Catching Rays: Solar Energy for Today andTomorrow

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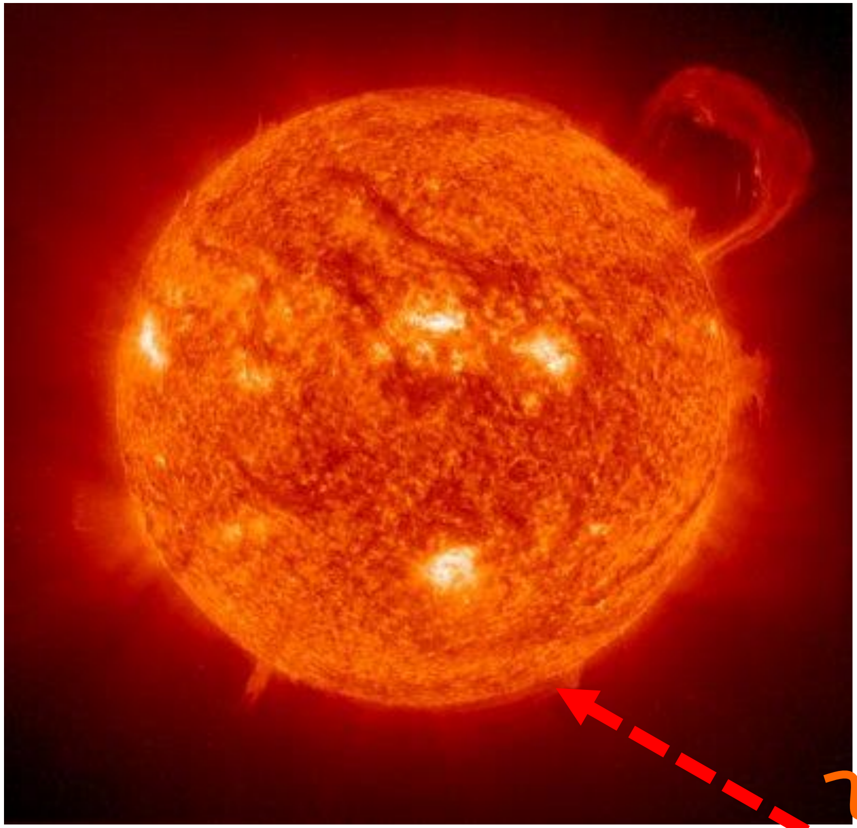
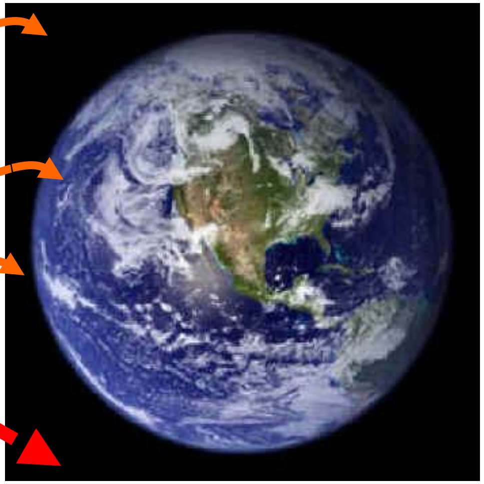
An energy shortage? … No way!



Every 90 minutes, enough solar energy hits the earth to supply the total energy needs of humanity for 1 year.

Giant Nuclear Reactor: Free, Lasts Billions of Years, No Maintenance Costs

Distance = 93 Million Miles

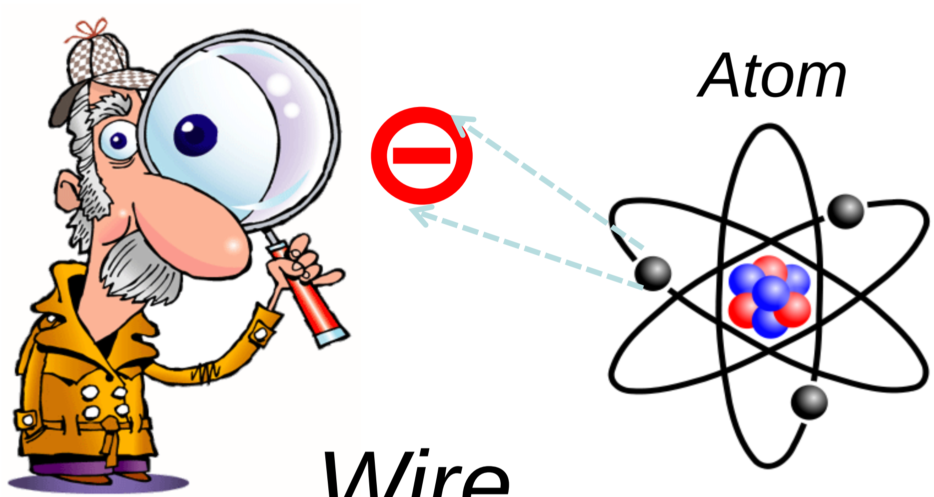


Recall: Energy can take many forms:

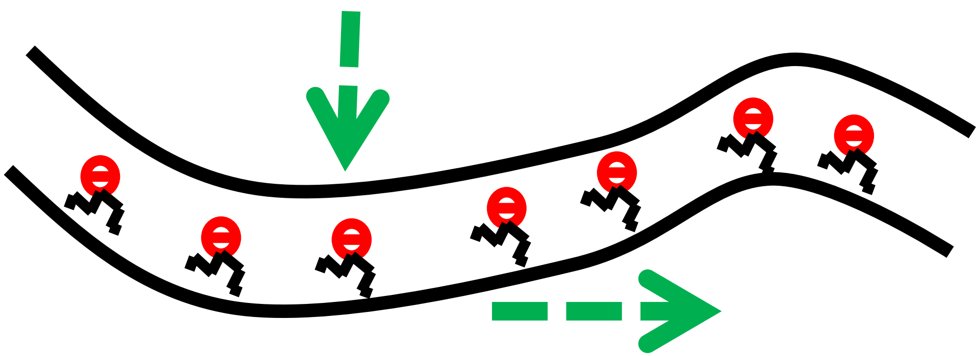
Heat Energy
Light Energy
Kinetic Energy
Chemical Energy

Most useful form of energy for modern human civilization = electrical energy

Atom

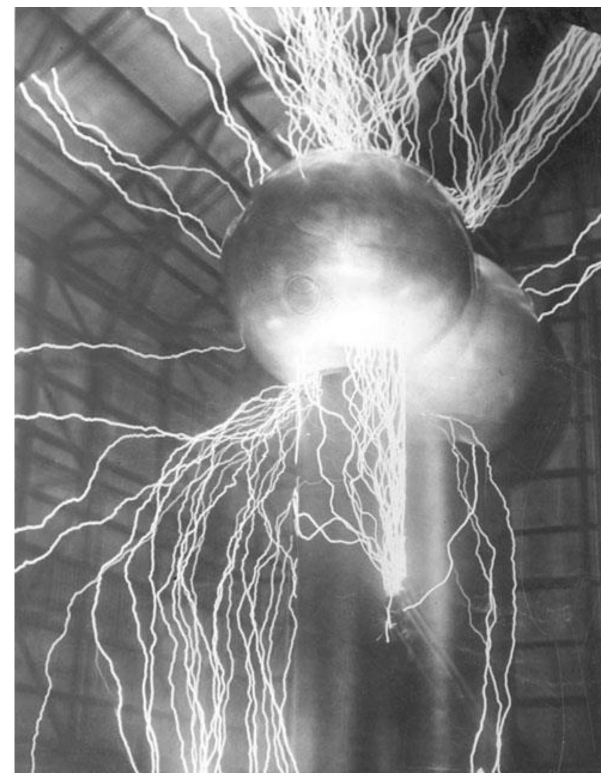


Wire



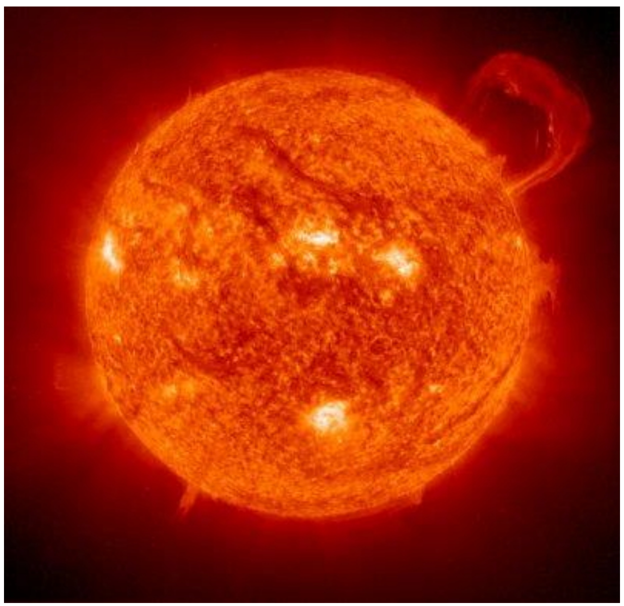
Current Flows

Electrical Energy = negatively charged electrons (current) driven by voltage potential



The Problem that has challenged Earth since the beginning of time:

How to change the Sun's photons into more useful forms of energy?



Chemical (Food)

Electrical

4 "Solar Revolutions" needed

Solar Revolution #1: Photosynthesis

3.5 Billion Years Ago

http://lotr.wikia.com/wiki/Category:Images_of_Mordor

CO_2 + light = food, O_2

Solar energy and H_2O used to transform CO_2 into sugars that fuel plant growth. O_2 is a waste byproduct.

https://odyssey.coe.cornell.edu/trips/8-day-backpacking-green-mountains

Solar Revolution #2: Agriculture

10,000 Years Ago

http://science-all.com/jungle.html

CO_2 + light = food, O_2

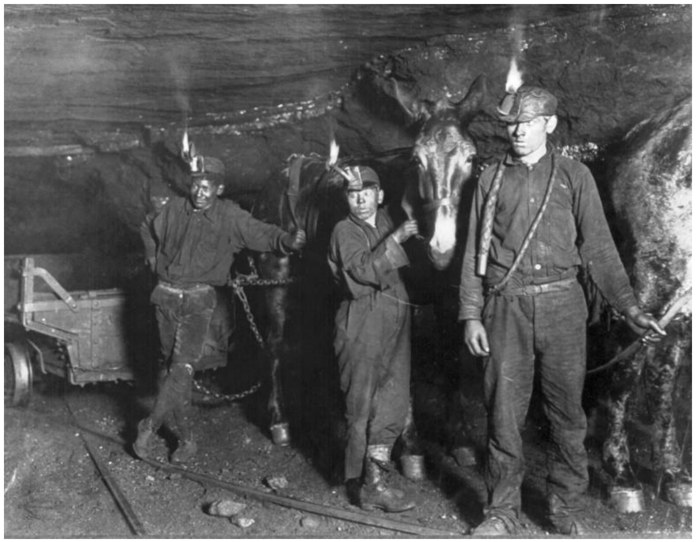
Construction of a "solar farm"

http://www.eoearth.org/view/article/149911/

Stop relying on random placement of random plants: organize high density solar conversion areas to transform CO_2 and light into food.

Solar Revolution #3: Fossil Fuels

200 Years Ago

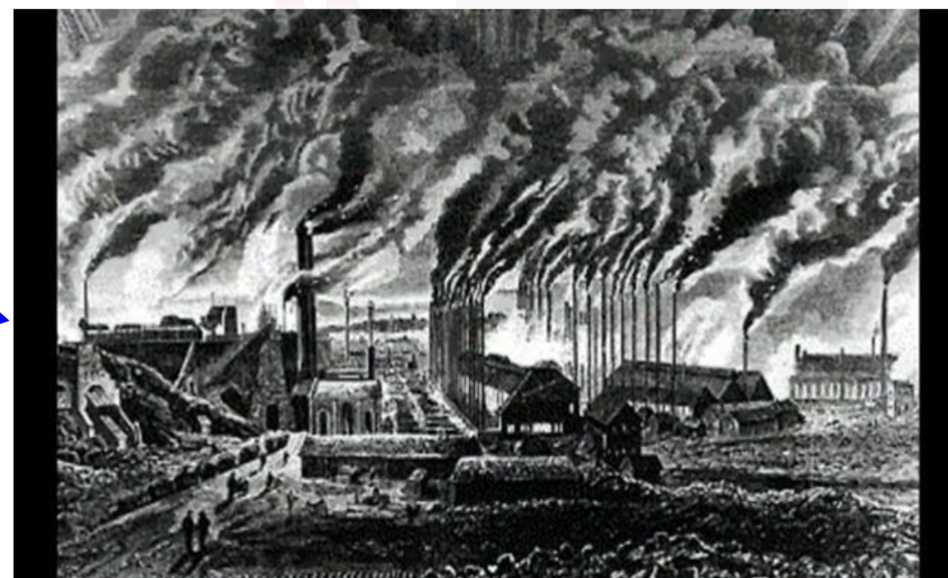


https://commons.wikimedia.org/w/index.php?curid=10326788

CO_2 + light + time = concentrated energy

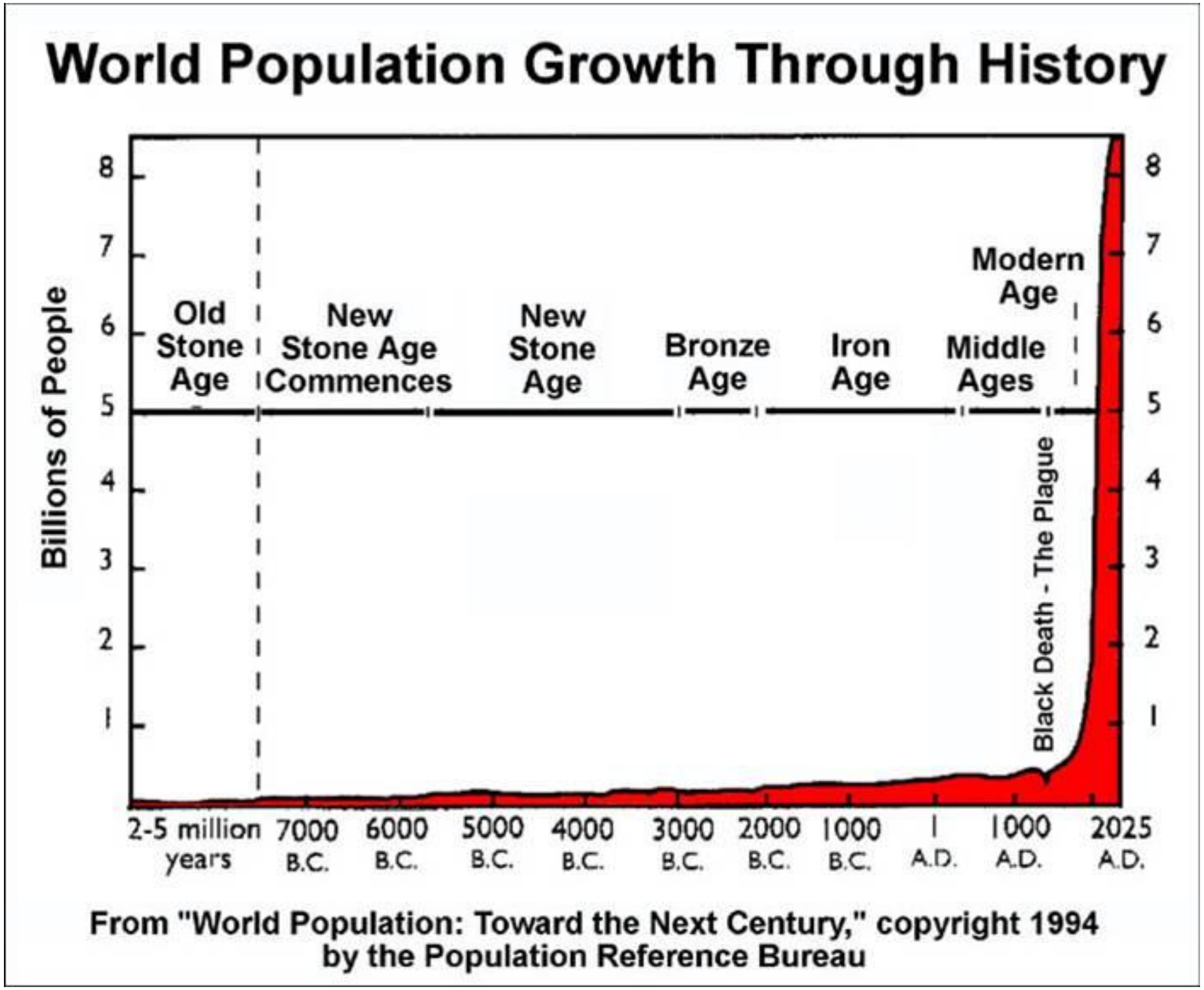
=

Realization that the Earth has a huge "savings account" of solar energy in the form of fossil fuels (coal and oil) that can be extracted and used at will.



http://wondergressive.com/90-companies-caused-climate-change/

Revolution #3 is when human population growth really began to accelerate: more energy = more people



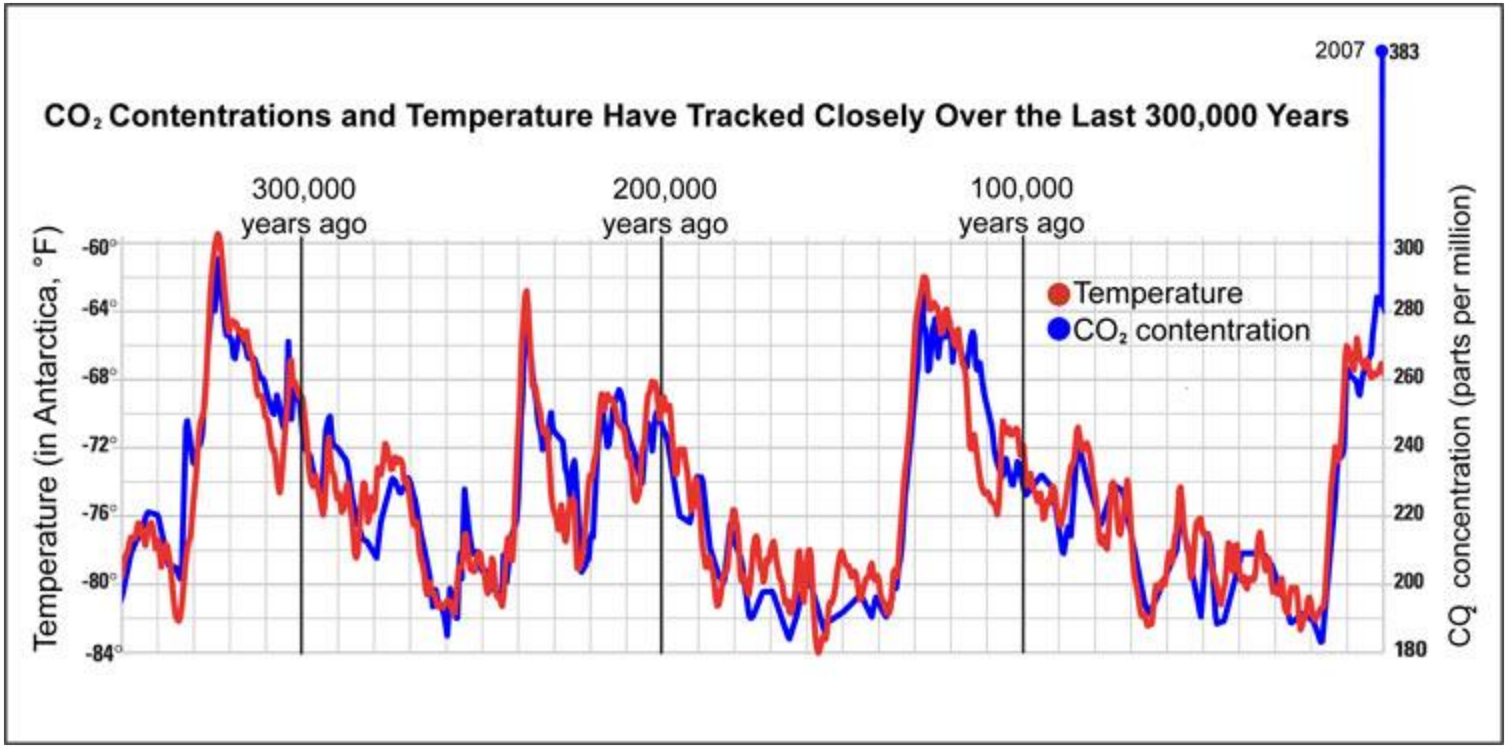
https://citizenactionmonitor.wordpress.com/2010/06/15/is-humanity-inherently-unsustainable-pt-7-oil-triggers-population-explosion/

Solar Revolution #4:
Direct Light-to-Energy Conversion

Today

Why the urgency? Climate Change.

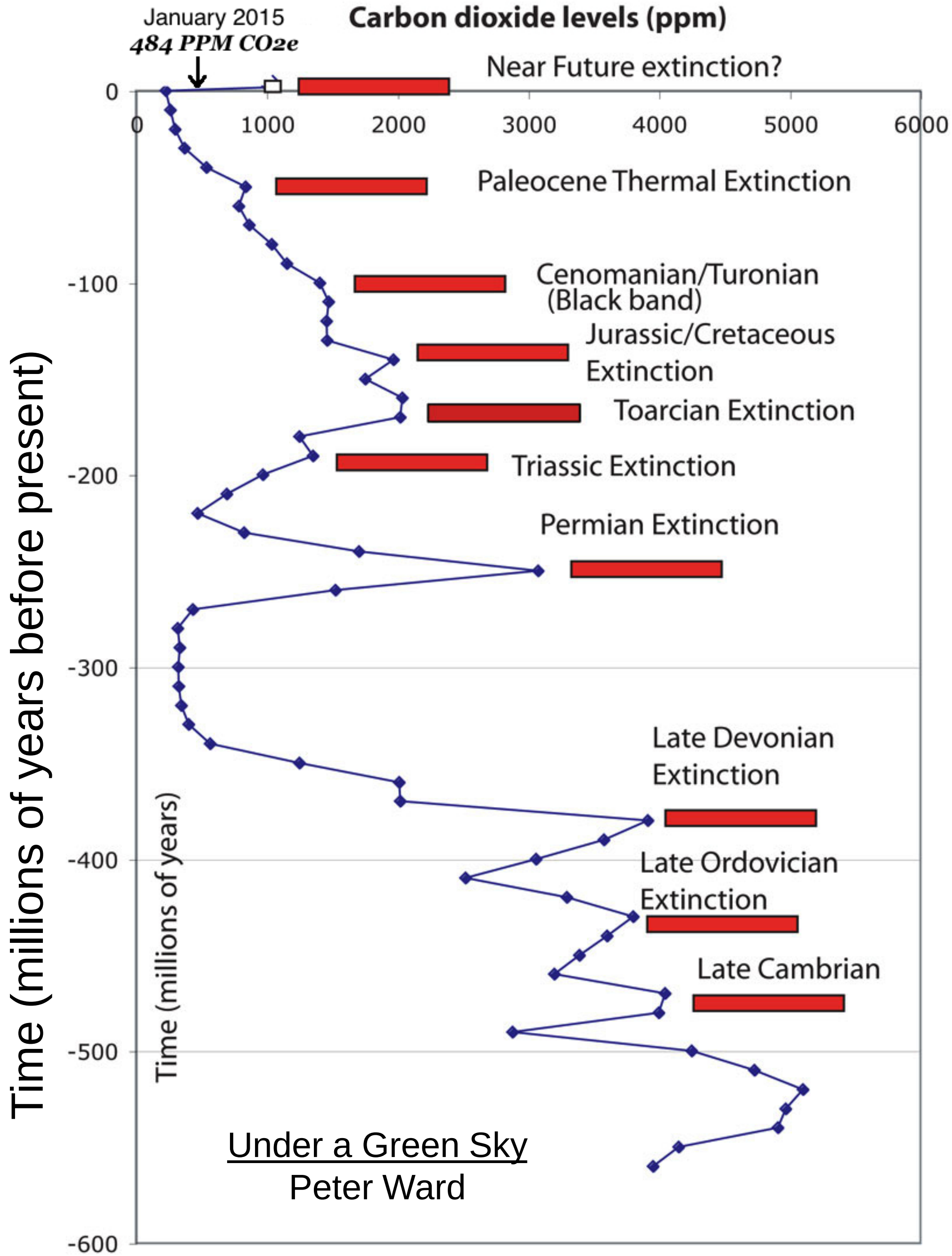
Burning fossil fuels returns CO_2 to the atmosphere – we are going back in time… hotter, acidic oceans, and ?



http://www.southwestclimatechange.org/climate/global/past-present

Does the past predict the future? We hope not…

Over history, spikes in CO_2 correlate with extinction events. In most cases, past CO_2 release was probably due to volcanic events over several million years.



Under a Green Sky
Peter Ward

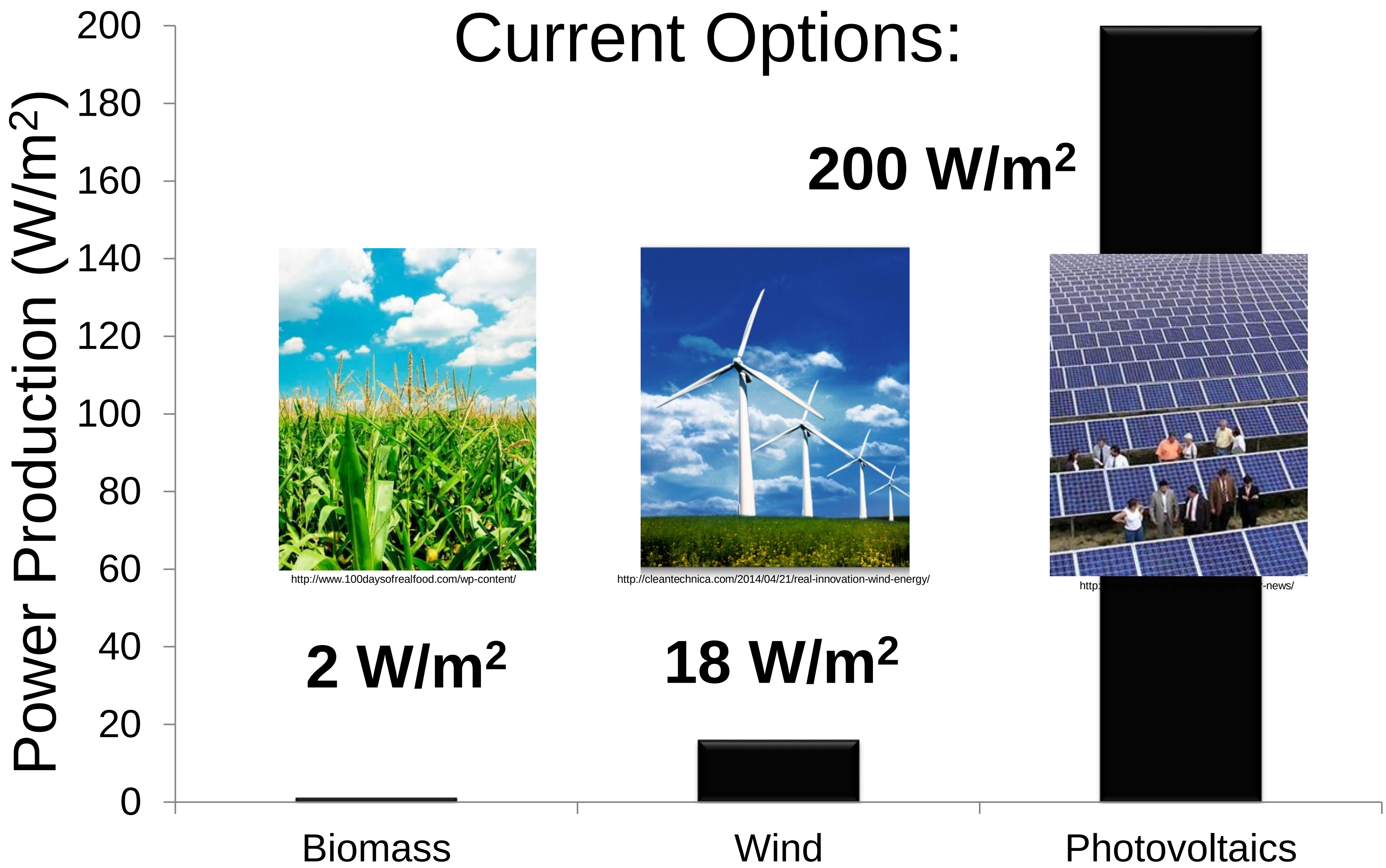
We would like to harvest energy from the sun. What are our alternatives?

Current US requirements = $3x10^{12}$ W = 3 Terawatts

1. **Biomass energy** – convert solar photons to sugars via photosynthesis, then convert sugars to fuels like biodiesel or ethanol
2. **Wind energy** – convert solar photons to heat, which expands air and causes wind, which turns turbines
3. **Photovoltaic energy** – directly convert solar photons to electric power via the photovoltaic effect

For any of these options, we will have to use some land to generate the power. How much depends on how efficient the conversion is….

Alternative Energy Sources



https://www.masterresource.org/smil-vaclav/smil-densitynewrenewables/

Biomass Power: Energy Density = 2 W/m^2

Requires covering entire USA with biomass crops

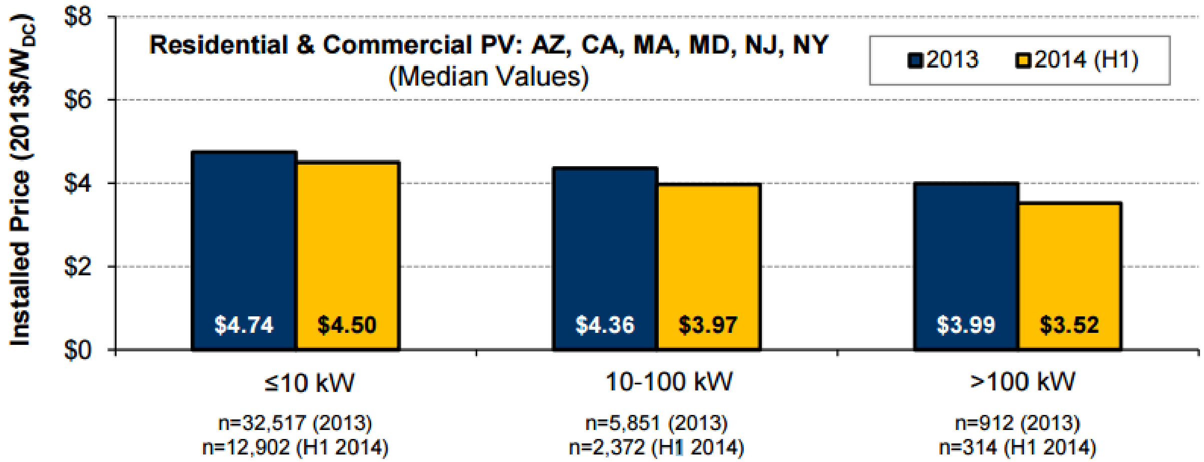
Wind Power: Energy Density = 18 W/m^2

Solar Power (10% efficiency): Energy Density = 200 W/m^2

Nate Lewis, Caltech

The best way to cuut Solar Energy Costs: raise solar cell efficiency

Current prices for solar panels are just below $0.50/W and are expected to fall to $0.36/W by 2017. **PV panels only account for ~15% of solar installation cost**.



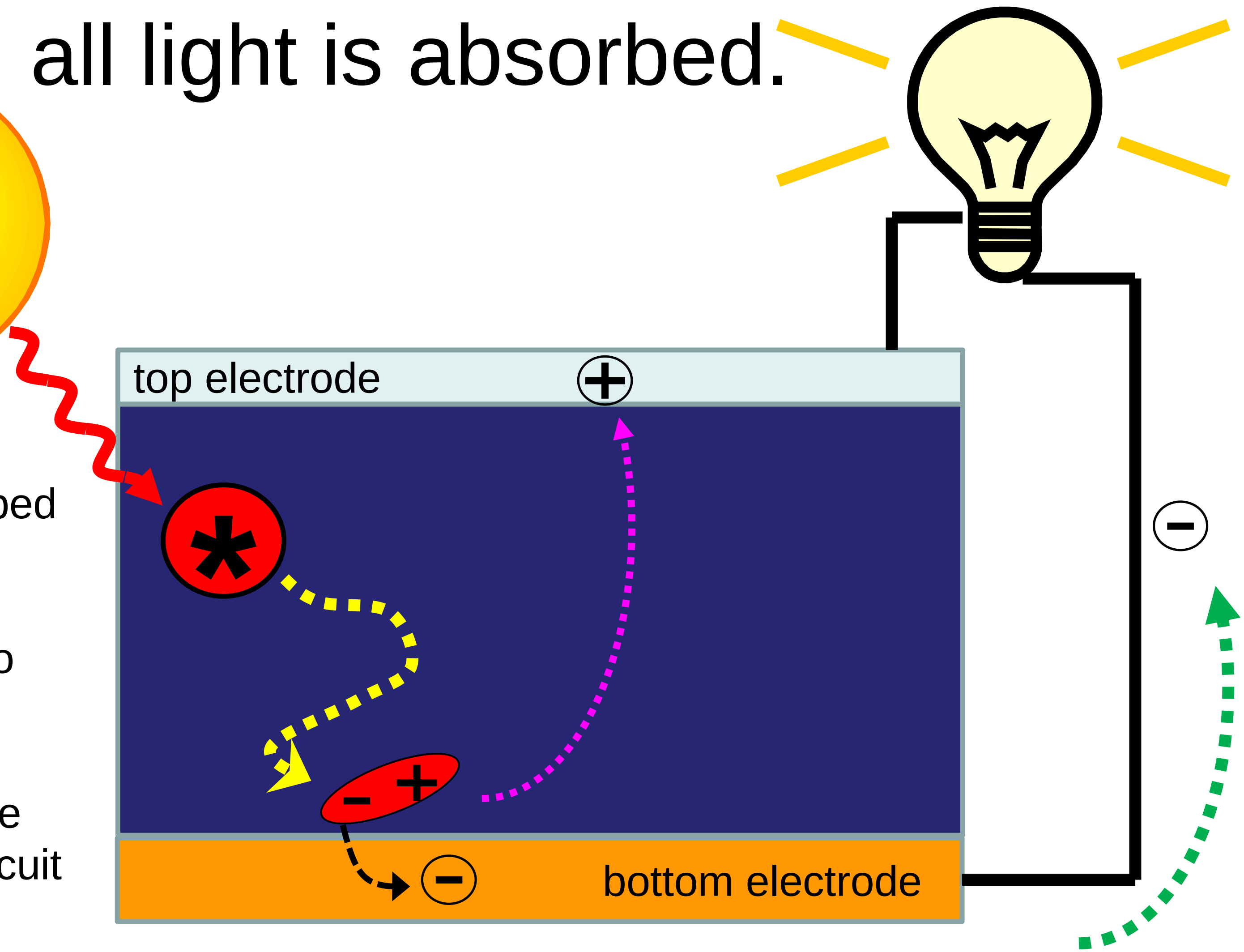
Note: The 2013 and H1 2014 values in this figure are based on data from a smaller set of states than elsewhere in this section, and thus the 2013 values differ from the national median values cited previously.

These are the expensive parts:

Increasing efficiency would cut down installation prices by requiring less square footage of already cheap solar panels.

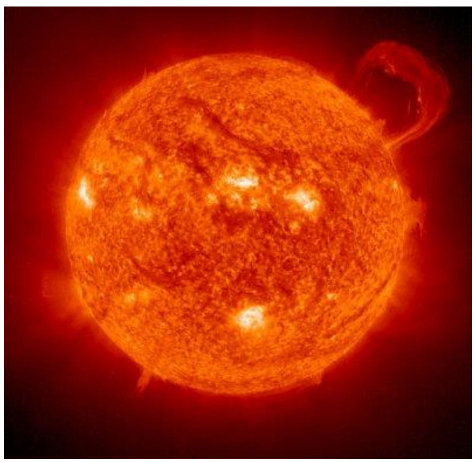
http://www.nrel.gov/docs/fy12osti/53938.pdf
http://www.apollo-solar-panels.com/regions/solar-panels-barnsley.php
http://www.greentechmedia.com/articles/read/solar-cost-reduction-drivers-in-2017
http://www.greentechmedia.com/research/report/pv-technology-and-cost-outlook-2013-2017

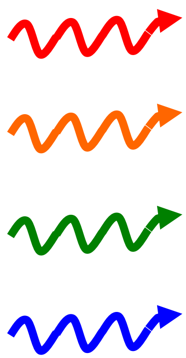
Solar cells can only absorb photons in a certain wavelength range – not all light is absorbed.

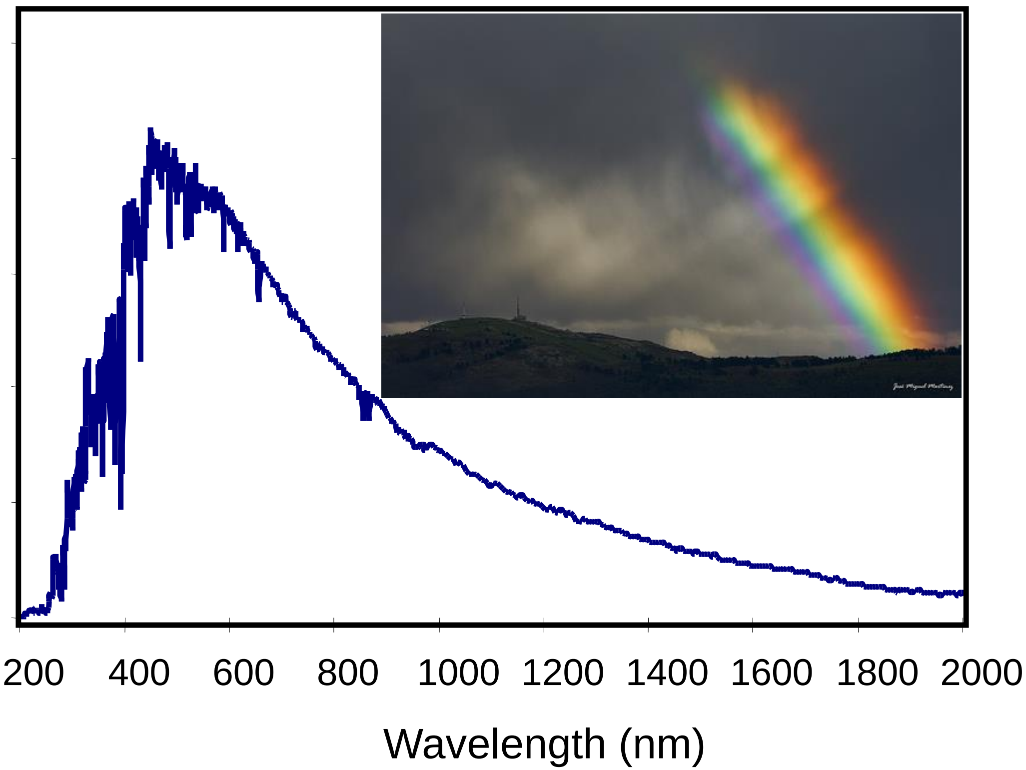


1. Photon is absorbed to make an excited state ("Exciton").
2. Exciton moves to interface where it is ionized.
3. Electrons migrate through external circuit as electricity.

Why aren’t solar cells 100% efficient? Sun produces photons in many different colors (wavelengths) – white light.

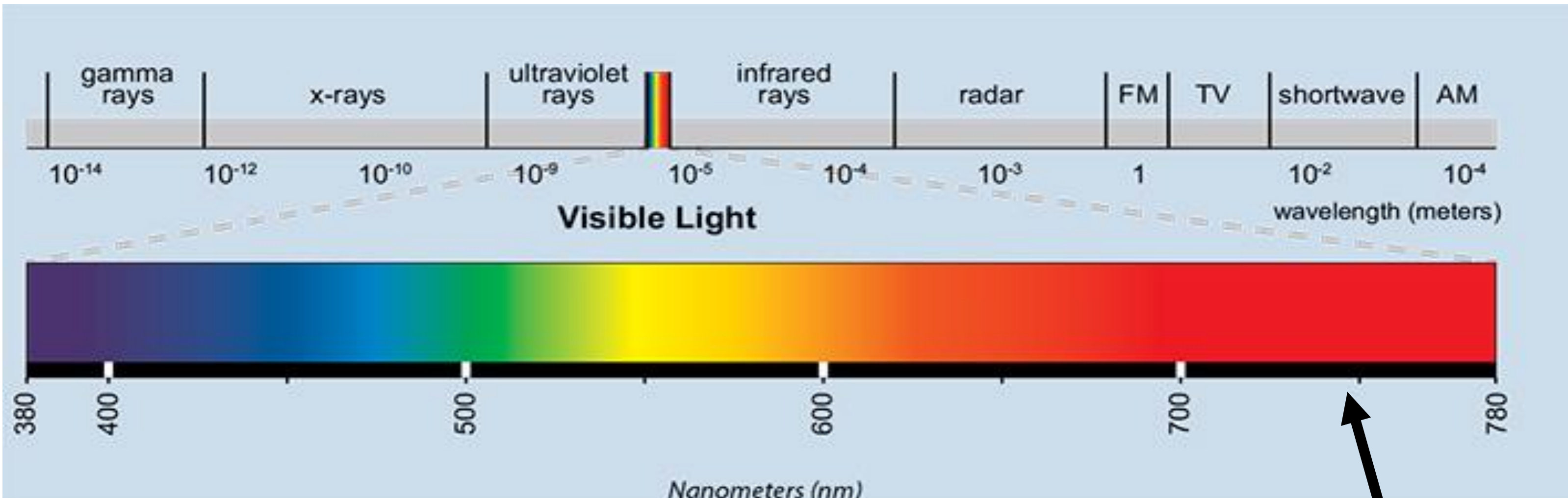






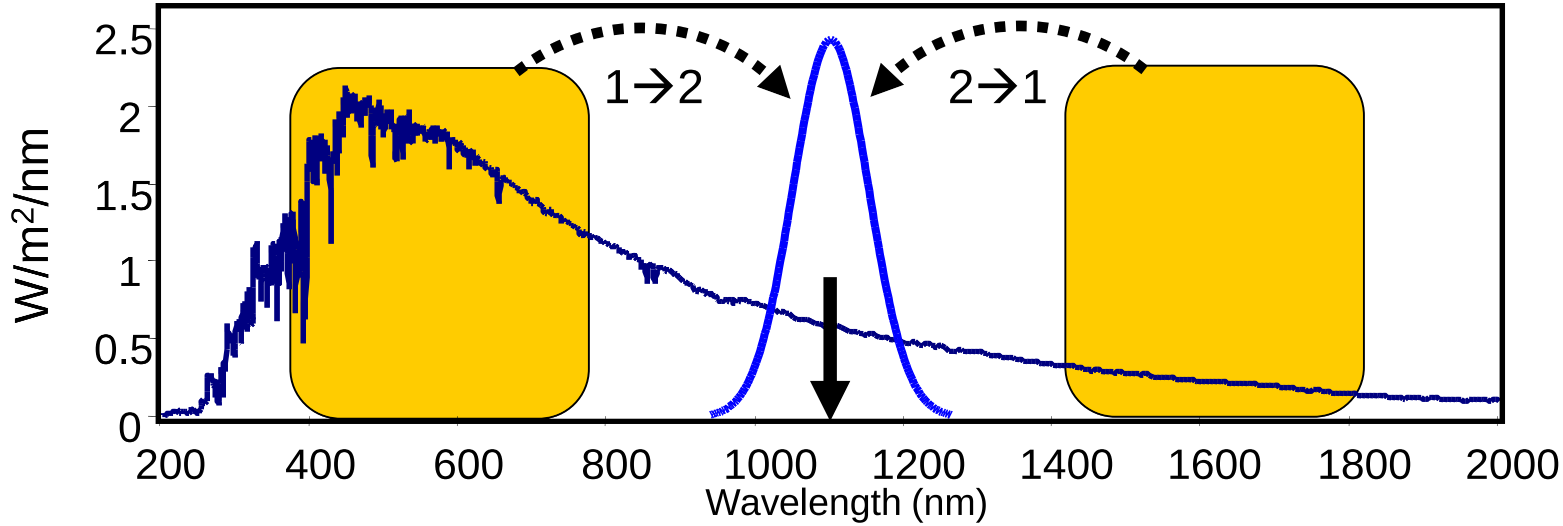
Sun Spectrum : photons everywhere!

Many colors = good for rainbows, bad for solar energy conversion

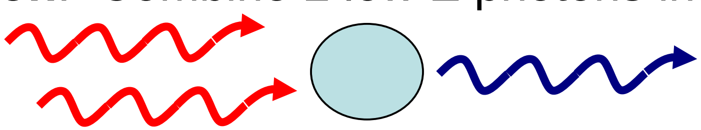


Every solar cell runs at highest efficiency at its <u>bandgap wavelength</u> – different for every semiconductor

One solution: reshape the solar spectrum to match the solar cell bandgap

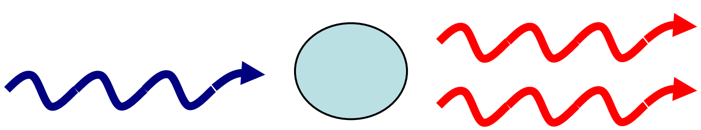


Upconversion: Combine 2 low E photons into a single high E photon



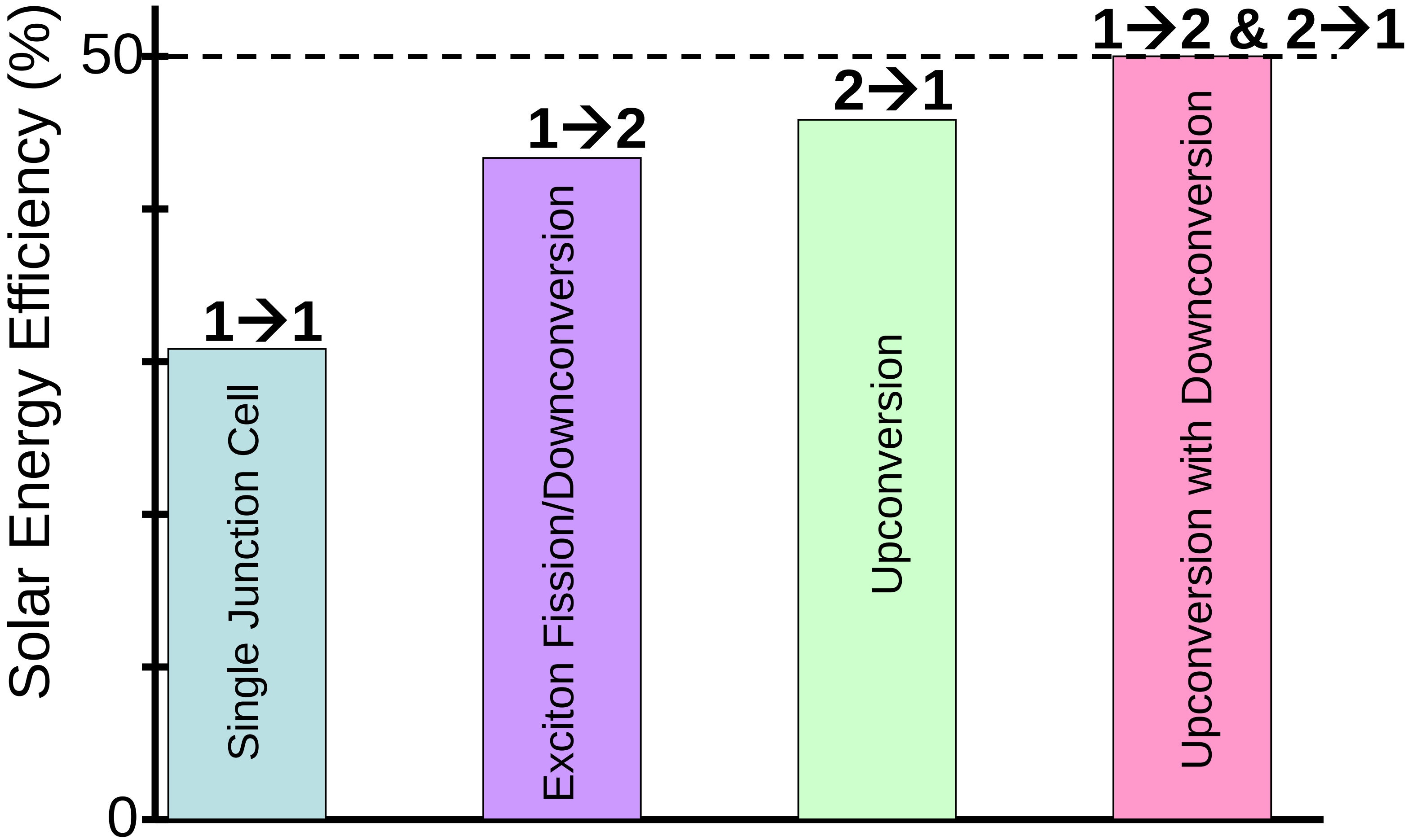
(for $E_{photon} < \Delta E_{bandgap}$)

Downconversion (Quantum Cutting): Split 1 high E photon into 2 low E photons



(for $E_{photon} > \Delta E_{bandgap}$)

If we can combine/split photon energy, we get big gains in solar efficiency

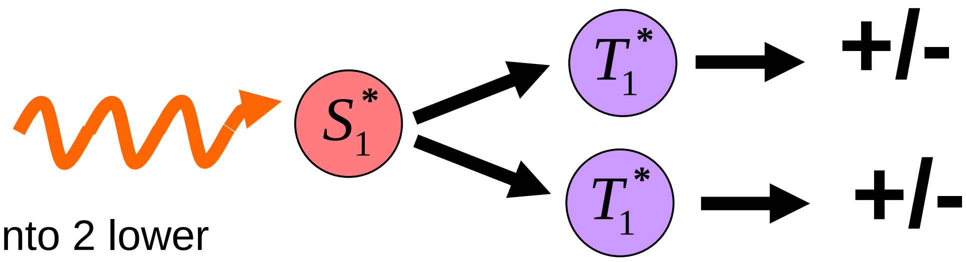


Trupke, J. Appl. Phys. 92, 1668 (2002); Hanna & Nozik, *J. Appl. Phys*. **100**, 074510 (2006); Shpaisman et al., *Sol. En. Mater. Sol. Cells* **92**, 1541 (2008)

Our strategy: absorb photons, then use excitons to combine/split energy

<u>Key: we will use organic molecules with singlet/triplet states</u>

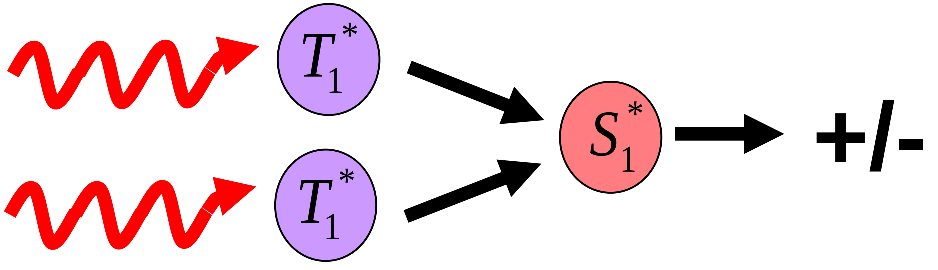
1→2 Conversion: Exciton Fission



Convert 1 high energy photon into 2 lower energy excitons. A photon that could only produce 1 can now produce 2 electrons.

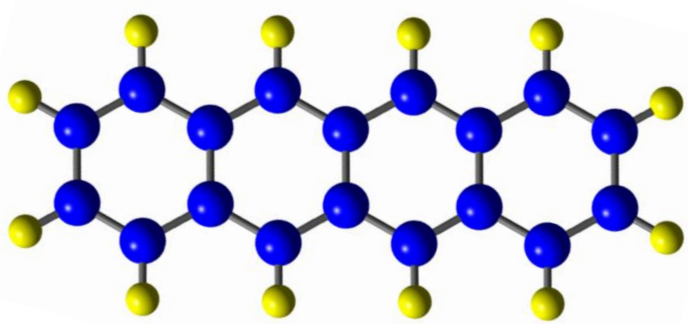
2→1 Conversion: Exciton Fusion

Convert 1 low energy photons into 1 higher energy exciton that can produce an electron. Photons that could not produce any electrons now produce 1.

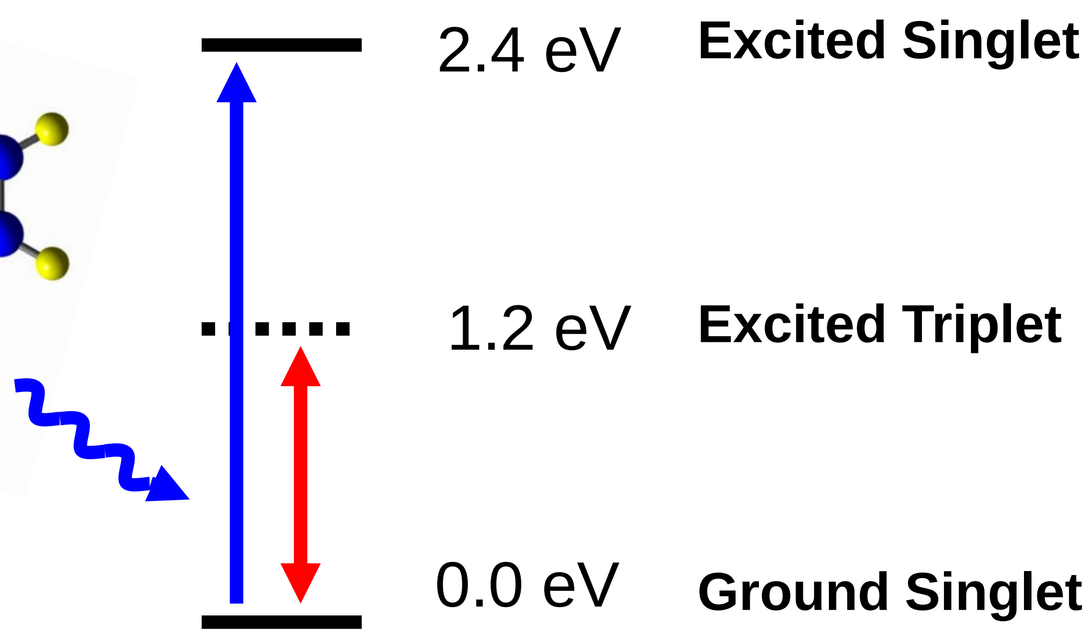


2→1 conversion: we need new molecules that have the right energy levels:

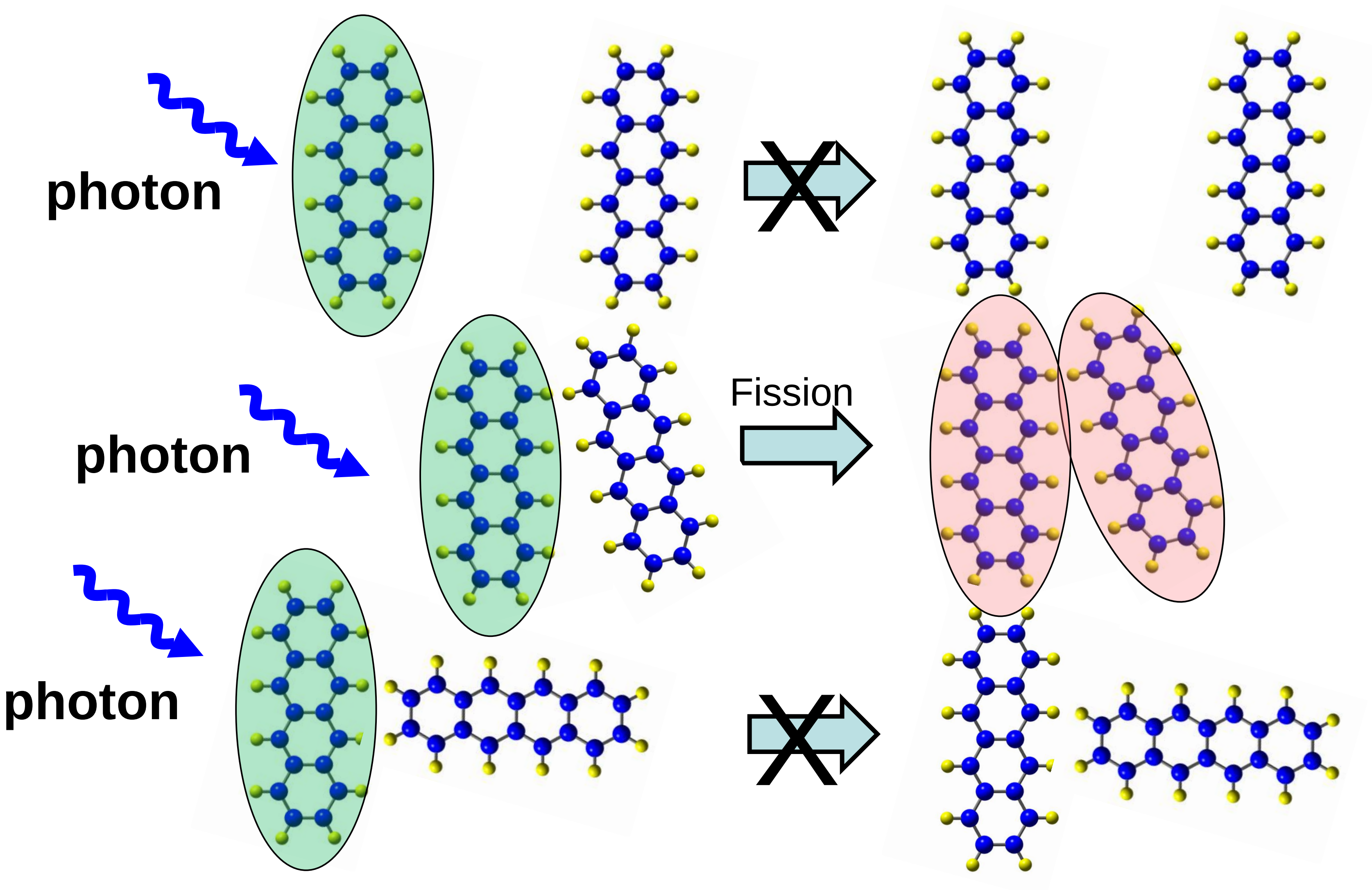
1. We need 2xE(triplet) $\leq$ E(singlet).
This means we have to look for the right molecule…



Tetracene



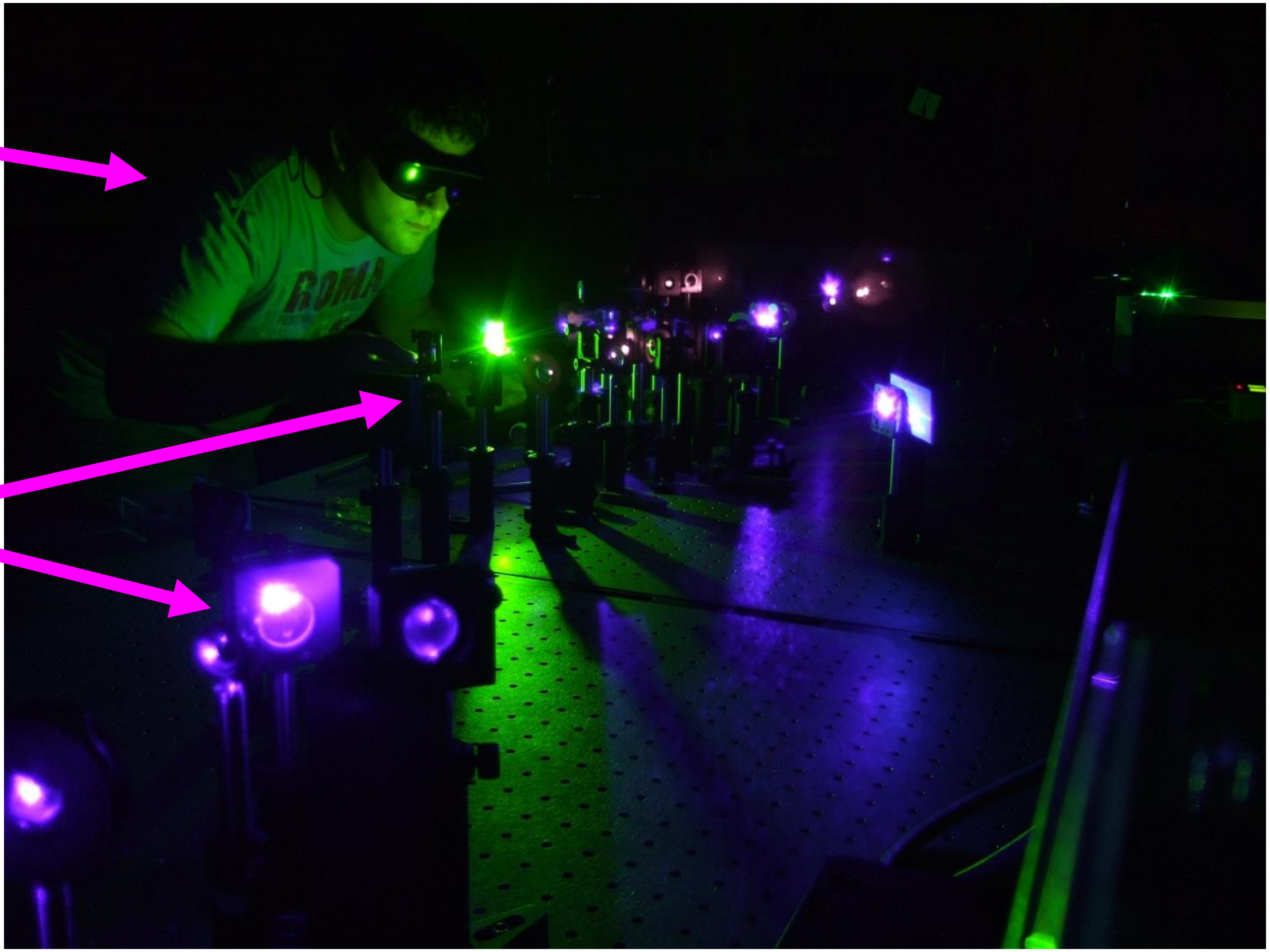
We also need to figure out how to arrange these molecules so they undergo fission



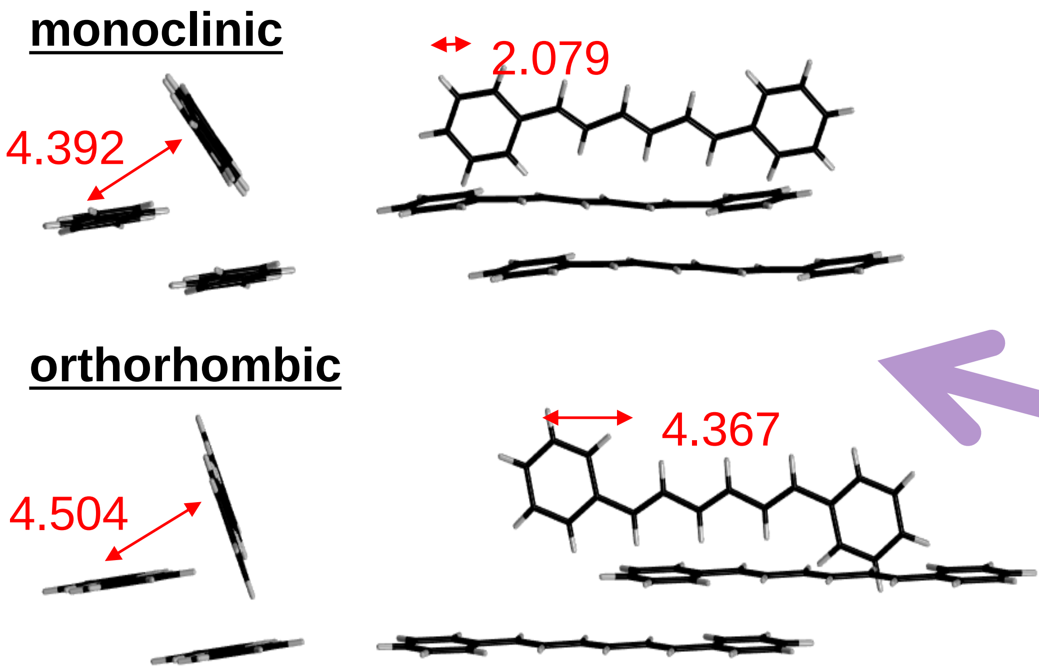
Experimental study: we use lasers (not the sun!) to generate photons and see what happens in the material.

Graduate student Robert Dillon

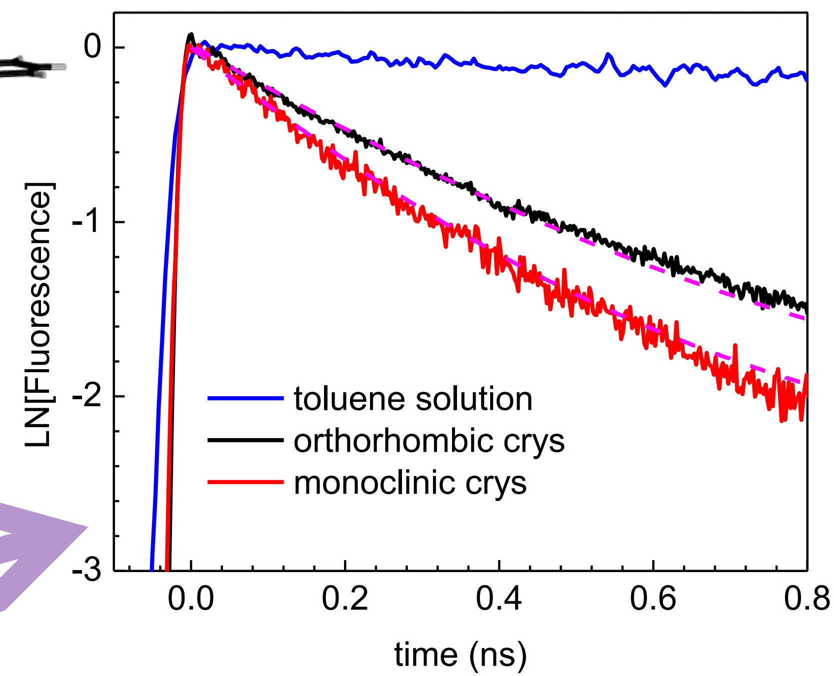
Laser Beams



Examples of Geometry Dependence:

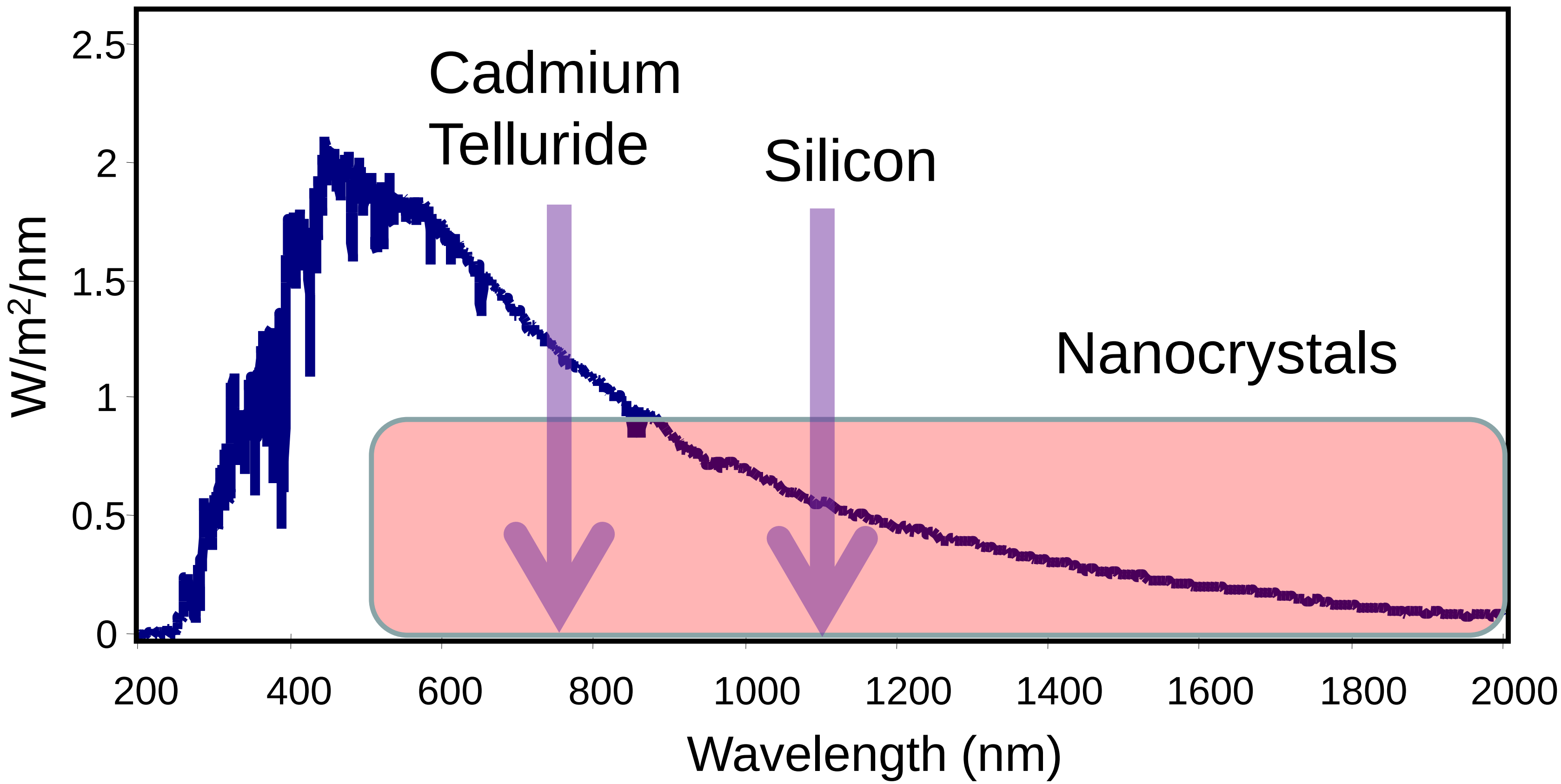


Diphenylhexatriene is a molecule that crystallizes in 2 polymorphs: monoclinic and orthorhombic. This change in packing affects how fast fission occurs.



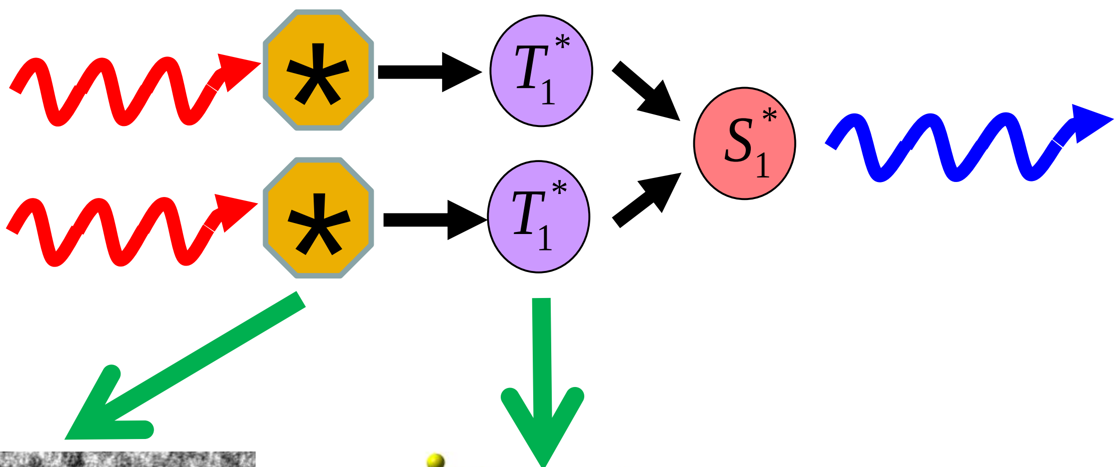
Monoclinic crystal form has more rapid decay → faster exciton fission → more efficient material

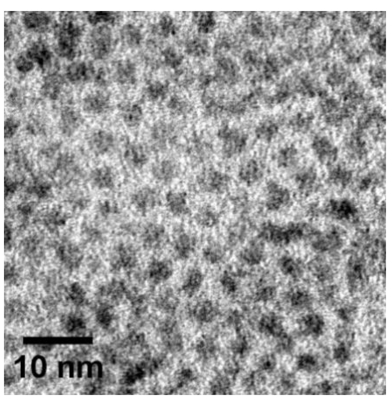
What about 2→1 upconversion to make long wavelength photons contribute?



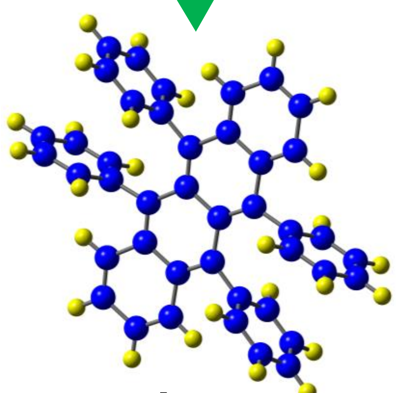
We need something that absorbs infrared light… semiconductor nanocrystals might work

2→1 upconversion: we use nanocrystals to absorb, then give energy to organic molecule.





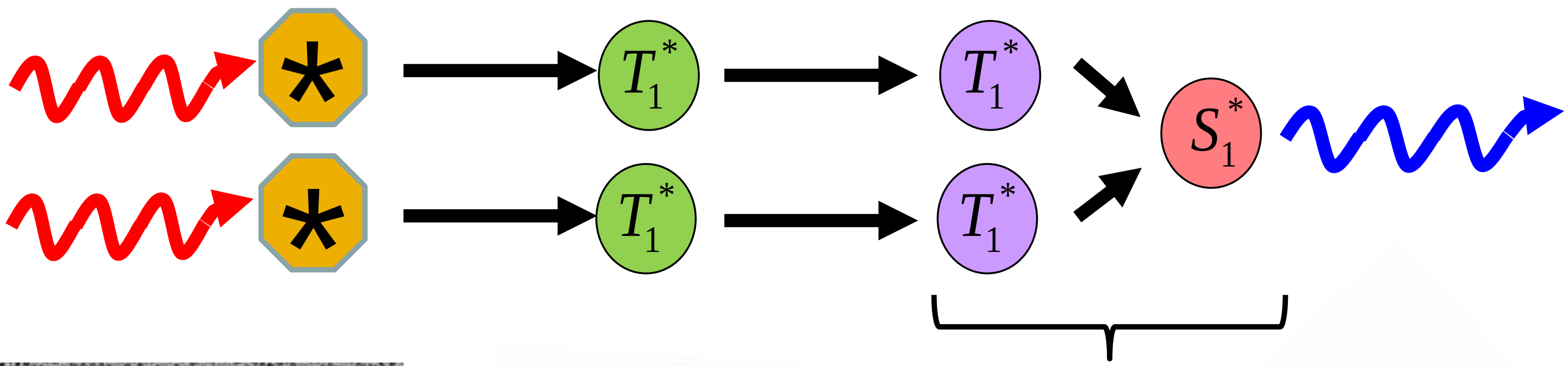
PbSe nanocrystals
Sensitizer

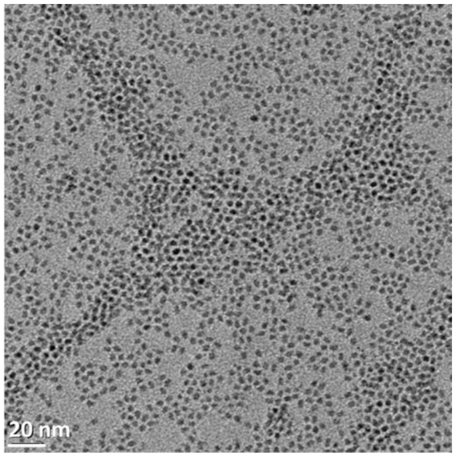


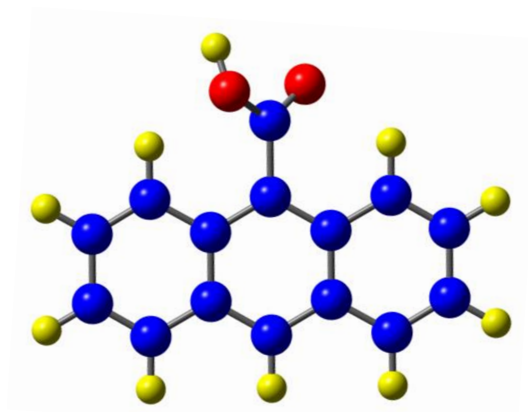
Rubrene
Triplet Acceptor
Emitter

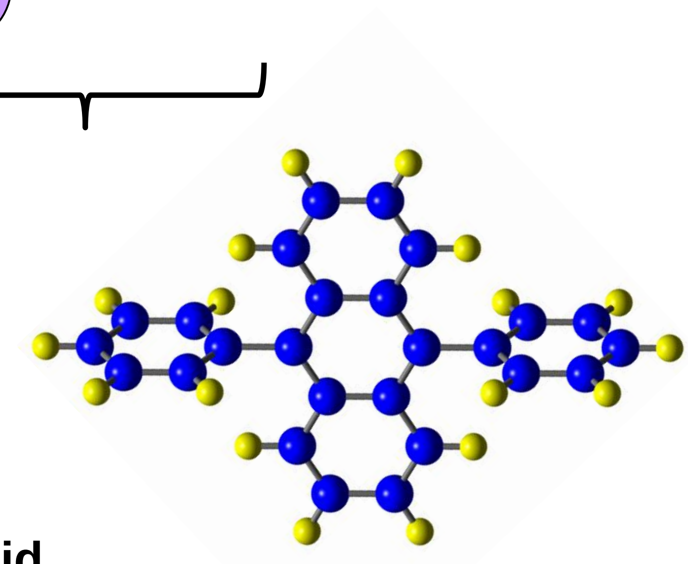
Spot where infrared 980 nm laser hits sample. It works, but low efficiency.

To improve efficiency, we use another molecule to help the transfer from nanocrystal to emitter molecule. CdSe-diphenylanthracene test system.









CdSe nanocrystals
Sensitizer

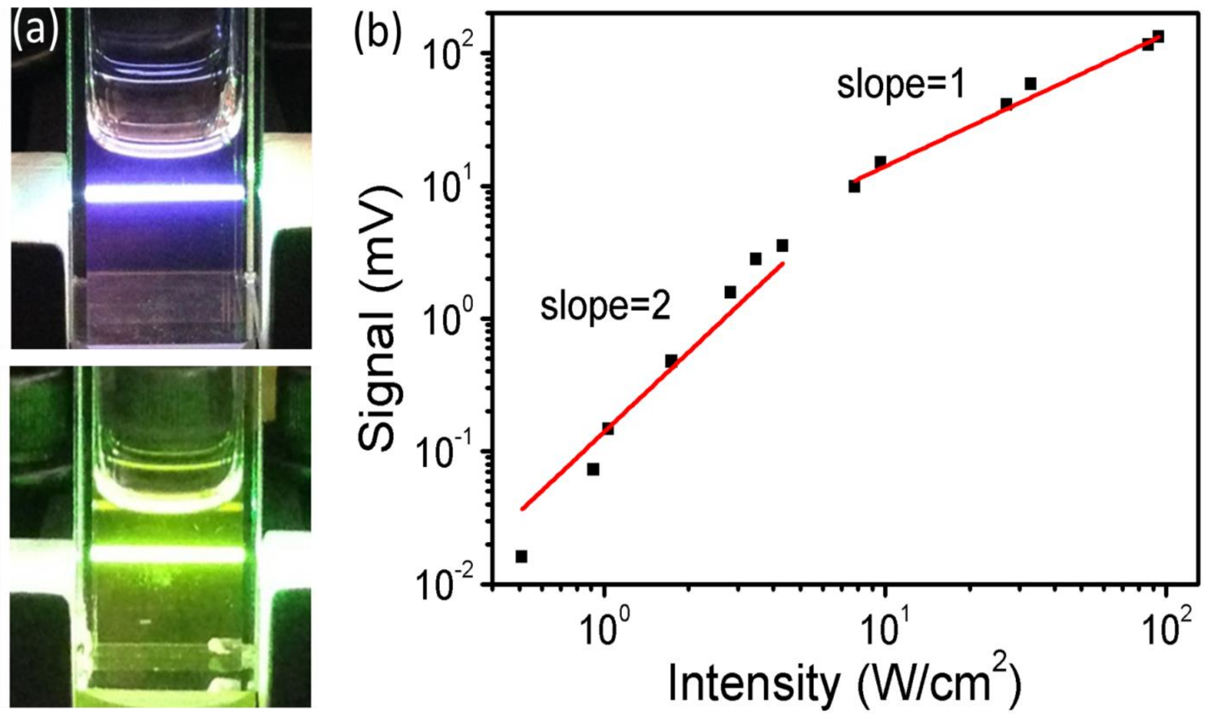
9-anthracene carboxylic acid
Ligand Triplet Acceptor
Transmitter

Diphenylanthracene
Triplet Acceptor
Emitter

Ligand-Mediated energy transfer works: Upconversion efficiency is 1000x higher.

With 9-ACA ligand: 10^3 enhancment in upconverted light

Without 9-ACA ligand: we only see green-yellow CdSe emission, no upconverted light



“Hybrid molecule-nanocrystal photon upconversion across the visible and near-infrared,” Z. Huang, X. Li, M. Mahboub, K. M. Hanson, V. M. Nichols, H. Le, M. L. Tang and C. J. Bardeen, *Nano Lett*. **15**, 5552-5557 (2015).

“Solid-state infrared-to-visible upconversion sensitized by colloidal nanocrystals,” Baldo, Bulovic, Bawendi and coworkers, *Nat. Photon*. **10**, 31-34 (2016).

“Direct observation of triplet energy transfer from semiconductor nanocrystals,” Castellano and coworkers, *Science* **351**, 369-372 (2016).

<u>Important Points:</u>

1. Solar Energy technology is just a continuation of Earth's efforts to harvest free energy coming from the sun.
2. Rapid rise of CO_2 due to fossil fuels makes it urgent that we find carbon-free energy sources.
3. The current challenge in solar cell technology involves efficiently using the sun's photons at <u>all</u> wavelengths.
4. Efforts at UCR and many other places are developing new materials for Upconversion and Downconversion to improve solar cell efficiencies.

But won't this take a long time?

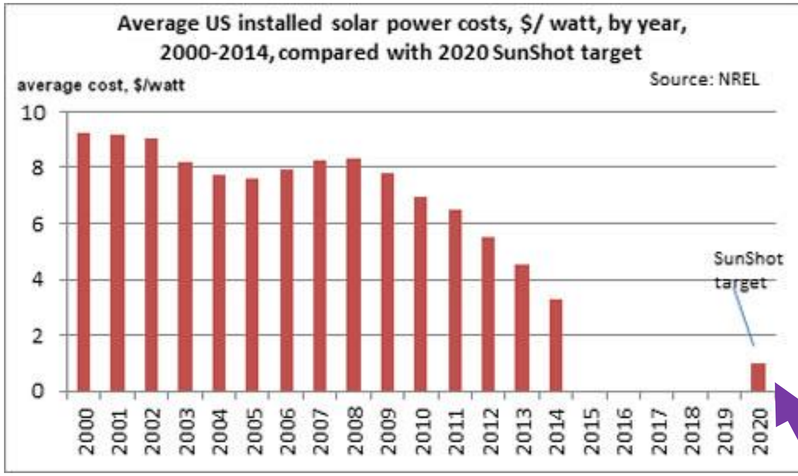
Will it be too late?

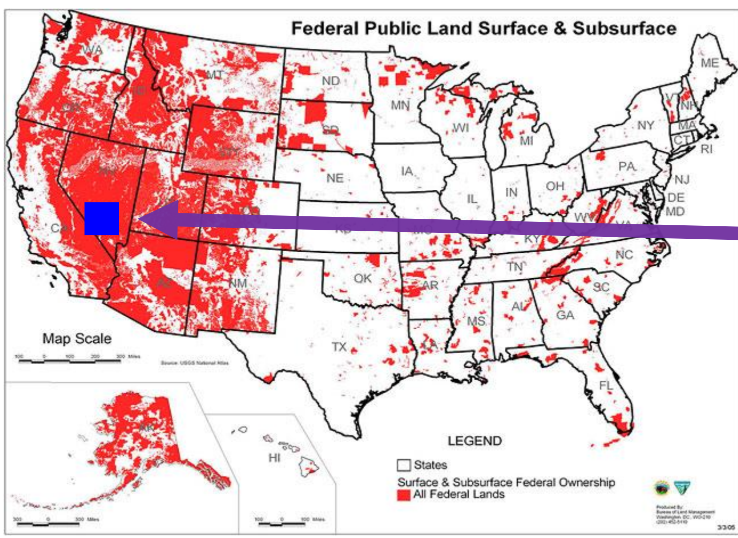
?

We could do it in the next 10 years.

“Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes” *Proc. Nat. Acad. Sci.* **112** 15060 (2015)

Energy storage is possible even without new batteries





Total US energy use = 25.5×10^{15} W.h
20% already non-CO_2, so
Nonrenewable energy = 20.4×10^{15} W.h
1 Watt installed solar = 2000 W.h

We need 10^{13} installed Watts, or
10 trillion installed Watts

If we hit the Sunshot target in 2020 for $1/Watt installed Solar,

Total cost of converting 100% to solar is $10 trillion (assuming free land).

US annual GDP = $16.7 trillion
War on Terror cost = $5 trillion

Bardeen Research Group

Tang Research Group

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Department of Energy