Energy for the 21st Century: Problems & Opportunities

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What is Energy?

- (many textbooks): "Energy is the ability to do work."
- "It is important to realize that in physics today, we have no knowledge of what energy *is*."

Richard Feynman, 1963

Energy is Conserved

- Energy can be transformed from one type to another, but the total sum of all energy types stays constant

Types of Energy

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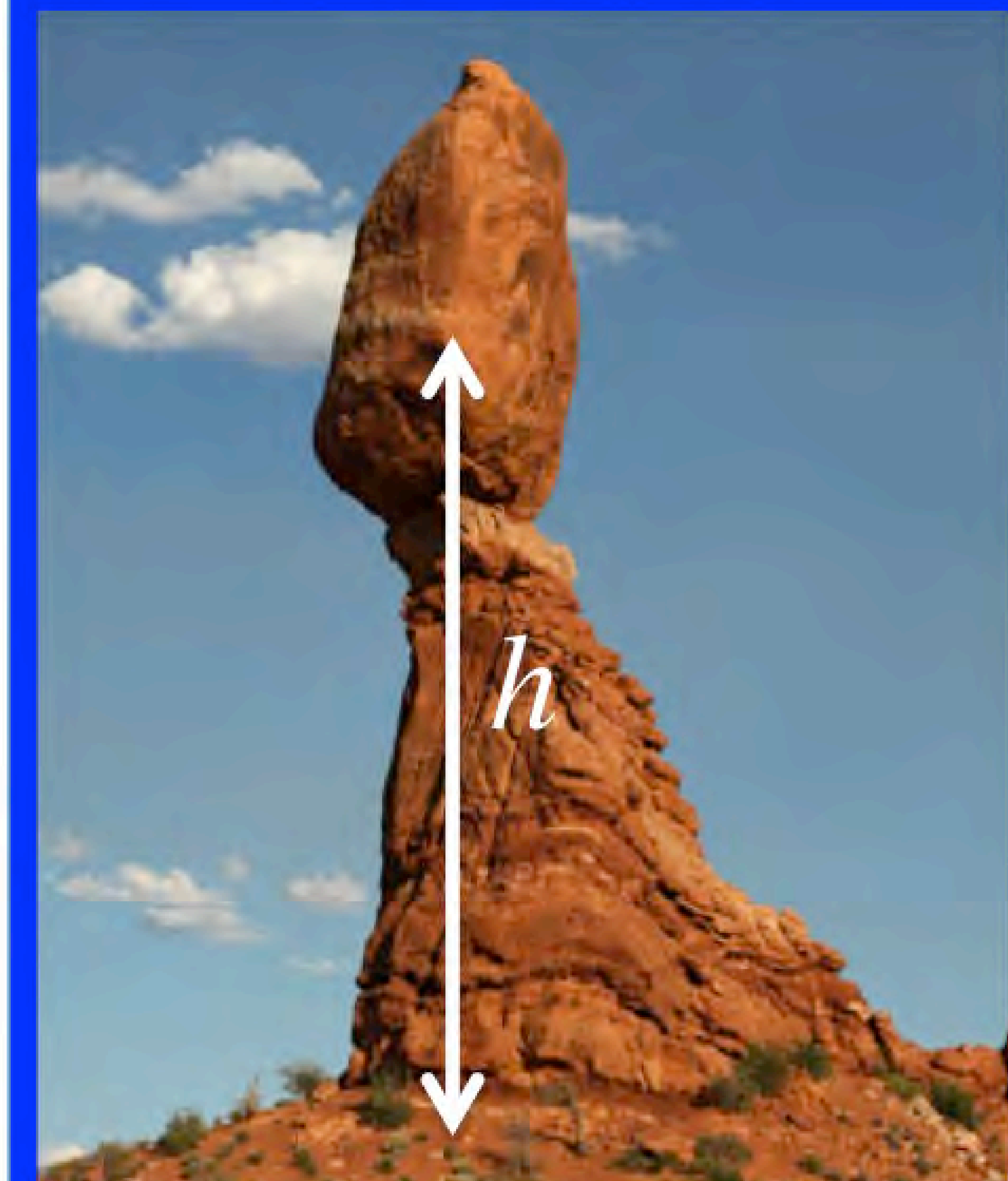
Potential



configuration

$$U = mgh$$

Kinetic

ordered motion

$$K = \frac{1}{2}mv^2 \geq 0$$

Thermal

random motion

$$\bar{K} = \frac{3}{2}k_B T$$

Types of Energy

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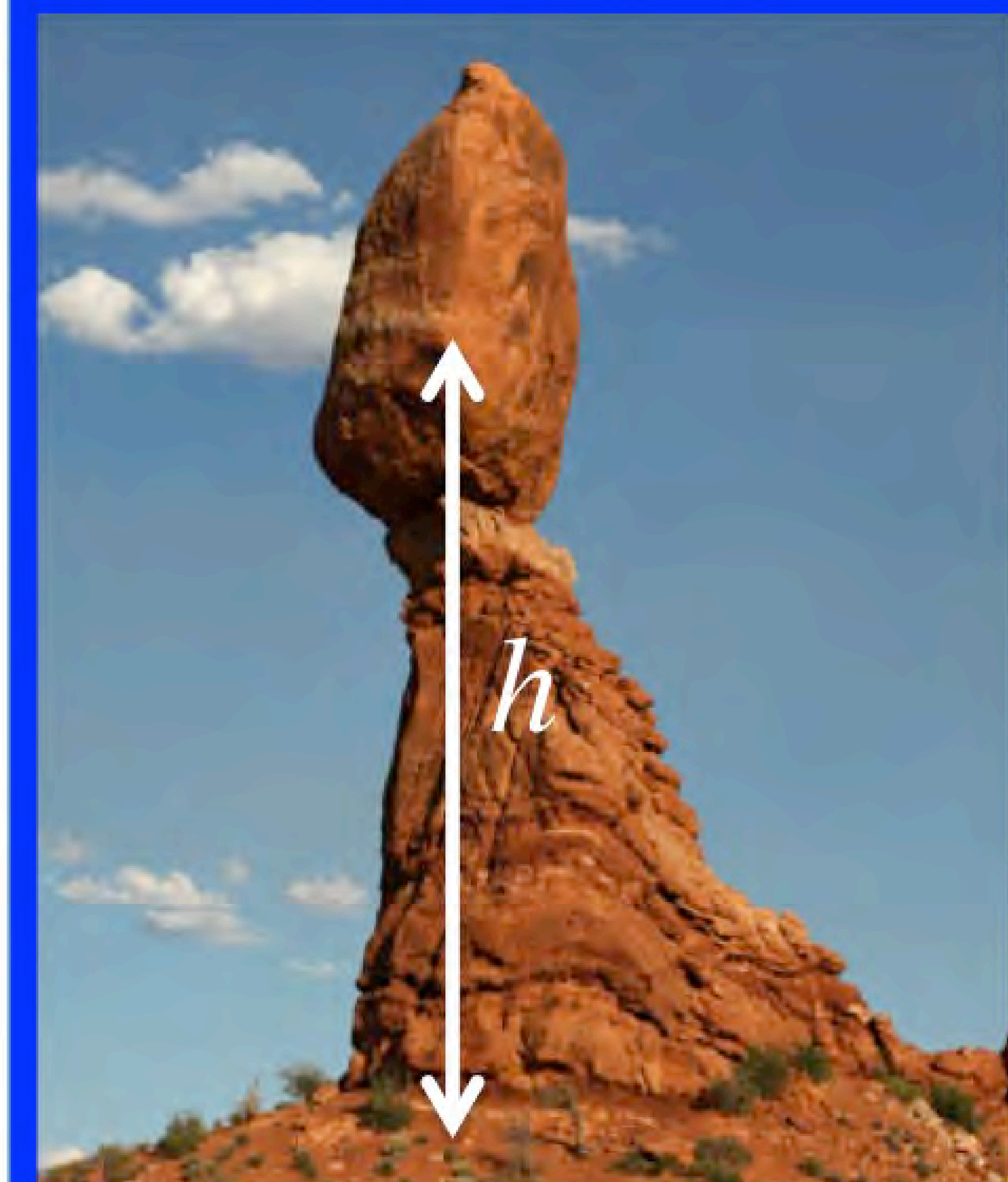
Potential



configuration

$$U = mgh$$

Electricity

&

Transportation

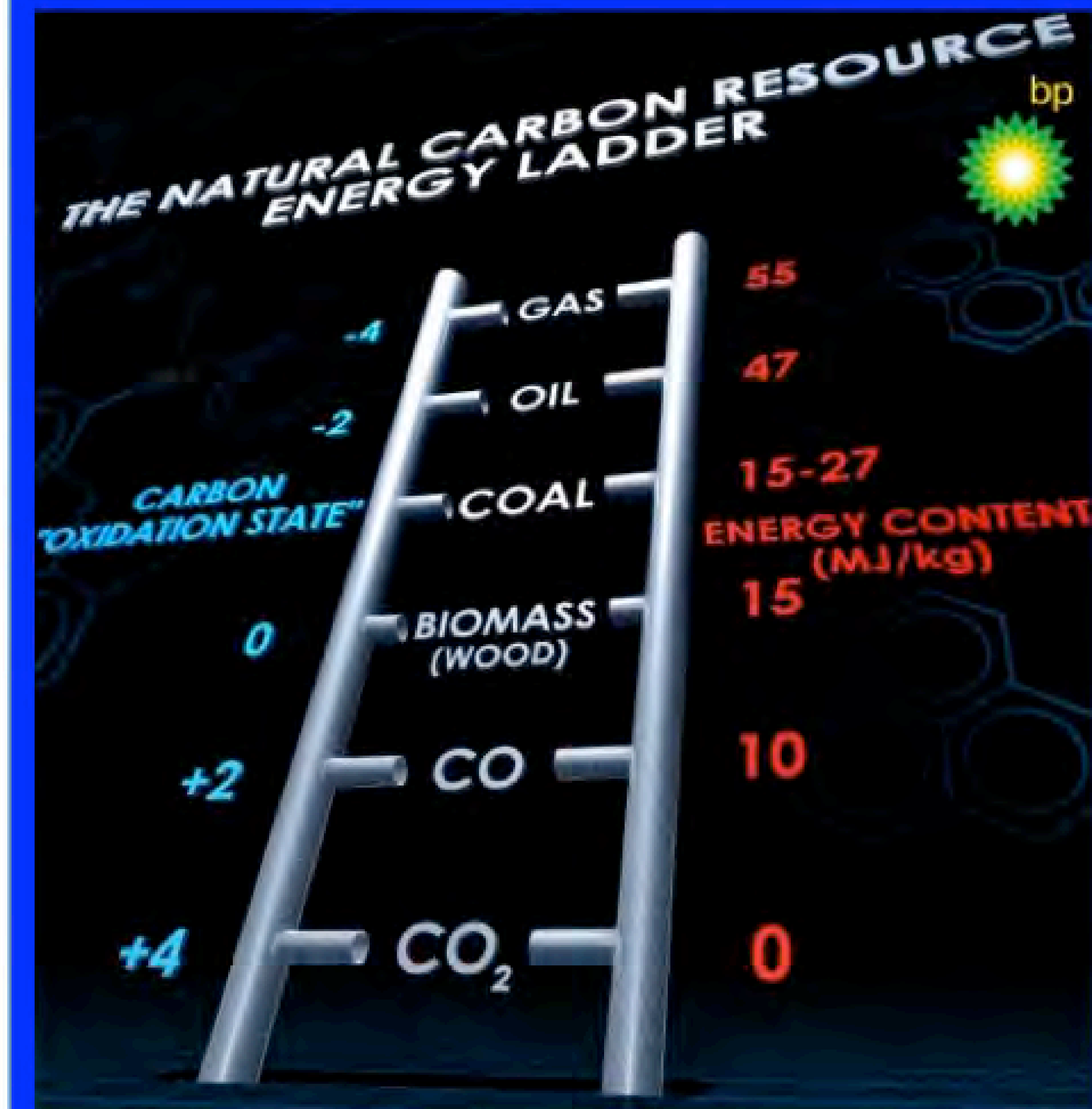
Thermal

random motion

$$\bar{K} = \tfrac{3}{2} k_B T$$

Types of Energy

Chemical



Example: Carbon
(all fossil fuels)

Electricity

&

Transportation

Thermal

random motion

$$\bar{K} = \tfrac{3}{2} k_B T$$

Units of Energy

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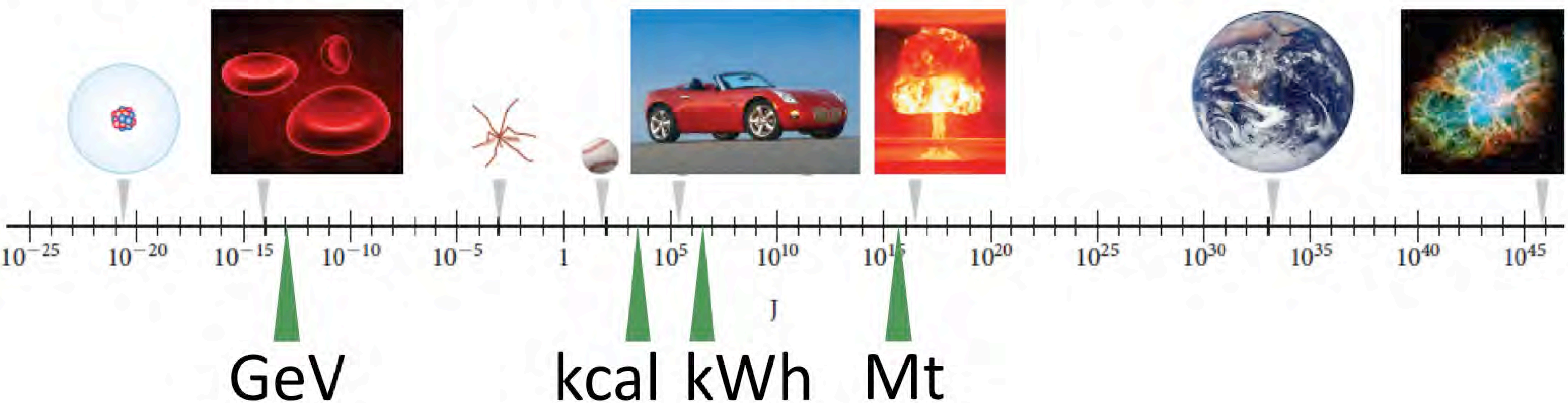
- Joule (SI unit): $1\ \mathrm{J} = 1\ \mathrm{kg\ m^2 / s^2}$
- kcal (= food calorie = Cal): 1 kcal = 4186 J
- GeV (= electron-Volt): $1\ \mathrm{eV} = 1.602 \cdot 10^{-13}$ J
- Mt (= million tons of TNT): $1\ \mathrm{Mt} = 4.18 \cdot 10^{15}$ J
- kWh (kilo-Watt hour): $1\ \mathrm{kWh} = 3.6 \cdot 10^{6}$ J

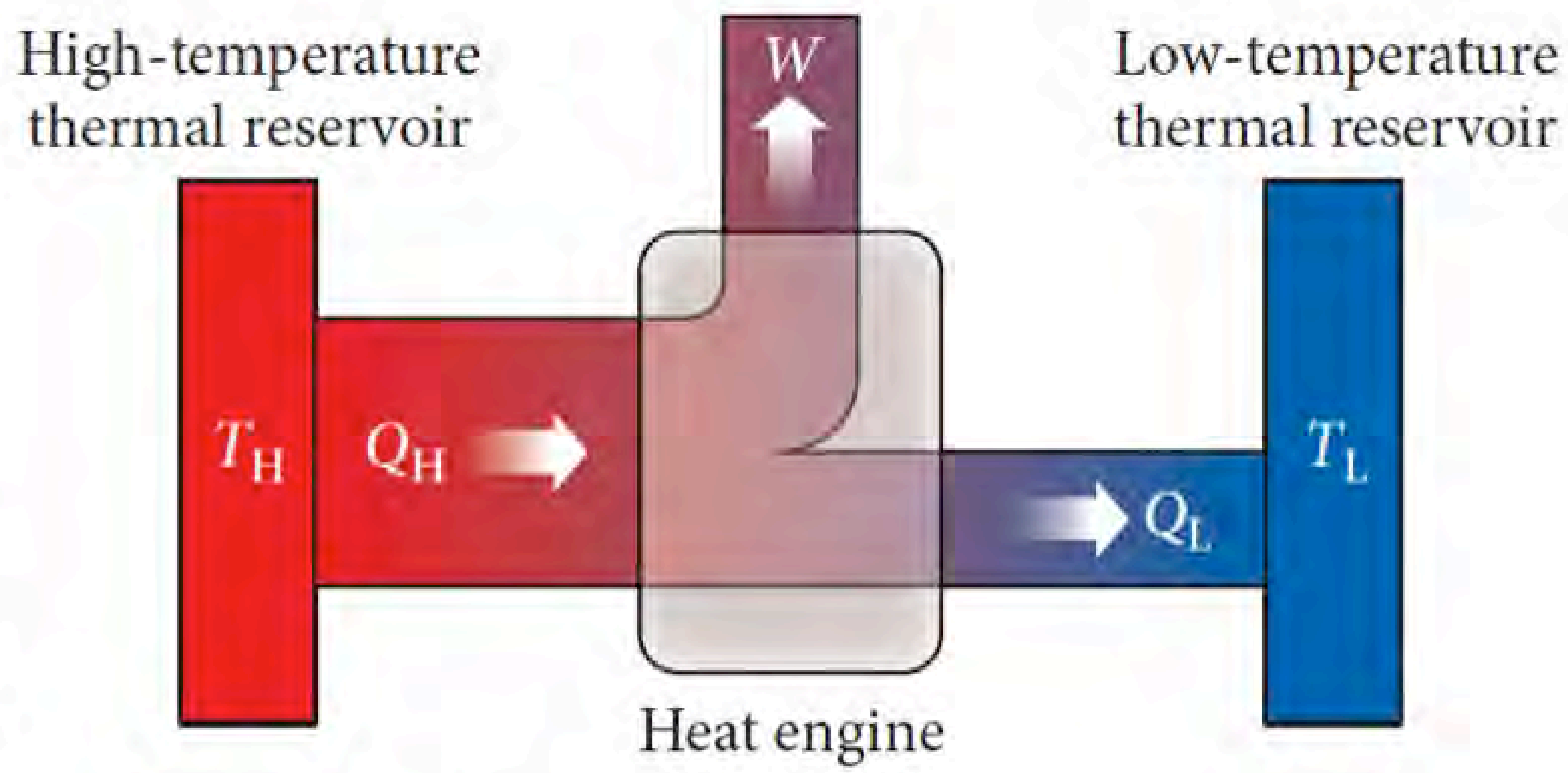


Efficiency

- For any energy conversion, the efficiency is

$$\varepsilon = \frac{\text{work or energy output}}{\text{total energy input}} \leq 1$$

  - Not in contradiction to total energy conservation, because the rest goes to heat!

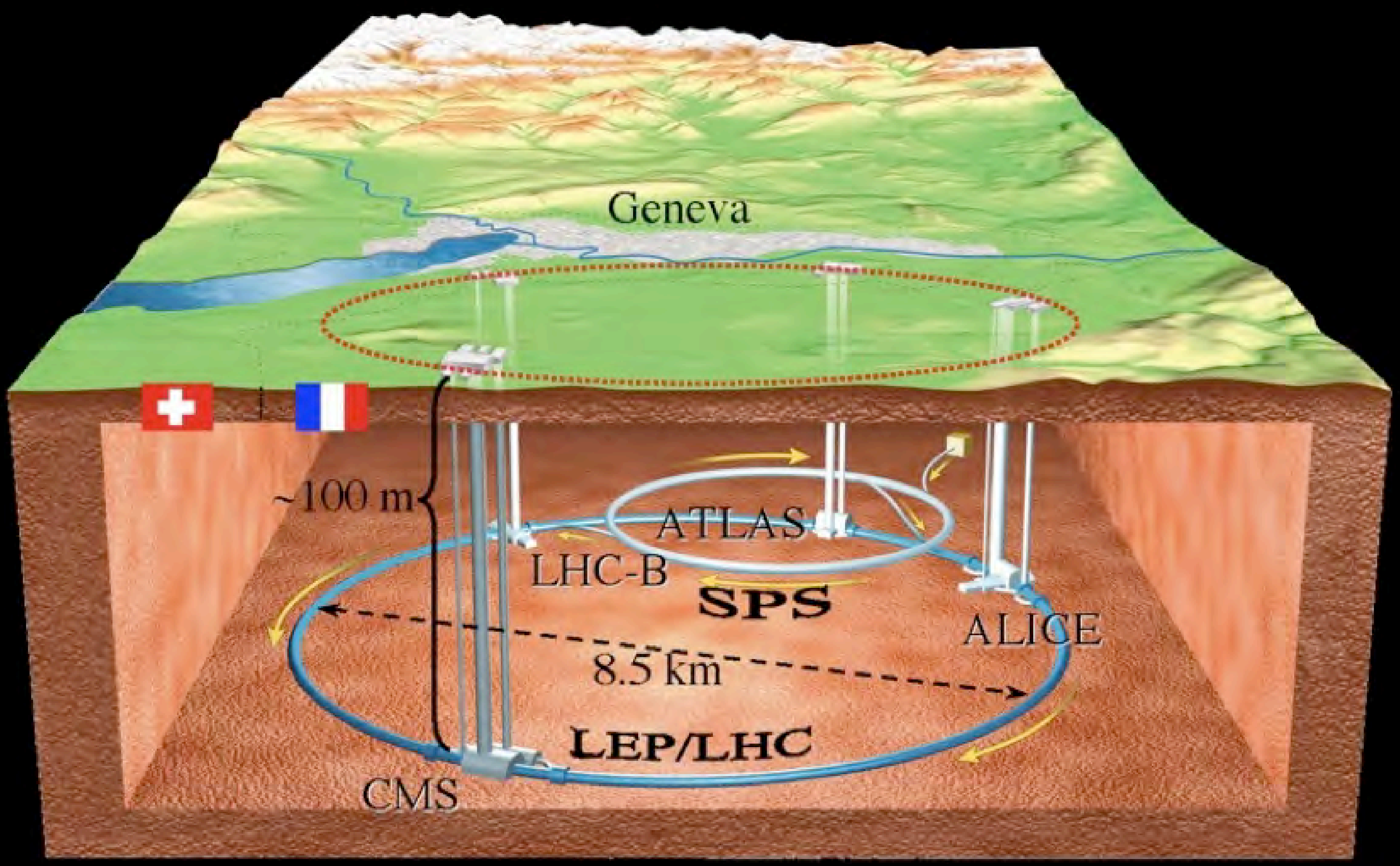


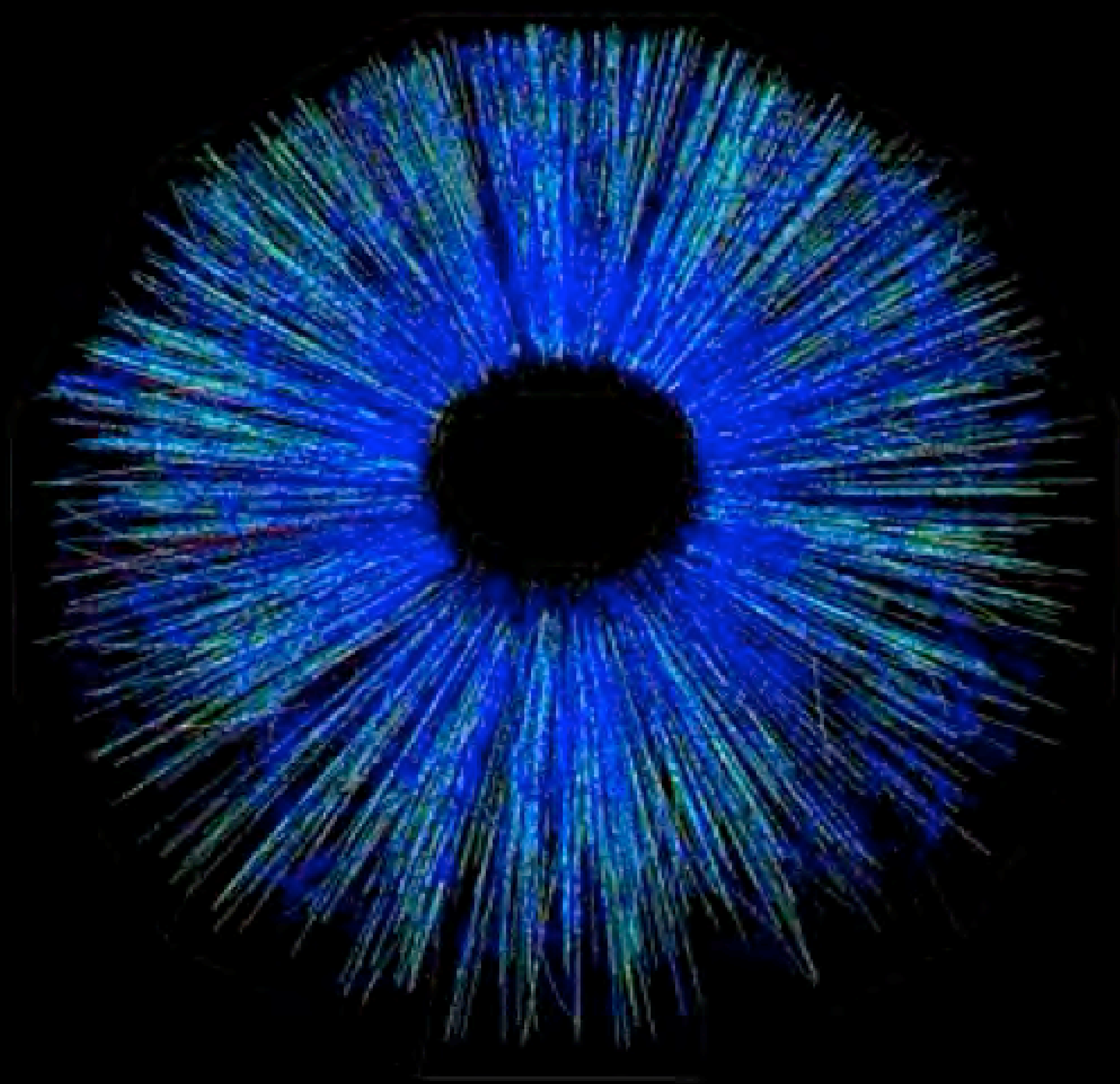
- Heat can be converted to work, but not at 100%
- Efficiency of a car engine ~ 20%-30%

$E = mc^2$

QuarkMatter attendance:

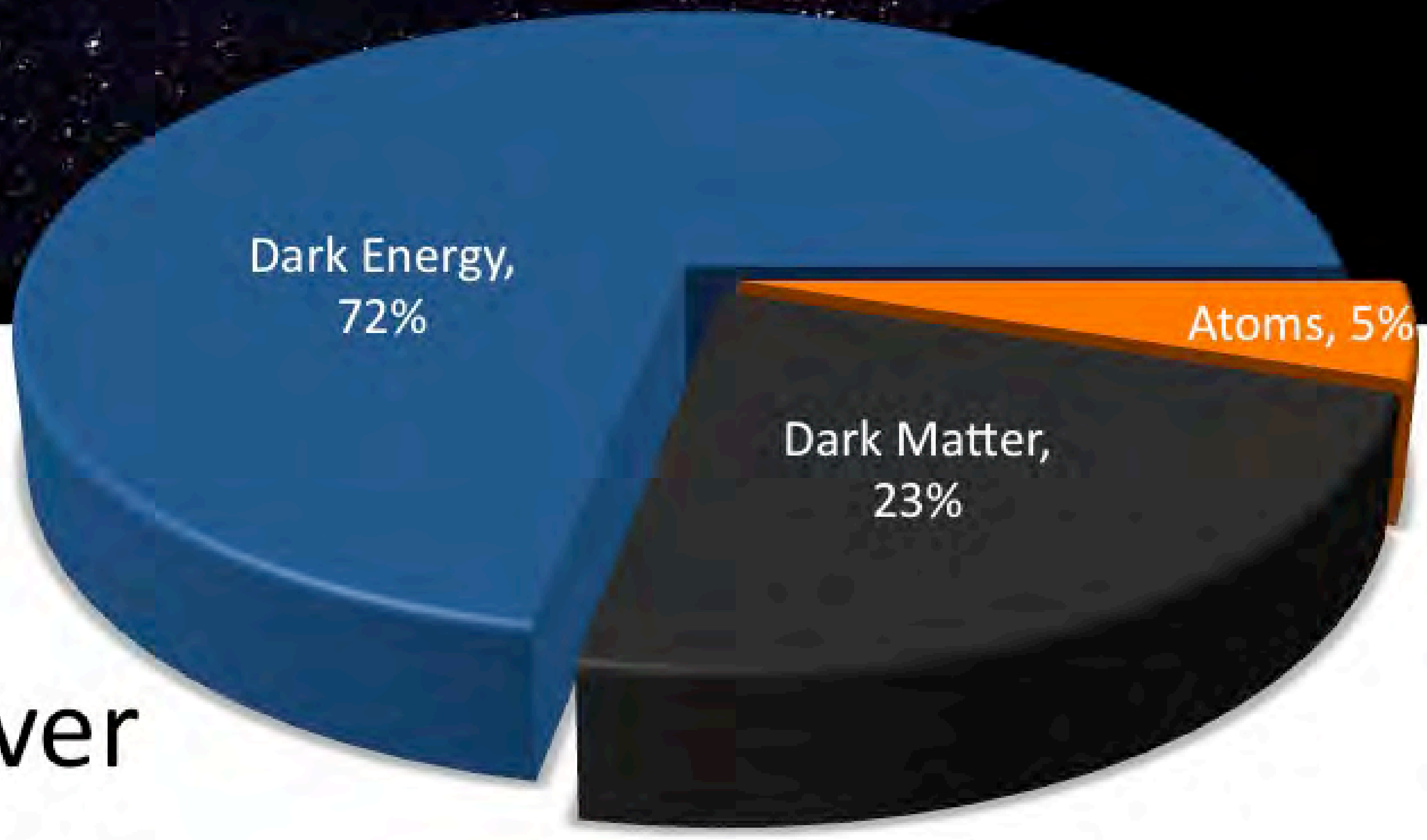
- Accelerate nuclei to highest possible kinetic energy
- Smash them together
- $E = mc^2$ produces thousands of particles
- Sift through debris to find out how the universe began





Total Energy of the Universe

Image credit
Axel Mellinger, U. Potsdam, Germany



$E_{\text{Universe}} = 0$: Universe is flat ✓
$E_{\text{Universe}} < 0$: Universe is closed, oscillates
$E_{\text{Universe}} > 0$: Universe is open, expands forever

The most important equation of this evening is …

$E = \$$

International versions: $E = €$, $E = ¥$, $E = £$, …

$E = \$$

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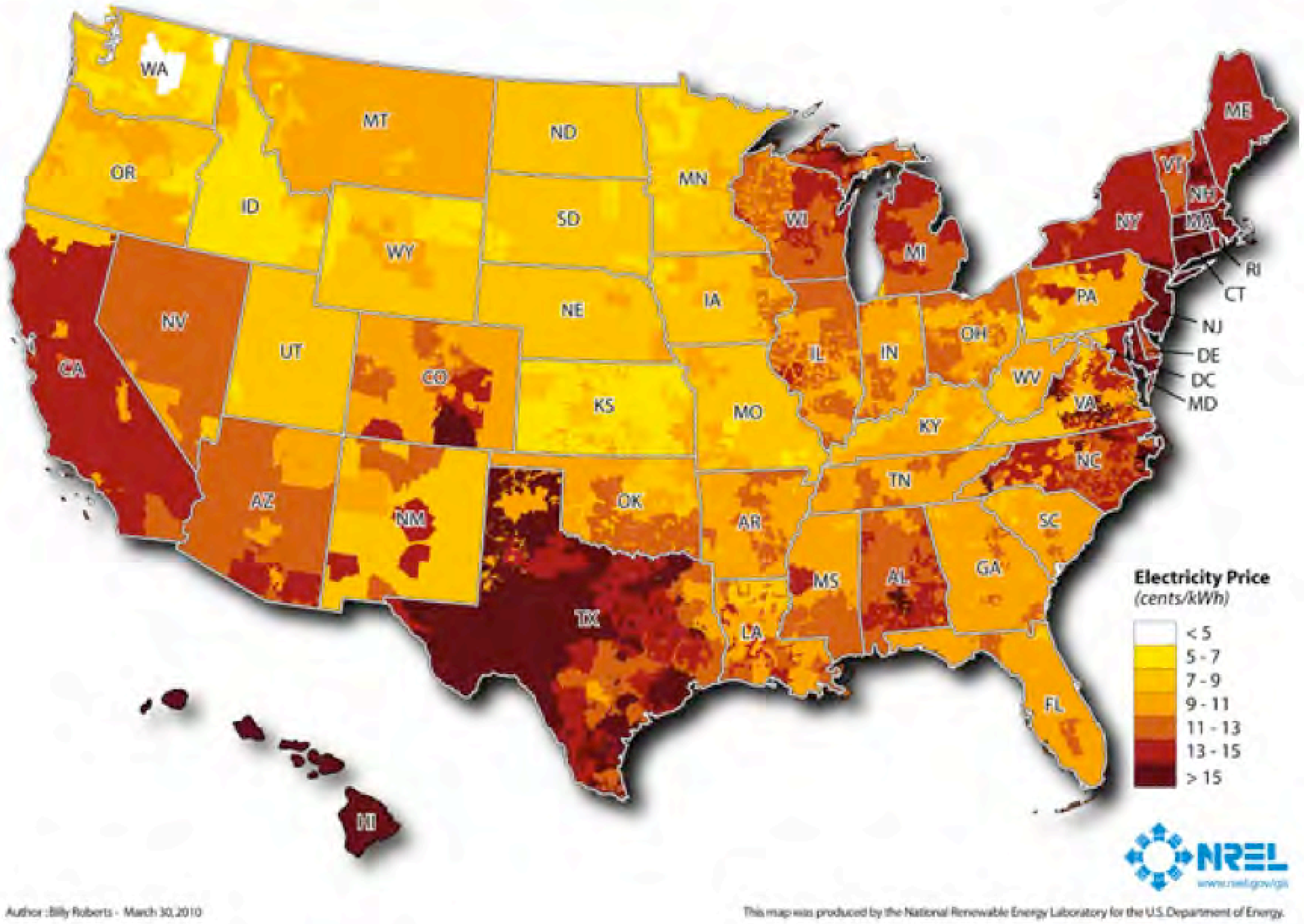

- Electricity
  1 kWh ~ \$0.1
- Gasoline (1 gal ~ \$4, 35 MJ/L = 36.6 kWh/ gallon)
  1 kWh ~ \$0.1
- 2% Milk (122 Cal/cup = 2.28 kWh/gallon, 1 gal ~ \$4)
  1 kWh ~\$1.75
- Big Mac meal w large fries & coke (1350 Cal = 1.57 kWh, ~\$6)
  1 kWh ~ \$3.8

Power = Energy/Time

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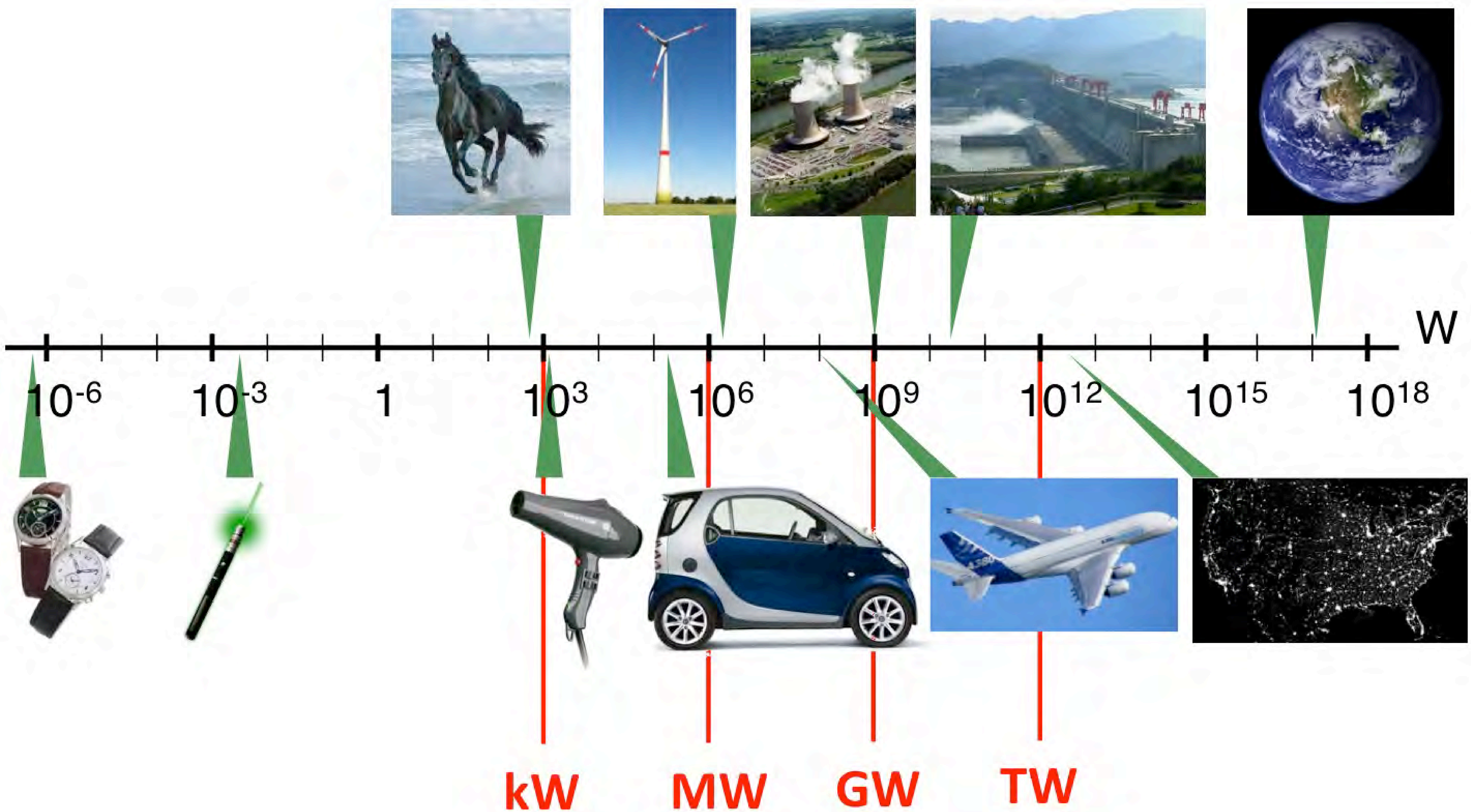

Power of Niagara Falls

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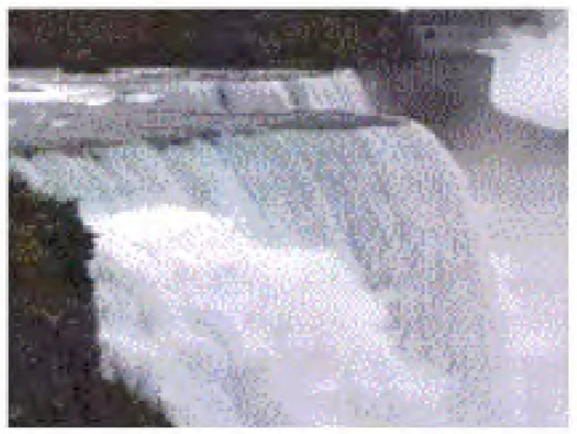
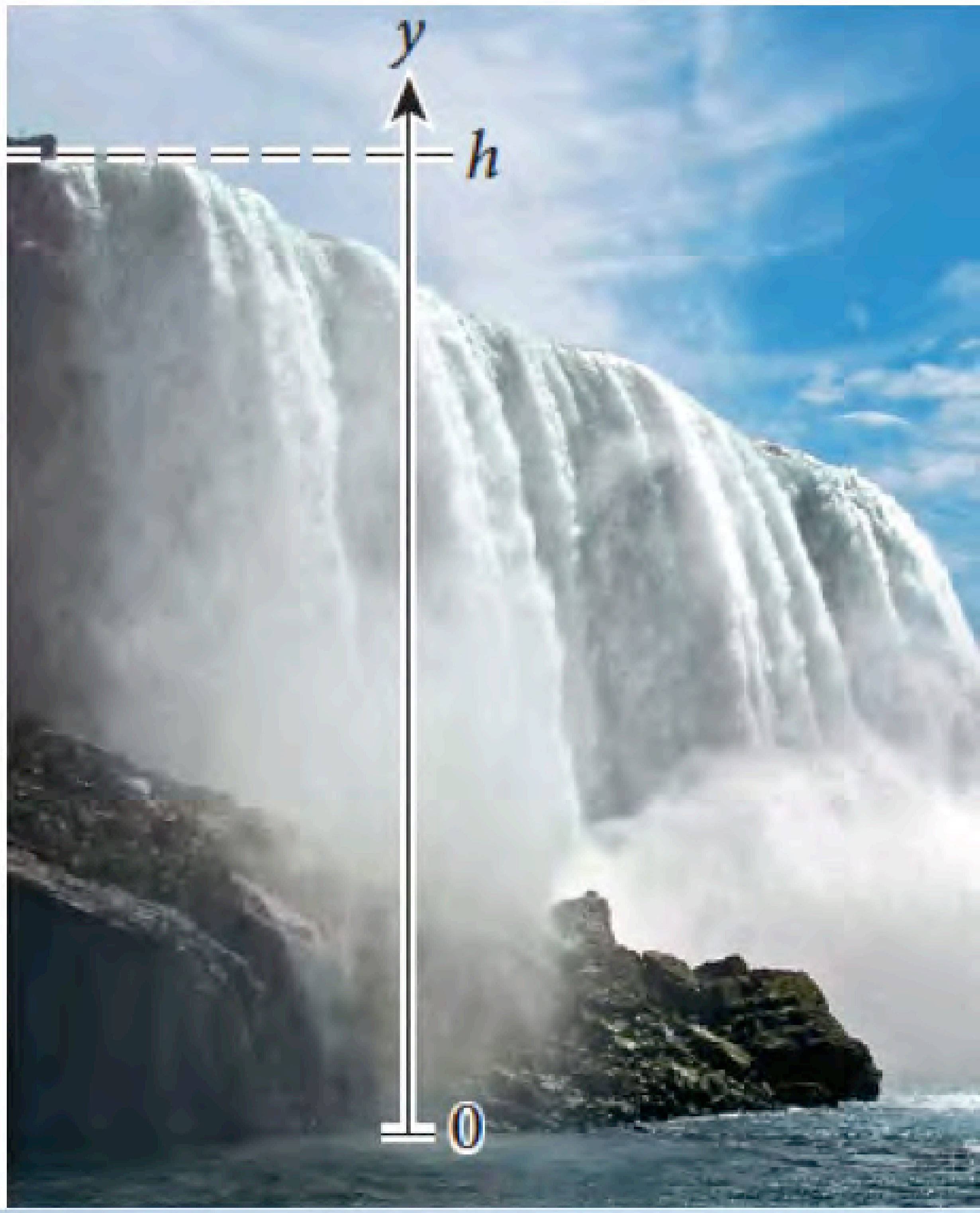
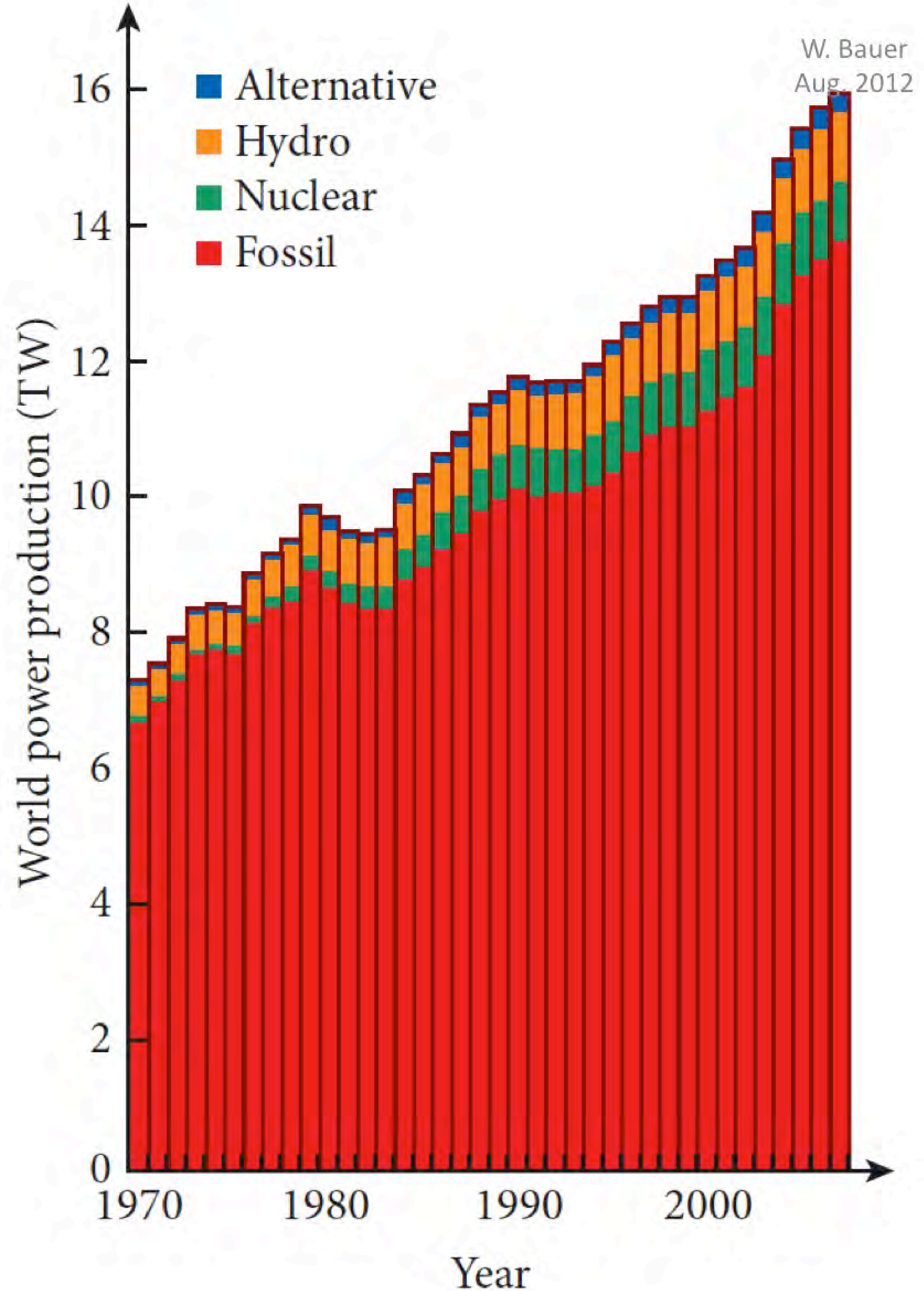


- Flow volume ~ 3 million liters/second
- Height h = 50 m
- *Power* = mgh/t = 1.5 GW



World Power Consumption

- Increasing strongly with time
- Overwhelmingly satisfied with fossil fuels
- ~~Biggest Problem facing the World~~
- **Biggest Opportunity of our lifetime**



US Power Consumption ~ 4 TW

Energy Use & Prosperity

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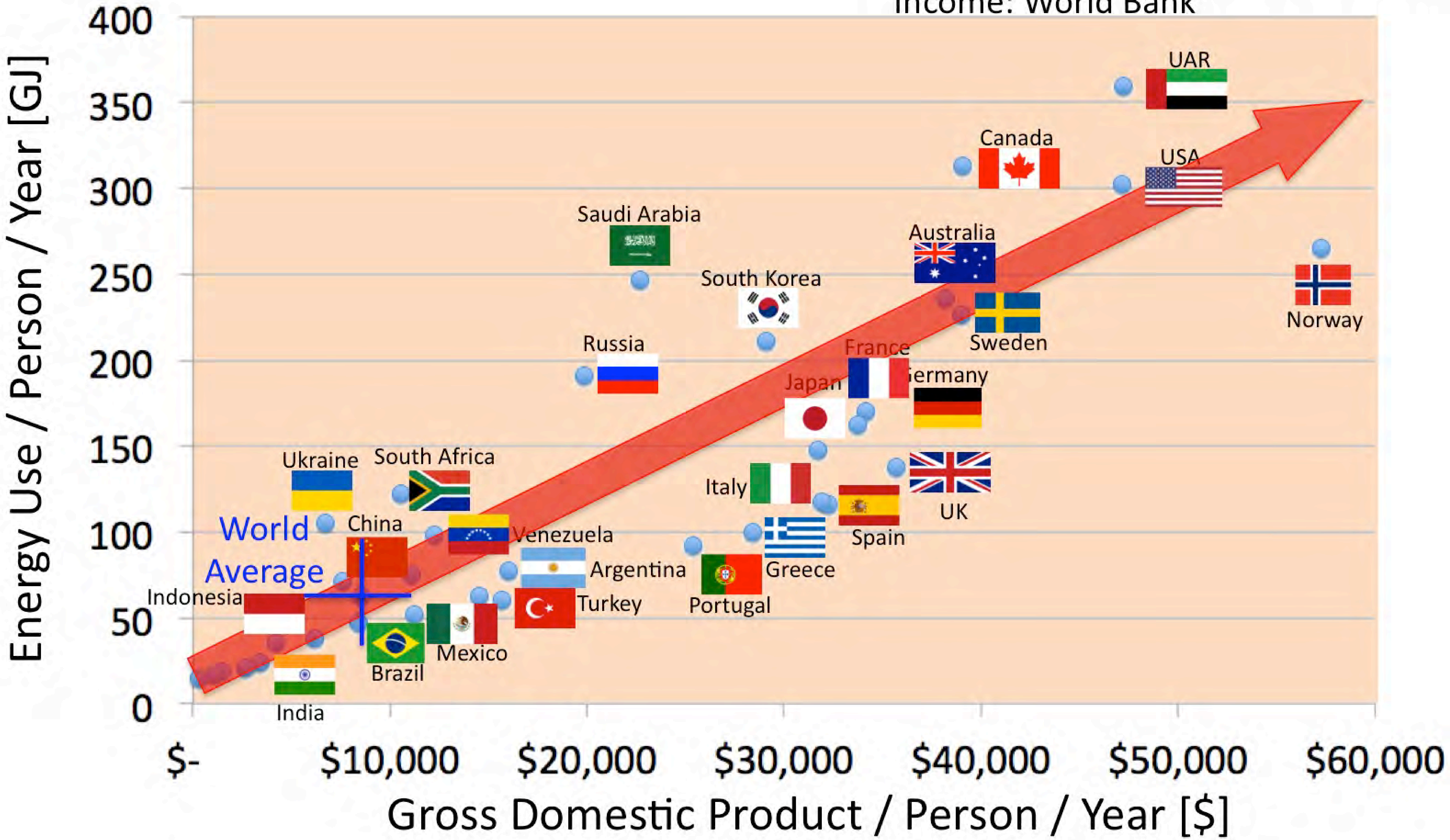


PART 1:

Fossil Fuels

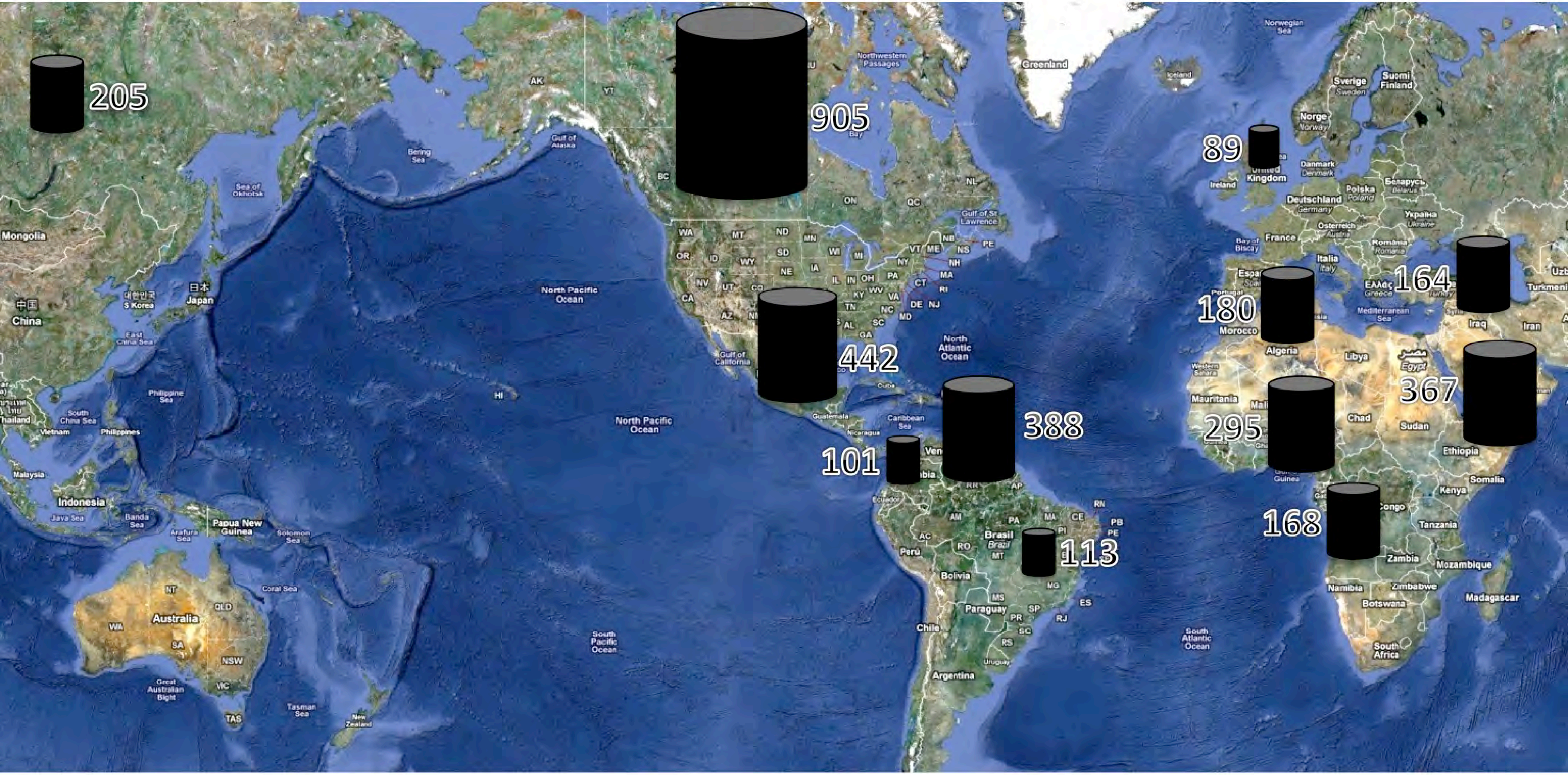
Where do fossil fuels come from?

- **Carboniferous period:**
  - 360 million years ago plants evolved to grow wood (lignin)
  - 300 million years ago microbes evolved to digest lignin
- **Fossil fuels are a finite resource and do not renew**
  - All present resources were produced during ~60 million year
  - We are using up fossil fuels at a ~500,000 times faster rate

US Oil Imports 2010

Source:
U.S. Energy Information Administration
Independent Statistics and Analysis

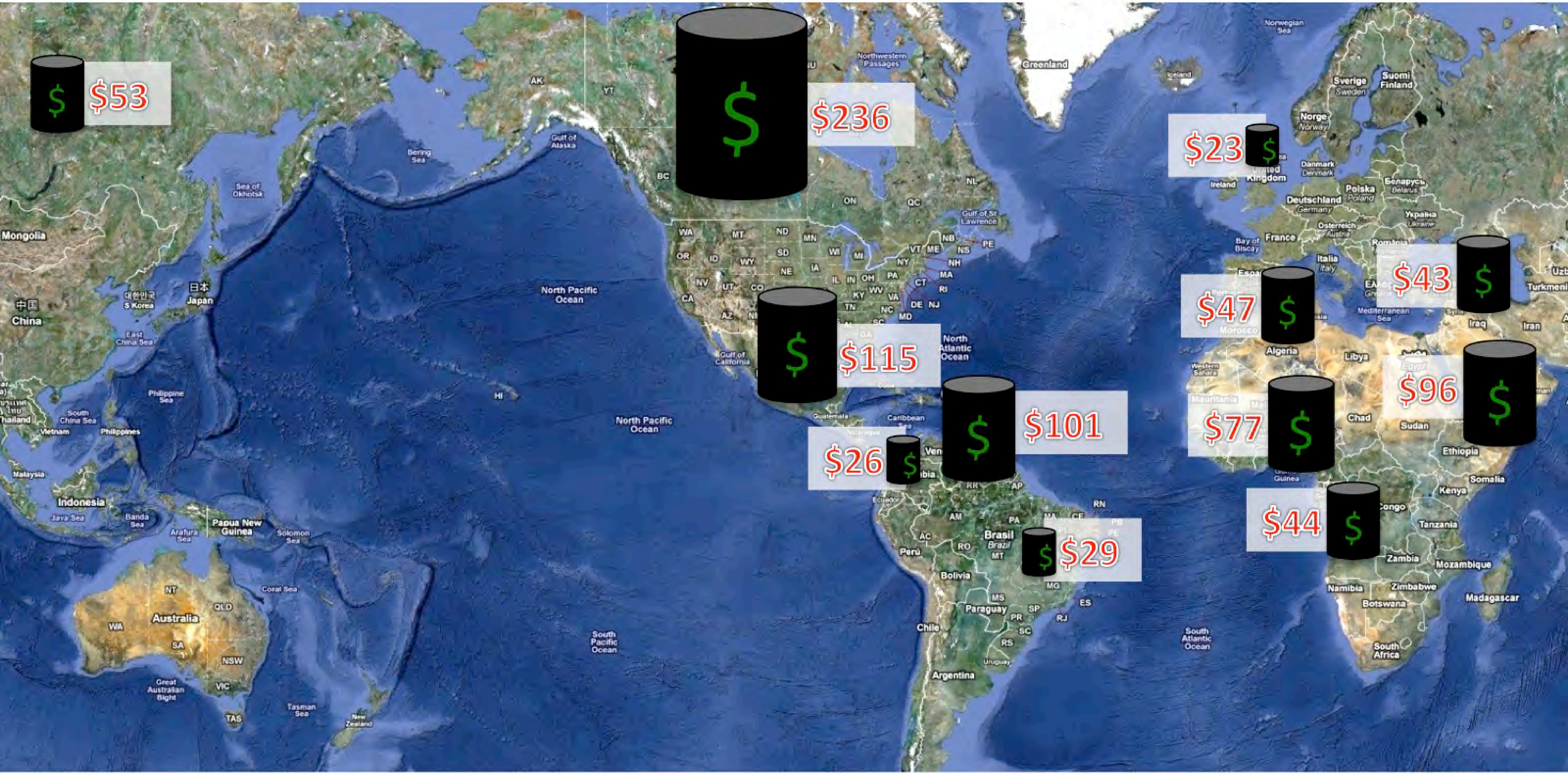
(by country, in million barrels)



Top imports from: Canada, Mexico, Venezuela, Saudi Arabia, Nigeria, Russia, Algeria, Angola, Iraq, Brazil, Columbia, United Kingdom

Total: 4267 million barrels

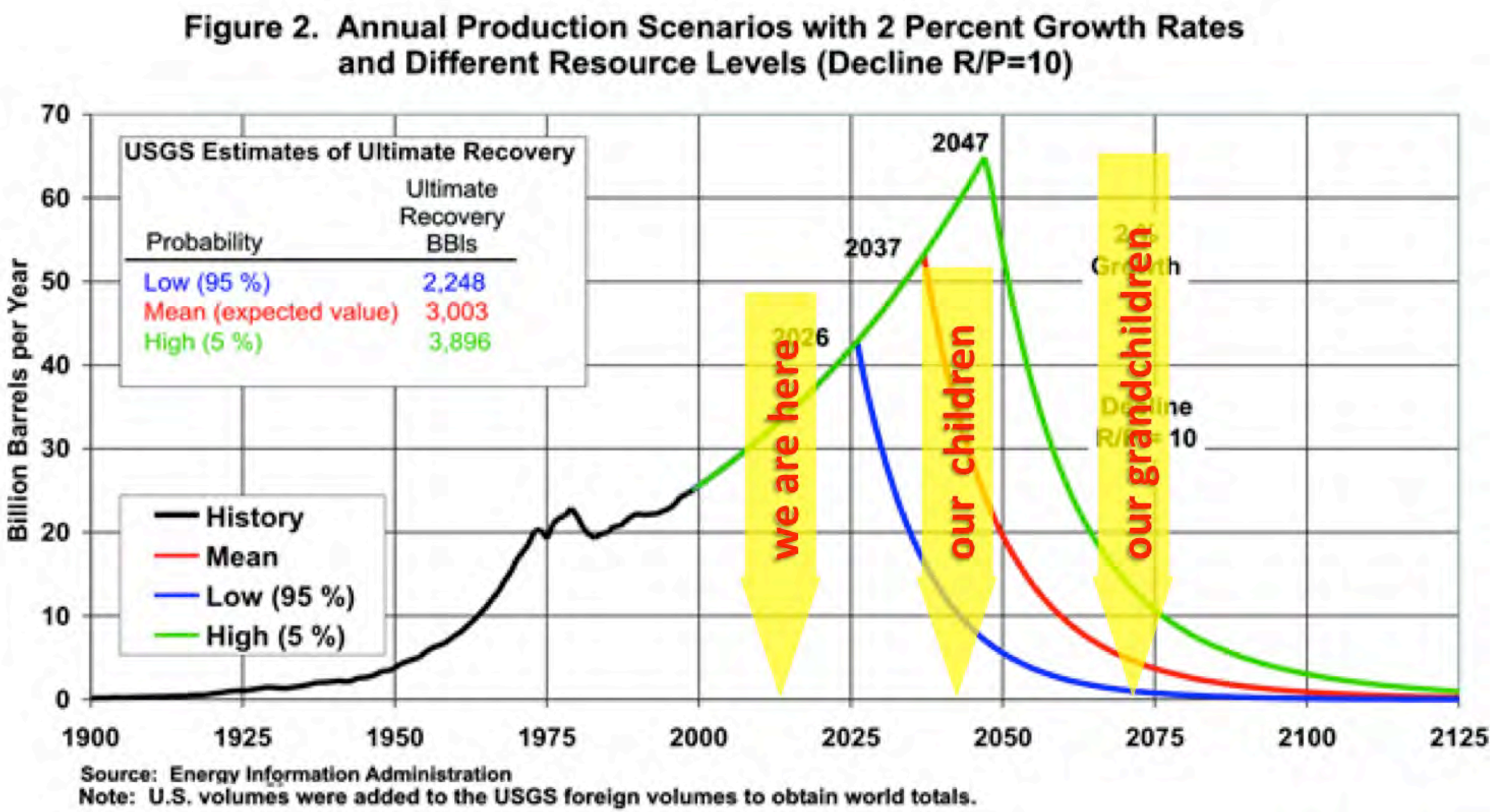
Costs for you



US population: 307 Million
Oil price in 2010: ~$80/barrel
Total oil *import* cost per US citizen in 2010: ~**$1100**

Total cost for the US economy in 2010:
$340 billion

We are running out of oil!



http://www.eia.doe.gov/

S.E. Koonin, BP

Drilling for oil gets more expensive and dangerous

http://gcaptain.com/wp-content/uploads/2011/01/Deepwater-Horizon-oil-rig-explosion.jpg

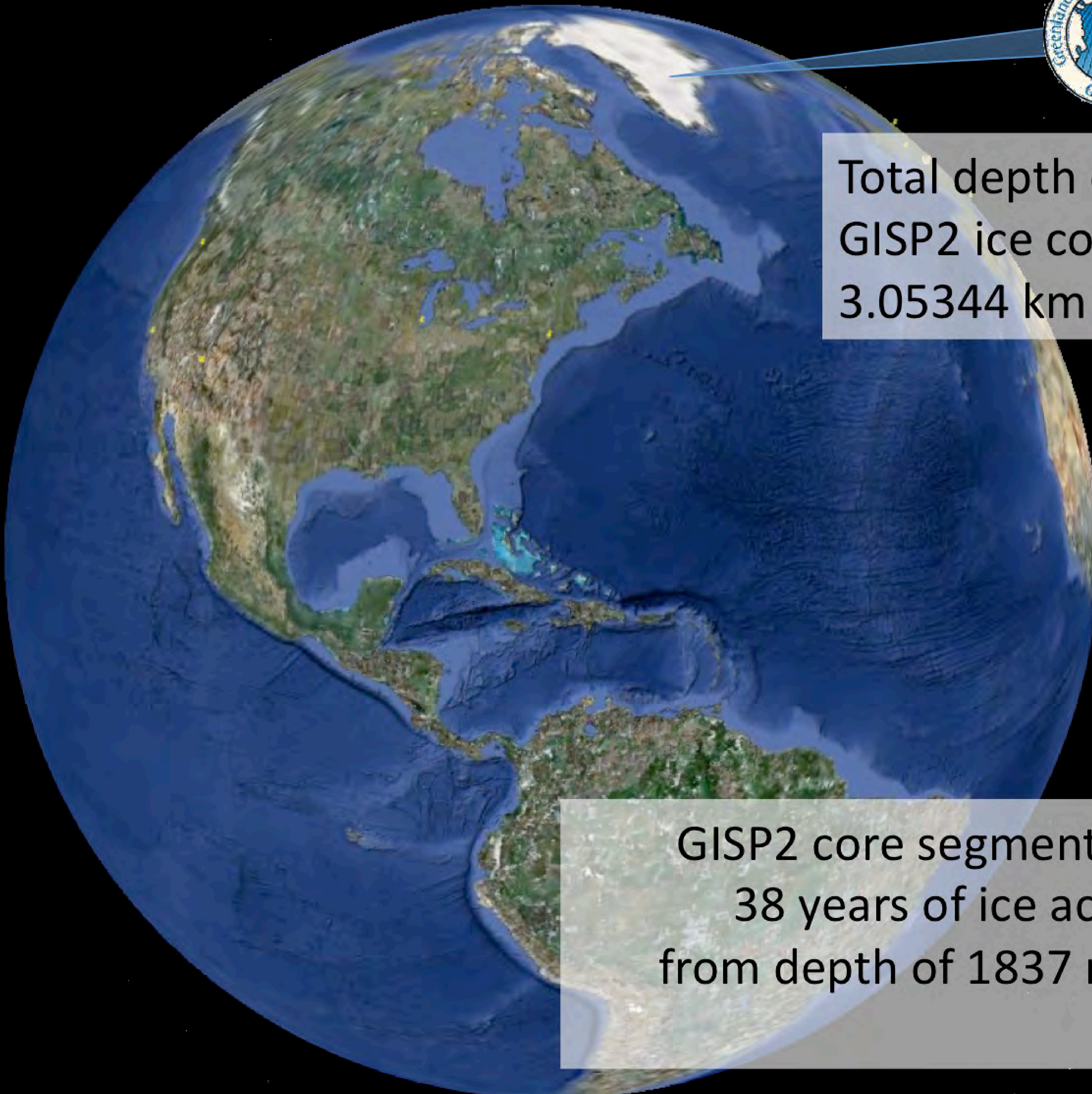
PART 2:

Earth's Atmosphere

Atmosphere

- **Composition**
  78.08% nitrogen, 20.95% oxygen,
  0.93% argon, 0.039% (= 390 ppm) CO_2
- Total mass = $5.2 \cdot 10^{18}$ kg
- 1 ppm_{volume} CO_2 = $7.9 \cdot 10^{9}$ tons

National Ice Core Laboratory
(NICL)
Denver Federal Center,
Lakewood, CO

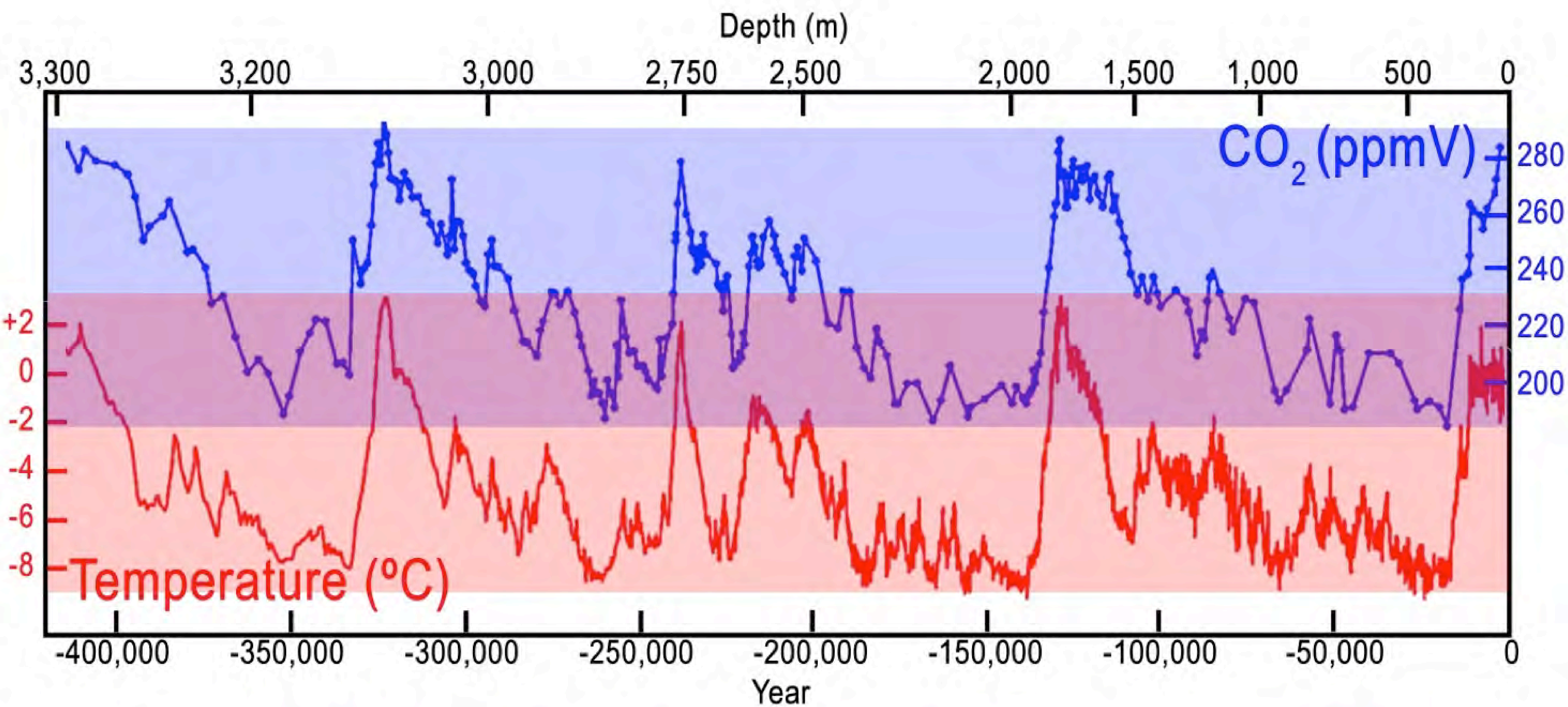


Total depth of
GISP2 ice core:
3.05344 km

GISP2 core segment, 1 m long,
38 years of ice accumulated
from depth of 1837 m, ~16,250
year old,

Total ice core depth
3645 m

CO_2 and Surface Temperature



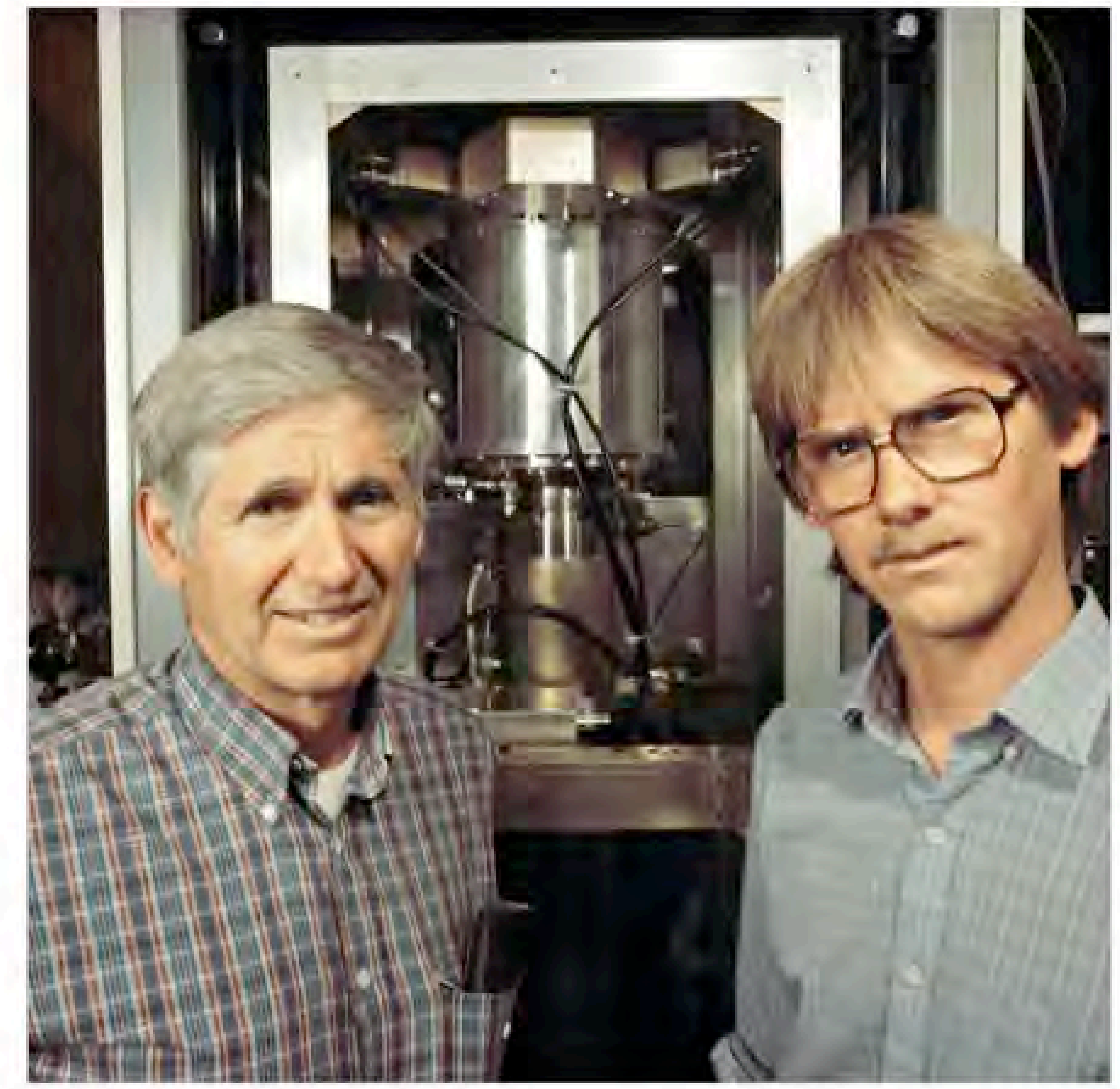
CO_2 in a range between 190 and 290 ppmV during last ~ half million years

Relative temperature range +3 °C to -9 °C during last ~ half million years

Very strong correlations between the two data sets; indicates a **strongly coupled system**

Keeling Curve

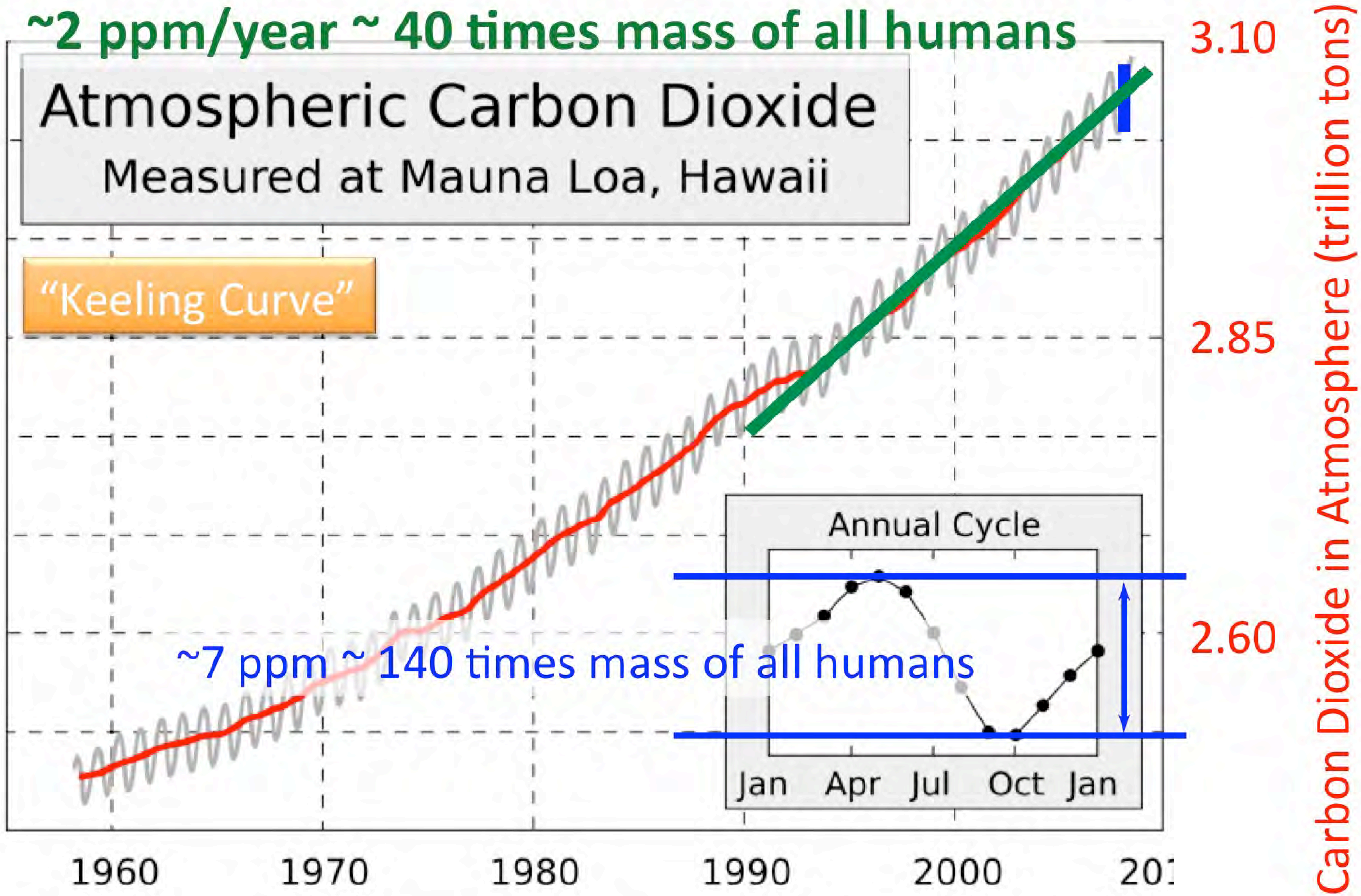
Mauna Loa Observatory
Jonathan Kingston/Aurora Select, for The New York Times



C. & R. Keeling, 1989
Scripps Institution of Oceanography / UC San Diego

- Charles Keeling (1958): Measure CO_2 concentration in atmosphere periodically at Mauna Loa observatory
- Ralph Keeling continues work of his father after Charles' death in 2005

How big is the problem?



Global Temperature

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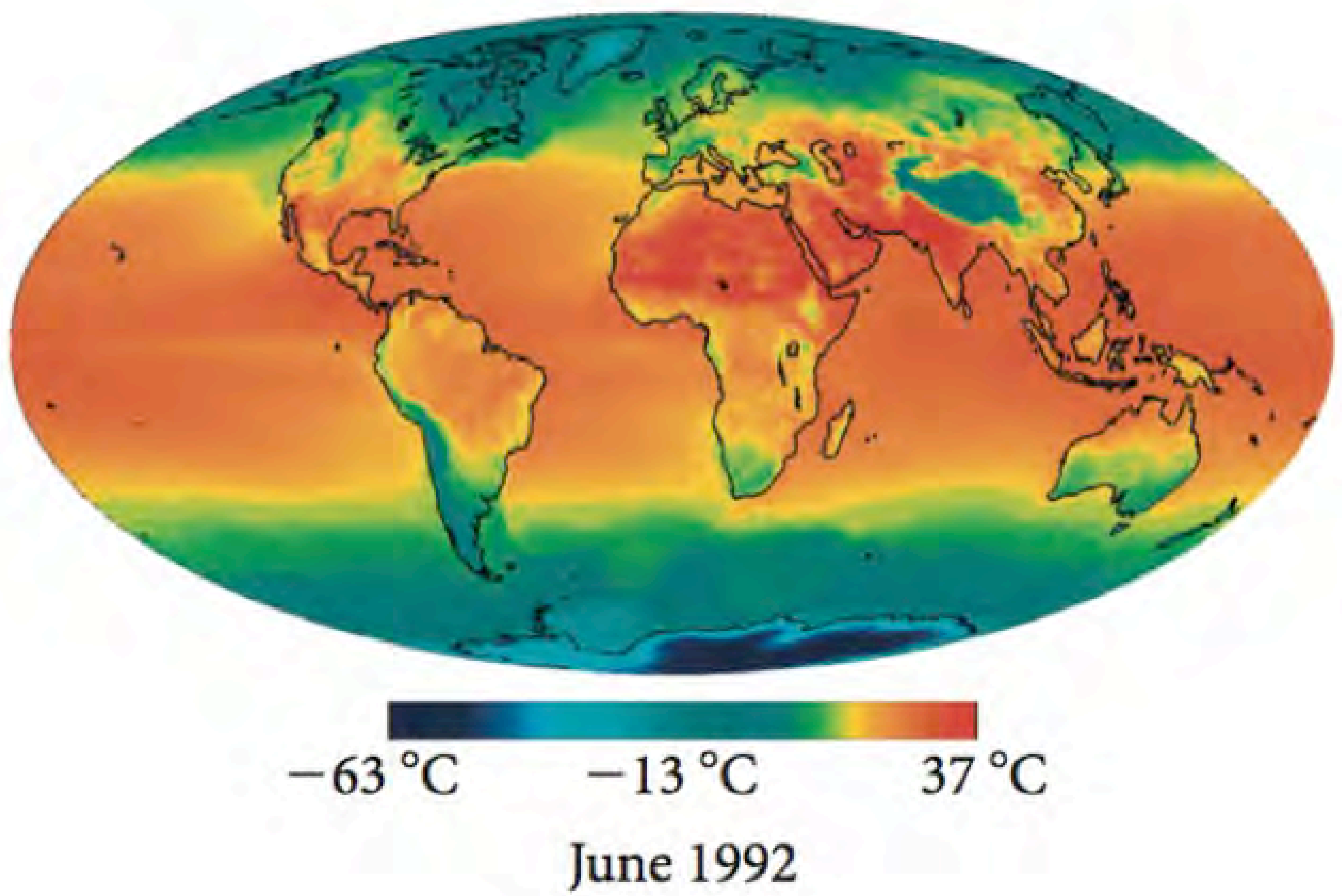
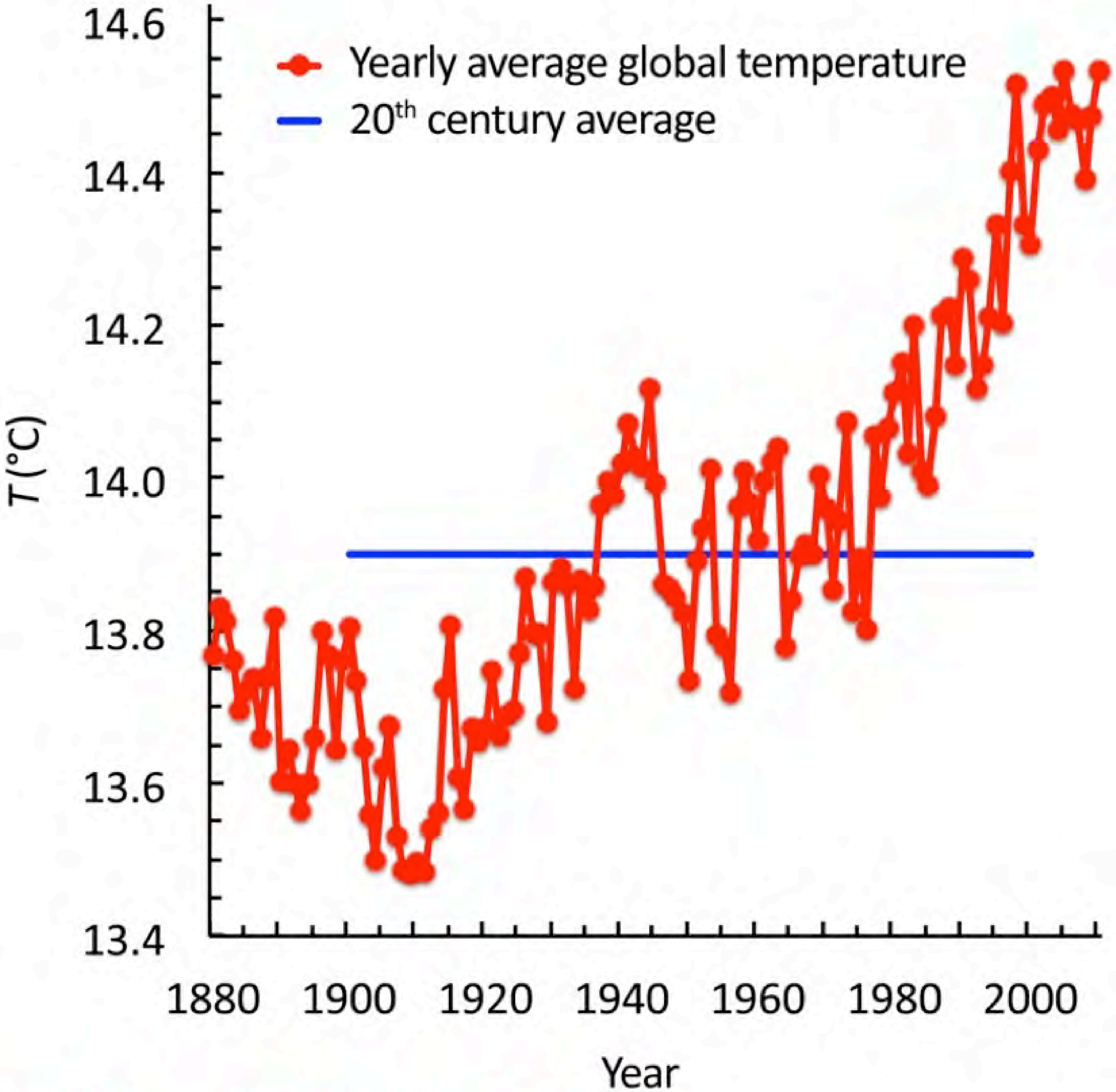
- Careful averaging needed (over *space* and *time*)



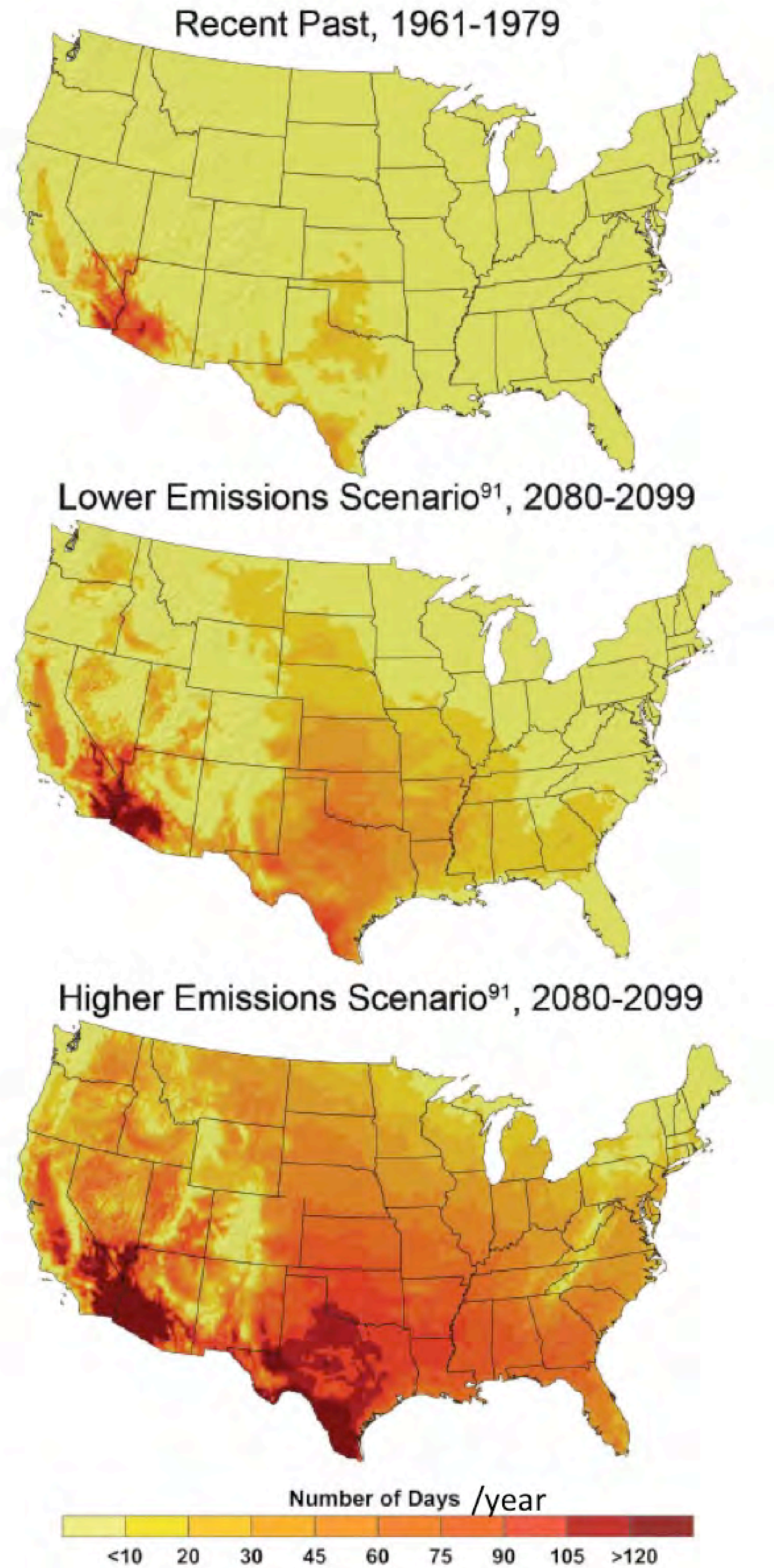


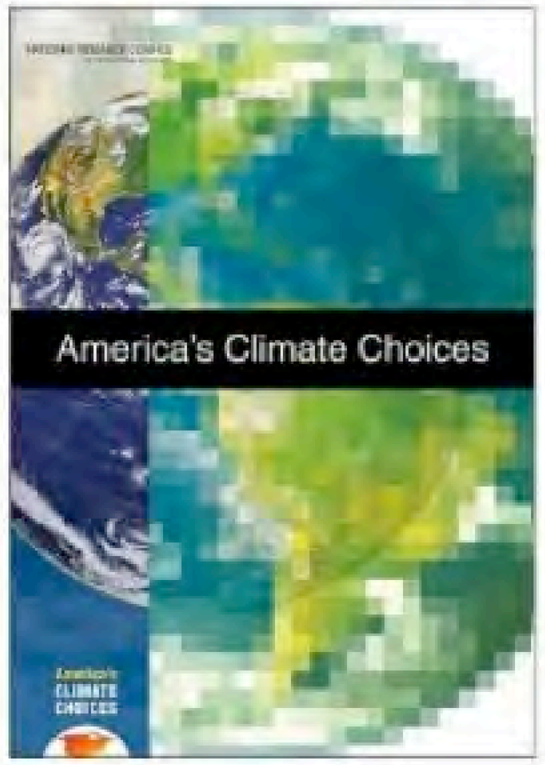
Global Warming of ~0.2°C/decade is happening

Is it man-made?

Data: National Climatic Data Center U.S. Department of Commerce

Predictions (1): More >100°F days





"America's Climate Choices", NRC Report

http://www.nap.edu/catalog.php?record_id=12781

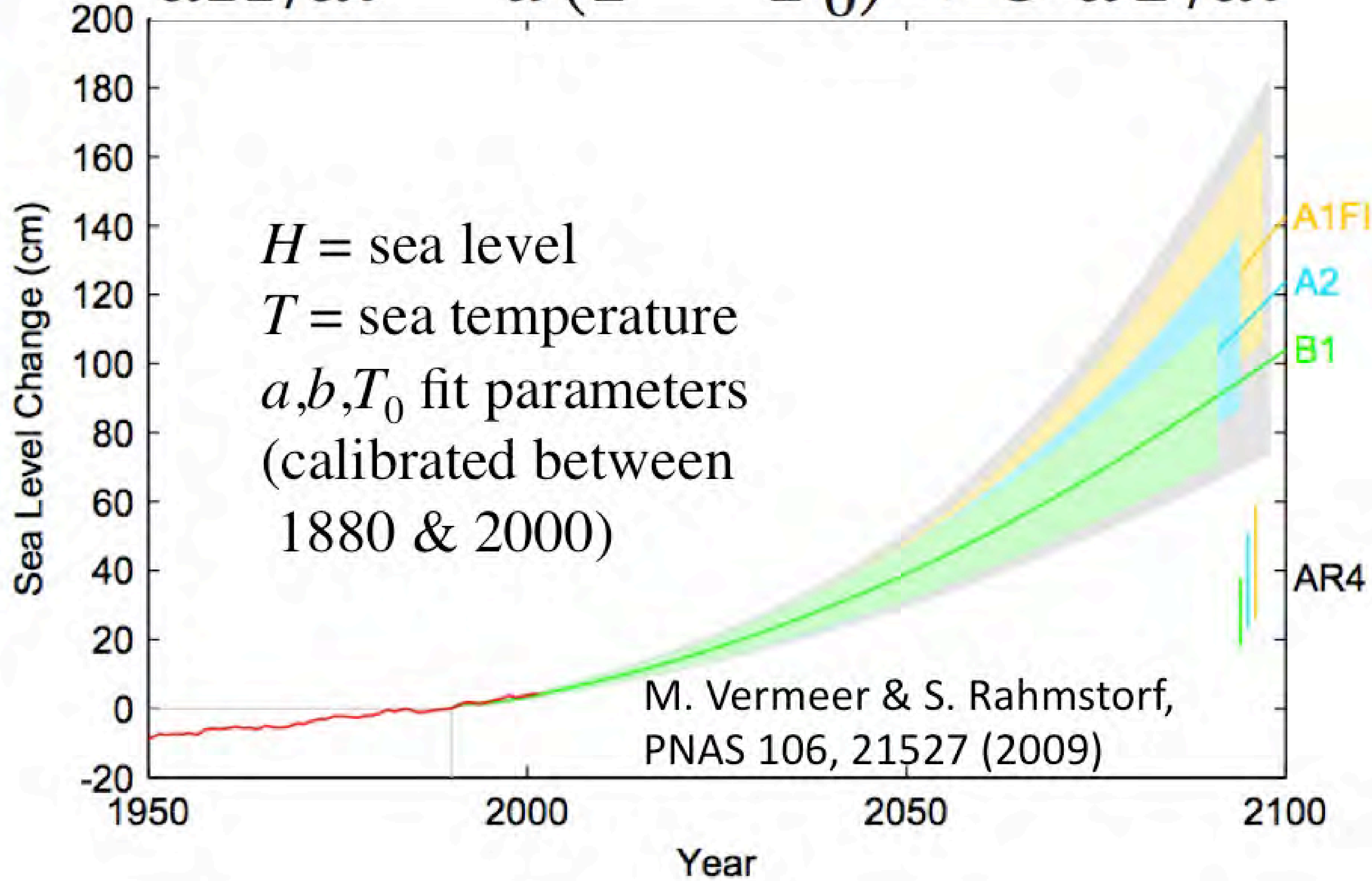
Predictions(2): Sea Level Rise

Earth surface area = 510M km^2,
361M km^2 covered by oceans
40-50M km^2 covered by ice

Message:
do not buy beachfront property!

Ice source	Ice Volume	Sea rise
Greenland	2.8M km^3	7.2 m
Antarctic	30M km^3	76 m
North Pole	5-25M km^3	0
Total	**33M km^3**	**83 m**

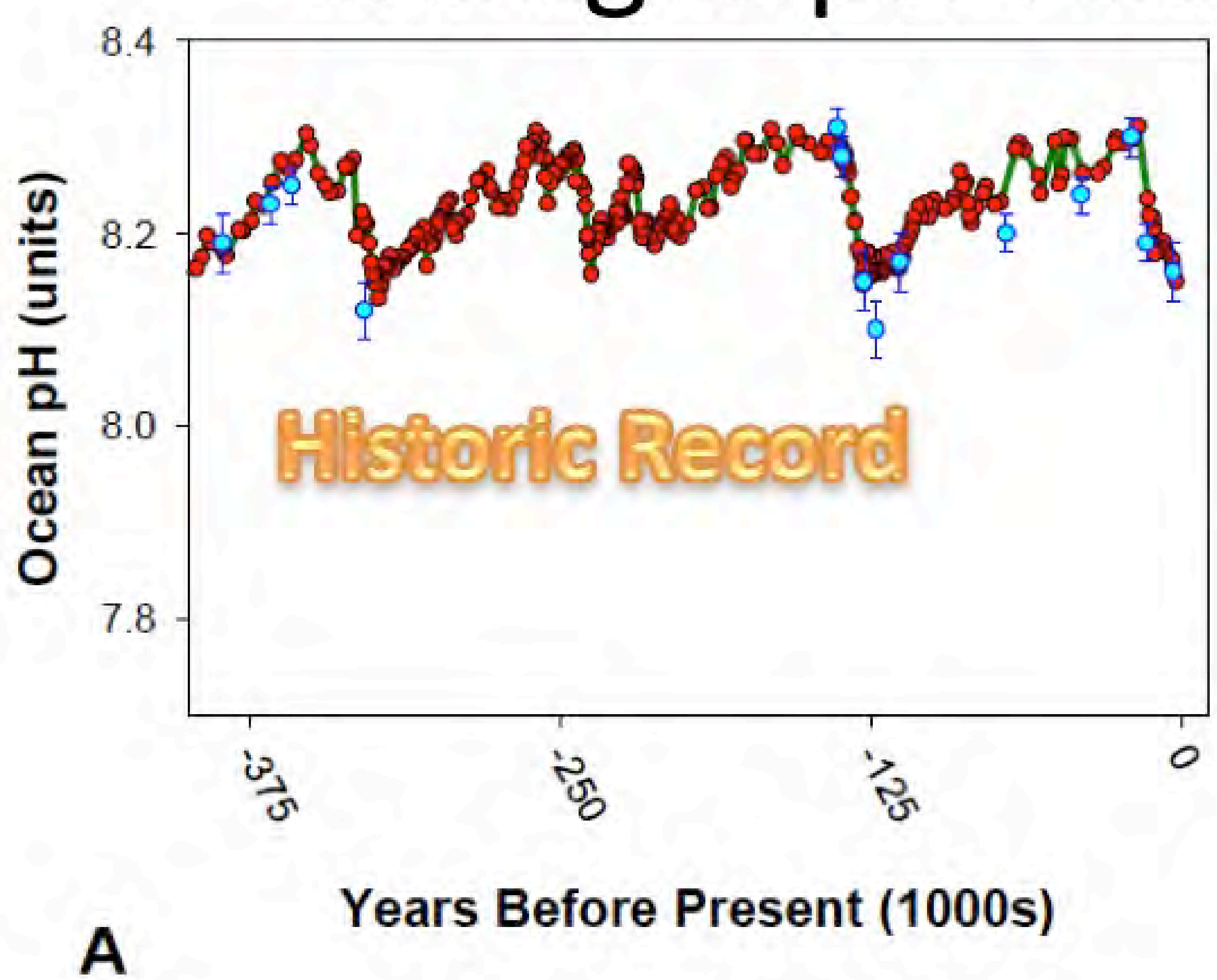
$$dH/dt = a(T - T_0) + b\, dT/dt$$

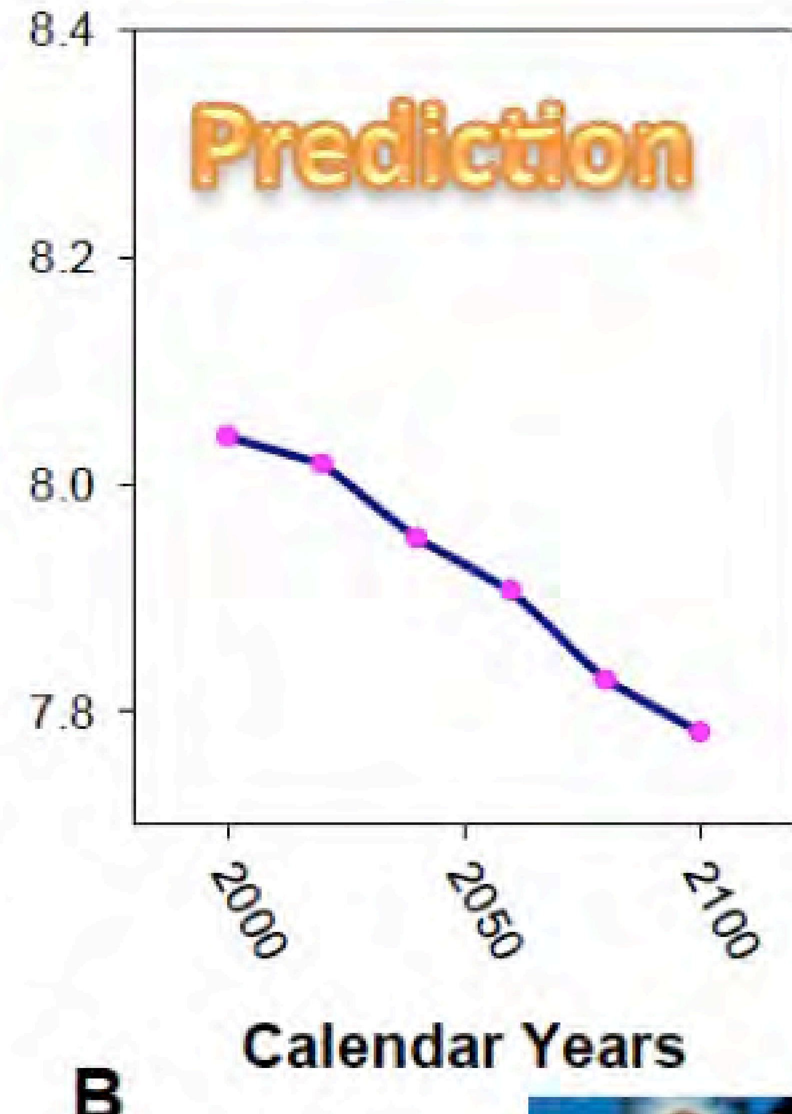


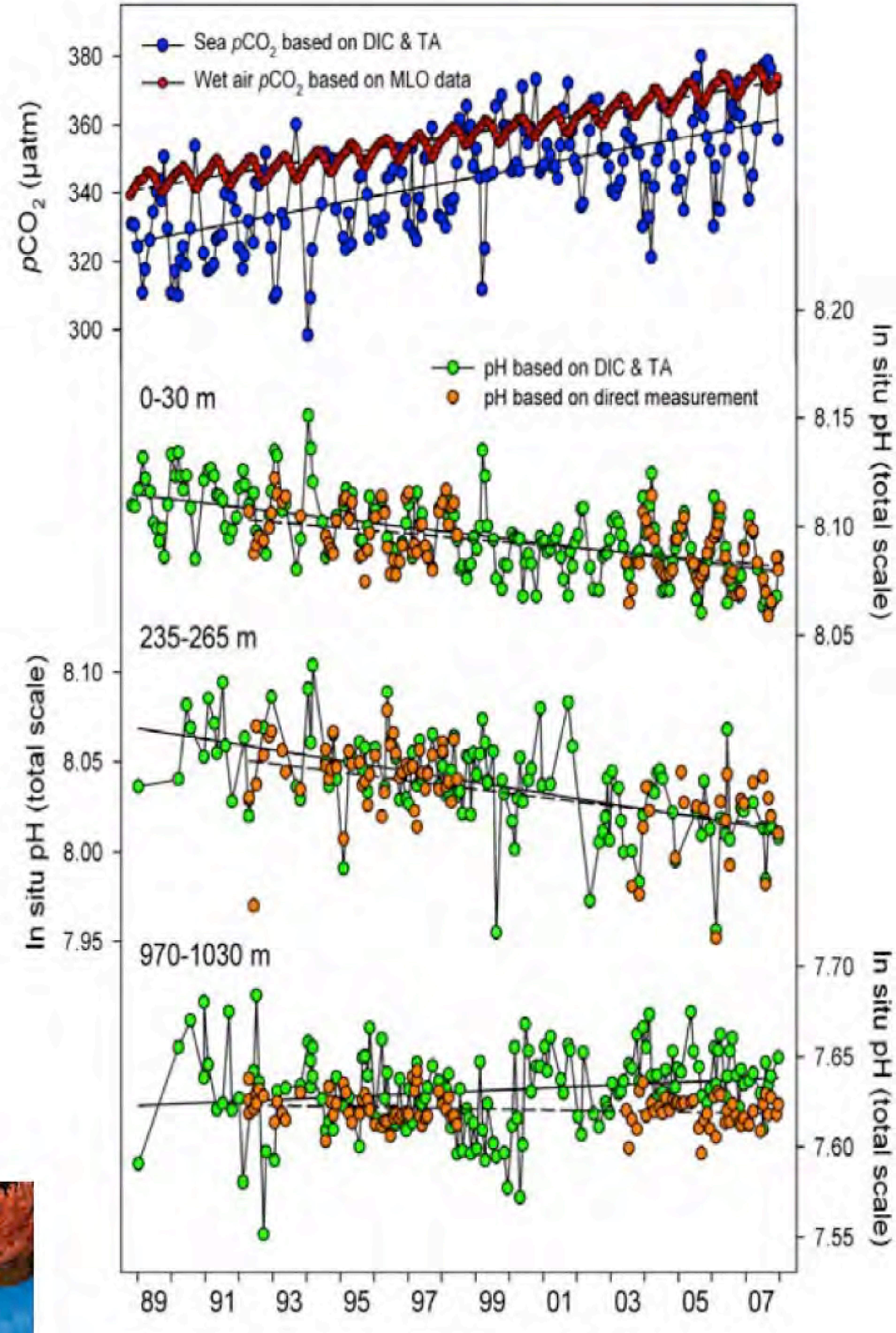
M. Vermeer & S. Rahmstorf, PNAS 106, 21527 (2009)

Predictions(3): Ocean Acidification

- ~10 billion tons/year of CO_2 absorbed in oceans
- Changes pH value!

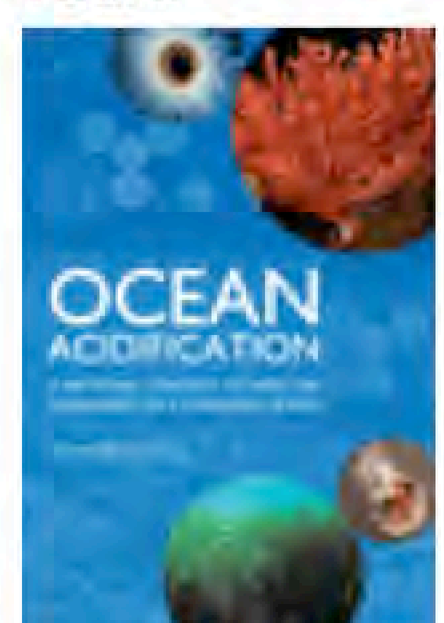






"Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean", NRC Report

http://www.nap.edu/catalog.php?record_id=12904



Dore, J.E., et al. 2009.
PNAS 106(30): 12235–12240.

What could happen?

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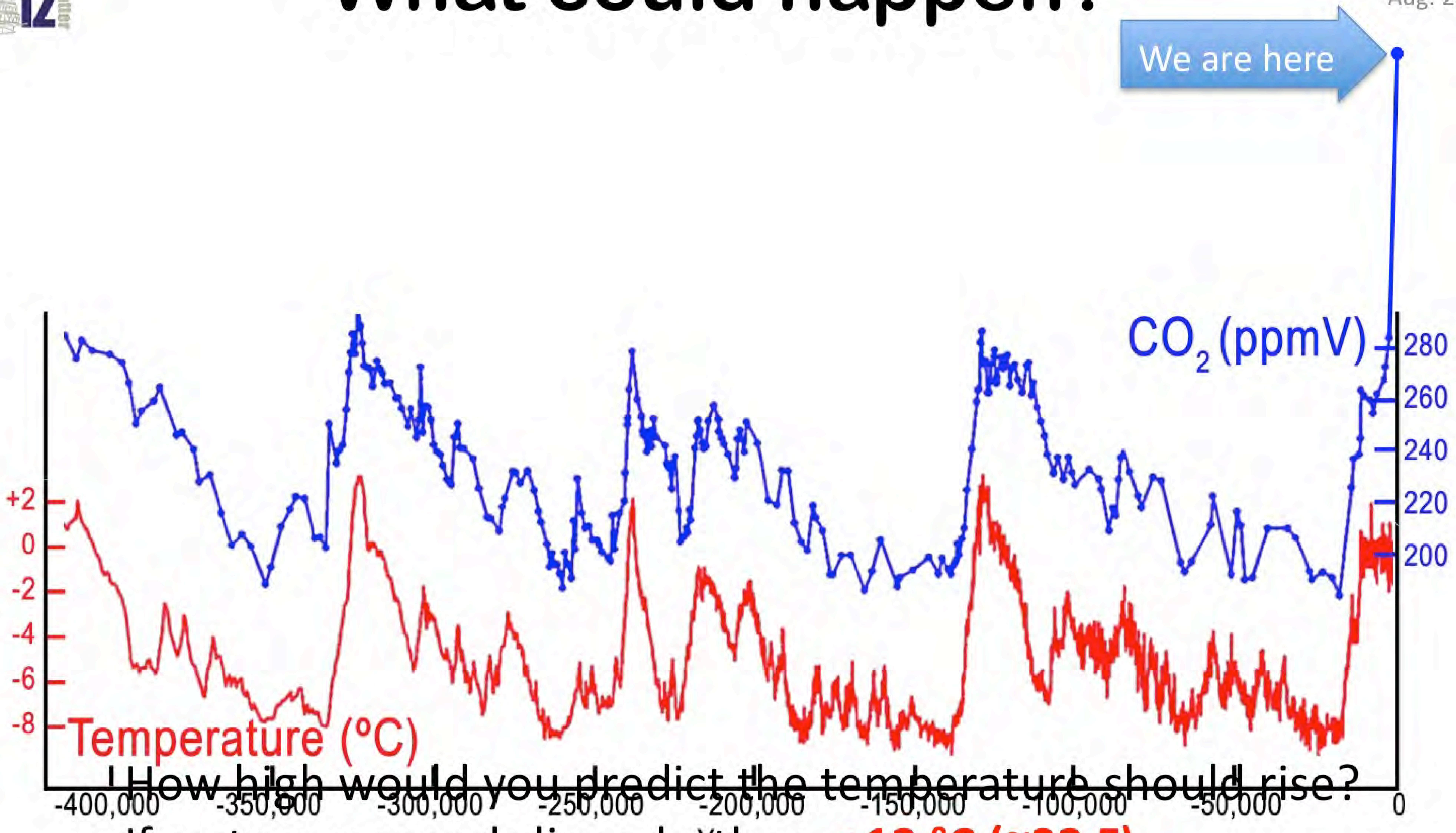

How high would you predict the temperature should rise?

If system responds linearly, then: **+13 °C (~23 F)**

PART 3:

Alternatives

Power from the Sun

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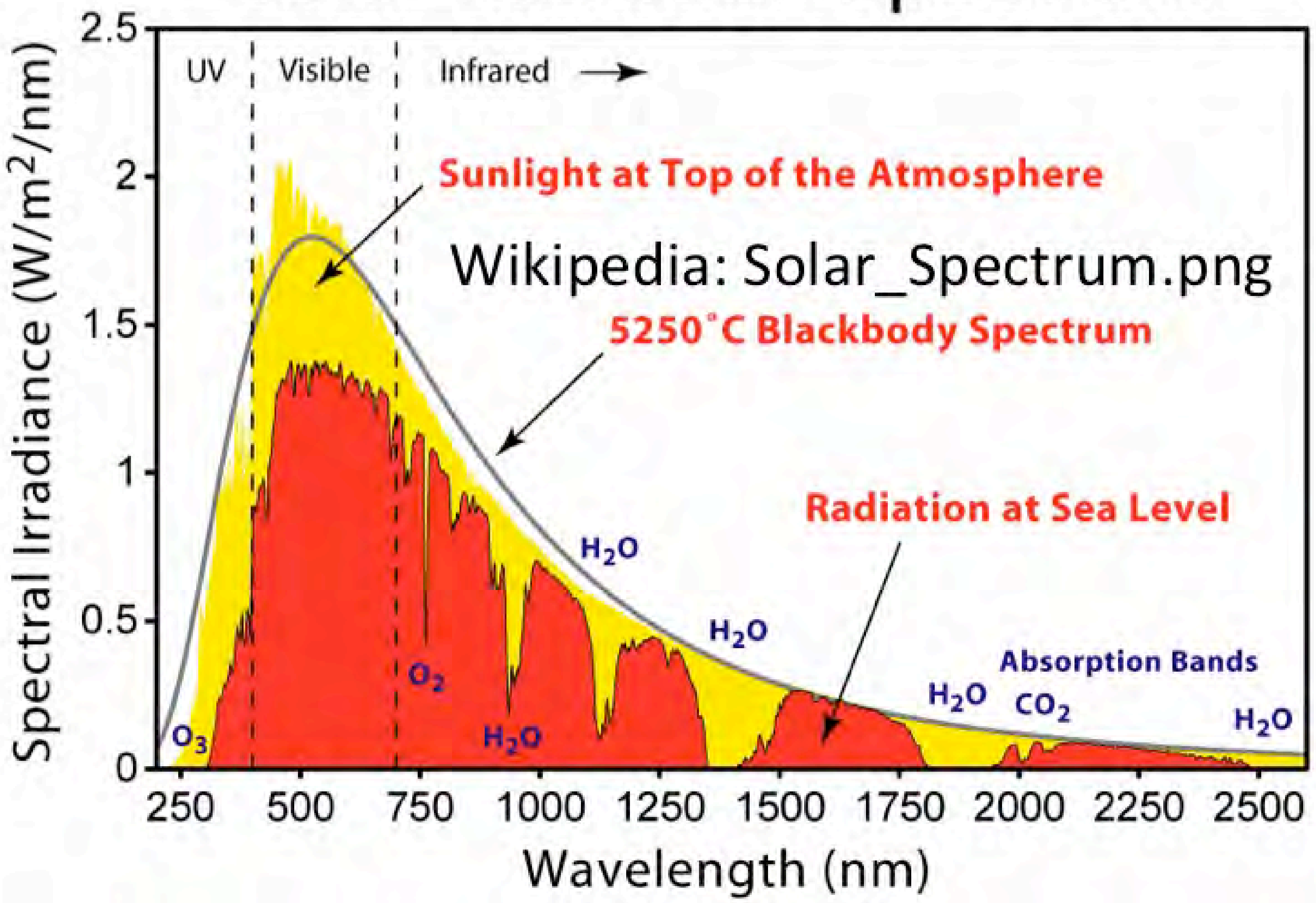
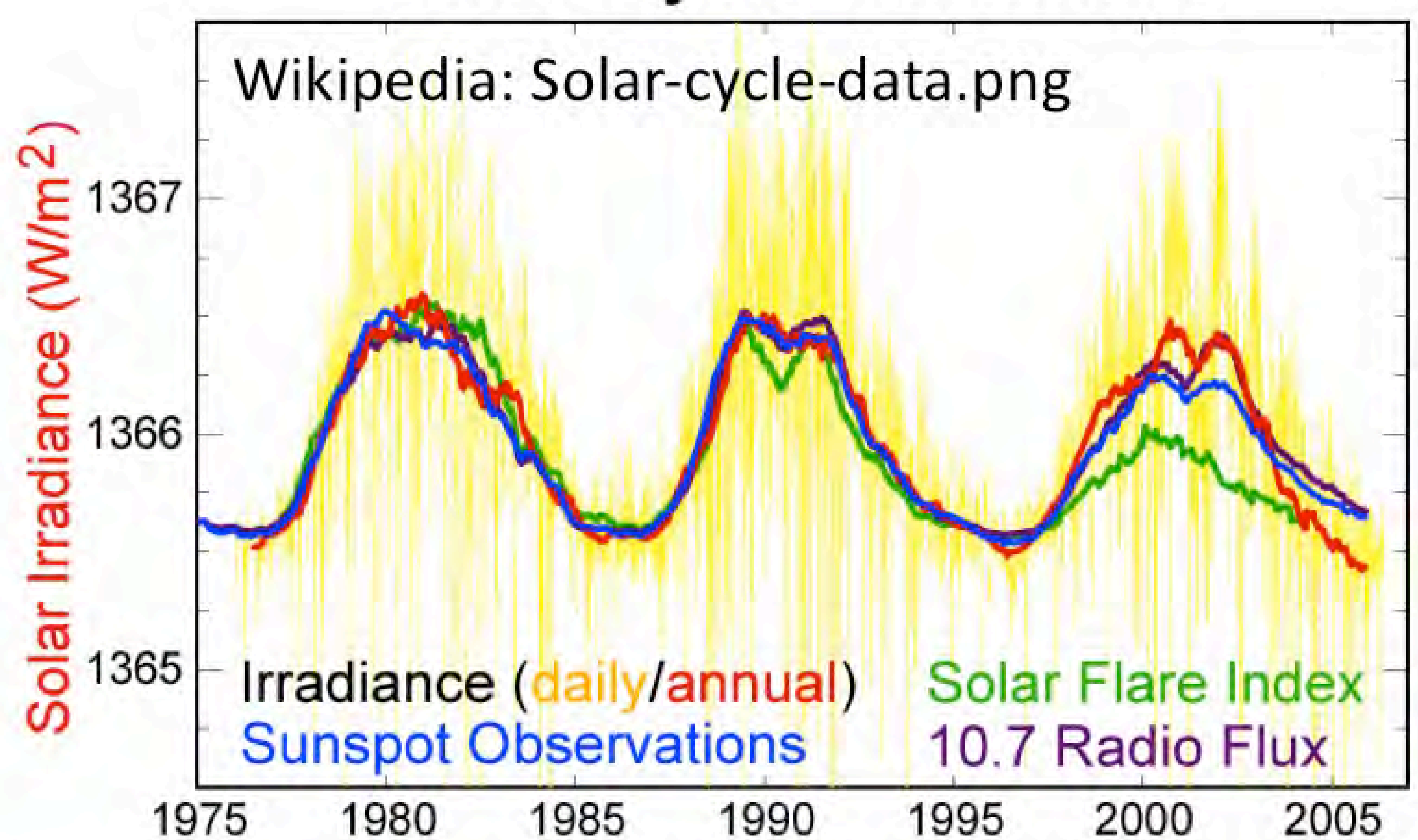
- Solar "constant" = 1.366 kW/m^2
  (1.41 kW/m^2 in Jan., 1.31 kW/m^2 in July)
- Average radiation hitting any point on the ground **200 W/m^2** (= 55% of 1.366 kW/m^2/4)
- Total: **~100,000 TW** (> 5,000x humanity's demand)

Solar Radiation Spectrum

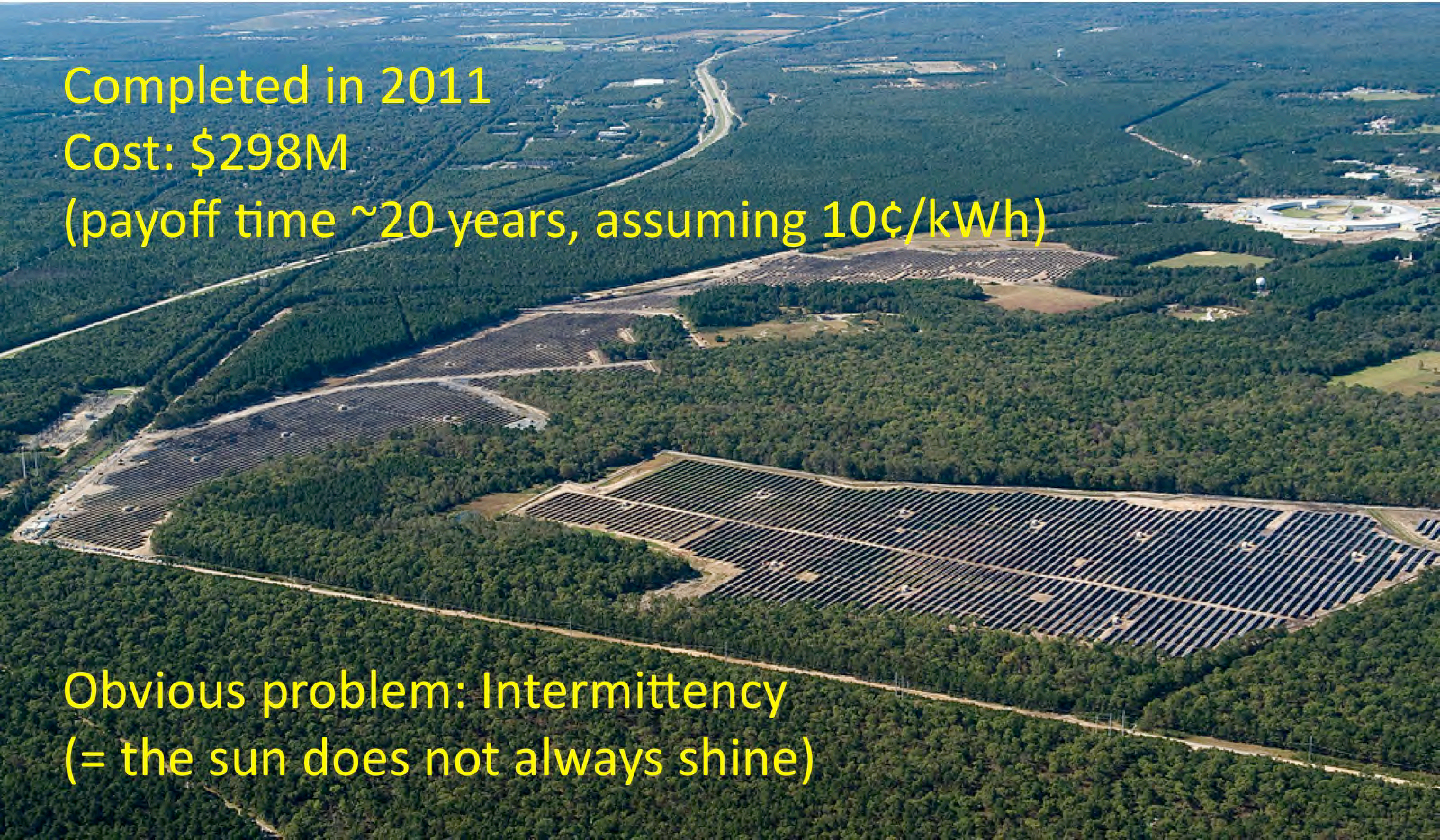


Solar Cycle Variations



Power from the Sun: Photo-Voltaic

32 MW (peak) Brookhaven solar farm (BP Solar, MetLife, LIPA, DOE)



Completed in 2011
Cost: \$298M
(payoff time ~20 years, assuming 10¢/kWh)

Obvious problem: Intermittency
(= the sun does not always shine)

Power from the Sun: Solar-Thermal

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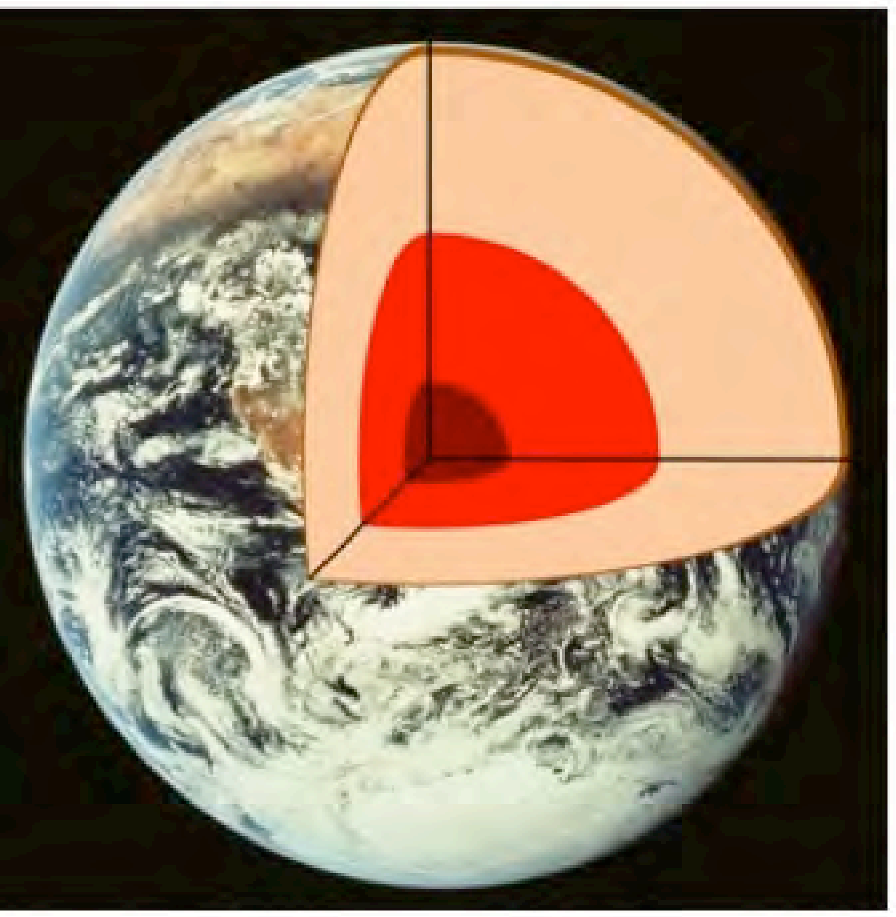
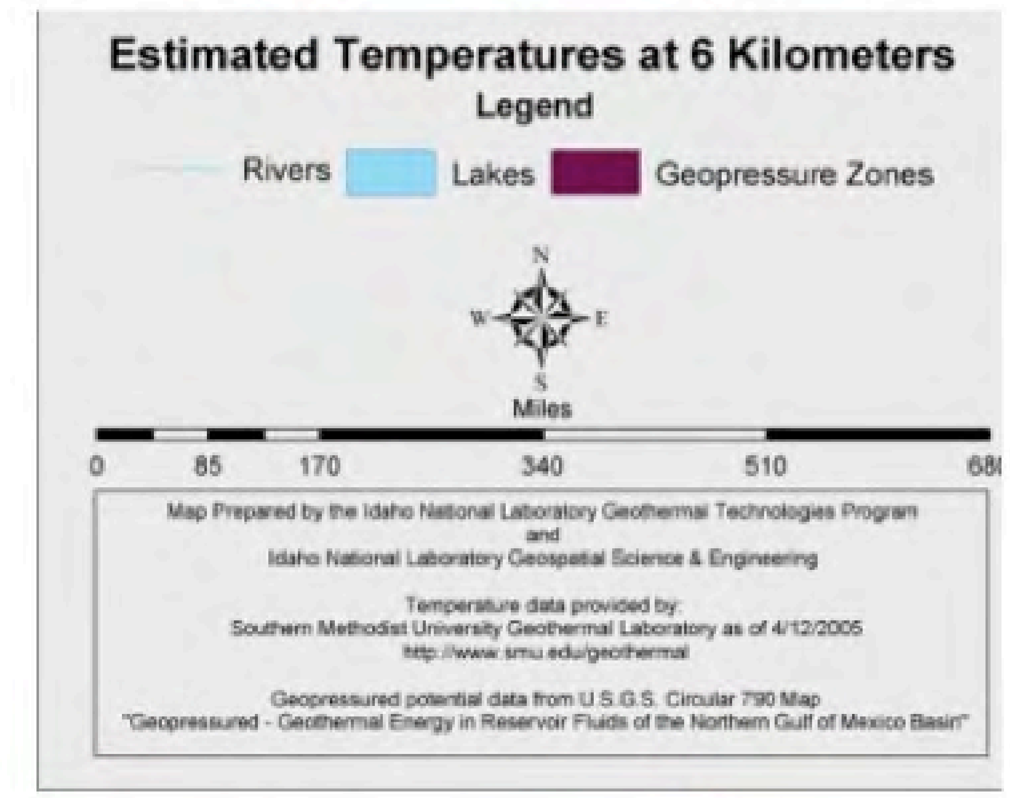
Power from the Earth



Earth's thermal energy ~ 10^{31} J

Heat flow density: 0.1 W/m^2

Total heat flow: 44 TW



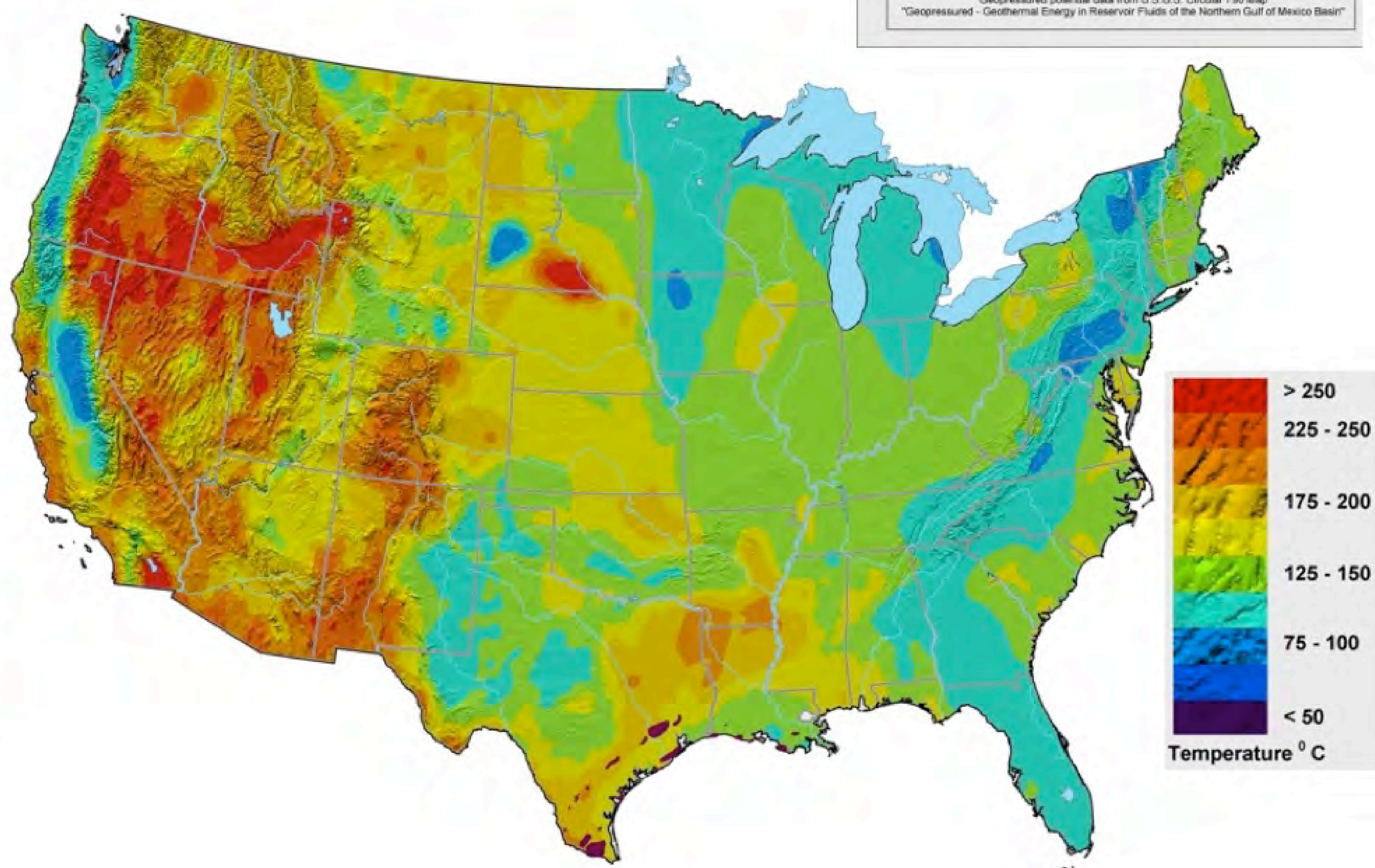


FIGURE 18.32 Nesjavellir Geothermal Power Station in Southwest Iceland, which generates 120 MW of electrical power.

Enhanced Geothermal

Enhanced **G**eothermal **S**ystem

- 2 or more bore holes
- Hydraulic fracturing
- Cost: ~ \$20 million
- Capacity: 4 MW
- Payoff time (@10¢/kWh): 6 years
- Risks
  - Induced seismicity
  - Ground water contamination

GSA Topical Session, Denver 2010
Warren Wood
Wolfgang Bauer

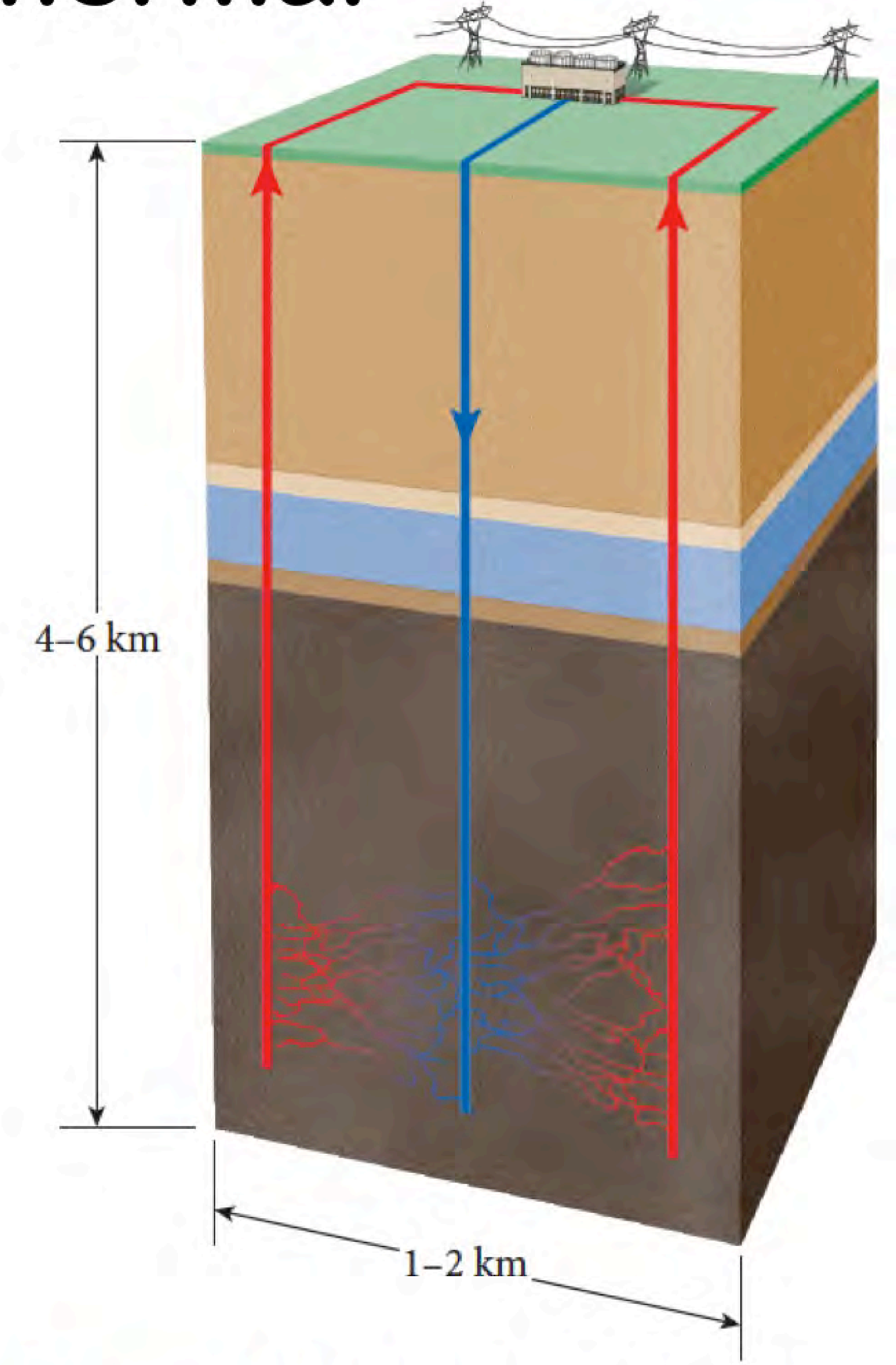
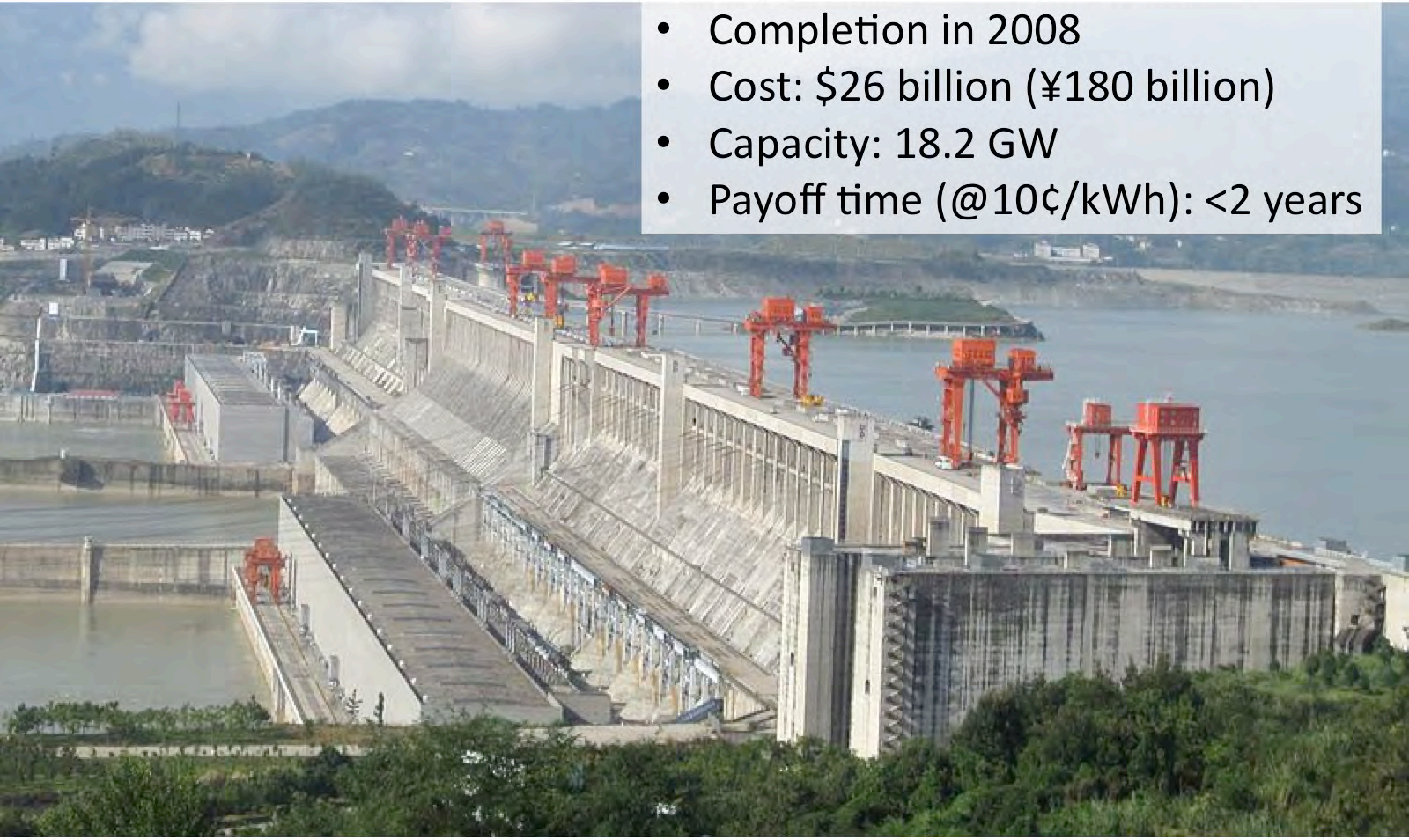


FIGURE 18.33 Diagram of an enhanced geothermal system.

Hydro

Example: Three Gorges Dam

- Completion in 2008
- Cost: $26 billion (¥180 billion)
- Capacity: 18.2 GW
- Payoff time (@10¢/kWh): <2 years



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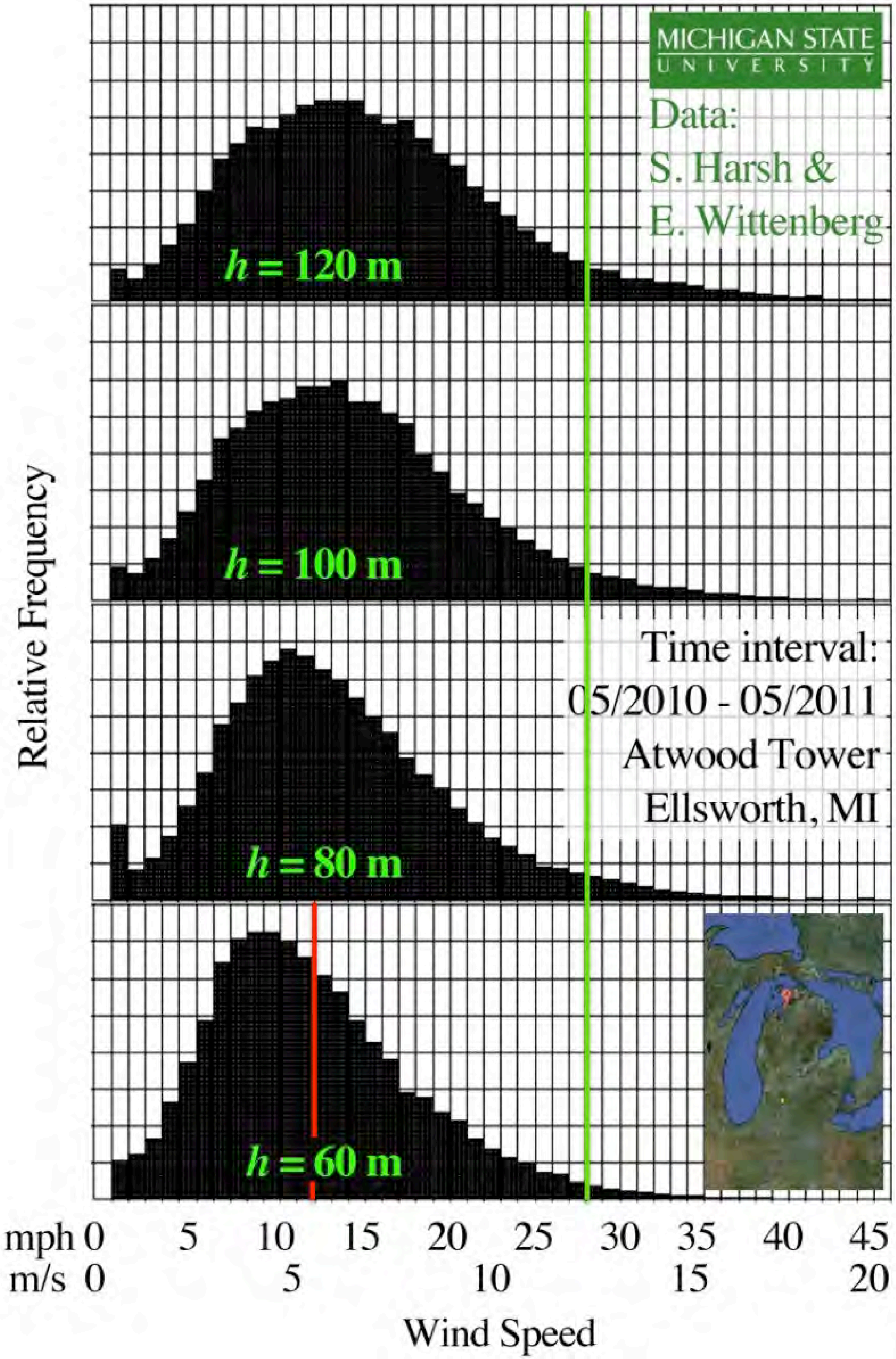
Wind



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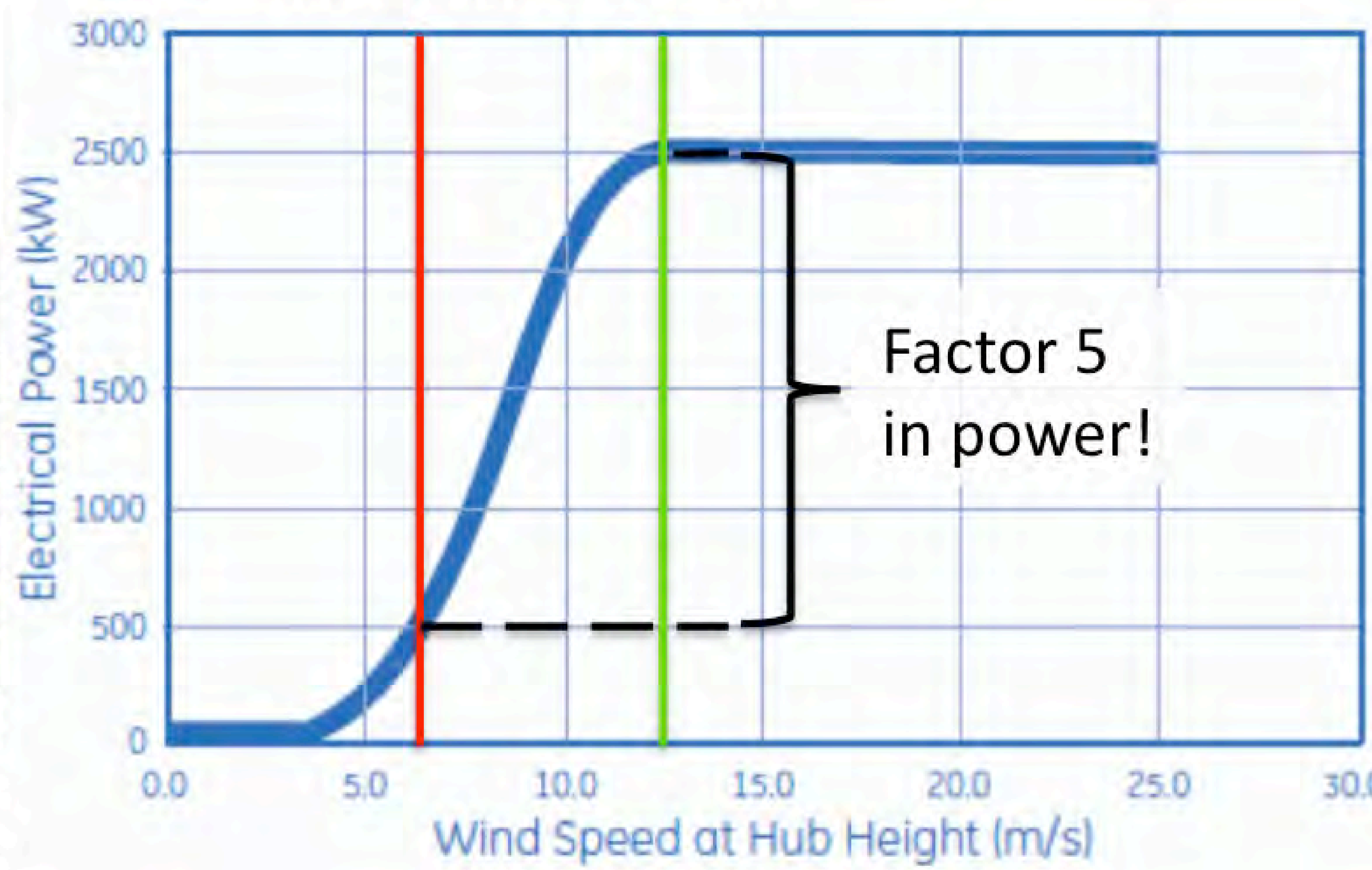
Wind Speed

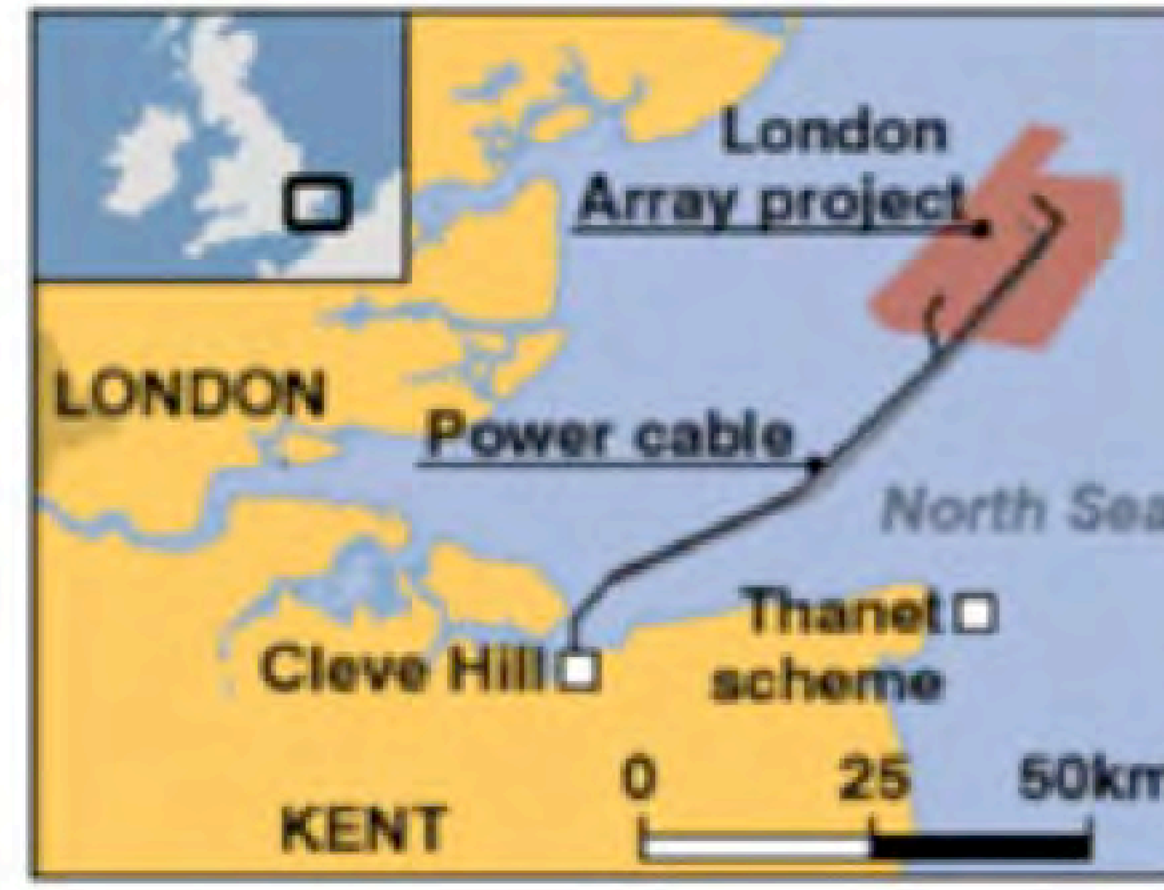
- Wind speed increases with altitude
  - More power from taller towers
- Broad distribution
  - Intermittency



Bottom line: Wind

Most efficient: Offshore wind farms

- Example: London Array
  - Completion in 2012
  - Cost: €2.2 billion (~$2.6 billon)
  - Peak capacity: 630 MW
  - Payoff time (@10¢/kWh): ~10 years



Denmark: ~20% of electricity from wind, ~4 GW capacity. Intermittency? Smoothing via Norwegian hydro.

Middelgrunden offshore wind farm near Copenhagen, Denmark
http://en.wikipedia.org/wiki/File:DanishWindTurbines.jpg

Ocean Currents

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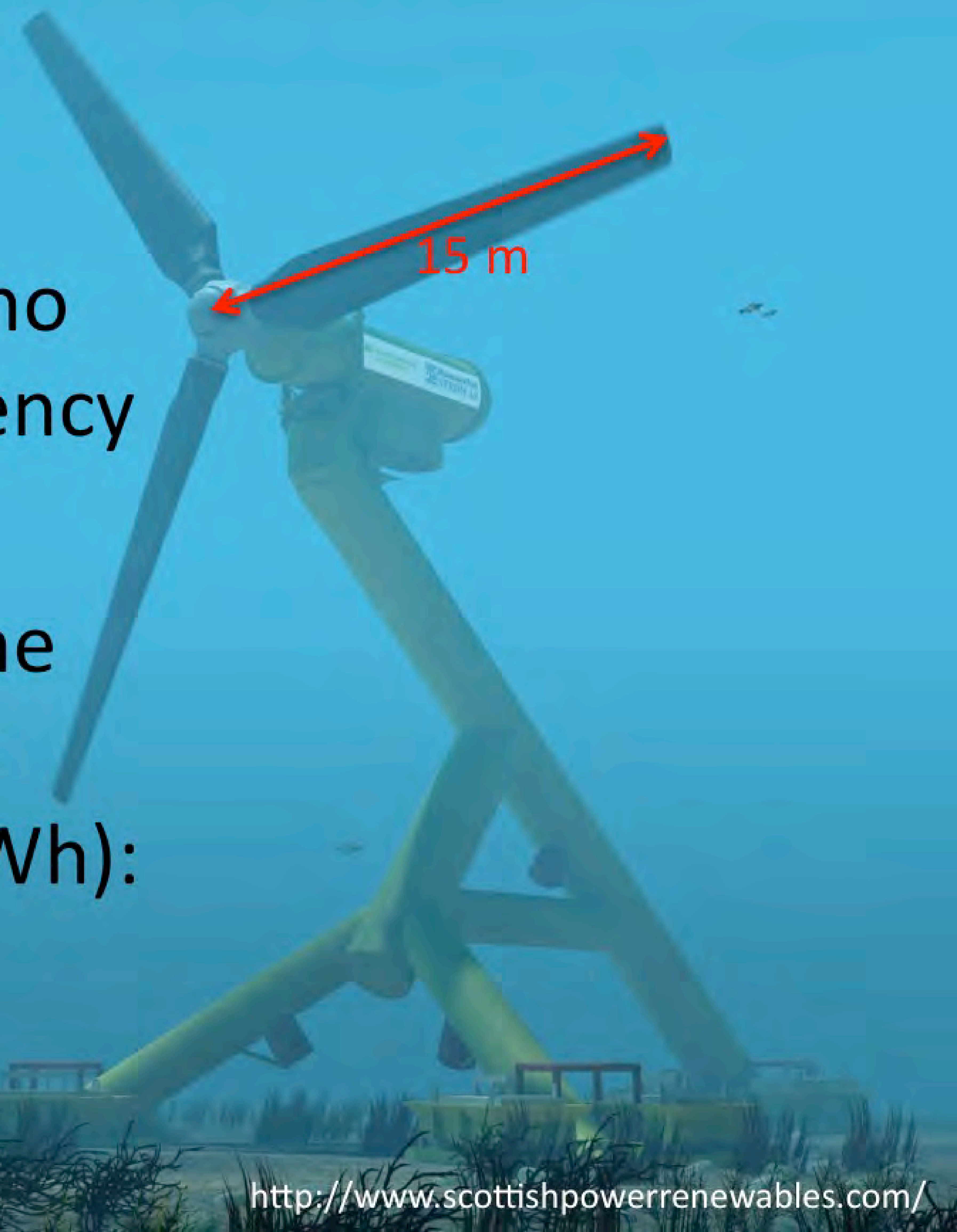
- Sound of Islay, Orkney Islands, UK
- HS1000 sub-sea turbine
- 1 MW
- $11M
- (Almost) no intermittency
- Payoff time ~12 years (@10¢/kWh):



Energy Storage

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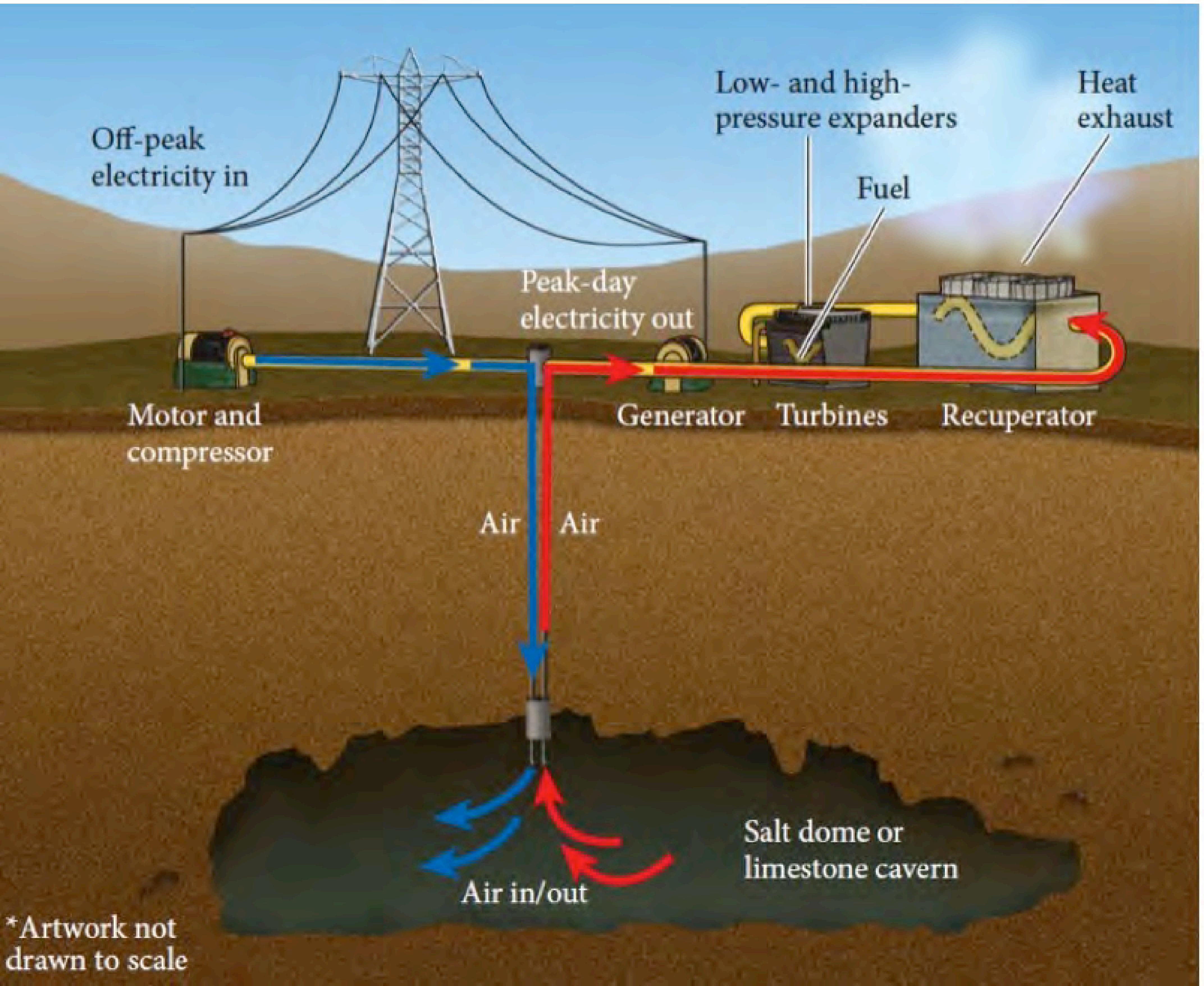

- Intermittent power sources need macroscopic energy storage
  - Pump-storage hydro
  - Compressed air caverns
  - Molten salt (high latent heat)

Really BIG Plans: DESERTEC

Transportation

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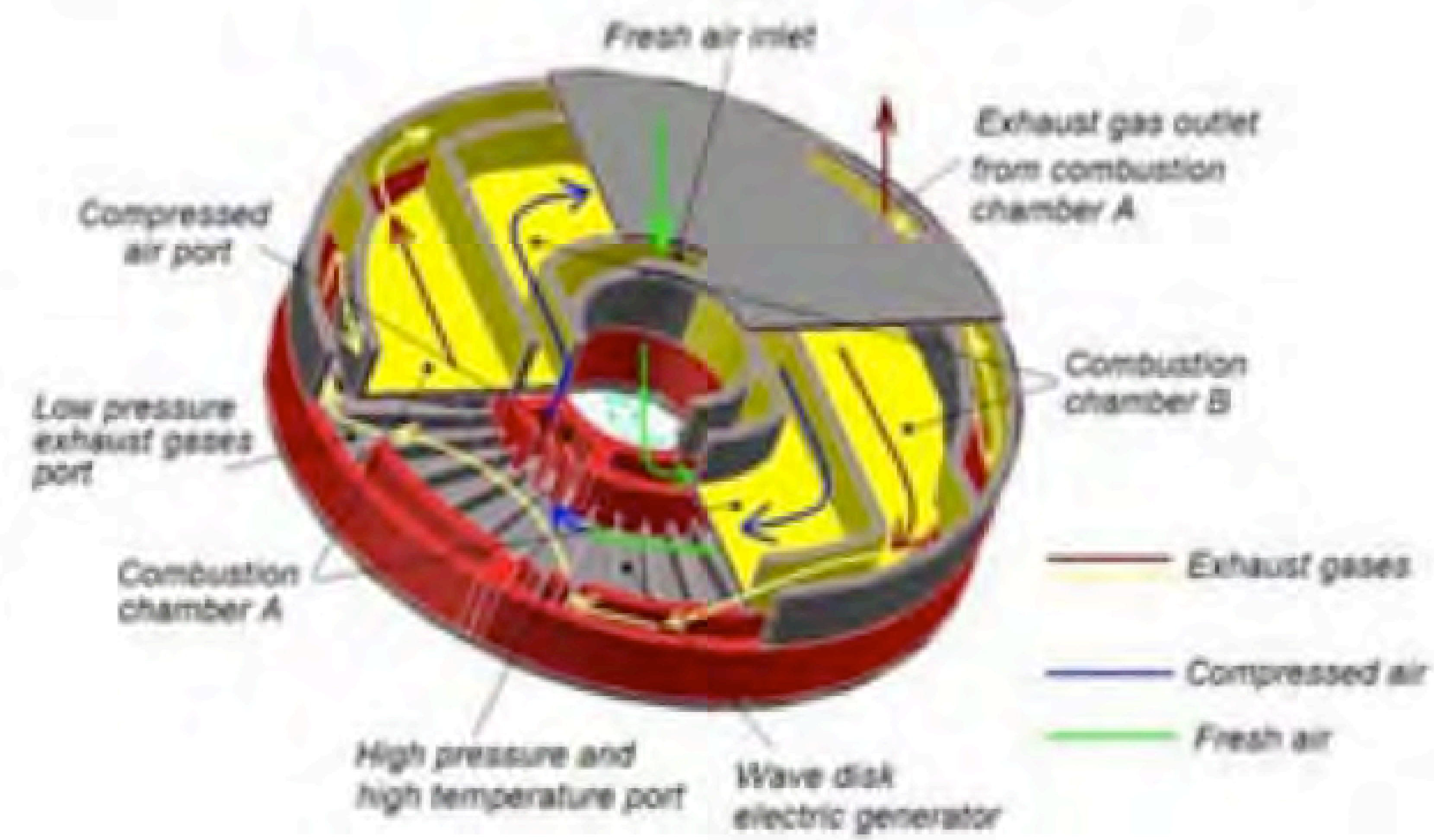
- Public transport: Bus & train(!)
- More efficient engines (e.g. Norbert Müller's wave disk)
- Alternative fuels:
  - Ethanol (from sugar cane)
  - Methane
  - Hydrogen
- Hybrids with regenerative brakes
- Hybrid-electric (e.g. Chevy Volt)
- All-electric



Corn-Based Bio-Ethanol: Big Problems

- Ethanol production receives > $3 billion/year in subsidy in US
- Goal: become independent of fossil fuels
- But: corn ethanol production requires 29% more fossil energy input than the energy output in the fuel produced
  (switch-grass 45%, wood 57%)
- Bio-diesel from soybeans
  or sunflowers (27%, 118%)

David Pimentel & Tad Patzek,
Natural Resources Research (Vol. 14:1, 65-76)

Best Deal?

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	MJ/L	kWh/gal	$/gal	$/kWh
Diesel	38.6	40.5	$3.649	0.090
Regular	34.8	36.5	$3.459	0.095
Premium	34.8	36.5	$3.659	0.100
E85	25.2	26.5	$3.099	0.117

E85 = 85% ethanol (23.5 MJ/kg)
+ 15% regular gasoline

Cellulosic Bio-Ethanol

- Future: perhaps cellulosic ethanol
- $500M BP grant to Berkeley, LBNL, Illinois
- $125M DoE grant to MSU, Wisconsin
- Nature's expert: microbes in termite gut (break down wood cellulose into "fuel")

Energy Biosciences Institute

GREAT LAKES BIOENERGY RESEARCH CENTER

Transportation

W. Bauer
Aug. 2012

More than 13,000 yellow cabs in NYC transport ~250 million passengers/year!

2007 (Bloomberg): Switch to hybrids!

"My hybrid saves me more than $20 in gas each day"

Progress!
(Remember: ***E* = $**)

Time Square, NYC. Photo: Jessica Bauer

Transportation

- Shanghai *CAPABUS*
  - Powered by 5 kF (!) super-capacitors, with regenerative brakes
  - Recharges quickly every 3-5 miles at bus stops
  - Saves estimated **$200,000** in fuel cost over lifetime (***E* = $**)

Don't forget efficiency!

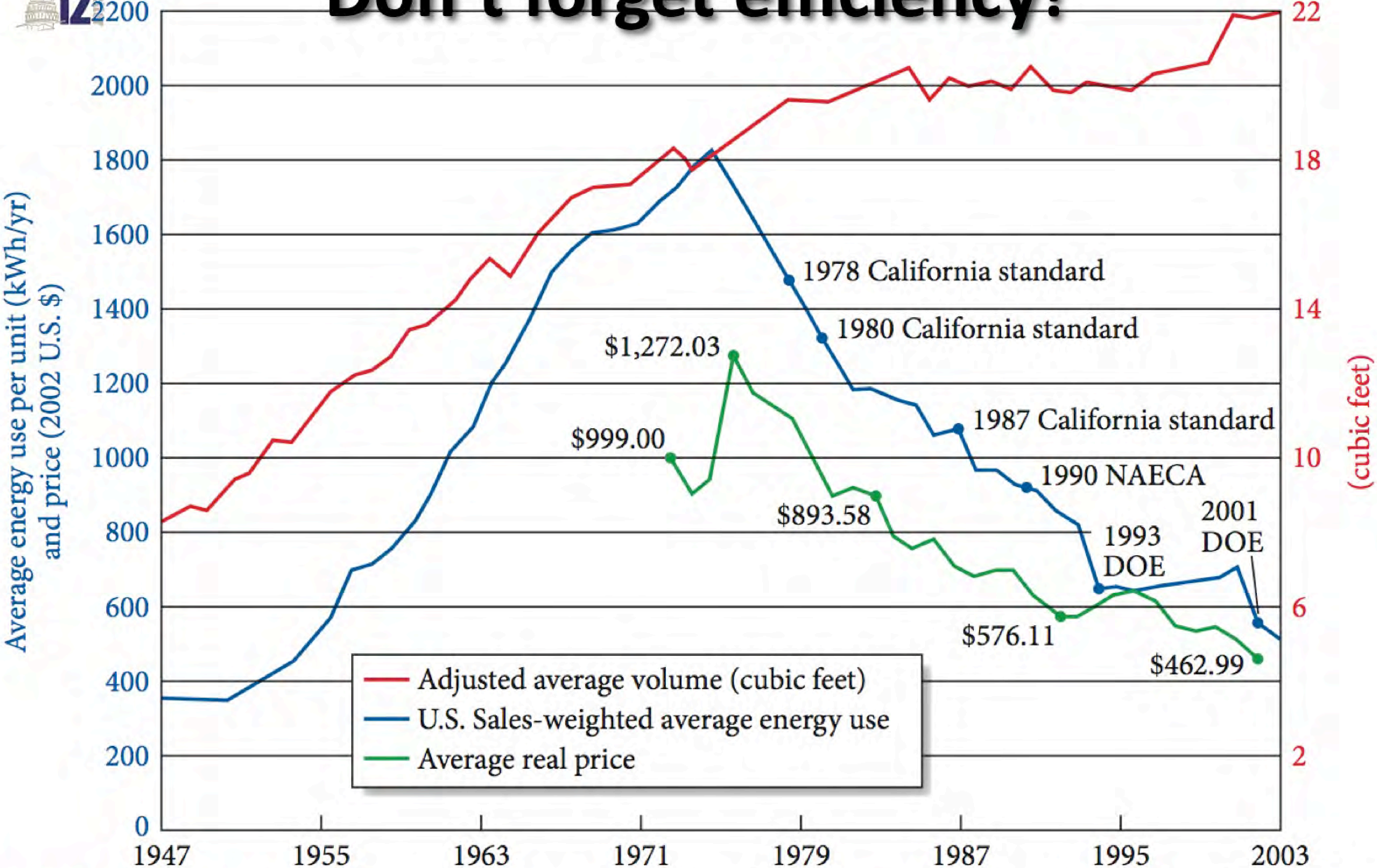

FIGURE 20.13 Average U.S. refrigerator volume (red line), price (green line), and energy use (blue line) from 1947 to 2003. (Original figure: Steve Chu)

Efficiency: Lighting

LEDs: 130-170 lm/W (record as of April 2012: 254 lm/W*)
Fluorescent: 30-95 lm/W
Halogen: 20-30 lm/W
Incandescent: 5-20 lm/W

US energy use for lighting:
~100 billion kWh/year
(=22% of total electricity use)

Switching to all-LED lighting:
Savings of ~10 GW

* http://www.cree.com/news-and-events/cree-news/press-releases/2012/april/120412-254-lumen-per-watt

Reducing Demand = Saving Money

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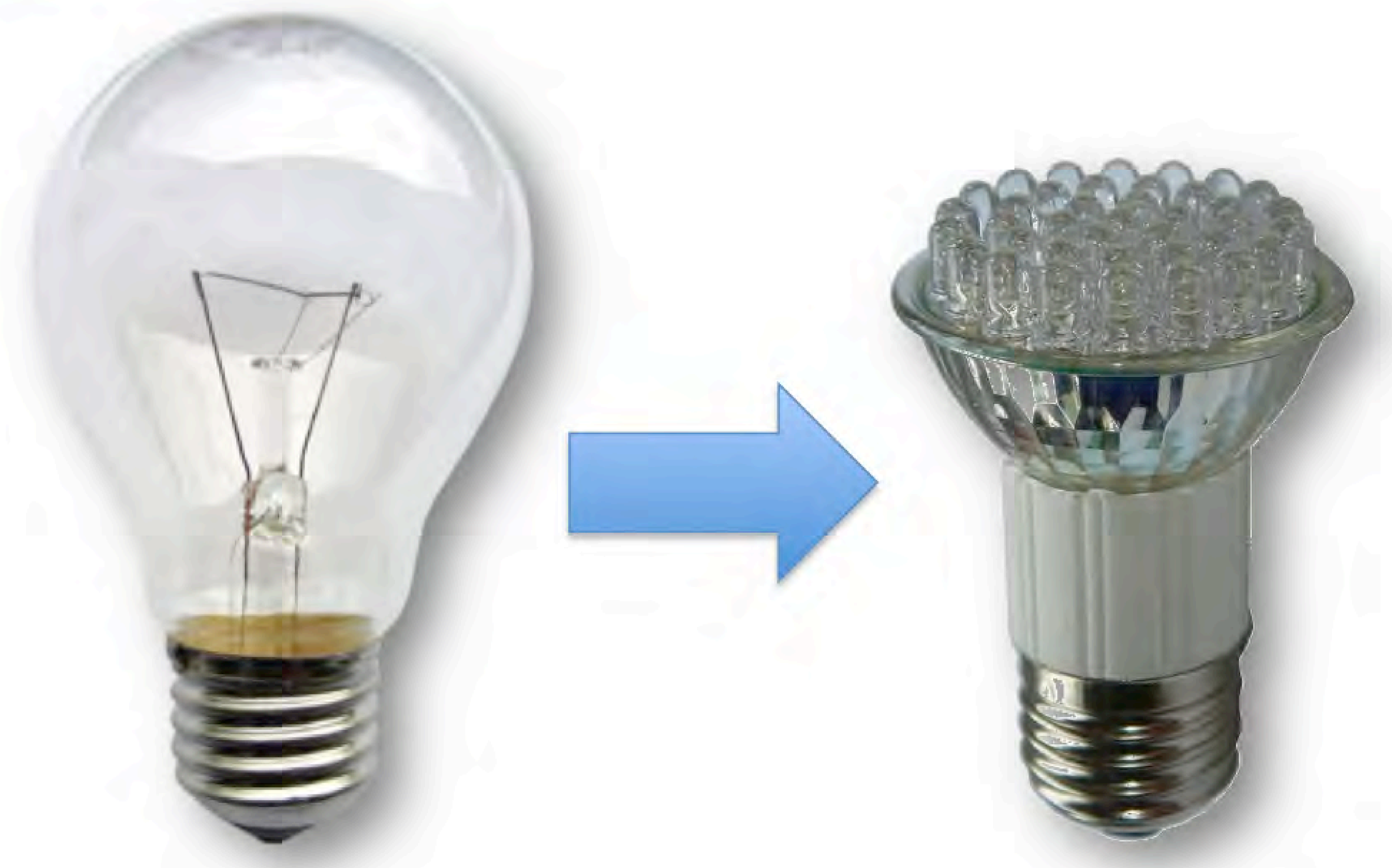
Aug. 2012

“A ~~penny~~ kWh saved is a ~~penny~~ kWh earned”
Benjamin Franklin (Jan.17, 1706 –Apr.17, 1790)



= up to $20 savings in electricity per year
for a light left on overnight

MW Biogas Power Plant

- Basic principle: grow corn, shred it, store in silo, then ferment in an anaerobic digester
- Initial investment: ~ $3-5 million
- Land required to grow biomass: 150 hectares (= 370 acres)
- 6.2 million kWh of electrical energy/year
- 6.5 million kWh of co-generated thermal energy
- Payoff time (@10¢/kWh): 3-4 years
- NO INTERMITTENCY (can buffer wind/sun energy production with leverage factor 3-10)

Net Energy Ratio

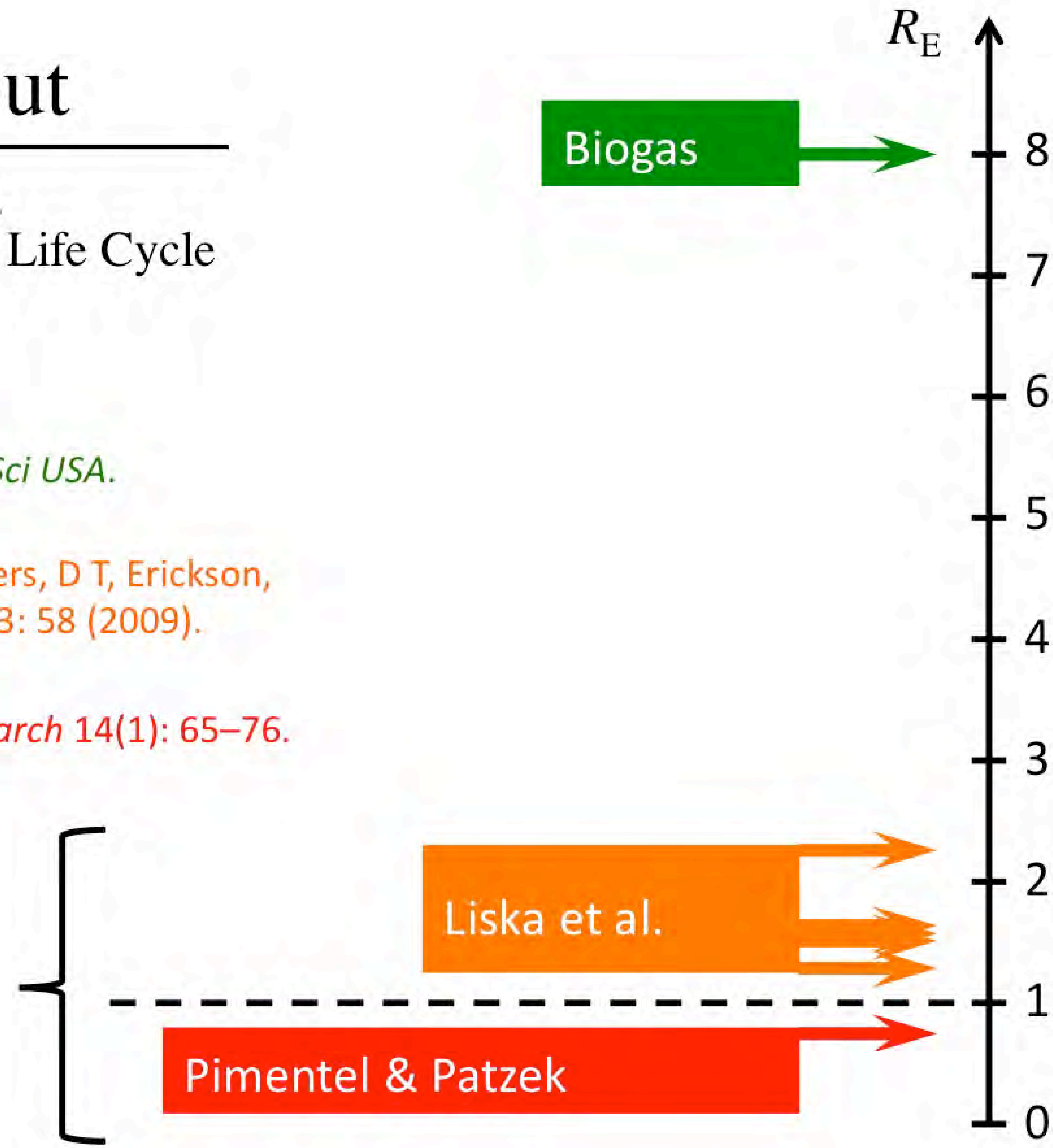
$$R_E = \frac{\text{Net Energy Output}}{\langle \text{Fossil Energy Input} \rangle_{\text{Life Cycle}}}$$

Bauer, W, Bauer, S, Bauer, T (2011, sub) *Proc Natl Acad Sci USA*.

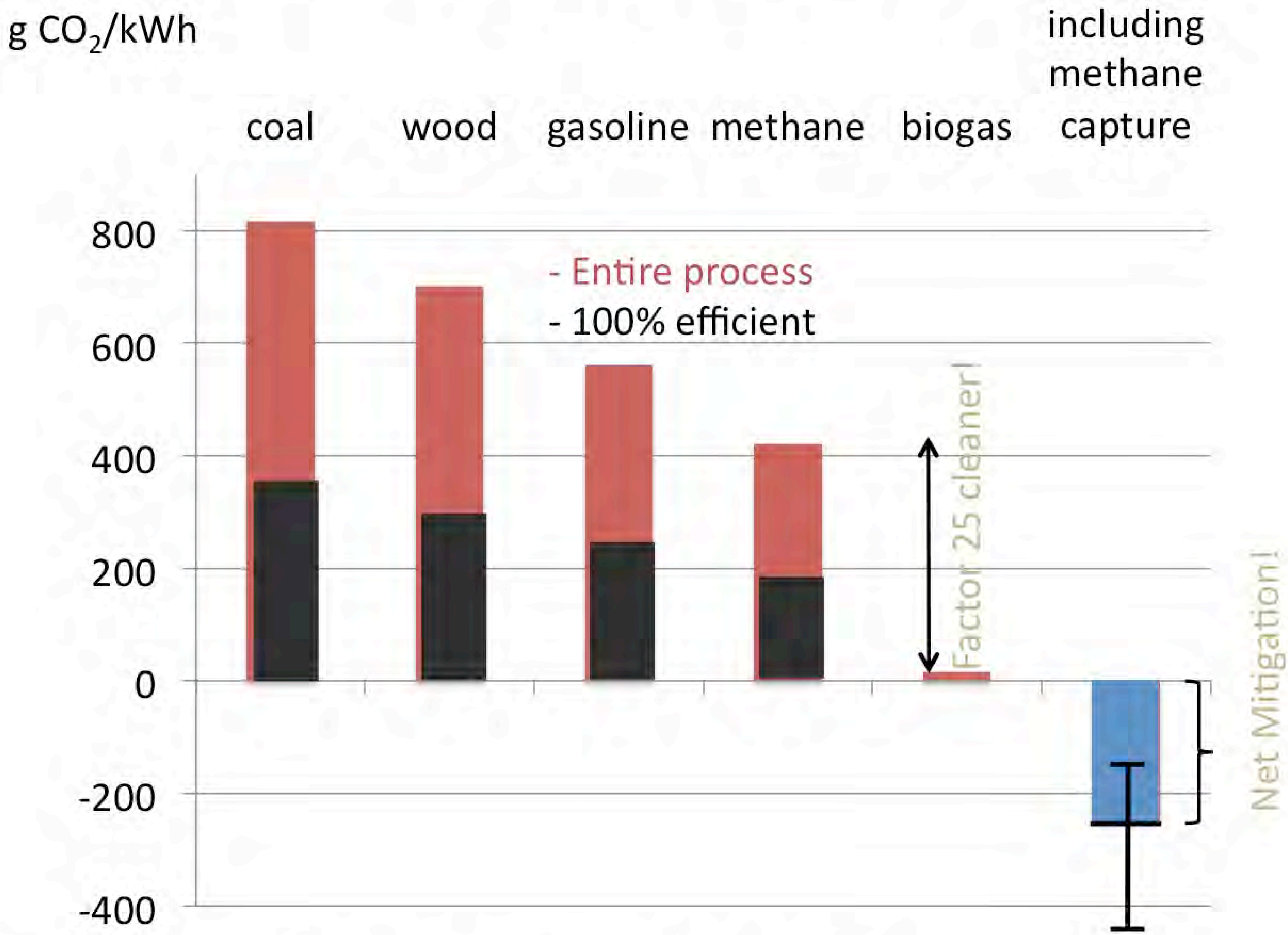
Liska, A J, Yang, H S, Bremer, V B, Klopfenstein, T J, Walters, D T, Erickson, G E, Cassman, K G (2009) Journal of Industrial Ecology 13: 58 (2009).

Pimentel, D, Patzek, T W (2005) *Natural Resources Research* 14(1): 65–76.

Bio-Ethanol from Corn

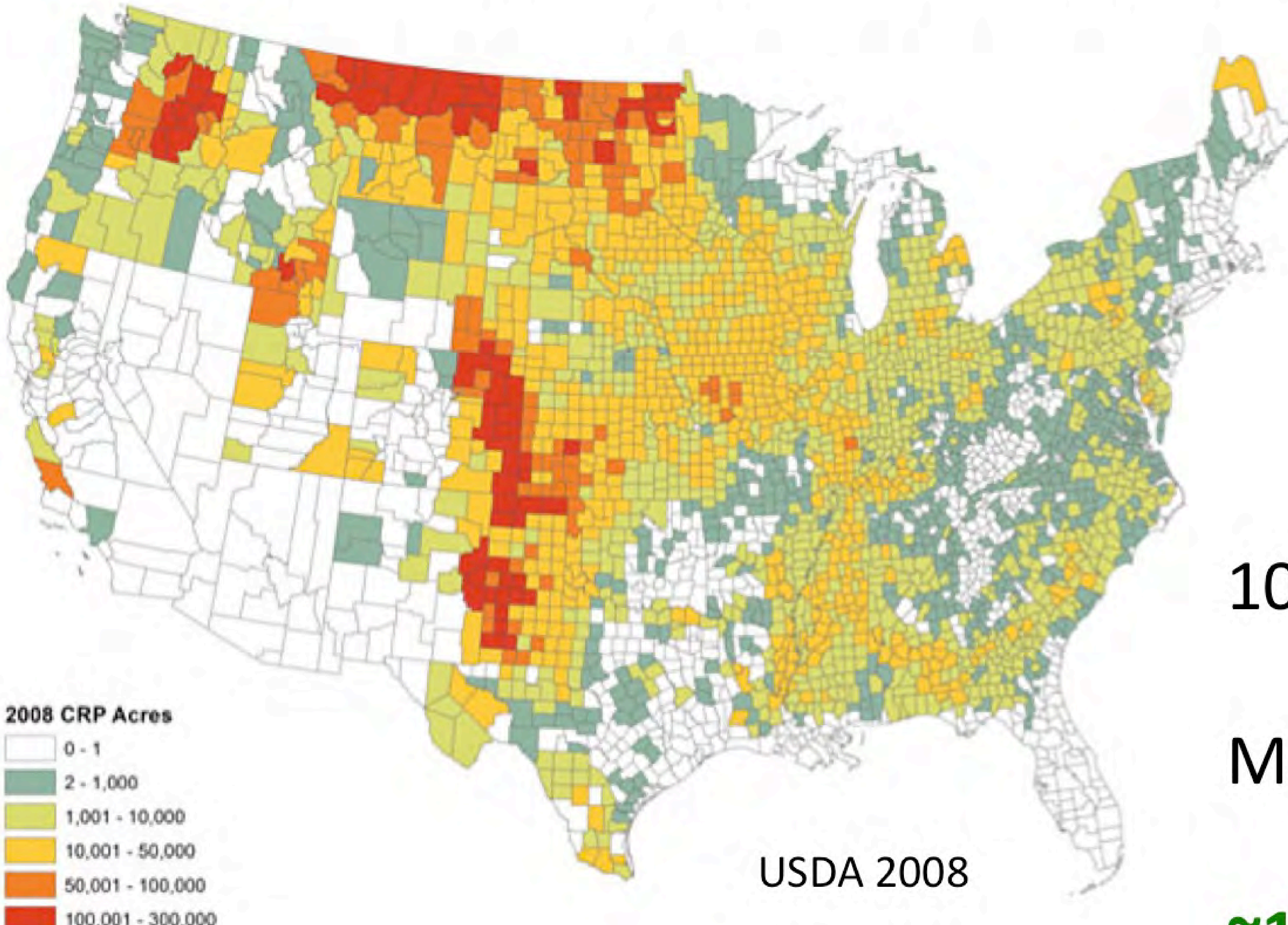


Greenhouse Gas Balance



Methane is ~25 times more powerful greenhouse gas than CO_2
- our process prevents methane from cow dung to escape

Food vs. Fuel?
Conservation Reserve Program



USDA 2008

10 M hectare

Marginal land(?)

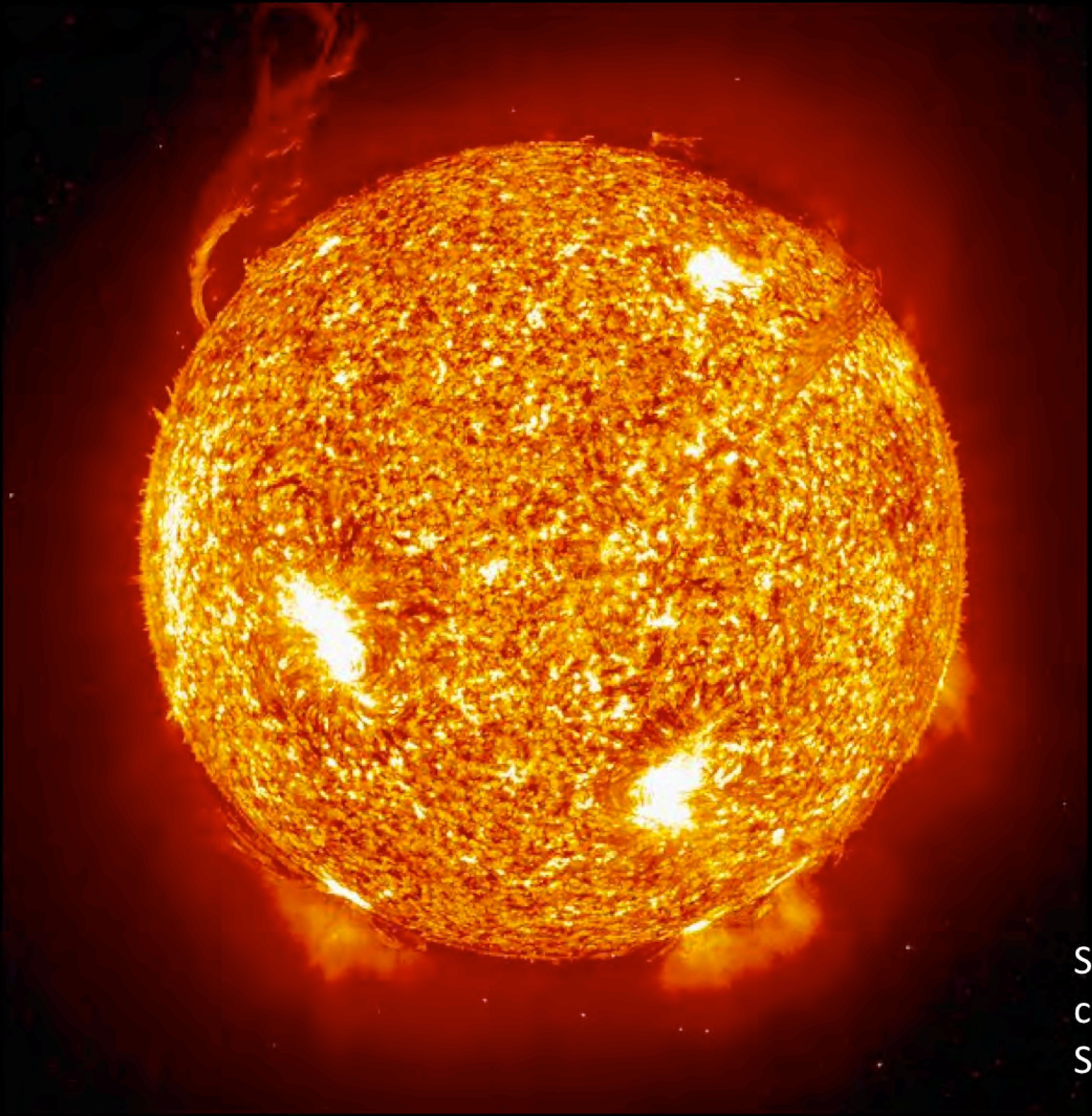
~100 GW potential

PART 4:

How Nuclear Physicists Can Help

Nuclear Power

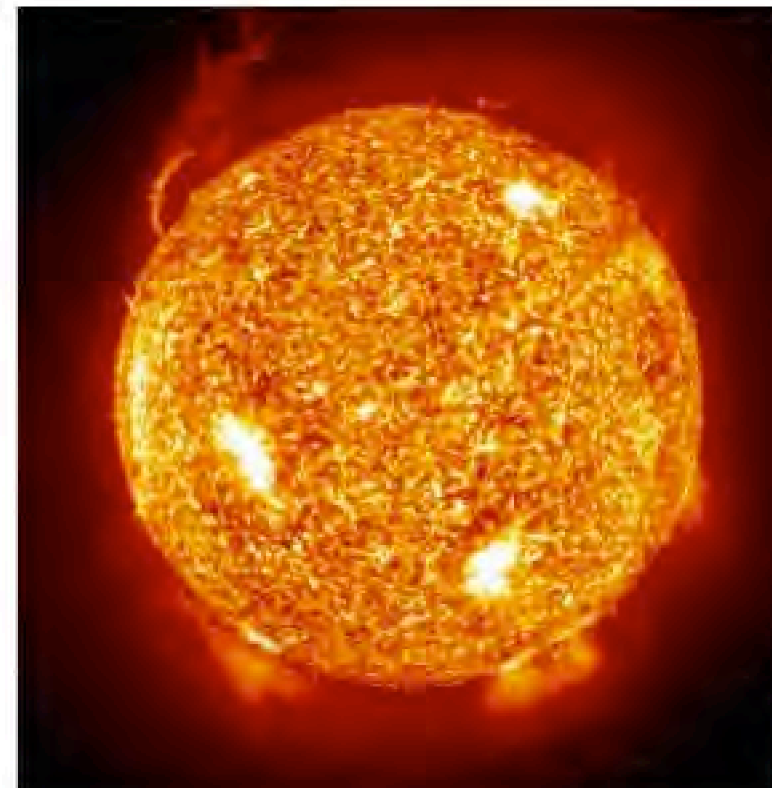
W. Bauer
Aug. 2012

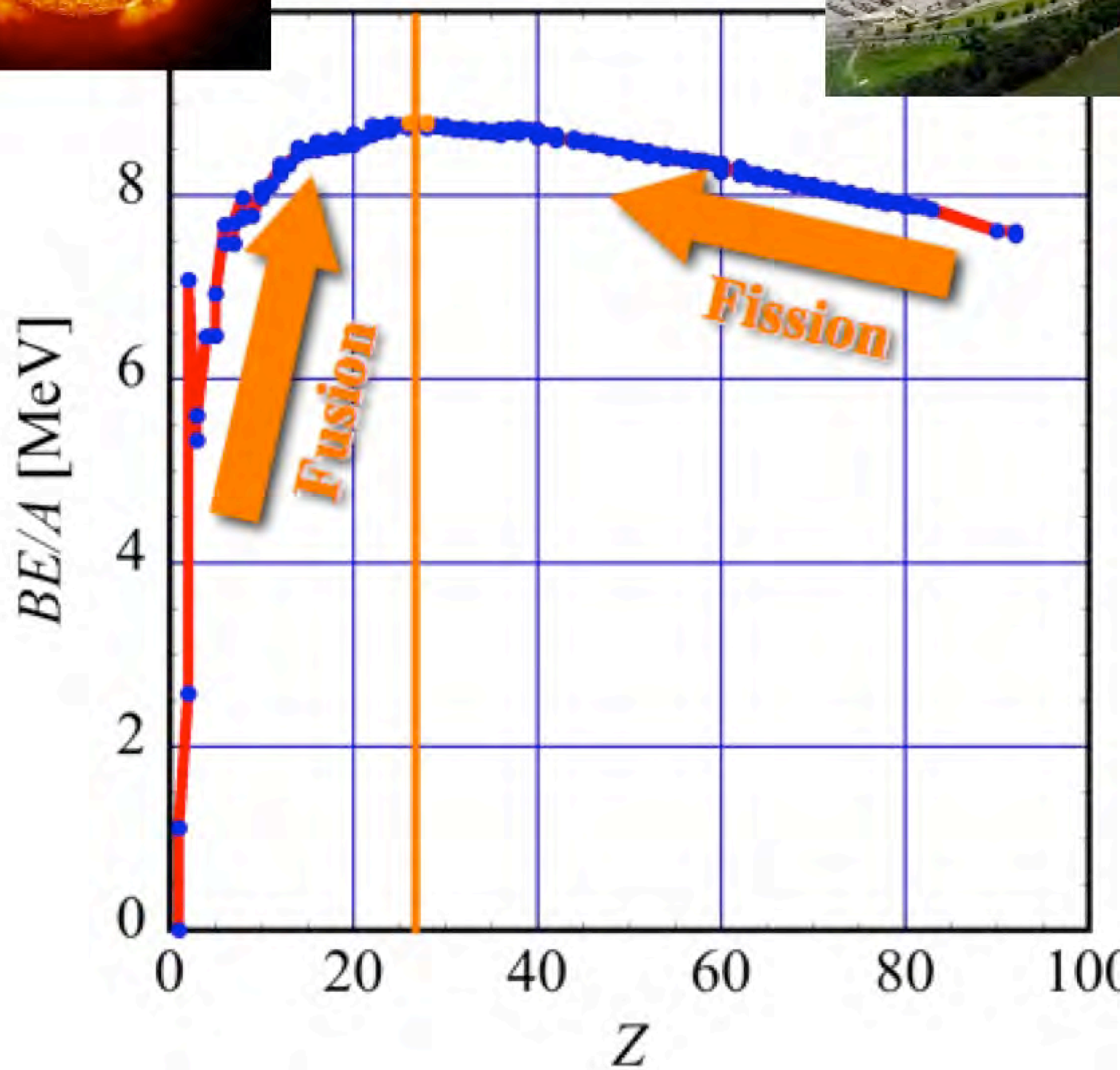


Sun at 30.4 nm
credit:
SOHO, NASA

Nuclear Power

- Back to $E = mc^2$
- Nucleus made of Z protons and N neutrons
- $M_{\text{nucleus}} < Zm_{\text{p}}+Nm_{\text{n}}$
- Binding energy!





Nuclear Power

- Typical chemical reaction

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

  - Heat of combustion: 802 kJ/mol
  - $\Delta E / mc^2 = 802 \text{ kJ} / [(0.08 \text{ kg})(3 \cdot 10^8 \text{ m/s})^2] = 10^{-10}$

Ratio ~10^7

- Typical nuclear fission reaction

$$n + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3n$$

  - $\Delta E / mc^2 = 173.3 \text{ MeV} / 219{,}882 \text{ MeV} = 8 \cdot 10^{-4}$

Wikipedia

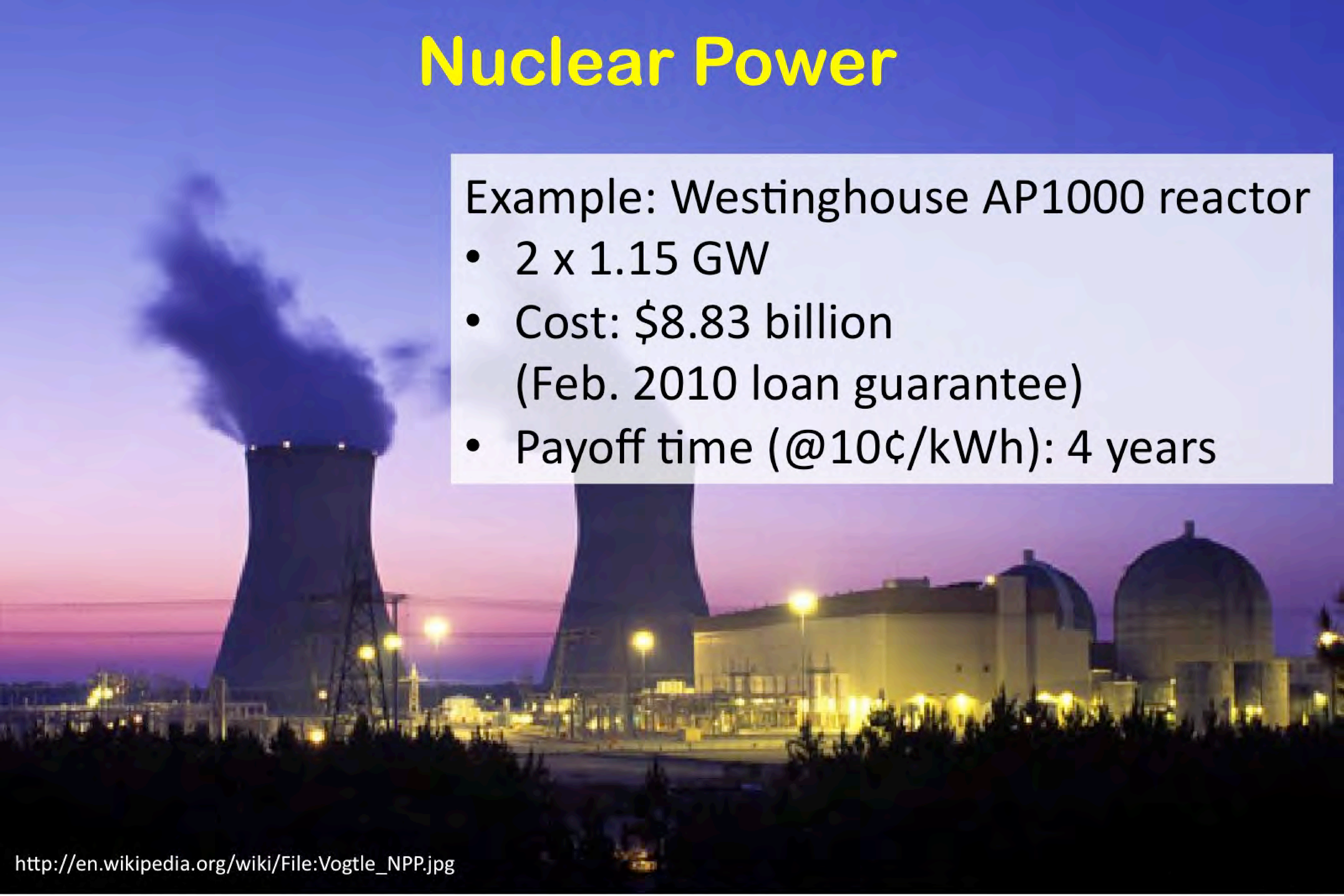
~

Wikipedia

Nuclear Power

Example: Westinghouse AP1000 reactor

- 2 x 1.15 GW
- Cost: $8.83 billion
  (Feb. 2010 loan guarantee)
- Payoff time (@10¢/kWh): 4 years

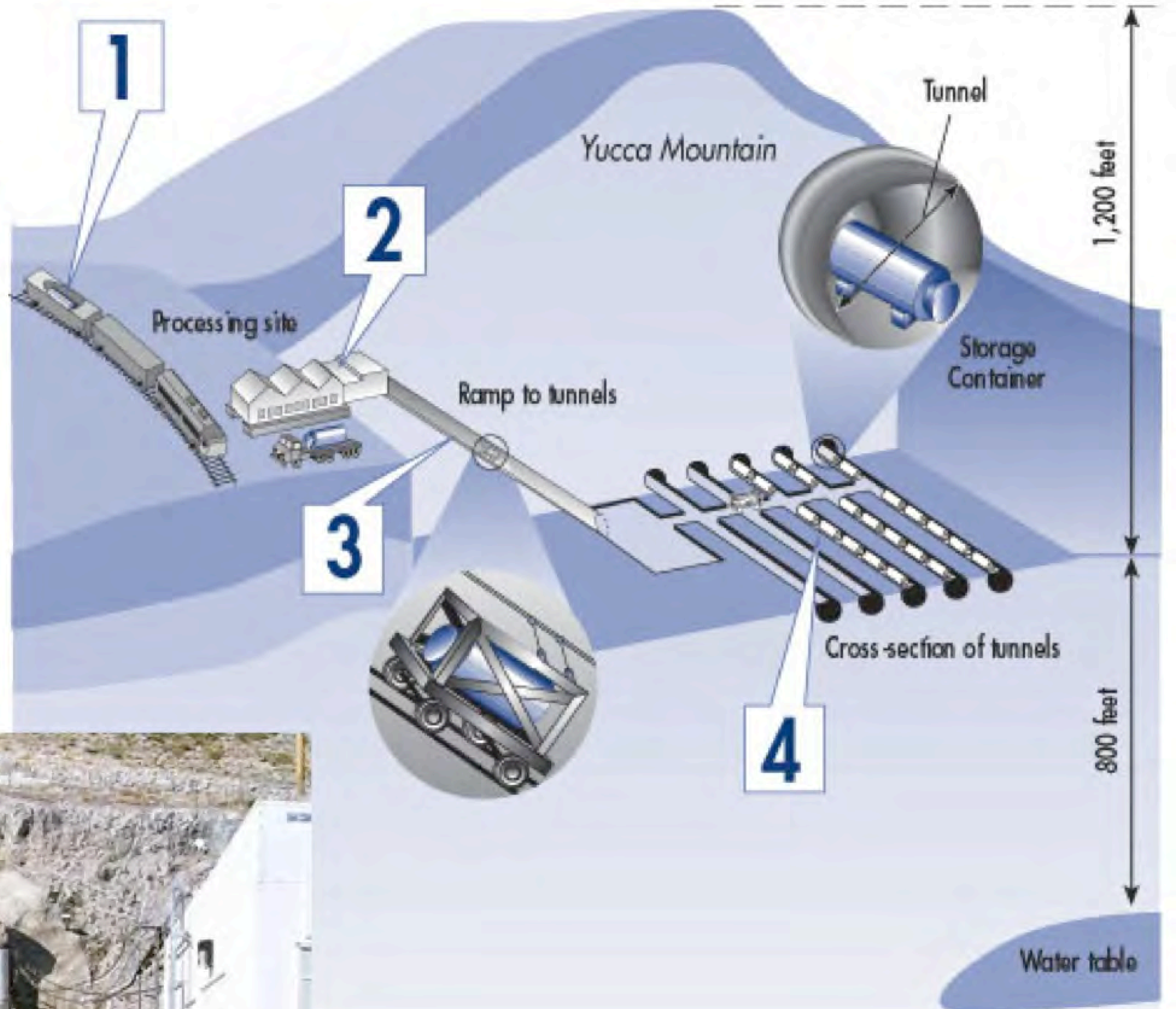


http://en.wikipedia.org/wiki/File:Vogtle_NPP.jpg

Alvin W. Vogtle Electric Generating Plant, Waynesboro, Georgia
(site for first new construction of 2 nuclear reactors in the USA since Three Mile Island)

Problems with Nuclear Fission

- Really big waste storage problems



Problems with Nuclear Fission

- Potential for really big accidents

Better Nuclear Fission

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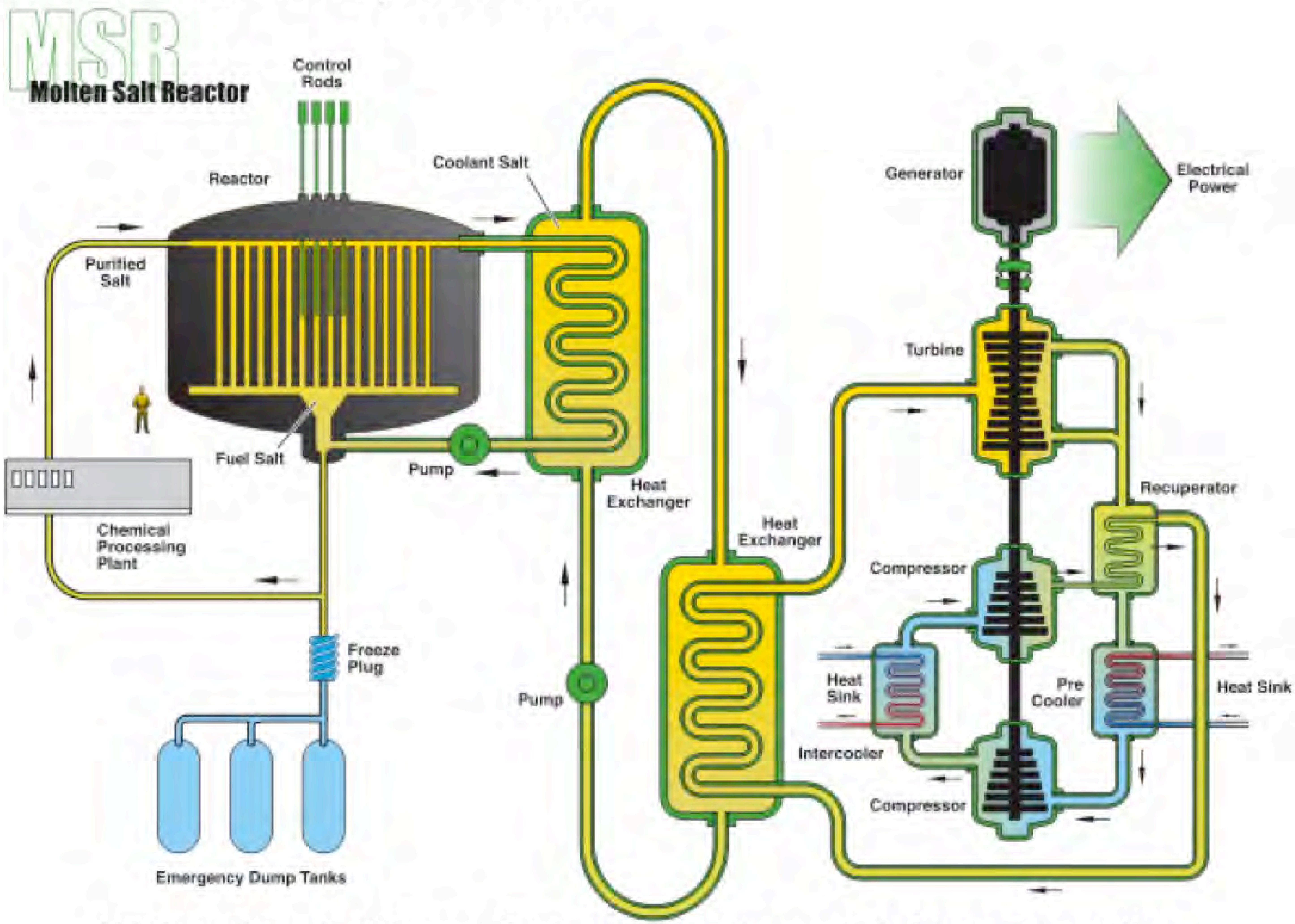
Aug. 2012

- Better reactor design
  - Generation IV reactors
  - Subcritical Accelerator-Driven System (?)
  - Molten salt reactor (?)
- Less waste
  - Breeder (?)
- Better fuel
  - Thorium (?)

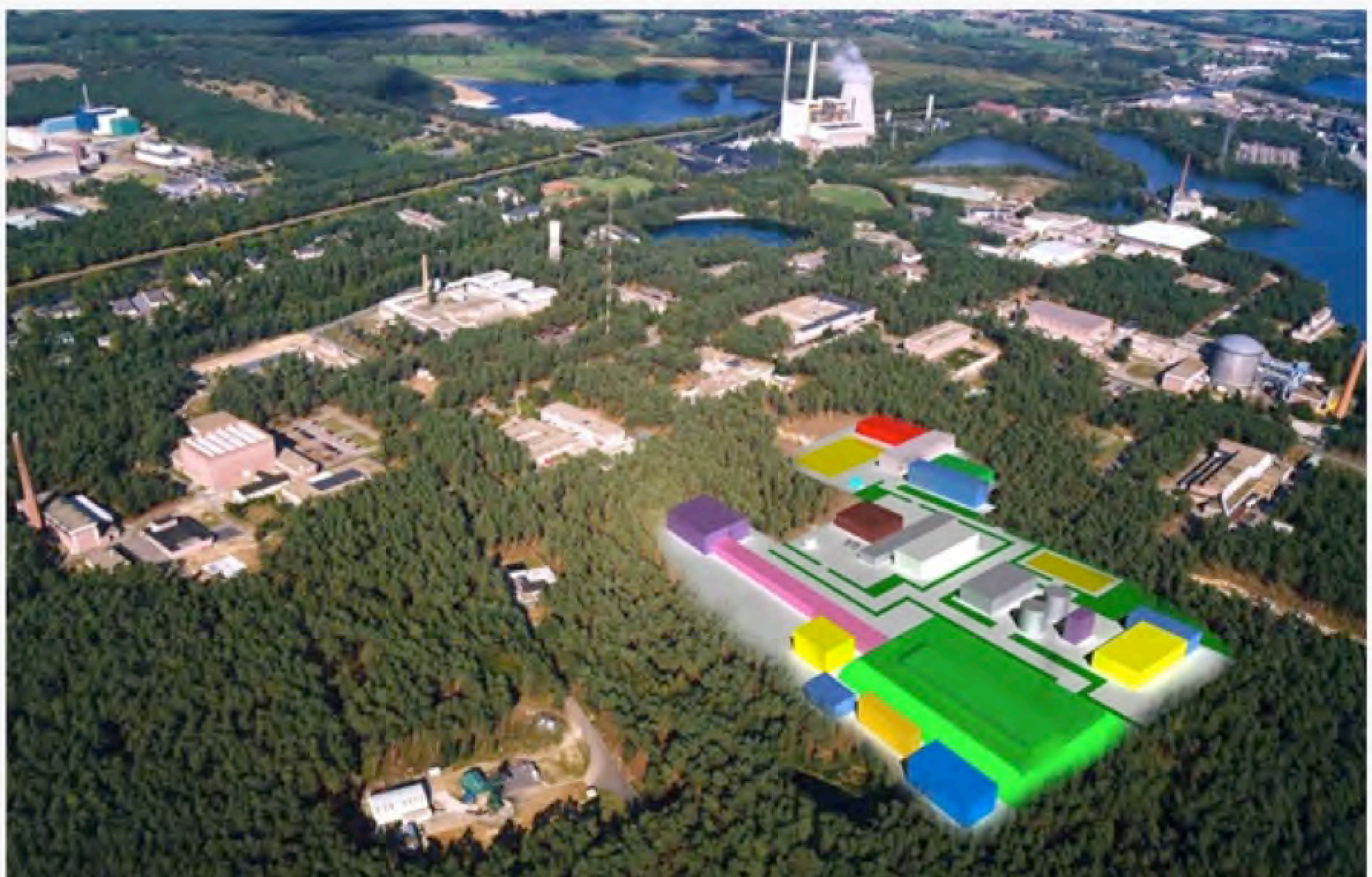


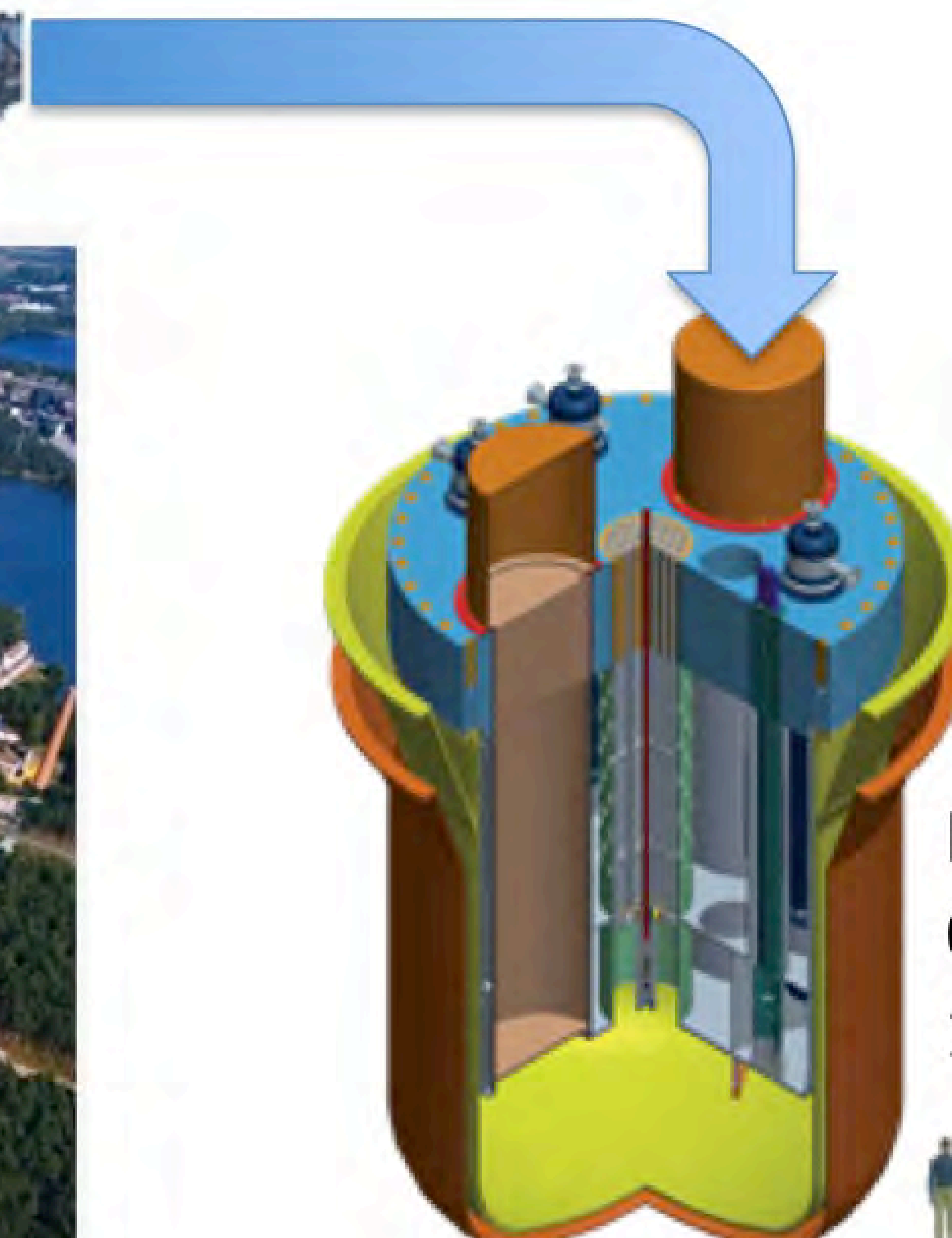
US Department of Energy Nuclear Energy Research Advisory Committee

Accelerator-Driven System (ADS)

- Example: MYRRHA reactor (Belgium)
  - MOX fuel
  - M€960
  - To be operational in 2023

600 MeV, 4 mA, proton



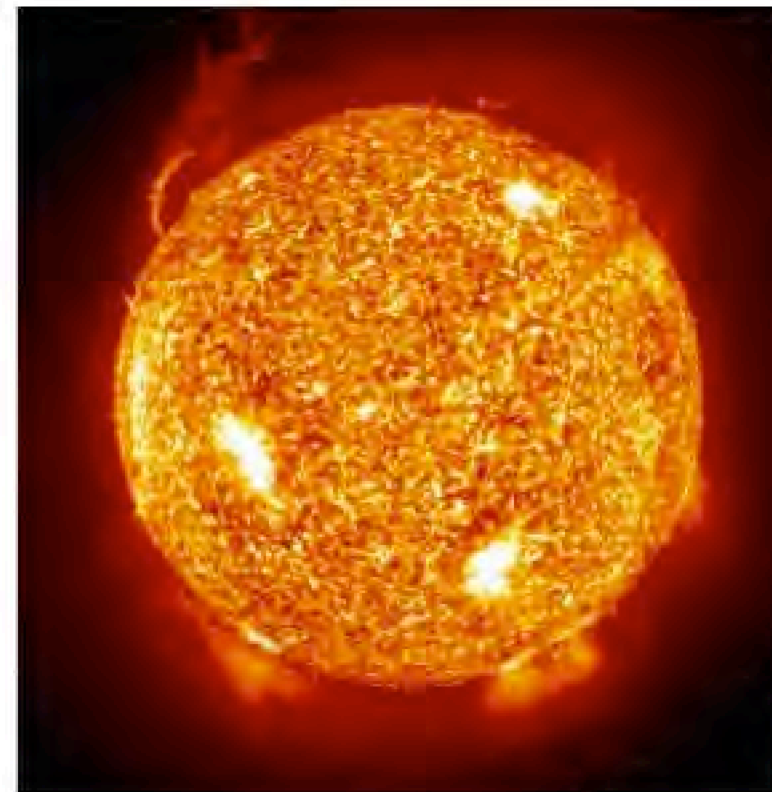


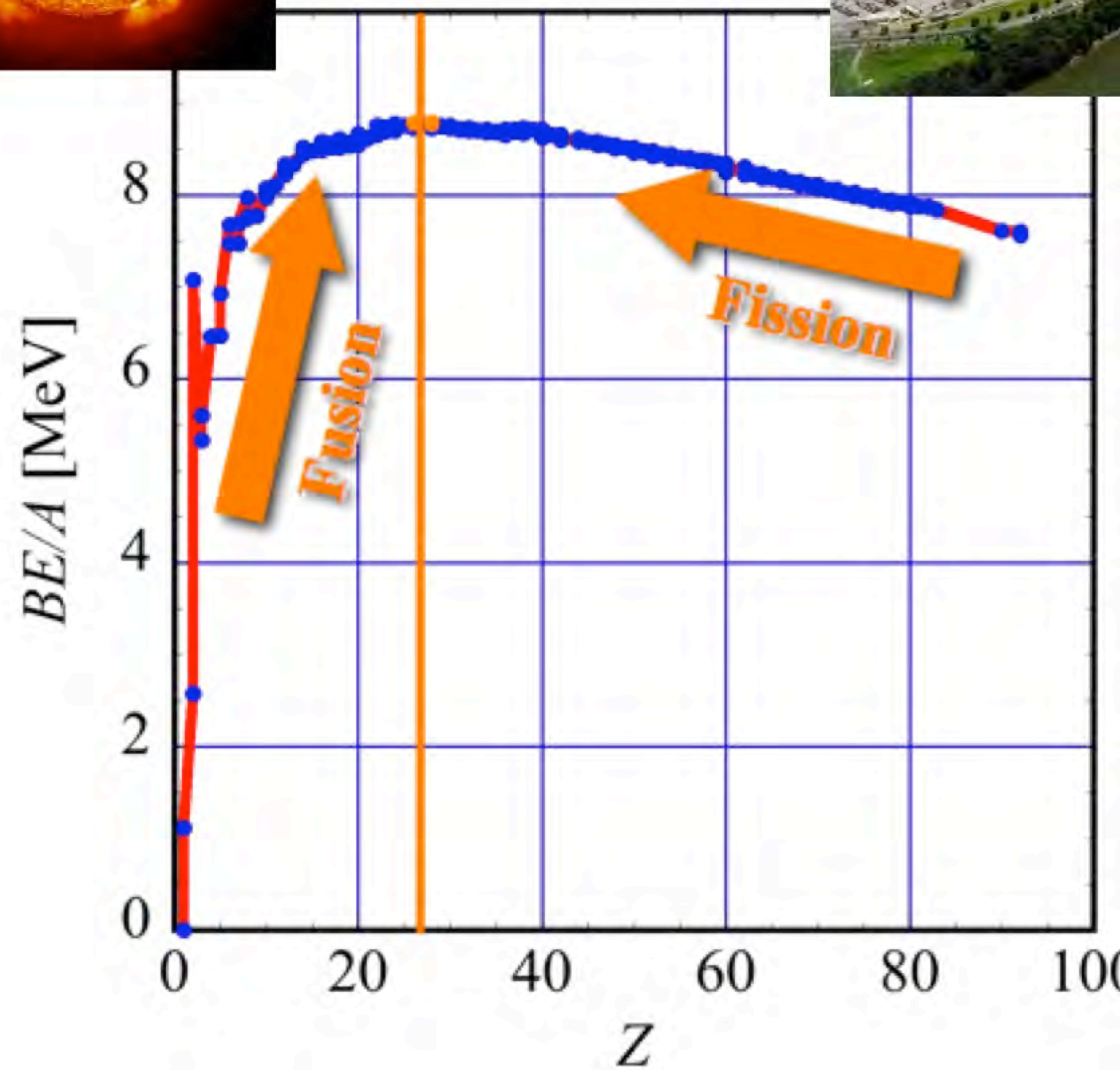
Reactor
65 MWth subcr.
100 MWth crit.

http://myrrha.sckcen.be/

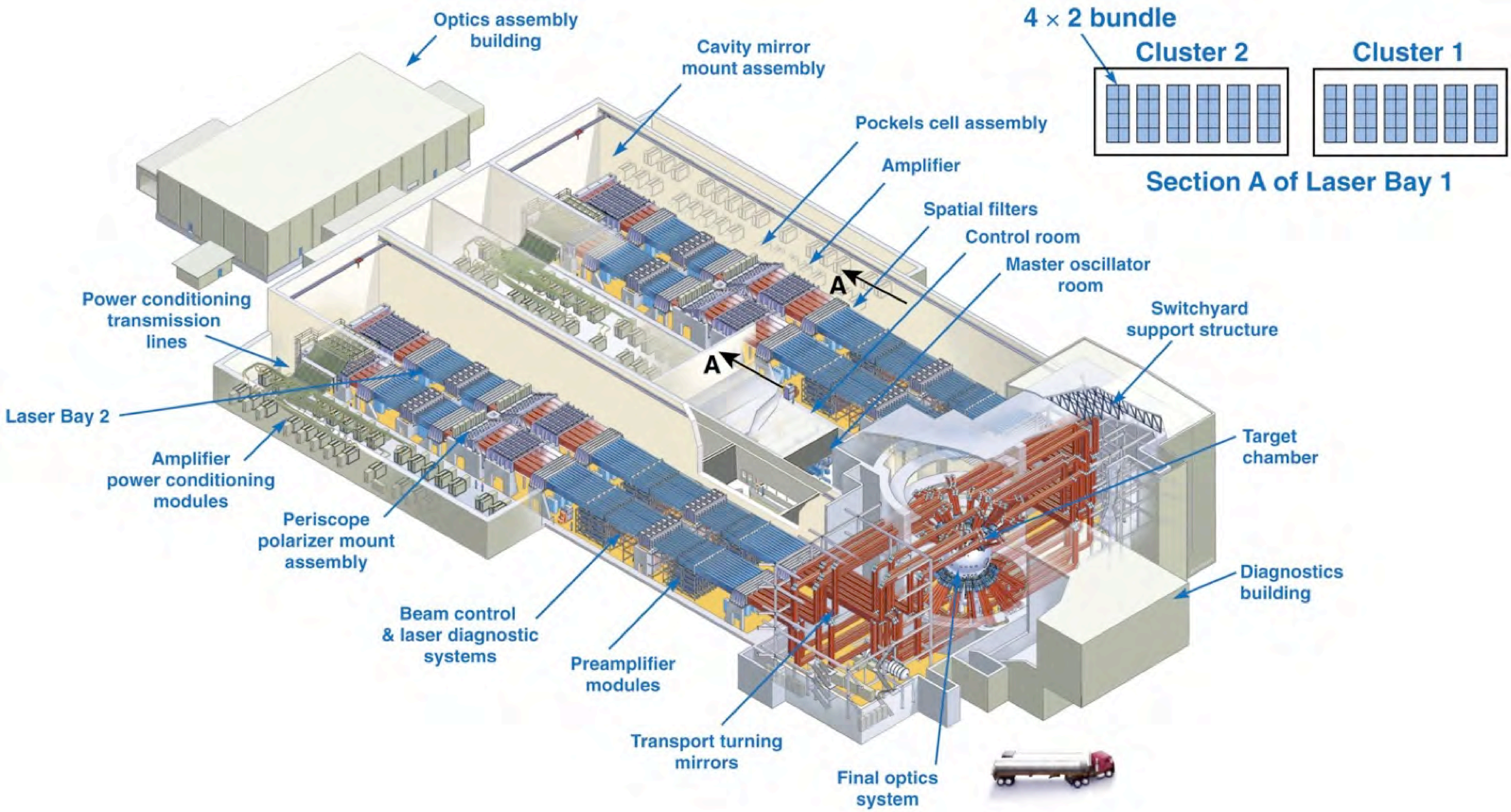
Nuclear Power

- Back to $E = mc^2$
- Nucleus made of Z protons and N neutrons
- $M_{\text{nucleus}} < Zm_{\text{p}} + Nm_{\text{n}}$
- Binding energy!





NIF


Optics assembly building
Cavity mirror mount assembly
4 × 2 bundle
Cluster 2
Cluster 1
Section A of Laser Bay 1
Pockels cell assembly
Amplifier
Spatial filters
Control room
Master oscillator room
Switchyard support structure
A
A
Power conditioning transmission lines
Laser Bay 2
Amplifier power conditioning modules
Periscope polarizer mount assembly
Target chamber
Diagnostics building
Beam control & laser diagnostic systems
Preamplifier modules
Transport turning mirrors
Final optics system

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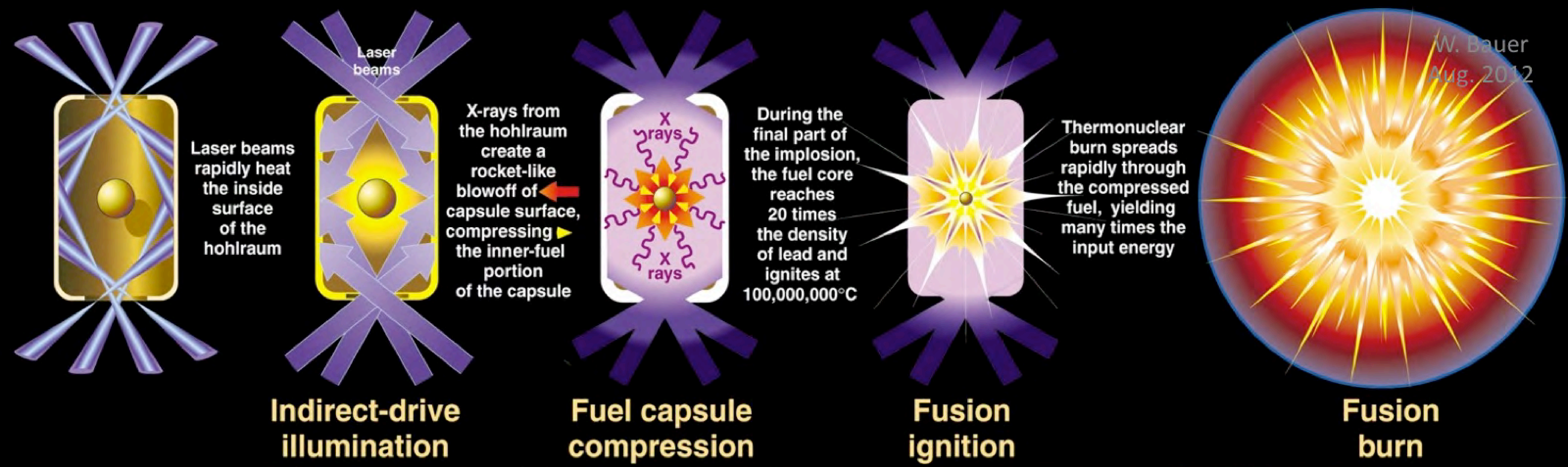

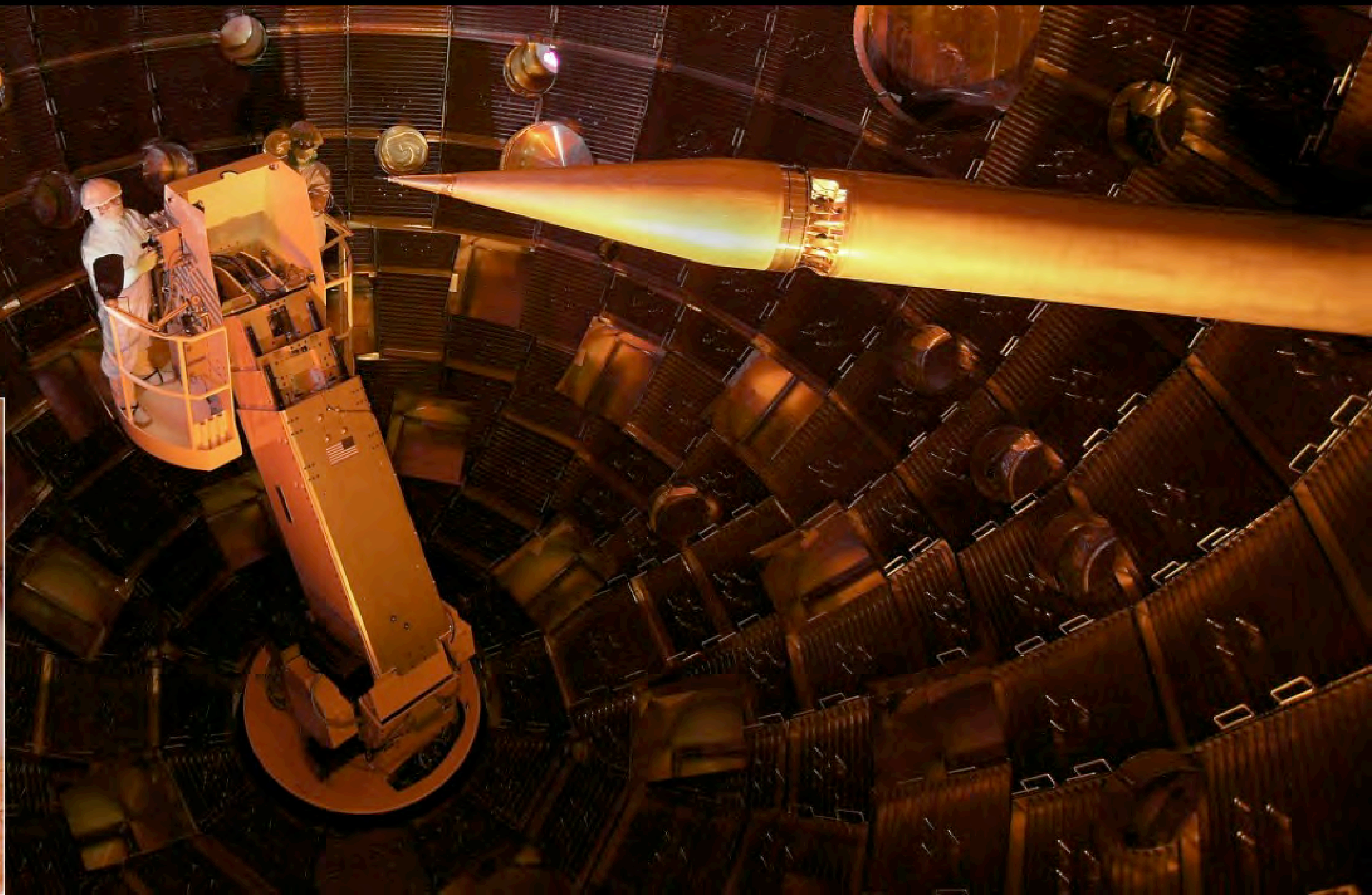

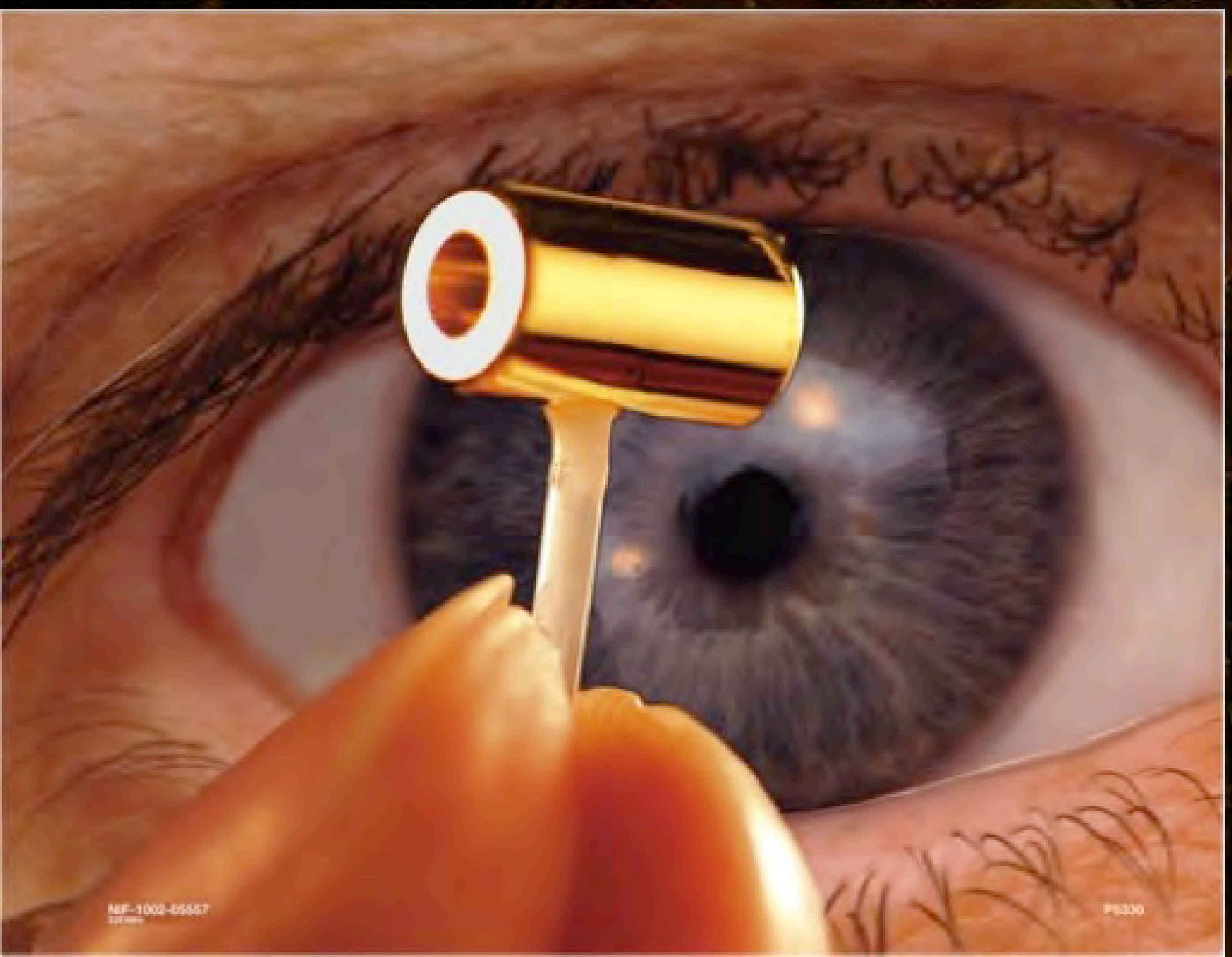

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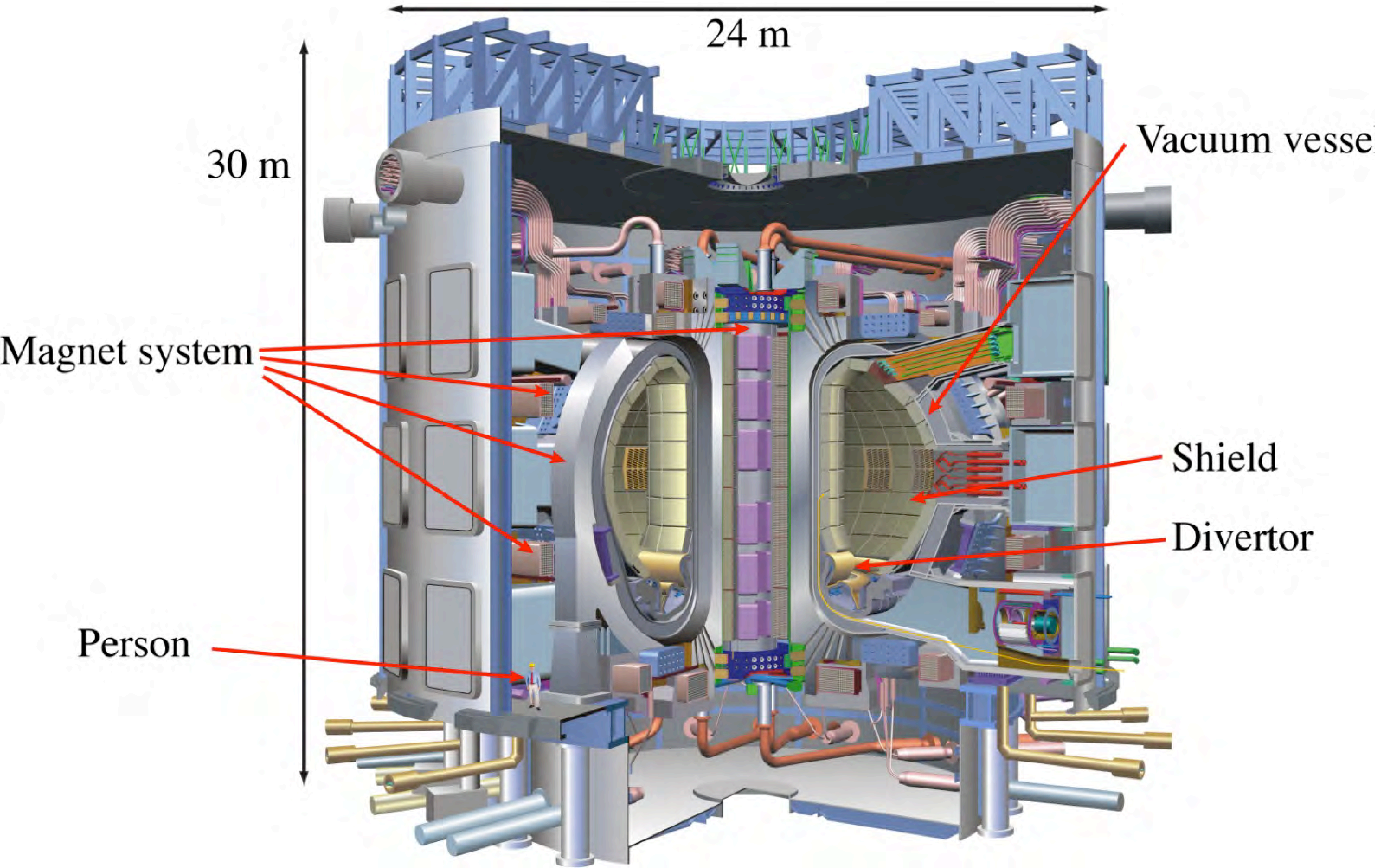
ITER



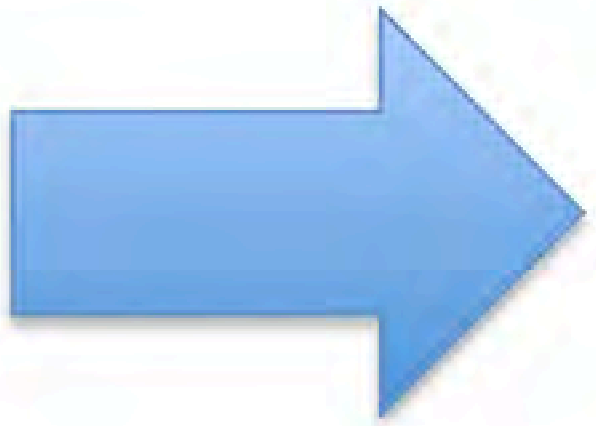
Summary:

Paradigm Shift

- Scientist are in the business of solving interesting puzzles, not overthrowing paradigms
- Current paradigms dictate which puzzles are considered interesting
- Paradigms are shifted by new research results … *in scale-invariant steps, anywhere from evolution to revolution*
- Is it time for a new energy paradigm?

Previous Paradigm Shifts

- "Outhouse to indoor plumbing" transition



  - Last 2 centuries … (even going on now in some parts of World)
  - Giant grid of millions of miles of pipes, connection every building to water treatment plants
- Was it worth the effort and expense?

Life Expectancy

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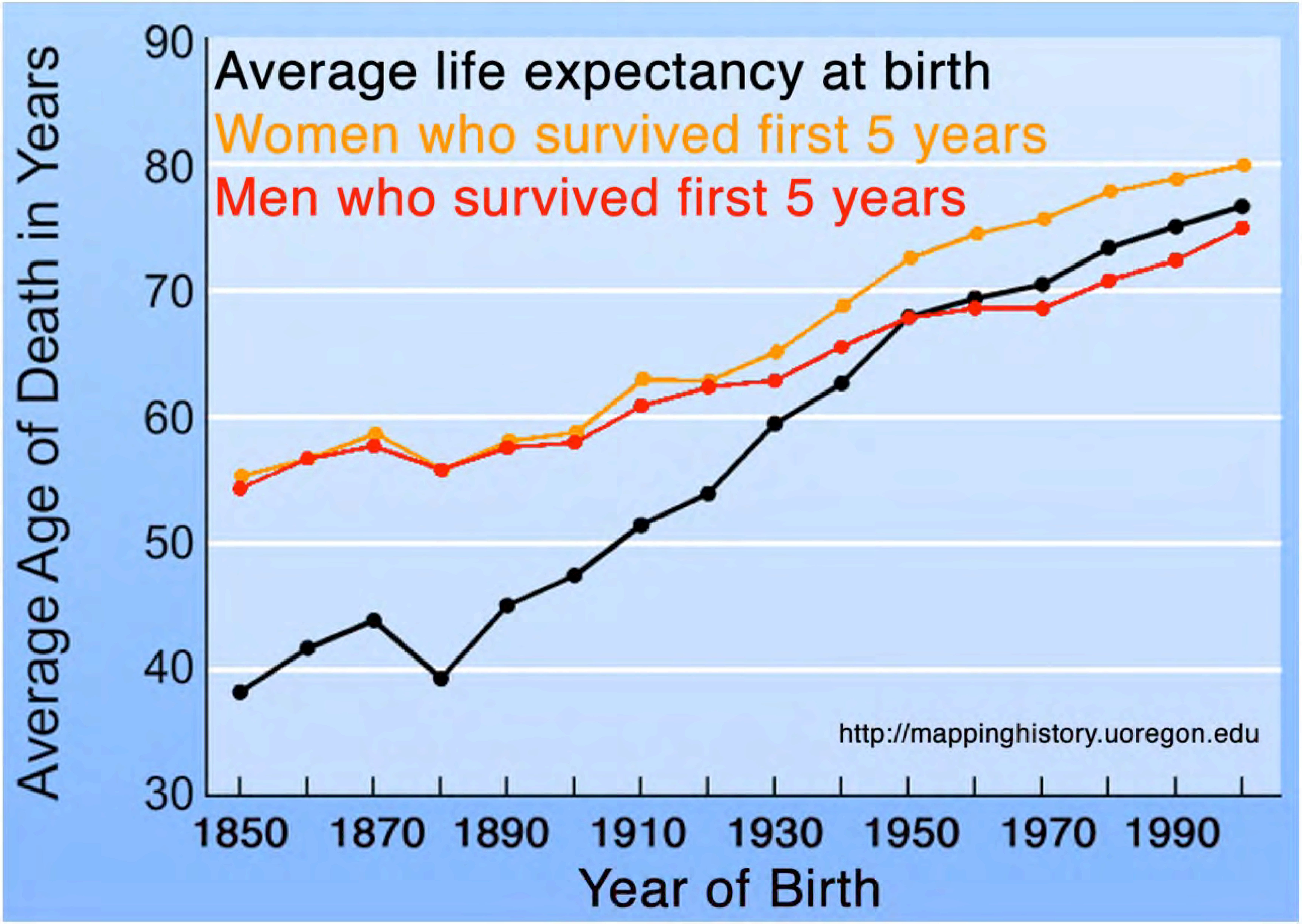
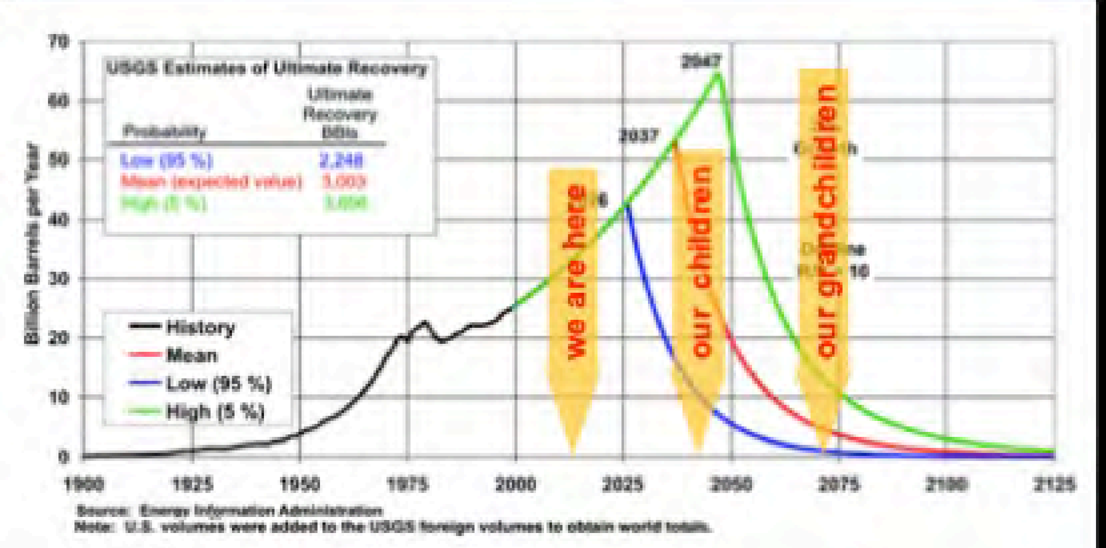
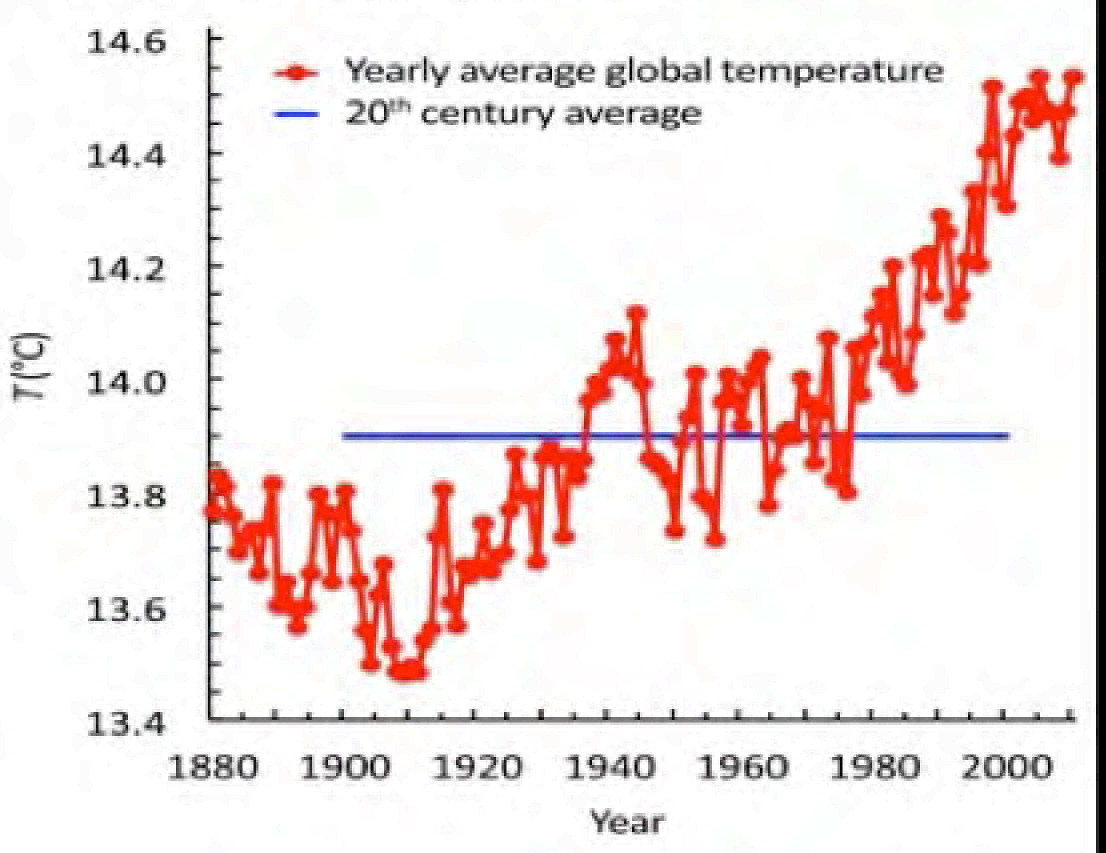


Summary

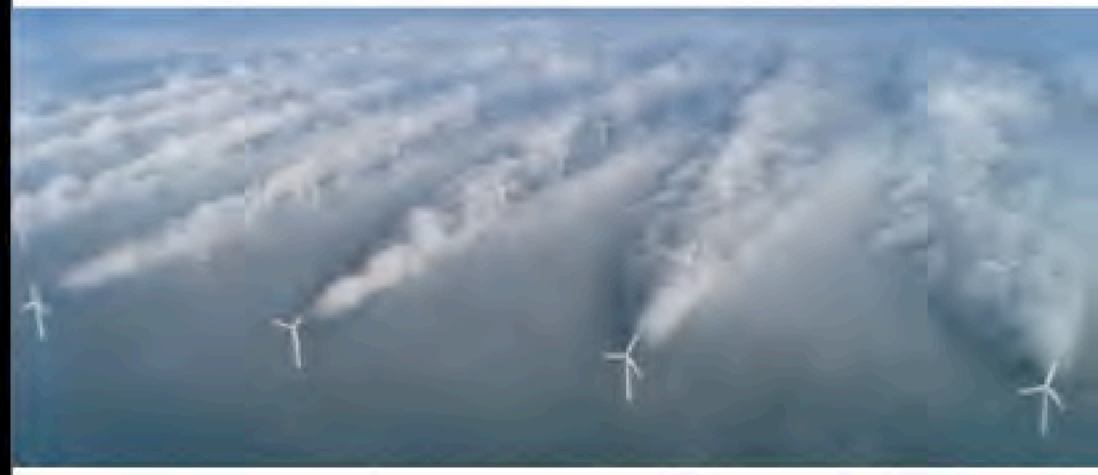


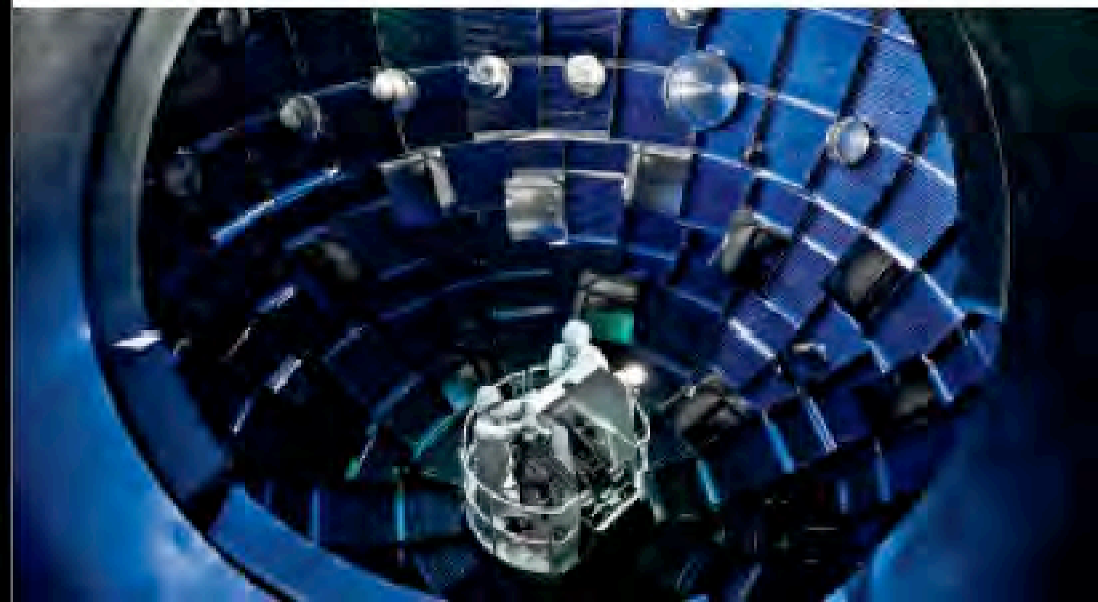


Biggest Opportunity of our Time:

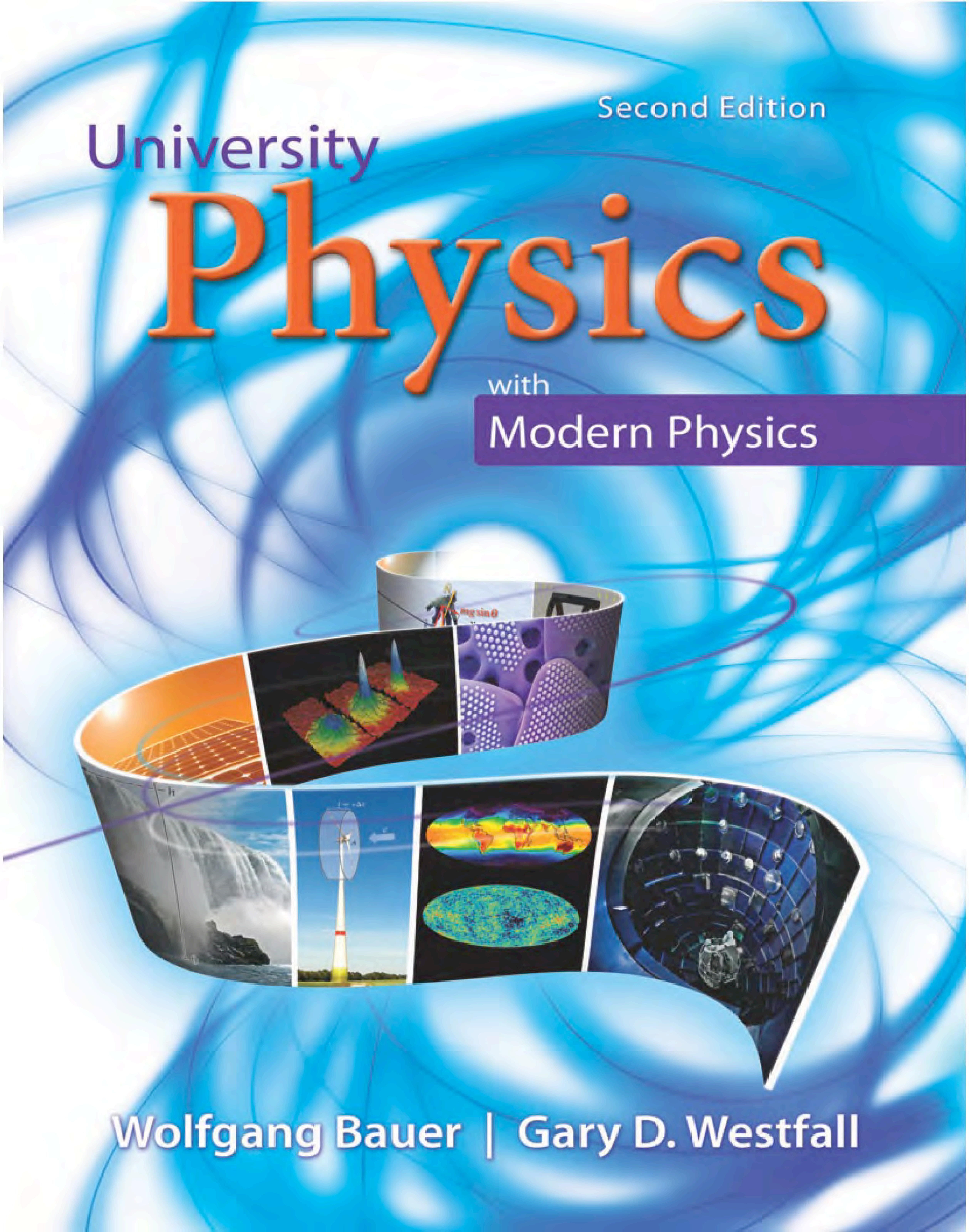
- Replace ~ 14 TW of fossil fuel-based power
- Installation cost ~ $5/W
- ~**$70 trillion** economic growth opportunity!

... and it helps the planet!





in case you ask ..



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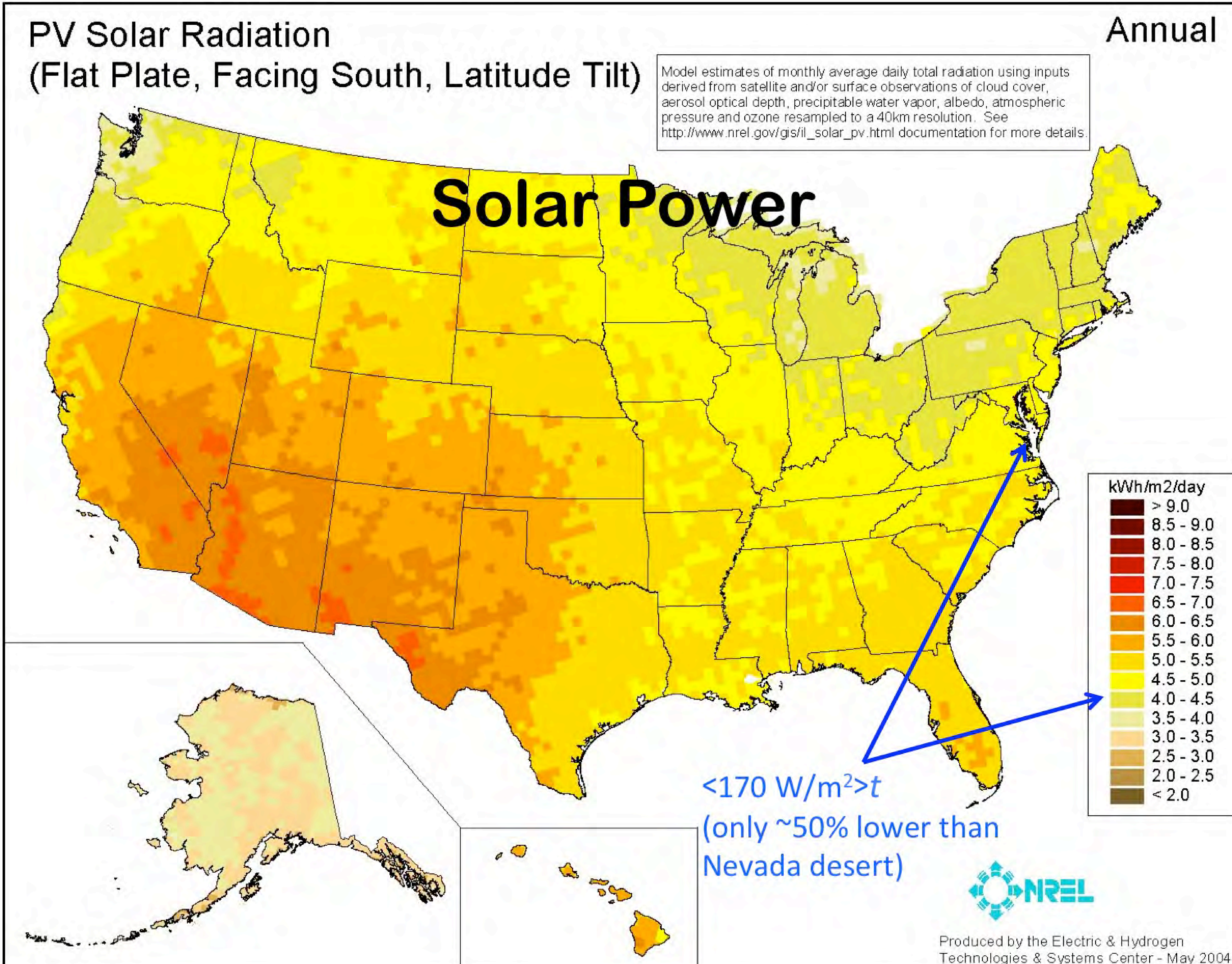
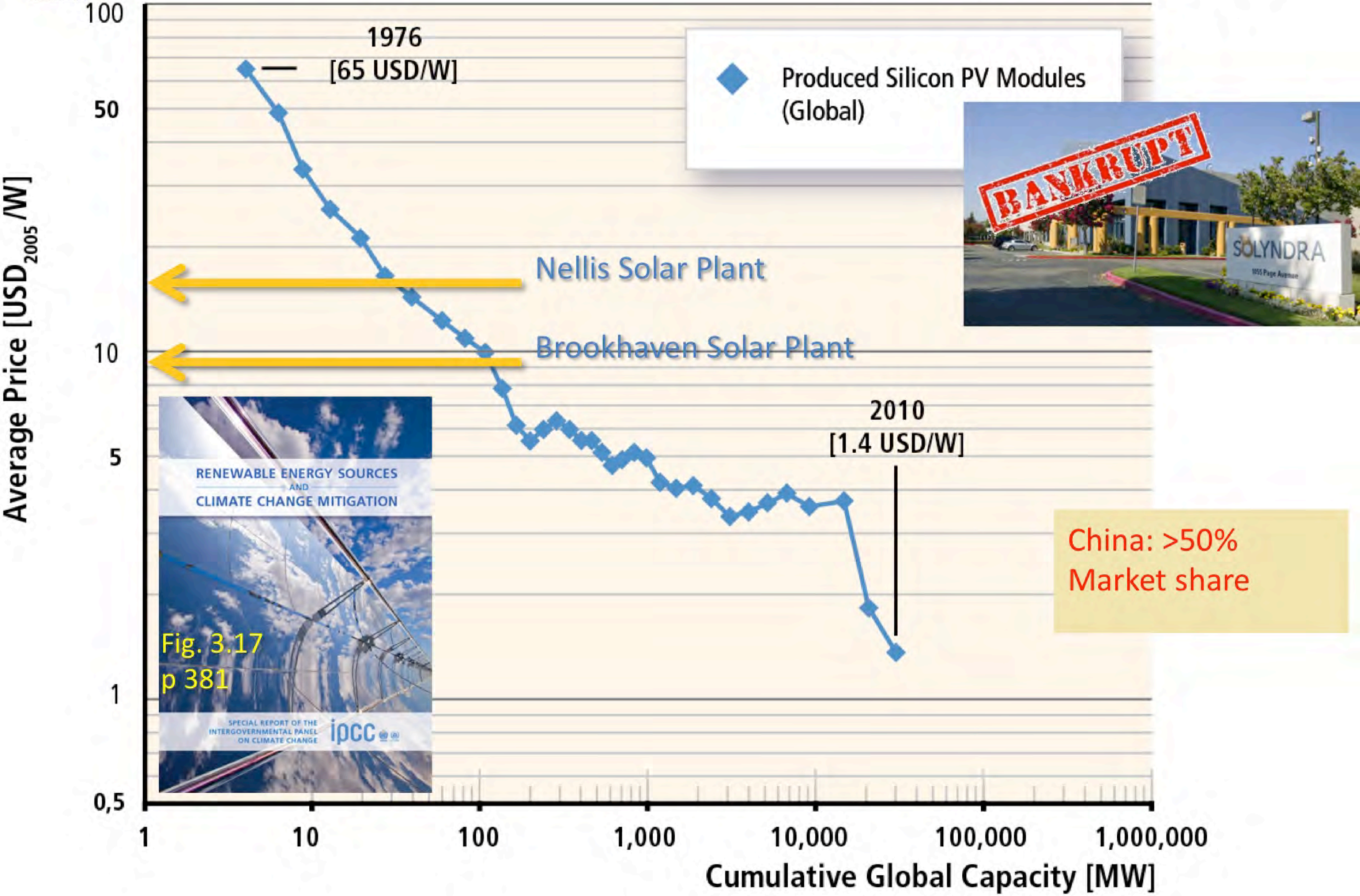
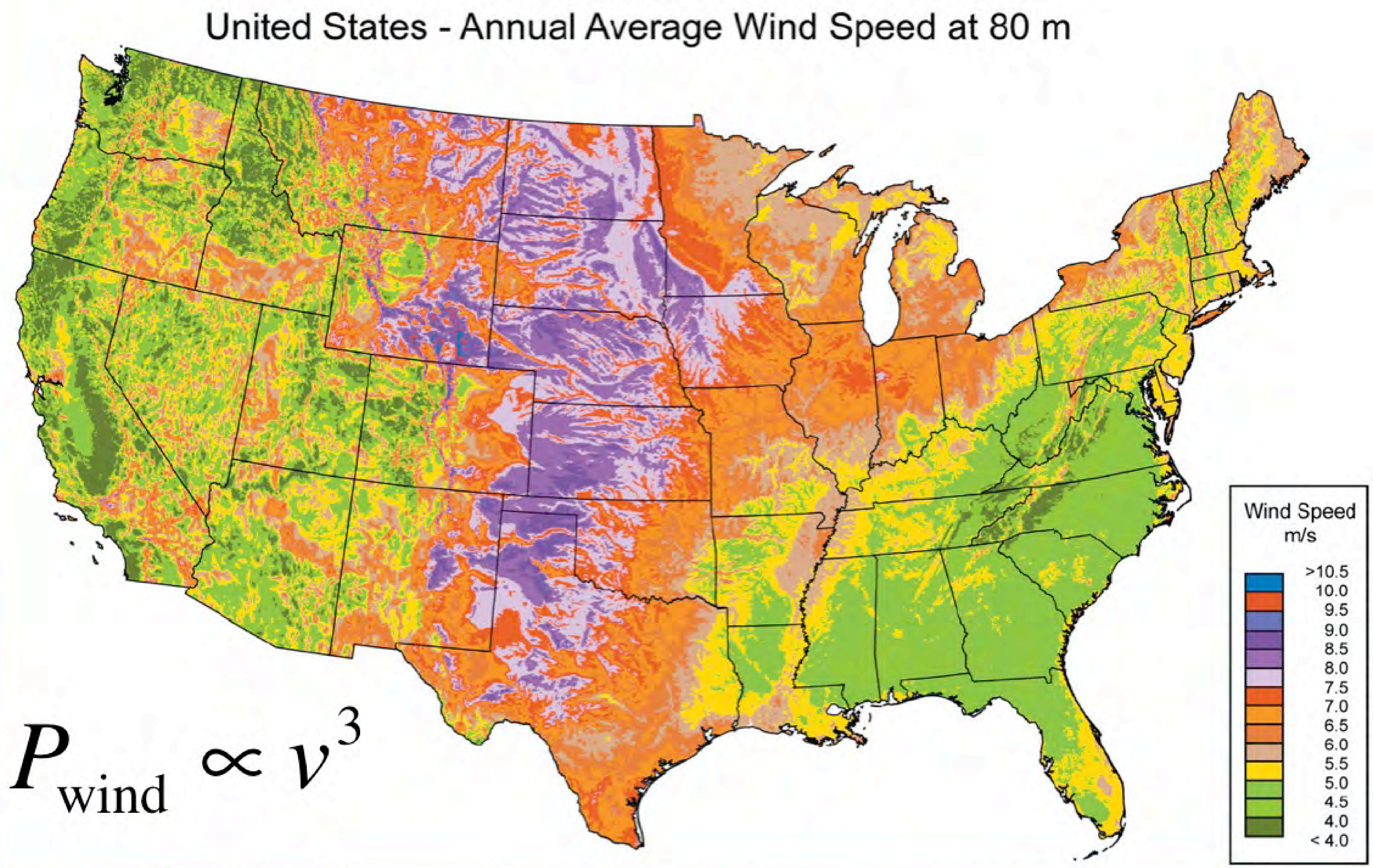

PV Solar Radiation
(Flat Plate, Facing South, Latitude Tilt)
Annual
Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/il_solar_pv.html documentation for more details.
Solar Power
kWh/m2/day
> 9.0
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2.0
<170 W/m^2>t
(only ~50% lower than Nevada desert)
NREL
Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004

... and cheap!



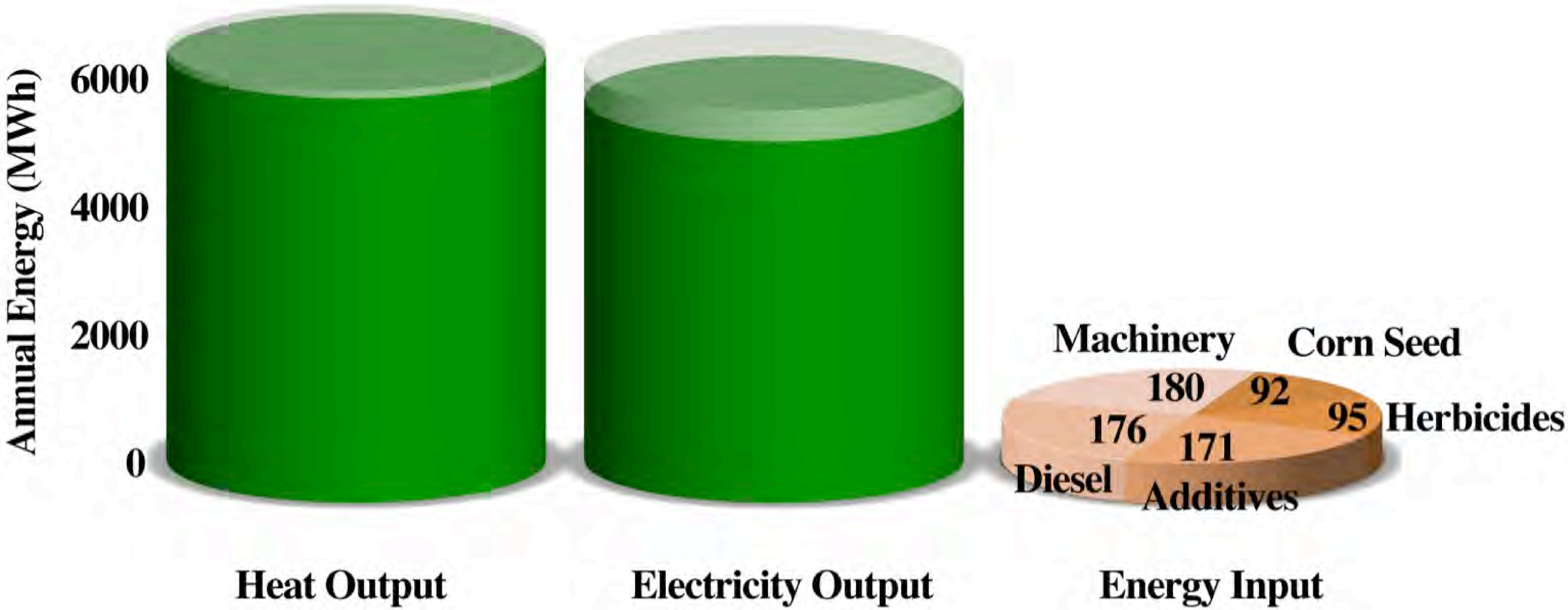
China: >50%
Market share

Wind



$$P_{\text{wind}} \propto v^3$$

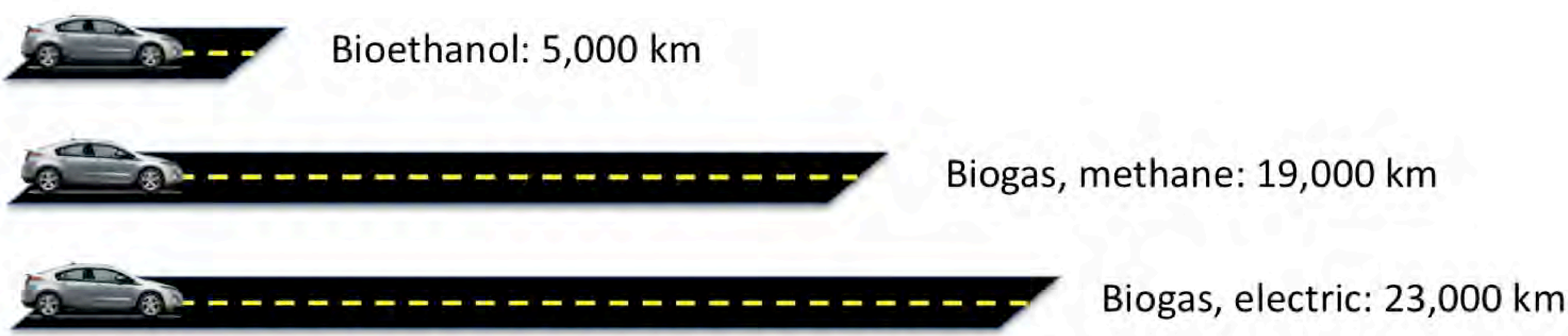
Energy Balance



Factor **8** more electricity output than total energy input!
(comparison bioethanol: energy-out/energy-in [0.75,2.2])

Transportation Fuel

- Could produce 0.68 M liter of ethanol / year
  - Industry standard output from our corn yield on 150 ha
- Are producing 2.6 M liter of (liquid) CH_4 / year
- Factor of **3.8** better yield!
  (heat of combustion per liter almost identical for ethanol and methane, ~ 2/3 of gasoline)



Driving distance per hectare (numbers for Chevy Volt)

US Economic Impact

2015 projected bioethanol yield: 50 billion liters

Proposal: Convert to biogas reactors

Make 190 billion liters methane

More than **$100 billion/year** profit!

MSU Anaerobic Digester

- Approved by MSU Board of Trustees, Jan. 2012
- Research on better bacteria, plants, & processes