GGSB at HZDR: cooperation in Geophysical and Astrophysical Fluid Dynamics

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Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

E. Kharadze Georgian National Astrophysical Observatory

GEORGIAN NATIONAL ASTROPHYSICAL OBSERVATORY

Georgian-German ScienceBRIDGE

CONNECTING PEOPLE AND KNOWLEDGE

HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

GGSB 2026: A Student and Collaboration Workshop

Outline

- Current cooperation between HZDR and Georgian National (Abastumani) Astrophysical Observatory – the main research topics and status

- Research activities at HZDR in the field of geophysical and astrophysical magnetohydrodynamics (MHD)

- Future plans for GGSB activities at HZDR

Mitglied der Helmholtz-Gemeinschaft

Topics of collaborative research:

Dynamics and evolution of geo- and astrophysical shear flows: accretion disks, solar and planetary interiors, solar wind and space plasma

— Linear modal/nonmodal stability theory

— Magnetohydrodynamic (MHD) instabilities, turbulence and magnetic dynamo processes

Mathematical tools: solving differential equations of MHD analytically and numerically via simulations using advanced fluid dynamics codes run on HZDR's high-performance computing facilities (HEMERA, ROSI)

Large-scale MHD experiments with liquid metals: DRESDYN, MATISSE, Magnetoconvection, Spherical Taylor-Couette setup

Georgian National (Abastumani) Astrophysical Observatory (ABAO)

(https://abao.ge/)









GEORGIAN NATIONAL ASTROPHYSICAL OBSERVATORY

The main research and education center in Astronomy and Astrophysics in Georgia, founded in 1932 by Acad. Prof. Evgeni Kharadze in picturesque landscape of mountain Kanobili, Abastumany, 1700m above sea level

Georgian National (Abastumani) Astrophysical Observatory (ABAO) (https://abao.ge/)

New ASA-150 Telescope

Meniscus telescope

Astrograph

Telescop-reflector

Refractor

Chromospheric Telescop

Coronograph







Departments at ABAO

- Sun and Solar System

- Galaxies and Stellar Systems

- Theoretical Astrophysics and Cosmology

Staff

9 Principal Research Scientists – constituting scientific council

13 Senior Research Scientists

16 Research Scientists

10 PhD and Masters students

Memorandum on exchange of students with Tbilisi State University (TSU)

Regular outreach activities — Observatory tours and lectures

Helmholtz-Zentrum Dresden-Rossendorf

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF





Cutting-edge research in Energy, Health and Matter

Distributed in 13 Institutes/departments:

1. High Magnetic Field Lab
2. Fluid Dynamics
3. Ion Beam Physics and Materials Research
4. Radiation Physics
5. Radio Oncology — OncoRay
6. Radiopharmaceutical Cancer Research
7. Resource Ecology
8. Resource Technology (in Freiberg)
9. CASUS (center for Advanced Systems Understanding
10. Theoretical Physics
11. Department of Research Technology
12. Department of Information Services and Computing
13. HEDI — Institute of High Energy Density Physics

DRESDEN concept

HZDR

GGSB at HZDR

In line with the main spirit of GGSB — connecting scientists from Georgian and Germany via common research projects and supporting students and young researchers via education and exchange programs
we assist talented students from Georgia to come to HZDR for carrying out masters or PhD research projects as well as organize conferences and workshops



Our first GGSB event at HZDR:
QUALI-Start-Up Lectures, 19-23 August 2025

GGSB speaker at HZDR:

Prof. Christian Richter

GGSB coordinators at HZDR:

Dr. Sandra Hamann
Dr. George Mamatsashvili

Students at HZDR within GGSB since 2025 jointly funded by HZDR and Rustaveli National Science Foundation of Georgia

3 PhD students:

Luka Burdiladze (TSU, ABAO) — MHD turbulence in shear flows: non-ideal MHD effects

Daviti Kobaidze (TSU, ABAO) — Magnetic dynamo in astrophysical disks

Mariami Kavtaradze (TSU, ABAO) — MHD turbulence in the Solar Wind: effects of velocity shear

1 Masters student:

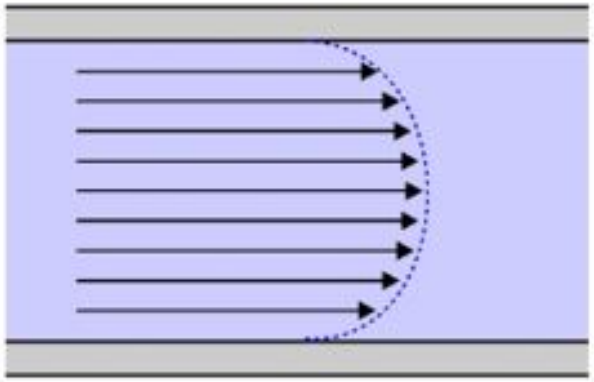
Luka Tsulukidze (TSU) — Shear-driven dynamos in liquid cores of the Earth

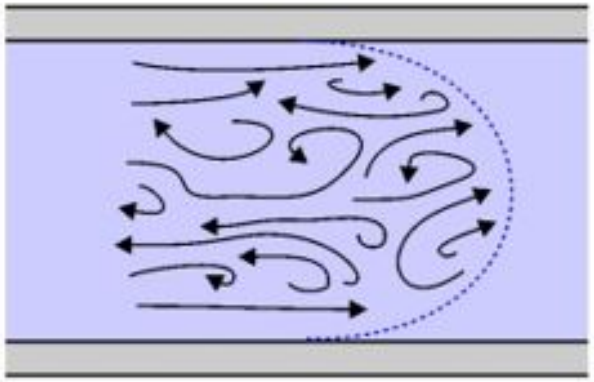
2 Intership students:

Mariam Kenkadze (FUT) — Rariopharmaceutical Cancer Research

Nika Chakhunashvili (ISU) — Radiation Physics

The collaborative research between HZDR and ABAO mainly focusses on geo- and astrophysical objects (accretion disks, the Sun, planets, solar wind, space plasma etc.) and dynamical processes therein, which contain inhomogeneous, or shear flows using state-of-the art numerical simulations and large-scale experiments





Governing equations of non-ideal magnetohydrodynamics (MHD)

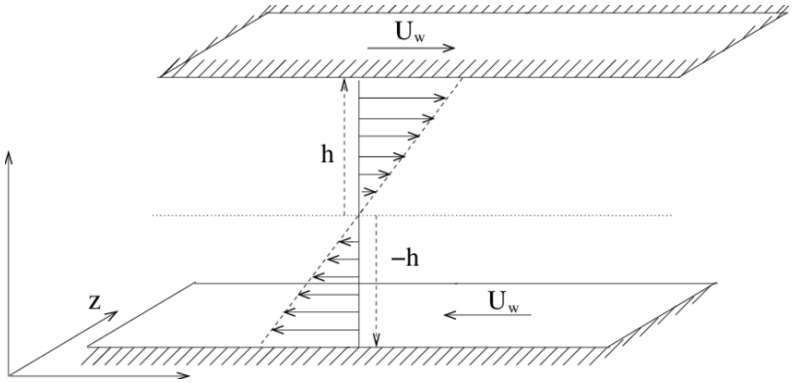
$$\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U}\cdot\nabla)\,\mathbf{U} = -\frac{\nabla P}{\rho} + \frac{(\mathbf{B}\cdot\nabla)\,\mathbf{B}}{4\pi\rho} + \nu\nabla^2\mathbf{U},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{U}\times\mathbf{B}) + \eta\nabla^2\mathbf{B},$$

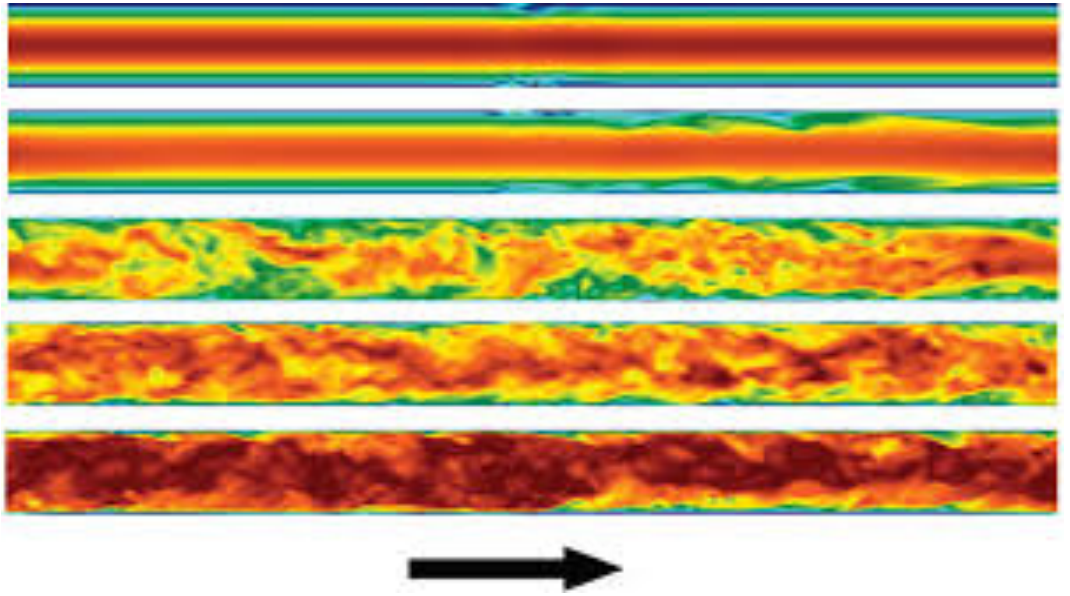
$$\nabla\cdot\mathbf{U} = 0,$$

$$\nabla\cdot\mathbf{B} = 0,$$

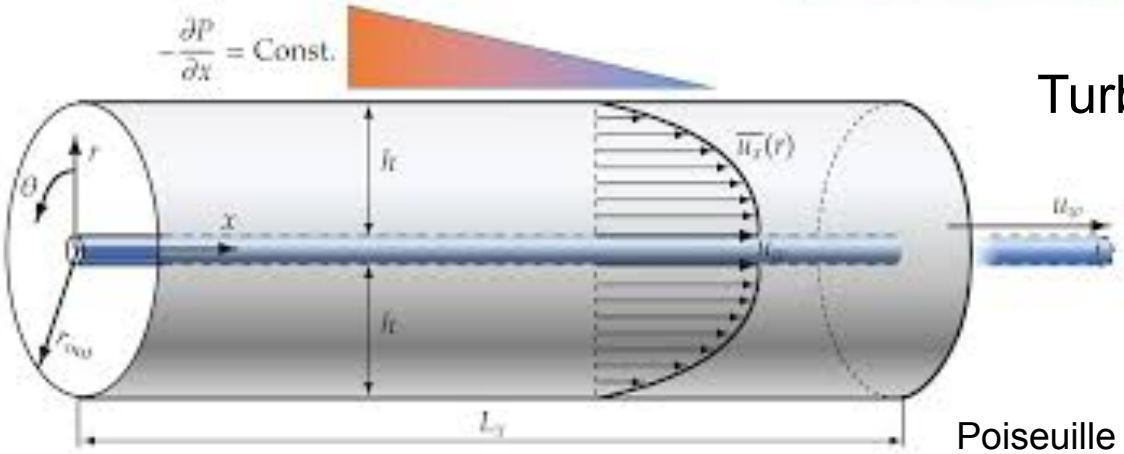
Simple/basic (but very important) plane Couette and pipe Poiseuille shear flow in engineering



Plane Couette flow



Turbulization of the laminar flow



Poiseuille flow

The classical (modal) stability theory of shear flows has been around since 19th century, however, there has been increasing evidence for deviations of experimental and theoretical results for shear flows — there were cases when instabilities and turbulence emerge in experiments but not in modal theory!

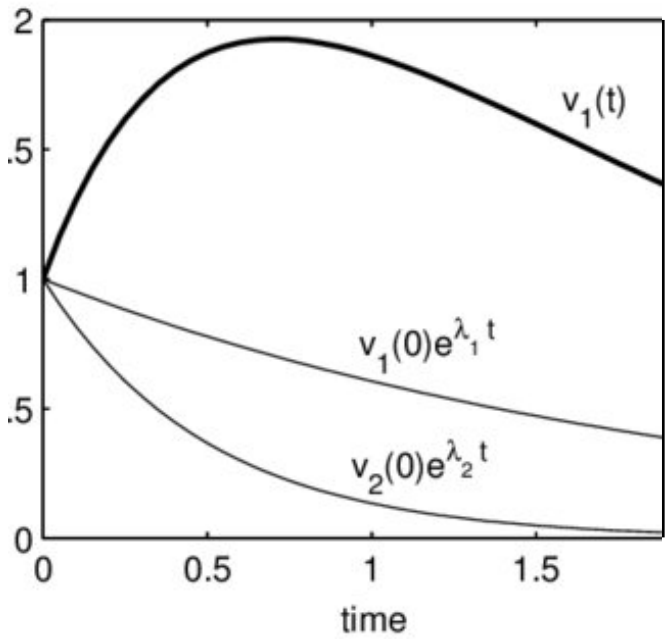
Breakthrough by hydrodynamical community in the 90s

(Schmid & Henningson 2001, Schmid 2007)

Rethinking of shear flow phenomena — demonstration of the non-orthogonal (non-self-adjoint) nature of the linear dynamics of perturbations in shear flows and its consequences — transient growth and mode coupling

A new mathematical approach -- **non-modal analysis** developed

Linear nonmodal/transient growth of perturbations in shear flows



Nonmodal growth -- very important process, which is capable of causing transition to turbulence in the shear flow even when the flow is apparently stable according to classical modal analysis (i.e., has decreasing in time normal modes)

Mitglied der Helmholtz-Gemeinschaft

The Plasma Astrophysics Group at ABAO actively participated and greatly contributed to the progress in understanding shear flow phenomena in the 1990-2010s and showed their importance in geophysical and astrophysical shear flows, in particular in **accretion disks** and **the Sun**

(e.g., Lominadze et al. 1988, Chagelishvili et al. 1992, 1996, 1997, 2002, Tevzadze et al. 2003, 2008, 2010, Gogoberidze et al. 2004, Gogoberidze et al. 2007, Mamatsashvili & Chagelishvili 2007, Mamatsashvili et al. 2010, ……)

Mitglied der Helmholtz-Gemeinschaft

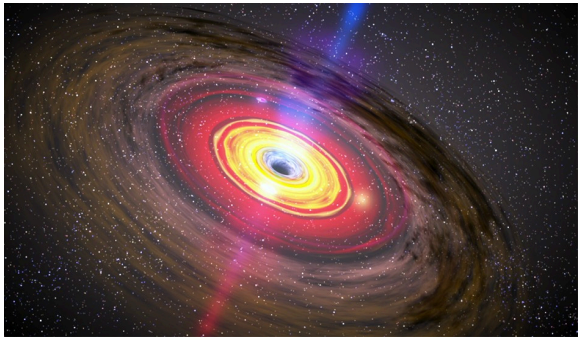
Geo- and astrophysical shear flows of our interest

Keplerian accretion disks — sites of intense radiation and planet formation

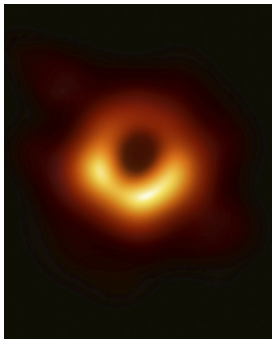
MHD instabilities (MRI), turbulence and magnetic dynamo in Astrophysical Disks

turbulence ensures accretion of matter from the disk onto the centeral object and resulting energy dissipation and strong radiation, which is observed

Goal: understanding onset and sustenance of turbulence and dynamo action in the disks under different non-ideal MHD effects: Ohmic, Hall and ambipolar diffusion







black hole accretion disk in the supergiant elliptical Galaxy M87

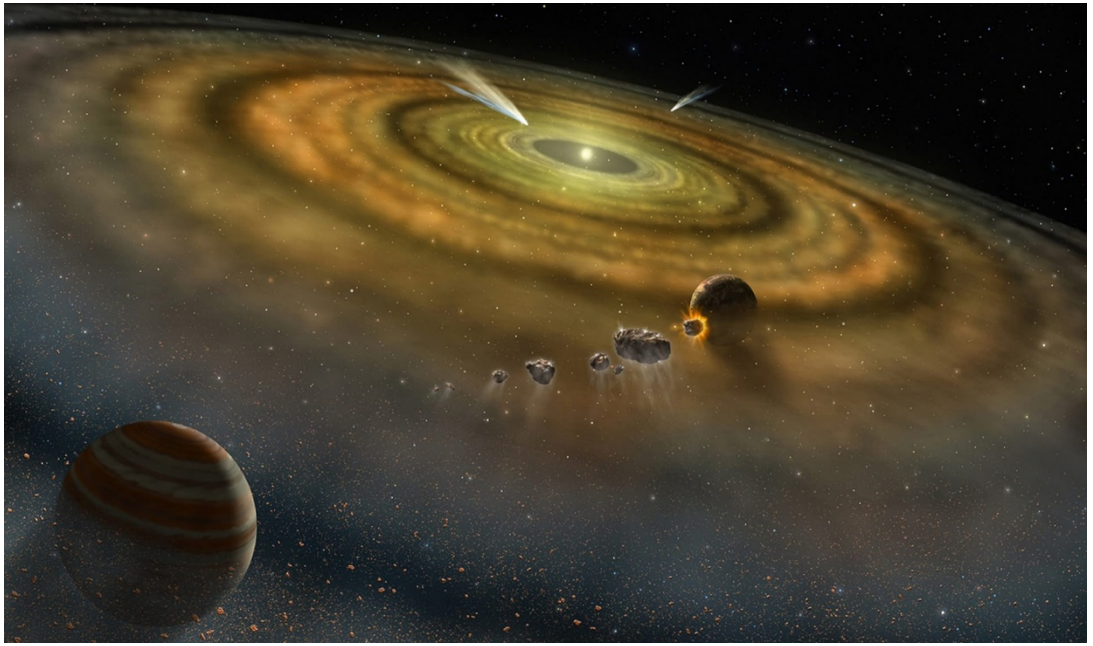
Black hole accretion disk with corona and jet (credit: NASA)

Geo- and astrophysical shear flows of our interest

Protoplanetary disks around Young Stellar Objects – birthplace of planetary systems



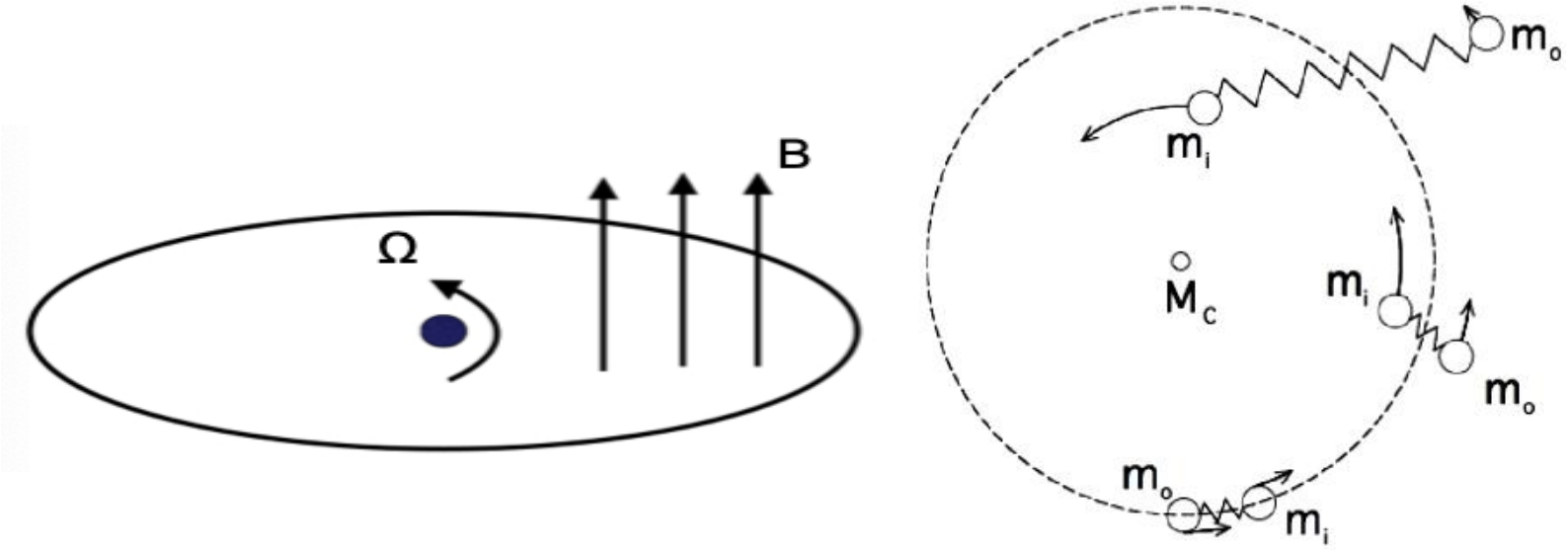
HL Tauri (Credit: ALMA)



Credit: NASA

Magnetorotational instability (MRI)

Powerful dynamical instability arising in the presence of differential rotation (shear) threaded by background magnetic field

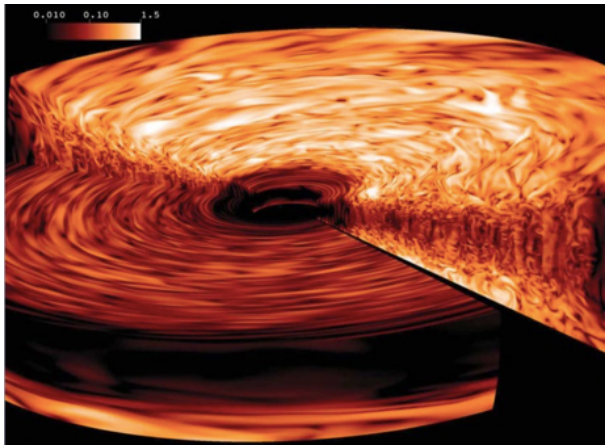


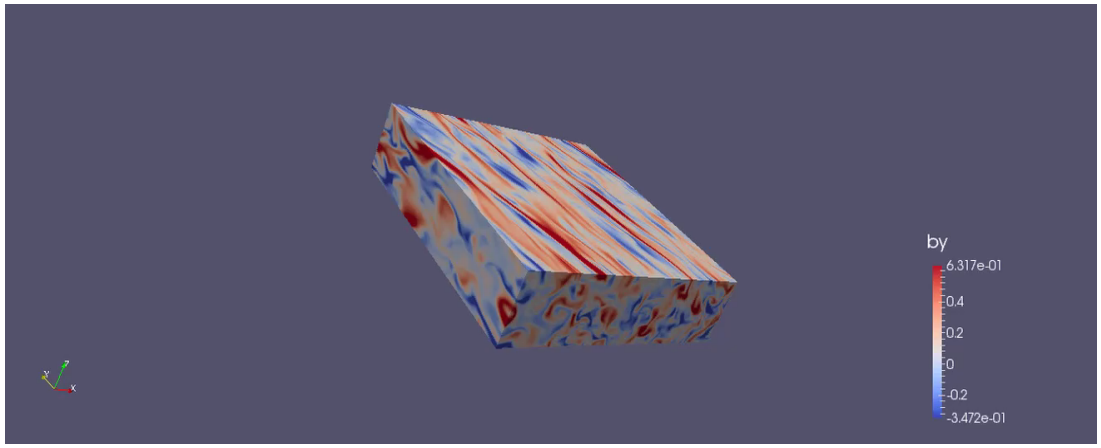
MRI is one of the most important instabilities in astrophysics, driving angular momentum transport and mass accretion in disks

(Balbus & Hawley 1991, 1998)

Mitglied der Helmholtz-Gemeinschaft

Nonmodal growth of MRI triggers turbulence in astrophysical disks



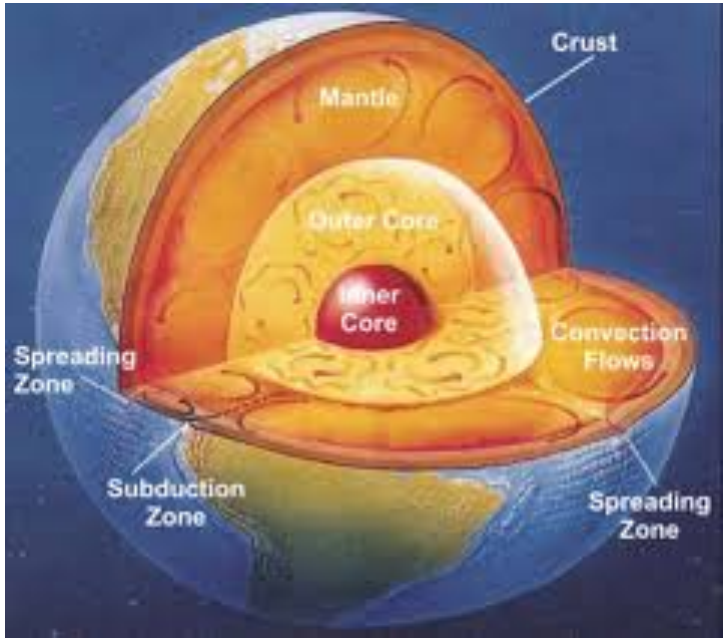


We investigate self-sustenance and dynamics of MHD turbulence in disk shear flow by analyzing individual linear and nonlinear dynamical processes in basic MHD equations in Fourier space under non-ideal MHD effects — Ohmic, Hall and ambipolar diffusion

(Mamatsashvili et al. 2020, Goichaishvili, Mamatsashvili et al. 2017, Held & Mamatsashvili 2022)

Geo- and astrophysical shear flows of our interest

Rotating shear flows in the liquid metal outer core of the Earth — drivers of Geodynamo

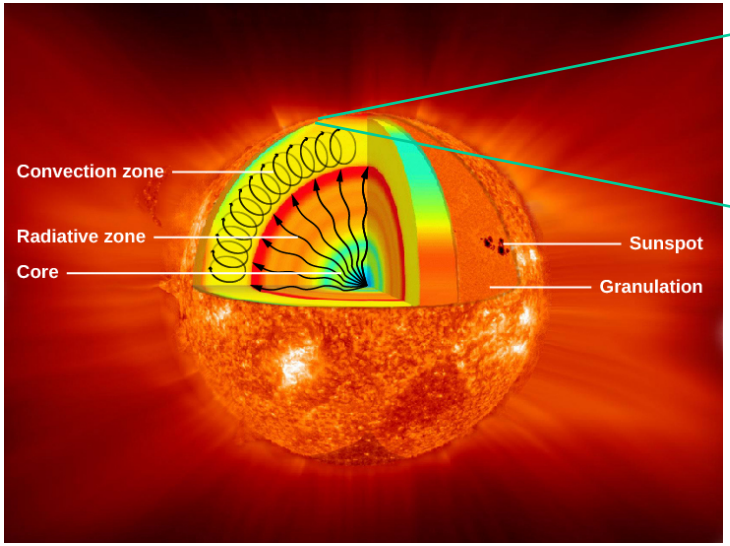




Important for understanding the Geodynamo process — origin, evolution and variability (excursions, reversals) of the geomagnetic field

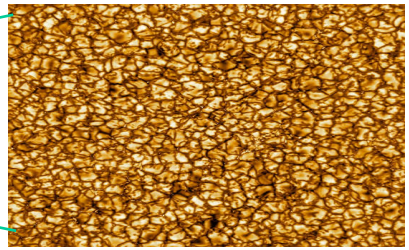
Geo- and astrophysical shear flows of our interest

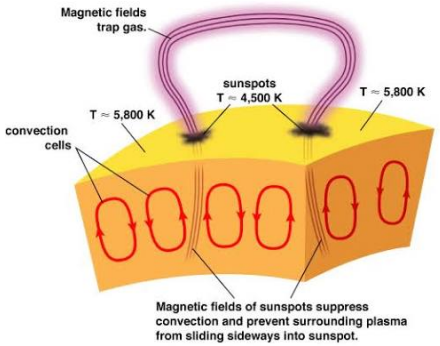
Interplay of the solar differentially rotation (shear) and magneto-convection in driving the solar dynamo

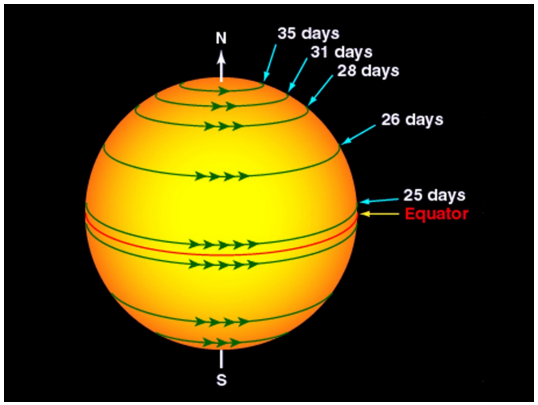


Solar interior

Convection cells on the solar surface





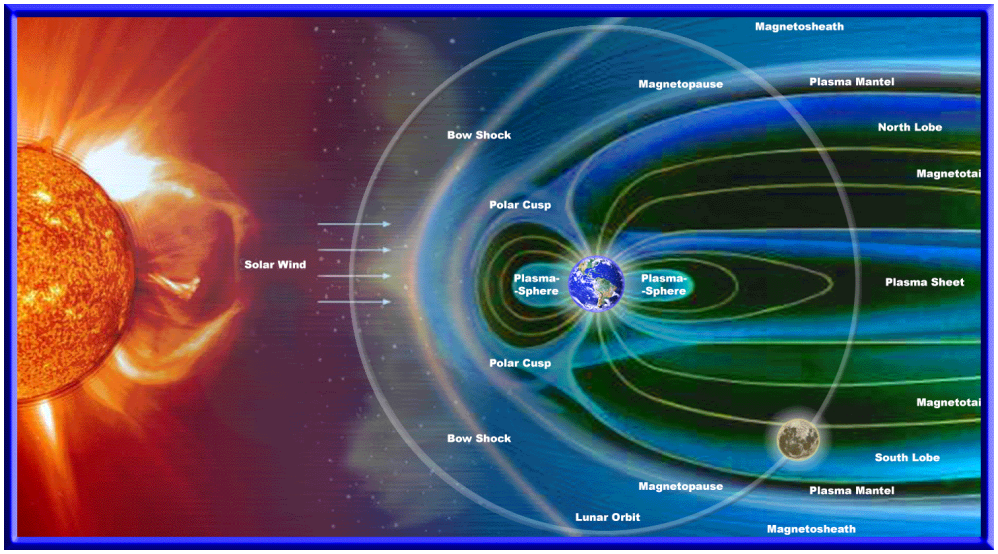


Solar differential rotation (shear)

Important for understanding the origin of the Sun's magnetic field and its variability of different time-scales

Geo- and astrophysical shear flows of our interest

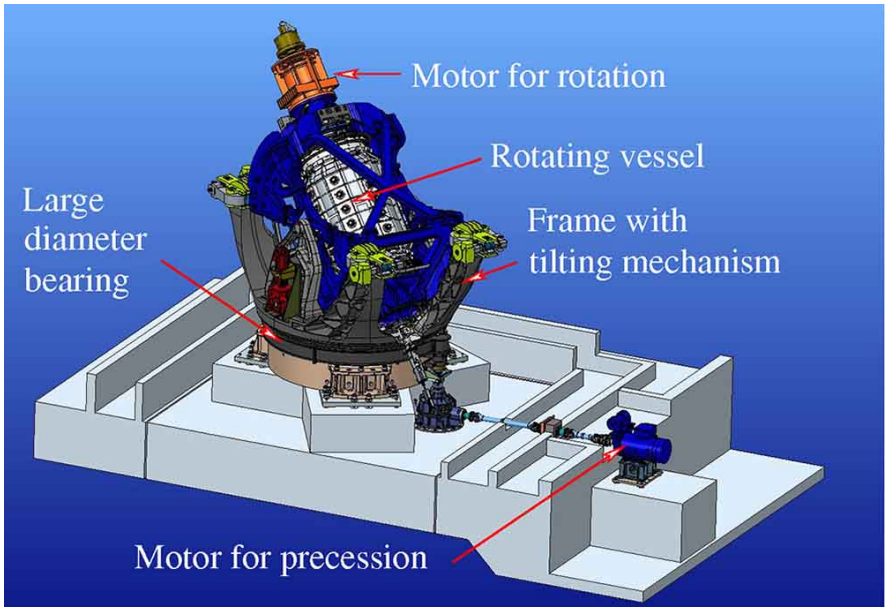
Solar wind and space plasma flows



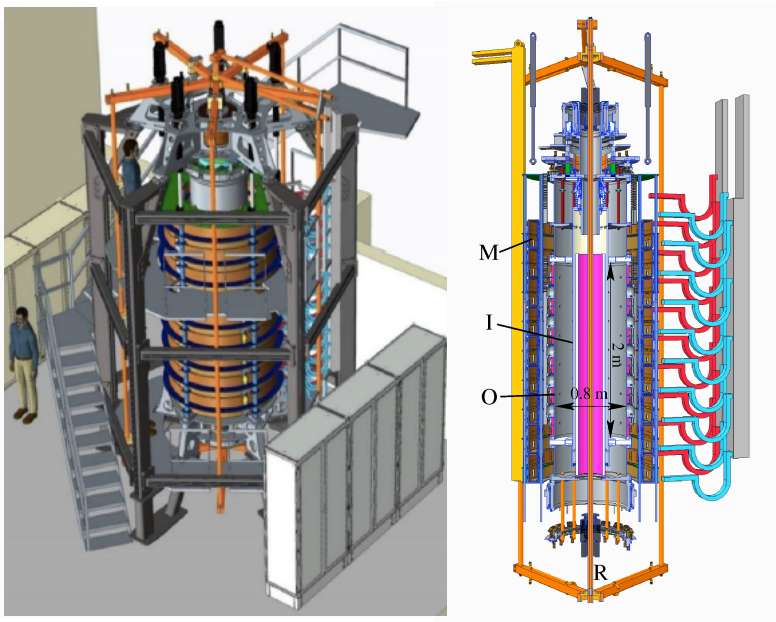
Energetic processes in the solar atmosphere drive MHD turbulence in the solar wind which propagate towards the Earth and, interacting with geomagnetic field, shapes **space weather**

Our goal is to understand the role of velocity shear of the solar wind in the dynamics and spectral properties of MHD turbulence

Cutting-edge precession dynamo and MRI/TI experiments



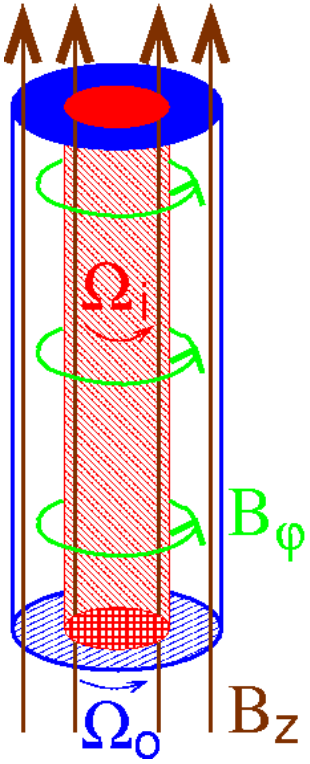
DRESDYN — Precession dynamo experiment

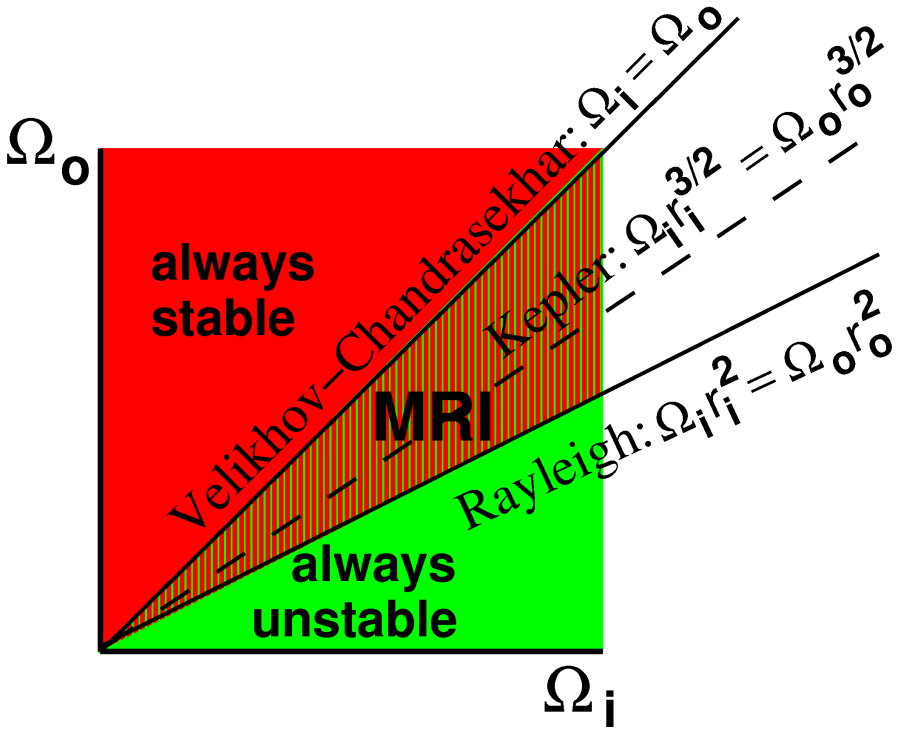


MATISSE — MRI/TI experiment

MRI in the lab — magnetized Taylor-Couette (TC) flows

Cylindrical MHD Taylor-Couette setup threaded by external magnetic field is used for laboratory studies of MRI





Liquid metals have small magnetic Prandtl numbers = viscous/ magnetic diffusivity

$Pm = \nu/\eta$ ~ 10^{-6}-10^{-5}

Mitglied der Helmholtz-Gemeinschaft

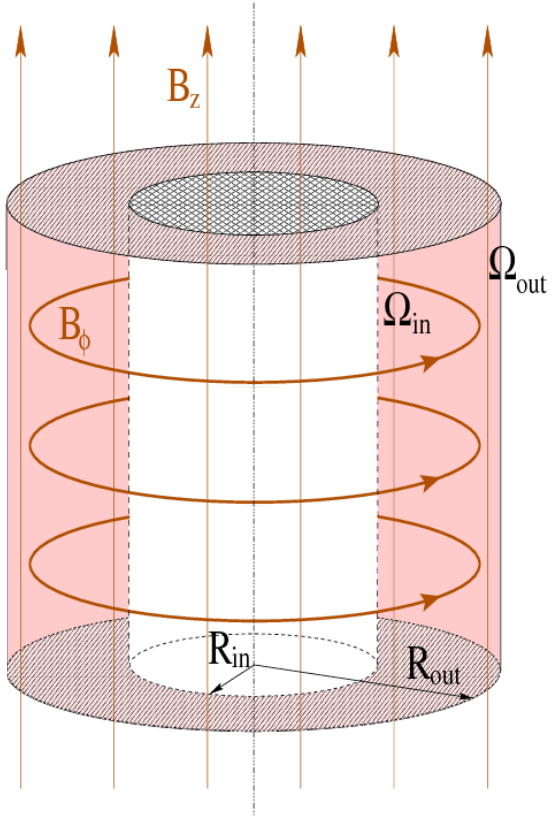
Main equations of non-ideal incompressible MHD in cylindrical geometry and relevant parameters

$$\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U}\cdot\nabla)\mathbf{U} = -\frac{1}{\rho}\nabla\left(P + \frac{\mathbf{B}^2}{2\mu_0}\right) + \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{\mu_0\rho} + \nu\nabla^2\mathbf{U},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{U}\times\mathbf{B}) + \eta\nabla^2\mathbf{B},$$

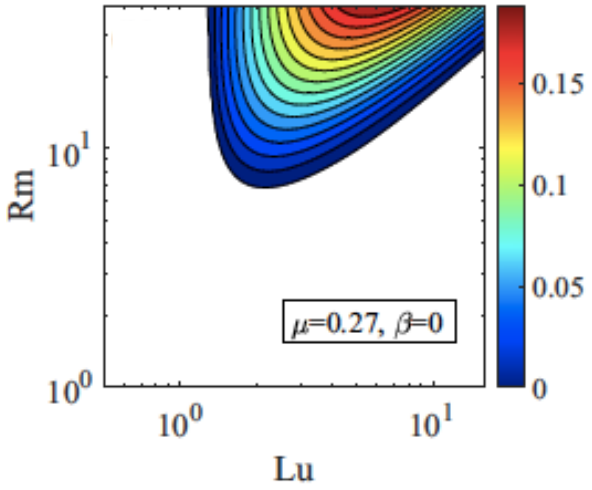
$$\nabla\cdot\mathbf{U} = 0, \quad \nabla\cdot\mathbf{B} = 0.$$

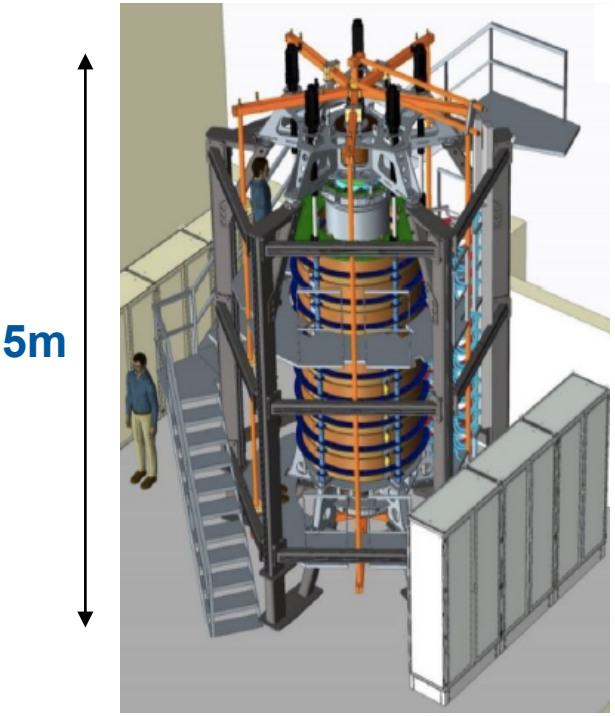
Dimensionless Parameter	Definition
μ	Ω_{out}/Ω_{in}
β	$B_\phi(r_{in})/B_0$
Normalised height of TC device (L_z)	H/r_{in}
Renolds number (Re)	$\Omega_{in}r_{in}^2/\nu$
Hartmann number (Ha)	$B_0 r_{in}/\sqrt{\rho\mu_0\nu\eta}$
Magnetic Prandtl Number (Pm)	ν/η
Magnetic Reynolds Number (Rm)	$RePm$
Lundquist Number (Lu)	$Ha\sqrt{Pm}$
Azimuthal *Hartmann number* (Ha_ϕ)	$B_\phi(r_{in})r_{in}/\sqrt{\rho\mu_0\nu\eta}$
Azimuthal *Lundquist Number* (Lu_ϕ)	$Ha_\phi\sqrt{Pm}$

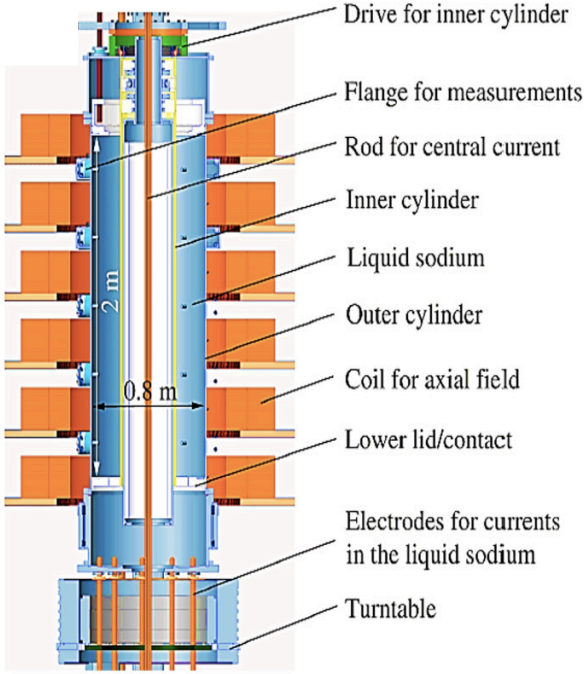


The new MRI/TI experiment MATISSE

Physical Parameter	Values
r_{in}	0.2 m
r_{out}	0.4 m
H	2 m
Ω_{in}	$\leq 2\pi \cdot 20$ Hz
Ω_{out}	$\leq 2\pi \cdot 6$ Hz
Axial magnetic field (B_0)	≤ 150 mT
Current through central rod (I)	≤ 50 kA
Conductivity (σ)	$9.5 \times 10^6 S/m$
Viscosity(ν)	$6.512 \times 10^{-7} m^2/s$
Density (ρ)	920 kg/m^3







Higher magnetic fields

Lu<10 and higher Rm<40

sufficient for capturing standard MRI in MATISSE experiment

DRESDYN project — DREsden Sodium facility for DYNamo studies — is a platform for large-scale liquid sodium experiments devoted to fundamental geo- and astrophysical problems as well as to various applied problems related to the conversion and storage of energy

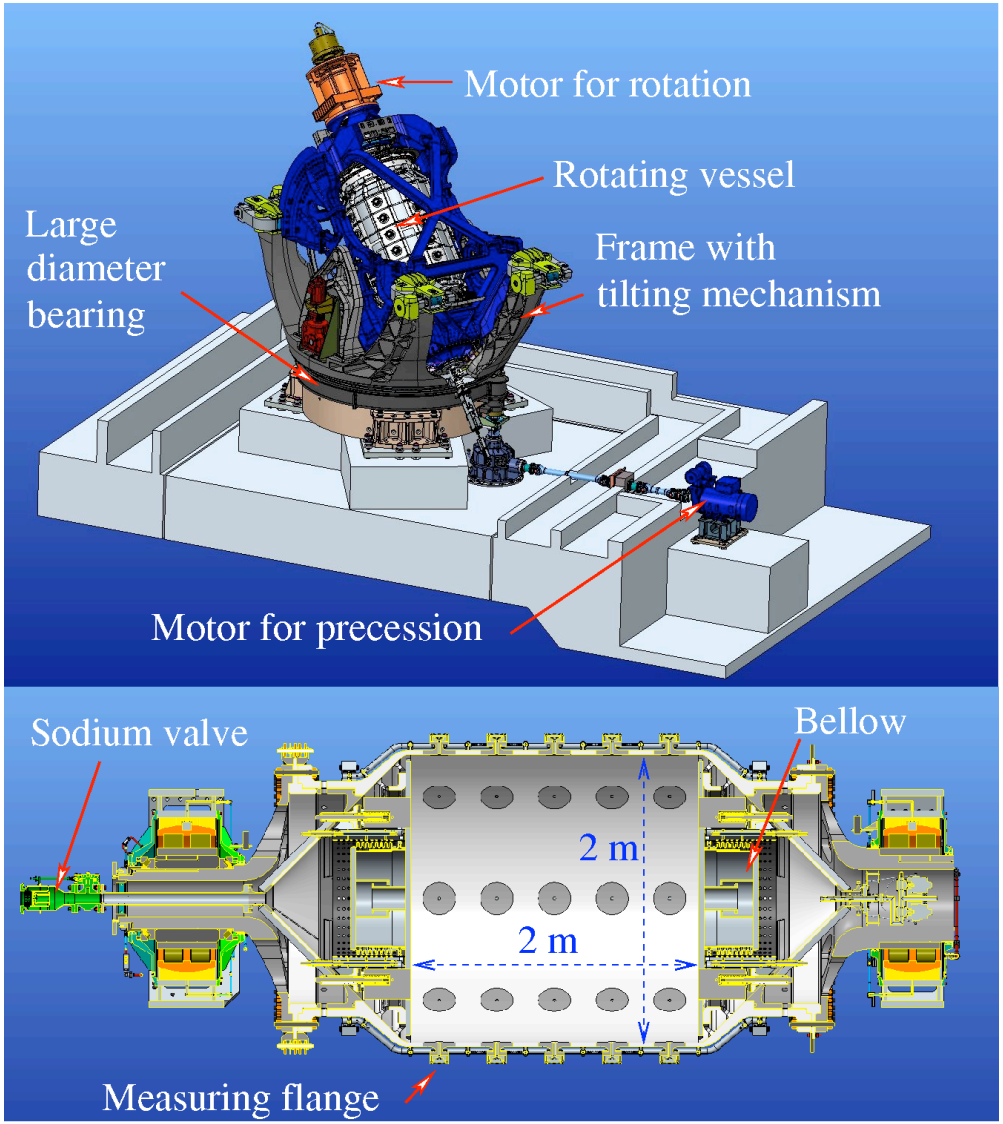
- **Precession driven dynamo experiment** with separate strong basement
- Large experimental hall for **MRI/TI experiment**

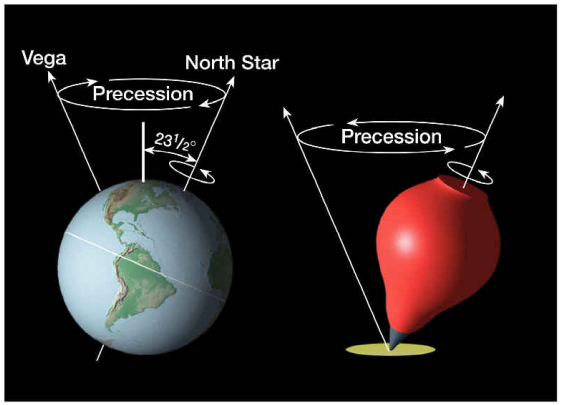




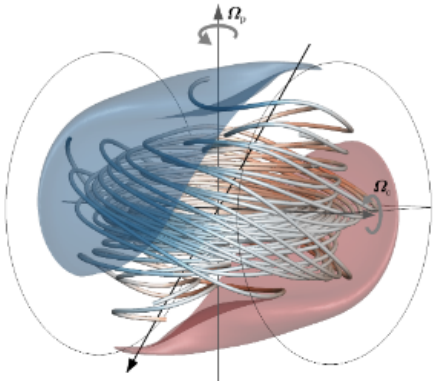
Stefani et al (2019)

The precession-driven dynamo experiment in DRESDYN





Earth's precession is the gradual shift in the orientation of its rotation axis with a cycle of 26,000 years



Flow structure in the cylinder that can amplify the magnetic field

DRESDEN concept

HZDR

GEORGIAN-GERMAN Joint Programme for Master and PhD Students

Further collaboration topics between HZDR and ABAO/TSU in the field of Geophysical and Astrophysical MHD

1. MRI-turbulence and dynamo in disks — Hall effect and ambipolar diffusion

2. SMRI in magnetized TC flows — the effects of endacps and detection in MATISSE experiment

3. Alfvén waves in the Sun and in the laboratory — the role in Coronal Heating

4. Planetary and Geo-dynamo — the origin and variability of planetary magnetic fields

Organization of future GGSB Workshops and Lecture Weeks

Mitglied der Helmholtz-Gemeinschaft

Thank you for attention