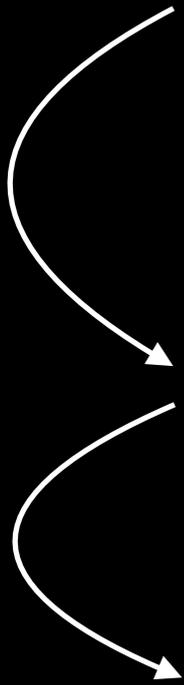


How to Model a Living Planet?

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3 Big Challenges

1. Multi-Scale Planetary Physics: Integrated theory connecting atomic to planet-scale phenomena, and everything between.
 2. Planet Behaviorism: Complexity in planet evolution, memory effects, hysteresis, stochasticity, chaos, etc..
 3. Planetary Metabolism: Whole-planet deep-time open-systems process science, including habitability, sustainability, etc..
- 

1. Multi-Scale Planetary Physics

Scale Issues in Dynamics of Fluid Parts of Planets/Moons

- Turbulence: The greatest issue in multi-scale physics of fluids is the treatment of turbulence, in electrically conducting fluids (MHD), stably stratified fluids, and other complex scenarios. Present models use very simple/crude turbulence parameterizations.
- Rapid Rotation: Resolving the nominal Eckman layer (~ 1 cm thick in Earth's outer core) is not plausible, robust methods to upscale boundary layer dynamics to larger scales are needed. Rotation also increases the importance of boundary topography on the dynamics.
- Time Scales: Dynamo model time scales are of order the magnetic diffusion time (up to ~ 1000 years), however, the boundary conditions imposed by mantle convection evolve over >10 Myr time scales. More complex, turbulent, small Eckman number dynamos may exhibit complex long term behavior, lacking steady state behavior even in the absence of changes in boundary conditions.

Scales in Dynamics of Rocky Parts of Planets/Moons

How do these scales interact with one another to produce the collective dynamics of the solid regions of terrestrial planets/moons?

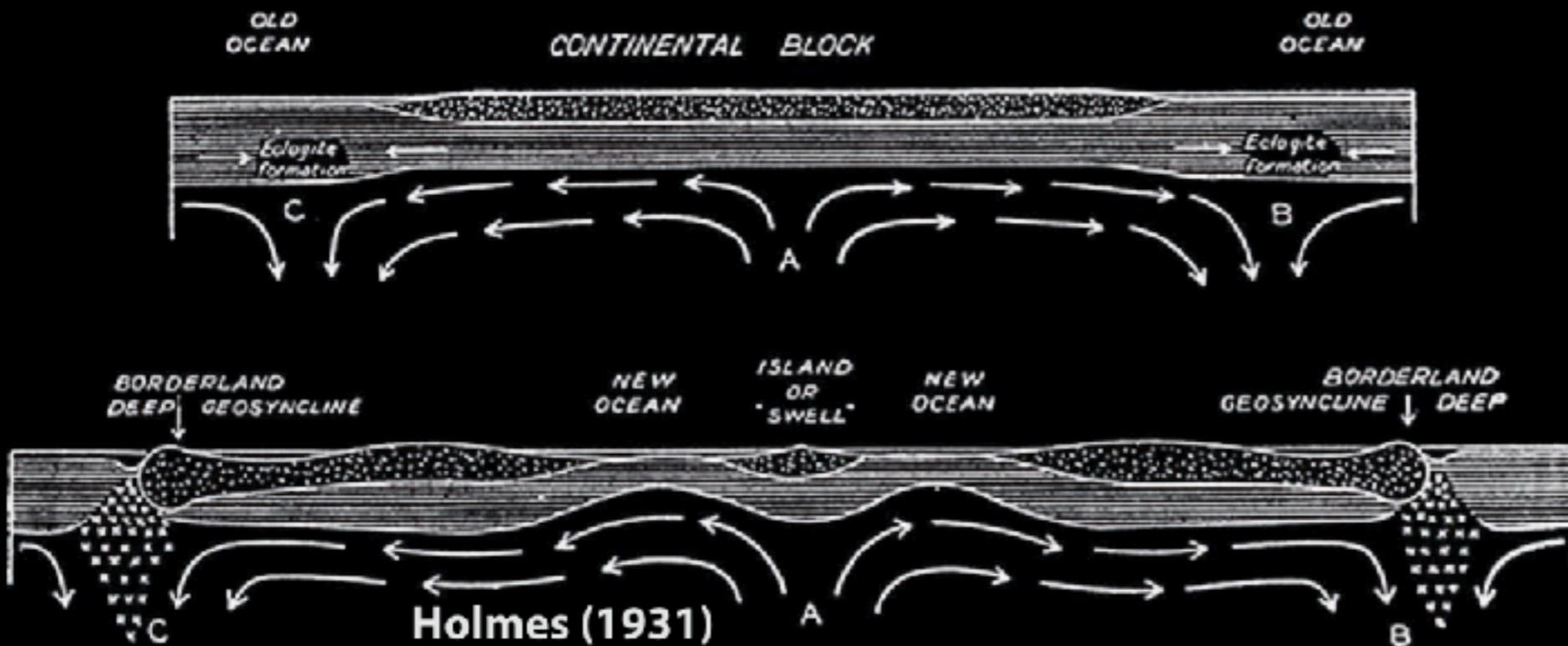
What is the influence of non-linear behaviors between these regions, sub-critical regimes, memory effects, hysteresis, etc.?

To what extent does our ignorance of the multi-scale physics affect our ability to model geodynamical phenomena?

- Atomic scale (~0.1-1 nm): Vacancies, diffusion, impurities
- Sub-grain scale (~10 nm-1 μ m): Dislocations, grain boundaries
- Grain scale (~10 μ m-~10 cm): Grain-grain interaction, grain growth/reduction, inter-connection
- Rock scale (~10 cm- ~1 m): Phase segregation, fabric, LPO, SPO
- Zone scale (~10 m- ~1 km): Shear zones, plate boundaries
- Crust scale (~1 km- ~10 km): Surface and subducted crust, seismic scatterers, phase changes, ULVZ
- Meso-scale (~100 km): Plate boundaries, asthenosphere, D''
- Regional Scales (~1,000 km): Plate deformation, mid-degree mantle dynamics, LLSVP
- Mantle Scale (~10,000 km): Low-degree structure and dynamics, plate re-organization

Assumptions About Mantle Rheology

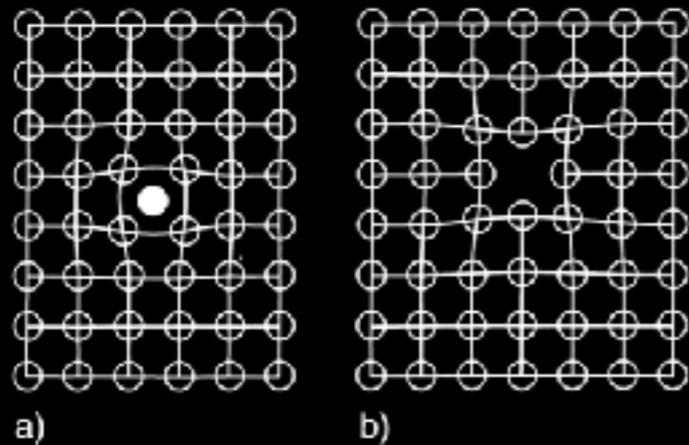
The mantle “behaves like a fluid”



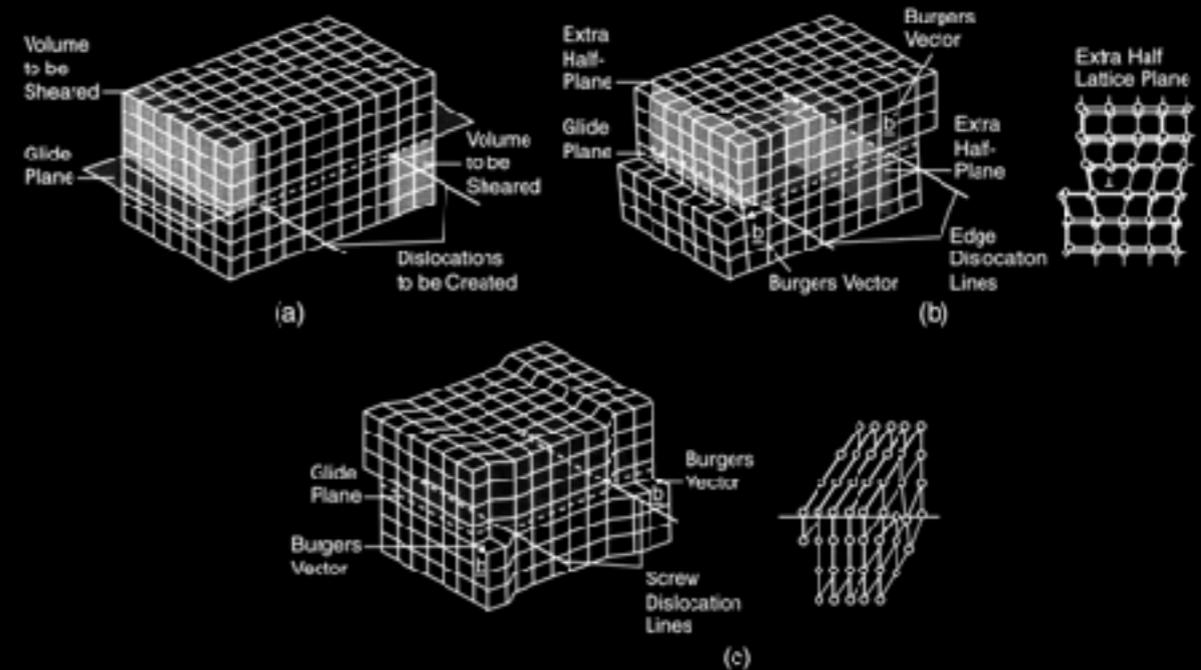
Assumptions About Mantle Rheology

Atomic/Sub-Grain Scale

Diffusion Creep



Dislocation Creep



Schubert, Turcotte, and Olson

Mantle Scale

No

Regional Scales

No

Meso-scale

No

Crust scale

No

Zone scale

No

Rock scale

No

Grain scale

What is a “Fluid”

Basic “Fluid” Conception

Rocky Mantle

✓ Deforms under deviatoric stress $\xleftrightarrow{\text{Yes}}$ ✓ Deforms under deviatoric stress

✓ Strain-rate increases with stress $\xleftrightarrow{\text{Yes}}$ ✓ Strain-rate increases with stress

☐ Diffuse deformation pattern $\xleftrightarrow{\text{No}}$ ☐ Shear localization

☐ No “memory” $\xleftrightarrow{\text{No}}$ ☐ Strong hysteresis/memory

These areas of disagreement between “fluid” conception and actual rocks is fundamentally important to central questions of mantle geodynamics: **plate tectonics**, and **preservation/mixing of isotopic heterogeneity** over the history of the Earth.

Reverse-Engineering the Fluid Assumption

- Yield-stress rheology (Tackley & others): Still a fluid, but gives plate-like behavior. No memory effect, unrealistic rheology.
- Grain-size reduction (Berco-Ricard & others): Strain-weakening mechanism with hysteresis via Zener pinning.
- Weak-phase inter-connection (Karato & others): Strain-weakening observed in lab experiments in mixture of bridgmanite and periclase

■ ■ ■

We still have a lot of work ahead

2. Planet Behaviorism

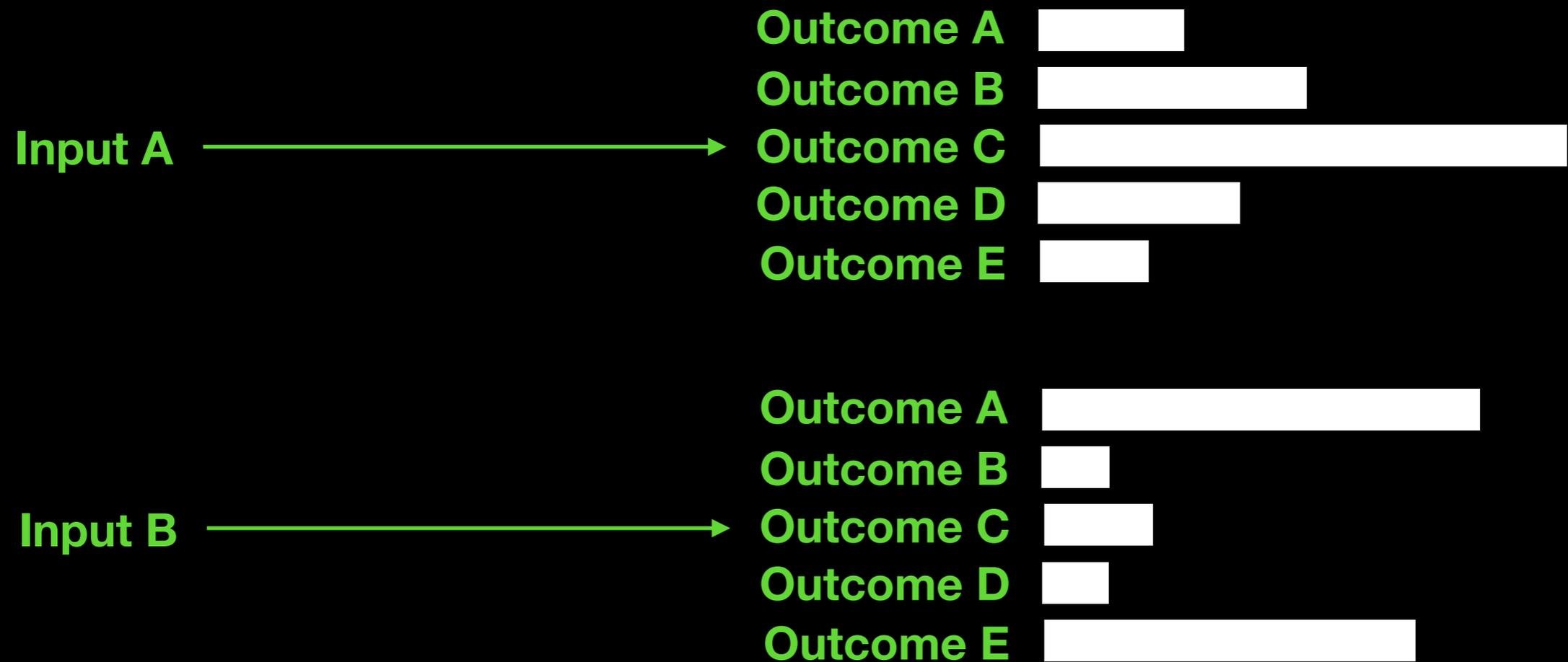
Is Planet Evolution Deterministic or Stochastic?

Outcomes = *Function(Inputs)*

- **Deterministic**: The same inputs always yield the exact same outcomes.
- **Stochastic**: A given input yields a probability distribution of all possible outcomes.

Is Planet Evolution

Deterministic or Stochastic?



Deterministic Epidemiological Models

SEIR Model (Deterministic):

$$\frac{dS}{dt} = -\beta \frac{SI}{N}$$

$$\frac{dE}{dt} = \beta \frac{SI}{N} - \sigma E$$

$$\frac{dI}{dt} = \sigma E - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$

S=Susceptible

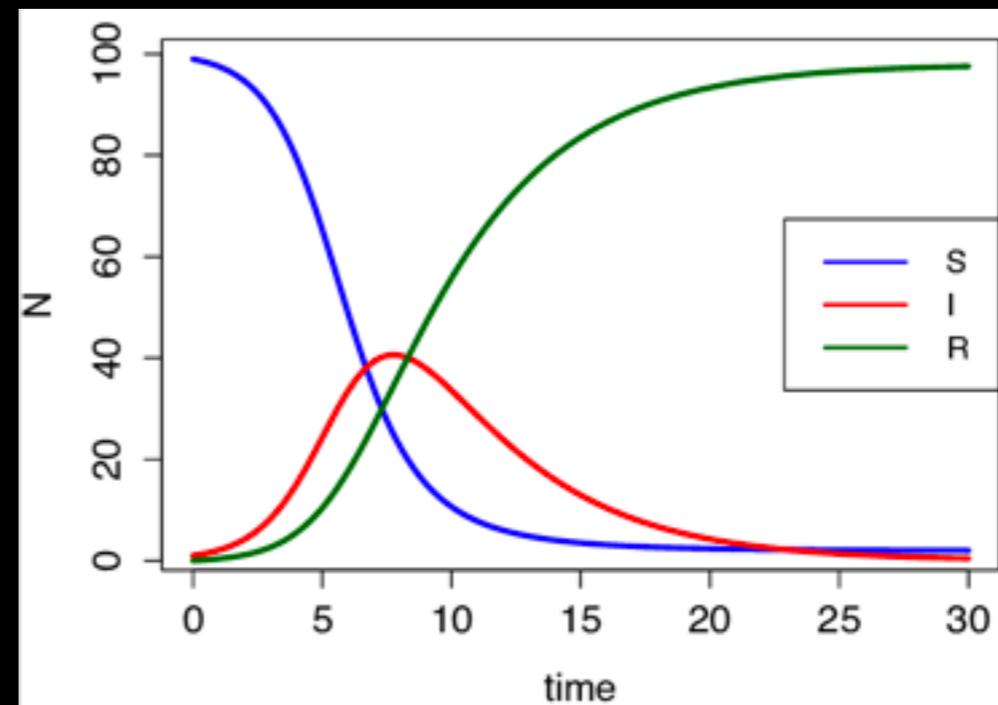
E=Exposed

I=Infected

R=Recovered

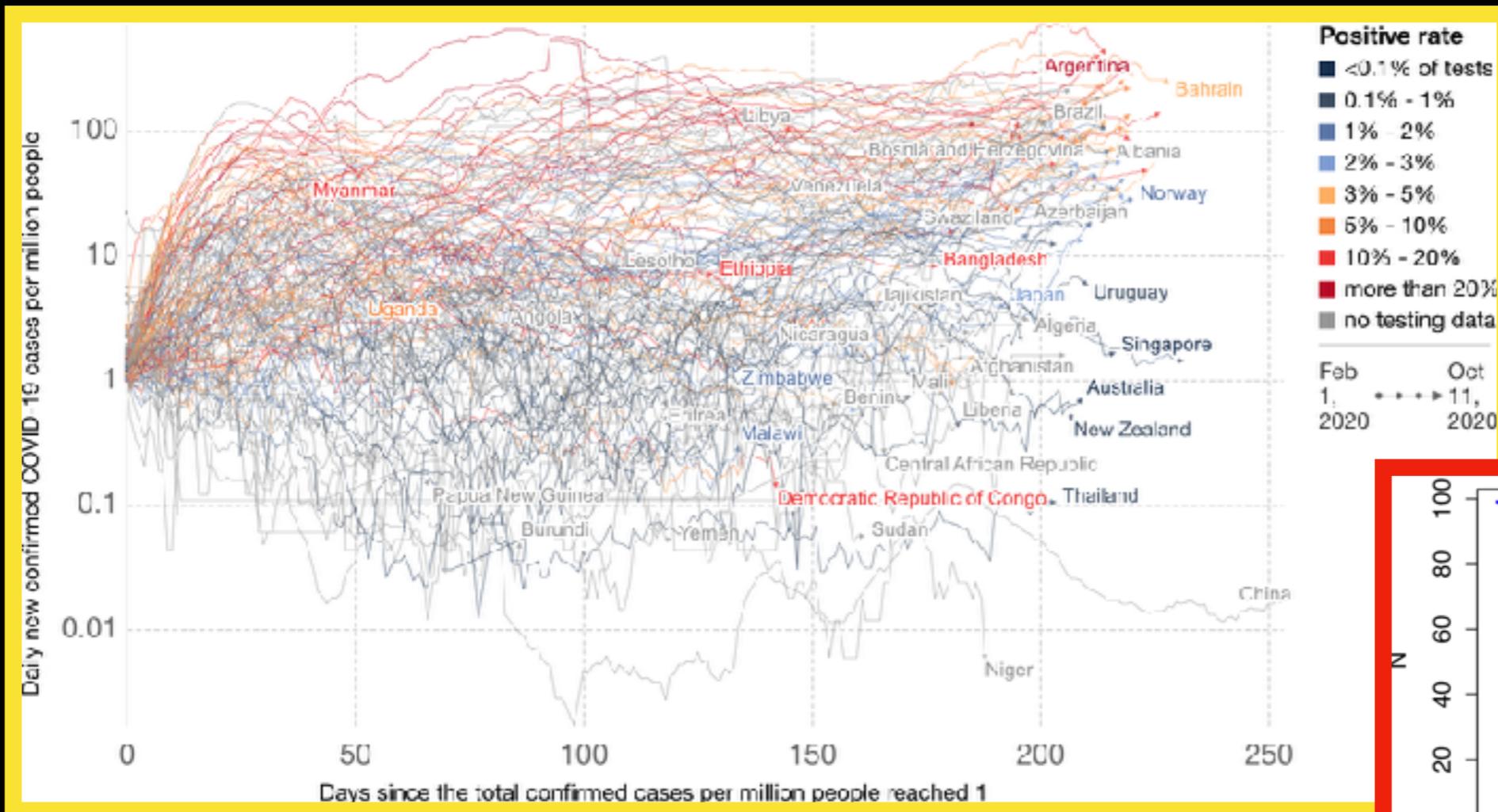
$$R_t = \beta/\gamma$$

Typical Solution Behavior:

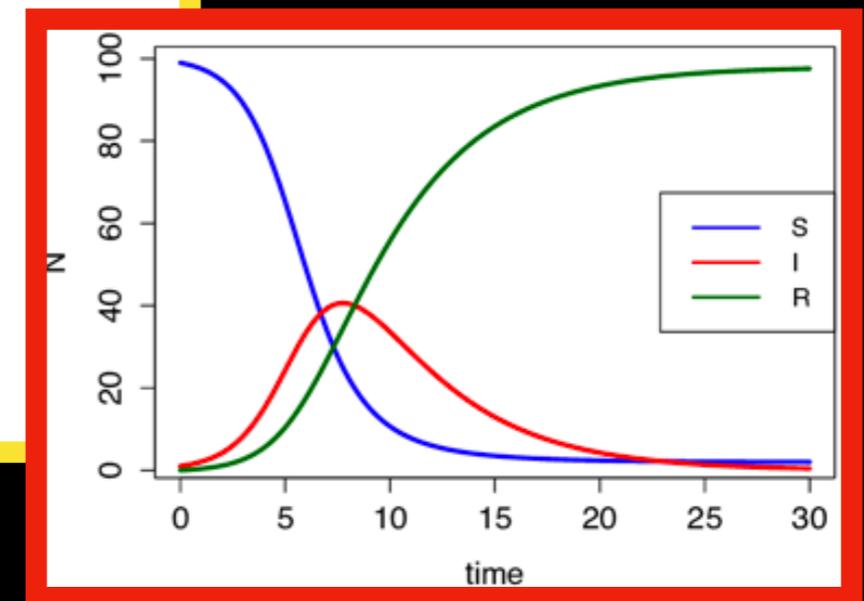


Actual COVID-19 Outbreak

Global Compilation of Cases



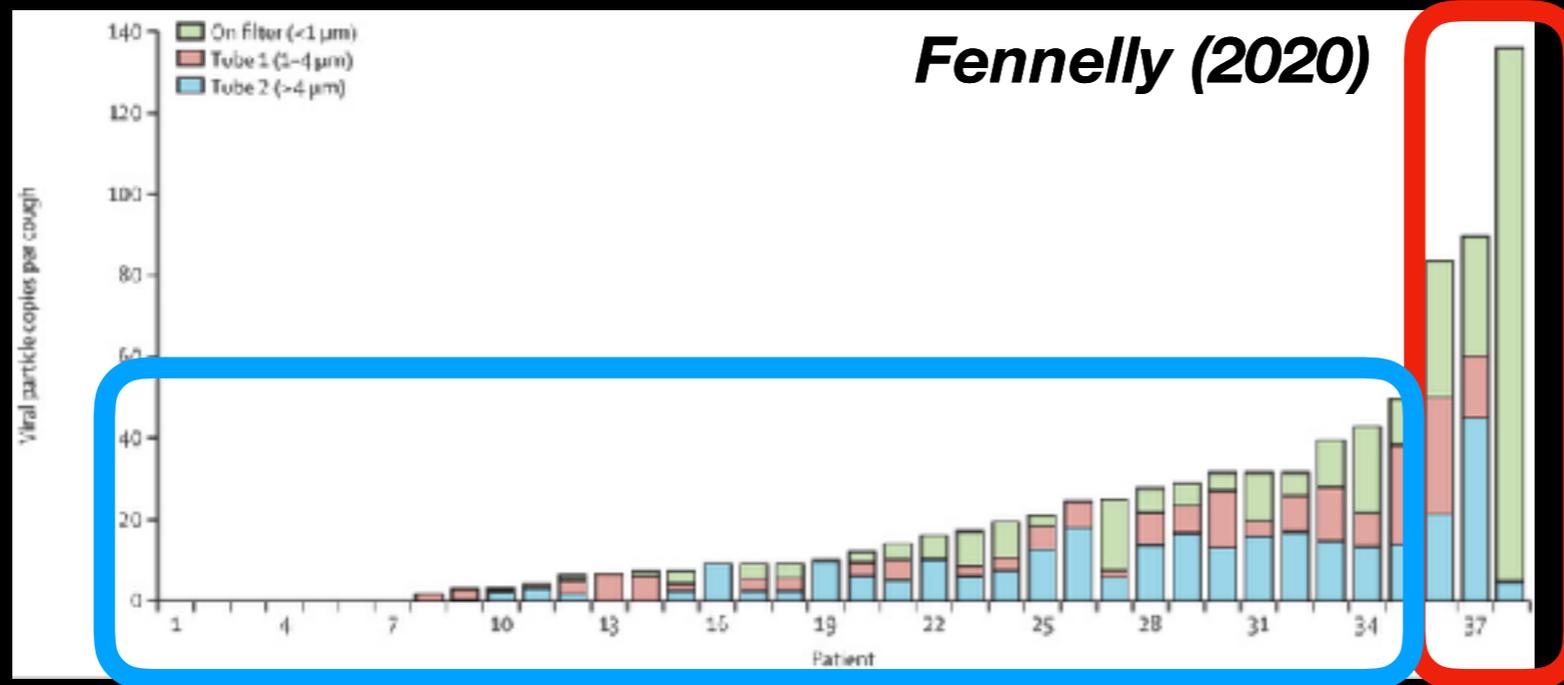
SEIR Model:



<https://ourworldindata.org/coronavirus-data>

- The COVID-19 pandemic has seen widely varying outcomes in different regions, even among some in similar geographical contexts and employing similar policies.

Heterogeneous Agents



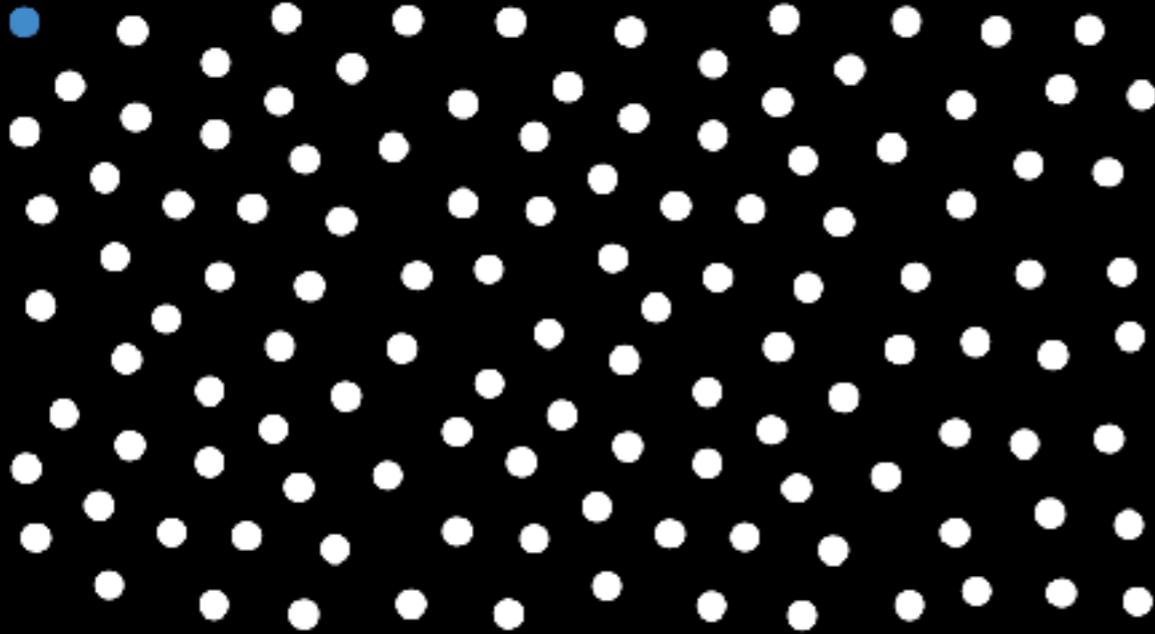
Super-Spreaders

Normal-Spreaders

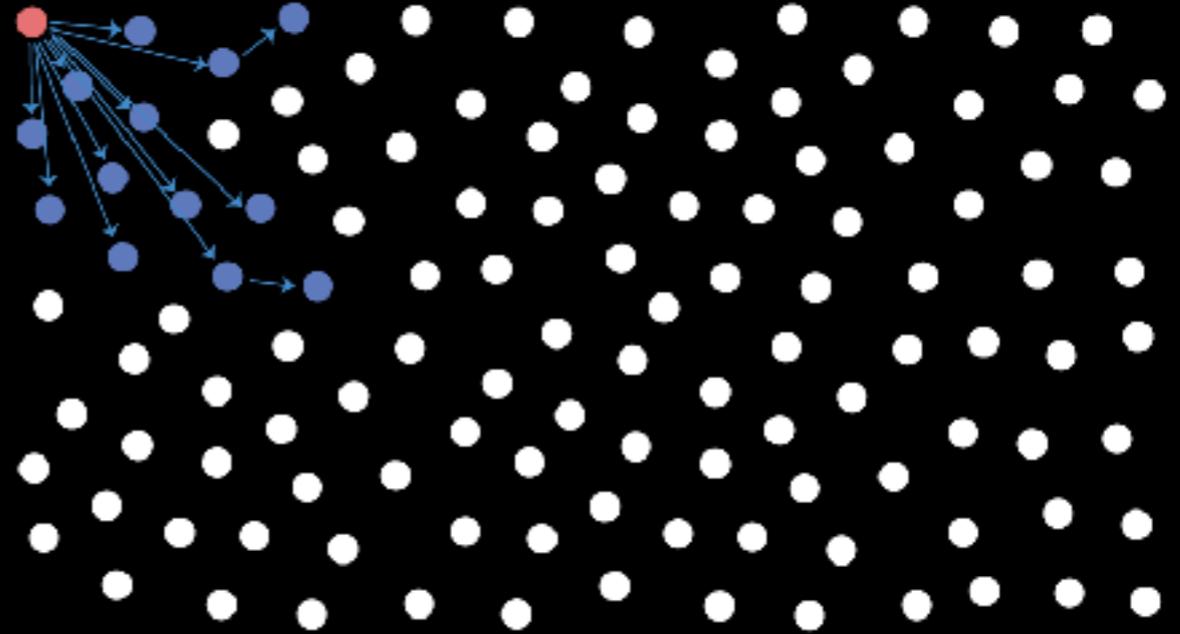
- Laboratory tests show that some patients produce significantly larger amounts of viral particles.
- These “super-spreaders” introduce heterogeneity into the population, altering the dynamics.
- Many of the largest and most rapid outbreaks have been linked to clusters, and super-spreader events.

Different Behaviors

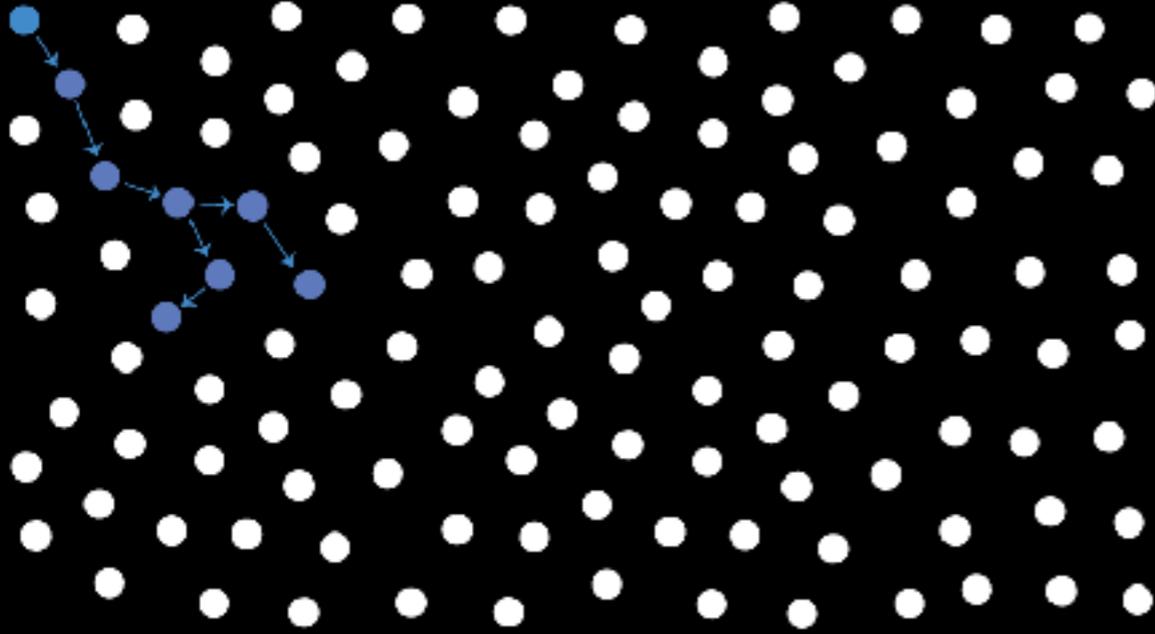
Case 1: Normal with no spread ($R \sim 0$)



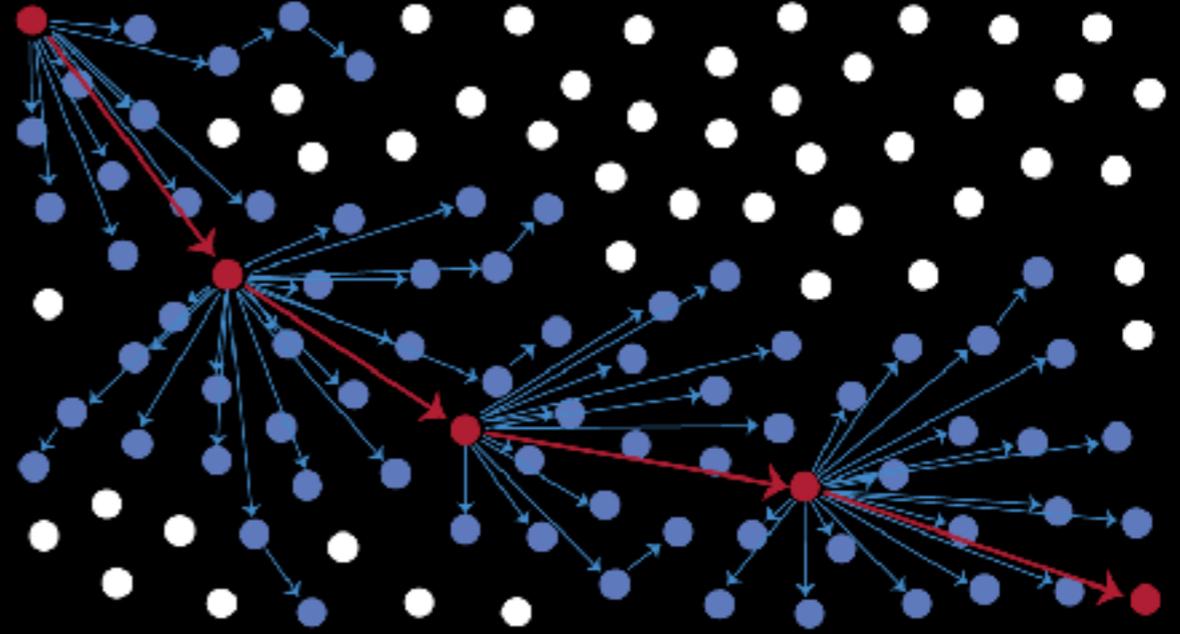
Case 3: Super infects normals ($R \sim 4$)



Case 2: Normals infect normals ($R \sim 1.2$)

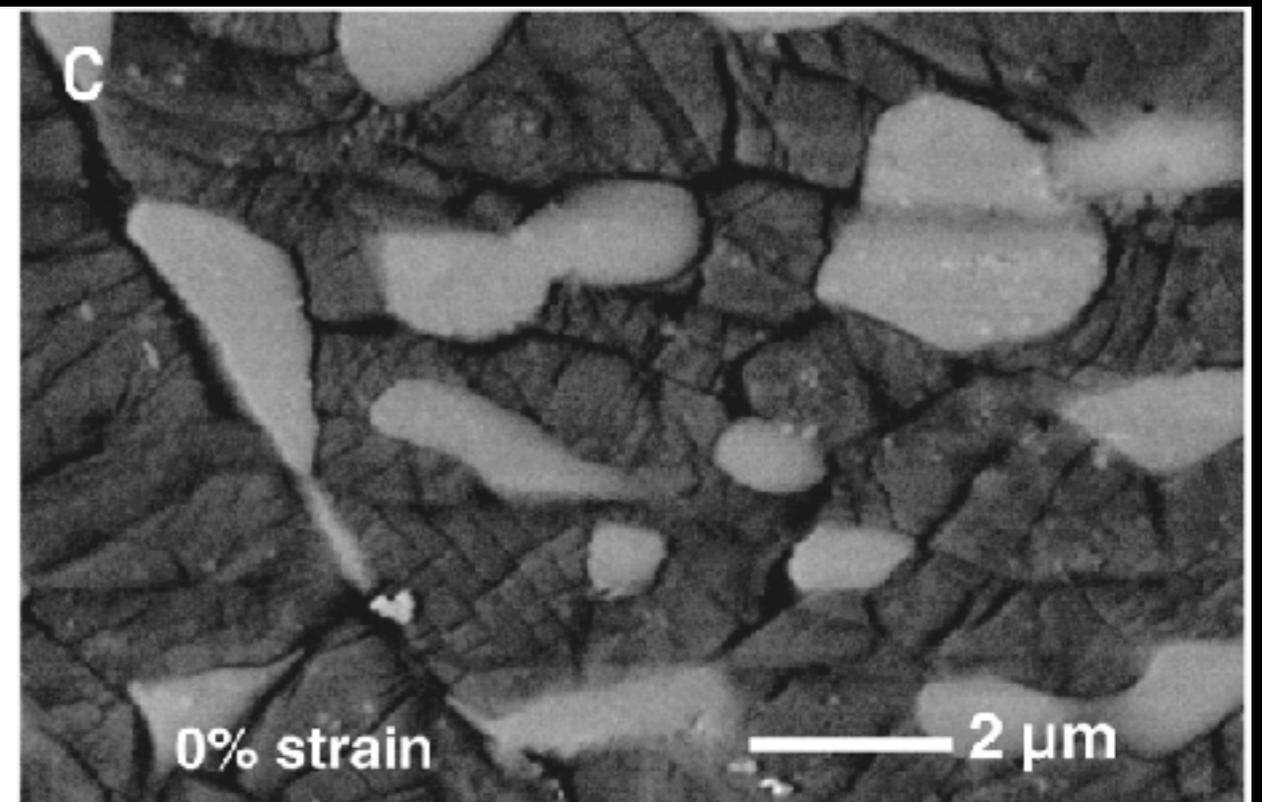
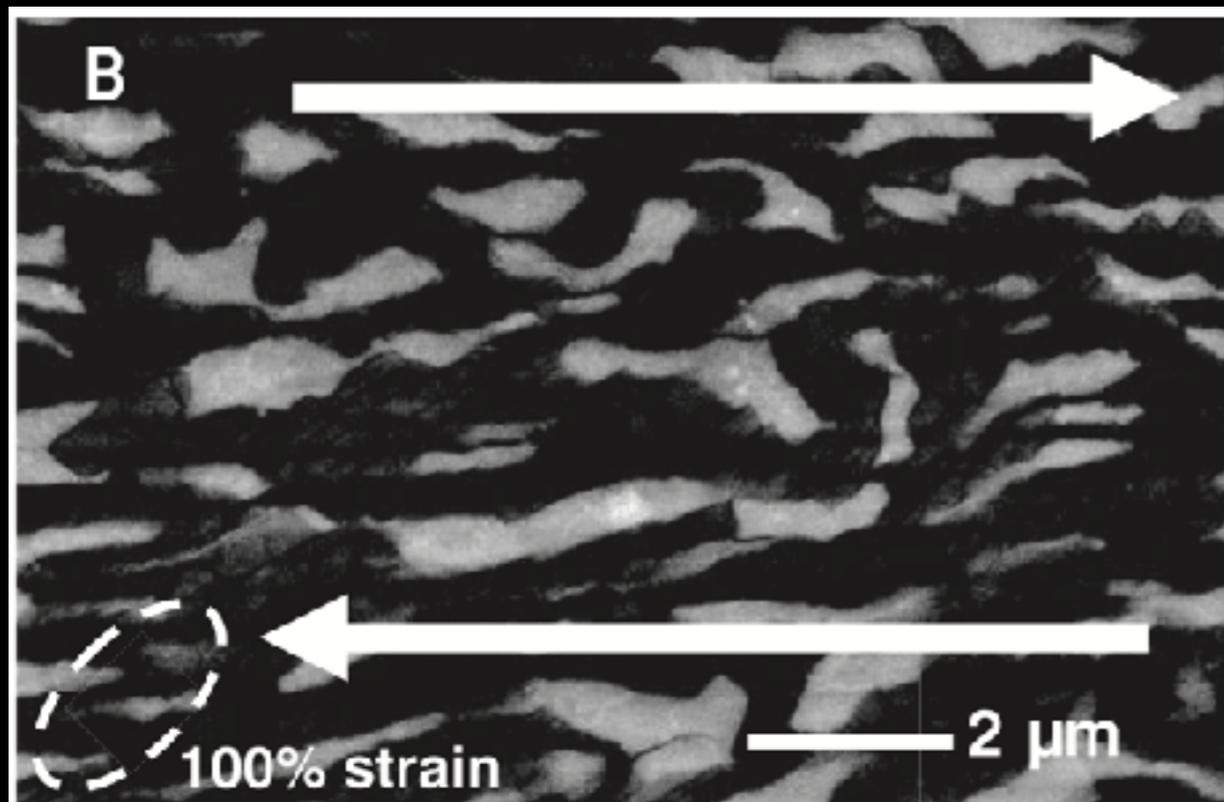
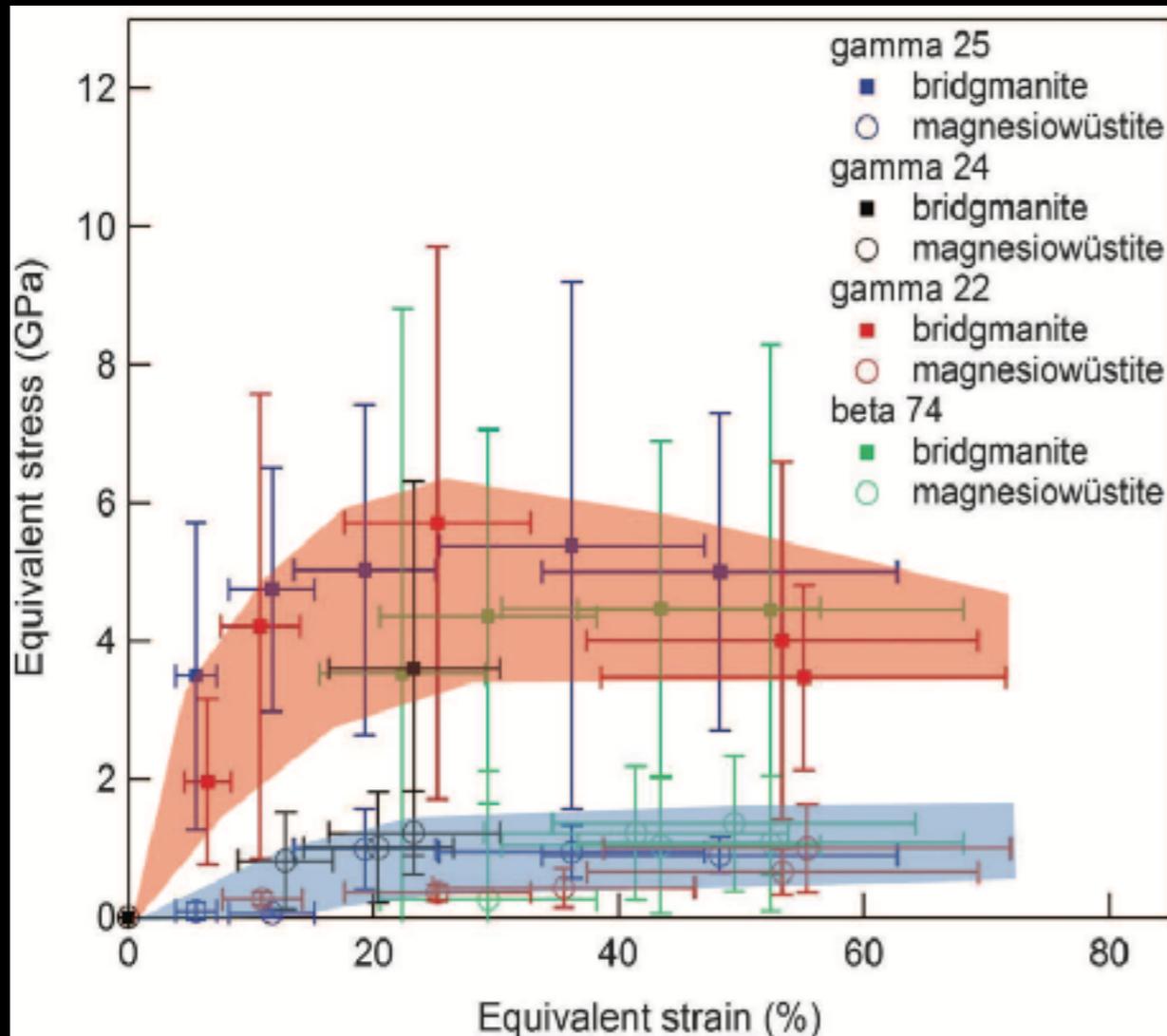


Case 4: Supers beget supers ($R \sim 10$)



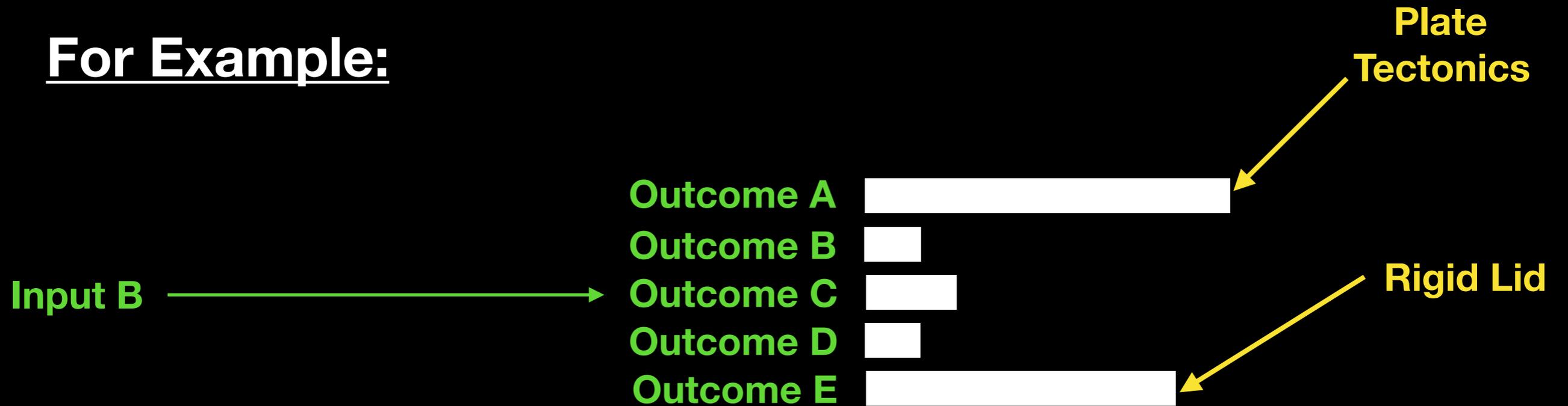
Mantle Super-Spreaders?

- Girard et al. (2016)* deform samples and report “onset of weakening behavior” and inter-connection of weak periclase grains.



A Stochastic Planet?

For Example:



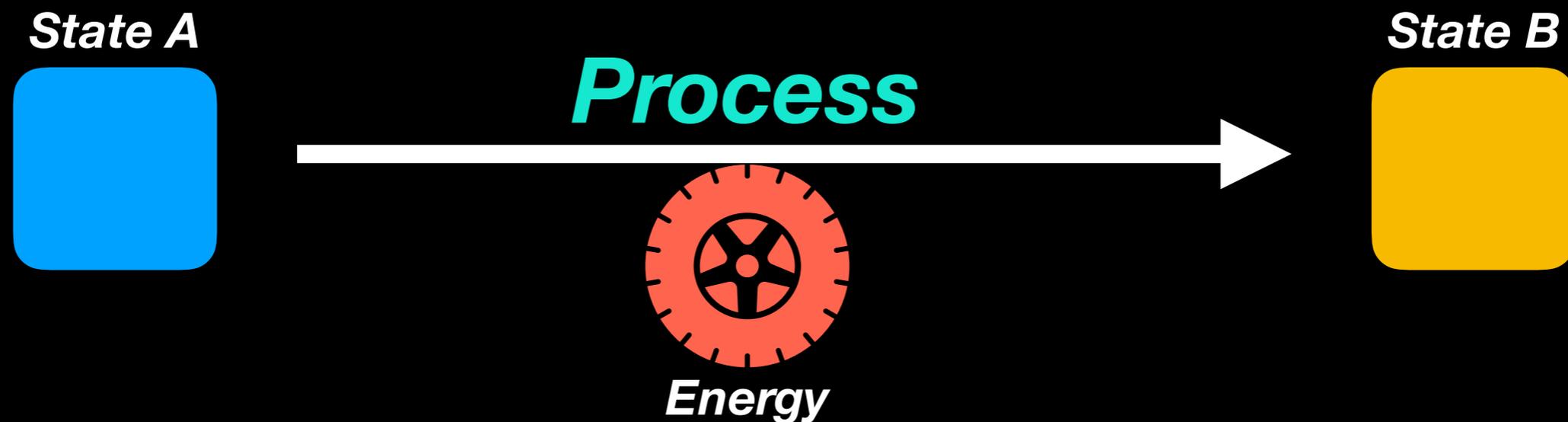
Open Questions:

- How to construct stochastic geodynamical models?
- How to convey/account for uncertainties?
- New opportunities for modeling strategies?

3. Planetary Metabolism

Process?

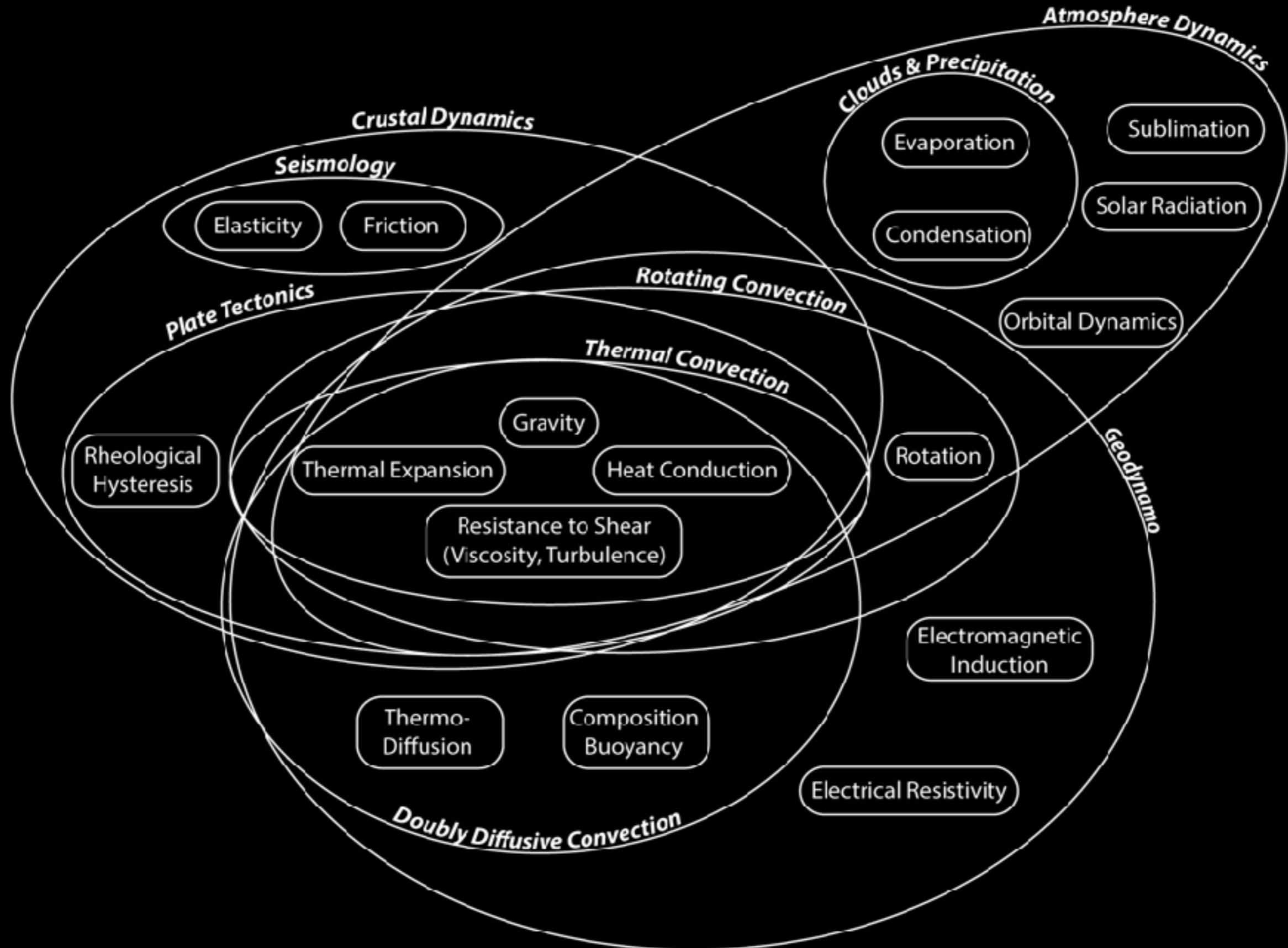
Process: That which utilizes available energy to transform the state of matter



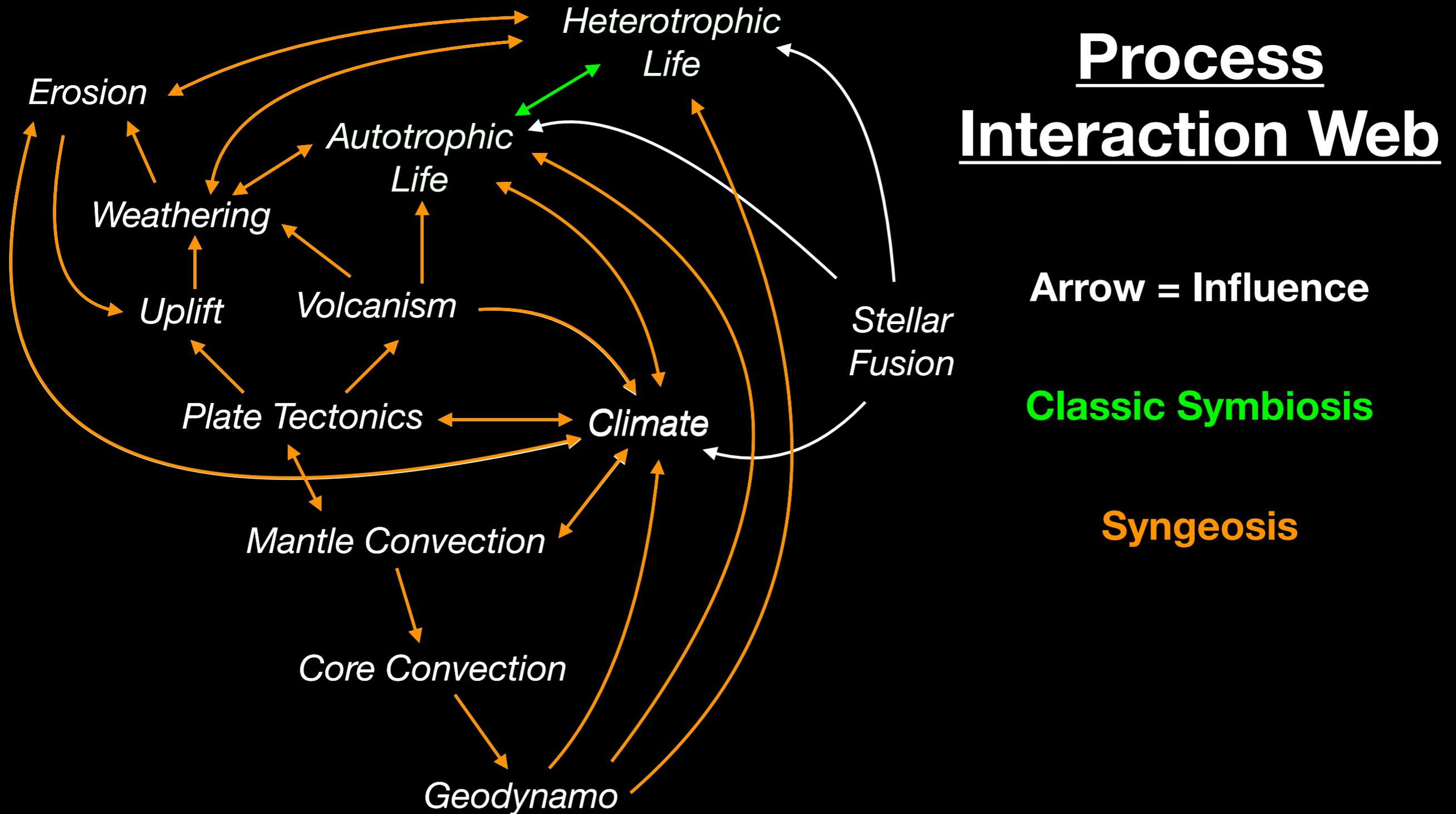
Geology is fundamentally about the study of *process*, what happened in the past to transform matter into the rock record that remains today?

Geodynamics is fundamentally about the modeling of geological *processes*, and rendering quantitative predictions about their outcomes and interactions.

Process Collaboration

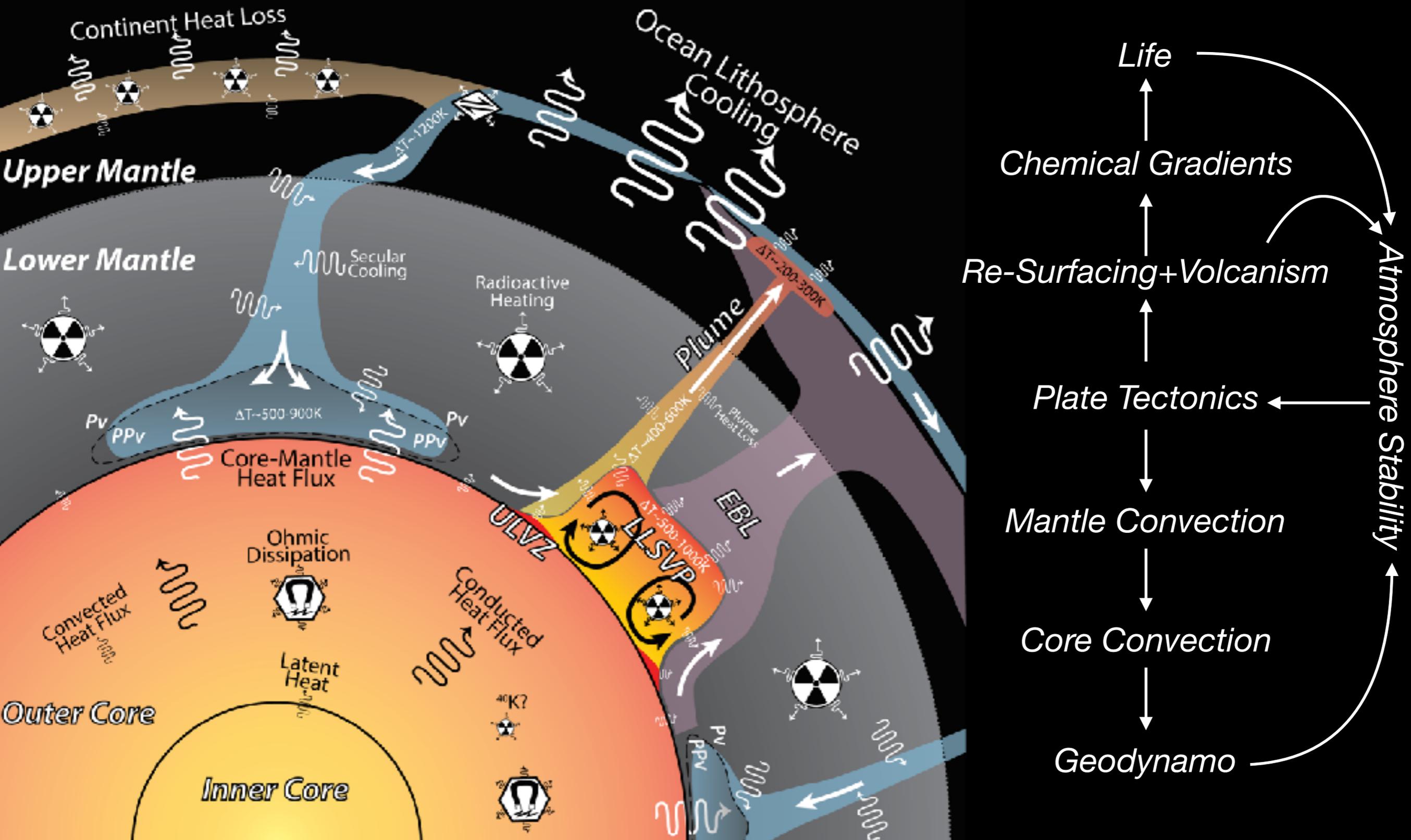


Planetary Metabolism



The Living Planet

The Science of Processes Exchanging Matter and Energy as Open Systems



More Follow-On Topics

- Diversity, ecology, evolution of planets at stellar and galactic scales.
- Planetary biography: From birth to death.
- Deep time climate evolution, coupling to biological, orbital, stellar, and galactic dynamics.
- Drivers of chemical disequilibrium between Earth's dynamical systems, coupling to habitability, life.
- Sustainability, syncing human behavior with the planet's carrying capacity to avoid more extinctions (including our own).



“Geodynamics”

What are we doing?

Where are we going?

What is our purpose?

How are we relevant?

Geodynamics in the Deep Earth is not a Predictive Science

- All of our models in the core and mantle rely on numerous assumptions, many of which are not well-substantiated.
- Mantle convection and dynamo models are underpinned by extremely simplistic multi-scale conceptions.
- When our simplistic models fail to explain phenomena, we often do the easiest fix, avoiding the hard problem.
- The “standard model of geodynamics” awaits...

Critical Self-Assessment is Important for Growth

- History of science (and everything else) reveals human tendency to fall into ruts.
- Turn the same old crank, recycle the same stale concepts, write the same papers nobody reads, sit in comfy office jobs, obtain small grants, follow the path of least resistance, maintain status quo.
- Problem 1: Such an enterprise will lose relevance, respect, jobs, funding, and grind to a halt.
- Problem 2: We don't want to do this!



If we are stuck in a rut, can
CIG be a vehicle to get us out?



CIG IV Role?

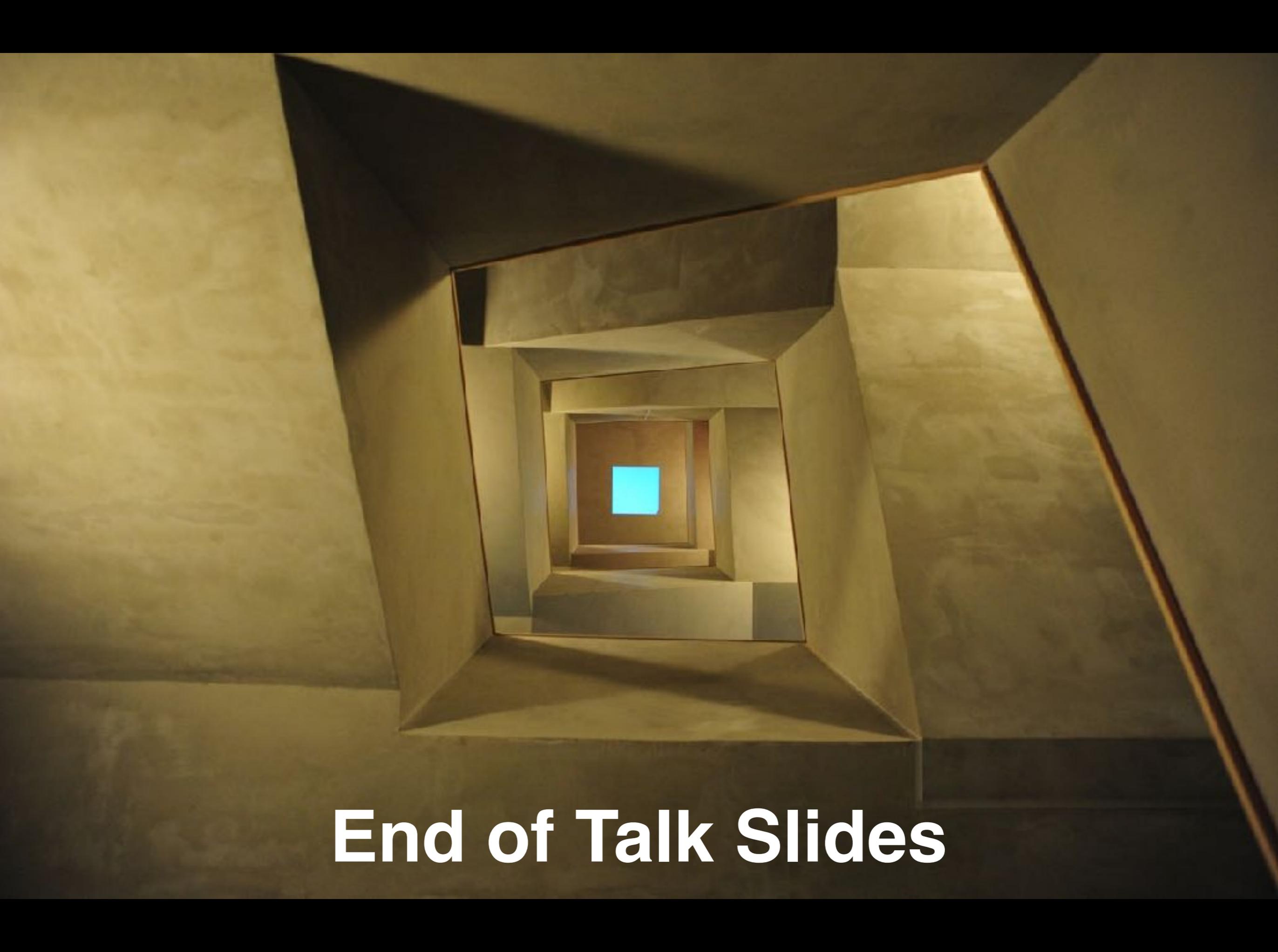
A boilerplate tool developer?

- Top-shelf cutting edge tools to run the same kinds of models as in the past, but better than before...faster, more accurate, higher resolution, etc..
- Some innovations might be enabled if disparate code development efforts can be bridged.
- Disseminate tools to the community, even if predictive capacity is limited.

Enabler of frontier science?

- Tackle frontier science challenges, such as multi-scale physics of planets (complex rock rheology, MHD turbulence), deep-time whole-planet systems evolution, etc.
- Become a catalyst for science that can only be advanced as a community.
- May require re-organization of the community, moving closer to team-based (particle physics-like) model.

Note: I'll be available for further dialogue in the discussion forum for this workshop.



End of Talk Slides