How Do You Like Your Materials with Multi-functionality and Reconfigurability or Just Lightweight?

Materials by Design: Additive Manufacturing of 3D-Architected Materials

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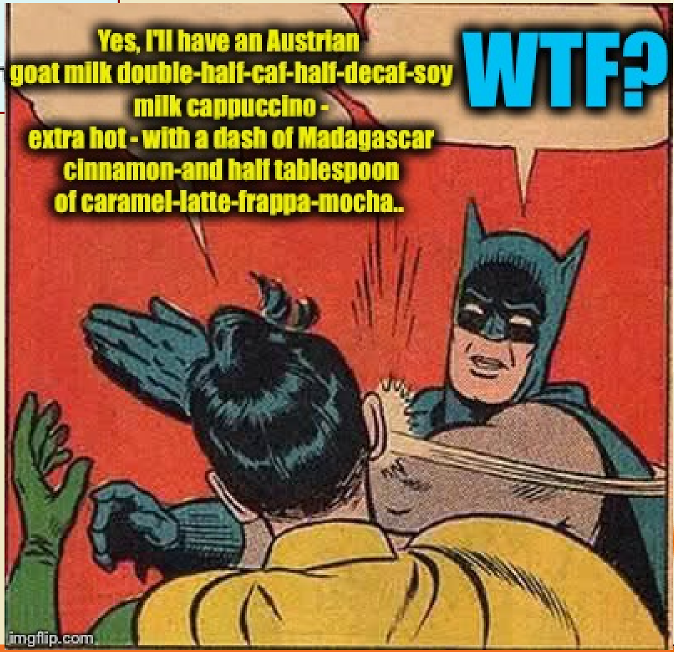
So what is this "by Design" concept?

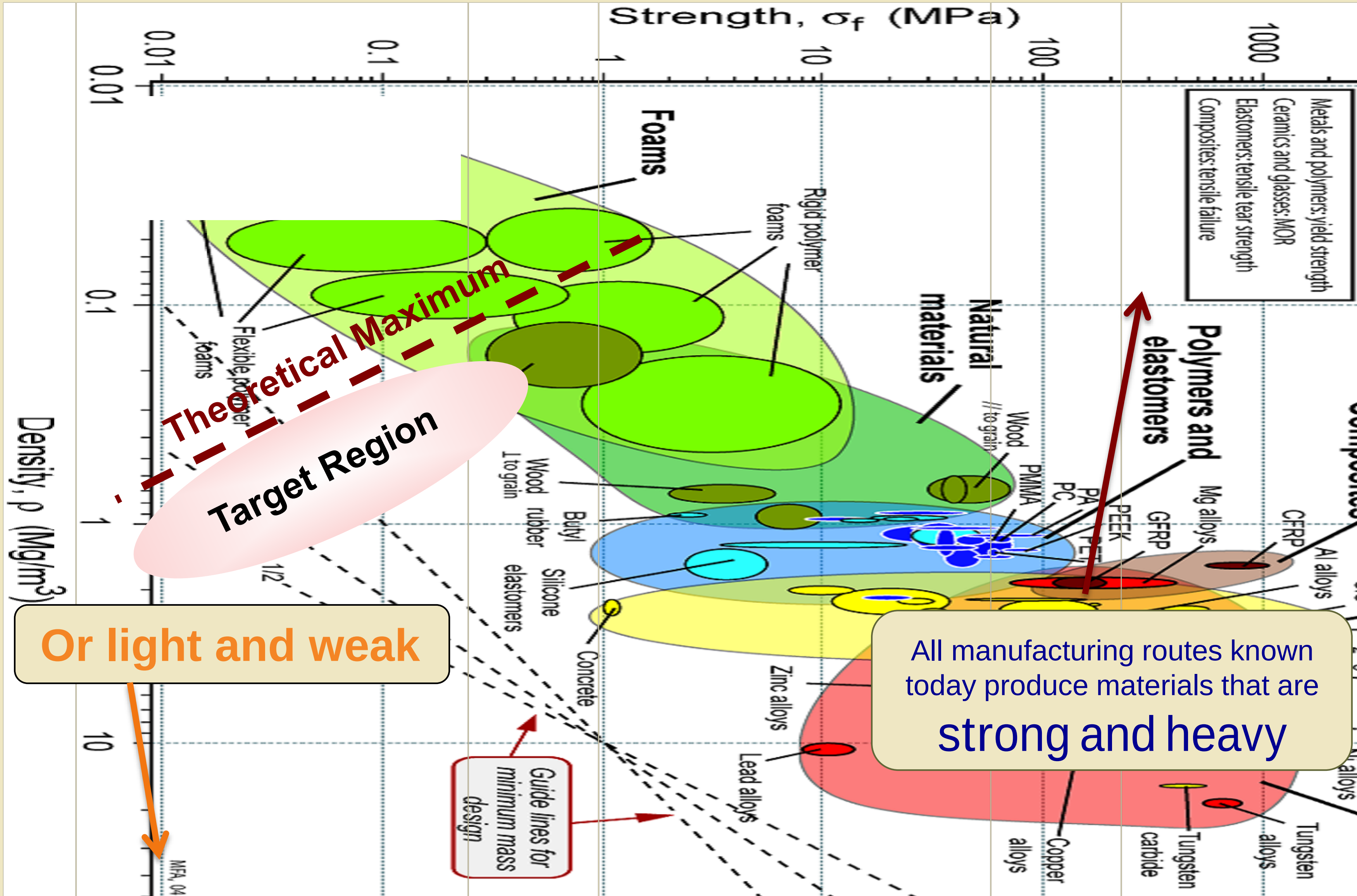
20 years ago… (coffee or no coffee (asleep))

10 years ago (categorized by color)…

Today (fully designed)…



Strength vs. Density: **A HUGE PROBLEM** for every technology



Or light and weak

All manufacturing routes known today produce materials that are

strong and heavy

Architecture in Material Design

Great Pyramid of Giza

largest man-made stone monument

Original height: 147 m
Weight: 5.75×10^6 tons
Weight at base: 10,500 tons/m^2

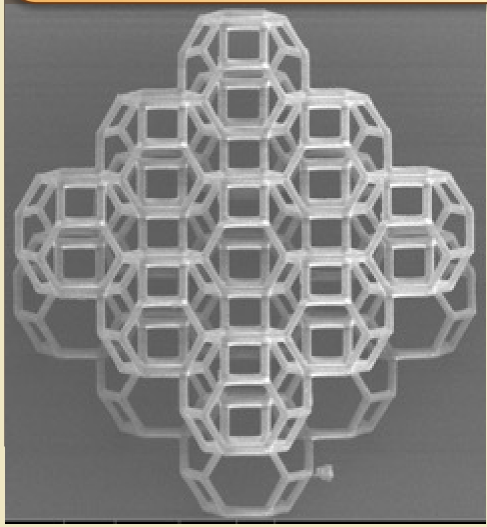
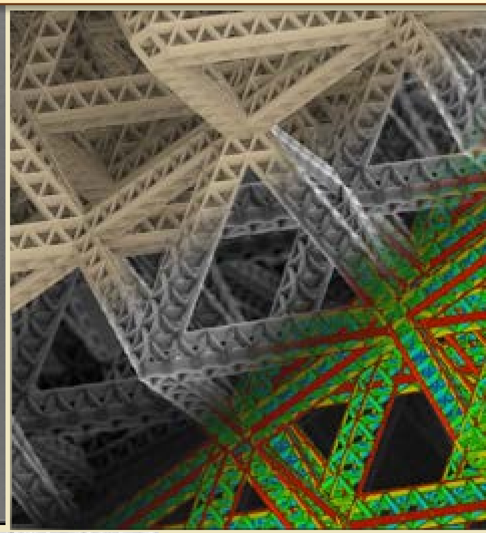
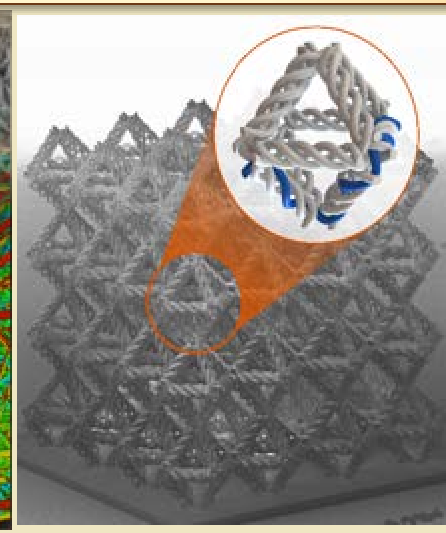
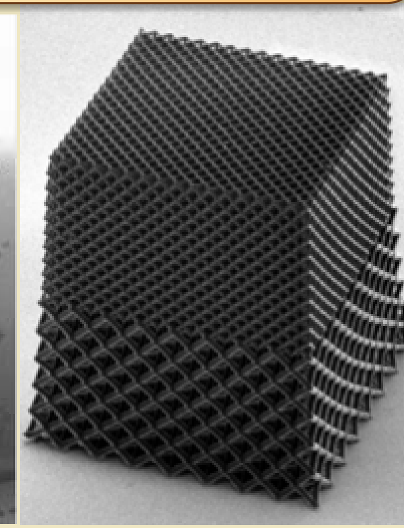
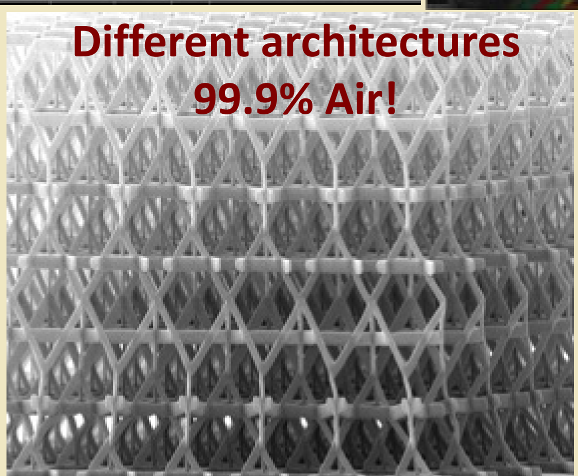
Tour Eiffel

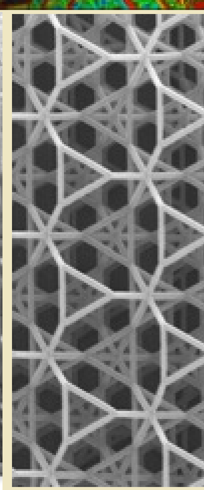
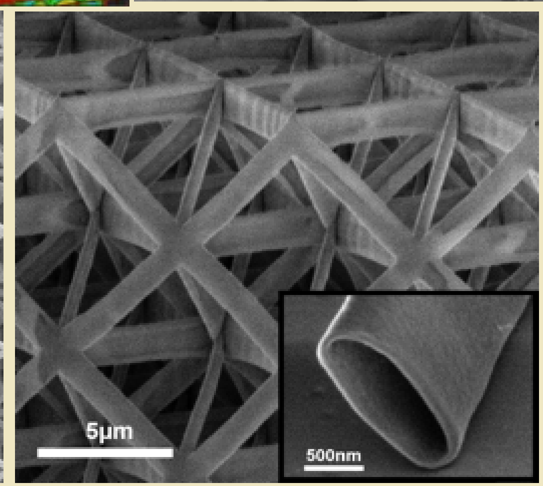
twice-as-tall engineered structure

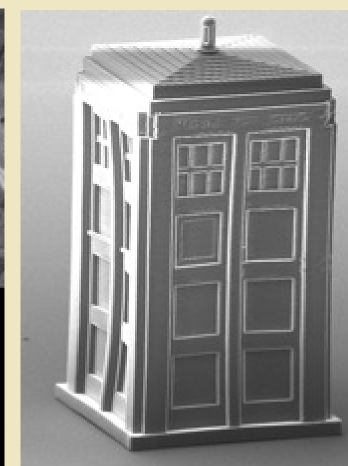
Height: 324 m
Weight: 9.4×10^3 tons
Force on foundation: 45,000kg/m^2

Creating ultra-light, strong, and damage tolerant materials

Architected structures with nano-sized solids merge structural and material properties into a single meta-material

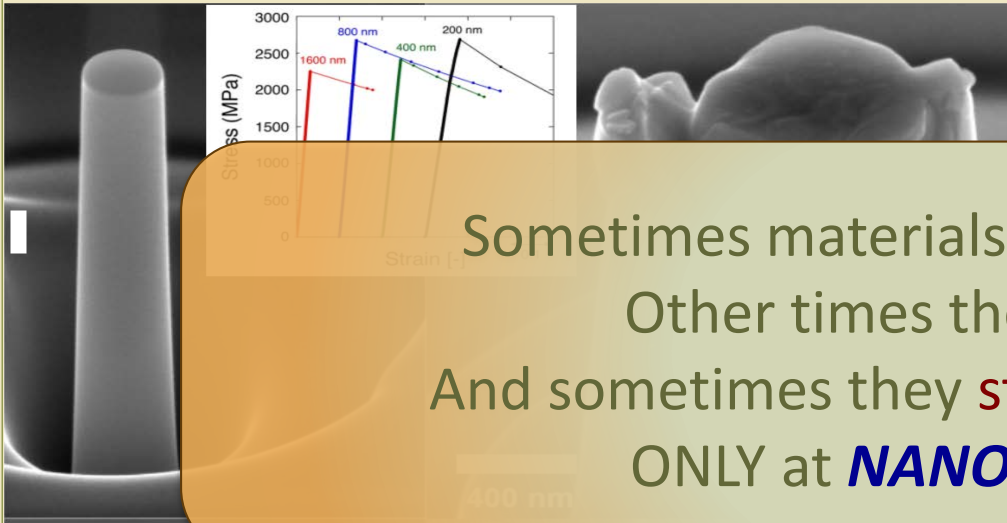


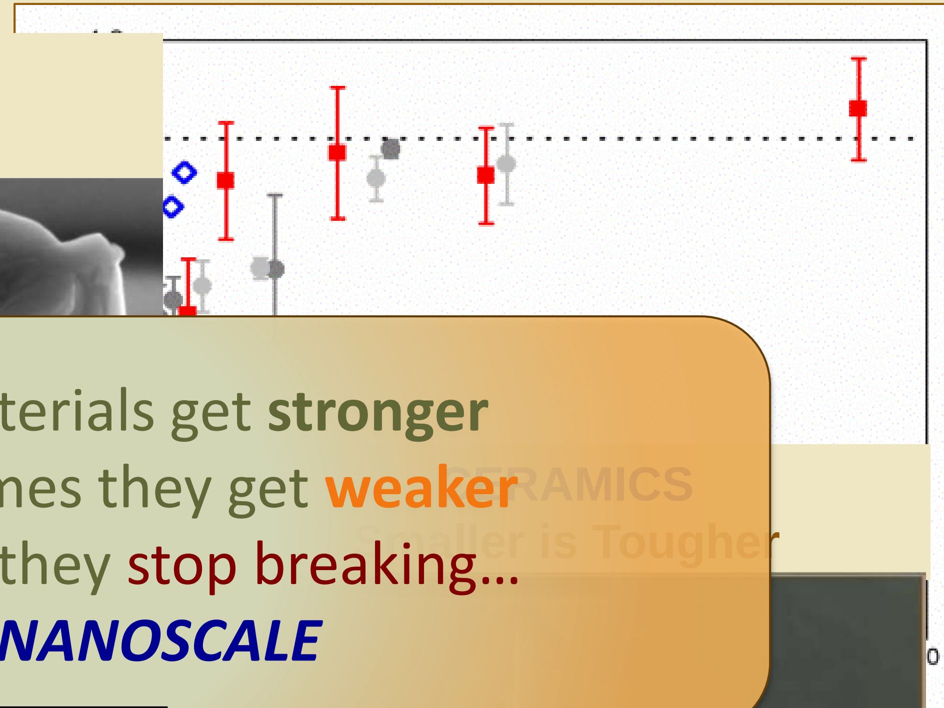
Schaedler, T. et al ***Science* 334** (2011)
L.R. Meza, et al ***PNAS* 112** (37) (2015)
W. Moestopo, et al ***Advanced Science*** 7 (20) (2020)
L.R. Meza, et al **Science 345** (2014)
Jang, D. et al ***Nature Mater.* 12** (2013)

Nearly All Common Metals*
Smaller is Stronger

SAME METALS
Smaller is Weaker

METALLIC GLASSES
Smaller is Ductile





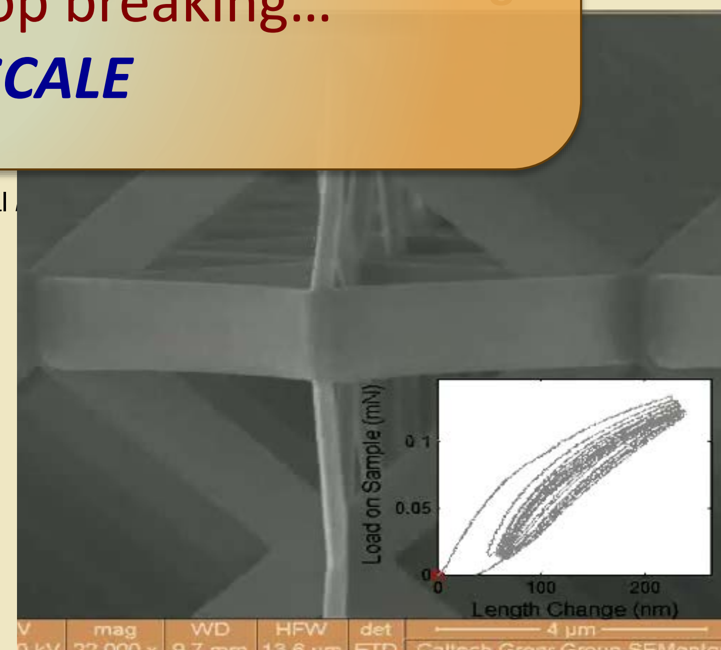
Sometimes materials get **stronger**

Other times they get **weaker**

And sometimes they stop breaking…

ONLY at ***NANOSCALE***

CERAMICS
Smaller is Tougher



D. Jang, et al. ***Nature Mater.*** 9 (2010)

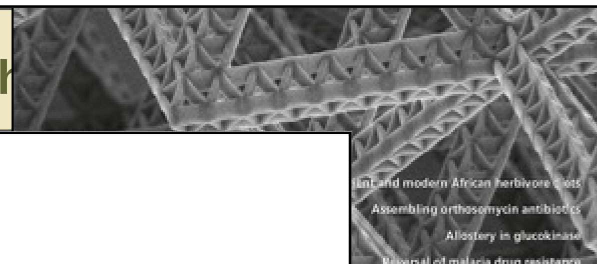
R. Liontas, et al ***Acta Mater*** 118 (2016)

D. Jang, et al. ***Nature Mater.*** 12 (2013)

Thinking Outside the Box: Doesn't have to be Periodic

Work of L. Meza, M. Lifson, C. Portela

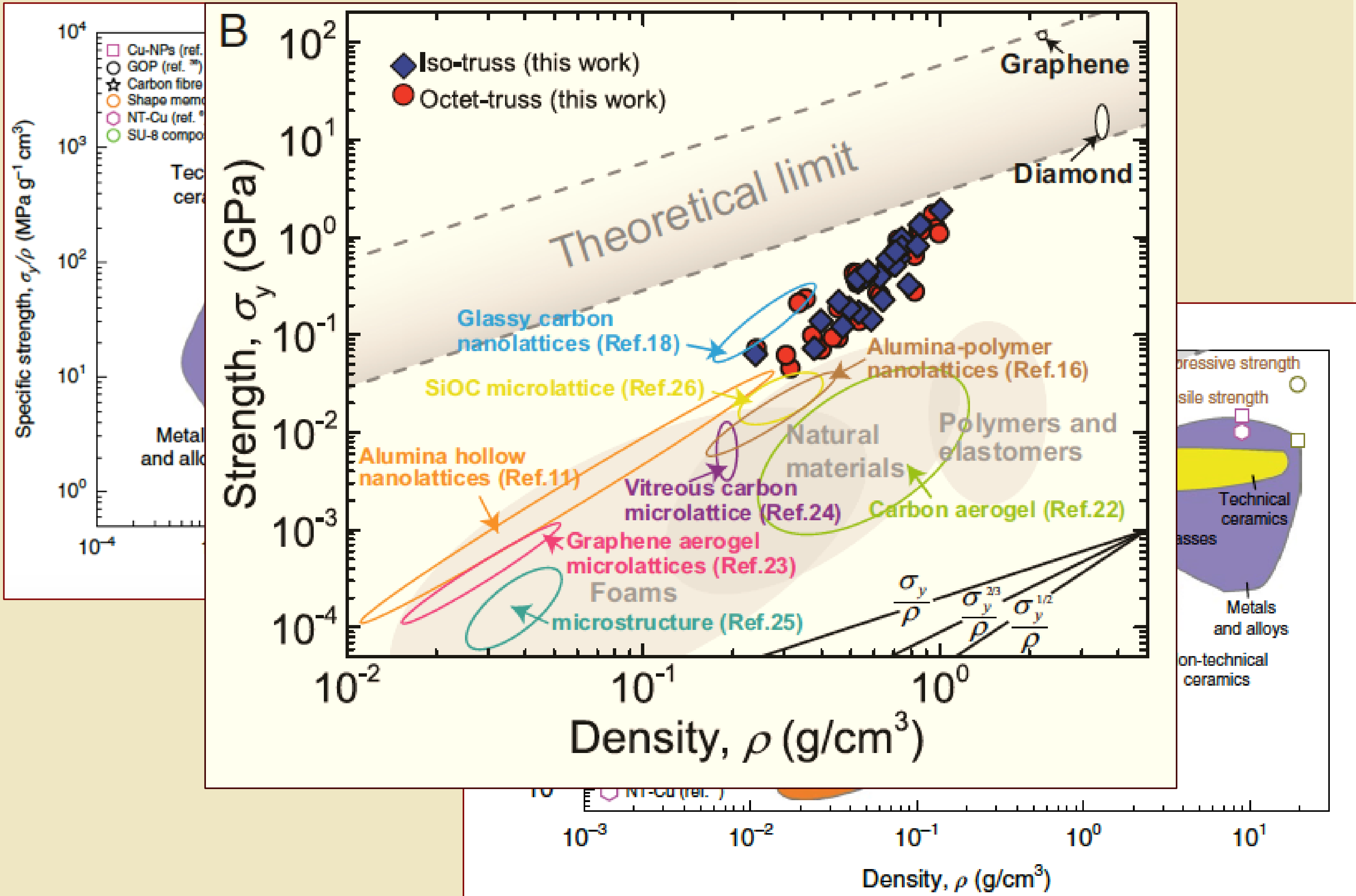
Doesn't have to have h



ry complex (fractal)

L.R. Meza, et al ***Science*** 345 (2014) L.R. Meza, et al ***Proc Nat'l Acad Sci*** 112 (2015) C.M. Portela et al ***Proc Nat'l Acad Sci*** *117* (2020)

Nano-Architected Pyrolitic Carbon Attains Multiple White Spaces



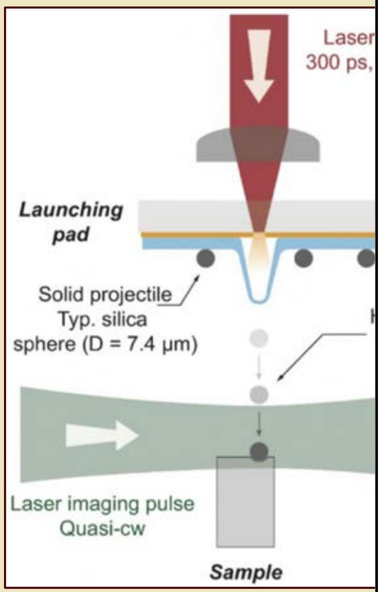
Zhang, X. et al., ***Proc Nat's Academy of Sci, USA*** 116 (2019)

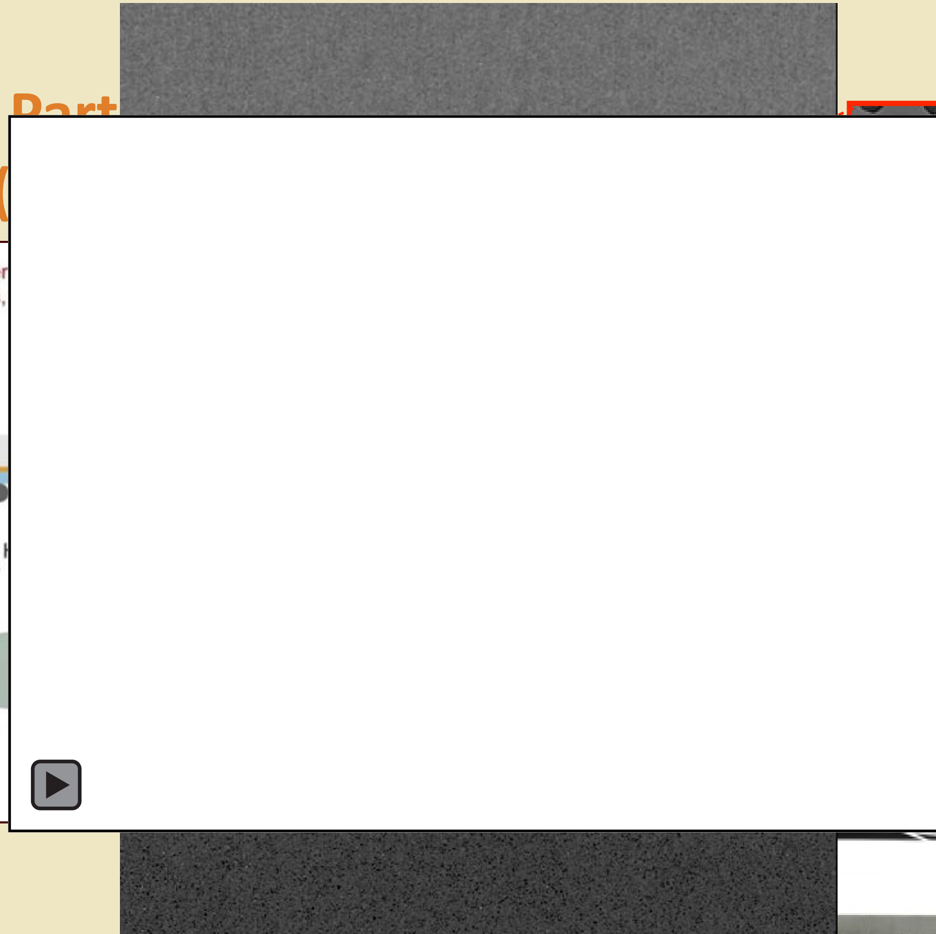
Zhang, X. et al ***Nature Nanotech*** 14 (8) (2019)

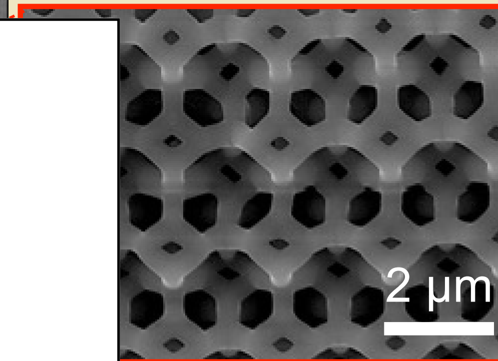
Switching Gears:
Impact Experiments on Micro-architected Carbon

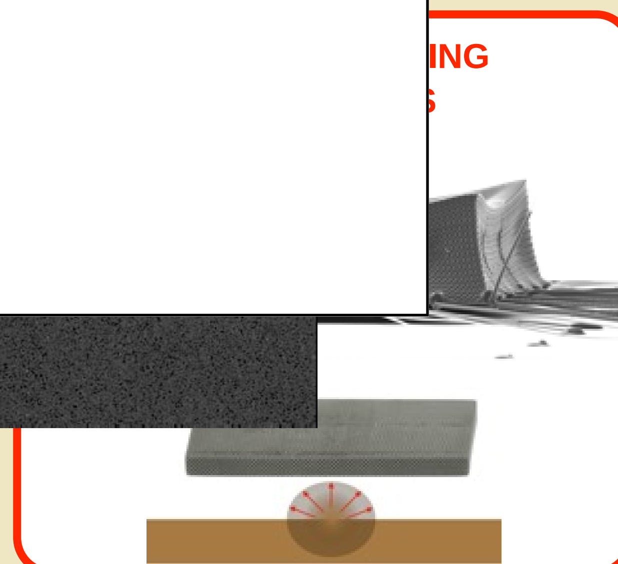
Collaboration w C. Portela, K. Nelson (MIT) and D. Kochmann (ETH)

Laser-Induced Part
Impact Test (



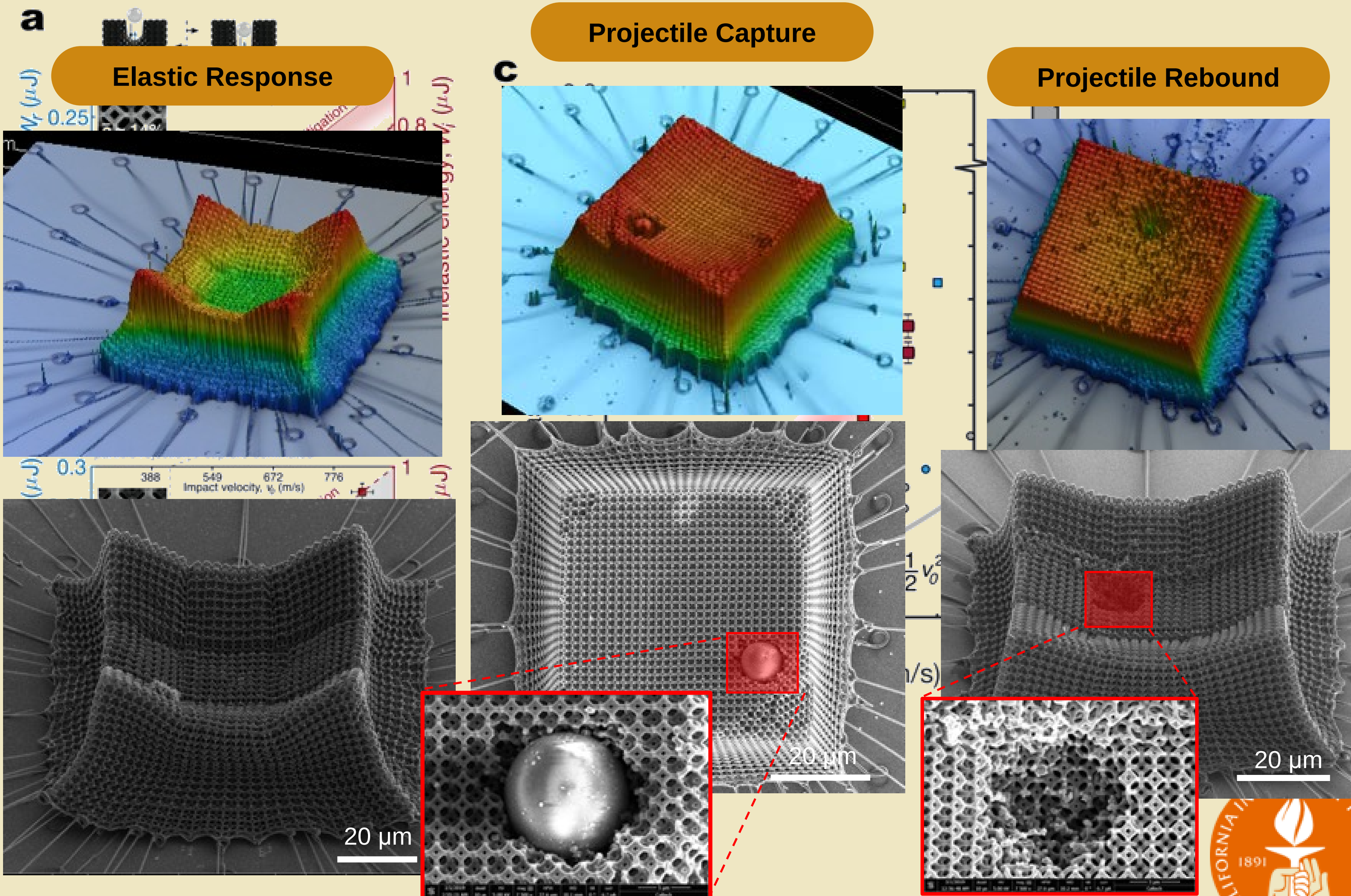






Portela, C.M., *et al.* . ***Nature Mater.*** https://doi.org/10.1038/s41563-021-01033-z (2021).

Nano-architected Materials can Shield Impact



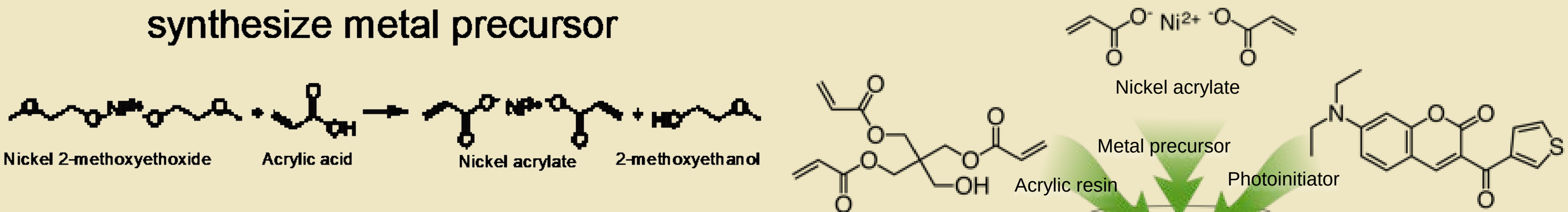
Portela, C.M., *et al.* . ***Nature Mater.*** https://doi.org/10.1038/s41563-021-01033-z (2021).

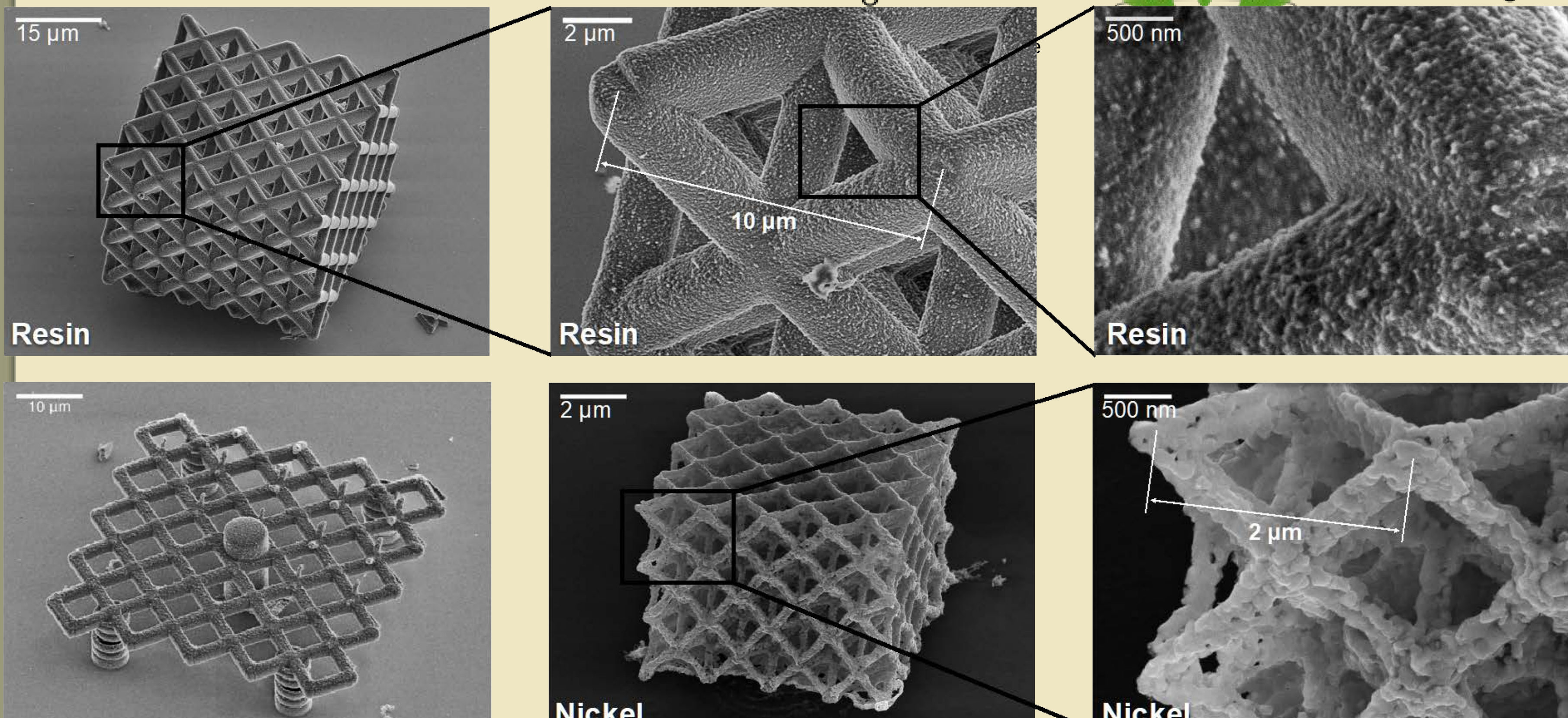
Venturing into Additive Manufacturing (AM) of Nano-Architected Metals

Work of A. Vyatskikh

Ligand exchange reaction to synthesize metal precursor

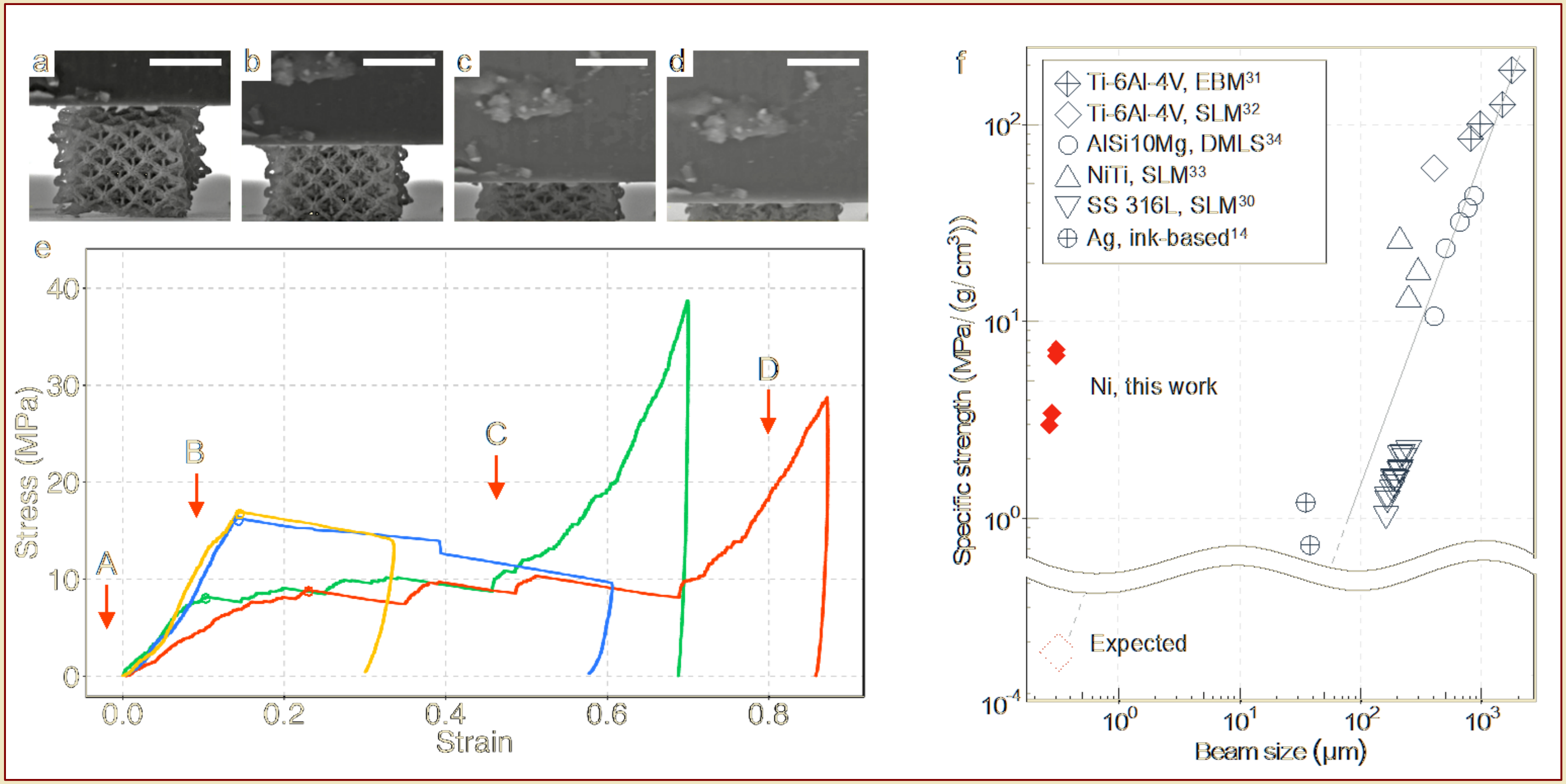
Hybrid organic-inorganic photoresist





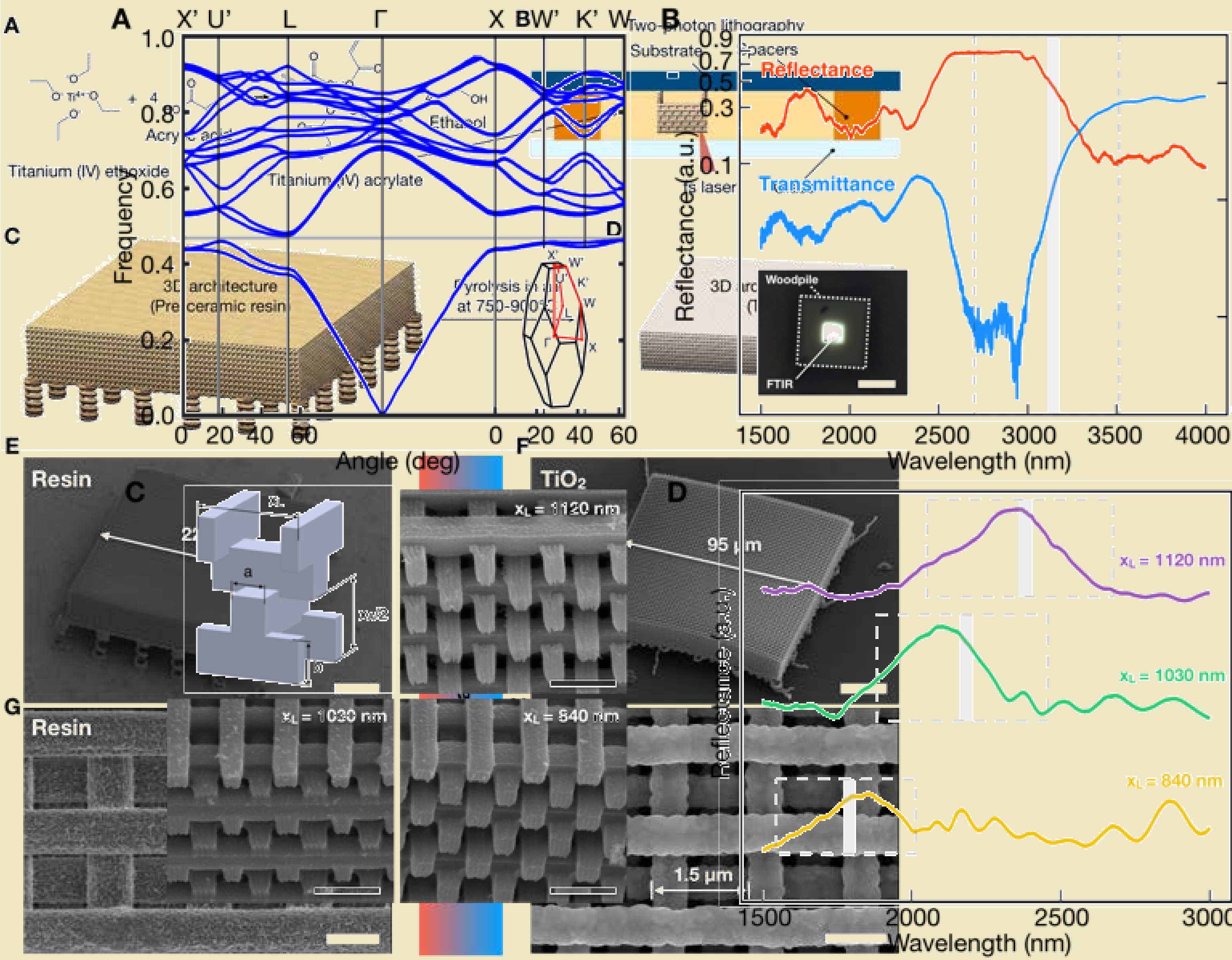
Vyatskikh, A. et al., ***Nat. Commun.* 9**, 593 (2018)

Ultra-strong Nanocrystalline Nanoporous Ni Nanolattices



AM of nano-sized TiO_2 for nano-photonics

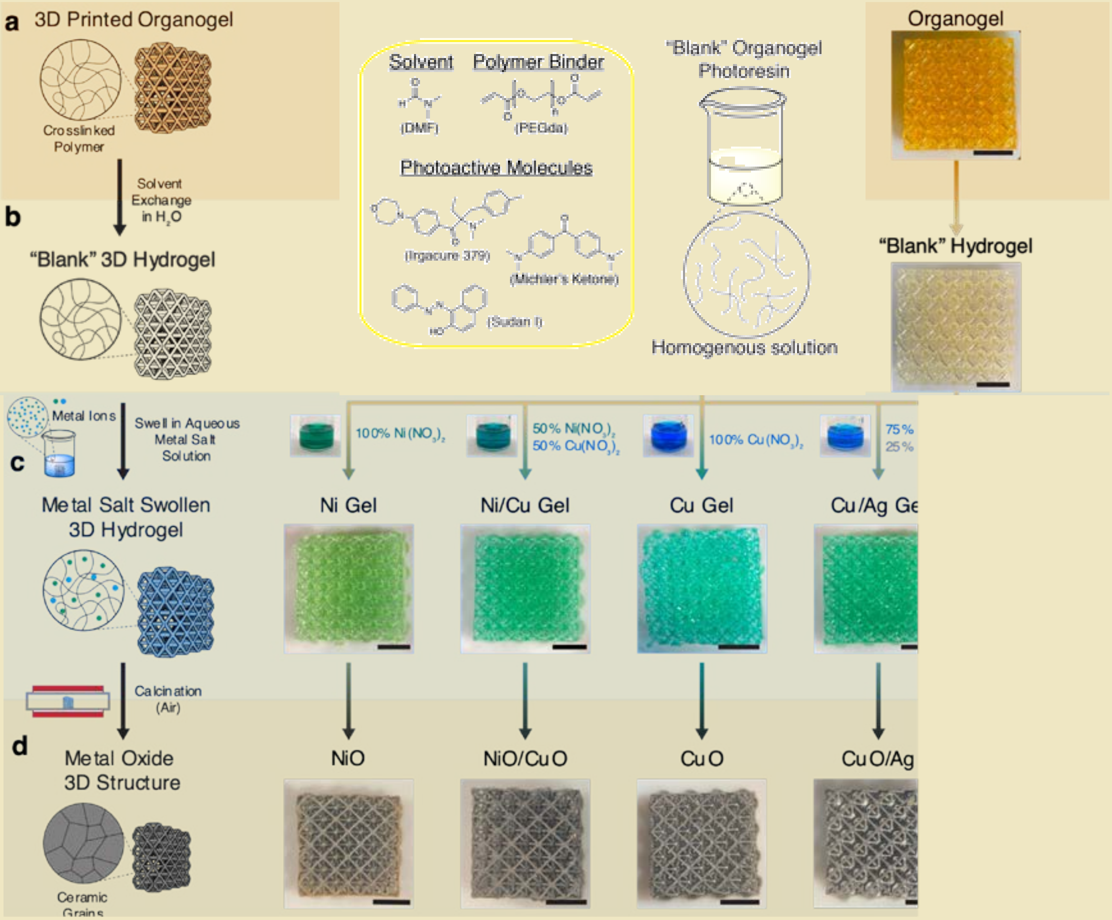
Work of A. Vyatskikh and R. Ng



Vyatskikh, A. Ng, R.C. et al., ***Nano Letters* 20**, 593 (2020)

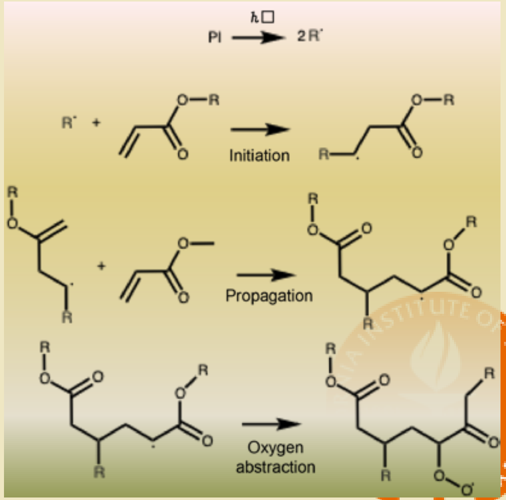
From metal oxides to metals:
Vat Polymerization for Hydrogel Infusion AM process

Work of Daryl Yee, Max Saccone, Kai Narita



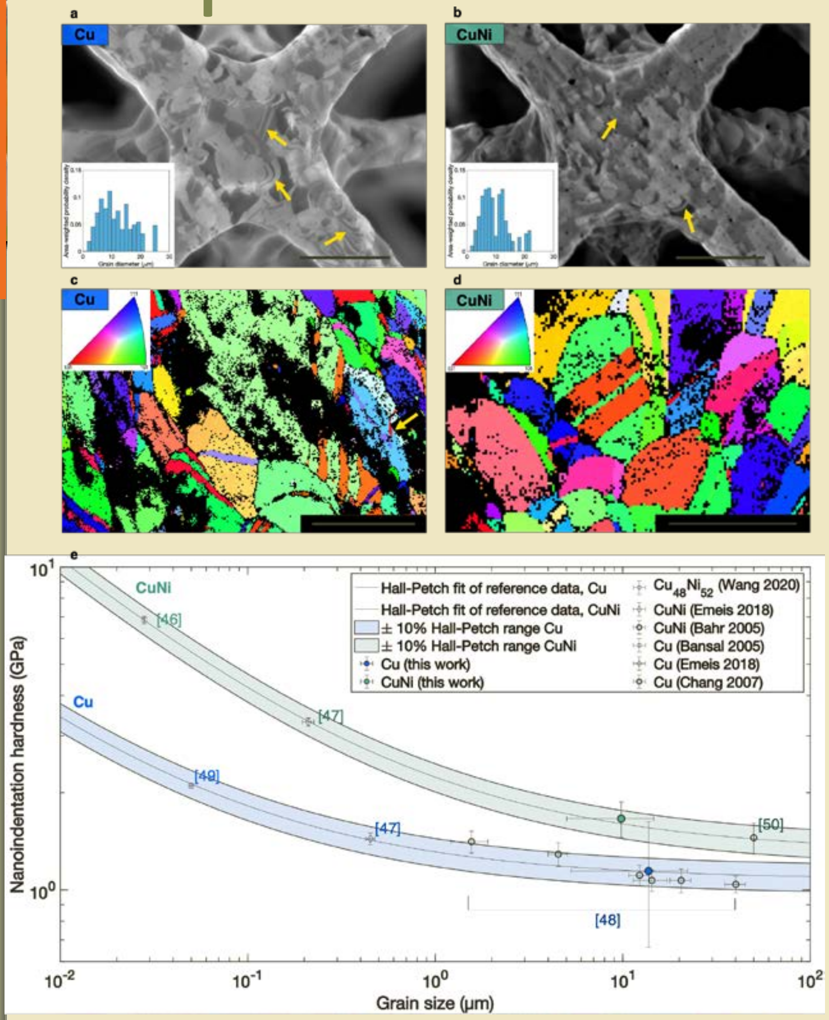
The basics

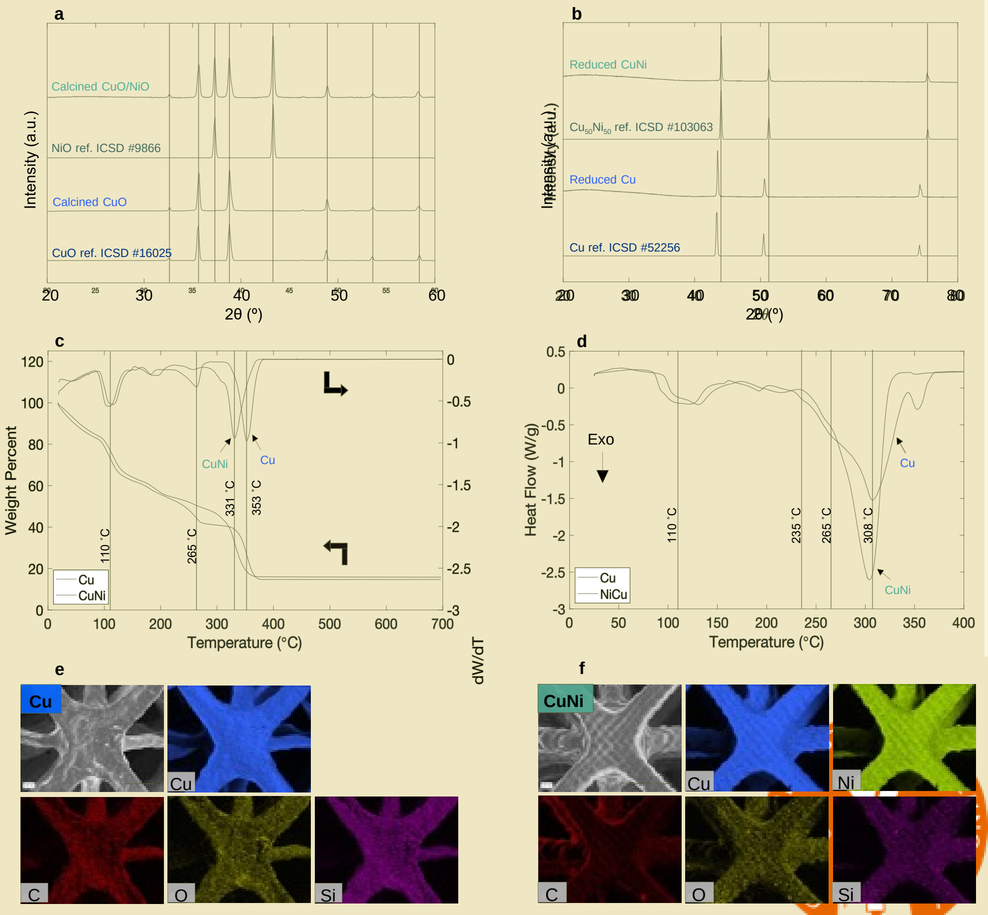
- Liquid resin bath containing oligomer(s), photoinitiator, and UV blocker (dye)
- Pattered light is projected into the resin bath
  - SLA: (1D) laser rastering
  - DLP: 2D image projection
- Light initiated free radical polymerization
- Common assumptions[2]
  - Beer-Lambert Law: $I = I_0 e^{-\frac{z}{D_P}}$
  - Polymer network becomes insoluble at gel point



M. A. Saccone, D. W. Yee, K. Narita, R. A. Gallivan, J. R. Greer, *in preparation* (2021)

Properties of Chemically-Derived Metals

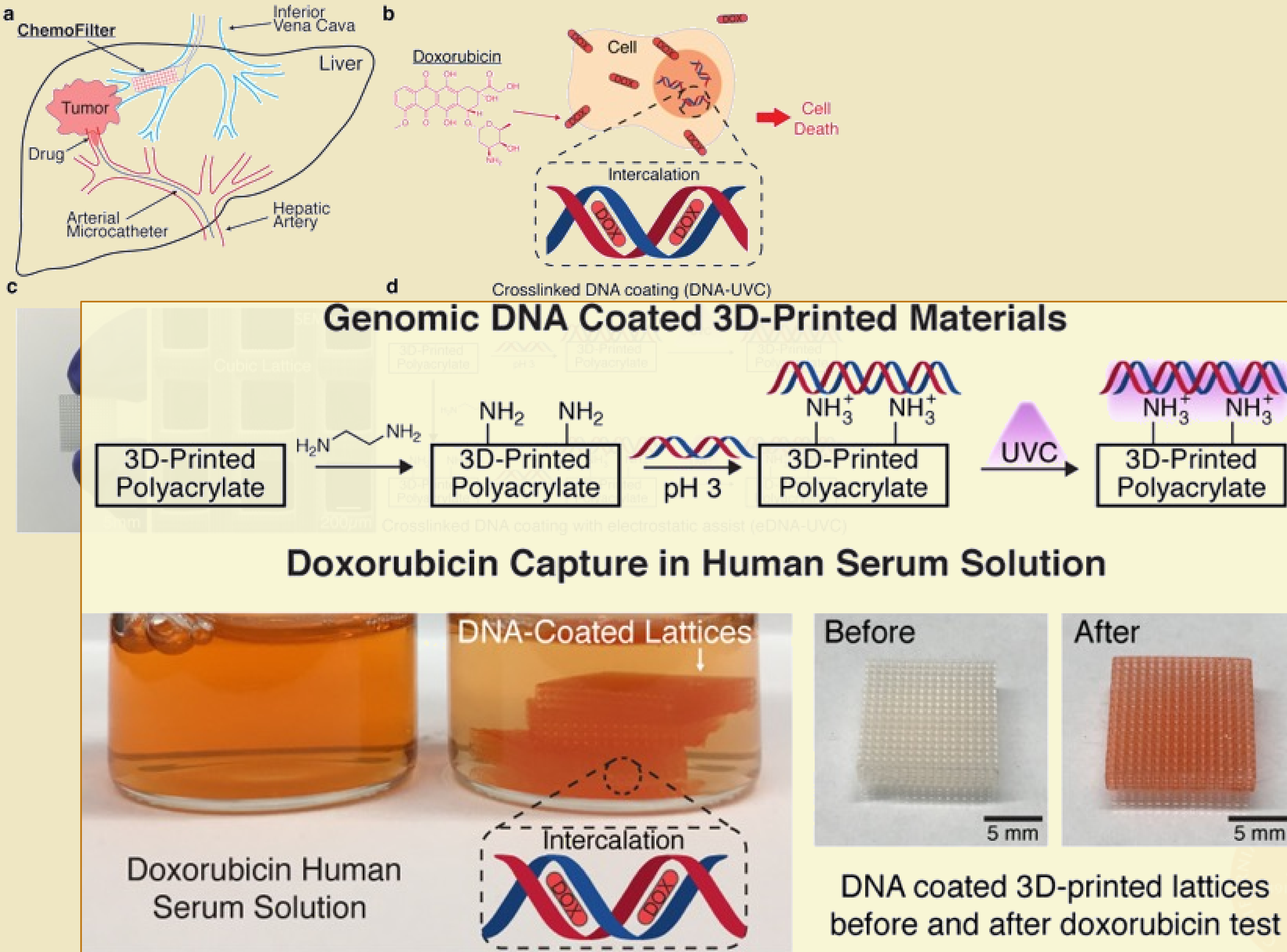




M. A. Saccone, D. W. Yee, K. Narita, R. A. Gallivan, J. R. Greer, *in preparation* (2021)

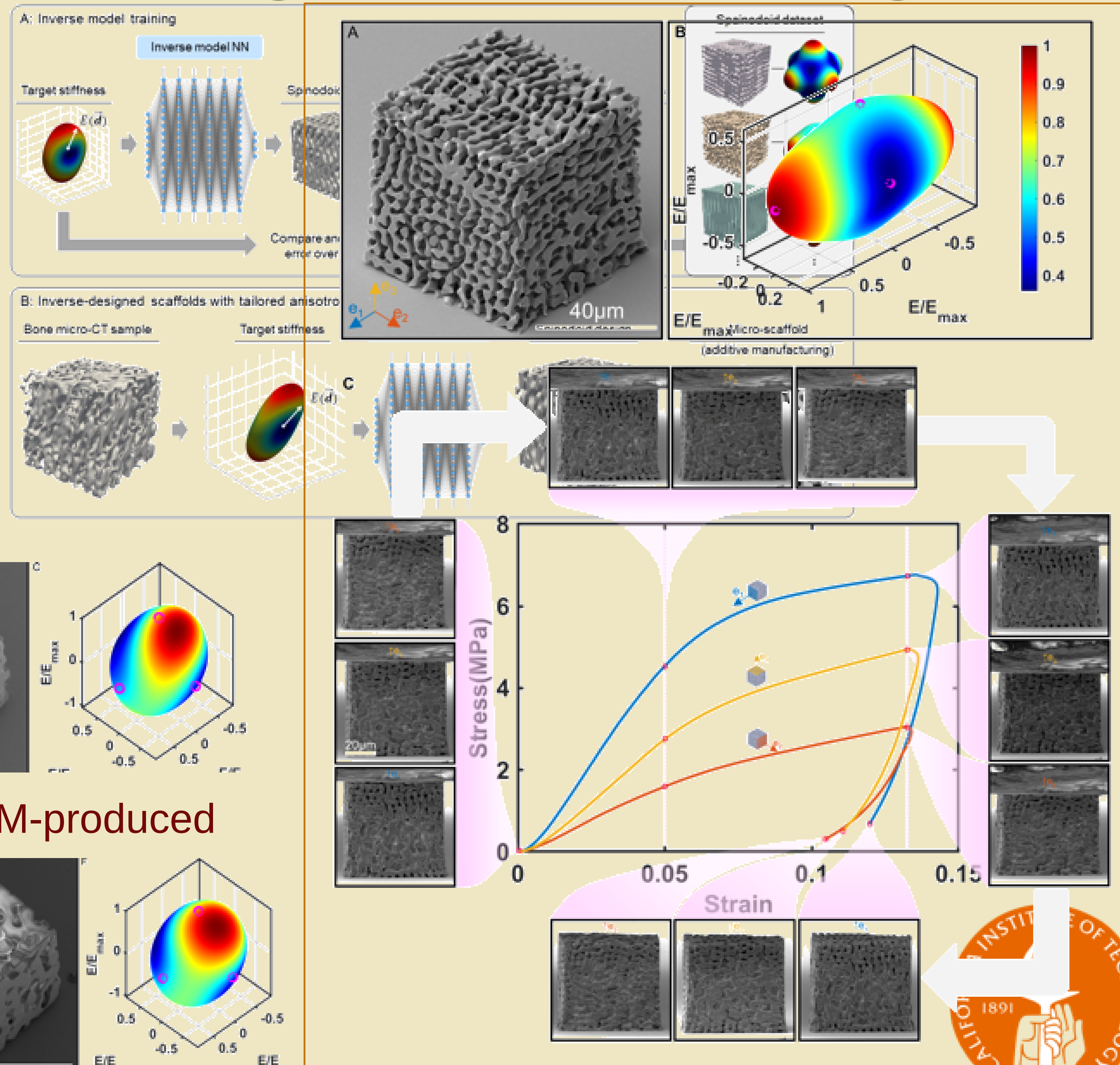
Biomolecular Surface Functionalization

Collaboration with S. Hetts (UCSF) and R. H. Grubbs (Calteh)

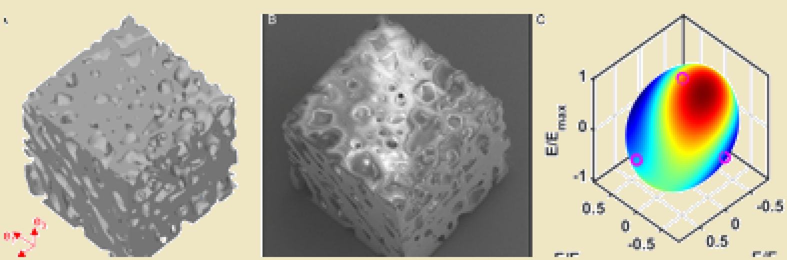


Machine Learning in Bio-scaffold Design

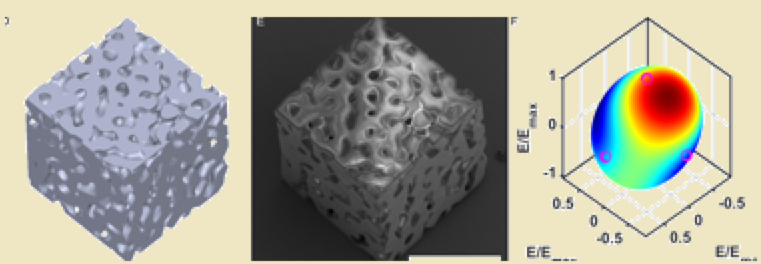
Collaboration with D. Kochmann (ETH) and S. Kumar (Delft)



Reconstructed Bone

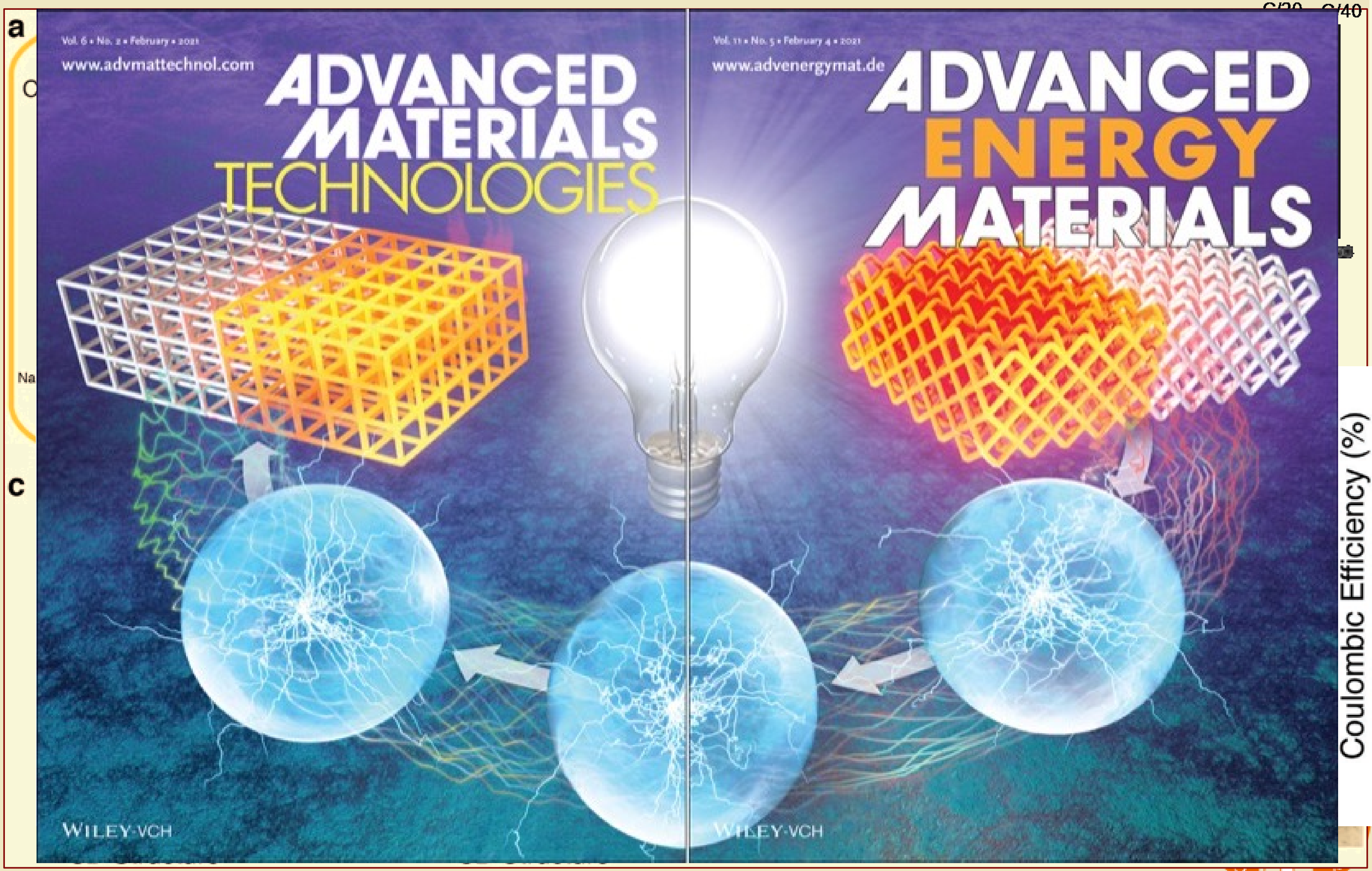


AI-generated, AM-produced



Energy Storage: Towards safer, lighter Li-ion Batteries:
LiCoO (cathode) and Glassy Carbon (anode)

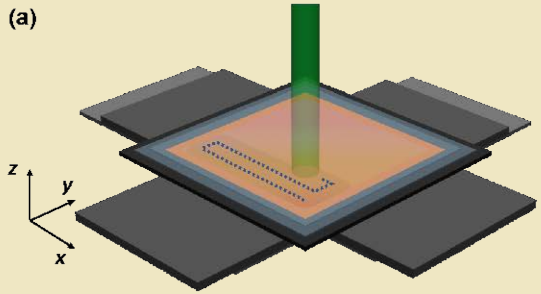
Work of Daryl Yee (MS PhD 2020 and Kai Narita

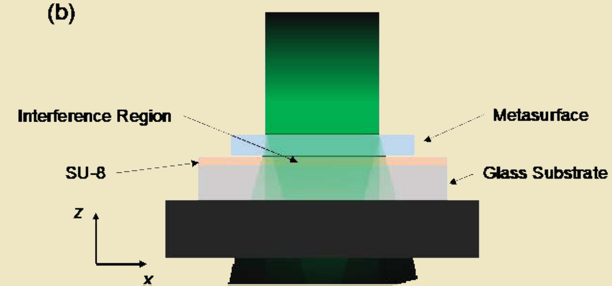


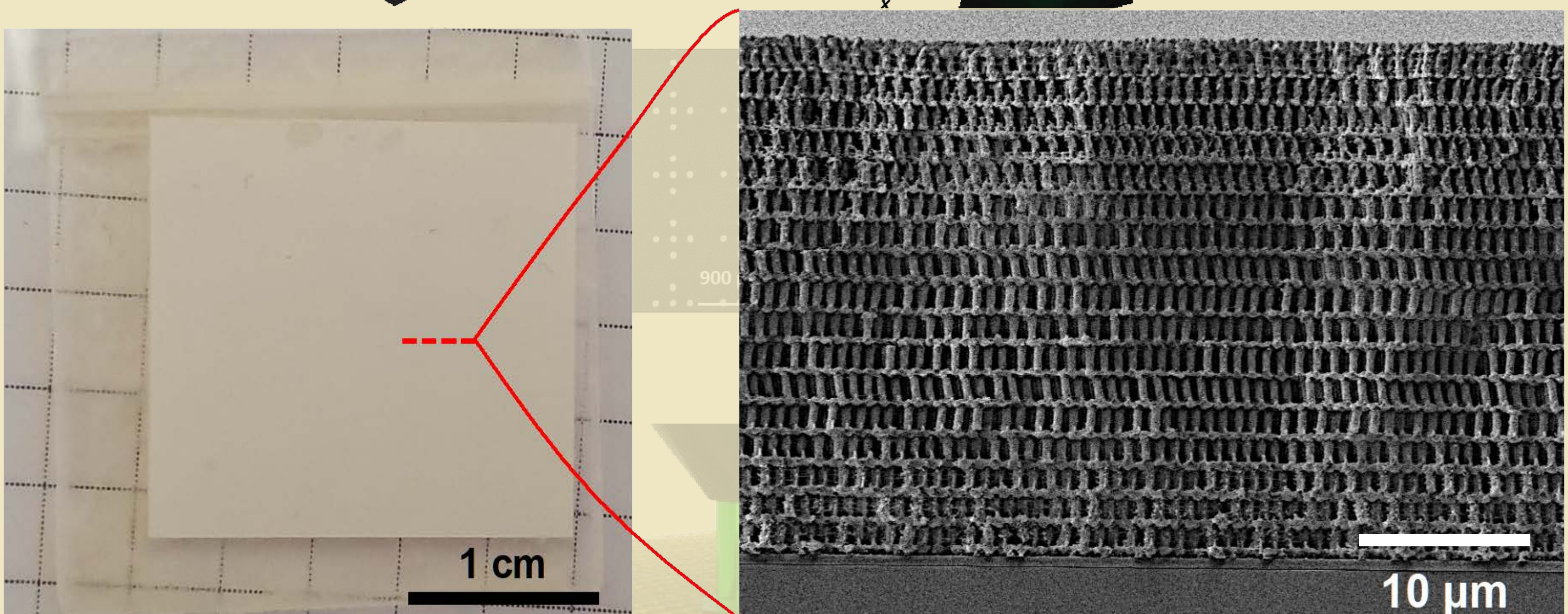
Yee, D. W., et al ***Adv. Mater. Technol***. 6 (2) (2021)

Narita, K., et al ***Adv. Energy Mater.* 11 (5) *(*2021)**

Scalability of Nano-architected Materials





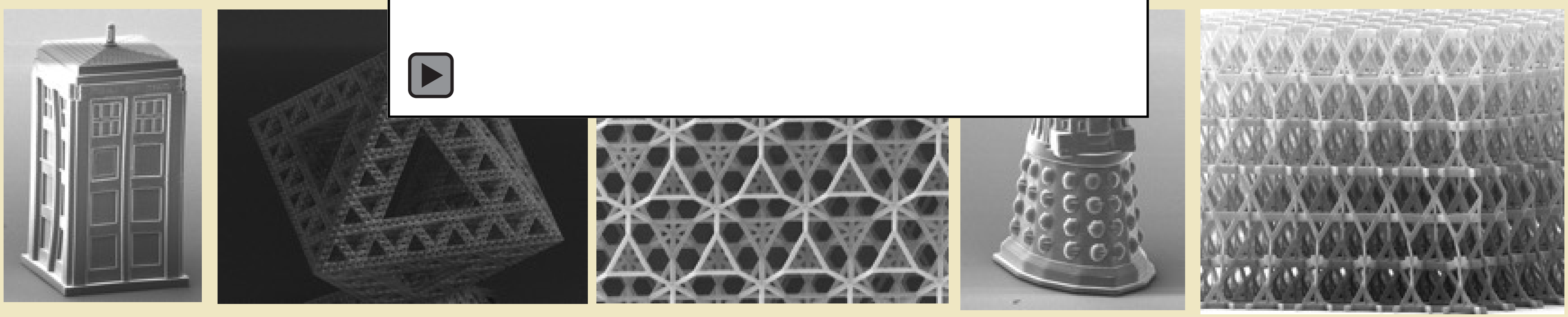


Work of Matias Kagias and Andrew Friedman

SUMMARY: so what?

Clever use of (1) ARCH OMIC ARRANGEMENTS
as tuning kn IAL CLASSES

⇒ Can be made of j
⇒ Offer extremely lig
⇒ De-couple proper ner



Nano-architectrures merge structural and material properties into a single "meta-material"

Acknowledgements of Awesome “Resources”

NIH National Institutes of Health
Turning Discovery Into Health

KV KAIROS VENTURES

Keck Institute for Space Studies

Keck

Vannevar-Bush Faculty Fellowship

RESNICK INSTITUTE
science + energy + sustainability

DARPA

Basic Energy Sciences
DOE ERE

kni CALTECH
The KAVLI NANOSCIENCE INSTITUTE

Caltech Tianqiao and Chrissy Chen Institute for Neuroscience

AMGEN

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Huajian Gao (Brown U)
Y.-W. Zhang (IHPC Singapore
D. Kochmann (ETH)
3. Grubbs, A. Faraon (Caltech
S Hetts (UCSF)