

# Yale West Campus Energy Sciences Institute

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Yale University




Yale West Campus

Physics Club

September 20, 2021

# Outline

1. Energy Introduction;
2. Yale History;
3. West Campus and Energy Sciences Institute History;
4. Current Energy Sciences Institute Faculty and Research Topics;
5. Energy Sciences Institute Space;
6. Materials Characterization Core;
7. My Research.

A world map at night, showing the continents and oceans. The map is dark blue, and the city lights are visible as bright yellow and white dots. The text is overlaid on the map in a bold, white, sans-serif font.

**We use a lot of  
Energy!**

**About 18 TW; mostly from fossil fuels.**

# Humanity's Top Ten Problems for the next 50 years

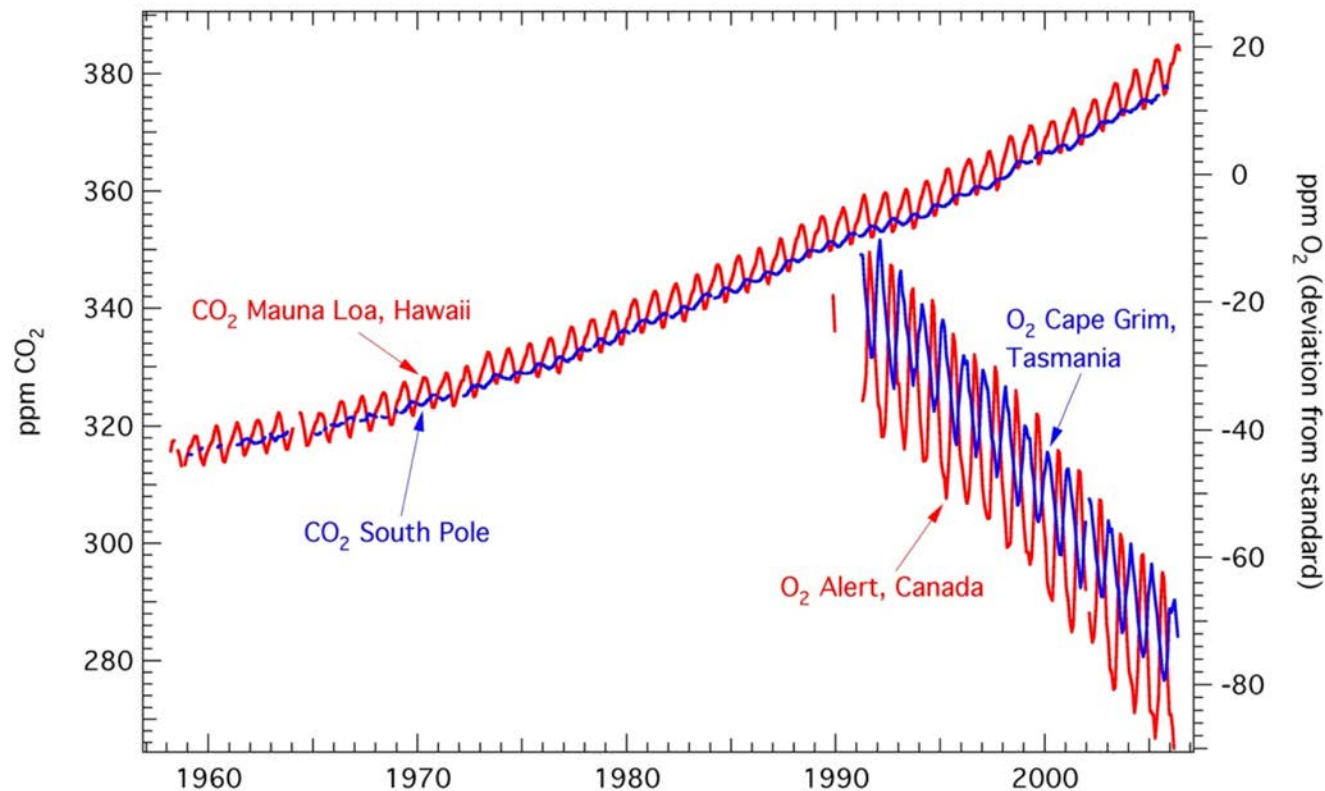
1. **ENERGY**
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION



2004	6.5	Billion People
2050	~ 10	Billion People

R. E. Smalley, Rice University (April 2005)

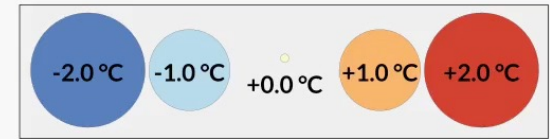
# Earth's Carbon Dioxide Level Hits 400 ppm



The concentration of carbon dioxide in the atmosphere at a site near the summit of Mauna Loa on the Island of Hawaii has been measured continuously since 1958 by Charles D. Keeling of the Scripps Institution of Oceanography and the National Oceanic and Atmospheric Administration. The site was chosen because there was little local contamination of the air and because the air over this part of the globe is probably well mixed.

# Temperature Anomalies by Country Years 1880 - 2017

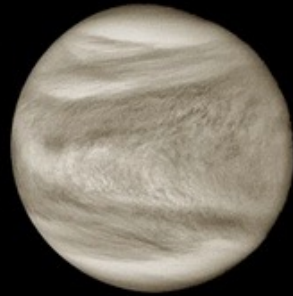
# 1880



Data Source:  
 NASA GISS, GISTEMP Land-Ocean Temperature Index (LOTI), ERSSTv5, 1200km smoothing  
<https://data.giss.nasa.gov/gistemp/>  
 Average of monthly temperature anomalies. GISTEMP base period 1951–1980.

Video license: CC-BY-4.0  
 Antti Lipponen (@anttilip)

atmosphere 96%  
CO<sub>2</sub>  
Ave temp 460° C



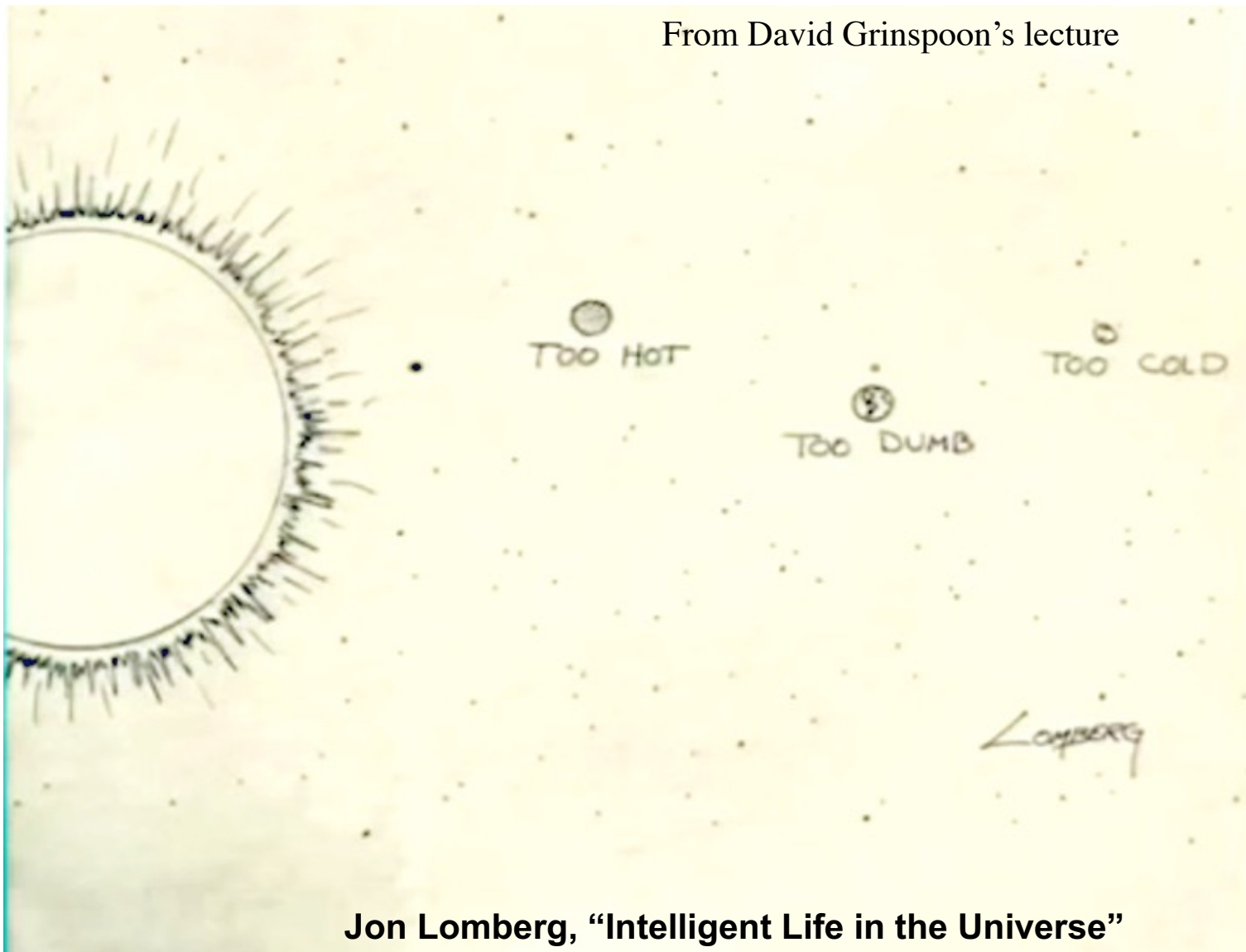
0.04% CO<sub>2</sub>  
+ water vapor  
Ave temp 15° C



CO<sub>2</sub> frozen in the  
ground  
Ave temp -50° C



From David Grinspoon's lecture



**Jon Lomberg, "Intelligent Life in the Universe"**



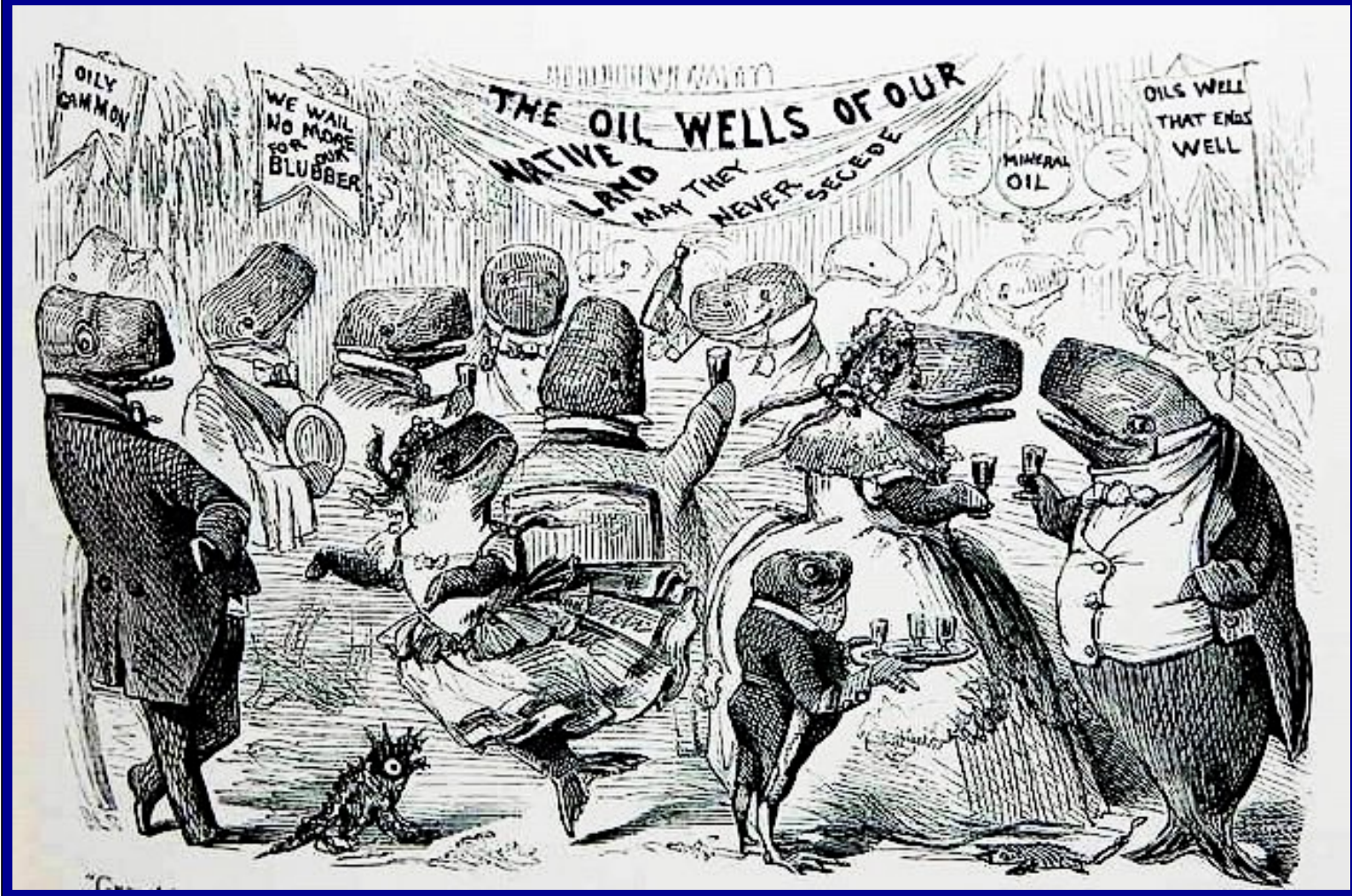
# The Silliman Report

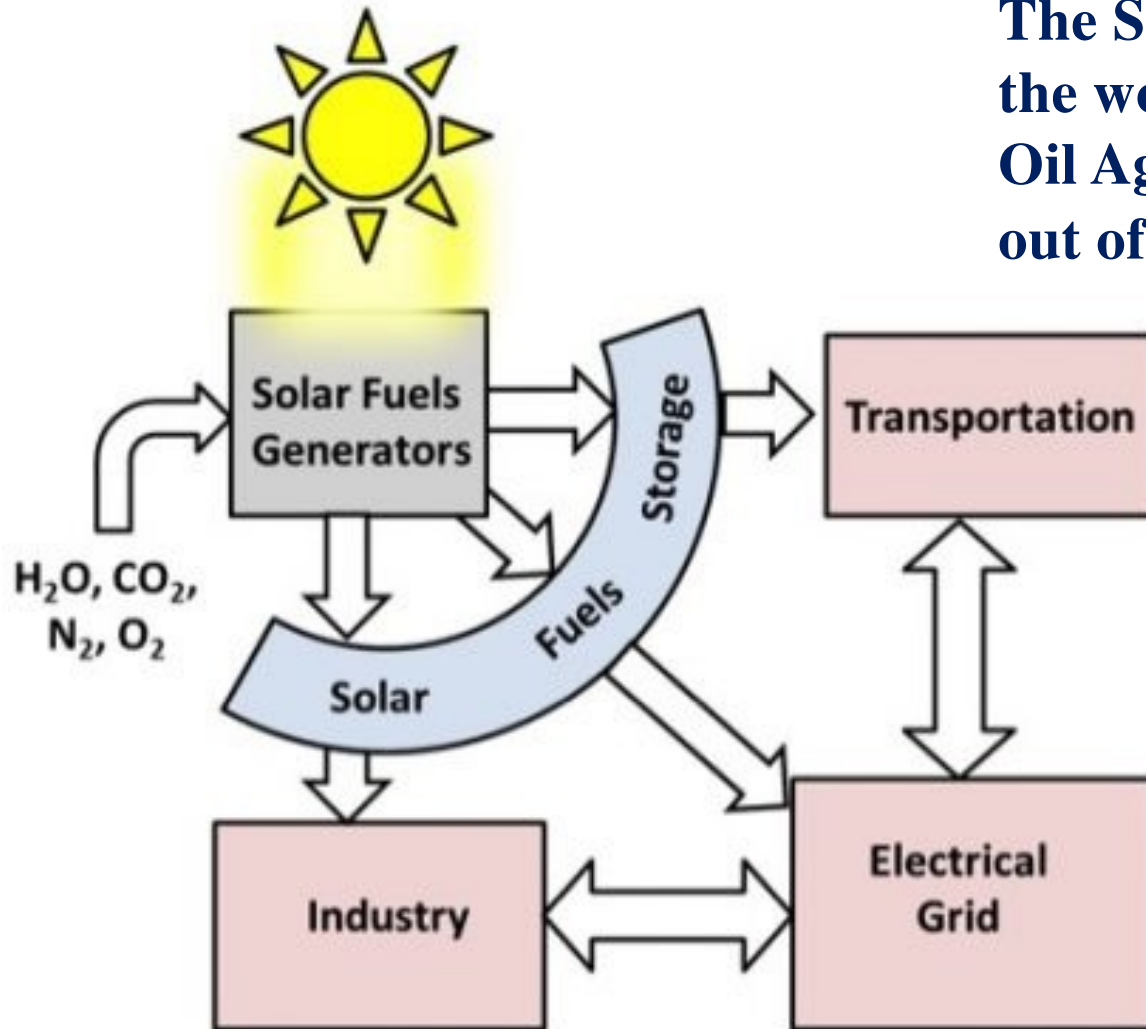
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*“During the winter months of 1855, Benjamin Silliman, Jr., professor of general and applied chemistry at Yale, conducted a series of pioneering experiments on the properties and uses of petroleum gathered from springs near Titusville Pennsylvania. His detailed and optimistic report, completed April 16 1855, led the drilling of the first successful oil well by Edwin L. Drake at Titusville in 1859, and the founding of the modern petroleum industry.”*

# Vanity Fair 1861





**The Stone Age did not end because the world ran out of stones, and the Oil Age will not end because we run out of oil.**

*- Don Huberts, Shell Oil*

# Yale's West Campus – Interdisciplinary Research



Purchased from Bayer HealthCare  
in 2007.

## **Scientific Research Institutes**

Cancer Biology Institute

Chemical Biology Institute

Microbial Sciences Institute

Nanobiology Institute

Systems Biology Institute

## **Scientific Core Facilities**

Yale Center for Molecular Discovery

Yale Center for Genome Analysis

High Performance Computing Center

West Campus Analytical Chemistry Core

# Yale's West Campus – Interdisciplinary Research



Two New Institutes  
Established in 2012.

## **Scientific Research Institutes**

Cancer Biology Institute

Chemical Biology Institute

Energy Sciences Institute

Institute for the Preservation of Cultural Heritage

Microbial Sciences Institute

Nanobiology Institute

Systems Biology Institute

## **Scientific Core Facilities**

Yale Center for Molecular Discovery

Yale Center for Genome Analysis

High Performance Computing Center

West Campus Analytical Chemistry Core

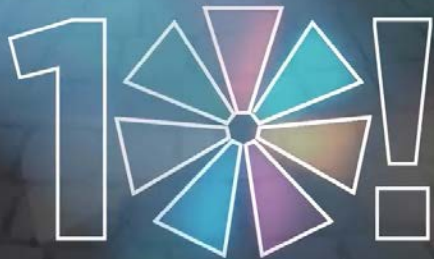
Materials Characterization Core

# Yale *Energy Sciences Institute*

- Established in 2012 on Yale's West Campus with a \$25M gift from Tom Steyer and Katherine Taylor
- The Energy Sciences Institute is dedicated to two overarching questions:
  - Can clean energy sources be improved and implemented on a scale that will replace fossil fuels?
  - And in a world still dependent on oil, coal, and gas, can better technology support the transition from a carbon-based economy to one grounded in sustainable fuels and practices?
- Interdisciplinary research in the ESI involves the departments of **Chemistry**, **Mechanical Engineering & Materials Science**, **Chemical & Environmental Engineering**, **Applied Physics**, **Physics** and **Electrical Engineering**.



YALE WEST CAMPUS



## Energy Sciences Institute

One place for Yale's energy research to come together to solve the energy challenge.

Youtube:

In film: Yale West Campus @ 10  
(2017)





# ESI: People Behind Energy Solutions

Interdisciplinary Research From 6 Depts (Chem, Phys, MEMS, CEE, AP, EE)

## Energy Production / Storage



Brudvig



Crabtree



Batista



Miller



Ozolins



Qiu



Bozovic

## Theory

## Quantum Materials



Hu



Wang



Guo



Konezny



Gozar



Da Silva Neto



Cha

## Measurements

# Cutting-Edge Energy Science at Yale

## Materials for Energy Conversion

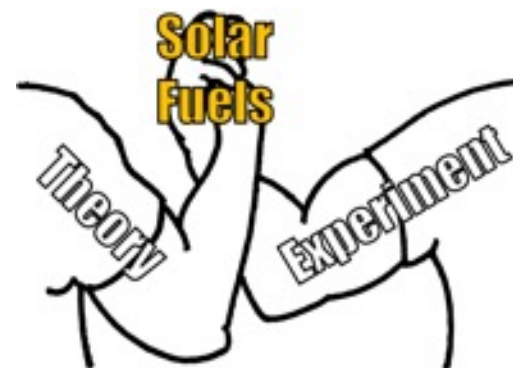
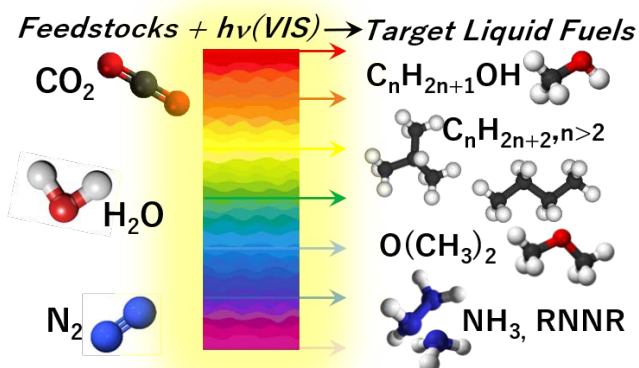
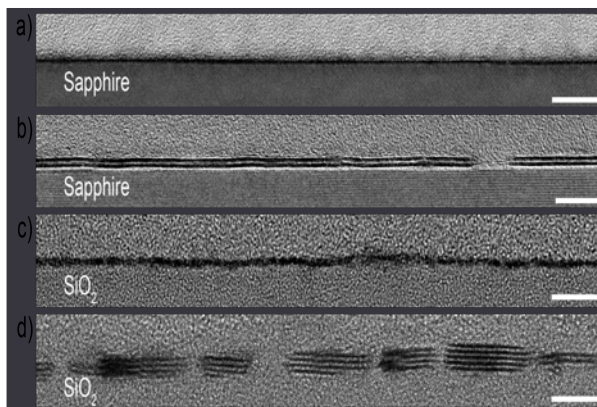
- Quantum Materials
- Materials by Design
- Photocatalytic Materials

## Catalysts for Energy Conversion

- CO<sub>2</sub> Capture & Conversion
- N<sub>2</sub> Reduction to Ammonia
- Water Splitting

## Collaboration between Experiment and Theory in Solar Fuels Research

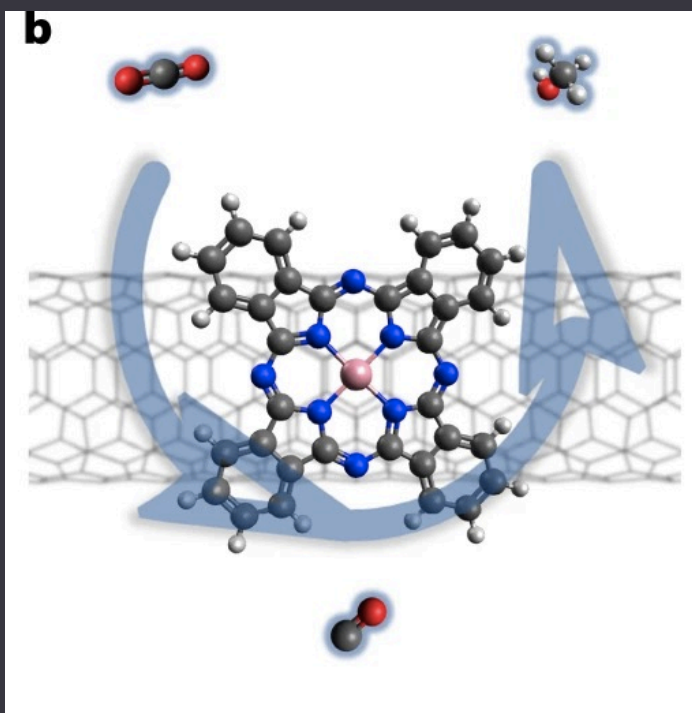
- Machine Learning for Catalyst Discovery
- Theoretical Modeling of Catalysis
- Design of Catalytic Materials



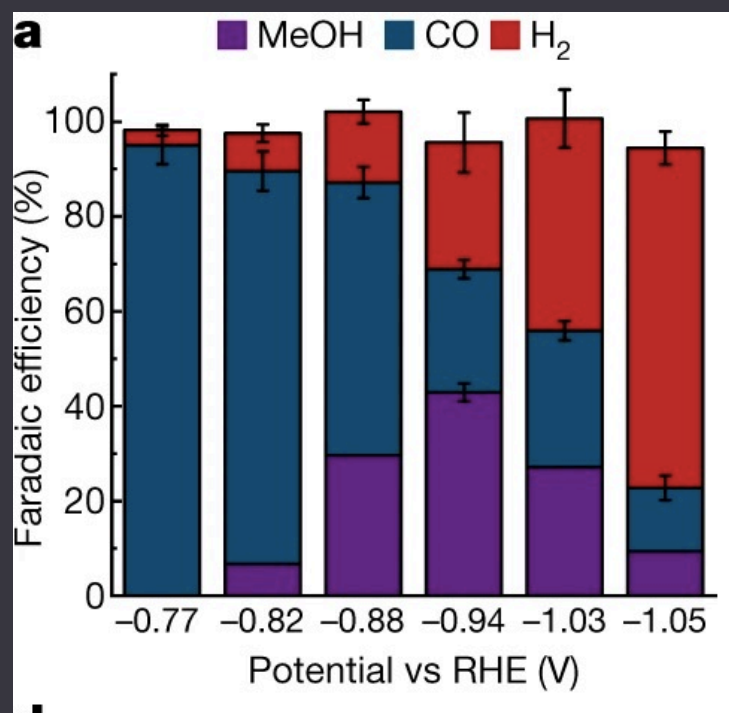
# Molecular Catalysts For CO<sub>2</sub> Reduction

( Batista, Brudvig, Crabtree, Wang)

- Cobalt-complex: 2 e<sup>-</sup> reduction of CO<sub>2</sub> → CO
- 6 e<sup>-</sup> reduction: CO<sub>2</sub> → CH<sub>3</sub>OH (Methanol)
- Homo- vs. hetero-generous catalysis
- Heterogeneous conversion



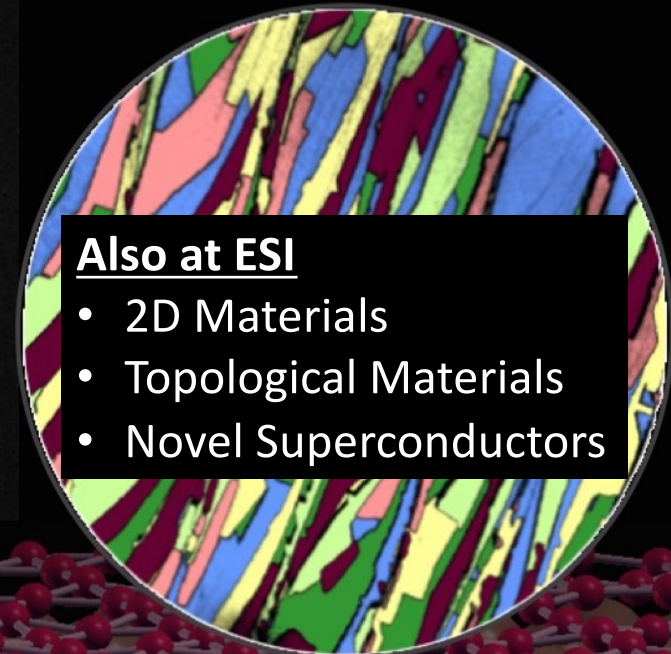
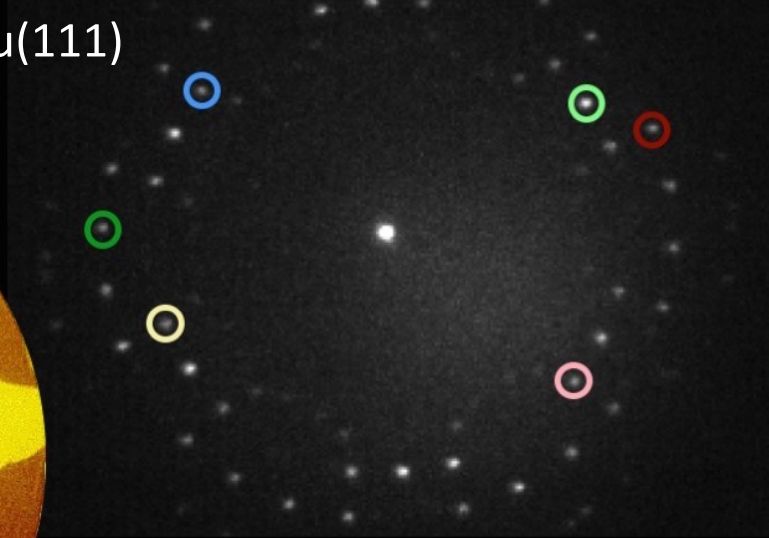
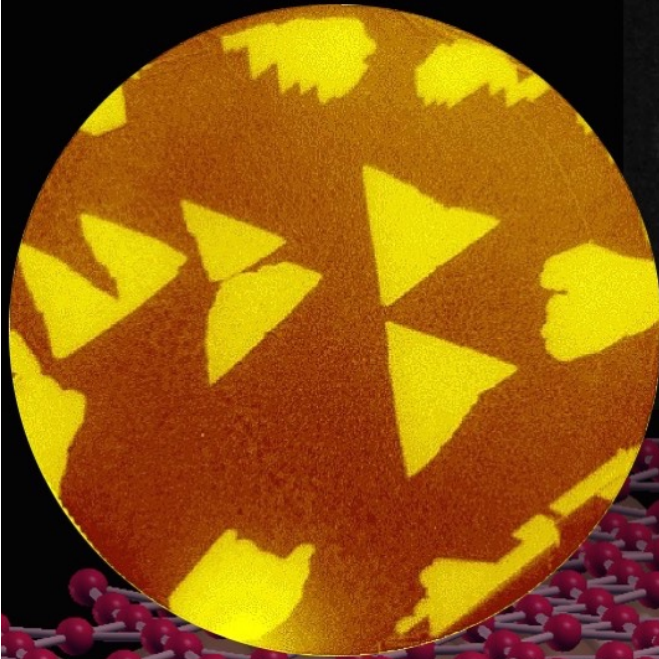
Wang Group, Nature **575**, 639 (2019)



Brudvig / Wang Group, ChemSusChem **2020**

# New Quantum Materials

Large Area Borophene on Cu(111)



## Also at ESI

- 2D Materials
- Topological Materials
- Novel Superconductors

Gozar/Bozovic, Nature Nanotech 14, 44 (2019)

# Energy Sciences Institute – I

Hood-intensive space for flexible chemistry research.



# Energy Sciences Institute – II

Phase One of renovation of ESI-II was completed in 2015.

~30,000 square feet for instrumentation,  
bench chemistry, offices and interactive common areas.





Yale University

# West Campus Materials Characterization Core

[HOME](#) [ABOUT US](#) [INSTRUMENT](#) [USERS](#) [GALLERY](#) [PUBLICATIONS](#) [NEWS](#) [CONTACT US](#)



Rigaku SmartLab X-ray Diffractometer

## Contact:

Min Li  
Director, Materials  
Characterization Core  
203-737-8270 (office)  
203-737-7846 (fax)  
[min.li@yale.edu](mailto:min.li@yale.edu)

## Core Address:

ESC II, Room A119  
810 West Campus Dr  
West Haven, CT 06516

## Quick Links:

[FOM login](#)  
[Yale FOM Registration](#)



# Materials Characterization Core (MCC)

Director, Materials  
Characterization  
Core



Min Li



**PHI VersaProbe II Scanning  
XPS Microprobe**



**Hitachi SU8230 UHR Cold  
Field Emission (CFE) SEM**



**Rigaku SmartLab  
X-ray Diffractometer**



**Rigaku ZSX Primus II  
XRF Spectrometer**

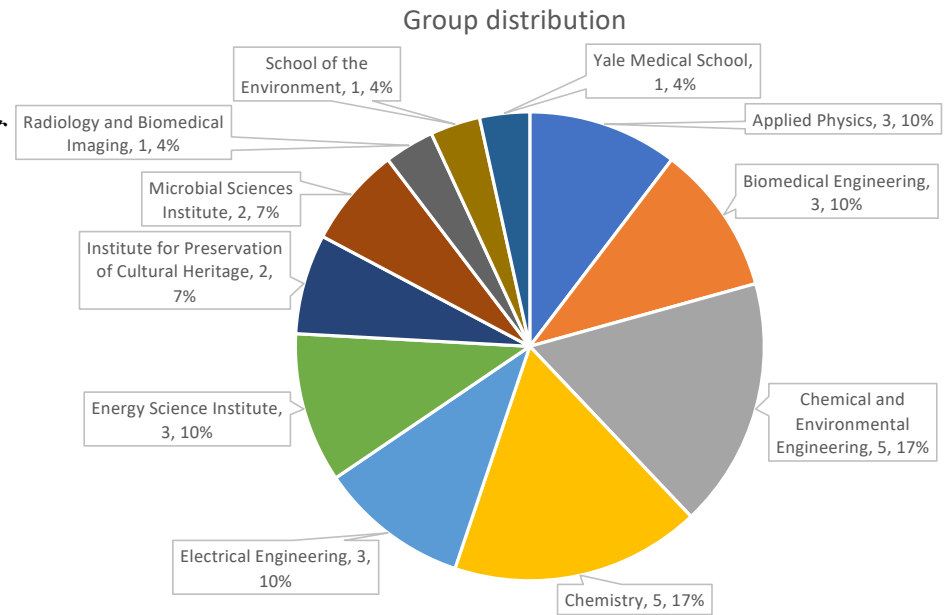
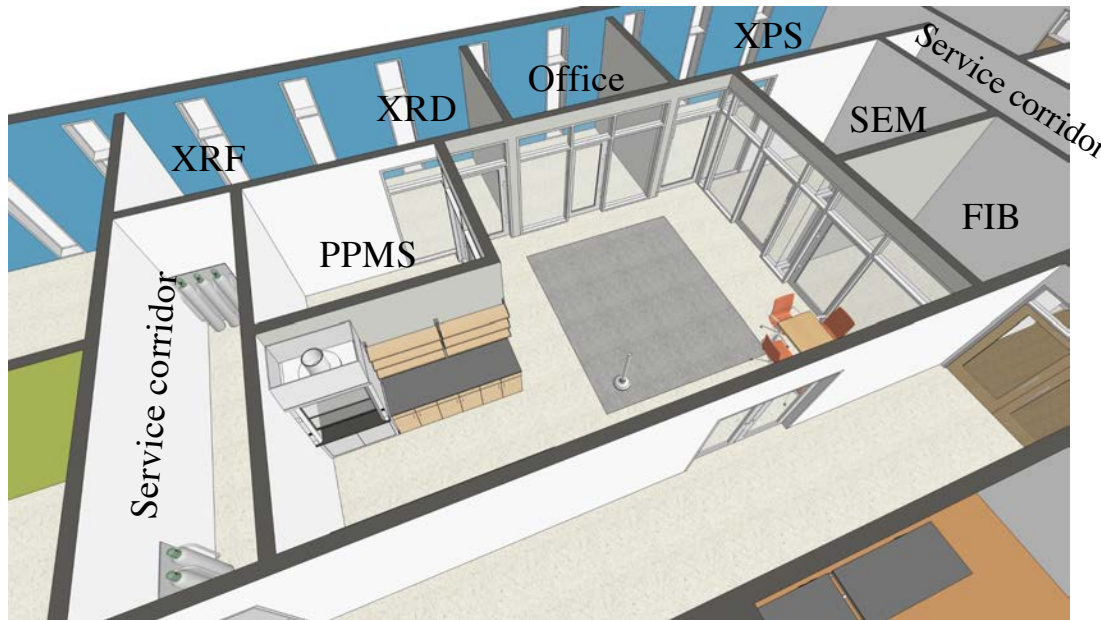


**Quantum Design PPMS®  
DynaCool™**



**FIB-SEM (FEI Helios G4 UX)**

# West Campus Materials Characterization Core





# Solar Energy Could Power the Planet

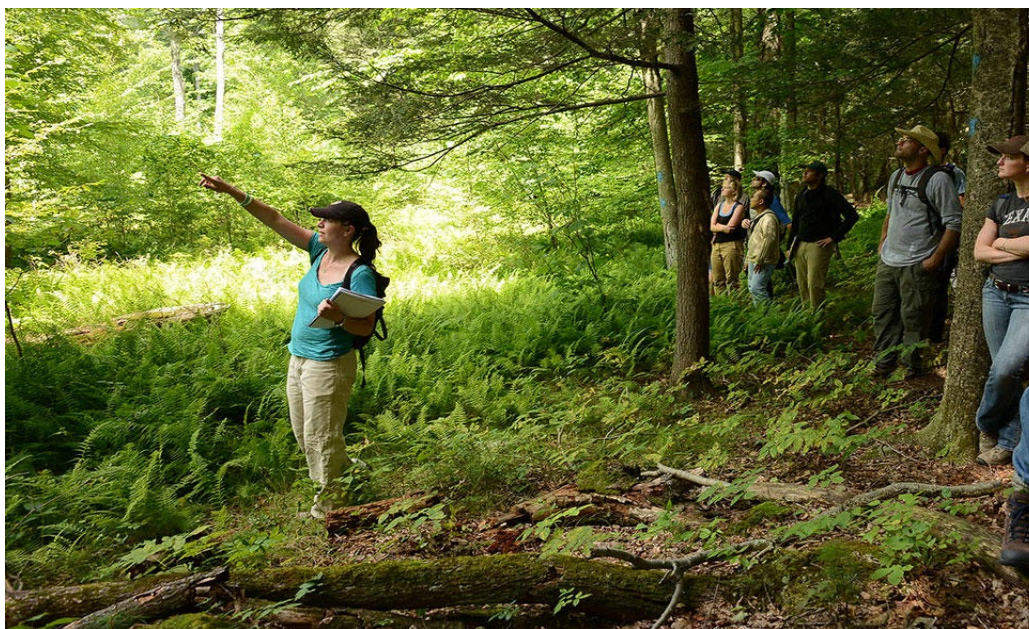


Solar electricity in the grid must constantly match demand, but solar energy is intermittent



**Need for Storage**

# Learning from Nature How to Make Solar Fuels



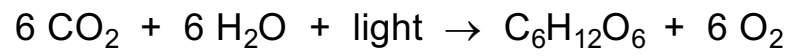
Yale-Myers Forest



Artificial Leaf

# Photosynthesis

Fossil Fuels



Ocean level lowered  
by 4.8 meters

21 % of our  
atmosphere



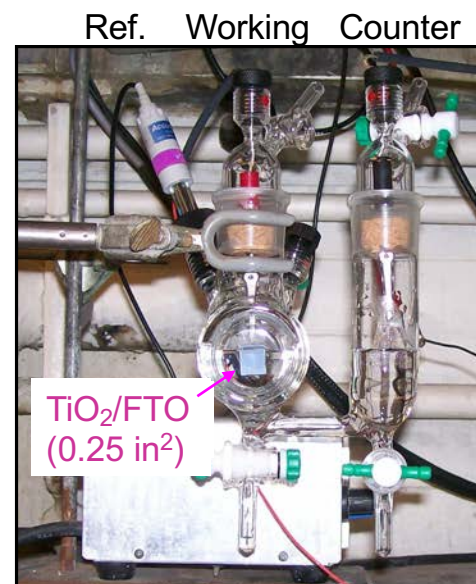
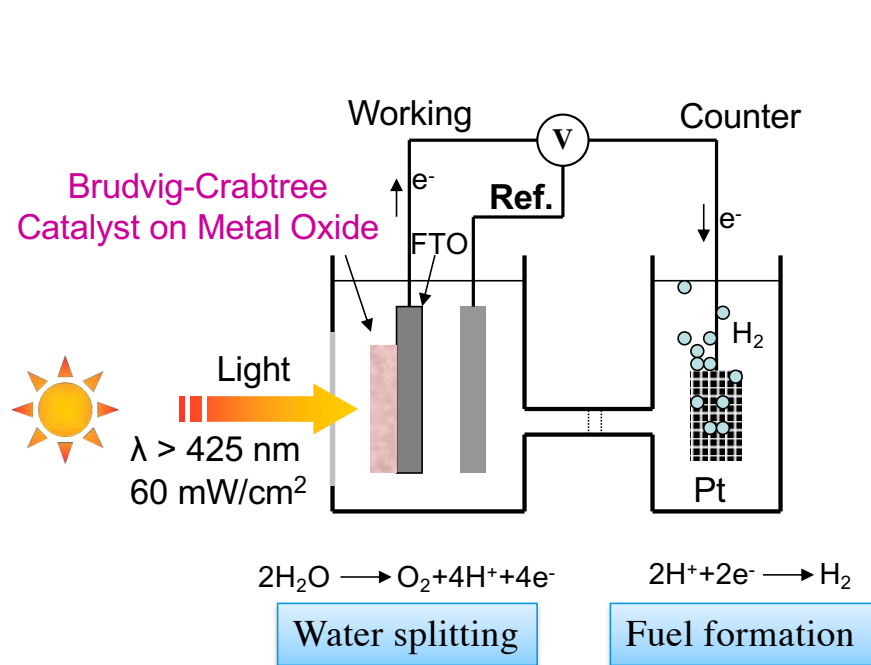
Cornfield, Orange, CT



Sleeping Giant State Park, CT



# Photochemical Water Splitting with Visible Light



Department of Chemistry

Yale University

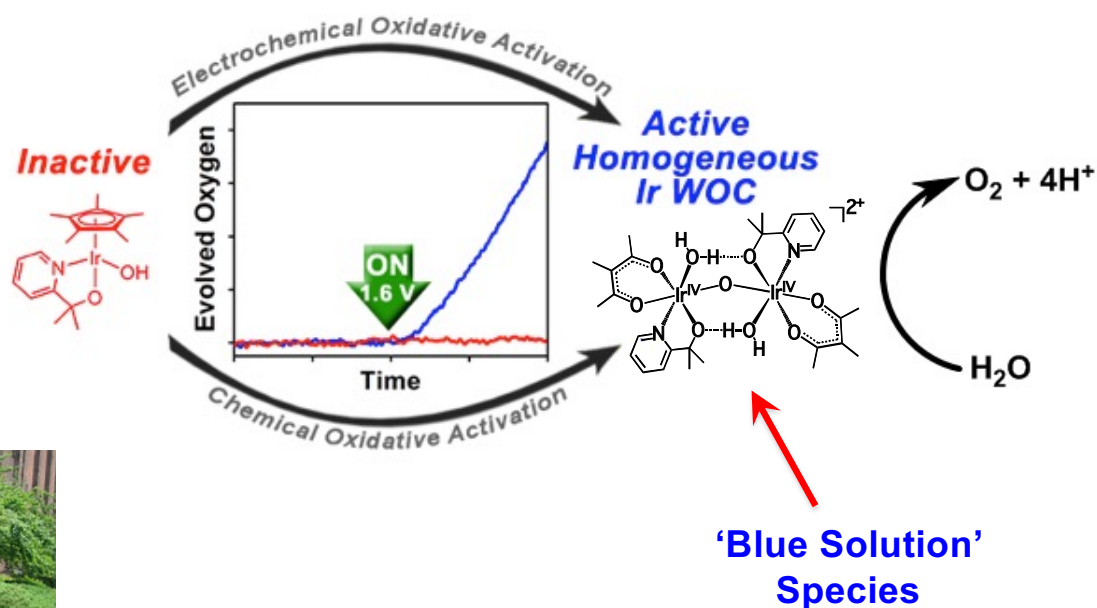
Catalytic Evolution of O<sub>2</sub> by  
[(terpy)(H<sub>2</sub>O)Mn(O)<sub>2</sub>Mn(OH<sub>2</sub>)(terpy)]<sup>3+</sup> + Oxone



“Mn-terpy dimer” Limburg *et al.* (1999) *Science* **283**, 1524.

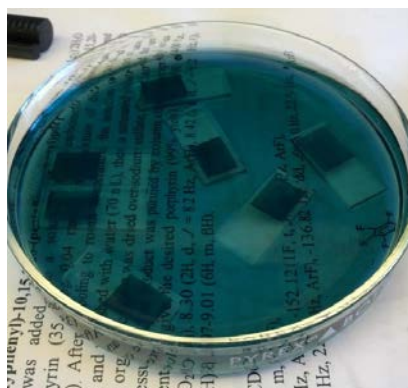


# Electrochemical Activation of Cp\* Iridium Complexes for Electrode-Driven Water-Oxidation Catalysis

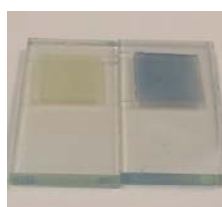


Julianne Thomsen *et al.* (2014) *J. Am. Chem. Soc.* **136**, 13826.

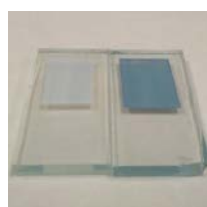
# Blue Solution Species Adsorbs Tenaciously on a Variety of Metal Oxides



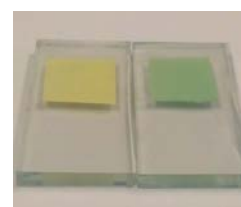
Deposits over 3 hours



Ti



Sn



W

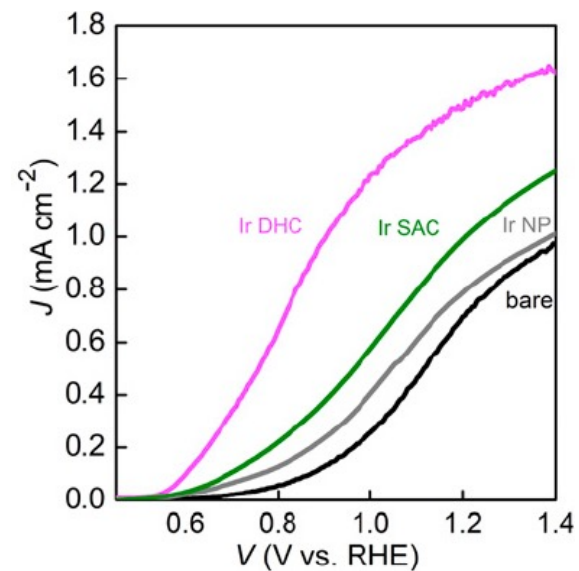
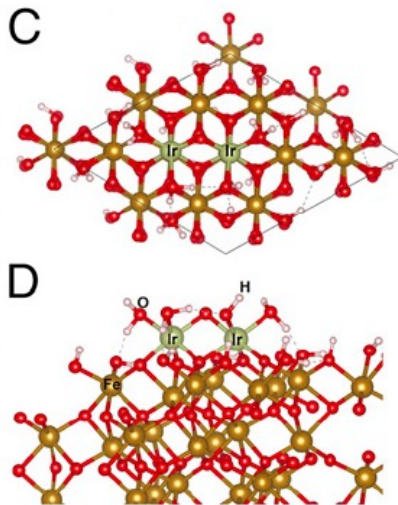
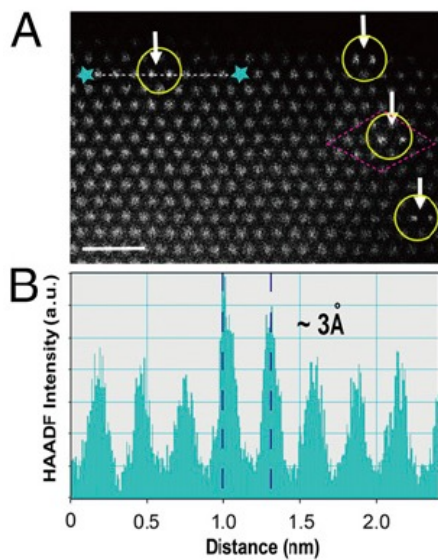
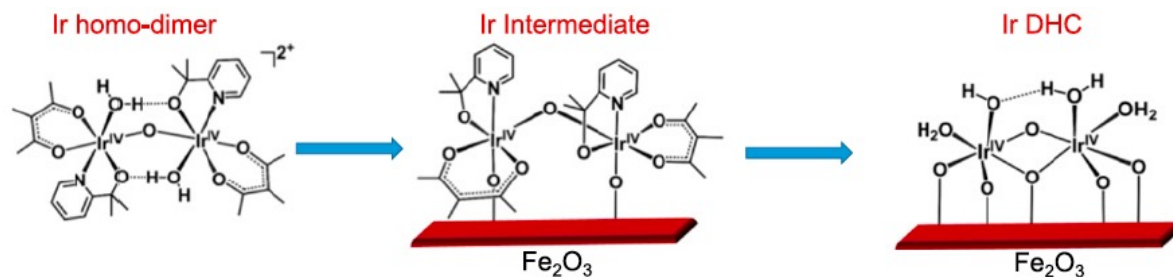


Fe

Staff Sheehan *et al.* (2015)  
*Nature Comm.* **6**, 6469.

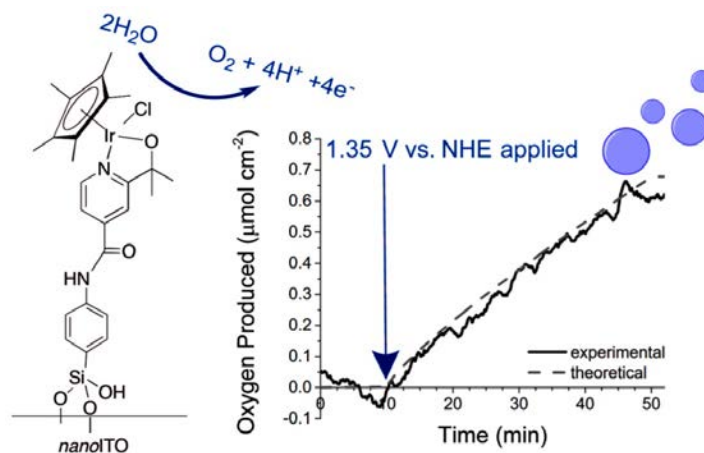
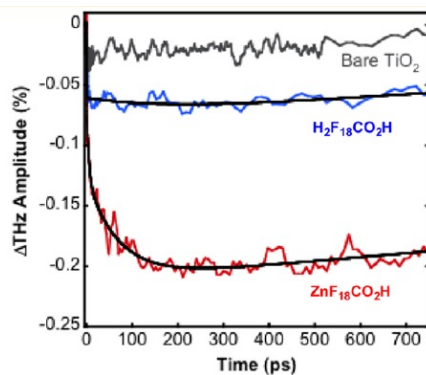
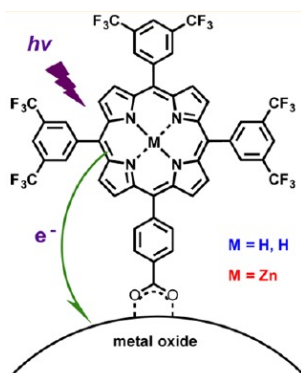
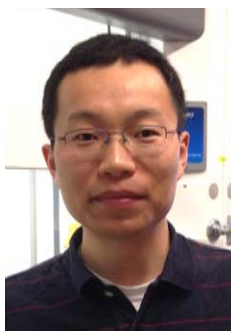
Convenient form for study

# Dual Atom Ir Catalyst Supported on Hematite Surface



with Dunwei Wang (Boston College) (2018) *Proc. Natl. Acad. Sci. U.S.A.* **115**, 2902-2907.

# Photochemical Water Oxidation



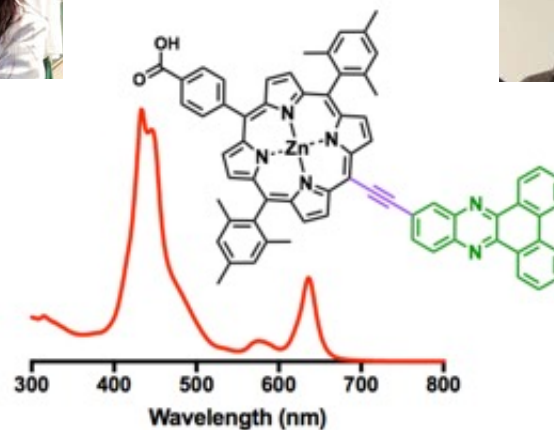
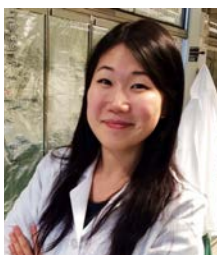
Jiang *et al.* (2016)  
*J. Phys. Chem. C* **120**, 28971.

Materna *et al.* (2016)  
*ACS Catalysis* **6**, 5371.

## Collaboration between Experiment and Theory in Solar Fuels Research



Jacob Spies, Ethan Perets, Katherine Fisher, Benjamin Rudshteyn, Victor Batista, Gary Brudvig and Charles Schmuttenmaer *Chem. Soc. Rev.* (2019) **48**, 1865.

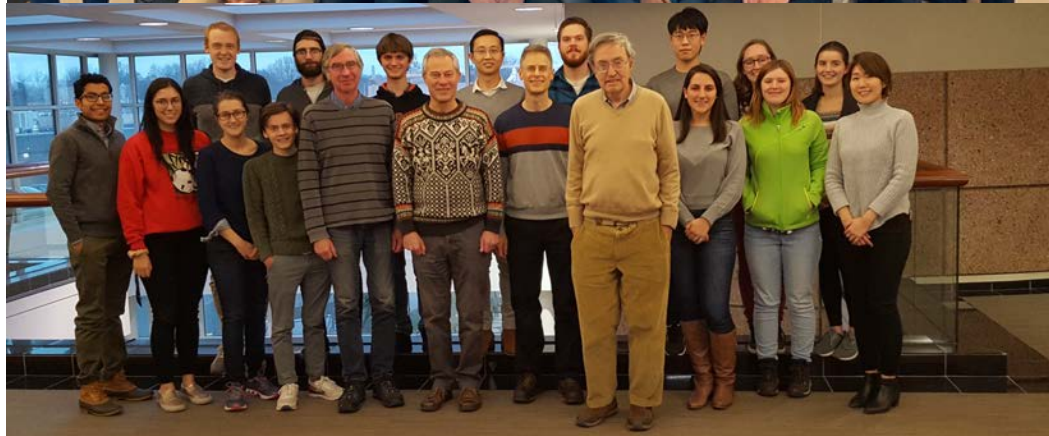


### New class of ethynyl-linked panchromatic dyads

- Synthesis
- Quantum chemical calculations
- Photophysical measurements

Shin Hee Lee, Adam Matula, Gongfang Hu, Jennifer Troiano, Christopher Karpovich, Robert Crabtree, Victor Batista and Gary Brudvig *ACS Appl. Mater. Interfaces.* (2019) **11**, 8000.

# ACKNOWLEDGMENTS



Yale *Energy Sciences Institute*