Characterization of acoustic and elastic parameters of porous media

Luc Jaouen

Characterization of acoustic and elastic parameters of porous media

Thanks to

François-Xavier Bécot

Fabien Chevillotte

Stephen Hillenburg (for the inspiration)

These are the slides of the plenary lecture I gave during SAPEM 2011 - Ferrara, Italy.

I have drawn all images of Sponge Bob from scratch and credit his creator so I assume it is a fair use of intellectual property.
Correct me if I am wrong.

For more information on the topic of porous media characterization, check
http://apmr.matelys.com
Section "Characterization of parameters"

NOTE I focus on porous materials...

NOTE I focus on porous materials… composed with 2 phases

ACOUSTIC characterization
provides parameters
describing
visco-thermal dissipation
in fluid phase.

VISCO-ELASTIC characterization
provides parameters
describing
the skeleton motion

OUTLINE

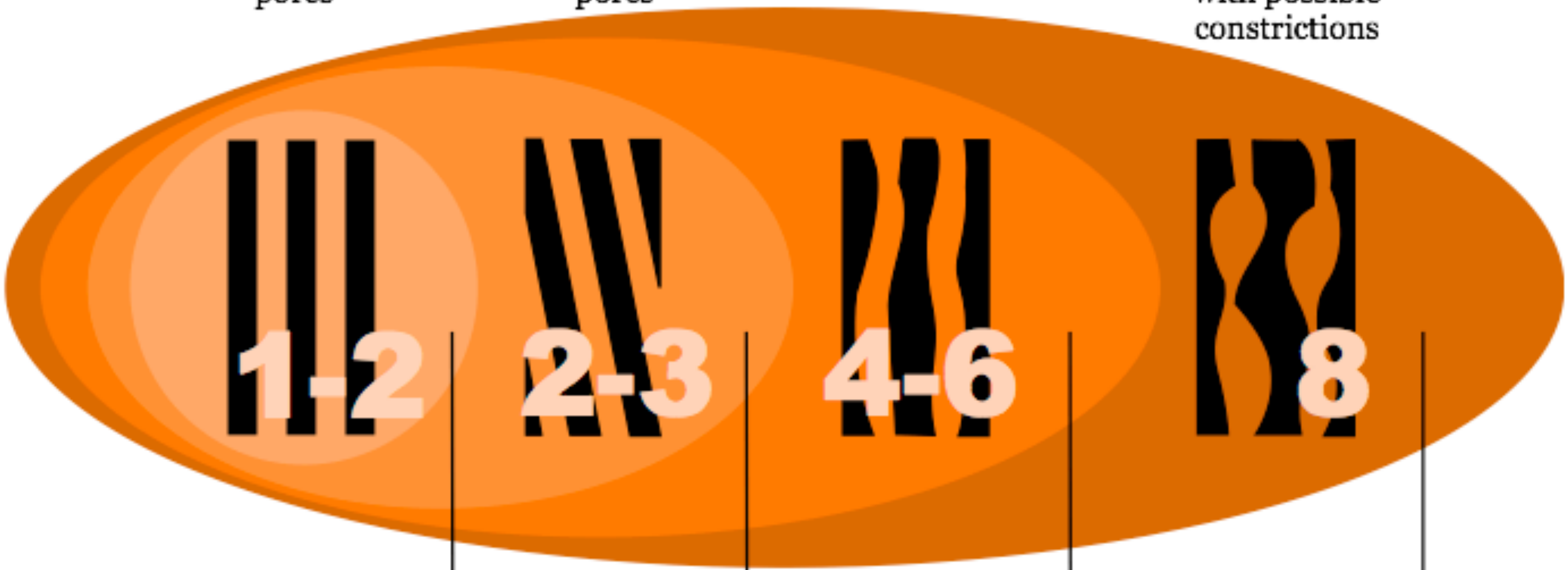
- Scientific issues
- Acoustic characterization
- Visco-elastic characterization
- Conclusion & perspectives

SCIENTIFIC ISSUES

1/5: Many acoustic parameters

Material morphology and number of parameters

Straight cylindrical pores	Slanted cylindrical pores	Non uniform sections	Non-uniform sections with possible constrictions



Model and parameter examples

Zwikker-Kosten
$\phi \;\; \sigma = \eta / k_0$

Miki
$\phi \;\; \sigma \;\; \alpha_\infty$

Attenborough
$\phi \;\; \sigma \;\; \alpha_\infty \;\; b$

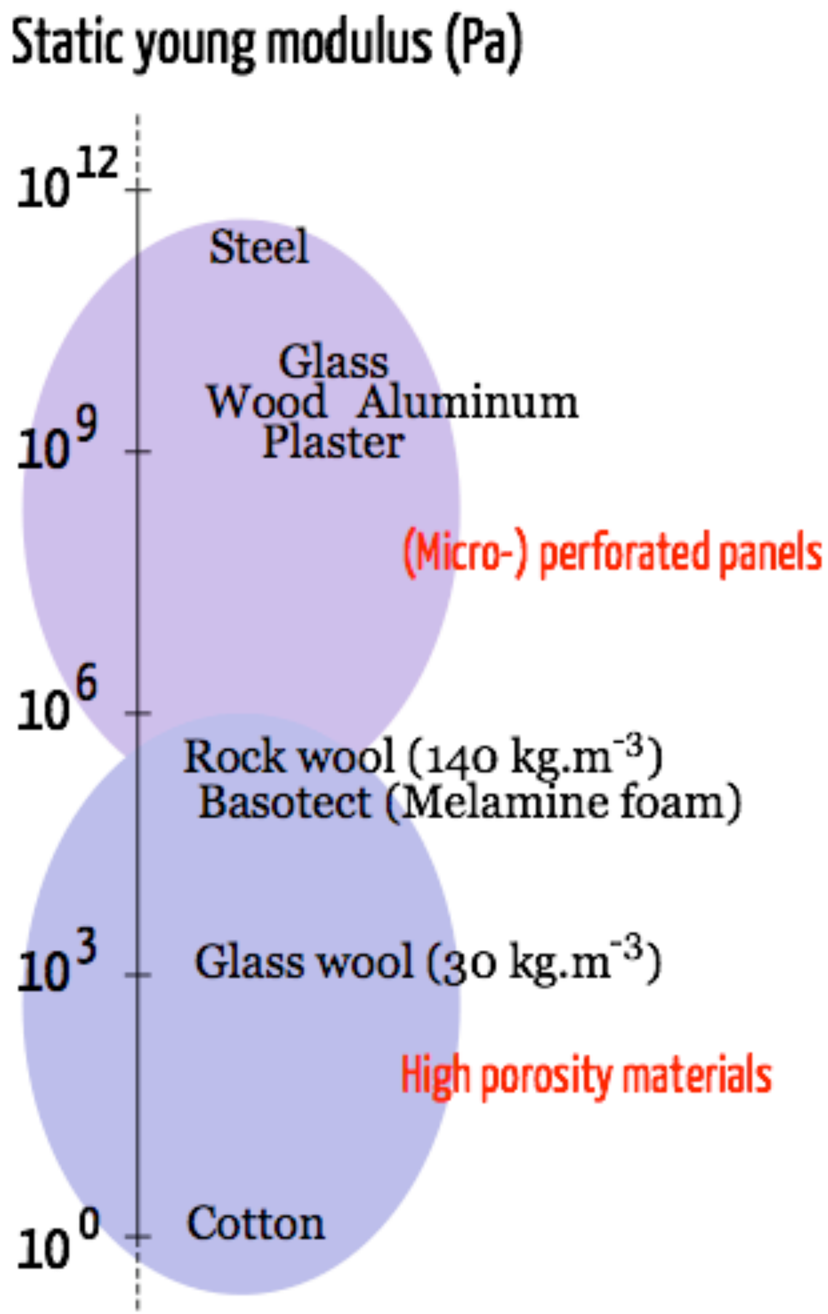
Wilson
$\rho_\infty \;\; \tau_{\mathrm{vor}} \;\; K_\infty \;\; \tau_{\mathrm{ent}}$

Johnson-Champoux-Allard
$\phi \;\; \sigma \;\; \alpha_\infty \;\; \Lambda \;\; \Lambda' \;\; k_0'$

Johnson-Champoux-Allard-Pride-Lafarge
$\phi \; \sigma \; \alpha_\infty \; \Lambda \; \alpha_0 \; \Lambda' \; k_0' \; \alpha_0'$

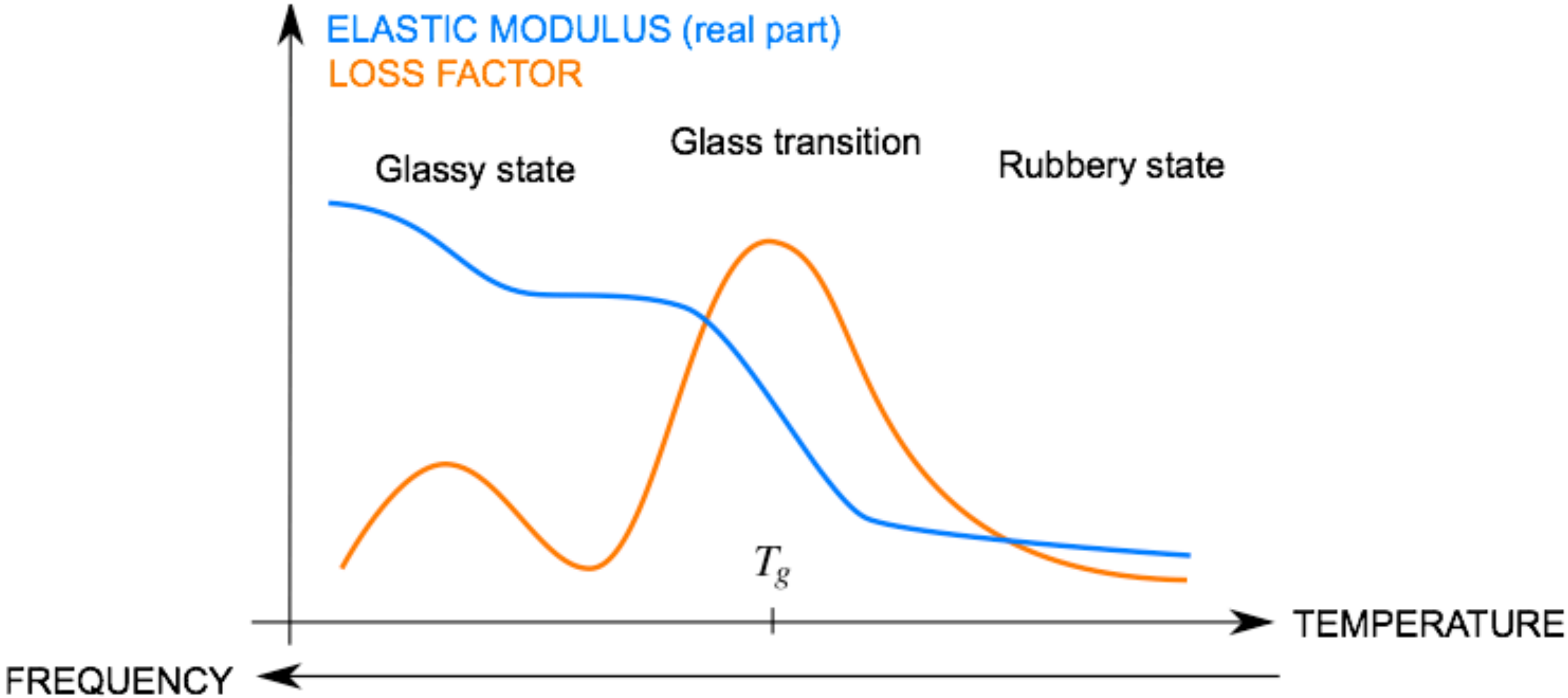
→ Most descriptive models need 5 to 8 acoustic parameters

2/5: Large range of magnitude for elastic parameters



→ Values of elastic parameters almost cover the known range

3/5: Frequency dependence of elastic parameters



→ Glass transition around ambiant temperature (i.e. in the audible freq. range) for most plastics

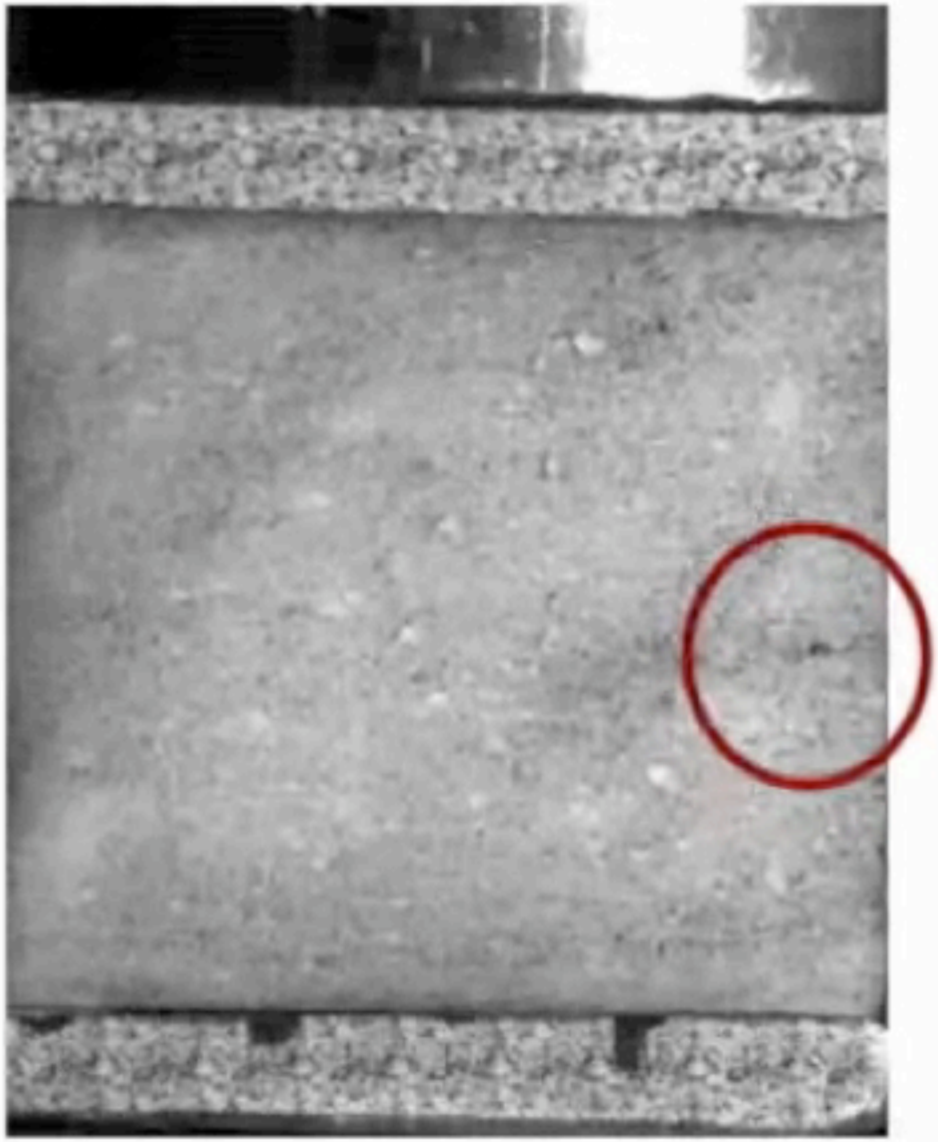
4/5: Anisotropy of materials

→ anisotropy of materials implies even more parameters to characterize

Melon et al. 1998, DOI: 10.1121/1.423897

Göransson et al. 2009, DOI: 10.1016/j.jsv.2009.06.028

5/5: Heterogenity of material samples



Video courtesy of P. Göransson

ACOUSTIC

Characterization

Adjust parameter values to reduce the difference between measurements and numerical simulations

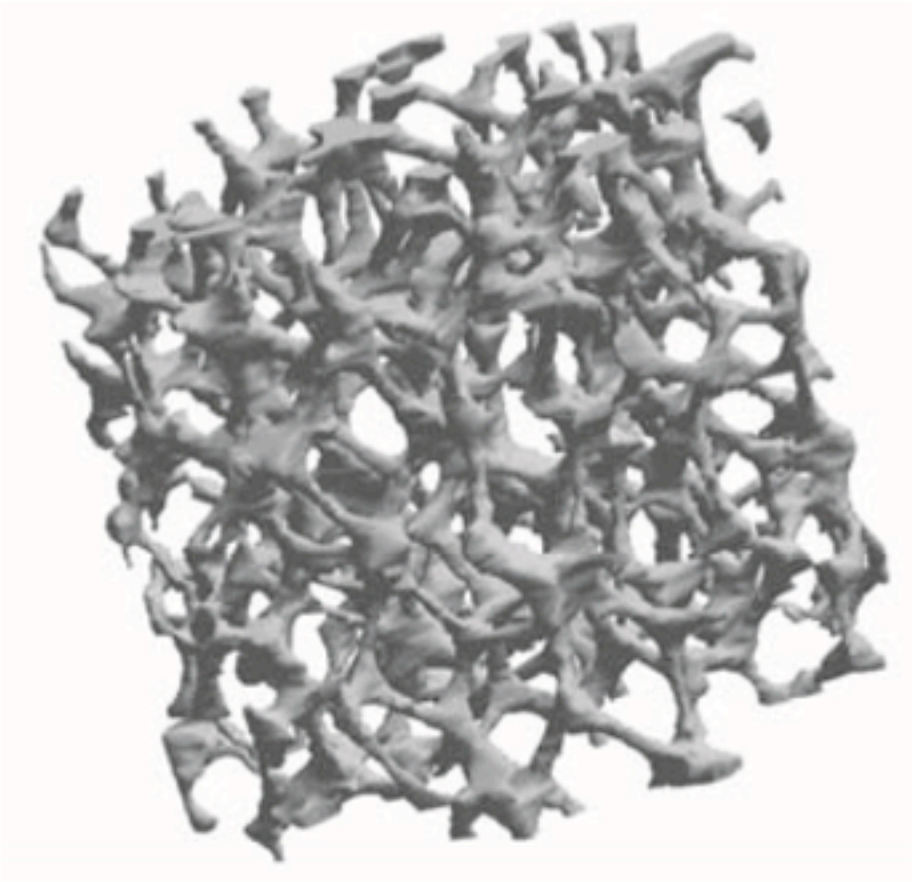
Techniques involve Monte-Carlo or genetic algorithms

M. Garoum 2008, link: sapem2008.matelys.com
Chazot et al. 2009, link: www.icsv16.org
Chedly et al. 2010, link: hal.inria.fr

Adjust parameter values to reduce the difference between measurements and numerical simulations

Techniques involve Monte-Carlo or genetic algorithms

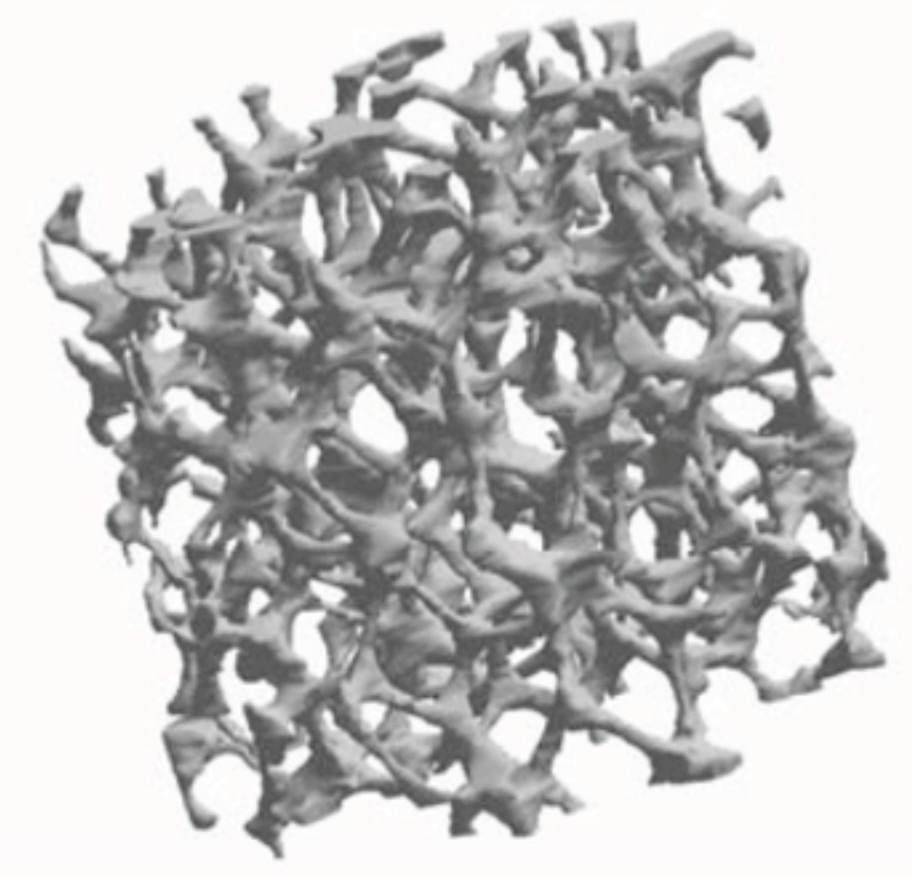
PROS	CONS
Can be applied to all types of materials	Need a priori information



Picture courtesy of C. Perrot

P. Adler 1992, Link: www.sisyphe.upmc.fr/~adler/

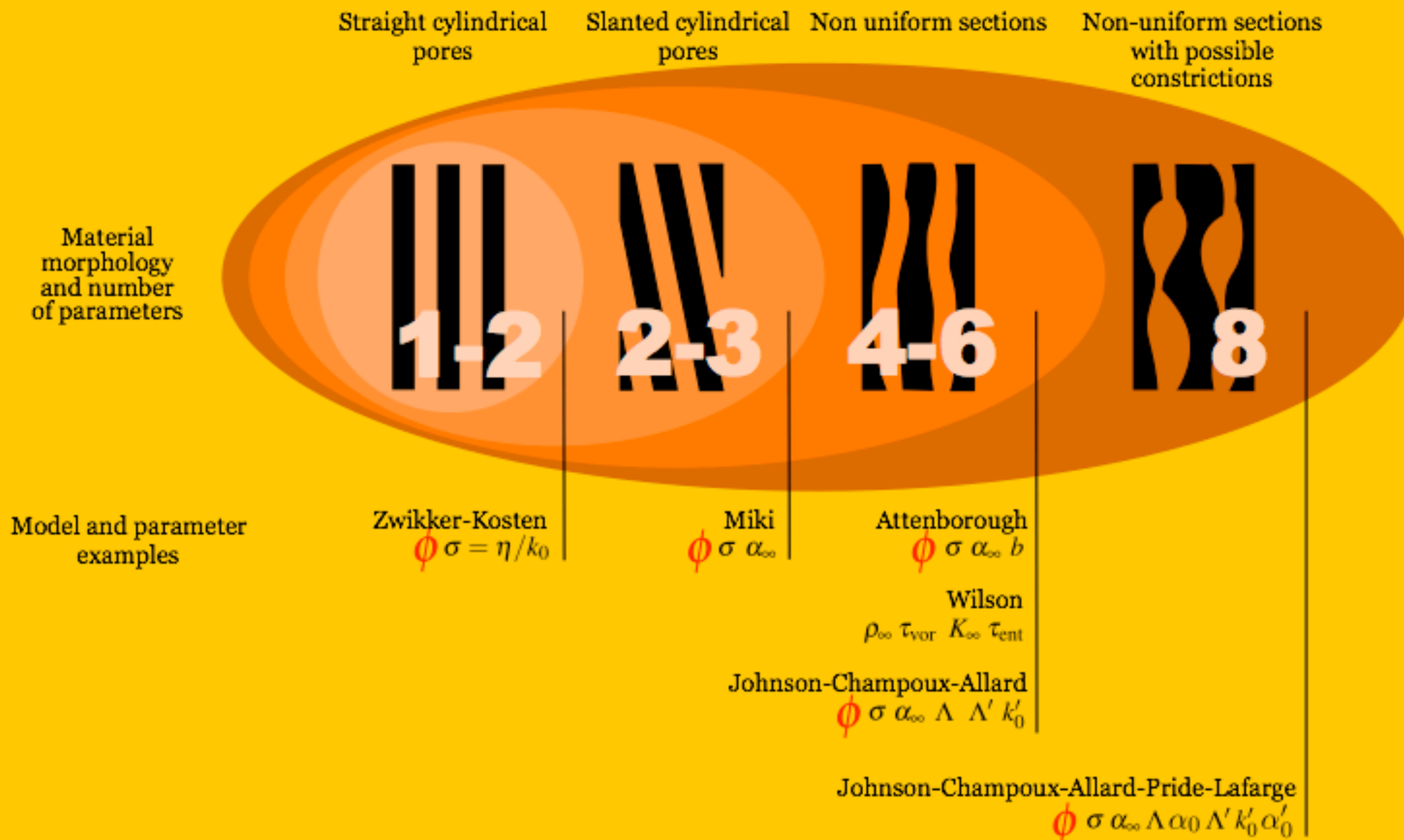
S. Torquato 2002, Link: cherrypit.princeton.edu/sal.html



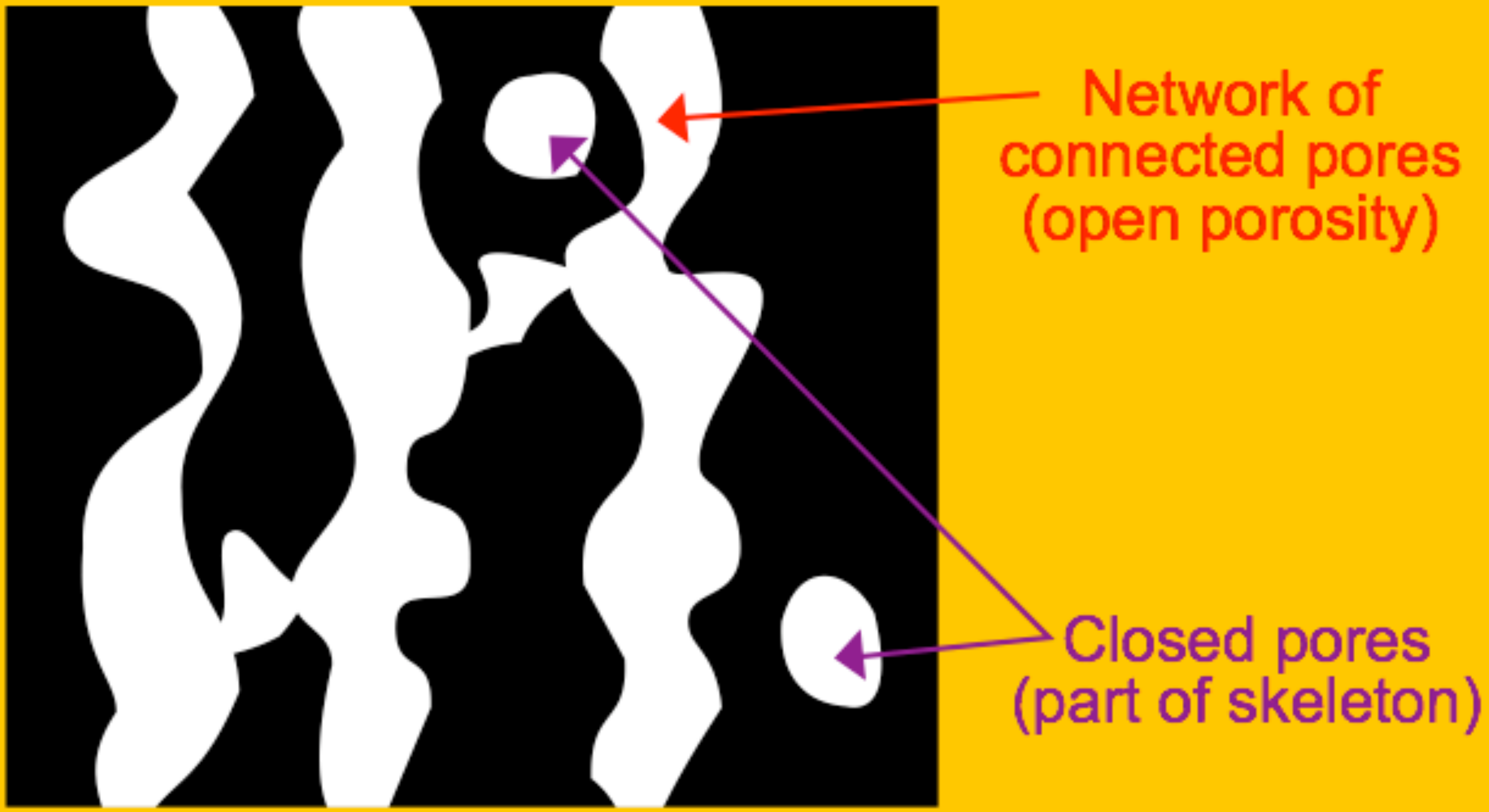
Picture courtesy of C. Perrot

PROS	CONS
Computation on 3D pore morphology.	Require important numerical resources.

Open porosity



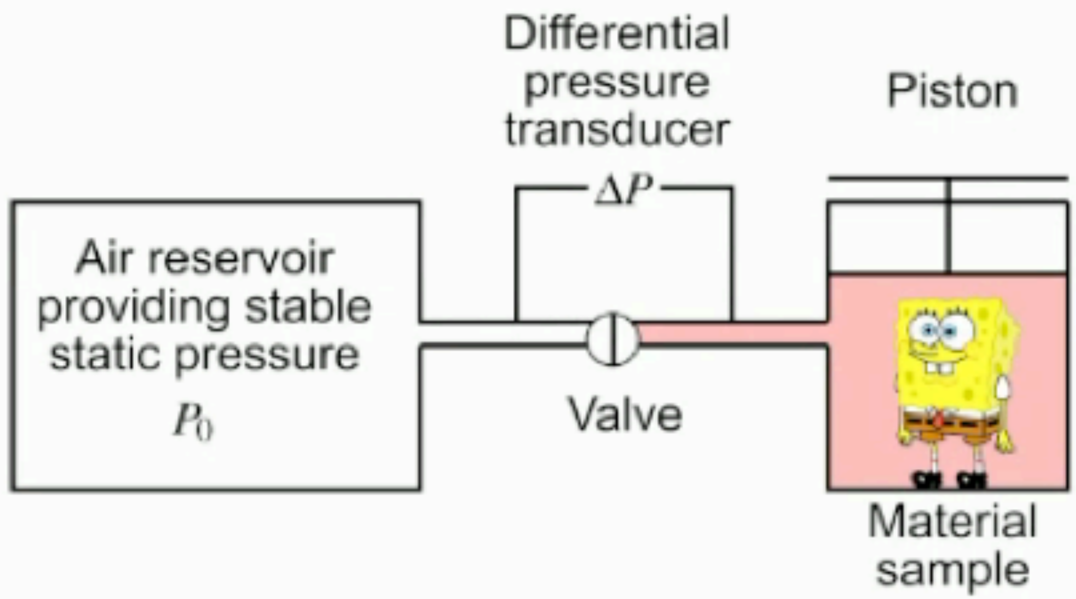
Open porosity



Range of values:

less than 0.01 to more than 0.99

Open porosity > Pressure difference (~pycnometer)



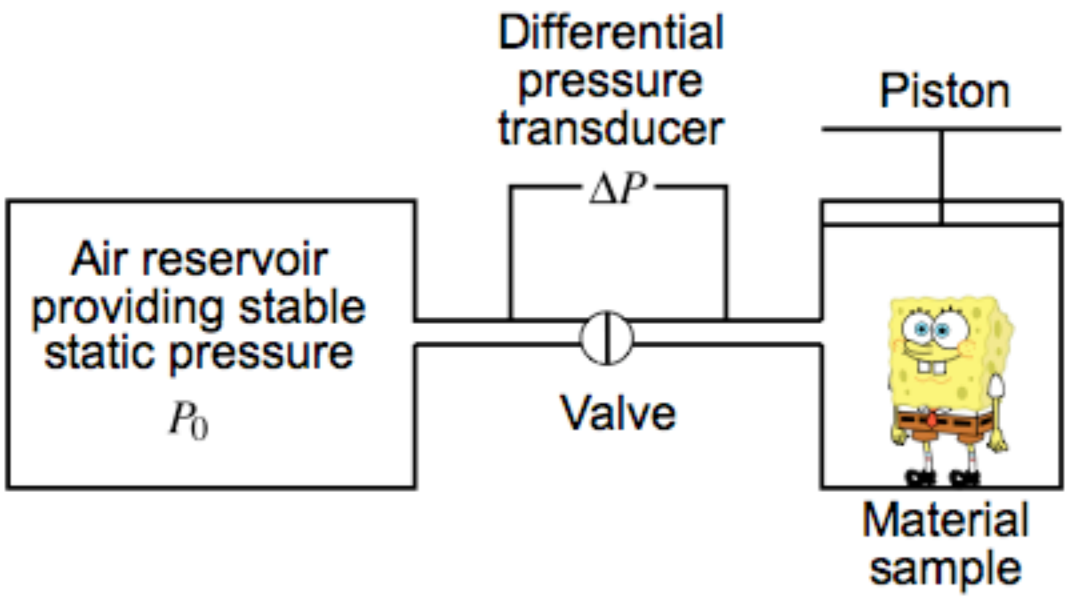
L. L. Beranek 1942, DOI: 10.1121/1.1916172

Champoux et al. 1990, DOI: 10.1121/1.1894653

Leclaire et al. 2003, DOI: 10.1063/1.1542666

ISO 4590 (2002), Link: www.iso.org

Open porosity > Pressure difference (~pycnometer)



PROS

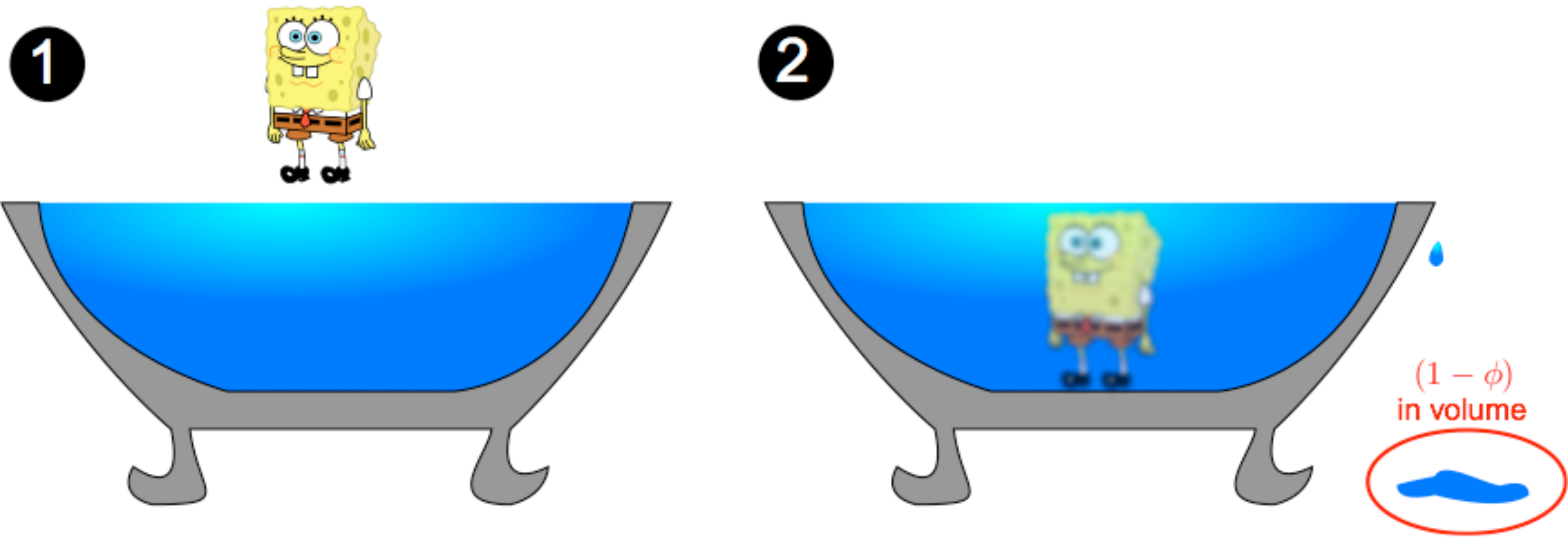
Applied on all types of materials

Accuracy of 0.01

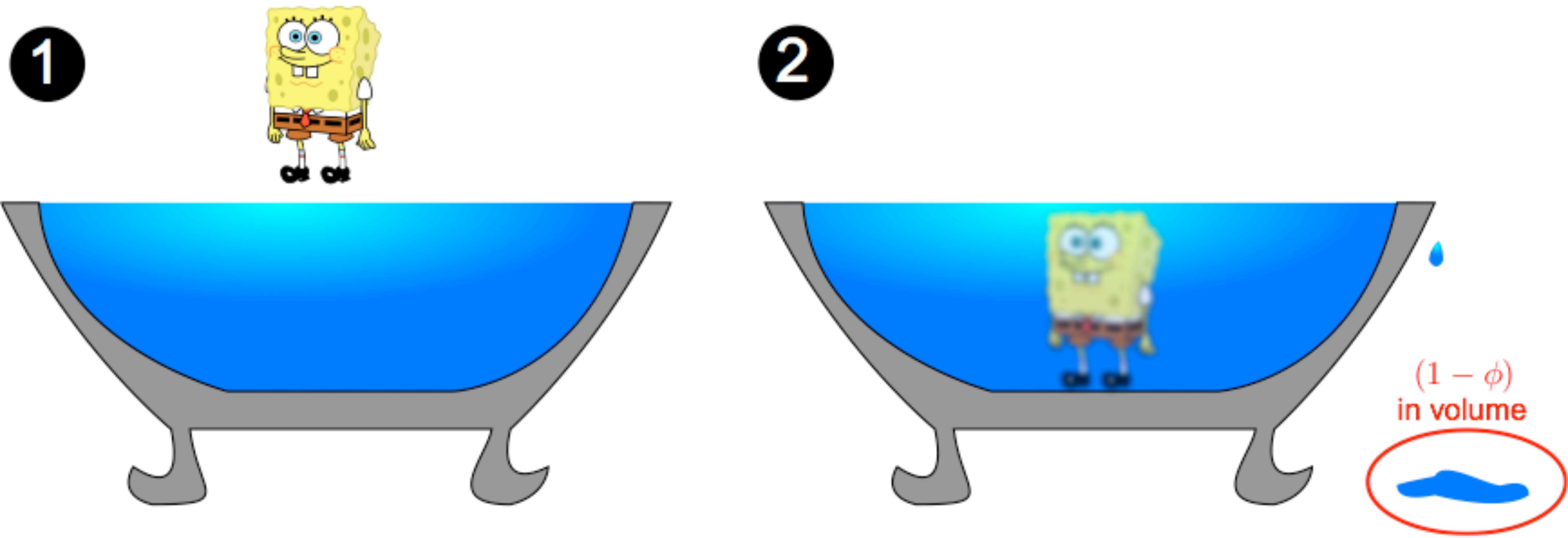
CONS

Larger samples give accurate results

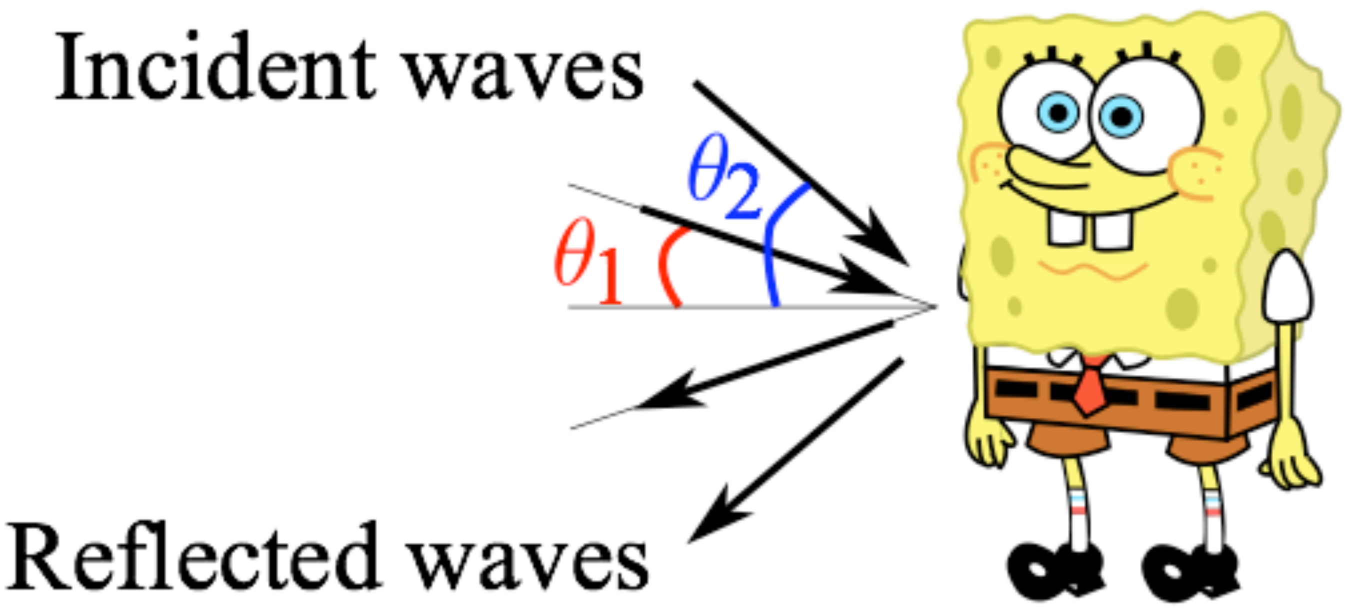
Method based on Archimedes' principle

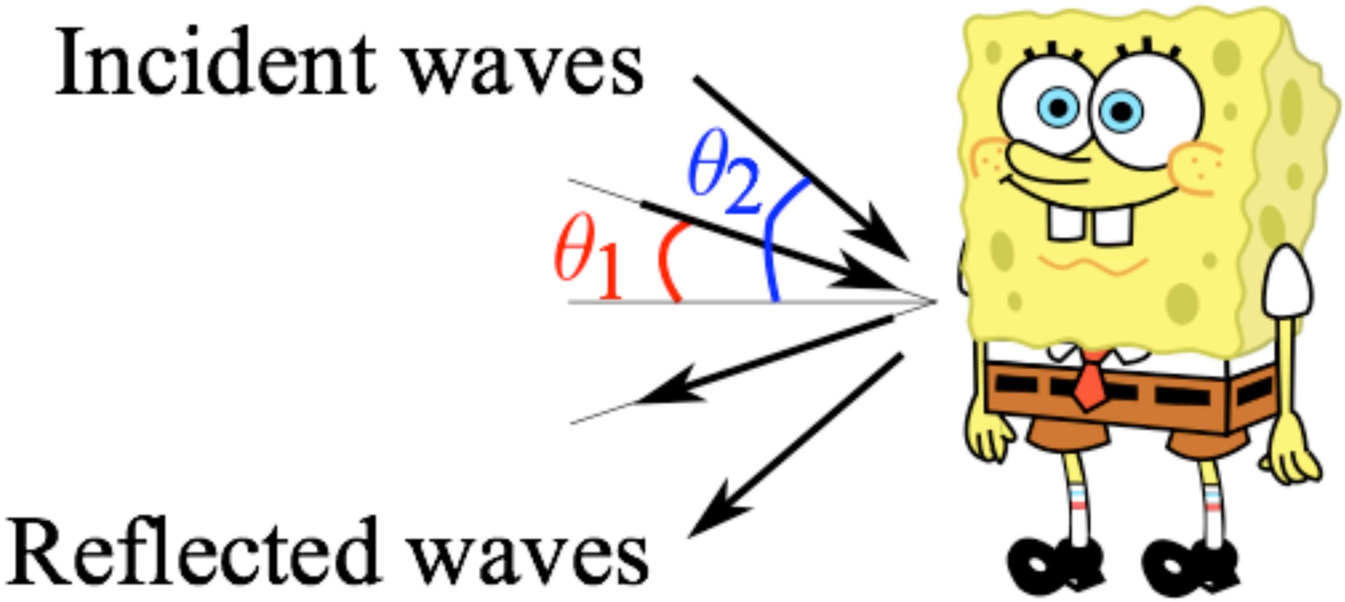


Method based on Archimedes' principle



PROS	CONS
Accessible to everyone.	Low accuracy (saturate the pore network is difficult)


Incident waves
θ_2
θ_1
Reflected waves



PROS	CONS
simultaneous estimation of tortuosity	Usuable on highly absorbing samples (reflected waves approximated with first interface ones)

$$\phi \simeq \frac{P_0}{\text{thickness} \times \omega} \qquad \lim_{\omega \to 0} \left[\text{Im}(\text{Admittance}) \right]$$

$$\phi \simeq \frac{\rho_0 \alpha_\infty}{\lim_{\omega \to 0} \left[\text{Re}(\text{dynamic density}) \right]}$$

N. Selen 2003, Link: bibli.ec-lyon.fr
Bonfiglio & Pompoli 2007, Link: www.materiacustica.it

$$\phi \simeq \frac{P_0}{\text{thickness} \times \omega} \qquad \lim_{\omega \to 0} \Big[\text{Im}(\text{Admittance}) \Big]$$

$$\phi \simeq \frac{\rho_0 \alpha_\infty}{\lim_{\omega \to 0} \Big[\text{Re}(\text{dynamic density}) \Big]}$$

PROS	CONS
Quick way for an estimation	Low accuracy or inconsistent results

Static air flow resistivity

Straight cylindrical pores | Slanted cylindrical pores | Non uniform sections | Non-uniform sections with possible constrictions

Material morphology and number of parameters

Model and parameter examples

Zwikker-Kosten
$\phi\ \sigma = \eta / k_0$

Miki
$\phi\ \sigma\ \alpha_\infty$

Attenborough
$\phi\ \sigma\ \alpha_\infty\ b$

Wilson
$\rho_\infty\ \tau_{\mathrm{vor}}\ K_\infty\ \tau_{\mathrm{ent}}$

Johnson-Champoux-Allard
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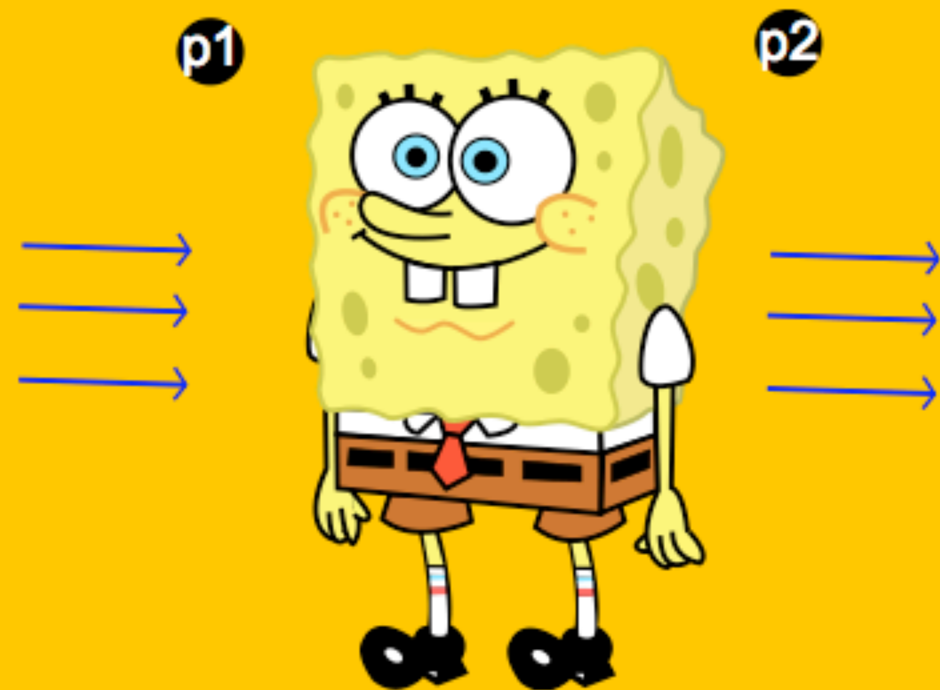
Johnson-Champoux-Allard-Pride-Lafarge
$\phi\ \sigma\ \alpha_\infty\ \Lambda\ \alpha_0\ \Lambda'\ k_0'\ \alpha_0'$

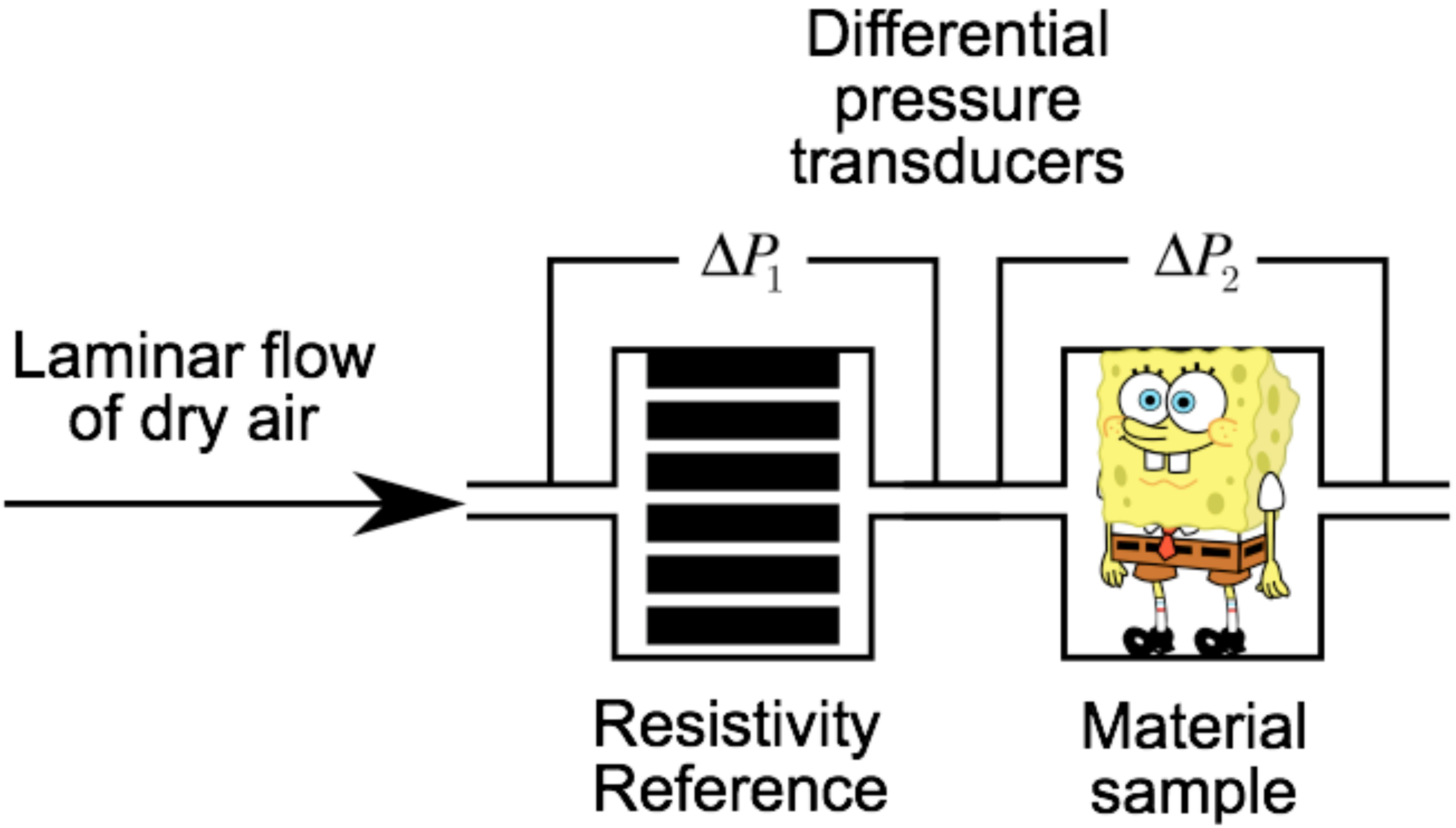
Static air flow resistivity

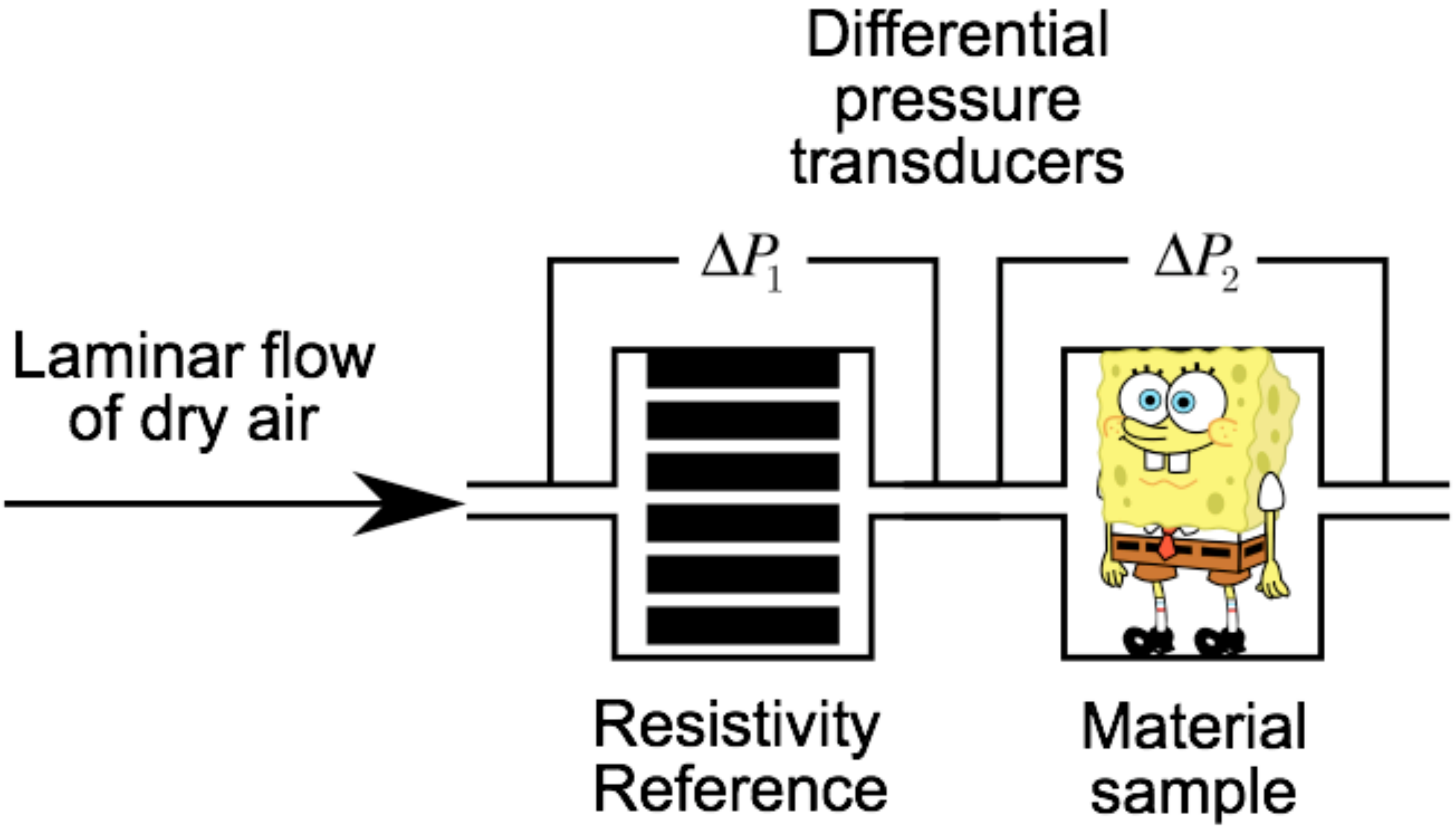


$$\phi\vec{v} = -\frac{1}{\sigma}\vec{\nabla}p$$

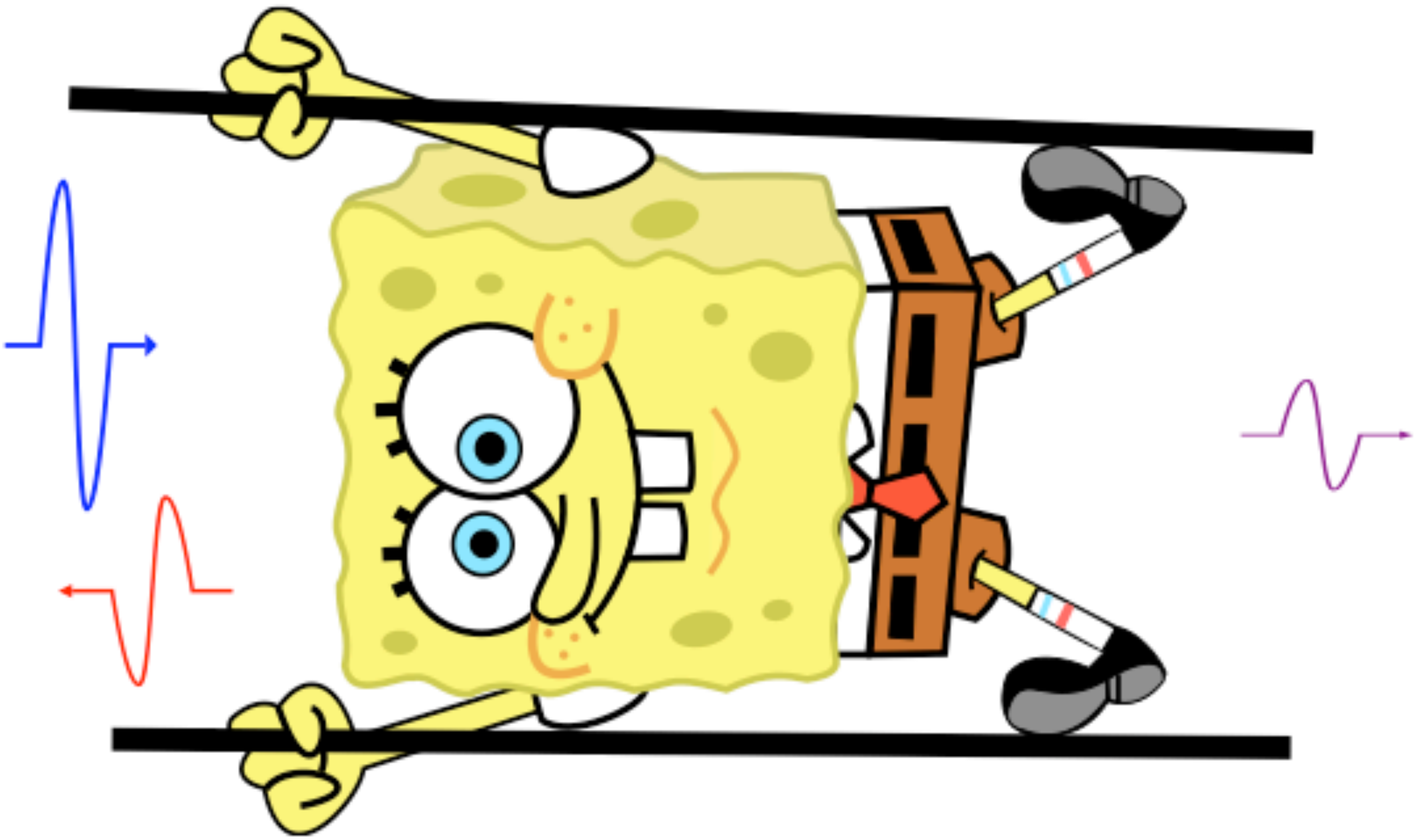
Range of values:

$[0 \quad - \quad +\infty[\quad N.s.m^{-4}$


Differential
pressure
transducers
ΔP1
ΔP2
Laminar flow
of dry air
Resistivity
Reference
Material
sample

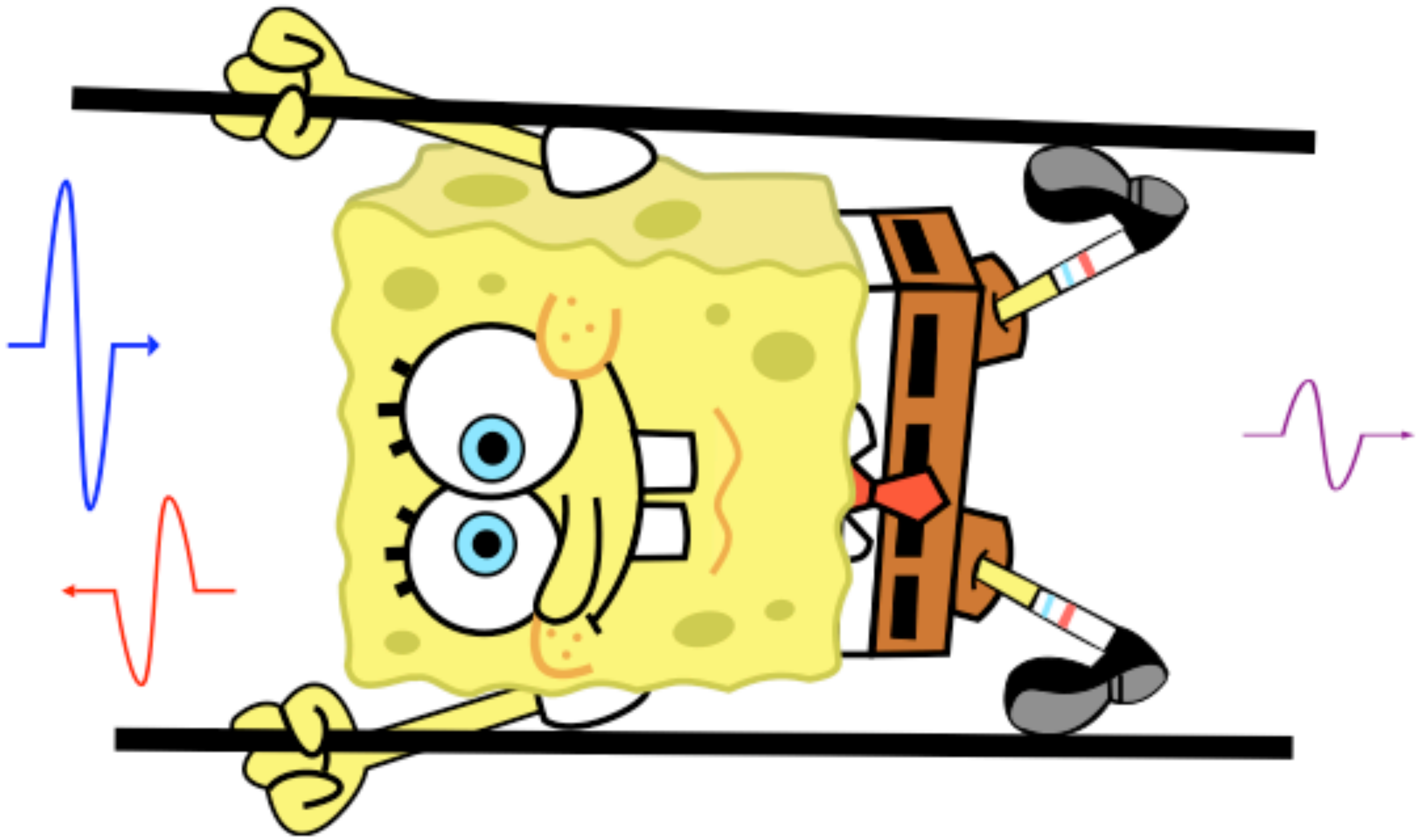


PROS	CONS
Direct measurement	Boundary conditions can impact results

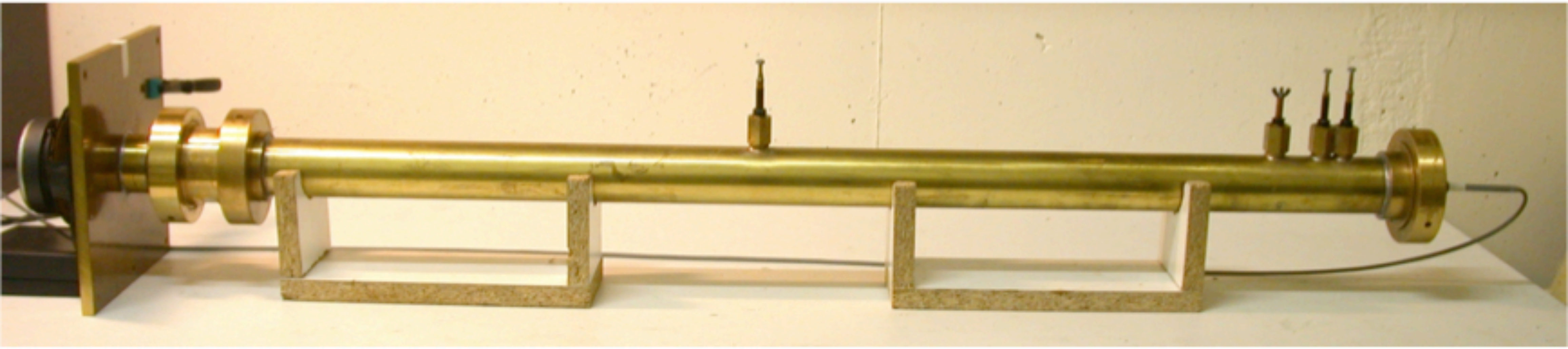


Sebaa et al. 2005, DOI: 10.1063/1.2099510
Fellah et al. 2006, DOI: 10.1121/1.2179749

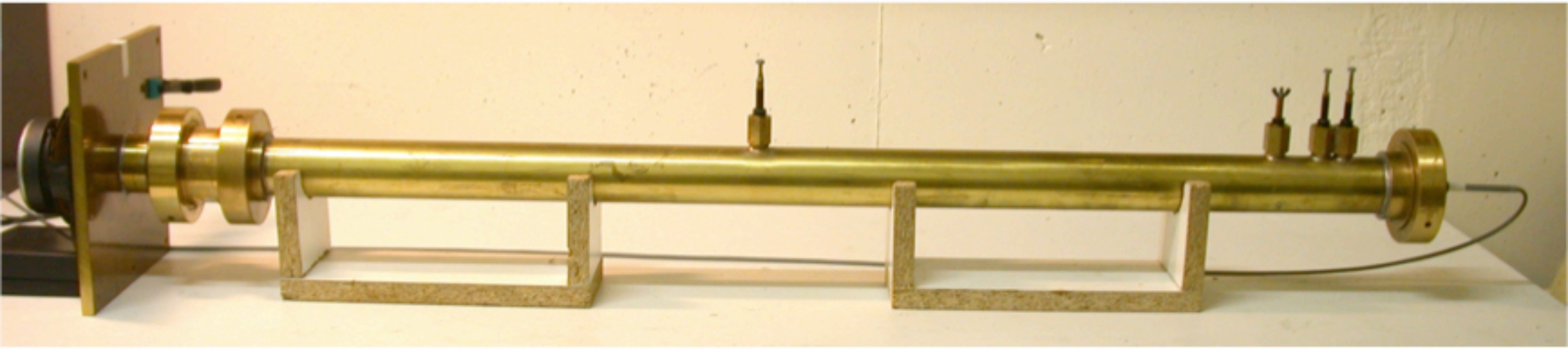
Static air flow resistivity > Pulse reflection or transmission



PROS	CONS
Closer to the actual conditions of use	Numerical inversions are used (requiring a priori information)



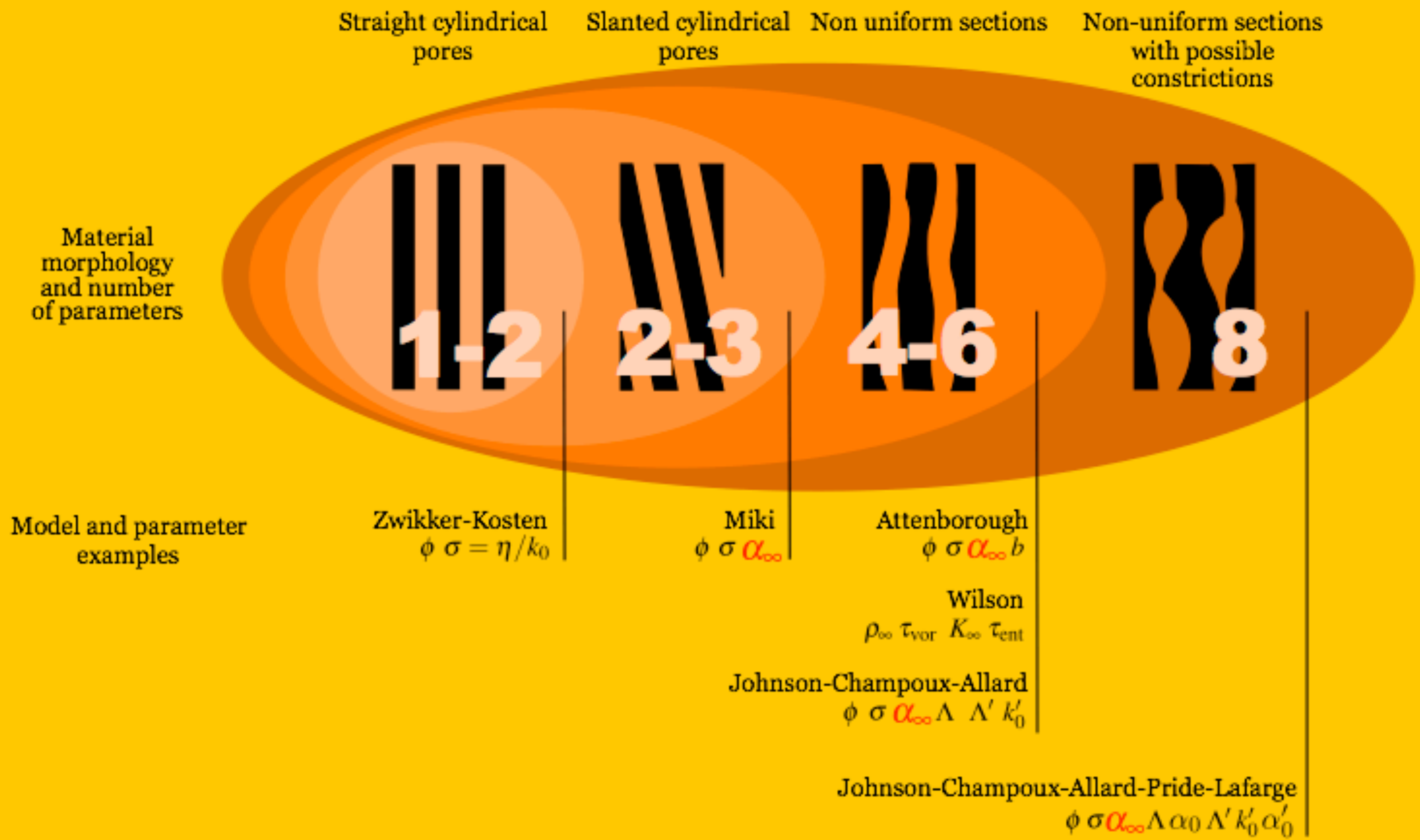
Set-up at ENTPE



Set-up at ENTPE

PROS	CONS
Measurements at audible frequencies.	Asymptote can be difficult to identify.

High freq. limit of dynamic tortuosity



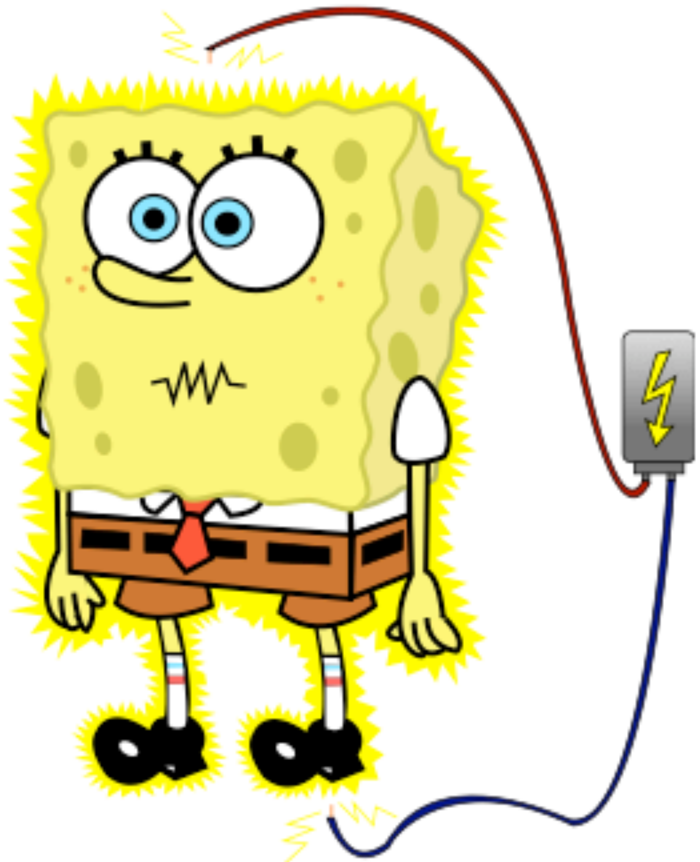
HF limit of the dynamic tortuosity

"We shall consider the value of α_∞ to be **a measure of the disorder in the sytem.**"

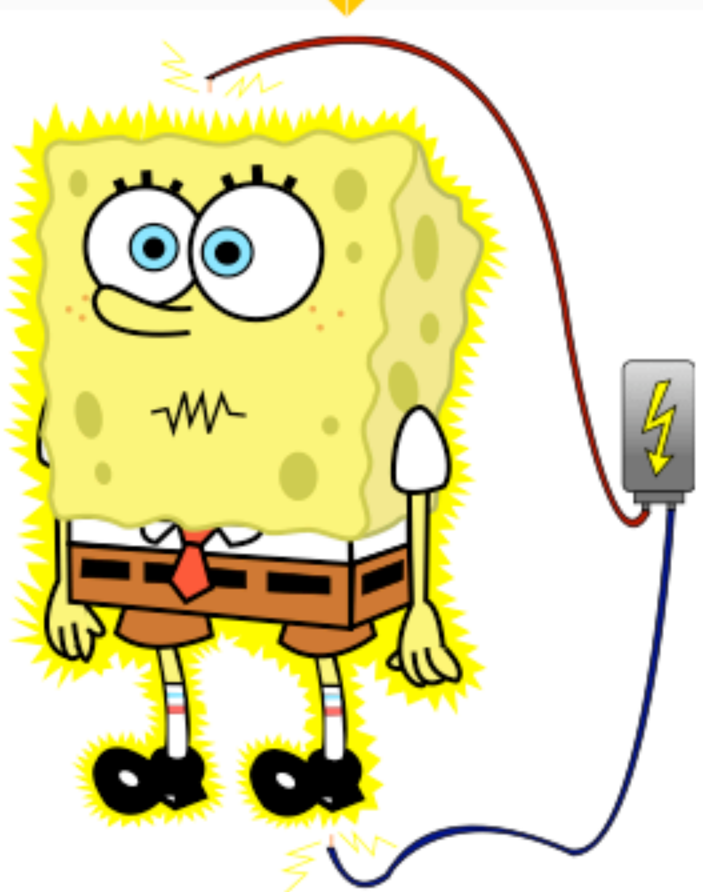
D. L. Johnson, J. Koplik, R. Dashen

Range of values:

$[1 \quad - \quad 3]$



R. J. S. Brown 1980, DOI: 10.1190/1.1441123
Johnson et al. 1982, DOI: 10.1103/PhysRevLett.49.1840

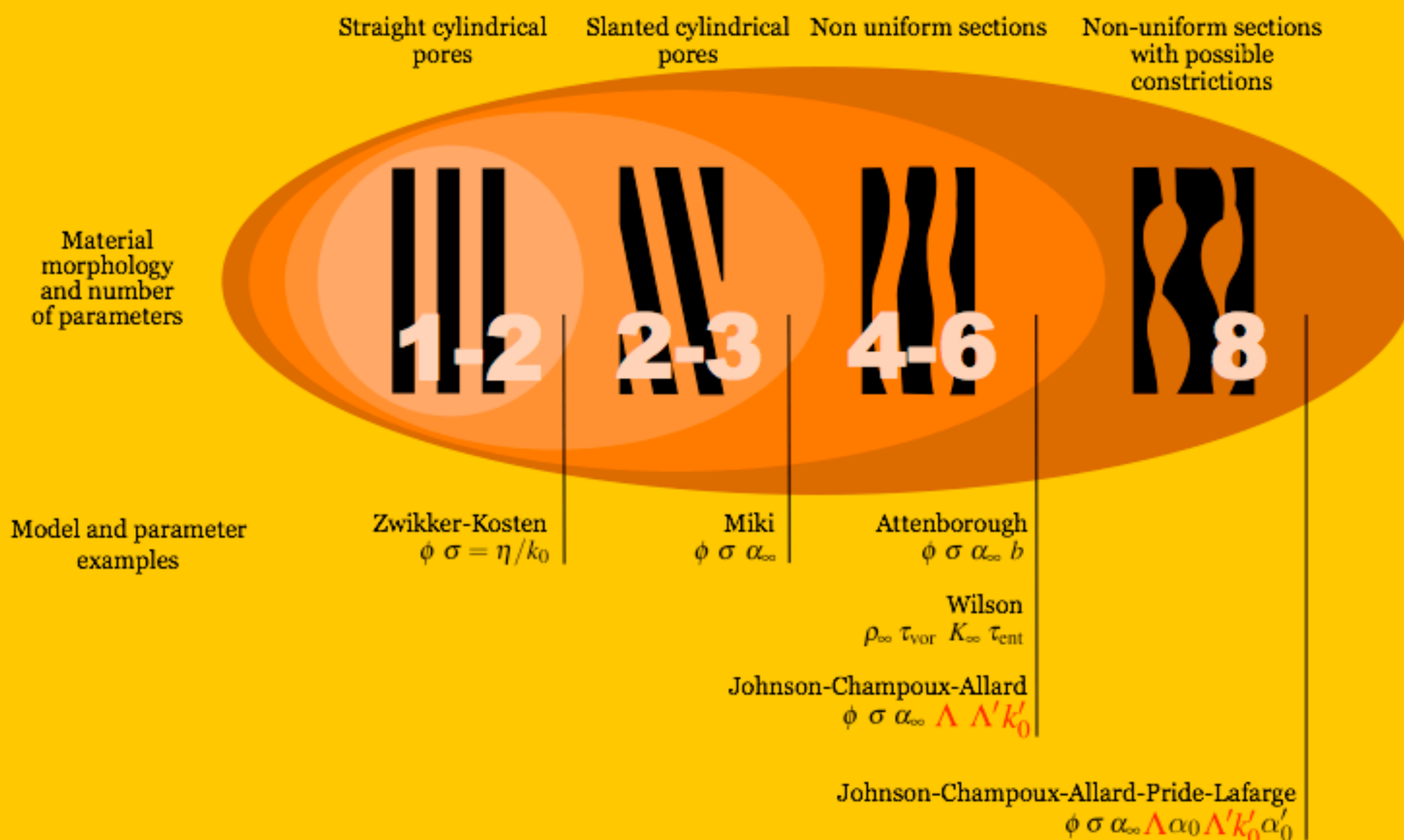


PROS	CONS
Direct measurement.	Skeleton must be an electrical insulator. Open-porosity is required.

- Ultrasound waves:
  Give estimations for α_∞ and Λ, Λ', (ϕ)

- Impedance tube:
  Give estimations for α_∞ and k'_0, Λ, Λ'

Static thermal permeability + Viscous & thermal characteristic lengths



Static thermal permeability

t1

t2

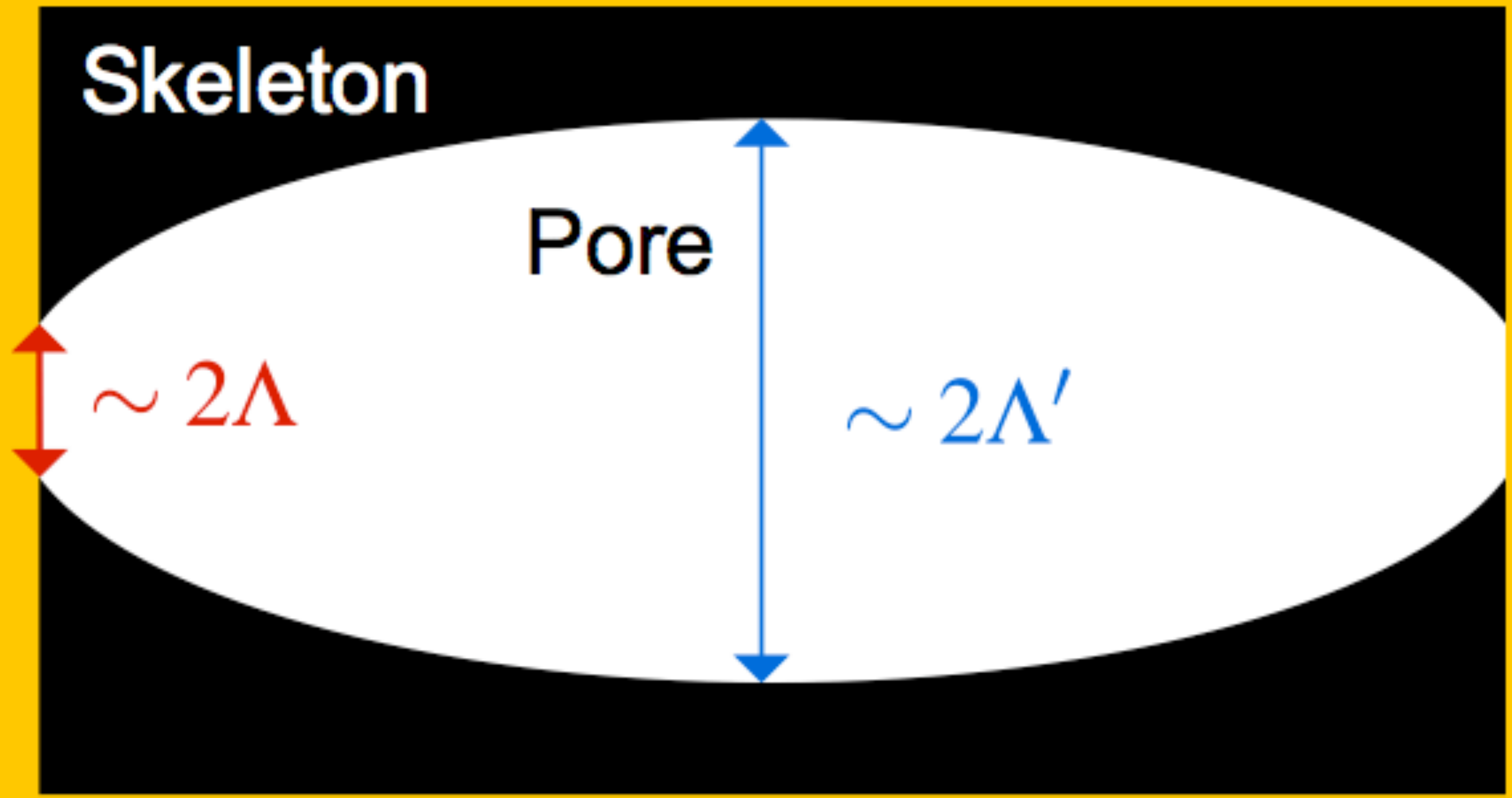
$$\phi\tau = k'_0 \alpha \, \frac{\partial p}{\partial t}$$

Range of values:

$[0 \; - \; +\infty \, [\; m^2$

with $k'_0 \geq k_0$

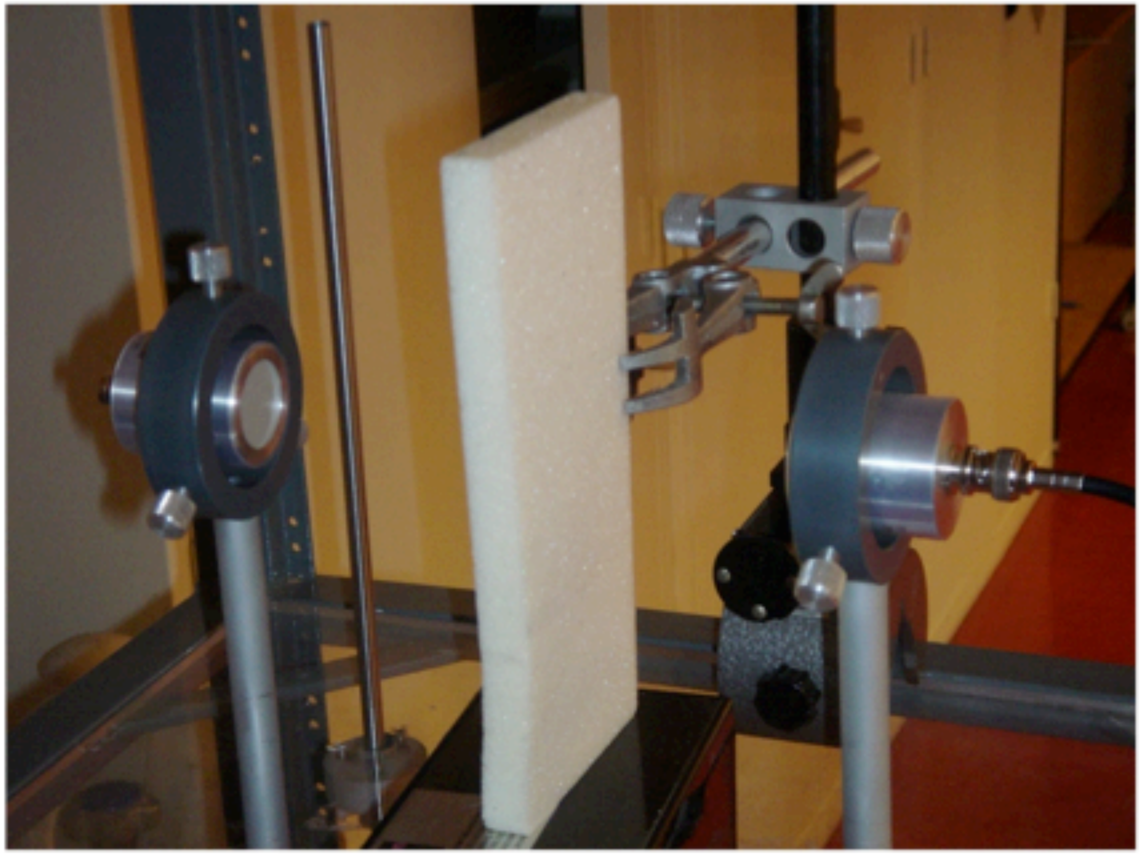
Viscous & thermal characteristic lengths



Range of values:

$$[10 \quad - \quad 1\,000]\ \mu\text{m}$$

$$(\Lambda \leq \Lambda')$$



Picture courtesy of W. Lauriks

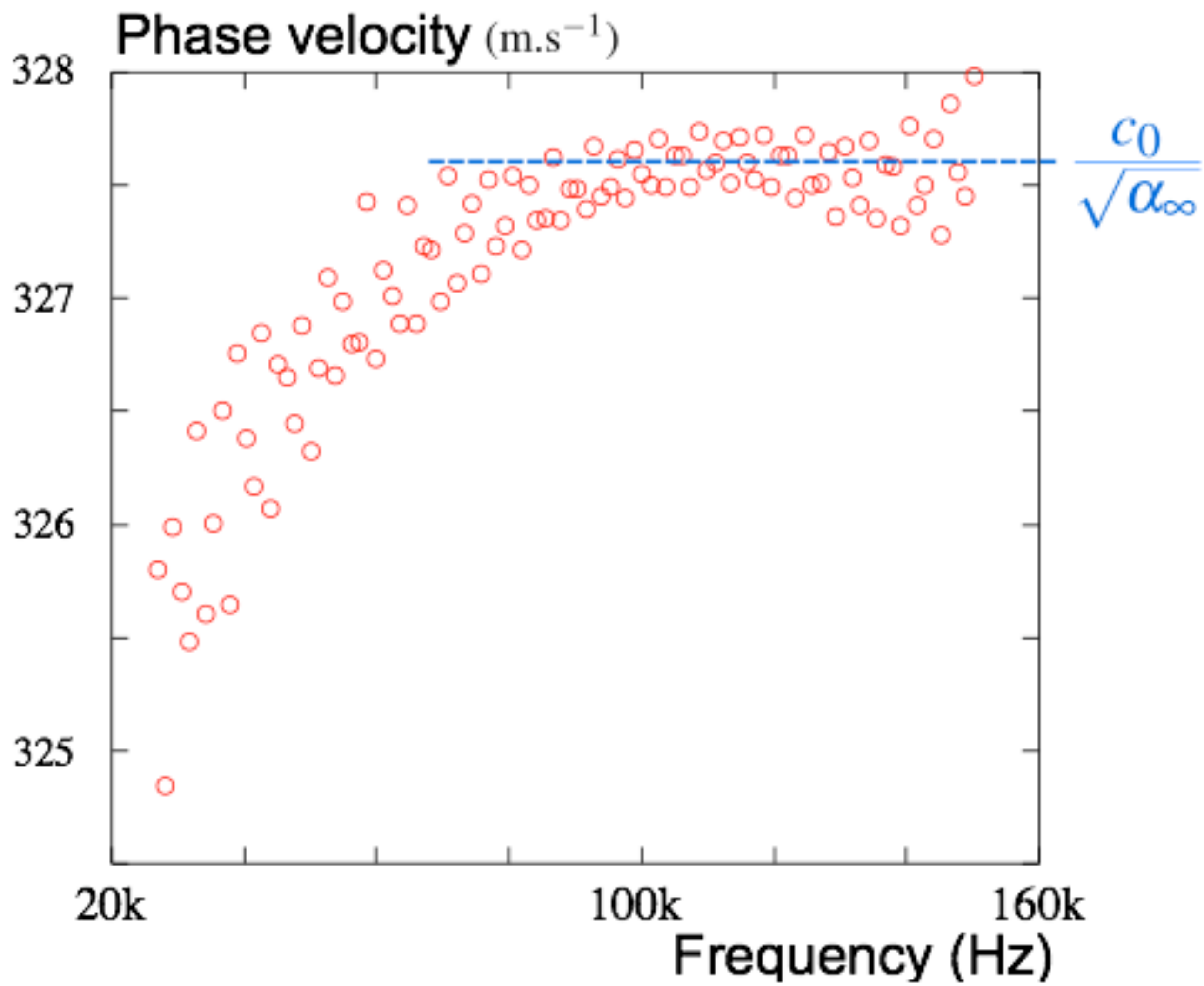
Allard et al. 1994, DOI: 10.1063/1.1145097

Leclaire et al. 1996, DOI: 10.1121/1.415378

Leclaire et al. 1996, DOI: 10.1063/1.363817

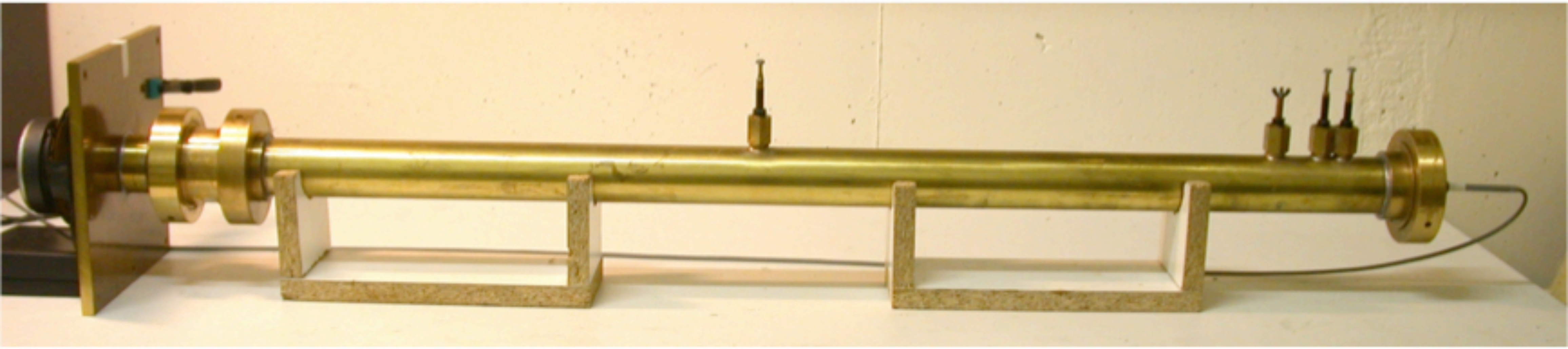
Groby et al. 2010, DOI: 10.1121/1.3283043

ACOUSTIC $\alpha_\infty, \Lambda, \Lambda', (\phi)$ > Ultrasounds



PROS	CONS
Can quickly mapped heterogenity	Multiple scattering can occur (measurements with 2 fluids thus needed)

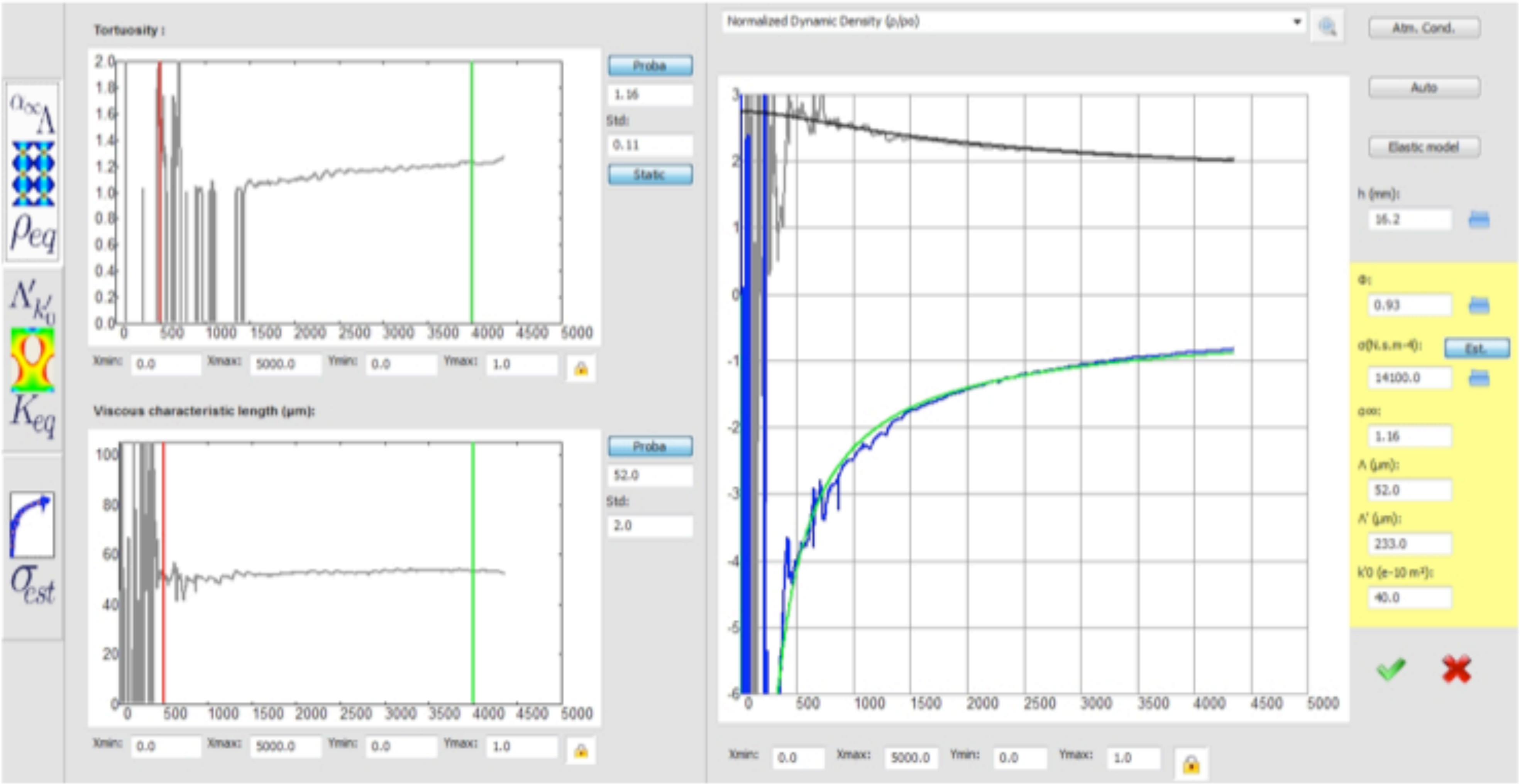
ACOUSTIC $\alpha_\infty, \Lambda, \Lambda', k'_0$ > Impedance tube



Set-up at ENTPE

Panneton & Olny 2006, DOI: 10.1121/1.2169923
Olny & Panneton 2008, DOI: 10.1121/1.2828066

ACOUSTIC $\alpha_\infty, \Lambda, \Lambda', k'_0$ > Impedance tube



PROS

Measurements at audible frequencies.
Analytical inversions (no fit).

CONS

Porosity and resistivity must be known.
Sensible to frame vibrations, air leakages.

Static tortuosities

Straight cylindrical pores | Slanted cylindrical pores | Non uniform sections | Non-uniform sections with possible constrictions

Material morphology and number of parameters

Model and parameter examples

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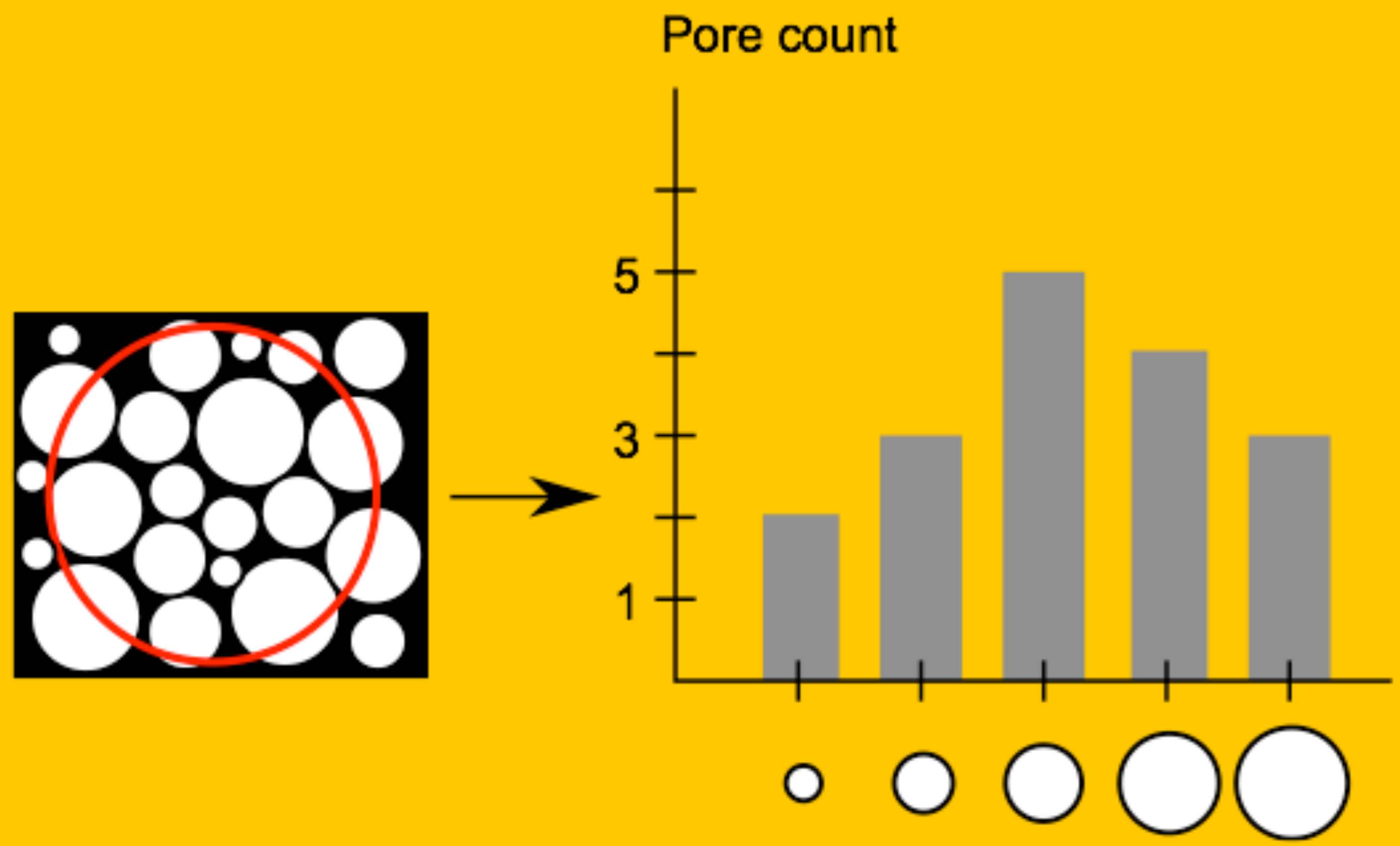
Johnson-Champoux-Allard-Pride-Lafarge
$\phi\ \sigma\ \alpha_\infty\ \Lambda\ \alpha_0\ \Lambda'\ k_0'\ \alpha_0'$

Pore size distribution

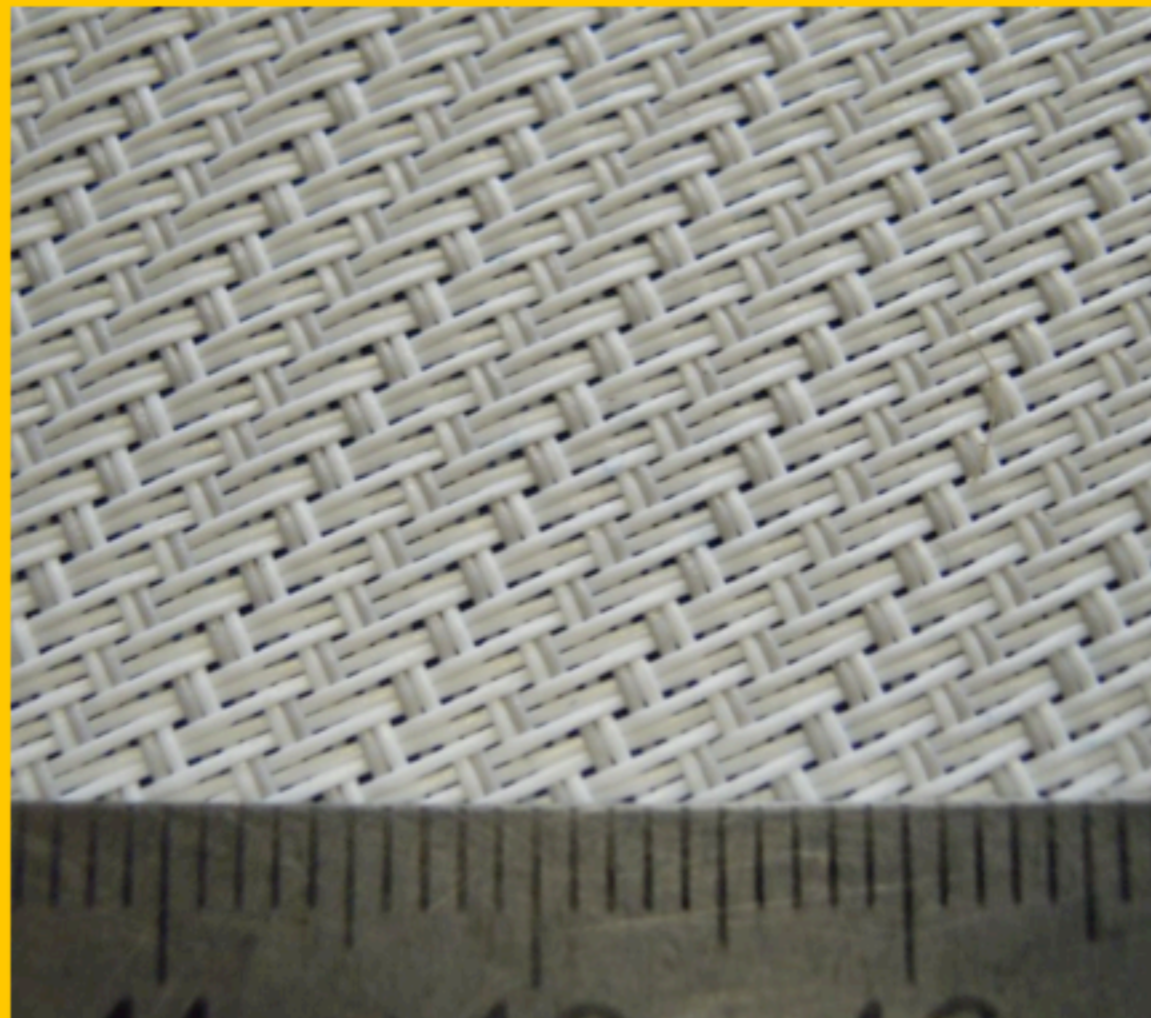


Pore size distribution

Two methods:

- optical analysis of 2D images or 3D tomography acquisitions,
- mercury intrusion.

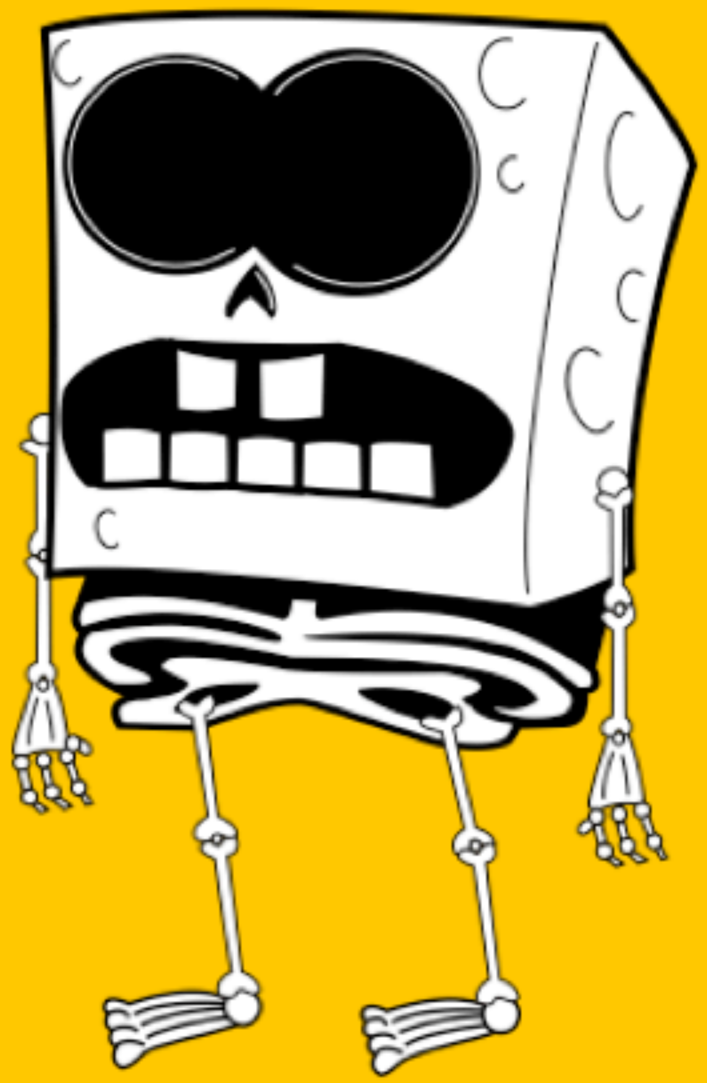
A note about perforated facings



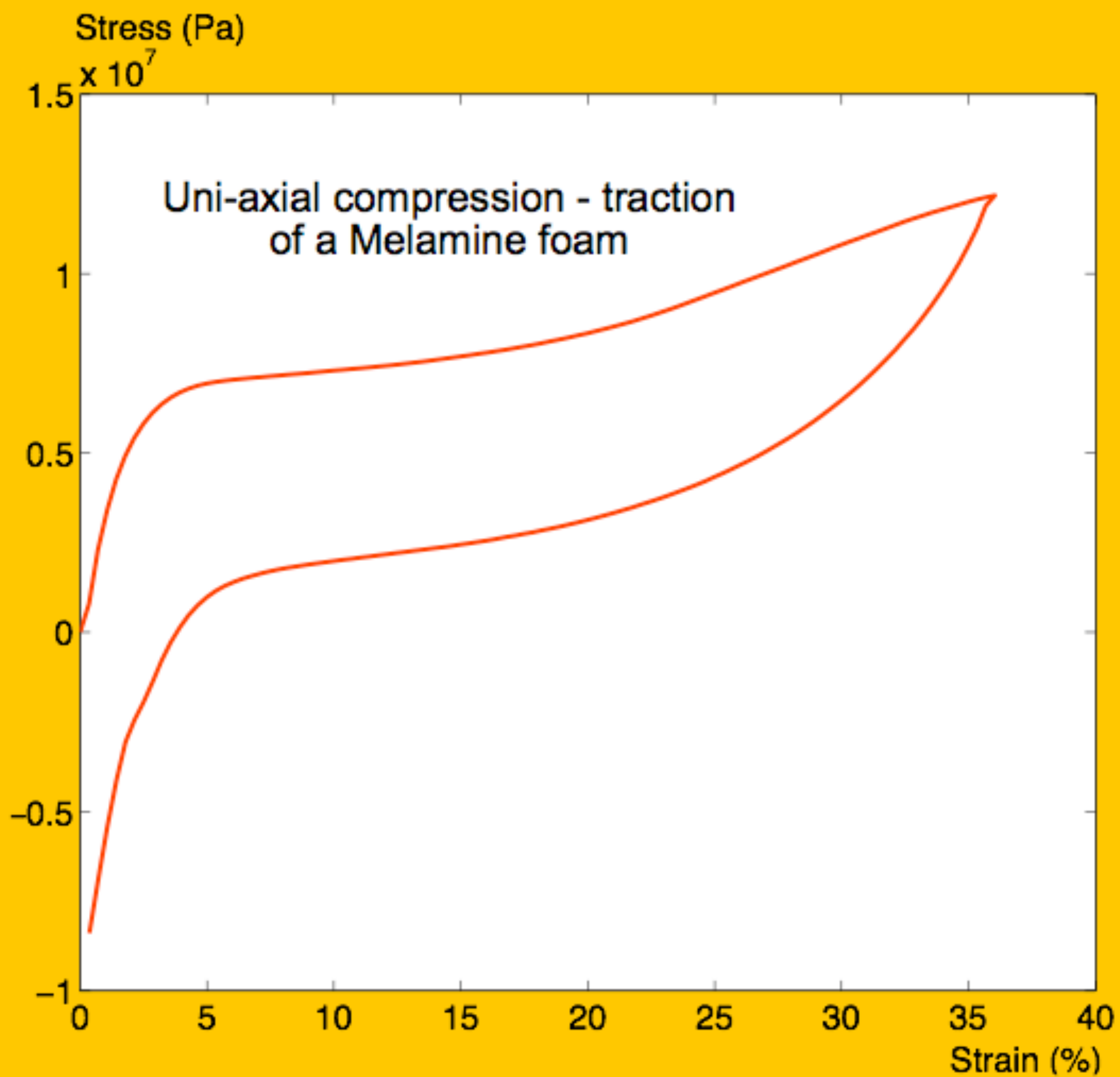
Jaouen & Bécot 2011, DOI: 10.1121/1.3552887

VISCO-ELASTIC

Characterization



Linear elastic domain

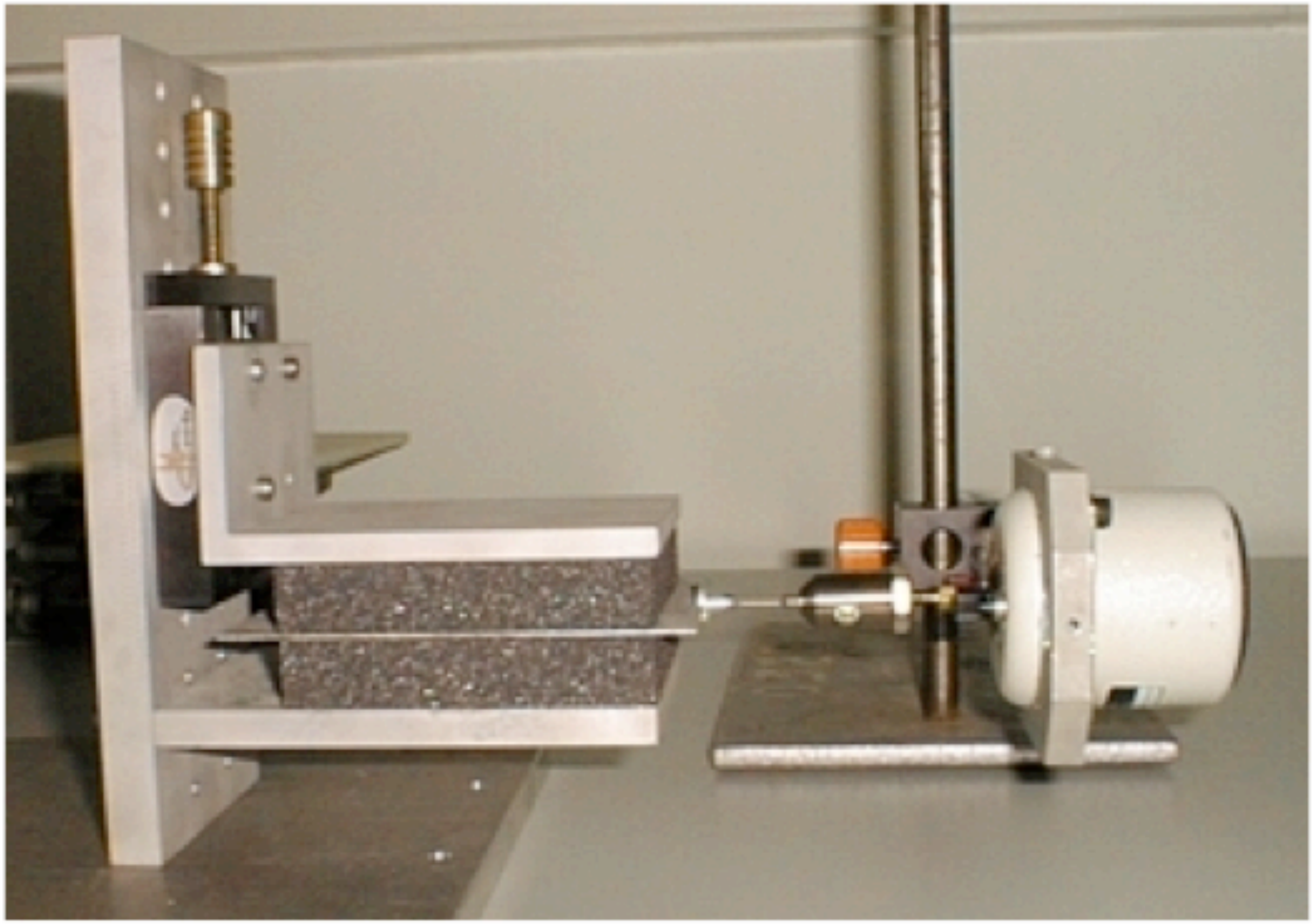


Characterization strategies

1. **Quasi-static measurements at different temperatures**
   and use of Time-Temperature Superposition principle
   +: Low coupling between phases at low frequencies (< 100 Hz)

2. **Dynamic measurements**
   (and eventually use of TTS principle)
   +: Estimation in the audible frequency range (~ 100 to 10 000 Hz).

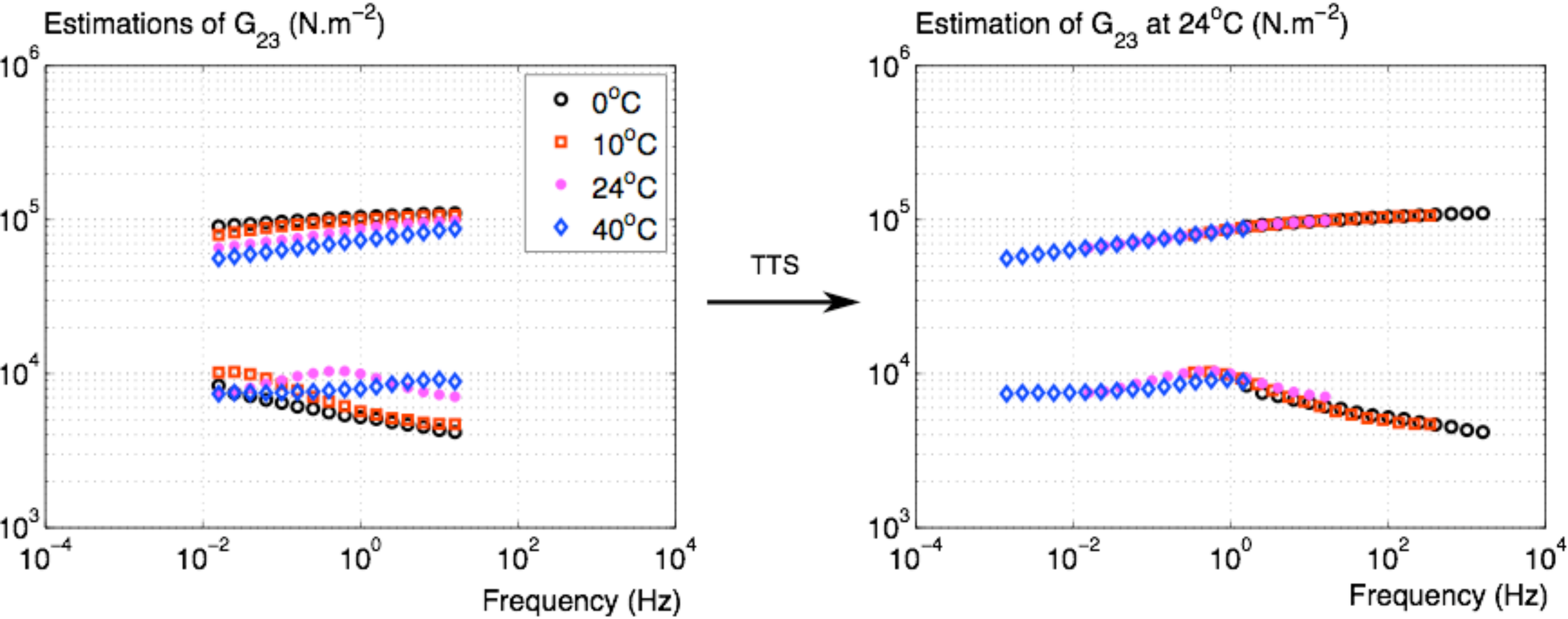
Shear modulus



Picture courtesy of W. Lauriks

Etchessahar et al. 2005, DOI: 10.1121/1.1857527
V. Tarnow 2005, DOI: 10.1121/1.2118267
Jaouen et al. 2008 , DOI: 10.1016/j.apacoust.2007.11.008

VISCO-ELASTIC Shear modulus



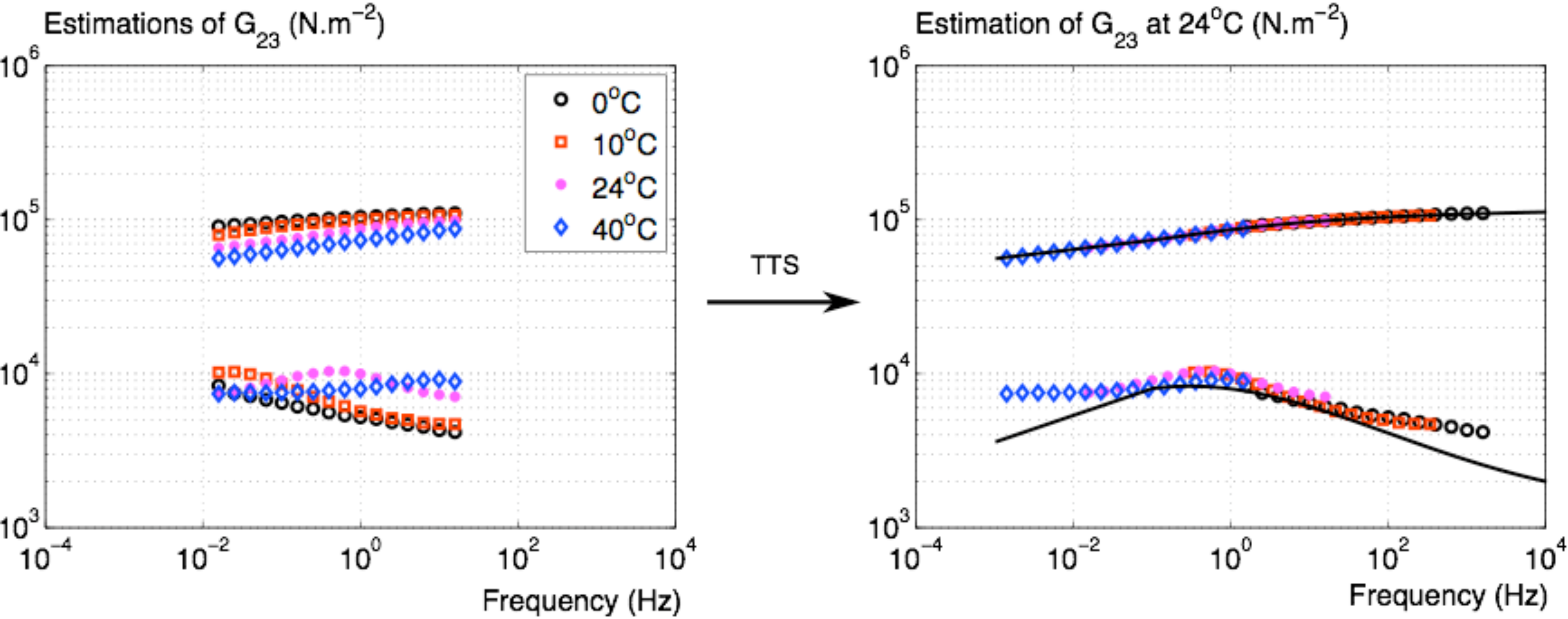
PROS

Low coupling between phases (no change in volume, no shear in fluid).

CONS

No coupling taken into account in model.

VISCO-ELASTIC Shear modulus



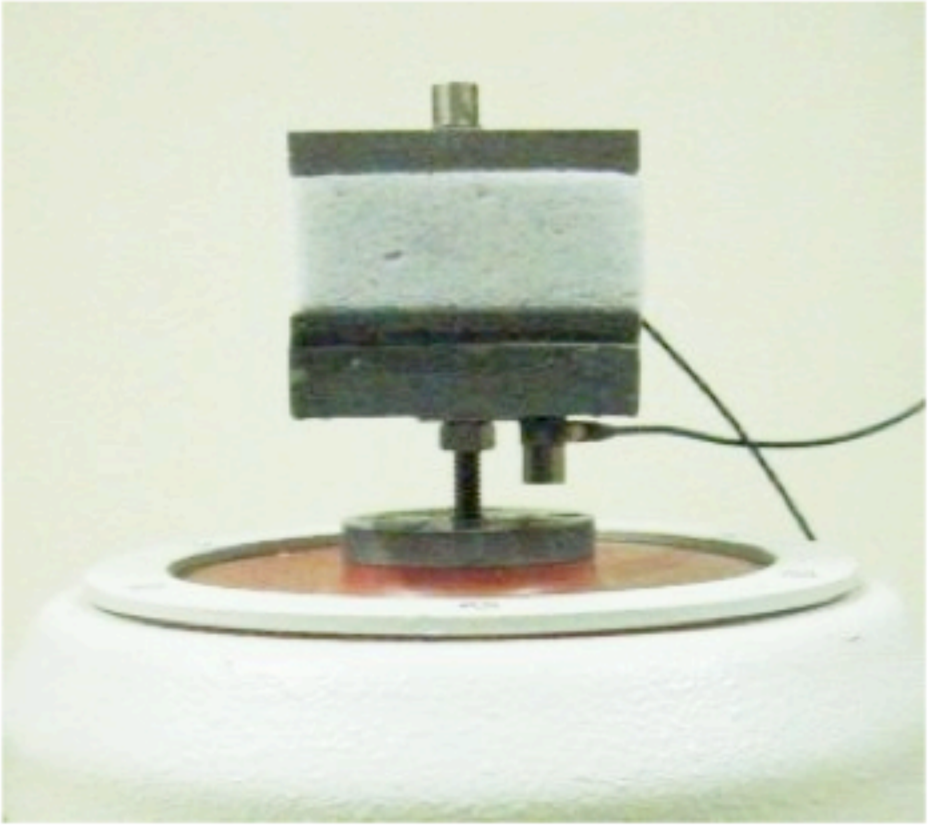
PROS

Low coupling between phases (no change in volume, no shear in fluid).

CONS

No coupling taken into account in model.

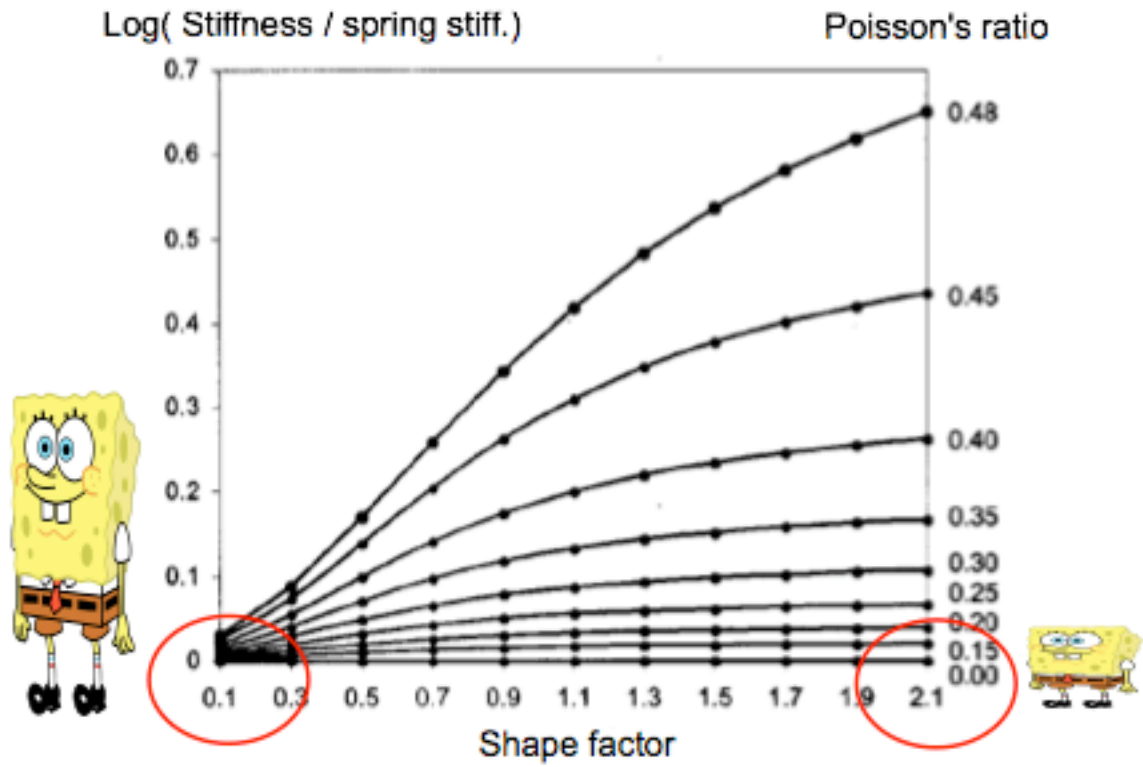
Young's modulus & Poisson's ratio



Set-up at ENTPE

T. Pritz 1980, 1982, 1994, DOI: 10.1006/jsvi.1994.1488
Melon et al. 1998, DOI: 10.1121/1.423897
Langlois et al. 2001, DOI: 10.1121/1.1419091
Danilov et al. 2004, DOI: 10.1016/j.jsv.2003.08.036

VISCO-ELASTIC Young's modulus & Poisson's ratio



PROS

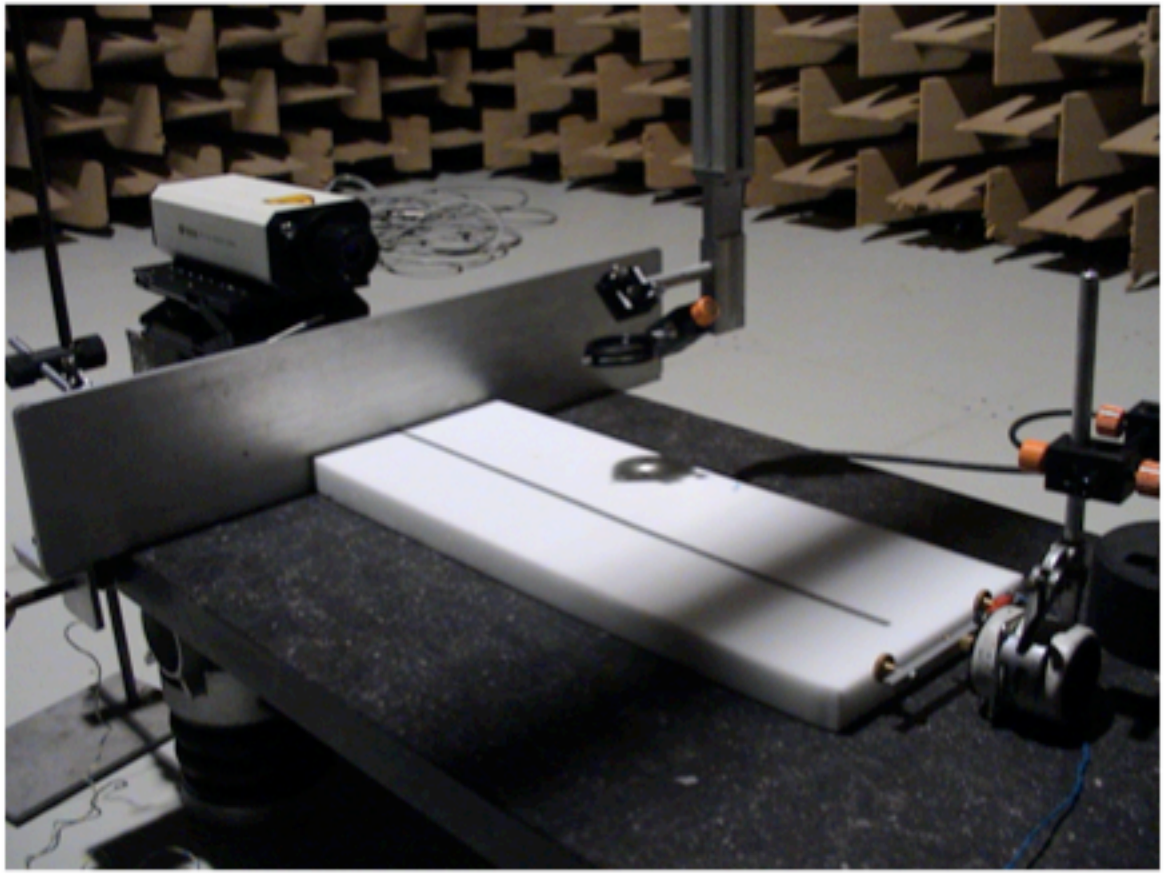
E and ν from one test (two samples).

CONS

Material is supposed isotropic.

Numerial inversions (abacus).

Shear modulus & Poisson's ratio

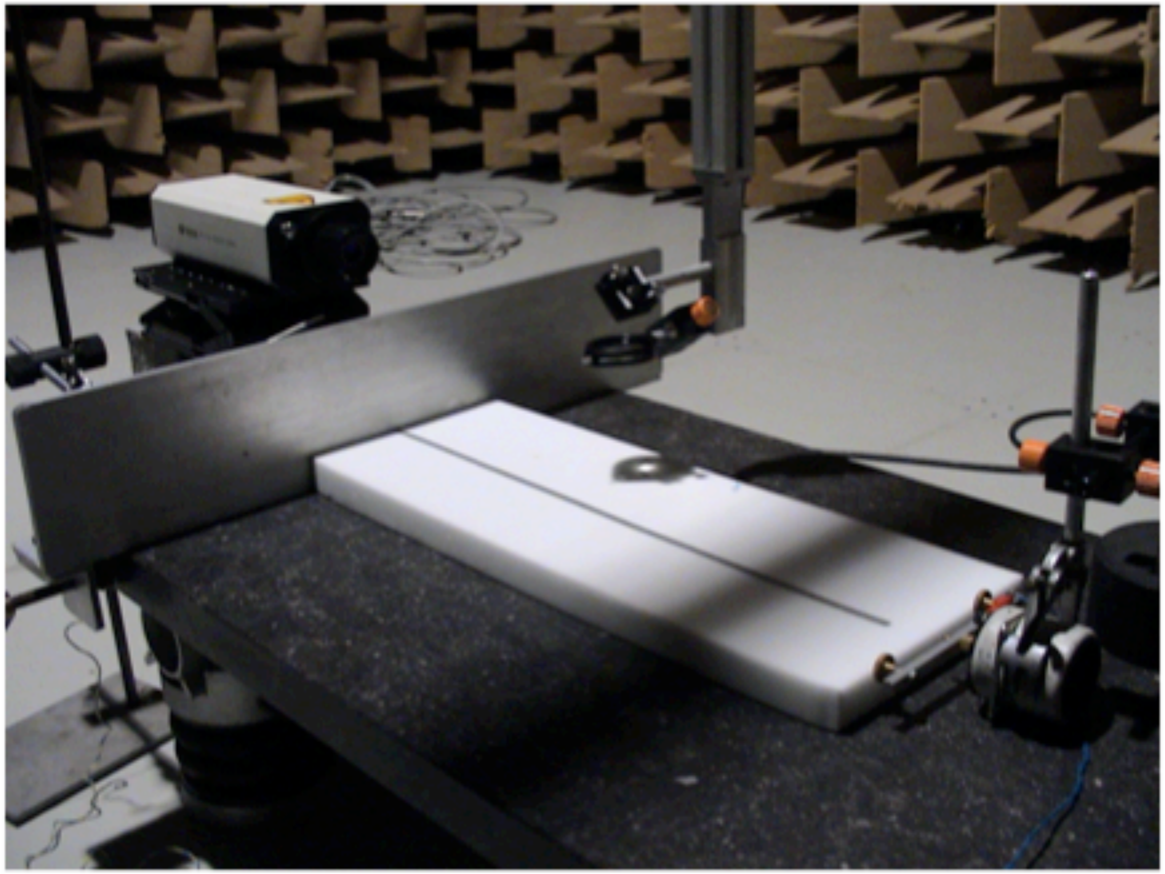


Picture courtesy of W. Lauriks

Boeckx et al. 2005, DOI: 10.1121/1.1847848
Boeckx et al. 2005, DOI: 10.1063/1.1886885
Geebelen et al. 2007, Link: www.ingentaconnect.com

VISCO-ELASTIC

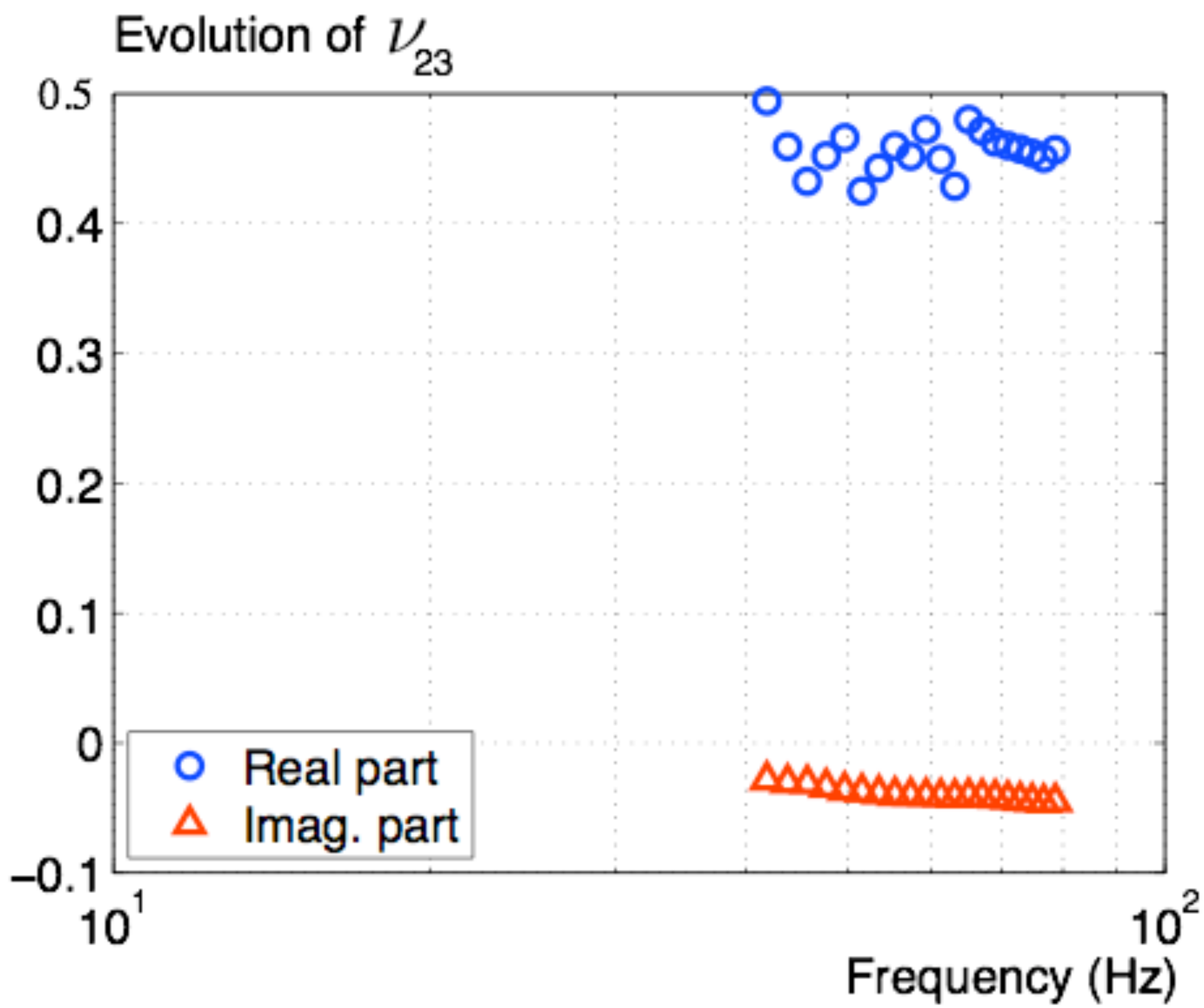
Shear modulus & Poisson's ratio



Picture courtesy of W. Lauriks

PROS	CONS
Measurements in acoustical freq. range.	Numerical inversions are used. Measurement at one temperature only.

A note about Poisson's ratio



T. Pritz 1998 DOI: 10.1006/jsvi.1998.1534
Jaouen et al. 2008 DOI: 10.1016/j.apacoust.2007.11.008

For transversely isotropic materials (1st order approximation):

$$\nu_{LT} \simeq (1-\phi)\nu_{solid}$$

and

$$\nu_{ji} = \nu_{ij}\frac{E_j}{E_i}$$

J.-M. Berthelot 1998, Link: www.springer.com

Rice & Göransson 1999, DOI: 10.1016/S0020-7403(98)00082-4

FIRST CONCLUSION

There is and will be
no perfect method
but
a bundle of complementary methods.

CONCLUSION & PERSPECTIVES

Acoustic characterization

- Many methods exist,
- still α_0' (and α_0) are not characterized.
  (perspectives at low freq. with long impedance tube).

Visco-elastic characterization

- Broadband characterization is still the exception.
- Too few work on anisotropy.

THE LAST WORDS

"Some works suggest that the curiosity of the methods is more important than the results... In my opinion, **the simpler the method the better to have reliable results**".

Tamas Pritz


Thank you
for
your attention