Progettazione di Materiali e Processi

Università degli Studi di Trieste

Modulo 1 – Lezione 8

Corso di Laurea in Ingegneria Chimica e dei Materiali

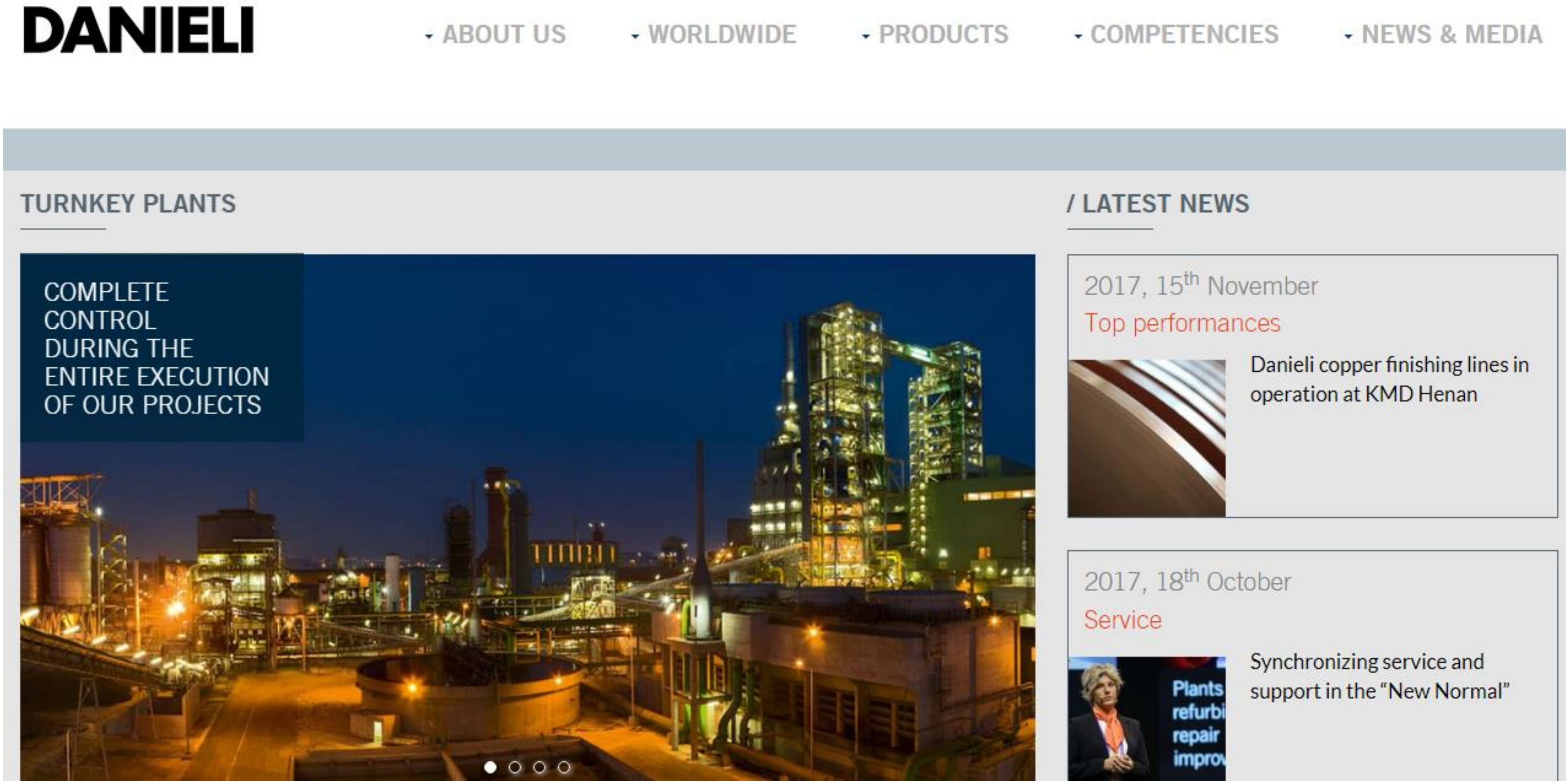
A.A. 2021-2022

Empowerment: Bridging Theory to Practice

The «Empowerment» seminar provides young, motivated, brilliant students to explore their potential to become entrepreneurs

Trieste 13 Dicembre 2017
2PM – 6PM Aula 3B H2bis
Relatore dott. Giovanni Loser

"Failure is not going to kill you, but not trying is worse than anything you can imagine."
Seth Godin (TED Conference, Monterey California (USA), March 7–10, 2007)



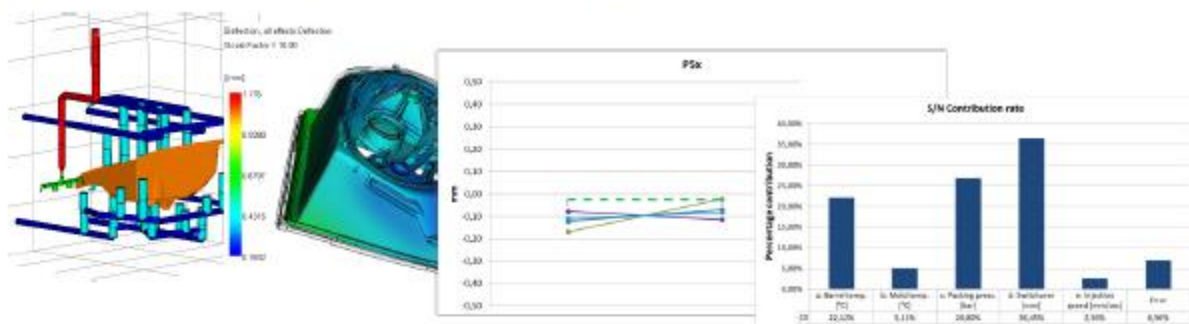
Visita a Buttrio, 11-12-2017 ore 15.00 (partenza ore 13.00).

AUTOMOTIVE LIGHTING

Rear Lamp Development and Production

Seminar: ROBUST DESIGN - TAGUCHI METHODS

Application on injection molding, simulation and trials



UNIVERSITA' di TRIESTE – Ingegneria Meccanica

29th November 2017 16.00-18.00

Designing new materials

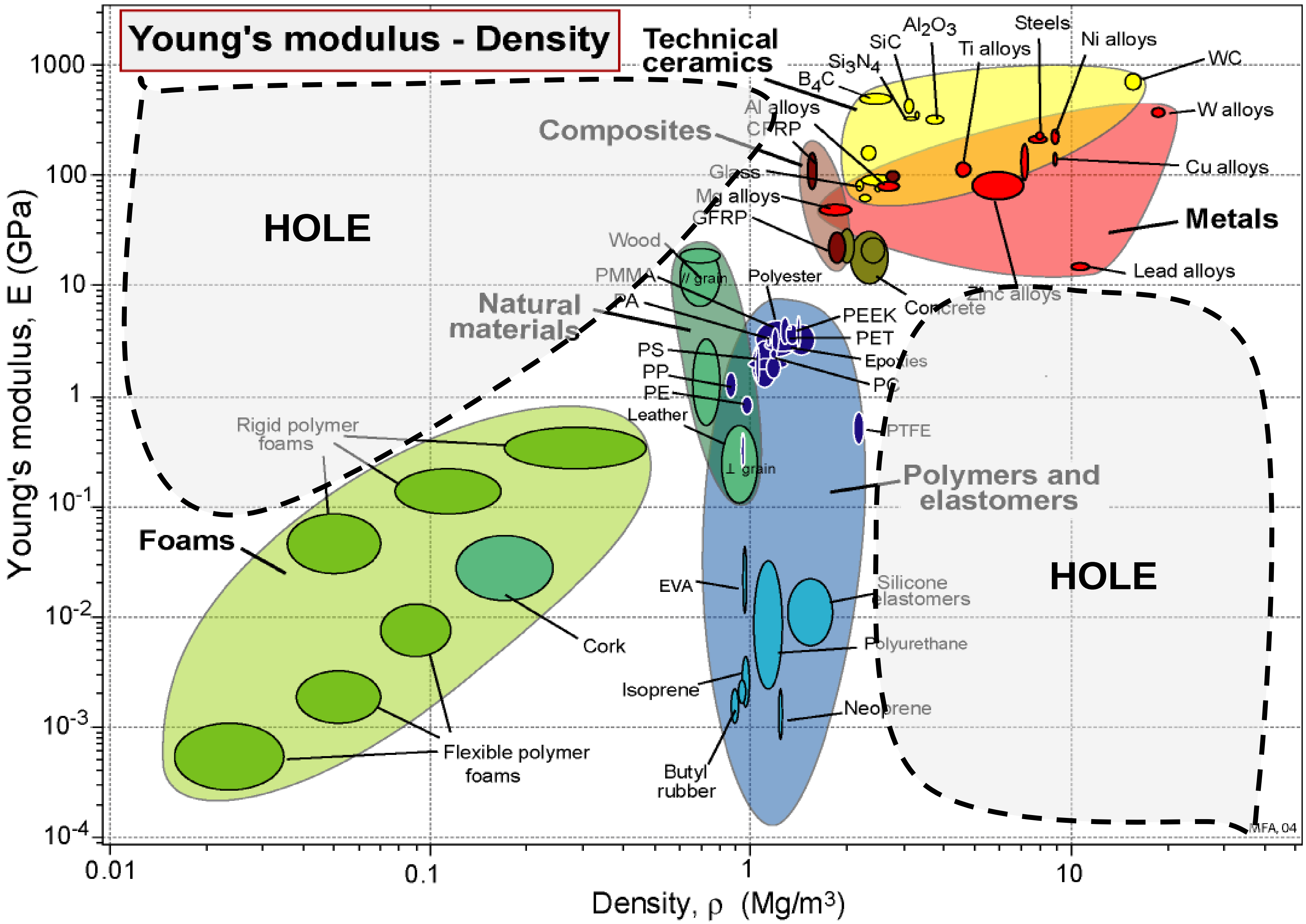
Outline

- **Holes in material property space**
- **History of hole-filling**
- **Fundamental limits**
- **Hybrid materials as a way forward**

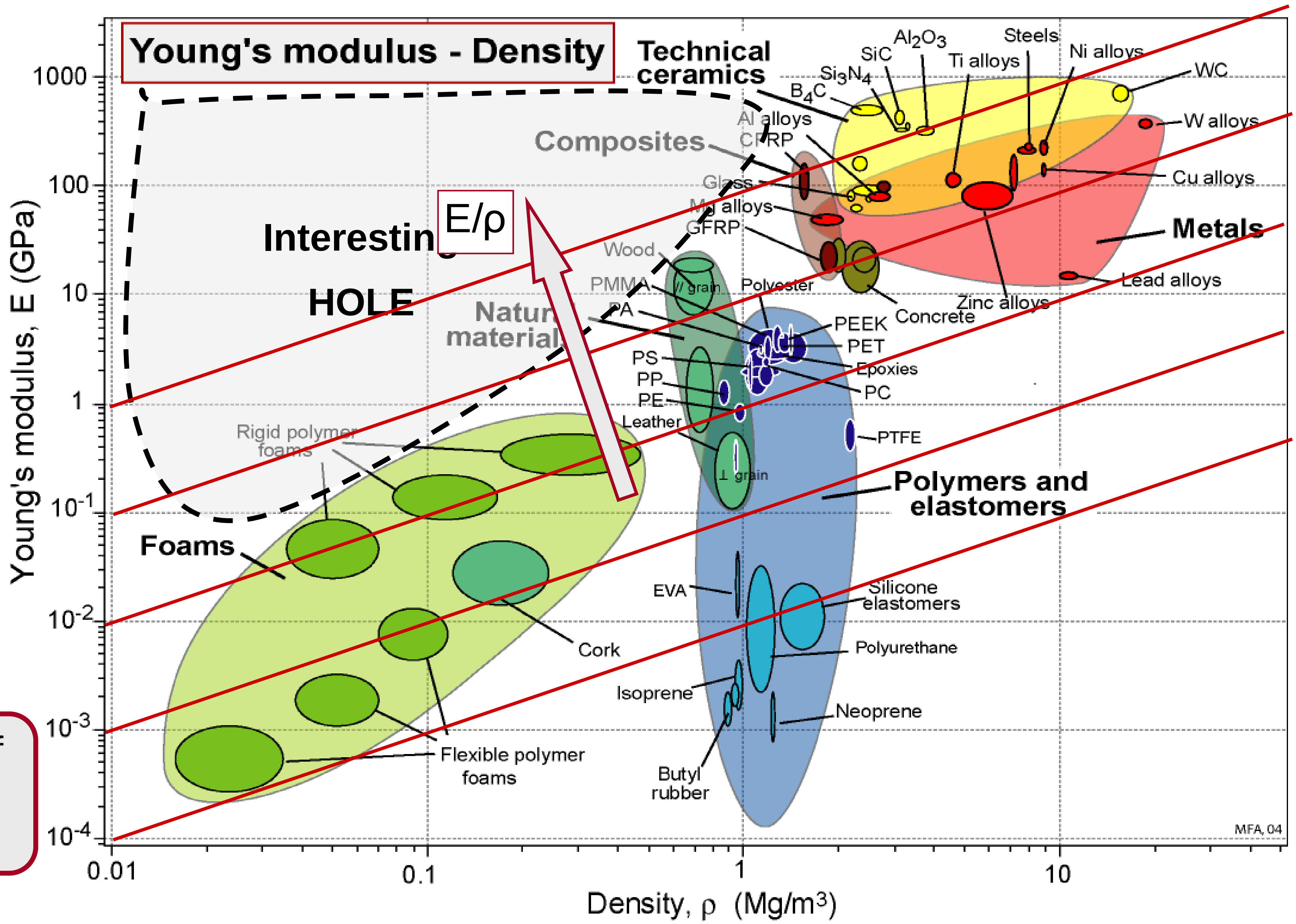
Resources

- **"Materials Selection in Mechanical Design",** 4th edition by M.F. Ashby, Butterworth Heinemann, Oxford, 2011, **Chapters 11 and 12**.

Material-property space: E and ρ

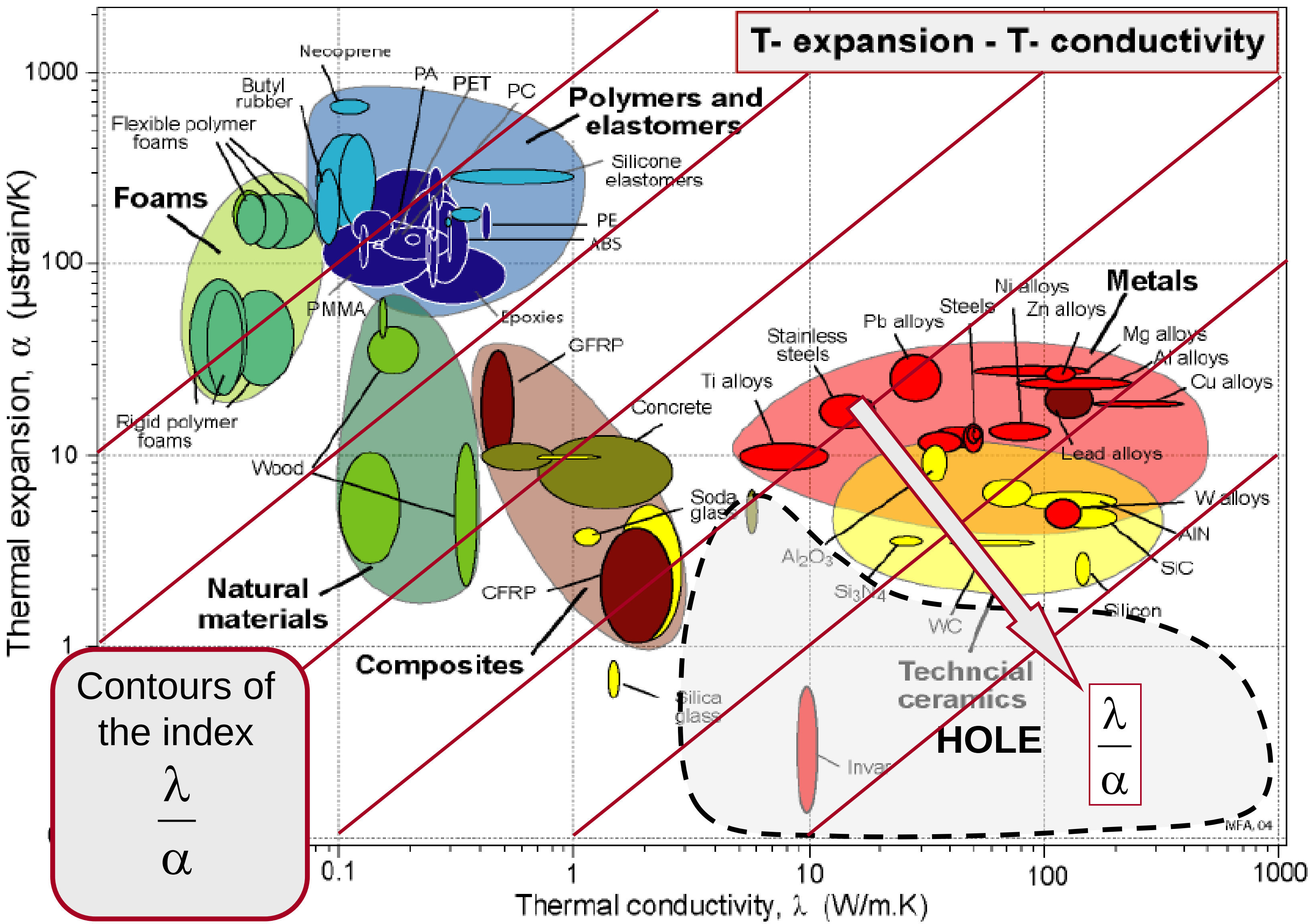


Material-property space: E and ρ

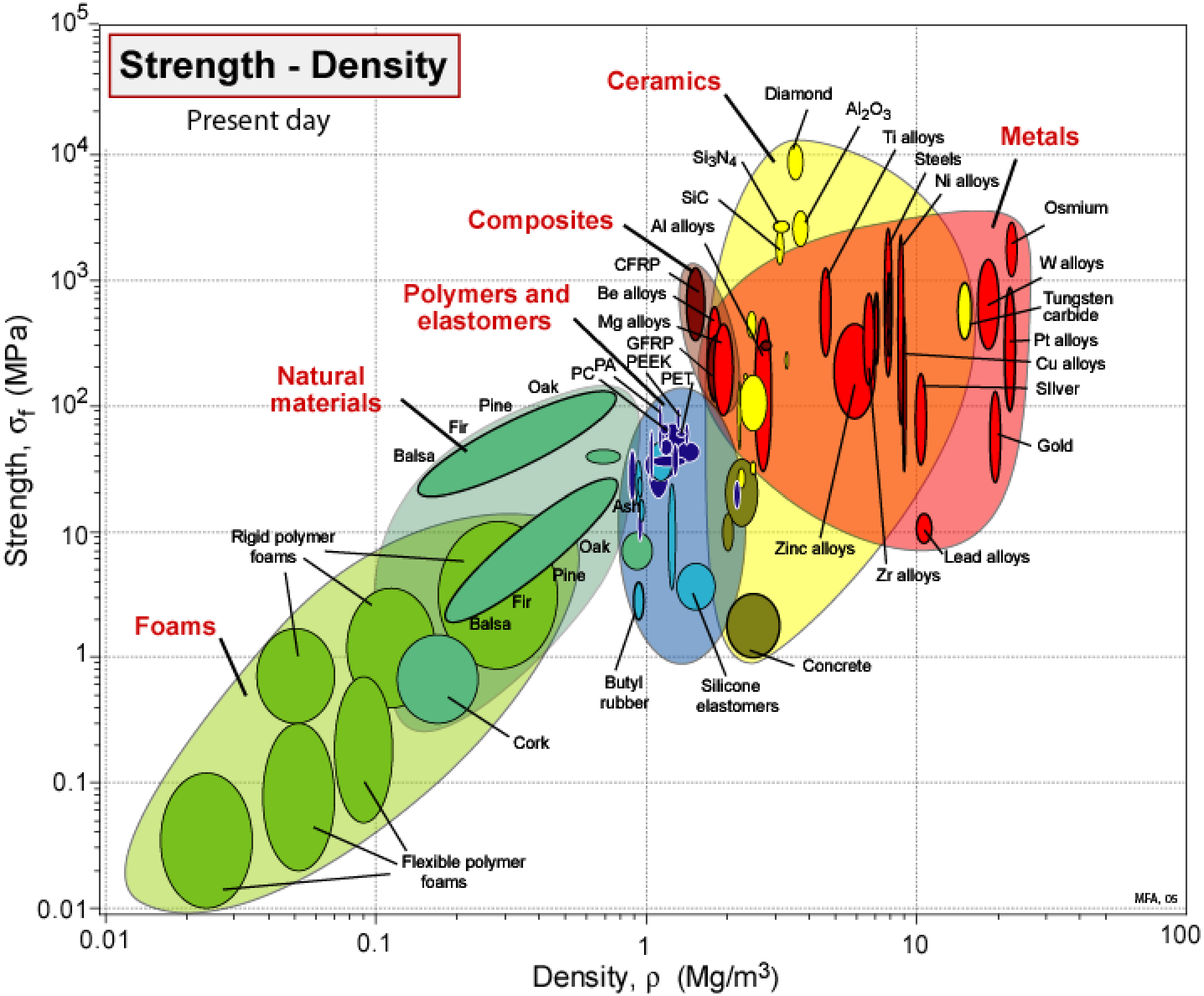


Contours of the index E/ρ

Material-property space: α and λ

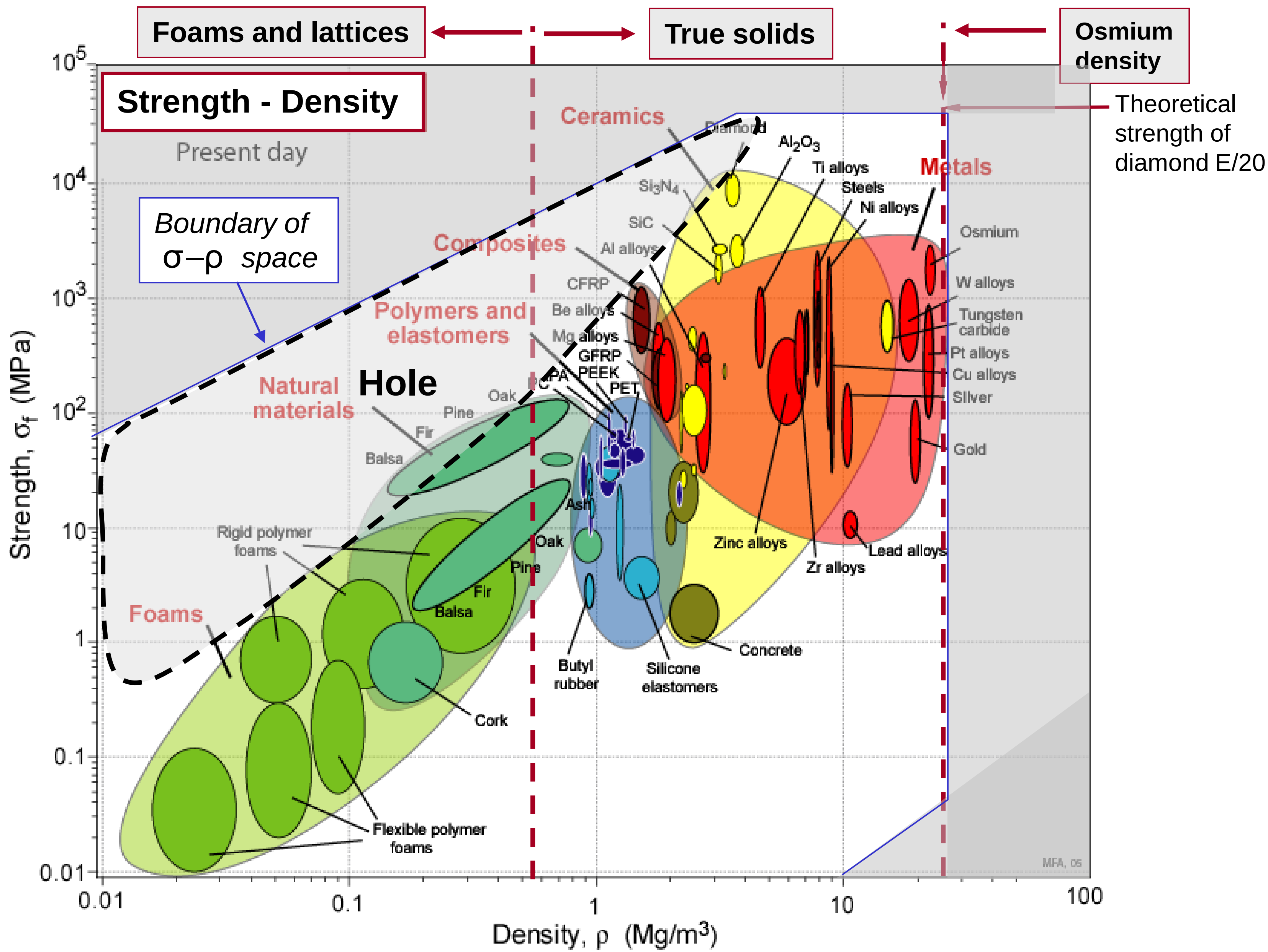


The evolution of structural materials

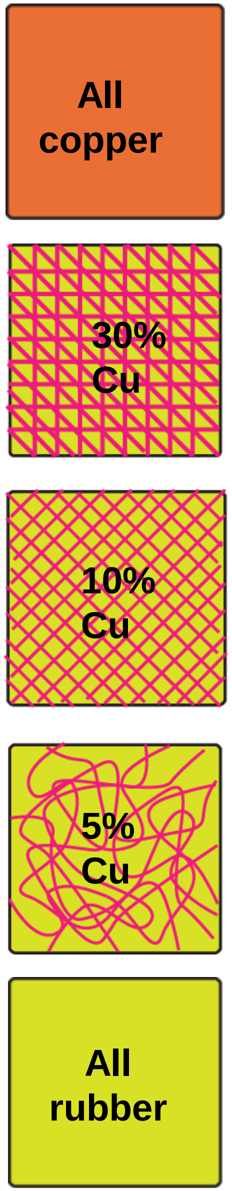


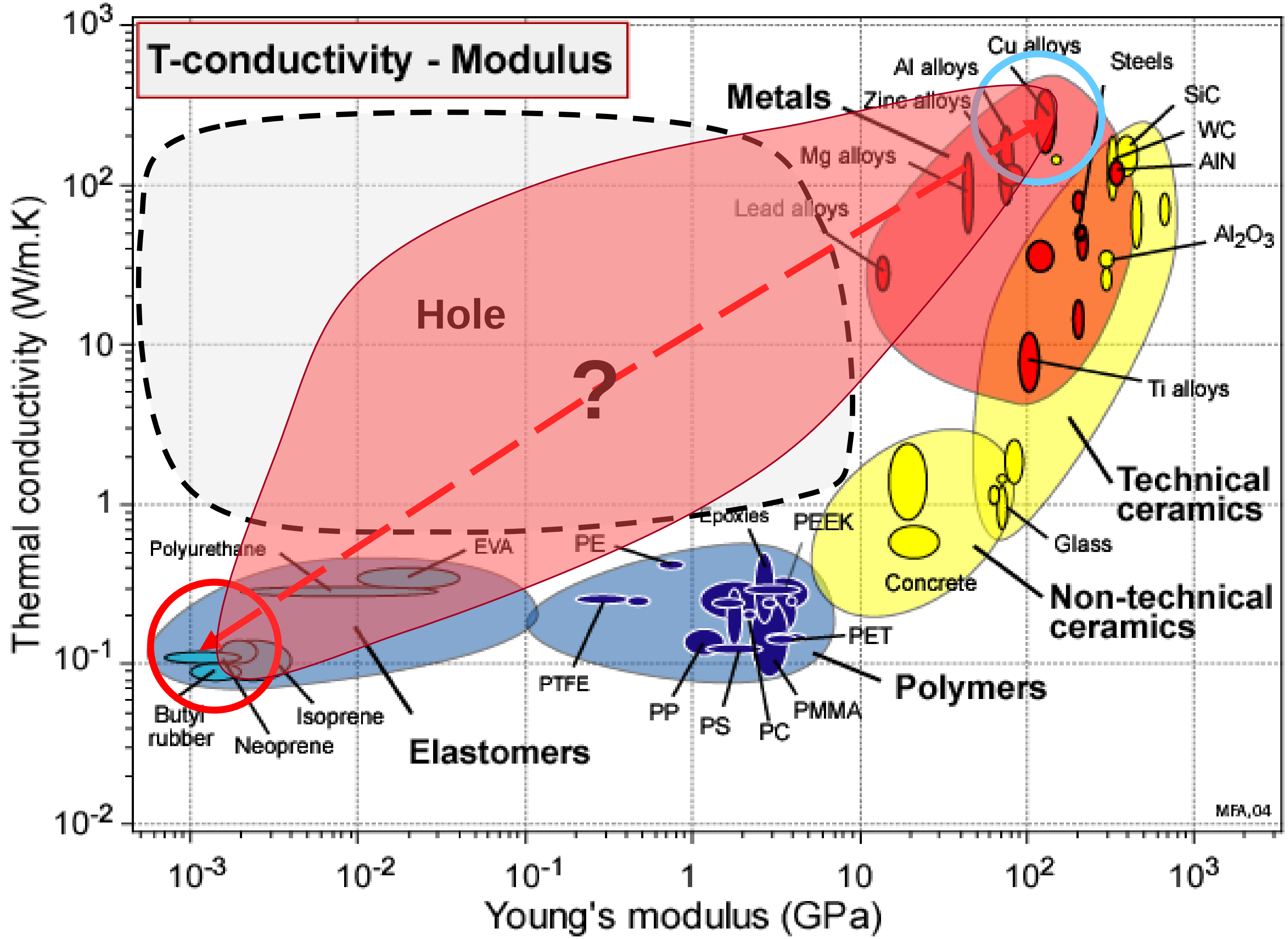
21st Century

Boundaries of material property space



Filling holes: hybridization

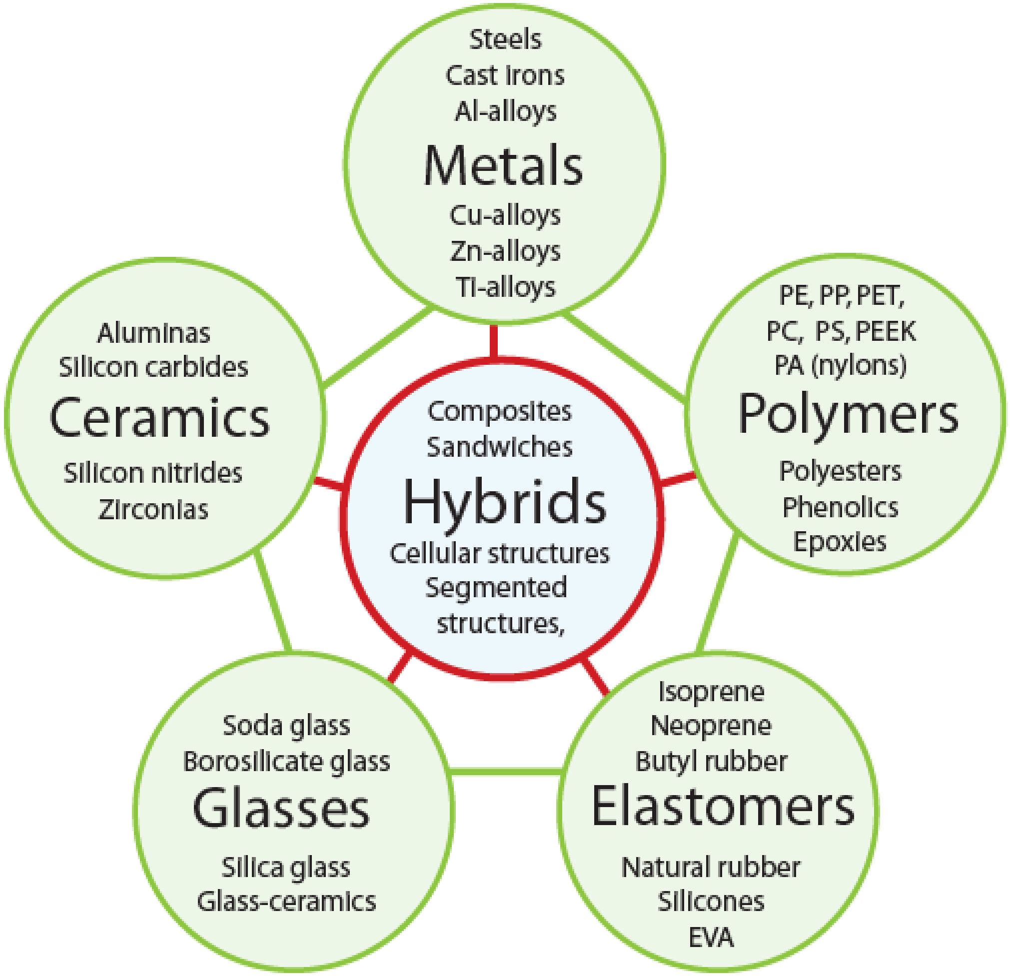




Hybrids or "multi-materials"

"A hybrid material is a combination of two or more materials in a pre-determined configuration and scale, optimally serving a specific engineering purpose"

Kromm et al, 2002



Design variables:

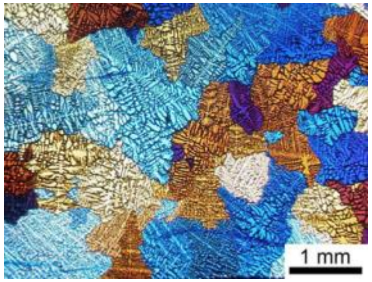
- **Choice of materials**
- **Volume fractions**
- **Configuration**
- **Connectivity**
- **Scale**

The hybrid synthesizer

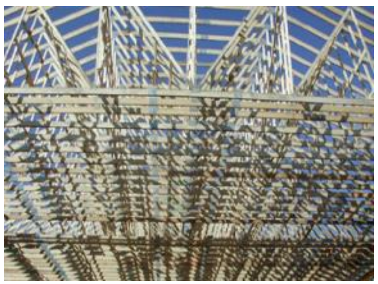
- **Explore configurations, with free material choice**
- **Explore structured-structures**
- **A shell: insert models for other configurations**

Designing hybrid materials

Three parallel approaches



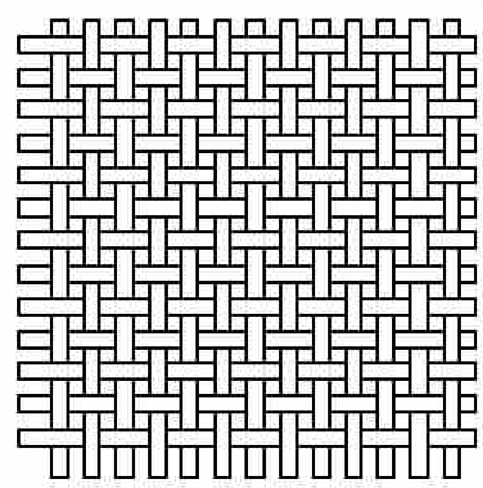
- **Materials – relate properties to microstructure: controlled nature, scale through alloy design and processing.**



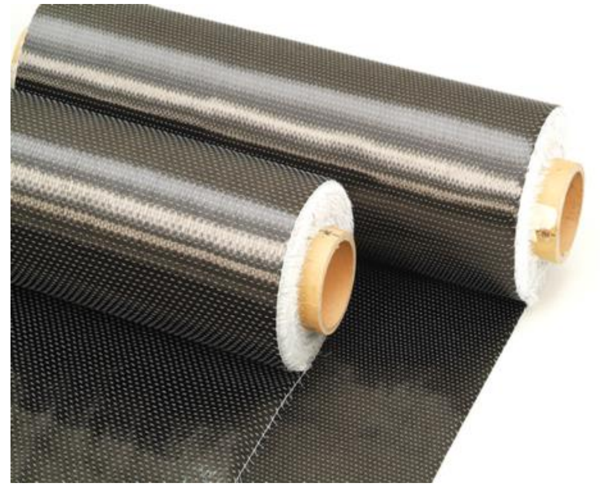
- **Mechanics – accept properties as "given", optimise the geometry**

- **Textile technology – exploit unique strength and blending properties of fibers**

Combining textile technology, mechanics and material

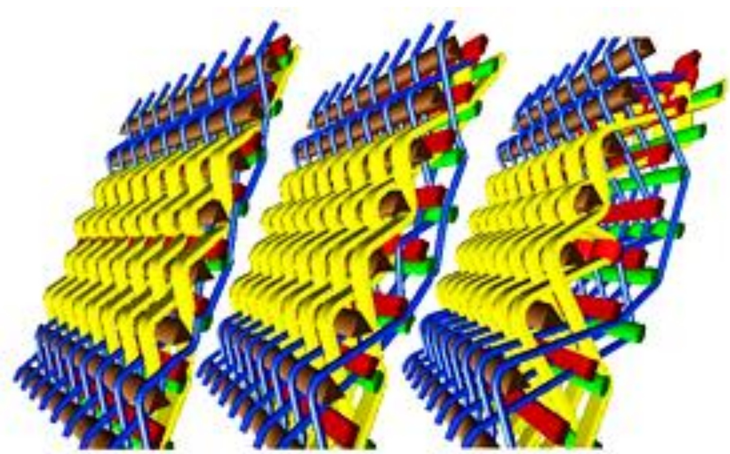


(a) Simple weave

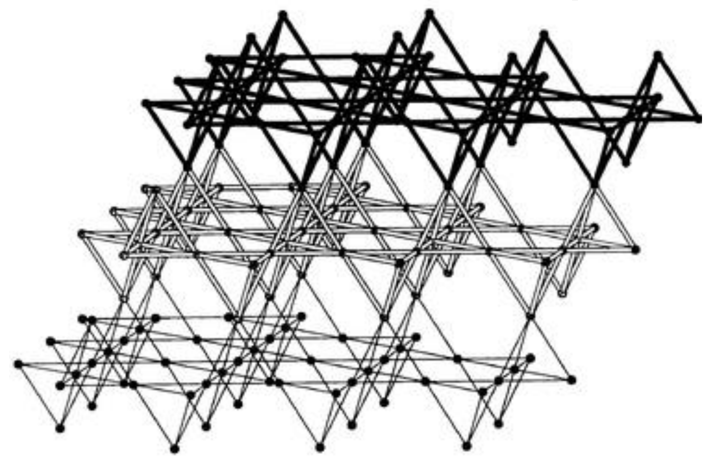


Woven carbon fiber

CFRP product

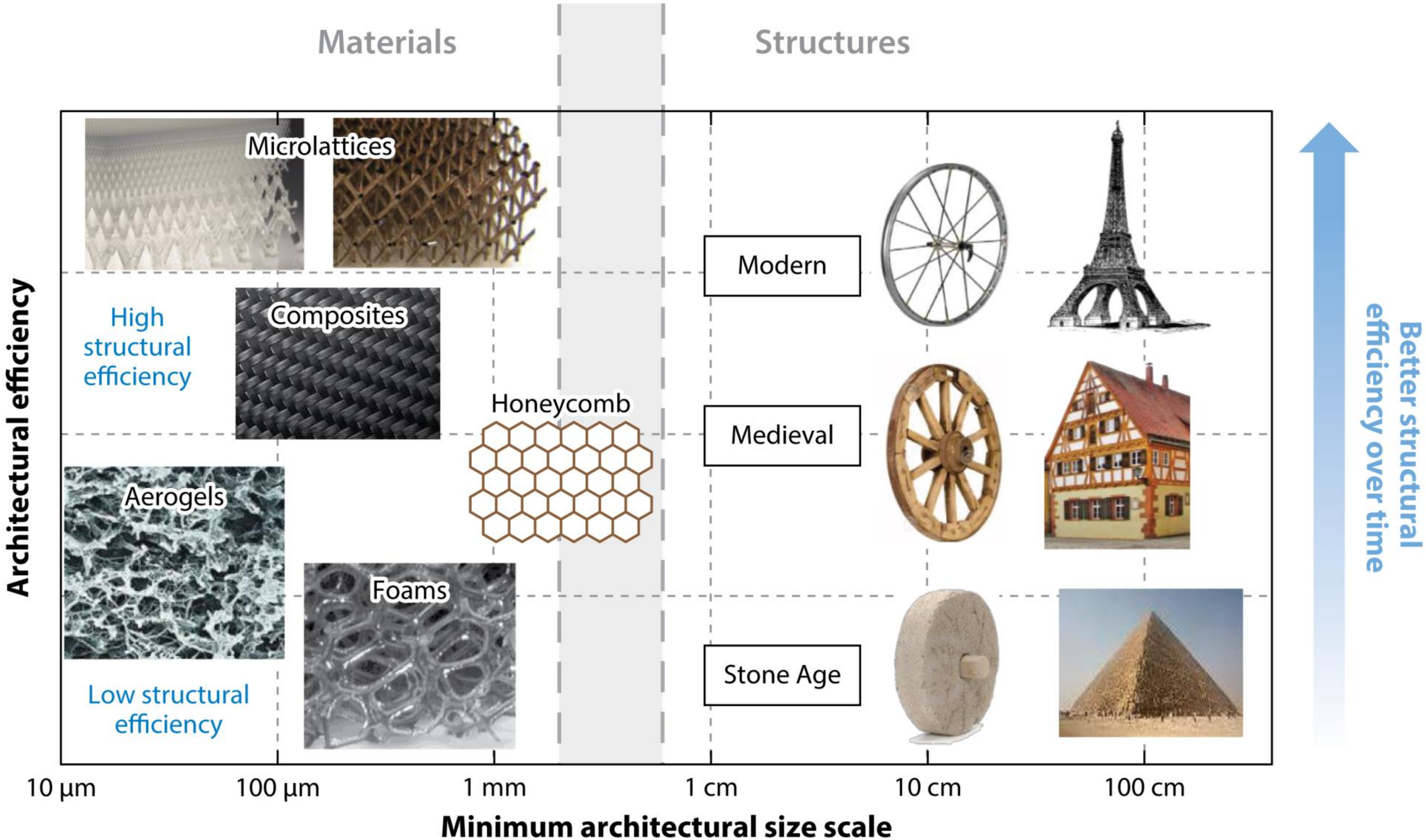


(b) 3-dimensional weaving



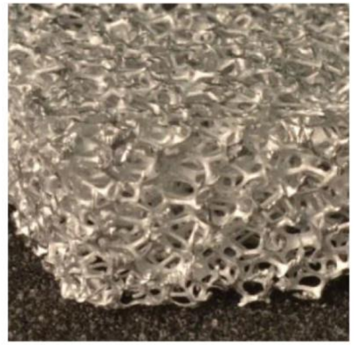
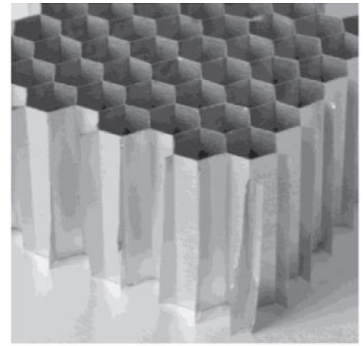
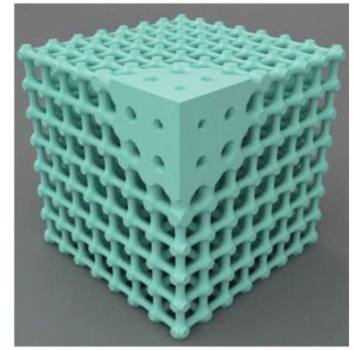
(c) The kagome weave

Architected Cellular Materials



Schaedler TA, Carter WB. 2016.
Annu. Rev. Mater. Res. 46:187–210

Architected Cellular Materials

				
Cellular architecture	None	Random	Ordered	Ordered and location specific
Properties	Continuous and homogeneous	Homogeneous at scales > cell	Homogeneous and highly anisotropic	Inhomogeneous and highly anisotropic
Design degrees of freedom	Solid constituent	Solid constituent, cell size	Solid constituent, cell size, and orientation	Cell size/shape, node topology, ligament shape, material...

Schaedler TA, Carter WB. 2016.
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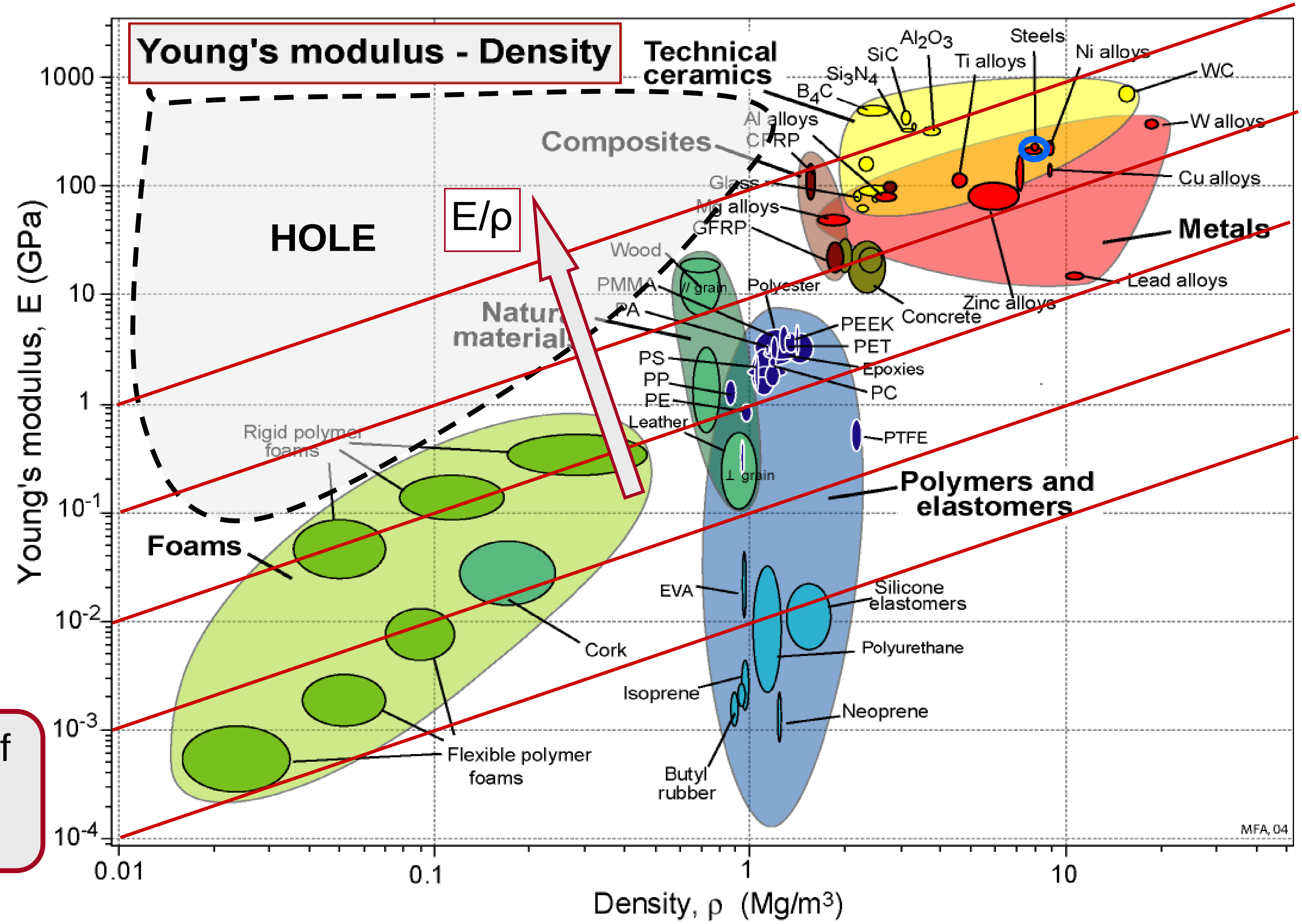
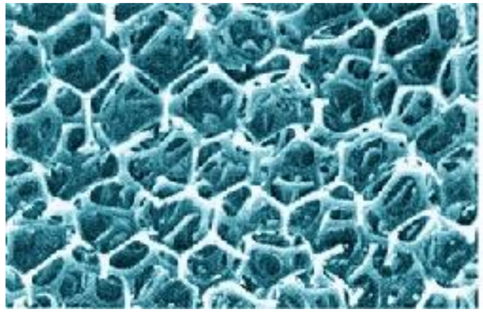
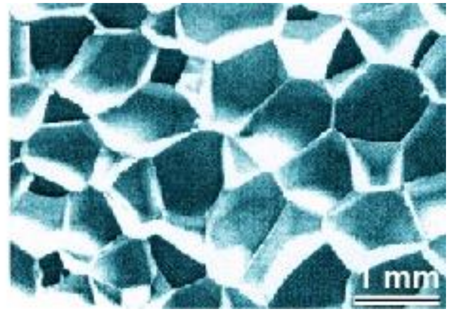
Material-property space: E and ρ



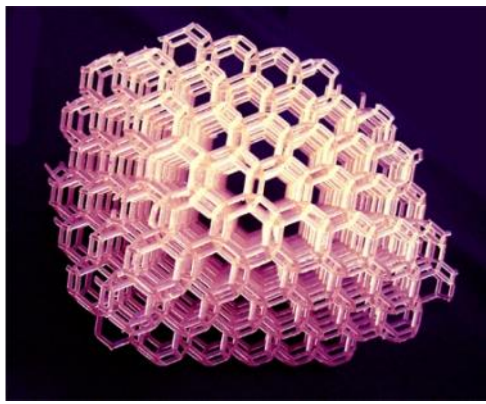
Contours of the index E/ρ

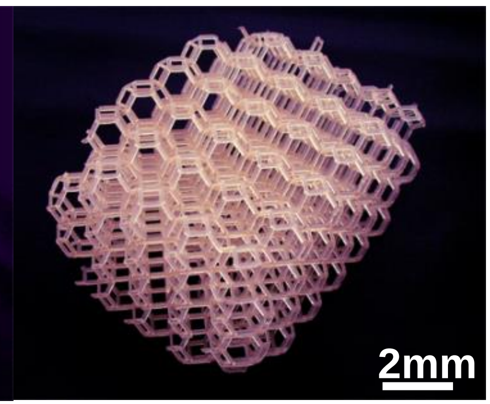
Foams and micro-lattices



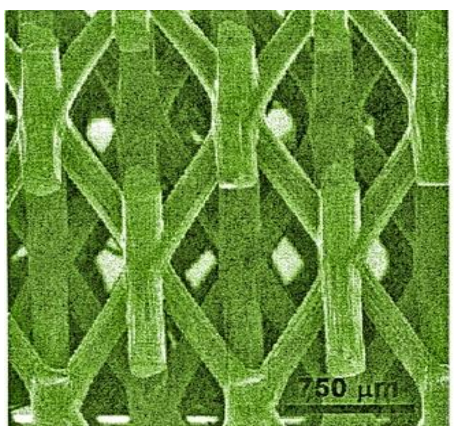


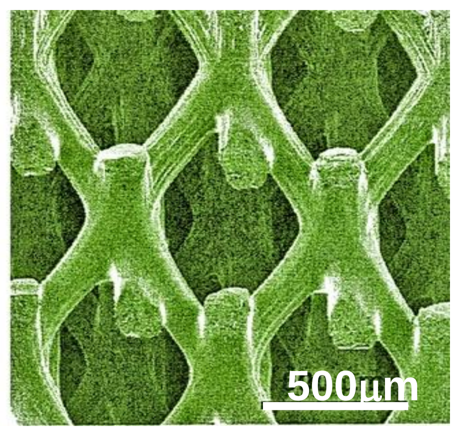
Polymer foams





Bending-dominated micro-lattices

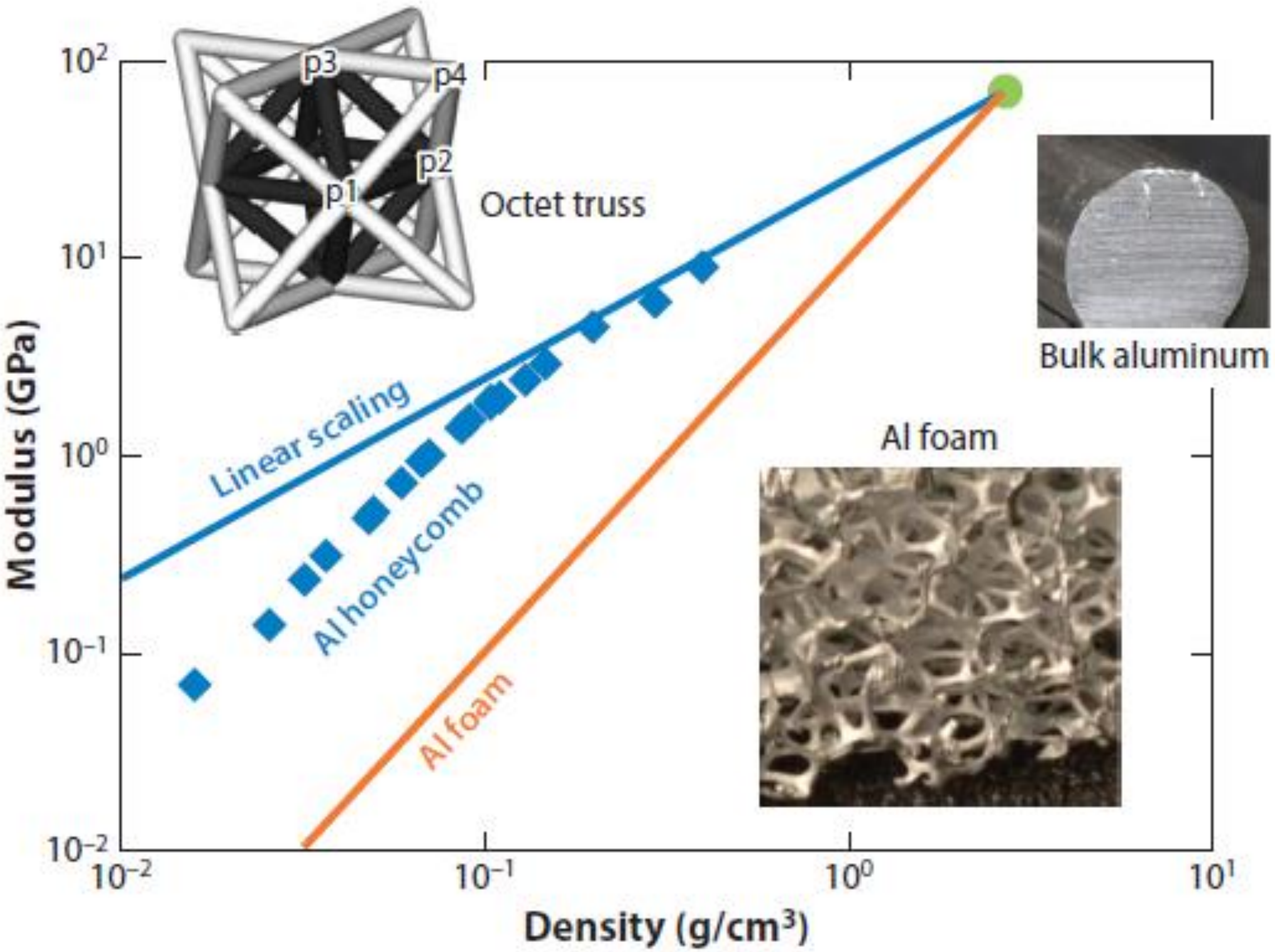


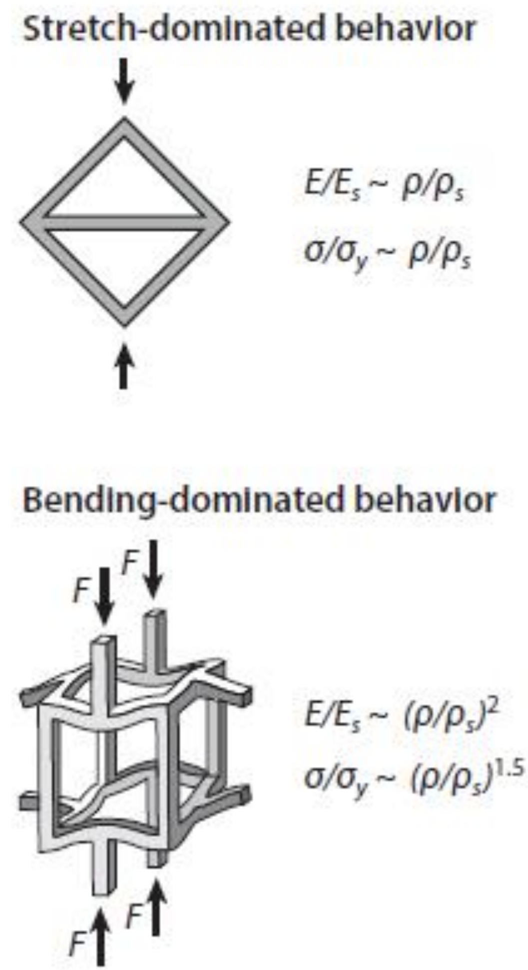


Stretch-dominated micro-lattices

Architected Cellular Materials for Enhancing E/ρ

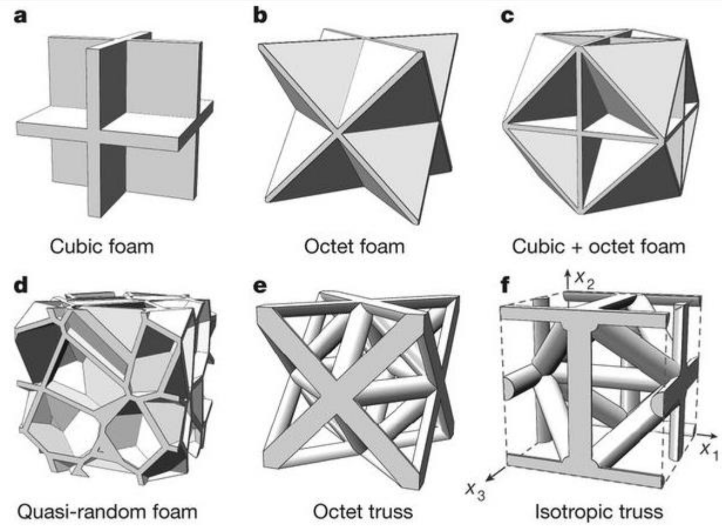
Foams vs Trusses → Bending-dominated vs Stretch-dominated structures



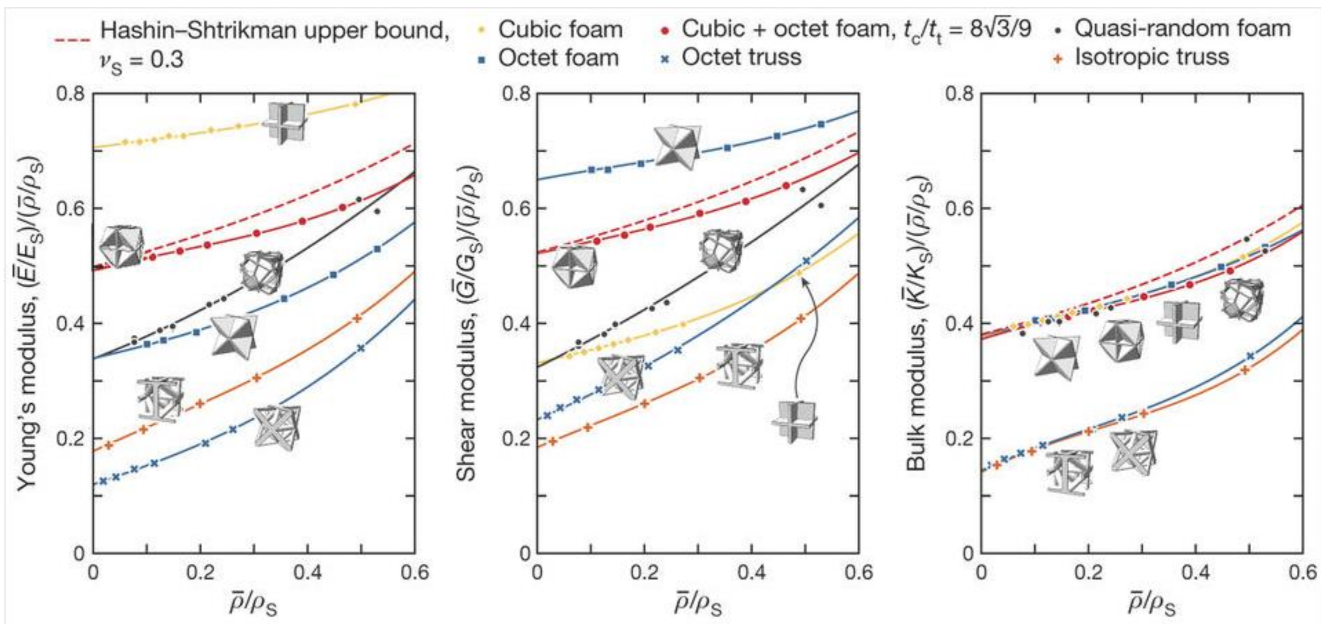


Architected Cellular Materials for Enhancing E/ρ

Best performing materials



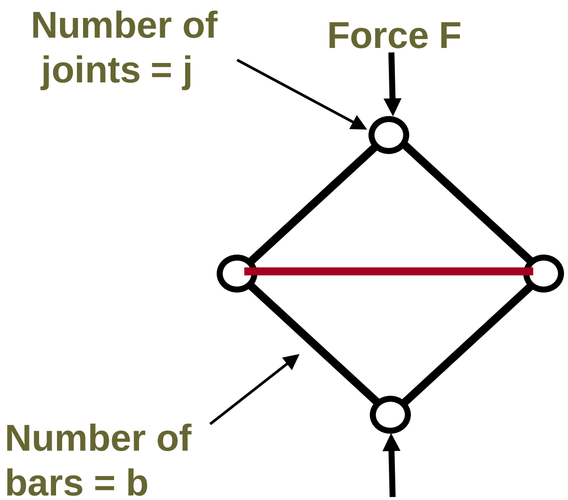
J. B. Berger, H. N. G. Wadley & R. M. McMeeking, Mechanical metamaterials at the theoretical limit of isotropic elastic stiffness, Nature 543, 533–537 (2017)



The elastic stiffness of the six material geometries, characterized by *E*, *G* and *K*—the Young's, shear and bulk modulus, respectively (data points); results are fitted to third-order polynomials (solid lines). The theoretical Hashin–Shtrikman upper bounds for isotropic stiffness are plotted for each modulus (red dashed line). Only anisotropic materials can have stiffnesses in excess of these upper bounds. Open-cell materials ('×' and '+' symbols) underperform closed-cell materials by a large margin.

Bending and stretch dominated structures

Pin-jointed frame with **b** bars and **j** joints



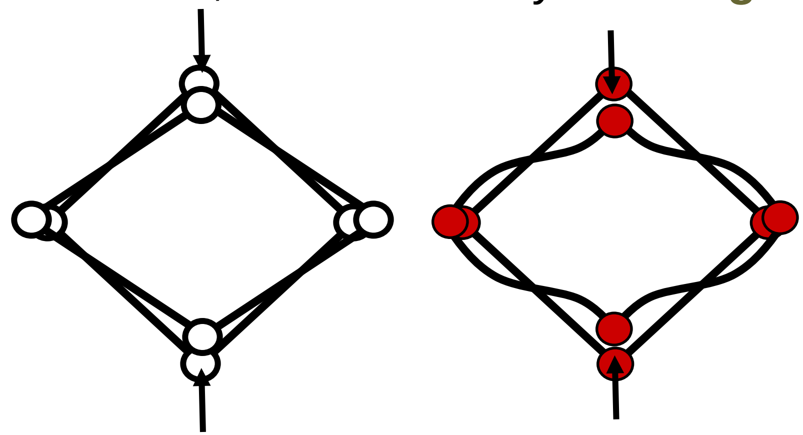
Statically determinate
0 degrees of freedom
0 states of self-stress

Condition for stretch dominance

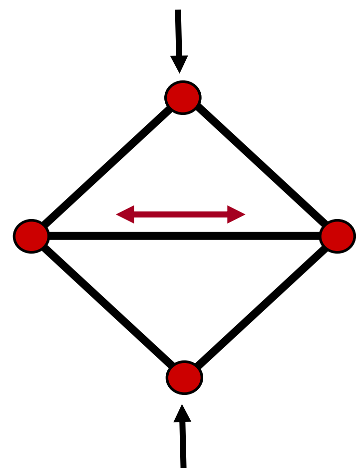
$$M = b - 2j + 3 = 0 \quad \text{2-dimensions}$$

$$M = b - 3j + 6 = 0 \quad \text{3-dimensions}$$

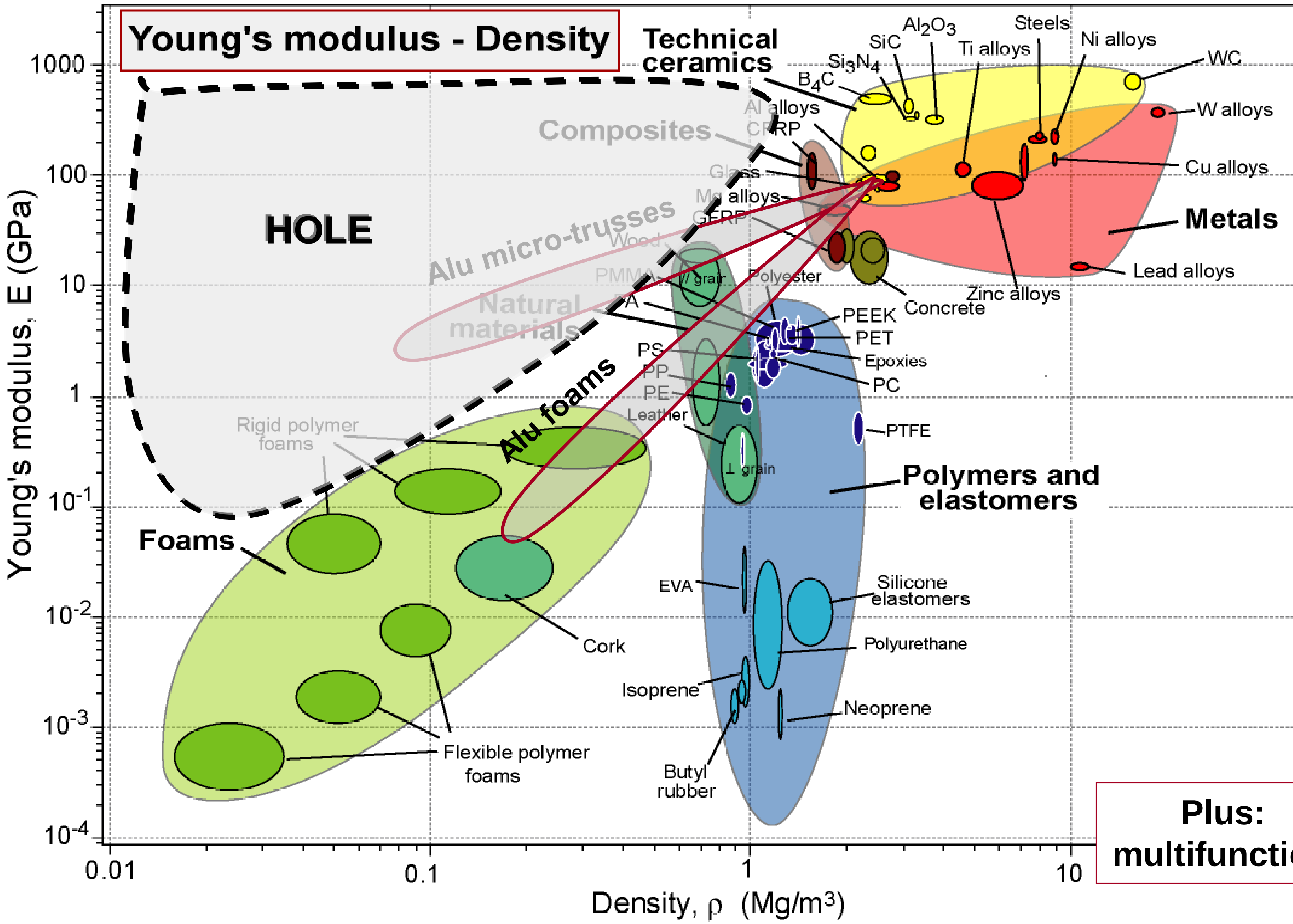
- Lock joints in a ***mechanism*** prevents rotation, deformation by **bending**



- Lock joints in a *structure* - **stretching** still dominates

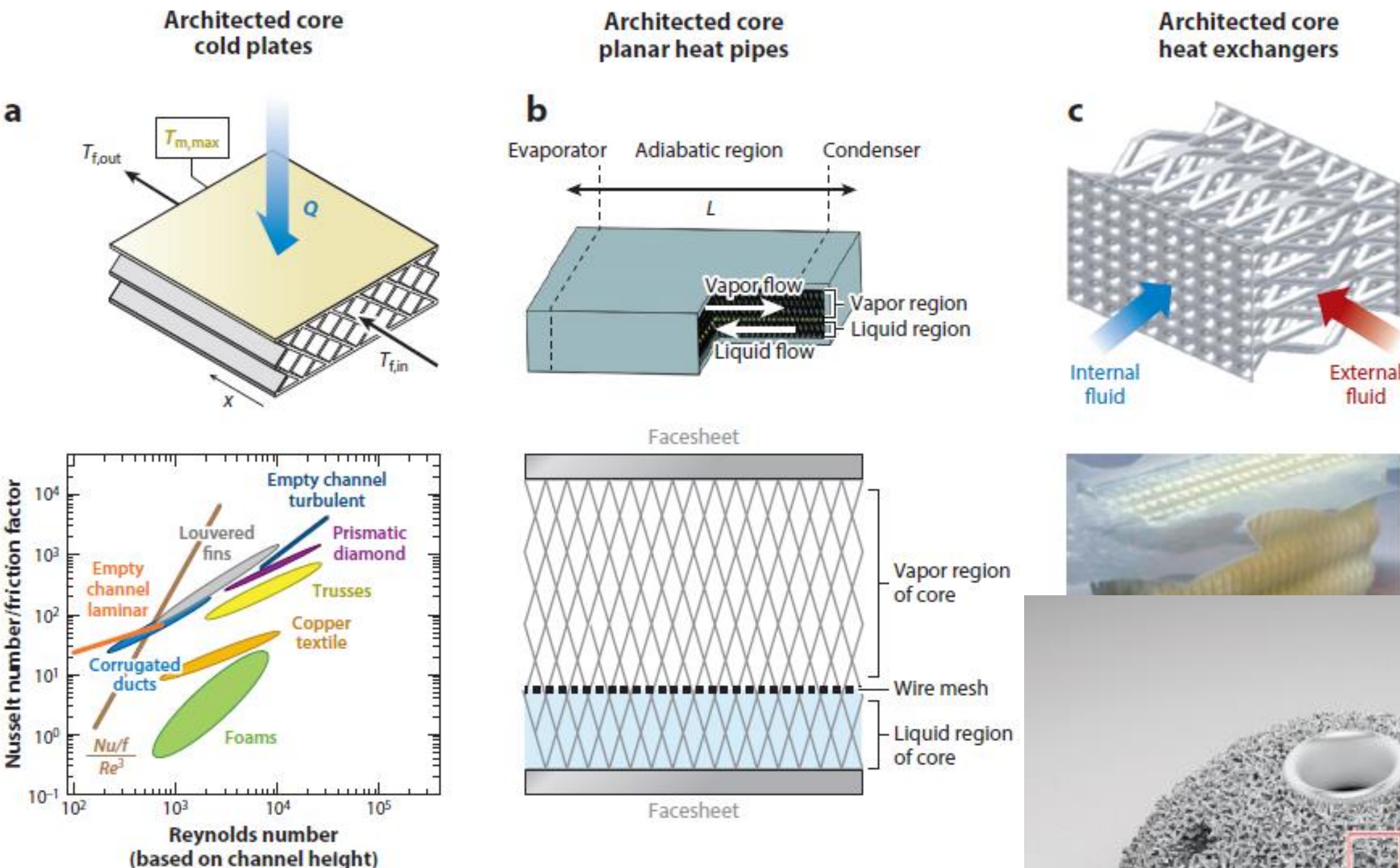


Micro-trusses

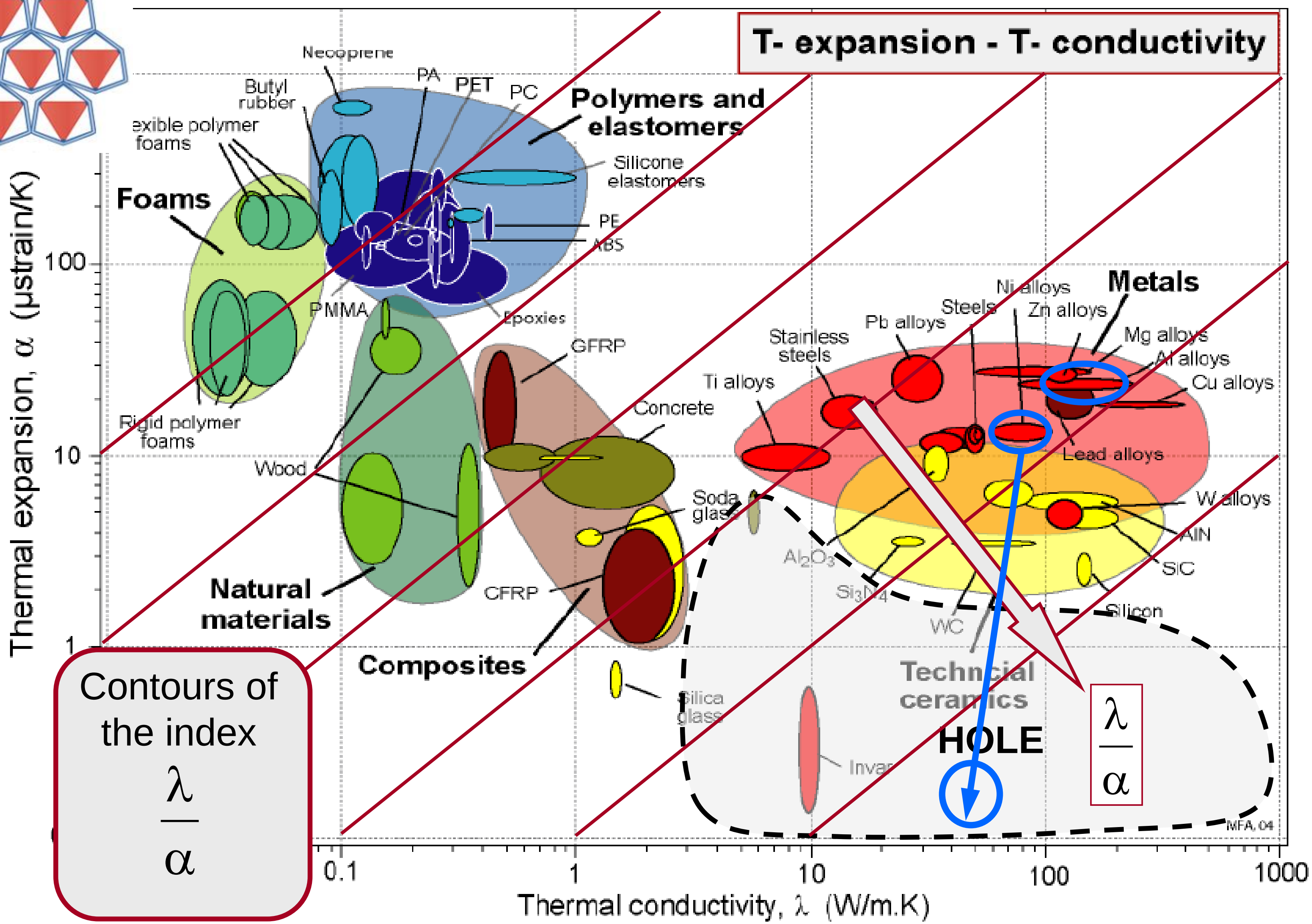


Plus: multifunctionality

Functionality Enabled by Architecture

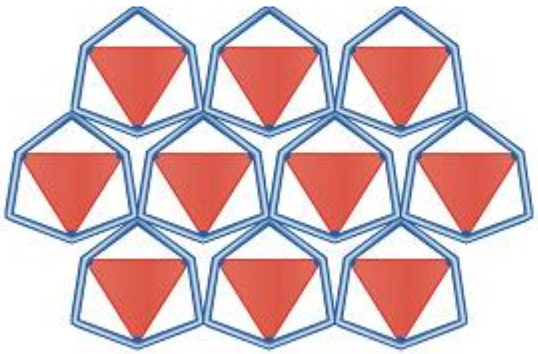


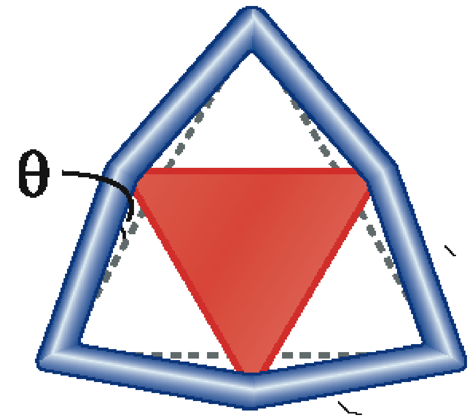
Material-property space: α and λ

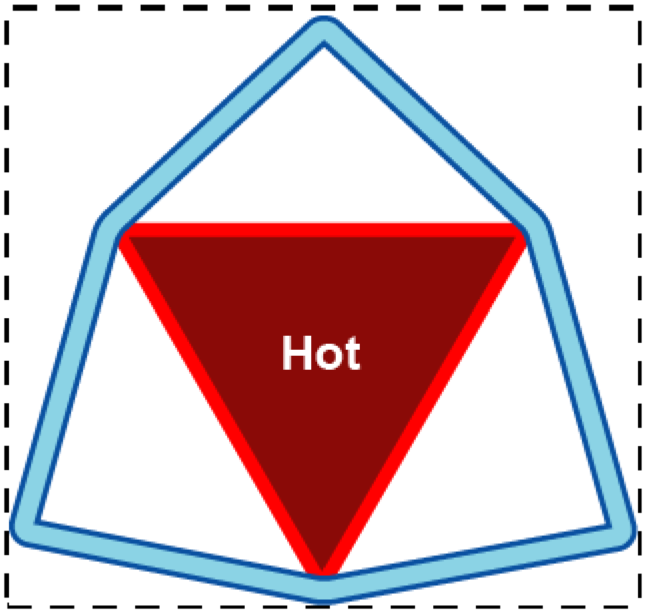


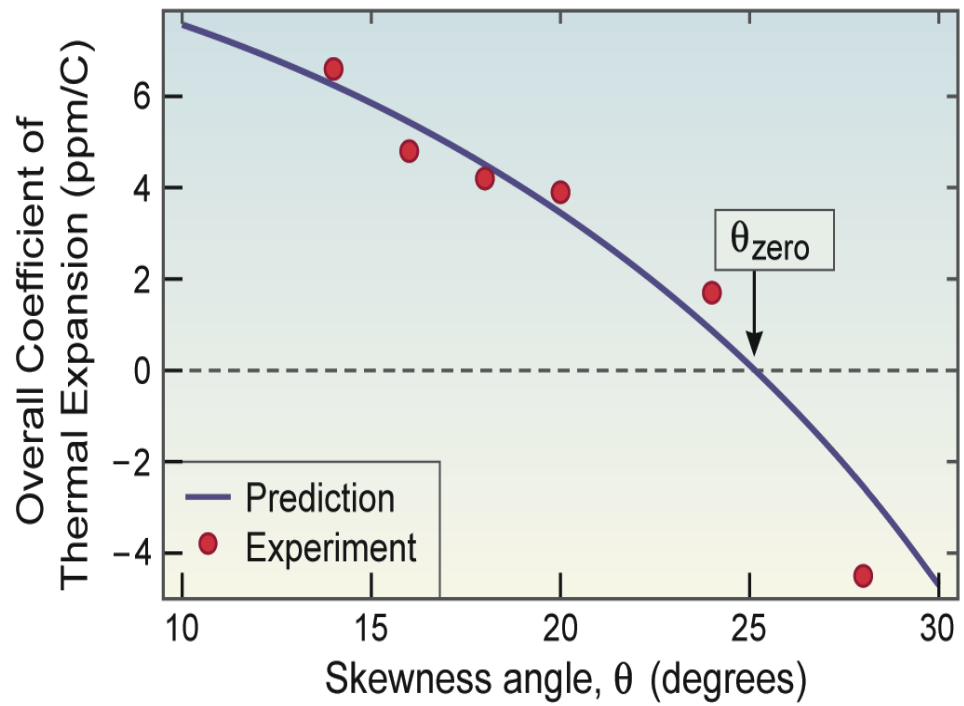
Contours of the index $\frac{\lambda}{\alpha}$

Configuration: controlling expansion



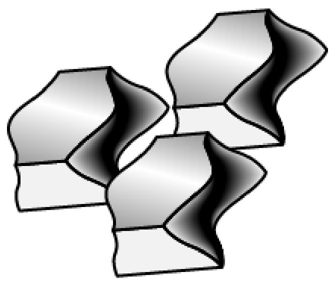




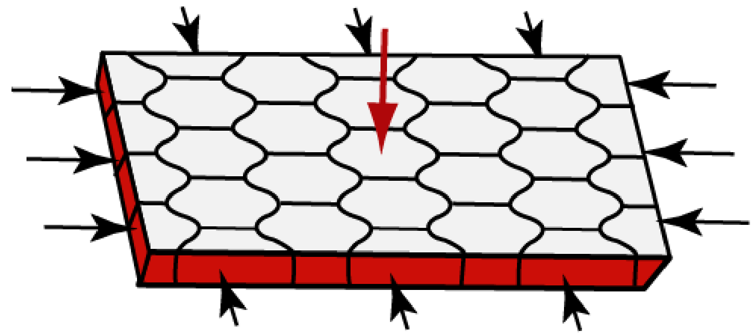


Segmented structures

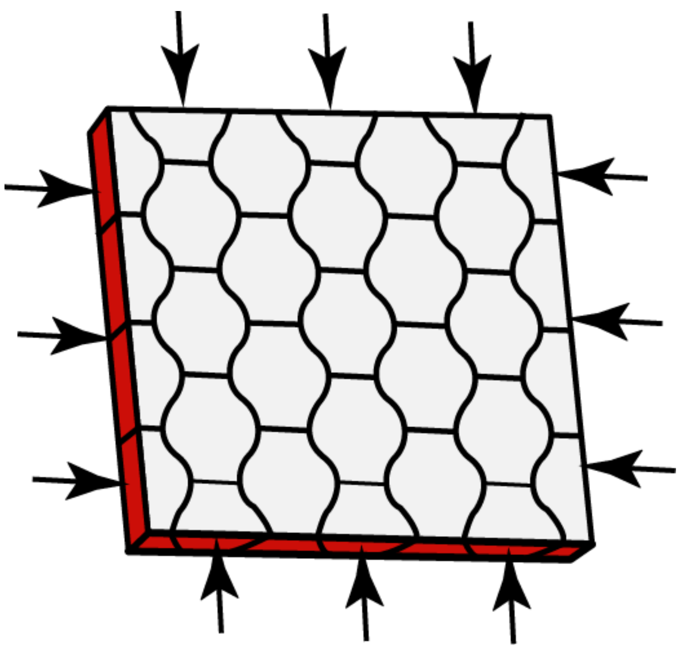
Segments

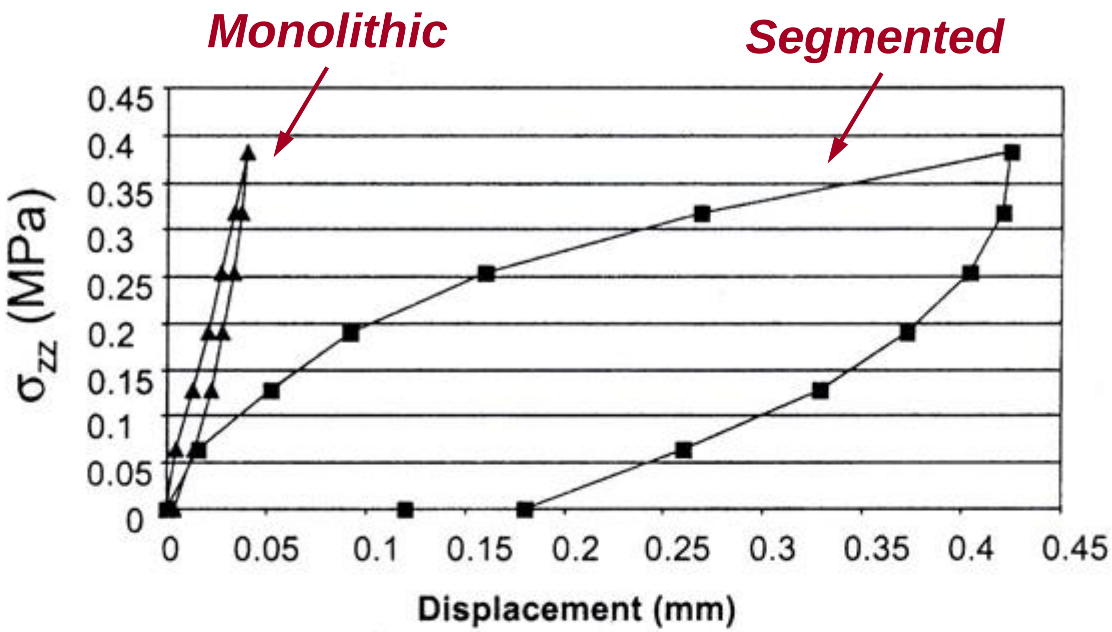


Load – deflection response

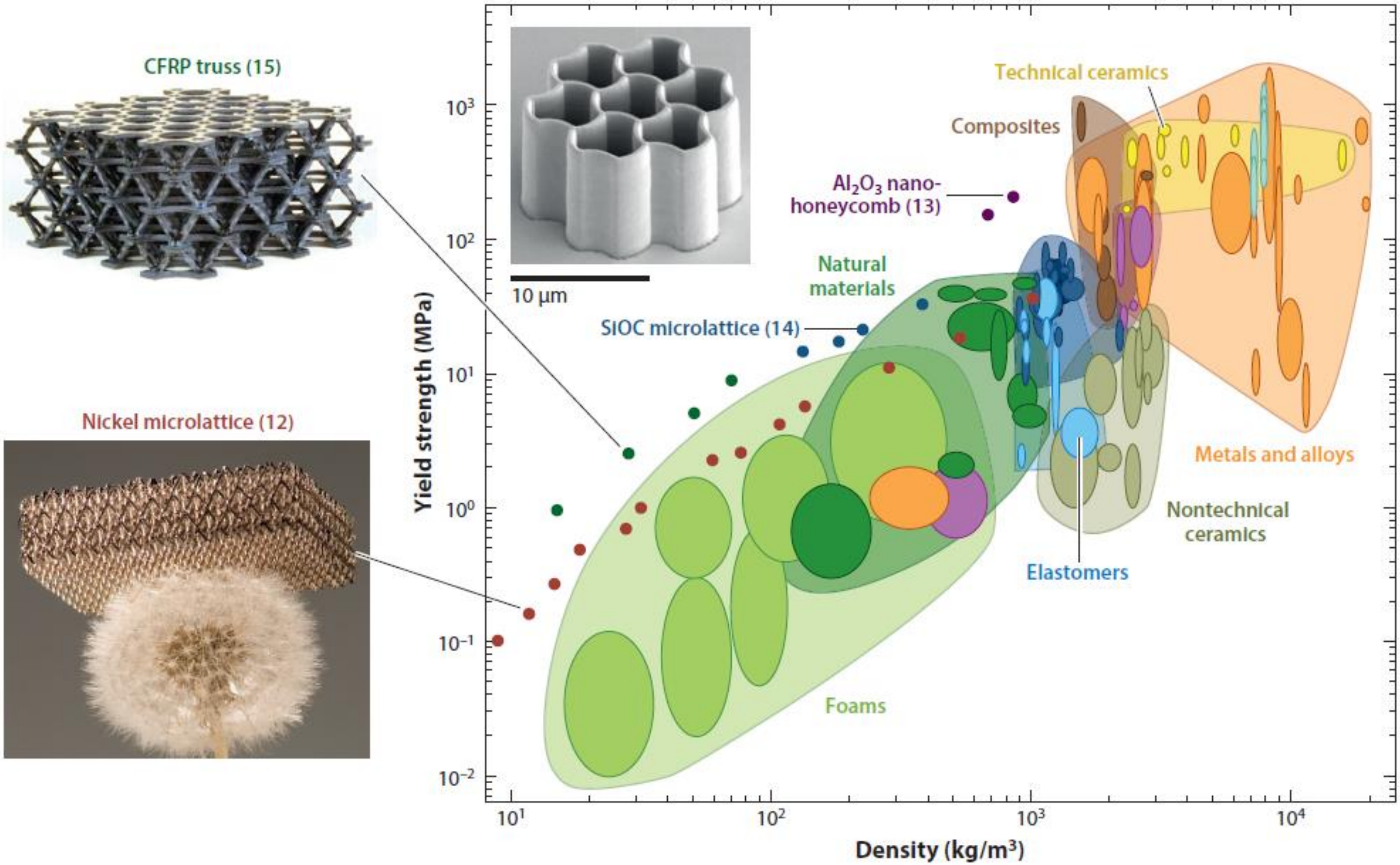


Assemble, compressive boundary conditions

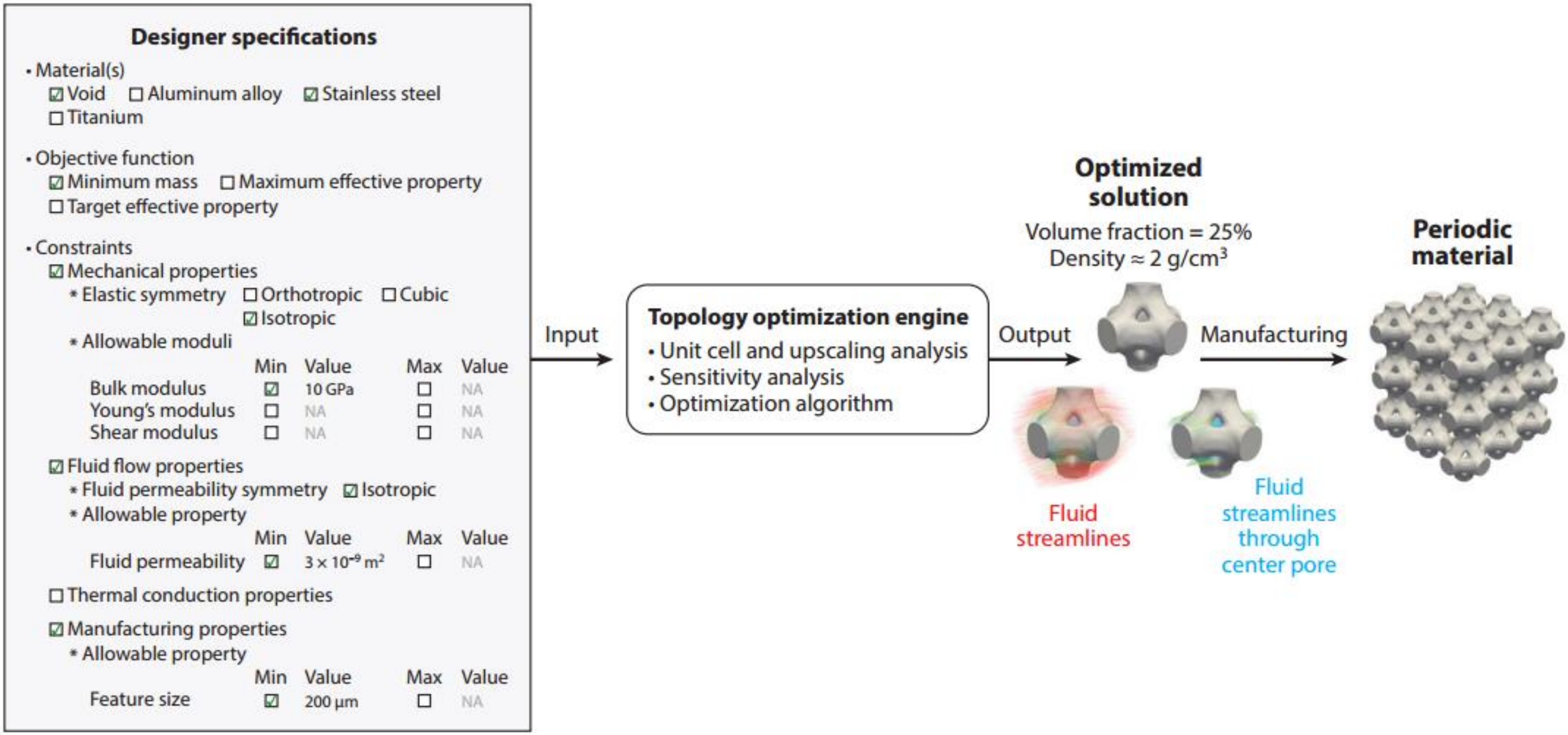




Advanced Cellular Design

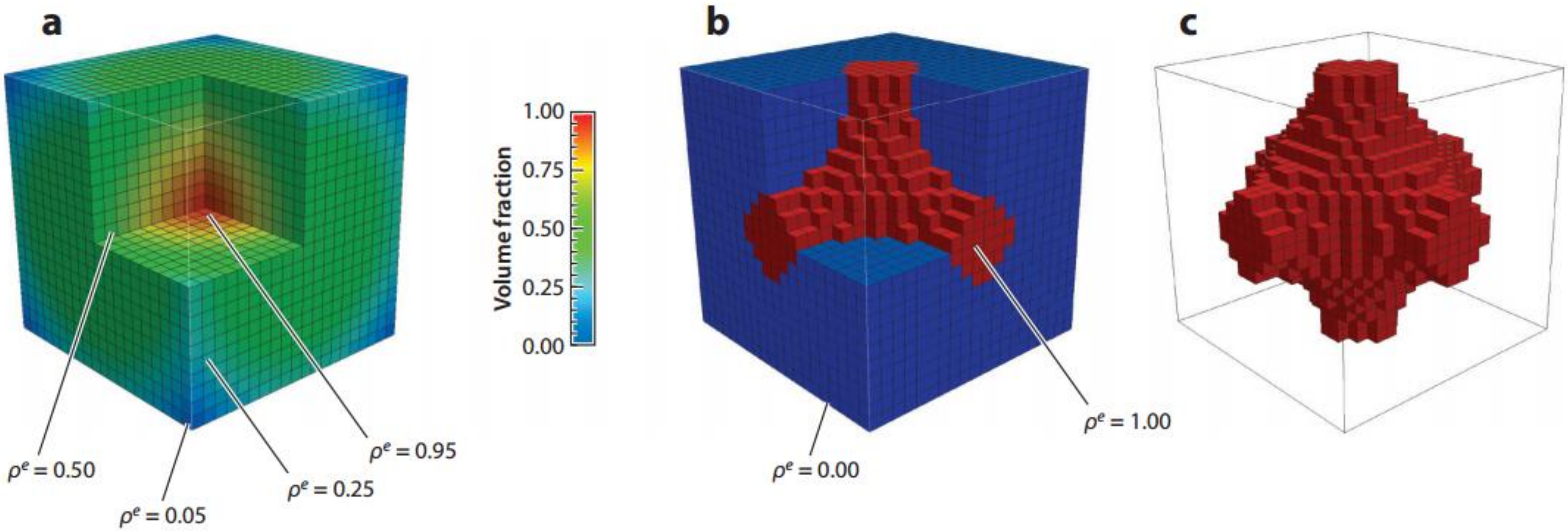


Optimizing Structural Topology



Annu. Rev. Mater. Res. 2016. 46:211–33

Finite Element Modeling for Topology Optimization



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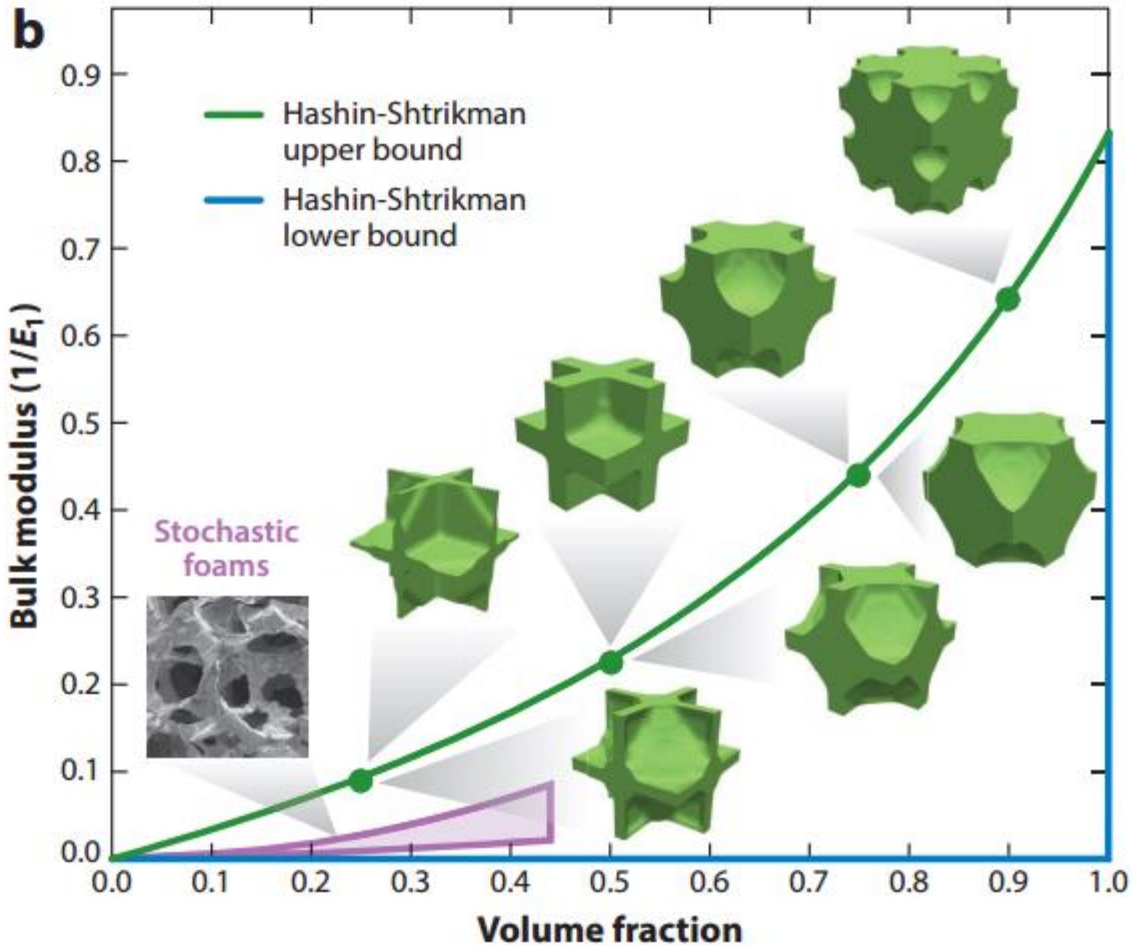
Example of Topology Optimization

Maximum Stiffness vs Minimum Density



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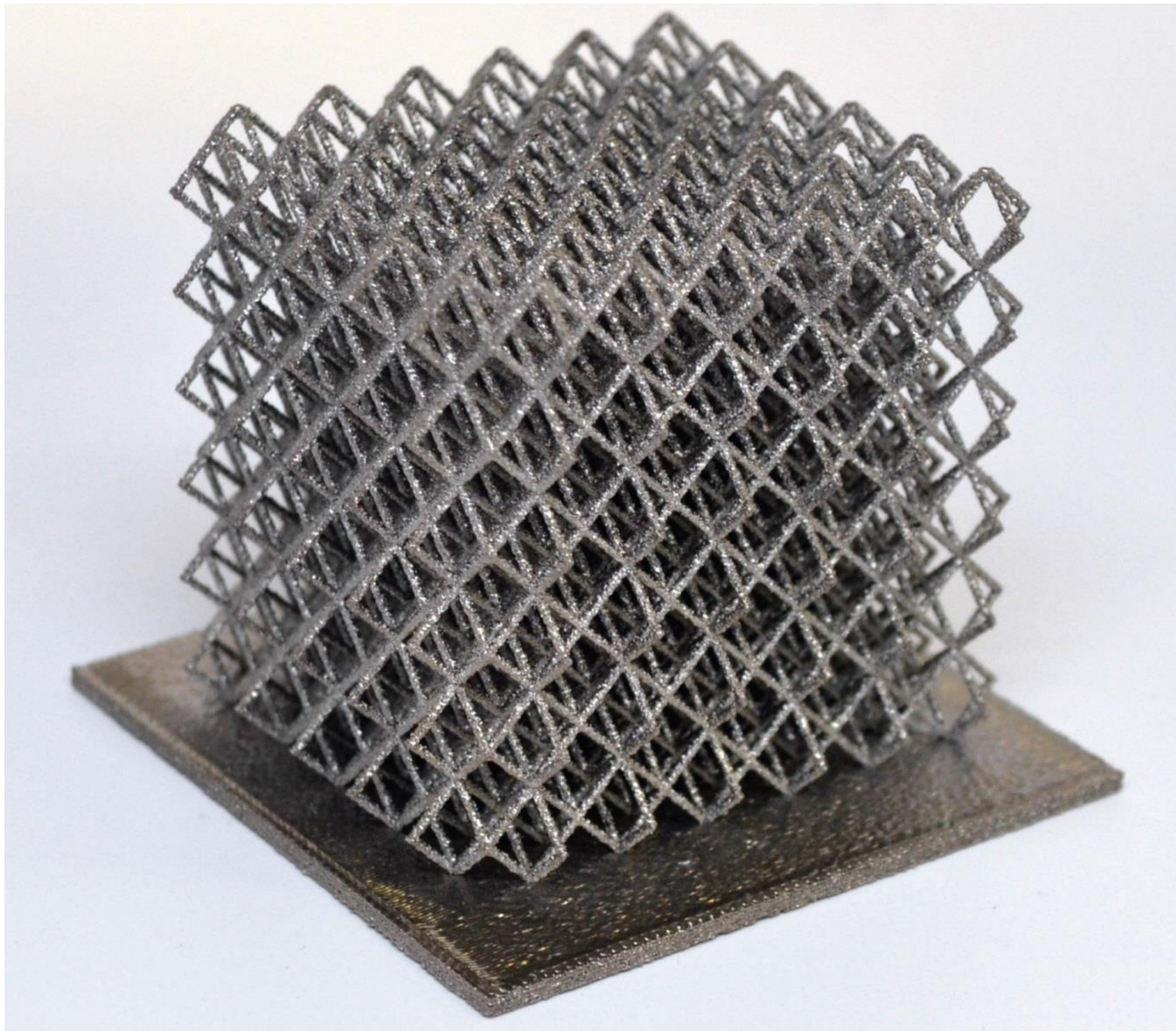
Additive Manufacturing (AM)

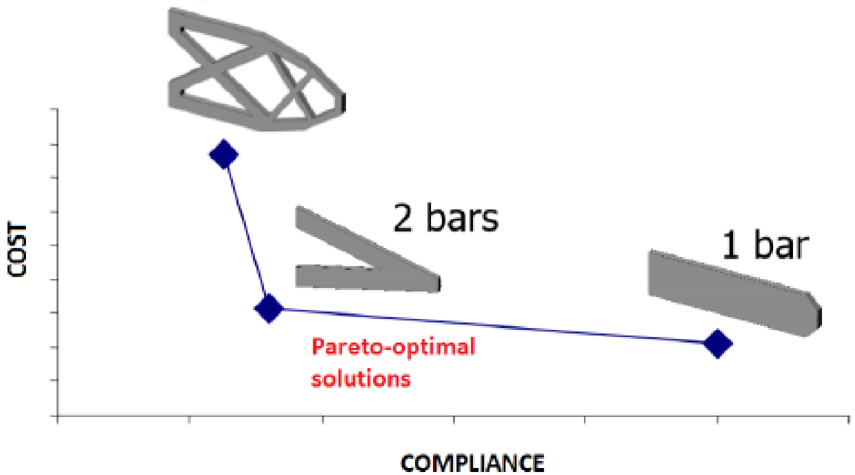
A convenient way to fabricate components with complex structural topologies



Additive Manufacturing (AM)

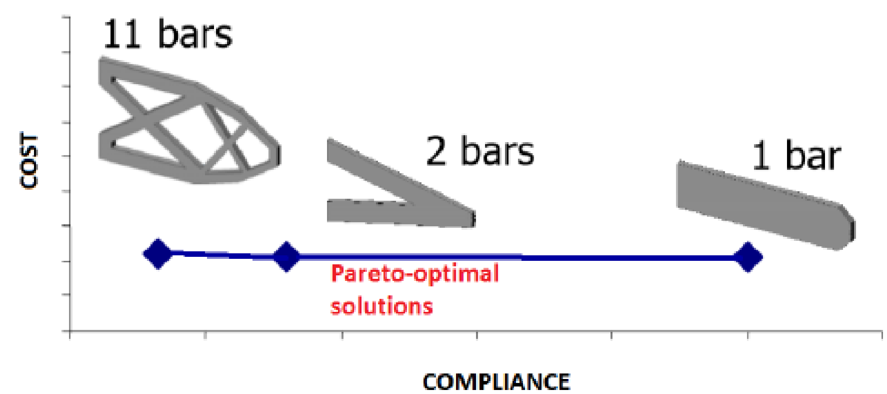
A convenient way to fabricate components with complex structural topologies

Traditional manufacturing process



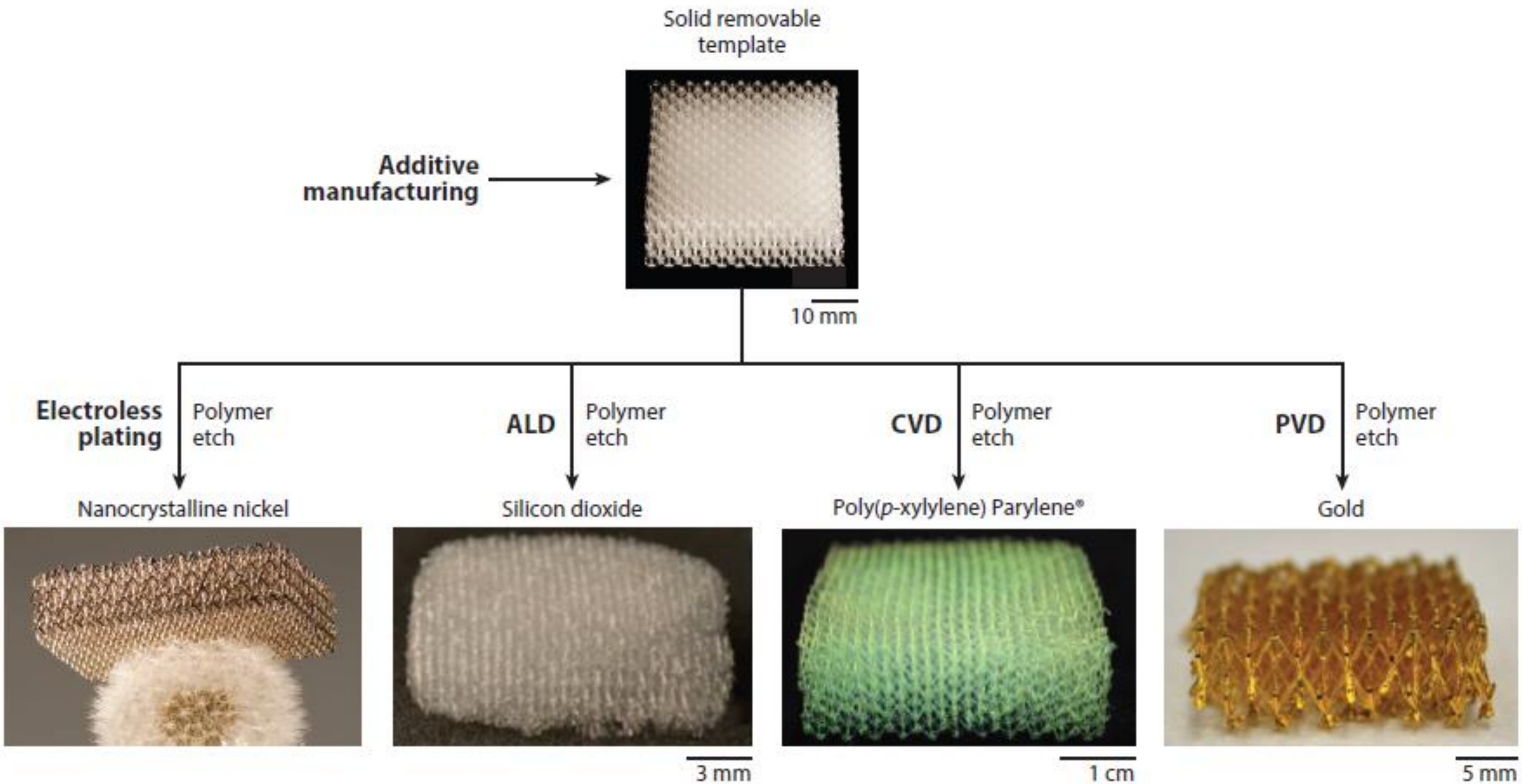
Additive Manufacturing

almost no cost increase !



Complex, Light Topologies

Using AM + Thin film deposition techniques



So what?

- **Multi-dimensional material-property space**
  - **Only part-filled** by monolithic materials
  - True of **mechanical, thermal, electrical, magnetic** and **optical** properties

- **Material development strategies**
  - **Classical** (classical alloy development, polymer chemistry….)
  - **“Nano” (sub-micron) scale** (exploiting scale-dependence of properties)
  - **Hybridization** (exploiting materials, configuration and connectivity)

- **The strategy:**
  - Map out the filled areas
  - Explore the ultimate boundaries
  - Explore ways of filling the empty space.
  - Hybrids, exploiting potential of novel configurations, have potential for this

The Hybrids Synthesizer:
a tool for design and
dissemination

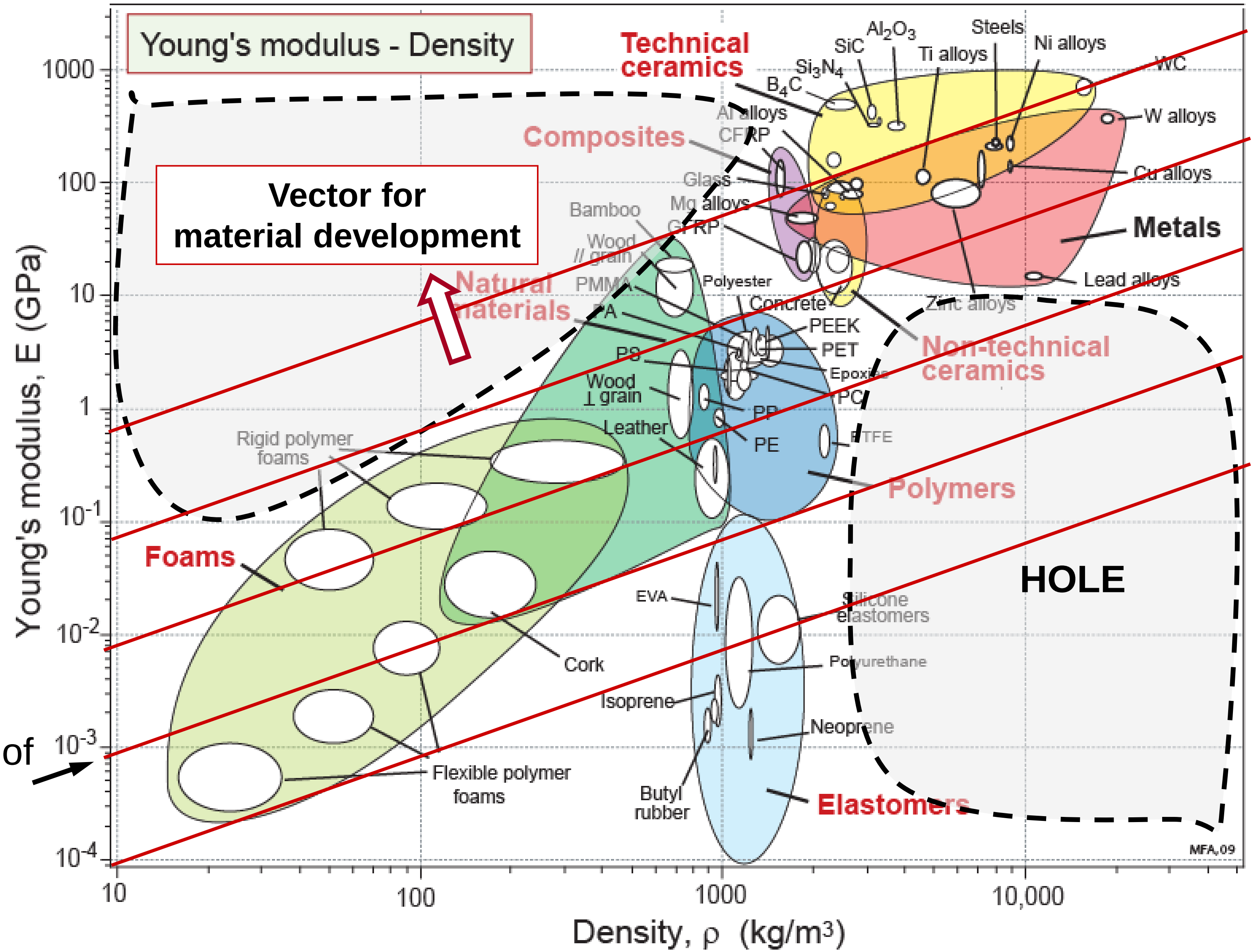
Outline

- **Holes** in material-property space
- **Hybrids materials** – expanding the filled space
- Example1 – **cellular materials**
- Example 2 – **sandwich structures**
- New developments – **Multi-layers**

Resources

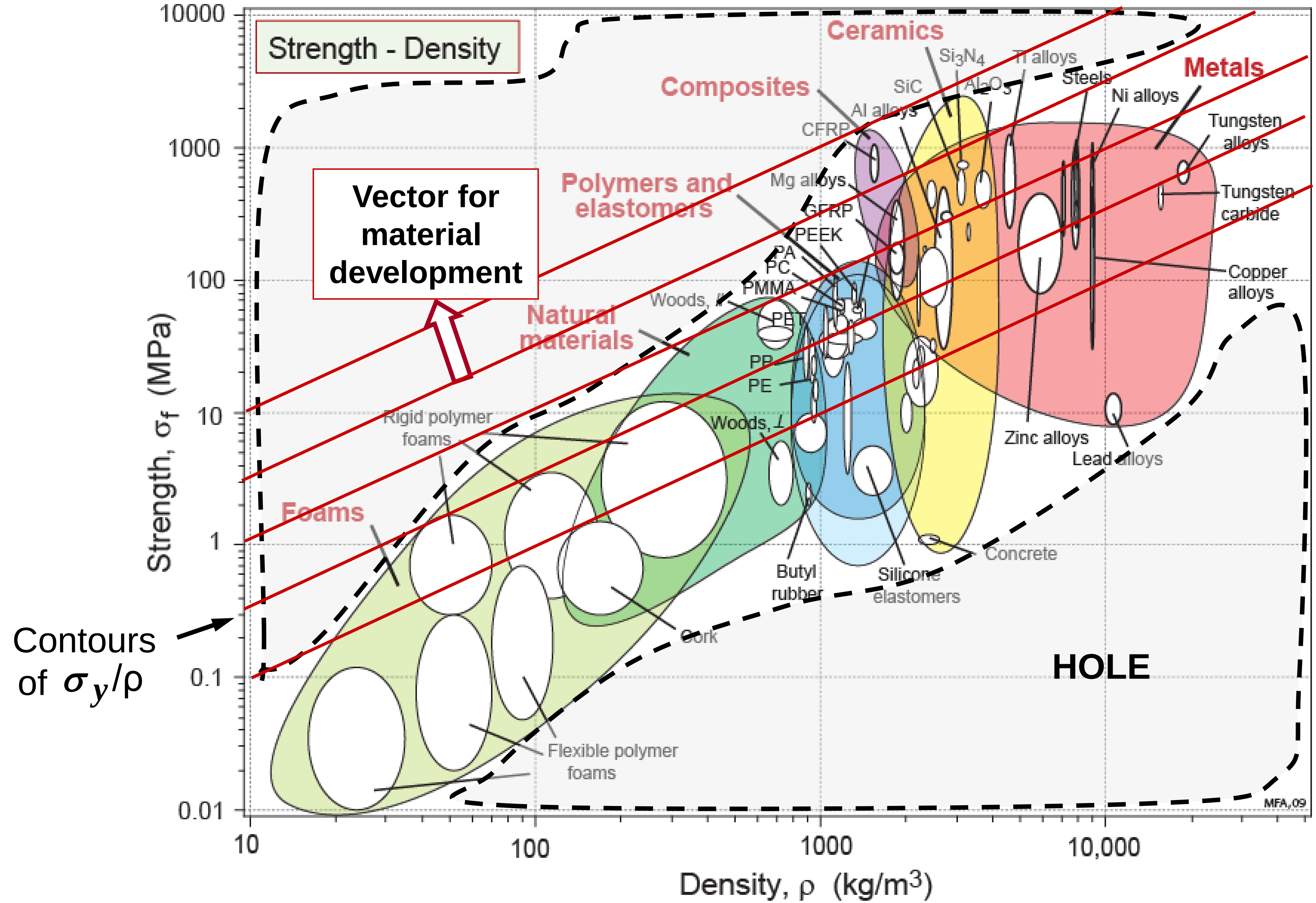
- Text: ***"Materials Selection in Mechanical Design",*** 4rd edition by M.F. Ashby, Butterworth Heinemann, Oxford, 2011, Chapters 11 - 12.
- White paper **"*The hybrid synthesizer*"** , available from CES EduPack Help file
- Software: ***CES EduPack Hybrids synthesizer tool*** (Grantadesign.com)
- "Hybrid synthesizer – Model writer's guide" for CES Selector users (Grantadesign.com)

Modulus and Density

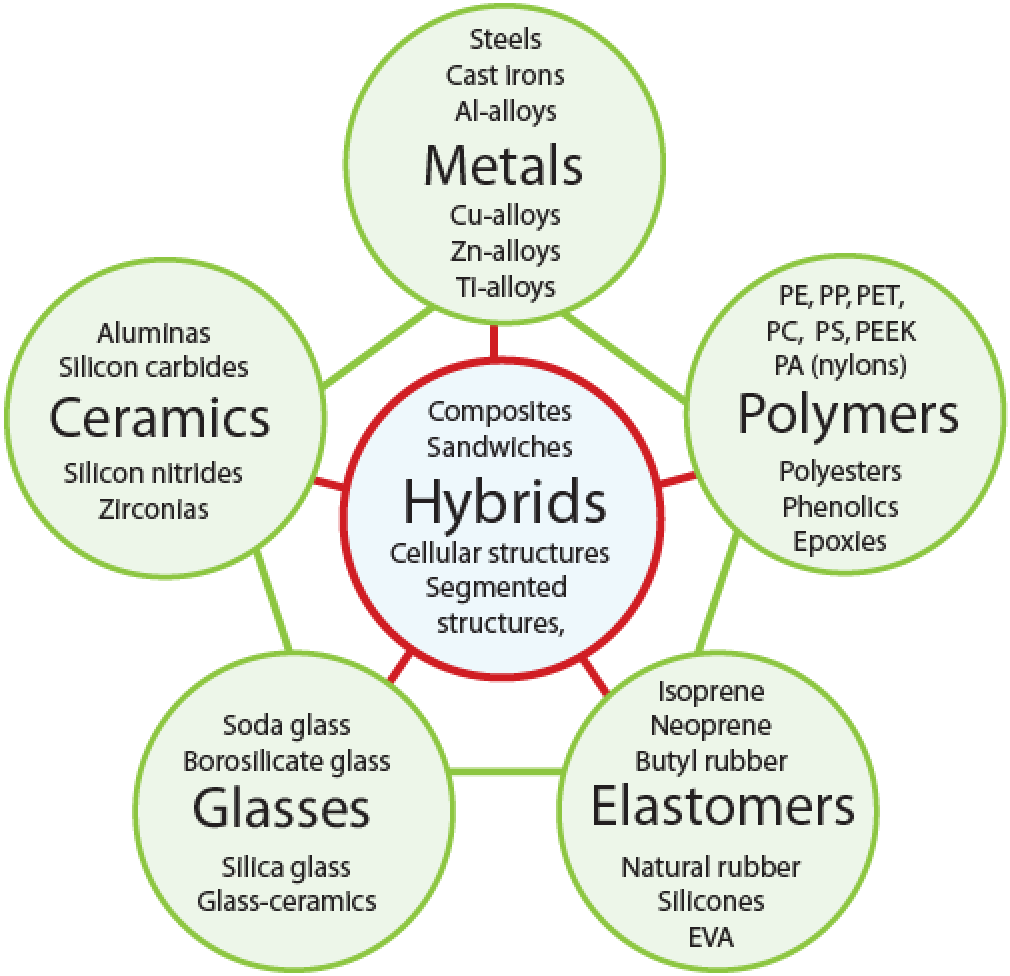


Contours of E/ρ

Strength - Density



Hybrid materials



Design variables:

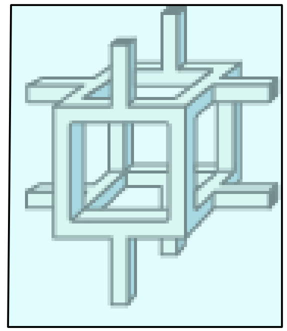
- Choice of materials
- Volume fractions
- Configuration
- Connectivity
- Scale

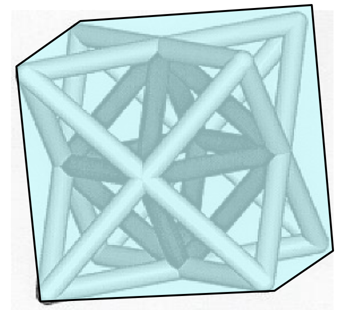
The hybrid synthesizer

- Explore configurations, with free material choice
- Explore structured-structures
- A shell: insert models for other configurations

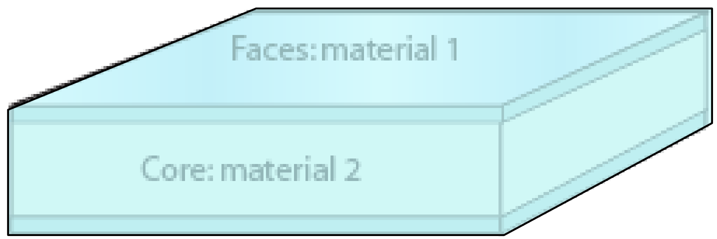
Configurations and equivalent properties

Foams and Lattice structures

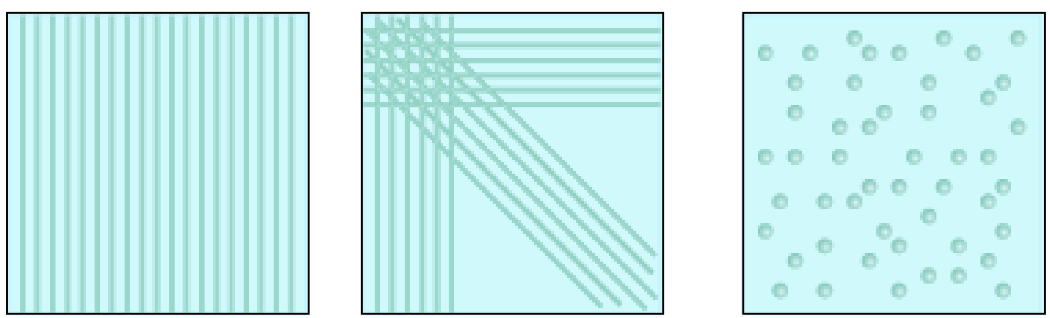




Sandwich structures



Composite structures



Equivalent properties =

Material properties of a monolithic material with the same mechanical, thermal and electrical response.

What the synthesizer does

CES retrieves models for

Physical properties

- *Equivalent density, ρ*

Mechanical properties

- *Equivalent Young's modulus E, shear modulus G, bulk modulus K, flexural modulus E_{flex}*
- *Yield strength σ_y, compressive strength σ_c, tensile strength σ_{ts}, flexural strength σ_{flex}*
- *Fracture toughness K_{ic}*

Thermal properties

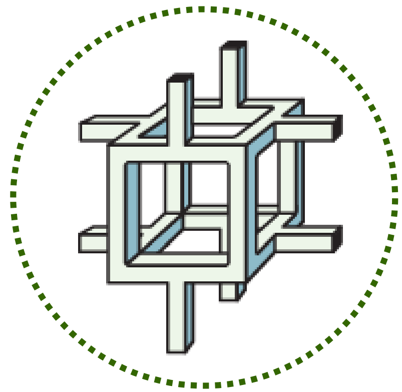
- *Thermal conductivity λ, expansion coefficient α and specific heat C_p*

Electrical properties

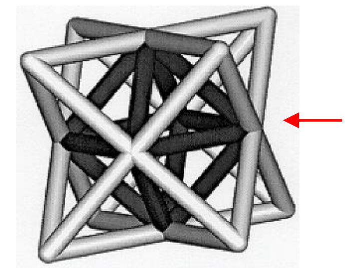
- *Resistivity ρ_e, dielectric constant ε_r and dielectric loss tangent D*

Foam and lattice models

Configurations



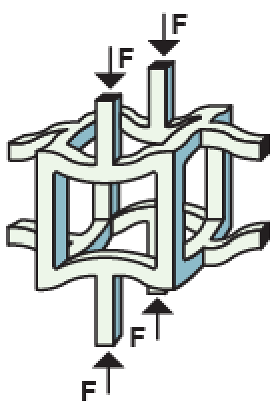
Foam cell



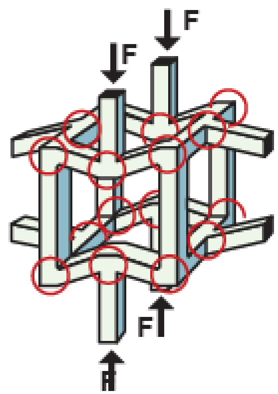
Triangulated cell faces

Lattice cell

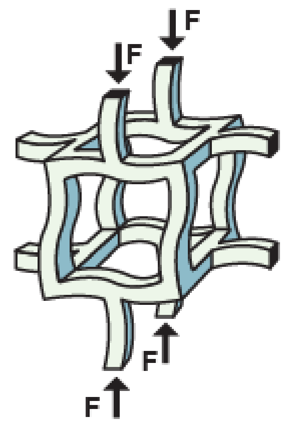
Mechanical response



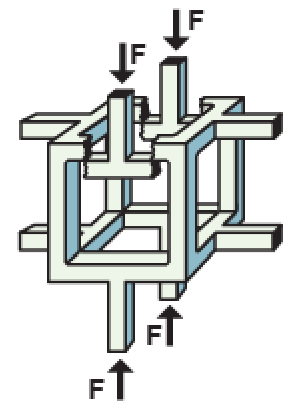
Elastic deformation



Plastic collapse



Cell edge buckling



Cell edge fracture

Plus **thermal and electrical properties**

Typical record

Al 6061 Foam (0.1)

General properties

Density	110			kg/m^3
Relative density	0.037			

Mechanical properties

Young's modulus	1.3	-	1.4	GPa
Flexural modulus	1.3	-	1.4	GPa
Shear modulus	0.5	-	0.51	GPa
Bulk modulus	1.3	-	1.4	GPa
Poisson's ratio	0.33			
Yield strength (elastic limit)	4.7	-	5.1	MPa
Tensile strength	6.3	-	7	MPa
Compressive strength	4.7	-	5.1	MPa
Flexural strength	6.3	-	7	MPa
Fracture toughness	0.88	-	1.2	MPa.m^0.5

Thermal properties

Thermal conductivity	2.1	-	2.2	W/m.°C
Specific heat capacity	920	-	940	J/kg.°C
Thermal expansion coefficient	15			µstrain/°C

Electrical properties

Electrical resistivity	230			µohm.cm

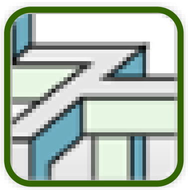
Notes

Source Materials: Bulk material = Al-20%SiC(p), powder product

The Hybrid-material synthesizer

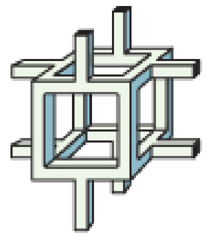
Add record
Eco Audit
Synthesizer

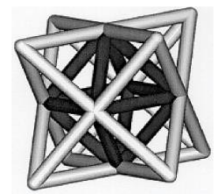
Choice of configuration



Cellular structures

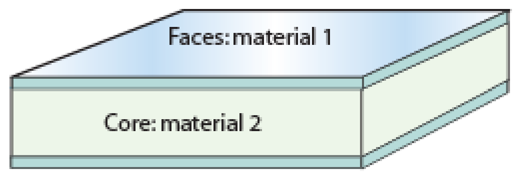
- *Foams*
- *Triangulated lattices*





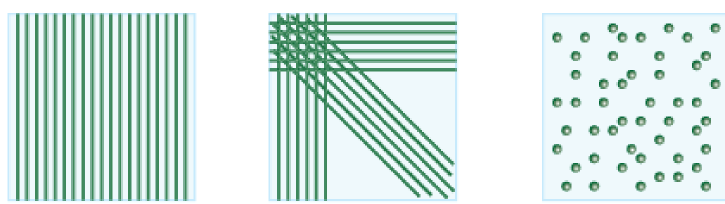
Sandwich structures

- *Symmetric sandwiches*



Composites

- *Unidirectional*
- *Quasi-isotropic*
- *Particulate*



Select:

- Configuration
- Materials
- Control parameters
- Click “Create”

Exploring metal foams - inputs

Foam

Source material

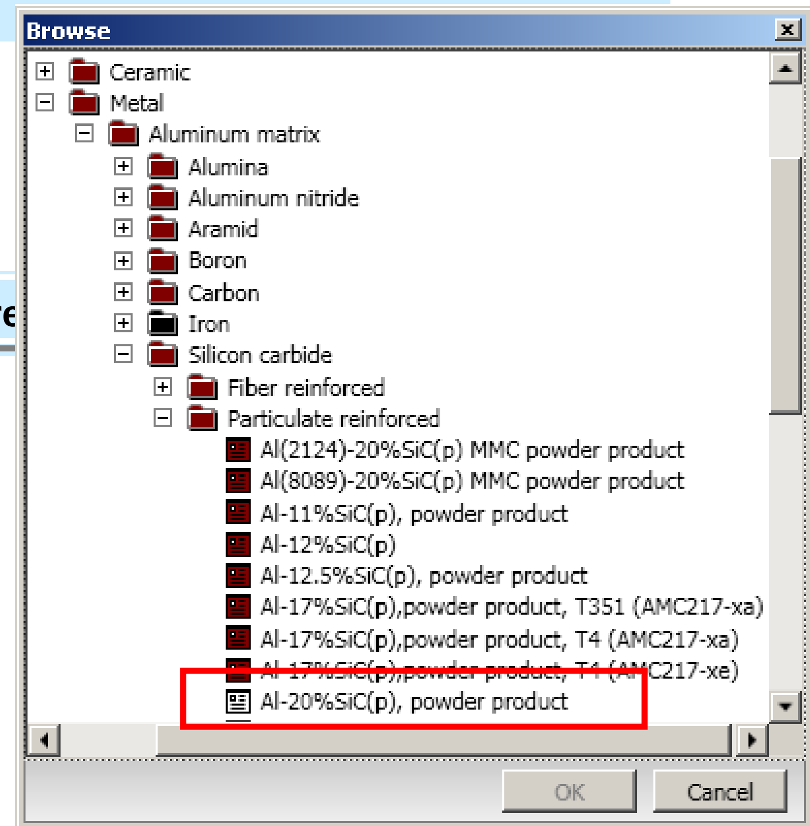
Bulk material Aluminum 20% SiC (p) **Browse**

Model variables

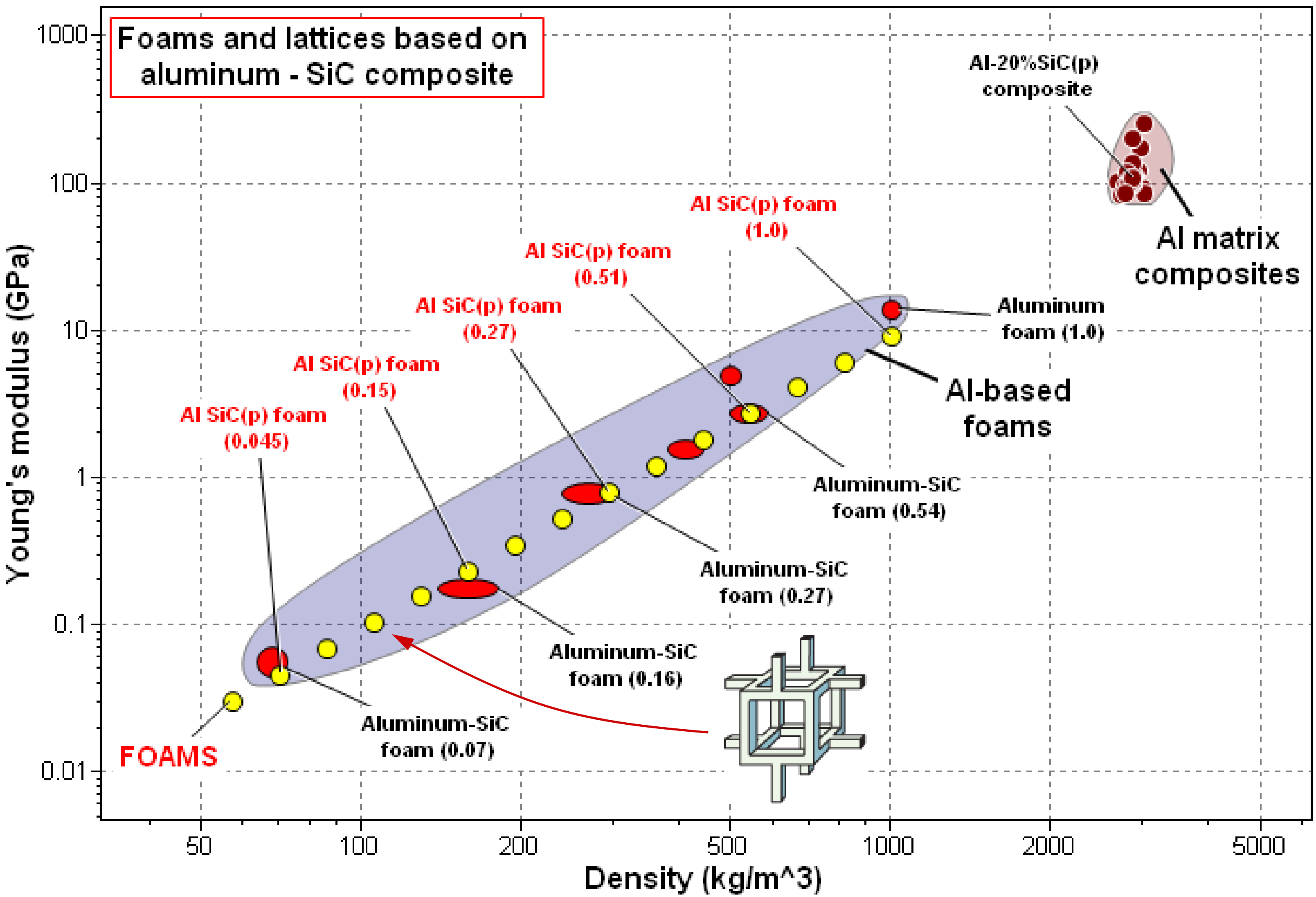
Number of densities 15

Relative density range 2 - 35 %

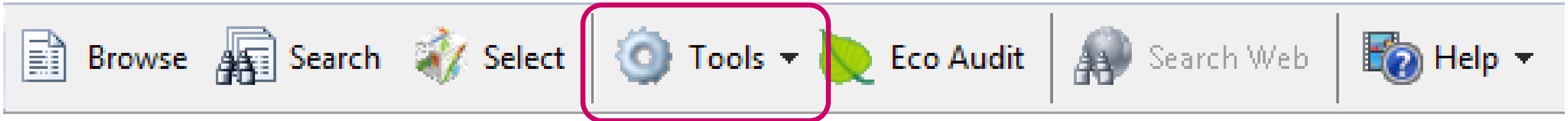
Model



Aluminum SiC composite foams

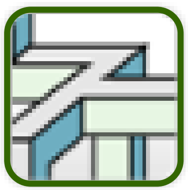


The Hybrid-material synthesizer



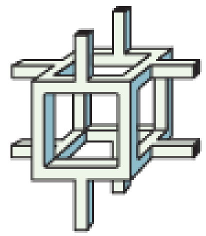
Add record
Eco Audit
Synthesizer

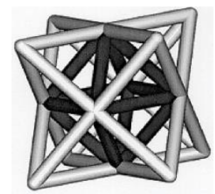
Choice of configuration



Cellular structures

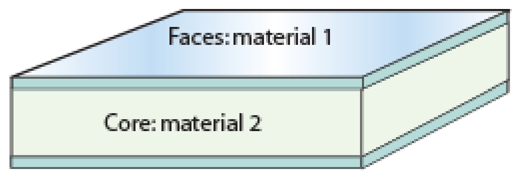
- ***Foams***
- ***Triangulated lattices***





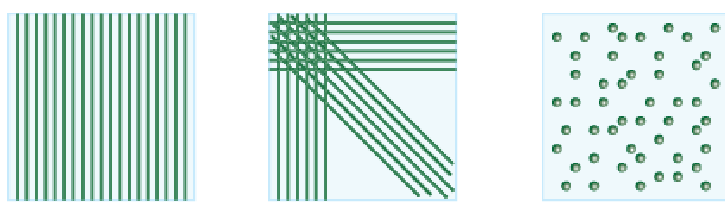
Sandwich structures

- ***Symmetric sandwiches***



Composites

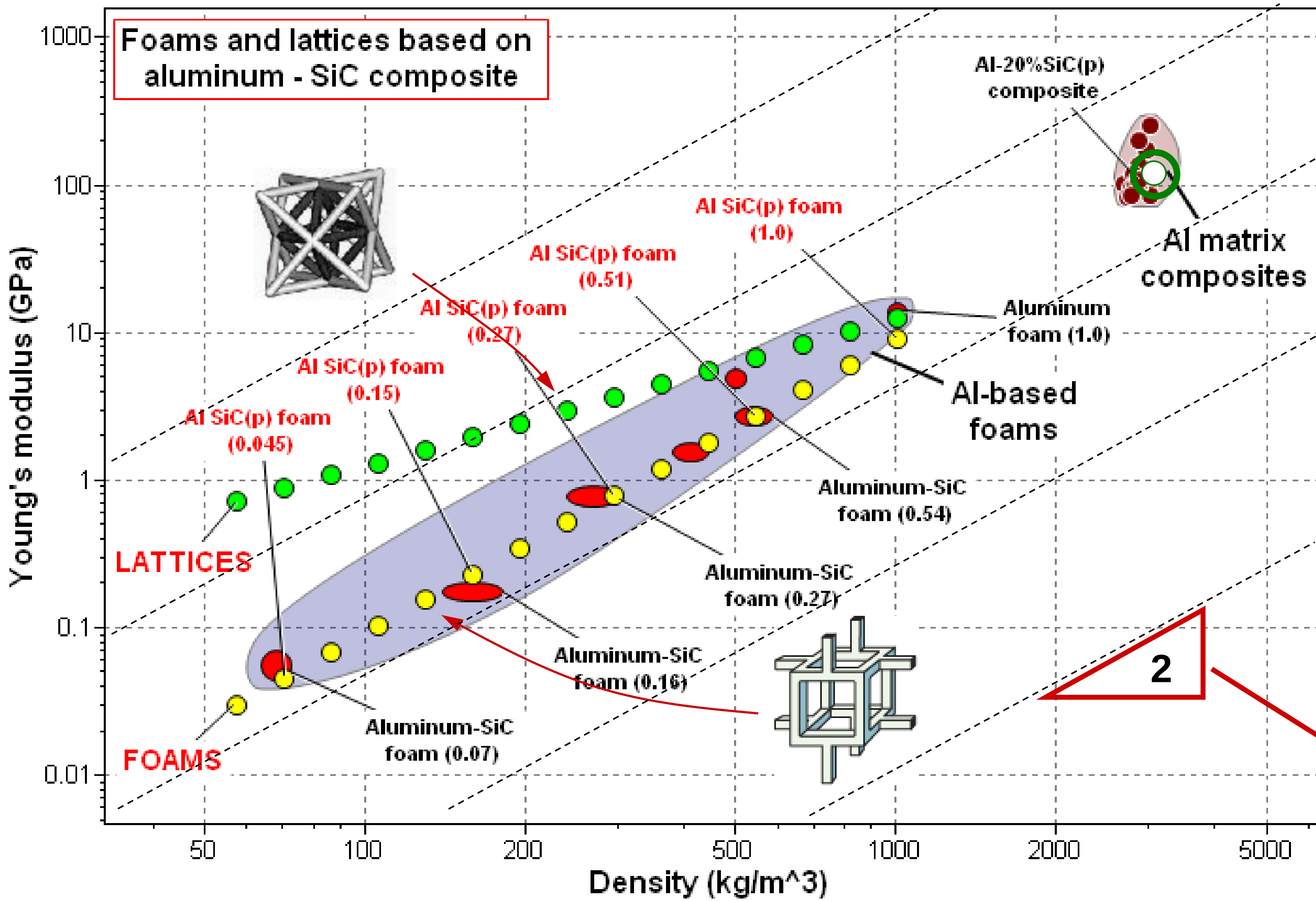
- ***Unidirectional***
- ***Quasi-isotropic***
- ***Particulate***



Select:

- **Configuration**
- **Materials**
- **Control parameters**
- **Click "Create"**

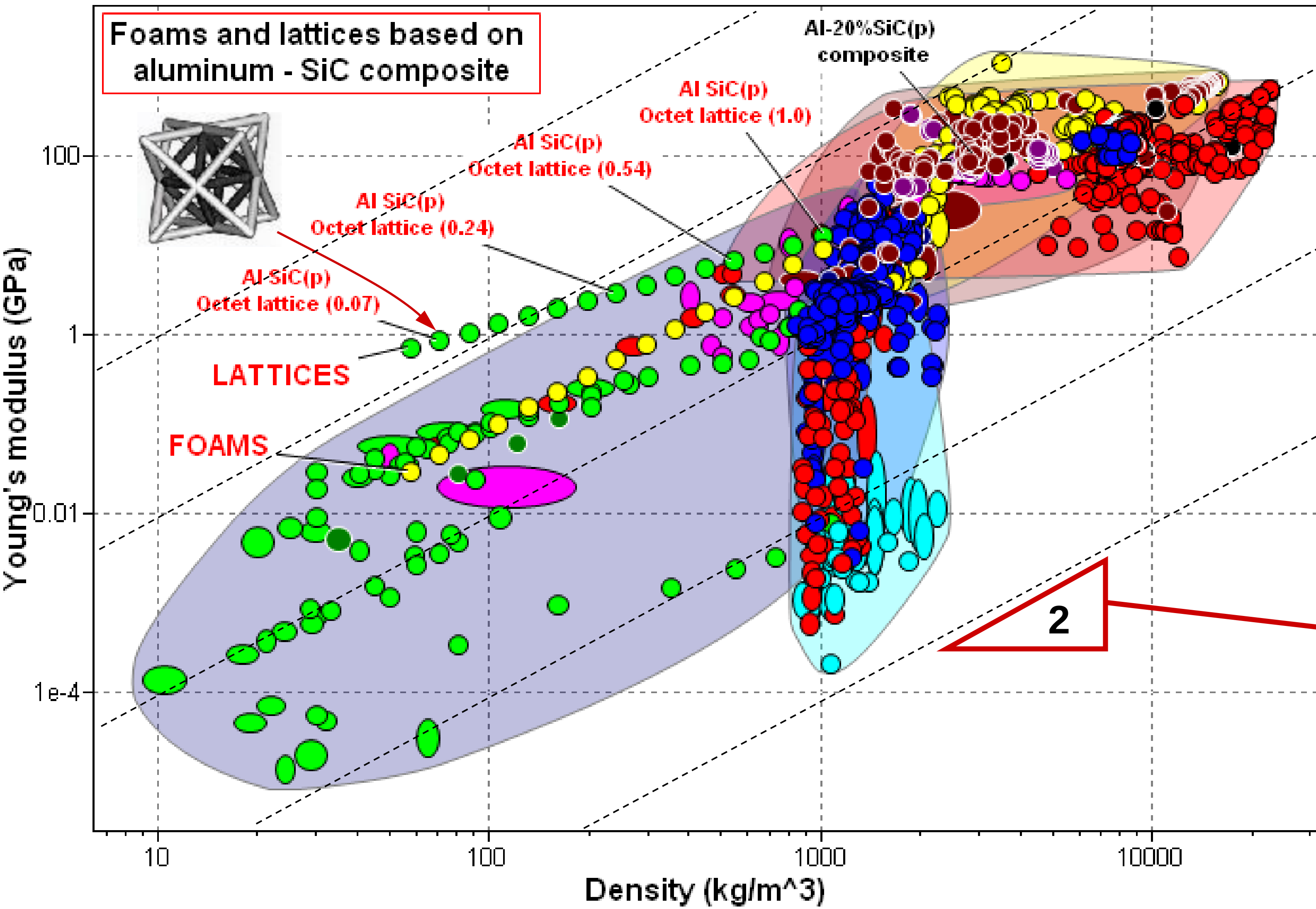
Aluminum SiC composite foams



Criterion of excellence

$E^{1/2}/\rho$

Lattices expand material property space



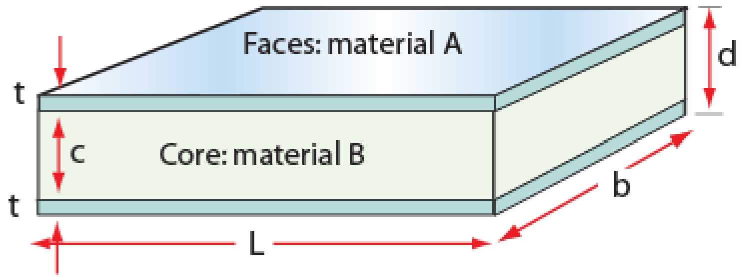
2800 materials

Criterion of excellence

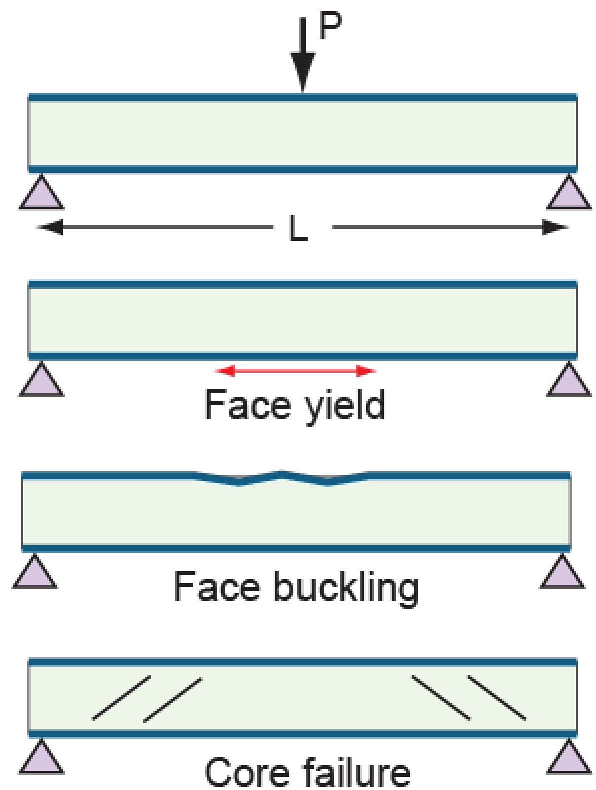
$E^{1/2}/\rho$

Sandwich panel models

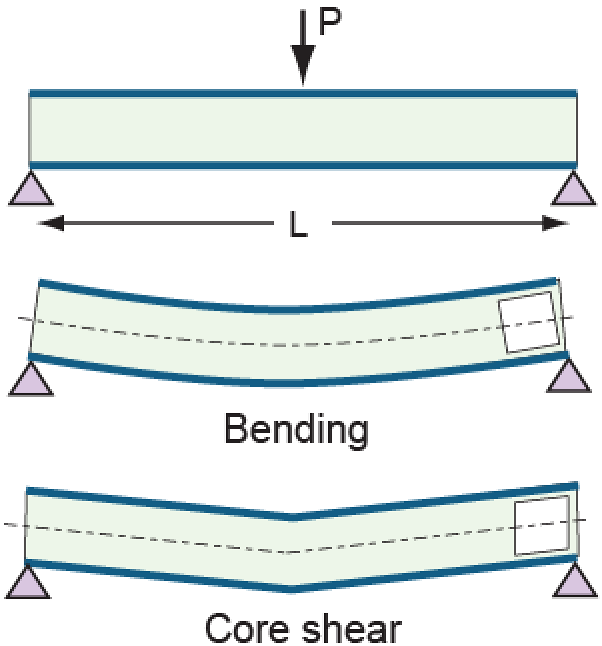
Configuration



Collapse response



Elastic response



Plus **thermal** and **electrical properties**

Sandwich panels - inputs

Sandwich panel

Source material

Face sheet | Aluminum 6061 T4 | **Browse**

Core | PVC cros

Model variables

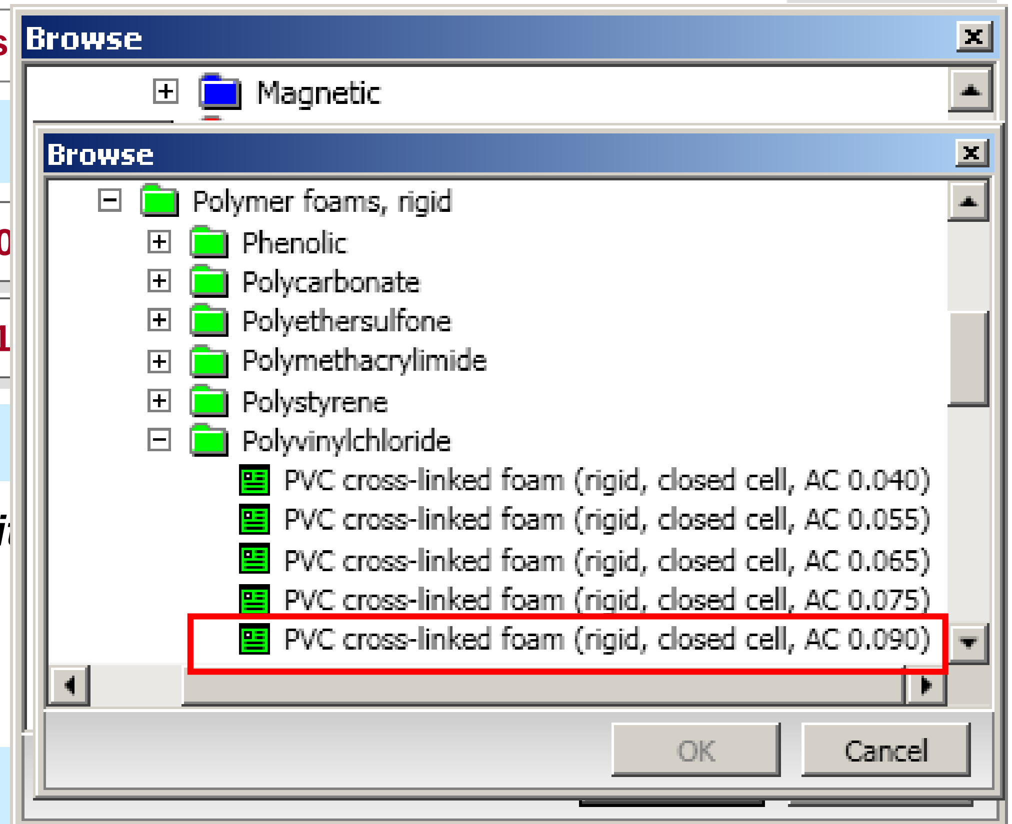
Face-sheet thickness 0

Core thickness - 1

Model parameters

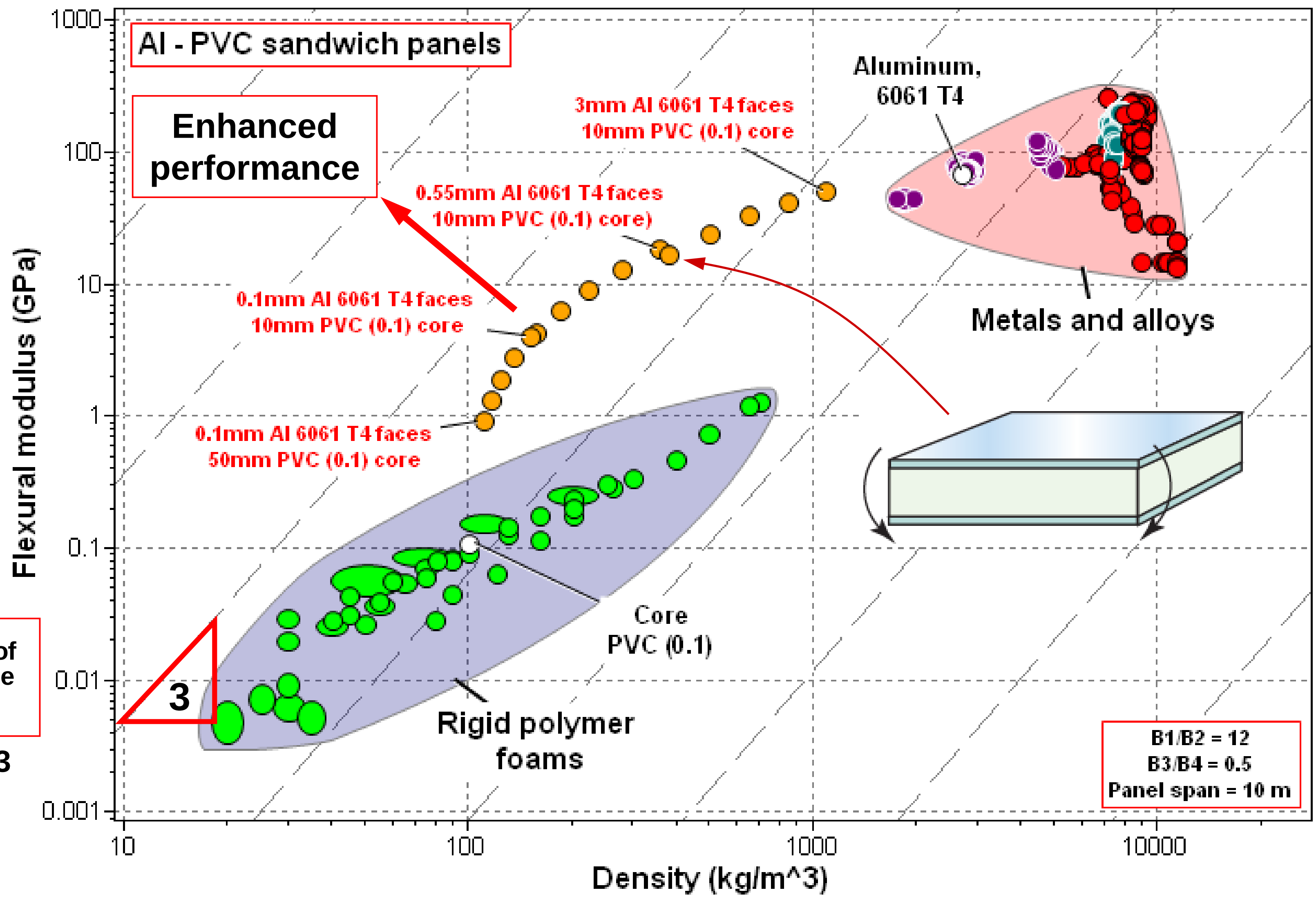
Support and load condi

Span 3 ***m***



Model

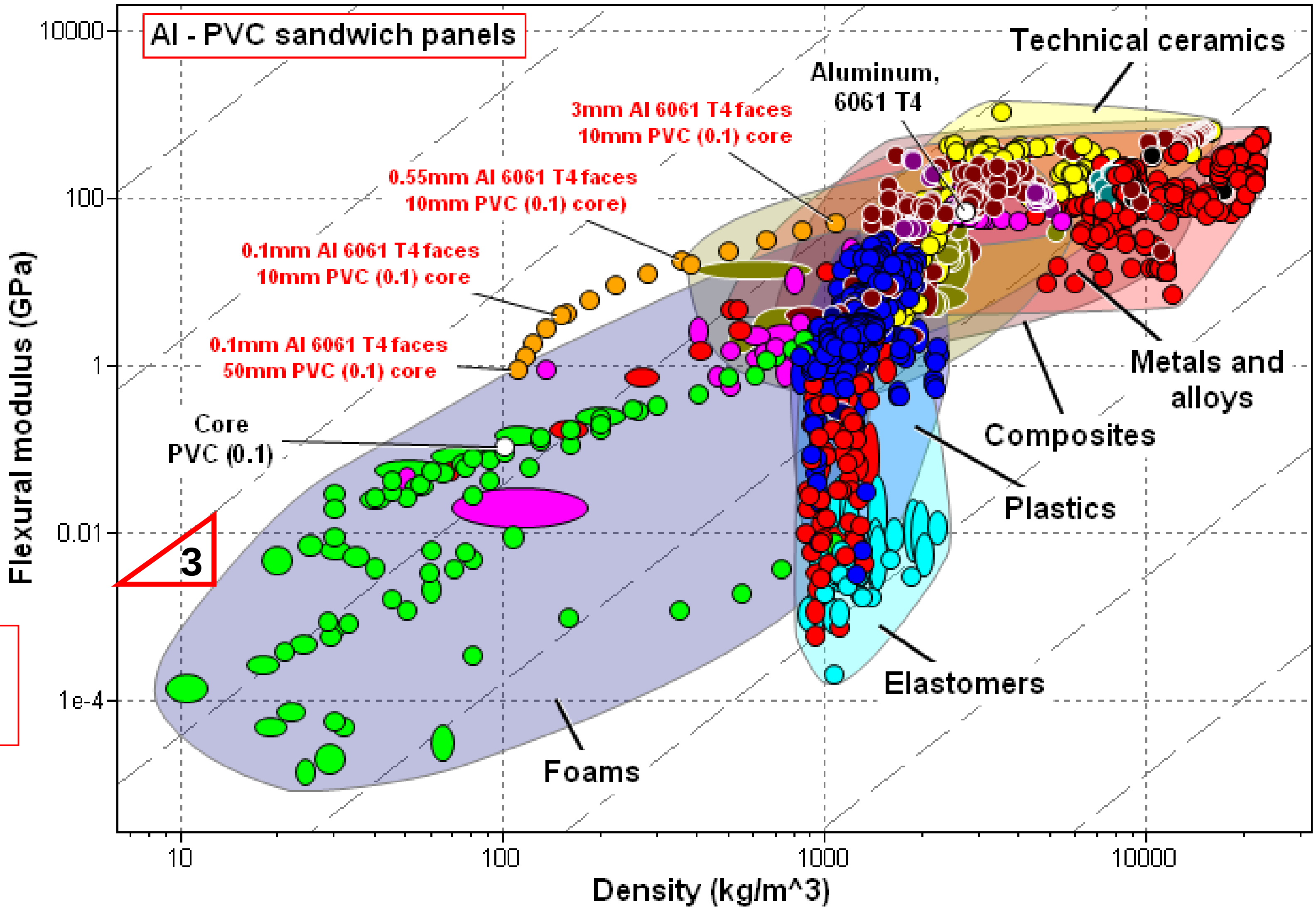
Stiff sandwich panels



Criterion of excellence $E^{1/3}/\rho$

Slope 3

Sandwiches expand material property space



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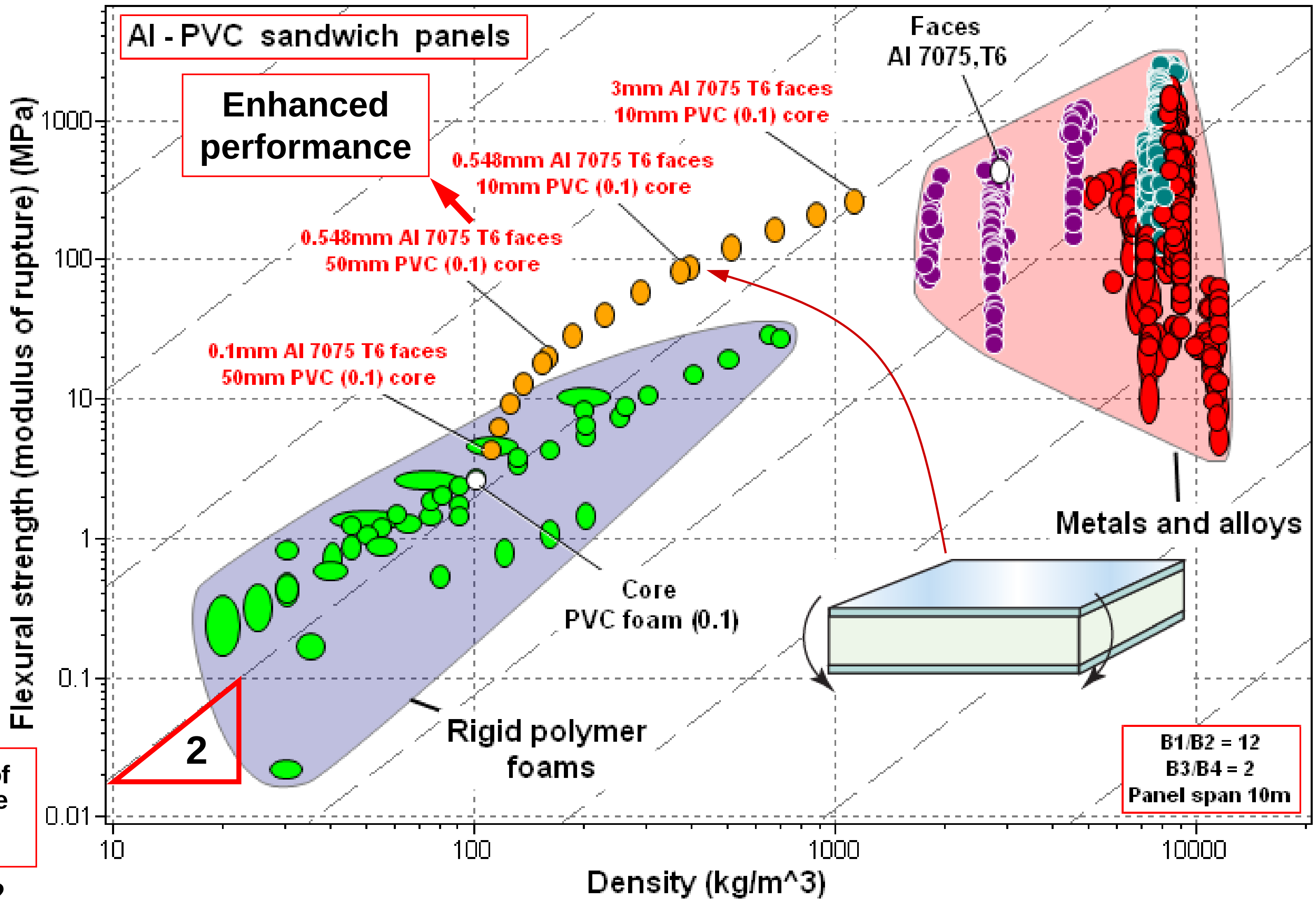
Criterion of excellence $E^{1/3}/\rho$

Slope 3

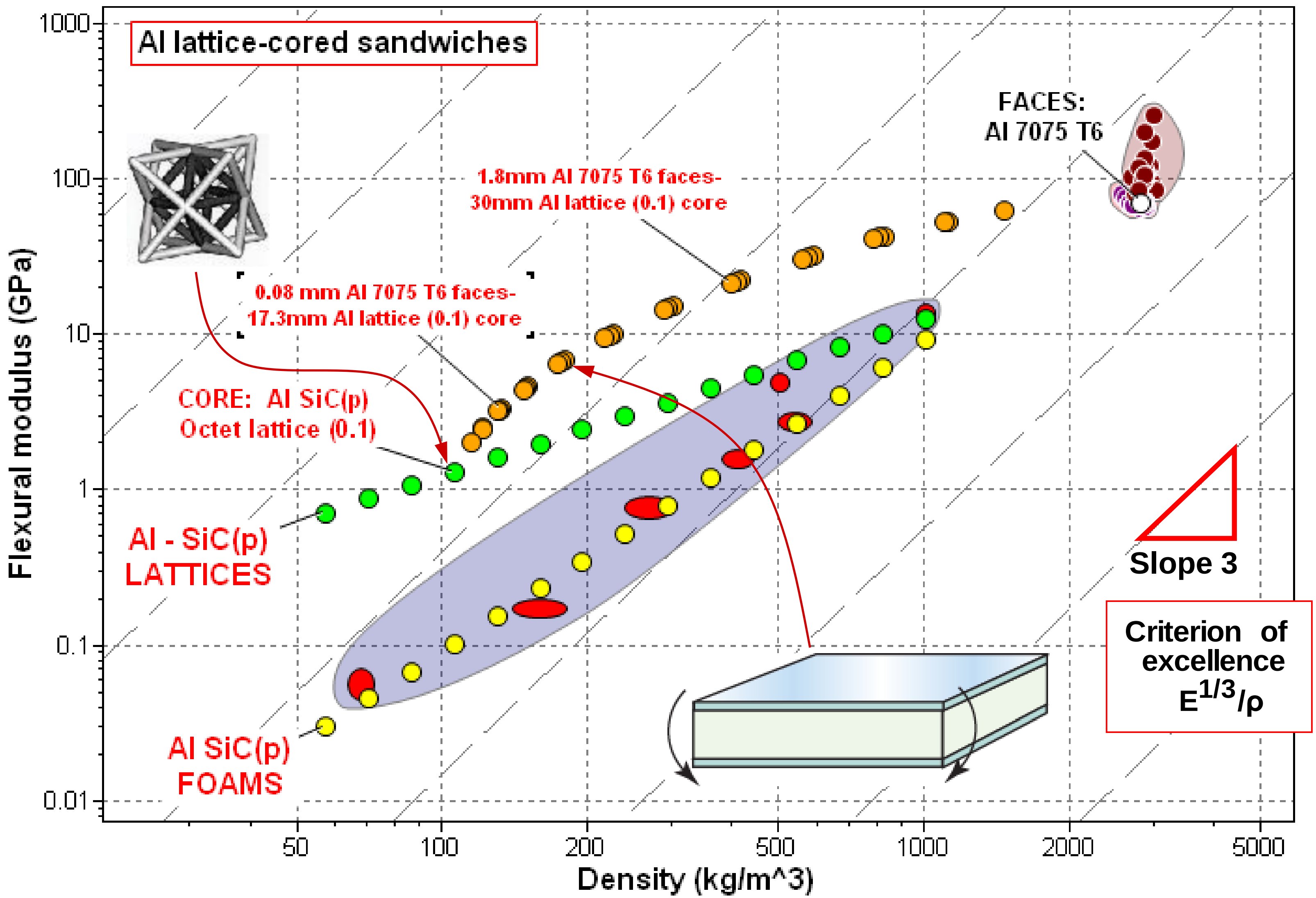
Strong sandwich panels



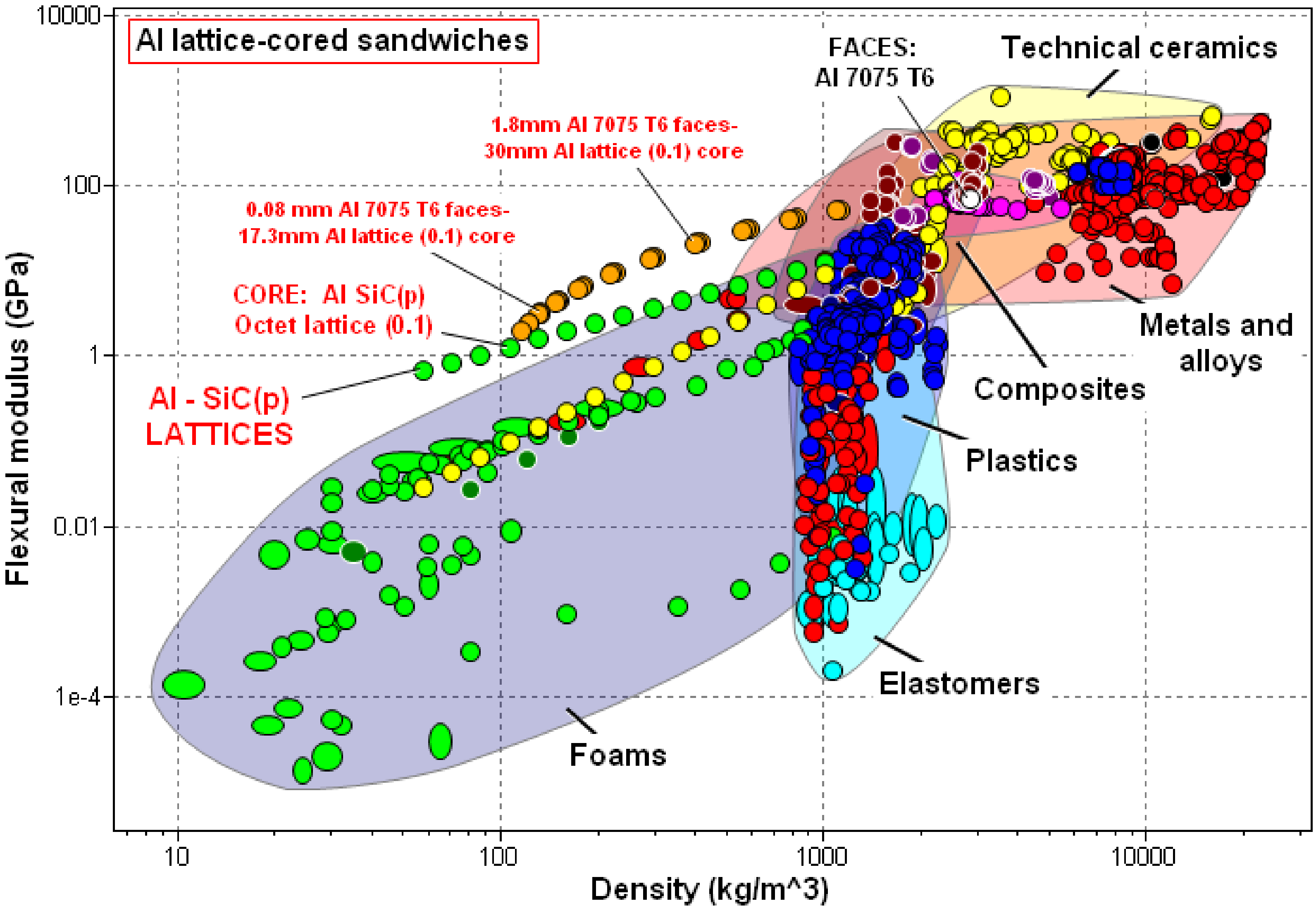
Criterion of excellence $\sigma_{flex}^{1/2}/\rho$

Slope 2

Lattice cored sandwich panels



Structures expand material property space



2800 materials

So what?

The synthesizer allows

- Display of potential properties of novel material combinations
- Testing and deploying of models for “architectured” materials
- Direct comparison with the standard materials of engineering
- Exploration of structured-structures
- This is a first generation tool – models very simple

  Welcome ideas for refining it.

Author

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University of Cambridge, Granta Design Ltd.

www.grantadesign.com

www.eng.cam.ac.uk

Accuracy

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The website also contains other resources contributed by faculty at the 800+ universities and colleges worldwide using Granta's CES EduPack.

The teaching resource website contains both resources that require the use of CES EduPack and those that don't.

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