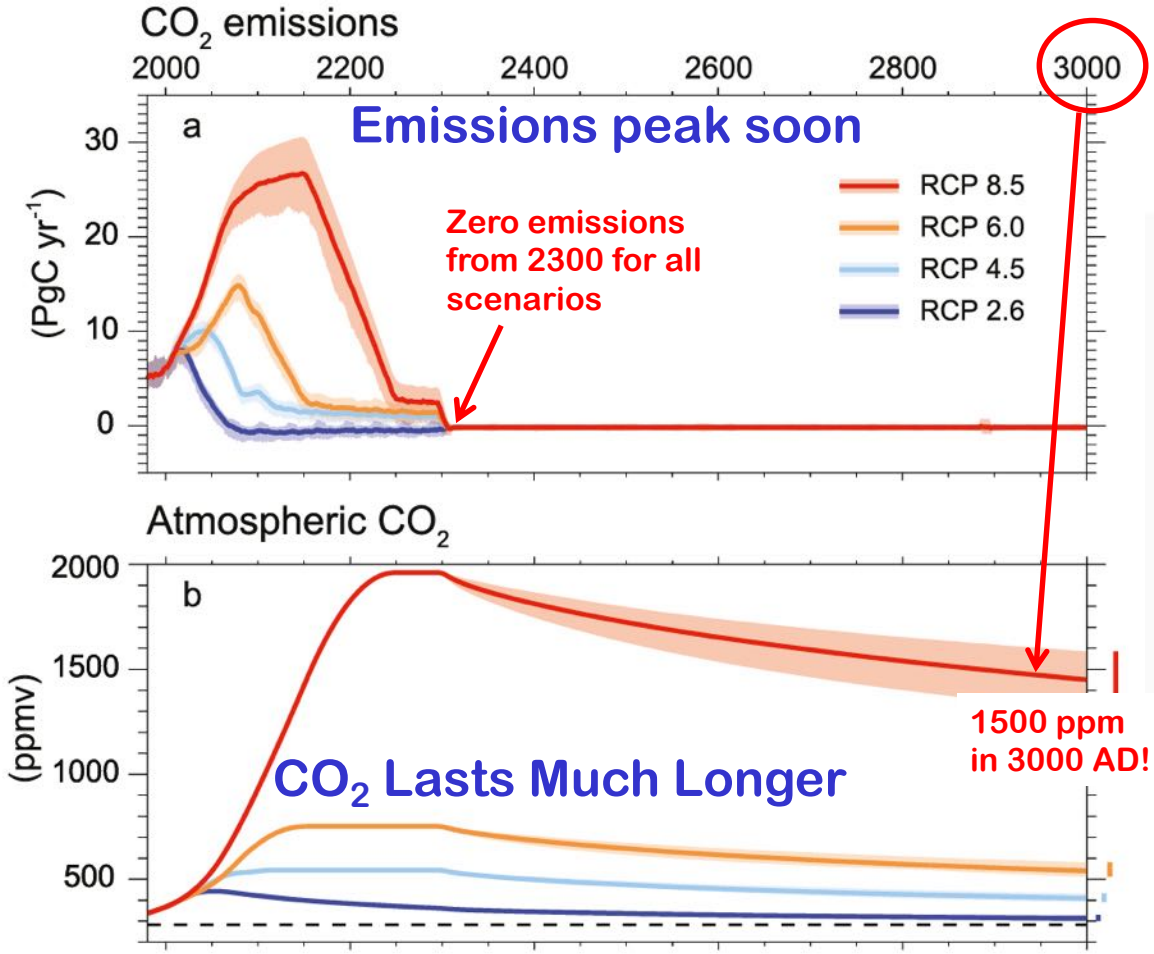
Cleaning Up the Mess

One-Way Warming

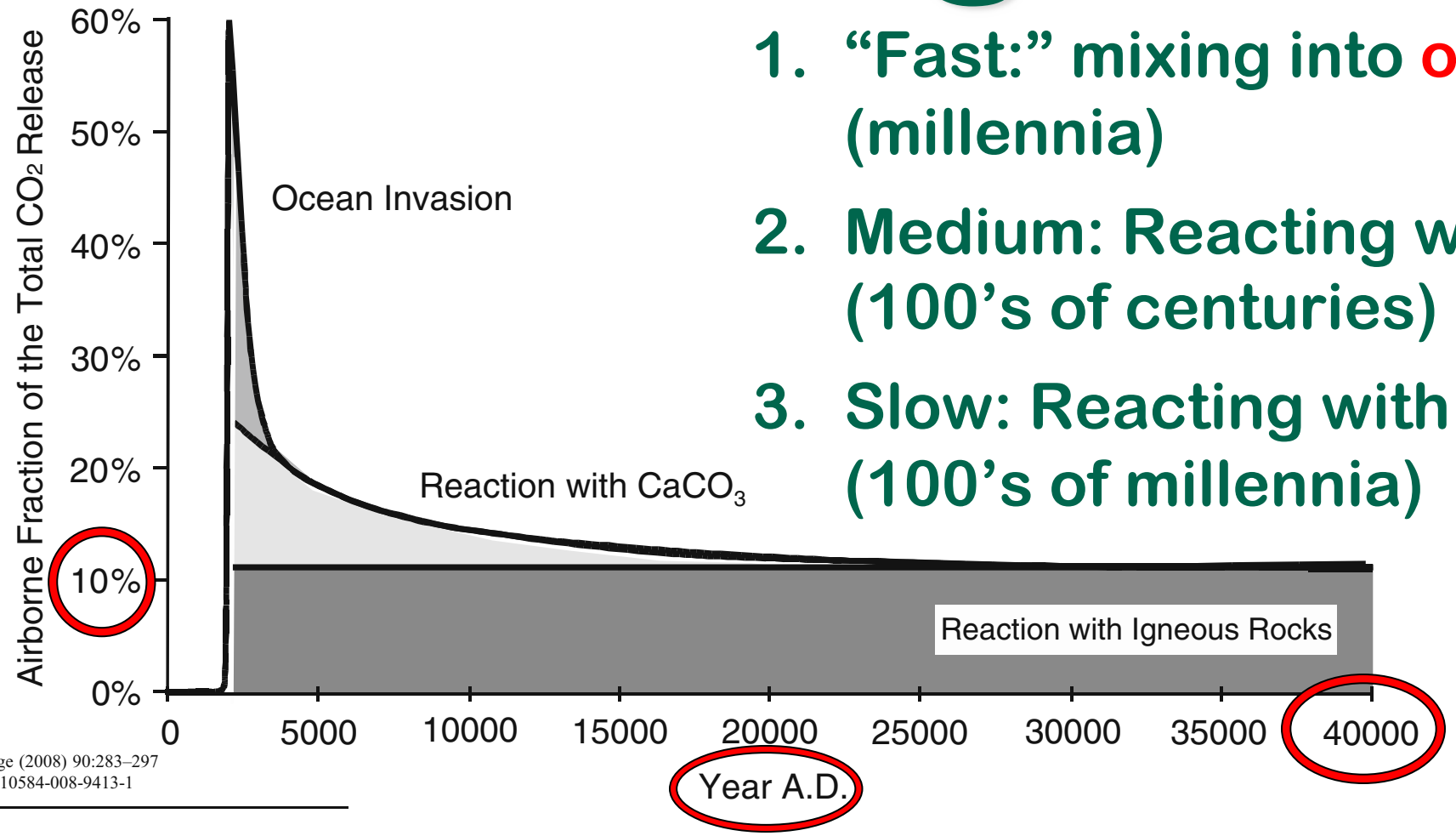
- Heating continues until we stop burning carbon
- After we stop burning coal, oil, & gas the CO_2 will stay in the air
- Climate will remain hot for thousands of years



Thermostat only turns one way!

The Long Tail

1. "Fast:" mixing into oceans (millennia)
2. Medium: Reacting w/seashells (100's of centuries)
3. Slow: Reacting with rocks (100's of millennia)



up to 40%

Climatic Change (2008) 90:283–297
DOI 10.1007/s10584-008-9413-1

The millennial atmospheric lifetime of anthropogenic CO_2

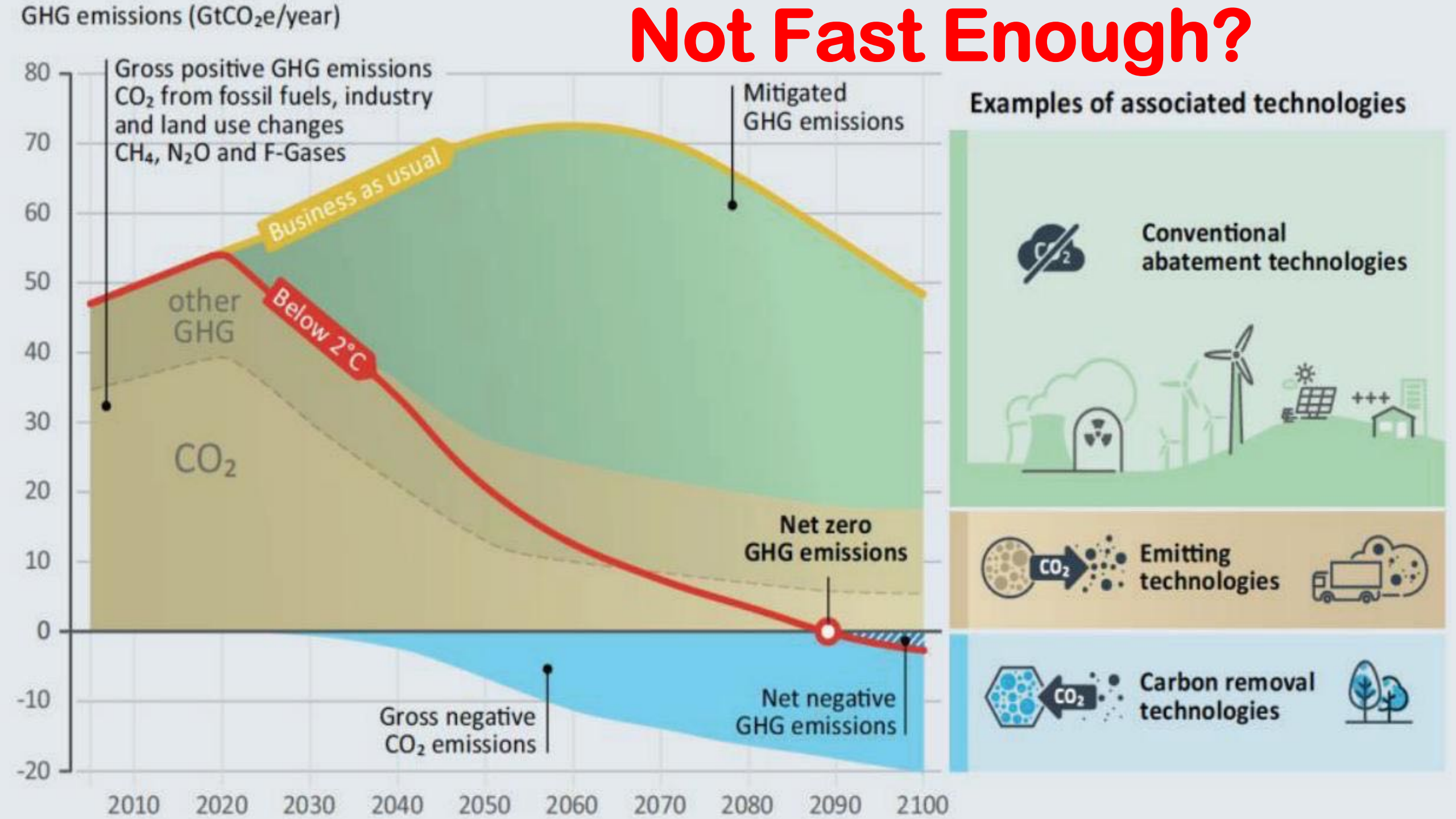
David Archer · Victor Brovkin

Some of the CO_2 we emit today will still be warming the climate 100,000 years from now!

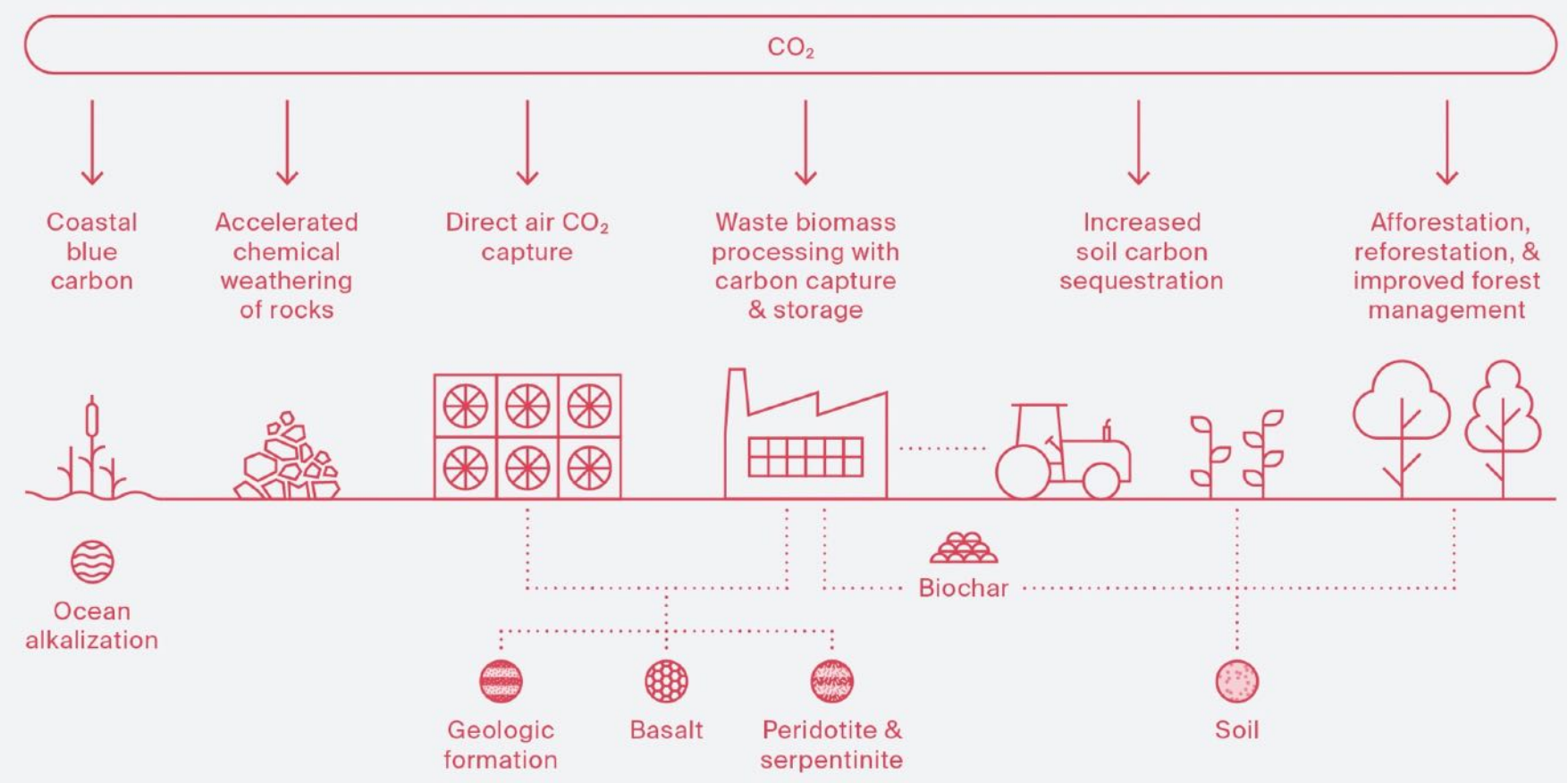
Stop setting stuff on fire

Not just you and me – everybody, everywhere, forever

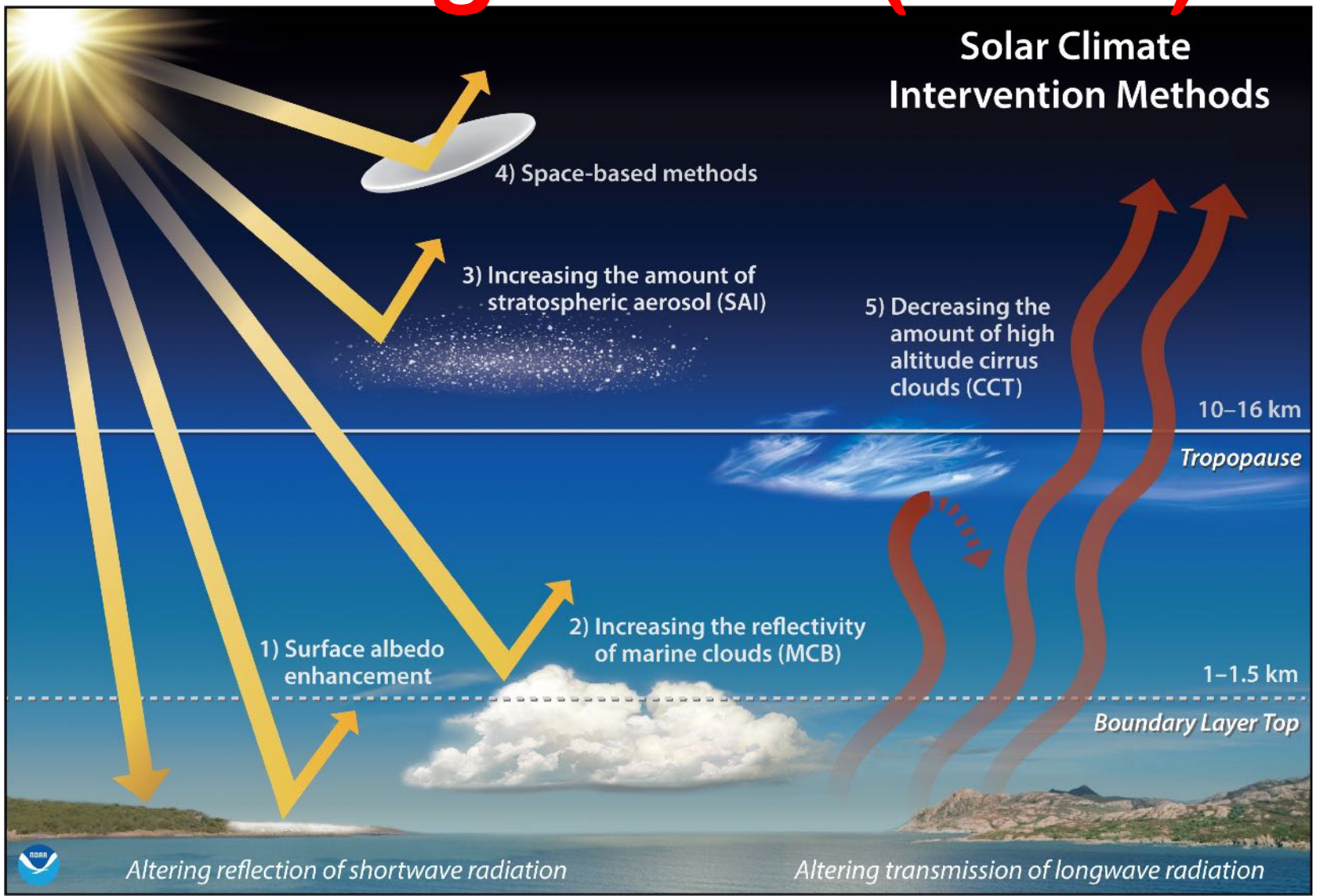
Not Fast Enough?



Carbon Dioxide Removal (CDR)



Solar Radiation Management (SRM)

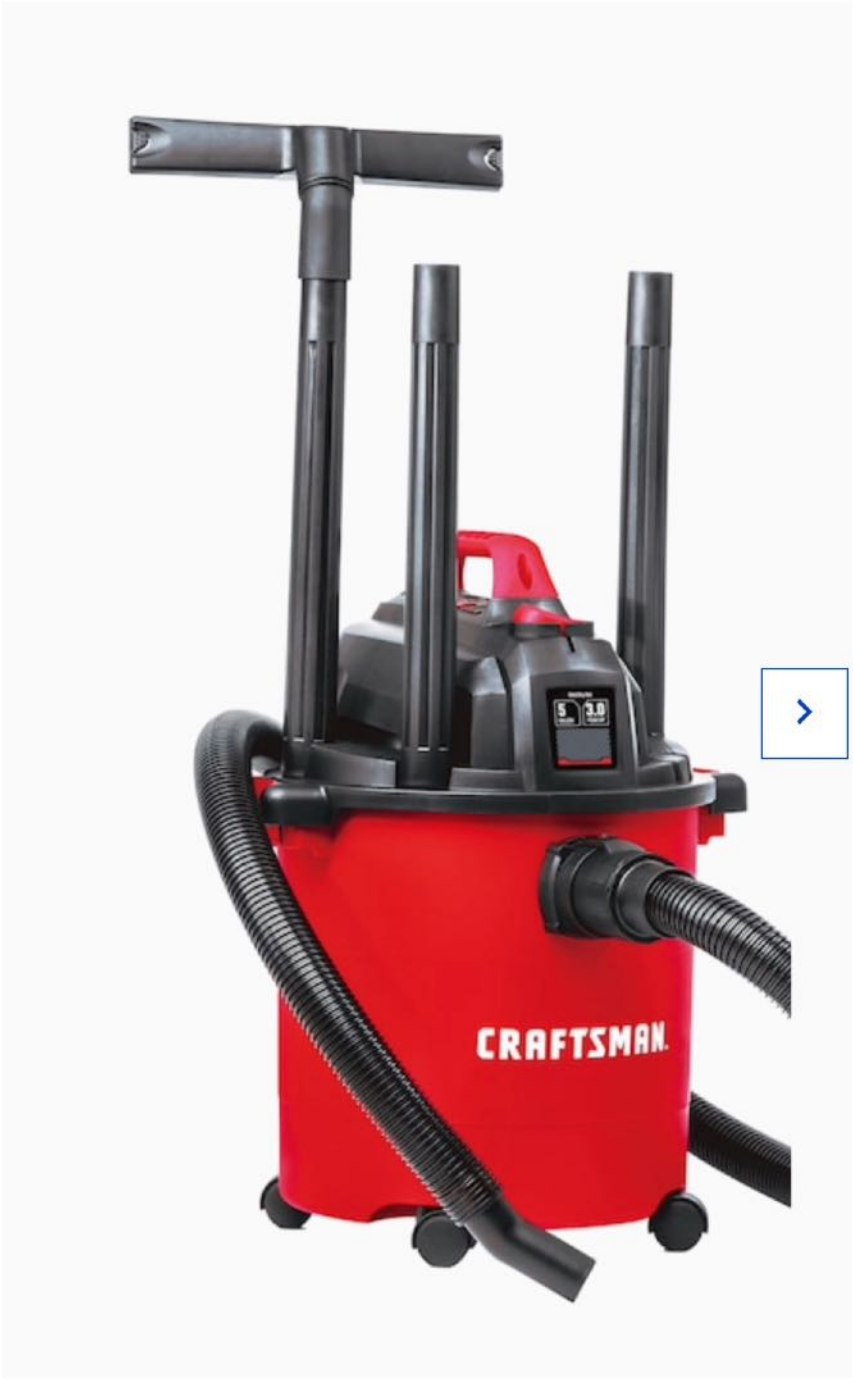


Uh oh!
What should we do?

Unplug the drain!

Mop the floor!

Order a wet-vac!



Deal with the damage!


TURN OFF THE WATER!

Carbon Dioxide Removal

Read the *Carbon Dioxide Removal Primer* from Lawrence Berkeley Laboratory:

https://cdrprimer.org/read/chapter-2

Longstanding *Imbalance*

- To transfer carbon from air to land,

"Plants must grow faster than they die"

- Not true everywhere, but must be true of the Earth as a whole!
- Over many decades, this means there's more and more biomass on Earth
- **THIS IS HARD TO ARRANGE!!**

All Things Must Pass

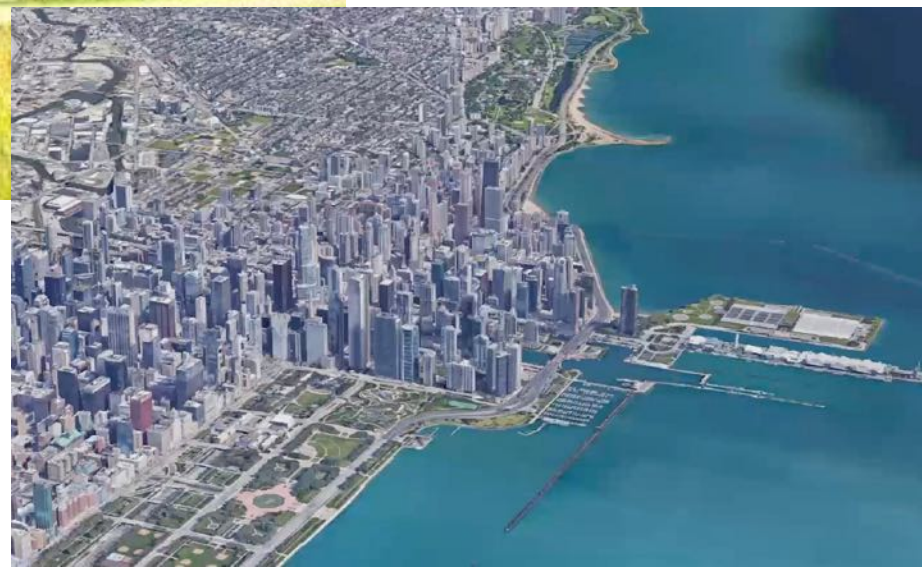
- Plants die.
- Eventually ~ everything is eaten by microbes, which respire 100% of the carbon back to CO_2

Easy: Afforestation

- Replace nonforest land (low carbon content per hectare) with mature forest (high carbon content per acre)

Cost = Land

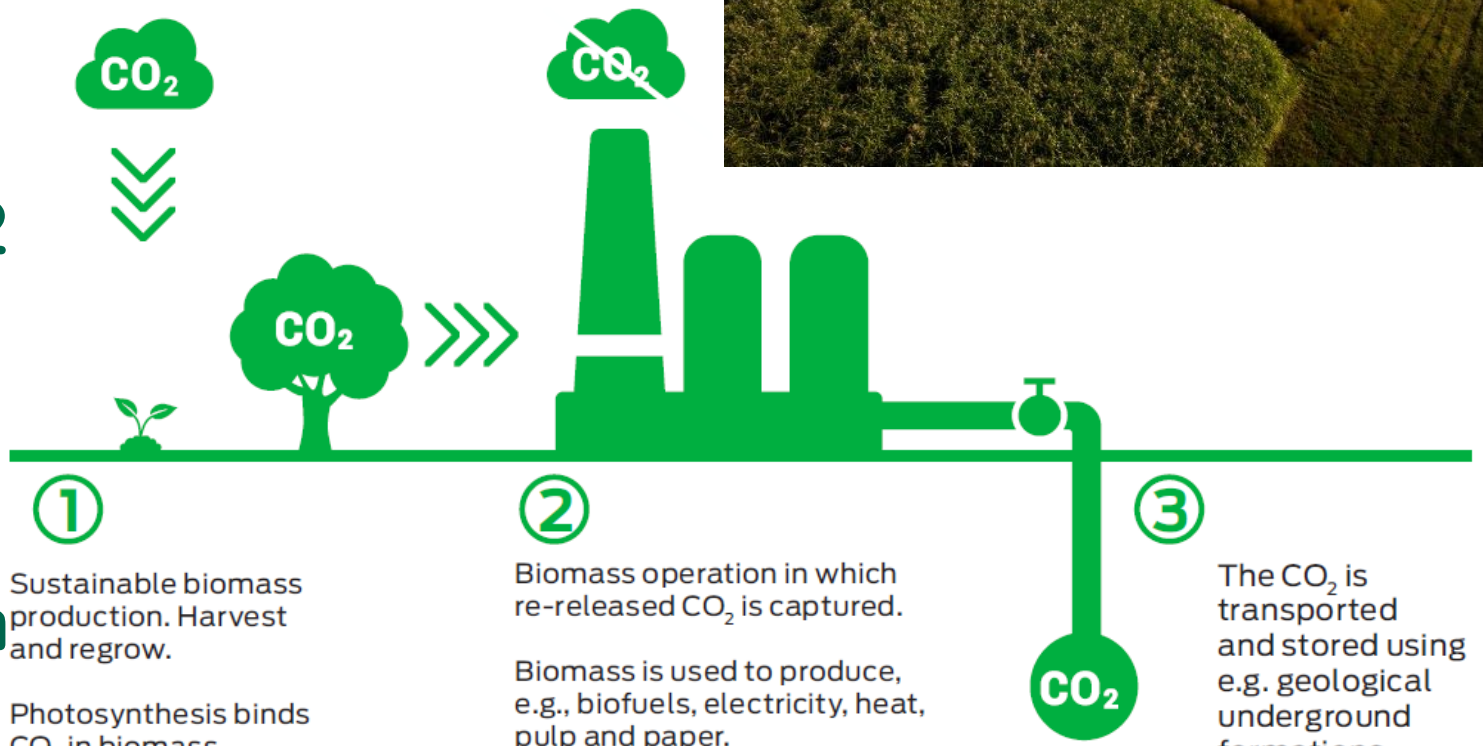
- Challenge 1: most land that can support forest is already forested
- Challenge 2: Nearly all land that could support forests but isn't currently forest is valuable agricultural and urban land



Harder: BECCS

- Biomass Energy with Carbon Capture & Sequestration
- Replace fossil fuel with bioenergy crops like switchgrass (for ethanol) and soy (for biodiesel)
- Capture concentrated CO2 from powerplant effluent
- Store liquified CO2 forever
- **Challenge**: divert land from food production to carbon sequestration

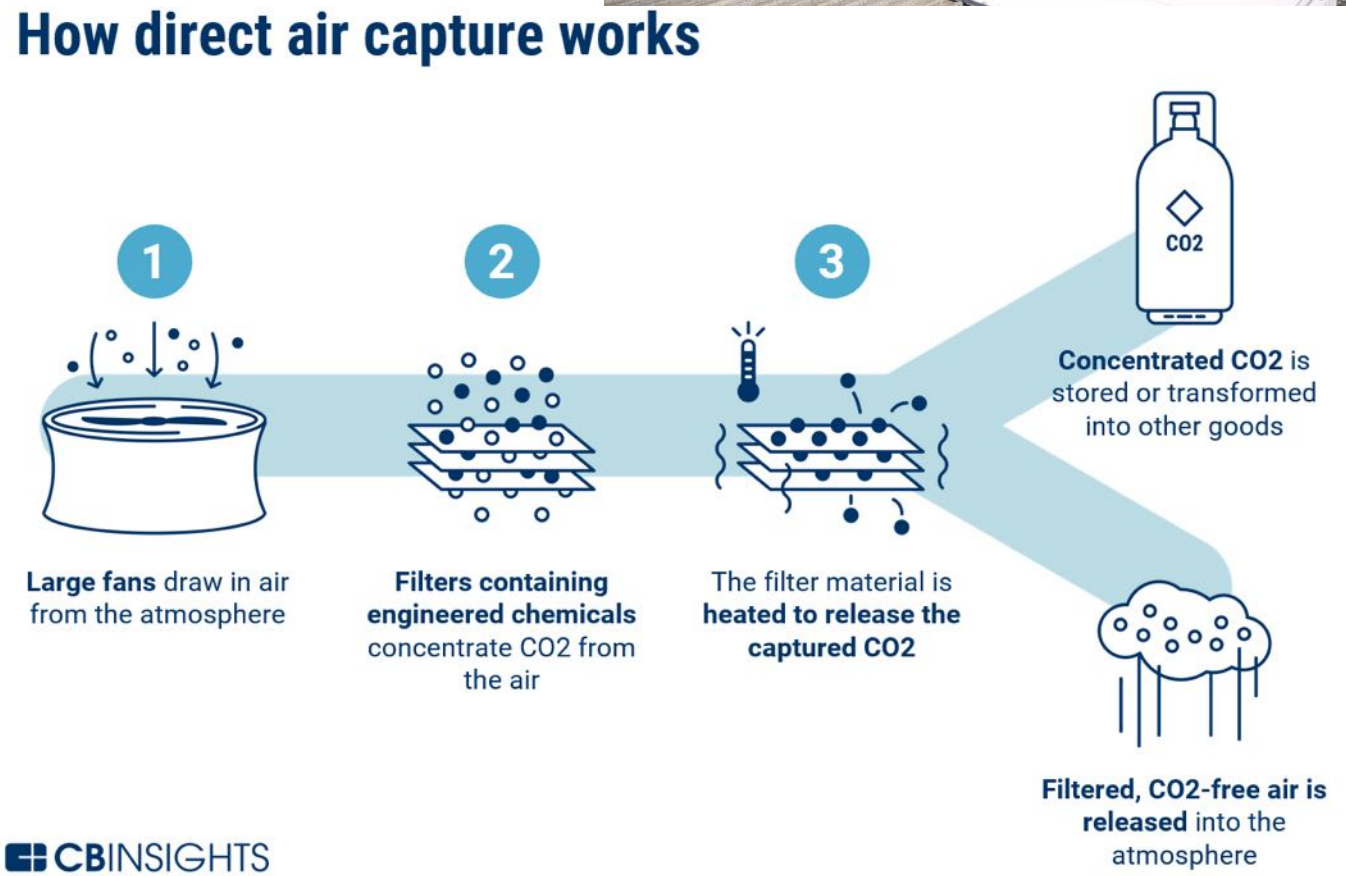
$50-200/ton of CO2



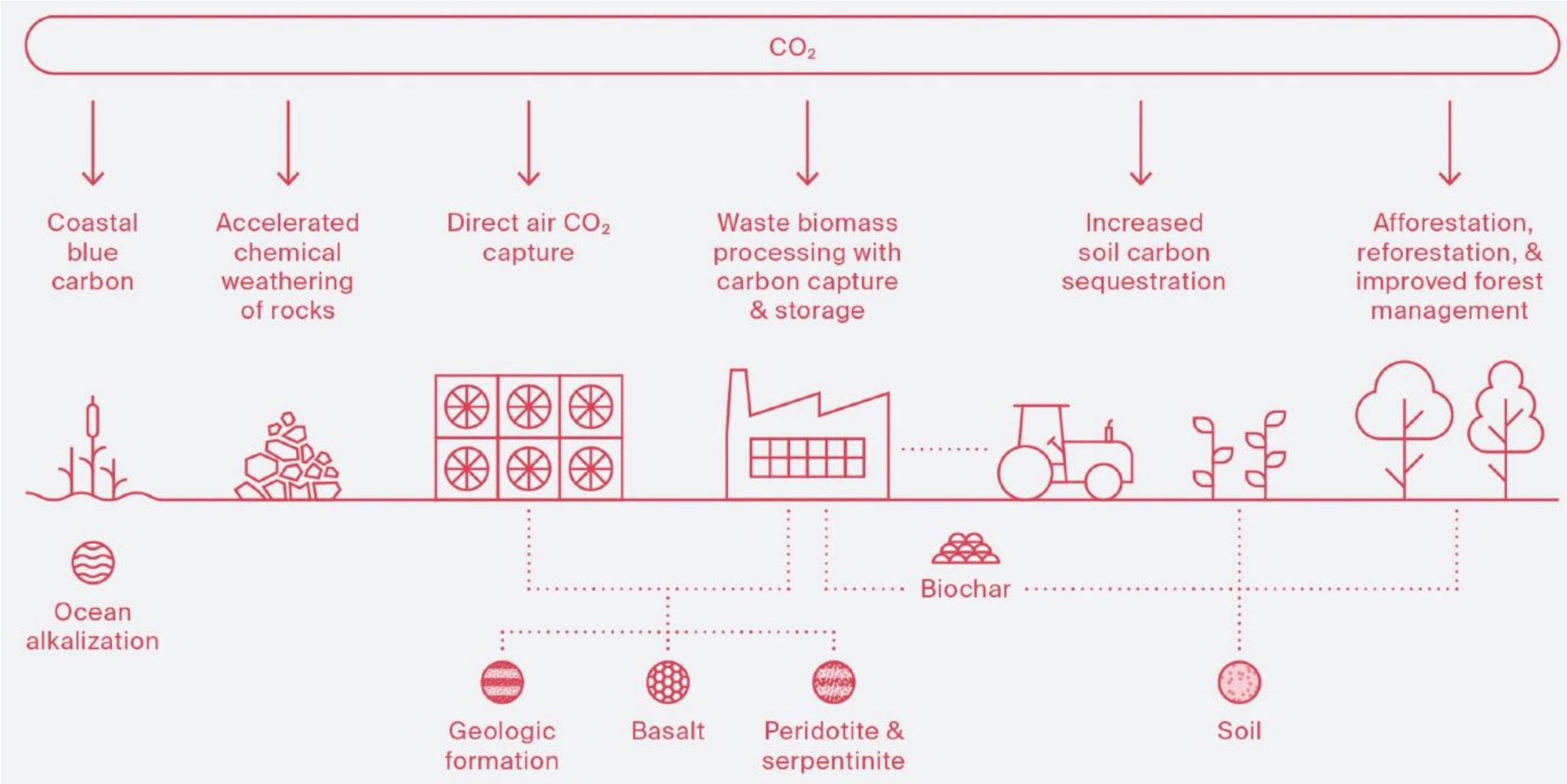
Hardest: DAC-CS

$600/ton of CO2

- Blow ambient air over solvent/sorbtant medium
- Strong base dissolves CO2
- Heat capture medium to extract concentrated CO2
- Store liquified CO2 forever
- CHALLENGE: takes a LOT of energy to gather dilute CO2 from thin air!

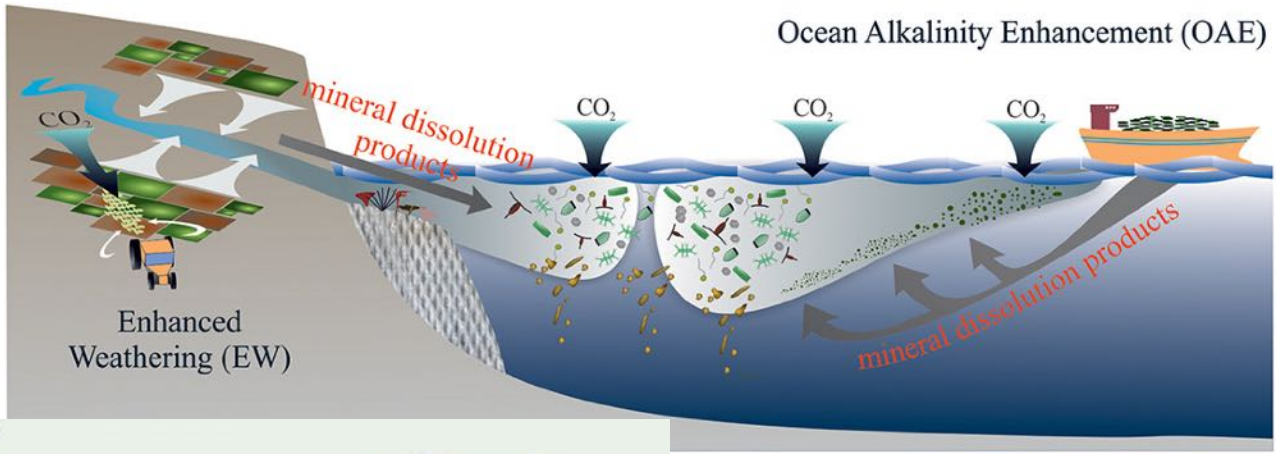


Negative CO_2 Emissions

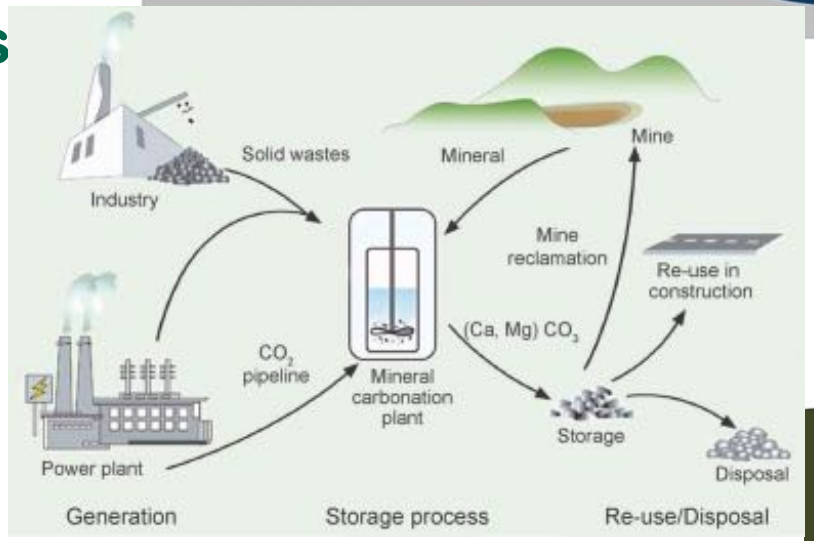


Negative Emissions

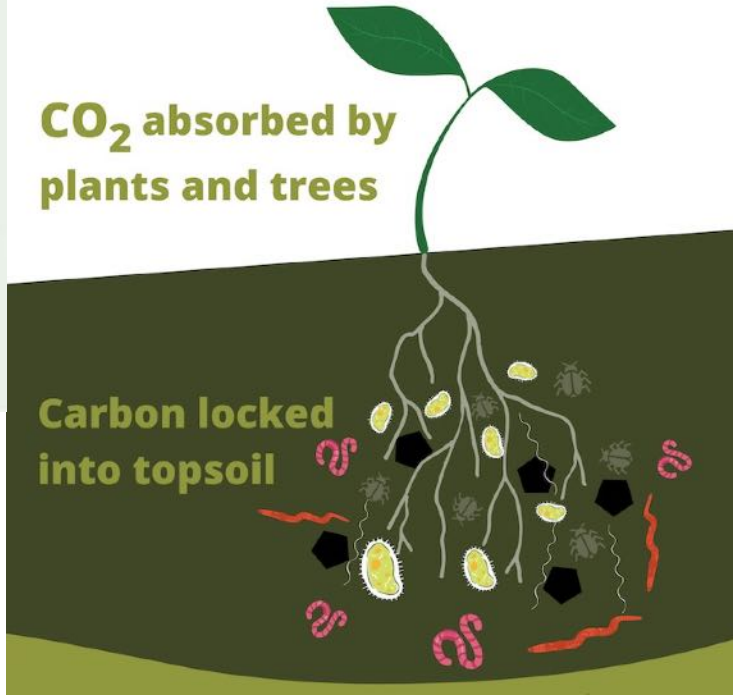
- **Ocean Alkalinity Enhancement**: increasing the charge balance of ions in the ocean to enhance its natural ability to remove CO2 from the air.



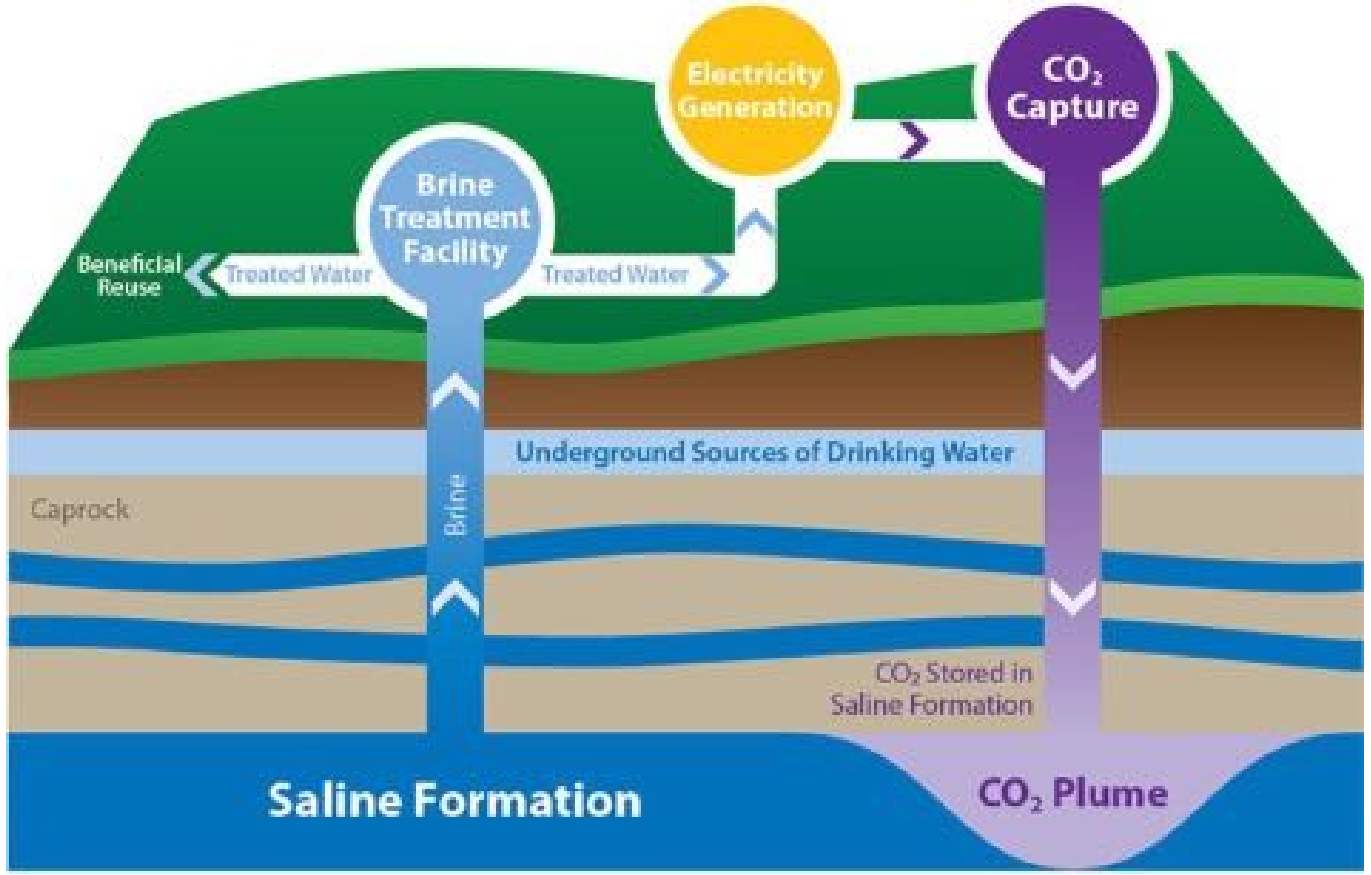
- **CO2 Mineralization**: processes by which certain minerals react and form a bond with CO2, removing it from the atmosphere and resulting in inert carbonate rock.



- **Soil Carbon Sequestration**: the use of land or agricultural practices to increase the storage of carbon in soils.

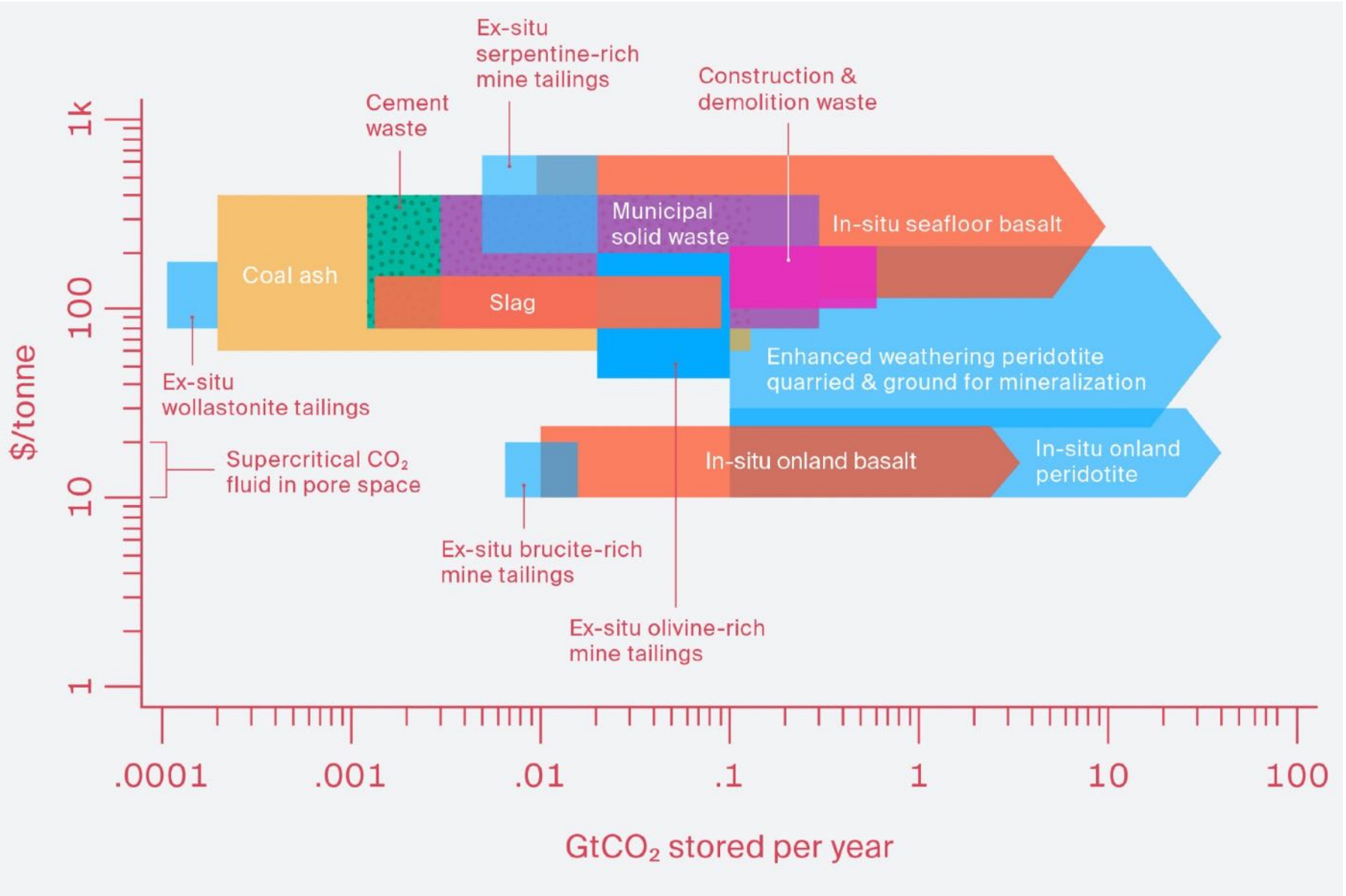


Geological CO2 Storage



- Injection of liquified CO2 into a geologic formation deep underground for essentially permanent timescales.
- Challenge 1: requires a specific rock environment that is not found everywhere
- Challenge 2: gather the CO2 and get it to the storage sites

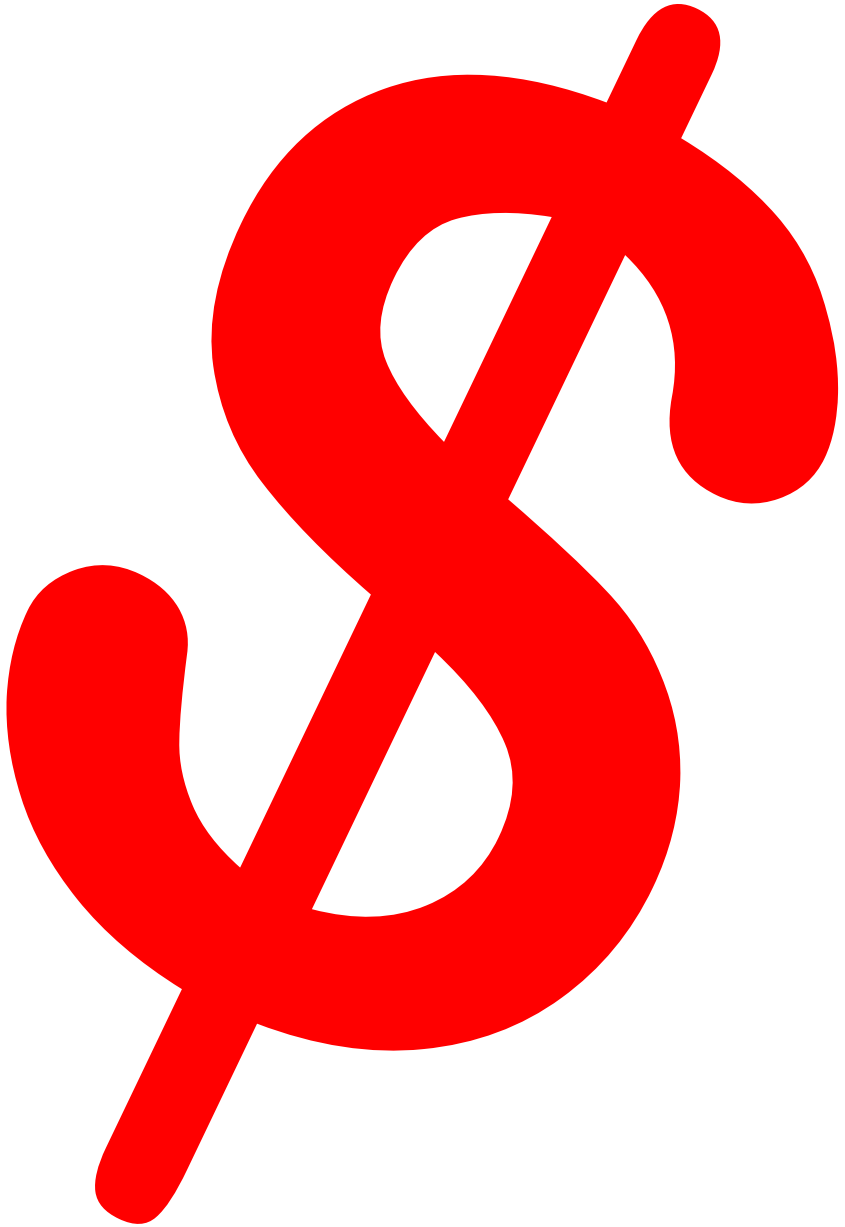
Where can we put it?



Summary of annual storage potential versus cost in US$/$tCO_2$ for proposed solid storage using fluids enriched in CO_2. *NOTE*: Costs should be compared to the cost of storage of supercritical CO_2 in subsurface pore spaces, ~$10-20/$tCO_2$ (NASEM, 2019).

Carbon Arithmetic (h/t Morey Wolfson)

- 1 GtC reacts with O_2 to make 3.7 $GtCO_2$
- This adds 0.47 ppm to CO_2 concentration in air
- So 1 ppm of CO_2 weighs 3.7 Gt / 0.47 (ppm per $GtCO_2$) = 7.9 Gt (let's call it 8 Gt = 8 billion tons)
- CDR costs between \$10/tCO_2 and \$600/tCO_2. Let's be ridiculously optimistic and call it \$100/ton
- So every ppm CO_2 removed will cost \$800 billion
- (US Dept of Defense budget is \$778 billion)



Uh oh …

- Over the past decade, atmospheric CO_2 increased about 2.5 ppm / year
- That means we're currently running up a bill that's 250% the size of the US Defense budget

EASY

Oxidizing condensed carbon in an O_2 atmosphere is *easy-peasy* and *liberates* a huge amount of *energy*

CHEAP
EXOTHERMIC

HARD

Capturing dilute CO_2 gas at ppm levels is hard, and extracting the carbon in an O_2 atmosphere is *really hard* and *consumes* a huge amount of *energy*

EXPENSIVE
ENDOTHERMIC

How Much Energy?

With breakthroughs and economies of scale DAC may reach efficiency of 5 GigaJoule / tonCO2

World annual energy production ~ 6 x 10^{20} Joule

Offsetting today's FF emissions would use 31% of global energy

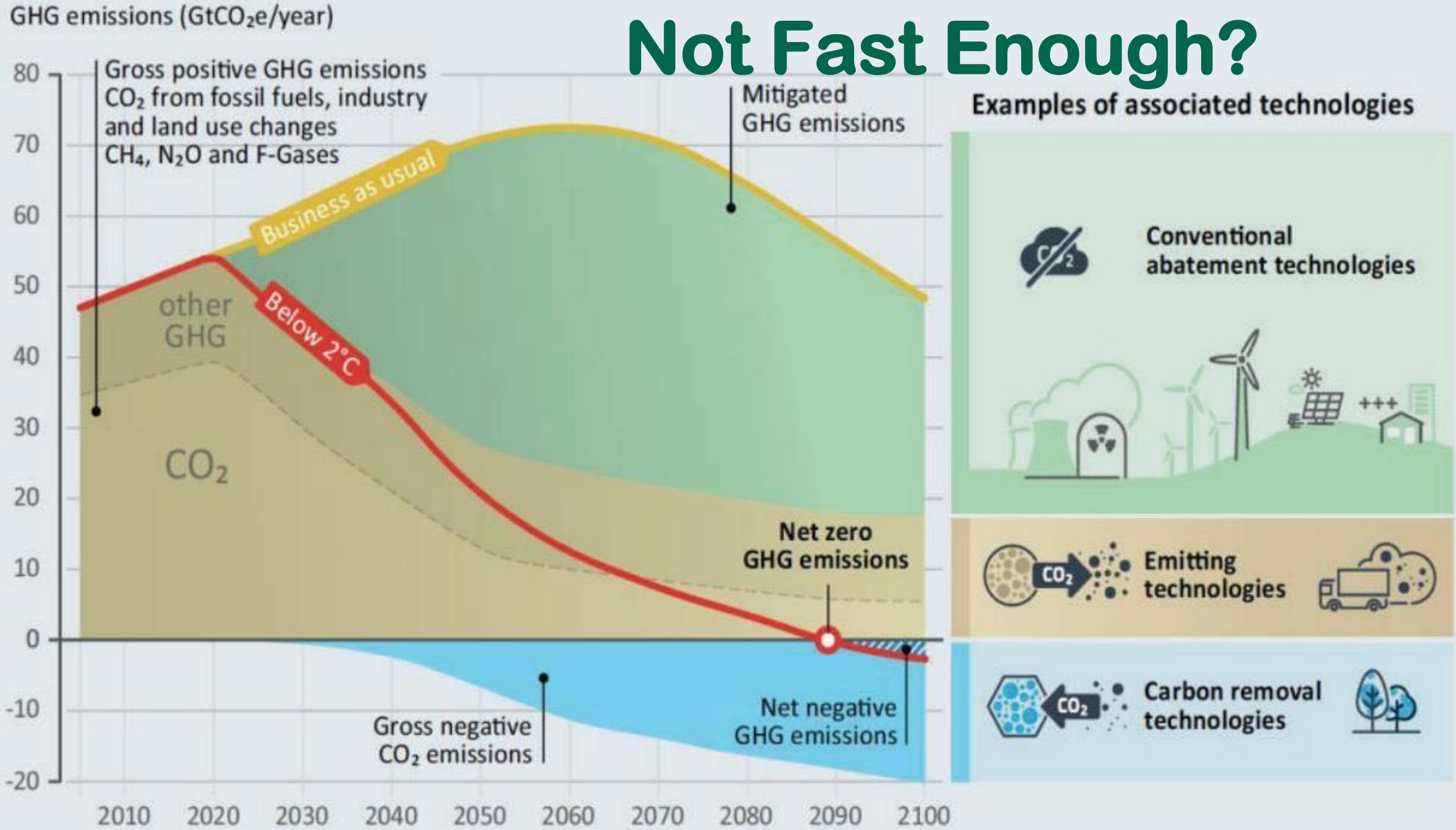
Also **removing CO_2 would add 8% of global energy for each 1 ppm/yr**

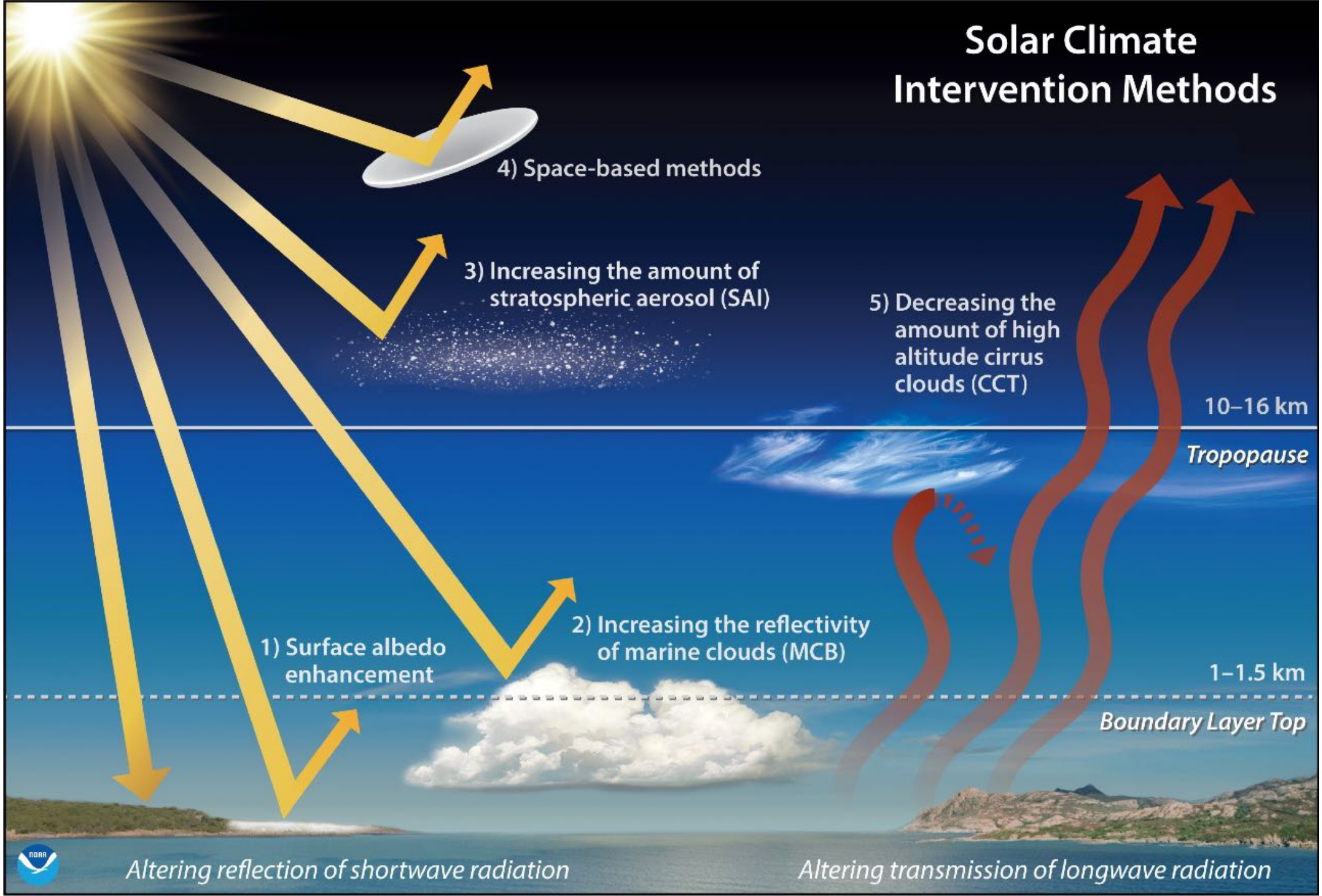
Source *Carbon Dioxide Removal Primer* US DOE
https://cdrprimer.org/read/chapter-2

Solar Geoengineering

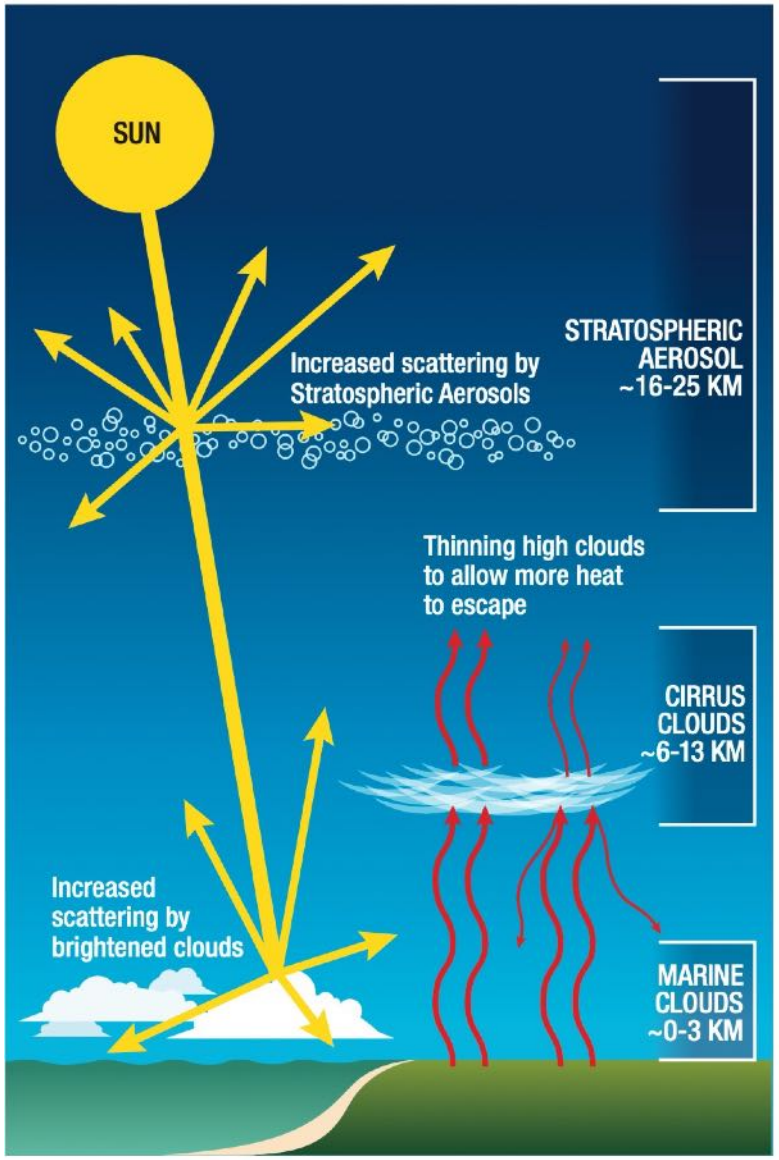
Read *Reflecting Sunlight*
Recommendations for Solar Geoengineering Research and Research Governance (2021)

Not Fast Enough?



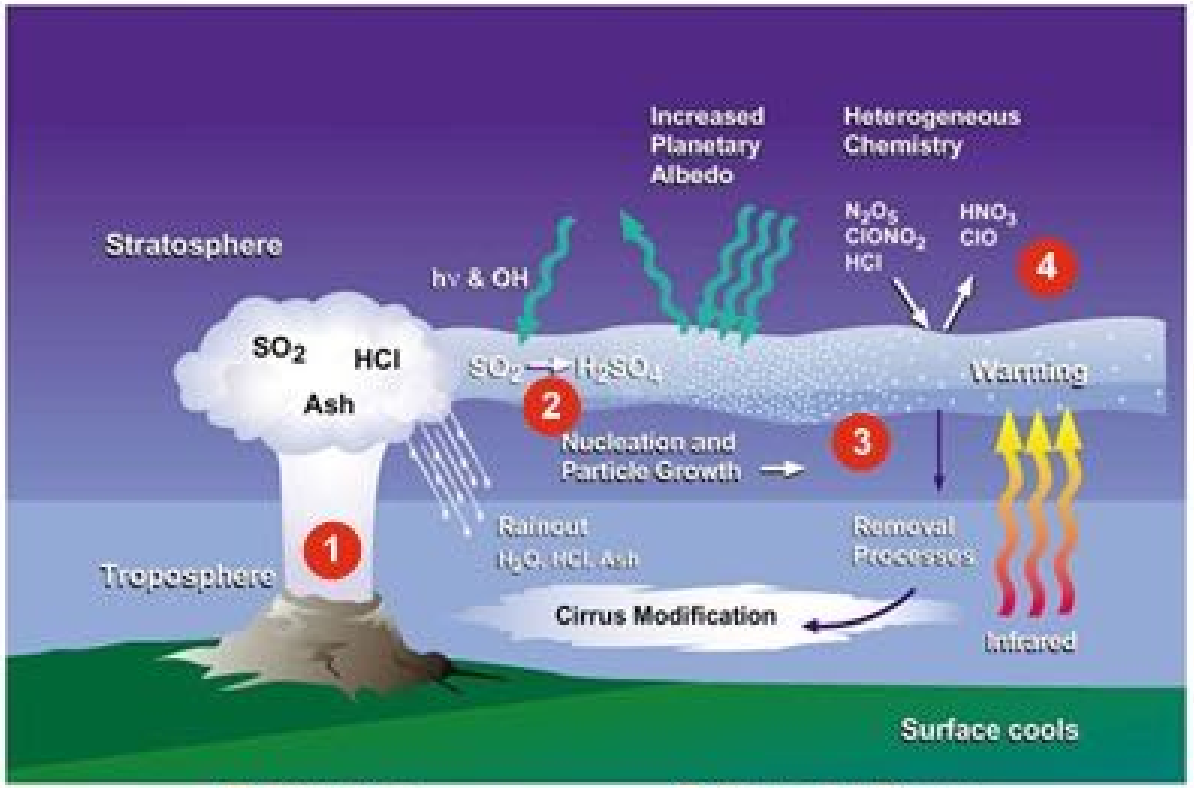

Solar Climate Intervention Methods
4) Space-based methods
3) Increasing the amount of stratospheric aerosol (SAI)
5) Decreasing the amount of high altitude cirrus clouds (CCT)
10–16 km
Tropopause
1) Surface albedo enhancement
2) Increasing the reflectivity of marine clouds (MCB)
1–1.5 km
Boundary Layer Top
Altering reflection of shortwave radiation
Altering transmission of longwave radiation

Radiation Management



- **Stratospheric Aerosol Injection (SAI)**
  - Inject long-lasting particles into upper atmosphere
  - Enhance scattering of solar radiation back to space
- **Marine Cloud Brightening (MCB)**
  - Modify properties of microscopic droplets in low clouds to reflect more sunlight
- **Cirrus Cloud Thinning (CCT)**
  - Modify high-altitude ice particles to allow more IR out

Stratospheric Aerosol Injection



Credits: Windows to the Universe staff (Lisa Gardiner)

- "Aerosol" is just a fancy words for "solid particles in the air"
- Particles scatter (reflect) some incoming sunlight
- Tropospheric particles get washed out by precipitation
- Stratospheric particles (> ~ 15 km ~ 40,000 feet) settle in a few years
- Very well studied effect of volcanic eruptions!

Sulfur in the Stratosphere

Past volcanic eruptions have cooled the earth substantially by injecting sulfur dioxide (SO_2) gas into the upper atmosphere. Atmospheric scientists have proposed that SO_2—already emitted in vast quantities into the lower atmosphere by burning fossil fuels—could have the same cooling effect if it were lofted into the stratosphere.

Light is scattered by clouds of sulfate droplets

DEPLOYMENT BY BALLOON

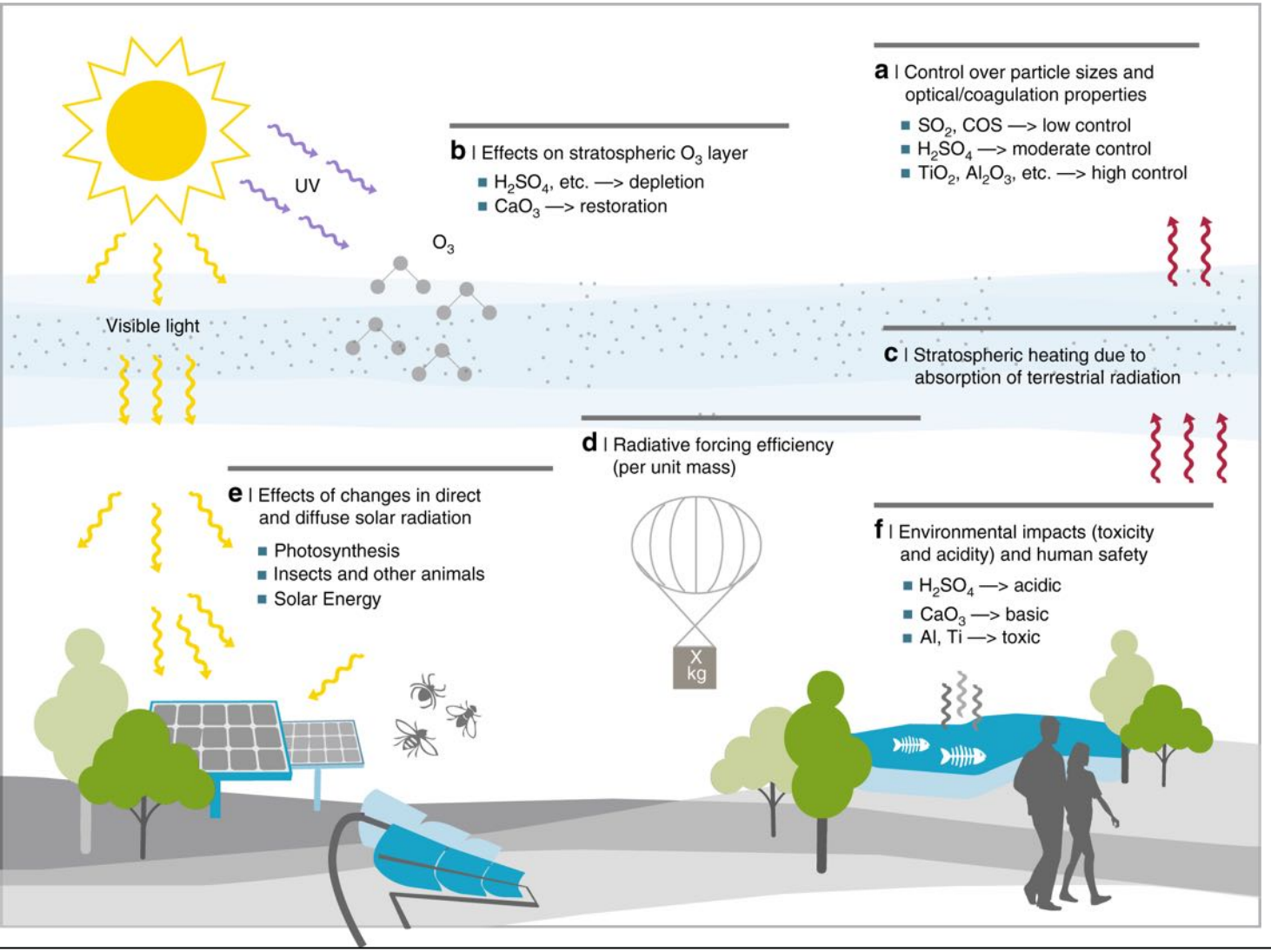
Lighter-than-air craft would require very little energy to raise a cargo of SO_2 at least six miles high.

DEPLOYMENT BY PLANE

Running on "dirty," high-sulfur fuel at cruising altitudes, airplanes could add plenty of SO_2 to the stratosphere.

STRATOSPHERE

Problems with SAI



- Stratospheric particles enhance ozone loss
- Sulfate particles would acidify water & soils
- Toxic materials like Ti or Al with unknown effects
- Reduced sunlight would reduce photosynthesis (food & ecosystem prod)
- Reduced effectiveness of solar power generation

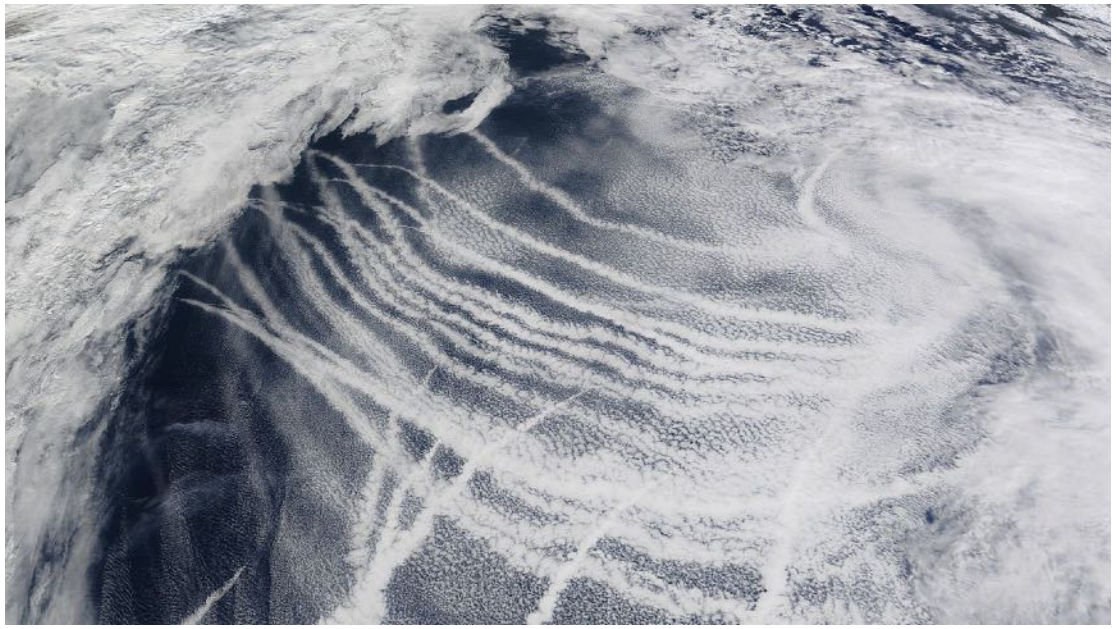
nature COMMUNICATIONS

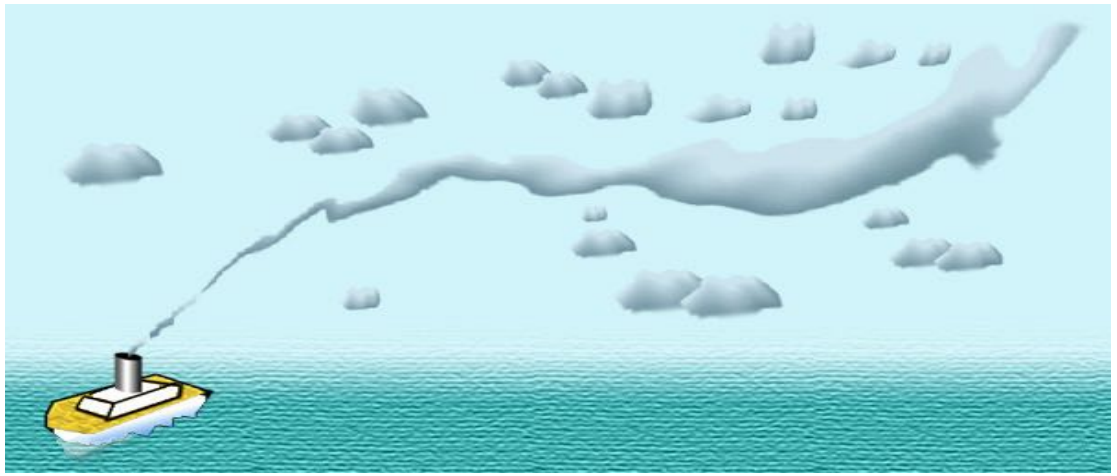
REVIEW ARTICLE

DOI: 10.1038/s41467-018-05938-3

Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals

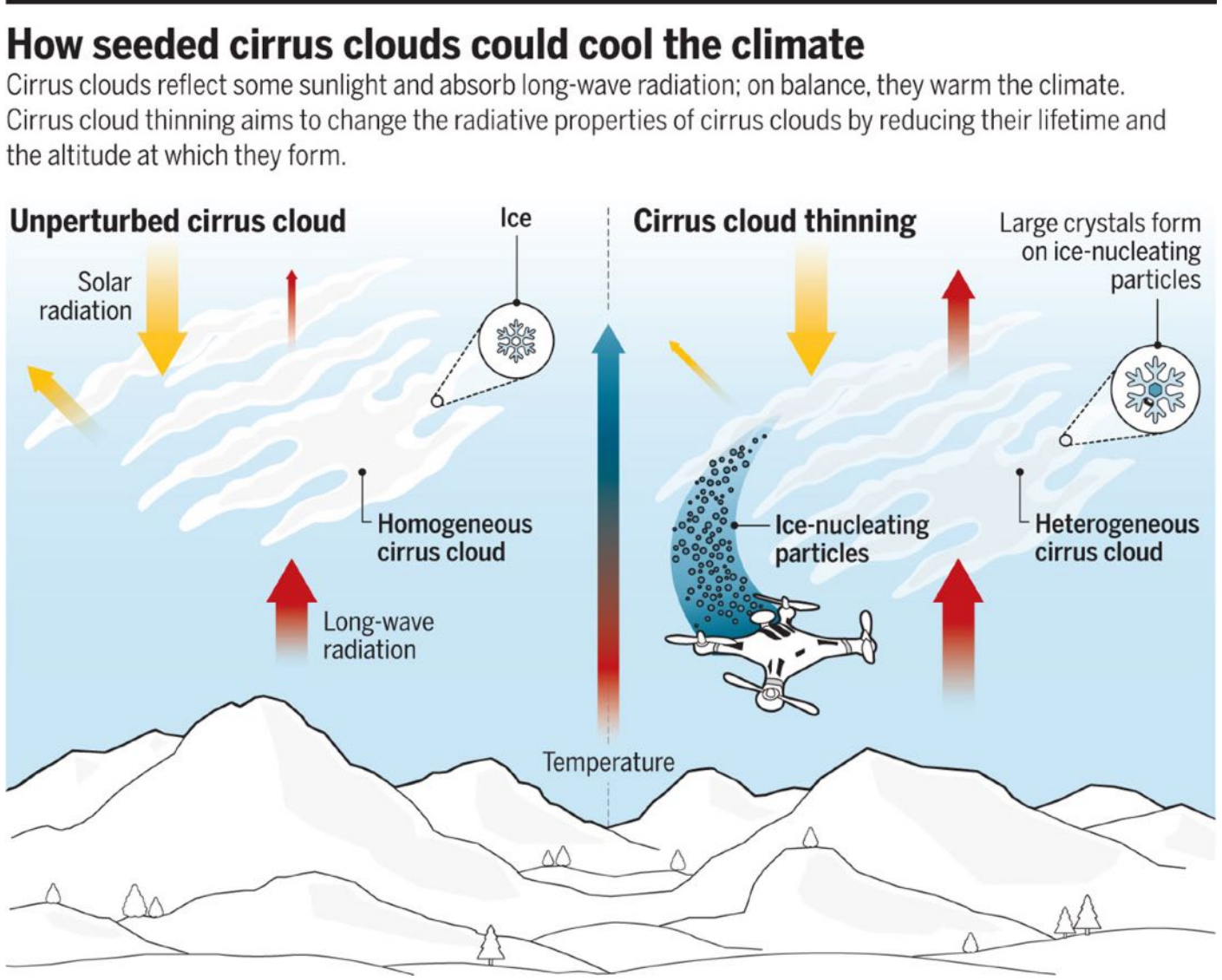
Marine Cloud Brightening





- Low “stratocumulus” clouds cover vast areas of subtropical oceans
- Pollution particles makes droplets smaller and more numerous
- Increases albedo (brightness) of marine cloud decks
- Very well-documented in ship tracks and downwind of cities

Cirrus Cloud Thinning



- Cirrus clouds are very high and cold – ice particles,
  not water droplets
- Pretty transparent to sunlight
- Almost opaque (blackbodies!) in thermal IR wavelengths
- Cloud “seeding” might make crystals big enough to fall

Cautions about Geoengineering

- Does nothing about ocean acidification from CO2
- Must be maintained forever to avoid warming shock when intervention stops
- Sulfur particles harm ozone, soils, water, etc
- Reduced sunshine
- Poorly understood

"We're too busy mopping the floor to turn off the faucet."

Do We Have To?

- Maybe!
- But it's going to suck!
- Let's do as little geoengineering as we possibly can by going all out on *faucet reduction ASAP!*