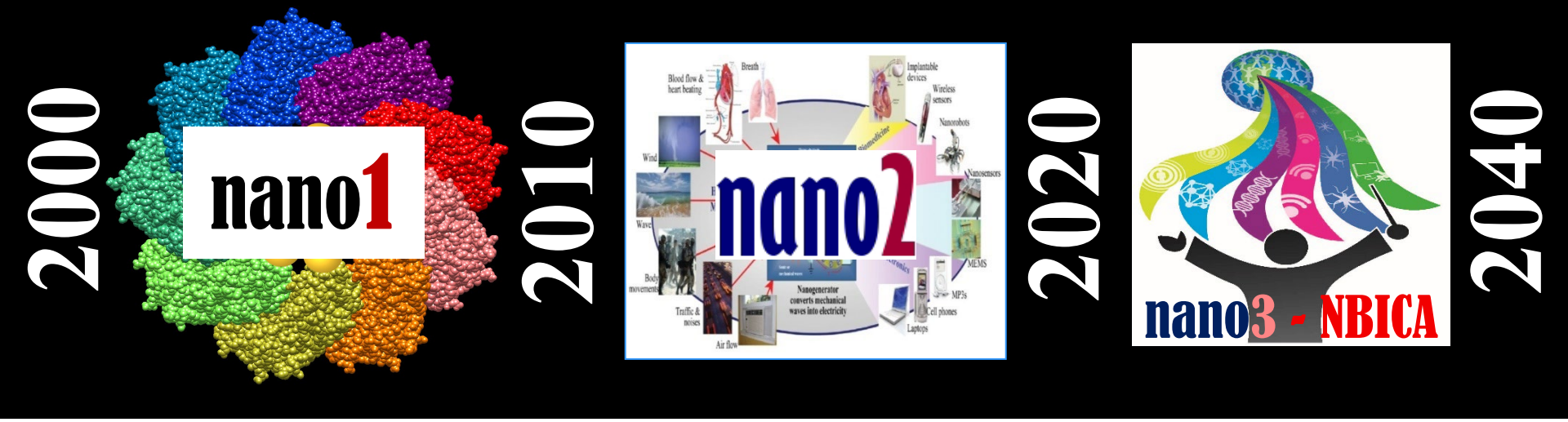


NANOTECHNOLOGY FOUNDATION for Emerging Technologies

Mike Roco
National Science Foundation and National Nanotechnology Initiative

17th US-Korea NanoForum,
Seoul, April 3-4, 2023


1st Korea-U.S. NanoForum
Seoul, Oct 14-15,2003
Oct 14, 2003


THE 9th KOREA-U.S. NANOFORUM
Exploring New Direction for Convergence of Nano Science and Technology to Applications
June 4(Mon)~5(Tue), 2012 HIT, HANYANG UNIVERSITY
June 4, 2014

September 23, 2019

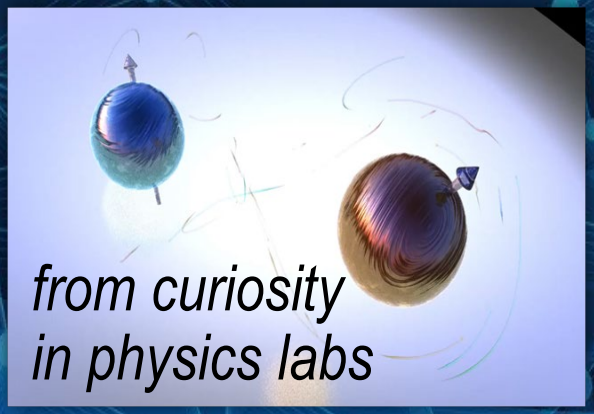
Outline

- **Long view of nanotechnology development in the international context**
- **A foundation for the global S&T system**
- **Contributing NSF programs**
- **Opportunities for bi-lateral collaboration**

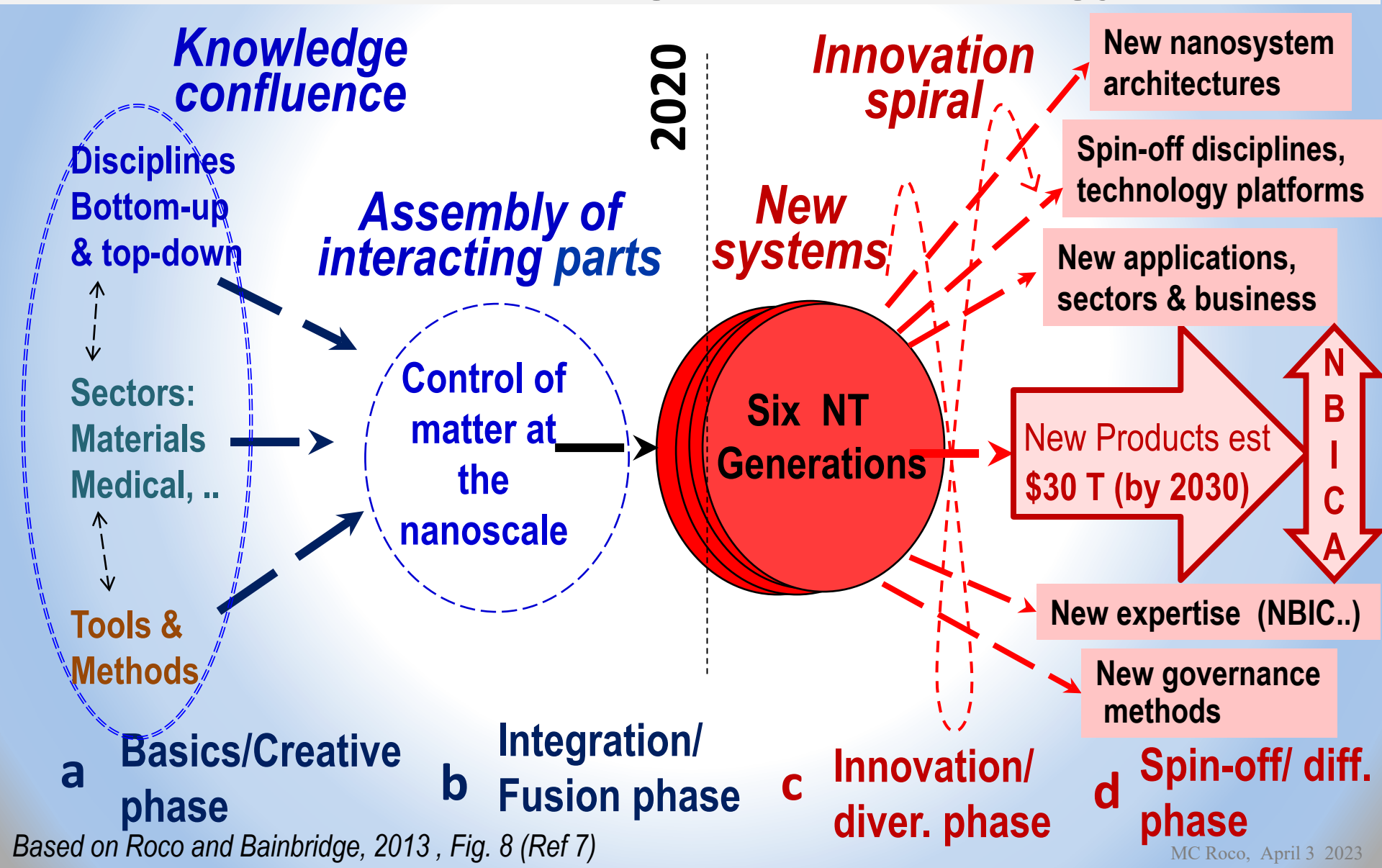
Long view of establishing nanotechnology

2000 (unified definition) -

2040 (systematic, by design, economic use in economy)



2000-2040 Convergence-Divergence cycle for establishing nanotechnology



Based on Roco and Bainbridge, 2013 , Fig. 8 (Ref 7)

40-year vision for establishing nanotechnology in 4 stages

GENERATIONS OF NANOPRODUCTS (prototypes stage)

2040

Emerging industries and services

nanoD Diffusion in Economy

2030-2040

New socio-economic capabilities, architect

nano3 Technology divergence

2020-2030

To general purpose technology, moduls

nano2 System integration

2010-2020

Create library of nanocomponents, function

nano1 Component basics

2000-2010

DIVERGENCE

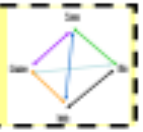
CONVERGENCE

Foundation for new S&T fields

Emerging Societal Solutions

6. Nanosystem Conv. Networks

5. NBICA Techn Platforms

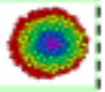


4. Molecular Nanosystems

3. Systems of Nanosystems

2. Active Nanostructures

1. Passive Nanostructures

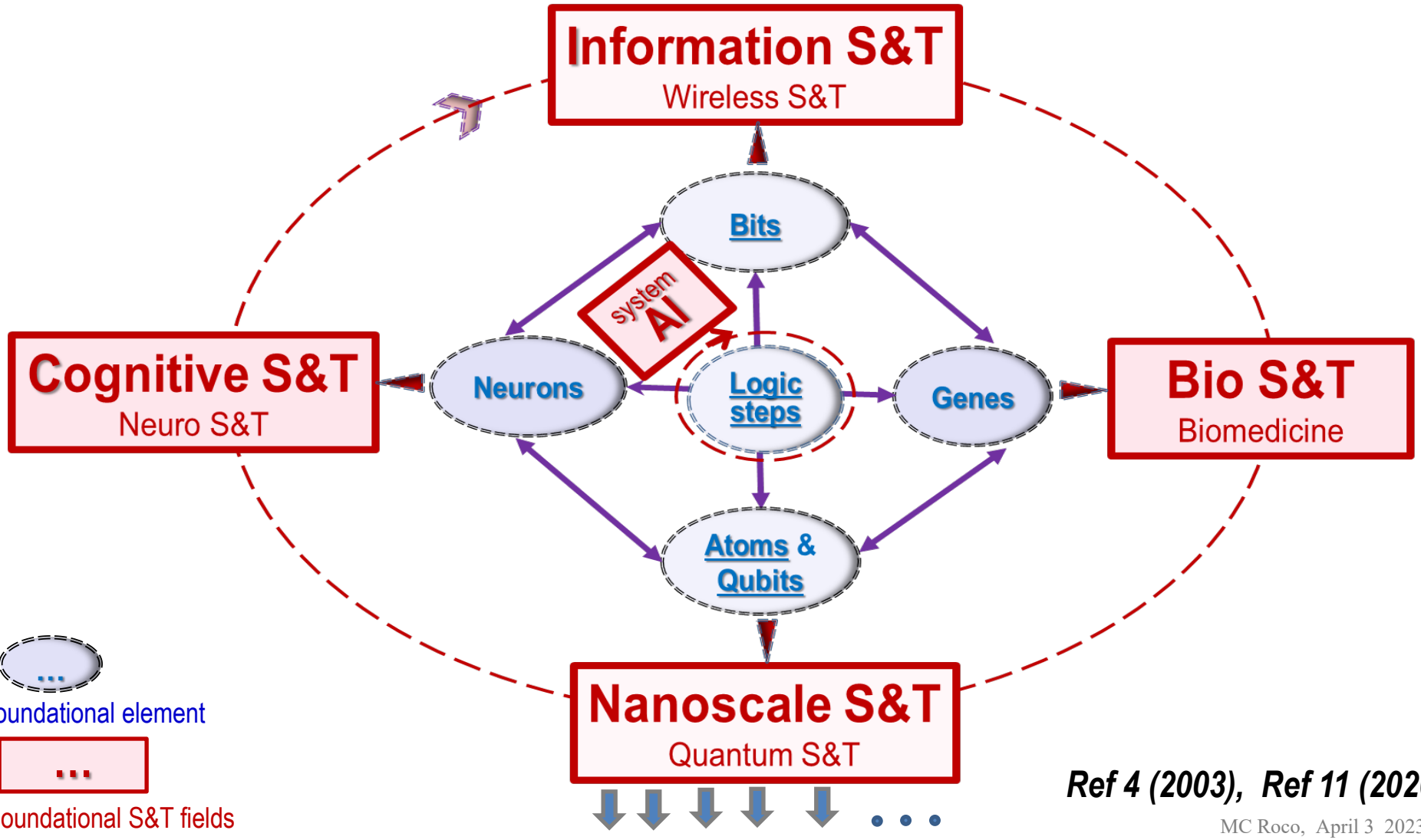


MC Roco Sept 29 2020

NANO is a foundation for converging S&T system

Foundation fields**: Nano, Bio, Information, Cognitive, and system AI- **(NBICA)

***from 5 foundation elements**: atoms/qubits, genes, bits, neurons, logic steps*



Ref 4 (2003), Ref 11 (2020)

Nanotechnology spin-off S&T areas

2000-2020 (top 20 topics) *(i)*

- **Quantum systems** - *Quantum S&E 2003; expansion NQI 2018*
- **Nano-Environment, EHS & ELSI** 2003 activities, 2005 NNI WG
- **Metamaterials** – 2004
- **Plasmonics** – 2004
- **Nanomedicine –** 2004 (NIH focused program)

- **Synthetic biology** – 2004 (NSF increase of awards)
- **Nanoelectronics Research Initiative** 2005; expansion 2015;
- **Nano antennas and devices for wireless,** 2006
- **Modeling / simulation** - *Materials Genome Initiative 2011*
- **Nanophotonics** - *National Photonics Initiative 2012*

Nanotechnology spin-off areas

2000-2020 (top 20 topics) *(ii)*

- **Nanofluidics**
- **Carbon electronics**
- **Nano sustainability**
- **Nano wood fibers, nanocellulose**
- **Nano-AI** 2017 steep increase of awards and publications
- **DNA nanotechnology**
- **Protein nanotechnology**
- **Nanosystems-mesoscale**
- **Quantum biology**
- **Nano NEURO …. Nano in plants ….**

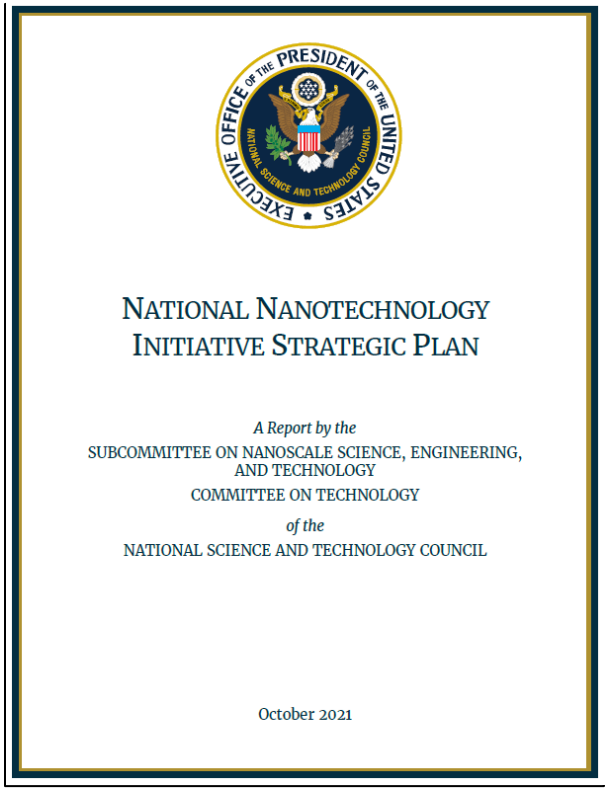
NNI divergence of nanotechnology

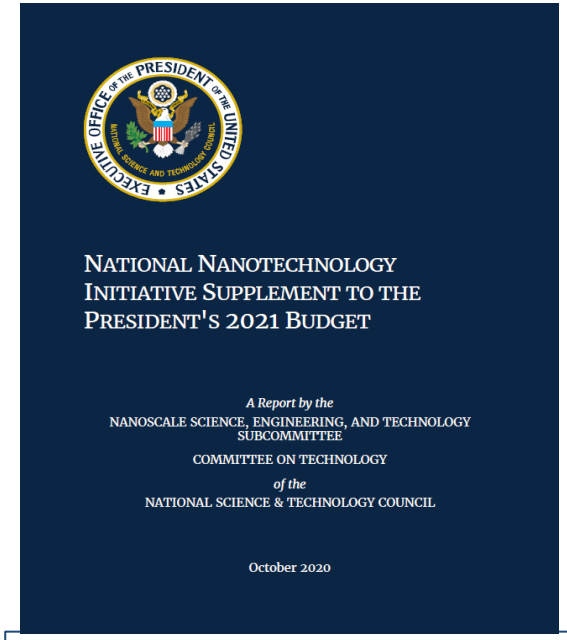
MC Roco, April 3 2023

U.S. National Nanotechnology Initiative, $40B, by 2023

Knowledge divergence: 80 countries have created nano R&D programs

National Nanotechnology Initiative in 2023





PCAST report on NNI

NAS/NRC report on NNI

2023 Annual NNI Supplement to the President's Budget: ~ 2 B

2021-2026 NNI Strategic Plan

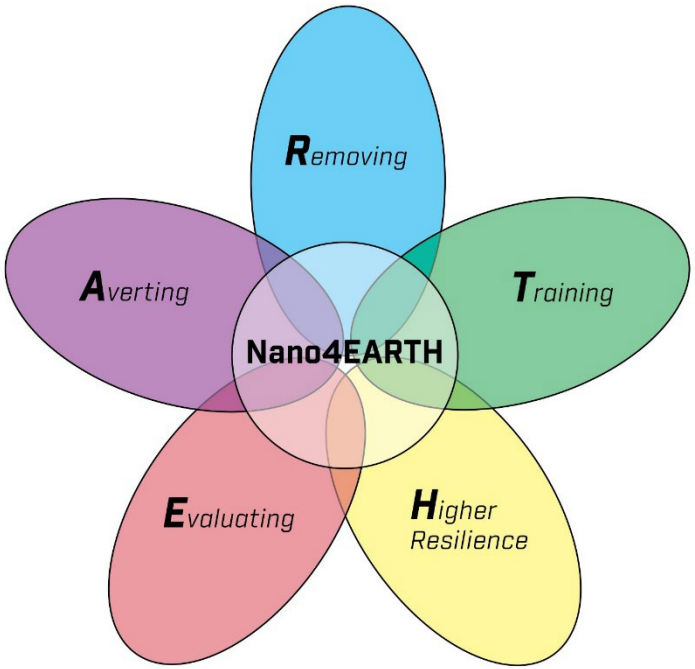
Note: The actual NNI investment **by 2023 ~ $40 billion**, including $1.7 billion from BARDA in 2021

- HEHI
- Nano-plastics
- Nanotechnology for Sensing
- Water Sustainability Through Nanotechnology

Networks, Comunities of research, Webinars, Videos, …

Signature Initiatives (2011~2022) ; National Nanotechnology Challenges

NNI: National Nanotechnology Challenge



Nano4EARTH:

Evaluating, monitoring and detecting climate change status and trends;

Averting future greenhouse gas emissions

Removing existing greenhouse gasses;

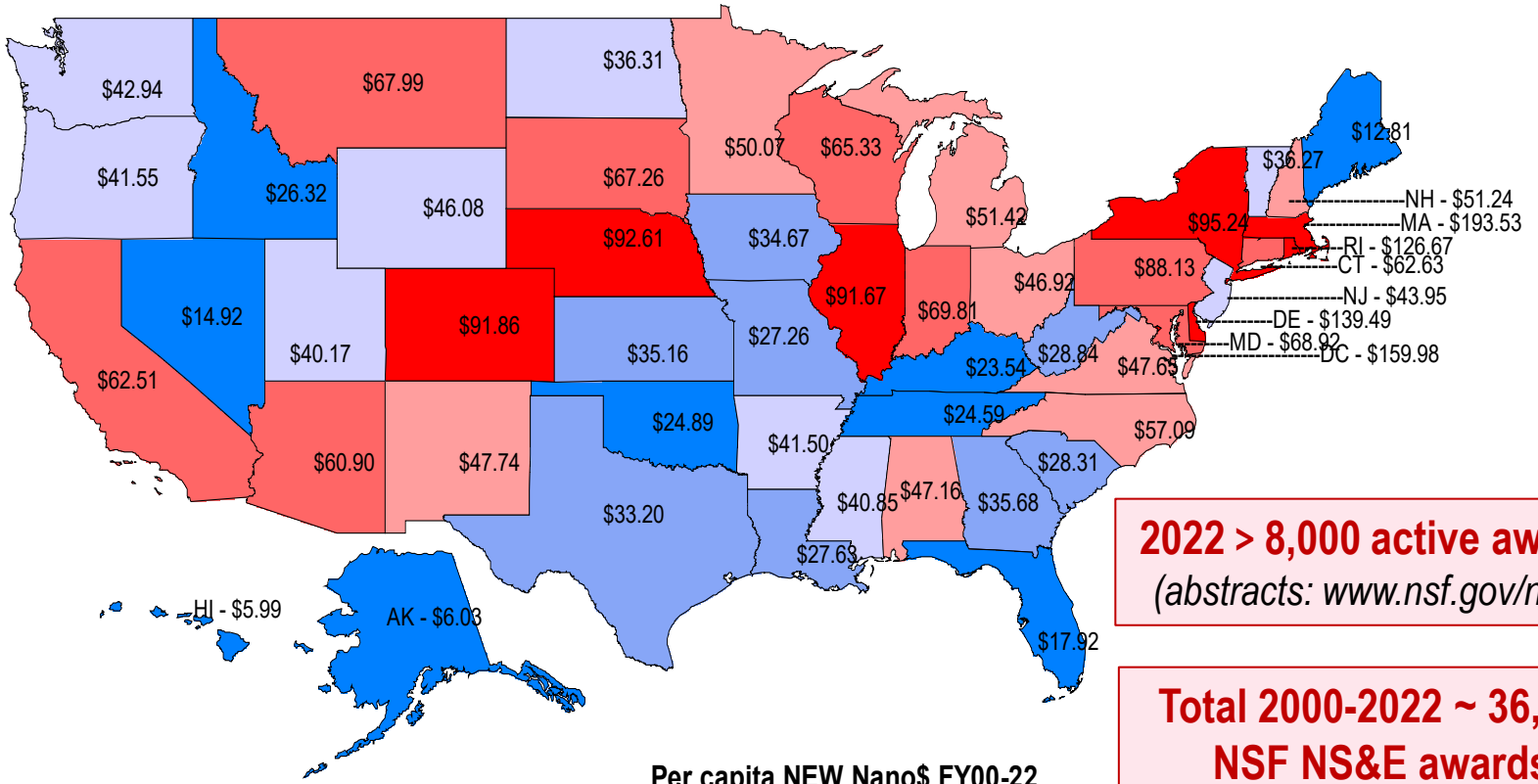
Training and educating a highly skilled workforce to harness nanotechnology solutions; and

Higher resilience

Research areas: *(1)* decarbonize electricity, *(2)* electrify end uses and switch to other clean fuels, *(3)* cut energy waste, *(4)* reduce methane and other non-carbon dioxide emissions, *(5)* scale up carbon dioxide removal

NSF's NS&E amount new awards per capita

FYs 2000 - 2022: U.S. average ~ $54 /capita



2022 > 8,000 active awards
(abstracts: www.nsf.gov/nano)

Total 2000-2022 ~ 36,000 NSF NS&E awards

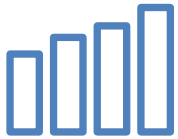
PR - $35.37

#1 MA $193 / capita (2000-2022)

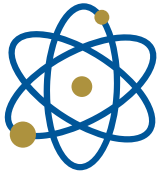
"CHIPS and Science" U.S. Congressional Act (8/2022)

$280 B over ten years to NSF, DOE, DOC/NIST, industry, of which:

- **$52.7B for domestic semiconductor industry: $39B in semiconductor incentives new fabs, $13B in R&D and workforce development, ….**
- **Provides support for key research and education areas (new + continuations)**



Authorizes a doubling of the NSF budget over 5 yrs.



Strengthens fundamental research (SEMI, BIO, others)

"Technology, Innovation & Partnerships (TIP)" - new

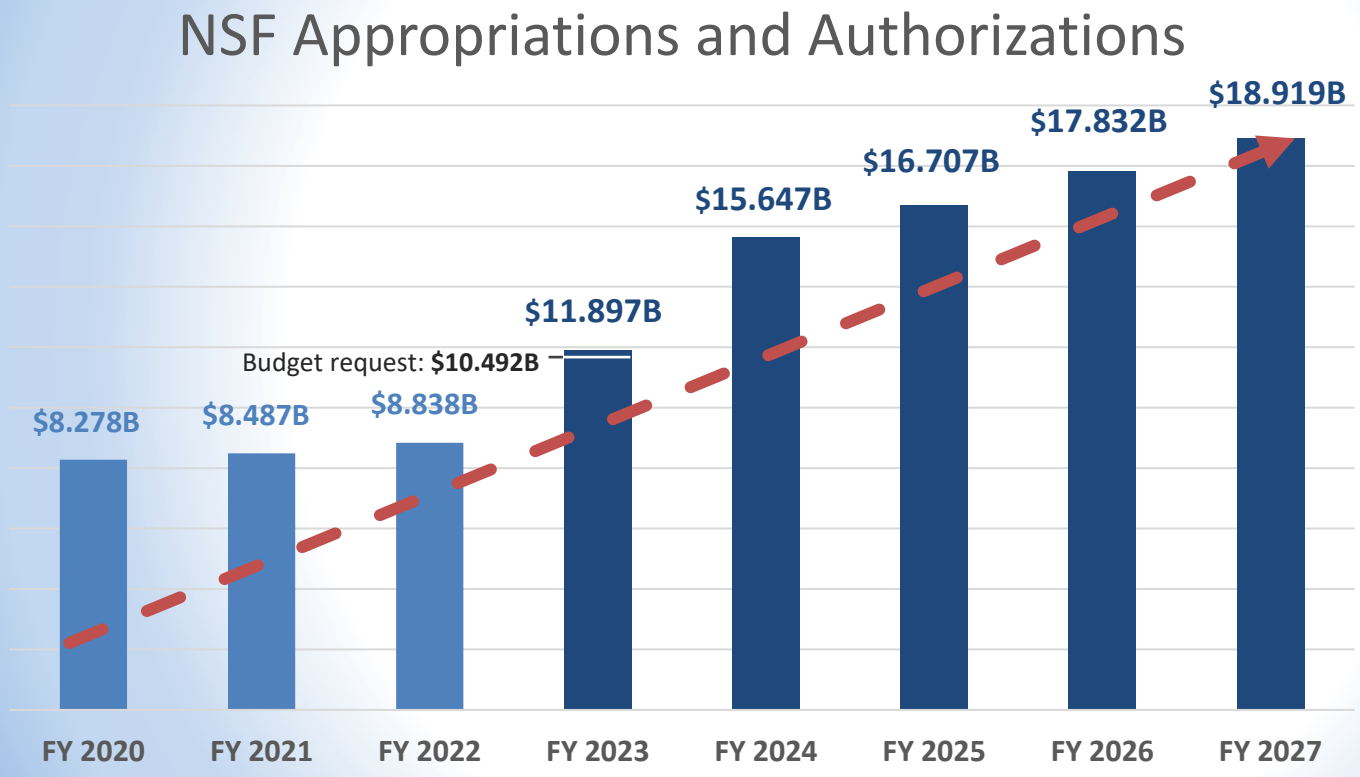
Invests in STEM Education

Advances diversity in STEM

Addresses research security

“CHIPS and Science” Act for NSF

Authorization $81B for FY 2023 - 2027



FY 2022 appropriation: $8.8 billion

FY 2023 request: $10.492 billion

It includes authorization for +$20B for TIP (~25% of all NSF) for the next five years

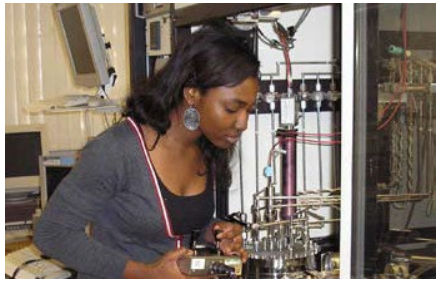
Advanced semiconductors: *support at NSF/NNI 2001-2022*

- **2001 Program with a focus on nanoelectronics, nanomagnetics, nanophotonics**
- **2001-2022 investments in teams, centers on nanoelectronics, manufacturing for computing and memory devices, quantum devices** ("*beyond Moore Law*")
- **2005-2020 Nanoelectronics Research Initiative with SRC** ("*for 2020 and beyond*")
- **2016-2020 Energy-Efficient Computing: from Devices to Architectures** (NSF16526)

Future of semiconductors: *seed NSF announcements since 2022*

- "**Future of Semiconductors**" (FuSe) program solicitation (NSF 22-589; 23-552 $50M)+ SynBio , a partnership with Ericsson, IBM, Intel, and Samsung to co-design methods, simultaneously consider the device/system performance, manufacturability, recyclability, and impact on environment. Partners have privilege to access any IP of the funded awards.
- "**Research Coordination Networks for Semiconductors**" (NSF DCL 22-116)
- "**Supplements for Access to Semiconductor Fabrication**" (NSF DCL 22-113)
- "**Partnership for Prototyping of CMOS+X Systems**" (NSF DCL 22-076)
- **Semiconductors (S) topic SBIR-STTR Program**

NSF – student education and training in semiconductors



- **NSF and SRC** to support semiconductor research experiences **for undergraduates**, 5-year agreement (NSF 19-582)
- **EDU DCL**: Enhancing Engineering Technology and Advanced **Semiconductor Manufacturing Technician Education** (NSF 22-120)
- Micro Nano Technology Education Center and National Institute for Technology and Innovation: **National Talent Hub for semi - nano**
- **NSF-Intel** ($10M) and **NSF-Micron** ($10M) for semiconductors Research & Education
- **INTERN** – for graduate students in industry

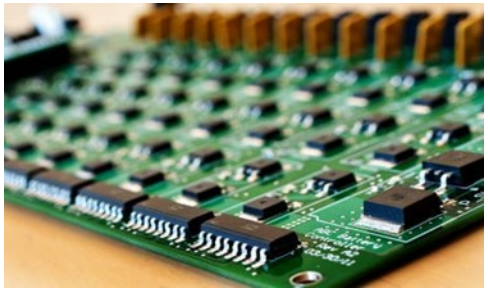
Other focused announcements supporting semiconductor research and innovation

- **Advanced Chip Engineering Design and Fabrication** (ACED Fab) (NSF 22-636). Supports collaborations on design and fabrication projects of semiconductor chips utilizing Taiwan's semiconductor foundries (e.g., TSMC) with reduced cost (US PIs pay 20%)

- **Addressing Systems Challenges through Engineering Teams** (ASCENT) (NSF 23-541). Theme 1: Integrated Electronic Systems enabled by Semiconductors for Climate Change Mitigation

- **Future Manufacturing (FM);** NSF 23-550 Solicitation

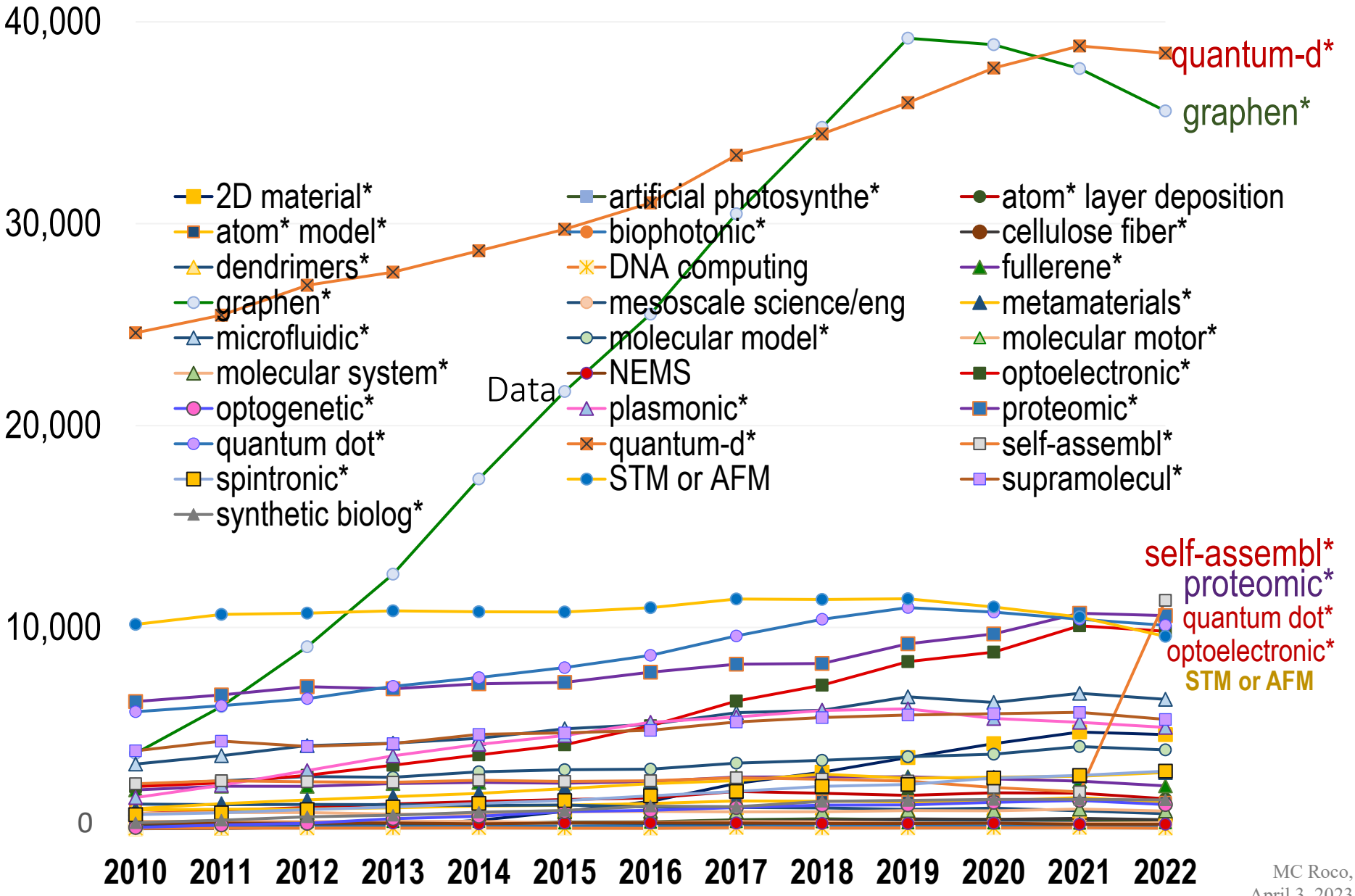
- **Expanding Capacity in Quantum Information Science and Engineering** (ExpandQISE) (NSF 23-551). Supports research and training.



- **National Semiconductor Technology Center** (Dept. of Commerce) Proposed NY Albany Nanotech Complex

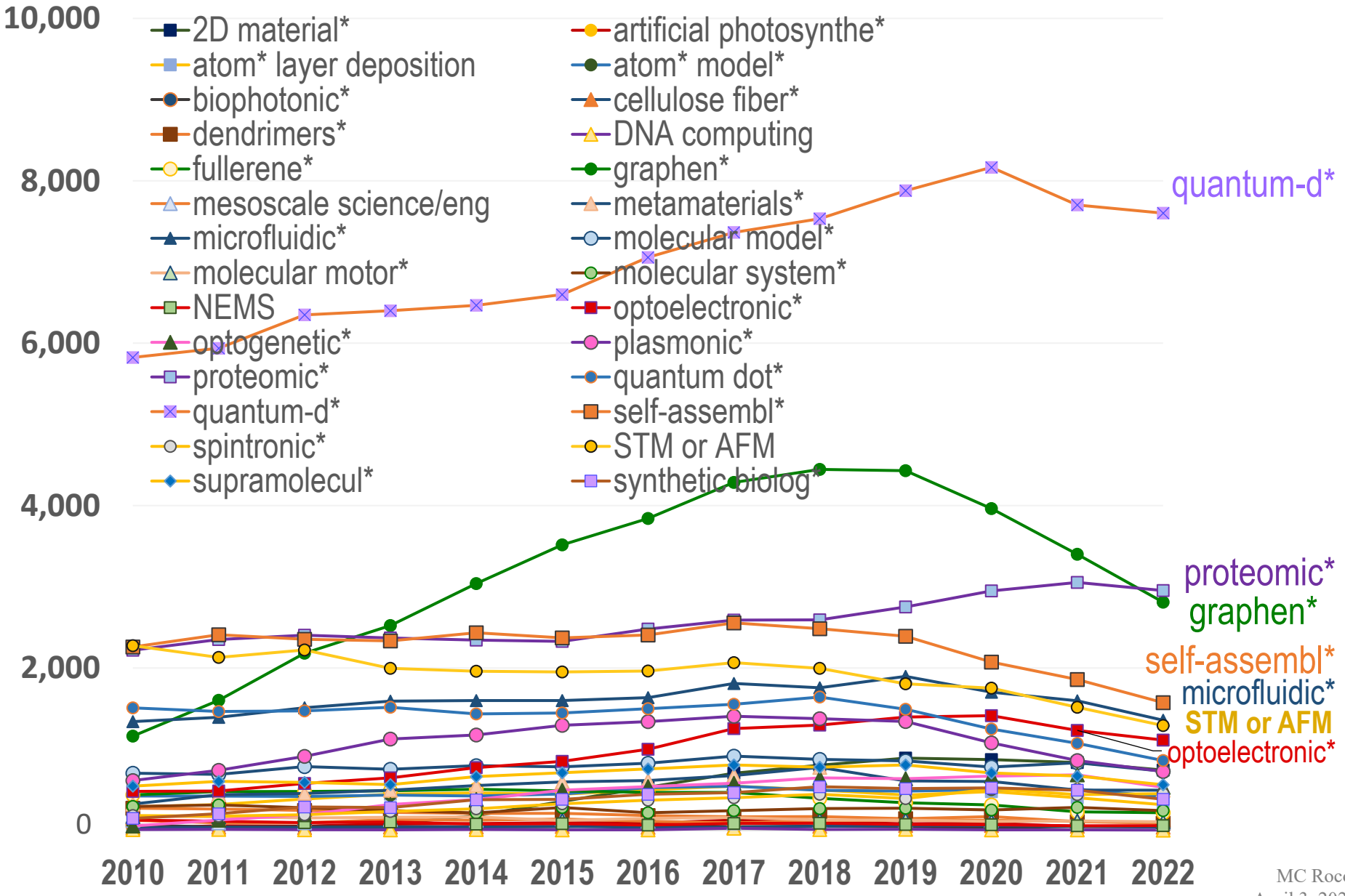
International context

Nanotechnology topics in WoS from authors WORLD (2010-2022)



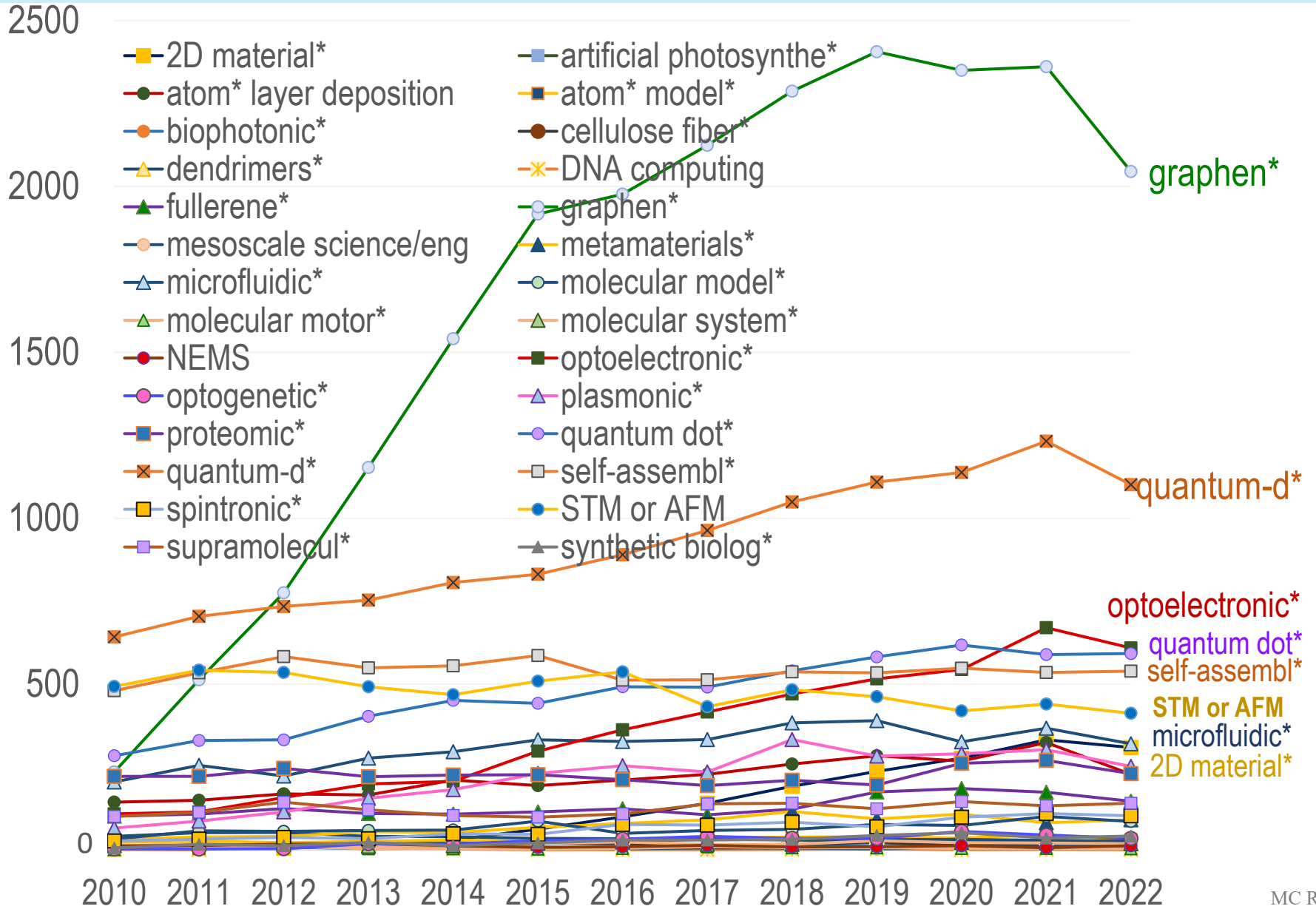
MC Roco,
April 3 2023

Nanotechnology topics in WoS from authors US (2010-2022)



MC Roco,
April 3 2023

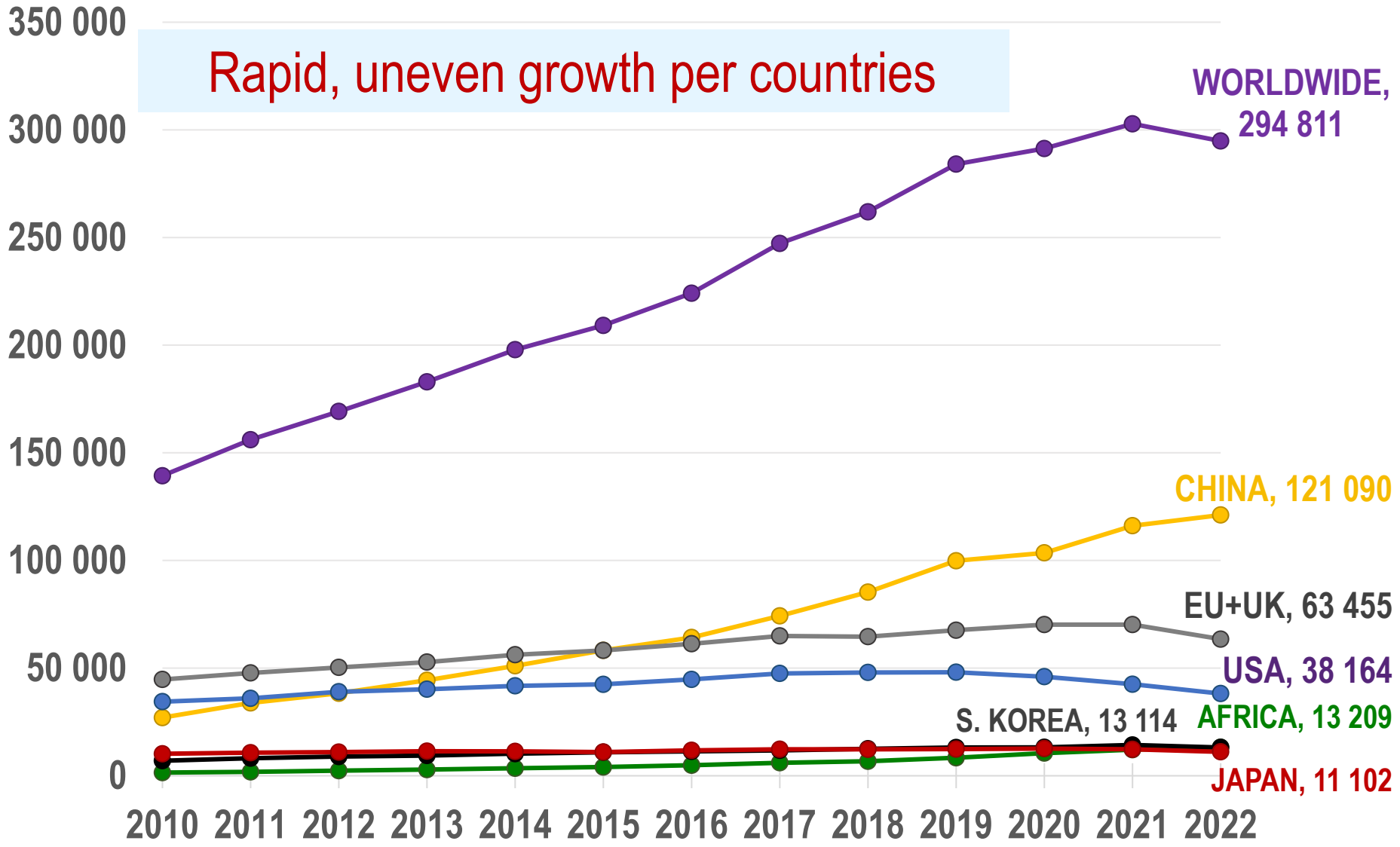
Nanotechnology topics in WoS from authors ROK (2010-2022)



MC Roco,
April 3 2023

Nanotechnology papers in the WoS: 1990 - 2022

"Title-abstract" search for nanotechnology by keywords (update from NANO 2020, Ref 3)

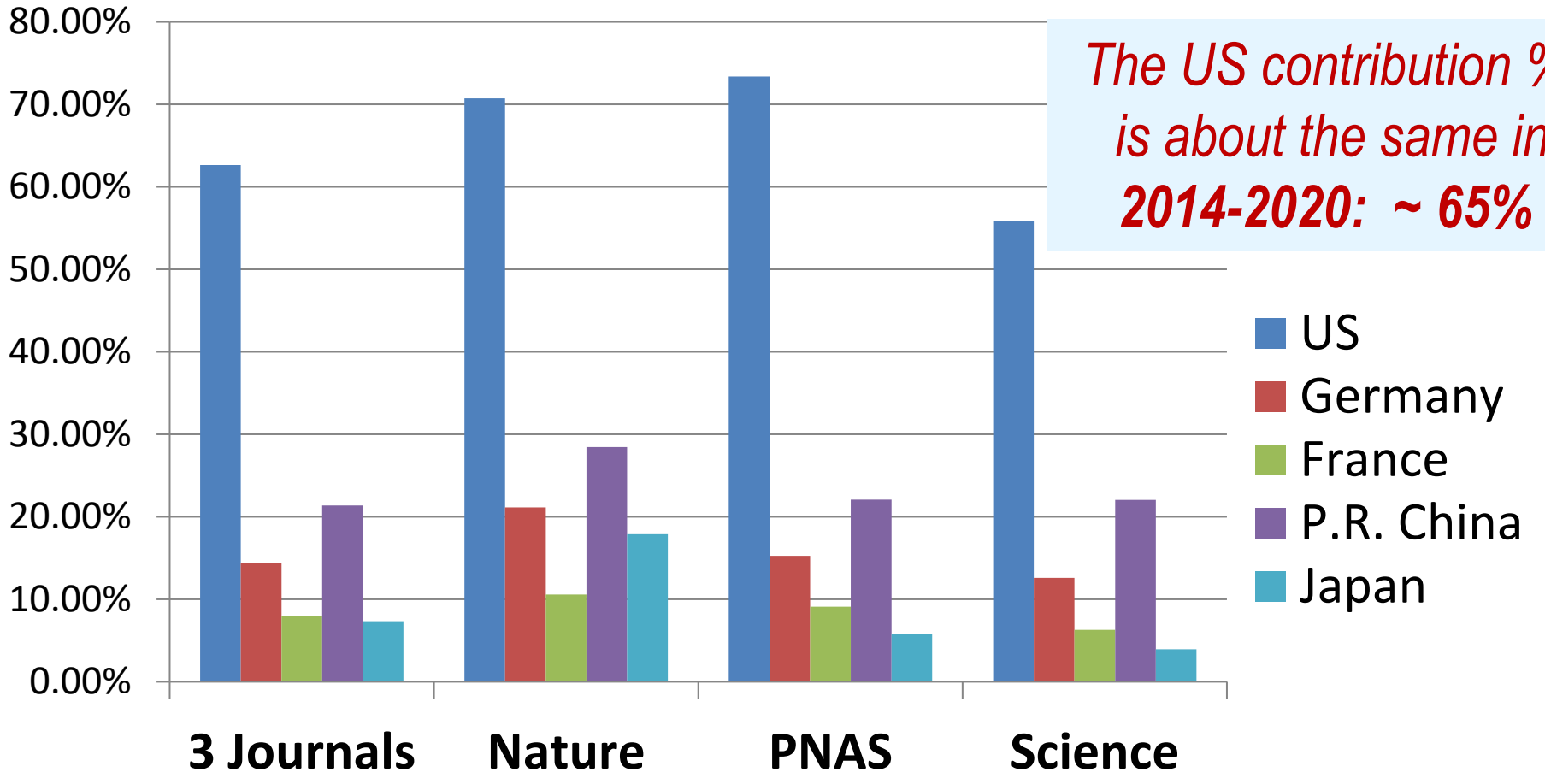


Data as of March 5. 2023

MC Roco, April 3 2023

Five countries' contributions to Top 3 journals in 2020

"Title-abstract" search for nanotechnology by keywords (update from NANO 2020, Fig 1; Ref 3)



The US contribution % is about the same in ***2014-2020: ~ 65%***

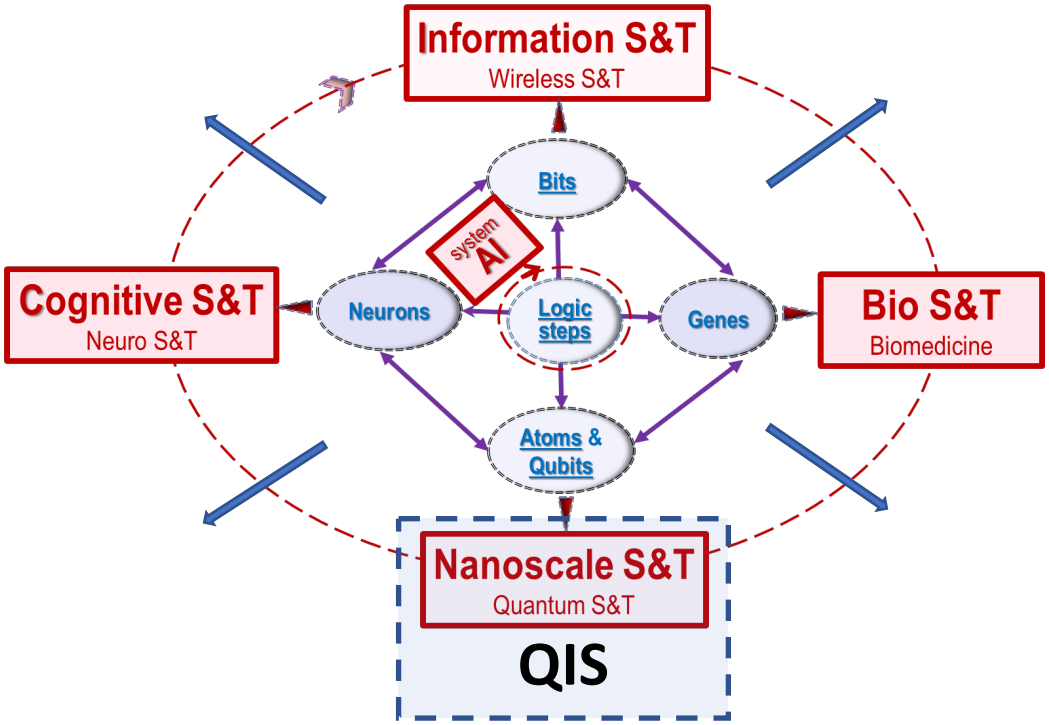
*Each article is assigned to multiple countries if its authors have different nationalities. Therefore, the sum of percentages from five countries exceeds 100%.

Nanotechnology provides a foundation for the emerging S&T system

reflected in NSF programs

NNI Retrospective video at 20 years:
https://www.tvworldwide.net/Player/VideoId/1893/UseHtml5/True

About ½ NSF's NNI awards are part of converging technologies
from advanced semiconductor and synthetic biology to AI systems, quantum information systems, and advanced wireless (5G, 6G)...

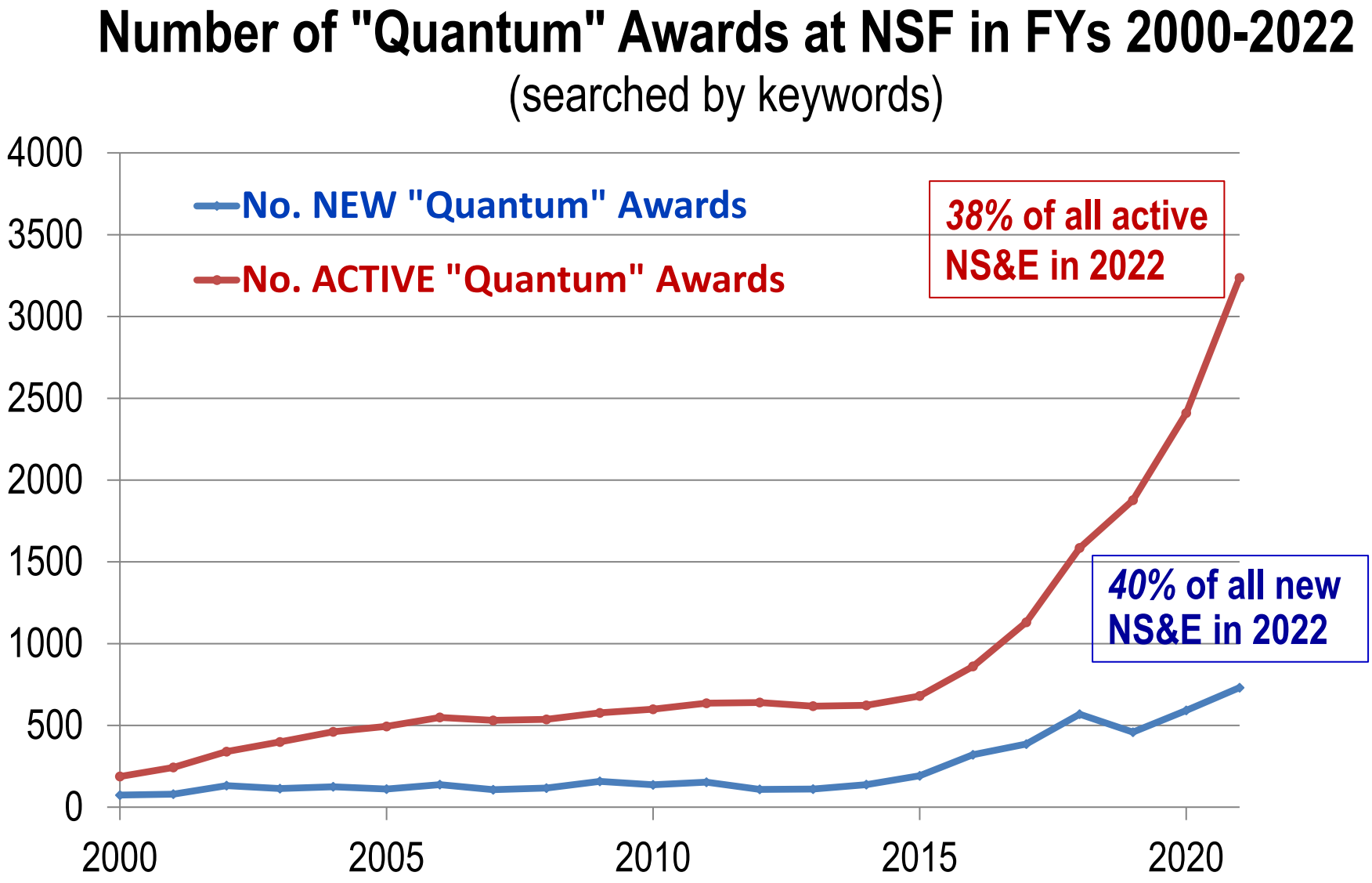


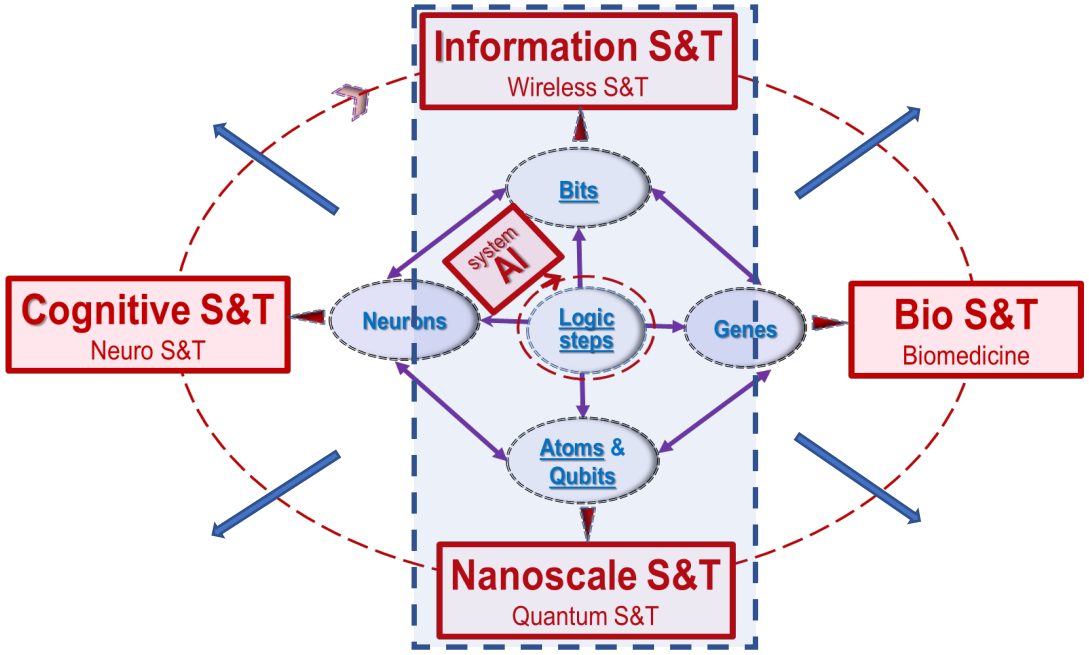
Nanotechnology supporting **quantum information systems**

*Quantum National Initiative (**QIS**) is an outgrowth of NNI*

- ***Ex. Topics***: Quantum materials, Quantum communication, Quantum computing, Quantum biology, Quantum sensors
- ***Ex. Outcomes***: First quantum device in 2010; Quantum internet; IBM and Google quantum computer systems, highly efficient
- ***Ex. NSF programs***: in core programs; *Network of Quantum Centers; Convergence Accelerators on Quantum Systems*

Confluence NS&E with QIS

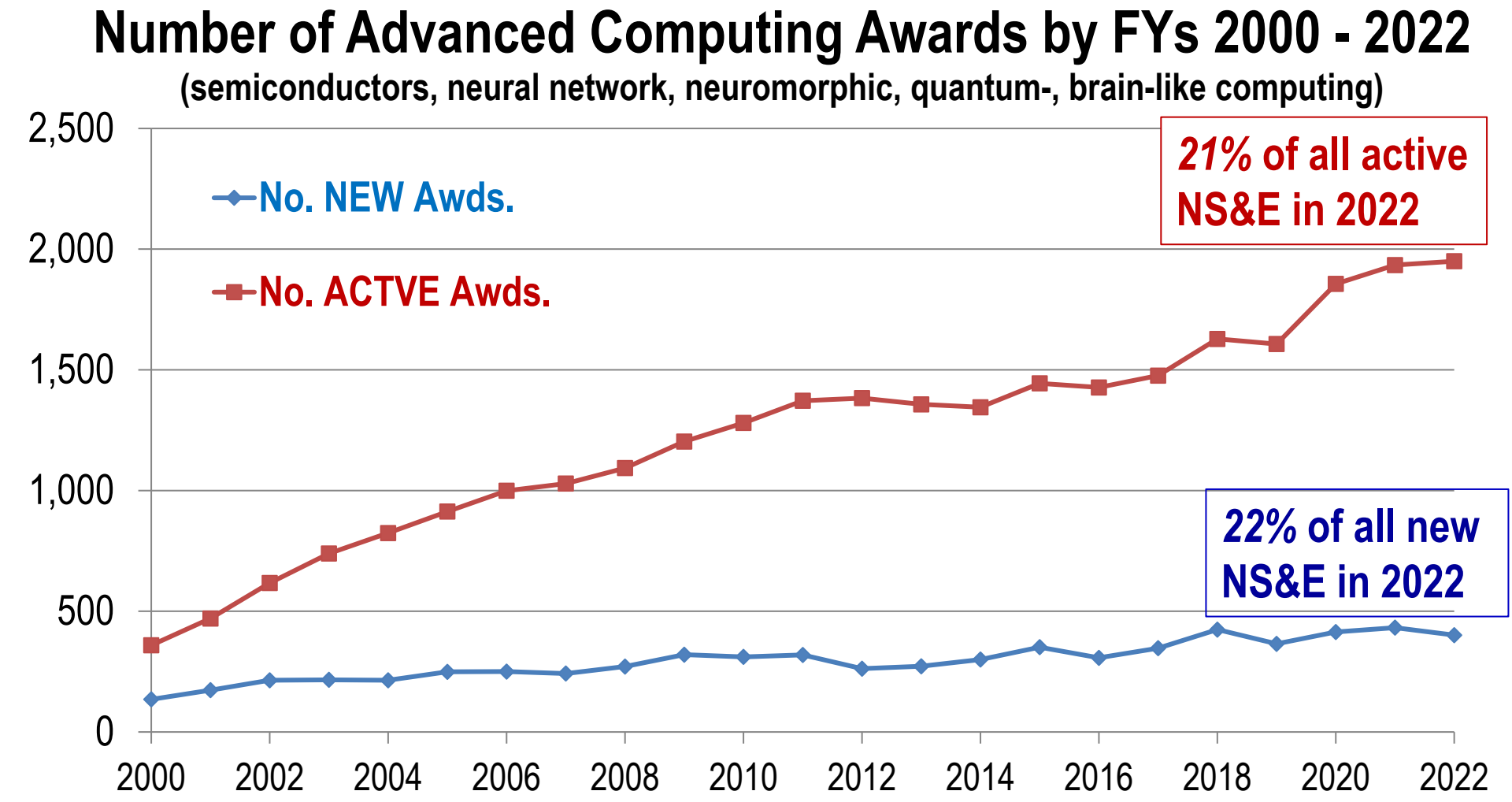




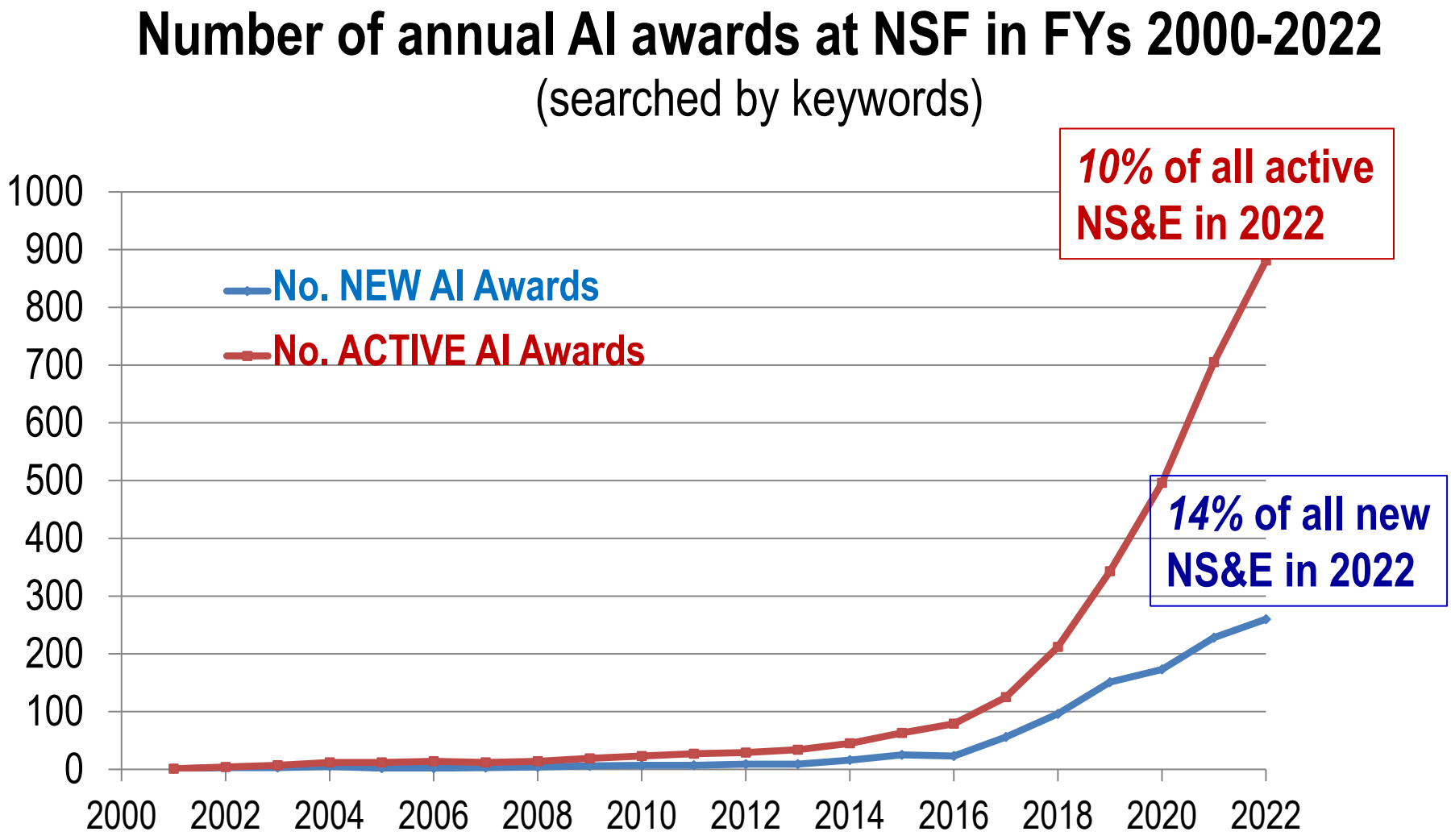
Nano - Info – AI :
advanced computing, AI systems, robotics and communication

- ***Ex. Topics***: 3D nanosystems; Nanorobots; Soft robots; Nano-sensors; Natural language –AI; Semiconductors; Advanced materials; Neural networks; Neuromorphic engineering
- ***Ex. Outcomes***: AI design nanoarchitectures; Superconductors; AI for Sustainable Nanomanufacturing
- ***Ex. NSF programs***: Energy efficient Components - Devices - Architectures (NSF-SRC); National AI Res. Institutes (18, $360M)

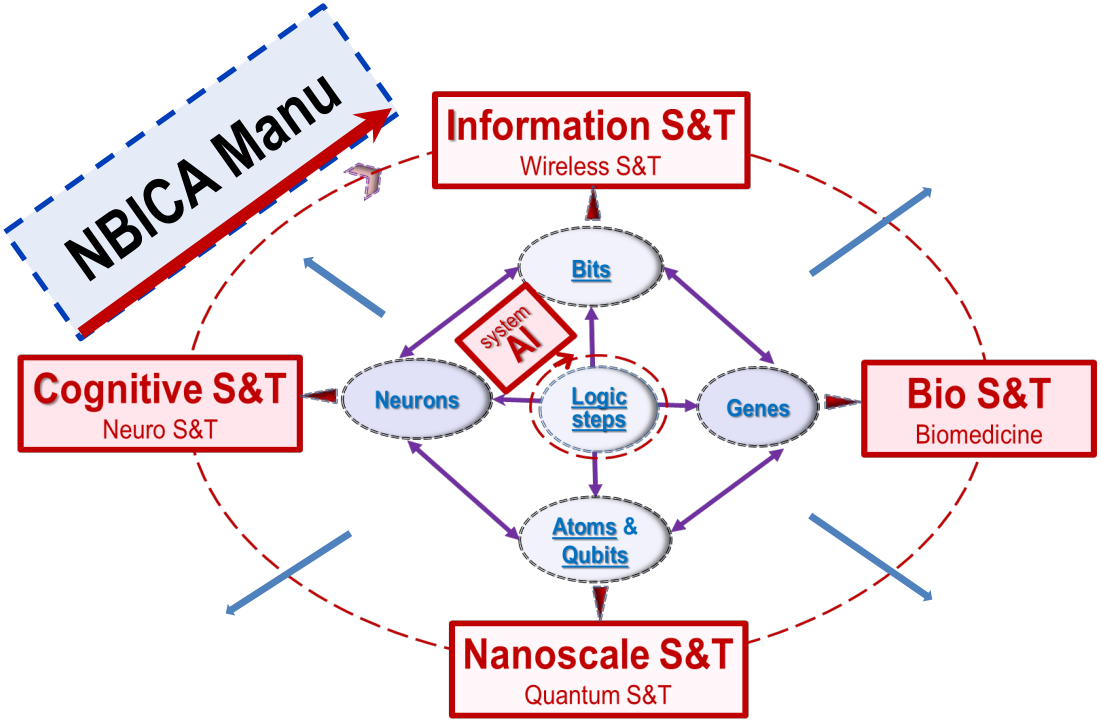
Confluence NS&E with advanced computing (AC)



Confluence NS&E with artificial intelligence (AI)



MC. Roco, April 3 2023

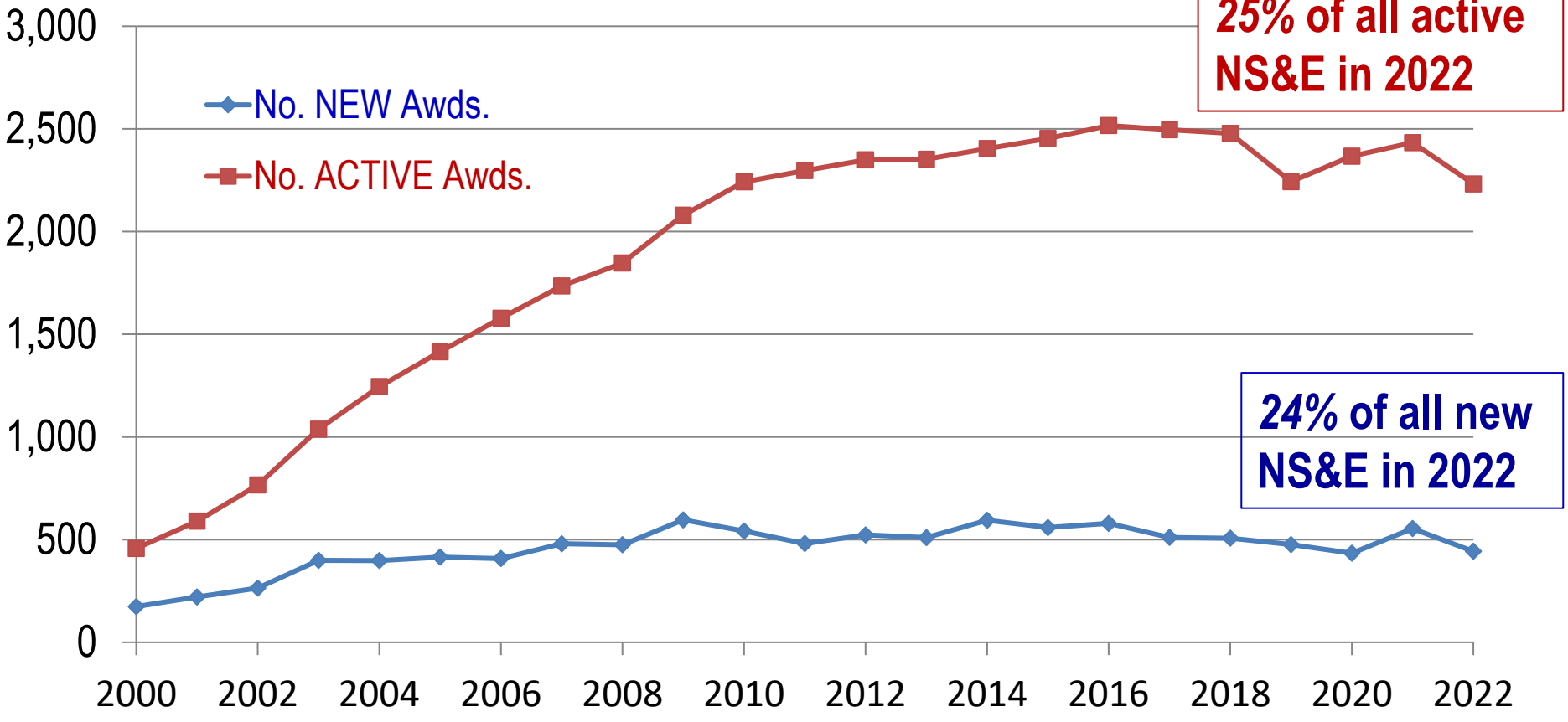


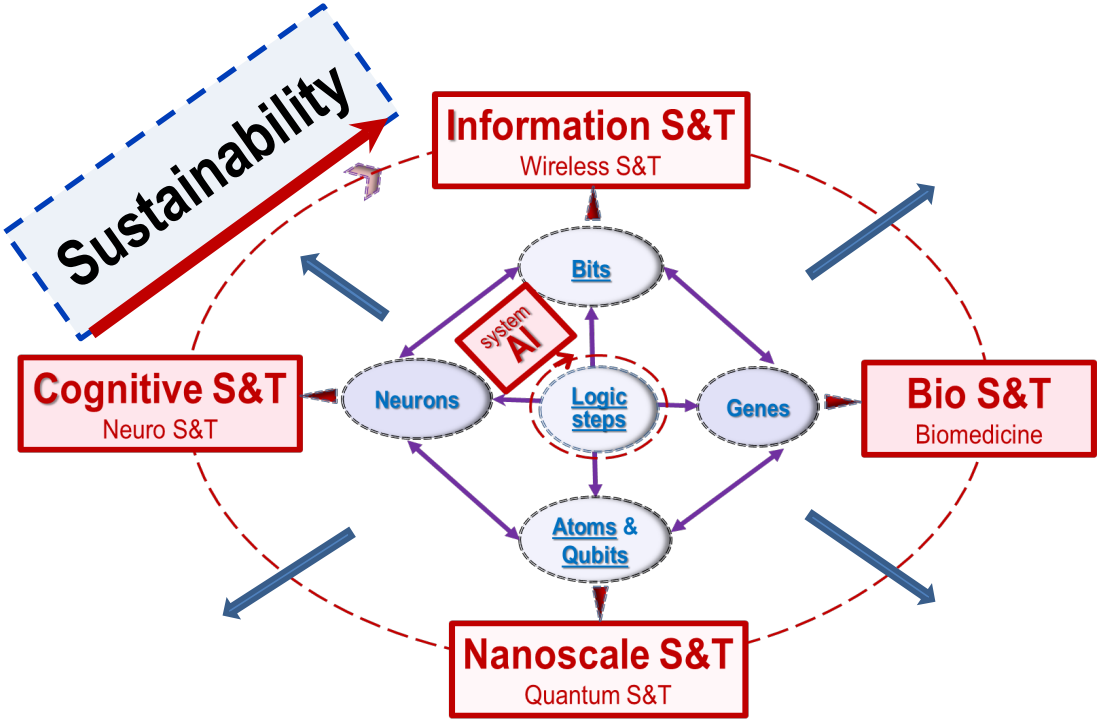
Convergence NBICA *Manufacturing*

- ***Ex. Topics:*** Nanomanufacturing convergence with Bio, remote IT, AI, neuro, other fields; Cellular manufacturing
- ***Ex. outcomes:*** Hierarchical design; Additive manufacturing of 3D nanoarchitectures; Vaccine microneedles; 2-D nanomanufacturing; DNA and RNA manuf.; Self-healing mat.
- ***Ex. Programs:*** "Manufacturing for the Future"; "Hierarchical nanomanufacturing" node of Network for Comput. Nanotech.

Confluence NS&E with NBICA Manufacturing

Number of NS&E Manufacturing Awards in FYs 2000 - 2022

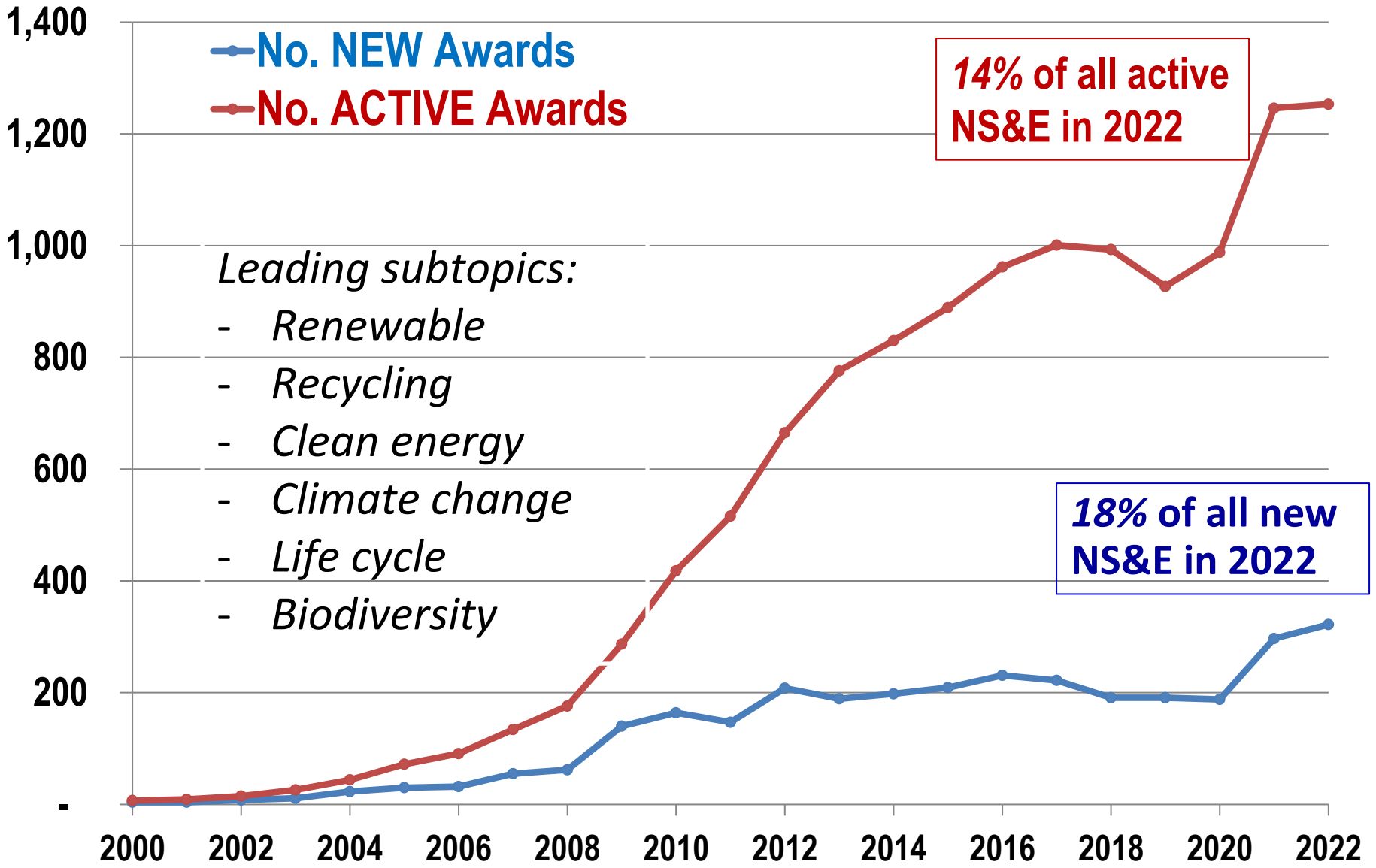




Using converging NBICA technologies ***for societal sustainability***

- ***Ex. Topics:*** Transport phenomena and nano-EHS issues; Nanostructures for energy conversion and storage; Water filtration;
- ***Ex. Outcomes:*** Sustainable communities; Renewable resources; Recyclable materials; Supporting biodiversity; Circular economy, Life cycle performance and assessment; Nanostructured batteries
- ***Ex. Programs:*** Critical Aspects of Sustainability (CAS, NSF 21124): Micro- and Nanoplastics (MNP, DCL NSF 20-050); NEWT; Sustainable Regional Systems Research Networks.

Number of NS&E sustainable society awards FY 2000-2022 is about 1/8 of all NS&E awards



Remediation of Per- and polyfluoroalkyl substances (PFAS), not possible before

(Northwestern University, 2022)

PFAS are anthropogenic substances containing multiple C–F bonds

Using nanocharaterization tools at low temperatures where the specific bonds of PFAS compounds were broken leaving behind only benign end products

Ref 1: "Low-temperature mineralization of perfluoro carboxylic acids", Brittany Trang Science, 18 Aug 2022. Support from NSF, NIH and State of Illinois, incl. from Soft and Hybrid Nanotechnology Experimental (SHyNE) Resource

Ref 2. https://pubs.rsc.org/en/content/articlelanding/2023/EM/D2EM00350C (waste)

Ref 3. PFAS Report, US NSTC, March 2023 (research needs)

PFAS is used in in lithographic patterning for producing semiconductors.

nano3

2020-2030

Horizon: Create nano-inspired solutions for the industries / sectors of the future

- **Artificial intelligence (AI)** – use and design nanosystems
- **Quantum Information S&T** - a part of nanoscale S&T
- **Wireless Connectivity (5G, IoT)** – incl. use nanosystems
- **Advanced Manufacturing** - a focus on nanomanufacturing
- **The Bioeconomy** - a focus on nanobiotechnology, gene edit.

- **Computing systems** – semiconductors, neuromorphic, data
- **Sustainable society** – for materials/water/energy/food/env/climate
- **Flight and space exploration** – for fuel, light loads, bio-loop
- **Reshaping education** – unifying concepts, virtual learning
- **Independent aging** – includes nano-medicine and robotics
- **Increase human capacity** – physical, mental, group
- **Enhancing life** – co-evolution of S&T and human development

2022 Nobel Prize in chemistry
Carolyn Bertozzi, Morten Meldal and K. Barry Sharpless

Assembling of macromolecules based on shape, surface and molecular recognition ("click chemistry", "biorthogonal" chemistry) without fundamentally changing the original macromolecules. Creating novel molecules, incl. in the cells of living organisms; *where unwanted by-products are avoided in manufacturing.*

2022 Nobel Prize in physics
John F. Clauser, Alain Aspect and Anton Zeilinger

Pioneering experiments i**n quantum information science on entangled quantum states in photons**. Creating a foundation for quantum information systems; *for smart and economic communication*.

Collaborative Opportunities

Possible mechanisms of collaboration

A. Supplements to existing NSF grants for U.S. investigators to access semiconductor nano user facilities in Korea, to support U.S. students for intern research, and/or add active Korean collaborators (Ad-hoc supplements or via DCL)

B. One-way Lead Agency Opportunity for joint funding opportunities – Requires MOU and (DCL or solicitation)

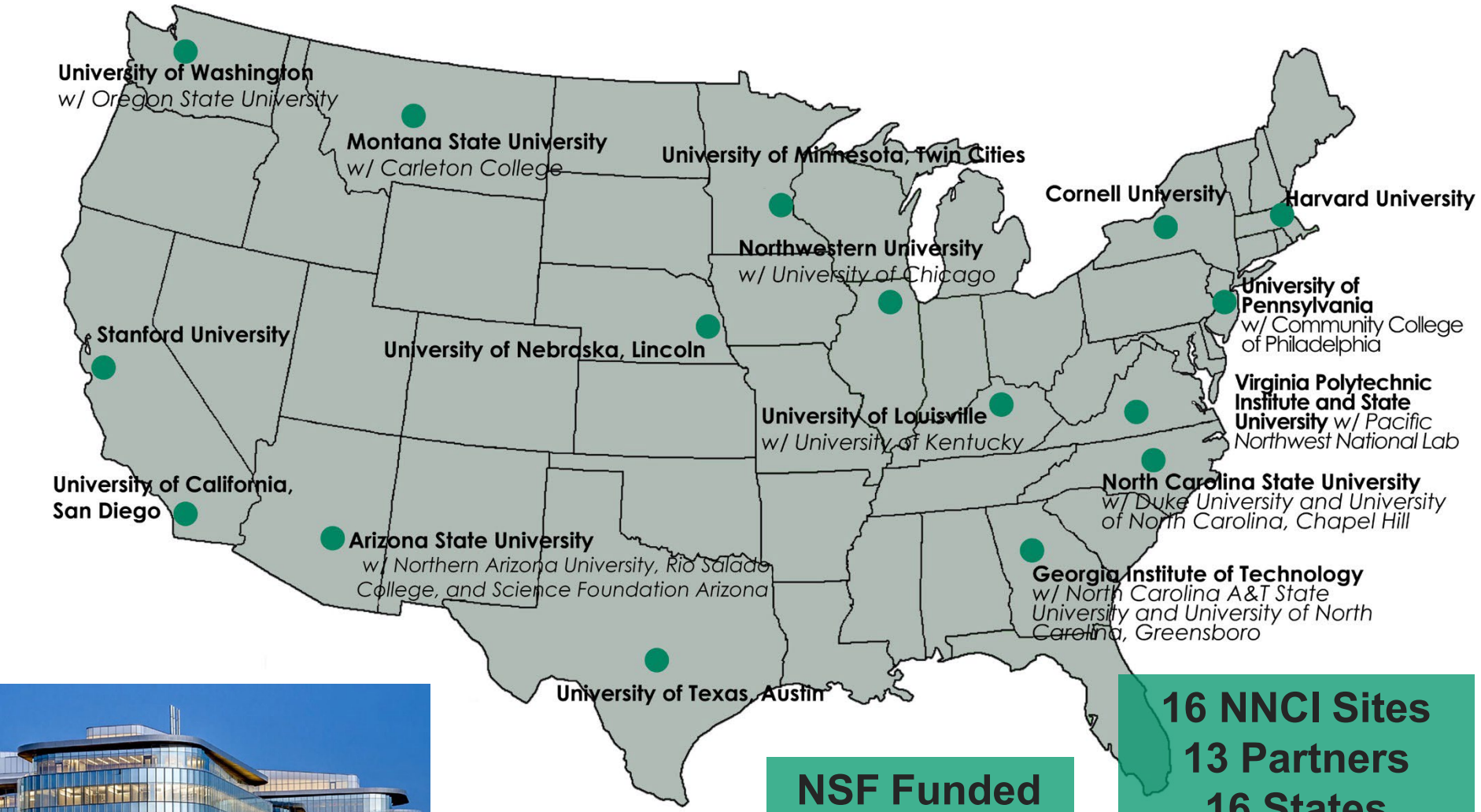
C. Direct partnerships with NSF nanotechnology centers

D. Bi-lateral collaboration may be included in any NSF proposal

E. International office (NSF/OISE): from workshops to centers

NNCI Network

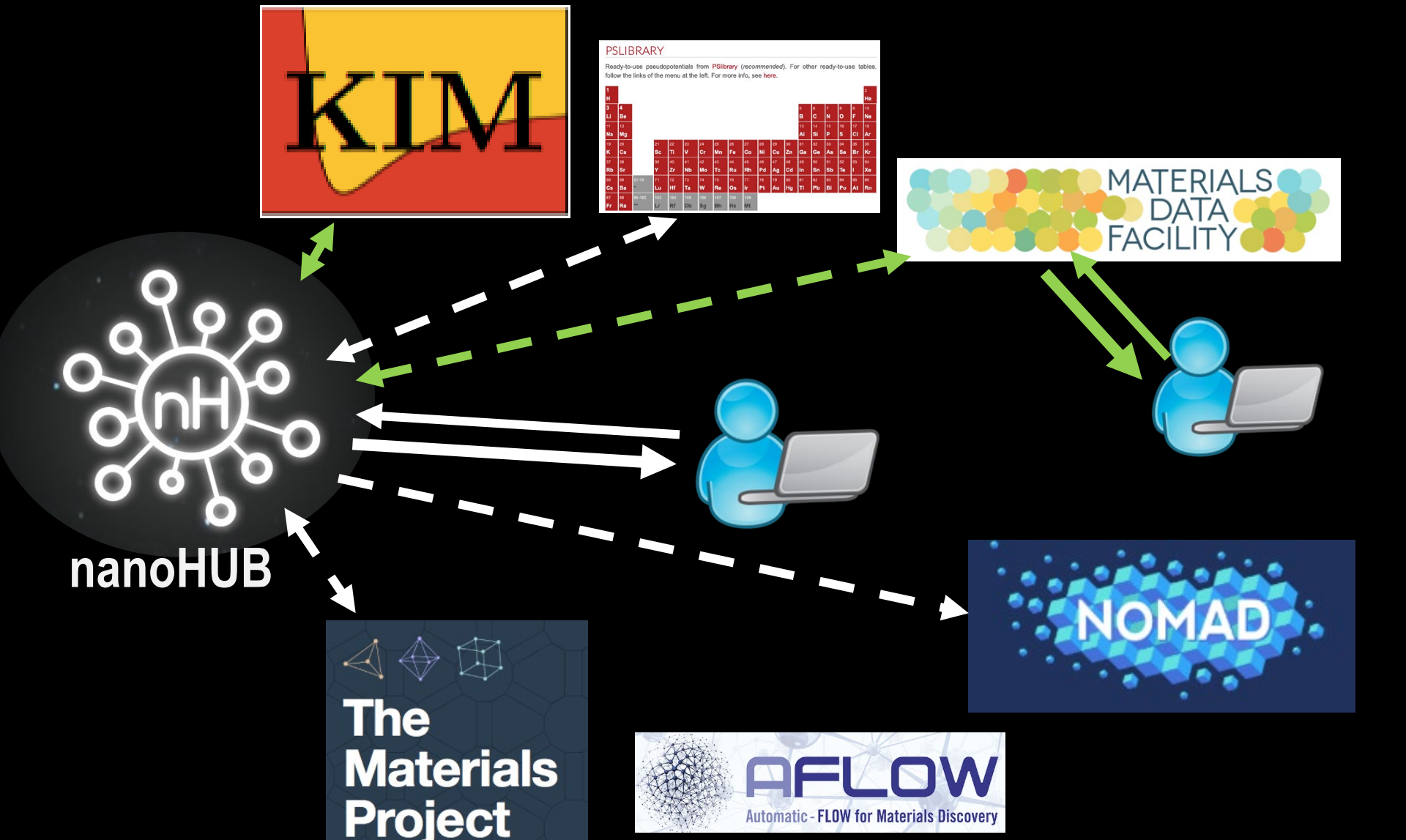
National Nanotechnology Coordinated Infrastructure



NSF Funded
2015 - 2025
$165M total

16 NNCI Sites
13 Partners
16 States
69 Facilities
>2,200 Tools

A cyber ecosystem for nano science & engineering



PURDUE UNIVERSITY

NSF-ROK collaborative opportunities on semiconductors and environmental impact

- **Supplements for *user facilities, researcher exchanges*** *(DCL)*
- **NSF-NRF Lead Agency Awards :** *Future of Semiconductors, Energy efficiency, New Devices, Integration, Environmental impact (MOU, DCL)*
- **Advanced Chip Engineering Design and Fabrication with Samsung Electronics** (MOU, DCL), with access to IP of the awards
- ***A regional workshop on semi environmental implications***
- ***Global Centers (GC):*** Use-Inspired Research Addressing Global Challenges in Climate Change and Clean Energy (NSF/OISE 23557)
- ***Individual collaborative awards –*** *based on merit review*
- ***Other existing NSF announcements.*** *Ex.:* U.S. NSF and Korean ***IITP*** Collaborative Research Opportunities(DCL 21-079)

Related publications

1. ***"Nanotechnology: Convergence with Modern Biology and Medicine",*** (Roco, Current Opinion in Biotechnology, 2003)
2. ***NANO1: "Nanotechnology research directions: Vision for the next decade"*** (Roco, Williams & Alivisatos, WH, 1999, also Springer, 316p, 2000)
3. ***NANO 2020**: "Nanotechnology research directions for societal needs in 2020"* (Roco, Mirkin & Hersam, Springer, 690p, 2011a)
4. ***NBIC**: "Converging technologies for improving human performance: nano-bio-info-cognition"* (Roco & Bainbridge, Springer, 468p, 2003)
5. ***CKTS**: "Convergence of knowledge, technology and society: Beyond NBIC"* (Roco, Bainbridge, Tonn & Whitesides; Springer, 604p, 2013b)
6. ***"Long View of Nanotechnology Development: the NNI at 10 Years"(JNR, 2011)***
7. ***"The new world of discovery, invention, and innovation: convergence of knowledge, technology and society"*** (Roco & Bainbridge, JNR 2013a, 15)
8. ***"International perspective on nanotechnology papers, patents, and NSF awards (2000–2016)"*** (Zhu, Jiang, Chen & Roco, JNR 2017, 19-370)
9. ***Proc. NSF NSE Grantees*** *Dec. 2020, available on www.nseresearch.org/2020/*
10. ***"Overview: Affirmation of Nanotechnology between 2000 and 2030"*** (MC Roco, Ch.1 in Nanotech. Commercialization, Wiley, Ed. T. Mensah et al., 2018)
11. ***"Principles of convergence in nature and society and their application: from nanoscale, digits, and logic steps to global progress*** *(MC Roco, JNR 2020, 22:321)*