Etude de la microstructure de la neige par tomographie : le cas des mesures de surface spécifique à partir d'images 3D

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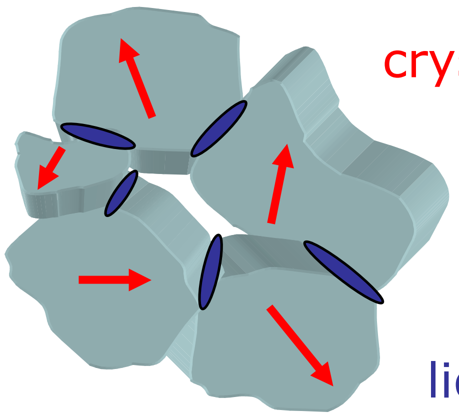
Partie 1: Etude de la microstructure de la neige par tomographie

Partie 2: Mesures de surface spécifique à partir d’images 3D

Remerciements : S. Cabanes, B. Chareyre, A. Dufour, L. Gillibert, A. Hasan, J. Kozicki, B. Lesaffre, W. Ludwig, J. Meyssonnier, A. Philip, S. Rolland du Roscoat…

Why Studying Snow Microstructure?

- A complex material…

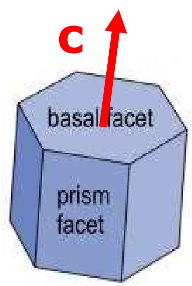


crystalline orientation

air/vapor

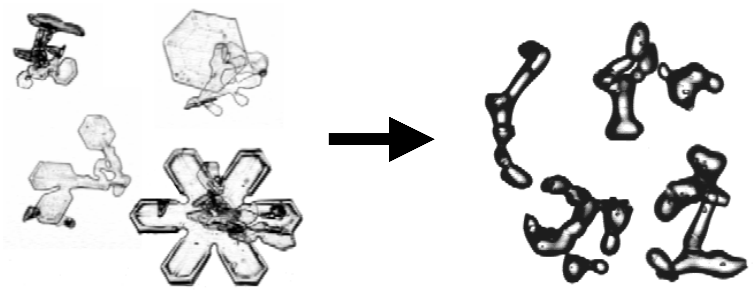
ice

liquid water



- porous
- granular
- polycrystalline
- polyphasic

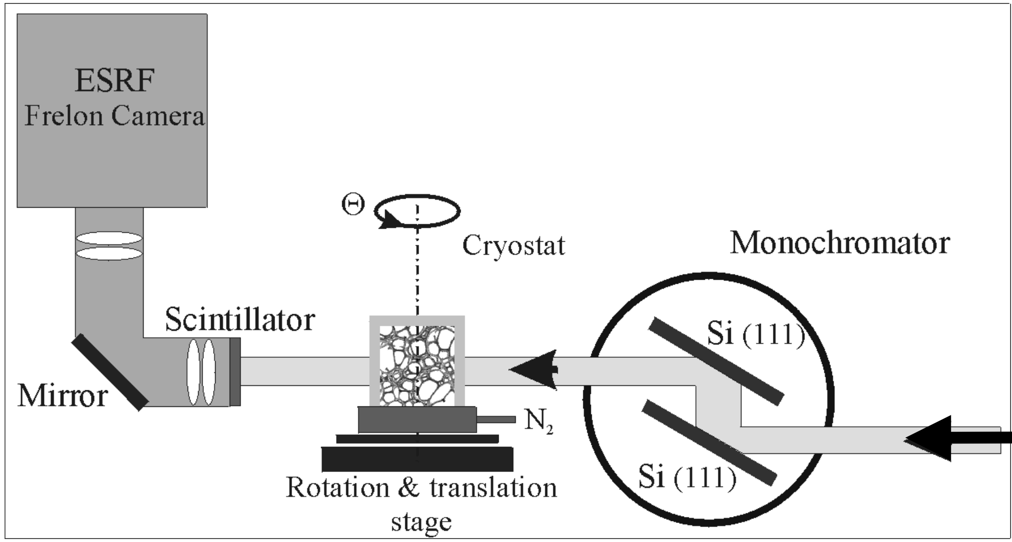
- …that transforms with time : « **Metamorphism** »



➔ Evolution of the snow properties

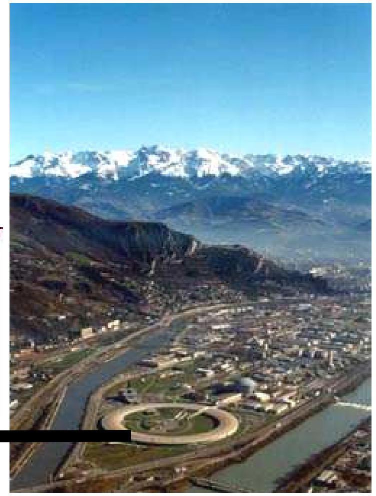
Final objective: better understanding of snow and application in large-scale models (Crocus, climate models…)

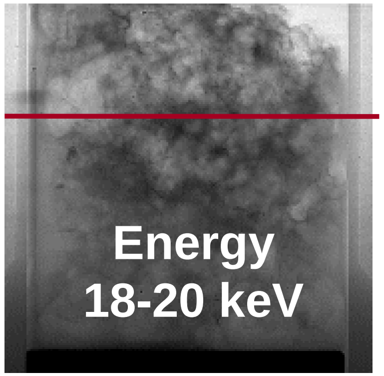
Method : X-ray Microtomography

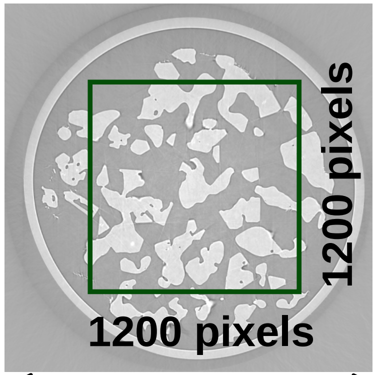


ESRF

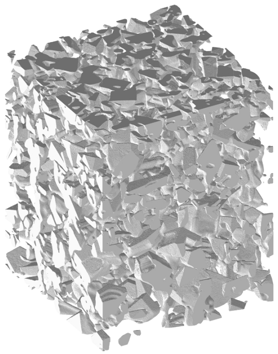
Laboratoire
Sols
Solides
Structures
Risques







10 mm



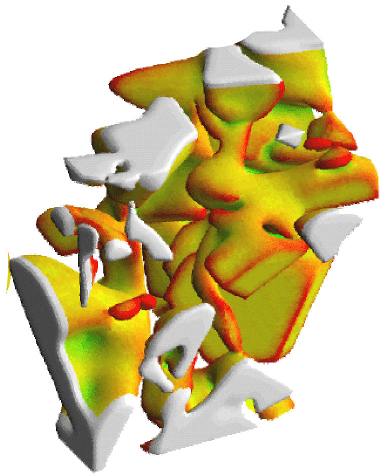
Optimal resolution :
1 pixel
=
4.92 microns

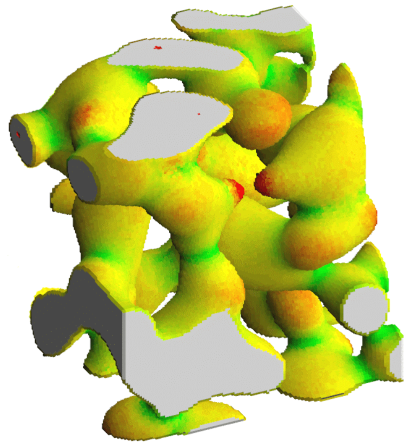
Room temperature experiments:
A cold cell is needed

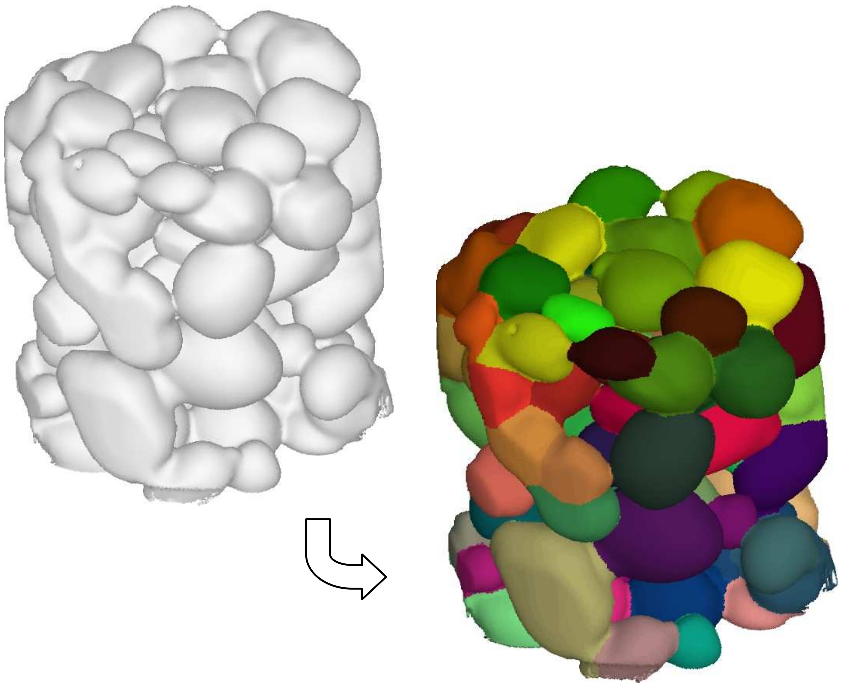
Image Analysis

- Algorithms
  - Normal vectors [1,2]
  - Surface area [1,2]
  - Local curvatures:
    - Mean [3]
    - Gaussian [4]
  - Grain segmentation [5, 6]

$$C_m = \frac{1}{2}\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad C_g = \frac{1}{r_1} . \frac{1}{r_2}$$



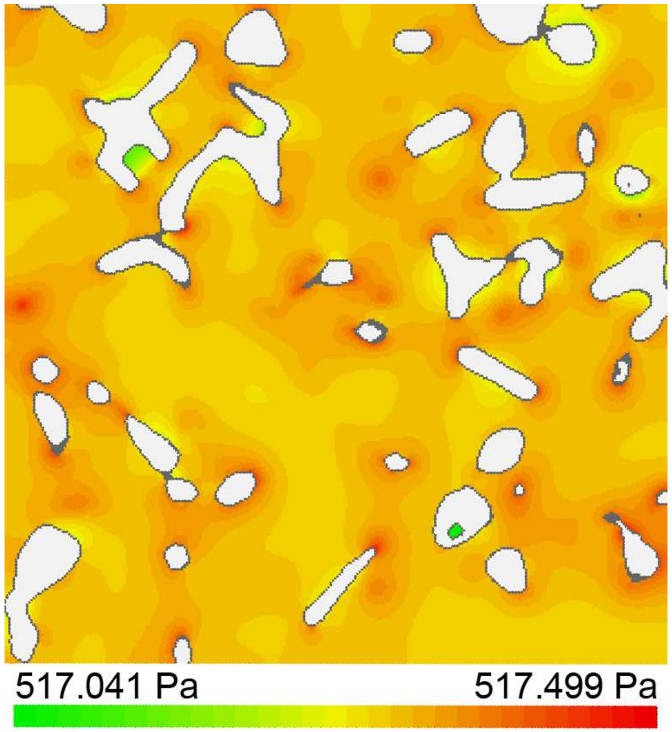


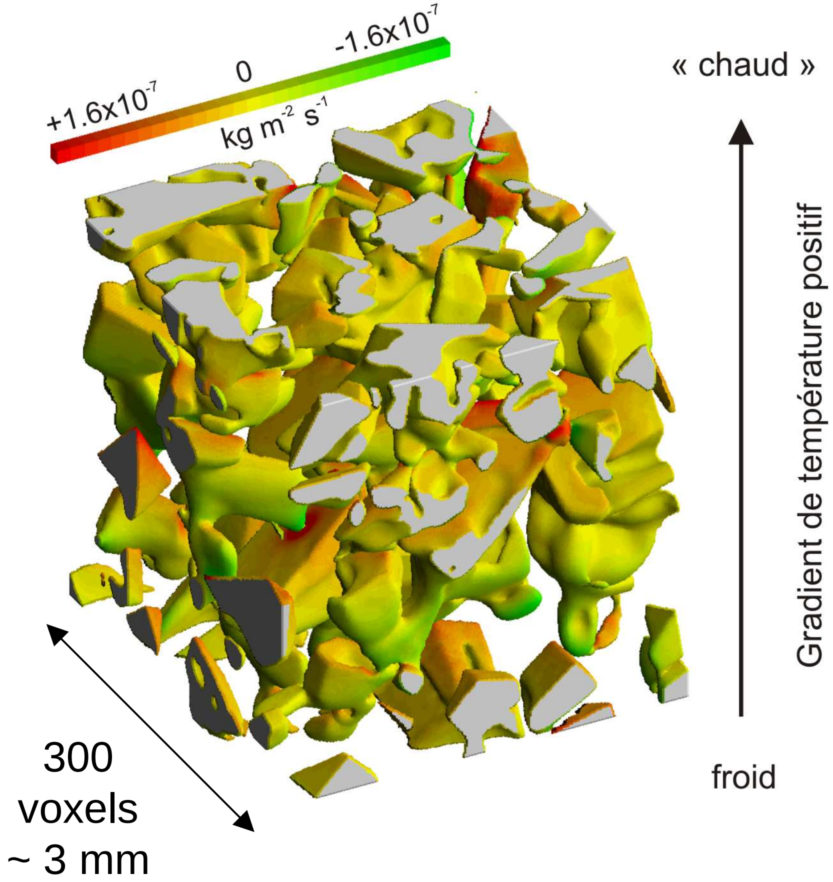


[1]Flin *et al.*: IEEE Trans. Image Process. (2005)
[2]Coeurjolly *et al.*: LNCS (2003)
[3]Flin *et al.*: Ann. Glaciol. (2004)
[4]Ogawa *et al.*: Memoirs of HIT (2006)
[5]Brzoska *et al.*: Proceedings of PCI (2007)
[6]Gillibert *et al.*: Proceedings of W3D (in press)

Metamorphism

- Mechanisms involved in snow metamorphism: modelling the water vapor diffusion in the pore space



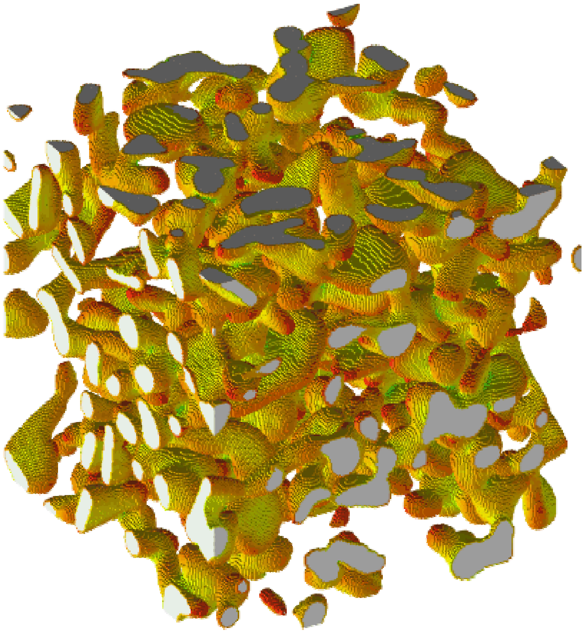


Brzoska *et al.*: Ann. Glaciol. (2008)
Flin and Brzoska : Ann. Glaciol. (2008)

Metamorphism

- Better understanding of snow metamorphism :
  - Modeling and comparing to structures obtained experimentally

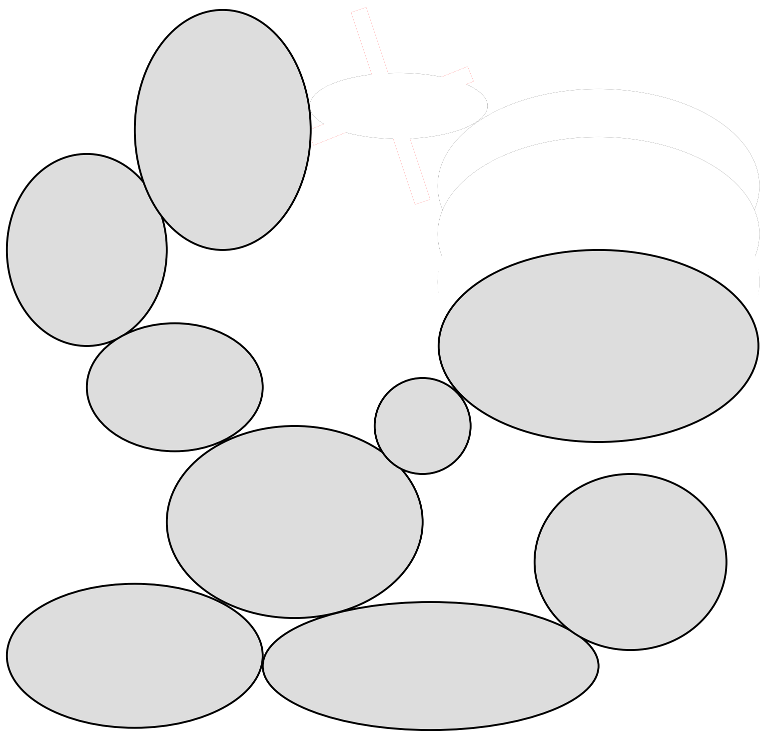
300
voxels
~ 3 mm



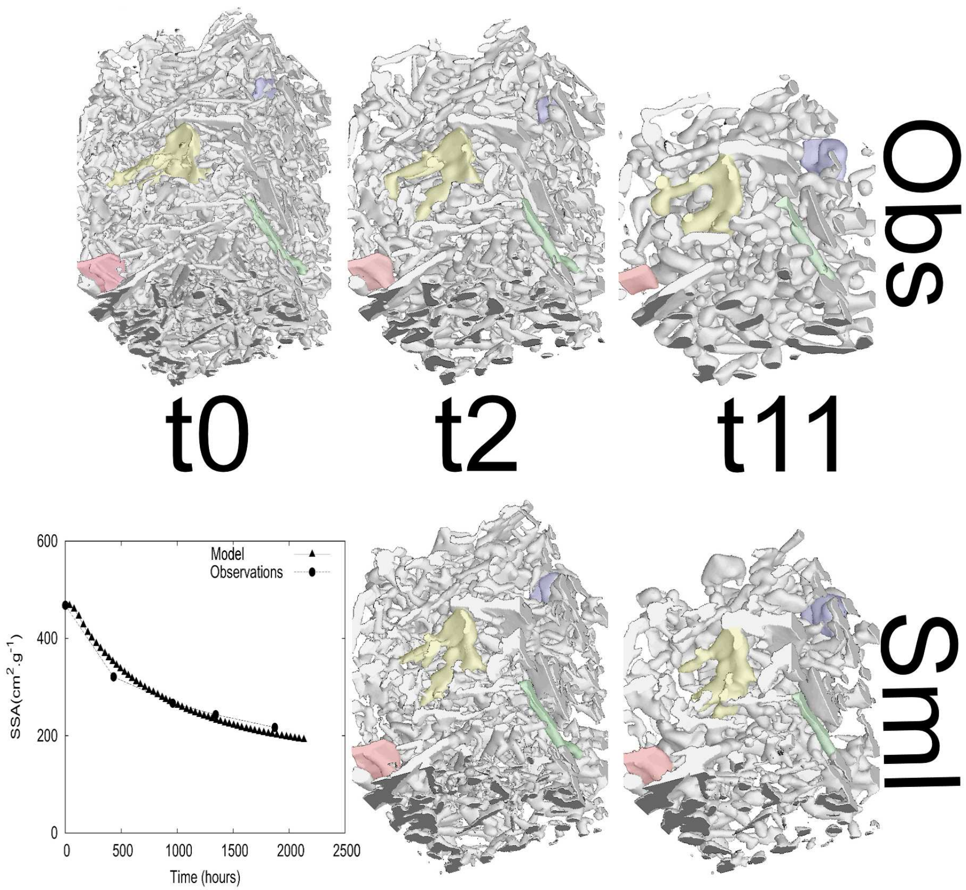
Stages of the metamorphism
obtained experimentally

Metamorphism

- Coupling to mechanical processes
  - –Modelling settling phenomena with basic grain re-arrangement after neck breaking (Dufour et al, 2009)



Improvement with DEM (Yade Model, Alsidqi Hasan)

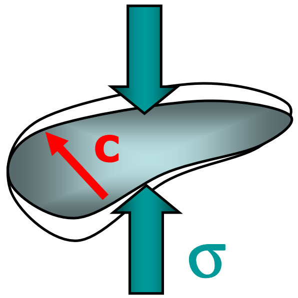


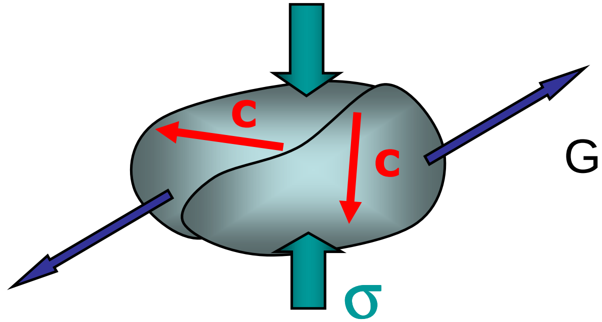
Experiments obtained in SLF

Mechanical processes

- Motivation

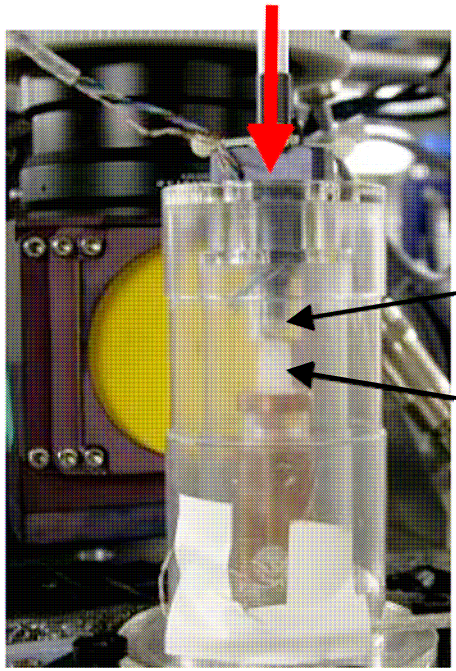
Viscoplastic Deformation

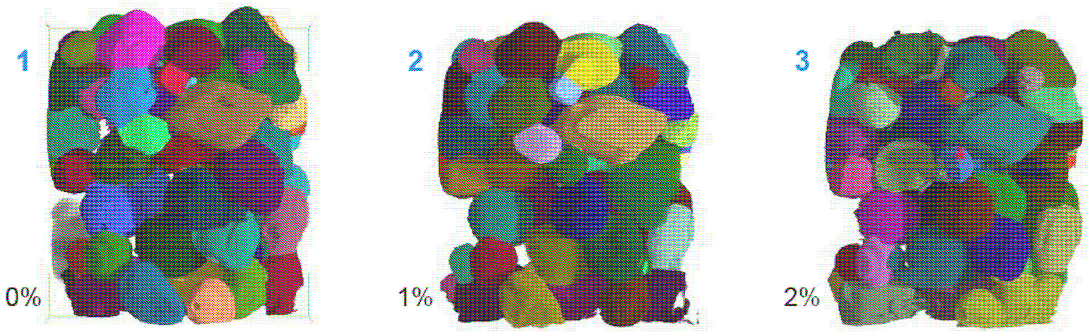




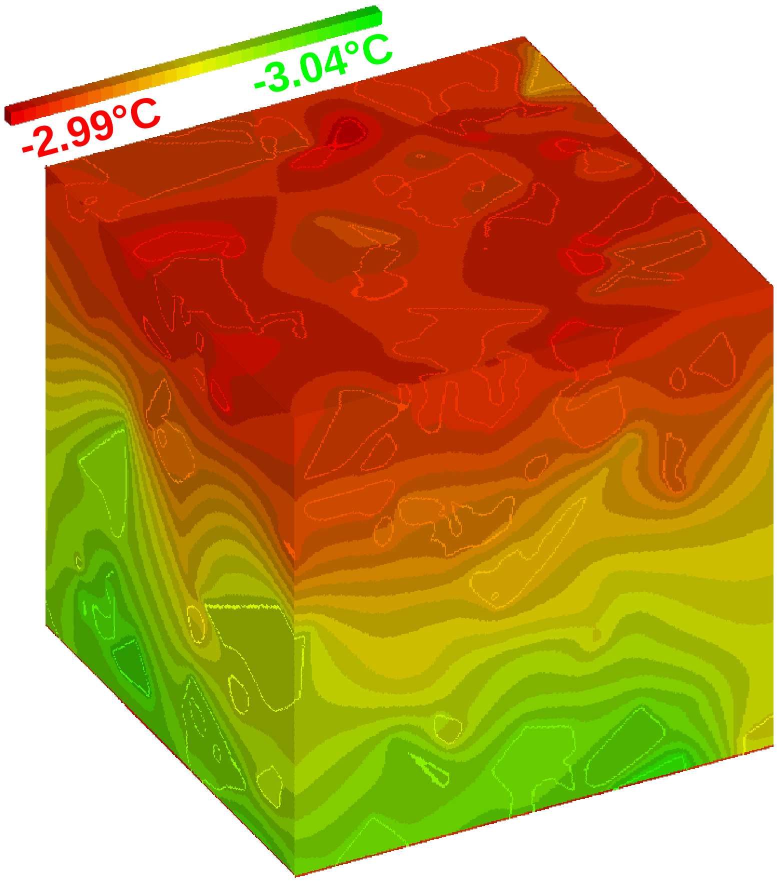
Grain Boundary Sliding

- Evolution of a snow specimen submitted to mechanical stresses (ANR « Snow-White » project)

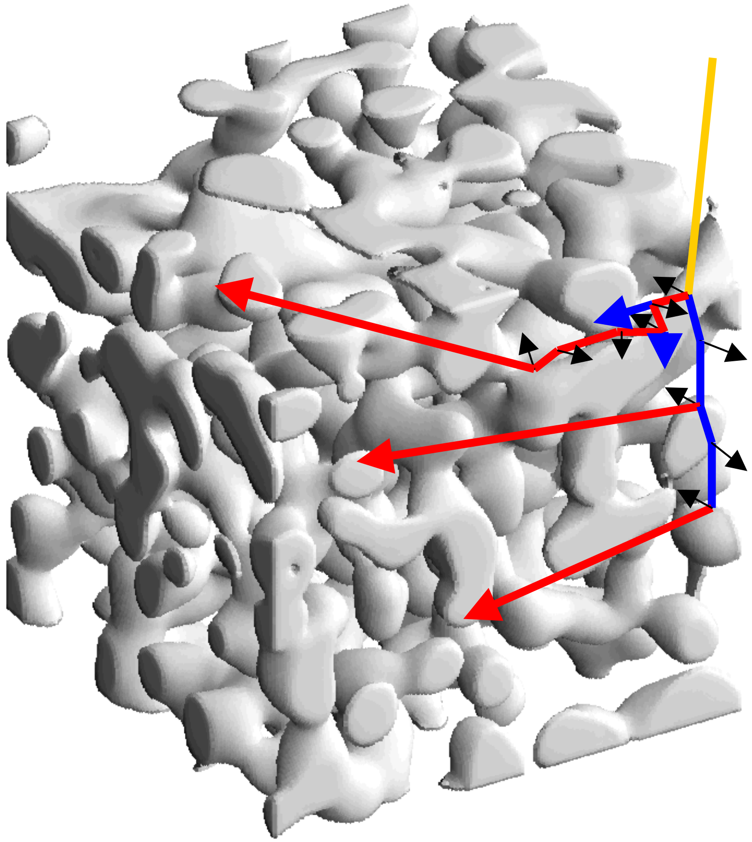




Physical Properties



300
voxels
~ 3 mm



➔ Thermal properties
(Kaempfer et al, 2005)

➔ BRDF estimations from real structures with ray-tracing methods (Kaempfer et al, 2007)

Part 2:
Specific Surface Area (SSA) from 3D images

Some reminders about SSA

- Definition

$$\boxed{SSA = S / M}$$

S: surface area
M: mass

- Importance
  - Related to grain size (spherical approximation) $[L^{-1}]$
  - Characterize snow metamorphism evolution
  - Surface available for chemical reactions

- Measurements
  - CH_4 adsorption (Legagneux et al, 2002; Kerbrat et al 2008)
  - Tomography (Flin et al, 2004; Schneebeli and Sokratov, 2004)
  - Near Infra Red methods (Gallet et al, 2009; Arnaud et al, in press) → the fastest and most field-compliant methods

Why studying SSA measurements from 3D images ?

- An important physical parameter that can be measured from field measurements AND from 3D images → **link between microscale experiments and snowpack studies**

- Increasing number of tomographs and SSA computation methods in the world (SLF, AWI, Dartmouth College & CRREL, UAF, SASE…)

- Questions:

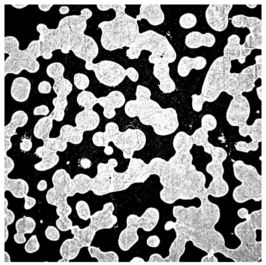
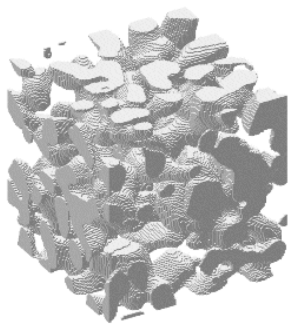
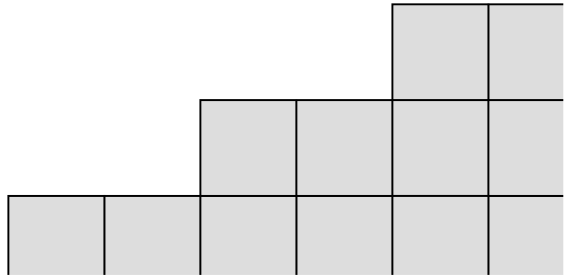
  Q1. Do all the numerical methods give the same results and is a minimal image resolution necessary to compute accurate SSA ?

  Q2. What is the typical Representative Elementary Volume (REV) for the SSA of a snow specimen ?

  Q3. Would it be possible to access informations about Grain Contact Area in order to better characterize snow ?

SSA numerical measurements

- General method

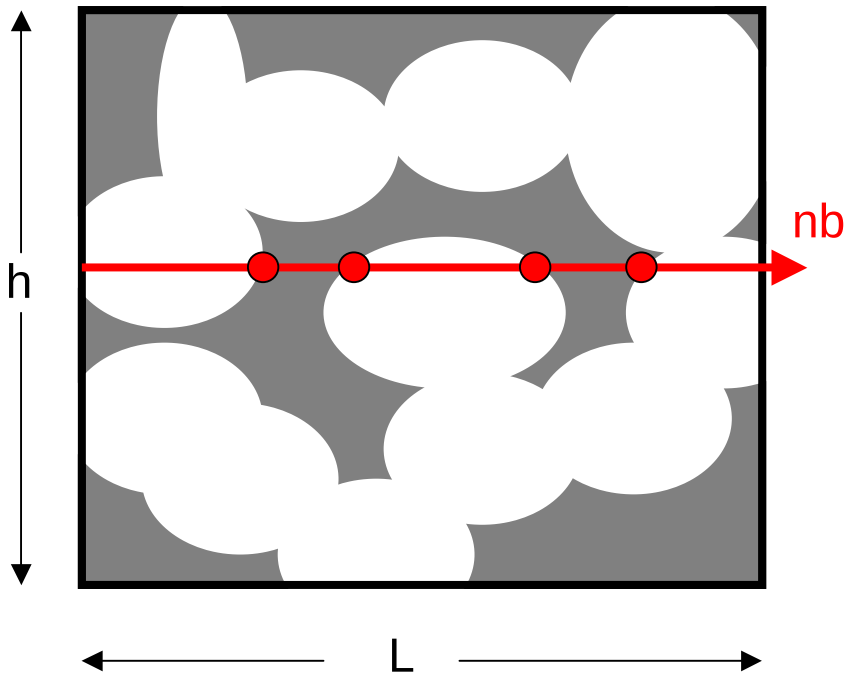




Surface area estimation
from a digital image

- 3 different approaches for surface computation
  – Method 1: stereology
  – Method 2: triangulation
  – Method 3: projection methods

Method 1: Stereology

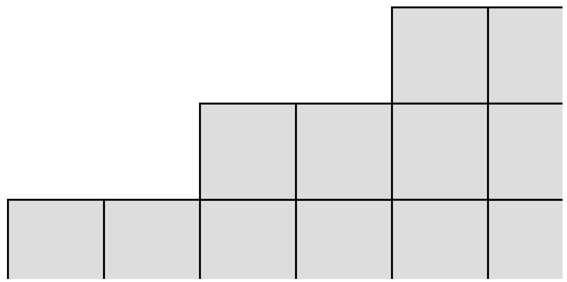
- Intercept computation



Underwood, 1970
Torquato, 2002

Method 2: Triangulation

- Marching Cubes approach



Method 2: Triangulation

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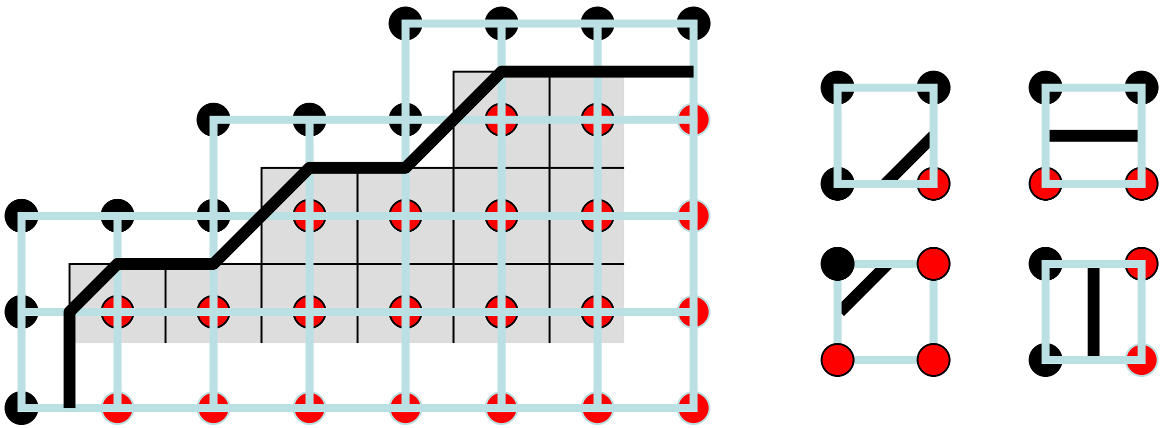
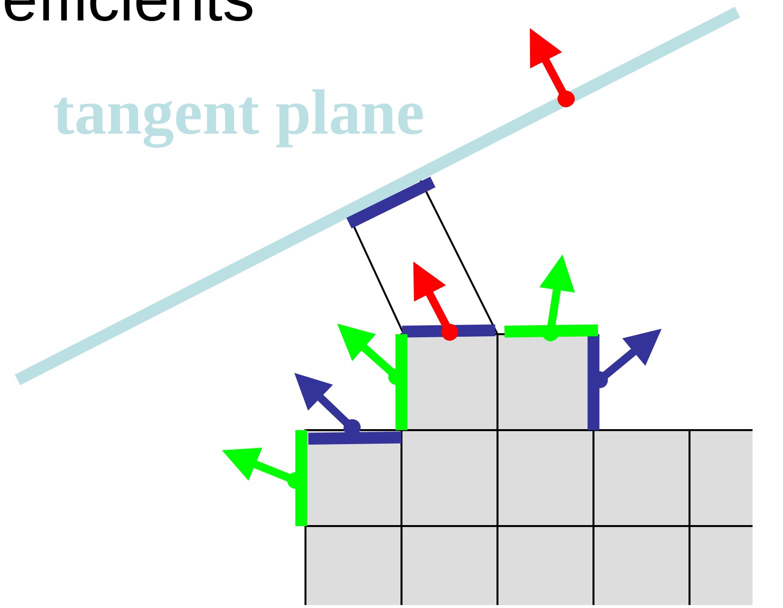


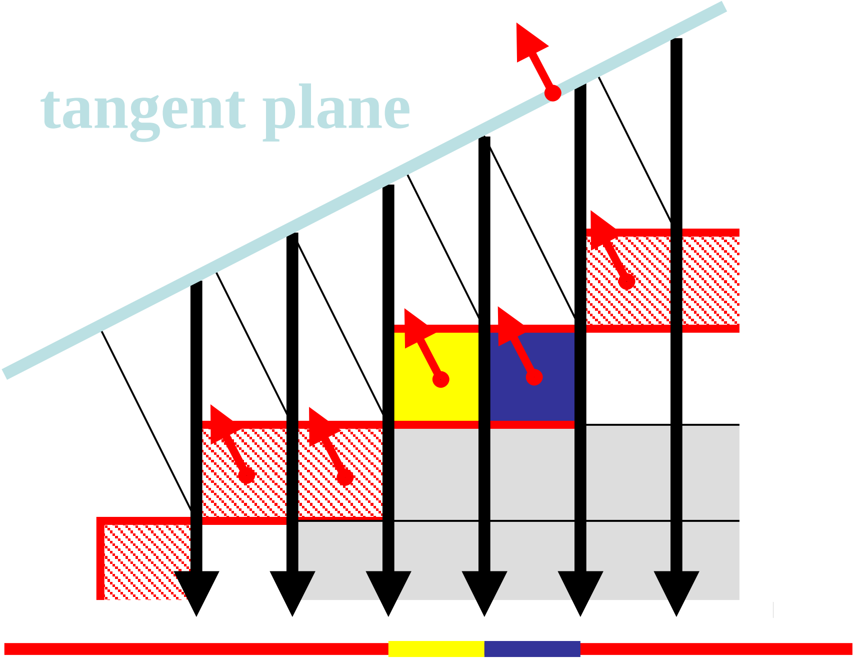
Method 3: Voxel Projection

- Use all the **information contained in the normal** of each voxel to improve the area estimation:
  - Tangent plane approximation
  - Normal dependent coefficients
- Lenoir et al. (1996)



Method 3: Voxel Projection

VP method:



Fonctional plane :
the **coordinate** plane
along which **each** voxel presents
a unique facet

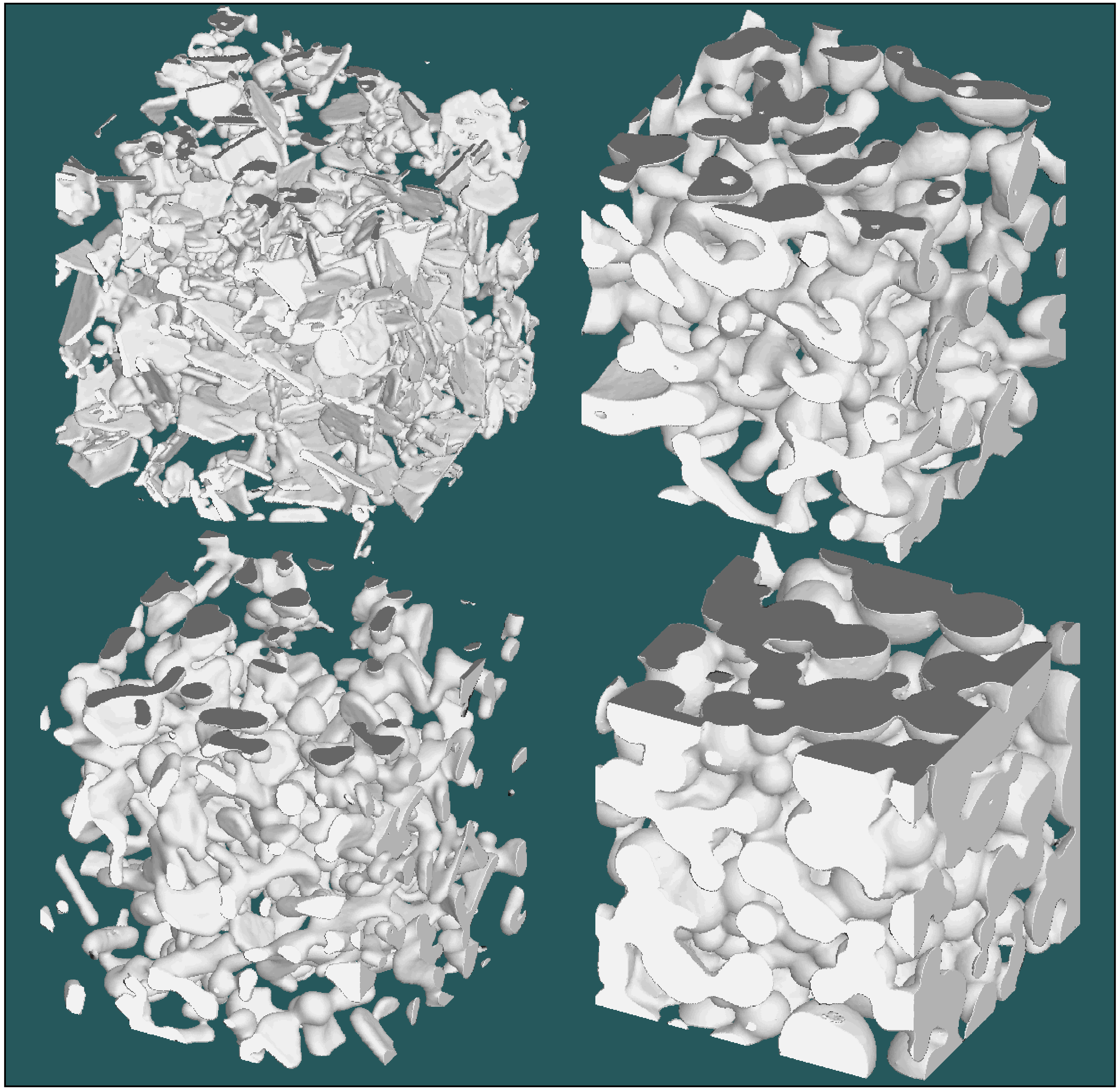
Flin *et al.*, 2005

Surface contribution:
The projection ratio is obtained by projecting
the **tangent plane** on the **fonctional plane**

Tests on diverse snow types :

Fresh Snow
edge: 2.5 mm

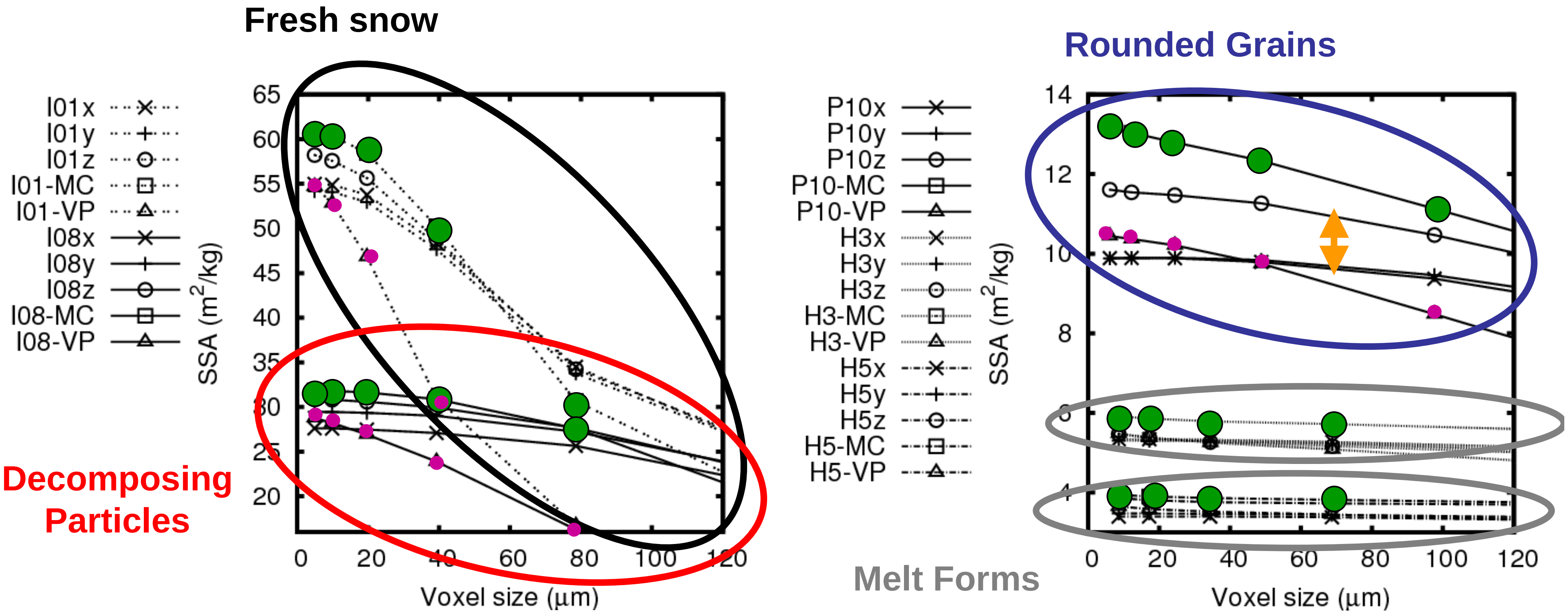
Rounded Grains
edge: 2.5 mm



Decomposing Particles
edge: 2.5 mm

Melt Forms
edge: 4.5 mm

Q1. Impact of Methods and Resolution



→ At high resolution, all methods agree within ± 15%

→ Results strongly depend on the snow type

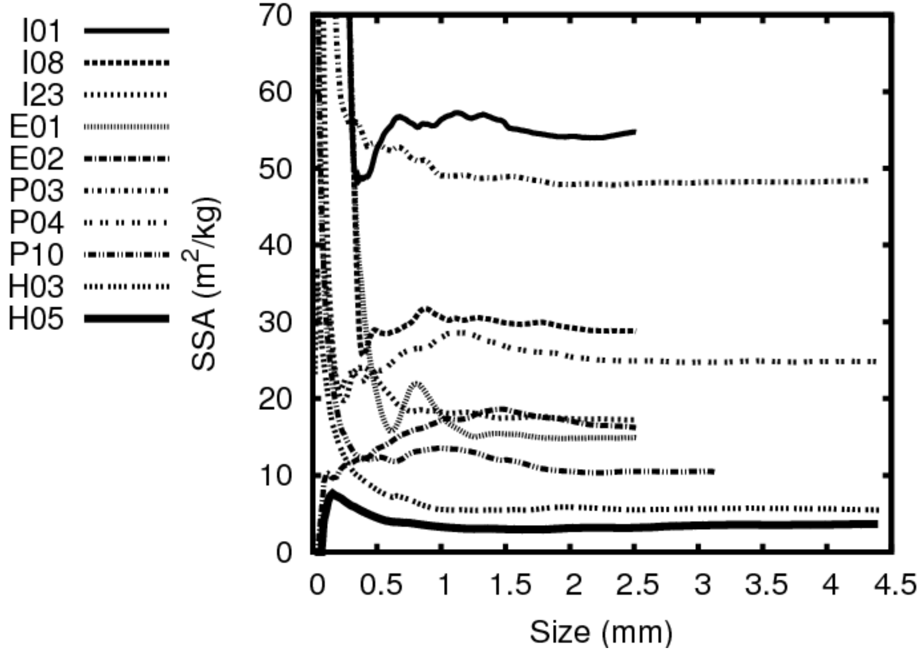
→ **ST** methods give different estimations between z and x-y directions

→ **Marching Cubes** systematically overestimates SSA

→ **VP** is particularly sensitive to resolution decrease

Q2. REV estimation

- Method: growing neighborhoods
- Result:

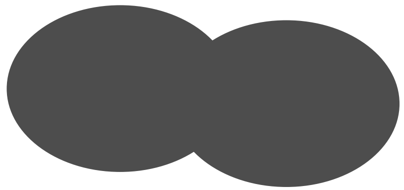


- Conclusion

For all the studied samples, the REV seems to be attained for cubic volumes of edge = 2.5 mm.

Q3. Estimation of Grain Contact Area

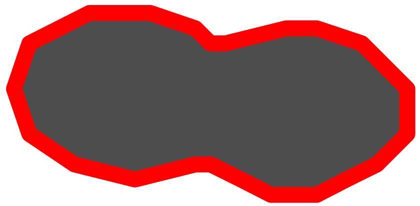
- Idea: estimating the size of the contact area between grains



- Method:

Q3. Estimation of Grain Contact Area

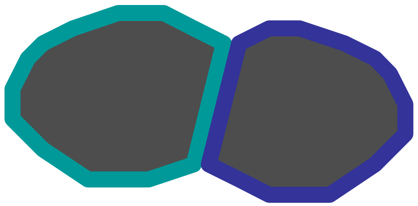
- Idea: estimating the size of the contact area between grains



- Method:
  - Estimate the SSA of the snow sample

Q3. Estimation of Grain Contact Area

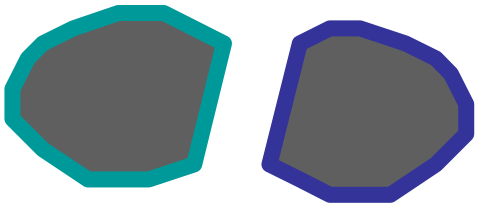
- Idea: estimating the size of the contact area between grains



- Method:
  - Estimate the SSA of the snow sample
  - Estimate the average SSA for the grains constituting the snow sample (SSA_{tot})

Q3. Estimation of Grain Contact Area

- Idea: estimating the size of the contact area between grains

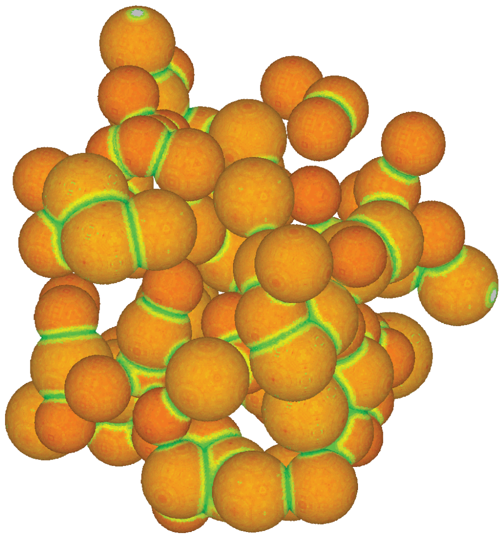


- Method:
  - Estimate the SSA of the snow sample
  - Estimate the average SSA for the grains constituting the snow sample (SSA_{tot})
  - SGCA = SSA_{tot}-SSA is the SSA that would be released by neck breaking

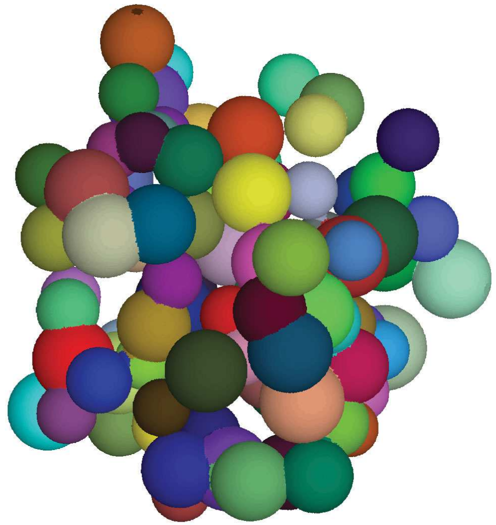
Q3. Estimation of Grain Contact Area

- Curvature-Driven Grain Segmentation (CDGS) algorithm: snow labeling into different geometrical grains

Sign of the lowest principal curvature →



→

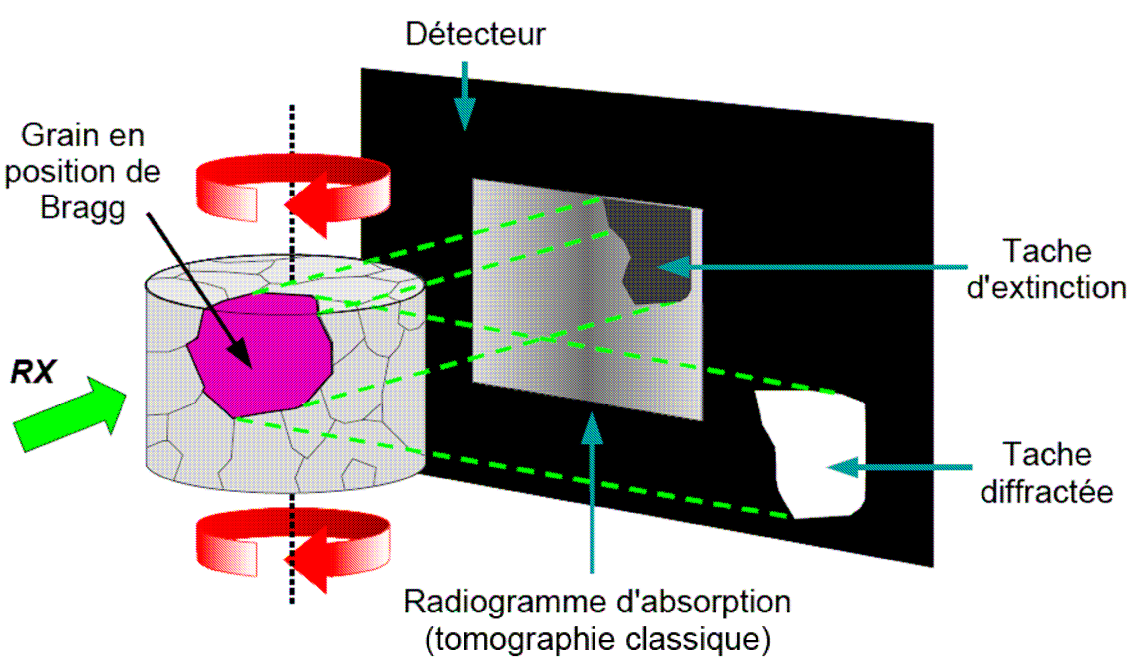


- Main idea: detect necks with a curvature analysis (Gaussian and Mean curvature)

Gillibert et al, 2010

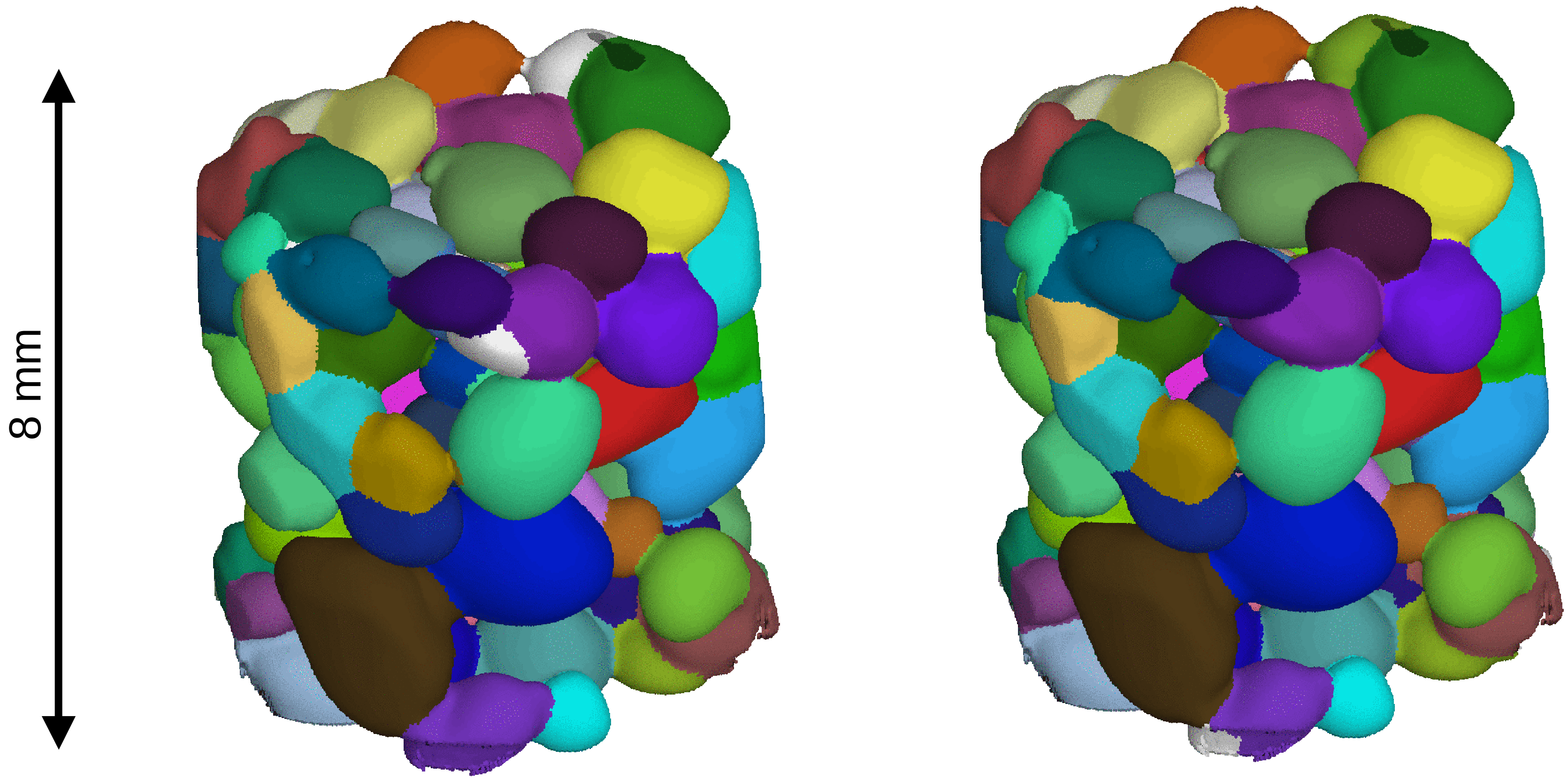
Q3. Estimation of Grain Contact Area

- Comparison to DCT: “Diffraction contrast tomography”



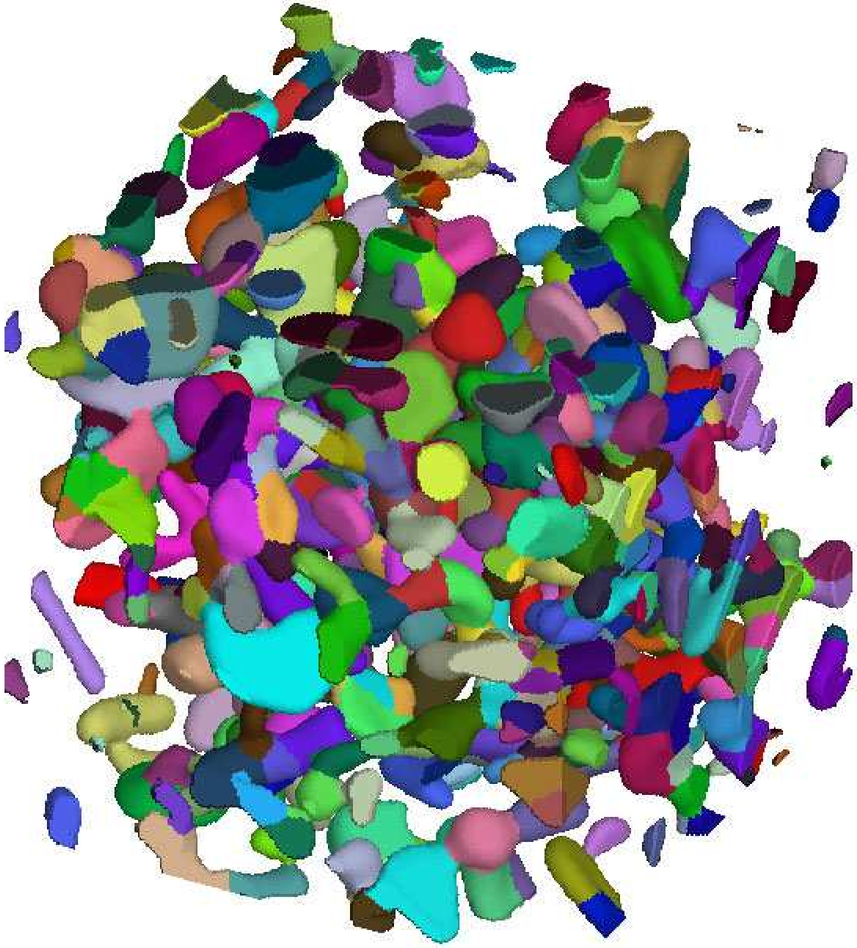
Ludwig et al. 2009, Rolland *et al.*: Adv. Eng. Mater. (in press)

Validation by Diffraction Contrast Tomography

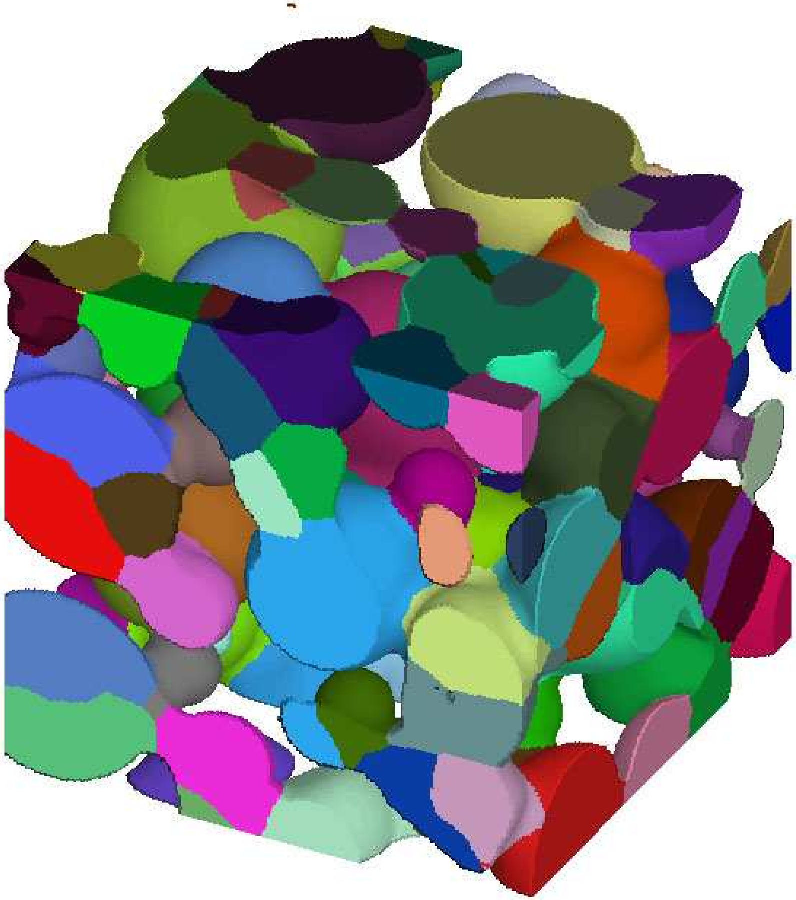


DCT CDGS

Exemples of CDGS

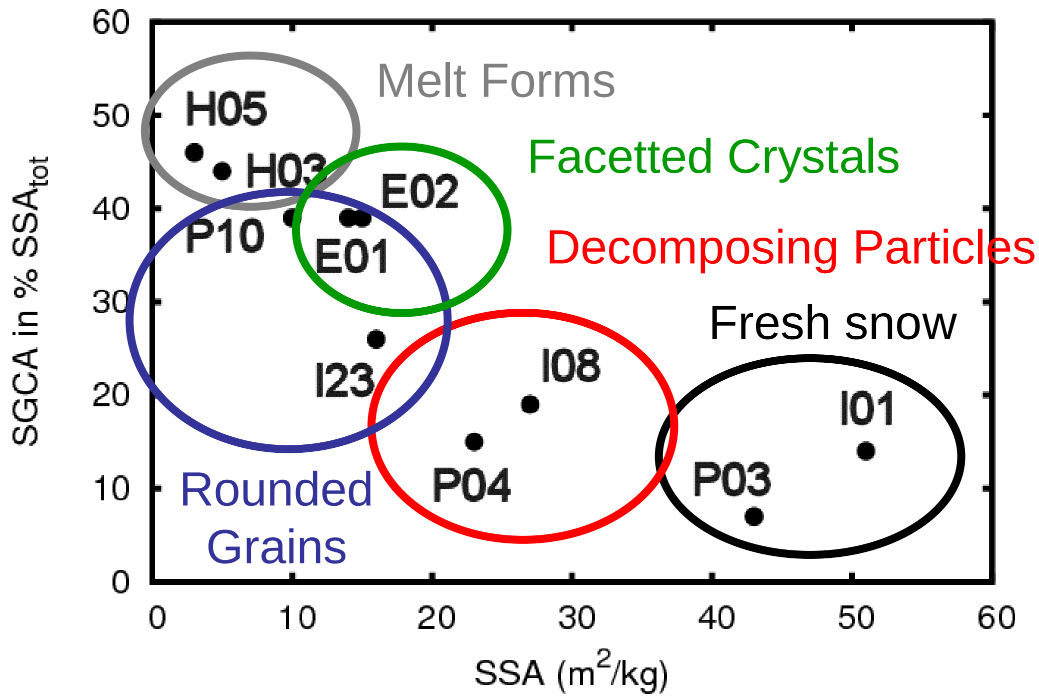


Decomposing Particles / Rounded Grains
Edge size = 2.5 mm - 604 grains



Melt Forms
Edge size = 4.5 mm -129 grains

Q3. Estimation of Grain Contact Area



→ Relationship between SSA (grain size) and SGCA (neck size).

→ Mechanically processing "old" snow samples would double their SSA

→ SGCA seems a potential parameter to help in determining the snow type

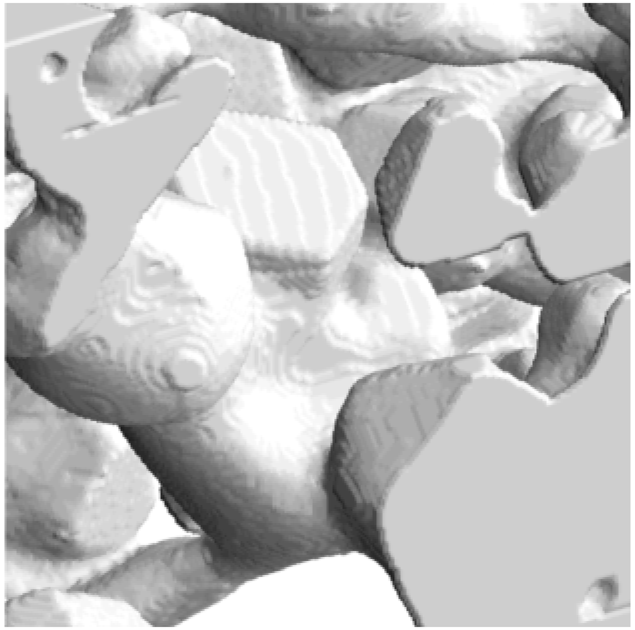
Conclusions

- The main numerical methods that are commonly used to determine SSA from 3D images give slightly different results
- Each method has its own drawbacks: ST is not adapted to anisotropic media, MC overestimate SSA and VP is particularly sensitive to resolution decrease.
- Depending on the method, SSA estimation of recent snow require high resolution images (voxel size < 5 µm)
- REV for SSA is attained for cubes of 2.5 mm edge
- Thanks to the combination of SSA and CDGS algorithms, SGCA values can be estimated: this opens new outlooks for the study of snow microstructure

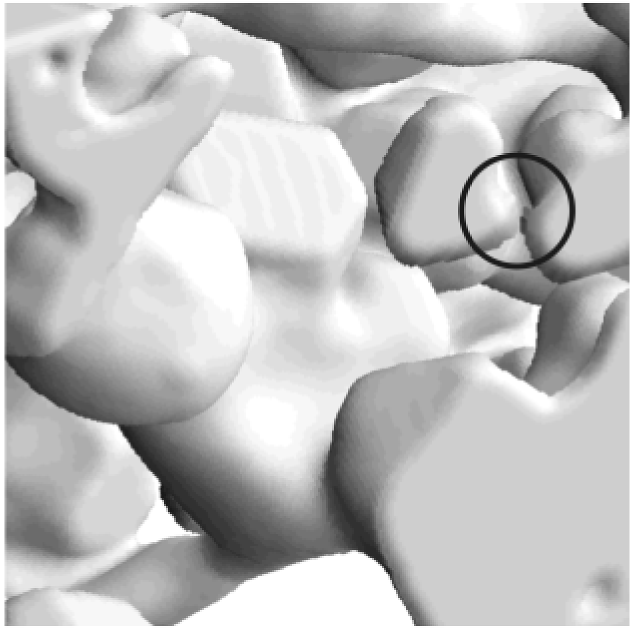
Snow and Firn Tomography in the World

- **SLF, Davos, Switzerland** (M. Schneebeli, H. Loewe)
  - 2 tomographs (SCANCO, 10 & 18 μm) in cold room
- **AWI, Bremerhaven, Germany** (J. Freitag)
  - 3 tomographs (SKYSCAN, 5 & 40 μm + ICE-CT, 4 to 40 μm) in cold room
- **Dartmouth College & CRREL, Hanover, USA** (I. Baker, T. Kaempfer)
  - 1 tomograph (SKYSCAN, 5 μm) in cold room
- **UAF, Fairbanks, USA** (Yuan et al., 2010)
  - 1 tomograph (SKYSCAN, 5 μm) in cold room
- **SASE, Manali, India** (Srivastava et al., 2010)
  - 1 tomograph (SKYSCAN, 5 μm) in cold room

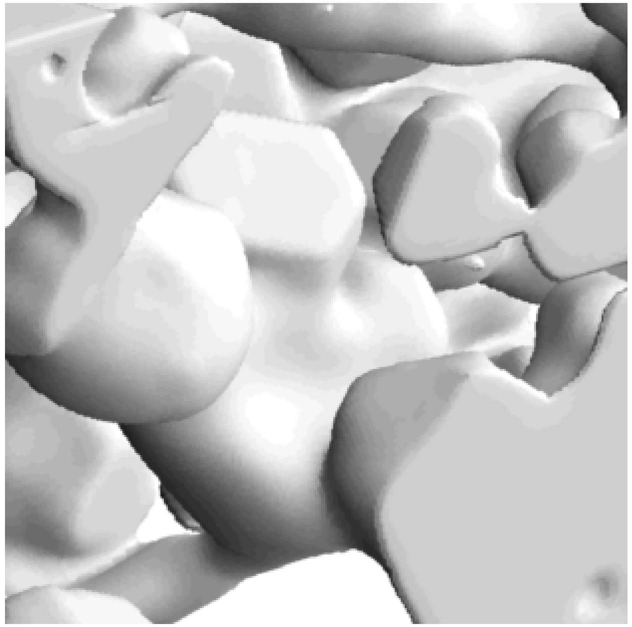
Application to snow



MC



Gaussian smooth + MC

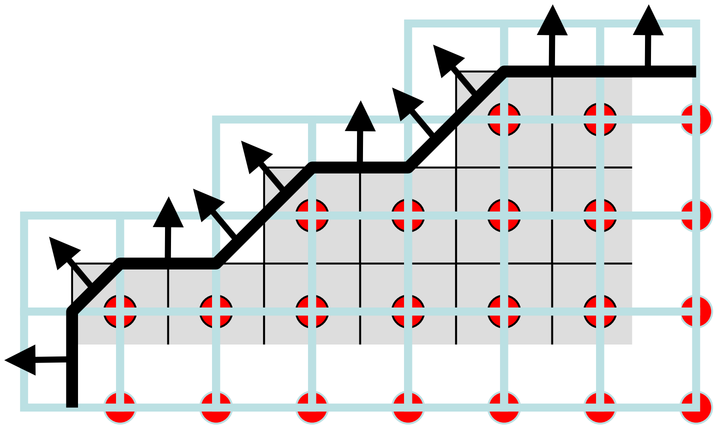


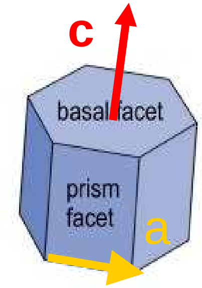
ADGF method

Flin *et al.*, 2005

Method 2: Triangulation

- Marching Cubes approach

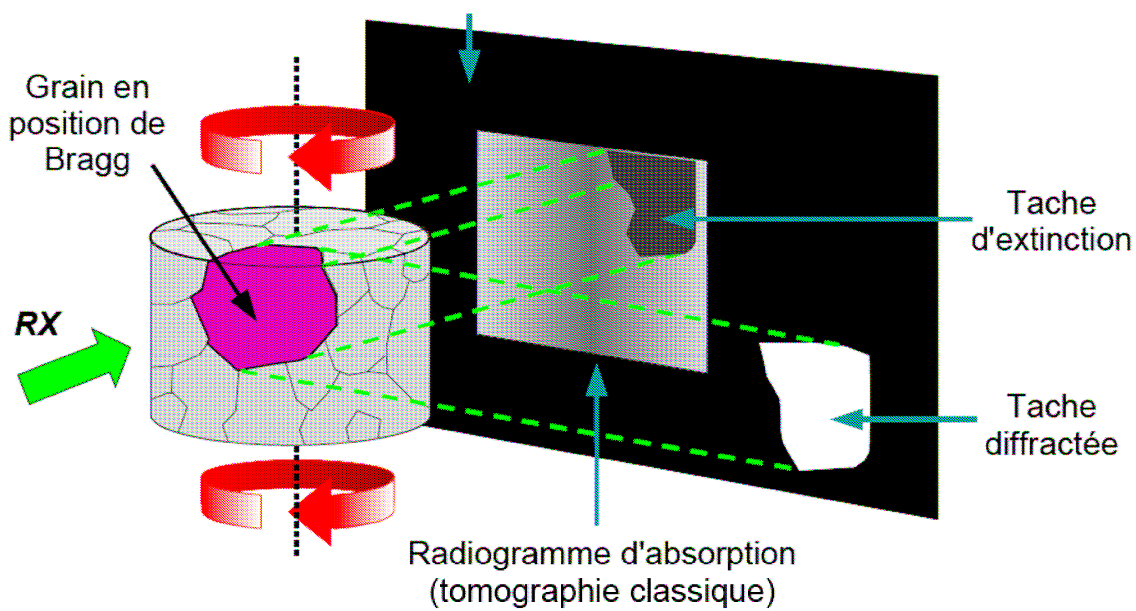




Orientations cristallines

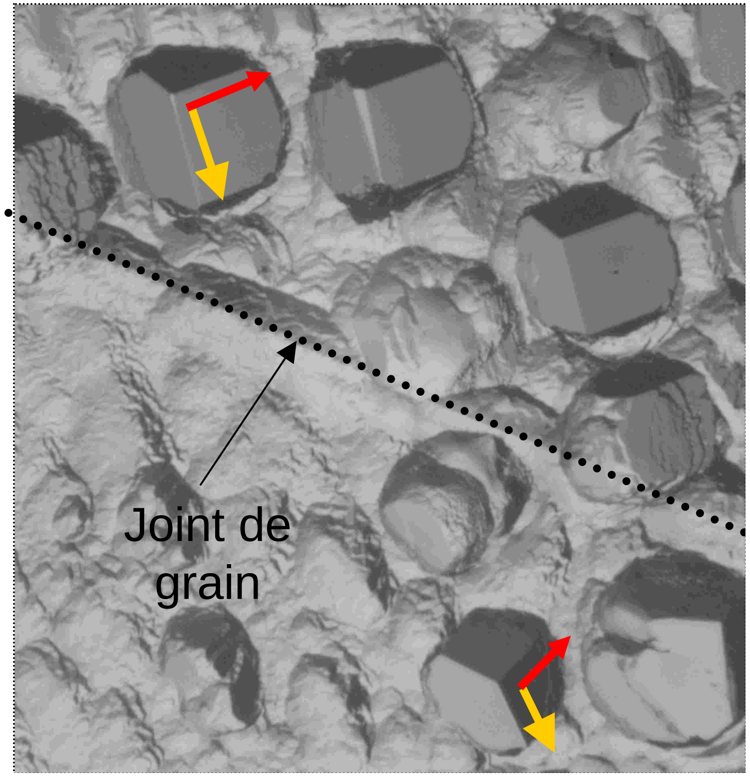
Paramètre clef : Détection des orientations cristallines en 3D

➔ Méthode 1 : « Diffraction contrast tomography » W. Ludwig (ESRF/INSA Lyon)

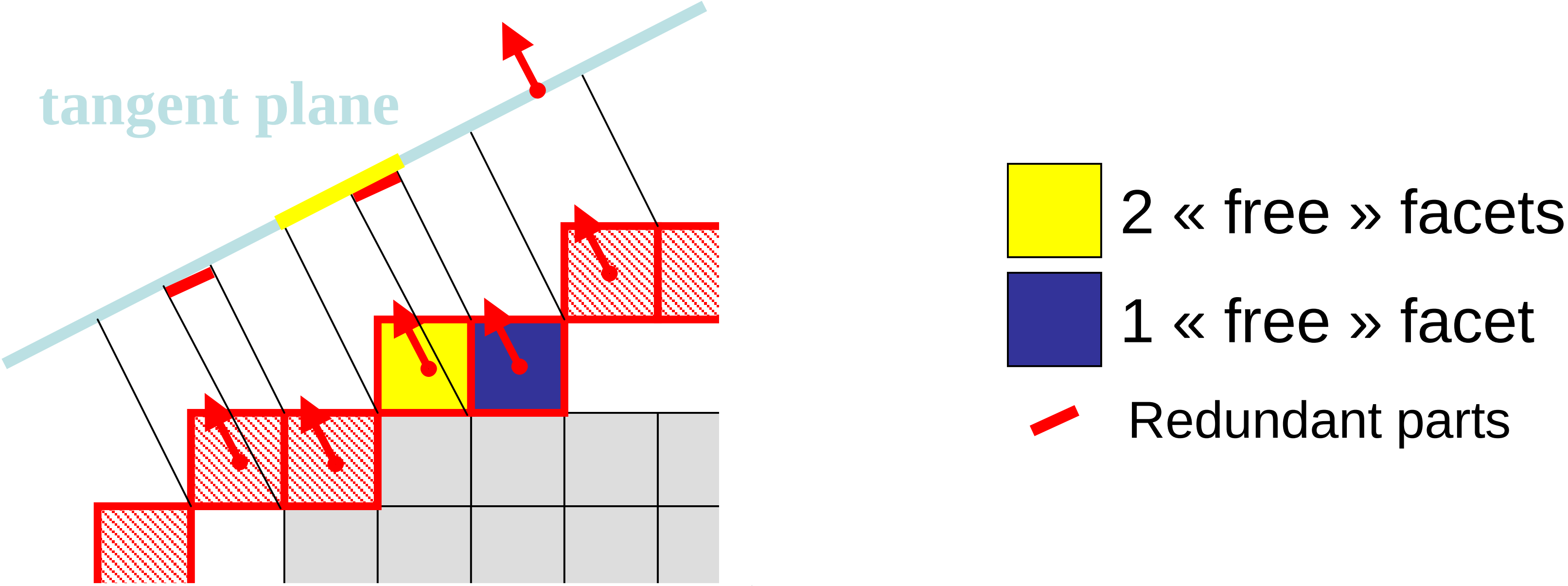


Rolland *et al.*: Adv. Eng. Mater. (in press)

➔ Méthode 2 : Obtention de figures d'attaques (travail en cours, collaboration LGGE)



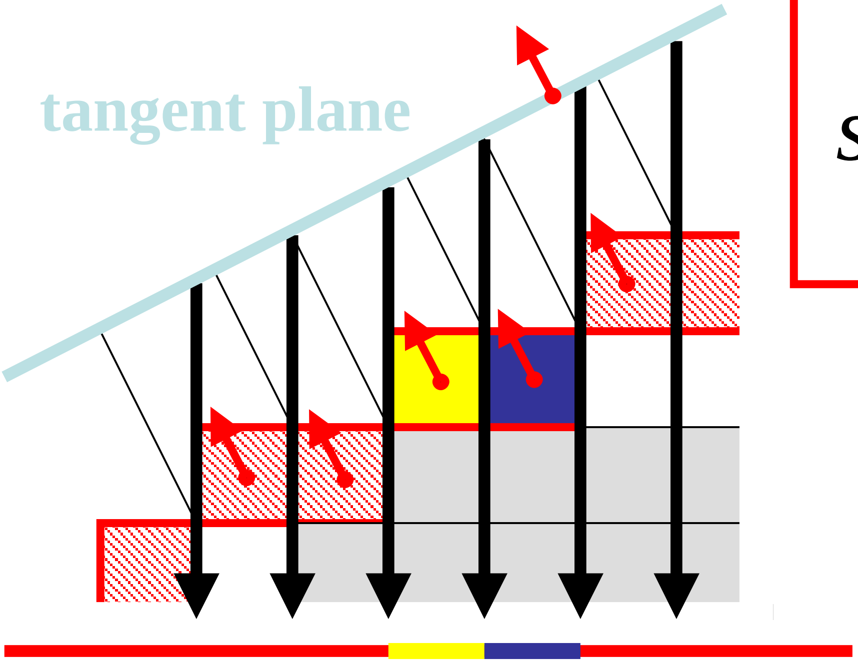
In our case, normals are located in the center of each voxel:
Lenoir’s method cannot be used directly



Tangent plane approximation

Surface area for one voxel:

VP method:



$$s(\vec{n}) = \frac{\|\vec{n}\|}{\max(|n_x|, |n_y|, |n_z|)}$$

Flin *et al.*, 2005

Surface contribution:

The projection ratio is obtained by projecting the **tangent plane** on the **fonctional plane**