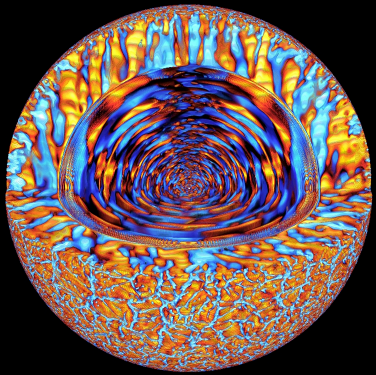
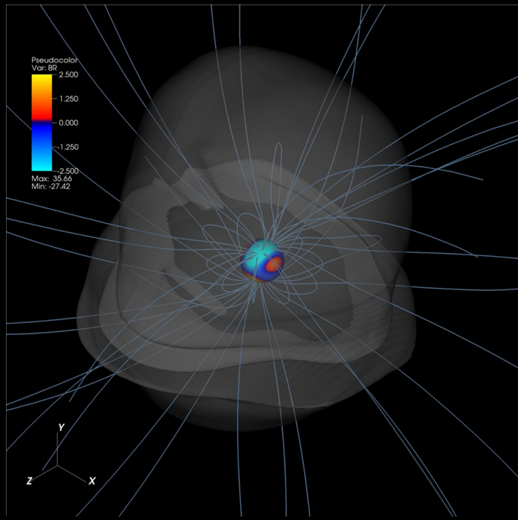
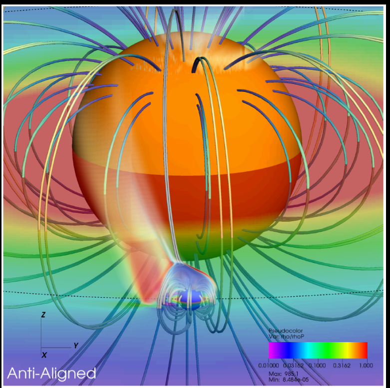
Simulations Numériques du Soleil, des étoiles et de leurs interactions avec les planètes

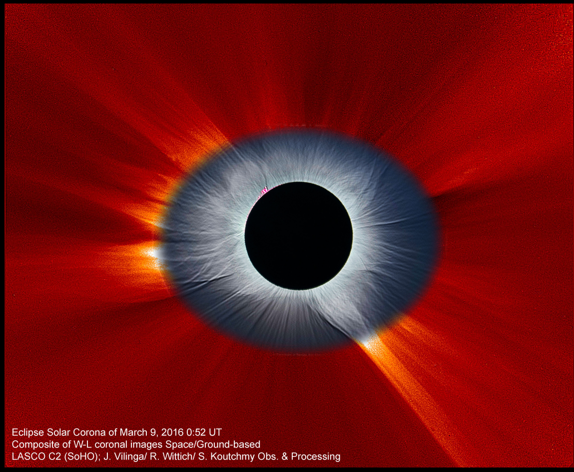


Allan Sacha Brun
DRF/IRFU/SAp/LDEE & AIM

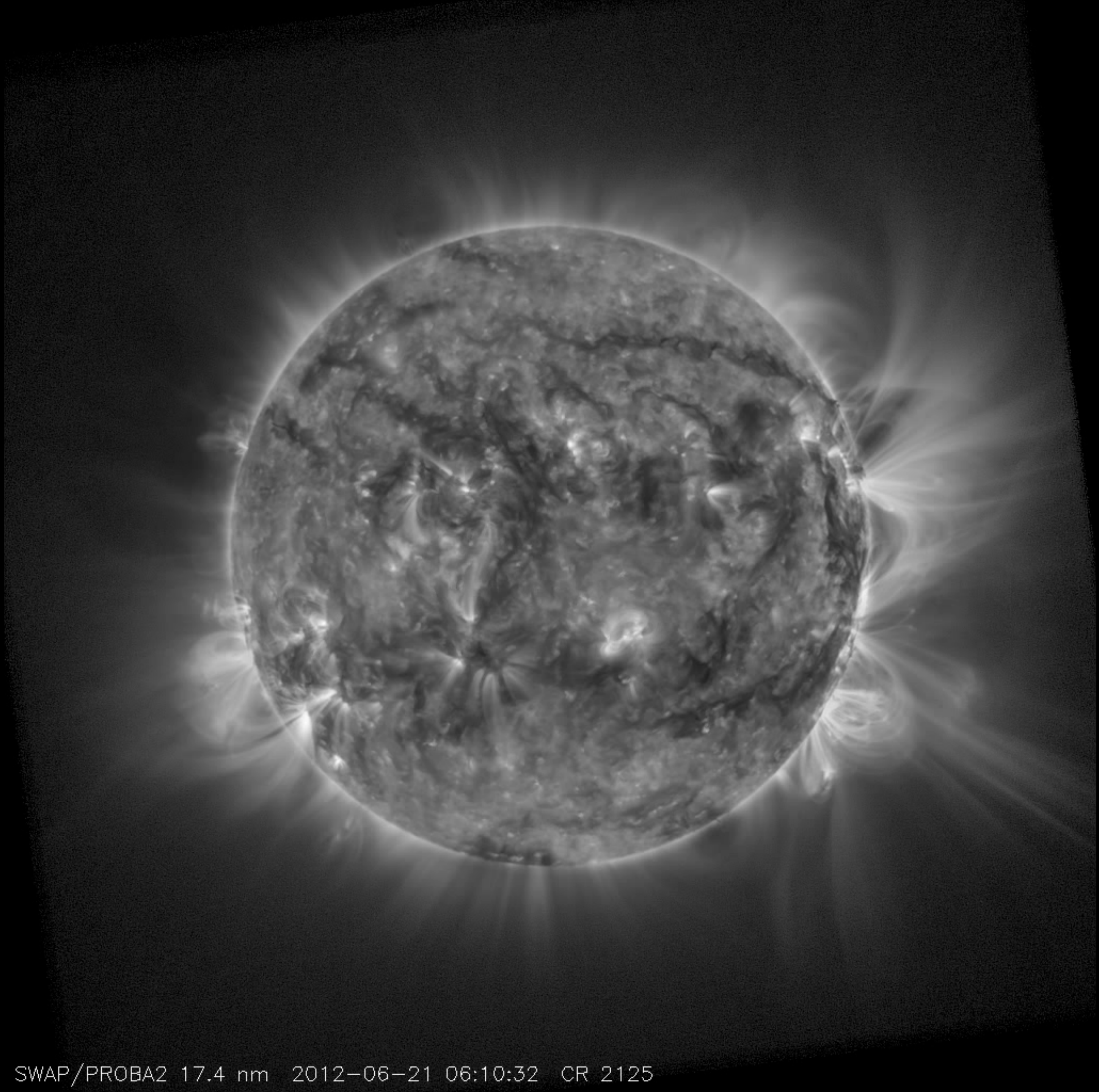


- Codes de calculs: ASH et PLUTO
- Magnétismes du soleil et des étoiles
- Interactions étoile-planète

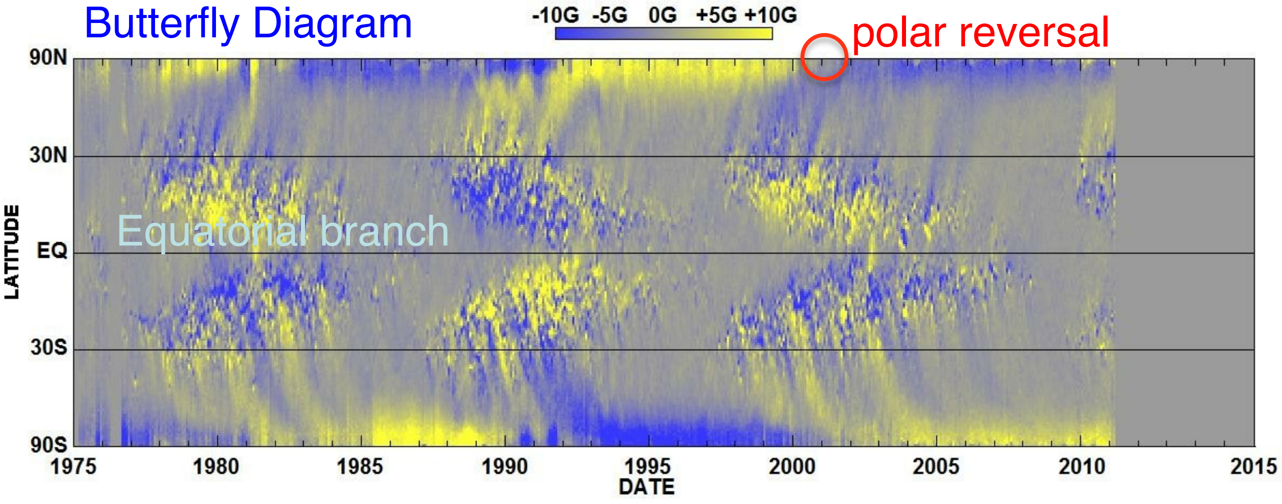




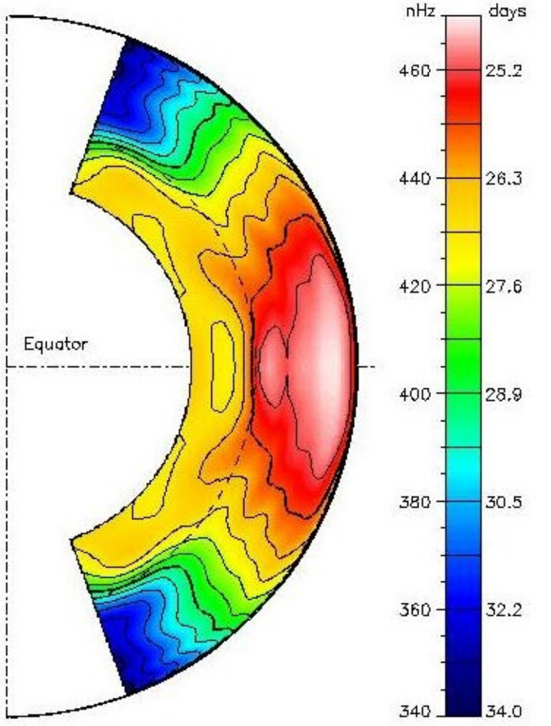
Eclipse Solar Corona of March 9, 2016 0:52 UT
Composite of W-L coronal images Space/Ground-based
LASCO C2 (SoHO); J. Vilinga/ R. Wittich/ S. Koutchmy Obs. & Processing

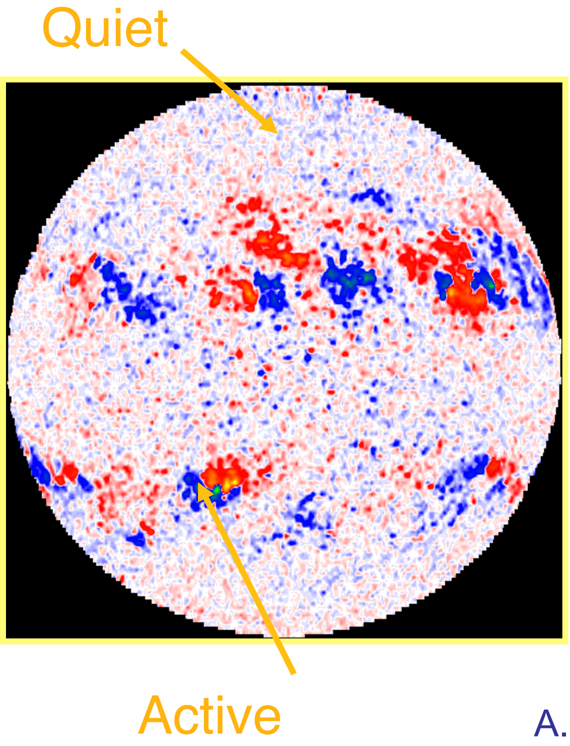

SWAP/PROBA2 17.4 nm 2012-06-21 06:10:32 CR 2125

Solar Cycle and Flows

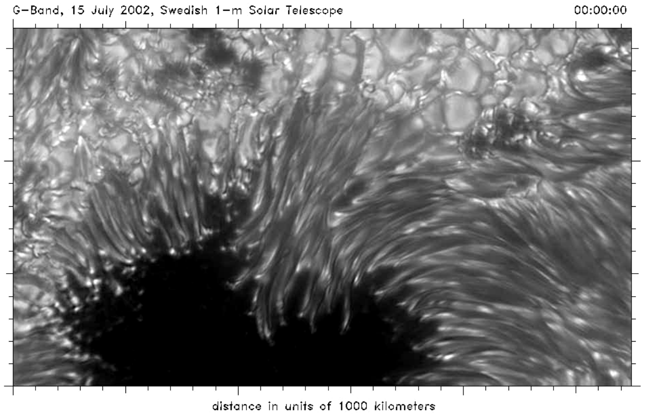


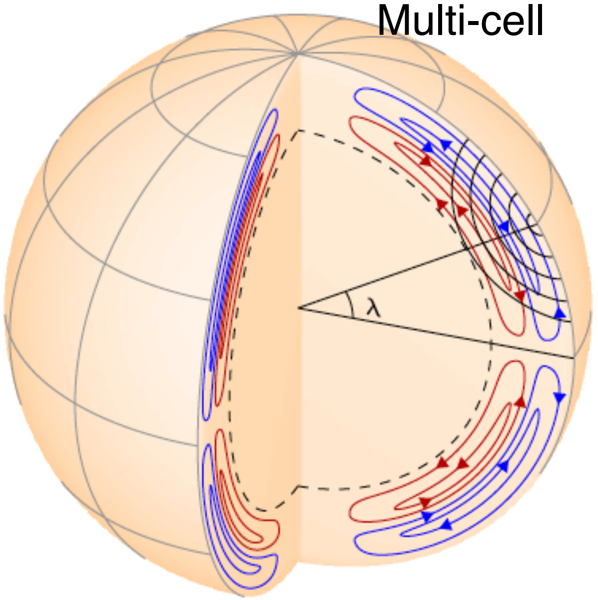
Hathaway/NASA/MSFC 2011/04





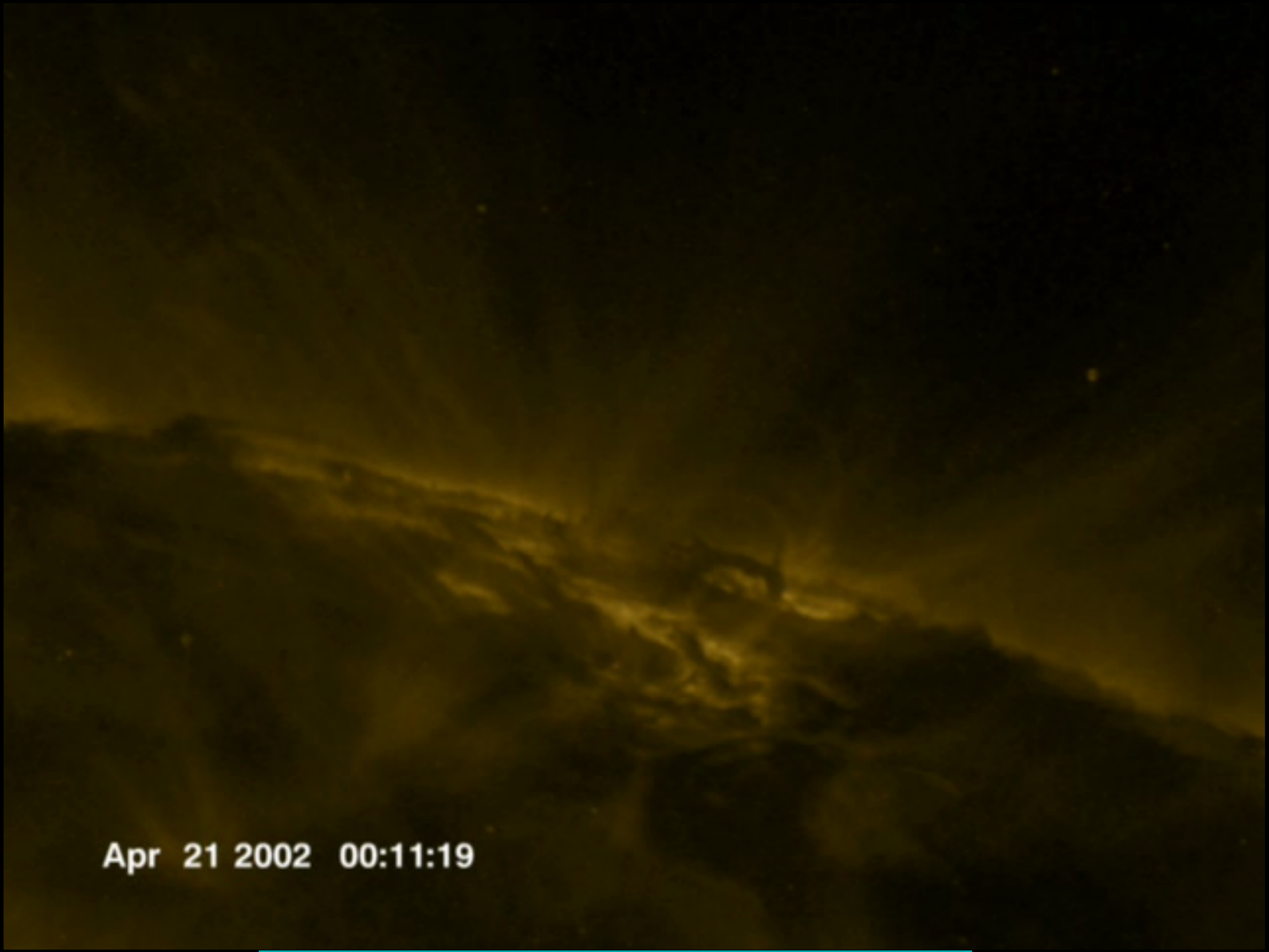
Small vs Large Scale Dynamos





Zhao et al. 2013

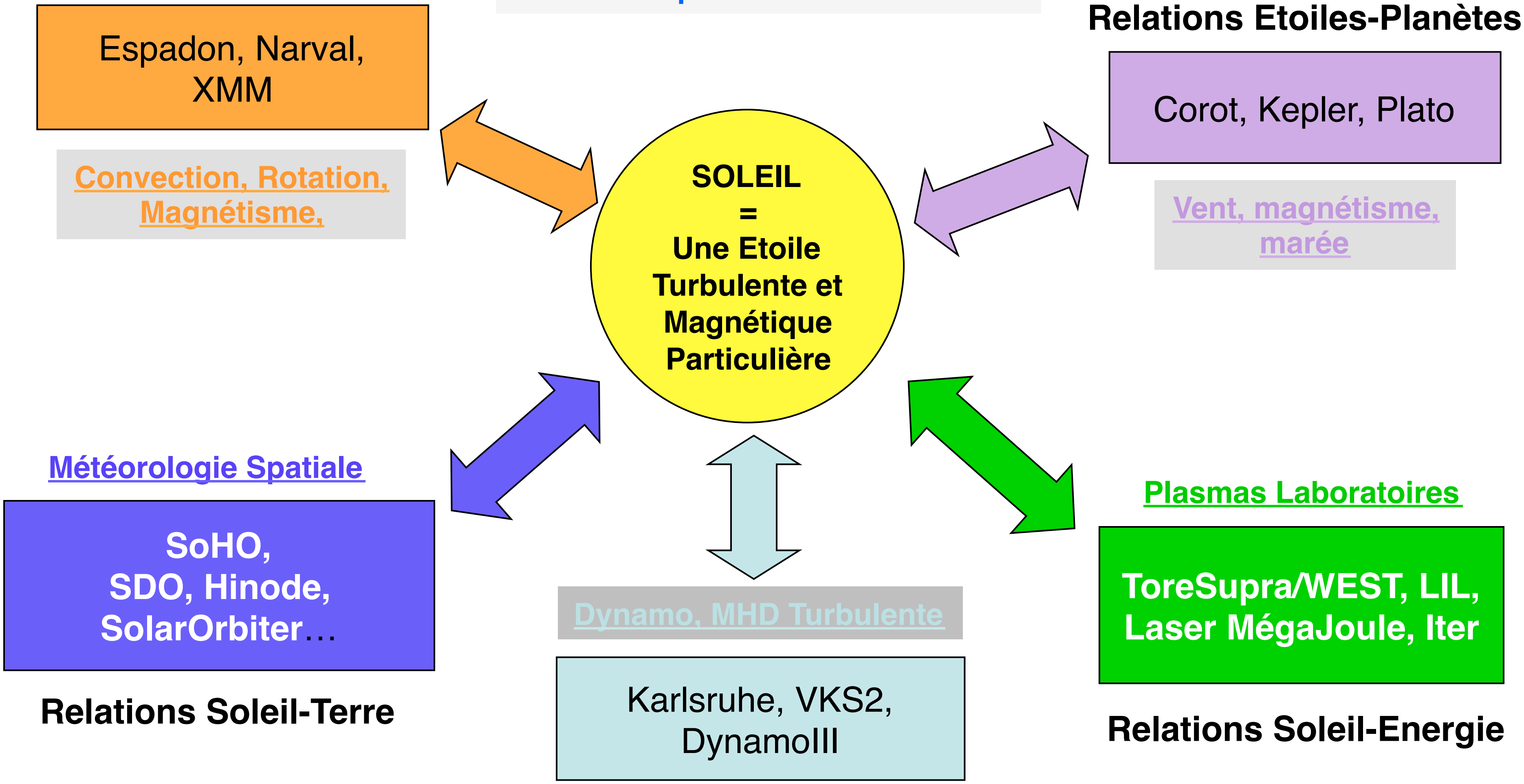
Loops-Eruptions *(TRACE Data)*



http://vestige.lmsal.com/TRACE/

Démarche et Contexte Scientifiques au SAp/LDEE

4 Outils Complémentaires:
Simulations numériques
Développements Théoriques
Observations directes et indirectes
Expérimentations



Relations Soleil-Etoiles

Espadon, Narval,
XMM

Convection, Rotation, Magnétisme,

Relations Etoiles-Planètes

Corot, Kepler, Plato

Vent, magnétisme, marée

SOLEIL
=
Une Etoile Turbulente et Magnétique Particulière

Météorologie Spatiale

SoHO,
SDO, Hinode,
SolarOrbiter…

Relations Soleil-Terre

Dynamo, MHD Turbulente

Karlsruhe, VKS2,
DynamoIII

Plasmas Laboratoires

ToreSupra/WEST, LIL,
Laser MégaJoule, Iter

Relations Soleil-Energie

Relations Soleil-Effet Dynamo

Questions Astrophysiques

Comment le Soleil fonctionne-t-il? Quelle est son influence?

Peut on prédire les humeurs du Soleil? Quel impact sur notre société?

Expliquer la diversité des étoiles, de leur magnétisme (cycles), l'évolution et la dynamique des étoiles

Quelle sera l'intensité du prochain cycle solaire? Peut on anticiper les éruptions?

Historique de la rotation des étoiles, vent et éruptions,

Comment les systèmes étoiles-planètes évoluent? Quelles conditions d'habitabilité?

Simulations HPC de la dynamo solaire

le code ASH (Boulder-Saclay)

Anelastic MHD Equations

$$\nabla\cdot(\bar{\rho}\mathbf{v}) = 0, \qquad \boxed{\nabla\cdot\mathbf{B} = 0},$$

$$\begin{aligned}
\bar{\rho}\left(\frac{\partial\mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} + 2\mathbf{\Omega_o}\times\mathbf{v}\right) &= -\nabla P + \rho\mathbf{g} \\
+\boxed{\tfrac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B}} &- \nabla\cdot\bar{\mathcal{D}} - [\nabla\bar{P} - \bar{\rho}\mathbf{g}], \\
\bar{\rho}\bar{T}\frac{\partial S}{\partial t} + \bar{\rho}\bar{T}\mathbf{v}\cdot\nabla(\bar{S}+S) &= \boxed{\frac{4\pi\eta}{c^2}\mathbf{j}^2} + \boxed{\bar{\rho}\epsilon}, \\
+\nabla\cdot(\kappa_r\bar{\rho}c_p\nabla(\bar{T}+T)) &+ \boxed{\nabla\cdot(\kappa\bar{\rho}\bar{T}\nabla(\bar{S}+S))} \\
+2\bar{\rho}\nu[e_{ij}e_{ij} &- 1/3(\nabla\cdot\mathbf{v})^2]
\end{aligned}$$

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}) - \nabla\times(\eta\nabla\times\mathbf{B})$$

$$\bar{\mathcal{D}}_{ij} = -2\bar{\rho}\nu[e_{ij} - 1/3(\nabla\cdot\mathbf{v})\delta_{ij}],$$

Case of a Stratified Compressible Fluid under the influence of Rotation and Magnetic field

Model's Hypothesis

Anelastic** approximation filters sound waves*$(\partial\rho/\partial t = 0)$ ***but retains stratification** (linear expansion of thermodynamic variables)**:

$$\rho(r,\theta,\phi,t) \rightarrow \bar{\rho}(r,t) + \rho(r,\theta,\phi,t),$$

Simpler continuity eq: $\nabla \cdot (\bar{\rho}\mathbf{v}) = 0$

Numerical stability (Courant-Friedrich-Lewy) criteria is based on convective velocity instead of sound speed:

$\Delta t \leq \left|\Delta X/V_{conv}\right|_{min}$, **(> 5 minutes)**

We assume a Large-Eddy-Simulation (LES) and subgrid scale treatment (SGS): effective (turbulent) diffusivities ν, κ, η and unresolved energy Flux, F α κdS/dr

Work in progress with N. Mansour's group to improve subgrid scale modelling
In the spirit of Wong & Lilly 1994, subgrid scale modelling

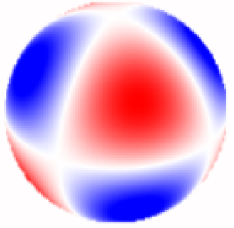
Numerical Methods

Spectral Method *(Boyd 1989, Bonazzola et al. 1998, cf Talk Grandclément):*

Horizontal Dimensions: Projection on spherical harmonics $\mathbf{Y}_l^m$ (up to $l=l_{max}=(2N_\theta-1)/3$)

$$W(r,\theta_i,\phi_j,t)=\sum_{m=-m_{max}}^{m_{max}}\sum_{\ell=|m|}^{l_{max}(m)}W_\ell^m(r,t)Y_{\ell m}(\theta_i,\phi_j)\,,$$

with
$$Y_\ell^m(\theta,\phi)=C_\ell^m P_\ell^m(\cos\theta)\exp^{im\phi}$$



where P_{lm} are the associated Legendre polynomials and the coefficients C_{lm} are defined:

$$C_\ell^m=(-1)^m\left[\frac{2\ell+1}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}\right]^{1/2}$$

We then need to determined the coefficients $W_{lm}(r,t)$ at the N_θ and N_ϕ Legendre and Fourrier collocation points ϕ_i and θ_i ,which are (assuming Gaussian quadrature for numerical accuracy when converting integrals into sums) :

$$\phi_j=\frac{2\pi j}{N_\phi}\ \text{and}\ \theta_i=\ \text{zeroes of}\ P_{N_\theta}(\cos\theta)$$

Numerical Methods

Spectral Method *(Boyd 1989, Bonazzola et al. 1998, cf Talk Grandclément):*

Radial Dimension: Projection on Chebyshev polynomials (N_r Gauss-Lobatto collocation points).

$$W_\ell^m(r_k,t) = \frac{2}{N_r - 1} \sum_{n=1}^{N_r}{}'' W_{\ell n}^m(t) T_n(r_k)\,, \text{ avec } 1 \le k \le N_r.$$

With $$T_n(x) = \cos(n \arccos x) \text{ and } x \in [-1,1]$$

The physical radii r_k is related to collocation gridpoints x_k by: $r_k=0.5*[(r_{bot}+r_{top})+(r_{top}-r_{bot})x_k]$

For new class of supercomputers (> 20,000 nodes) we have chosen to develop ASH 2.0,
Using a fourth order finite difference scheme for irregular mesh => advantage less communication,
Save 2 global transposes, more flexibility for location of mesh points

$$\frac{\partial \phi_i}{\partial x} = \frac{A\phi_{i-2} + \phi_{i-1} + B\phi_{i+1} + C\phi_{i+2} - \phi_i\,(1 + A + B + C)}{-A(\alpha+\beta) - \beta + B\gamma + C(\gamma+\epsilon)}$$

with the weights given by

$$C = \frac{-\beta^2\left[\beta^2(\alpha+\beta+\gamma) - (\alpha+\beta)^2(\beta+\gamma) - \gamma^2\alpha\right]}{(\gamma+\epsilon)^2(\alpha+\beta+\gamma)\epsilon[\alpha+\beta+\gamma+\epsilon]},$$

$$B = \frac{-\beta^2\alpha - C(\gamma+\epsilon)^2[\alpha+\beta+\gamma+\epsilon]}{\gamma^2(\alpha+\beta+\gamma)},$$

$$A = \frac{1}{(\alpha+\beta)^2}\left[-\beta^2 - B\gamma^2 - C(\gamma+\epsilon)^2\right].$$

Numerical Methods

Temporal Evolution: we want to solve an initial value problem

$$\frac{\partial y}{\partial t} = f(y(t), t) \text{ with } f(y_0, t = 0) = f_0$$

We can approximate this formula by the following explicit or implicit variations:

$$\frac{y_{i+1} - y_i}{\Delta t_i} = f_i \text{ or } \frac{y_{i+1} - y_i}{\Delta t_i} = f_{i+1}$$

Linear Terms: 2nd order Crank - Nicholson (implicit method, weighted average of the forward and backward Euler 1st order approximation):

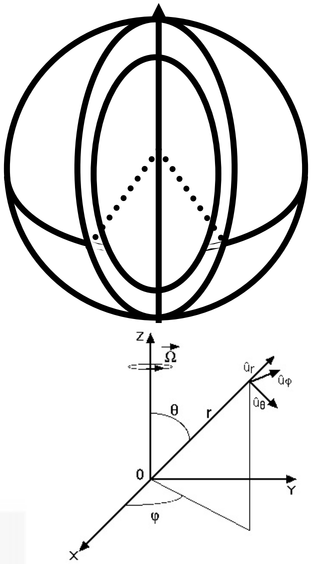
$$\frac{y_{i+1} - y_i}{\Delta t_i} = \alpha_{CN} f_{i+1} + (1 - \alpha_{CN}) f_i$$

NonLinear, Coriolis & Lorentz Terms : 2nd order Adams-Bashforth (multistep explicit method).

$$\frac{y_{i+1} - y_i}{\Delta t_i} = \alpha f_i + \beta f_{i-1} \text{ with } \alpha = 1 + \frac{1}{2}\frac{\Delta t_i}{\Delta t_{i-1}} \text{ and } \beta = -\frac{1}{2}\frac{\Delta t_i}{\Delta t_{i-1}}$$

Stratégie de parallélisme avec ASH
Améliorations récentes (> 20,000 cpus)

Numerical Methods



Summary of Parallel Data Configurations:

1. Primary configuration: l in processor and r & m distributed,
2. Implicite solver configuration: r & m in processor & l distributed,
3. Physical space configuration: r & θ distributed and φ in processor.

Optimal/static Load balance in spectral space

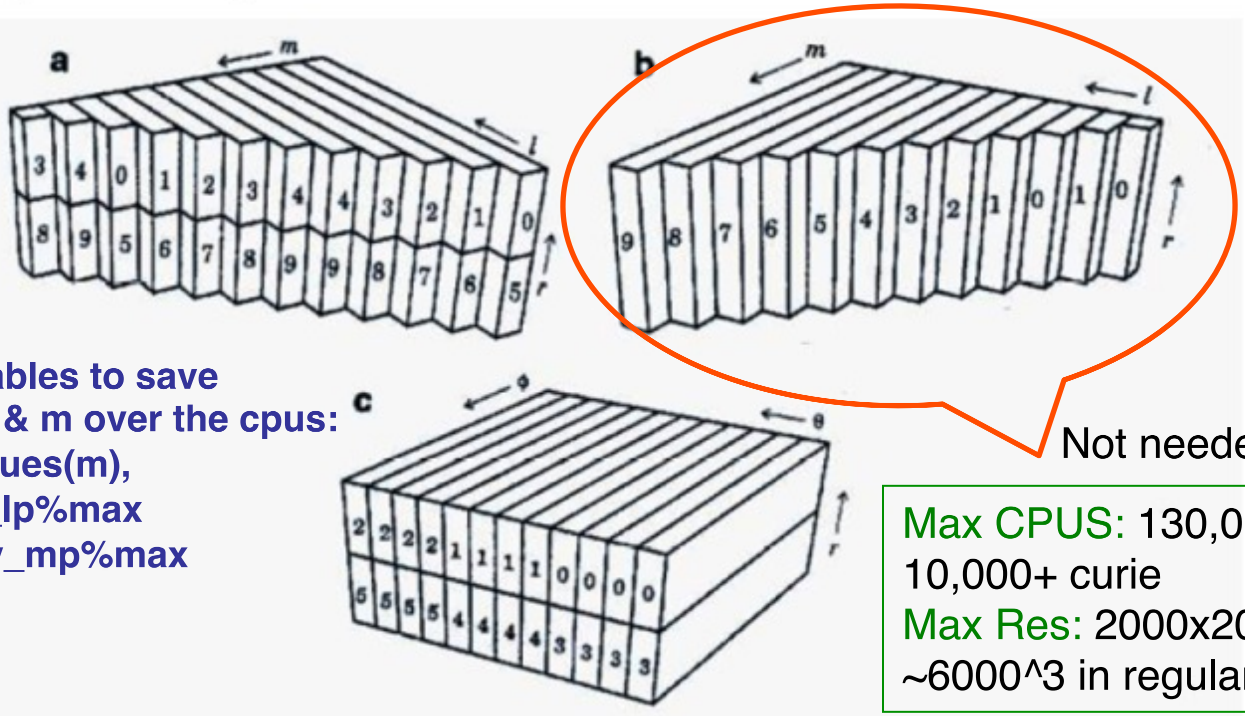


Fig. 1. (a) Primary configuration (*l* in processor, *m* and *r* distributed). The numbers correspond to the computing nodes 0, . . . , 9; in this case $N_{\mathrm{RAD}} = 2$, $N_{\mathrm{ANG}} = 5$ and $l_{\max} = 11$. (b) Corresponding implicit-solve configuration (*m* and *r* in processor, *l* distributed). (c) Physical-space configuration (ϕ in processor, θ and *r* distributed) for $N_{\mathrm{RAD}} = 2$, $N_{\mathrm{ANG}} = 3$ and $N_\theta = 12$.

ASH uses lookup tables to save the distribution of l & m over the cpus:
L_values(lp), m_values(m),
lp=my_lp%min,my_lp%max
m=my_mp%min,my_mp%max

Not needed with ASH_FD

Max CPUS: 130,000 (BG),
10,000+ curie
Max Res: 2000x2048x4096
~6000^3 in regular Cartesian box

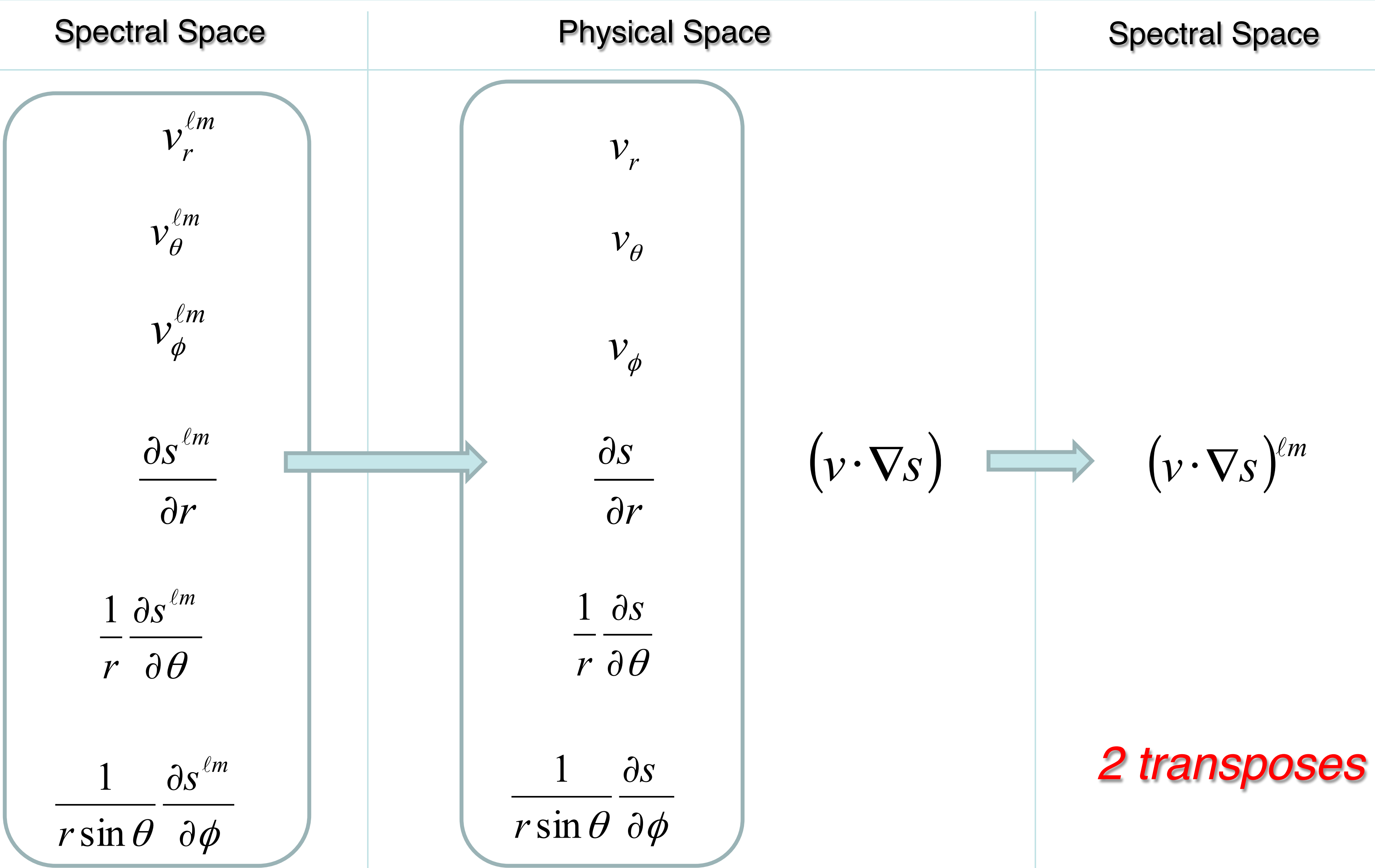
Nonlinear Term Computation: One Possibility

Entropy Advection

Spectral Space		Physical Space			Spectral Space
$v_r^{\ell m}$	$\Rightarrow$	v_r			
$v_\theta^{\ell m}$	$\Rightarrow$	v_θ			
$v_\phi^{\ell m}$	$\Rightarrow$	v_ϕ			
$\frac{\partial s^{\ell m}}{\partial r}$	$\Rightarrow$	$\frac{\partial s}{\partial r}$	$\left(v\cdot\nabla s\right)$	$\Rightarrow$	$\left(v\cdot\nabla s\right)^{\ell m}$
$\frac{1}{r}\frac{\partial s^{\ell m}}{\partial\theta}$	$\Rightarrow$	$\frac{1}{r}\frac{\partial s}{\partial\theta}$			
$\frac{1}{r\sin\theta}\frac{\partial s^{\ell m}}{\partial\phi}$	$\Rightarrow$	$\frac{1}{r\sin\theta}\frac{\partial s}{\partial\phi}$			*7 transposes*

Nonlinear Term Computation: Alternative Possibility

Pack one Large Buffer



Spectral Space

$$v_r^{\ell m}$$

$$v_\theta^{\ell m}$$

$$v_\phi^{\ell m}$$

$$\frac{\partial s^{\ell m}}{\partial r}$$

$$\frac{1}{r}\frac{\partial s^{\ell m}}{\partial \theta}$$

$$\frac{1}{r\sin\theta}\frac{\partial s^{\ell m}}{\partial \phi}$$

Physical Space

$$v_r$$

$$v_\theta$$

$$v_\phi$$

$$\frac{\partial s}{\partial r}$$

$$\frac{1}{r}\frac{\partial s}{\partial \theta}$$

$$\frac{1}{r\sin\theta}\frac{\partial s}{\partial \phi}$$

$$\left(v\cdot\nabla s\right)$$

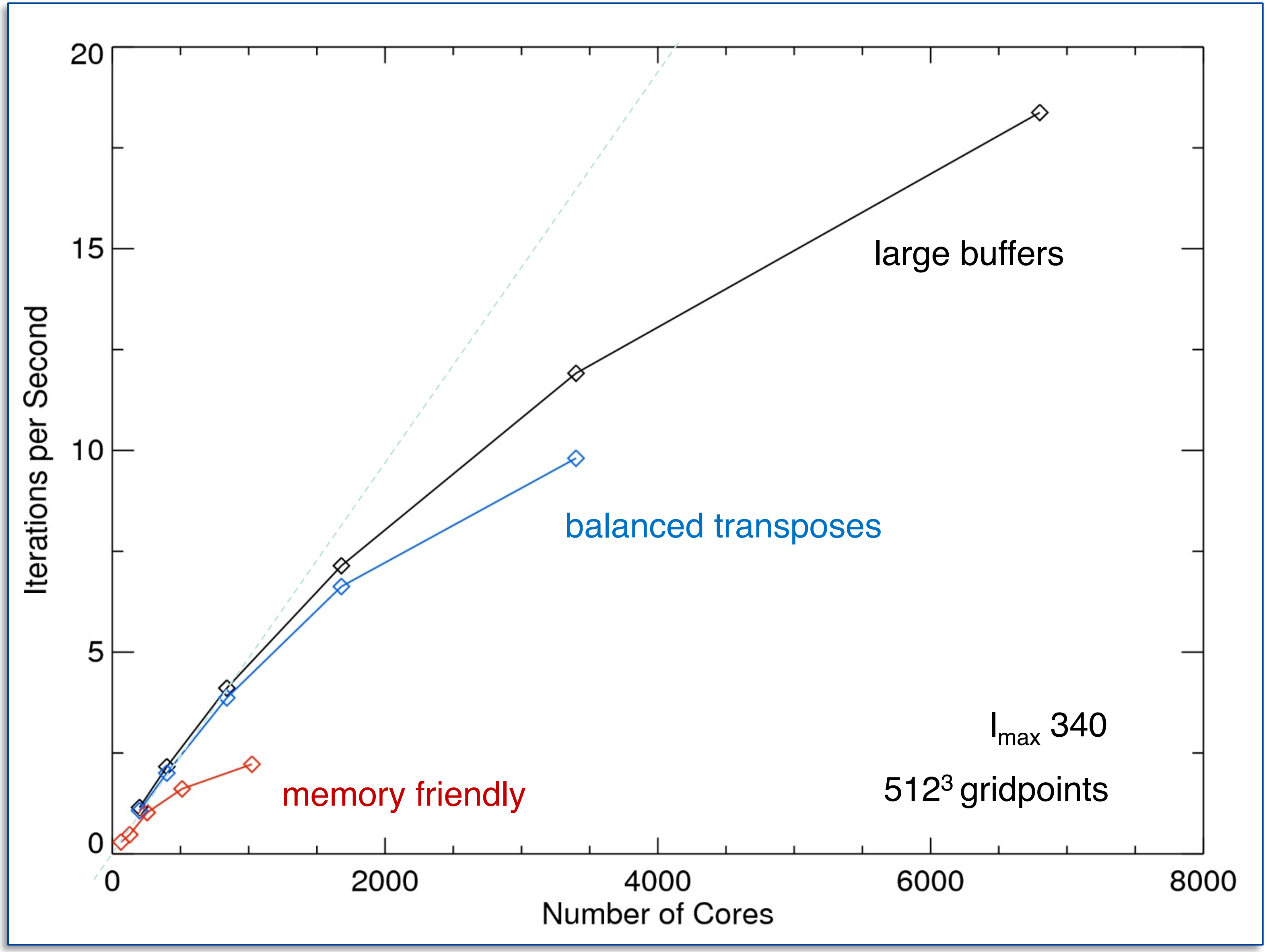
Spectral Space

$$\left(v\cdot\nabla s\right)^{\ell m}$$

2 transposes

Strong Scaling: Large Buffers

(NASA Pleiades)



Simulations du Soleil et des étoiles

Simulations 3-D Hautes Performances de la MHD Stellaire

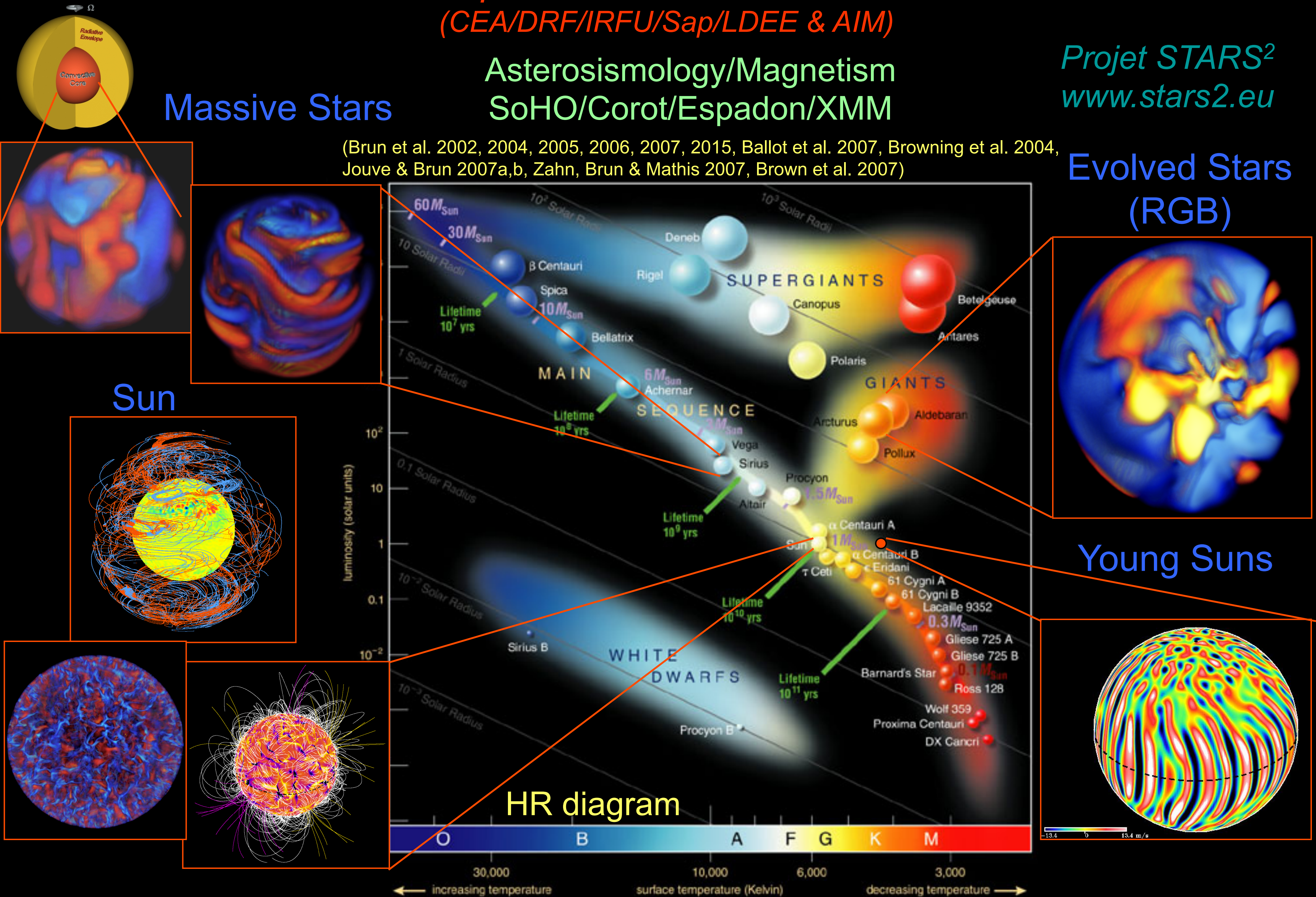
par Allan Sacha BRUN

(CEA/DRF/IRFU/Sap/LDEE & AIM)

Projet STARS^2
www.stars2.eu

Asterosismology/Magnetism
SoHO/Corot/Espadon/XMM

(Brun et al. 2002, 2004, 2005, 2006, 2007, 2015, Ballot et al. 2007, Browning et al. 2004, Jouve & Brun 2007a,b, Zahn, Brun & Mathis 2007, Brown et al. 2007)



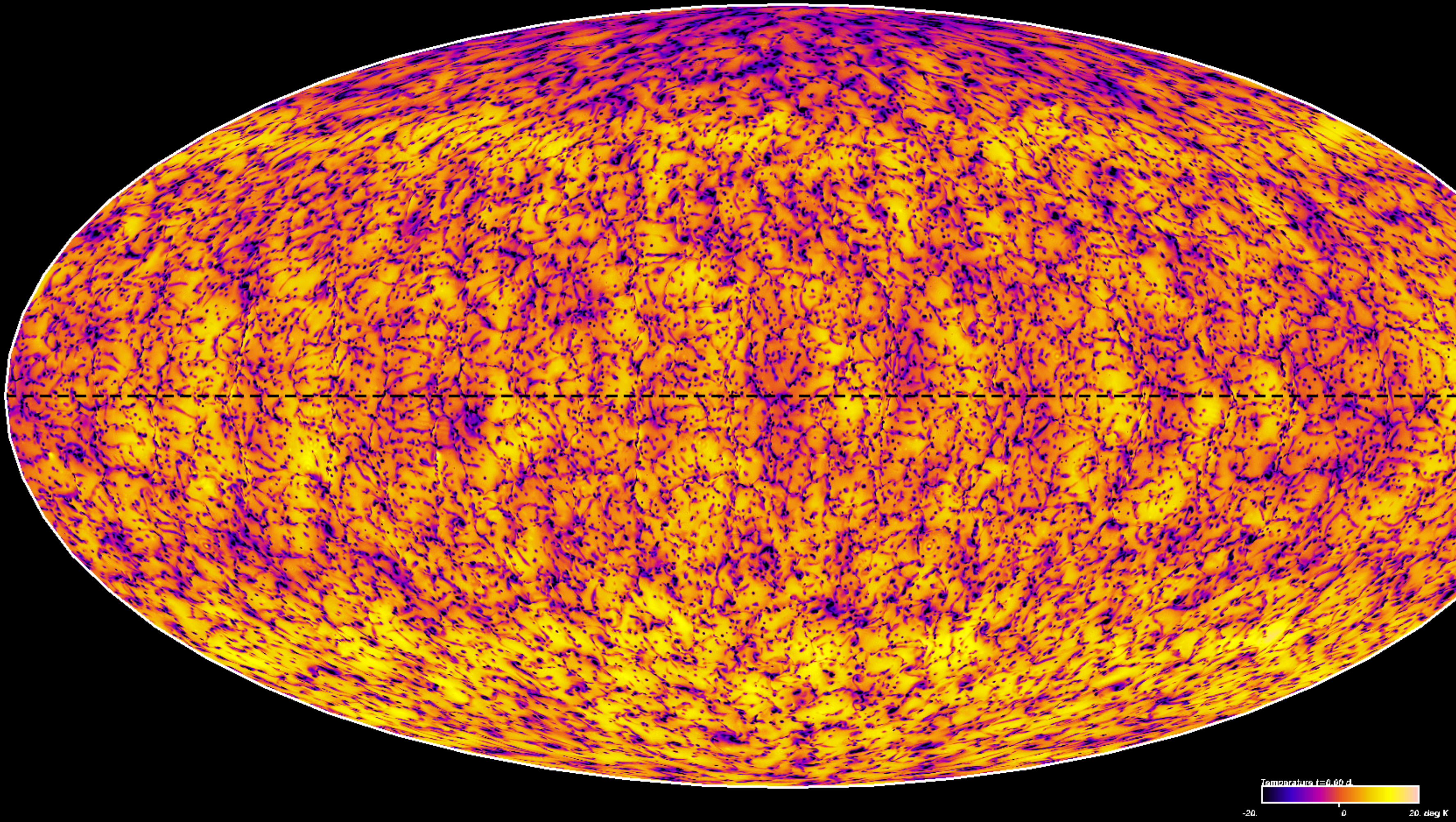
Massive Stars

Evolved Stars (RGB)

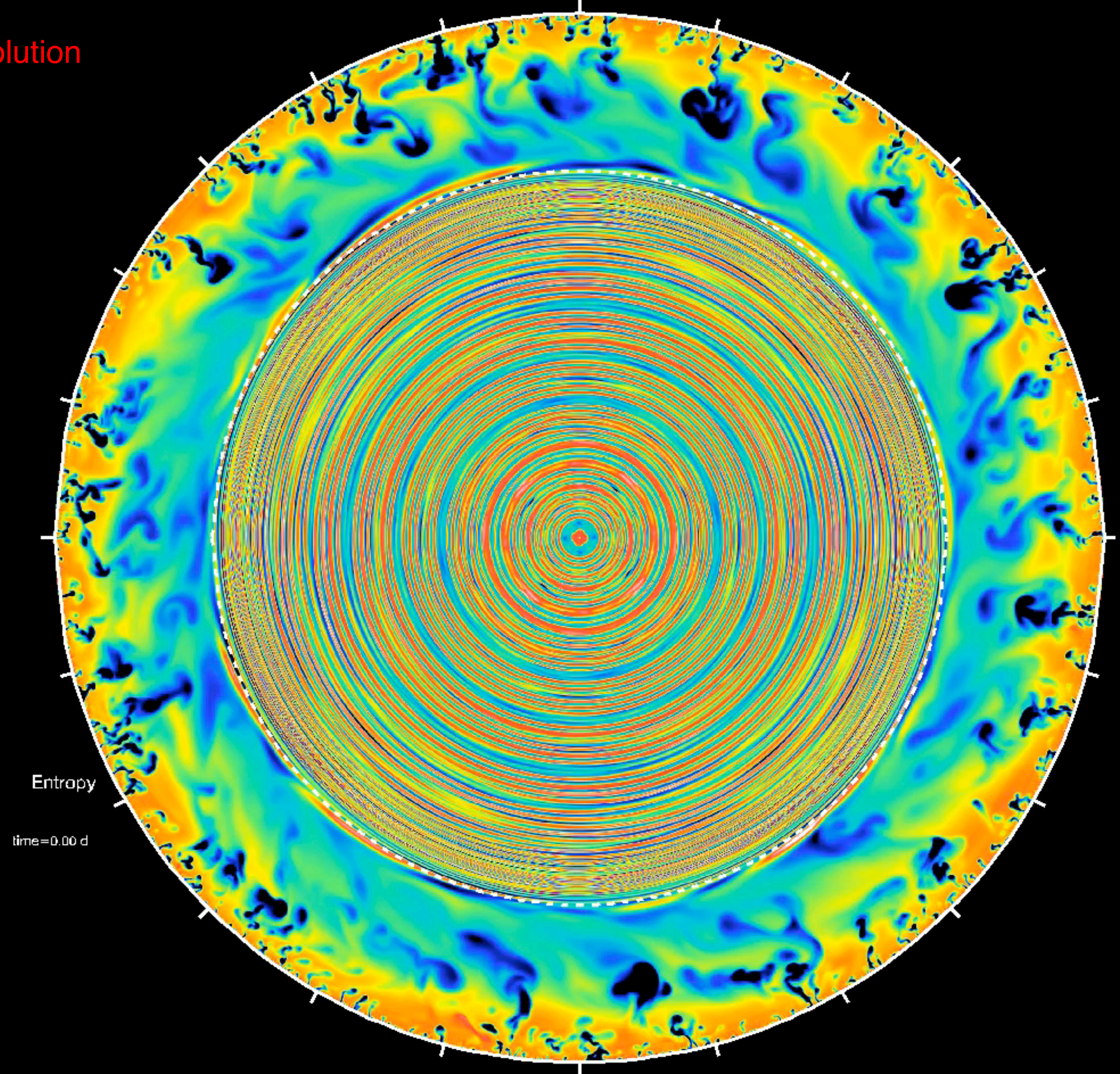
Sun

Young Suns

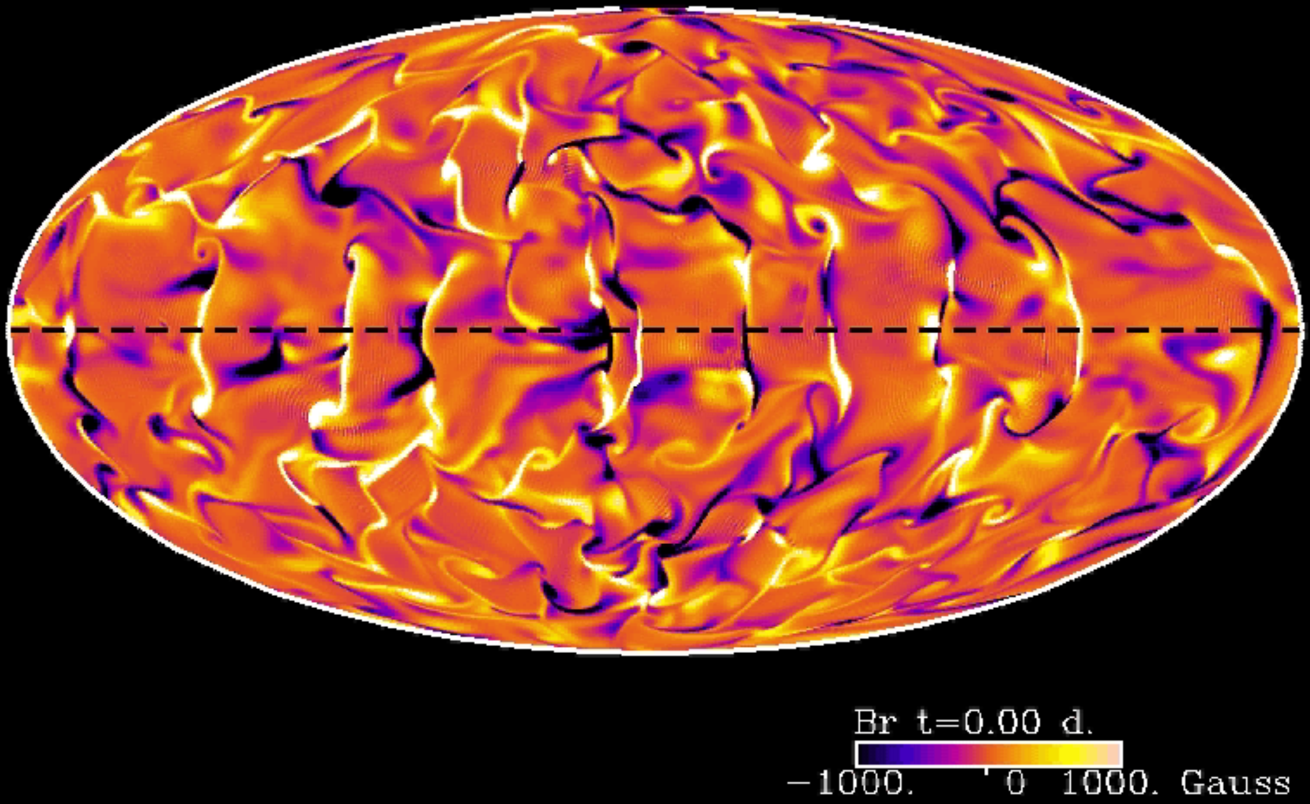
HR diagram


Temperature t=0.00 d.
-20.
0
20. deg K

Higher Resolution



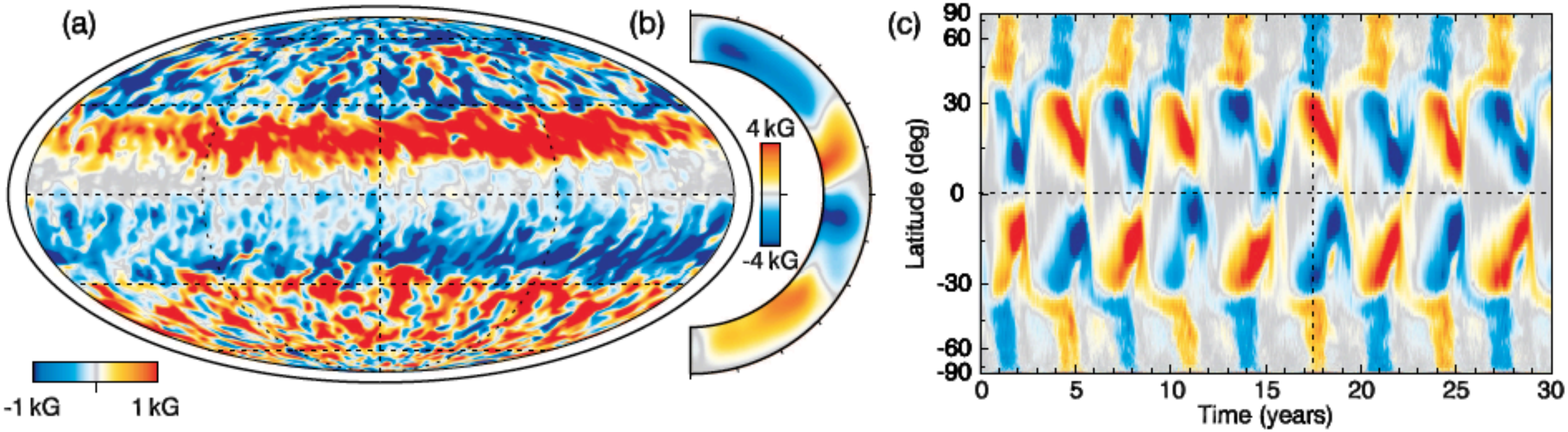
Magnetic Convection



Radial
component of B

stretching and
shearing of B
(folding too)

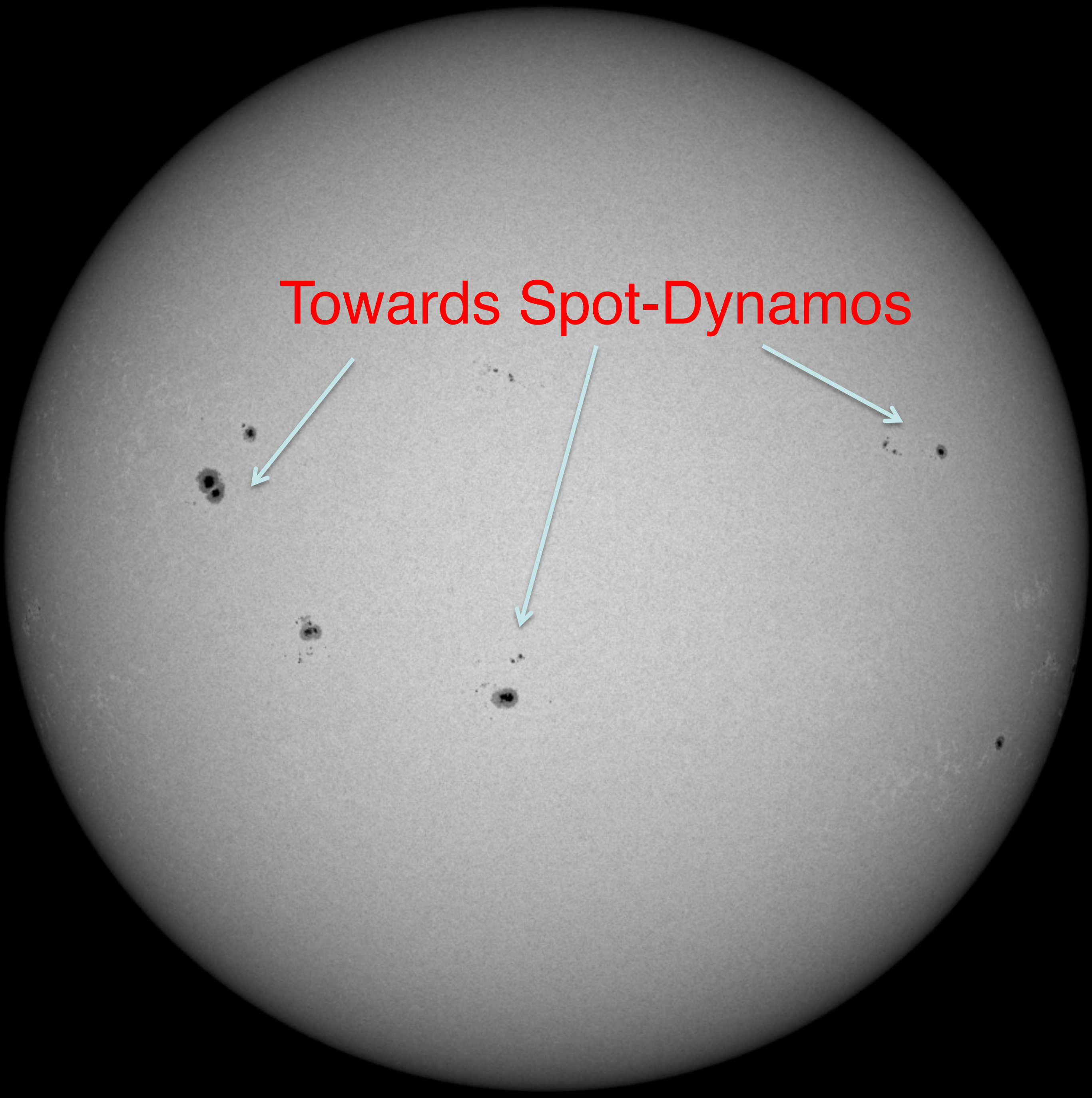
Latest solar-like case D3: getting cycle and equatorward branch



Reducing nu even further nu by using SLD scheme makes the simulation develop a more regular cyclic behavior

Augustson, Brun et al. 2015, ApJ

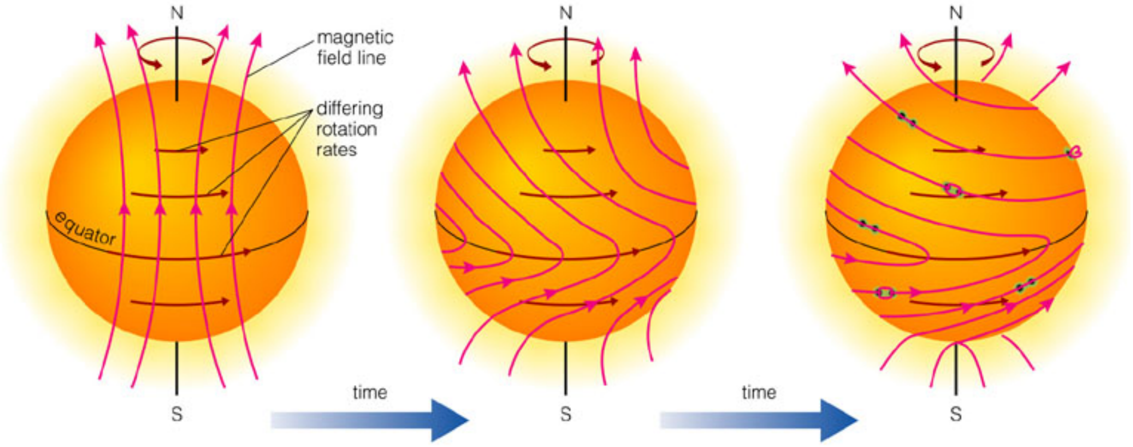
Towards Spot-Dynamos



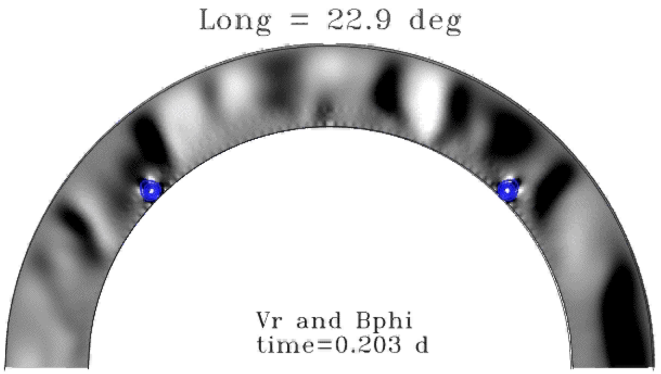
SDO/HMI Quick-Look Continuum: 2013.12.12_21:16:30_TAI

Transport et génération du champ toroidal Btor

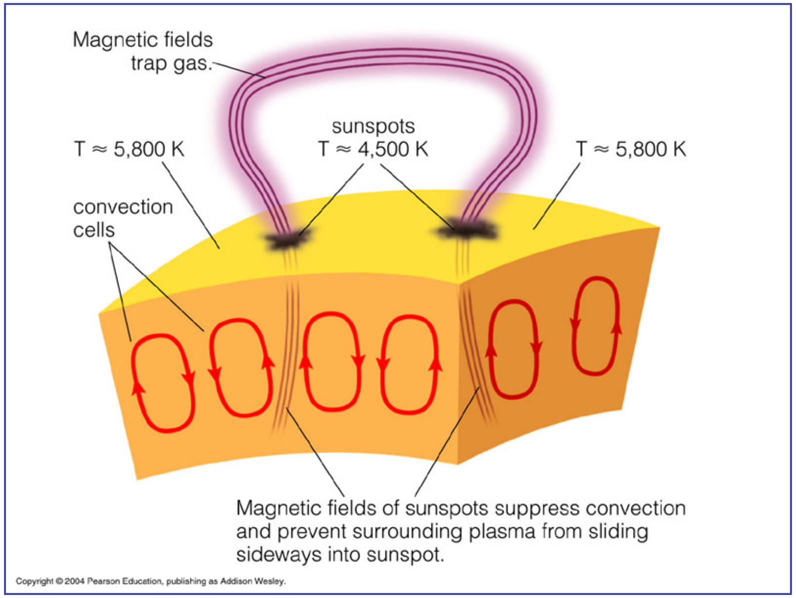
Effet Omega (Ω): enroulement des lignes de champ



Jouve & Brun 2007, AN, in press



Simulations CEA
projet STARS2



Magnetic Wreath and Intermittency yielding flux emergence

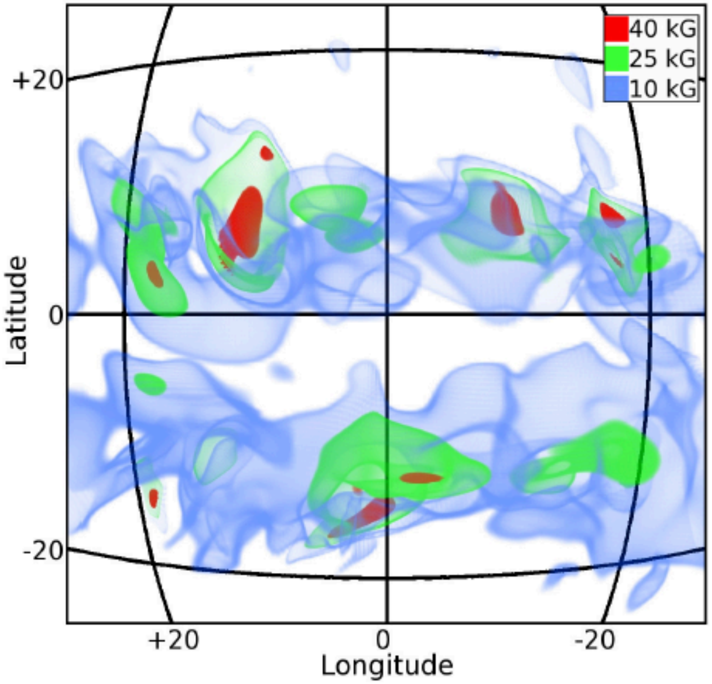


Figure 17. Three-dimensional volume renderings of isosurfaces of magnetic field amplitude in case S3. Blue surfaces have amplitudes of 10 kG, green surfaces represent 25 kG, and red surfaces indicate 40 kG fields. Grid lines indicate latitude and longitude at 0.72 $R_\odot$ as they would appear from the vantage point of the viewer. Small portions of the cores of these wreaths have been amplified to field strengths in excess of 40 kG while the majority of the wreaths exhibit fields of about 10 kG or roughly in equipartition with the mean kinetic energy density (see Figure 2).

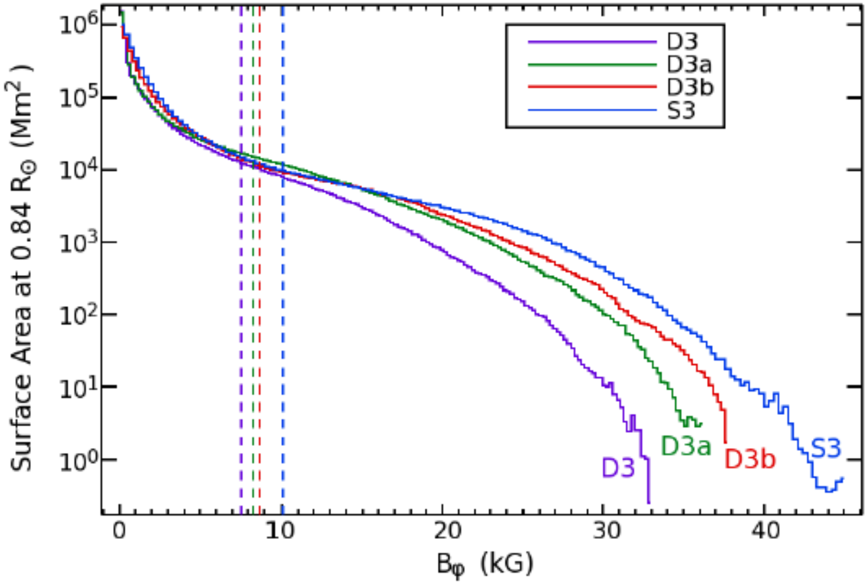
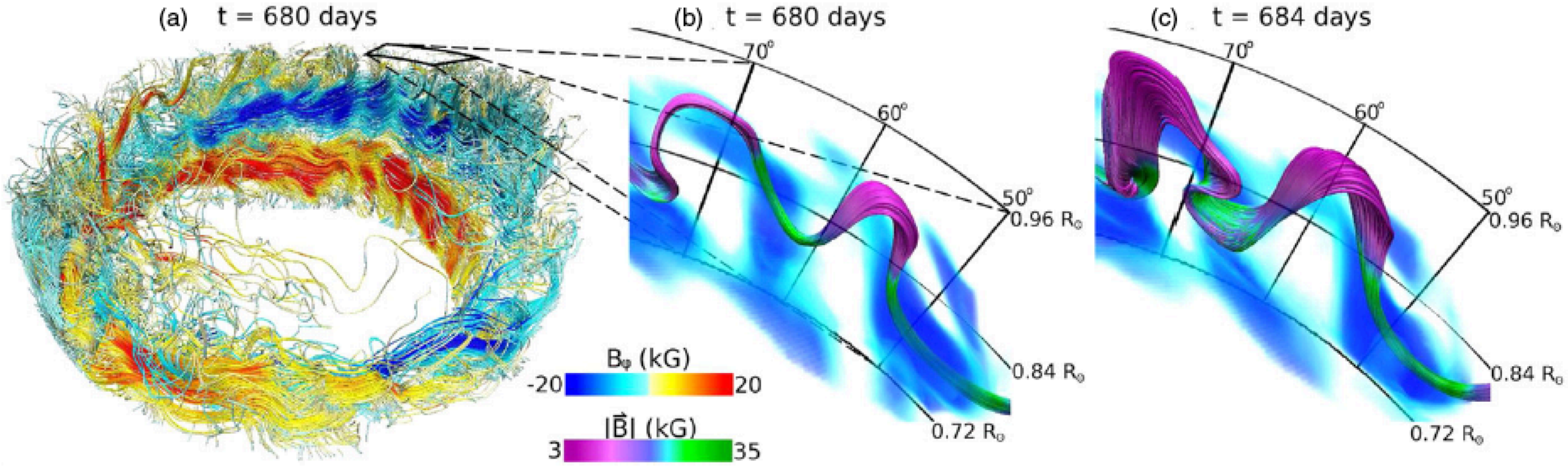


Figure 2. Probability distribution functions for unsigned B_ϕ at mid-convection zone for cases D3 (purple), D3a (green), D3b (red), and S3 (blue) showing the surface area covered by fields of a given magnitude. Distributions are averaged over about 300 days when fields are strong and as steady as possible. Dashed vertical lines show the field-strength at which equipartition is achieved with the maximum fluctuating kinetic energy (FKE) at mid-convection zone for each case. Case D3b shows a deficit of field in the 10 kG range, but an excess of surface area covered by extremely strong fields above 25 kG range, as well as higher peak field strengths. Case S3 shows significantly greater regions of fields in excess of 20 kG than all other cases.

Nelson et al. 2013, ApJ

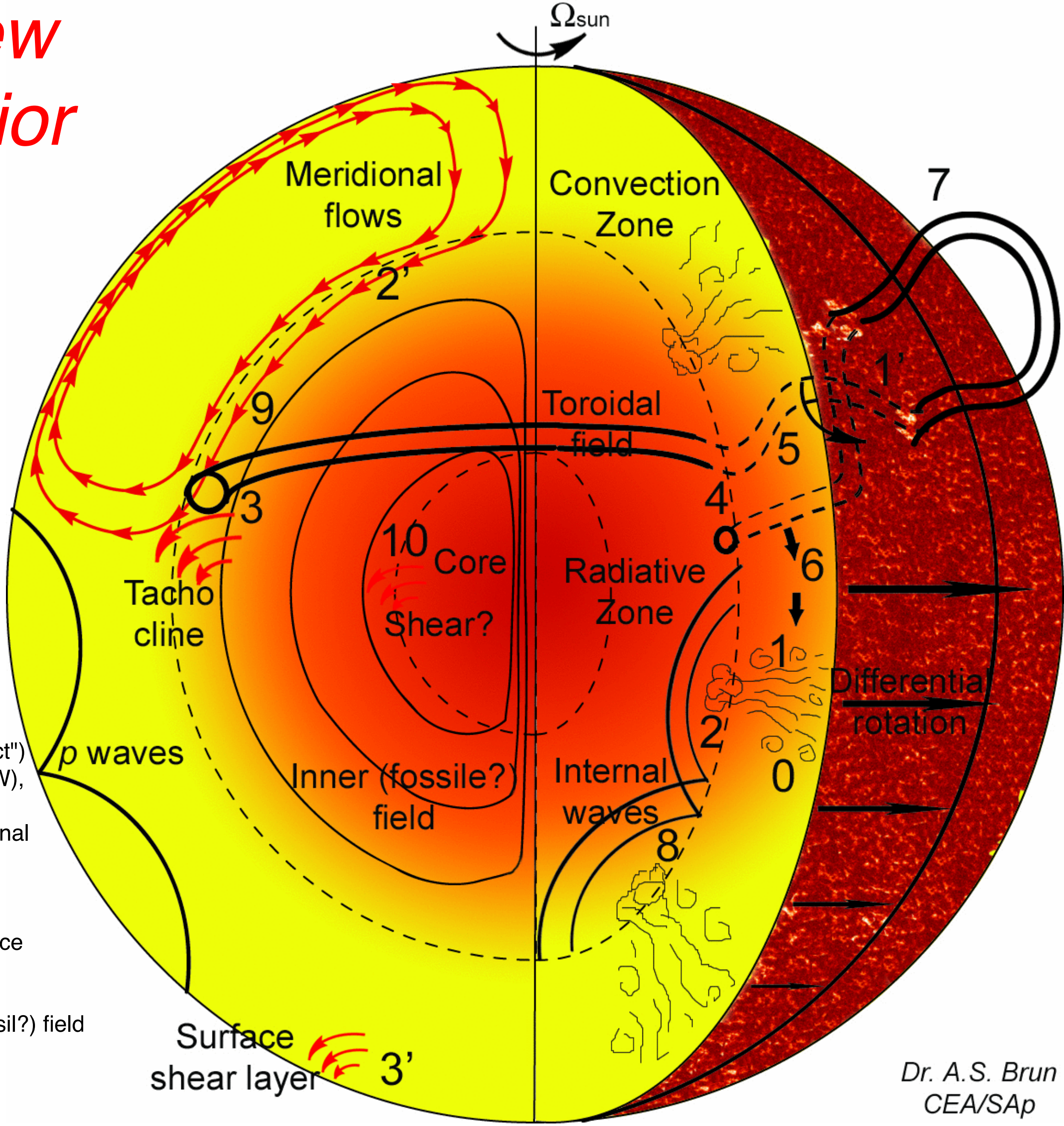
Wreaths can generate Buoyant Loops



Nelson et al. 2011, 2013a, 2013b, Brun et al. 2015

Towards getting first “spot-dynamos”…

A Theoretical View of the Sun's Interior Dynamics

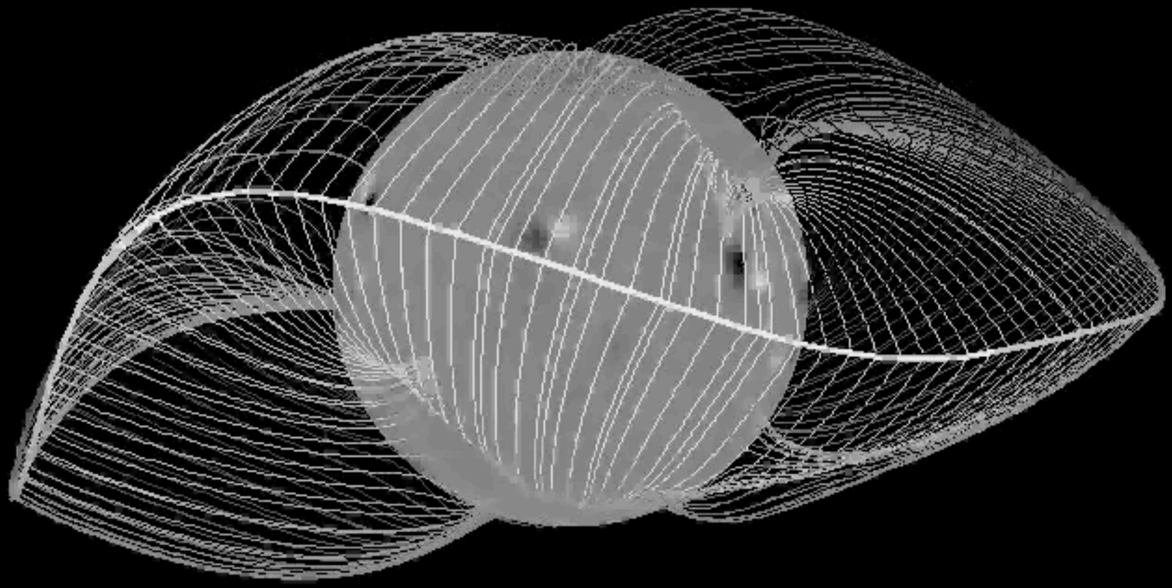


Dr. A.S. Brun
CEA/SAp

Figure Caption:
0: Turbulent convection (plumes)
1: Generation/self-induction of B field ("alpha-effect")
or 1': Tilt of active region, source of poloidal field
2: Turbulent pumping of B field in tachocline
or 2': Transport of B field by meridional flows
in CZ into the tachocline
3: Field ordering in toroidal structures by large scale
(radial and latitudinal) shear in tachocline ("omega-effect")
3': Surface shear layer, Solar sub surface weather (SSW),
surface dynamics of sun spot?
4: Toroidal field becomes unstable to m=1 or 2 longitudinal
instability (Parker's)
5: Rise (lift) + rotation (tilt) of twisted toroidal structures
6: Recycling of weak field in CZ
or 7: Emergence of bipolar structures at the Sun's surface
8: Internal waves propagating in RZ and possibly
extracting angular momentum
9: Interaction between dynamo induced field, inner (fossil?) field
in the tachocline (with shear, turbulence, waves, etc...)
10: Instability of inner field (stable configuration?)
+ shearing via "omega-effect" at nuclear core edge?
Is there a dynamo loop realized in RZ?

The sun: a complex temporal evolution as well…

credit M. De Rosa



t = 0.0 y (27–day synodic reference frame) ϕ = 0.00

Code PLUTO open source (Prof. A. Mignone (Turin))

Adaptation pour la dynamique stellaire externe:

- Vent
- Intéraction étoile-planéte

Code MHD compressible modulaire. Solveur de Riemann (HLL, HLLD, ROE)
Rafinement de maille via librairie CHOMBO
Traitement champ magnétique séparé

MHD Wind Simulations

Why are they necessary ?

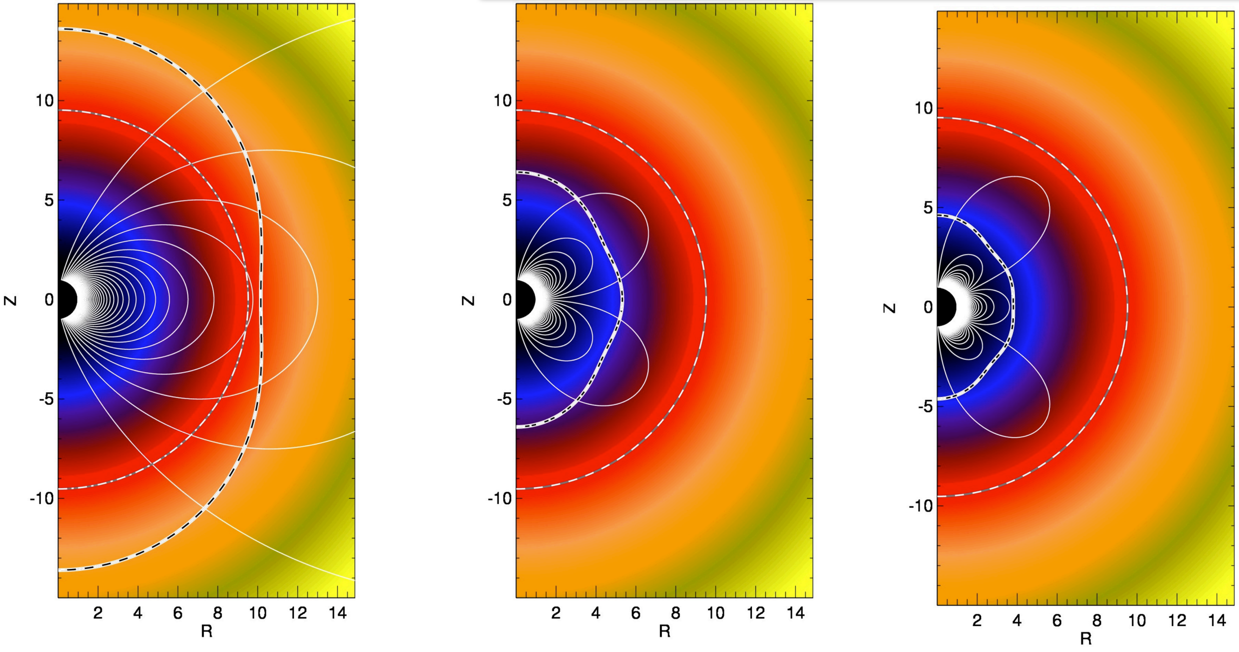
- Magnetic fields > split monopole
- Rotation
- 3D, non-axisymmetry

Parametric study of the torque as a function of:

Decreasing Alfvén surface !

Rotation
Magnetic field strength
Magnetic field topology

Coronal temperature and gamma held fixed.



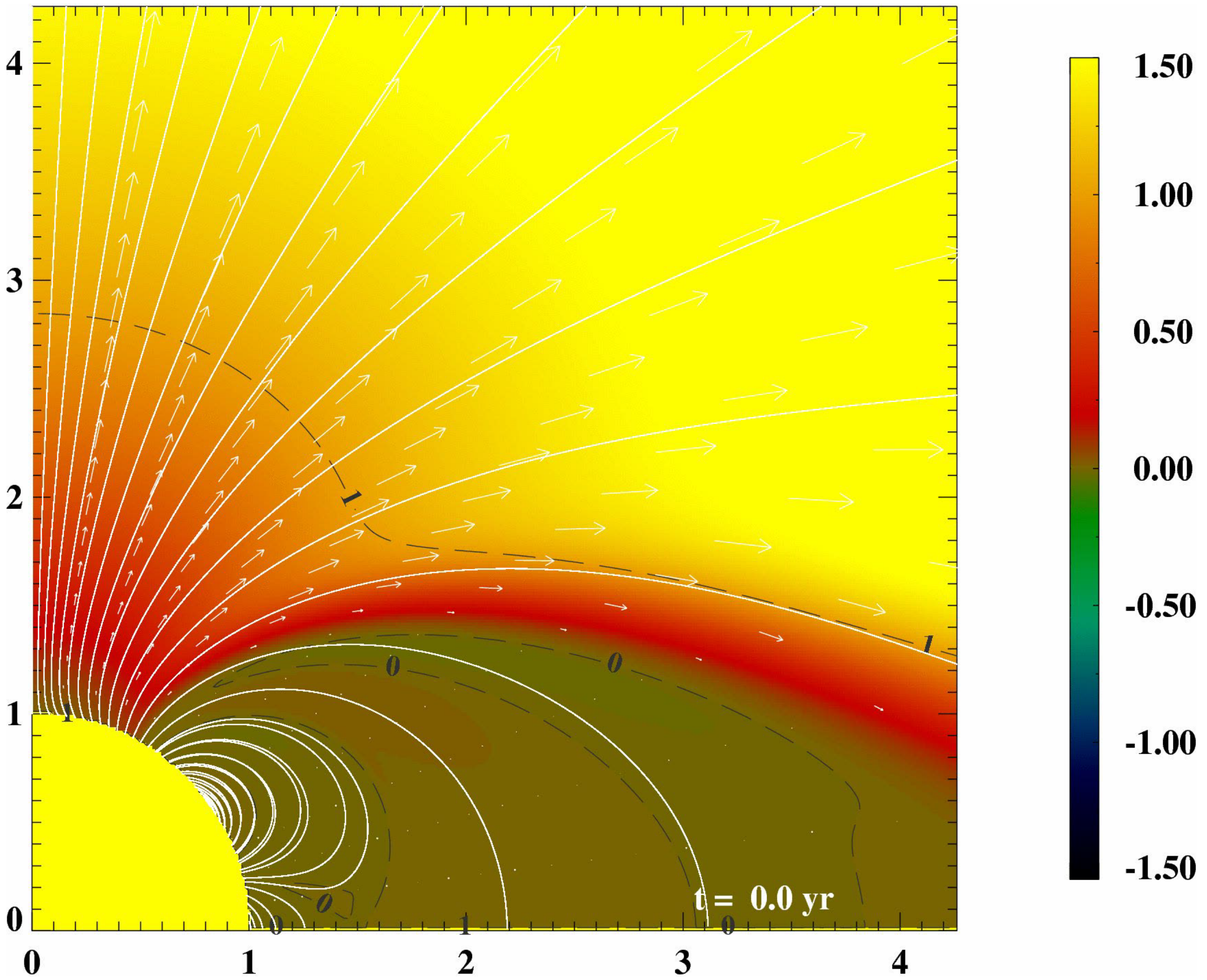
Dipole *Quadrupole* *Octupole*

60 cases with compressible MHD code PLUTO

(Réville et al. 2015, ApJ)

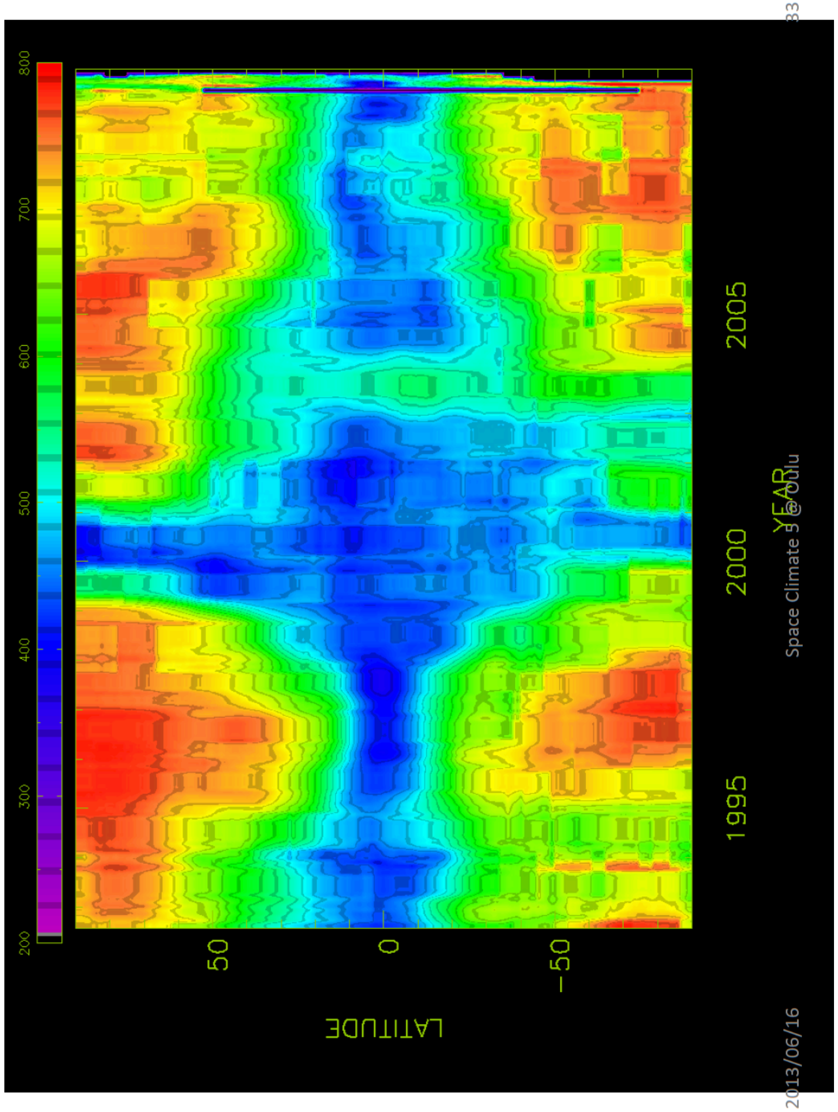
Coupling Solar Dynamo to Solar Wind

Pinto, Brun et al. 2011, ApJ



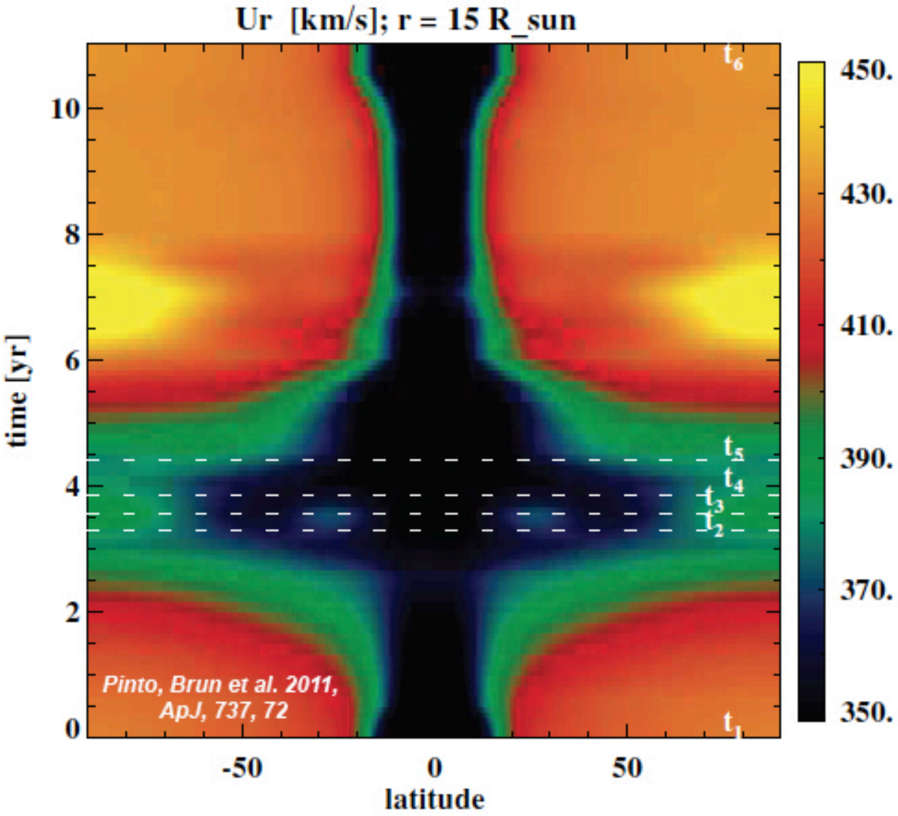
11-yr Cycle Variations of Solar Wind

Solar Wind Speed



Observations

Tokumaru et al.

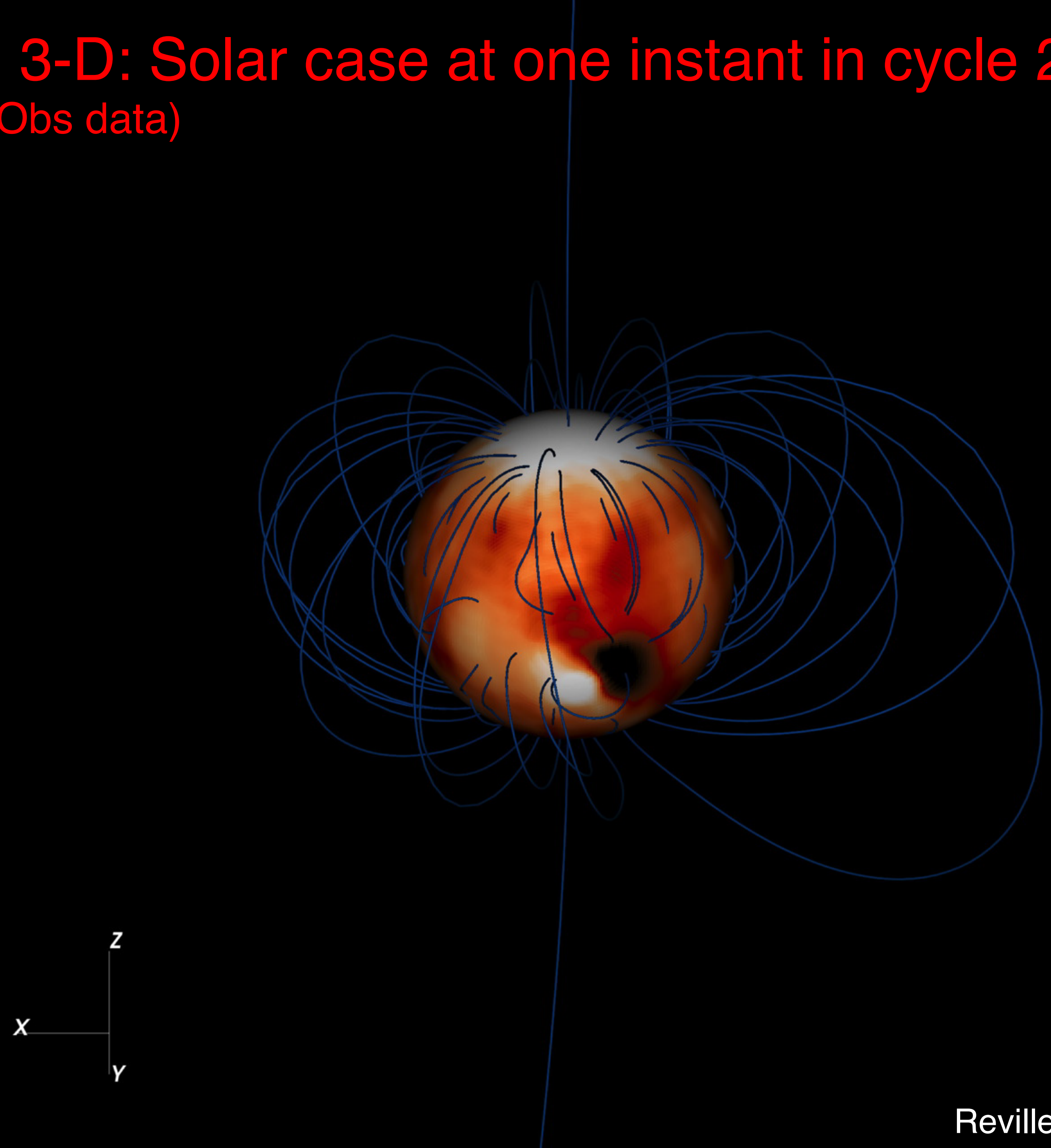


Dynamo-wind model

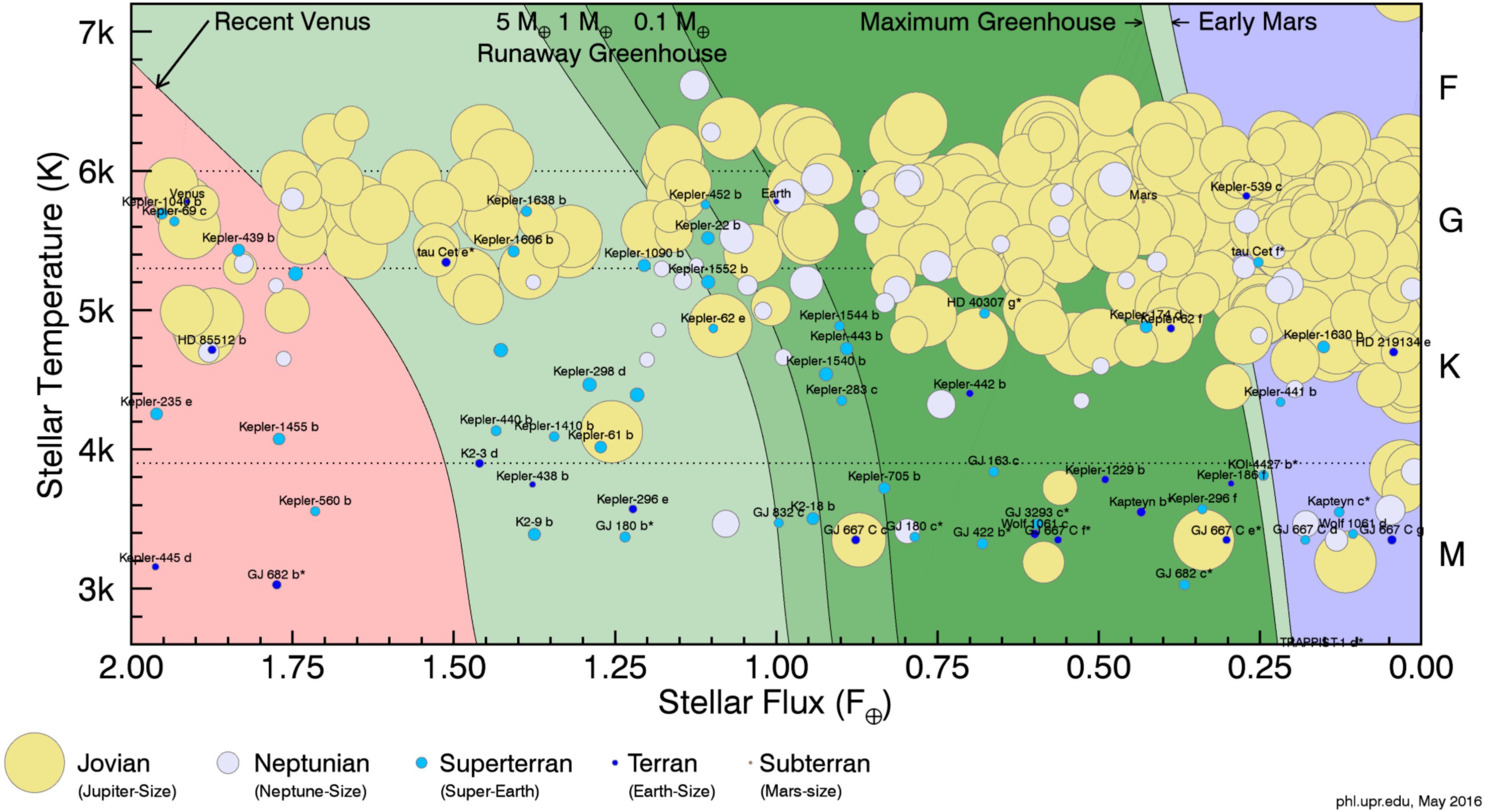
Pinto, Brun et al. 2011
Réville, Brun et al. 2016

Going 3-D: Solar case at one instant in cycle 22

(Wilcox Obs data)



Reville, Brun et al. 2016



http://phl.upr.edu/projects/habitable-exoplanets-catalog/media/pte

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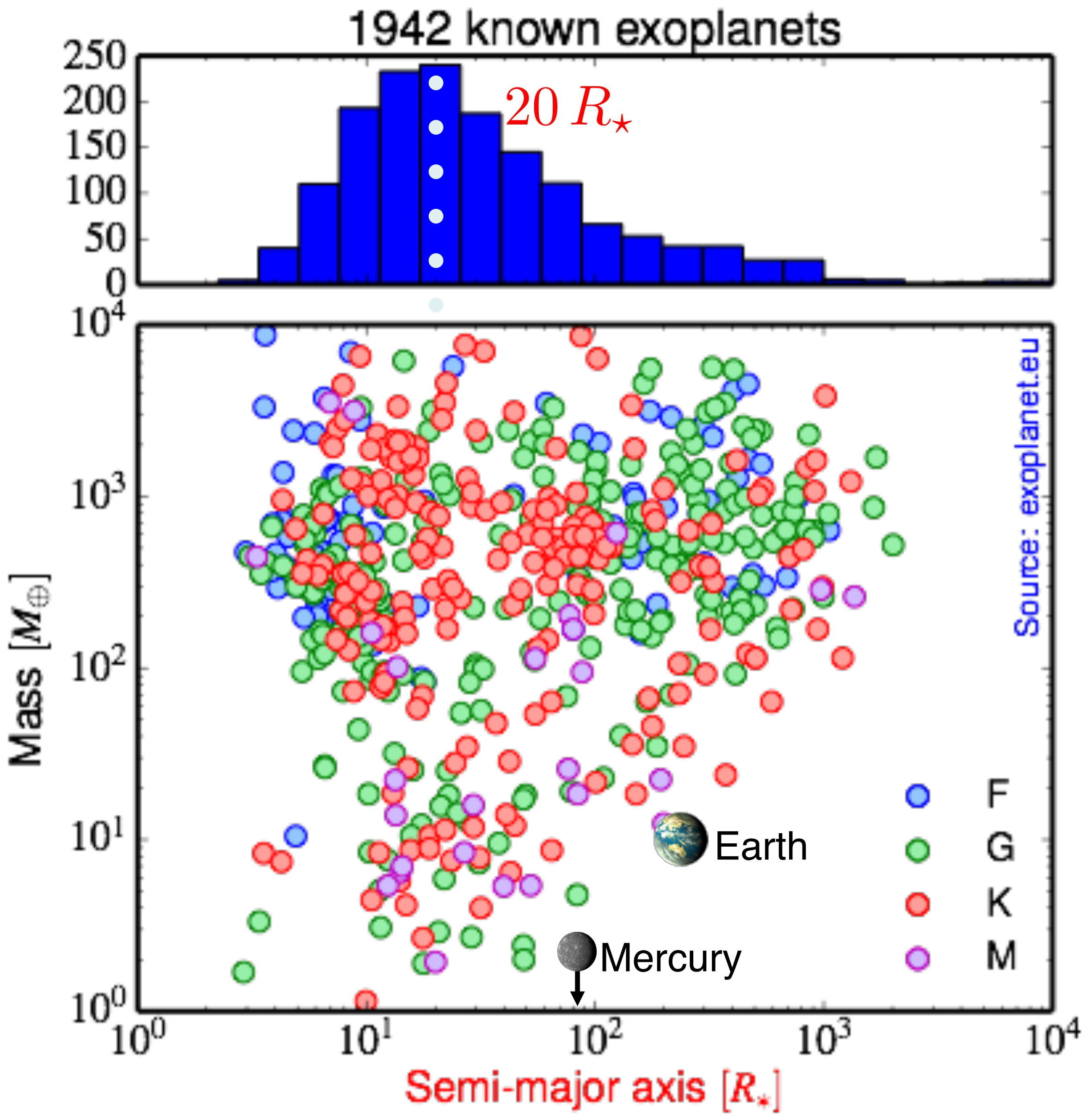
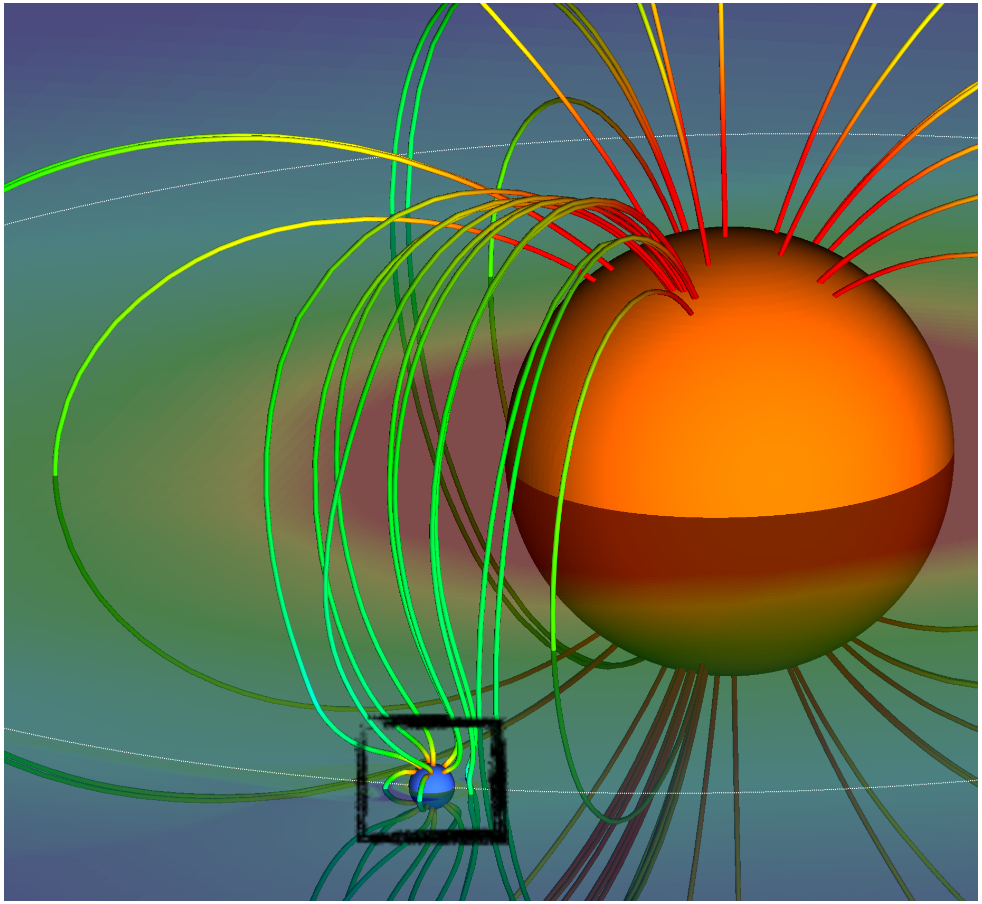
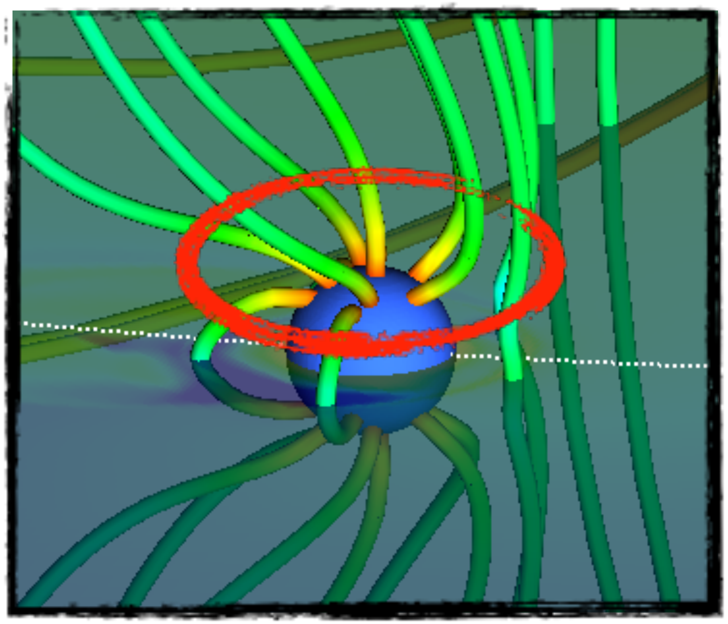
Many are very close exoplanets (because of obs biais)



Origin of the planet migration: a 3D picture



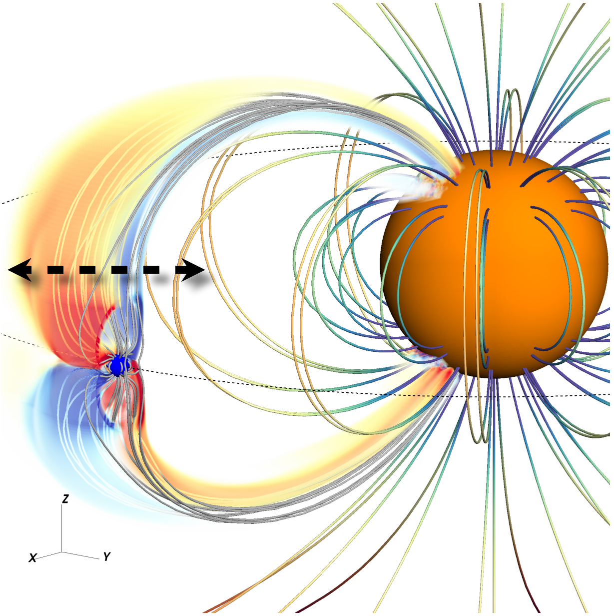


Integrate the flux of angular momentum on concentric spheres around the planet

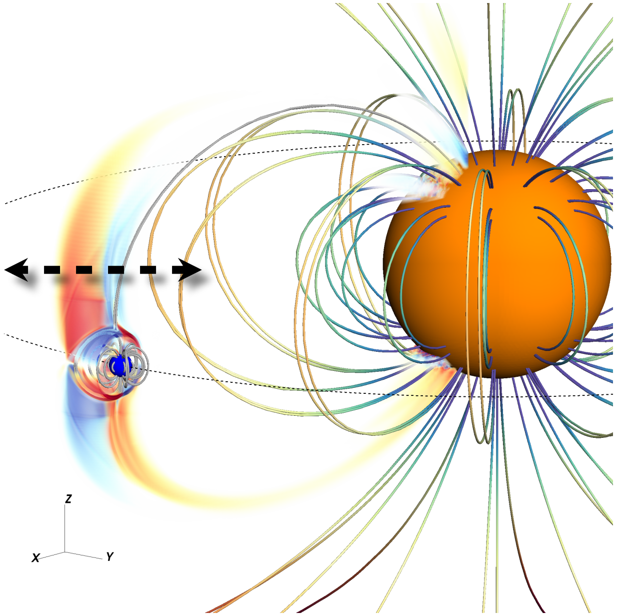
The magnetic torque originates mainly from the connection of the planet’s field to the ambient magnetic field

[Strugarek+ 2015, ApJ]

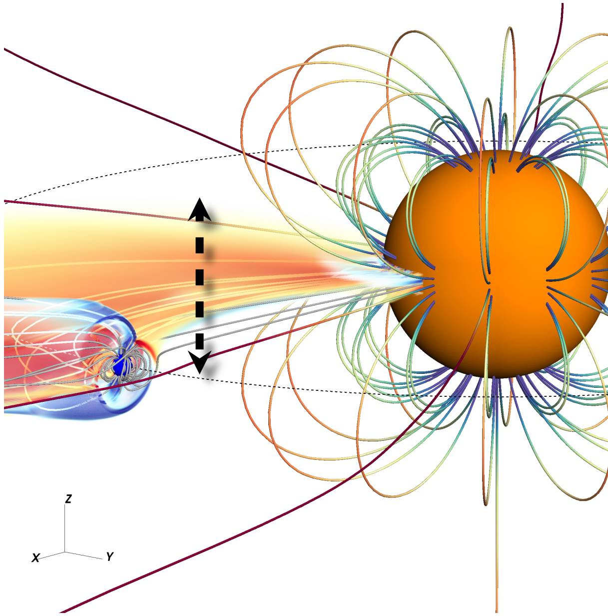
3D modelling of star-planet interactions



Two strong Alfvén wings



Two weak Alfvén wings



One strong Alfvén wing

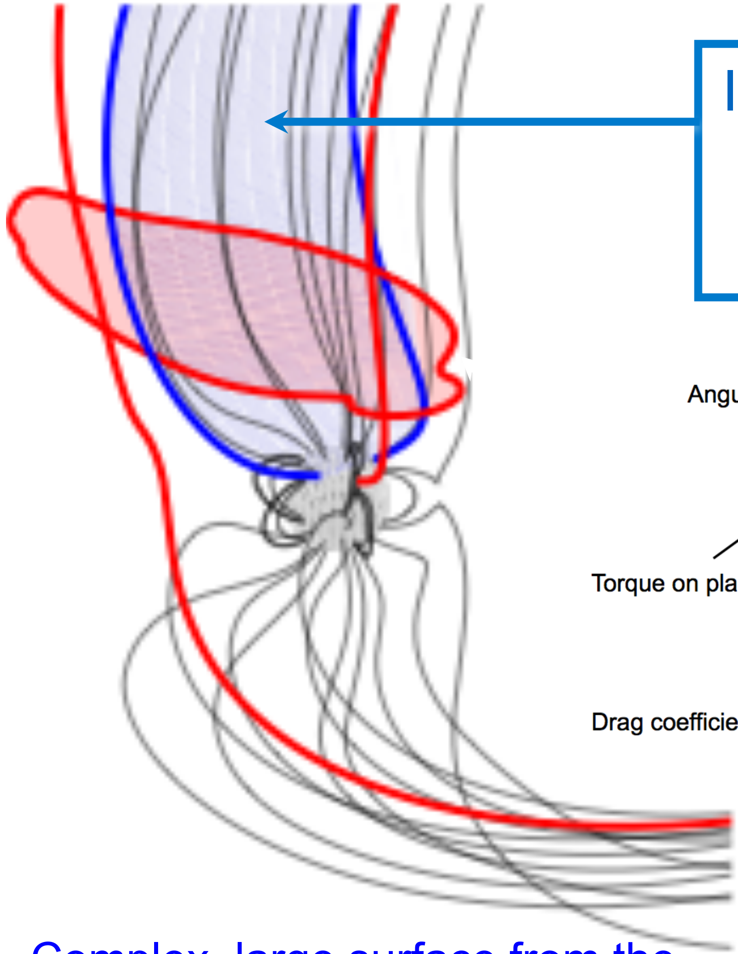
Alfvén wings foot point localized at specific latitude and longitude

Alfvén wing foot point localized at the equator over a large longitudinal range

[Strugarek+ 2015, ApJ]

Two configurations of the magnetic interaction

Anti-aligned



Aligned

Interaction surfaces leading to magnetic torques

$$T_P = c_d \, r_o \, \overbrace{A_{eff} \, P_t}^{\text{Angular momentum convected on the } \textit{obstacle}}$$

Torque on planet

Drag coefficient ~ $(1+M_A^2)^{-1/2}$

Orbital radius

Effective area of the obstacle

Wind total pressure (ram+thermal+magnetic)

Complex, large surface from the whole Alfvén wing

Simple magnetospheric size estimate from pressure balance

Accompagnement missions spatiales (Solar Orbiter, Plato)

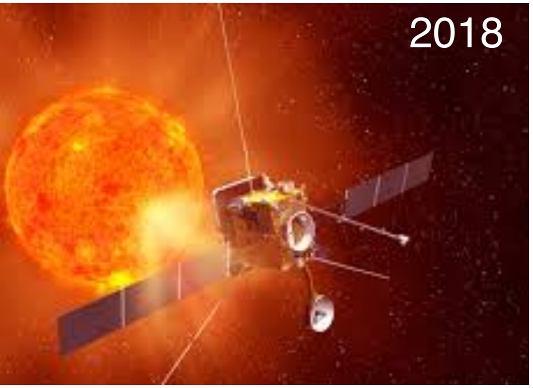
Collaboration sur la physique avec l’IRFM – Astro-Fusion

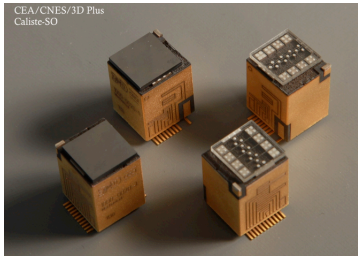
ESA M1: Solar Orbiter+STIX:

Assimilation de données et Prévision du cycle

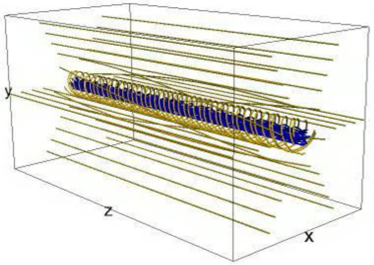
le Soleil et son héliosphère, impact sur la Terre (météo de l'espace)

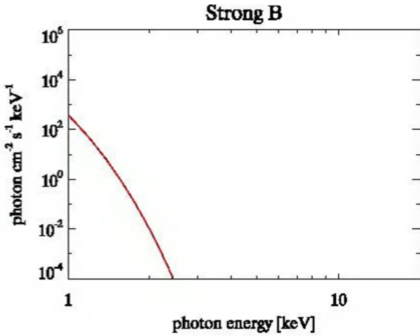
Co-animation scientifique france





Soutien scientifique
R&T SAp + IHP-Sorento



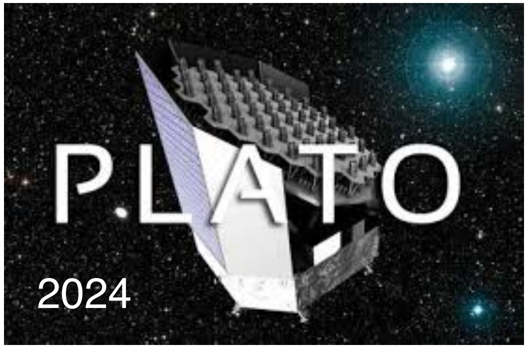


Simulations HPC

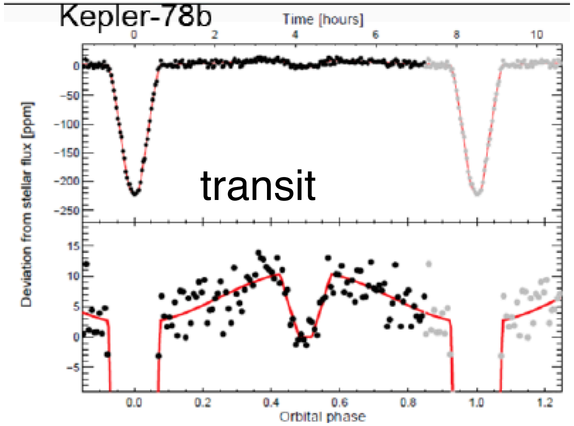
ESA M3: PLATO:

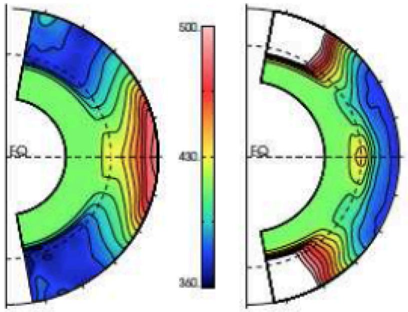
Trouver une exo-Terre autour d'un analogue solaire

Astérosismologie
Interaction étoile-planètes
Habitabilité



WP, Génération et analyse courbes lumières





Cas solaire et anti-solaire

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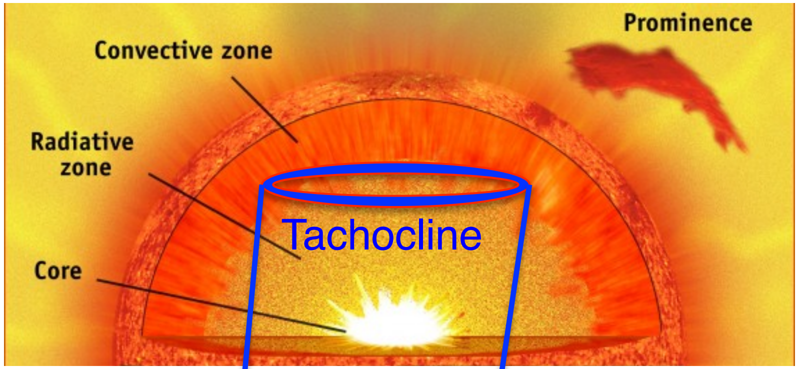
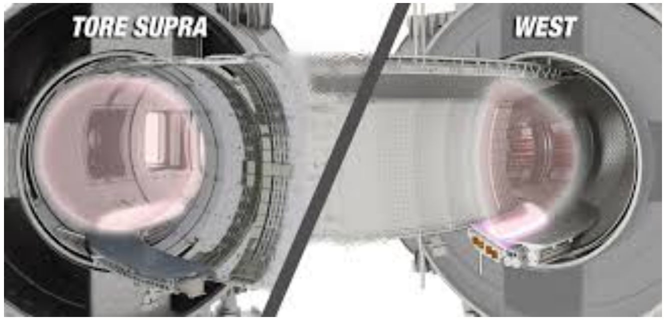
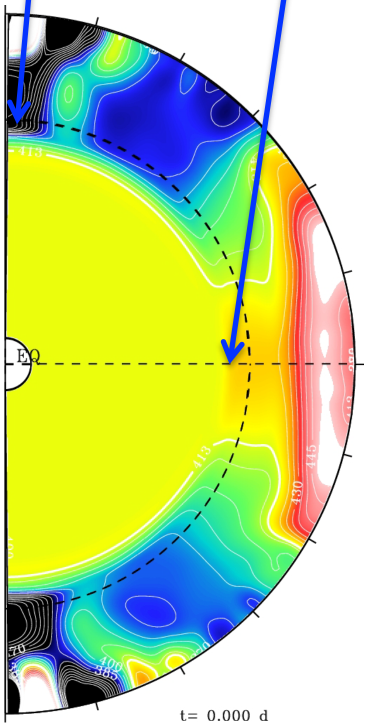
Plasma et barrières de Transport

Role des écoulements cisaillés, de la turbulence et du magnétisme, qualité du confinement





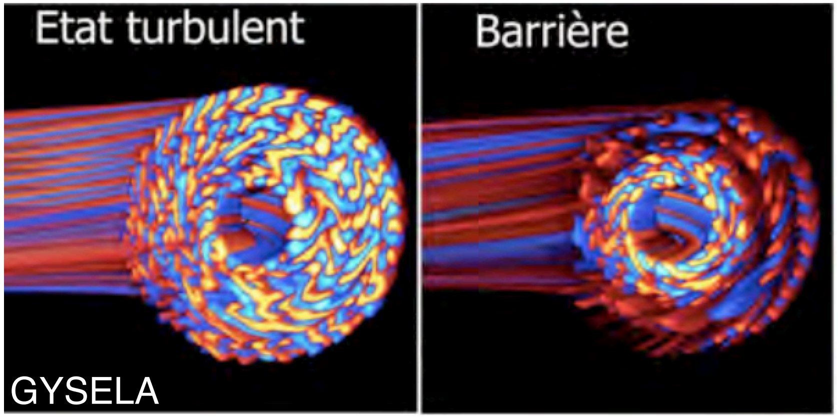


ASH

Double Confinement

Thèse A. Strugarek
(Prix SF2A)

Nouvelle thèse:
C. Emeriau



Complémentarité
mécanismes et diagnostiques

Instabilité INTERCHANGE -> TURBULENCE

(1) Fonctionnement de la tachocline?

(2) Contrôle du confinement tokamak?

Strugarek, Brun, Sarazin, ApJ 2013
Strugarek, Sarazin, … Brun, PRL 2013

HPC simulation in solar and stellar physics are essential

Complex multi scales (space, time), multi physics contex

Allows to predict new physics or properties not yet observed or to help calibrating Instruments/satellites

STARS2 project uses 25 Millions node hours per year