

地磁気、陰陽、仮想現実

神戸大学

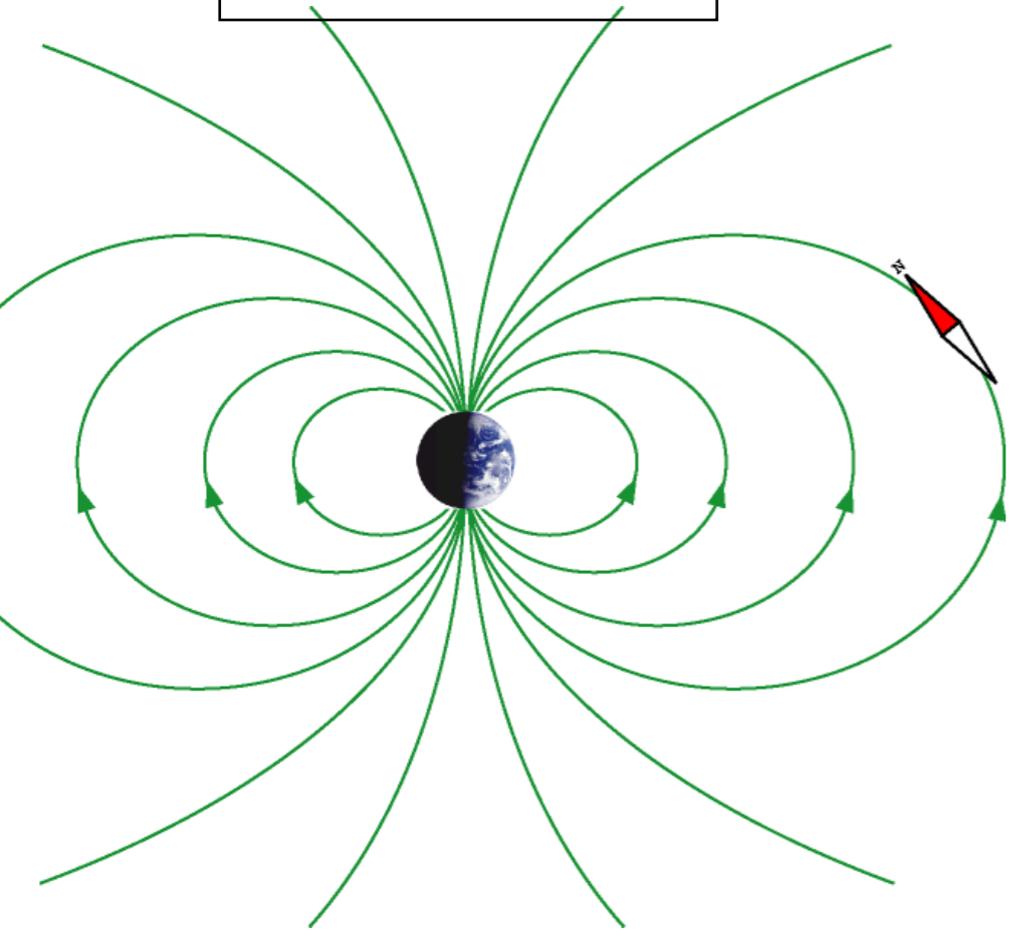
大学院システム情報学研究科

計算科学専攻

陰山 聡

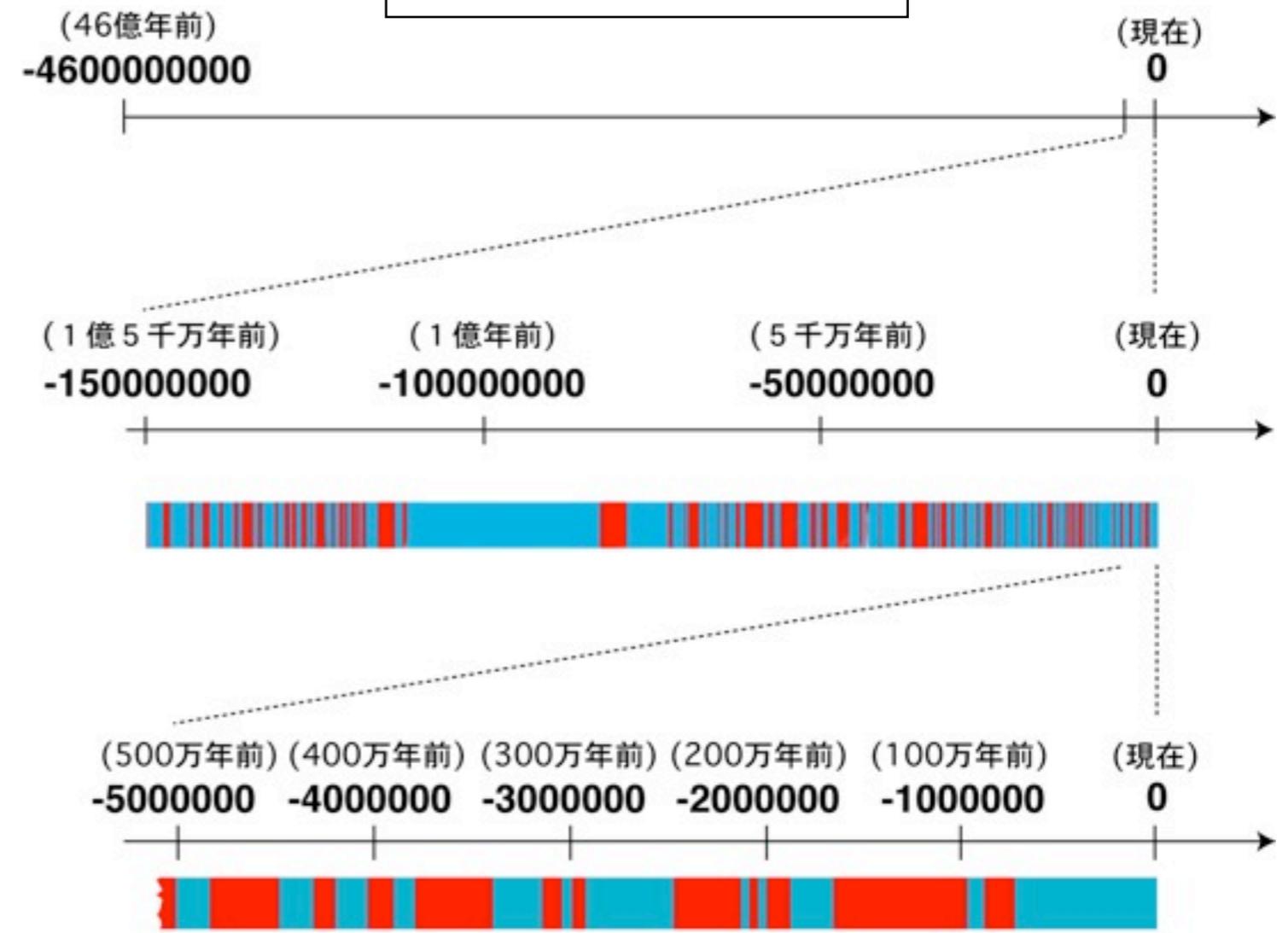
地磁気の2大特徴

双極子磁場



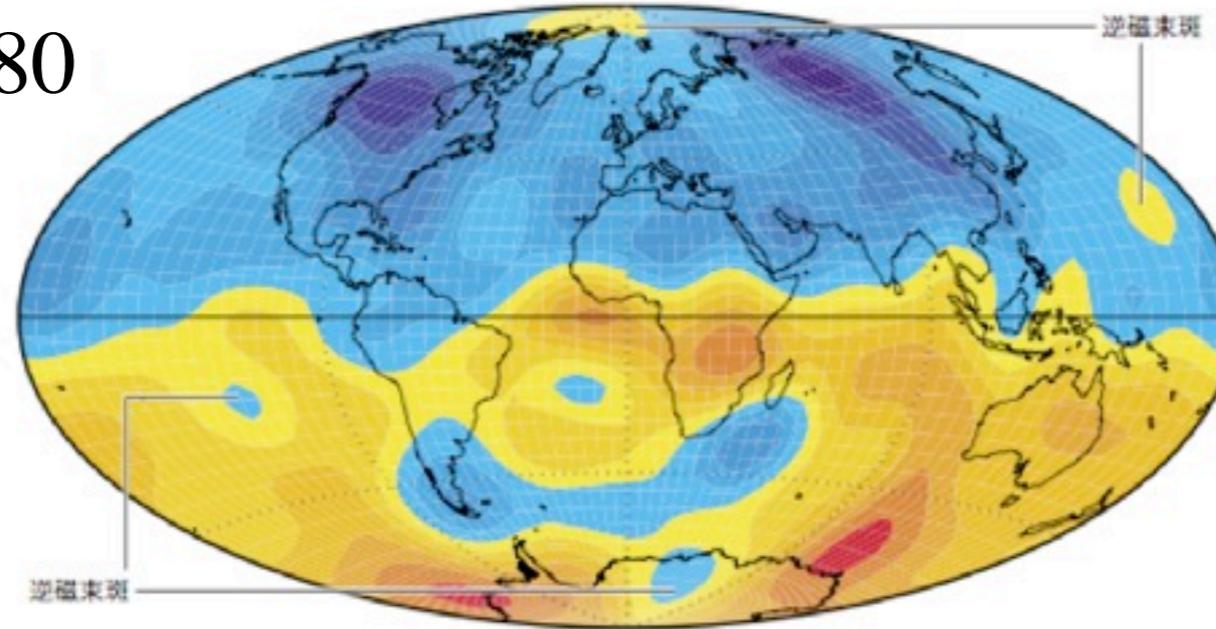
$B = 20 \sim 50 \mu\text{T}$ (地表)

非周期的 逆転

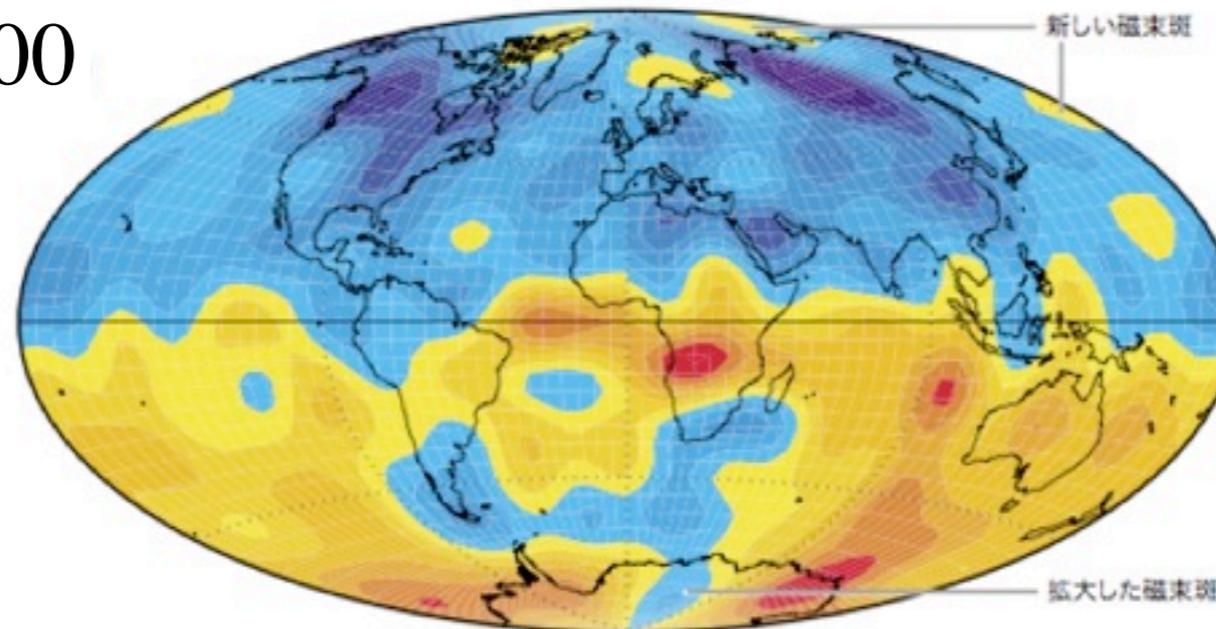


衛星観測によるコア表面上の磁場 (半径方向成分) の分布

1980



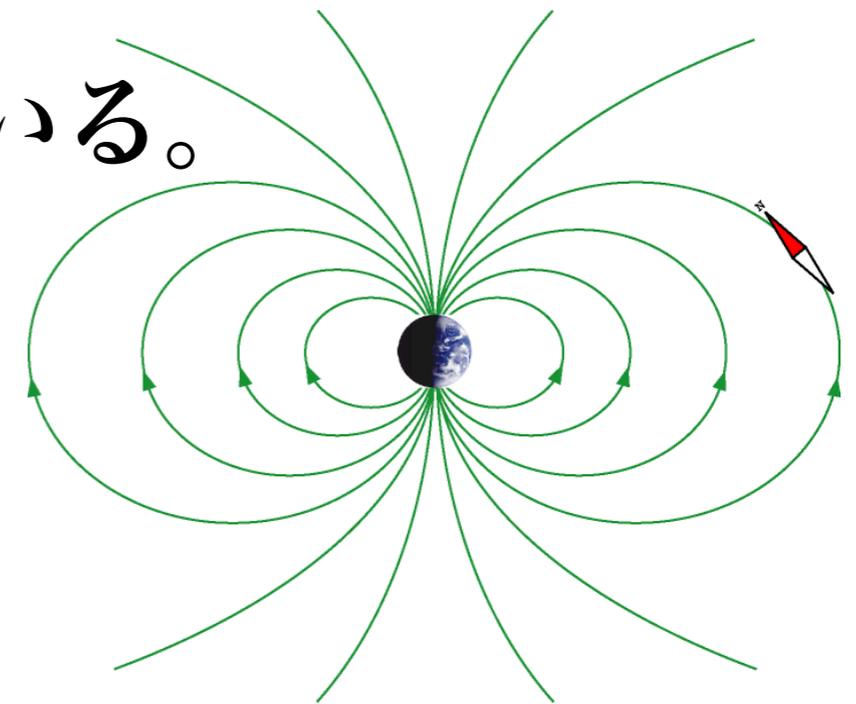
2000



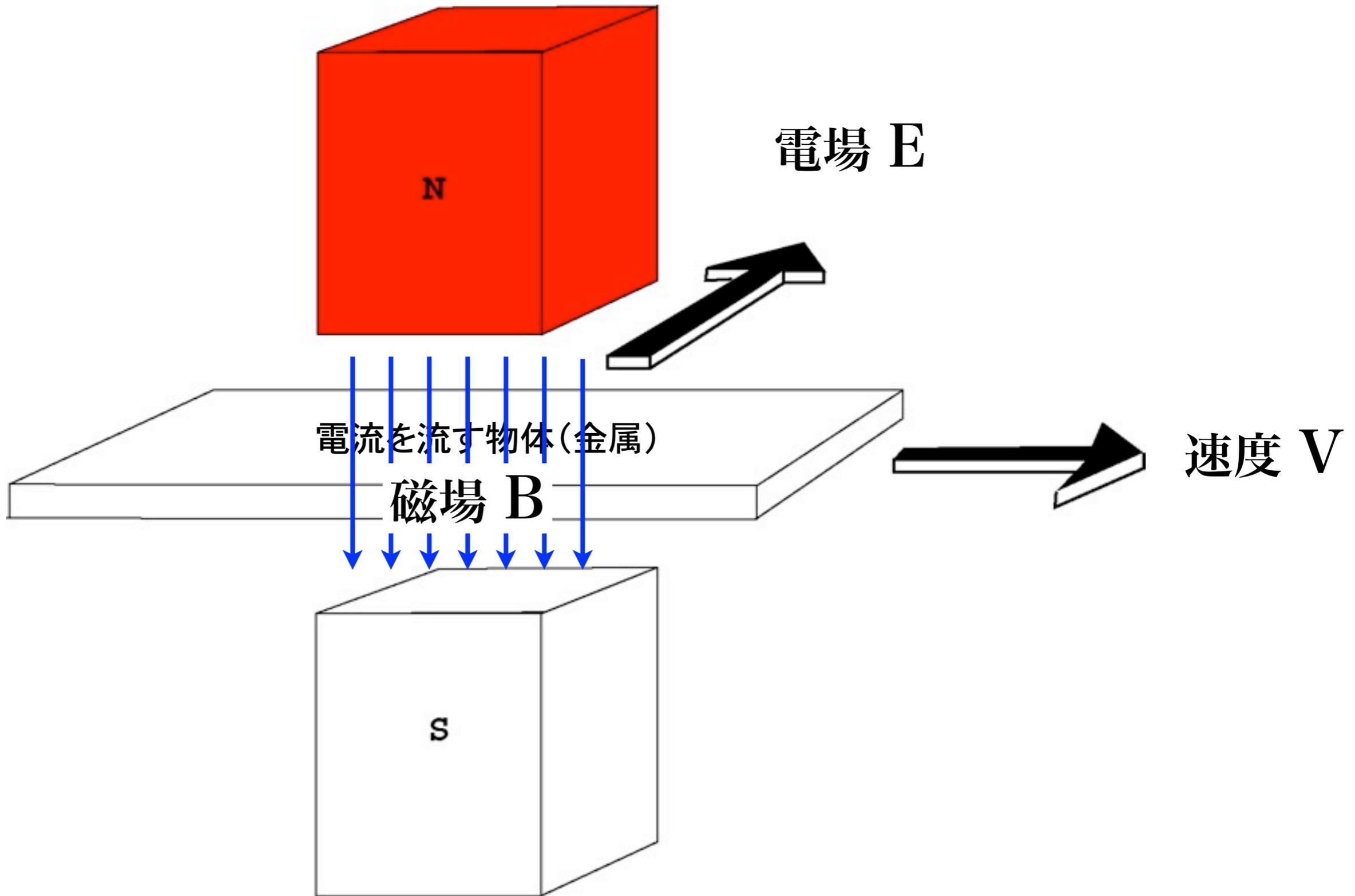
磁石方式



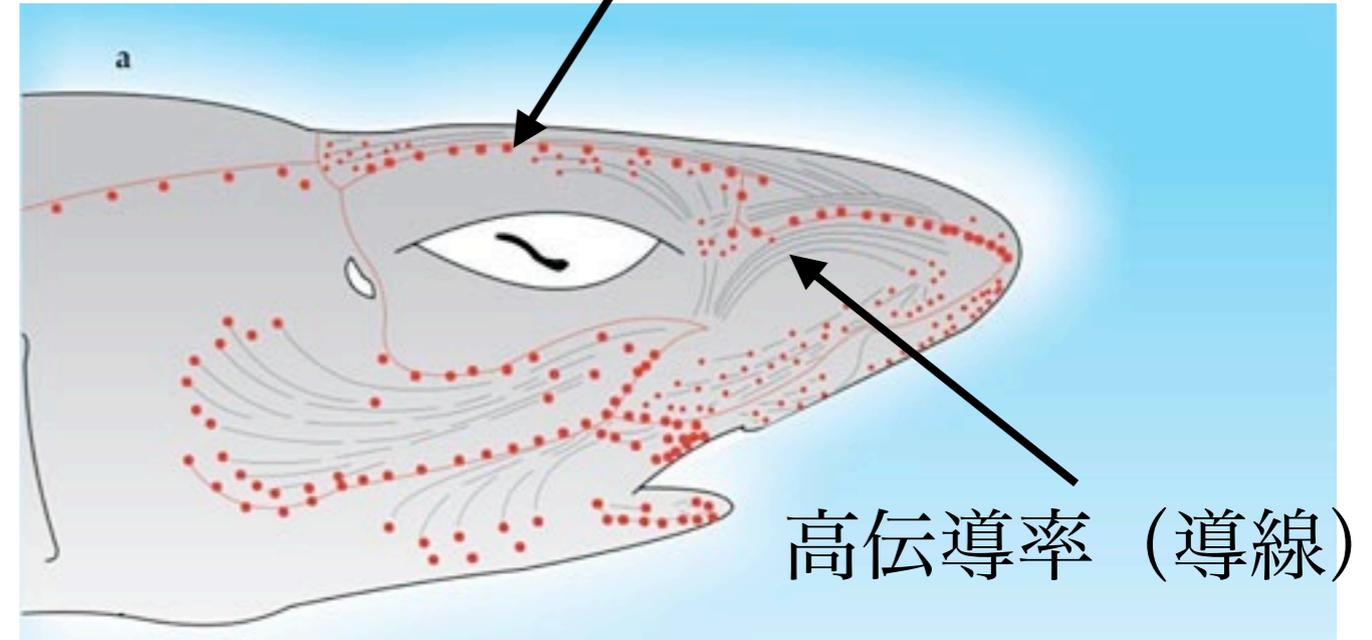
- 走磁性細菌。池（泥）の中。嫌気性。
- 1975年 米国。国内でも発見されている。
- 磁鉄鉱の粒（約20個が連結）
- 粒 40 nm = 単一の磁区
- 南北ではなく上下を知るため。
- 北半球ではS極を好む種類。南半球では逆。



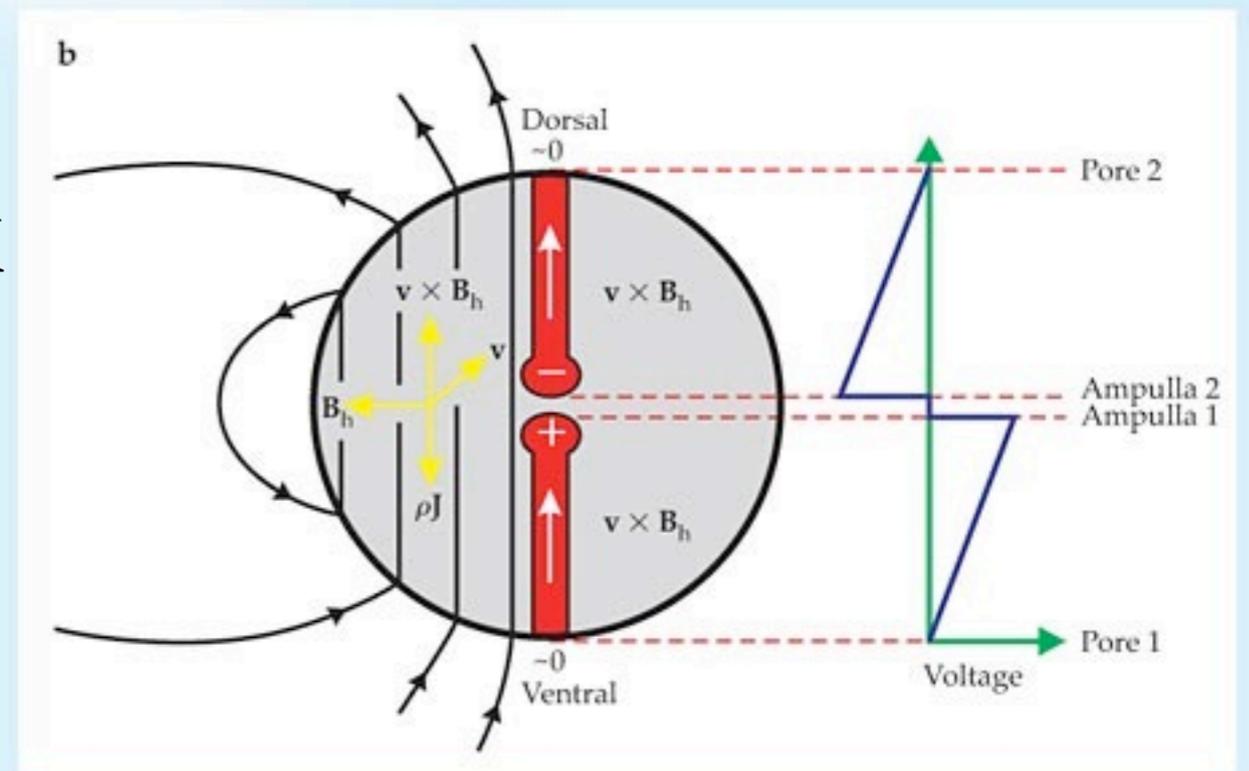
電磁誘導



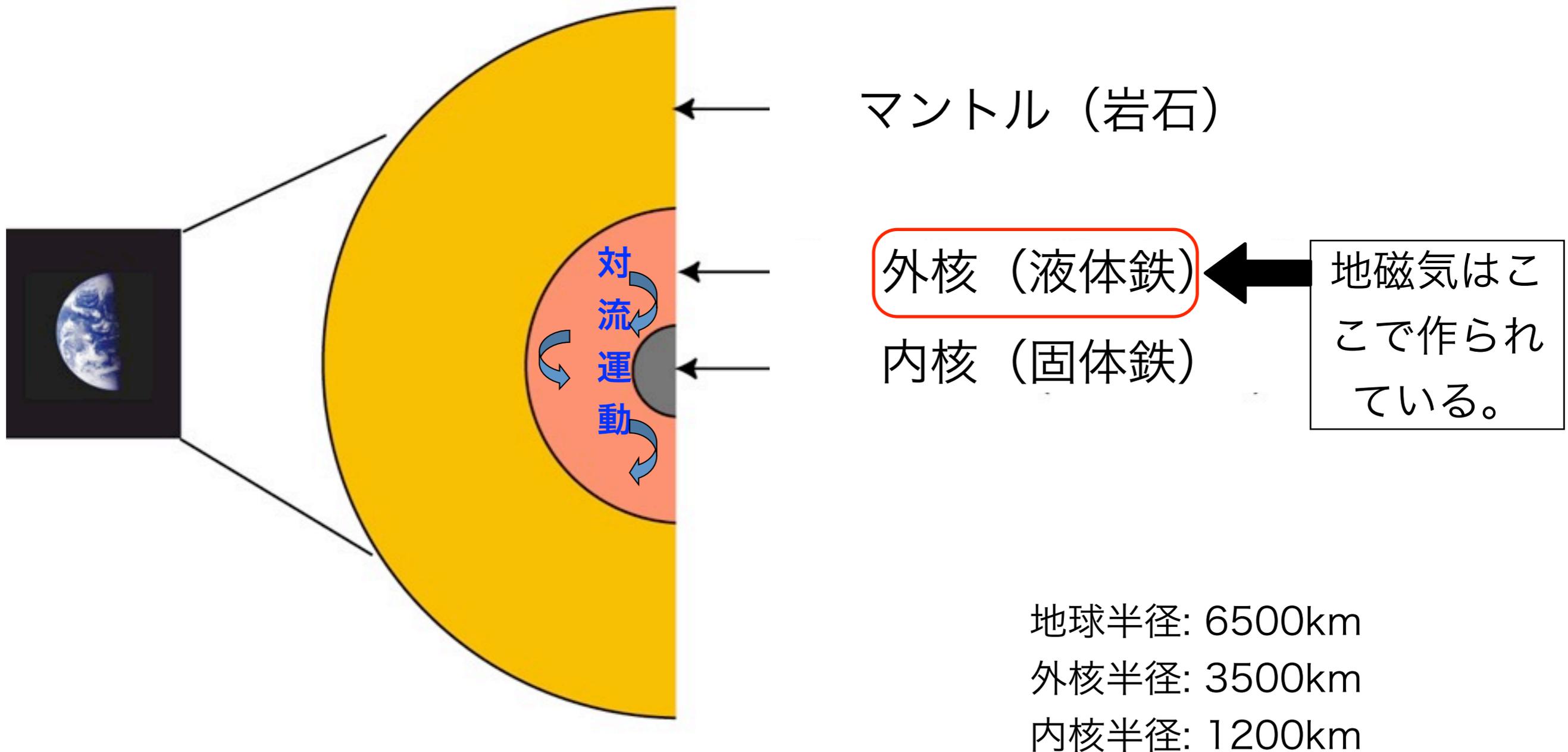
電磁誘導方式



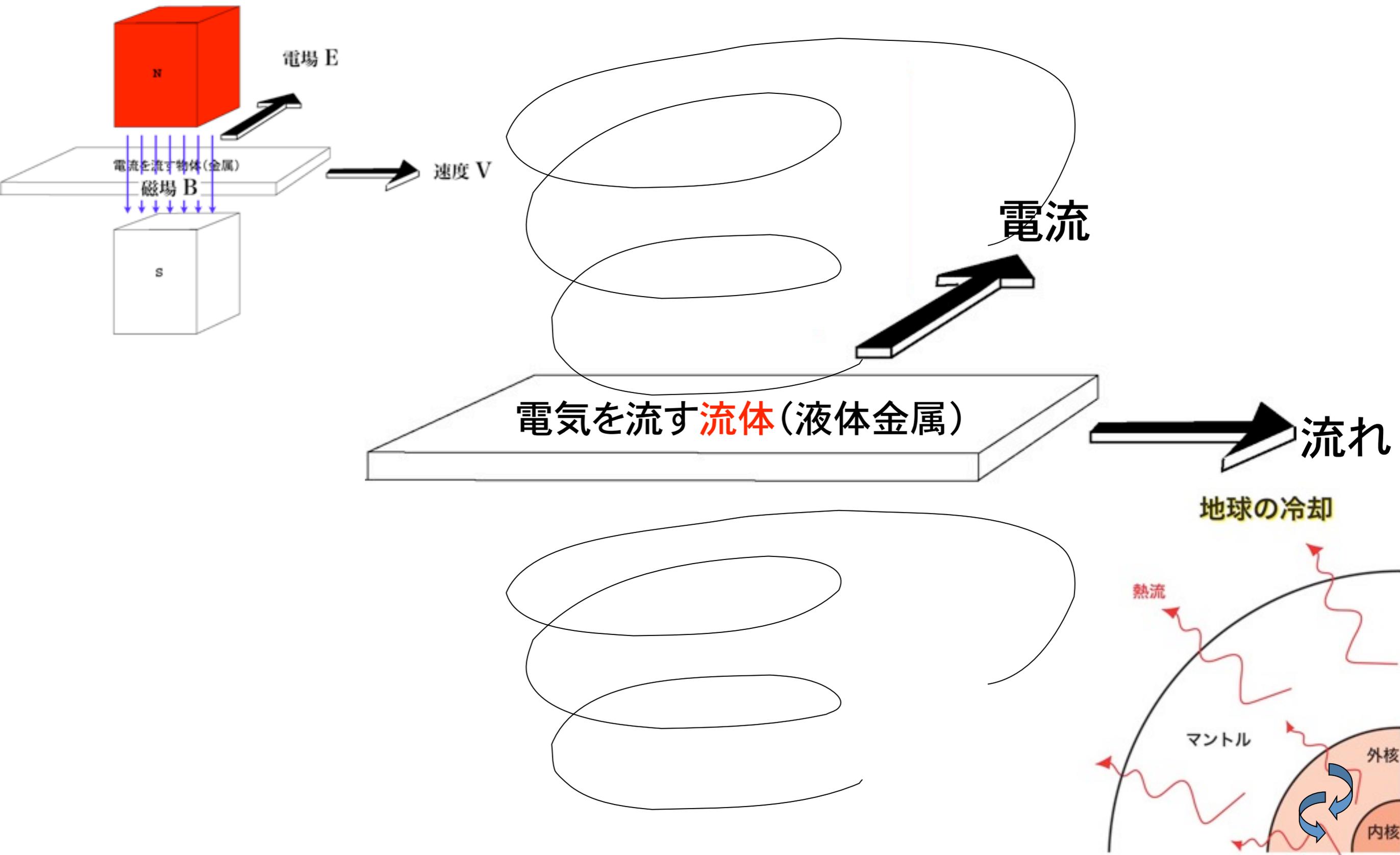
- サメ、エイ
- 2004年 Oak Ridge Shark Laboratory
- 地磁気 (B_h) 中を、動く (V_h) \rightarrow 鉛直電場 (E_v)
- 二つの器官の間の電位を検知



地球の構造



電磁流体 (MHD) ダイナモ



MHDシステムとしての地球外核

無次元量

Outer core radius $R_o = 3.5 \times 10^6 m$

Thermal diffusivity $\kappa \sim 5 \times 10^{-6} m^2/sec$

Viscosity $\nu \sim 1 \times 10^{-7} m^2/sec$

Electrical resistivity $\eta \sim 2 m^2/sec$

Mass density $\rho \sim 1 \times 10^4 kg/m^3$

Poloidal magnetic field $B = O(10^{-4}) T$

Flow velocity $V \sim O(10^{-4}) m/sec$

Sound velocity $V_s \sim O(10^4) m/sec$

Alfvén velocity $V_A \sim O(10^{-3}) m/sec$

Rayleigh number $Ra \sim 10^{30}$

Reynolds number $Re = VR_o/\nu \sim O(10^9)$

Magnetic Reynolds $Rm = VR_o/\eta \sim O(10^3)$

Magnetic Prandtl $Pm = 5 \times 10^{-6}$

Prandtl number $Pr = 0.2$

Ekman number $Ek = \nu/2\Omega R_o^2 = 10^{-15}$

Elsasser number $\Lambda = B^2/2\Omega\mu_0\rho\eta \sim O(10)$

Magnetic energy density / Flow energy density

$$= \left(\frac{B^2}{2\mu_0} \right) / \left(\frac{\rho V^2}{2} \right) = (V_A/V)^2 \sim O(10^2)$$

地球ダイナモシミュレーション

Compressible MHD equations

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \mathbf{f},$$

$$\frac{\partial \mathbf{f}}{\partial t} = -\nabla \cdot (\mathbf{v}\mathbf{f}) - \nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g} + 2\rho \mathbf{v} \times \boldsymbol{\Omega} + \mu(\nabla^2 \mathbf{v} + \frac{1}{3}\nabla(\nabla \cdot \mathbf{v})),$$

$$\frac{\partial p}{\partial t} = -\mathbf{v} \cdot \nabla p - \gamma p \nabla \cdot \mathbf{v} + (\gamma - 1)K\nabla^2 T + (\gamma - 1)\eta \mathbf{j}^2 + (\gamma - 1)\Phi,$$

$$\frac{\partial \mathbf{A}}{\partial t} = -\mathbf{E},$$

- 直接数値計算は無理
- 粘性率 (Ek) を高くした計算

with

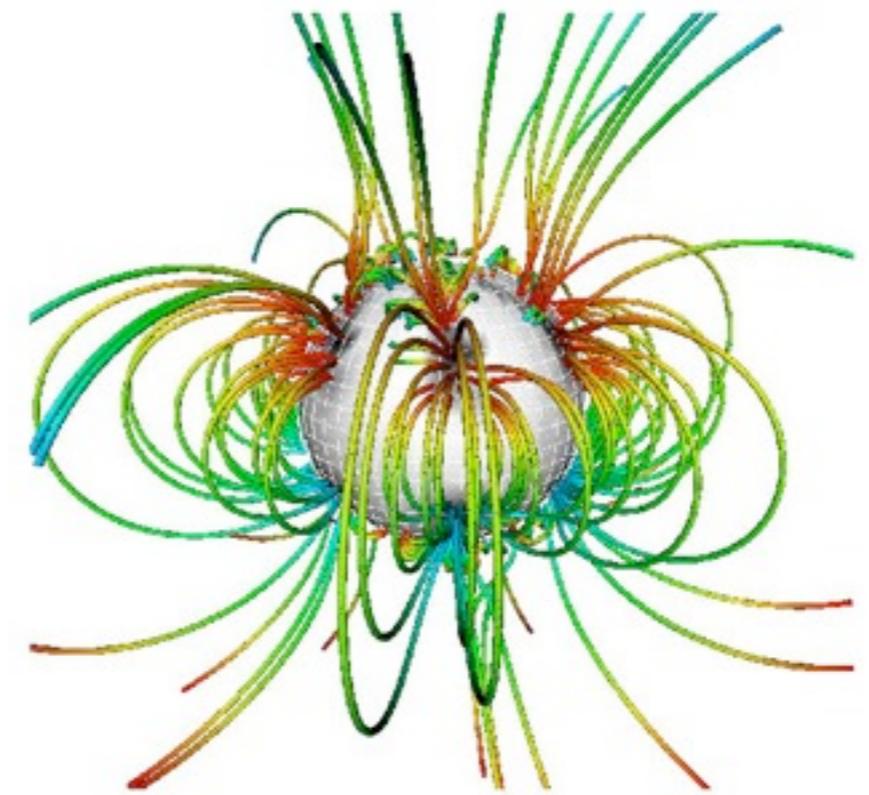
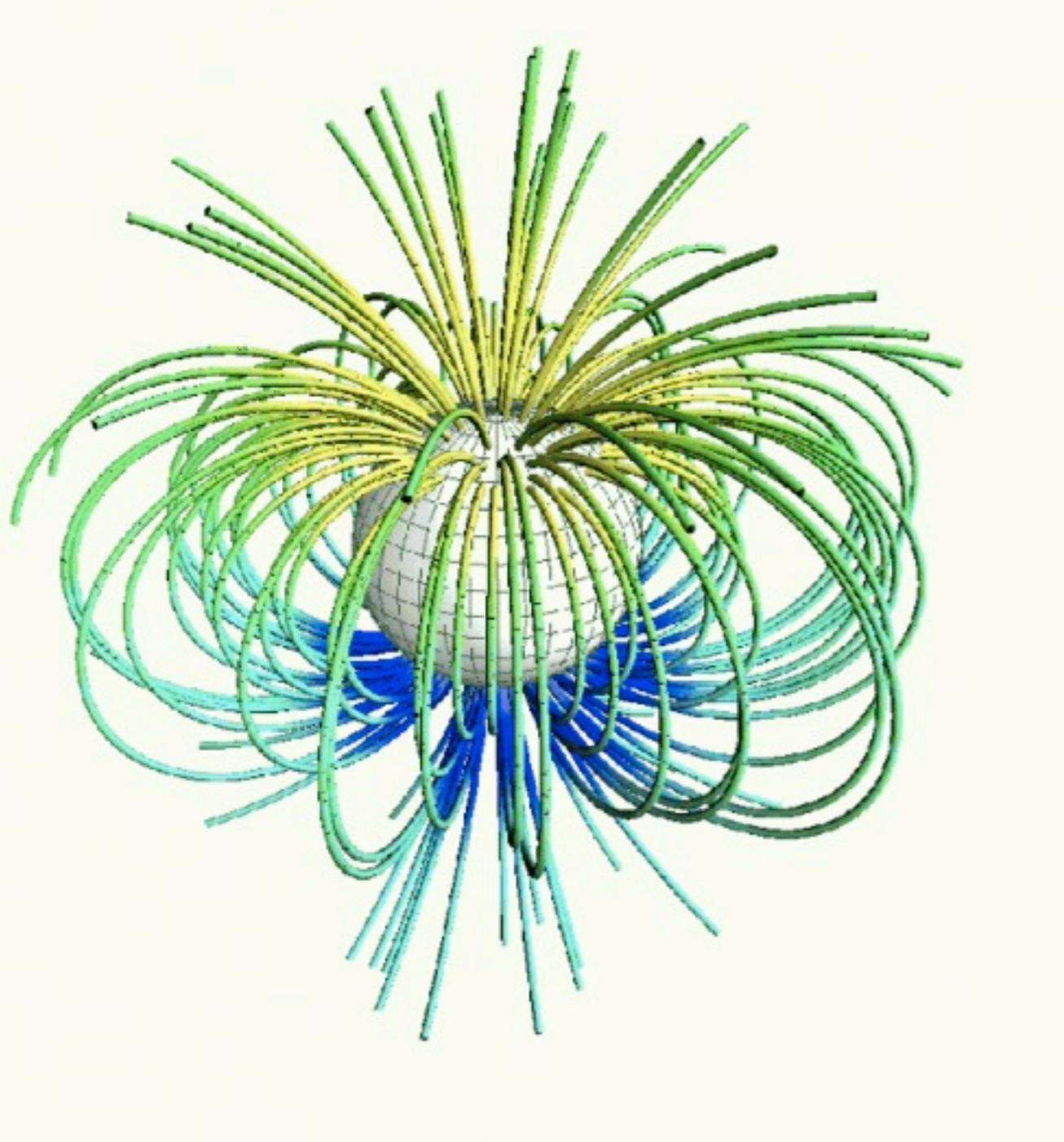
$$\mathbf{B} = \nabla \times \mathbf{A}, \mathbf{j} = \nabla \times \mathbf{B}, \mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta \mathbf{j},$$

$$p = \rho T, \mathbf{g} = -g_0/r^2 \hat{\mathbf{r}}, \Phi = 2\mu (\boldsymbol{\epsilon} \cdot \boldsymbol{\epsilon} - (\nabla \cdot \mathbf{v})^2 / 3).$$

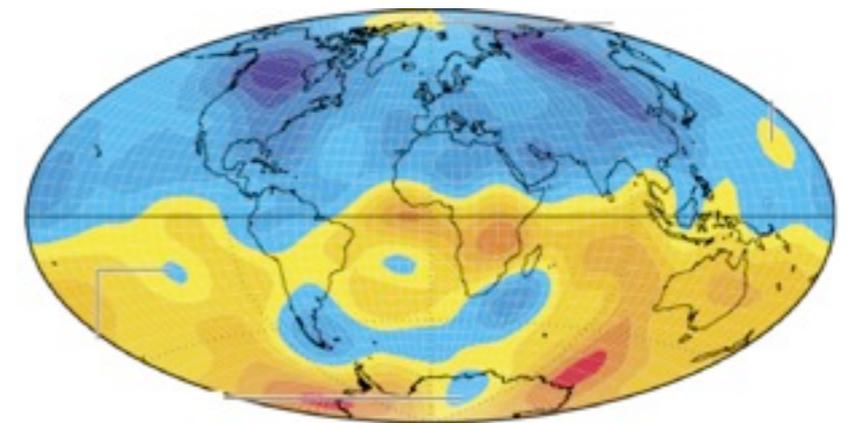
シミュレーションモデル

- 初期条件：
 - 不安定平衡状態（対流なし）、熱伝導
 - 弱い種磁場
 - 温度のランダムな擾乱
- 境界条件（外側&内側の球面上）
 - 流れなし（rigid boundary）
 - 磁場は垂直成分のみ
 - 温度固定

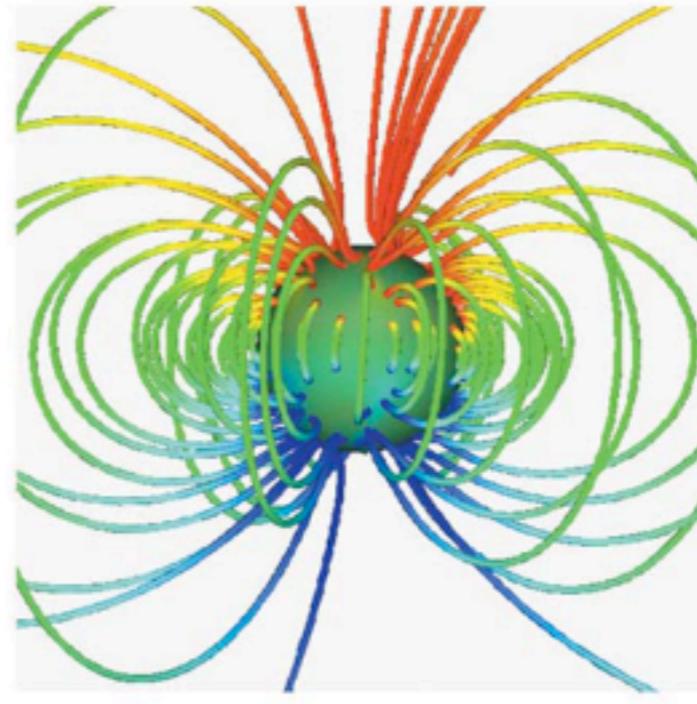
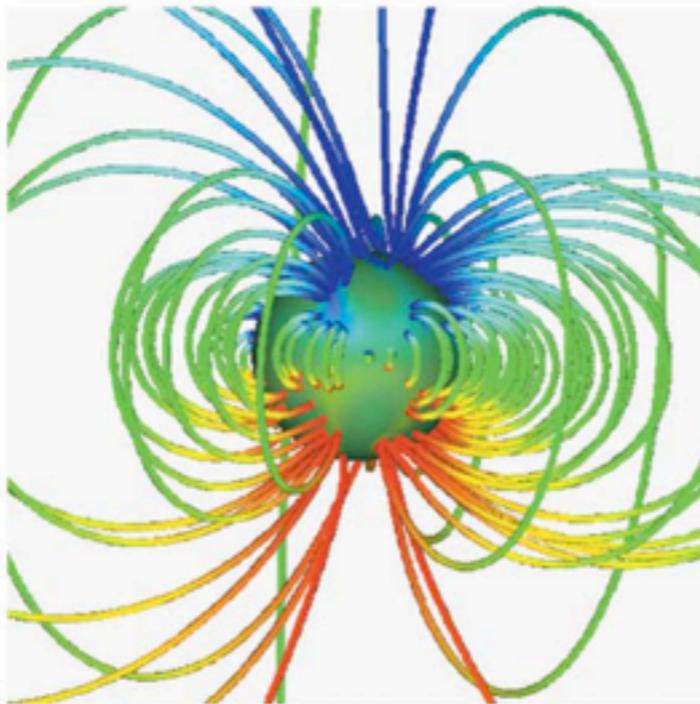
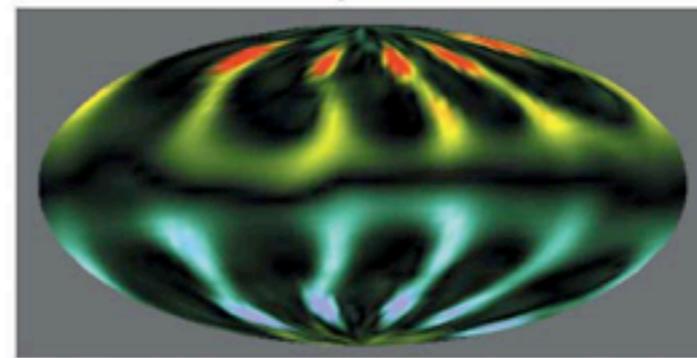
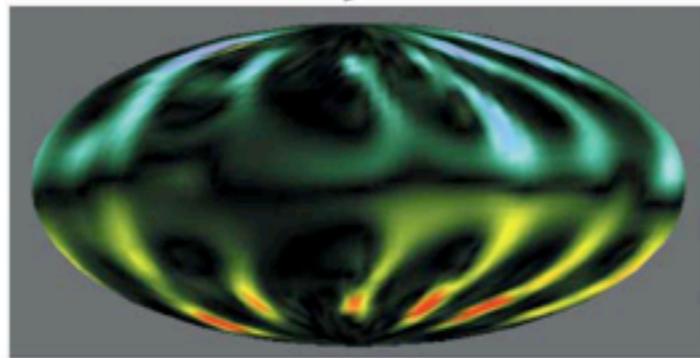
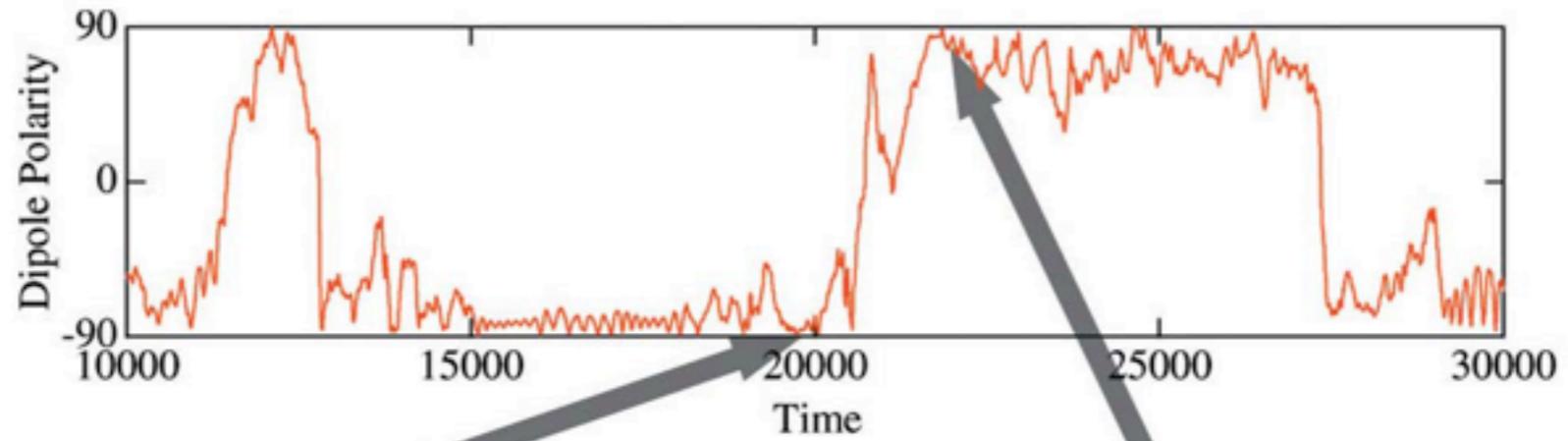
シミュレーションで再現された双極子磁場



コア表面上の磁場分布



Kageyama and Sato, 1997, *Phys. Rev. E*



地球ダイナモシミュレーション

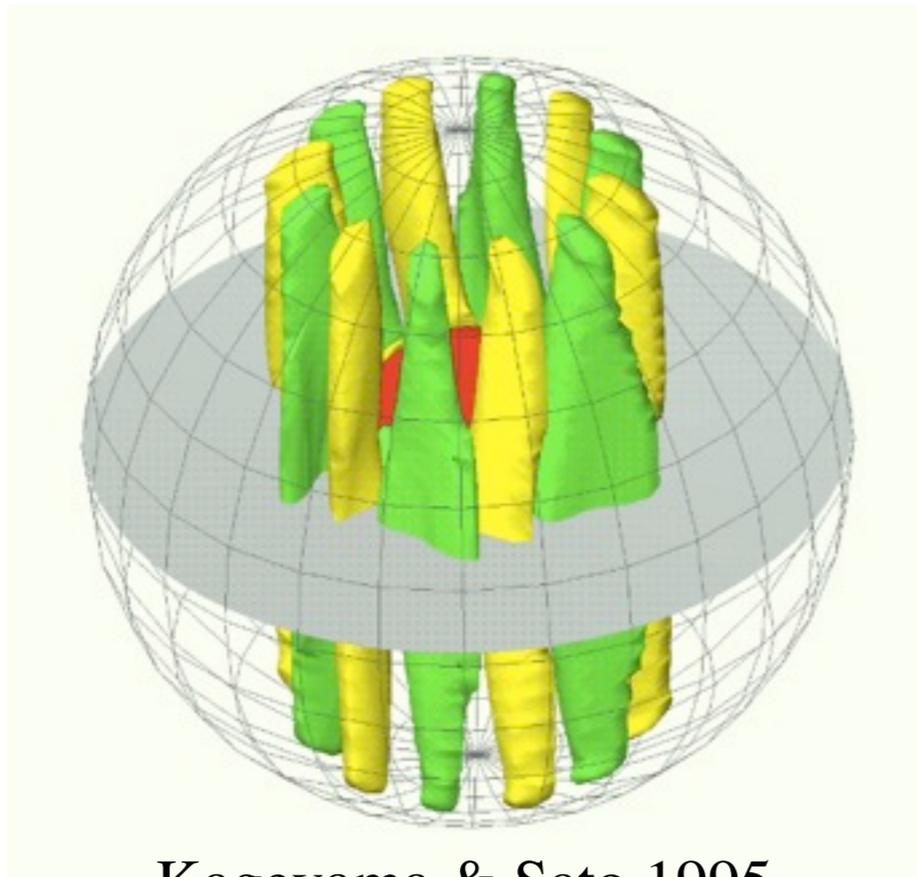
パラメータ（エクマン数）は全く違うが、地磁気の最も重要な二つの性質：

- (1) 双極子磁場であること
- (2) 突然、非周期的に逆転すること

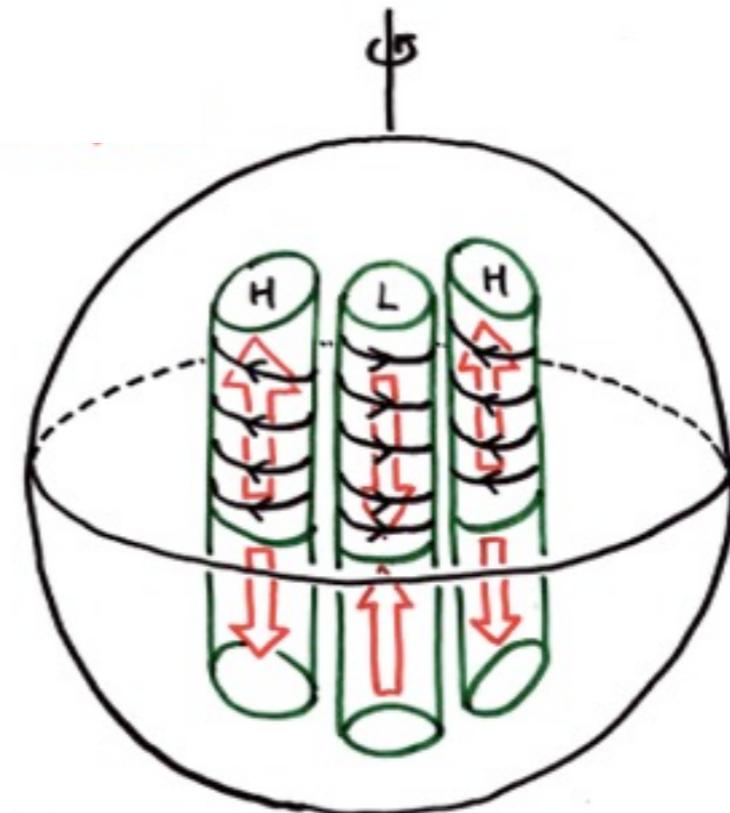
が計算機内で定性的には再現できている。

以前の計算 $Ek=O(10^{-4})\sim O(10^{-5})$

- 渦度分布
- 対流構造 = 円柱状の対流胞の集合



Kageyama & Sato 1995



螺旋型の流線

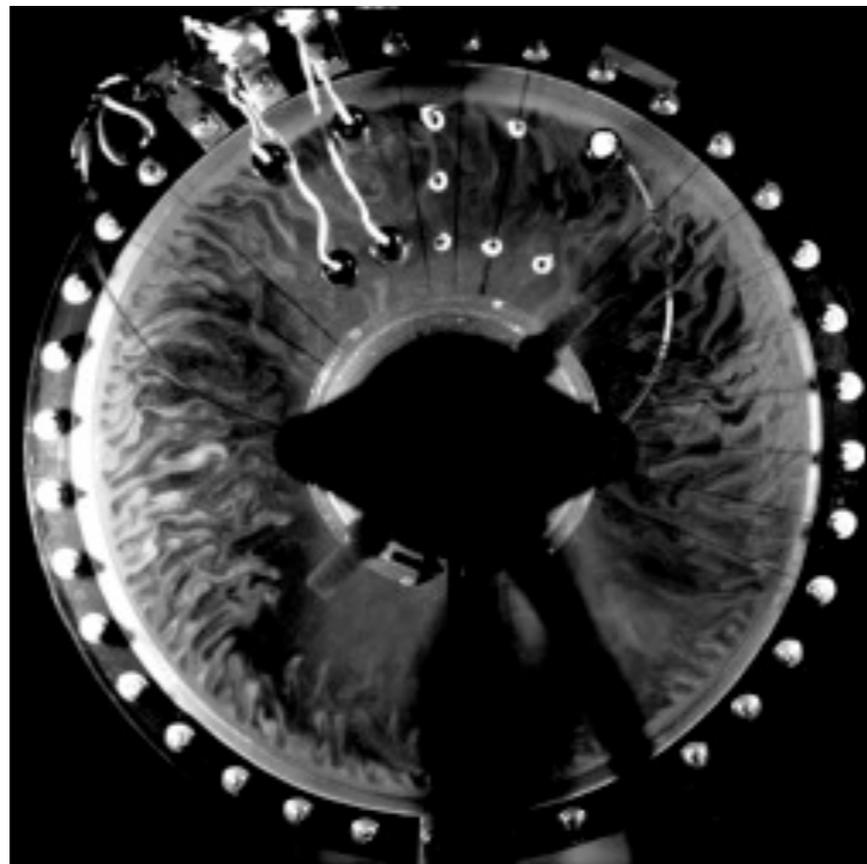
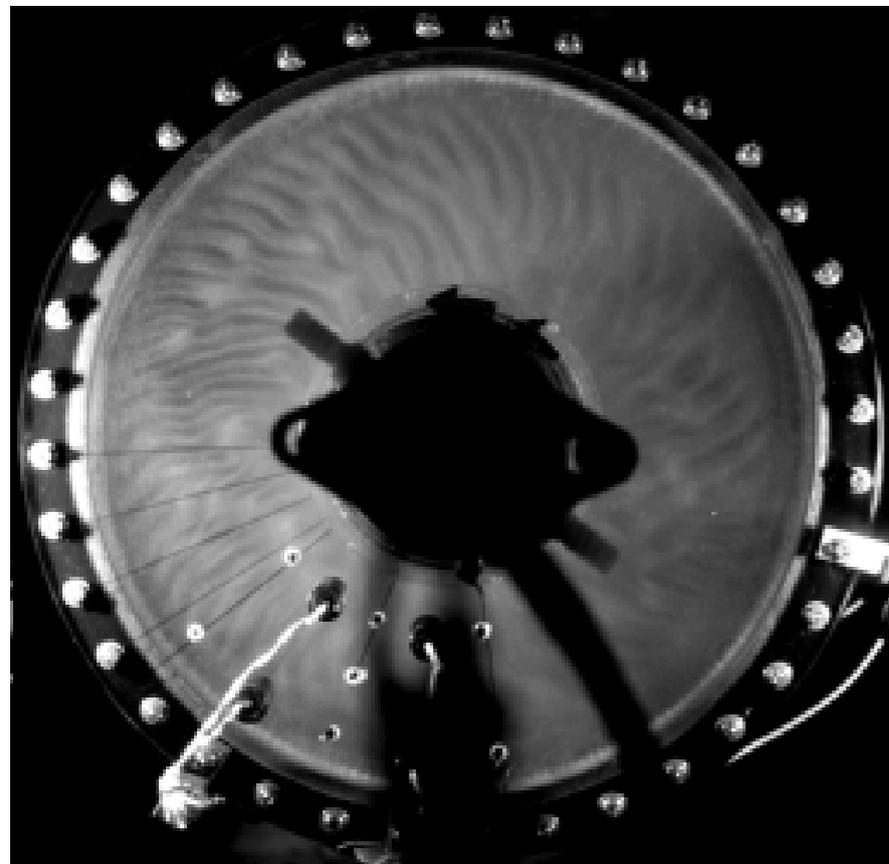
水の熱対流実験

- (半) 球殻対流実験

- Sumita and Olson, 2002, 2000, 1999

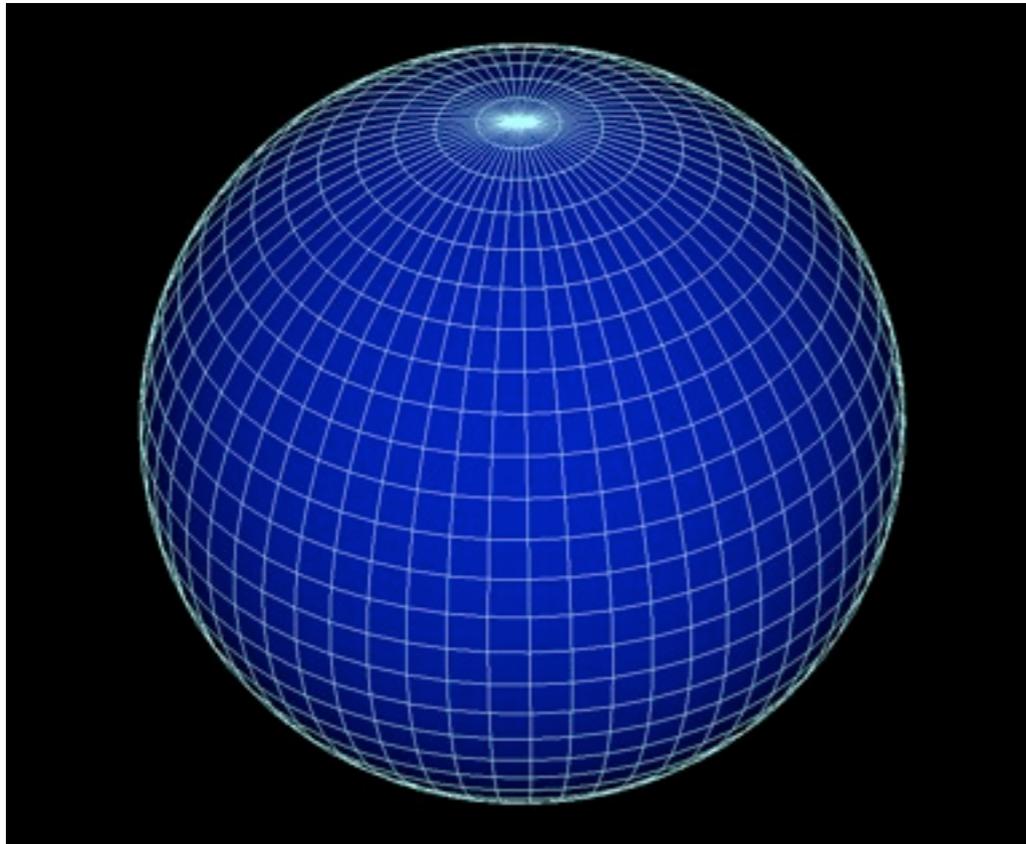
- $Ek = 5 \times 10^{-6}$

- 対流は円柱状ではなくプルーム状



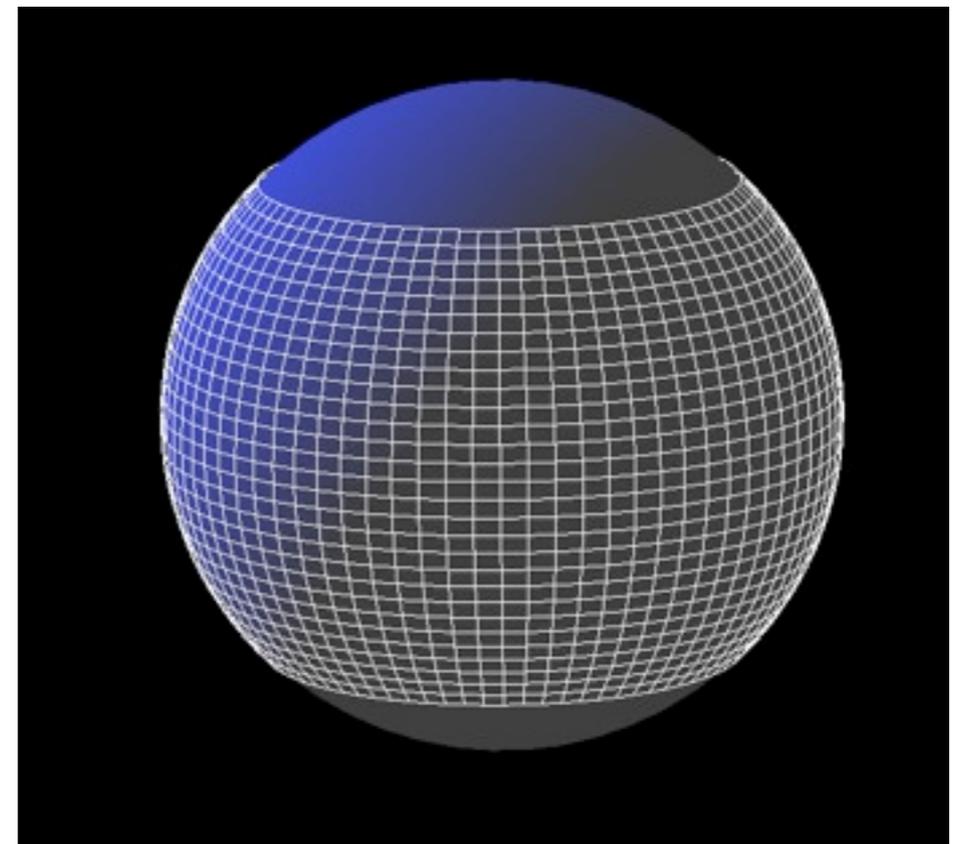
高解像度計算が必須

緯度・経度格子の問題

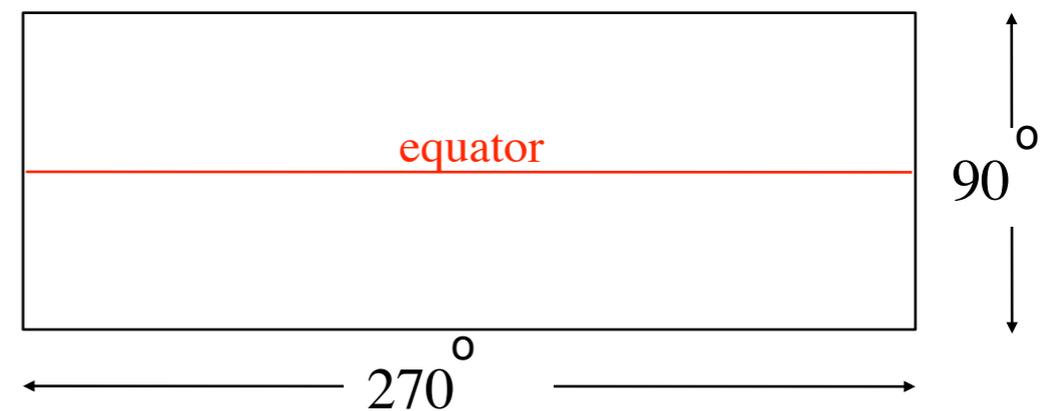
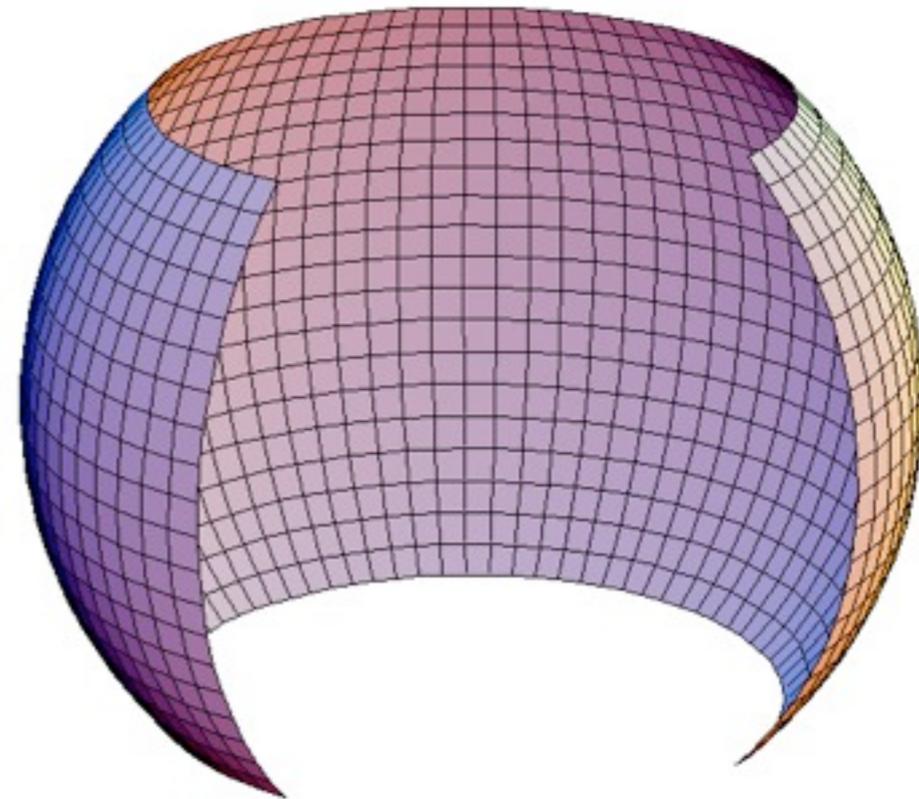
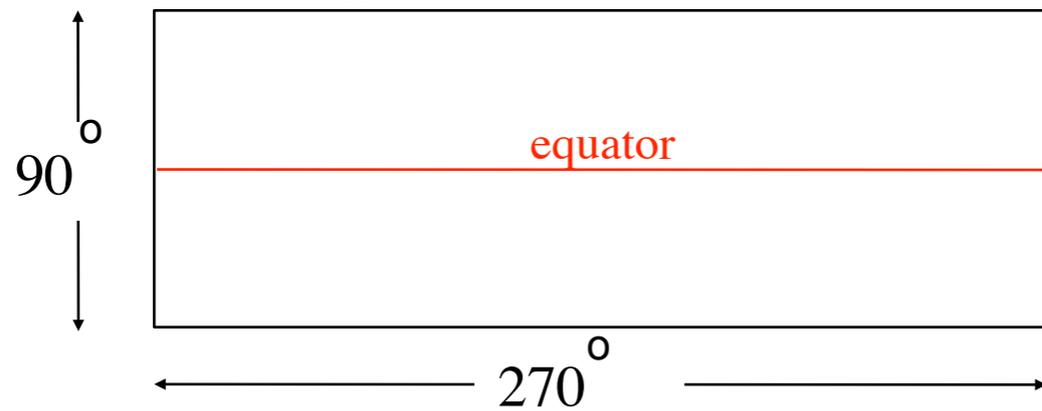
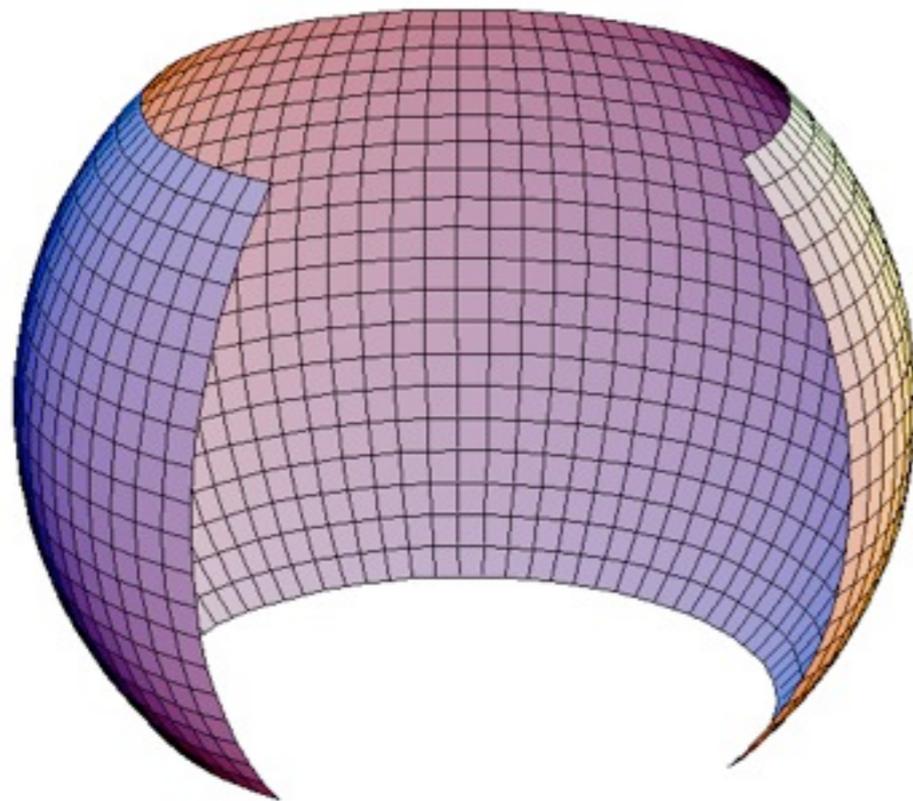


- 座標特異点 \rightarrow ロピタルの定理で解決
- 格子間隔の集中 \rightarrow . . .

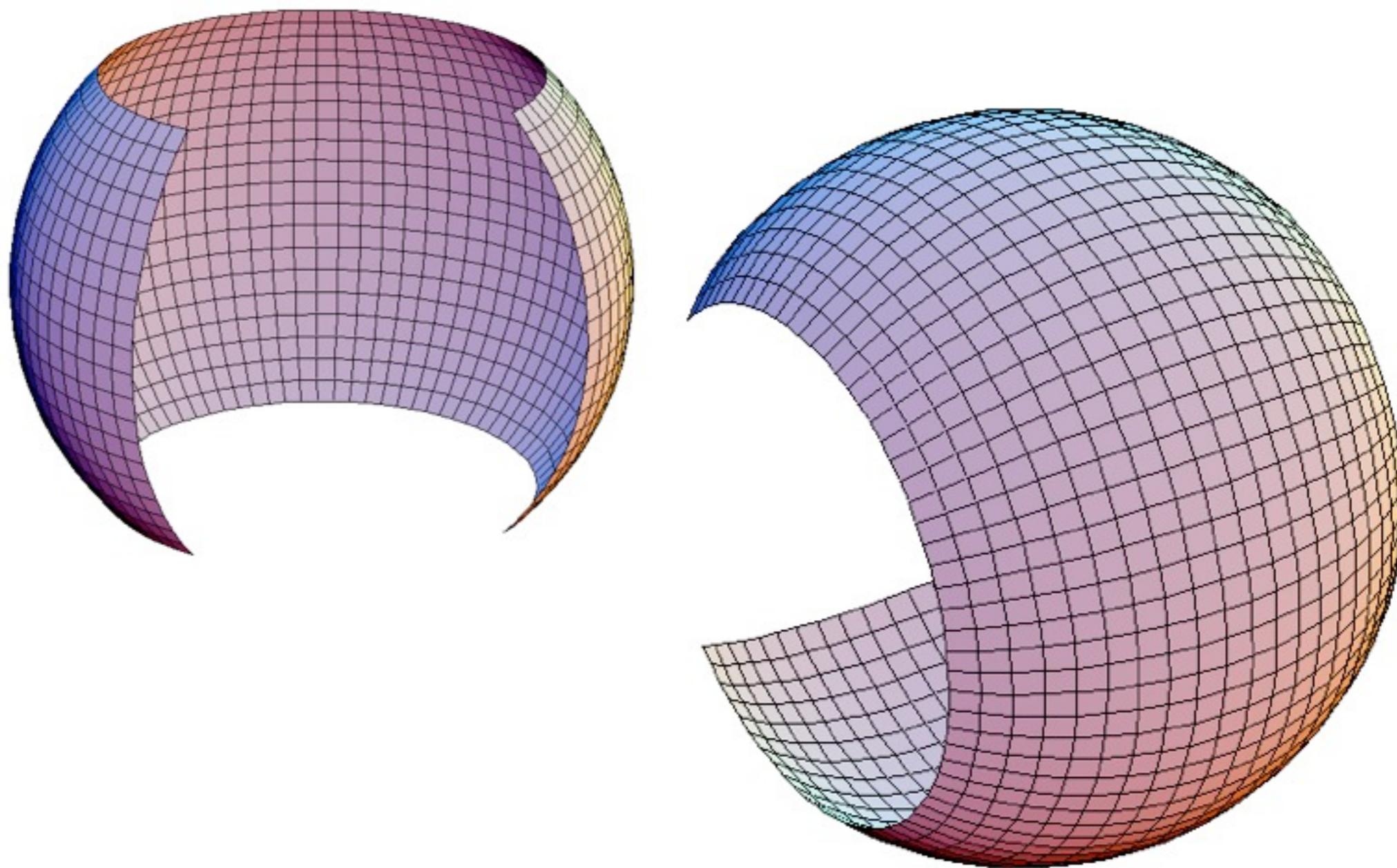
悪いのは高緯度部分だけ。
低緯度部分は良い格子系。



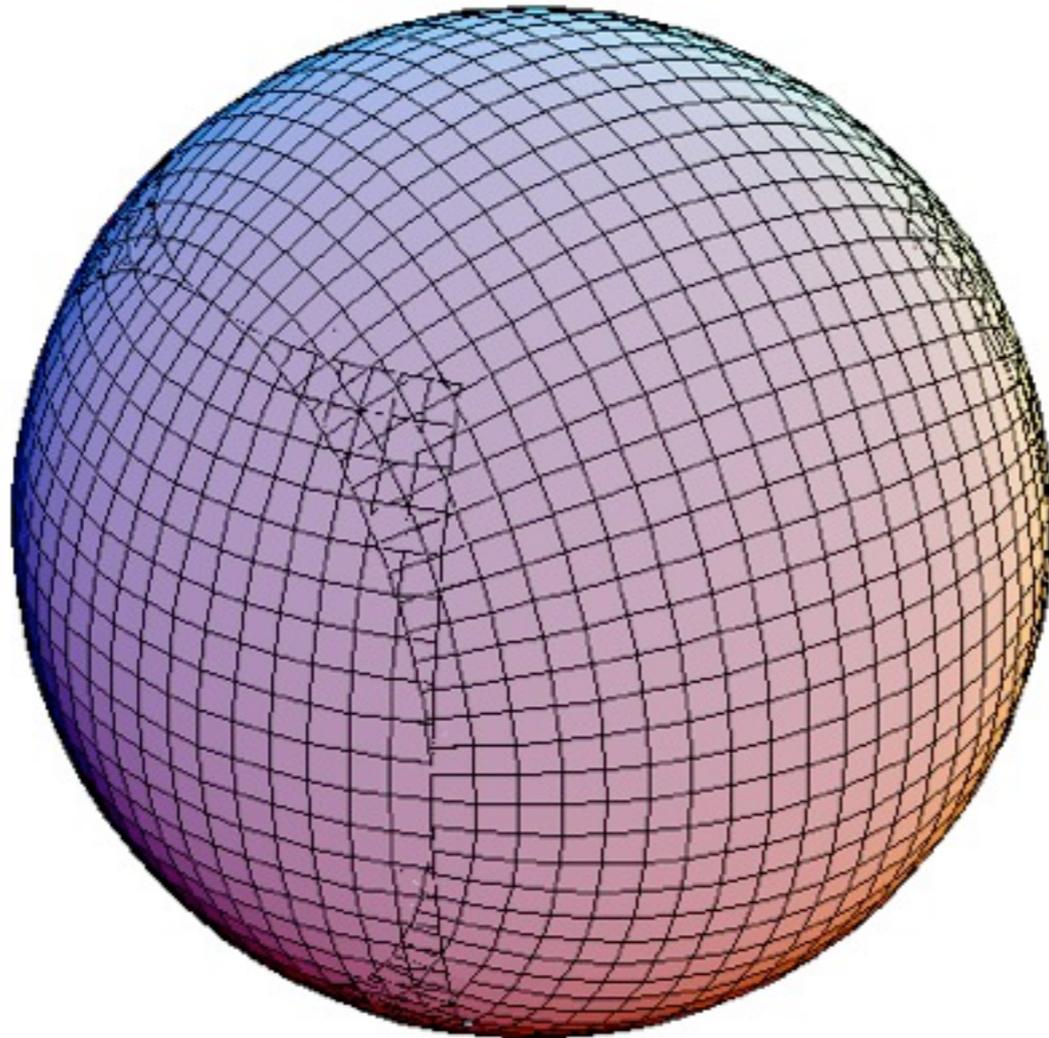
インヤン 陰陽 (Yin-Yang) 格子



インヤン (Yin-Yang) 格子



インヤン (Yin-Yang 陰陽) 格子



相補的な配置

インヤン格子の広がり

大気・海洋 GCM

カナダ

Quarterly Journal of the Royal Meteorological Society

Q. J. R. Meteorol. Soc. (2011)



The Canadian Global Environmental Multiscale model on the Yin-Yang grid system

Abdessamad Qaddouri* and Vivian Lee

Meteorological Research Division, Atmospheric Science and Technology Directorate, Environment Canada, Dorval, Québec, Canada

*Correspondence to: A. Qaddouri, Environment Canada, 2121 Trans-Canada Hwy, Dorval QC H9P 1J3, Canada.
E-mail: Abdessamad.Qaddouri@ec.gc.ca

日本

Q. J. R. Meteorol. Soc. (2006), **132**, pp. 979–996

doi: 10.1256/qj.05.18

Conservative constraint for a quasi-uniform overset grid on the sphere

By XINDONG PENG^{1*}, FENG XIAO^{2,3} and KEIKO TAKAHASHI¹

¹Earth Simulator Center, JAMSTEC, Yokohama, Japan

²Tokyo Institute of Technology, Yokohama, Japan

³Chinese Academy of Meteorological Sciences, Beijing, China

英国

1 On the solution of elliptic problems on overset/Yin-Yang

2 grids *

3 M. Zerroukat[†] and T. Allen

Met Office, FitzRoy Road, Exeter EX1 3PB, U.K.



VERSION

インヤン格子の広がり

マントル対流

スイス

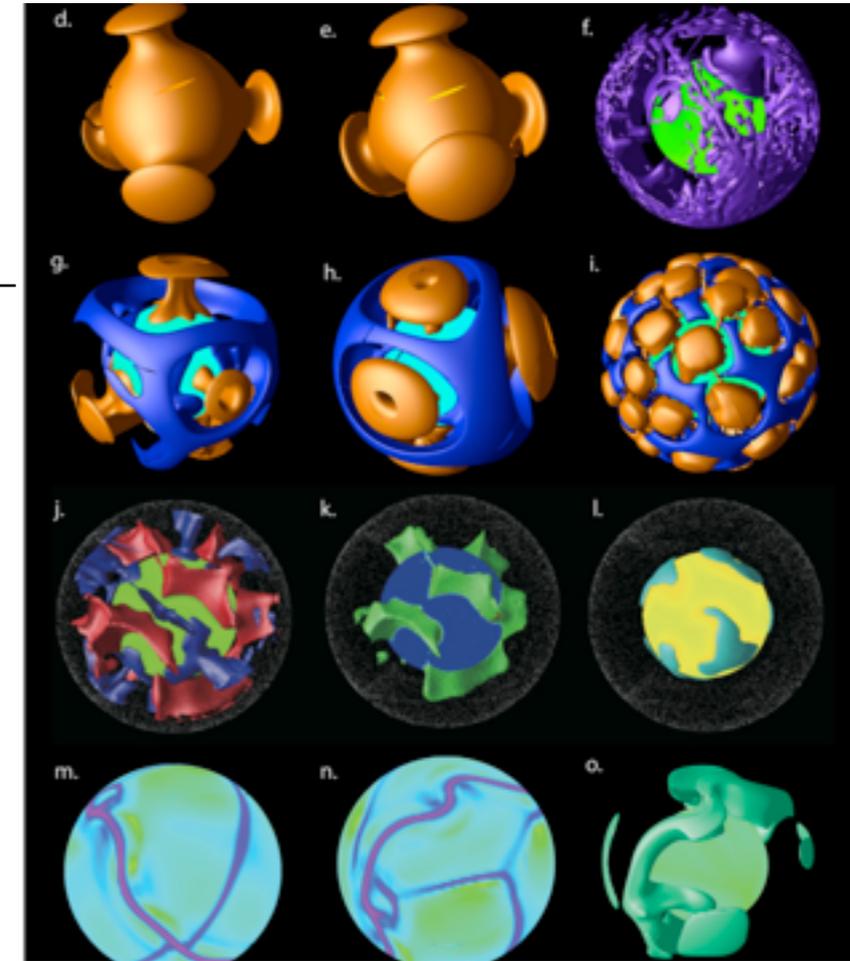
日本

P. Tackley

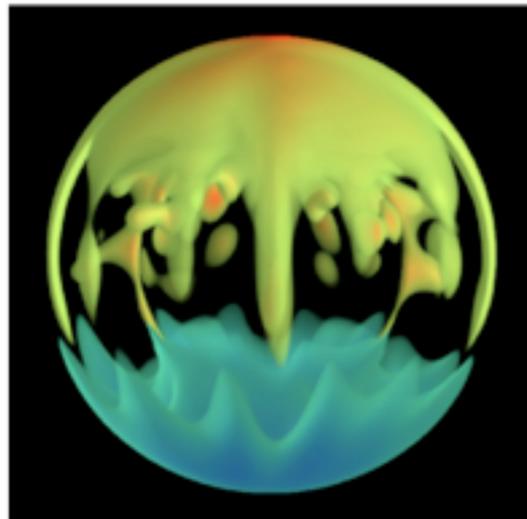
JAMSTEC (中川)

JAMSTEC (吉田)

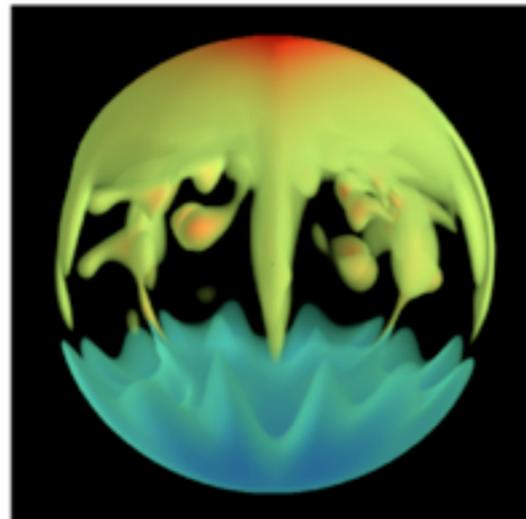
愛媛大 (亀山)



(c) $t = 3.26877093 \times 10^{-1}$

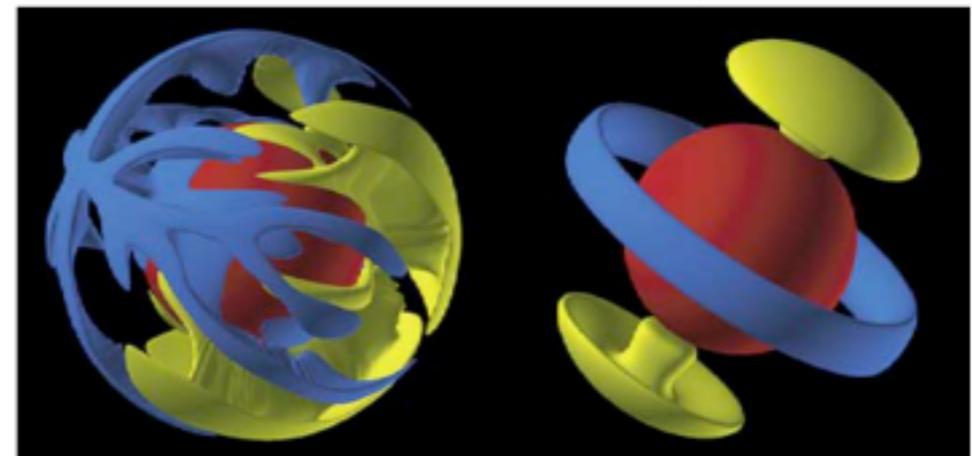


(d) $t = 3.50540068 \times 10^{-1}$



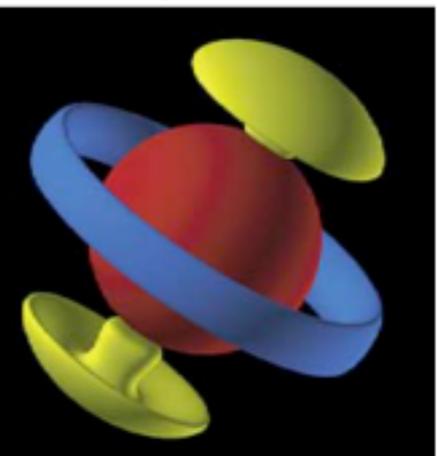
(a)

$\gamma_{\eta} = 10^0$



(b)

$\gamma_{\eta} = 10^3$

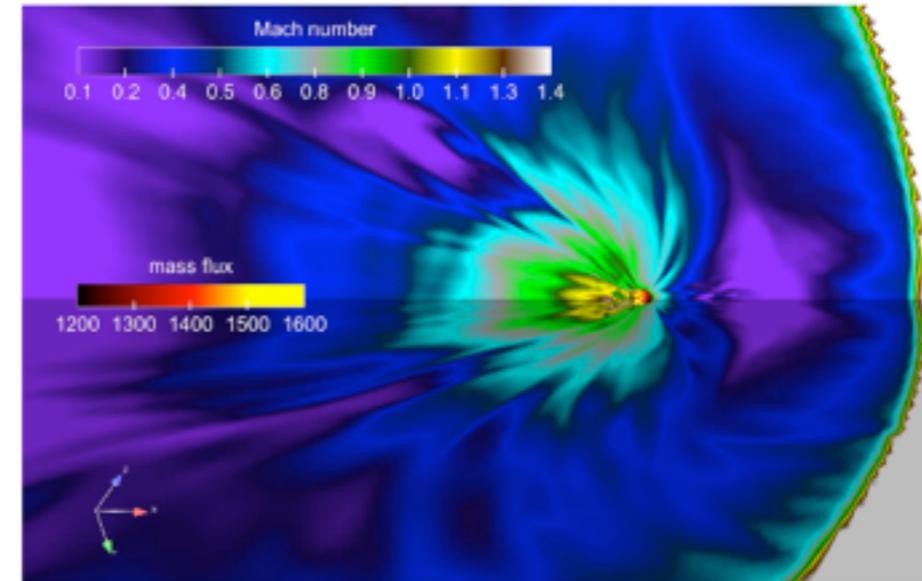


インヤン格子の広がり

天体

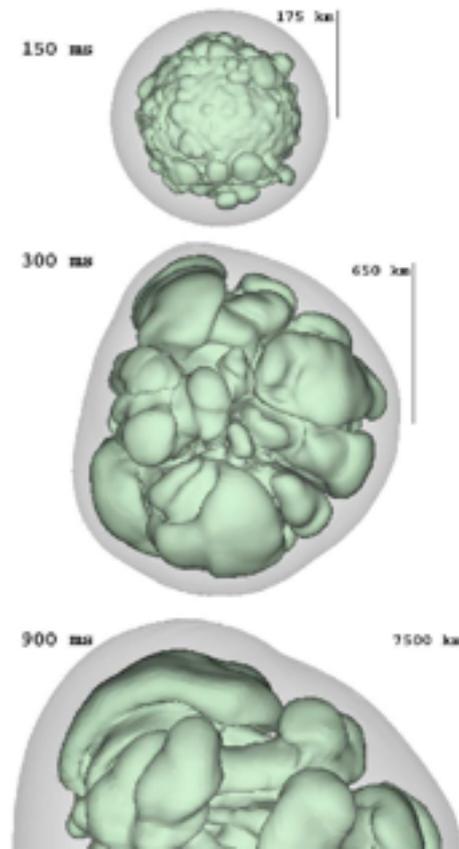
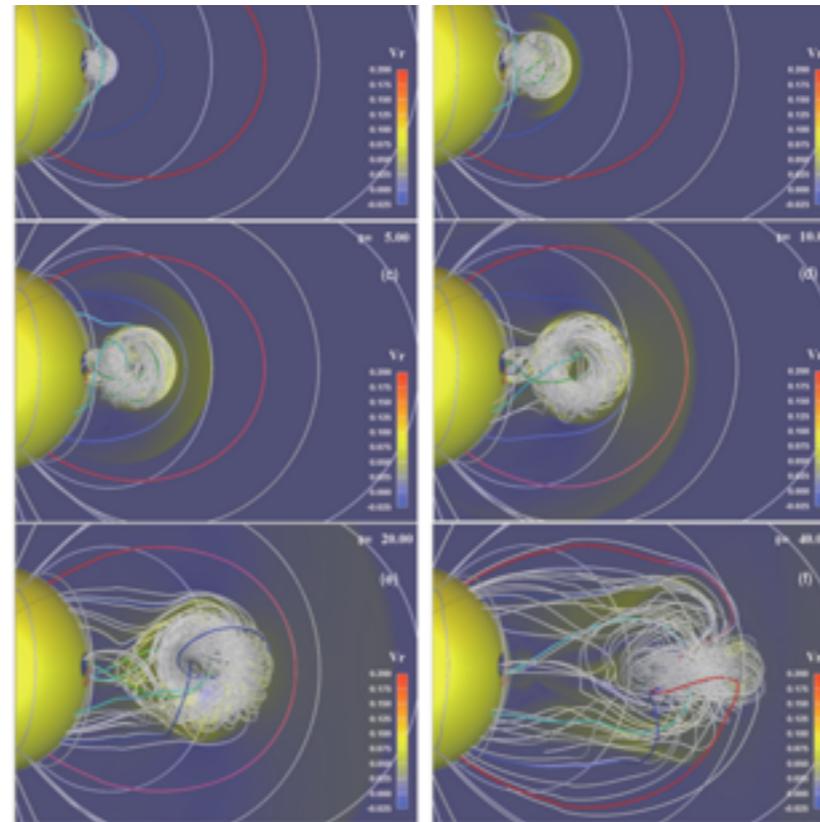
米国

J. Blondin & E. Raymer
天体への質量降着



日本

塩田
太陽CME



ドイツ

E. Muller
超新星爆発

Simulation Parameters

- Rayleigh number

- $Ra = 2.0 \times 10^8$ (at top)
= 1.5×10^{10} (at bottom)
= 300-1000 $\times Ra_c$

- Prandtl number

- $Pr = 1$

- 4096 cores of Earth Simulator
- 15 TFLOPS (46% of peak performance)

- Magnetic Prandtl number

- $Pm = 1$

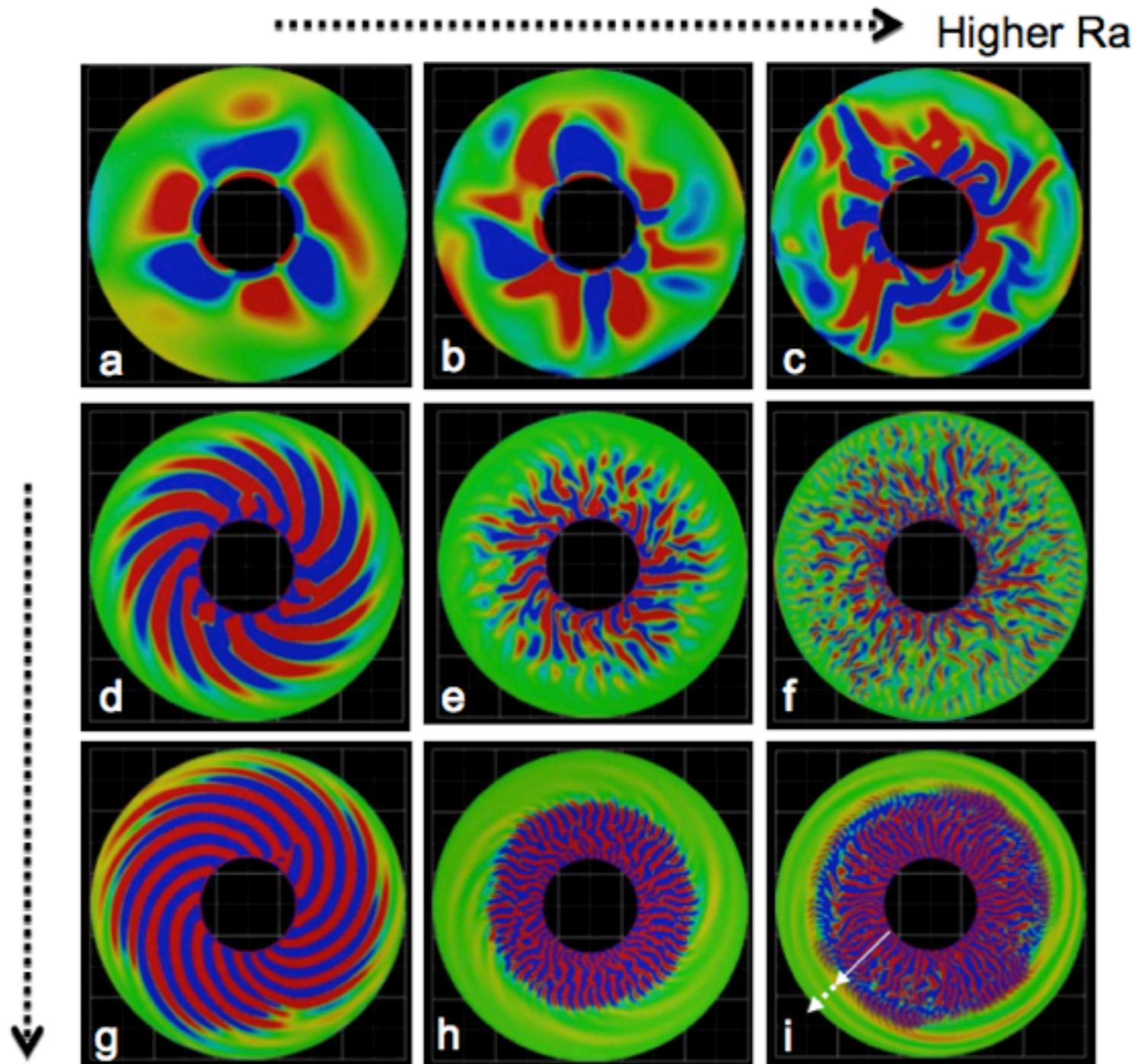
- Ekman number

$$E = \frac{\nu}{2\Omega r_o^2}$$

- $E = 2.3 \times 10^{-7}$ [World record]

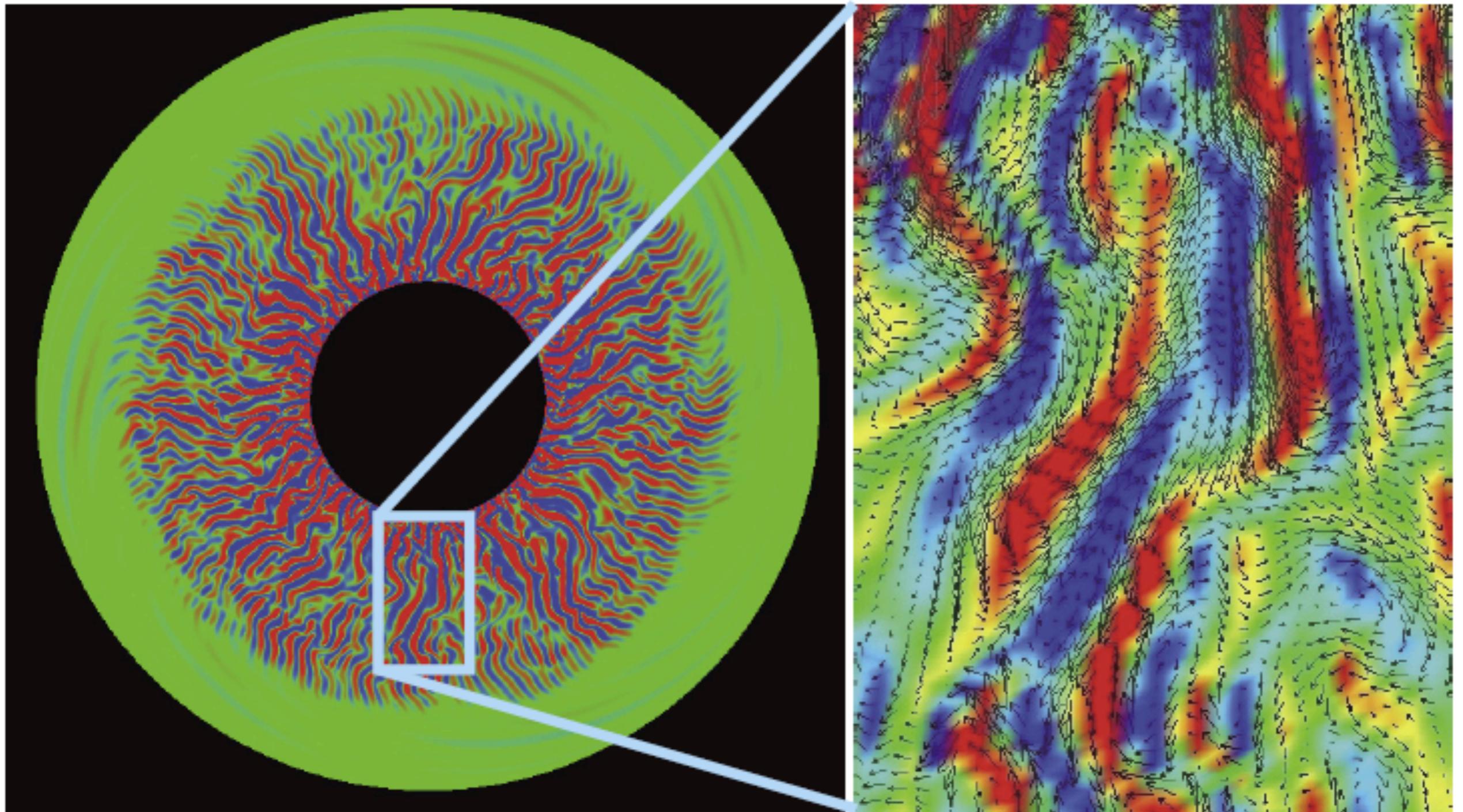
$E = O(10^{-15})$ in Earth's core

パラメータ依存性



Higher Ω

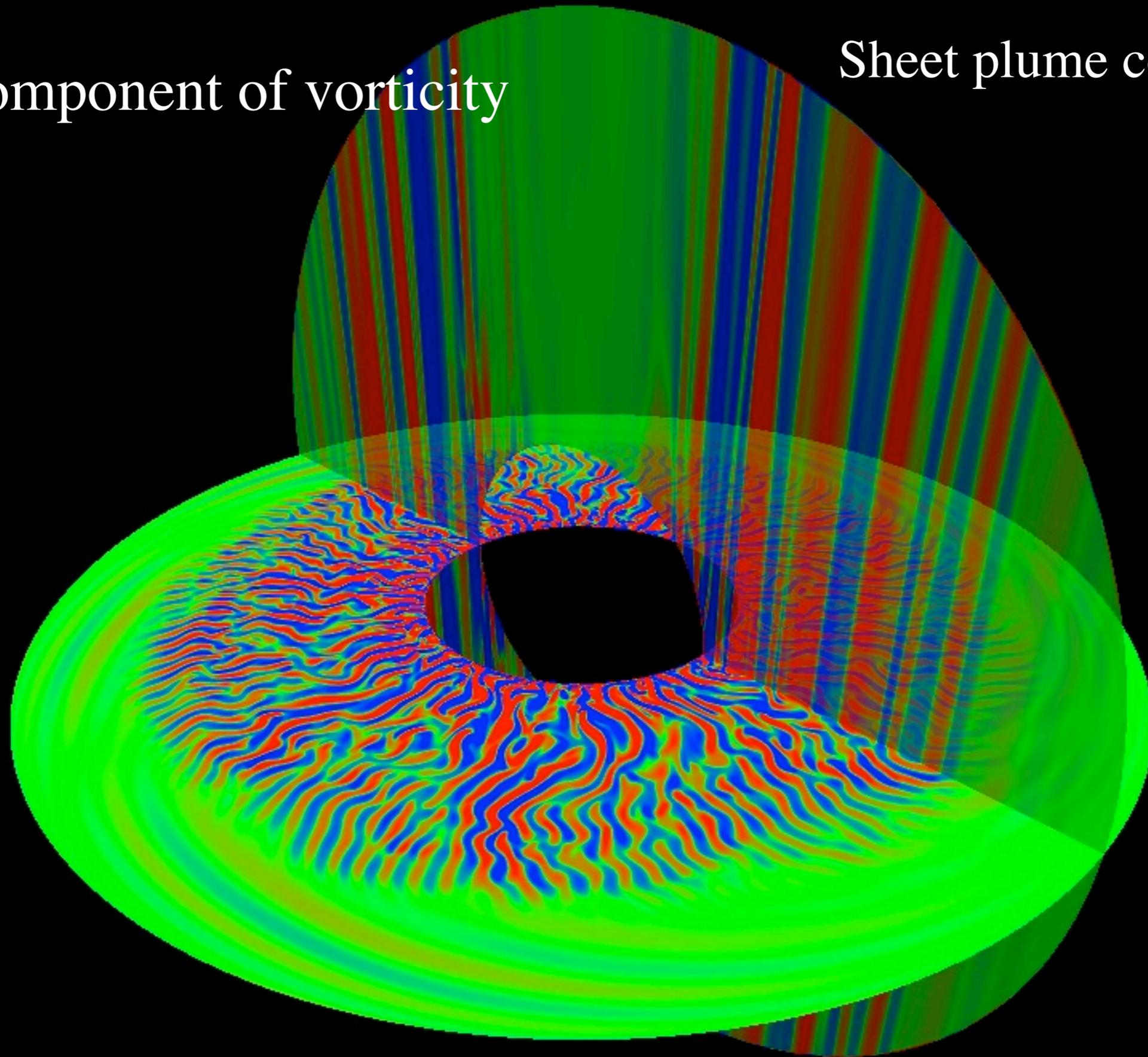
渦度の自転軸方向成分 ($E=2.3 \times 10^{-7}$)



flow arrows

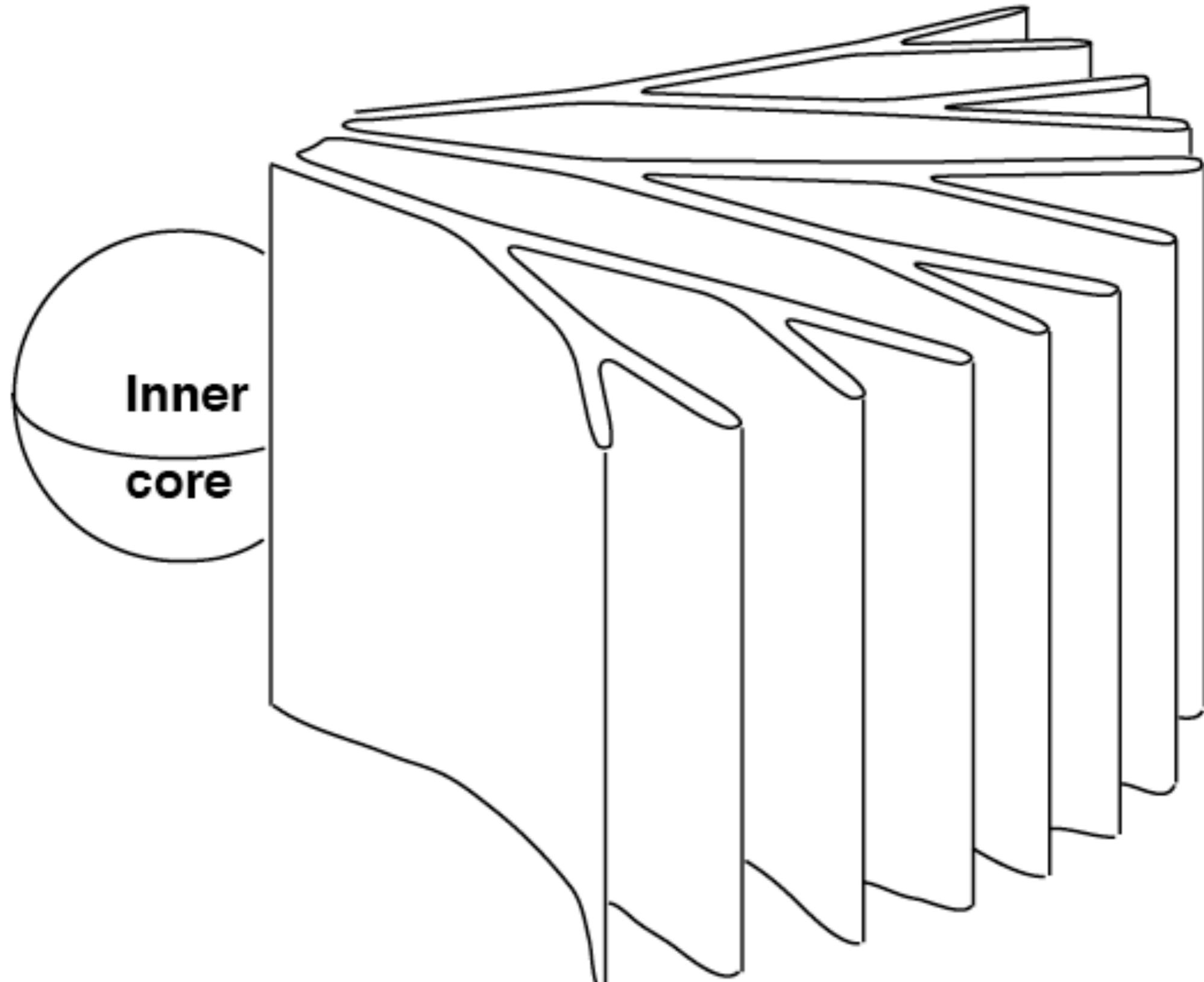
Axial component of vorticity

Sheet plume convection

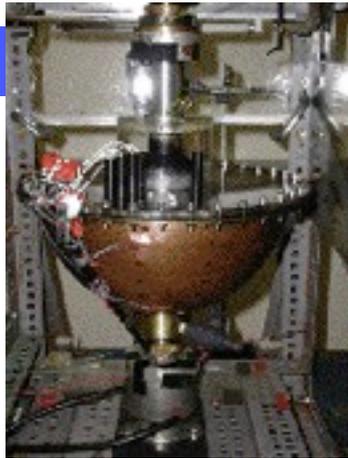


Visualized with *Armada* developed by N. Ohno

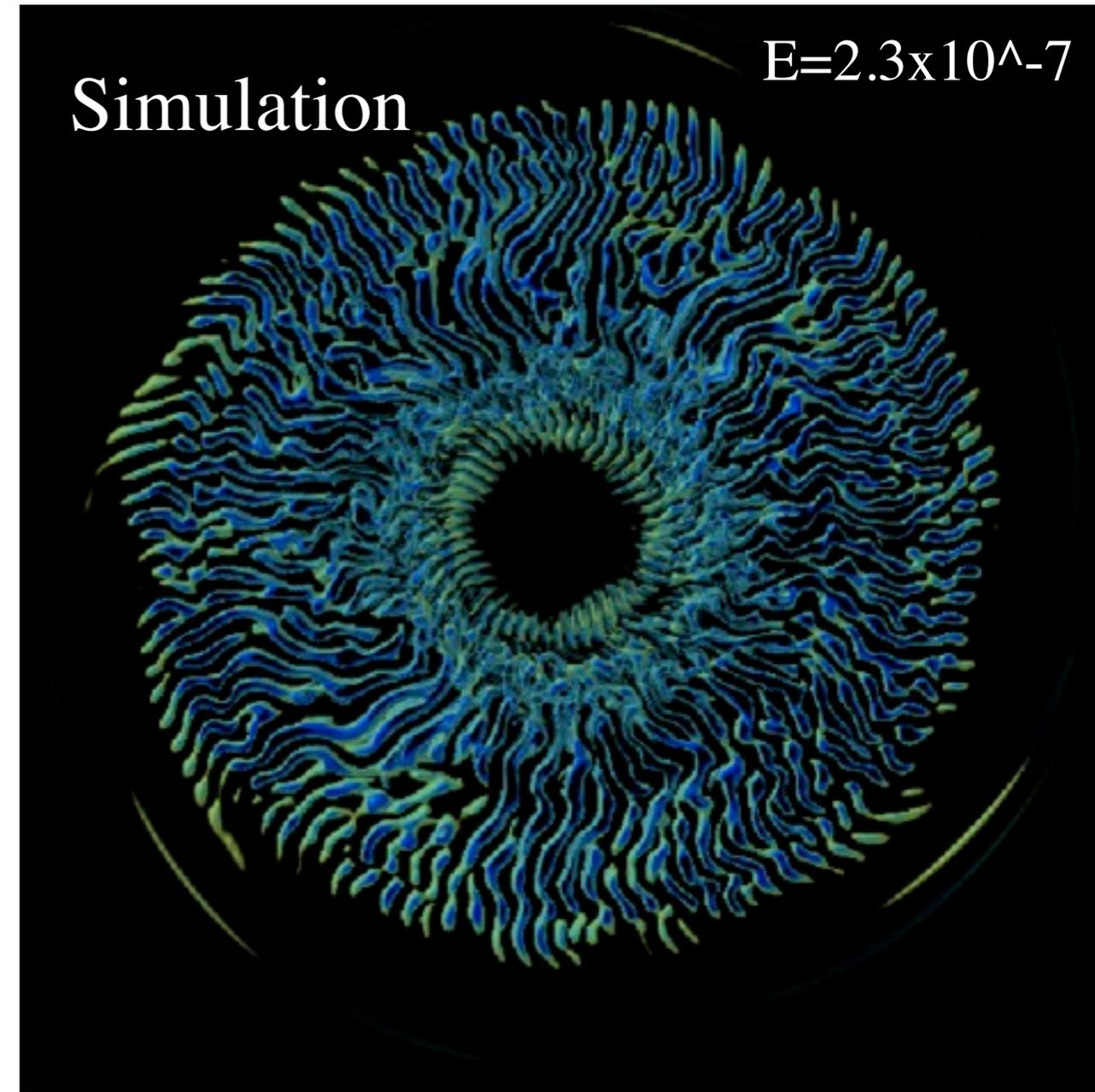
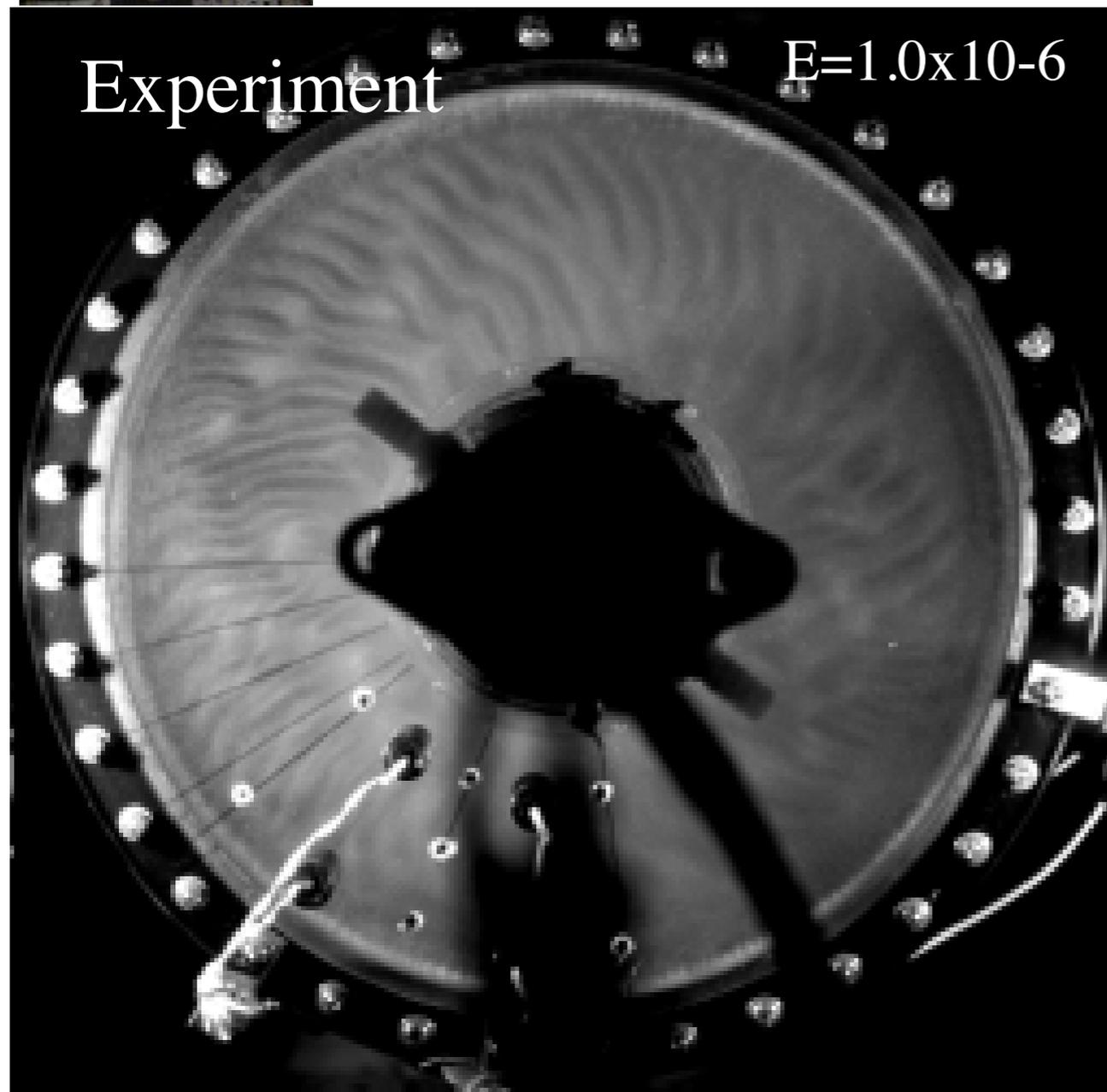
Sheet Plume Convection



Sheet Plume Convection in Water Experiment

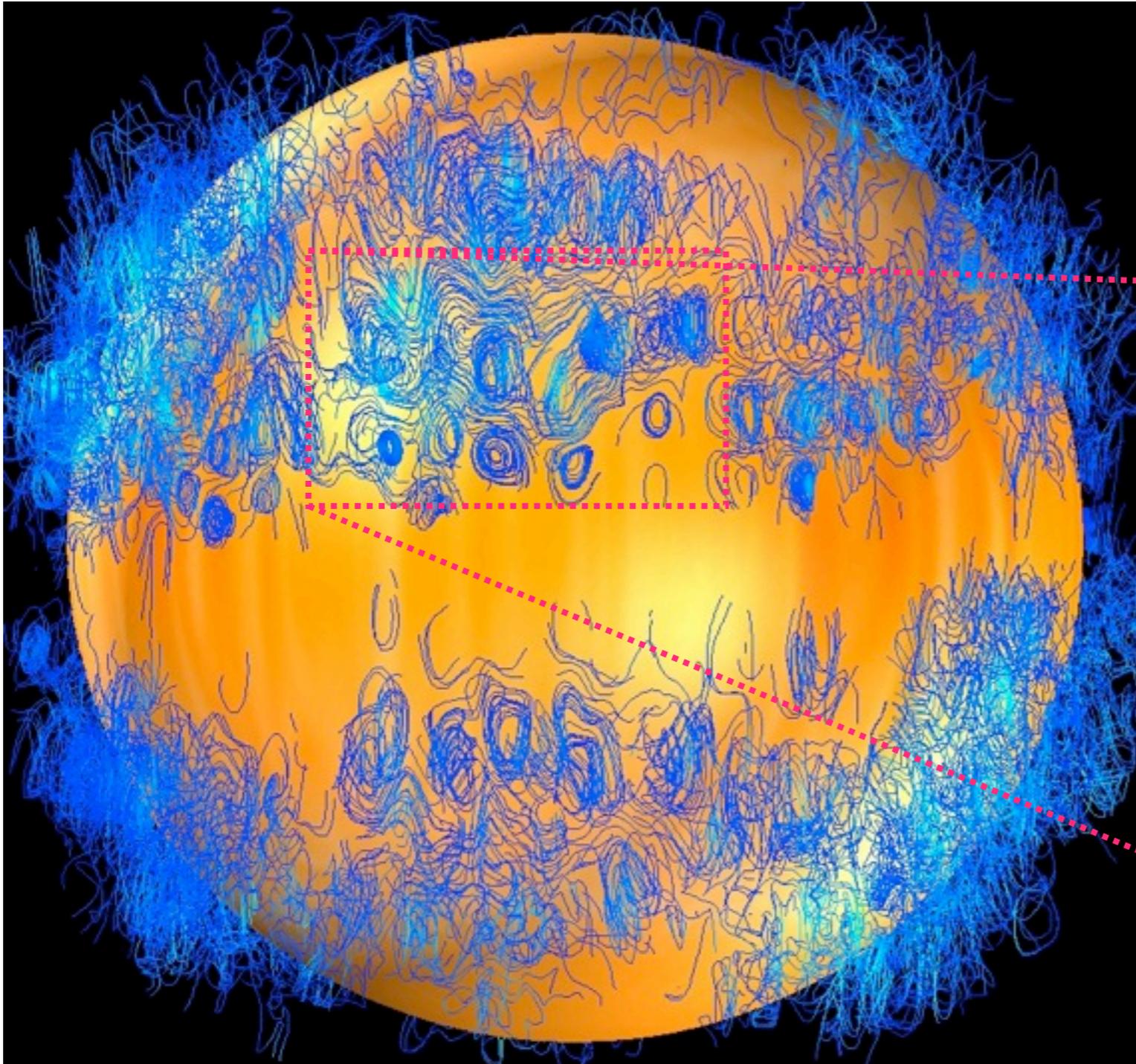


Hemispherical shell convection experiments by Sumita and Olson

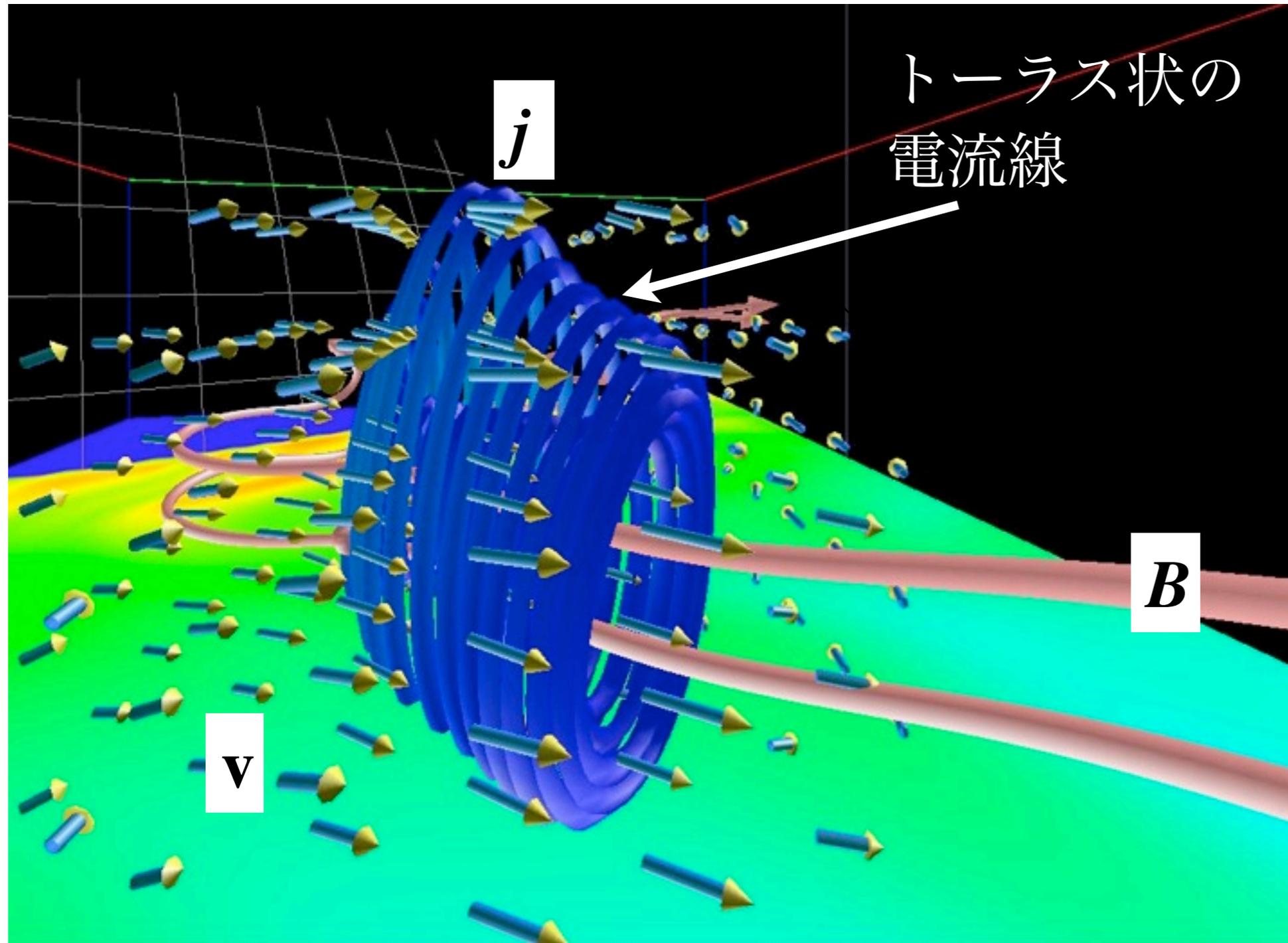


電流場（電流の力線）

A lot of current coils



Dynamo Mechanism

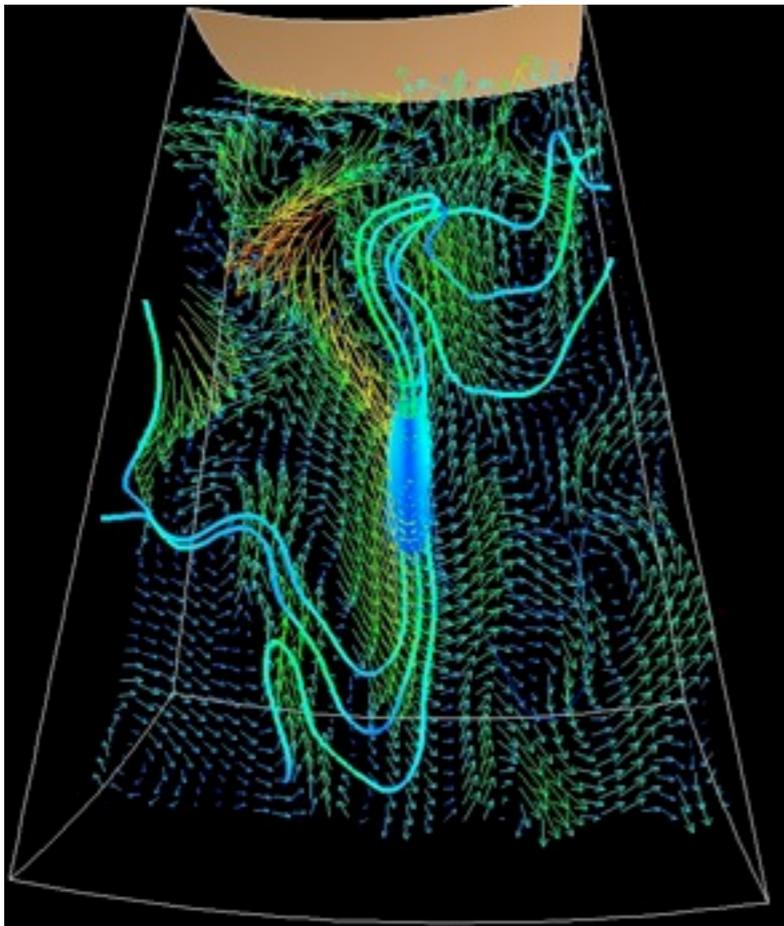


ムービー

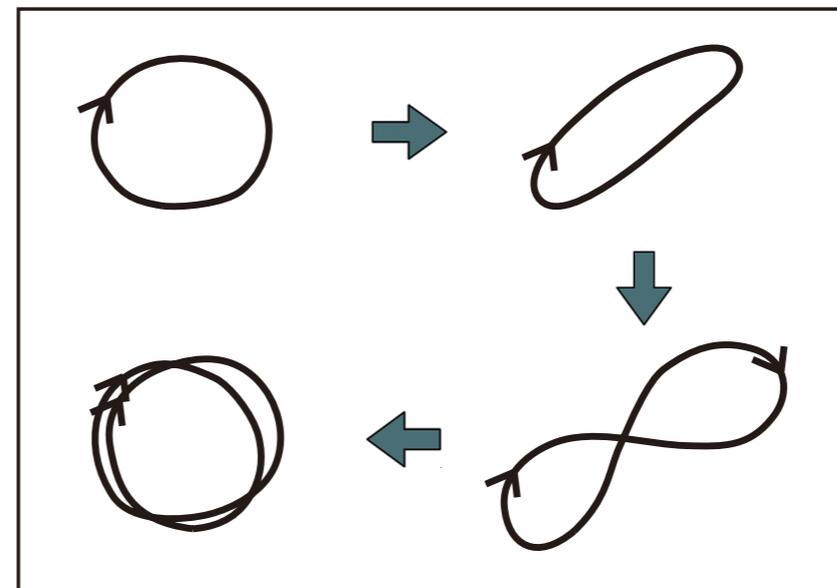
磁力線のStretch = 磁場生成

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

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



磁力線の流れ場への凍りつき



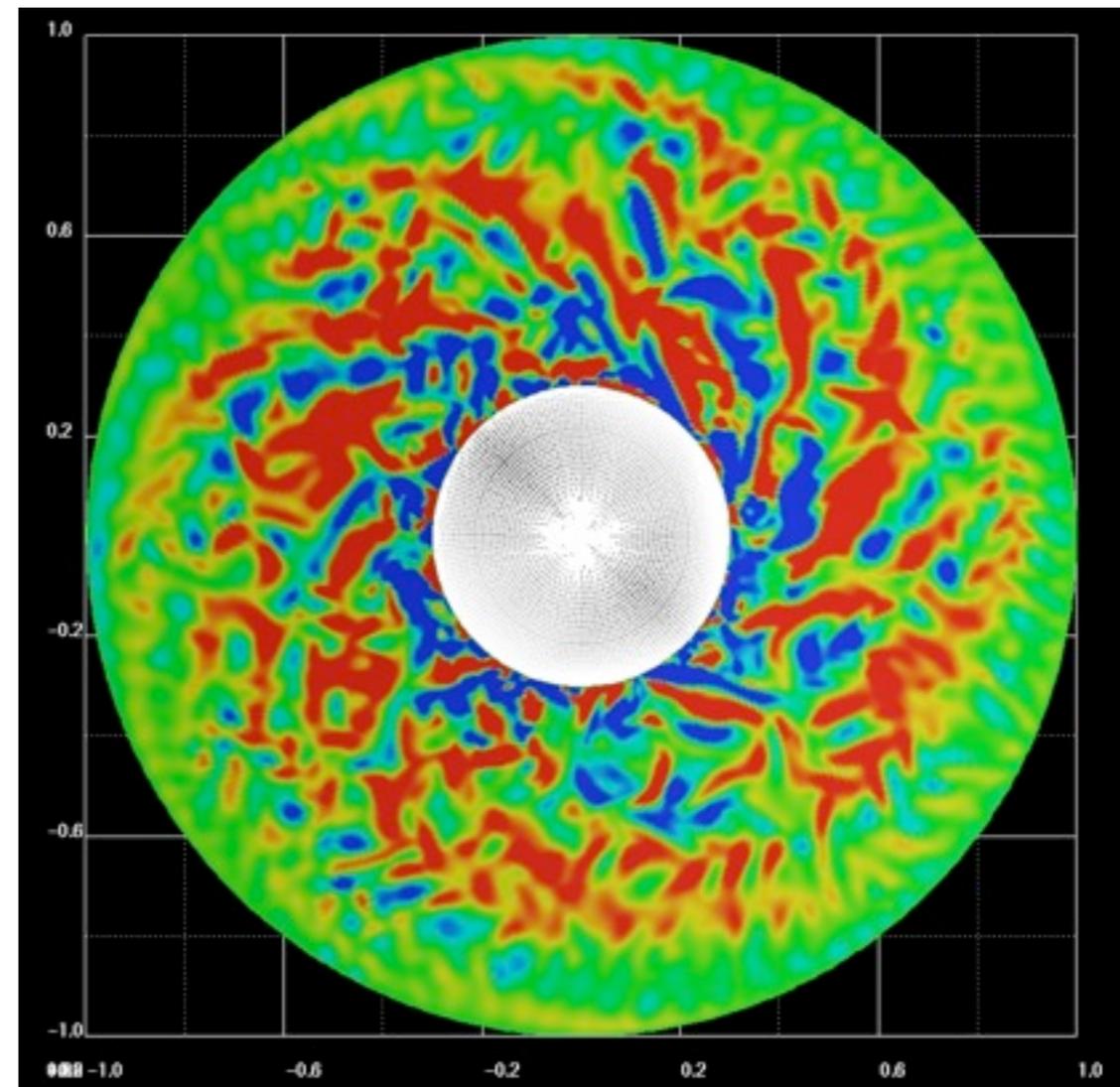
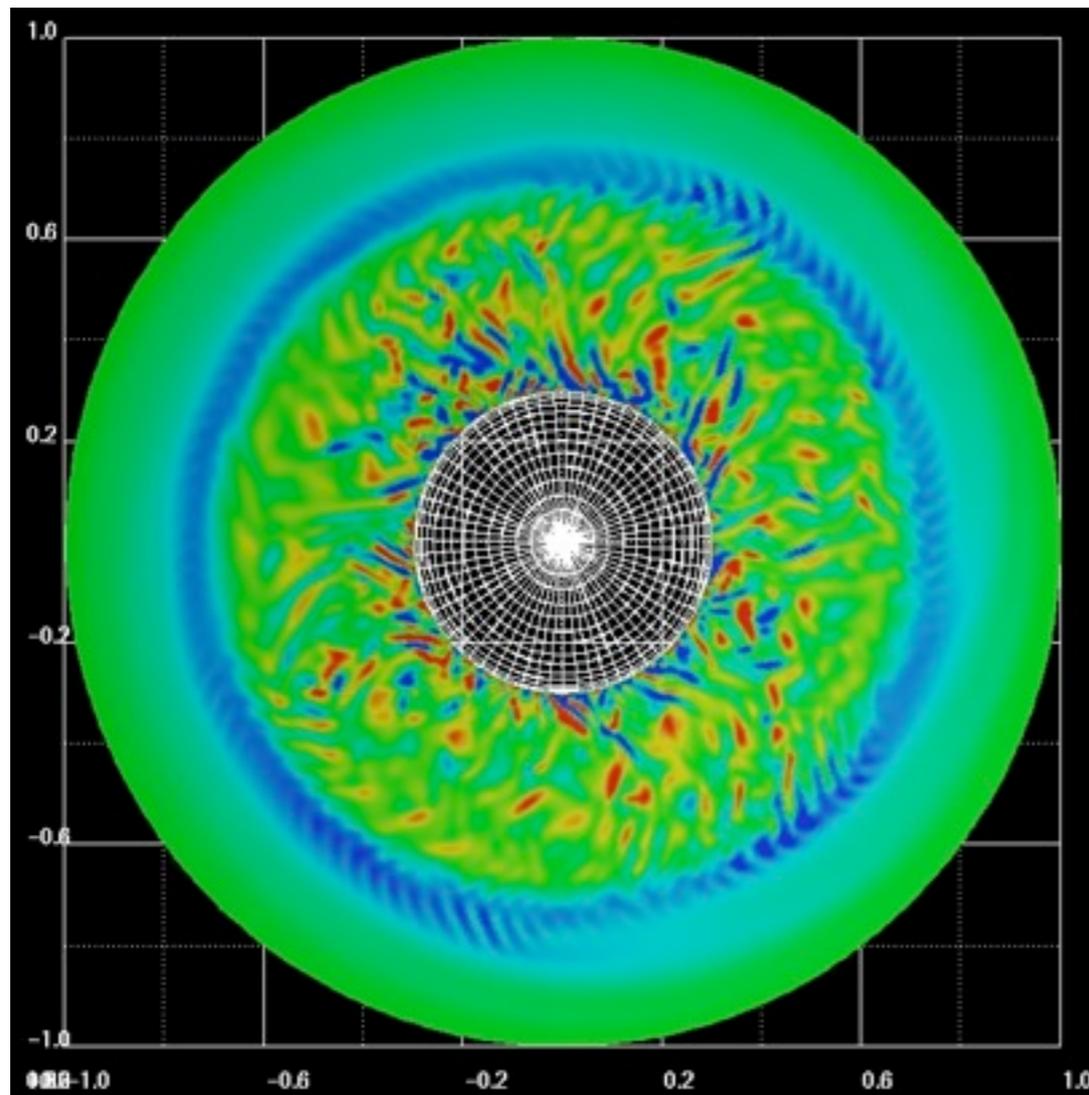
Stretch-Twist-Fold過程

Stretchはわかった。だがTwistとFoldの過程が不明。

赤道面上の v_ϕ (流れの東西成分)

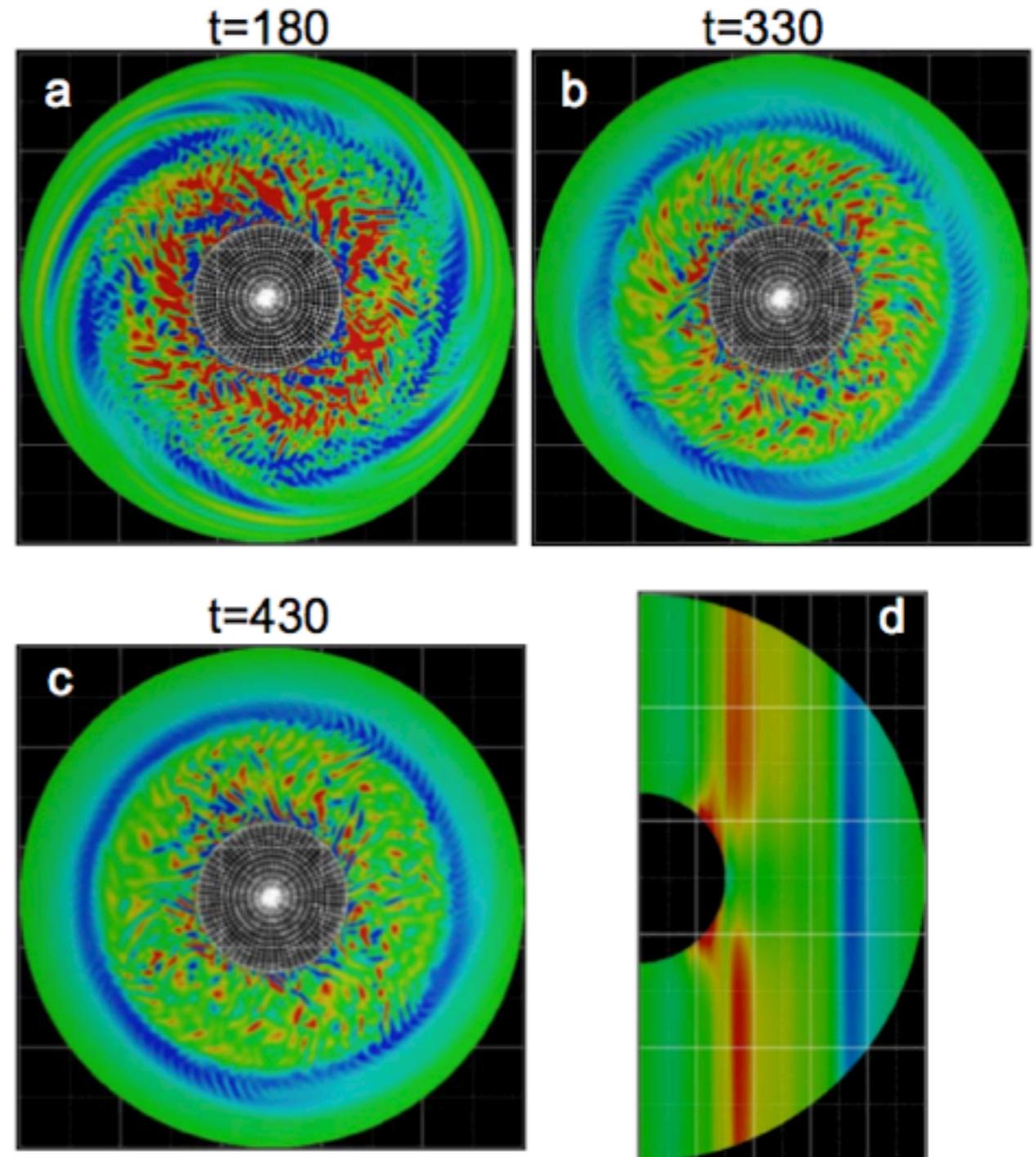
$$E_k = 2.3 \times 10^{-7}$$

$$E_k = 2.6 \times 10^{-6}$$



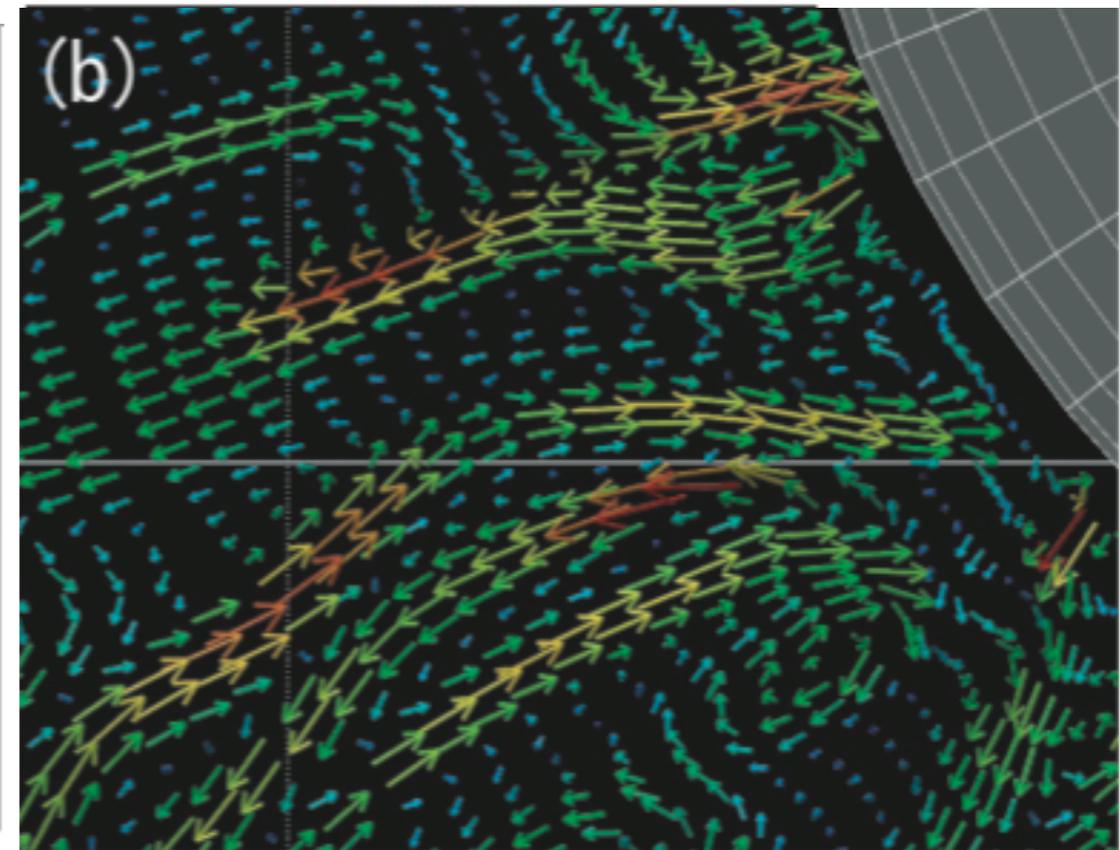
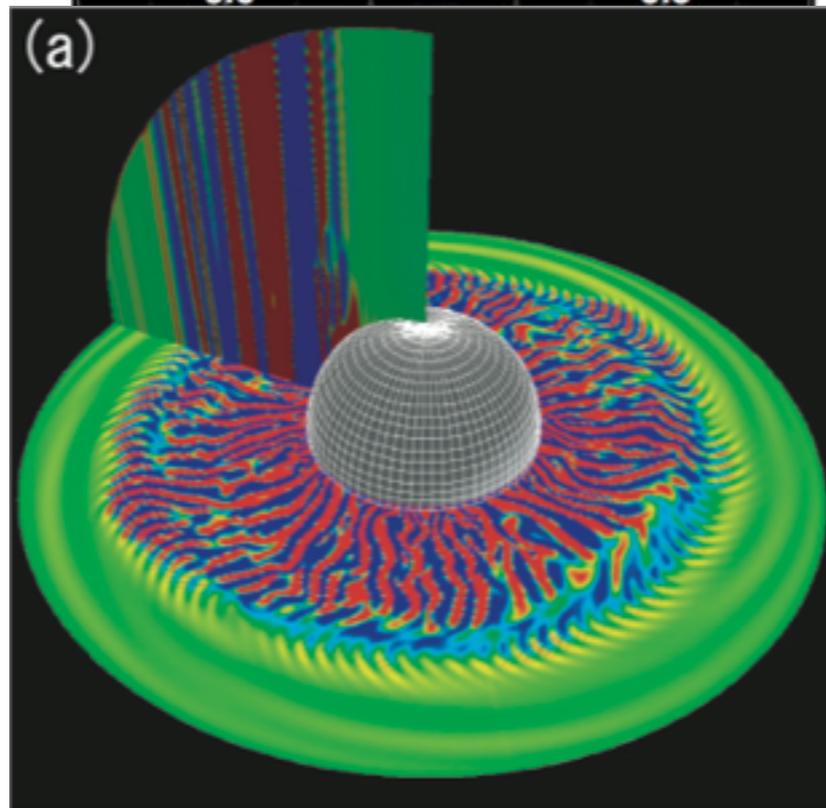
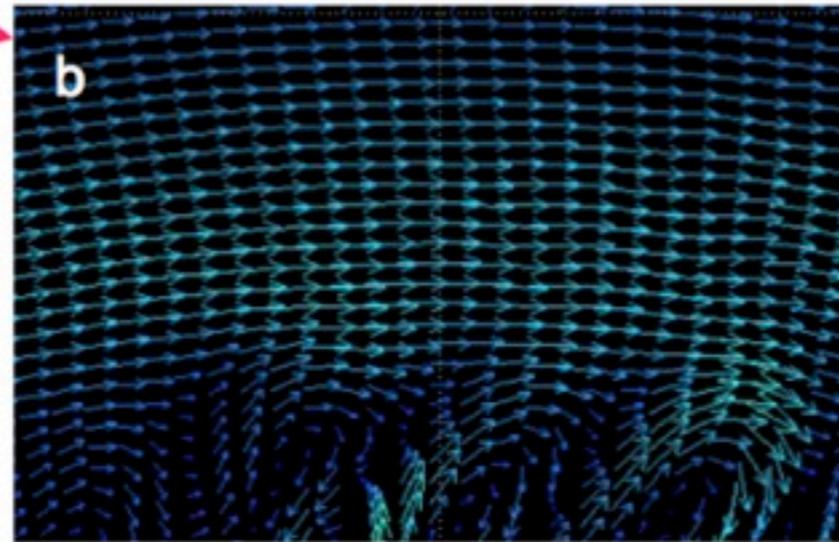
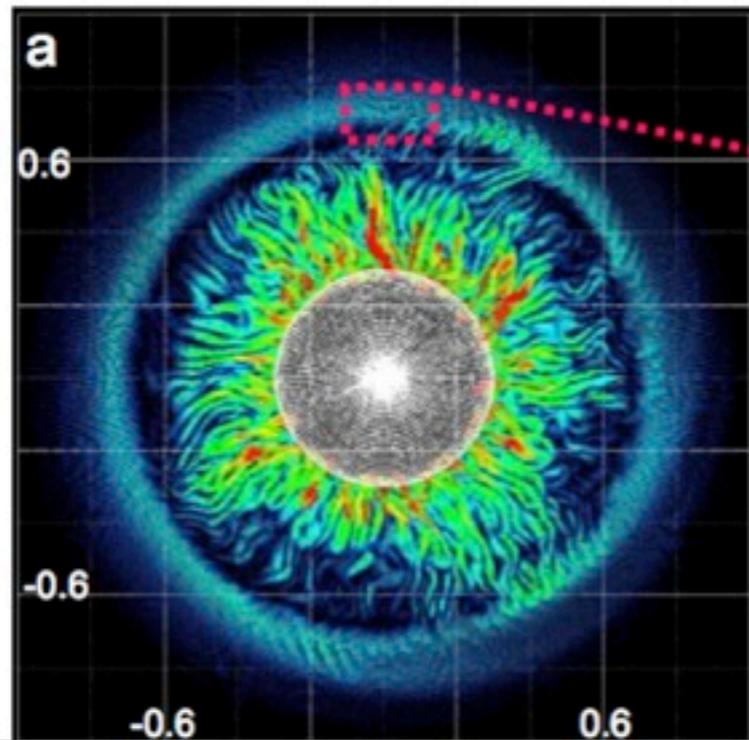
帯状流の形成

- シート状・プルーム状の対流
- 帯状の流れの形成



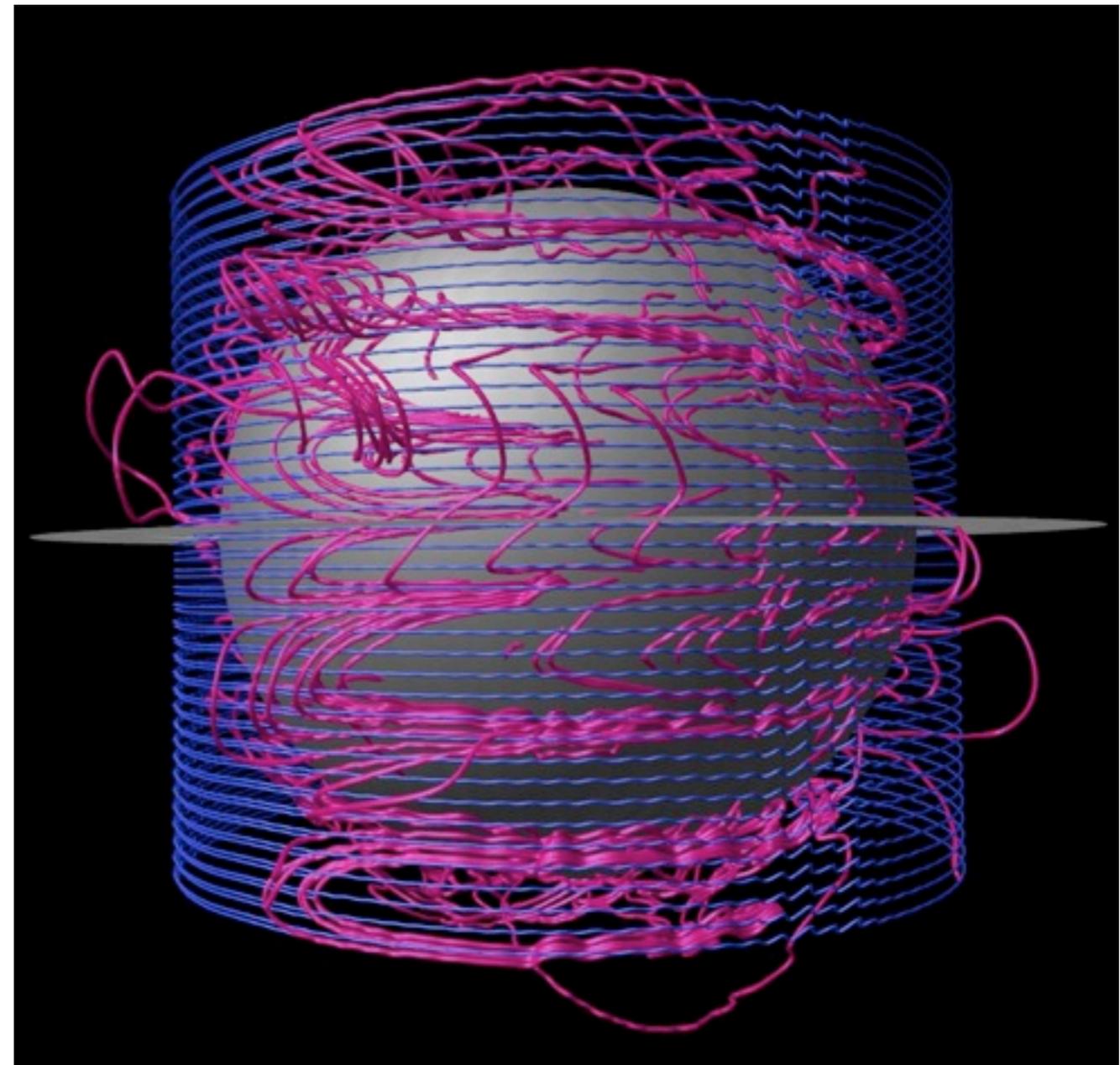
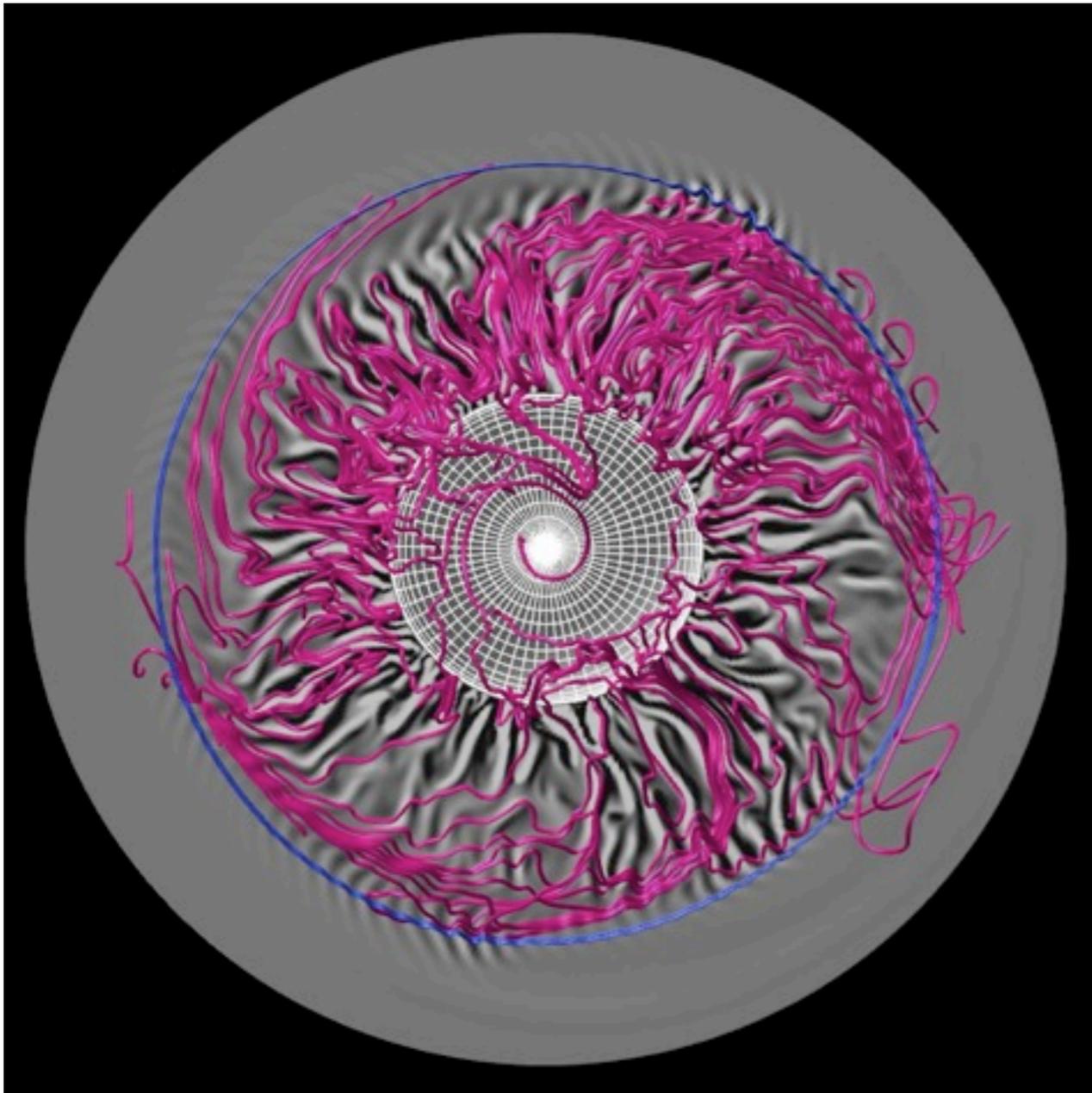
- Kageyama, Miyagoshi, Sato, 2008, Nature
- Miyagoshi, Kageyama, Sato, 2010, Nature
- Miyagoshi, Kageyama, Sato, 2011, Phys. Plasmas

シートブルームと帯状流



Magnetic field lines (pink)

Stretching by the inner sheet-like plumes and the outer zonal flow.

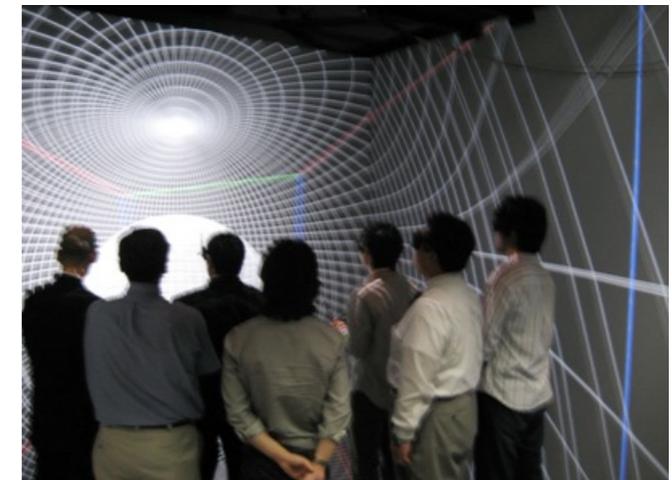
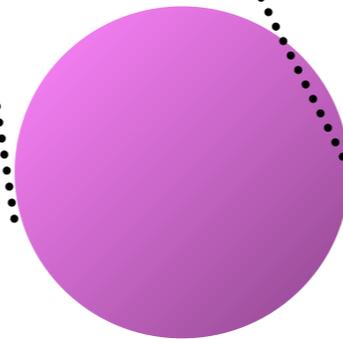
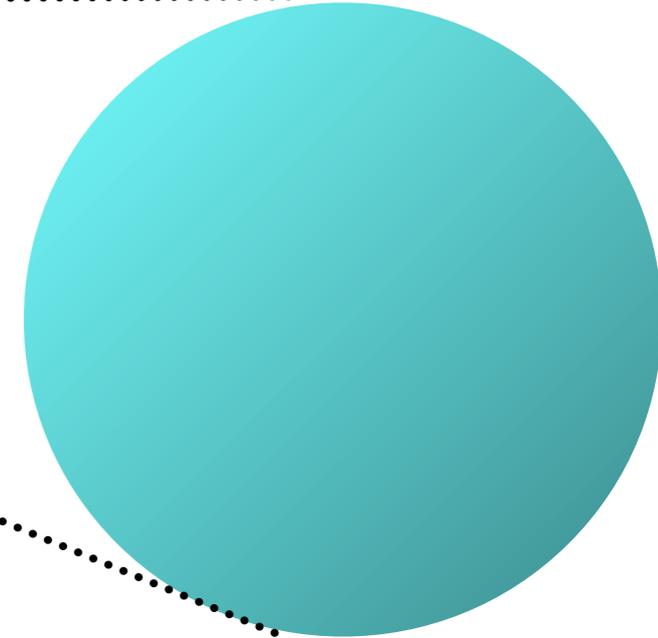
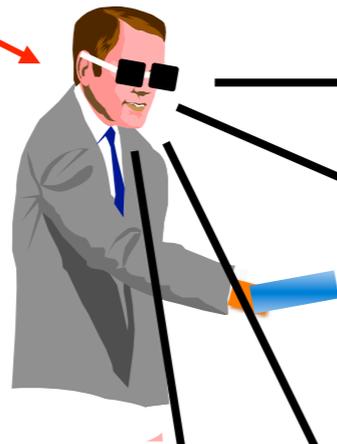


CAVE型バーチャルリアリティ装置

3.5-CAVE

部屋の中を自由に歩くことが可能。
全てが自然に見える。

位置・方向センサ



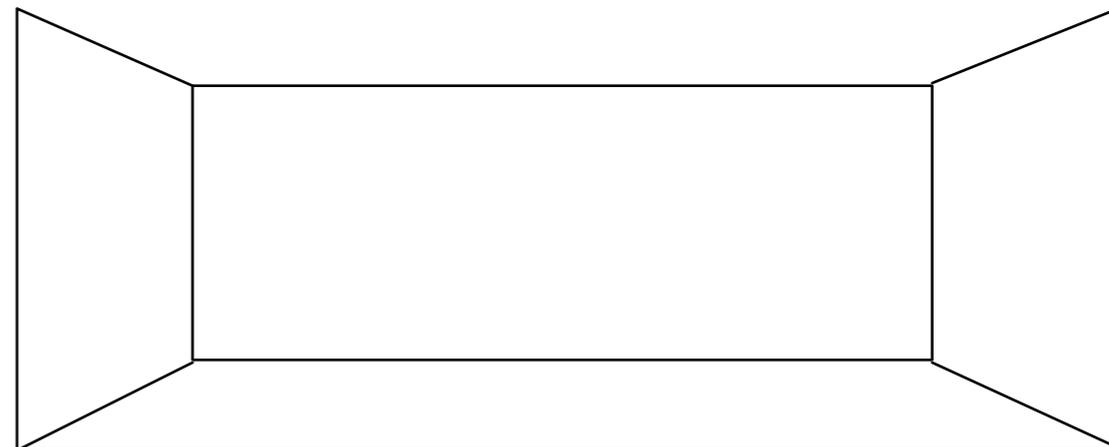
神戸大学 『 π -CAVE』

日本最大のCAVE装置
神戸大学統合研究拠点
(ポートアイランド)

Port Island

→ P. I.

→ π



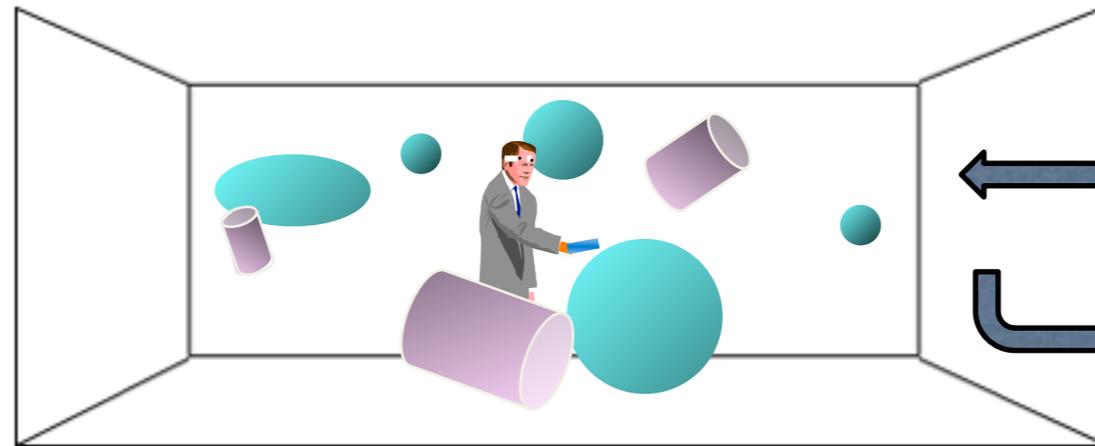
π -CAVE



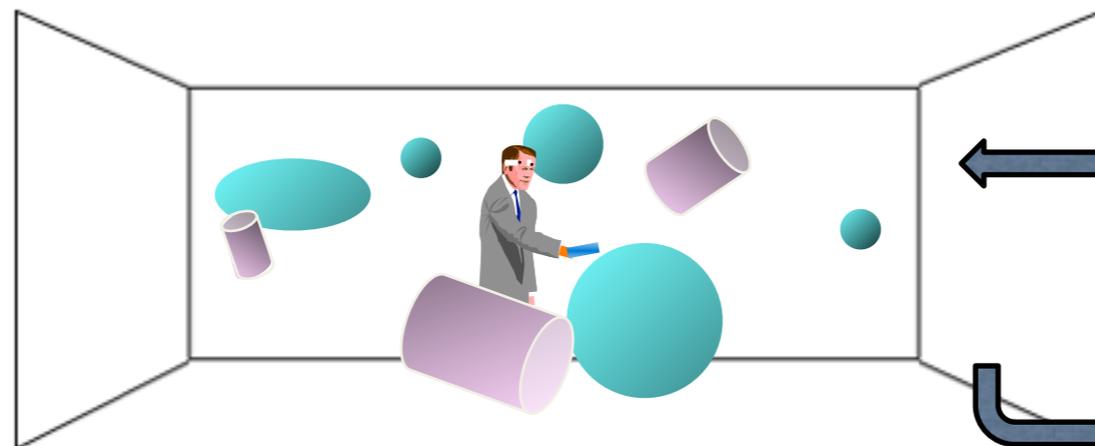
Necessity of middleware

- When we have multiple VR visualization programs to be run in CAVE...

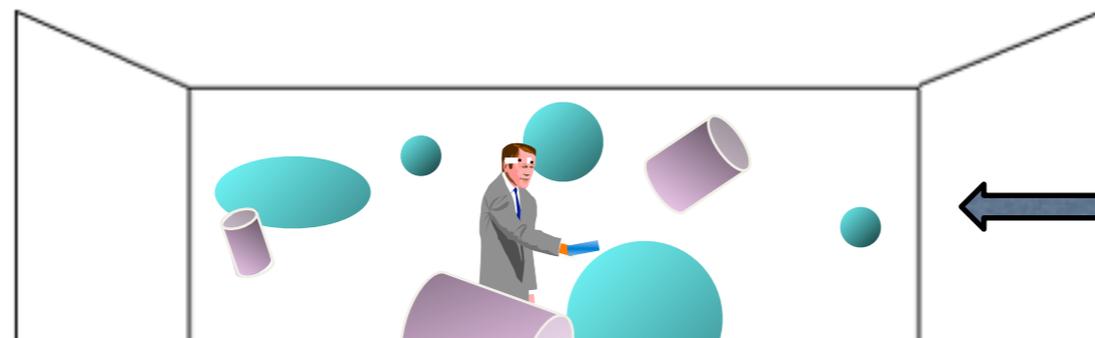
App 1



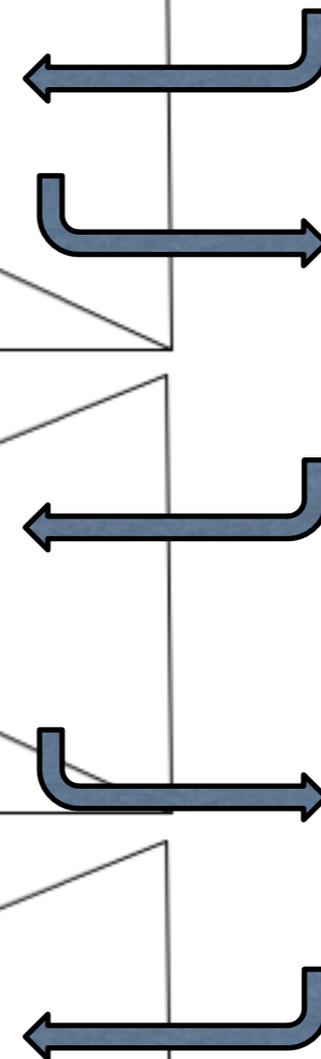
App 2



App 3



...



Multiverseの開発

- 3D “デスクトップ”
- アプリケーションランチャ
- 可視化アプリ = 仮想現実世界 = “ユニバース”



Multiverse Developers



Lead developer
Y. Yamaura



D. Meno



Y. Masada



K. Yoshizaki



K. Yamada



T. Morimoto



T. Yamada



M. Yuki



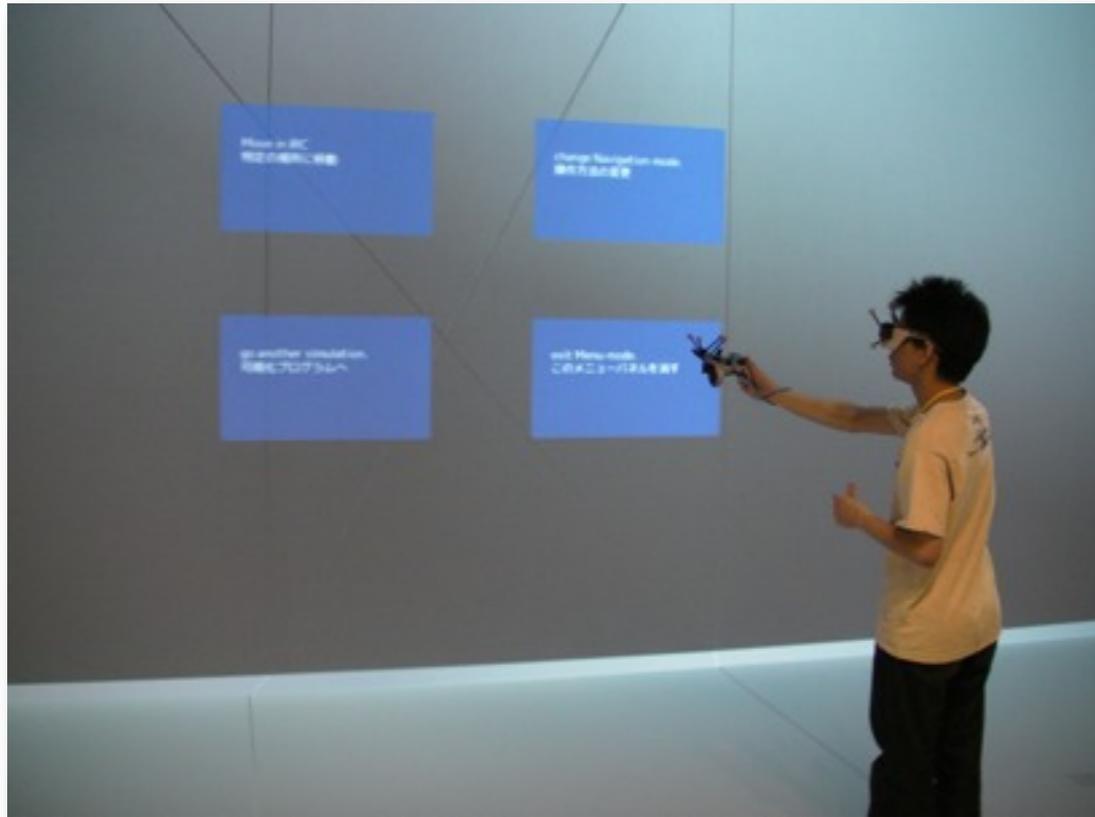
Y. Nishida



Y. Ohno

要素技術開発

仮想タッチパネル

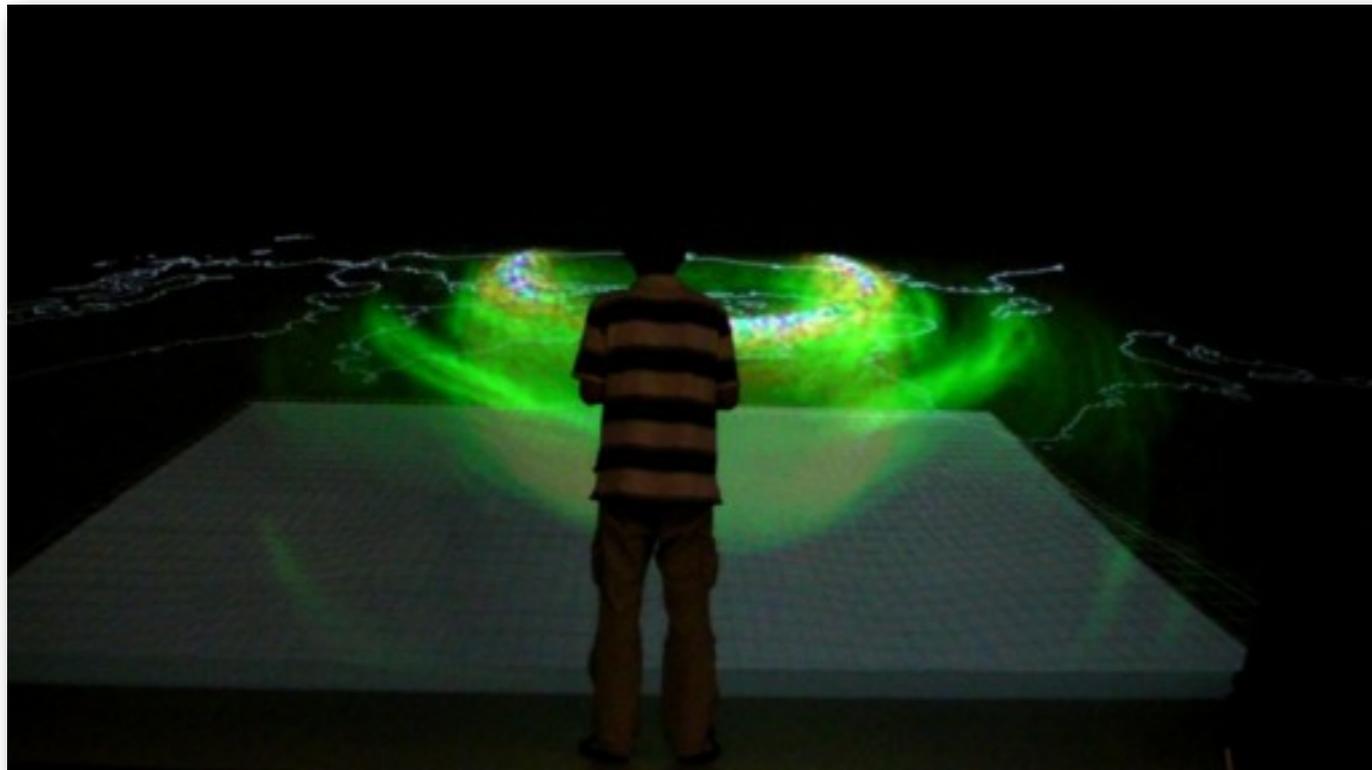
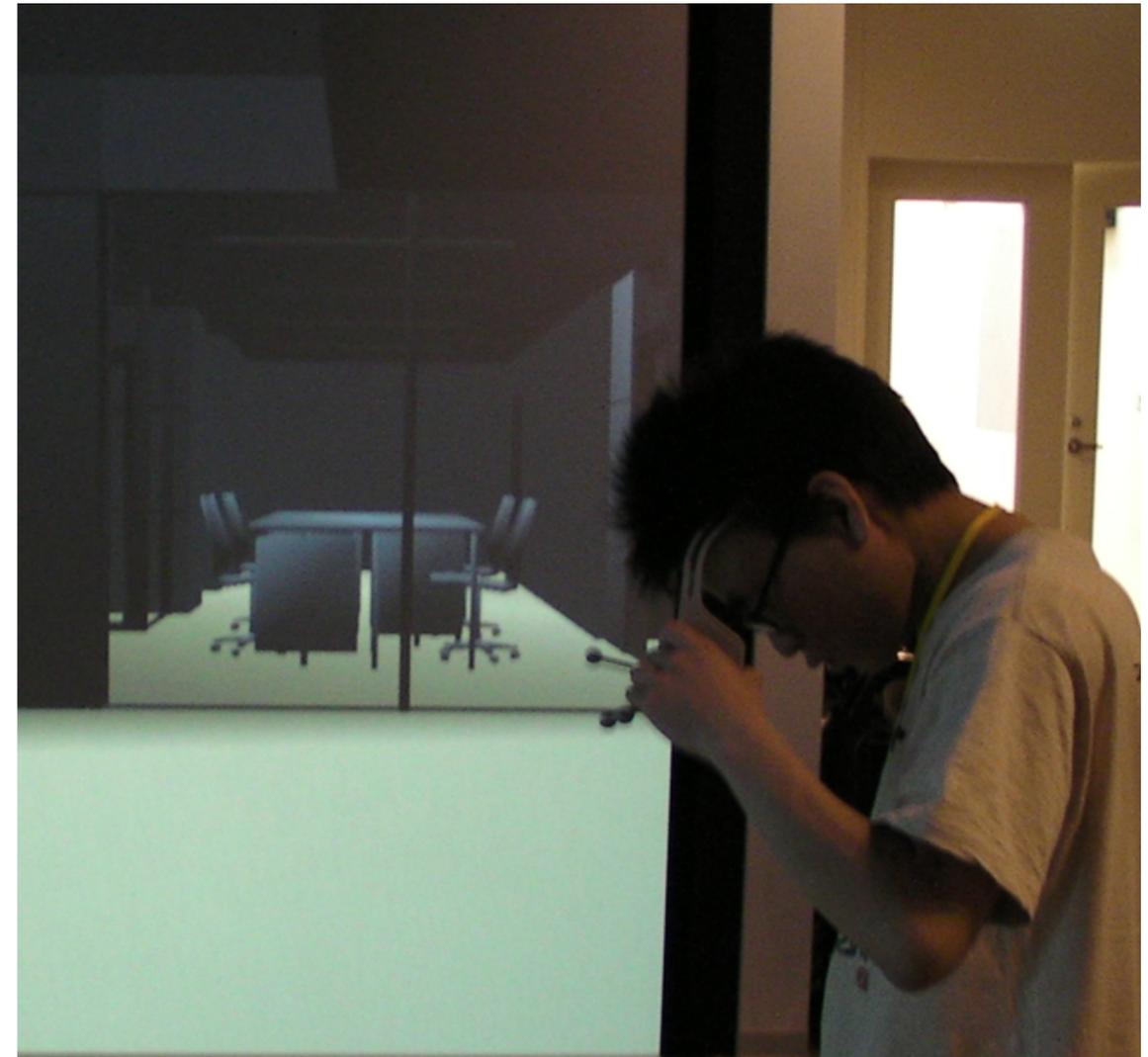


2D動画再生



要素技術開発

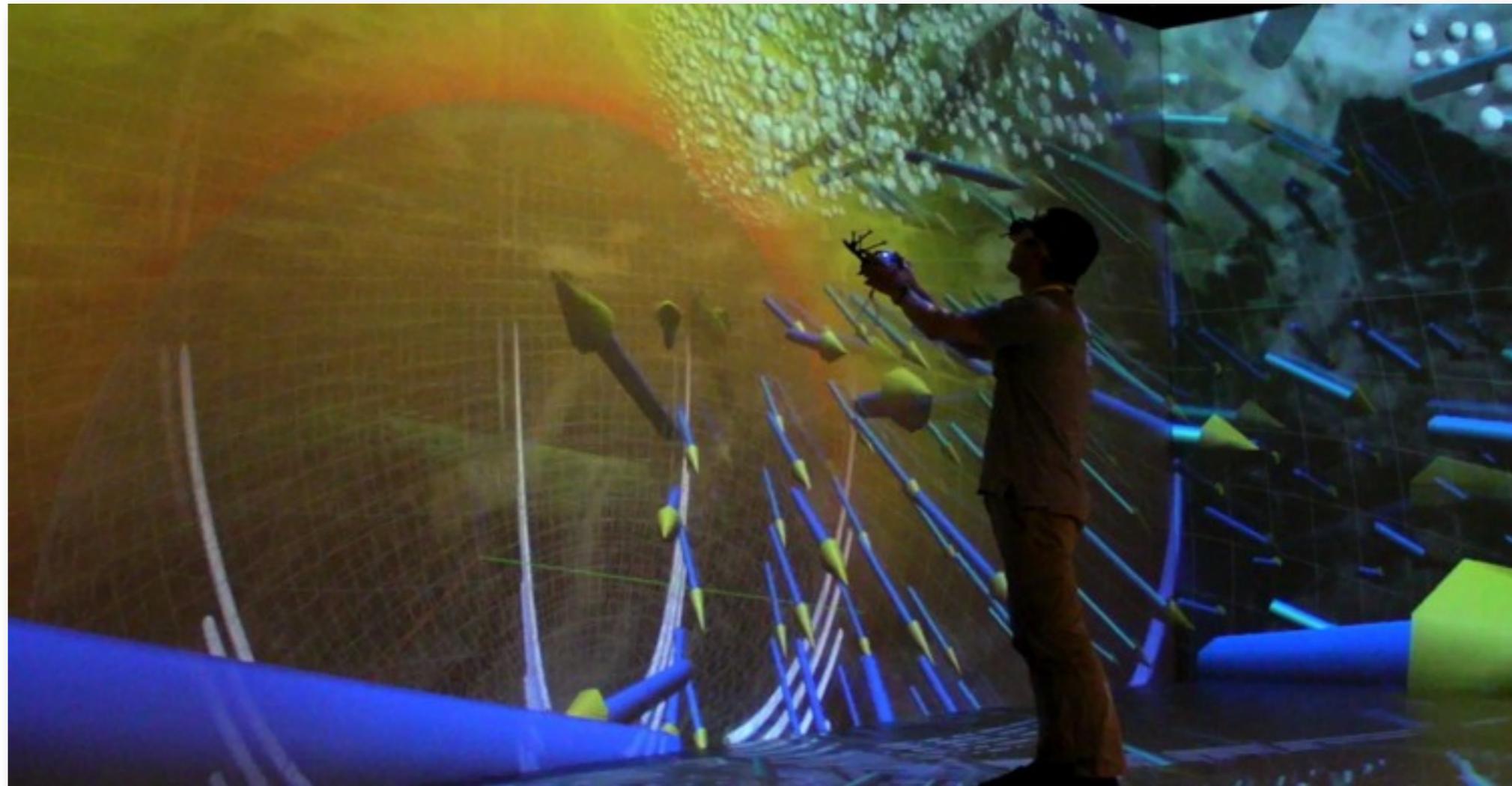
3Dオブジェクトデータの
取り込みと表示



3次元高速立体ボリューム
レンダリング

π -CAVE装置での可視化

3D-CAVE



まとめ

- 地磁気：自然界の謎
- 陰陽：計算法の工夫
- 仮想現実：解析の技術

JSST 2012

International Conference on Simulation Technology



Sep. 27-28, 2012
Port Island, Kobe, Japan
Integrated Research Center, Kobe Univ.

The purpose of this conference is to disseminate progress in the state-of-the-art of simulation methods and to report applications in natural & social sciences.

JSST 2012 is held at Port Island, Kobe, Japan, where the supercomputer "K computer" (ranked first of TOP500 supercomputers in Jun. & Nov. 2011) is located.

May 16 Submission of extended abstract

June 27 Notification of acceptance

August 6 Submission of full paper

Technical tour : K Computer

The number of participants is limited... Register EARLY!

Financial support is available for international participants.



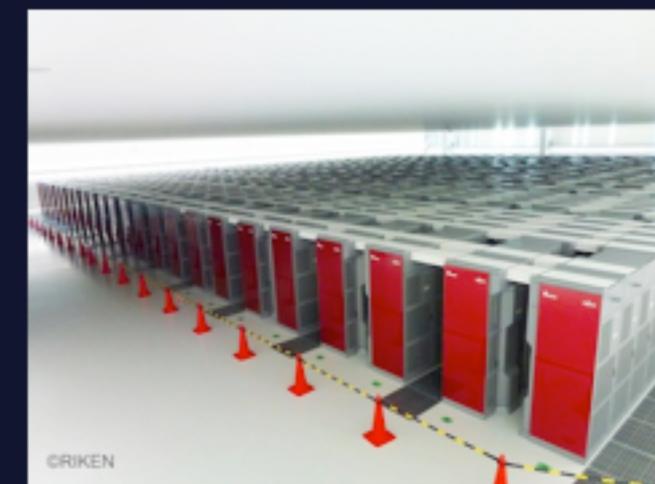
Technical Tour

Technical Tour

Technical tour to K Computer

Date: Thursday, September 27, 2012

Time: 1:30 p.m. - 2:30 p.m.



The number of participants is limited... Register to the conf

Banquet

Ship

Luminous Kobe 2

See the official site of Luminous Kobe 2 (in Japanese)

