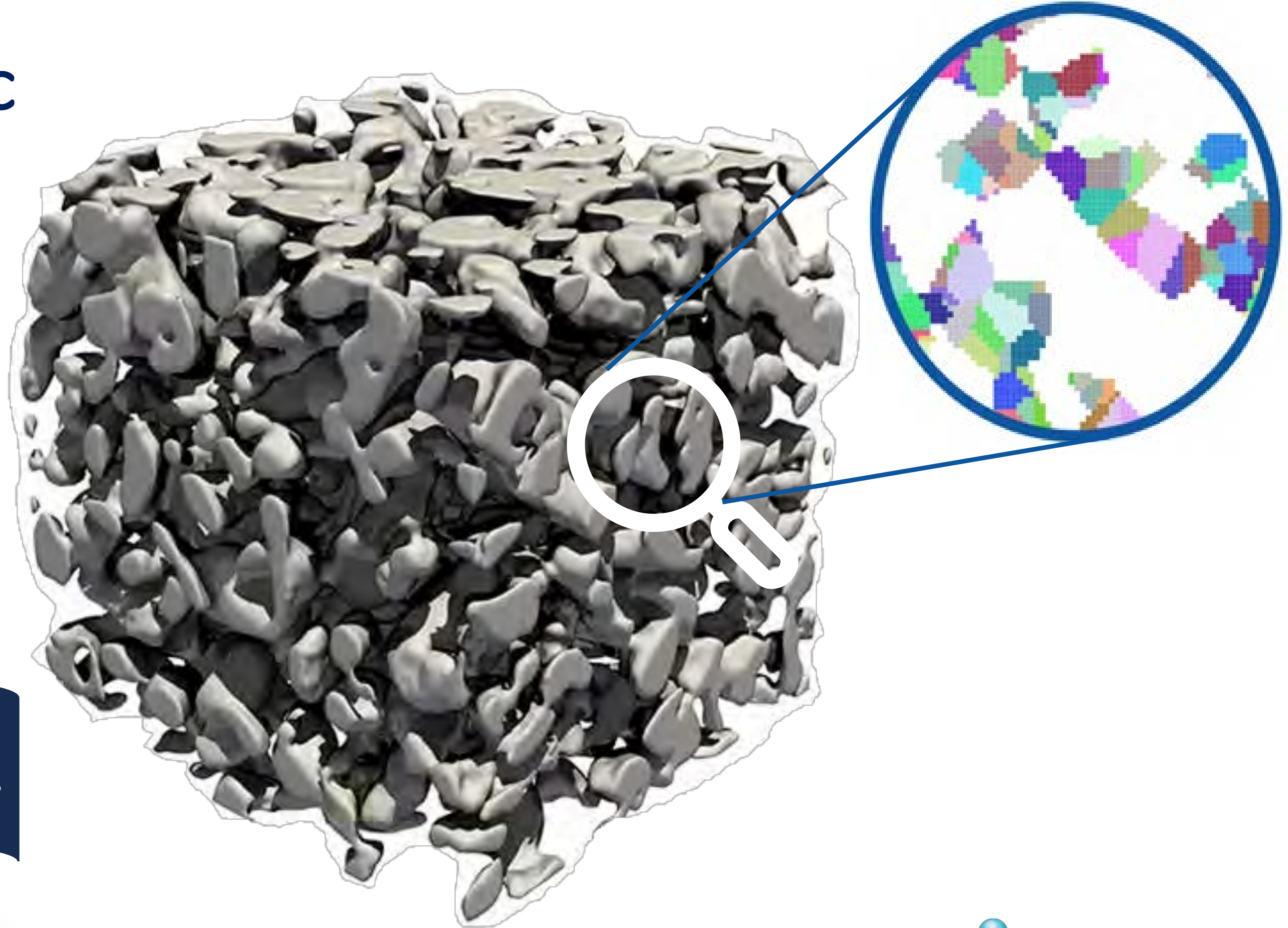
The Dual Geometric and Crystalline Structure of Snow controls its evolution.



Louis Védrine

Atelier Neige

27/03/2025

Avec Pascal H. et Henning L., Oscar D., Maurine M., Benoit L., Kevin F., Antoine B., Mathilde B., Lionel G., Emmanuel R.

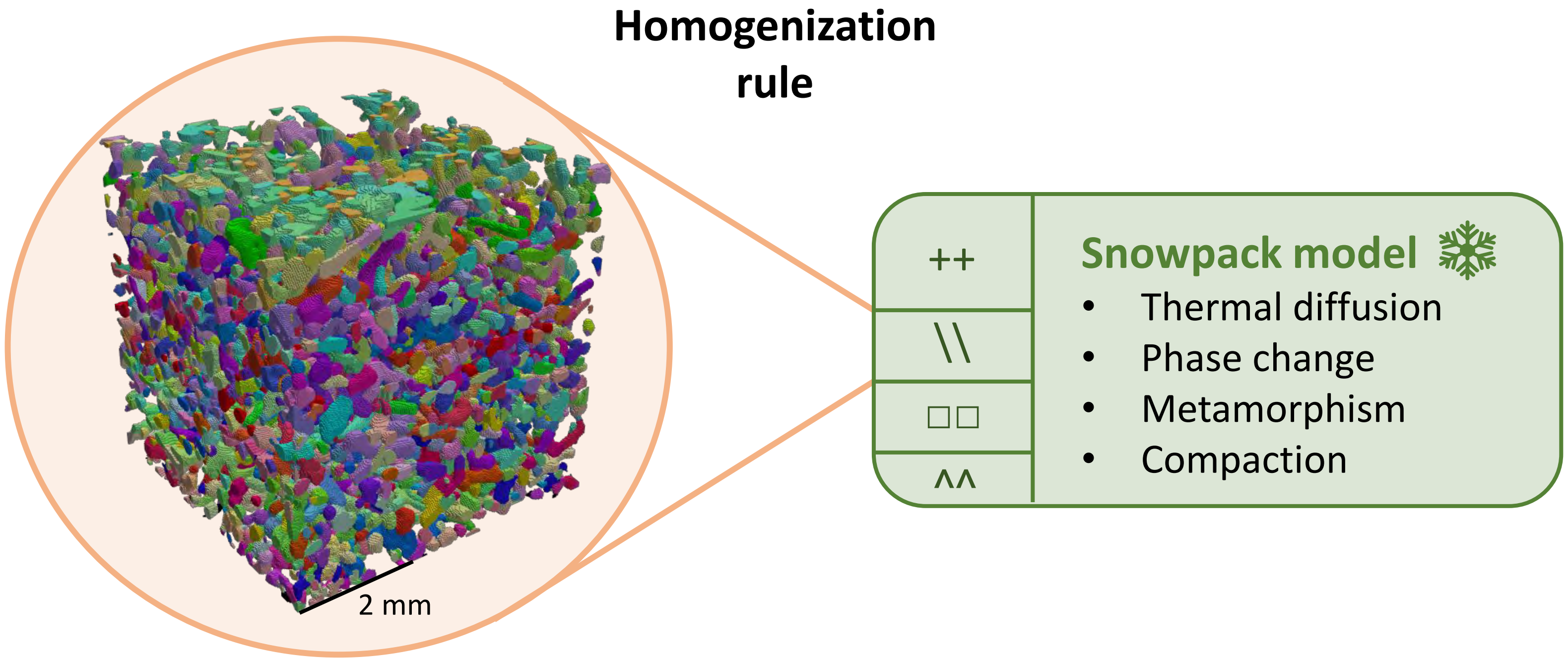
Context: Snow evolution at different scales

++ \\ □□ ^^	**Snowpack model** ❄ • Thermal diffusion • Phase change • Metamorphism • Compaction

$10^{-1} - 1$ **Scale (m)**

Snowpack model

Context: Snow evolution at different scales

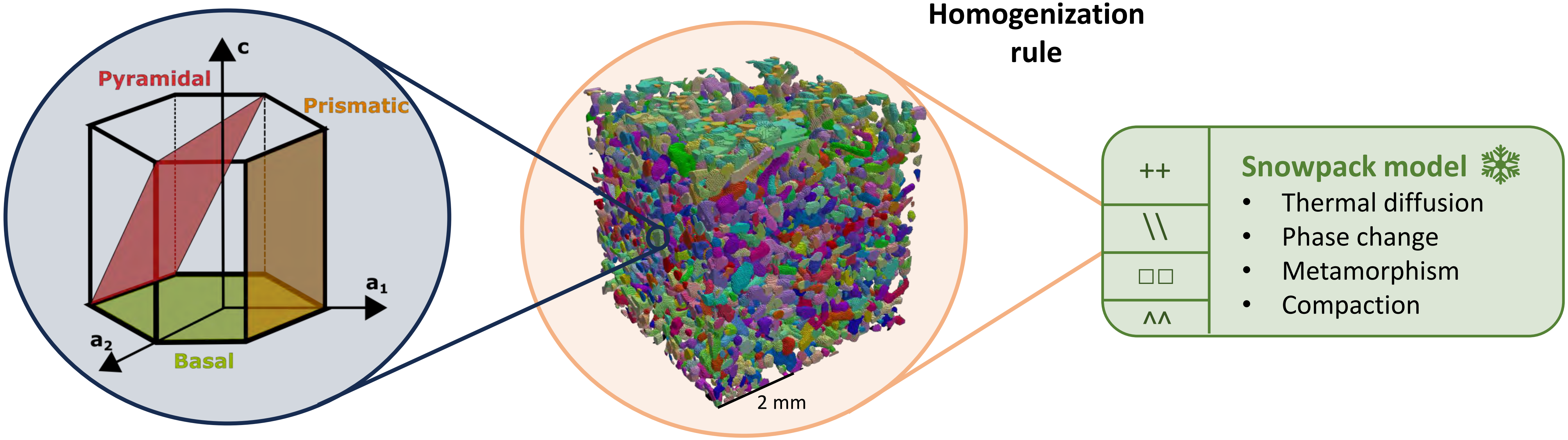


$10^{-3} - 10^{-2}$ $10^{-1} - 1$ **Scale (m)**

Microstructure scale
Fabric
Effect of geometric structure

Snowpack model

Context: Snow evolution at different scales



$10^{-6} - 10^{-4}$ | $10^{-3} - 10^{-2}$ | $10^{-1} - 1$ | **Scale (m)**

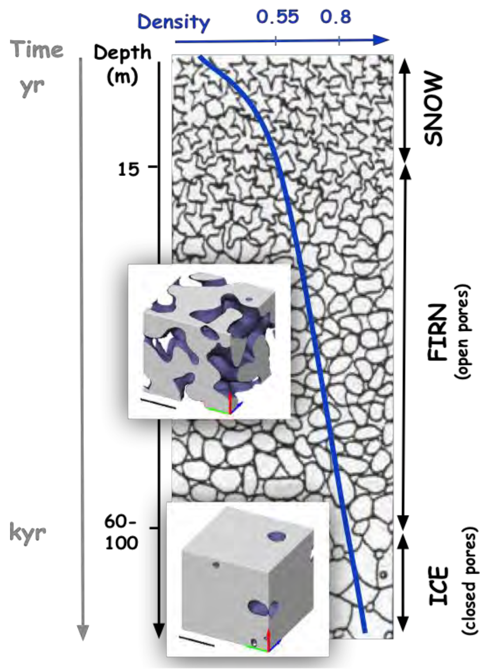
Crystal scale
Highly anisotropic material

Microstructure scale
Fabric
Effect of geometric structure

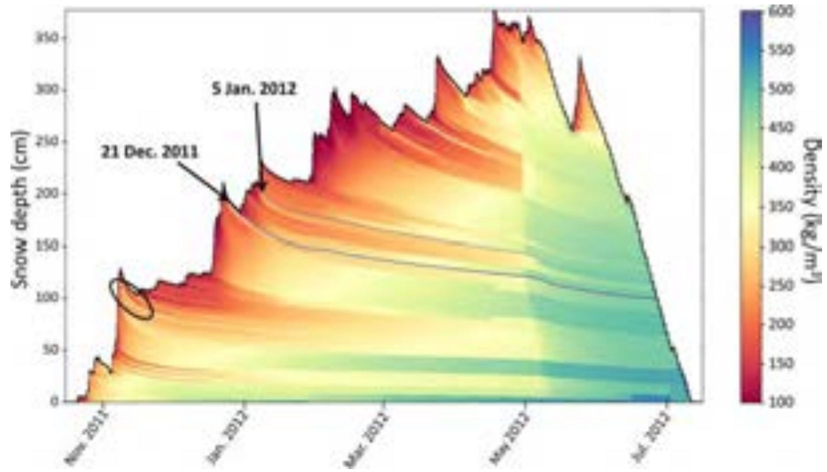
Snowpack model

Context: Snow evolution at different scales

++	**Snowpack model**
\\	• Thermal diffusion
□□	• Phase change • Metamorphism
^^	• Compaction



Snow-firn-ice transition (Dumont et al., 2020) and ice-core



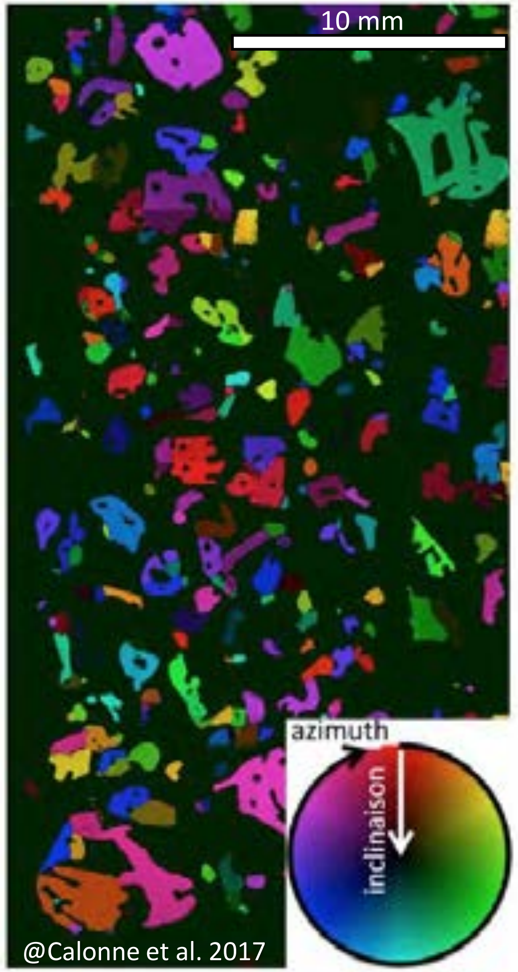
Snow density profile (kg,m−3), Crocus scheme (Quéno et al., 2017)

Snowpack model

Context: Observation of snow dual structure

Absorption contrast X-ray microtomography

Coléou et al., 2001



Diffraction Contrast Tomography (DCT)

Ludwig et al., 2009; *Rolland du Roscoat et al.*, 2011

Diffraction of X-rays by the ice crystalline lattice

And also, EBSD, DRX…

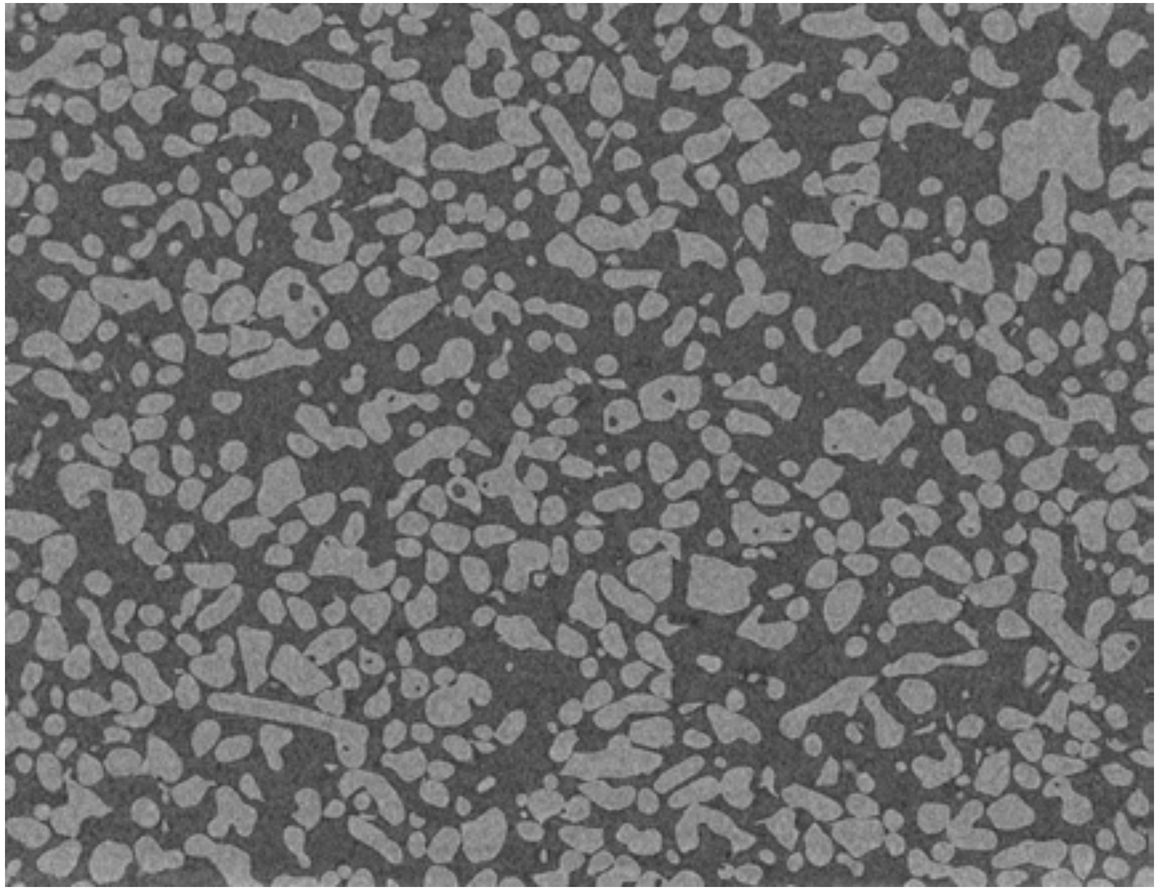
Automatic Ice Texture Analyser (AITA)

Wilson et al., 2007; Riche et al., 2013; Calonne et al., 2017

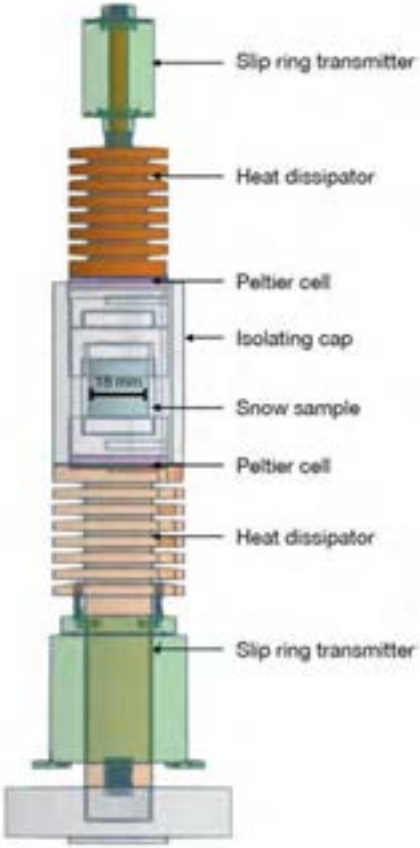
Polarized light to observe the c-axis of crystals in a thin section.

Metamorphism: Effect of crystalline structure?

How does the double structure affect grain growth?



PhD Oscar Dick.



Cell Benoit Laurent.

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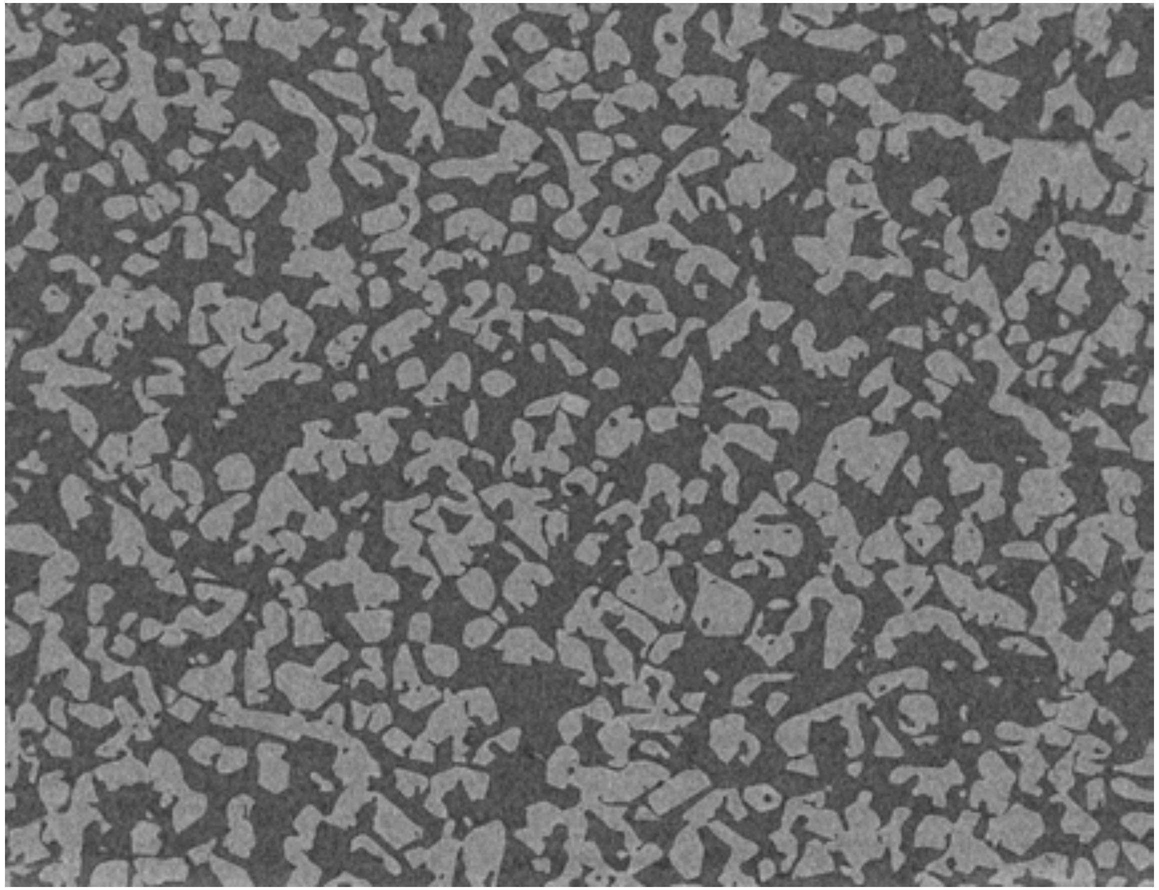

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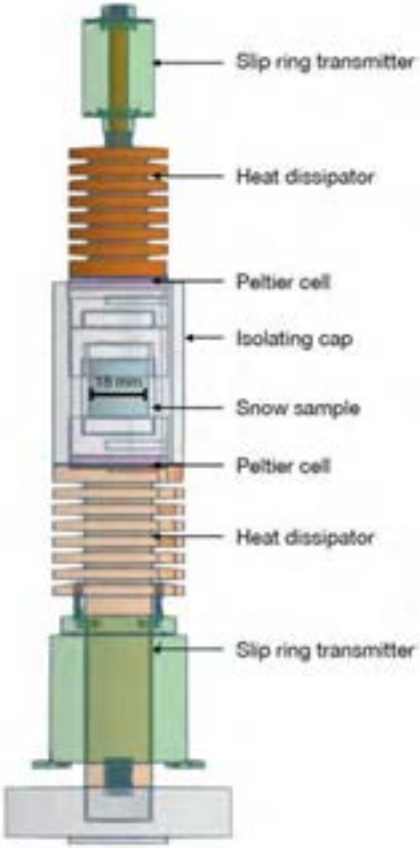

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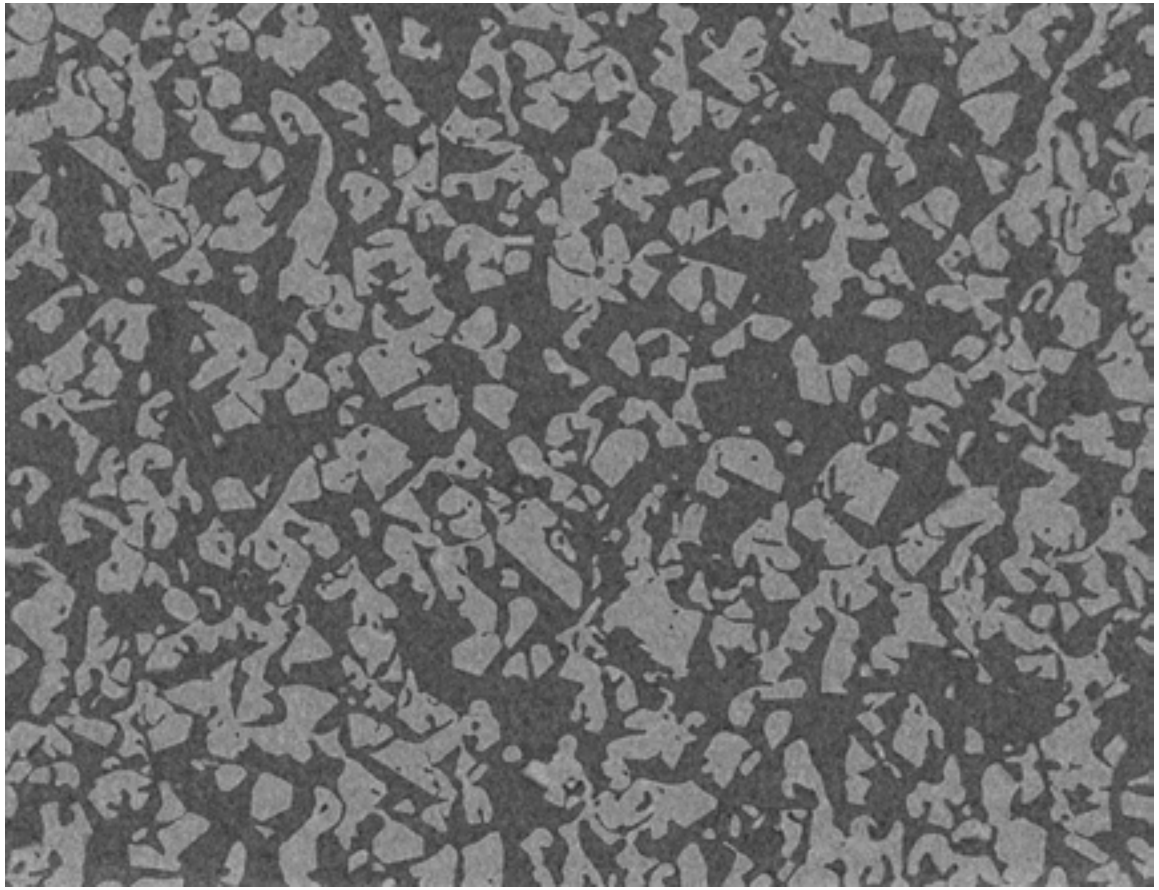

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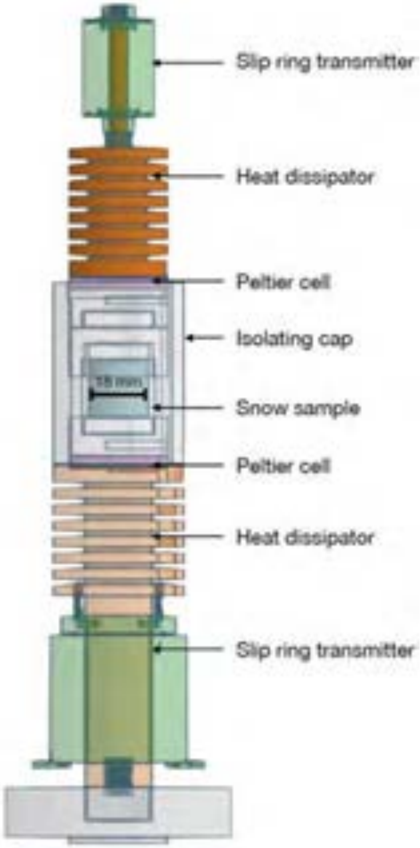

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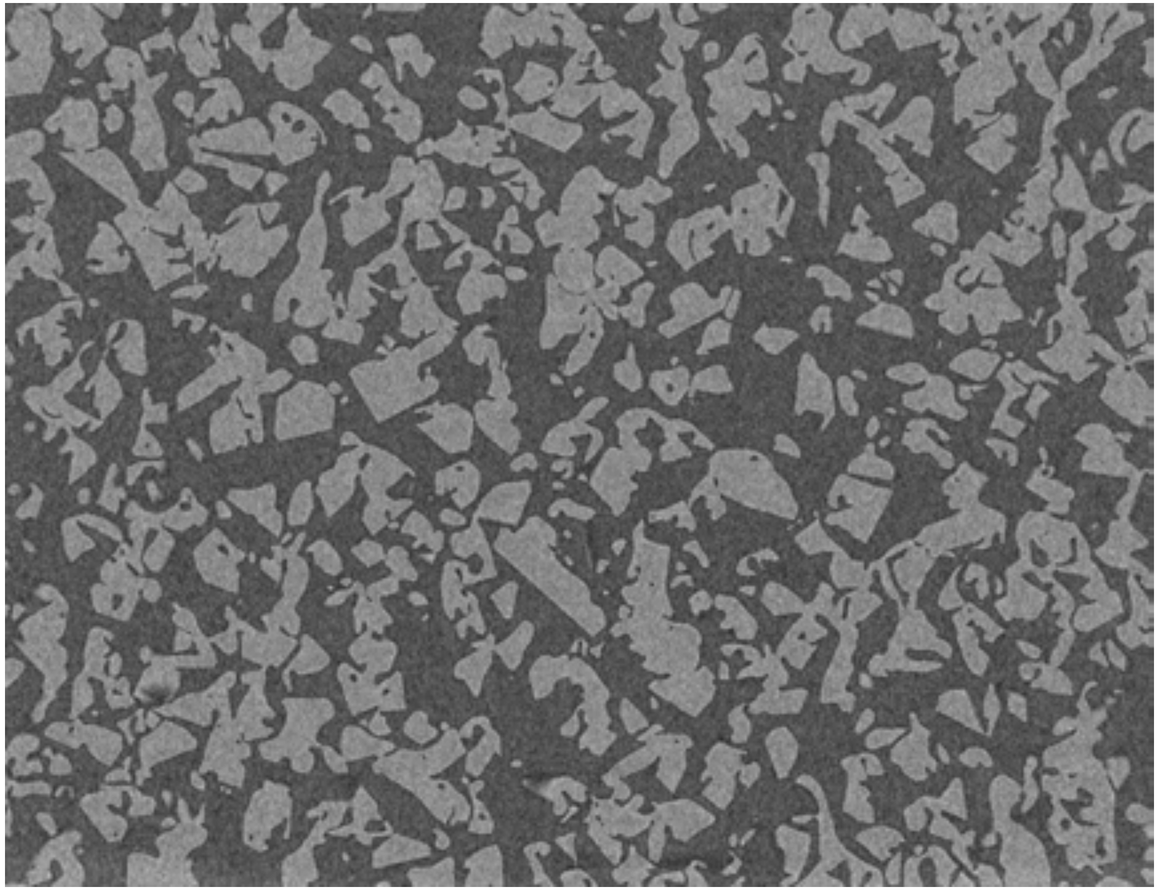
Metamorphism: eEffect of crystalline structure?

How does the double structure affect grain growth?



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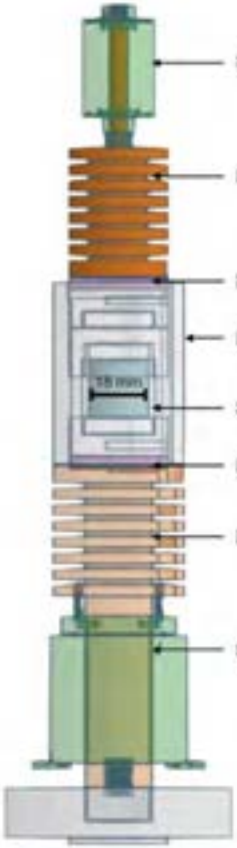
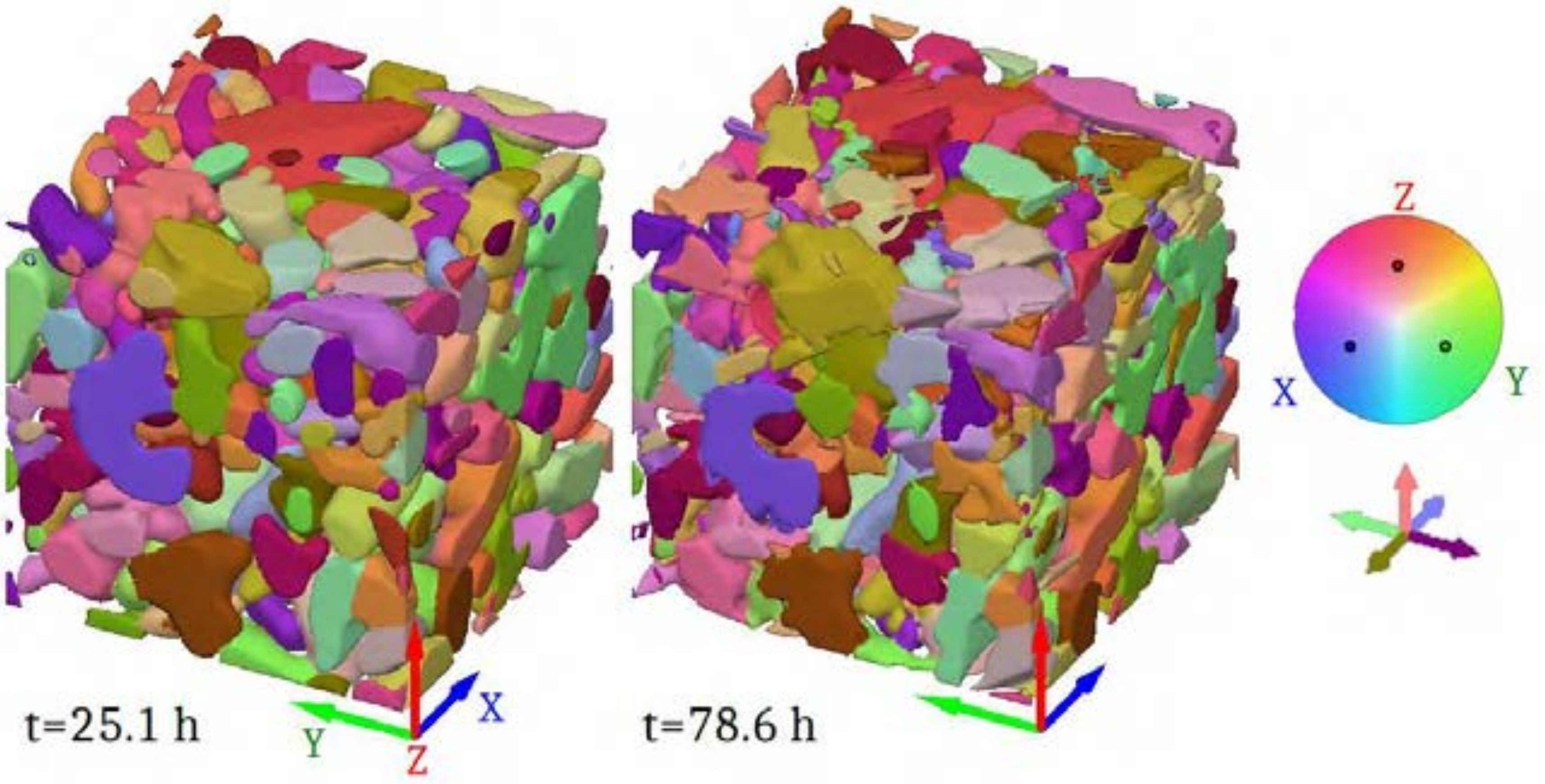


Cell Benoit Laurent.

Metamorphism: Effect of crystalline structure?

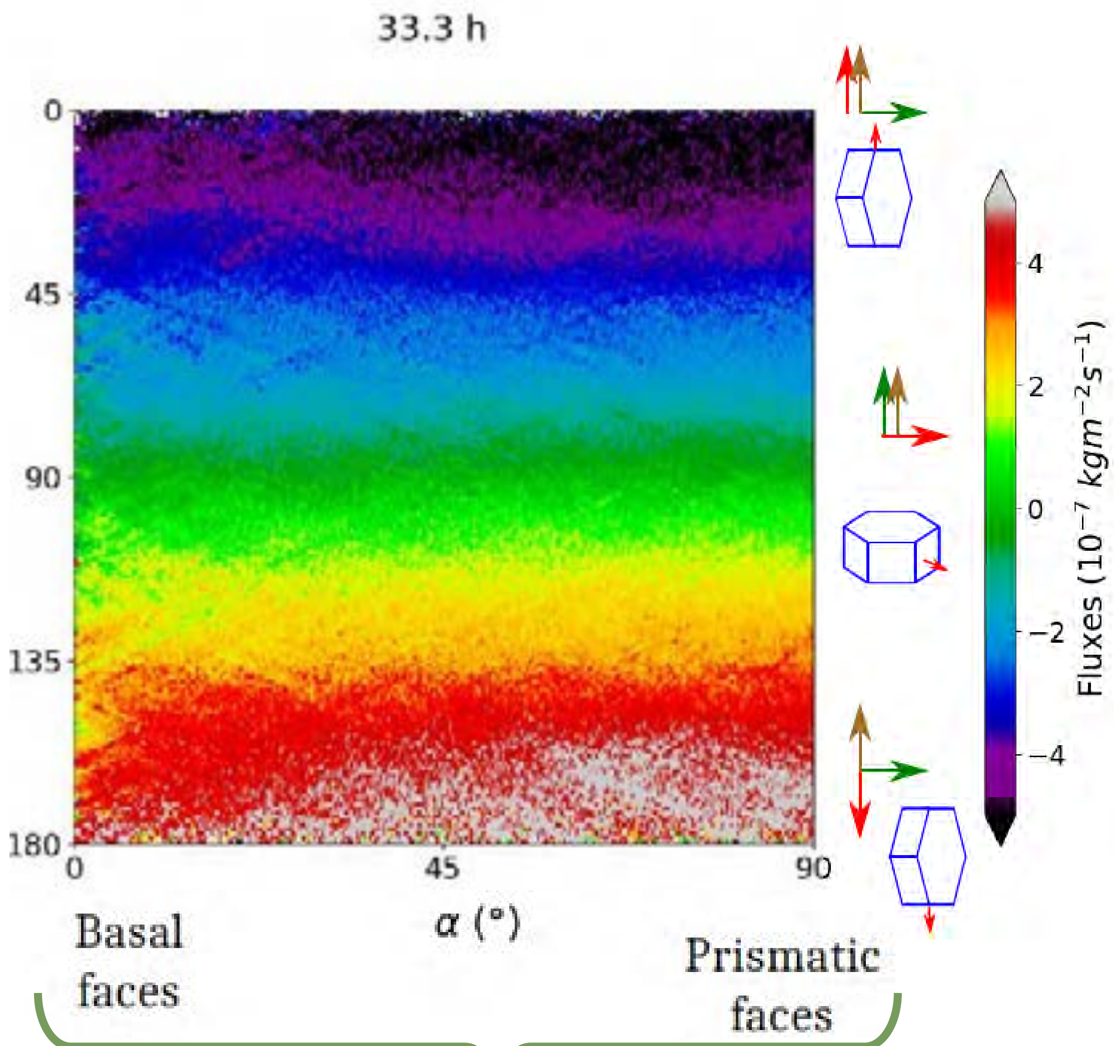
Snow under temperature gradient metamorphism observed with DCT *(Granger et al., 2017)*

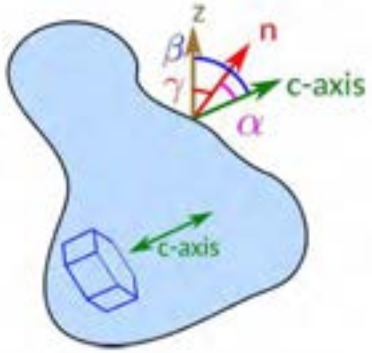


Metamorphism: Effect of crystalline structure?

Snow under temperature gradient metamorphism observed with DCT *(Granger et al., 2017)*

Effect of geometry

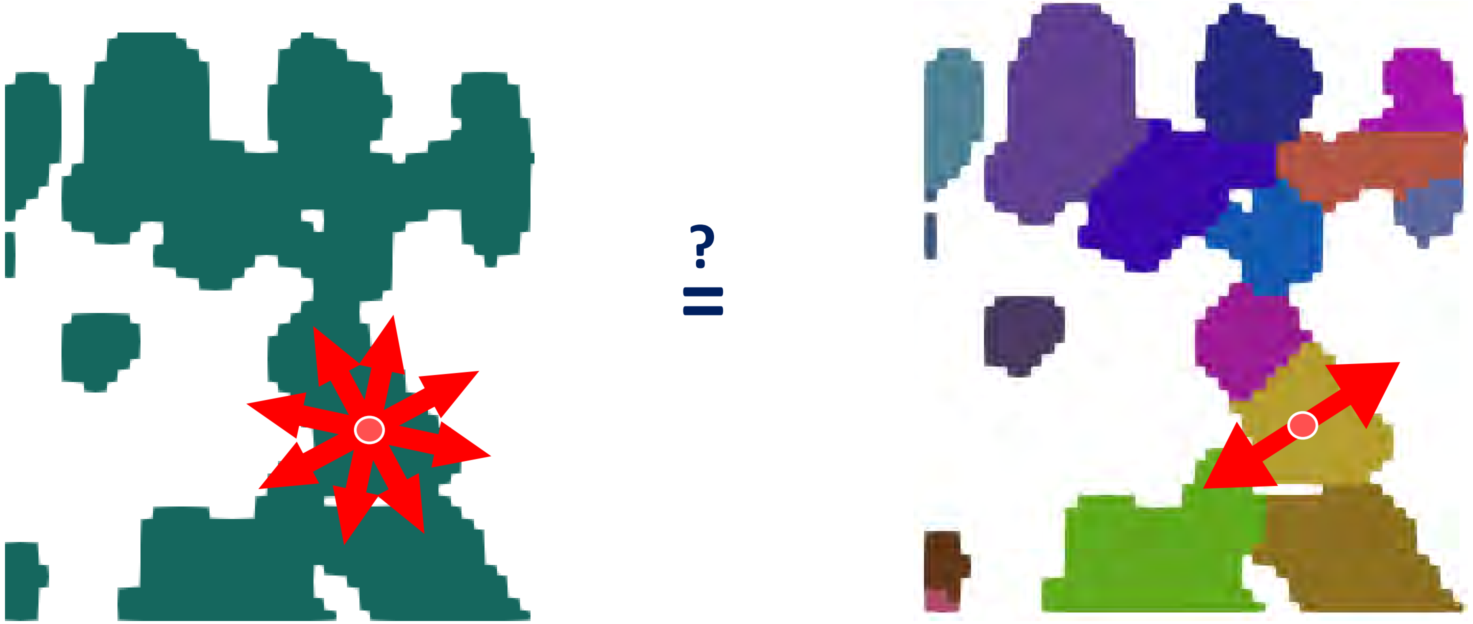




Effect of crystalline orientation

Viscoplasticity: Snow is a foam of ice?

Is the matrix of a porous polycrystal isotropic, or must the crystalline structure be considered?



Wautier et al., 2017, Fourteau et al., 2024

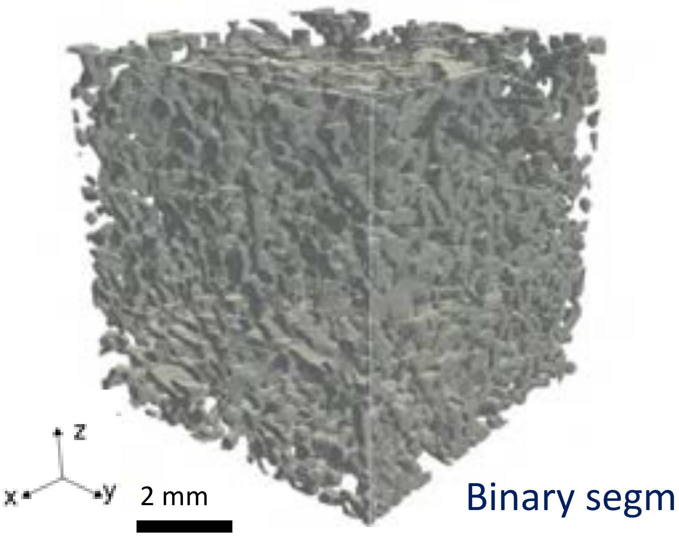
Védrine, L., Hagenmuller, P., Gélébart, L., Montagnat, M., & Bernard, A. (2024). Role of ice mechanics on snow viscoplasticity. *Geophysical Research Letters*.

Viscoplasticity: Snow is a foam of ice?

Methodology:

Homogeneous ice model

3D Norton law *(Suquet, 1983)*



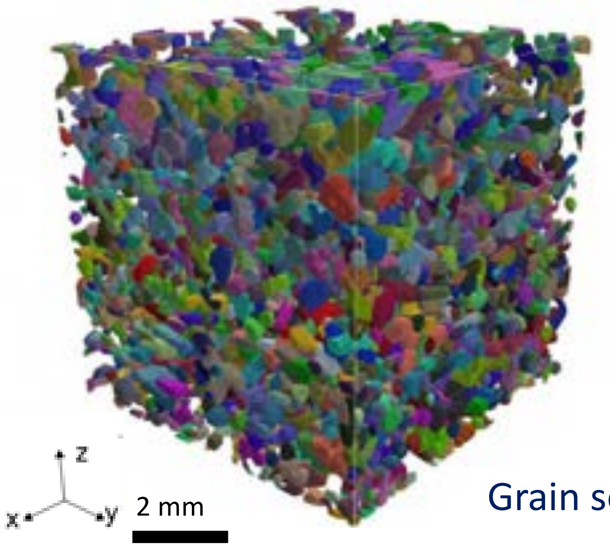
Binary segmentation

$$\dot{\boldsymbol{\epsilon}}_{\mathbf{vp}} = \frac{3}{2} A \, \sigma_{\mathrm{eq}}^{n-1} \, \boldsymbol{\sigma}'$$

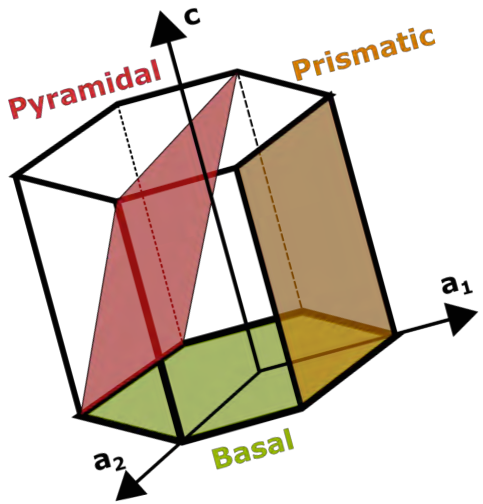
$A = 7.8 \; 10^{-8} \; \mathrm{MPa^{-n}} \; \mathrm{s^{-1}}$ and $n = 3$

from *Castelnau et al., 1998, Theile et al., 2011*

Sintered crystals model



Grain segmentation



$$\boldsymbol{\epsilon}_{vp} = \sum_{k=1}^{12} \gamma^{(k)} \boldsymbol{\mu}^k$$

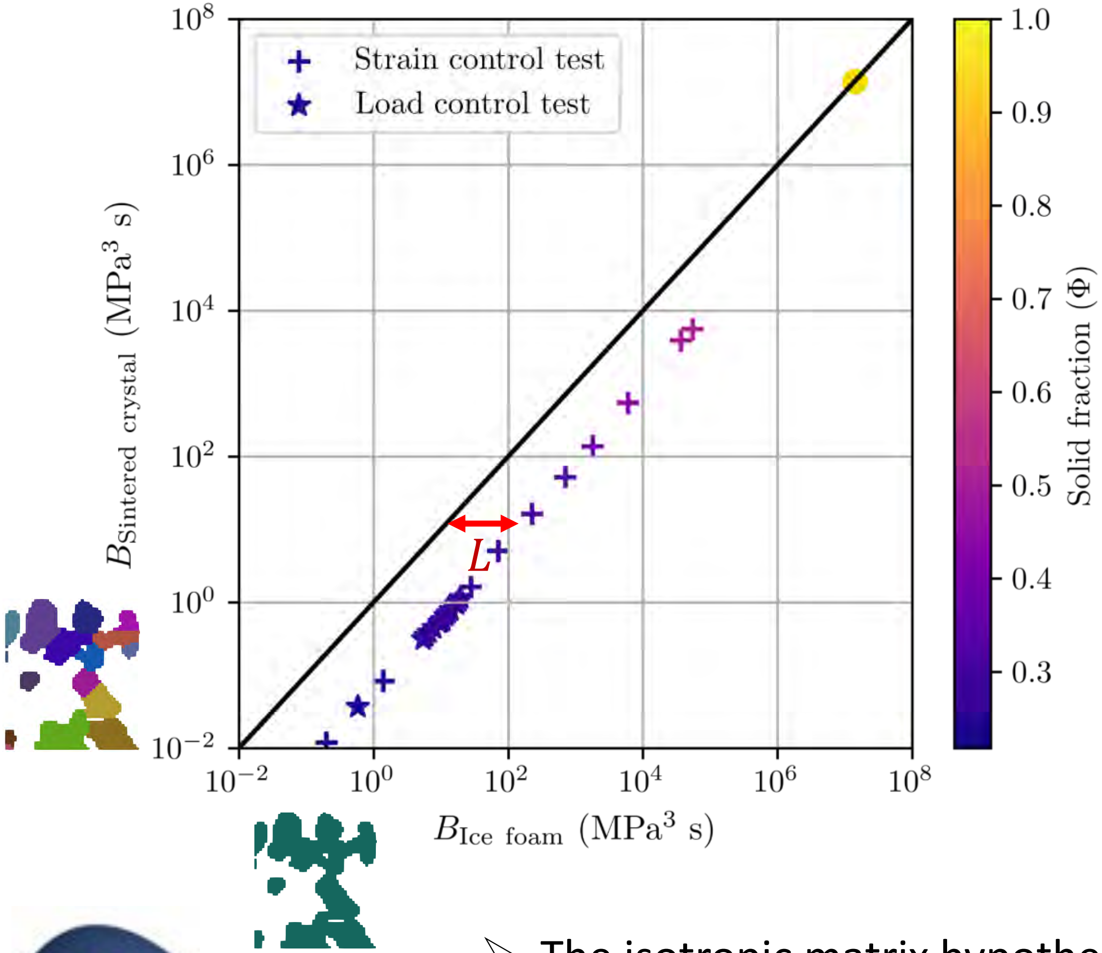
$$\boldsymbol{\mu}^k = \frac{1}{2}(n^k \otimes_s b^k) \text{ and } \dot{\gamma}^{(k)} = \dot{\gamma}_0^{(k)} \left(\frac{|\tau^{(k)}|}{\tau_0^k} \right)^{n^{(k)}} \mathrm{sgn}\left(\tau^{(k)}\right)$$

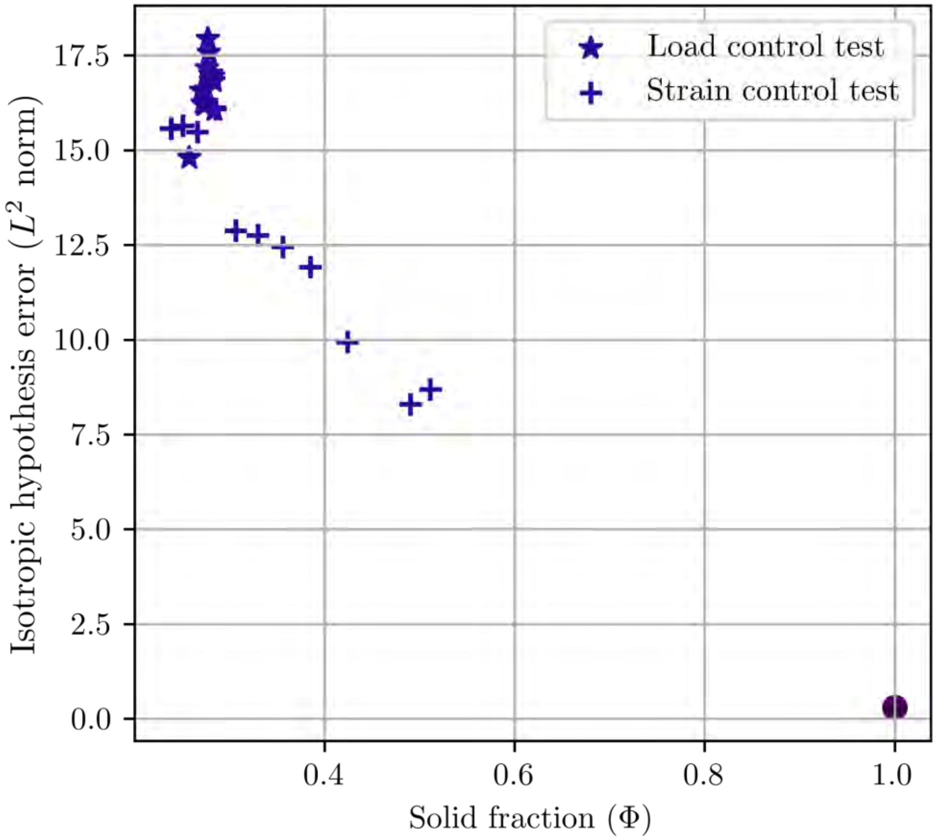
$$\text{with } \tau^{(k)} = \boldsymbol{\sigma} : \boldsymbol{\mu}^k \text{ and } \dot{\gamma}_0^{(k)} = 1 \; \mathrm{s}^{-1}$$

Viscoplasticity: Snow is a foam of ice?

Results:

$$\dot{\epsilon}_{macro} = \frac{1}{B}\sigma^n$$

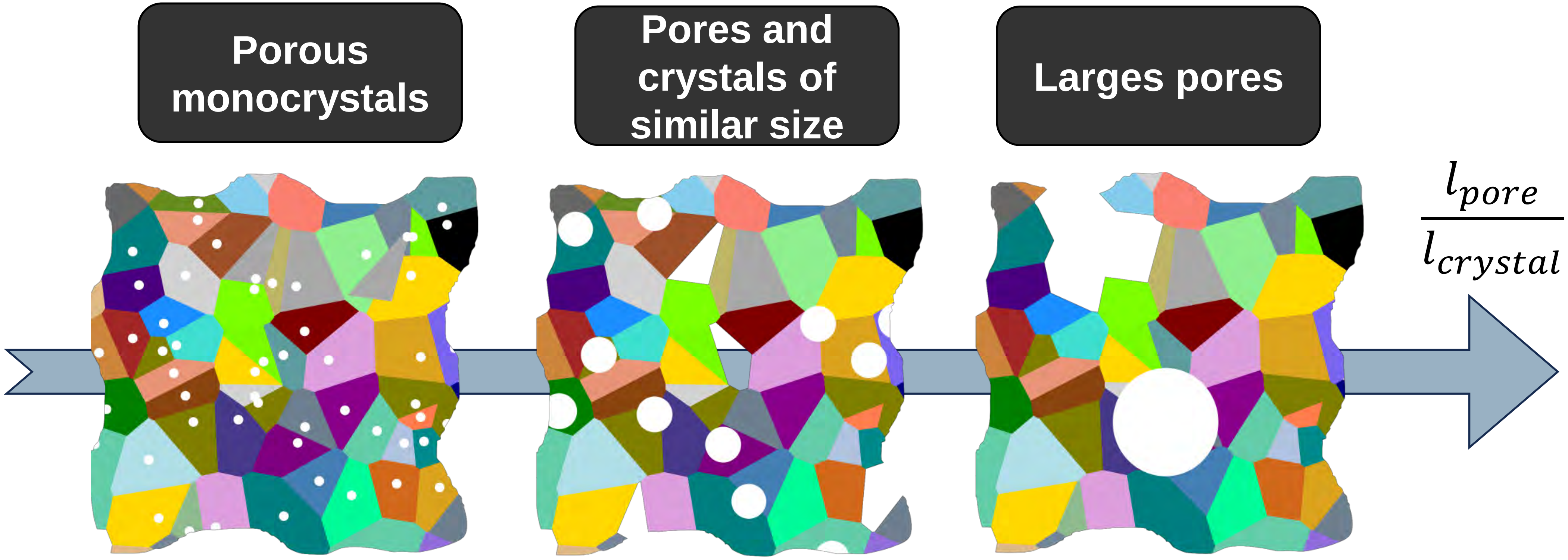




➢ The isotropic matrix hypothesis **is not valid** for highly **porous** polycrystals

Viscoplasticity: Effect of the dual structure on snow viscoplasticity

How does the pore size-to-crystal size ratio affect the viscous behavior of porous polycrystals, such as snow ?



Song and Ponte Castaneda, 2017
Joessel et al., 2018;

Lebensohn et al., 2011
Portellete et al., 2022

Wojtacki et al.,2020
Hure, 2021

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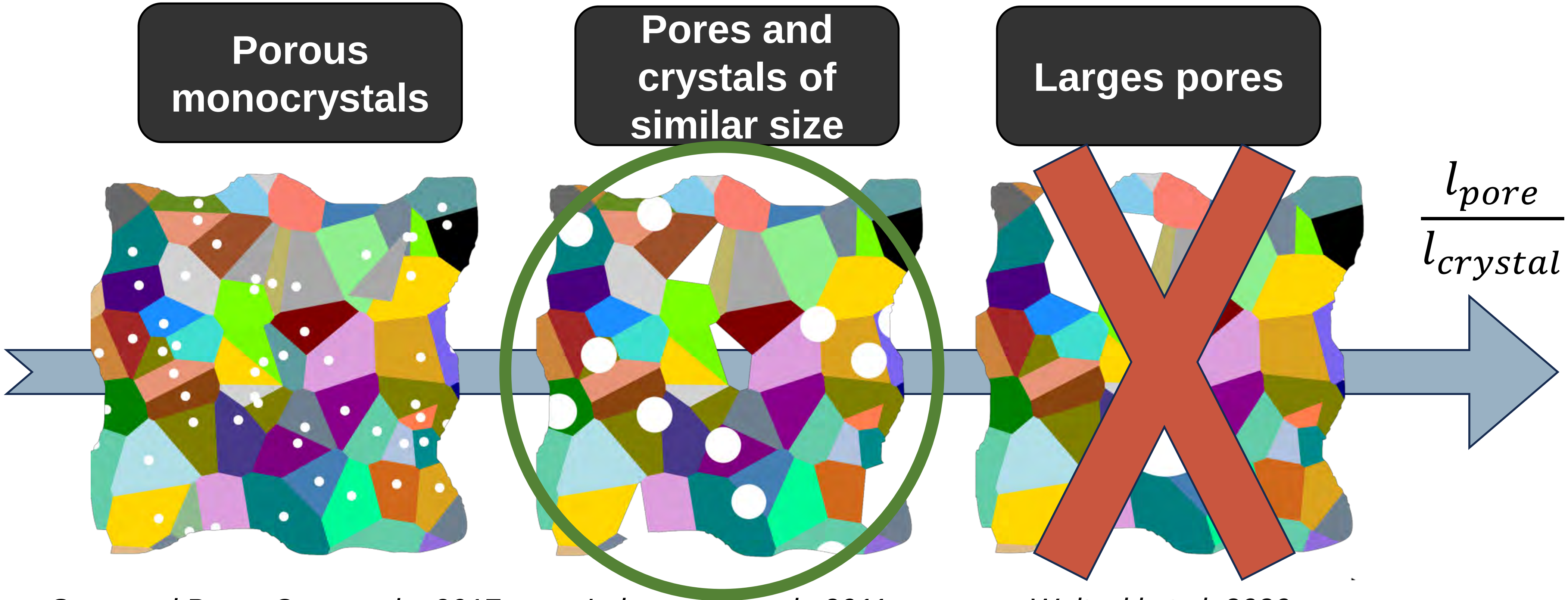


Song and Ponte Castaneda, 2017
Joessel et al., 2018;

Lebensohn et al., 2011
Portellete et al., 2022

Wojtacki et al.,2020
Hure, 2021

Snow

Viscoplasticity: Effect of the dual structure on snow viscoplasticity

Homogenized model:

$$\dot{\epsilon} = \left(\frac{\sigma_Y}{\sigma_0}\right)^n$$

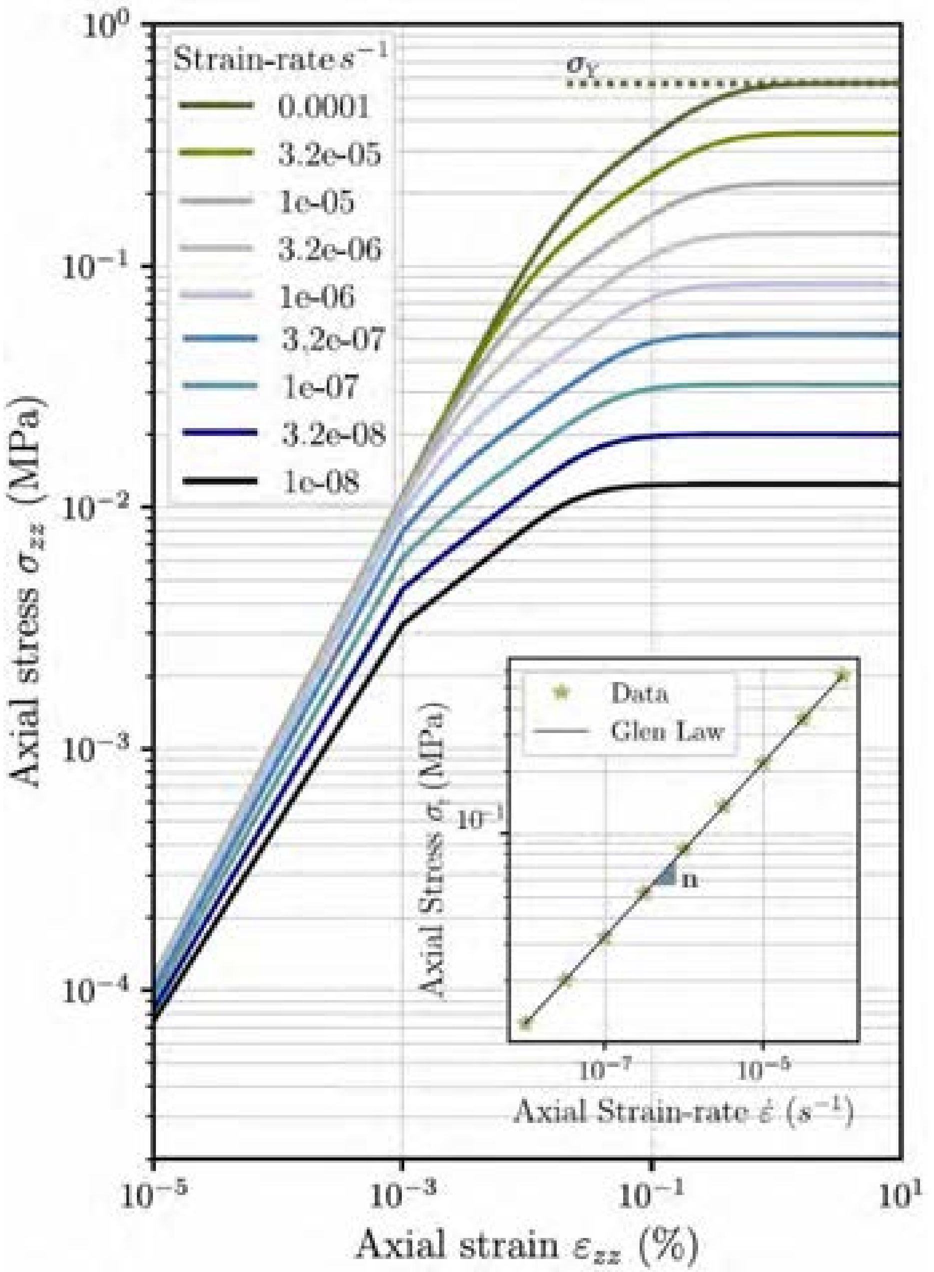
Two parameters:

- Reference stress (viscosity)

$$\sigma_0$$

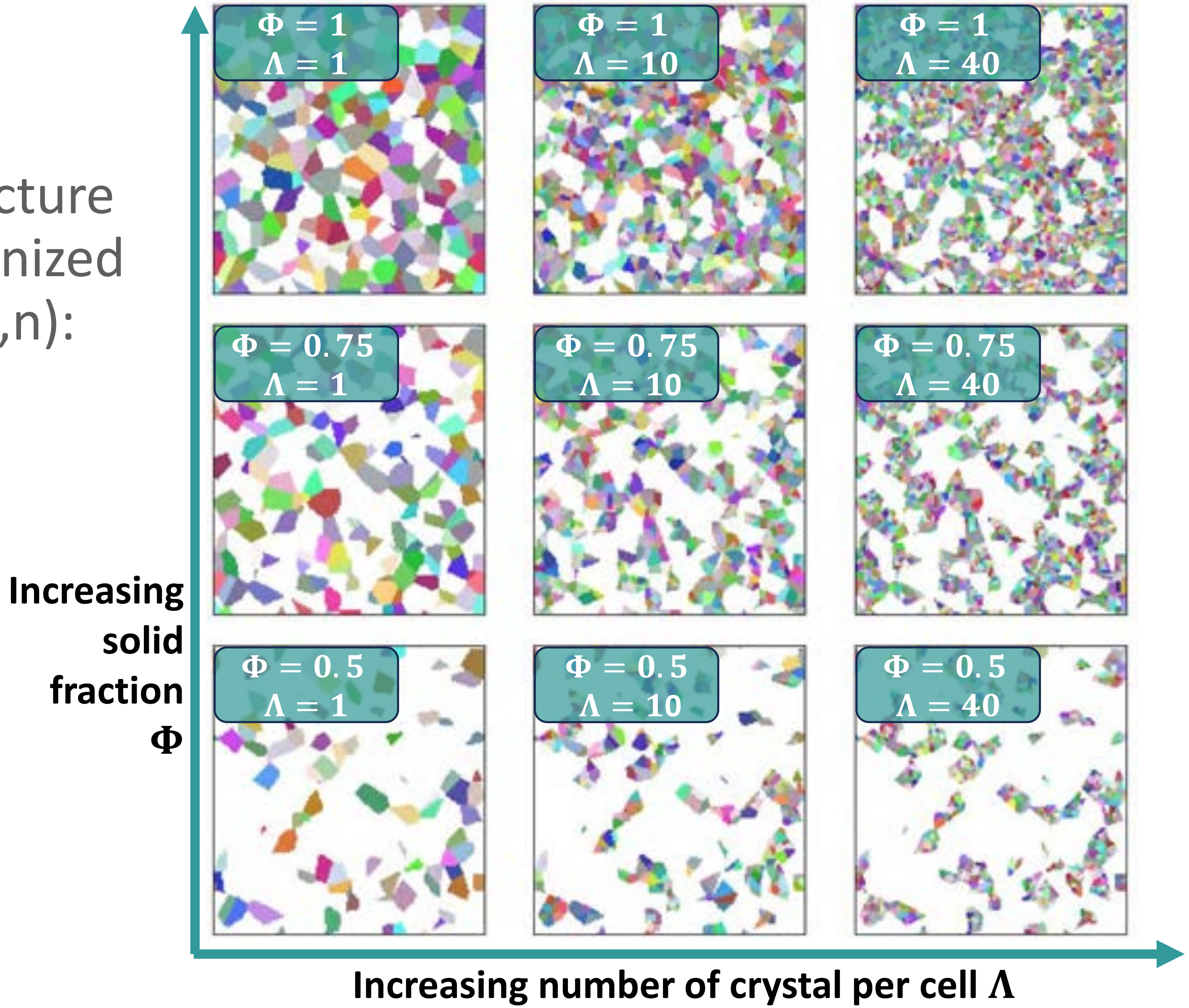
- Stress exponent

$$n$$



Viscoplasticity: Effect of the dual structure on snow viscoplasticity

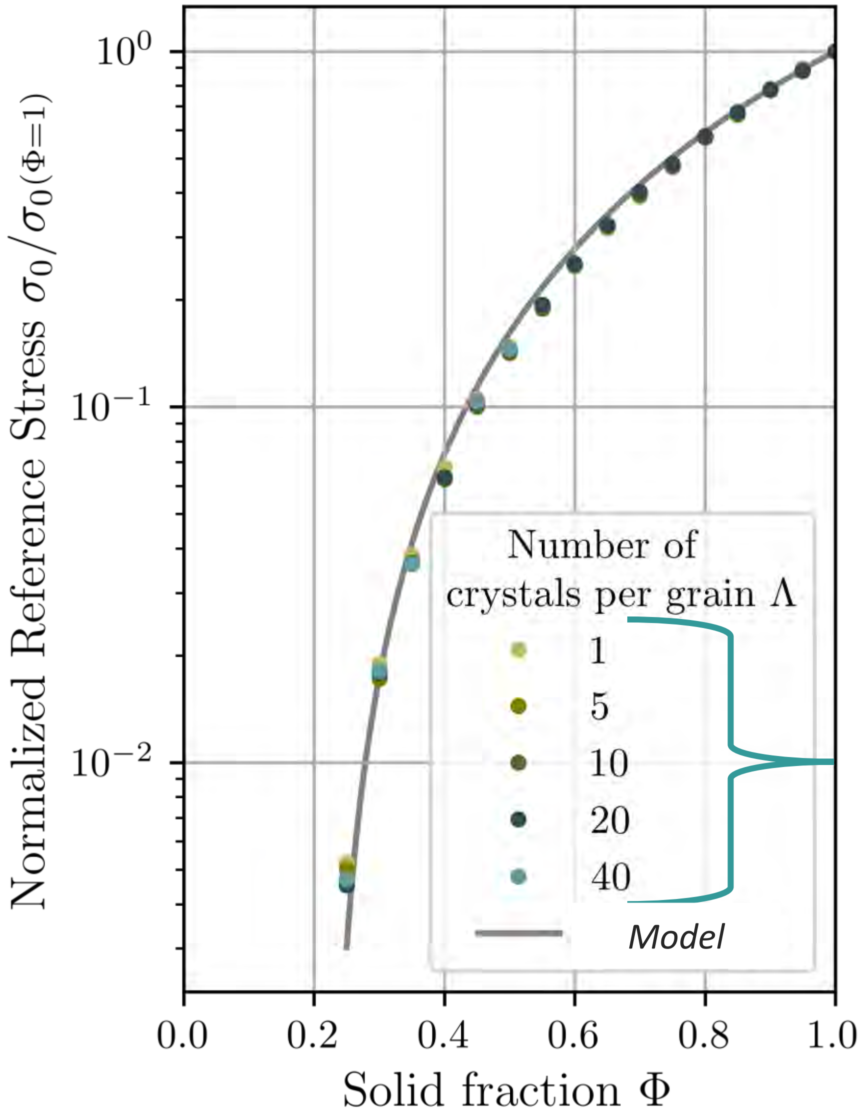
Effect of the **geometric** and **crystalline** structure on the homogenized parameters (σ_0,n):



Viscoplasticity: Effect of the dual structure on snow viscoplasticity

Reference stress σ_0:

$$\dot{\epsilon} = \left(\frac{\sigma_Y}{\sigma_0}\right)^n$$



Independent of the crystalline structure !!!

$$\boldsymbol{\sigma_0(\Phi) = \sigma_0(\Phi = 1)\left(\frac{\Phi - \Phi_t}{1 - \Phi_t}\right)^m}$$

with $\Phi_t = 0.2$ the percolation threshold
$m = 2.02$ the solid fraction sensitivity

The reference stress depends on the **solid fraction** and microstructure **morphology**

Viscoplasticity: Effect of the dual structure on snow viscoplasticity

Reference stress σ_0:

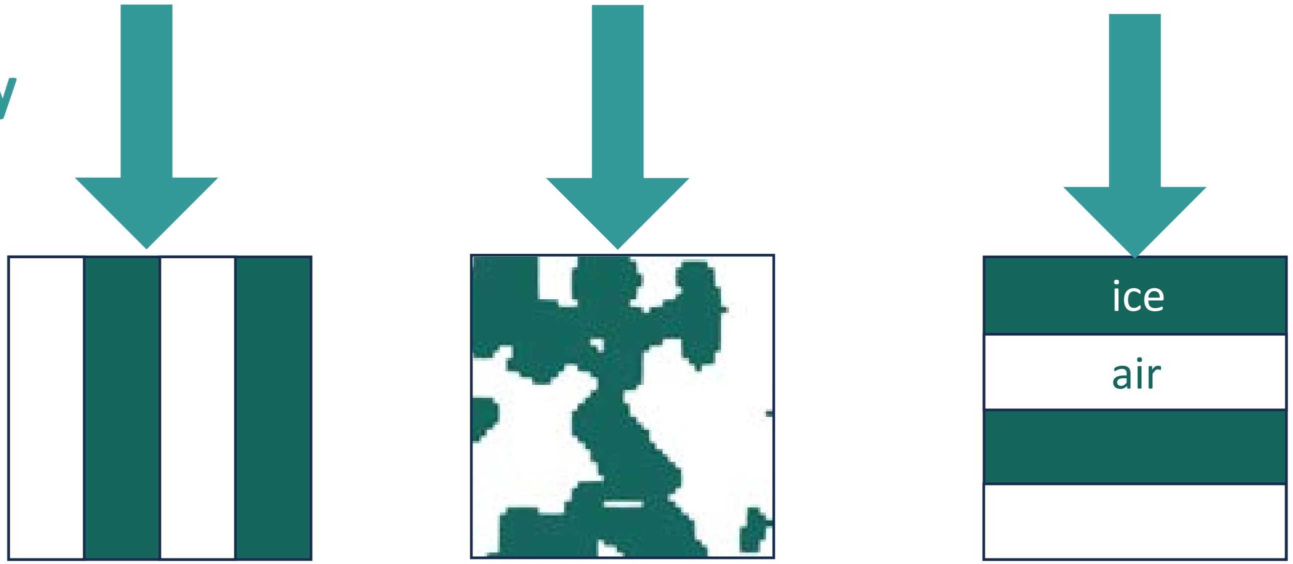
$$\dot{\epsilon} = \left(\frac{\sigma_Y}{\sigma_0}\right)^n$$

$$\boldsymbol{\sigma_0(\Phi) = \sigma_0(\Phi = 1)\left(\frac{\Phi - \Phi_t}{1 - \Phi_t}\right)^m}$$

- *"m"* characterizes the microstructural **morphology** and its **load-bearing capacity**

- Example of 1D compression test:

$$\Phi = 0.5$$

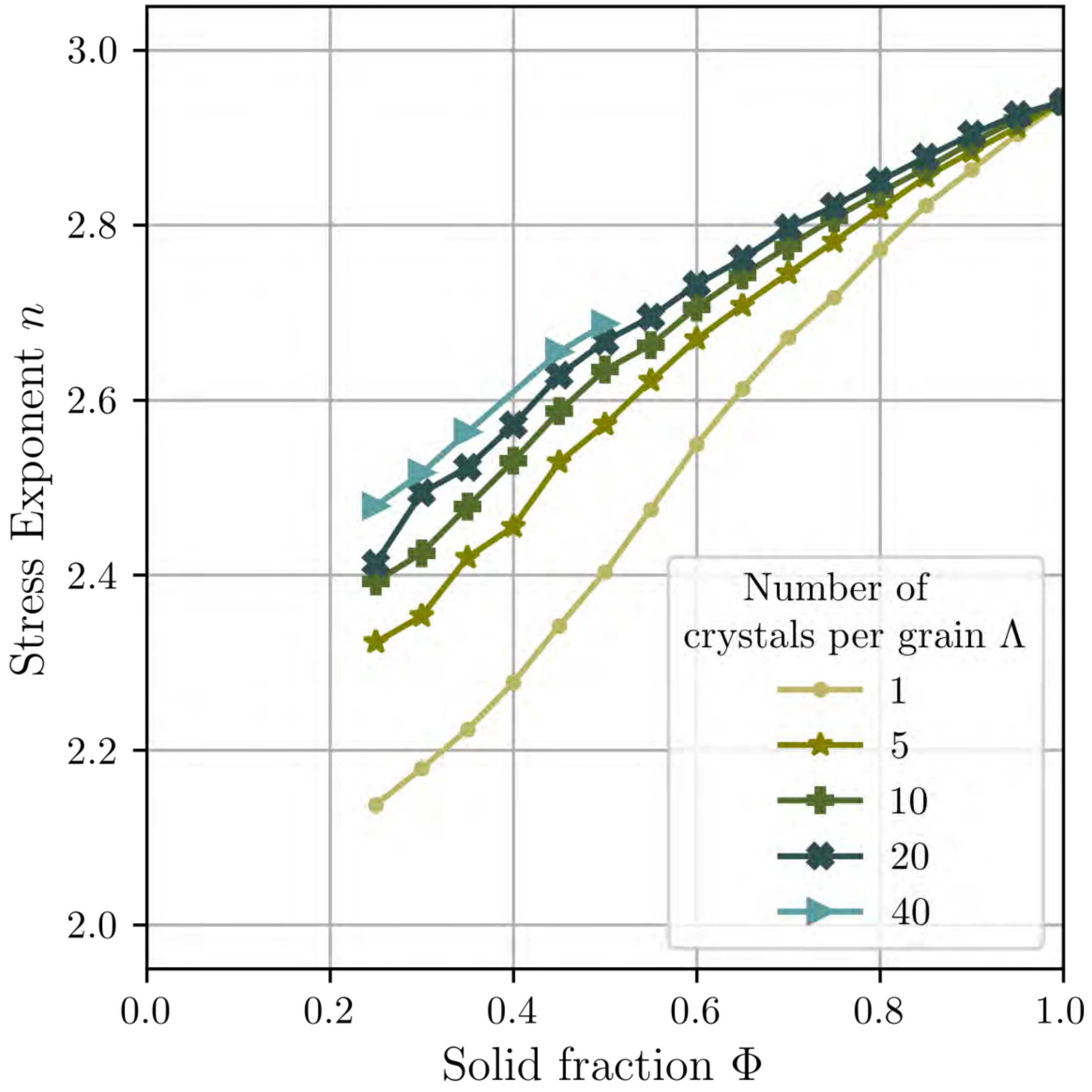


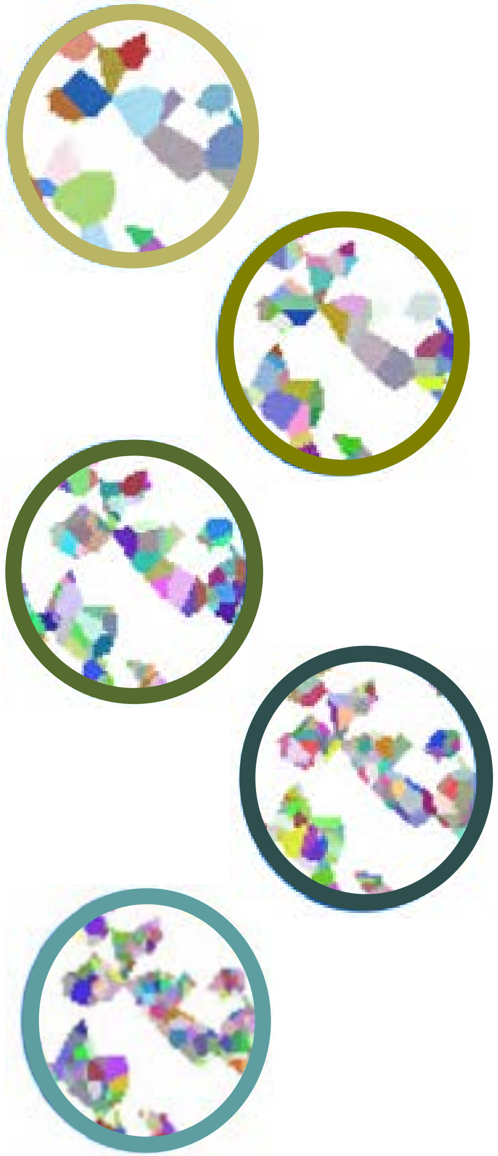
$m = 1$ $\quad$ $\boldsymbol{m_{snow} = 2.02}$ $\quad$ $m = \infty$

Viscoplasticity: Effect of the dual structure on snow viscoplasticity

Stress exponent n:

$$\dot{\epsilon} = \left(\frac{\sigma_Y}{\sigma_0}\right)^n$$





n depends on the **geometric** and **crystalline** structure

Viscoplasticity: Effect of the dual structure on snow viscoplasticity

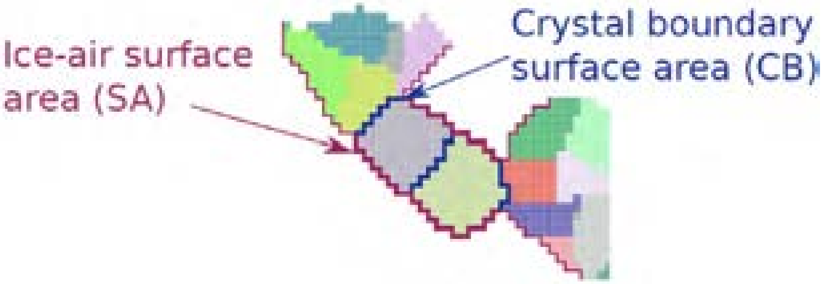
Stress exponent n: concept of **confinement**

$$\dot{\epsilon} = \left(\frac{\sigma_Y}{\sigma_0}\right)^n$$

Large intercrystallite area
and high solid fraction
= struggle between crystals

Small intercrystallite area
and low solid fraction
= happy crystals

Weighted contact density
$$\nu_Z = \Phi Z s$$

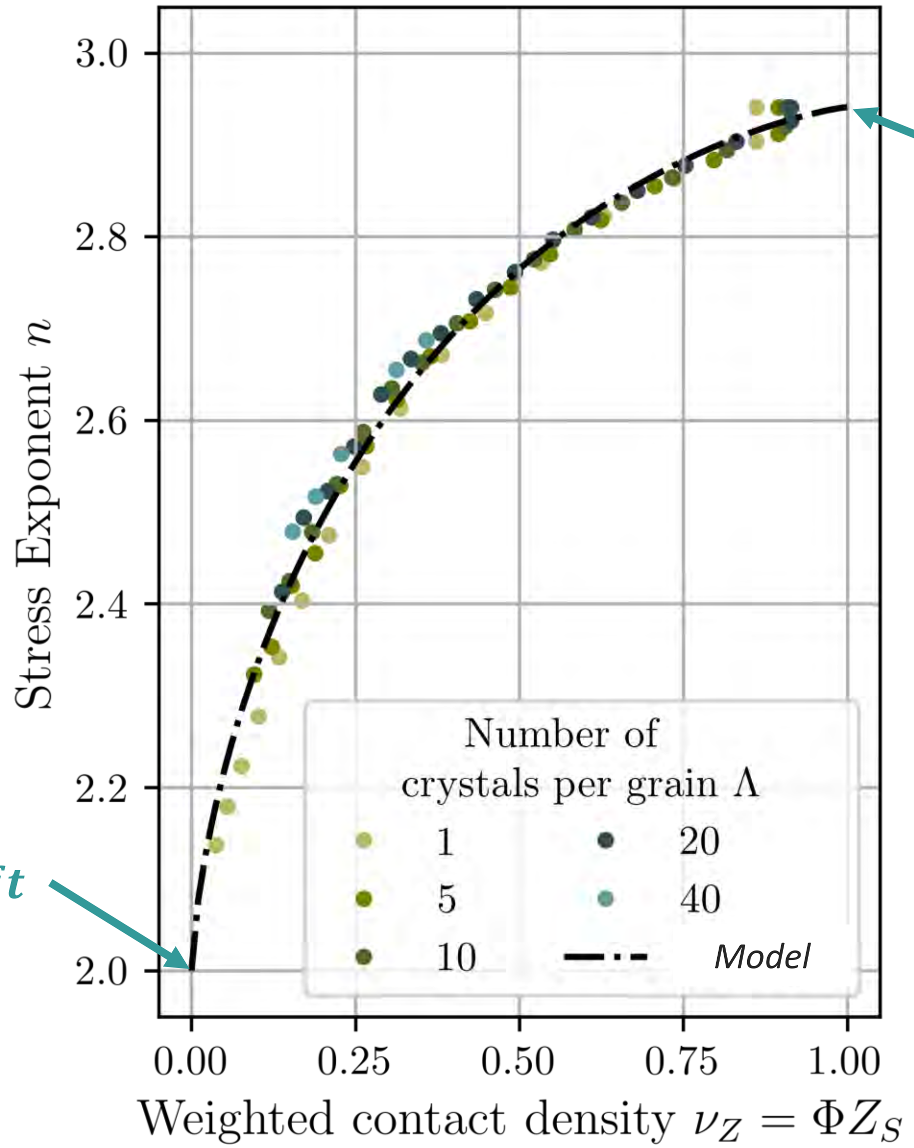


with $Z_s = \frac{GBA}{GBA+SA}$, the weighted coordination ratio

Viscoplasticity: Effect of the dual structure on snow viscoplasticity

Stress exponent n:

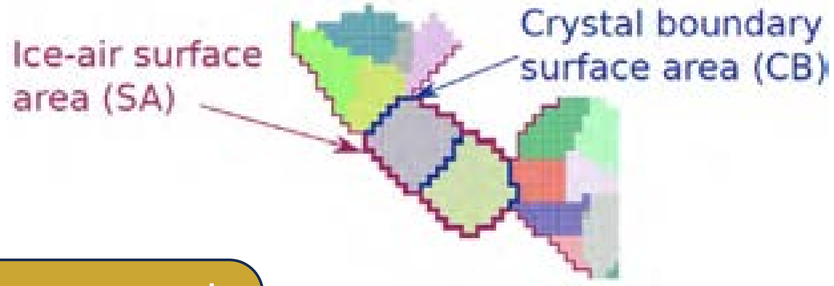
$$\dot{\epsilon} = \left(\frac{\sigma_Y}{\sigma_0}\right)^n$$



n_{poly}

n_{soft}

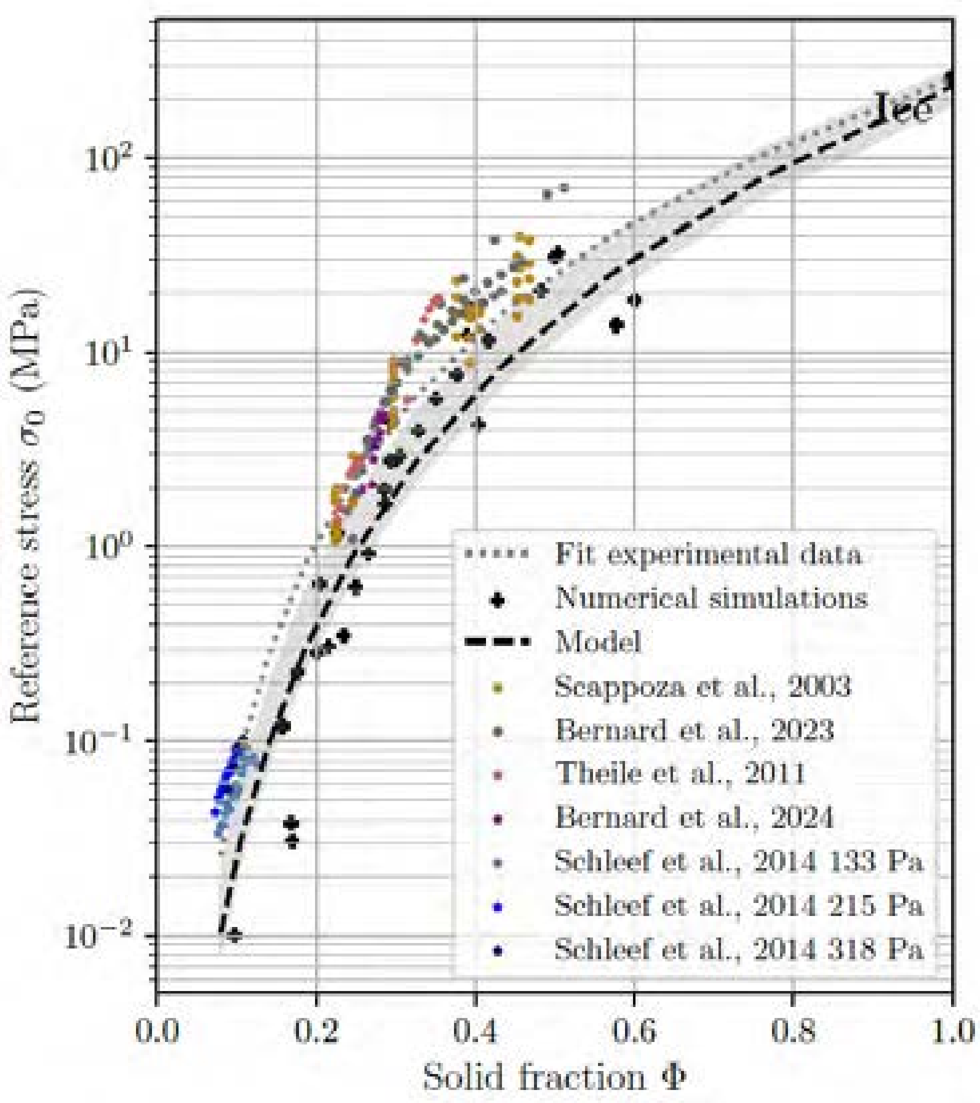
Weighted contact density
$$\nu_Z = \Phi Z s$$



Transition of stress exponent with dislocation creep only (without GBS)

$$n(\nu_Z) = n_{soft}(1 - \nu_Z) + n_{poly}\, \nu_Z^{0.74}$$

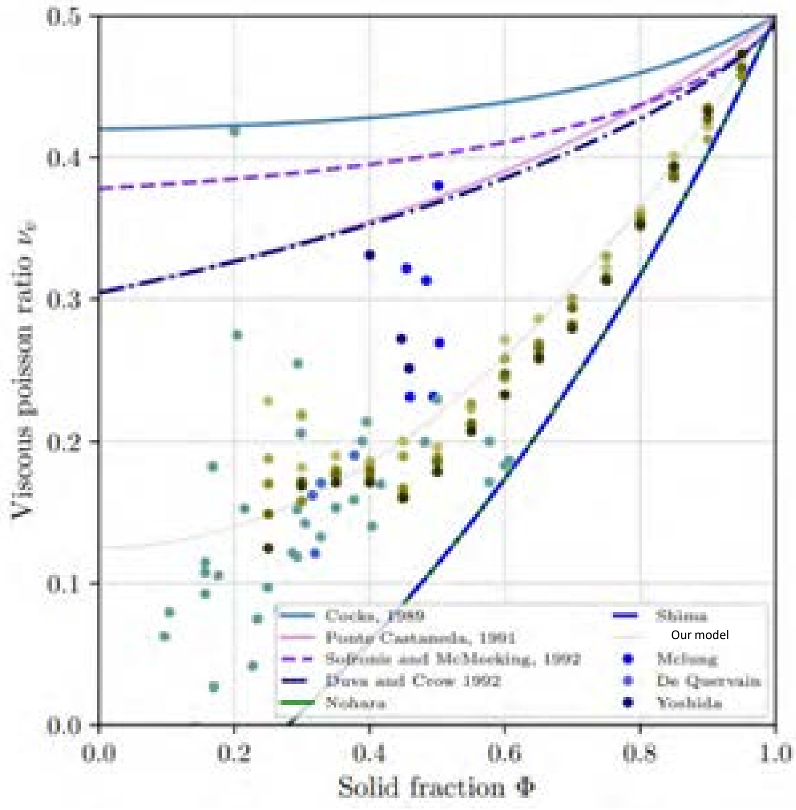
Viscoplasticity: A framework for a unified settlement law for the snows-firn-ice continuum.



→ Reinterpretation of 64 (all) **in-situ compression** test

→ A **new parametrization** of the densification law equivalent to Crocus (for the Col de Porte conditions).

→ Extended in **3D** (shear of firn, design of avalanche defense structures)



More soon ...

METEO FRANCE

Conclusion and outlooks

The dual geometric and crystalline structure of snow controls its evolution!

Metamorphism:

Orientation selective grain activity

(see F. Flin and O. Dick PhD work)

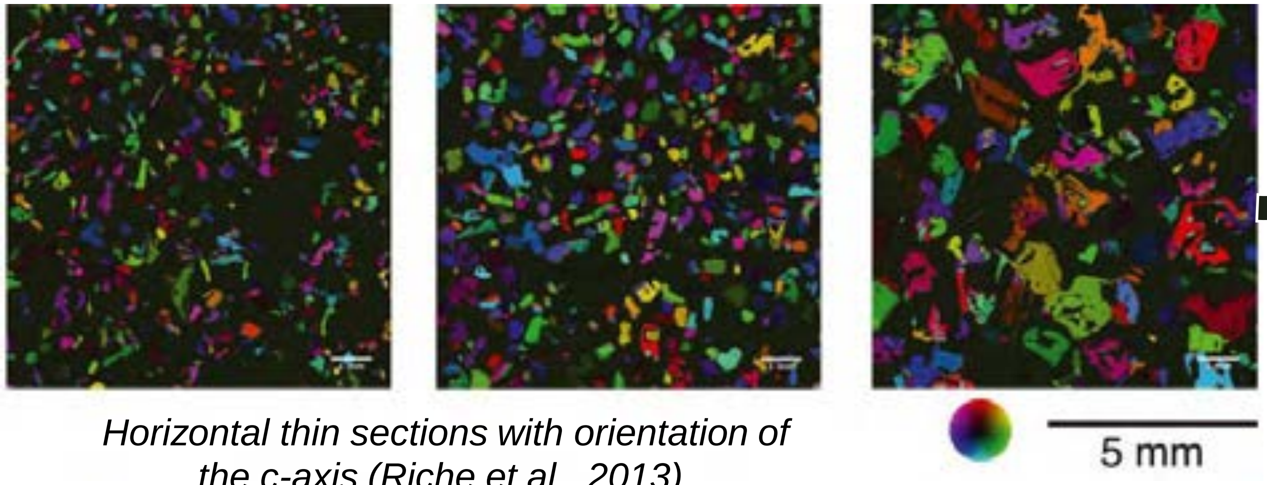
Impact of fabric with **preferred orientations**?

Viscoplasticity:

Unraveling the crystalline and geometric contributions

$$\dot{\epsilon} = \left(\frac{\sigma}{\sigma_0}\right)^n$$

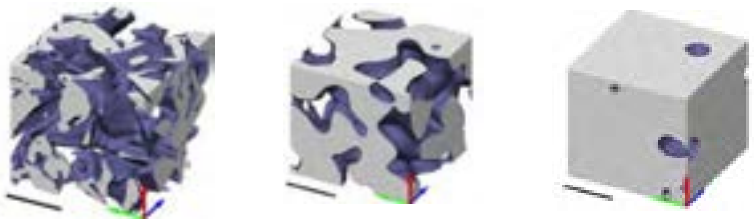
$\sigma_0(\Phi, \mu)$ and $n(\Phi, \text{intercrystalline surface})$



Horizontal thin sections with orientation of the c-axis (Riche et al., 2013).

Evolution of **intercrystallite surface:**

- with snow types?
- with and solid fraction?



Snow-firn-ice continuum

METEO FRANCE

II) A New Snow Densification Model:

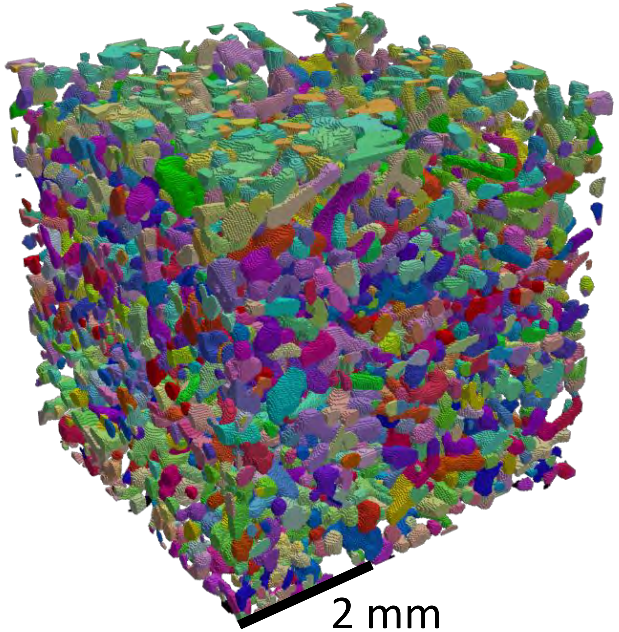
Reinterpreting Past Experiments Through Microstructure-Based Modeling of Snow Viscoplasticity

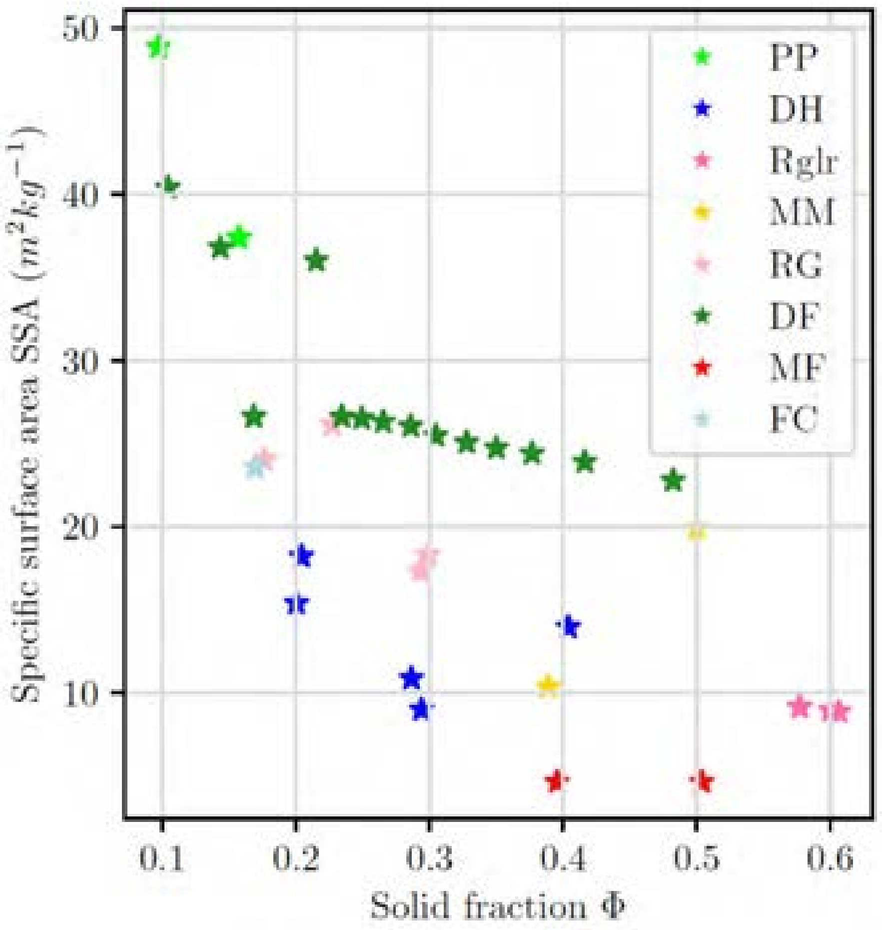
- **45 Real snow microstructures** captured through X-ray tomography.

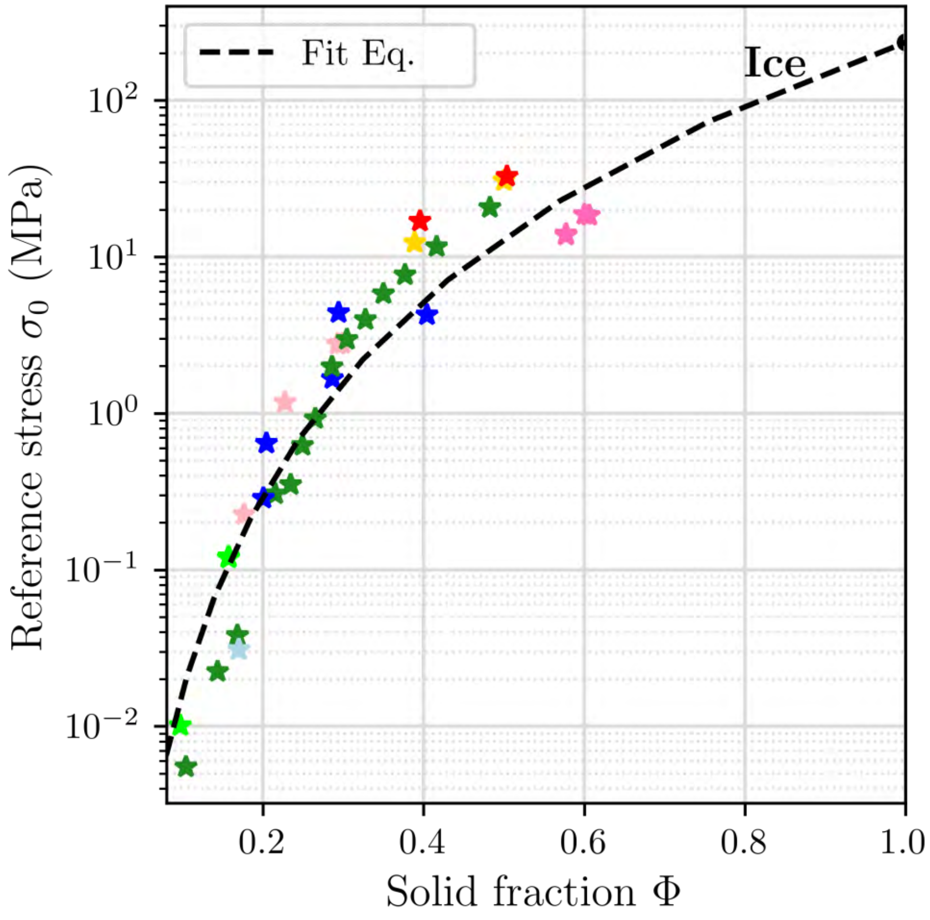
- **Segmented in individual grains**

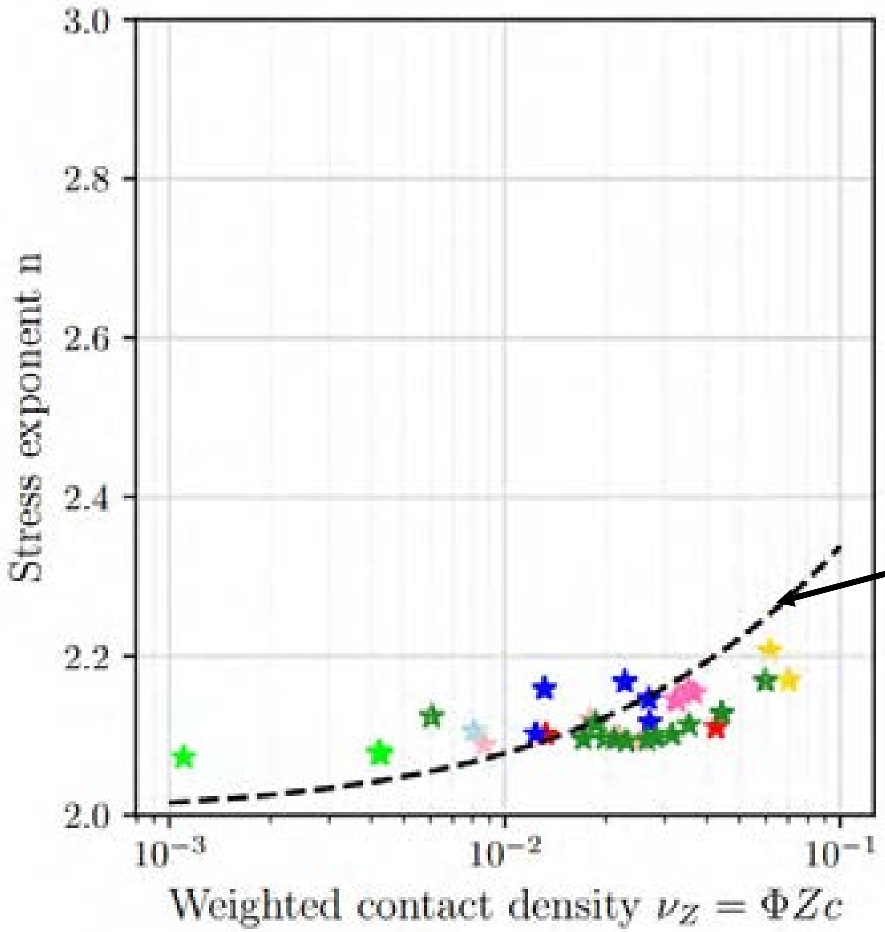
(Hagenmuller et al., 2014; Peinke et al., 2020).

Hypothesis: **one grain= one crystal**



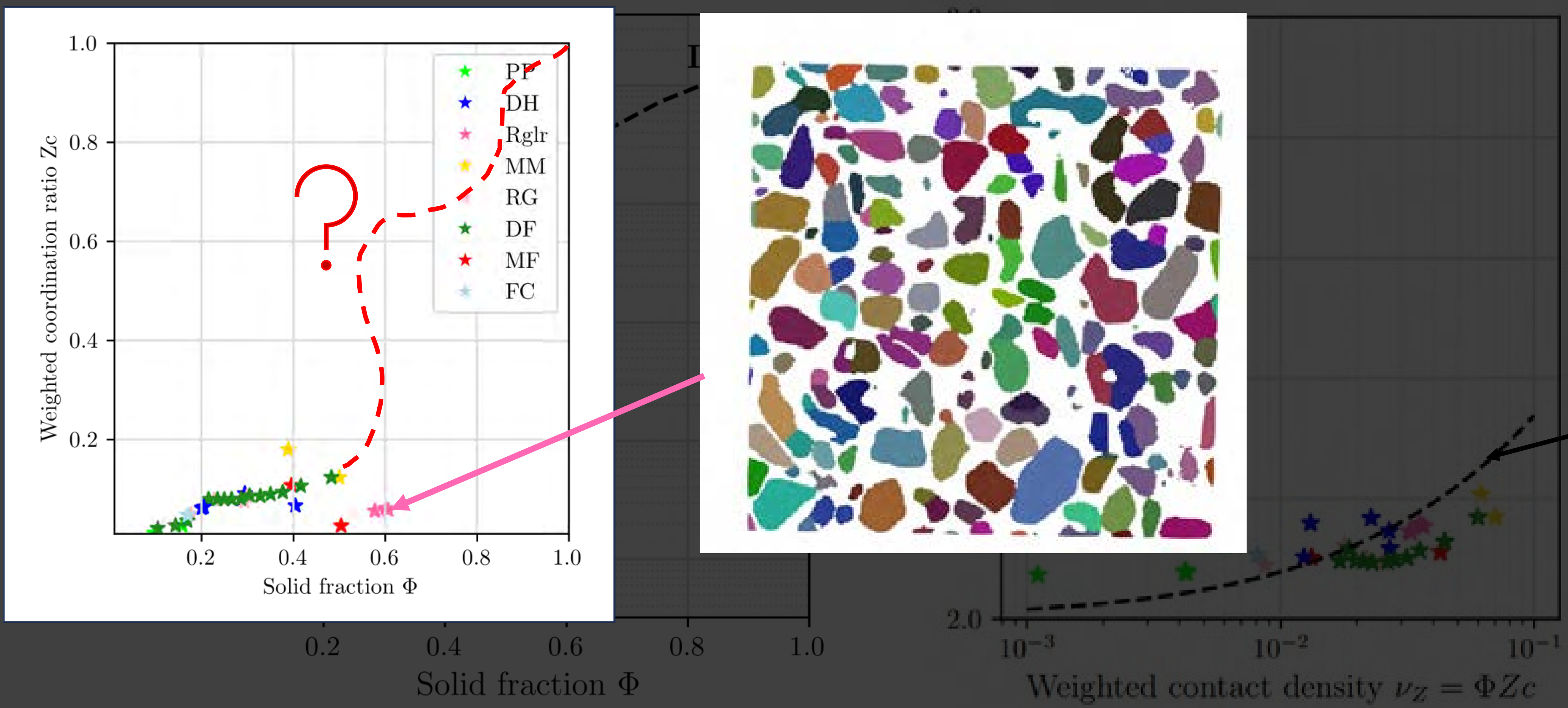






Generic viscoplastic model for porous polycrystals

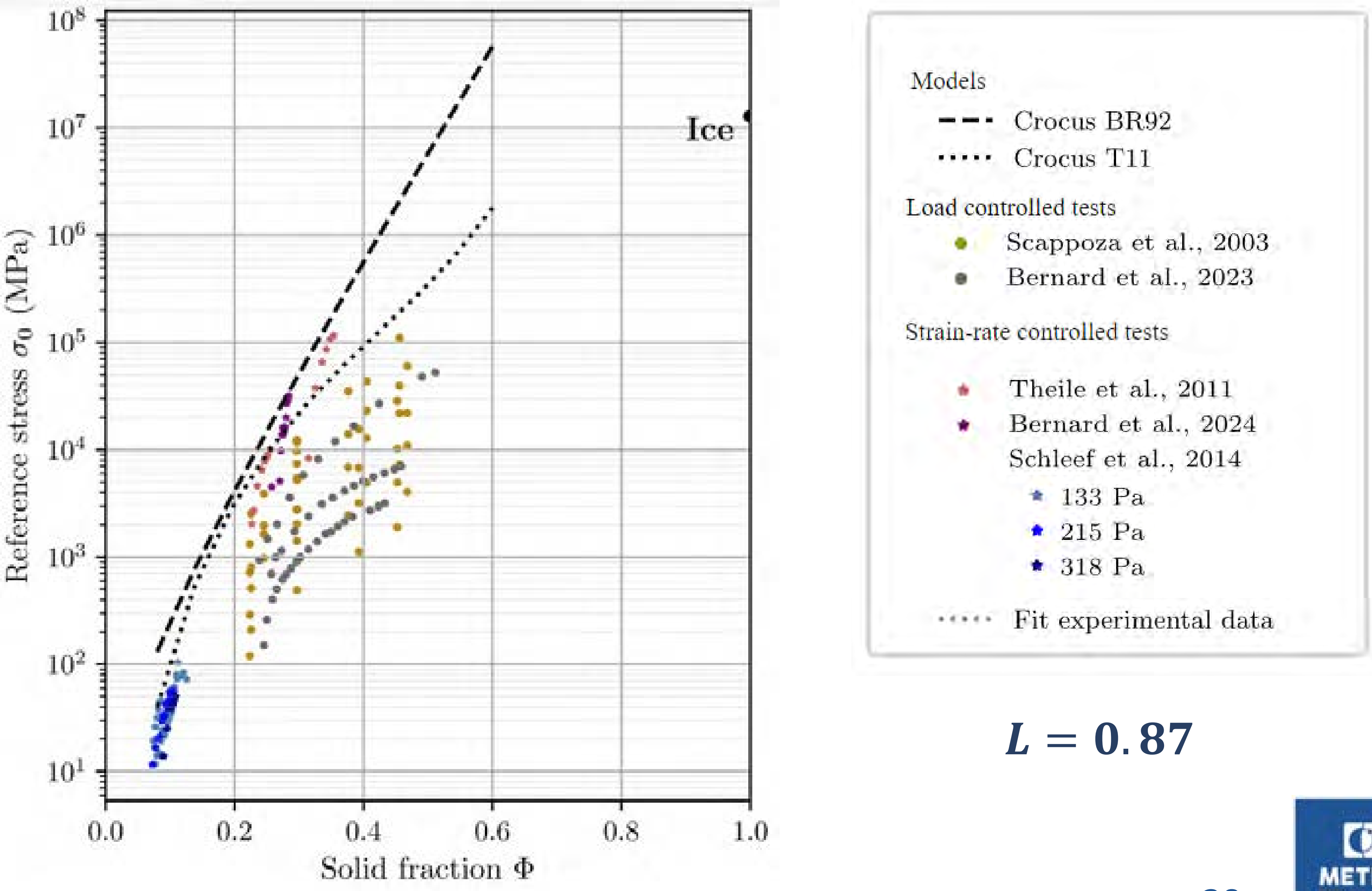
A New Snow Densification Model: effect of microstructure on homogenized parameters



A generic viscoplastic model for porous polycrystals

Hypothesis n=1

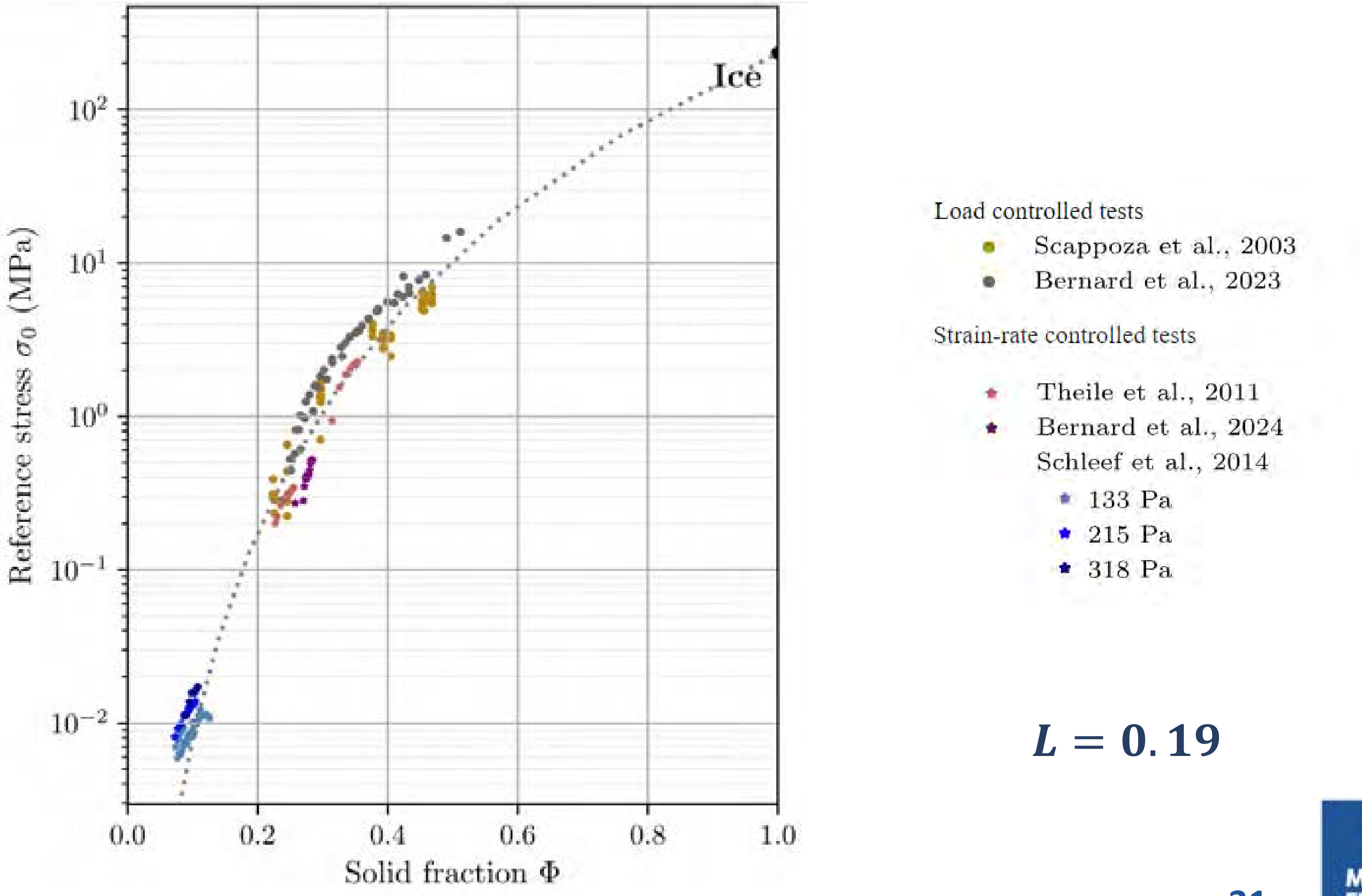
All snow densification model



$L = 0.87$

Hypothesis n=3

Classical microstructure-based models

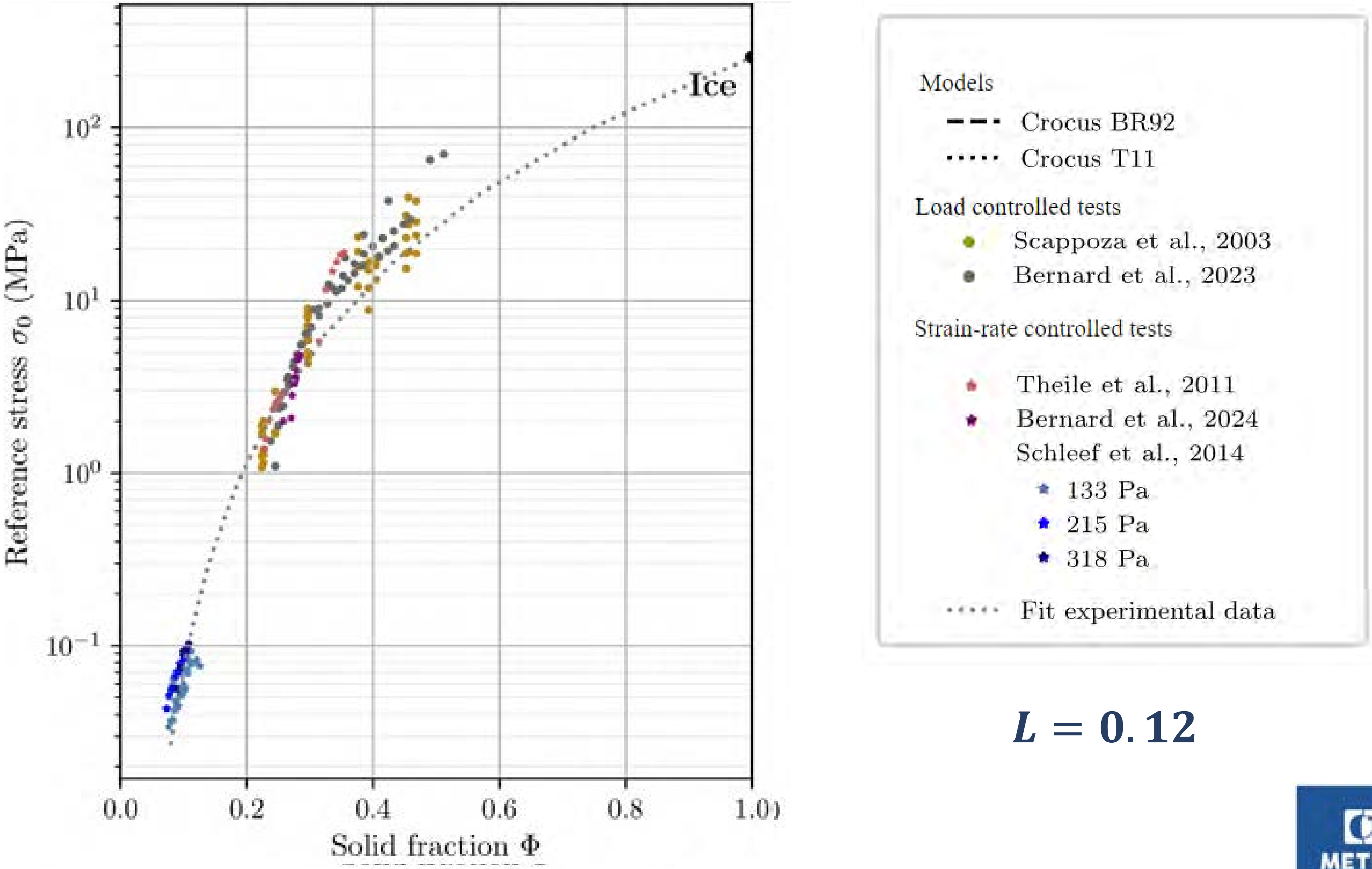


$L = 0.19$

Hypothesis

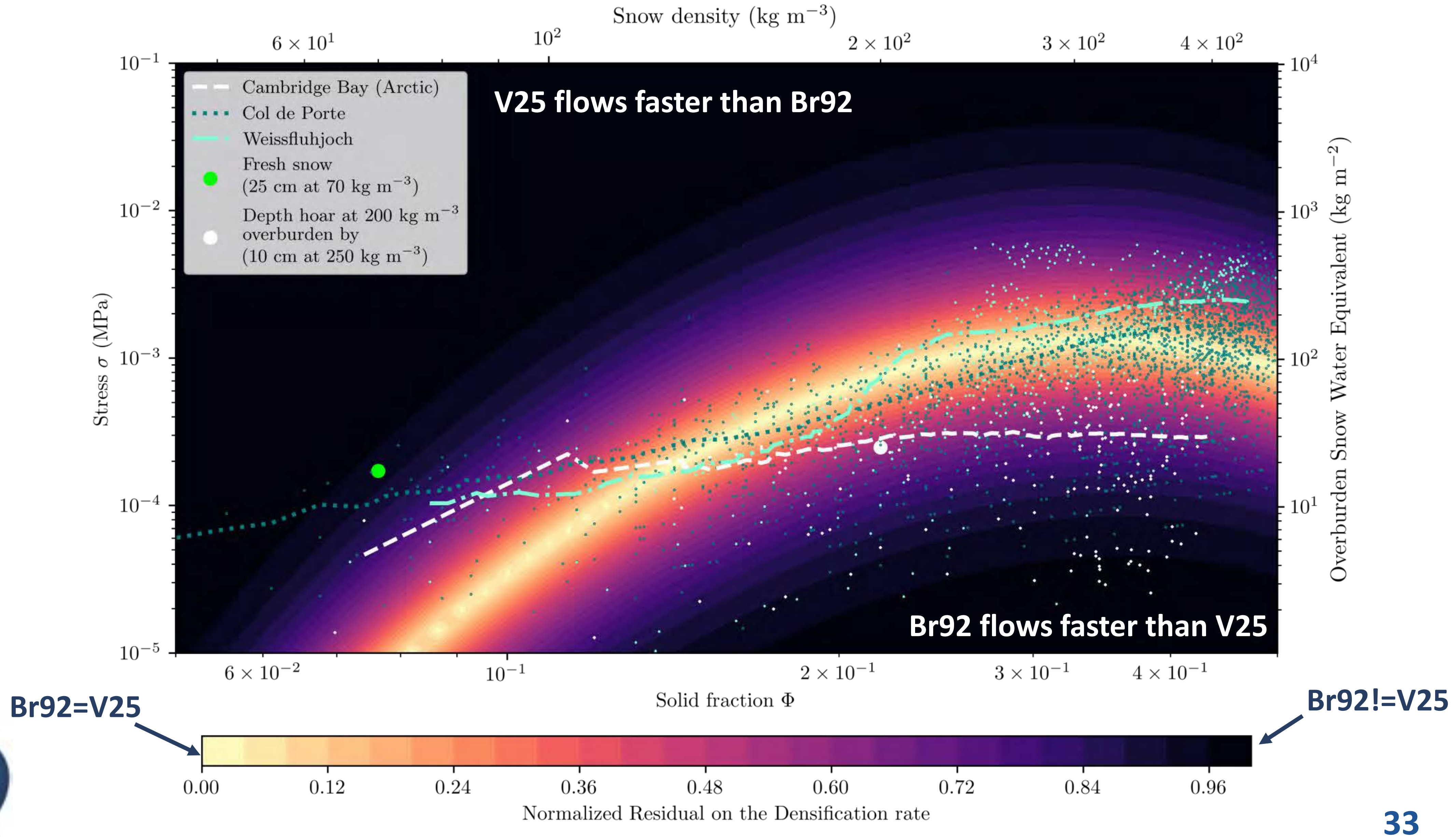
$$n = n(\nu_c)$$

Model V25

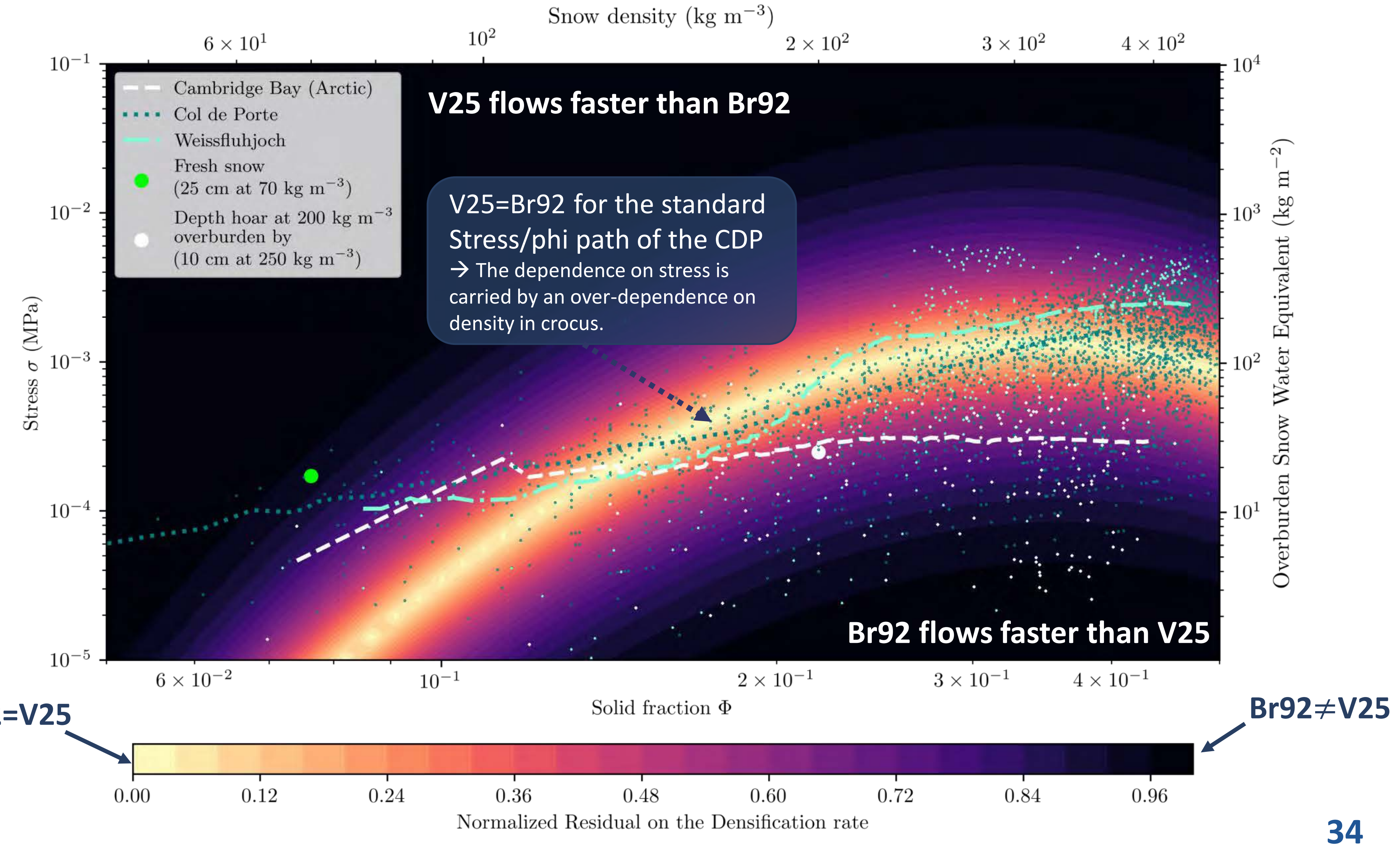


$$L = 0.12$$

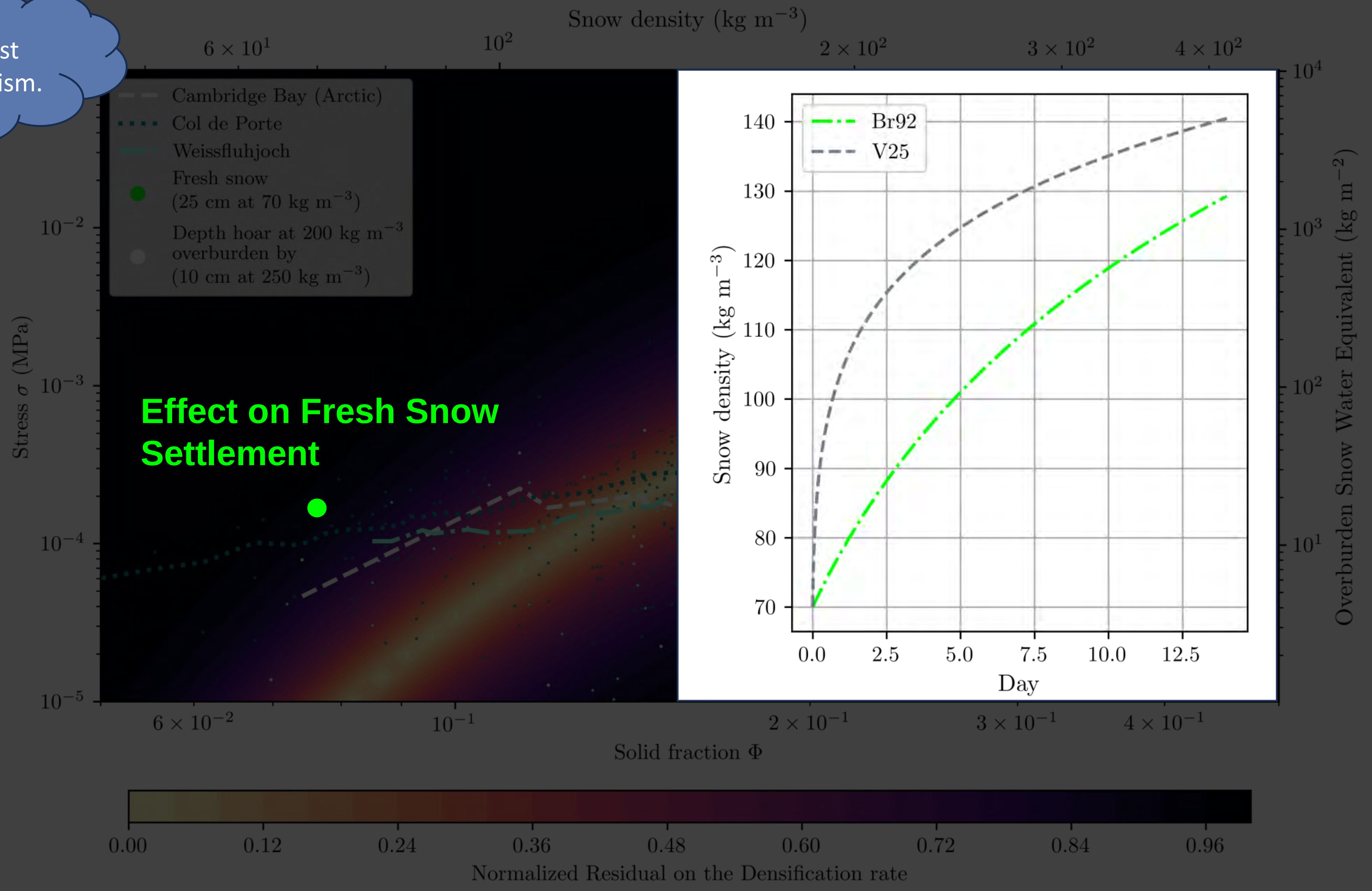
A New Snow Densification Model: comparison with Br92



A New Snow Densification Model: comparison with Br92



It's not just metamorphism.



A New Snow Densification Model: comparison with Br92