Developing Responsible Nanotechnologies

An Aerosol Perspective

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INRS, Nancy, 12/03/08

The

art and science

of building stuff

that does stuff

at the nanometer scale

Richard Smalley

Nanotechnology can... *Make better products*

I wish my sunscreen wasn't so unsightly

I wish my socks didn't smell so much!

I wish my tennis racquet was lighter and stronger

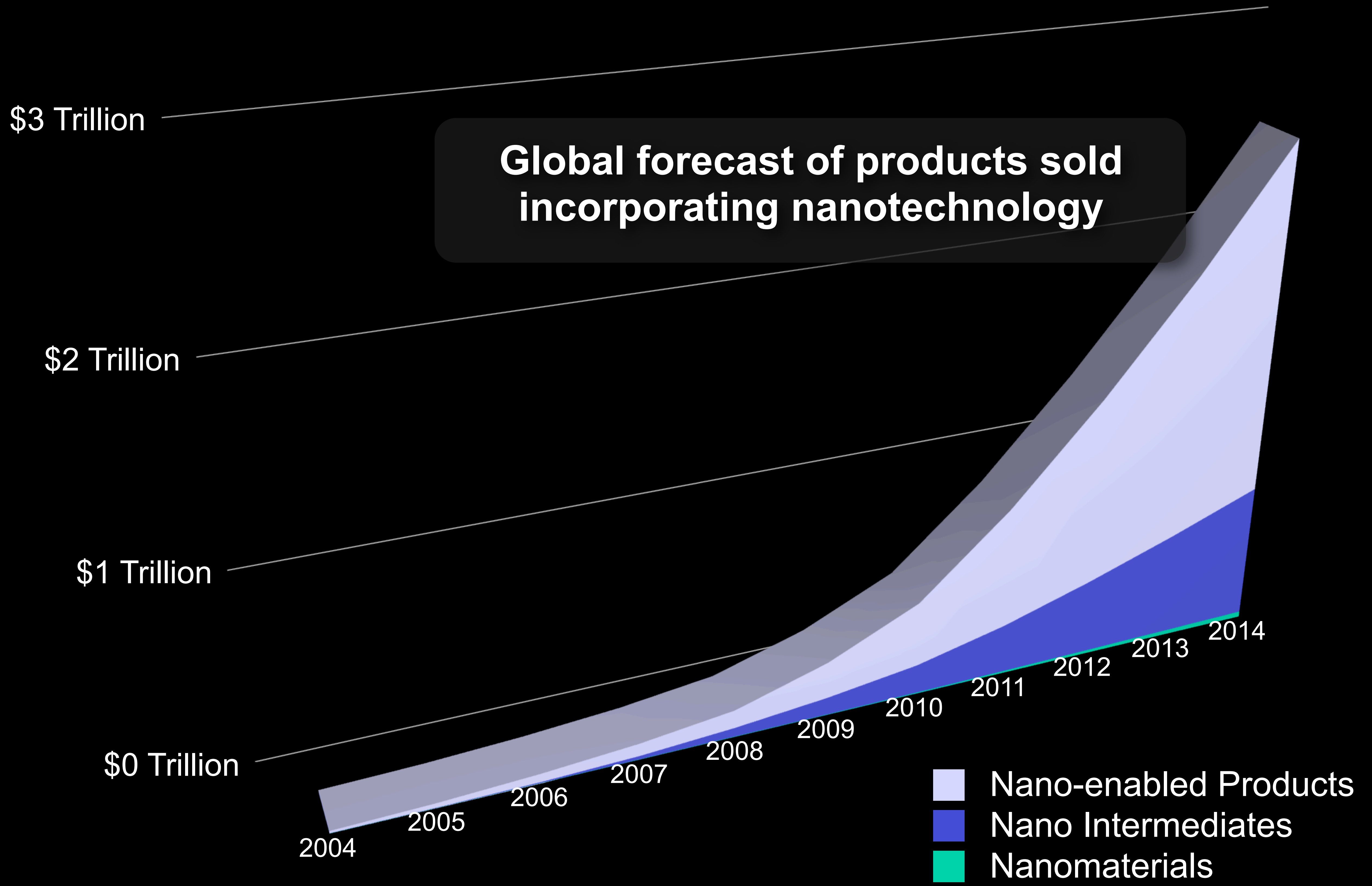
I wish I could keep leftovers for longer, before they go off

I wish spilt red wine would run off my pants without staining

I wish I could get more songs on my iPod

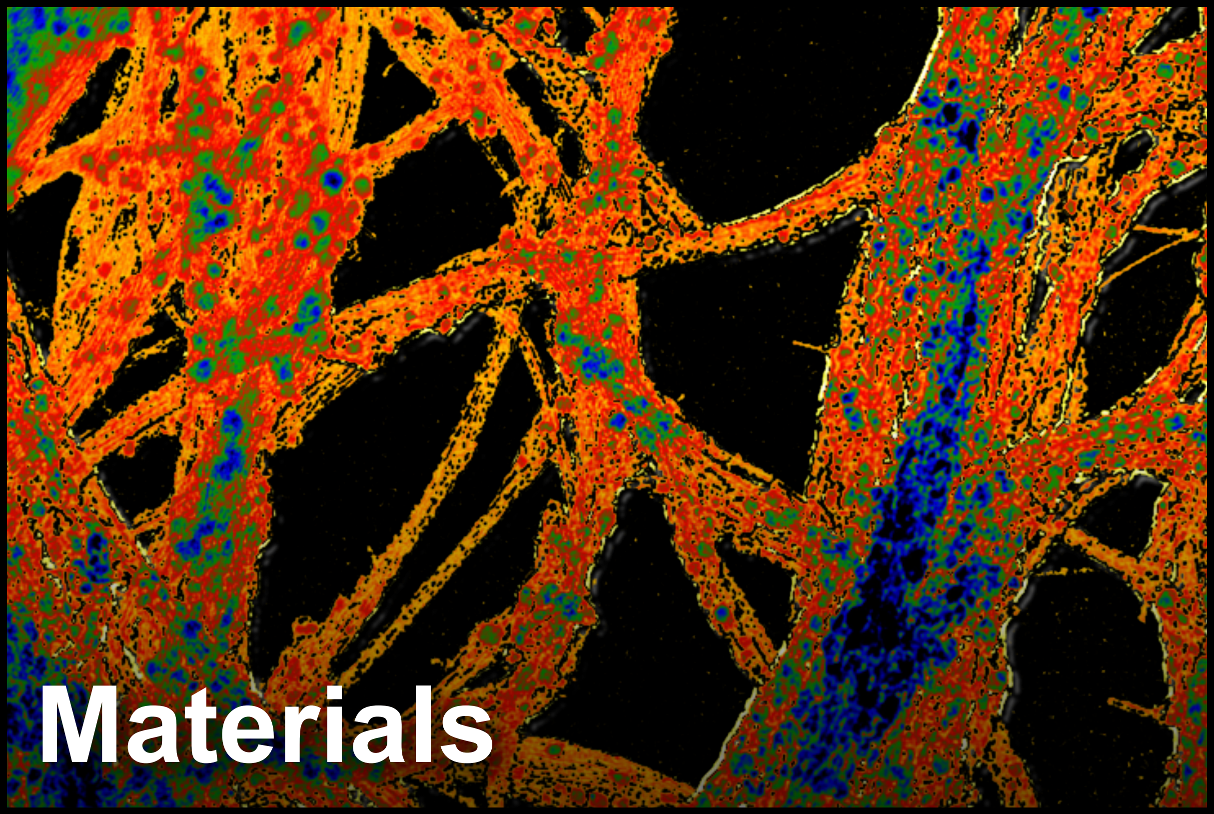
Over 800 listed manufacturer-identified nanotech consumer products:
www.nanotechproject.org/consumerproducts

Nanotechnology can... *Generate Wealth*

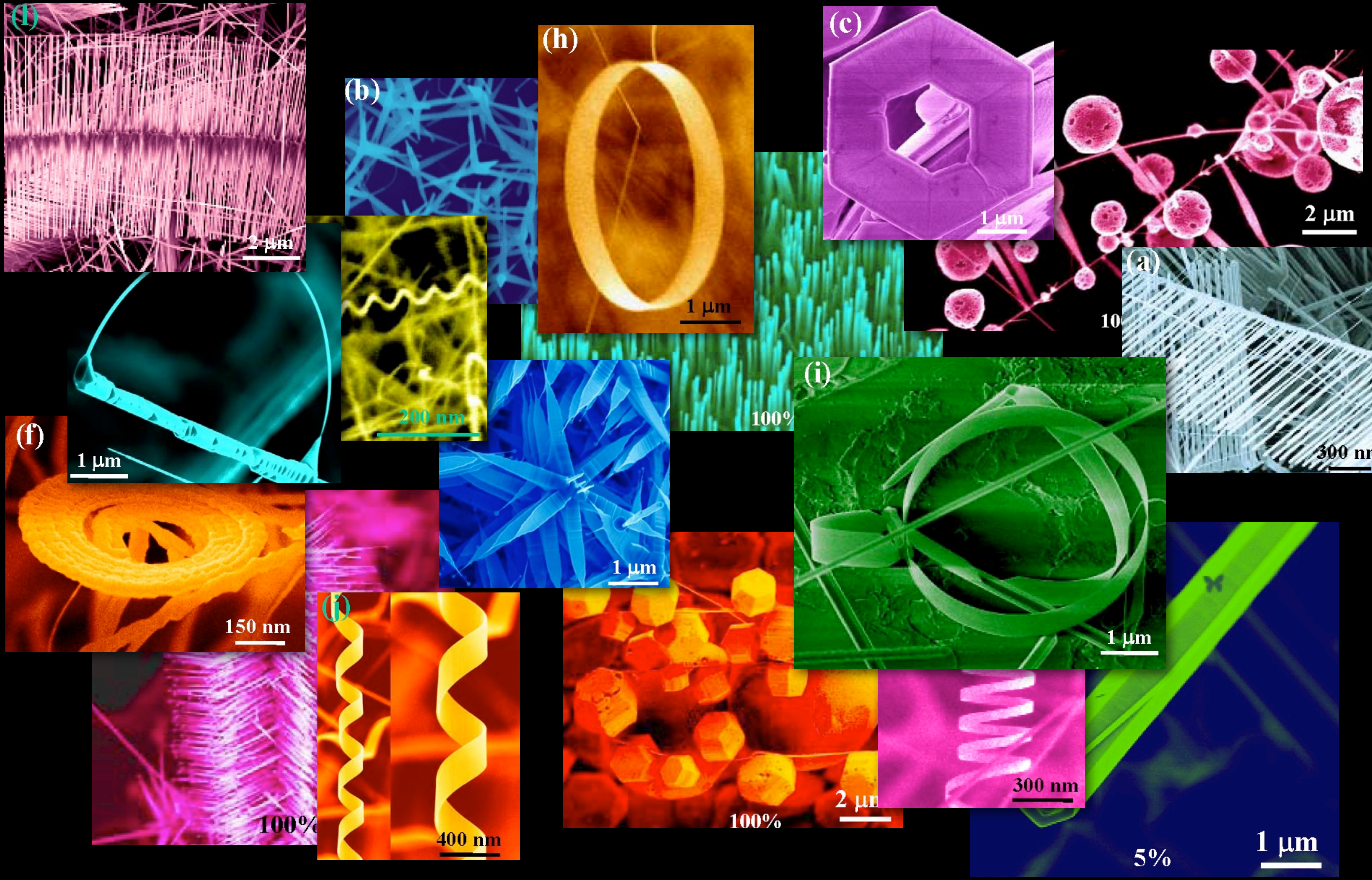


Source: 2004 Lux Research Report: "Sizing nanotechnology's value chain"

Nanotechnology can... *Make A Difference*



Does the ***added value*** that nanotechnology brings to products, lead to ***unconventional*** potential to cause harm?

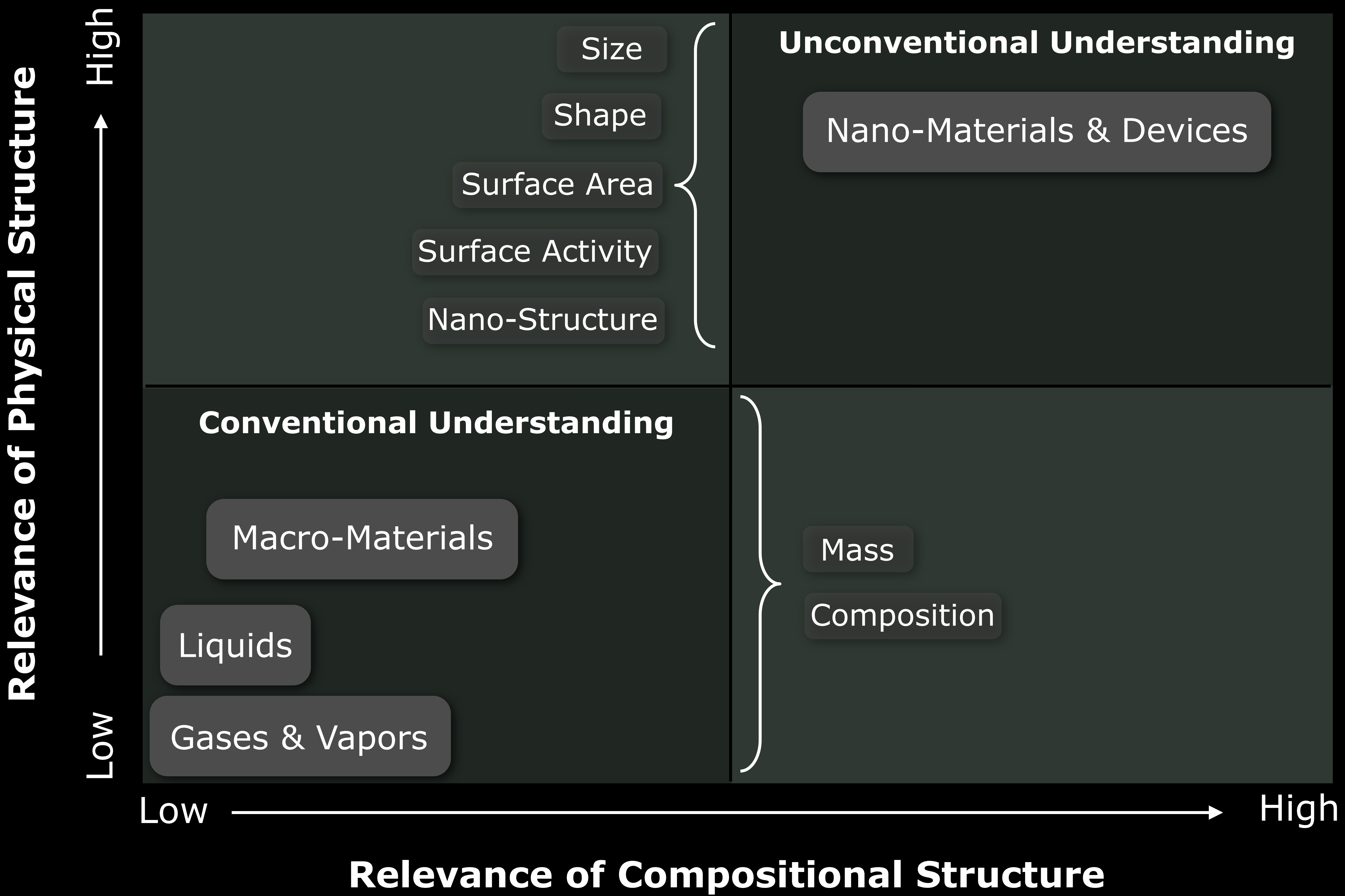


Nano-ZnO: One chemistry, many shapes

Courtesy of Prof. Z.L. Wang, Georgia Tech

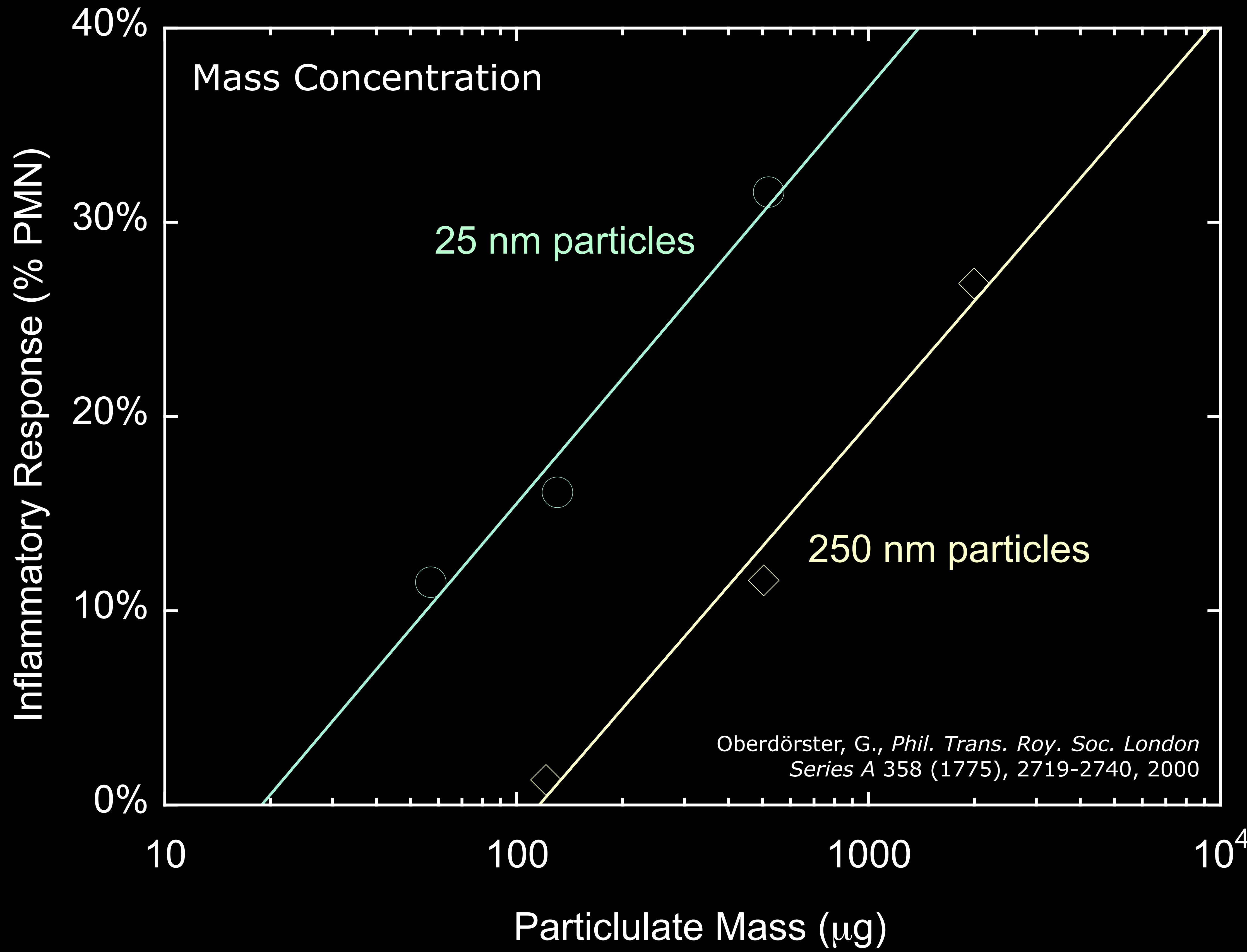
A thought experiment

The potential significance of structure on nanomaterial impact



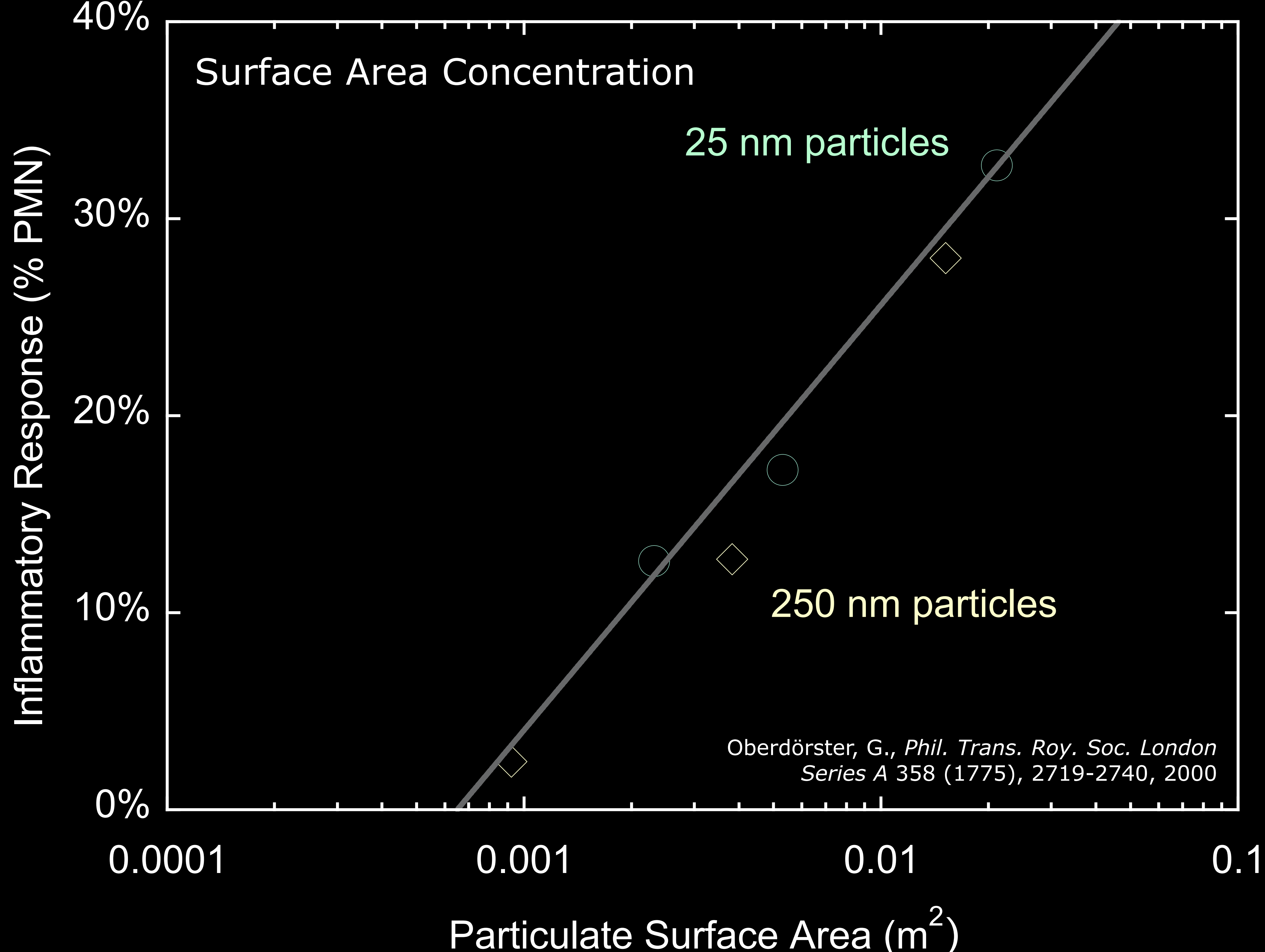
Structure-related hazard: Particle Size

TiO$_2$ Instillation in Rats



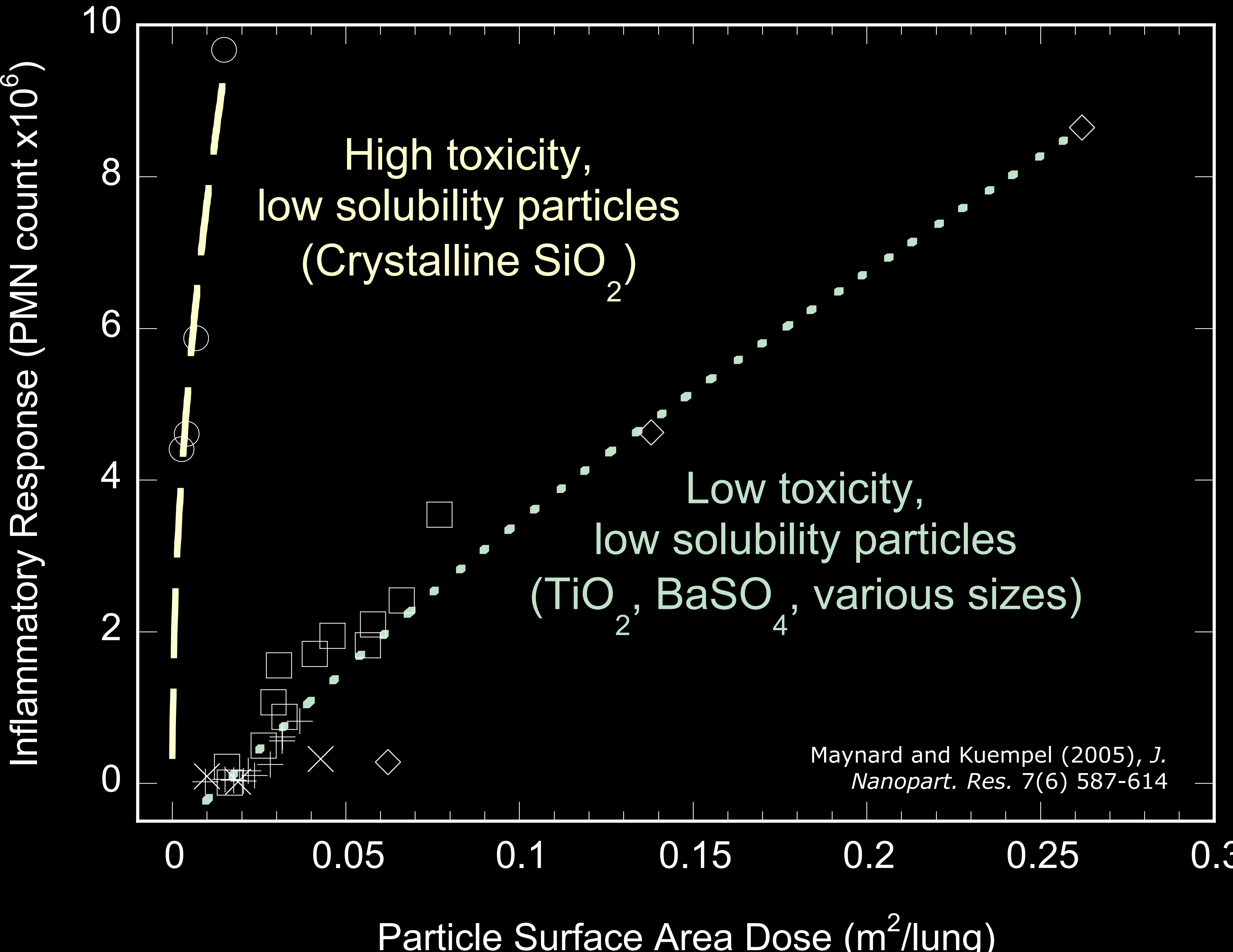
Structure-related hazard: Surface Area

TiO_2 Instillation in Rats



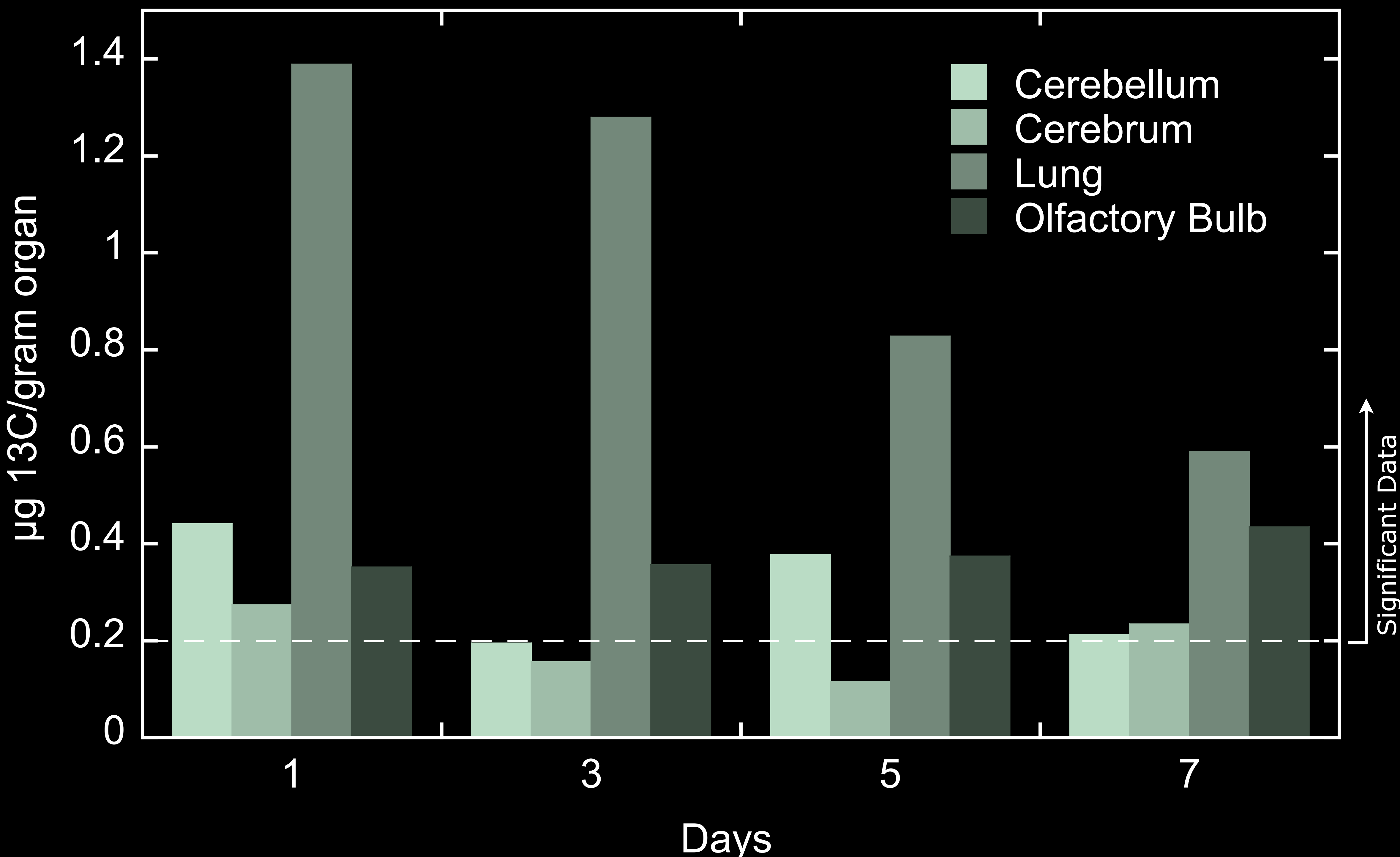
Structure-related hazard: Surface Chemistry

Rats



Structure-related hazard: Translocation

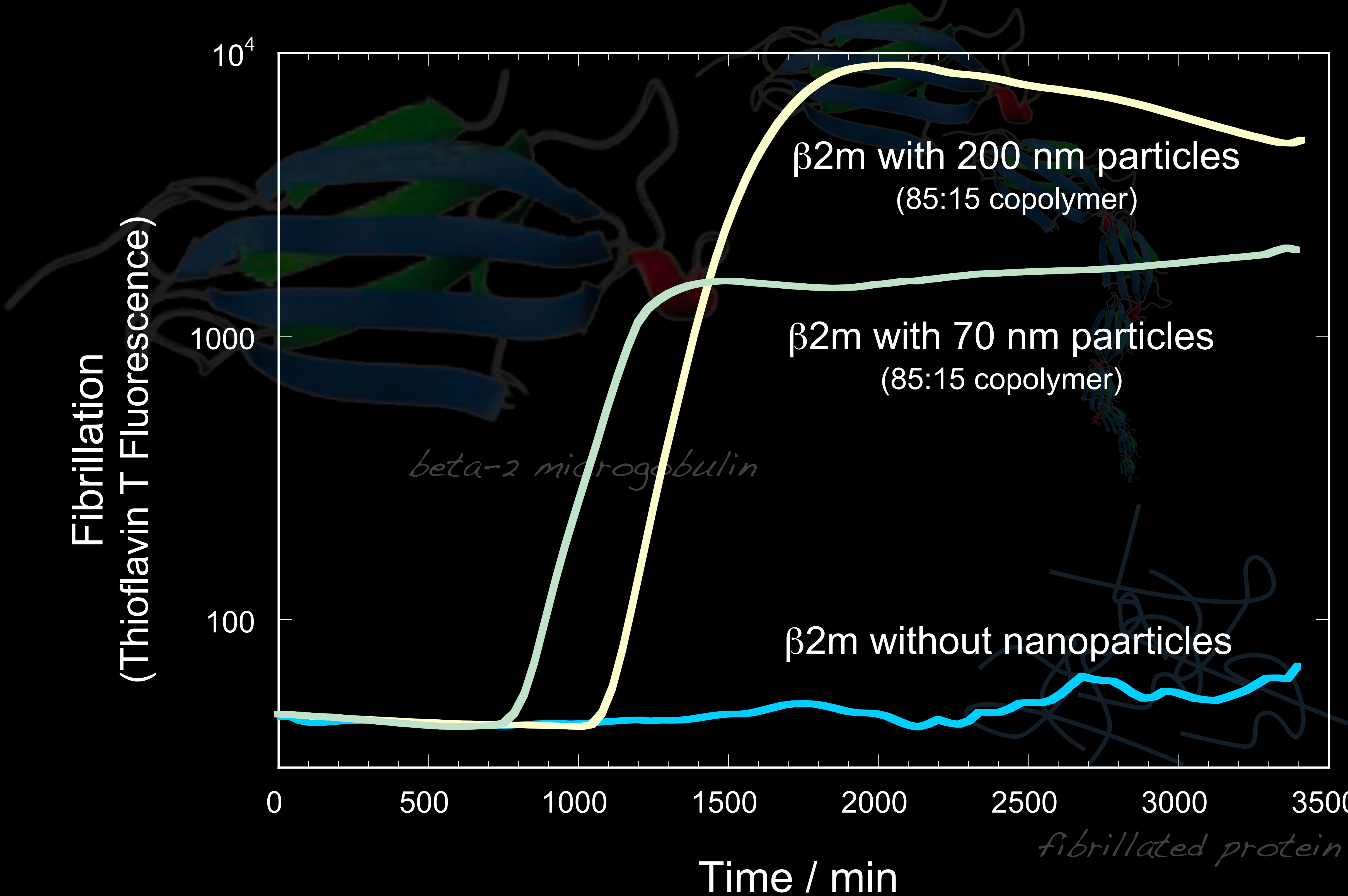
Translocation following inhalation - Nose to Brain



(Based on Oberdörster, G., *et al. (2004)*, *Inhal. Toxicol.* 16 (6-7), 437-445)

Scale-specific hazard: Form

Interfering with biology at the nanoscale

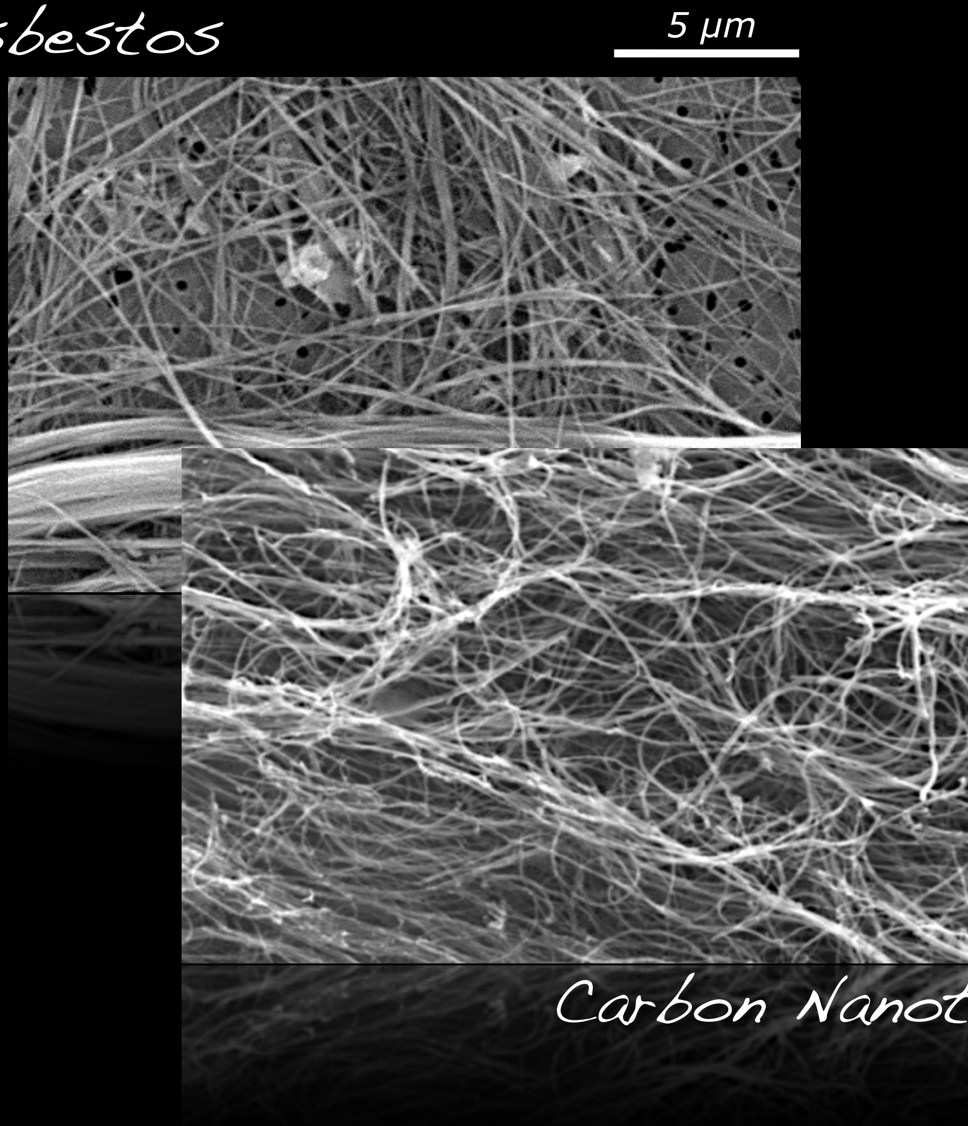


Linse, S., C. Cabaleiro-Lago, W.-F. Xue, I. Lynch, S. Lindman, E. Thulin, S. E. Radford and K. A. Dawson (2007). "Nucleation of protein fibrillation by nanoparticles." Proc. Natl. Acad. Sci. U. S. A. 104: 8691-8696.

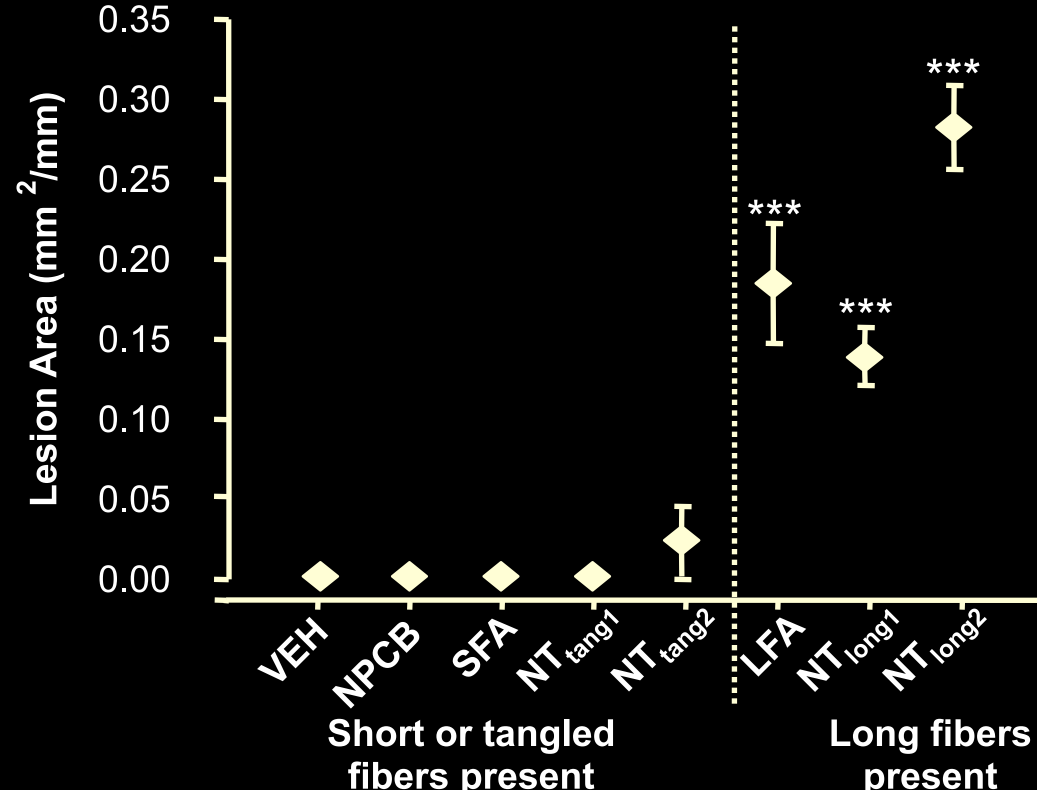
Structure-related hazard: Shape

Influence of shape on a material's risk profile

Asbestos



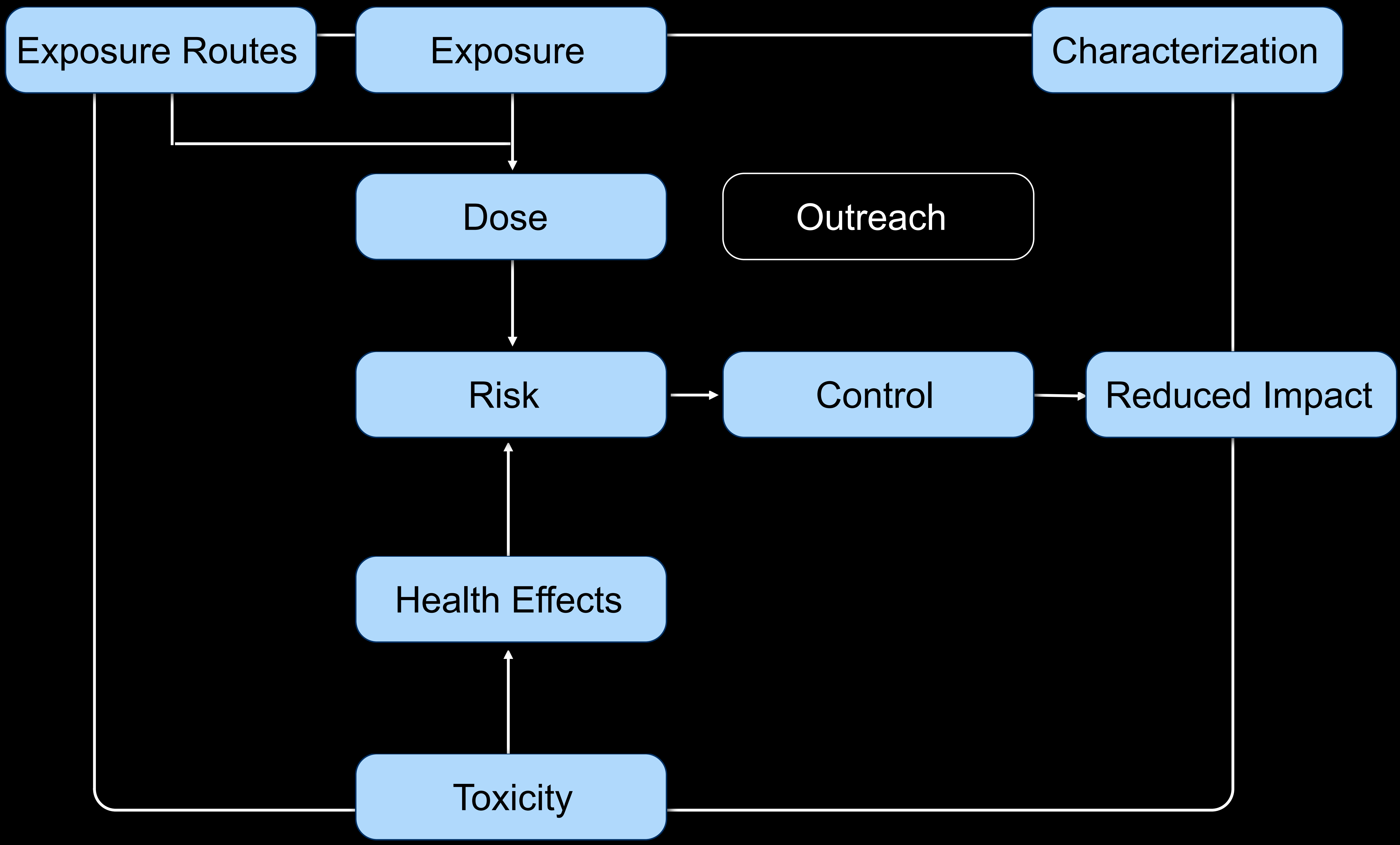
Carbon Nanotubes

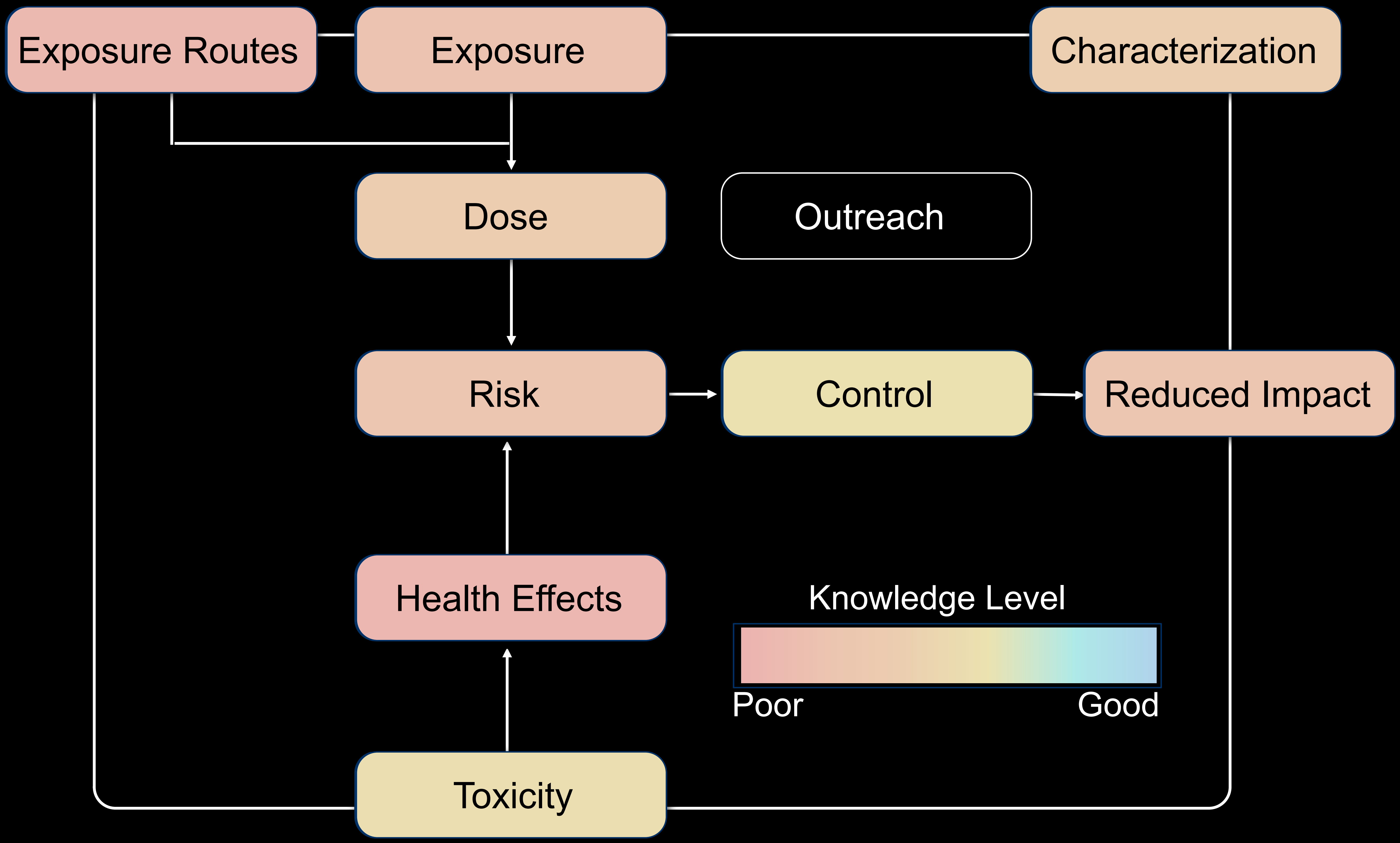


Carbon nanotubes that look like harmful asbestos fibers, behave like harmful asbestos fibers

Source: Craig Poland

Poland, C. A., R. Duffin, I. Kinloch, A. Maynard, W. A. H. Wallace, A. Seaton, V. Stone, S. Brown, W. MacNee and K. Donaldson (2008). "Carbon nanotubes introduced into the abdominal cavity of mice show asbestos-like pathogenicity in a pilot study." Nature Nanotechnology doi:10.1038/nnano.2008.111.

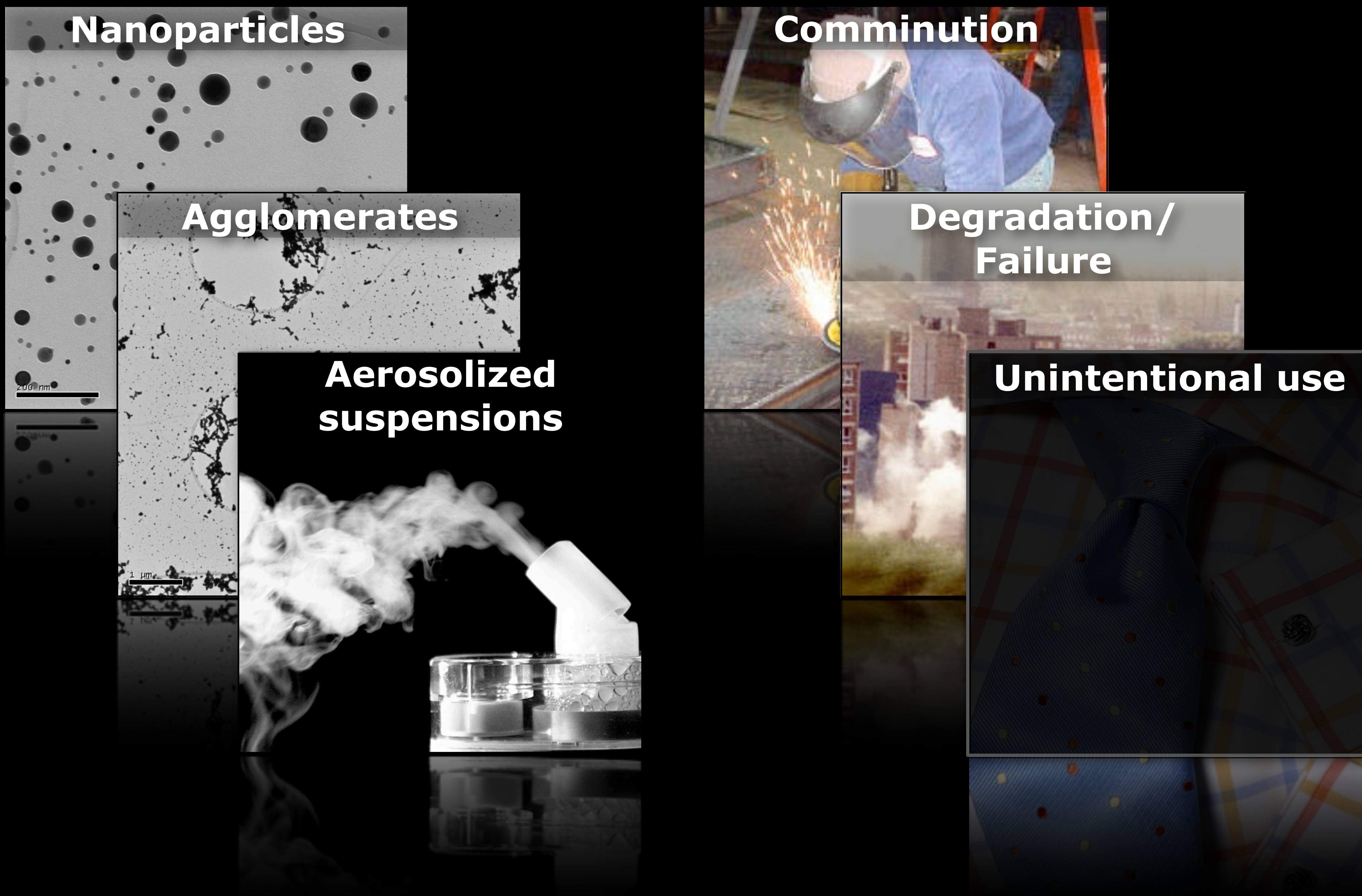

Exposure Routes
Exposure
Characterization
Dose
Outreach
Risk
Control
Reduced Impact
Health Effects
Toxicity



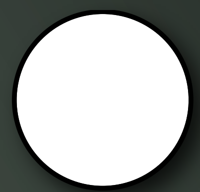
Exposure Routes
Exposure
Characterization
Dose
Outreach
Risk
Control
Reduced Impact
Health Effects
Knowledge Level
Poor
Good
Toxicity

Setting Boundaries

Engineered nanomaterials which potentially present new challenges



Classifying diverse nanoparticles

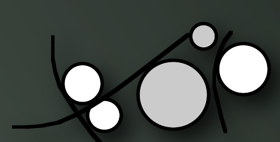


Compact/Sphere
Homogeneous

High aspect ratio
Homogeneous

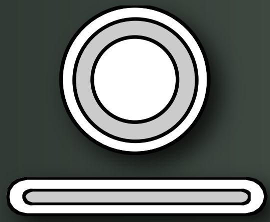
Complex non-spherical
Homogeneous

Homogeneous agglomerates
Single particle class

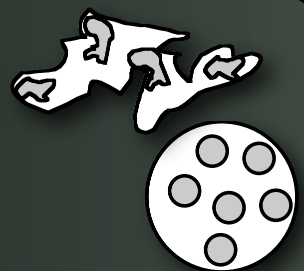


Heterogeneous aggregates
Many particle classes

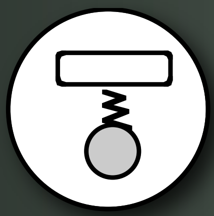
Heterogeneous
Core-surface



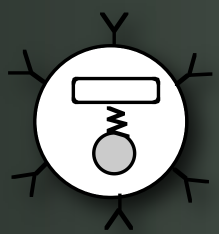
Heterogeneous
Distributed



Active
External stimuli



Multifunctional
Complex responses



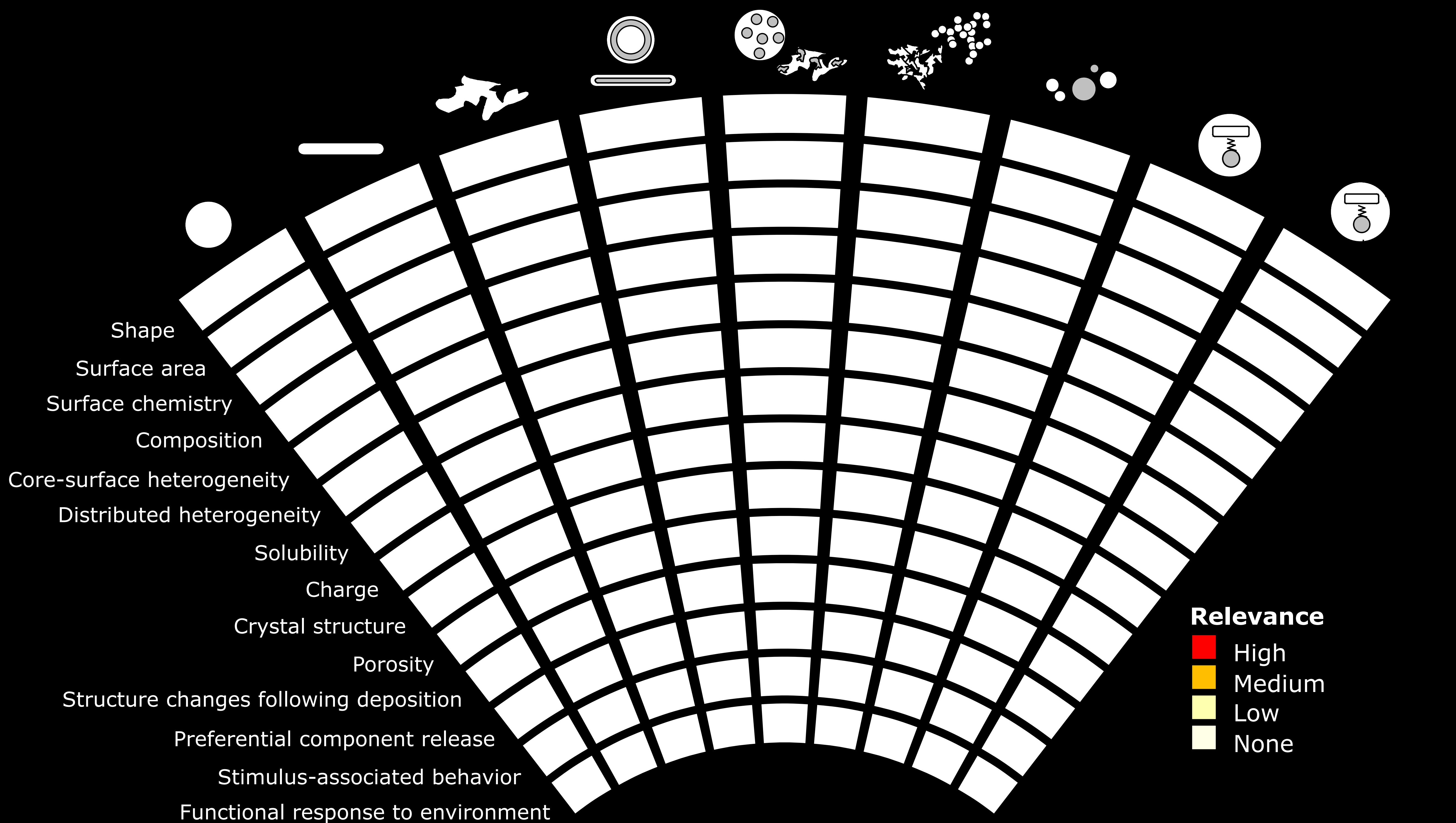
Maynard, A. D. and R. J. Aitken (2007). Nanotoxicology 1(1): 26-41.

Potentially significant attributes

- Differentiated component release
- Shape
- Core-surface Heterogeneity
- Charge
- Response to environment
- Porosity
- Response to stimulus
- Surface Area
- Surface Chemistry
- Crystal Structure
- Composition
- Distributed Heterogeneity
- Solubility
- Propensity to change structure

Maynard, A. D. and R. J. Aitken (2007). Nanotoxicology 1(1): 26-41.

Assessing the relevance of different exposure metrics



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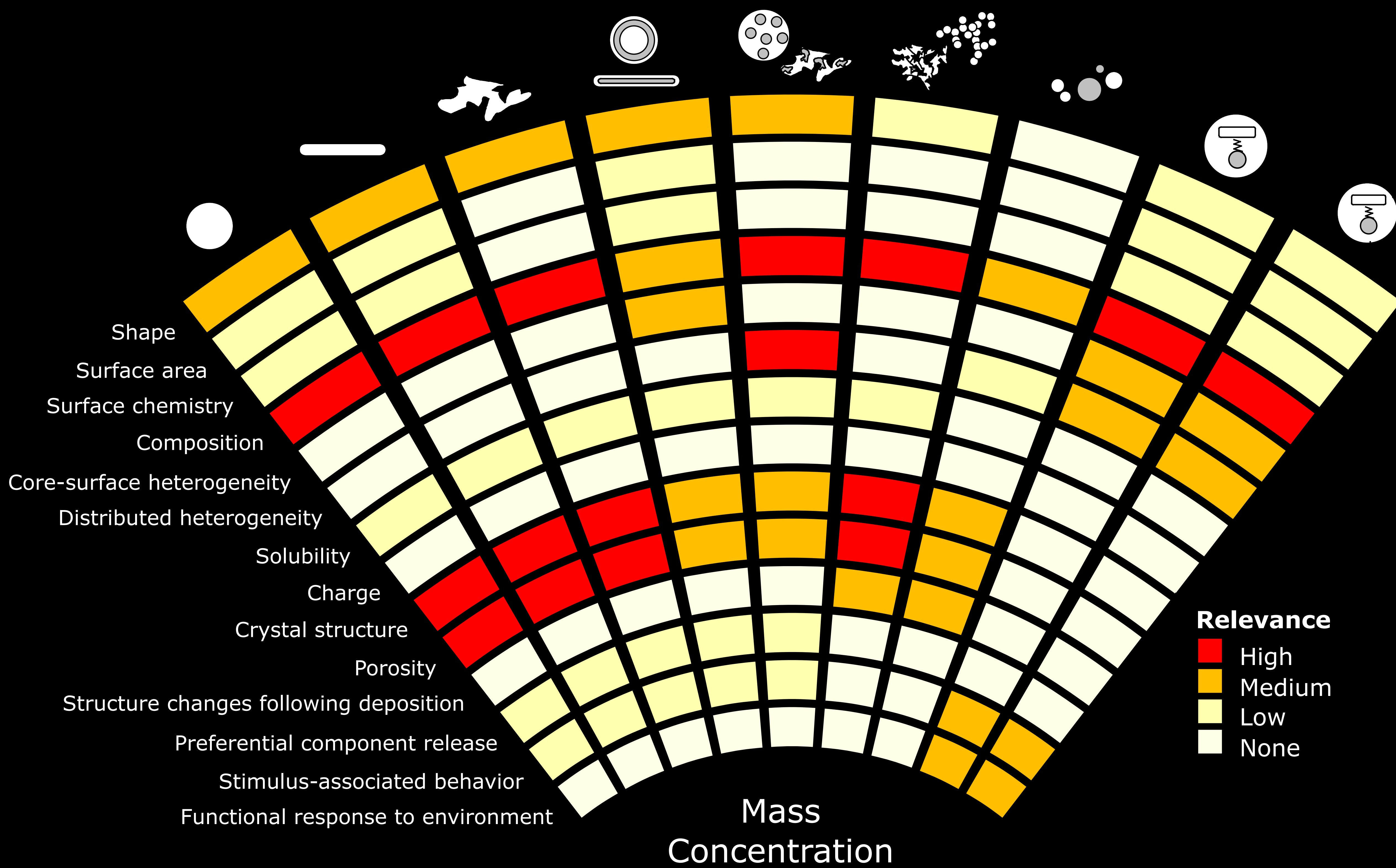
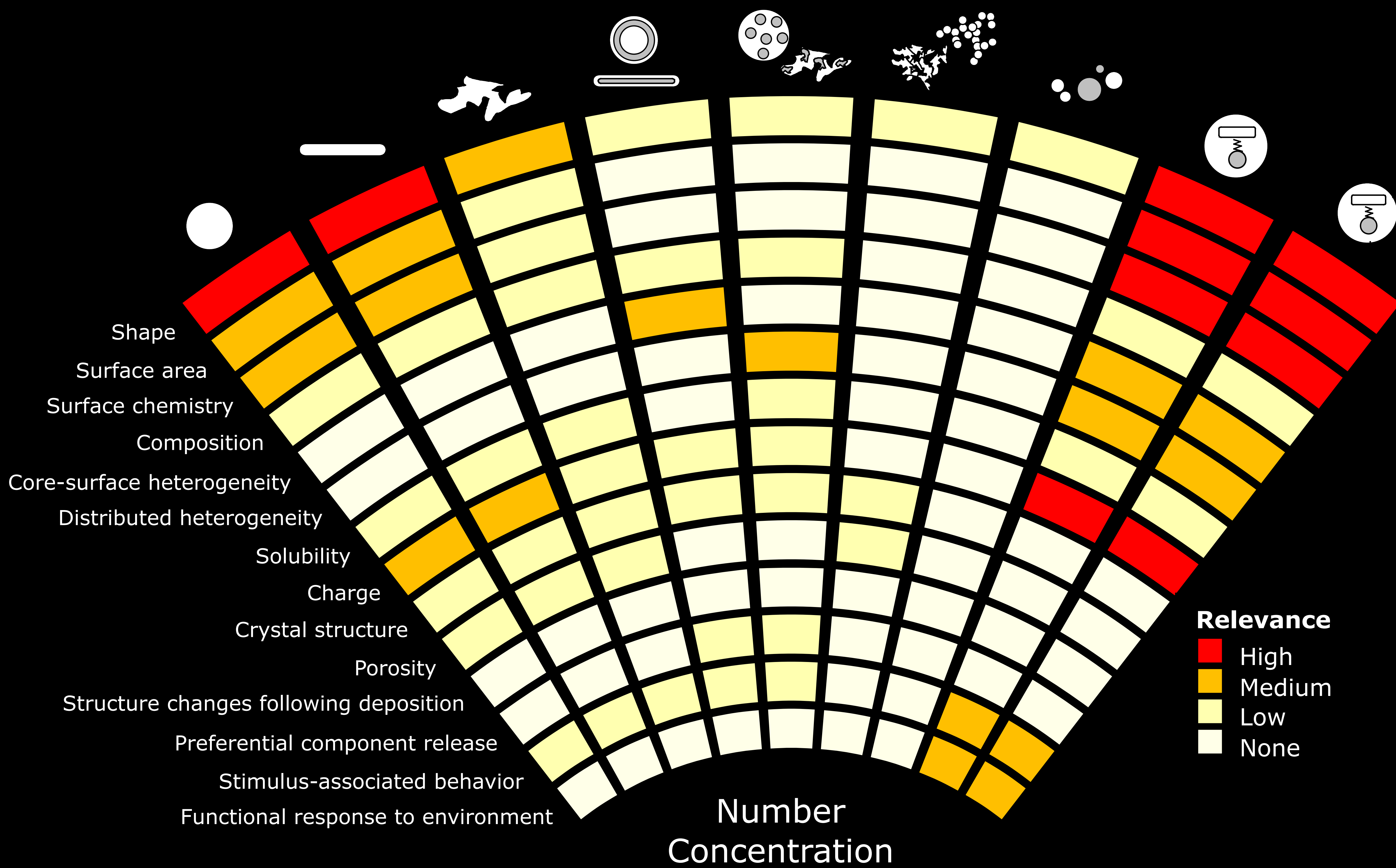
Mass



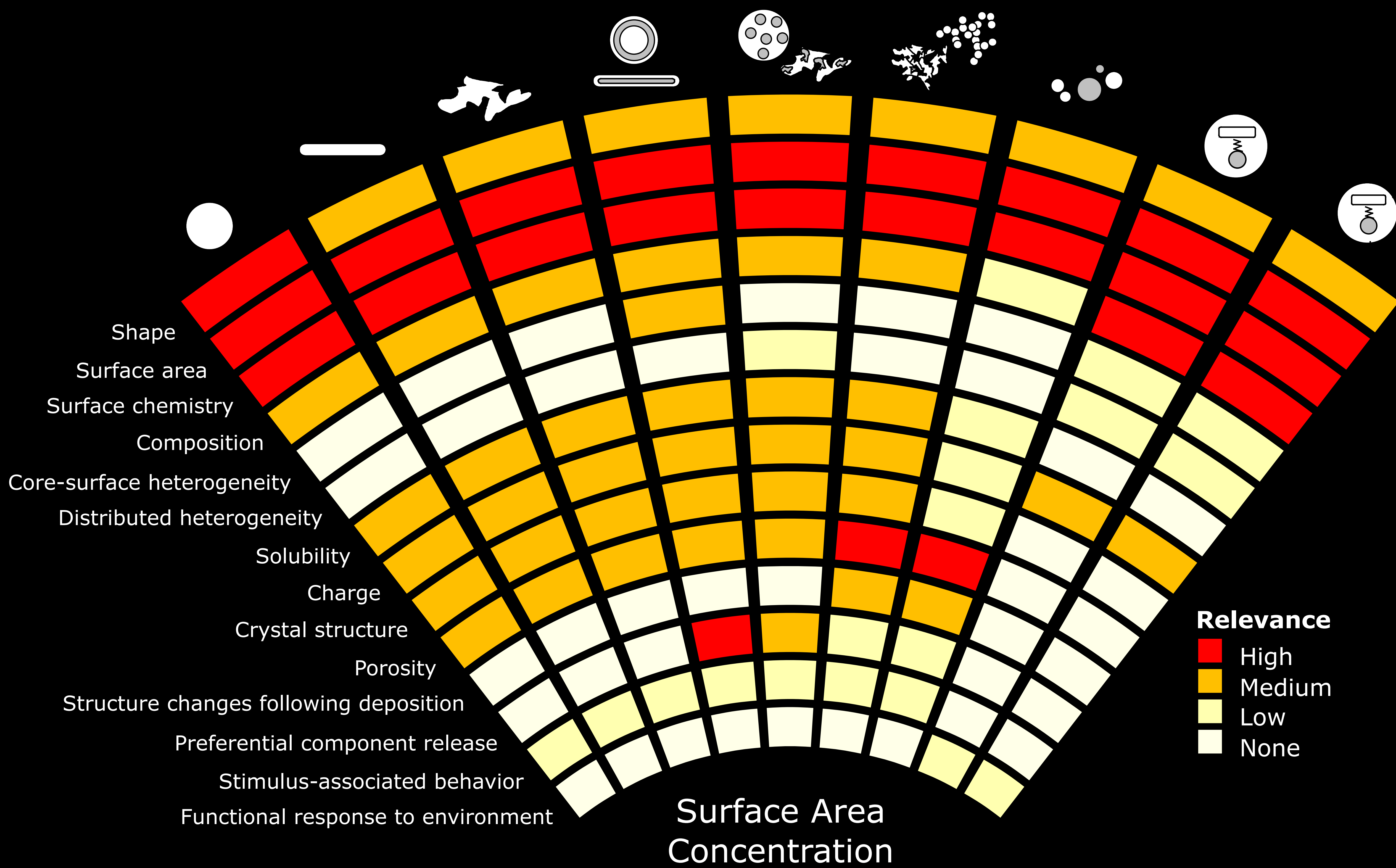
Maynard, A. D. and R. J. Aitken (2007). Nanotoxicology 1(1): 26-41.

Particle Number



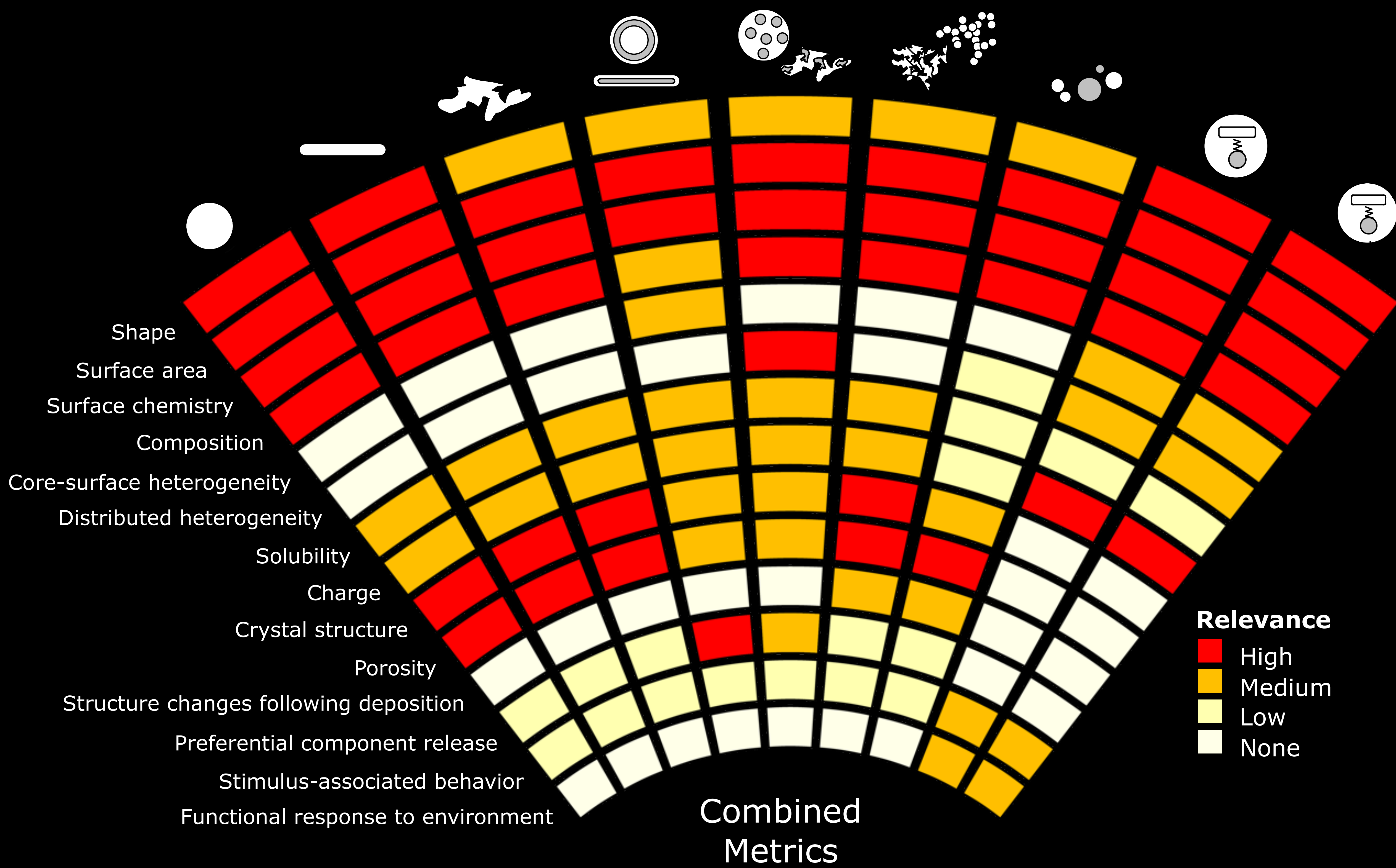
Maynard, A. D. and R. J. Aitken (2007). Nanotoxicology 1(1): 26-41.

Surface Area



Maynard, A. D. and R. J. Aitken (2007). Nanotoxicology 1(1): 26-41.

Number, Mass or Surface Area



Maynard, A. D. and R. J. Aitken (2007). Nanotoxicology 1(1): 26-41.

Nature Vol. 444/16
November 2006

Vol 444|16 November 2006 nature

COMMENTARY

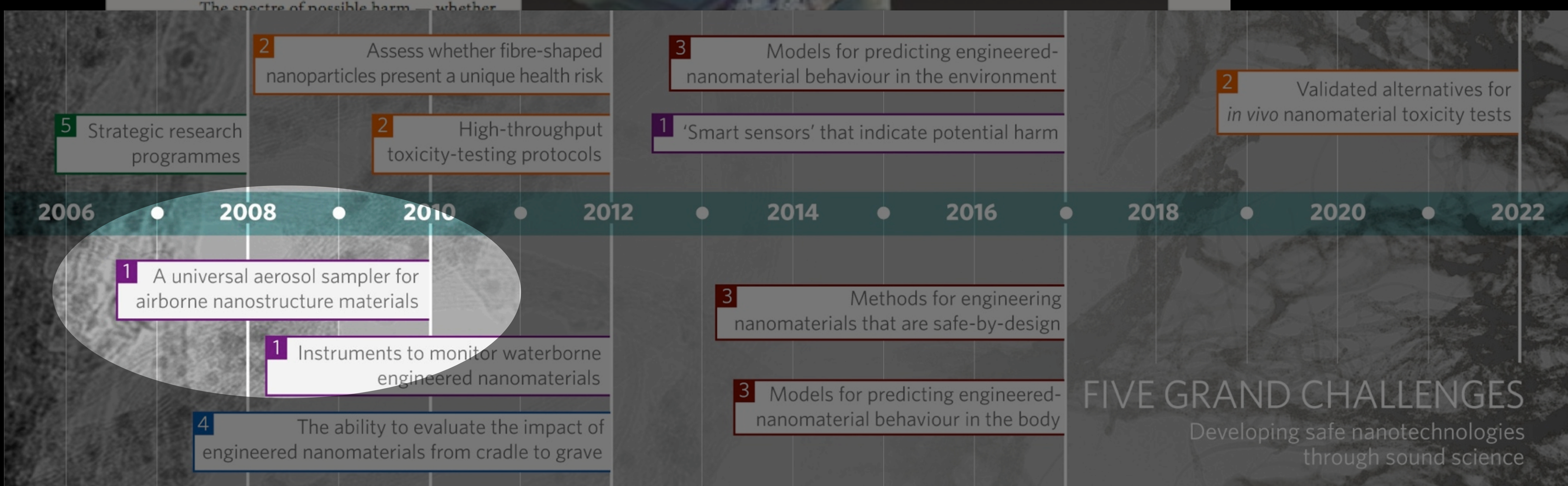
Safe handling of nanotechnology

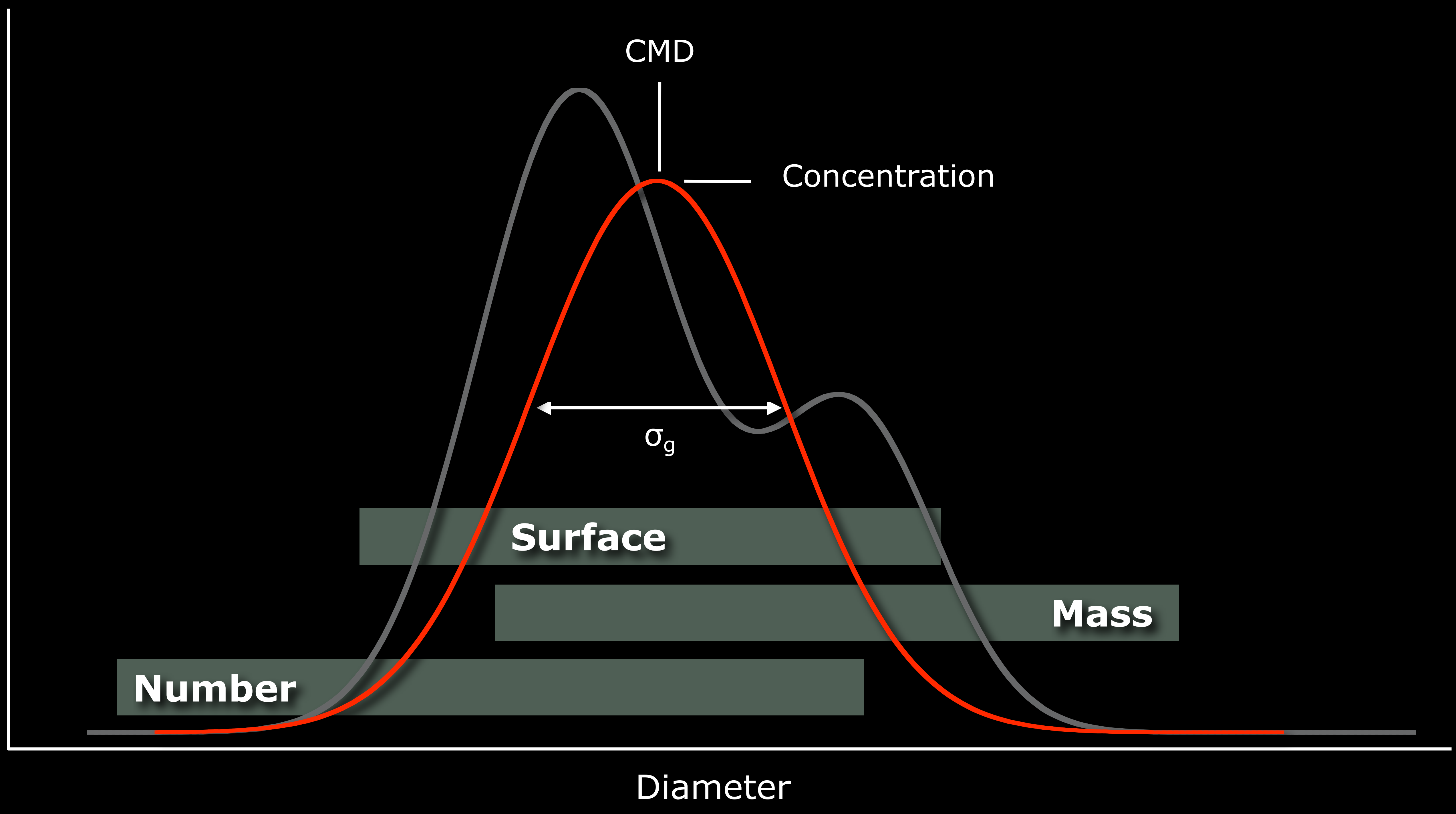
The pursuit of responsible nanotechnologies can be tackled through a series of grand challenges, argue **Andrew D. Maynard** and his co-authors.

When the physicist and Nobel laureate Richard Feynman challenged the science community to think small in his 1959 lecture 'There's Plenty of Room at the Bottom', he planted the seeds of a new era in science and technology. Nanotechnology, which is about controlling matter at near-atomic scales to produce unique or enhanced materials, products and devices, is now maturing rapidly with more than 300 claimed nanotechnology products already on the market[1]. Yet concerns have been raised that the very properties of nanostructured materials that make them so attractive could potentially lead to unforeseen health or environmental hazards[2].

The spectre of possible harm — whether

D. RAMSEY

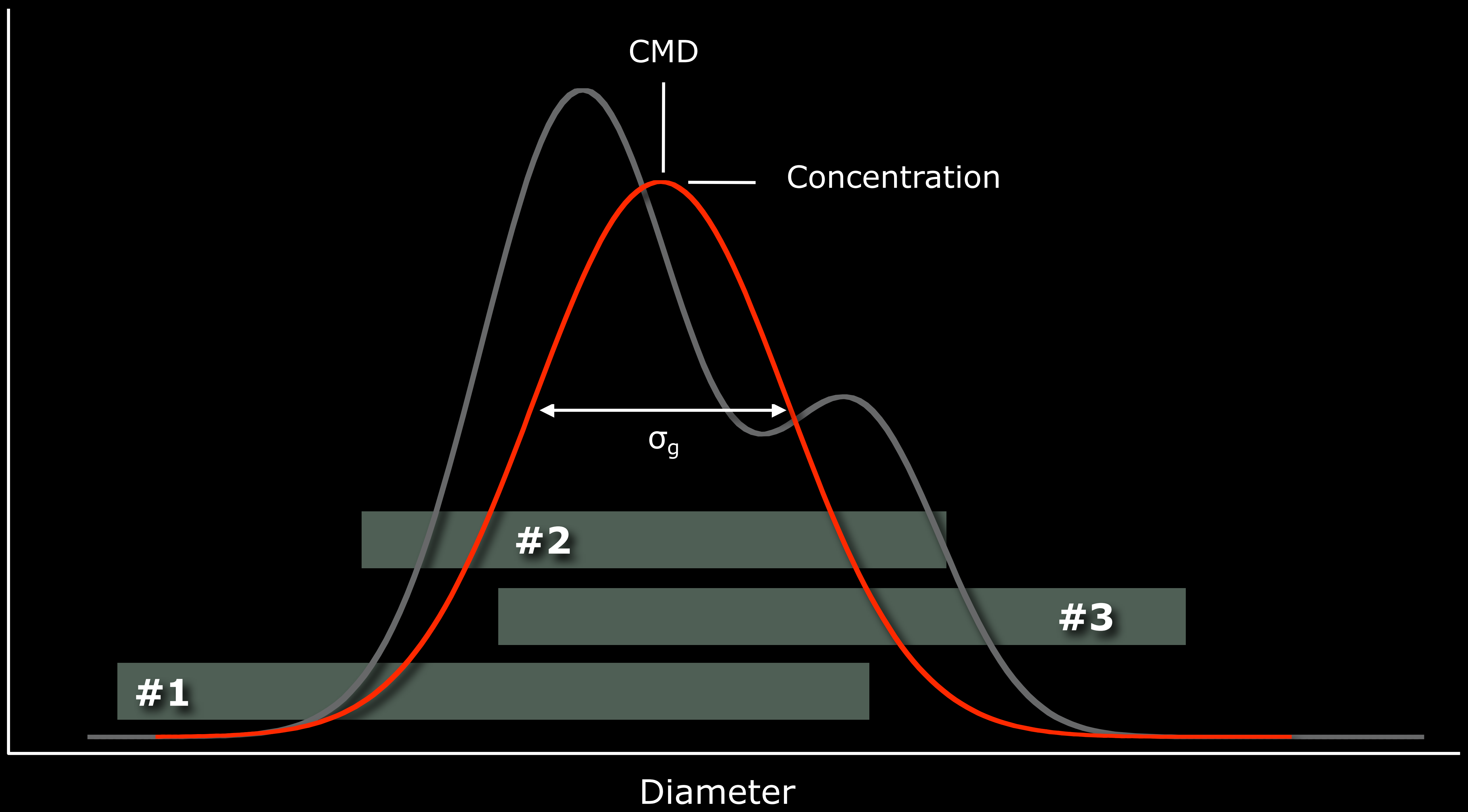




Woo, K.-S., Chen, D.-R., Pui, D. Y. H. and Wilson, W. E. (2001). Use of continuous measurements of integral aerosol parameters to estimate particle surface area. Aerosol Sci. Tech. 34:57-65.

Maynard, A. D. (2003). Estimating aerosol surface area from number and mass concentration measurements. Ann. Occup. Hyg. 47:123-144.

Sophisticated data inversion can offer insight into nano-aerosol exposure from relatively few measurements



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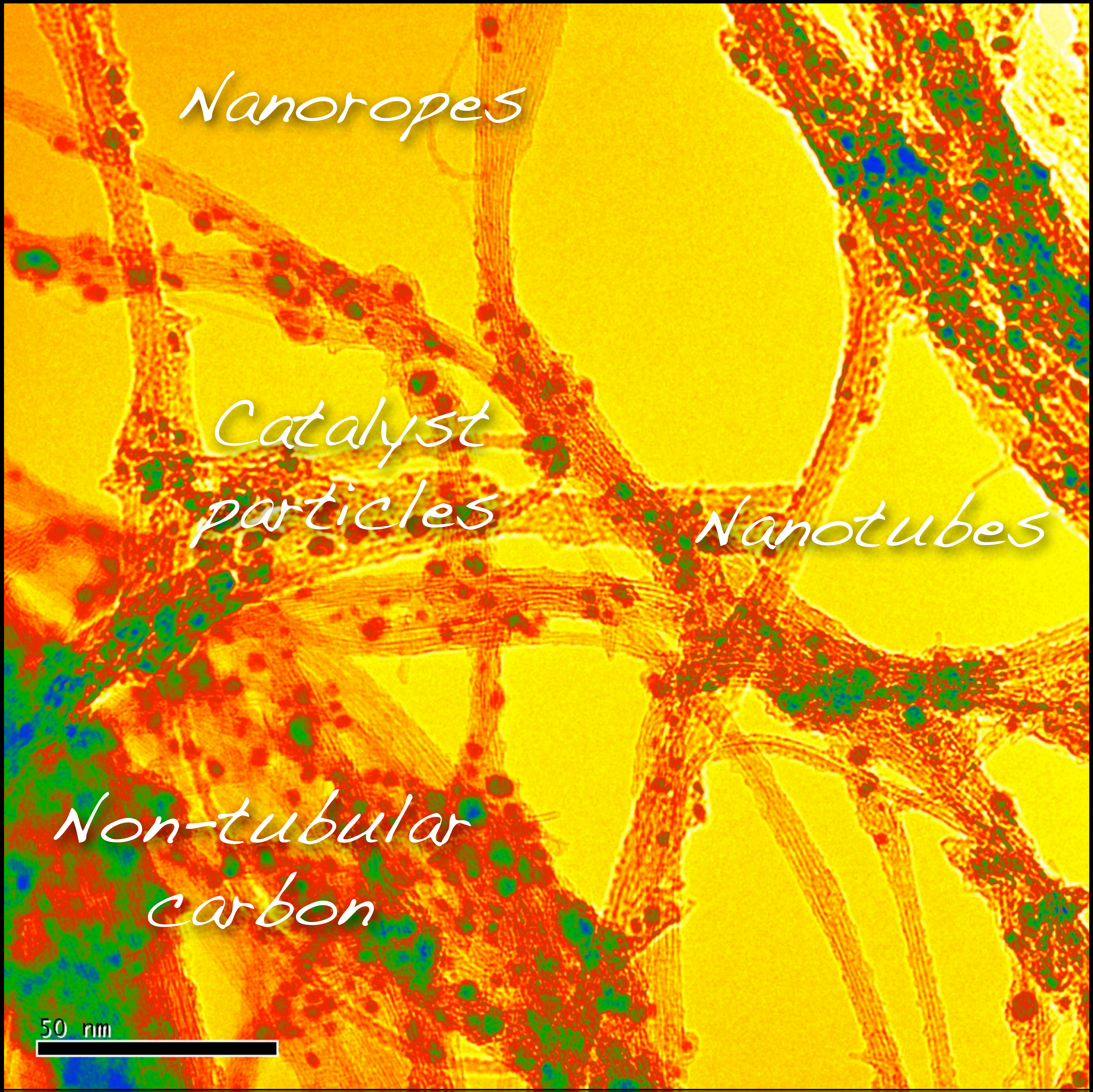
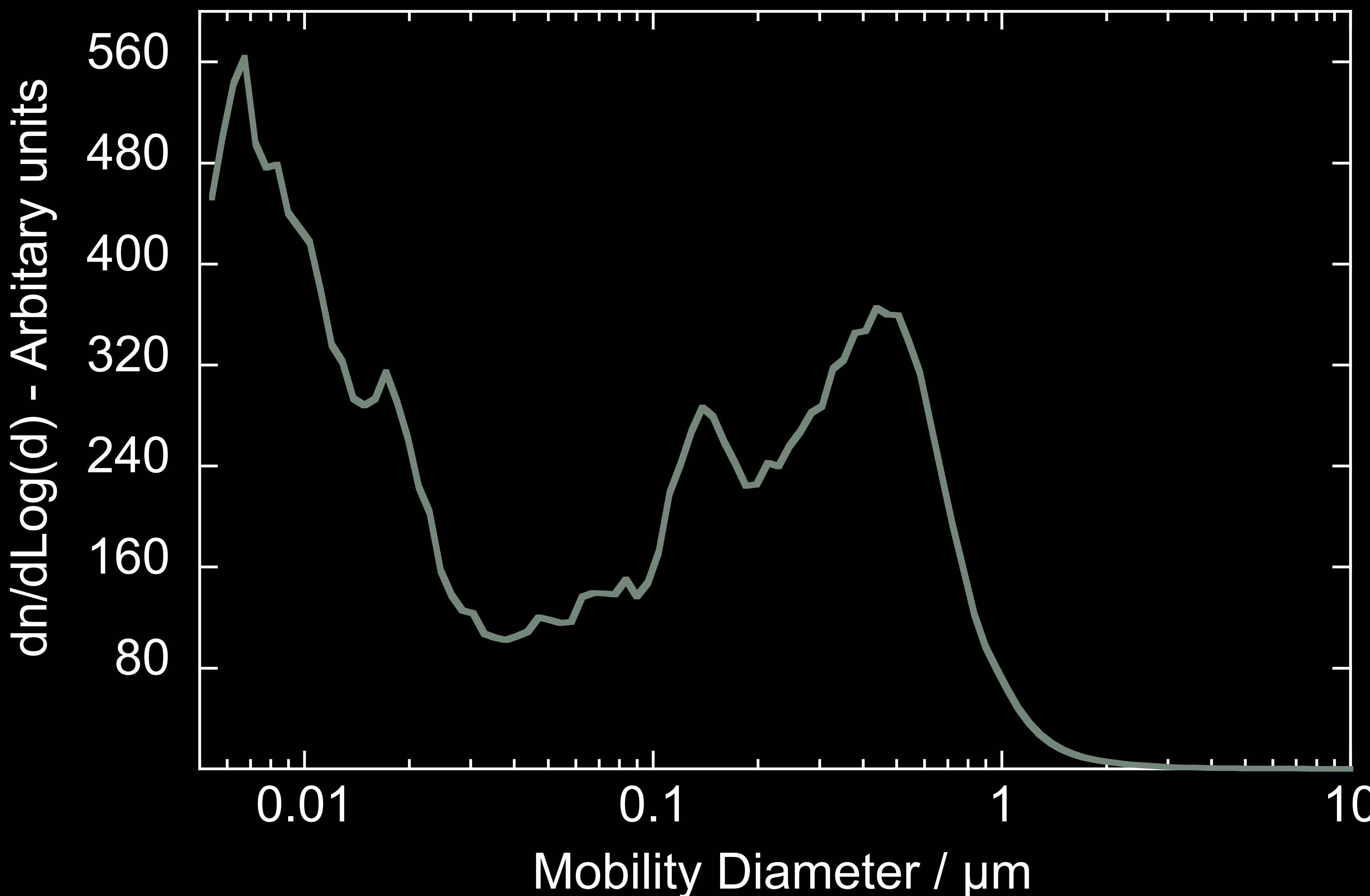


Unprocessed single walled carbon nanotube material, HiPCO Process

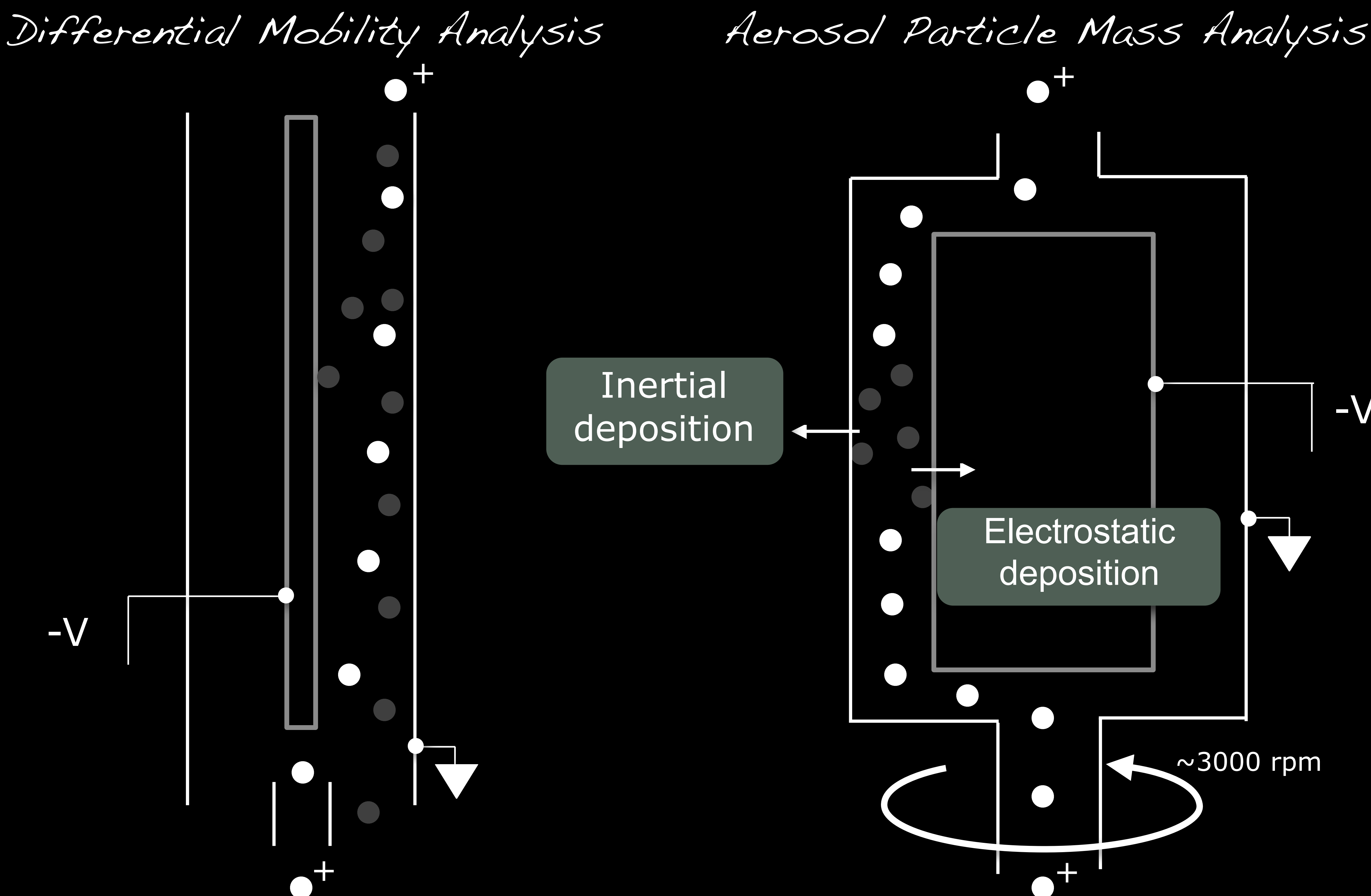
SWCNT Aerosol

Generated from dry material through energetic agitation



Maynard, A. D., P. A. Baron, et al. (2004). J. Toxicol. Environ. Health 67(1): 87-107.

Characterizing airborne carbon nanotubes



Structural Parameter

Proportional to specific surface area

$$Selection_{DMA} \propto \pi \bar{d}_m^2$$ - units of surface area

$$Selection_{APM} \propto qE \frac{\bar{r}}{\omega^2}$$ - units of mass

$$\Gamma = \frac{\pi \bar{d}_m^2}{q\bar{r}} \frac{\omega^2}{E}$$

Maynard, A. D., B. K. Ku, M. Emery, M. Stolzenburg and P. H. McMurry (2007). J. Nanopart. Res. 9(1): 85-92.

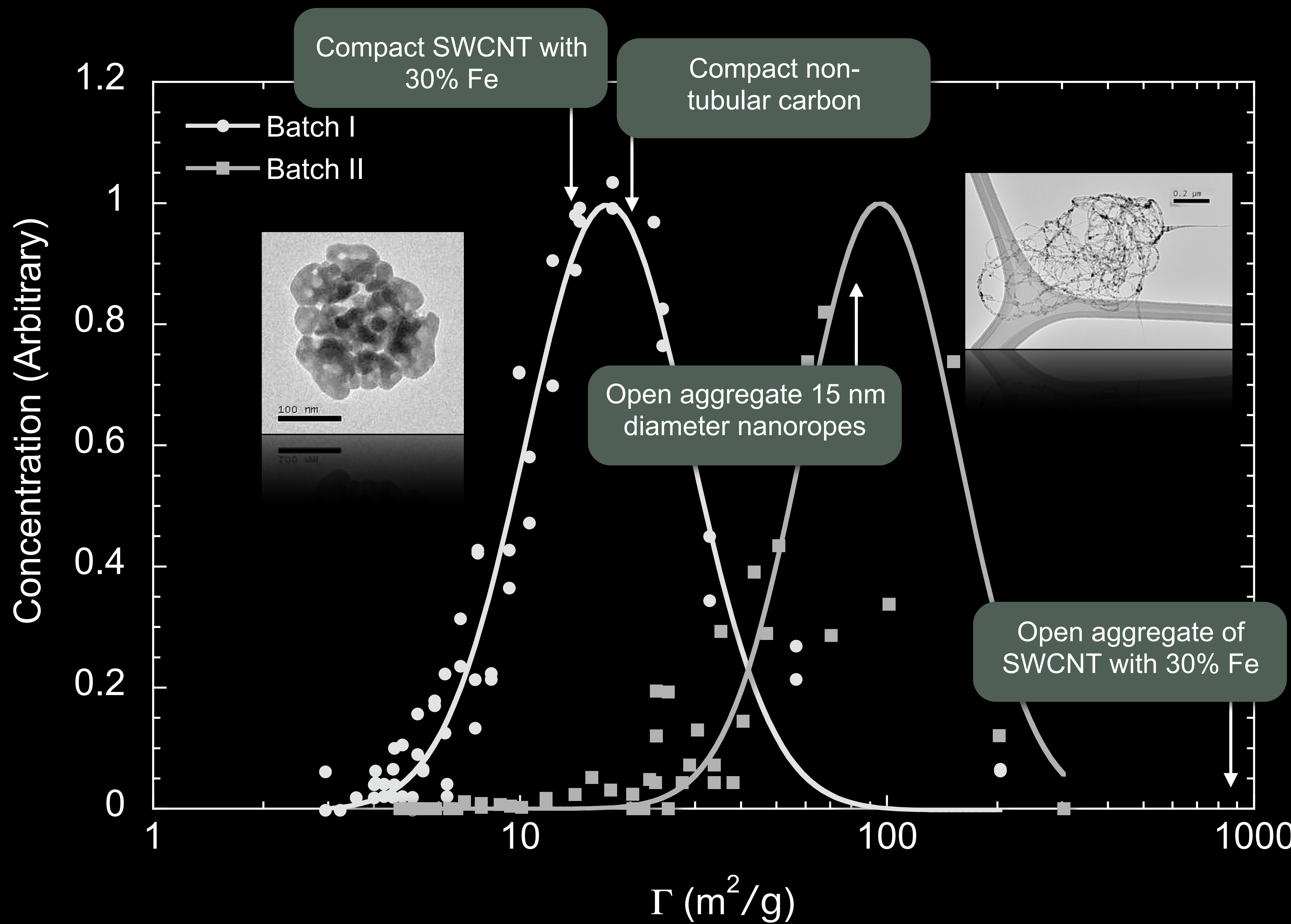
Structural Parameter

Predicted Values

Particle description	Mobility Diameter	Predicted value of Gamma (m^2/g)
Compact non-tubular carbon particles	150 nm	20
Open agglomerate of single walled carbon nanotube with 30% Fe	150 nm	860
Open agglomerate of 5 nm diameter Fe particles	150 nm	150
Compact single walled carbon nanotubes with 30% Fe	31 nm	58
Open agglomerate of 5 nm diameter nanoropes with 30% Fe	31 nm	240

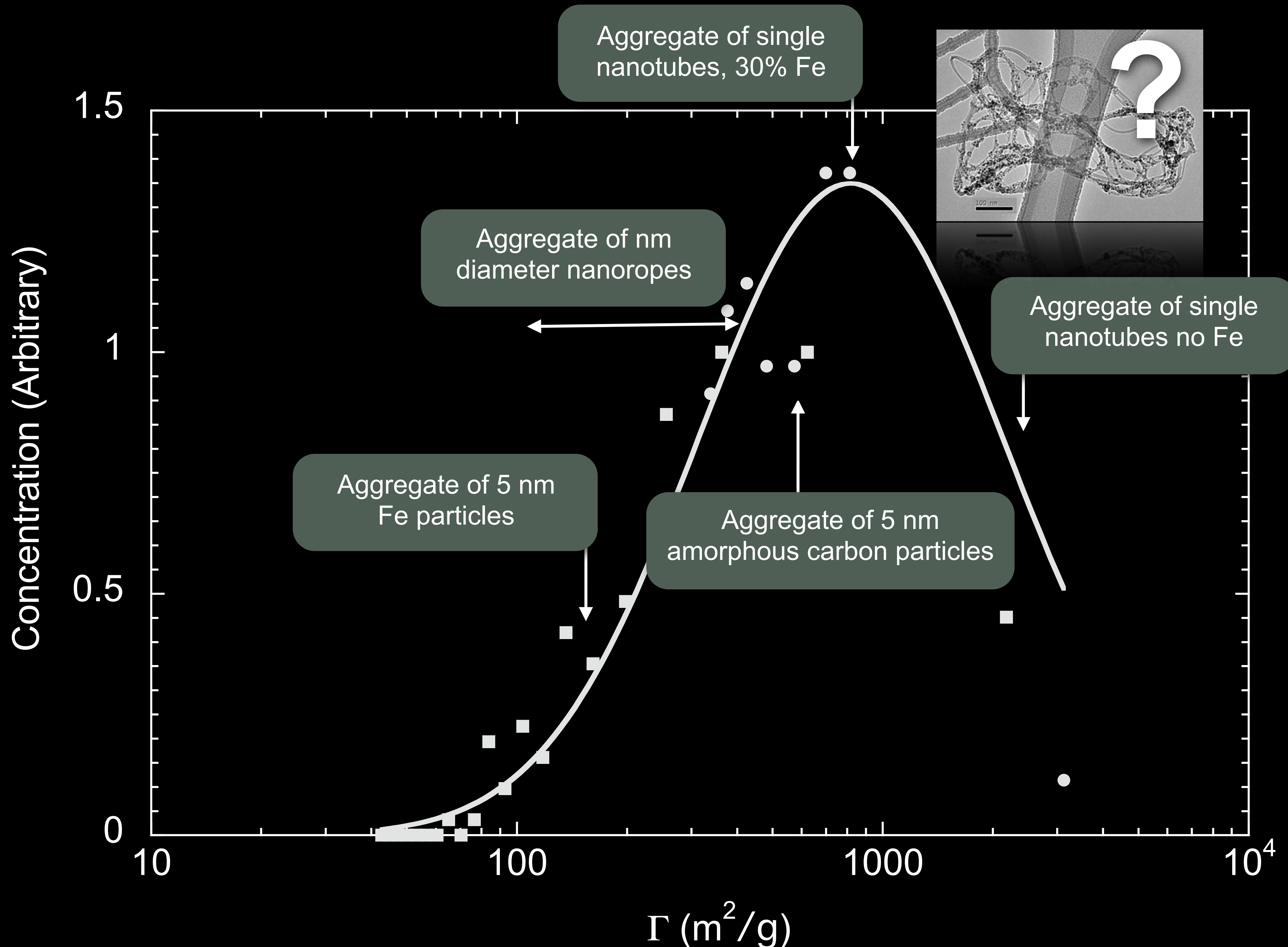
Maynard, A. D., B. K. Ku, M. Emery, M. Stolzenburg and P. H. McMurry (2007). J. Nanopart. Res. 9(1): 85-92.

150 nm mobility diameter particles



Maynard, A. D., B. K. Ku, M. Emery, M. Stolzenburg and P. H. McMurry (2007). J. Nanopart. Res. 9(1): 85-92.

31 nm mobility diameter particles



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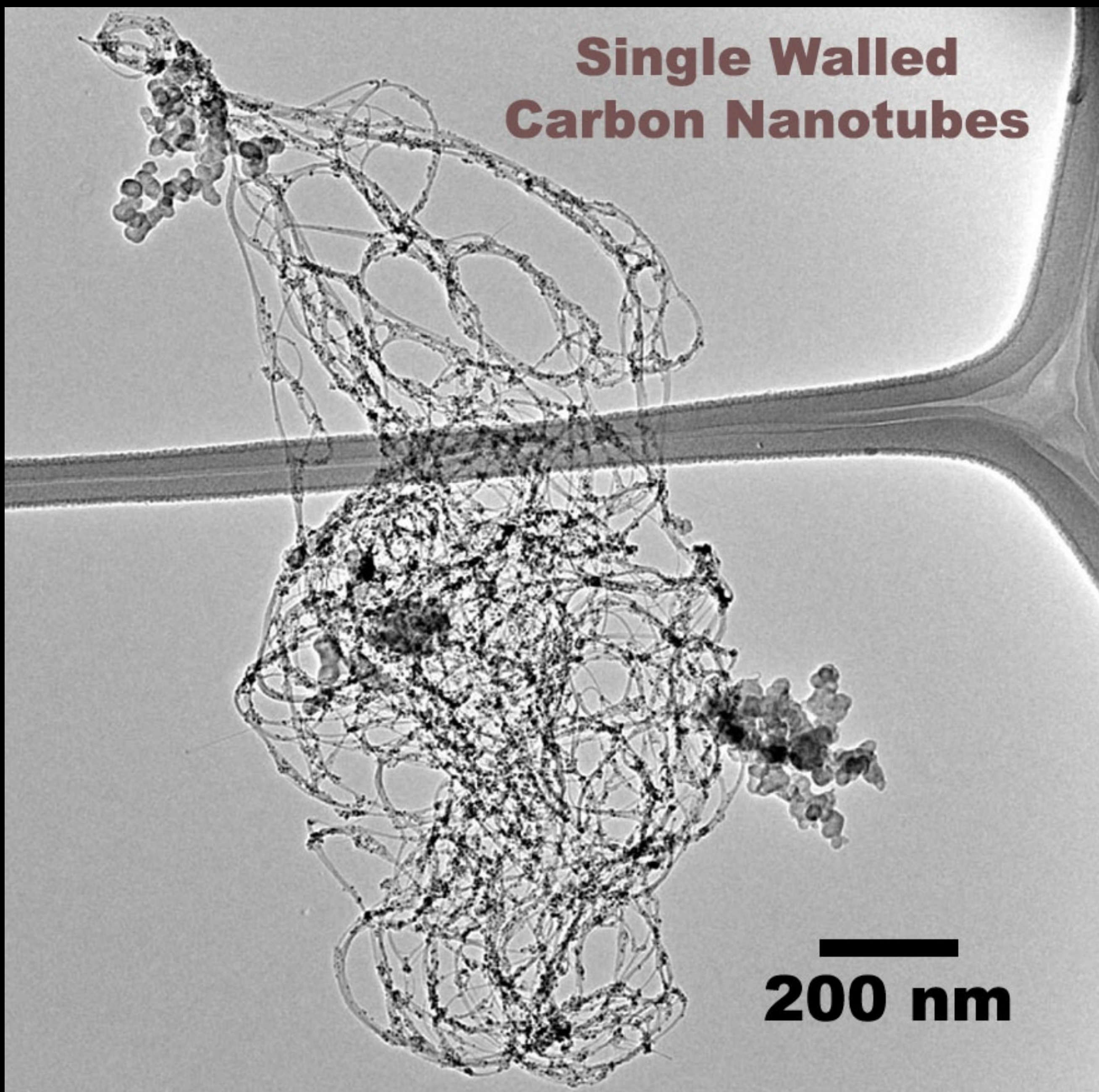
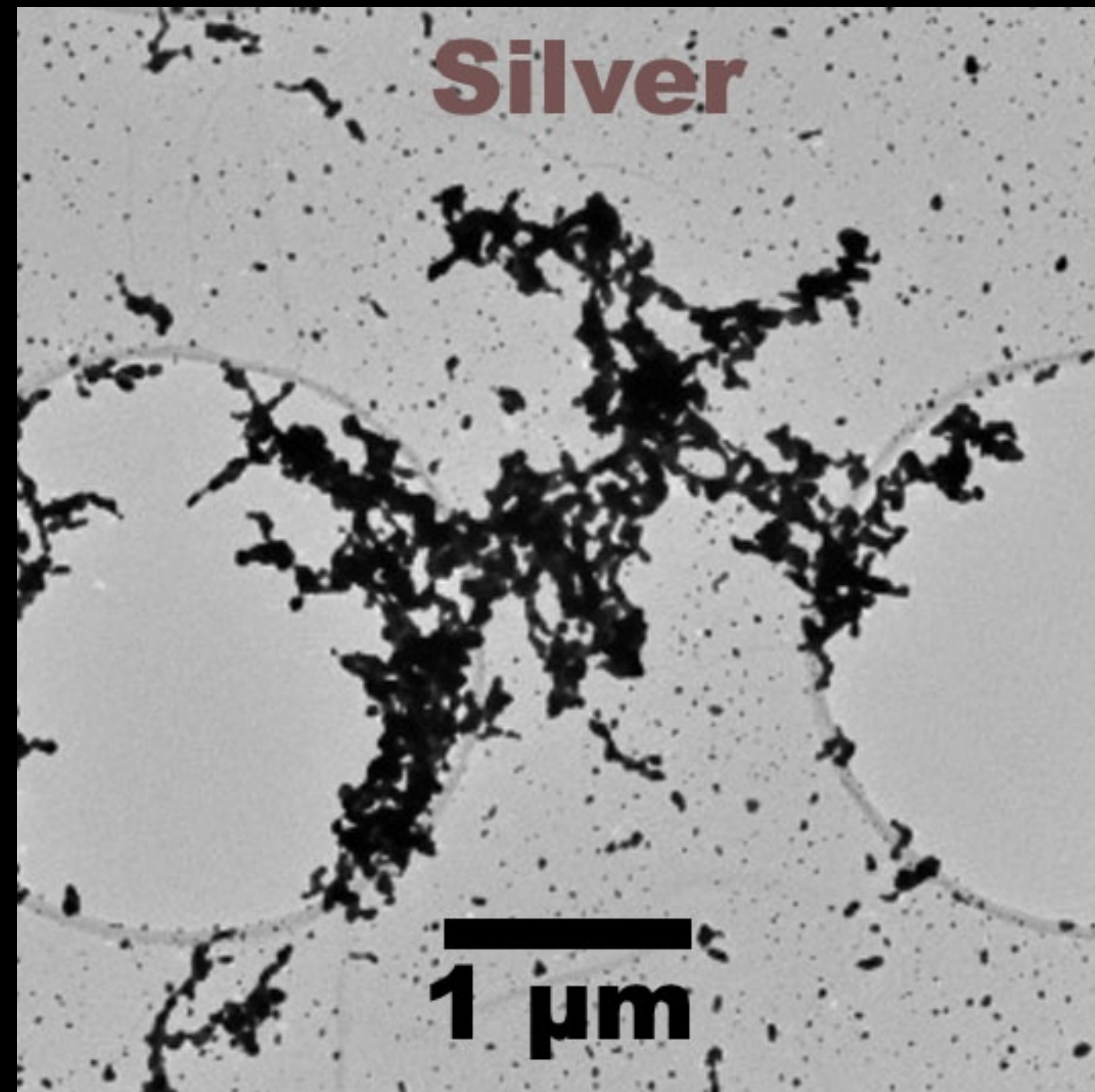
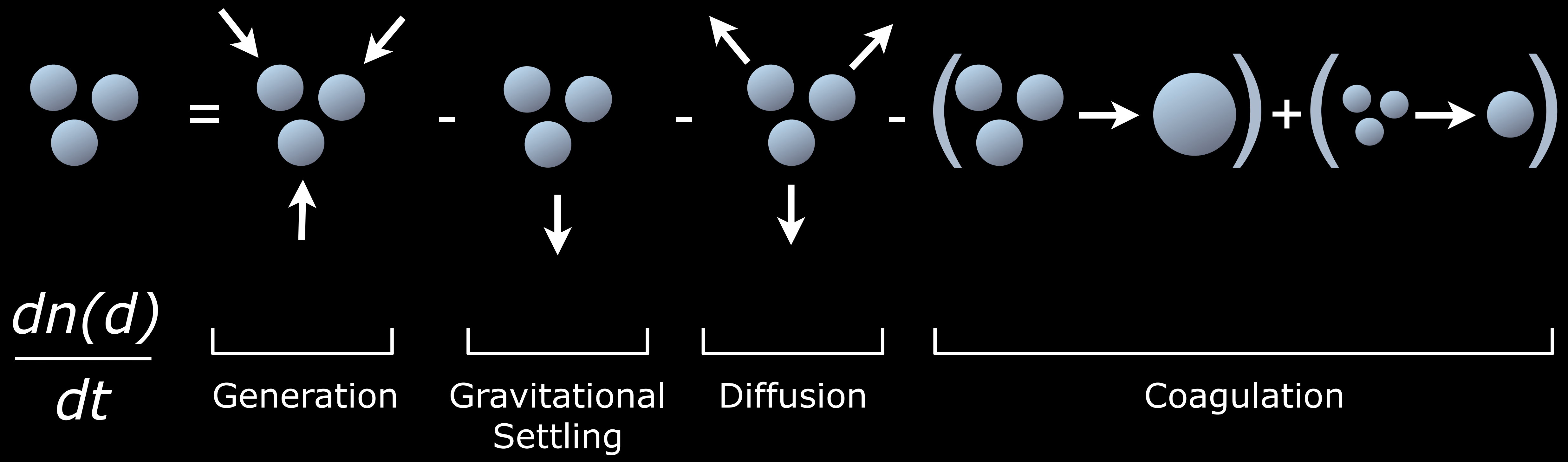
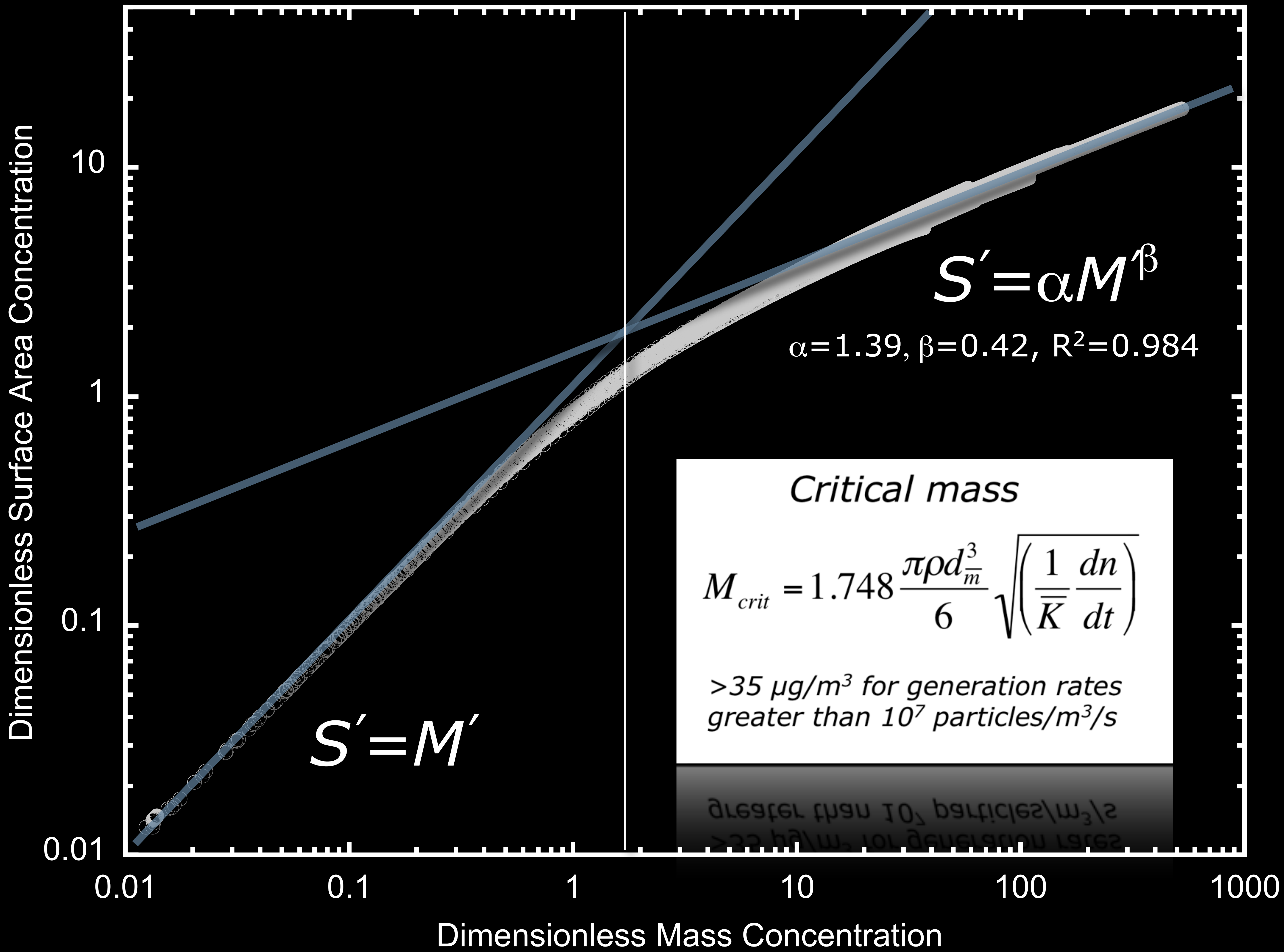

Single Walled
Carbon Nanotubes
200 nm


Silver
1 µm

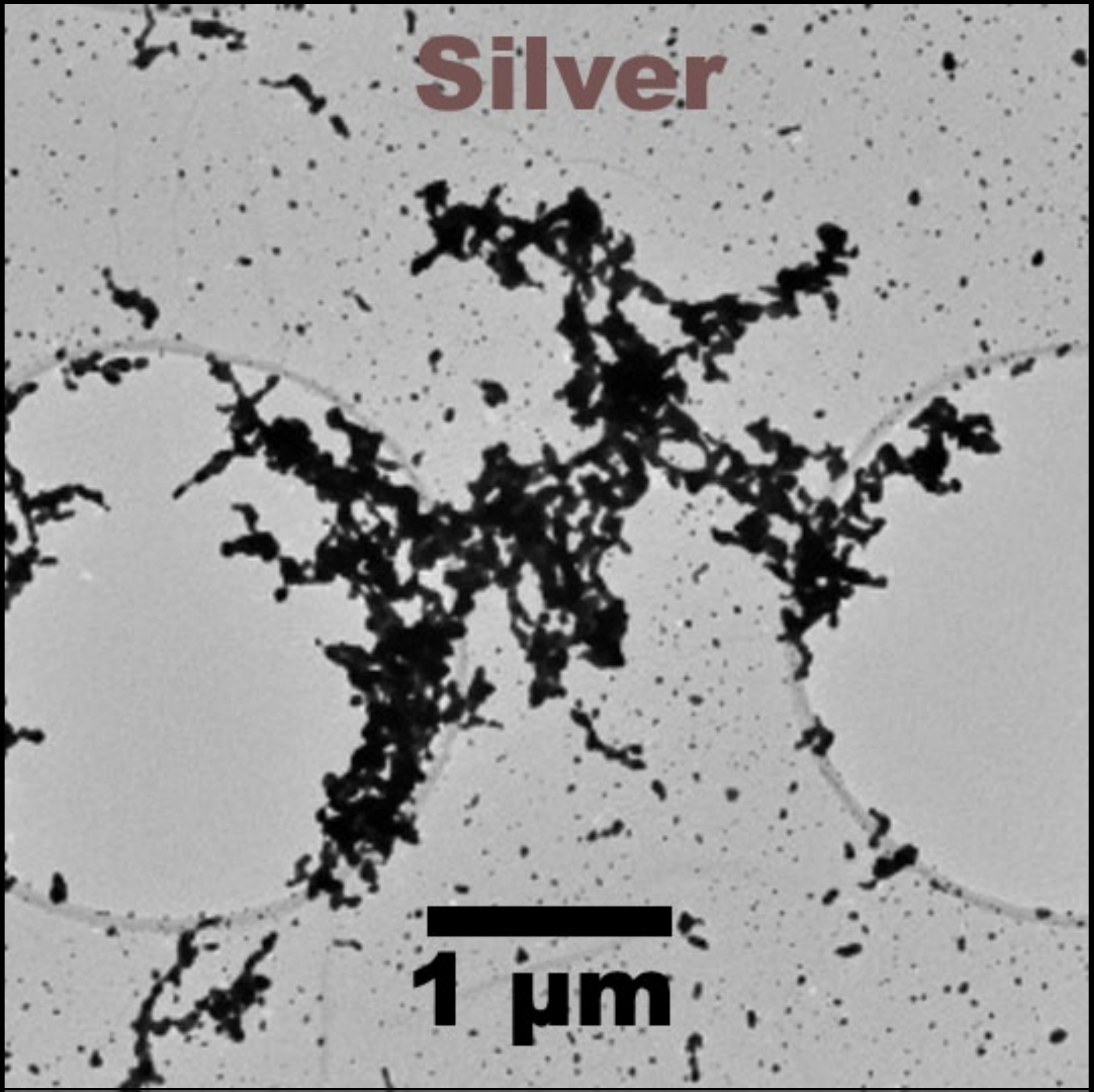
Agglomeration - complex model

Using the General Dynamic Equation

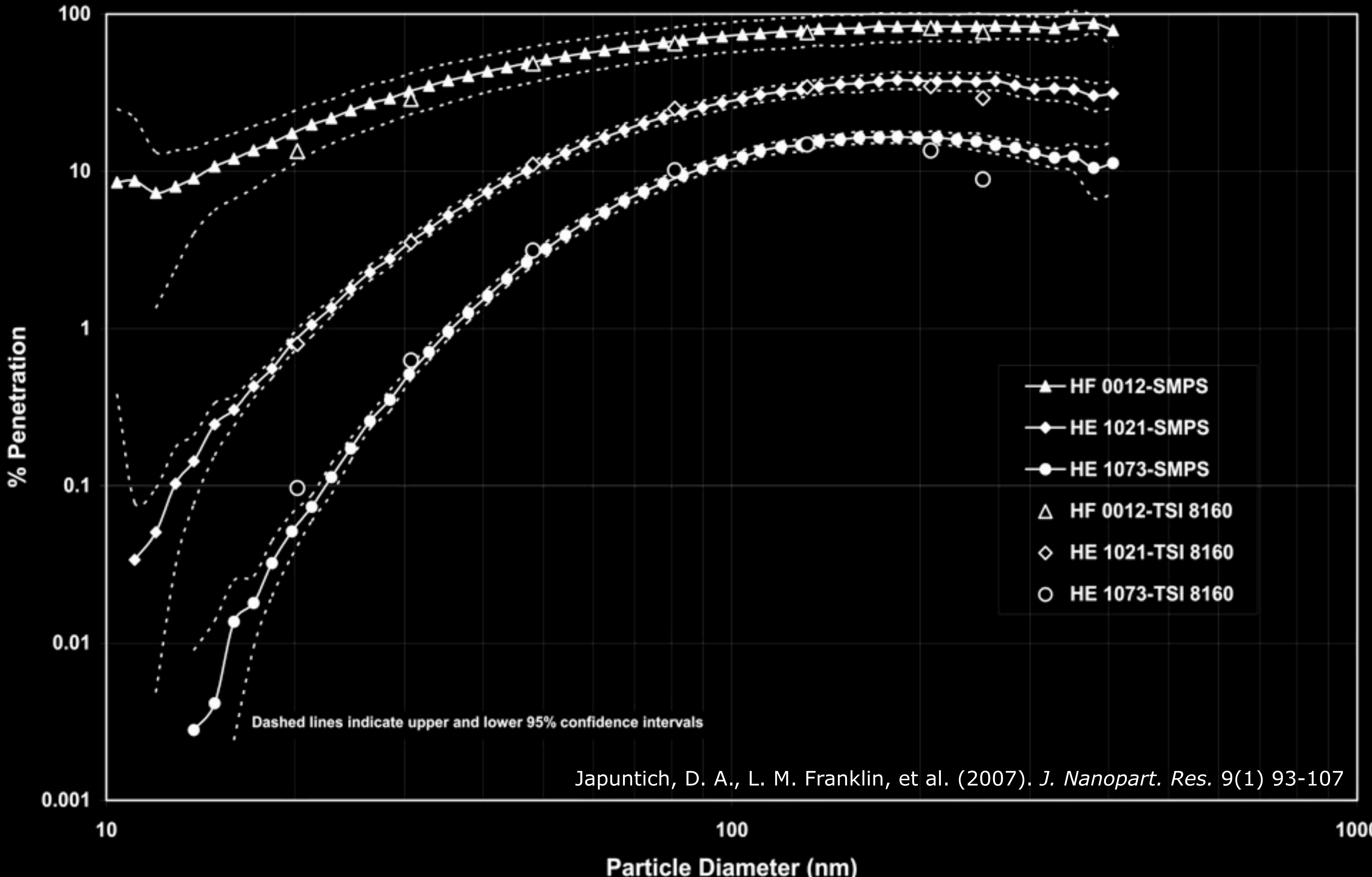




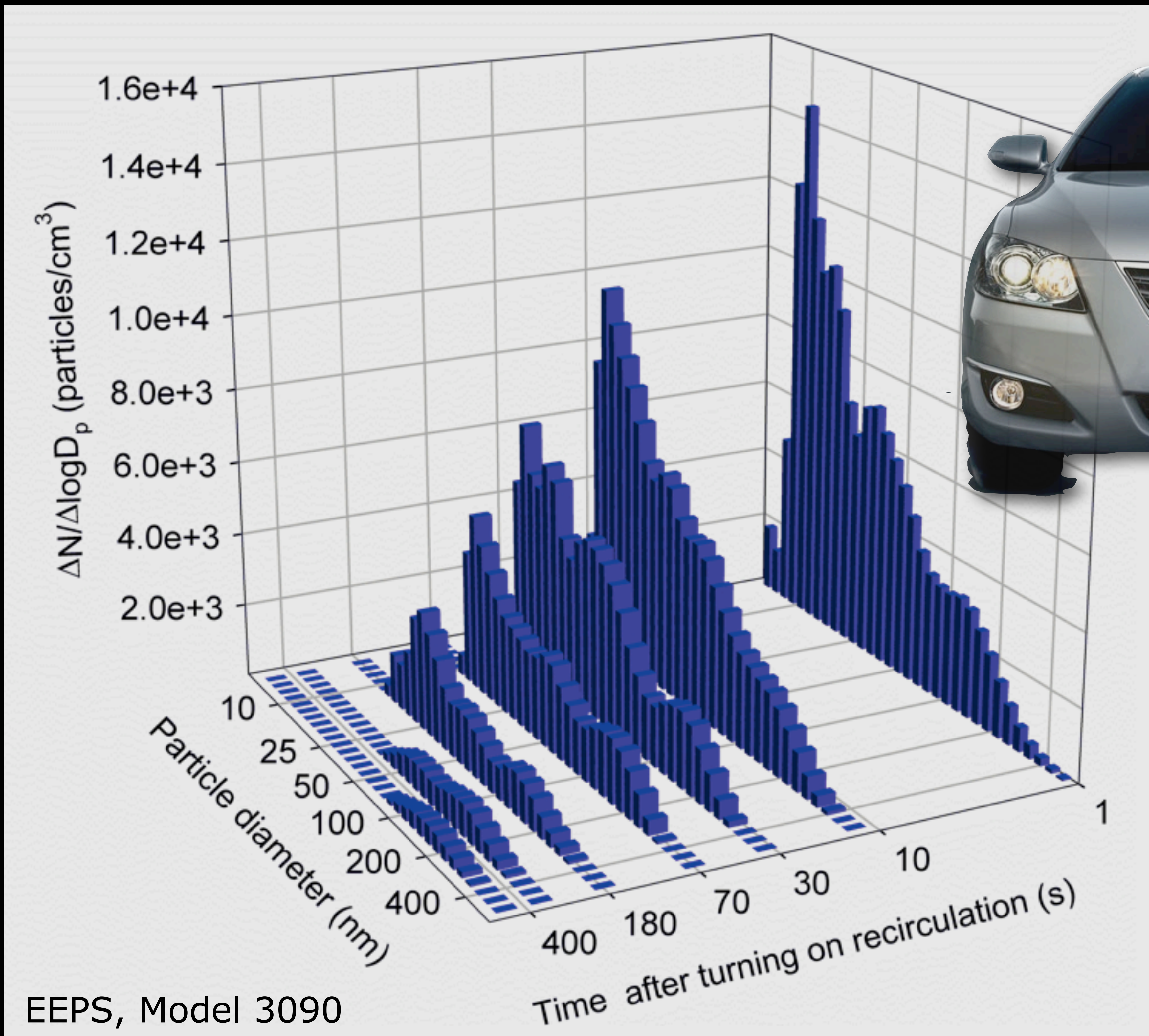
Maynard, A. D. and Maynard, R. L. (2002). A derived association between ambient aerosol surface area and excess mortality using historic time series data. Atmos. Env. 36:5561-5567.


Silver
1 µm

Filter penetration



Japuntich, D. A., L. M. Franklin, et al. (2007). *J. Nanopart. Res.* 9(1) 93-107



Min efficiency ~ 20%

Driving in heavy traffic, air recirculation on.

In-cabin aerosol < 4000 particles/m3 within 3 minutes

Pui, D. Y. H., Qi, C., Stanley, N., Oberdörster, G. and Maynard, A. (2008). Recirculating Air Filtration Significantly Reduces Exposure to Airborne Nanoparticles. Environ Health Perspect doi:10.1289/ehp.11169.

POLICY

(Science in Context)

Topless Humans Organized for Natural Genetics (THONG)

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Advanced Materials
Therapeutics
Renewable Energy
Clean Water

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