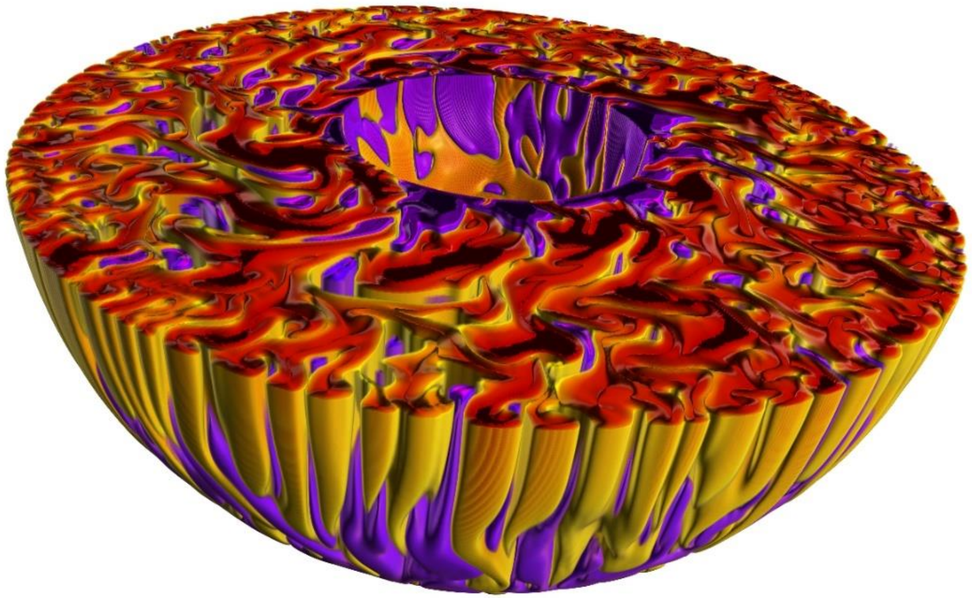
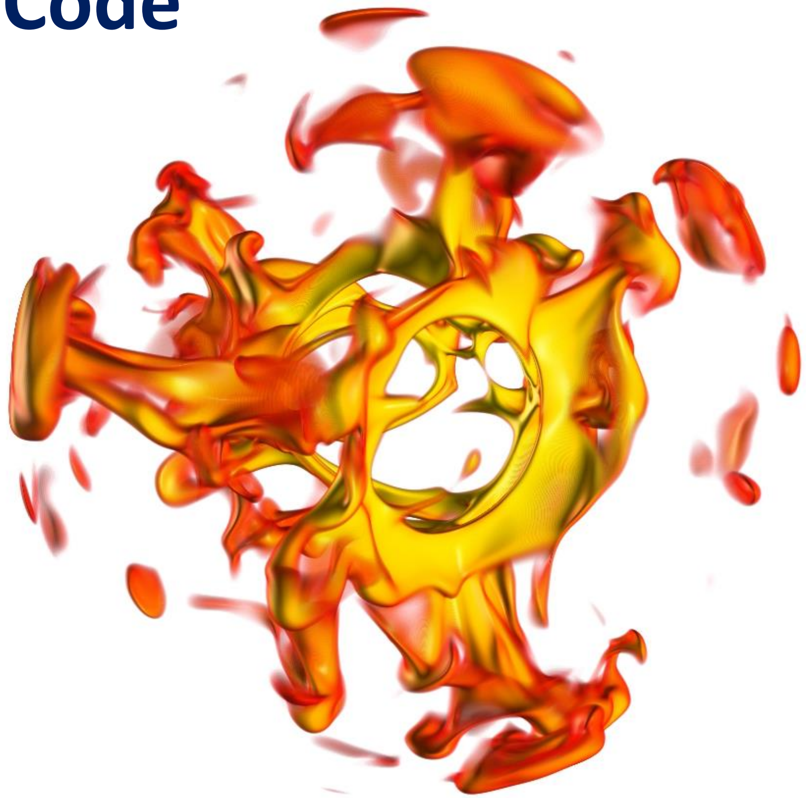
Rayleigh: An Open-Source, Scalable Pseudo-Spectral MHD Code





Nick Featherstone
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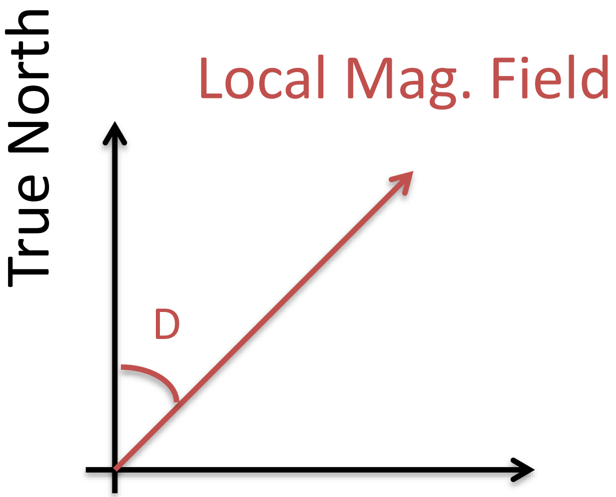
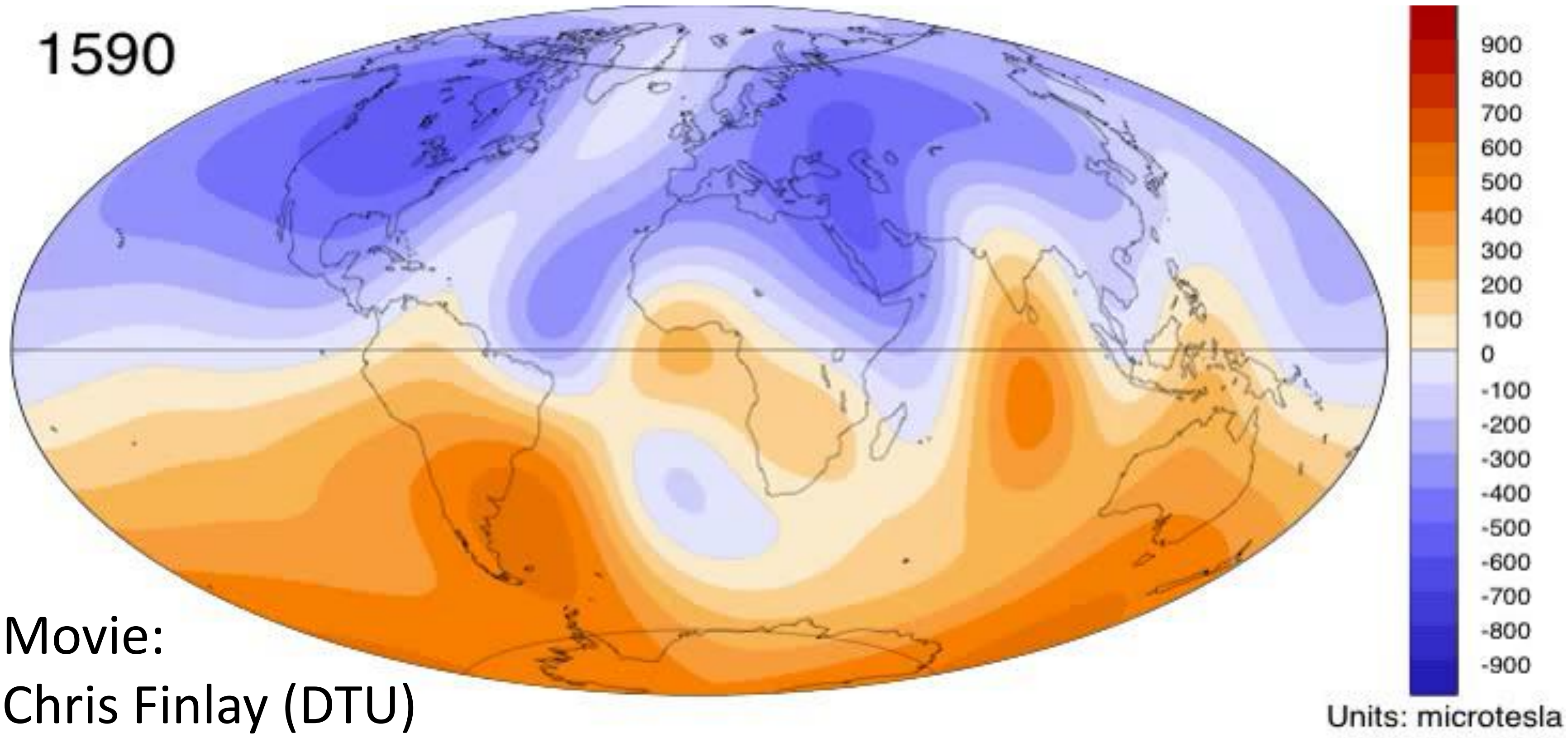
Solar System Science and Exploration Division

Geomagnetic Declination in 1701



[Edmond Haley, 1701]

History of Earth’s Magnetic Field



Movie:
Chris Finlay (DTU)

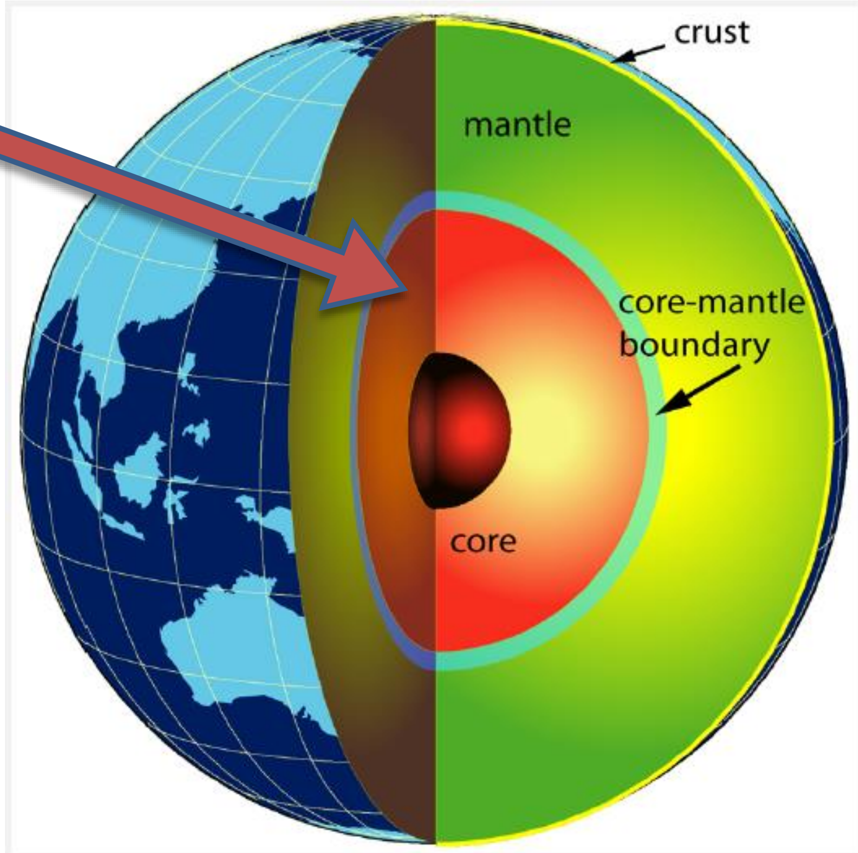
Geomagnetism is <u>Dynamic</u>
Something inside the Earth is causing this variation

Planetary Dynamo Schematic: The Geodynamo

- Liquid iron core:
  Convection + Induction
  Spherical geometry

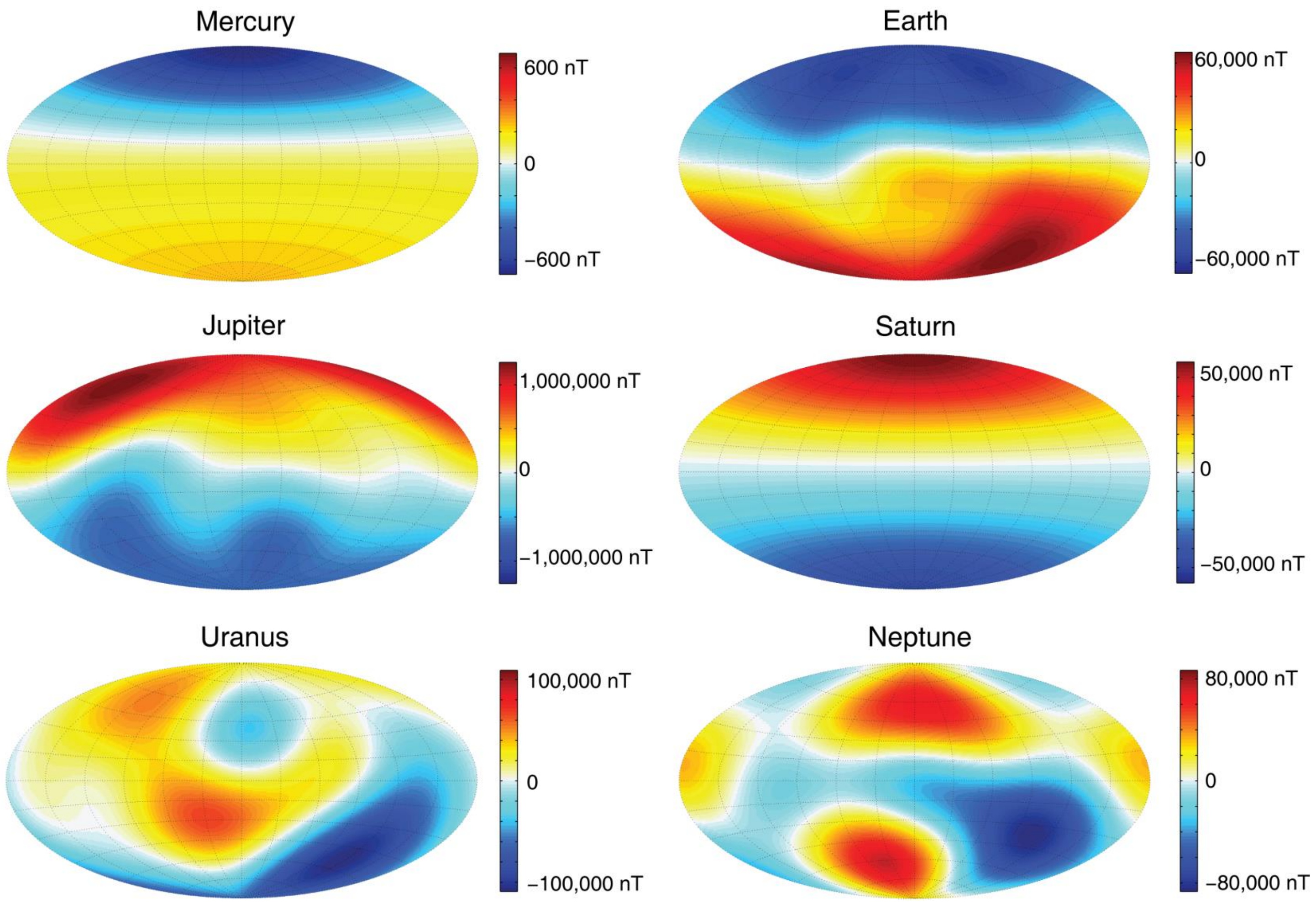
- Thermal or compositional forcing:
  Latent heat release
  Light element release

- Difficult to observe directly:
  Remote
  Mantle-filtering



Most Planets Possess Magnetic Fields

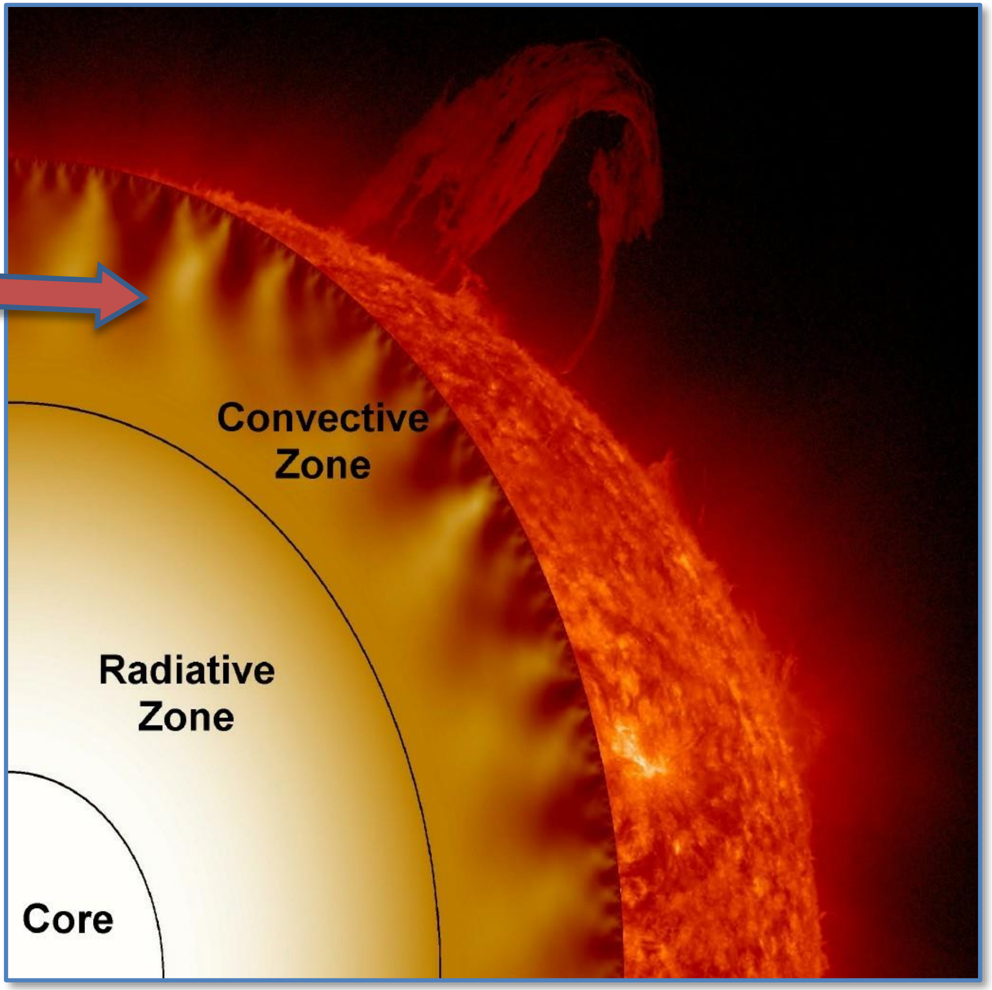
[Cao 2014]



…and of course the Sun too…

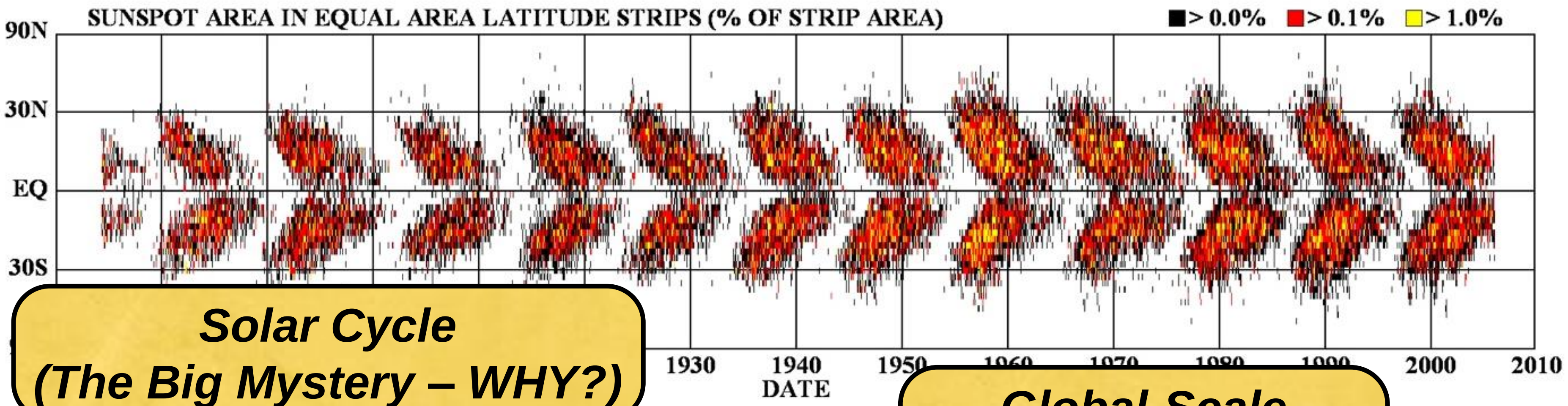
Stellar Dynamo Schematic: The Sun

- Dense plasma throughout:
  - Convection + Induction
  - Spherical geometry
- Thermal or compositional forcing:
  - Core fusion
- Difficult to observe below suface:
  - Helioseismology
- Magnetism is EVERYWHERE



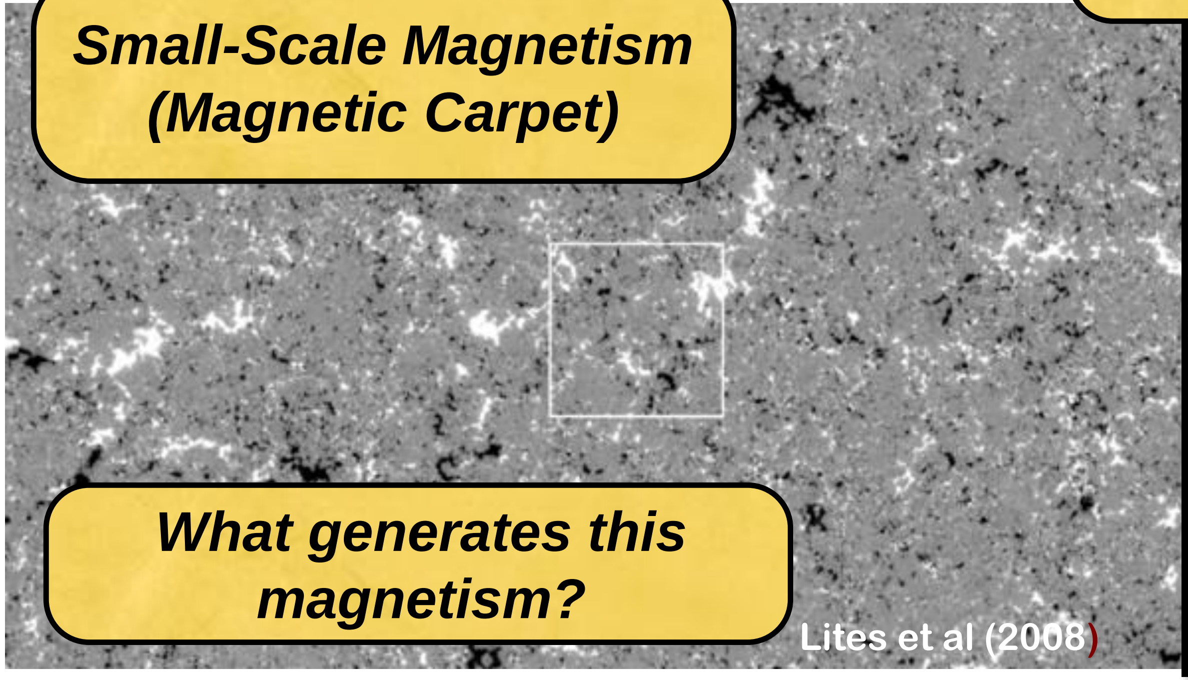
The Magnetic Sun

D. Hathaway (NASA MSFC)



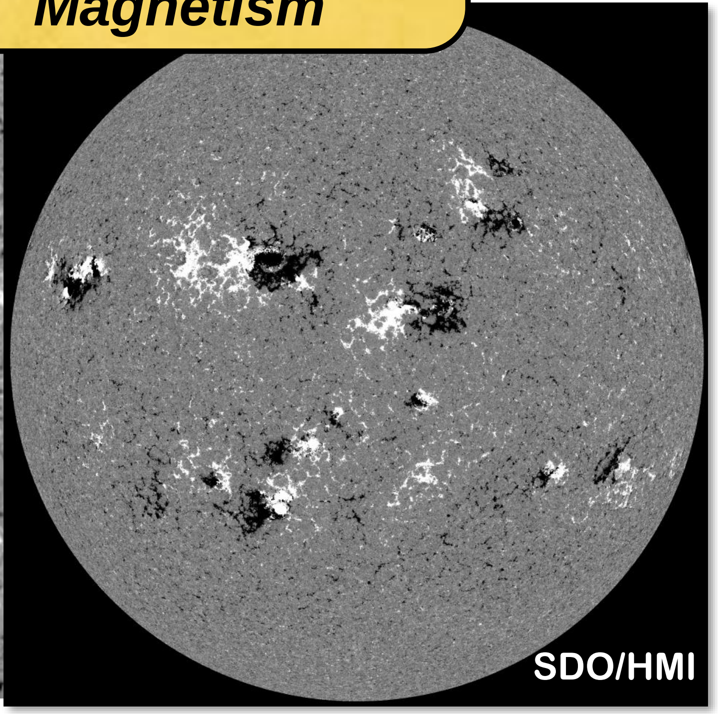
Solar Cycle
(The Big Mystery – WHY?)

Global-Scale Magnetism



Small-Scale Magnetism
(Magnetic Carpet)

What generates this magnetism?



The Big Question:

How do any of these rotating bodies generate a magnetic field?

The Challenge:

- ALL of these examples possess a WIDE range of spatial scales of convection.

- We have to resolve the big stuff (spherical-scale)

- We also have to resolve the small stuff

Geodynamo: The General Problem

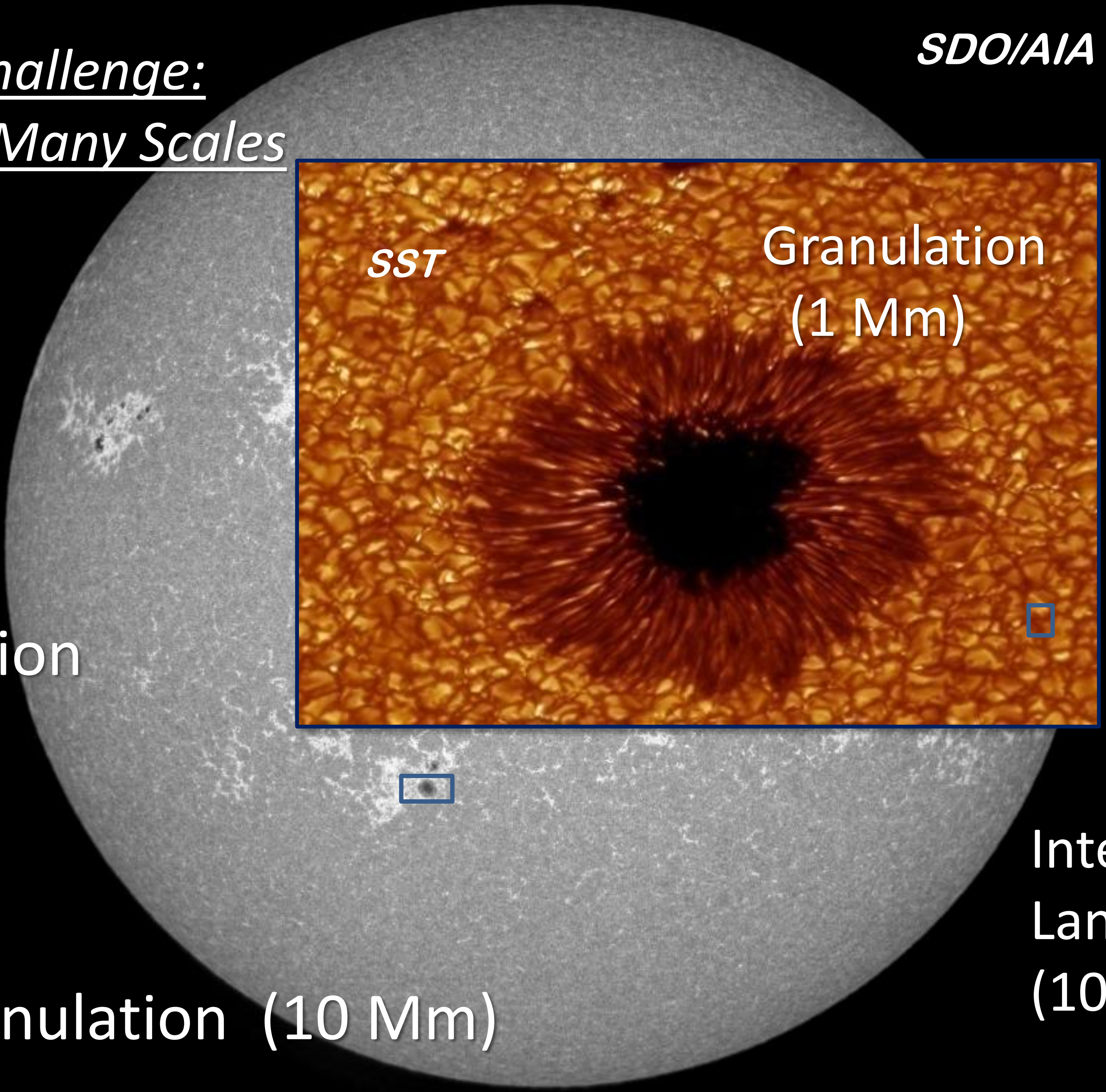
Earth's Core
~ 1 km

- The geodynamo is thought to be highly turbulent
- Large dynamic range of spatial and temporal scales
- Efficient, parallel codes needed to address questions about its operation

For every ONE viscous timescale:

- $O(10^{14})$ convective overturnings
- $O(10^{15})$rotation periods

The Solar Challenge: Convection on Many Scales



What is Rayleigh?

Rotating MHD convection in a sphere

Pseudo-spectral: Spherical Harmonics / Chebyshevs

Scalable: 2048^3 –sized problems on $O(10^5)$ cores

Open Source: Spring/Summer 2015

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

CIG Geodynamo Working Group (2013—2018)

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- Cian Wilson (Carnegie Science)

CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

Rayleigh Solves: The Boussinesq MHD Equations

$$\left[\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla}\boldsymbol{v} + \frac{2}{E}\hat{\boldsymbol{z}}\times\boldsymbol{v}\right] = \frac{Ra}{Pr}\left(\frac{r}{r_o}\right)^n \Theta\,\hat{\boldsymbol{r}} - \frac{1}{E}\boldsymbol{\nabla}P + \frac{1}{E\,Pm}(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B} + \boldsymbol{\nabla}\cdot\boldsymbol{\mathcal{D}}$$

$$\left[\frac{\partial \Theta}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla}\Theta\right] = \frac{1}{Pr}\boldsymbol{\nabla}\cdot\left[\tilde{\kappa}(r)\boldsymbol{\nabla}\Theta\right]$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla}\times\left[\boldsymbol{v}\times\boldsymbol{B} - \frac{1}{Pm}\tilde{\eta}(r)\boldsymbol{\nabla}\times\boldsymbol{B}\right]$$

$$\mathcal{D}_{ij} = 2\tilde{\nu}(r)e_{ij}$$

$$\boldsymbol{\nabla}\cdot\boldsymbol{v} = 0$$

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

Rayleigh Solves: The Anelastic MHD Equations

$$\hat{\rho}(r)\left[\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla}\boldsymbol{v} + 2\Omega_0 \hat{\boldsymbol{z}}\times\boldsymbol{v}\right] = \frac{\hat{\rho}(r)}{c_P} g(r)\Theta\,\hat{\boldsymbol{r}} + \hat{\rho}(r)\boldsymbol{\nabla}\left(\frac{P}{\hat{\rho}(r)}\right) + \frac{1}{4\pi}(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B} + \boldsymbol{\nabla}\cdot\boldsymbol{\mathcal{D}}$$

$$\hat{\rho}(r)\,\hat{T}(r)\left[\frac{\partial \Theta}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla}\Theta + v_r\frac{d\hat{S}}{dr}\right] = \boldsymbol{\nabla}\cdot\left[\hat{\rho}(r)\,\hat{T}(r)\,\kappa(r)\,\boldsymbol{\nabla}\Theta\right] + Q(r) + \Phi(r,\theta,\phi) + \frac{\eta(r)}{4\pi}\left[\boldsymbol{\nabla}\times\boldsymbol{B}\right]^2$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla}\times\left[\boldsymbol{v}\times\boldsymbol{B} - \eta(r)\boldsymbol{\nabla}\times\boldsymbol{B}\right]$$

$$\mathcal{D}_{ij} = 2\hat{\rho}(r)\,\nu(r)\left[e_{ij} - \frac{1}{3}(\boldsymbol{\nabla}\cdot\boldsymbol{v})\delta_{ij}\right]$$

$$\Phi(r,\theta,\phi) = 2\,\hat{\rho}(r)\nu(r)\left[e_{ij}e_{ij} - \frac{1}{3}(\boldsymbol{\nabla}\cdot\boldsymbol{v})^2\right]$$

$$\boldsymbol{\nabla}\cdot\left[\hat{\rho}(r)\,\boldsymbol{v}\right] = 0$$

$$\boldsymbol{\nabla}\cdot\boldsymbol{B} = 0.$$

Rayleigh Solves: Other Variations

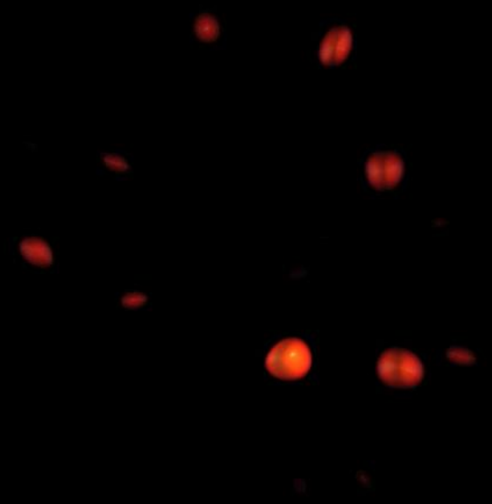
- Non-dimensional anelastic
- Custom equation sets
  - Alternative nondimensionalizations
  - Additional passive and active scale variables
    - Mixing studies
    - Compositional convection
- Described in the documentation and example notebooks provided in the Rayleigh repository

Warm plumes

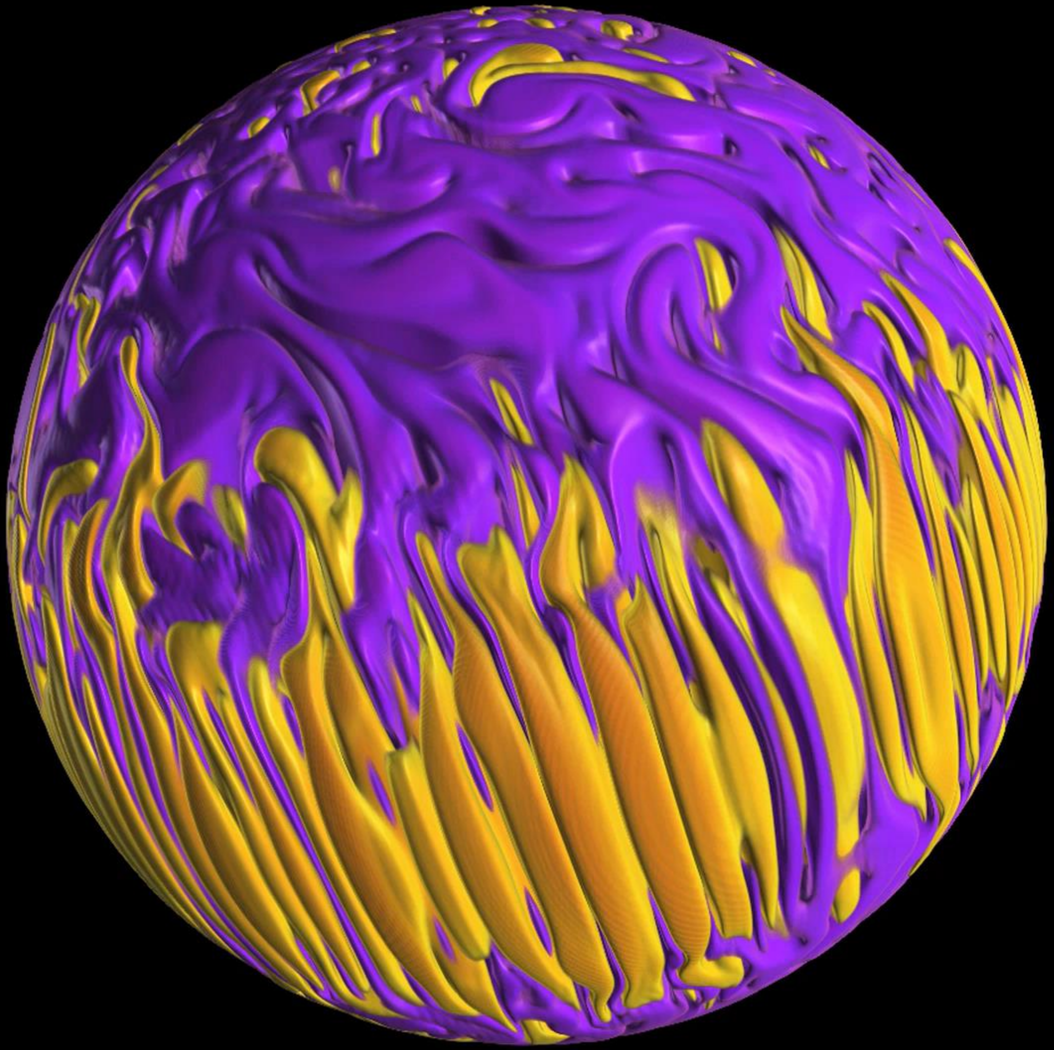
Earth-like
geometry

Pr= 1
Ra = 10^7

4,000 cores
4 hours
NASA Pleiades



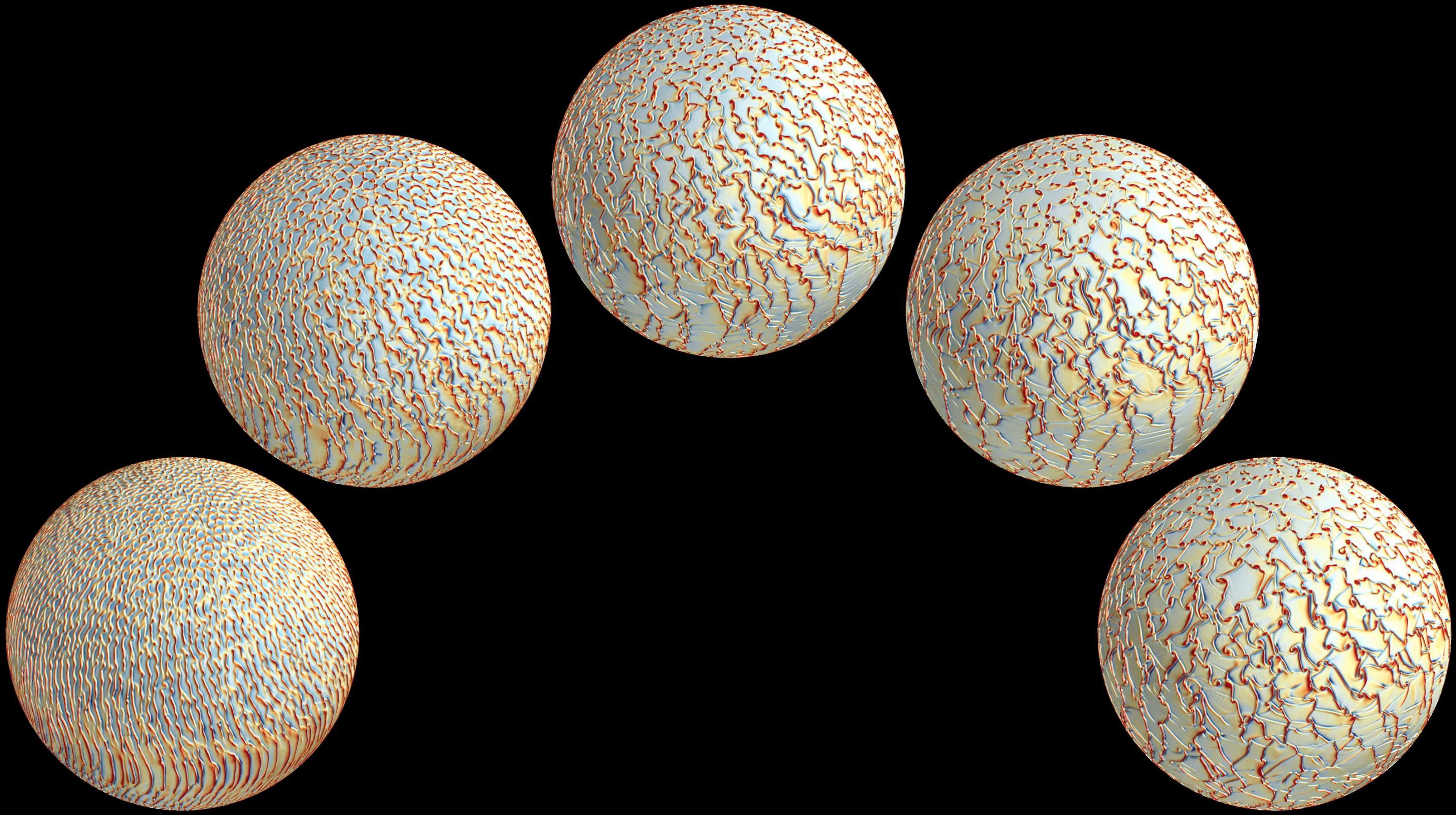
Rotating
(Exterior)



Rayleigh Code

4,000 cores
6 hours walltime
NASA Pleiades

Pr= 1
Ek = 10^{-5}
Ra = 2.5×10^{8}



Questions before we Begin?