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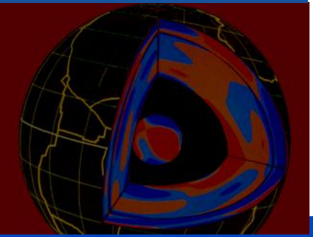
Seismic anisotropy of the inner core deduced from geodynamical and mineralogical models

COLLÈGE DE FRANCE 1530



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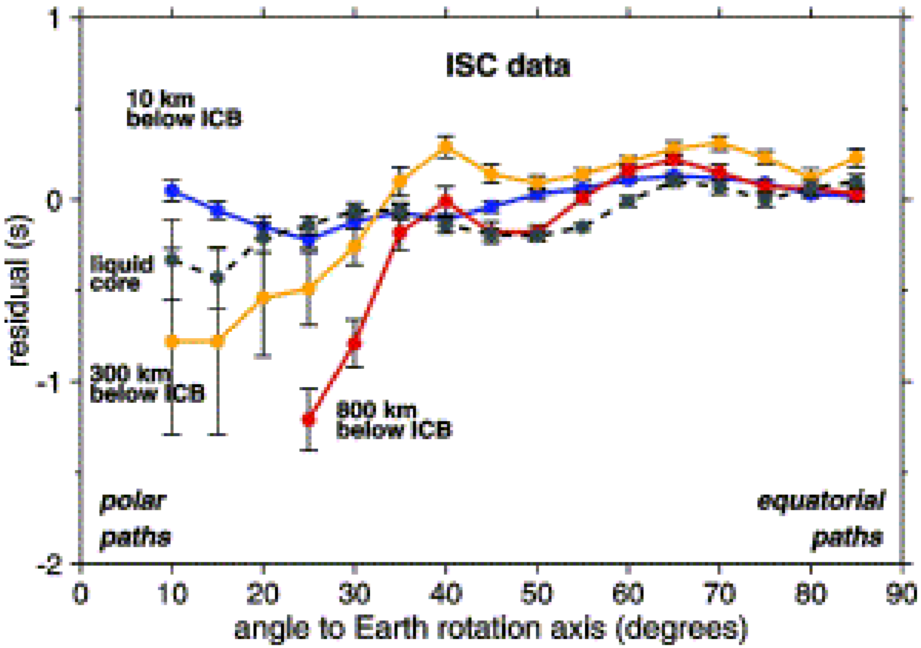
OSUG

Observatoire des Sciences de l'Univers de Grenoble

Outline

1. Seismological observations, anisotropy
2. Review of proposed mechanism
3. Dynamical state of the inner core
4. Thermal convection in the inner core
5. Stratified inner core and equatorial growth
6. Perspectives

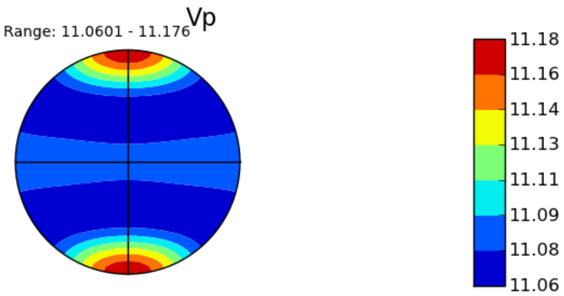
Seismological evidences?

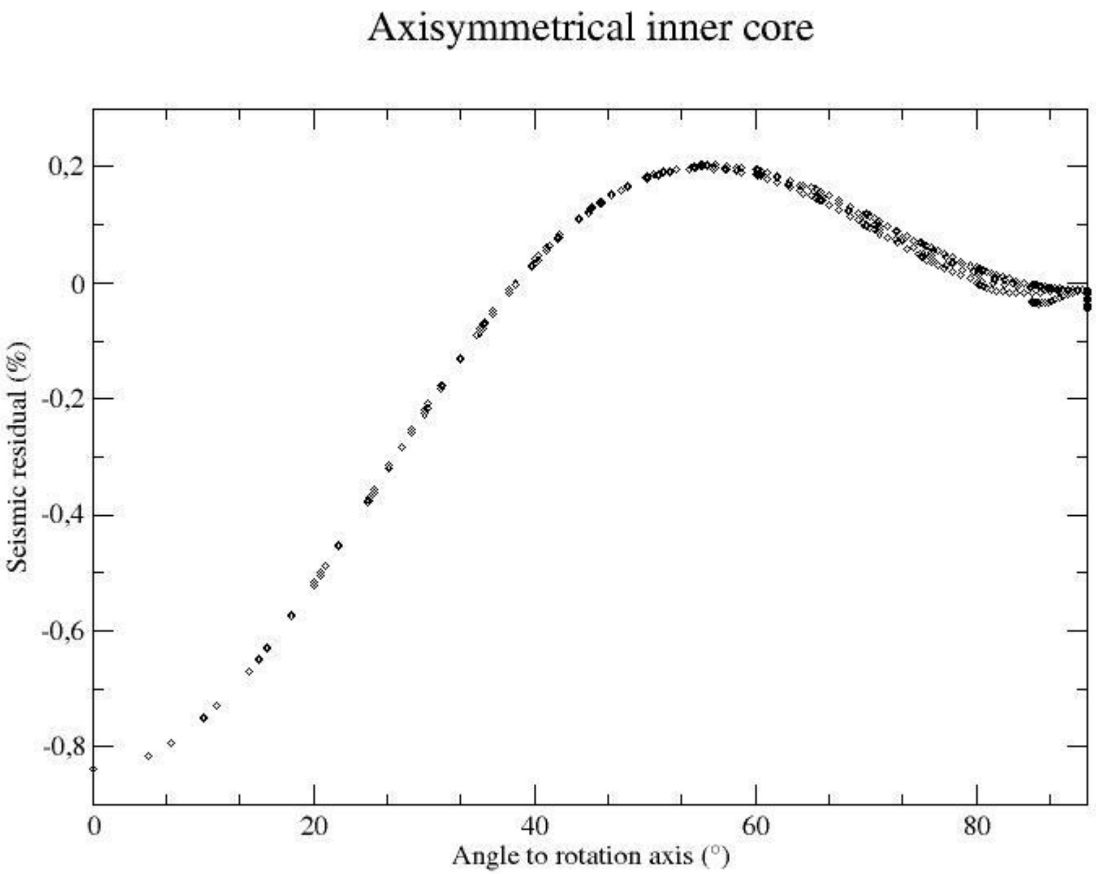


Souriau, Garcia et Poupinet 2003

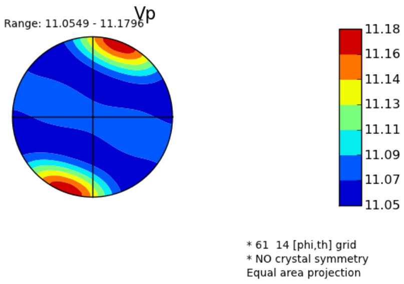
- 3% central anomaly
- Fast velocity almost NS (~10°)
- Isotropic superficial layer (100 to 400 km)
- With a hemispheric variation
- And peharps an innermost innercore

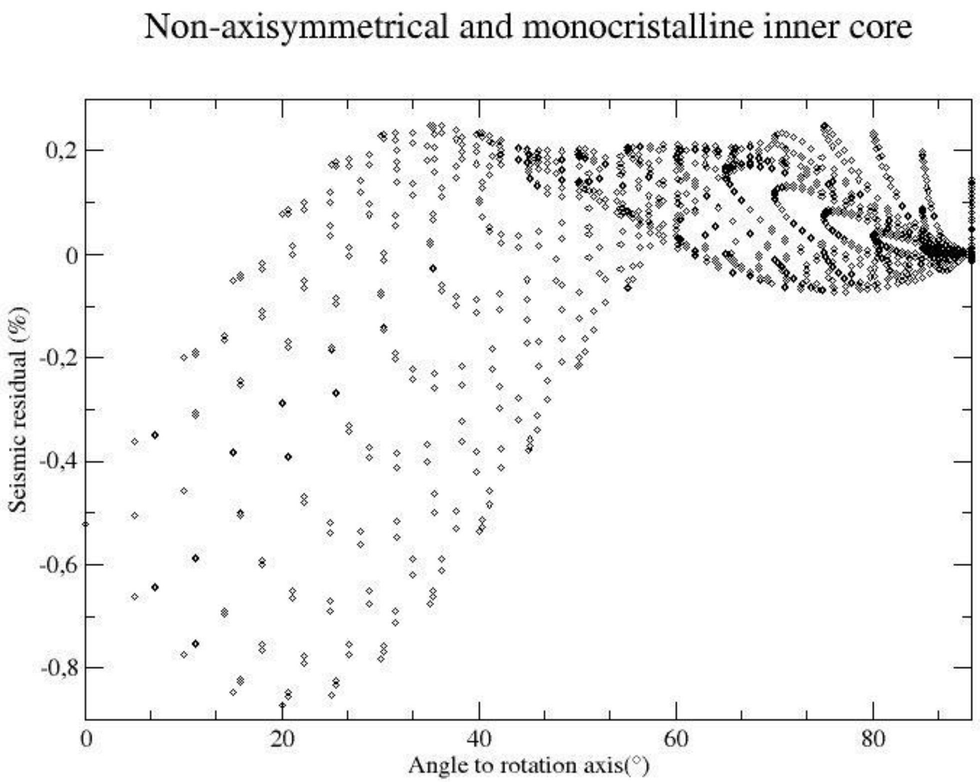
Direct model of anisotropy



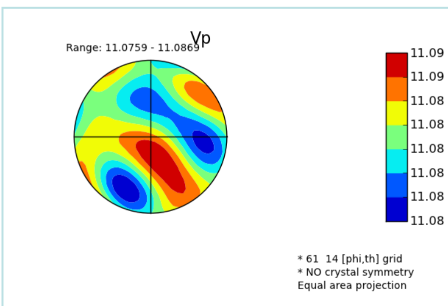


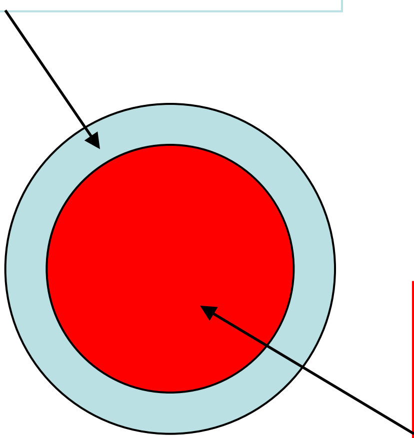
Model of anisotropy

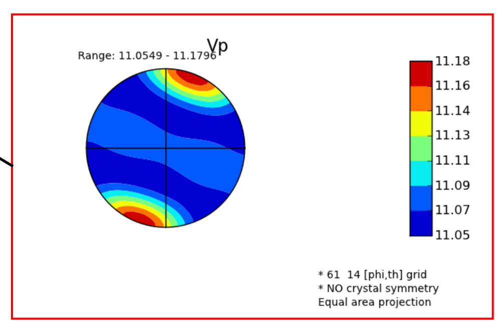




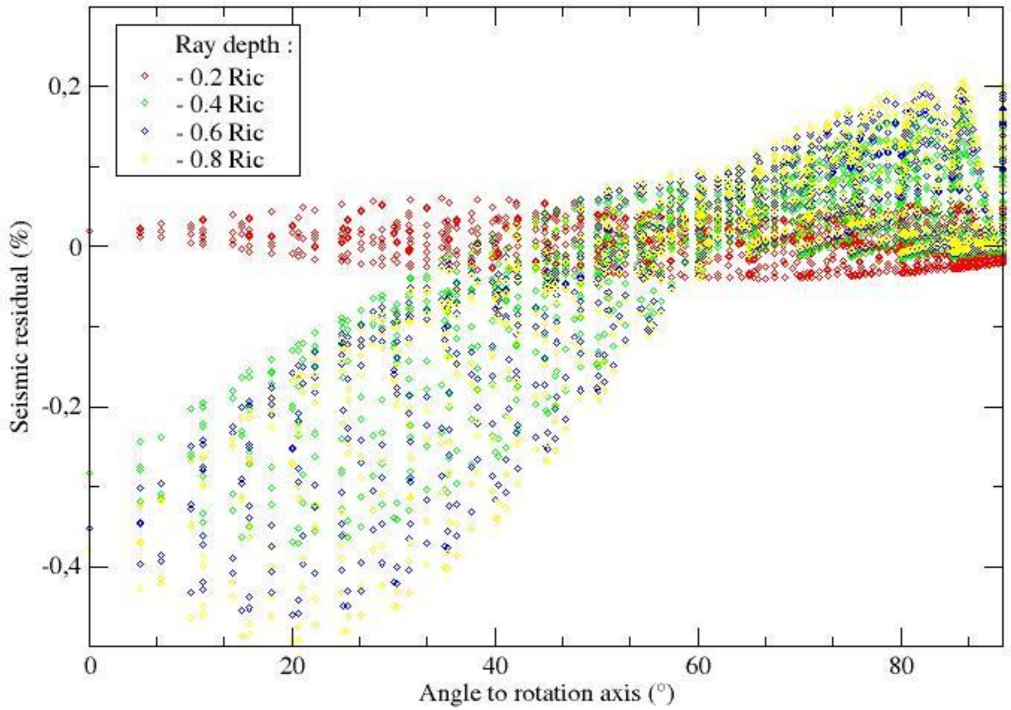
Anisotropy for a bilayered inner core







Bilayered and monocristalline inner core



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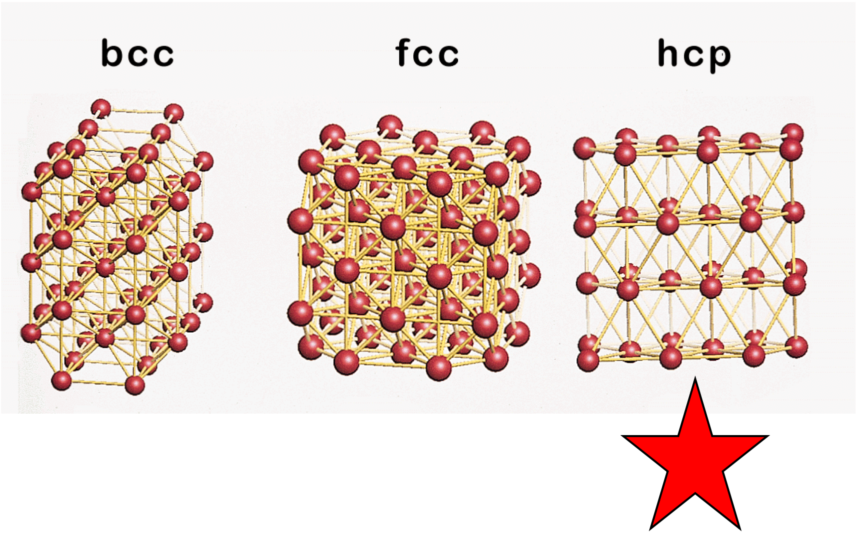
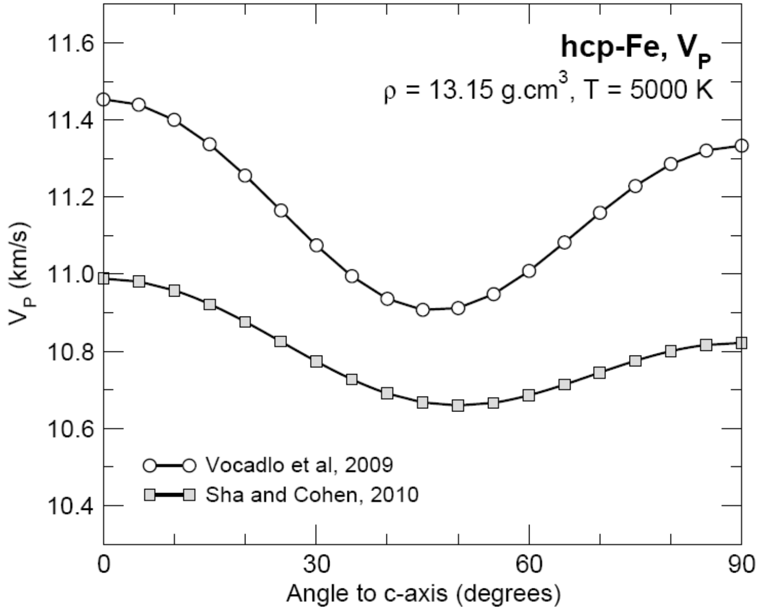
Anisotropic crystals of iron

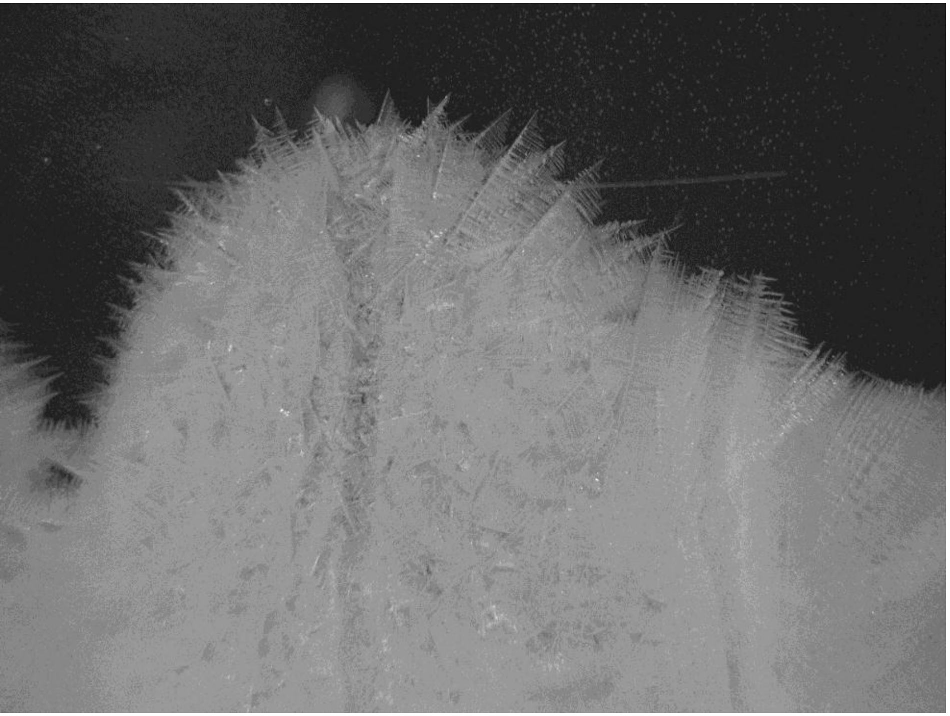




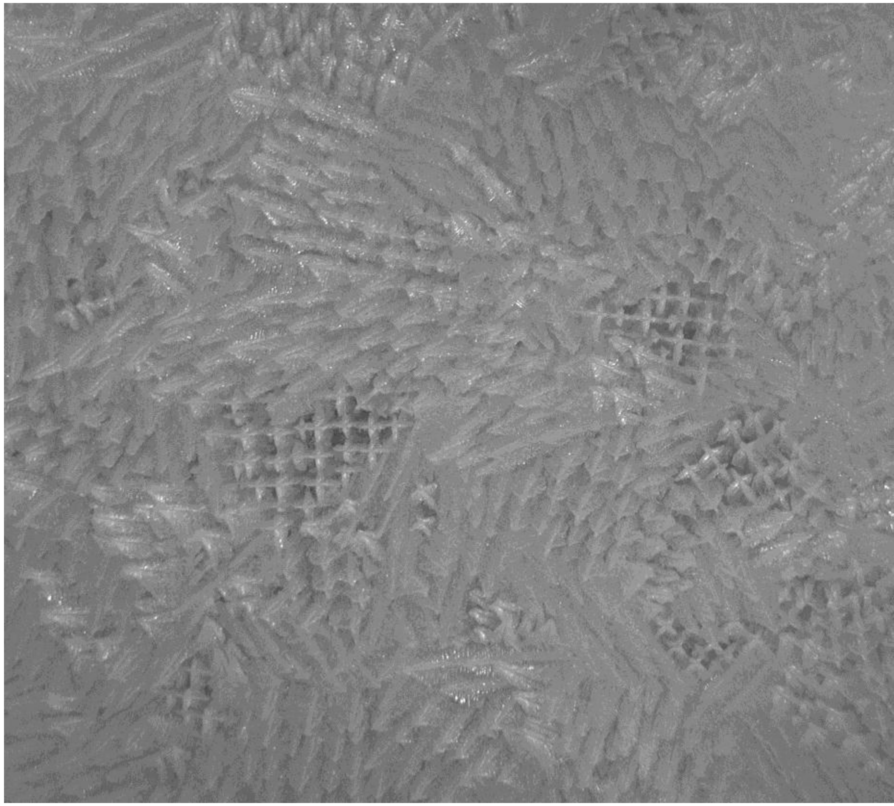
Experimental versus ab initio?

1-Texture by cristallisation

Dendrites

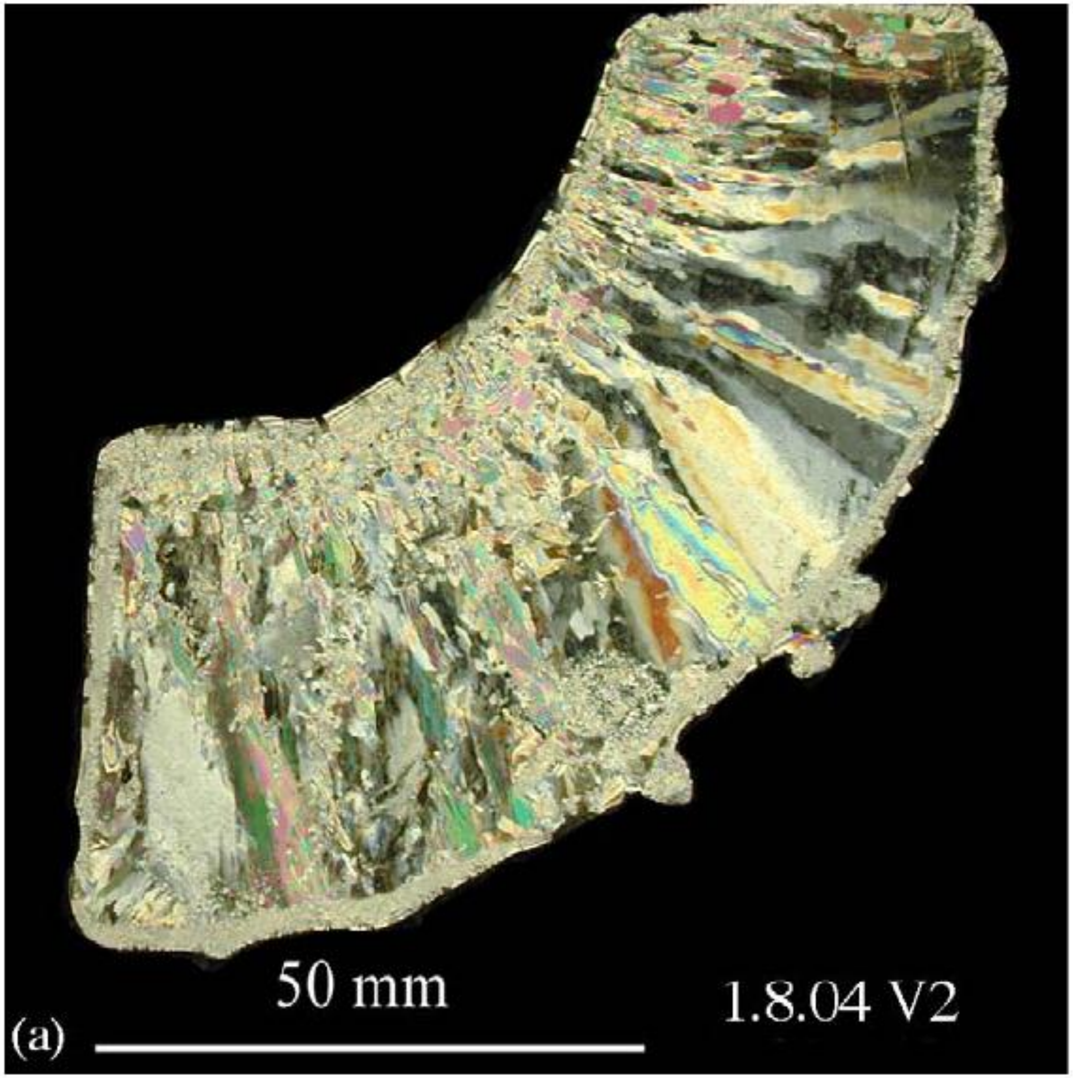


NH4Cl experiments



Deguen, 09

Solidification texturing



Salt water experiments

Radial symmetry of the cristals

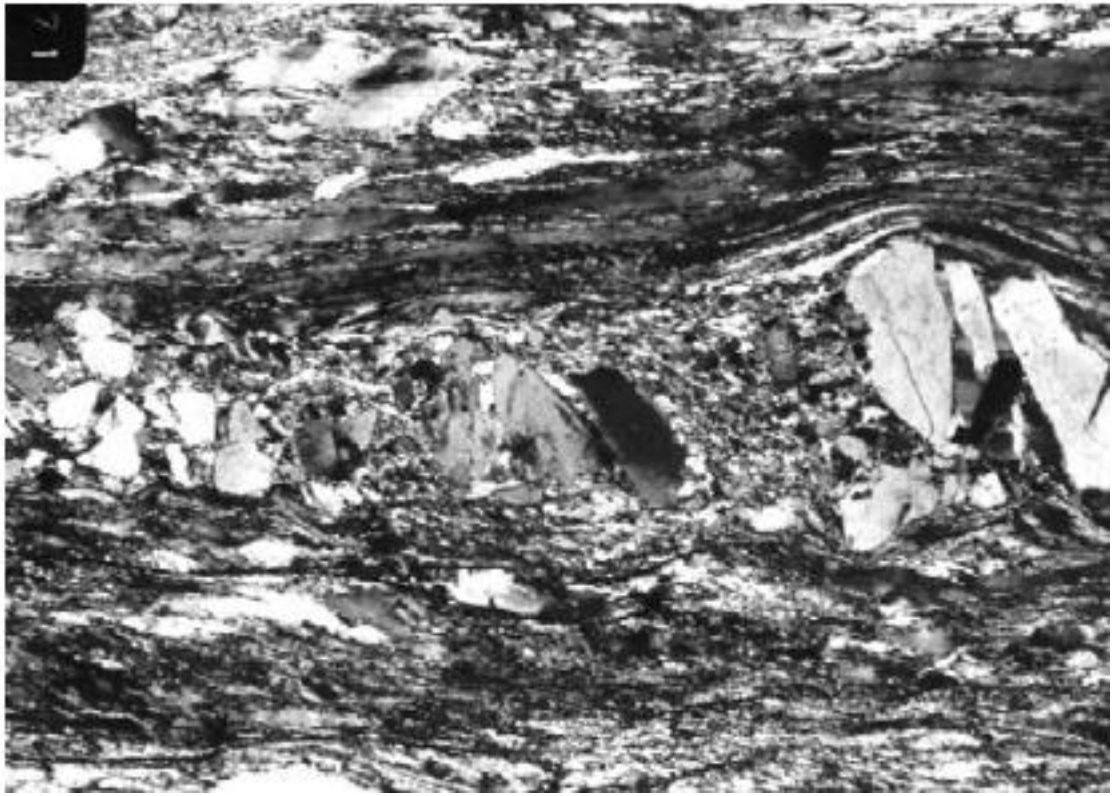
Effect of rotation, magnetic fields, heat flux variations

Bergman et al, 05

2- Texture by deformation

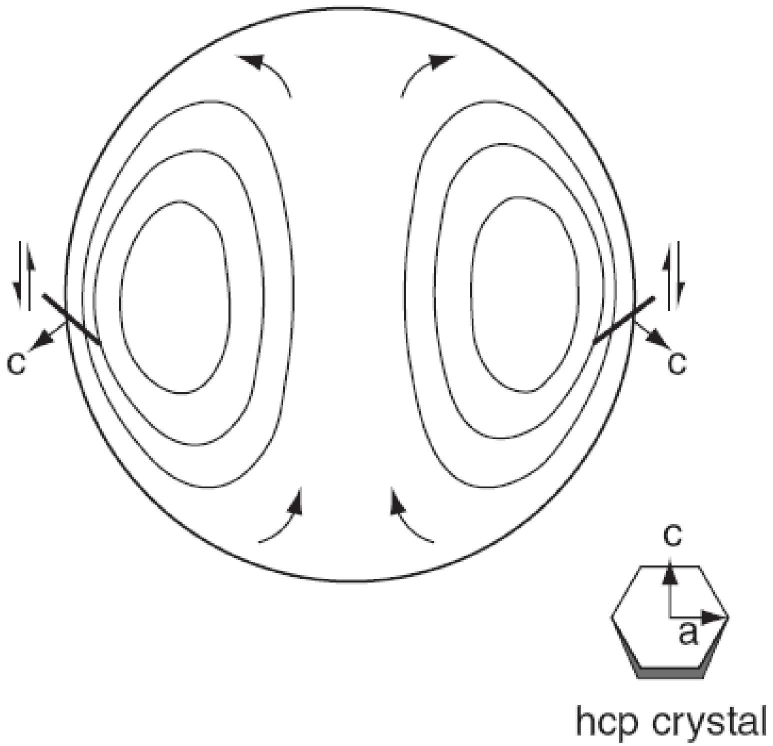
Plastic deformation

Or recristalisation



Deformation mechanism (1)

- Thermal convection in the inner core



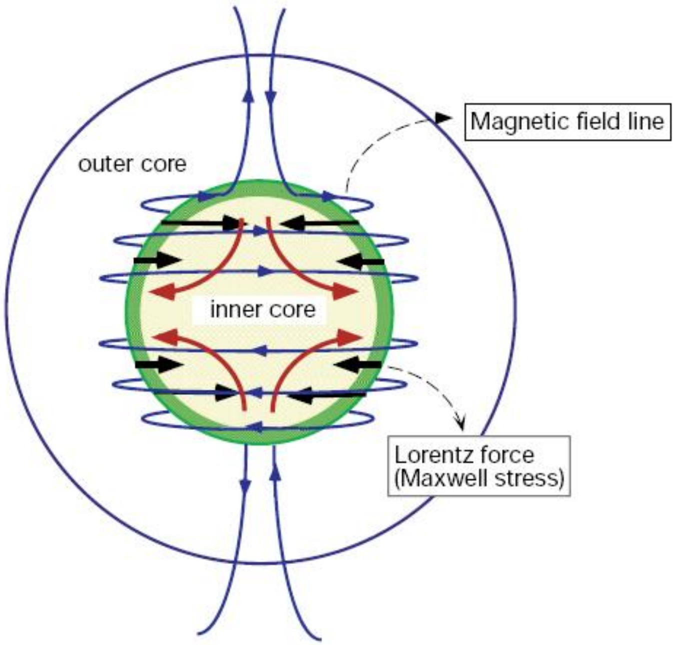
Weber et Machetel, 92

Wenk et al, 2000

Deformation mechanism (2)

- Maxwell stress

Poloidal motions



Karato, 1999

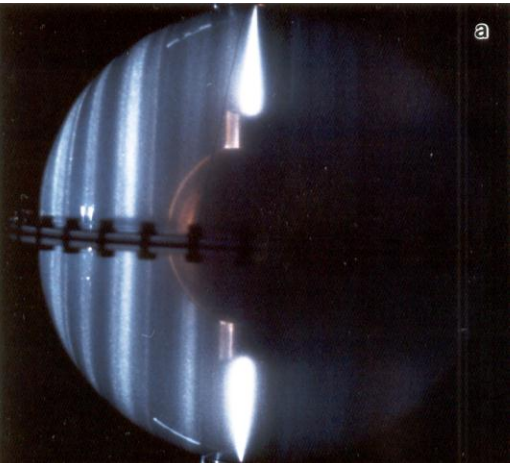
Toroidal motions

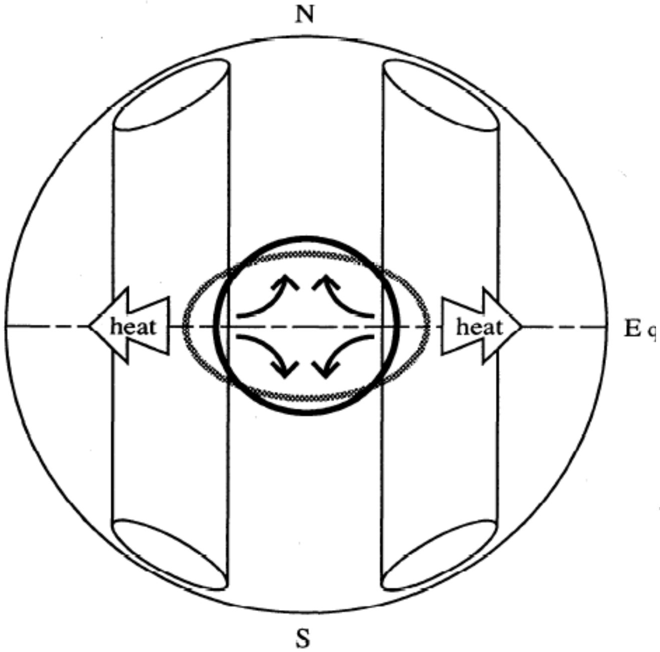
Differential motions between the gravitational torque at the ICB and the Lorentz forces in the bulk

Buffet and Wenk, 2001

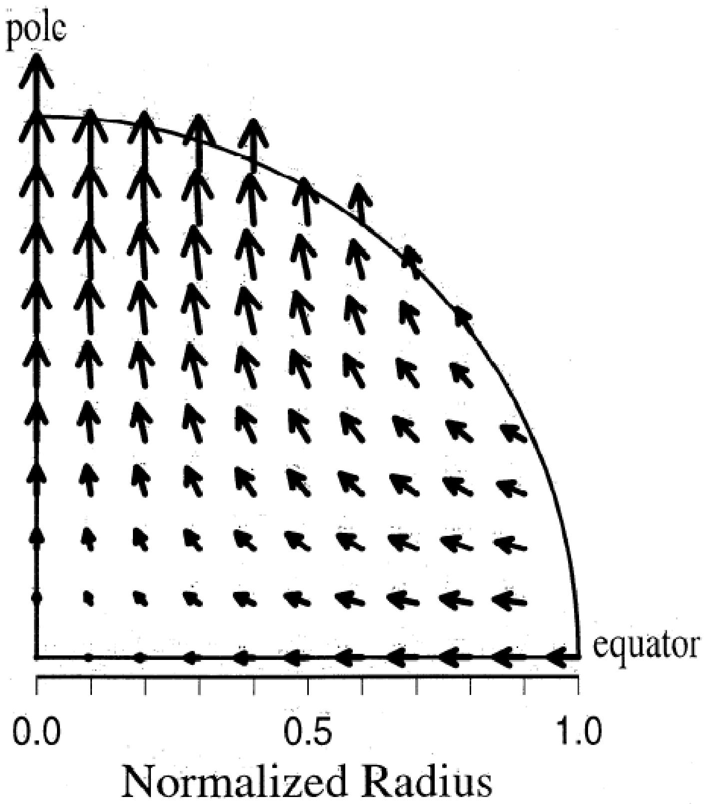
Deformation mechanism (3)

- Differential growth of the inner core





Yoshida et al, 1996



Review of proposed mechanism

summary

- HCP Fe crystal is anisotropic
- Texture by solidification (spherical)
- Texture by plastic deformation
  - thermal convection
  - Maxwell stress
  - differential growth

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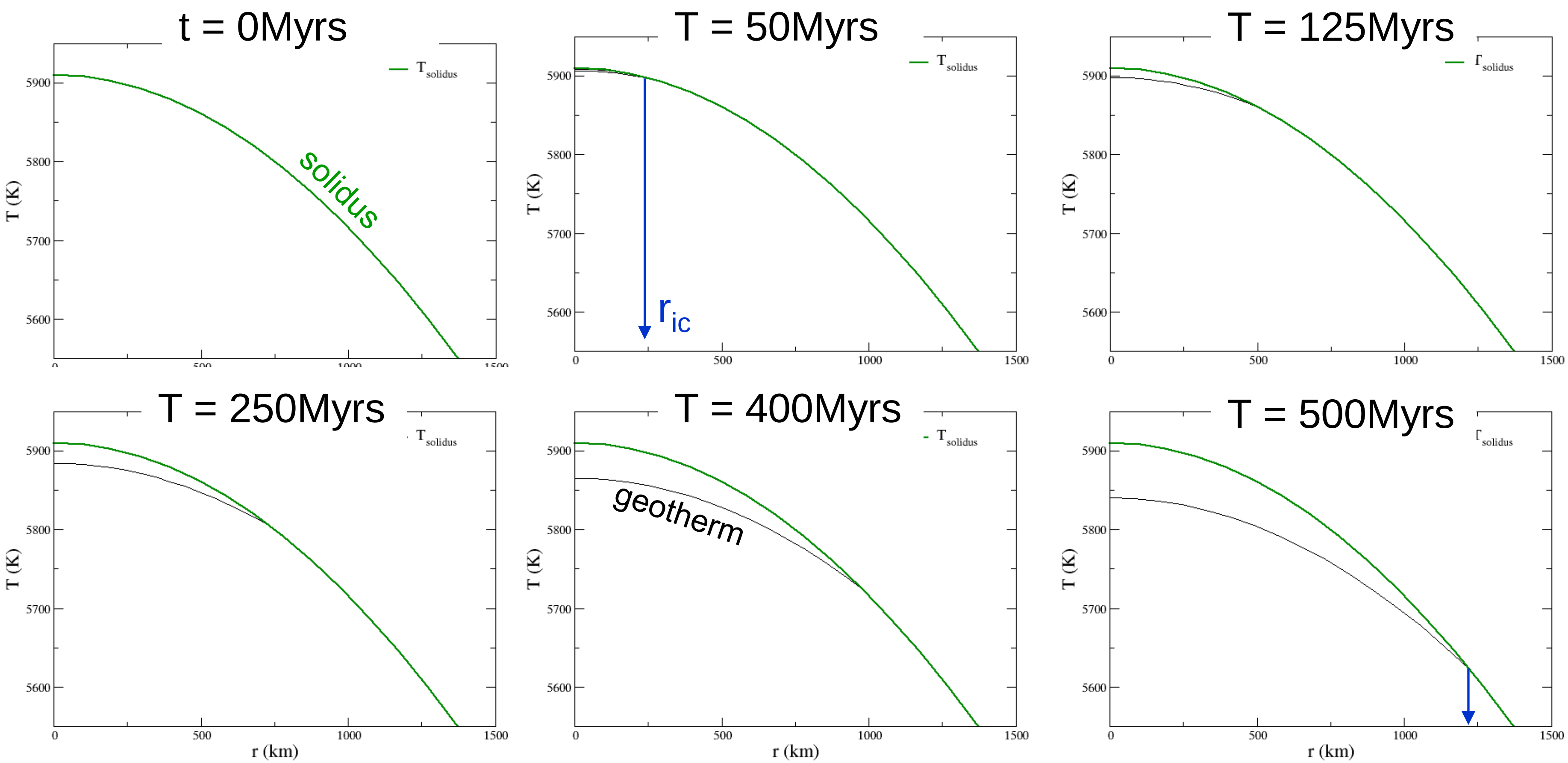
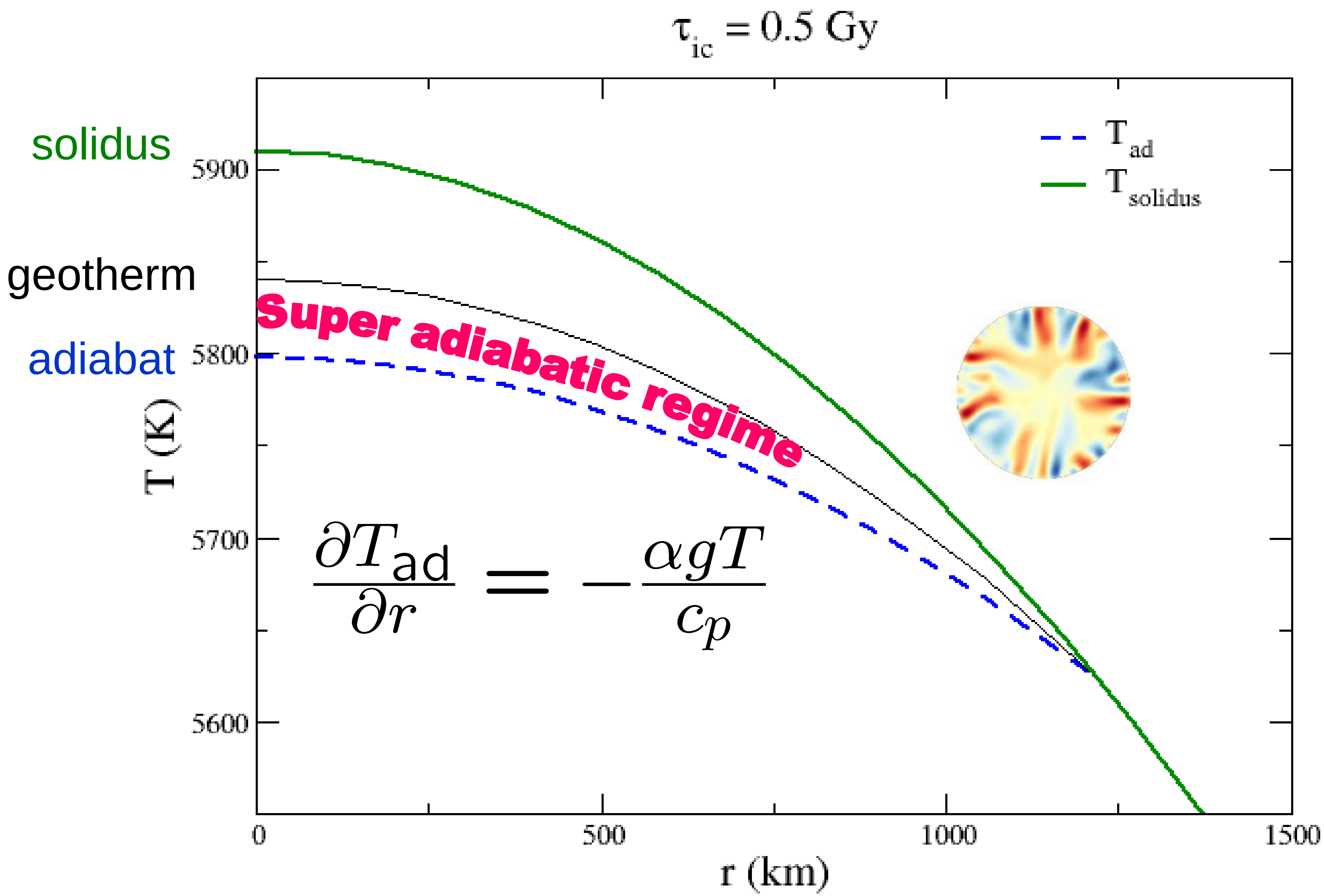
Time evolution of thermal state of the inner core

- Take an inner core of 500Myrs



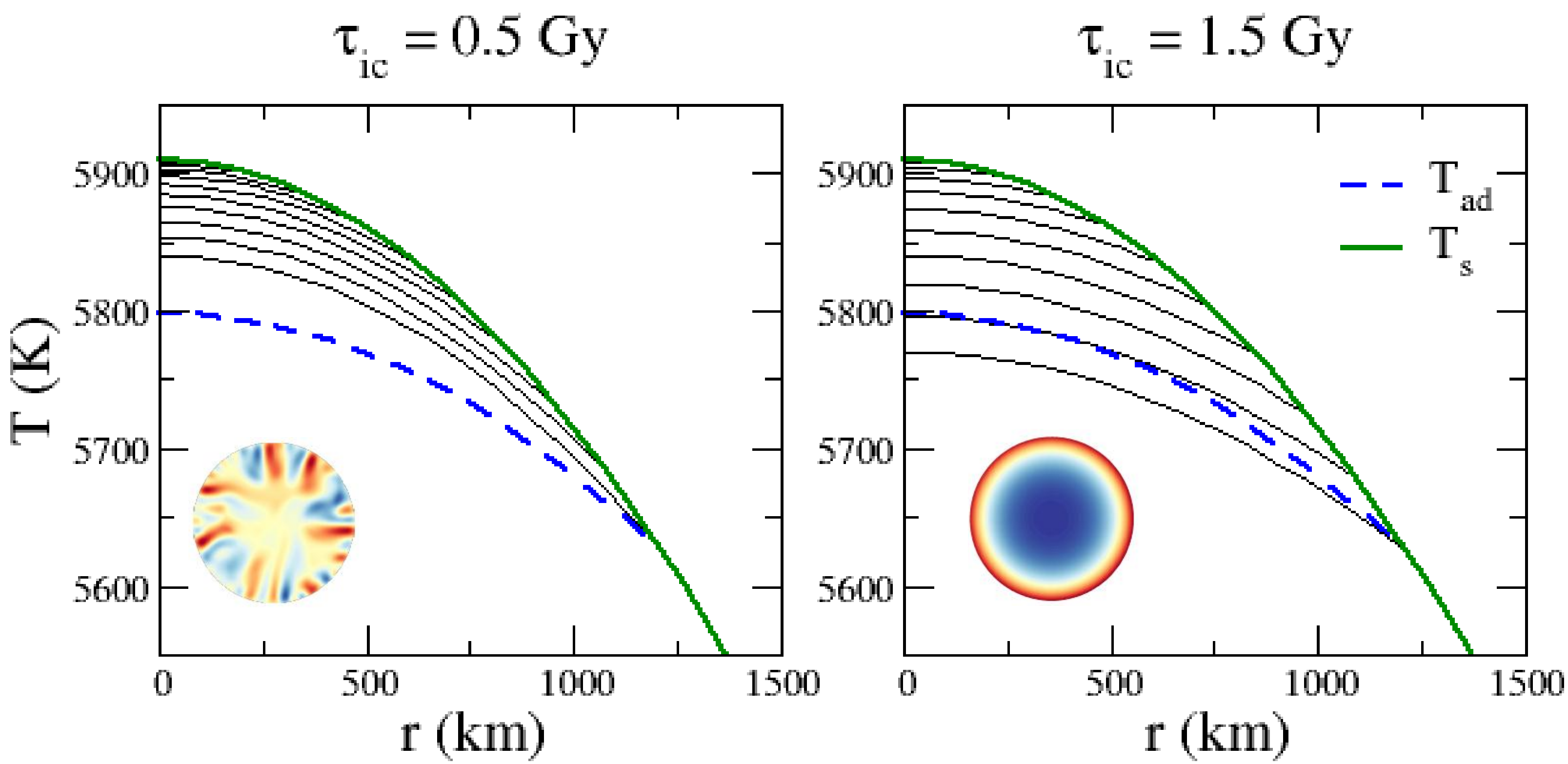
r_{ic}=1220km

Dynamical thermal state ?



$$\frac{\partial T_{\mathrm{ad}}}{\partial r} = -\frac{\alpha g T}{c_p}$$

Inner core age



Inner core cooling (age) is the key parameter to predict the dynamical state.

CMB heat flux

Thermal conductivity

Dynamical state of the inner core

- Age of IC is the key parameter:

$$\tau_{ic} < \tau_{\kappa} \left(\frac{dT_S}{dT_{ad}} - 1 \right) = \frac{r_{ic}^2}{3\kappa} \left(1 - \frac{1}{3\gamma} \right) \left(\frac{1}{\gamma} + \alpha T \right)$$

$$\tau_{ic}^{crit} = 0.9 \pm 0.6 Gy$$

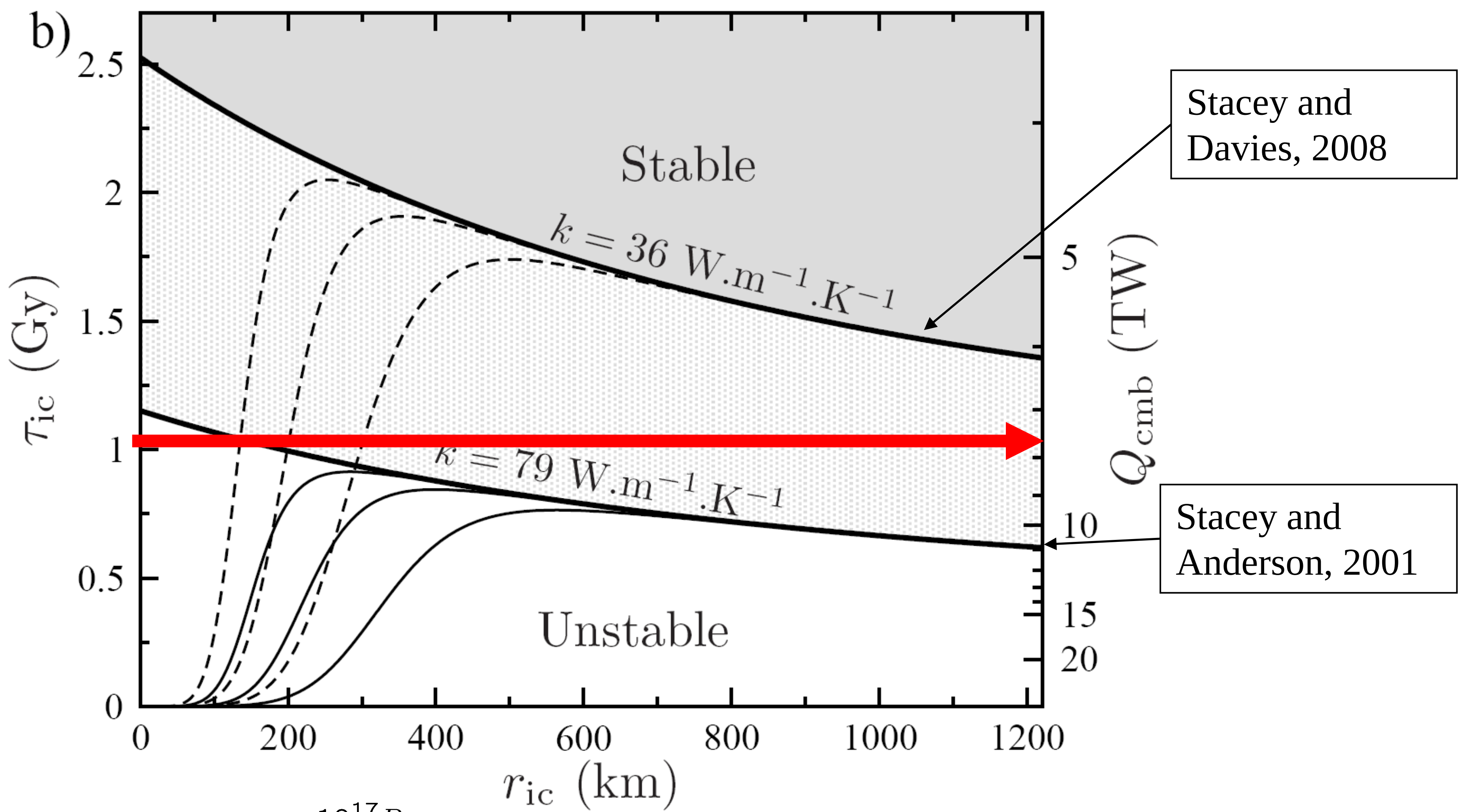
- Controled mainly by the CMB heat flux

$$\tau_{ic} = \frac{E_{tot}}{Q_{cmb}} = \frac{\int_0^{r_{ic}} P_c + P_g + P_L dr}{Q_{cmb}} = \frac{29 \pm 18 \; 10^{28} \; J}{Q_{cmb}}$$

$$\tau_{ic} = 0.6 Gy (12 TW) - 2.3 Gy (4 TW)$$

Labrosse et al, 2003

Adiabatic state of the inner core



$\eta = 10^{17} Pa.s$

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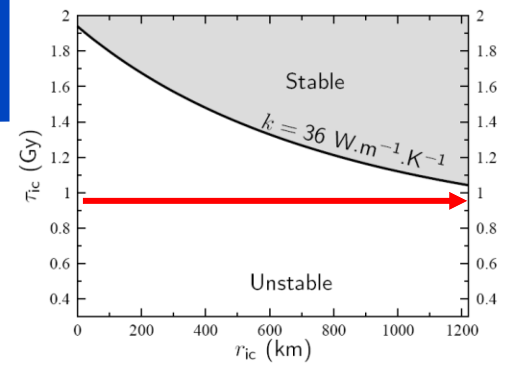
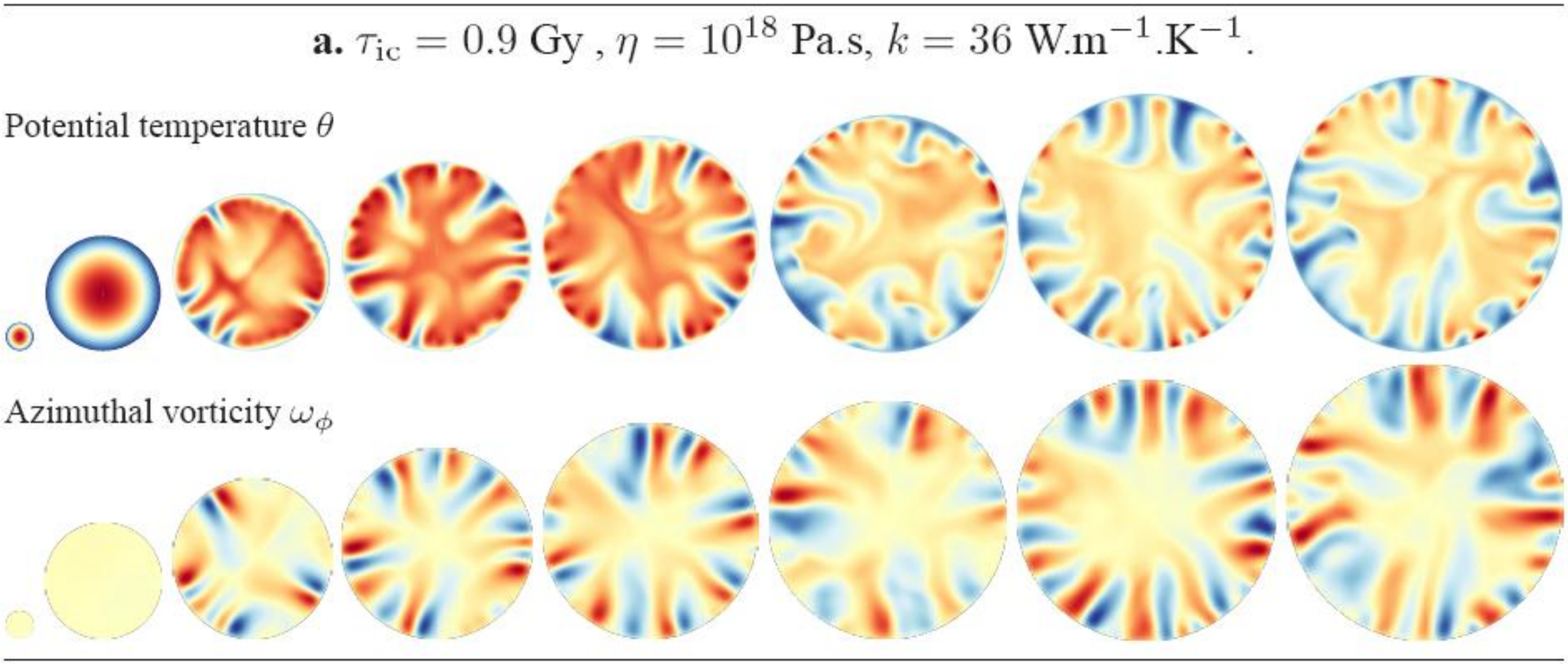
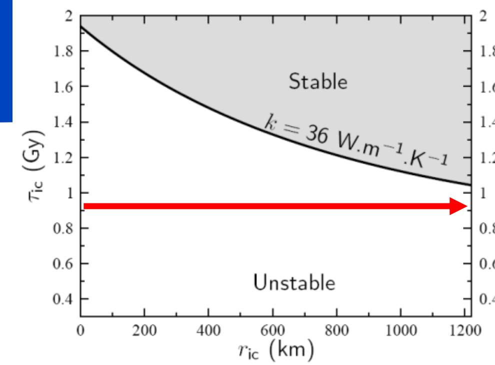
Thermal convection

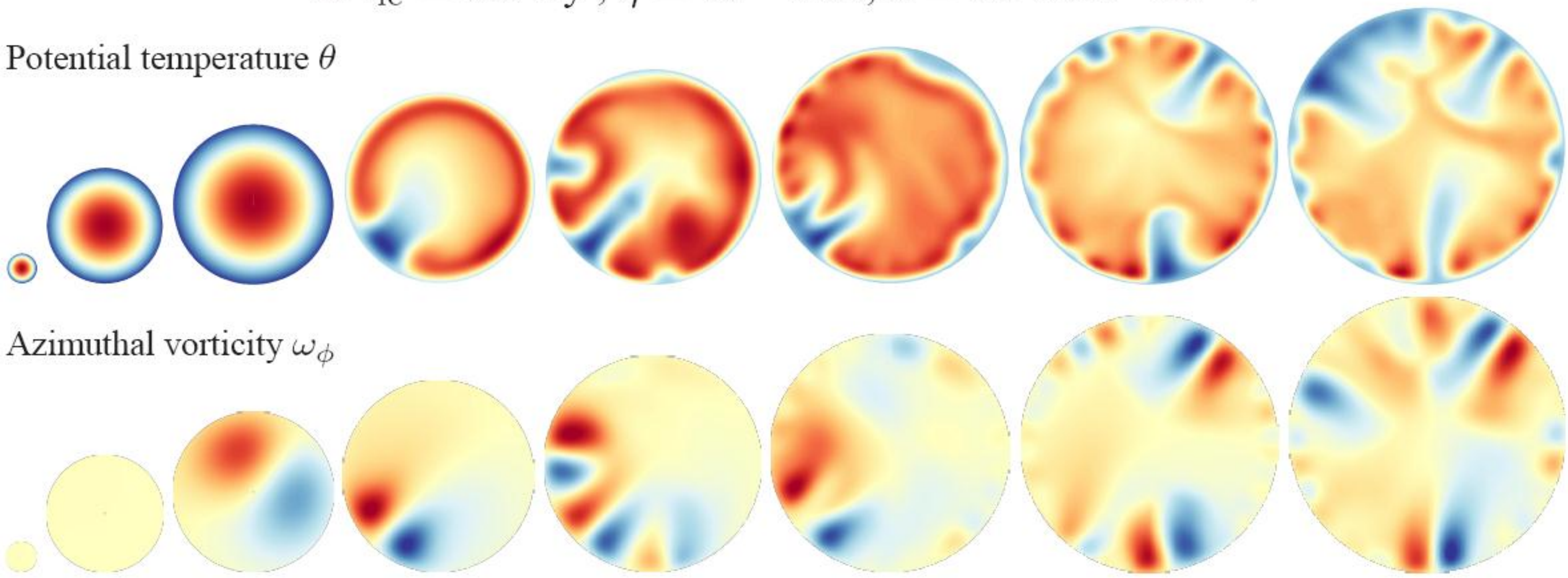




Thermal convection

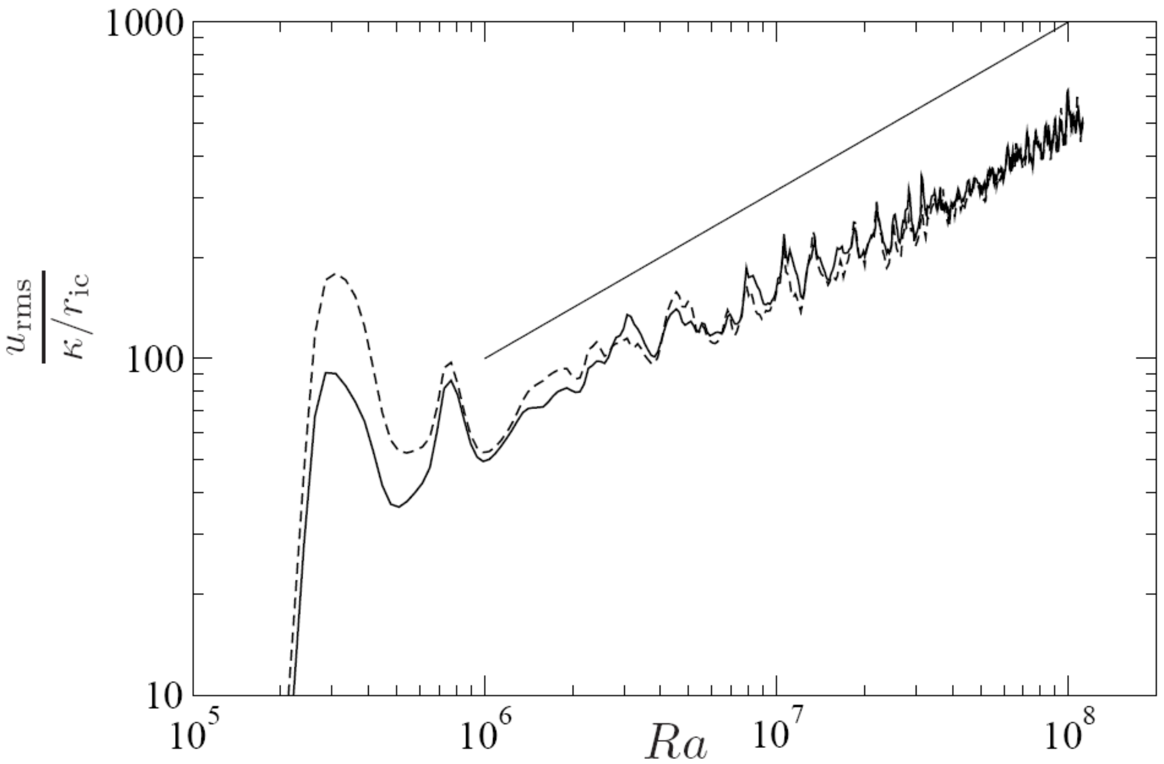


b. $\tau_{ic} = 0.9$ Gy , $\eta = 10^{19}$ Pa.s, $k = 36$ W.m^{-1}.K^{-1}.



Scaling laws

$$u_{rms} \approx 0.04 \frac{\kappa}{r_{ic}} Ra^{0.51}$$



$$u_{rms} \propto Ra^{1/2}$$

Parmentier and Sotin, 2000

$$\delta\theta \approx 1.4 \frac{S r_{ic}}{6\kappa} Ra^{0.27}$$

$$\delta\theta \approx 1 K$$

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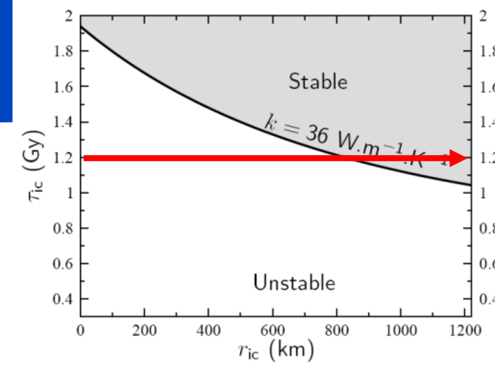
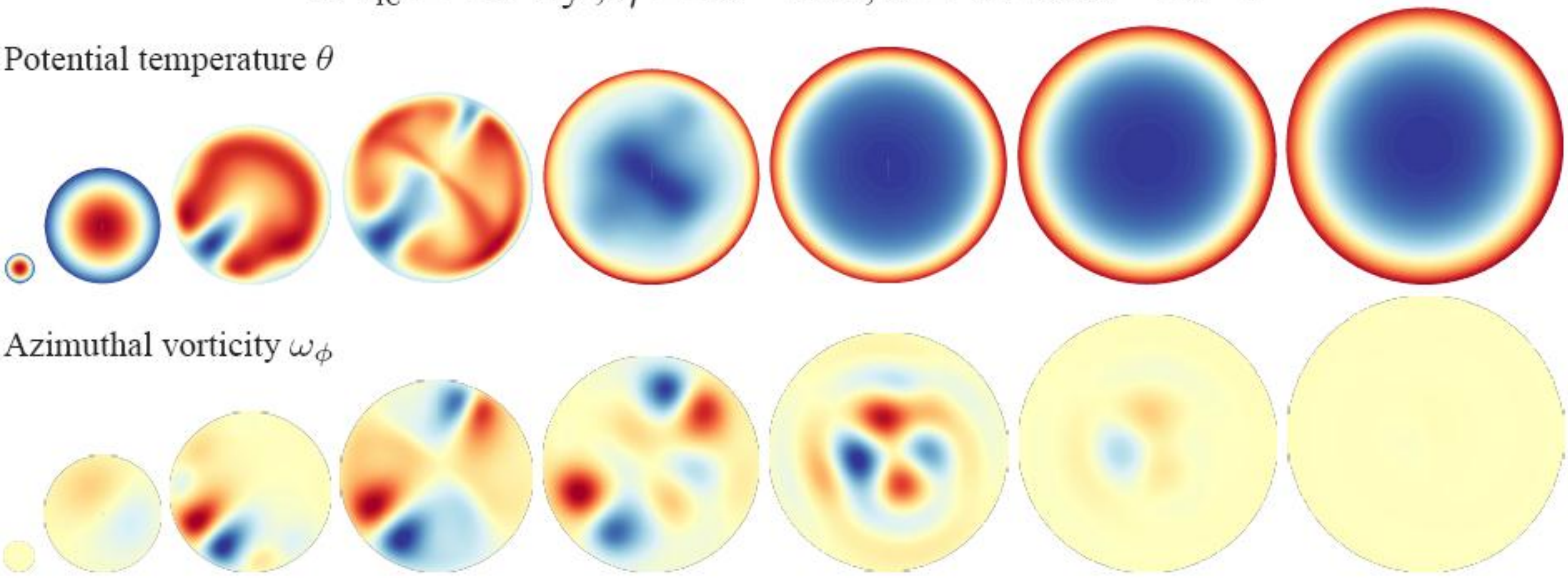
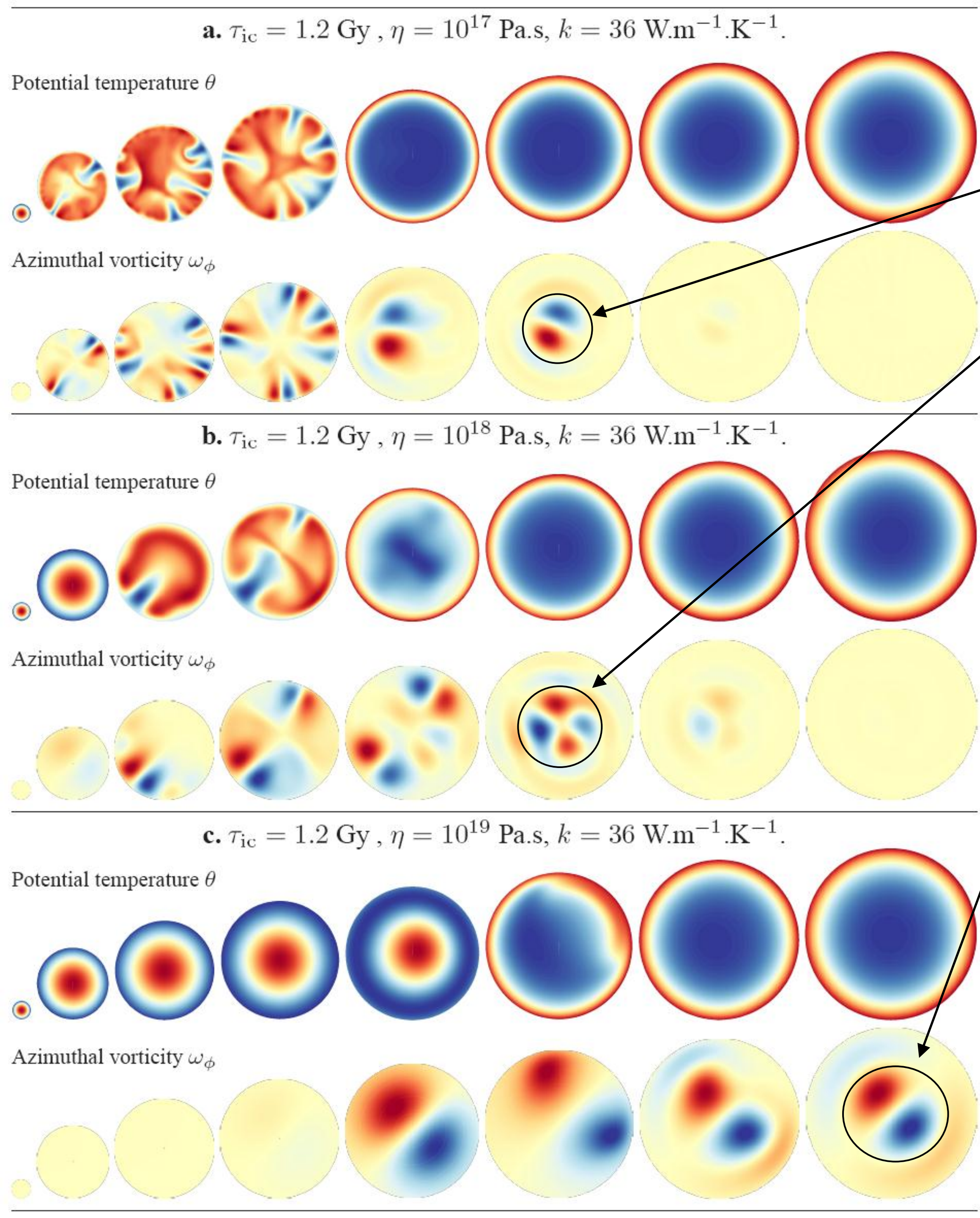
A convective window



b. $\tau_{ic} = 1.2$ Gy , $\eta = 10^{18}$ Pa.s, $k = 36$ W.m^{-1}.K^{-1}.

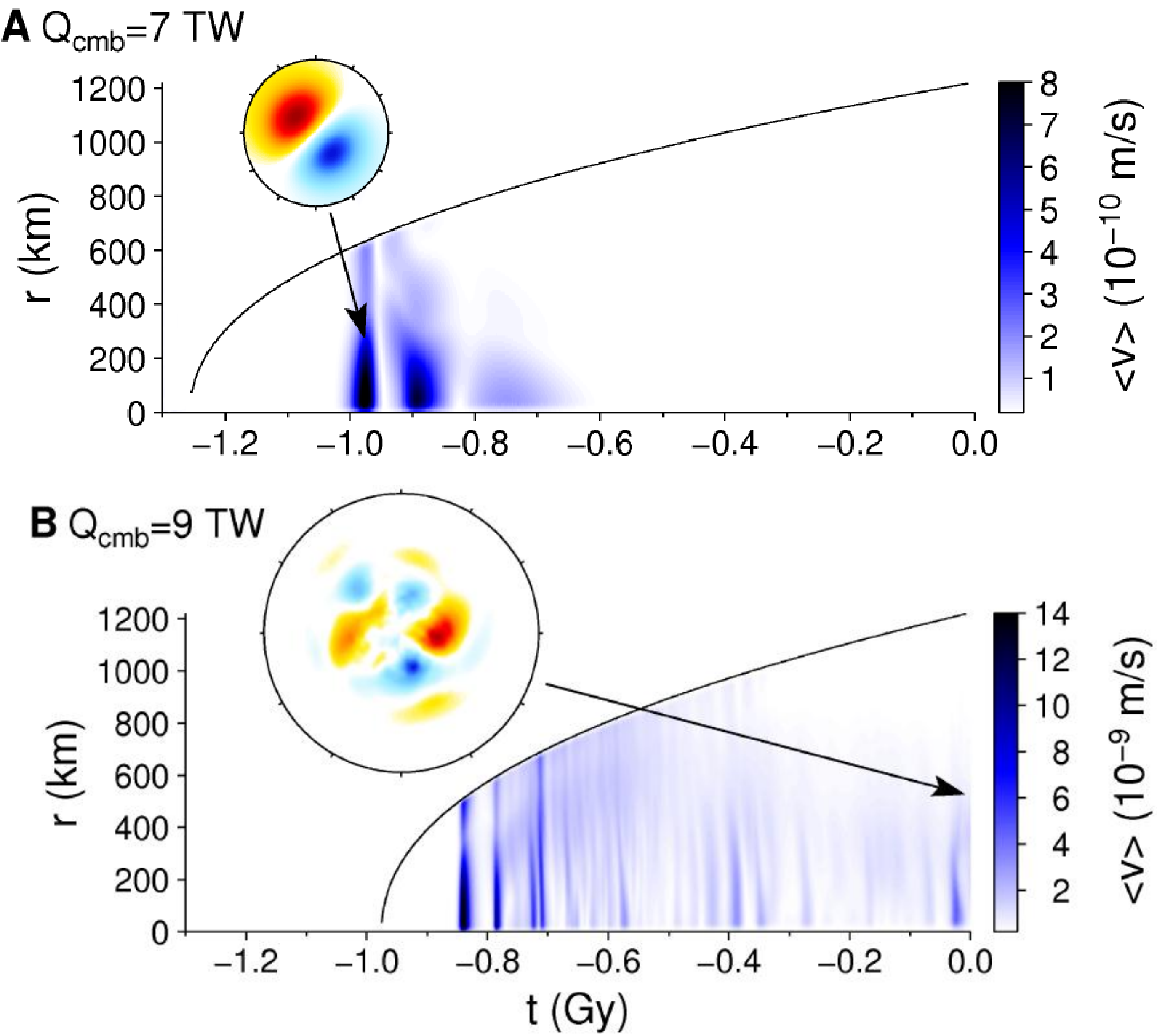




Innermost Inner Core ?

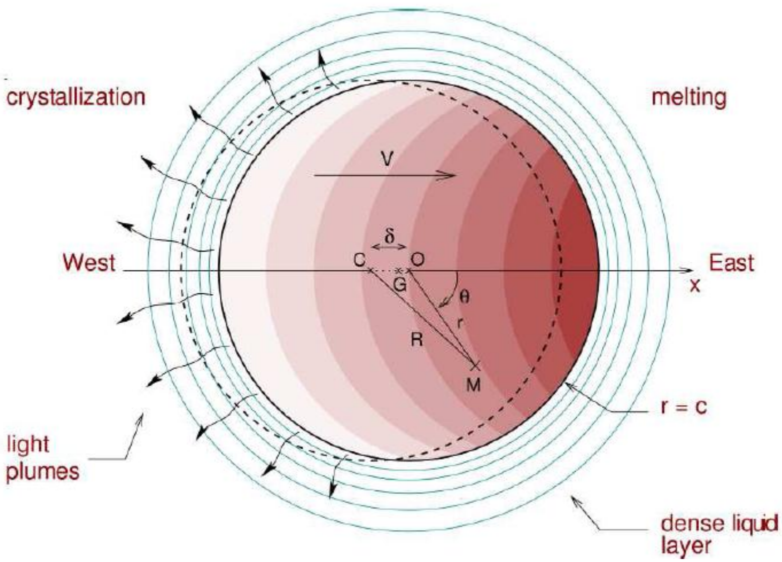
Higher viscosity

IIC: a thermal signature?



Translation of the inner core

- A rigid inner core
- EW pertubation of T, change the density field and the center of mass.
- Allow quick fusion and solidification.
- Misfit between center of mass and "center" of T.
- Archimedean force translate the inner core.



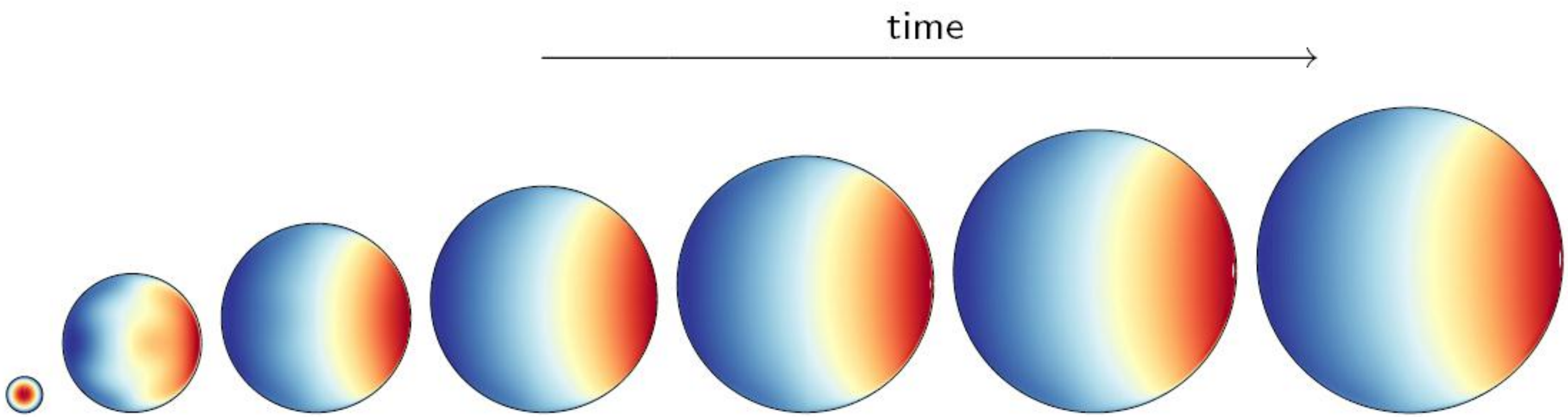
Alboussière et al, 2010

Monnereau et al, 2010

translation

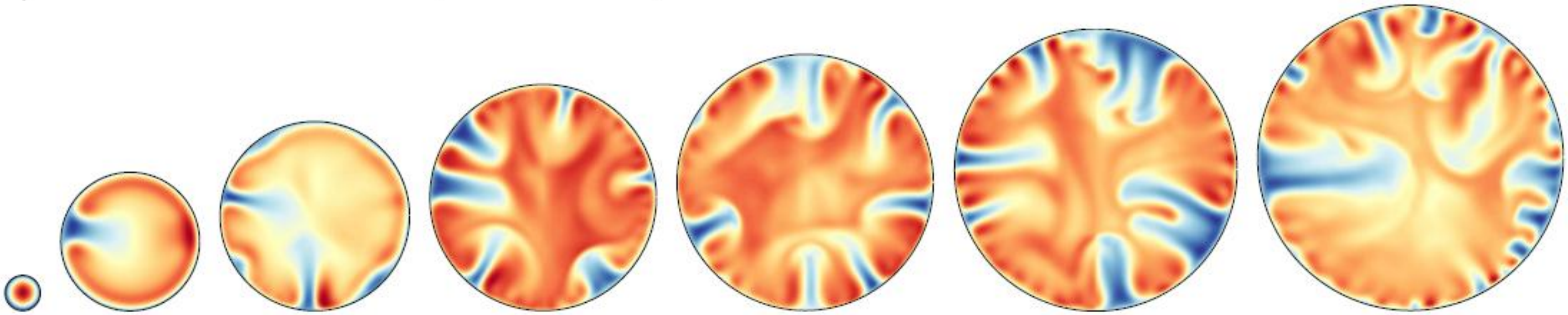
$\tau_{\text{ic}} = 0.9$ Gy , $k = 36$ W.m^{-1}.K^{-1}, potential temperature :

- $\eta = 10^{19}$ Pa.s, translation regime :

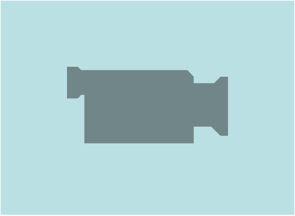


Convection and translation

- $\eta = 3 \times 10^{17}$ Pa.s, chaotic plume convection :



For moderate viscosity, thermal convection and translation together.



Thermal convection in the inner core

- Whole sphere convection with active cold plumes
- Convective time window: signature of the innermost inner core?
- Fusion and solidification may generate a translation regime dor a very viscous inner core.
- Convection and translation may coexist

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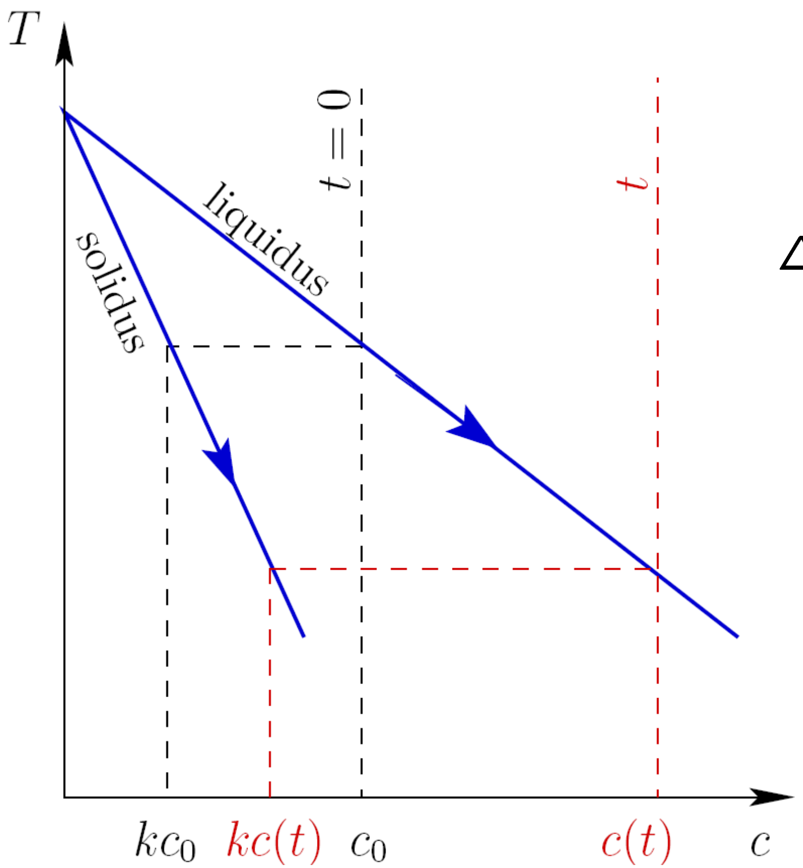
Ligth element in the core

$$c(t) = c_0 \left[\frac{r_c^3 - r_{ic}^3}{r_c^3}\right]^{k-1}$$

k, partition cœfficient



$$\begin{aligned}\Delta\rho(t) &= \beta\rho k c_0 \left[\left(1 - \left(\frac{r_{ic}}{r_c}\right)^3\right)^{k-1} - 1\right] \\ &\sim \beta\rho c_0 k(1-k)\left(\frac{r_{ic}}{r_c}\right)^3\end{aligned}$$

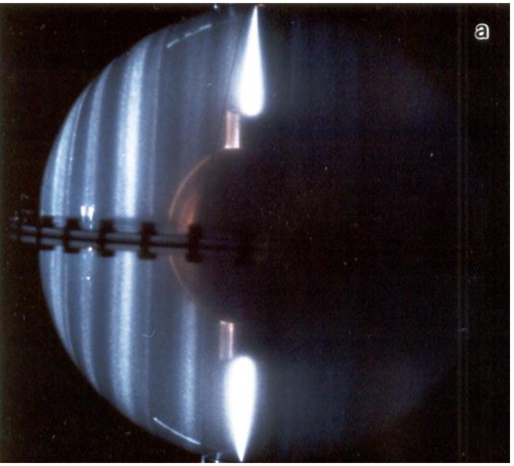
$$\beta = \frac{1}{\rho}\frac{\partial\rho}{\partial c}$$

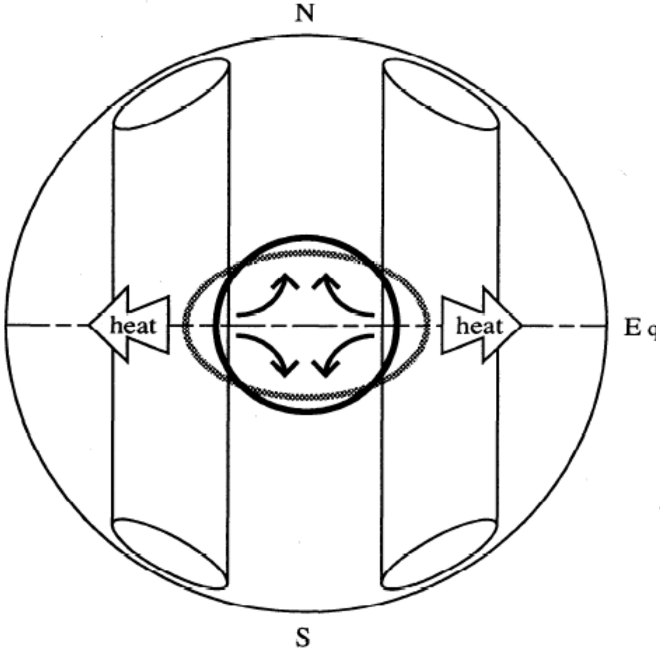
k_{Si} ~ k_S ~ 0.8, k_O ~ 2.5 10-3

(Alfè et al, 2002)

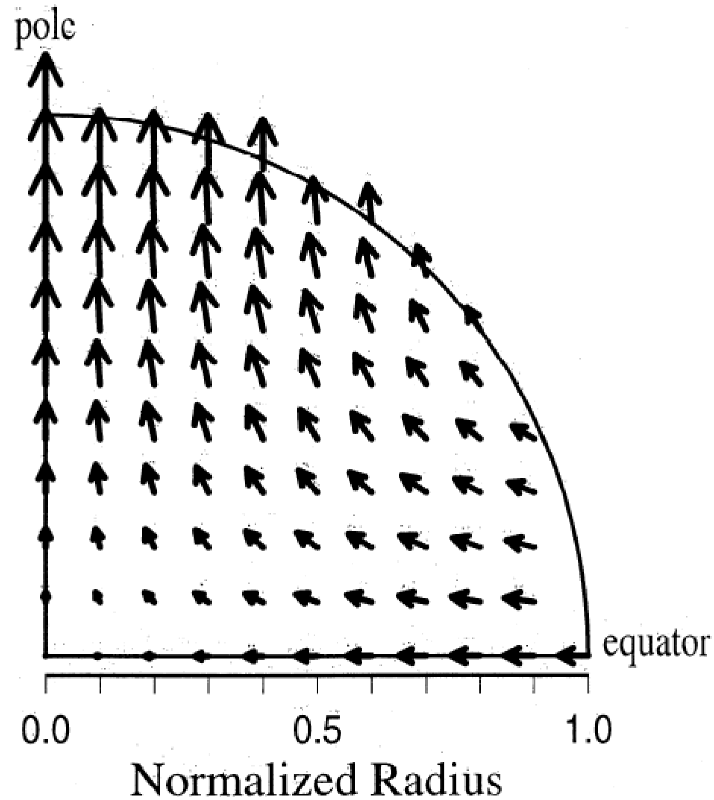
$$\Delta\rho \sim -5kg/m^3$$

Equatorial growth





Yoshida et al, 1996



$$B = \frac{g(t)\ \beta\ \rho\ \Delta c(t)\ r_{ic}(t)^2}{\eta\ u_{ic}(t)}$$

$$S_2 = 2/5$$

The rate of cristalisation in the equator is twice the polar one

$$u_r(r_{\mathrm{ic}}, \theta) = -S_2 u_{\mathrm{ic}} P_2(\cos\theta)$$

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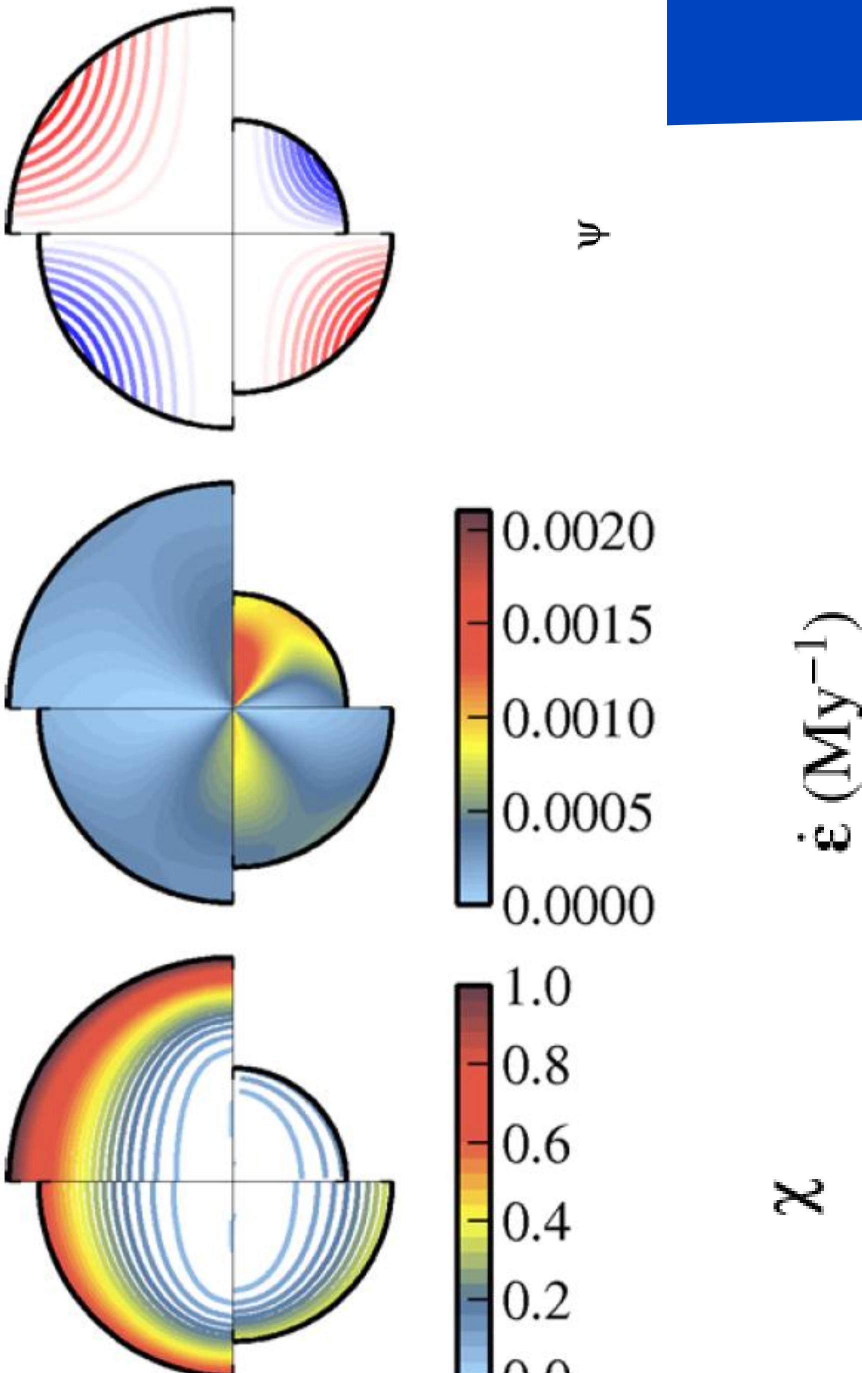
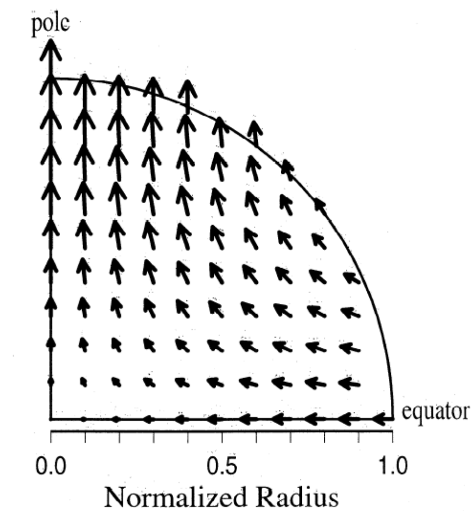
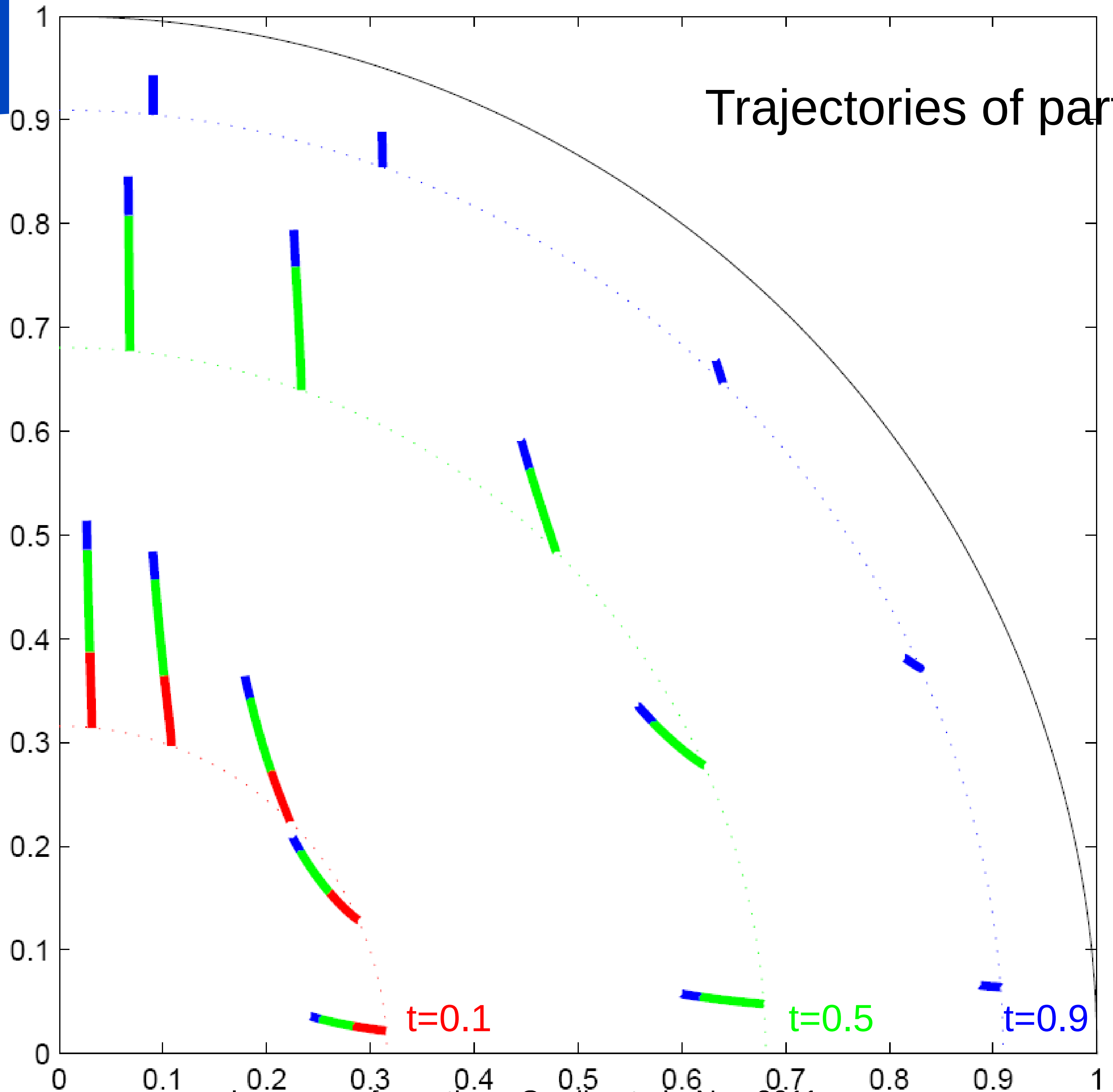


No stratification



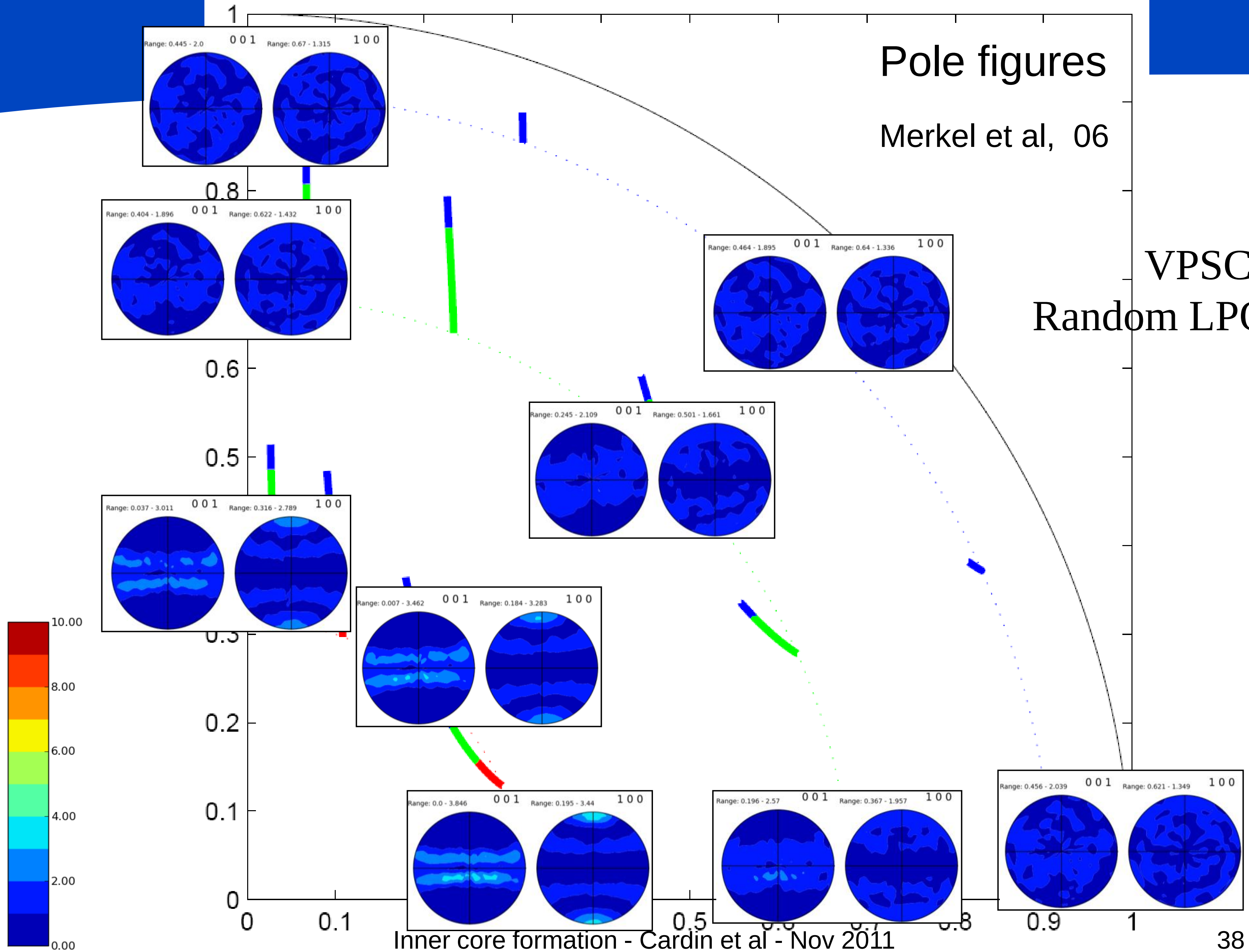
Trajectories of particles

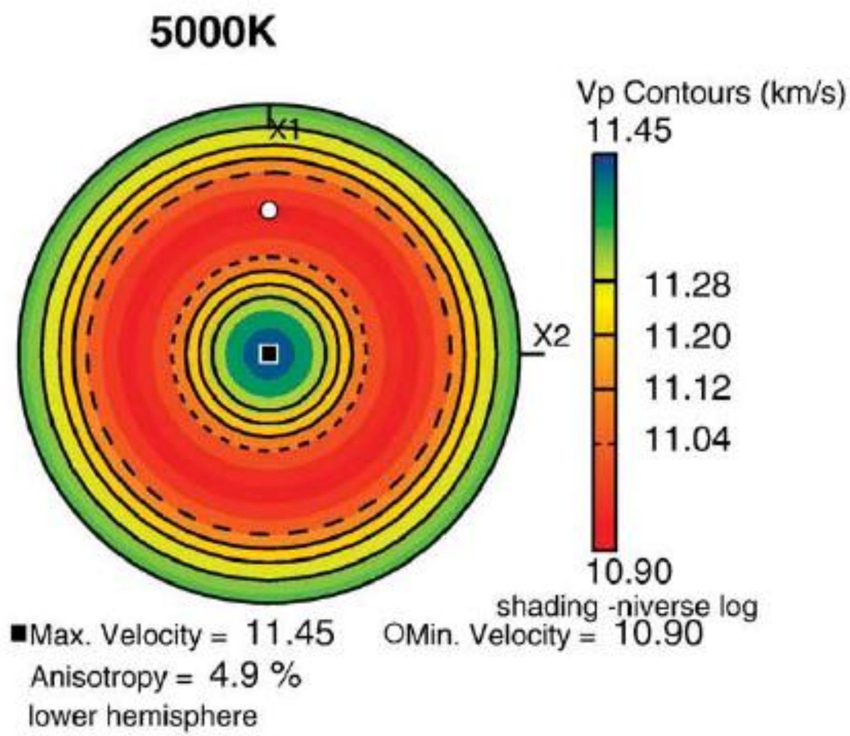


Pole figures

Merkel et al, 06

VPSC
Random LPO





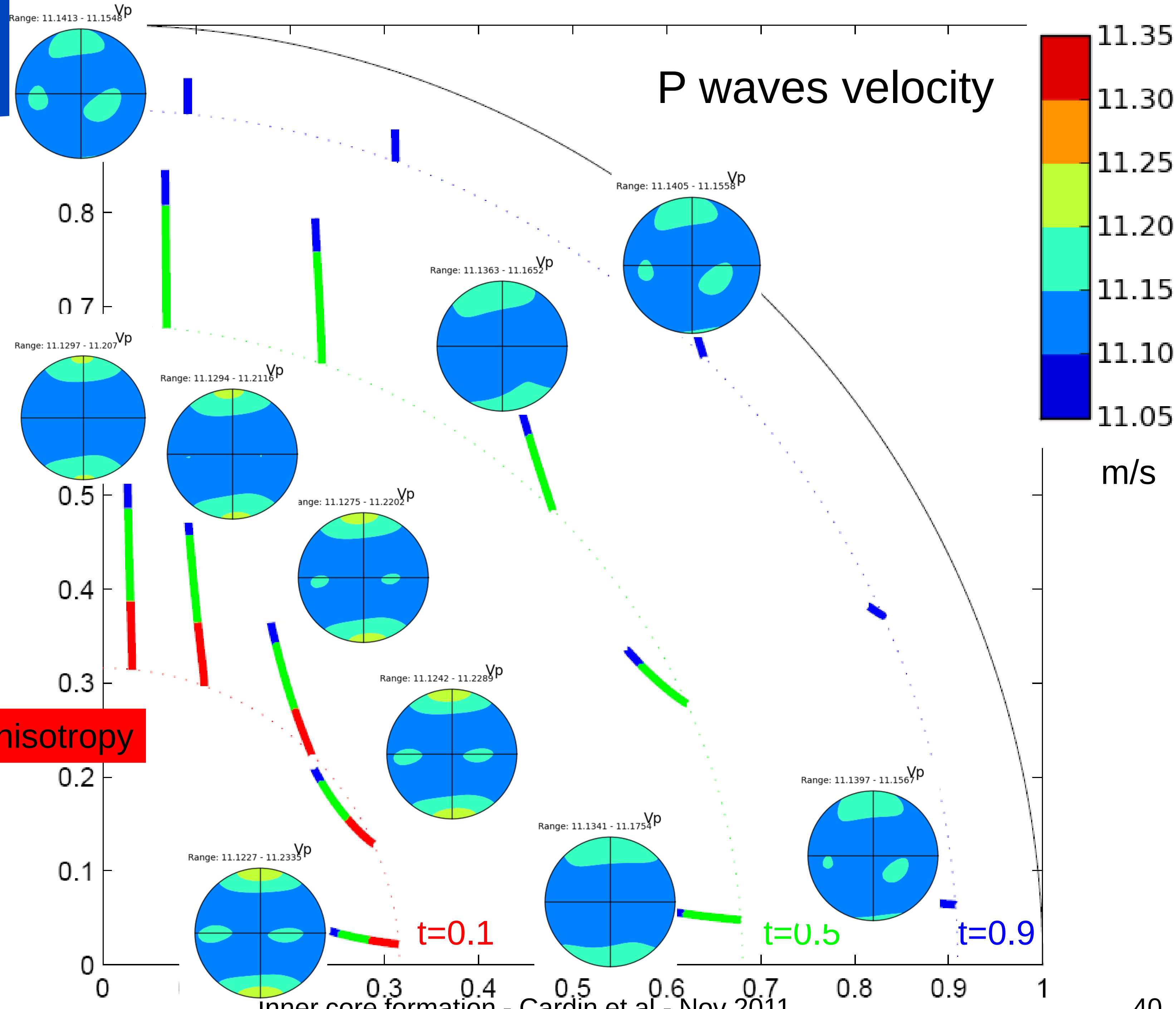
Vocadlo et la, 09

L. Vočadlo et al. / Earth and Planetary Science Letters 288 (2009) 534–538 535

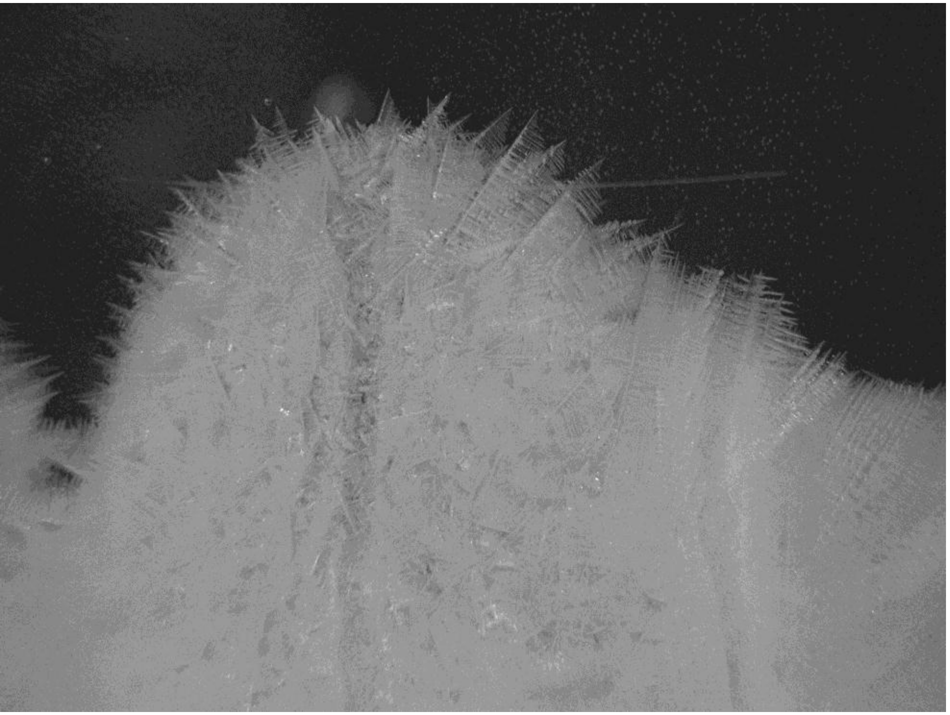
Table 1
Isothermal elastic constants (in GPa), adiabatic incompressibility, shear modulus and sound velocities for hcp-Fe as a function of temperature.

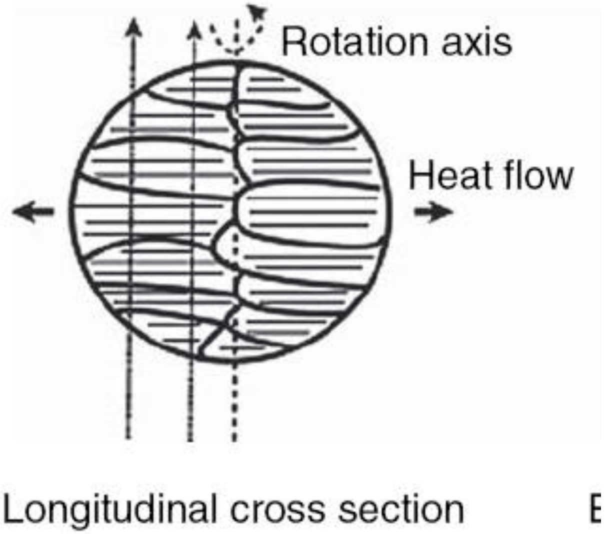
T (K)	c/a	ρ (kgm^{-3})	P (GPa)	c_{11}	c_{33}	c_{12}	c_{23}	c_{44}	c_{66}	K_S (GPa)	G (GPa)	V_P (kms^{-1})	V_S (kms^{-1})
0	1.585	13698	295	2205	2418	1053	950	479	576	1419	564	12.59	6.42
2000	1.59	13401	290	1998	2183	1111	986	375	444	1412	444	12.23	5.75
3000	1.60	13324	293	1915	2109	1121	986	313	397	1407	394	12.05	5.44
4000	1.61	13236	298	1830	1905	1150	1004	248	340	1399	328	11.78	4.98
5000	1.62	13154	308	1689	1725	1186	990	216	252	1365	266	11.44	4.50
5500	1.62	13155	316	1646	1559	1253	995	153	197	1363	208	11.17	3.97

c_{66} is not independent and is equal to 1/2 ($c_{11} - c_{12}$). Uncertainties in c_{ij}<2.5%; uncertainties in V_P and V_S are ~1%. The values for c/a were taken from Gannarelli et al. (2005).



<1% of anisotropy



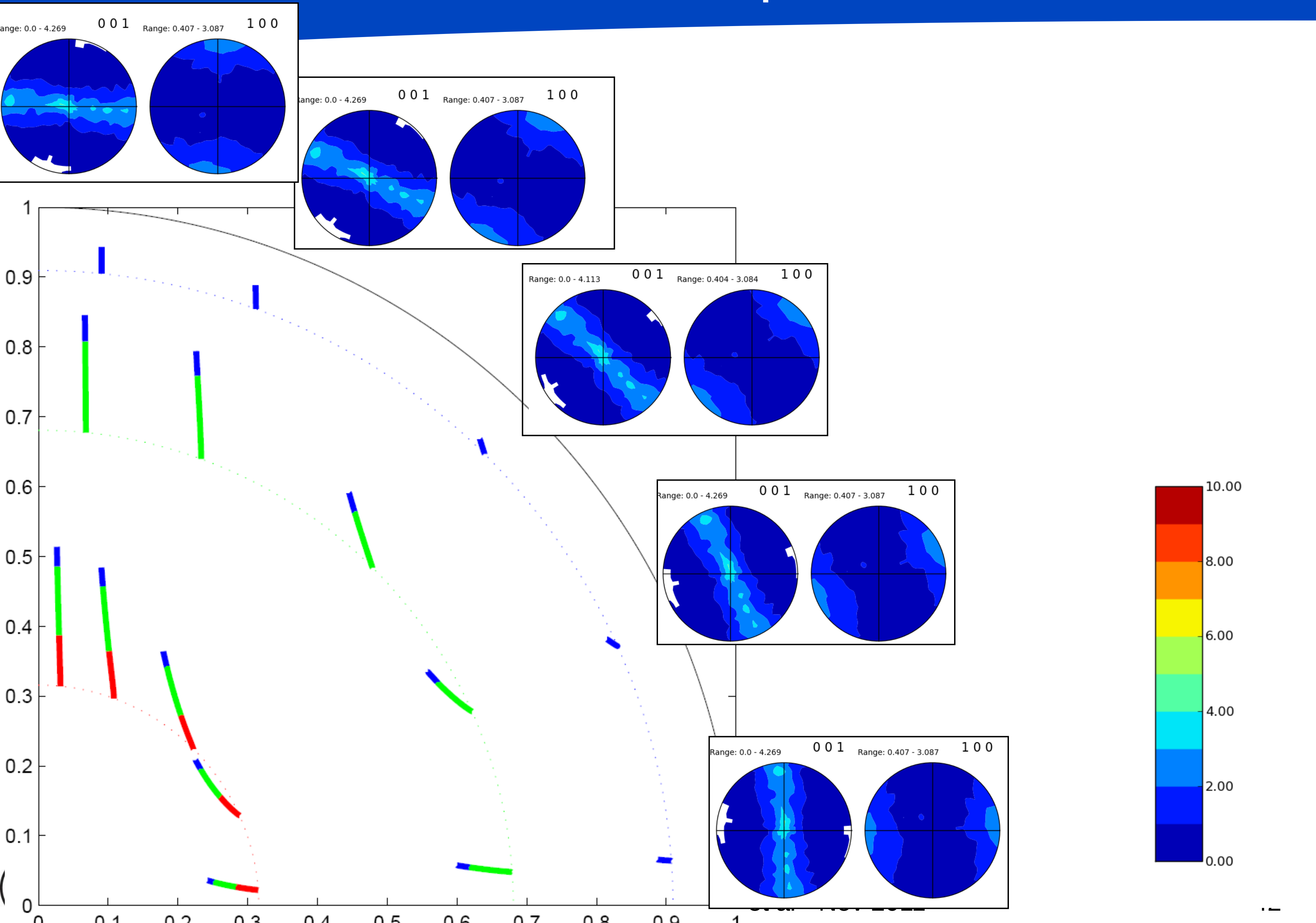


Bergman, 97

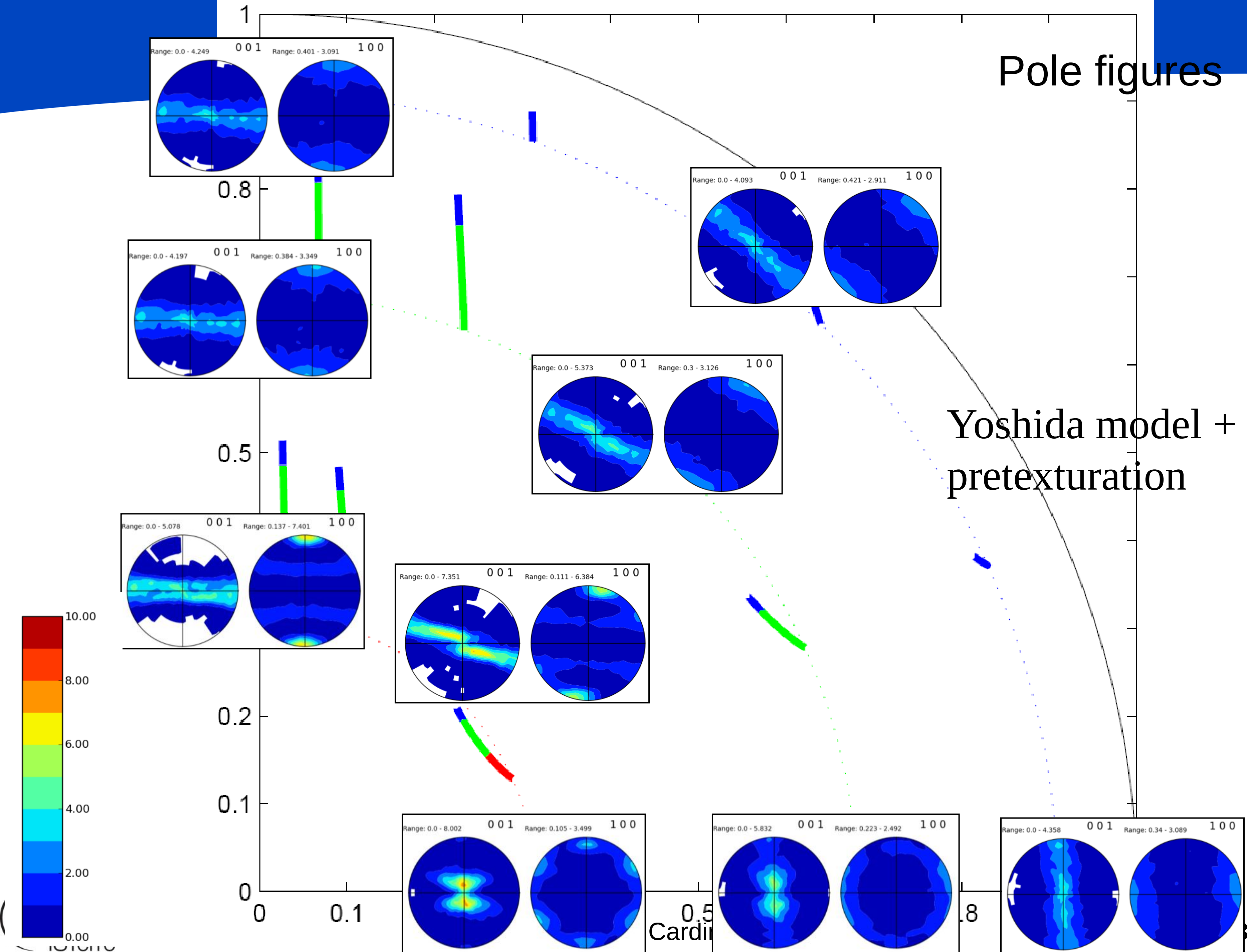
Deguen, 09

C axes parallel to cristallisation front

Surface pretexturation

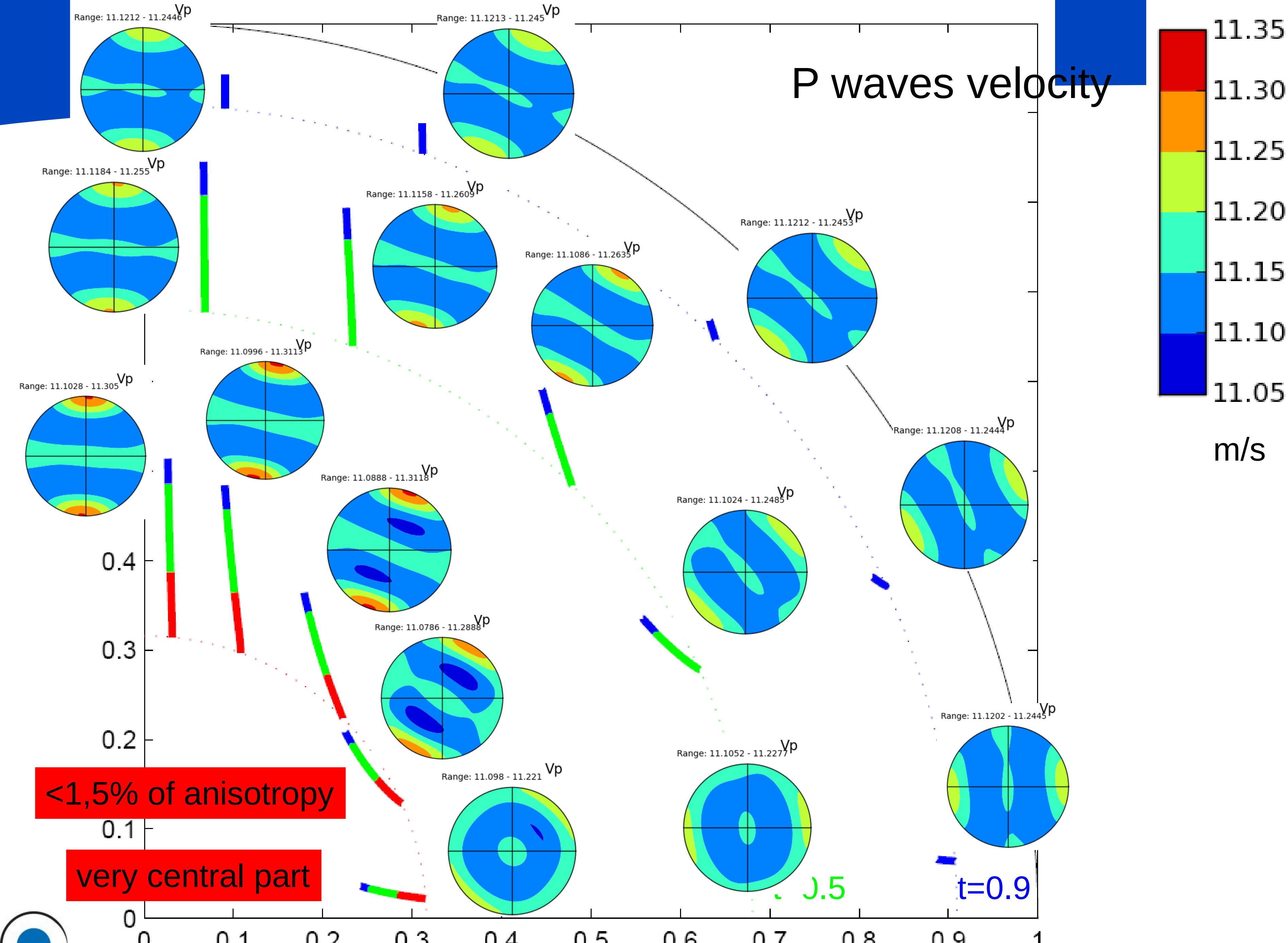


Pole figures



Yoshida model + pretexturation

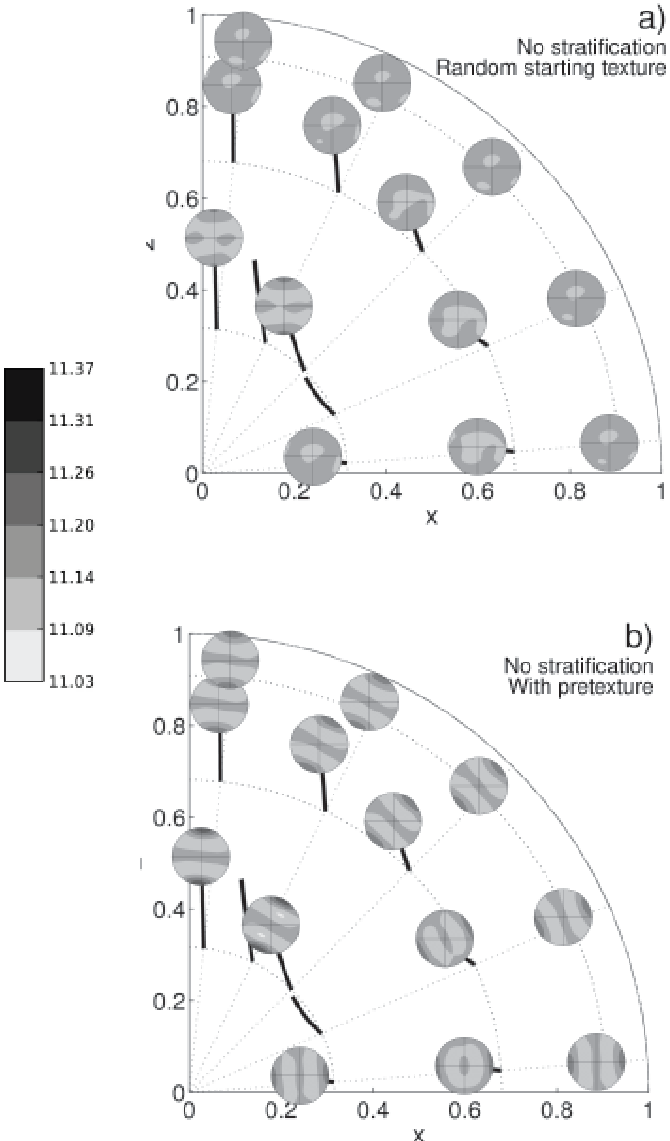
P waves velocity

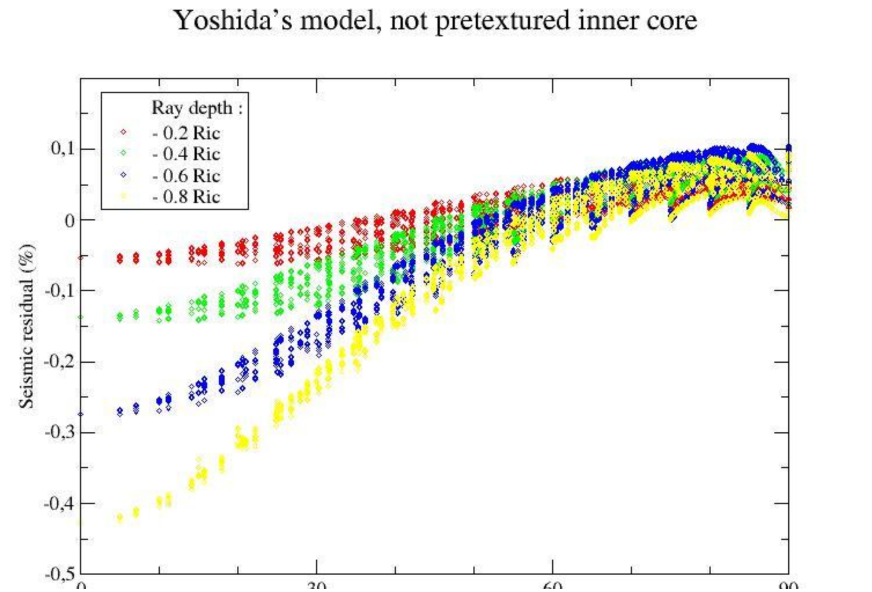


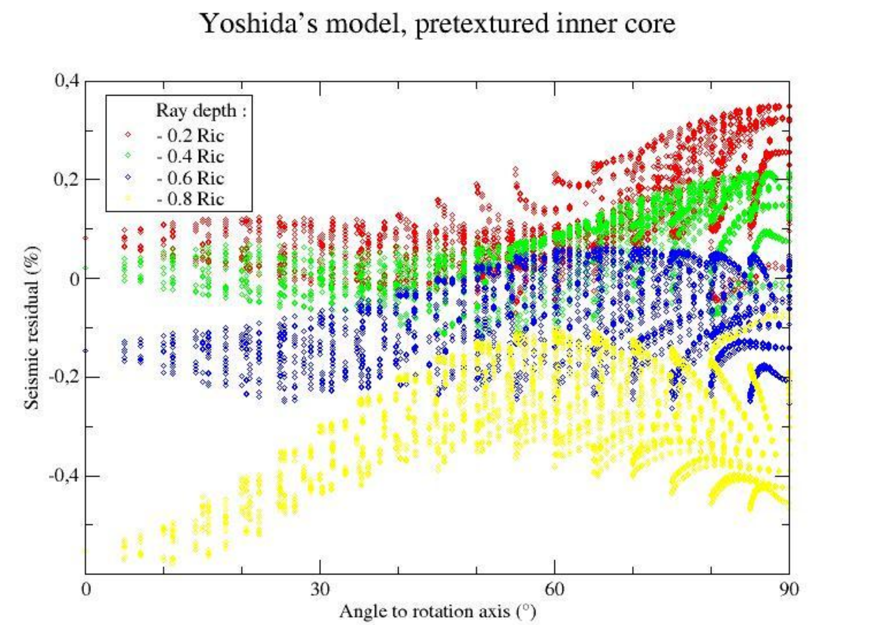
<1,5% of anisotropy

very central part

Residuals for Yoshida model

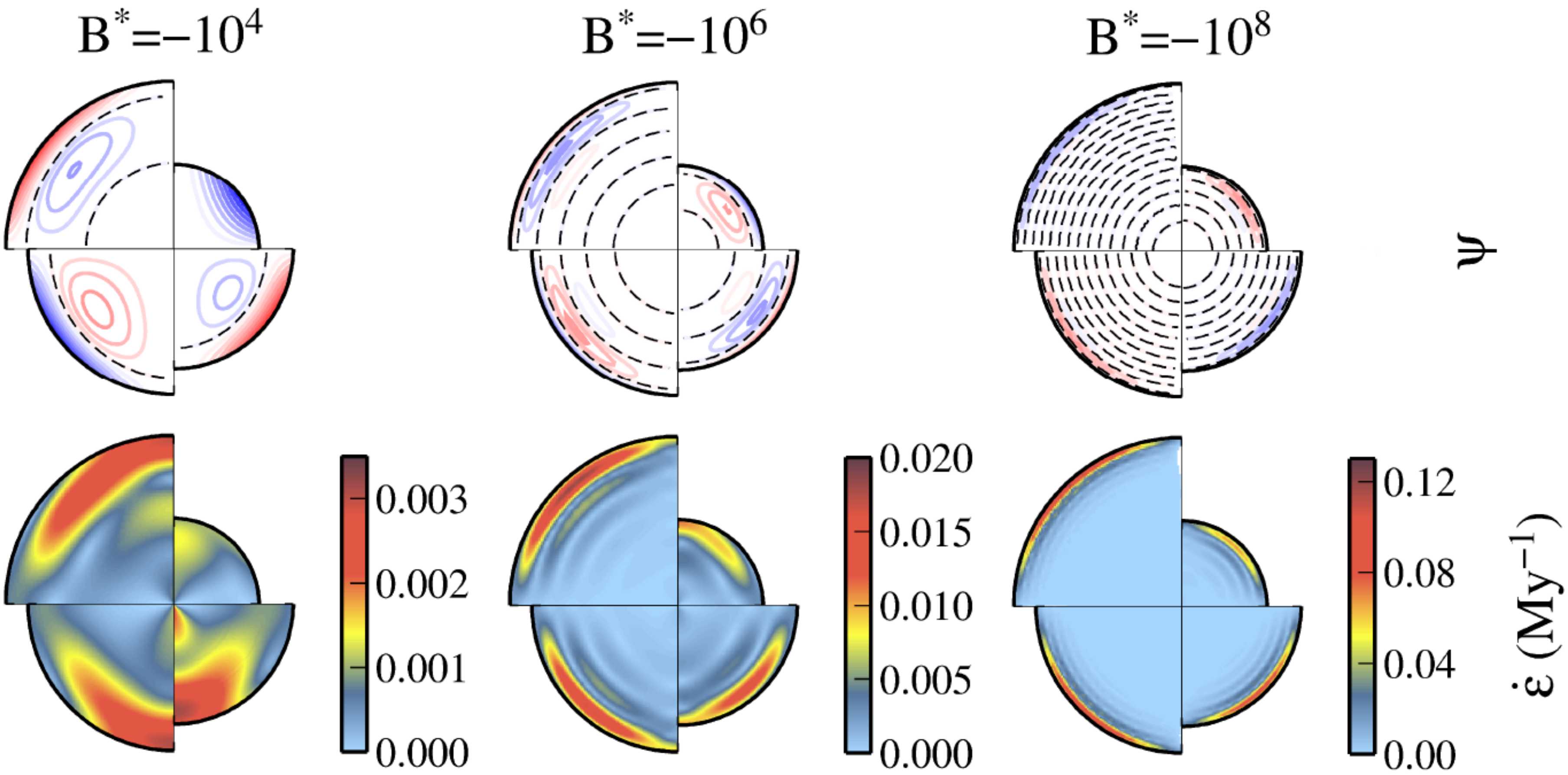






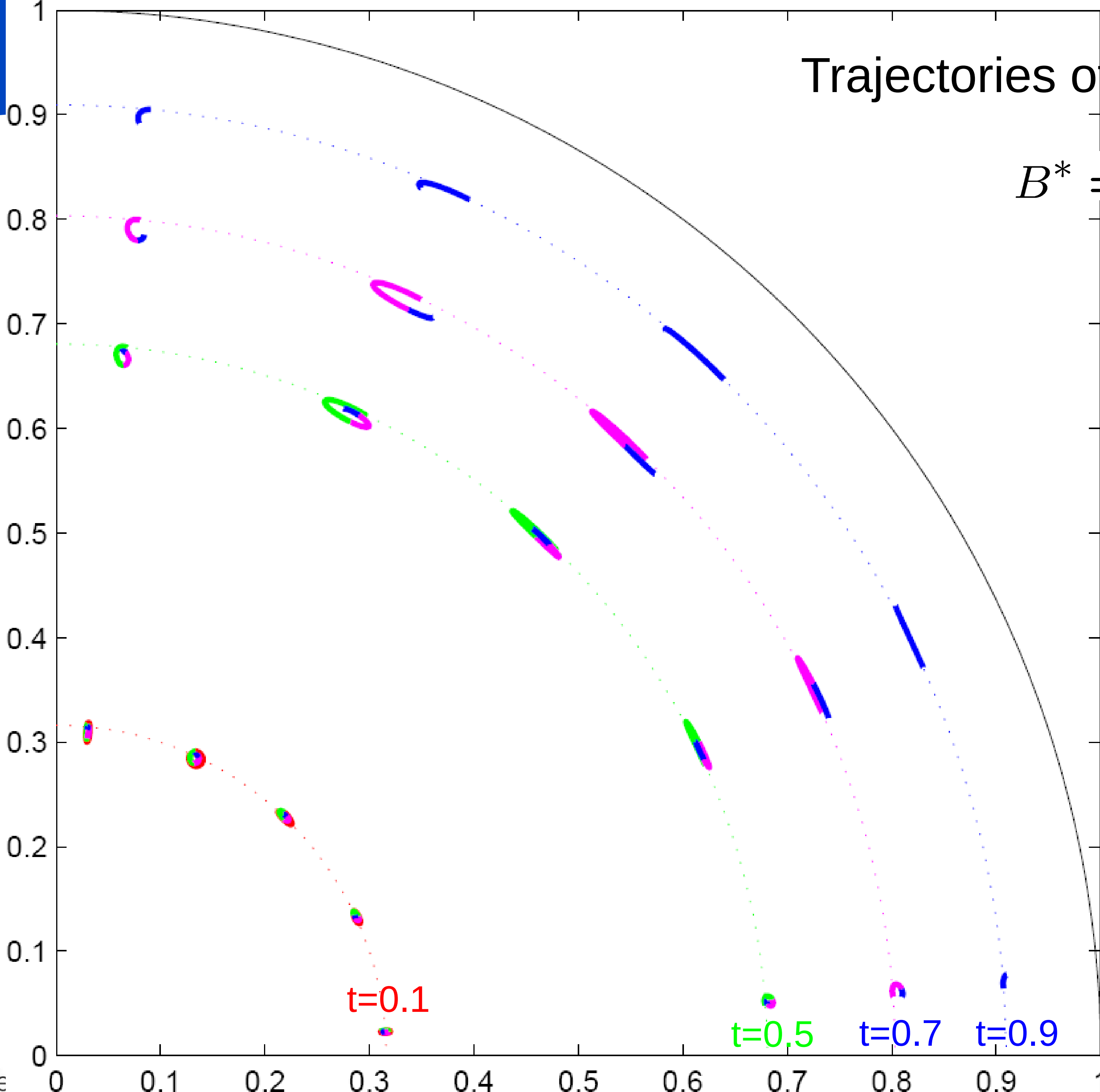
Stratified models

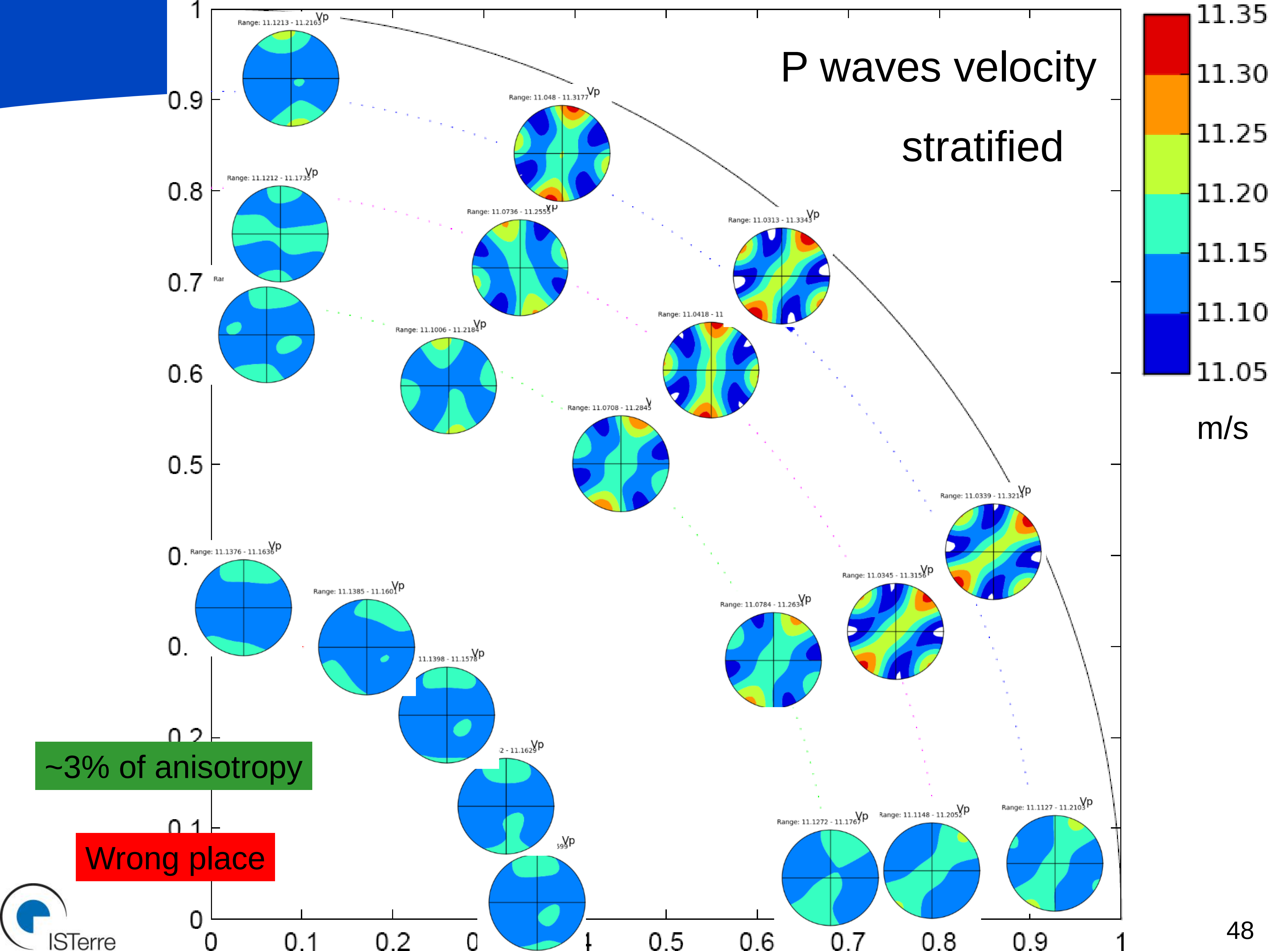
More and more stratification



Trajectories of particules

$B^* = -10^6$



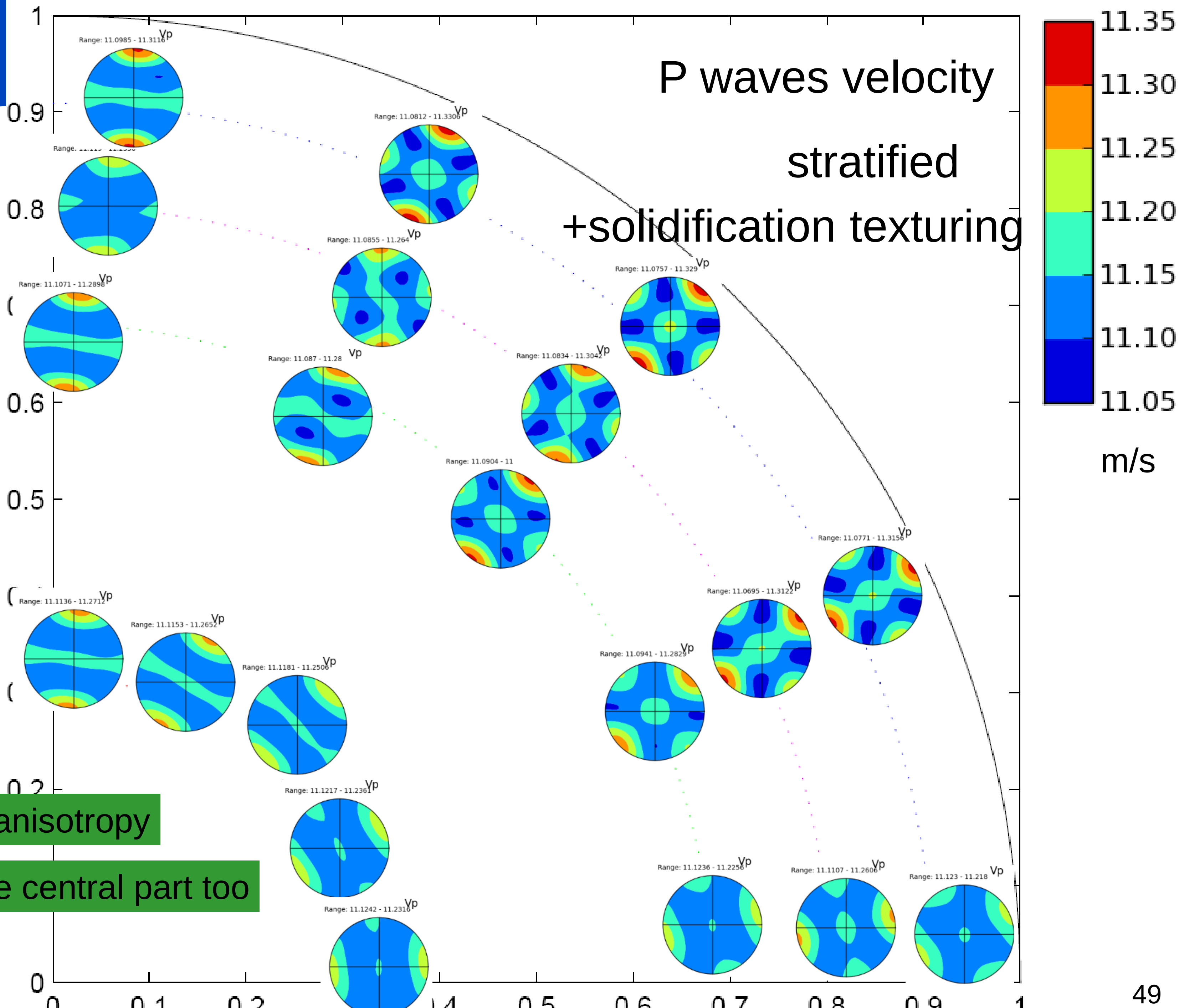

P waves velocity
stratified
11.35
11.30
11.25
11.20
11.15
11.10
11.05
m/s
~3% of anisotropy
Wrong place

ISTerre

P waves velocity

stratified

+solidification texturing



~3% of anisotropy

In the central part too

ISTerre

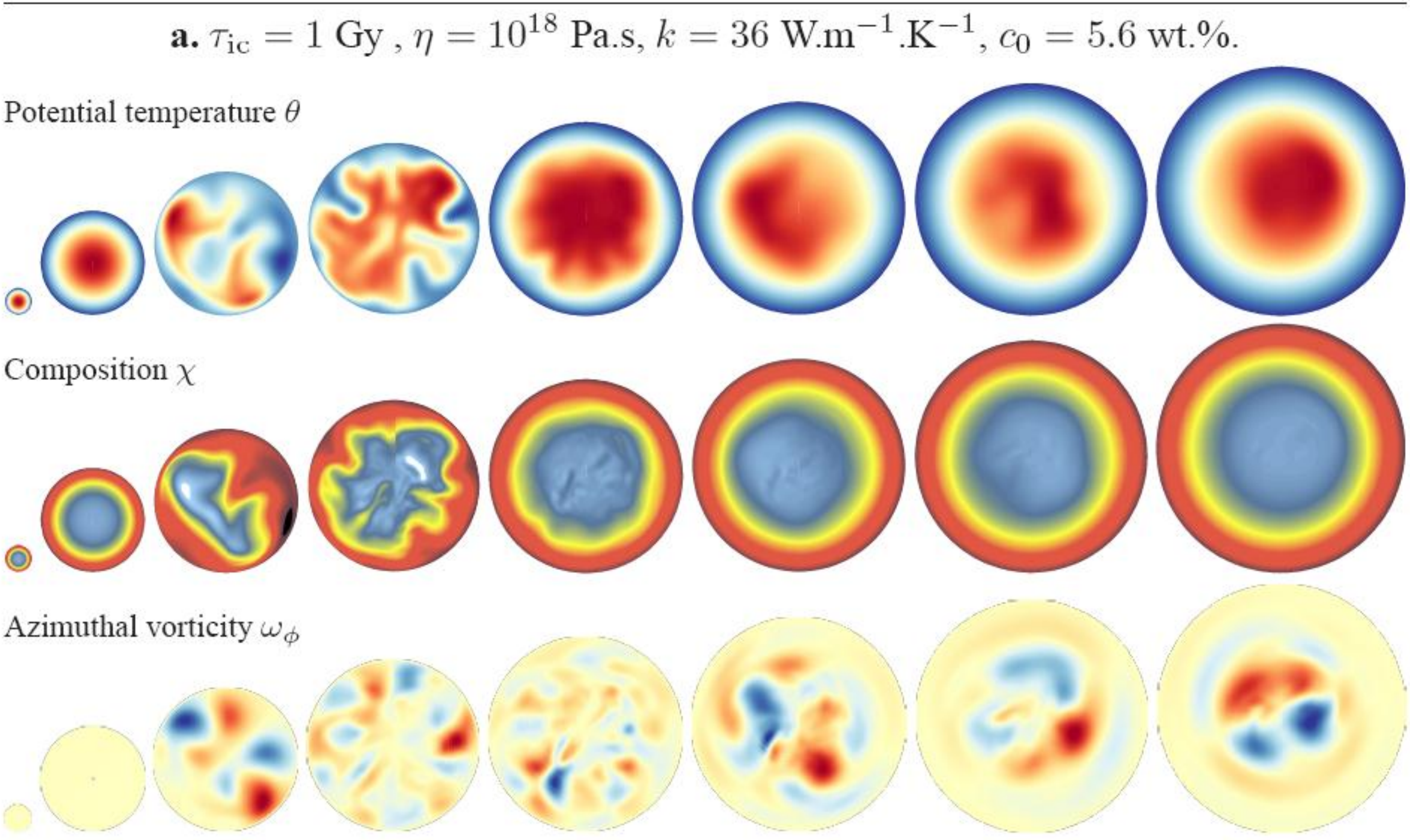
Stratified inner core and equatorial growth

- Stratification inhibits radial motion
- Superficial layer with larges stresses
- With no stratification, anisotropy is too small
- Stratification and solidification texture produce Vp maps compatible to seismic observation.

Outline

1. Seismological observations, anisotropy
2. Review of proposed mechanism
3. Dynamical state of the inner core
4. Thermal convection in the inner core
5. Stratified inner core and equatorial growth
6. Perspectives

Double diffusive convection



References

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- Texturing in the Earth's inner core due to preferential growth in its equatorial belt, R. Deguen, Ph. Cardin, S. Merkel, R. Lebensohn, PEPI, 2011
- Thermo-chemical convection in the Earth's inner core, R. Deguen and P. Cardin, Geophysical Journal International, 2011
- Thèse en cours Ainhoa Lincot