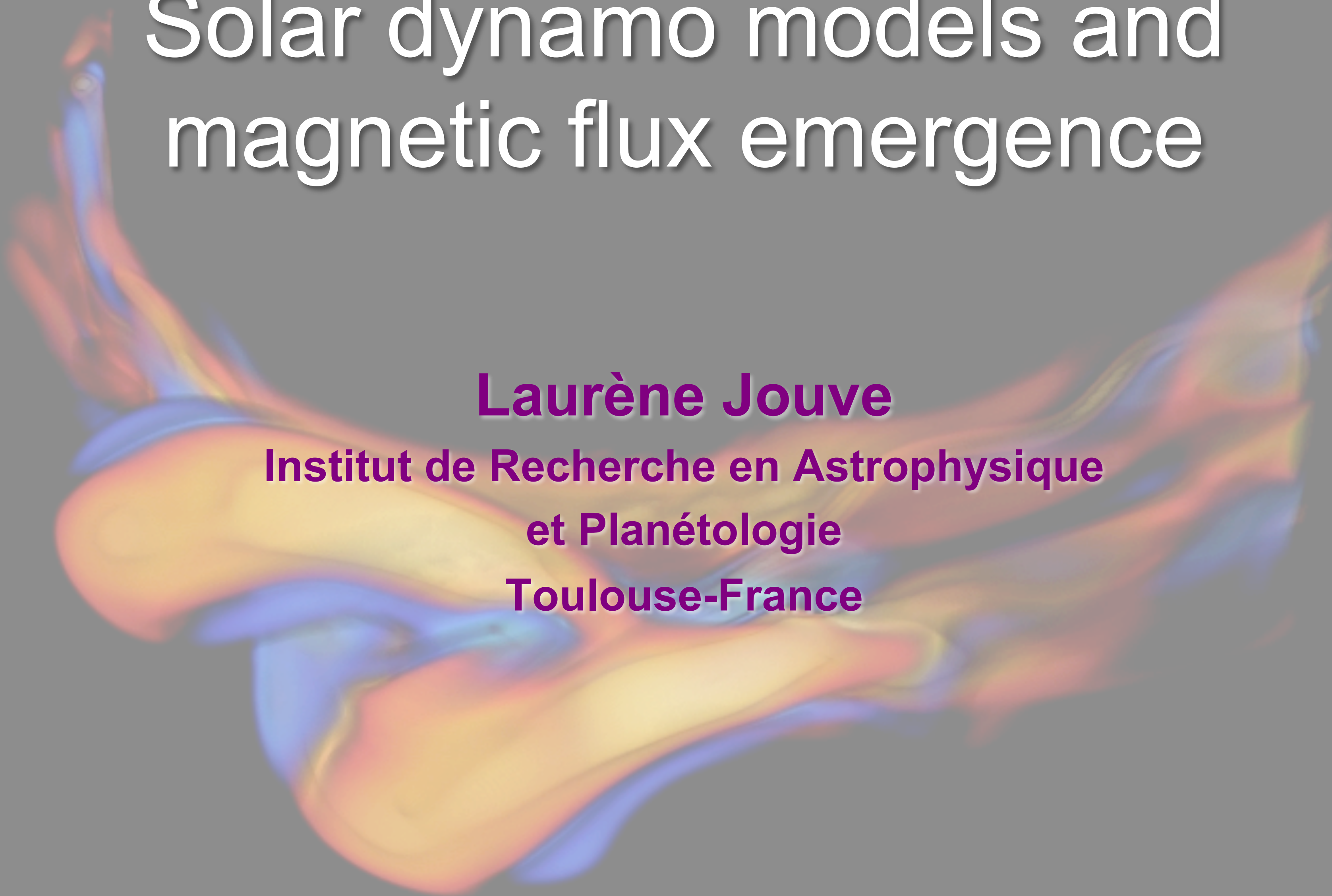
Solar dynamo models and magnetic flux emergence



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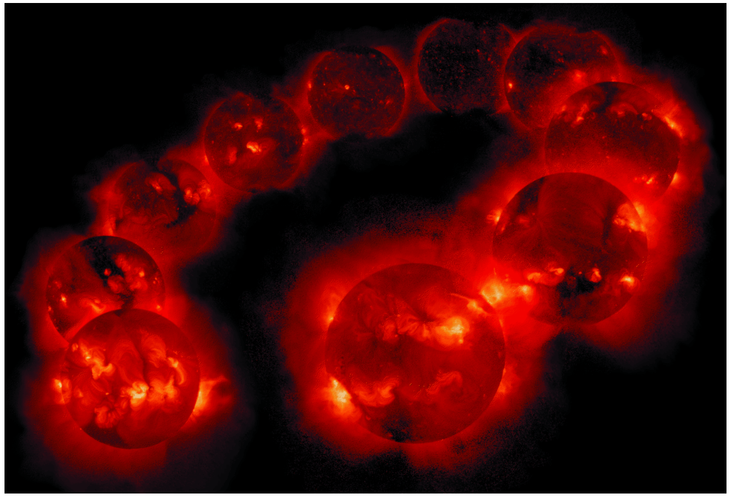
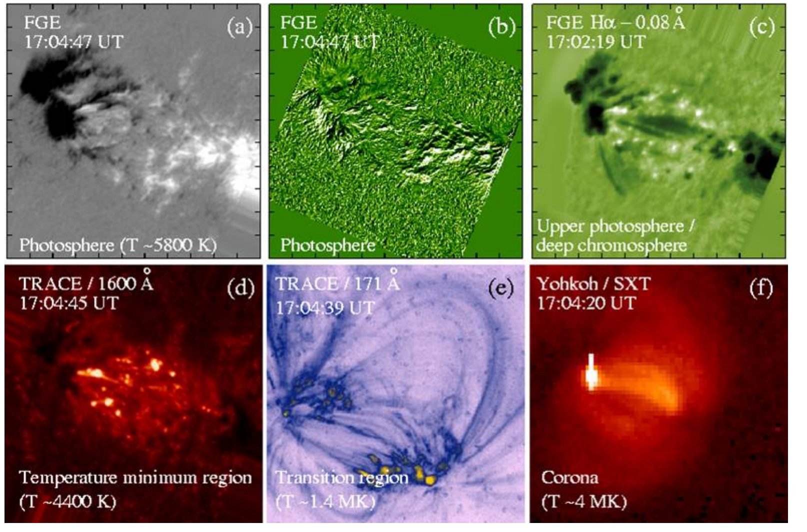
The magnetic solar cycle

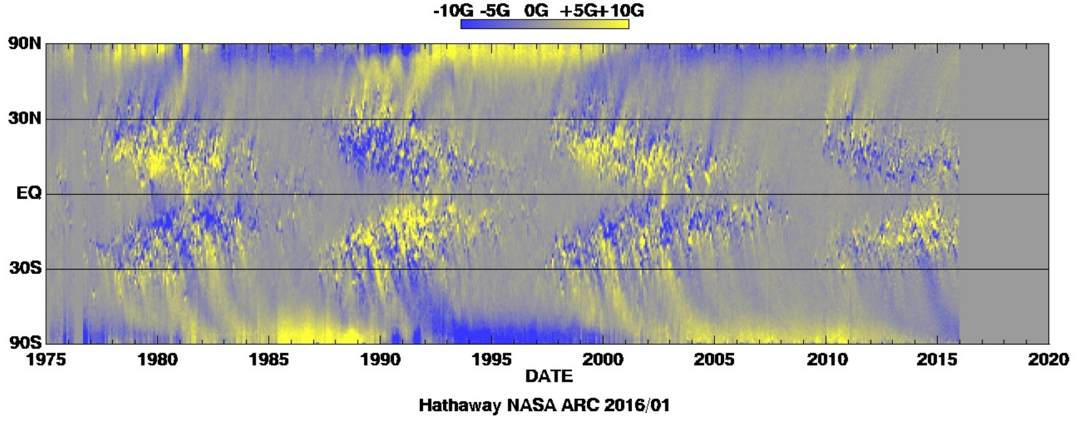
Yohkoh soft Xray images over a whole solar cycle (1991-2001)



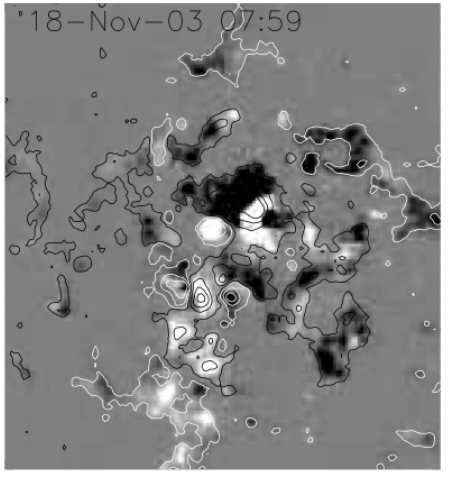
Flux emergence observed at different wavelengths (Georgoulis et al. 2004, Schmieder et al. 2004)



Butterfly diagram (observed radial field) (D. Hathaway)



Complex active regions with mixed helicity (Chandra et al, 2010)

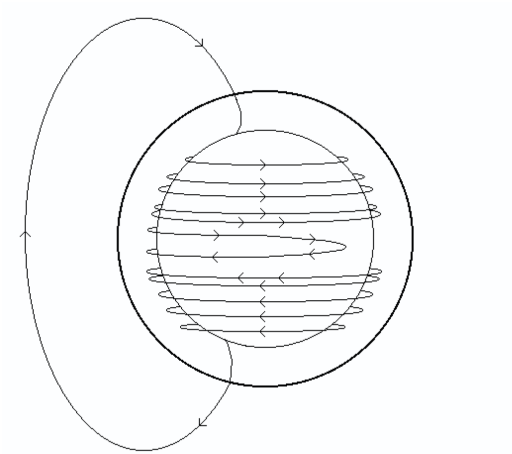


Theory: the dynamo mechanism

Dynamo mechanism: process through which motions of a conducting fluid can permanently regenerate and maintain a magnetic field against its ohmic dissipation

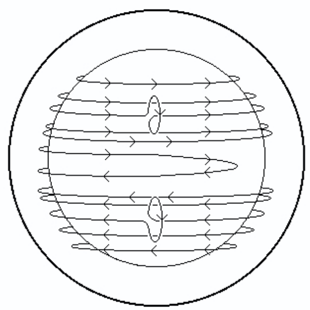
It consists of the regeneration of both poloidal and toroidal fields

Poloidal → Toroidal

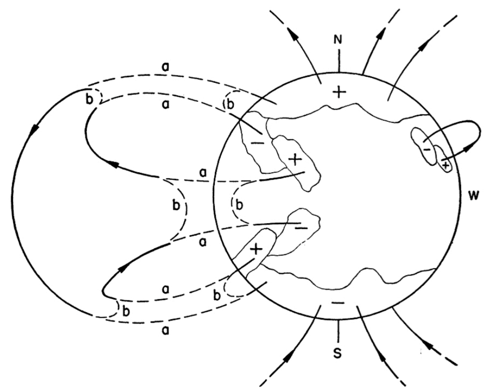


Ω effect

Toroidal → Poloidal

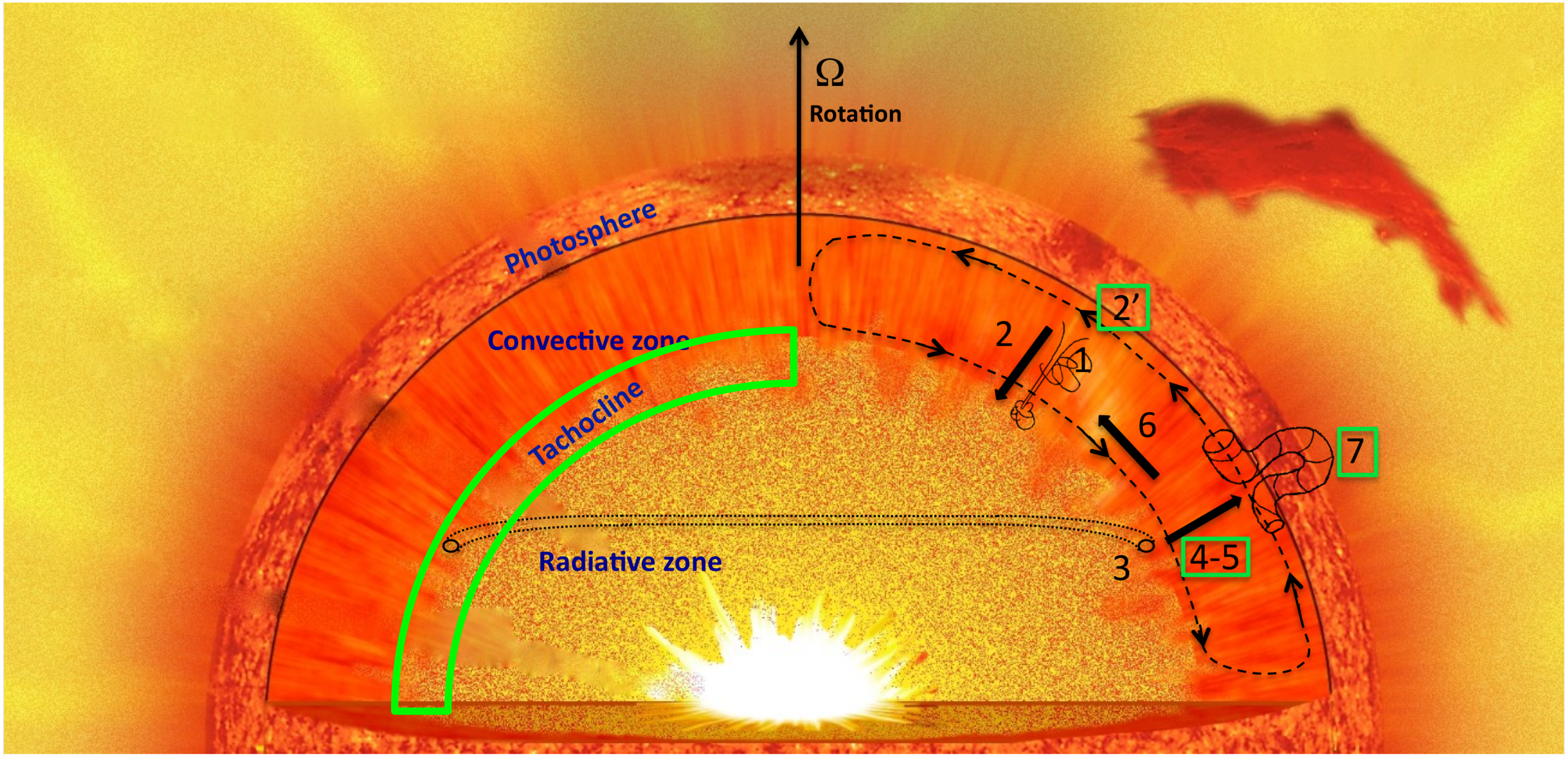


α effect



Babcock-Leighton effect

Schematic theoretical view of the solar cycle



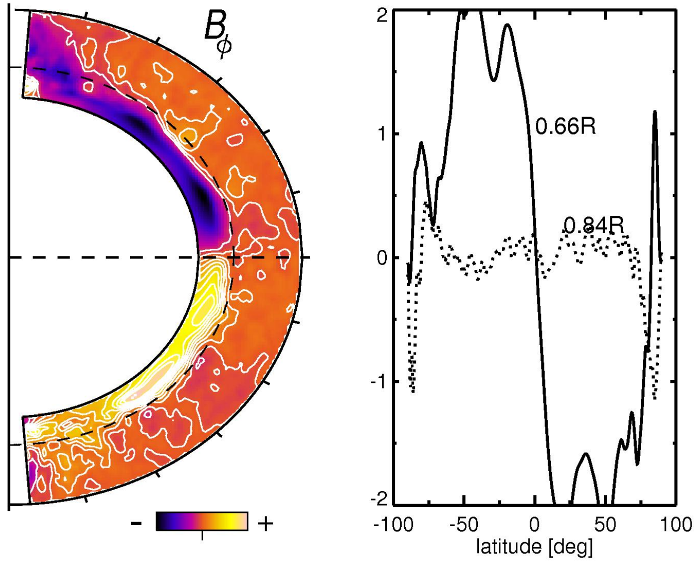
1: magnetic field generation, self-induction
2: pumping of mag. field
or
2': transport by meridional flow
3: stretching of field lines through Ω-effect

4: Parker instability
5: emergence+rotation
6: recycling through α−effect or
7: emergence of twisted bipolar structures at the surface

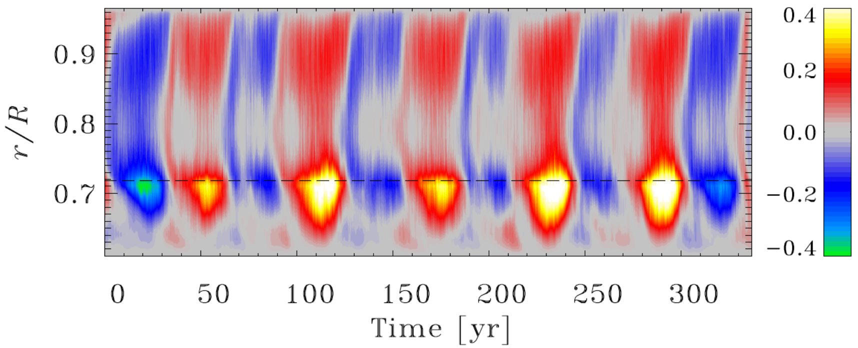
Tachocline helps for field organisation

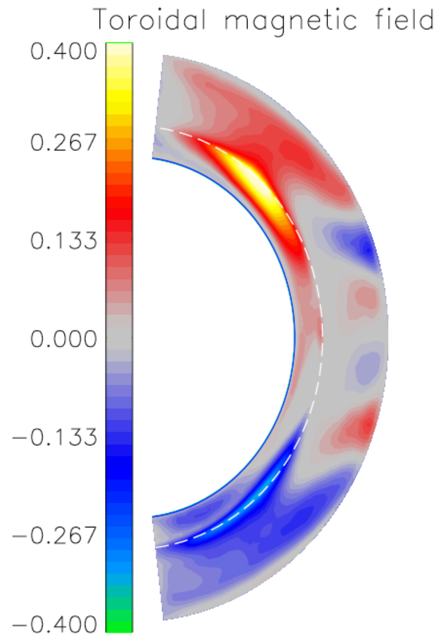
- Large-scale magnetic field built by the dynamo
- Stored in the sub-adiabatic layer at the base of the convection zone

Browning et al 2006



Ghizaru et al 2010
Racine et al 2011

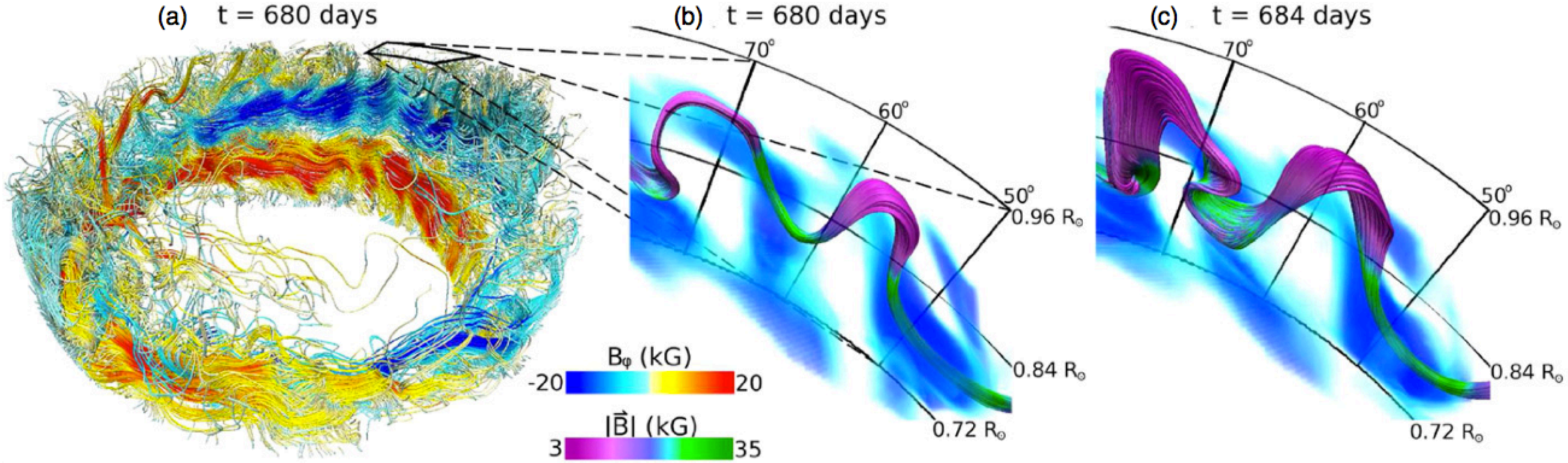


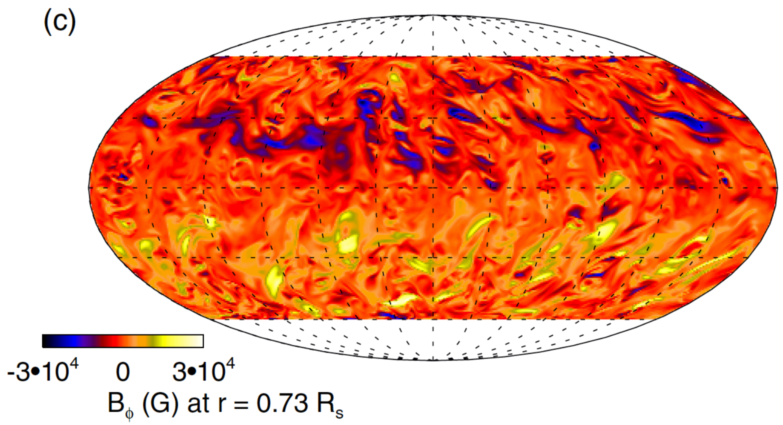


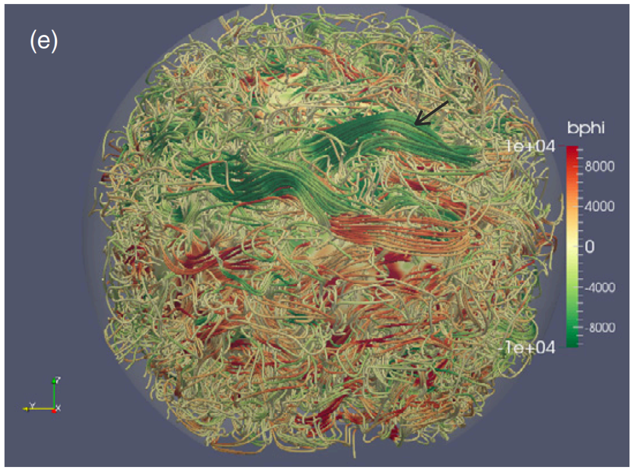
Buoyant loops are generated (even without a tachocline)

- Buoyant magnetic loops form and rise up quite coherently
- They are intrinsically twisted by convective motions

Nelson et al., 2011, 2014

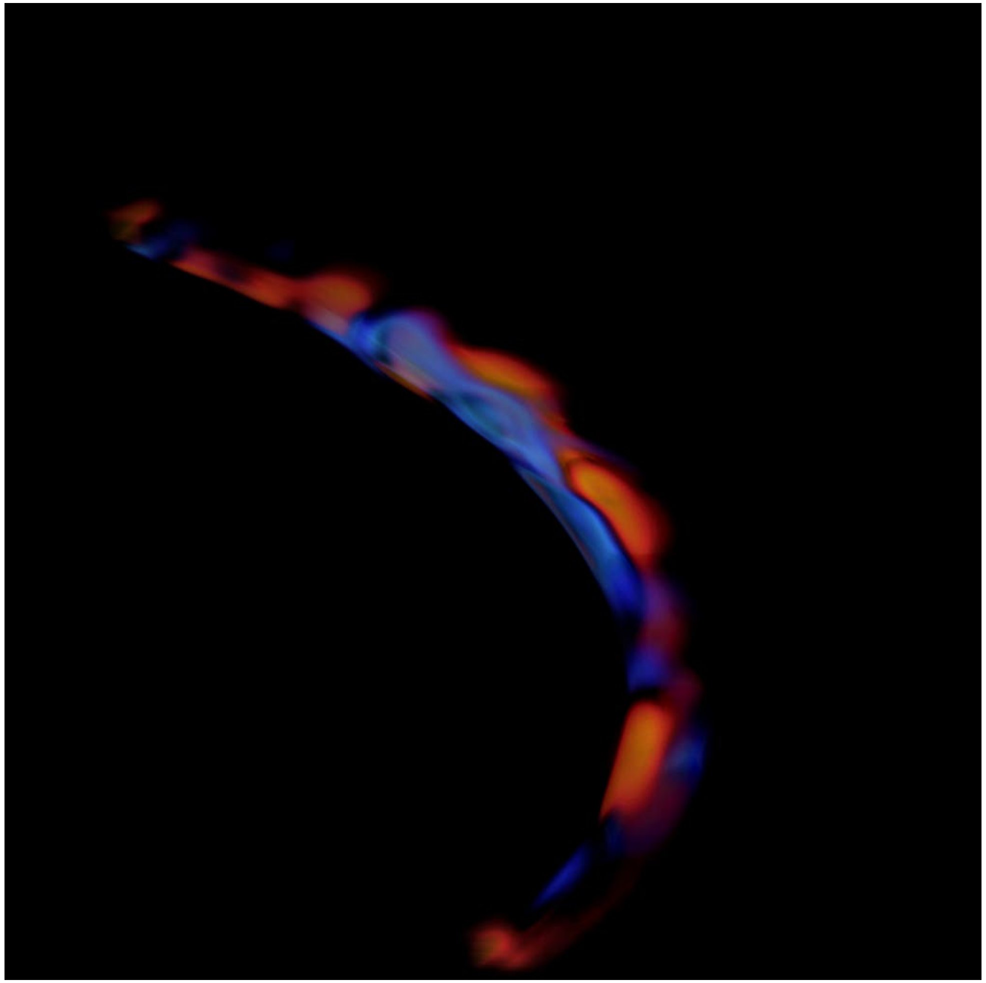






Fan & Fang 2014

Simulations of individual buoyant loops



Convective layer

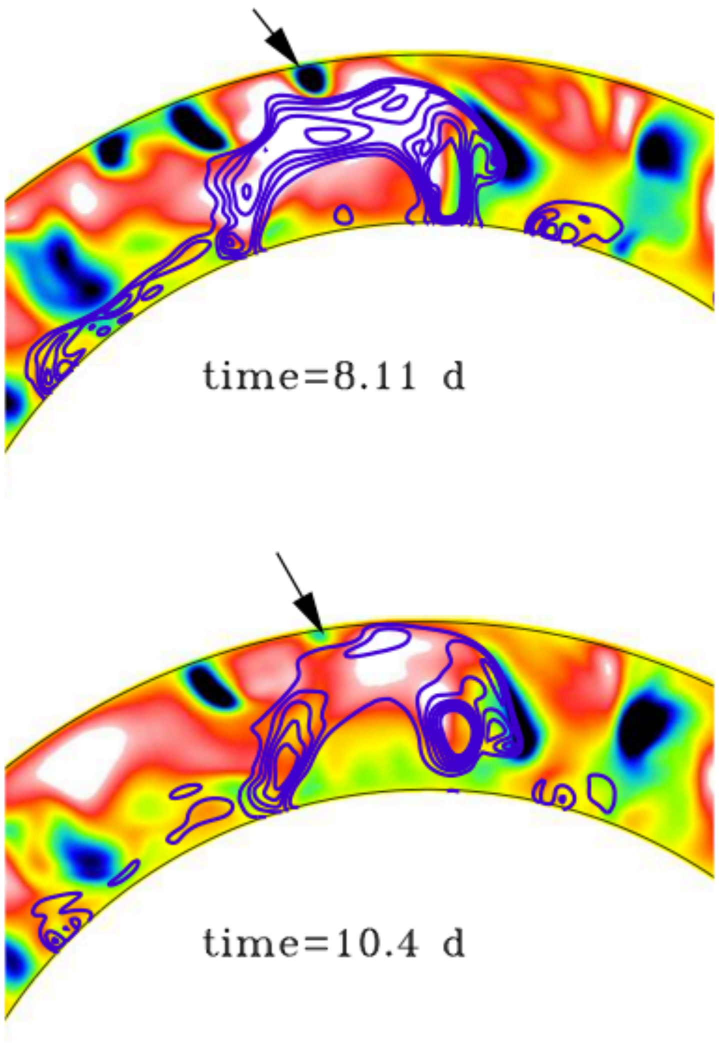
Movie created with SDvision@CEA

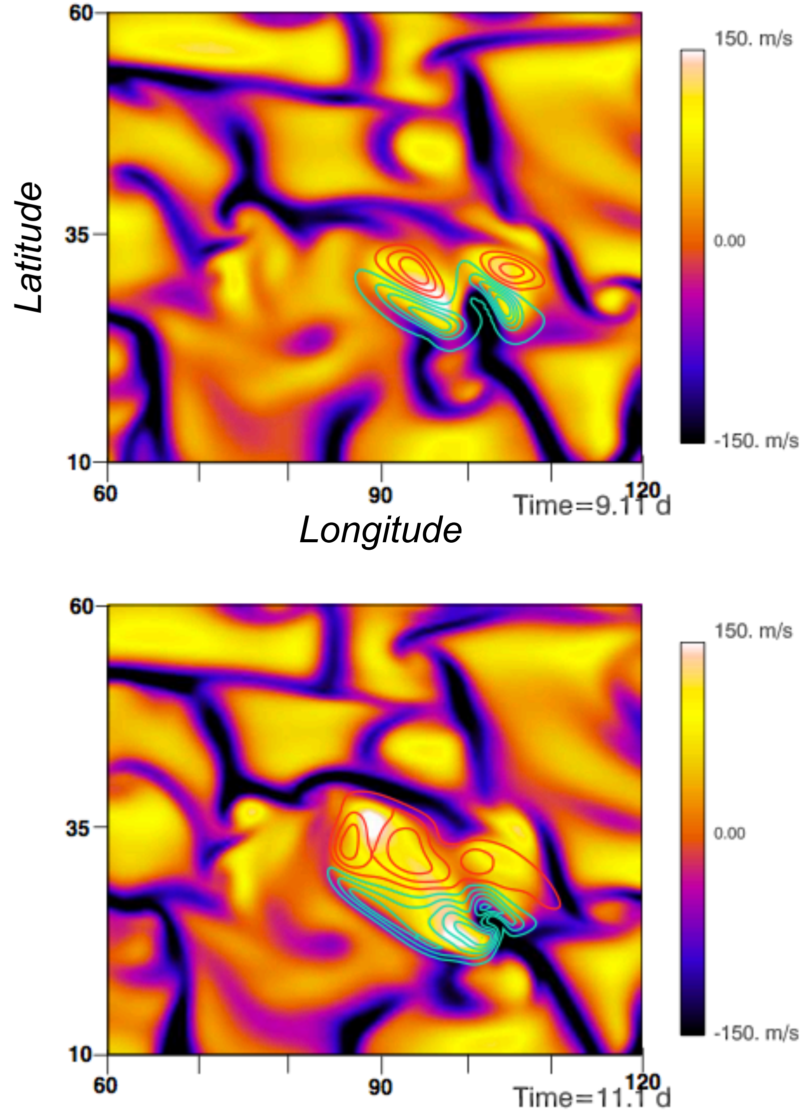
Jouve, Brun & Aulanier 2013

- Creation of negative toroidal field through the Omega-effect is even more efficient.
- Same kind of asymmetries.
- Strong deformation of the rising structure because of convective motions.
- Similar rise time for the same field strength.

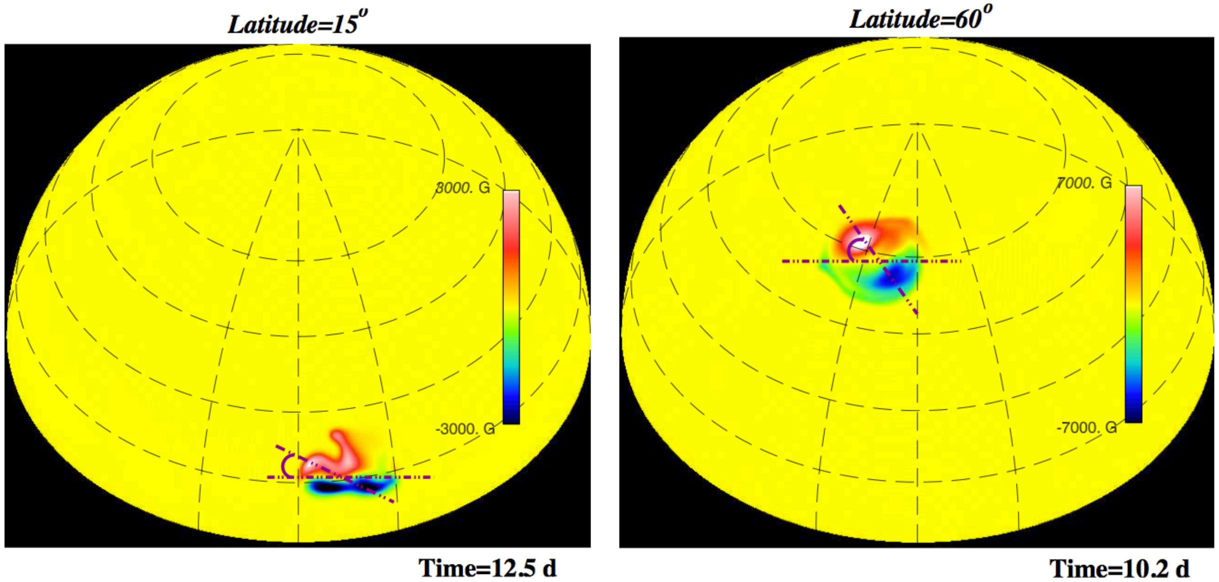
Simulations of individual buoyant loops

Convective upflows and downflows control the rise velocity of the loop and modify the morphology of emerging regions



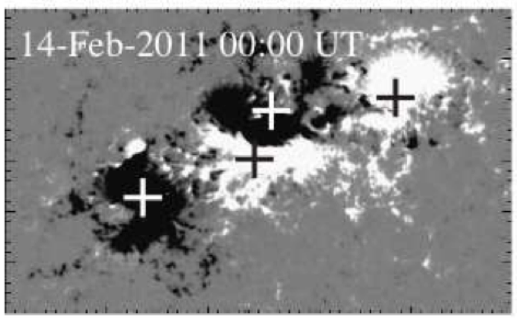


Emerging regions

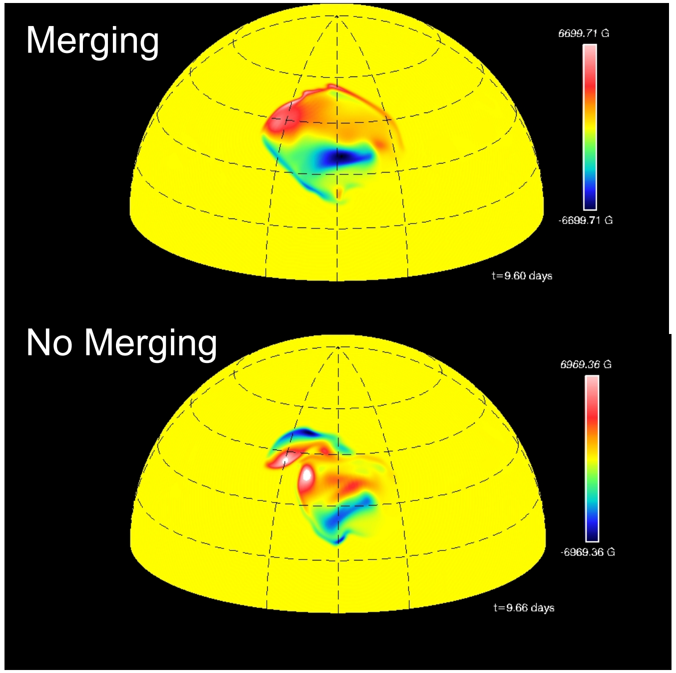


- Faster rise at high latitudes, thus stronger fields: effect of rotation
- Shift in longitude: effect of differential rotation
- Tilt angle higher at high latitudes (in agreement with observations)

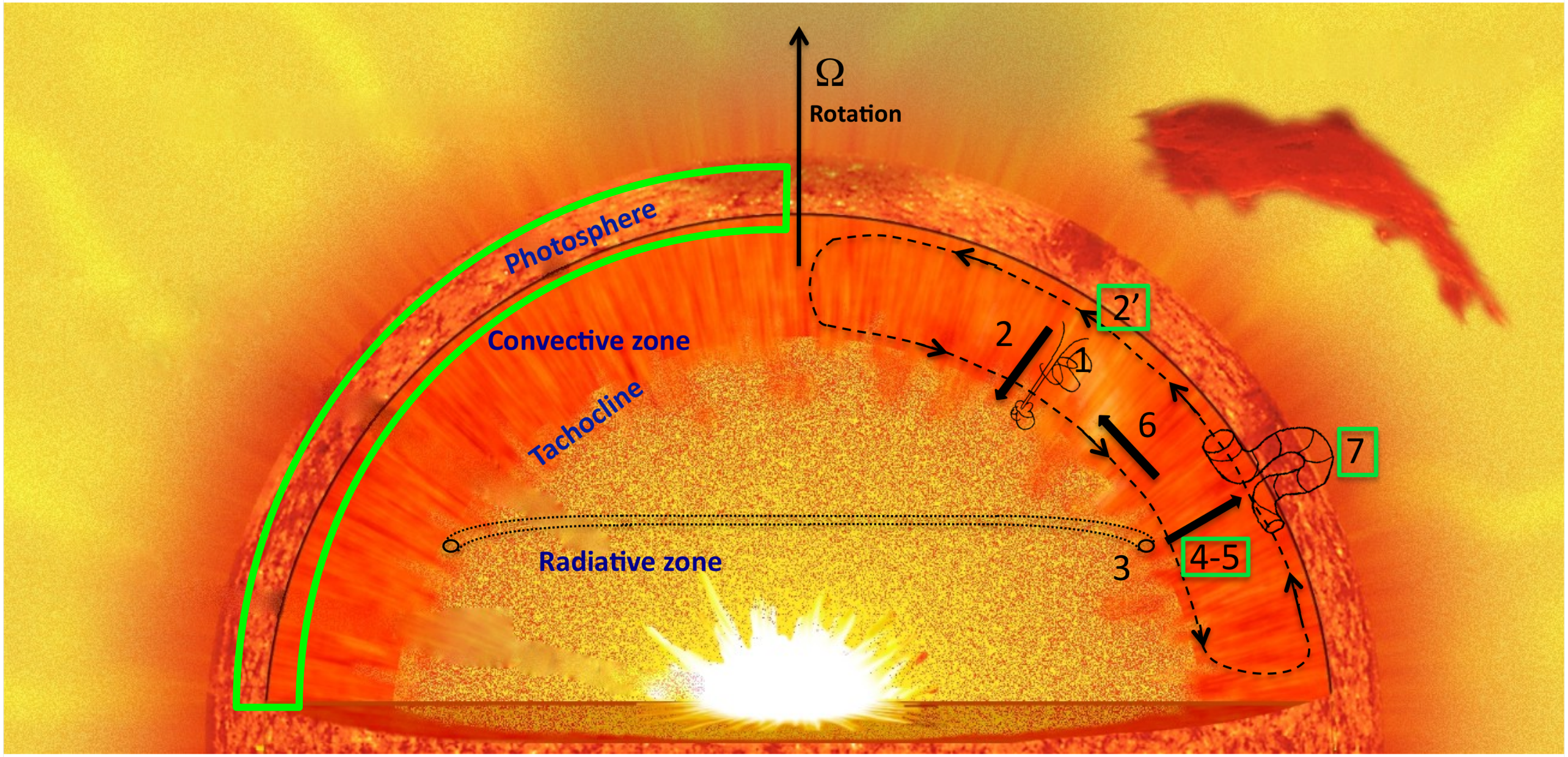
- Origin of complex active regions with mixed helicity or polarity?
 (Chandra et al 2010,
 Toriumi et al 2014, Fang & Fan 2015)



- Loop interactions (Jouve, Brun & Aulanier, in prep.)



Schematic theoretical view of the solar cycle



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A mean-field dynamo model

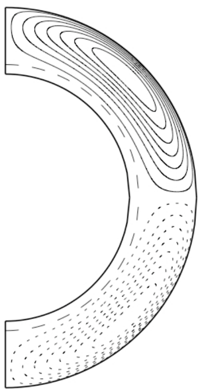
- Mean-field induction equation
- Poloidal/toroidal decomposition
- 2 coupled PDEs

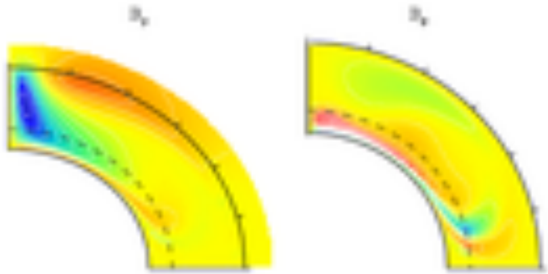
$$\frac{\partial A_\phi}{\partial t} = \frac{\eta}{\eta_t}\left(\nabla^2 - \frac{1}{\varpi^2}\right)A_\phi - R_e \frac{\mathbf{u}_p}{\varpi}\cdot\nabla(\varpi A_\phi) + \cancel{C_\alpha \alpha} B_\phi + \boxed{C_s S(r,\theta,B_\phi)}$$

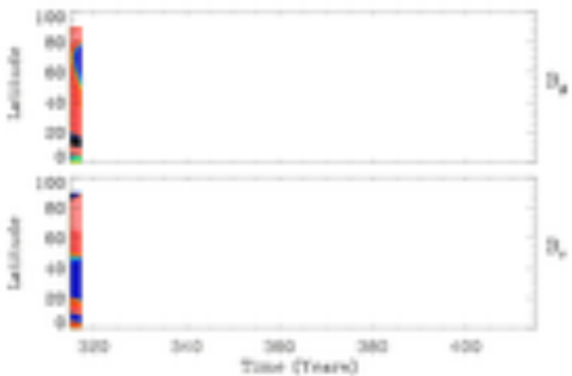
$$\frac{\partial B_\phi}{\partial t} = \frac{\eta}{\eta_t}\left(\nabla^2 - \frac{1}{\varpi^2}\right)B_\phi + \frac{1}{\varpi}\frac{\partial(\varpi B_\phi)}{\partial r}\frac{\partial(\eta/\eta_t)}{\partial r} - R_e \varpi \mathbf{u}_p \cdot \nabla\left(\frac{B_\phi}{\varpi}\right) - R_e B_\phi \nabla\cdot\mathbf{u}_p + C_\Omega \varpi (\nabla\times(\varpi A_\phi \hat{\mathbf{e}}_\phi))\cdot\nabla\Omega$$

Standard model: single-celled meridional circulation

MC







Cyclic field

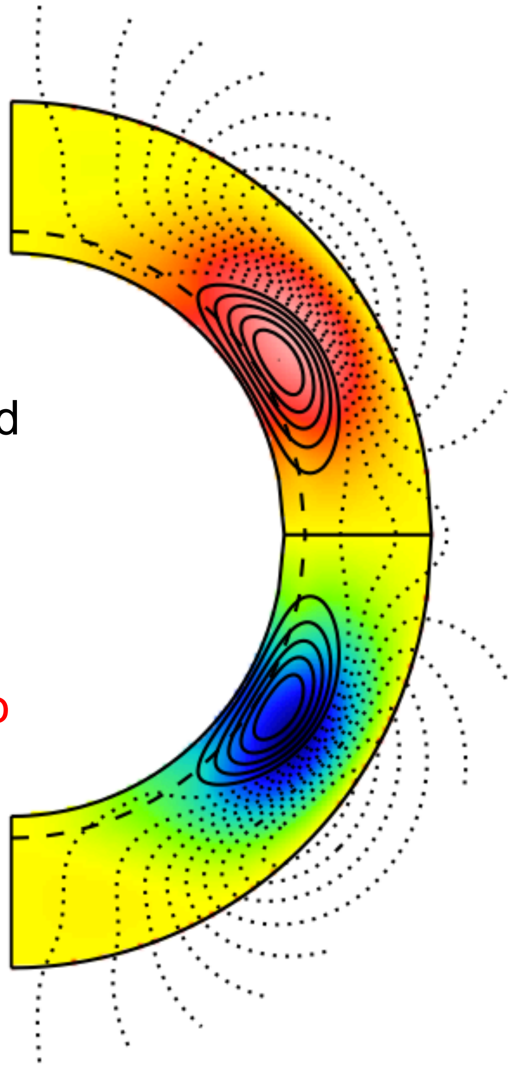
Butterfly diagram close to observations

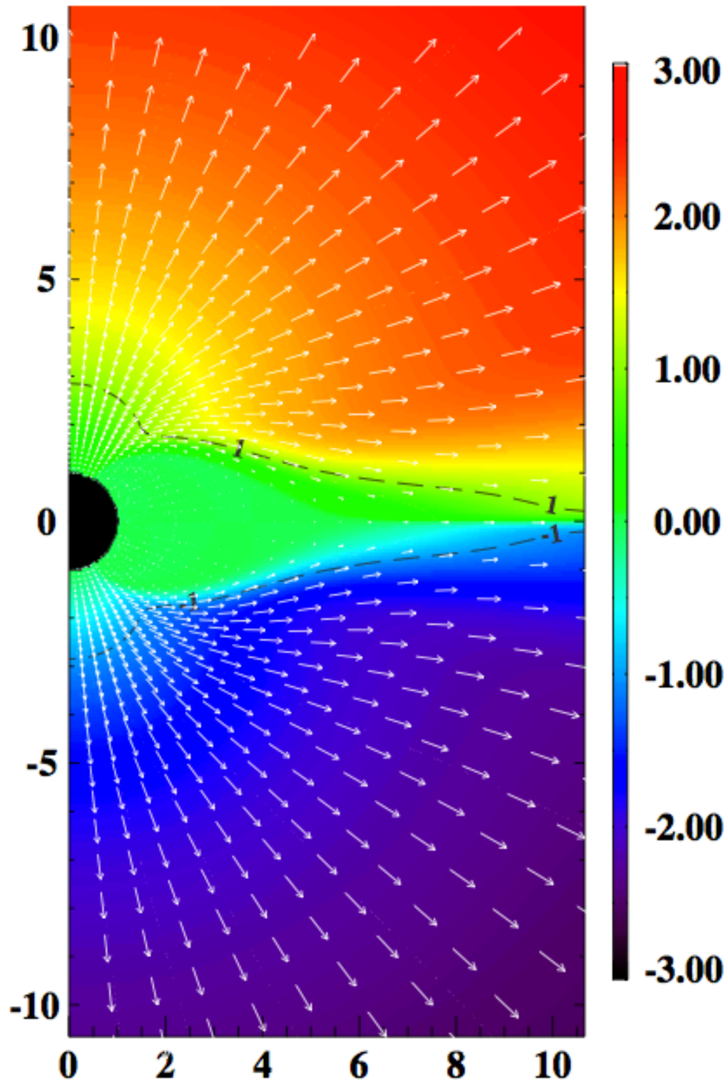
Link to the external Sun: *coupling codes*

Kinematic dynamo ⟹ Corona, solar wind

Pinto et al, 2011

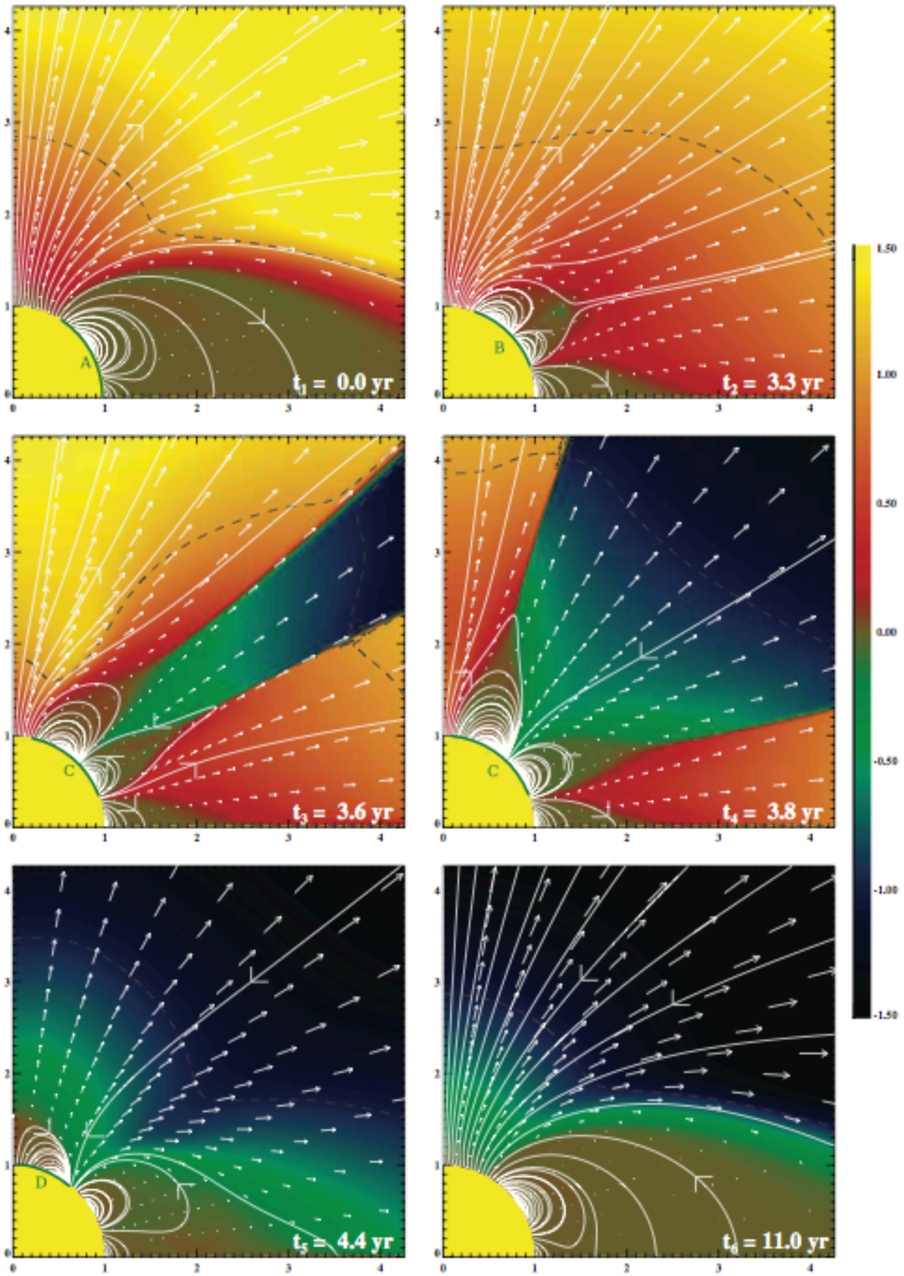
The solar wind code is fed with the surface magnetic field produced by the dynamo code



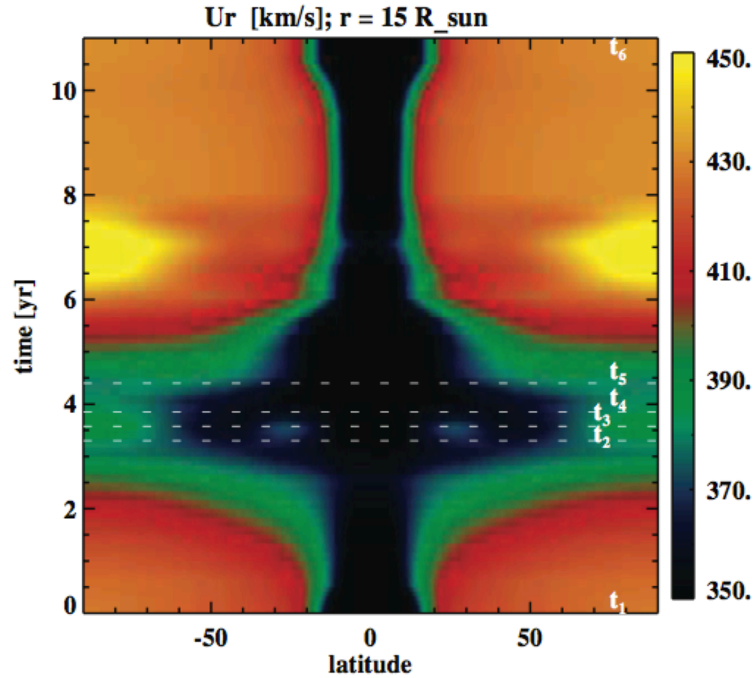


Solar wind responds to cyclic variations of the external field

Link to the external Sun: *coupling codes*



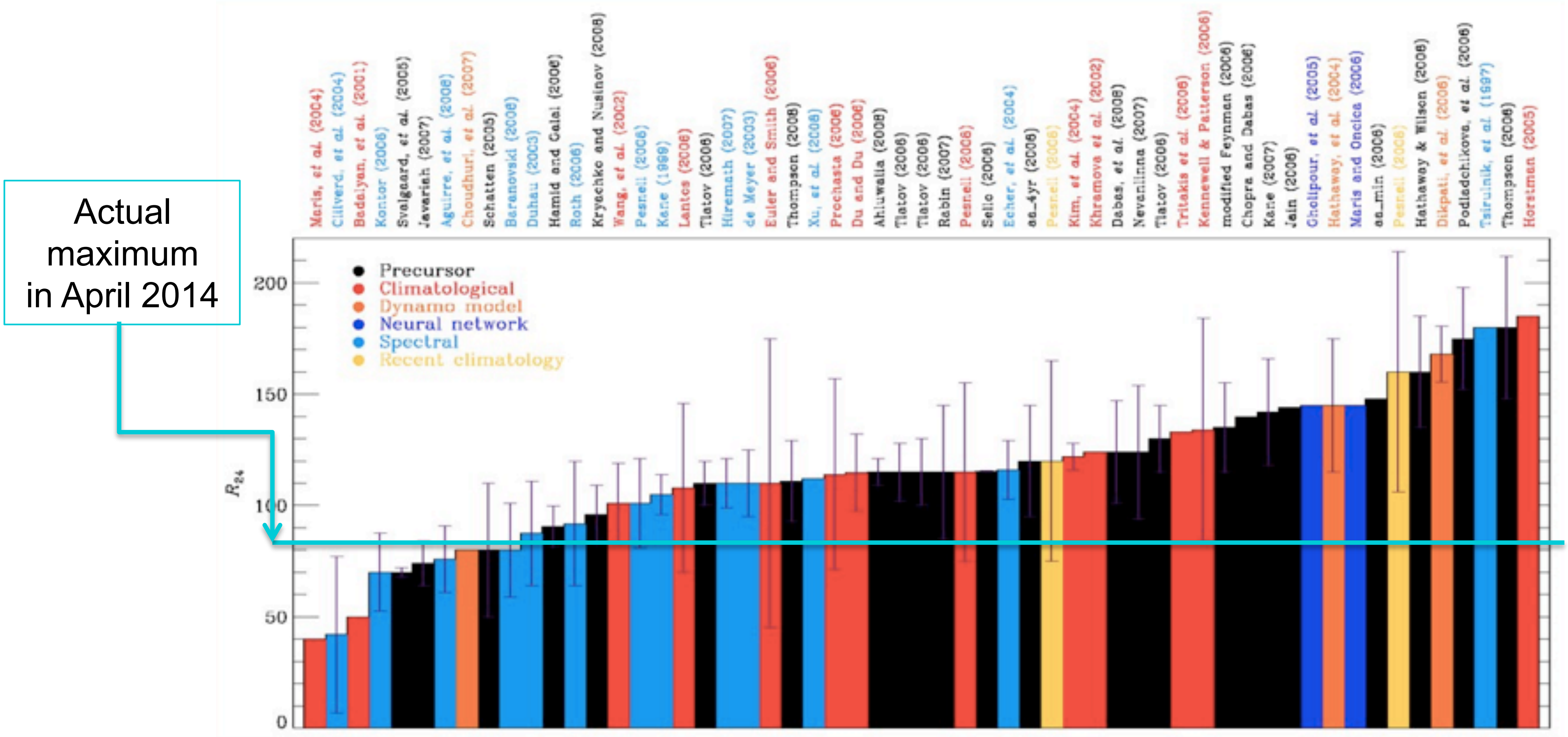
Solar wind speed at 15R
in agreement with
observations of Ulysses
(Wang & Sheeley, 2006)



Poster 3.11 (Pinto)

Connections with space weather

- Can we predict the next sunspot maximum?

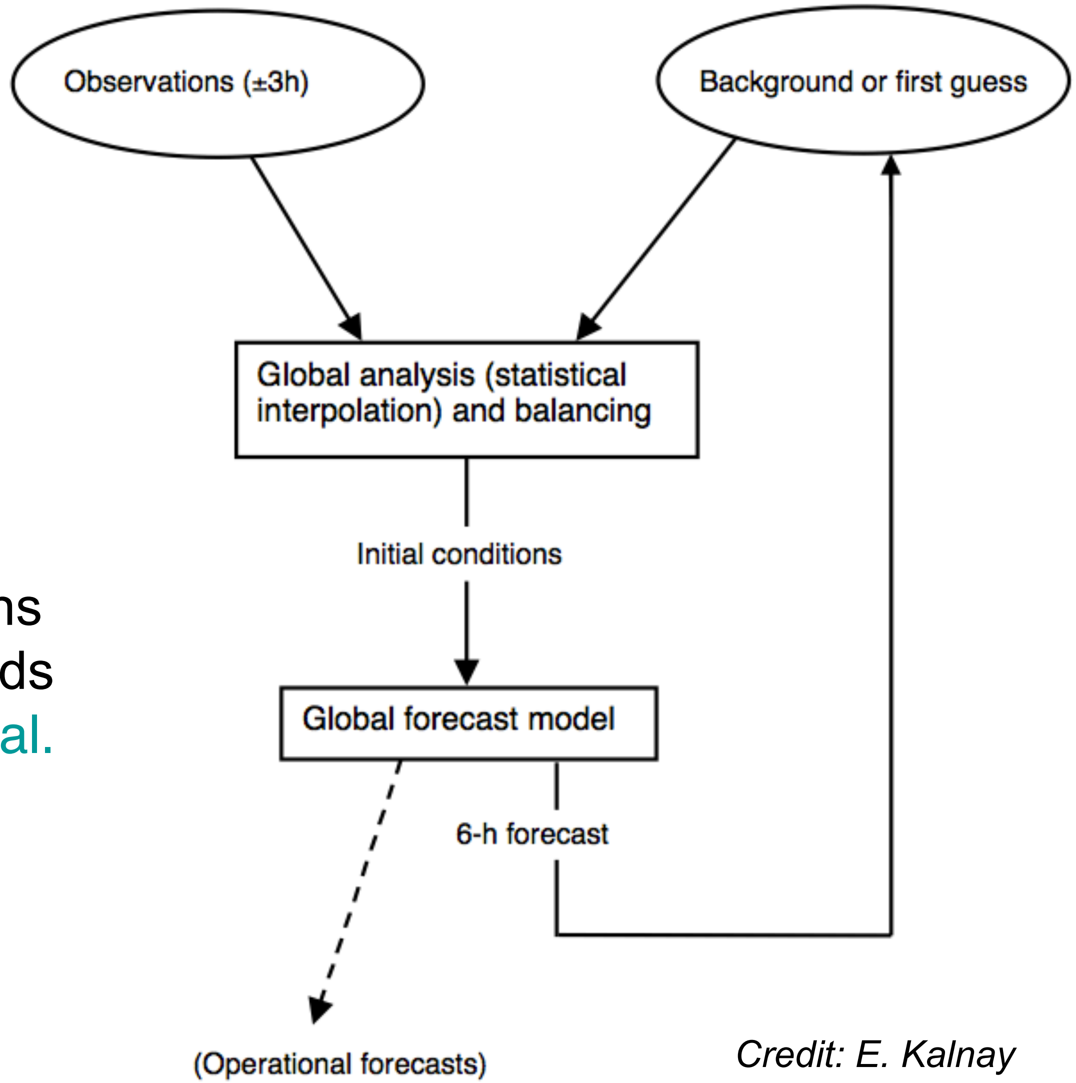


Pesnell 2012

Connections with space weather

- Inspired from weather forecasting on Earth: Physics-based models and observations combined through
  data assimilation

- Dynamo models+ observations of surface flows and mag. fields
  (Kitiashvili et al. 2008, Jouve et al. 2010, Hung et al. 2015)
  Poster 1.9 (Hung)



Credit: E. Kalnay

Conclusions

- *Tools to study dynamo action in stars and interfaces between key regions:*
  - observations
  - simplified models of a global mechanism
  - more complex and realistic models of particular steps of the dynamo loop
  - coupling codes which deal with different regions

- *We have seen that:*
  - the tachocline region may help to organise the magnetic field
  - 3D simulations of loops rising on a convective zone produce bipolar structures with properties in agreement with observations
  - data assimilation starts to be applied to solar physics for cycle predictions

- *Several open questions remain:*
  - is the tachocline a major player in the dynamo mechanism?
  - where do the active regions and their complexity actually come from?
  - what are the best ways to connect simulations of the solar interior/exterior?