

# The Global Race for A Better Battery

*Y. Shirley Meng*

The University of Chicago

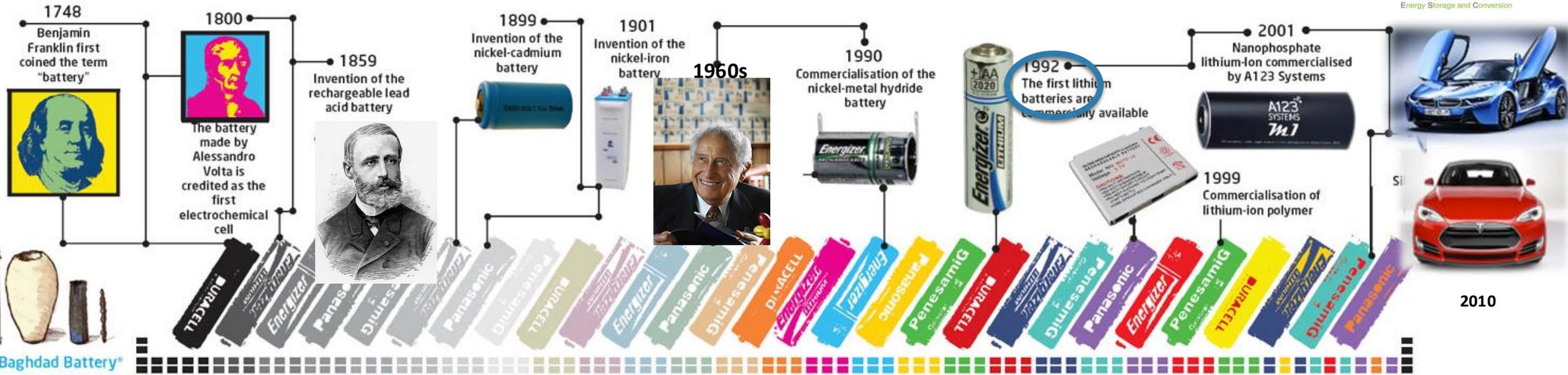
Argonne Collaborative Center for Energy Storage Science

Energy Storage Research Alliance

Watt Launch Event

Nov. 23, 2025

# A Brief History of Battery and Industrialization



**Baghdad Battery\***  
 \*There is a possibility that the battery was invented twice. Discovered by German archaeologist Wilhelm König on the outskirts of Baghdad, terracotta jars with a copper sheet inlay and an iron rod. These two combine to form an electrochemical couple in an electrolyte, the building blocks of a battery. The jars are believed to be 2000 years old.



## Intercalation Chemistry – Nobel Chemistry 2019 !

IoT  
mWh

Robots  
Wh

Drones  
kWh

Aviation / SemiTruck  
MWh



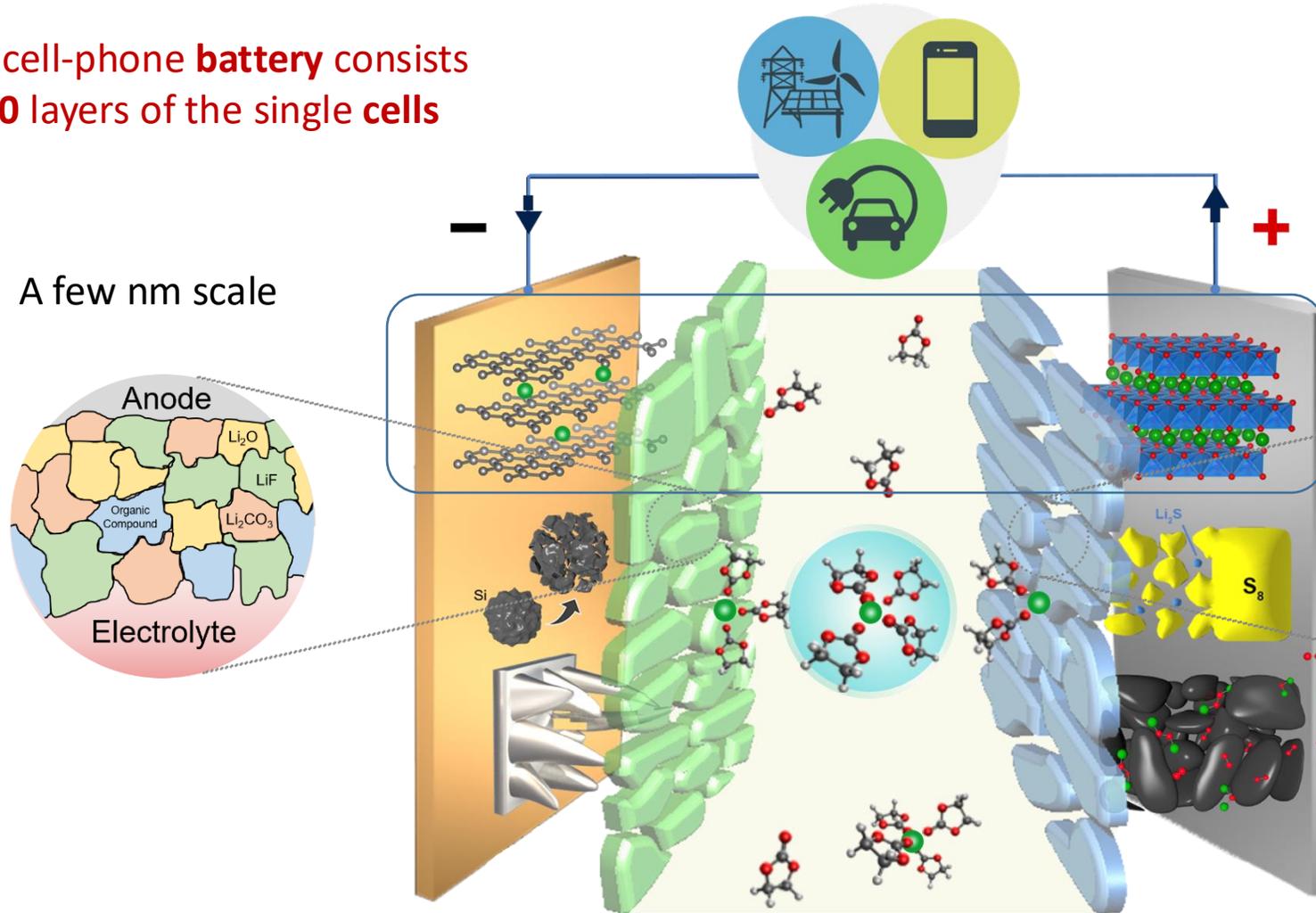
1Whr is a large energy unit = 3600 W.s (J)

Energy Storage for Renewables  
GWh

# Rechargeable Battery - A Complex Engineering System

Kang Xu, Venkat Srinivasan and Y. Shirley Meng, Science 2023

One cell-phone **battery** consists **10-20** layers of the single **cells**



Moving Ions  
(Chemical Bond)

Dynamic Phenomena

Strain - Fatigue

Thermodynamically Closed  
System 99.9% efficiency  
needed

**SEI** – Life and Safety  
Differentiators

# World Production of LIB >1TWh/Year 2024 (Today)

The Top 10

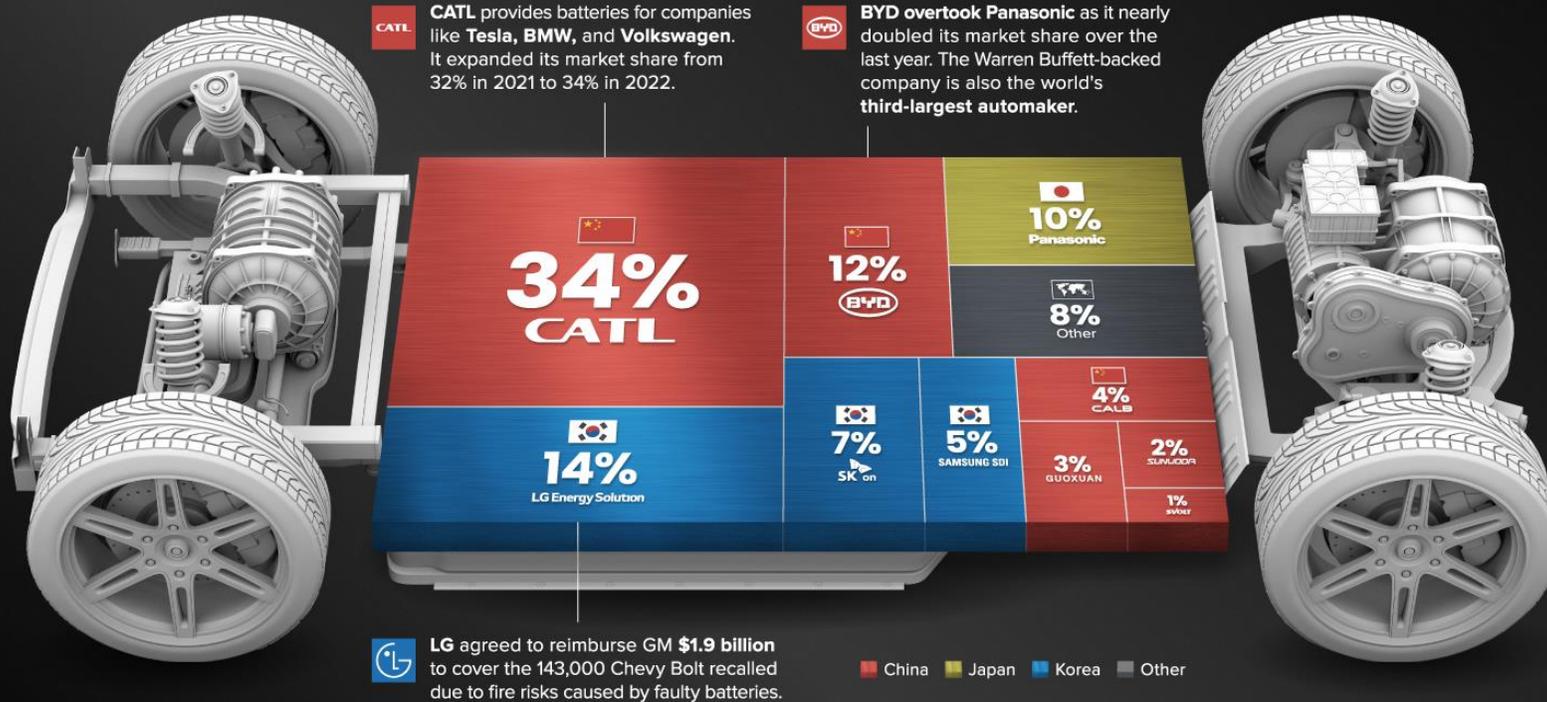
## EV BATTERY MANUFACTURERS

in 2022

E

The EV battery market is expected to grow from \$17 billion in 2019 to \$95 billion by 2028.

Here are the world's biggest battery manufacturers in 2022.



**CATL** provides batteries for companies like **Tesla, BMW, and Volkswagen**. It expanded its market share from 32% in 2021 to 34% in 2022.

**BYD** overtook **Panasonic** as it nearly doubled its market share over the last year. The Warren Buffett-backed company is also the world's **third-largest automaker**.

**LG** agreed to reimburse GM **\$1.9 billion** to cover the 143,000 Chevy Bolt recalled due to fire risks caused by faulty batteries.

China Japan Korea Other

Source: SNE Research via Bloomberg

**In 1998**, Academician Chen Liquan, built the first production line using a complete set of Chinese equipment.

**In 1999**, South Korea entered the lithium-ion battery market, and LG Chem completed South Korea's first battery product.

**In 2000**, BYD won an order from Motorola

**In 2001**, China entered WTO

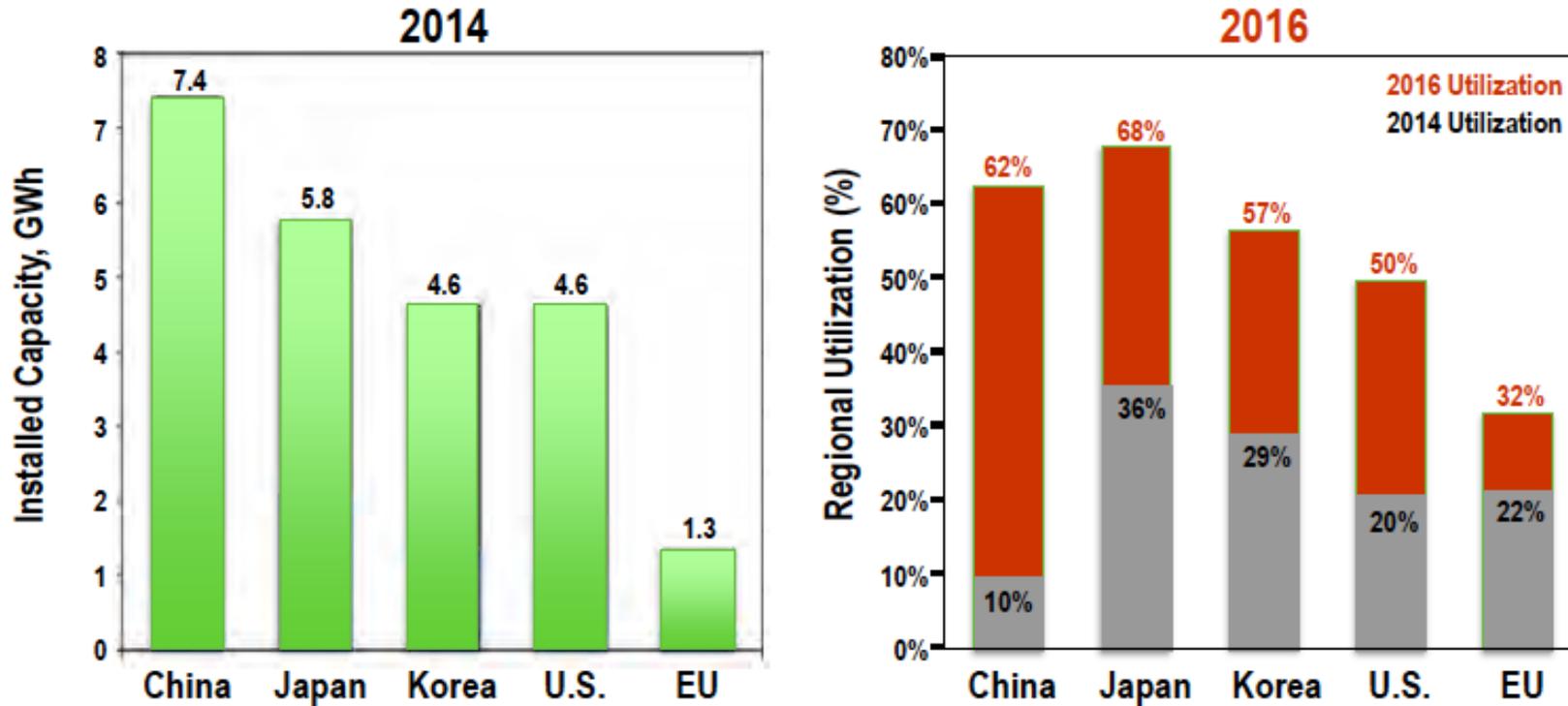
**In 2004**, CATL became an iPod supplier. China's lithium battery industry emerged. China's annual output of lithium-ion batteries is 800 million units, accounting for 38% of the global share, second only to Japan.

**Start in 2002** "Electric Vehicle Key Project"  
 - 863 National High-Tech Development Plan  
 - Spent **880 million yuan** for EV research in five years

- Start in 2013** China Central government subsidies
- ▶ 60,000 yuan for passenger electric cars (>250 km)
  - ▶ 300,000 yuan for electric buses
  - ▶ Exemption from vehicle purchase tax
  - ▶ Local subsidies: up to 60% of EV retail price
  - ▶ Non-subsidy measures: license-plate restrictions

# 2014 We All Started from The Same Spot! (Past)

## Regional Automotive LIB Cell Capacity and Utilization



- Automotive lithium-ion battery demand growing but short of global manufacturing capacity.
- Utilization of U.S. plants increased from 20% in 2014 to ~50% in 2016.
- Forecasted compound annual growth rates in lithium-ion demand: 22%–41% (through 2020).

# A Vision for the Future (World View)

ONLY 2% done with what we need , that is 200-300TWh batteries !

- 8.5 Billion People by 2030 – More than half in developing countries  
each person has about 10kWh battery – we will need 85TWh battery

- 6 Billion Smartphones/Smart Tablets – All connected via 5G

This is a small market now – but people with real 5G need fast charging/fast discharging

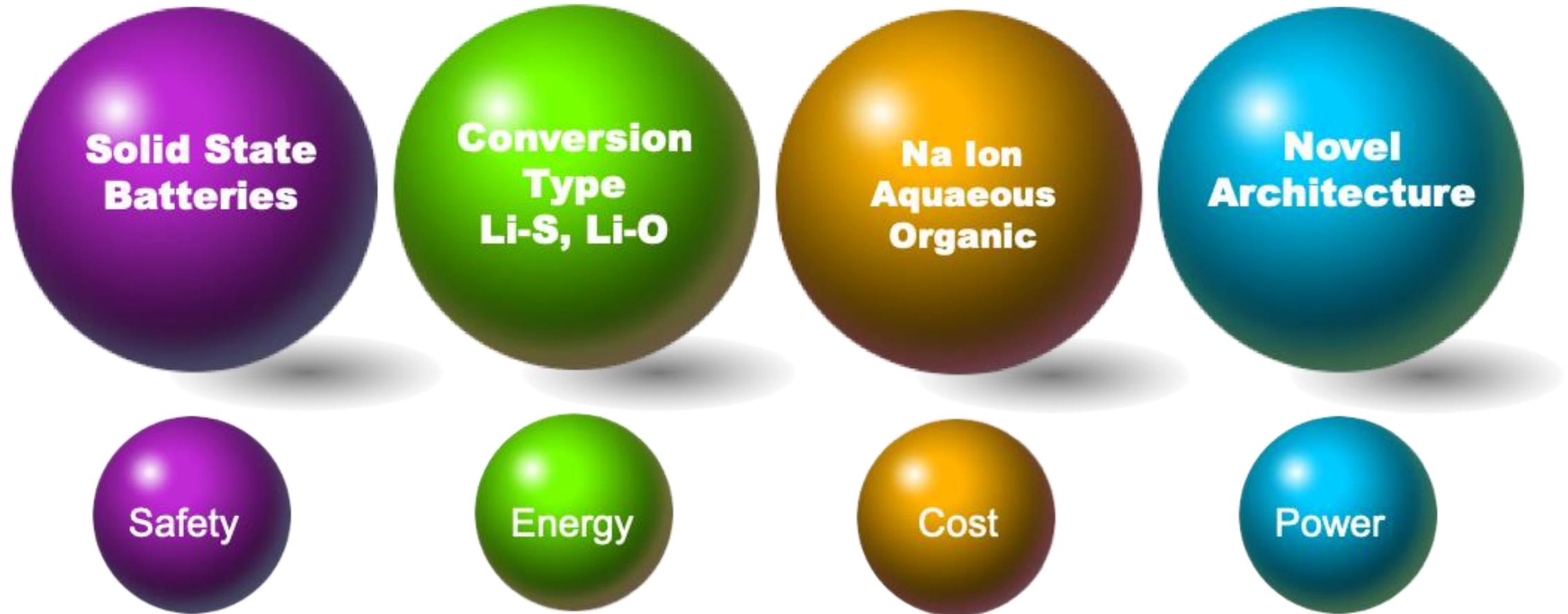
- 1 Billion Cars to be Electrified – Possibly Electric Planes

We predict that total number of cars will reduce, cars will be better utilized and we will have electric heavy duty trucks and possible V2G enabled – 100TWh

- Grid of the Future

Long duration needs can be fulfilled by technologies other than batteries (H<sub>2</sub>+Hydro+Thermal) – 100TWh

# Next Decade of Energy Storage and Battery Technology



**Solid State Batteries**

**Conversion Type  
Li-S, Li-O**

**Na Ion  
Aqueous  
Organic**

**Novel  
Architecture**

**Safety**

**Energy**

**Cost**

**Power**

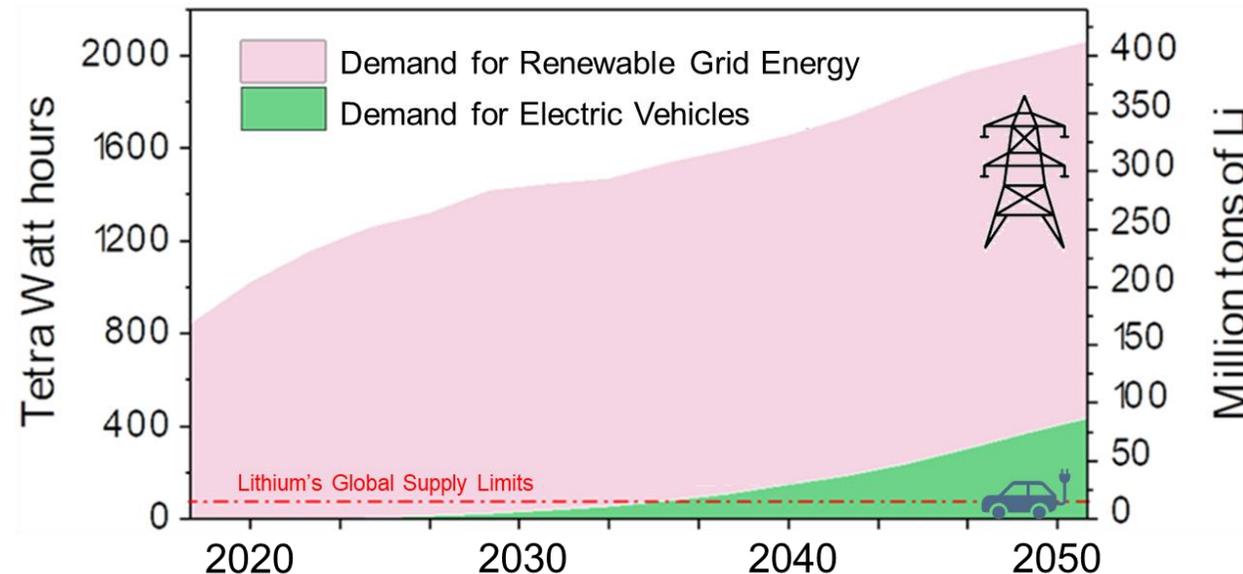
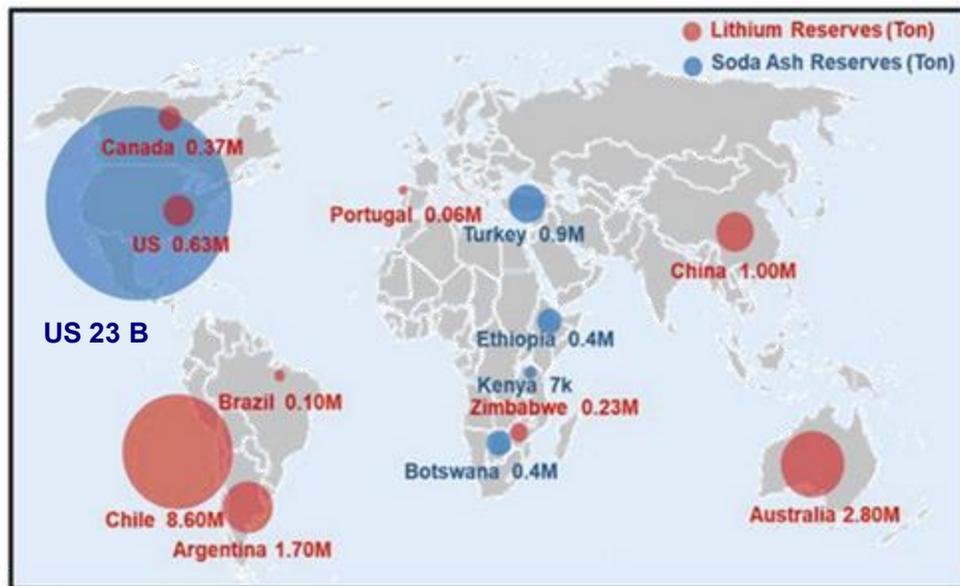
High energy batteries that never catch fire

Batteries last more than 30 years

Batteries can be 100% recycled (supply chain)

Batteries that can be charged full in 5 minutes

# Na vs Li Materials Sustainability



## US Energy Storage : Scale

### 1) Electrical Grid

- Per capita - 12000 kWh / year
- 400 tera-watt hours if just 10% storage  
→ 60 million tons of Li Needed

### 2) Vehicles

- 17 million / year, if all EVs
- 0.85 tera-watt hours  
→ 0.13 million tons of Li Needed

**Abundant Sodium in the U.S. is needed to accelerate energy transition**

**Na battery will reduce the demand for Li, Cu, Co and possibly Ni**

**Na battery can be shipped more safely**

**Na battery can allow more customer choices**



# Collaborators and Funding

Na Batteries Since 2010  
NSF CAREER



National Science Foundation  
DMR program (Na Batteries)



Dr. Daniel Lee  
Ph.D. 2013

Dr. Jing Xu  
Ph.D. 2014

Dr. Mark Ma  
Ph.D. 2017

Dr. J. Alvarado  
Ph.D. 2017

University Research Program  
Since 2019



LGES Frontier Research Laboratory (2021 – present)

Various Industrial Partners including  
(LG Energy Solution / ThermoFisher Scientific / Shell / UL / Nissan  
/Cummins/ SES/ Supernal /GM / Applied Materials)

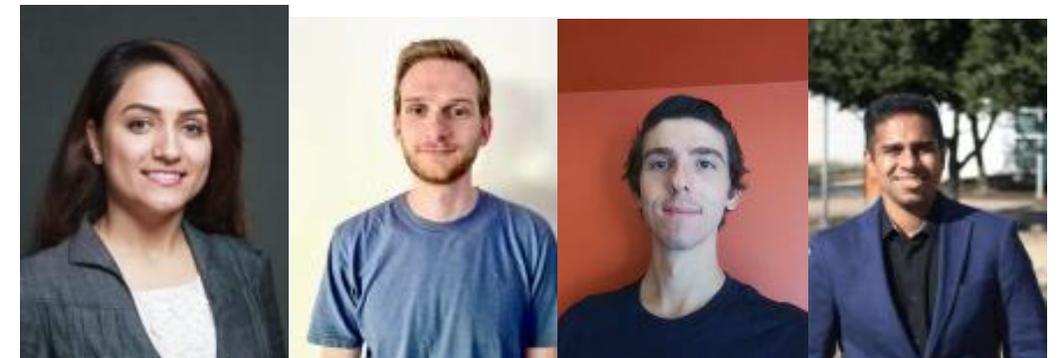


Dr. M. Zhang  
Ph.D. 2018

Dr. Erik Wu  
Ph.D. 2020

Dr. H. Hirsh  
Ph.D. 2021

Dr. Darren Tan  
Ph.D. 2021



Dr. Baharak S  
Ph.D. 2023

Dr. P. Ridley  
Ph.D. 2024

Dr. G. Deysher  
Ph.D. 2024

Dr. Raghavendra  
Ph.D. 2025

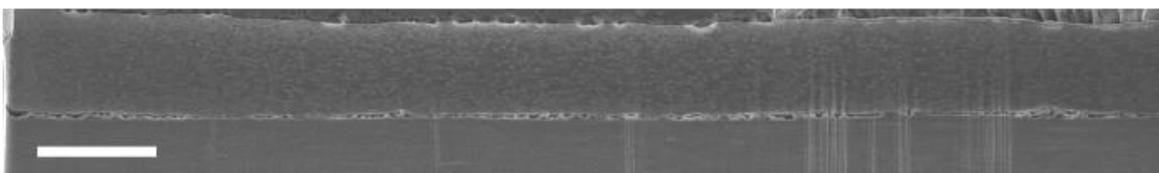


UC IRVINE MATERIALS RESEARCH INSTITUTE



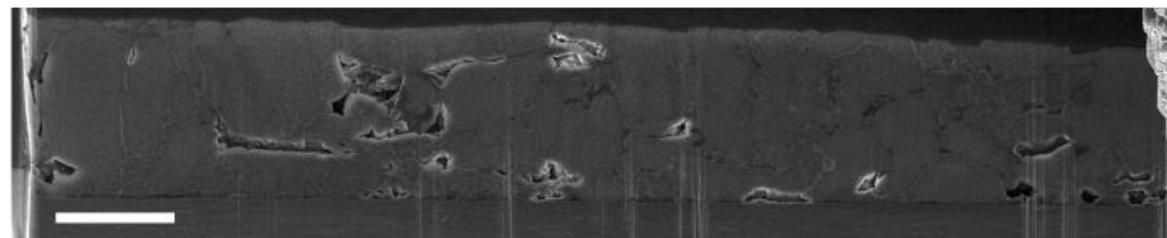
# Analysis of Na Metal Deposition and Stripping

(a) **1 M NaPF<sub>6</sub> in DME**



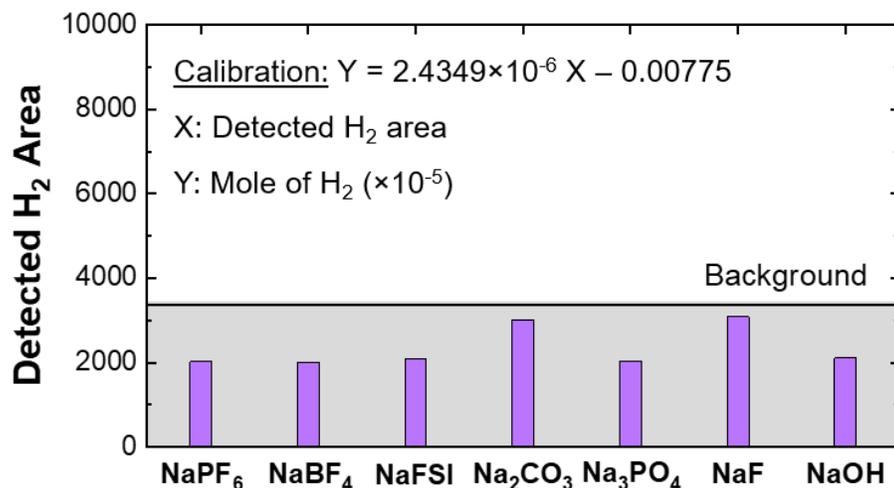
**180 kPa**

(b) **1 M NaPF<sub>6</sub> in EC:DMC (1:1)**



**250 kPa**

The sodium was plated at 0.5 mA/cm<sup>2</sup> for 1 mAh/cm<sup>2</sup> on Al foil. The images are acquired under 5kV voltage and 0.2 nA current using a TLD detector. The scale bars are 10 μm.



Standard	Detected H <sub>2</sub> Area
NaPF <sub>6</sub>	2025
NaBF <sub>4</sub>	2004
NaFSI	2100
Na <sub>2</sub> CO <sub>3</sub>	3013
Na <sub>3</sub> PO <sub>4</sub>	2037
NaF	3127
NaOH	2115

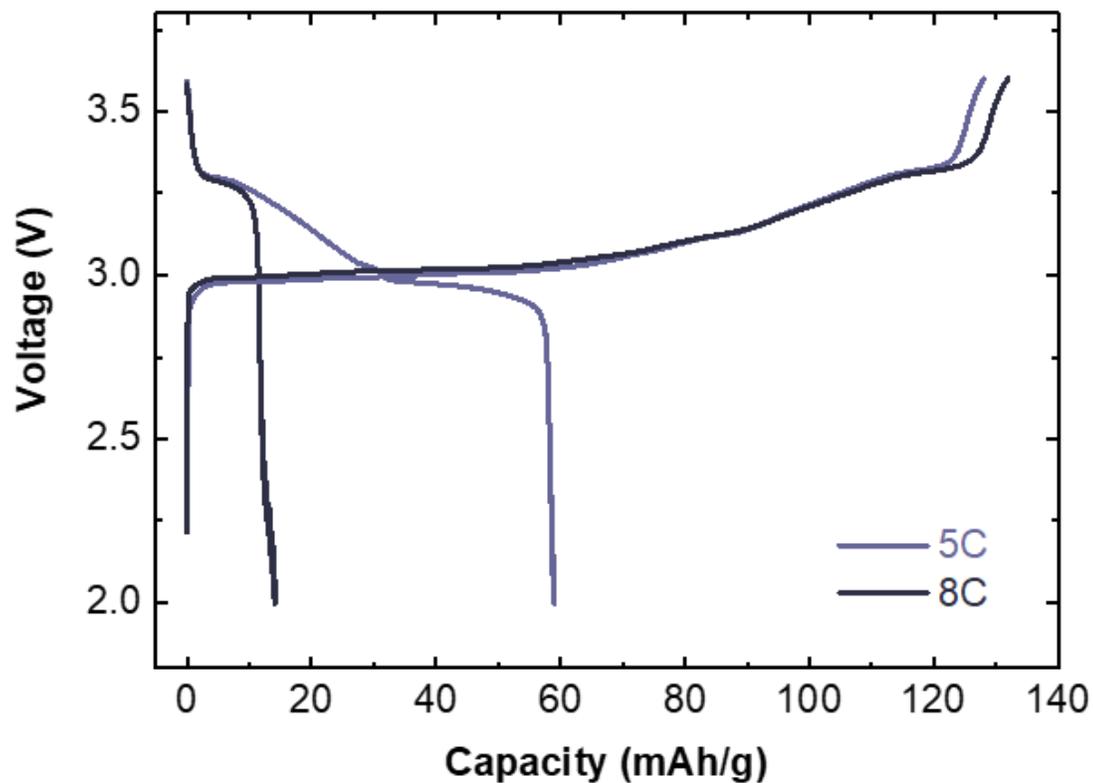
The controlled TGC experiment on standard commercial powders showed no hydrogen generation. This test was performed using ethanol as the solvent.

# Power of Sodium Battery

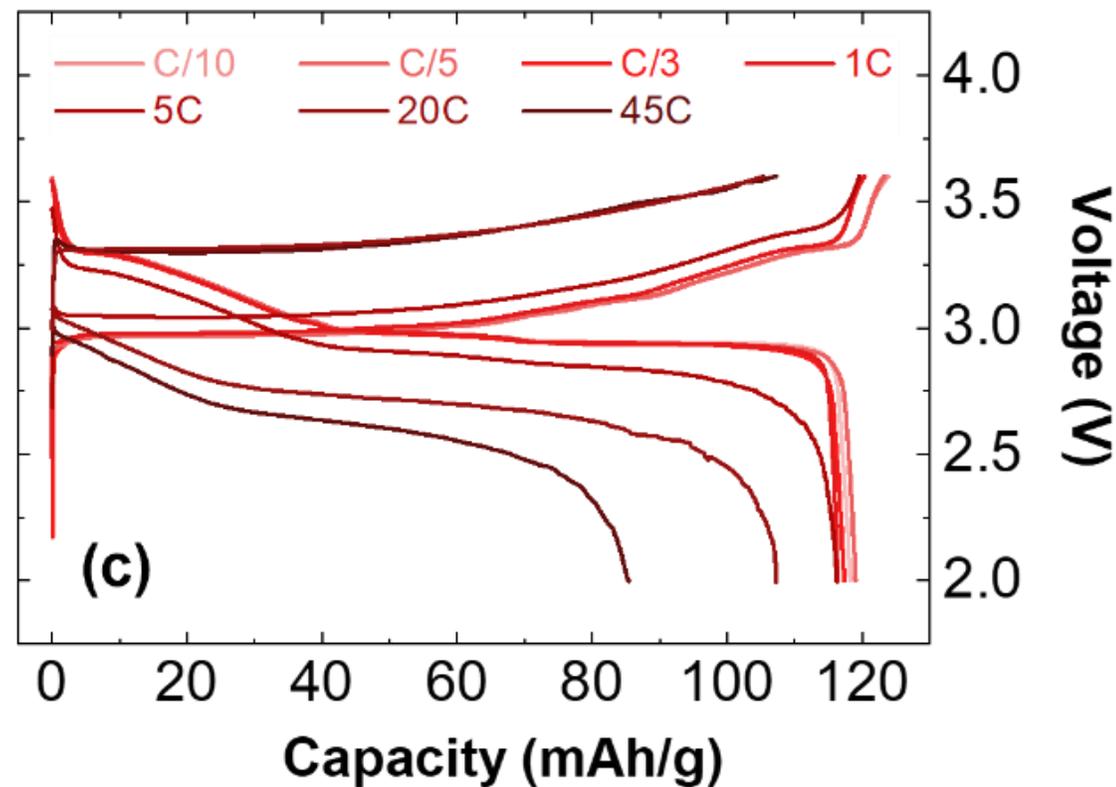
1C = 1 hour charging/ 20C = 3 min charging!



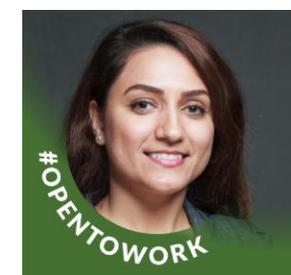
Na Metal as anode, NaCrO<sub>2</sub> as the cathode. The cells have controlled 100% excess of sodium inventory.



1M NaPF<sub>6</sub> in EC:DMC (1:1)



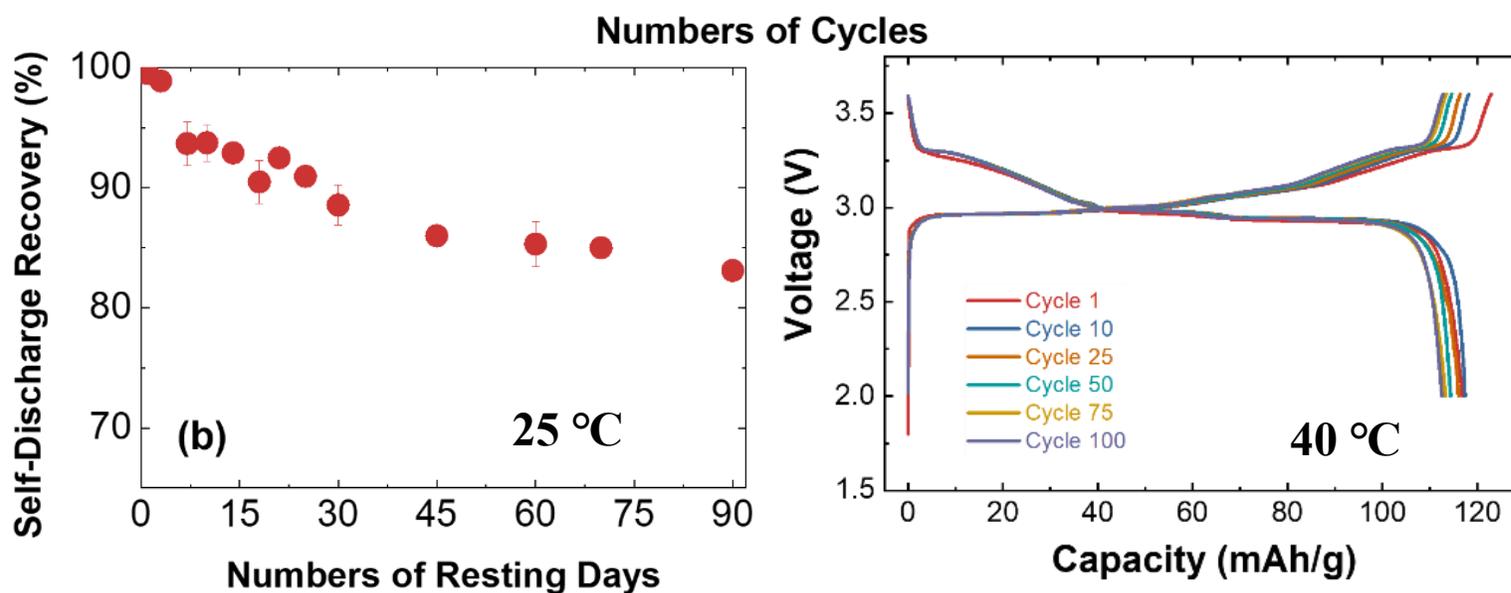
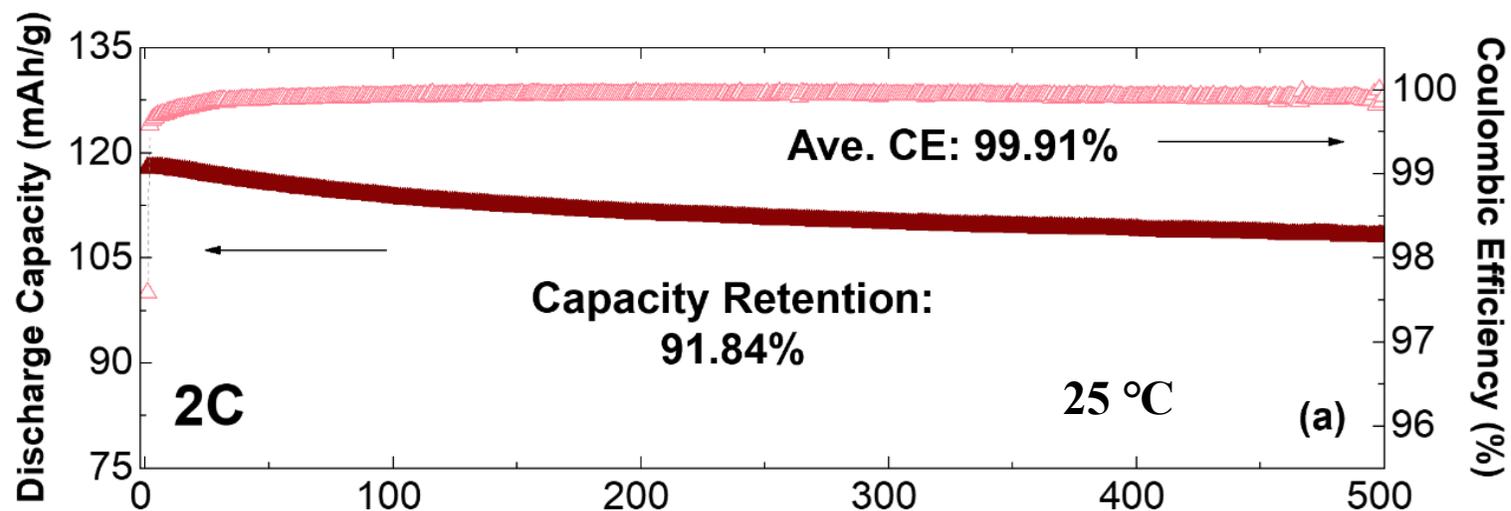
1M NaPF<sub>6</sub> in DME



Dr. Baharak Sayahpour  
(ASML)

We made the  
anode, electrolyte,  
cathode

Active work since  
my CAREER award  
in 2010



National  
Science  
Foundation

# UNIGRID's Value: Energy & Safety

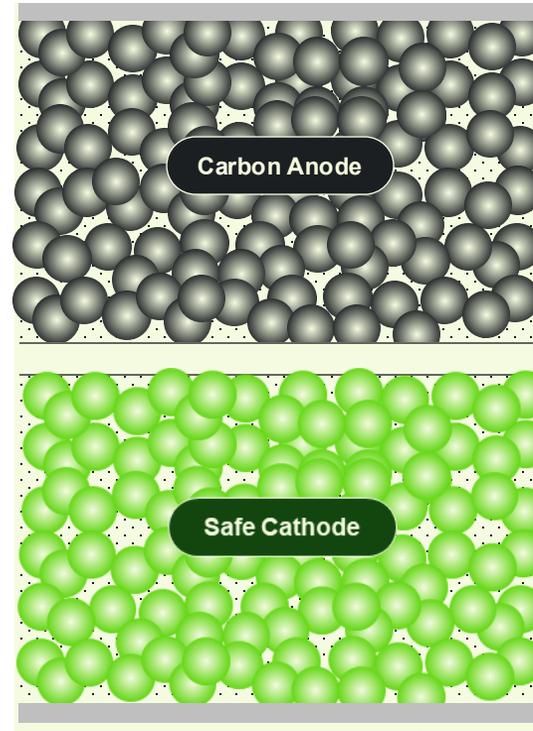


Dr. Darren Tan

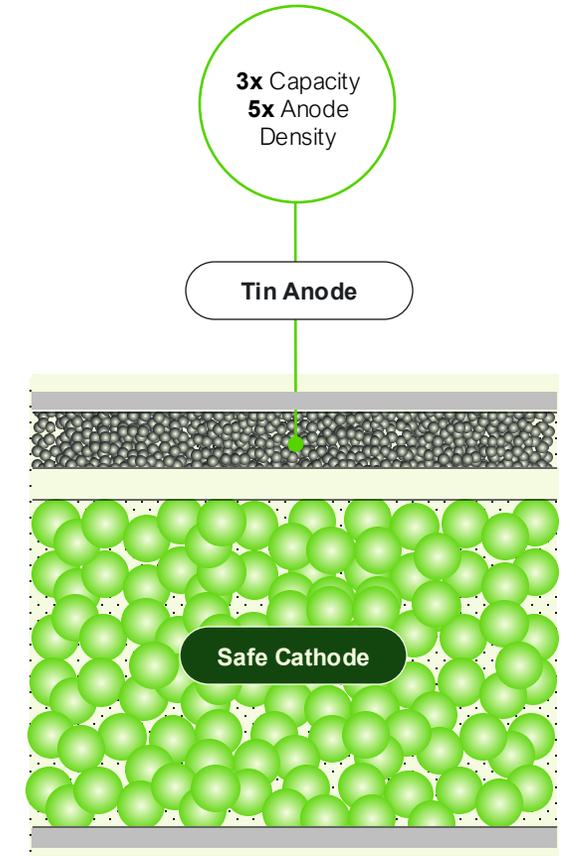
Sodium Ion Battery Landscape	Key IP	Cathode	Anode	Wh/kg	Wh/L	Cycles	Market	
<b>UNIGRID</b>		Anode	Any	Alloy	180 Wh/kg	450 Wh/L	>3000	EV / ESS
		Cathode	Layered Oxide	Carbon	160 Wh/kg	200 to 300 Wh/L	>3000	EV / ESS
		Cathode	Layered Oxide / PBAs	Carbon	160 Wh/kg	200 to 300 Wh/L	—	EV / ESS
		Cathode	Symmetric Prussian Blue Analogues	—	20 Wh/kg	18 Wh/L	>50000	Backup Power
		Cathode	Layered Oxide	Carbon	145 Wh/kg	180 to 300 Wh/L	>4500	EV
		Cathode	Prussian Blue Analogues	Carbon	—	180 to 300 Wh/L	—	EV / ESS
		Cathode	Poly-anionic	Carbon	—	180 to 300 Wh/L	—	EV / ESS
		Cathode	Layered Oxide & Poly-anionic	Carbon	145 Wh/kg	180 to 300 Wh/L	>5000	EV / ESS
		Cathode	Layered Oxide	Carbon	145 Wh/kg	180 to 300 Wh/L	>5000	EV / ESS
		Cathode	Poly-anionic	Carbon	110 Wh/kg	180 to 300 Wh/L	>5000	EV / ESS
		Cathode	Layered Oxide / PBAs	Carbon	140 Wh/kg	180 to 300 Wh/L	>4000	EV / ESS
		Separator	Layered Oxide	Carbon	—	—	—	ESS
		Cathode	—	Carbon	140 Wh/kg	180 to 300 Wh/L	>1000	ESS
		Cathode	—	Carbon	160 Wh/kg	180 to 300 Wh/L	>2000	EV / ESS

UNIGRID

# Anode - Energy Innovation



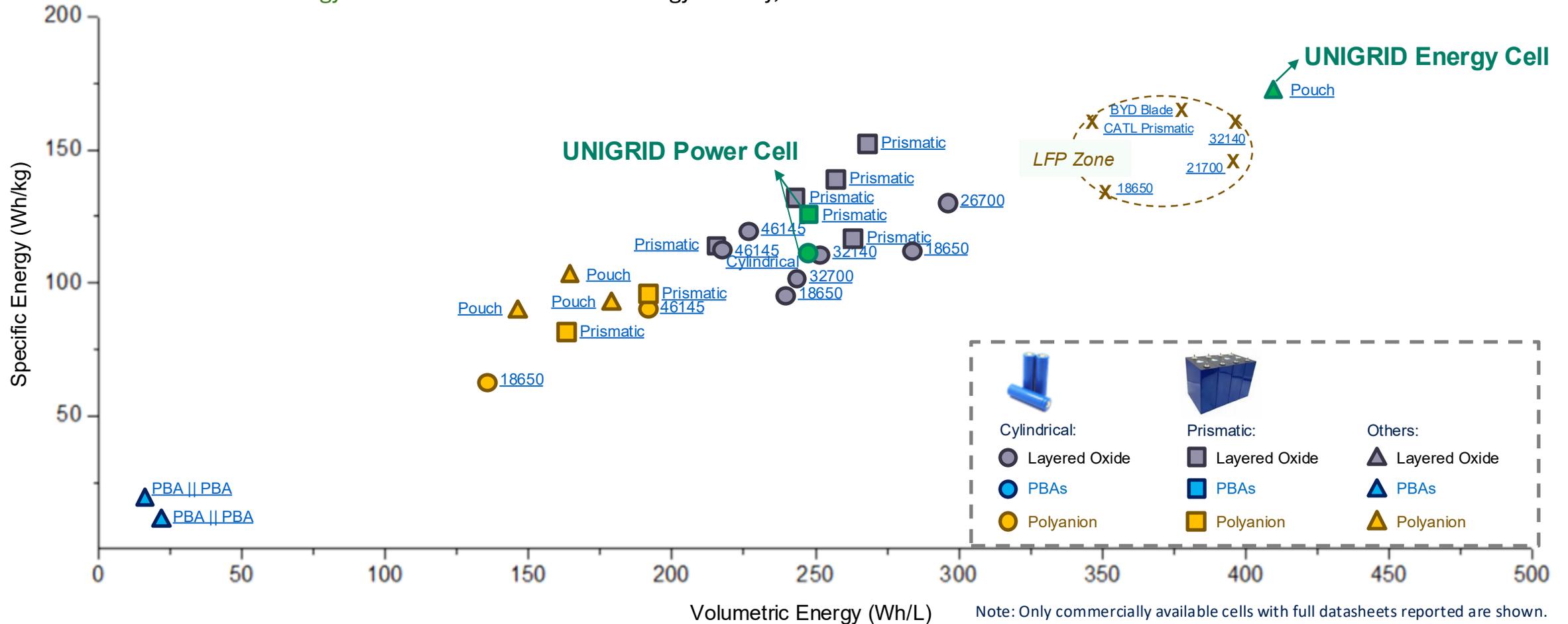
UNIGRID  
Power Cell



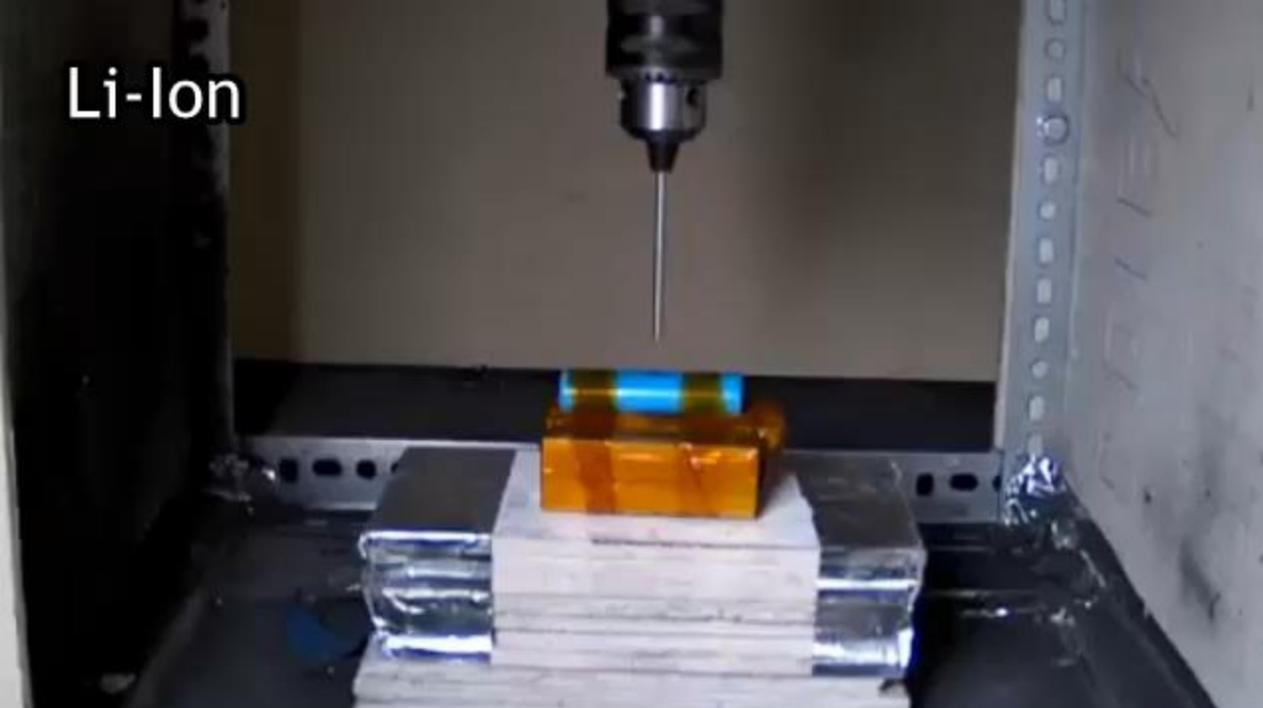
UNIGRID  
Energy Cell

## Sodium-ion - Reported Energy Densities

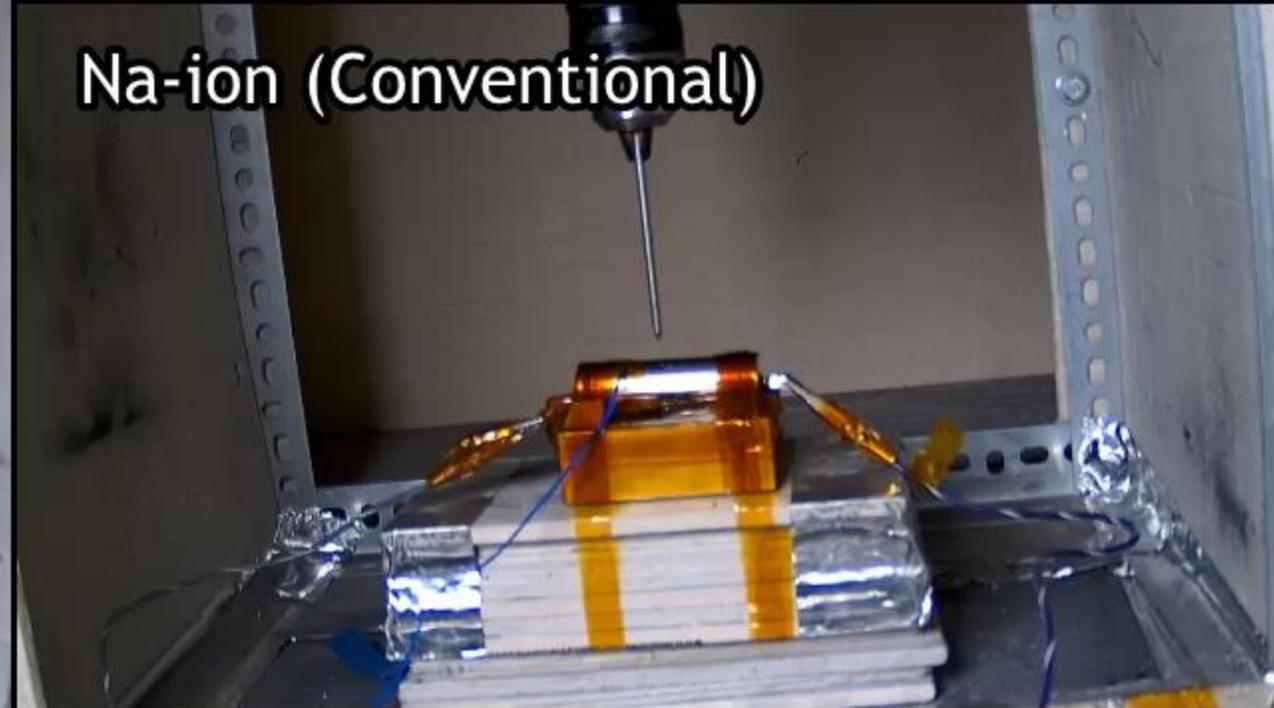
- UNIGRID Energy Cell sets record in Na-ion energy density, as the **Na-cell that exceeds LFP**



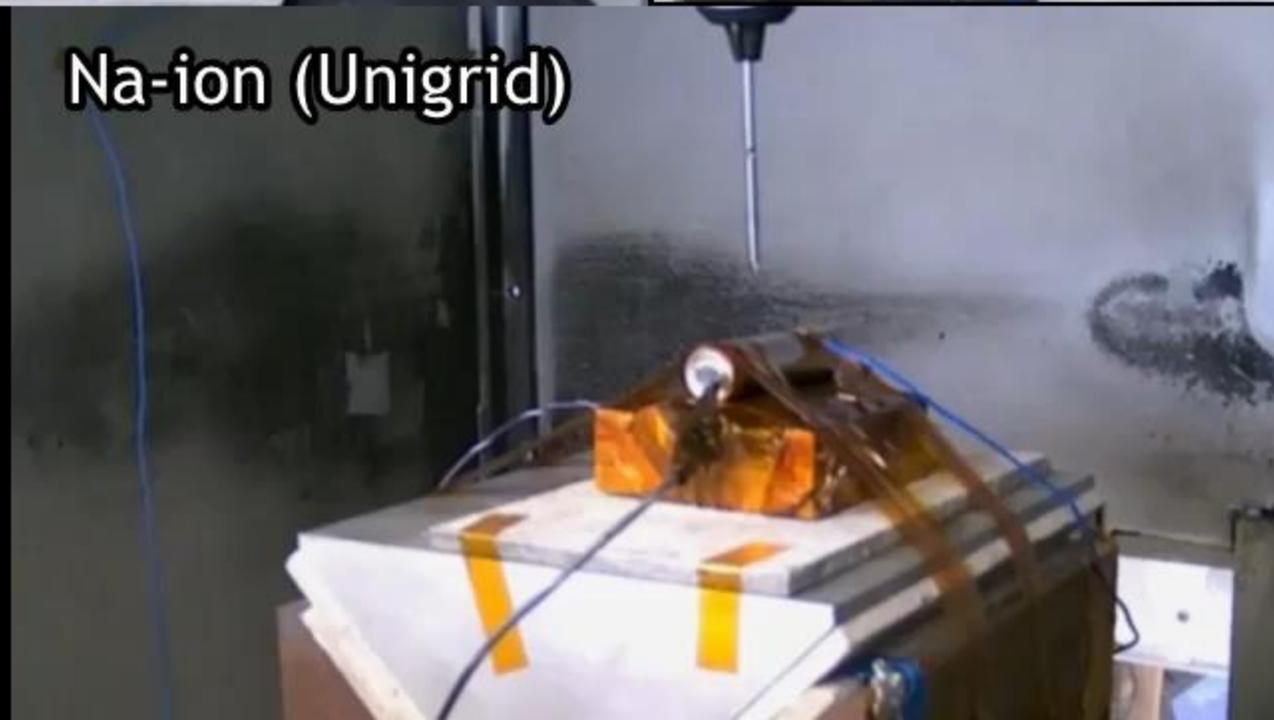
Li-Ion



Na-ion (Conventional)



Na-ion (Unigrid)



# UNIGRID

## Founding Team



**Darren H. S. Tan | Ph.D.**  
CEO



**Erik A. Wu | Ph.D.**  
CTO



**Zheng Chen | Ph.D.**  
Strategic Advisor



**Shirley Meng | Ph.D.**  
Scientific Advisor



## Proudly Supported By:

TRANSITION



RITZ Venture Capital



SILENCE



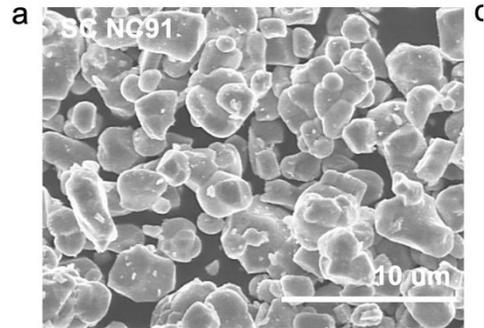
# The Race is NOT Over Yet for Lithium Batteries



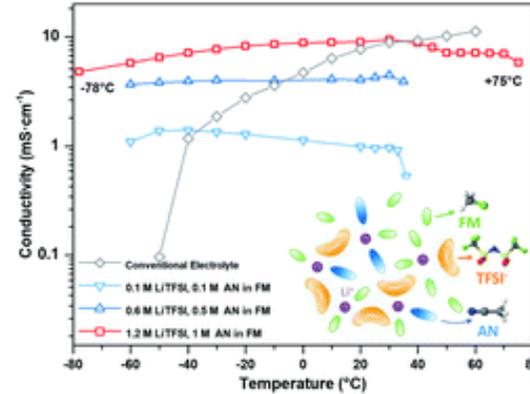
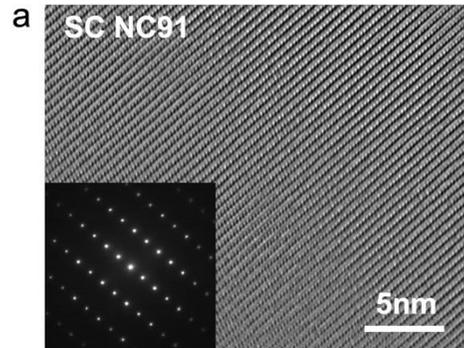
Maxwell Technologies 2017

Tesla Acquisition 2019

All Dry 4680 in Cybertruck 2024

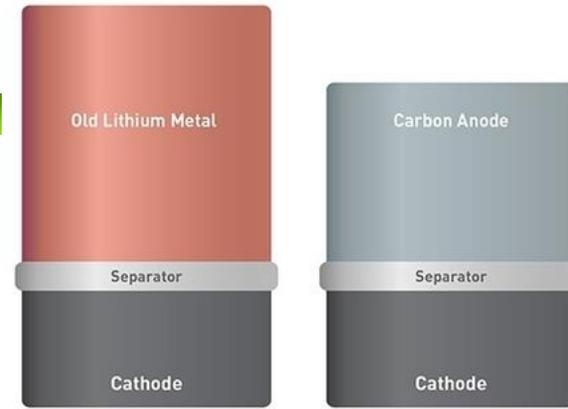


Better Cost Performance Ratio



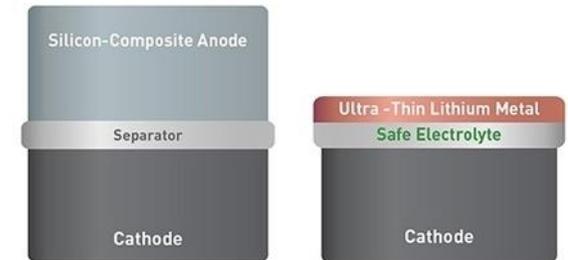
-60 to +60 C

Wider operation temperatures



**Gen 0**  
Li-Metal  
100-200 Wh/kg  
200-300 Wh/L  
Dangerous

**Gen 1**  
Li-ion  
200-250 Wh/kg  
600 Wh/L  
Safe



**Gen 2**  
Li-ion  
250-300 Wh/kg  
700 Wh/L  
Safe

**Gen 3**  
Li-Metal  
400-500 Wh/kg  
1200 Wh/L  
Safest

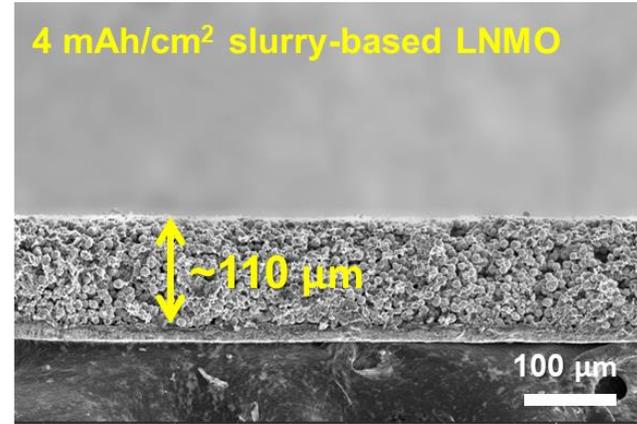
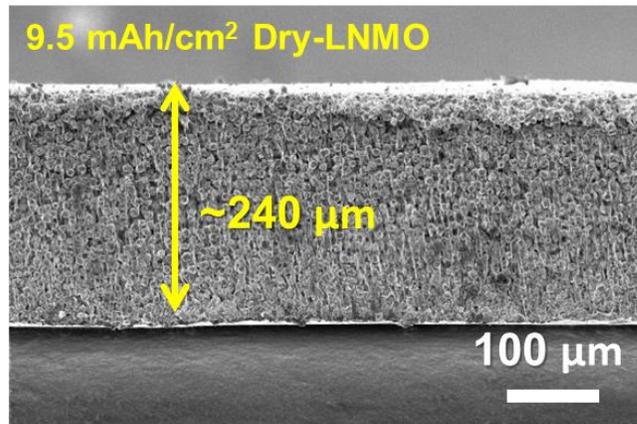
Dry Battery Electrode  
(DBE) Processing

Single Crystal NMC/NCA

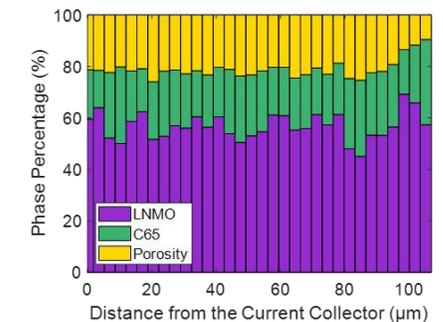
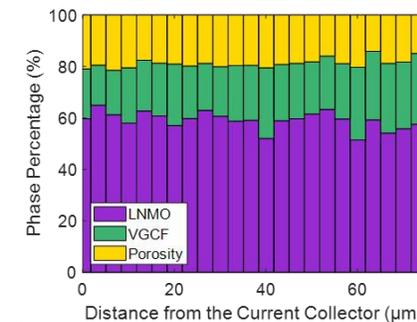
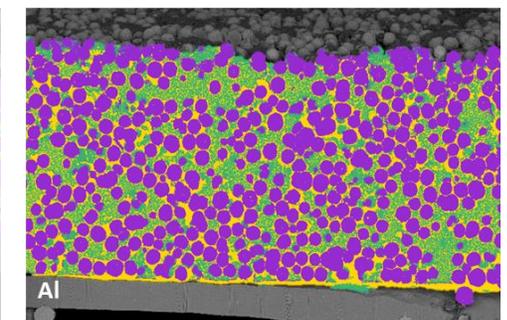
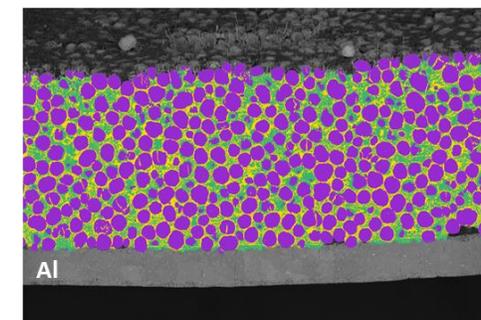
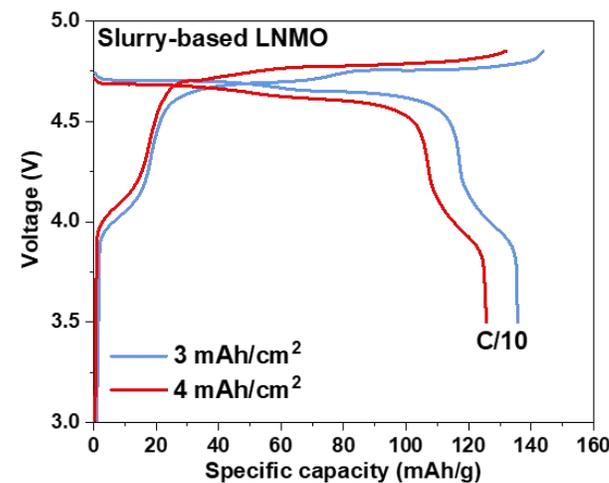
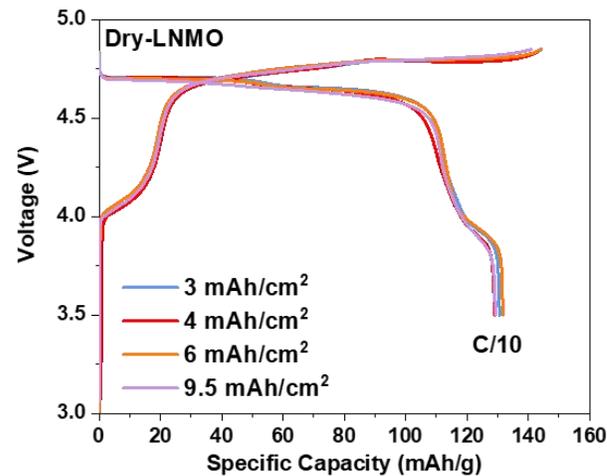
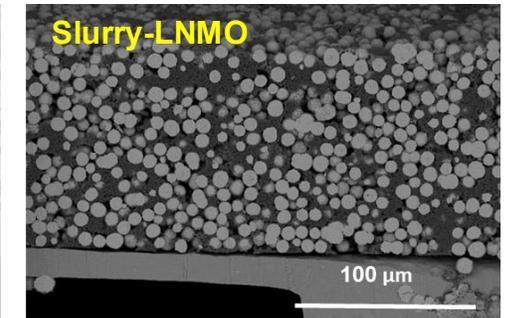
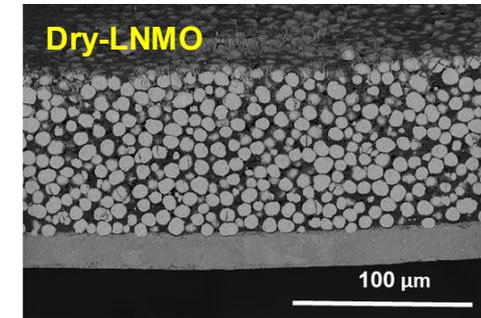
Electrolyte Genome

Anode-Free

# Comparison of Slurry-based and Dry LNMO Electrodes

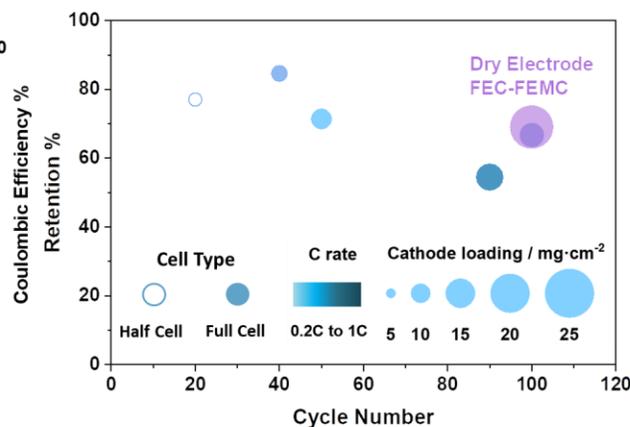
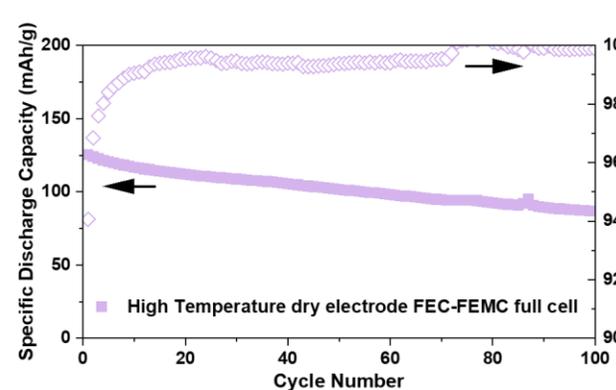
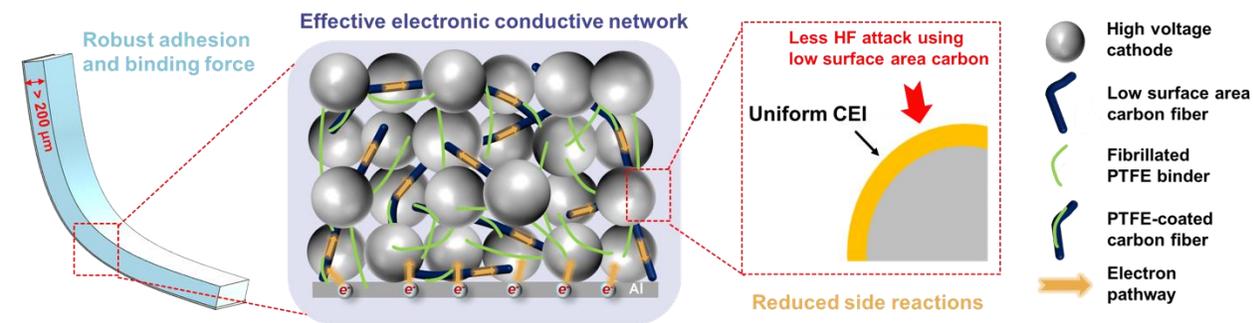
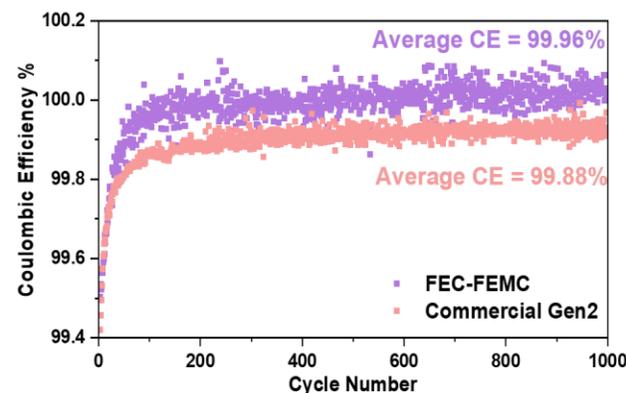
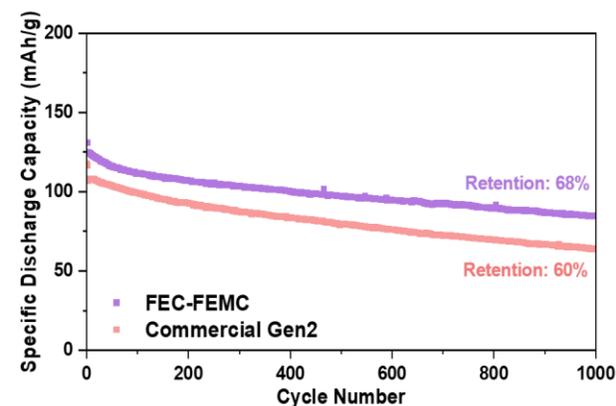


Plasma-FIB SEM of Electrode Cross-sections and Phase Segmentations



- Uniform carbon distribution in dry electrodes.
- Unchanged performance even with tripled electrode thickness.

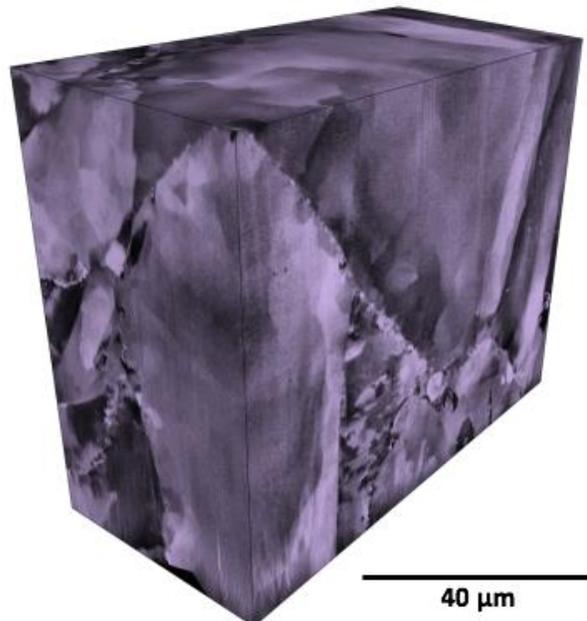
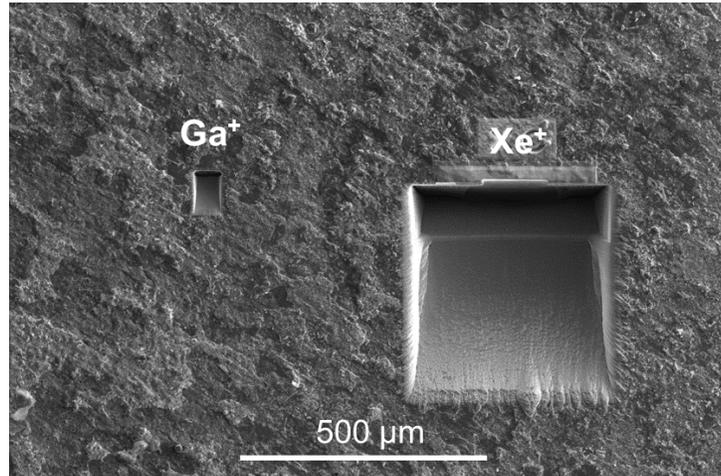
# Cycling Stability of Dry LNMO Electrodes



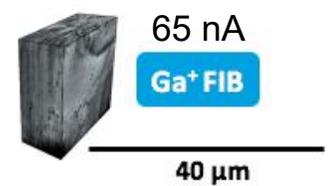
In dry LNMO full cells:

- Achieved ~68% capacity retention in 1000 cycles at room temperature and C/3 rate.
- Achieved ~70% capacity retention in 100 cycles at 55 °C and C/3 rate.
- Enabled with robust mechanical strength, effective carbon network using low surface area carbon and less Li inventory loss.

# Quantitative Analysis of Large Volume Thick Electrode



2500 nA  
Xe<sup>+</sup> PFIB

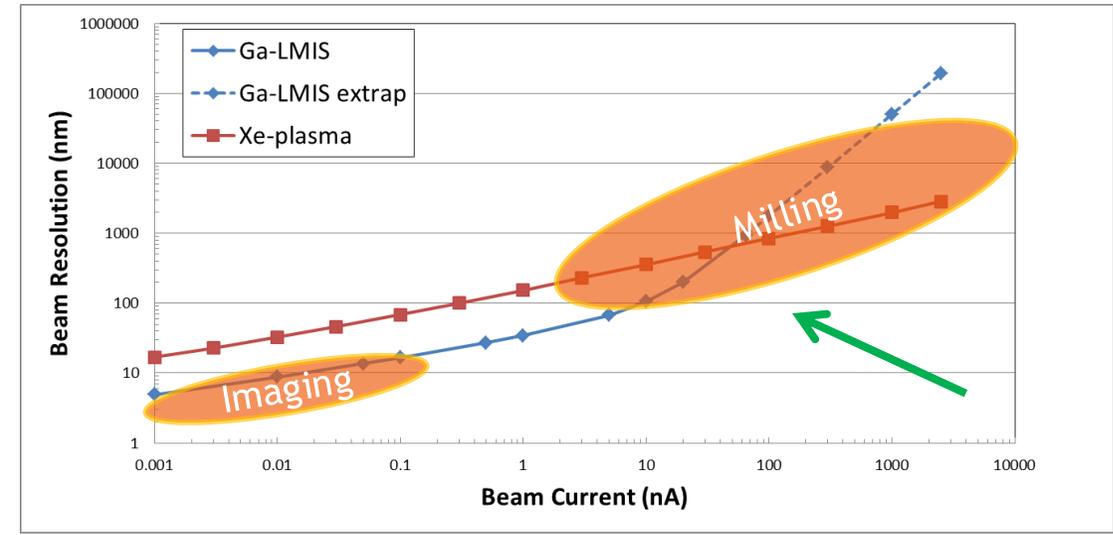


65 nA  
Ga<sup>+</sup> FIB

40 μm

40 μm

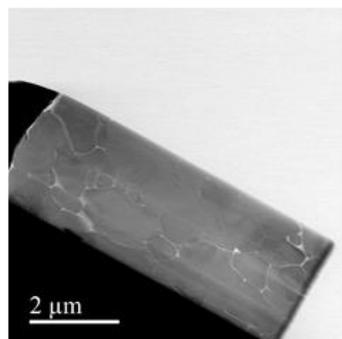
Almost 40x more beam current



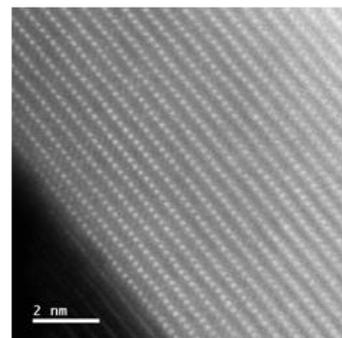
- Both systems offer excellent ion beam performance;
- Gallium offers the lowest accelerating voltages (down to 500 V);
- Plasma offers the highest beam current (2.5 μA) and Ga-free milling.

# Thick Electrode-Nanoscale Reaction Inhomogeneity

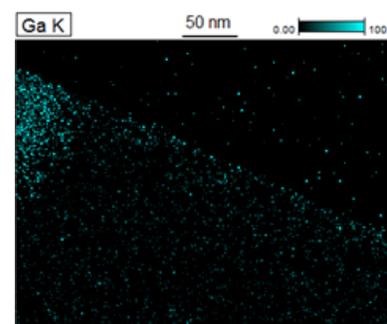
**FIB/STEM**



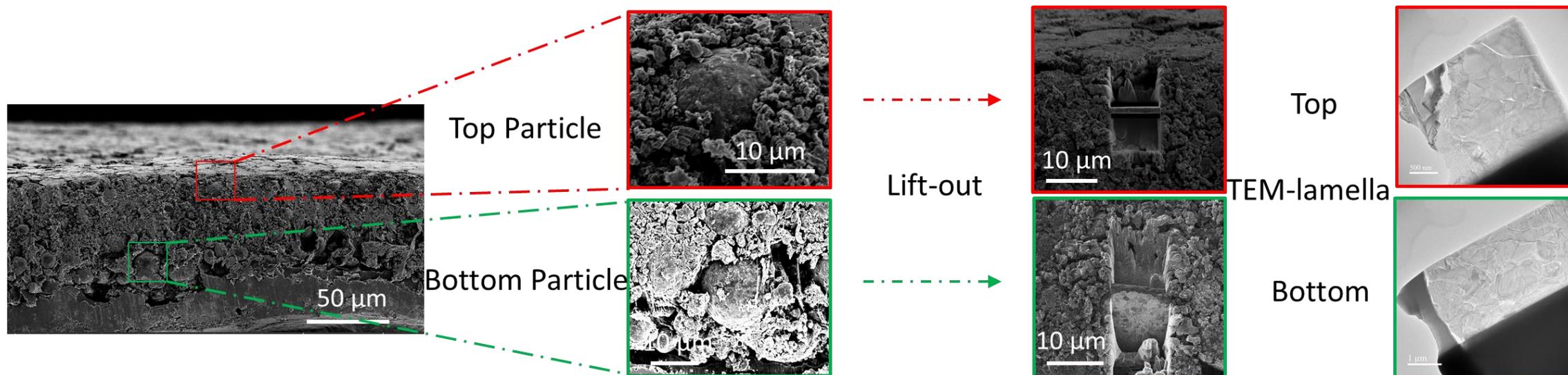
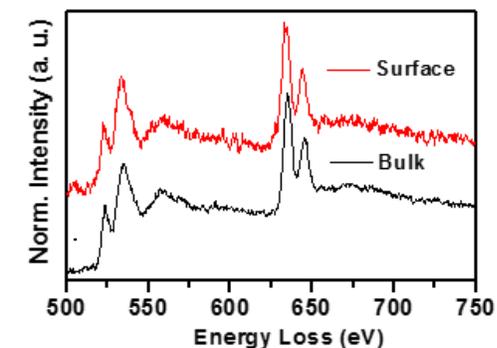
**STEM/HAADF**



**EDX**

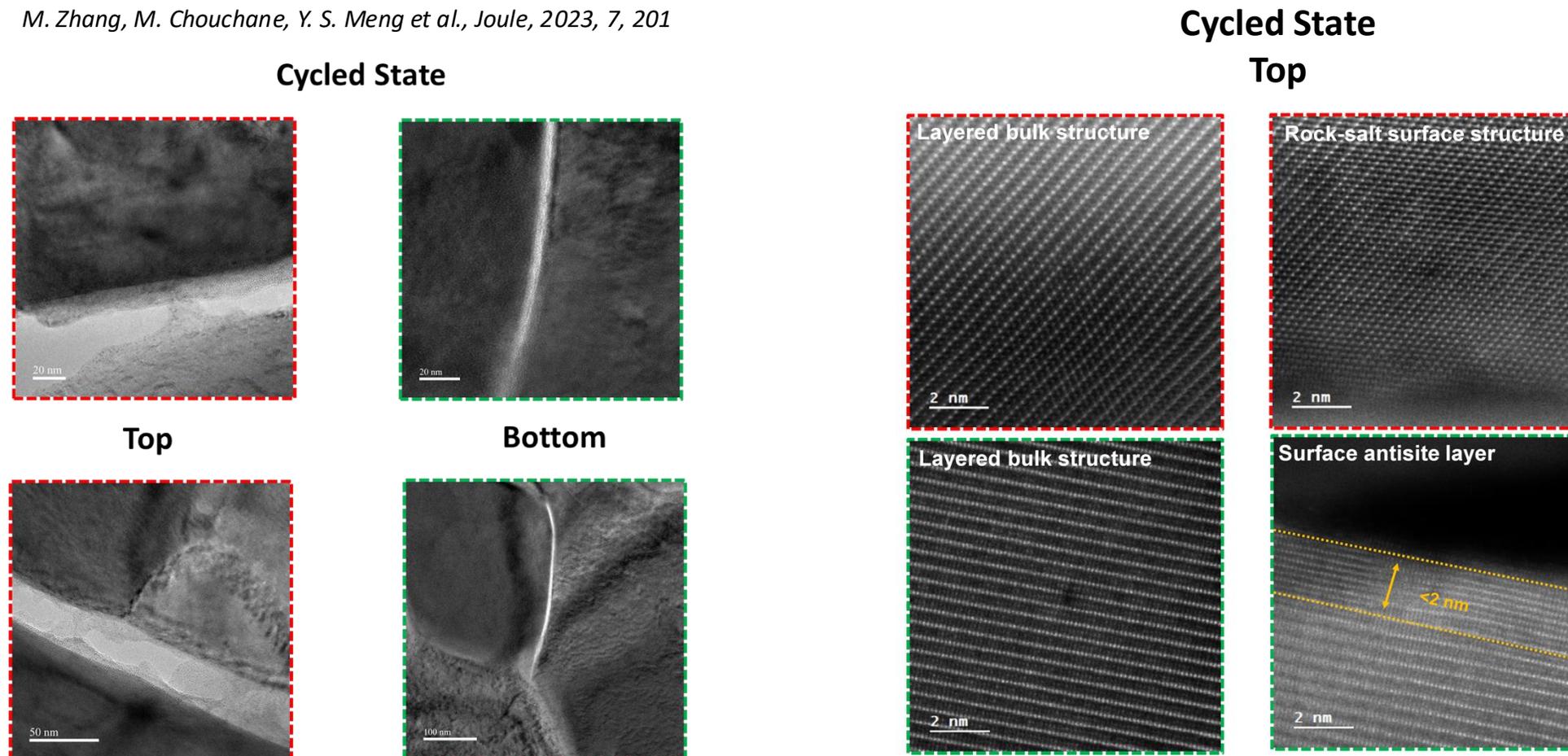


**EELS**



# Thick Electrode-Nanoscale Reaction Inhomogeneity

*M. Zhang, M. Chouchane, Y. S. Meng et al., Joule, 2023, 7, 201*

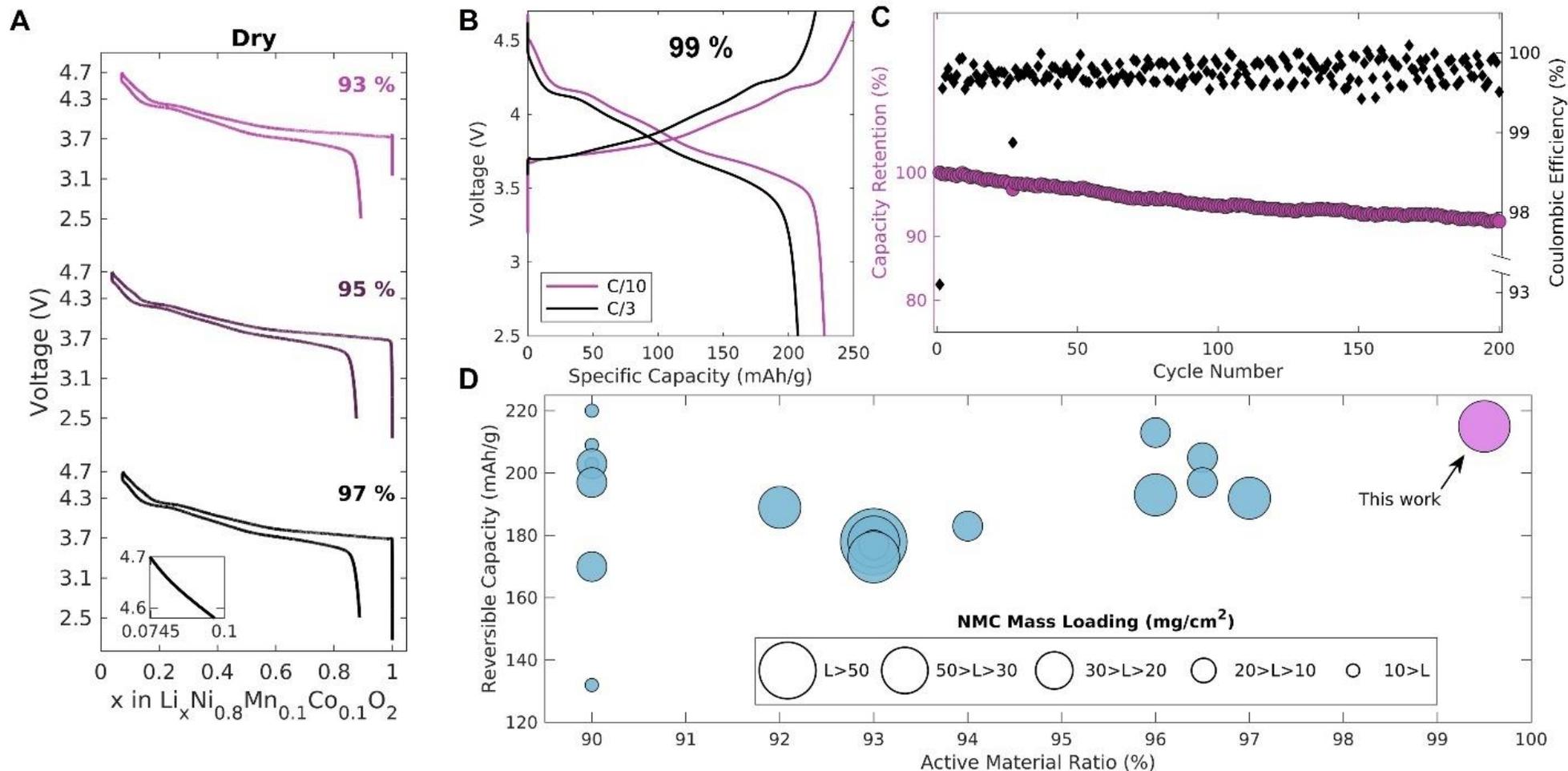


The particles lifted out from the top of the thick electrode (closer to the separator) have more corrosion on surface and uneven CEI growth.

**Cycled State**  
**Bottom**

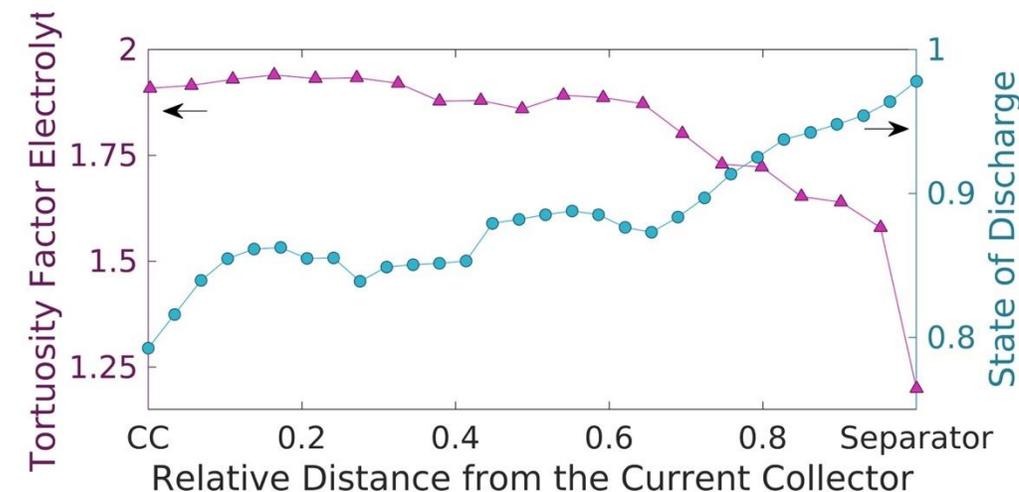
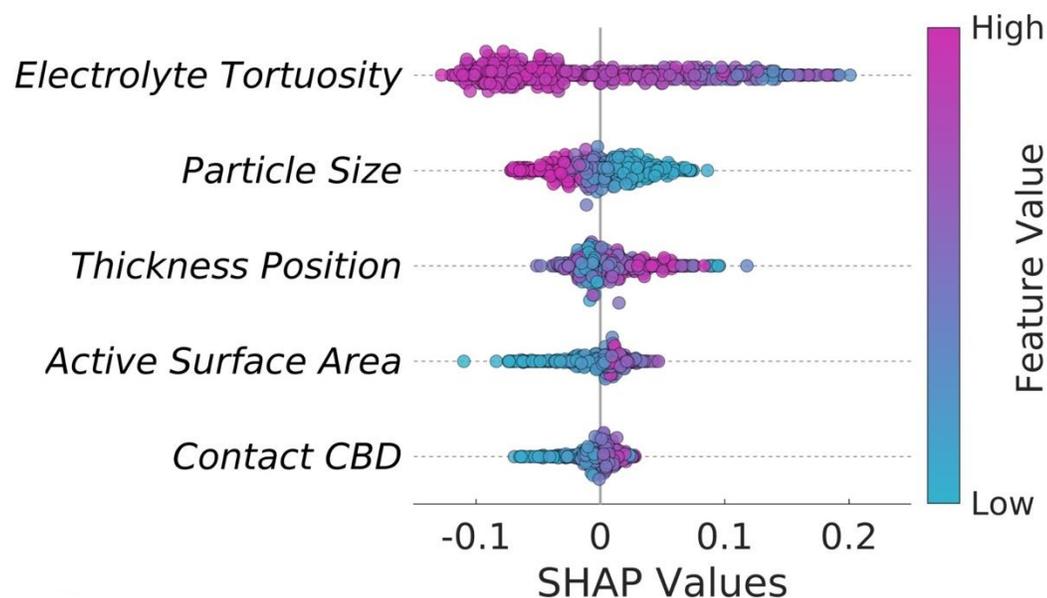
# Electrochemical Performance of Dry Thick Electrode

M. Zhang, Y. S. Meng\* et al., Nature Energy, 2025, under review



No overpotential is observed when increased the active material ratio over 99 wt% at the areal capacity loading of  $6 \text{ mAh}/\text{cm}^2$  level and it can cycle well at C/3-rate charging and discharging.

# Outlook for Dry Electrode Fast Charging: Tortuosity



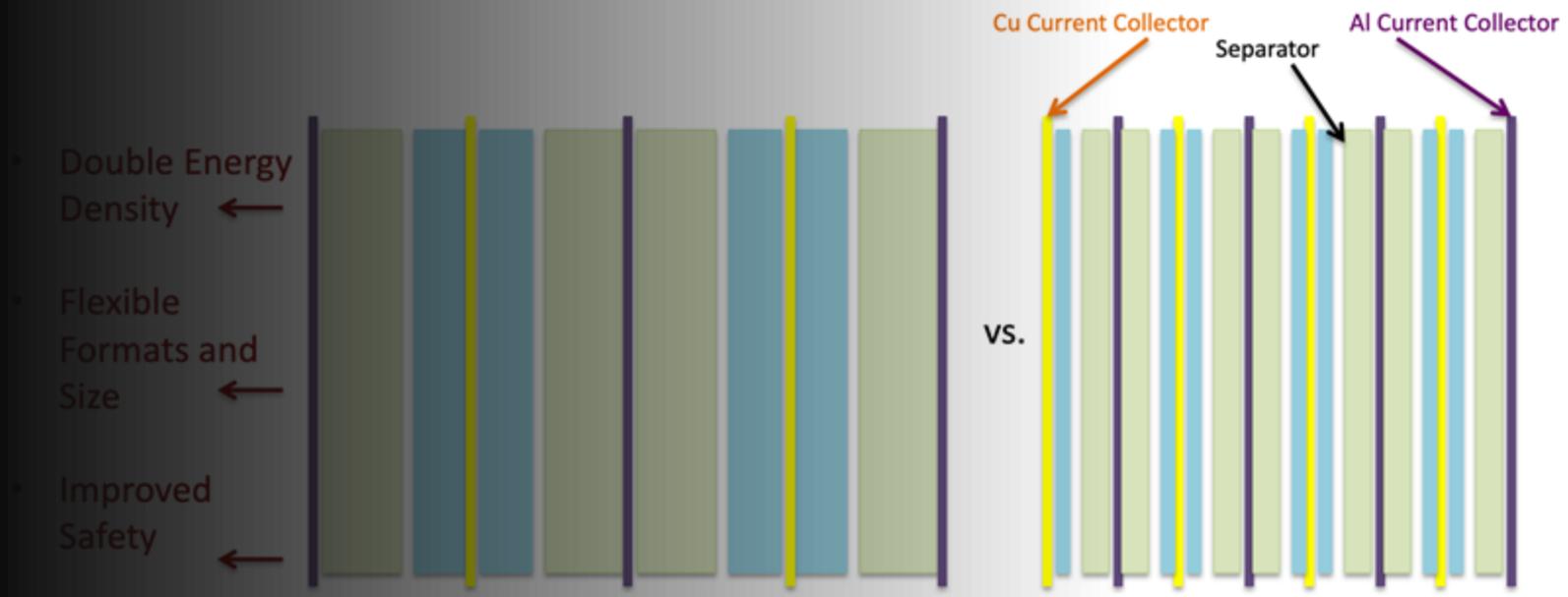
The study of the Shapley additive explanation (SHAP) values has been on the rise in the battery field. The strength of this approach is to identify for each input feature its impact on the SOD depending on its relative value.

The ionic transport through the electrolyte tortuosity is the feature with the highest range of SHAP values, with low tortuosity inducing a better NMC utilization.

My presentation  
to Maxwell  
Nov. 14, 2016

## Advantages of THICK Electrode in Li Ion Technology

MAXWELL CONFIDENTIAL

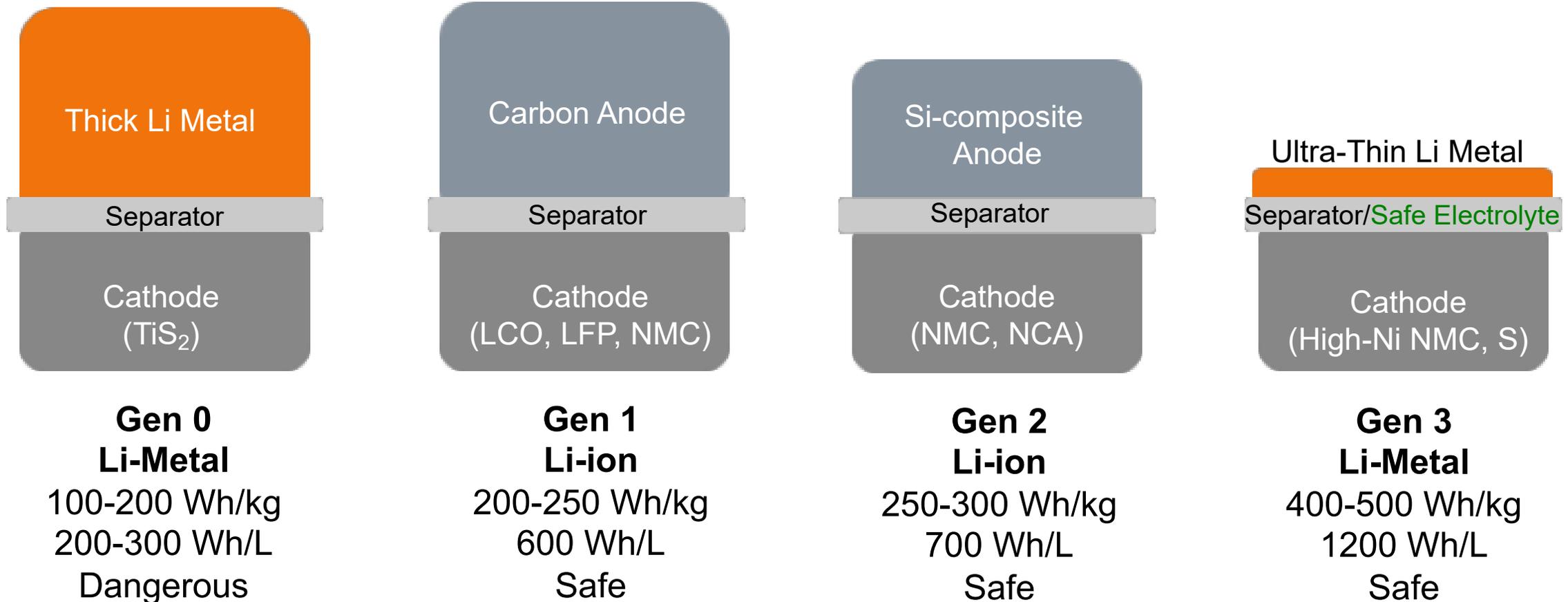


Dry Electrode  
Processing widely  
adopted 2024



# Li Metal Batteries and Battery500 Consortium

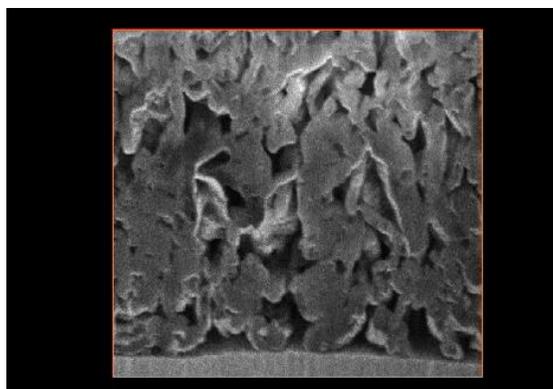
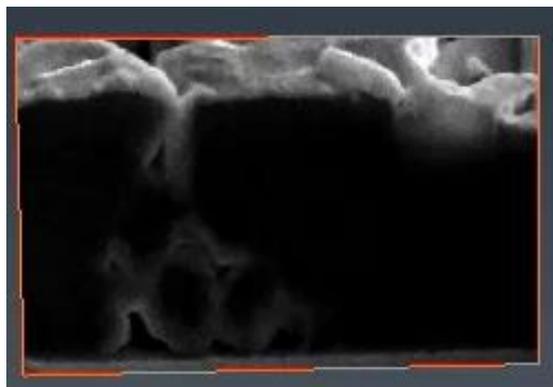
This will ENABLE 500MILES per charge of EVs



# Cryogenic Imaging of Reactive Metal

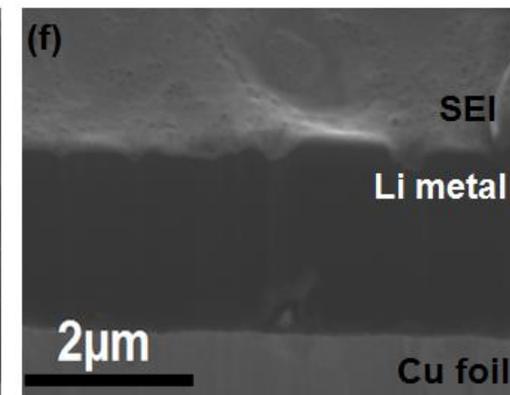
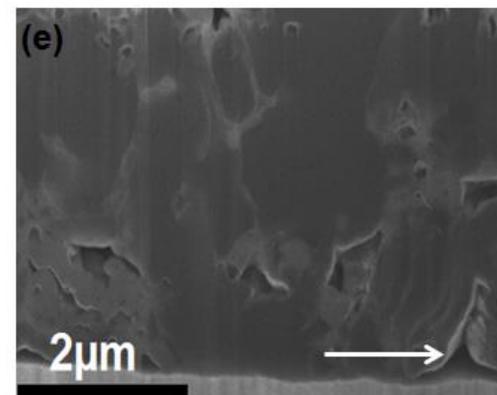
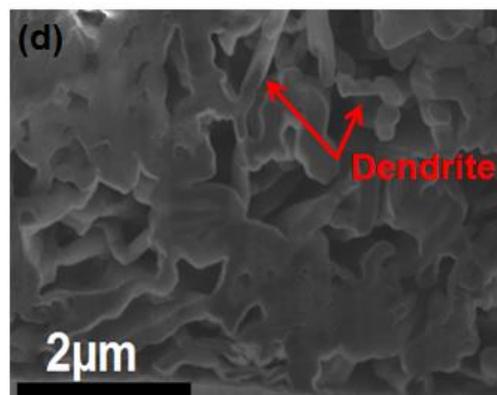
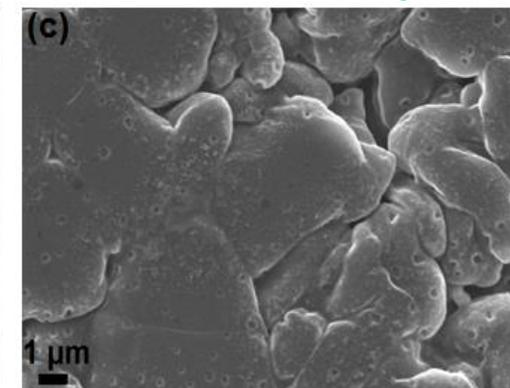
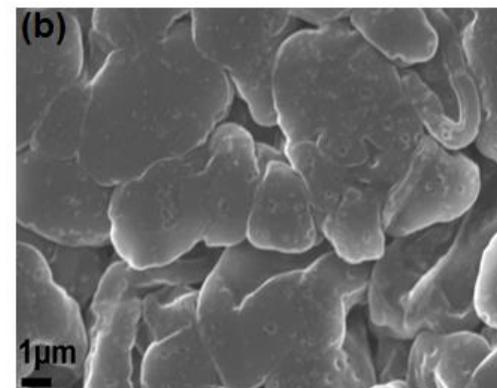
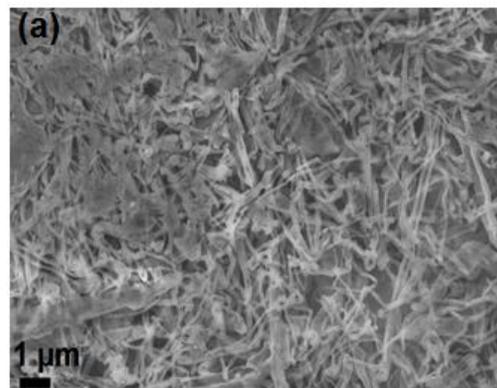
Lee et al., ACS Energy Lett. 2019, 4, 489–493

## Gen II



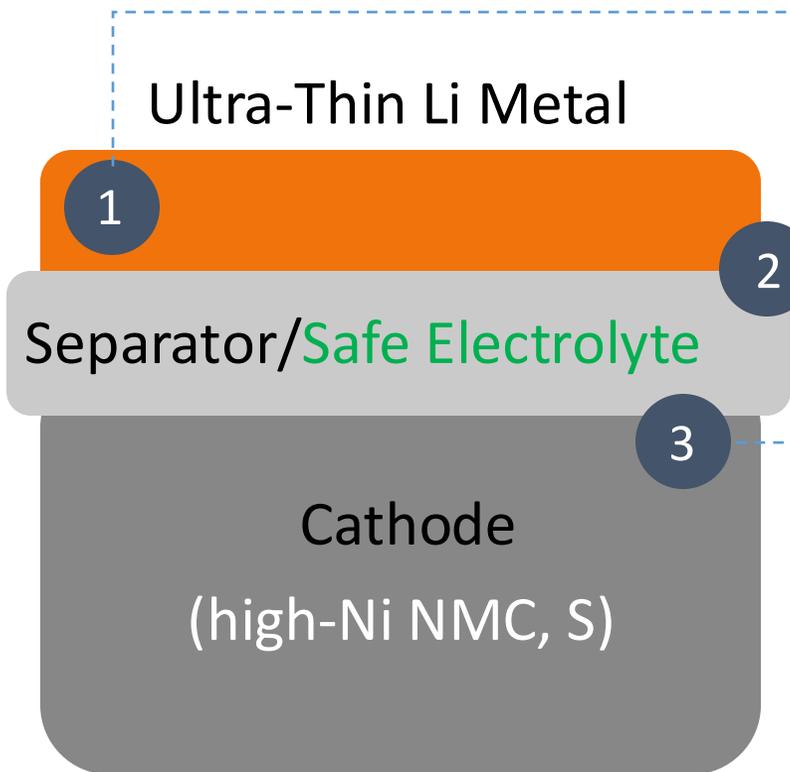
## New Salts

## New Electrolyte



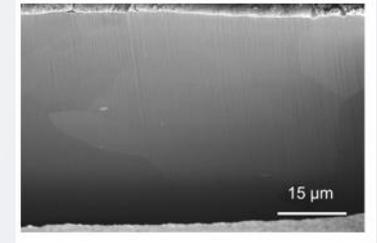
Breakthroughs in Electrolytes - Concentrated, Locally Coordinated, Non-carbonate  
**Coulombic Efficiency increases from 98% to 99.6%**

# Challenges in Imaging and Analysis of Li-Metal Battery



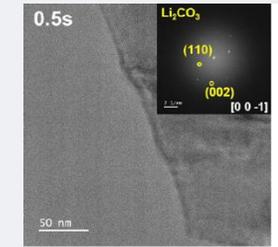
## Lithium Metal: SEM, FIB-SEM, and TEM

- Morphology
- Composition
- Crystallographic



## SEI and CEI: TEM

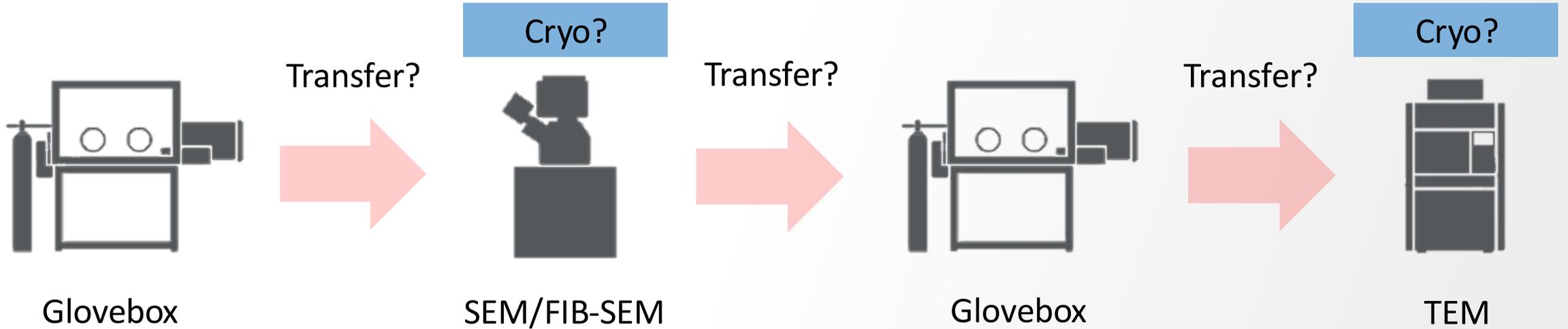
- Morphology
- Composition
- Distribution



## Imaging and Analysis Challenge

- How to preserve the native state with external probe impacts
  - Environmental impact – sample handling
  - Electron/ion beam and matter interaction

# The Journey: from Glovebox to Atomic Imaging



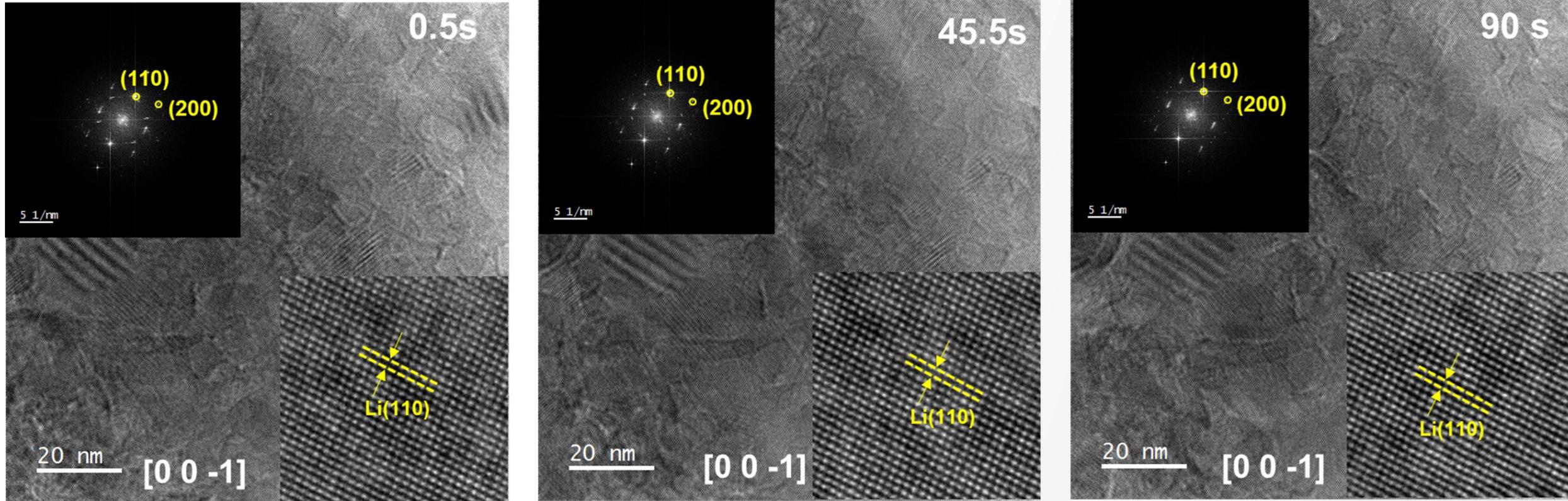
\* Only sample in dry-state is considered

## Current practice in the field

- Standardized protocols for sample transfer are still absent.
- Cryo-FIB and cryo-TEM are increasingly being applied for the characterization of Li-metal battery samples.
- Beam interaction with materials is not well controlled if characterization is implemented under cryogenic temperature.

# First Room Temperature Imaging of Lithium Metal

Commercial Li metal at RT @  $\sim 10000 \text{ e A}^{-2}\text{s}^{-1}$



- Atomic characterization of Lithium metal can be achieved at room temperature in TEM



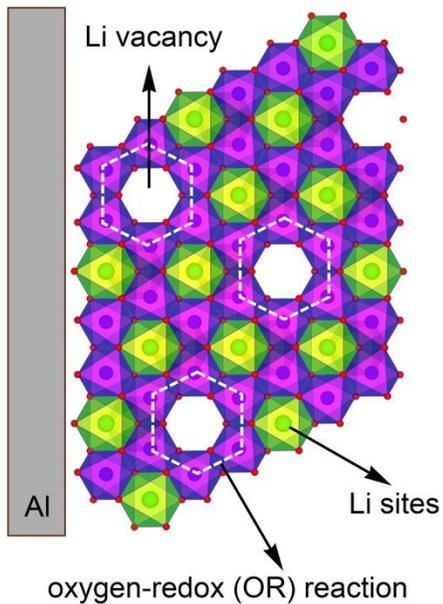
# Lithium Metal (Thin Foil or Anode Free) – “Holy Grail”

Collaboration with Dr. Bao Qiu and Dr. Zhaoping Liu (NIMTE)

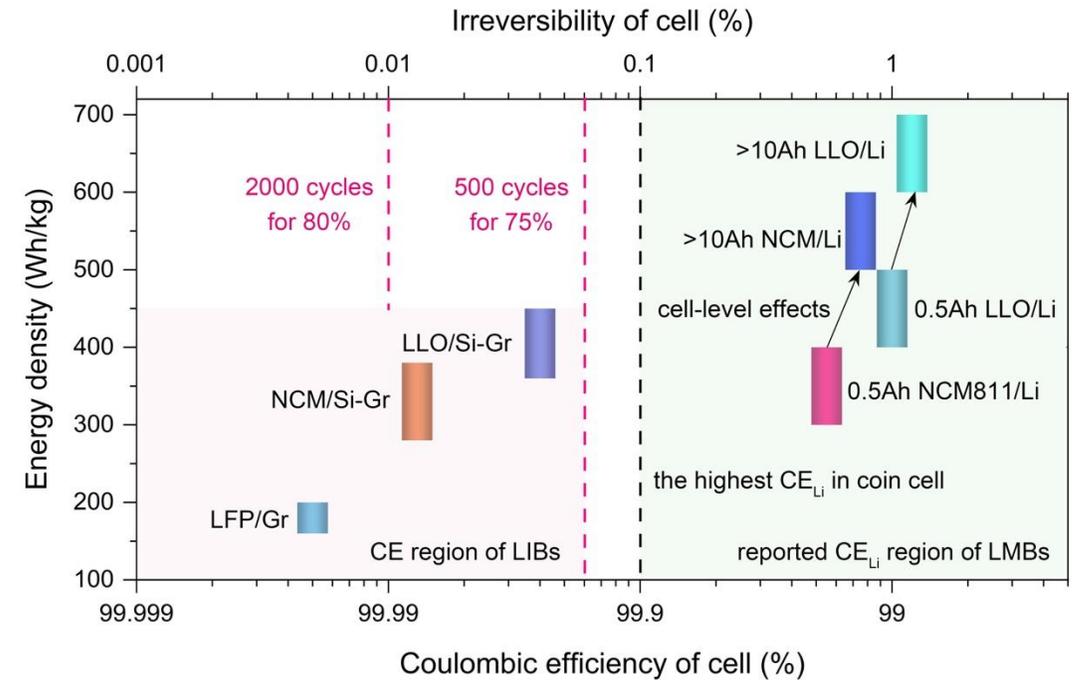
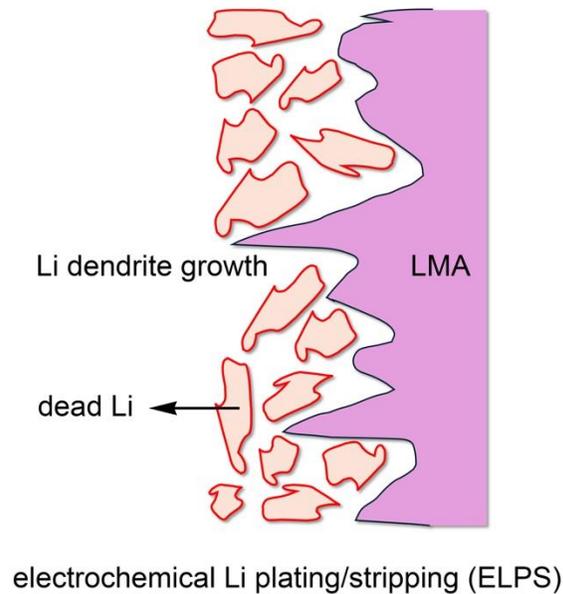
- ◆ Li-rich layer oxide cathode is the promising layer oxide cathode for lithium metal battery beyond 600Wh kg<sup>-1</sup>
- ◆ the huge Coulombic efficiency gap between current lithium metal anode and the target

lithium metal battery beyond 600 Wh/kg

Li-rich layer oxide (LLO) cathode



lithium metal anode (LMA)



How can we achieve the Coulombic efficiency of Li > 99.90%?

# Possible to Invent More Electrolytes to Enable Metal

Aradoc

DispatchDate: 22.09.2021 · ProofNo: 910, p.1

nature  
energy

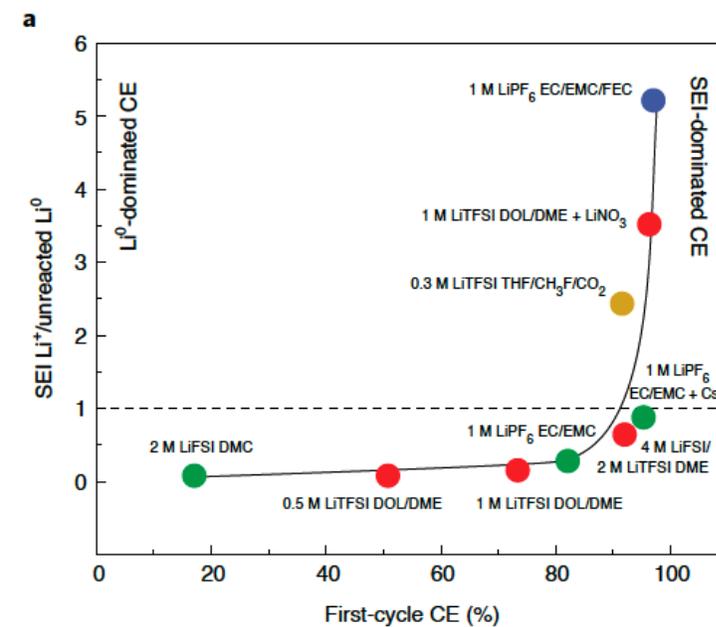
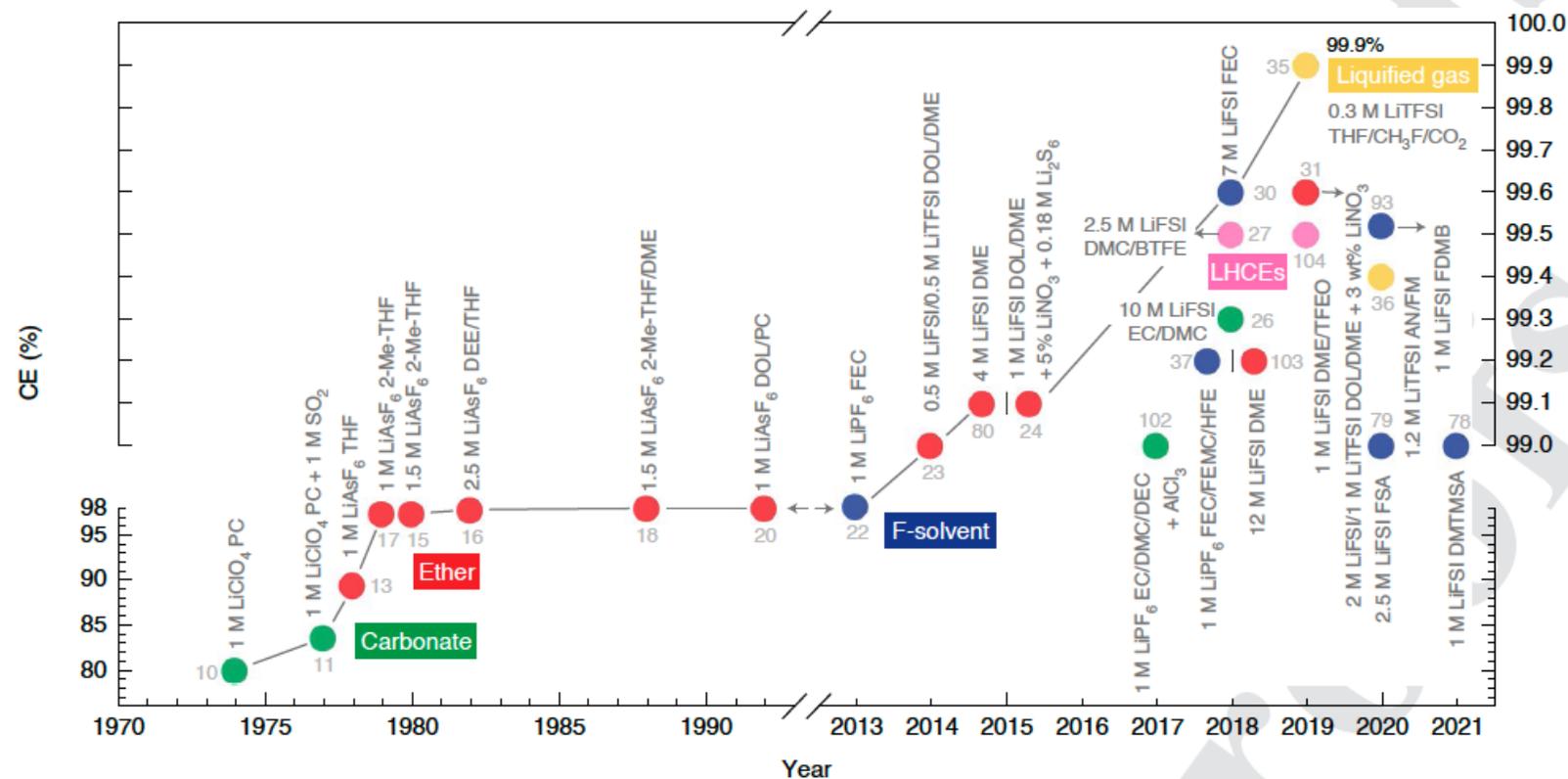
REVIEW ARTICLE

<https://doi.org/10.1038/s41560-021-00910-w>

Check for updates

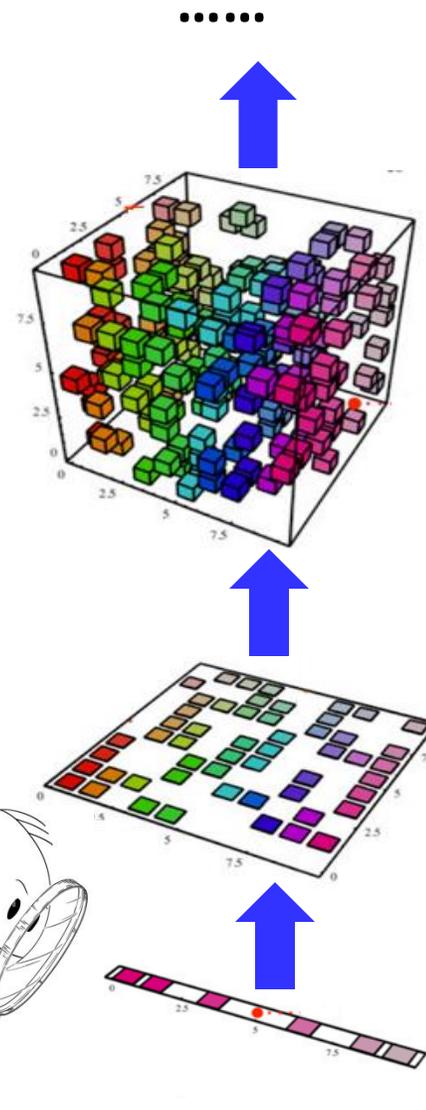
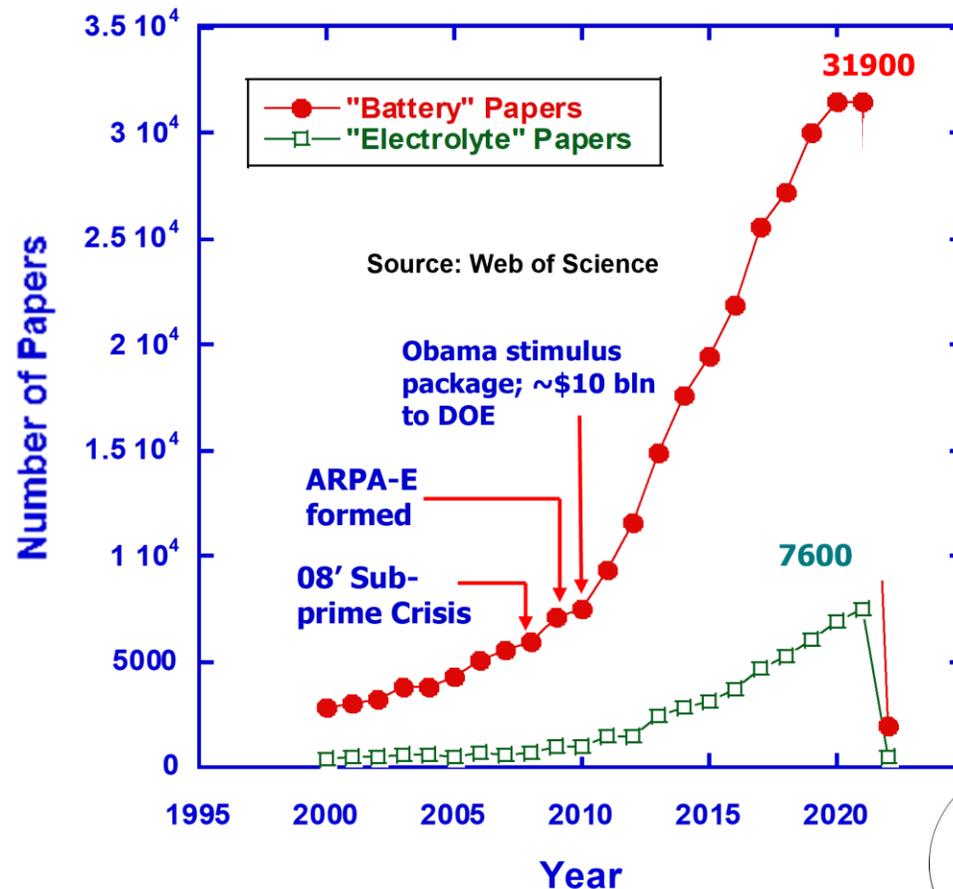
Collaboration with  
Prof. Betar Gallant and Yang Shao-Horn

## Moving beyond 99.9% Coulombic efficiency for lithium anodes in liquid electrolytes



# Electrolyte Literature – A New Barrier for New Discovery?

- Battery research has been “hot” since 2010
- In **2021**, around **650** battery papers published per week
  - ~150 papers on “battery electrolyte”
- Not a single individual can follow the literature
- Let alone understanding in-depth, or identifying patterns/relations underneath the text



Make Contact  
with the Molecular  
Universe.



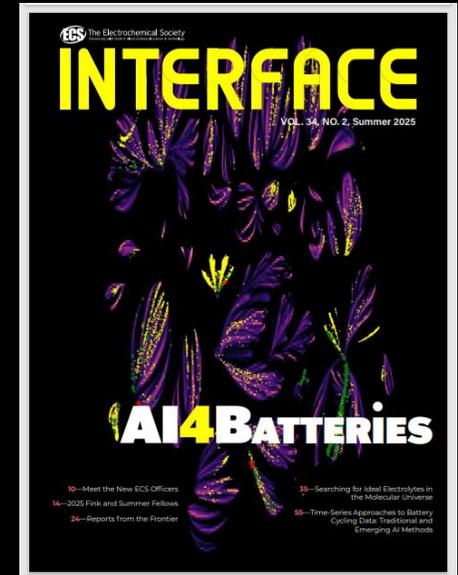
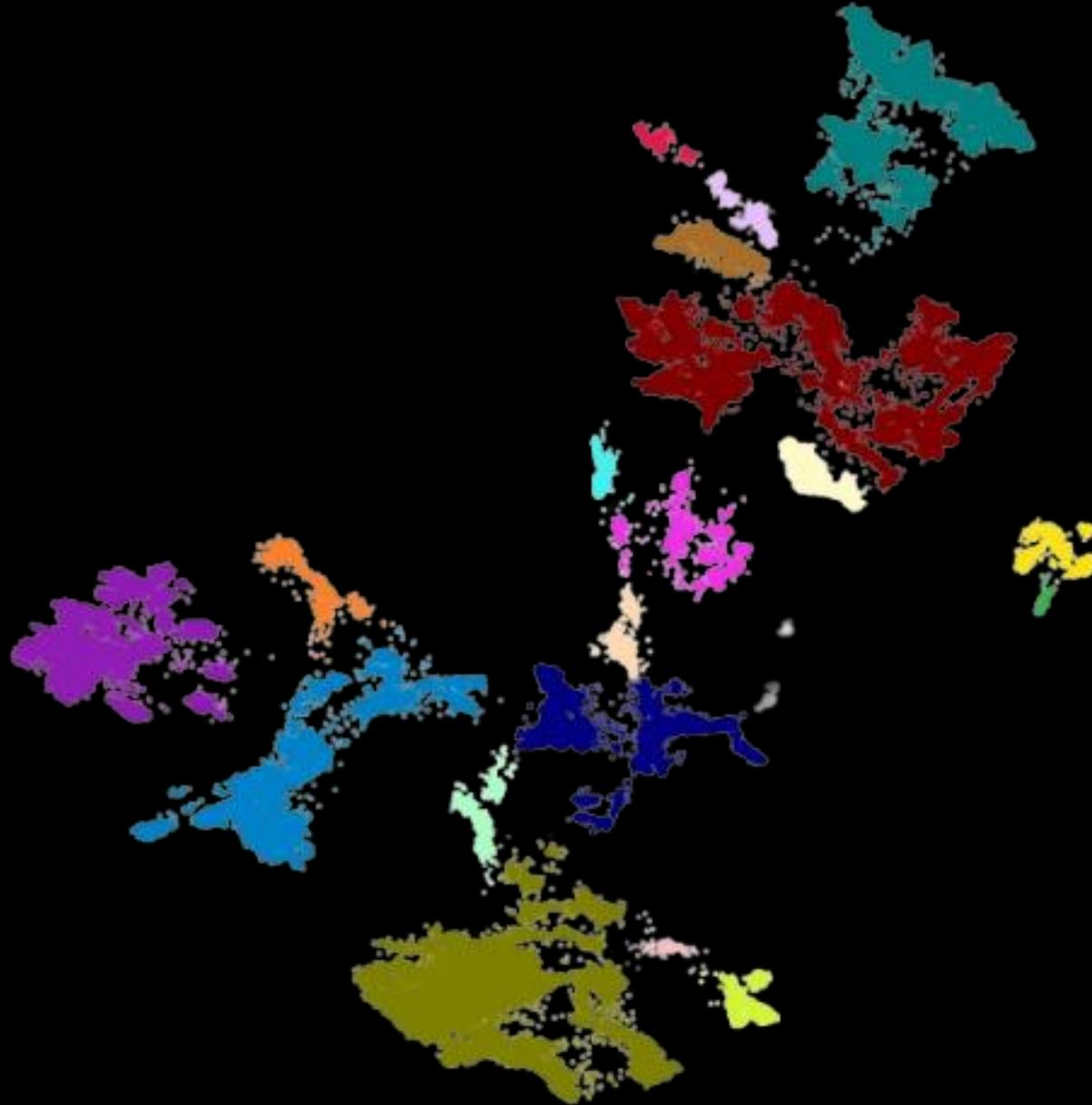
# Molecular Universe: World's 1<sup>st</sup> AI Platform for Battery Materials

## Databases

- $10^{12}$  Exhaustive structures
- $10^8$  DFT properties
- $10^7$  Articles
- $10^4$  Patents
- $10^2$  Books
- $10^4$  Cell performances

## Tools

- Battery-domain LLMs
- Multi-agent systems
- Battery-domain RAG
- ML models

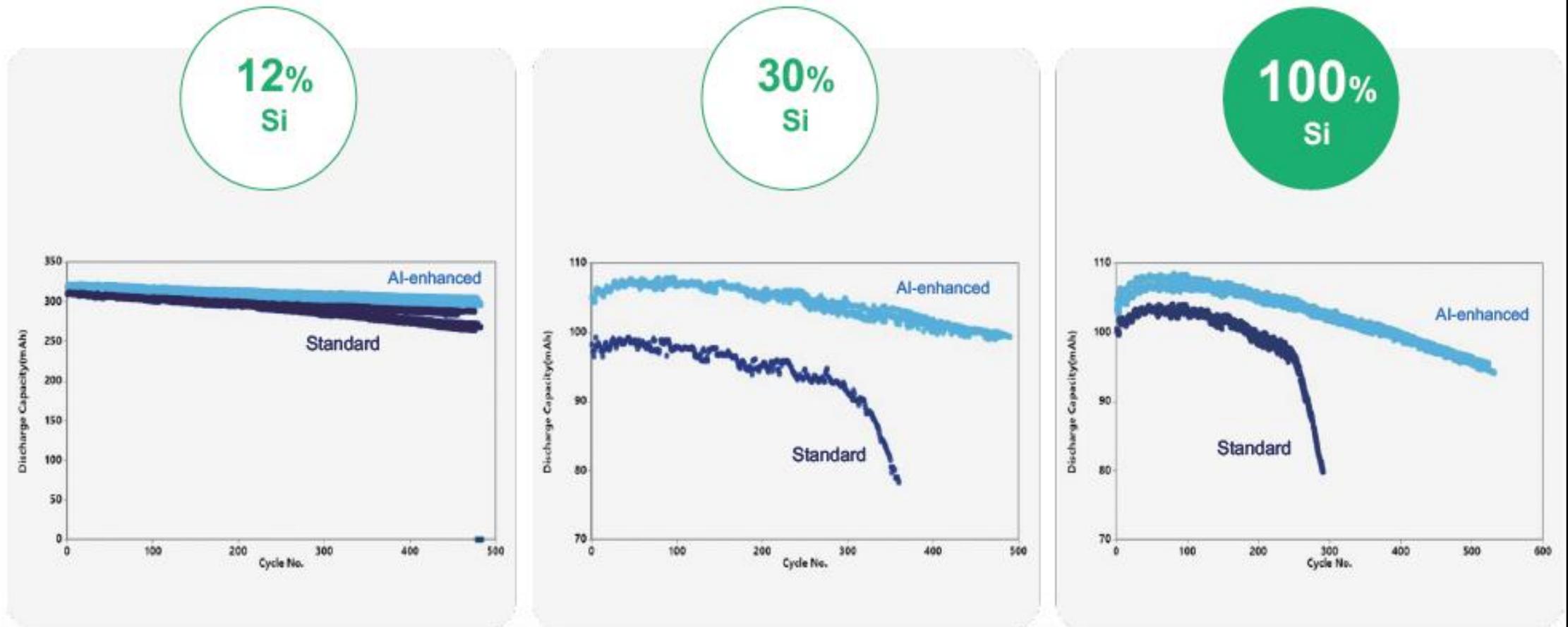


**ECS Interface  
2025 Summer Issue**

# Success Examples in Real World

- >20 AI-discovered electrolytes made and tested
- 4 very successful (IP application)

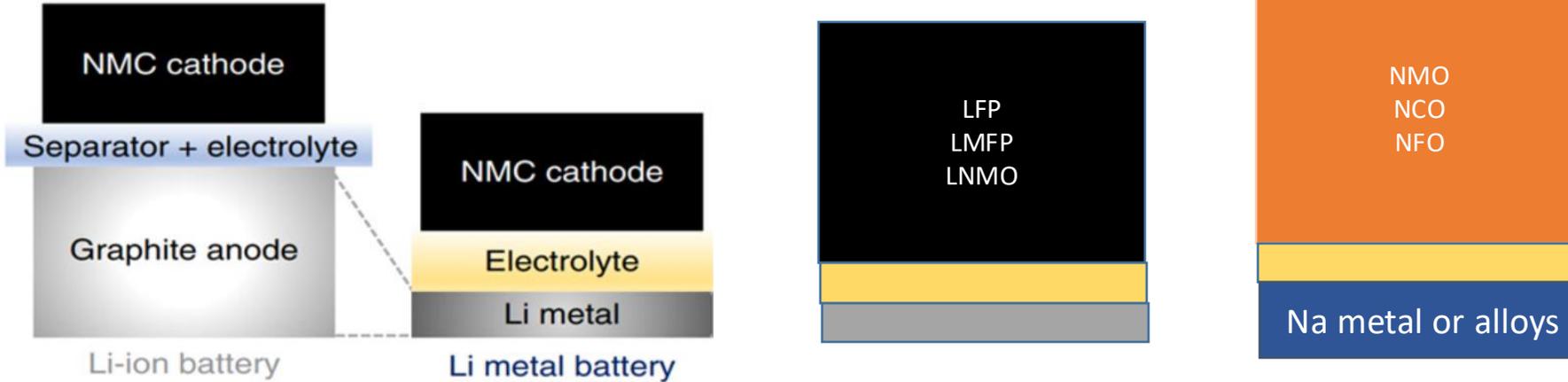
Improved 100% Si LIB cycle-life by 100+%



# All Solid-State Batteries – Platform Technology

## High-Energy-Density and Safe Batteries

### with Solid-State Electrolyte



**Energy Density > 500Wh/kg**

Conversion type Cathodes

Metal Anodes

Ultra Thin Separator

### Safety

Particularly for Oxides Sulfides ?

Polymers X

**Fluorine - Free Chemistry**

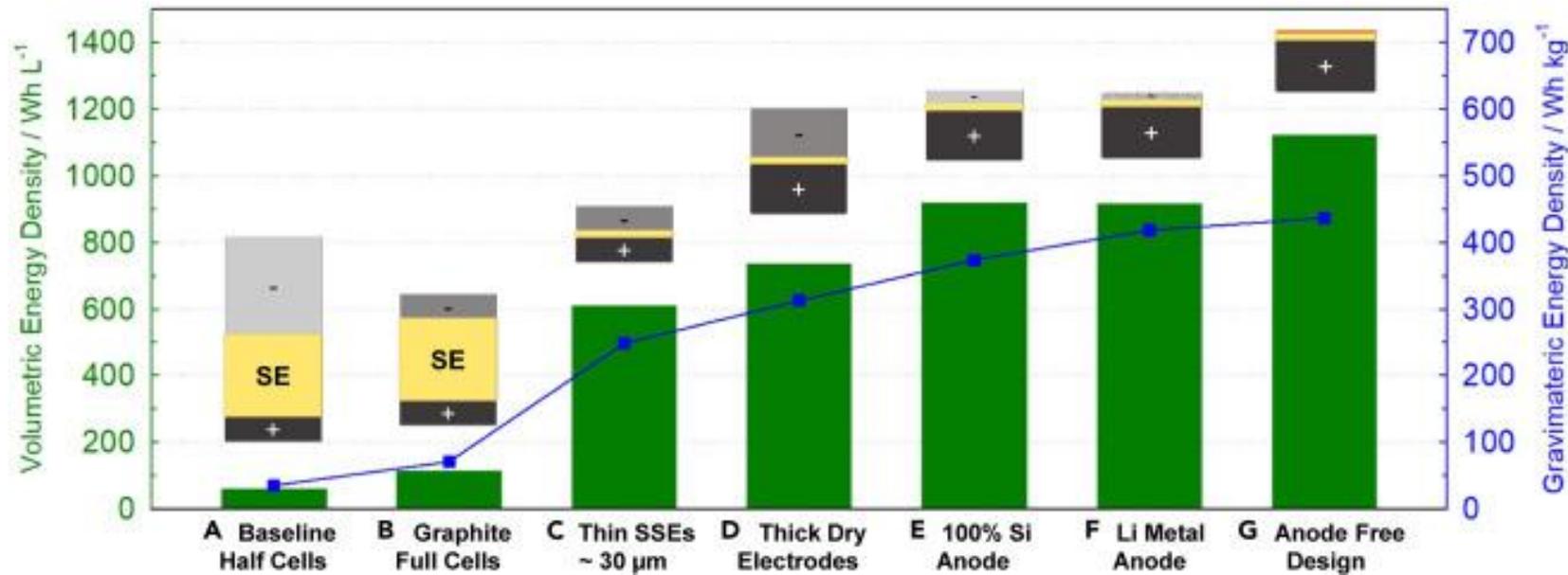
**Stackable Design**

**Dry Processing**

**Ultralong Cycle Life**

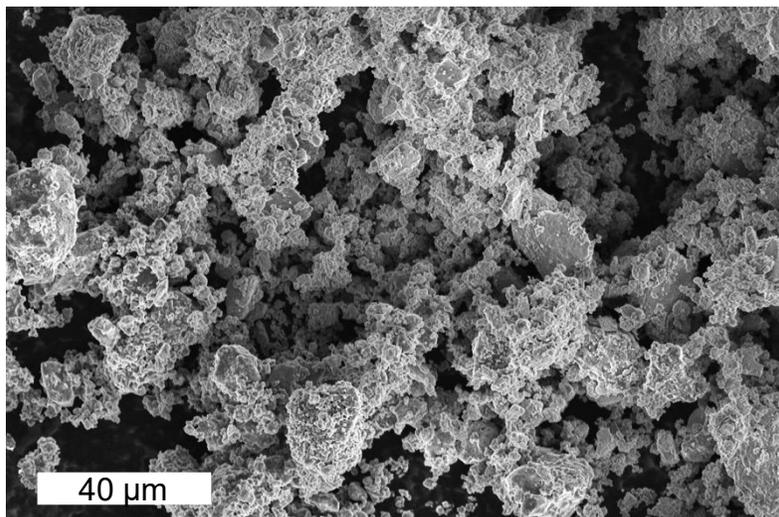
**Wider Operation Temperature**

**Enable Conversion Chemistry**

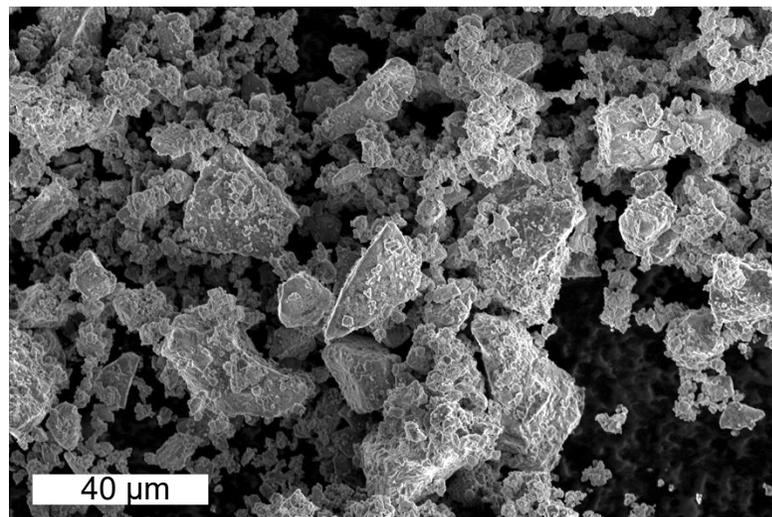


# Why do We Choose $\text{Li}_6\text{PS}_5\text{Cl}$ – Metric Ton Quantity

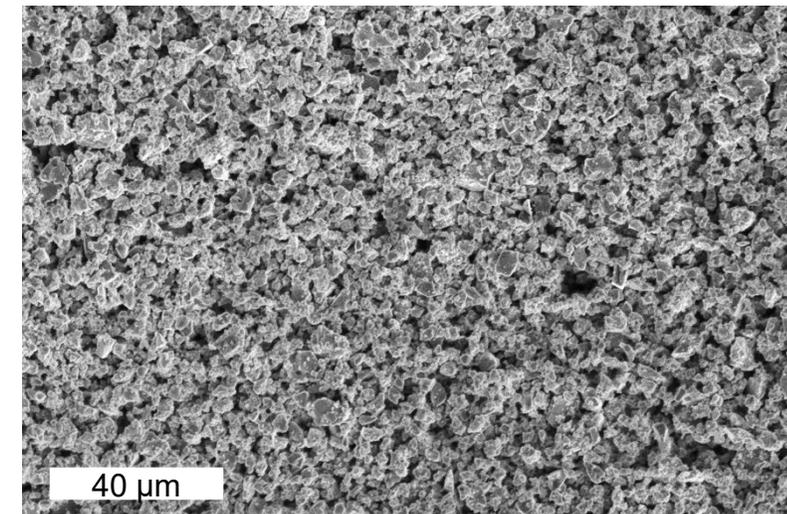
USA Supplier 1:



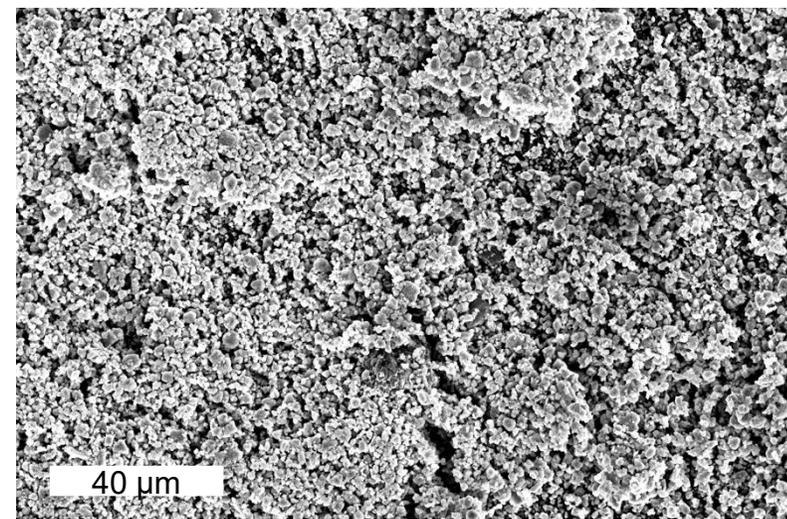
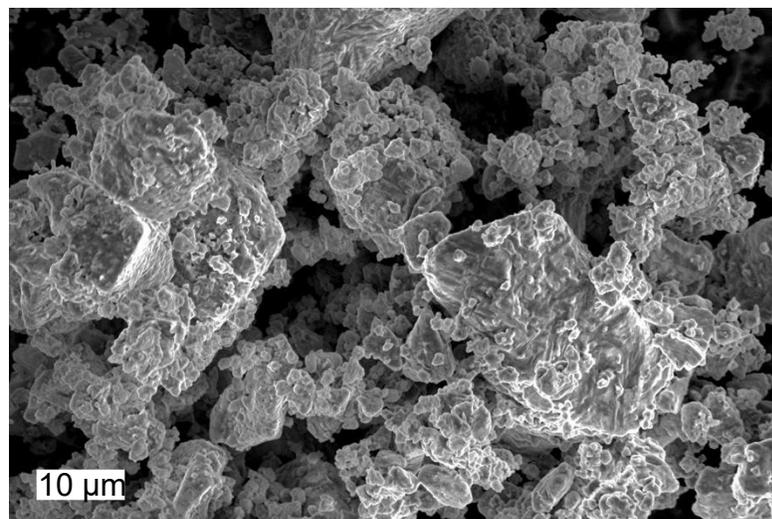
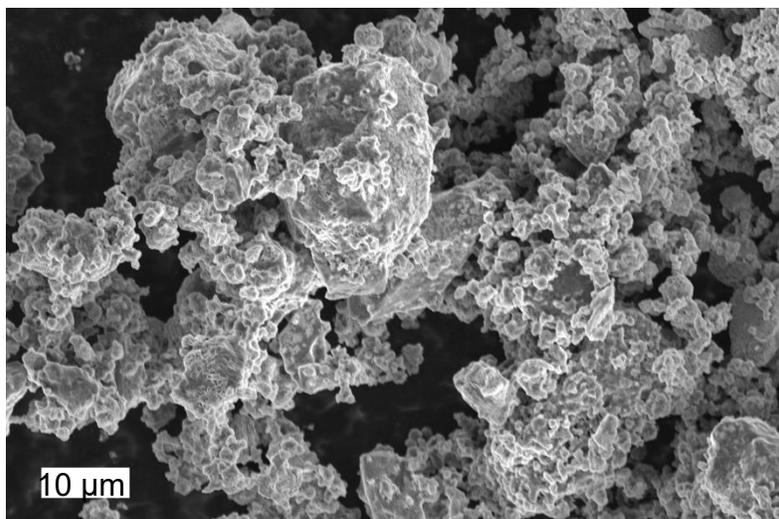
USA Supplier 2:



Japan Supplier 1



(A)

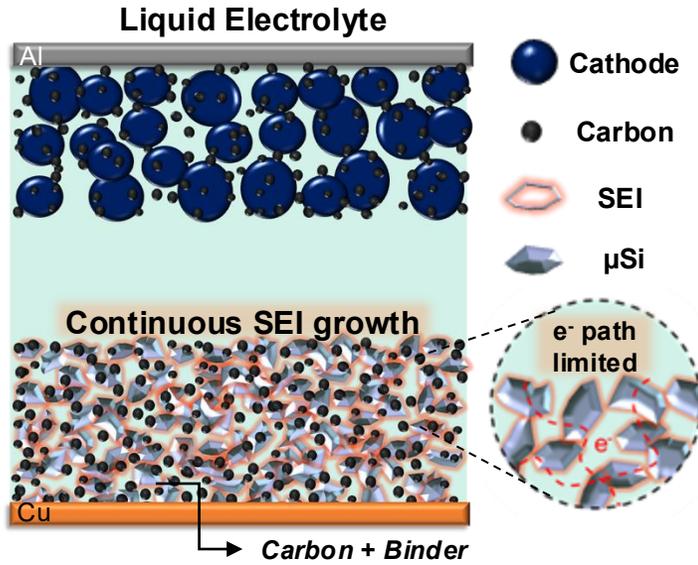


(B)

# All Solid-State Battery with Pure Si Anode

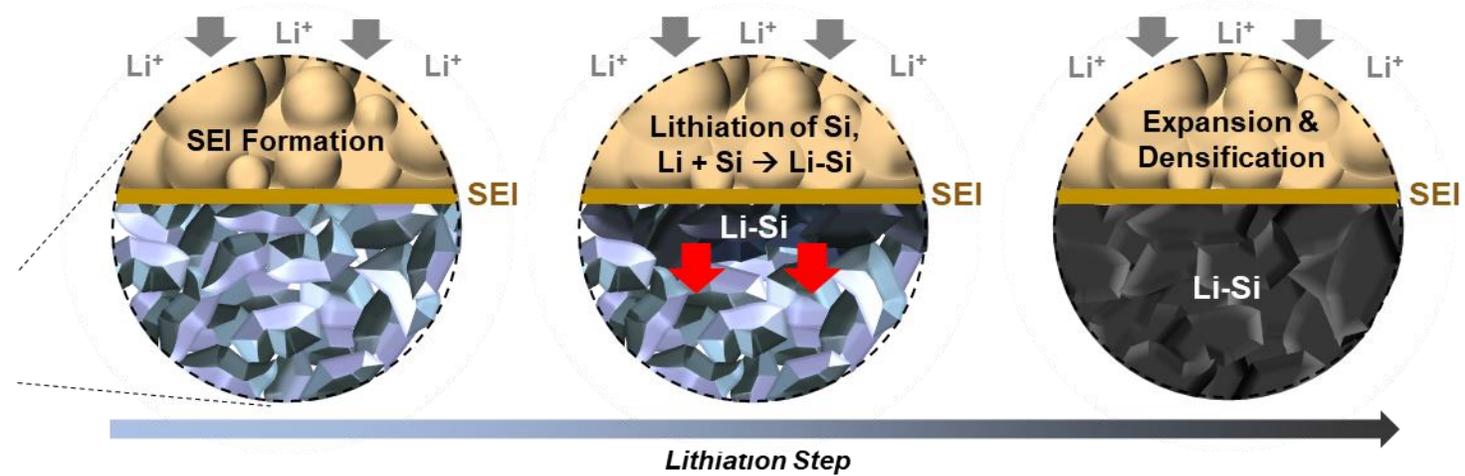
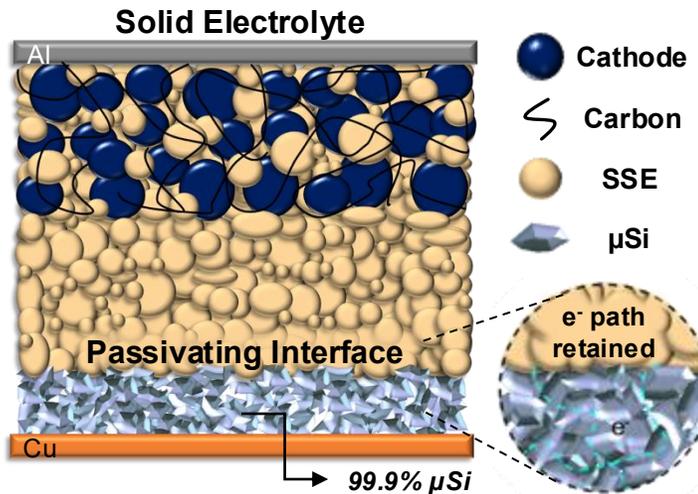
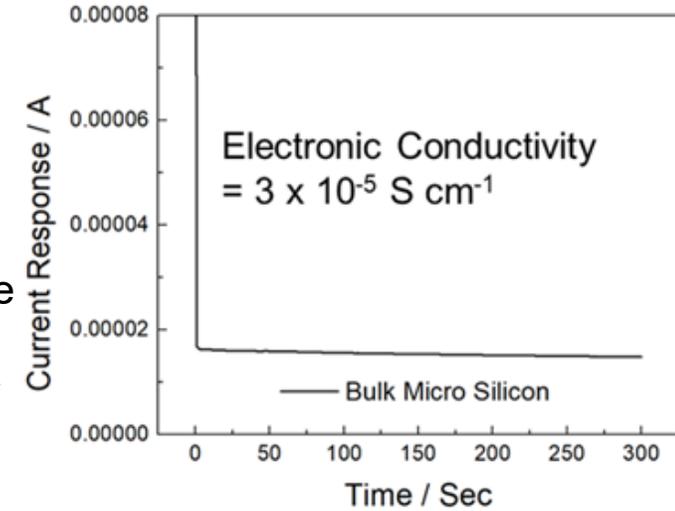


Dr. Darren Tan  
CEO of UNIGRID

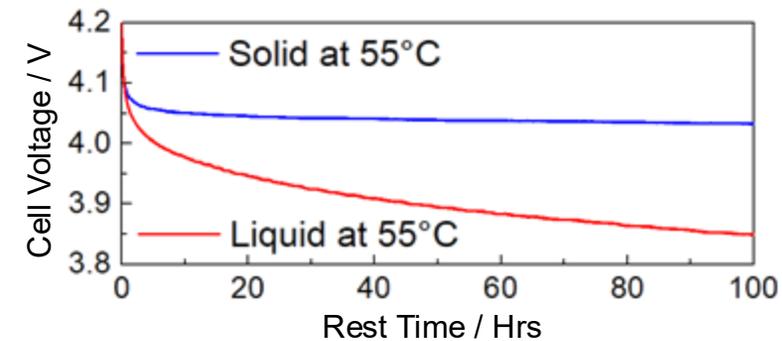
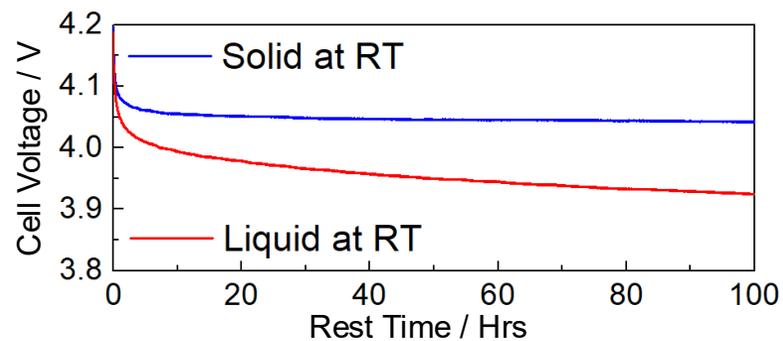
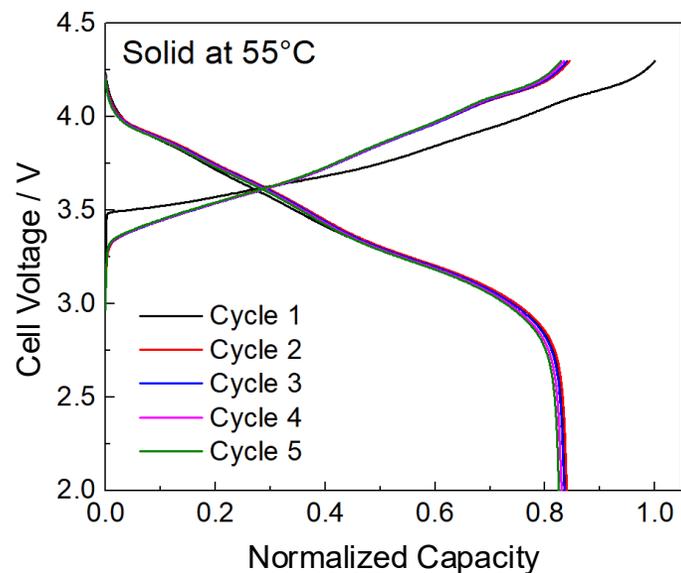
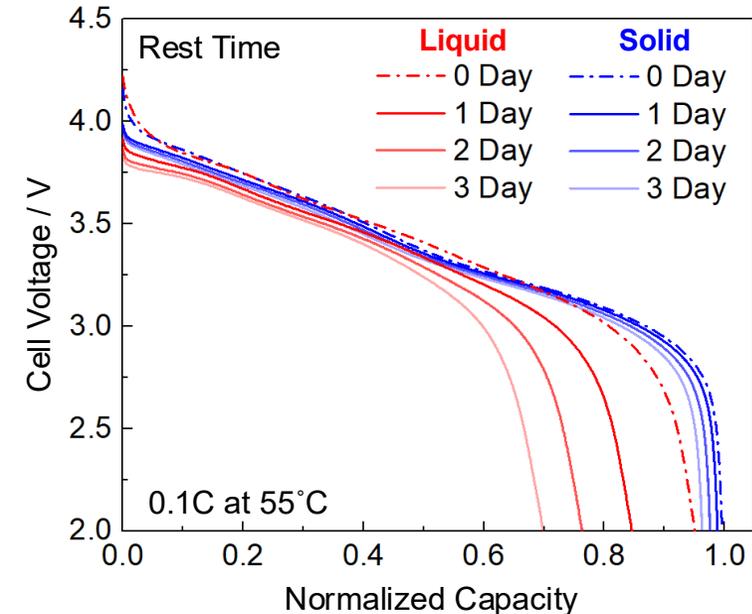
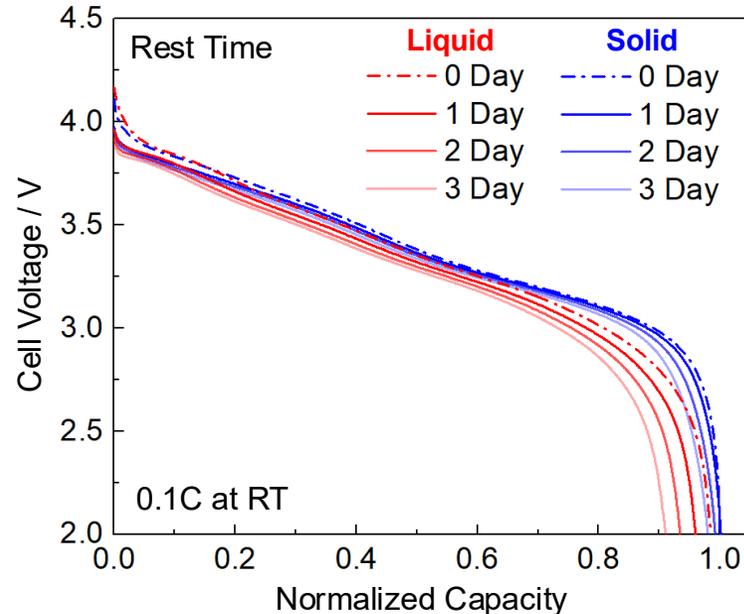
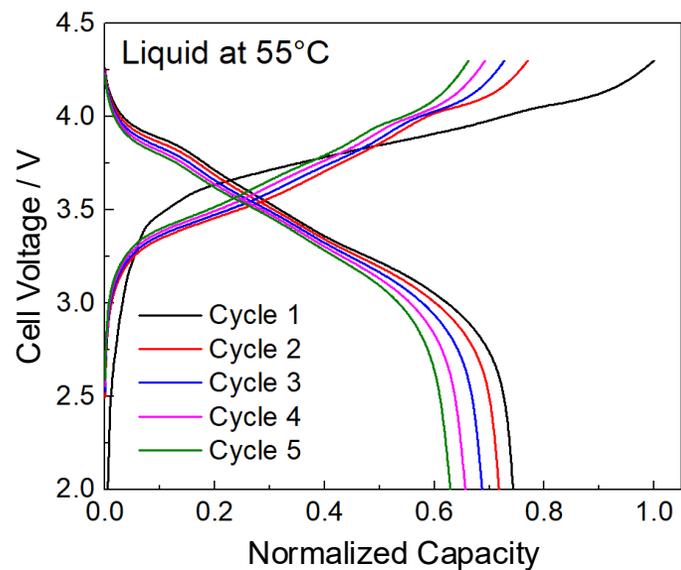


## Silicon in Liquid

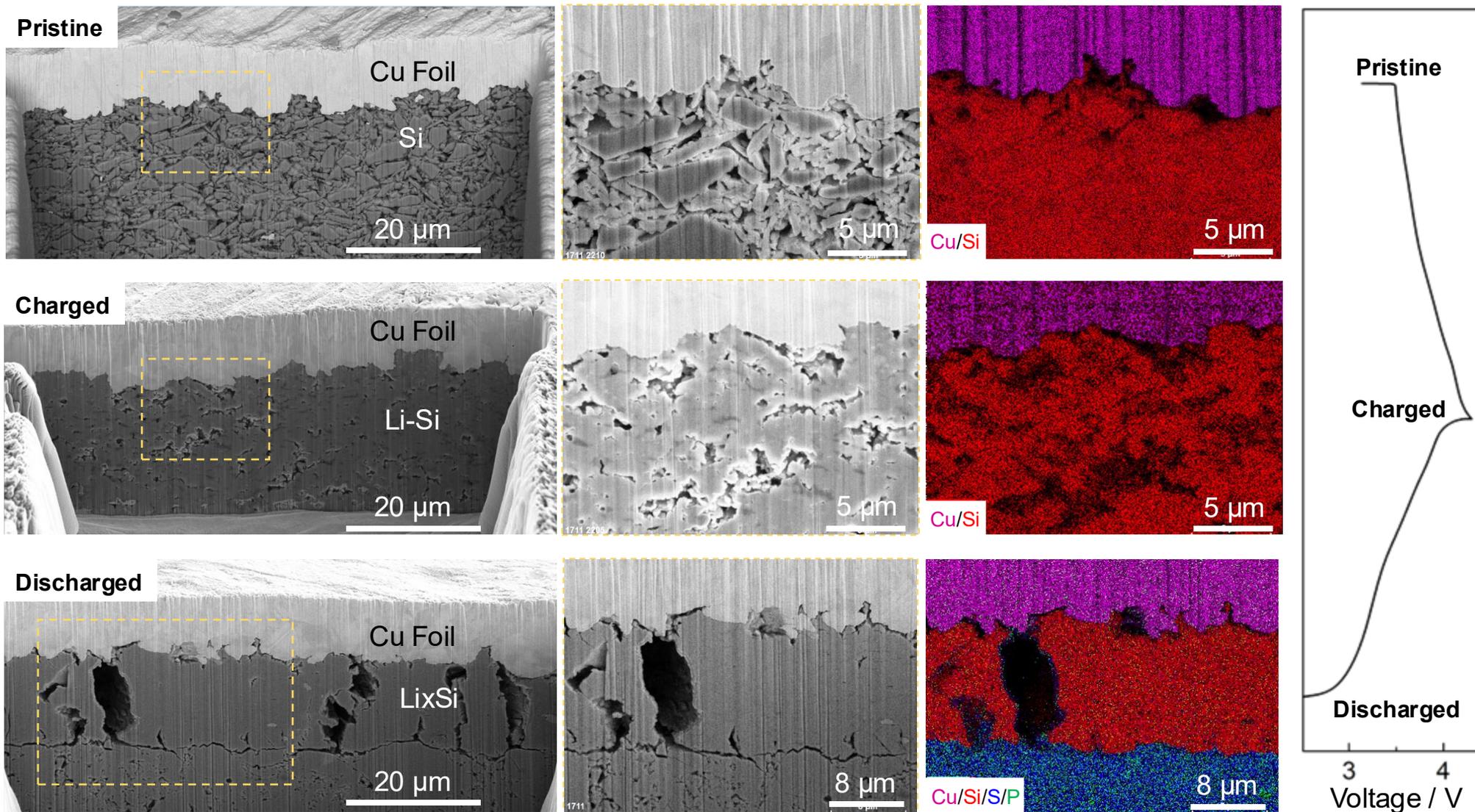
- Continuous SEI Growth
  - Trapped Li-Si accumulation
  - Poor calendar life / self discharge
- Excess carbon + binder (20-40%)
  - Poor specific / volumetric energy



# Passivating Interfaces – Self Discharge Rates

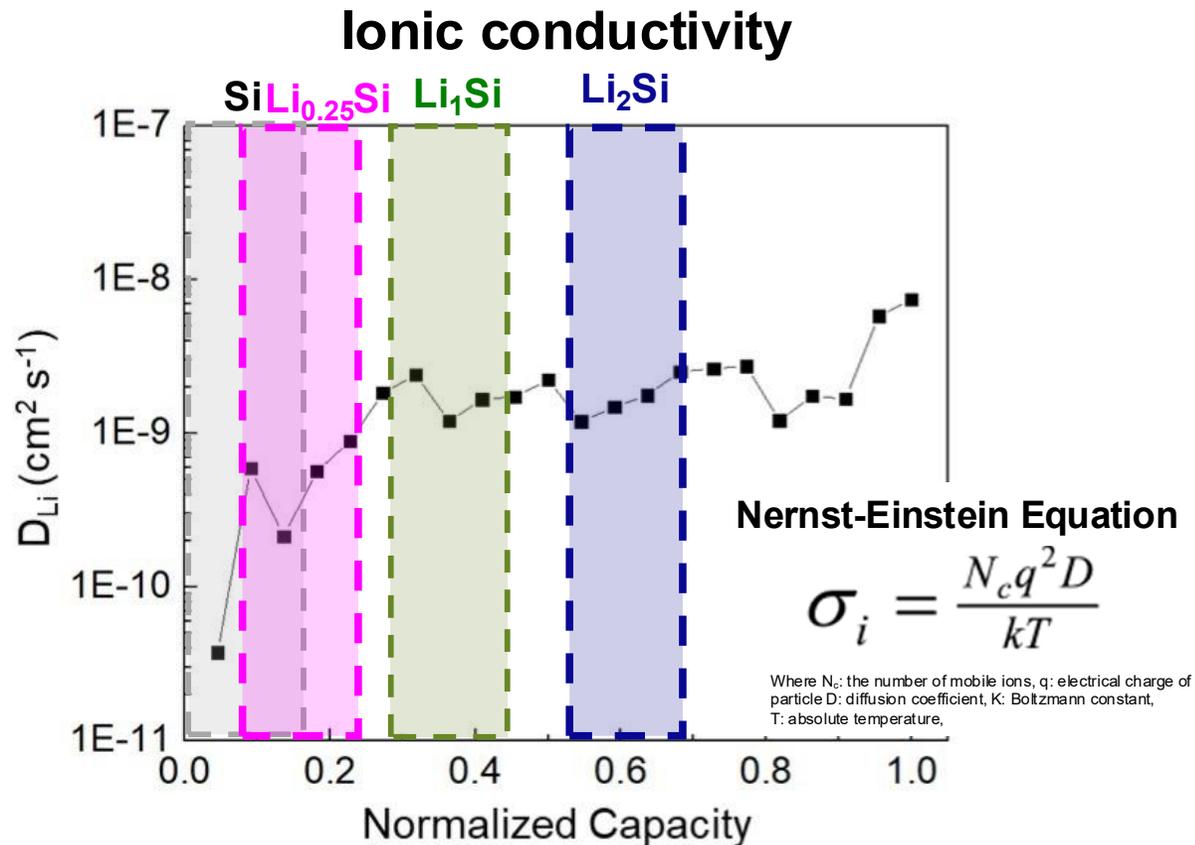
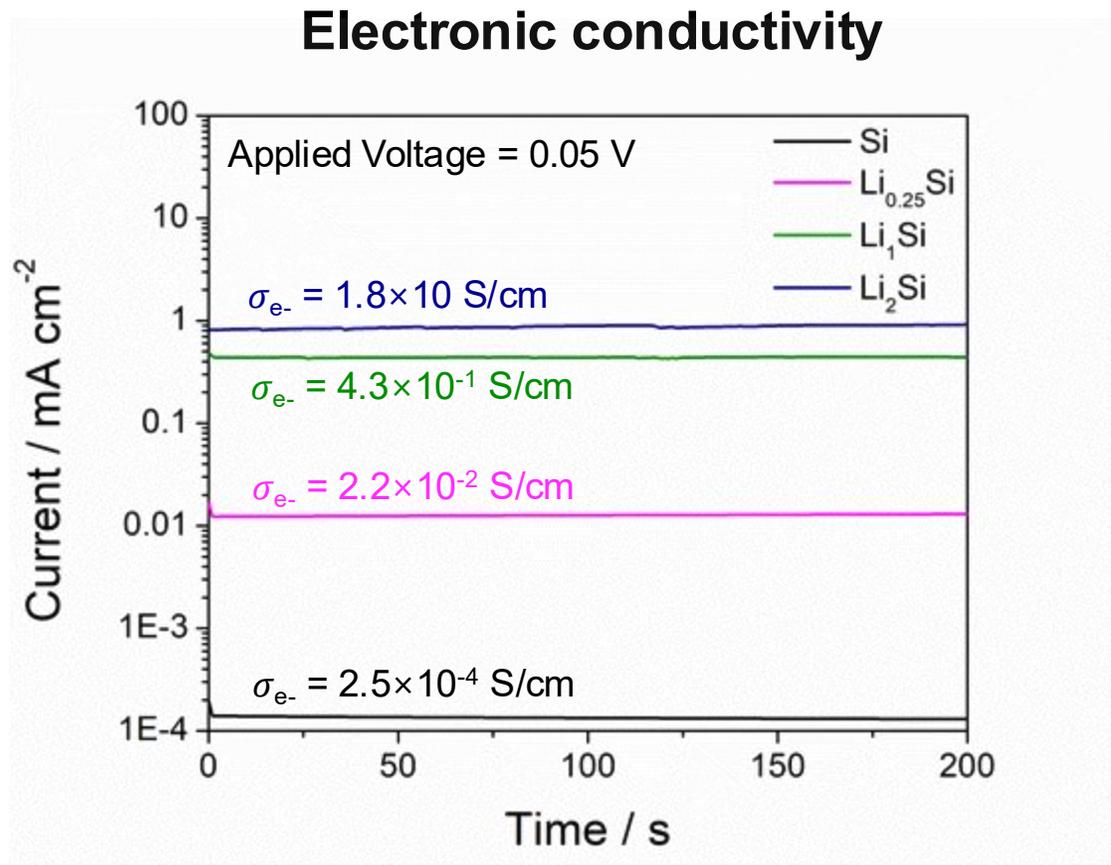


# Si anode morphology changes



# Physical Properties of Pure Si and $\text{Li}_x\text{Si}$

Ham et al., Nature Communications, (2024)



- **Higher Electronic conductivity:**

Increase by orders of magnitude with more Li content

- $\text{Li}^+$  diffusivity in Si : Higher in higher SOC
- Prelithiation  $\rightarrow$  Faster  $\text{Li}^+$  diffusion in Si
- **Higher ionic conductivity** increased by prelithiation

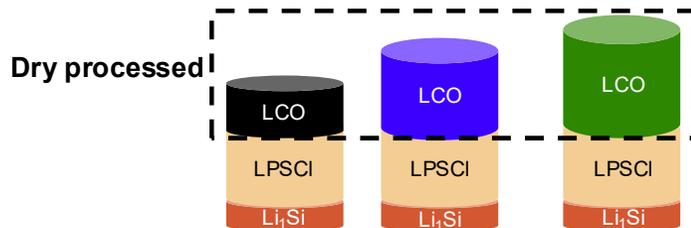
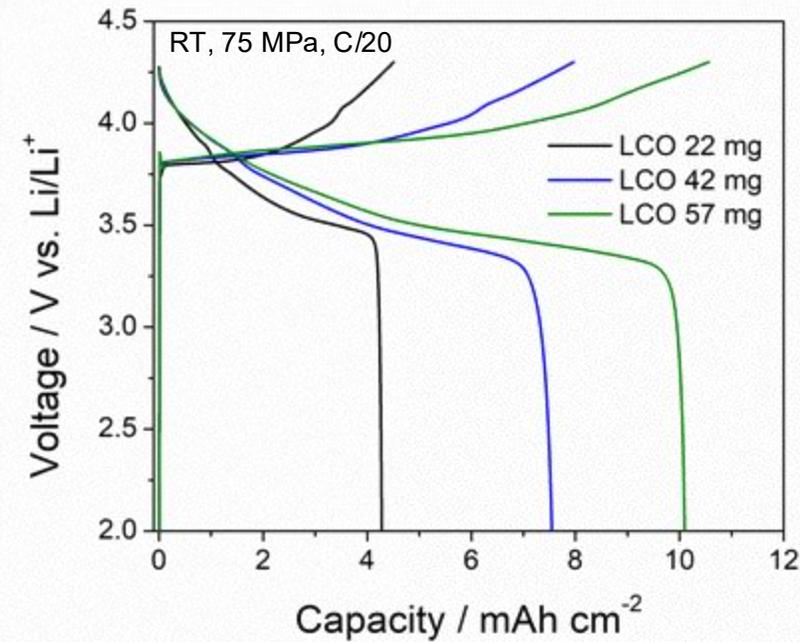
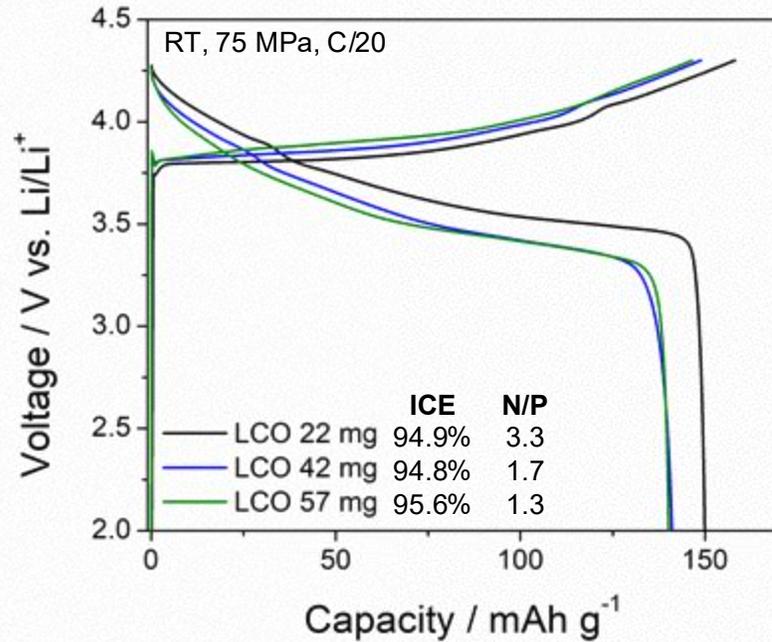
# Prelithiation of Si – Unlock 10mAh/cm<sup>2</sup> Capacity



Dr. So Yeon Ham

Higher LCO loading cells by stacking dry films paired with 5 mg of lithiated Si (Li<sub>1</sub>Si)

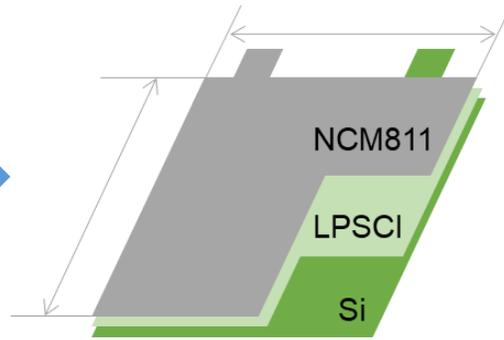
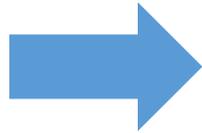
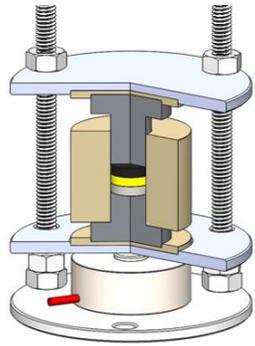
- Similar ICE for all loadings



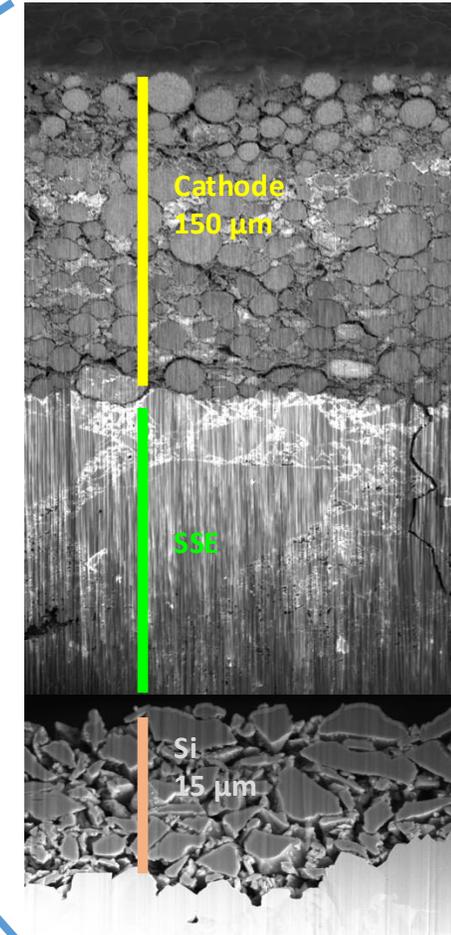
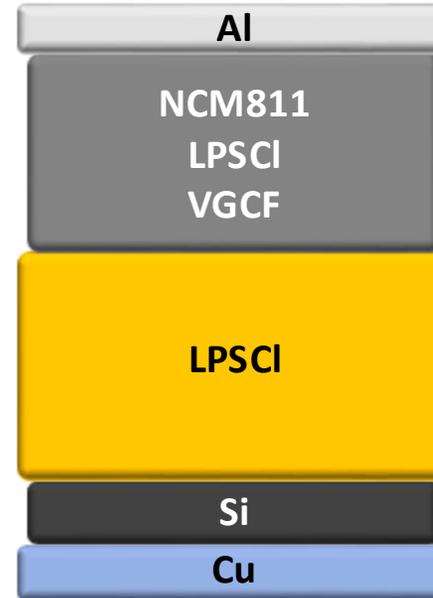
- Higher polarization for high loading but still achieved 140 mAh/g
- **5 mg lithiated Si** enough for areal capacity of **10 mAh cm<sup>-2</sup> discharge capacity**

# Defining Cell Configuration

LGES-UCSD Frontier Research Laboratory



Requirements:	Pellet Type	Pouch Type
SSE Thickness	~ 700 $\mu\text{m}$	< 100 $\mu\text{m}$
Areal Loading	< 2 $\text{mAh cm}^{-2}$	4-6 $\text{mAh cm}^{-2}$
Cell Size	< 1 $\text{cm}^2$	> 10 $\text{cm}^2$
Stack Pressure	~ 50 MPa	< 5 MPa
Layers	1	$\geq 1$



- LPSCI is dry room compatible → Ready for pouch cells
- Setting key parameters for pouch demonstration based on  $\mu\text{Si}$  | LPSCI | NCM811

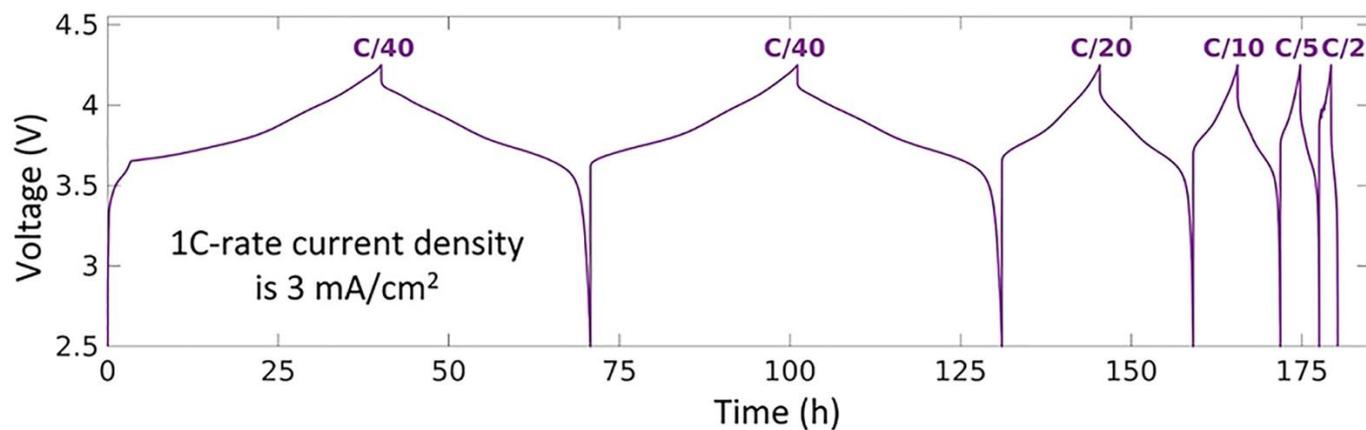
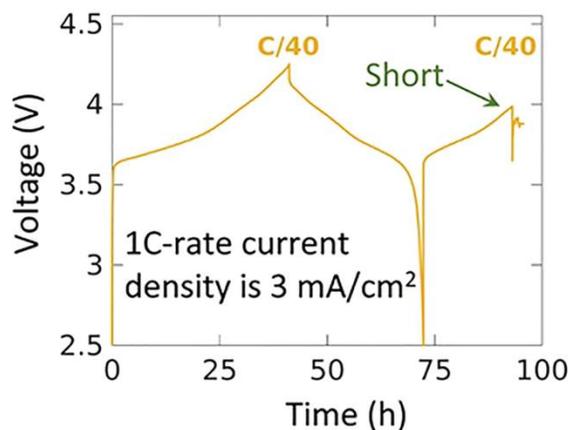


Single layer all-solid-state pouch cell

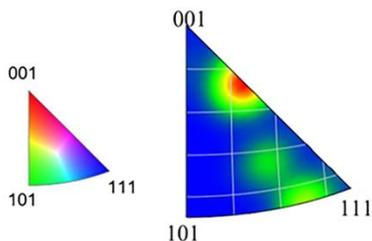
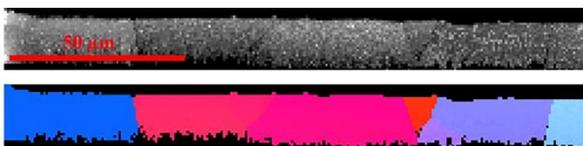
# Directed Texture Improves Critical Current Density



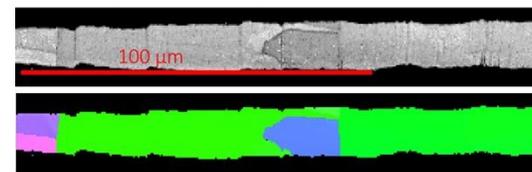
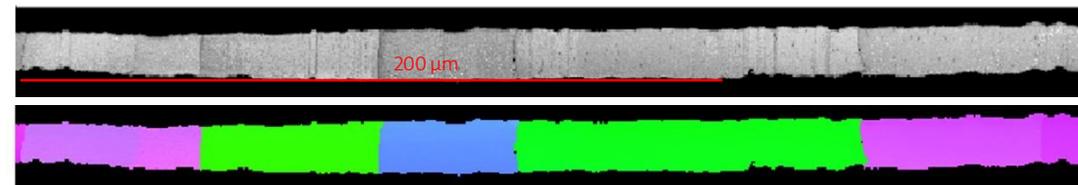
$\text{Li}_x\text{Si}$  substrate with tailored mechanical property triggered **101** grain growth



Li deposition on **Cu** at 25 °C, 5 MPa



Li deposition on **Li<sub>x</sub>Si** at 25 °C, 5 MPa



# Remaining Challenges

## Precursors

Li<sub>2</sub>S price needs to come down by 5X -10X  
SSE particle size control must be done

## Processibility

Dry room compatibility - yes!  
Dry processing – at scale!!!

Pressure reduction from 100MPa – 50MPa – 5MPa  
Design SSB component and architecture for 1-2MPa

## Pressure

# Sodium Anode-Free Solid-State Batteries

Can achieve 3 goals simultaneously...

## 1. Maximize energy density

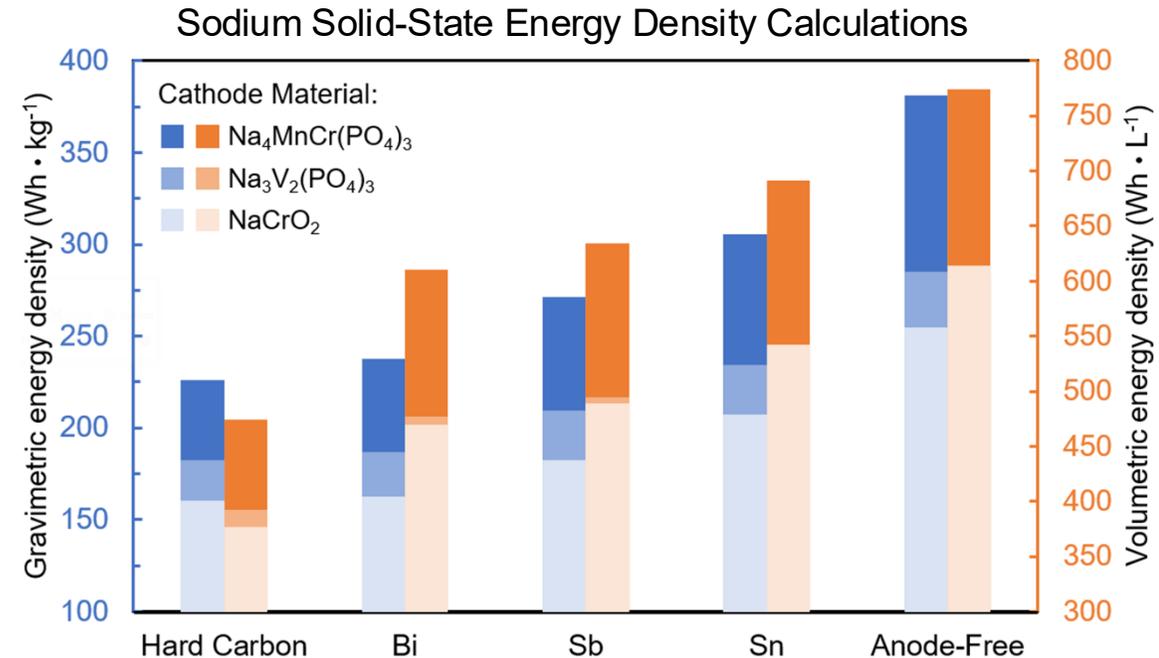
- Lowest reduction potential → highest cell voltage
- Smaller and lighter cells

## 2. Minimize cost

- No anode material cost, lower processing cost
- Sodium cheaper than Lithium

## 3. Improved safety

- No flammable organic liquid electrolytes
- No large amounts of sodium metal foils

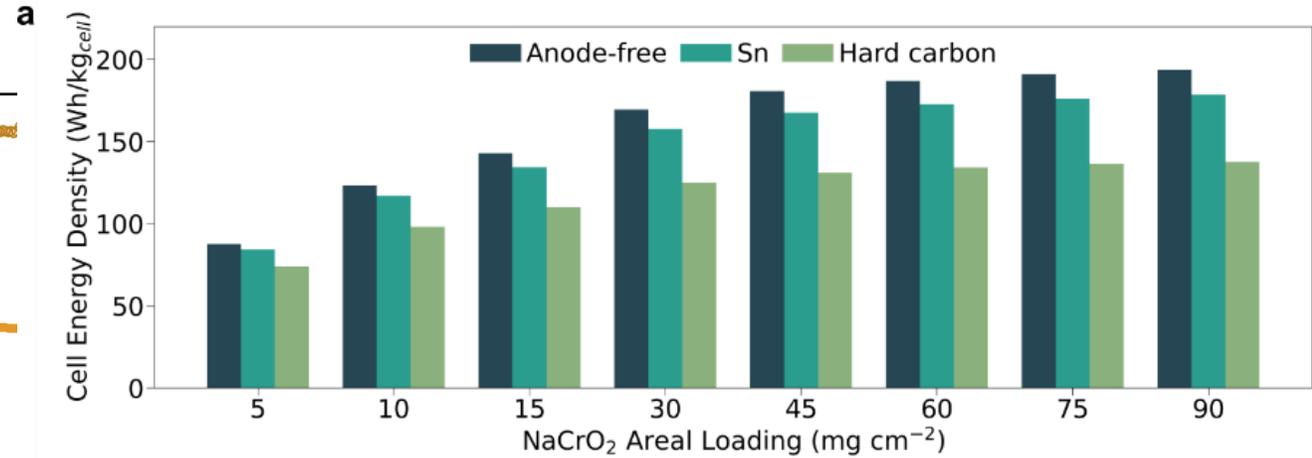
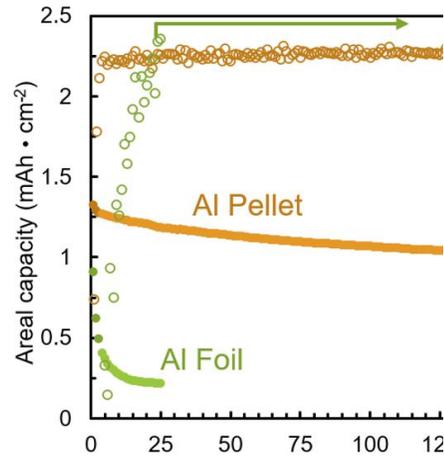
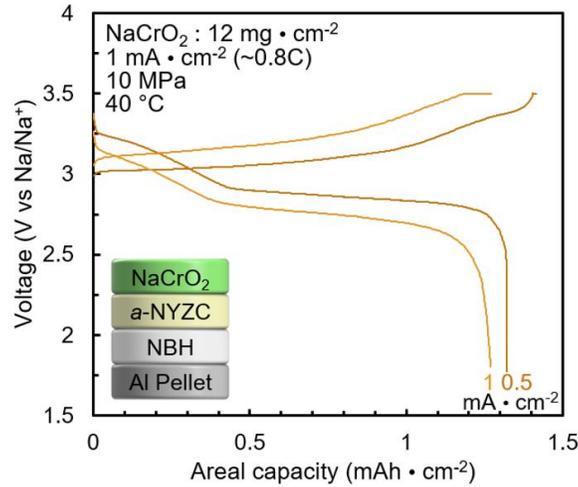


# Sodium All Solid-State Full Cell

G. Deysler, J.A.S. Oh, ... Y.S. Meng, "[An Anode-Free Sodium All-Solid-State Battery](#)", 2024, Nature Energy

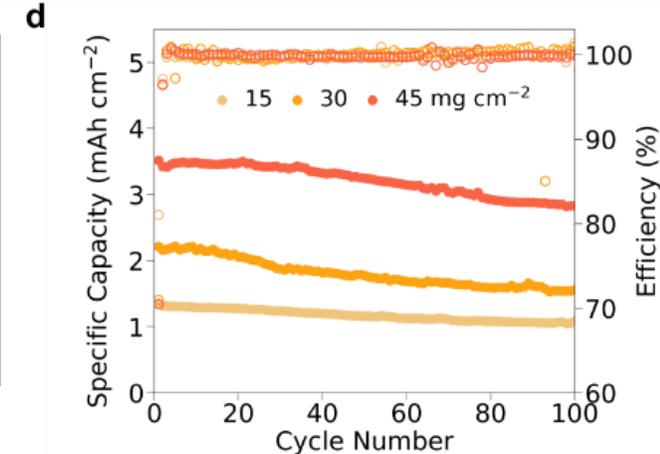
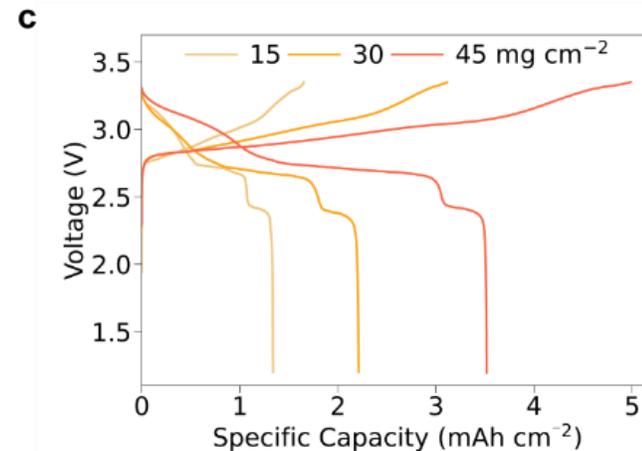
Patent Pending

- Enable full-cell cycling (NaCrO<sub>2</sub> cathode)



Thick Battery Cathode enabled by novel superionic Na conductor

Dr. J.A.S. Oh [Patent Pending and To be Submitted](#)



e

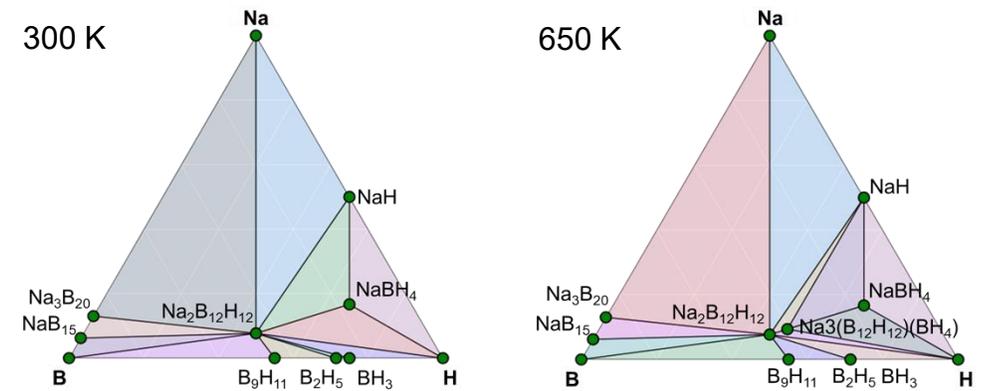
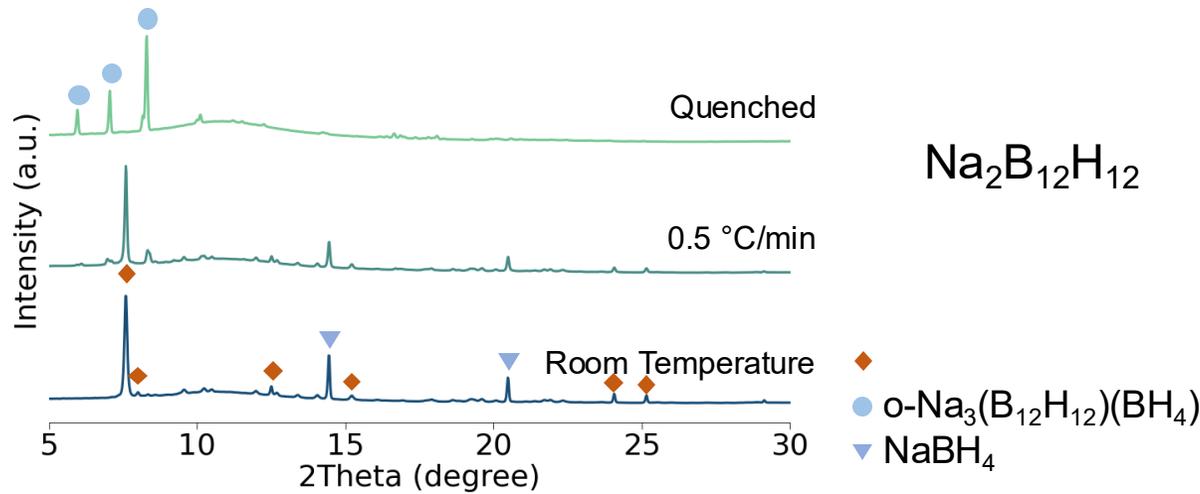
# Materials Discovery – Metastable o-NBH

Patent Pending



Dr. Sam Oh

- $\text{Na}_2\text{B}_{12}\text{H}_{12}$  reacted with  $\text{NaBH}_4$
- Both are poor  $\text{Na}^+$  conductors on their own



- Different cooling rate exhibits different crystal structure at room temperature
  - o-NBH stabilized with quenching
  - $\text{Na}_2\text{B}_{12}\text{H}_{12}$  and  $\text{NaBH}_4$  patterns when cooled slowly
  - Metastable nature of o-NBH stabilized by rapid cooling

# Activation Energy

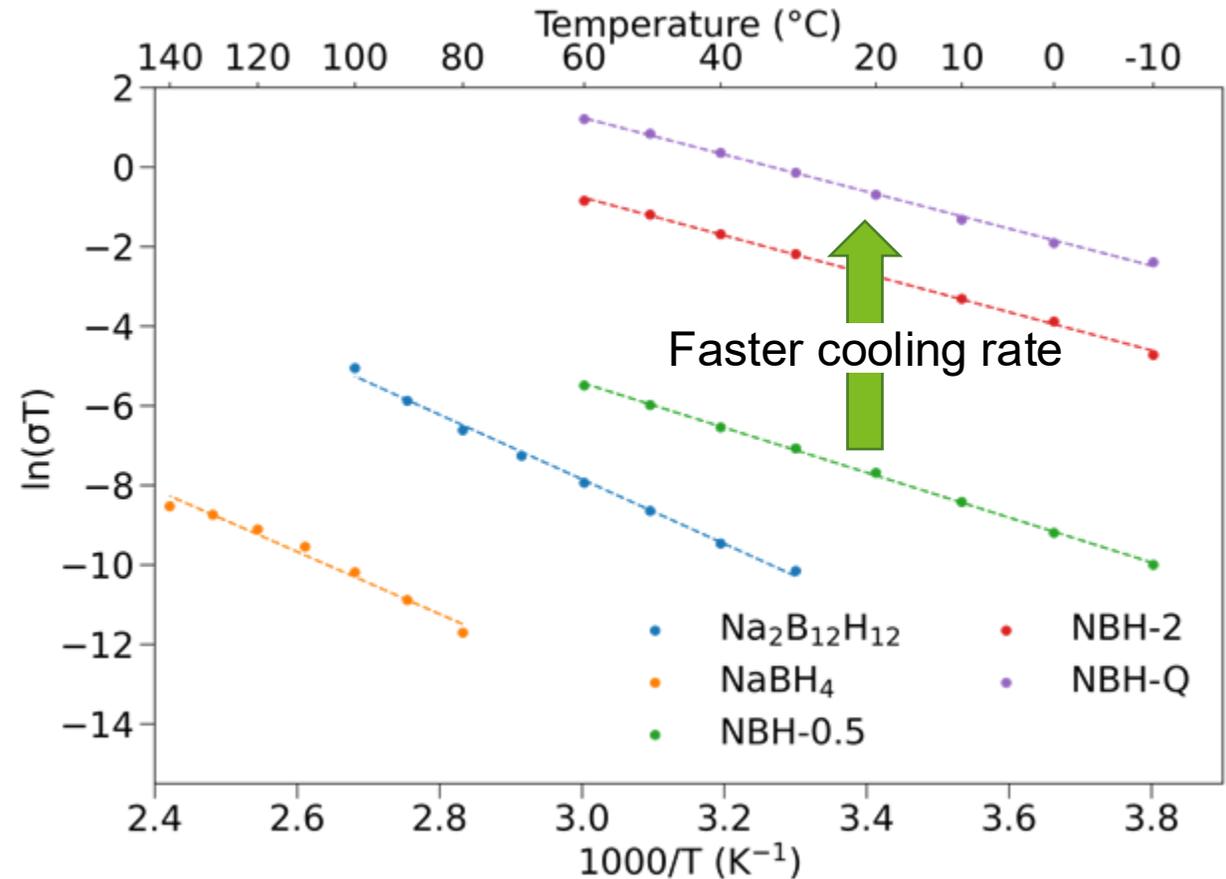
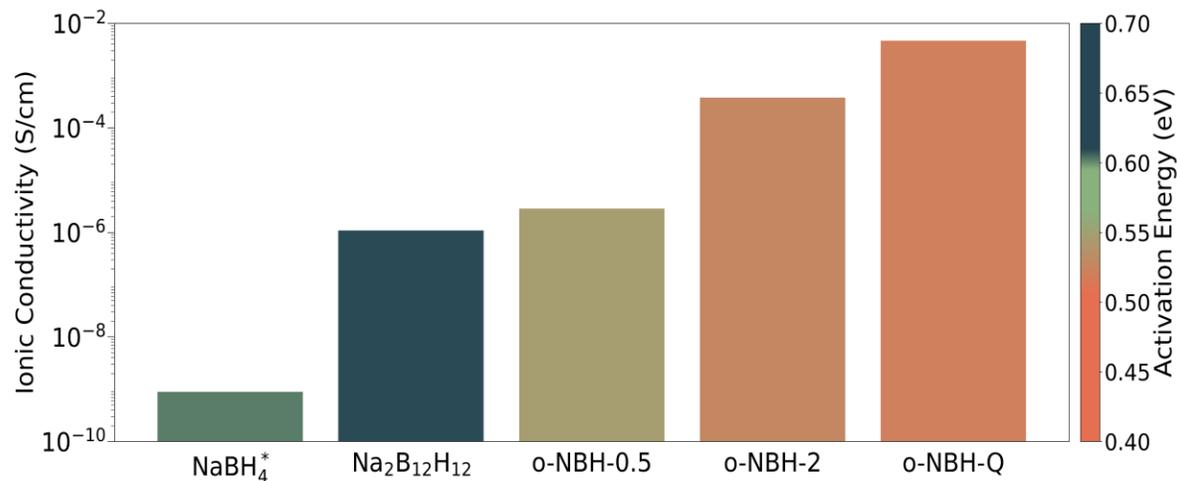
Activation energy estimated by EIS measure at different temperature

➤ Ionic conductivity – temperature follows the Arrhenius relationship

$$\sigma_T = \sigma_T \exp^{-E_a/kT}$$

➤ Faster cooling rate maximizes ionic conductivity

➤ Quenched

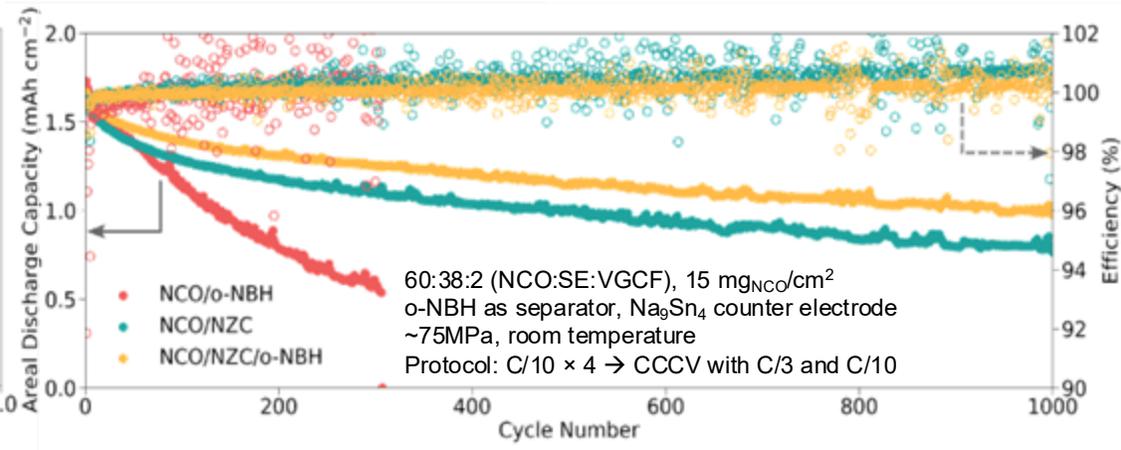
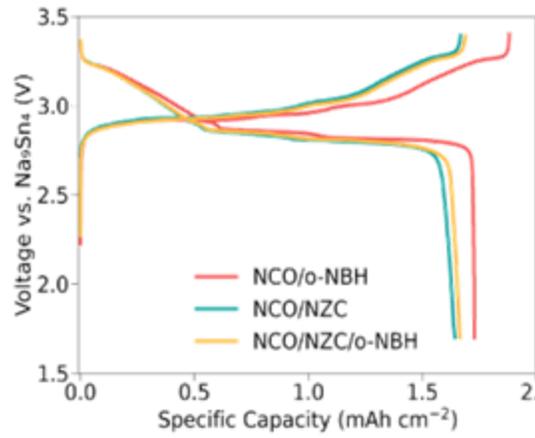
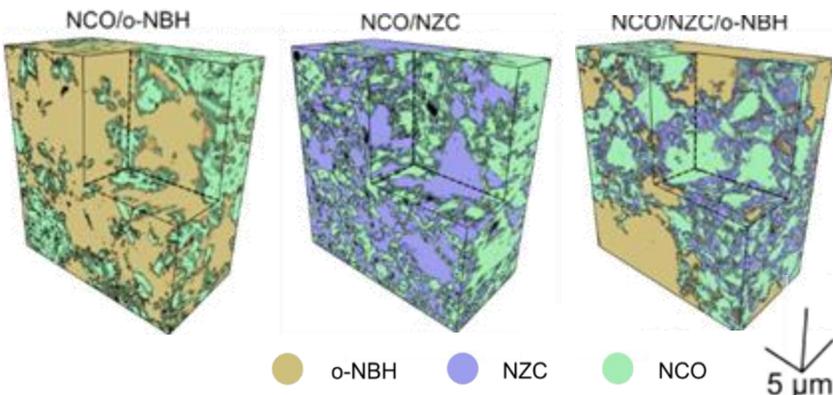
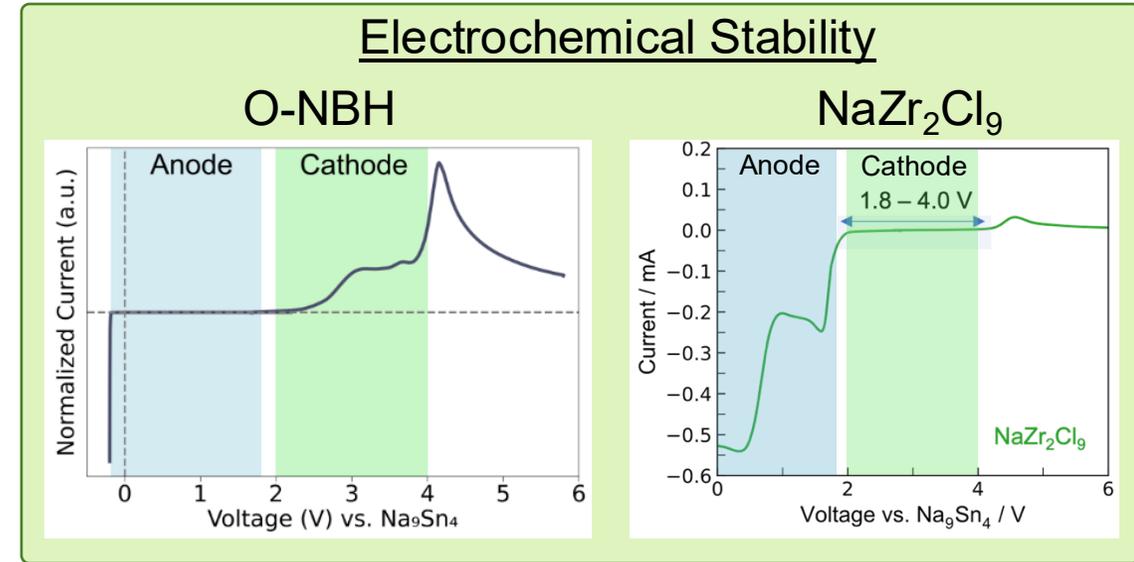


# Cathode Composite Electrochemical Performance

- o-NBH is not stable at cathode potentials
- Oxidizes around 2.5 V

New cathode design strategy →

- Coat  $\text{NaCrO}_2$  cathode with stable  $\text{NaZr}_2\text{Cl}_9$
- Stable cathode-electrolyte interface
- Mix in o-NBH for fast  $\text{Na}^+$  conduction



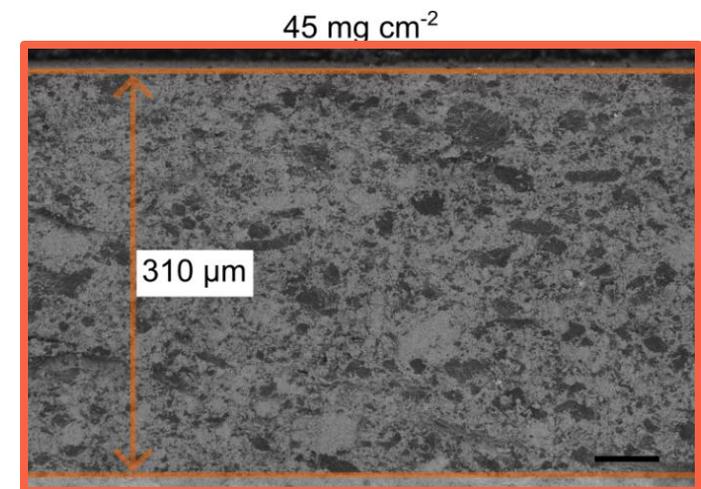
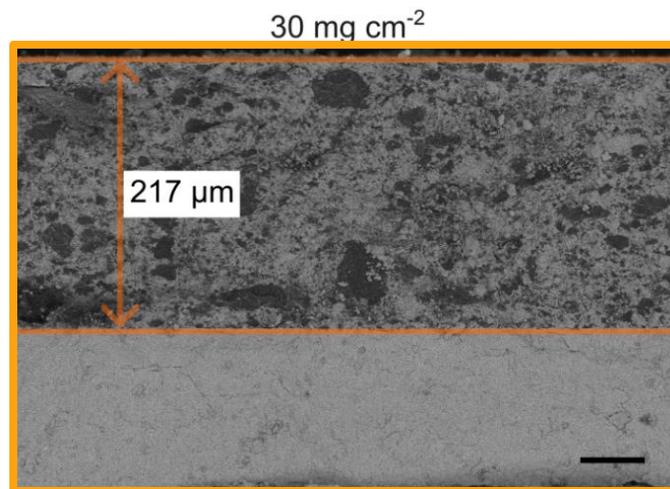
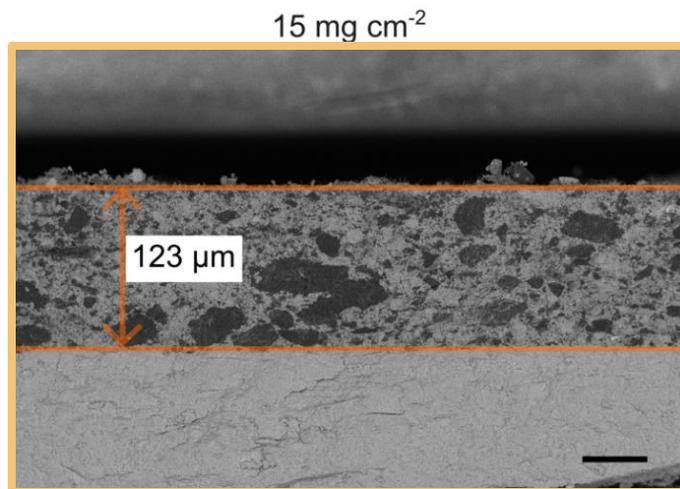
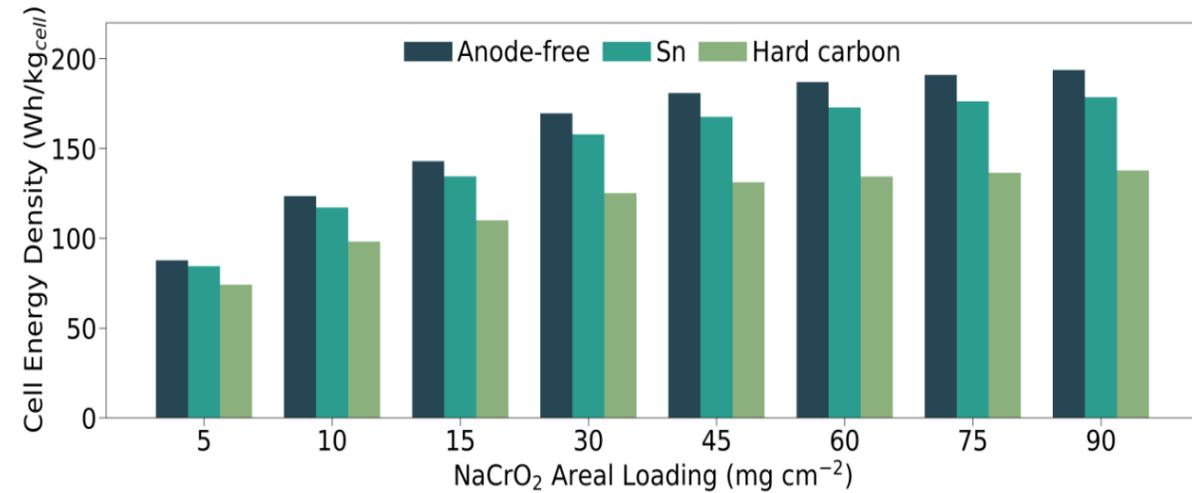
# High Loading Full Cell Cycling

Energy density increases with higher cathode loading

- Plateaus after  $\sim 45 \text{ mg/cm}^2 \text{ NaCrO}_2$

Cathode composites fabricated up to  $\sim 300 \mu\text{m}$  thick

- Theoretical capacity =  $5.4 \text{ mAh/cm}^2$



# Global Race for Solid State Battery – West vs. East

