#EGU22-7698 | session GD2.5 | Tue 24 May

EGU General Assembly 2022

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# Narrow, fast, and “**cold**” **mantle plumes** on Earth explained by **strain-weakening** rheology in the lower mantle

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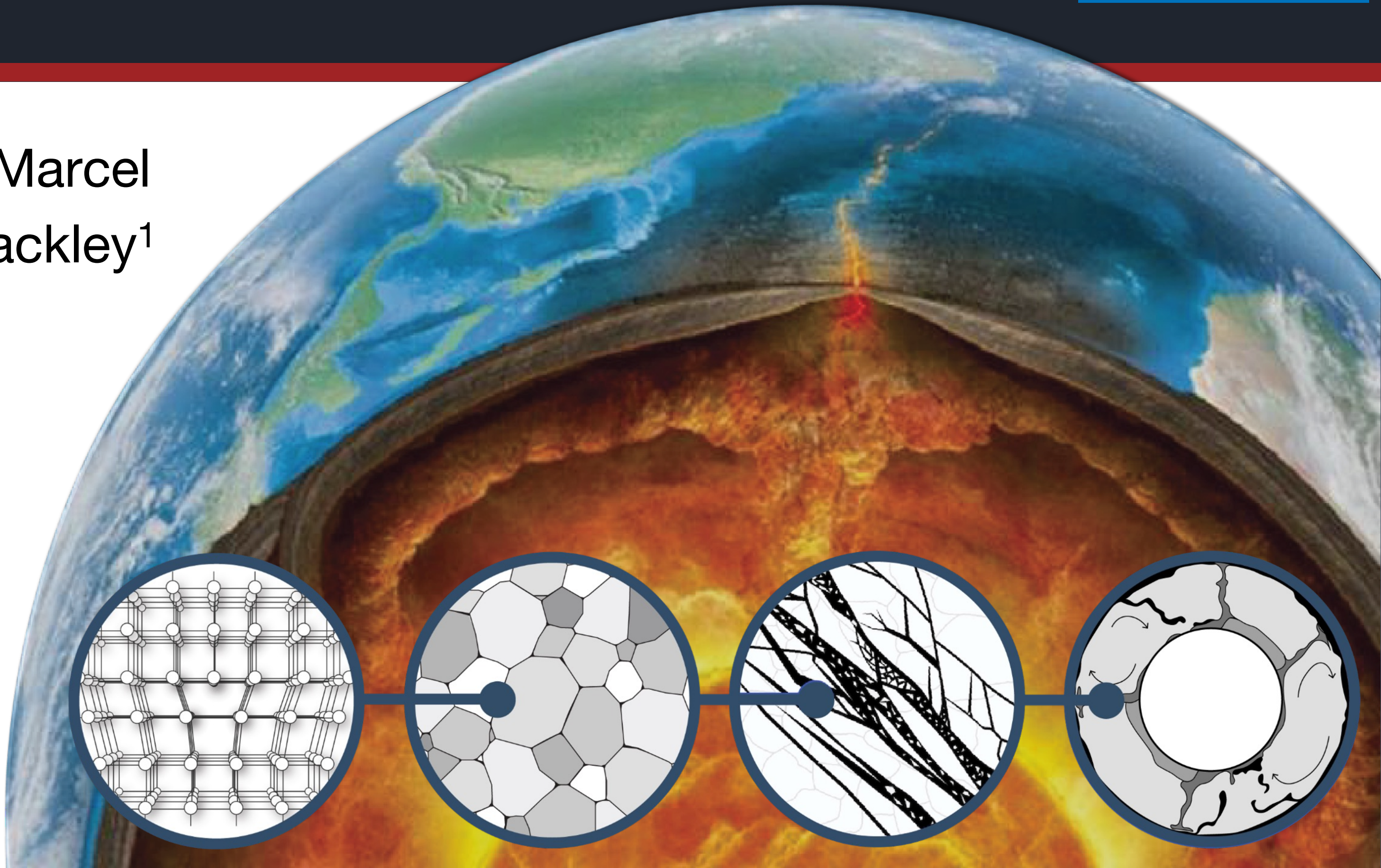

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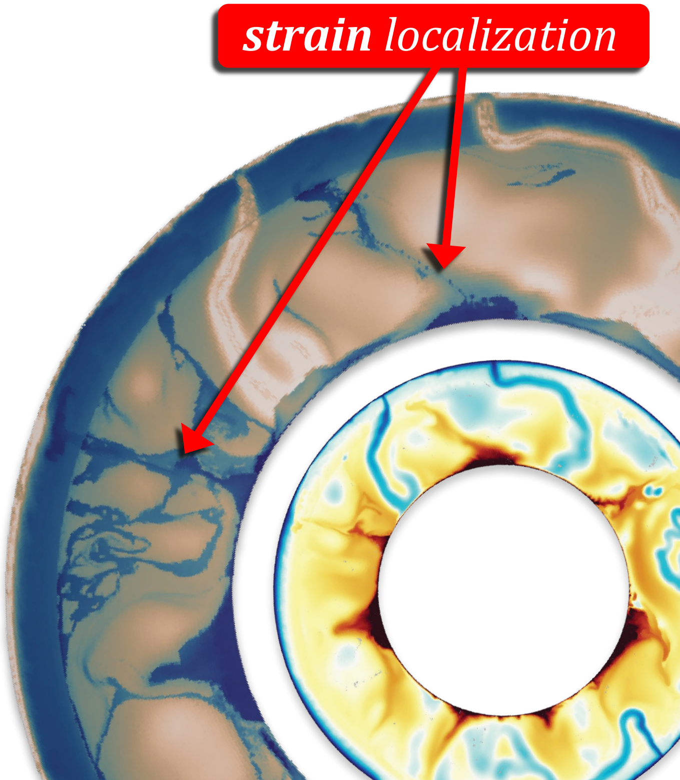
# Narrow, fast, and “**cold**” **mantle plumes** on Earth explained by **strain-weakening** rheology in the lower mantle

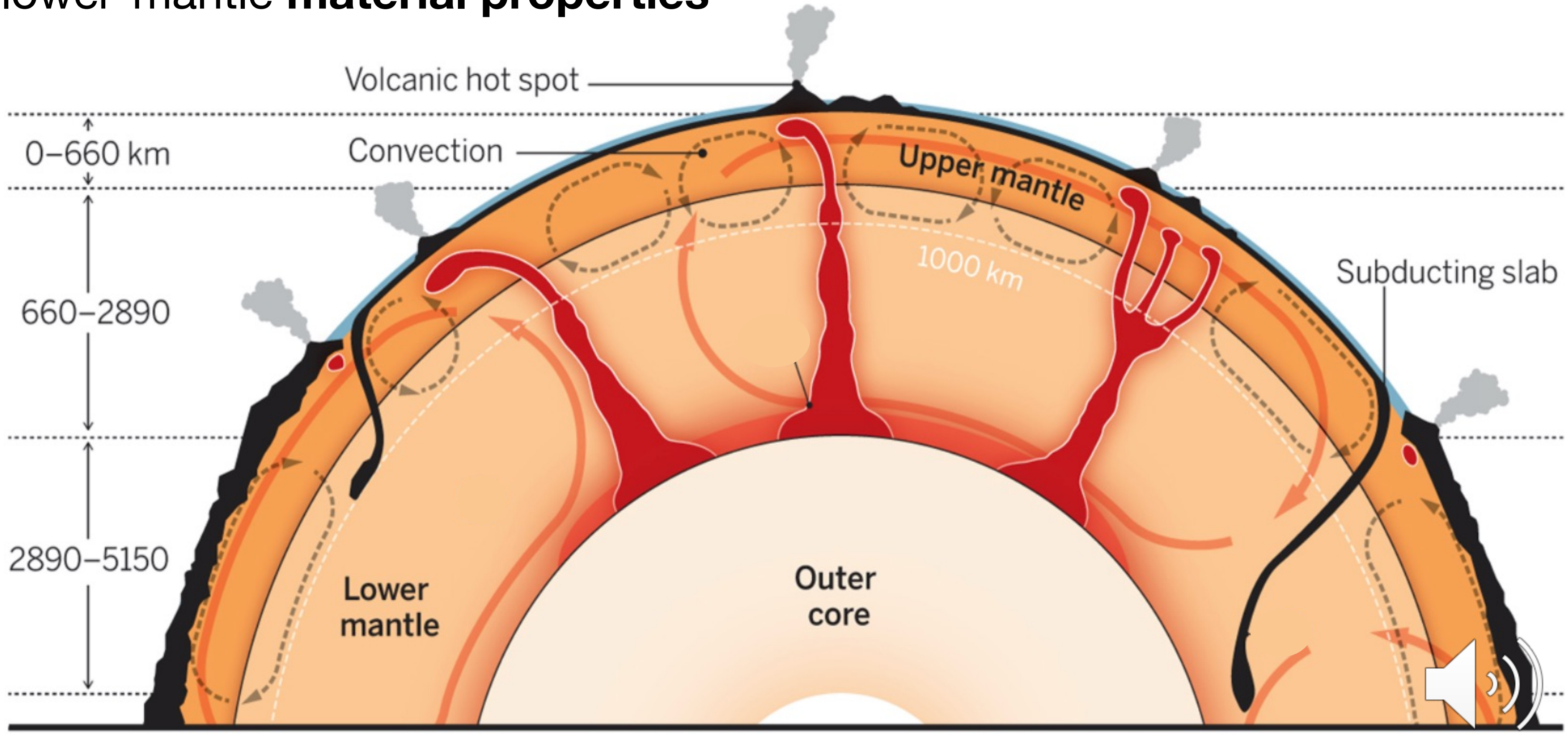
*Article under review for G-cubed:* https://doi.org/10.1002/essoar.10509746.1

- New parametrisation of lower-mantle **strain-weakening rheology** in mantle convection code
- Causes **weakening of plume conduits**, forming **narrow lubrication channels** through which hot material rapidly rises.
- Could help explain the **discrepancy** between expected and observed **thermal anomalies** of deep-seated mantle plumes on Earth?



# Shaping a planet by mantle flow

- Mantle: largest **geochemical reservoir** (60 vol%)
- Control of **mantle convection** and **mantle plumes**
- Dependent on lower-mantle **material properties (rheology)**

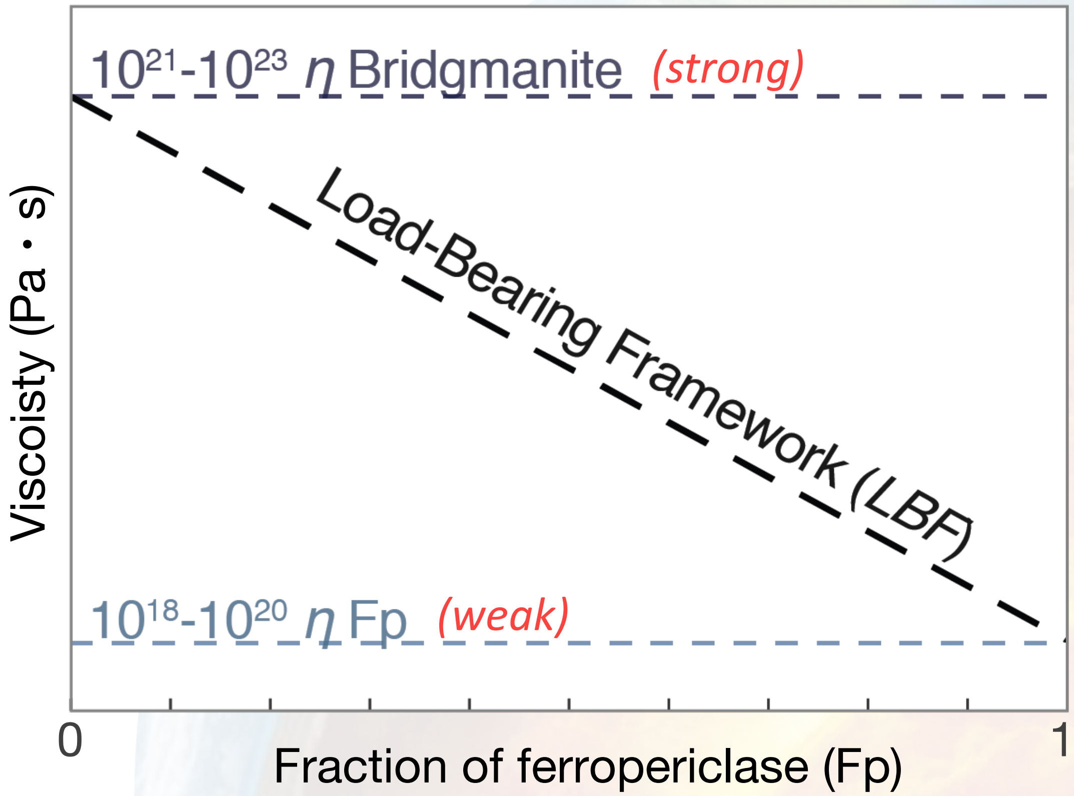


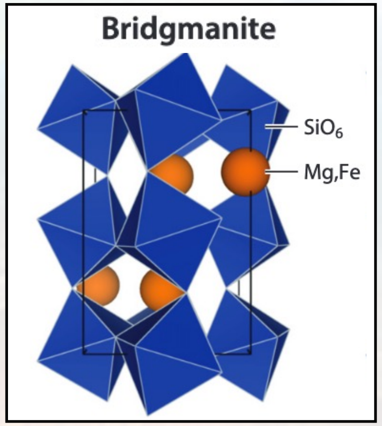

*Hand, E. (2015), Science*

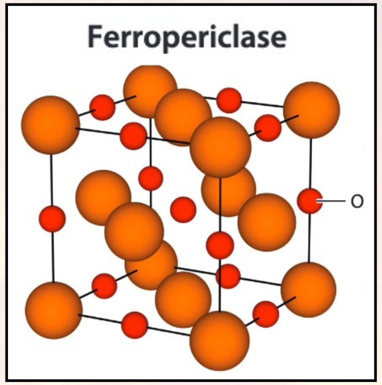
# Earth's lower mantle - rheology

- >75% **Bridgmanite** $(Mg,Fe)SiO_3$
- 0-25% **Ferropericlase** $(Mg,Fe)O$
- few % other phases

*Modified from Ballmer et al. (2017)*



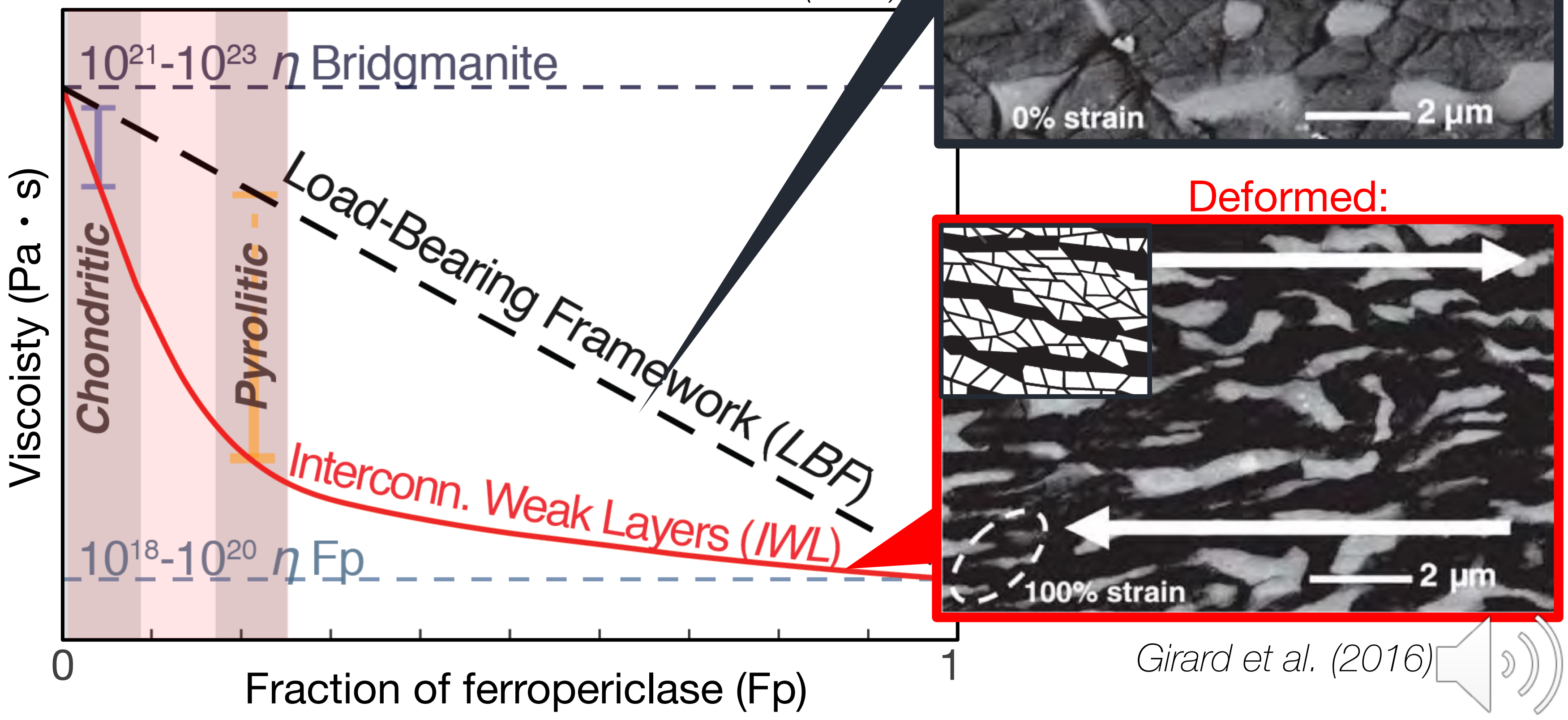



# Earth's lower mantle - rheology

- Lower mantle rheology is **deformation history** **(strain-)** dependent!
- **Shear localization** in the lower mantle?

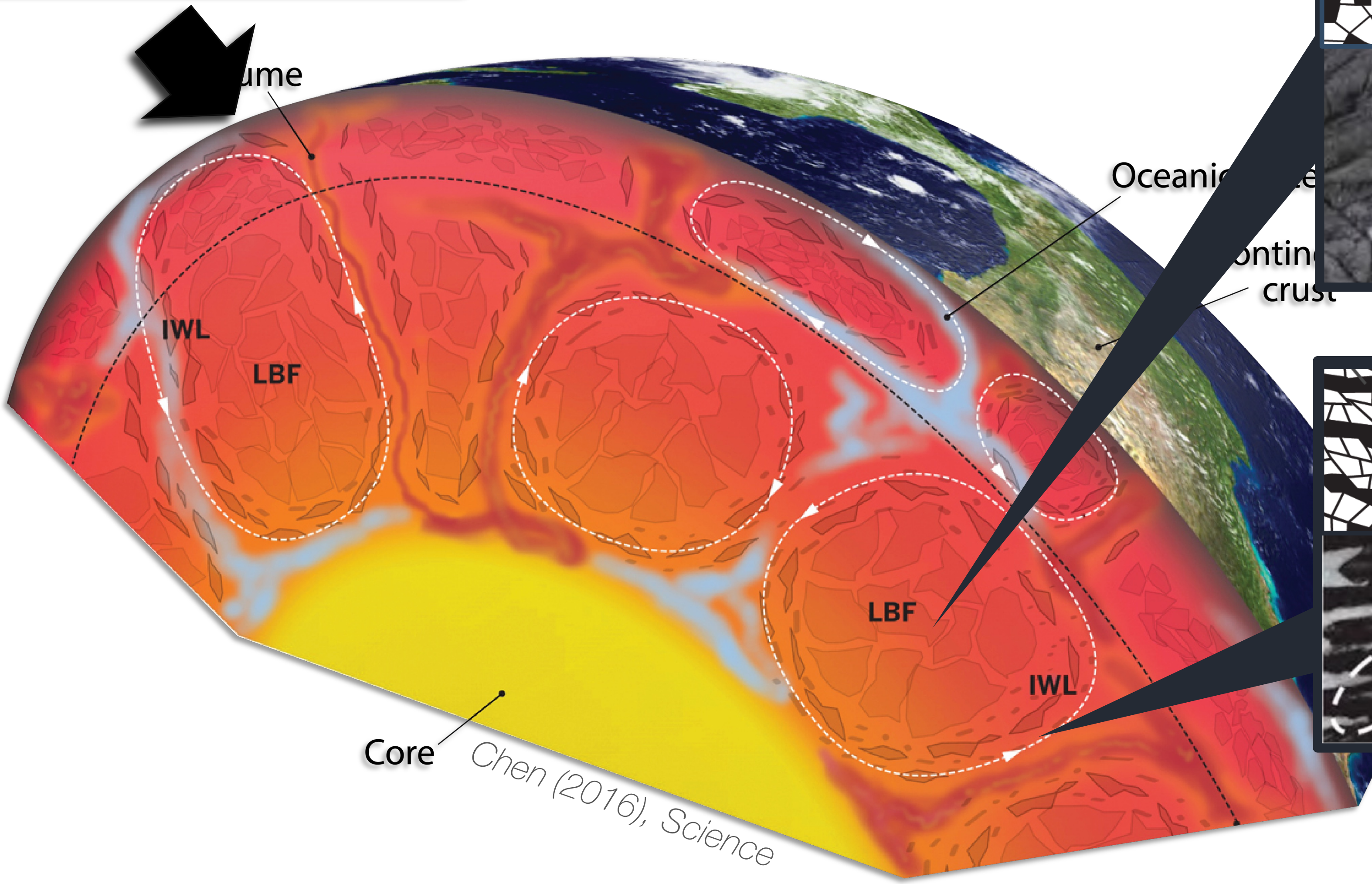
*Modified from Ballmer et al. (2017)*

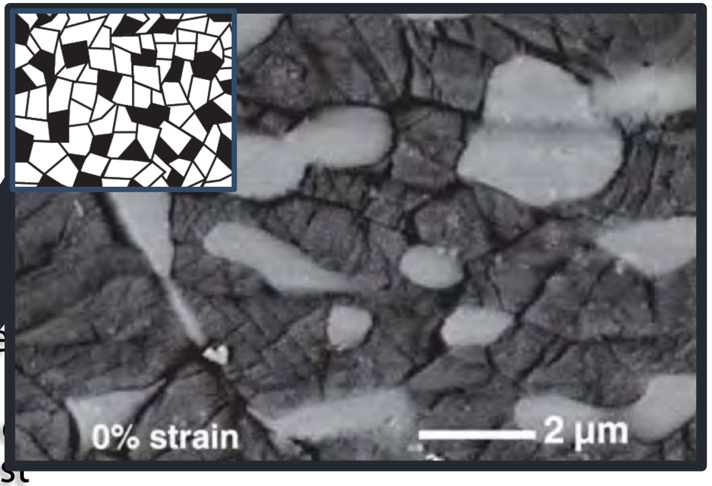


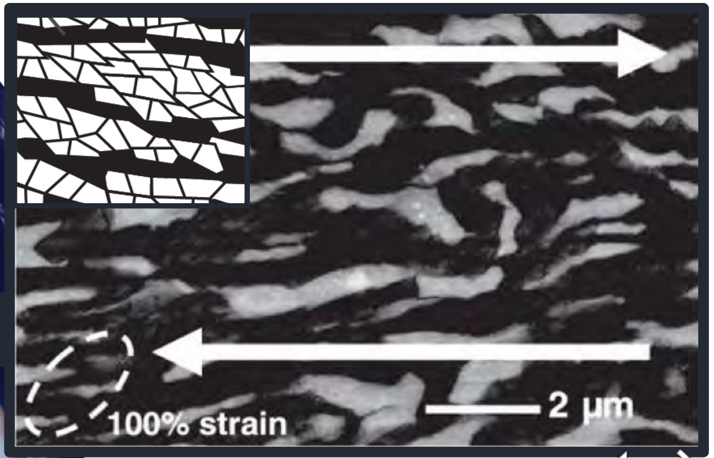

*Girard et al. (2016)*

# Earth's lower mantle – strain-dependent rheology

$$\eta(T, P, c, \varepsilon, \ldots)$$



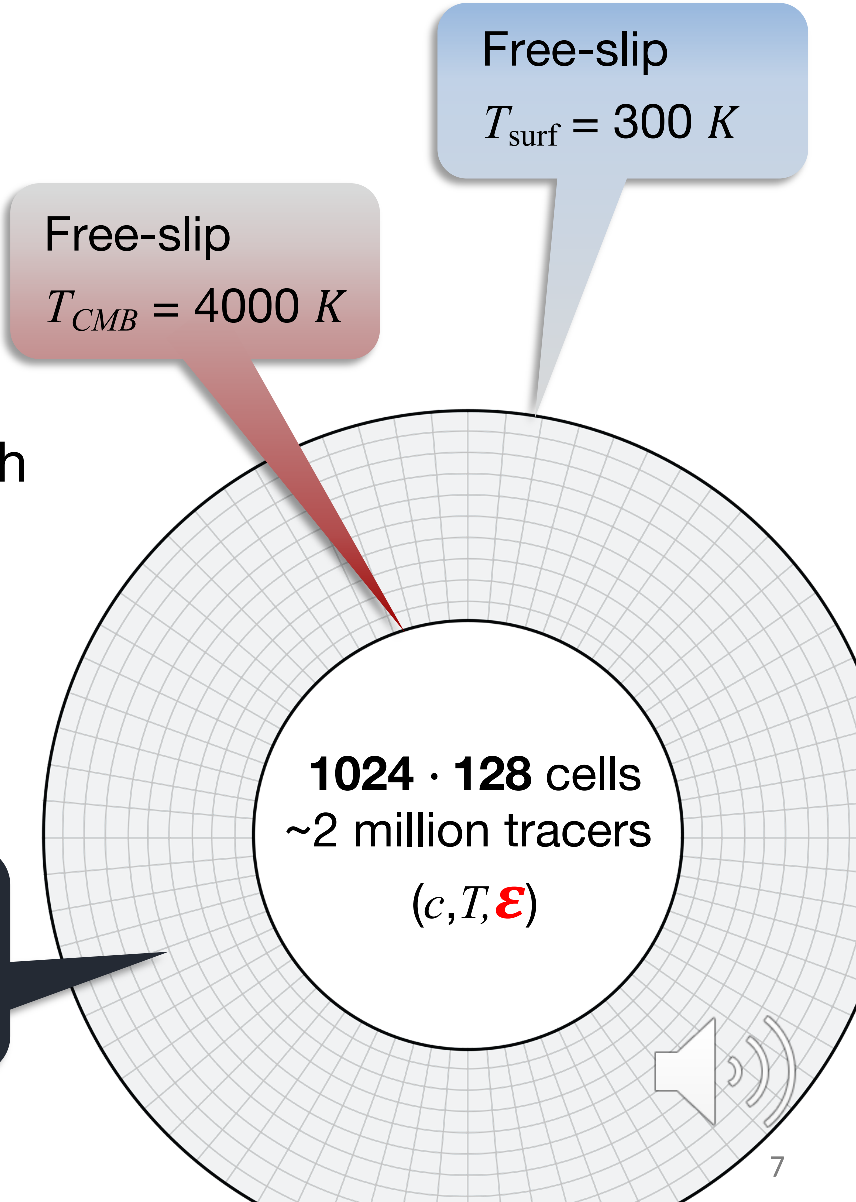

Girard et al. (201

# Methods: geodynamic modelling (StagYY, *Hernlund and Tackley, 2008*)

- Mantle convection in **2D spherical annulus geometry**
- Pyrolitic mantle with **phase changes** and **melting**
  (80% hz + 20% bs)

- **Visco-plastic rheology:** Arrhenius-type viscosity law with lithospheric yielding → '**Plate tectonic**' behavior
- Newly-implemented **strain-weakening rheology**

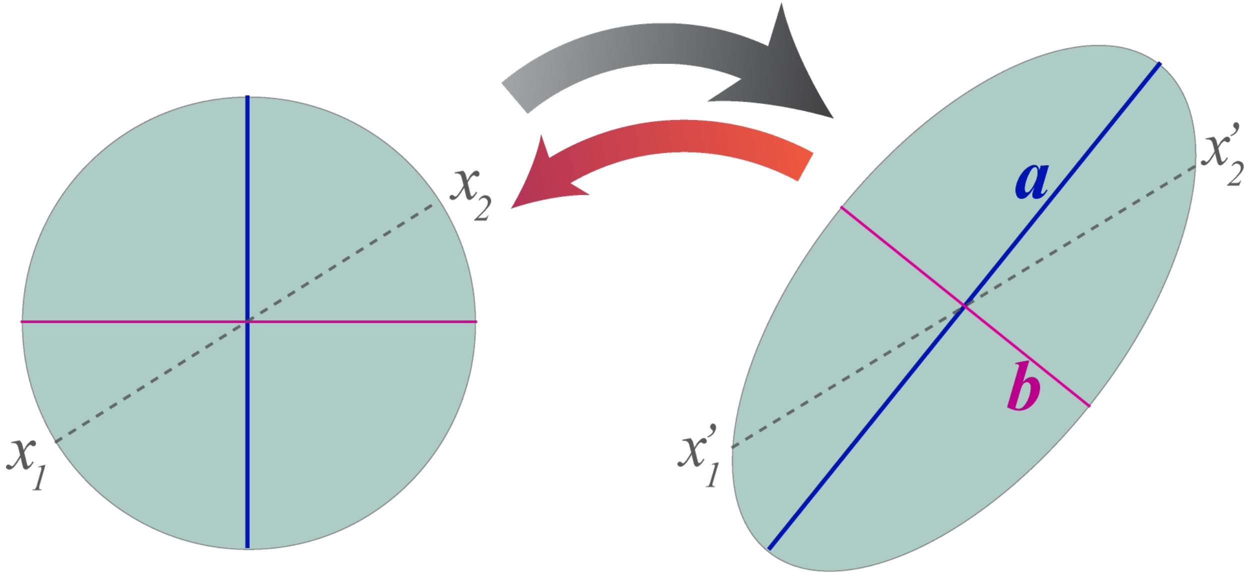
$$\eta(T,P,c,\varepsilon) = \eta_0\, \lambda_C\, f_W(\varepsilon)\, exp\left(\frac{E_a+PV_a}{RT} - \frac{E_a}{RT}\right)$$



# Methods: tracking strain

- The **deformation tensor** $M$ is tracked on each tracer (**finite deformation**, McKenzie, 1987)
- $MM^T$ → **strain ellipse**
- Strain is **reset** ($M = I$) at 660 boundary (Solomatov & Reese, 2008)

$$dM/dt = -H(M - I)$$

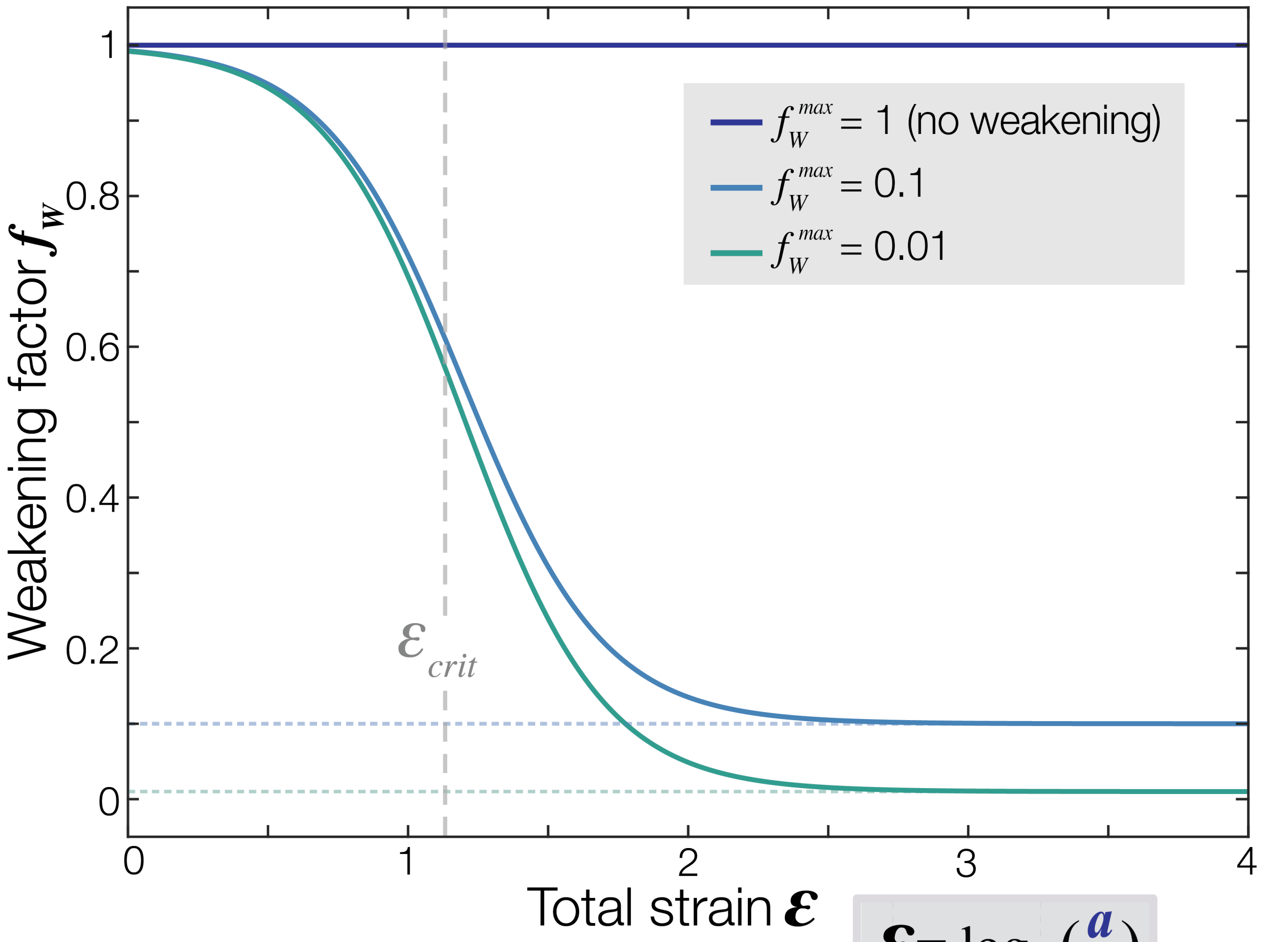



- **Strain definition:** $\varepsilon = \log_{10}\left(\frac{a}{b}\right)$
- **Healing term $H(P,T)$ relaxes** $M$ and lowers strain (annealing, grain growth, ..)

# Methods: strain-dependent weakening

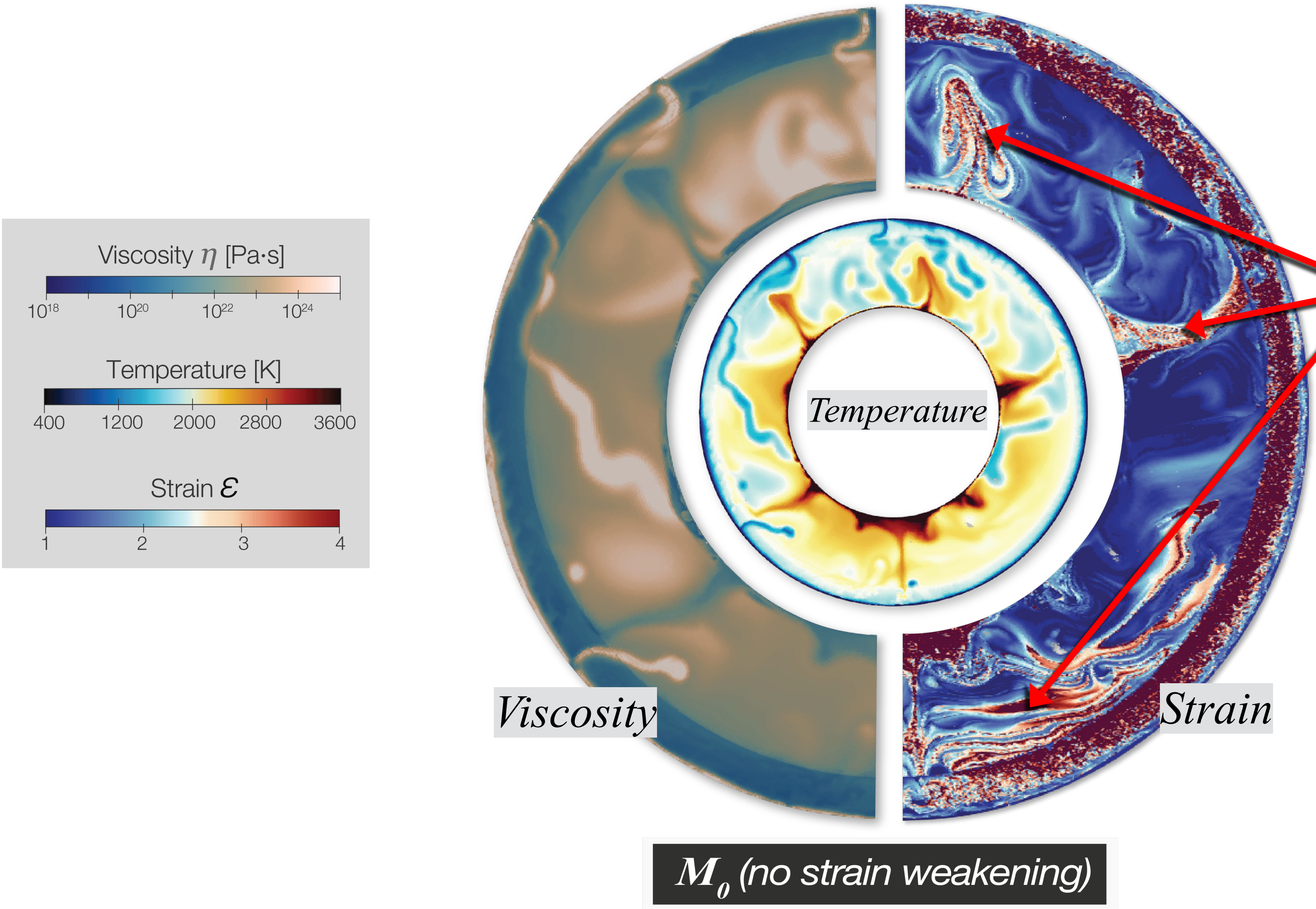
- Lower-mantle material may **weaken** according to:

$$\eta(T, P, c, \varepsilon) = \eta_0 \lambda_C f_W(\varepsilon) exp(\ldots)$$




$$\varepsilon = \log_{10}\left(\frac{a}{b}\right)$$

# Results: reference model




***strain localization:***

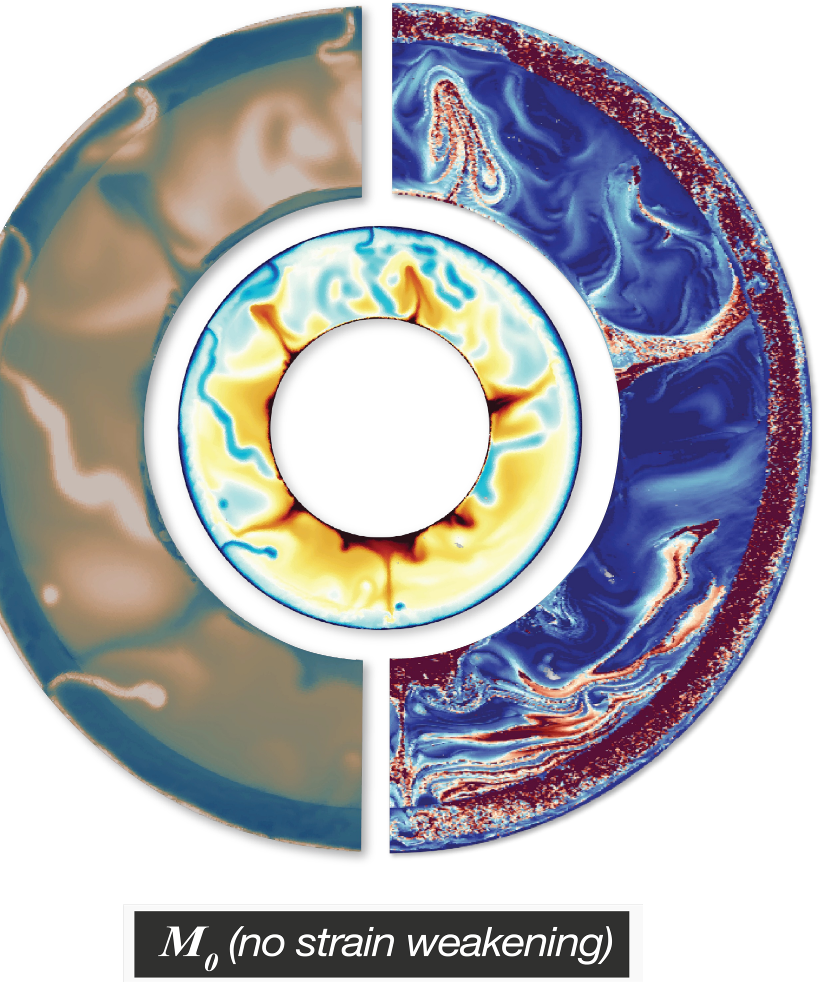
→ Hot **upwellings**

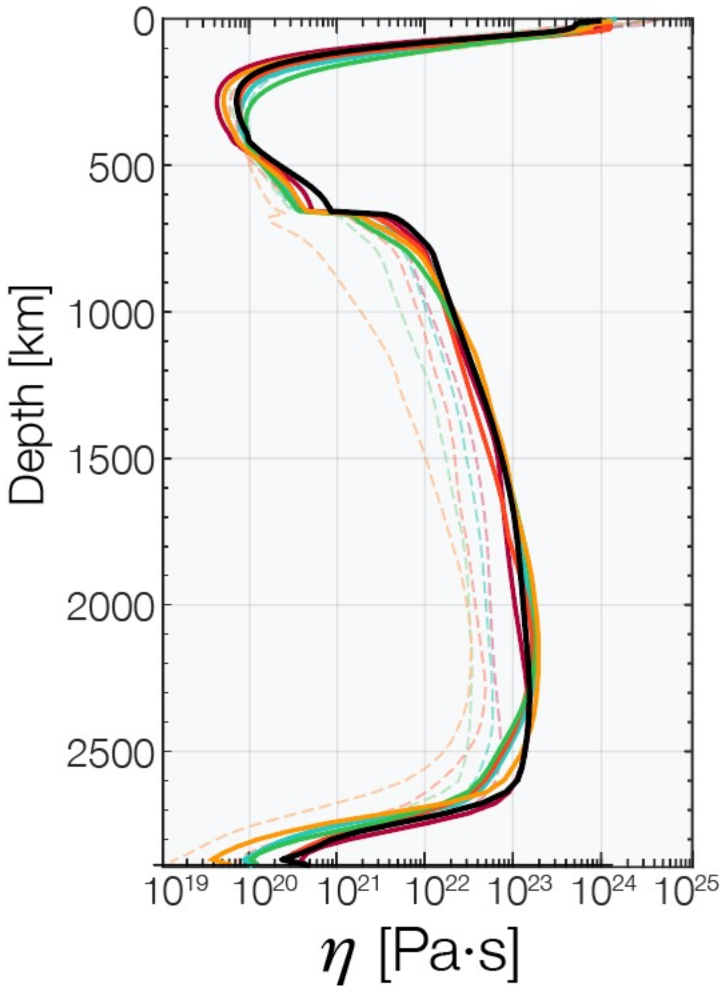
→ **Deflected** regions around sinking slabs

Gülcher et al., (in review for G3)

# Results: SW rheology - comparison

***Remove*** effect of **changing Rayleigh number** → Establish **first-order effect** of SW rheology

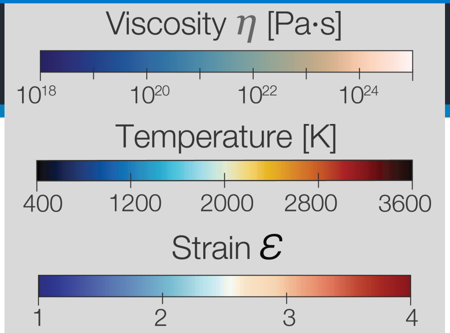


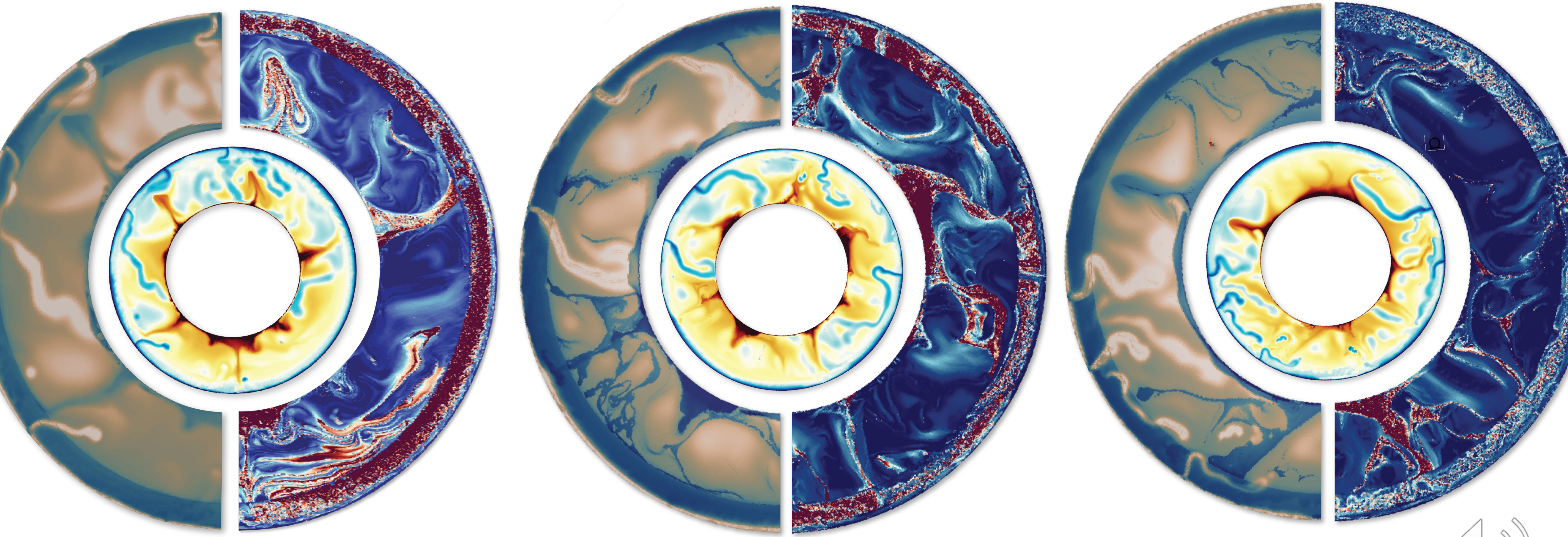




- Models with similar…
  … final **viscosity profile**
  … **thermal evolution**

# Results: SW rheology – comparison

Gülcher et al., (in review for G[3])



$M_0$ (no strain weakening)

No healing; much weakening

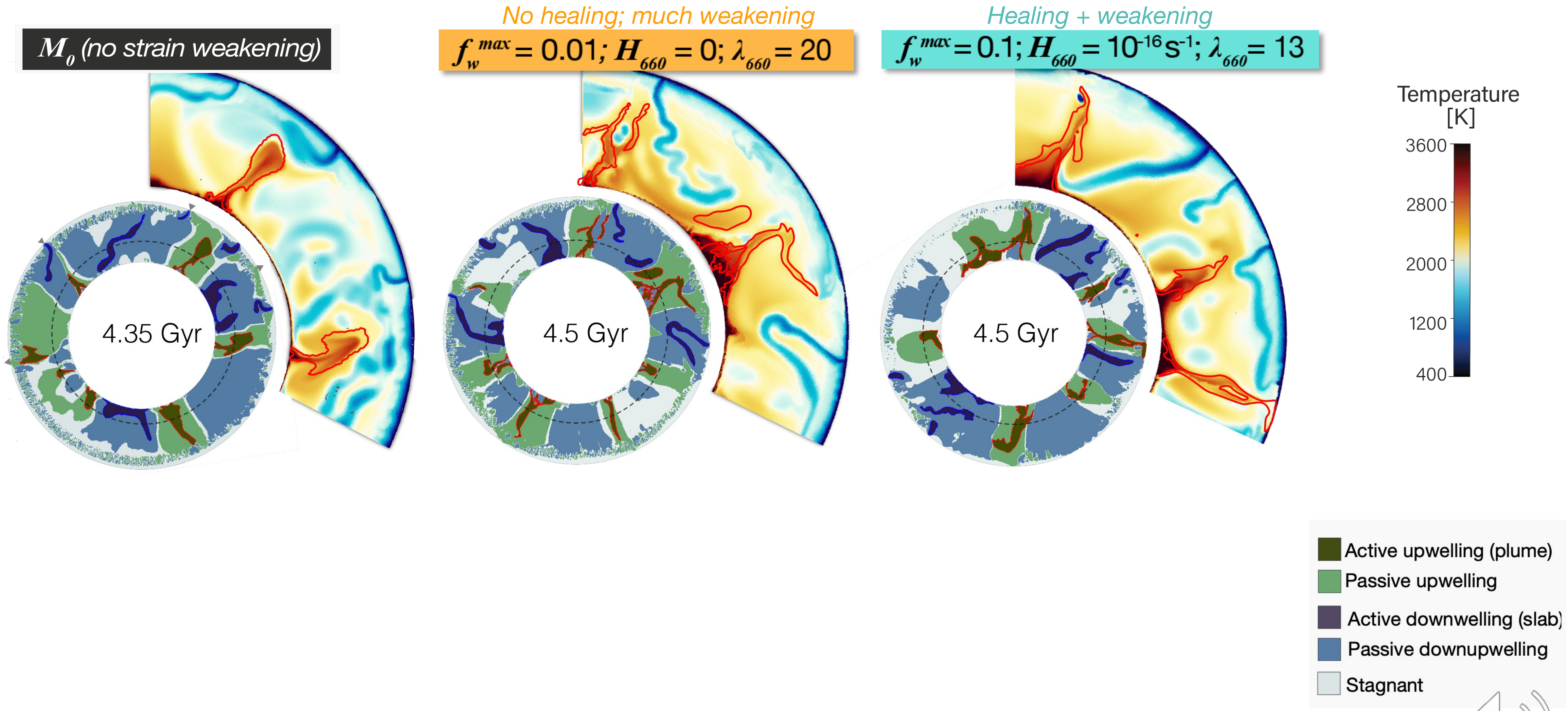
$f_w^{max} = 0.01; H_{660} = 0; \lambda_{660} = 20$

Healing + weakening

$f_w^{max} = 0.1; H_{660} = 10^{-16} s^{-1}; \lambda_{660} = 13$

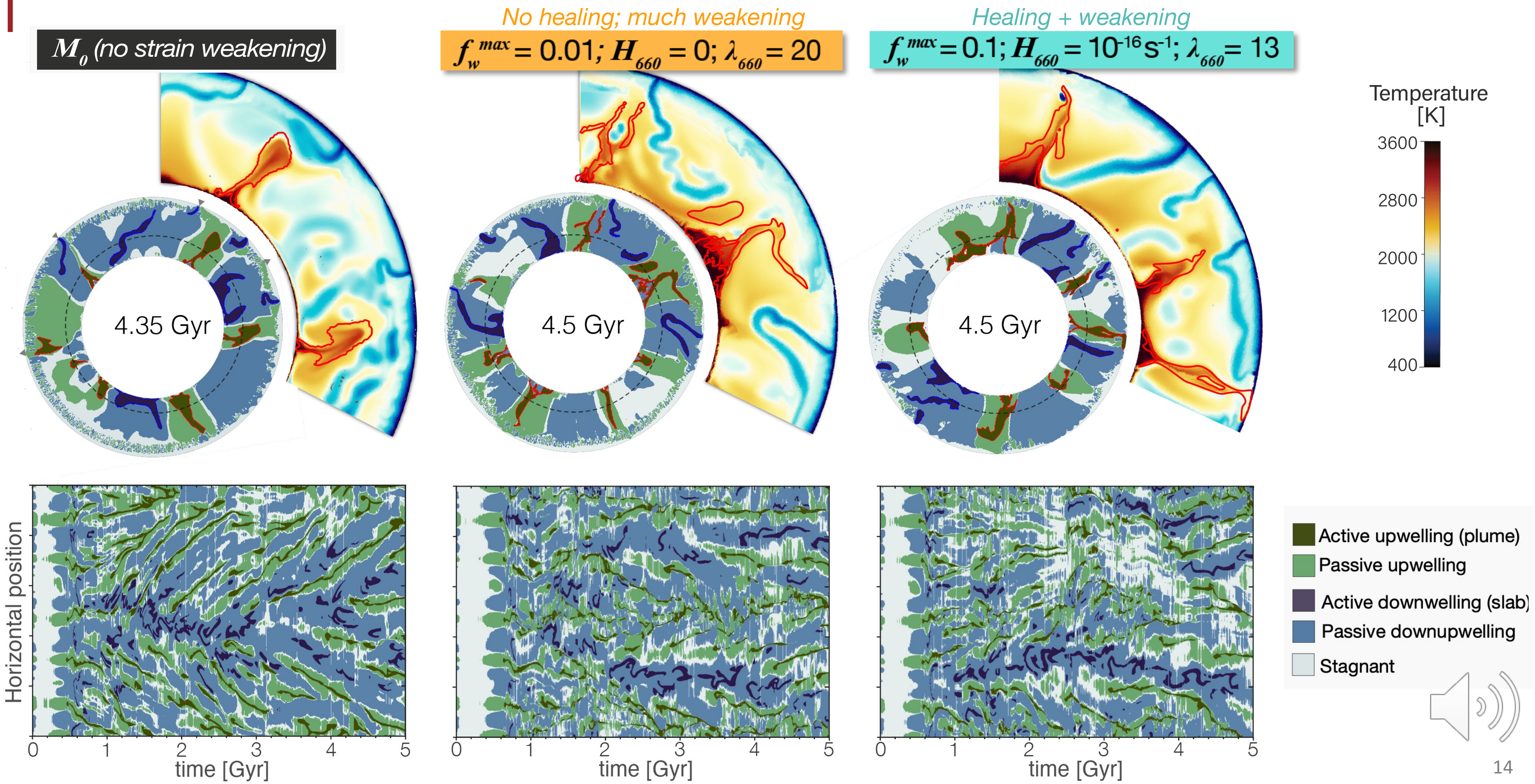
Gülcher et al., (in review for G3)

# Results: SW rheology – mantle convective pattern



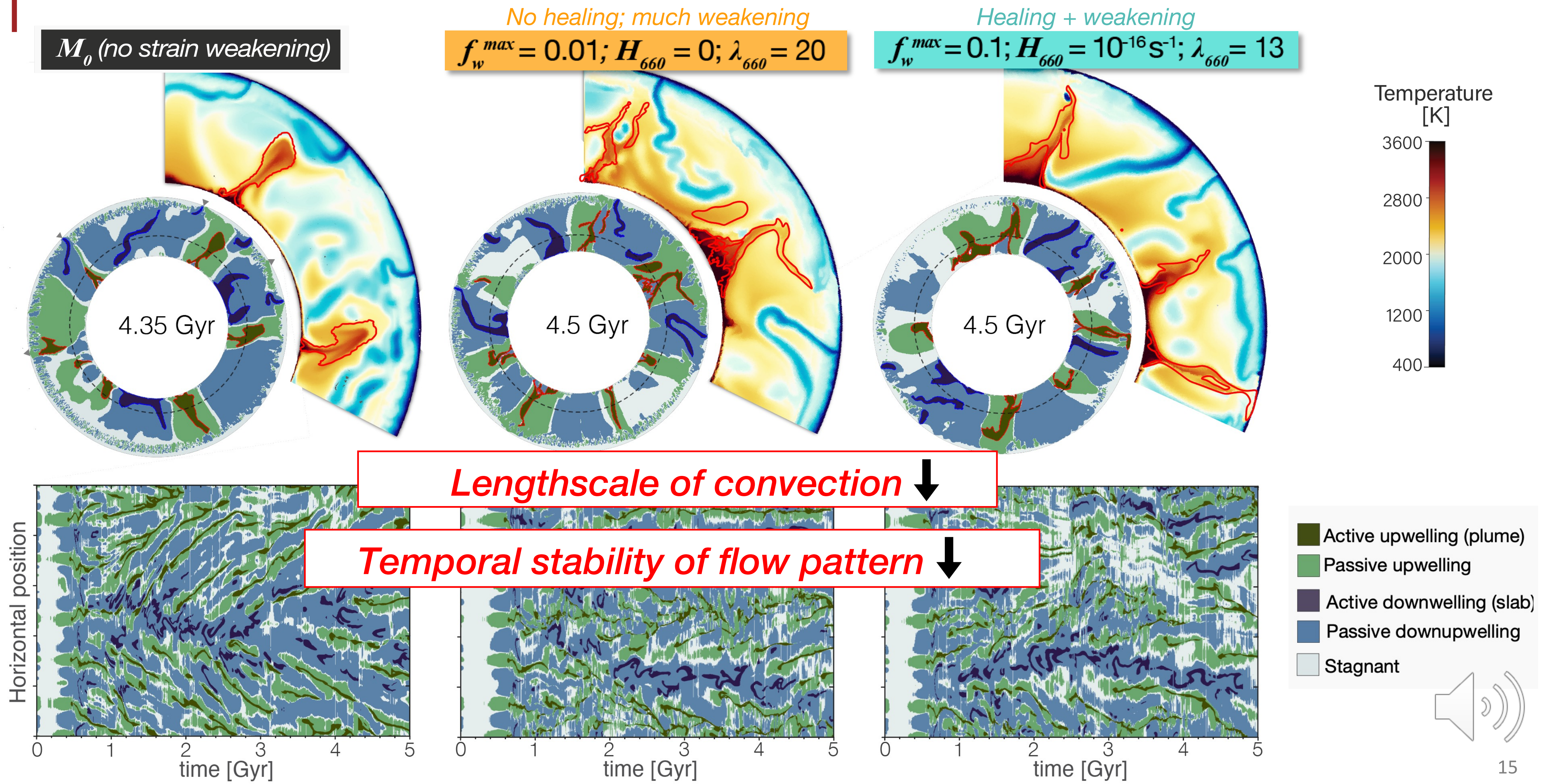
Gülcher et al., (in review for G3)

# Results: SW rheology – mantle convective pattern



# Results: SW rheology – mantle convective pattern

Gülcher et al., (in review for G[3])



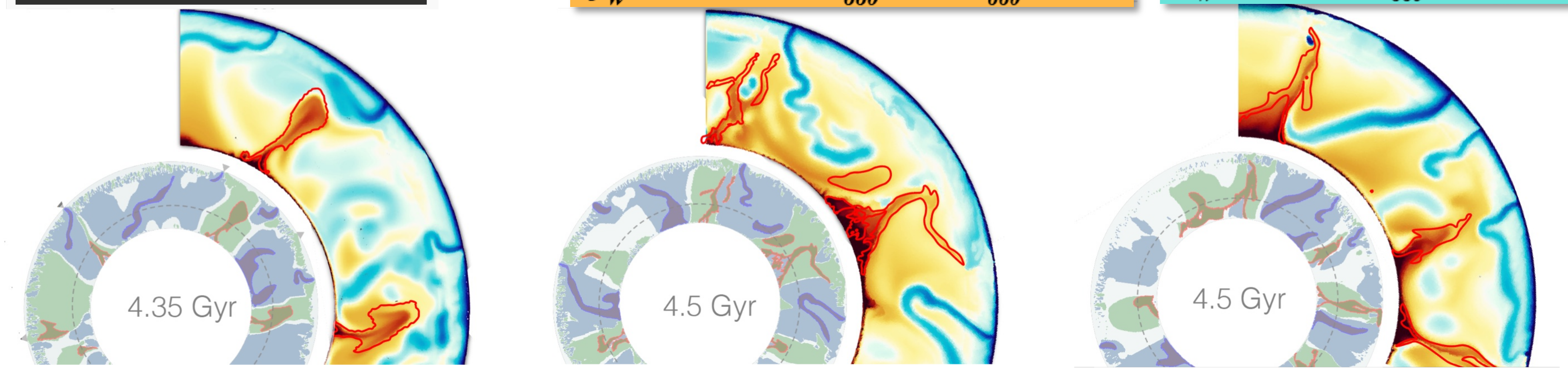
Gülcher et al., (in review for G[3])

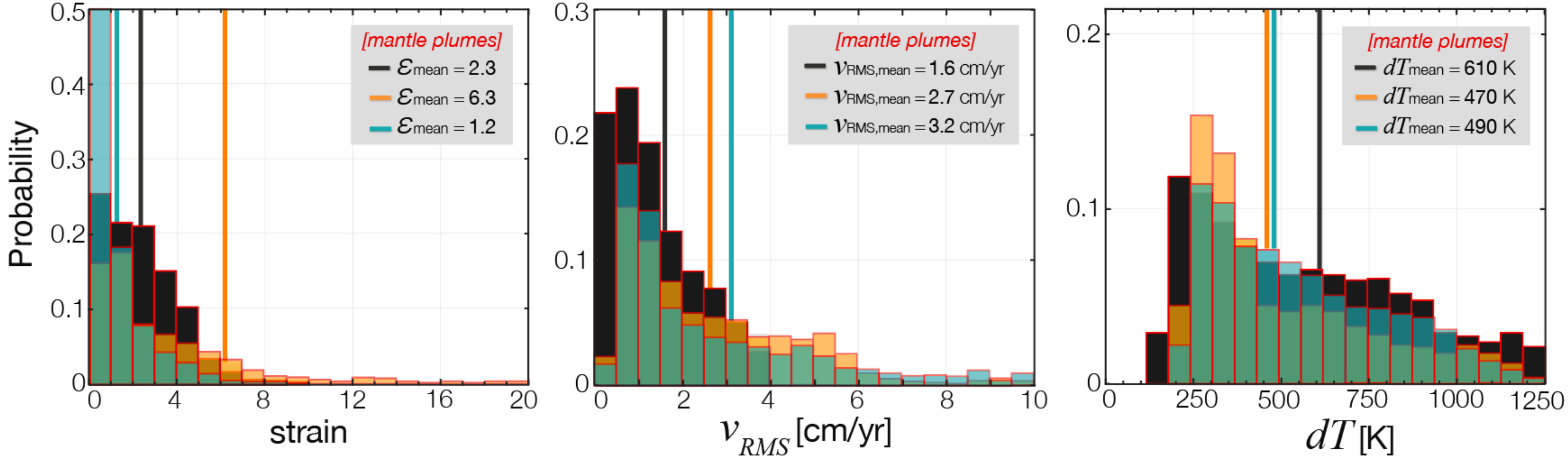
# Results: SW rheology – mantle plumes

$M_0$ (no strain weakening)

No healing; much weakening — $f_w^{max} = 0.01$; $H_{660} = 0$; $\lambda_{660} = 20$

Healing + weakening — $f_w^{max} = 0.1$; $H_{660} = 10^{-16}$ s$^{-1}$; $\lambda_{660} = 13$



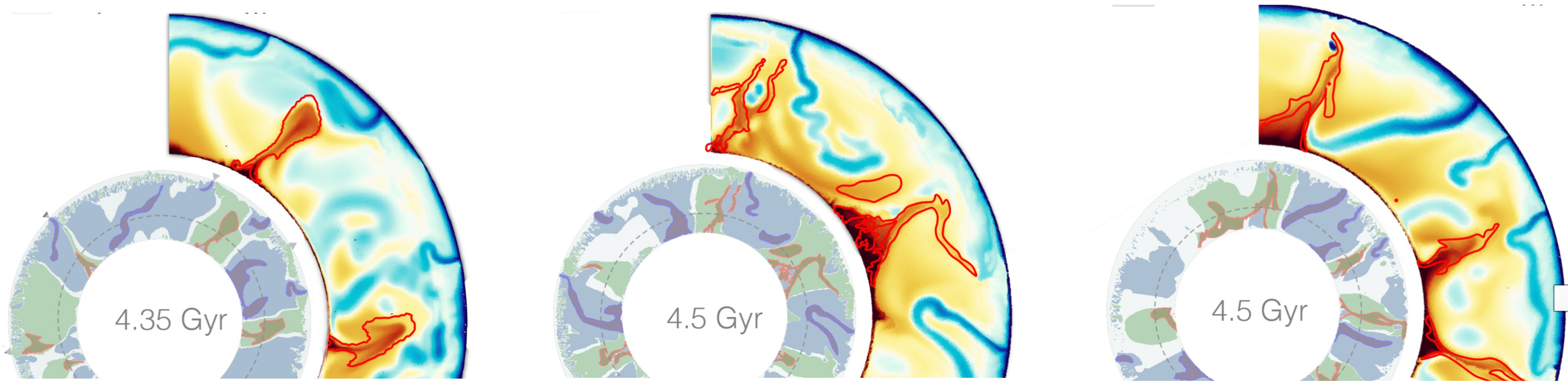

Weakened plumes are:

- **Thinner**
- **Faster**
- **Colder**

# Results: SW rheology – summary

SW rheology in the lower mantle:

- **Reduced length-scale** of mantle convection
- Increased thermochemical **pile stability**
- Thinner, faster, and **colder mantle plumes**



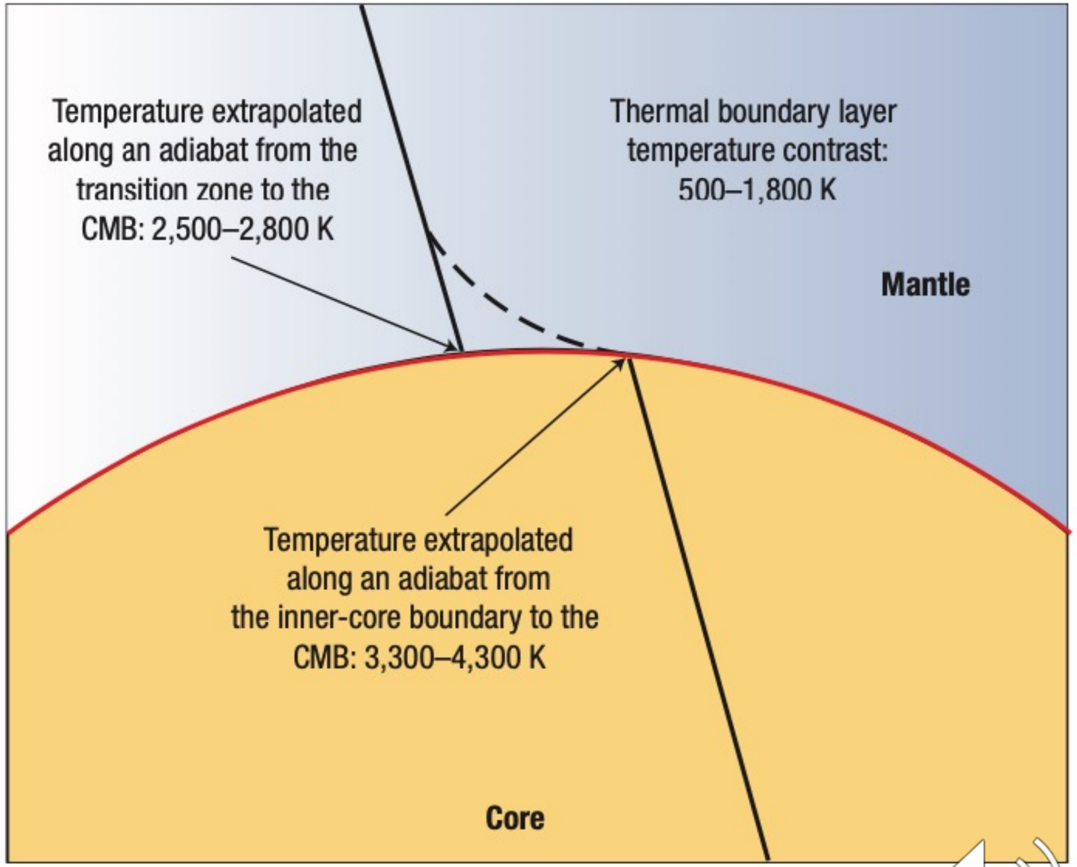
# Discussion – mantle plumes

- Weakened plumes are: **faster, colder, & thinner**

- Earth observations:
  - **1000-1500 K** super-adiabatic temperature rise across CMB (Jeanloz & Morris, 1986; Lay et al., 2008)

    ↕ ***Mismatch!***

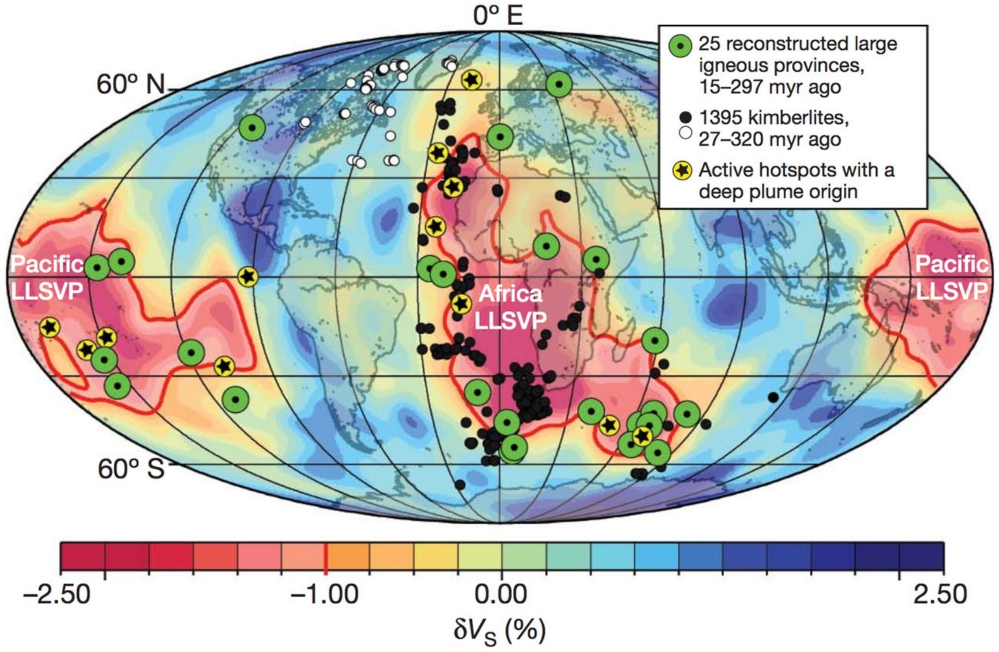
  - Deep-seated plume $T$ excess of only **100-400 K** (e.g., Albers & Christensen, 1996)



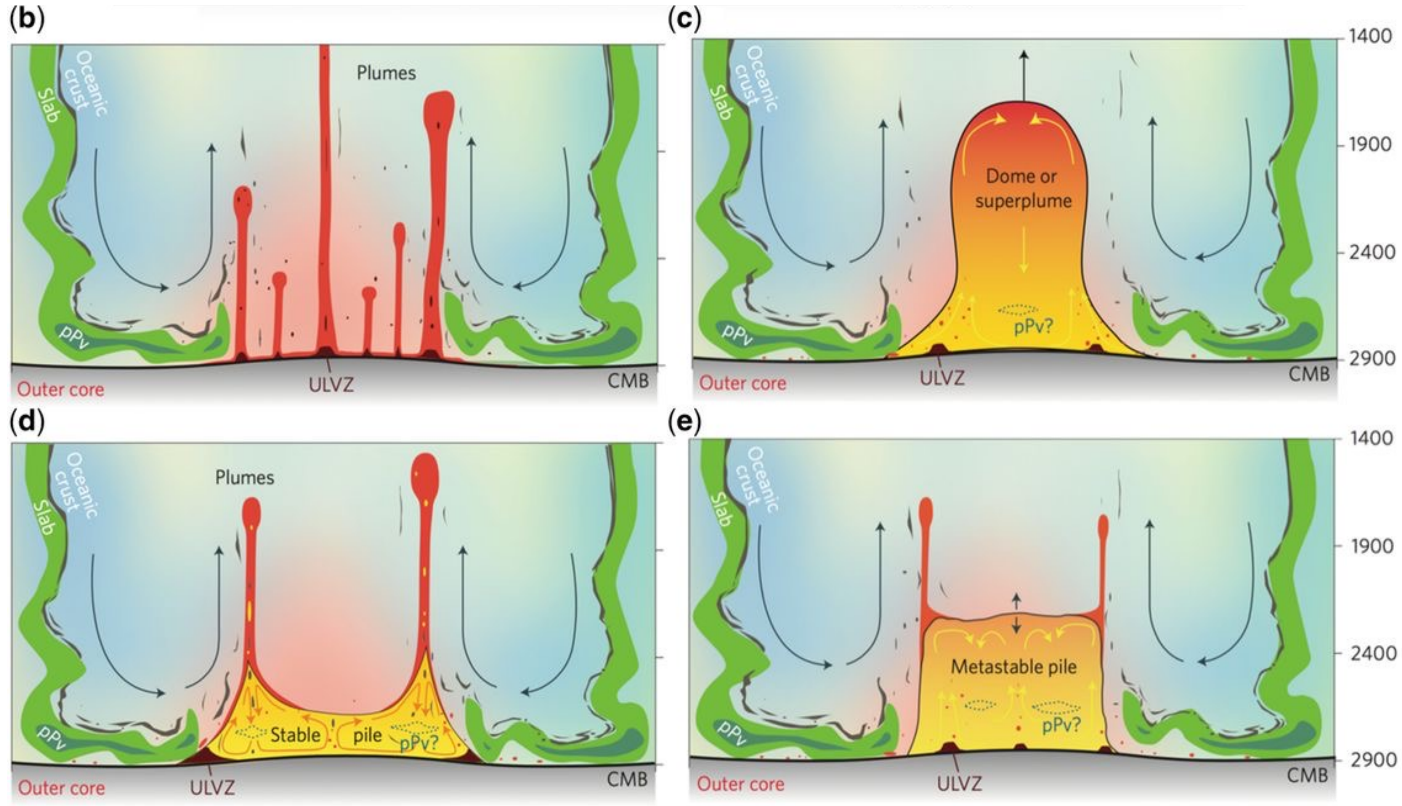

Lay et al., (2008)

# Discussion – mantle plumes

- Weakened plumes are: **faster, colder**, & **thinner**




Torsvik et al. (2010)




Garnero et al. (2016)

# Discussion – mantle plumes

- Weakened plumes are: **faster, colder**, & **thinner**

LETTER

doi:10.1038/nature14876

**Broad plumes rooted at the base of the Earth's mantle beneath major hotspots**

Scott W. French[1]† & Barbara Romanowicz[1,2,3]

Tectonics

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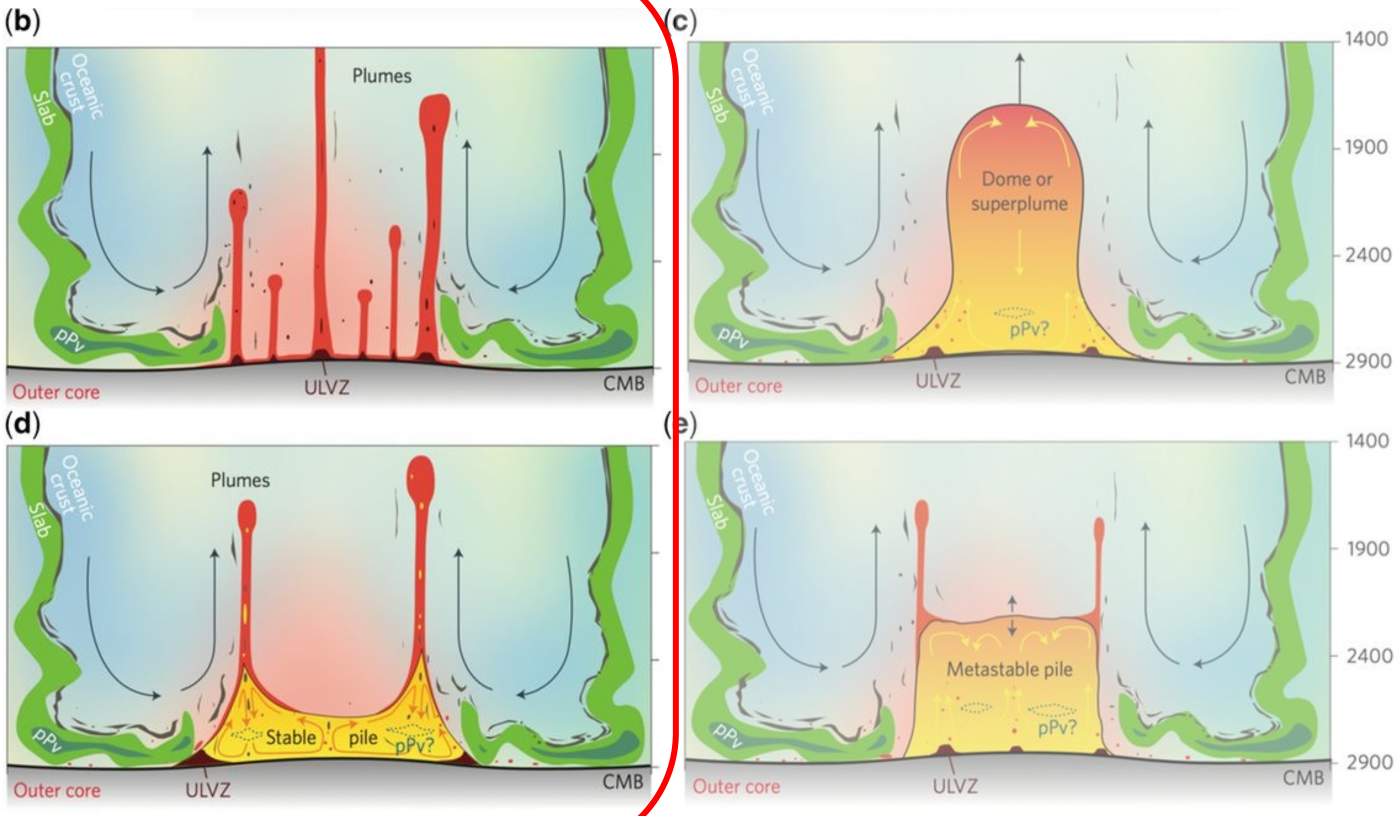
**Deflating the LLSVPs: Bundles of Mantle Thermochemical Plumes Rather Than Thick Stagnant "Piles"**

Anne Davaille[1] and Barbara Romanowicz[2,3,4]



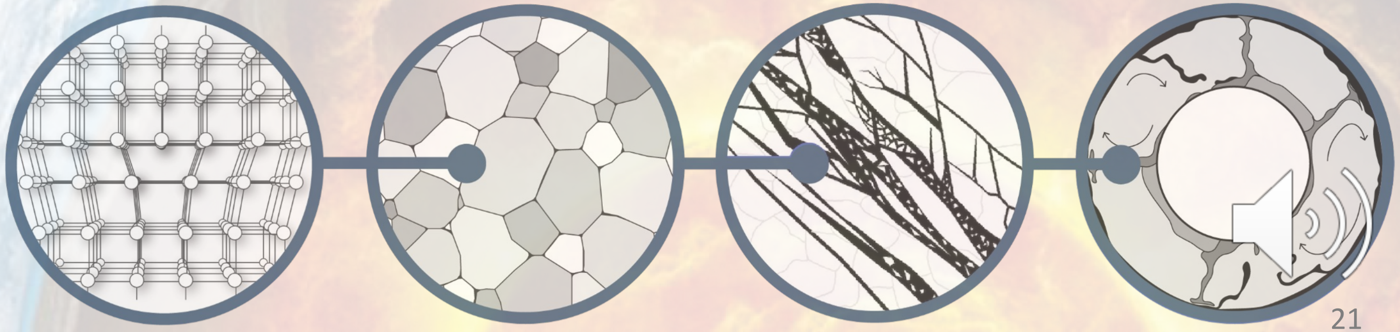

Garnero et al. (2016)

Gülcher et al., (in review for G³)

# Key points

https://doi.org/10.1002/essoar.10509746.1

- A new parametrisation of **strain-dependent rheology** for lower mantle materials is implemented in *StagYY*
- Such rheology particularly causes **weakening of plume conduits**, forming **narrow lubrication channels** through which hot material easily rises.
- Could help explain the **discrepancy** between expected and observed **thermal anomalies** of deep-seated mantle plumes on Earth?



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