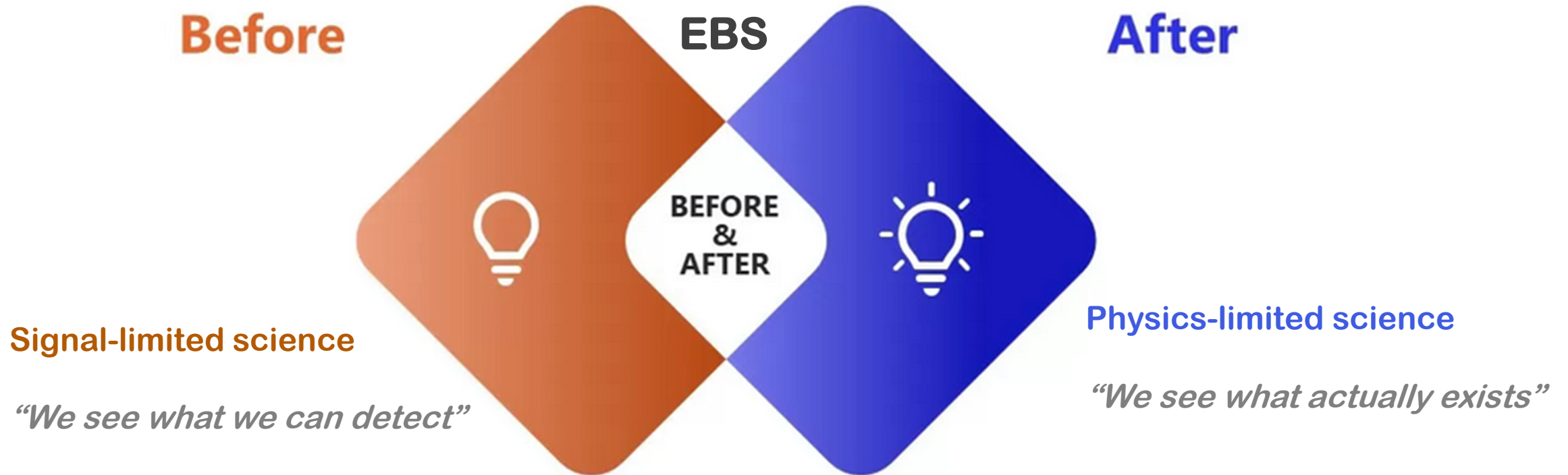




How EBS changed what science is possible

4 September 2026

*Gema Martinez-Criado,
Director of Research, ESRF*



This shifts whole fields into **new experimental regimes**

WHAT CHANGED PHYSICALLY ?

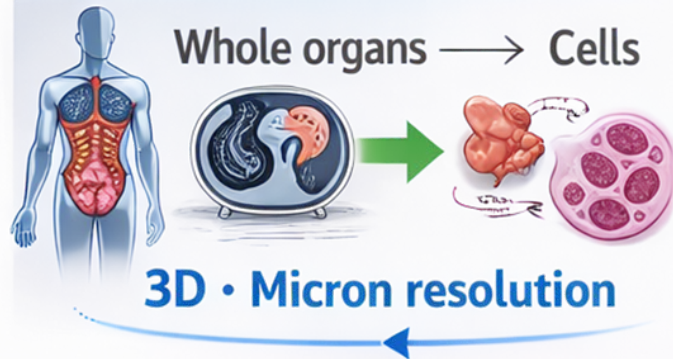
PARAMETER	PRE-EBS ESRF	ESRF-EBS	WHY THIS MATTERS
 Coherent photon flux	 ×1	 ×100	 Weak scattering, strain, defects become measurable
 Beam focusing	 ~1 μm	 30–50 nm	 Many BLs: Individual grains, cells, nano-features resolved
 Beam stability	 ~1 μm	 <50 nm	 Long scans, movies, tomography without drift
 Required detector speed	 ~100 Hz	 1–10 kHz	 Experiments move from seconds to milliseconds
 Typical detector	Pilatus 3	Jungfrau, Pilatus-4, Tempus	 Designed for coherent high-rate beams
 Effective data rate	 ×1	 ×100–1000	 Real-time 3D, operando, time-resolved physics



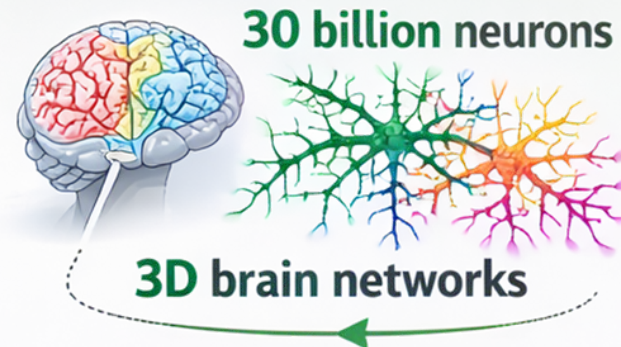
EBS unlocked regimes where complexity becomes measurable:
operando is now the norm, coherent experiments dominate, multiscale and diffraction are routine.

WHAT NEW SCIENCE BECAME POSSIBLE ?

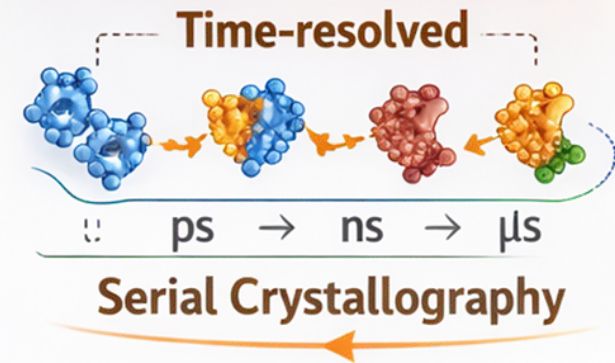
Biomedical Imaging



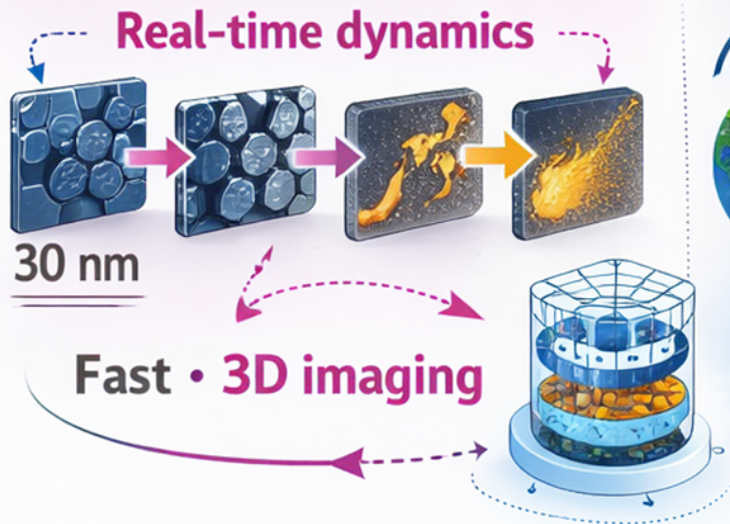
Connectomics



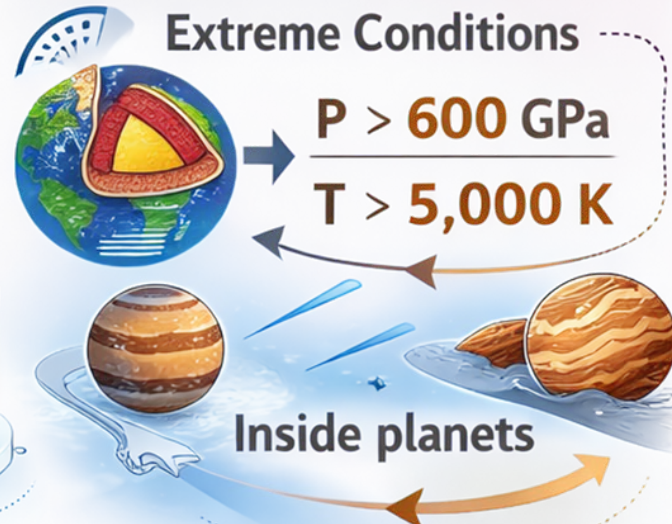
Proteins in Motion



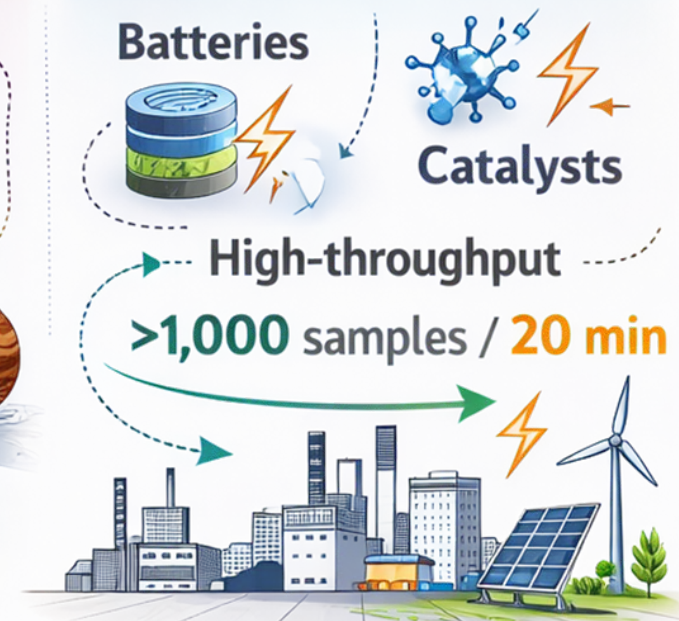
Materials at the Nanoscale



Geoscience & Planetary



Energy & Industry

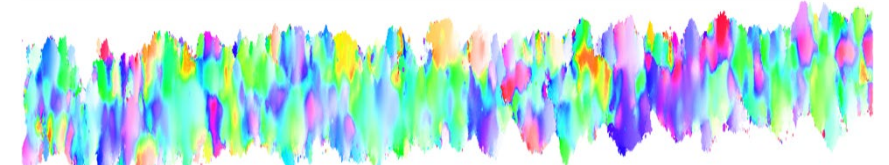


WHAT EBS ACTUALLY DELIVERED ?

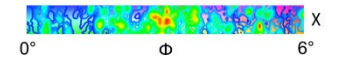


October 2018

From hours to minutes

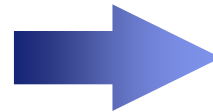


April 2021



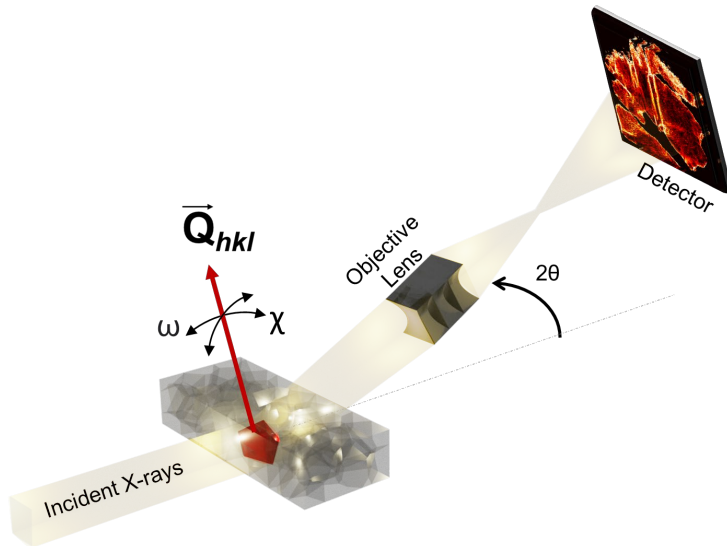
Problem 1 : Weak signal from deformed grains

Problem 2 : Missing surrounding information

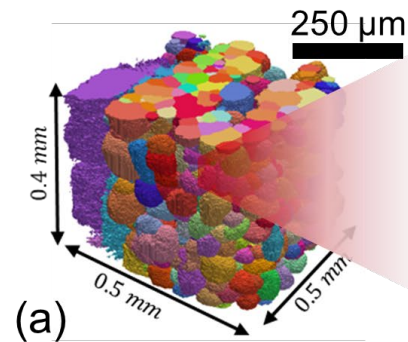


Solution 1: 100x faster using **pink beam DFXM**

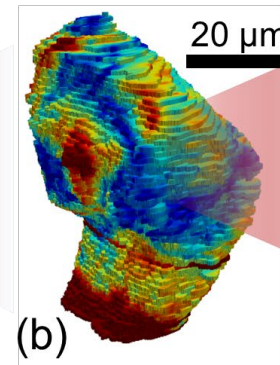
Solution 2: 3DXRD + DFXM in *same* instrument



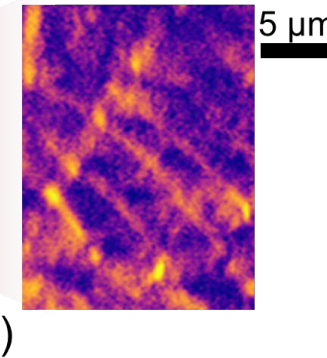
Grains in Polycrystals



Grain of Interest



Dislocation Structures



Novelty on ID03:
Radically different way of studying annealing-related phenomena

Multi-scale Orientation/Strain Mapping from mm to nm range

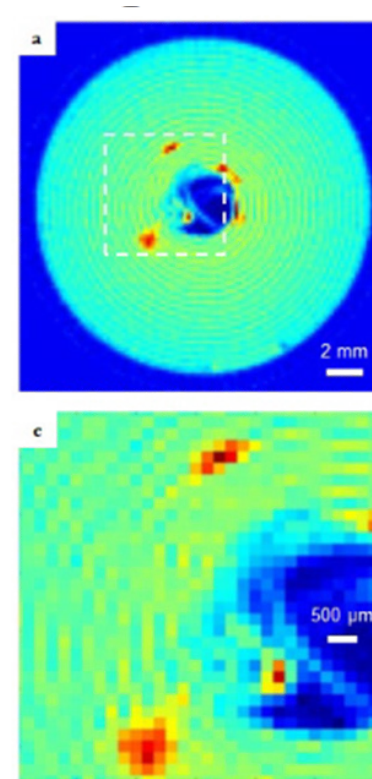
Before EBS: only simplified model (coin) cells could be studied!



Novelty on ID15A: Radically different dimensions - we now watch batteries fail, not infer why

Before EBS

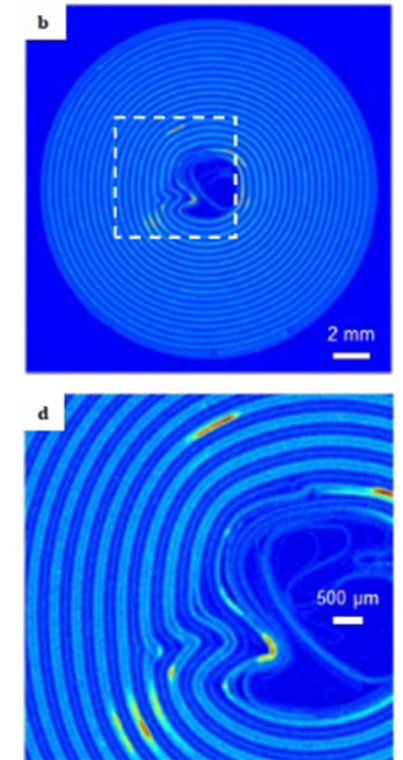
- Time resolution too slow
- Averaged diffraction
- No spatial structure



PILATUS 3 (200 Hz) vs

After EBS

- Real devices (18650 cells)
- Millisecond time resolution
- Spatially resolved phase evolution

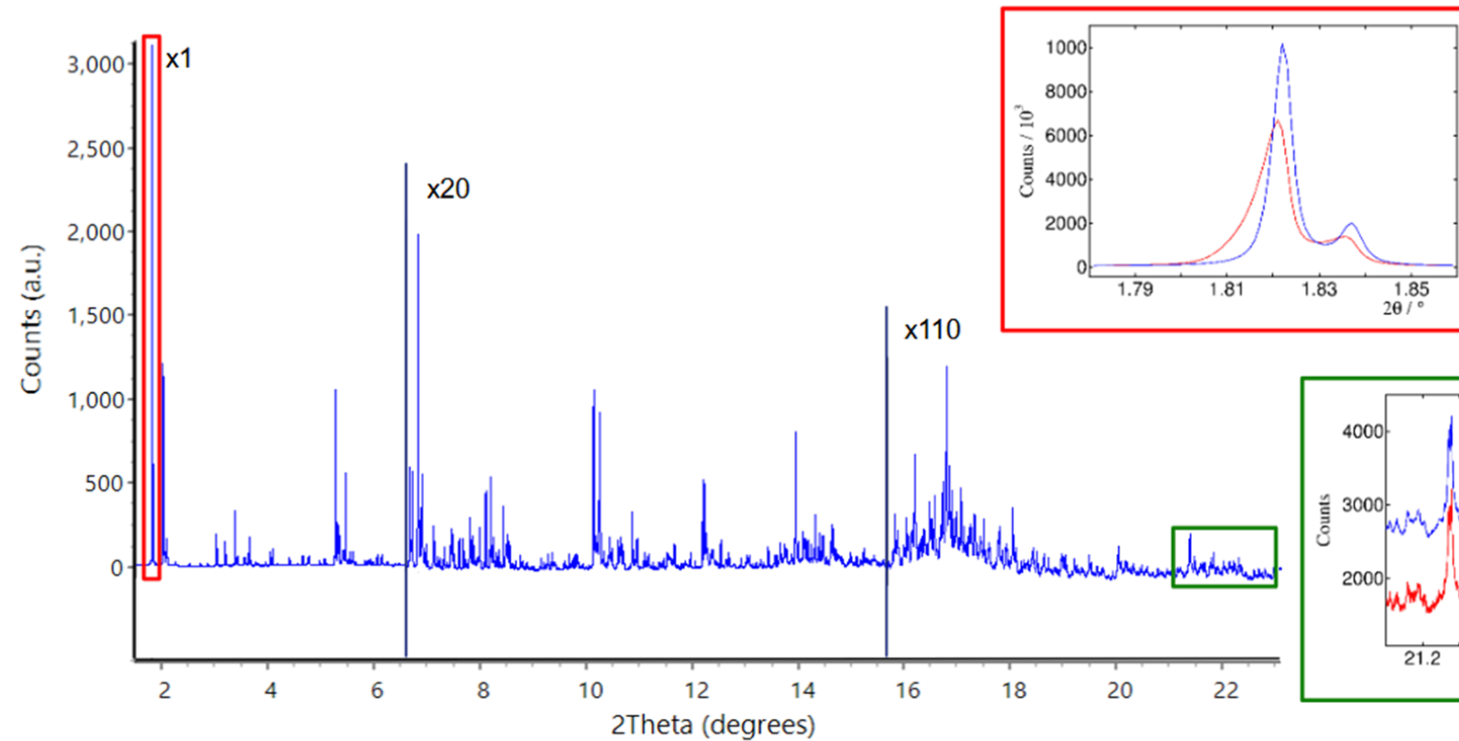


PILATUS 4 (4350 Hz)

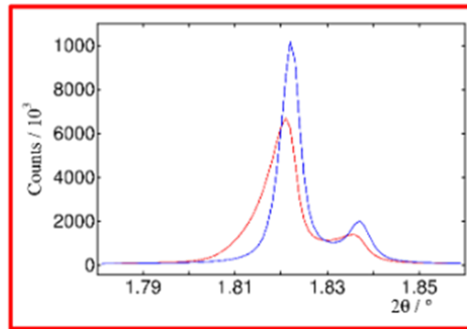
WHAT EBS ACTUALLY DELIVERED ?

EBS pushed powder diffraction from peak detection into quantitative lattice physics!

(Higher brilliance + coherent beam + fast low-noise detectors)

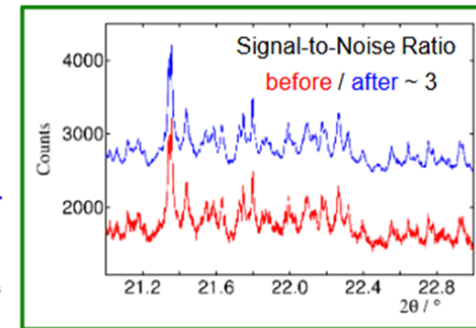


High-resolution X-ray powder diffraction pattern – ID22 – Silicalite zeolite – $\lambda = 0.354283 \text{ \AA}$



Before EBS: weak peaks buried in noise

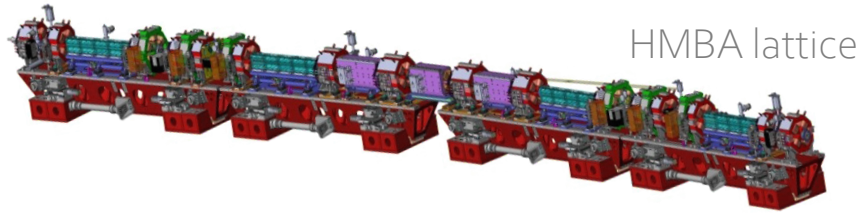
After EBS: better angular resolution, low/high-Q lattice distortions become measurable



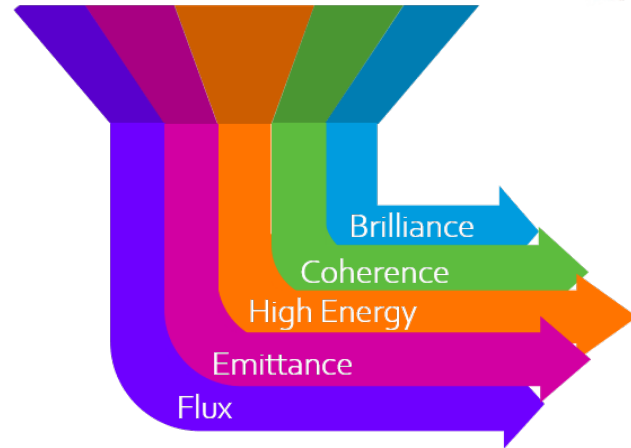
Fitch & Dejoie
J. Appl. Cryst. 54, 1088-1099, 2021

Novelty on ID22: Radically different physics threshold - weak, distorted, more dynamic matter became measurable

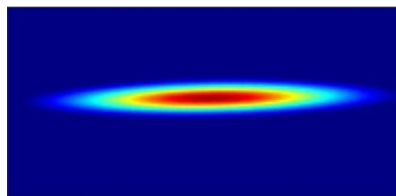
WHAT EBS ACTUALLY DELIVERED ?



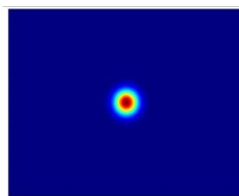
HMBA lattice



$\epsilon_x \sim 4000\text{pm}$



$\epsilon_x \sim 133\text{pm}$



Beam sizes
from nm to
320 mm

X-Ray Microscopies
Larger field of view

Higher
energies
with higher
fluxes

Larger penetration
Low dose in vivo imag.
In situ, operando, AM,
extreme (T,P,H), etc

Greater
coherence-
based
approaches

CDI, Phase Contrast,
Holography, XPCS
High quality Optics

Higher
throughput
with dose
tolerance

Faster dynamics
Time-resolved
experiments, cryo...

Superior
photon
hungry
techniques

R(NR)IXS, RESX,
NRS, XES, XDS,
WDS, XBIC, XEOL

Better
sensitivity
Artifact
mitigation

Better detection
limits, noise
reduction



**EBS DID NOT MAKE INCREMENTAL IMPROVEMENTS — IT ENABLED A NEW EXPERIMENTAL REGIME.
THESE ARE NOT INCREMENTAL — THEY ARE **PHASE TRANSITIONS**.**

FOUR NEW EXPERIMENTAL REGIMES

1 REGIME 1

Seeing inside materials

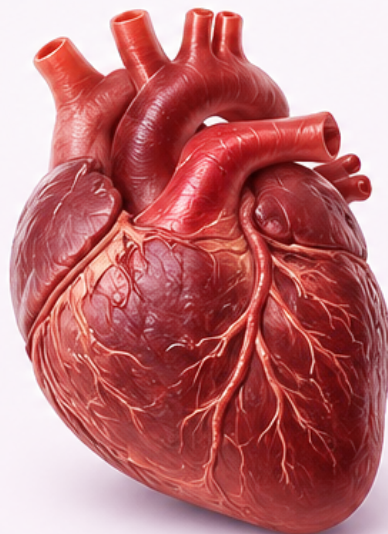
From average materials to every single grain



2 REGIME 2

Whole human organs

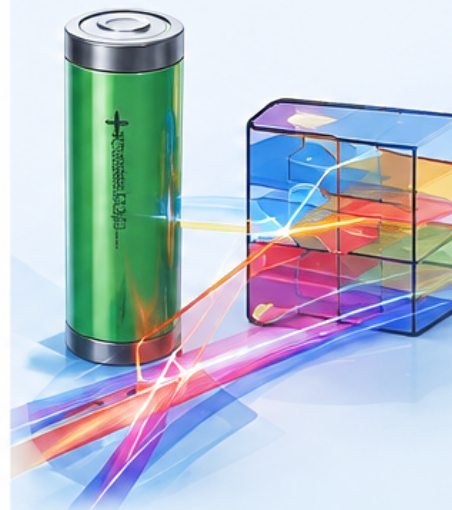
From cells and tissue slices to intact organs



3 REGIME 3

Chemistry in motion

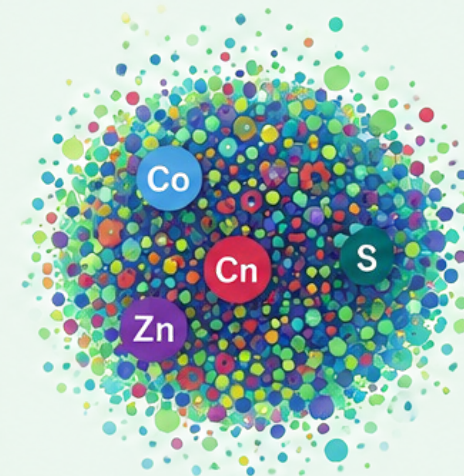
Watching real devices work



4 REGIME 4

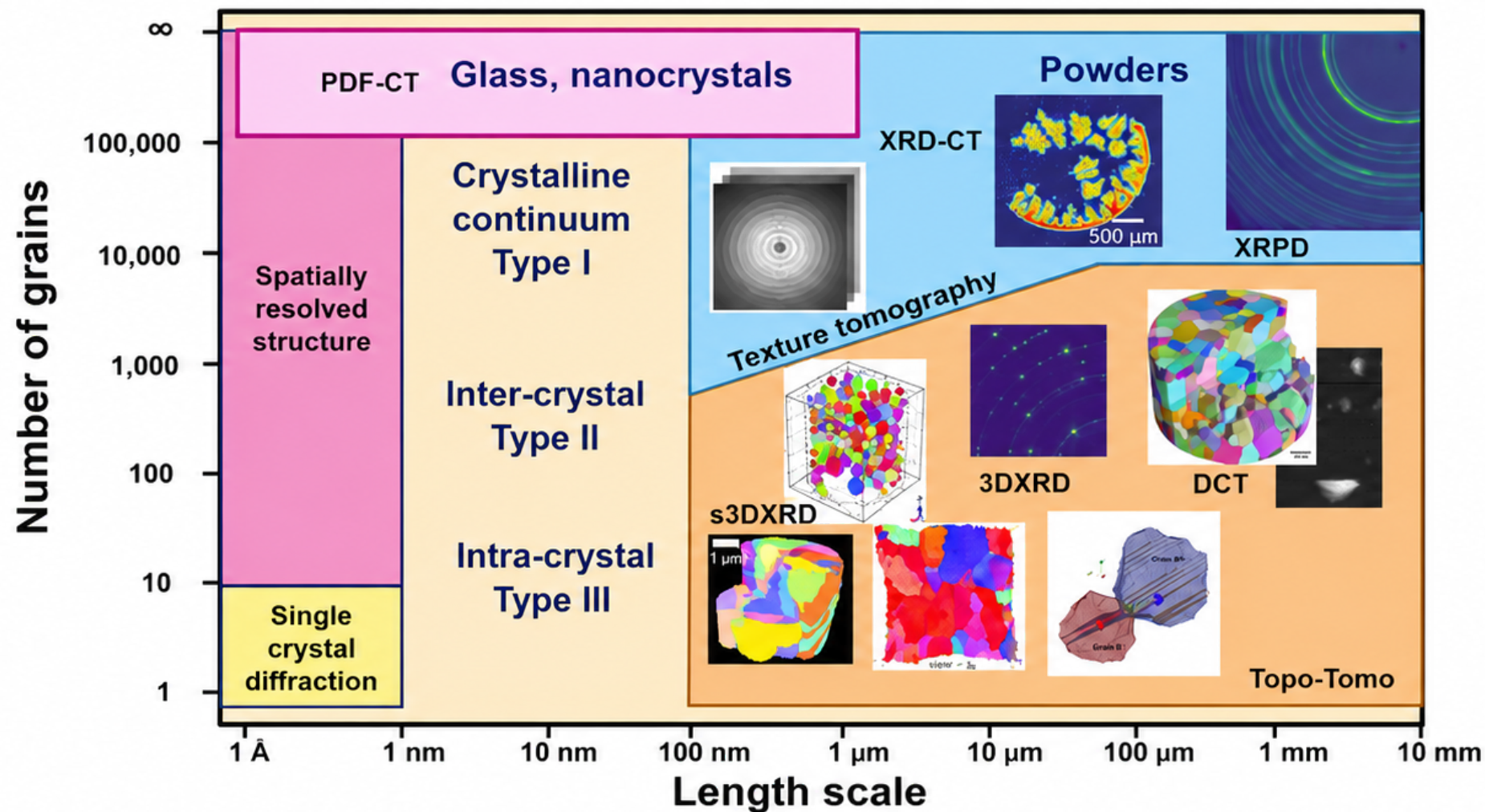
The weak becomes visible

Single particles, trace elements, tiny distortions

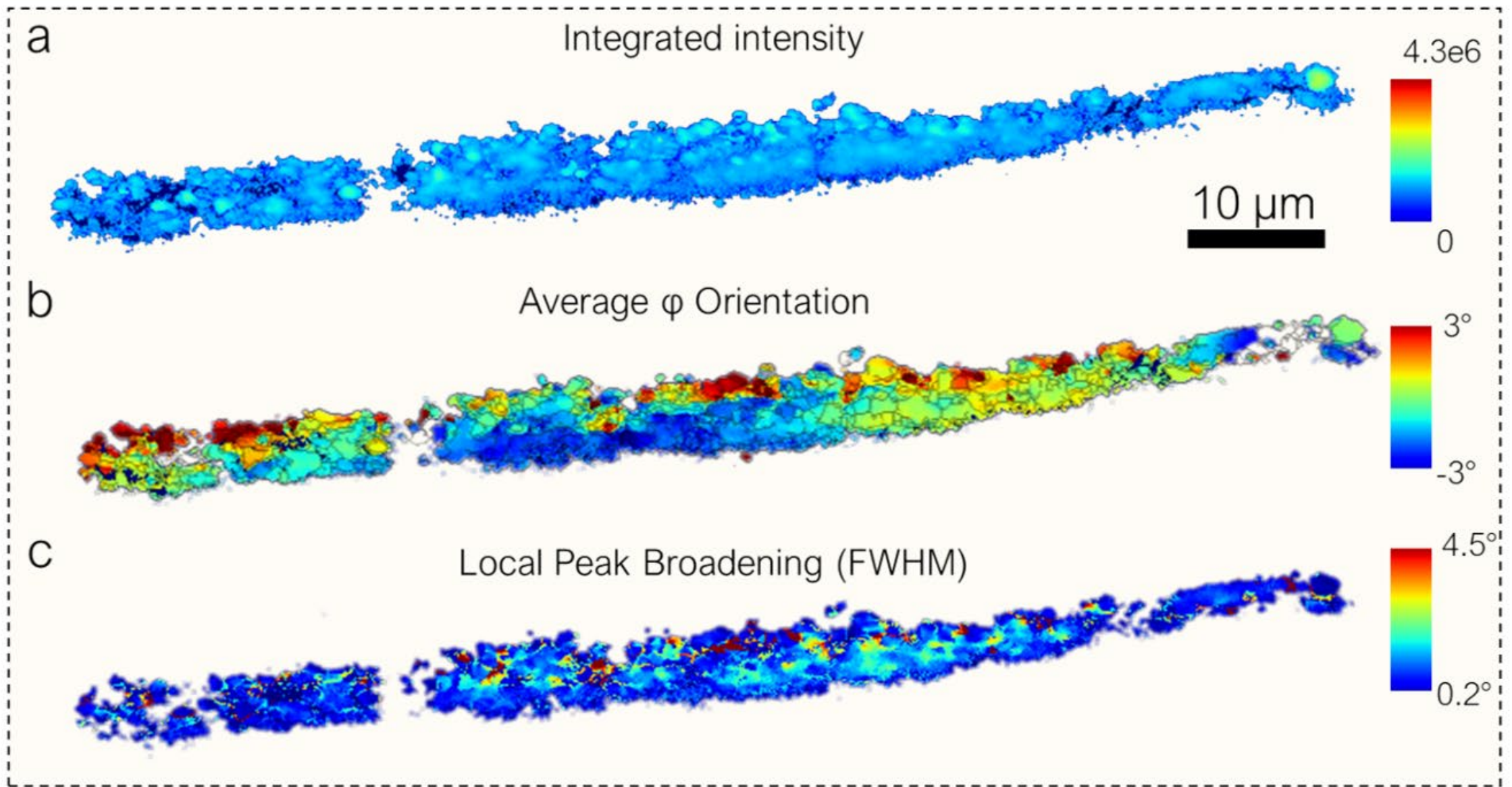


EBS pushed us from 'signal limited' to 'physics limited'

REGIME 1: SEEING INSIDE MATERIALS - FROM AVERAGE MATERIALS TO EVERY SINGLE GRAIN

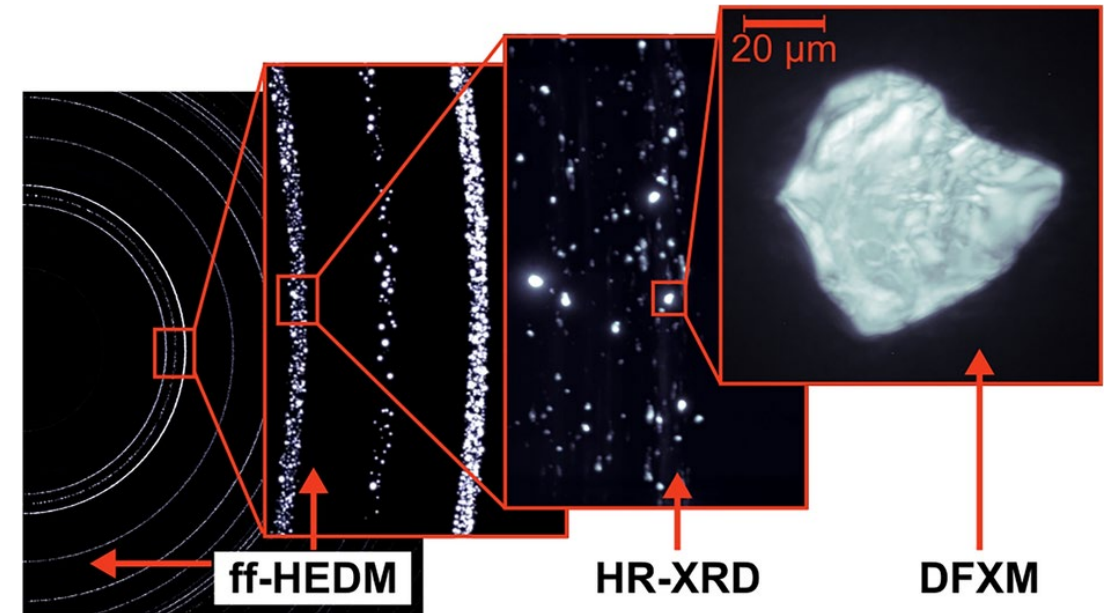
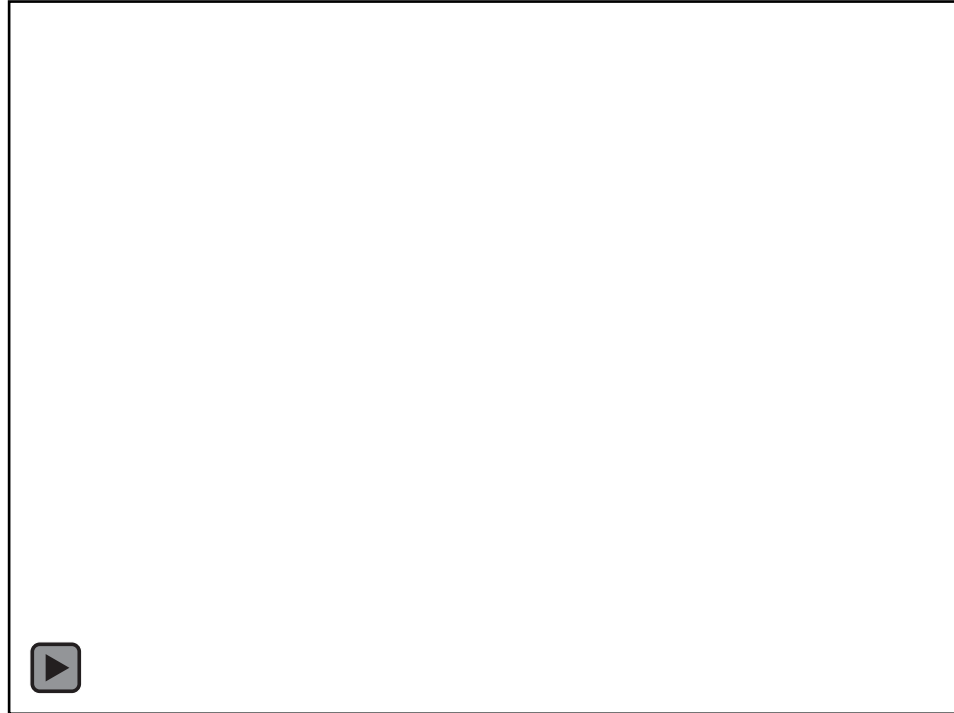


We can now follow how every crystal in a metal evolves under stress —
in 3D, in real time



Projection **p**DFXM maps showing subgrain structure and orientation mapping in highly deformed ferritic Fe-3%Si.

REGIME 1: SEEING INSIDE MATERIALS - FROM AVERAGE MATERIALS TO EVERY SINGLE GRAIN

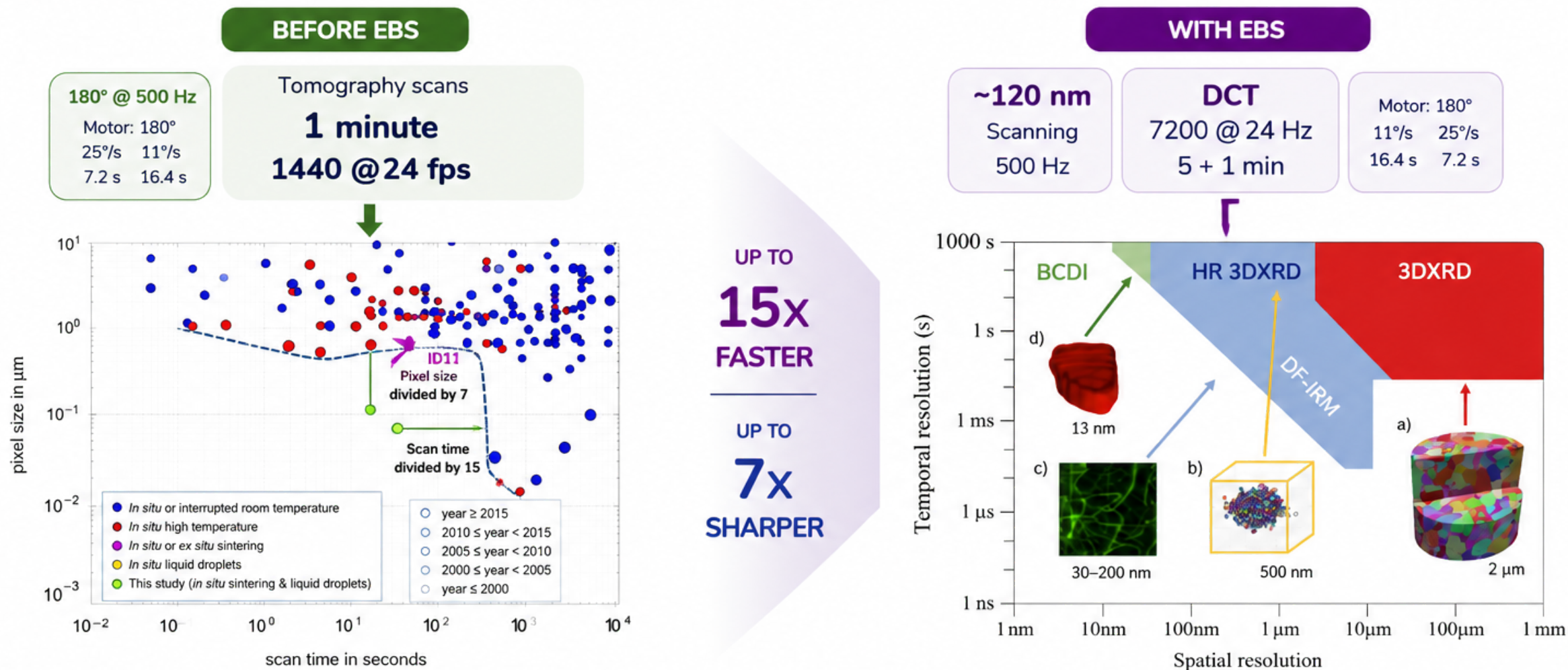


- First demonstration of Pink-Beam Dark Field X-ray Microscopy (pDFXM) published in 2025 by ERC grantee Can Yildirim et al. <https://arxiv.org/abs/2503.05921>
- Imaging of highly deformed and weakly diffracting crystals previously impossible to observe
- Tracking grain growth in real time, capturing intragranular lattice distortions as they develop, showing that recrystallized grains keep evolving under mechanical forces (**27x more photon flux at 60 keV**)



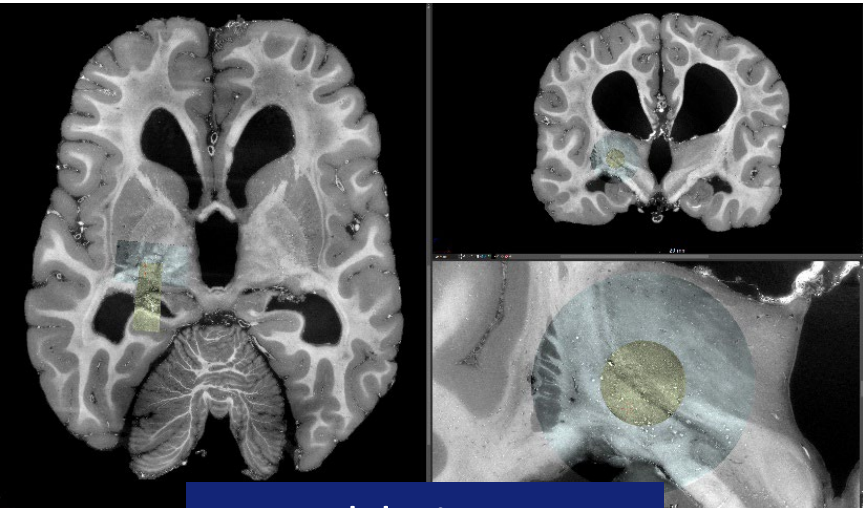
We can now follow how every crystal in a metal evolves under stress — in 3D, in real time

EBS OPENS A NEW SPACE-TIME WINDOW: FASTER, SHARPER, WIDER 3D IMAGING IN MILLISECONDS

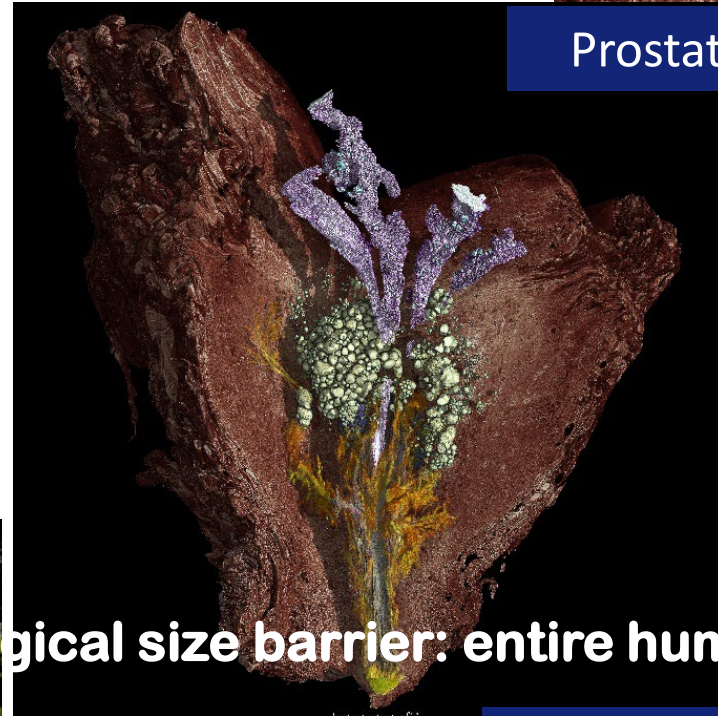


This was simply not possible before EBS.

REGIME 2: WHOLE HUMAN ORGANS



Alzheimer



Prostate disease

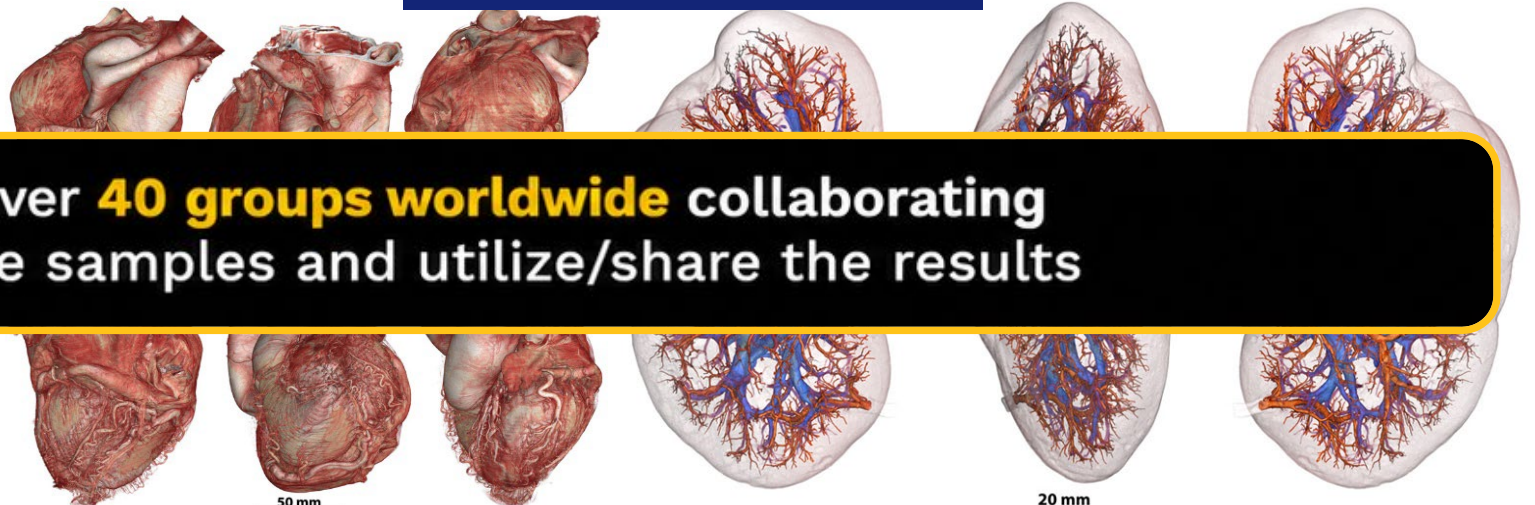


Heart / Kidney diseases

We crossed the biological size barrier: entire human organs at cellular resolution!



Already over **40 groups worldwide** collaborating to provide samples and utilize/share the results



REGIME 2: WHOLE HUMAN ORGANS



Cinematic Rendering, Siemens Healthineers

More than 300 organs already scanned on BM18!



375
datasets



over 60
publications
from the HOA group

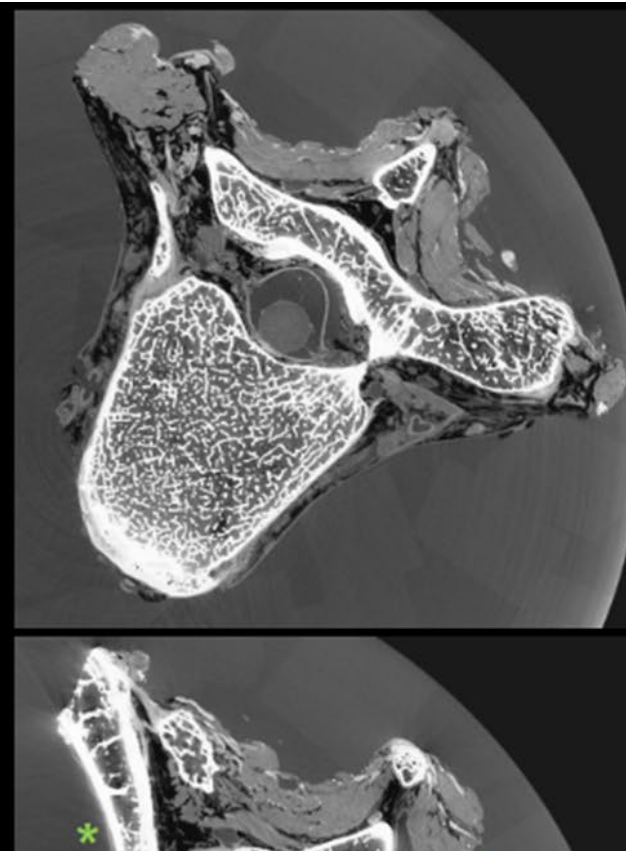
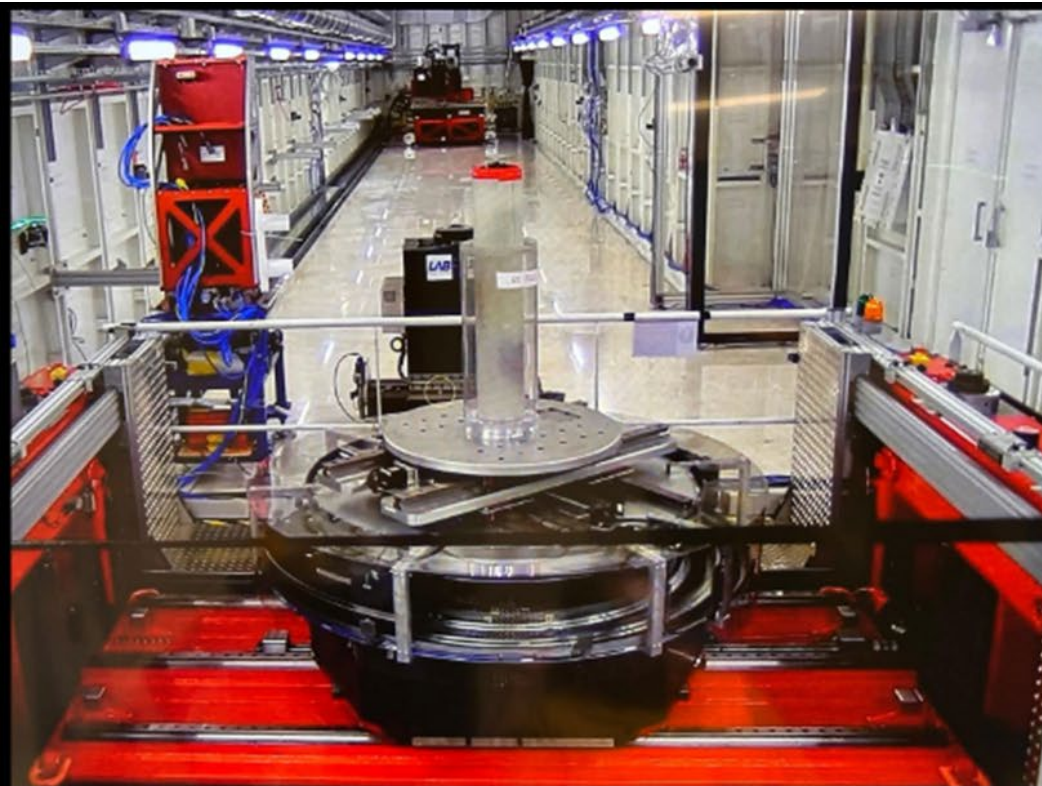


over 16
publications
from other groups
using HOAHub data



13,393
downloads
(as of May 27)

REGIME 2: WHOLE HUMAN ORGANS

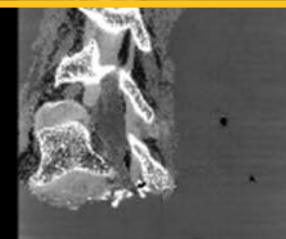


Whole adult
16.5 $\mu\text{m}/\text{voxel}$ and

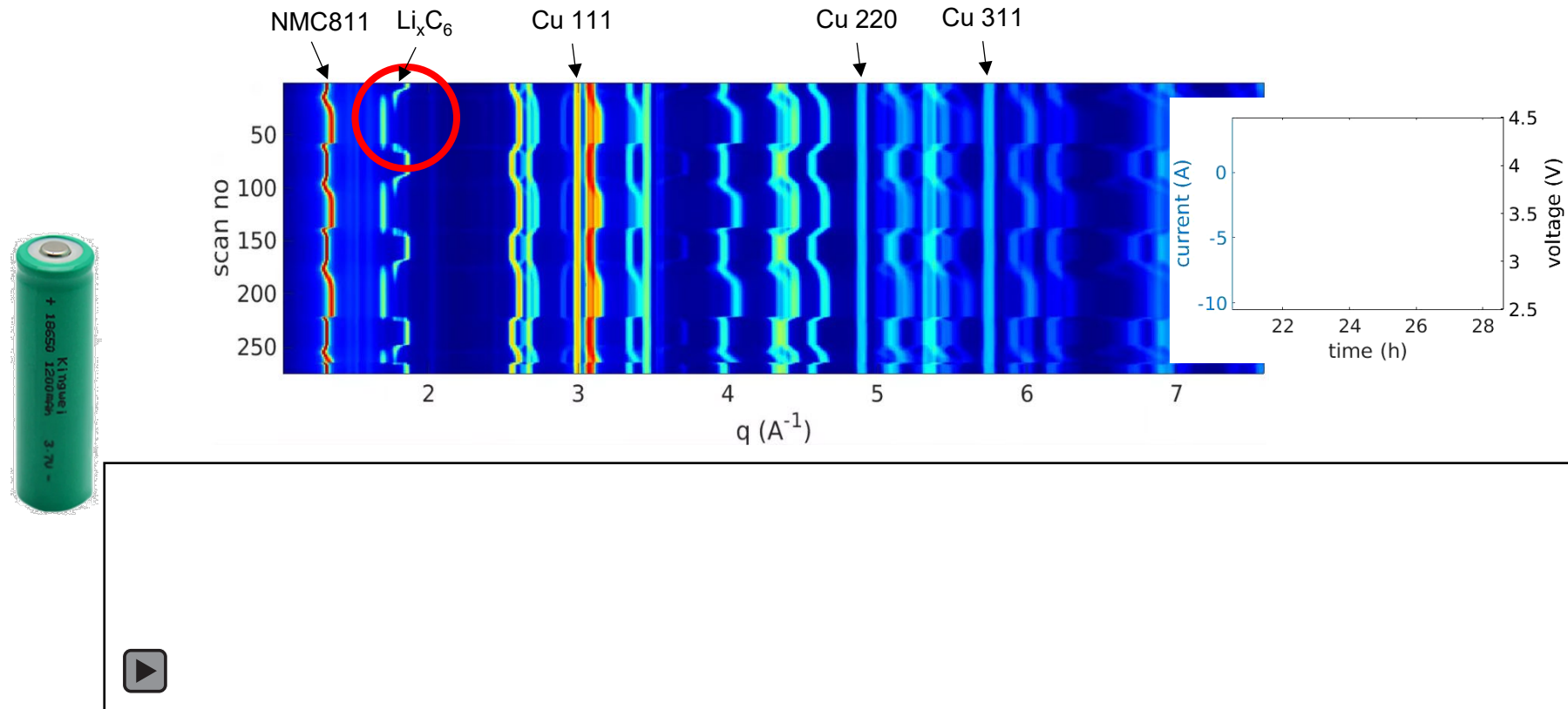


300 kg & 2.5 metre large-sample stage fully operational!

Vertebra
Intervertebral disk
Spinal cord
Musculature

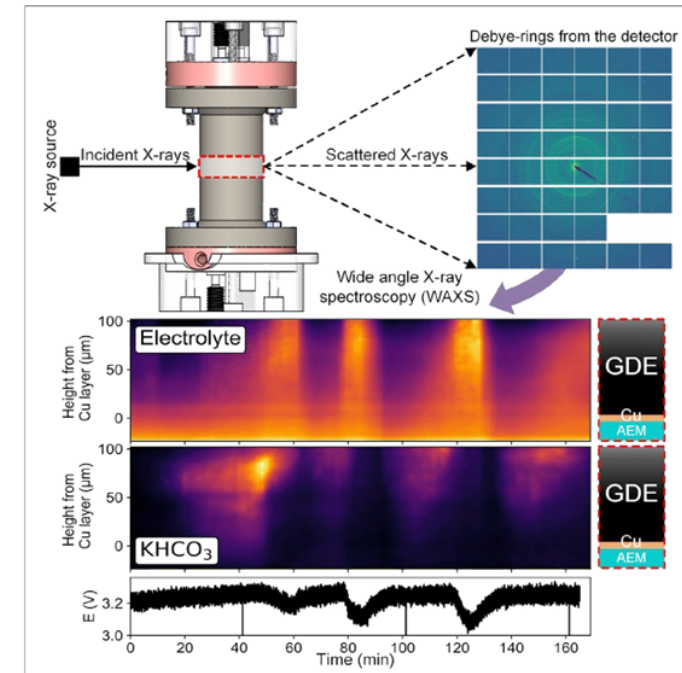
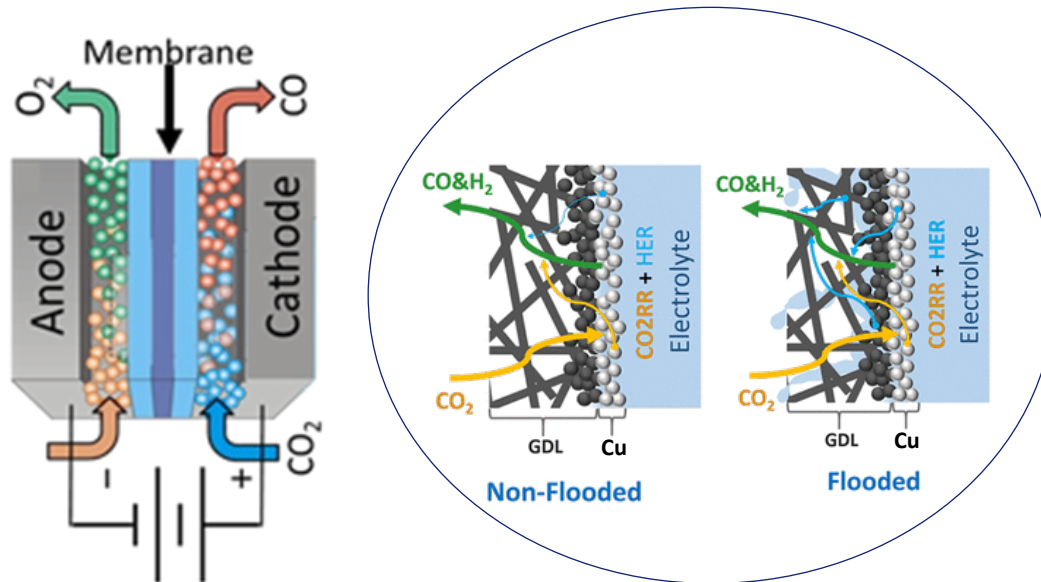


High charge/discharge rates can create potentially dangerous temperature rises



- Internal temperatures (45-70°C): largely dictated by the electrical current, not by cell chemistry
- Internal stress is only related to SoC, not to charge/discharge rate;
- ESRF-EBS: faster acquisitions at high energy (**x40 gain photon flux at 100 keV**) at ID15A

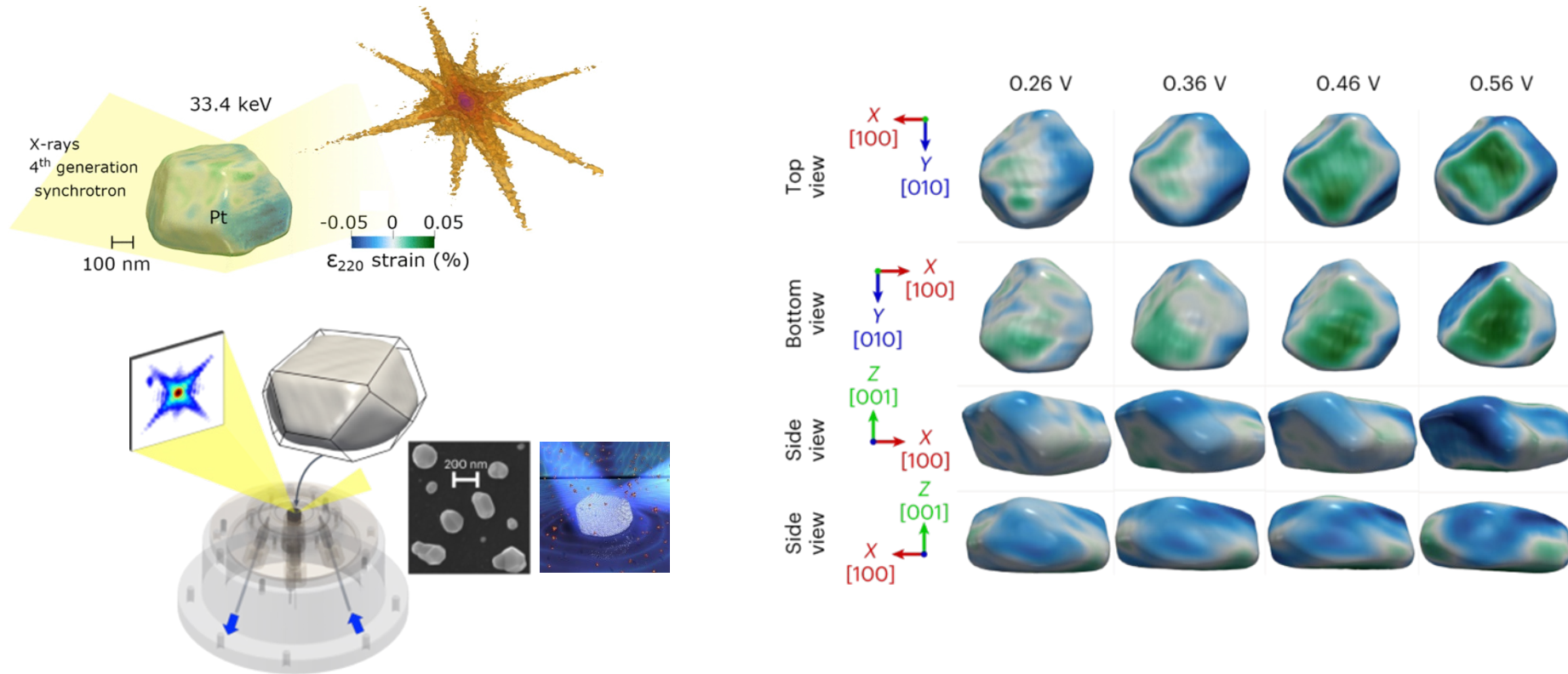
CO₂ electrolyzers: CO₂ reduction + value added chemicals and fuels



Poor stability owing to cathode flooding → increase of HER (Hydrogen Evolution Reaction)

- Salt formation exacerbates the electrolyte flooding, causing a shift in CO₂ reduction reactivity toward HER (salt precipitated as bicarbonates)
- ESRF-EBS: faster operando acquisitions at high energy (**x30 gain photon flux at 68 keV**) at ID31

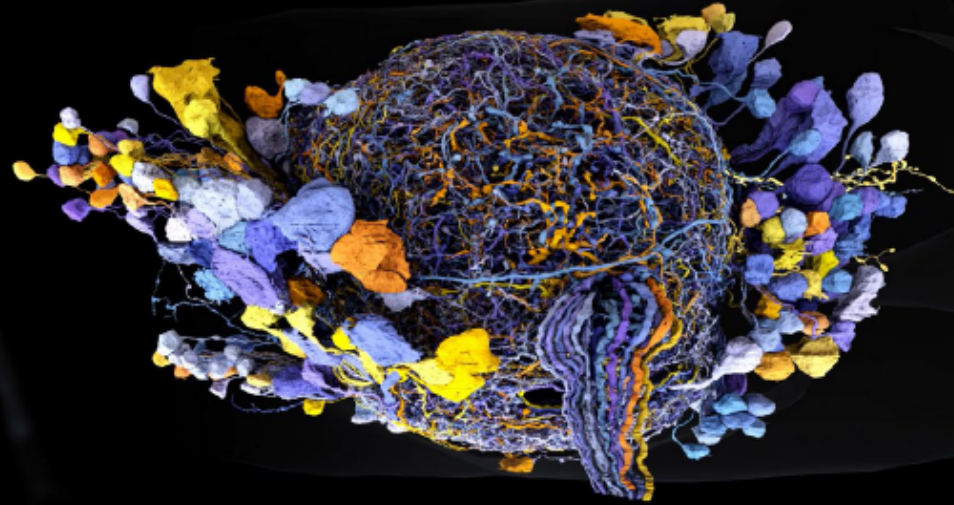
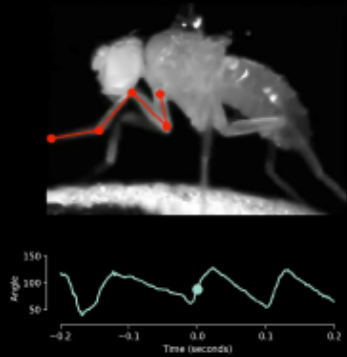
Imaging the strain evolution of a Pt nanoparticle under electrochemical control



Surface strain → control the binding energies of adsorbates on active sites

- Heterogeneous and potential dependent strain distribution → critical for chemisorption of adsorbates onto metals, and thus acceleration of the rate of (electro)catalytic reactions
- ESRF-EBS: higher coherence & photon flux at high energy (**x28 gain at 33.4 keV**) for BCDI at ID01

Neuromuscular anatomy and sensorimotor circuits that control the legs and the wings uncovered.



Tuthill Lab
Washington Univ.

Lee Lab
Harvard Medical School

Motor and Premotor neurons

HOW THE CENTRAL NERVOUS SYSTEM CONTROLS THE BODY?

Data could be used to train artificial neural network and generate a virtual fly that reproduces physics of walking and flying

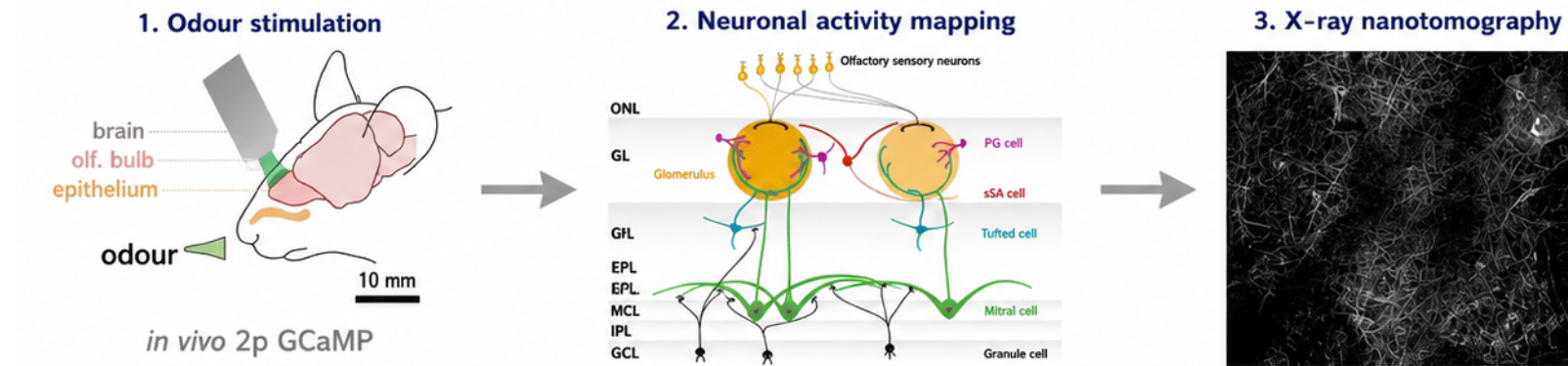


Mamiya et al., *Neuron* 2023

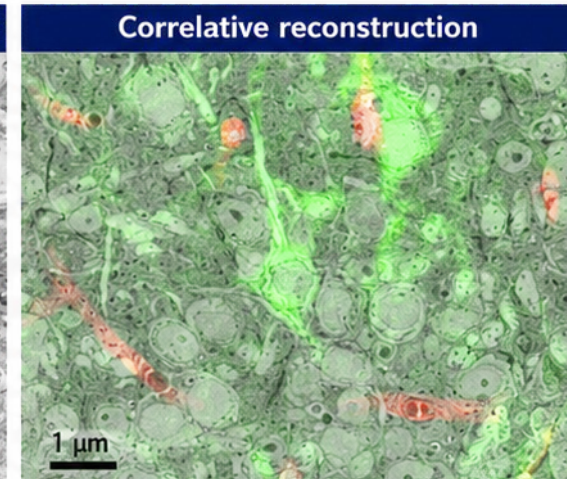
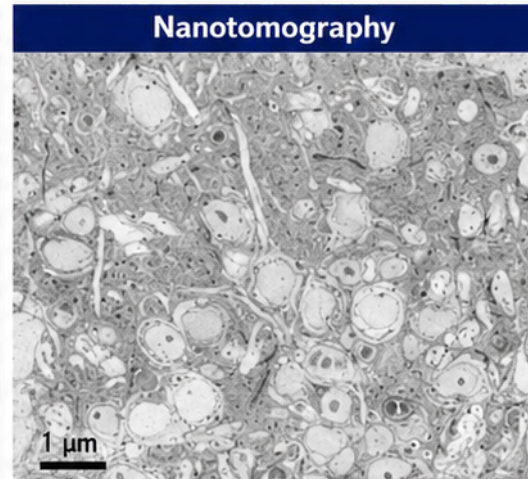
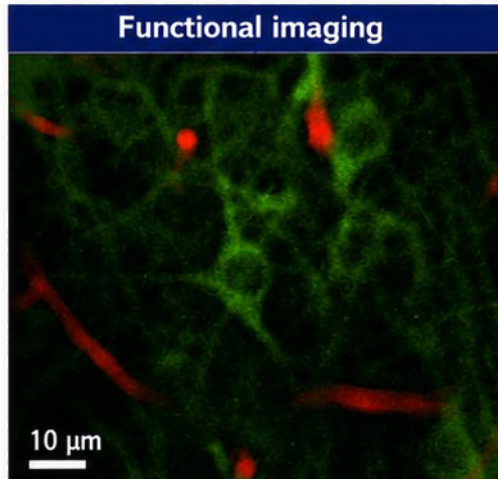
Azevedo et al., *Nature* 2024

Vaxenburg et al., *Nature* 2025

REGIME 4: THE WEAK BECOMES VISIBLE



FOR THE FIRST TIME:
Neuronal activity observed *in vivo*
can be directly linked to nanoscale brain architecture

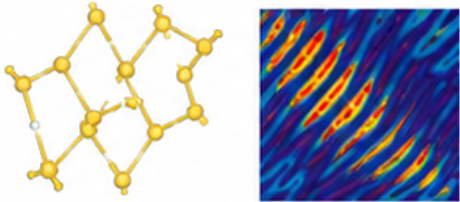


From function to structure — *in the same neurons*

REGIME 4: THE WEAK BECOMES VISIBLE

2021

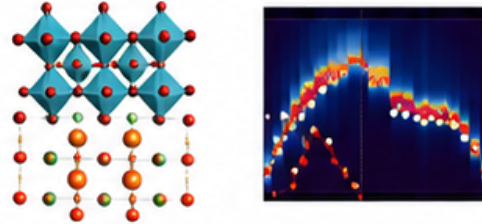
Quantum Strangers in Superconductors



- Strain tuning of **YBCO cuprates** reveals control of strange metal behaviour (ID32)

2022

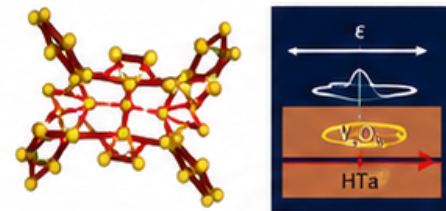
Fractional Spins & Quantum Nickelates



- Identifying **fractional spin** excitations in a 2D cuprate (ID32)
- Phonon-**spin** coupling limits qubit coherence (ID28)
- **Spin nematic phase** in a square-lattice iridate (ID20)

2023

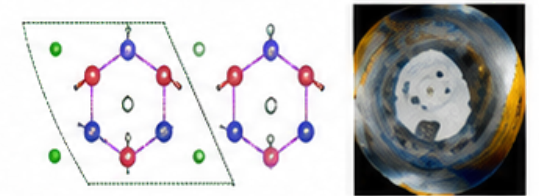
Lattice-Driven Quantum Transitions



- Soft phonons driving **charge order** in kaagome metals (ID28)
- Ultrafast strain waves triggering **IMT** (ID09) transition in V_2O_3
- Hidden structural layers in a **HTc nickelate** (ID27)

2025

Quantum Entanglement & Magnetoelasticity



- Magnetic **spin collapse** in solid oxygen (ID27)
- **Magnon-phonon** hybrid excitations in a kaagome magnet (ID28)
- **Intertwined orders** in a quantum-entangled metal: a hidden coupling (ID27, ID20)

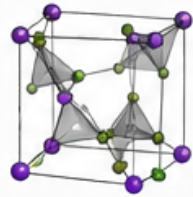


EBS reveals quantum matter —
from strained superconductors to emergent electronic order

RIXS AS A PROBE TO DETECT QUANTUM ENTANGLEMENT: APS + ESRF

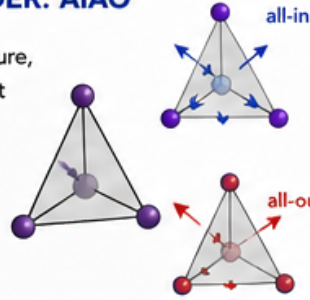
THE MATERIAL $\text{Nd}_2\text{Ir}_2\text{O}_7$

A pyrochlore iridate at the edge of a metal-insulator transition.



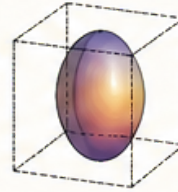
KNOWN ORDER: AIAO

At low temperature, Ir moments point all-in or all-out within each tetrahedron.



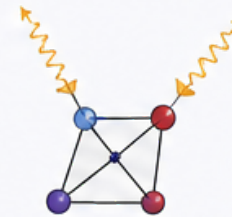
THE DISCOVERY: HIDDEN ORDER

A nematic order coexists with AIAO, breaking the cubic symmetry — like a sphere becoming egg-shaped.



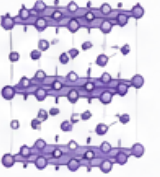
HOW THEY DETECTED IT: RIXS INTERFEROMETRY

Entangled electrons on two Ir sites scatter X-rays and interfere. The interference pattern reveals the quantum state.

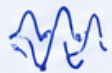
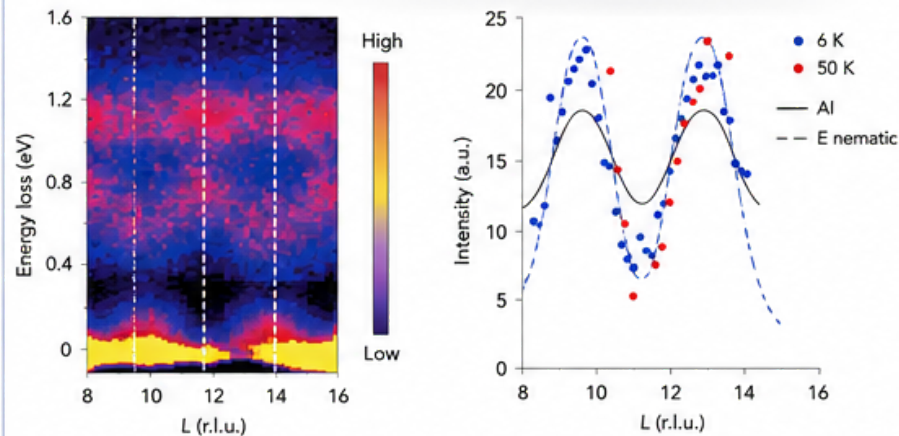


WHY IT MATTERS

Intertwined orders arise from one entangled quantum state — with echoes in high- T_n cuprate superconductors.

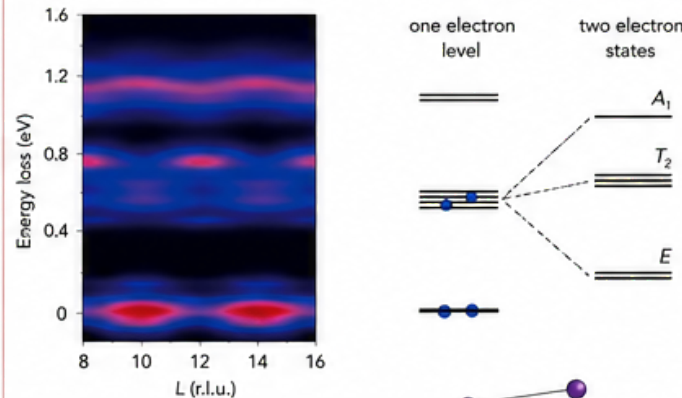


1. RIXS INTERFERENCE: FINGERPRINT OF ENTANGLEMENT



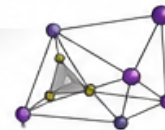
Clear oscillations in intensity along L demonstrate interference between scattering paths — direct evidence of entangled electronic states.

2. ENERGY DEPENDENCE & MODEL



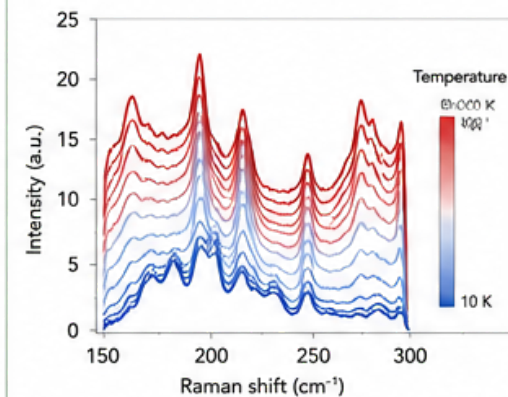
Model system

$\text{Nd}_2\text{Ir}_2\text{O}_7$ pyrochlore iridate
Ir tetrahedra on an fcc lattice
interpenetrating the Nd network.



Two electrons in different orbitals contribute to magnetism. The full quantum state is reconstructed from the RIXS signal.

3. RAMAN SPECTROSCOPY: SYMMETRY BREAKING



Phonon modes split below ~ 205 K, well above the magnetic transition at 33 K.



Symmetry is broken in the lattice — evidence for hidden nematic order.

KEY MILESTONES IN 30 + 2 YEARS OF ESRF'S HISTORY



ESRF convention signed

First electron beam in the storage ring



First ESRF Highlights

1988

1989

1992

1994

1995

First Users Meeting

User operations begin with 15 beamlines

Number of beamlines: 44 (CM01)

Nobel Prize in Chemistry for ESRF User: Brian Kobilka (G-protein-coupled receptors)

Phase I Upgrade Programme (UP)

Number of Beamlines: 40

First ESRF News magazine

2018

2017

2015

2012

2009

1998

1996

20-month EBS shutdown

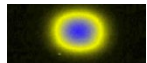
Phase II UP: EBS project launched

The ESRF designs a revolutionary storage ring (H7BA Lattice)

Nobel Prizes in Chemistry for ESRF Users: Ada Yonath Venkatraman Ramakrishnan (Ribosome)

SR current: 200mA; 4000 pmrad
B: 10^{20} ph/mm²/mrad²/0.1%bw

Restart User operations with EBS



Remote experiments



Number of Beamlines: 45

2020



2021

2024

2026

Horizontal emittance: 134 pmrad
B: 10^{22} ph/mm²/mrad²/0.1%bw
Coherent flux: x 30- x 40

Nobel Prizes in Chemistry for ESRF collaborators: David Baker & John Jumper (protein design)

Nobel Prize in Chemistry for ESRF collaborator Omar Yaghi (for metal-organic-frameworks)

Shaping the future of the
ESRF Science & Innovation Programme
2026 - 2035

A bottom-up approach founded on daily interactions with users on the beamline

1 Conferences and workshops

More than **30 events** held at ESRF since 2022



2 Cross-cutting Reviews

Sustainable energy generation & storage technologies; Neuro-degenerative diseases; High-Pressure Science; Catalysis & Industry; Cultural & Natural Heritage

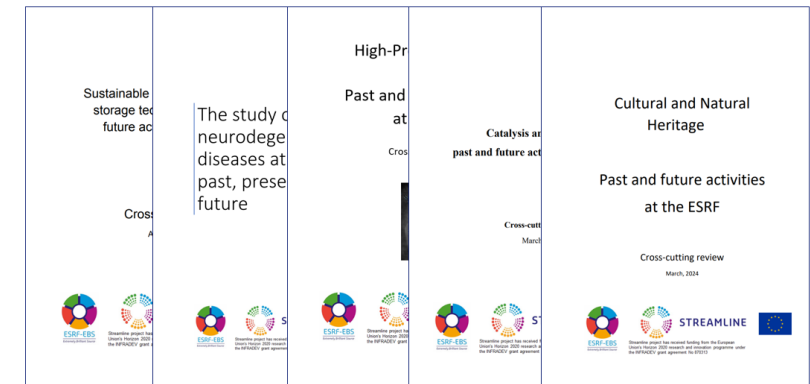
3 Beamline Reviews

18 ESRF & **9** CRG beamlines since 2022
Partnership for Structural Biology
Partnership for Soft Condensed Matter



4 Strategy Meetings

Autrans 2022 - 2025; Data & IT strategy; EXPD & ASD Focus (**12 events**)



WHAT DID THE EBS ALREADY ENABLE ?

WHAT 4TH GENERATION BROUGHT TO THE FIELD



Coherence & Spatial Resolution

Reveal structure and dynamics with nano-to atomic detail



Temporal Resolution

Capture processes from picoseconds to hours



High Throughput

Statistics and large data sets



Sensitivity

Detect small signals from dilute or buried elements & states

WHAT MAKES HIGH-ENERGY UNIQUE



Penetration

See deep inside real materials and devices



Multiscale Experiments

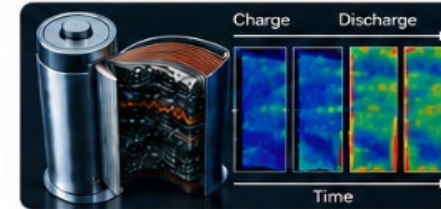
Connect structure and function across many length scales



Operando Experiments in Real Systems

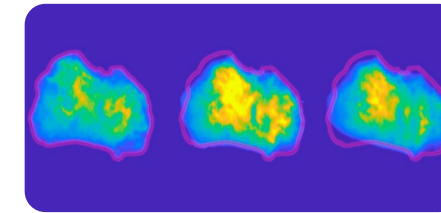
Observe under realistic environments while systems work

ENABLING DISCOVERIES THAT MATTER



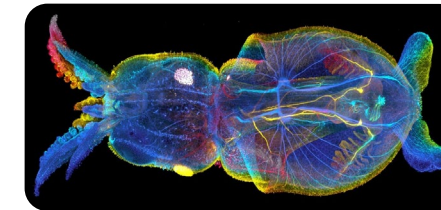
Battery degradation in real time

See chemical changes in a battery as it cycles



Unlocking materials at the nanoscale

Capturing the hidden nanoscale dynamics that governs material performance in real time



Imaging neural system wiring

Deciphering how the brain works and controls function



Human Organ Atlas

3D imaging of entire human organs down to the micron level

ESRF-EBS opened unprecedented scientific opportunities
The LTSP defines how we turn this into transformative science

WHERE WE ARE AND WHERE THE LTSP WILL BRING US

1

SCIENCE IS
ENTERING
A NEW ERA



BIOLOGY and
HEALTH



CLIMATE
CHANGE



ENERGY
TRANSITION



GENERATIVE
AND AGENTIC AI



QUANTUM
REVOLUTION

With disruptive breakthrough expected in **BIOLOGY and HEALTH**,
needed to cope with **CLIMATE CHANGE** and support the **ENERGY TRANSITION**,
leveraged by **GENERATIVE AND AGENTIC AI**, with the **QUANTUM REVOLUTION** ahead of us

2

WHAT WE
HAVE BUILT
TOGETHER

STRONG ACHIEVEMENTS AFTER ORANGE AND PURPLE BOOKS (330 M€ INVESTED IN 2 UPGRADE PHASES)

Outstanding EBS operation for
6 years, producing massive
volumes of high-quality data

Full software ecosystem
deployed from beamline control
to data portals

Strategic partnerships, new
community access modes and
establishment of framework for
AI readiness

3

KEY CHALLENGES
TO PRESERVE
THE INVESTMENT

Ageing injector (40 yrs.)
Injector matching SR
performance & ready for next
steps

Beamline technology under
stress by EBS and not AI-ready
AI-enabled beamlines

Inadequate IT infrastructure
IT infrastructure allowing full
exploitation of EBS data

Continue innovating for the benefit on the entire community

FIVE SCIENTIFIC DIRECTIONS FOR THE NEXT DECADE

FIVE MAJOR SCIENTIFIC DIRECTIONS IDENTIFIED IN THE LTSP IN WHICH THE ESRF CAN PROVIDE BREAKTHROUGH AND UNIQUE OPPORTUNITIES



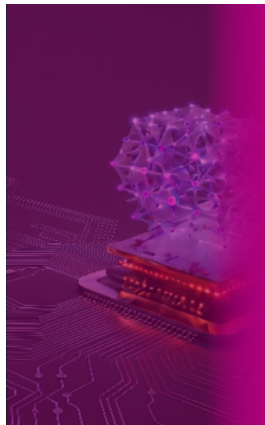
 **ATLAS-SCALE BIOLOGY**

From molecules to cells, tissues and organs: building 3D/4D atlases to decode biology and advance precision medicine



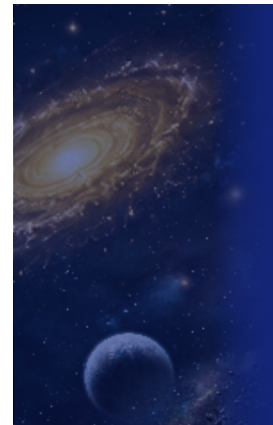
 **ENERGY TRANSITION & CLIMATE RESILIENCE**

From fundamental understanding to solutions



 **QUANTUM & POST-SILICON SYSTEMS**

Understanding and engineering quantum materials and devices, defects, strain and interfaces for quantum technologies beyond CMOS computing



 **SPACE SCIENCE**

Probing matter and extreme environments from the Solar System to the Universe, informing and benefiting all other directions



 **AI-NATIVE SCIENCE**

AI integrated across the entire discovery pipeline, from data acquisition and analysis to experiments and new scientific insight

GRAND CHALLENGES SUPPORTED BY FUNDAMENTAL RESEARCH:

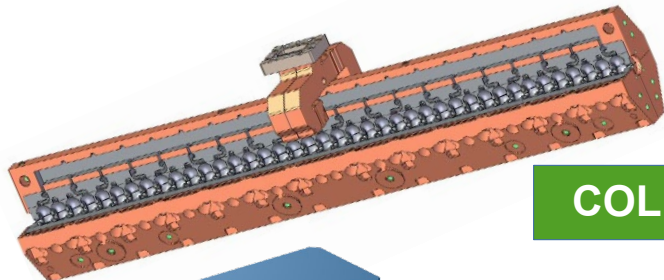
Life sciences and health, energy, catalysis and reaction pathways, advanced materials, quantum science and technology, environment and food safety, earth and planetary science, cultural and natural heritage

ACCELERATORS

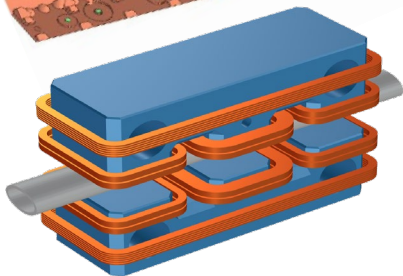
SHORT TERM:

- Solid State Amplifiers
- Injector upgrade 4th harmonic cavity Non-linear kicker

PREPARING THE FUTURE:



COLD



HTS IDs

LONG TERM: full energy LINAC,
Next generation DLSR

BEAMLINES AND ENABLING TECHNOLOGIES

SHORT TERM:

- Refurbishments: ID26, ID10-COH, ID11, ID12, ID13, Ind. tomography

New flagship
BL ID18



PREPARING THE FUTURE:

- AI readiness programme
- New generation of beamlines



AI AND IT INFRASTRUCTURE

AI REVOLUTION IMPACTS:

Beamline control and data collection

Data analysis, reconstruction, segmentation

Software engineering

Data analytics, knowledge production

- New data center
- AI ready beamline
- Collaboration with AI-HPC centers

From user access to a scientific ecosystem



Goal: maximise scientific impact in a collaborative framework

ACADEMIC ACCESS BEYOND STANDARD & LONG-TERM PROPOSALS



STRATEGIC OBJECTIVES:

Further development of community access projects and Open Data Portals
Deployment of AI tools for the beam time review & allocation process

INDUSTRY & INNOVATION A CHANGE OF PACE

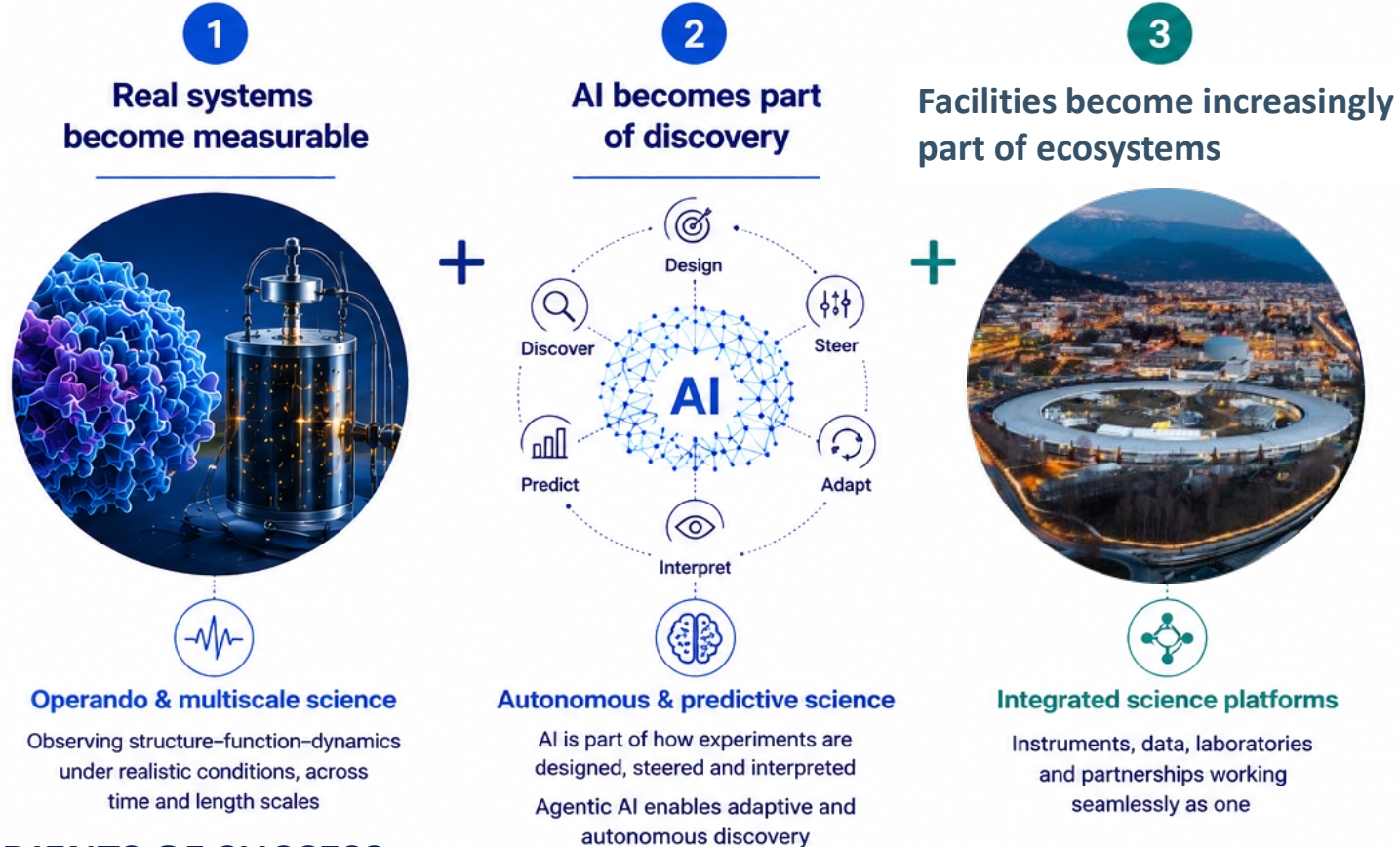
Synchrotron X-ray methods: a predictable and reliable component of industrial R&D workflows

Strategy

- Strengthen links with RTOs, Technology Infrastructures, scientific service companies, and start-ups
- Develop data-driven innovation workflows
- Adopt artificial intelligence and machine learning in industrial R&D

Expected outcome

- A structured industrial R&D workflows.
- Accelerated development of advanced materials and technologies
- Increased technology transfer and industrial valorisation of ESRF developments



AI is no longer simply a tool for analysing data after the experiment. **It is becoming part of how experiments are designed steered and contribute to scientific discovery**



Agentic AI may fundamentally change the relationship between instruments data and discovery.

THE INGREDIENTS OF SUCCESS:



1. FULLY EXPLOIT EBS

Maximise the scientific impact of EBS to deliver discoveries that address Europe and world's challenges



2. CONTINUE INNOVATING

Invest in next-generation instrumentation, methods and digital infrastructures to stay at the frontier



3. PREPARE THE NEXT GENERATION

Develop talent, skills and partnerships to ensure a vibrant, diverse and sustainable scientific community



4. BRING TOGETHER ANALYTICAL FACILITIES & IT CENTERS TO ENABLE AI-BASED DISCOVERIES

Develop AI ready databases

This is not ESRF success — this is the blueprint for next-generation rings!!



THANK YOU FOR YOUR ATTENTION