Magnetic flux emergence and the solar dynamo

Laurène Jouve
IRAP Toulouse

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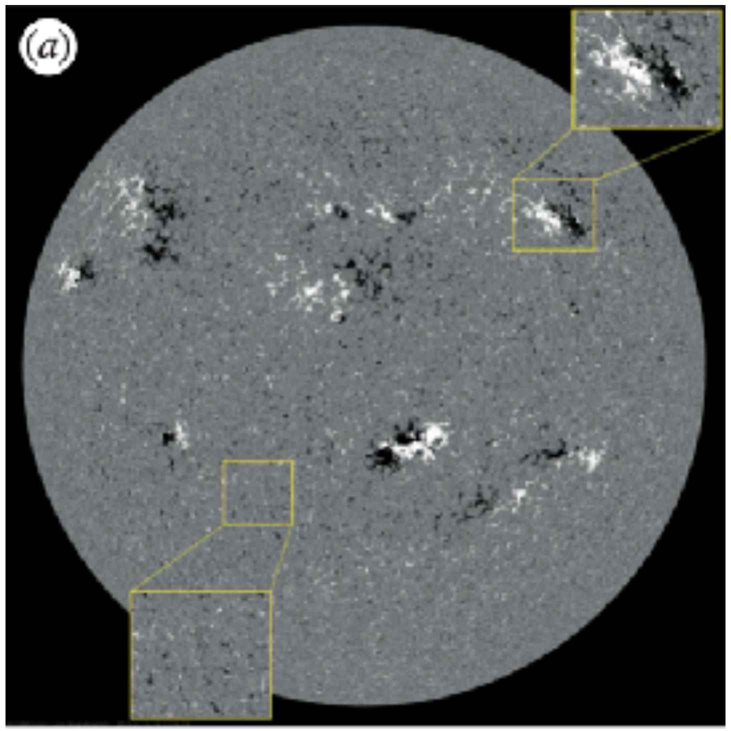
Magnetic flux emergence

Large variety of spatial and temporal scales

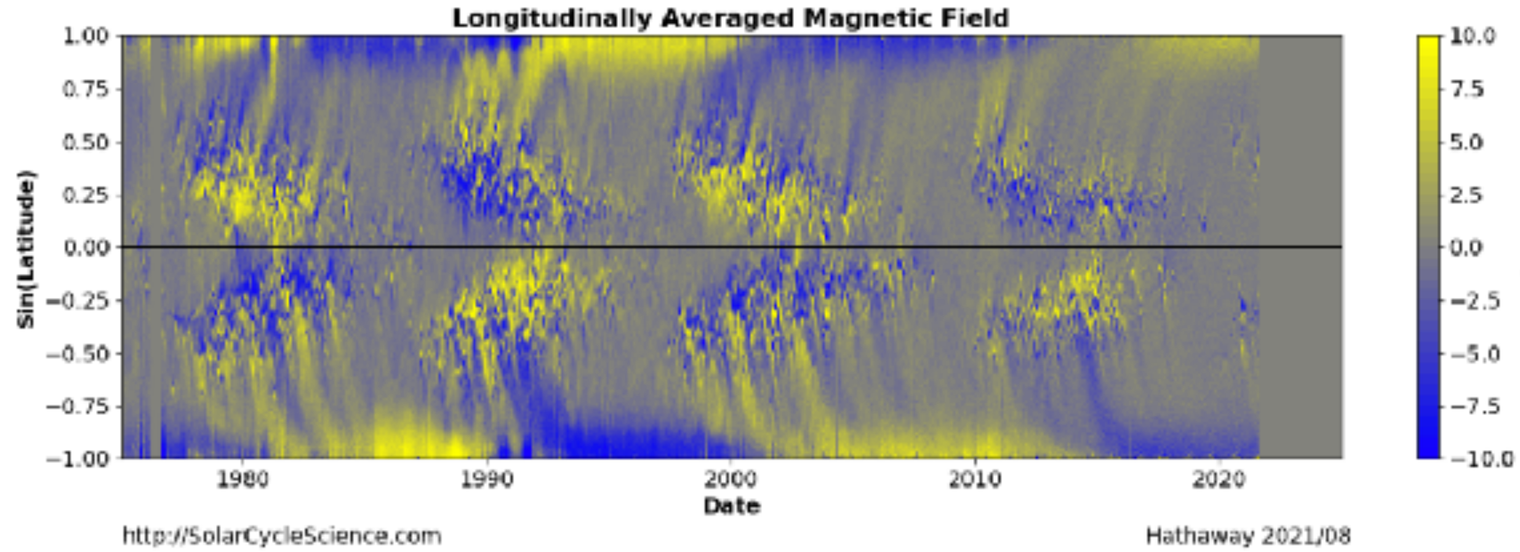
Flux emergence: appearance of new magnetic field concentrations at the solar surface

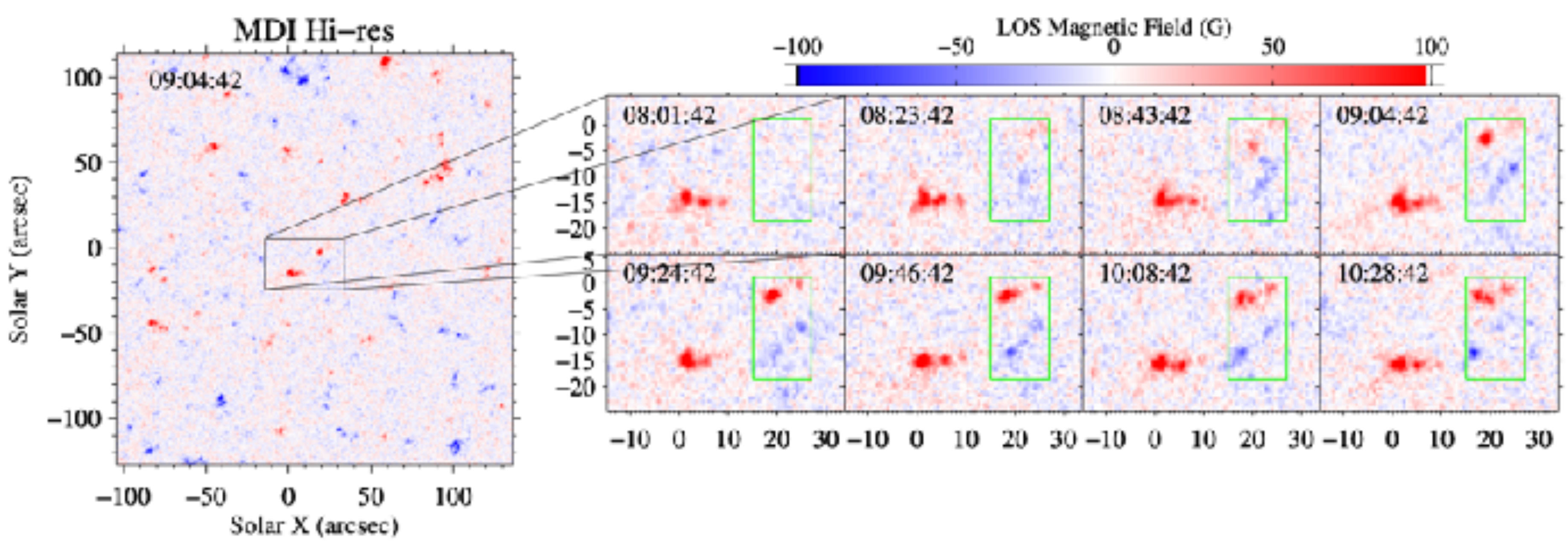


Archontis et al. 2012

Butterfly diagram (observed radial field)

(D. Hathaway)



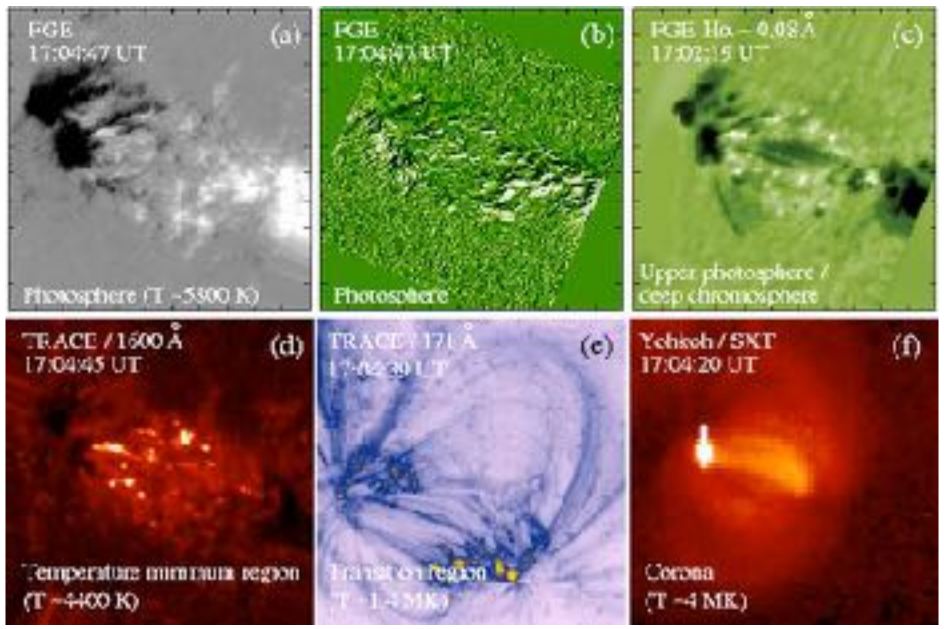


Kontogiannis et al. 2020

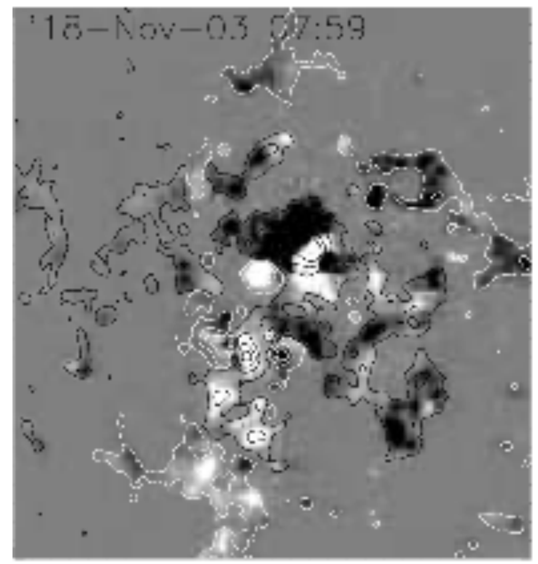
Focus in this presentation on large-scale flux emergence

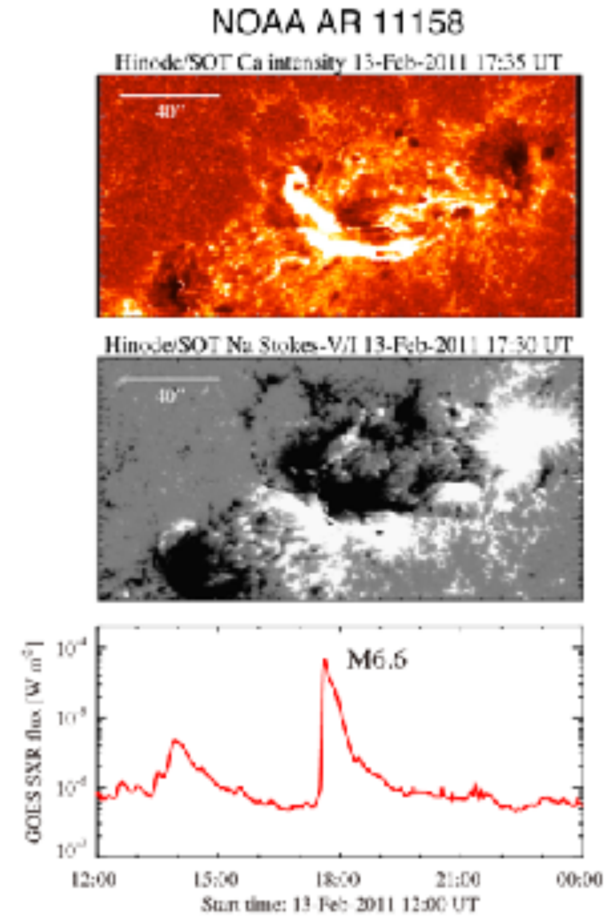
Magnetic flux emergence
Complexity and role in flaring activity

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



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





Flaring AR
(Toriumi et al. 2013)

Region	Magnetic flux (Mx)	Lifetime	Rise/Lifetime
Large (with sunspots)	$5 \times 10^{21} - 3 \times 10^{22}$	weeks – months	1 – 3%
Small (pores, no spots)	$1 \times 10^{20} - 5 \times 10^{21}$	days – weeks	15 – 27%
Ephemeral	$3 \times 10^{18} - 1 \times 10^{20}$	hours – $\approx$ 1 day	$\sim$ 30%

(Van-Driel & Green 2015)

Some key questions:

Where does this emerging flux come from?

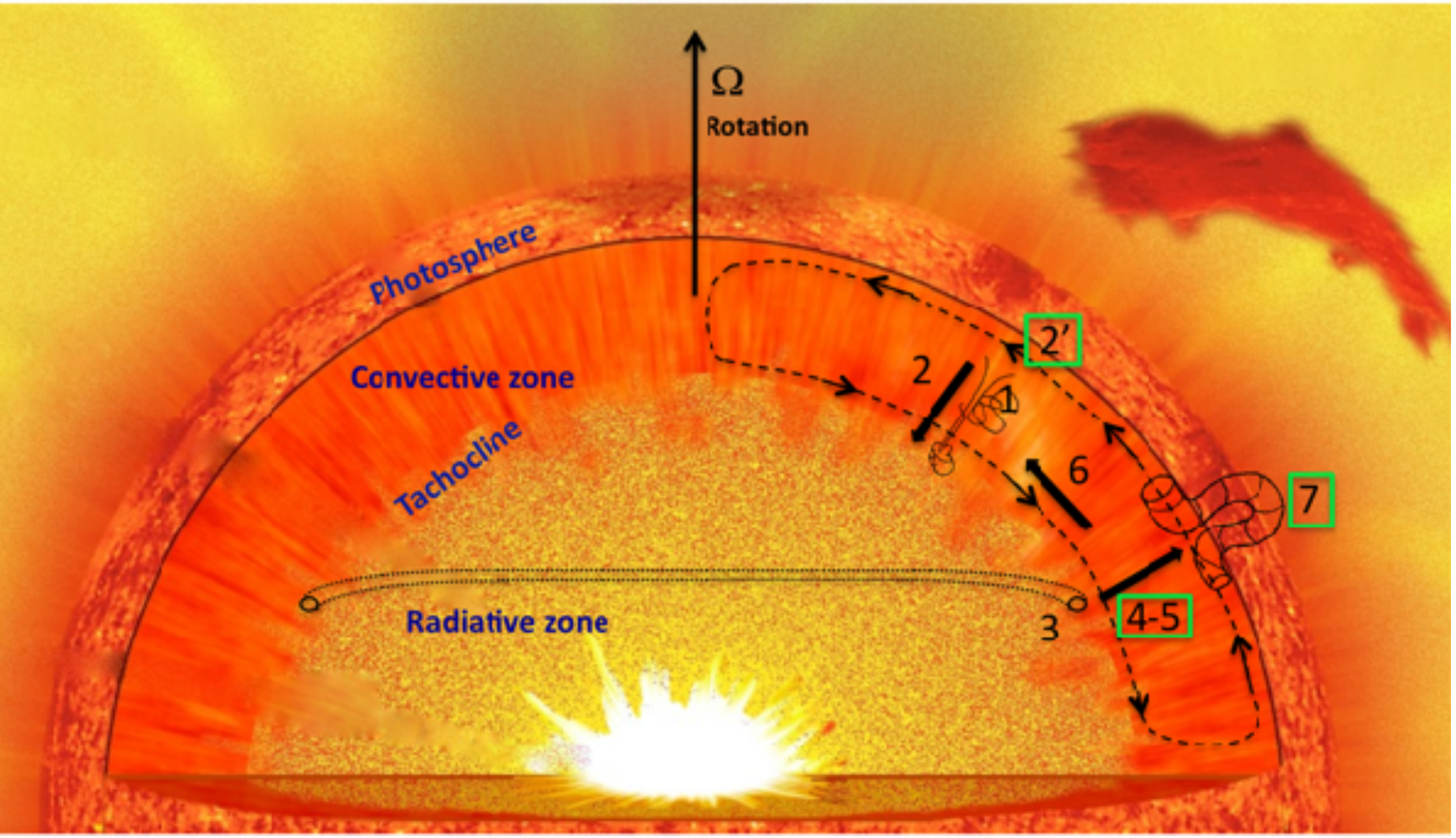
How are (complex) active regions formed?

What is the role of magnetic helicity?

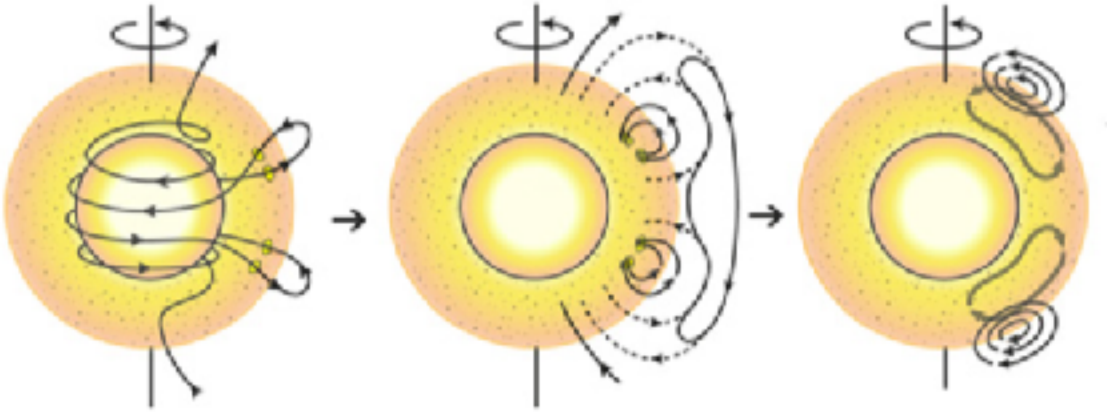
What is the role of emerging flux in flaring activity?

Magnetic flux emergence:
Link with the solar cycle

Magnetic buoyancy $p_i + \frac{B^2}{8\pi} = p_{amb}$ $\xrightarrow{T_i = T_{amb}}$ $\Delta\varrho/\varrho \approx -\beta^{-1}$ where $\beta = 8\pi p/B^2$



Babcock-Leighton mechanism



Sanchez et al. 2014

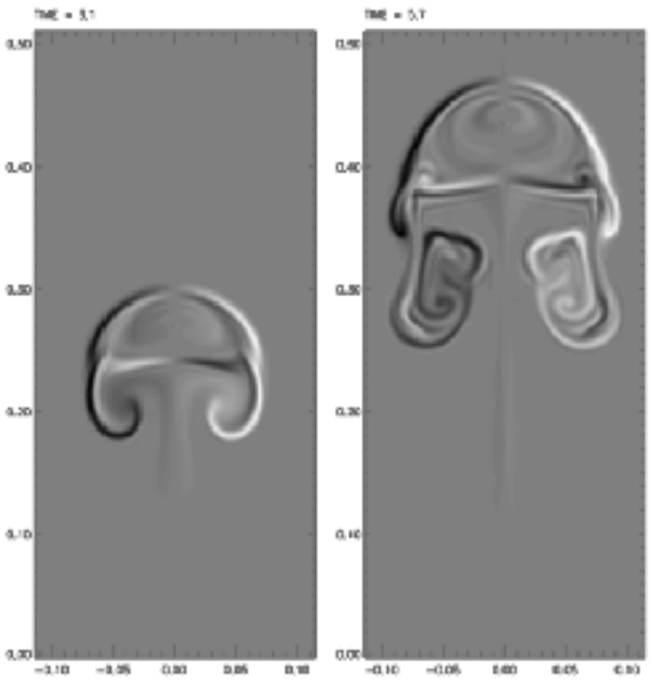
Some key questions:

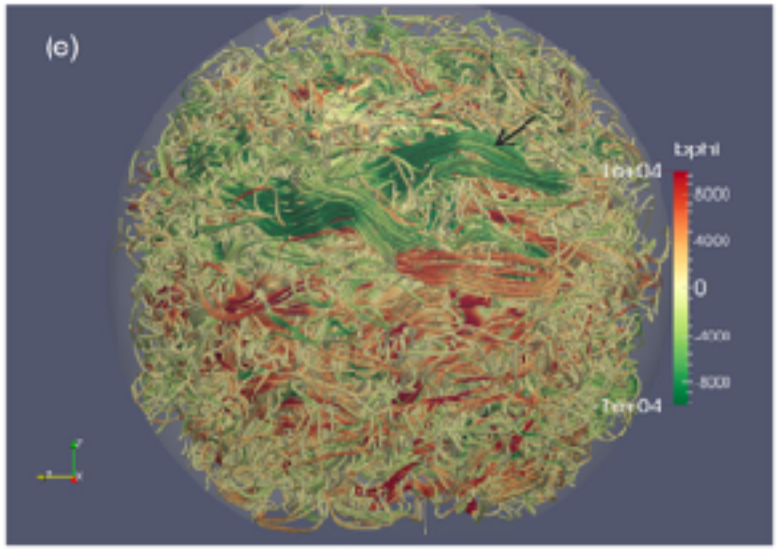
- **Role of the tachocline in building flux concentrations?**
- **Transport of flux at the surface to reverse polar fields?**
- **Role of sunspots in dynamo process?**
- **Origin of twist/tilt?**

Magnetic flux emergence
A diversity of numerical models

Need to rely on numerical models for emergence below photosphere (not observed- except with helioseismology?-) and for coupling with emergence in chromosphere and corona (for physical understanding of numerous phenomena)

- **Various approximations for fluxtubes introduced in the CZ:**
  - Thin flux tubes: all the variables only vary along the tube axis (Spruit, 1981)
  - 2D MHD simulations: local or global (e.g. Emonet & Moreno-Insertis, 1998)
  - 3D MHD simulations (anelastic): with or without convection (e.g. Fan et al., 2003, Fan 2008, Jouve & Brun 2009)
  - 3D HD simulations + thin flux tubes: (Weber et al. 2011)





- **Global convective dynamo simulations (anelastic):** Nelson et al. (2011, 2014), Fan & Fang 2014
  - Flux « bundles » self-consistently created but lack of coherent rising structures

Magnetic flux emergence

A diversity of numerical models

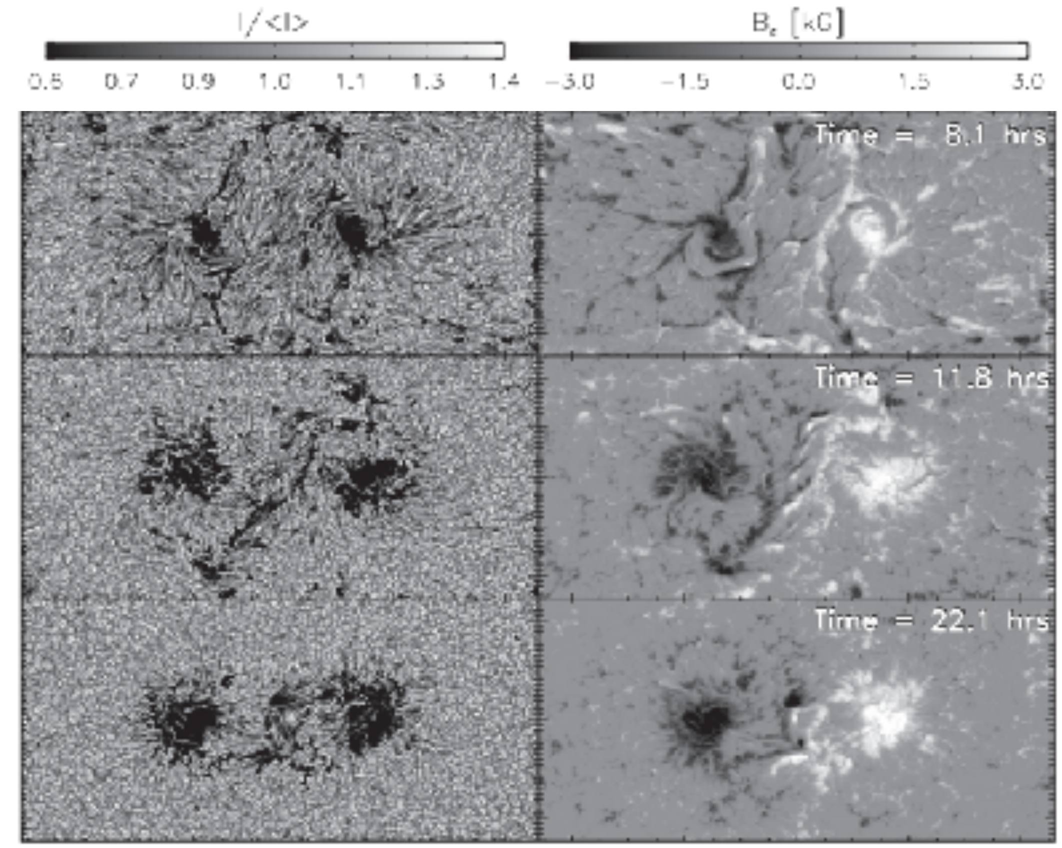
- **In the photosphere**

To understand how emergence proceeds
when density drops, interaction with granulation

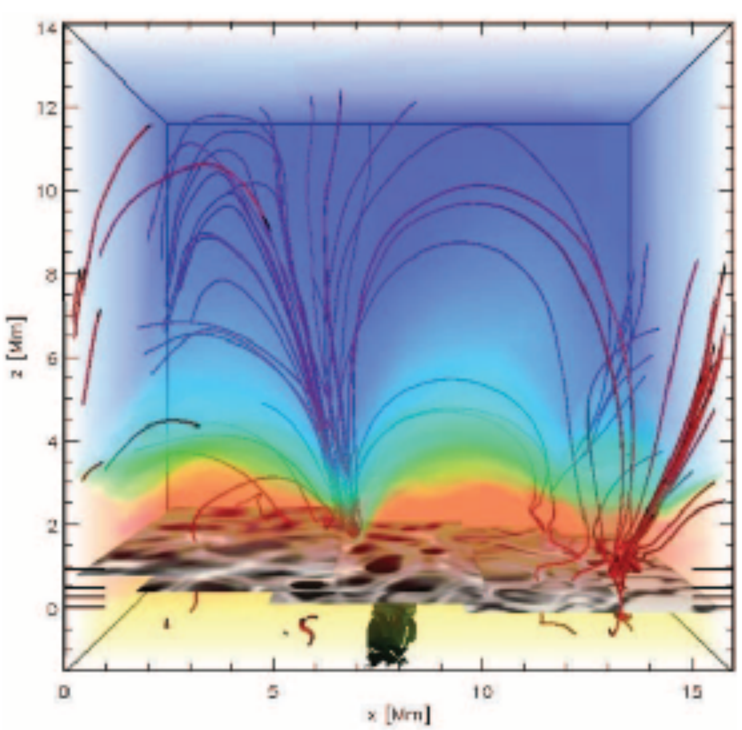
To understand formation, maintenance
and decay of sunspots

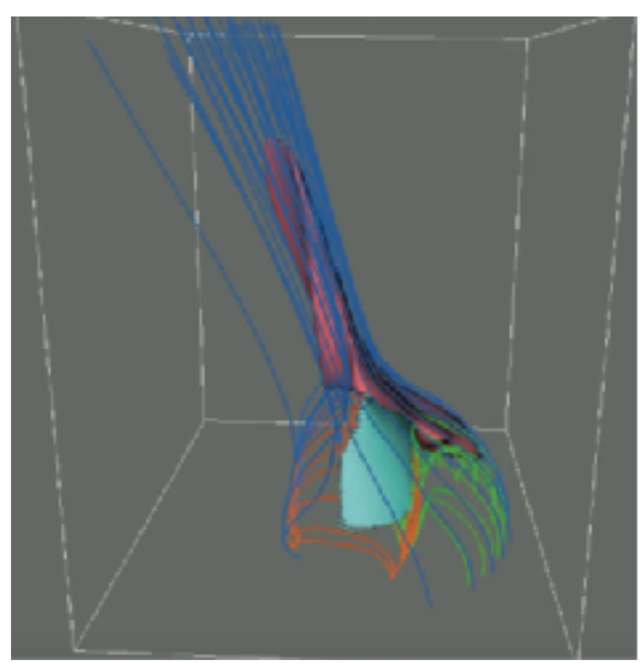
Fully compressible models
Radiative transfer

Cheung et al. 2010



(Martinez-Sykora et al. 2008, Moreno-Insertis et al. 2008)





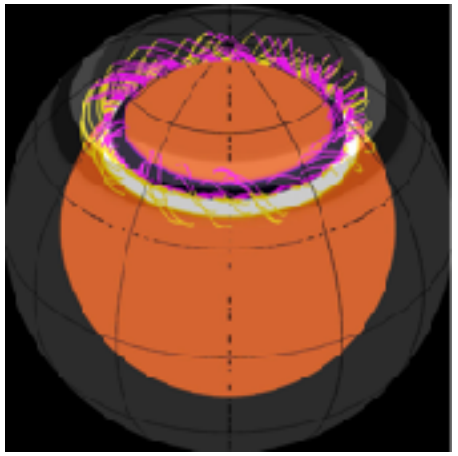
- **In the chromosphere and corona**

To understand interactions with ambient coronal
field, triggering of eruptions, to produce
synthetic data

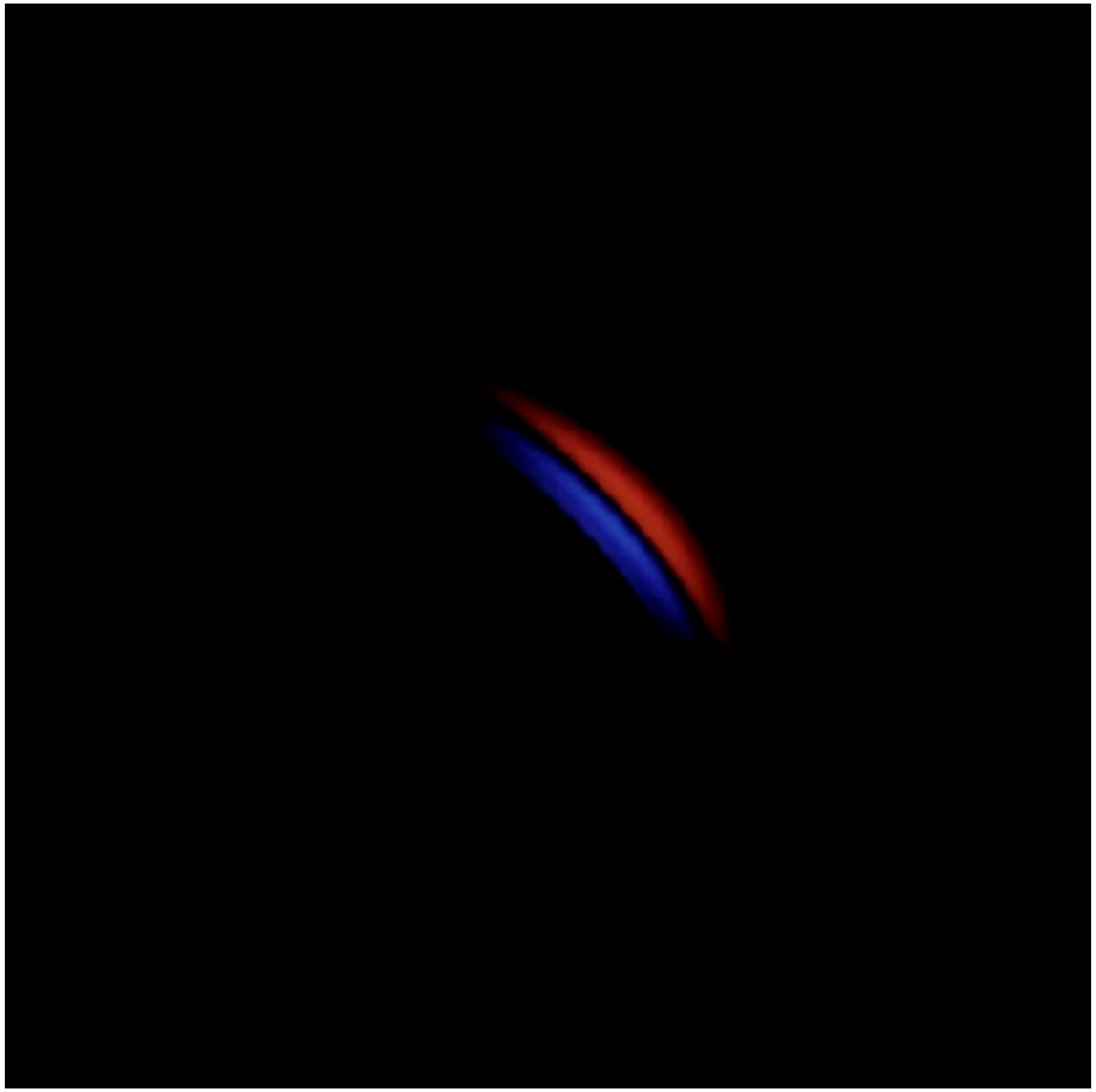
Fully compressible models
Radiative transfer
Huge variations of plasma beta, temperature,
density

3D MHD models

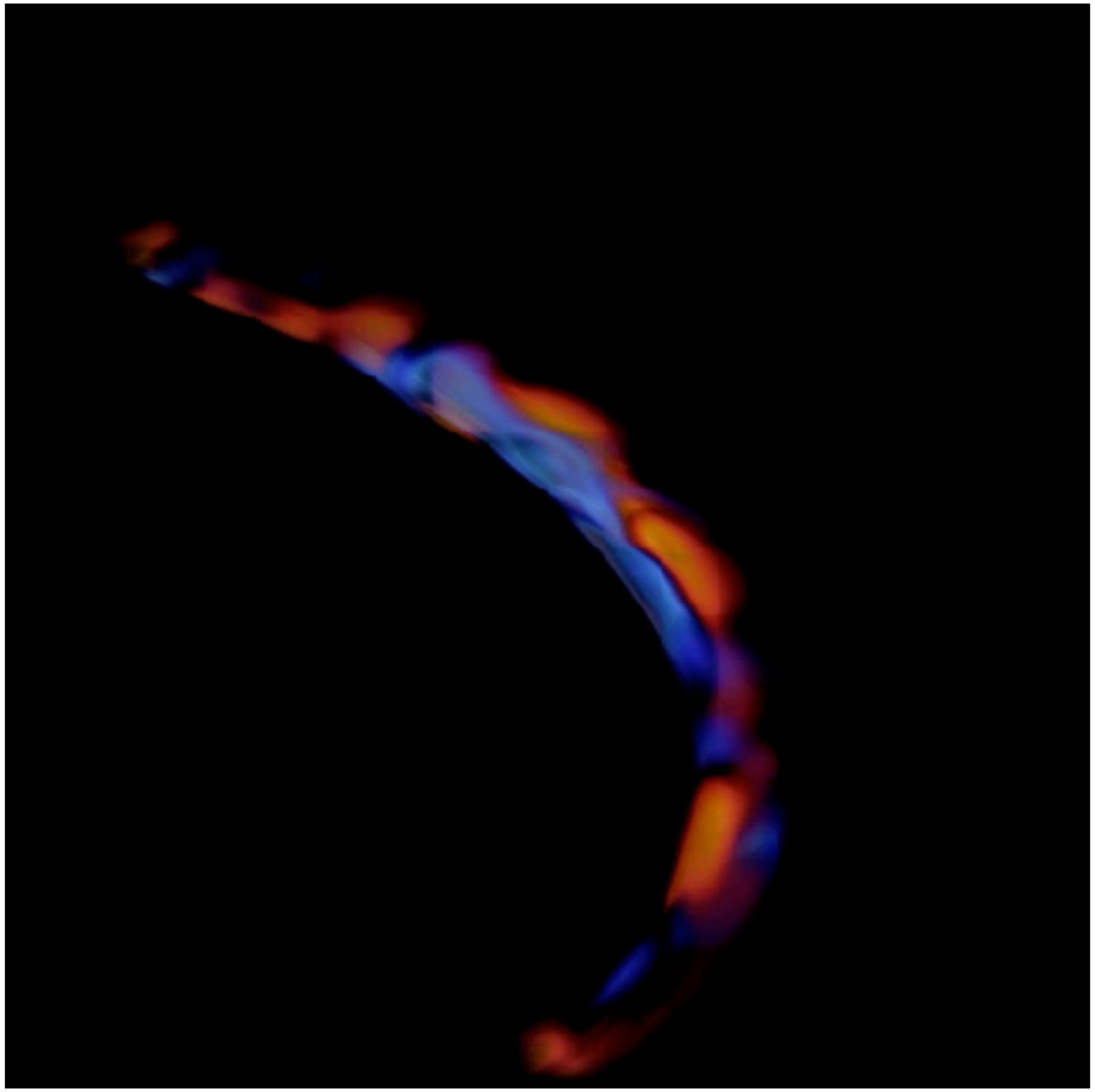
Evolution inside the convection zone



Non convective case



Convective case

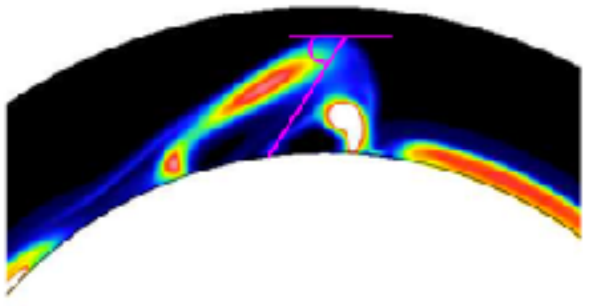


Movies created with SDvision@CEA

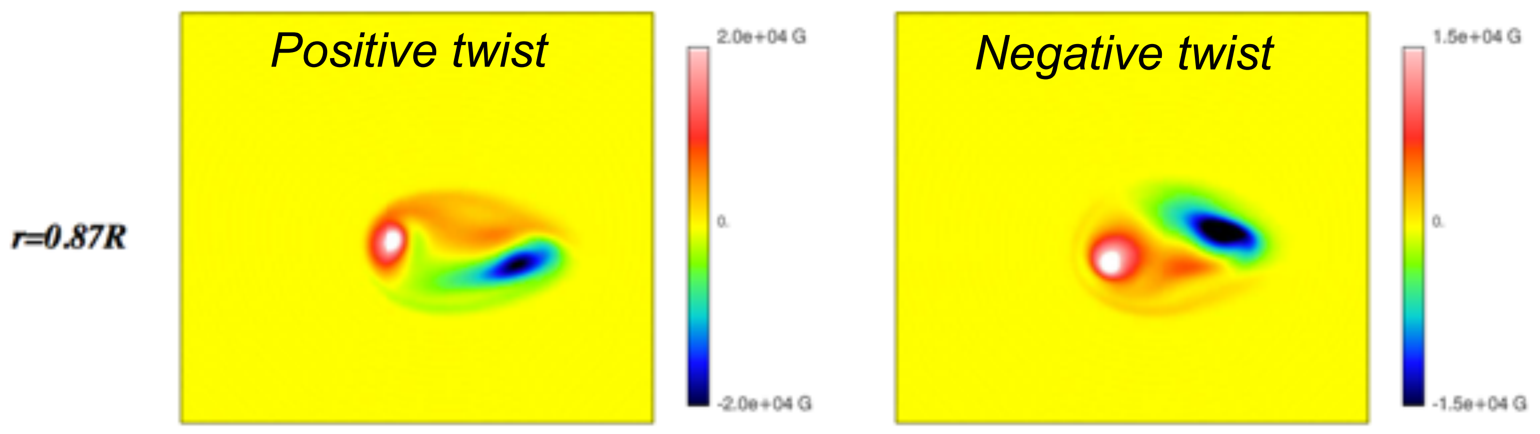
Jouve, Brun & Aulanier, 2013

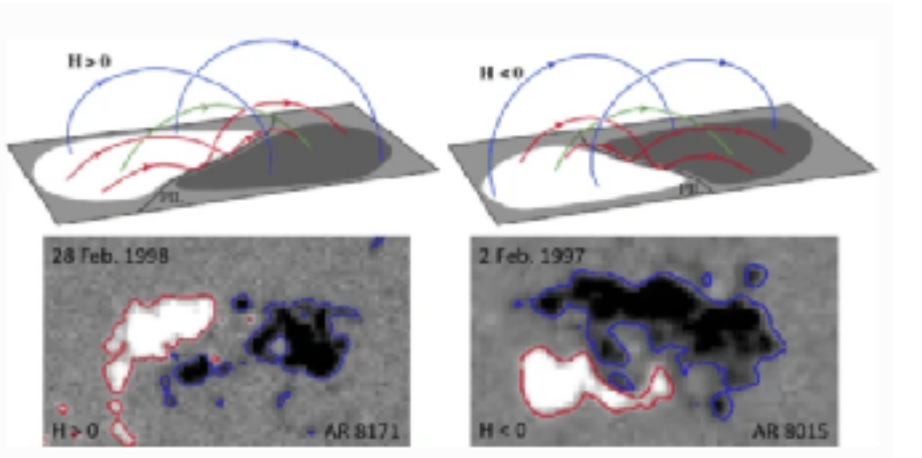
3D MHD models

Evolution inside the convection zone



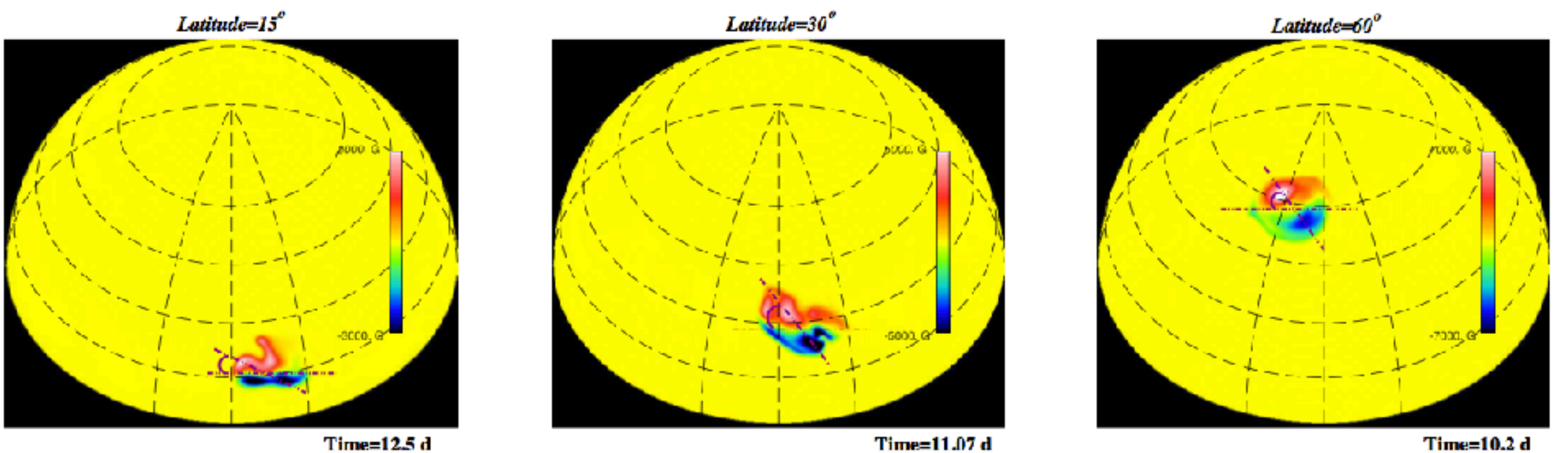
- Asymmetry between trailing and leading legs
- Relationship between tilt and twist
- Magnetic tongues





Luoni et al. 2011

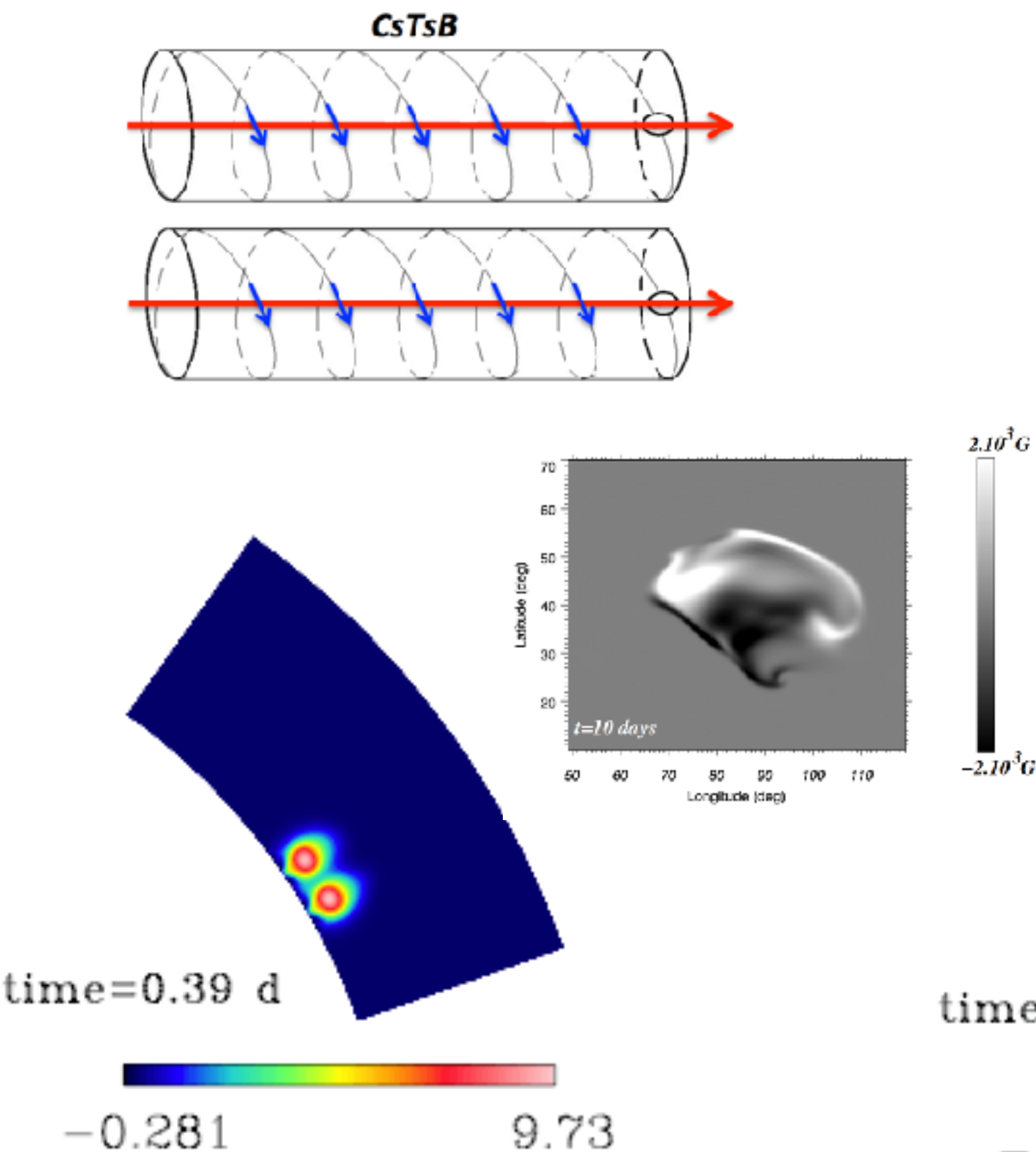
- Dependence of tilt, rise velocity, longitude of emergence on latitude

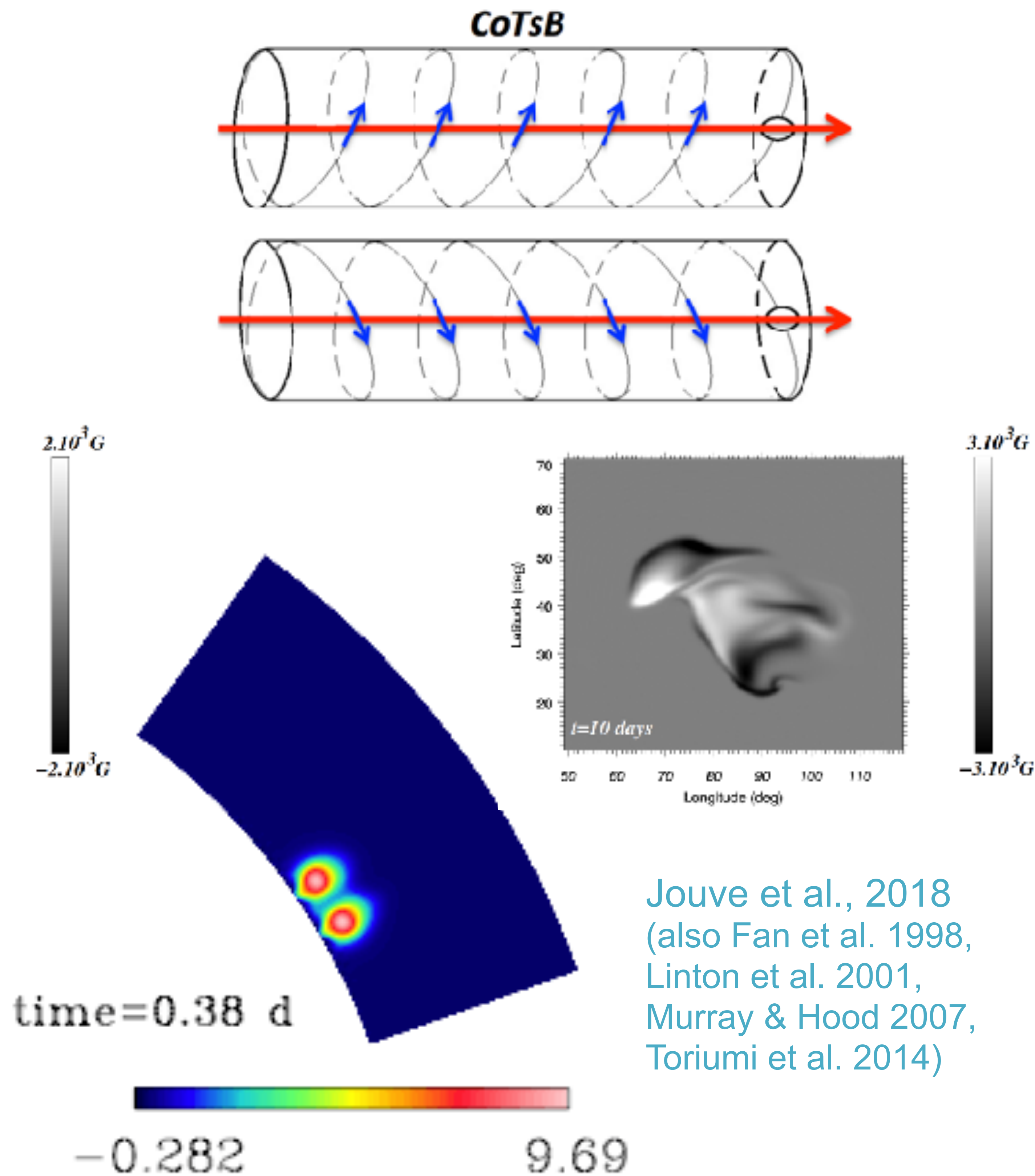


Formation of complex active regions

Interactions with other magnetic structures

- Simulations of interacting loops to produce complex active regions



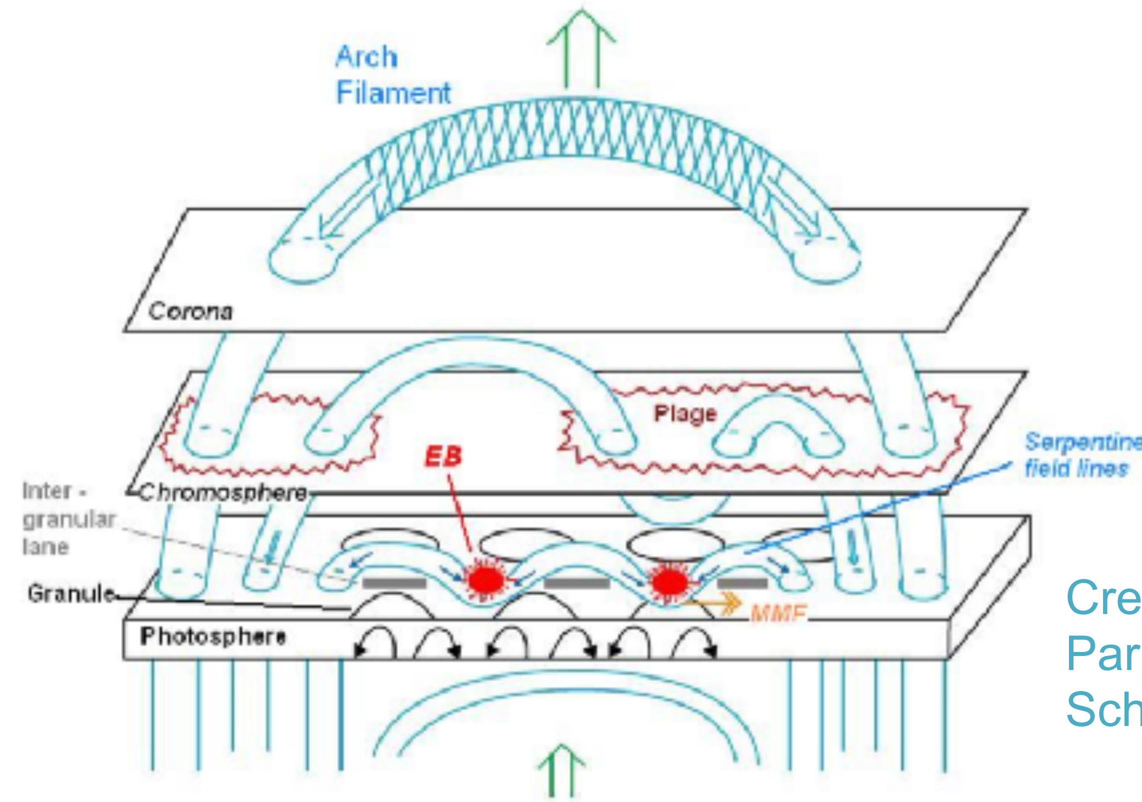


Jouve et al., 2018
(also Fan et al. 1998,
Linton et al. 2001,
Murray & Hood 2007,
Toriumi et al. 2014)

Formation of active regions

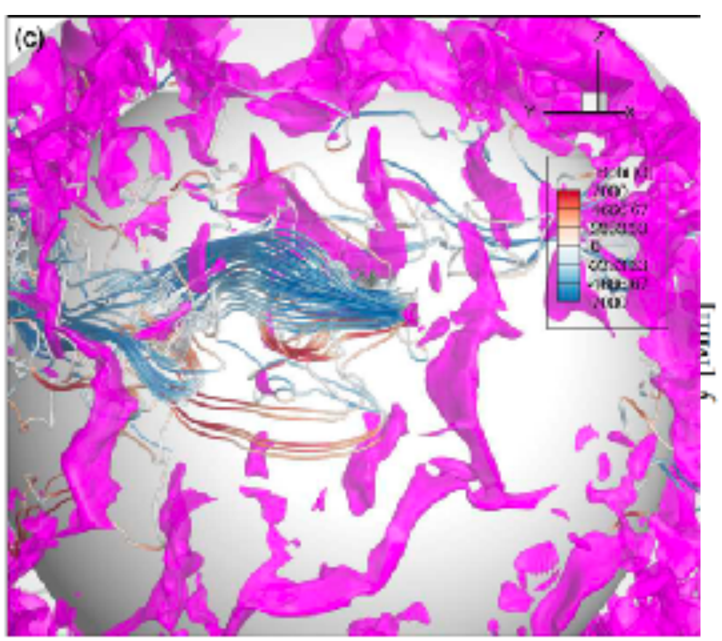
Connections with above? Coupling models?

- Emergence at photosphere may involve very complex phenomena with observational evidence

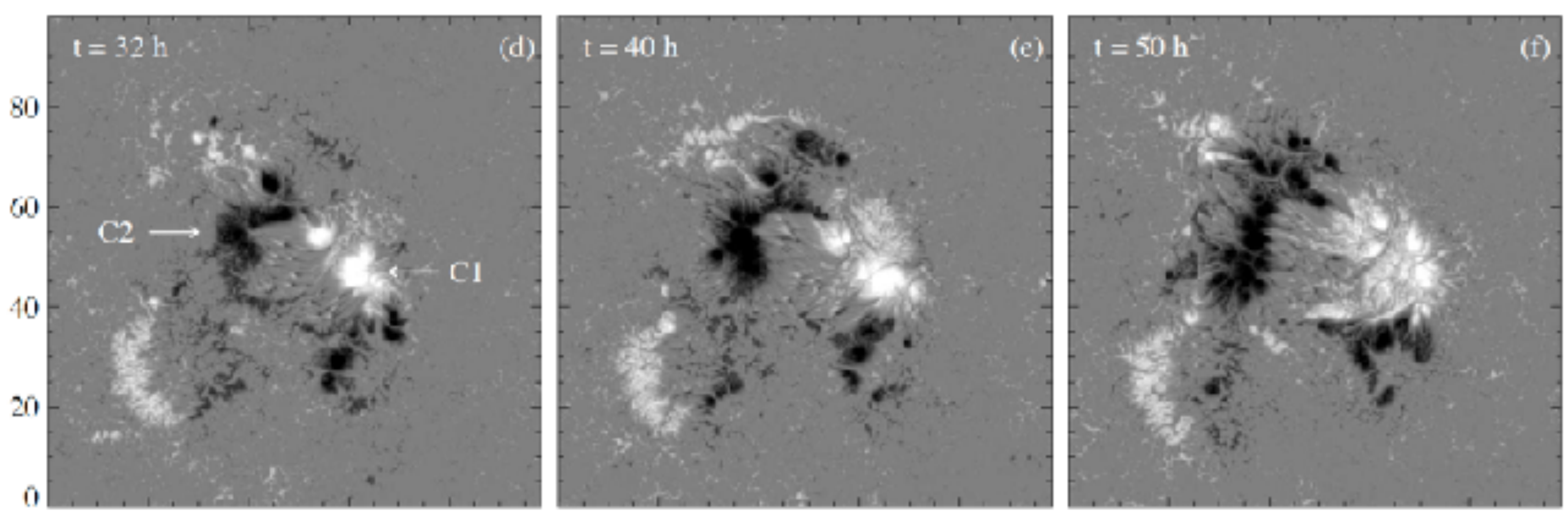


Credit: Pariat, Schmieder

- A way to model emergence from deep CZ to photosphere (and above) could be to couple models



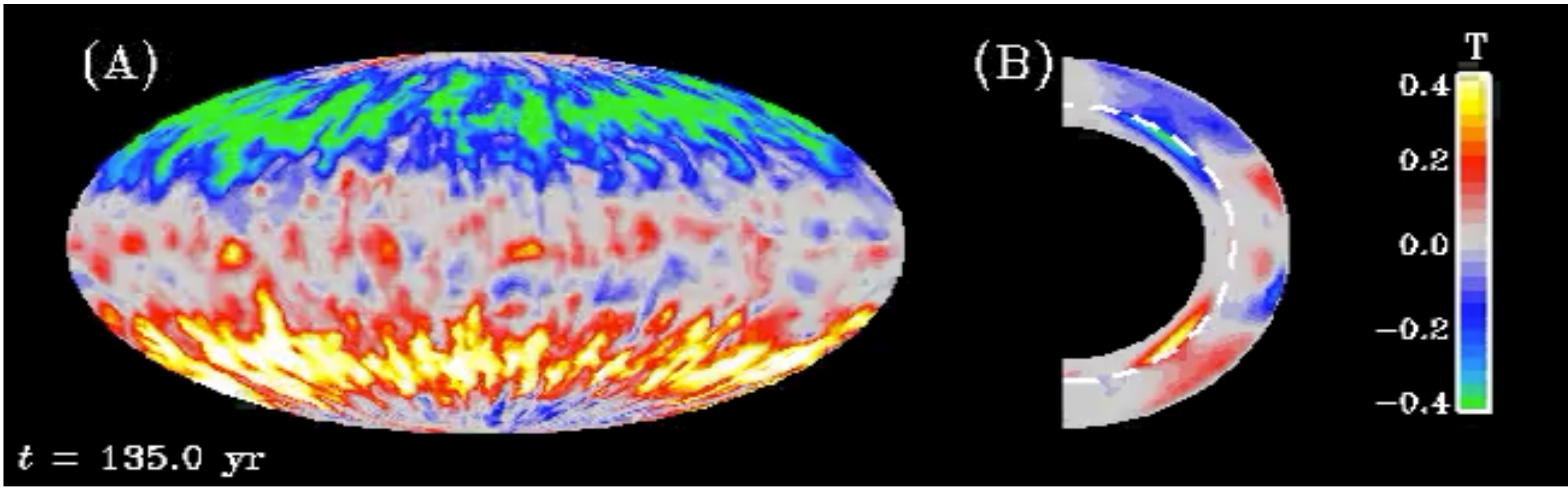
Chen et al. 2017



- Full CZ (tachocline to photosphere) calculations start to be feasible?
  Hotta et al. 2020 + Whole Sun Project (ERC Synergy grant: http://wholesun.eu/)

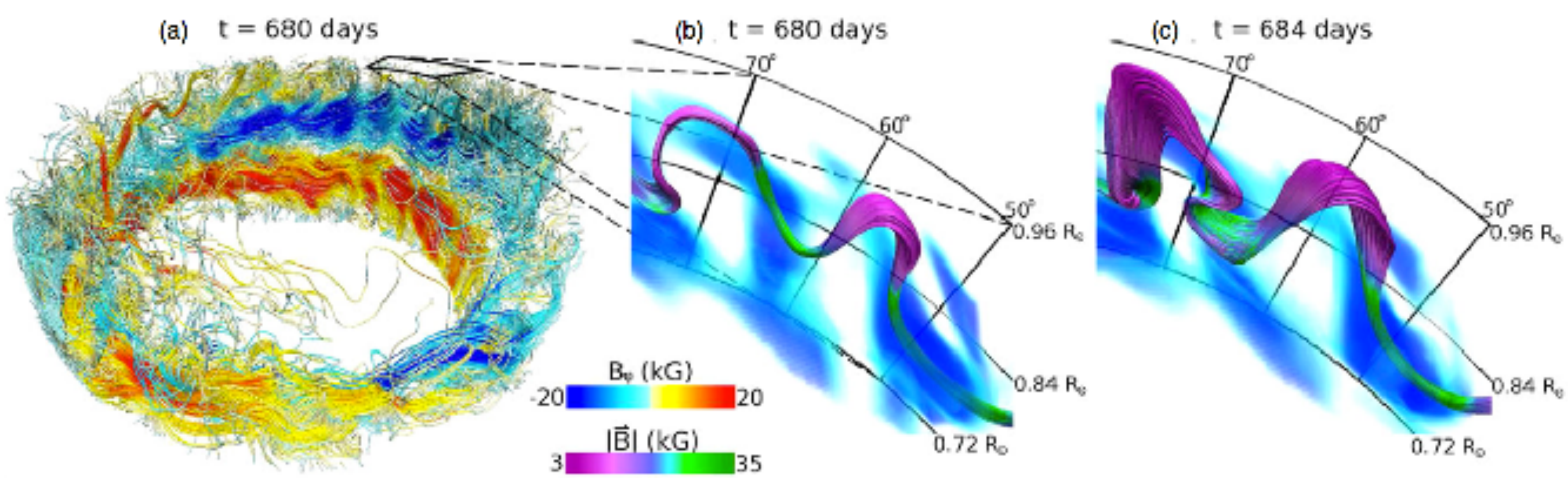
Role in the dynamo mechanism

- 3D models produce magnetic cycles **without producing spots** and meridional circulation does not seem to set up the cycle period (Brown et al. 2011, Ghizaru et al. 2010, Nelson et al. 2013, Käpylä et al. 2013, Augustson et al. 2015, Hotta et al. 2016)



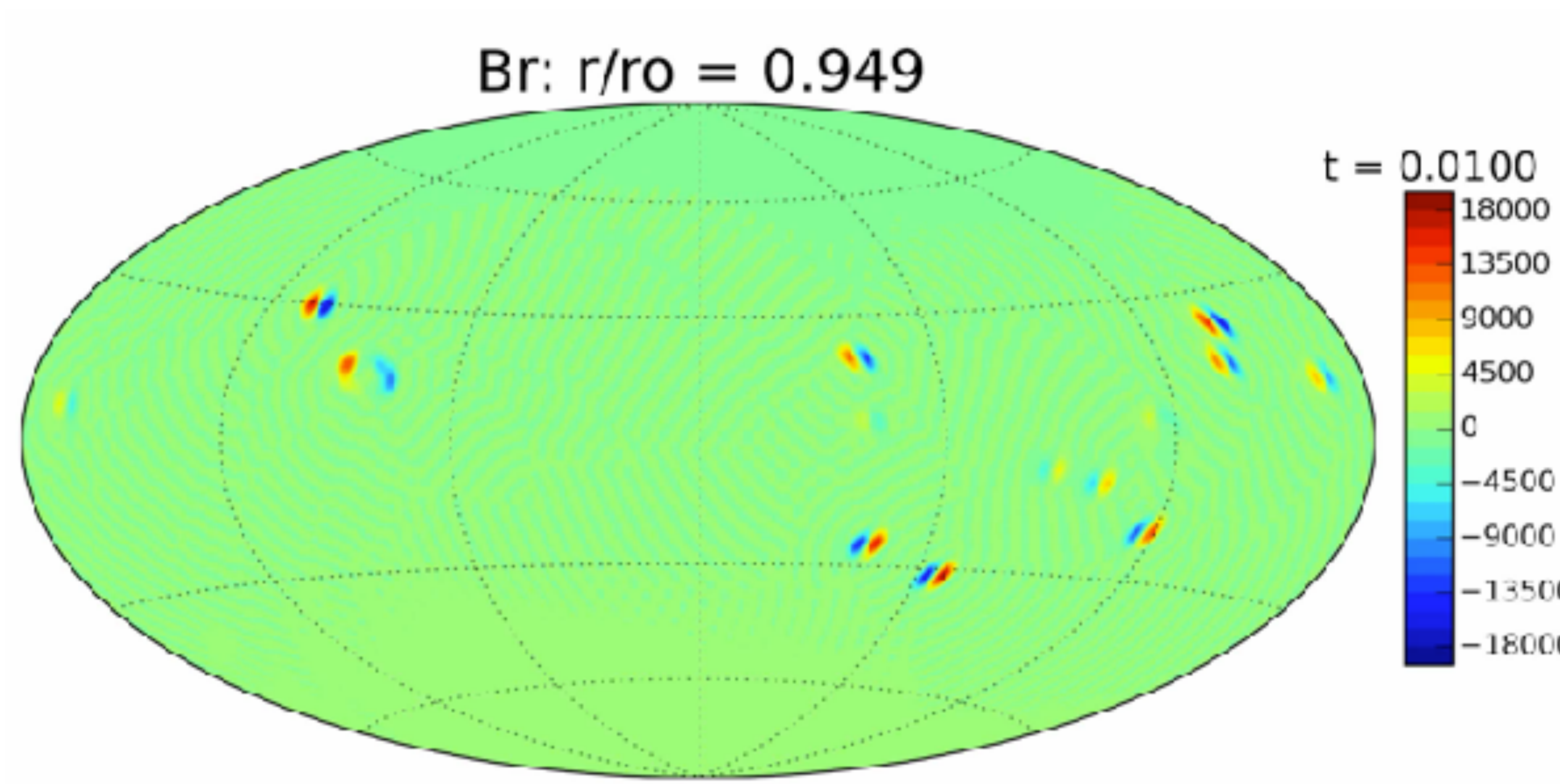
- Strong concentrations of toroidal field can still be built but buoyant structures do not make it to the top to produce spots!

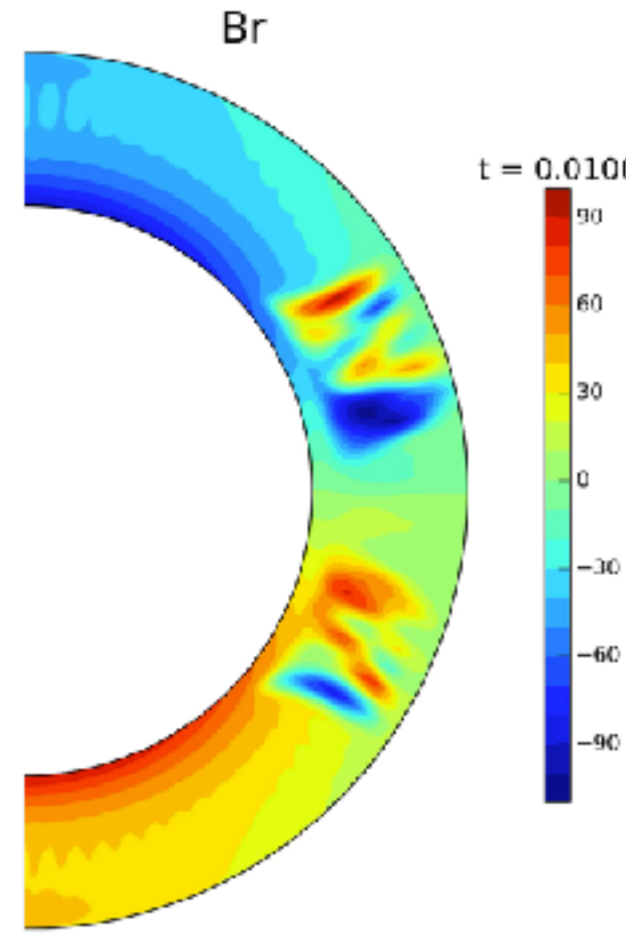
Nelson et al. (2011, 2014)

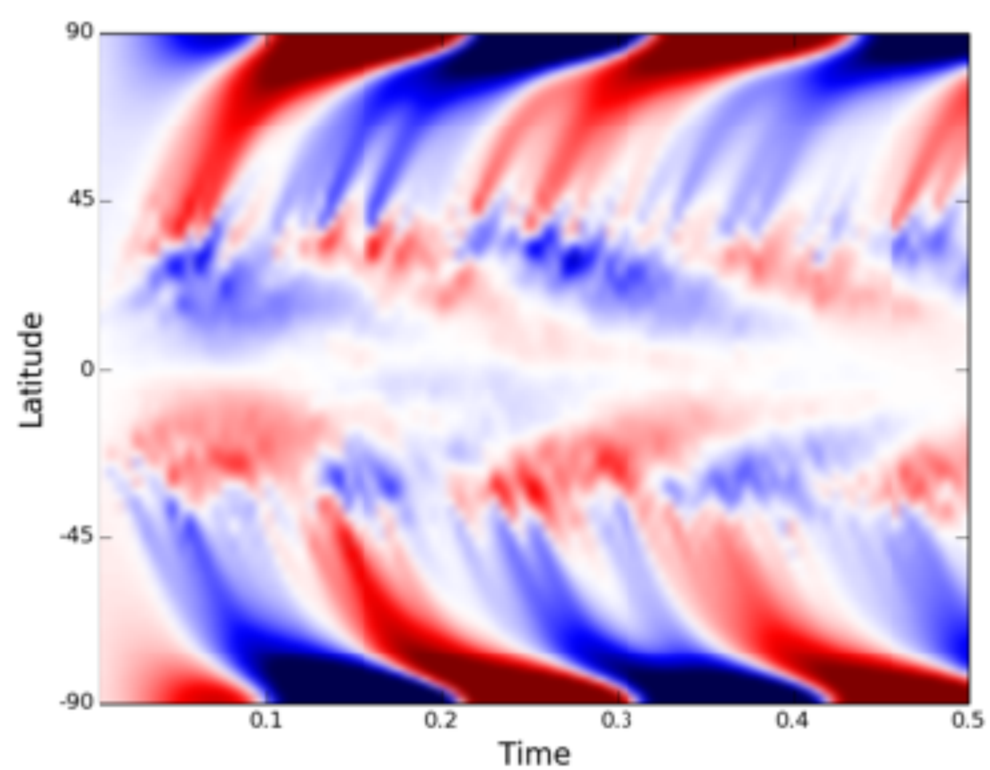


Role in the dynamo mechanism

- Mean-field dynamo models + 3D flux emergence and spot formation (Yeates & Munoz Jaramillo 2013, Miesch & Dikpati 2014, Miesch & Teweldebirhan 2016, Hazra et al. 2017, 2018, Kumar et al. 2018)







Self-consistent butterfly diagrams

Kumar, Jouve, Pinto & Rouillard , 2018

Kumar, Jouve & Nandy, 2019

Conclusions

- Main results

MHD anelastic models adapted to bulk of CZ enable to emphasize:
- importance of twist in rise of flux tubes / the transport of magnetic helicity
- interactions between convective flows and rising flux structures
- interactions between magnetic flux systems to create complex active regions

Fully compressible models with radiative transfer enable to study further evolution in photosphere/chromosphere/corona:
- mechanism of emergence at solar surface
- origin of eruptive phenomena
- mechanisms of coronal heating

- Remaining questions

Connections between models to follow the whole evolution ?
Connections between small-scale and large-scale emergence ?
Predictions of flares ?
Importance of sunspots in the whole dynamo mechanism ?

Living reviews in Solar Physics by Fan (2004), Cheung & Isobe (2014), Van-Driel & Green (2015), Toriumi & Wang (2019)