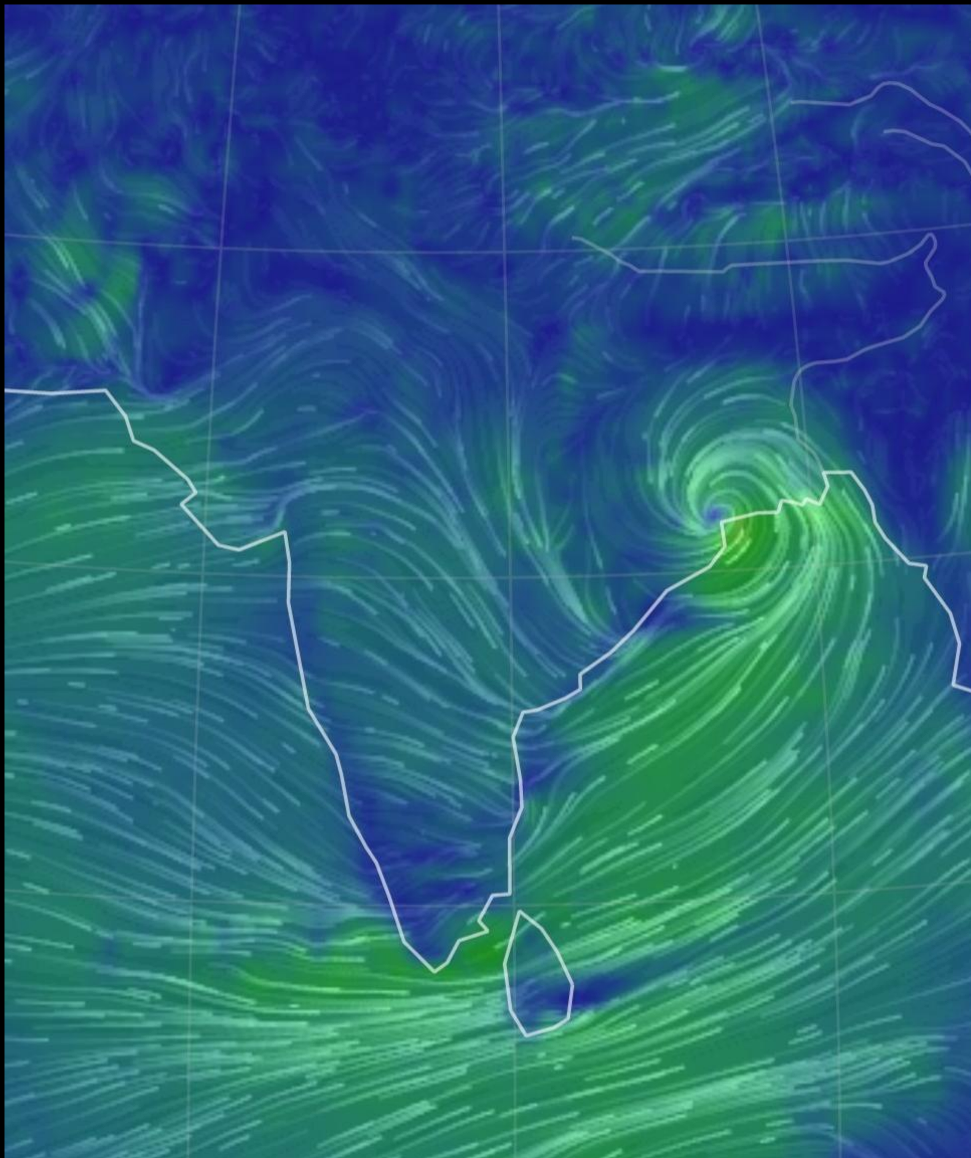
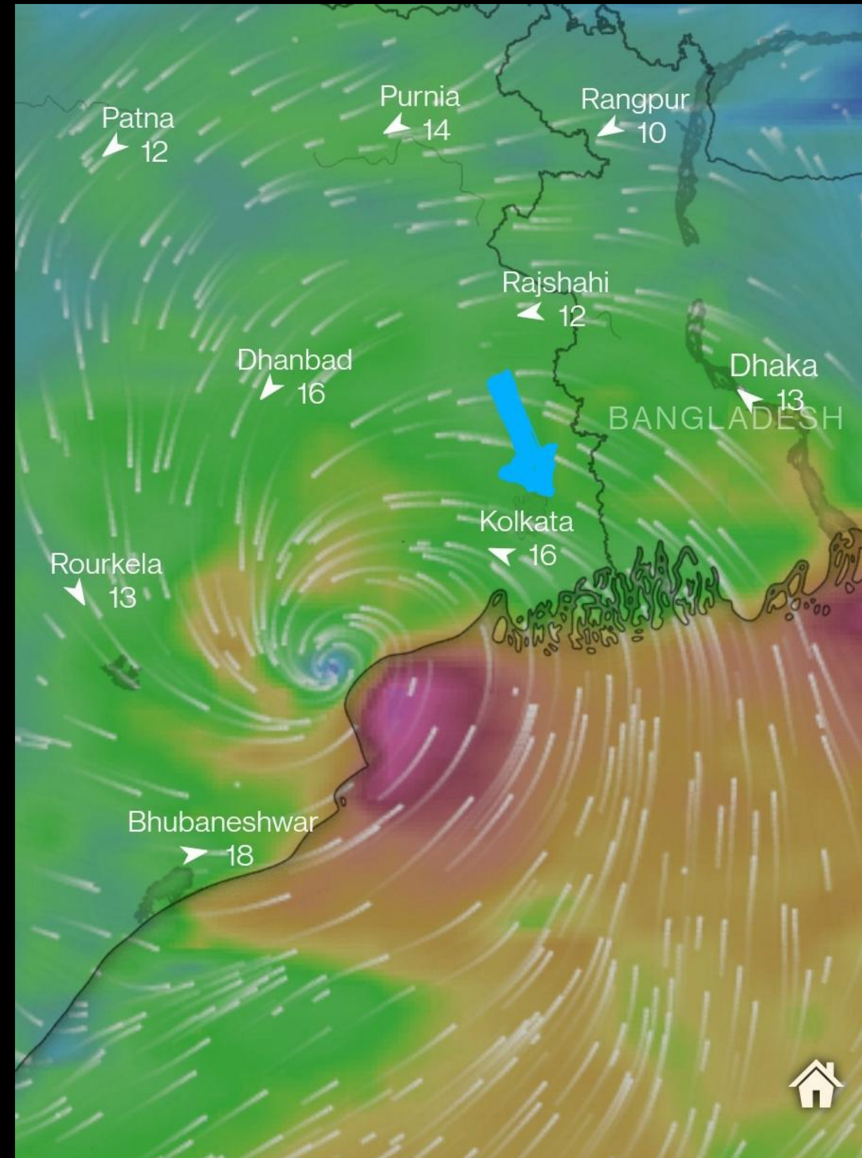


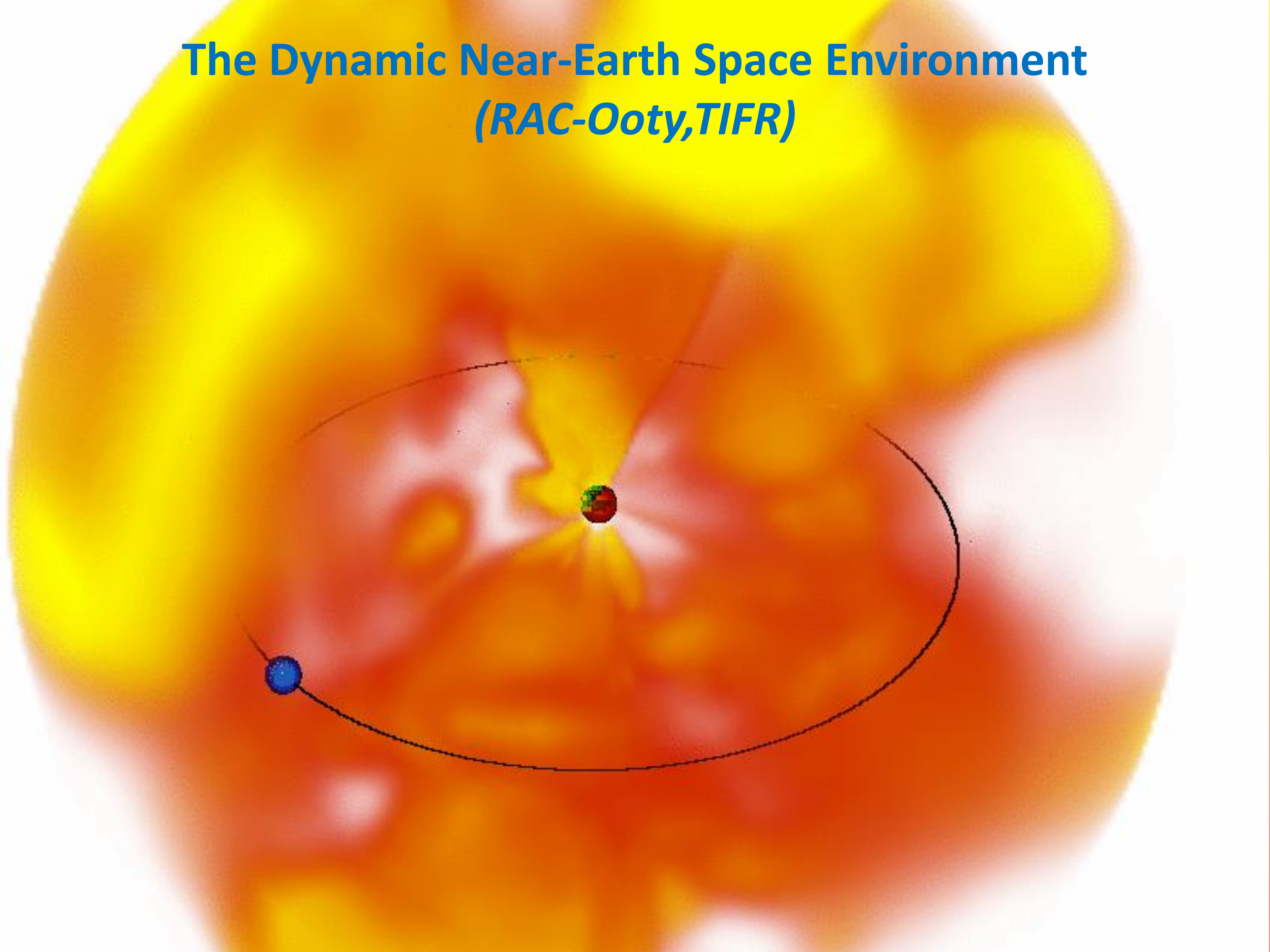
Hellos from Kolkata India



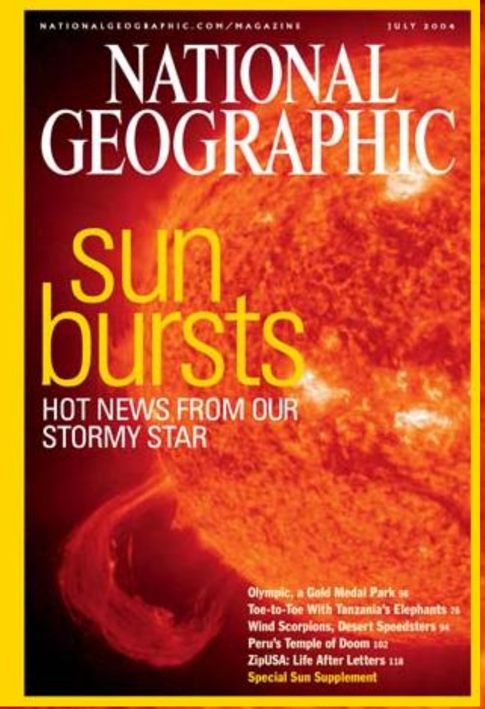


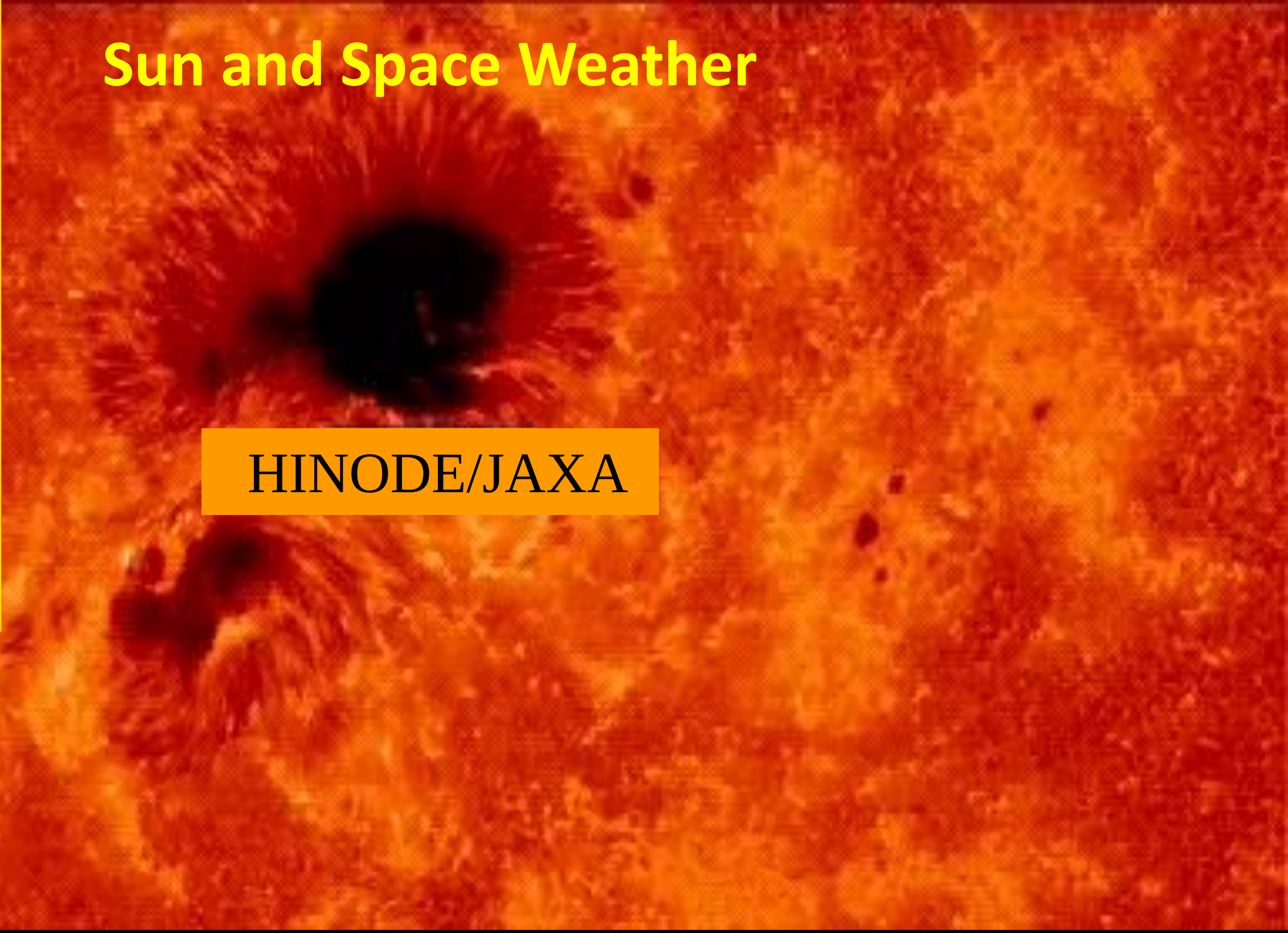
The Dynamic Near-Earth Space Environment

(RAC-Ooty,TIFR)



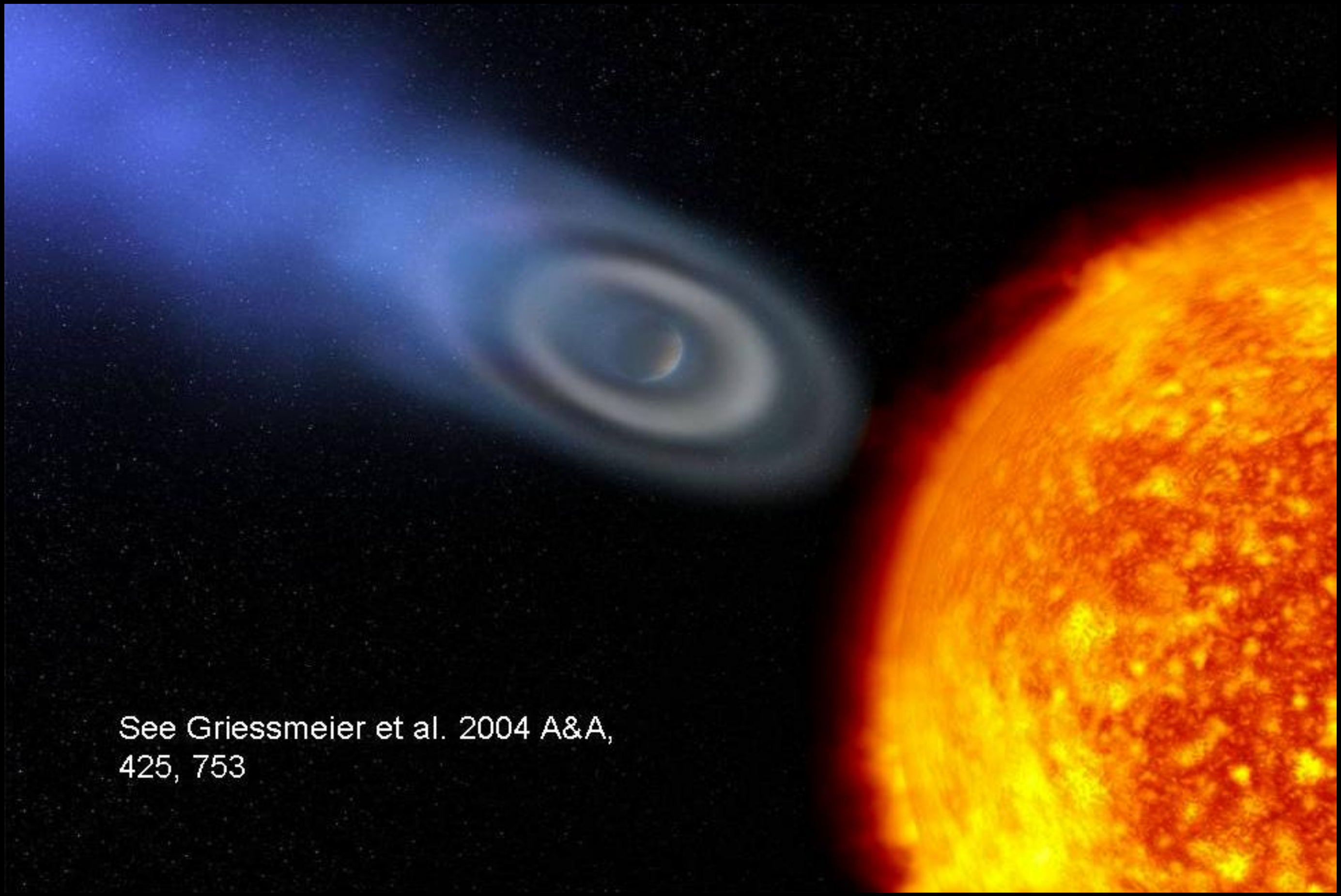
Sun and Space Weather





In our own solar system, studies of solar flares and CMEs, solar wind and radiative flux variations create space weather, predicting which is a major goal in space sciences

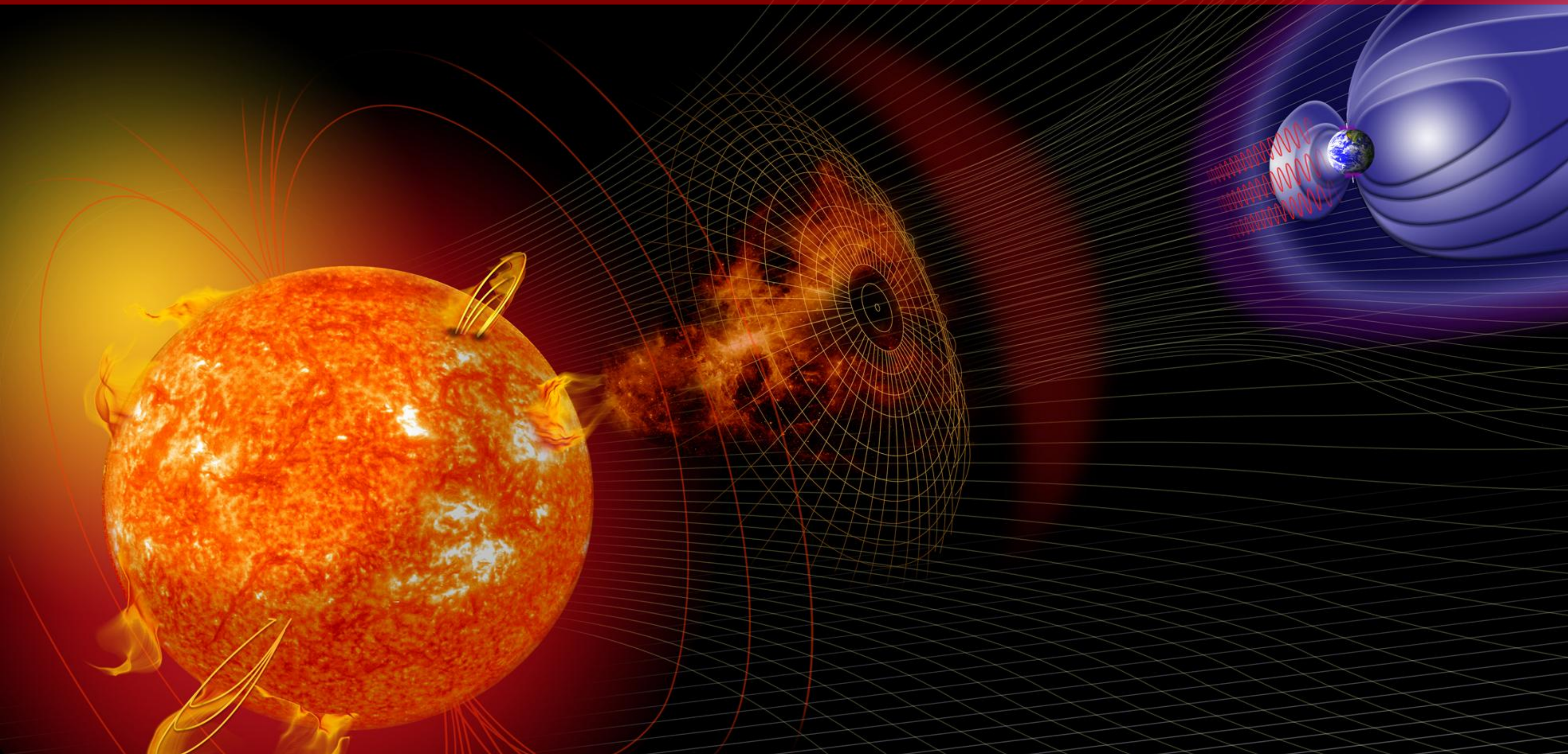
Window to (Exo)Planetary Environments



The most energetic dynamical phenomena near planetary atmospheres involve the stellar wind, stellar radiative and particle fluxes. Planets with weak or no magnetic field may lose their atmosphere due to sputtering processes driven by stellar radiation (EUV) and wind, thus becoming inhabitable; relevant for searches for habitable exoplanets

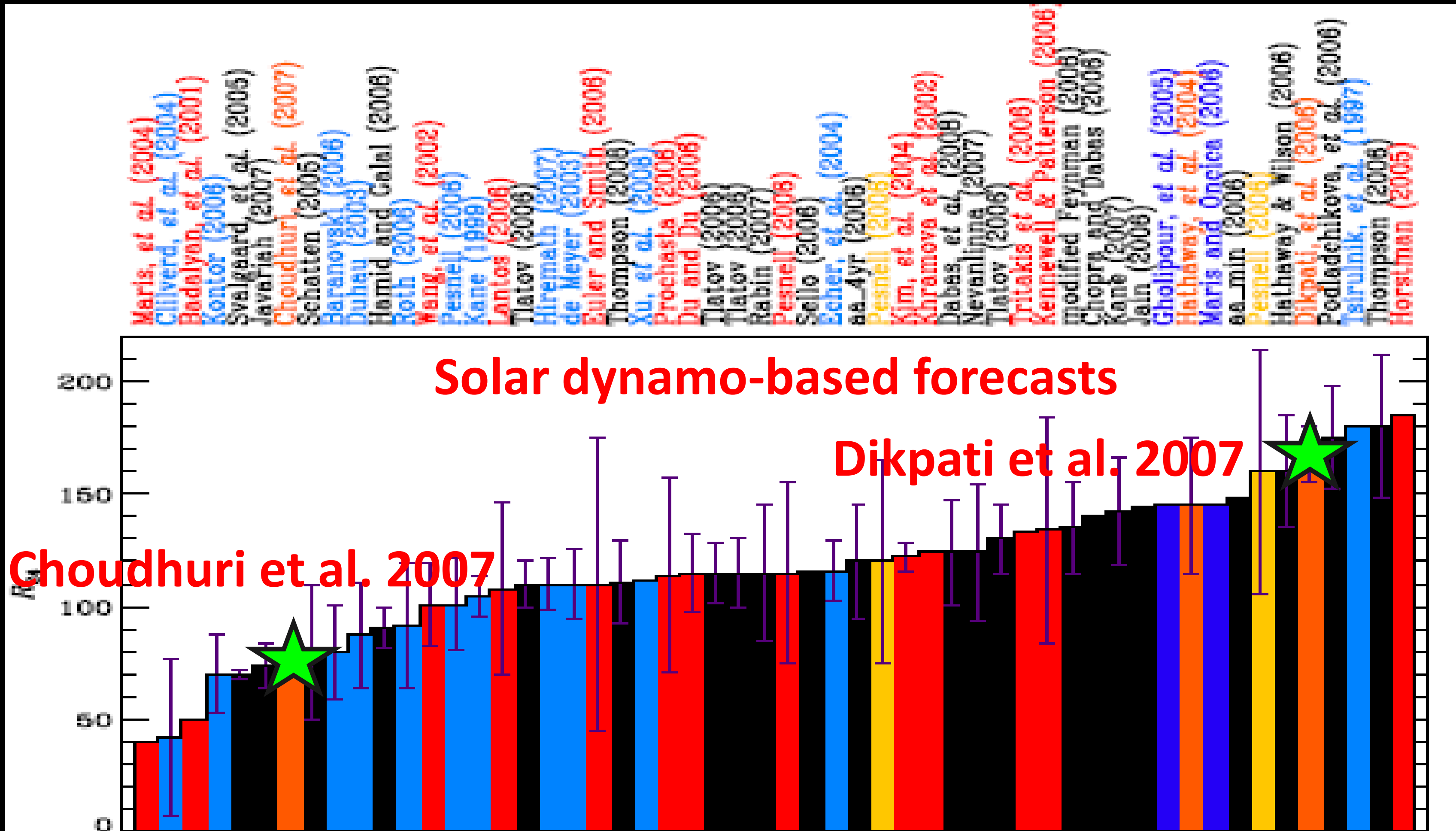
Connected Domains of Star-Planet Systems

PLASMA β > 1	PLASMA β < 1	PLASMA β > 1
Surface + Interior	Corona	(Helio)Astrosphere



Solar Cycle	Flares, CMEs	Star-Planet
Flux Evolution	Plasma Winds	Interactions

Predicting the Solar Magnetic Cycle



Spread of predictions for solar cycle 24 spanned the entire range of all sunspot cycles ever directly observed

(Pesnell 2008, Solar Physics)

The Context

It is desirable that assimilation of physical understanding of the Sun's interior and the solar dynamo mechanism should lead to predictive models of the solar cycle

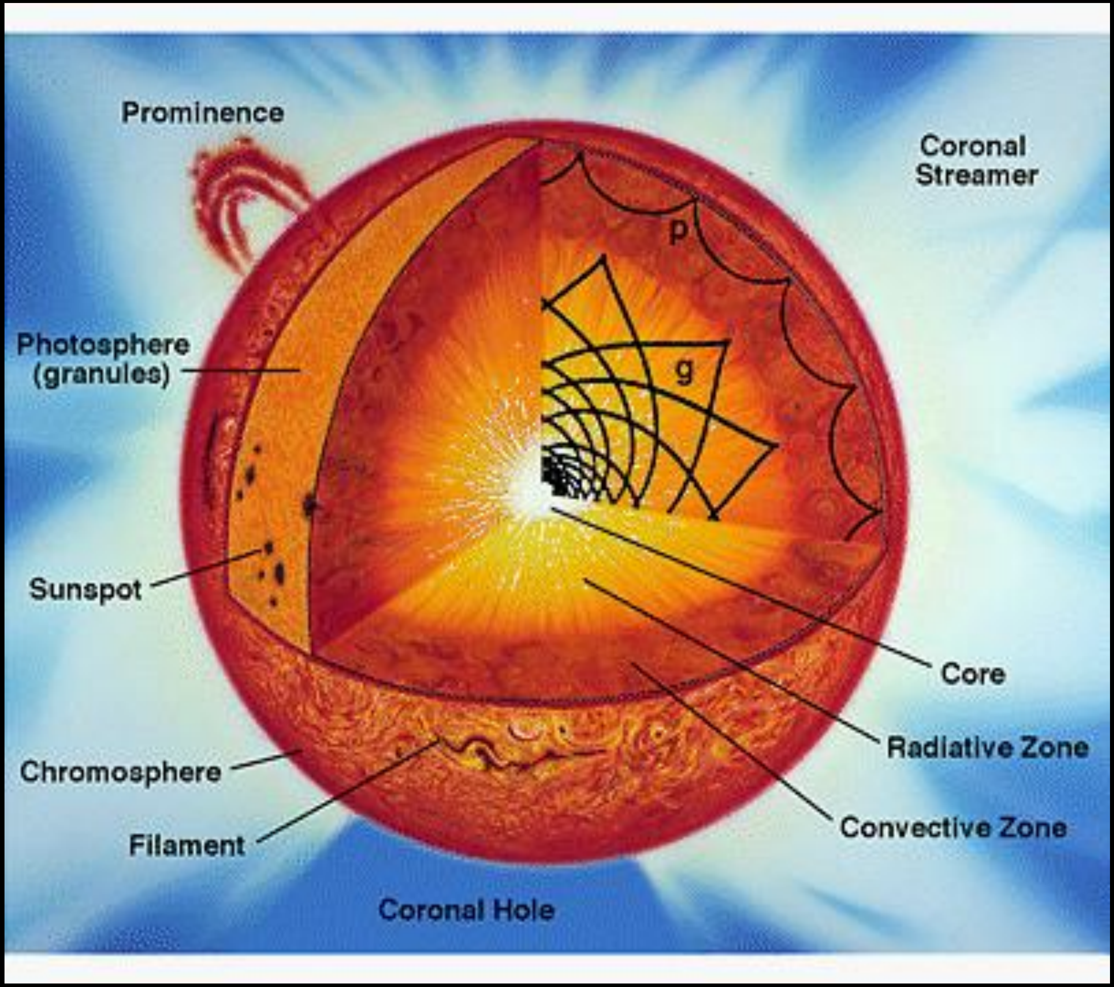
Such convergence, e.g., has been achieved to a reasonable degree of satisfaction in the global climate modeling community, but has (apparently) continued to evade the solar physics community

It is important for the community to know that in recent times, we have made significant progress in our understanding of the predictability of the sunspot cycle…

An important point to keep in mind…

Organized efforts for predicting weather / global climate have evolved over many decades; in contrast, only about a decade of efforts spent to understand the predictability of the sunspot cycle from the physical perspective

Window to the Solar Interior: Plasma Motions



- Matter exists in the plasma state (highly ionized) inside Sun
- Convection zone has both small scale turbulent flows and large scale structured flows
- So we are dealing with the dynamics of magnetized plasmas

Magnetohydrodynamic Considerations

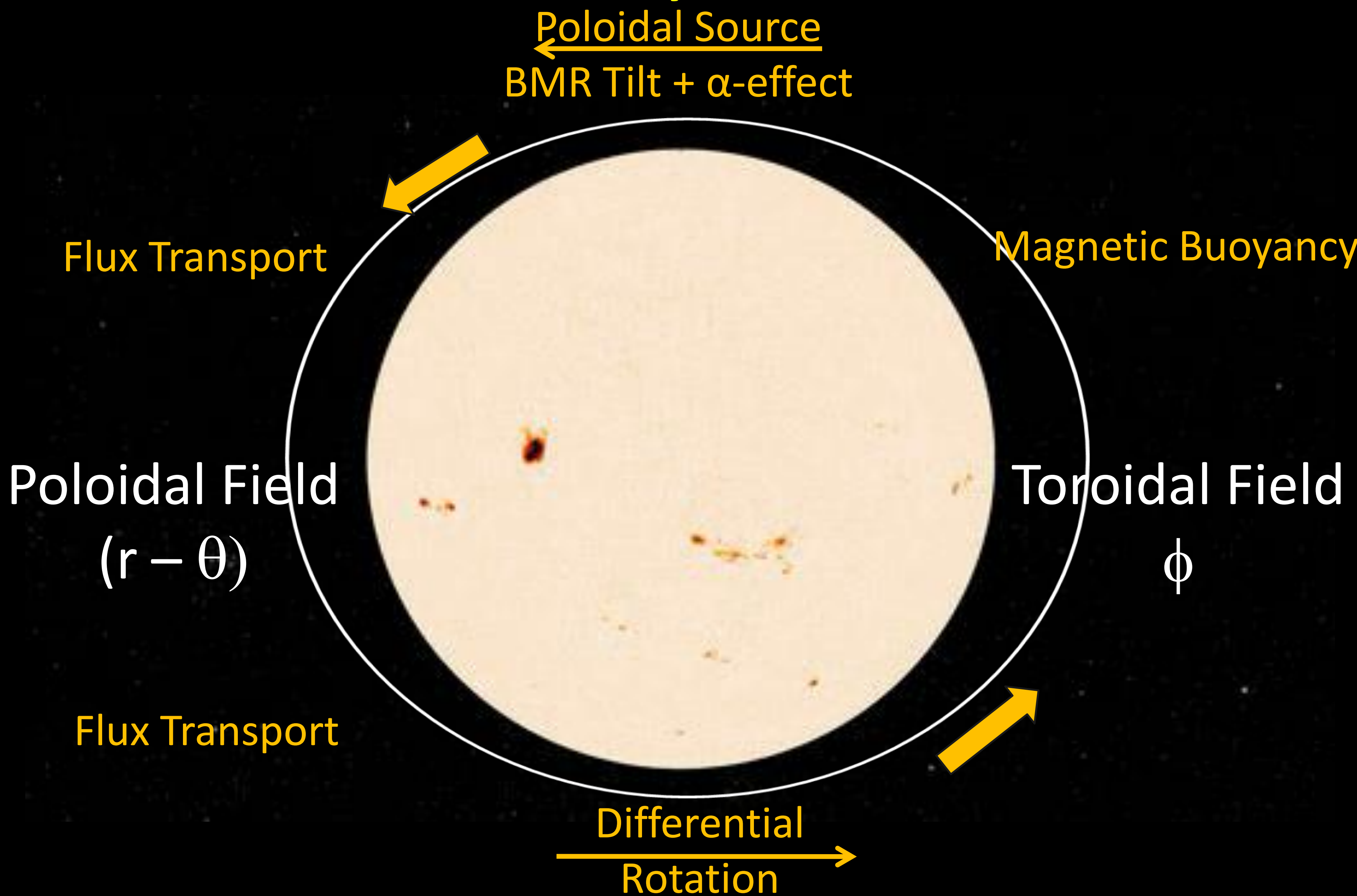
- Governing equation: $$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}$$

- Magnetic Reynolds Number: $$R_m = \frac{VB/L}{\eta B/L^2} = \frac{VL}{\eta}$$

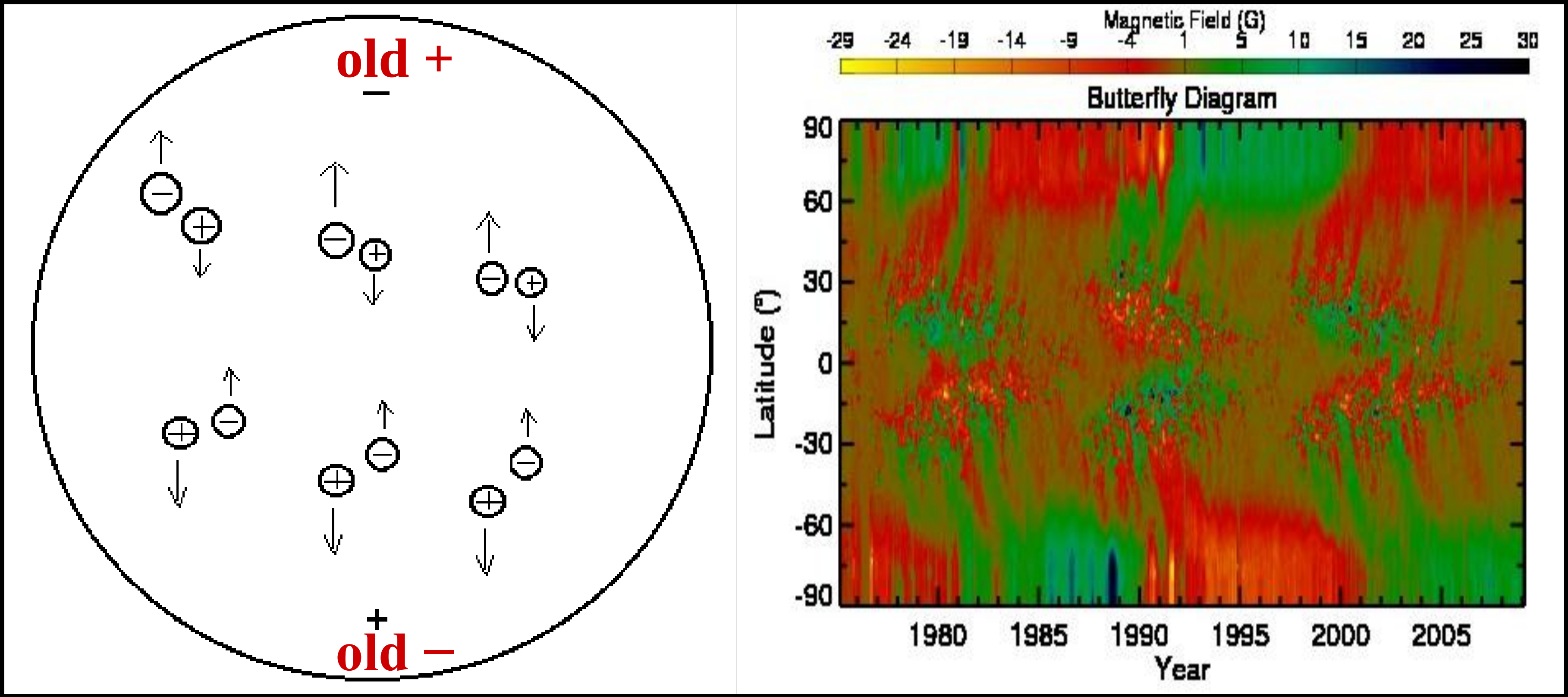
- In Astrophysical systems, R_M usually high, magnetic field creation and sustenance possible and fields are "frozen" in the plasma (Hannes Alfvén 1942)
  —Diffusion timescale τ_η > Flow timescale τ_v

- Plasma β parameter (ratio of gas-to-magnetic pressure) is high inside the Sun; allows plasma flows to influence magnetic fields

Premise of Solar Dynamo Mechanism

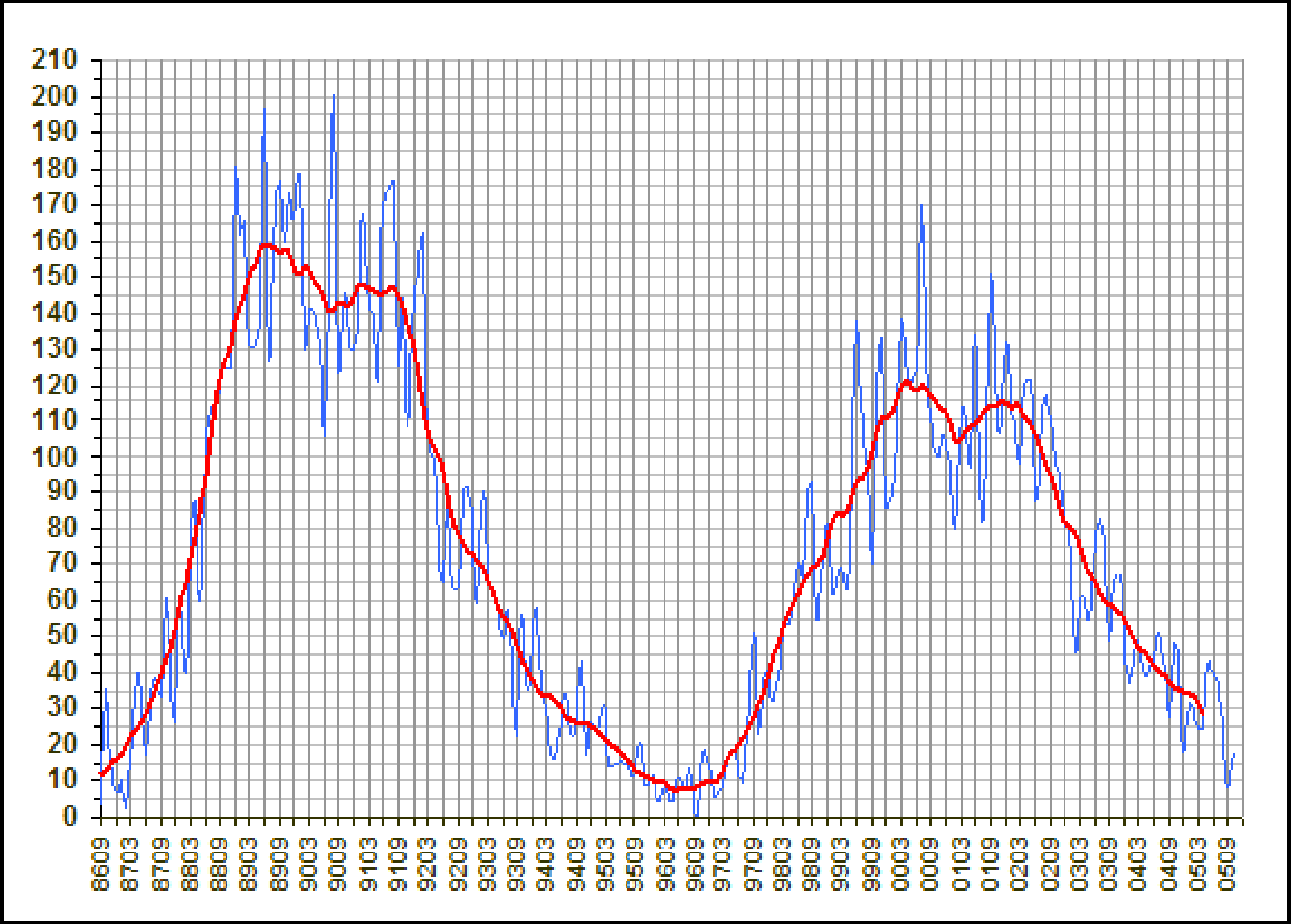


The Poloidal Field Generation Mechanism



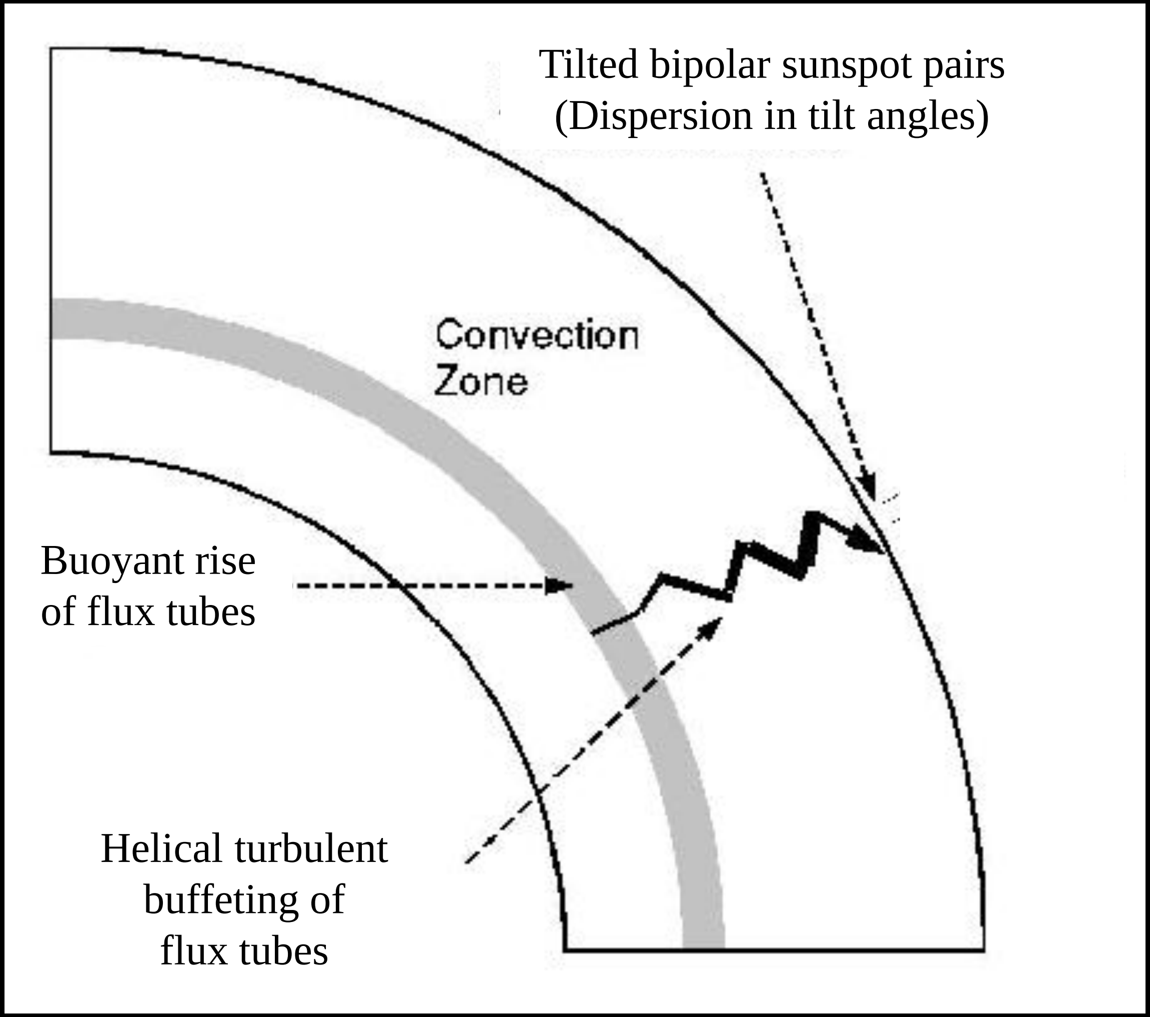
- Babcock (1961, ApJ) & Leighton (1969, ApJ) idea: tilted bipolar sunspots pairs decay and disperse near surface – <u>is observed</u>
- Numerous dynamo models have been based on the BL idea
- Theory supports this (Cameron & Schuessler 2015, Science)
- Data-driven models support this (Bhowmik & Nandy 2018, NatCom)

Fluctuations in the Solar Cycle and Predictability



The first step towards prediction is to understand dynamo processes that contribute to solar cycle strength and modulates it

Origin of Cycle Amplitude Fluctuations?



Poloidal field source (eruption of tilted bipolar sunspots) is stochastic due to turbulent buffeting of rising magnetic flux tubes, with observed scatter around Joy's law (mean tilt due to Coriolis force)

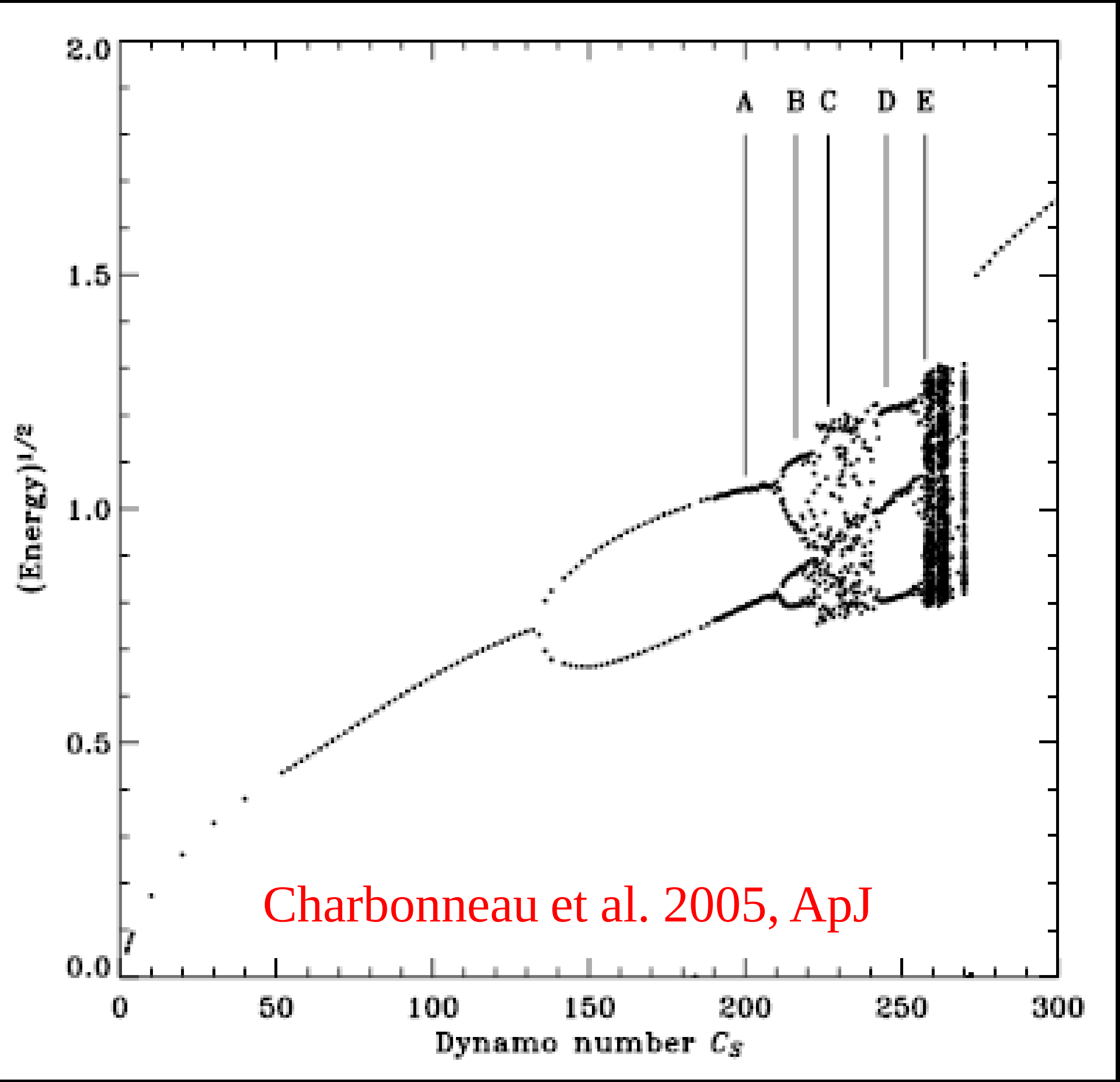
Non-linear Dynamics of the Solar Cycle

Dynamical nonlinearities are inherent in the dynamo system

—Magnetic feedback on internal and surface flows
(Tobias 1997, A&A, Wilmot-Smith et al. 2005, MNRAS, Rempel 2005, ApJ, Jiang et al. 2010, A&A)
—Helicity quenching
(Blackman & Brandenburg 2002, ApJ)
—Time delay effects
(Wilmot-Smith et al. 2006, ApJ, Jouve, Proctor & Lesur 2010, A&A)
—Dynamical buoyancy effects
(Kumar, Jouve & Nandy, 2019, A&A)
—Magnetic feedback on active region tilts and tilt quenching
(D'Silva & Choudhuri A&A, 1993, Jha et al. 2020, ApJL)

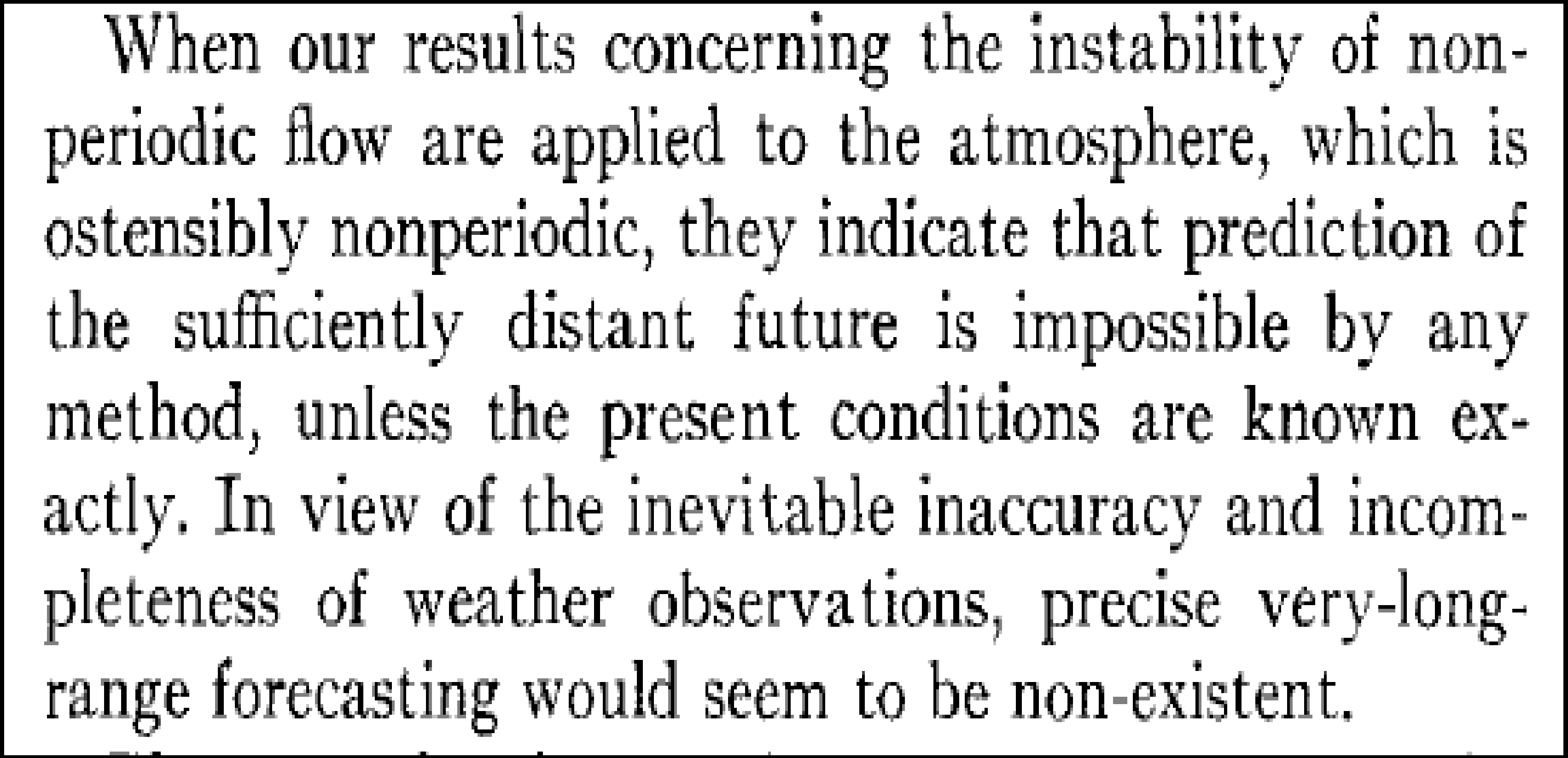
Non-linear feedback especially important in super-critical regime; when the source term dominates over the sink term, random "kicks" in the forcing become very important…

Fluctuations and the Solar Cycle: The Path to Chaos



In high dynamo number (strongly super-critical regime) – random forcing can lead to irregular (chaotic) behavior

Chaotic Systems and Predictability: Lessons from History



When our results concerning the instability of non-periodic flow are applied to the atmosphere, which is ostensibly nonperiodic, they indicate that prediction of the sufficiently distant future is impossible by any method, unless the present conditions are known exactly. In view of the inevitable inaccuracy and incompleteness of weather observations, precise very-long-range forecasting would seem to be non-existent.

(Lorentz 1963, J. Atmos. Sci.)

- Chaotic regime: small differences in initial conditions diverge, leading to loss of predictive accuracy over long time-scales

Is short-term prediction possible?

If yes, how long is the predictive window or predictive memory in the system?

A Paradigm for Solar Cycle Predictions: Underlying Physics

Flux transport terms deterministic

- Toroidal field evolution:

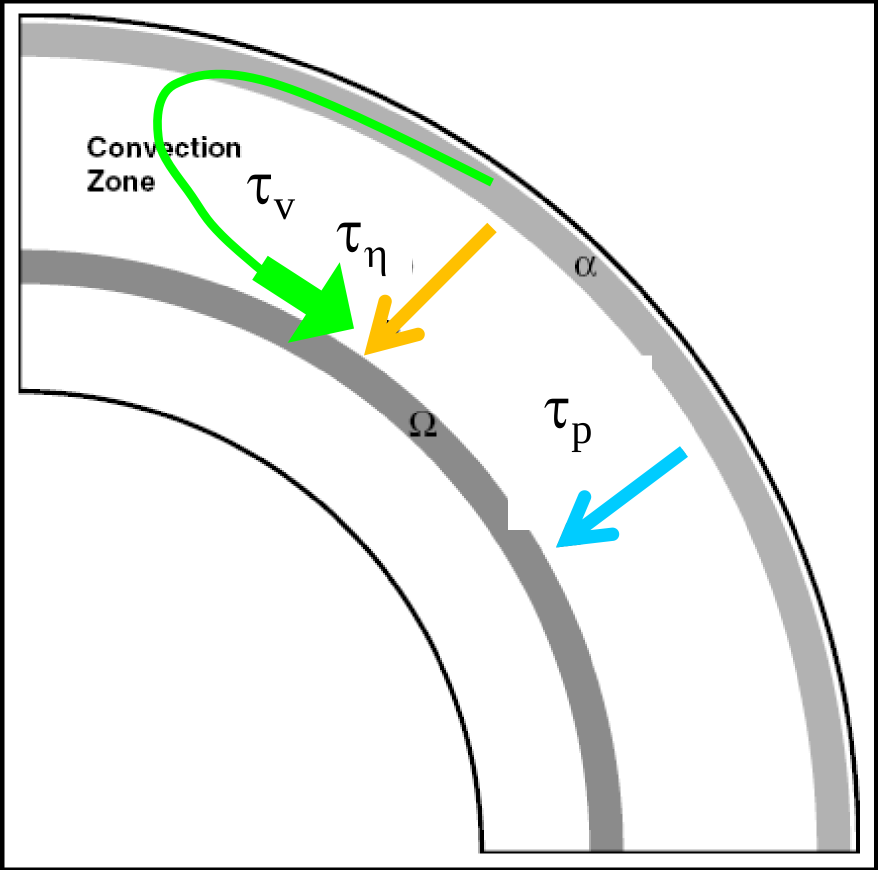
Introduces time delay = memory

$$\frac{dB_\phi(t)}{dt} = \frac{\omega}{L} A(t - T_0)$$

Predictive memory lasts roughly over time-scale T_0 and not beyond

Predictions possible (roughly) spanning over memory timescale

Competing Flux Transport Mechanisms Determine Memory



- Meridional Flow (15—20 m/s)
  τ_v = 20 yrs (slow process)

- Turbulent Diffusion (1×10^{12} cm^2/s)
  τ_η = 14 yrs (intermediate)

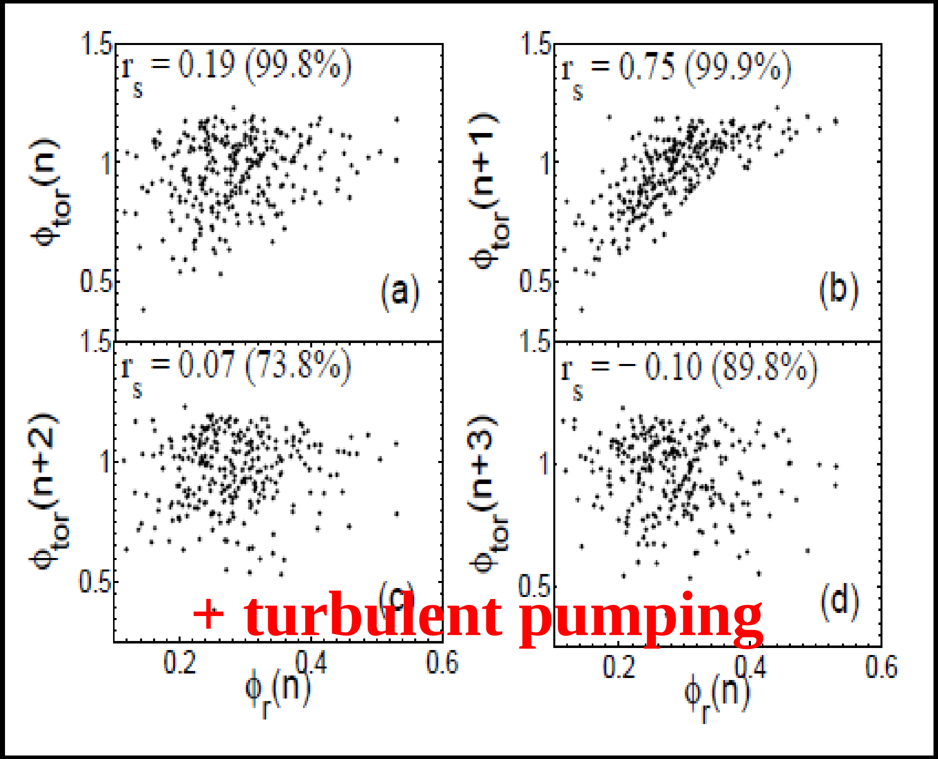
- Turbulent Pumping (v =2 m/s)
  $\tau_{pumping}$ = 3.4 yrs (fast)

Solar cycle memory determined by dominant flux transport mechanism

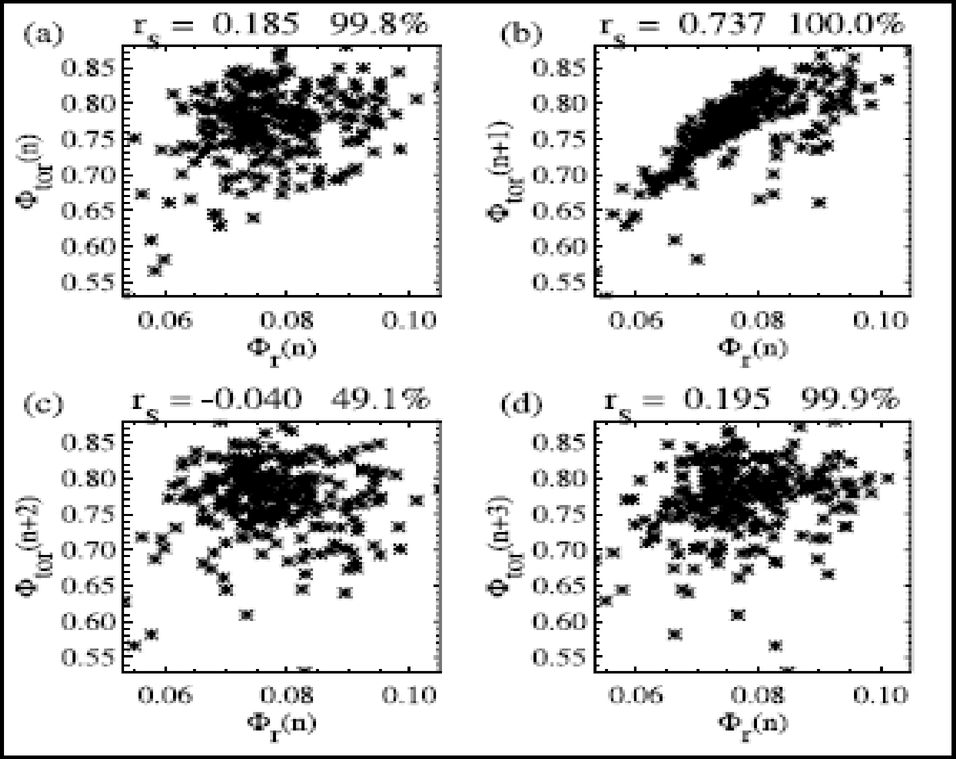
Charbonneau & Dikpati, 2000, ApJ
Yeates, Nandy & Mackay, ApJ, 2008
Karak & Nandy, ApJ, 2012
Hazra, Brun and Nandy A&A, 2020

Memory in Stochastically Forced Dynamo Simulations

Yeates, Nandy & Mackay 2008, ApJ, Karak & Nandy 2012, ApJL
Hazra & Nandy 2016, ApJ, Hazra, Brun & Nandy 2020, A&A



(Advection dominated – low η)

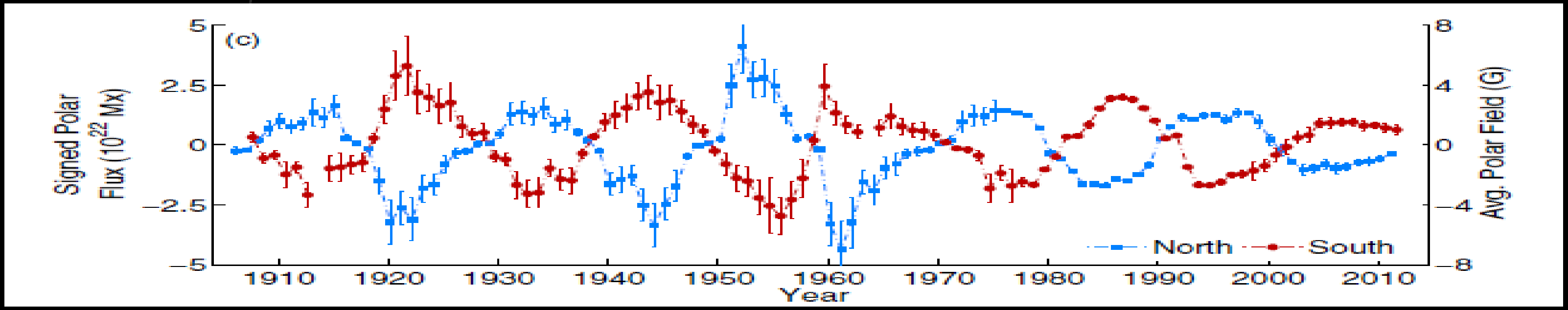


(Diffusion dominated – high η)

- Simulations indicate a dynamical memory across (n) and (n+1) cycle
- Only previous cycle polar field (at minima) important, best predictor
- Explains (in part) diverging model based forecasts for cycle 24

Observational Verification of Short Solar Cycle Memory

(*Muñoz-Jaramillo* et al. 2013, ApJL)



Polar Source

Stochastic; distribution of tilt angles of ARs random, breaks predictive link

Theory of solar cycle predictability in agreement with observations

Toroidal Source

Deterministic; maintains predictive link for next cycle amplitude only

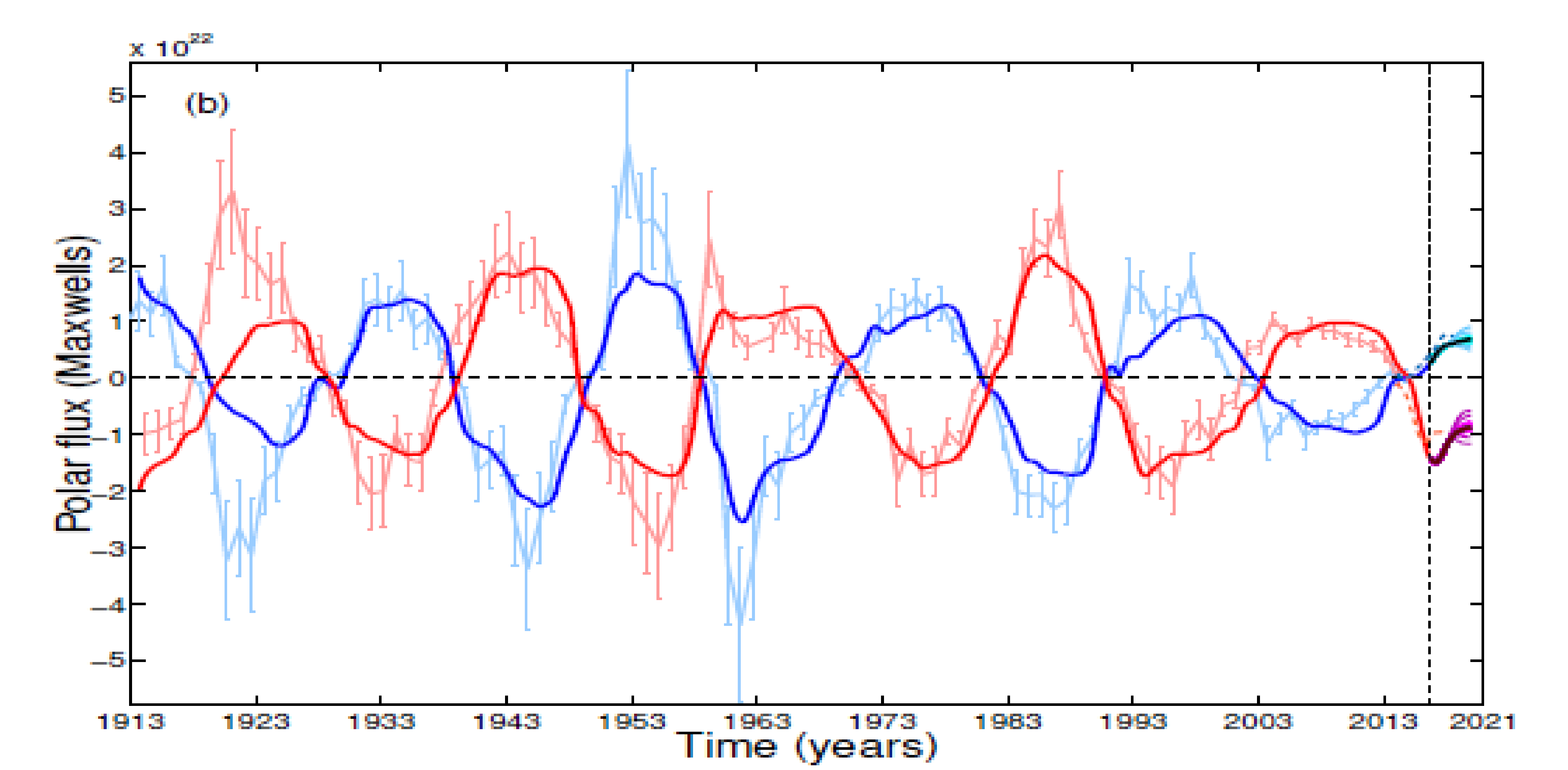
Extending the Time Window for Predictions

With empirical precursor methods (or only using dynamo) one has to wait until minima to predict next cycle. Are earlier predictions possible?

Yes! If we can first predict the poloidal component (polar field) at cycle minima and then utilize this to forecast the toroidal component which generates the sunspot cycle

We drive a 2D kinematic dynamo model with output from a 2D surface flux transport model to extend forecasting window and predict cycle 25

Simulating and Predicting the Polar Field



(Bhowmik and Nandy 2018, Nature Communications)

Ensemble prediction runs (> 100) with fluctuations in tilt, flux and location of sunspots in the declining phase of cycle 24, to estimate uncertainty range in prediction

Prediction of Solar Cycle 25

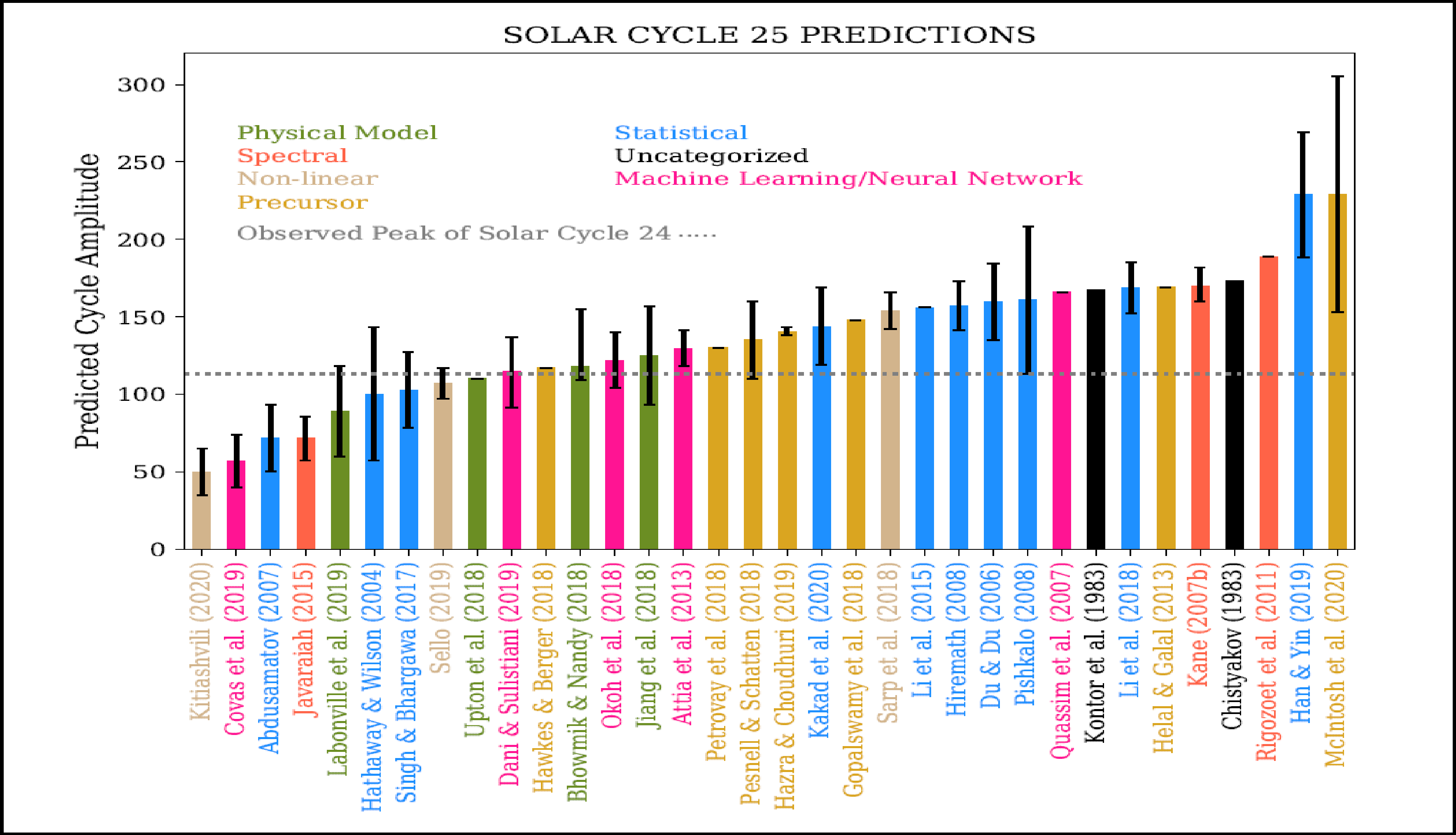
Table 1 Amplitude and timing of the maximum of solar cycle 25

	Prediction	Range
Flux (maxwells)	2.29×10^{23}	$(2.69\text{–}2.11) \times 10^{23}$
Yearly mean sunspot number	118	139-109
Time of peak	2024	2023-2025

(Bhowmik and Nandy 2018, Nature Communications)

- First century-scale, data-driven SFT+Dynamo simulations
- No model parameters fine-tined after initialization
- Previous cycles well-reproduced (except cycle 19)
- Weak cycle 25 predicted, peaking in the year 2024; don't ignore range!

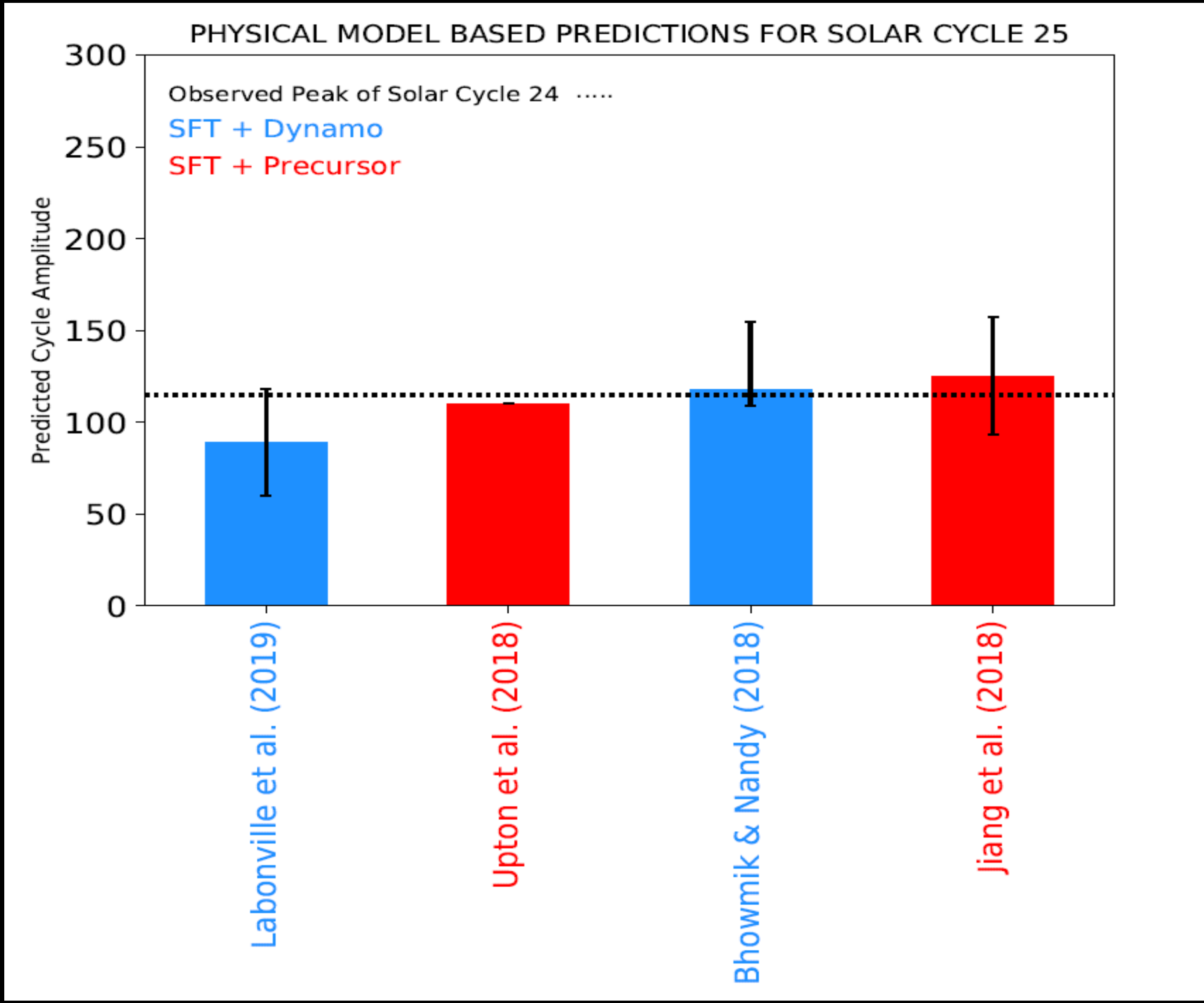
Have we achieved consensus in Cycle 25 Forecasts?



Disagreement in solar cycle predictions using diversity of techniques persists across solar cycles 24 and 25

(Nandy 2021, Solar Physics)

Physical BL Mechanism based Solar Cycle 25 Predictions



Model-based predictions for solar cycle 25 based on the Babcock-Leighton mechanism have converged and indicate weak cycle (Nandy 2021, Solar Physics)

Solar Cycle Predictability: The Progress

Answers gleaned over solar cycle timescale (2006-2018)

- Is it possible to predict the solar cycle: ***Yes***

- If yes, what is the best proxy for prediction: ***Polar field / flux***

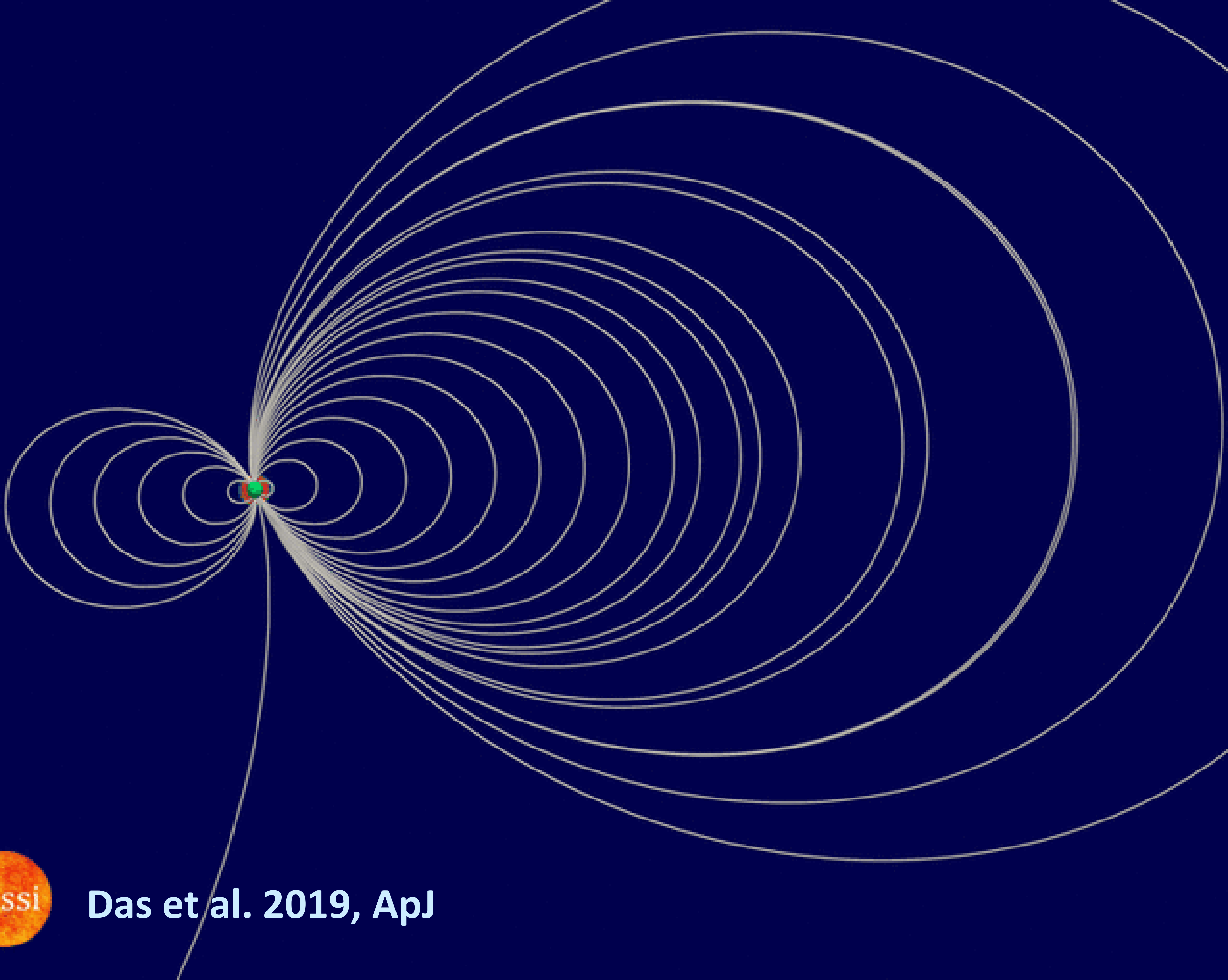
- Do we understand why one dynamo prediction matched past cycles quite well, but got cycle 24 completely wrong and why the only two dynamo-based cycle 24 forecasts disagreed: ***Yes***

- What can we predict and how accurately: ***Cycle amplitude & timing, assessment of accuracy may be made based on statistical possibilities***

- How early can we predict: ***Not before the previous maxima***

- What is the early outlook for cycle 25: ***Weak, but not insignificant***

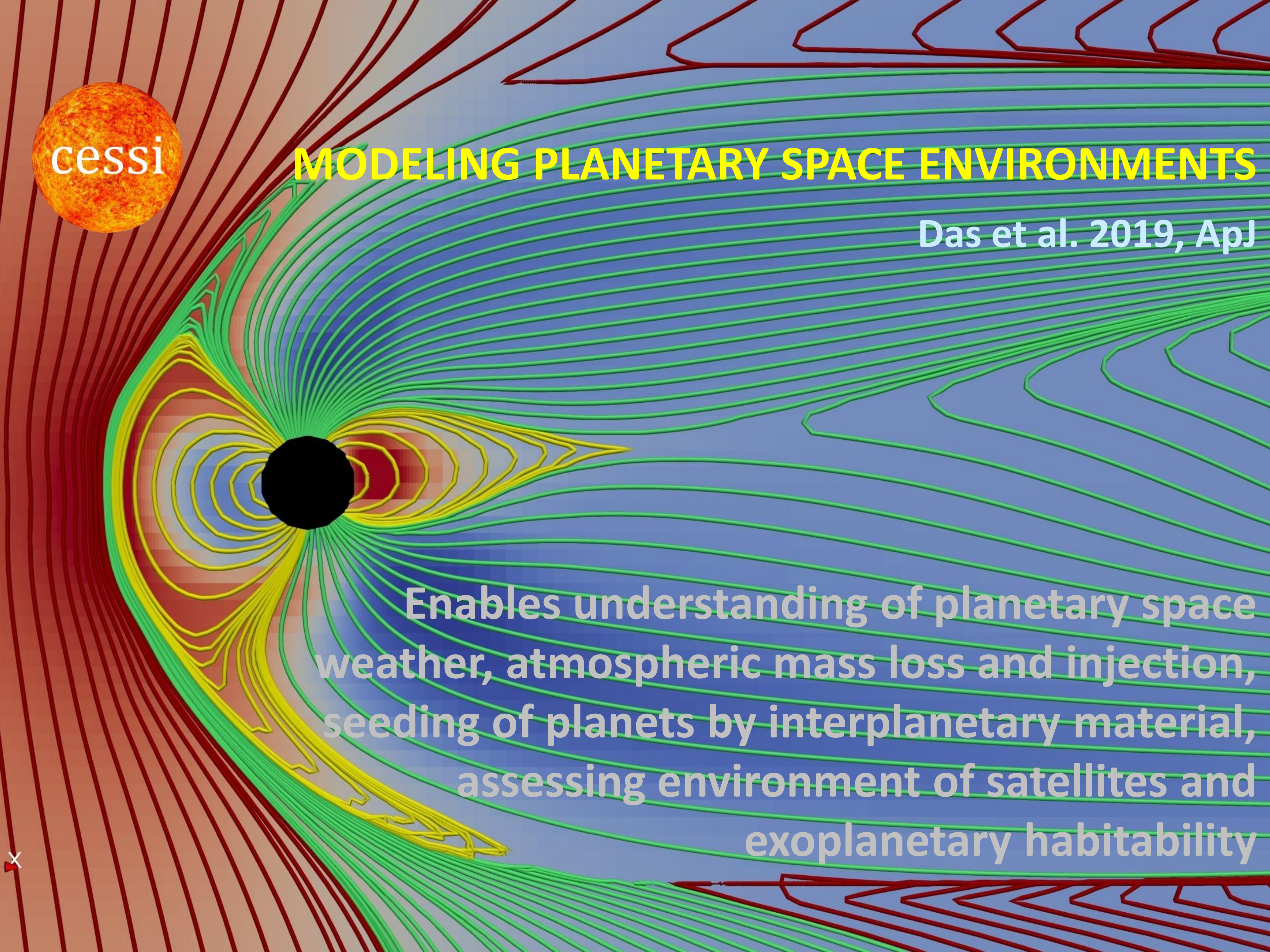
Modelling the (Exo)-Planetary Space Environment



Das et al. 2019, ApJ

MODELING PLANETARY SPACE ENVIRONMENTS

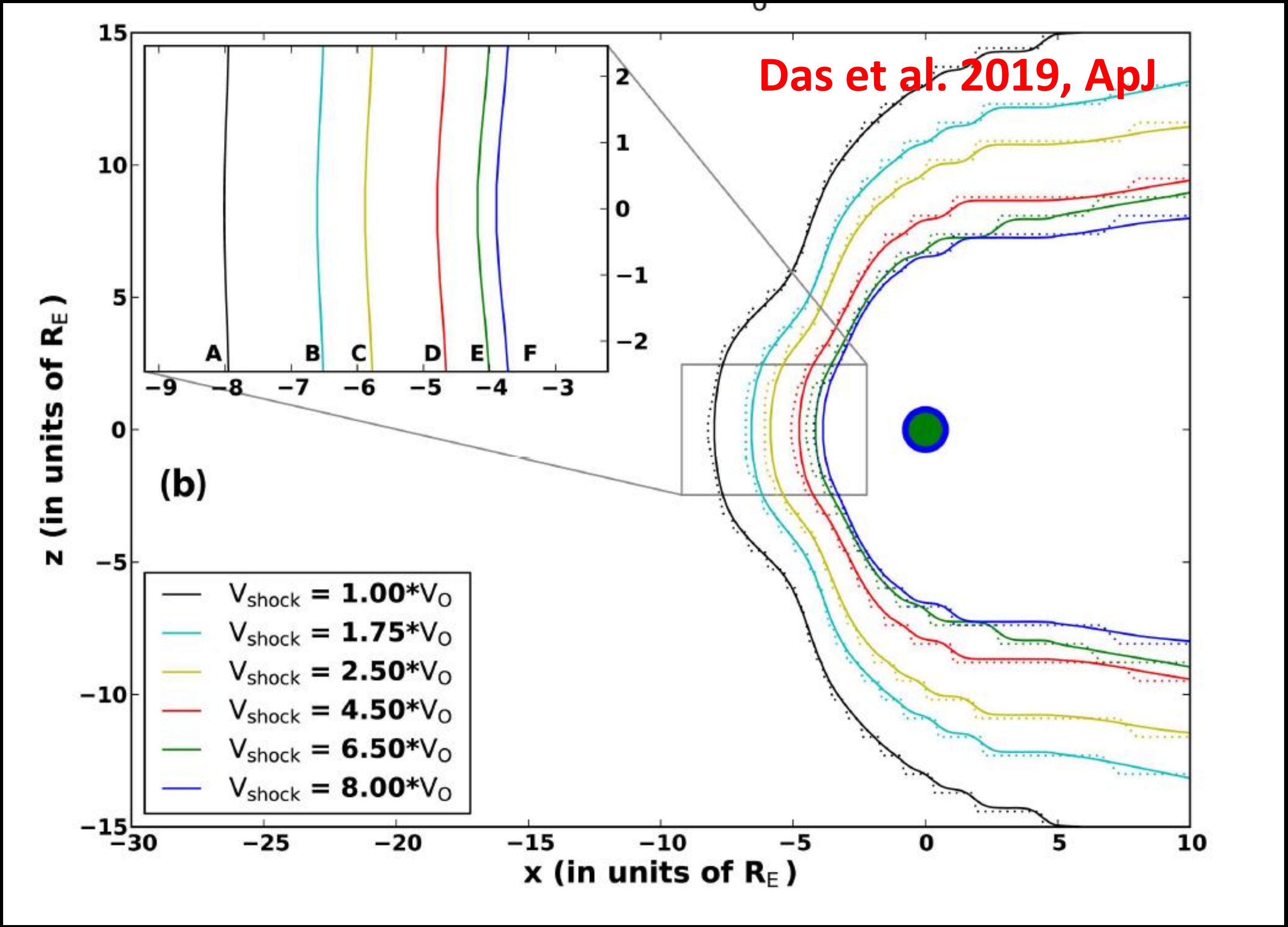
Das et al. 2019, ApJ



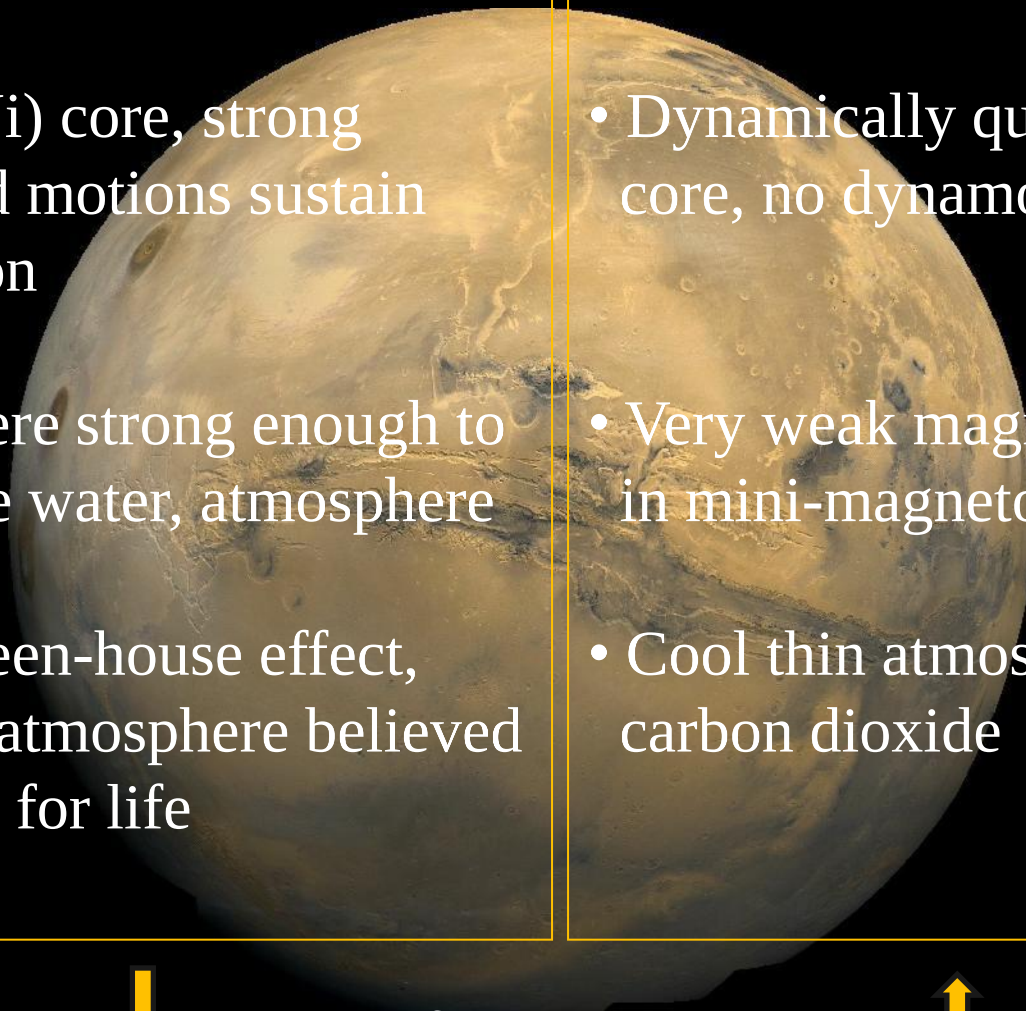
Enables understanding of planetary space weather, atmospheric mass loss and injection, seeding of planets by interplanetary material, assessing environment of satellites and exoplanetary habitability

Impact on Solar Wind on Earth's Magnetosphere

Physics of the Magnetopause or why Earth hosts Life



Space Environment and Habitability: Mars Case Study



Past (Age 1.5 billion years)

- Liquid (Fe-Ni) core, strong rotation, fluid motions sustain dynamo action
- Magnetosphere strong enough to shield surface water, atmosphere
- Sustained green-house effect, warm, moist atmosphere believed to be suitable for life

Present (Age 4.56 billion years)

- Dynamically quiescent solid core, no dynamo action
- Very weak magnetic field, mostly in mini-magnetospheres
- Cool thin atmosphere, rich in carbon dioxide

Loss of Magnetosphere

Space Environment of Mars-like Non-magnetized Planets

Without Magnetosphere, Stellar Wind Penetrates Closer to Planet

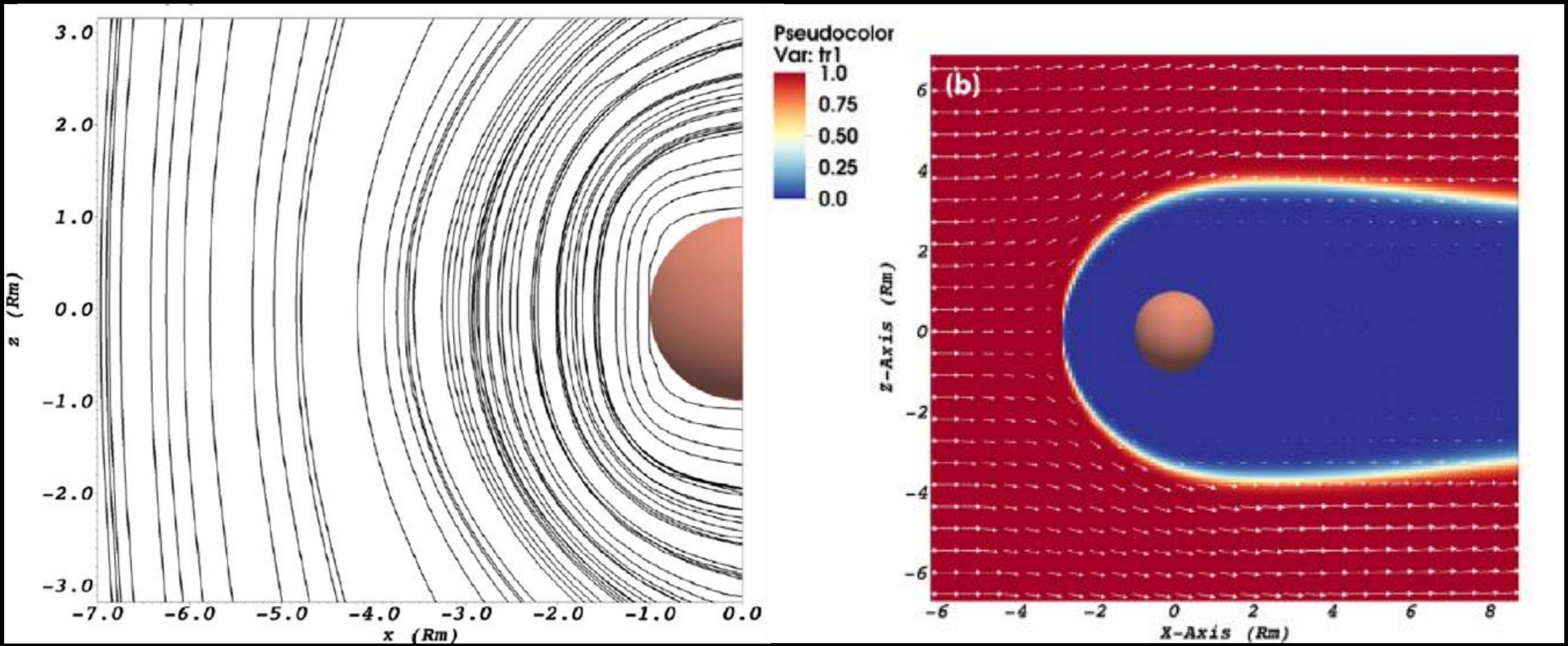


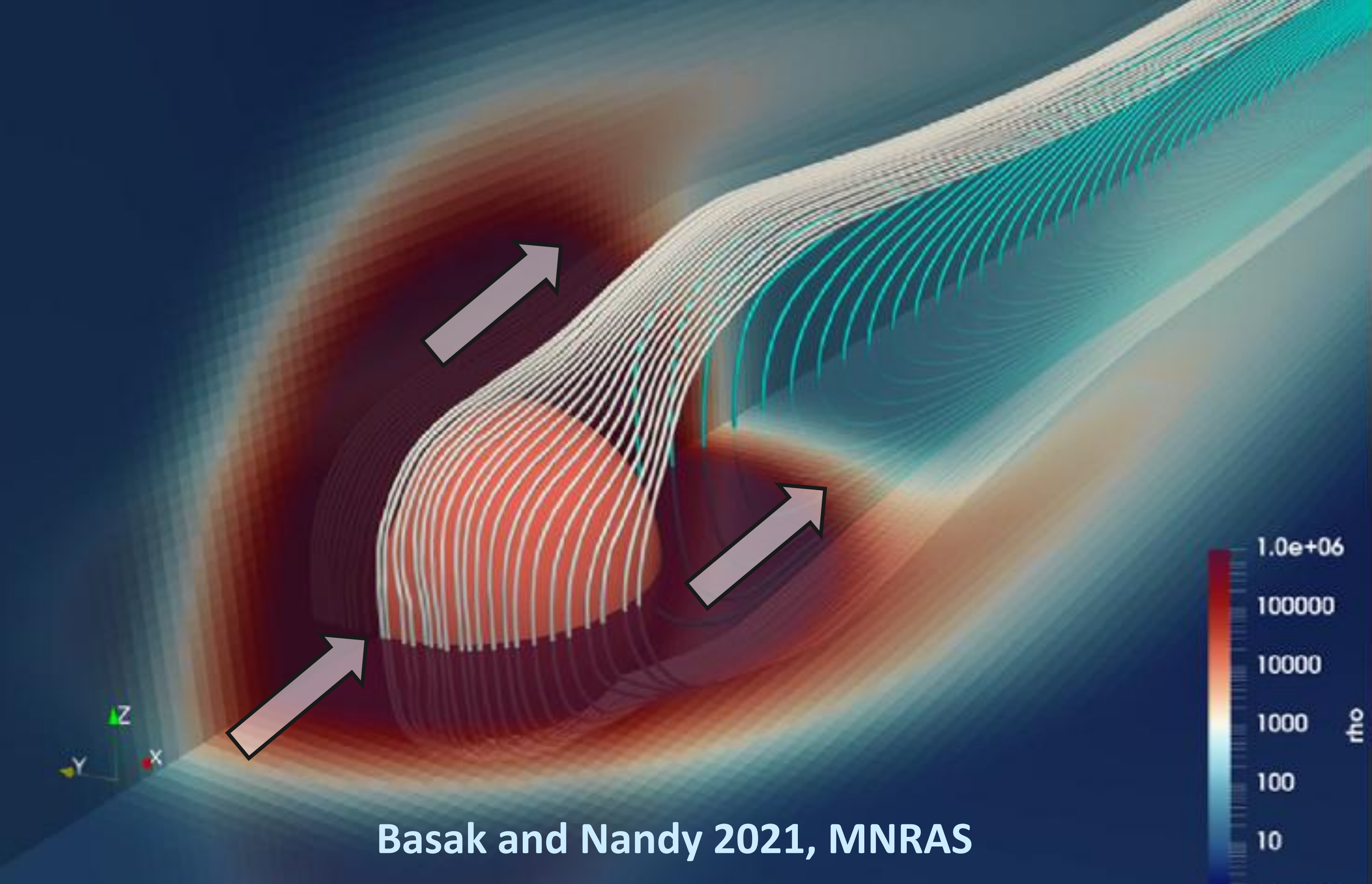
Table 2. List of bow shock (R_{bs}) and magnetopause (R_{mp}) stand-off distances (in units of R_m) for the cases depicted in Fig. 2.

Case⟶ Stand-off distance	$B_0 = 0.1B_e$ (NIMF)	$B_0 = 0.1B_e$ (SIMF)	$B_0 = 0.01B_e$ (NIMF)	$B_0 = 0.01B_e$ (SIMF)	$B_0 = 0$ (both)
Bow shock (R_{bs})	10.9	11.3	7.9	8.0	7.8
Magnetopause (R_{mp})	5.4	4.2	4.0	3.9	3.8

Basak and Nandy 2021, MNRAS

The Imposed Magnetosphere of Mars

Penetrating Stellar Winds Induce Atmospheric Losses



Basak and Nandy 2021, MNRAS

Concluding Remarks

The activity of stars shape planetary environments. Taking the solar system as a test bed we have developed several numerical models to understand and predict stellar magnetic activity such as the solar magnetic cycle. We have also explored the impact of stellar winds on planets to understand how stellar activity influences habitability. We are opening up windows to understand space weather near Earth, and habitability in solar and exoplanetary systems.

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