Climate Change and technical paths to a sustainable future:
How to change the world and be cool

UC Davis Energy Graduate Group

6 October, 2017

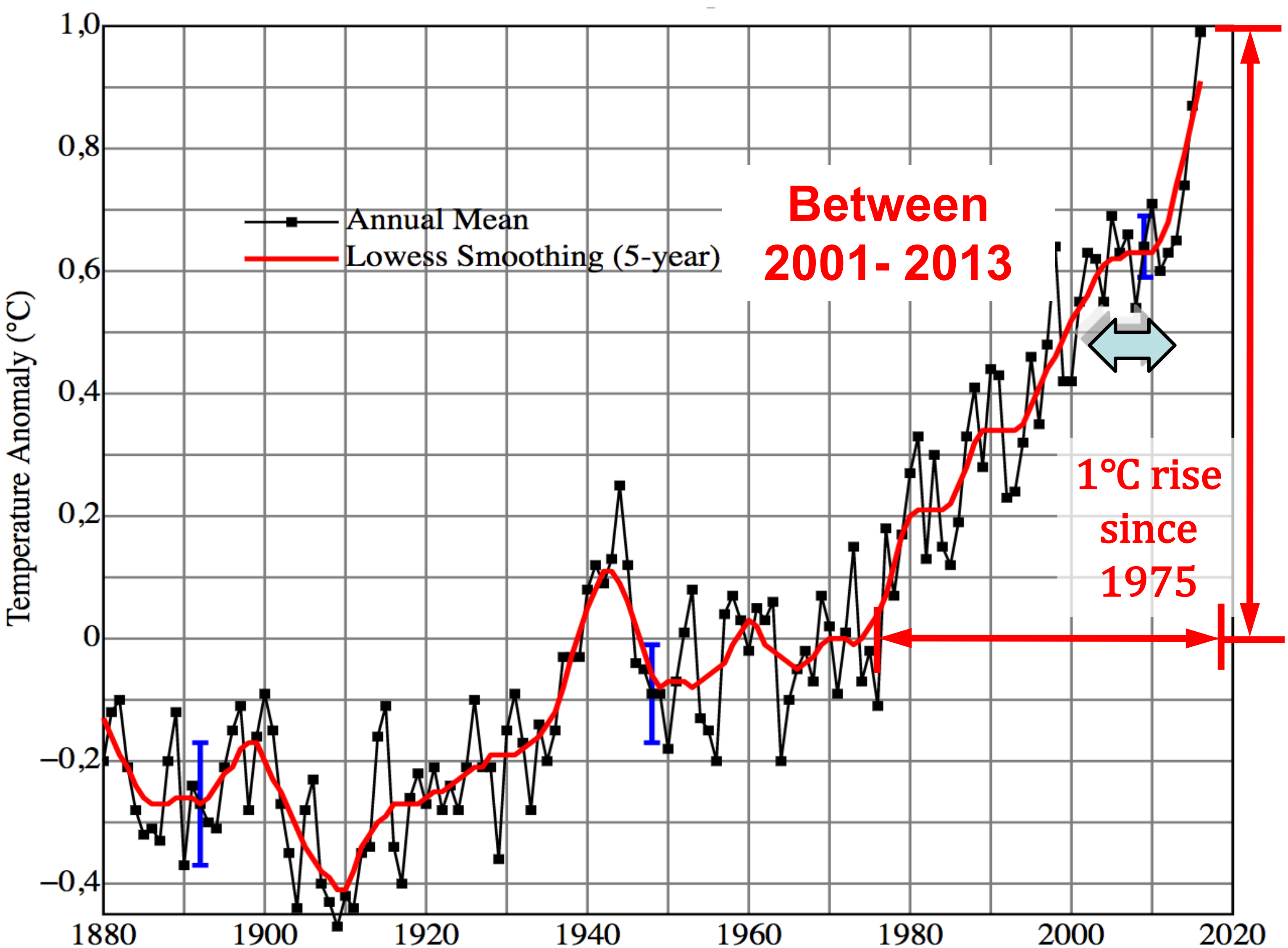
Outline of talk

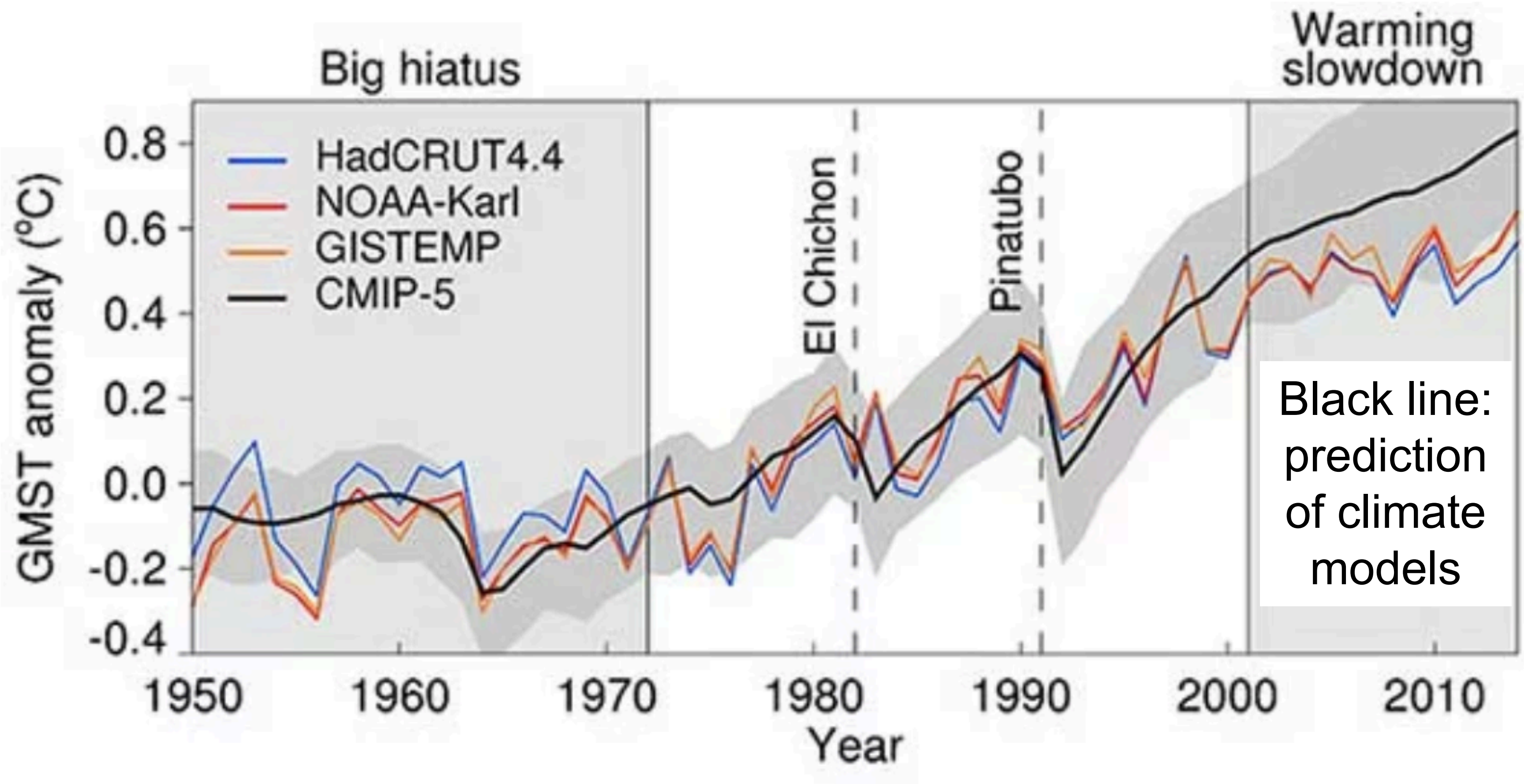
- The risks of climate change: new data
- The rapidly changing landscape of energy

Outline of talk

- The risks of climate change: new data

Global average temperature increased by 1º C since 1970





This graph shows a "slowdown" in rising temperatures until 2010. The black line shows temperatures as predicted by climate models, and the red line shows actual temperatures. Warming has recently increased, breaking historical records in 2014 and 2015.

Nature Climate Change (2016) *doi:10.1038/nclimate2938*

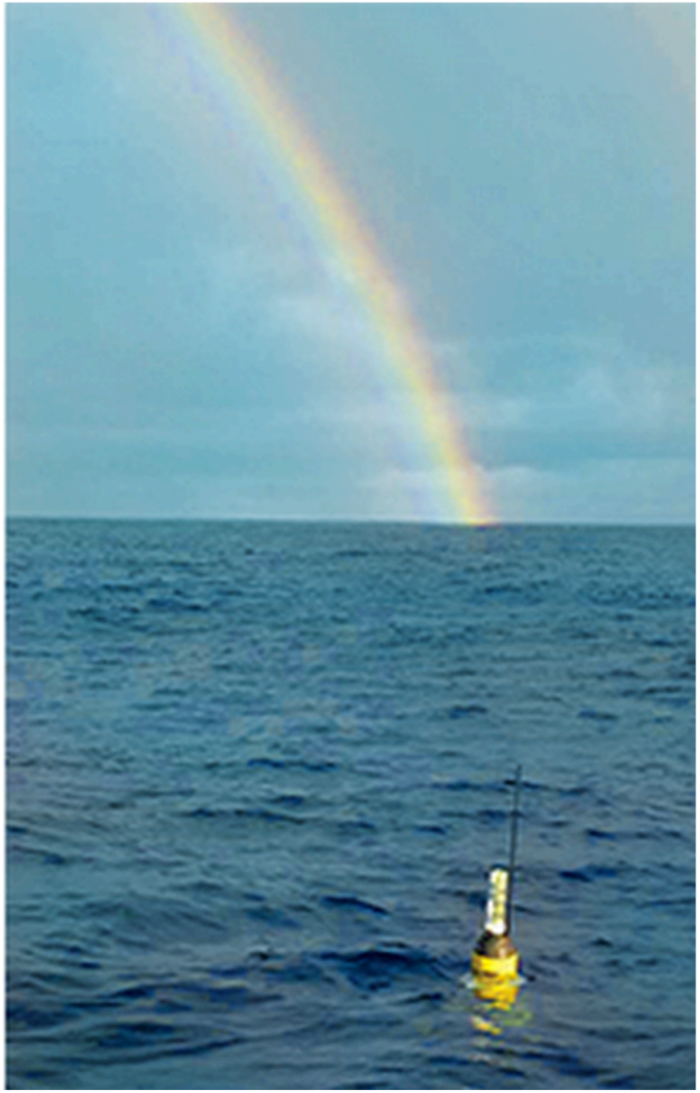
Why did the climate models miss the energy plateau?

Predicting climate change on a 10-year time frame is difficult. (e.g. details of an *el Niño* and *la Niña*

Deep Ocean thermal mixing also fluctuates

Argo Float used to measure sea temperature (0 – 2 km deep)

4 year operation, surfaces every 10 days to transmit data

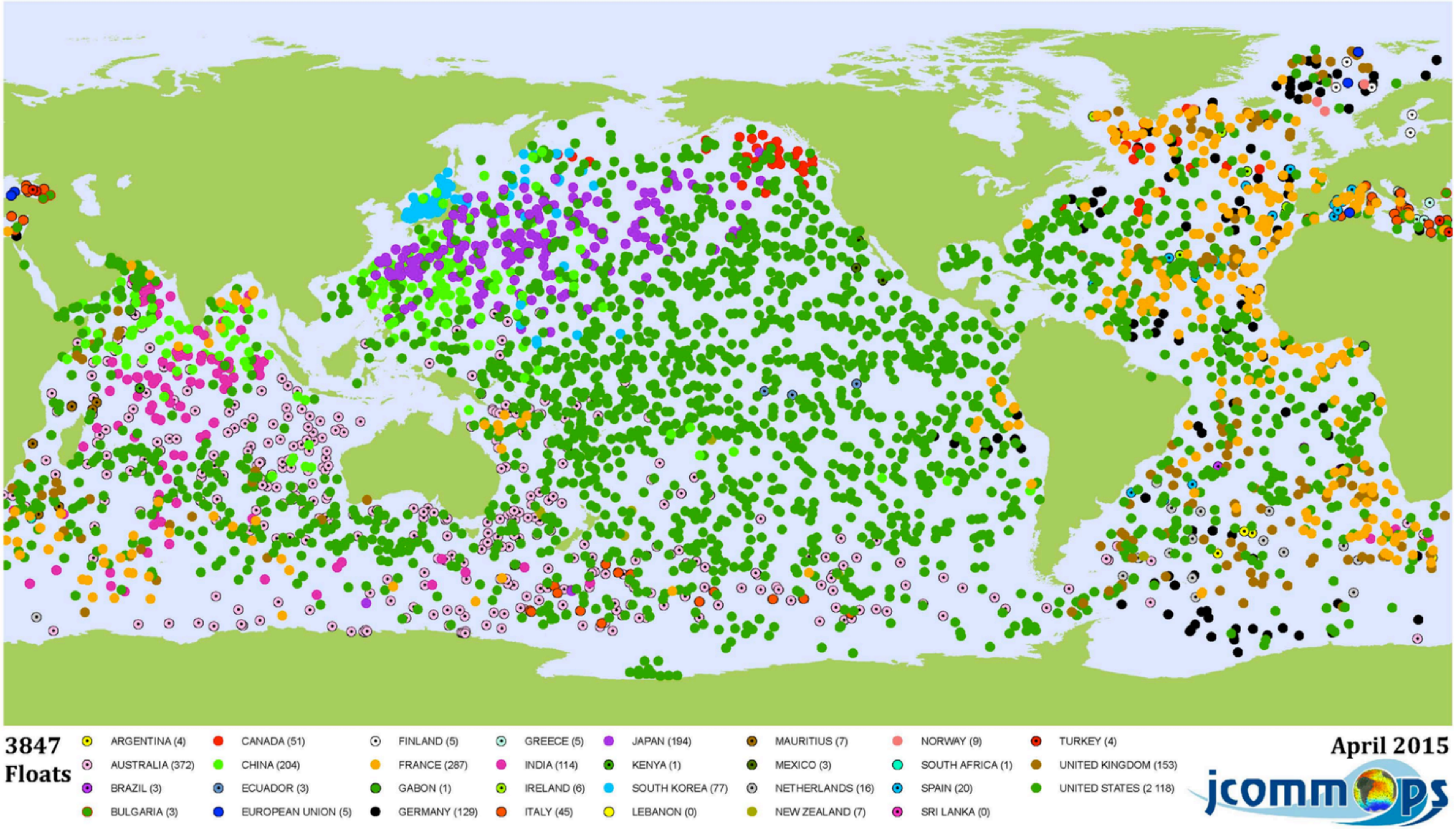


3847 Argo Floats (April, 2015)

Energy is still conserved! The heat went into heating the oceans.

Global Heat Content anomaly 0 - 2,000 m depth (2006 -2014)

D. Roemmich, et al., Nature Climate Change **5**, 240 – 245 (2015)



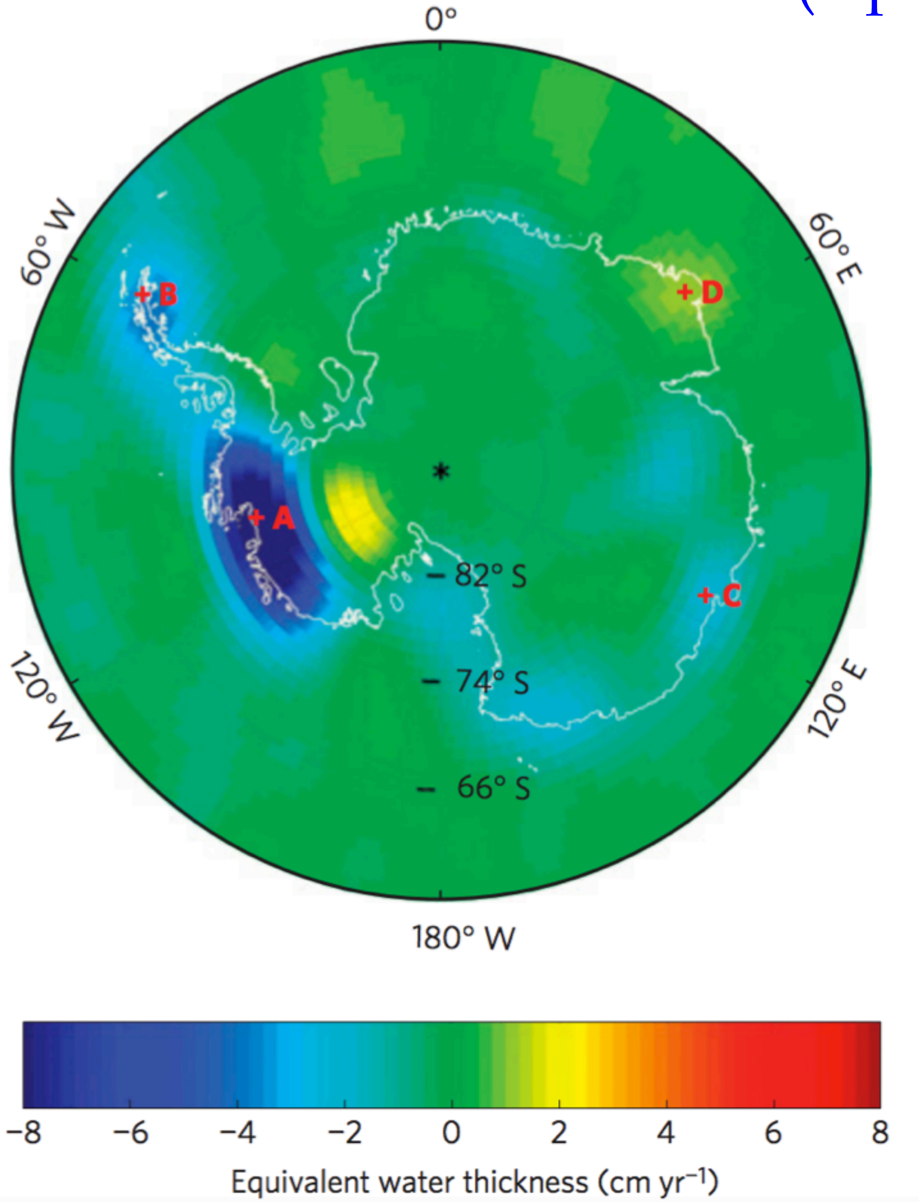
Are the glaciers melting?

Is the sea level rising?

Are the glaciers melting?
Is the sea level rising?

YES

Accelerated Antarctic ice loss from satellite gravity measurements (Apr. 2002 – Jan. 2009)

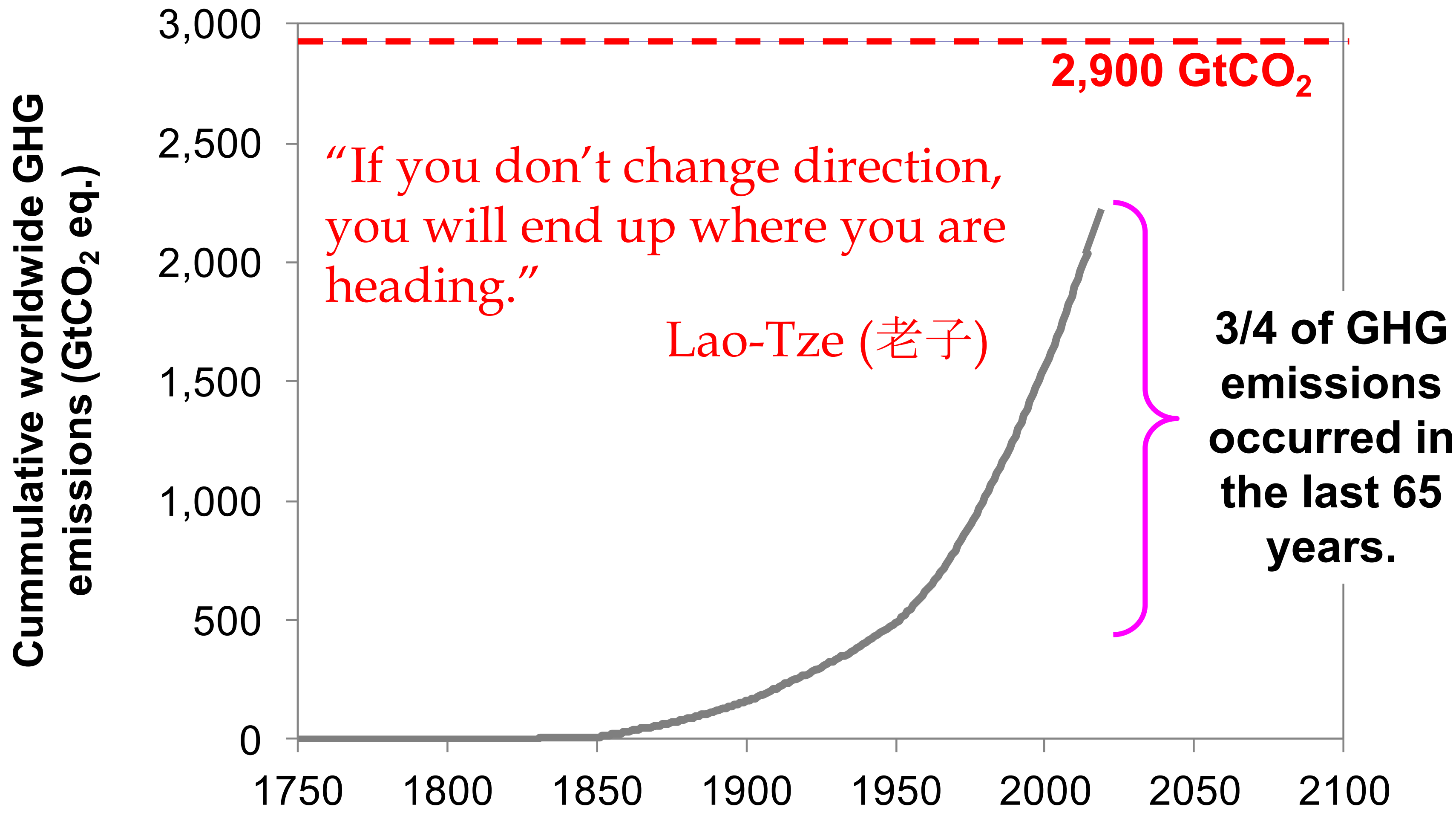


In the last interglacial period (129,000 to 116,000 years ago), the average temperature was **only** ~ 1° C warmer than today.

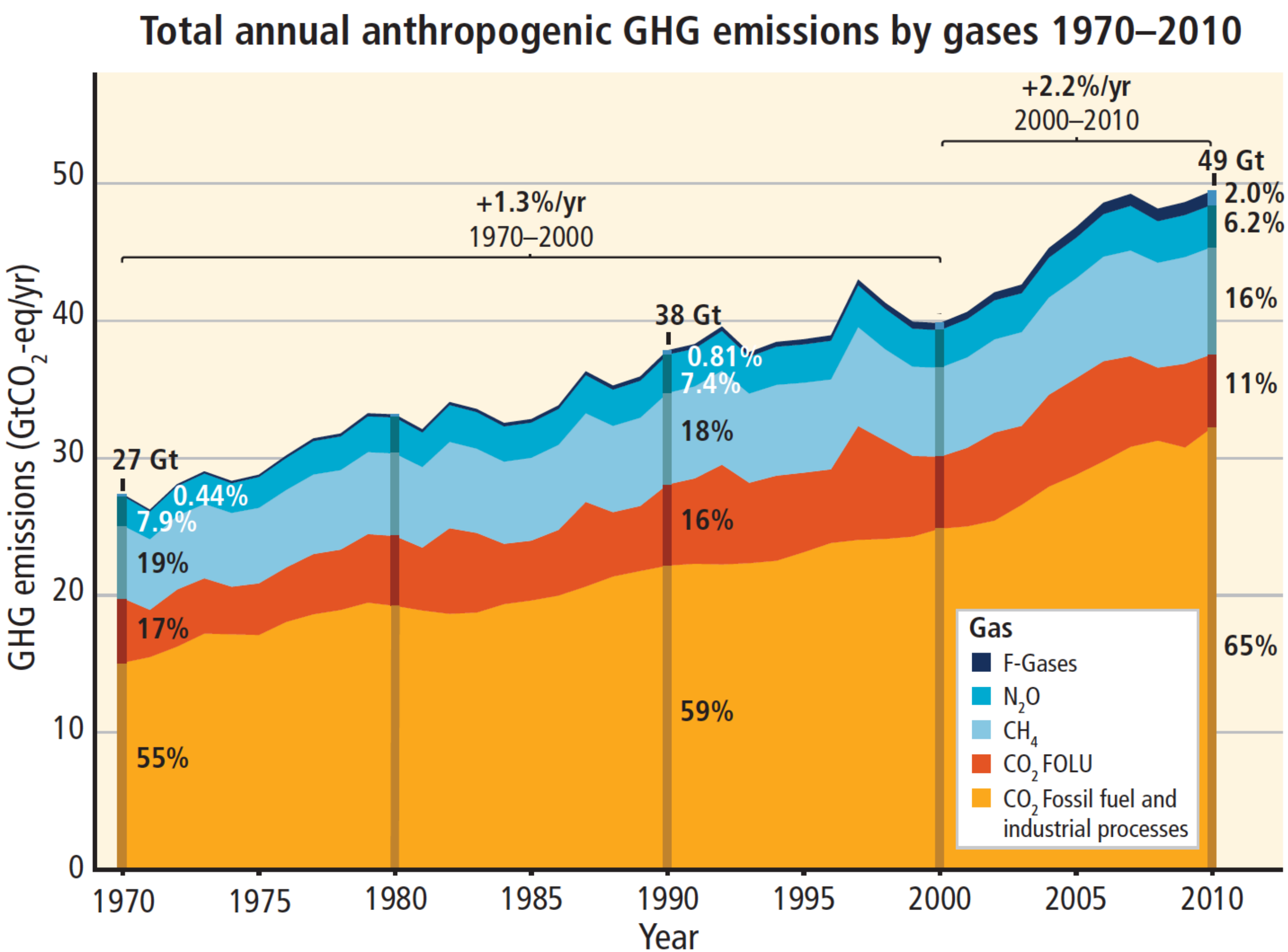
Geological records: the sea level was 6 - 9 meters higher than today. We used to believe would take 1000s of years. We now fear seas could rise 5 meters in < 100 years.

Chen, Wilson, Blankenship, Tapley, *Nature Geoscience* **2**, 859 - 862 (2009)

We are at ~ 490 ppm CO_2 equivalent today. The U.N. goal is 450 ppm to keep temperature rise to 1° C increase from today's temperature. We will go over 550 and may go over 600 ppm.



~ 30% of GHG emissions is from agriculture, land use and forestry. There is a big opportunity to use CRISPER-Cas systems + high-throughput manipulation of microbial and plant genes to increase productivity, restore soil fertility and sequester carbon.



Mostly agriculture and land use

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- The rapidly changing landscape of energy

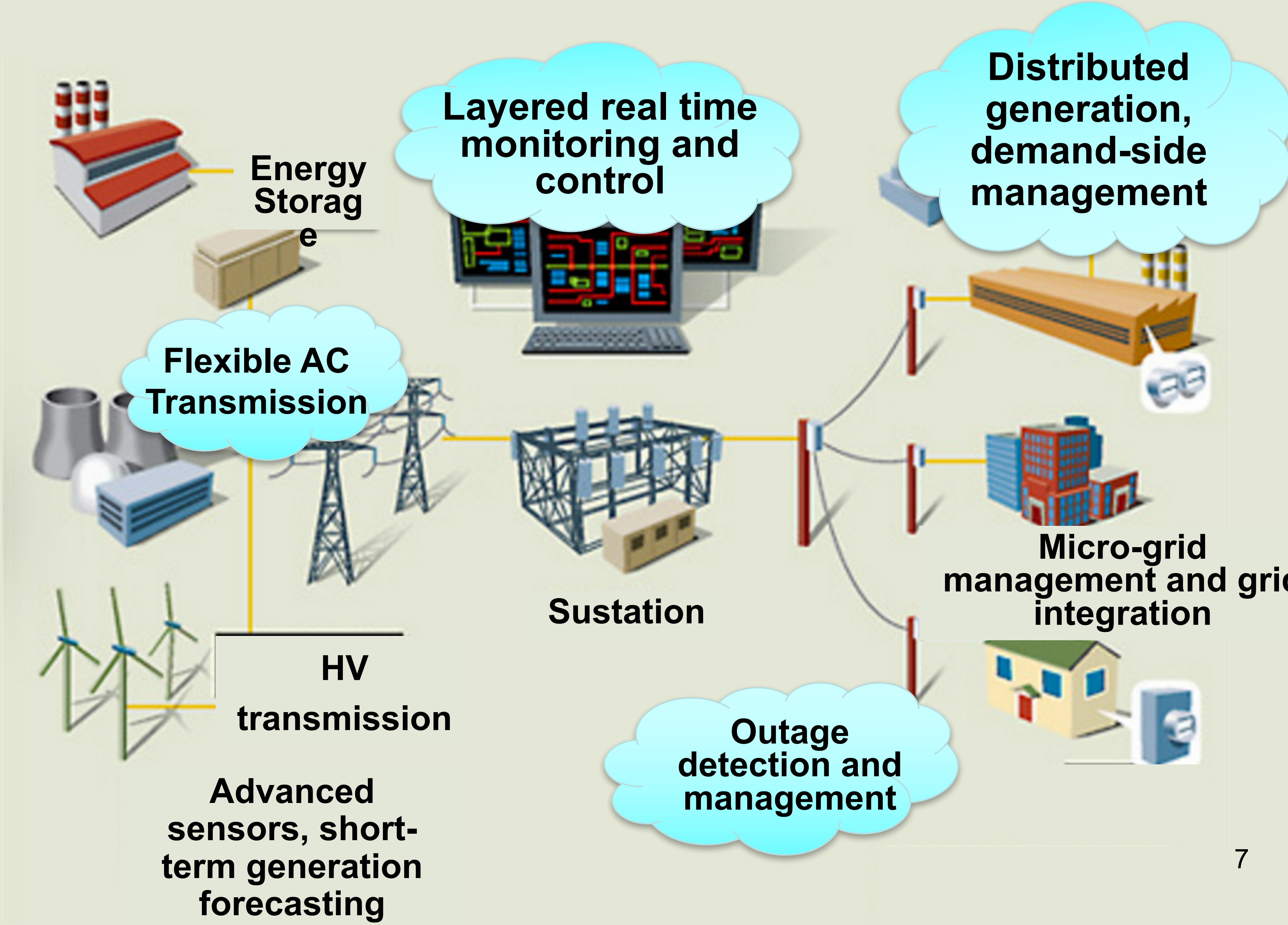
Lazard *Levelized Cost of Energy Analysis Version 10.0* (2016)
(unsubsidized costs)

Wind energy:	\$32 - \$62 /MWh
Solar utility energy:	\$46 - \$61 /MWh
Gas Combined Cycle:	\$48 - \$78/MWh

Renewable energy costs (L.C.O.E.) at the best sites around the world is likely to achieve 3 ¢/kWh by 2020.

Costs may continue to decline to 2 ¢/kWh by 2030

Machine Learning can be used to manage electricity distribution, learn patterns of energy use, improve weather predictions and more.



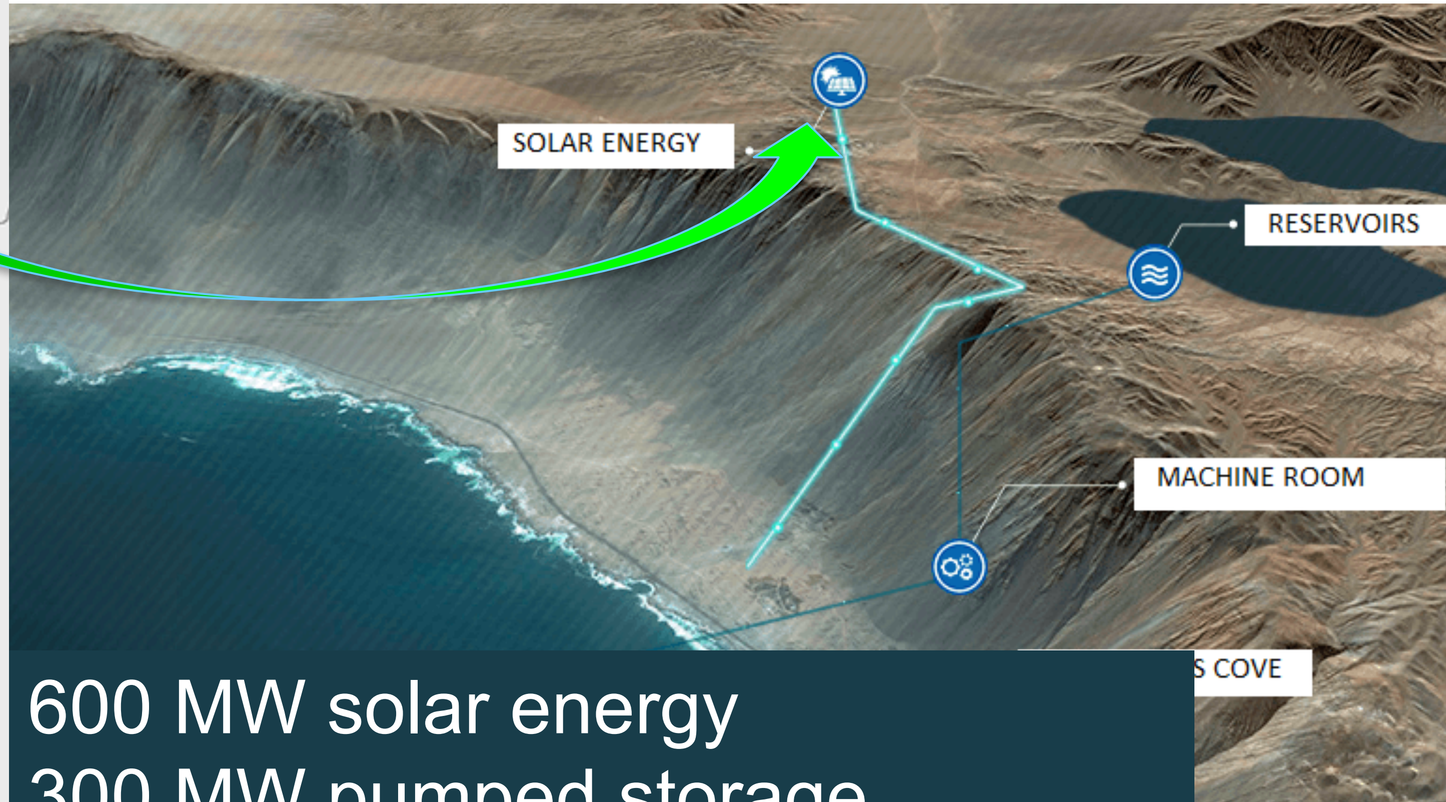
Energy Storage

Progress in Batteries and other forms of energy storage

Pump water when the wind blows or the sun shines

VALHALLA

Chile Solar farm and pumped storage

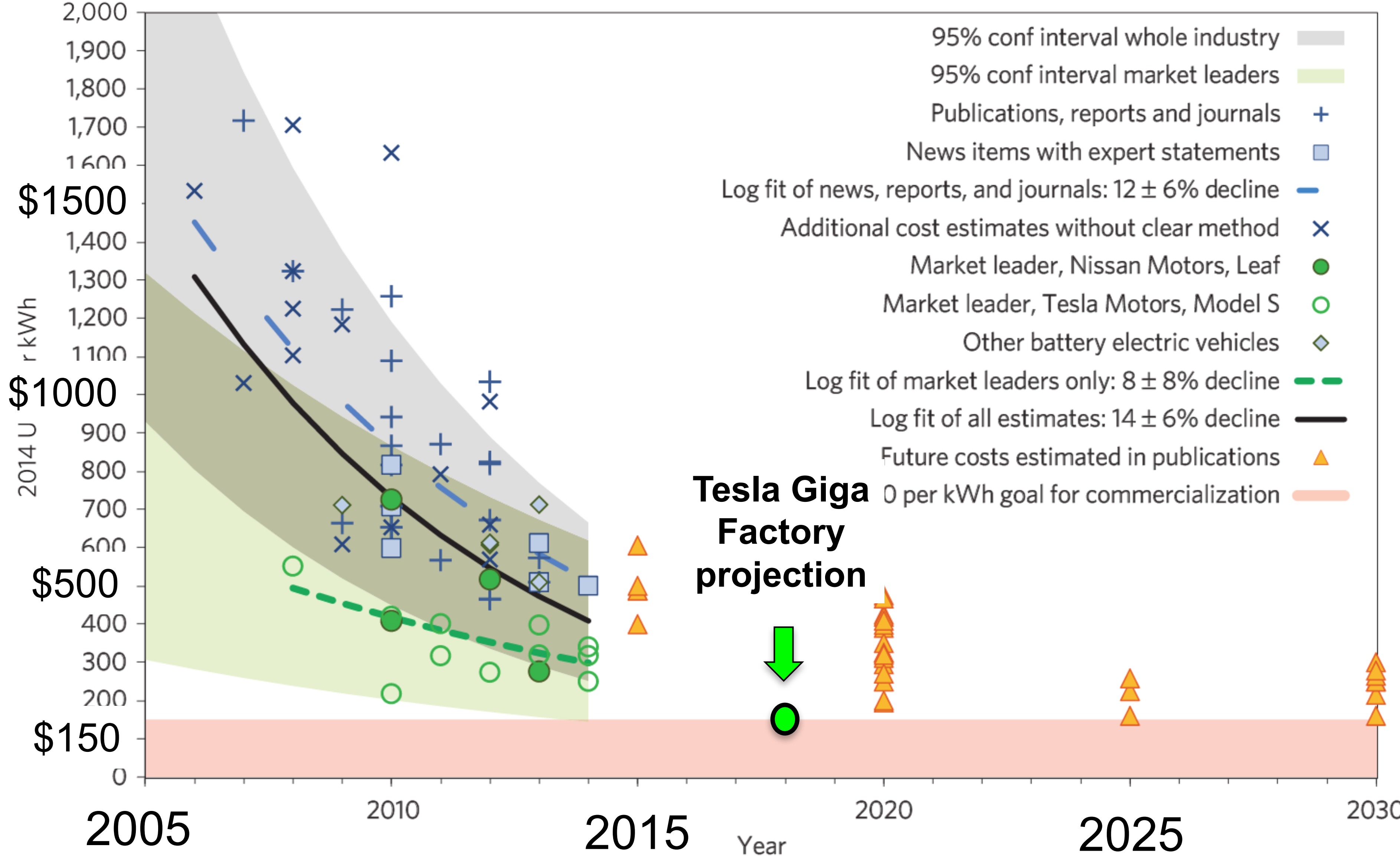


600 MW solar energy
300 MW pumped storage
(@ $1.30/W)

Stanford Energy System Innovations (SESI) project

Thermal storage: Two 5 M gallon cold water tanks, one 2.3-million-gallon hot water tank

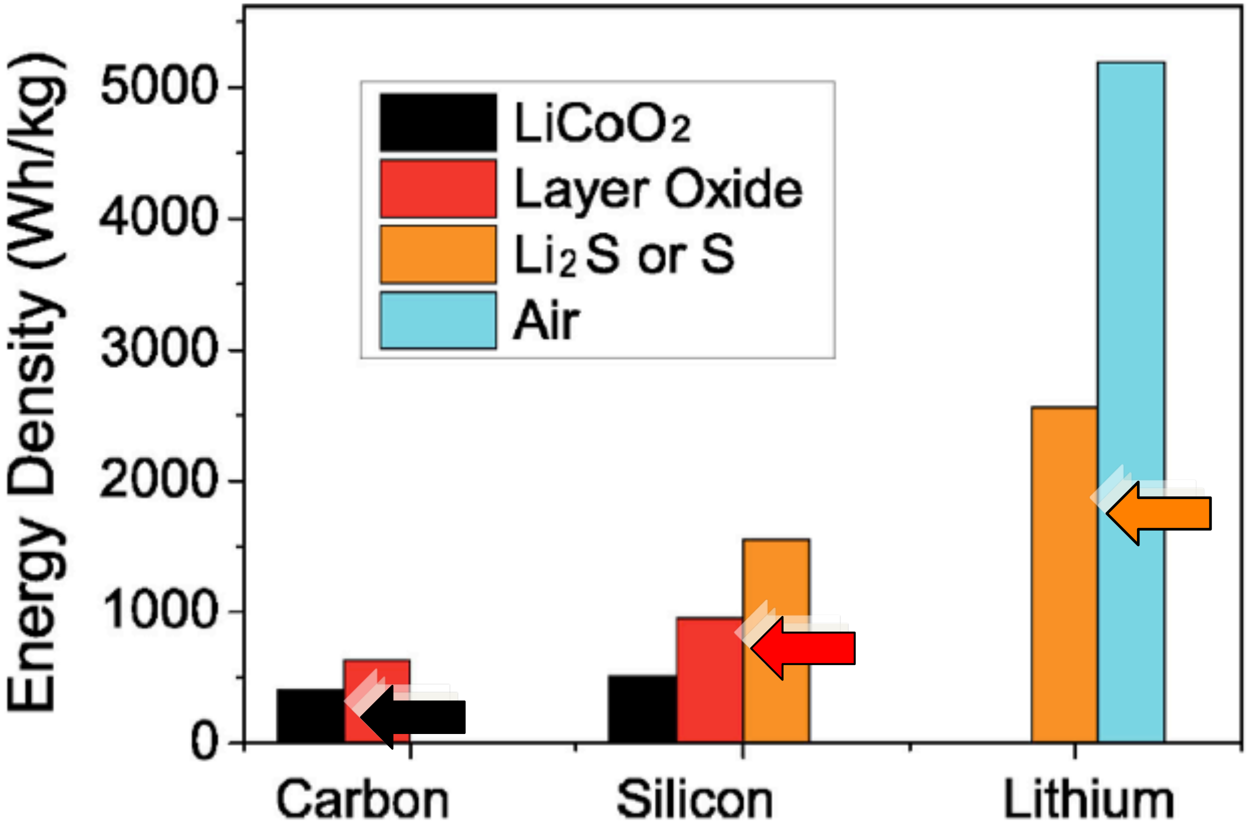
The cost of lithium ion batteries for electric vehicles are expected to drop to 10% of the 2006 price.



Yi Cui
Materials Science Department, Stanford University

Yi and I are seeking a new generation of lithium metal - batteries that may increase the energy density and **charging rate** 4x.

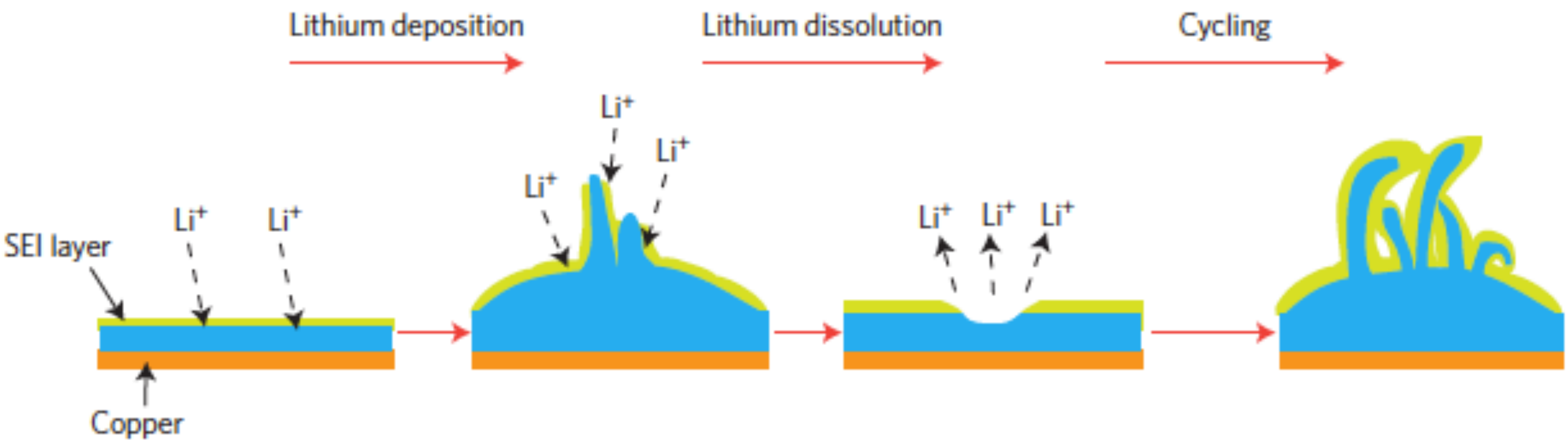
Maximum theoretical energy density



amprius

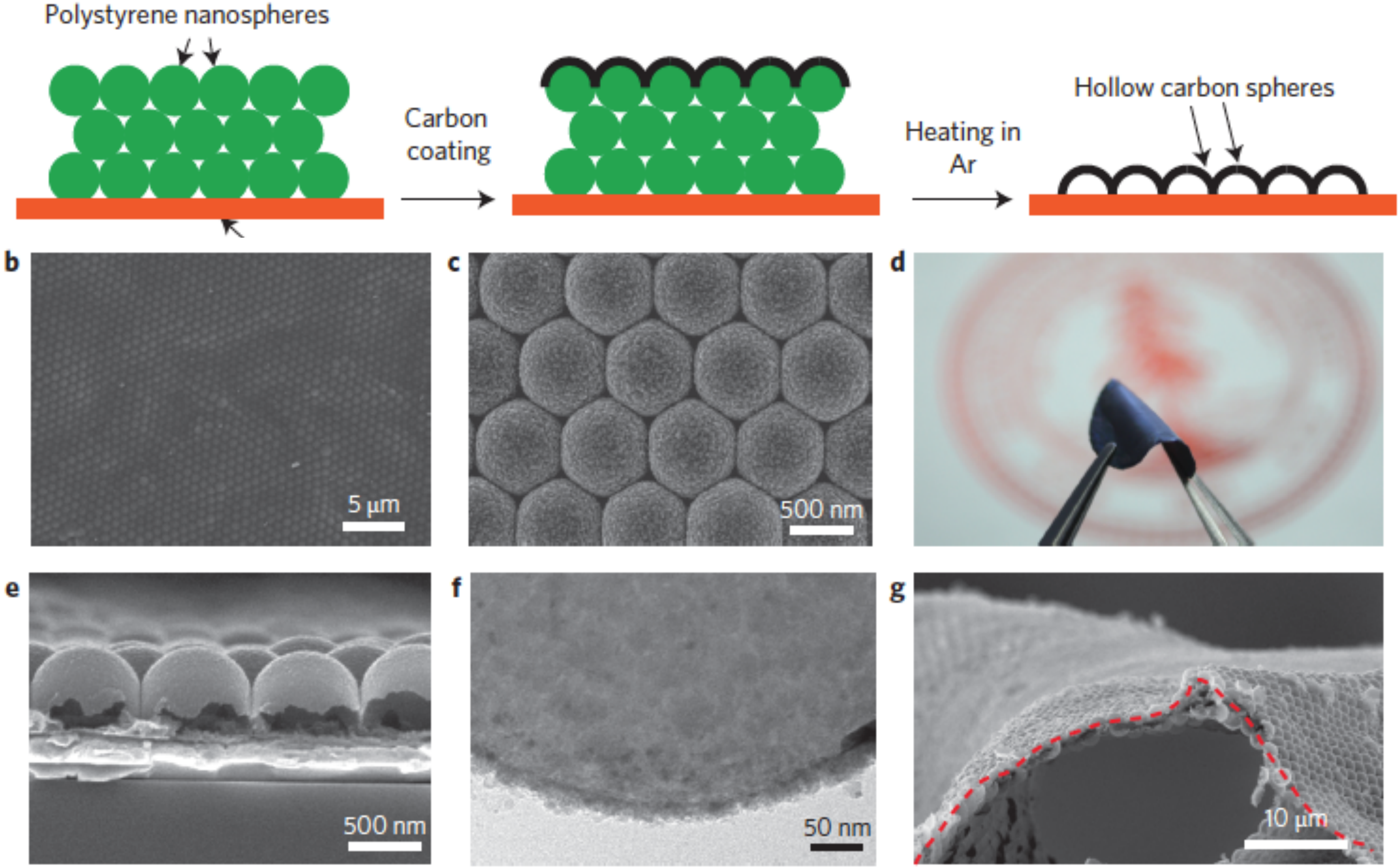
Silicon Anode manufacturing tool
(achieving world record results)

Nanoscale Interfacial Materials Design

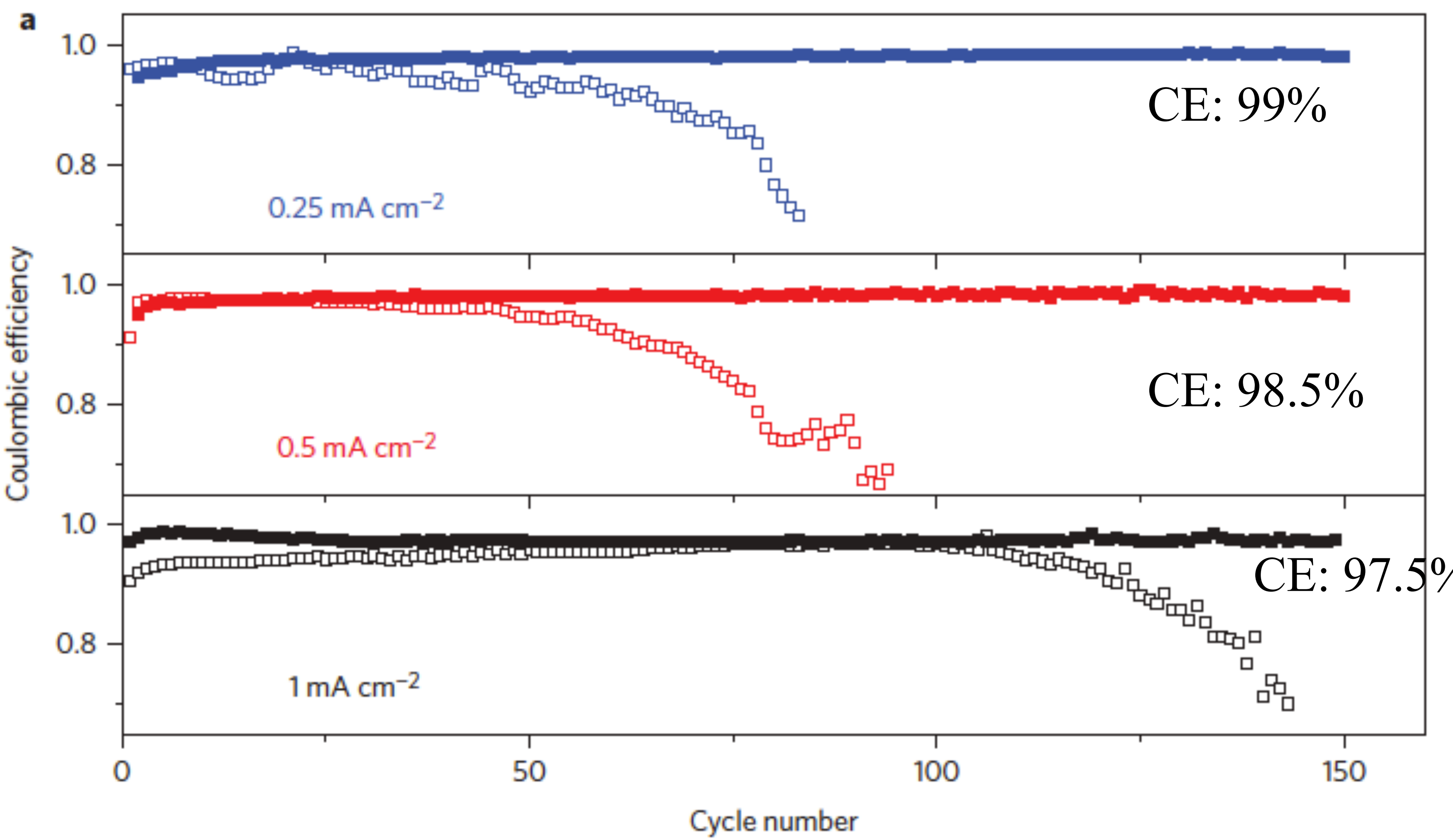


Guangyuan Zheng, … Steven Chu, Yi Cui . *Nature Nanotechnology* 9, 618 (2014).

Interconnected Hollow Carbon Sphere Fabrication



Guangyuan Zheng, Steven Chu, Yi Cui . *Nature Nanotechnology* 9, 618 (2014).



1 M LiTFSI in DOL:DME w/ 2% $LiNO_3$

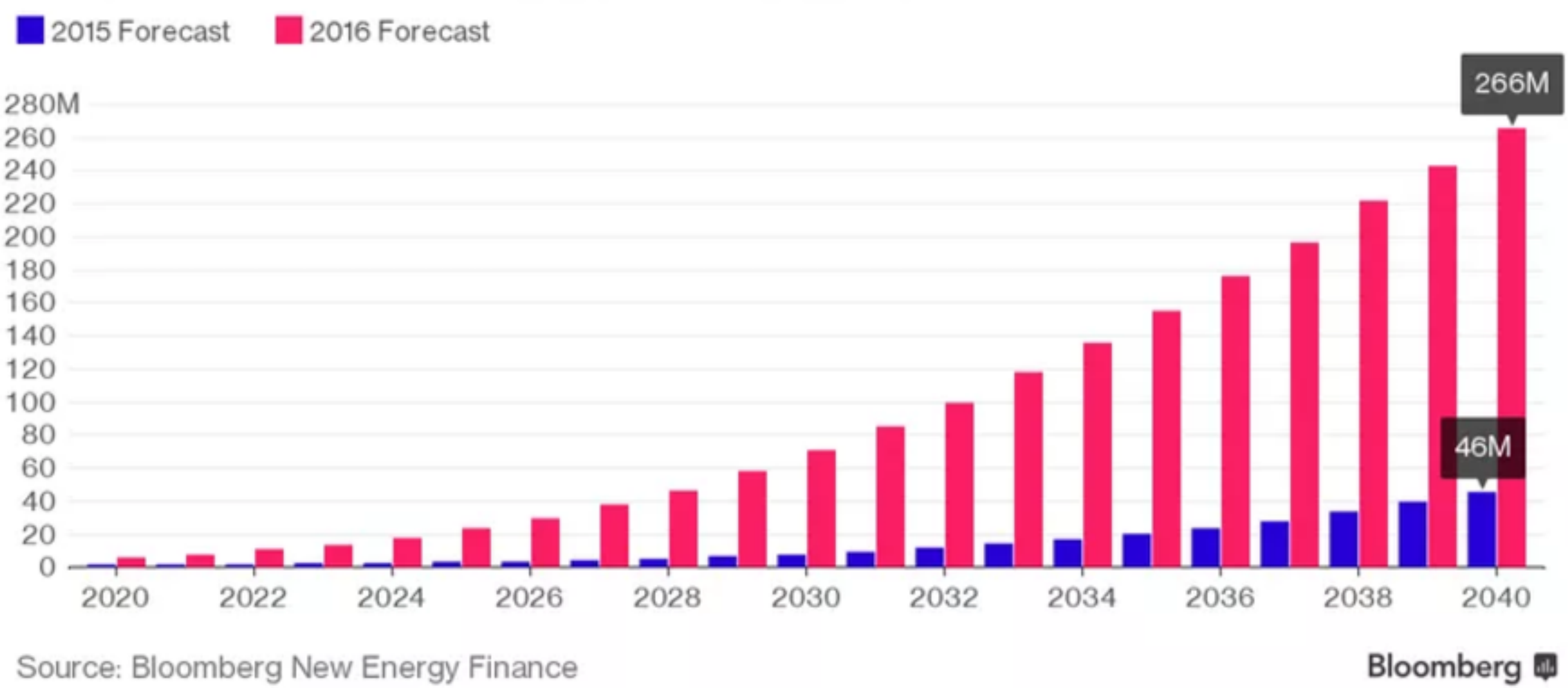
Guangyuan Zheng, Steven Chu, Yi Cui . *Nature Nanotechnology* 9, 618 (2014).

2015 and 2016 forecasts of electric vehicles sales

500% increase in sales estimate in 1 year

By 2032, 100 million EVs on the road?

By 2040, EVs may be 35% of car sales ~ 35 - 40 million EVs/year



http://fortune.com/2017/01/11/chinas-tesla-electric-cars/

The gasoline-powered internal combustion engine rapidly replace horse powered vehicles.

New York, 5th Avenue, ~1890s

Detroit, circa 1920

Automobile technology ultimately proved to be superior, but required a oil-gasoline supply chain, paved roads, and other infrastructure.

A serious environmental pollution issue hastened the transition.

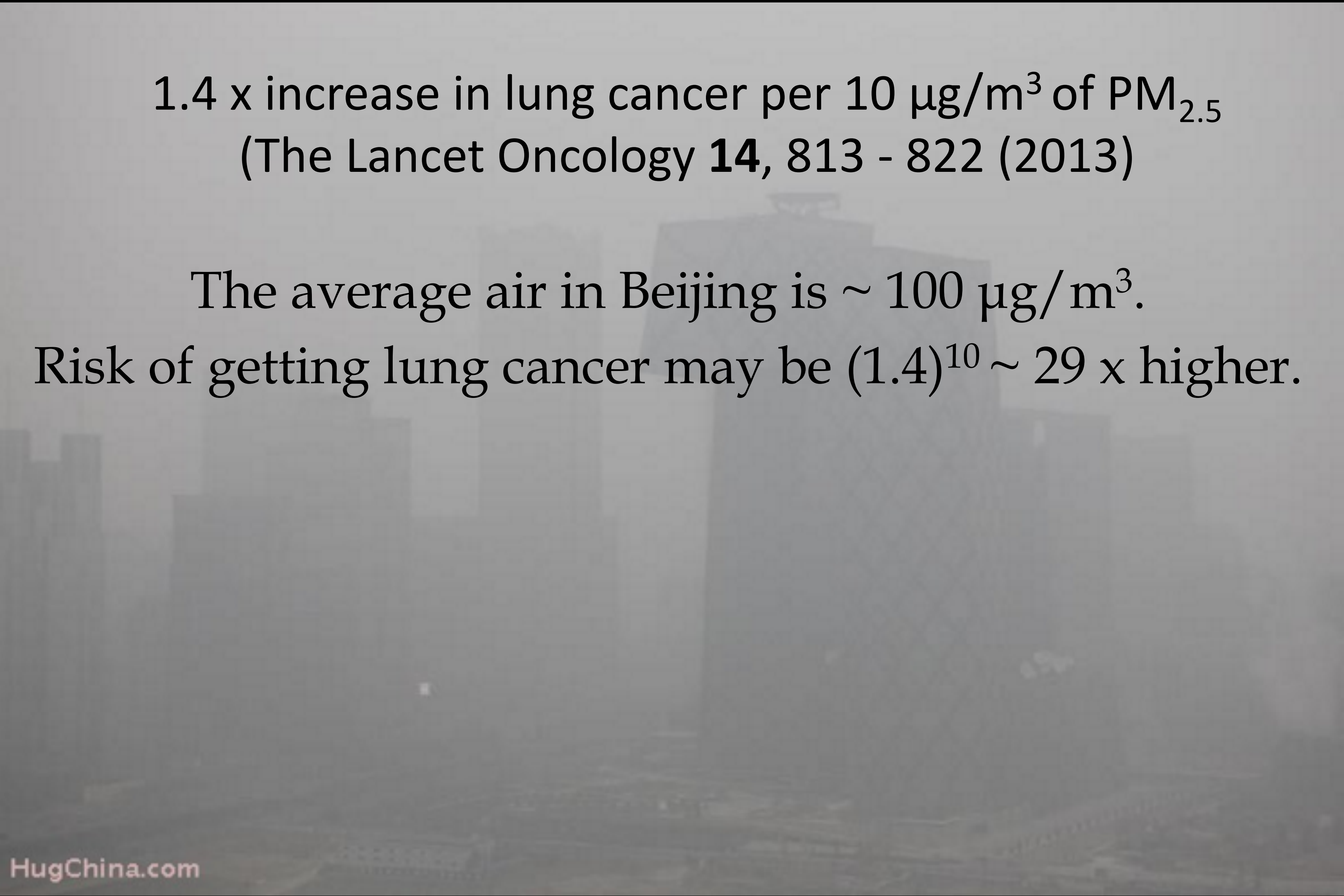
The ~160,000 horses in New York in 1880 were producing 3 - 4 millions pounds of horse manure and 40,000 gallons urine a day.

Air pollution

Particulate matter $PM_{2.5}$ (diameter < 2.5 μm) is especially deadly.

1.4 x increase in lung cancer per 10 μg/m^3 of $PM_{2.5}$
(The Lancet Oncology **14**, 813 - 822 (2013))

The average air in Beijing is ~ 100 μg/m^3.
Risk of getting lung cancer may be $(1.4)^{10} \sim 29$ x higher.



Nanofiber filtration: 98% filtration of $PM_{2.5}$ with 30% light transmission

a

b

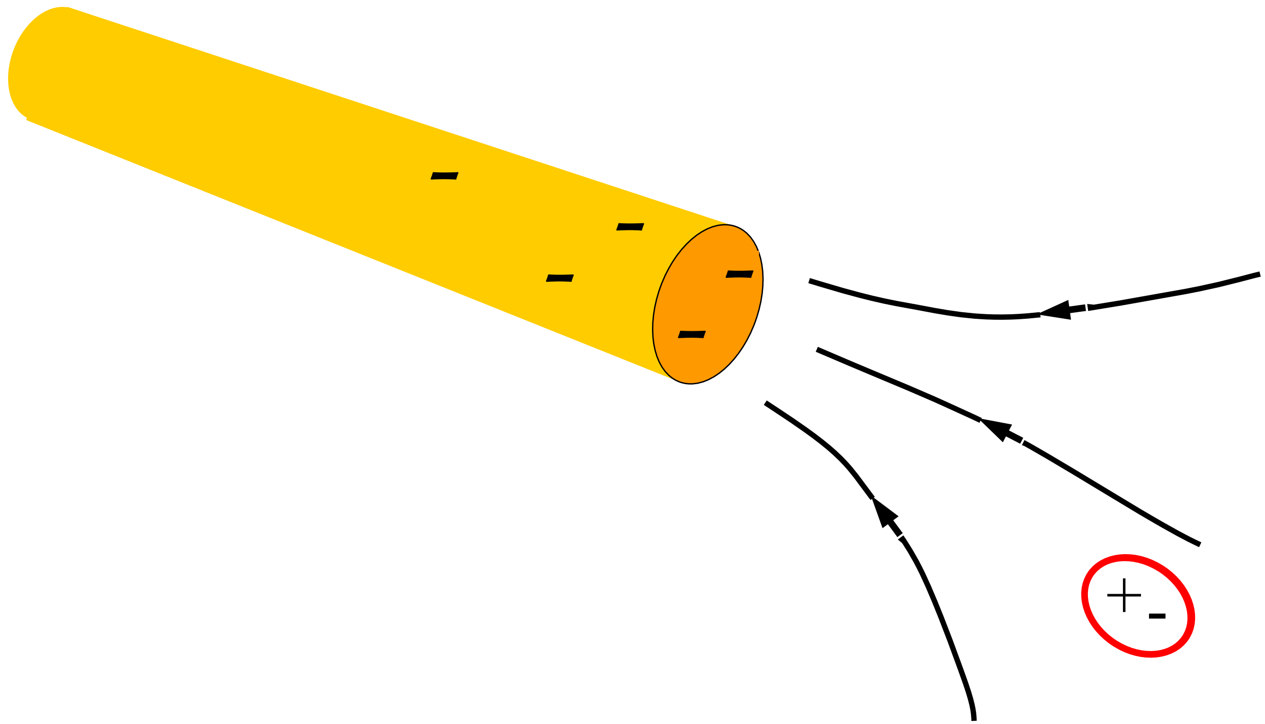
Prof Yi Cui and I have started a company to quickly commercialize the production of the filter material that can be used in home and building filters, face masks, coal plants, and vehicle exhaust systems.

0.0 0.2 0.4 0.6 0.8 1.0
Transmittance

0.0 0.2 0.4 0.6 0.8 1.0
Transmittance

Transparent air filter for high-efficiency PM2.5 capture,
Chong Liu, Po-Chun Hsu, … Yi Cui, Nature (2015)

A lesson in static electricity

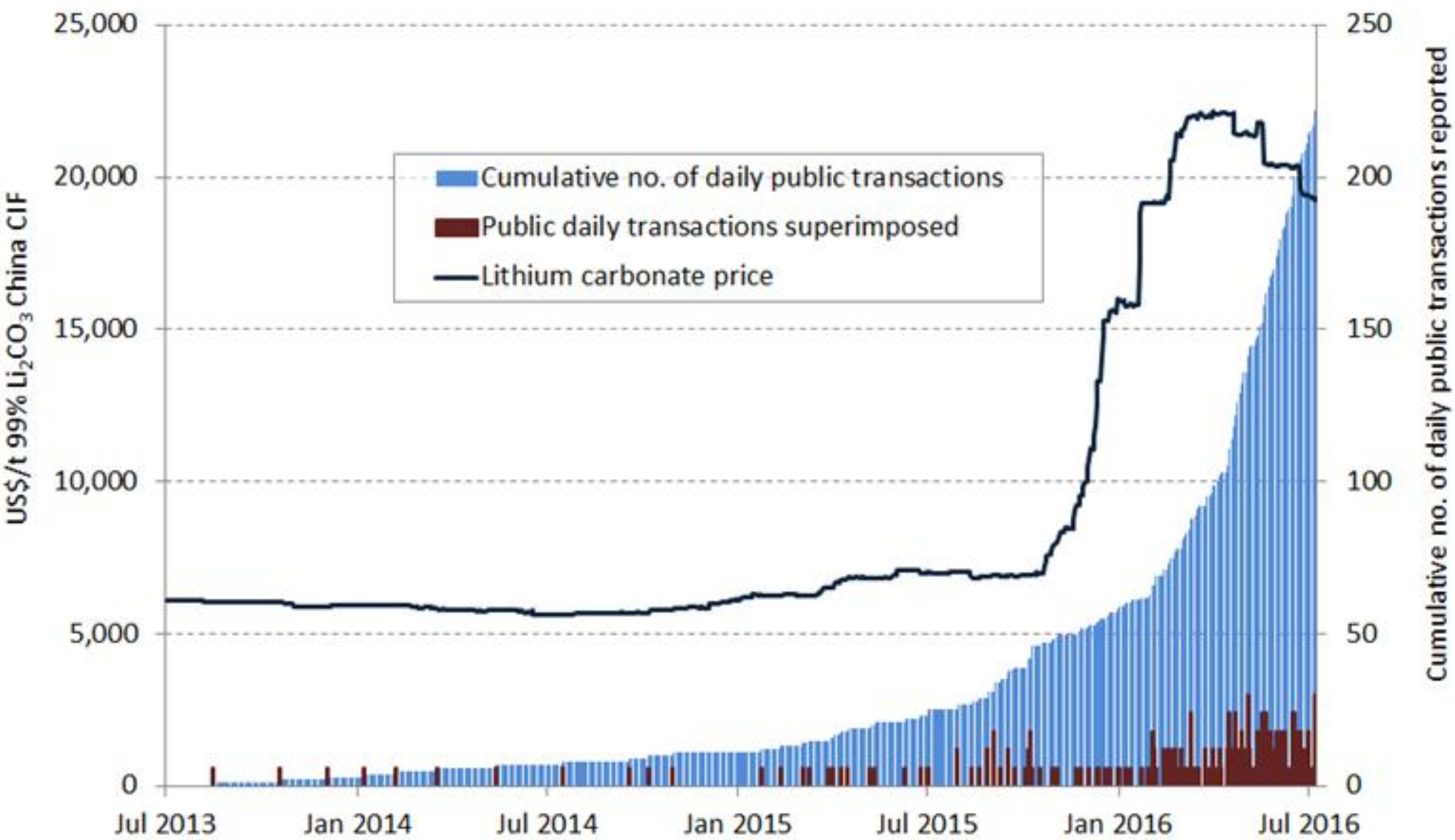


The particle is attracted to where the electric field is strongest

Clean electricity at 2 – 3 ¢/kWh opens up exciting opportunities in electrochemistry

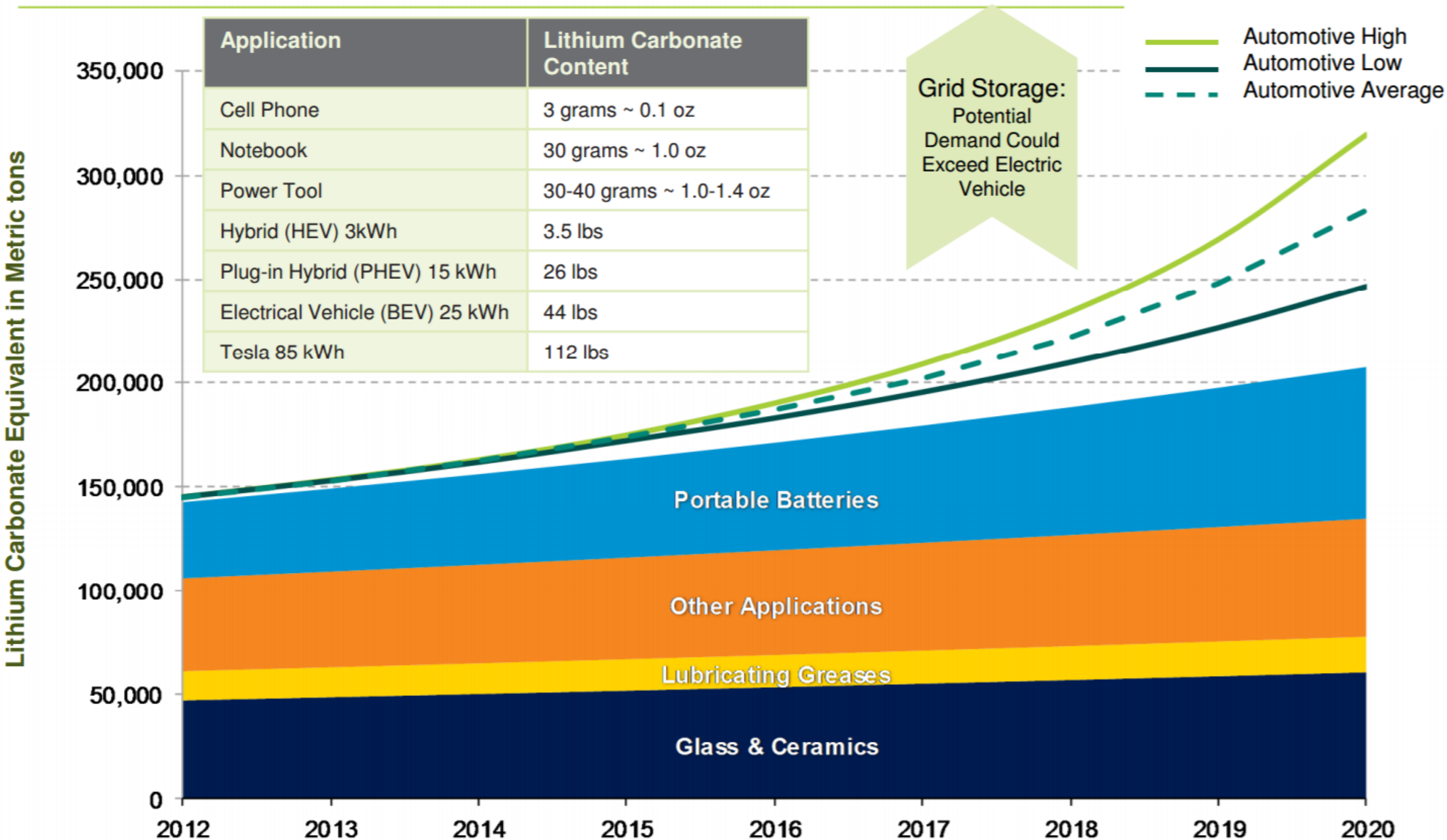
Atomic weight ratio: Li/Li_2CO_3 = 7/ 73.9 = 5.28

$\Rightarrow$ $100,000 / tonne of lithium metal



Trends for Lithium demand

Application	Lithium Carbonate Content
Cell Phone	3 grams ~ 0.1 oz
Notebook	30 grams ~ 1.0 oz
Power Tool	30-40 grams ~ 1.0-1.4 oz
Hybrid (HEV) 3kWh	3.5 lbs
Plug-in Hybrid (PHEV) 15 kWh	26 lbs
Electrical Vehicle (BEV) 25 kWh	44 lbs
Tesla 85 kWh	112 lbs



Source: Rockwood Lithium estimates and market surveys from BCG, Bloomberg, Avicenne, Roland Berger, Pike Research, Frauenhofer IST, Deutsche Bank Research, McKinsey, CTI, Anderman, JD Powers

The Rise of Electric Cars

By 2022 electric vehicles will cost the same as their internal-combustion counterparts. That's the point of liftoff for sales.

~ 20M EVs by 2030?

100,000,000 EVs will be sold by 2032. Assuming 30 kWh/EV (30 kg Li_2CO_3) demand by will be 600,000 metric tons/year.

Sources: Data compiled by Bloomberg New Energy Finance, Marklines

Bloomberg

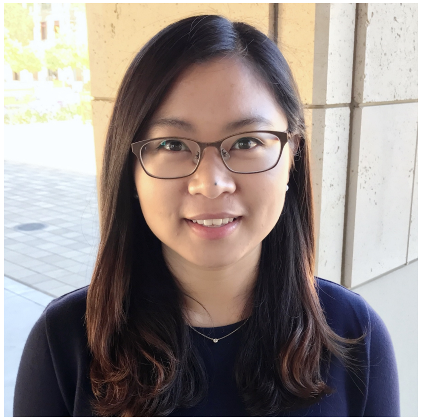
Lithium Resources

Location	Li Amount	Conc.	Price	Process
Mineral (Spodumene)	16.7 MT	1-4%	6-8 $/kg	Smash, Elution (concentrated chemical, energy-consuming)
Brines	26.9 MT	0.017-0.15%	2-3 $/kg	Evaporation (Slow, Weather dependence)
Sea Water	$\boxed{\text{231,000 MT}}$	~1.7 *10^{-5} % (177 ppb)	~80 $/kg ?	Adsorption

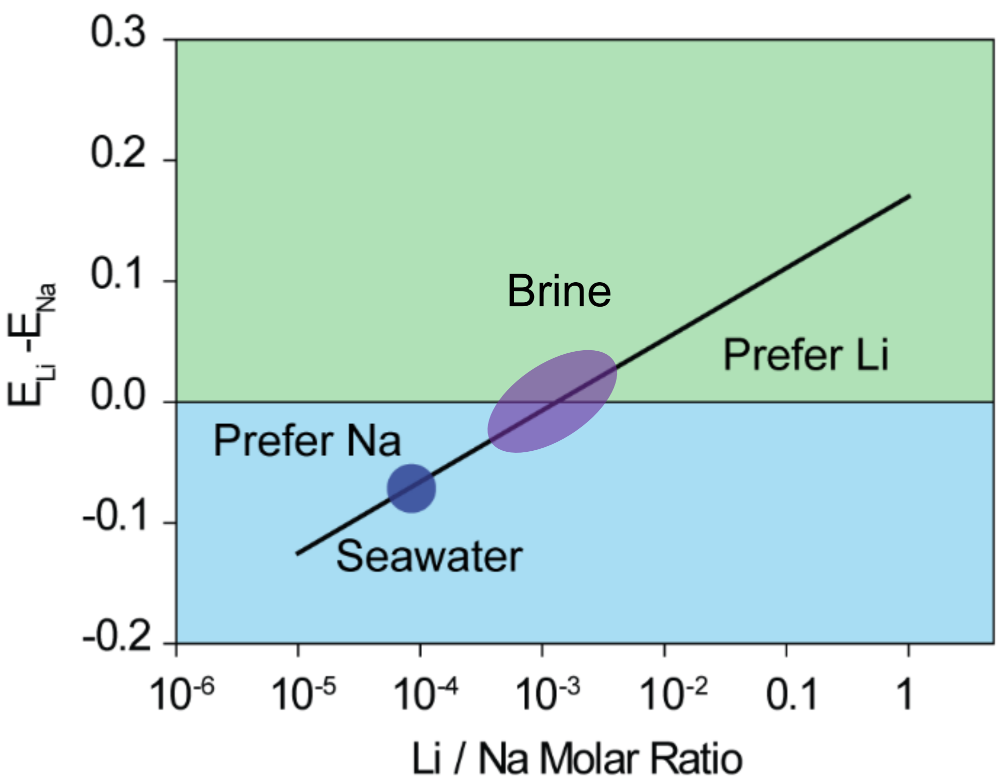
9,000 times more Li

From: Camille Grosjean et. al., Renewable and Sustainable Energy Reviews 16 (2012) 1735– 1744

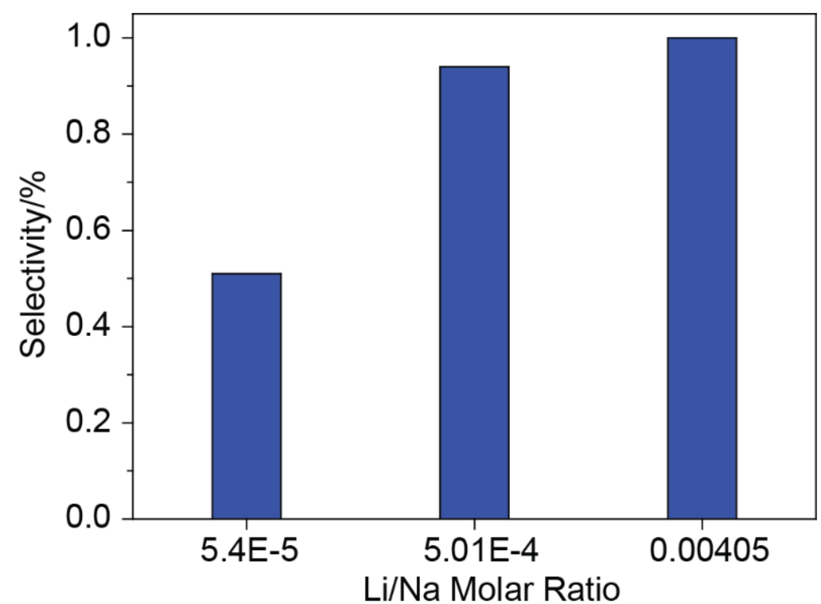
Li Extraction from salt water (Chong Liu, Yi Cui, et al.)



Location	Conc.	Li/Na molar
Brines	0.017-0.15%	1/1790 -1/202
Sea Water	~1.7 *10^{-5}	1/1.86×10^4



~95% ~100%



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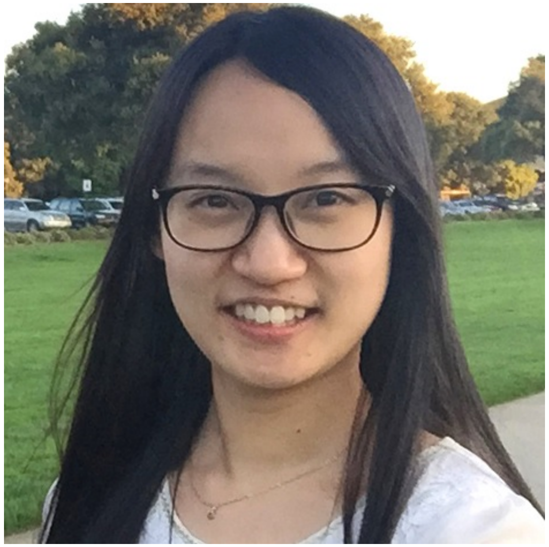
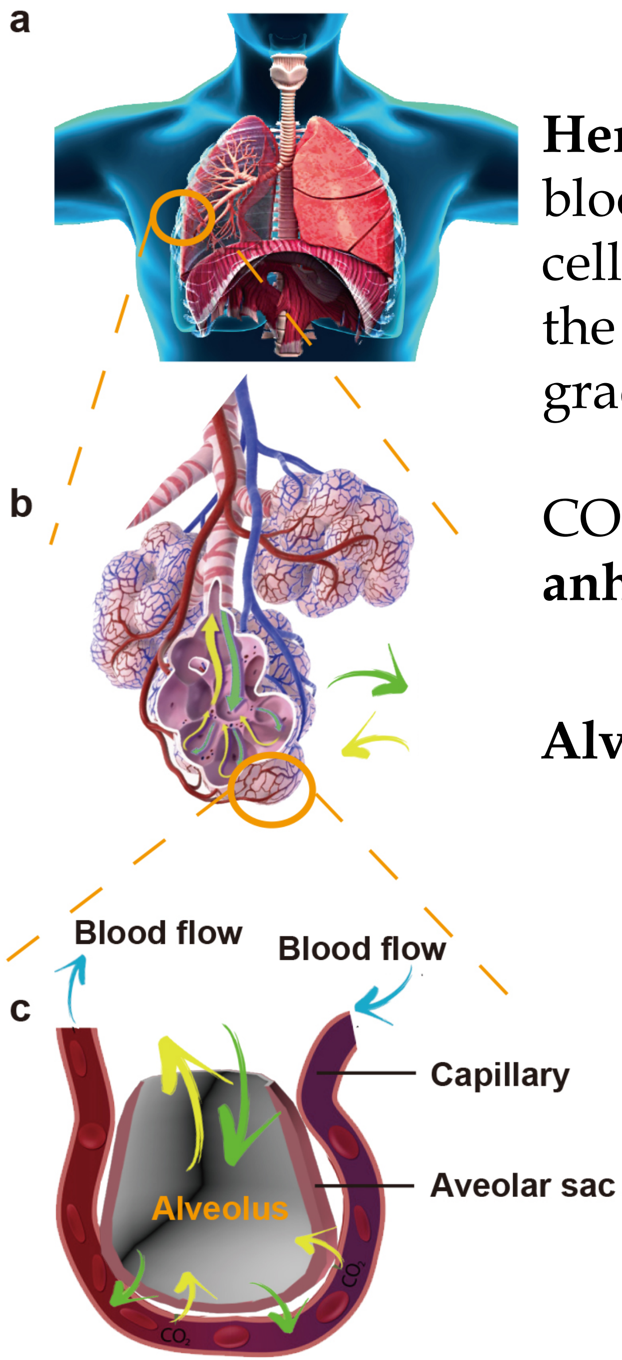
Artificial Alveolus for Highly Efficient Oxygen Reduction and Evolution

Jun Li … Steven Chu and Yi Cui (to be submitted)



Jun Li

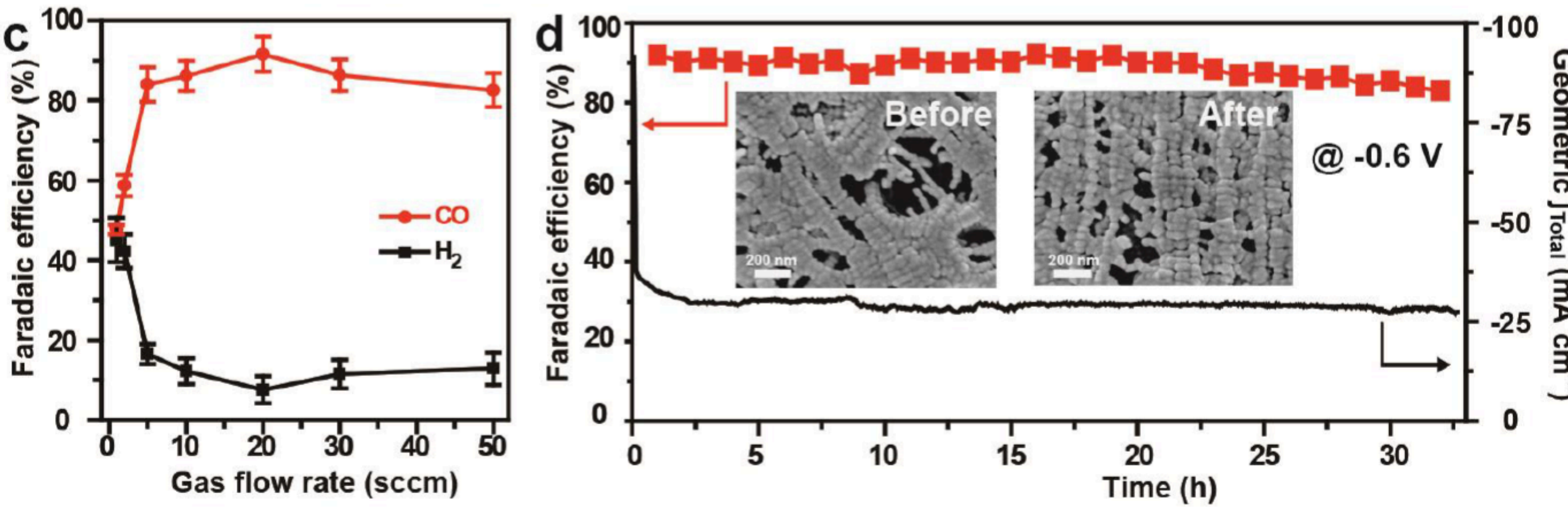


Hemoglobin protein in red blood cell carries oxygen to cells. Diffusion of O_2 from the lungs to cells is due to the gradient in O_2 concentration.

CO_2 is carried by **carbonic anhydrase,** another protein.

Alveolus: 200 μm in diameter

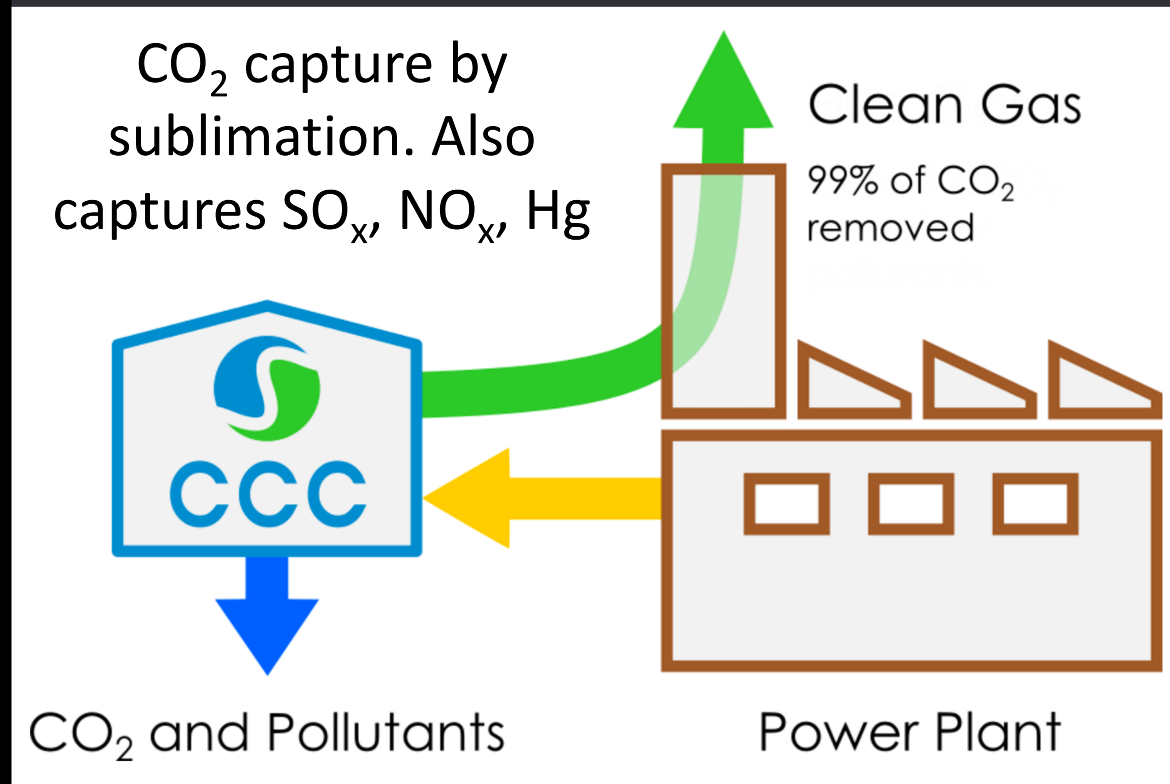
CO_2 reduction to H_2 and CO



"Near world-record CO2 reduction activity performance even with multiple times lower catalyst loading."

SES INNOVATION

The goal of these companies is to reduce the cost of carbon capture from \$70/ton of CO_2 to less than \$30/ton.



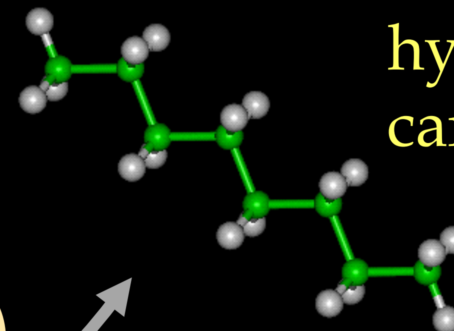
Cryogenic Carbon Capture™

inventys

Capture using structured materials such as MOFs (metal-organic frameworks.) (< \$30/ton of $C0_2$)

100% renewable energy will require **carbon recycling**

Captured CO_2 → CO, H_2 → liquid hydro-carbon



Carbon-Neutral Energy →

Electrochemical

Photochemical

Biochemical

Thermochemical

H_2: Need @ \$1.50/kg

Today @ \$5/kg

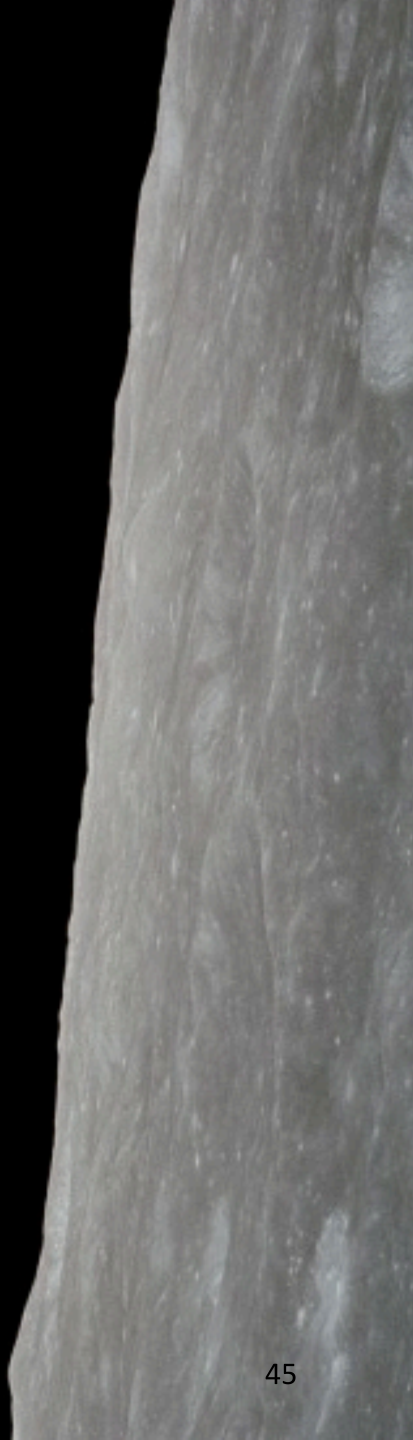
O_2

How much does it cost to ship oil any where in the world?

Answer: $0.02/gallon of gasoline.

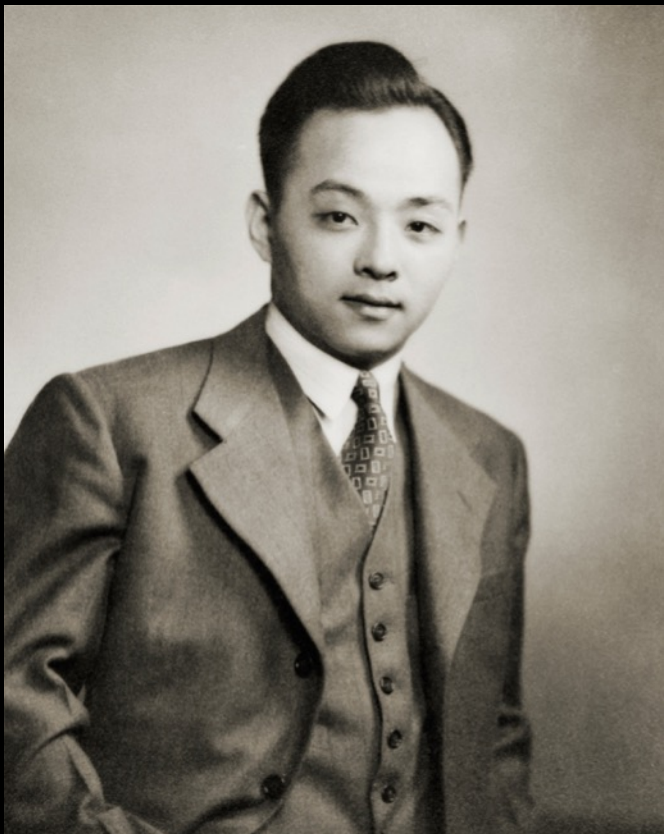
Oil tankers as transcontinental energy "transmission lines"

Earthrise from Apollo 8 (December 24, 1968)



"We came all this way to explore the moon and the most important thing is that we discovered the Earth."

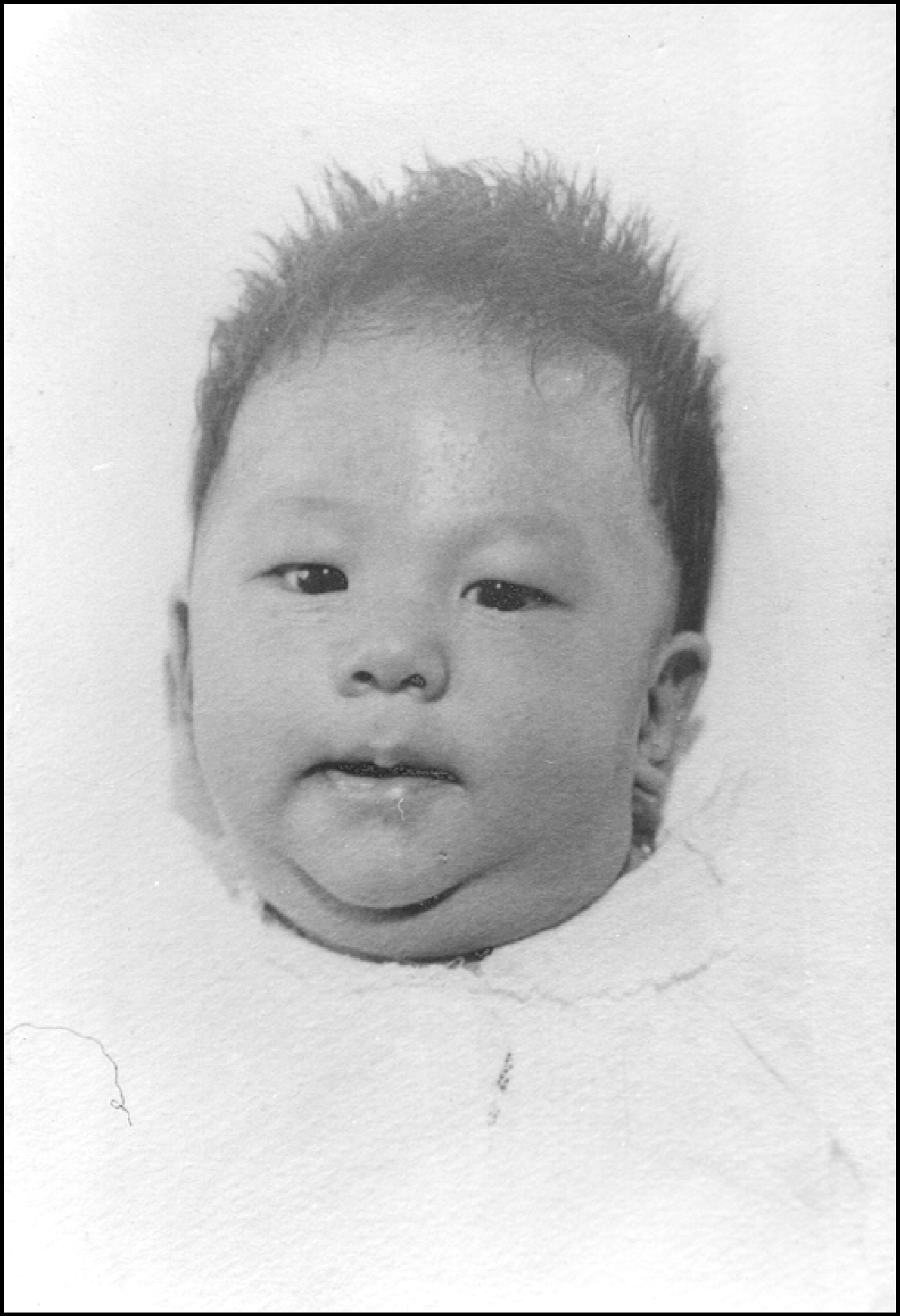
Bill Anders, Apollo 8 Astronaut



Ju-Chin Chu
朱汝瑾
Prof. of Chem. Eng.
Brooklyn Polytechnic

Edith Ju-hwa Chu
朱汝華
Prof. of Chemistry,
Tsinghua Univ.

Ching Chen Li
李靜貞



I was not only ugly,
I was the academic black sheep of my family.

- My older brother (Gilbert) went to Princeton, has a Ph.D. in physics form MIT, and an M.D./Ph.D. in medicine from Harvard/MIT. He is Professor of Oncology and Biochemistry at Stanford.

- My younger brother (Morgan) has five degrees including a Ph.D. at the age of 22 from UCLA, an MSL from Yale at 23 and a JD from Harvard at 24. He is one of the most famous patent litigators in the U.S., and was President of the Board of Overseers of Harvard, 2014 -2015.

At Stanford when the Nobel Prize was announced.(49 yrs old)

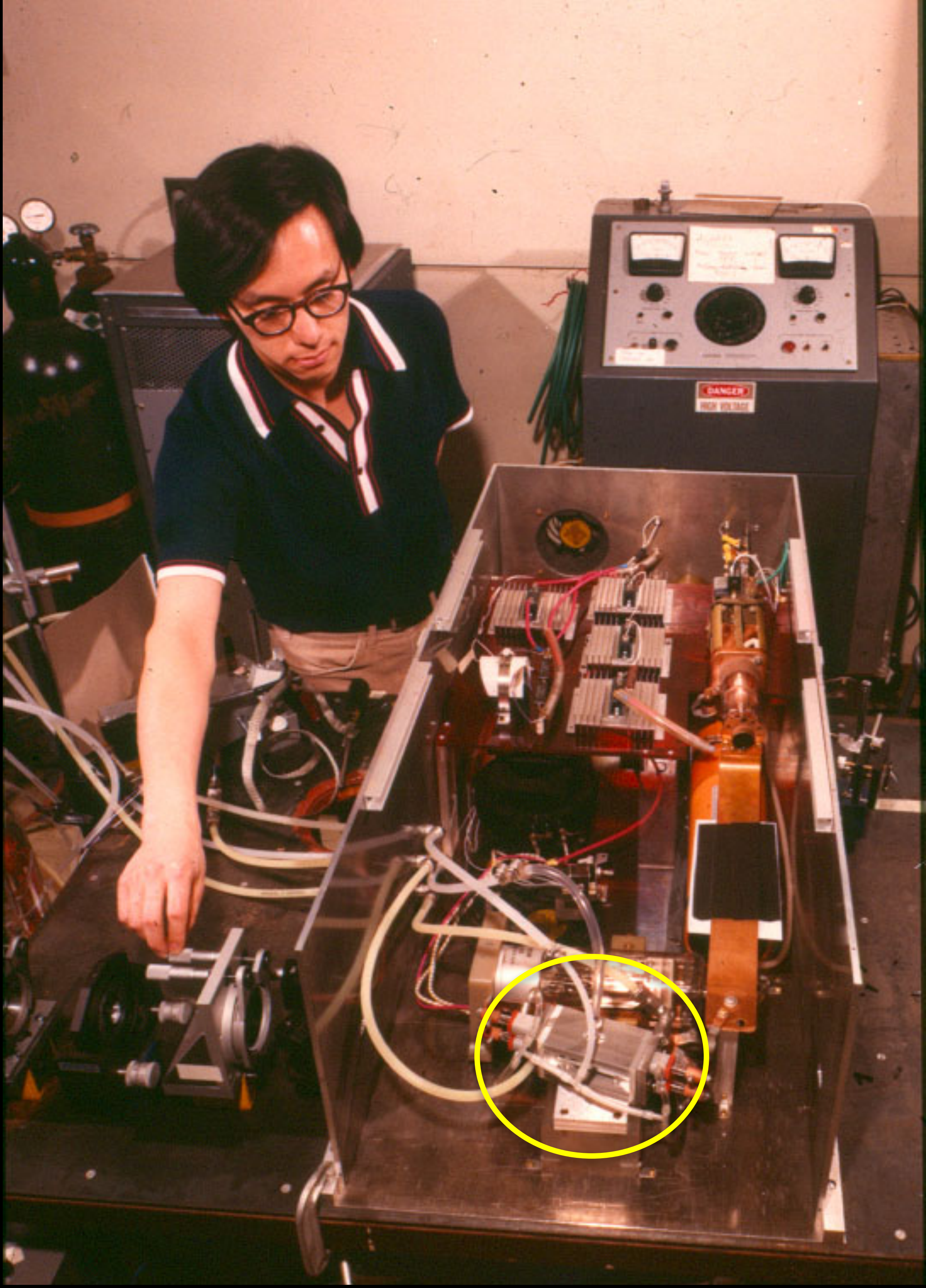
Getting a Nobel Prize leveled the playing field in my family.

Future Nobel Laureates who were Ph.D. students at Berkeley in the 1970s

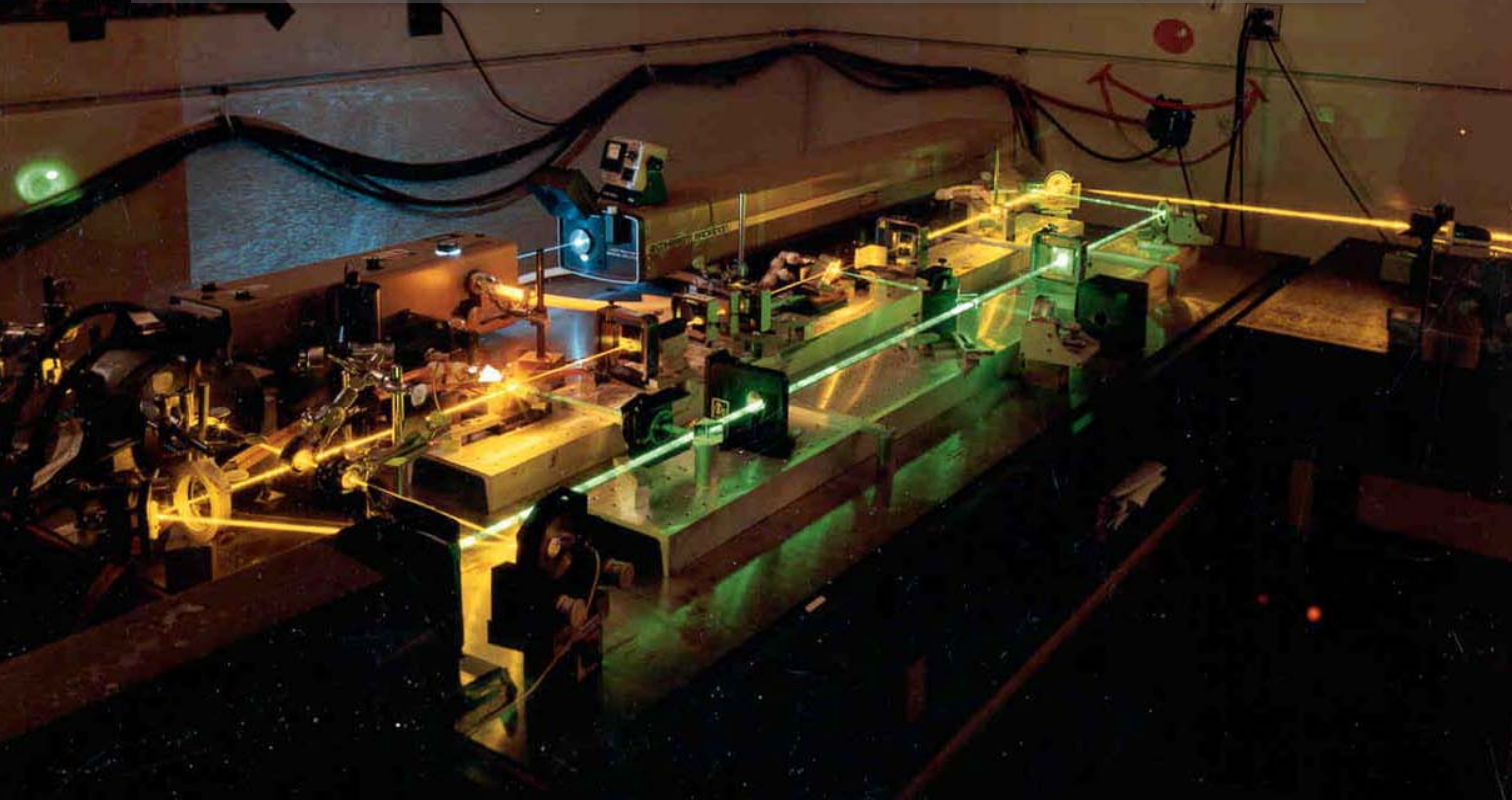
- Mario Molina (Chemistry 1972)
- Kary Mullis (MCB 1973)
- John Mather (Chemistry 1974)
- Tom Cech (Chemistry 1975)
- Steven Chu (Physics 1976)

My advisor and I dropped the test of quantum electrodynamics (QED) to test the Weinberg–Salam-Glashow theory unifying electro-magnetic and weak nuclear forces.

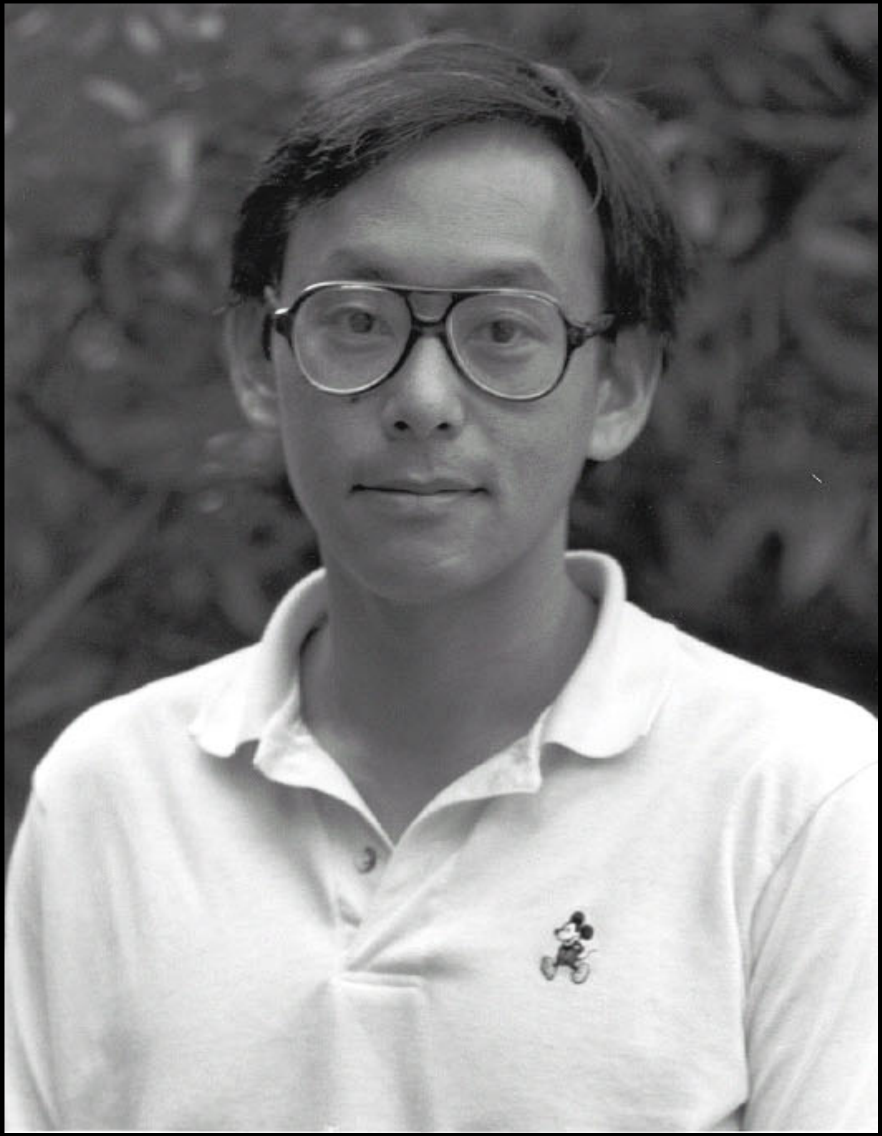
The laser I designed was much better than any commercial laser.



With a beginning graduate student, I used my start-up money to build the laser used for her Ph.D. thesis.

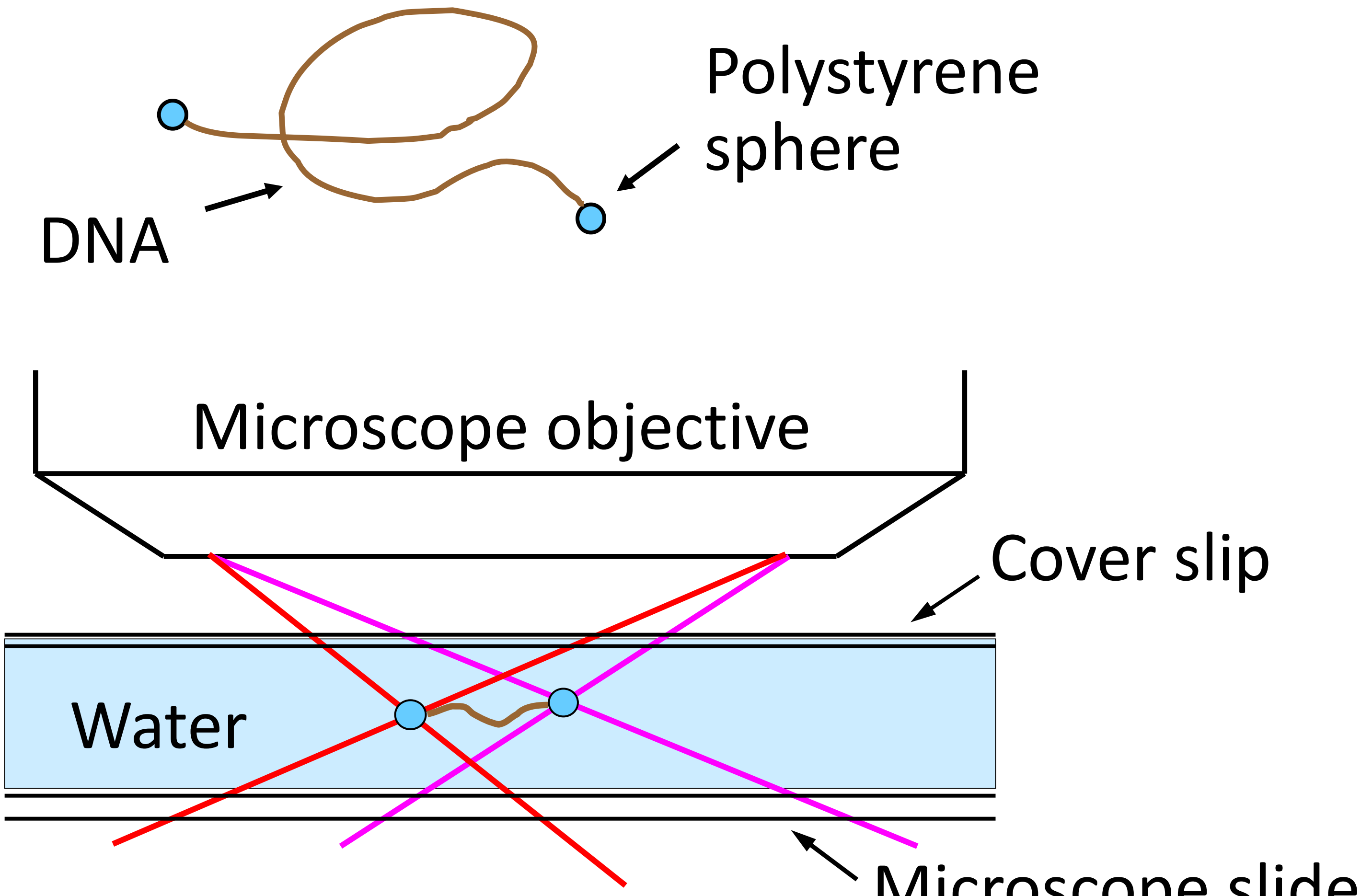


When I left Gene's group, I knew how to build lasers.



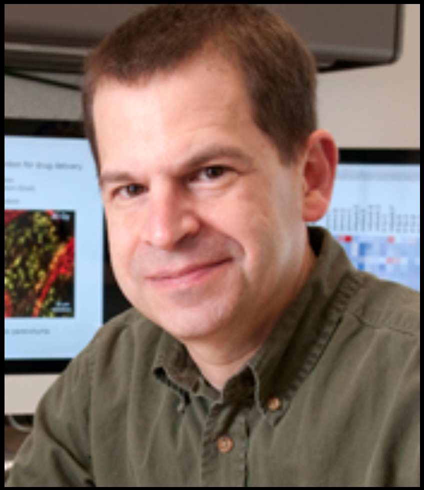
Me at 40 (First year at Stanford)

Laser Manipulation of DNA



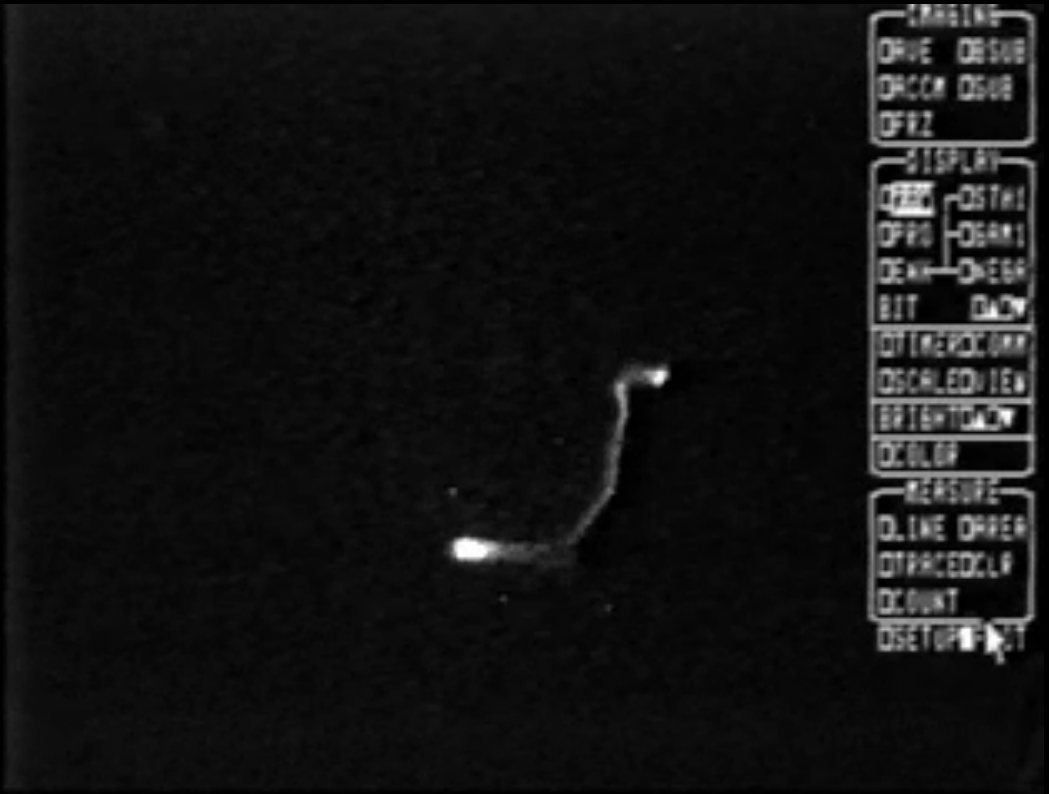
SC, Science **253**, 861 (1991)

Optical manipulation of DNA (1989)



Steve Kron
(U. of Chicago)

Steve Quake
Stanford



Director of Lawrence Berkeley National Laboratory, Professor of Physics, Molecular and Cell Biology (2004 – 2008)

January 2009 – April 2013

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