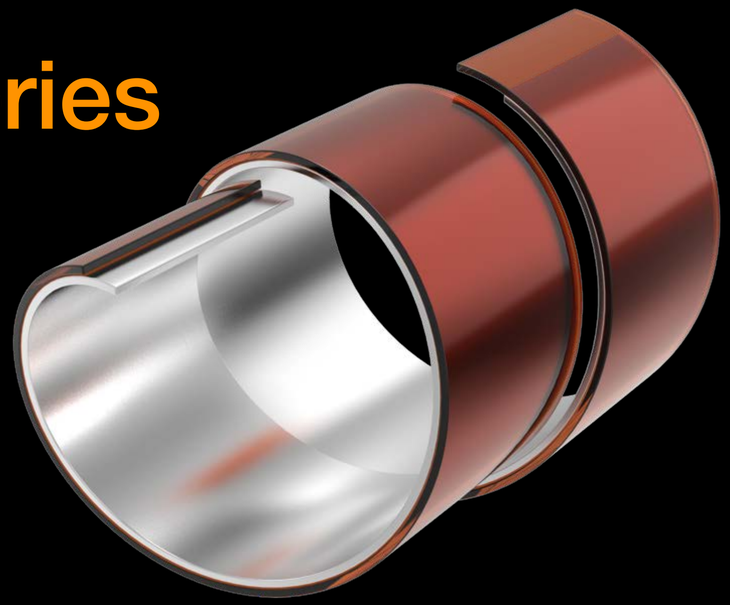
POLY
PLUS

Solid State (glass) electrolytes for rechargeable Next Generation Batteries

PolyPlus Battery Company
Berkeley, California



NAATBatt INTERNATIONAL

Langham Huntington Pasadena Hotel, February 10th-13th, 2020

Electric cars

The death of the internal combustion engine

It had a good run. But the end is in sight for the machine that changed the world

The Economist

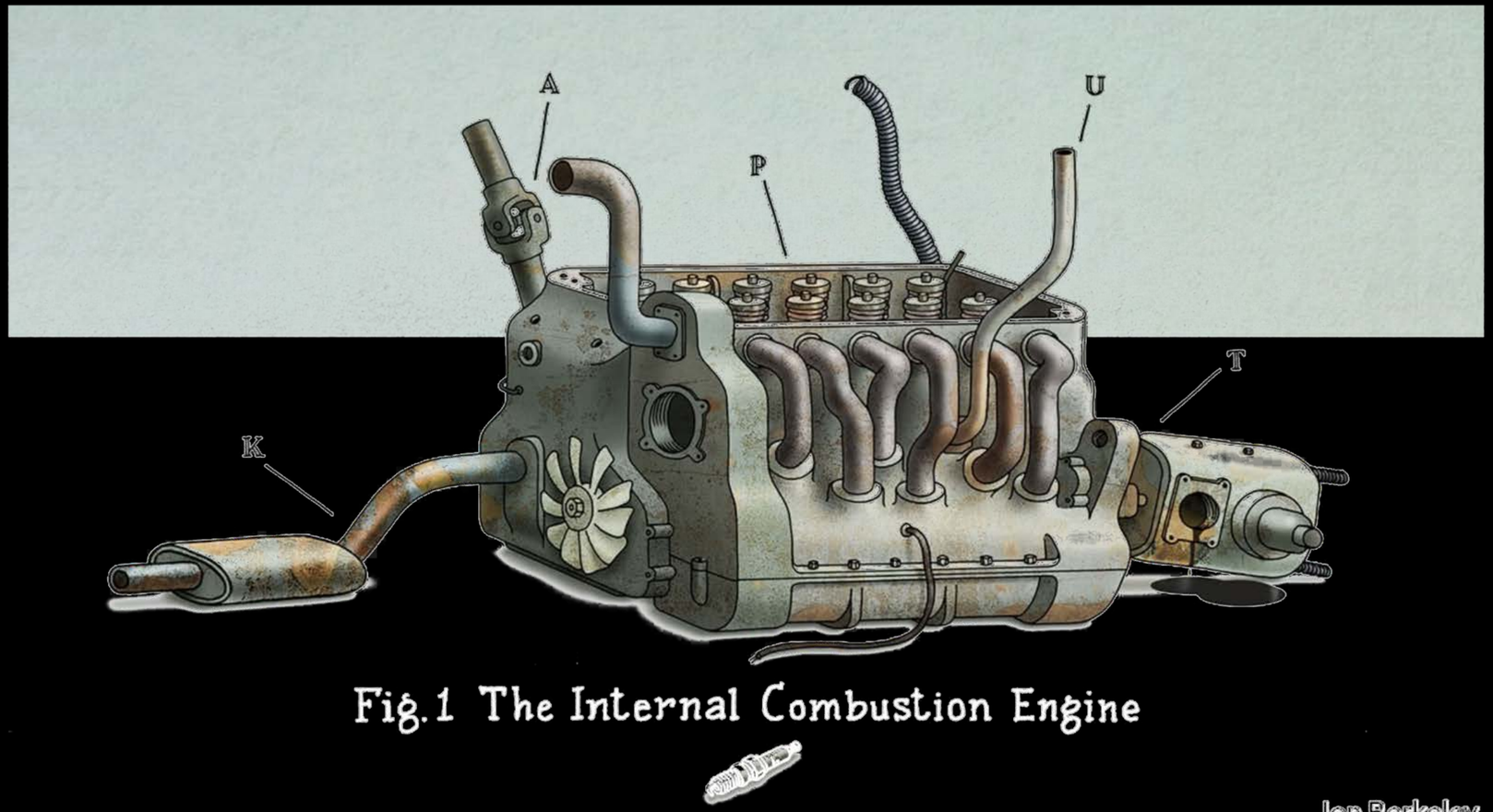
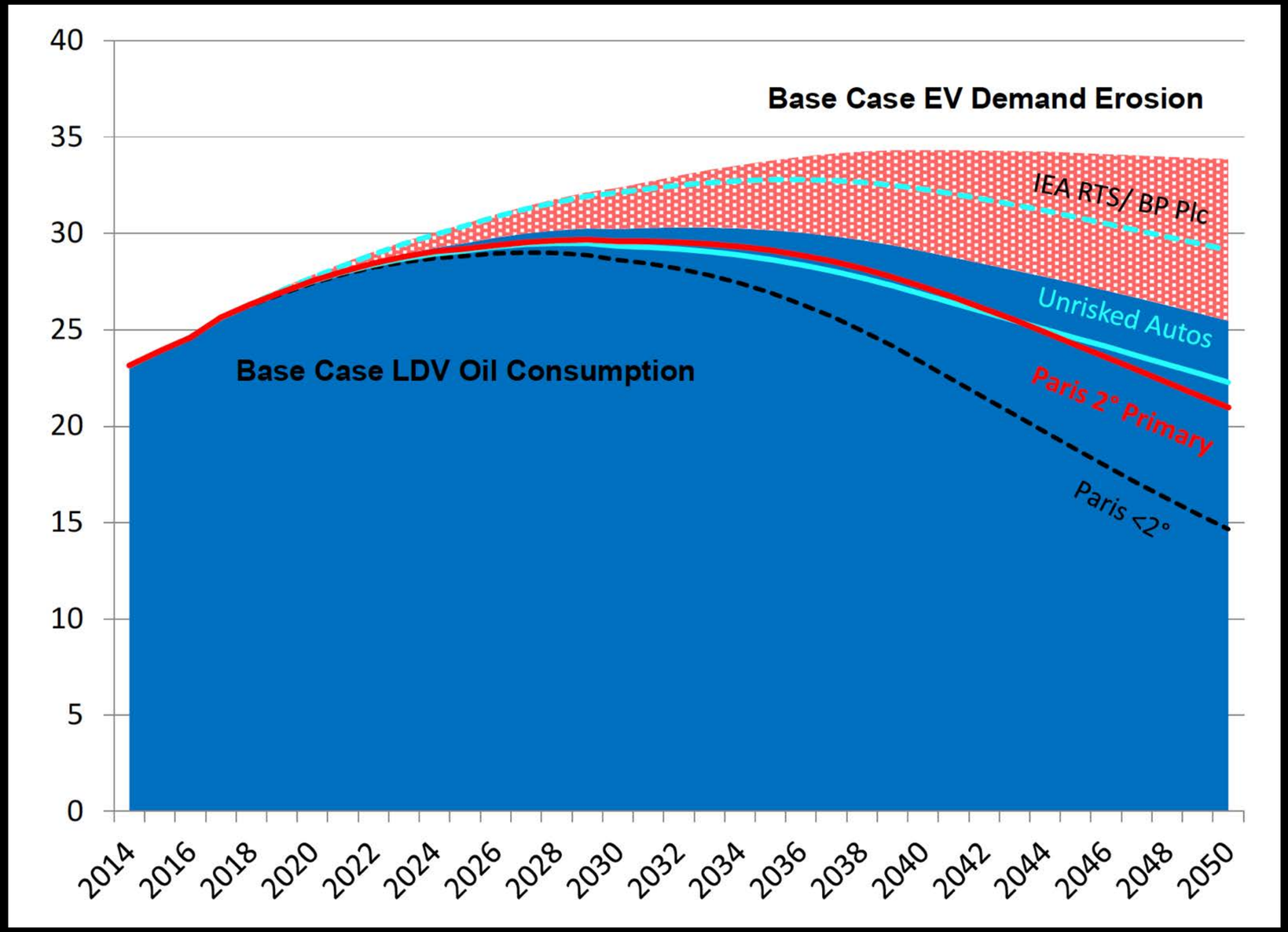


Fig.1 The Internal Combustion Engine

Jon Berkeley

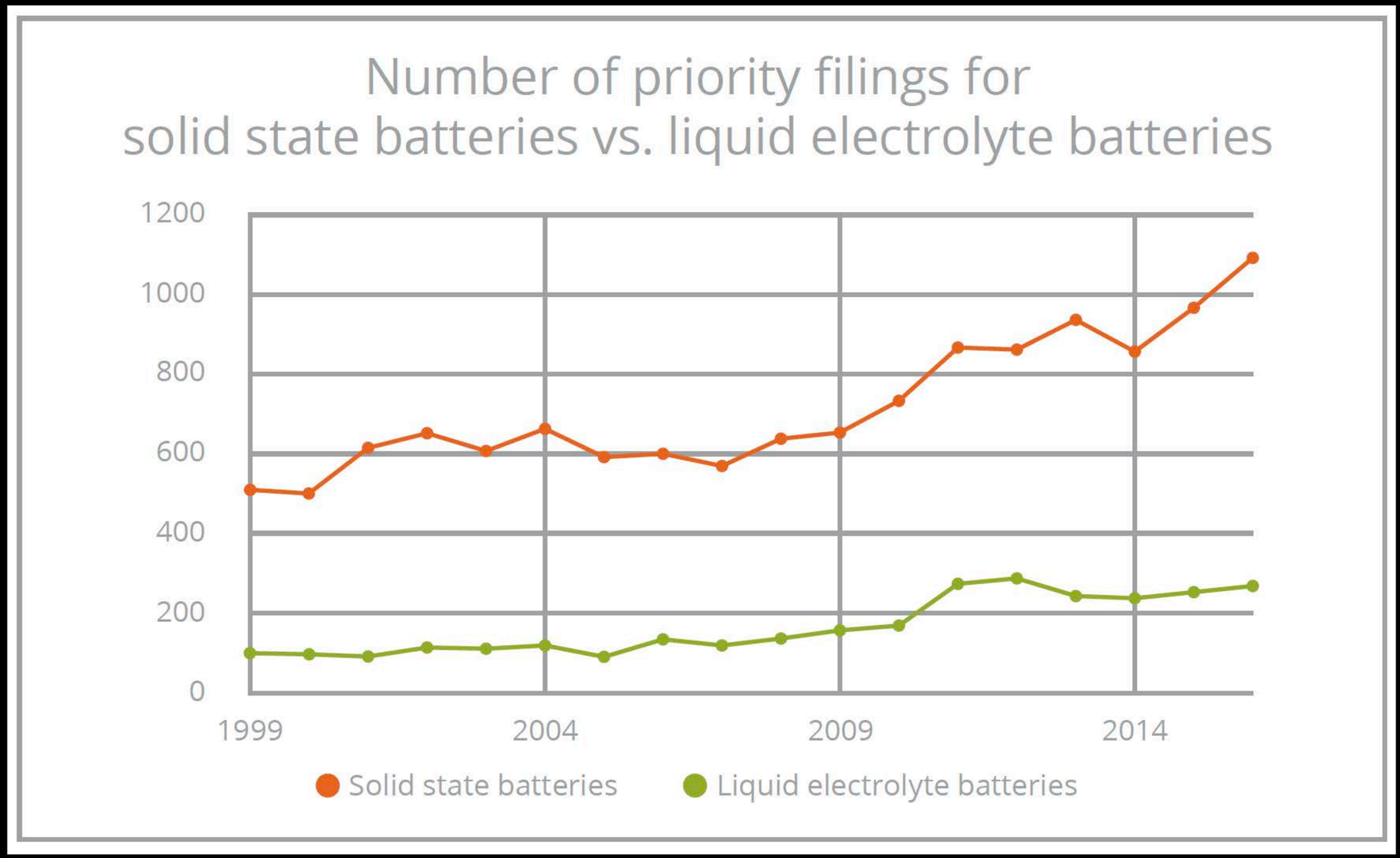
Aug 12th 2017

EV and Oil Demand Scenarios (million b/d)



How do we develop the next generation of high energy density batteries without compromising safety?

Vehicle Electrification



Solid-state batteries?

Twice the Energy,

Half the Size

Glass protected Li metal batteries

- A disruptive technology that can address the huge demand for smaller lighter batteries
- A solid-state lithium anode laminate that doubles the energy density of rechargeable batteries.
- Pilot manufacturing of lithium metal foil laminated to thin conductive glass to supply the battery industry with this key component

Strong IP portfolio

- 170 issued & 40 pending patents
- Successfully defended in court

POLY PLUS

Why Li Metal?

Li metal has 4 times the volumetric capacity density (mAh/cc) and 10 times the gravimetric capacity density (mAh/g) relative to the carbon electrode in Li-ion cells

Gravimetric and Volumetric Capacity of Lithiated LiC_6, $Li_{4.4}Si$ and Li Electrodes			
Electrode type	LiC_6	$Li_{4.4}Si$	Lithium
Theoretical capacity (mAh/g)	300	2010	3830
Theoretical Density (g/cc)	2.2	2.33	0.534
Electrode porosity (%)	30	30	0
Volumetric capacity density	462	3270	2029
Excess Li capacity ratio	0	~ 2	1.2
Practical capacity density (mAh/cc)	420	1100	1700
Practical specific capacity (mAh/g)	275	1000	3200

Solid Electrolytes for Rechargeable Li Metal Batteries

Crystalline & Polycrystalline materials

Oxide, sulfides

LLZO, LATP, LGPS

Non-Crystalline Materials

Polymers (PEO)

Glasses (LiPON)

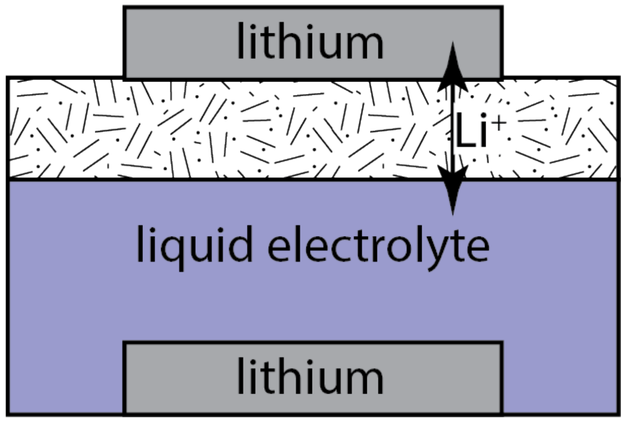
Material	Density (g/cm^3)
alumina	3.95
zirconia	5.68
LATP	3.10
LLZO	5.10
Glass	*1.9*
PEO	*1.2*

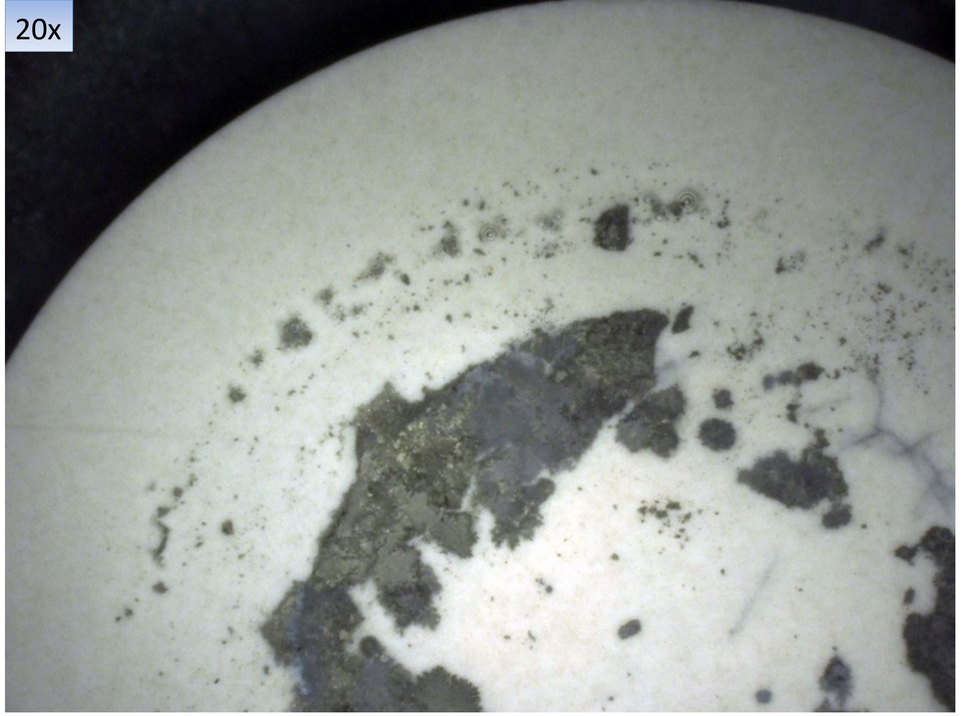
sufficiently high shear modulus to blunt Li dendrites (> 6 GPa)

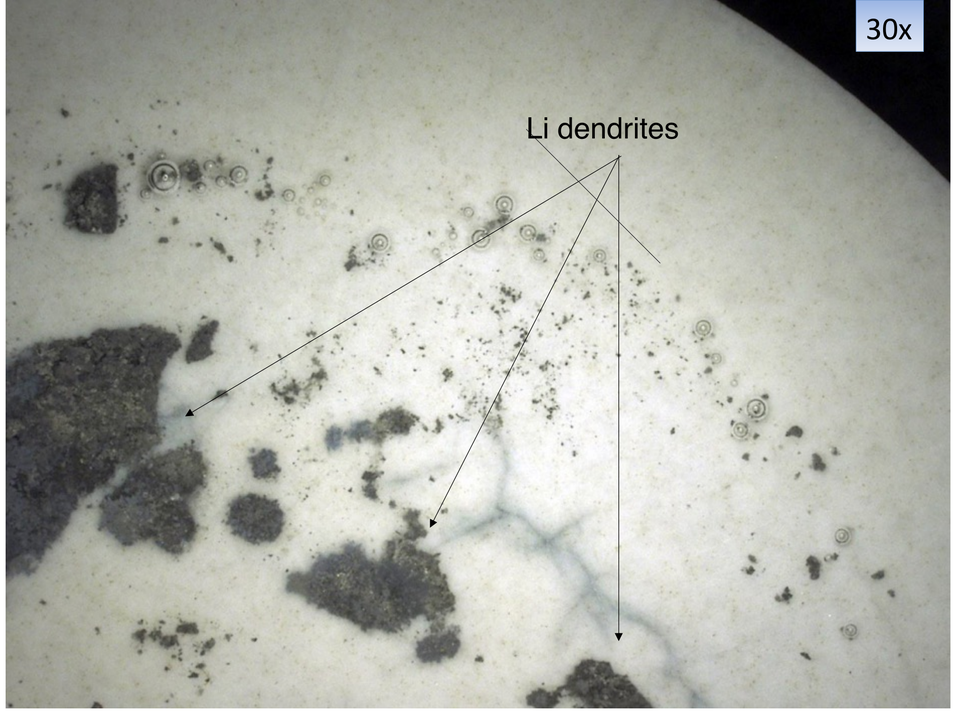
(*Monroe and Newman 2005*)

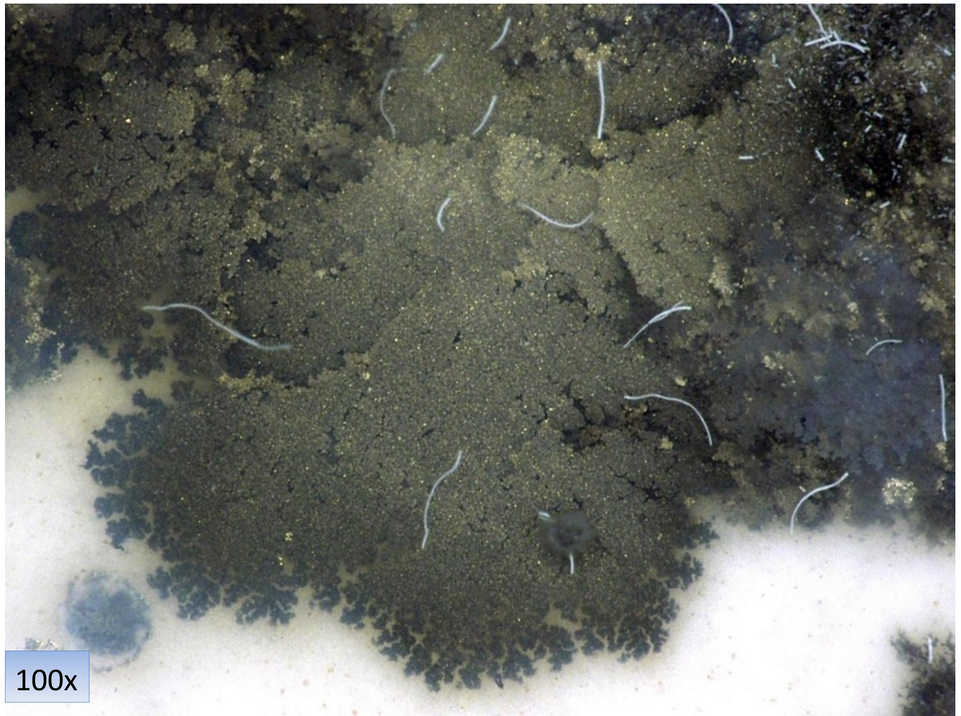
necessary but not sufficient condition

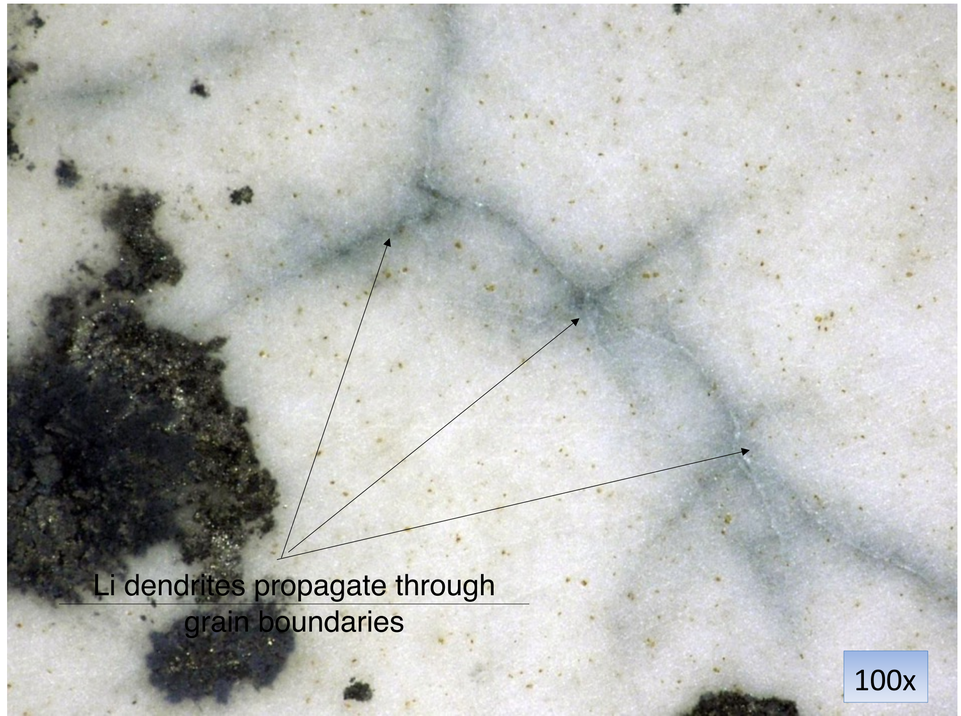
Electrochemical Cycling of Li through LLZO





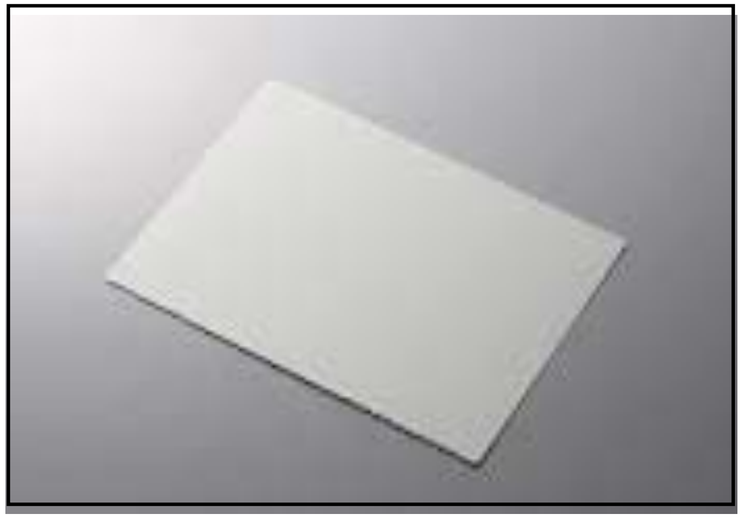






Retail pricing of globally scaled thin ceramic sheet

Alumina Substrates (200um)



$0.75/in^2 → $1,160/m^2

ENrG Ultra-Thin, Flexible Ceramic Substrate: 40µm

→ $5,000/m^2

Impact of Separator Pricing

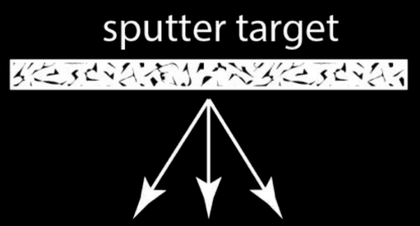
85 kWh EV battery
~ 280 m^2 of separator

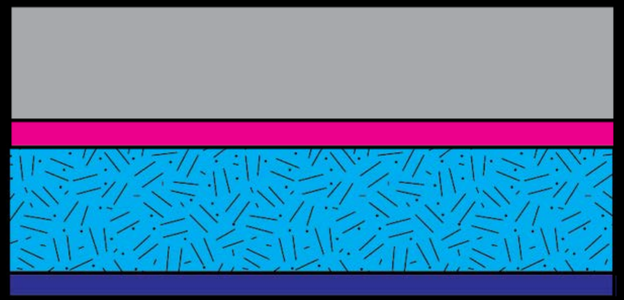
At \$1/m^2, the polymer separator costs \$280

At \$1000/m^2
a thin ceramic separator cost **\$280,000**

Need to reduce cost by 3 orders of magnitude
or increase electrode thickness from 60 µm to 60 mm

Solid-State Batteries





substrate

Lithium

LiPON (glass)

LCO

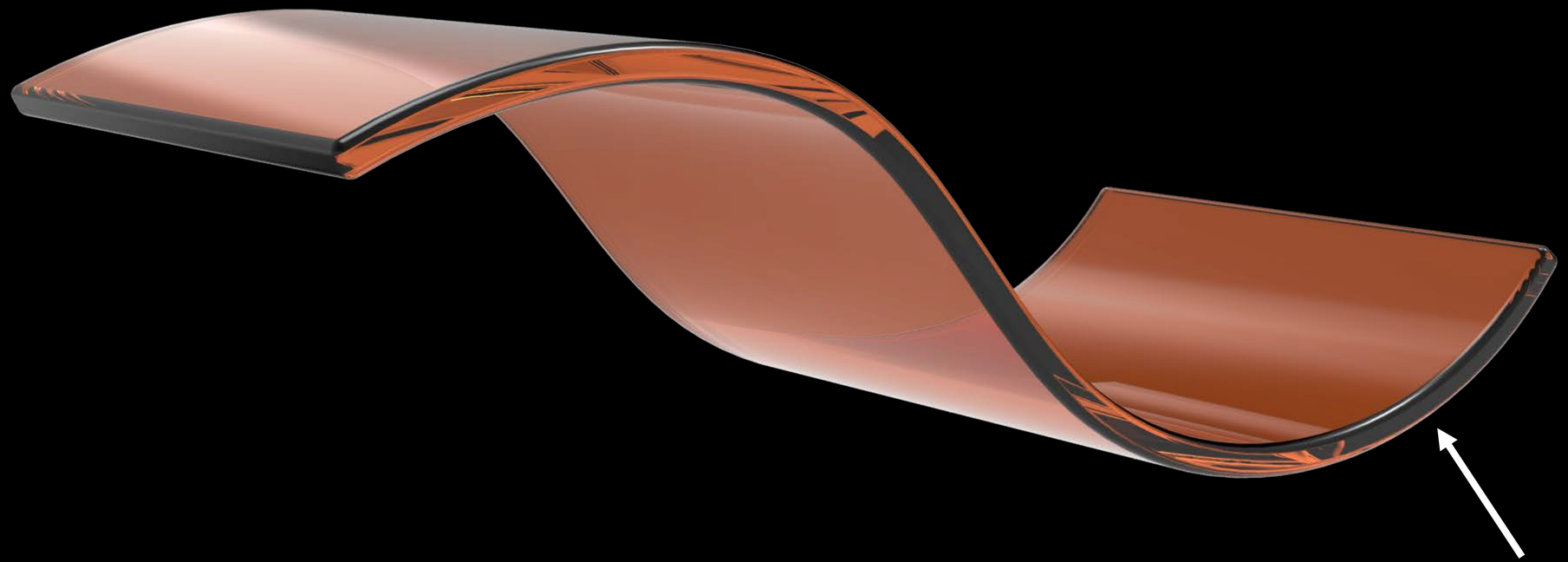
No voids or grain boundaries

10,000 cycles @ 100% DoD

Glass electrolytes

Scaleable High Conductivity Glass

Li^+ conductivity
10^{-4} to 10^{-3} S/cm at RT



20 to 30 μm thickness

Thin Glass Separators

−

+

- PolyPlus invented the first conductive glass separator for rechargeable Li metal batteries
- Our scientists recognized that thin monolithic glass sheets have sufficient flexibility and conductance for the application
- Monolithic glass sheet acts as a barrier to dendrites and facilitates efficient Li cycling
- Continuous thin glass can be produced in volume and at competitive cost

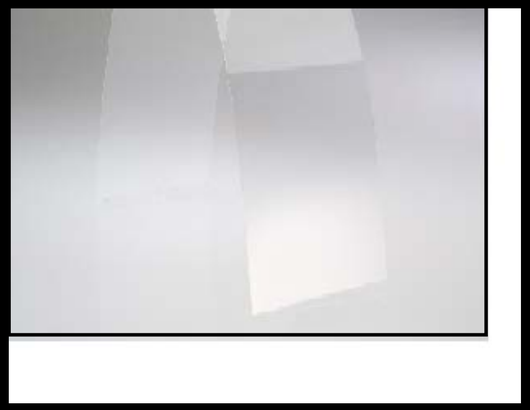
Thin-Glass Sheet Retail Pricing

Gorilla Glass Substrate (150um)

$0.026/in^2 → $41/m^2

based on 100 piece order

Willow Glass Substrate (100um)

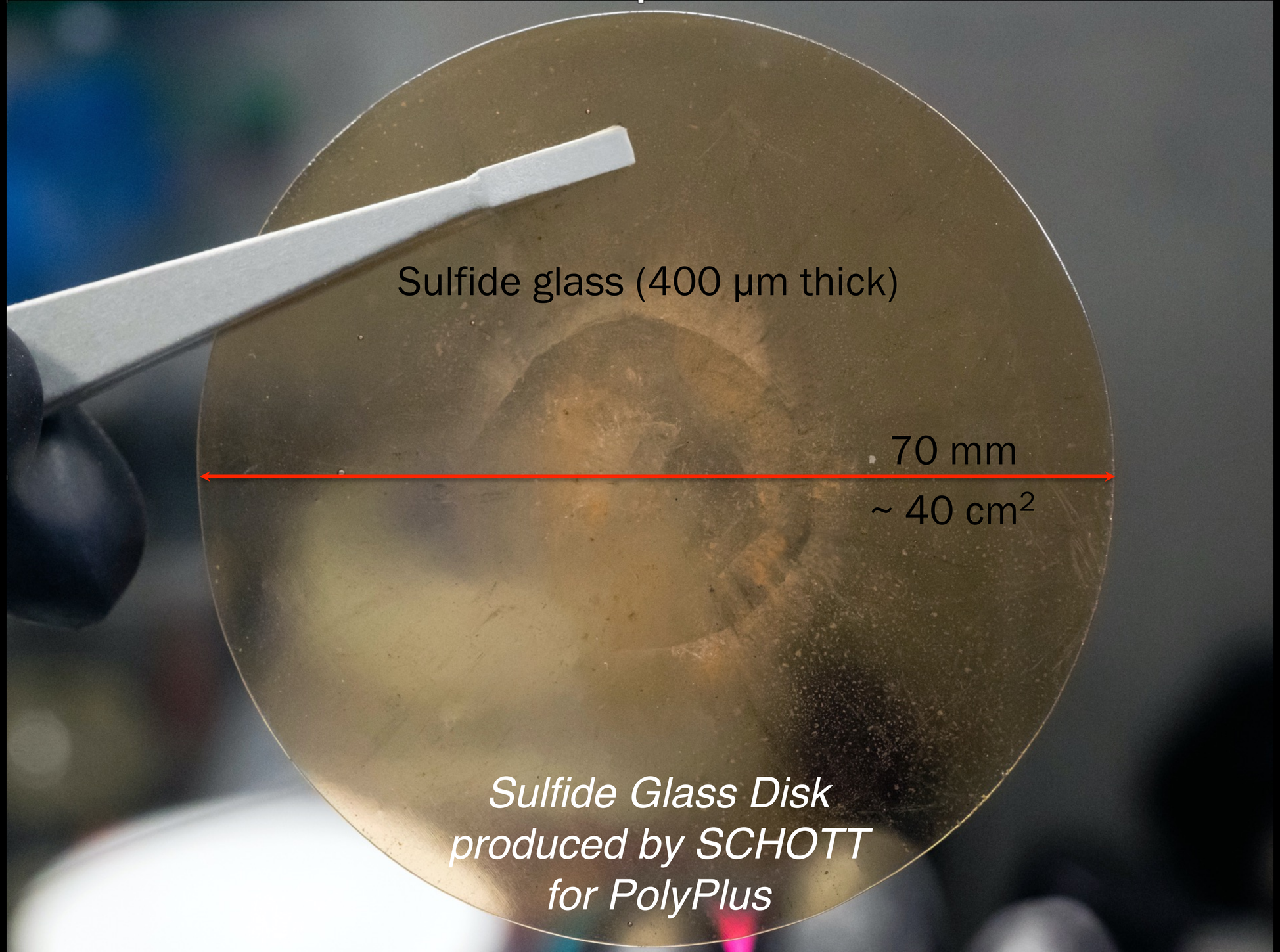


$0.005/in^2 → $7.8/m^2

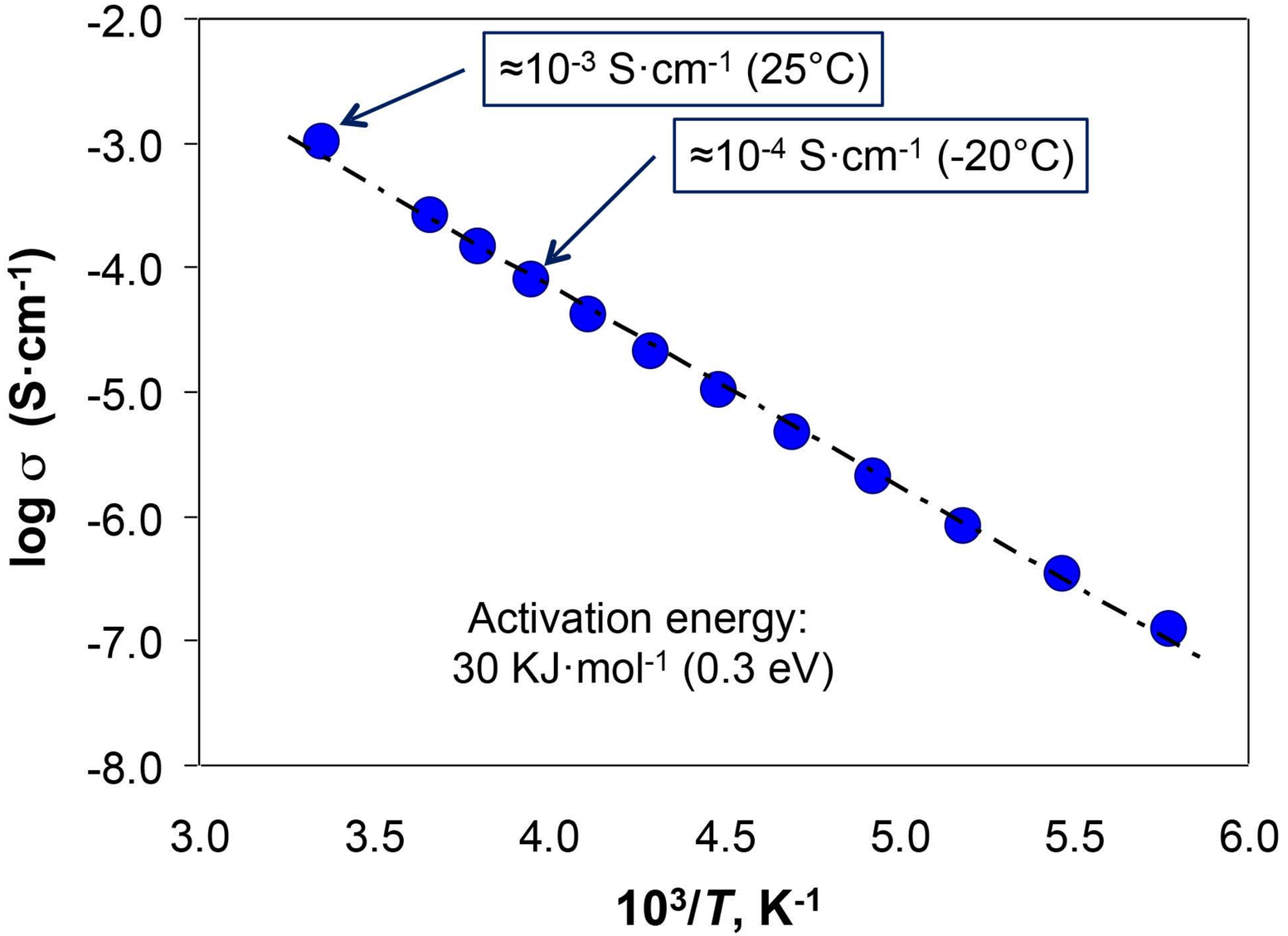
Thin Glass Sheet (300um)

$0.0007/in^2 → $1/m^2

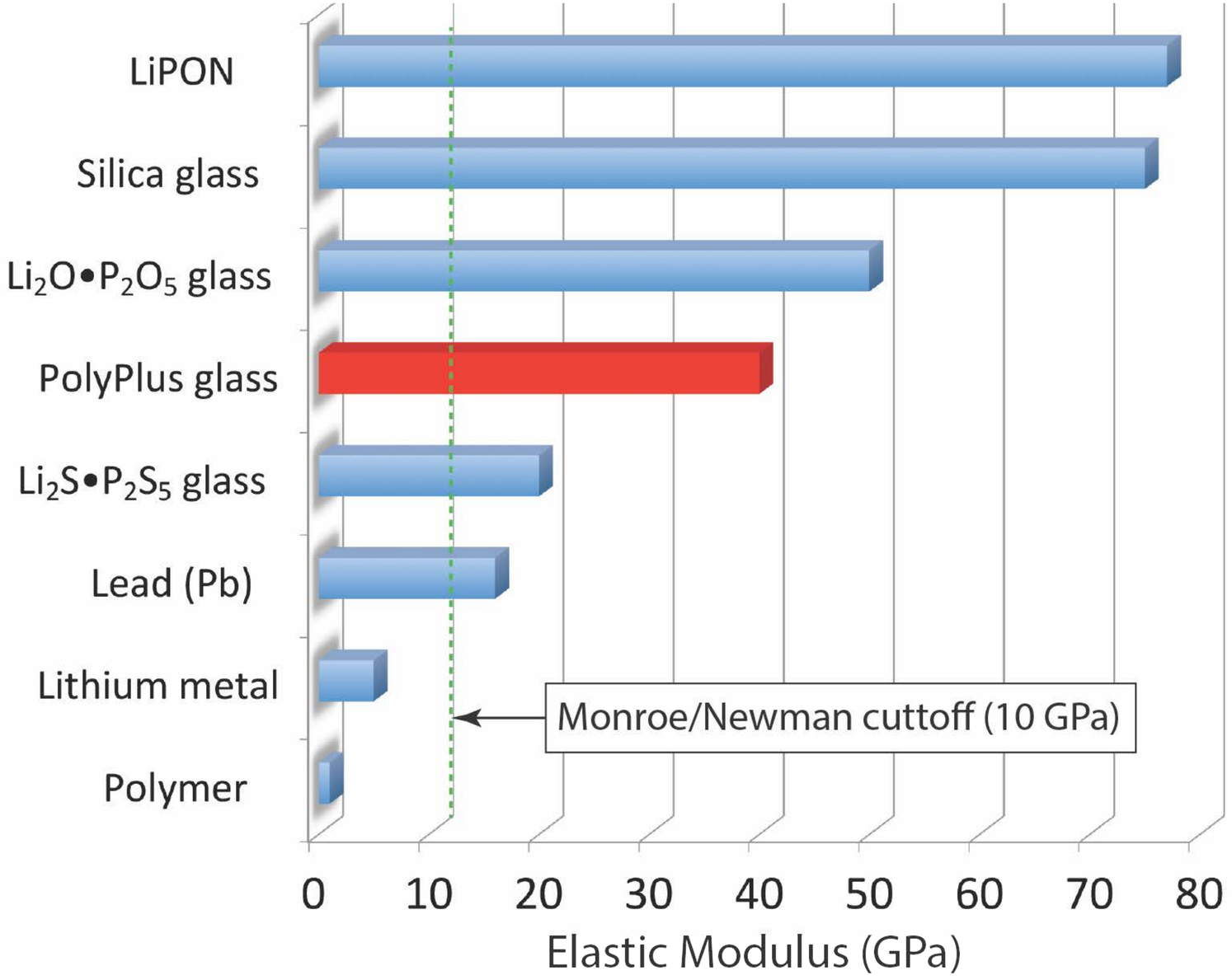
Alibaba: large scale


Sulfide glass (400 µm thick)
70 mm
~ 40 cm²
Sulfide Glass Disk
produced by SCHOTT
for PolyPlus

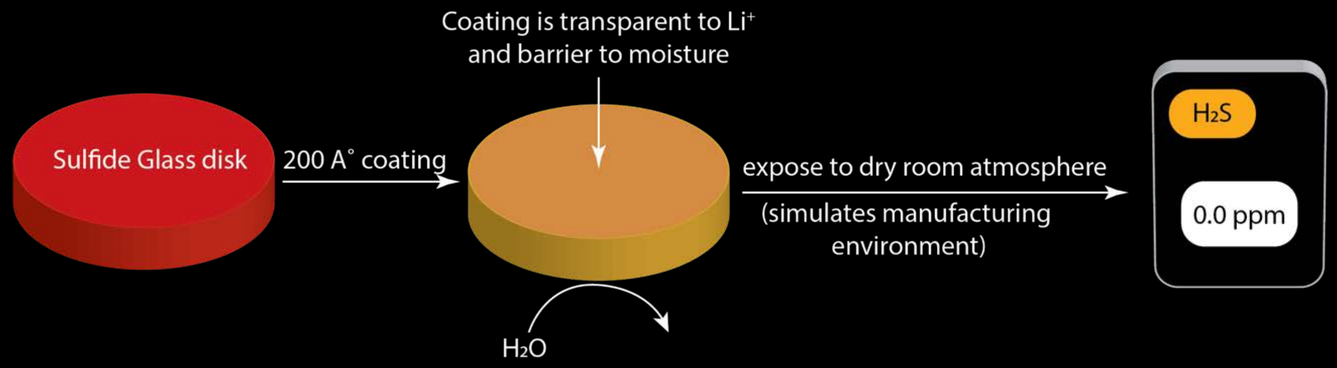
High Conductivity Glass



Mechanical Properties of PolyPlus Glass by nano indentation (Erik Herbert, Michigan Technological University)



PolyPlus moisture barrier for manufacturing



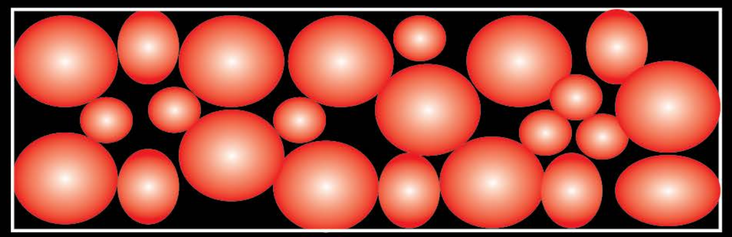
After 30 minutes exposure to dry room air, no evidence of H_2S

After 1 hour of exposure to dry room air, no evidence of H_2S

Dry Room Stability for Manufacturing

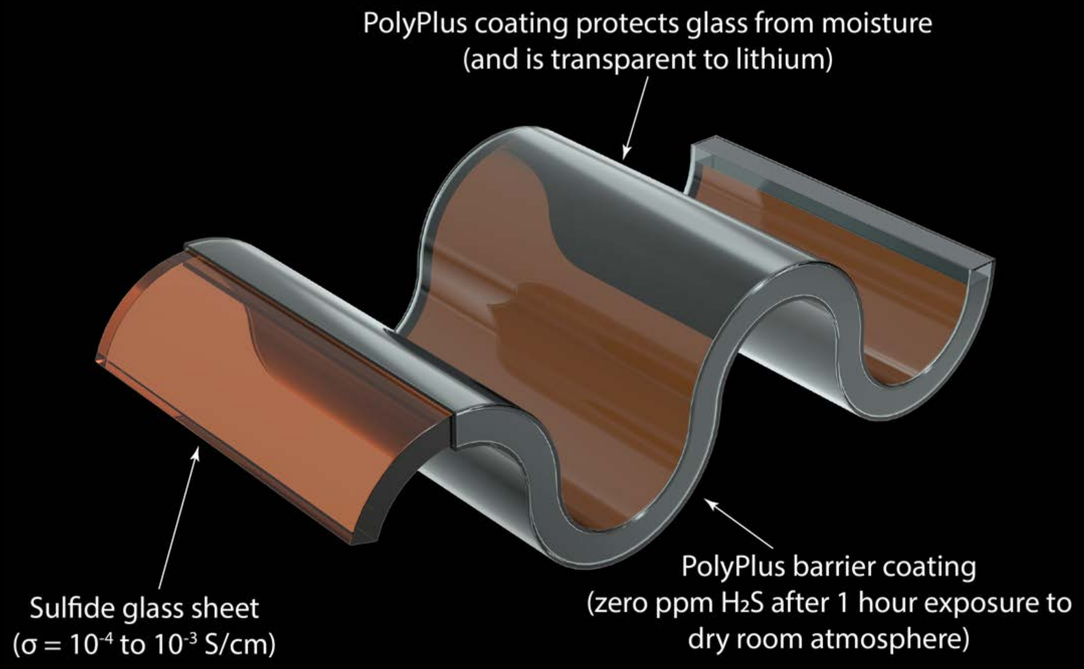
Sulfide Electrolyte Powders
(problematic-only stable in glove box environment)

pressed sulfide power solid electrolyte

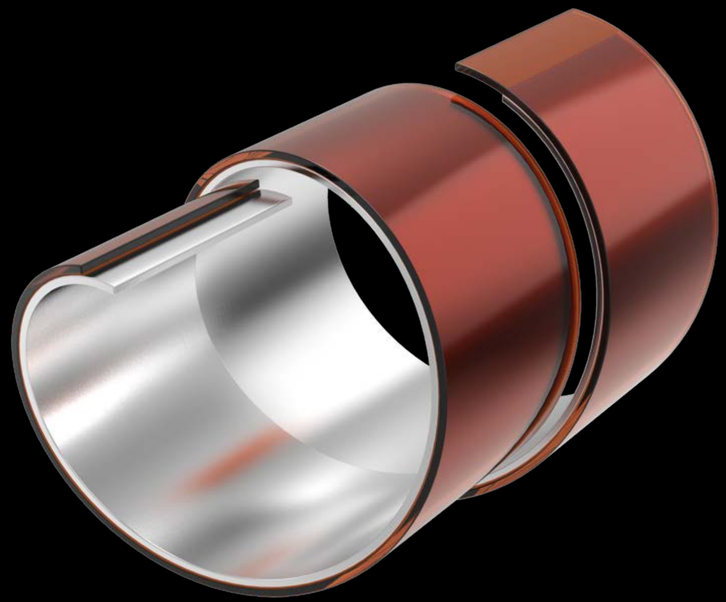


High surface area sulfide powers react quickly with moisture
(difficult to protect powders from moisture)

POLYPLUS APPROACH
(glass is stable in manufacturing environment)

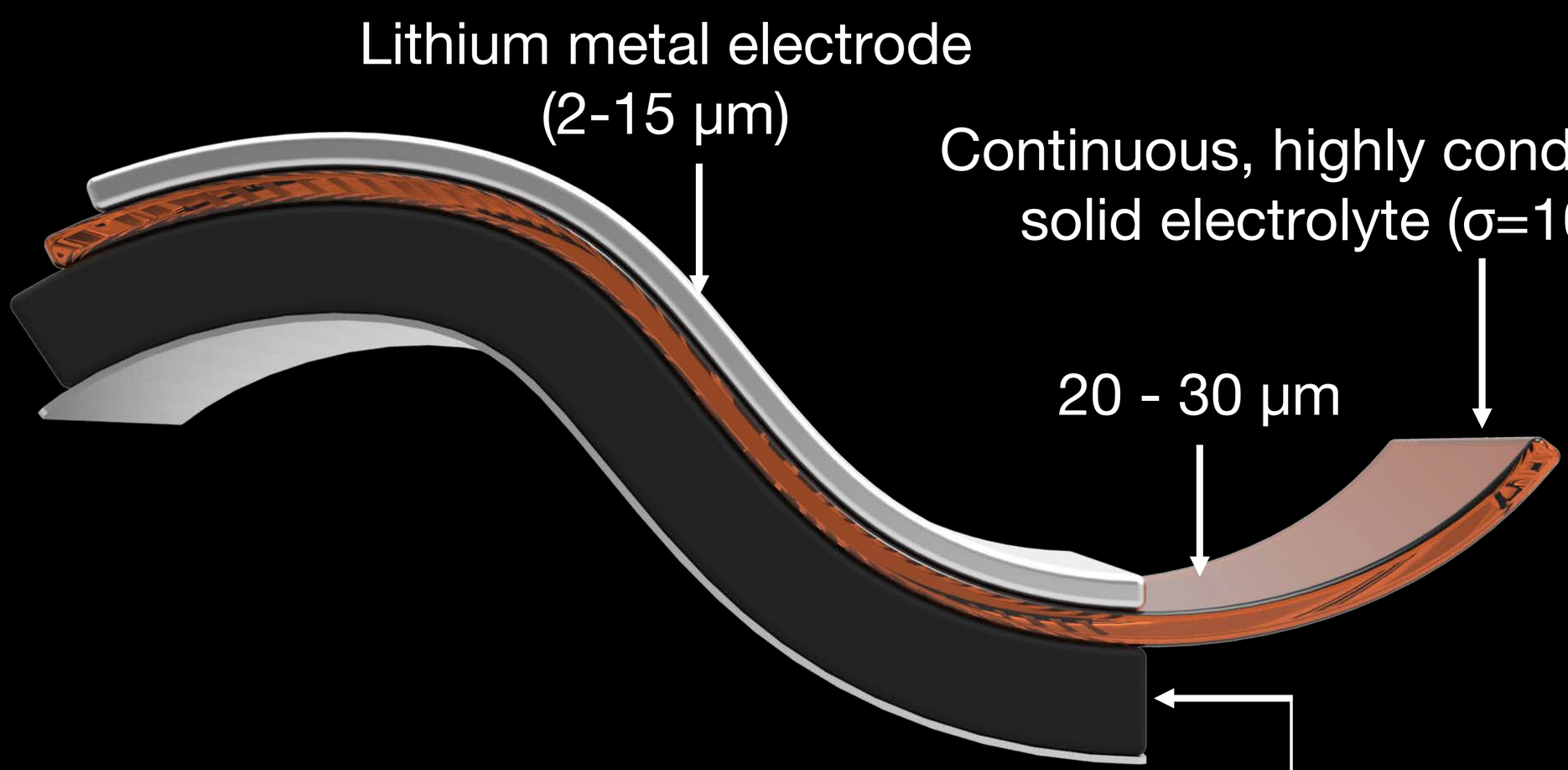


Global Consortium for Next Generation Battery



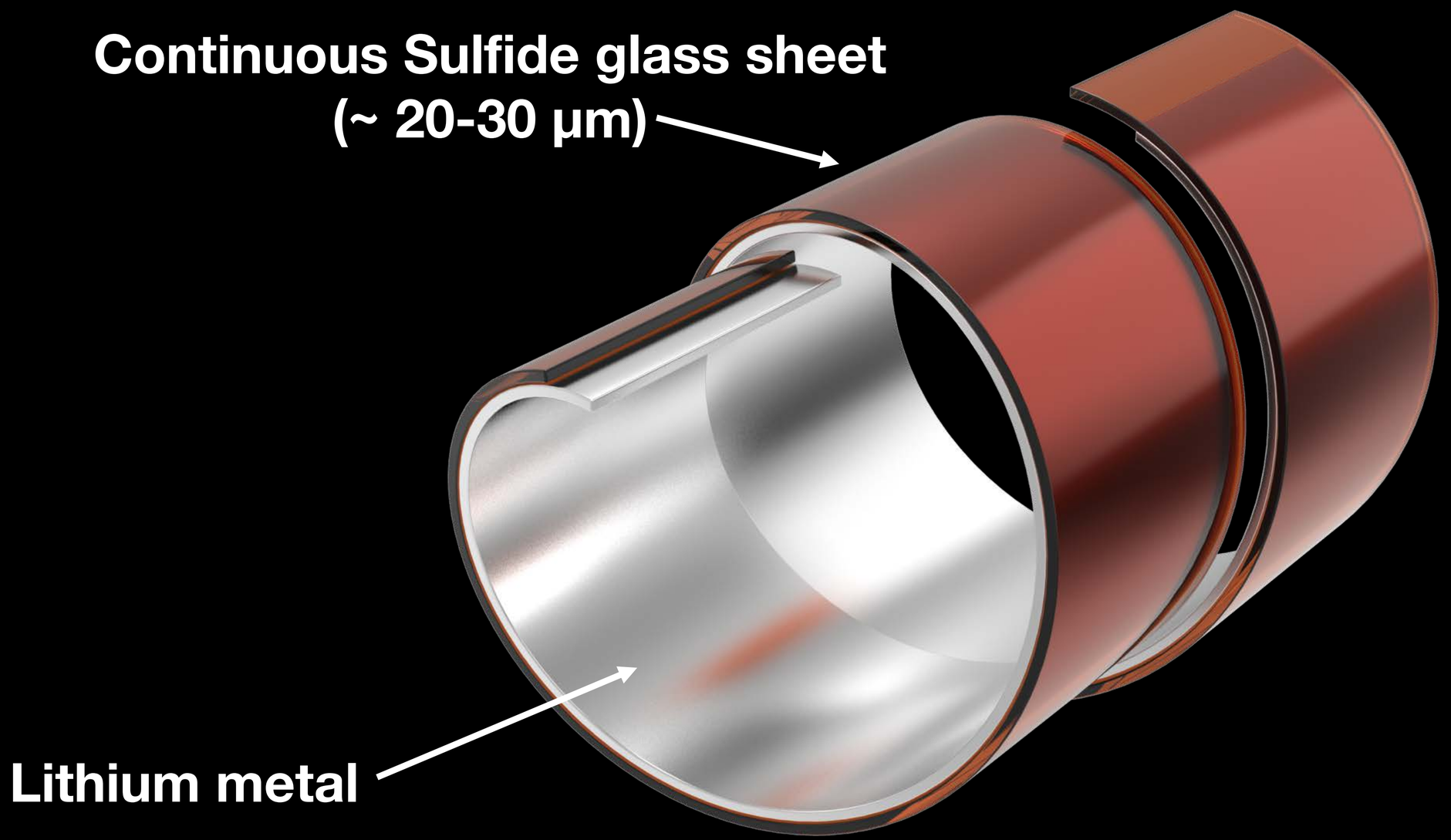
PolyPlus Battery Company
Berkeley, California

Glass Protected Li Metal Battery

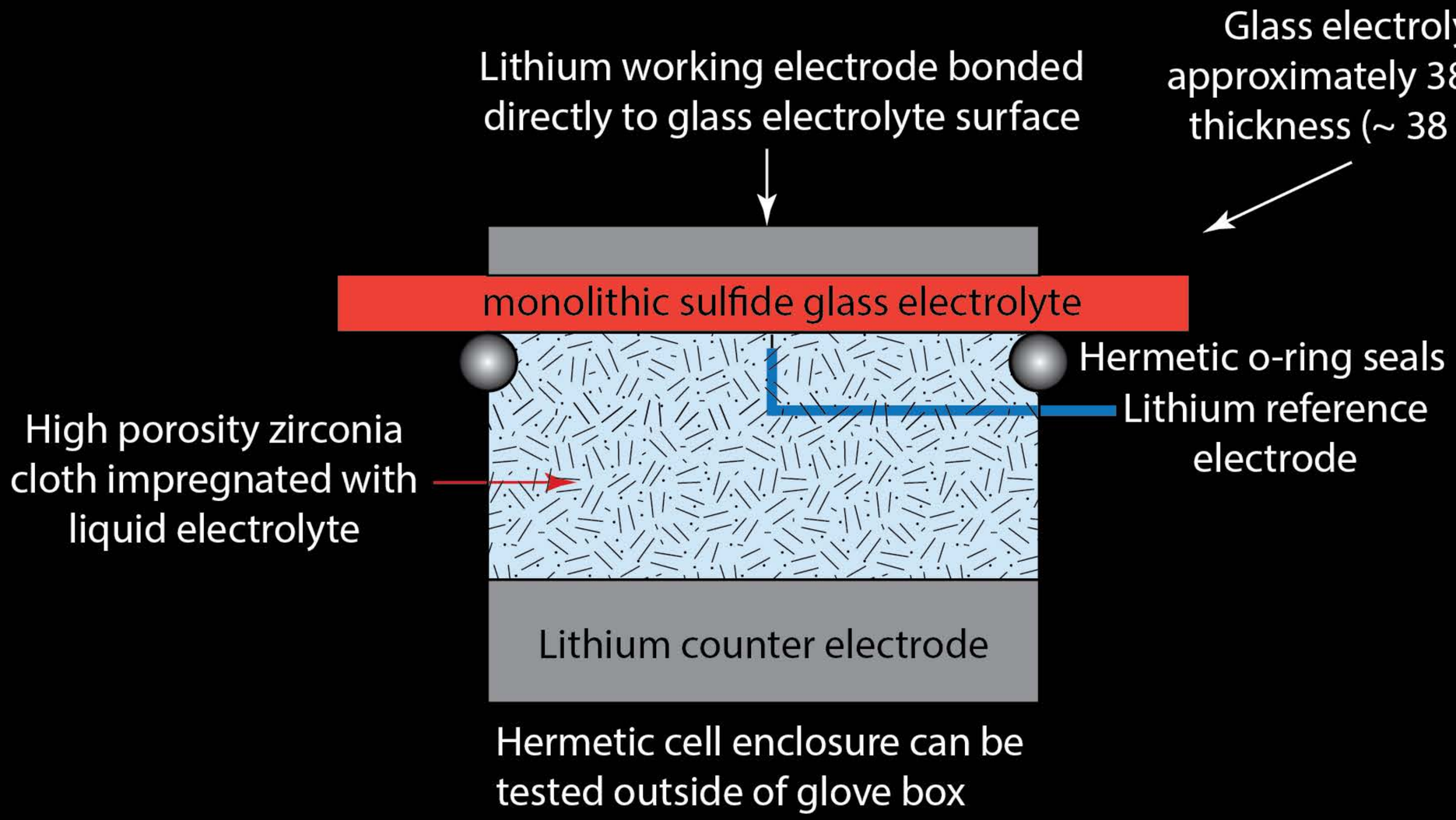



>1000.c

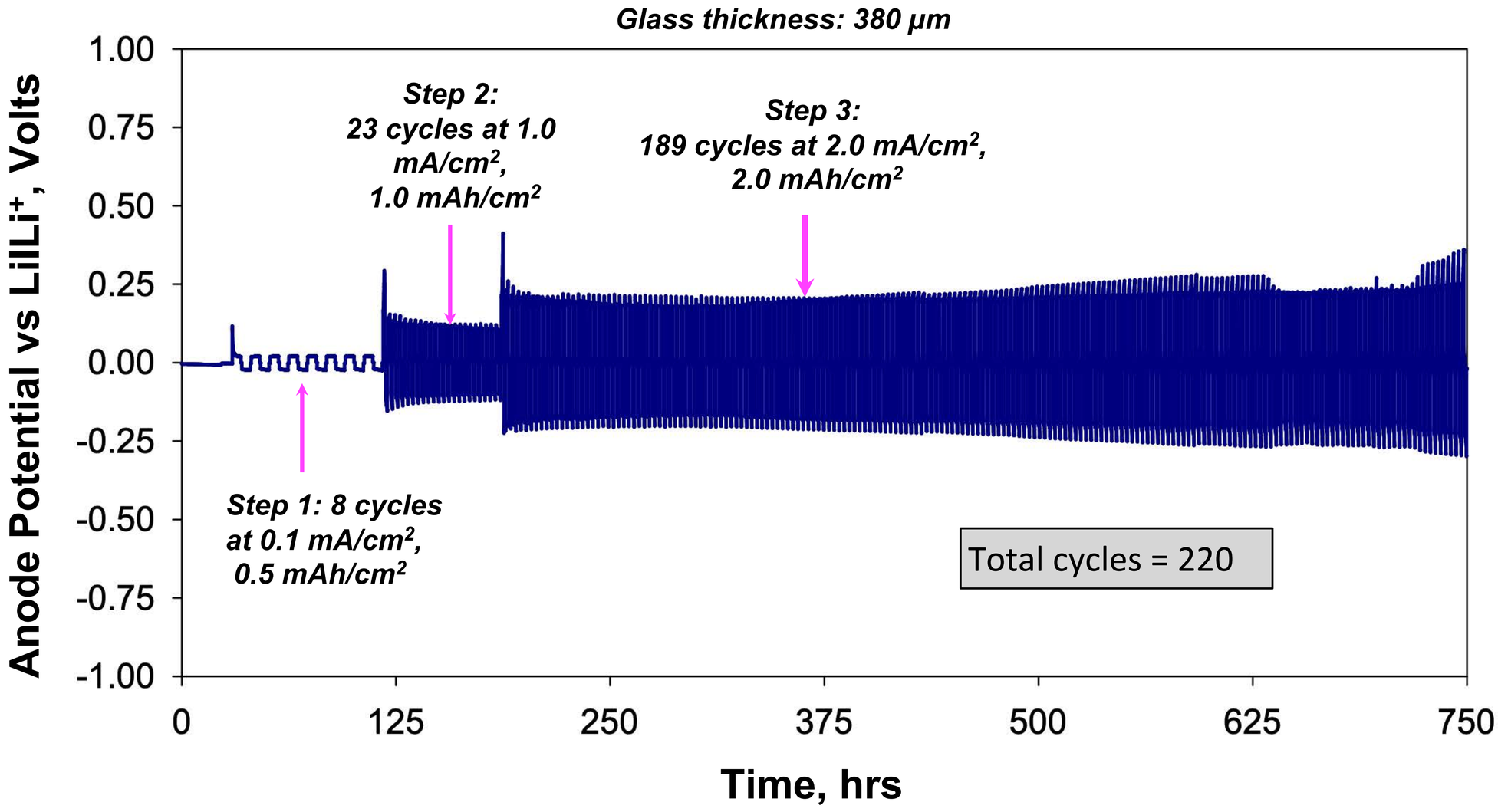
Commercialization



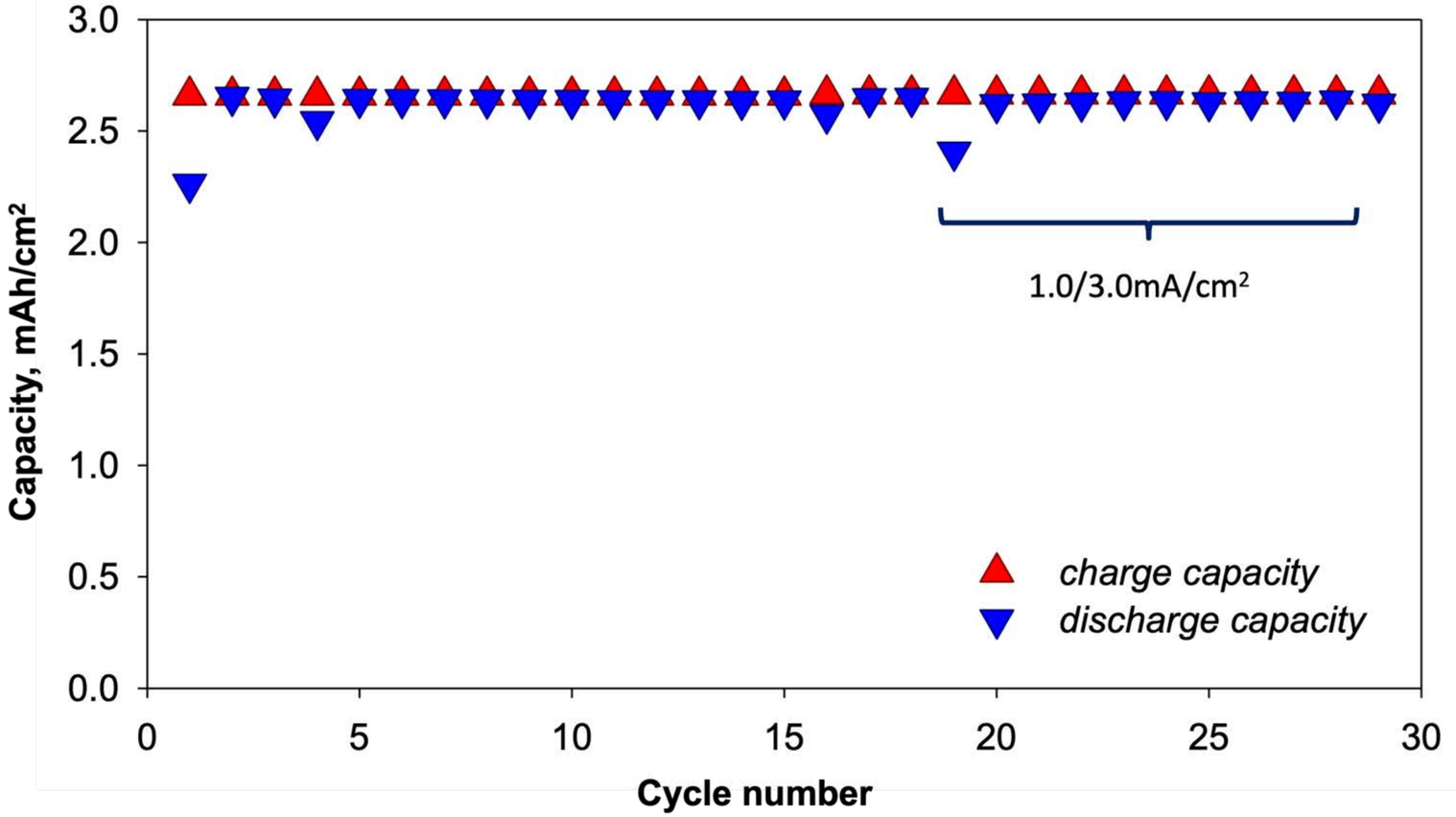
Lithium-glass/liquid-electrolyte/Li Cell Structure



Li|Li Cell with Li|Li$^+$ Ref. Electrode



Cycling of Li-NMC Cell with Li/Glass Anode

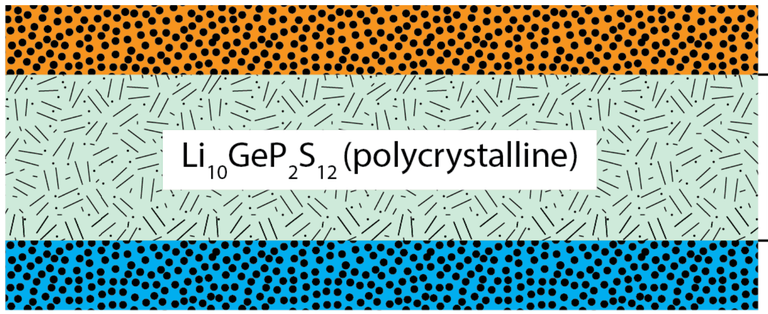


V823

All Solid-State Battery

(based on compacted amorphous sulfide powders)

$\sigma = 10^{-2}$ S/cm at RT



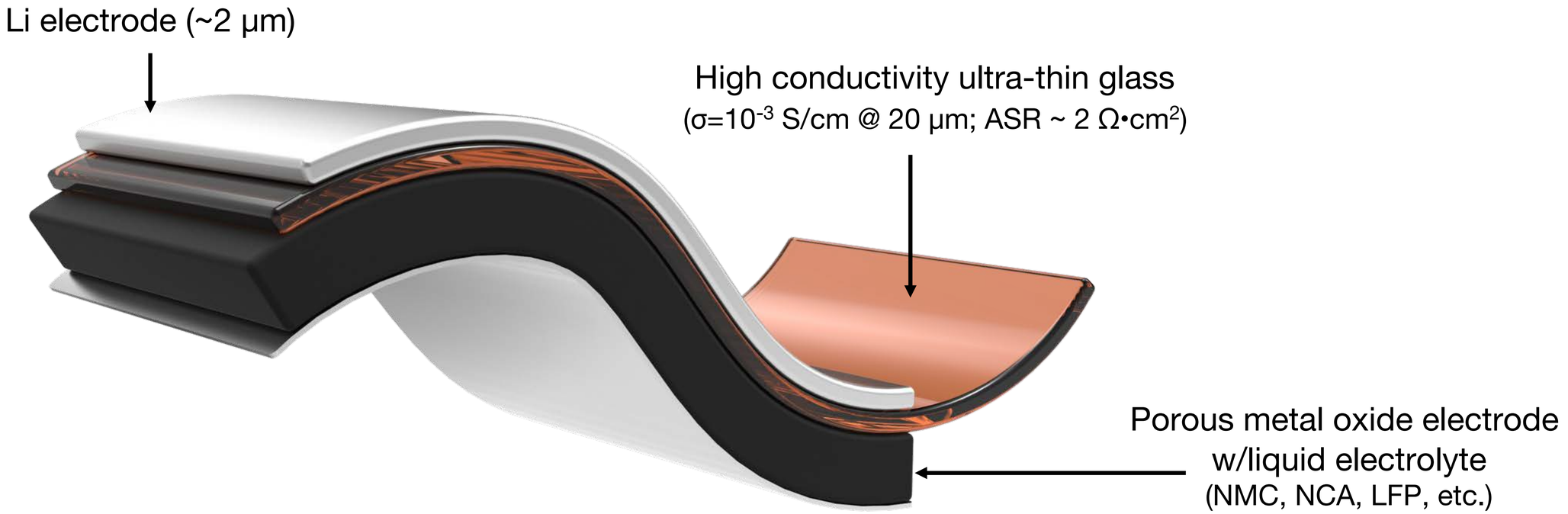
$0.75Li_2S0.25P_2S_5$ (glass) + carbon

500 microns = 5 Ωcm^2

$Li_{10}GeP_2S_{12}$ + LCO

Energy Density ~ 300 Wh/l

Ultra-high energy density battery manufacturing



Cell type	Energy Density	Specific Energy
PolyPlus Glass Battery	**1200 Wh/l**	**370 Wh/kg**
Li-ion battery	700 Wh/l	260 Wh/kg




Push the limits of what's possible with PolyPlus Consumer • Auto • Drones Robots • Medical Devices