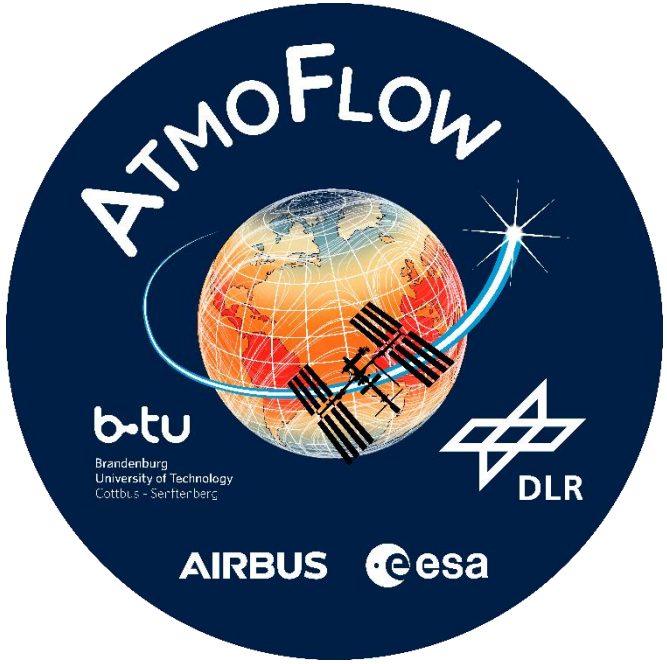
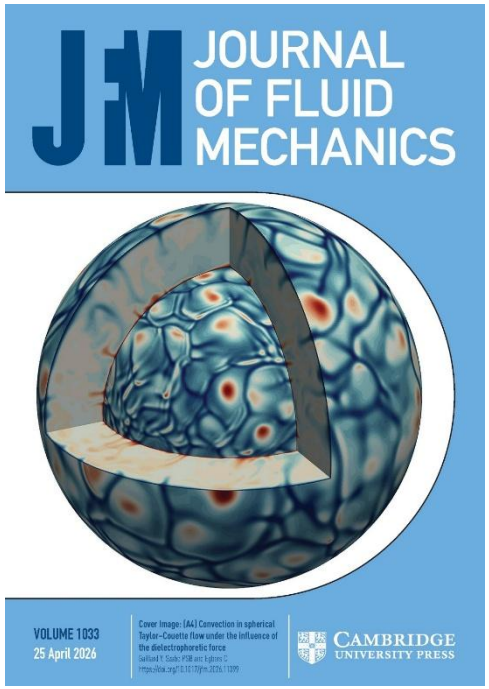
The GeoFlow and AtmoFlow experiments on ISS:

What came out and what is planned ?



ISS Experiment



Introduction

- GeoFlow-experiments on ISS
  - GeoFlow I-experiments
  - Results of GeoFlow I
  - GeoFlow II-experiments
  - Results of GeoFlow II
- AtmoFlow
  - Motivation
  - Research topics
  - Physical analogies
  - Experimental set-up
- Applications of TEHD
- Summary

Prof. Dr. Ing. Christoph Egbers & Prof. Dr. Innocent Mutabazi*

Dept. Aerodynamics & Fluid Mechanics, BTU Cottbus-Senftenberg, *LOMC, Univ. LeHavre

in co-operation and with financial support by

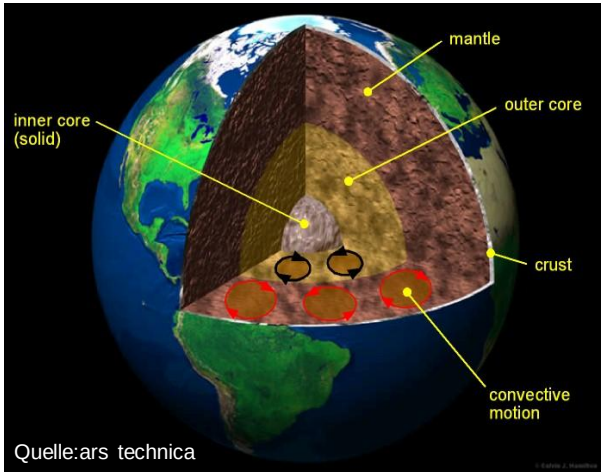
DLR esa DFG cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

GeoFlow I

Brandenburgische Technische Universität Cottbus - Senftenberg

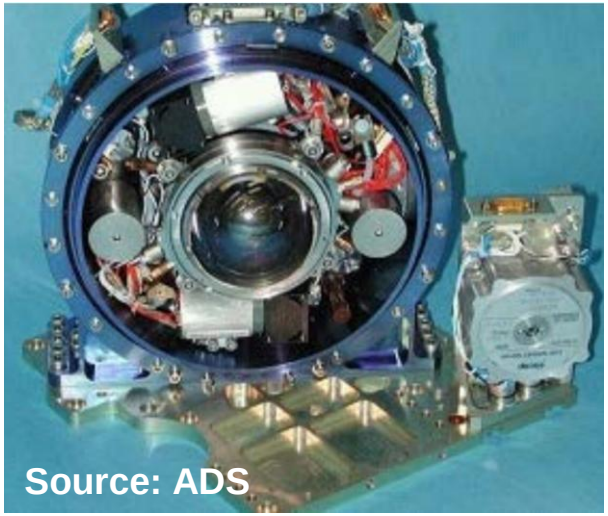
Investigation of convective flows in the Earth´s interior on ISS

Motivation



- Experiment under Microgravity
- Convection in the liquid outer Earth´s core
- Rotation inside of Planets
- Pattern formation
- Comparison between Theory and Experiment

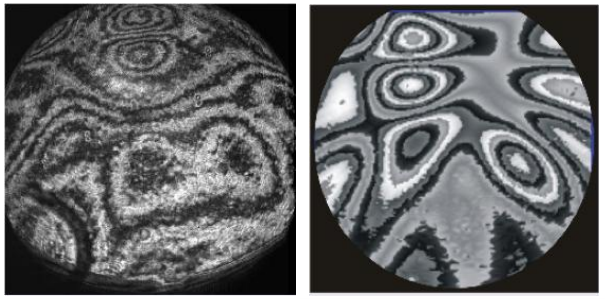
Experiment



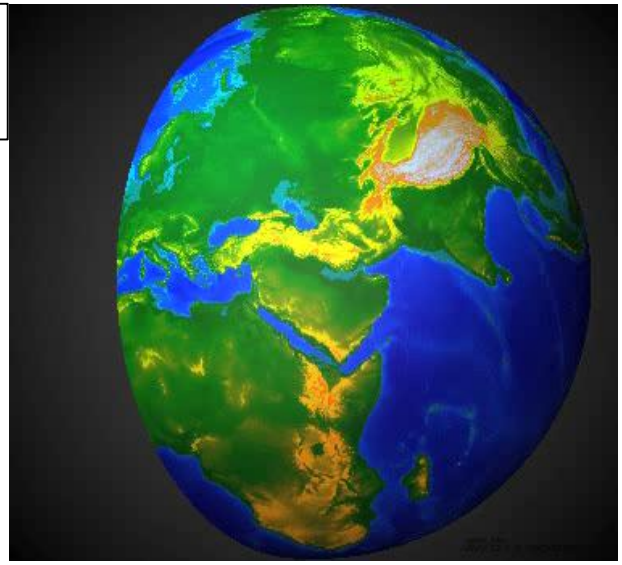
Operation on ISS: 2008-2009
114.000 Pictures/Data

Dept. Aerodynamics / Fluid Mechanics
GeoFlow
esa
DLR

Results



Experiment and numerical simulation in good agreement



GeoFlow I - Results

Brandenburgische Technische Universität Cottbus - Senftenberg

Futterer, B., Egbers, Ch., 2014, Geophysikalisches Strömungsexperiment auf der ISS, Der innere Kreislauf der Erde, **Physik in unserer Zeit**, 2014 **Wiley-VCH Verlag** GmbH & Co. KGaA, Weinheim, 45. Jahrgang, Mai 2014, ISSN 0031-9252 PHUZAH D 4787

PHYSICAL REVIEW E **87**, 023021 (2013)

Multistability in rotating spherical shell convection

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Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Strasse 24/25, 14476 Potsdam, Germany

L. S. Tuckerman
PMMH (UMR 7636 CNRS–ESPCI–UPMC Paris 6–UPD Paris 7), 10 rue Vauquelin, 75005 Paris, France

M. Gellert
Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
(Received 8 November 2012; published 27 February 2013)

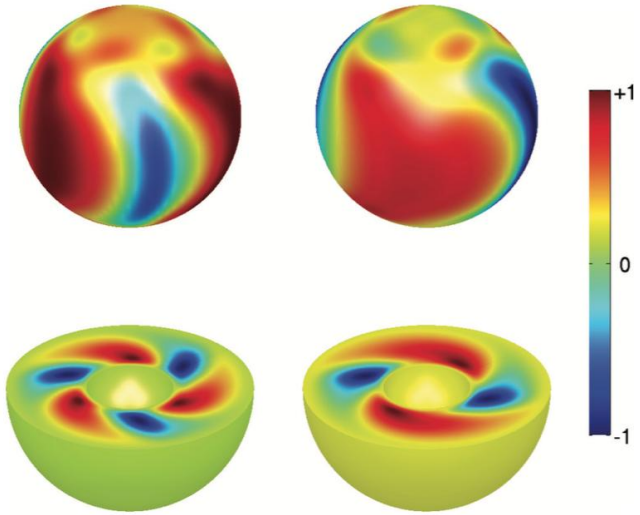


FIG. 2. (Color online) As Fig. 1 for RW3 (left) and RW2 (right).

Change of sign of drift velocity

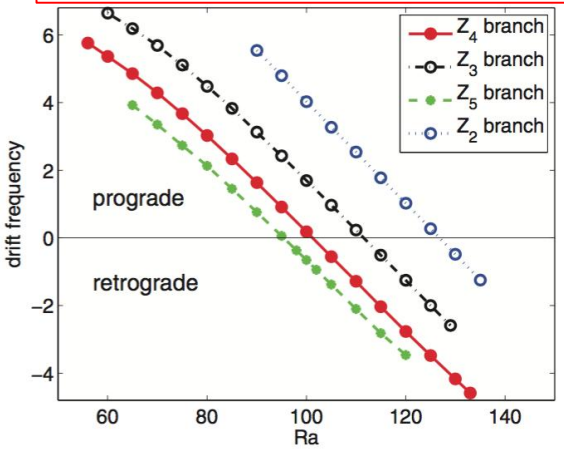
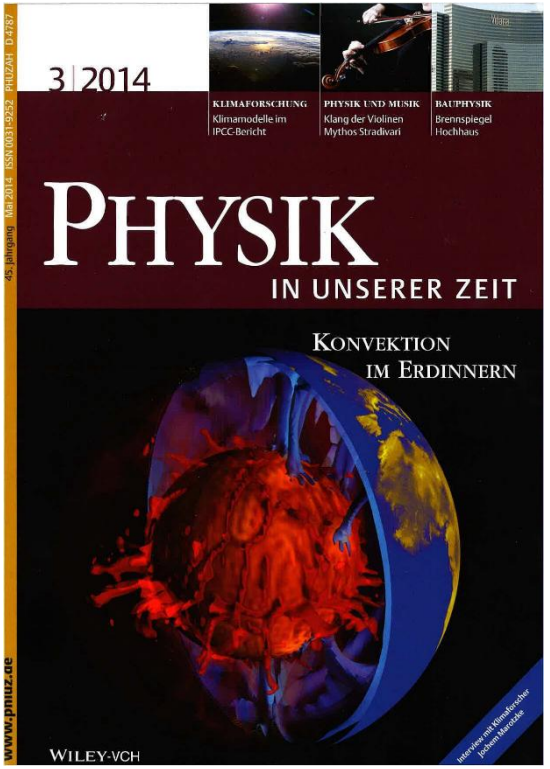
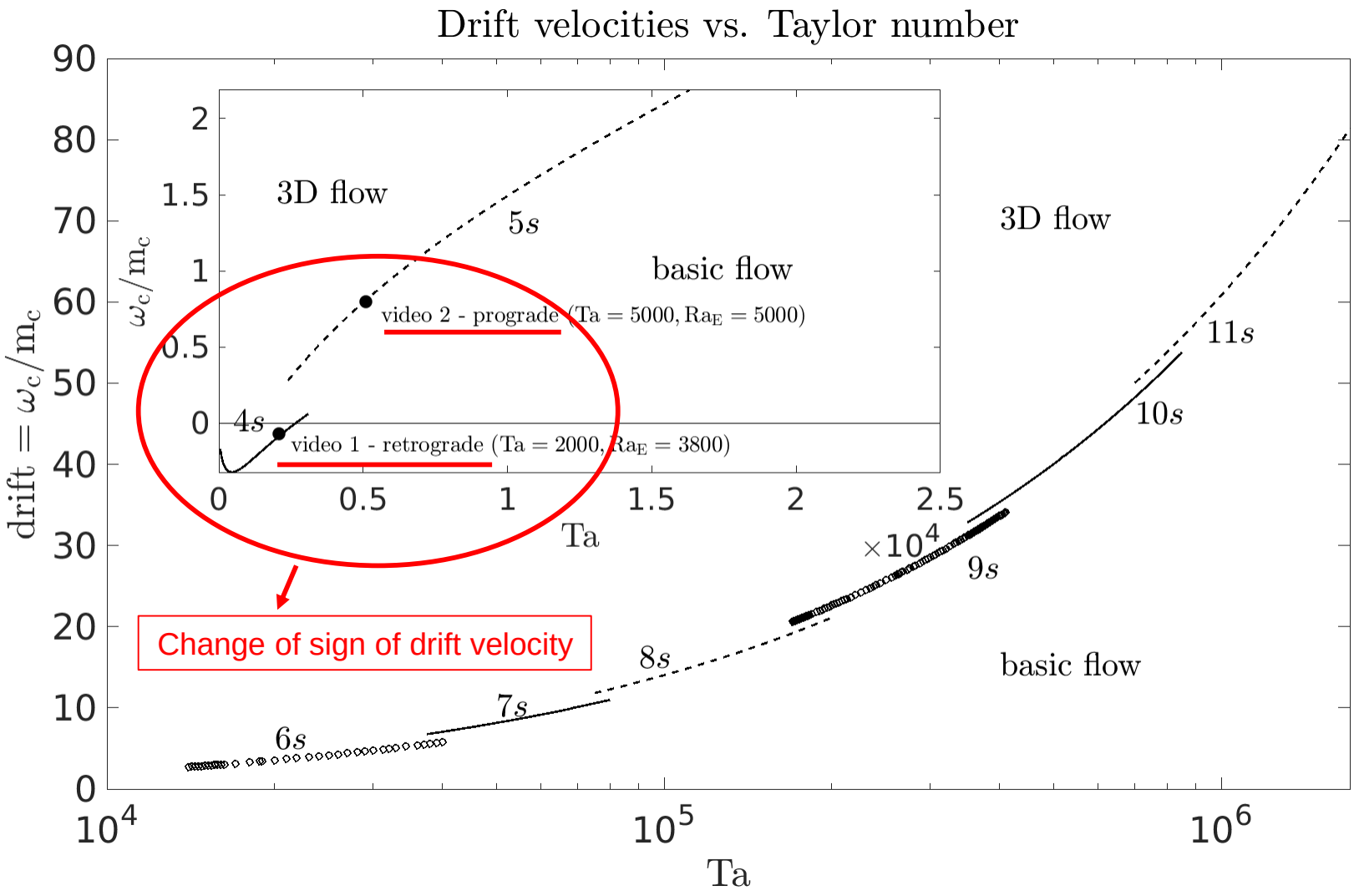


FIG. 4. (Color online) Drift frequency ω_{pr} of RWs vs Rayleigh number over the range of stability.



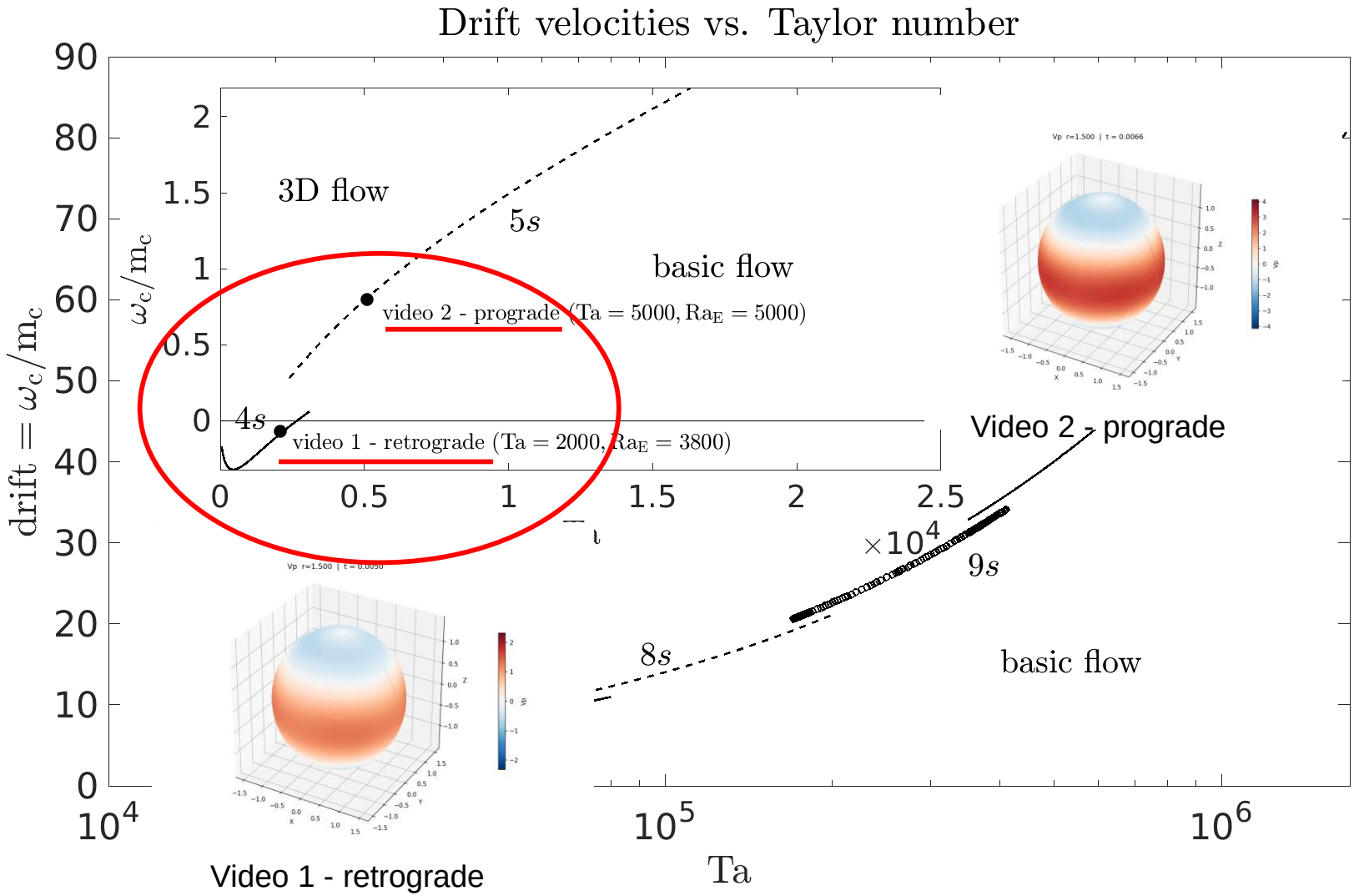
Futterer, B., Dahley, N., Koch, S., Scurtu, N., Egbers, Ch., 2012, From isoviscous convective experiment 'GeoFlow I' to temperature-dependent viscosity in 'GeoFlow II'—Fluid physics experiments on-board ISS for the capture of convection phenomena in Earth's outer core and mantle, **Acta Astronautica** 71 (2012), p.11-19

GeoFlow I - Results



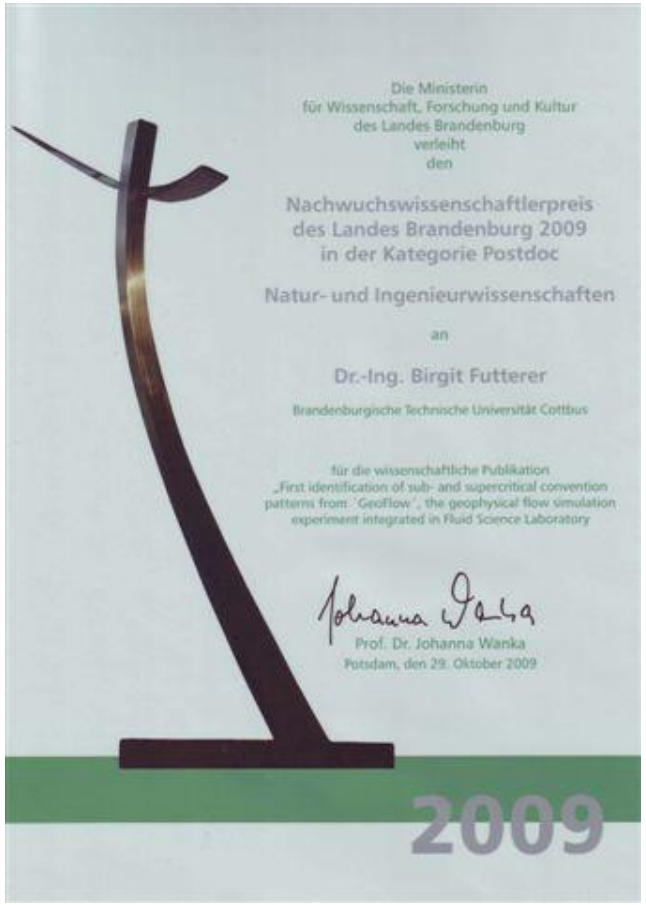
V. Travnikov & Ch. Egbers, **Phys. Rev. E 112**, 045109 (2025)

GeoFlow I - Results



V. Travnikov & Ch. Egbers, **Phys. Rev. E 112**, 045109 (2025)

GeoFlow - Awards





2009:
B. Futterer, Ch. Egbers, S. Koch, N. Dahley, L. Jehring:
First identification of sub- and supercritical convection patterns from ‚GeoFlow`, the geophysical flow simulation experiment integrated in Fluid Science Laboratory, „Brandenburger Wissenschaftspreis“
Acta Astronautica 66 (2010) 193-200

2010:
Birgit Futterer (with V. Travnikov, R. Hollerbach and Ch. Egbers) got the "Young Researchers Award for the best talk" during the **Europ. Fluid Mech. Conf. (EFMC 8th)** in Bad Reichenhall, organized by TU Munich, Sept. 13-16, 2010 for her talk:
Rapid rotating spherical shells in self gravitating force field - from the numerically onset of convection to its experimentally observed patterns.

2012:
Deutschland: Land der Ideen; „GeoFlow“ ausgewählter Ort 2012

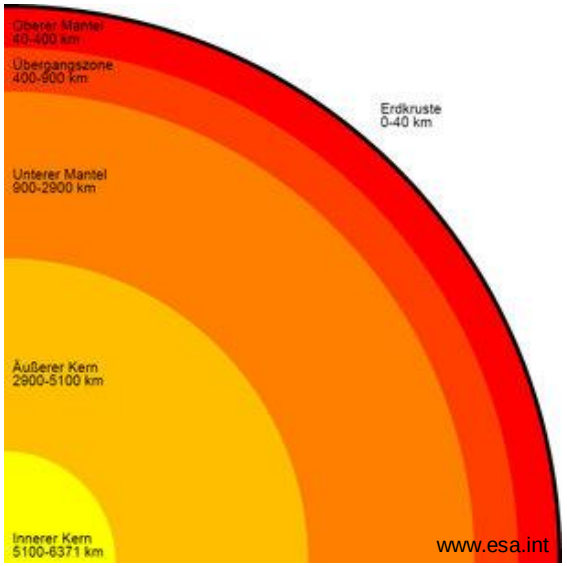
2015:
Futterer, B., Yoshikawa, H., Mutabazi, I., Egbers, Ch., 2015, **Facilities to alter weight** - Electric Fields Generation and Applications of Extra-Terrestrial Environments on Earth, River Publishers, Aalborg, Daniel Beysens, Jacobus van Loon, S. 91-100, ISBN 978-87-93237-53-7

GeoFlow II

Brandenburgische Technische Universität Cottbus - Senftenberg

Investigation of convective flows in the Earth´s mantle on ISS

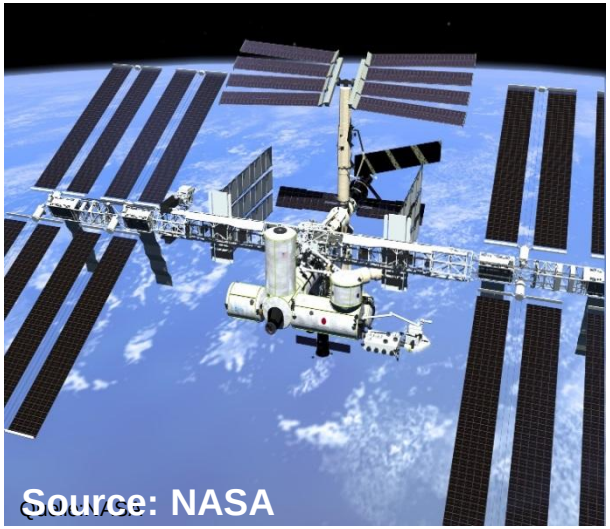
Motivation

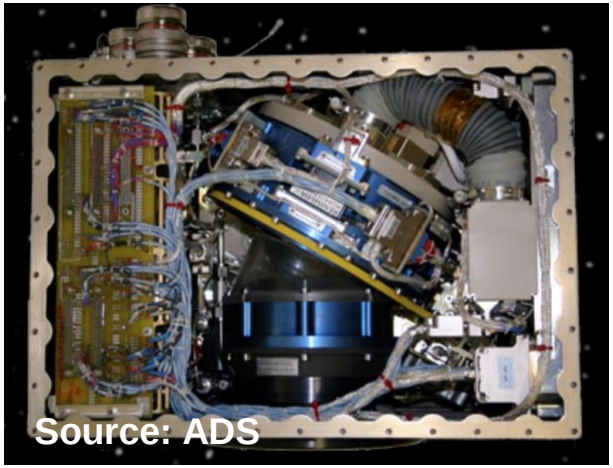


- Convective flows in the Earth´s mantle
- Influence of viscosity contrast
- Influence of dielectric heating
- Pattern formation
- Longterm studies

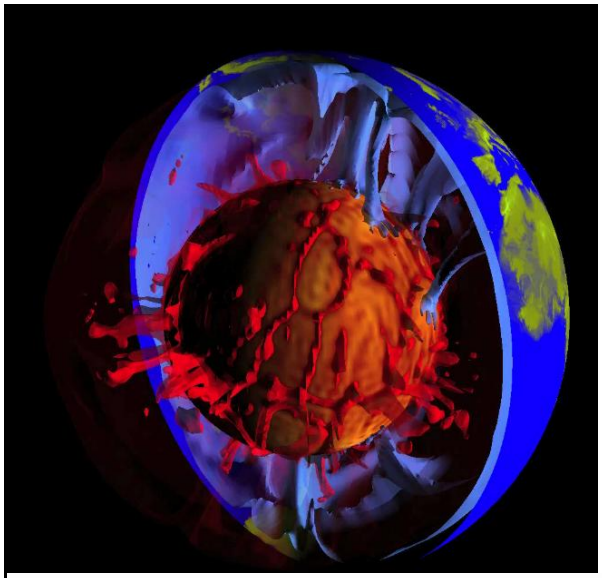
Experiment

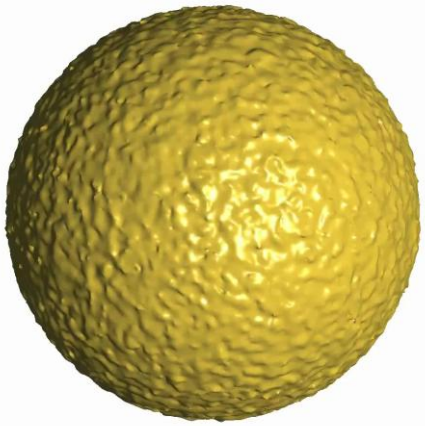
- 2011-2018 on ISS
- >1.4 Mio Pictures/Data



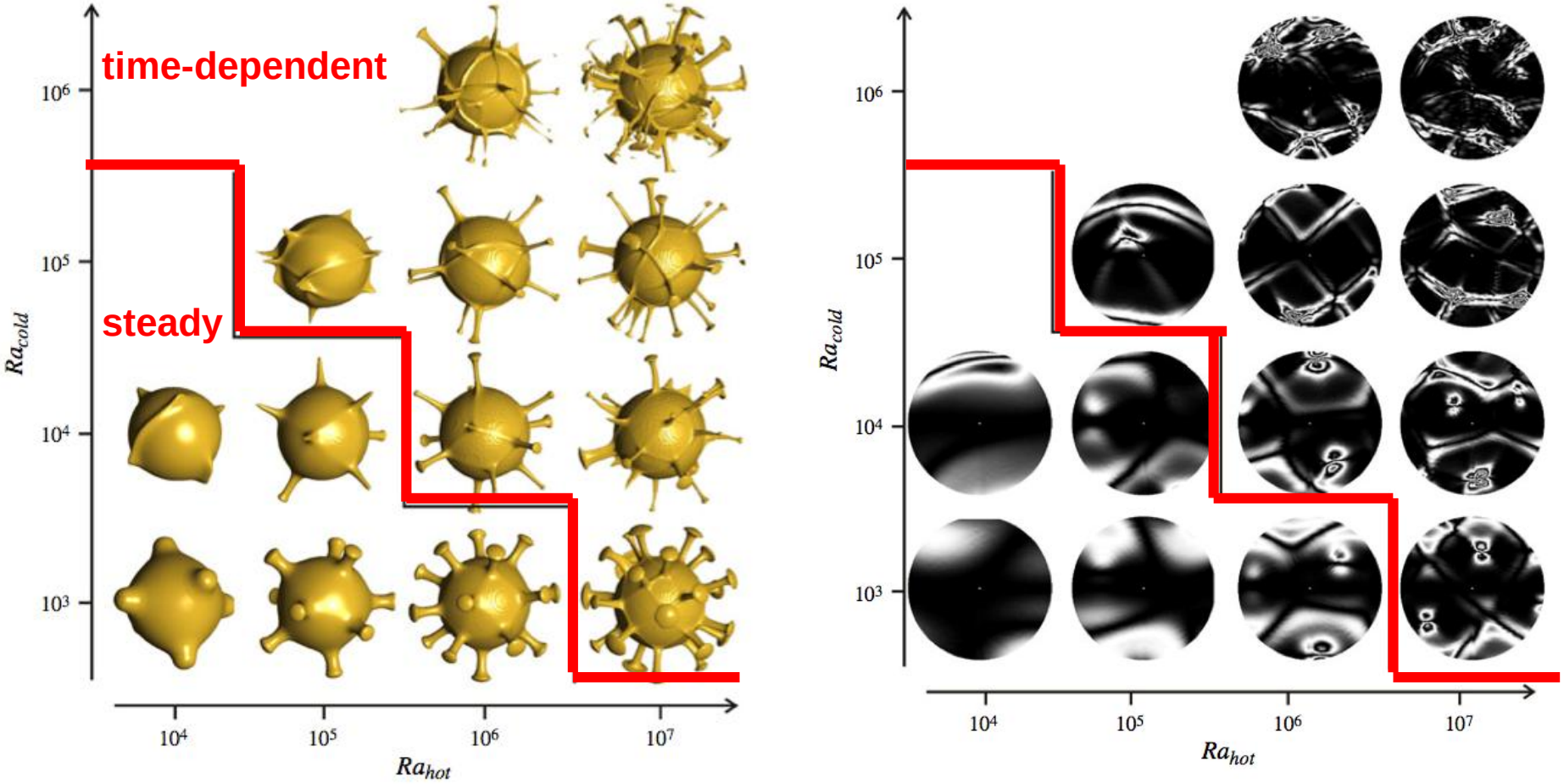


Results





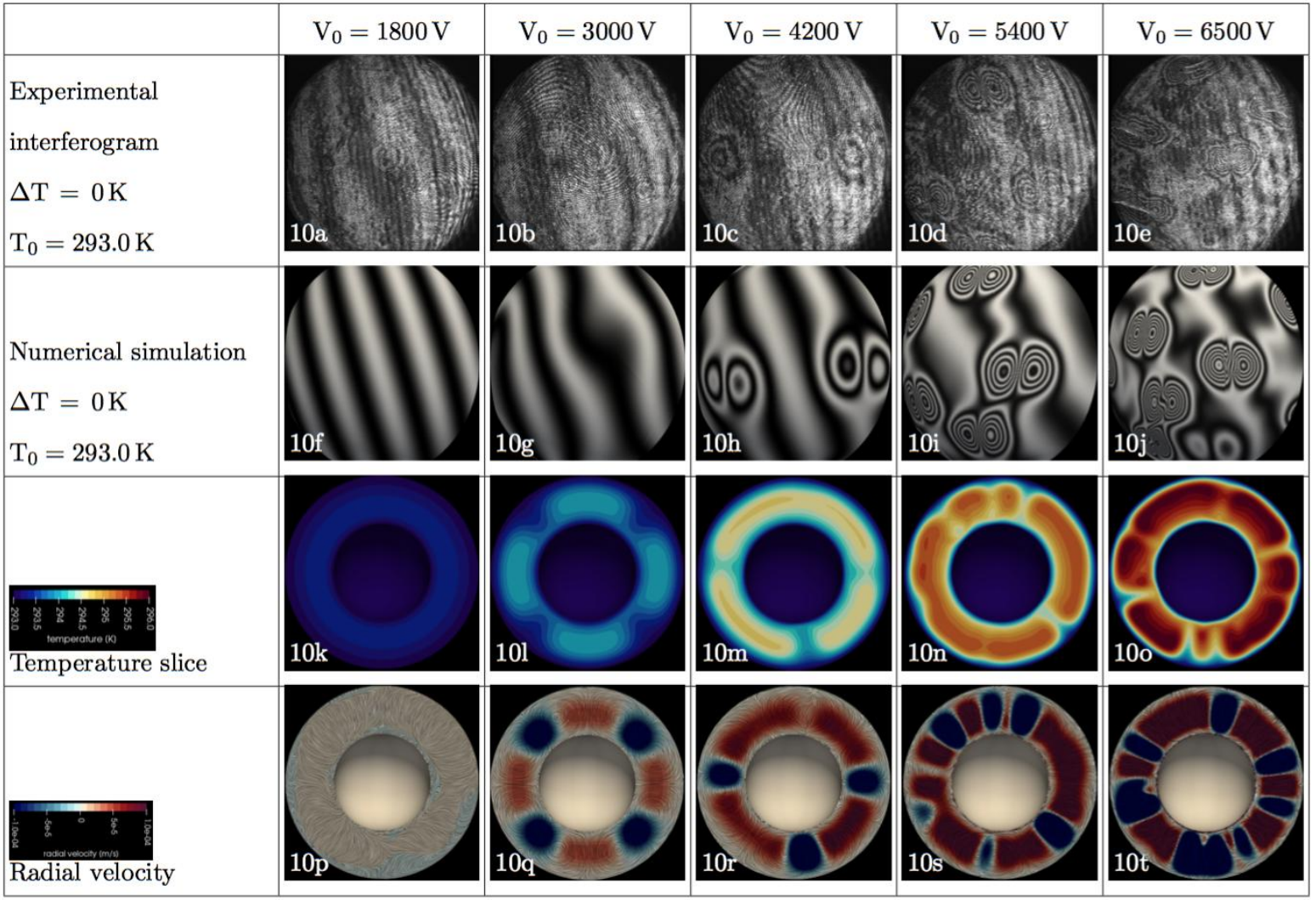
GeoFlow II - Results



Futterer, B., Krebs, A., Plesa, A.-C., Zaussinger, F., Hollerbach, R., Breuer, D. & Egbers, Ch.: Sheet-like and plume-like thermal flow in a spherical convection experiment performed under microgravity, **J. Fluid Mech**., **vol. 735**, pp. 647-683, 2013

V. Travnikov, F. Zaussinger, Ph. Beltrame, Ch. Egbers, Influence of the temperature-dependent viscosity on the convective flow in the radial force field, **Phys. Rev. E**, 96:023108, 2017

GeoFlow II - Results



F. Zaussinger, A. Krebs, V. Travnikov, Ch. Egbers, Recognition and tracking of convective flow patterns using Wollaston shearing interferometry, **Adv. Space Res., 60**:1327-1344, 2017

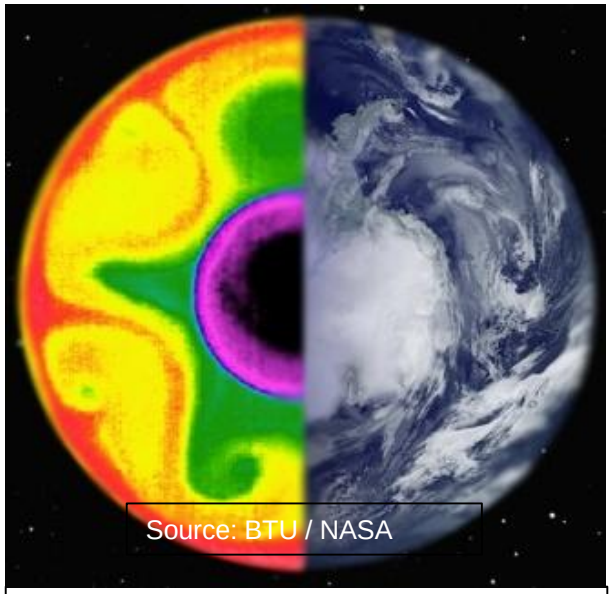
Zaussinger, F., Haun, P., Neben, M., Seelig, T., Travnikov, V. Egbers, Ch., Yoshikawa, H. & Mutabazi, I.: Dielectric driven convection in spherical gap geometry, **Phys. Rev. Fluids**, 3, APS,093501, 2018

AtmoFlow

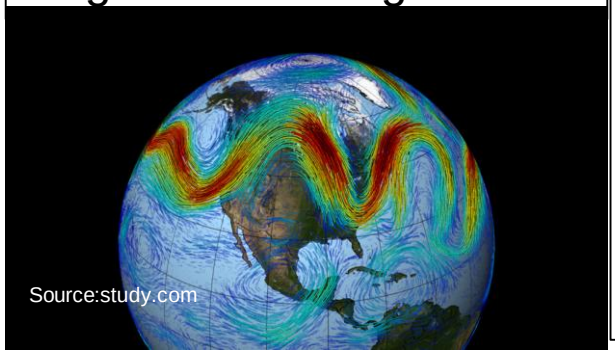
Investigation of planetary, atmospheric fluid flows on ISS

Brandenburgische Technische Universität Cottbus - Senftenberg

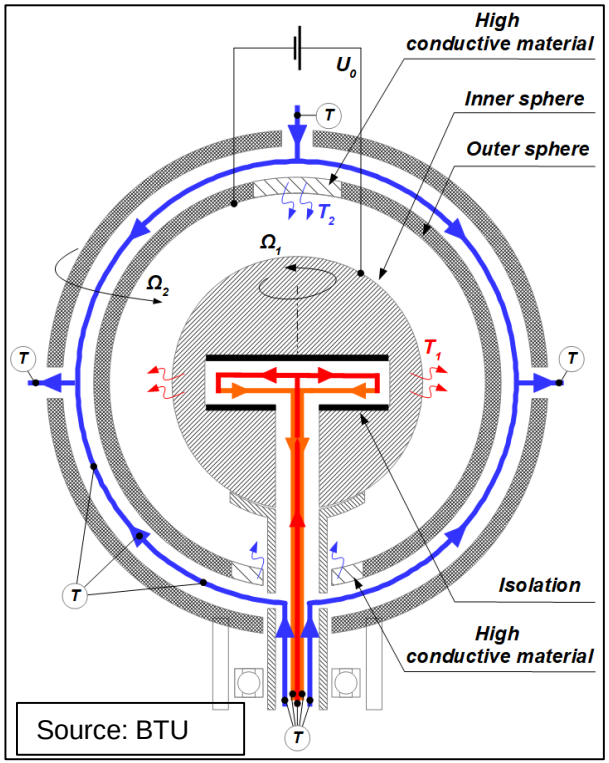
Motivation



- Behavior of the Earth´s atmosphere ?
- Effects of climate / global warming ?

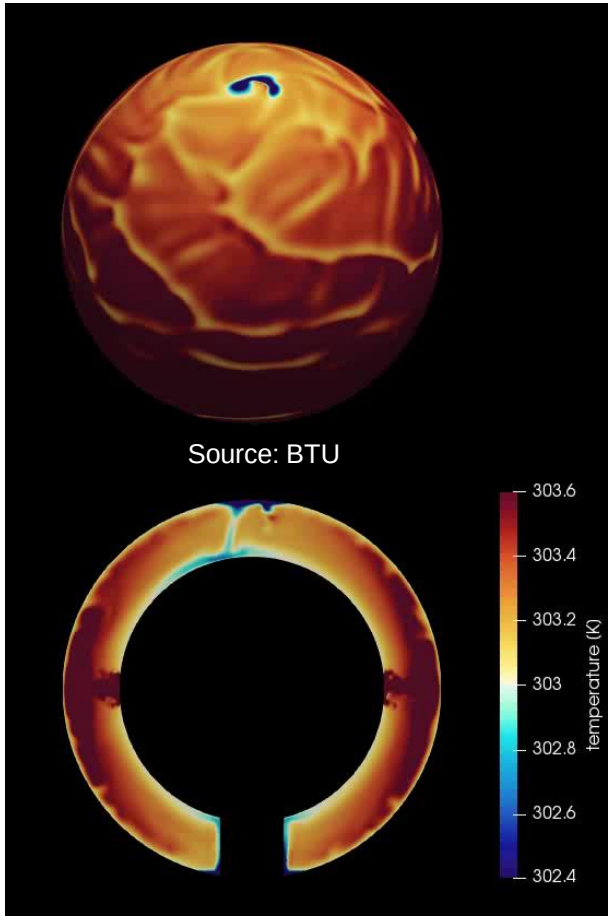


Experiment



- Phase C/D started
- Development of spherical shell hardware and interferometric b/b
- Comparison with numerical simulation

Results

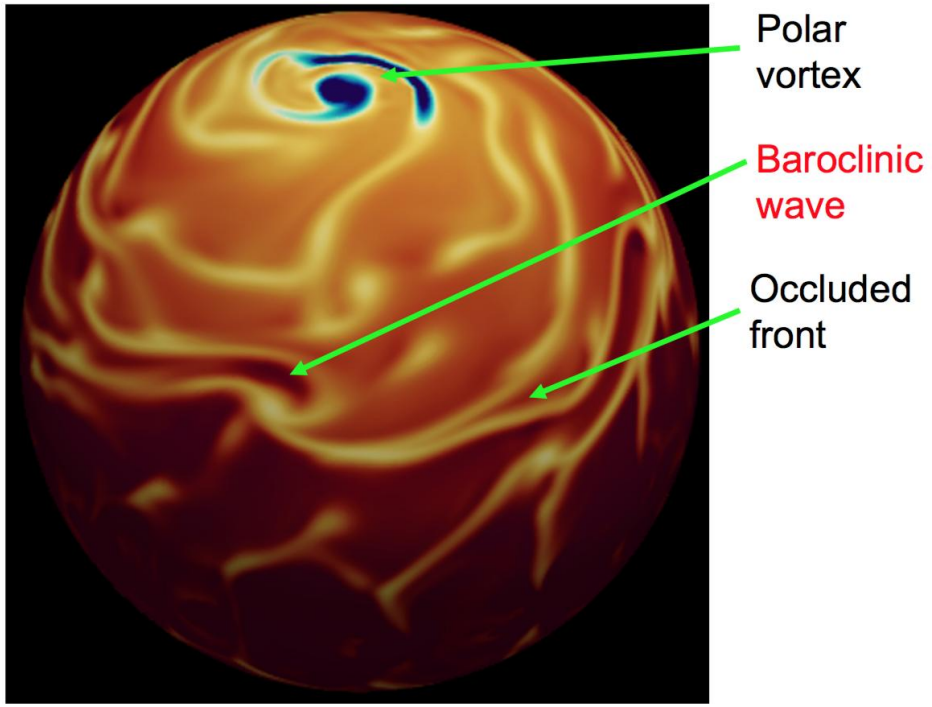


Simulation of fluid flows in planetary atmospheres

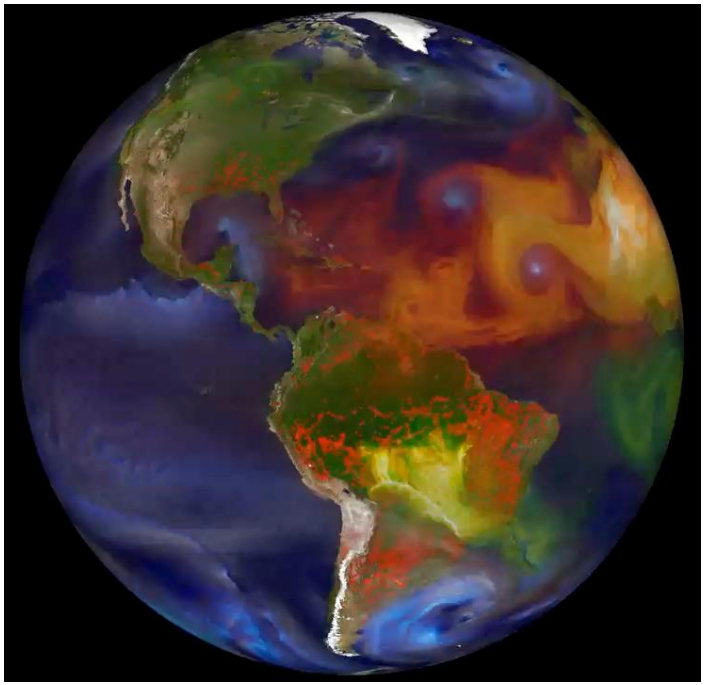
AtmoFlow: Motivation

Brandenburgische Technische Universität Cottbus - Senftenberg

- New insights into atmospheric flows present on Earth and exoplanets
- Excitation of planetary waves by differential rotation
- Better understanding of global cell formation and evolution, baroclinic instabilities, extreme value statistics, influence of global warming on atmospheric flows.
- Benchmark and comparison of ISS experiment data (AtmoFlow) with extraterrestrial observations from satellites and with laboratory data from baroclinic wave tank as well as with numerical models (weather forecast)



Source: BTU

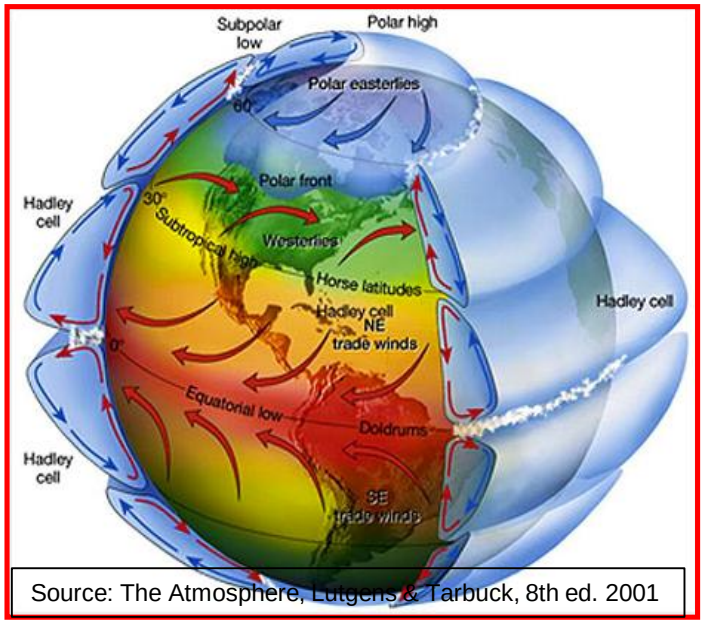


Source: NASA

AtmoFlow: Experiment / Analogies

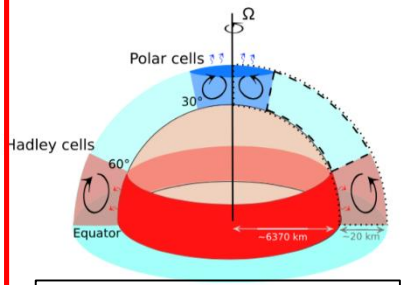
Brandenburgische Technische Universität Cottbus - Senftenberg

Lab experiments in rotating annulus are limited to mid-latitudes. Therefore, experimental investigations of atmospheric cell formation in spherical shells with temperature gradient from pole to equator under microgravity conditions with central force field are performed.

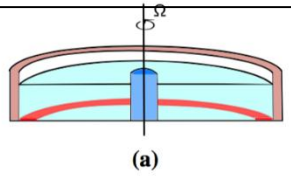


Source: The Atmosphere, Lutgens & Tarbuck, 8th ed. 2001

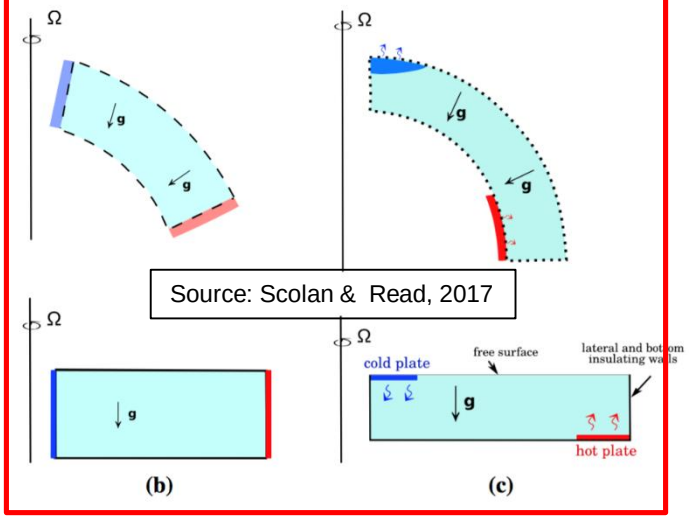
µg experiment



Source: Scolan & Read, 2017



Ground based lab experiments



Source: Scolan & Read, 2017

U. Harlander, Th. von Larcher, Y. Wang and Ch. Egbers, 2009, PIV- and LDV measurements of baroclinic wave interactions in a thermally driven rotating annulus, **Exp. in Fluids**, DOI 10.1007/s00348-009-0792-5

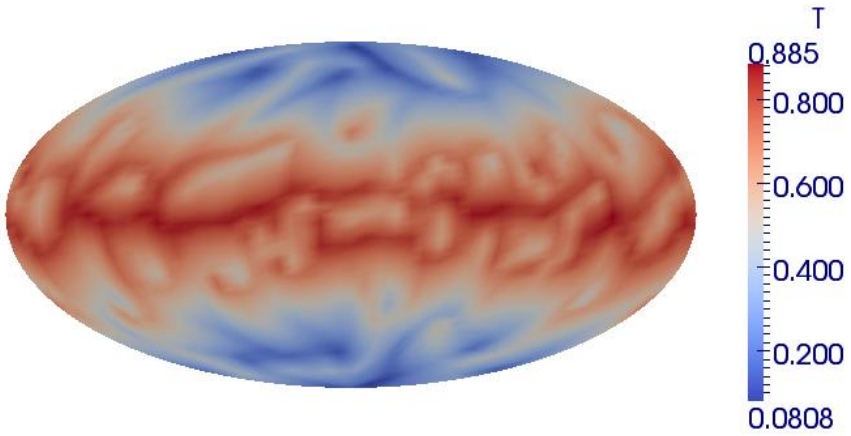
Harlander, U., Wenzel, J., Alexandrov, K., Wang, Y., Egbers, Ch., 2012, Simultaneous PIV- and thermography-measurements of partially blocked flow in a heated rotating annulus, **Exp. Fluids**, **52**, 1077-1085, DOI 10.1007/s00348-011-1195-y, 2012

Hoff, M., Harlander, U., Egbers, Ch., 2015, Empirical singular vectors of baroclinic flows deduced from experimental data of a differentially heated rotating annulus, **Meteor. Zeitschrift**, Stuttgart, 2015, DOI: 10.1127/metz/2014/0563

AtmoFlow: Experiment / Analogies

Brandenburgische Technische Universität Cottbus - Senftenberg

µg-experiment AtmoFlow (spherical shell)



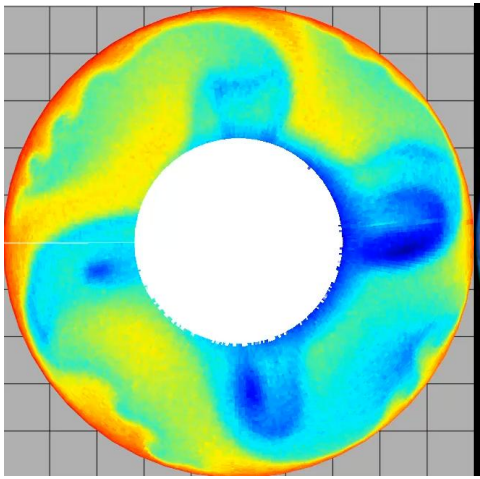
Temperature at $\eta = 0.7$
$Ra=10^6$, $Ta=10^5$,



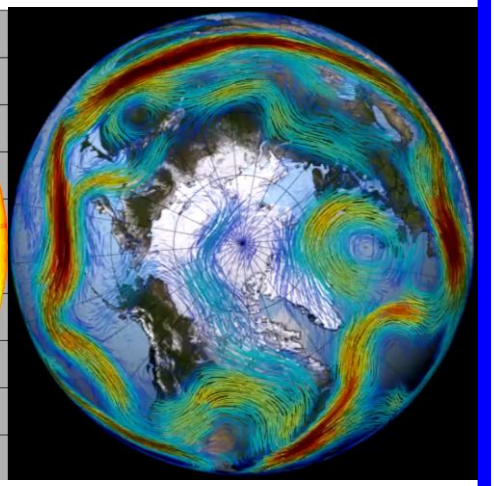
Vincze, M., Borchert, S., Achatz, U., von Larcher, Th., Baumann, M., Liersch, C. Remmler, S., Beck, Th., Alexandrov, K., Egbers, Ch., Fröhlich, J., Heuveline, V., Hickel, St., Harlander, U.: Benchmarking in a rotating annulus: a comparative experimental and numerical study of baroclinic wave dynamics, In: **Meteor. Zeitschrift (2015)**, PrePub DOI 10.1127/metz/2014/0600

Rotating annulus (Lab experiment)

„Co-existence of large scale and small scale structures in Meteorology, Geophysics and Fluid Mechanics“
BTU-Reference experiment,
DFG SPP „Metström“ 1276
EG 100/13-1, 13-2, 13-3, 2007 - 2013



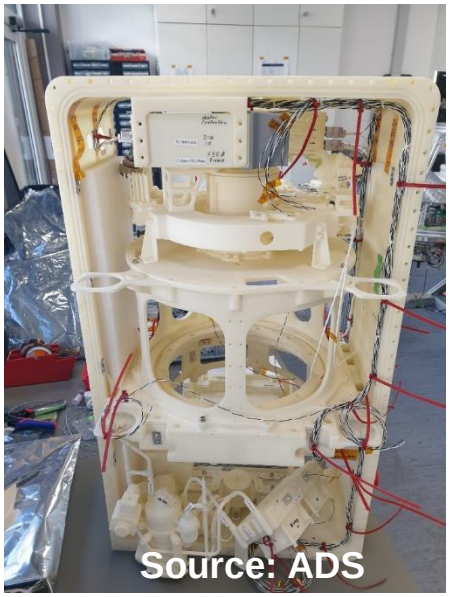
Source: BTU

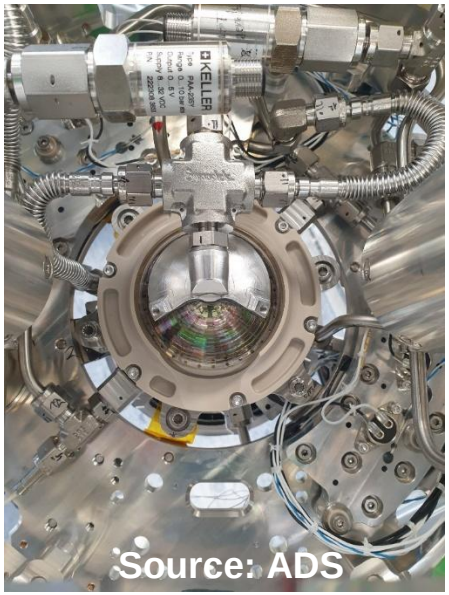


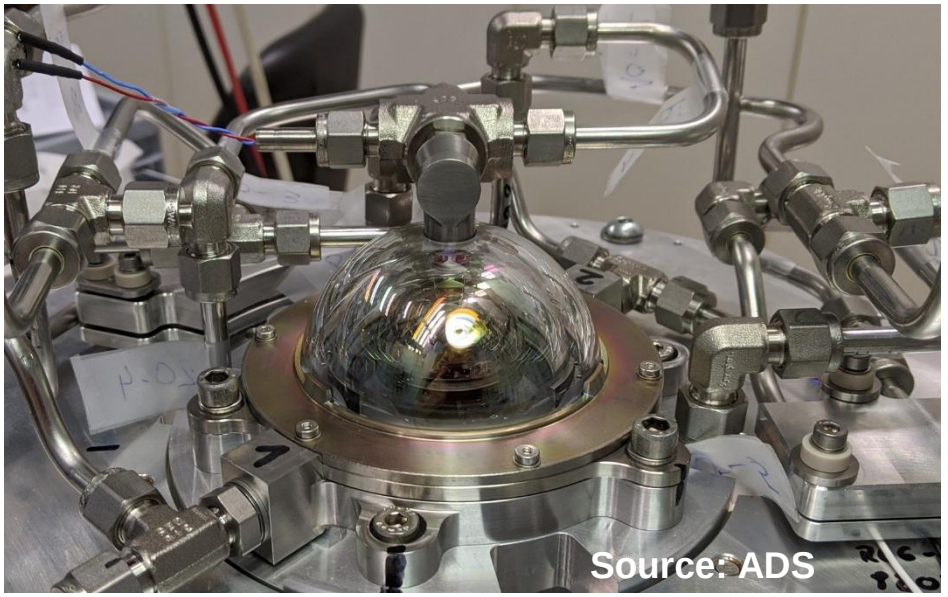
Source: NASA

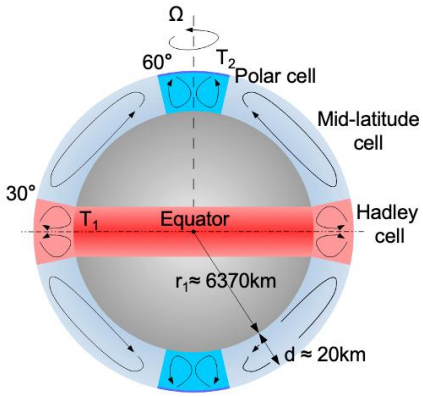
MetStröm DFG

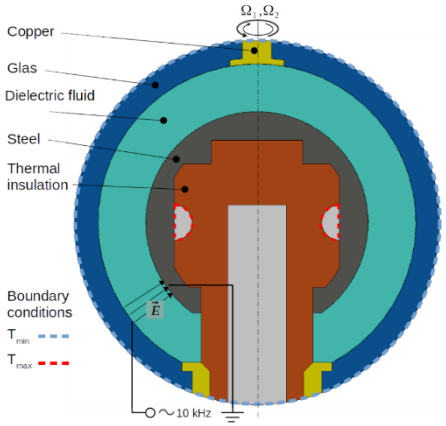
AtmoFlow: Space experiment











Zaussinger, F., et al., AtmoFlow - Investigation of Atmospheric-Like Fluid Flows Under Microgravity Conditions, **Microgravity Science and Technologie**, 2019, DOI: 10.1007/s12217-019-09717-7, pp 1-19

Geometry

- Inner radius, R_1, 18.90 mm
- Outer radius, R_2, 27.00 mm
- Radius ratio, $\eta = R_1 / R_2$, 0.70
- Rotation rate, f, 0 - 2.00 Hz
- Temperature difference, ΔT, 0 - 20.00 K

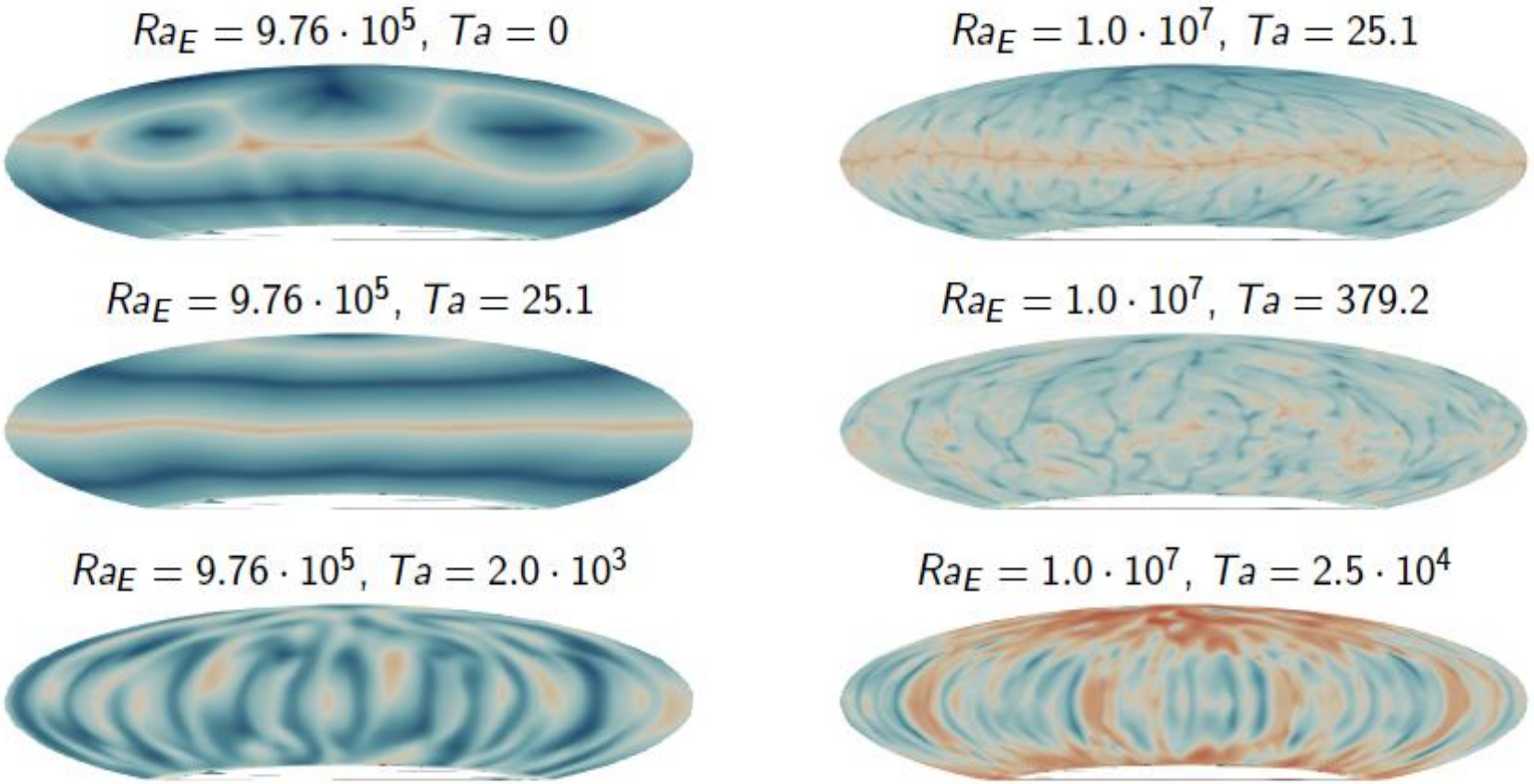
Forcing

- Ra_e 0 - $1 \cdot 10^7$
- Ta 0 - $1.2 \cdot 10^6$

AtmoFlow: 3D CFD-solid body rotation

Brandenburgische Technische Universität Cottbus - Senftenberg

ISO-thermal Hammer-Aitov projection of the radial integrated temperature profile *



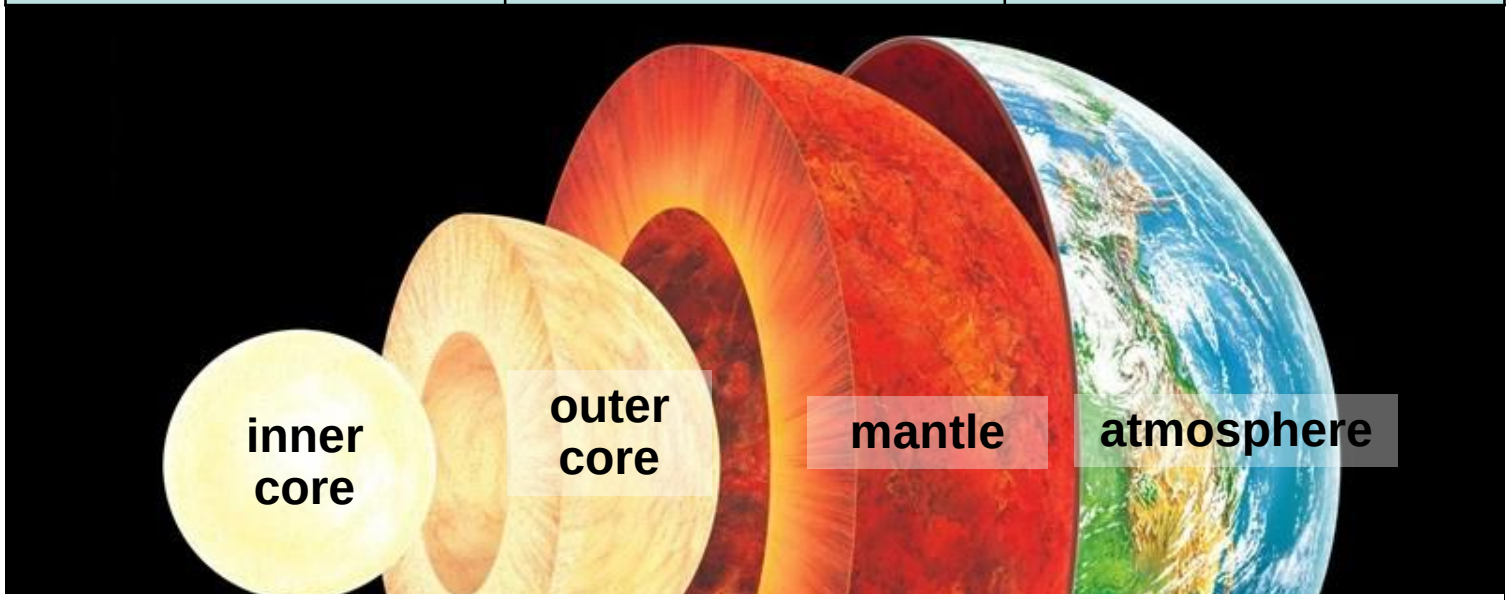
* Computational support acquired by the Northern-German Supercomputing Alliance (HLRN)

Gaillard, Y., Szabo, P.S.B, & Egbers, Ch., Convection in spherical Taylor–Couette flow under the influence of the dielectrophoretic force, **J. Fluid Mech., 1033**, (2026)

Summary:
Spherical shell experiments

Brandenburgische Technische Universität Cottbus - Senftenberg

GeoFlow I	GeoFlow II	AtmoFlow
2008-2009 on ISS	2011-2018 on ISS	since 2020 (currently in phase C/D)
Laminar convection in the spherical shell with focus on stability and influence of rotation.	Investigation of turbulent convection with viscosity-contrast and internal heating.	Atmospheric-like flows with complex boundary conditions and various rotation scenario.

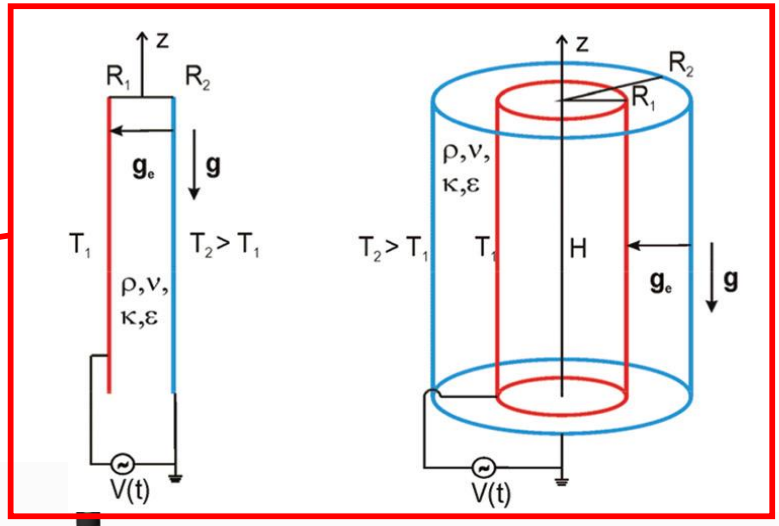


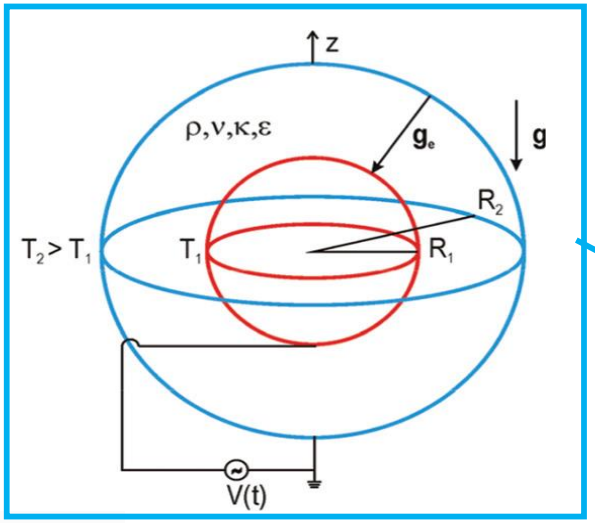
Applications

in Thermo-Electro-Hydro-Dynamics (TEHD)

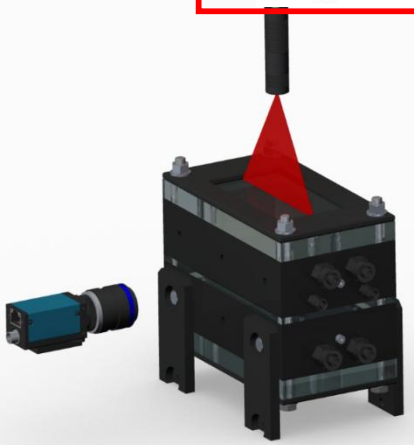
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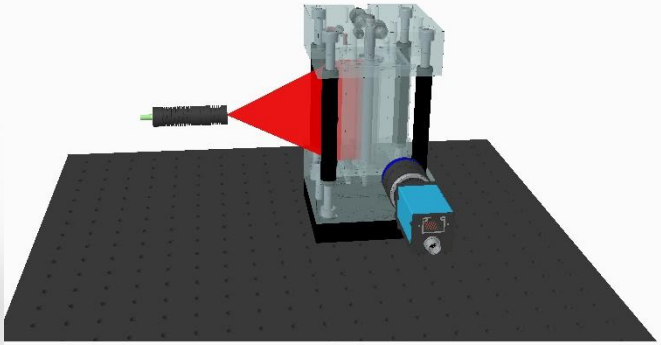
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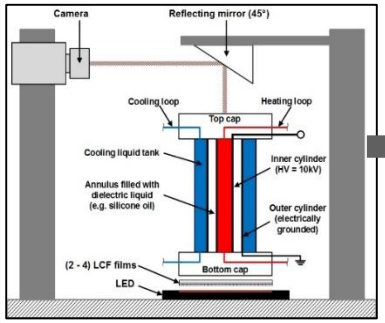


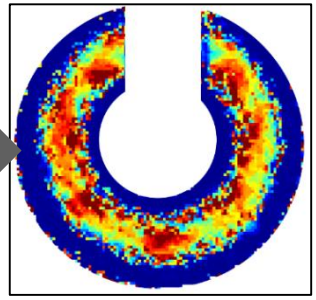


GeoFlow I, II
AtmoFlow









Mutabazi, I., Yoshikawa, H.N., TadieFogaing, M., Travnikov, V., Futterer, B. & Egbers, Ch., 2016, Thermo-Electro-Hydrodynamic Convection under microgravity: A review, **Fluid Dyn. Research**, 48, 061413

Meyer, A., Crumeyrolle, O., Mutabazi, I., Meier, M., Jongmanns, M., Renoult, M.-C., Seelig, T., Egbers, Ch., 2018: Flow patterns and heat transfer in a cylindrical annulus under 1g and low-g conditions: Theory and simulation. **Microgravity Science and Technology 30** (5), 653 – 662.

Many thanks to the ESA-TopicalTeam.....

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Prof. Rainer Hollerbach
(Numerics)

Prof. Laurette Tuckerman
(Path following methods)

Prof. Innocent Mutabazi
(TEHD)

Dr. Philippe Beltrame
(Non-linear dynamics)

Prof. Pascal Chossat
(Onset, stability)



Prof. Doris Breuer
(Numerics, GAIA code)

PD Dr. Fred Feudel
(Multistability)

Prof. Christoph Egbers
(PI Experiment)

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DLR esa DFG cnes

Collaboration within GeoFlow

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- Membership of the ESA Topical Team
- LOMC : theoretical and numerical investigation of thermoelectric convection in parallel plates and in cylindrical annulus to participate to the interpretation of the experiments and for the design of the new experiment
- PROCOPE project (2011-2012)
- LIA ISTROF (2013-2021)
- ERASMUS Exchange programs : 2 PhD with EU label + more than 10 short visits of graduate students
- Regular exchange between representatives of CNES and DLR for funding parabolic flights campaigns
- Annual meetings on thermo-electric convection (alternatively in Cottbus and in Le Havre)
- Common publications : 30

Many thanks to my Team at BTU...

Brandenburgische Technische Universität Cottbus - Senftenberg



Dr. Peter Szabo



M.Sc. Yarislau Sliavin



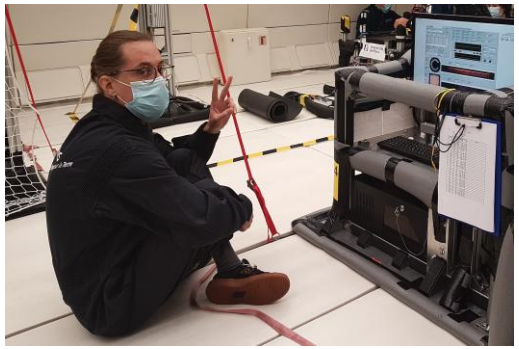
Dr. Vadim Travnikov



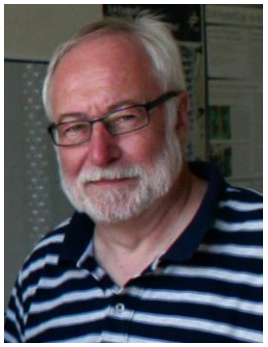
M.Sc. Yann Gaillard



M.Sc. Peter Haun



Dr. Antoine Meyer



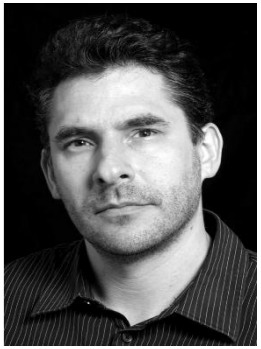
Dr. Martin Meier



M.Sc. Matthias Strangfeld



Dr. Birgit Futterer



Prof. Dr. Florian Zaussinger

Geo-/AtmoFlow



Stefan Rohark & Robin Stöbel



Tark Raj Bista



Dr. Vasyl Motuz

TEXUS / Parabolic Flights

Appendix

Many thanks to my Team at BTU...

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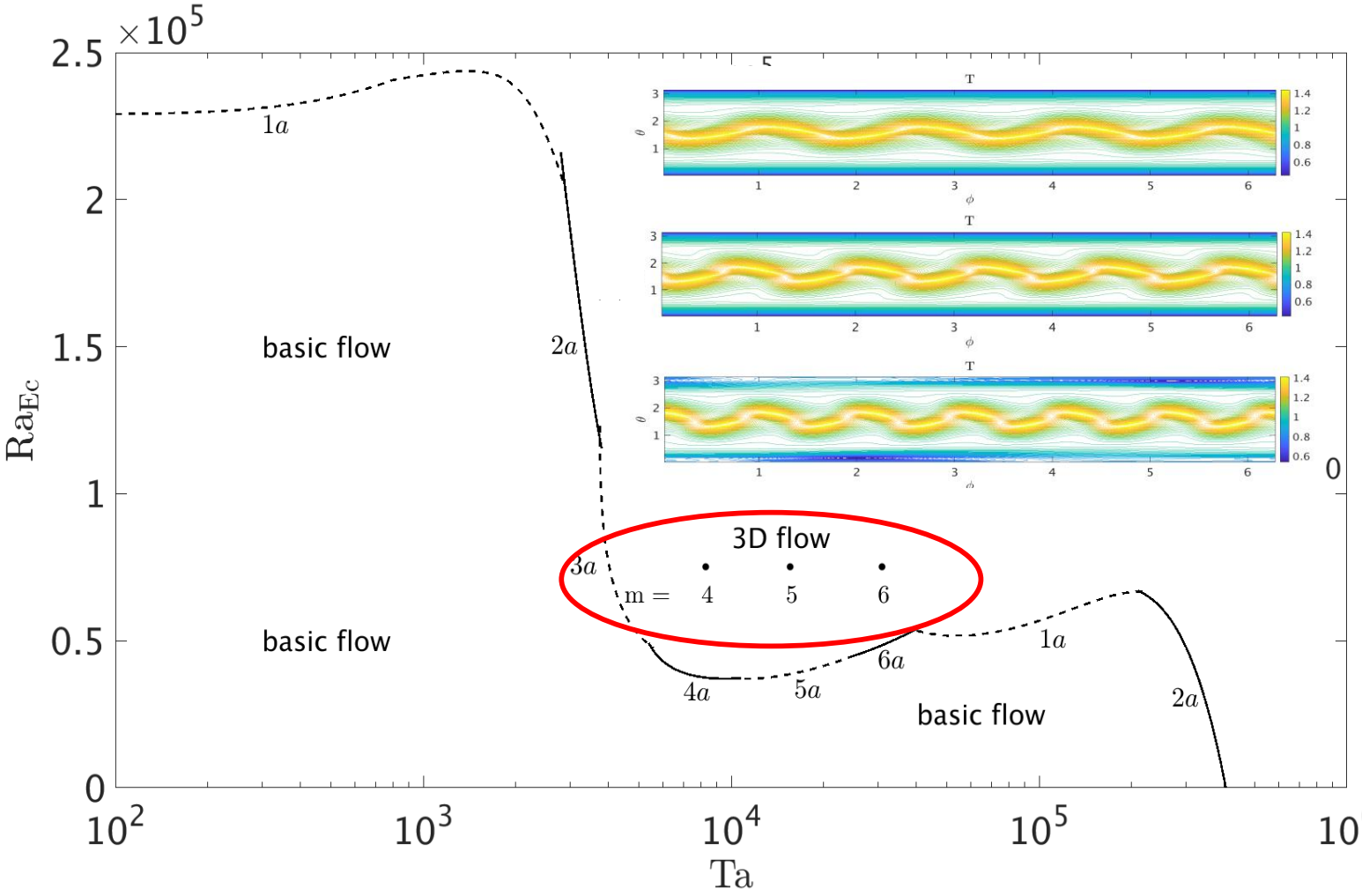




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AtmoFlow: Linear Stability Analysis



$Ta = 8000$
$m = 4$

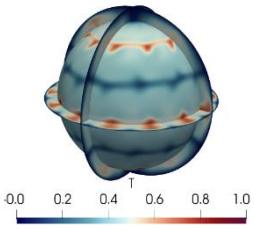
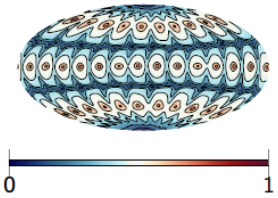
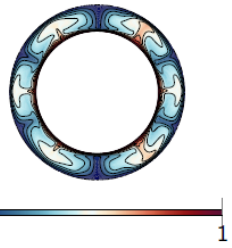
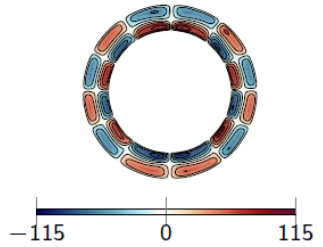
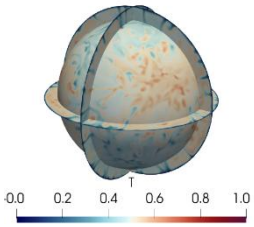
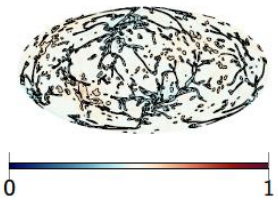
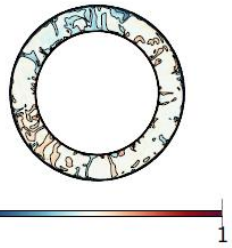
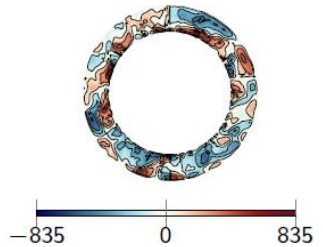
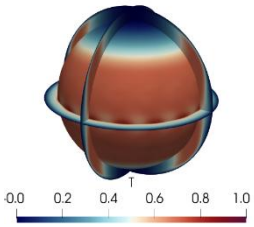
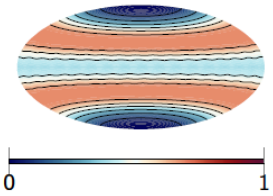
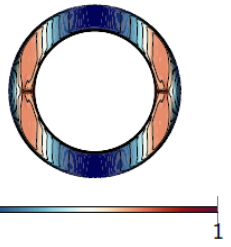
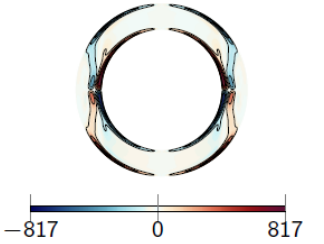
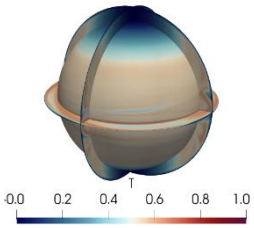
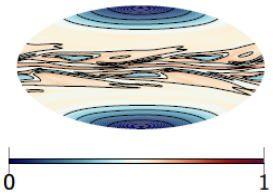
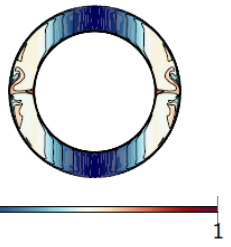
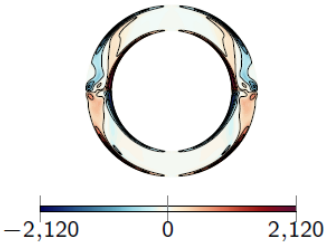
$Ta = 15000$
$m = 5$

$Ta = 30000$
$m = 6$

Travnikov, V., & Egbers, Ch. (2021). Numerical investigation of atmosphere like flows in a spherical geometry. **Phys. Rev. E**, **104(6)**, 065110.

AtmoFlow: 3D CFD - diff. rotation

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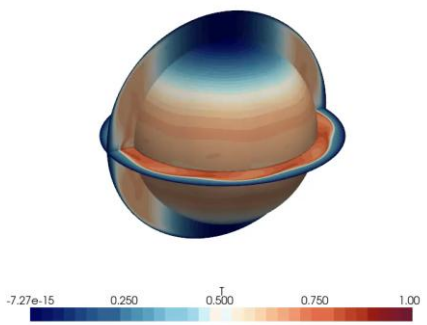
		Hammer-Aitov-projection, T	Pole to Pole plane, T	Pole to Pole plane, u_θ
Regular convective plumes[1] $Ra_E = 4.56\ \mathrm{E}5$ $Ta = 3.64\ \mathrm{E}3$ $Ro = 4.28\ \mathrm{E} - 1$				
Irregular convective flow[2] $Ra_E = 2.03\ \mathrm{E}7$ $Ta = 1.98\ \mathrm{E}4$ $Ro = 4.28\ \mathrm{E} - 1$				
Stable Stewartson layer in Keplerian flow[3] $Ra_E = 4.56\ \mathrm{E}5$ $Ta = 2.10\ \mathrm{E}7$ $Ro = 4.28\ \mathrm{E} - 1$				
Irregular flow with “wavy” Taylor vortex flow[4] $Ra_E = 1.83\ \mathrm{E}6$ $Ta = 2.10\ \mathrm{E}7$ $Ro = 1.14$				

[1]Zaussinger et al., Phys. Rev. Fluids, 2020
[2]Travnikov et al. Advances in Space Research, 2003
[3]Sawatzki et al., Acta Mechanica, 1970
[4]Hollerbach, JFM, 2003

AtmoFlow: 3D CFD - diff. rotation

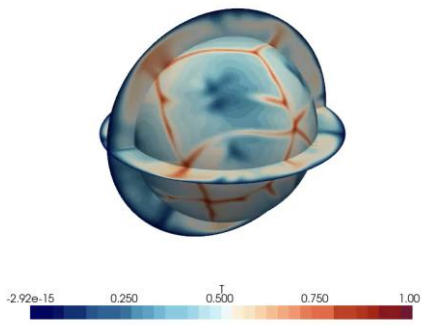
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Time:0.33



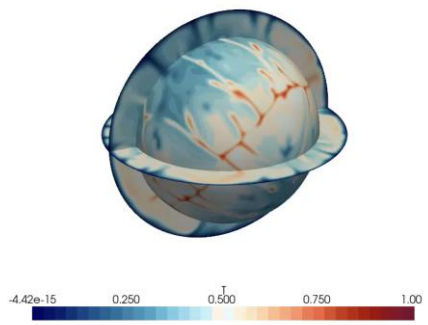
$Ra_E = 1.59e4$, $\mathrm{T}a = 6.37e5$, $\mathrm{Ro} = 0.708$

Time:0.86



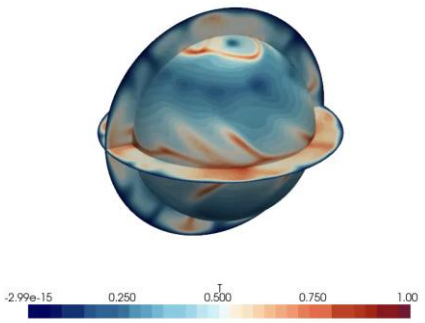
$Ra_E = 6.36e4$, $\mathrm{T}a = 110$, $\mathrm{Ro} = 0.429$

Time:2.07



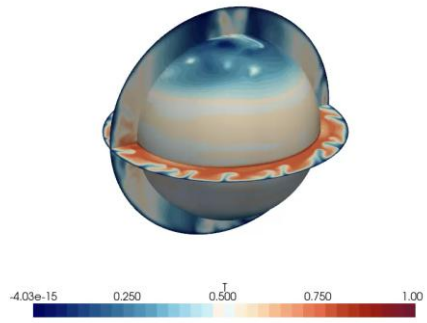
$Ra_E = 1.77e5$, $\mathrm{T}a = 110$, $\mathrm{Ro} = 0.429$

Time:10.01



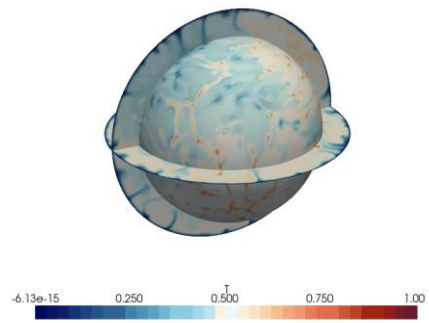
$Ra_E = 3.98e4$, $\mathrm{T}a = 610$, $\mathrm{Ro} = 0.429$

Time:0.82



$Ra_E = 4.42e5$, $\mathrm{T}a = 2.37e5$, $\mathrm{Ro} = 0.429$

Time:0.34



$Ra_E = 8.84e5$, $\mathrm{T}a = 110$, $\mathrm{Ro} = 0.429$

Gaillard, Y., Szabo, P.S.B, & Egbers, Ch., (2023), Thermo-electrohydrodynamic convection in the thermally driven spherical shell with differential rotation. **PAMM**, 24.1