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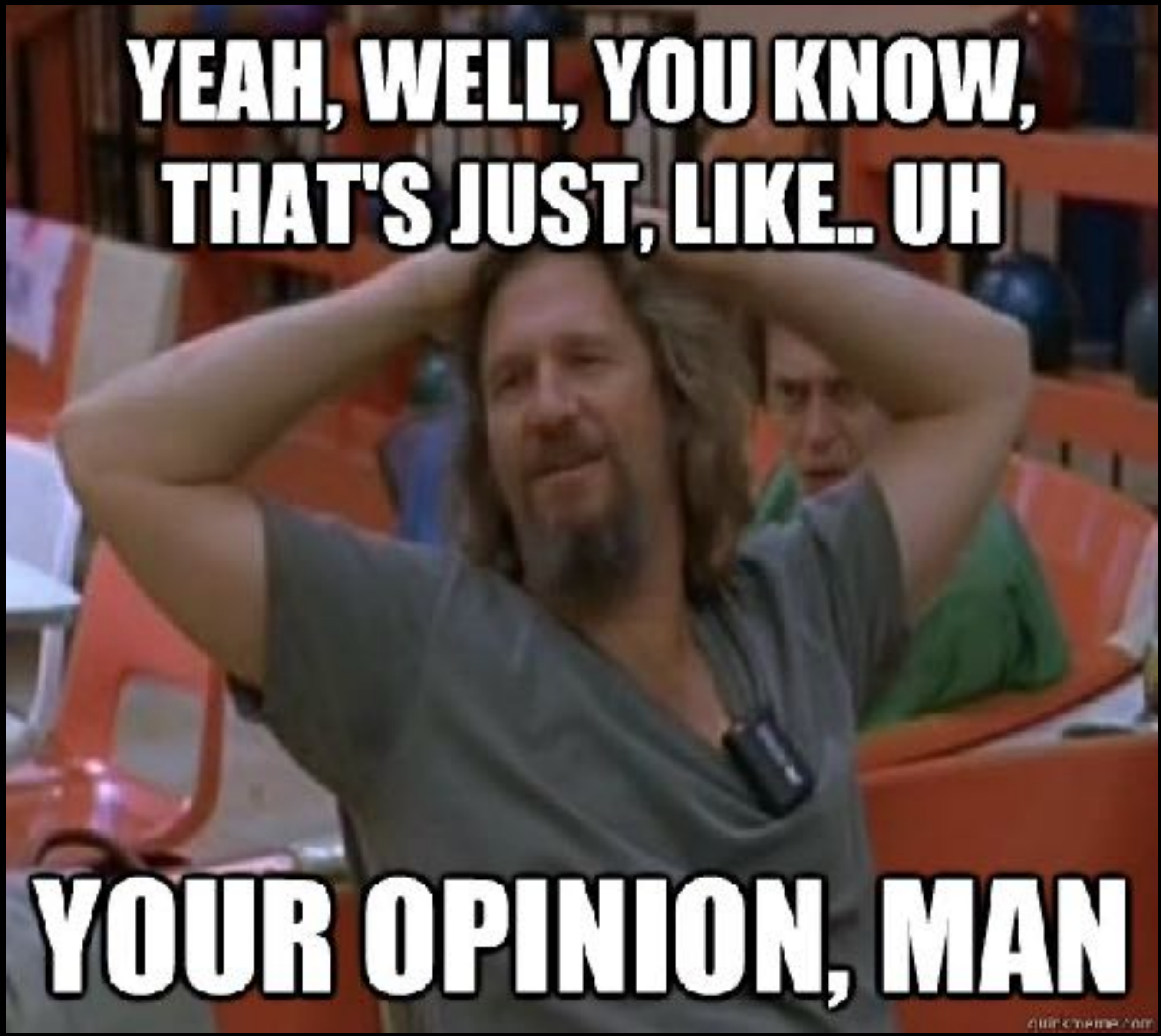
EARTH'S DYNAMICS AND ITS FUTURE

TALK OUTLINE

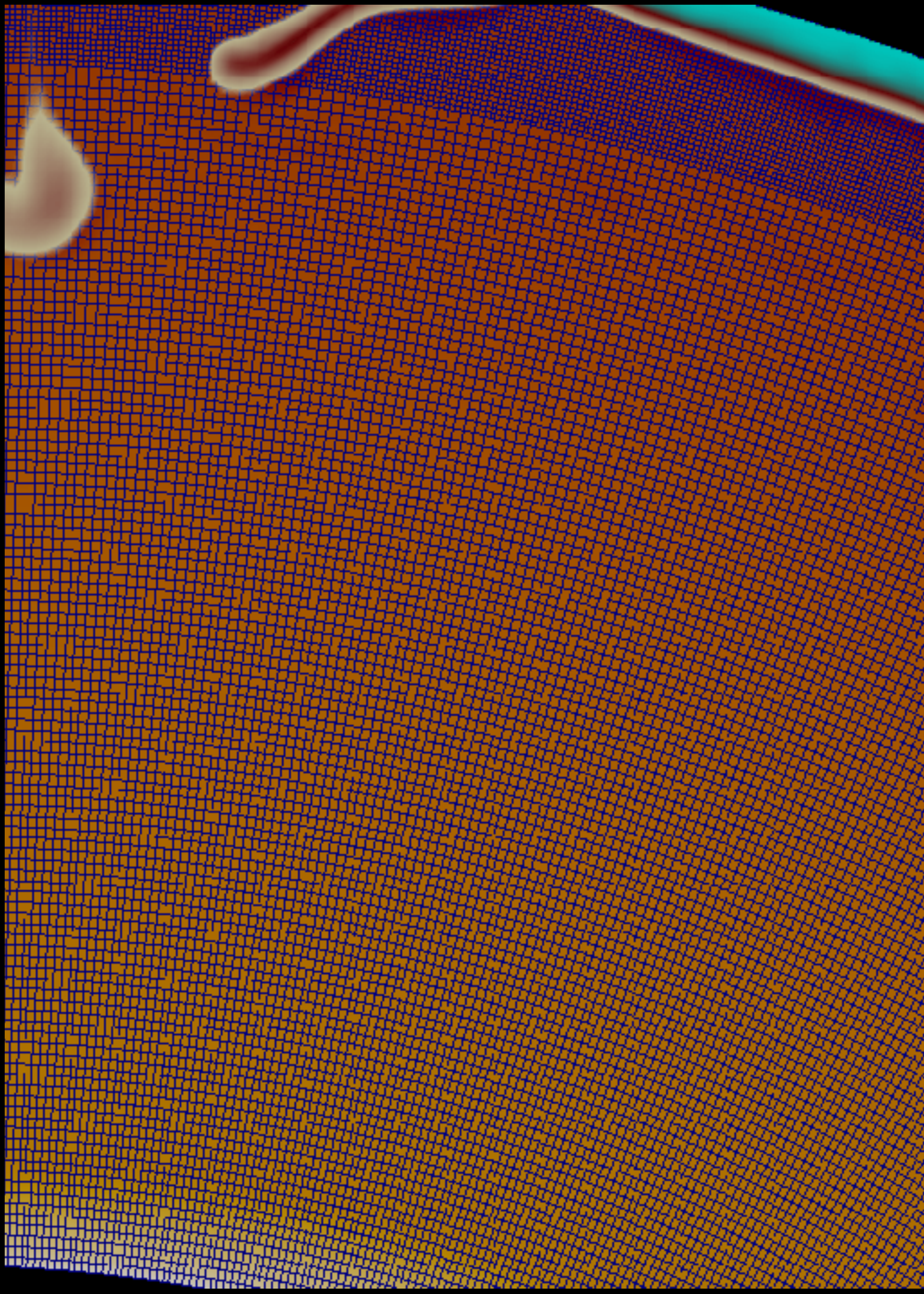
- Geodynamics: State of play
- 3 frontiers
- Approaches
- Gap analysis and roadmaps



STATE OF THE FIELD

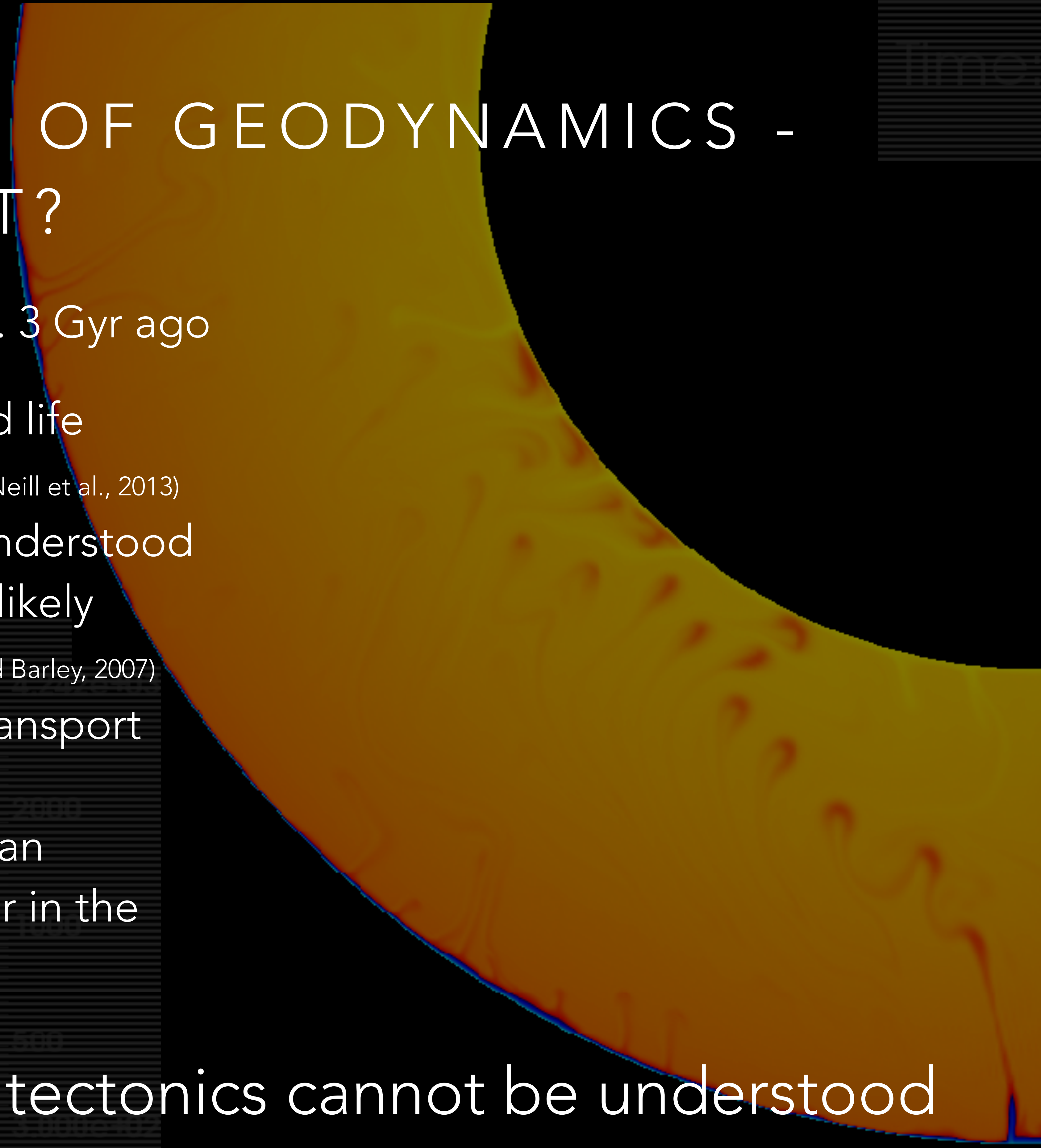
Recent advances include

- Supercomputing power - and more sophisticated 3D models
- Rapidly advancing mineral physics models
- Ab initio molecular dynamics simulations complementing existing experimental approaches
- Advances in detailed seismology of the Earth
- Geoneutrino constraints supplementing cosmochemical results



THREE FRONTIERS

1. THE FUTURE OF GEODYNAMICS - THE DEEP PAST?

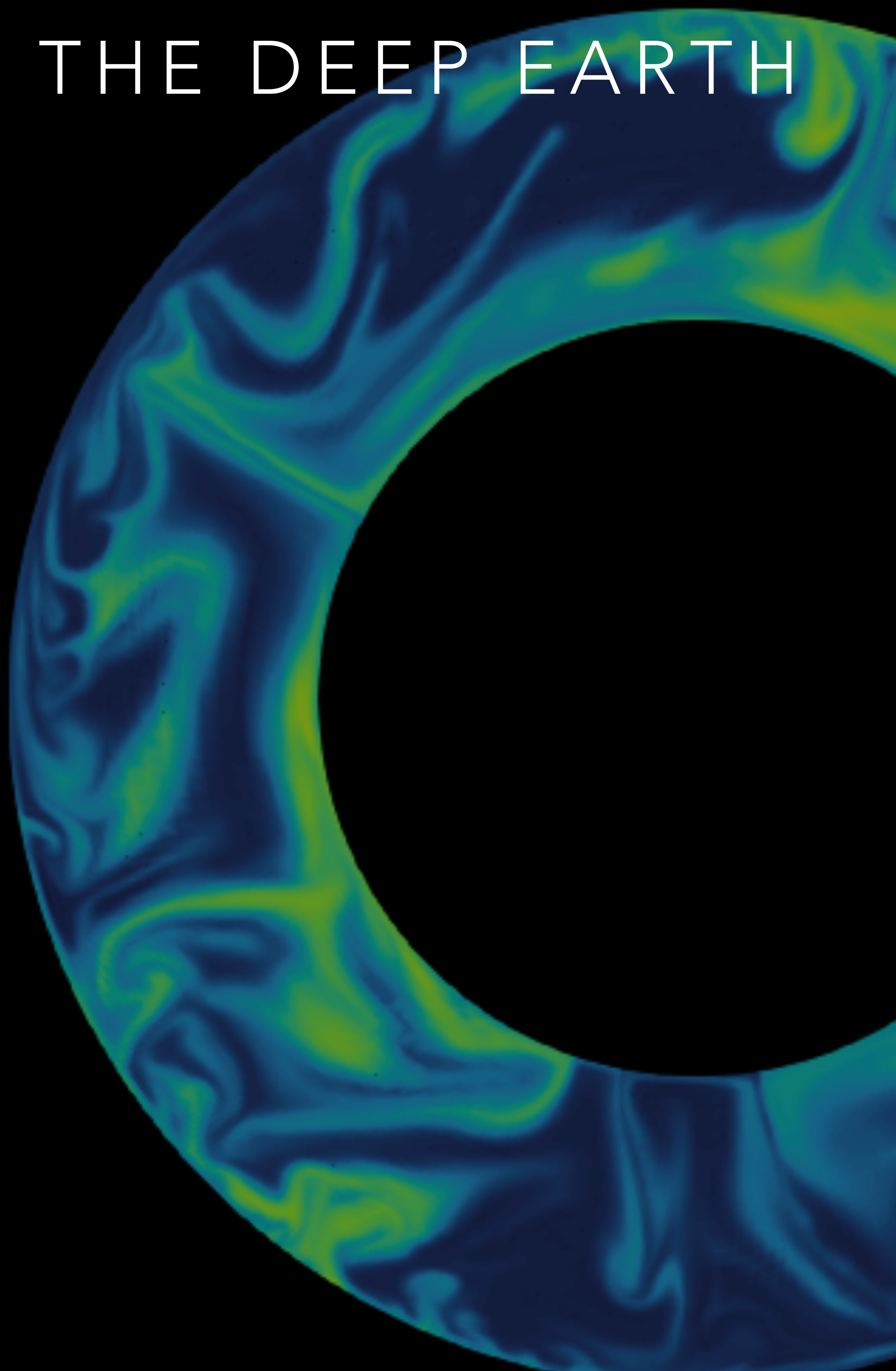


- Origins of plate tectonics ca. 3 Gyr ago (eg. Hawkesworth and Cawood, 2018)
- Evolution of atmosphere and life connected to tectonics (eg. O'Neill et al., 2013)
- Core and geodynamo not understood
- Exposed continental extent likely changed dramatically (Kump and Barley, 2007)
- Volcanism significant heat transport mechanism (Moore and Webb, 2013)
- Impact bombardment likely an important geodynamic driver in the Hadean (O'Neill et al., 2017, 2020)

Evolution of modern tectonics cannot be understood without context from the past

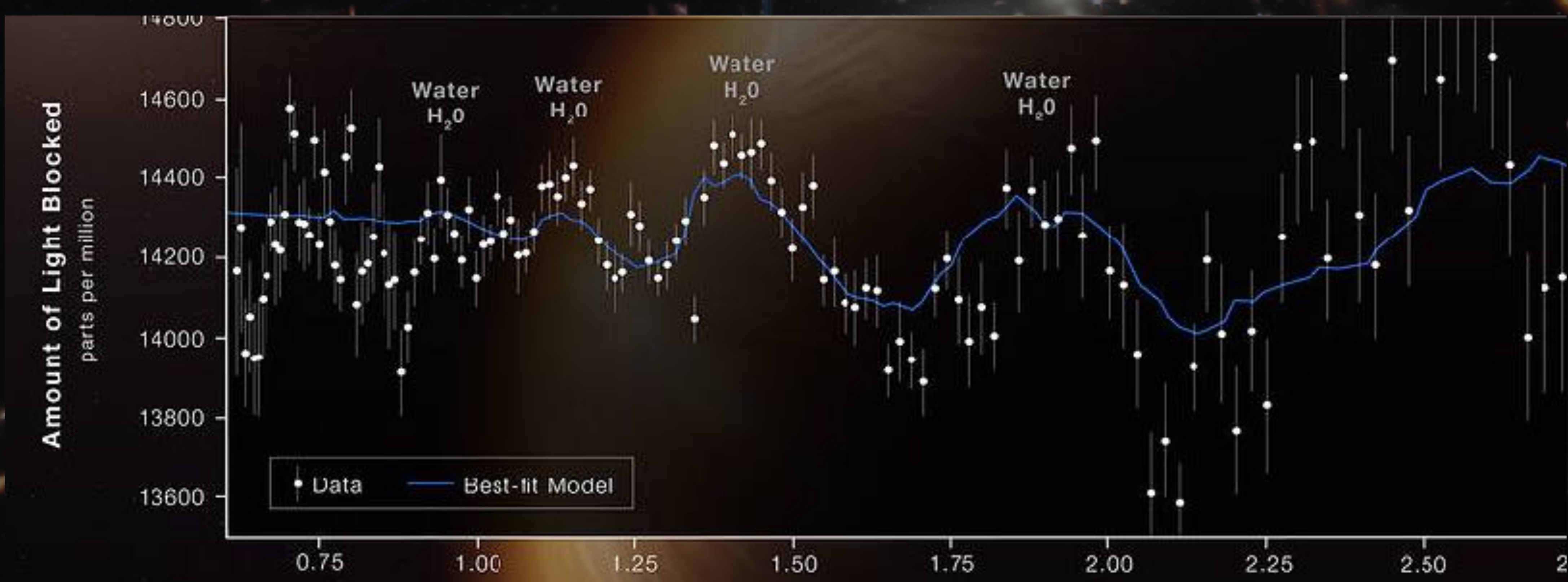
2. THE FUTURE OF GEODYNAMICS - THE DEEP EARTH

- Lower mantle is still poorly constrained
- Mixture of largely Bridgmanite, ferropericlase/magnesiowustite, and minor phases like Al and Ca perovskite
- Viscosity of these minerals has historically been difficult to obtain (experimental pressure, temperature and strain limits)
- Ab initio calculations is starting to shed light on this
- But bulk properties (viscosity) need mixing models, which aren't well developed experimentally
- Complexities - iron spin transition at 1000 km
- D", LLSVP structures, and post-perovskite behaviour



3. THE FUTURE OF GEODYNAMICS - THE FINAL FRONTIER

- Reasonably estimates suggest billions of planet's in the galaxy (let alone in the JWST image shown)
- A very small number have representatives in the solar system
- Different inherited cosmochemistry, planetary formation pathways and system histories (including radiogenic nuclides) (eg. Lugaro et al., 2014)
- Very different heat budgets, mineral assemblages, volatile budgets (and thus ocean to continent ratios - perhaps even ocean compositions)
- Plausibly very different behaviours (O'Neill and Lenardic, 2007; Valencia et al., 2007)

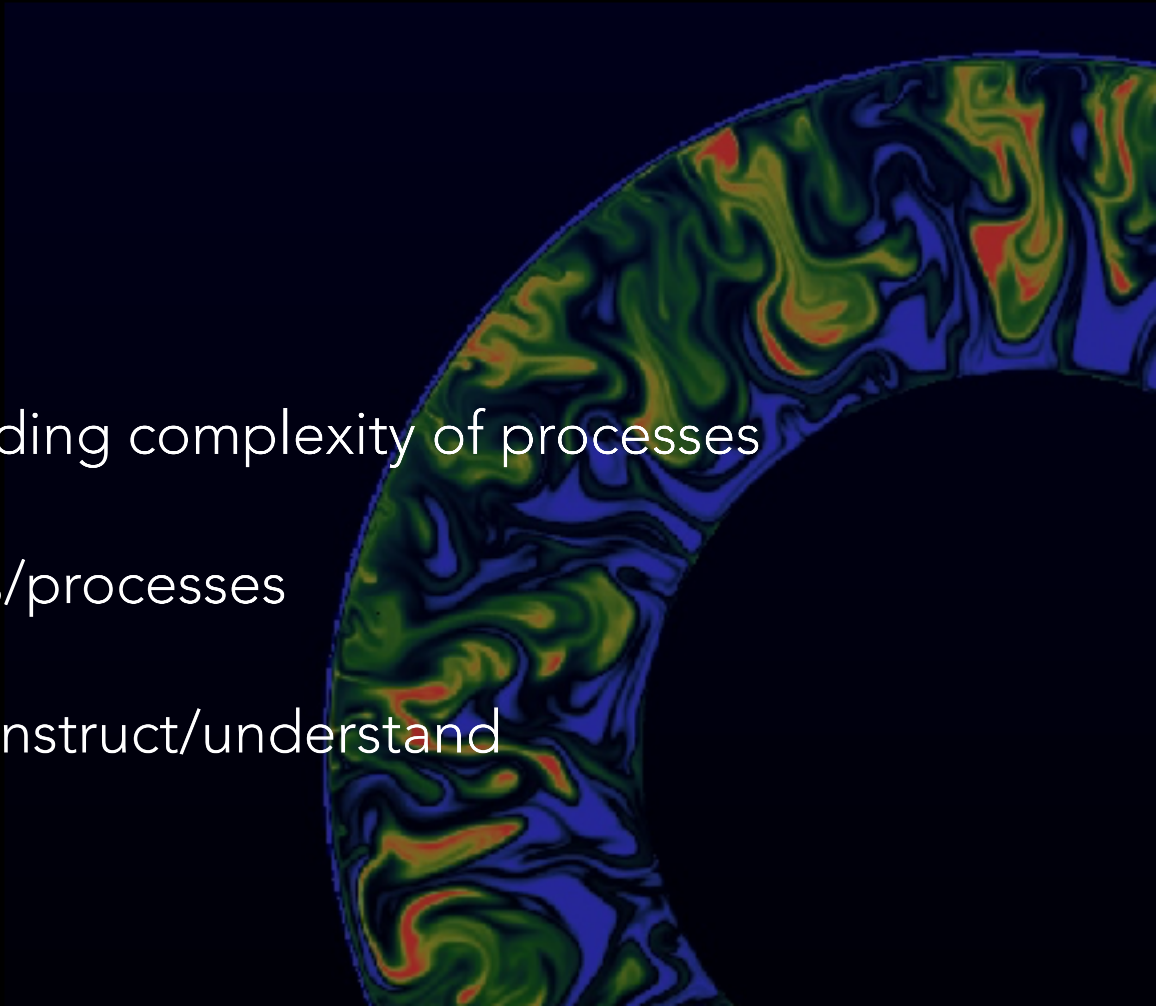


HOW DO WE MODEL THIS COMPLEXITY?

APPROACHES TO THIS DIVERSITY

REDUCTIONIST APPROACH

- Consider elements in problem and constrain them individually
- Consider implications of effect in simple geodynamics models
- Risks: Leaves out completing factors that may affect the impacts of individual components



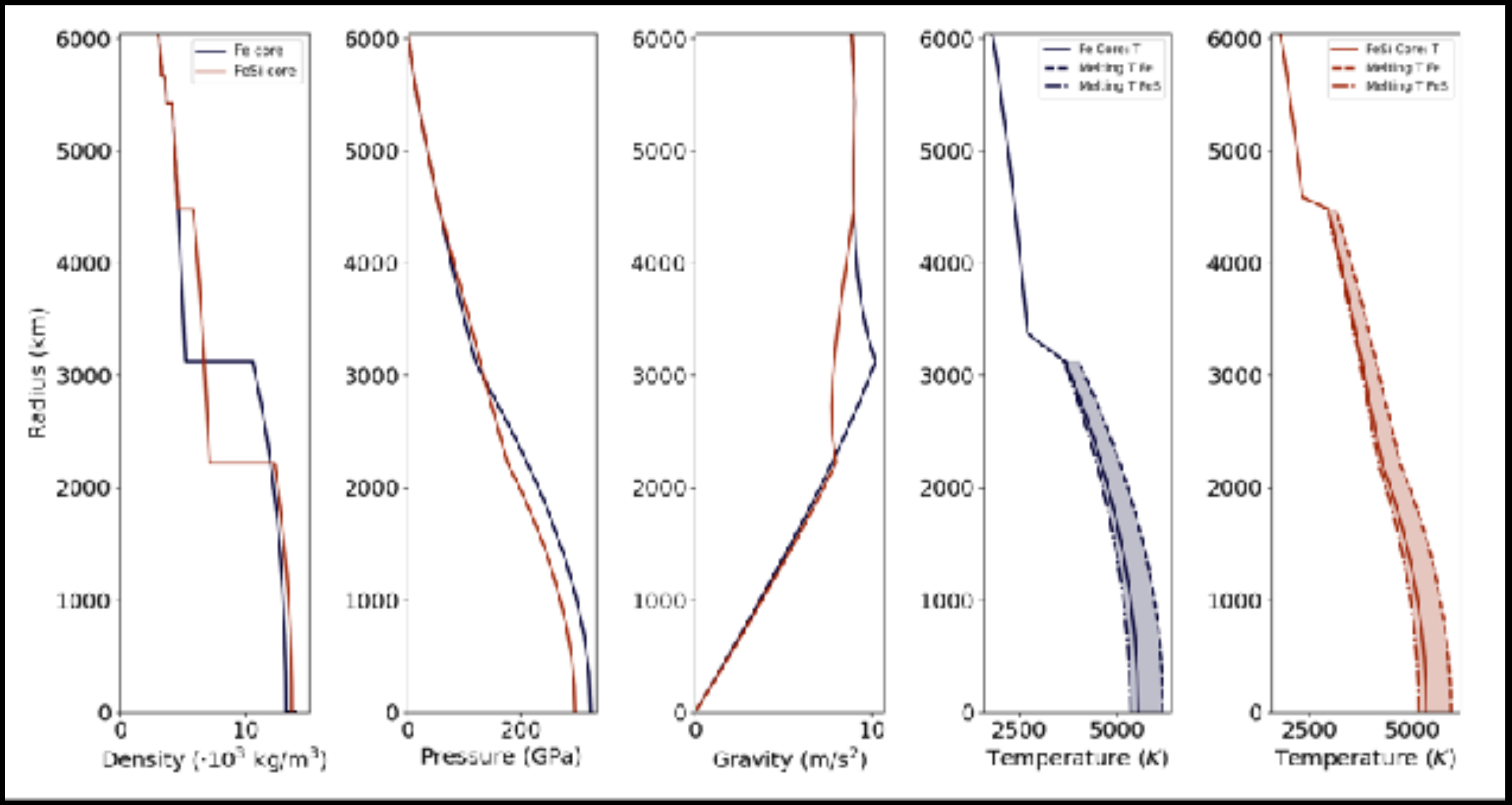
COMPLEX SYSTEMS APPROACH

- Treat geodynamics as an emergent phenomenon
- Include the diversity of mechanisms, consider cascading complexity of processes
- Identify emergent dynamics and priority parameters/processes
- Risks: system rapidly becomes too complex to deconstruct/understand

BENCHMARKING EMERGENT BEHAVIOURS

- Plate motions, tectonics styles, and geological constraints (Moresi and Solomatov, 1998; Tackley, 2001; O'Neill et al., 2013)
- Heat flow and volcanism (Davies, 2013; Rozel et al., 2015)
- Global seismology and planet structure (eg. Becker and Boschi (2002))
- Geoid, length of day, and moment of inertia (Rudolph et al., 2015)
- An example: Venus - Earth's Twin? Or Mercury's twin?

- Venus has no magnetic field and it has been suggested that it has no inner core
- This has profound implications for it's cooling history - no inner core would imply no plate tectonics
- New constraints on Venus's moment of inertia (MoI, Margot et al., 2021), together with mineral physics models (Burnman), allow assessment of possible endmembers (see O'Neill, 2021 for details)
- Venus either has no inner core (for an Earth-like composition), or a very large core (R = 4000 km, inner core R=2000 km) for a Mercury-like "light element" enriched core composition. Need better cosmochemical or geophysical models to constrain these possibilities

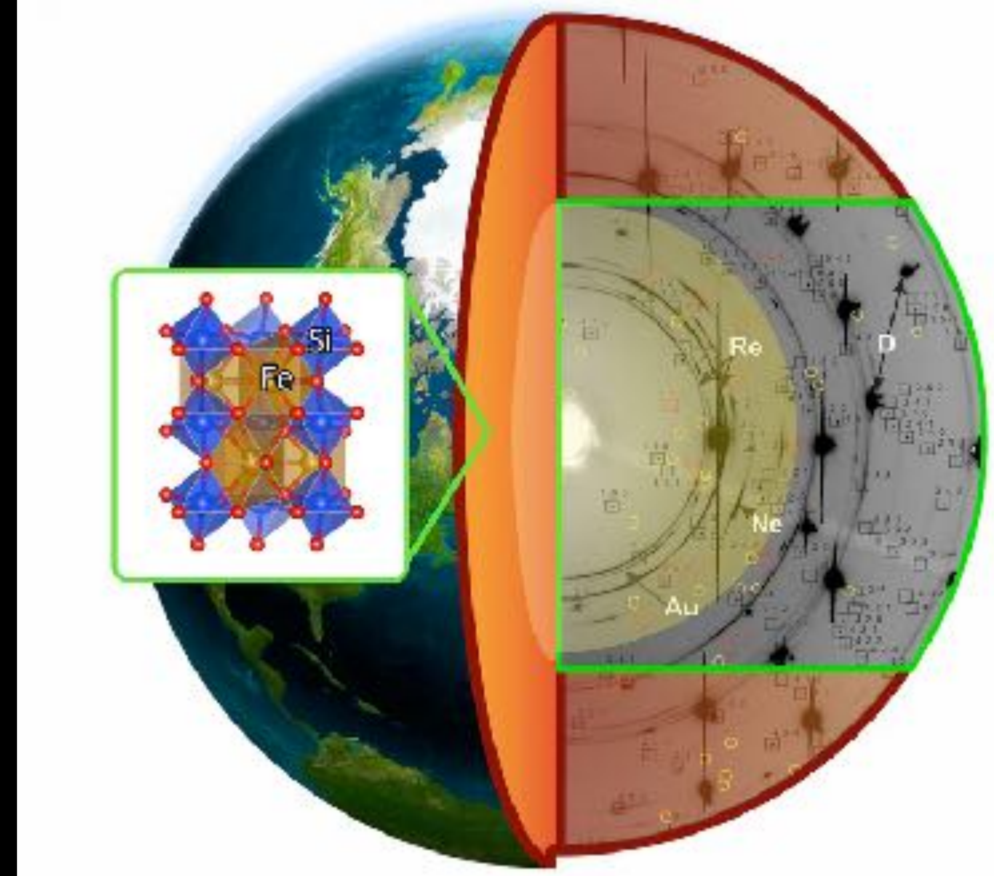


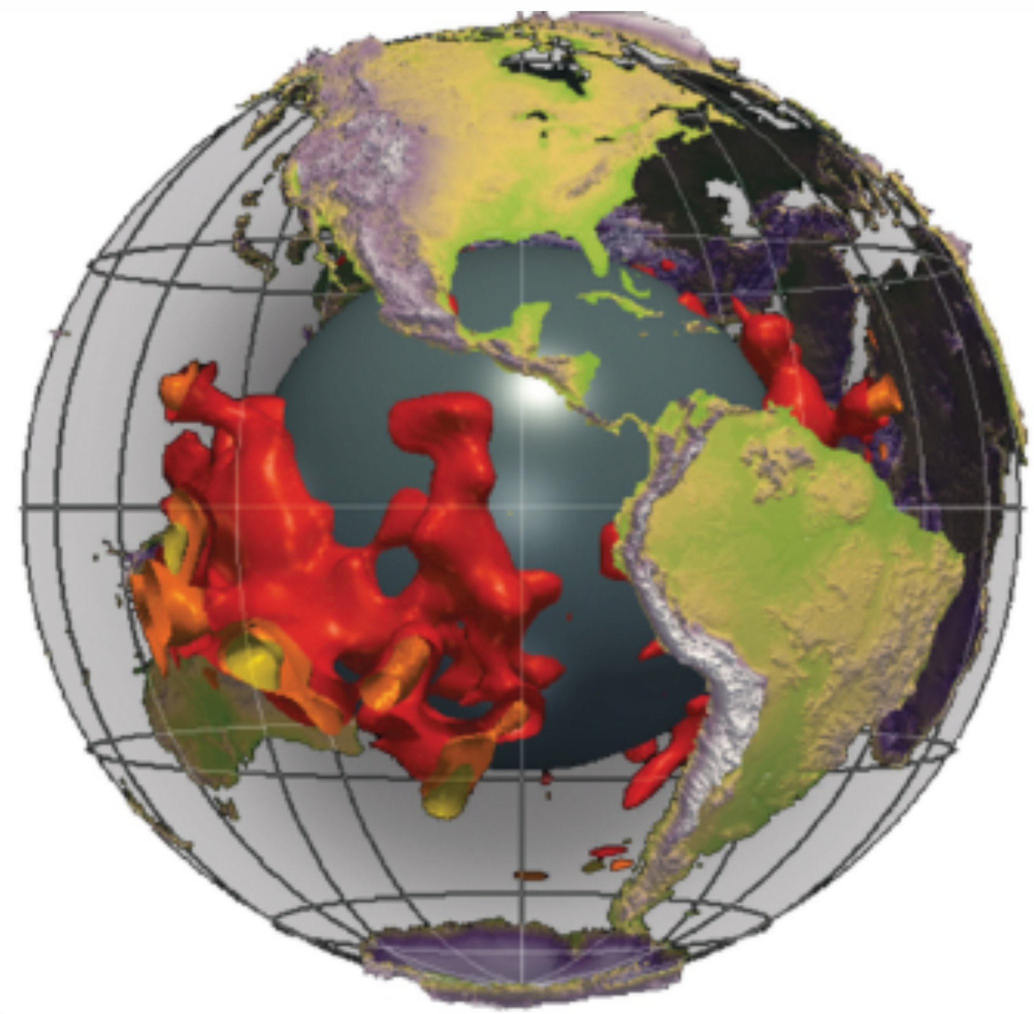
PROBING THE EARTH

Advances in probing the Earth are covered in upcoming talks, but briefly, there has been significant recent leaps in:

- Cosmochemistry, heat flow and thermal models, and neutrinos constraints on internal elemental structure
- Seismology
- Experimental and ab initio MD calculations

- **Significant work is required though to bridge the relevant scales inherent in these advances.**





PROBING OTHER WORLDS

- Planetary geochemistry is related to stellar chemistry - something that is observable. But a planets represents the end of a planetary formation process, including volatile loss and fractionation of elements, which is not a resolved problem and varies within the solar system (eg. Sun and McDonough, 1989, Lodders, 2003).

- Significant cosmochemical variation exists between planets, and thus differences in bulk mineral composition (eg. between Mars vs Earth vs asteroids)

- In the exoplanet catalogue even more chemical variation is expected -> what sort of mineralogical variation is implied? This is currently unknown.

BENCHMARKING BEHAVIOURS

We could (potentially) constrain exoplanet geodynamics from:

- Atmospheric composition - volcanism, degassing and recycling are tied to tectonics (and also geomicrobiology - see Kastings 2010). But - diagnostic atmospheric signals of plate tectonics not clear. Needs coupled geodynamics - volcanic - degassing - atmosphere models.

- Geoid, gravity, size and moment of inertia -> these can constrain heat (internal temperatures), internal composition and/or tradeoffs between them

- Length of day changes? 2004 Sumatra earthquake changed the LoD by 2.68 microseconds, and shifted the pole by 2.5 cm. This is remotely detectable from rotation. Technically, very challenging - but not impossible!

THE STATE OF THE FIELD

- Large advances in computational power and approaches, and enhancements in understanding high-pressure mineral physics.
- Critical frontiers in deep time, deep planetary interiors, and exoplanetary tectonics
- What is needed is a formal gap analysis, and a roadmap forward
- Some initiatives already underway:
  - Community codes (eg. https://geodynamics.org/)
  - Community rheology models
  - Computational resources (currently sourced locally, using national facilities, or commercially (eg. AWS)).
  - Observational test and data archive (eg. https://ggos.org/item/global-gravity-field-models/, https://www.ngs.noaa.gov/GEOID/, https://shtools.github.io/SHTOOLS/python-datasets-constants.html, https://pds.nasa.gov/).