Mechanisms for producing grand minima: a short review

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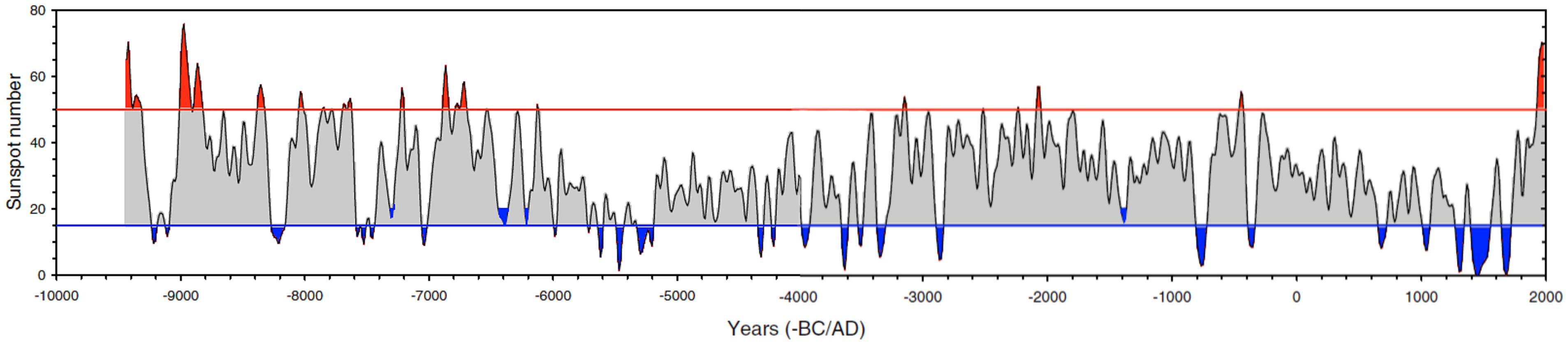
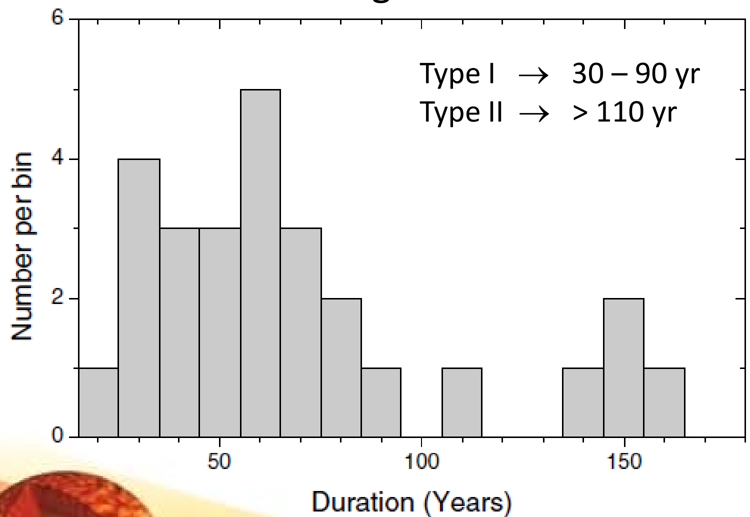
Grand minima in the past

Sunspot reconstruction based on ^{14}C radio isotope **(See talk R. Muscheler)**



Adapted from *Usoskin et al 2007*

Histogram of GM duration



→ SSN below 15 - 20 for at least 20 yrs

→ 27 grand minima

→ Duration time is bimodal

→ Hallstatt cycle ~ 2400 yr

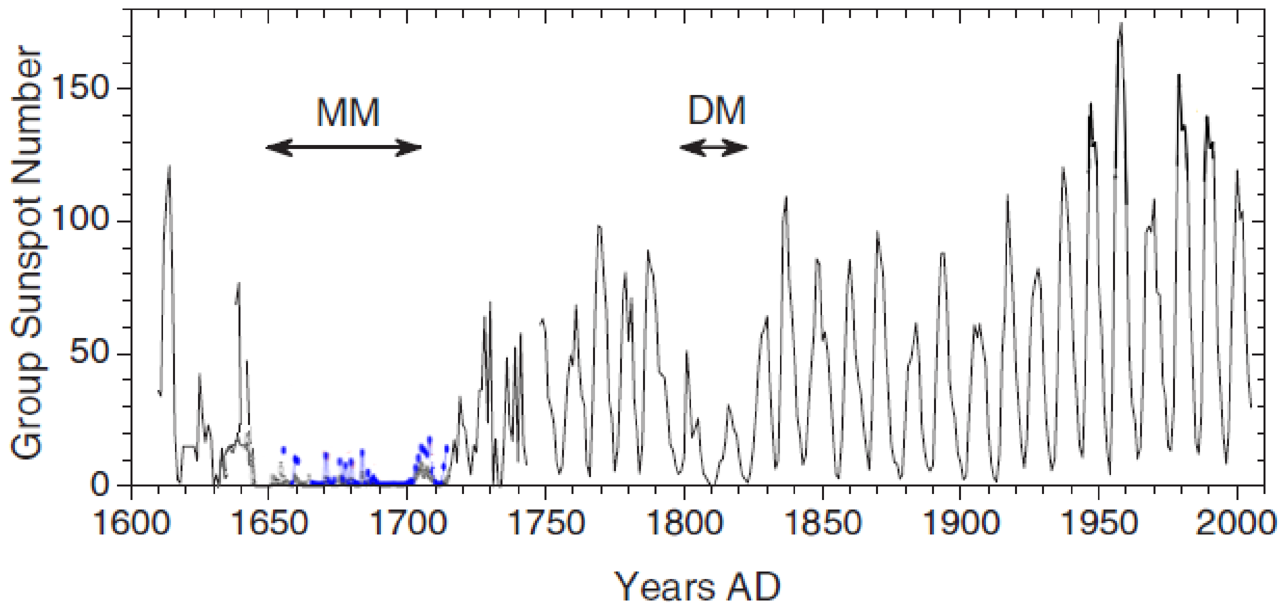
(GM clustering around minima)

Talk by K. McCracken

→ Waiting time distribution → power law

(indicative of selforganized criticality)

The Maunder Minimum



Adapted from *Usoskin et al 2012* and *Vaquero et al 2015*
Check talk by J. Vaquero later on!

→ "Very low" sunspot number

→ The cycle still goes on (radio isotopes and aurorae observations)

→ Gradual transition to and exit from MM

(Vaquero et al 2011, 2012)

→ Longer cycle period during MM

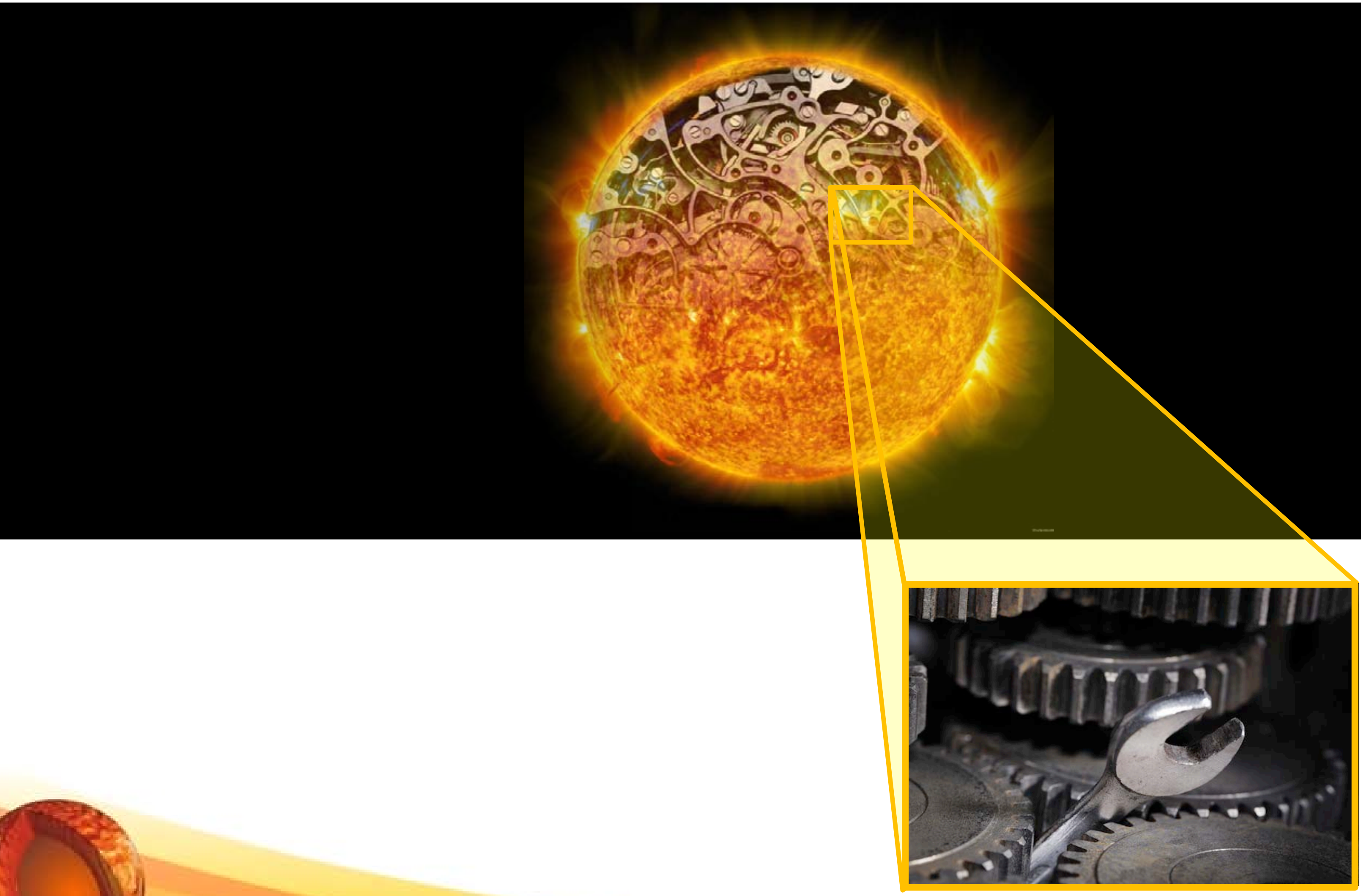
→ Possible correlation with Earth temperatures *(Anet et al 2013)*

→ Asymmetric sunspot eruptions between hemispheres

(*Ribes et al 1993, Sokoloff 2004*)

→ A challenge to dynamo models!!

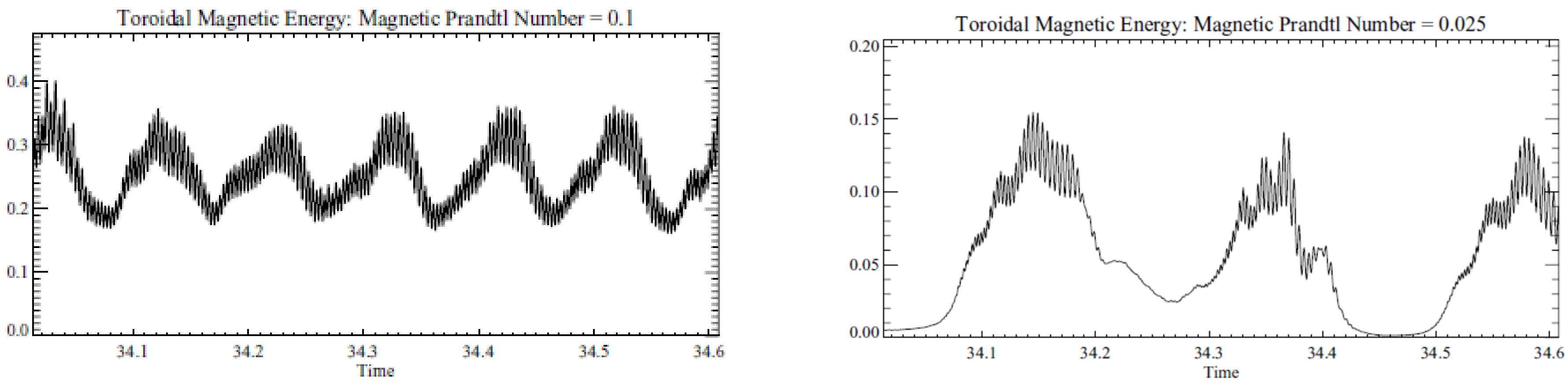
Physical mechanisms…



Magnetic feedback on rotation

Magnetic field "quenches" the Ω through the Lorentz force, effectively lowering the dynamo number and killing magnetic field. Once the mag. decreases, Ω is allowed to return to kinematic values.

Tobias 1996
Rüdiger et al 1999
Brooke et al 2002



Adapted *from Bushby 2006* (2D α–ω classical mean field model)

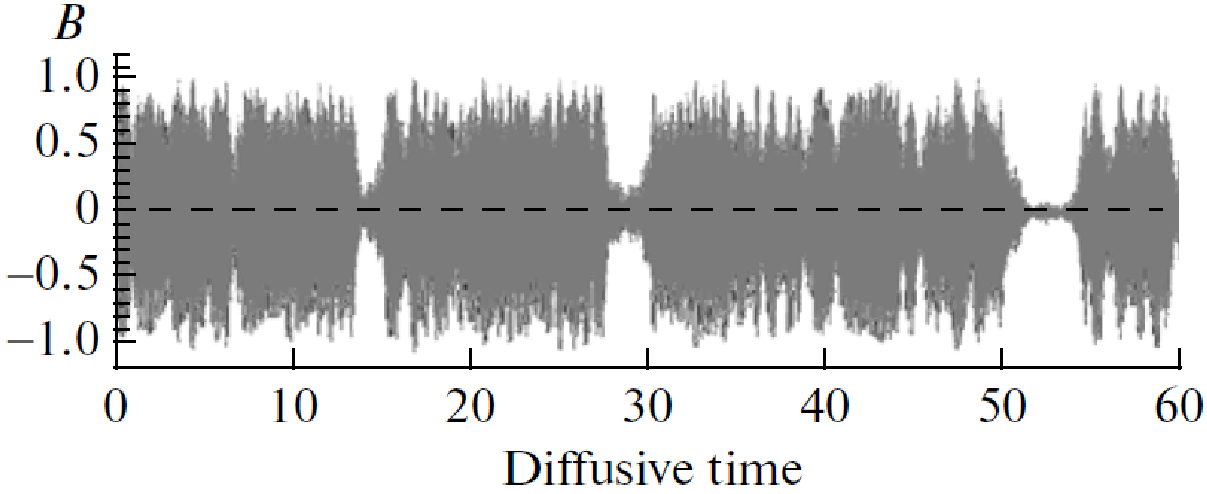
→ Strong modulation at low (<1) magnetic Prandtl number

→ Long term behavior somewhat different from observation and has compatibility problems with torsional oscillations .

Perturbations in the α effect (1)

Perturbations in the α source term can lead to grand minima specially if the dynamo is working near criticality.

Moss et al 2008
Usoskin et al 2009
Olemskoy et al 2013
Hazra et al 2014



Classical $\alpha-\omega$ mean field model with nonlinearities in α and η

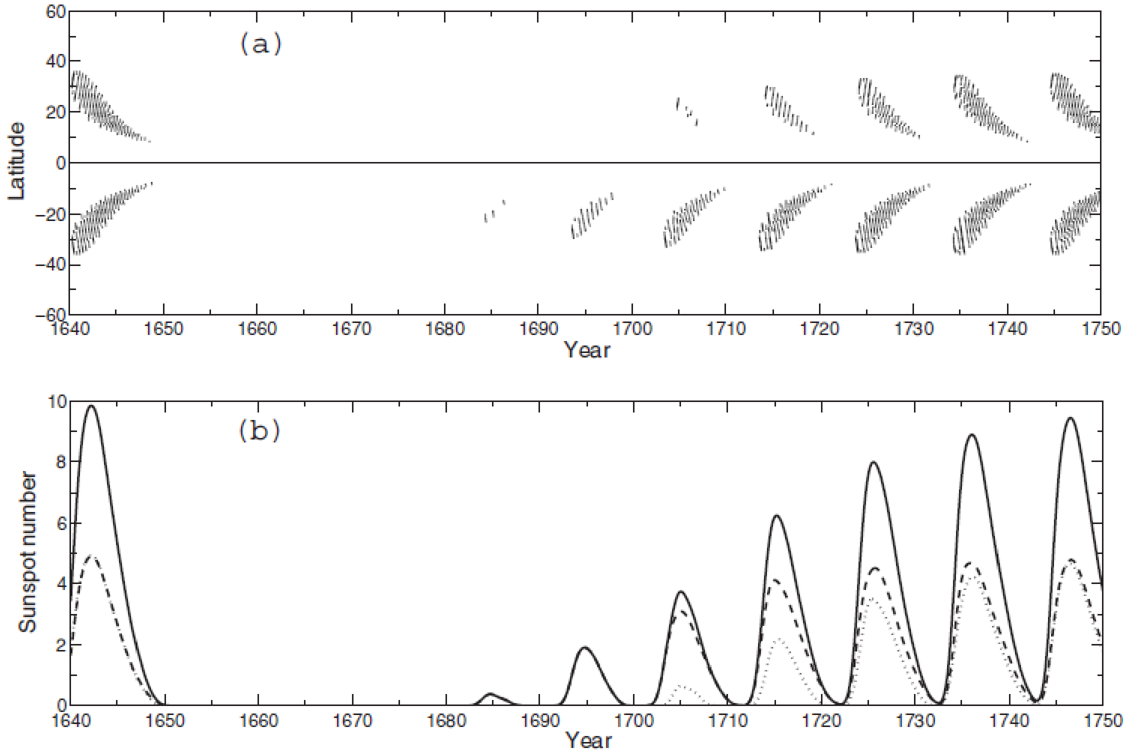
Adapted from *Kitchatinov et al 2010*

→ Behavior seen in low order (1D) and axisymmetric (2D) mean field models

→ Important factors: amplitude of the fluctuations and the coherence time

Perturbations in the α effect (2)

Perturbations in the α source term can lead to grand minima specially if the dynamo is working near criticality.



FT model with Babcock-Leighton α effect

Adapted from *Choudhuri et al 2009*

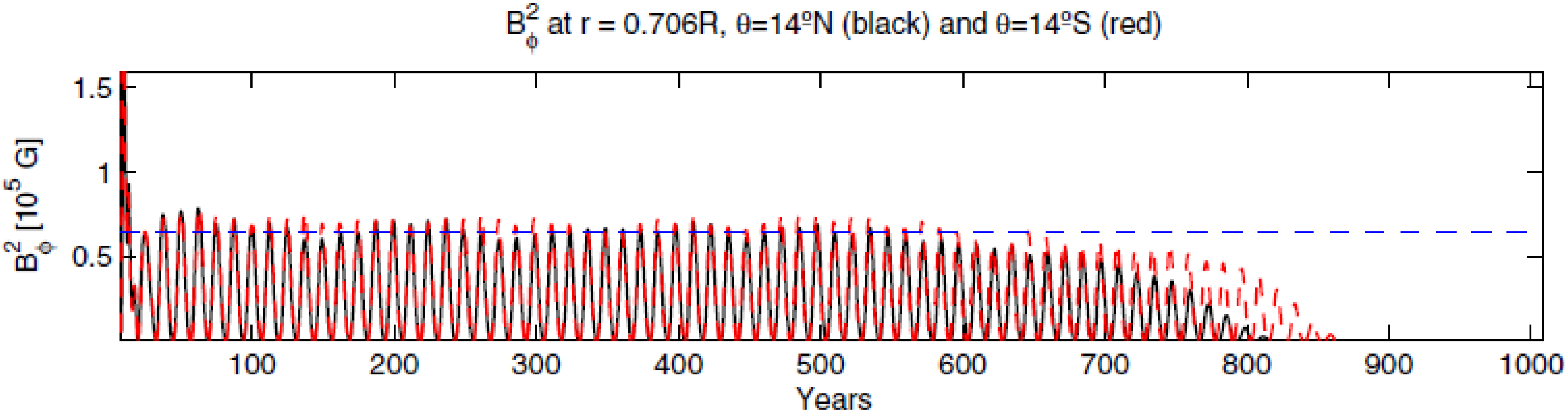
A pronounced decrease of the poloidal field can trigger GM. Asymmetric BL-α fluctuations lead different behavior in the recovering phase of the GM

Perturbations in the α effect (3)

Perturbations in the α source term can lead to grand minima specially if the dynamo is working near criticality.

FT model with Babcock-Leighton and Parker α effects

Adapted from *Passos et al 2014*



→ Fluctuations to the BL-α effect at short coherence times (6 months to a year)

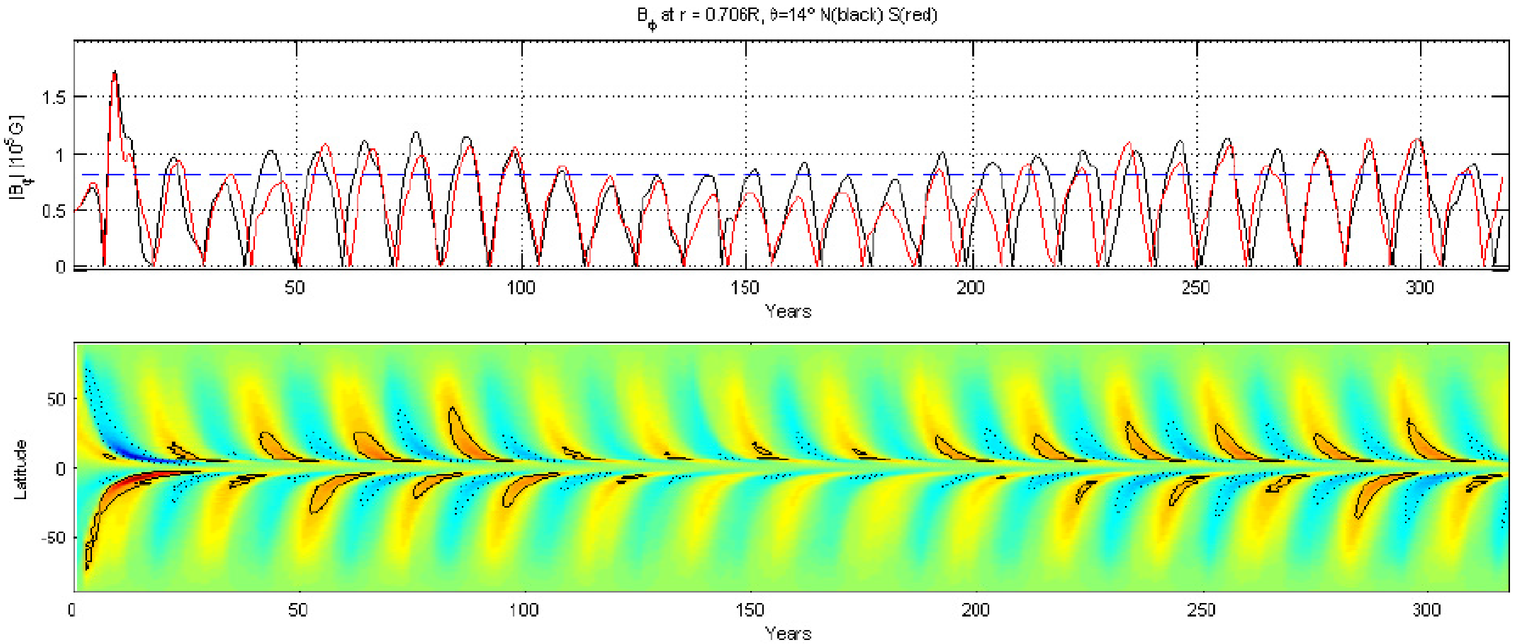
→ Improved parameterization of the surface BL-α effect implies that fluctuations in the BL-α effect can kill the dynamo solution (it does not recover!)

Perturbations in the α effect (3)

Perturbations in the α source term can lead to grand minima specially if the dynamo is working near criticality.

FT model with Babcock-Leighton and Parker α effects

Adapted from *Passos et al 2014*



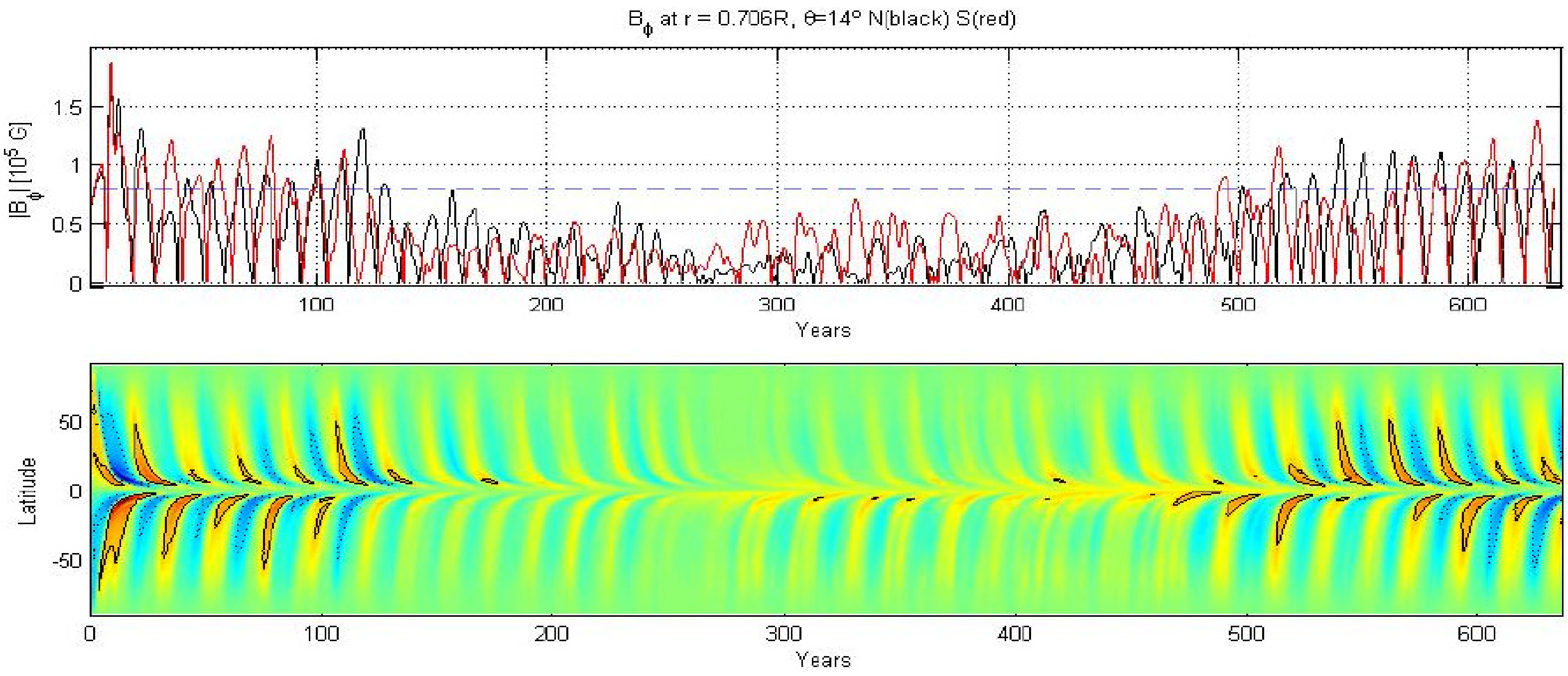
$\rightarrow$ Fluctuations in just the Parker α-effect can produce type I GM (a few cycles)

Perturbations in the α effect (3)

Perturbations in the α source term can lead to grand minima specially if the dynamo is working near criticality.

FT model with Babcock-Leighton and Parker α effects

Adapted from *Passos et al 2014*

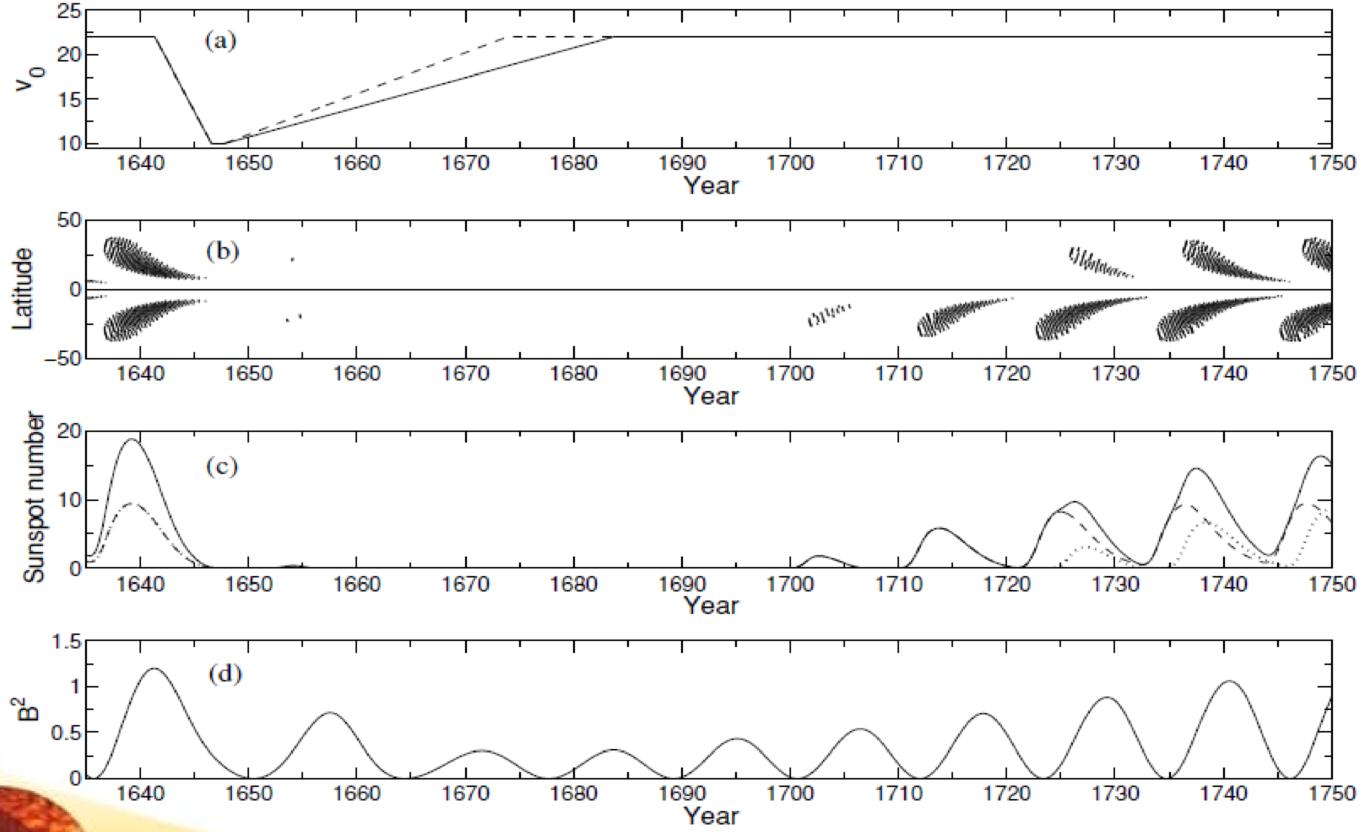


→ Fluctuations both α-effects can produce type II GM (many cycles)

Fluctuations in the meridional circulation (1)

In FT models a pronounced decrease in the amplitude of the MC can lead to GM.
Fluctuations (over cycle coherence times) can also lead to GM.

Lopes et al 2008
Passos et al 2010



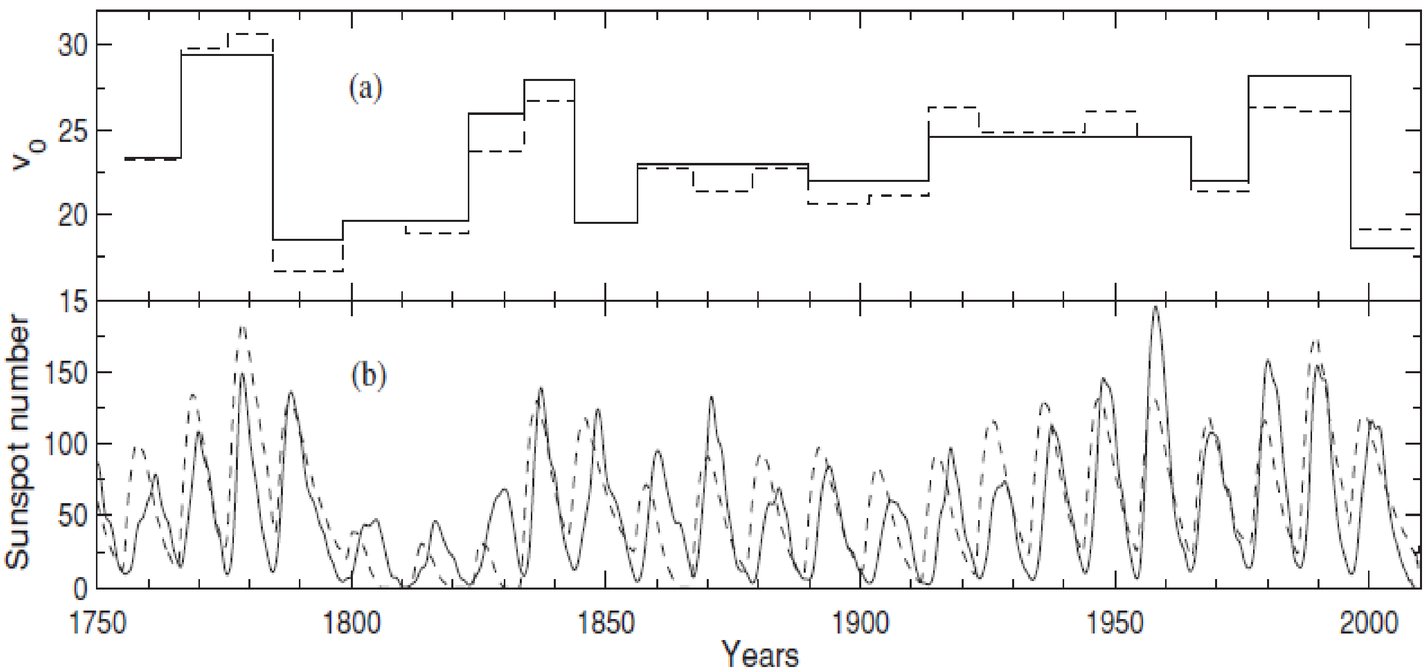
FT model with Babcock-Leighton α effect

Adapted from *Karak 2010*

Fluctuations in the meridional circulation (2)

In FT models a pronounced decrease in the amplitude of the MC can lead to GM.
Fluctuations (over cycle coherence times) can also lead to GM.

Lopes et al 2008
Passos et al 2010



FT model with
Babcock-Leighton
α effect

Adapted from *Karak 2010*

Fluctuations in the meridional circulation (3)

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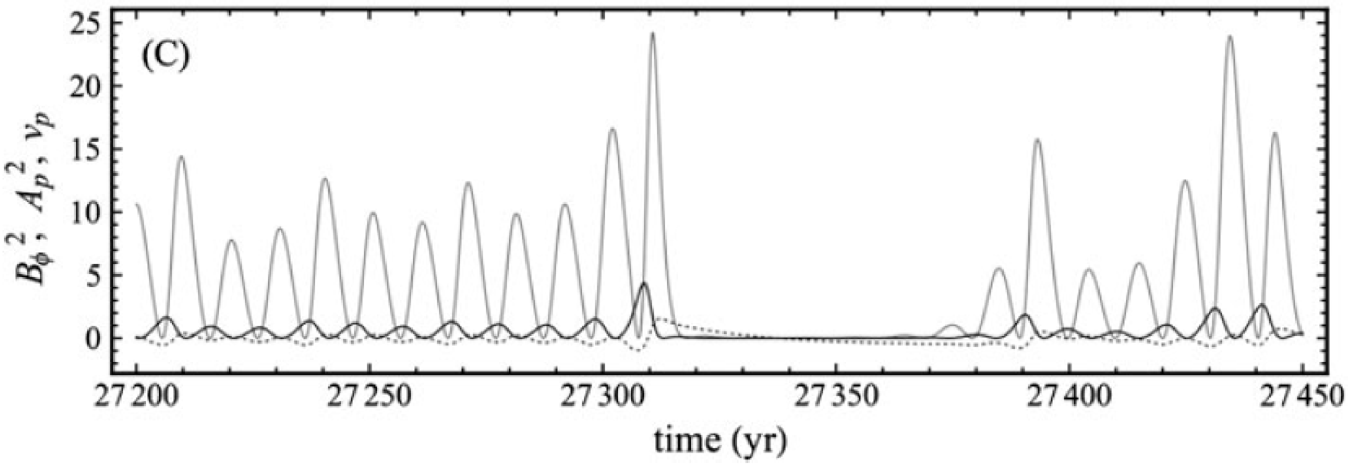


1D low order FT model with feedback from the magnetic field into the MC and fluctuations in the feedback efficiency

Adapted from *Passos et al 2012*

→ Pronounced decreases in the MC are (hard but) possible to justify if we consider magnetic field feedback and stochastic perturbations due to turbulence (at short coherence times)

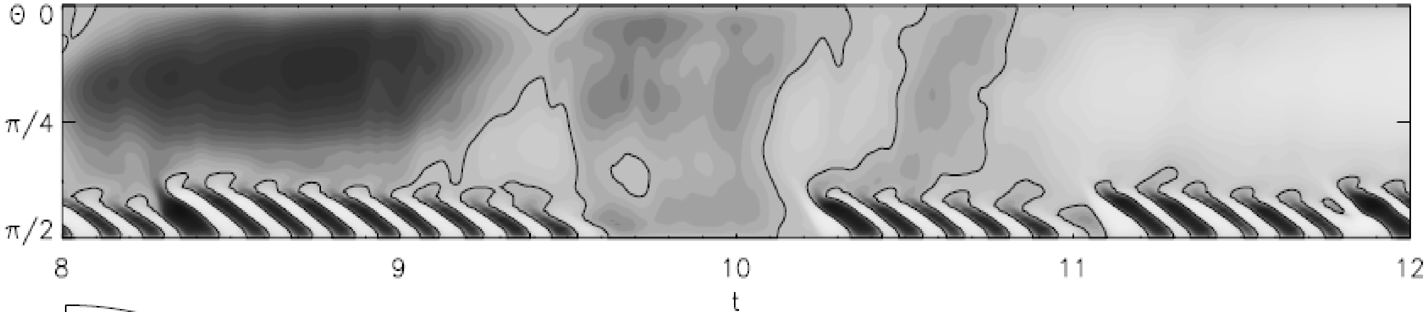
→ Systematic variations in the deep MC seem now less probable given the new observational constraints based on the butterfly migration patterns.

Perturbations in the meridional circulation and α effect

If one is good, two is even better…

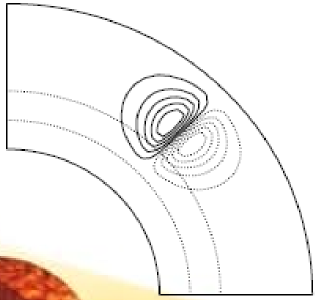
Karak 2010
Choudhuri 2012
Karak et al 2013

→ A combination of systematic MC variations and fluctuations in the surface BL source term seems to better reproduce the GM statistical properties (BL FT model).



Interface dynamo with stochastic turbulent pumping

Adapted from *Ossendrijver 2000*

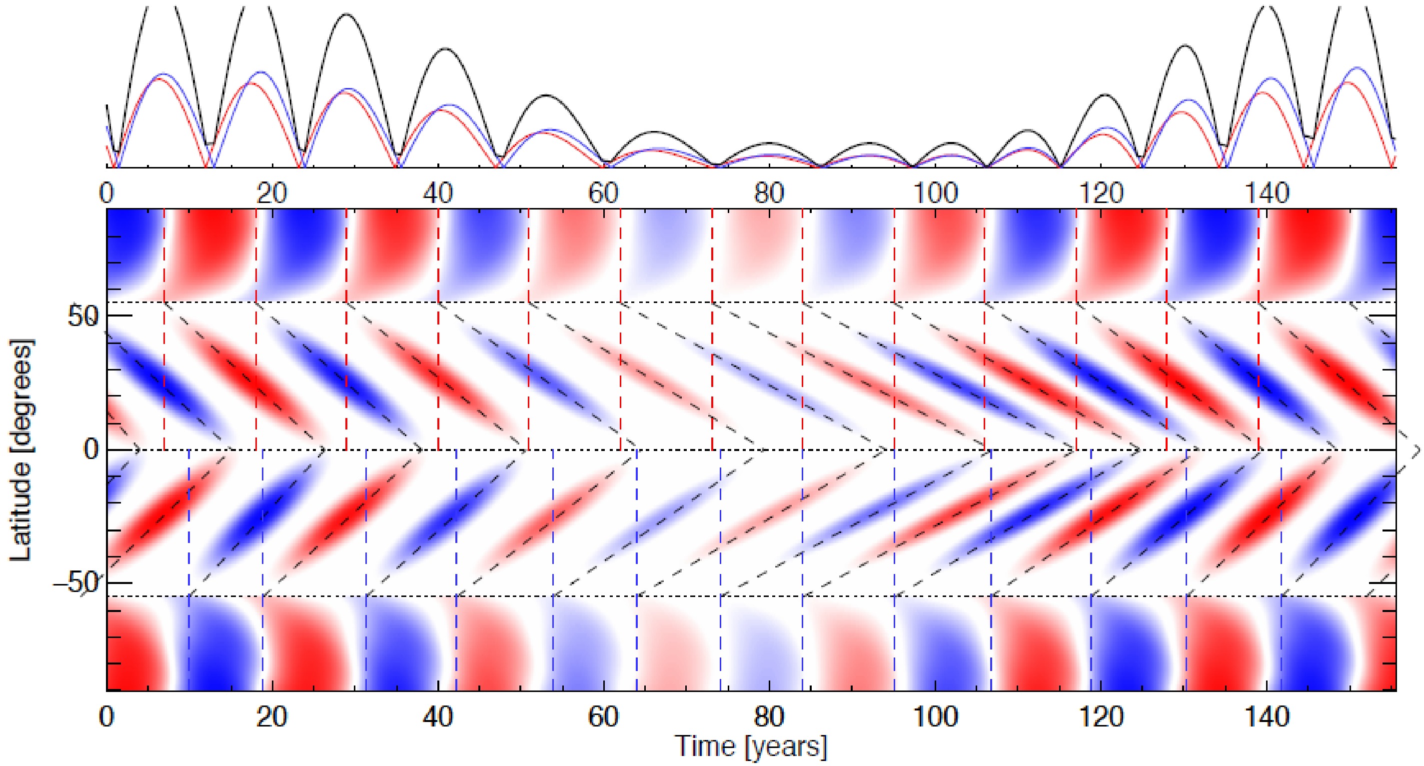


→ Stochastic downdrafts can induce perturbation in the α-effect triggering GM.

→ What actually trigger the GM is an interaction between dipolar and quadripolar modes for the magnetic field.

Magnetic bands interaction !

Interaction between overlapping magnetic band during their evolution



Migration of magnetic bands derived from coronal bright points

Adapted from *McIntosh et al 2015*

→ Extended overlap between bands produce small amplitude cycles

McIntosh et al 2014a, 2014b

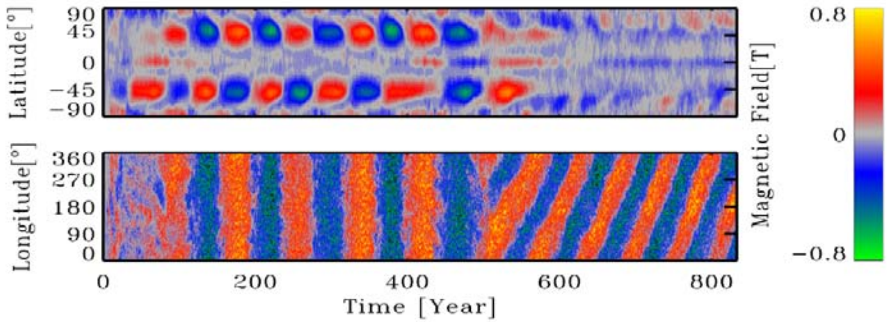
3D MHD instabilities

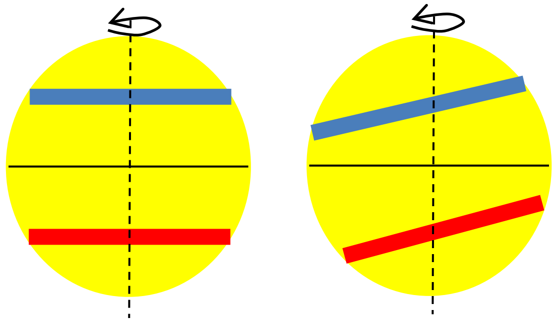
Simply because MHD is complicated! 3D MHD simulations as laboratories…

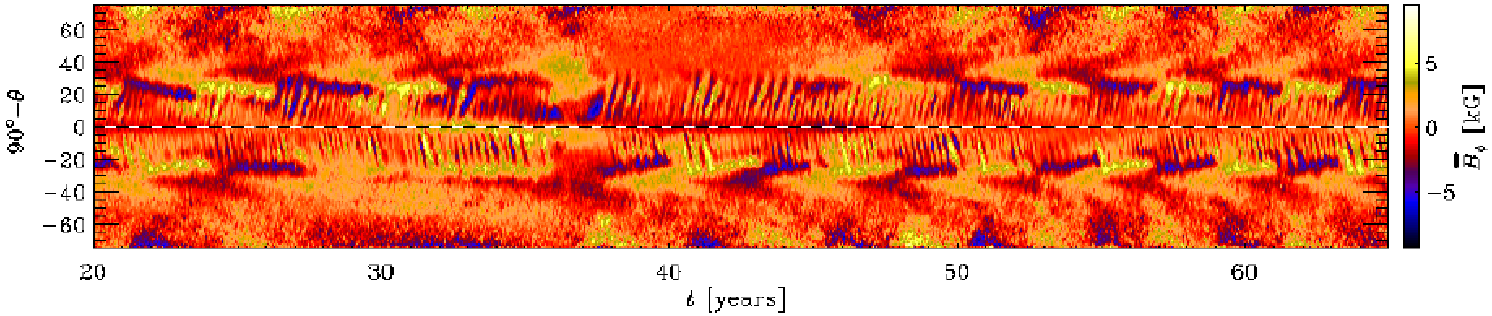
EUALG-MHD

<B_ϕ> near the BCZ

Adapted from
Lawson et al 2015







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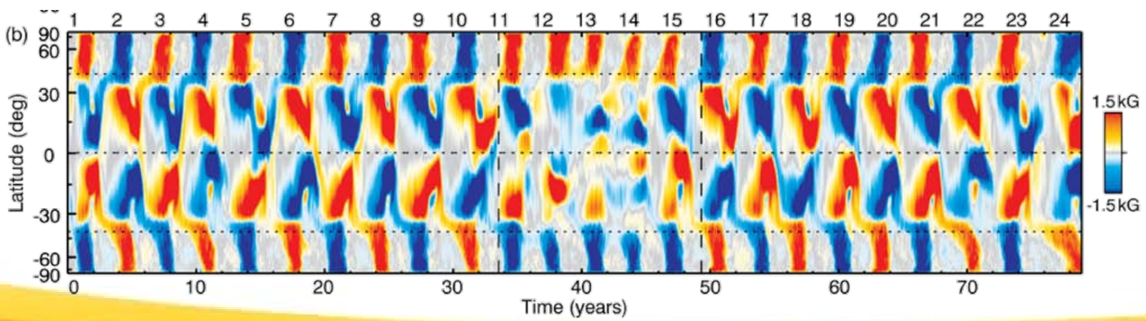
<B_ϕ> near the surface

Adapted from
Käpylä et al 2016
Check poster and talk!

ASH

<B_ϕ> near the surface

Adapted from
Augustson et al 2015



If you want to explore this area you can start here:

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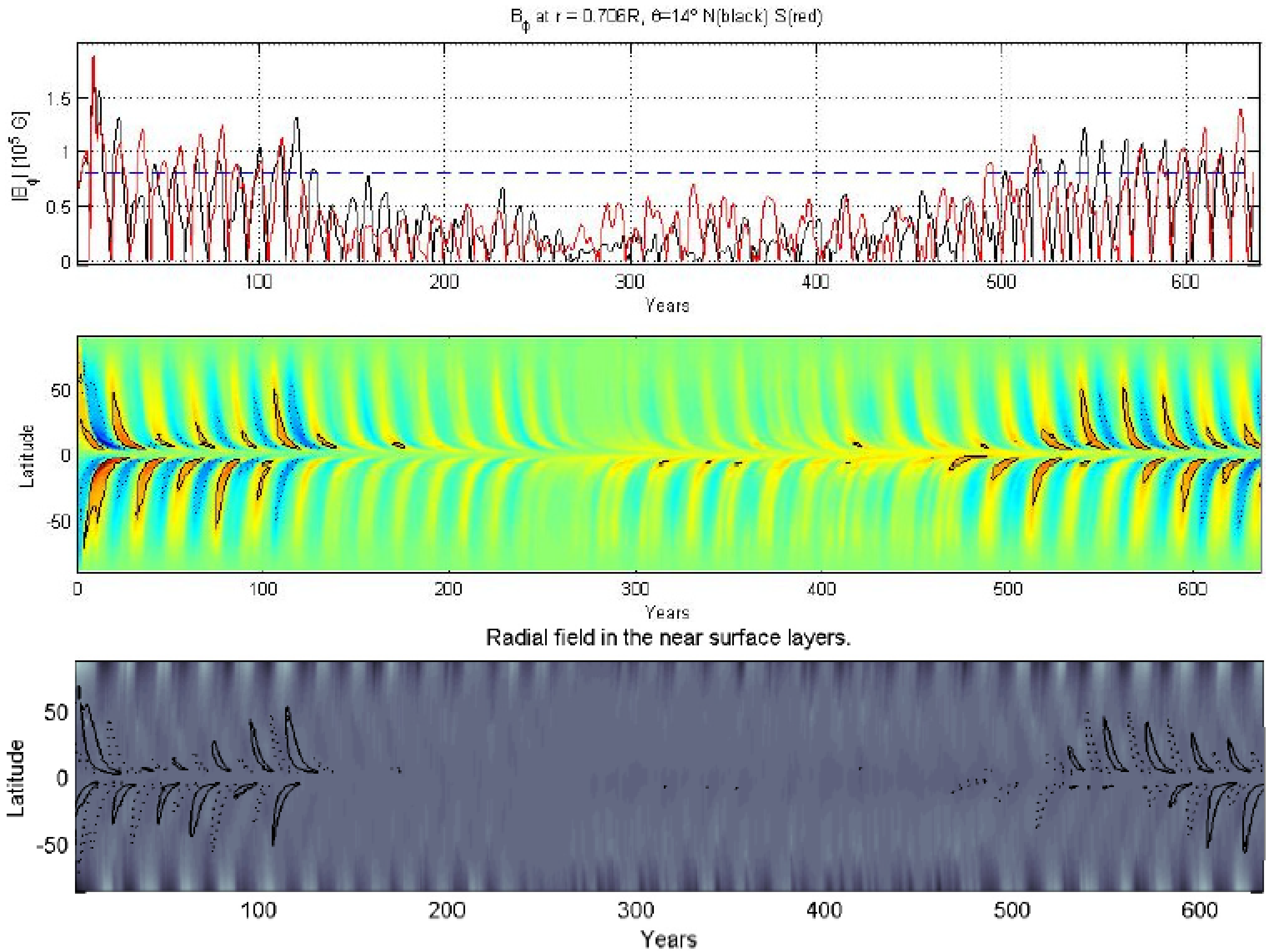
Thank you!



Bφ at r = 0.706R, θ=14° N(black) S(red)
|Bφ| [10^5 G]
0
0.5
1
1.5
100
200
300
400
500
600
Years
Latitude
50
0
-50
0
100
200
300
400
500
600
Years
Radial field in the near surface layers.
Latitude
50
0
-50
100
200
300
400
500
600
Years