Anelastic rotating convection modelling with Magic and Rayleigh: Zonal Flow and Vortices on giant planets.

Moritz Heimpel, Nick Featherstone and Jonathan Aurnou

CIG all hands meeting, Davis, June 23, 2016

Acknowledgments

- **Krista Soderlund** (University of Texas at Austin)
- **Thomas Gastine & Johannes Wicht**
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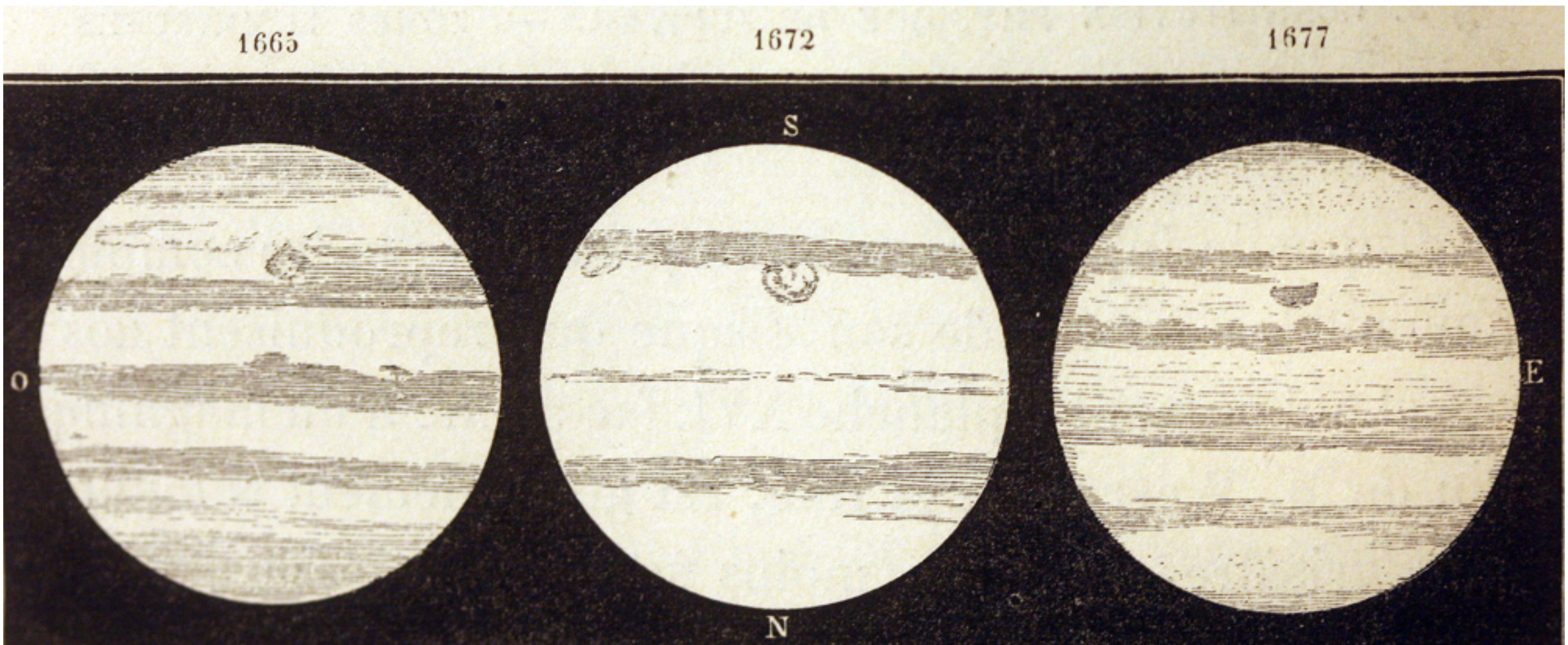
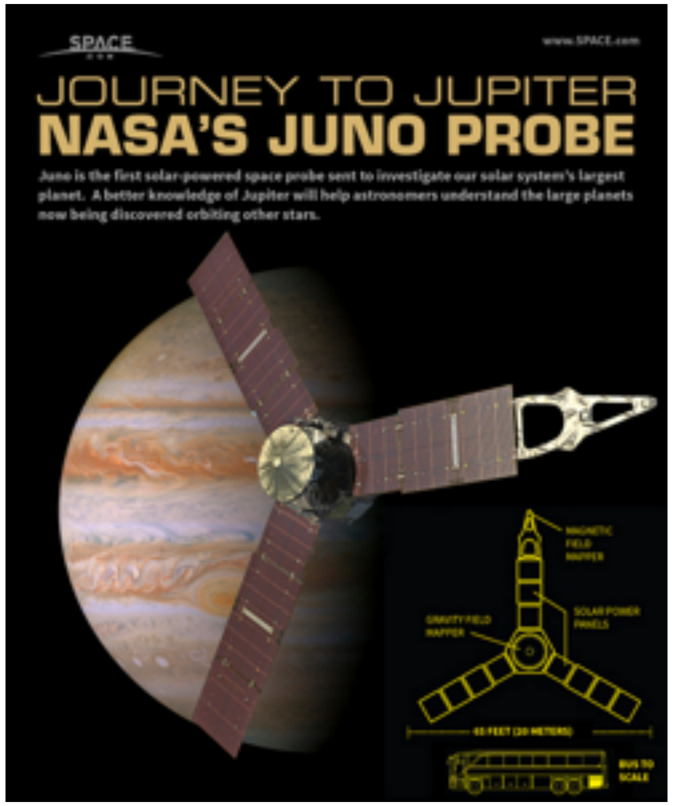
- **Keith Cuff** (University of Alberta)

- Compute Canada
- Westgrid
- Argonne National Laboratory (Mira)
- Computational Infrastructure for Geodynamics (CIG)

Giovanni Domenico Cassini's drawings of bands and a "permanent spot" on Jupiter

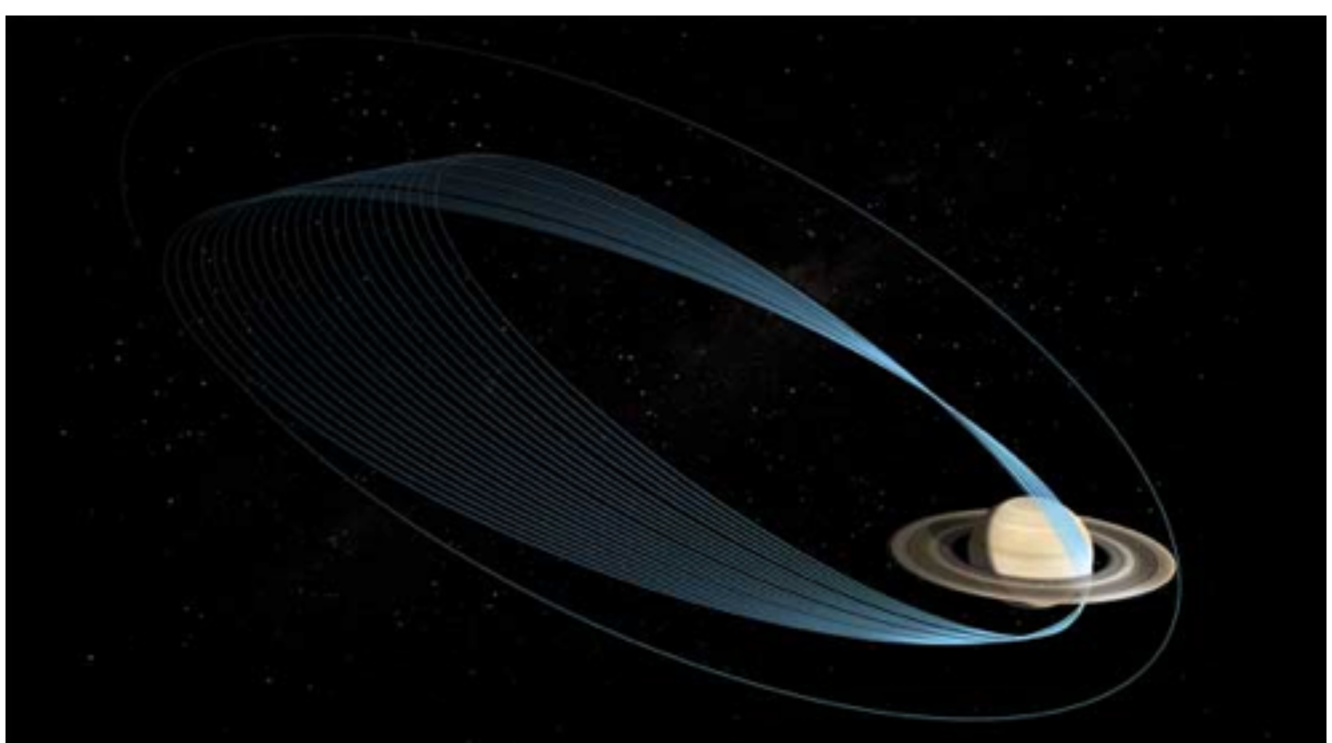


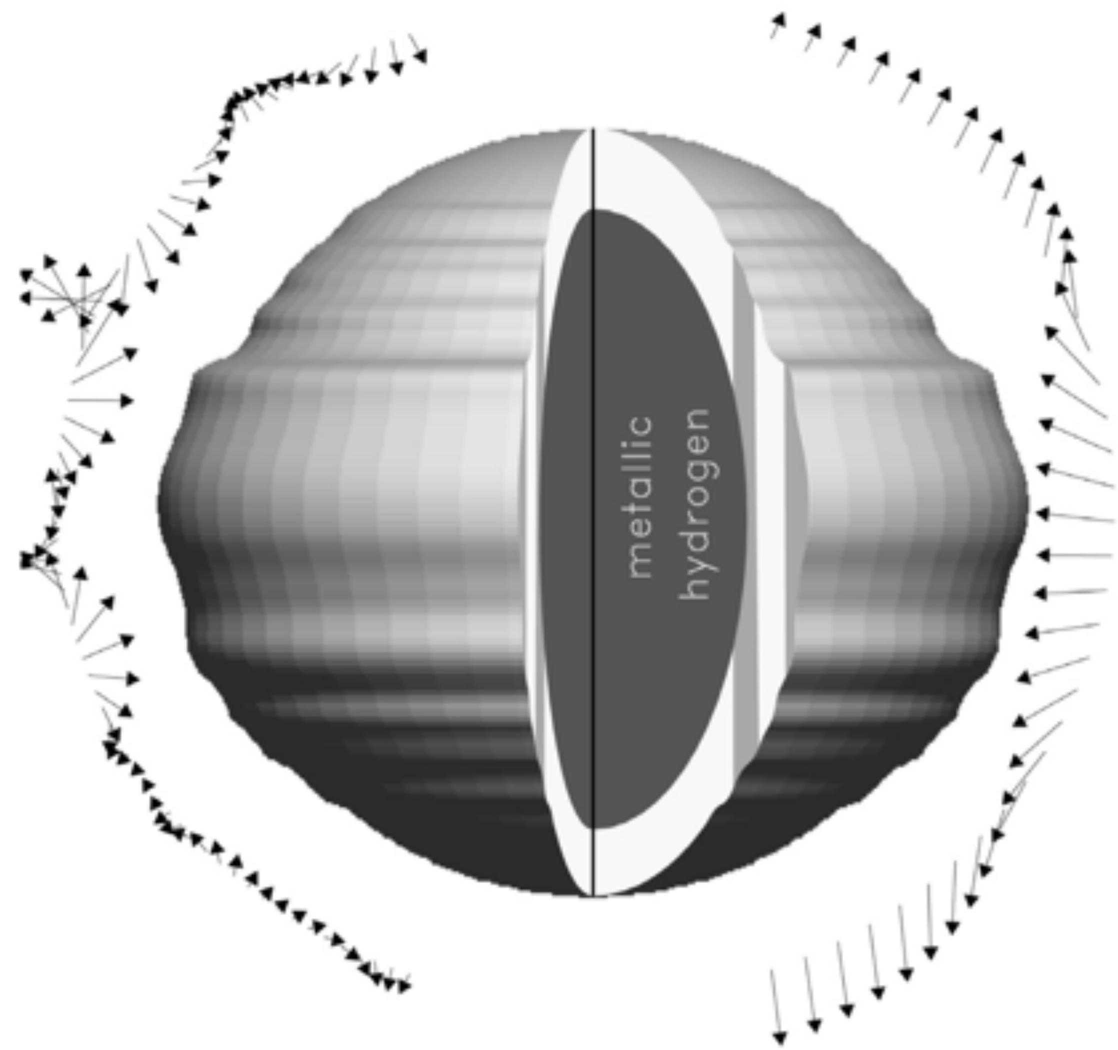
Jupiter: Juno (Orbit insertion July 4, 2016)



Future Observations will reveal the depth of zonal and vortical flows

Saturn: Cassini Proximal (Late 2016 - 2017)





Guillot et al., 2004

Outline

Part I (Very deep): Rotating convection, Jupiter's interior and the jovian dynamo.

Part IIa (Pretty deep): Zonal flows on Jupiter, Saturn, and in models of rotating convection for incompressible and compressible fluids

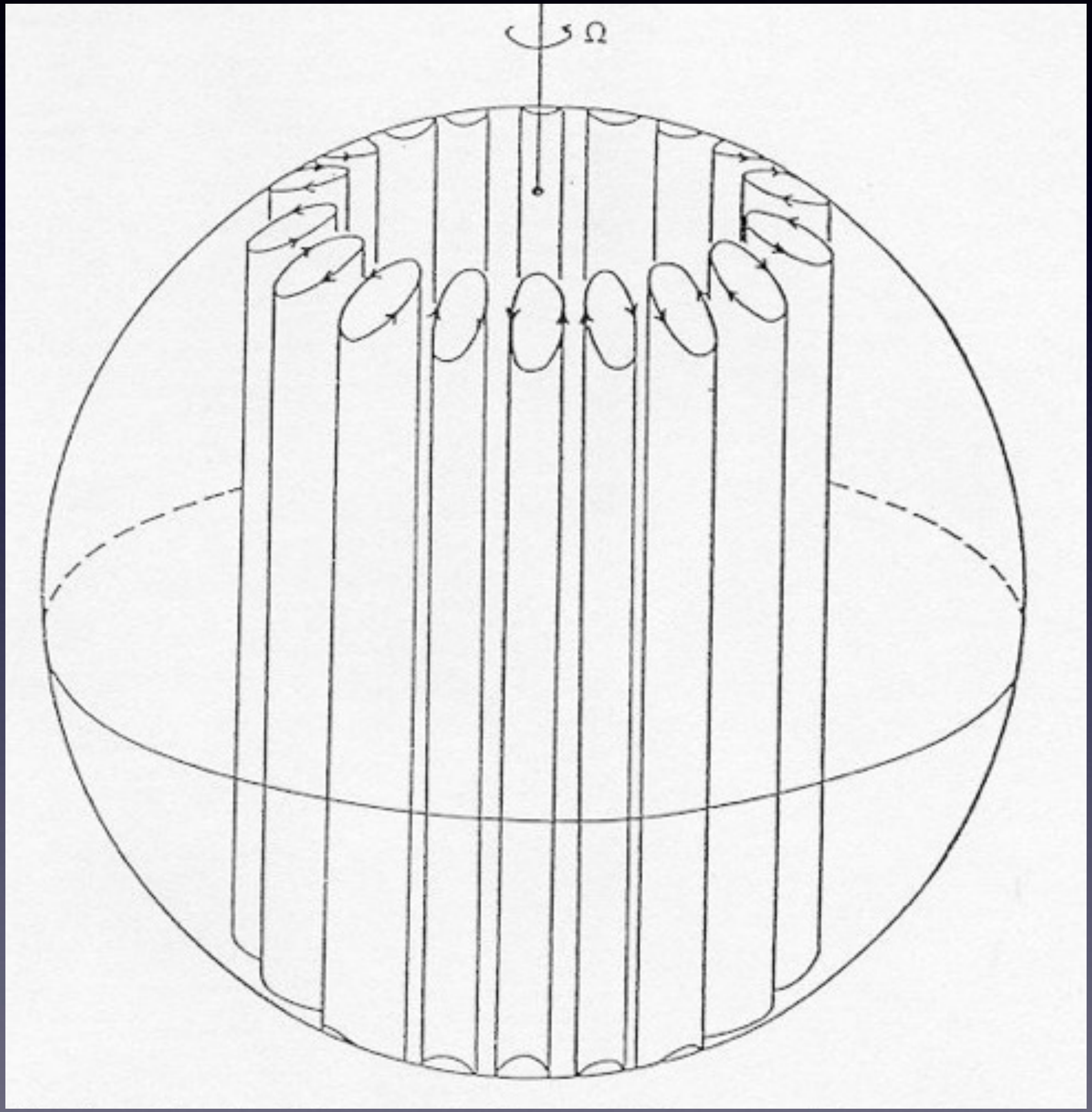
- The scale of bands and the effect of spherical geometry.

Part IIb (Relatively shallow): Storms and vortices on giant planets.

- Modelling the coexistence of zonal jets and vortices: The role of outer boundary stability conditions

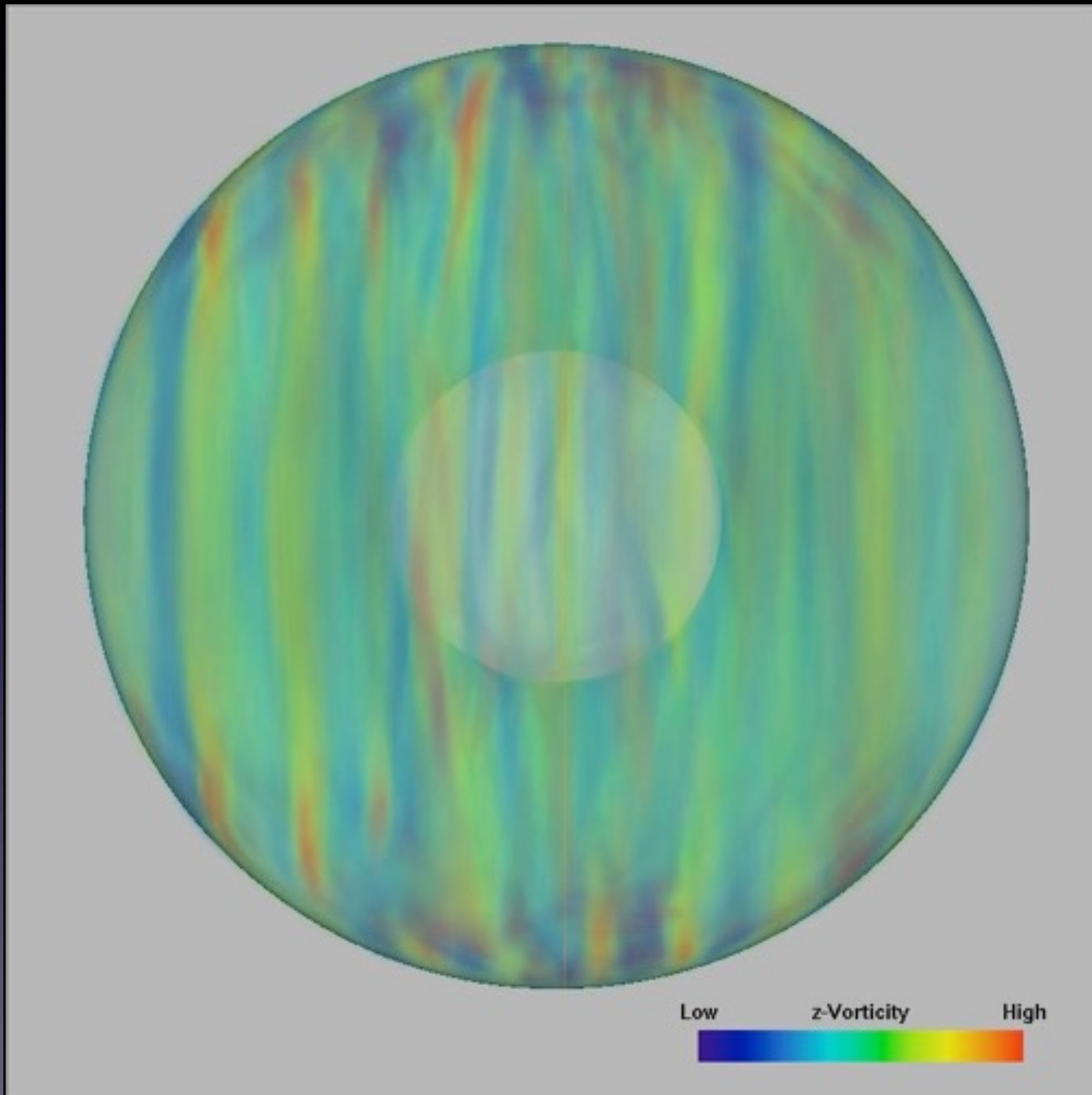
Columnar flow in deep rotating convection

Strong rotation: axially aligned flow structures (Taylor columns)

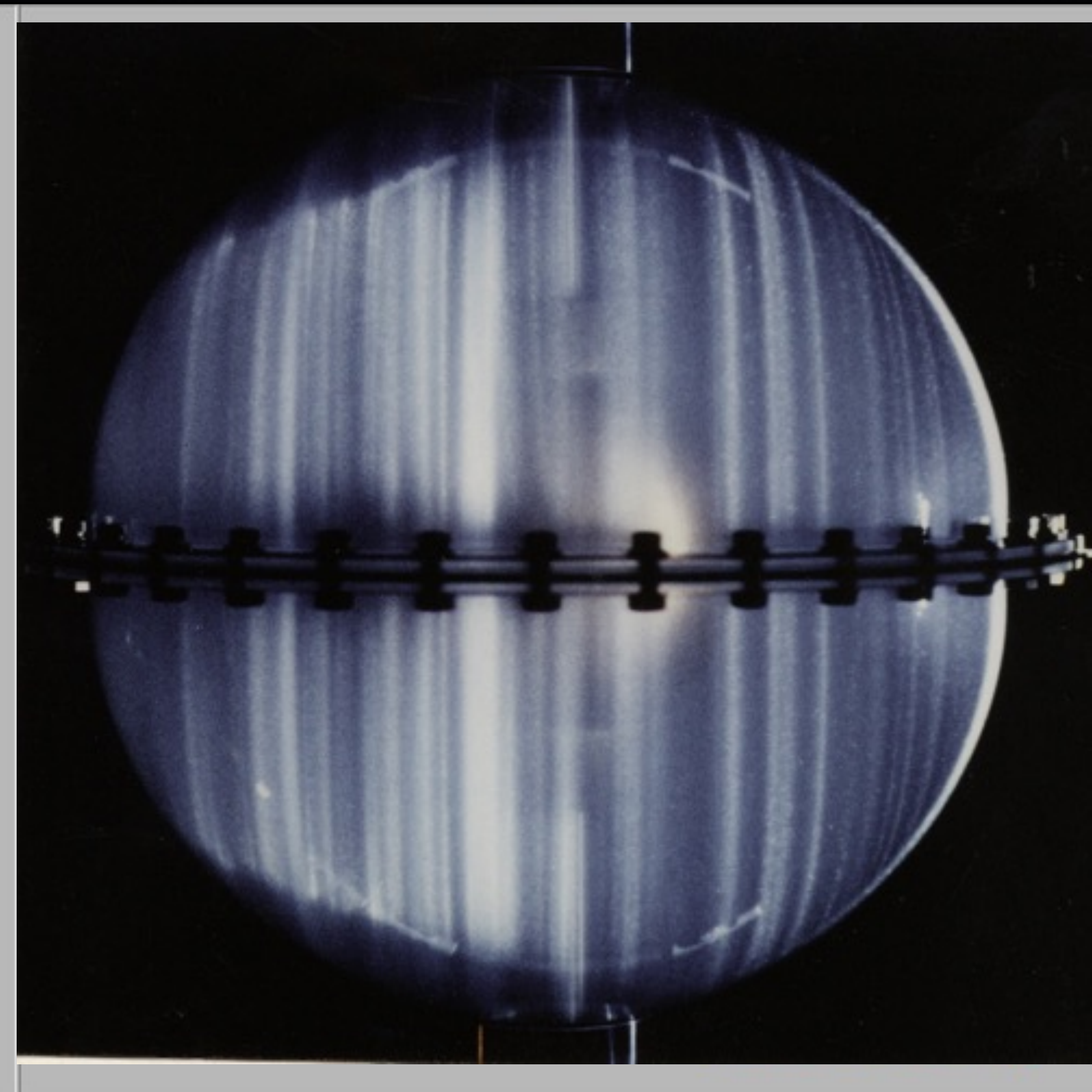


From Busse, *J. Fluid Mech.*, 1970

Numerical dynamo driven by columnar convection and laboratory rotating convection



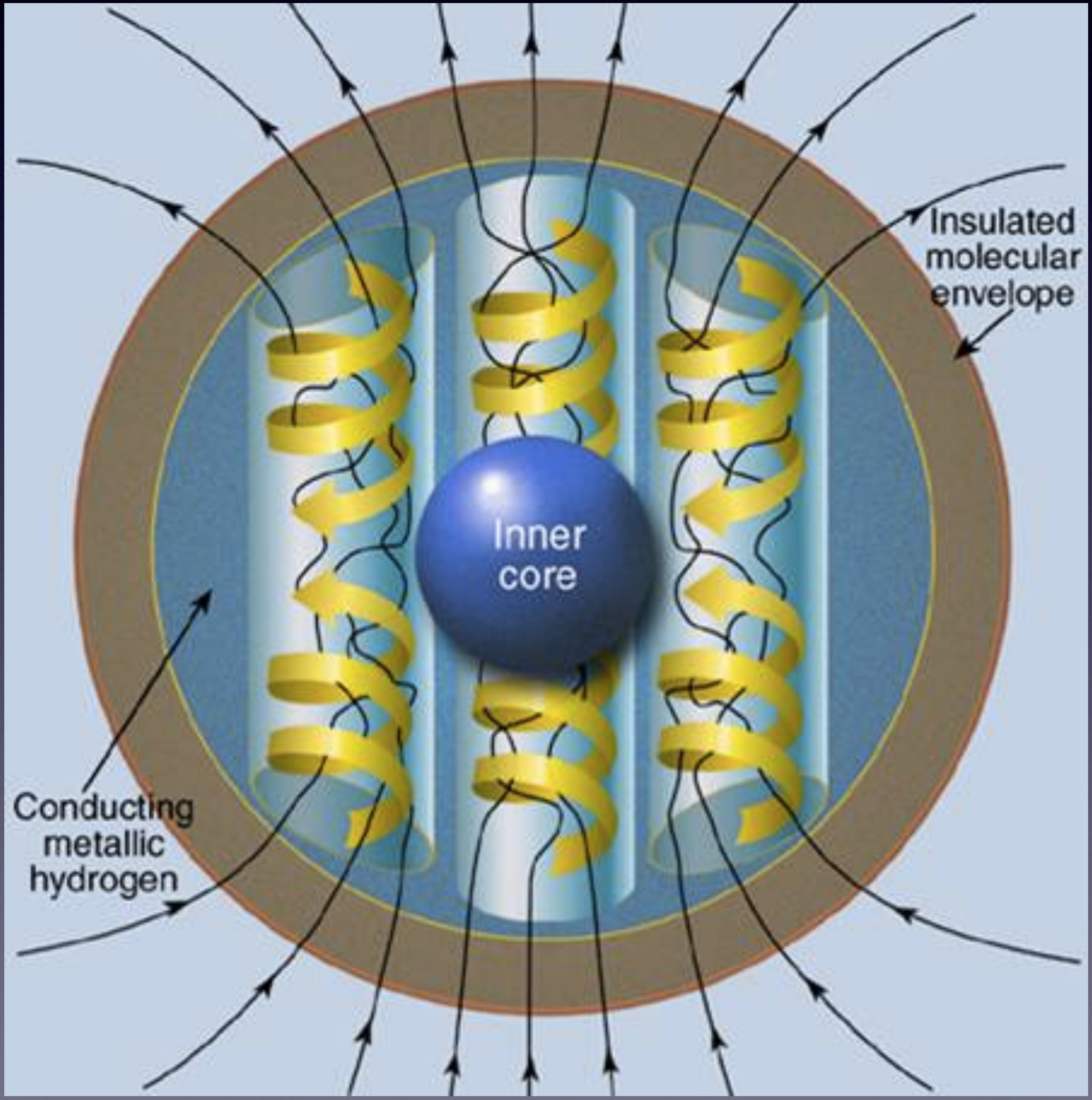
Dynamo: $E = 10^{-4}$, $Pm = 1$, $Ra = 10Ra_c$



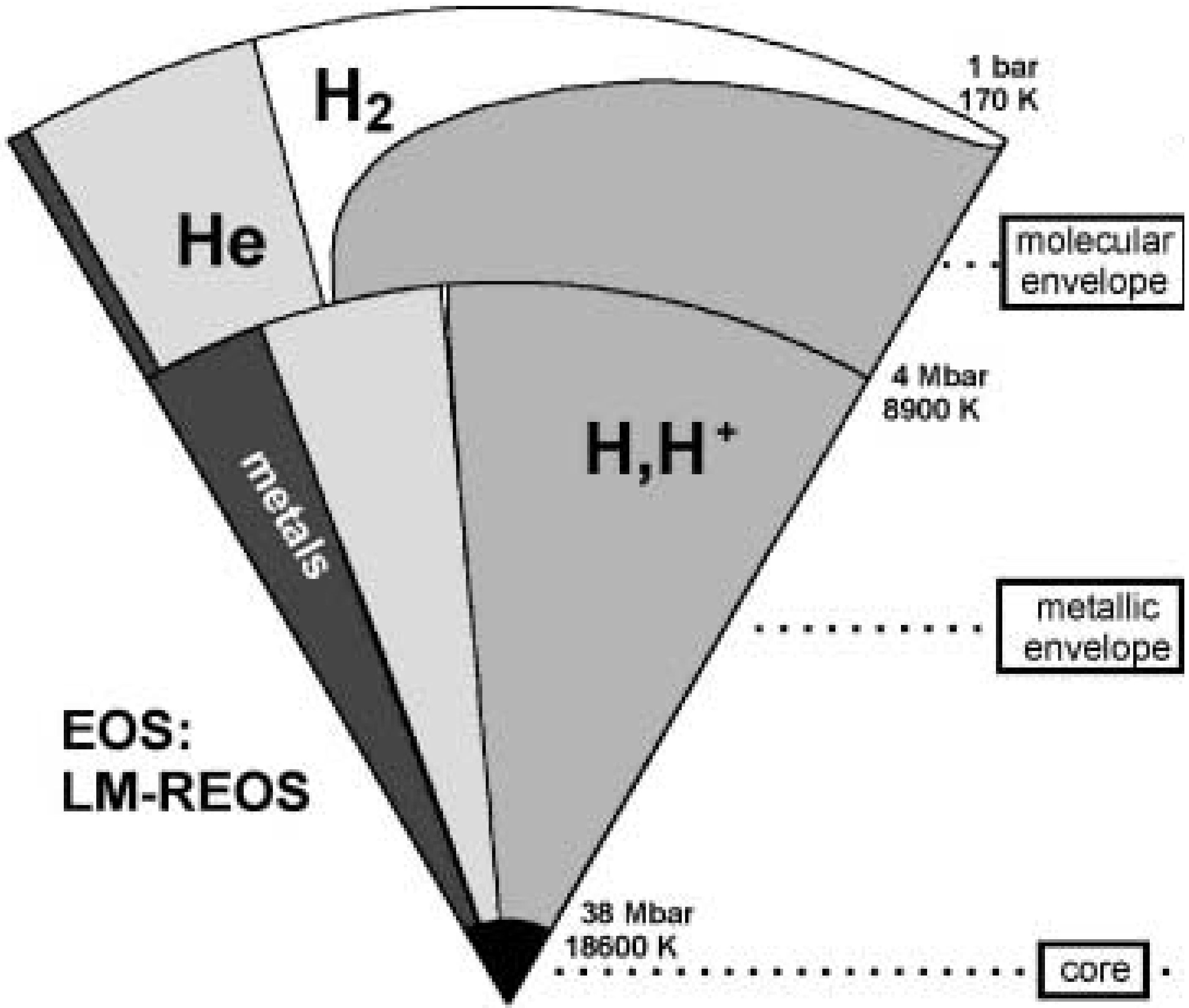
Rotating convection, cylindrical “gravity”
Cardin and Olson (1992)

Side views

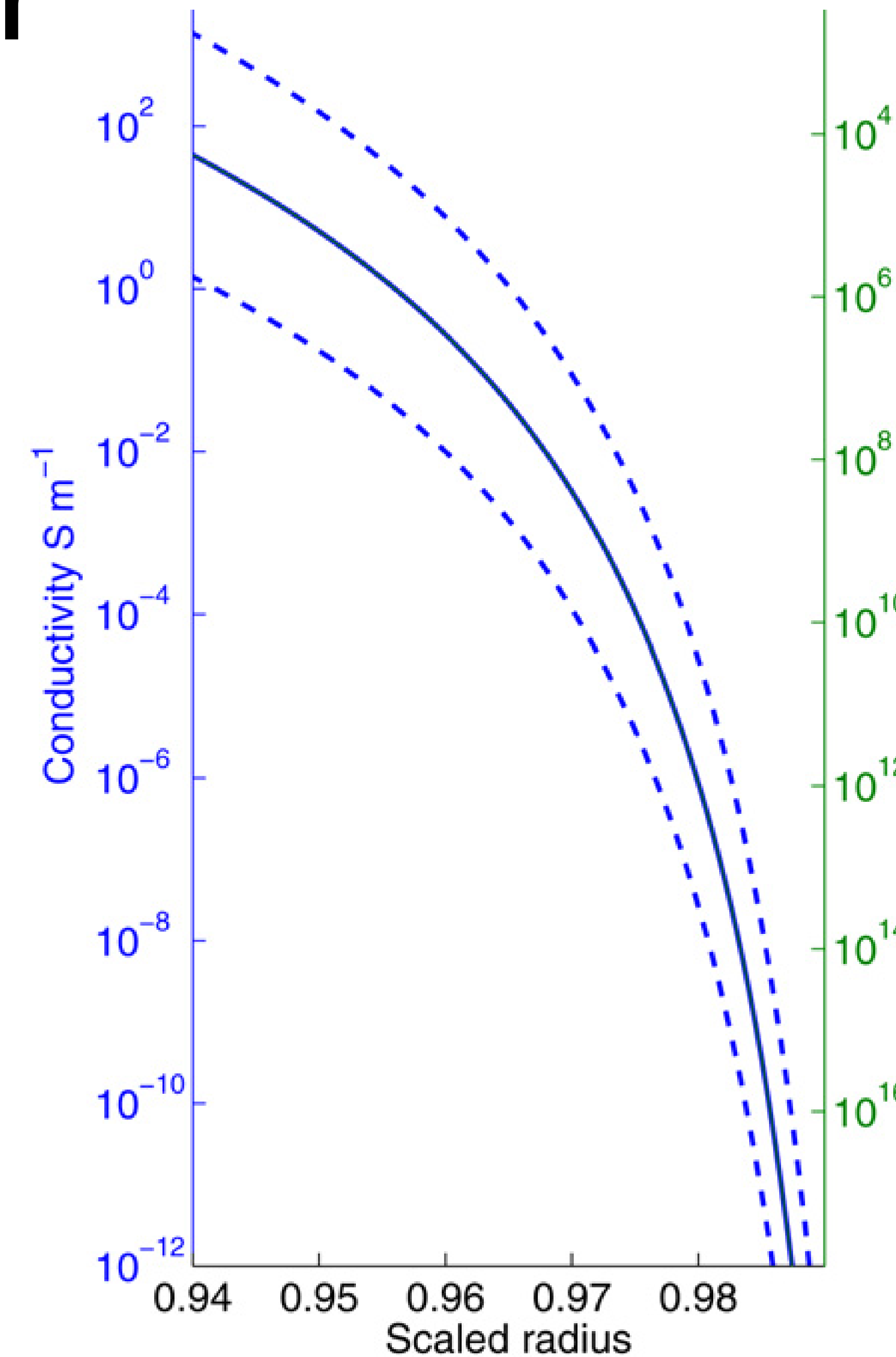
Busse-Taylor columns organize the flow and the magnetic field of a dynamo



Interior of Jupiter



Nettelmann et al., (2008):
Ab-initio equation of state



Liu et al., 1998:
Electrical conductivity in the molecular envelope

Periodic Table of Elements

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals: Alkali metals, Alkaline earth metals, Lanthanoids, Actinoids, Transition metals, Poor metals
Nonmetals: Other nonmetals, Noble gases

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.00794	Atomic # Symbol Name Atomic Mass																2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

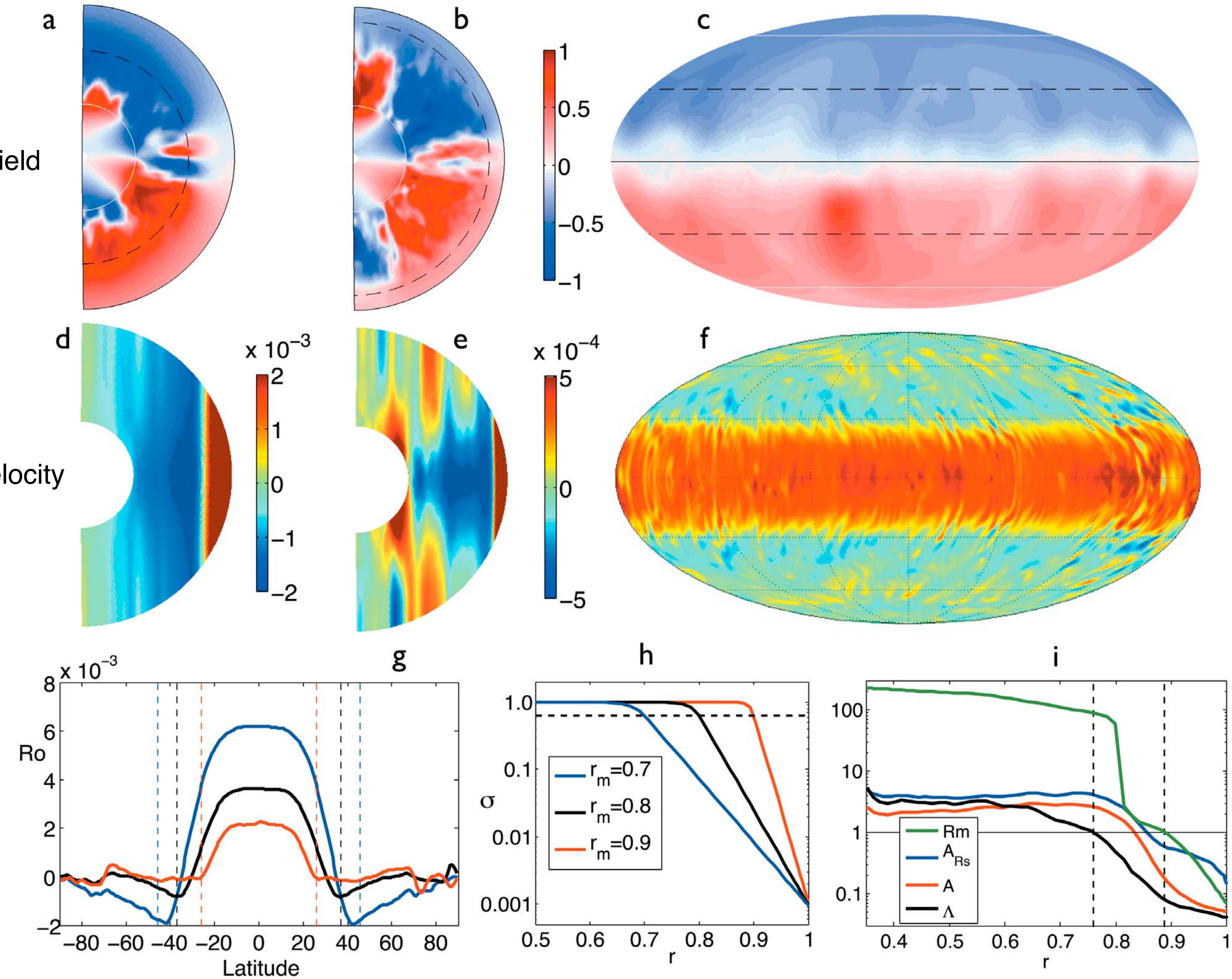
Ptable.com

Variable conductivity σ(r) dynamo:

High σ inside r_m, expon. decreasing σ outside r_m.

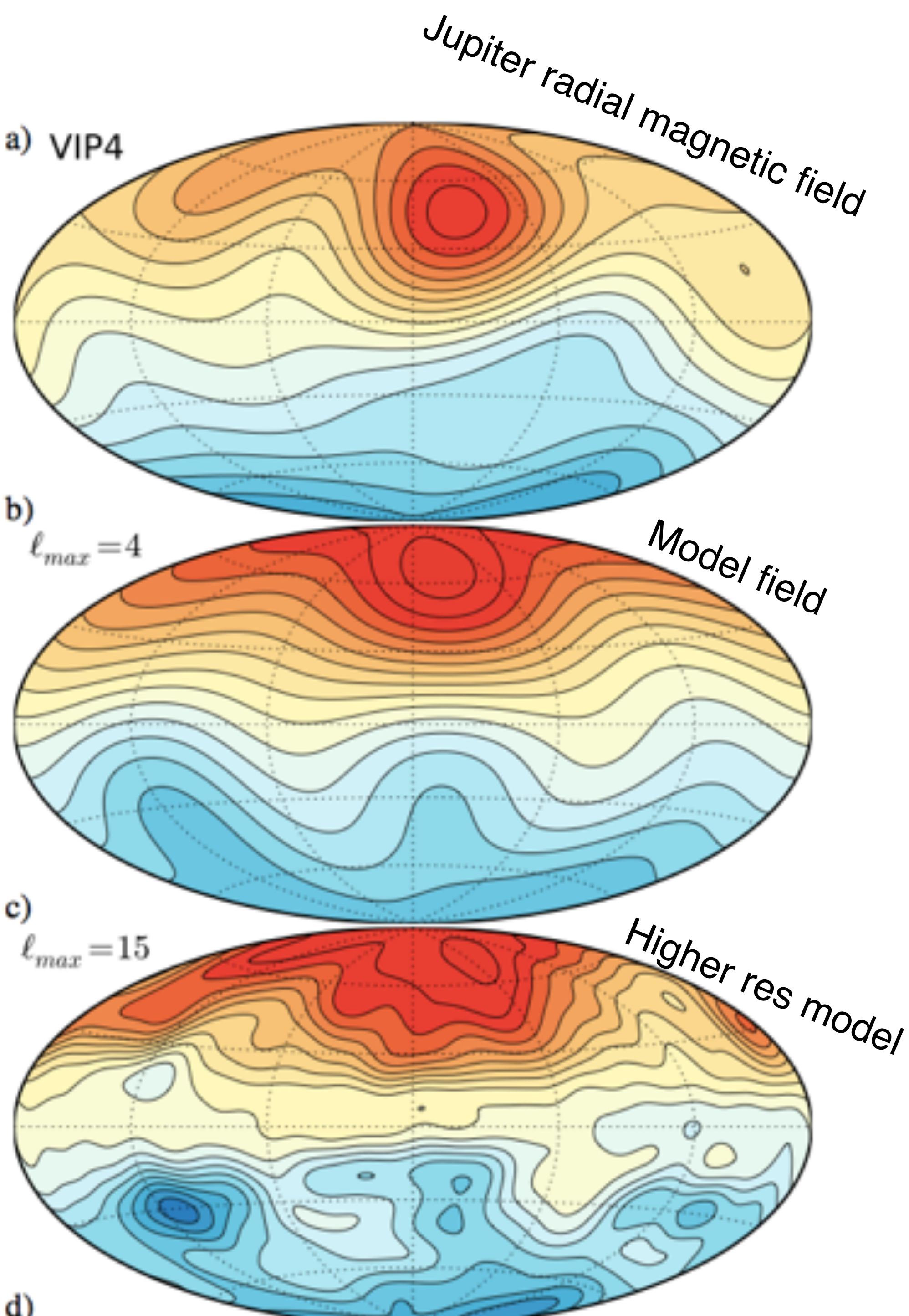
Radial magnetic field

Azimuthal (zonal) flow velocity

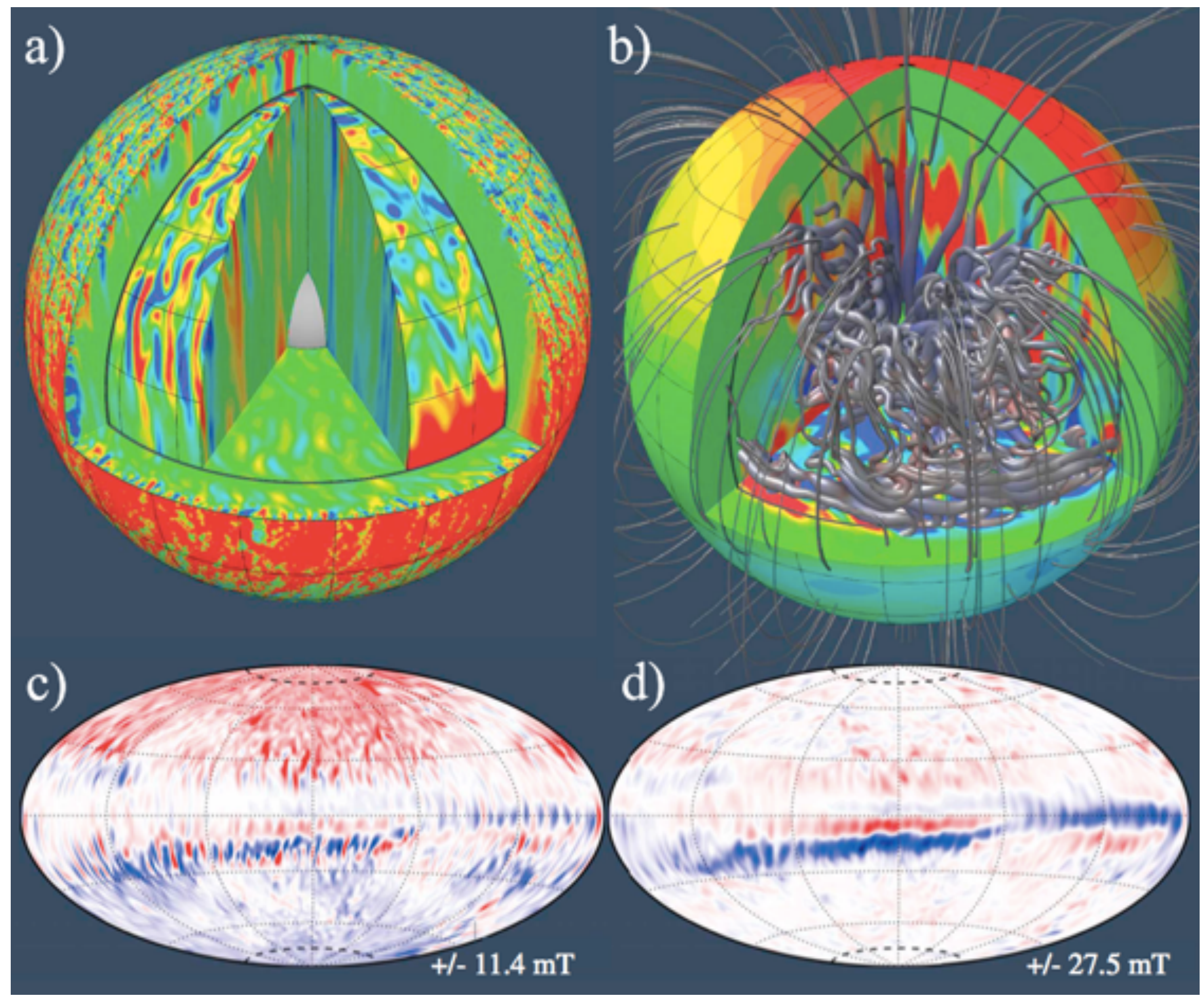


Heimpel and Gómez Pérez, 2011

Jupiter vs compressible dynamo model (anelastic dynamo code Magic, $E=10^{-5}$, $Pr=1$, $Pm=0.6$



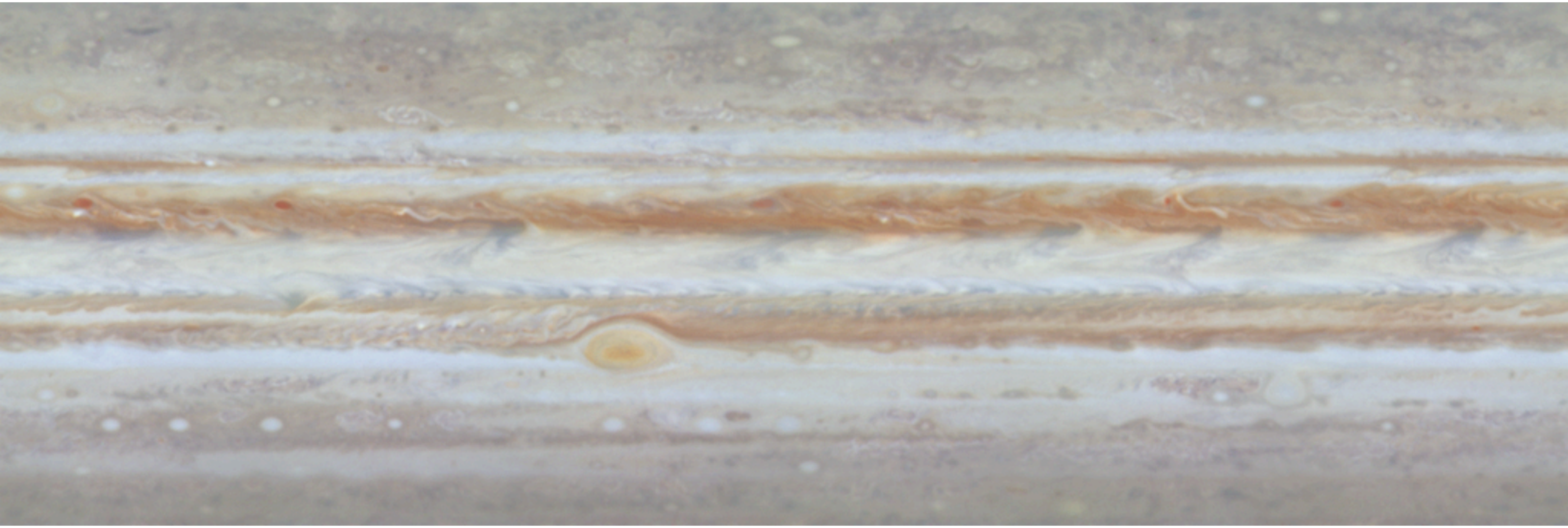
Flow field (deeper = slower) Magnetic field (deeper = stronger)



Radial magnetic field at r=0.87 Azimuthal magnetic field at r=0.87

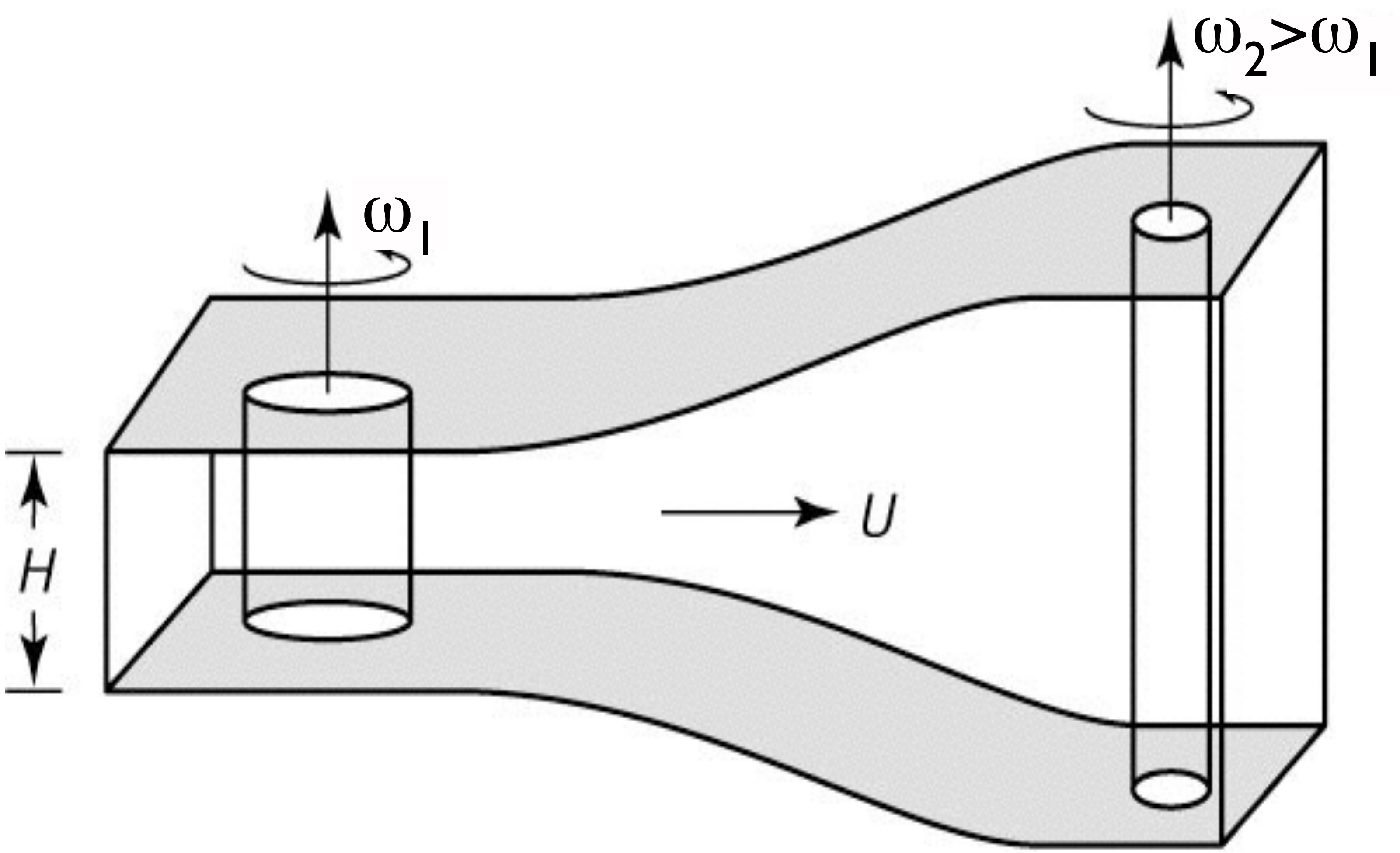
Gastine et al., 2014

Part IIa Zonal flows



NASA Movie PIA02863
(Cassini flyby of Jupiter: Oct 31-Nov 9, 2000)

Conservation of potential vorticity
Topographic effect



R.L. Stewart, 2004

For inviscid flow:

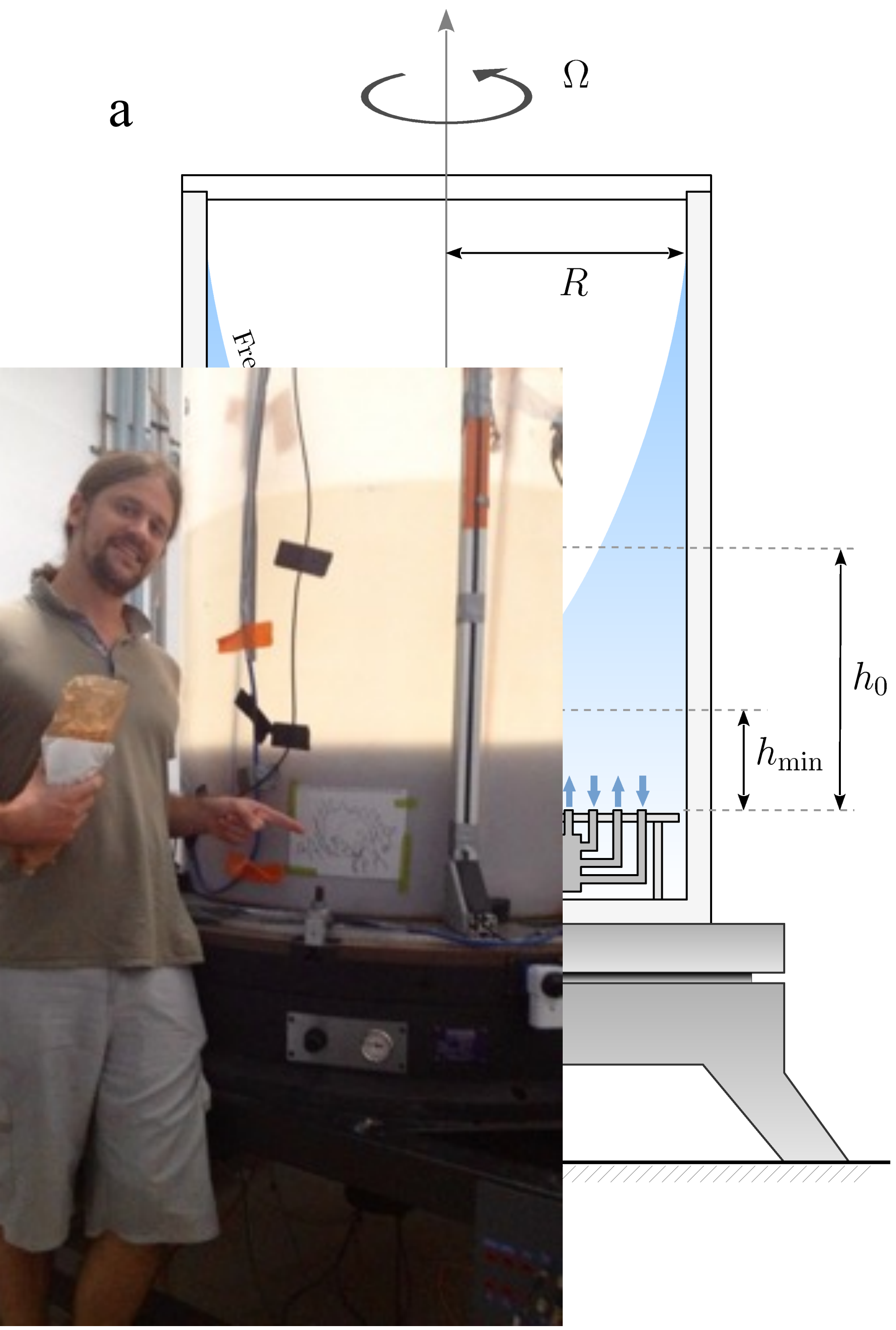
$\Pi = (\omega_z + f)/H.$

The motion of fluid columns conserves Π

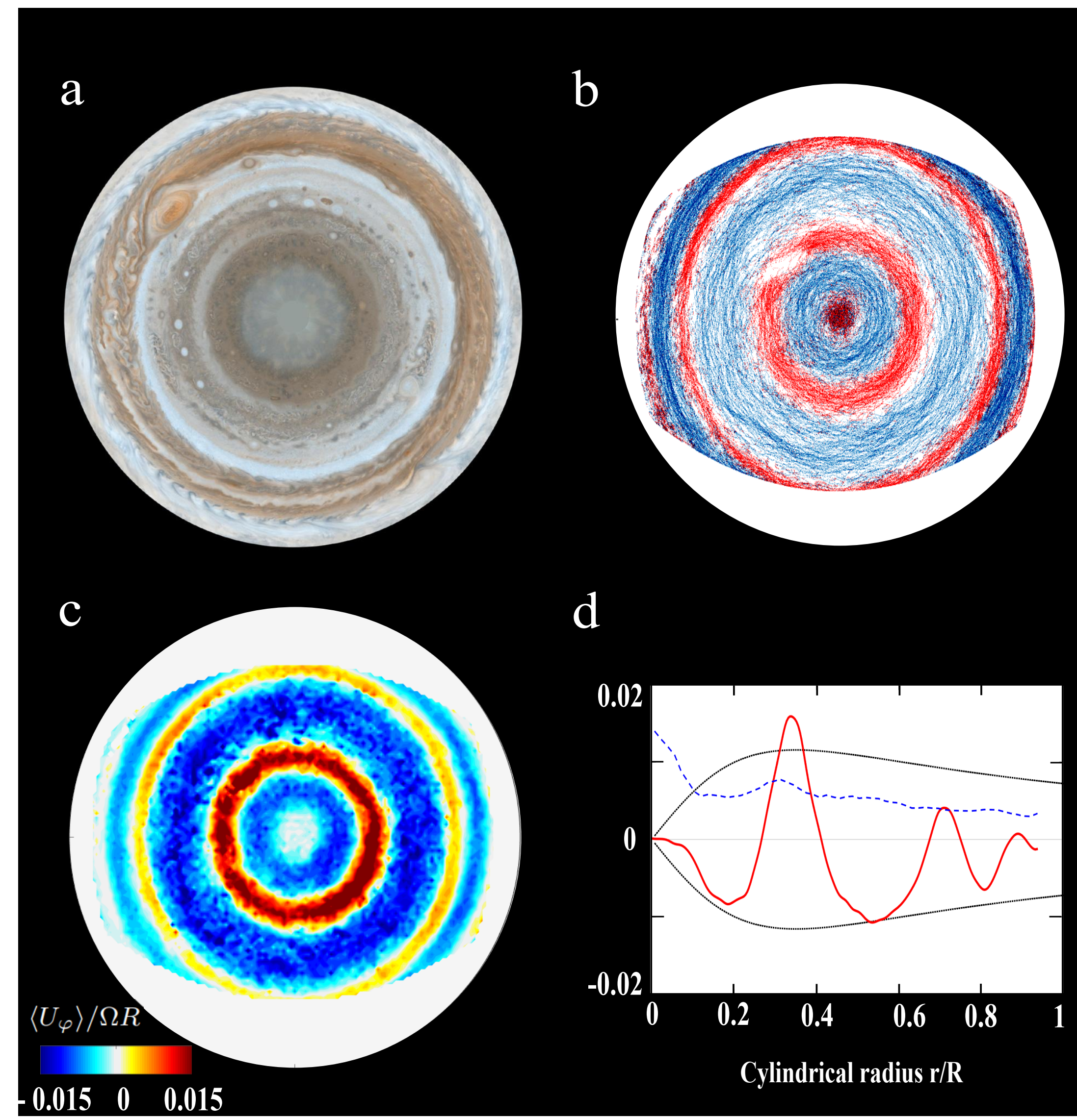
Leads to a *topographic* parameter

$\beta = -\, 2\Omega(dH/dx)/H$

Laboratory zonal jets
(Cabanes et al., 2016, in review)

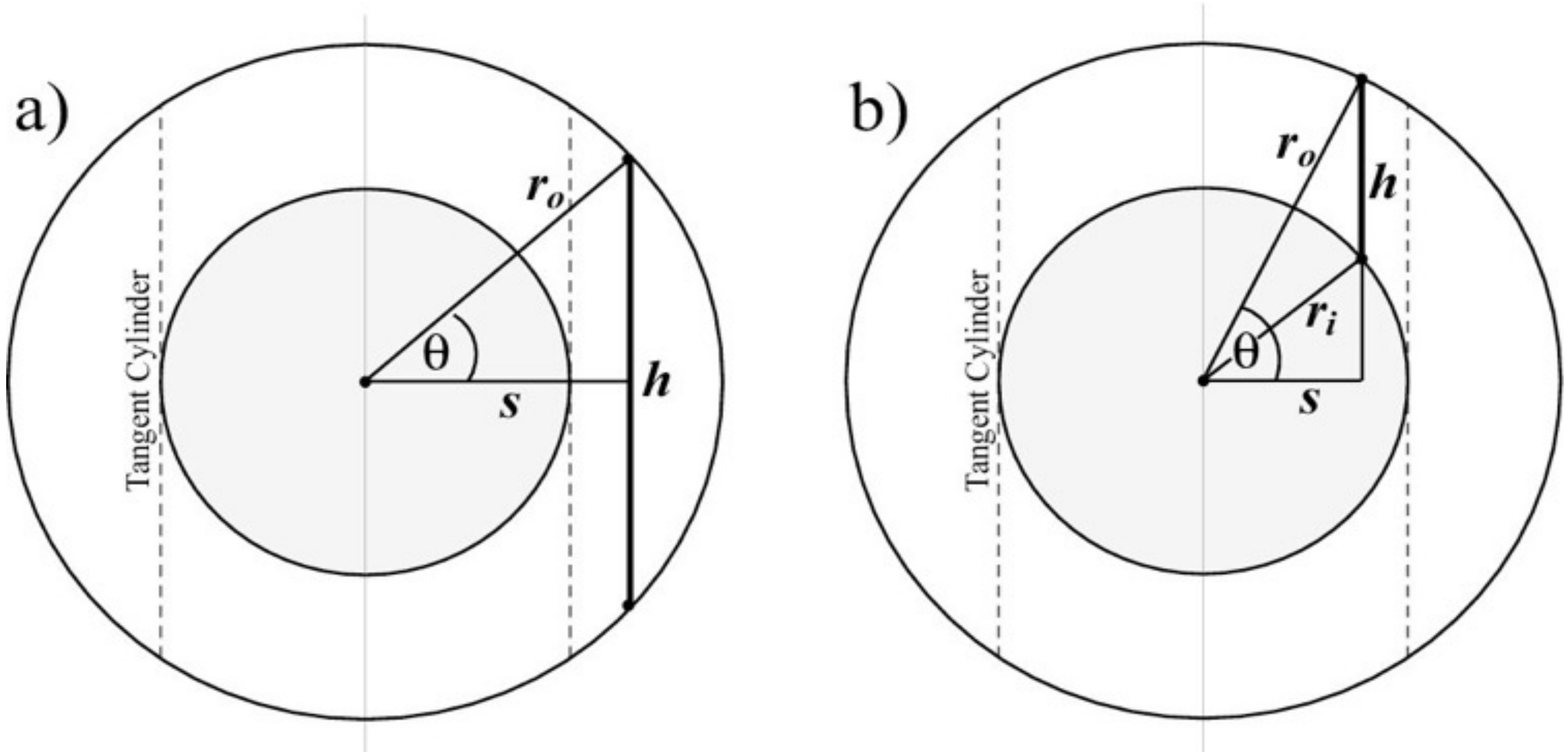


Jupiter vs. Lab



Spherical Shell Rhines Scale

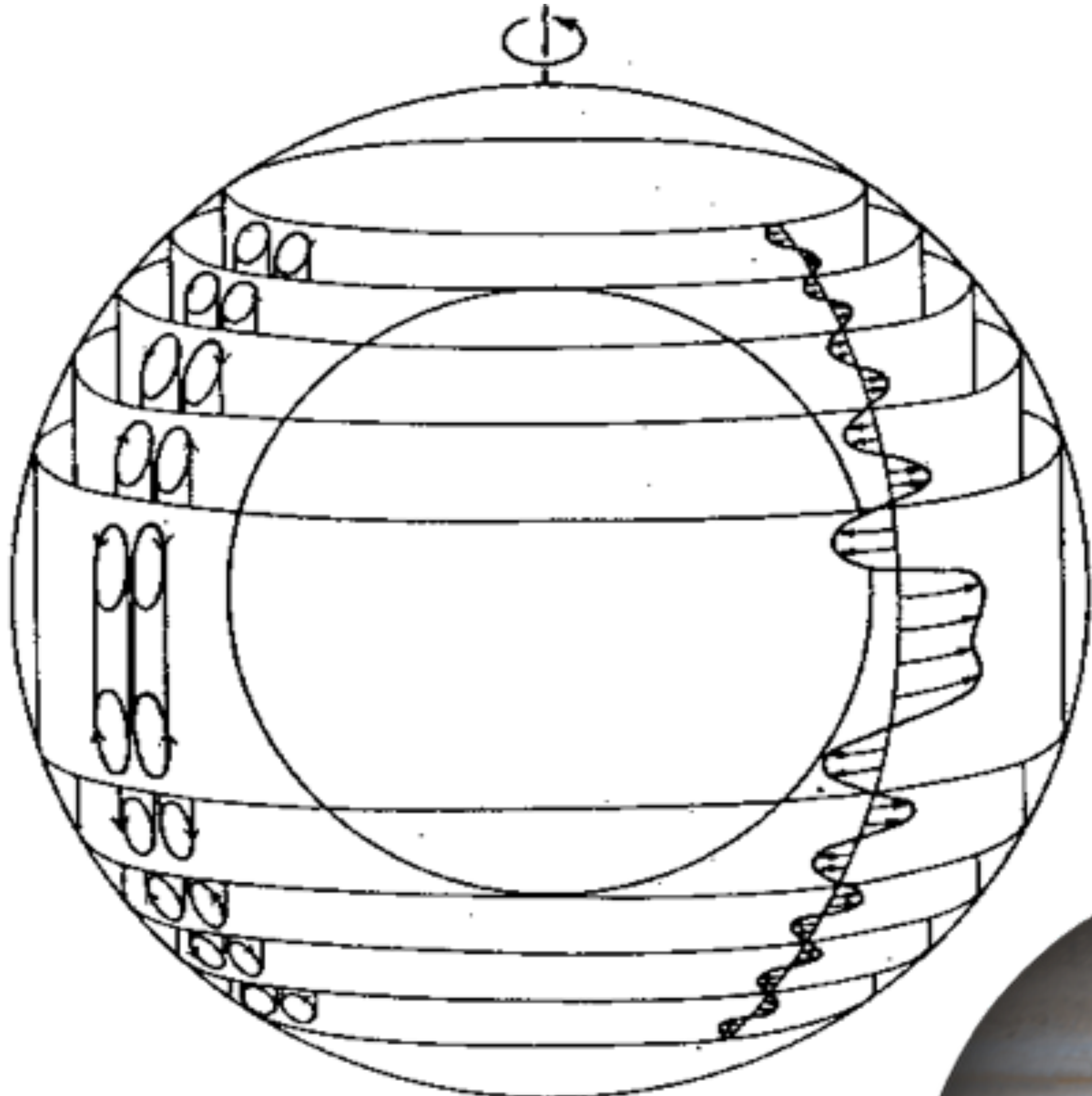
Outside TC | Inside TC



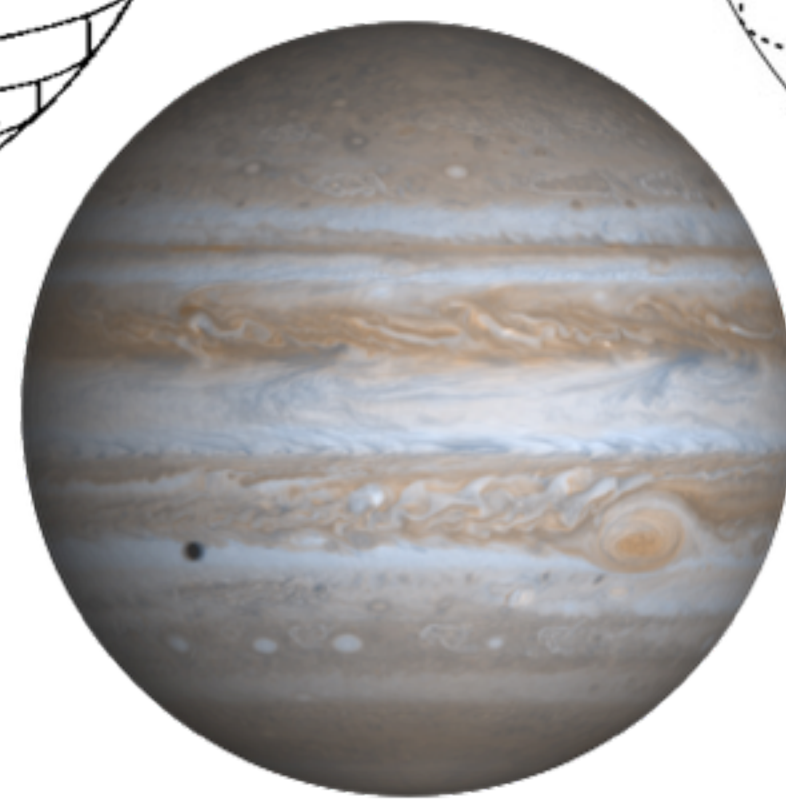
$$\lambda_g = 2\pi\sqrt{\frac{U}{r_o\Omega\cos\theta}} \quad \lambda_g = 2\pi\sqrt{\frac{U}{r_o\Omega}\left|\frac{(\chi^2-\cos^2\theta)^{1/2}}{\sin\theta\cos\theta}\right|}$$

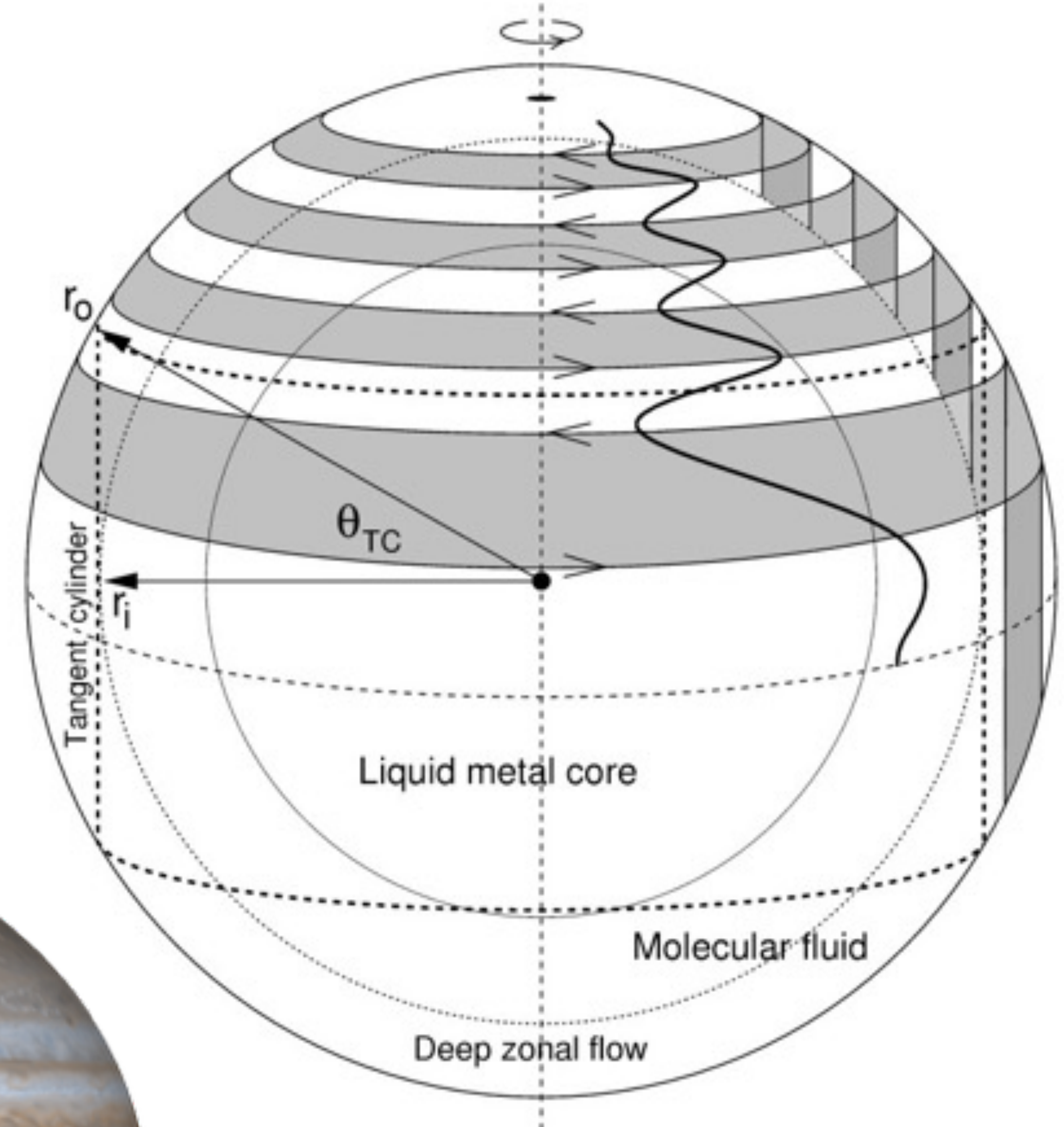
(Notes: 1. Scaling discontinuity across TC; 2. λ depends on U)

Zonal flow in spherical shells: Reynolds stress spins columnar convection (Busse columns) into zonal flows.



Busse, 1976



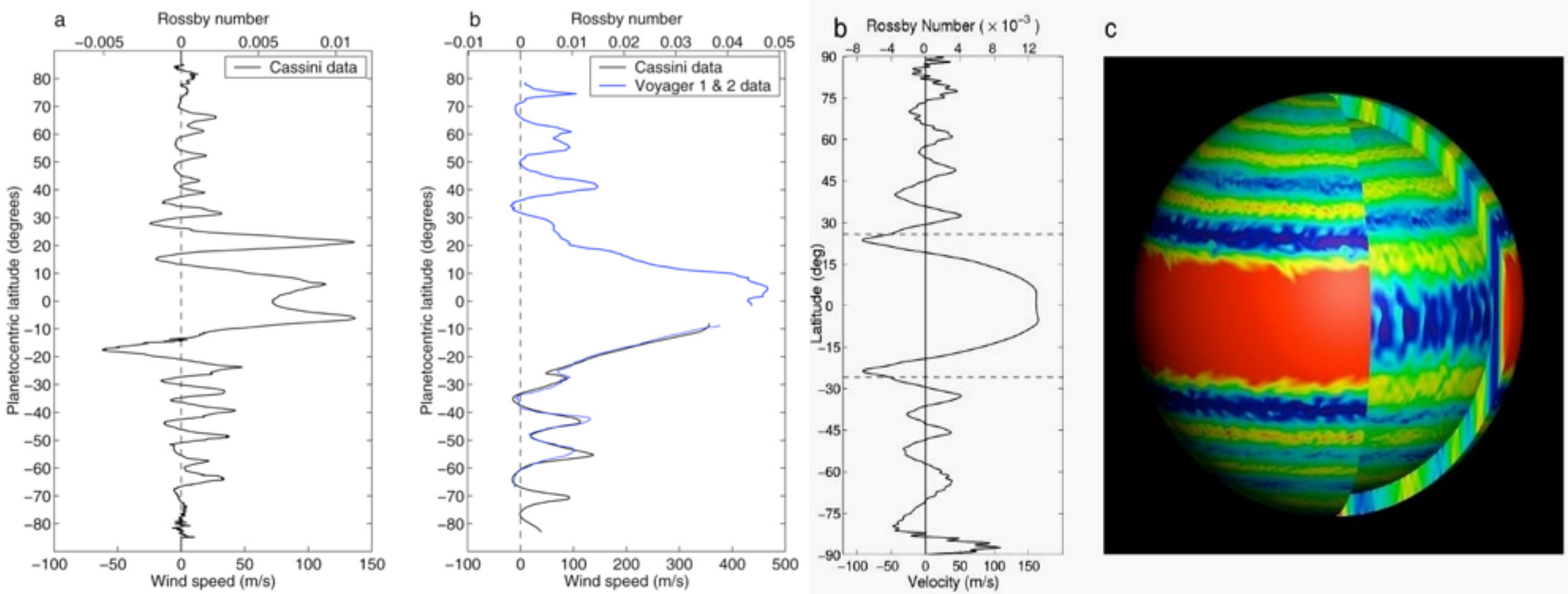


Heimpel, Aurnou & Wicht., 2005

Jupiter & Saturn winds, and numerical model

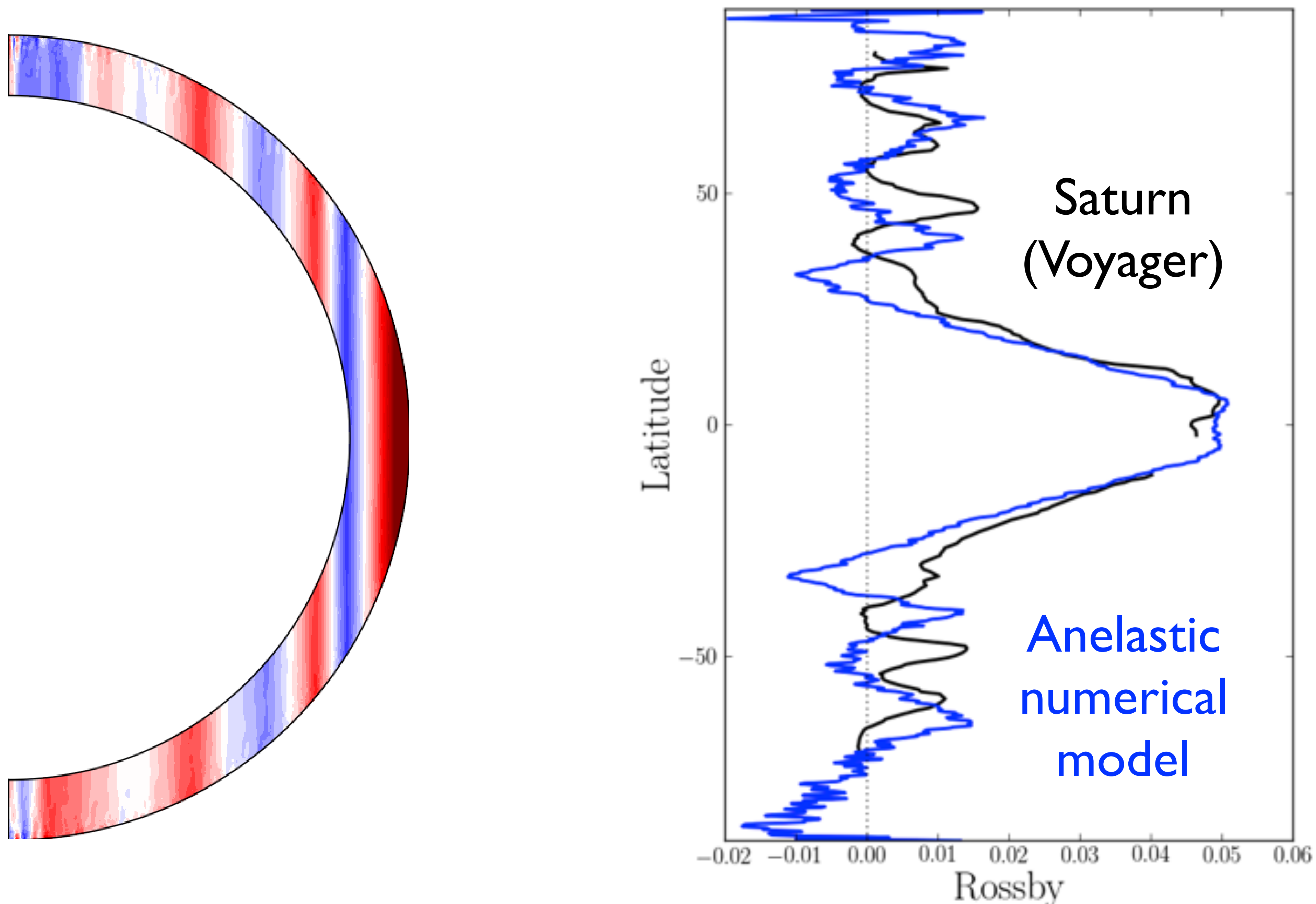
Model: E=3x10^{-6}, Ra=5.6 x 10^{8}, Pr=0.1, r_i/r_o=0.9, 8-fold symmetry
Boussinesq approximation.
Constant top-bottom temperature difference drives convection.
Free-slip top and bottom boundary conditions

Jupiter | Saturn | Numerical model



Heimpel, Aurnou & Wicht, 2005

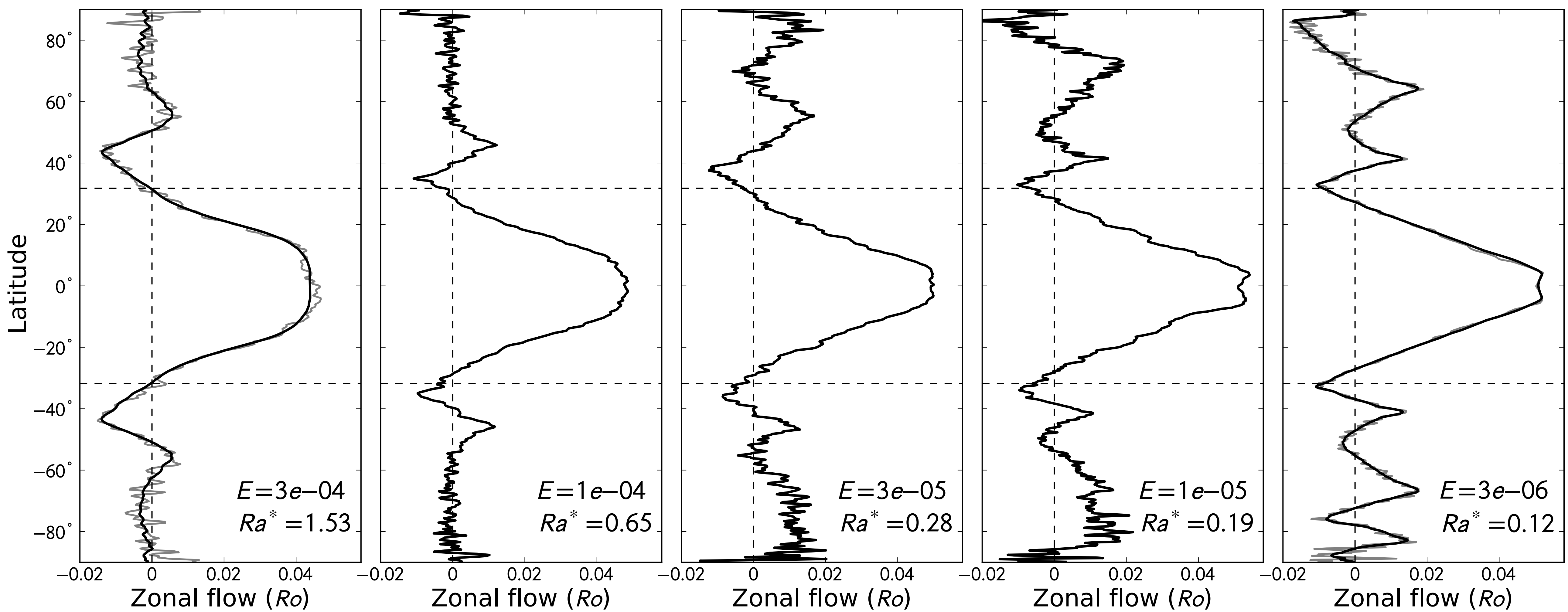
Anelastic model (Magic) with $E=3 \times 10^{-6}$, $Ra=1.5 \times 10^{9}$, $N_\rho=5$, $Pr=0.1$, and $r_i/r_o=0.85$. Comparison of zonal flow to cloud layer zonal wind of Saturn.



Gustine et al., 2014

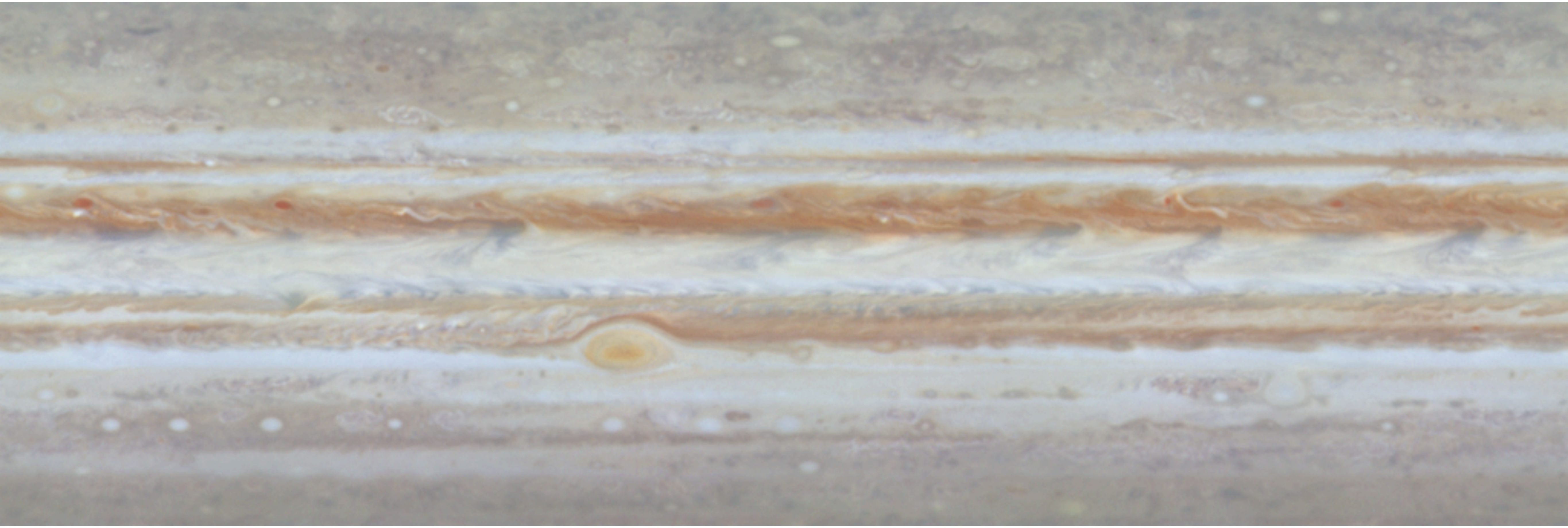
Why do we need high resolution models?

Well-defined multiple jets inside the tangent cylinder ($N_\rho = 5$, $r_i/r_o = 0.85$)



high viscosity or weak rotation → lower viscosity or strong rotation

Part IIb: Jets, Vortices and Storms

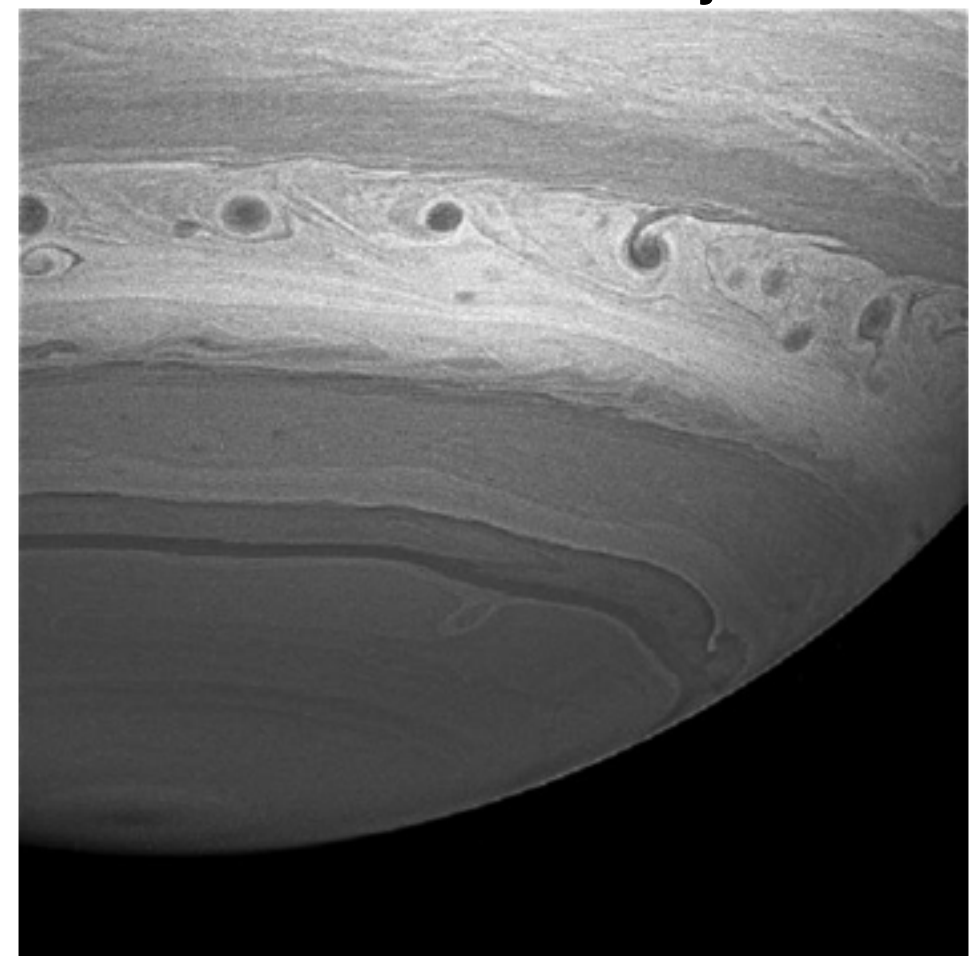


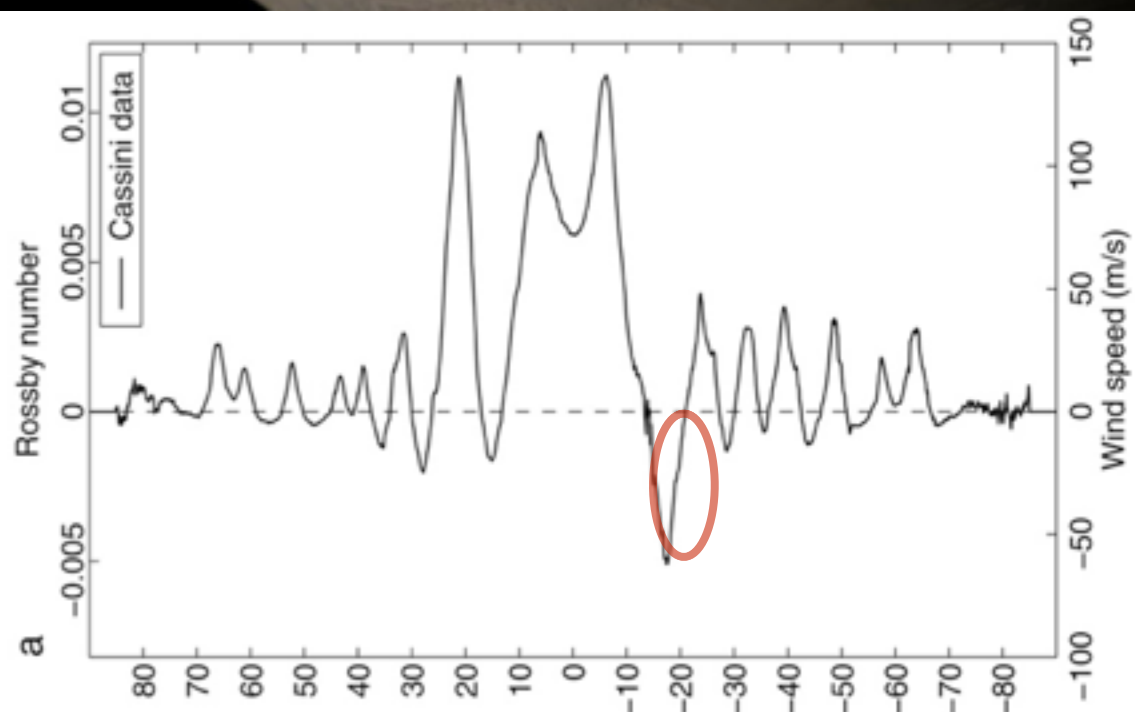
NASA Movie PIA02863

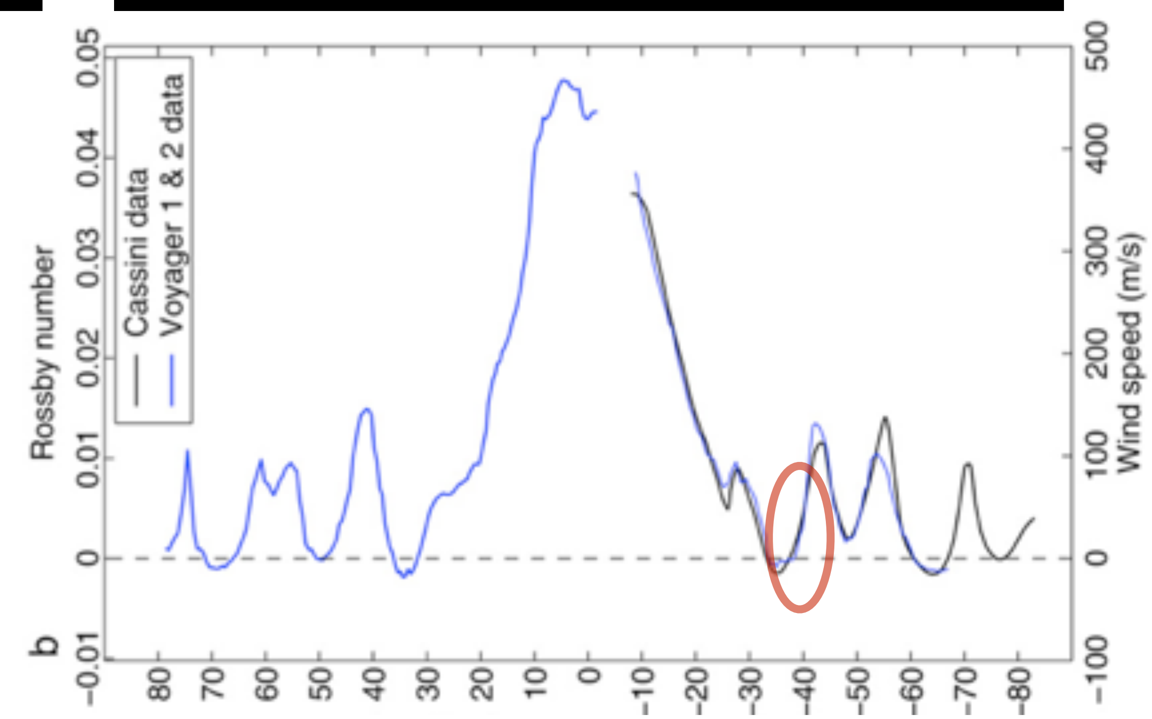
Vortices on Jupiter and Saturn

Jupiter Great Red Spot and White Ovals

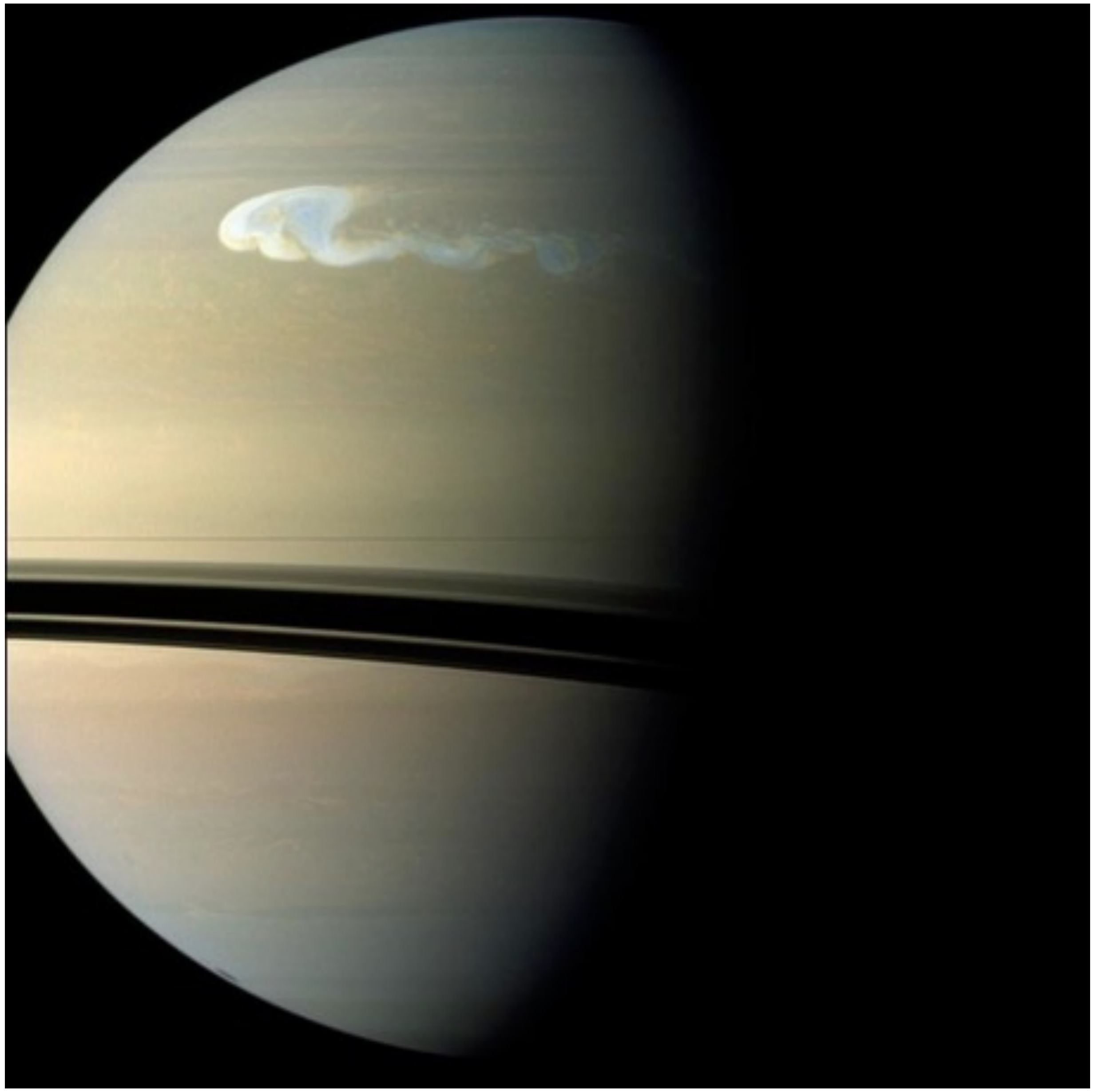
Saturn “Storm Alley”



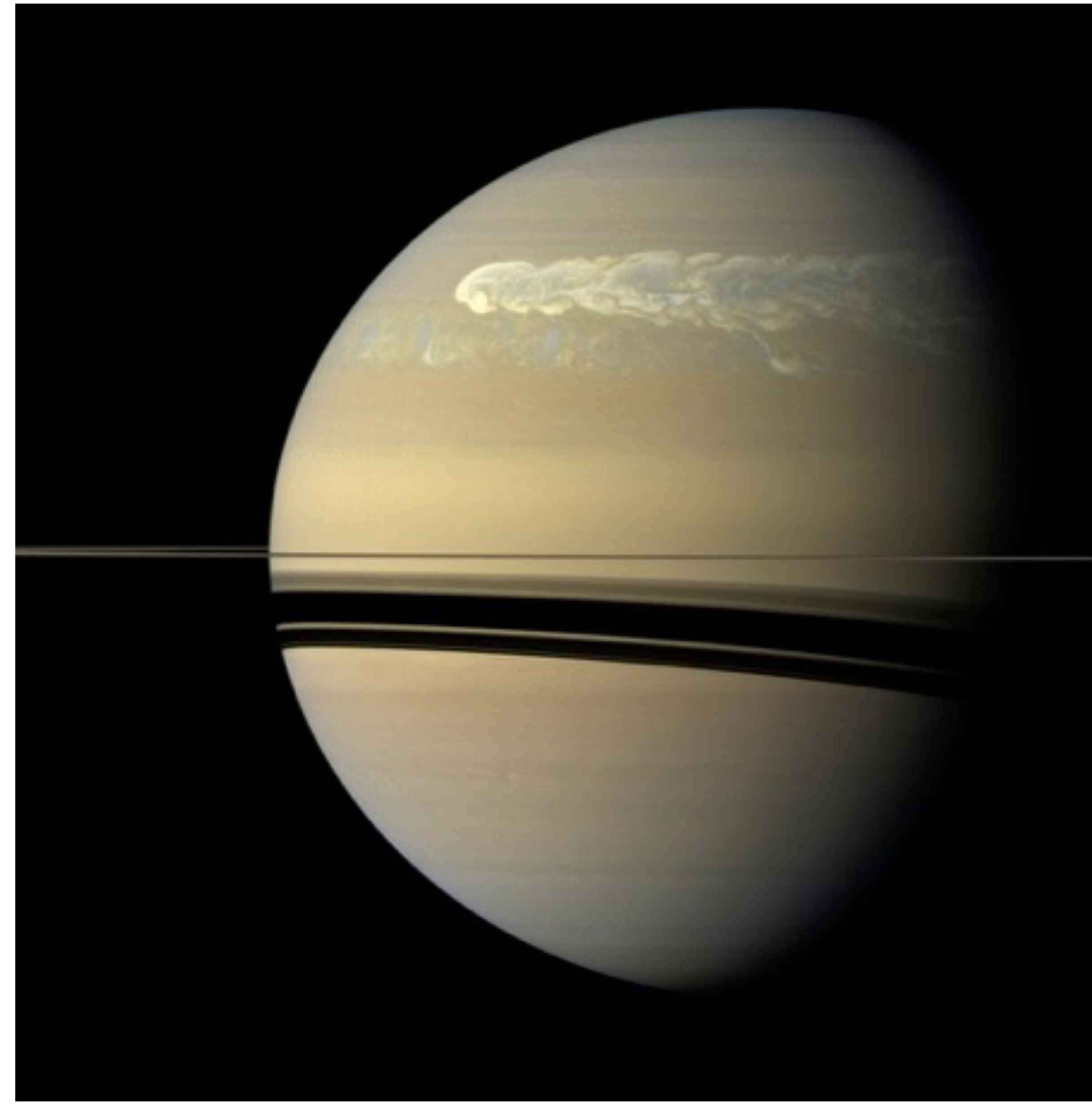




Saturn's great storm of 2010/2011



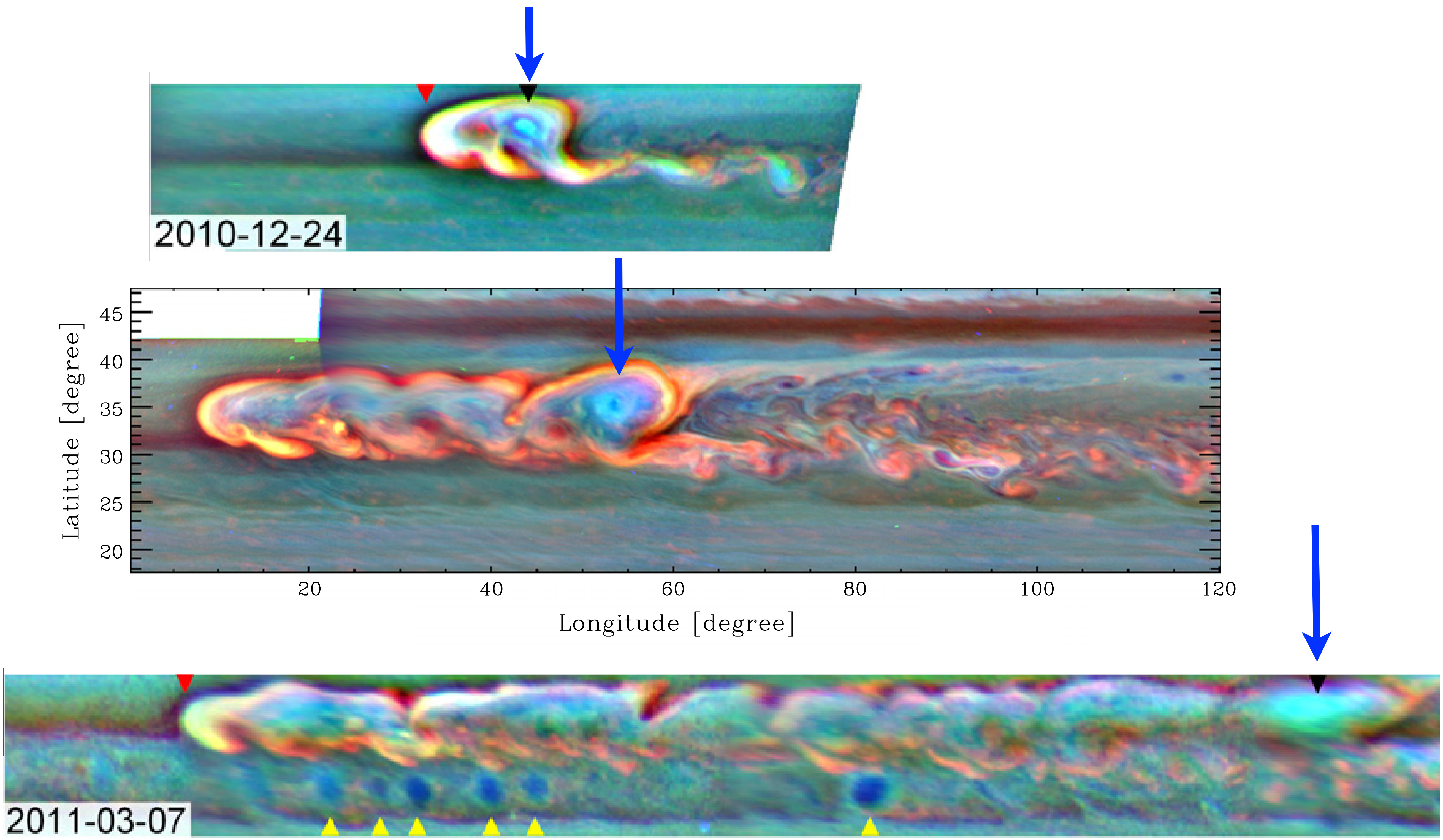
Dec 5, 2010



Feb 25, 2011

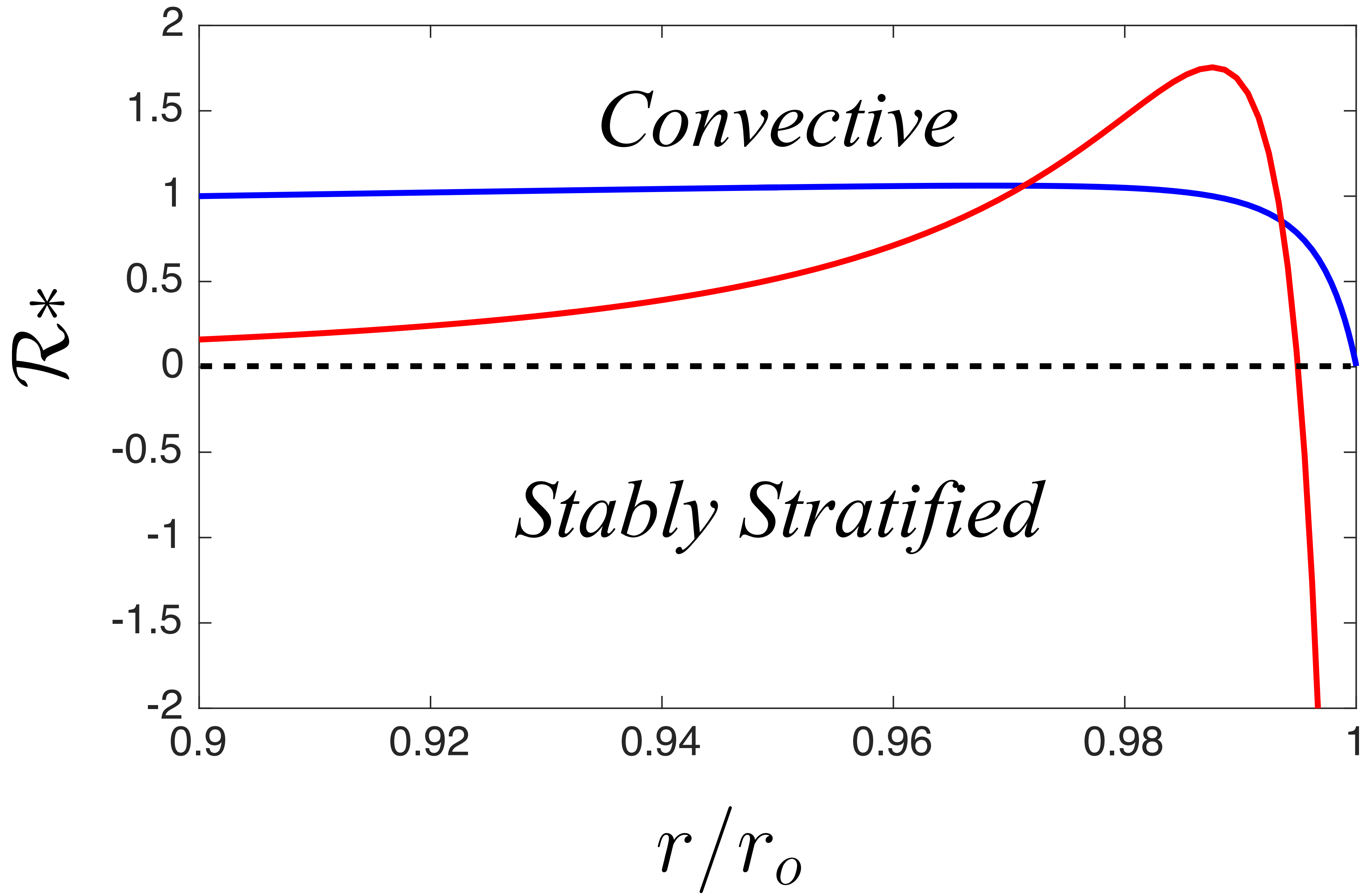
NASA Cassini images PIA12824 and PIA12826

Anticyclonic vortex initiated Saturn GWS



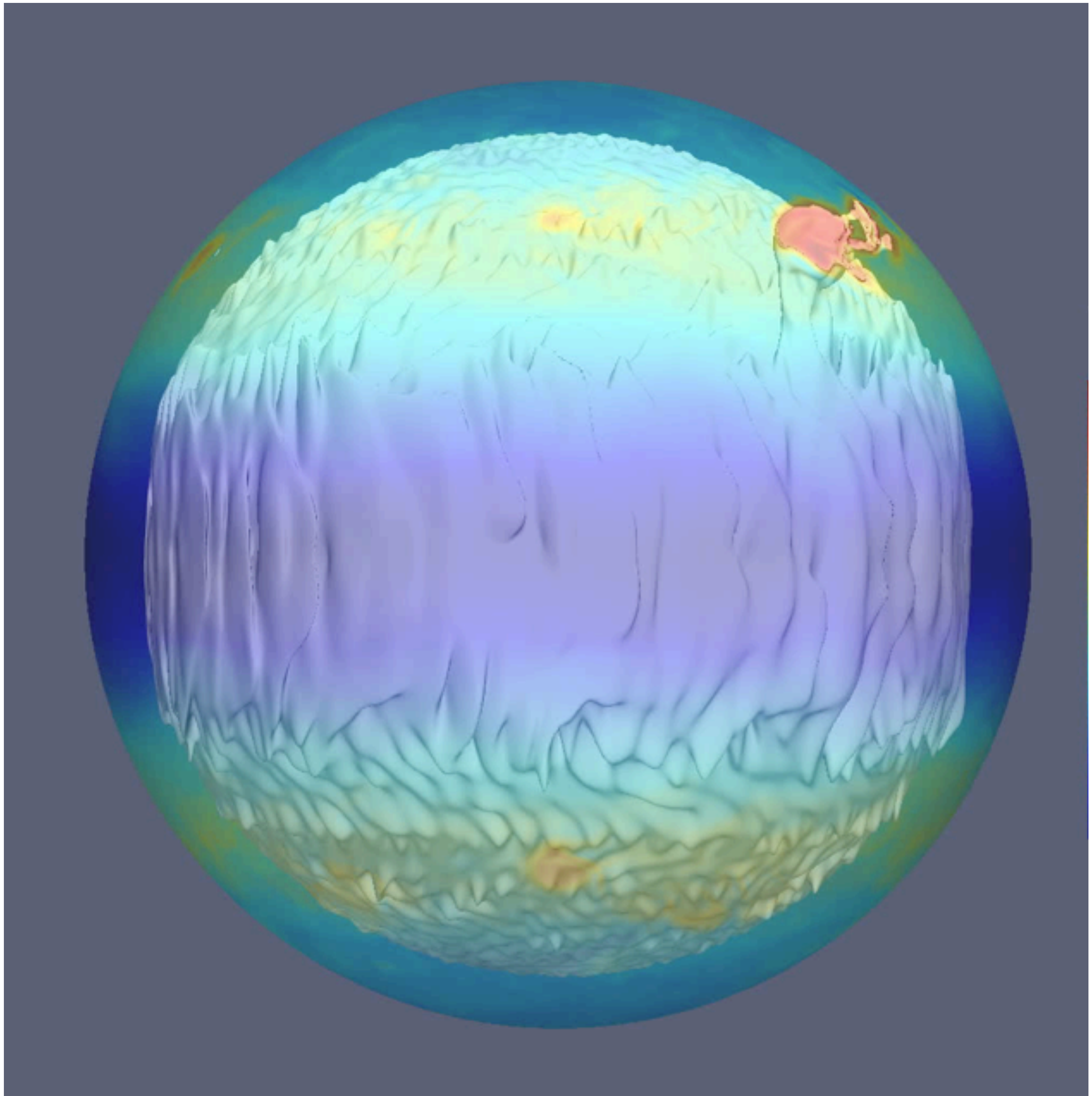
Sayanagi et al., Icarus, 2013

Compressible fluid (ideal gas, anelastic approximation). Constant entropy flux BC with stably stratified or neutral buoyancy outer boundary condition



- $R^* = \mathrm{RaE}^2/\mathrm{Pr}$
- Dimensionless $N_{BV}^2 = R^*\Omega^2$
- Rossby radius $= H_\rho (R^*)^{1/2}$

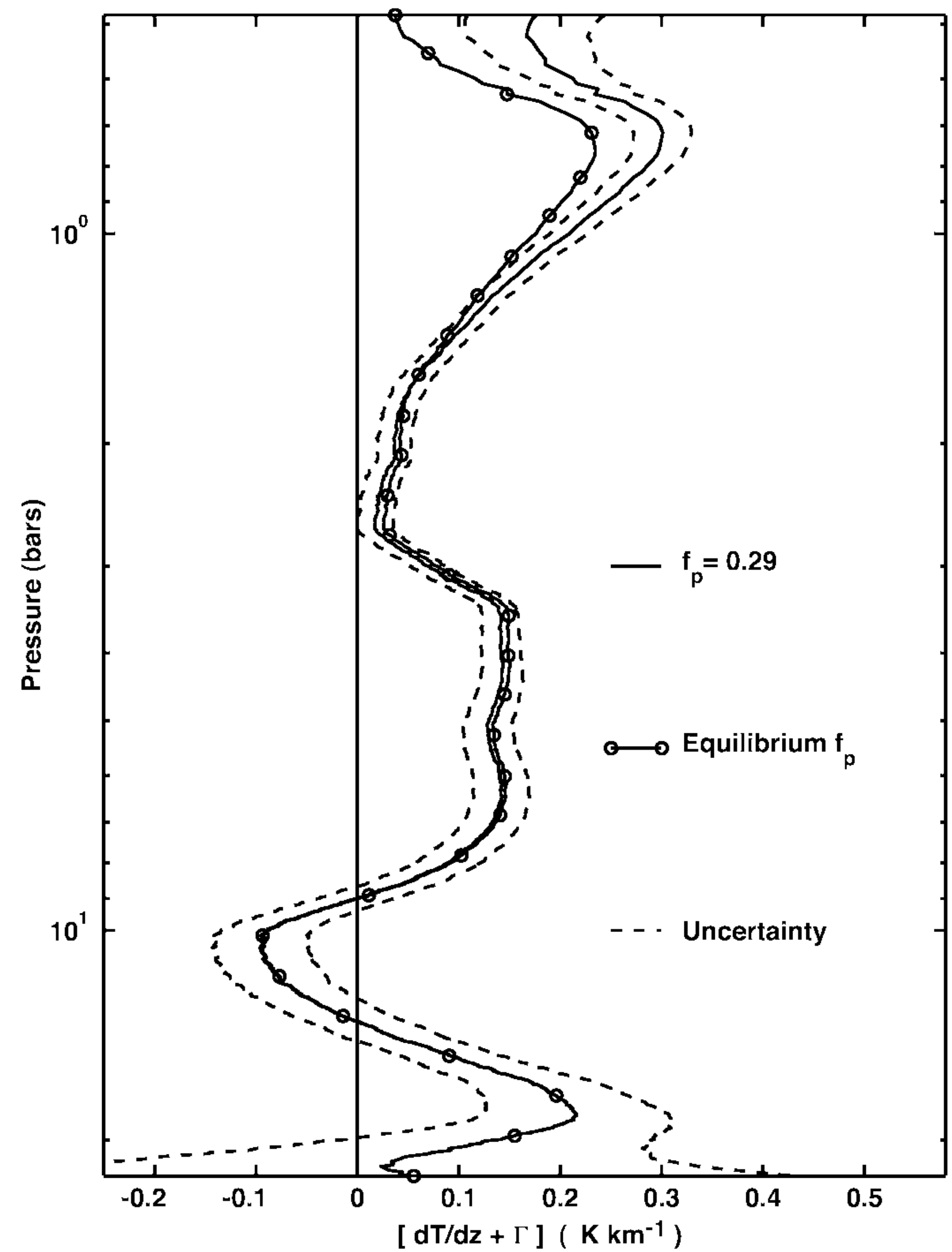
Vortices fed by rising plumes. Neutral stability outer boundary (visualization: Keith Cuff)



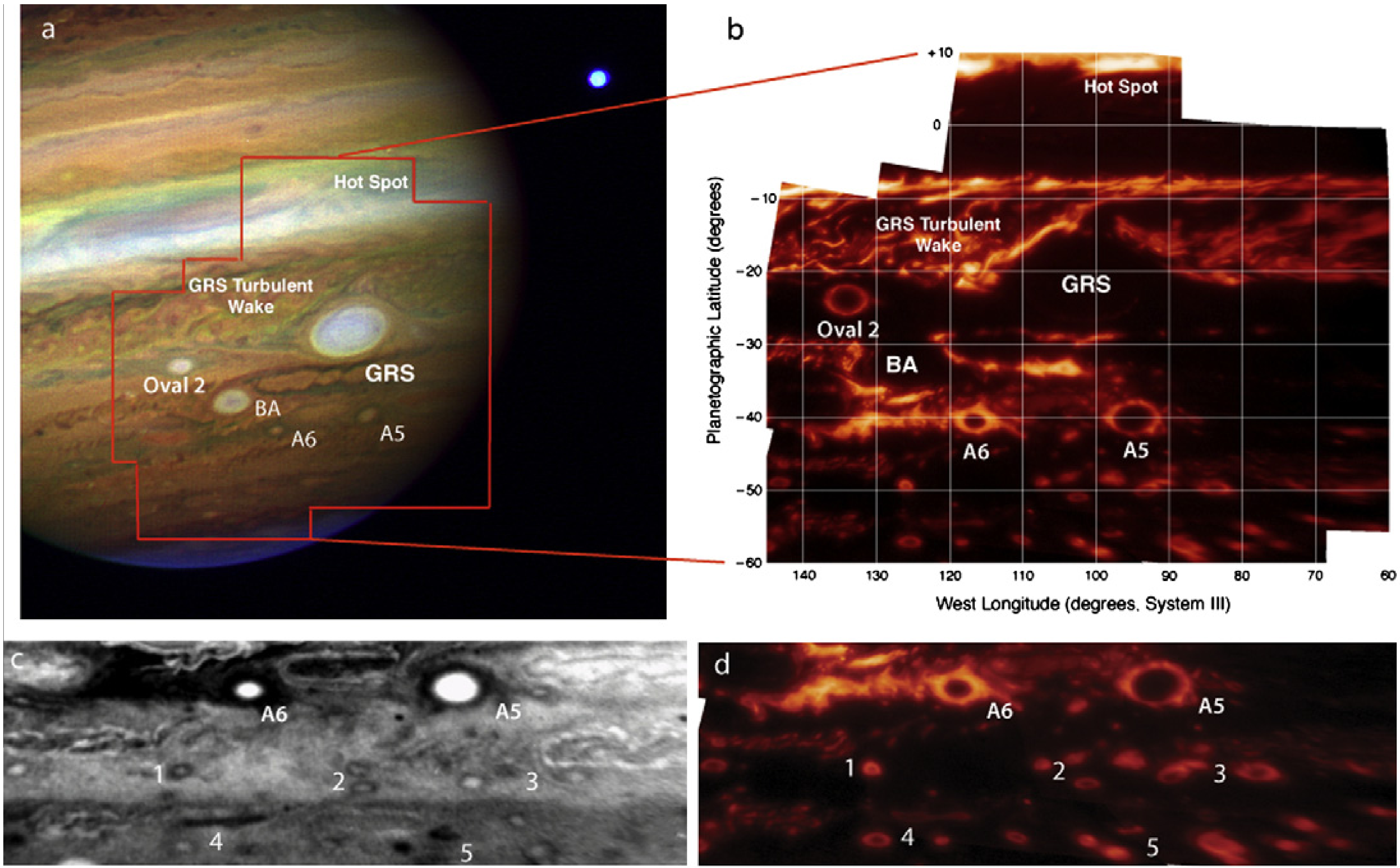
Depth and strength of static stability in Jupiter's deep atmosphere

- Magalhaes et al., 2002: Static stability layer reaches to maximum depth of Galileo probe (~ 22 bar, ~150km).

"Regions with static stability 0.1–0.2 K/km are found at 0.5–1.7 bars, 3–8.5 bars, and 14–20 bars. Between these layers, regions of weaker static stability are present."

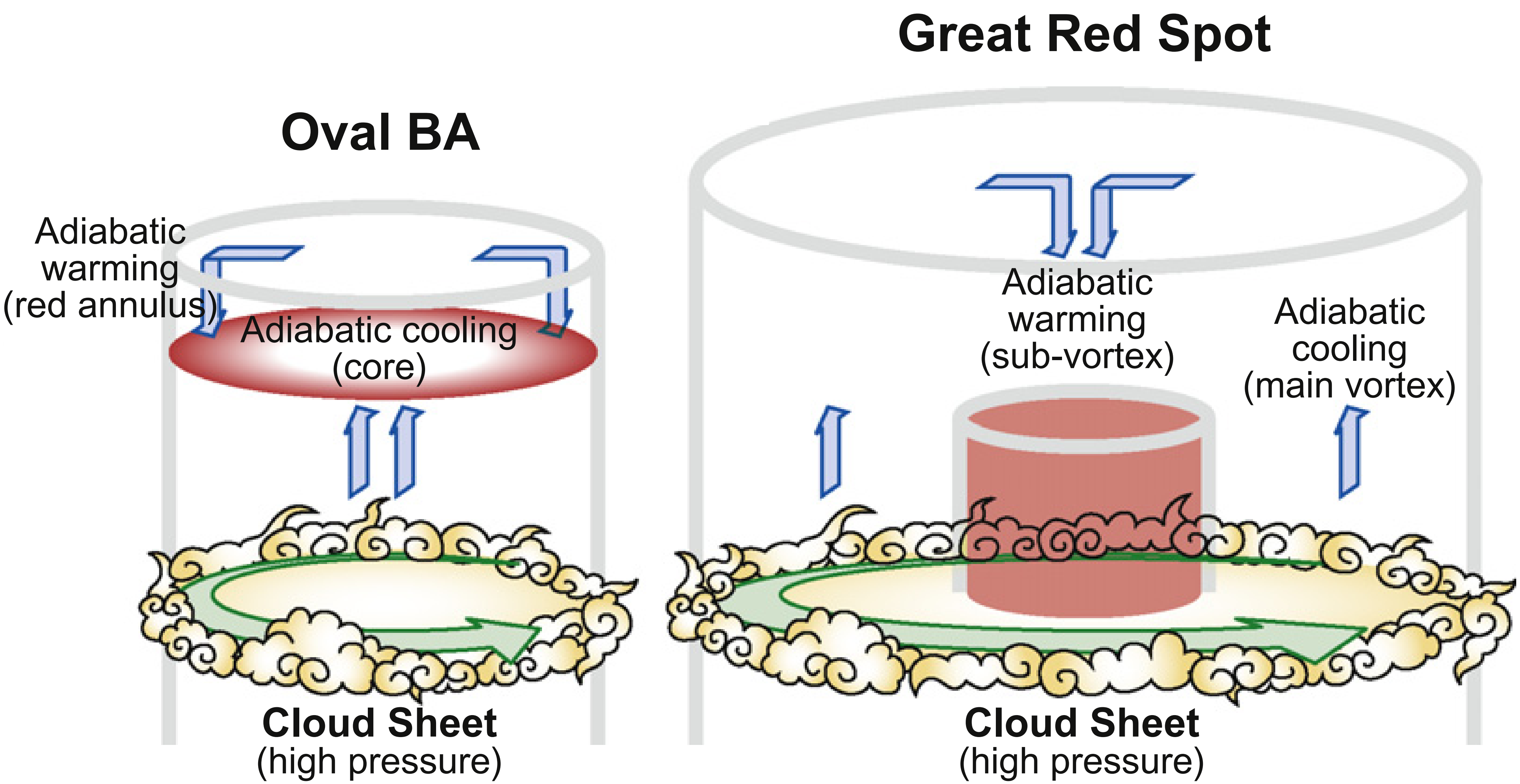


Jupiter anticyclones, visible and 5 micron IR.



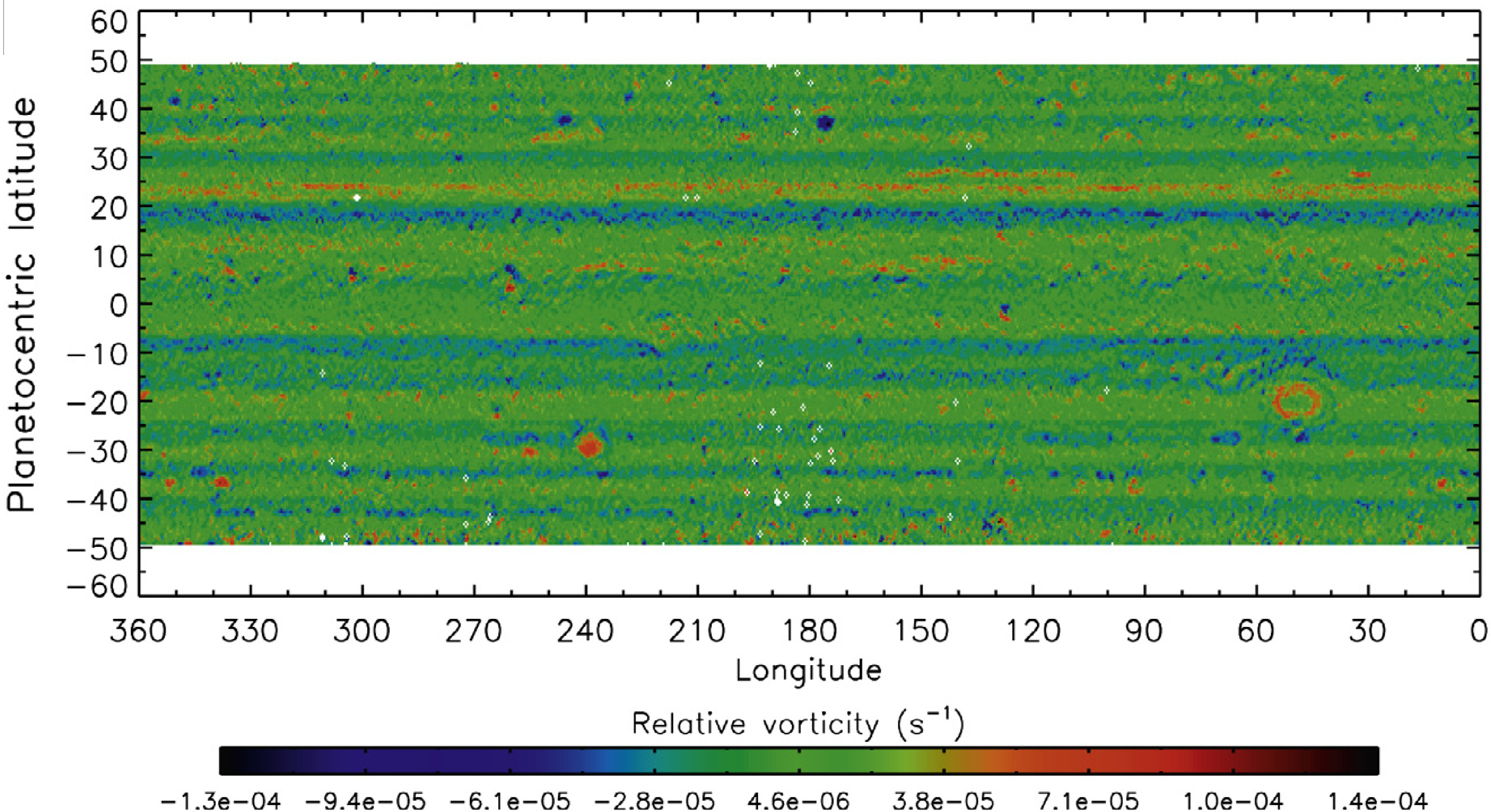
de Pater et al., 2010

Interpretation of Jupiter vortices observations



de Pater et al., 2010

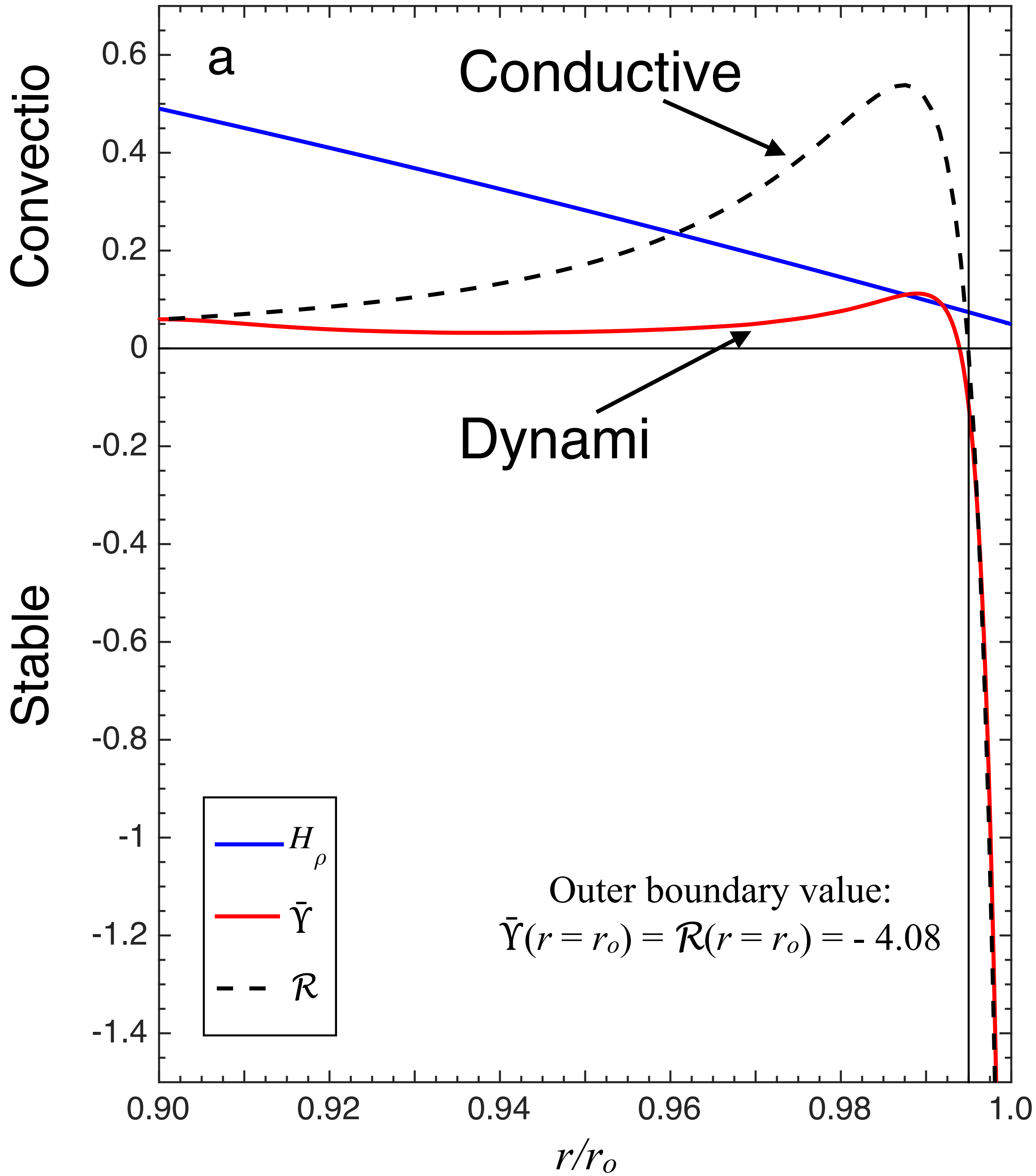
Jupiter radial vorticity at cloud level
note: Jovian Day = 9:55:30, Ω = 1.8e-4

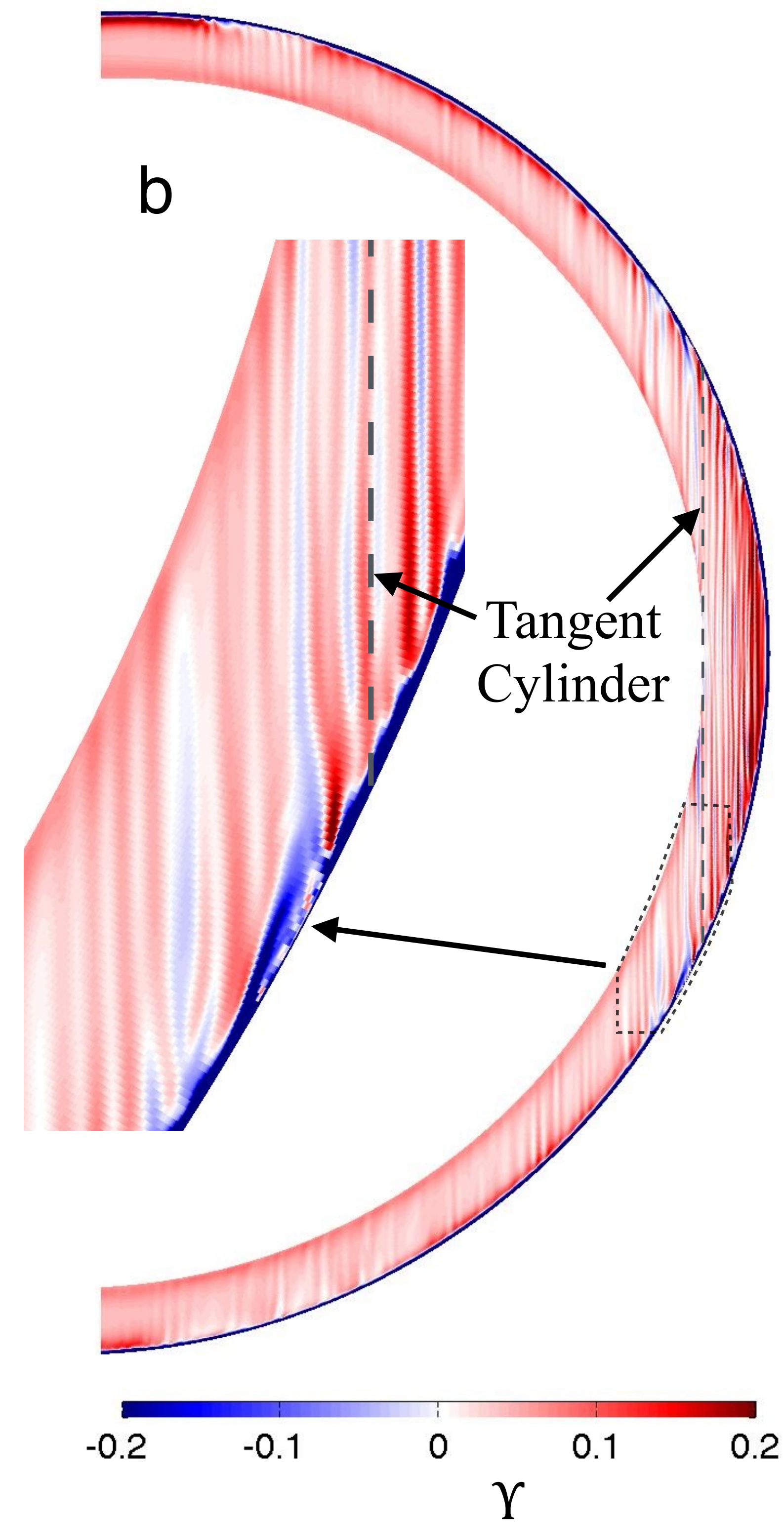


(b) Relative vorticity $\nabla \times \mathbf{u}$

Galperin et al., 2014

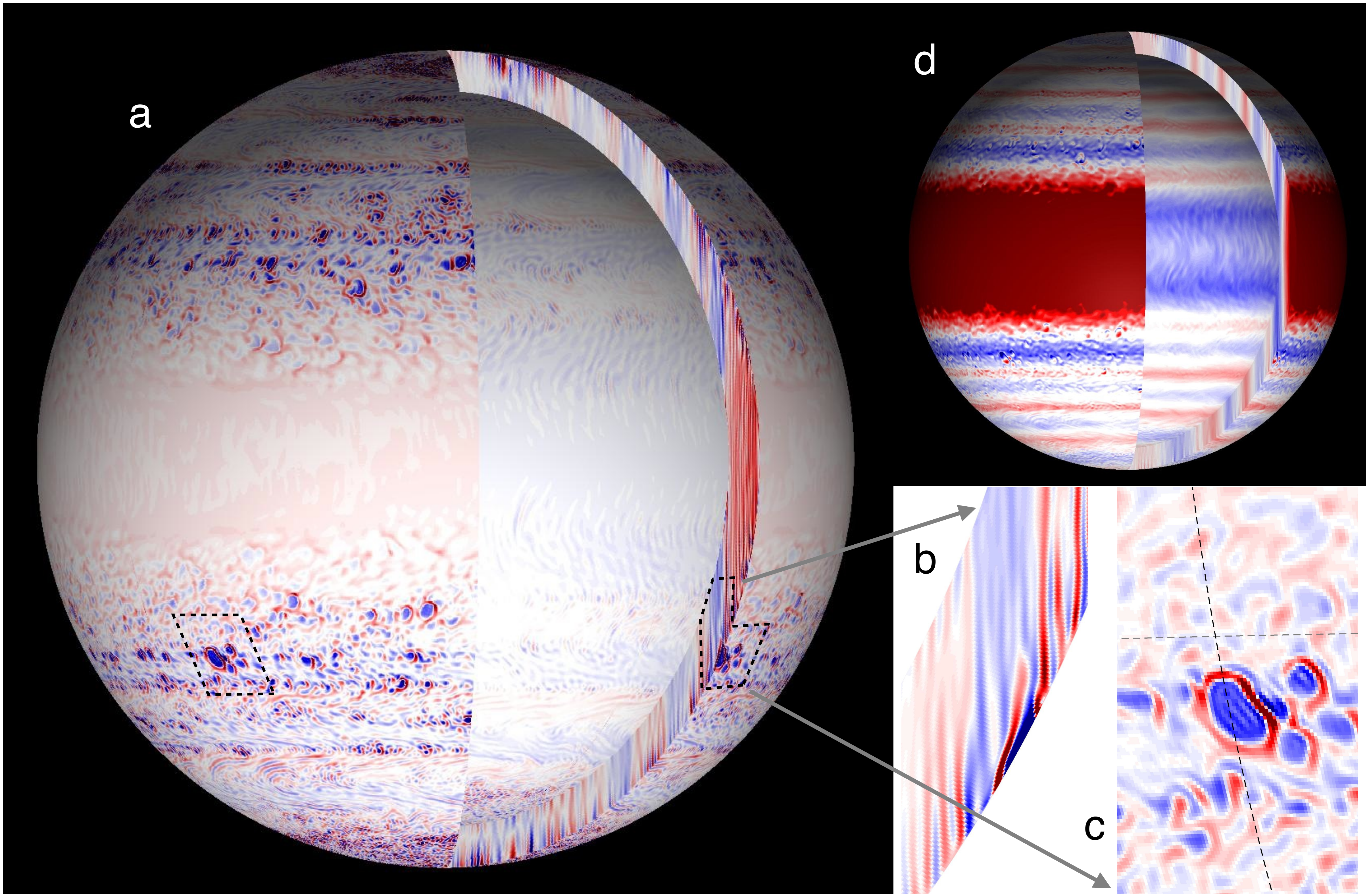
Local stability parameter $\mathcal{R}$(r) and stability field Υ(r, θ,φ,t)



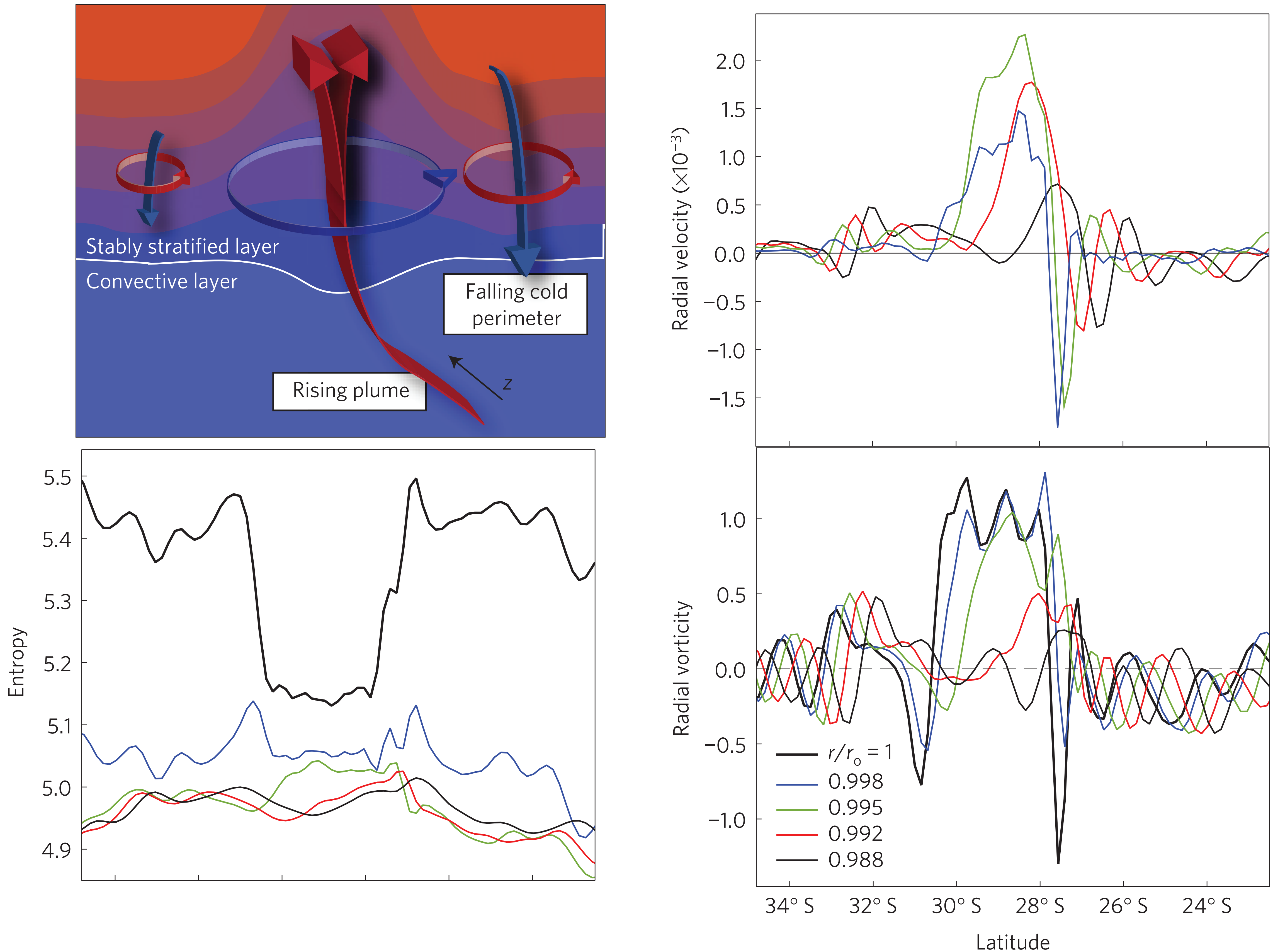


Heimpel et al., Nature Geoscience, 2016

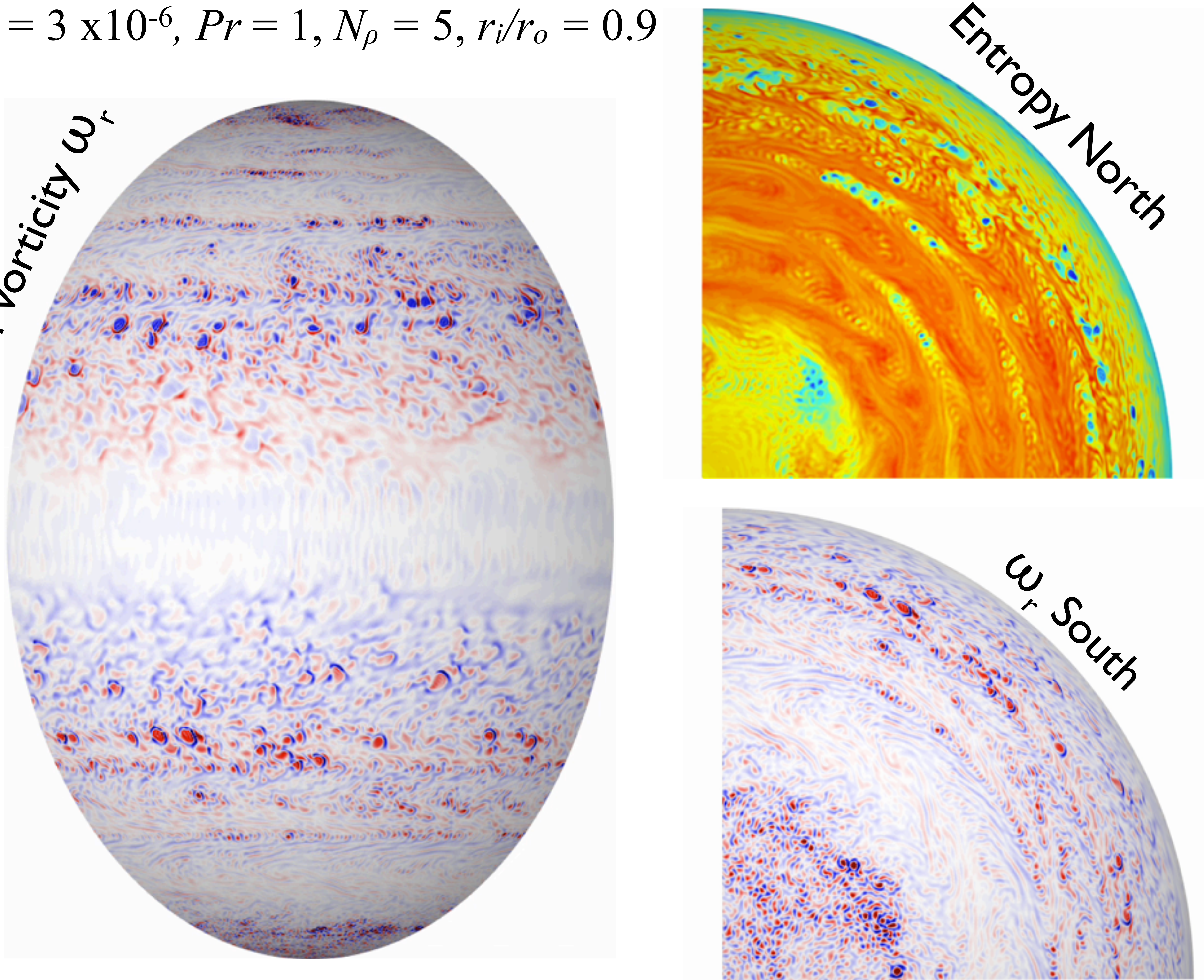
Outer & inner boundary and meridional slices of flow fields:
a, Axial vorticity; b & c, zoom-in details of a large vortex;
d, Eastward zonal velocity (Magic on MP2, Compute Canada)



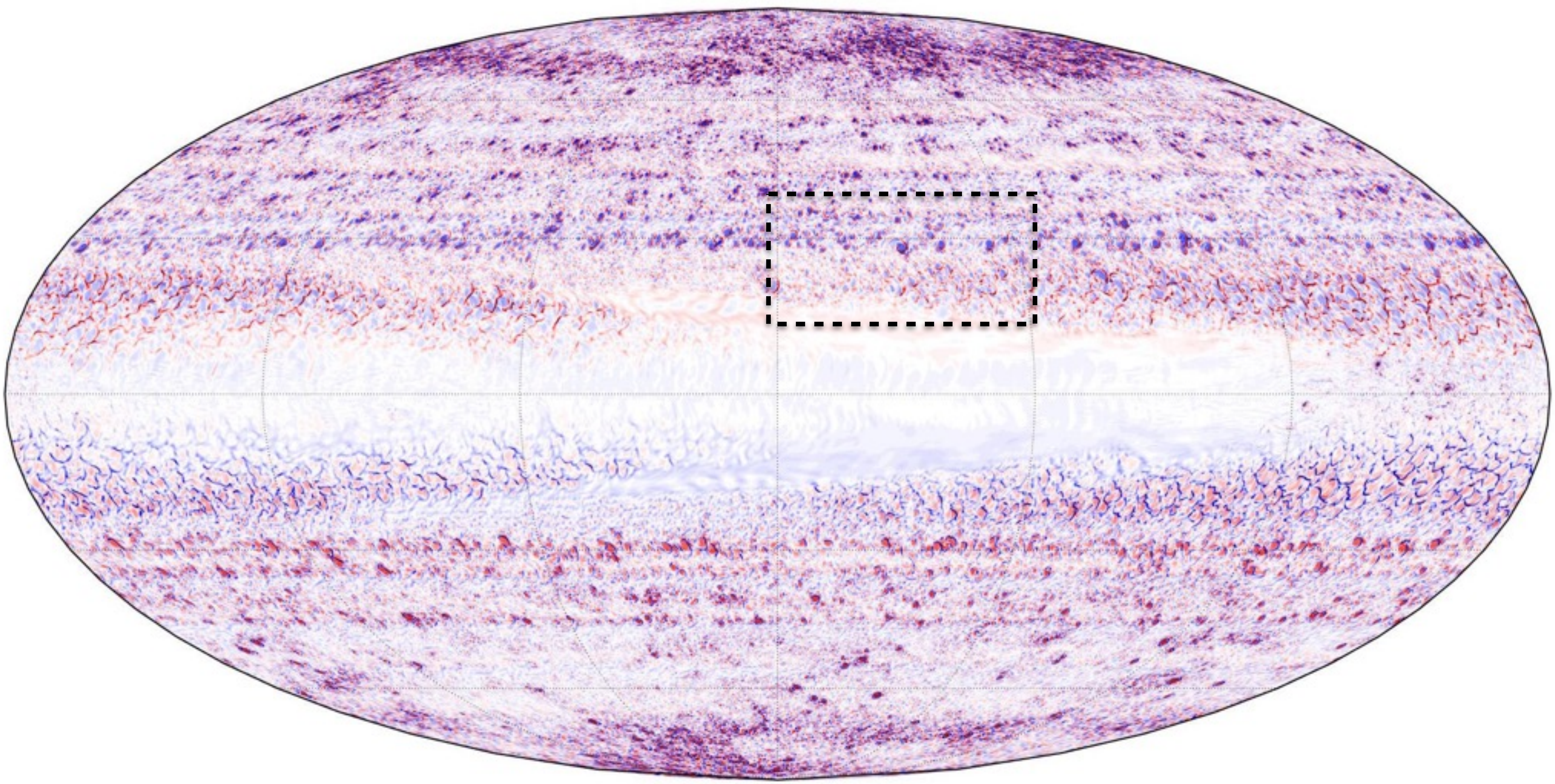
Dynamics of a large anticyclone



$E = 3 \times 10^{-6}$, $Pr = 1$, $N_\rho = 5$, $r_i/r_o = 0.9$

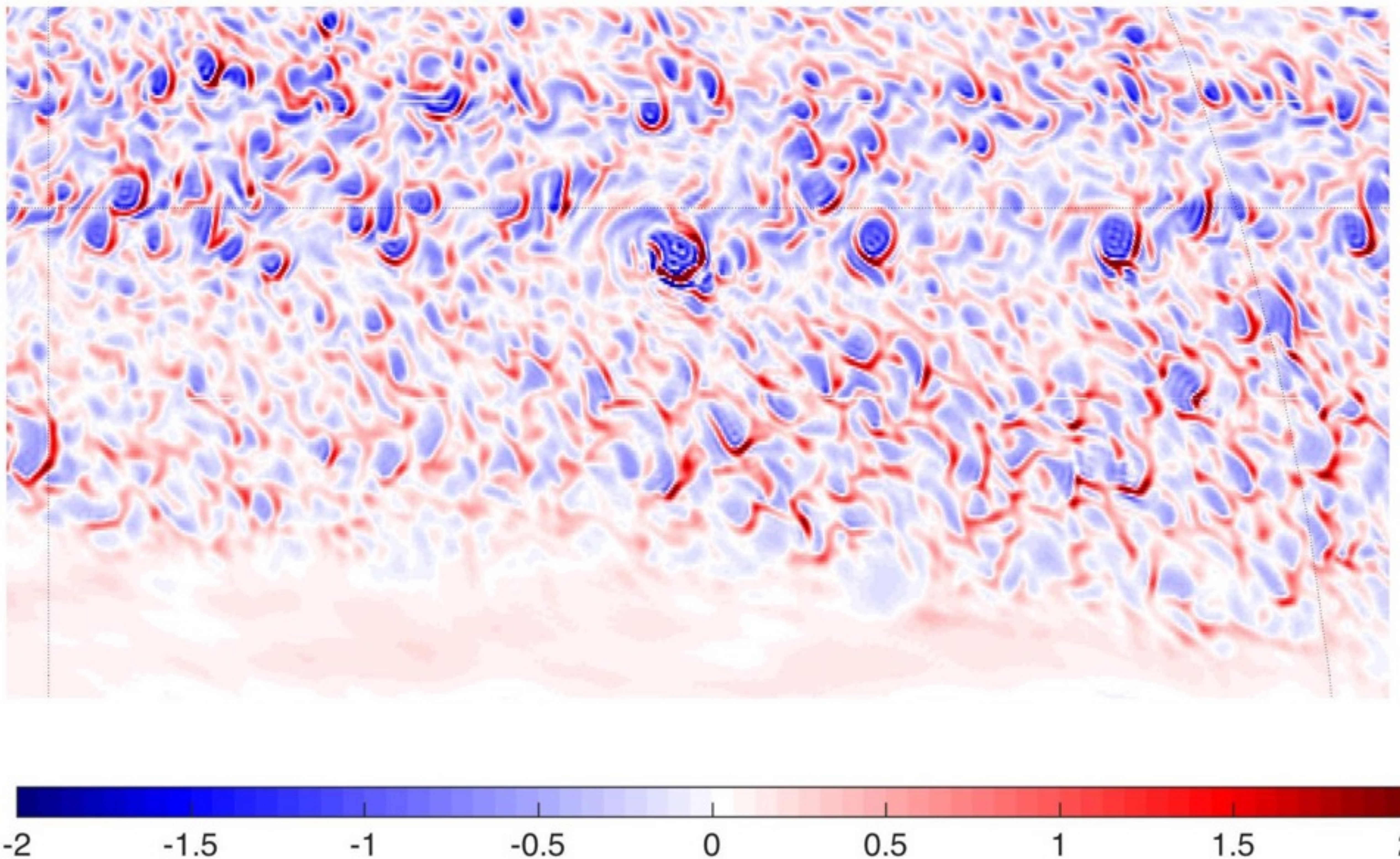


Mira (Argonne) running Rayleigh with 131072 cores (lmax+1=1024, 384 radial, 1.8e9 grid points in spherical shell)

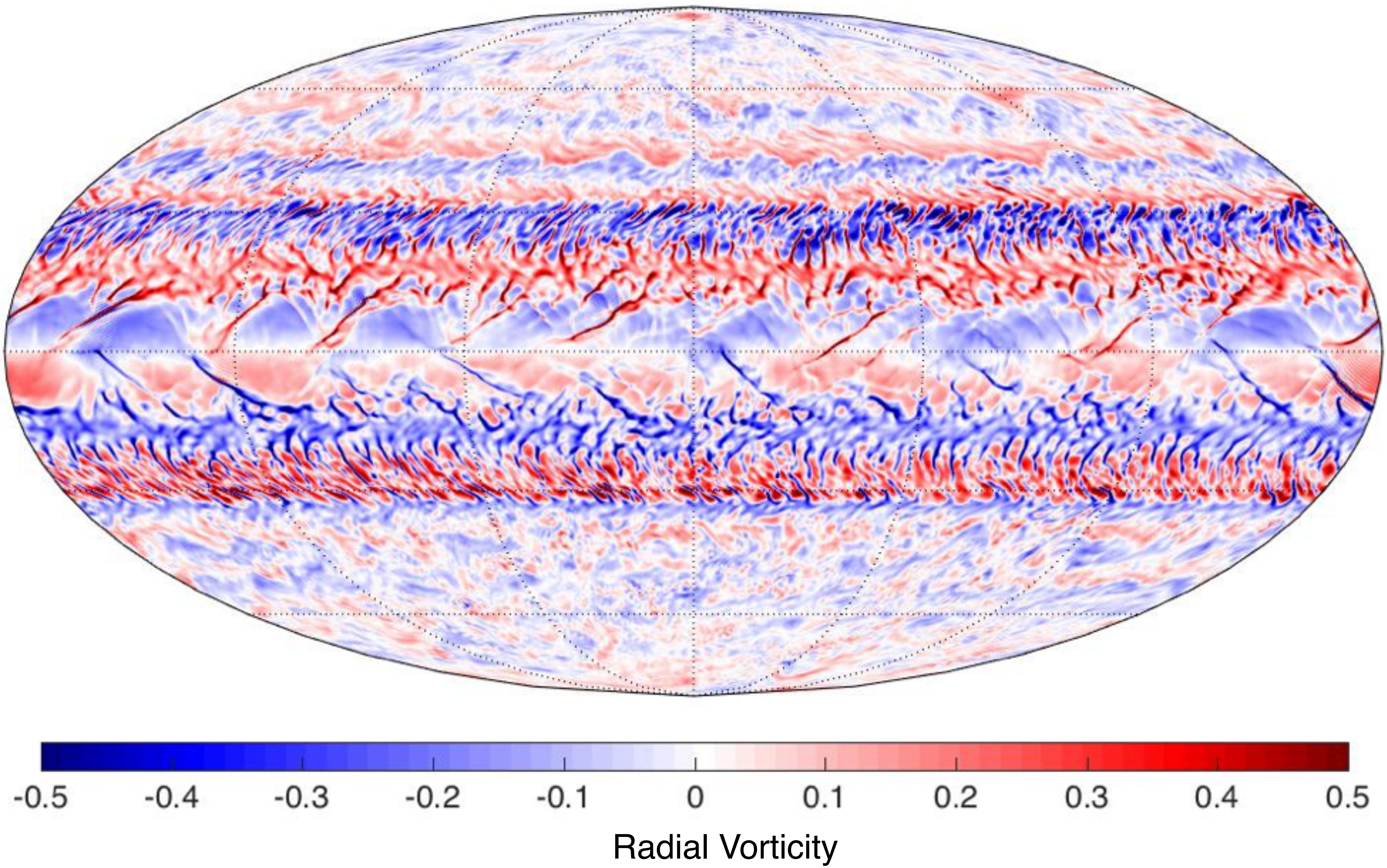


Radial Vorticity at outer boundary (Color saturation: -1.0 < Wr < 1.0)

Zoom in of radial vorticity. Outer boundary region of first anticyclonic shear zone

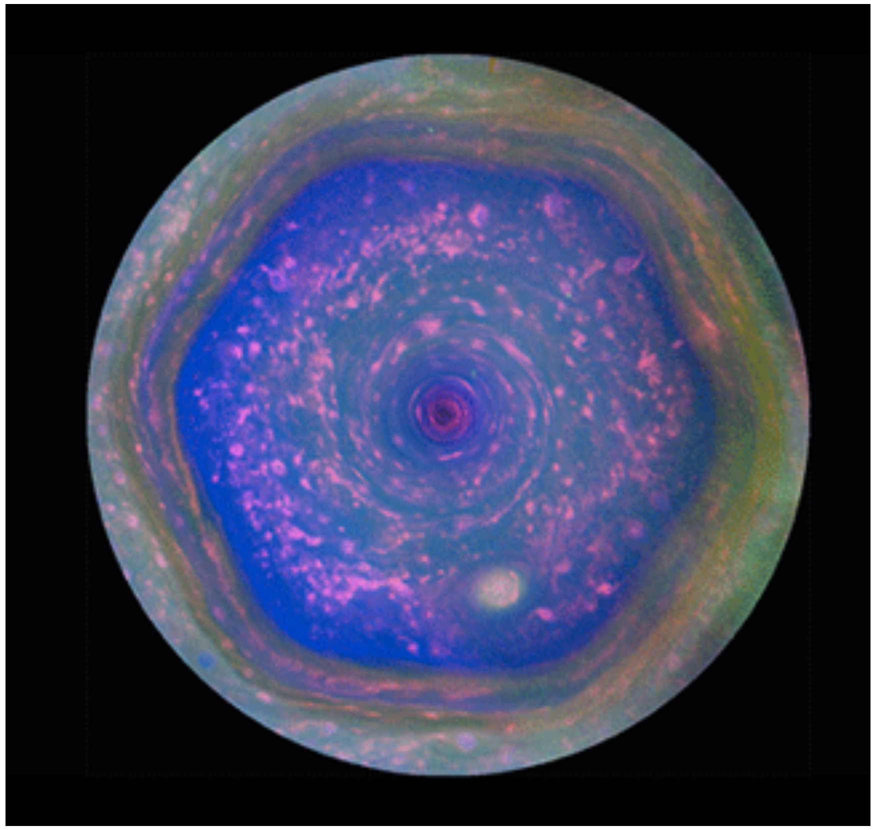


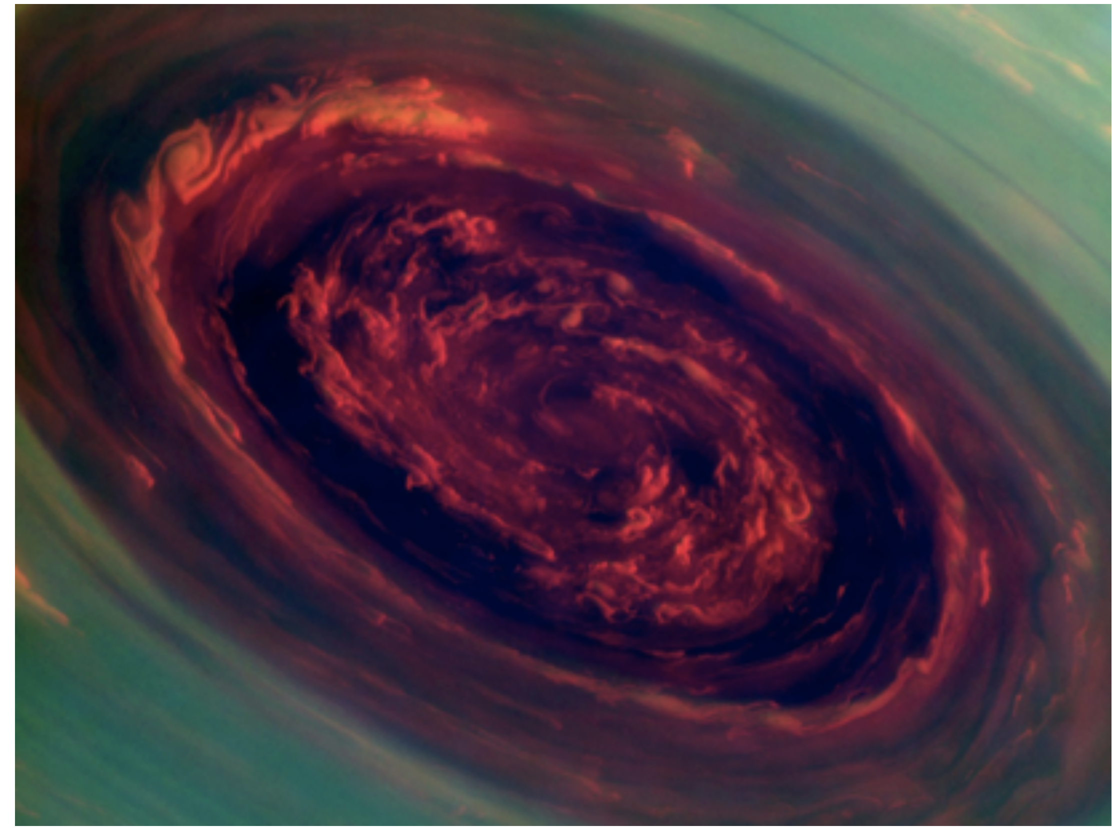
Preliminary Rayleigh run on Mira with $r_i/r_o = 0.95$, $E = 3 \times 10^{-5}$, $N_\rho = 7$ (density drop of 1097)



Why do we need High Performance Computing (Rayleigh/Mira)?

- Scale separation: Dynamo region ~ 10 x Jets region ~ 10 x Vortices region. (~ 10 density scale heights from planet center to 1 bar cloud level.)
- Low viscosity planetary fluids. (Multiple jets form at low Ro and high Re. That means we need low E and High Ra).
- Long-lived vortices favoured by strong stable stratification and large density contrast.
- Long time scale for formation and evolution of jets and vortices





Some questions for the near future

- Why do both poles of Saturn have cyclonic vortices? And what about the hexagon? What will Juno show us at Jupiters poles?
- Do the magnetic fields of Jupiter (dipolar but complex) and Saturn (nearly axisymmetric) relate to the hemispheric asymmetry (Jupiter) or symmetry (Saturn) of their zonal flow profiles?
- How has Jupiter’s great red spot persisted for hundreds of years?
- Will Cassini - Juno - Rayleigh - Mira - CIG help answer these questions? Yes!

Thanks!

Internal entropy sources/sinks

Jones 2014
Energy Equation
with constant heating H

$$\tilde{\rho}\tilde{T}\left(\frac{\partial s}{\partial t}+\mathbf{u}\cdot\boldsymbol{\nabla}s\right)=\frac{E}{Pr}\left[\boldsymbol{\nabla}\cdot\left(\tilde{\rho}\tilde{T}\boldsymbol{\nabla}s\right)+H\right]+\frac{E\,Di}{Ra^{*}}Q_{v}$$

$$\boldsymbol{\nabla}\cdot\left(\tilde{\rho}\tilde{T}\boldsymbol{\nabla}s\right)=-H$$

Heimpel et al., 2015
Energy Equation
with density dependent
heating H

$$\frac{\mathcal{D}S}{\mathcal{D}t}=\frac{Pm}{Pr}\left(\frac{1}{\bar{\rho}\overline{\overline{T}}}\nabla\cdot\bar{\rho}\overline{T}\nabla S+H\right)+\frac{Pr}{PmRa\overline{\overline{T}}}\left[\frac{\bar{\eta}}{E\bar{\rho}}(\nabla\times\mathbf{B})^{2}+Q_{v}\right],$$

$$\frac{1}{\tilde{\rho}\,\tilde{T}}\nabla\cdot\left(\tilde{\rho}\,\tilde{T}\,\nabla s\right)=-H$$

Both of these are options in Magic & Rayleigh