# Measuring and Modeling Exposures to Nanomaterials in Complex Systems

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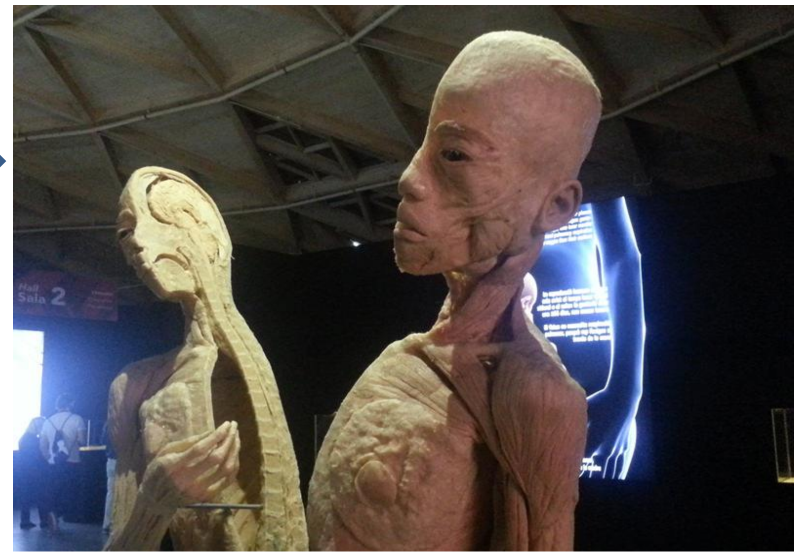
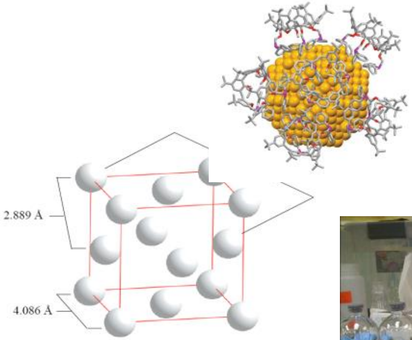
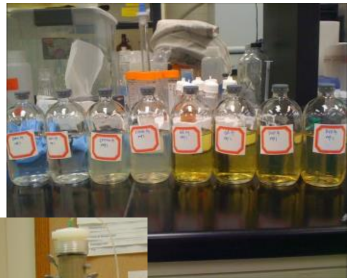


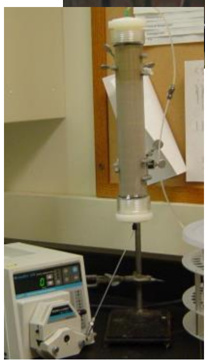
# Estimating Exposure to Nanomaterials

- What do you measure?
  - System inputs (Bernd Nowack/Westerhoff talks)
  - Key processes/factors affecting exposure
- How do you measure it?
  - New methods vs. adapting old methods
  - Transformations
- How do you get measurements into exposure models?
  - What models do you use?
  - How do you parameterize those models?

# CEINT Approach





Increasing Complexity

Simple systems

Managed complexity

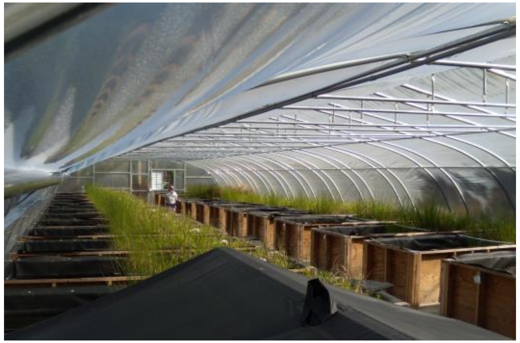
Models

Natural system "real"

Increasing Scale

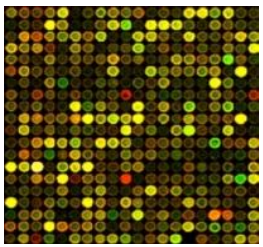
Ag, Au, CuO, Ni, ZnO, $TiO_2$, and $CeO_2$, CNT/$C_{60}$, 2-D materials

# Iterative Method for Understanding Complex Behaviors



mesocosm

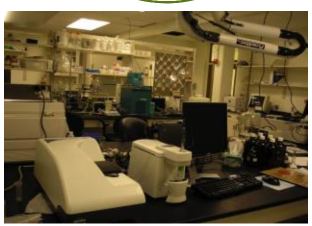
Theory
&
Risk Forecasting



HTS

lab

microcosm



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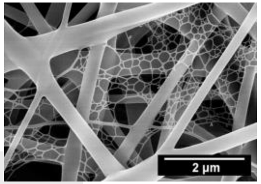
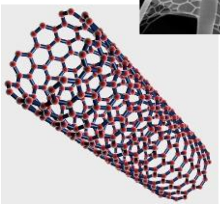
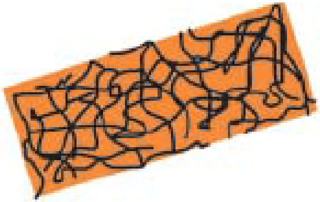
# Analogous Approach for Exposures from Consumer Products





Simple systems

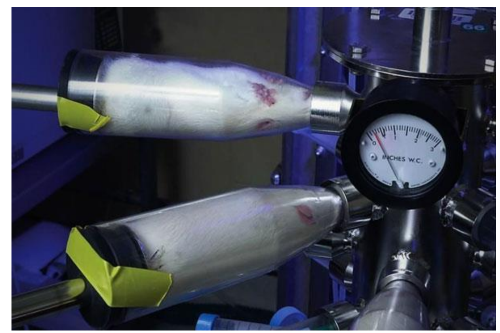
"real" products

Exposure routes

Real Exposures

Models

Increasing Complexity



Increasing Scale

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# Exposure Model for Diethyl phthalate in Personal Care Products

$$D_{ij} = \frac{1}{BW_i} \sum_k n_{ijk} \times A_{ik} \times wf_k \times ef_k$$

D=dose per day
n=number of products used containing diethyl phthalate
A=amount used
w=concentration of diethyl phthalate in each product
e=exposure fraction

Delmaar et al., 2015 *J. Exposure Sci. Environ. Epidimiol*. 25 p317

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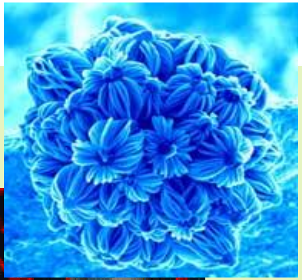
# Lessons Learned from CEINT

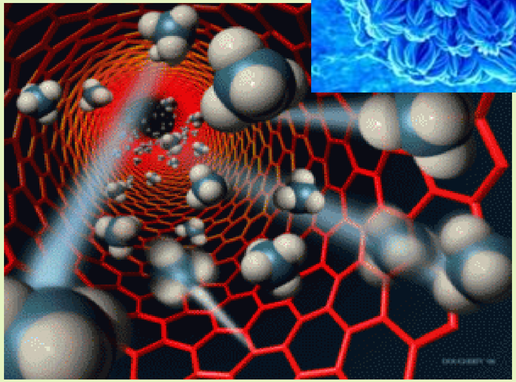
- Mapping NM properties directly to exposure is a long term goal
- The system matters (perhaps more than the NM itself!)
  - Consideration of value chain and exposure route
  - Transformations
- Natural and incidental NMs are ubiquitous
  - Can affect measurements and detection
- Measurement will need established and novel methods
  - Spatial and chemical information
- Common experimental facilities, models, and data management are needed to focus efforts
  - Ask the right questions!!

# In the Beginning……

What is it?

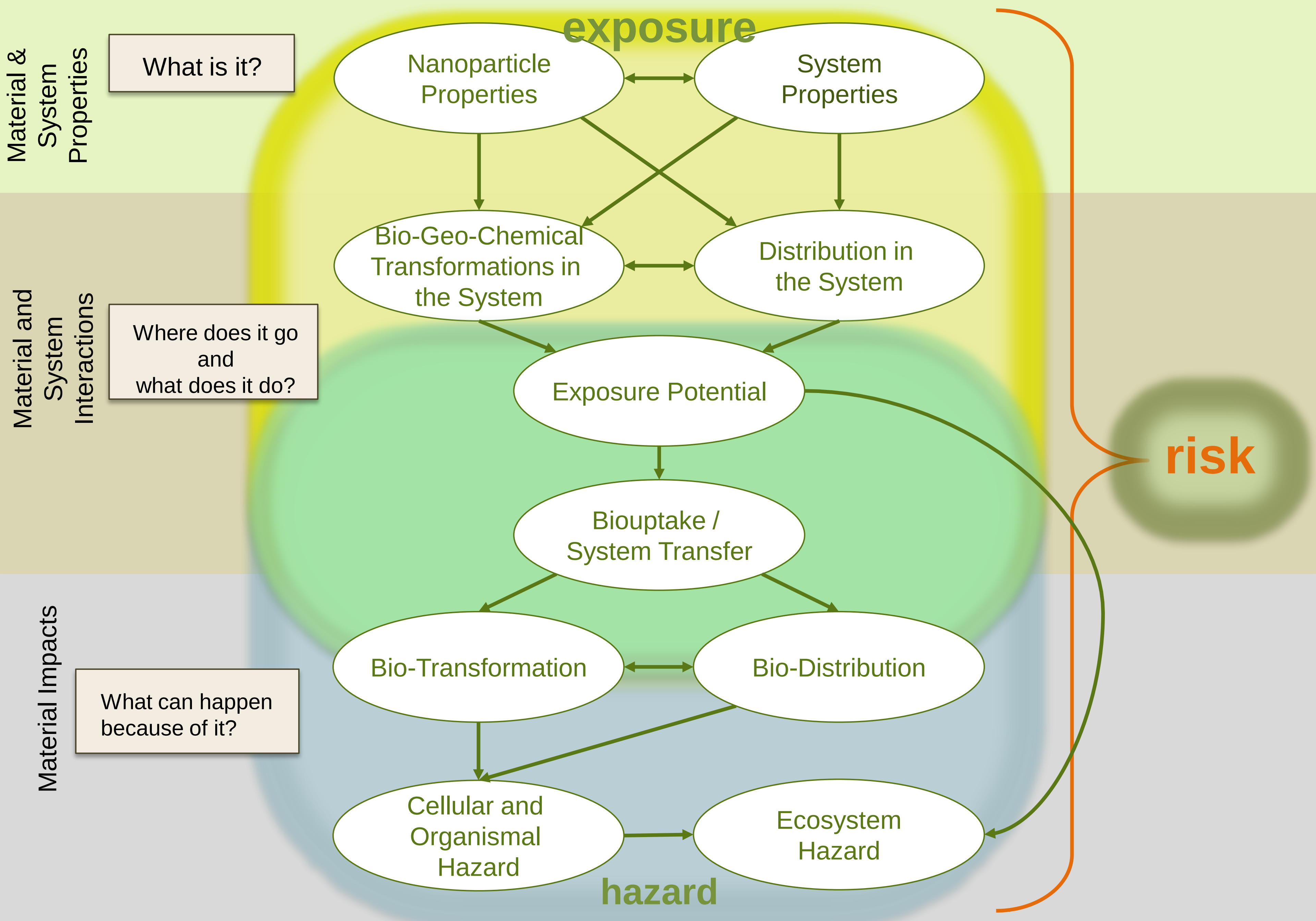
Nanomaterial Descriptors





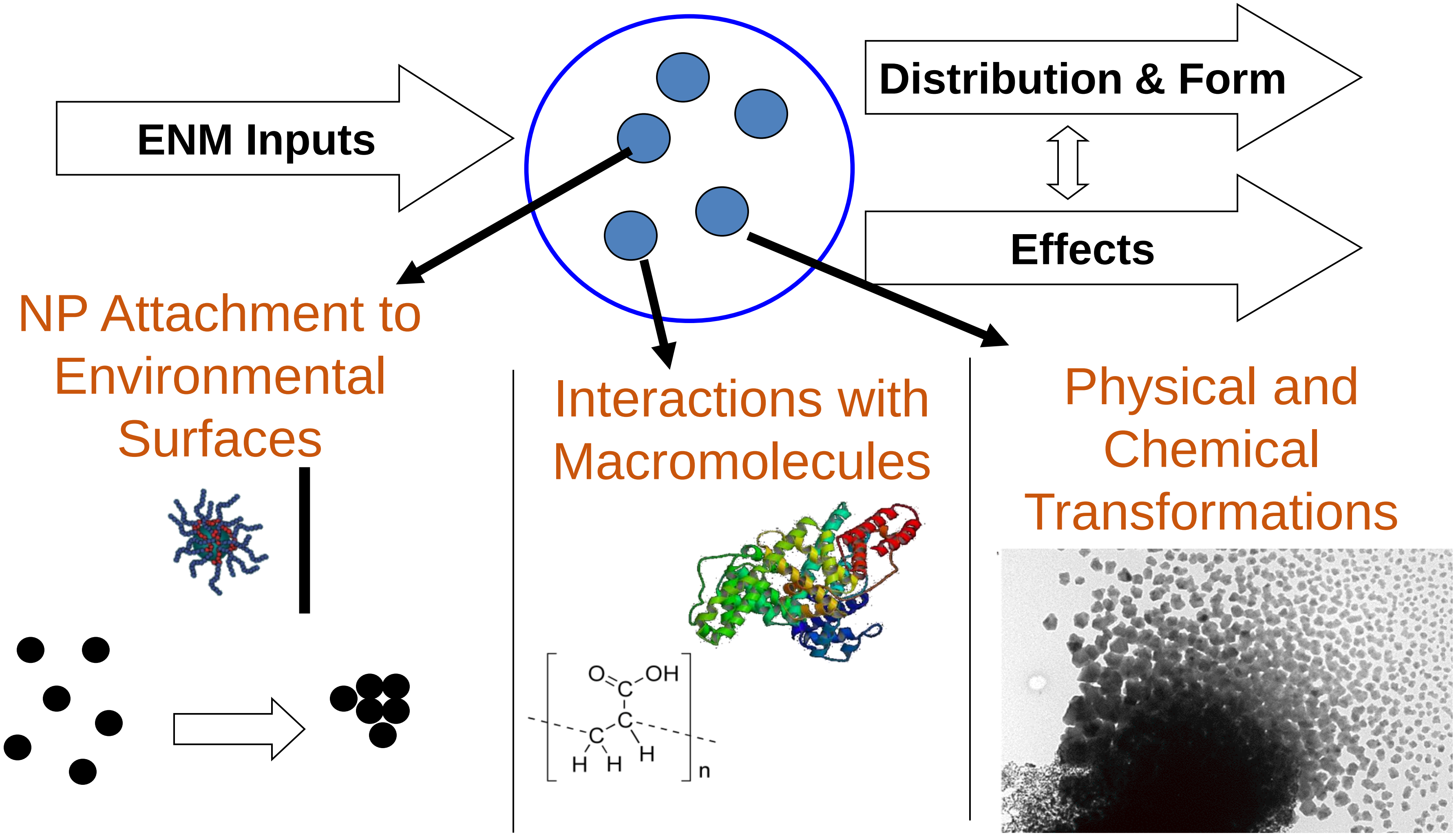
What can happen because of it?

Nanoparticle Impacts



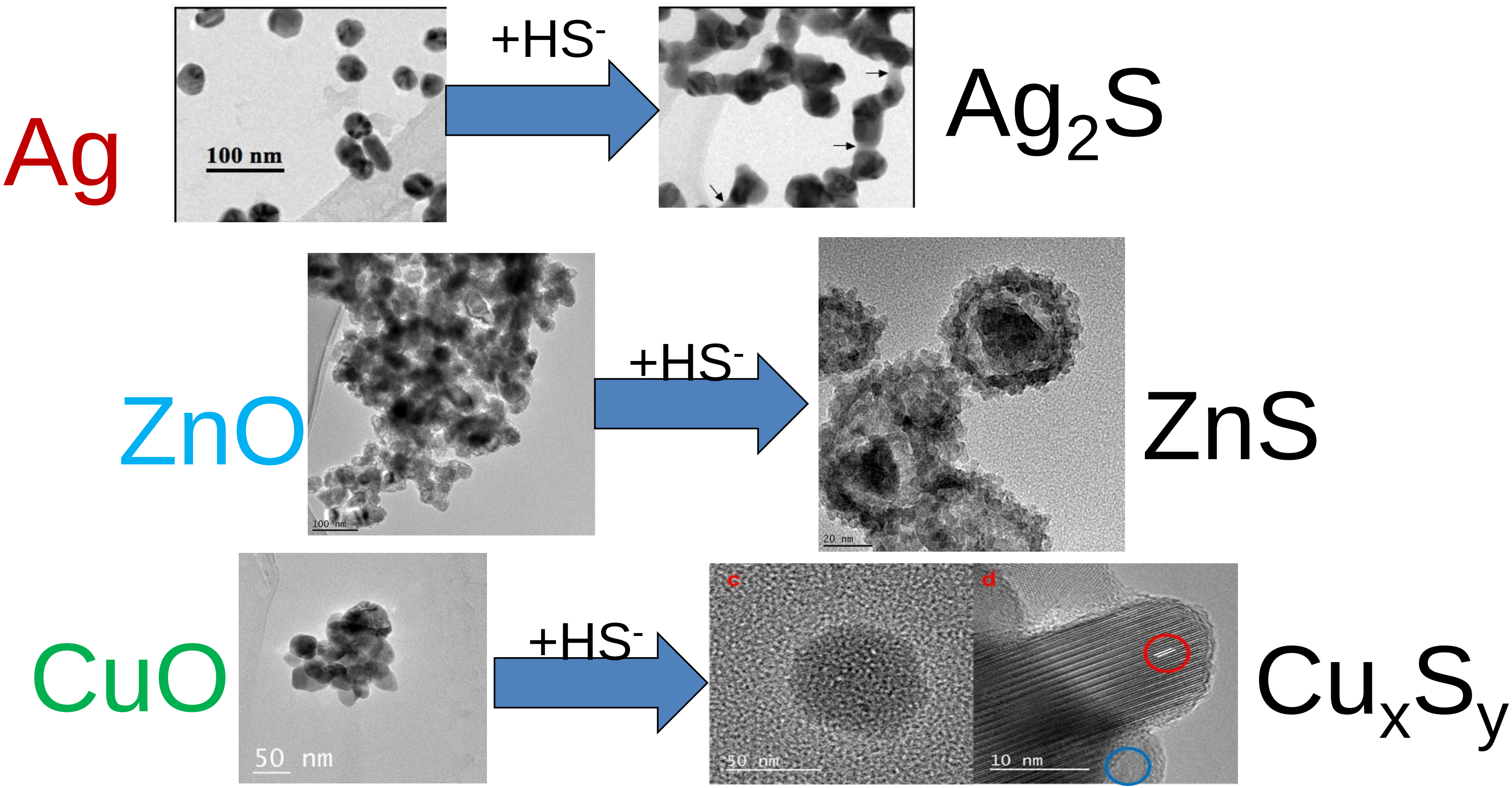
exposure
Material & System Properties
What is it?
Nanoparticle Properties
System Properties
Material and System Interactions
Where does it go and what does it do?
Bio-Geo-Chemical Transformations in the System
Distribution in the System
Exposure Potential
Biouptake / System Transfer
risk
Material Impacts
What can happen because of it?
Bio-Transformation
Bio-Distribution
Cellular and Organismal Hazard
Ecosystem Hazard
hazard

# The System Matters!!



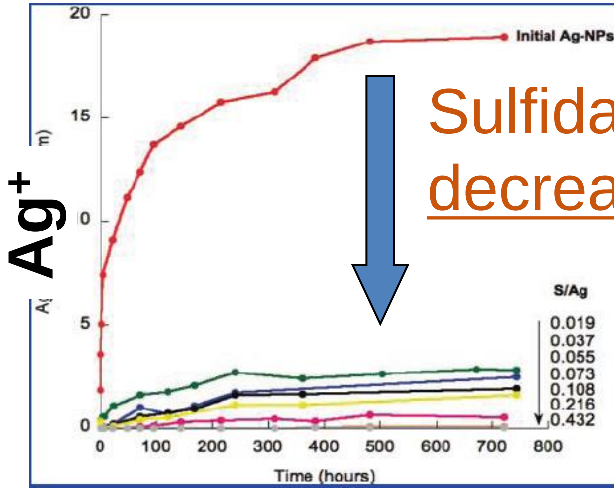

Adapted from NRC, 2012; Lowry et al., 2012 *ES&T* 46 (13) 6893−6899.

# Sulfidation of Ag, ZnO, and CuO NPs




Ma et al., 2013 *ES&T* 47 (6), pp 2527–2534; Levard et al., *ES&T 2011 45 (12)*, 5260.
Ma et al., 2014 *ES Nano* 1, 347-357

# Sulfidation Affects Dissolution Rate



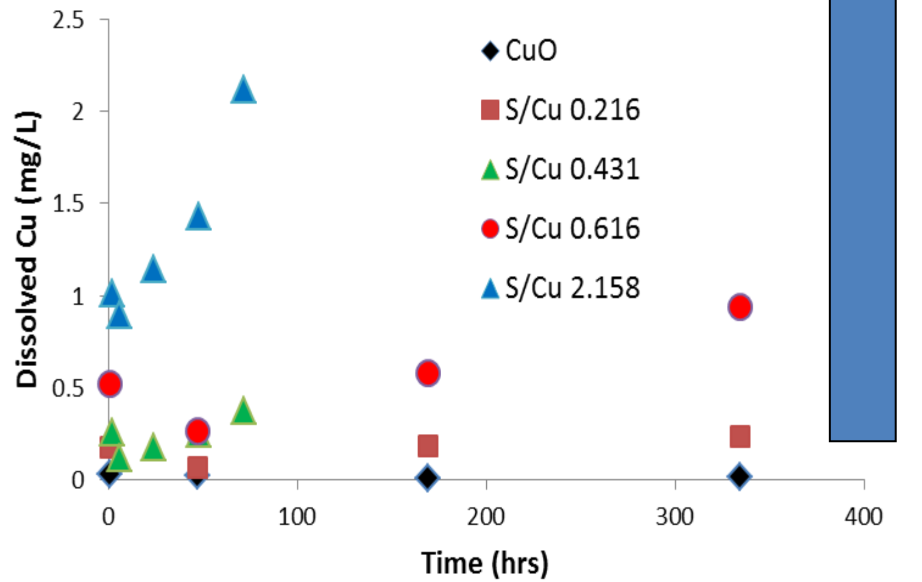

**Time**

Sulfidation greatly <u>decreases</u> $Ag^{+}$ release

Levard et al., *ES&T 2011 45 (12),* 5260.

Sulfidation <u>Increased</u> apparent Cu solubility

**CuO**




Ma et al., 2014 *ES Nano* 1, 347-357

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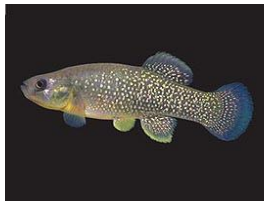
# Sulfidation Decreases Toxicity

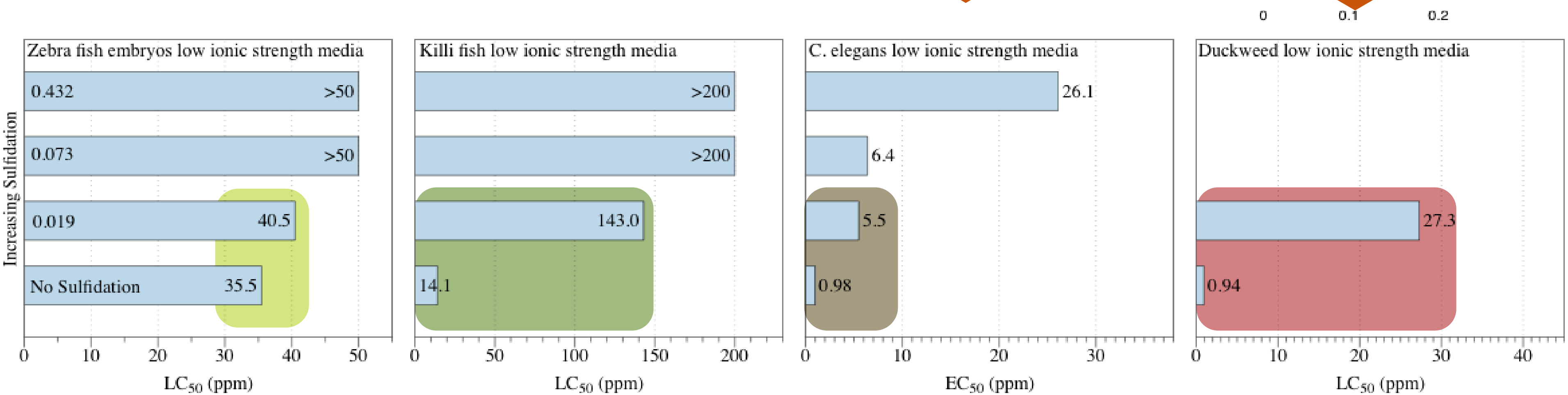
## Zebrafish

## Killifish



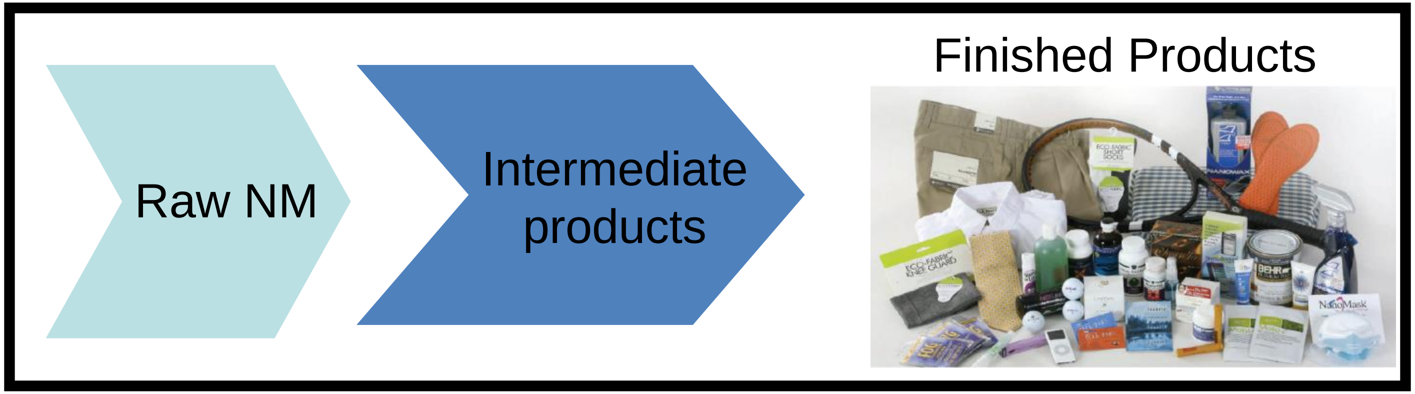
## C. Elegans

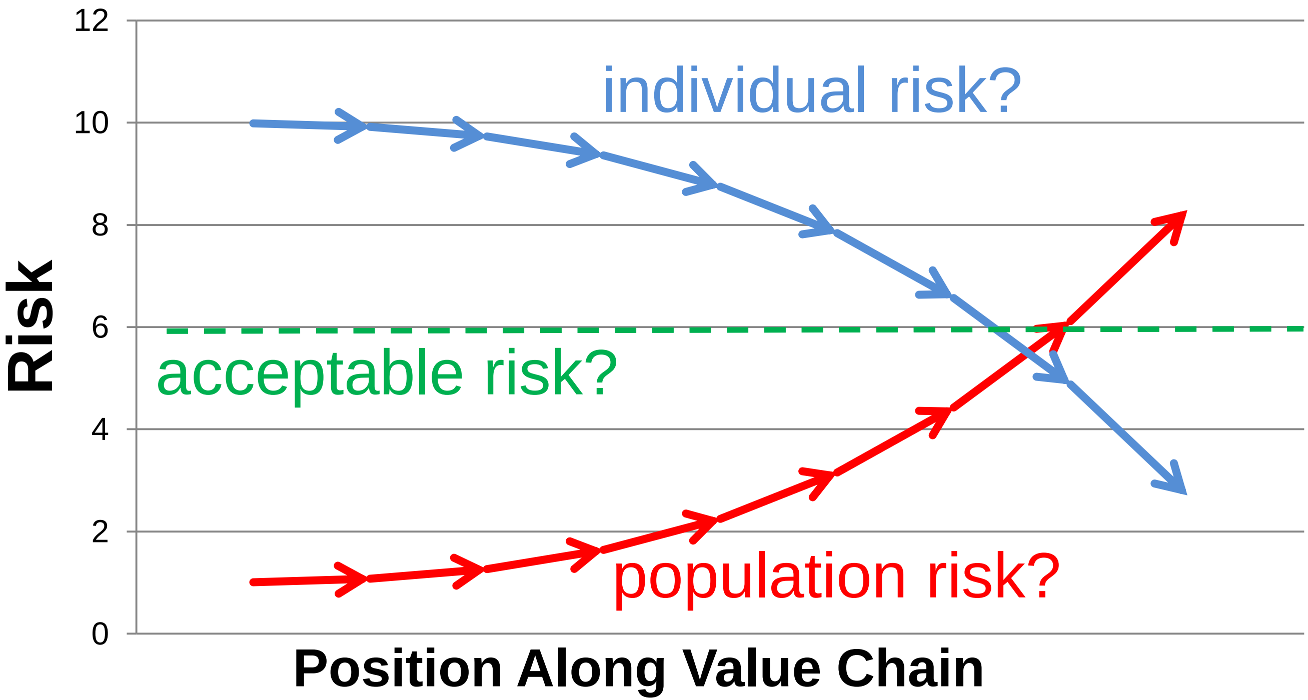
## Duckweed

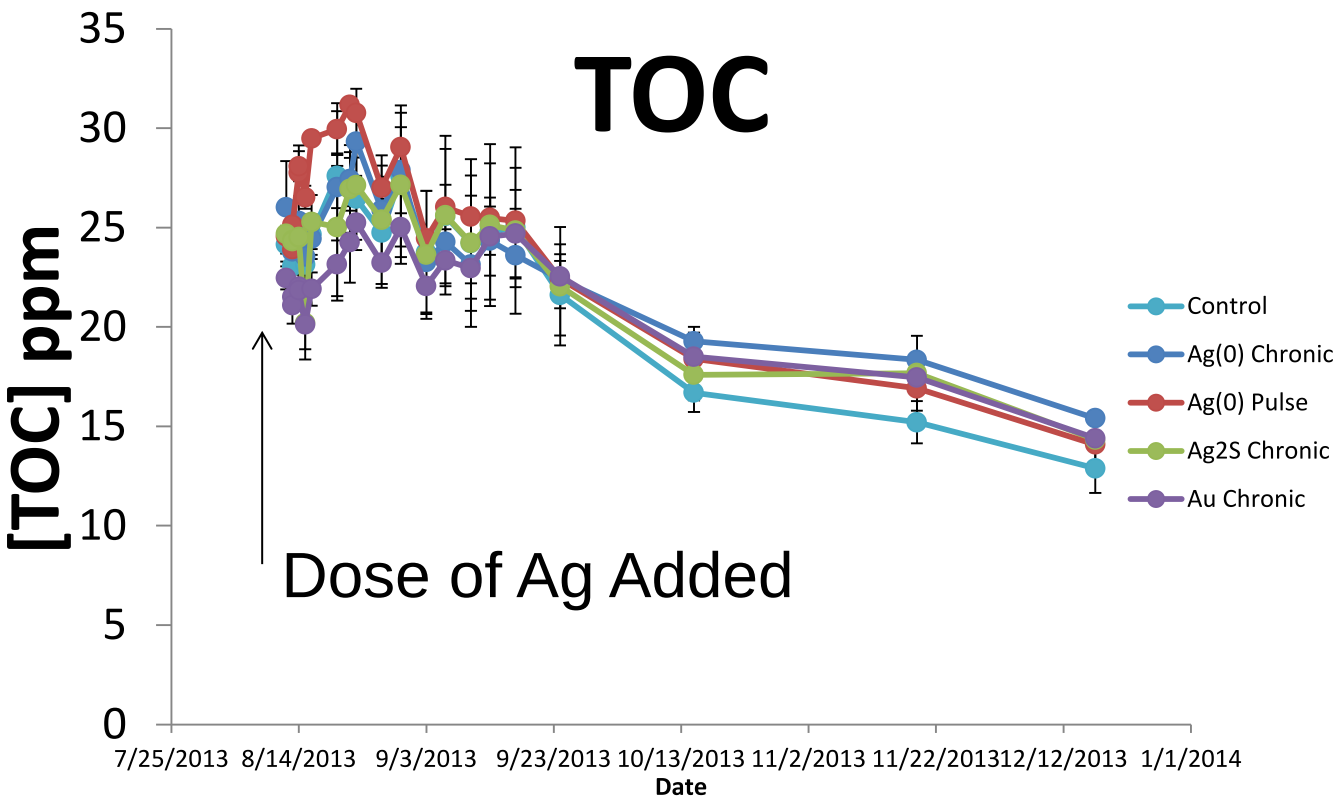

Levard, Hotze, et al., *ES&T 2013, 47, 13440−13448*

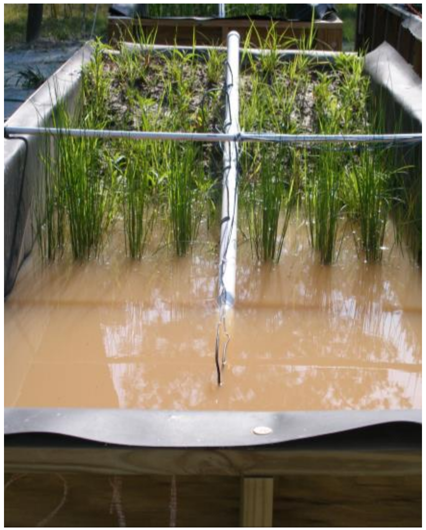
# Consumer Exposure Potential Across the Value Chain



# System Complexity Complicates Exposure Assessment



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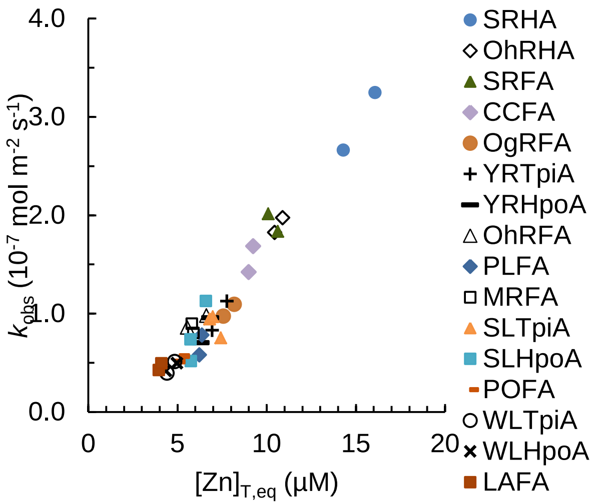
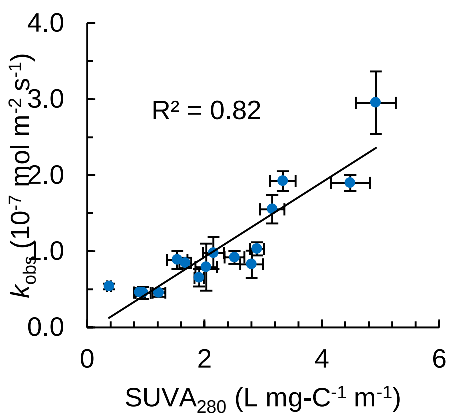
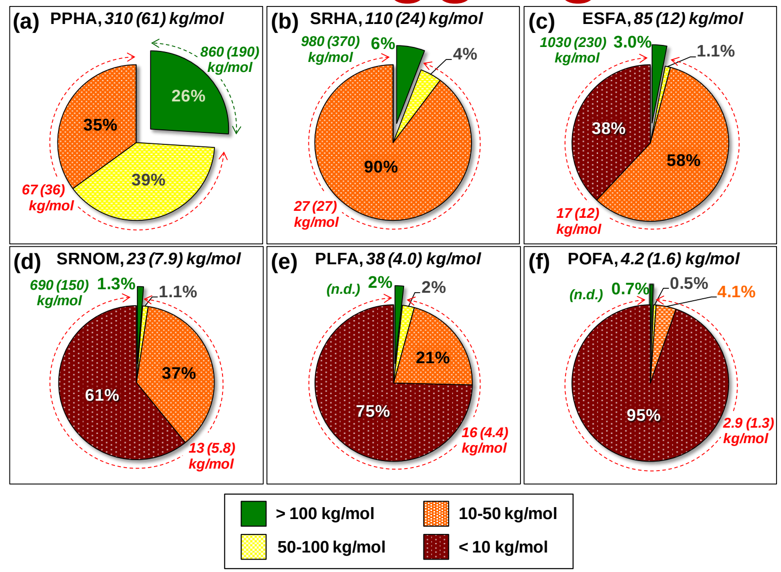
# Complexity can be Managed (Modeled)

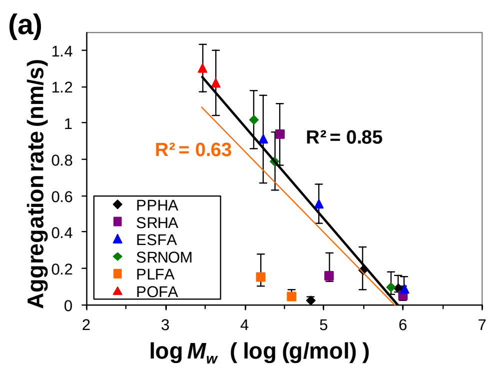
## ZnO dissolution

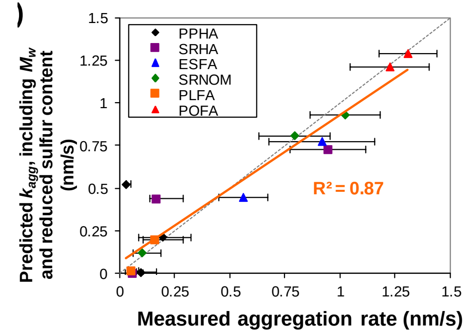



## Au NP Aggregation




Louie et al., 2015 *ES&T* 49 p2188

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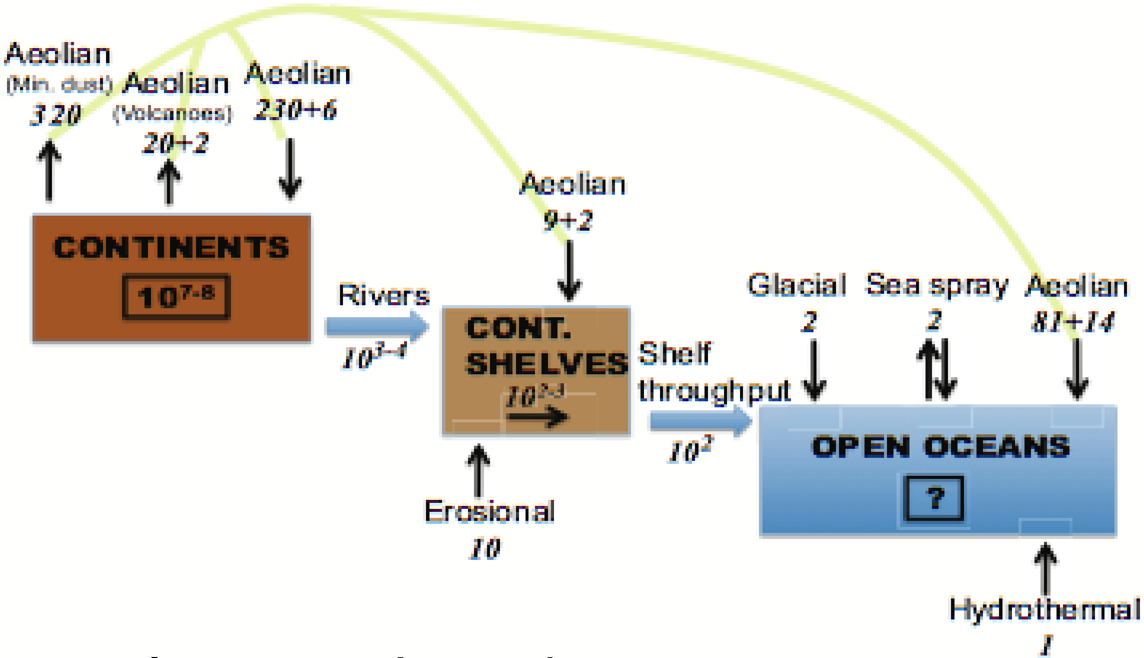
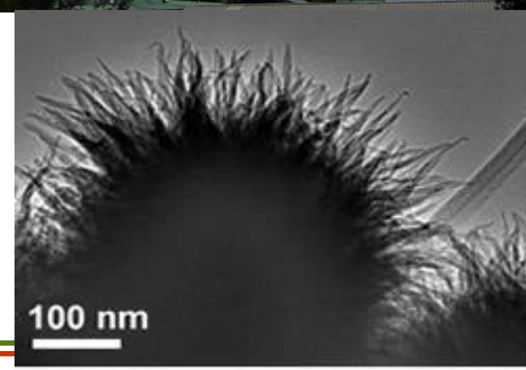
# Natural, Incidental, and Manufactured Nanoparticles are ubiquitous




Values are in Tg/yr




Hochella et al., 2012 In *Nature's Nanostructures*, Pan Stanford Publishing

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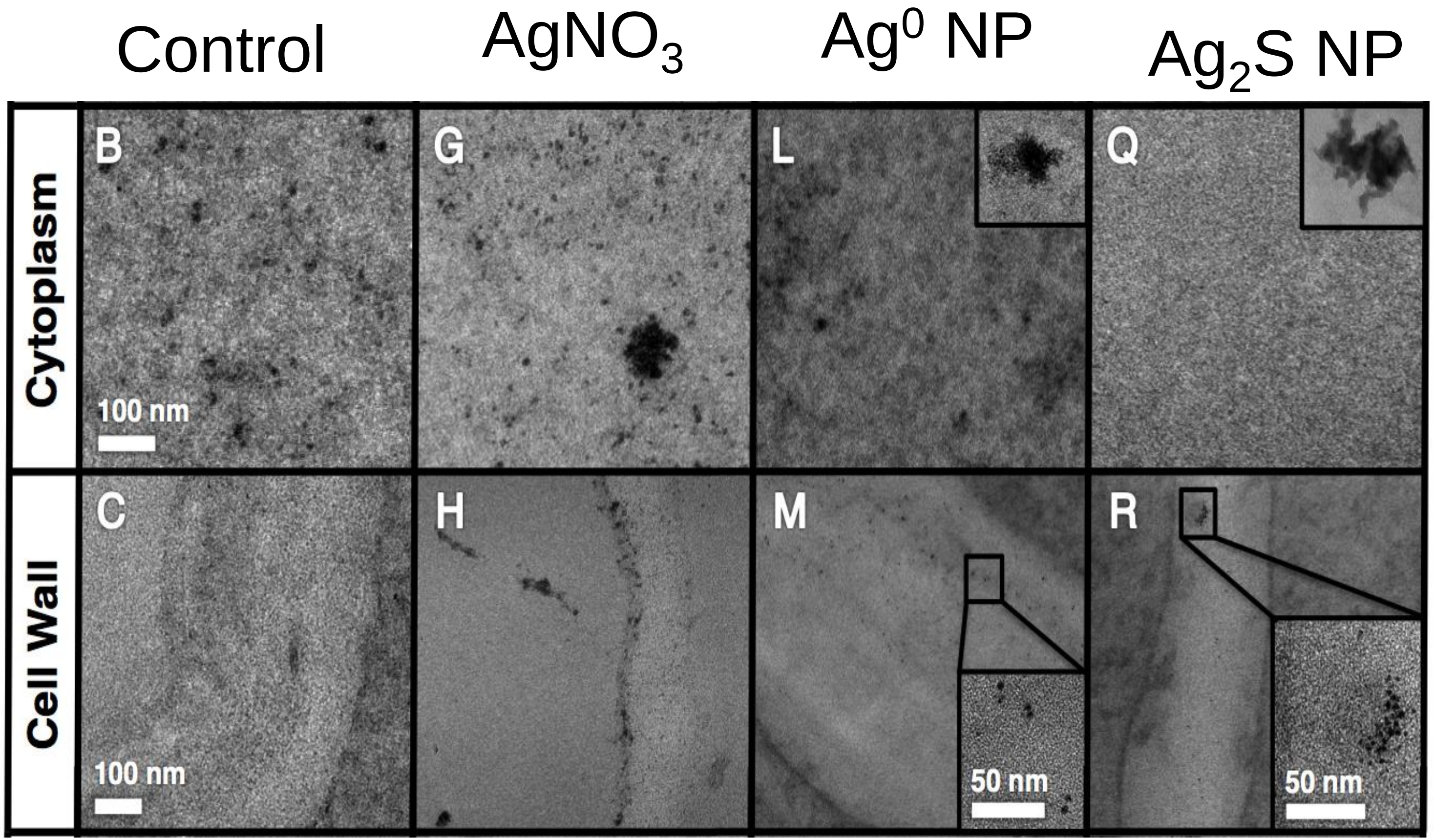
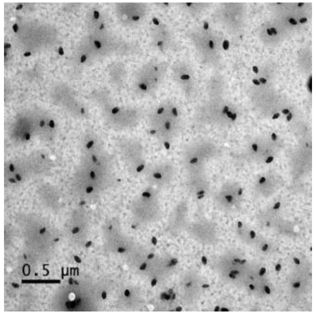
# Nanomaterials are Ubiquitous in Plants




Stegemeier et al. 2015 *ES&T* (in press)

# Measurement of NMs in Consumer Products and the Environment





- Need to measure distribution and chemical speciation of NMs
  - *In situ* measurements
- Distinguish between individual NPs and populations of NPs
  - NM property vs. average properties
  - Understand effects of heterogeneity
- Distinguishing between NMs and background
  - “Big Ten”-$SiO_2$, $TiO_2$, …..

# X-ray Characterization Methods

Expose NPs to various conditions

Wet or Dry Solids/Tissue

Filter (3kD)

Solids

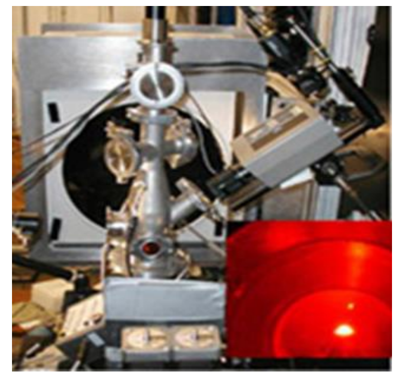
Supernatant

Dissolved species

ICP-MS

**Solids/Tissue Characterization**


XAS/XRF



XRD

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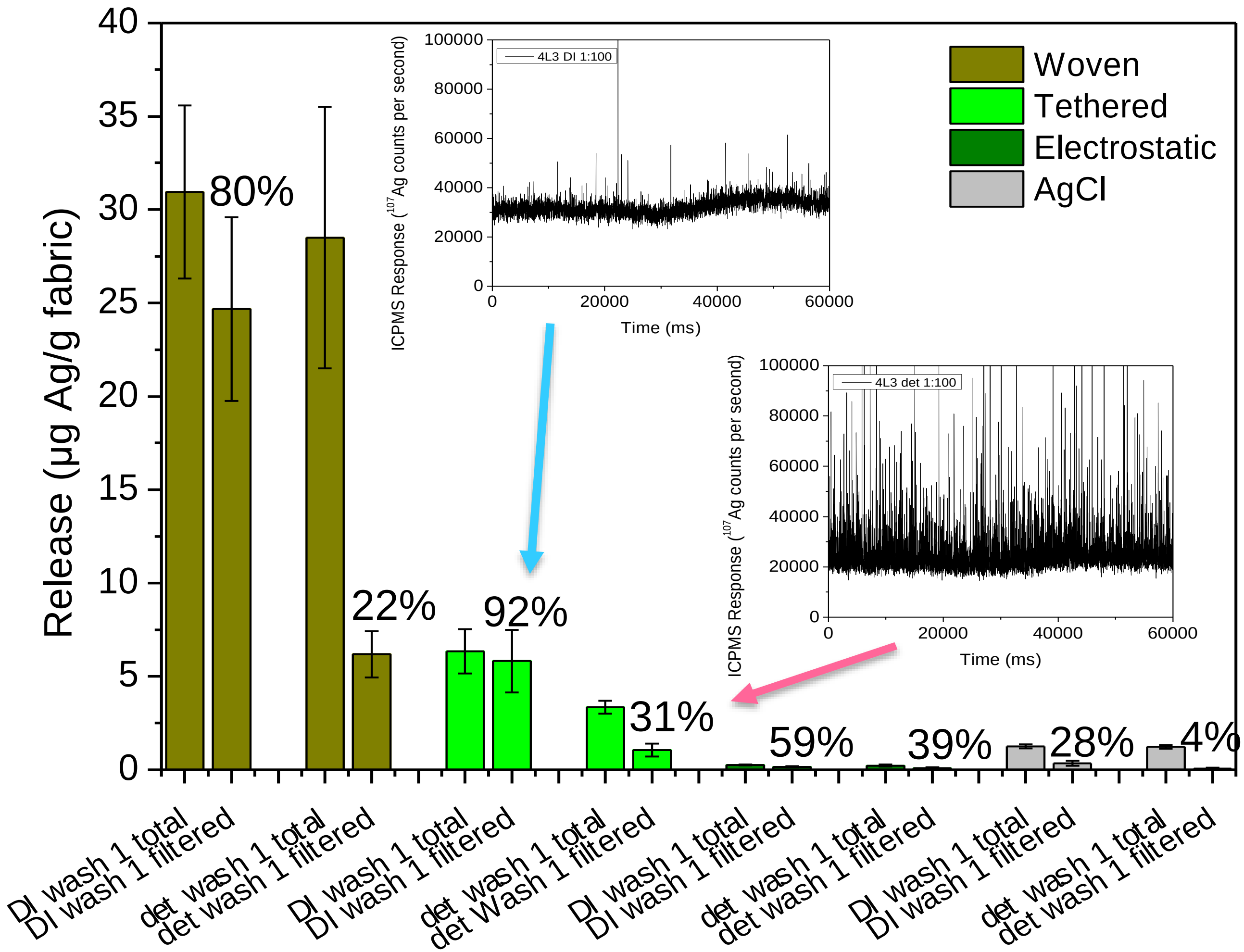
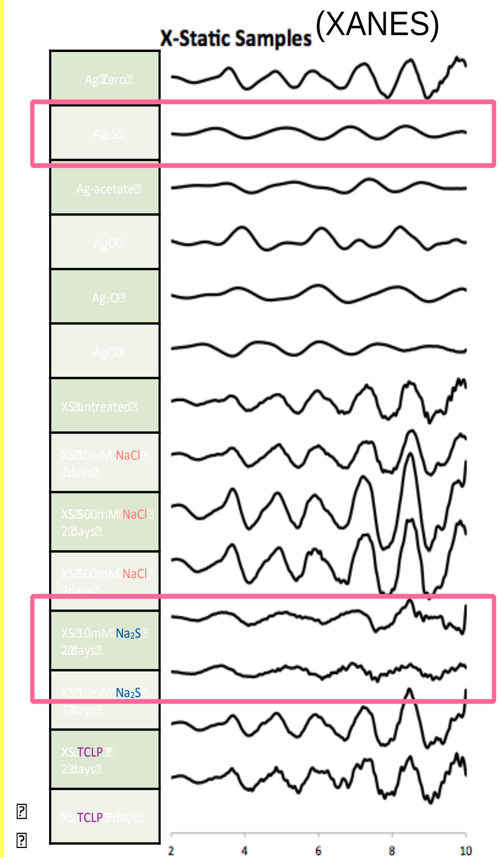
# How does Ag release from textiles vary with aging and transformation of NPs?



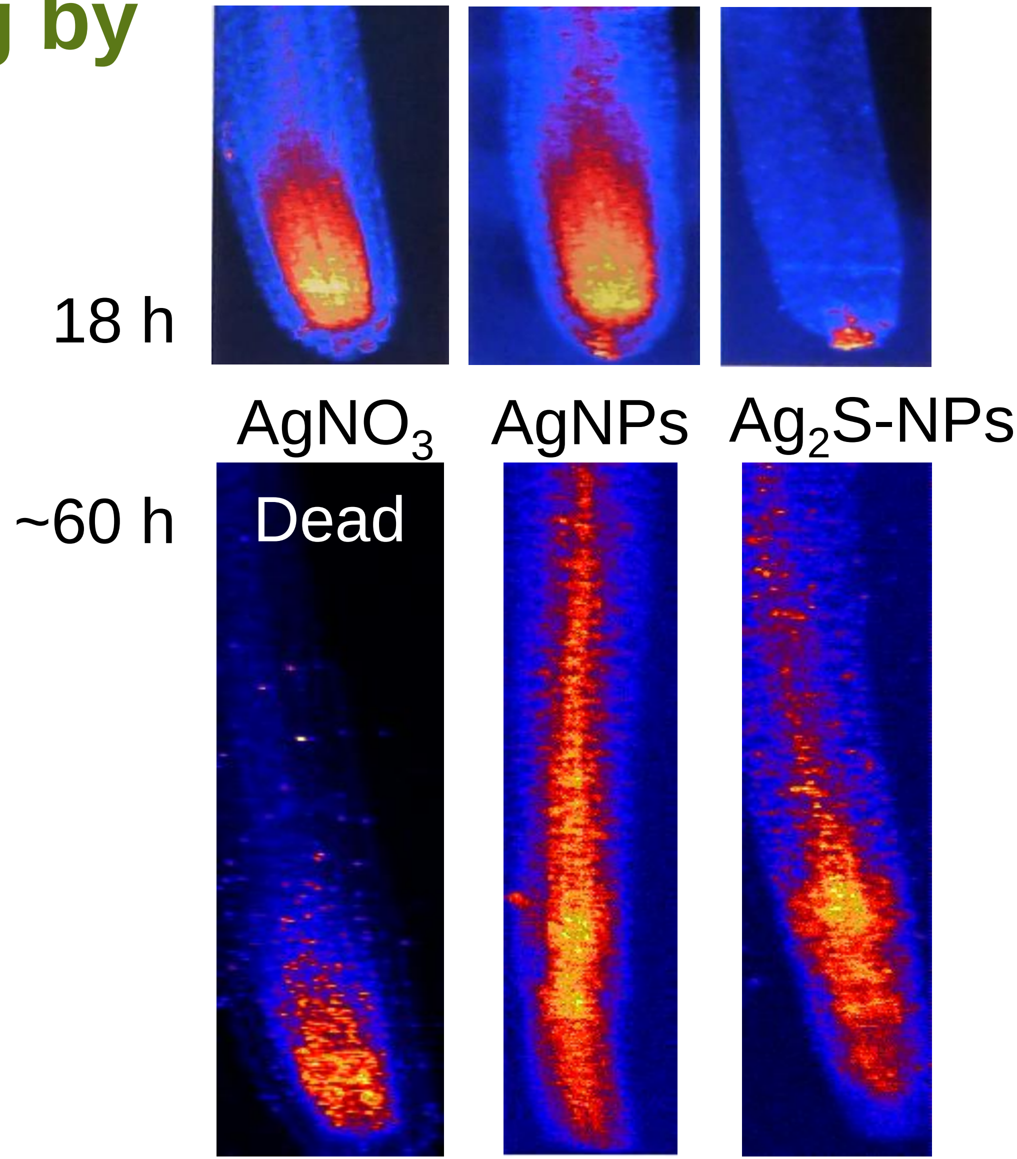

X-Static samples showed some changes:

- NaCl and TCLP: No reactions
- $Na_2S$: Rapidly transforms to $Ag_2S$

# Mode of Uptake of Ag by Duckweed

Duckweed

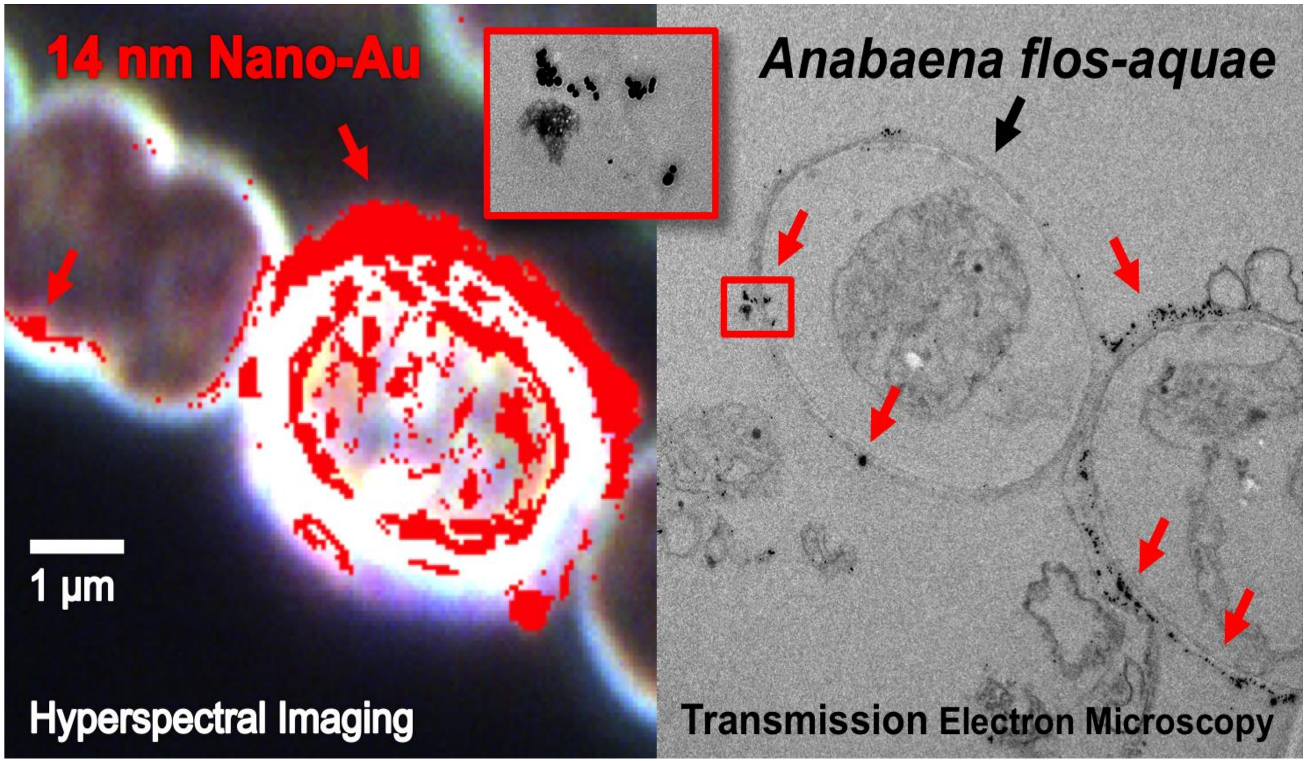
*Landoltia punctata*




Stegemeier et al., *ES&T* (in preparation)

# Visualization Methods for ENM Uptake by plants

Dark-field microscopy TEM/EDS

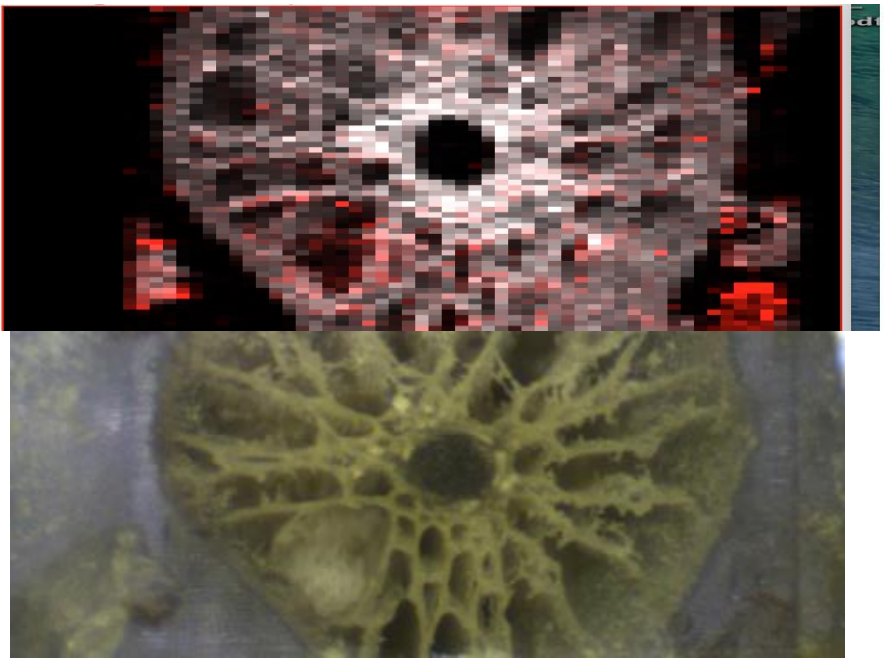



Accumulation of Au NPs in the cyanobacteria *Anabaena flos-aquae*.

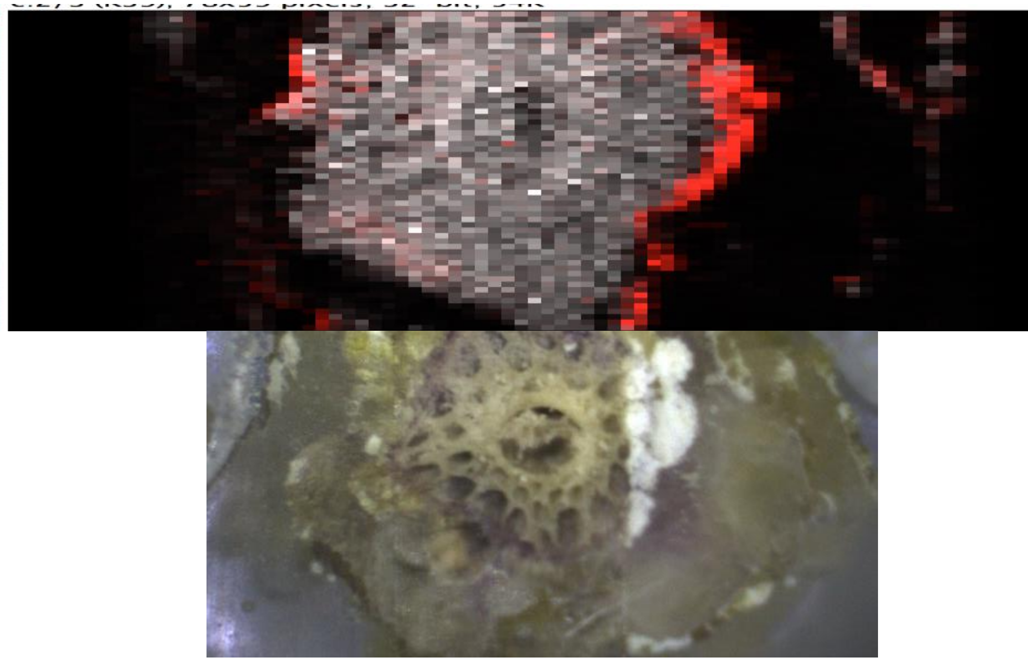
# Metal NP Exposures to *Egeria densa*

Laser Ablation-ICPMS Maps of Ag

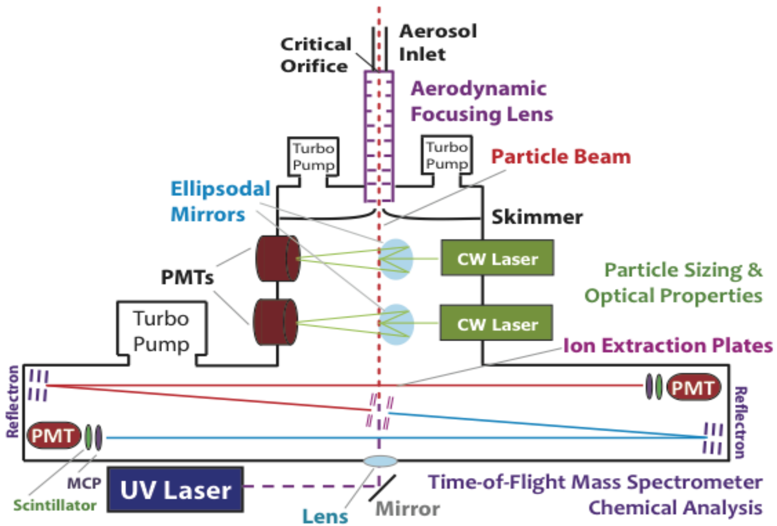
$Ag_2S$



$Ag^{\circ}$



# Single-particle measurements




SP-MS measures <u>individual</u> particle size and <u>chemical</u> <u>composition</u> in real-time

- Can analyze particles with:
  - Diameters from 50 to 3000 nm
- Measure ag amounts of individual compounds
- Detection rate:
  - > Several particles/second
- Semi-quantitative composition

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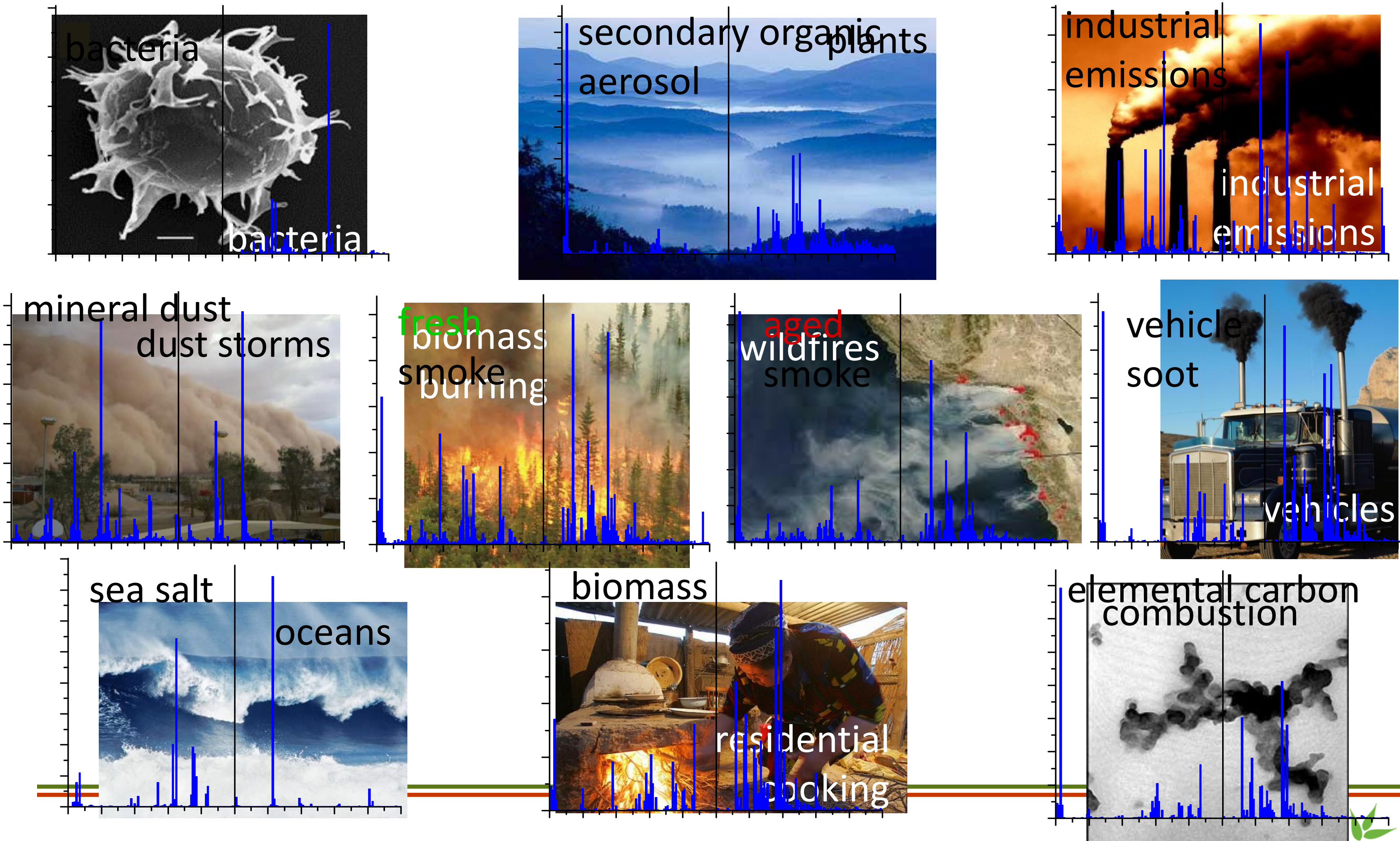
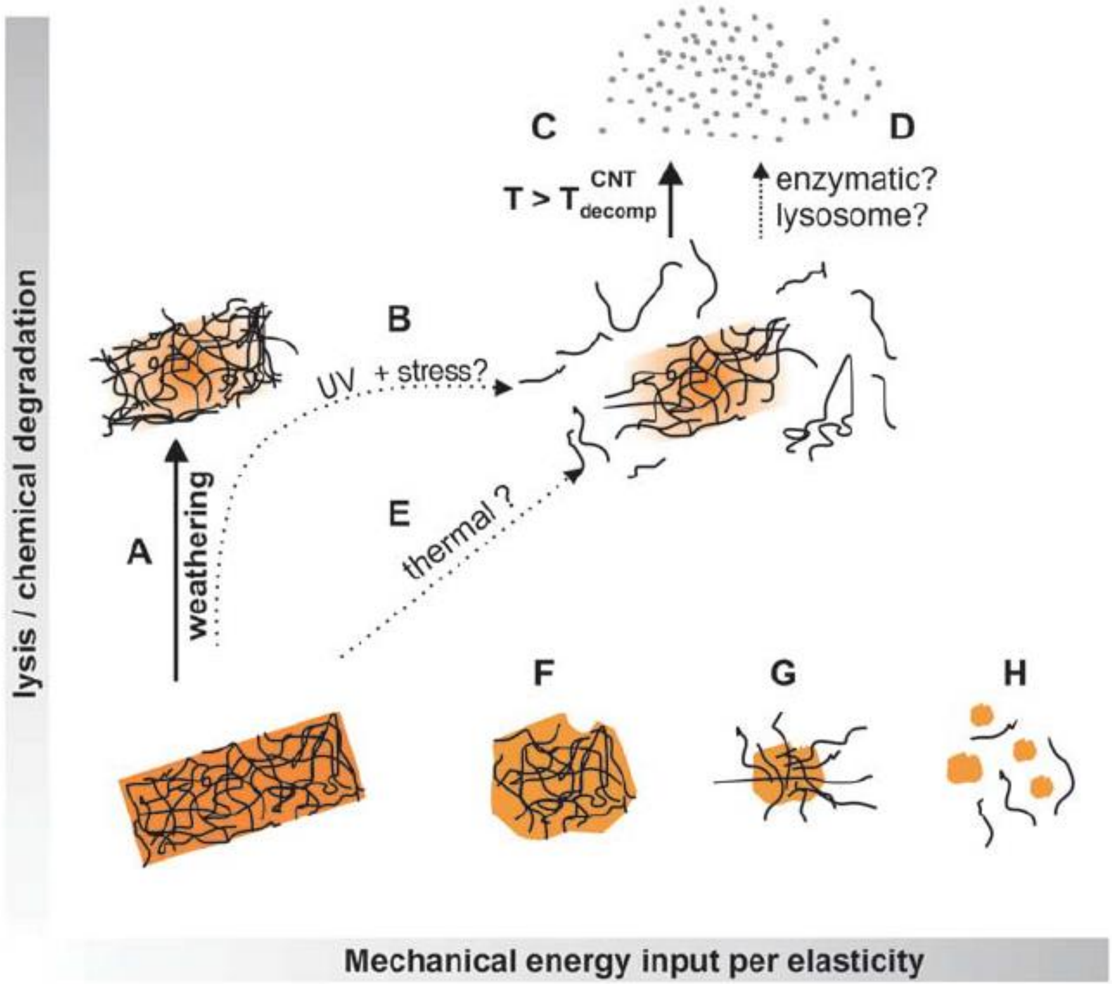
# Identifying individual particle sources

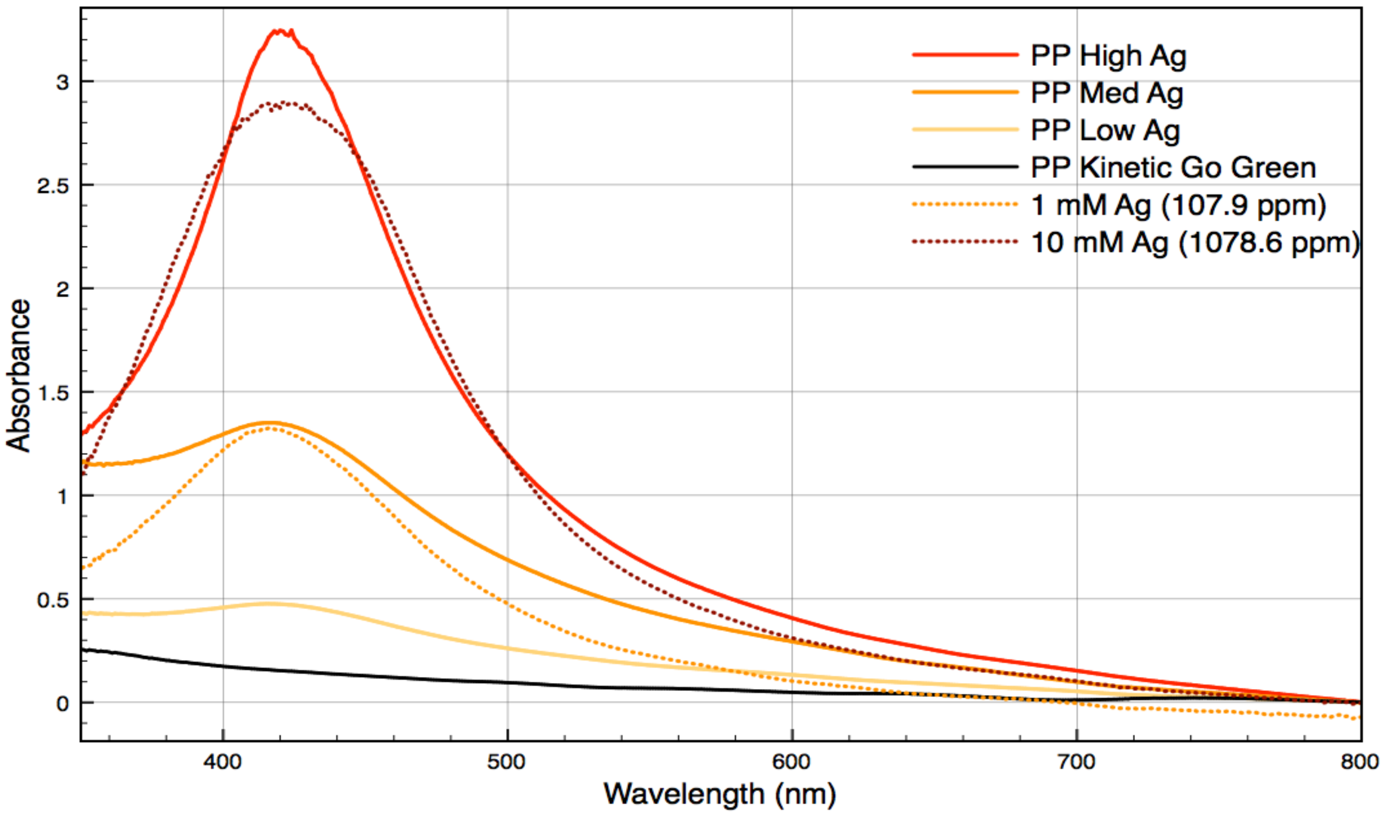


# Heterogeneity of Materials Released from CNT Polymer Nanocomposites




Harper et al., 2015 J. Phys. Conf. Ser. 617 012026

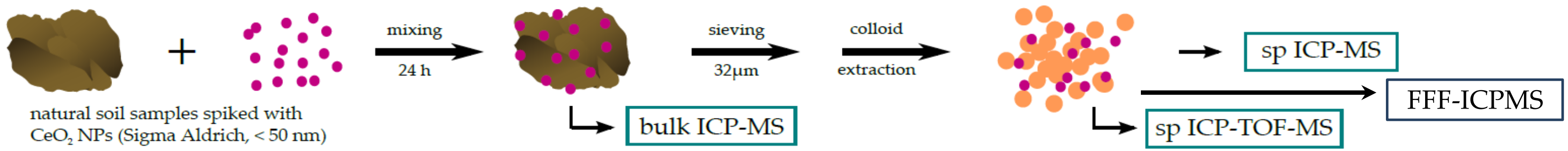
# UV/Vis Spectroscopy of AgNP-Polypropylene PNCs

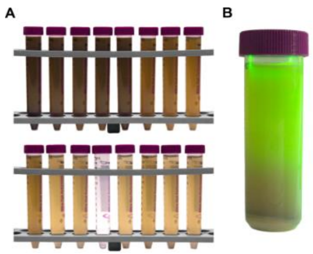



*Key Difference* - path of light through sample is much shorter in PP samples (~1-2mm for plastic vs 10 mm for sols)

# Distinguishing NPs from Background

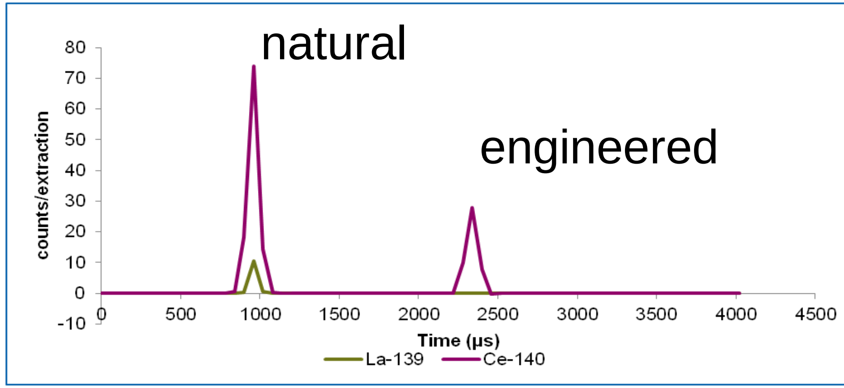
## Approach

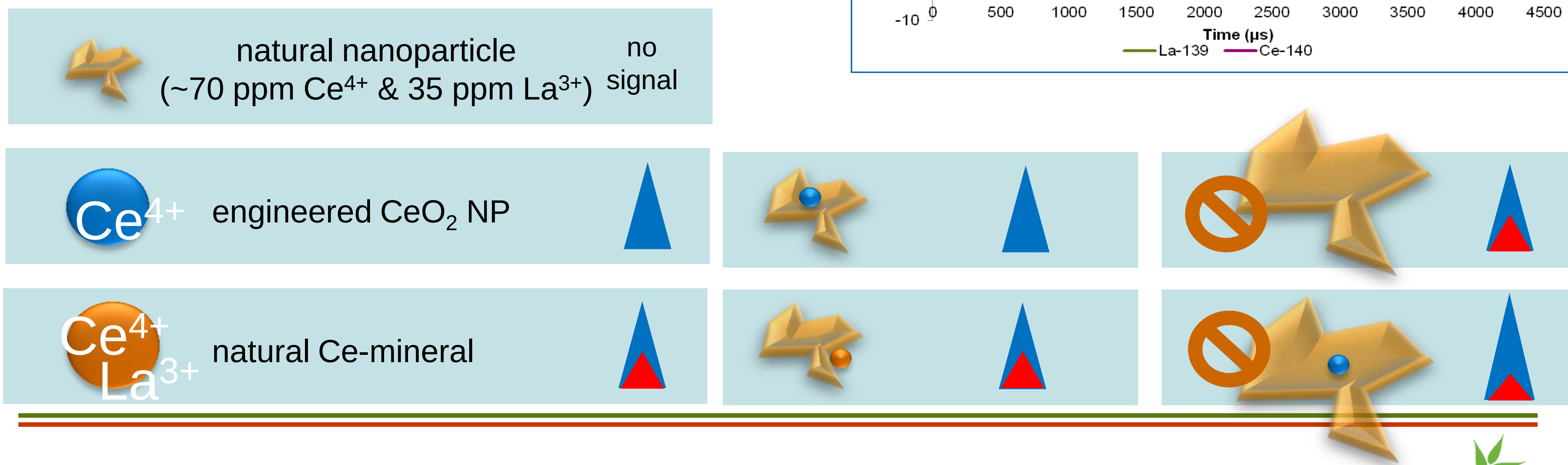



fast scan qpol-ICPMS

sp-ICP-TOFMS

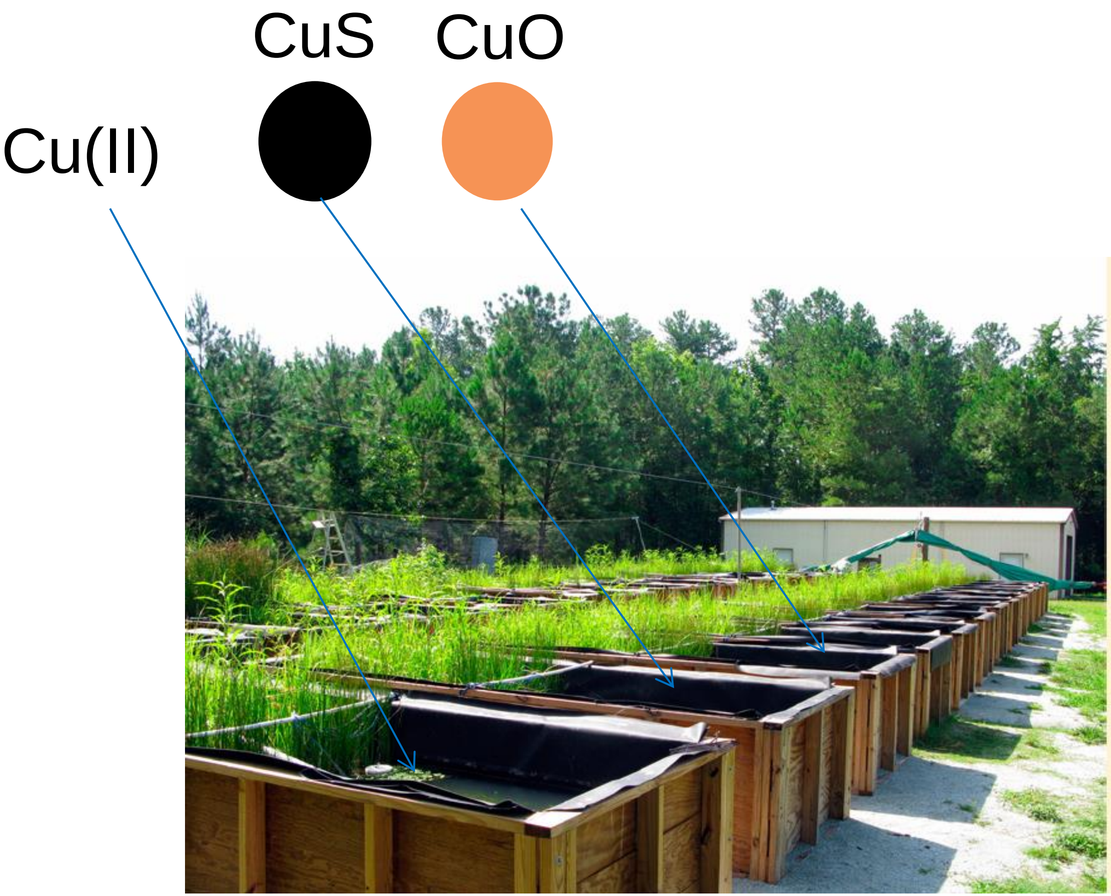


# Common Systems and Models as an Integrator


- 30 mesocosms
- year-long experiments
- Release form commercial productions
- Nano- Ag, $CeO_2$, Cu, Au, $TiO_2$, SWCNTs

# Provides the ability to study many aspects of the system in unity




- Does initial dosed form of NP affect fate, biouptake and effects?
- How quickly do they transform?
- What do they transform into?
- Are organism effects dependent on form of the metal dosed?

Stegemeier et al., *ES&T* (in prep)

# CuO NPs Transform rapidly….but

$CuO + H_2O \rightarrow Cu(II) + 2OH^-$ $\neq$ Cu(II)

| Input Metal | 1 month | 6 month |
|---|---|---|
| Cu(II) | **Cu-S-R (65%)**<br>Cu-FeOOH (34%) | **Cu-S-R (77%)**<br>Cu-FeOOH (23%) |
| CuO | **CuS (96%)**<br>Cu-FeOOH (4%) | **CuS (85%)**<br>Cu-FeOOH (14%)<br>Cu(0) (1%) |
| CuS | **CuS (66%)**<br>Cu-FeOOH (23%)<br>Cu(0) (10%) | **CuS (60%)**<br>Cu-FeOOH (30%)<br>Cu(0) (10%) |
| Ag(0) | Ag(0) (<10%)<br>Ag2S (>90%) | Ag(0) (<3%)<br>Ag2S (>97%) |
| Ag(s) | Ag2S (100%) | Ag2S (100%) |

Stegemeier et al., *ES&T* (in prep)

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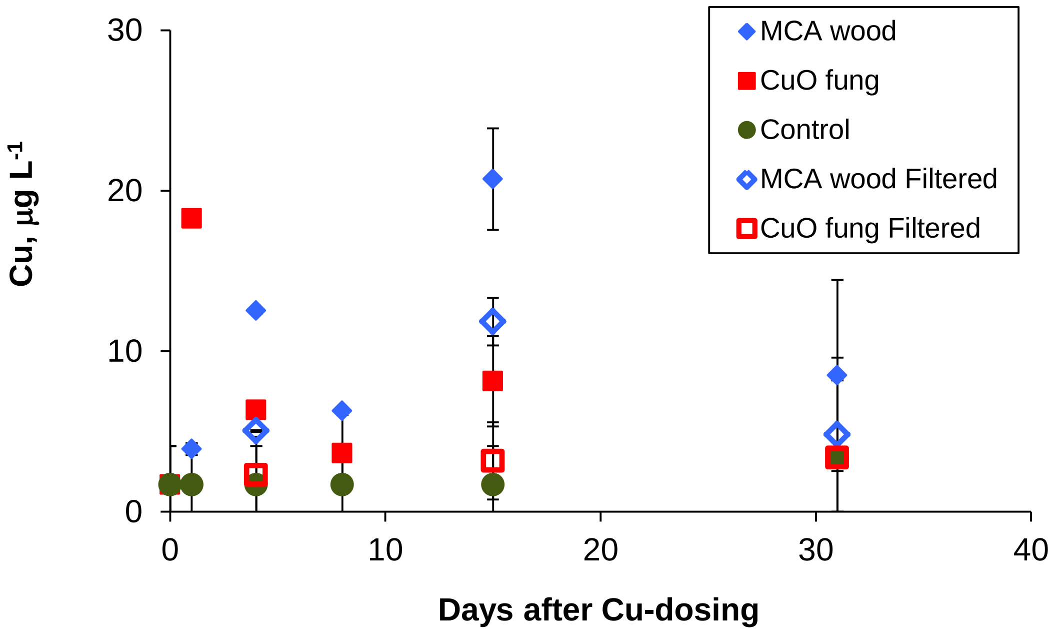
# Metal Releases from Cu NP-containing Products




- Cu release occur rapidly
- Cu released is ~3% of total Cu added
- Still working to determine form of Cu released

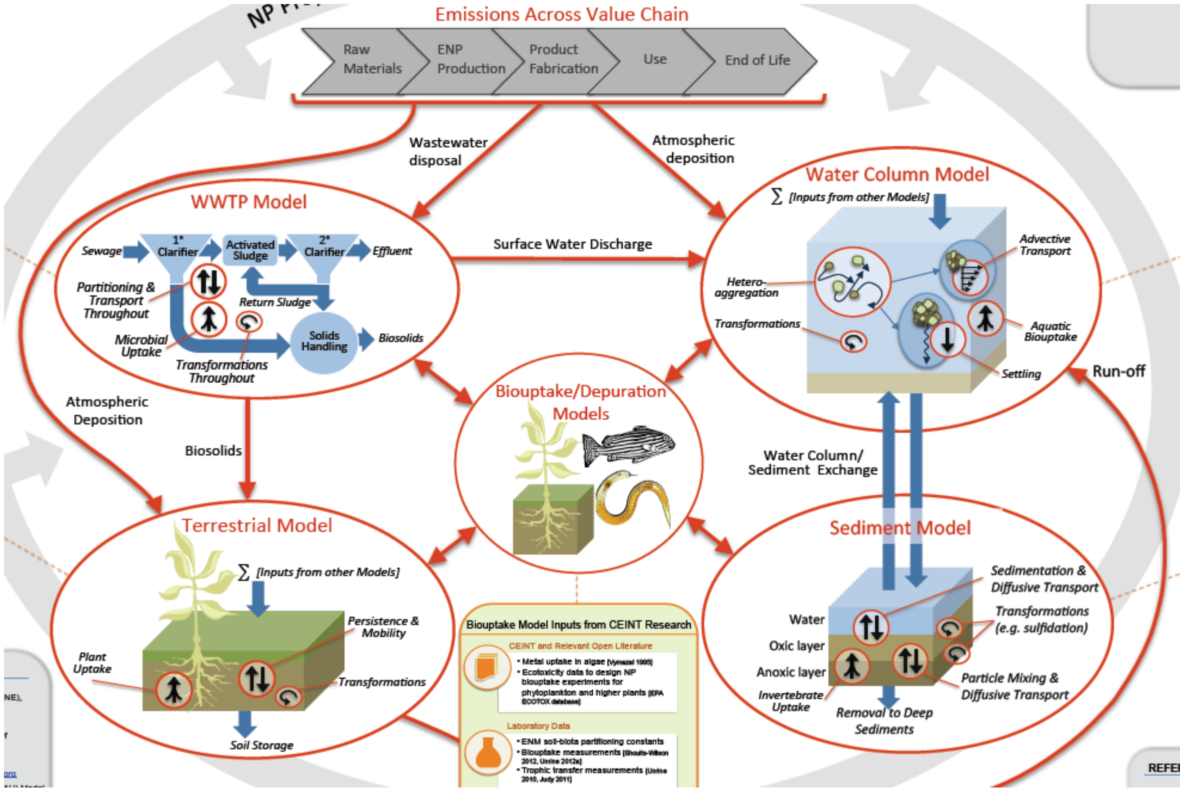
# Common Models as an Integrator

$$\frac{dn_{k_i}}{dt} = \pm\alpha\beta n_i\gamma_j - k_{dissolution}n_k + k_{formation}n_k + k_{transformation}n_k + k_{biouptake}n_k + k_{depuration}n_k$$

- Settling
- Aggregation
- Deposition

- Precipitation
- Bioproduction

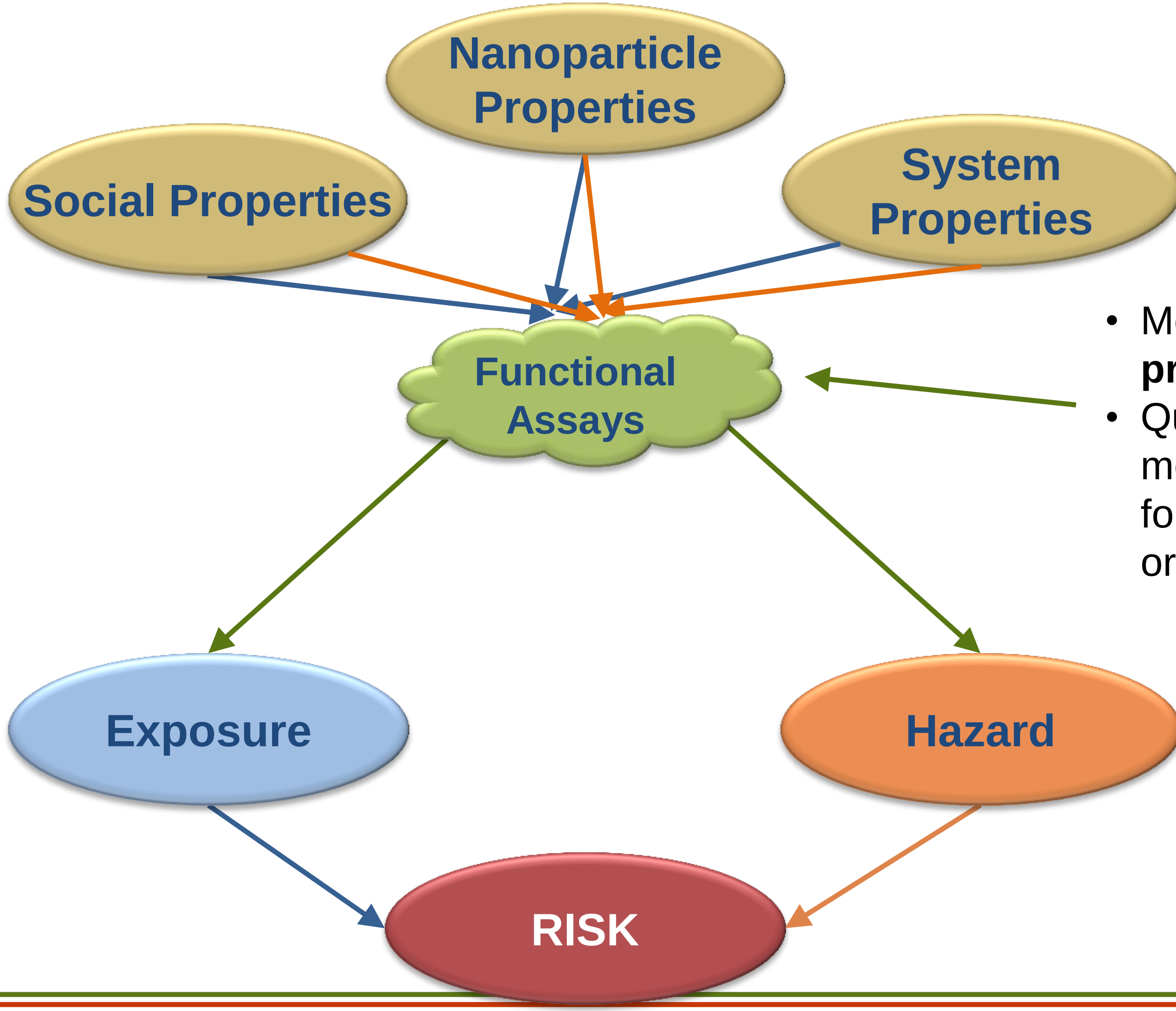
- Sulfidation
- Complexation
- Hydroxylation
- Oxidation/ Reduction …




## Key functional Assays:

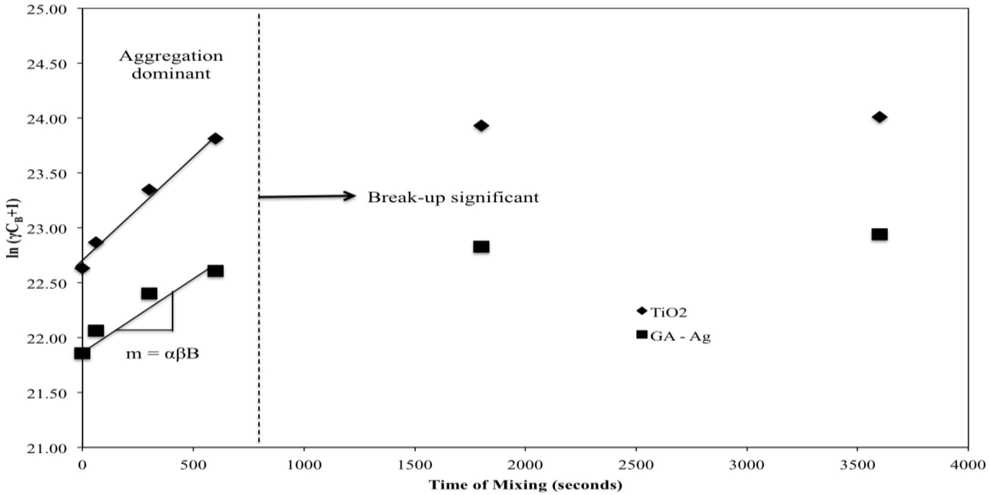
- Surface affinity
- Dissolution rate
- Transformation rates
- Bioüptake/ depuration

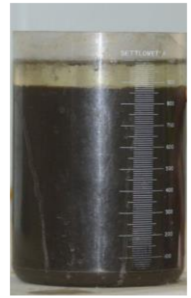
# Functional Assay Approach




- Measurement in **prescribed system**
- Quantifies a meaningful process for exposure, hazard or both

# Developing functional assays for parameterizing models



$\alpha$ for biosolids to predict behavior in WWTPs

Dissolution rate, $k_d$, to predict bioavailability to plants and toxicity

Barton et al., 2014 *Env. Eng. Sci* 31 p421

# Data Management and Modeling Tools

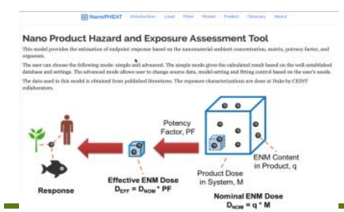
- NanoInformatics Knowledge Commons (NIKC) database to support data analyses and modeling
- Nano Product Hazard and Exposure Assessment Tool (NanoPHEAT)

**Database**

Query

**Dataset**

Input




**Modeling**

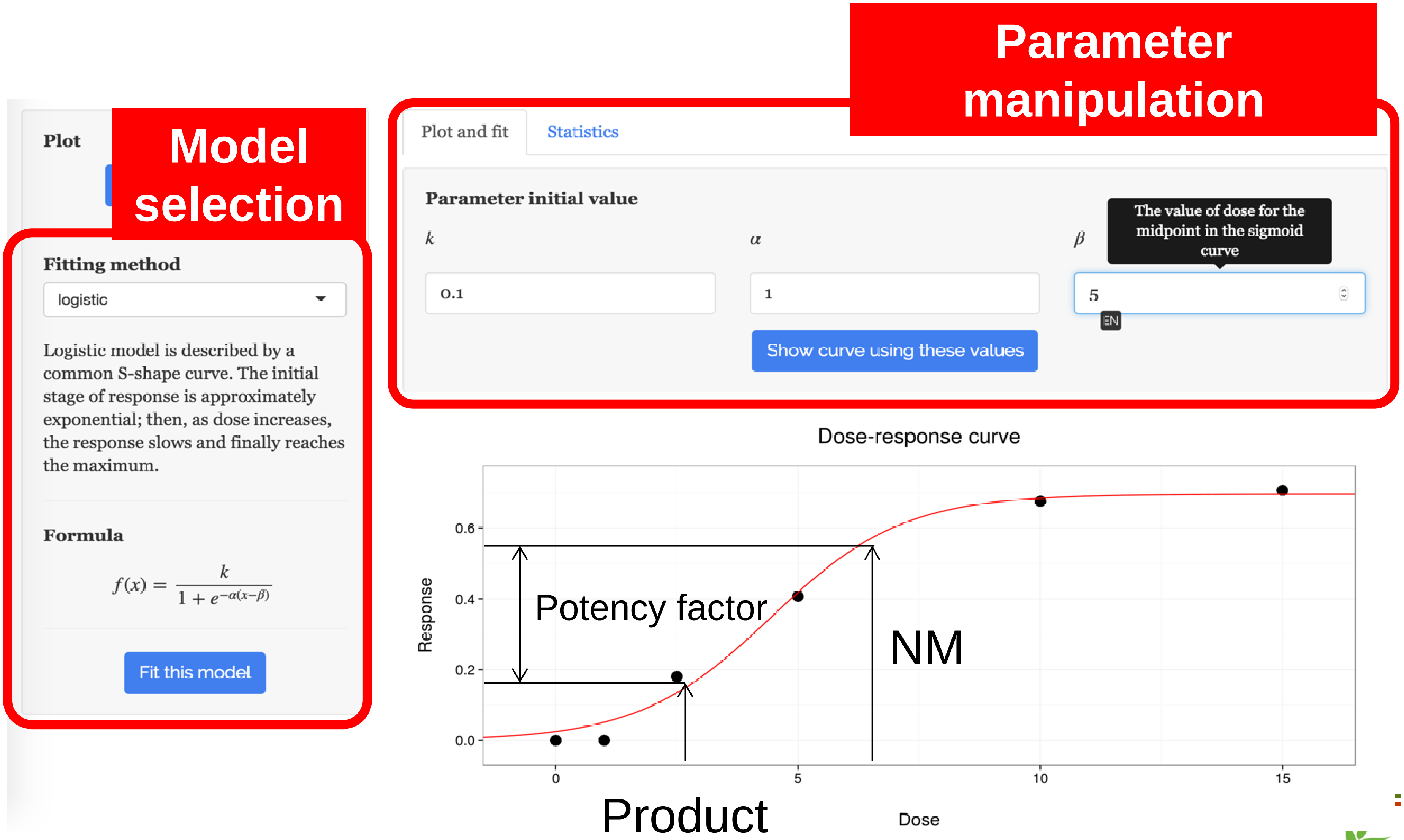
- Database infrastructure design
- Data curation from toxicity studies in the literature
- Data quality control

- Database query to extract dataset for nanomaterial type and dose, tested organism, measured endpoint, and biological response
- Queried dataset as data input for dose-response modeling

- Estimate the effective dose of nanomaterial released from product
- Predict responses based on existing toxicity data
- Smart user interactive interface for data handling and modeling

CEINT

# Dose-response model for NMs



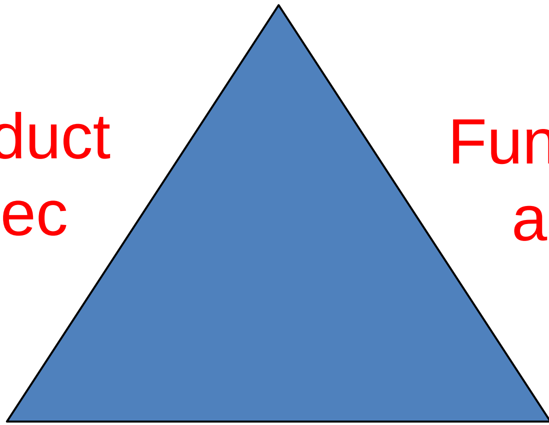
# Framework for Assessing Exposures to Consumer Products

**Process/system**

(e.g. UV, weathering, chewing, sanding)

Product spec

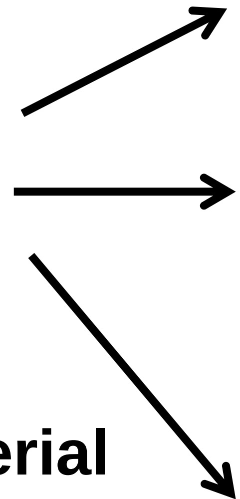
Functional assay



**Product Matrix**

Scientific discovery

**Nanomaterial**



Exposure Route

Oral

Dermal

Inhalation

# Thank You for your attention!

## Acknowledgements

SSRL

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