Dynamos of Ice Giant Planets

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Ice Giant Systems 2020

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Image: E. Karkoschka

Outline

1) Planetary Magnetic Fields
2) Ice Giant Dynamos
3) Looking Ahead

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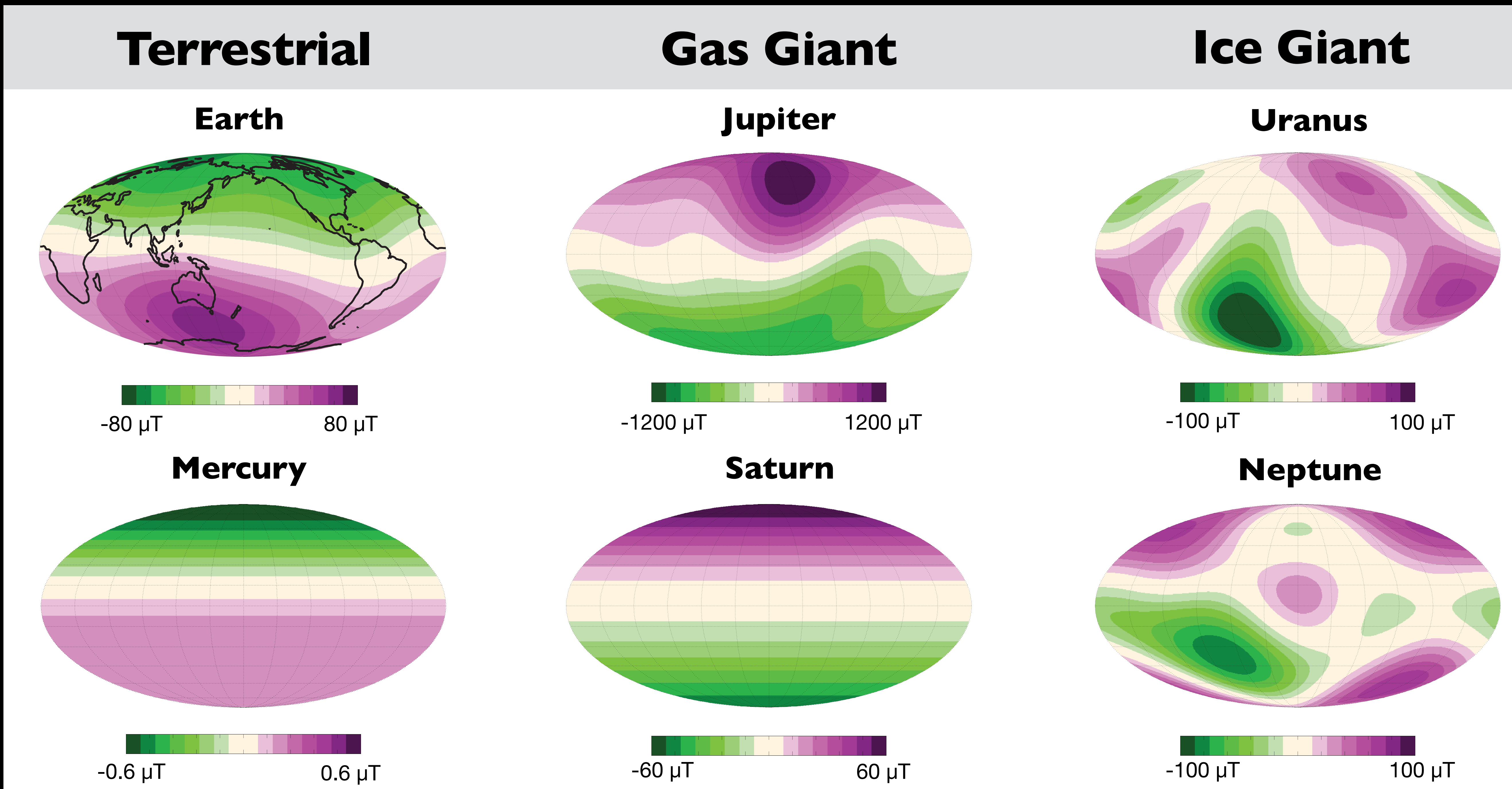
1) Planetary Magnetic Fields

2) Ice Giant Dynamos

3) Looking Ahead

Planetary Magnetic Fields

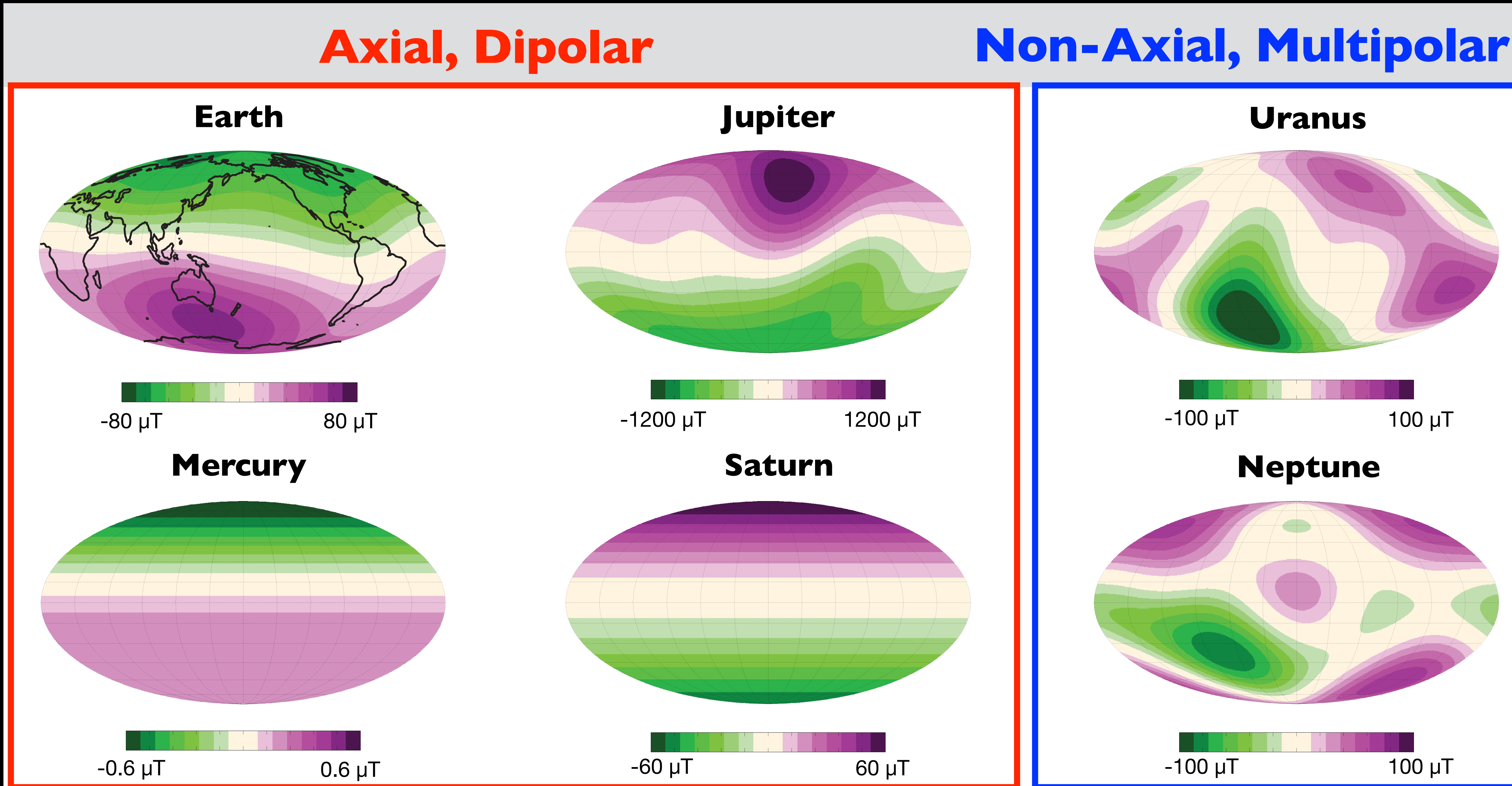
- Surface radial magnetic fields $(l_{max} \leq 3)$



Data taken from Uno et al. (2009), Kivelson et al. (2002), Yu et al. (2010), Burton et al. (2009), and Holme and Bloxham (1996).

Planetary Magnetic Fields

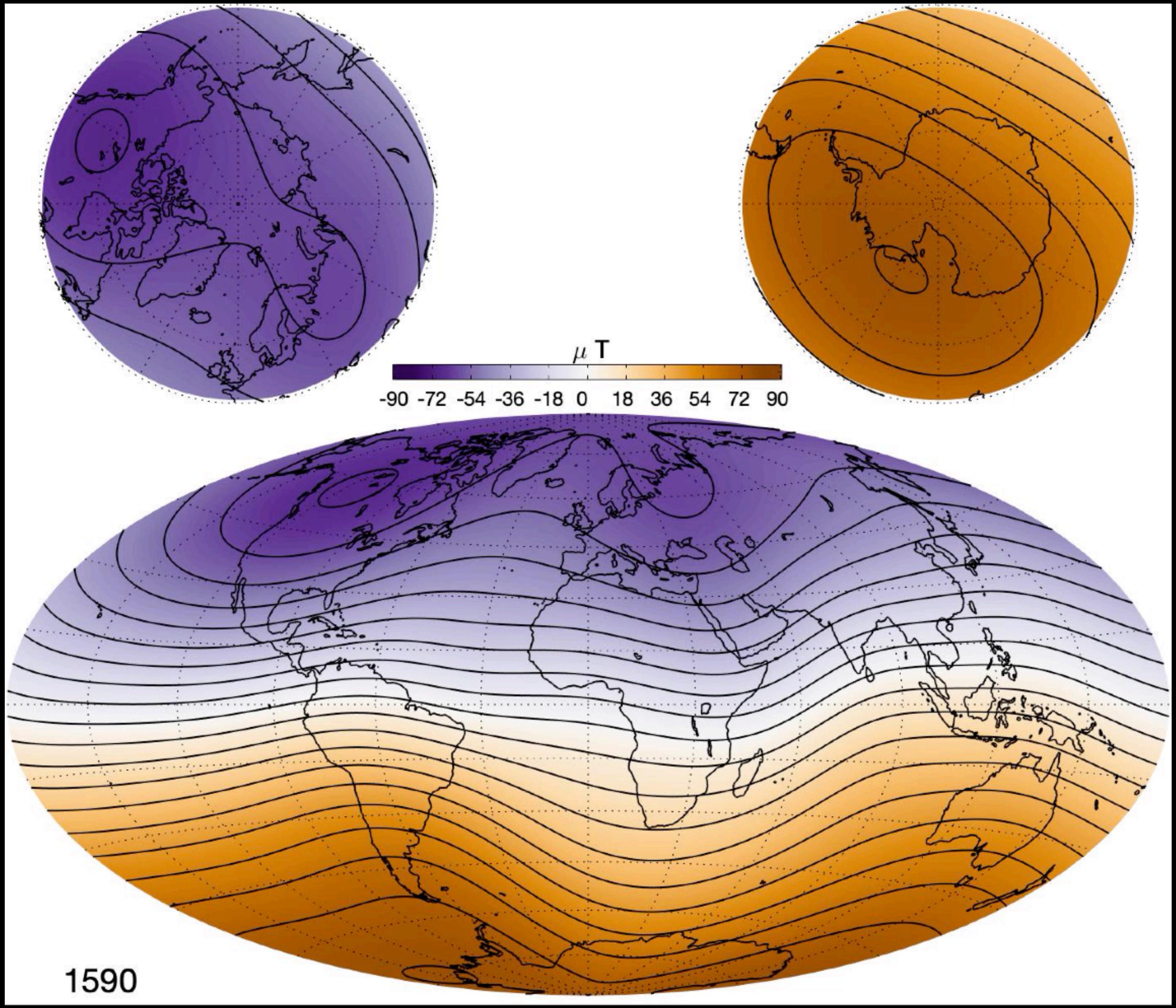
- Diverse magnetic field characteristics $(l_{max} \leq 3)$



Data taken from Uno et al. (2009), Kivelson et al. (2002), Yu et al. (2010), Burton et al. (2009), and Holme and Bloxham (1996).

Planetary Magnetic Fields

- Secular variation has been measured for the Earth

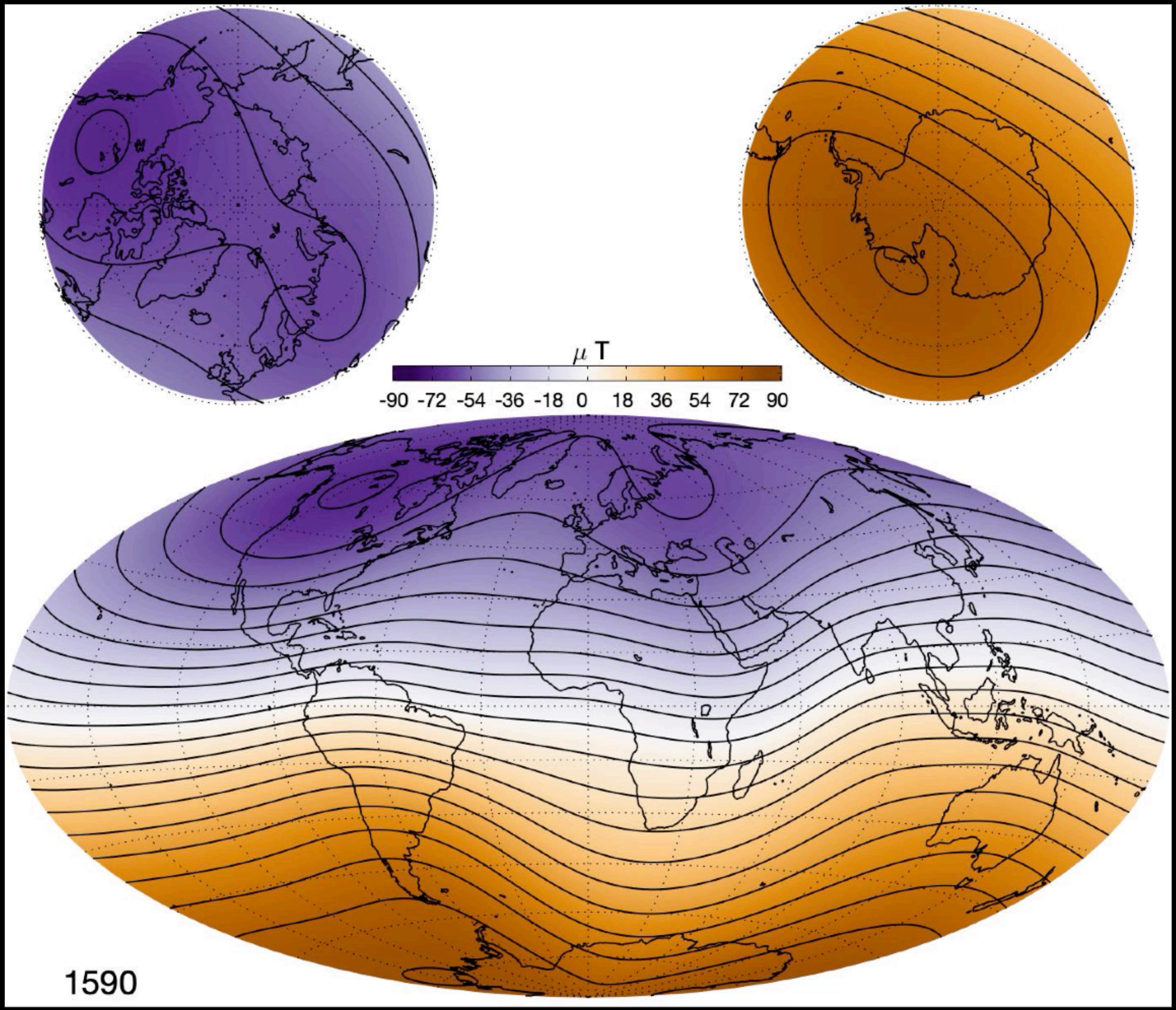


430 years (1590-2020)

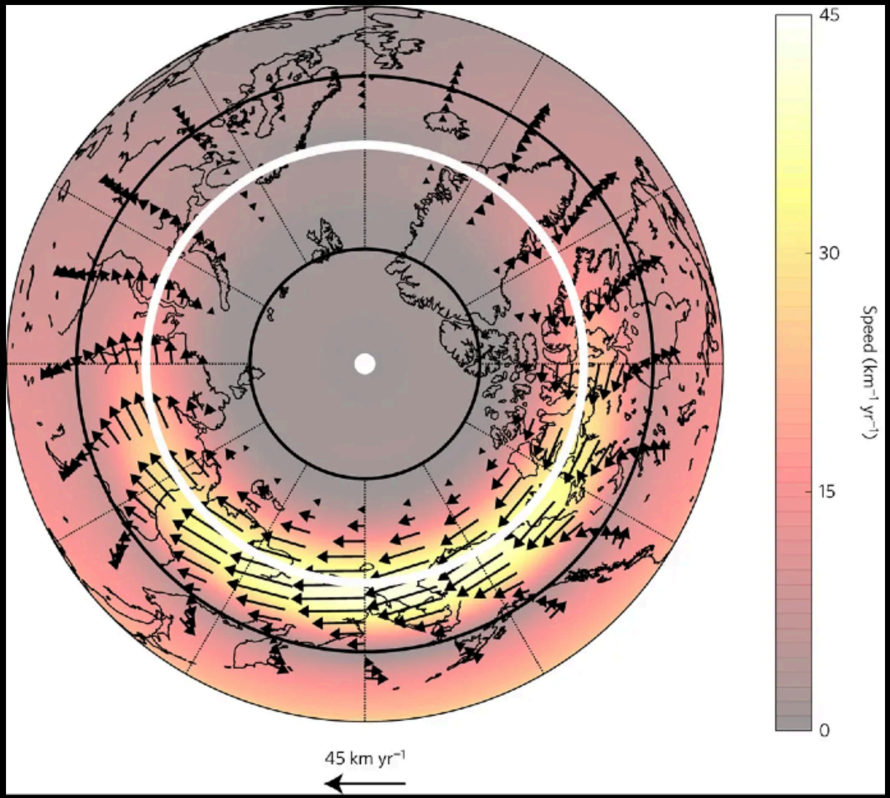
Jackson et al., 2000; Sabaka et al., 2004; Finlay et al., 2020, in prep

Planetary Magnetic Fields

- Secular variation has been measured for the Earth



Infer core flows

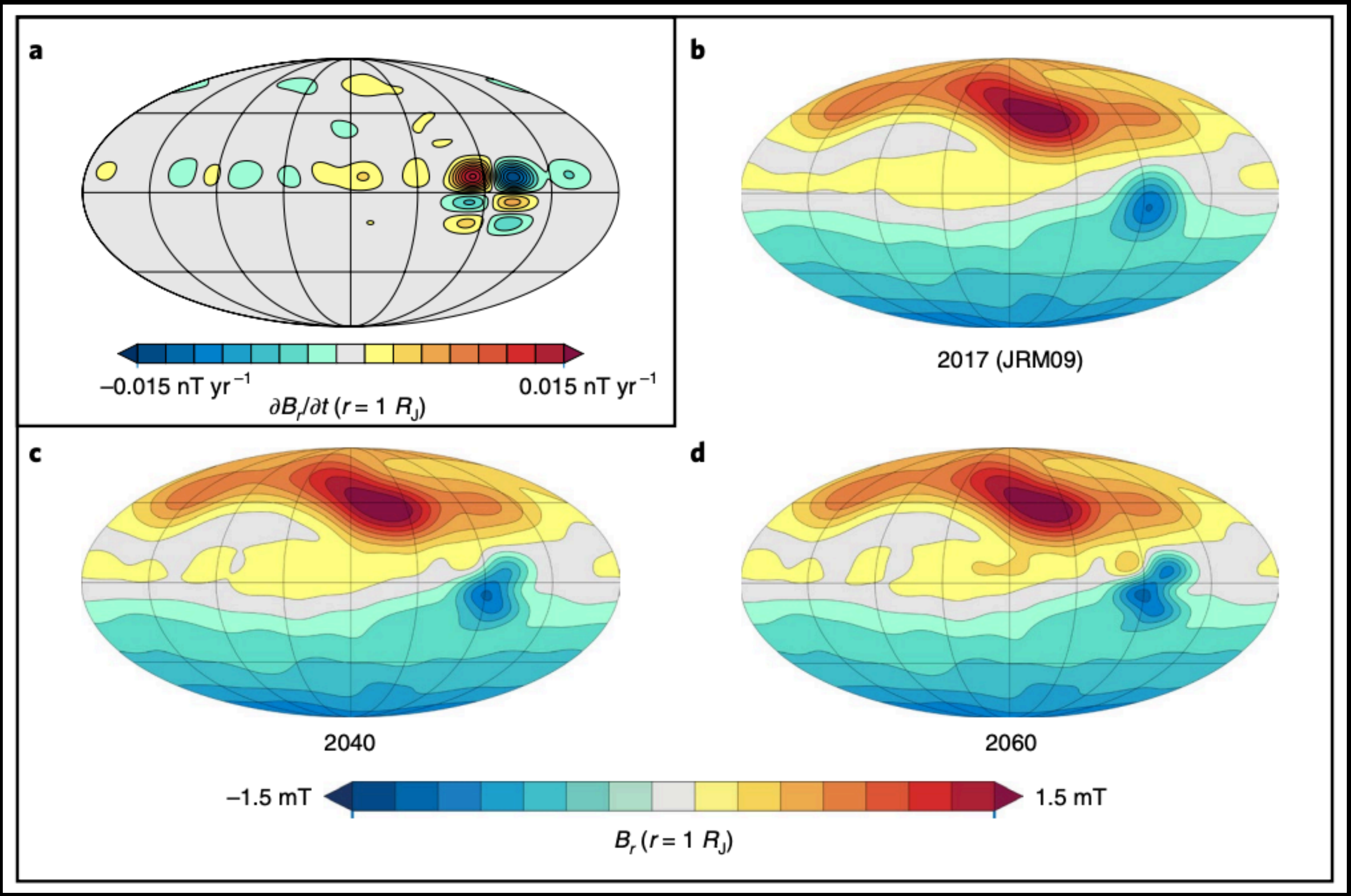


Jackson et al., 2000; Sabaka et al., 2004; Finlay et al., 2020, in prep

Livermore et al., 2016

Planetary Magnetic Fields

- Secular variation has been measured for Jupiter

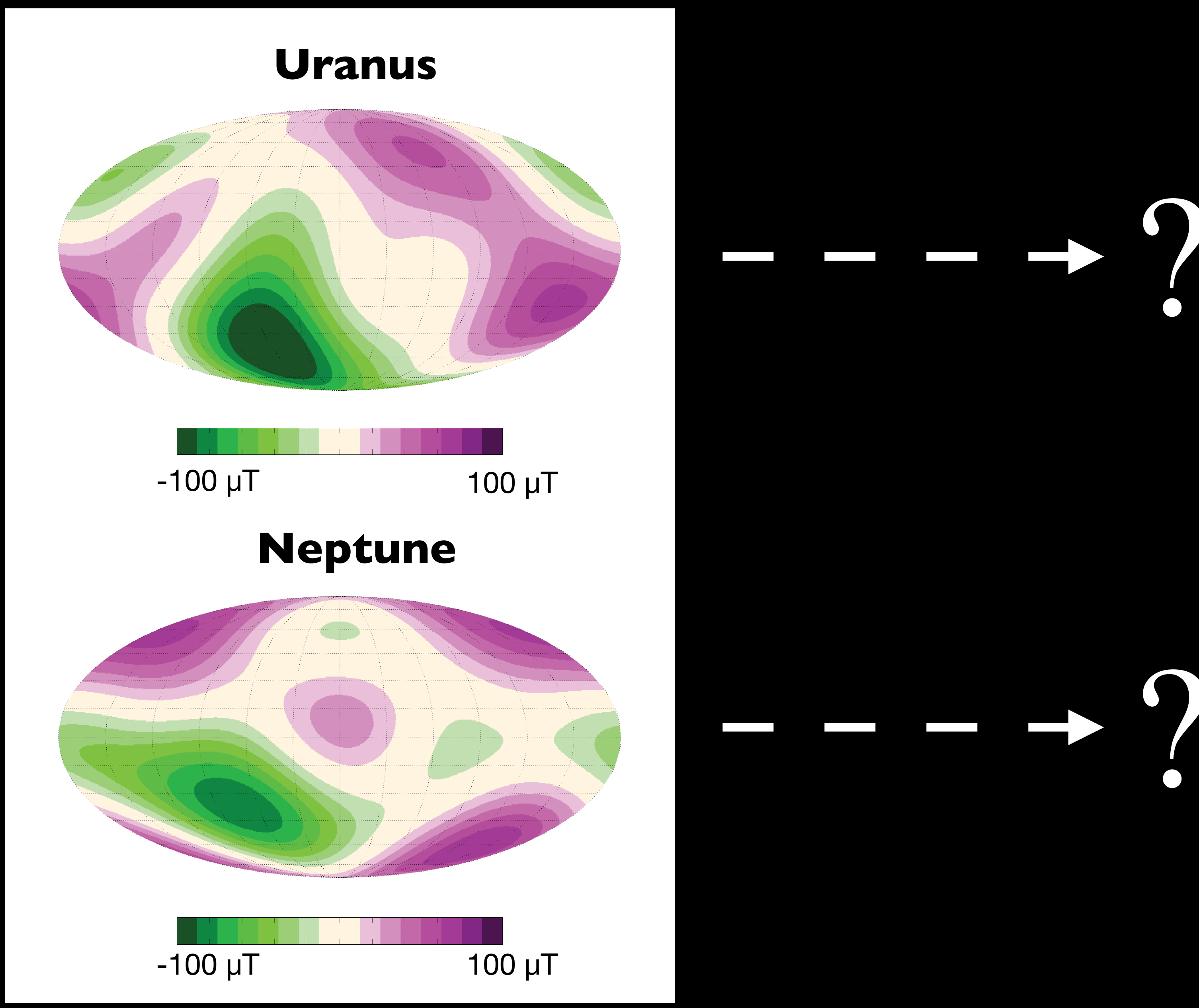


45 years (1973-2018)

Moore et al. (2019)

Planetary Magnetic Fields

- No knowledge of secular variation for the ice giants



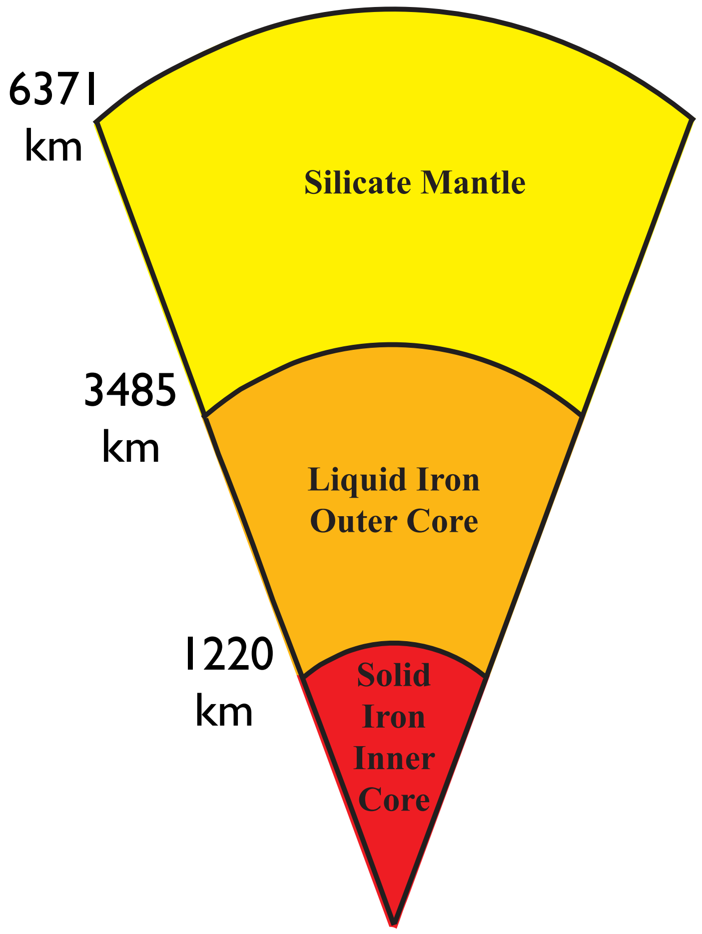
Planetary Magnetic Fields

- What controls the morphology, strength, and evolution of planetary magnetic fields?
- Comparative planetology serves as natural laboratory for hypothesis tests
    - Why do the ice giants have non-axisymmetric, multipolar magnetic fields while the gas giants have axial, dipole-dominated magnetic fields?
    - Why do the ice giants, Saturn, and Earth have similar magnetic field strengths?
    - Do the ice giants undergo secular variation?

Dynamo Generation

- Geomagnetic field generated by convective-driven dynamo in iron core

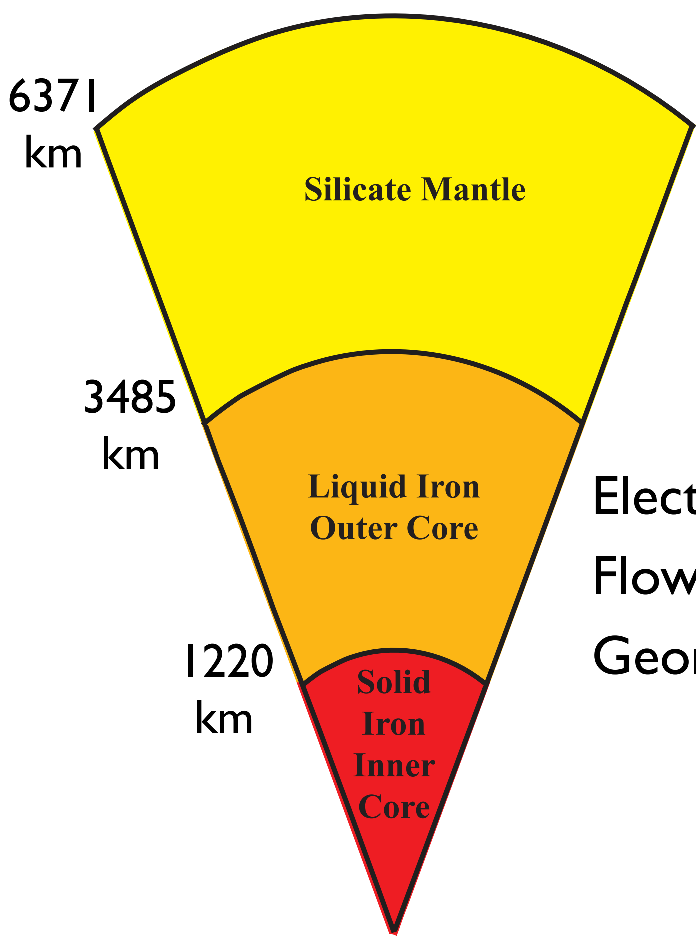
Terrestrial



Dynamo Generation

- Geomagnetic field generated by convective-driven dynamo in iron core

Terrestrial



Electrical conductivity, σ

Flow speeds, U

Geometry, D

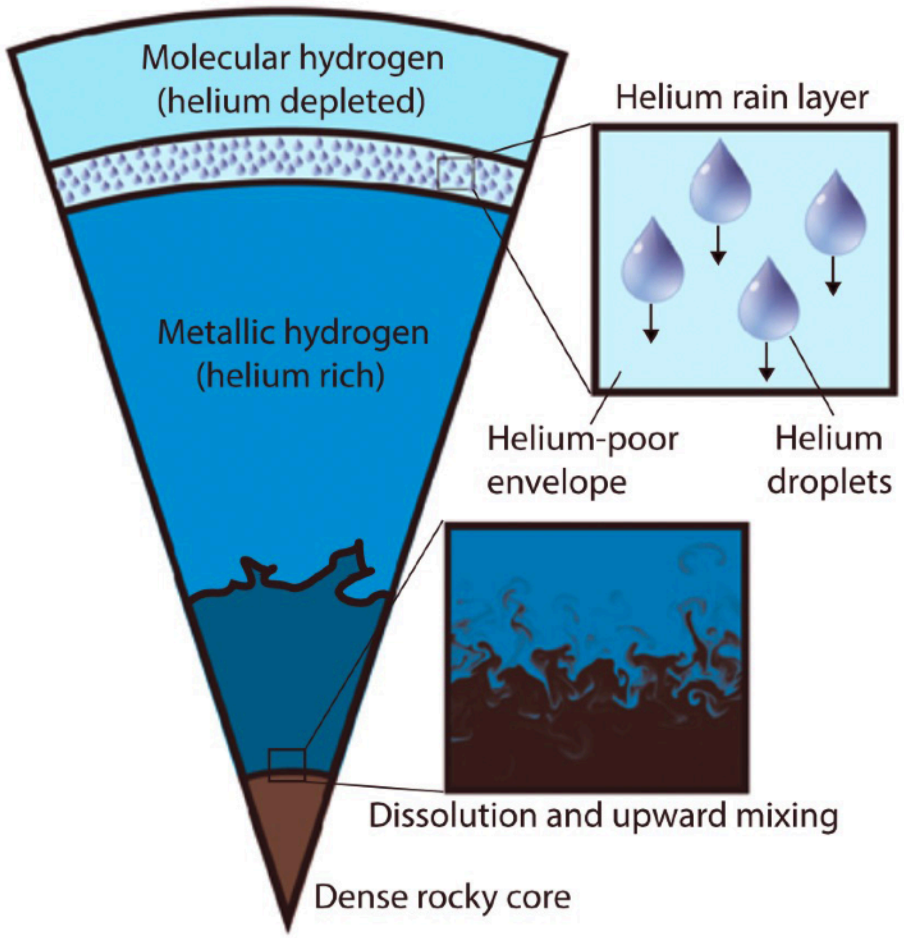
$$\underbrace{\frac{\partial \mathbf{B}}{\partial t}}_{\text{Temporal}} = \underbrace{\nabla \times (\mathbf{u} \times \mathbf{B})}_{\text{Induction}} + \underbrace{\frac{1}{\mu_o \sigma} \nabla^2 \mathbf{B}}_{\text{Diffusion}}$$

$$Rm = \frac{\text{Magnetic induction}}{\text{Magnetic diffusion}} = \mu_o \sigma U D \gtrsim 10^2$$

Dynamo Generation

- Magnetic fields generated by convectively-driven dynamos in electrically conducting fluid regions

Jupiter

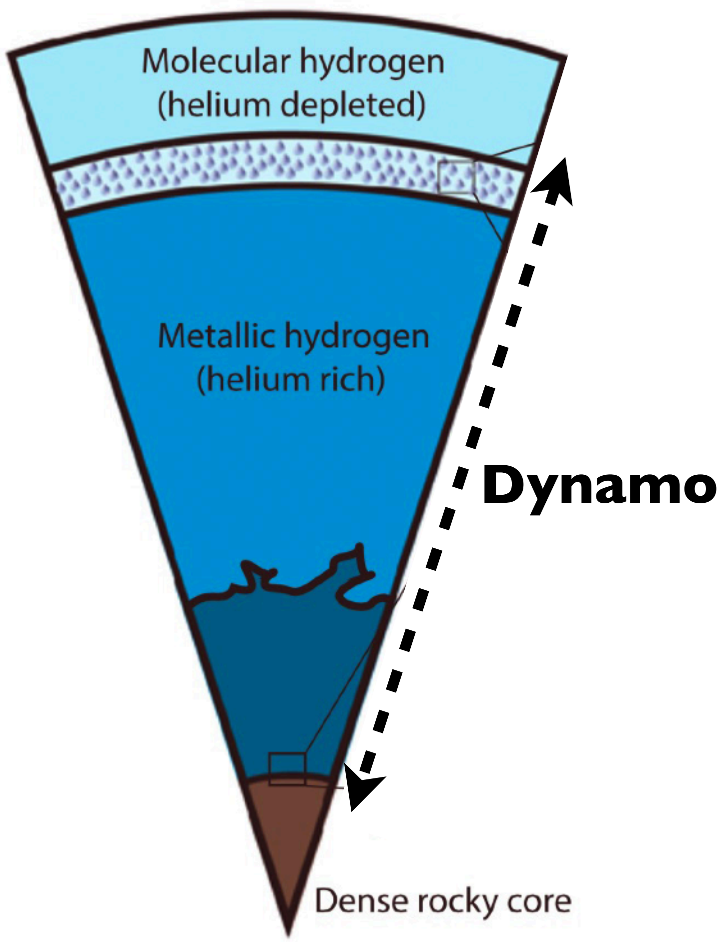


Wahl et al. (2017)

Dynamo Generation

- Magnetic fields generated by convectively-driven dynamos in electrically conducting fluid regions

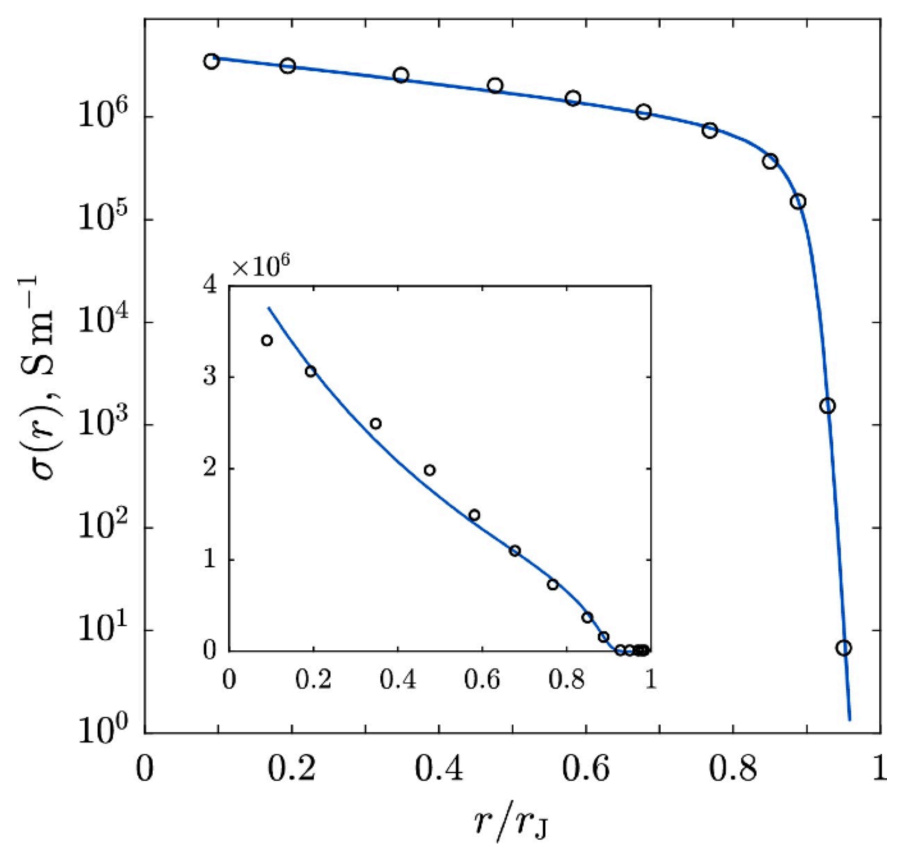
Jupiter



Wahl et al. (2017)

$$Rm = \mu_o \sigma U D \gtrsim 10^2$$

Electrical conductivity, σ
Flow speeds, U
Geometry, D

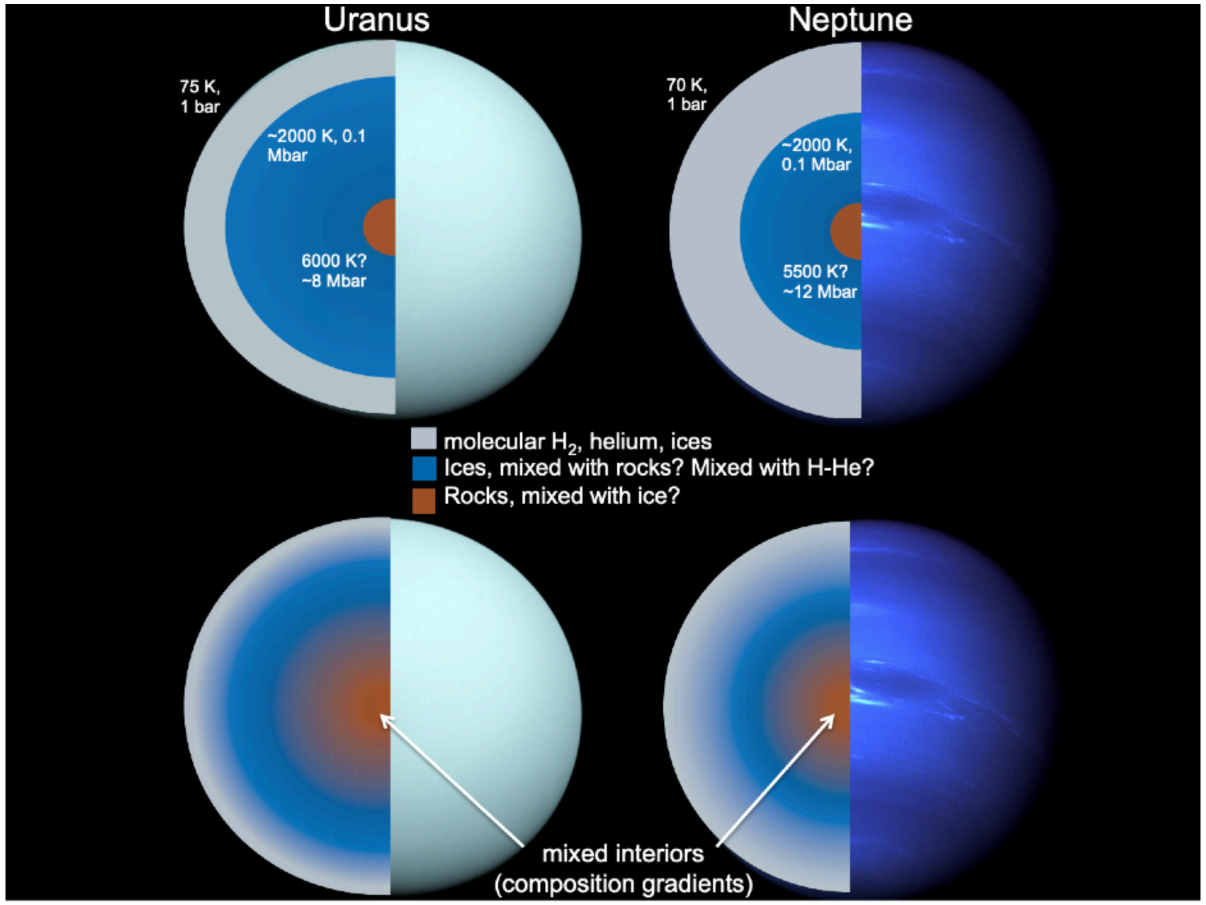


French et al. (2012); Tsang and Jones (2020)

Dynamo Generation

- Magnetic fields generated by convectively-driven dynamos in electrically conducting fluid regions

Ice Giants

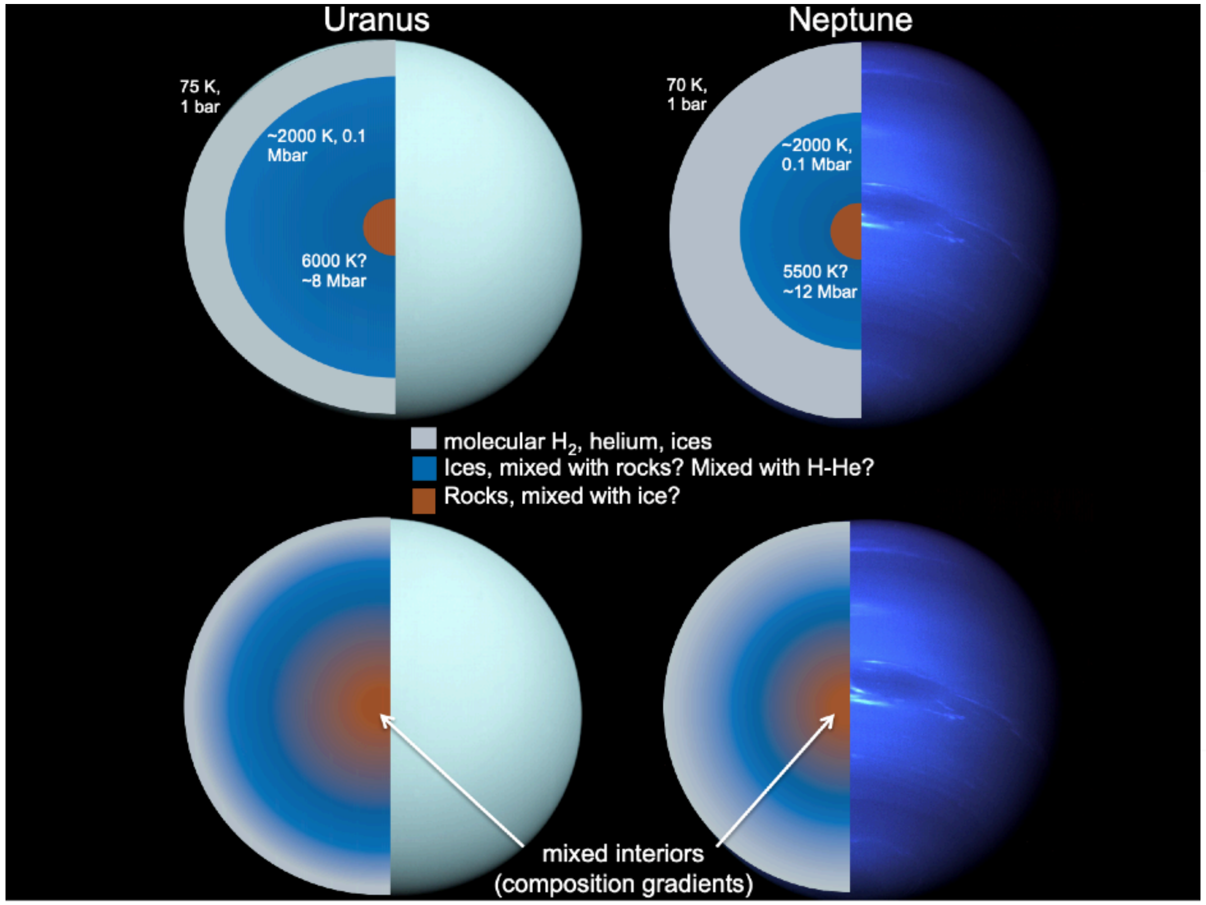


Helled et al. (2020)

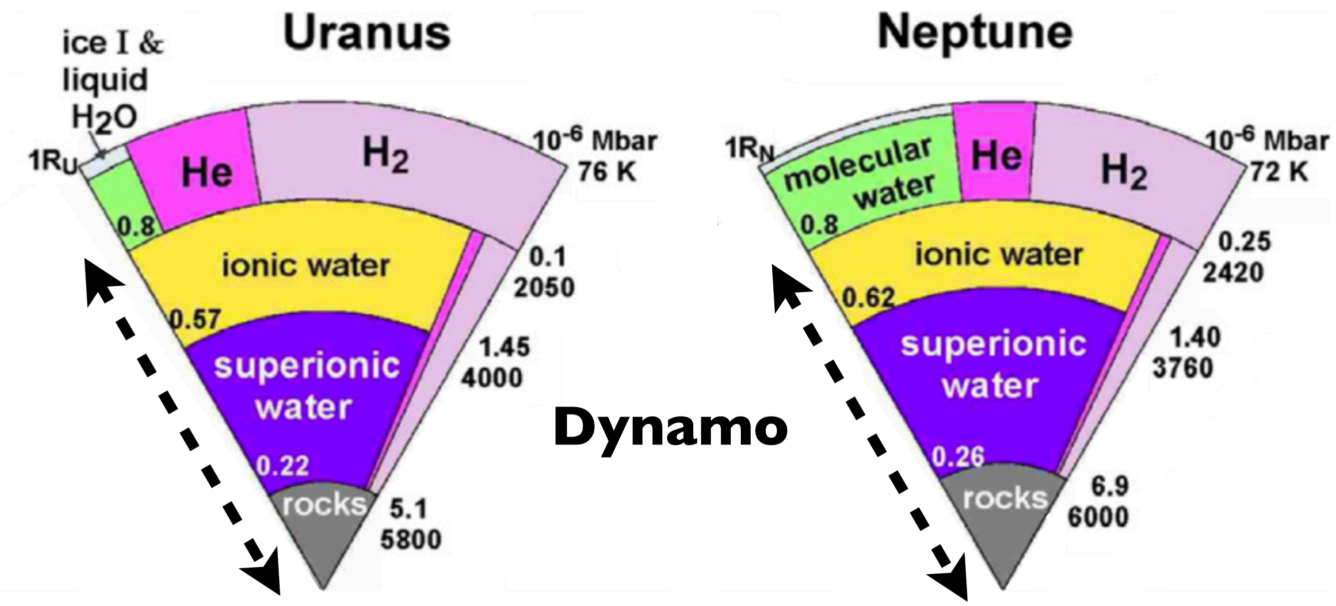
Dynamo Generation

- Magnetic fields generated by convectively-driven dynamos in electrically conducting fluid regions

Ice Giants



Helled et al. (2020)



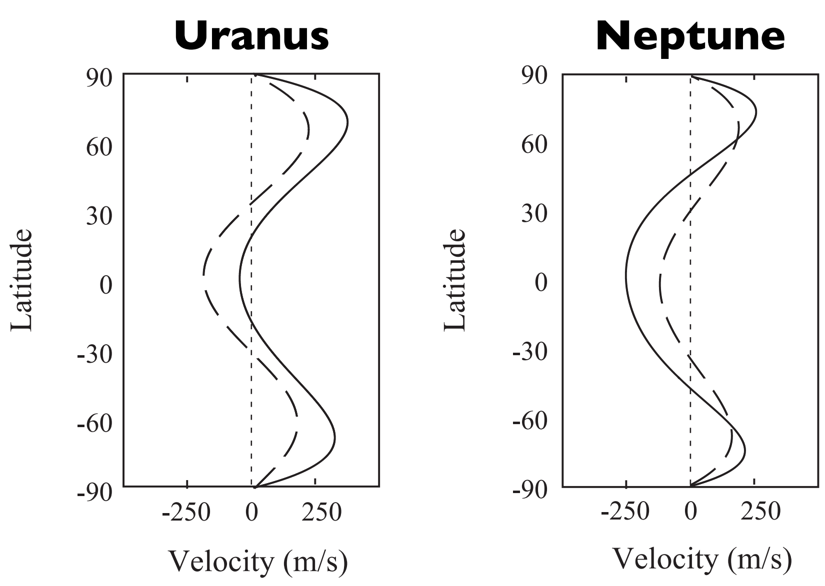
Redmer et al. (2011)

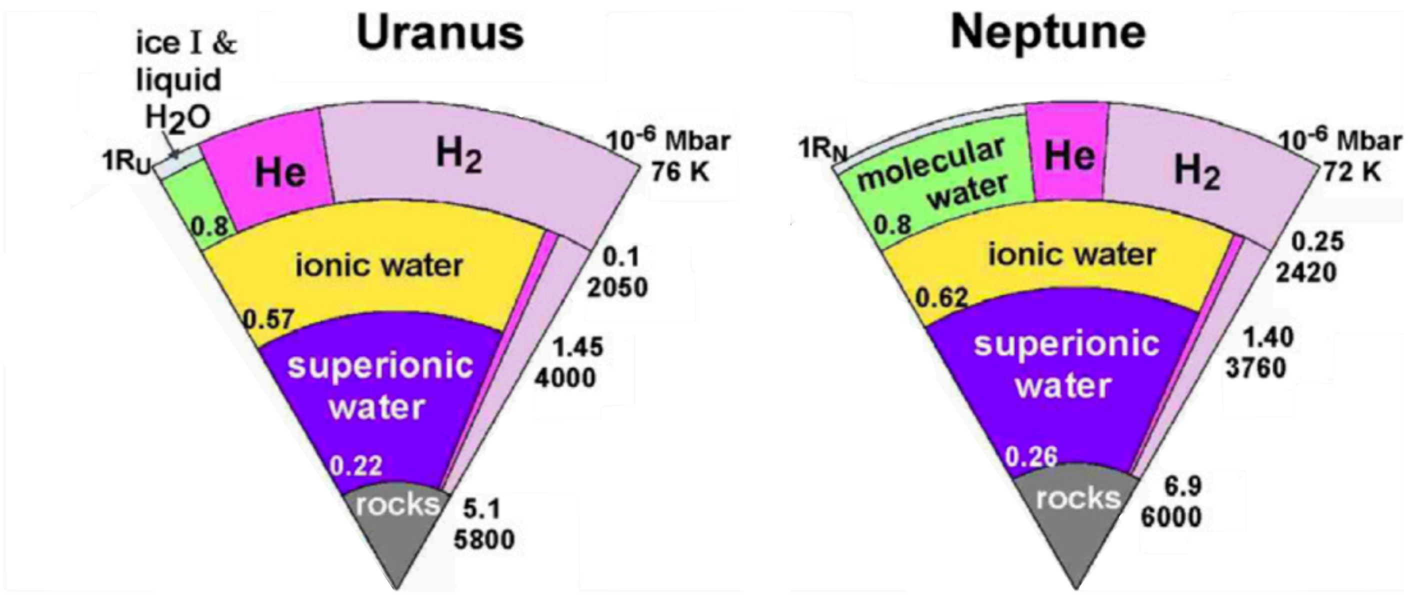
Dynamo Generation

- The interior and atmosphere may be coupled dynamically

Ice Giants

- Do the zonal winds interact with dynamo generation?





Soderlund et al. (2013)

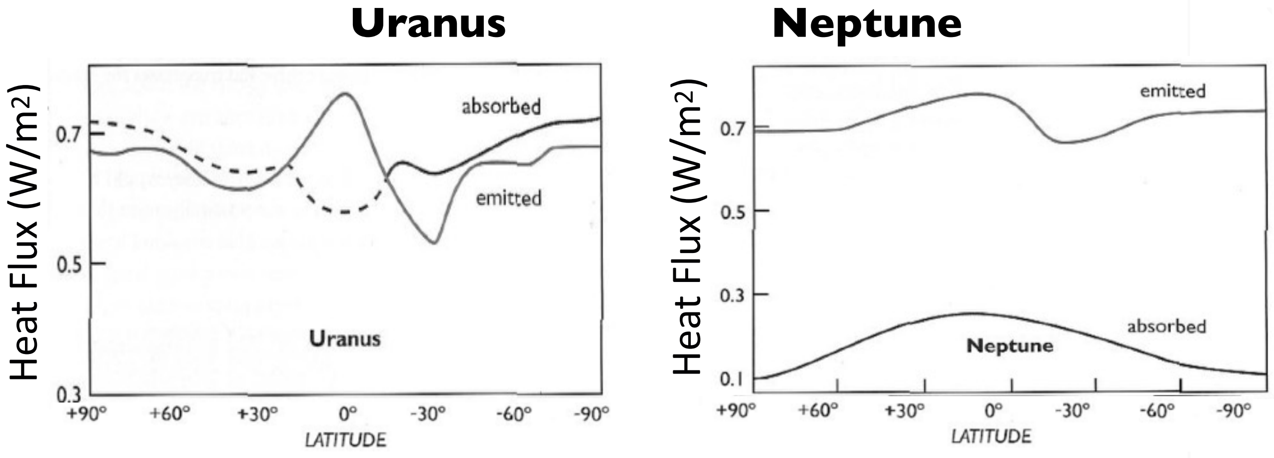
Redmer et al. (2011)

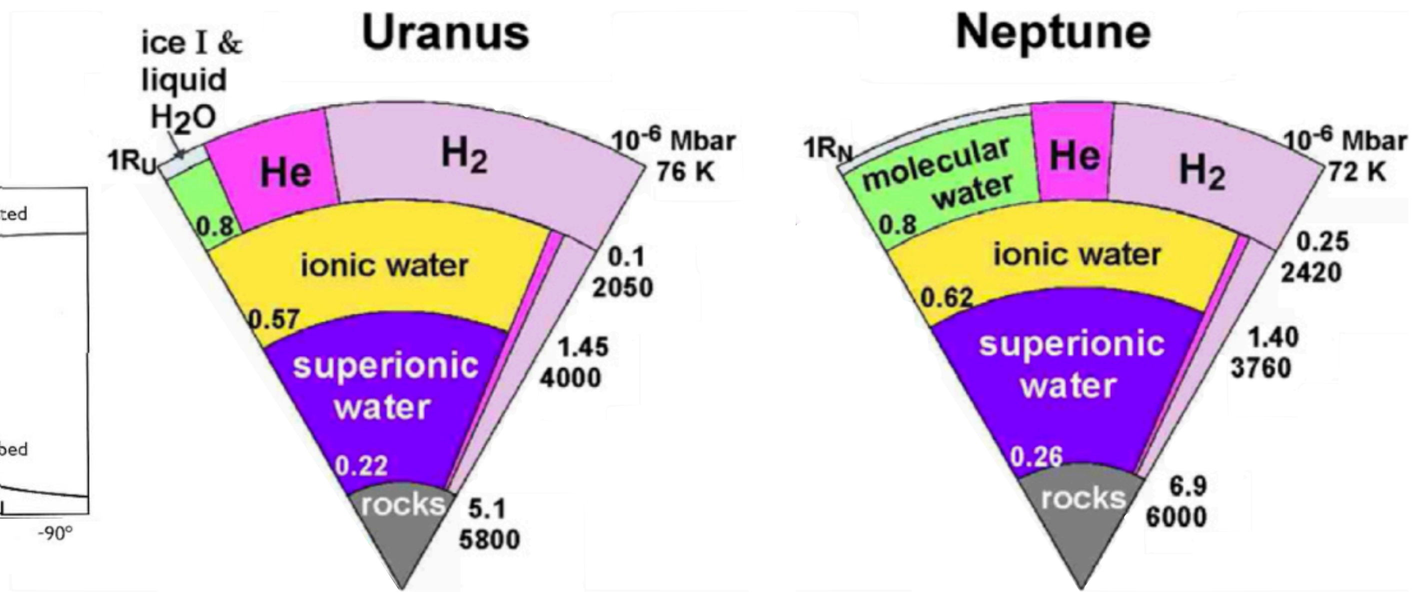
Dynamo Generation

- The interior and atmosphere may be coupled dynamically

Ice Giants

- Do stable layers exist in the interior?





Ingersoll (1999)

Redmer et al. (2011)

Planetary Dynamos

- By studying magnetic fields, we learn about a planet's internal structure, composition, dynamics, and evolution

Outline

1) Planetary Magnetic Fields

2) Ice Giant Dynamos

3) Looking Ahead

Magnetic Field Strength

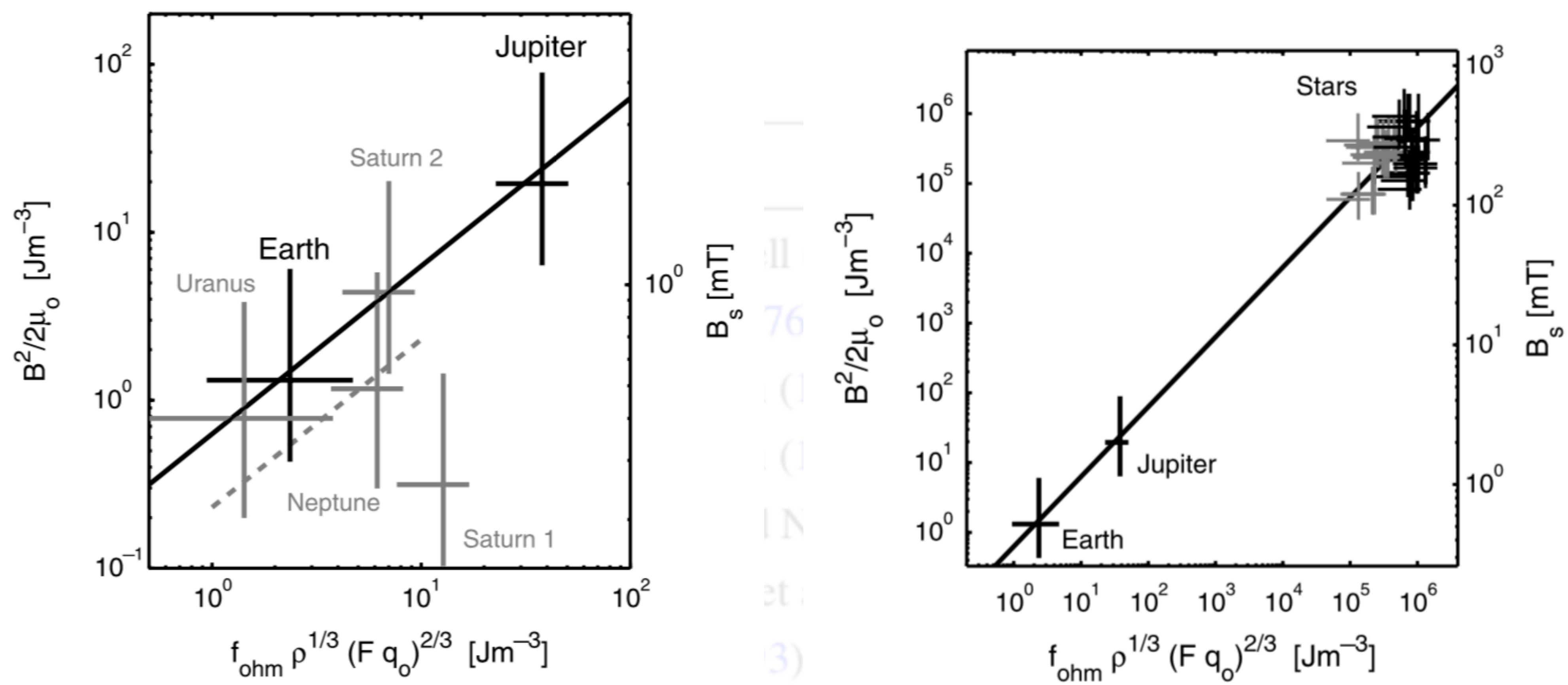
- Numerous scaling laws have been proposed to predict magnetic field strengths

#	Rule	Author	Remark
1	$B_p R_p^3 \propto (\rho \Omega R_p^5)^a$	e.g. Russell (1978)	magnetic Bode law
2	$B^2 \propto \rho \Omega^2 R_c^2$	Busse (1976)	
3	$B^2 \propto \rho \Omega \sigma^{-1}$	Stevenson (1979)	Elsasser number rule
4	$B^2 \propto \rho R_c^3 q_c \sigma$	Stevenson (1984)	at low energy flux
5	$B^2 \propto \rho \Omega R_c^{5/3} q_c^{1/3}$	Curtis and Ness (1986, modified)	mixing length theory
6	$B^2 \propto \rho \Omega^{3/2} R_c \sigma^{-1/2}$	Mizutani et al. (1992)	
7	$B^2 \propto \rho \Omega^2 R_c$	Sano (1993)	
8	$B^2 \propto \rho \Omega^{1/2} R_c^{3/2} q_c^{1/2}$	Starchenko and Jones (2002)	MAC balance
9	$B^2 \propto \rho R_c^{4/3} q_c^{2/3}$	Christensen and Aubert (2006)	energy flux scaling

Christensen (2010)

Magnetic Field Strength

- Energy flux scaling does a reasonable job explaining (most) planetary and stellar field strengths

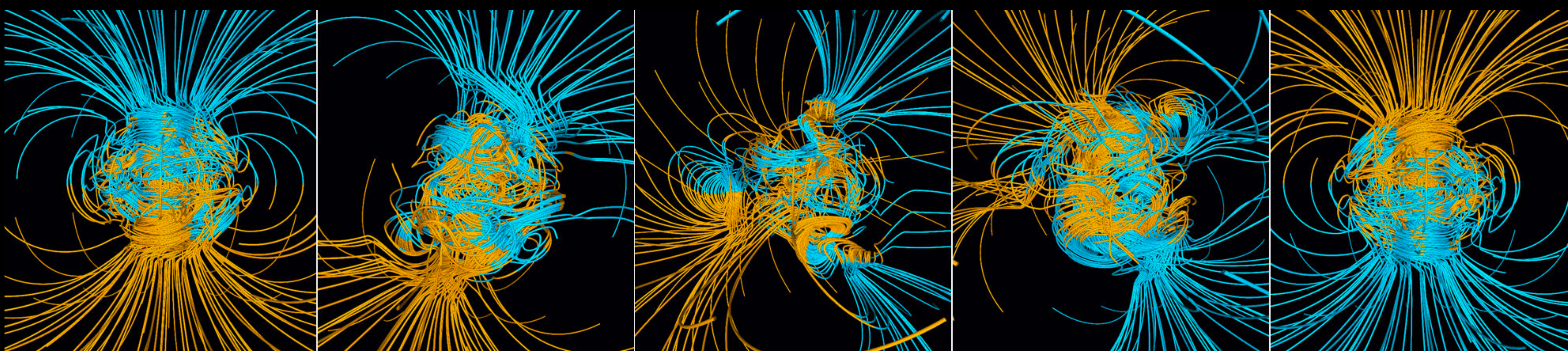


9	$B^2 \propto \rho R_c^{4/3} q_c^{2/3}$	Christensen and Aubert (2006)	energy flux scaling

Christensen (2010)

Magnetic Field Morphology

- Numerous hypotheses have been proposed to explain the multipolar magnetic field morphologies
    - Mid-reversal, but very unlikely to be occurring simultaneously at both Uranus and Neptune

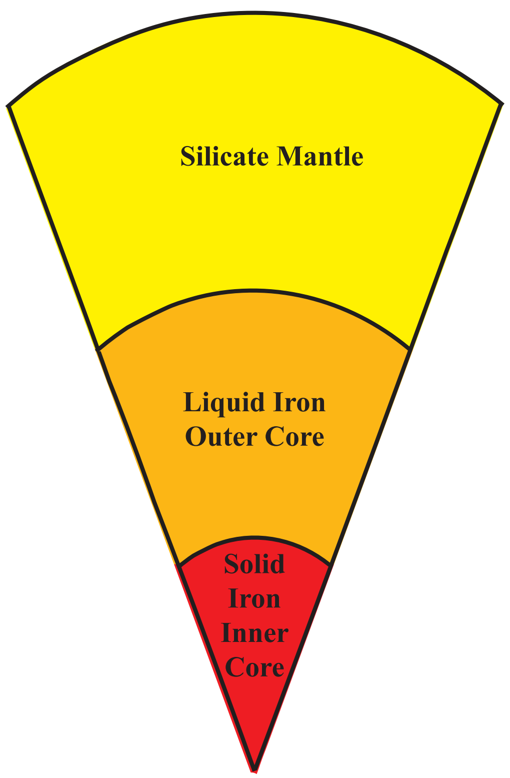


Credit: Glatzmaier, Plait

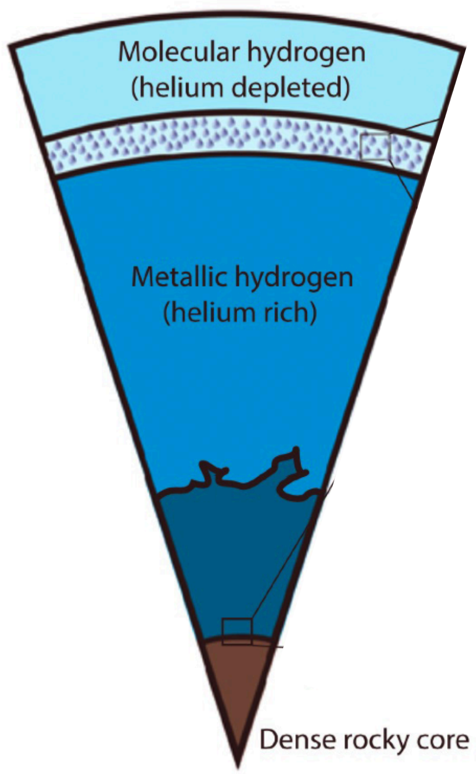
Magnetic Field Morphology

- Differences in dynamo source regions may explain planetary magnetic field differences
  - Geometry and Dynamics/Composition

Terrestrial

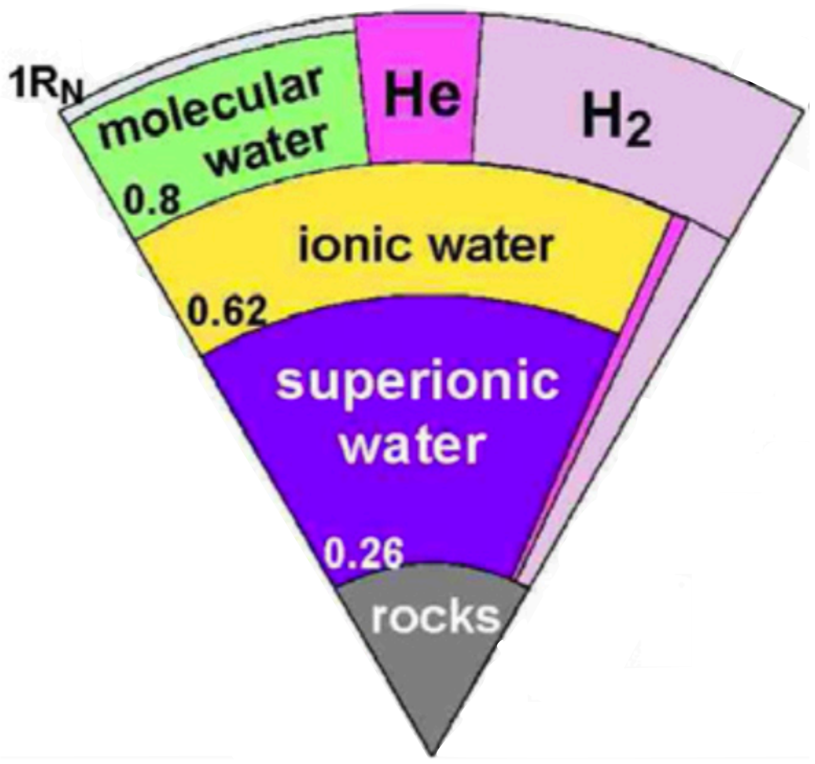


Gas Giant



Wahl et al. (2017)

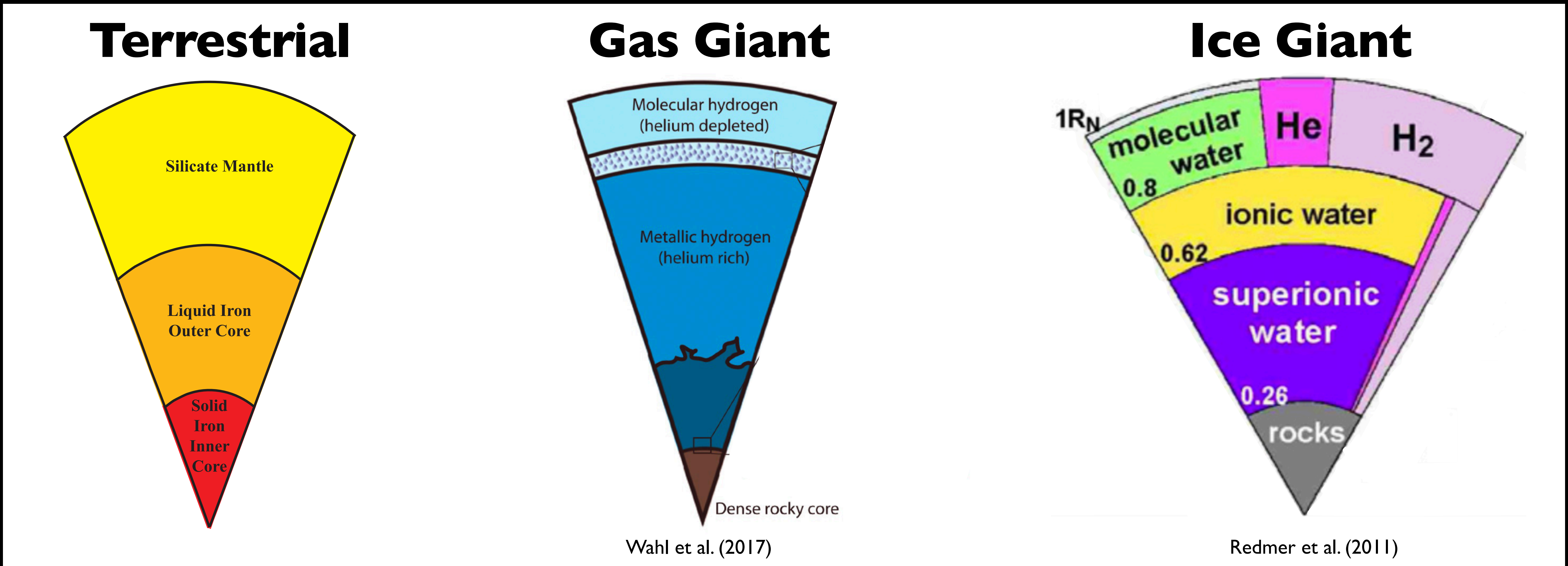
Ice Giant



Redmer et al. (2011)

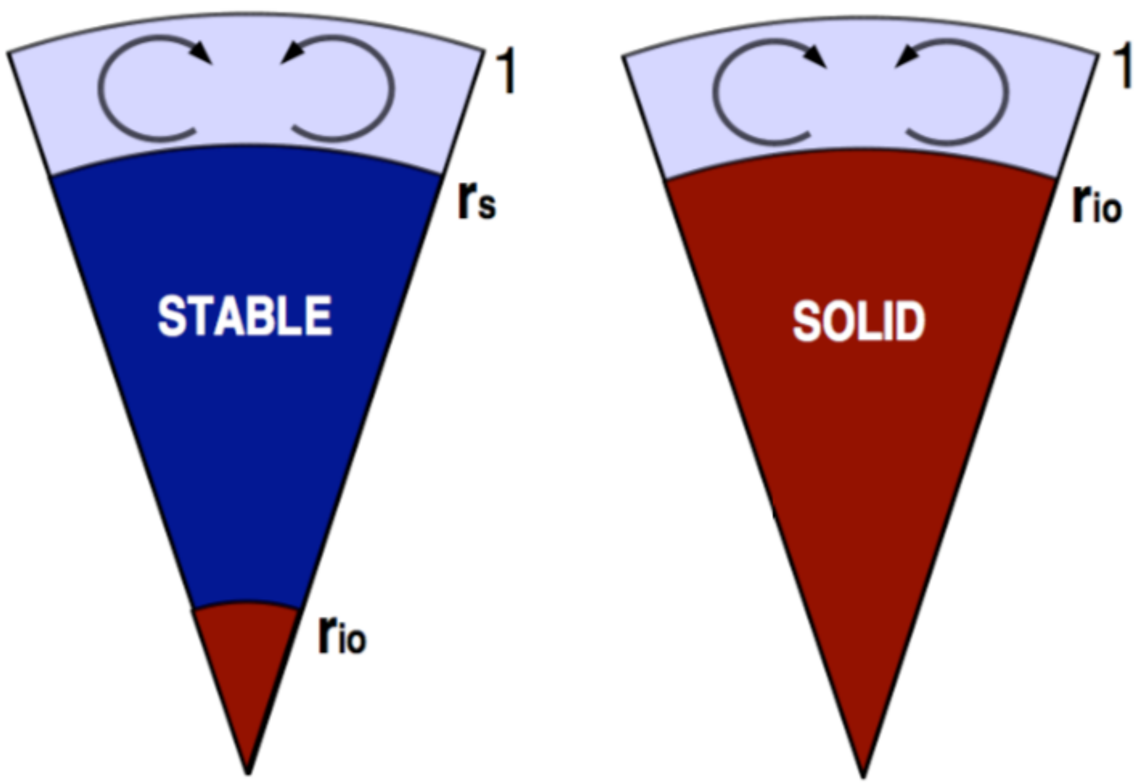
Magnetic Field Morphology

- <u>Hypothesis</u>: The ice giants have multipolar dynamos because their convective regions are geometrically thin with a deep stably stratified layer (Hubbard et al., 1995; Stanley and Bloxham, 2004)

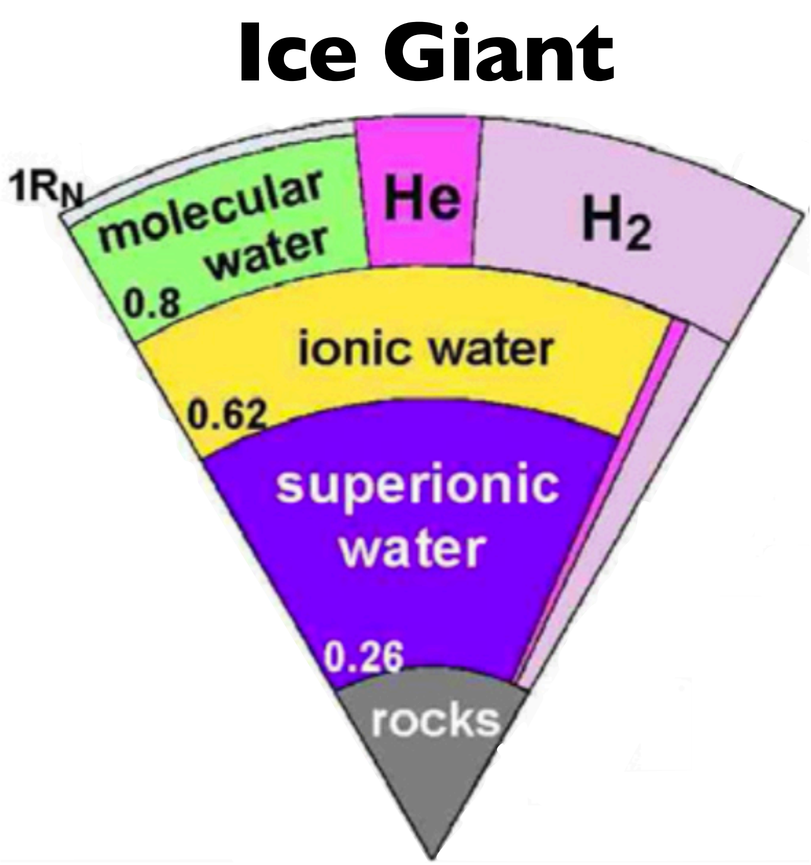


Numerical Dynamo Models

- Hypothesis Test: Dynamo models that vary the thickness of a stable liquid layer and the size of a solid inner core (Stanley and Bloxham, 2004, 2006)



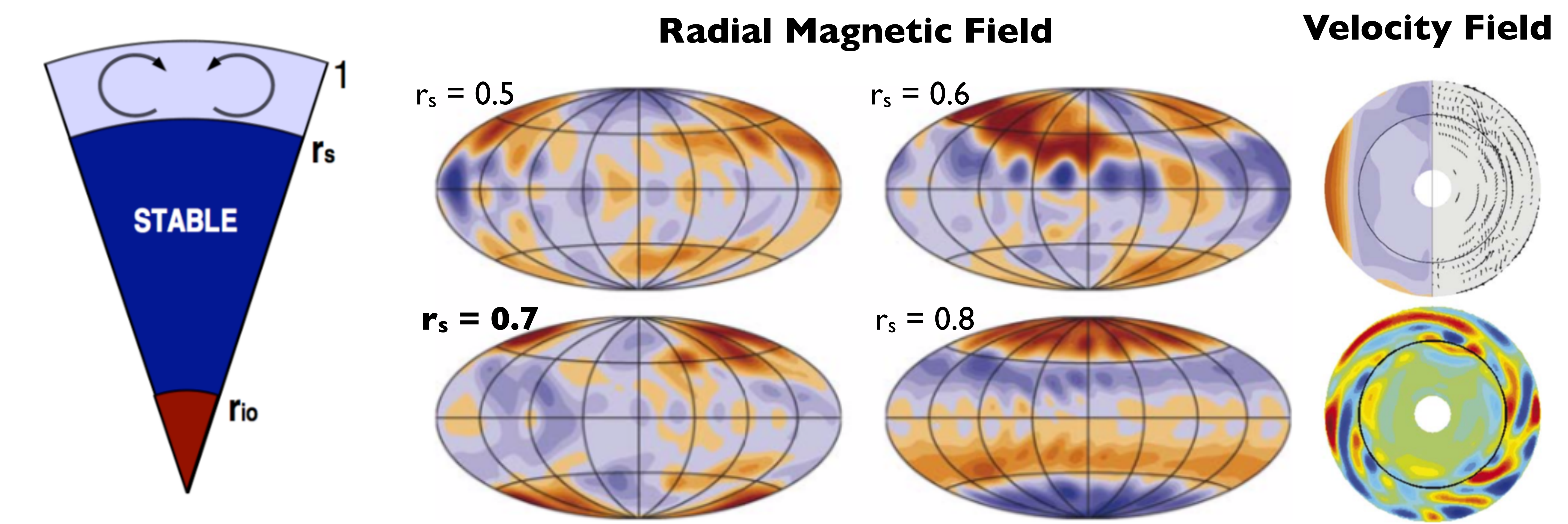
Stanley and Bloxham (2004, 2006)



Redmer et al. (2011)

Numerical Dynamo Models

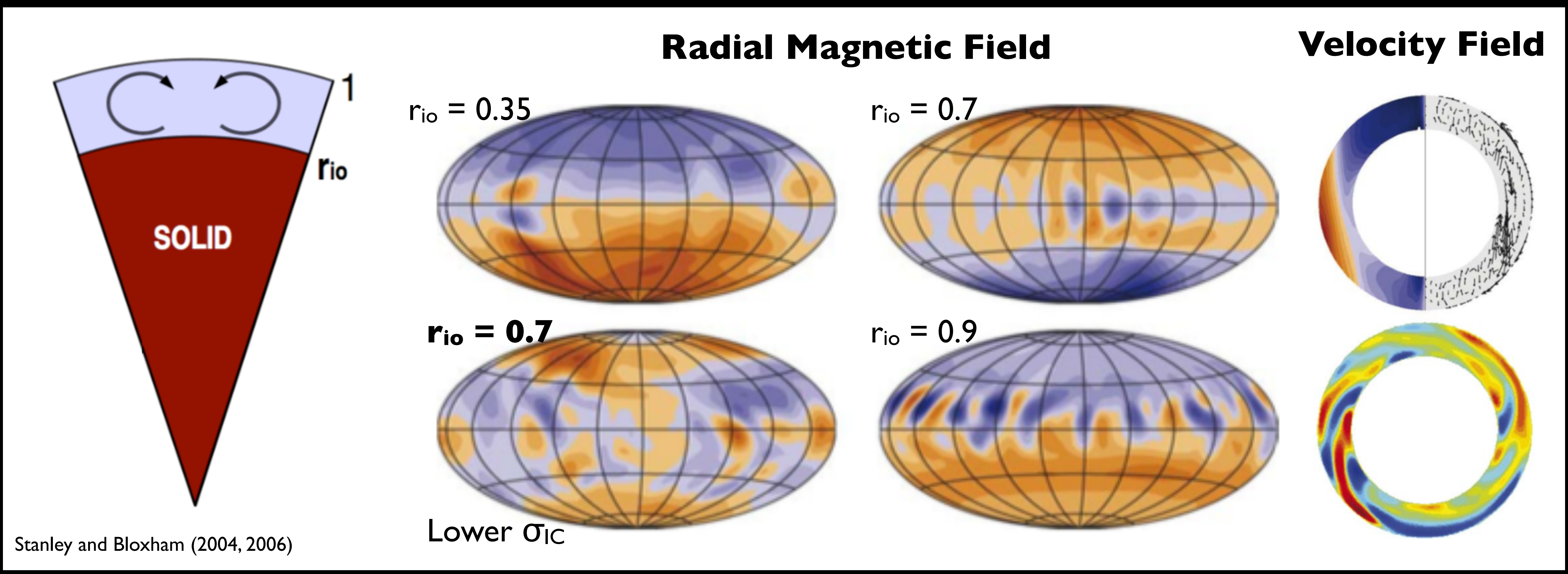
- Models with a thin convective region and stable fluid layer generate multipolar, non-axisymmetric magnetic fields
  - Columnar convection, prograde equatorial jet



Stanley and Bloxham (2004, 2006)

Numerical Dynamo Models

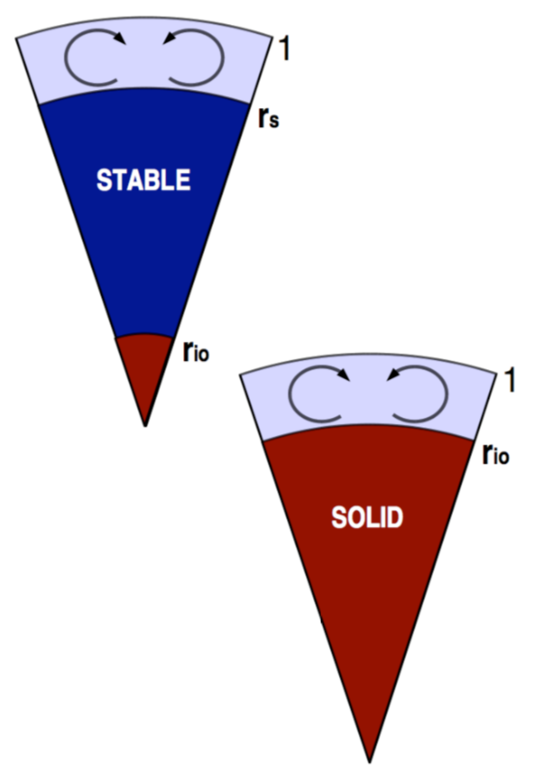
- Models with a thin convective region and solid inner core only generate multipolar, non-axisymmetric magnetic fields if the core has lower conductivity
  - Columnar convection, prograde equatorial jet



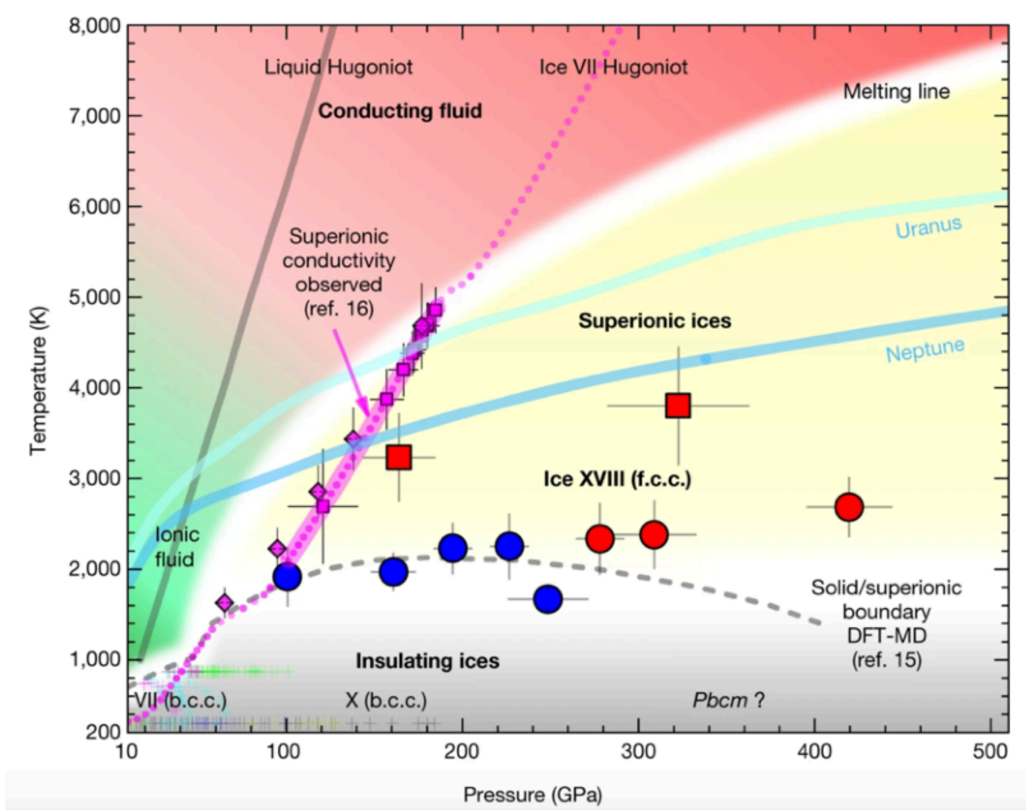
Numerical Dynamo Models

- Hypothesis: Multipolar dynamos due to convection in a thin shell geometry with deep stable fluid layer or deep weakly conducting solid layer

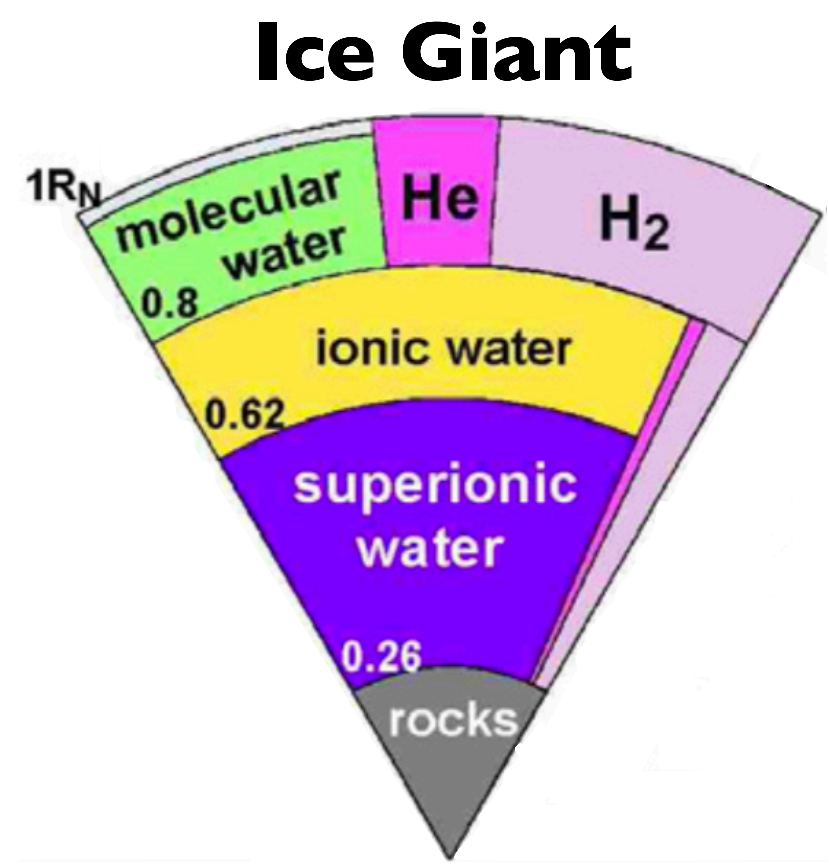
  - Superionic ices behave similar to a solid (Millot et al., 2019)



Stanley and Bloxham (2004, 2006)



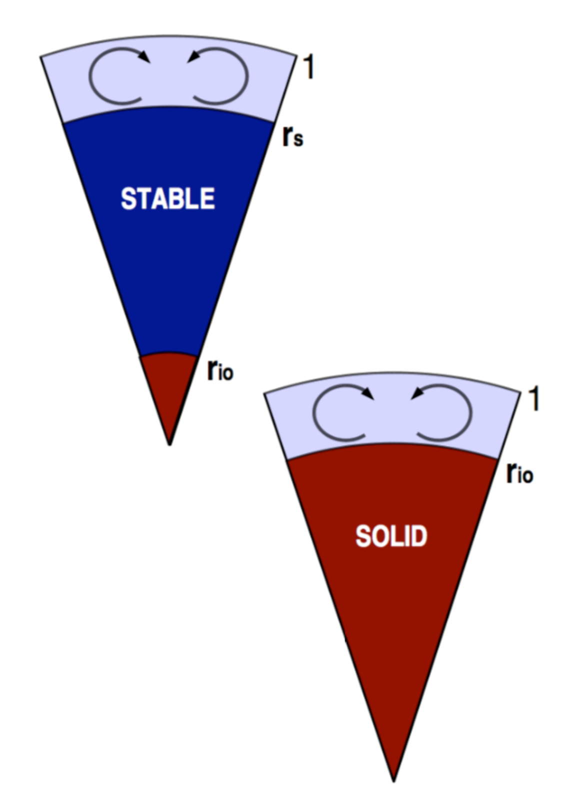
Millot et al. (2019)



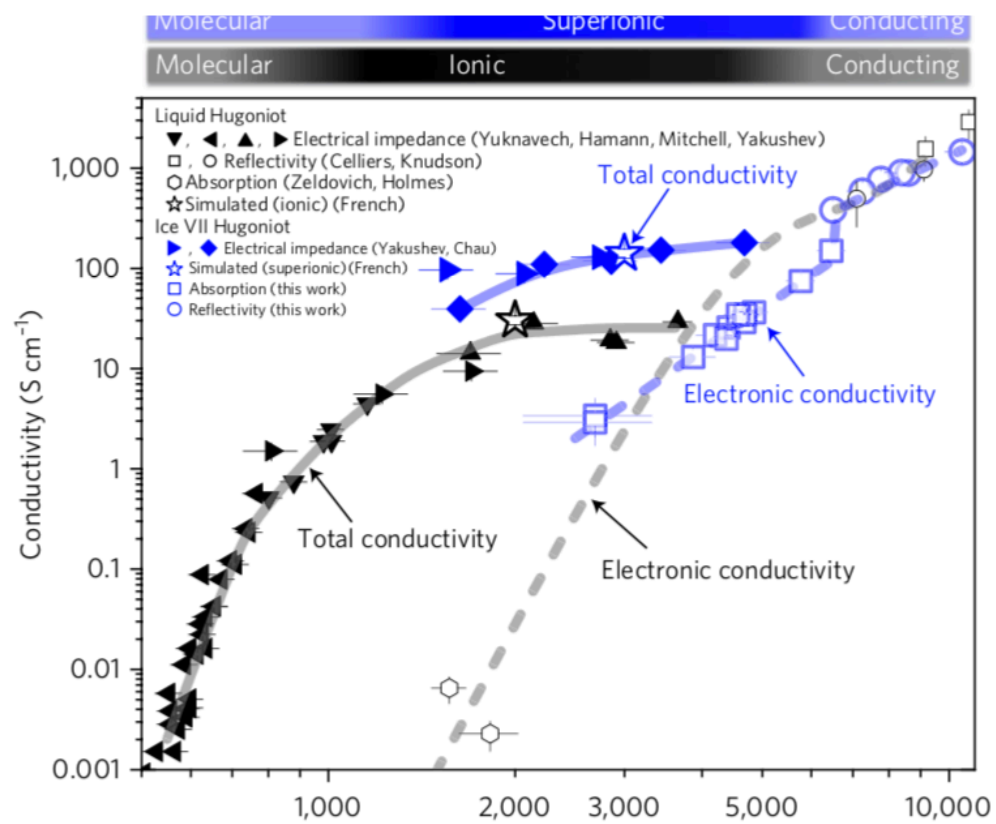
Redmer et al. (2011)

Numerical Dynamo Models

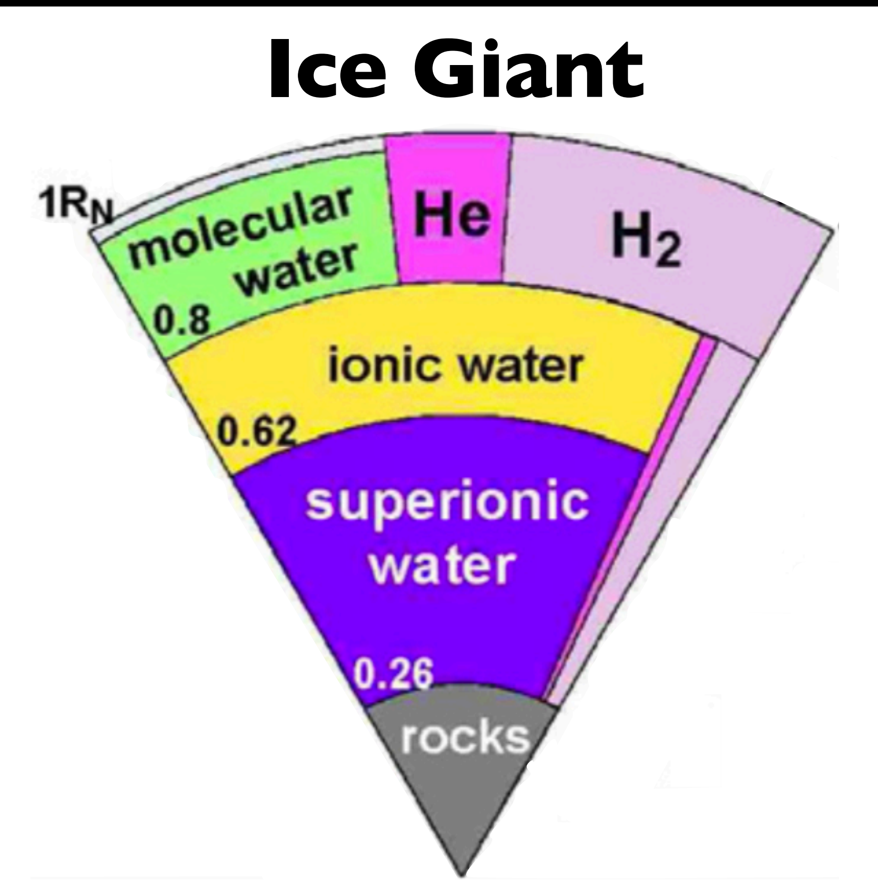
- Hypothesis: Multipolar dynamos due to convection in a thin shell geometry with deep stable fluid layer or deep weakly conducting solid layer
  - Superionic more conductive than ionic (Millot et al., 2018)



Stanley and Bloxham (2004, 2006)



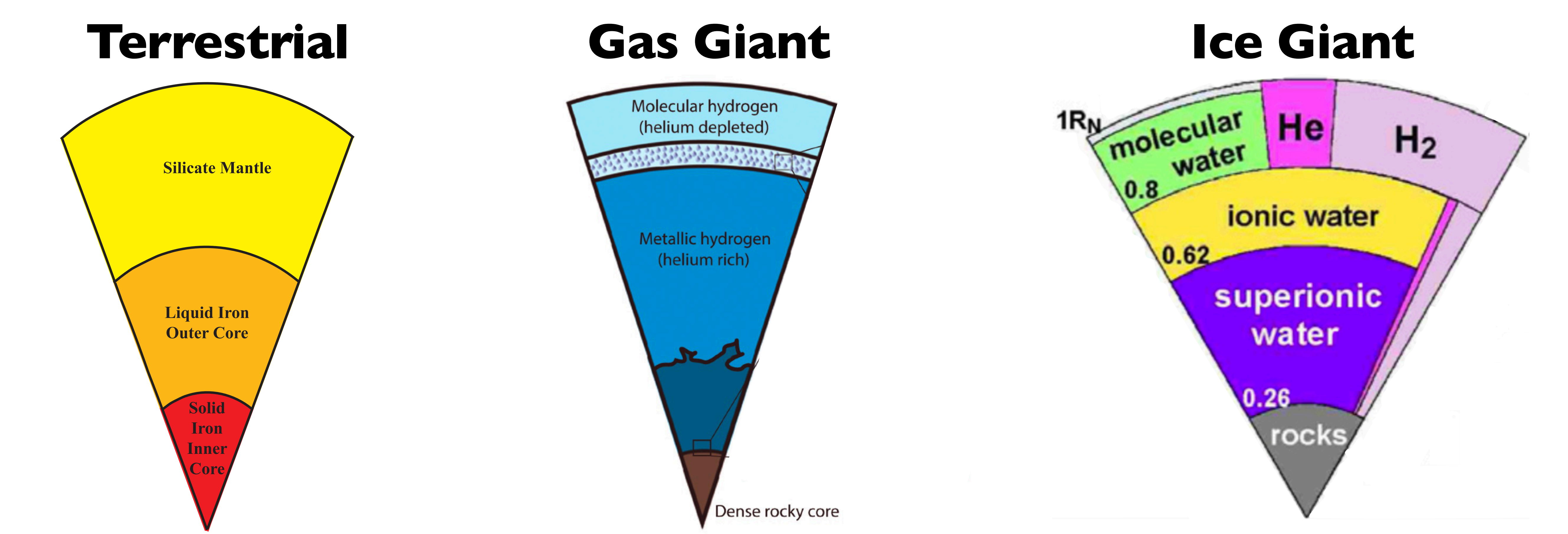
Millot et al. (2018)



Redmer et al. (2011)

Magnetic Field Morphology

- <u>Hypothesis</u>: The ice giants have multipolar dynamos because convective turbulence in their interiors is weakly constrained by rotation (Aurnou et al., 2007; Soderlund et al., 2013; King and Aurnou, 2013)

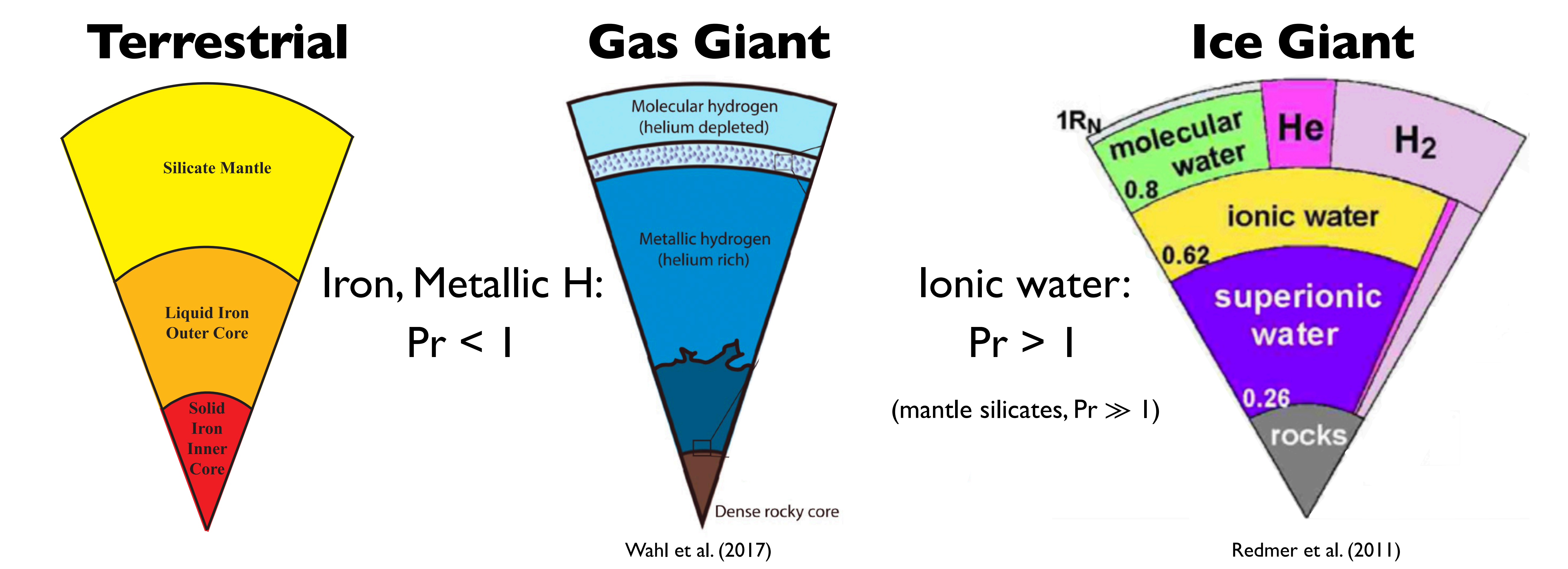


Wahl et al. (2017)

Redmer et al. (2011)

Magnetic Field Morphology

- Heat transfer efficiency regime transition depends on the ratio of momentum/thermal diffusivities (*Pr*)
  - Terrestrial and giant planet dynamo regions are liquid metals vs ionic water in ice giants

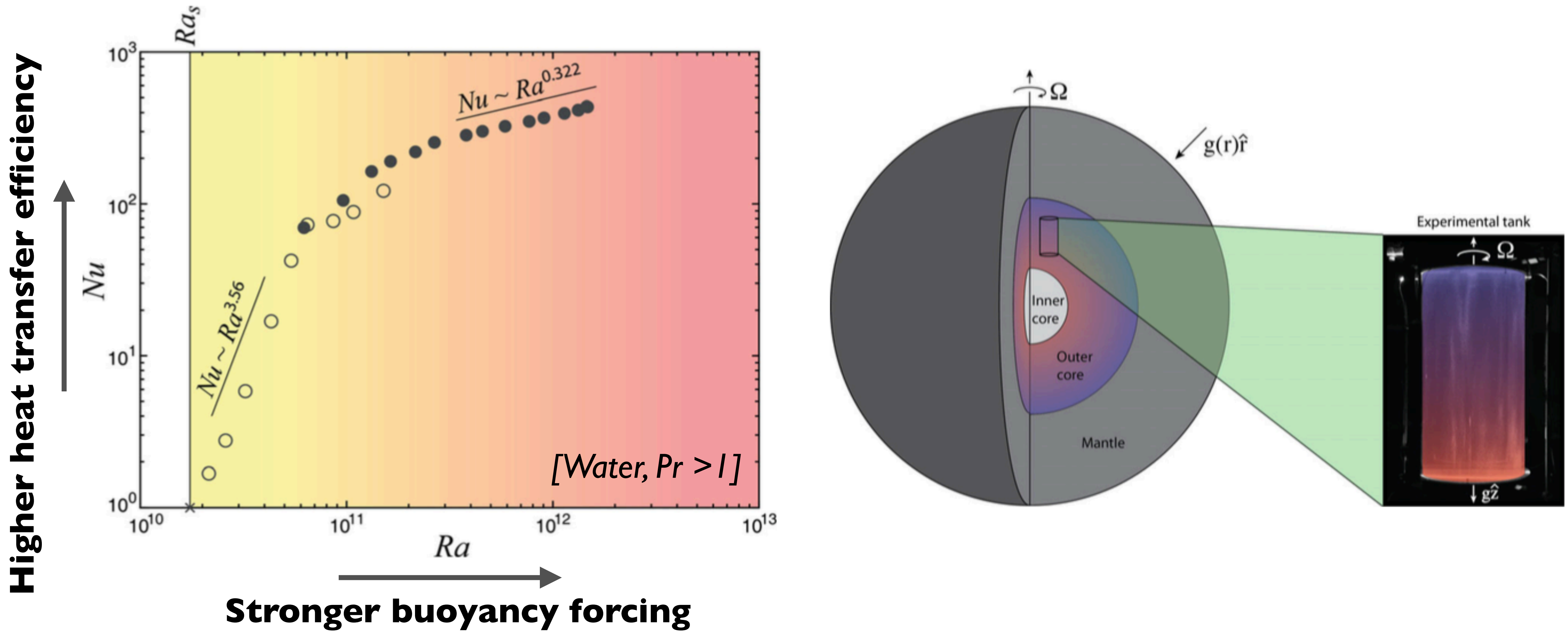


Wahl et al. (2017)

Redmer et al. (2011)

Magnetic Field Morphology

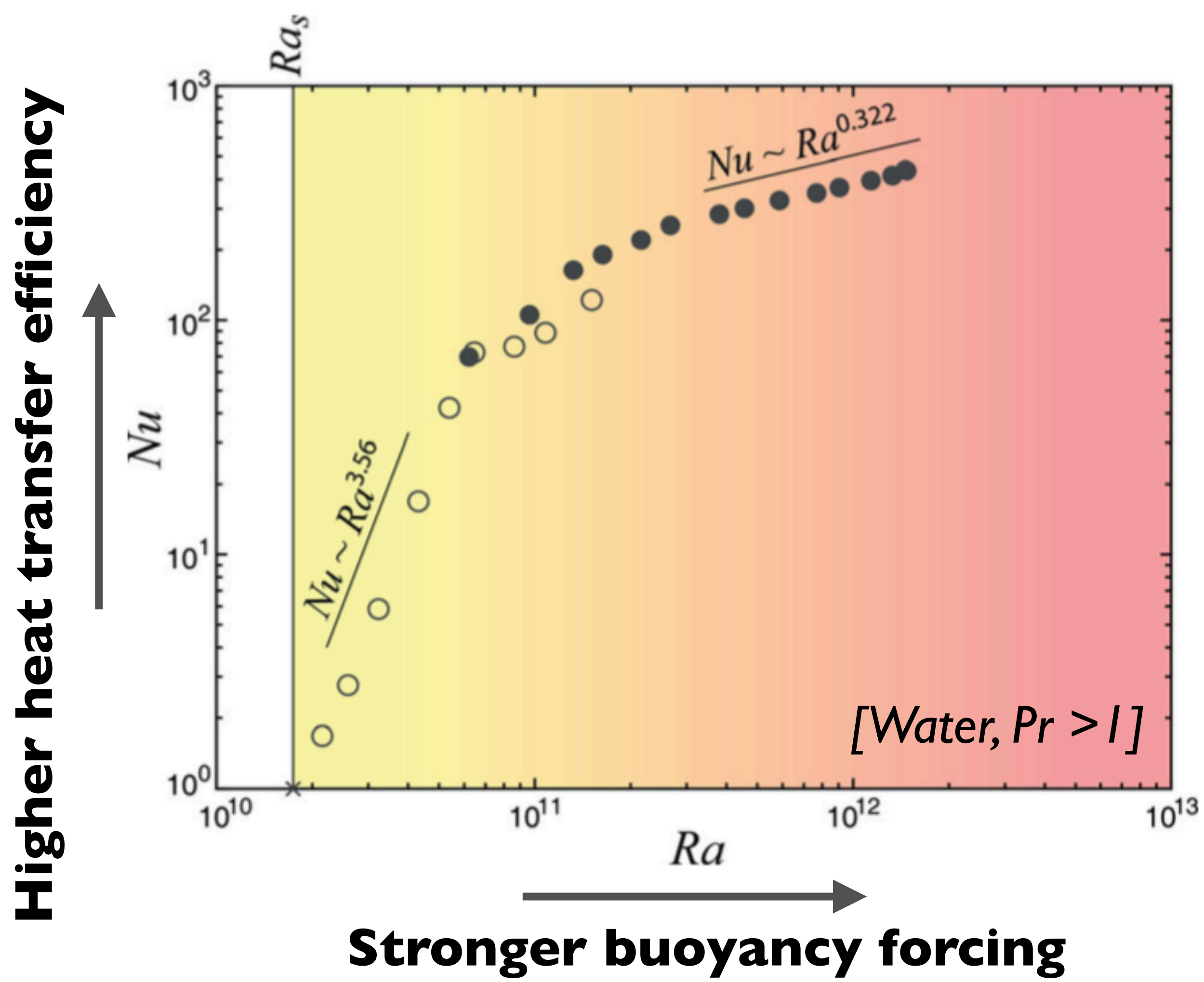
- Heat transfer efficiency regime transition depends on the ratio of momentum/thermal diffusivities
  (King & Aurnou, 2013)

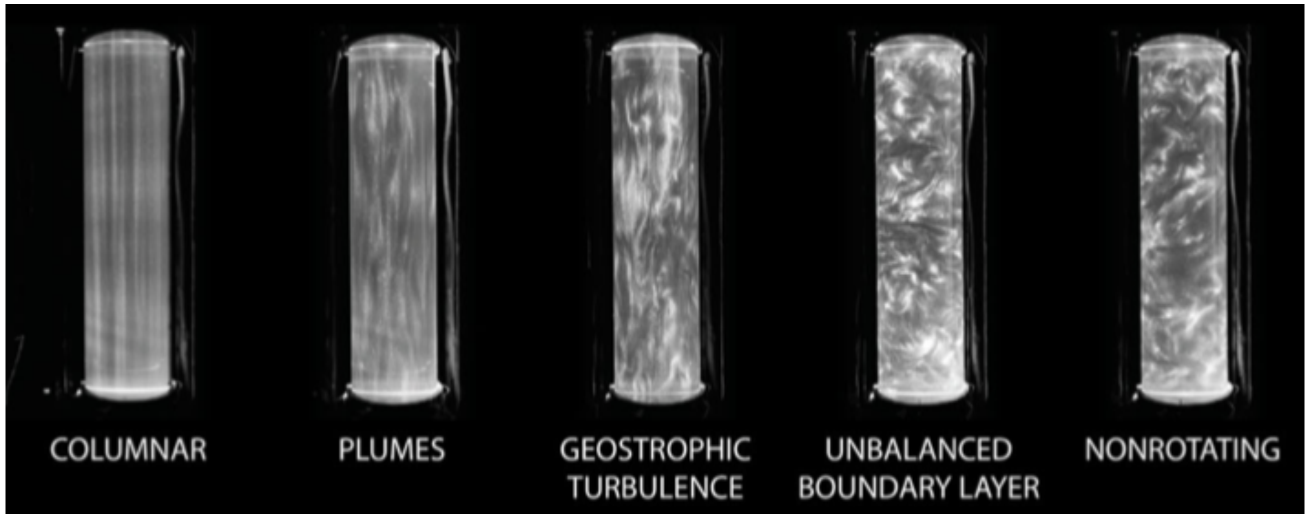


Cheng et al. (2015, 2018)

Magnetic Field Morphology

- Heat transfer efficiency regime transition depends on the ratio of momentum/thermal diffusivities
  (*King & Aurnou, 2013*)



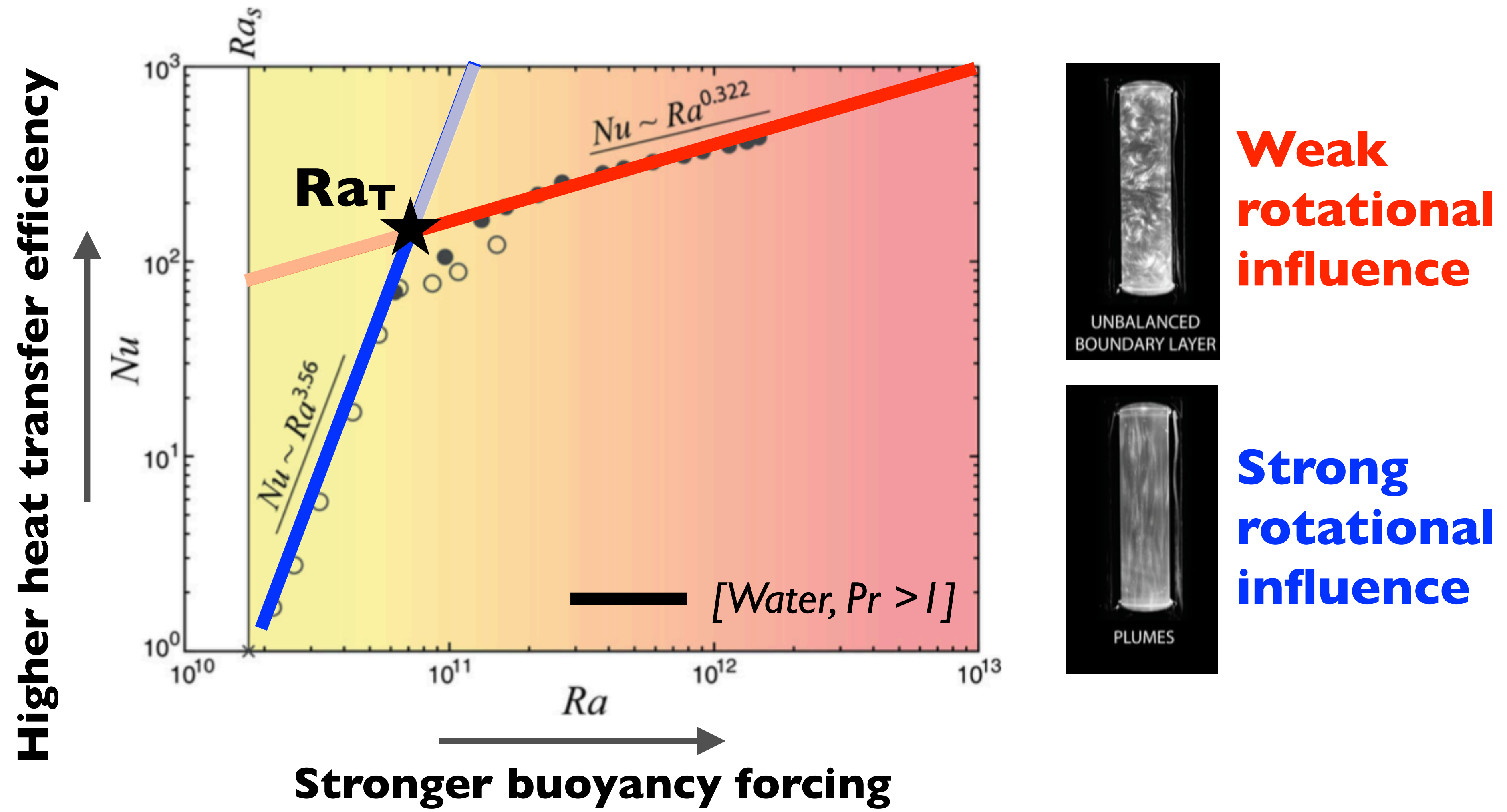


Planform of convection changes as the influence of rotation decreases

Cheng et al. (2015, 2018)

Magnetic Field Morphology

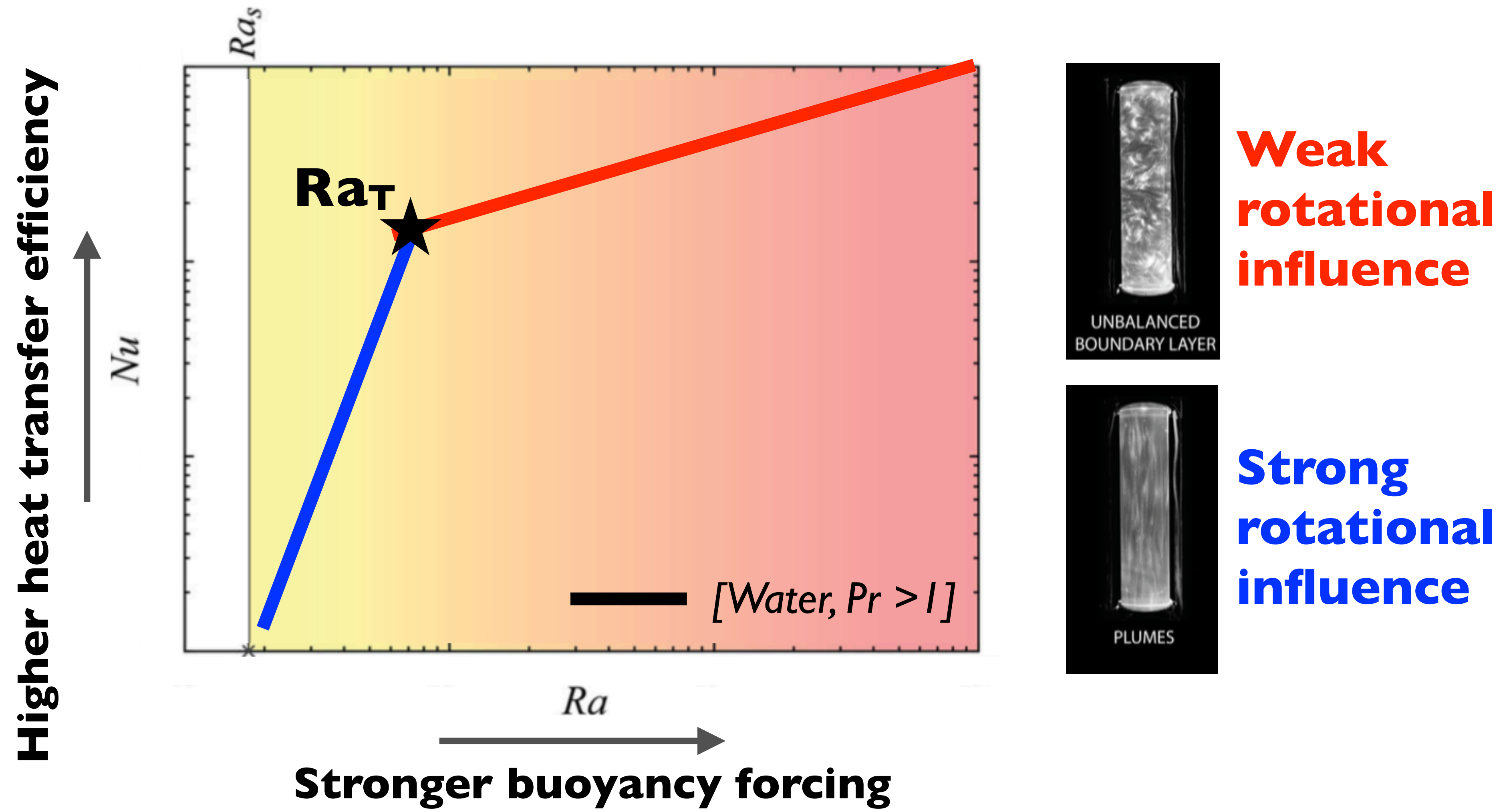
- Heat transfer efficiency regime transition depends on the ratio of momentum/thermal diffusivities
  (King & Aurnou, 2013)



Cheng et al. (2015, 2018)

Magnetic Field Morphology

- Heat transfer efficiency regime transition depends on the ratio of momentum/thermal diffusivities *(King & Aurnou, 2013)*



Cheng et al. (2015, 2018)

Magnetic Field Morphology

- Heat transfer efficiency regime transition depends on the ratio of momentum/thermal diffusivities
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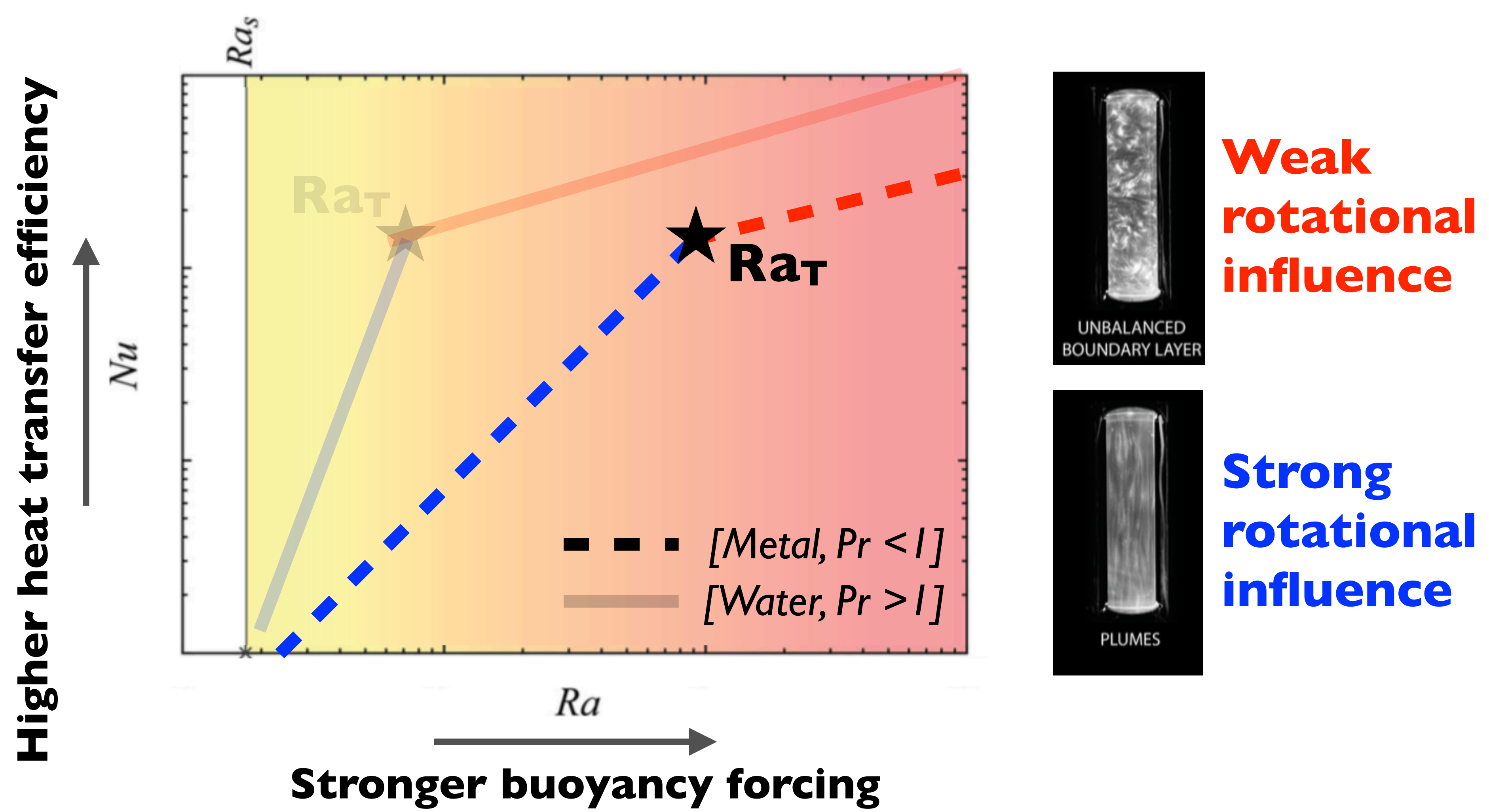

Cheng et al. (2015, 2018)

Magnetic Field Morphology

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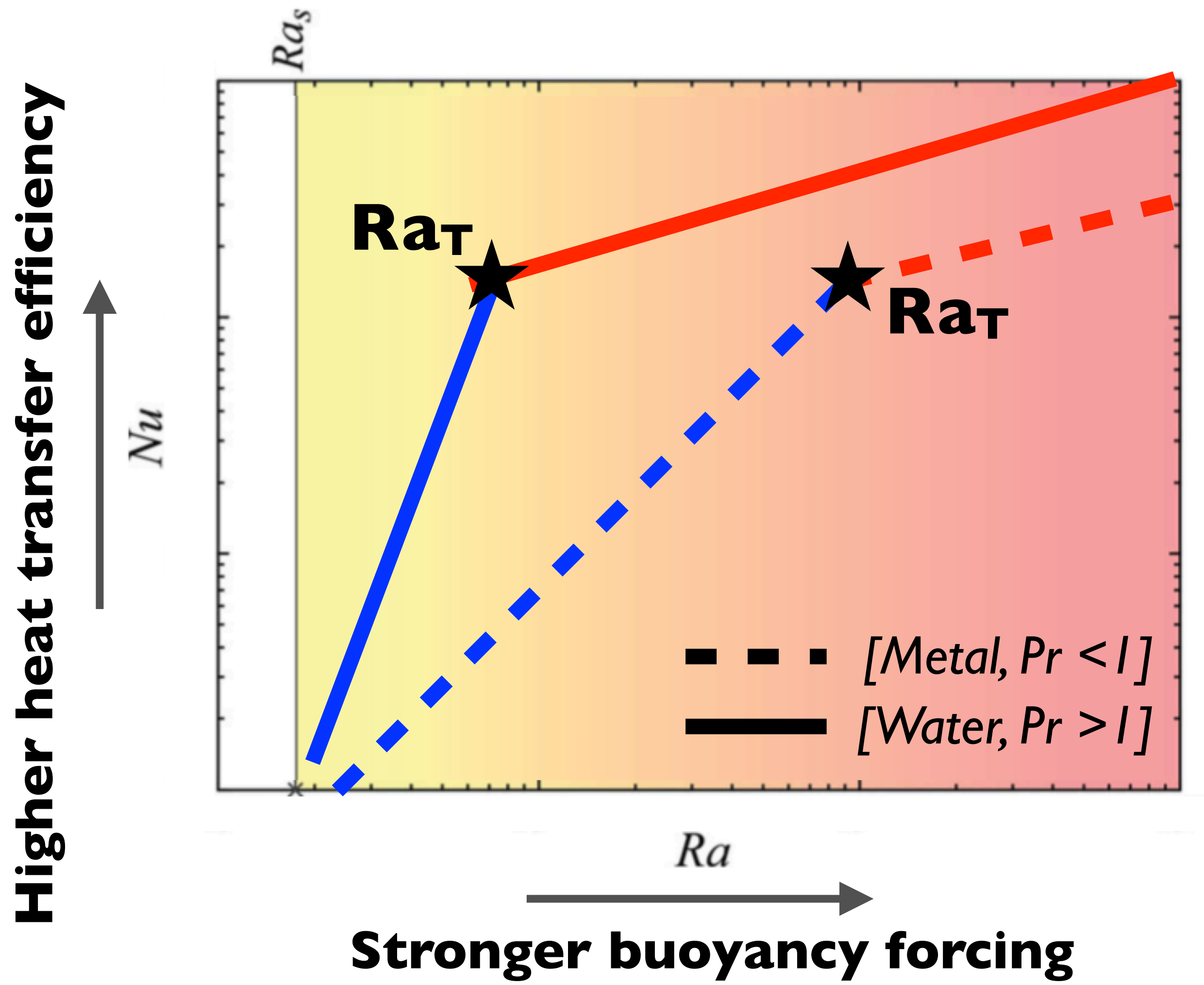
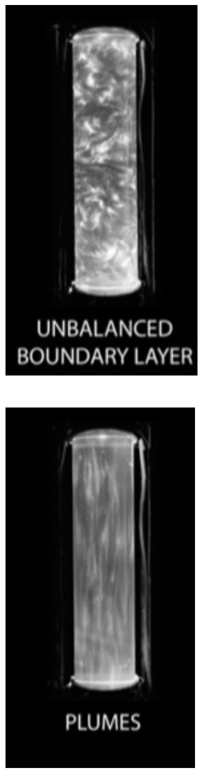




Weak rotational influence

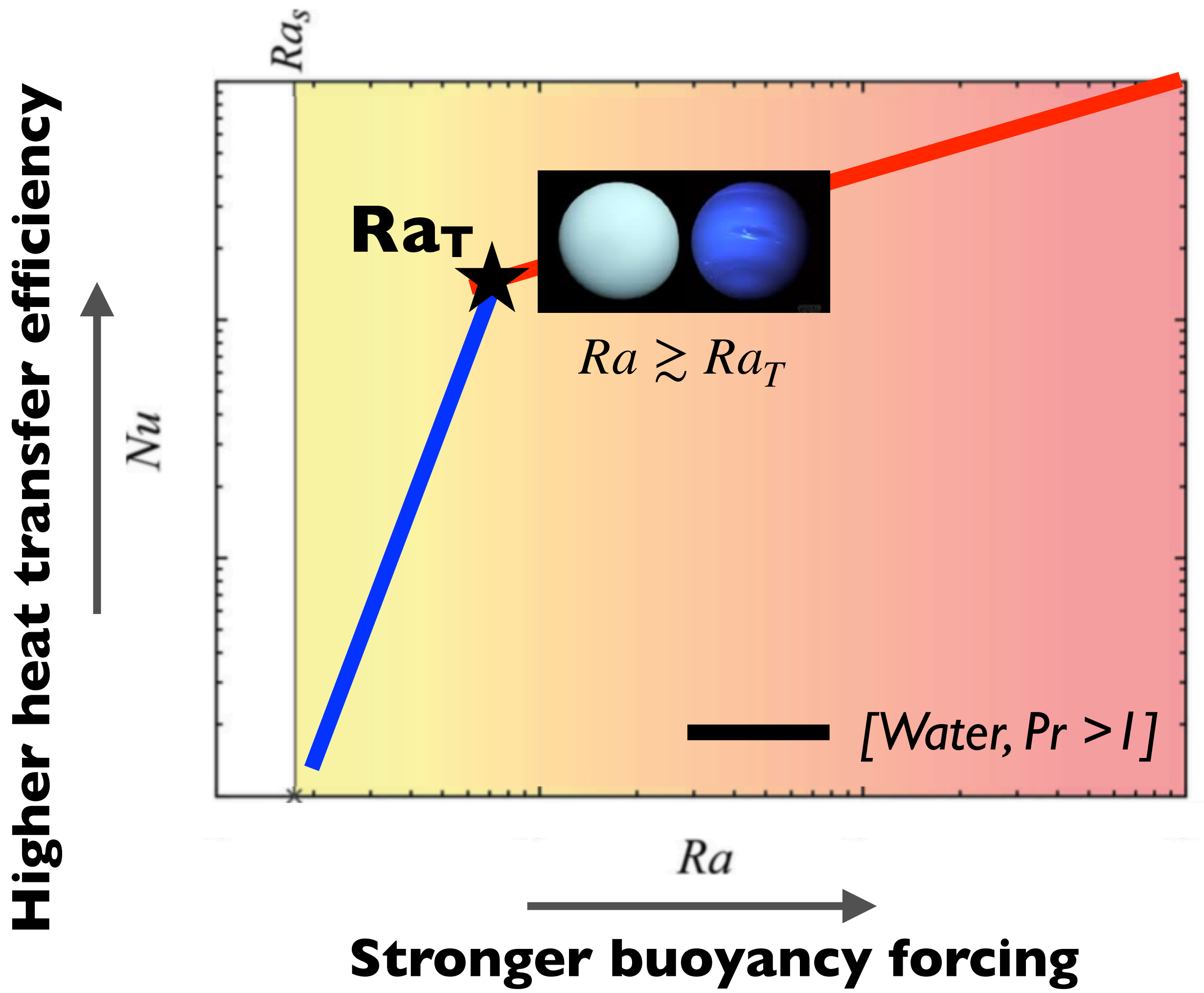
Strong rotational influence

Transition to weakly rotating convection requires stronger buoyancy forcing for liquid metals

Cheng et al. (2015, 2018)

Giant Planet Dichotomy

- Heat transfer efficiency regime transition depends on the ratio of momentum/thermal diffusivities *(King & Aurnou, 2013)*



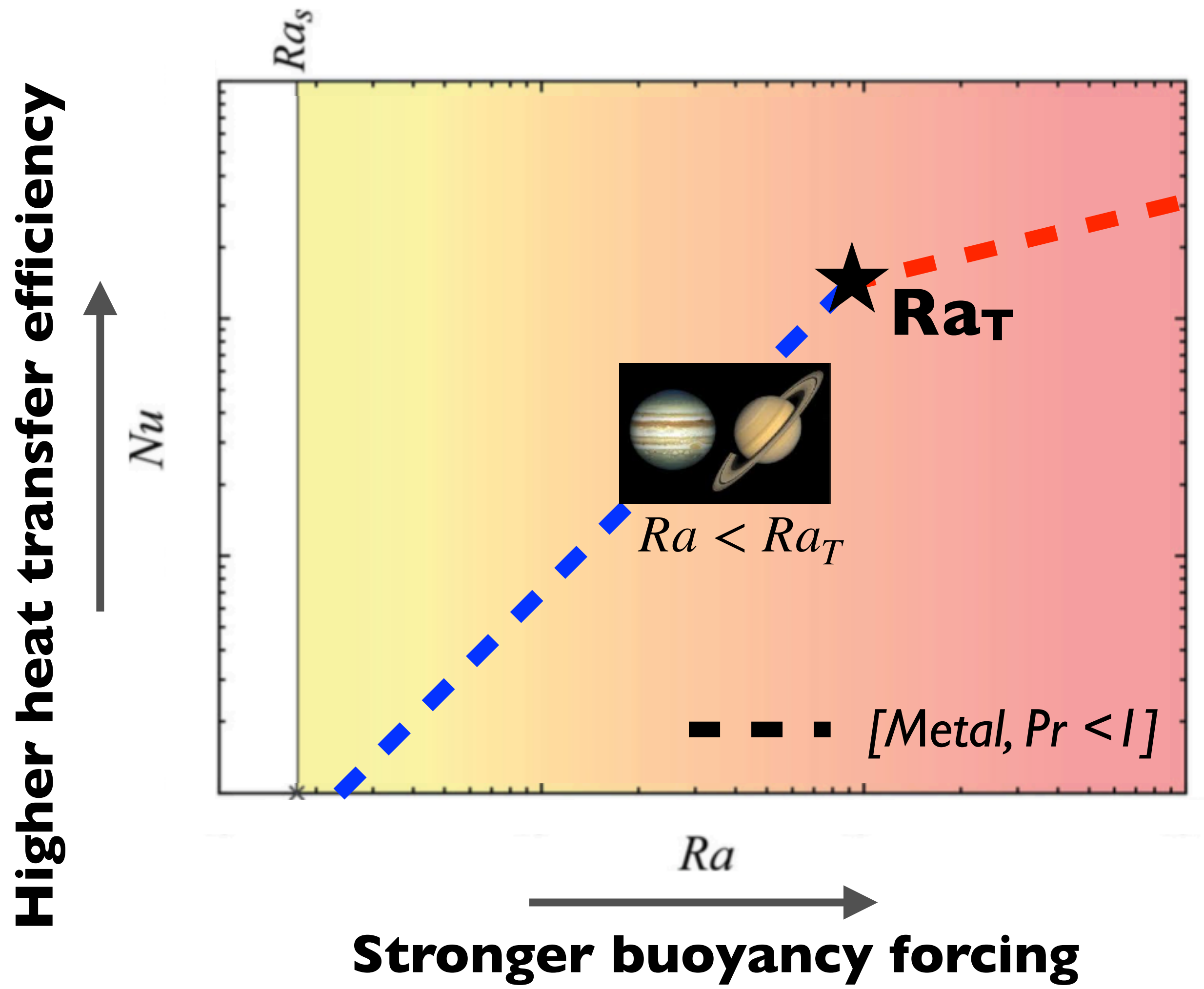
Weak rotational influence

Convection in ice giant interiors is predicted to be weakly constrained by rotation

Cheng et al. (2015, 2018)

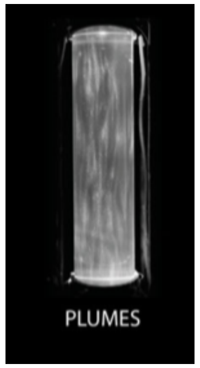
Giant Planet Dichotomy

- Heat transfer efficiency regime transition depends on the ratio of momentum/thermal diffusivities *(King & Aurnou, 2013)*



Cheng et al. (2015, 2018)

Convection in gas giant interiors is predicted to be strongly constrained by rotation



Strong rotational influence

Giant Planet Dichotomy

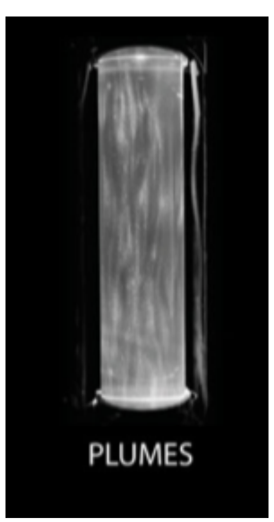
- The ice giants may have unique magnetic field characteristics because of differences in their convective regimes compared against the gas giants

Ice Giants

Weak rotational influence

Convection weakly constrained by rotation will generate ice giant-style dynamos

Gas Giants

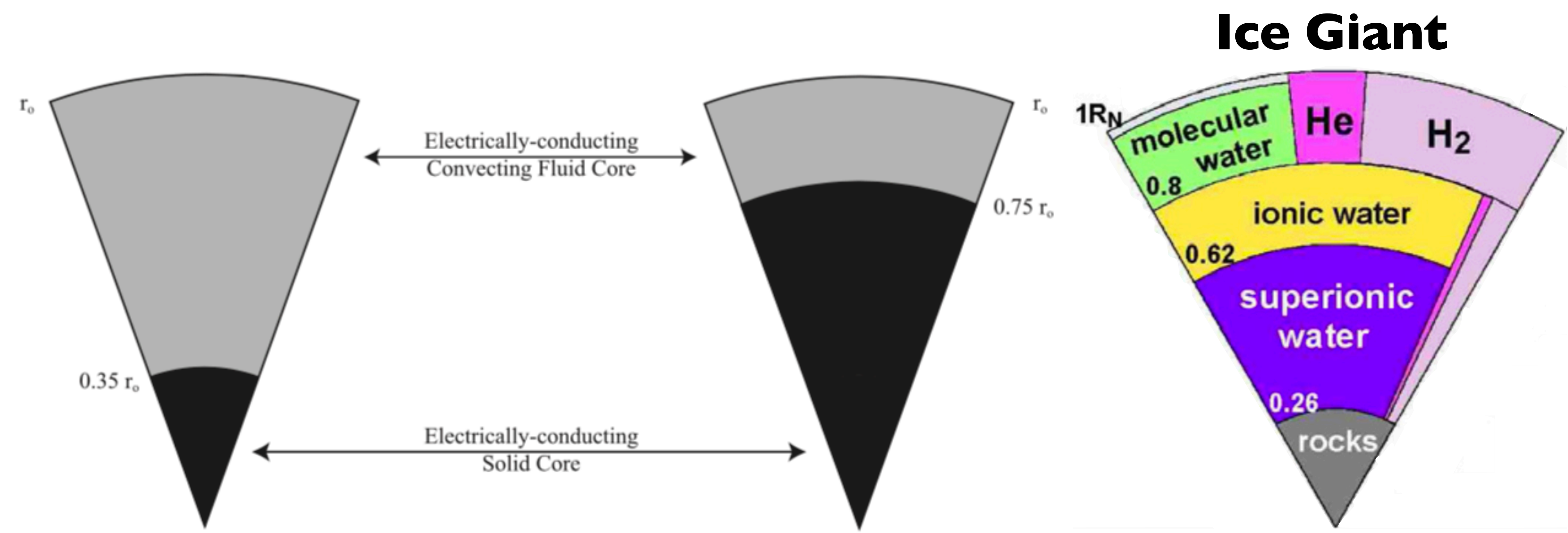


Strong rotational influence

Convection strongly constrained by rotation will generate gas giant-style dynamos

Numerical Dynamo Models

- Hypothesis Test: Dynamo models with convection weakly constrained by rotation and different inner core sizes (Soderlund et al., 2013)

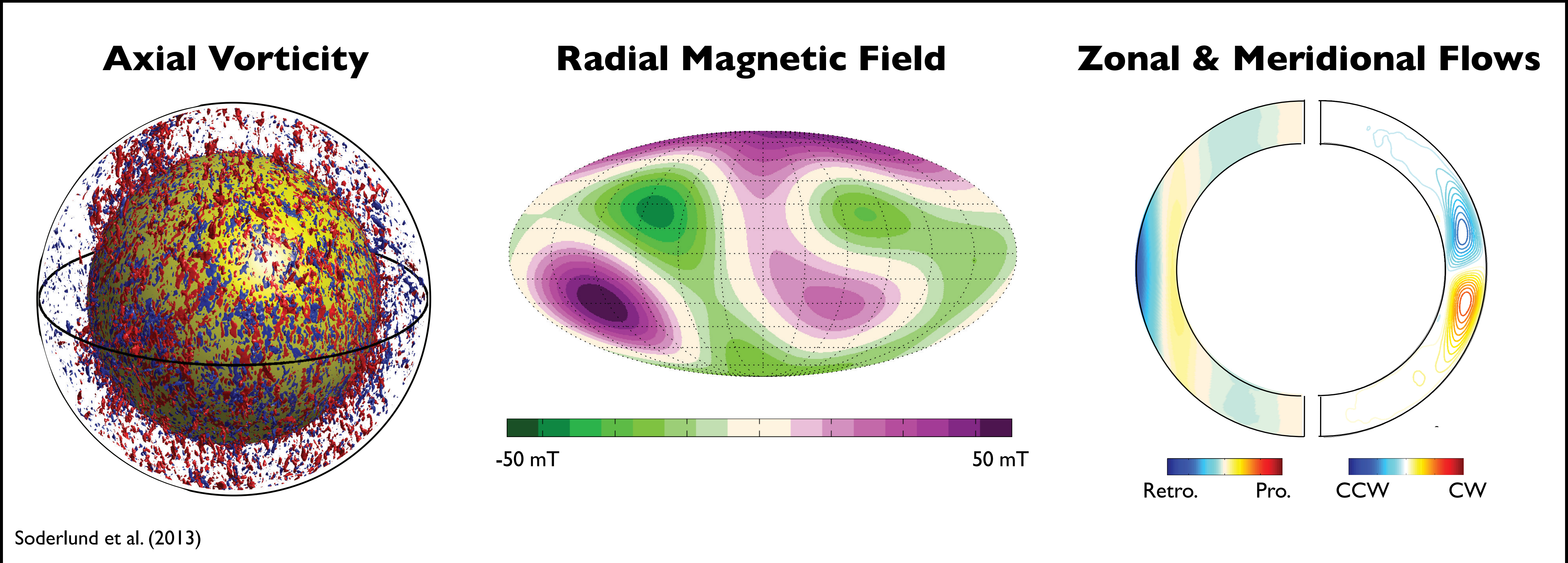


Soderlund et al. (2013)

Redmer et al. (2011)

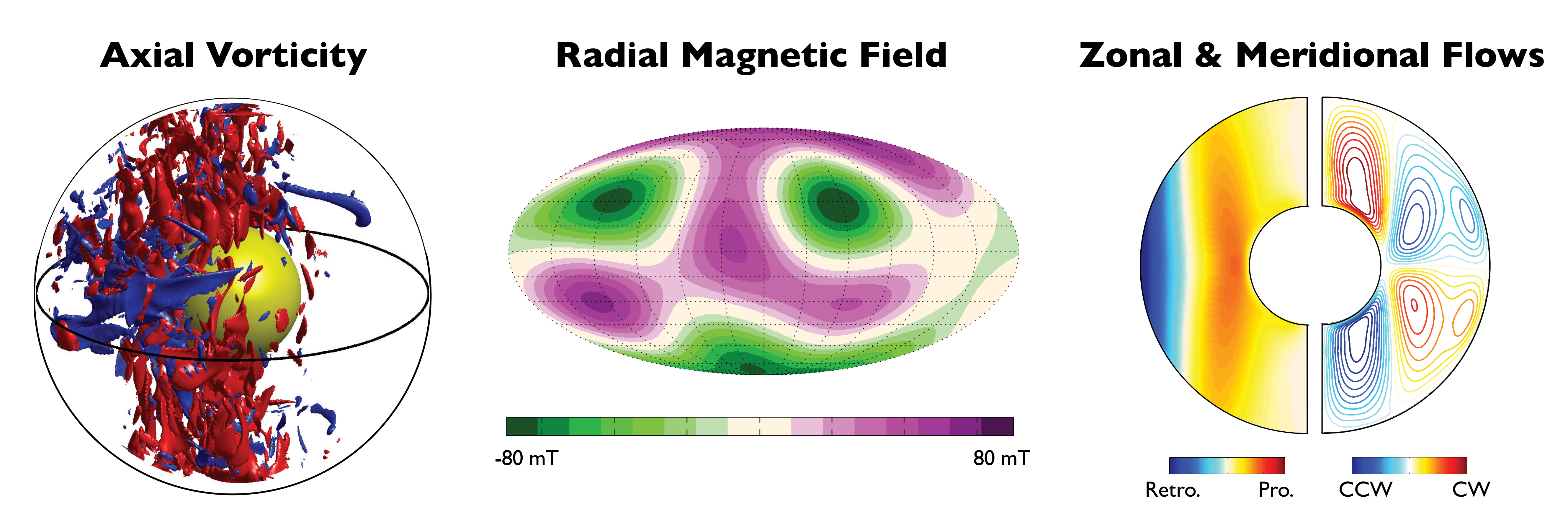
Numerical Dynamo Models

- Models with a thin convective region, solid inner core, and 3D turbulence generate multipolar, non-axisymmetric magnetic fields
  - Retrograde zonal jet, Hadley-like circulation cells



Numerical Dynamo Models

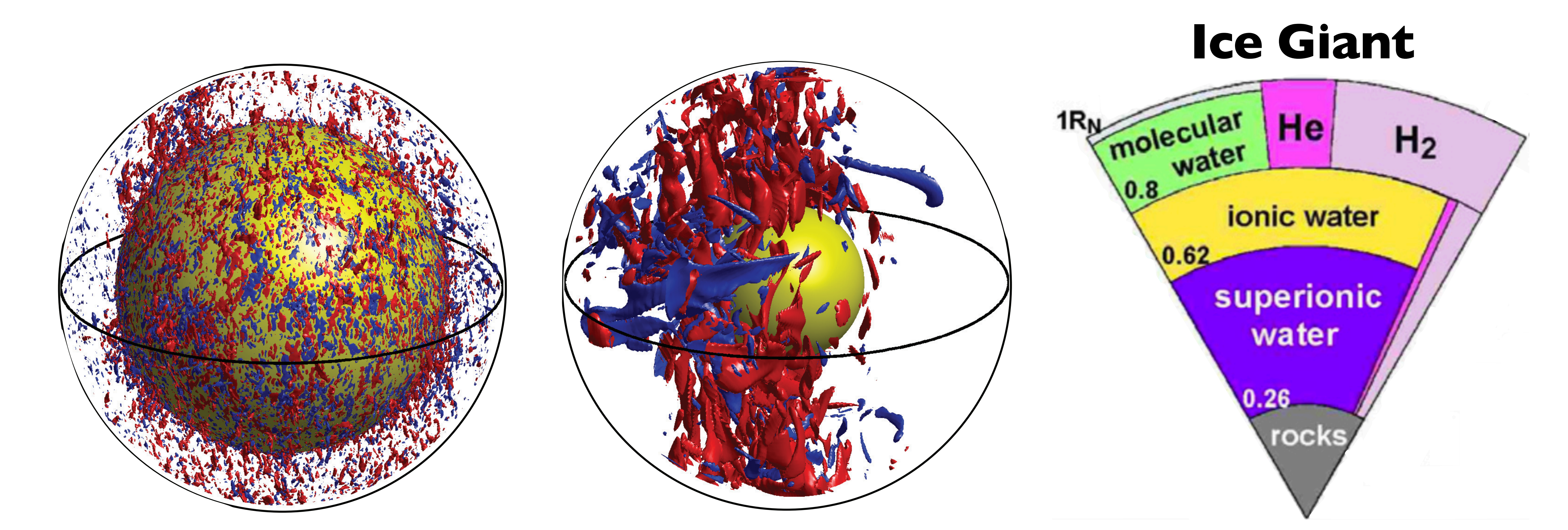
- Models with a thick convective region, solid inner core, and 3D turbulence generate multipolar, non-axisymmetric magnetic fields
  - Retrograde zonal jet, Hadley-like circulation cells



Soderlund et al. (2013)

Magnetic Field Morphology

✓ <u>Hypothesis</u>: The ice giants have multipolar dynamos because convective turbulence in their interiors is weakly constrained by rotation (Aurnou et al., 2007; Soderlund et al., 2013; King and Aurnou, 2013)



Redmer et al. (2011)

Giant Planet Dynamos

- Theoretical, laboratory, and numerical modeling are useful tools for studying planetary magnetic fields
    - Magnetic field strength for both planets and stars generally consistent with energy flux scaling law
    - Diversity of magnetic field morphologies appears to be a consequence of differences in dynamo source regions
        - Convection in a thin shell geometry with deep stable fluid layer or deep weakly conducting solid layer
        - Convection that is weakly constrained by rotation, regardless of shell geometry

Outline

1) Planetary Magnetic Fields

2) Ice Giant Dynamos

3) Looking Ahead

Looking Ahead

- A new ice giant mission, combined with advances in material properties and fluid dynamic theory, would provide additional constraints on dynamo models and test their predictions
    - Determine the configuration of the intrinsic magnetic field (*magnetic field magnitude, morphology, and variability*)
    - Constrain the structure, composition, and dynamics of the interior (*gravitational moments, magnetic field, planetary oscillations, internal heat flux maps, radial electrical conductivity and rheology profiles*)