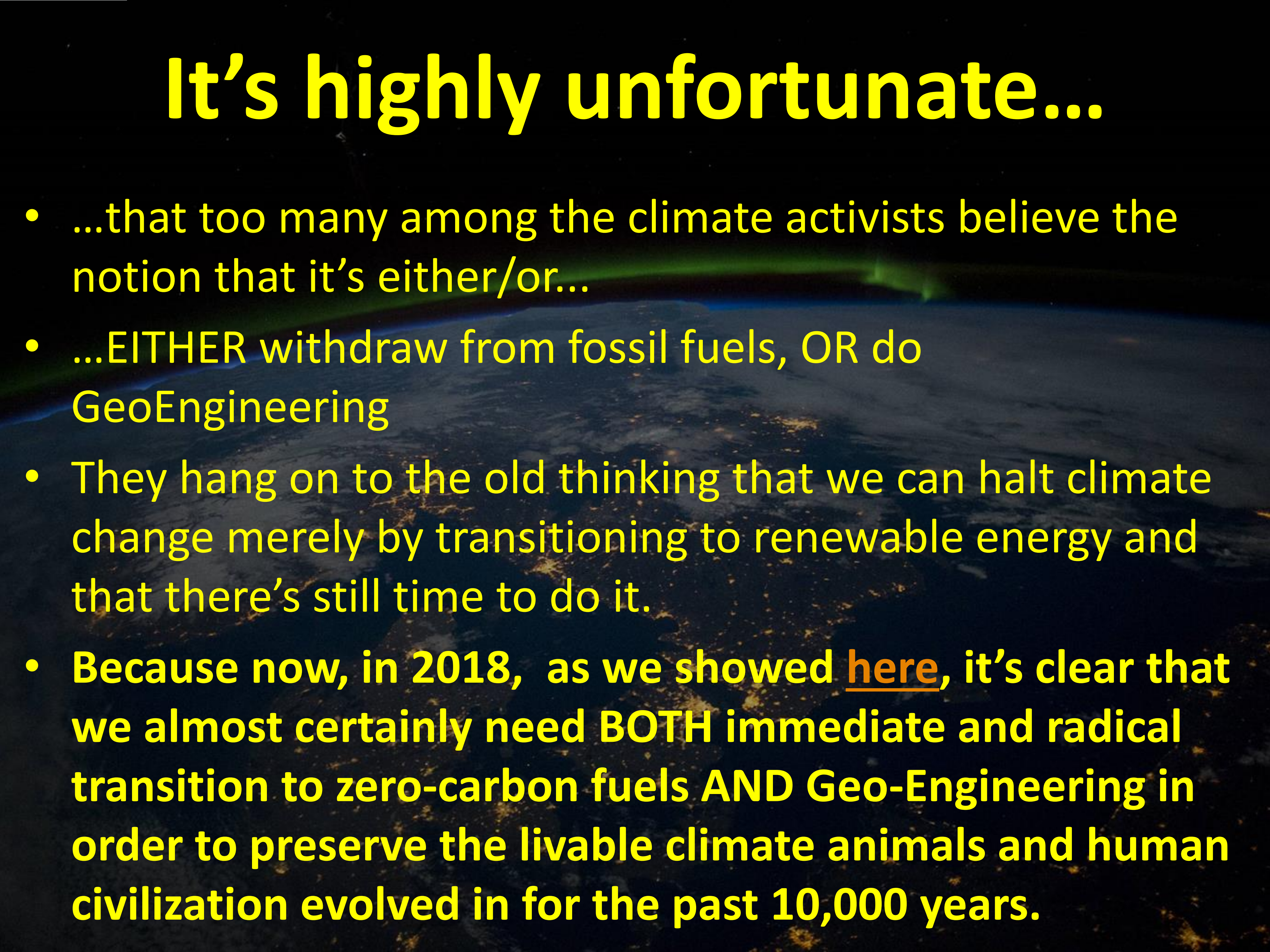
K46 - GeoEngineering: Global Climate Modification

No, this is not the “spraying the populace with mind-altering chem-trails” Conspiracy Theory…

- “GeoEngineering” here refers to engineering efforts which would affect global climate. I use the term to mean any engineering effort designed to alter global climate as its prime and perhaps only goal, to distinguish it from other strategies which have other prime benefits (*e.g.* soil rehabilitation).
- The Royal Society (Britain’s equivalent of the U.S. National Academy of Science), already concluded as early as 2009 that global climate modification was necessary to halt climate change. That merely lowering emissions and improving energy efficiency was not nearly enough.



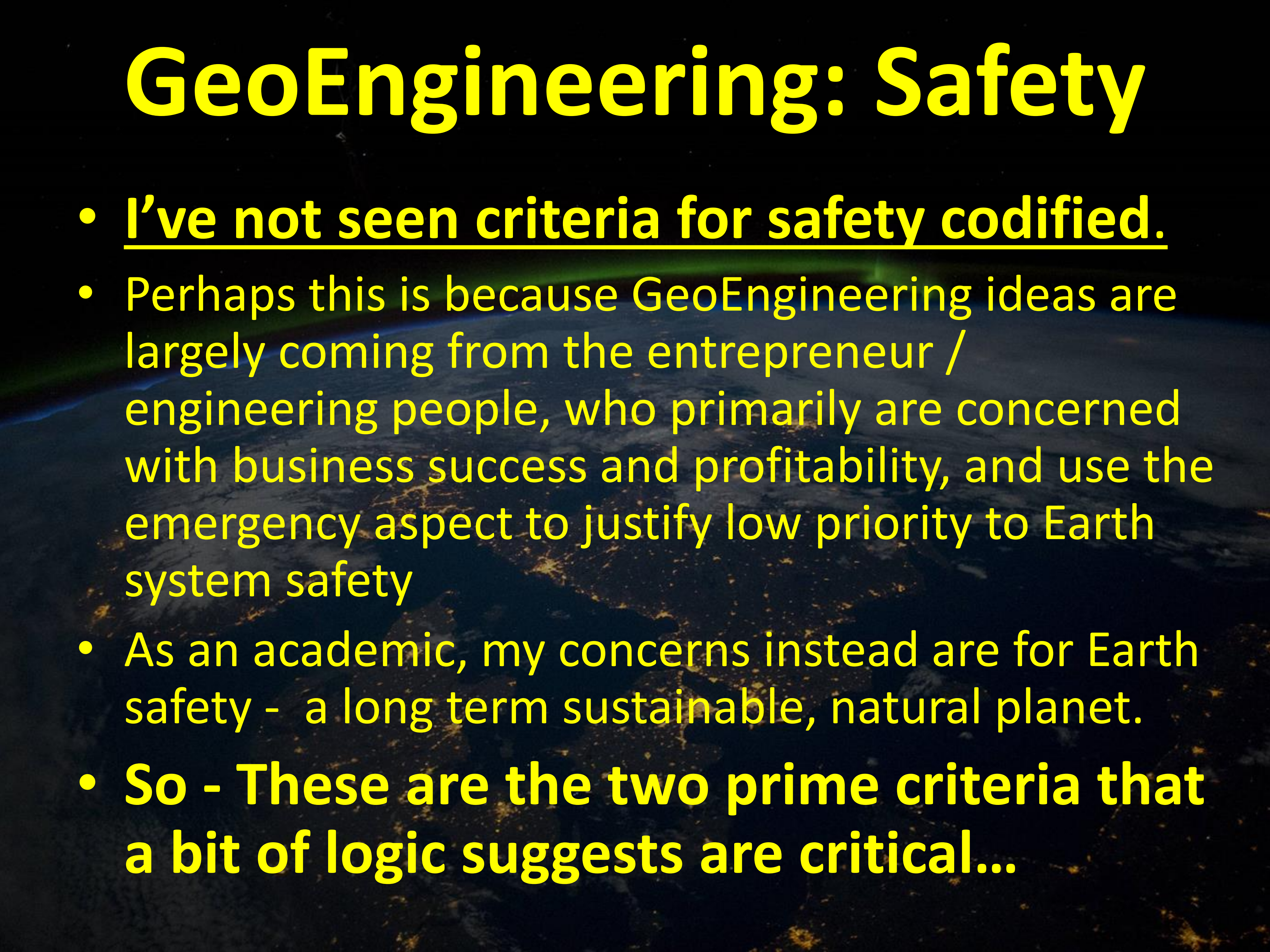
It’s highly unfortunate…

- …that too many among the climate activists believe the notion that it’s either/or...
- …EITHER withdraw from fossil fuels, OR do GeoEngineering
- They hang on to the old thinking that we can halt climate change merely by transitioning to renewable energy and that there’s still time to do it.
- **Because now, in 2018, as we showed here, it’s clear that we almost certainly need BOTH immediate and radical transition to zero-carbon fuels AND Geo-Engineering in order to preserve the livable climate animals and human civilization evolved in for the past 10,000 years.**

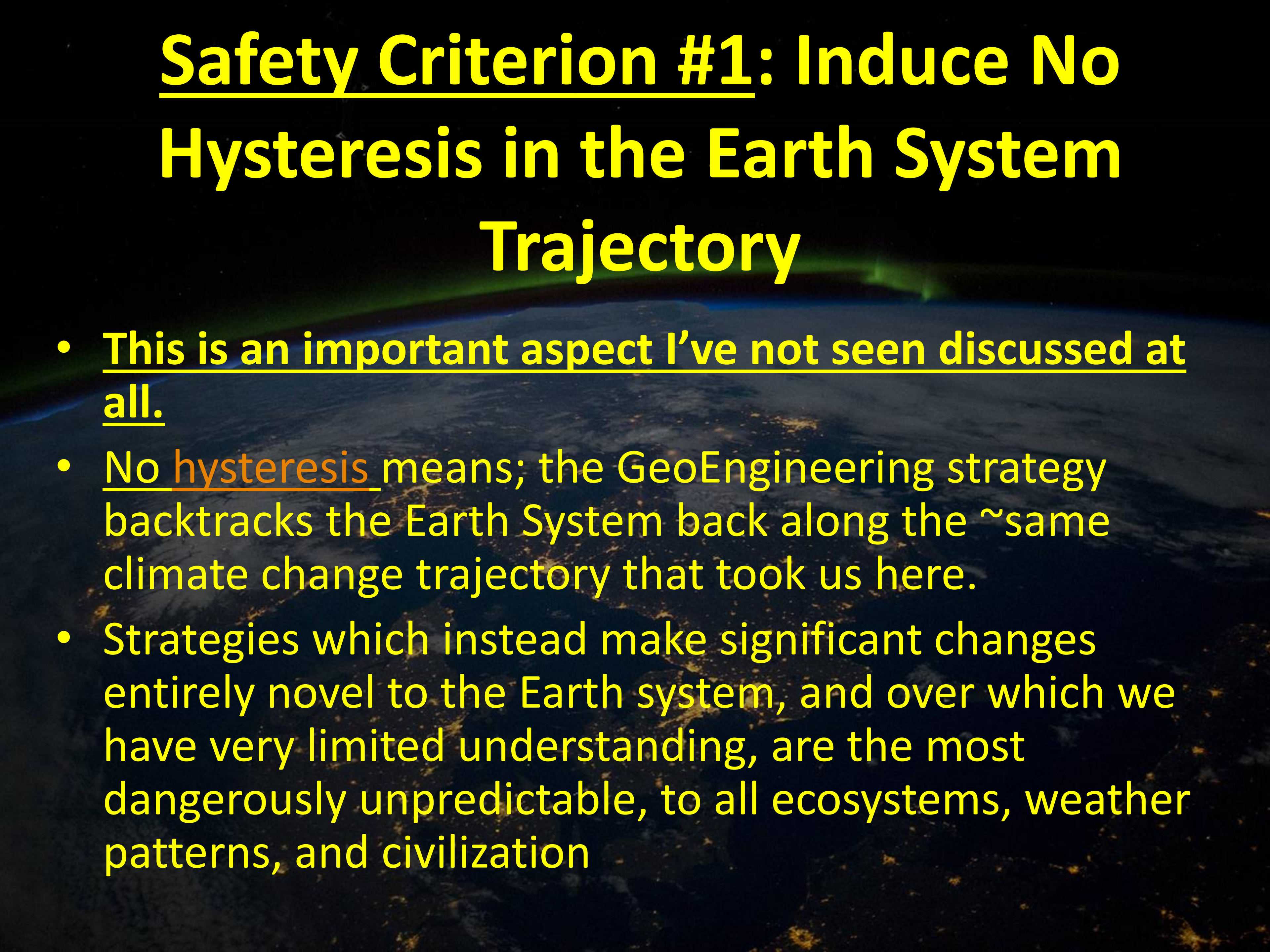
GeoEngineering: Efficacy

- **All GeoEngineering ideas must accomplish one or both of the following:**
- **1.** Reduce incoming sunlight. That is the source of our heating
- **2.** Enhance our crippled ability to re-radiate Earth’s heat back out to outer space
- These are well known and well accepted. Nothing new here.

GeoEngineering: Safety

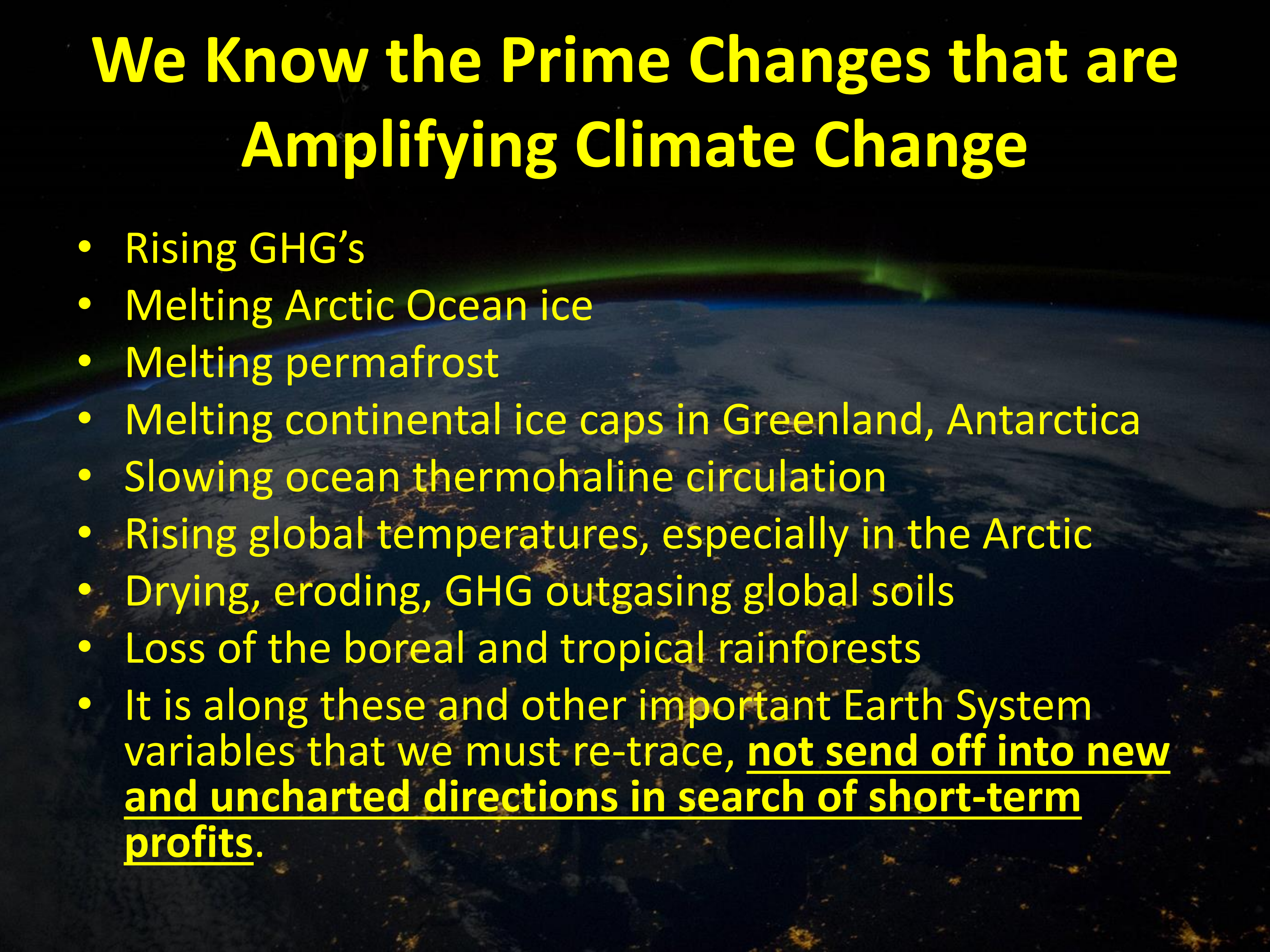


- **<u>I've not seen criteria for safety codified.</u>**
- Perhaps this is because GeoEngineering ideas are largely coming from the entrepreneur / engineering people, who primarily are concerned with business success and profitability, and use the emergency aspect to justify low priority to Earth system safety
- As an academic, my concerns instead are for Earth safety - a long term sustainable, natural planet.
- **So - These are the two prime criteria that a bit of logic suggests are critical…**



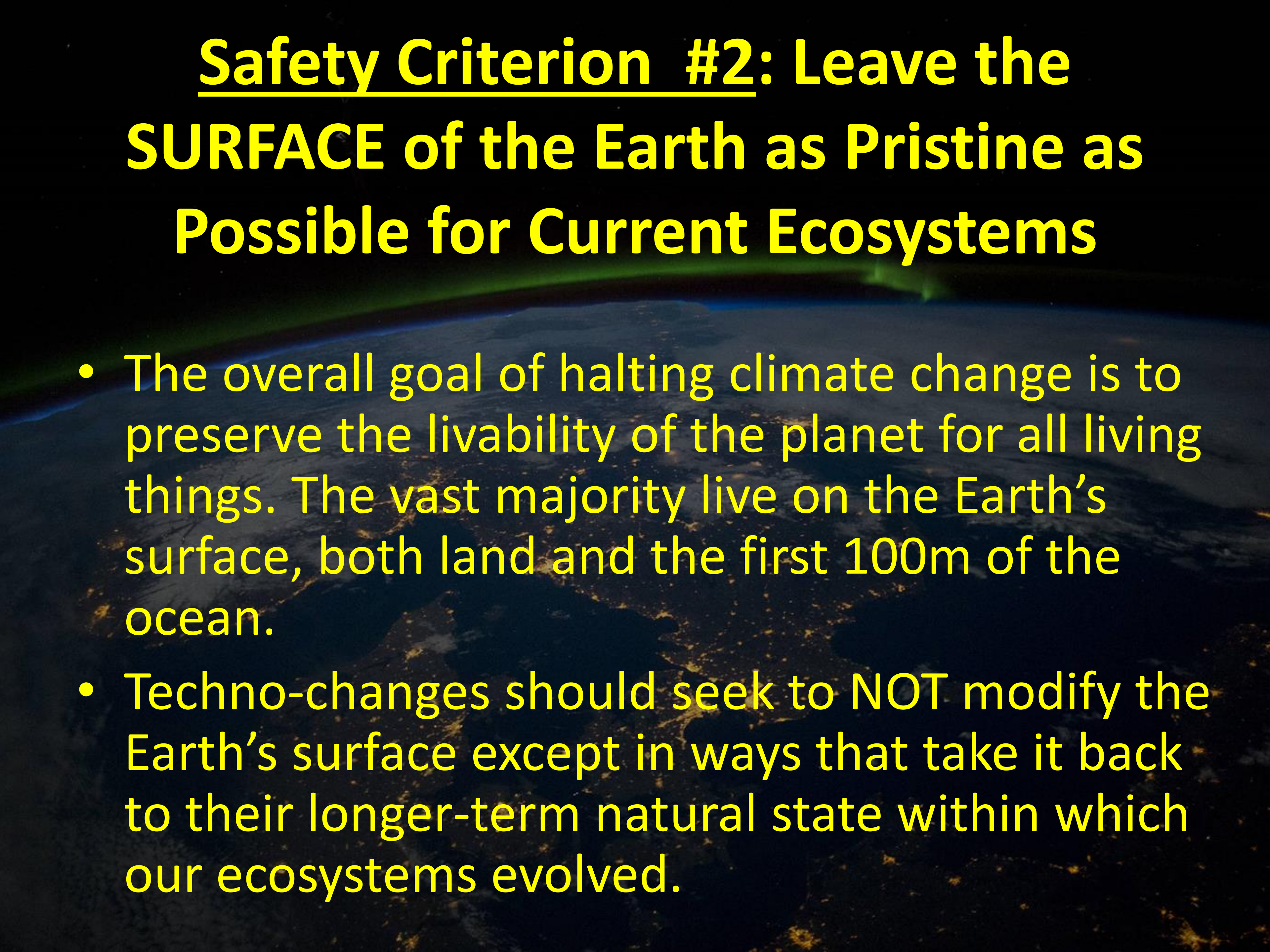
Safety Criterion #1: Induce No Hysteresis in the Earth System Trajectory

- **This is an important aspect I’ve not seen discussed at all.**
- No hysteresis means; the GeoEngineering strategy backtracks the Earth System back along the ~same climate change trajectory that took us here.
- Strategies which instead make significant changes entirely novel to the Earth system, and over which we have very limited understanding, are the most dangerously unpredictable, to all ecosystems, weather patterns, and civilization



We Know the Prime Changes that are Amplifying Climate Change

- Rising GHG’s
- Melting Arctic Ocean ice
- Melting permafrost
- Melting continental ice caps in Greenland, Antarctica
- Slowing ocean thermohaline circulation
- Rising global temperatures, especially in the Arctic
- Drying, eroding, GHG outgasing global soils
- Loss of the boreal and tropical rainforests
- It is along these and other important Earth System variables that we must re-trace, **not send off into new and uncharted directions in search of short-term profits**.

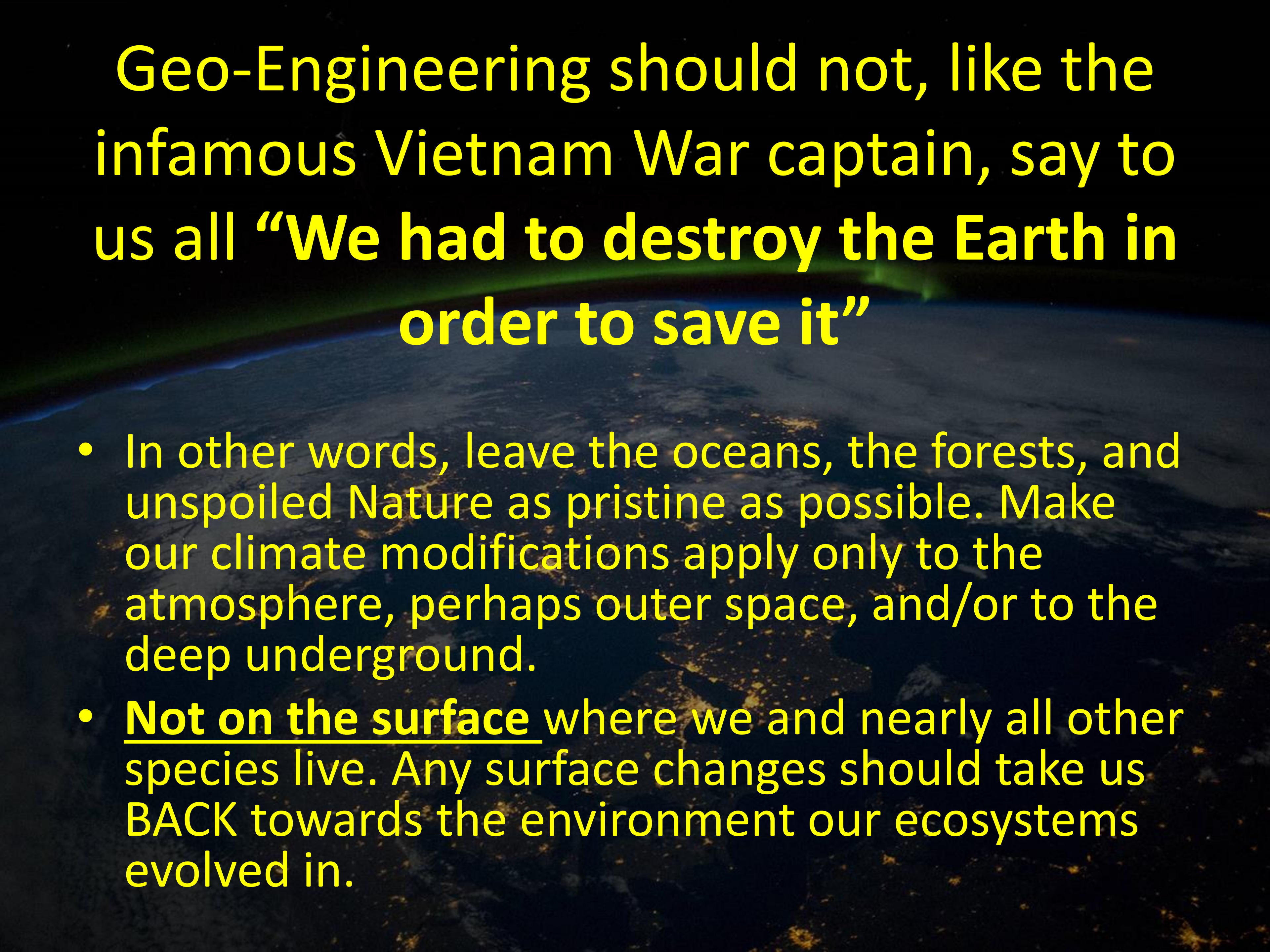


Safety Criterion #2: Leave the SURFACE of the Earth as Pristine as Possible for Current Ecosystems

- The overall goal of halting climate change is to preserve the livability of the planet for all living things. The vast majority live on the Earth's surface, both land and the first 100m of the ocean.
- Techno-changes should seek to NOT modify the Earth's surface except in ways that take it back to their longer-term natural state within which our ecosystems evolved.

“We had to destroy the environment in order to save it” (?)

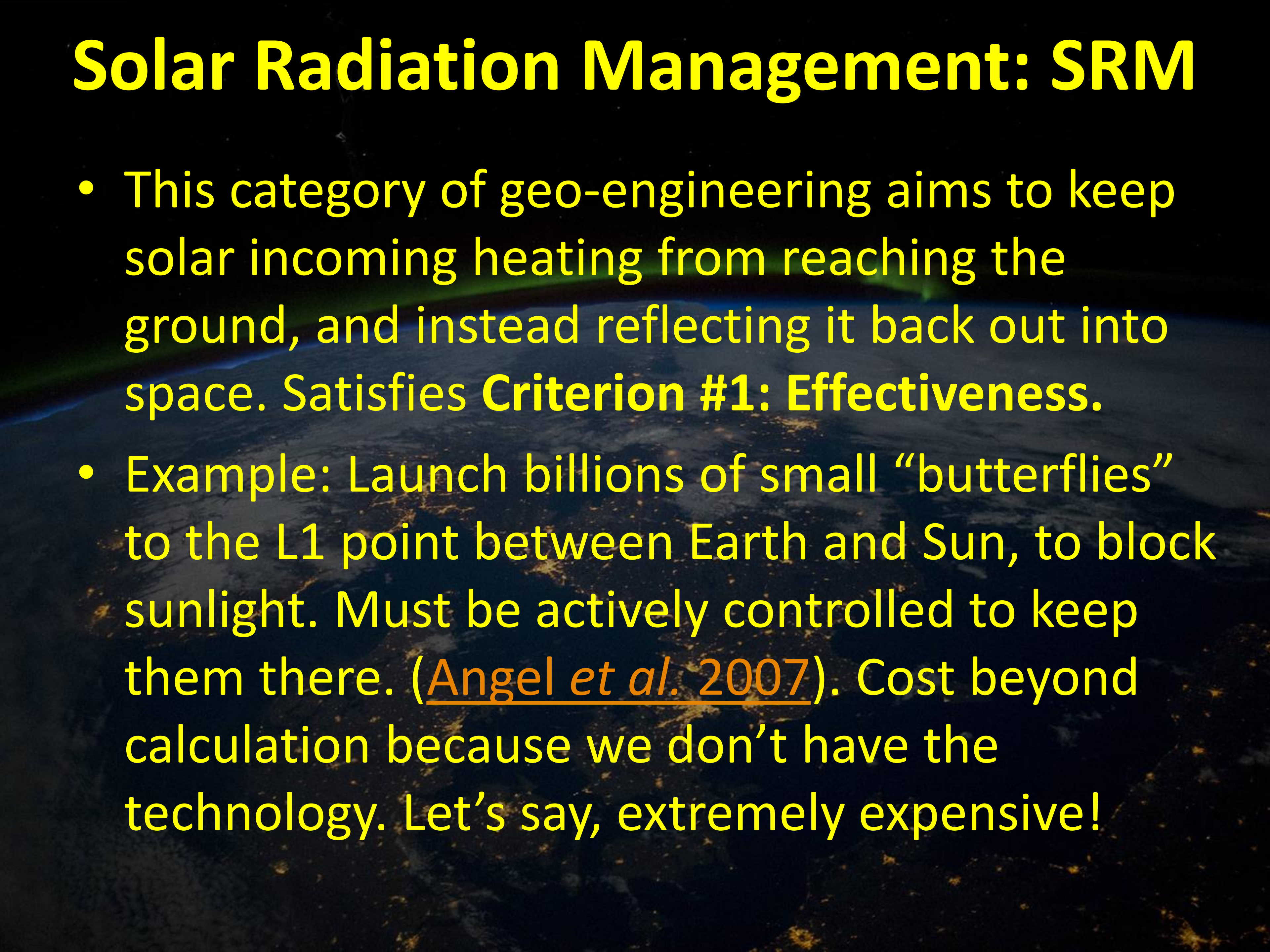
Rainforests cut to make way for palm oil plantations, incentivized with carbon offset financing for tree planting



Geo-Engineering should not, like the infamous Vietnam War captain, say to us all **“We had to destroy the Earth in order to save it”**

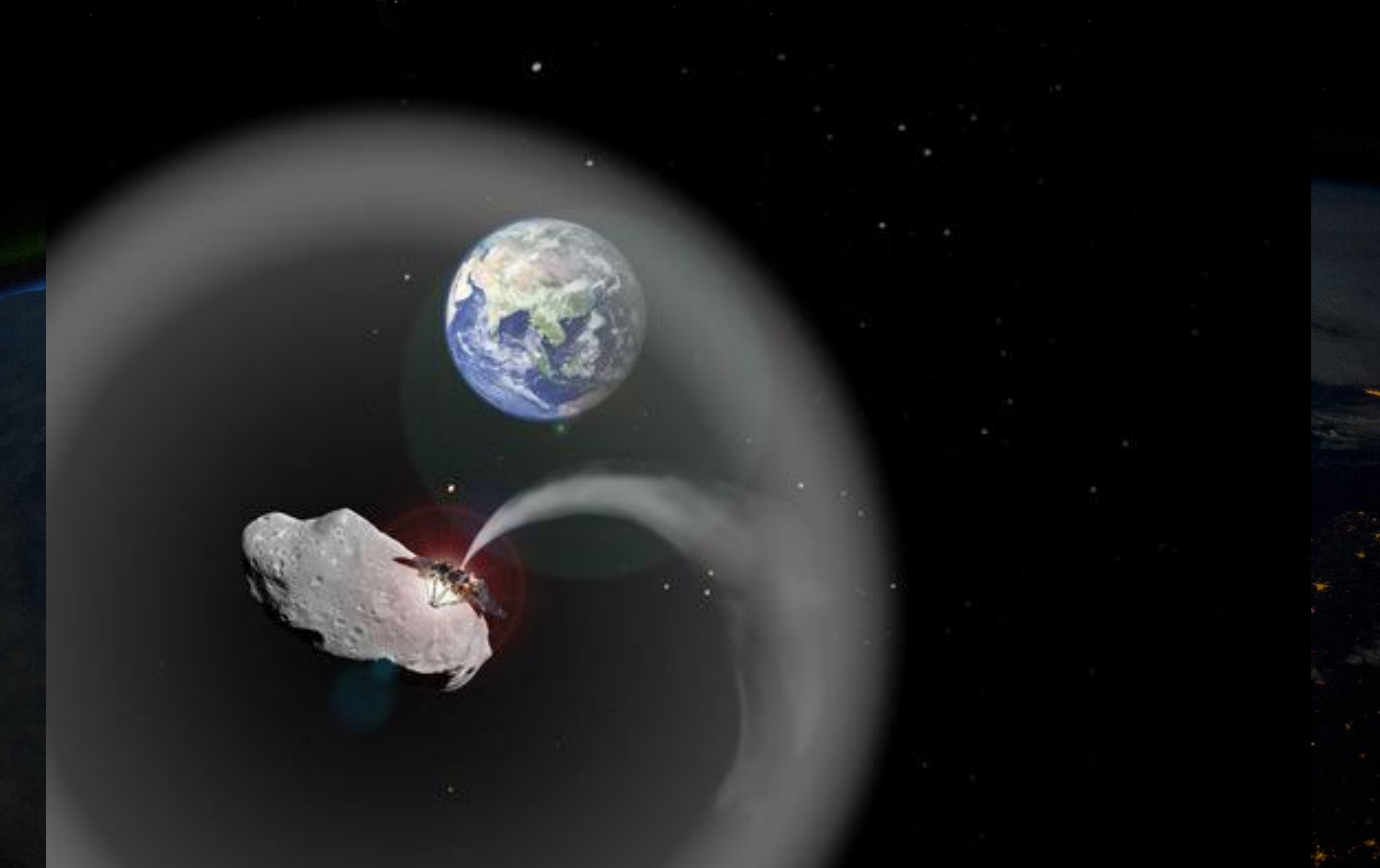
- In other words, leave the oceans, the forests, and unspoiled Nature as pristine as possible. Make our climate modifications apply only to the atmosphere, perhaps outer space, and/or to the deep underground.
- **Not on the surface** where we and nearly all other species live. Any surface changes should take us BACK towards the environment our ecosystems evolved in.

Solar Radiation Management: SRM



- This category of geo-engineering aims to keep solar incoming heating from reaching the ground, and instead reflecting it back out into space. Satisfies **Criterion #1: Effectiveness.**
- Example: Launch billions of small "butterflies" to the L1 point between Earth and Sun, to block sunlight. Must be actively controlled to keep them there. (Angel *et al.* 2007). Cost beyond calculation because we don't have the technology. Let's say, extremely expensive!

Or… Move one or more asteroids to the L1 Lagrangian point between us and Sun, and sputter dust off of it to attenuate sunlight



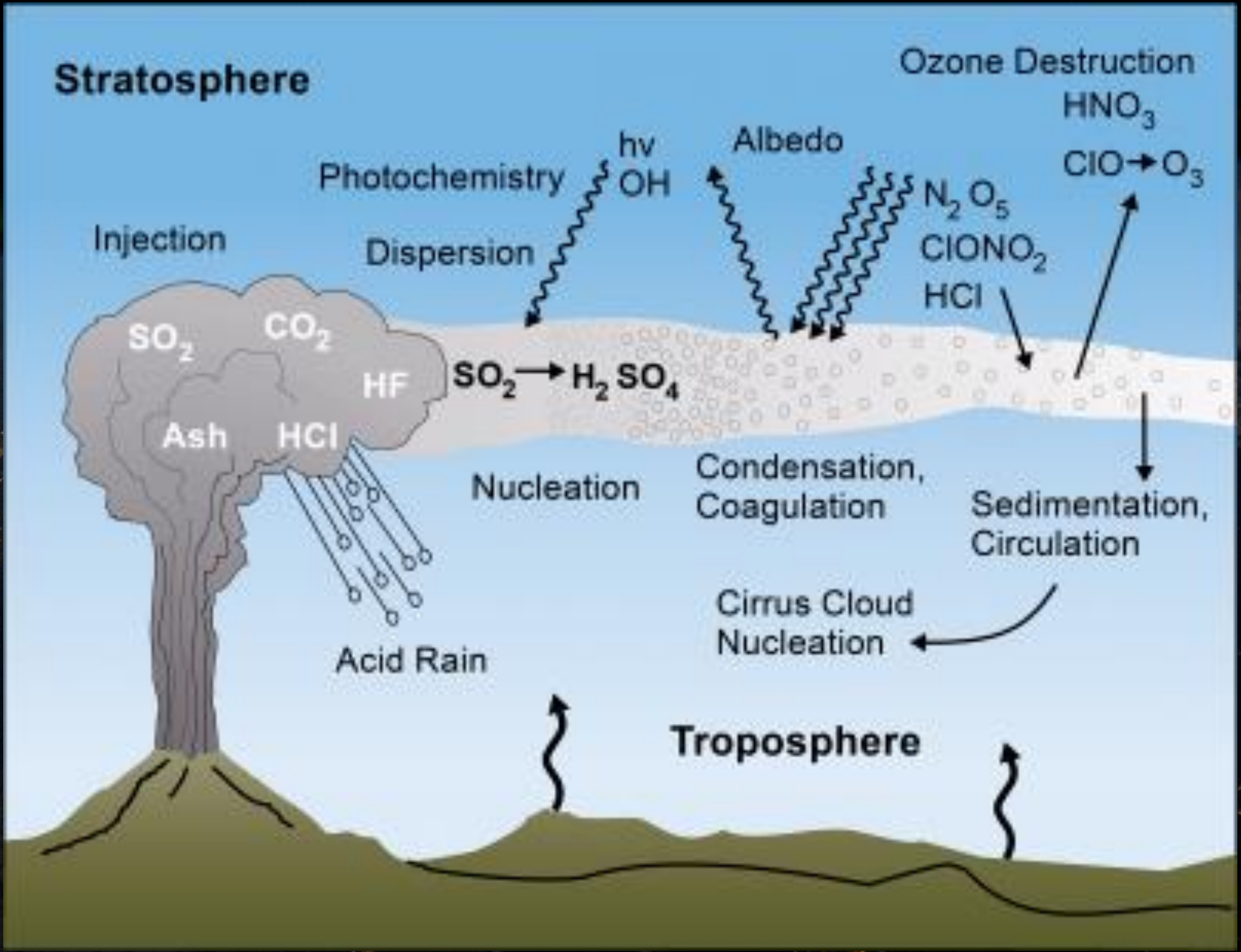
Tug an asteroid to the L1 Lagrangian Point, keep it there and blast off dust to block sunlight from Earth?

- But the L1 point is an unstable gravitational equilibrium point. When you run out of fuel to actively keep it there, the odds are 50/50 it'll head downhill and smash into Earth.
- This would seem quite dangerous to attempt and far too difficult to engineer for now (we need something NOW). Here's the relevant paper (**Bewick *et al.* 2012**), and more thoughts **here**.
- There is precedent, in that there is a great deal of circumstantial evidence that comet impact(s) / debris associated with the Taurid Meteor Shower may have been the culprit which initiated the Younger-Dryas cooling 12,900 years ago which reversed the exit from the last great Ice Age and cooled the Earth for an additional 1000 years (**Napier 2010 and references therein**), as well as wiping out the great mega-fauna, and Clovis culture of North America.
- Extremely dangerous, and extremely difficult to engineer. A non-starter as a strategy.

Injecting Reflective Aerosols into the Stratosphere

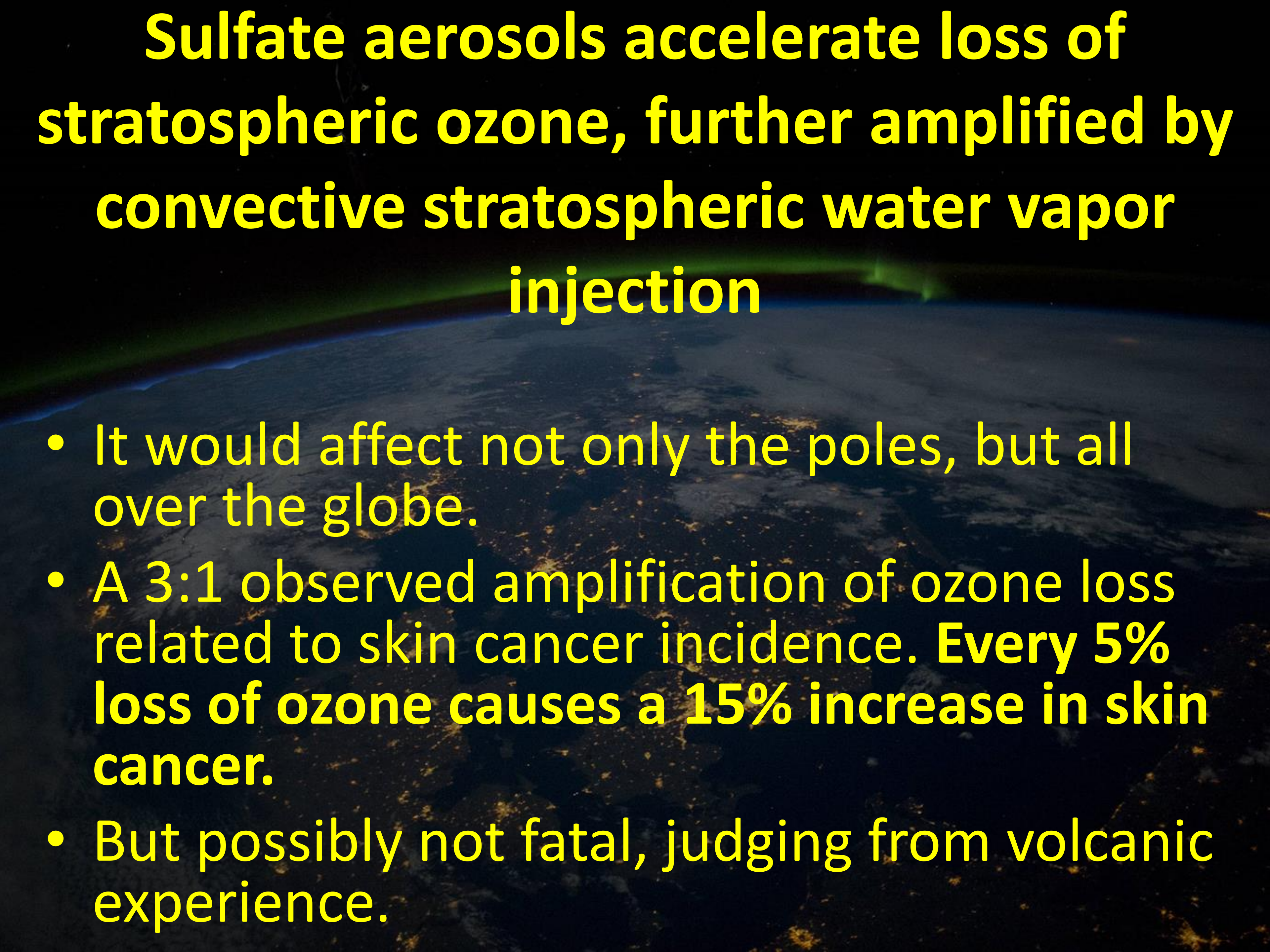
- This would mimic the effect of large volcanic eruptions in their climate effect, and so we are confident they would indeed cool the planet
- The “aerosol direct effect”, reflective sulfate aerosols injected into the lower stratosphere reflecting incoming sunlight, where they would remain for perhaps many months to a year or so because they’d be above the ability of rain clouds to pull them down and rain them out. Gravity, however, would still eventually pull them down.

Definitely cools climate, but danger to Ozone? At Climate Scales, not clear if significant destruction.



More Climate-warming High Clouds?

- The “aerosol indirect effect” (seeding clouds) would hopefully not apply. In fact, if the aerosols actually caused an excess formation of cirrus clouds at this altitude, this would WARM the Earth, not cool it.
- Currently, this altitude, fortunately, has fewer cloud nucleation aerosols than does the lower troposphere. But that would appear to change with this strategy.
- However, ice nucleation is less sensitive to CCN’s and the guess is that this will not be a serious problem



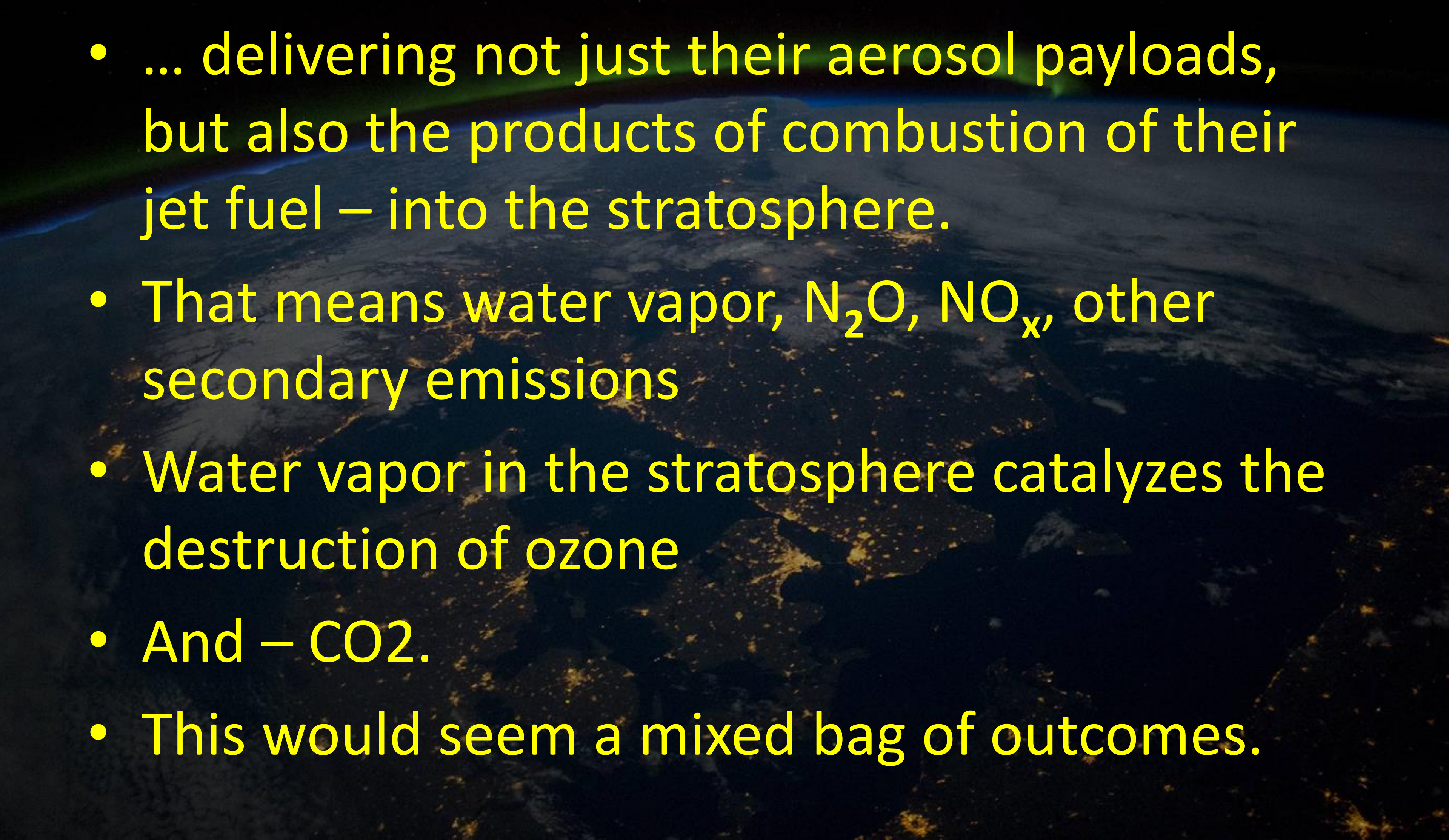
Sulfate aerosols accelerate loss of stratospheric ozone, further amplified by convective stratospheric water vapor injection

- It would affect not only the poles, but all over the globe.
- A 3:1 observed amplification of ozone loss related to skin cancer incidence. **Every 5% loss of ozone causes a 15% increase in skin cancer.**
- But possibly not fatal, judging from volcanic experience.

Energy, Technology Issues

- Cambridge University Engineering professor Hugh Hunt has looked at this.
- To lower Earth temperatures would take 1 million tonnes per year, delivered to the stratosphere.
- Current aircraft getting to that altitude can only climb carry a payload max of 1 tonne
- That means **30,000 jet flights PER DAY**, for delivery

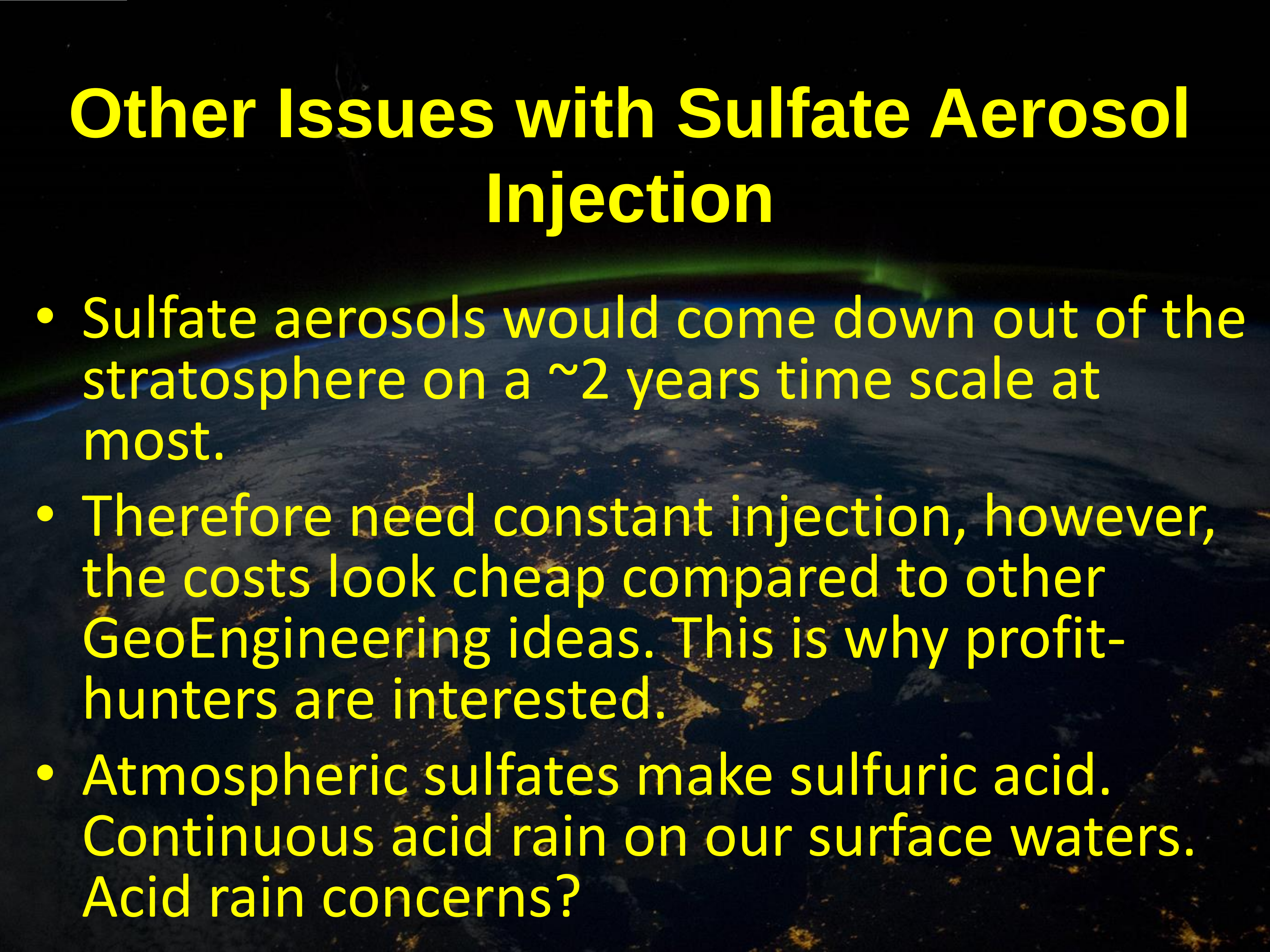
30,000 flights per day…



- … delivering not just their aerosol payloads, but also the products of combustion of their jet fuel – into the stratosphere.
- That means water vapor, N_2O, NO_x, other secondary emissions
- Water vapor in the stratosphere catalyzes the destruction of ozone
- And – CO2.
- This would seem a mixed bag of outcomes.

But Perhaps Reduced UV at Surface

- Madronich *et al.* 2018 find that stratospheric SO_2 injection sufficient to keep temperatures at 2020 levels despite “business as usual” emissions, actually reduces ground-level UV in the mid-latitudes by ~20-30%, as the aerosol-induced scattering and reflection more than compensate for ozone destruction.
- However, significantly higher water vapor into the stratosphere than was expected is being measured, especially over the US, from enhanced convection from enhanced surface warming. Water + SO2 = sulfuric acid, dangerous to stratospheric ozone.



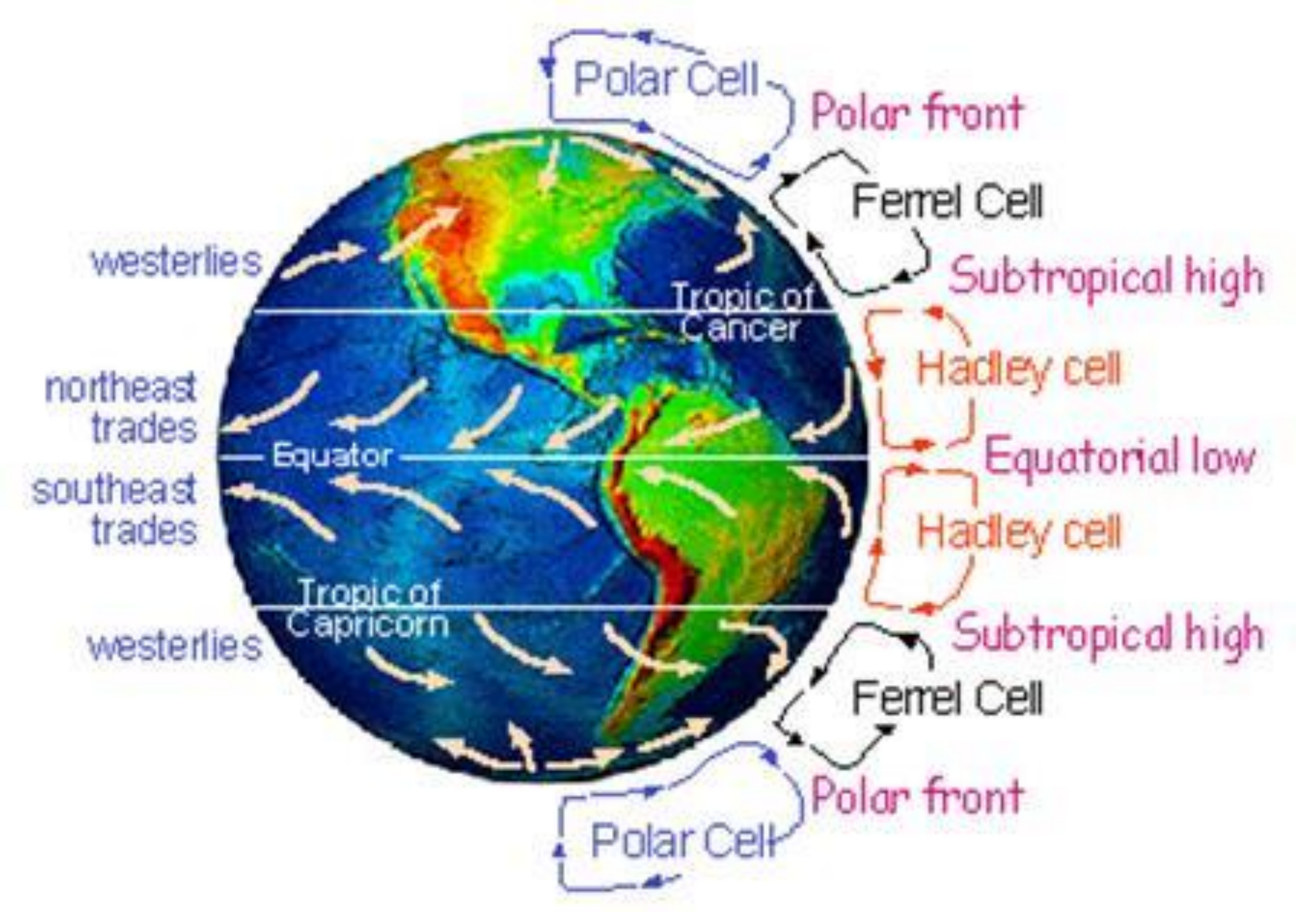
Other Issues with Sulfate Aerosol Injection

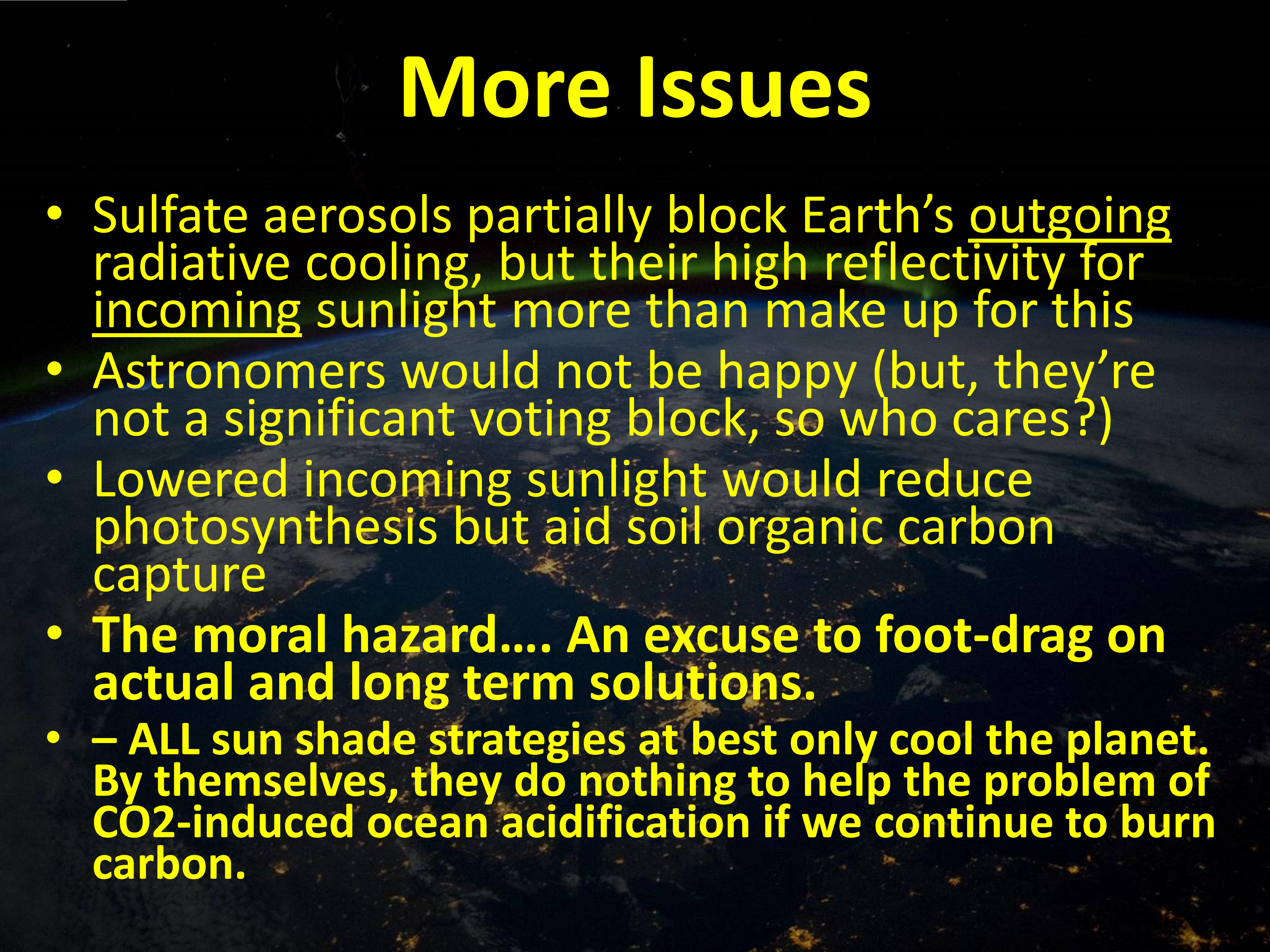
- Sulfate aerosols would come down out of the stratosphere on a ~2 years time scale at most.
- Therefore need constant injection, however, the costs look cheap compared to other GeoEngineering ideas. This is why profit-hunters are interested.
- Atmospheric sulfates make sulfuric acid. Continuous acid rain on our surface waters. Acid rain concerns?

Boomerang Trouble with Albedo Feedback from Aerosol Injection?

- These aerosols which, in the stratosphere, act as reflectors of sunlight before it heats the troposphere – it is hoped they would thus let ice remain frozen.
- But if the ice caps are the most important areas to cool, consider that those same aerosols will likely darken the ice onto which it falls.
- I’ve not seen this issue even mentioned, let alone quantified and discussed.

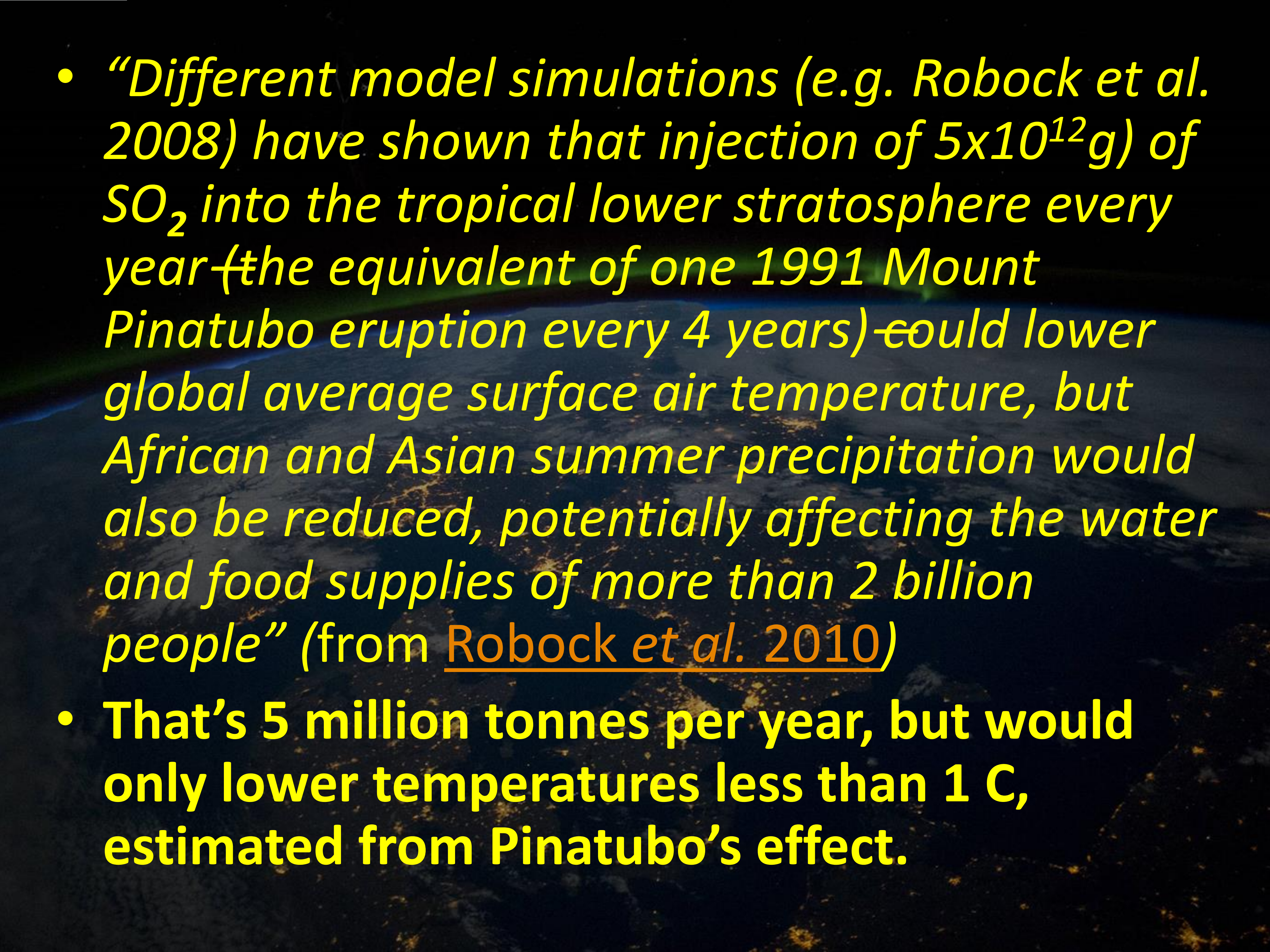
Remember, the ice caps are in the atmospheric circulation cell called the Polar Cell, in which tropospheric air descends onto the ice.





More Issues

- Sulfate aerosols partially block Earth’s outgoing radiative cooling, but their high reflectivity for incoming sunlight more than make up for this
- Astronomers would not be happy (but, they’re not a significant voting block, so who cares?)
- Lowered incoming sunlight would reduce photosynthesis but aid soil organic carbon capture
- **The moral hazard…. An excuse to foot-drag on actual and long term solutions.**
- **– ALL sun shade strategies at best only cool the planet. By themselves, they do nothing to help the problem of CO2-induced ocean acidification if we continue to burn carbon.**



- *“Different model simulations (e.g. Robock et al. 2008) have shown that injection of $5x10^{12}$g) of SO_2 into the tropical lower stratosphere every year ~~(~~the equivalent of one 1991 Mount Pinatubo eruption every 4 years) ~~c~~ould lower global average surface air temperature, but African and Asian summer precipitation would also be reduced, potentially affecting the water and food supplies of more than 2 billion people”* (from Robock *et al.* 2010*)*
- **That’s 5 million tonnes per year, but would only lower temperatures less than 1 C, estimated from Pinatubo’s effect.**

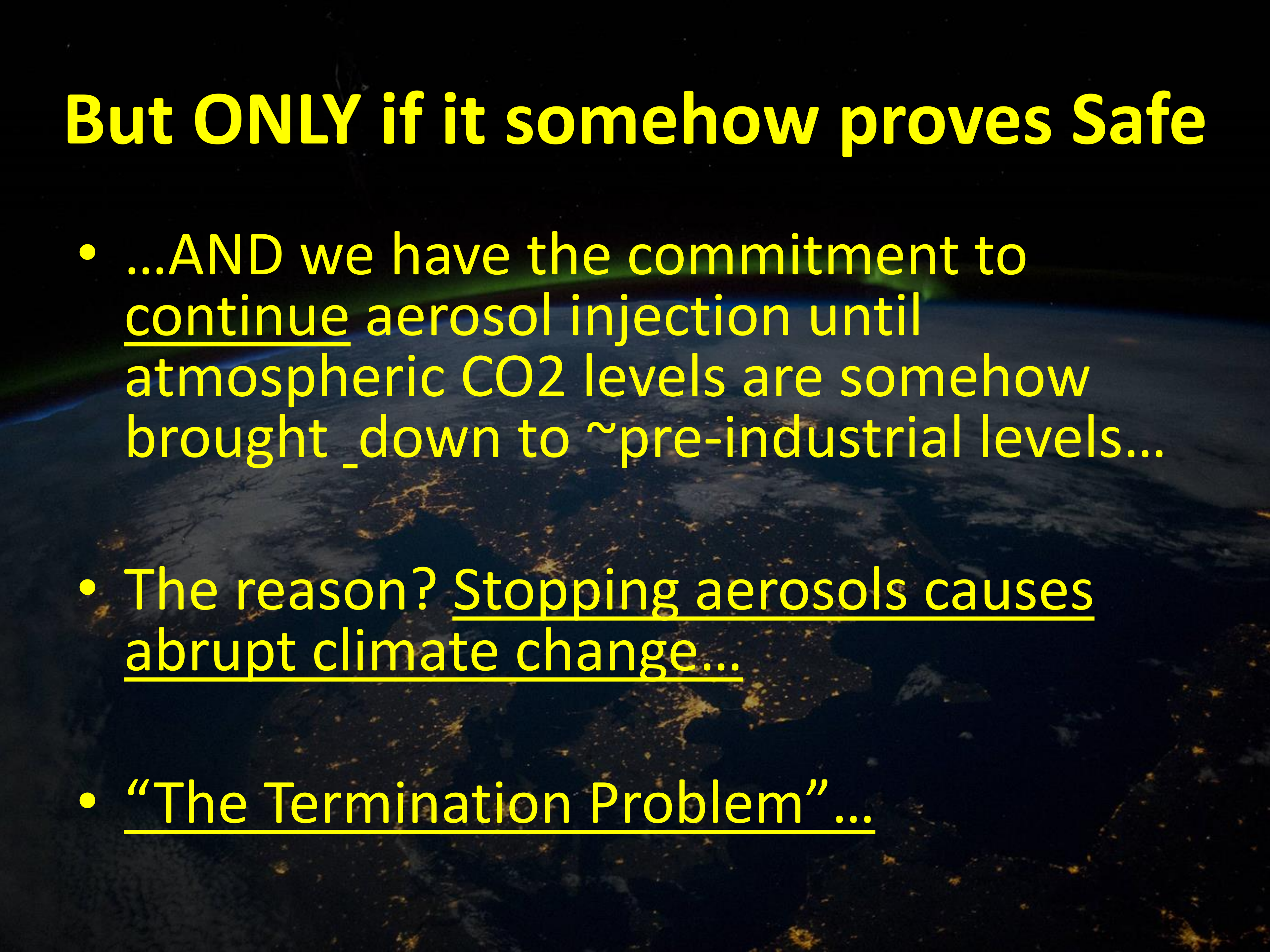
How Much Do We Need?

- Cambridge University's Hugh Hunt points out that to reverse our current warming would require about 1 billion tonnes of sulfates to reverse anthropgenic temperature completely.
- A more modest ambition would be 10 million tonnes of sulfates per year.
- Current aerospace technology can lift only 1 tonne per aircraft flight to the required altitude.
- Which translates to 30,000 flights into the mid stratosphere, far above where current jets fly…. per DAY. (Hunt – "Can we Refreeze the Arctic?" YouTube)
- We do about 100,000 commercial flights globally per day, so this is an additional 1/3 of that number.

Sulfate Aerosols and Corals

- **Kwiatkowski *et al.* 2015** find that higher CO2 emissions but paired with sulfate aerosol shading, does lower sea surface temperatures and therefore helps moderate coral bleaching, *vs.* no aerosol shading and lower CO2 emissions. (but, it hurts aragonite calcification of the corals via acidification, so maybe the algae would be temperature happier, but would they still have a coral host to be symbiotic with??)
- **As a desperation measure to halt temperature rise and therefore ice loss and sea level rise, they should continue to be investigated.**

But ONLY if it somehow proves Safe



- …AND we have the commitment to continue aerosol injection until atmospheric CO2 levels are somehow brought down to ~pre-industrial levels…
- The reason? Stopping aerosols causes abrupt climate change…
- “The Termination Problem”…

“Business as Usual” climate models with, and without, sulfate aerosol injection for 50 years only. At end, aerosols rain out, and high CO2 heat forcing from now too-cool Earth causes rapid catch-up warming (Robock 2014): SRM, once started, MUST be continued until atmospheric CO2 levels are artificially brought back down to levels in equilibrium with SRM-induced temperatures. In other words, the moral hazard is very high!

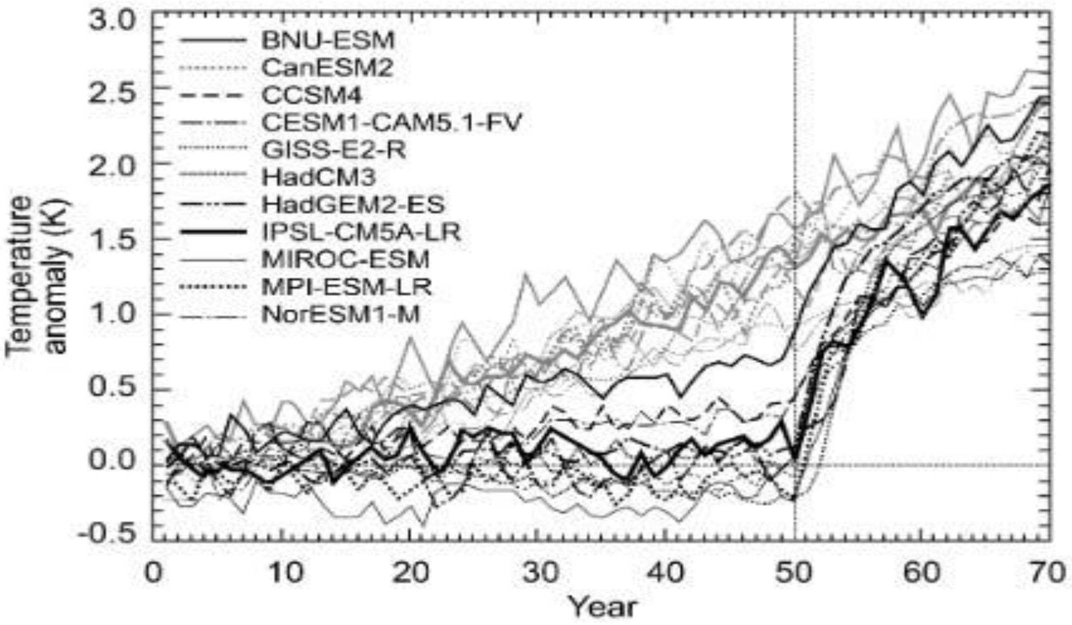


Figure 3 Evolution of annual mean anomaly of global mean near-surface air temperature (K) in the G2 simulations (black lines) with respect to the long-term mean from each model’s control simulation. Time series from corresponding 1% CO_2 year^{-1} increase simulations are also shown (gray lines). The termination of geoengineering in the G2 simulations is indicated by the dashed vertical line.
(Figure 1 from ref. 24; see this reference for climate model abbreviations and details).

Ozone Destruction: From an MIT Tech Review Article by Rotman 2013

- *(Harvard's James) Anderson says that adding sulfates to the stratosphere worries him "tremendously" because of the potential impact on ozone. He points to a study his group published last year in the journal* ***Science*** *showing that increasingly intense summer storms over the United States—triggered by climate warming—are injecting more water vapor into the stratosphere. That, he says, could speed the ozone-destroying reactions: "If nature is adding increased water vapor to the stratosphere and we're adding sulfates, it is a very lethal cocktail for ozone loss."*
- Indeed, Mt Pinatubo's 1991 injection of stratospheric sulfate aerosols caused a record loss of stratospheric ozone (Solomon 2009).

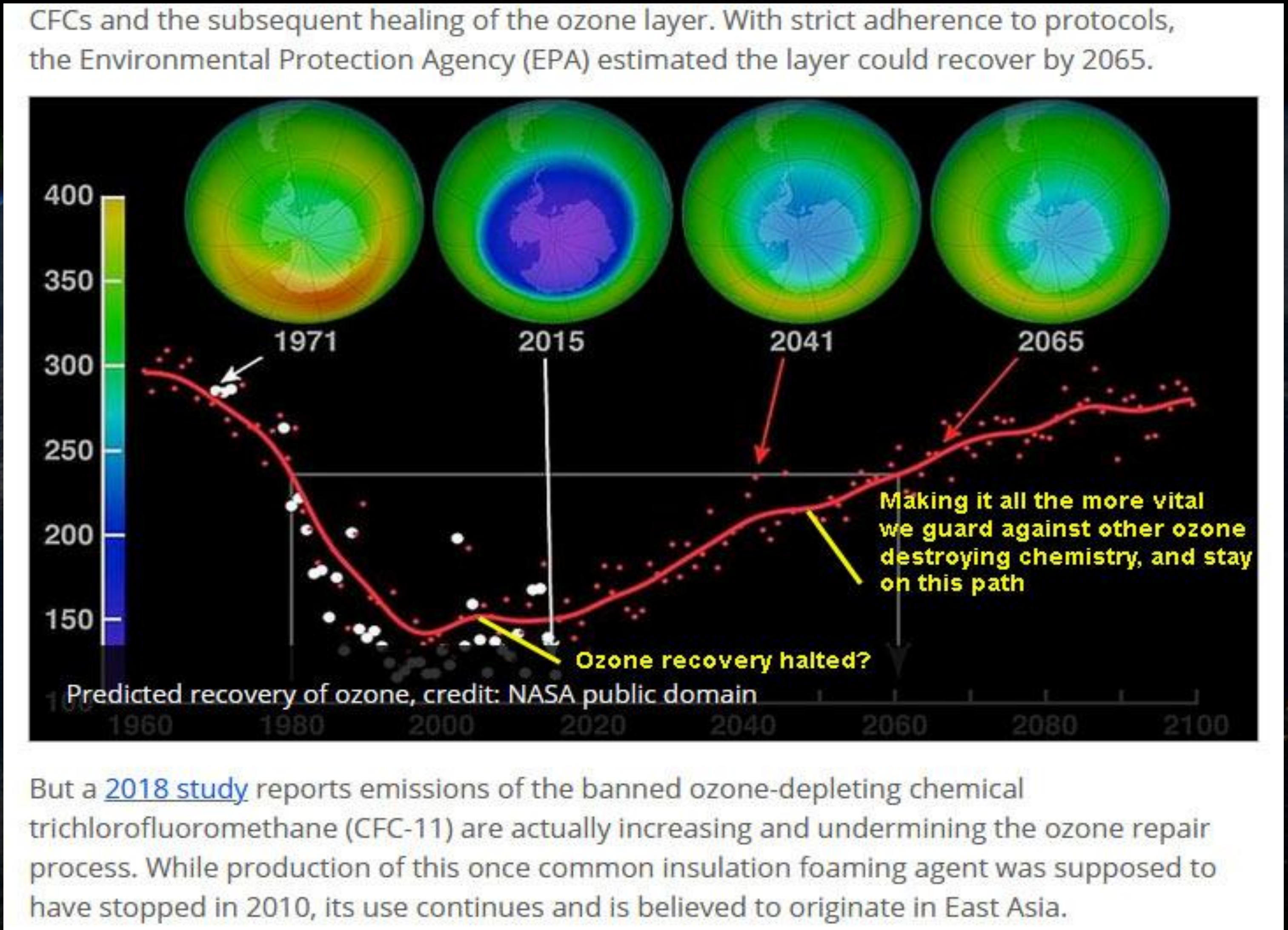
Other Stratospheric Aerosols Dangers

- How would it affect wind and hence weather patterns? A weakening of the Asian monsoon is predicted, other effects poorly known. Mt Pinatubo indeed altered global weather patterns. ANY changes could cause major wars initiated by adversely affected countries (Robock, 2014)
- Would real-world sulfate droplets combine to form larger droplets, as raindrops do? Bad – they would have less surface area/volume, and so reflect sunlight less well, and also fall to ground much faster, therefore causing more acid rain worries per ton injected and require higher injections rates

Ozone Loss: How Serious?

- Mt Pinatubo's eruption in 1991 caused losses of total column ozone of 6% (Schoeberl *et al.* 1993, Chandra 1993) for ~6 months.
- But we need continuous on-going injections. If these losses turn out not to be additive with the continuous aerosol injections, then ~6% decreases might not be unacceptable, given Robock's study of injections at the rate of ¼ of a Mt. Pinatubo per year.
- But what if they are additive, or worse – self-amplifying, as more chemicals gang-tackle fewer remaining ozone molecules?

Slow ozone recovery from 1992 Montreal Accords banning CFC's has halted, as profit motivates continued illegal CFC's



CFCs and the subsequent healing of the ozone layer. With strict adherence to protocols, the Environmental Protection Agency (EPA) estimated the layer could recover by 2065.

Making it all the more vital we guard against other ozone destroying chemistry, and stay on this path

Ozone recovery halted?

Predicted recovery of ozone, credit: NASA public domain

But a 2018 study reports emissions of the banned ozone-depleting chemical trichlorofluoromethane (CFC-11) are actually increasing and undermining the ozone repair process. While production of this once common insulation foaming agent was supposed to have stopped in 2010, its use continues and is believed to originate in East Asia.

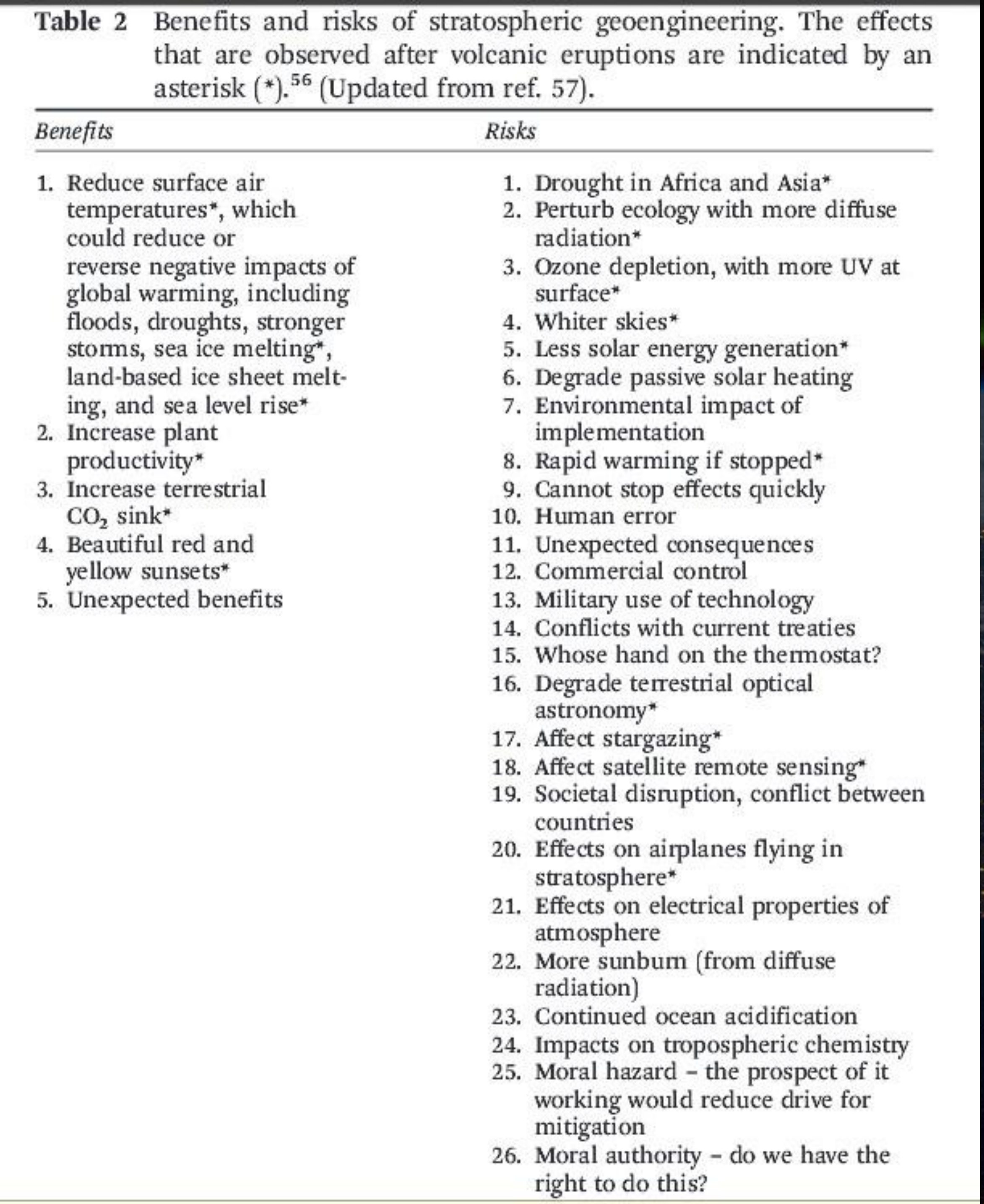
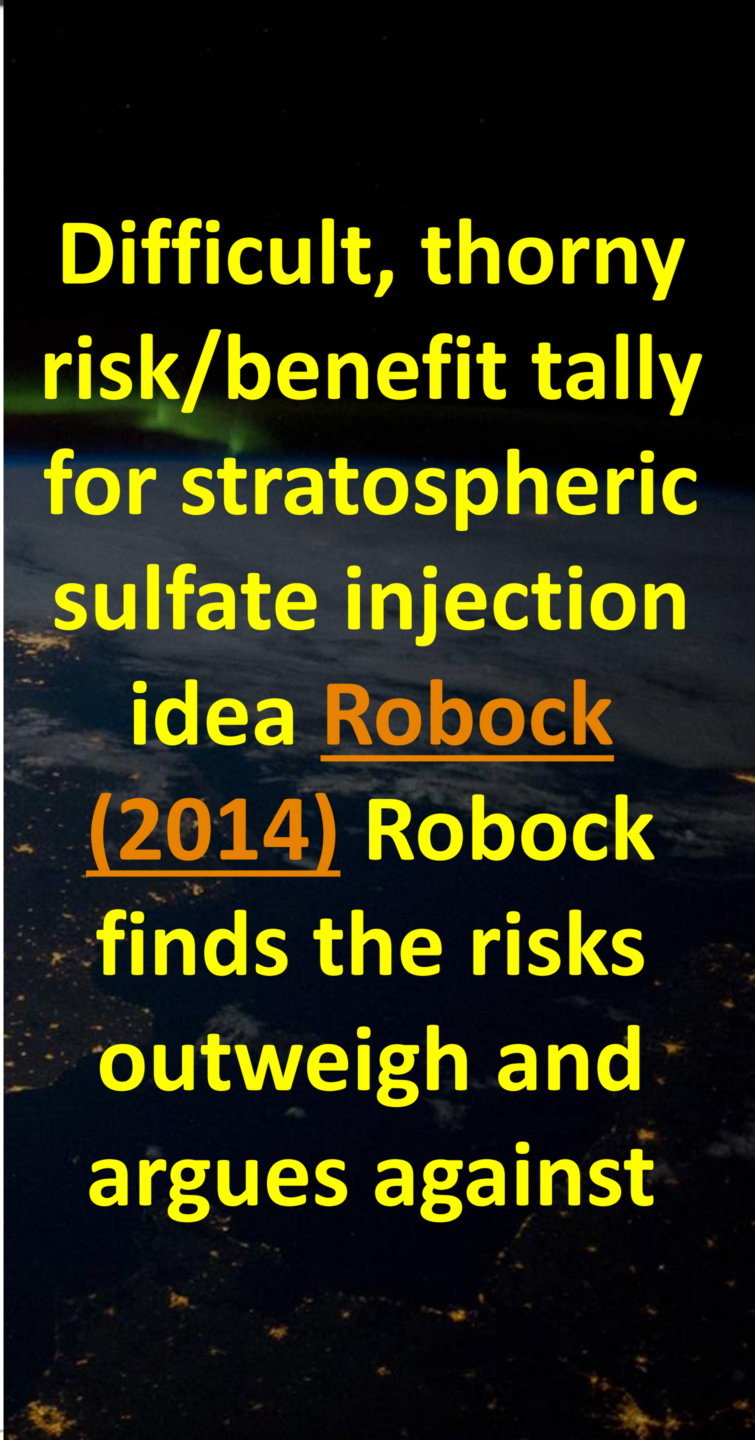


Table 2 Benefits and risks of stratospheric geoengineering. The effects that are observed after volcanic eruptions are indicated by an asterisk (*).[56] (Updated from ref. 57).

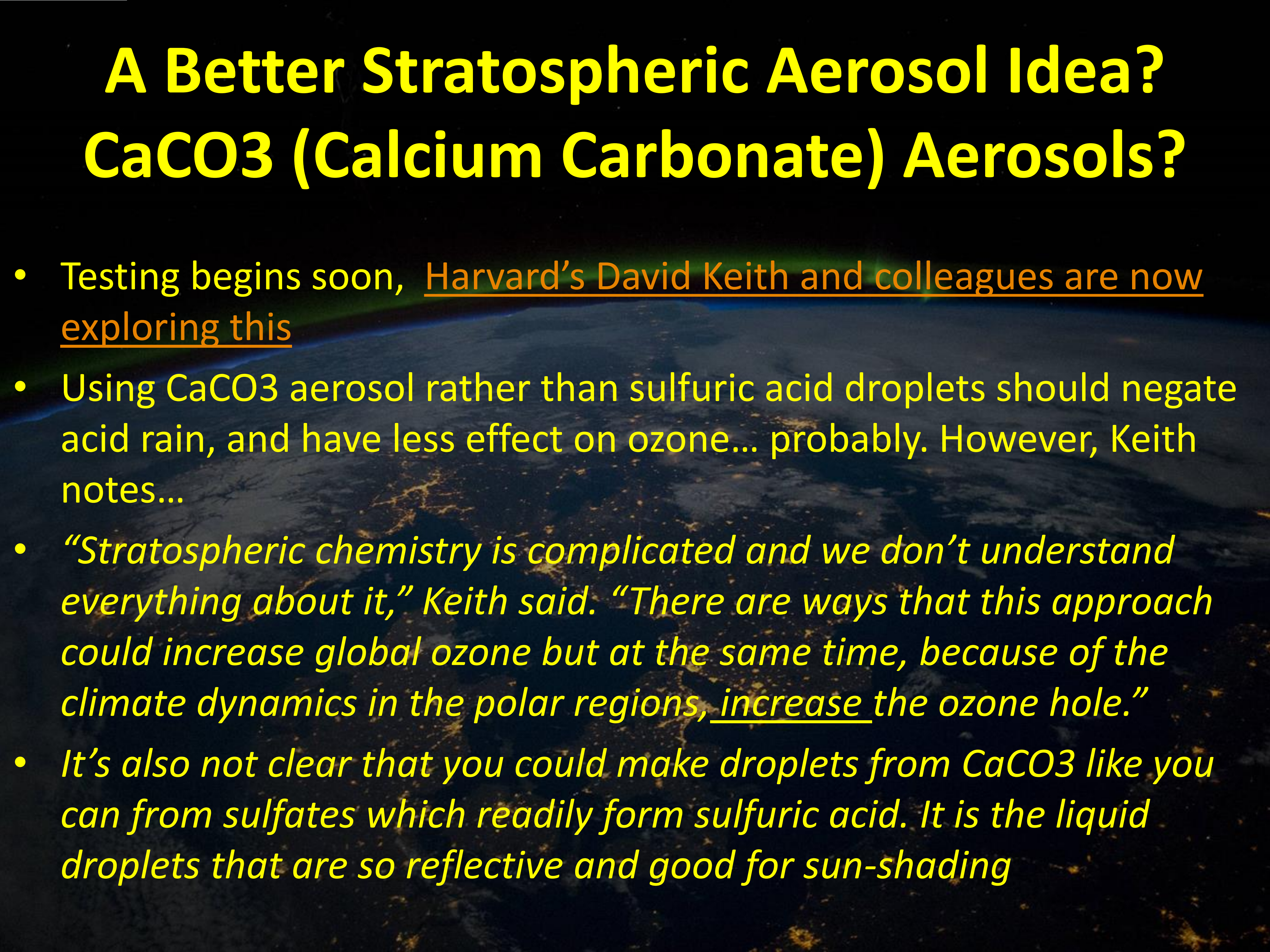
Benefits	*Risks*
1. Reduce surface air temperatures*, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting*, land-based ice sheet melting, and sea level rise* 2. Increase plant productivity* 3. Increase terrestrial CO_2 sink* 4. Beautiful red and yellow sunsets* 5. Unexpected benefits	1. Drought in Africa and Asia* 2. Perturb ecology with more diffuse radiation* 3. Ozone depletion, with more UV at surface* 4. Whiter skies* 5. Less solar energy generation* 6. Degrade passive solar heating 7. Environmental impact of implementation 8. Rapid warming if stopped* 9. Cannot stop effects quickly 10. Human error 11. Unexpected consequences 12. Commercial control 13. Military use of technology 14. Conflicts with current treaties 15. Whose hand on the thermostat? 16. Degrade terrestrial optical astronomy* 17. Affect stargazing* 18. Affect satellite remote sensing* 19. Societal disruption, conflict between countries 20. Effects on airplanes flying in stratosphere* 21. Effects on electrical properties of atmosphere 22. More sunburn (from diffuse radiation) 23. Continued ocean acidification 24. Impacts on tropospheric chemistry 25. Moral hazard – the prospect of it working would reduce drive for mitigation 26. Moral authority – do we have the right to do this?



Difficult, thorny risk/benefit tally for stratospheric sulfate injection idea Robock (2014) Robock finds the risks outweigh and argues against

“Barking Mad”?

- Harvard professor James Anderson: we need to do real-world experiments to find out.
- Geophysicist Raymond Pierre-Humbert judges the idea “barking mad”.
- Award winning environmental film maker David Suzuki calls the idea “insane”
- Rutgers Professor Martin Bunzl argues that the worst problem with stratospheric aerosol SRM is that it cannot be tested. It can only be fully implemented and then wait long enough for the signal of its effects to rise above the weather statistical noise and find out if it was a good idea. Global weather patterns WILL be affected, in poorly known ways.



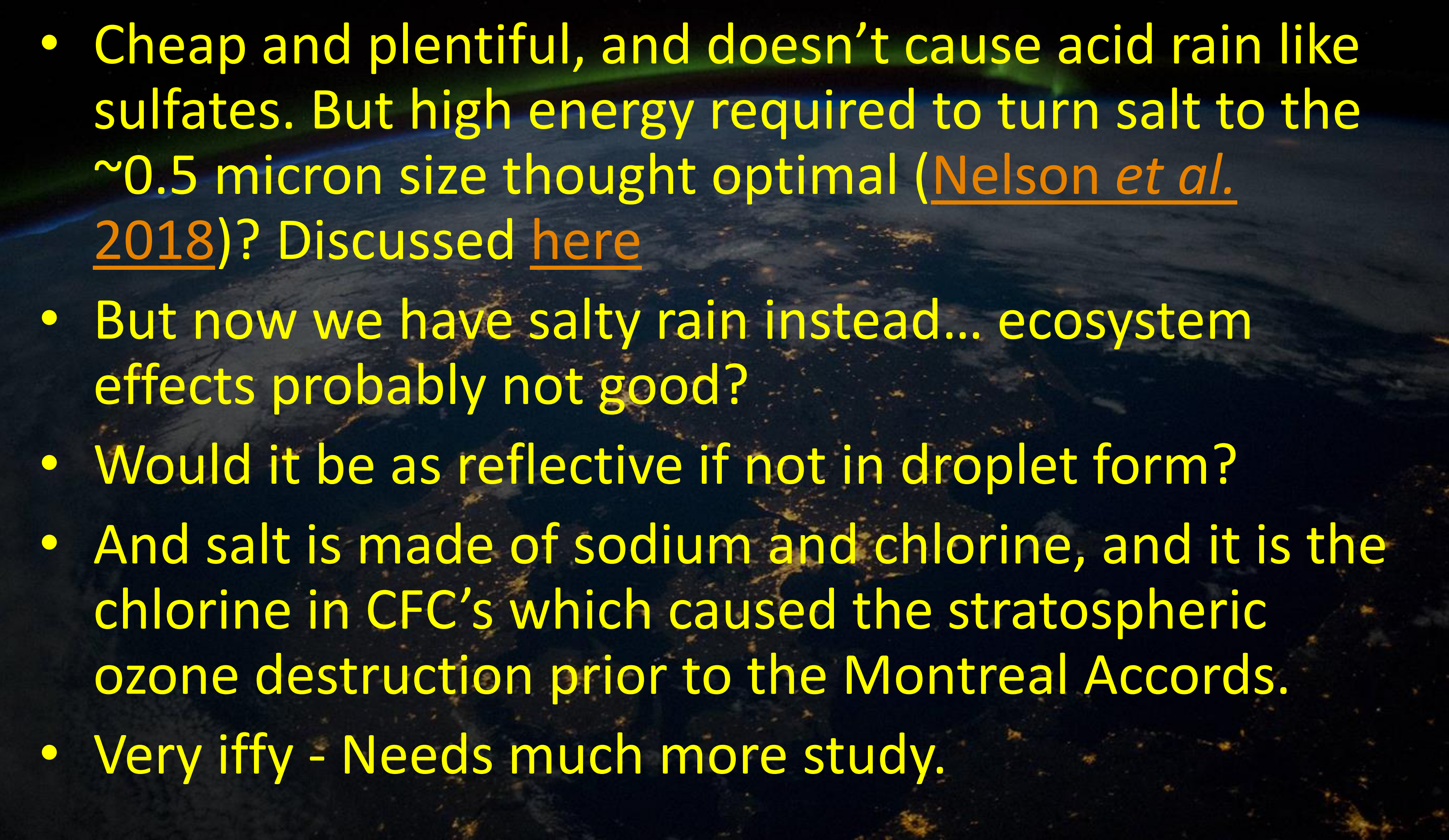
A Better Stratospheric Aerosol Idea?
CaCO3 (Calcium Carbonate) Aerosols?

- Testing begins soon, Harvard’s David Keith and colleagues are now exploring this
- Using CaCO3 aerosol rather than sulfuric acid droplets should negate acid rain, and have less effect on ozone… probably. However, Keith notes…
- *“Stratospheric chemistry is complicated and we don’t understand everything about it,” Keith said. “There are ways that this approach could increase global ozone but at the same time, because of the climate dynamics in the polar regions, increase the ozone hole.”*
- *It’s also not clear that you could make droplets from CaCO3 like you can from sulfates which readily form sulfuric acid. It is the liquid droplets that are so reflective and good for sun-shading*

Calcium Carbonate Problems

- Unlike sulfates, CaCO3 might require highly energy-intensive pulverizing of massive quantities of limestone, energy which now would have to be fossil-fuel energy.
- Would CaCO3 form droplets at all? It is the liquid droplets of sulfuric acid which are so highly reflective and accomplish the cooling with sulfate aerosol injection
- There are no acidic droplets using CaCO3, but that may also mean there’s not as much albedo help. Not clear at present.
- Alteration of global weather patterns still would remain a danger, just as with sulfates

How about Pulverized Salt in the Stratosphere?



- Cheap and plentiful, and doesn’t cause acid rain like sulfates. But high energy required to turn salt to the ~0.5 micron size thought optimal (Nelson *et al.* 2018)? Discussed here
- But now we have salty rain instead… ecosystem effects probably not good?
- Would it be as reflective if not in droplet form?
- And salt is made of sodium and chlorine, and it is the chlorine in CFC’s which caused the stratospheric ozone destruction prior to the Montreal Accords.
- Very iffy - Needs much more study.

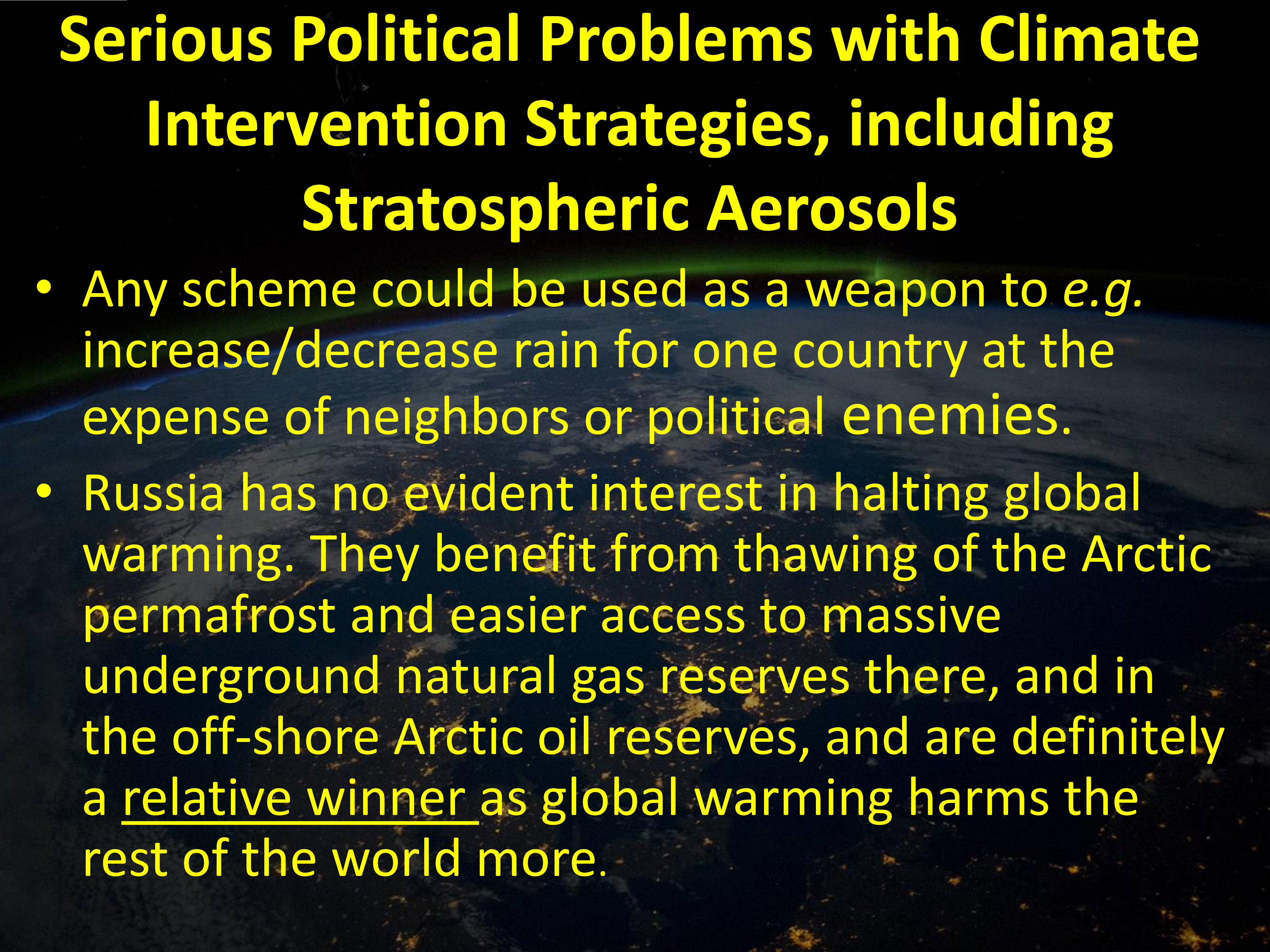
An SRM Issue I don’t see Discussed:

- The nature of the process means that the major cooling will be where there is the major sunlight – the tropics, daytime side.
- Yet radiative cooling is from all sides of Earth, and that is not changed in this strategy.
- A global shift in the temperature gradients across the Earth will cause large and hard to predict changes in the global atmospheric circulation and ocean currents which re-distribute heat, and also guide the rain-making weather systems.

Aerosol injection could be a strong disruptor of the climate the Earth System has adapted to for 10,000 yrs.

- Global civilization for thousands of years has been built and fine-tuned around precisely the rain patterns that have been stable during the history of civilization.
- Now, there will be rain “winners” and rain “losers” among continents and countries.
- What will the losers do? Shoot down the aerosol-makers? Start wars? Do their own counter-attacks with even more poorly understood climate weapons?

Serious Political Problems with Climate Intervention Strategies, including Stratospheric Aerosols



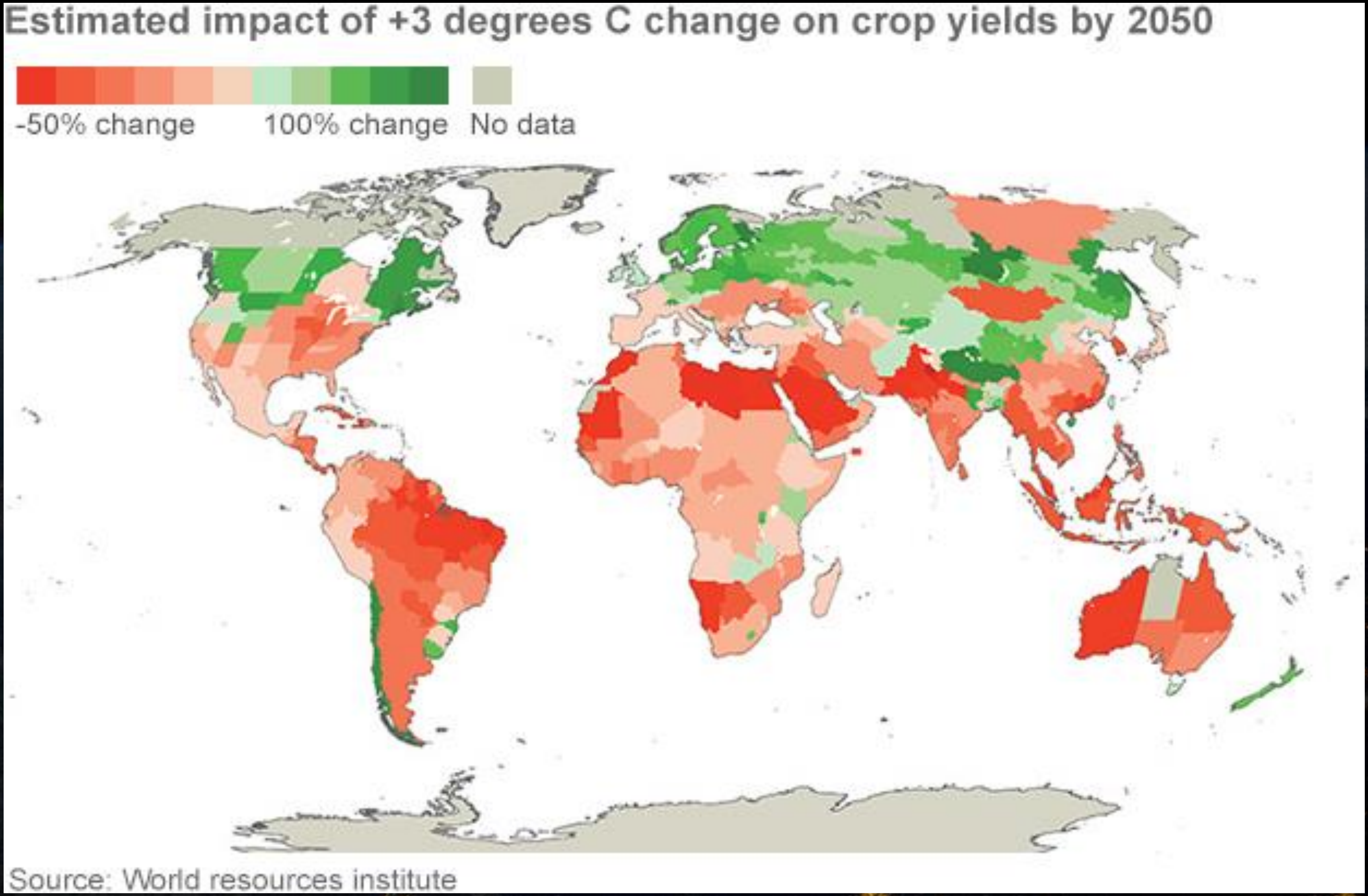
- Any scheme could be used as a weapon to *e.g.* increase/decrease rain for one country at the expense of neighbors or political enemies.
- Russia has no evident interest in halting global warming. They benefit from thawing of the Arctic permafrost and easier access to massive underground natural gas reserves there, and in the off-shore Arctic oil reserves, and are definitely a <u>relative winner</u> as global warming harms the rest of the world more.

Russian President Putin plans to take advantage of the melting of the Arctic (links here)

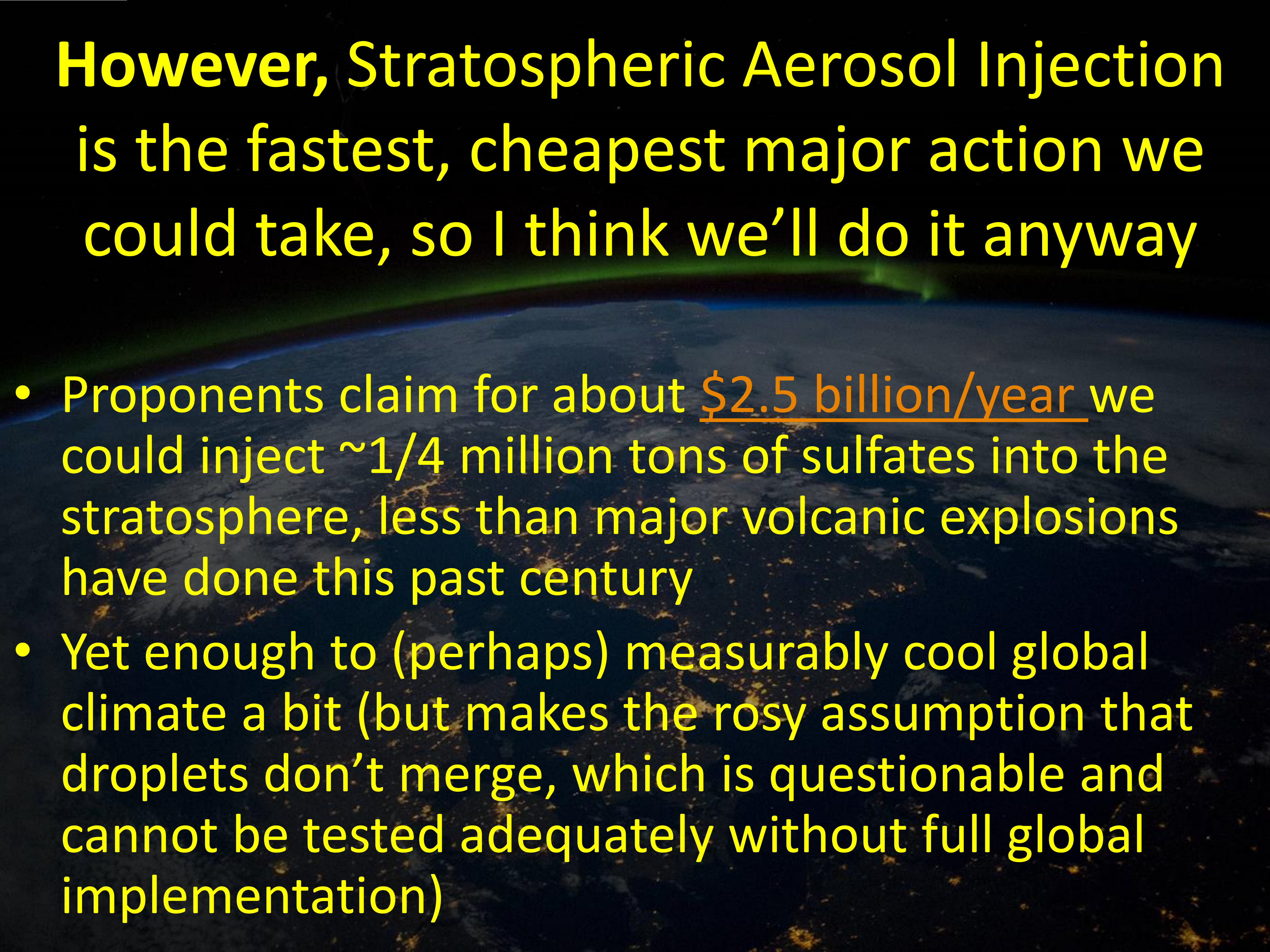
Climate change could make Russia great again - Science ...

Any unilateral attempt by the US and/or Europe to begin massive stratospheric aerosol injection may well be regarded as an Act of War.

Russia and Canada are also relative crop yield winners from climate change, and thawing permafrost also helps Russia access frozen oil, gas fields, Siberian Shelf carbon


Estimated impact of +3 degrees C change on crop yields by 2050

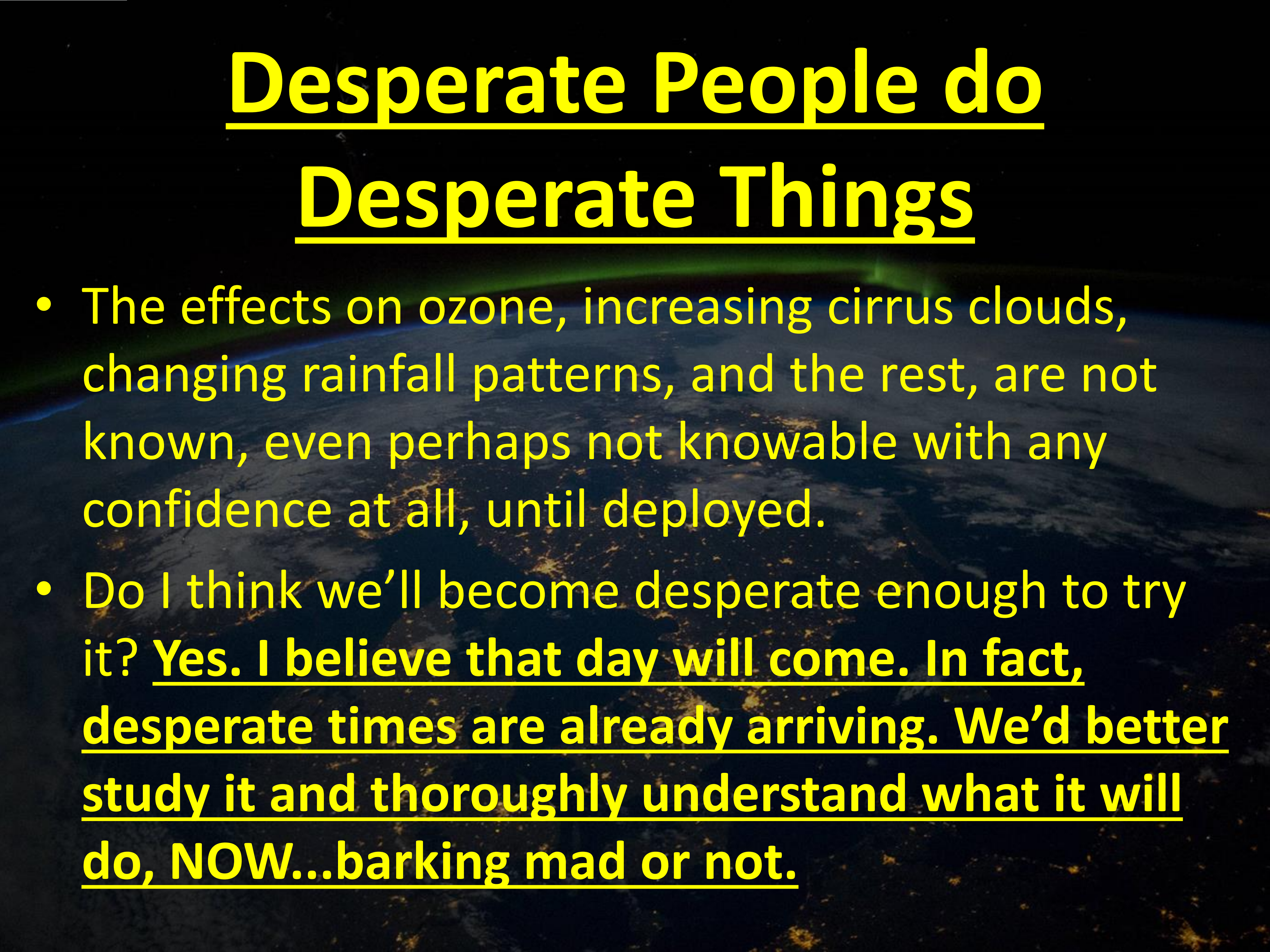
Source: World resources institute



However, Stratospheric Aerosol Injection is the fastest, cheapest major action we could take, so I think we’ll do it anyway

- Proponents claim for about $2.5 billion/year we could inject ~1/4 million tons of sulfates into the stratosphere, less than major volcanic explosions have done this past century
- Yet enough to (perhaps) measurably cool global climate a bit (but makes the rosy assumption that droplets don’t merge, which is questionable and cannot be tested adequately without full global implementation)

Desperate People do Desperate Things



- The effects on ozone, increasing cirrus clouds, changing rainfall patterns, and the rest, are not known, even perhaps not knowable with any confidence at all, until deployed.
- Do I think we'll become desperate enough to try it? **Yes. I believe that day will come. In fact, desperate times are already arriving. We'd better study it and thoroughly understand what it will do, NOW...barking mad or not.**

Capturing CO2 by Accelerated Weathering of Limestone

- Greg Rau (UCSC) - the basic idea is to crush limestone, combine it with carbonated water, and capture the CO2 in the form of calcium bicarbonate. The pH of the bicarbonate makes it fairly safe to simply deposit into the ocean

$$CO_{2(g)} + CaCO_{3(s)} + H_2O_{(l)} \Rightarrow Ca^{2+}_{(aq)} + 2HCO_3^{-}{}_{(aq)}.$$

- His paper explores the cost of CO2 capture from natural gas fired power plants. Cost estimated at ~$40/ton of **flue gas** CO2 sequestered. (YouTube promo seeking funding). But that's for high-CO2-concentration power plant flue gas, not dilute 400ppm atmospheric concentrations, which would be MUCH costlier.
- http://aftre.nssga.org/Symposium/2004-09.pdf
- I've not found updates to this, but Rau has a new process which may be better

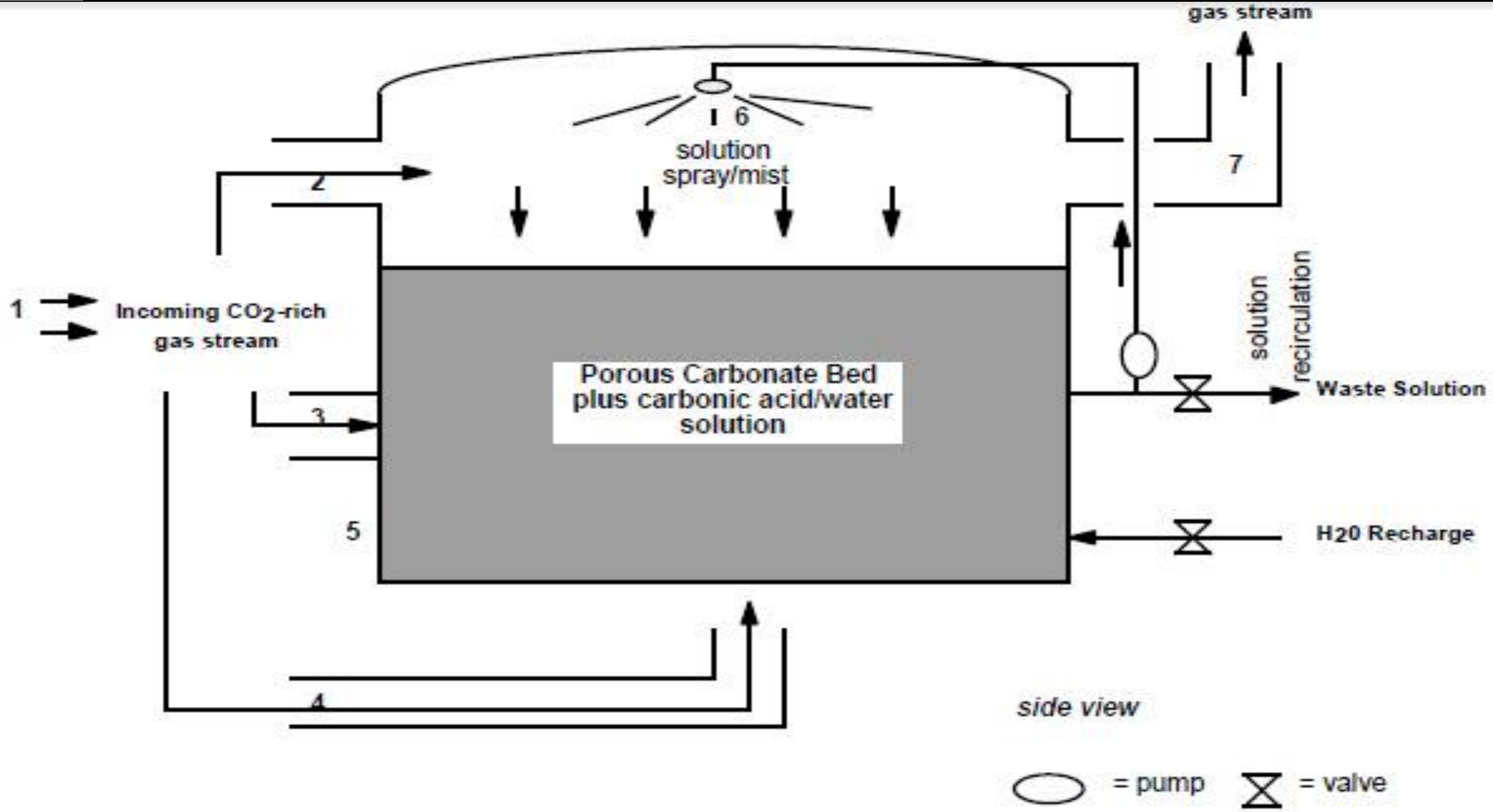
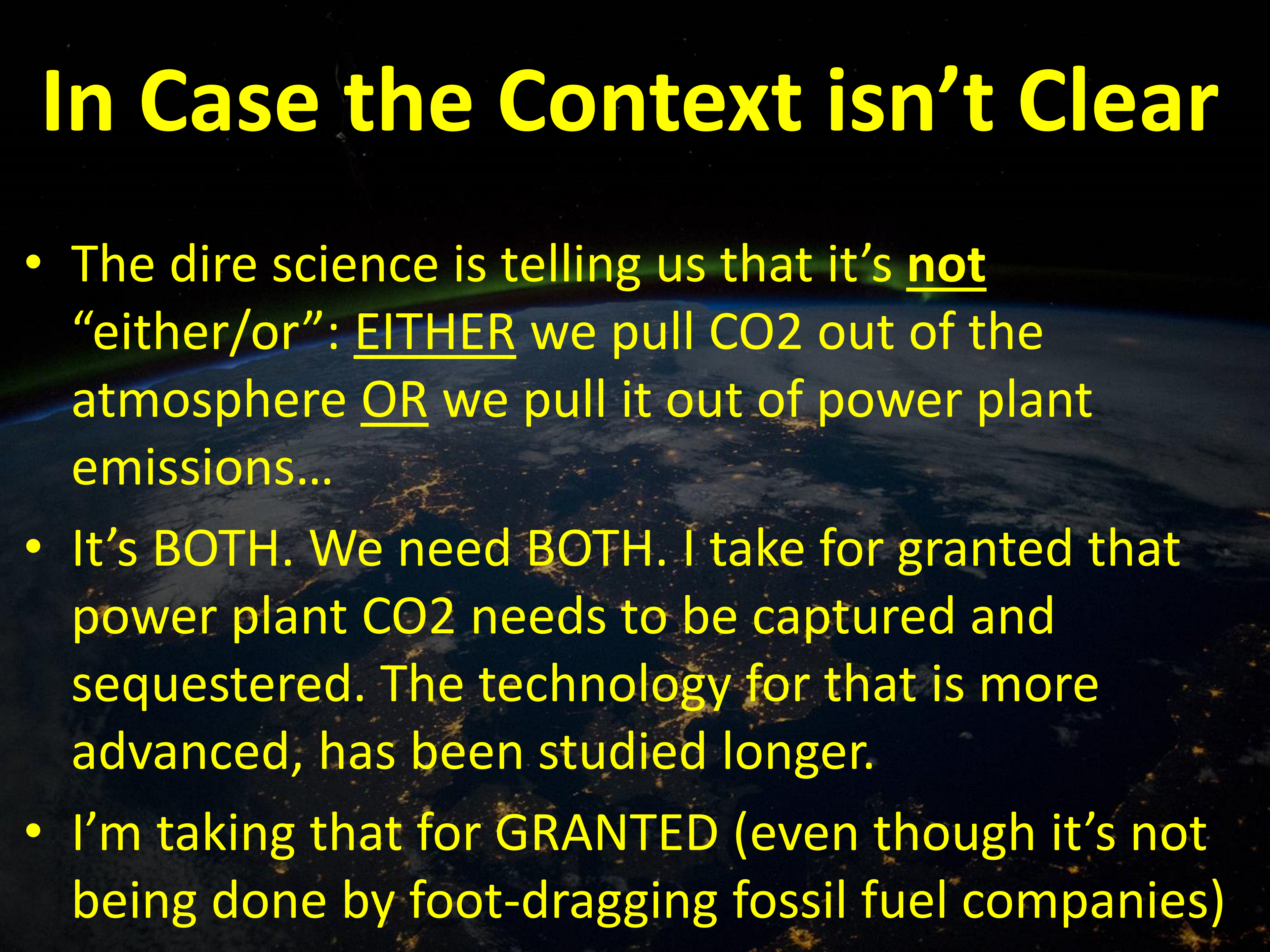


Figure 1. An example of a possible carbonate dissolution reactor design. A CO_2-rich gas stream (1) enters the reactor vessel (5) by one or more entryways (e.g., 2, 3, and/or 4). The gas stream then passes over or through a wetted, porous bed of limestone particles within the reactor. This carbonate mass is sprayed (6) and wetted with and partially submerged in a water/carbonic acid solution which is unsaturated with respect to bicarbonate ion. This arrangement exposes the incoming gas to a large surface area of water/solution in the form of droplets and wetted carbonate particle surfaces in (5), facilitating hydration of the entering CO_2 to form a carbonic acid solution within the reactor. CO_2-depleted gas then exits the reactor (7). The carbonic acid solution formed reacts with the carbonate to form calcium ions and bicarbonate in solution which is either recirculated or bled from the reactor and replaced with unreacted water within the reactor at a rate which maximizes benefit/cost.

In Case the Context isn't Clear



- The dire science is telling us that it's **not** "either/or": EITHER we pull CO2 out of the atmosphere OR we pull it out of power plant emissions…
- It's BOTH. We need BOTH. I take for granted that power plant CO2 needs to be captured and sequestered. The technology for that is more advanced, has been studied longer.
- I'm taking that for GRANTED (even though it's not being done by foot-dragging fossil fuel companies)

Rau’s method w/ outflow to the ocean results in minimal pH and pCO2 effects *vs.* letting atmospheric CO2 directly diffuse into surface waters

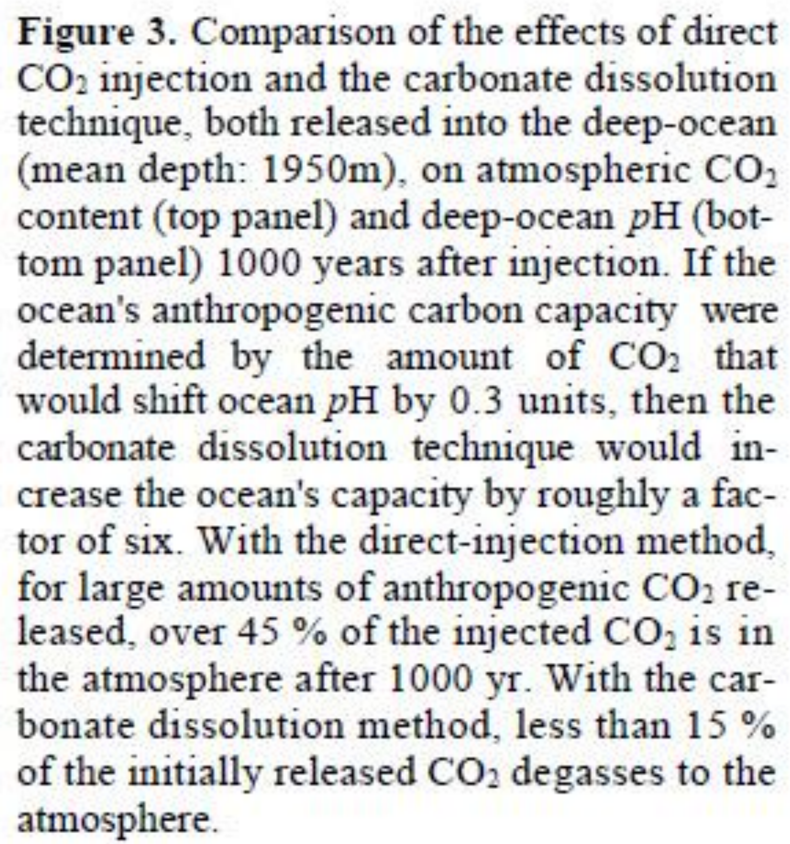
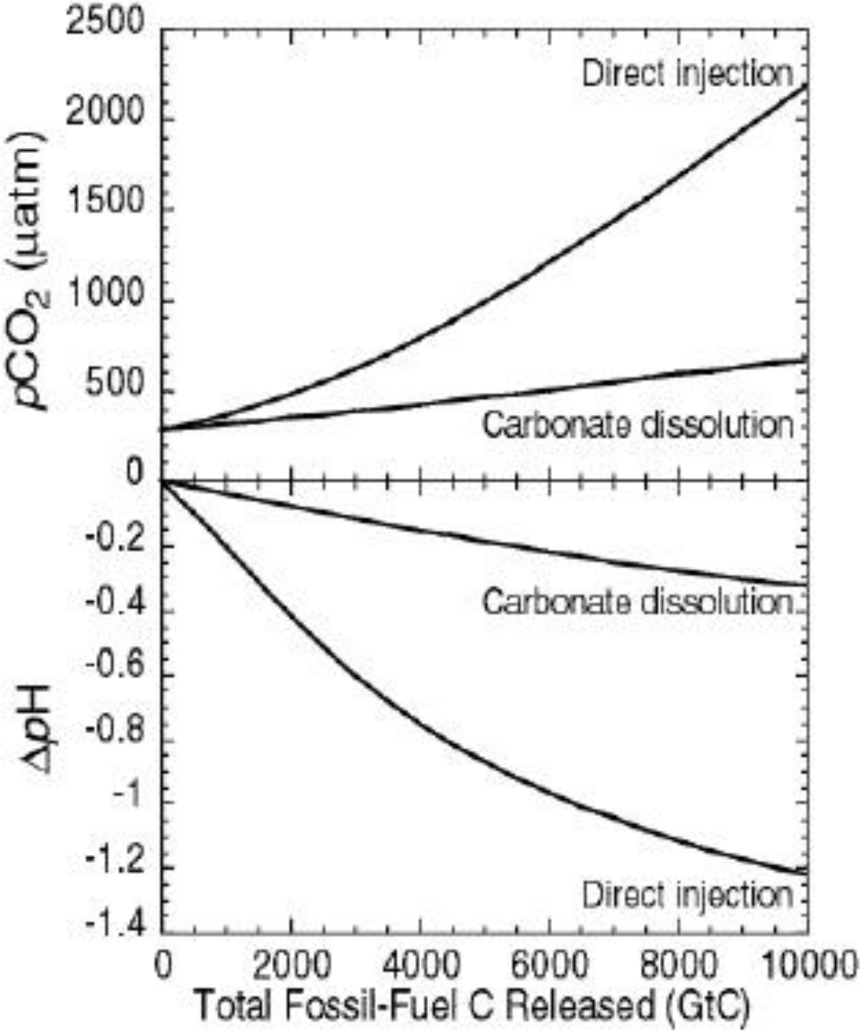


Figure 3. Comparison of the effects of direct CO_2 injection and the carbonate dissolution technique, both released into the deep-ocean (mean depth: 1950m), on atmospheric CO_2 content (top panel) and deep-ocean *p*H (bottom panel) 1000 years after injection. If the ocean's anthropogenic carbon capacity were determined by the amount of CO_2 that would shift ocean *p*H by 0.3 units, then the carbonate dissolution technique would increase the ocean's capacity by roughly a factor of six. With the direct-injection method, for large amounts of anthropogenic CO_2 released, over 45 % of the injected CO_2 is in the atmosphere after 1000 yr. With the carbonate dissolution method, less than 15 % of the initially released CO_2 degasses to the atmosphere.

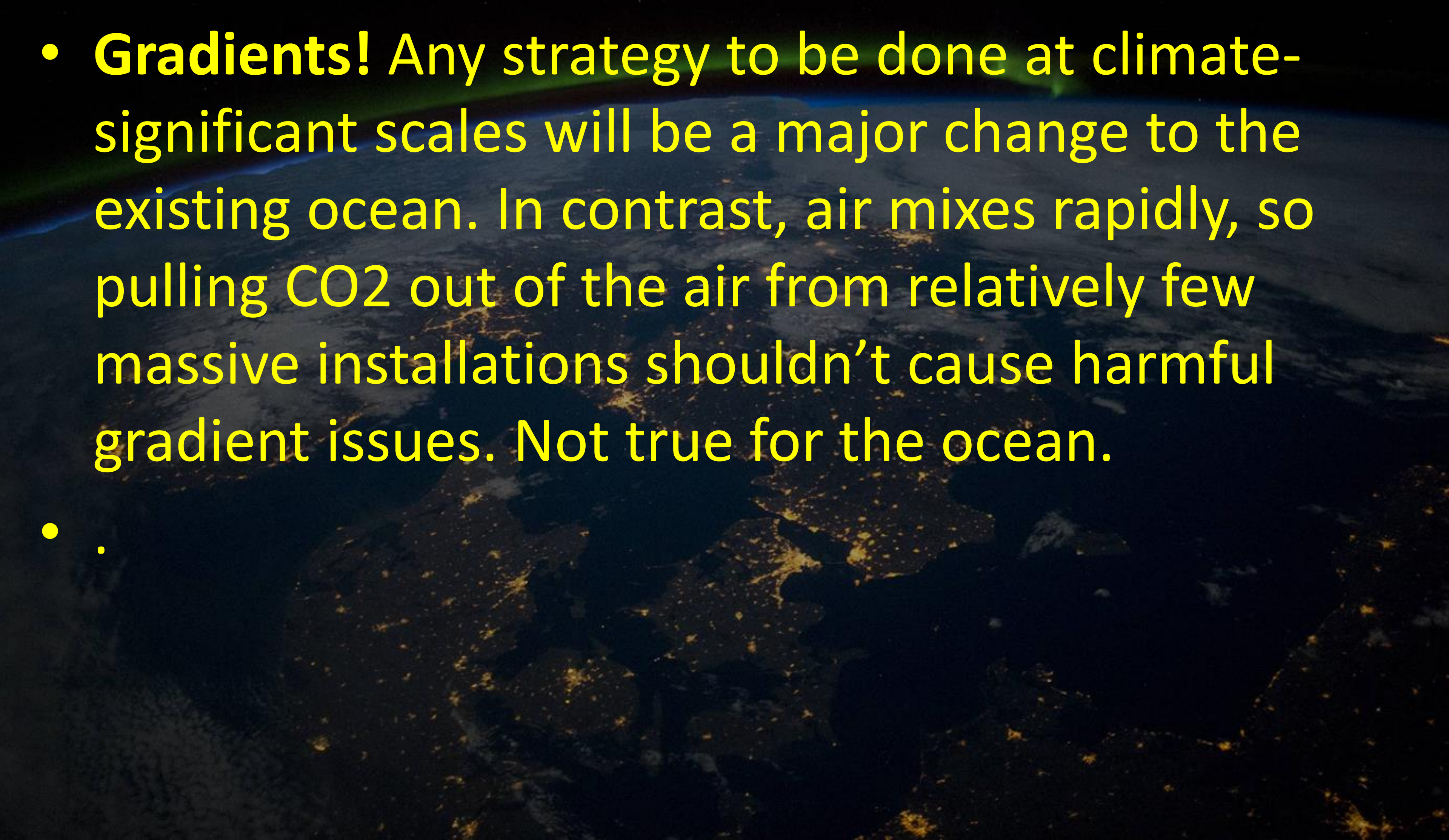


Rau’s Silicate or Limestone Processes are among the safer CO2 removal mechanisms I’ve yet found. However, up-scaling to address climate does not look feasible

- Requires ready source of limestone, so could only be done on large scale from certain coastal locations?
- Results in equilibrium pH change in ocean, after 1000 years, of -0.0014 per 35B tons CO2 processed. (35B tons CO2/yr was about the current rate that we’re injecting CO2 into atmosphere), and this is acceptable in terms of its effect on ocean life (compare to our ocean slide show on pH rate of change today)
- More figures and power requirements should be done – it’s worth a careful examination

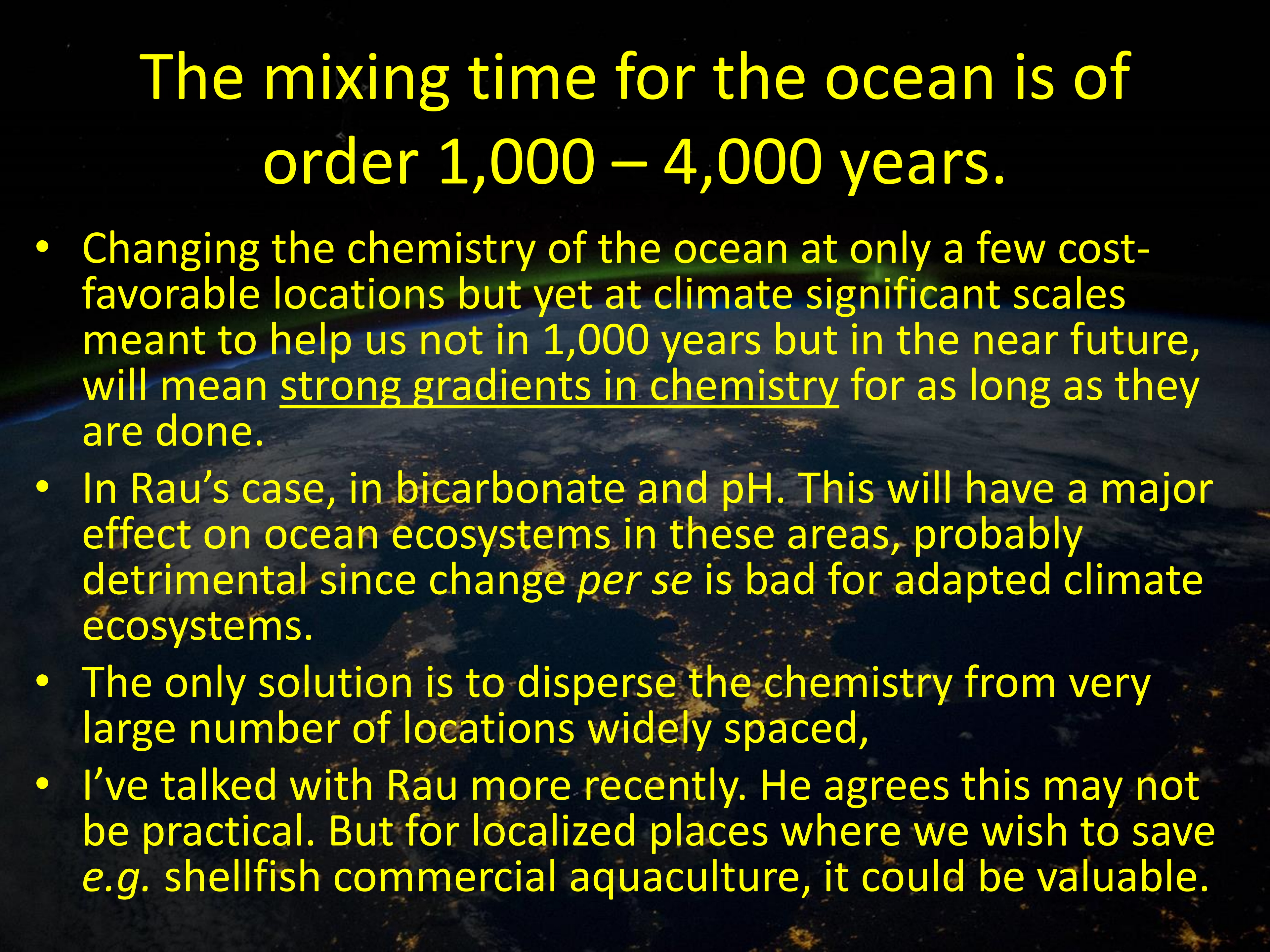
- In 2012 I contacted Greg Rau (he’s a professor here at UC Santa Cruz) and suggested he consider ways to apply his chemical process not only to flue gas, but to the atmosphere.
- He has since teamed with Klaus Lackner…
- Rau and Lackner – together! (but behind paywall!)
- Here’s a YouTube with Rau

Ocean Chemistry Modifications in General Share a Major Problem…

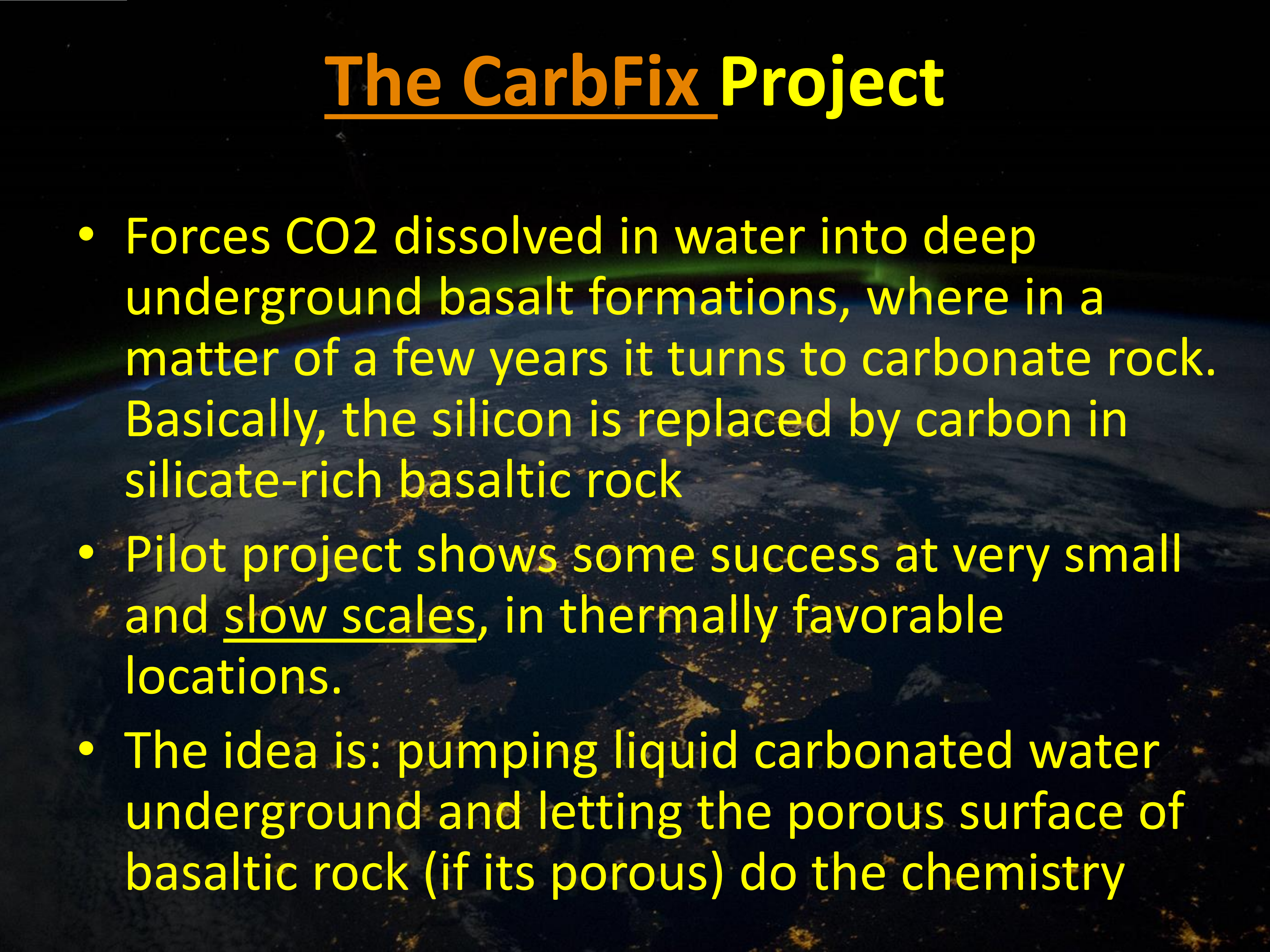


- **Gradients!** Any strategy to be done at climate-significant scales will be a major change to the existing ocean. In contrast, air mixes rapidly, so pulling CO2 out of the air from relatively few massive installations shouldn’t cause harmful gradient issues. Not true for the ocean.
- .

The mixing time for the ocean is of order 1,000 – 4,000 years.



- Changing the chemistry of the ocean at only a few cost-favorable locations but yet at climate significant scales meant to help us not in 1,000 years but in the near future, will mean strong gradients in chemistry for as long as they are done.
- In Rau’s case, in bicarbonate and pH. This will have a major effect on ocean ecosystems in these areas, probably detrimental since change *per se* is bad for adapted climate ecosystems.
- The only solution is to disperse the chemistry from very large number of locations widely spaced,
- I’ve talked with Rau more recently. He agrees this may not be practical. But for localized places where we wish to save *e.g.* shellfish commercial aquaculture, it could be valuable.



The CarbFix Project

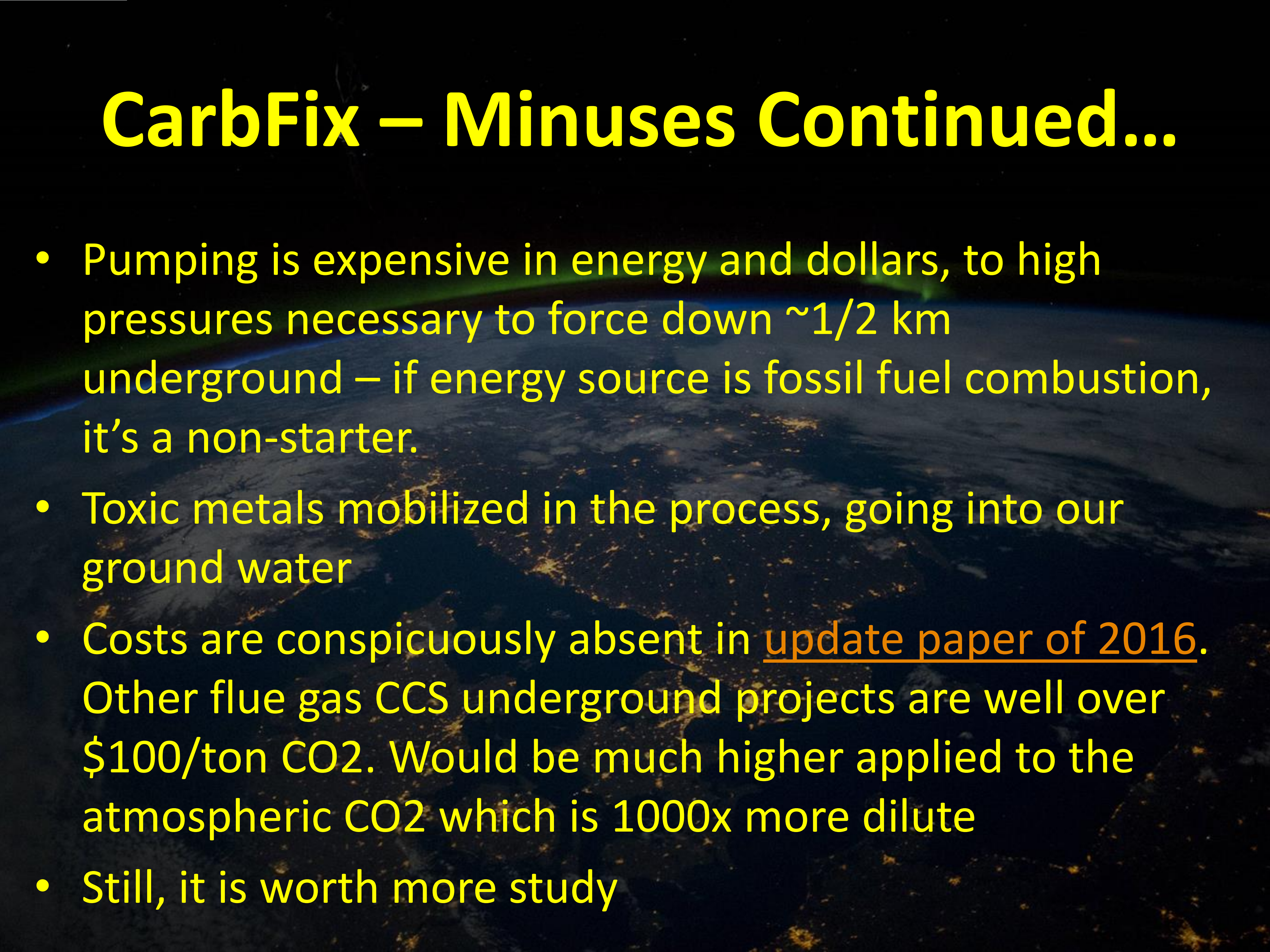
- Forces CO2 dissolved in water into deep underground basalt formations, where in a matter of a few years it turns to carbonate rock. Basically, the silicon is replaced by carbon in silicate-rich basaltic rock
- Pilot project shows some success at very small and slow scales, in thermally favorable locations.
- The idea is: pumping liquid carbonated water underground and letting the porous surface of basaltic rock (if its porous) do the chemistry

Can CarbFix Work on a GeoEngineering Scale?

- On the plus side…
- The required basalt is common worldwide. The Pacific Northwest Columbia River formation might, optimistically, hold 100 Gt of CO2, or ~3 years of current annual global CO2 emissions
- Original paper (Matter *et al.* 2009) was a decade ago. The latest update (Matter *et al.* 2016) shows that if the water is pre-alkalized sufficiently (cost??), then mineralization of their small pilot project amounts still took fully 2 years to happen. That's **Slow.**

CarbFix – Minuses…

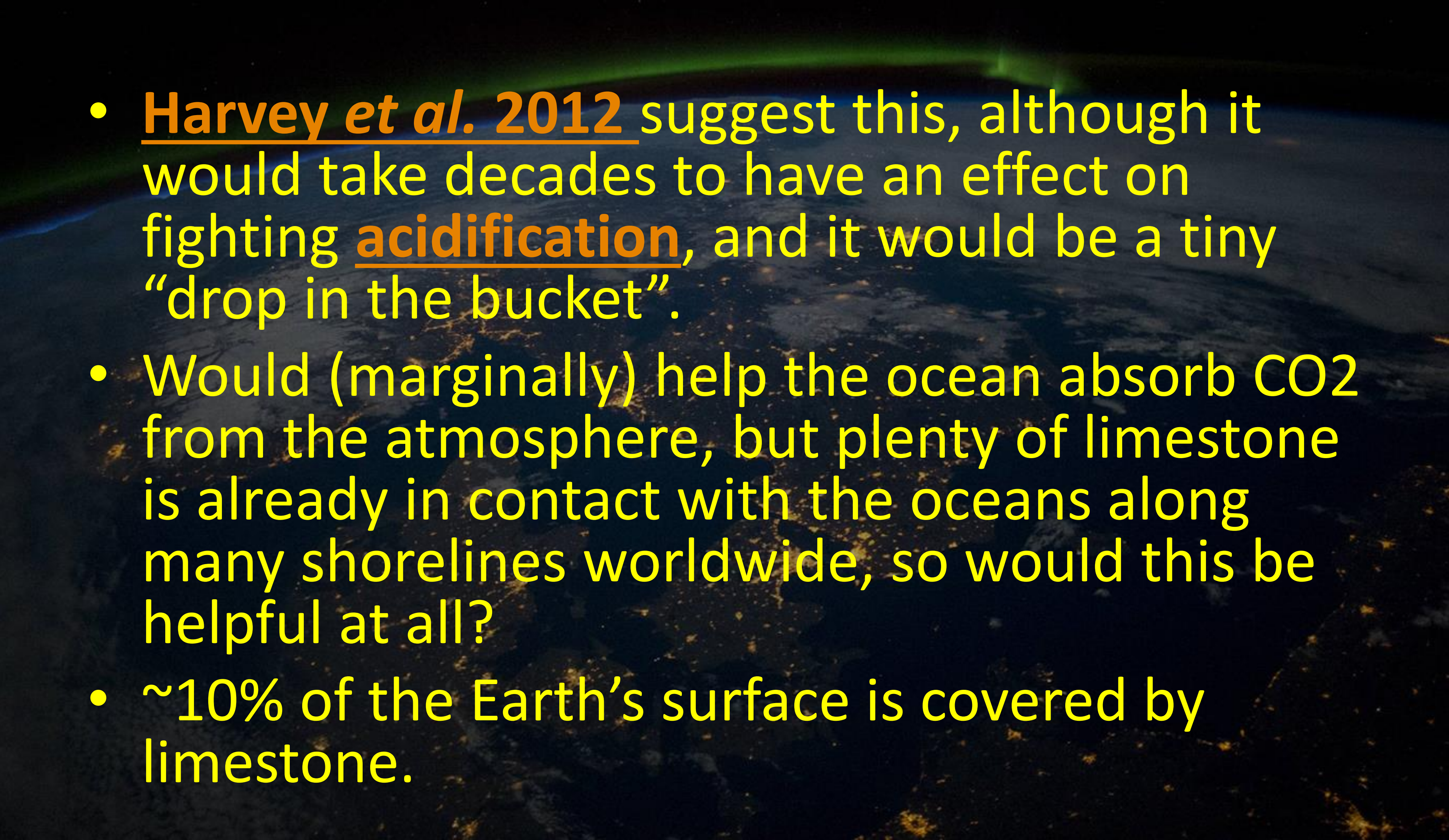
- Requires 25 tons of water for every 1 ton of CO2
- Pilot project only injected a few hundred tons of CO2. This is microscopic on climate scales. How much CO2 can really be injected at a given site before it plugs up, and yet after all the costly pumping infrastructure has been installed? Hard to know till it suddenly stops taking more injection.
- Once the contact space in the pores is covered, won’t further CO2 be isolated from the necessary rock chemistry? Not discussed, but especially worrisome on climate-relevant scales.
- Optimal contact requires powdered basalt, not rocks. Simply looking at tonnage of basalt makes the implicit assumption that all of that basalt is contact-available to the alkalized water. But basalt isn’t generally so porous that fossil ~millimeter size bubble pores connect with each other except a small fraction of the time



CarbFix – Minuses Continued…

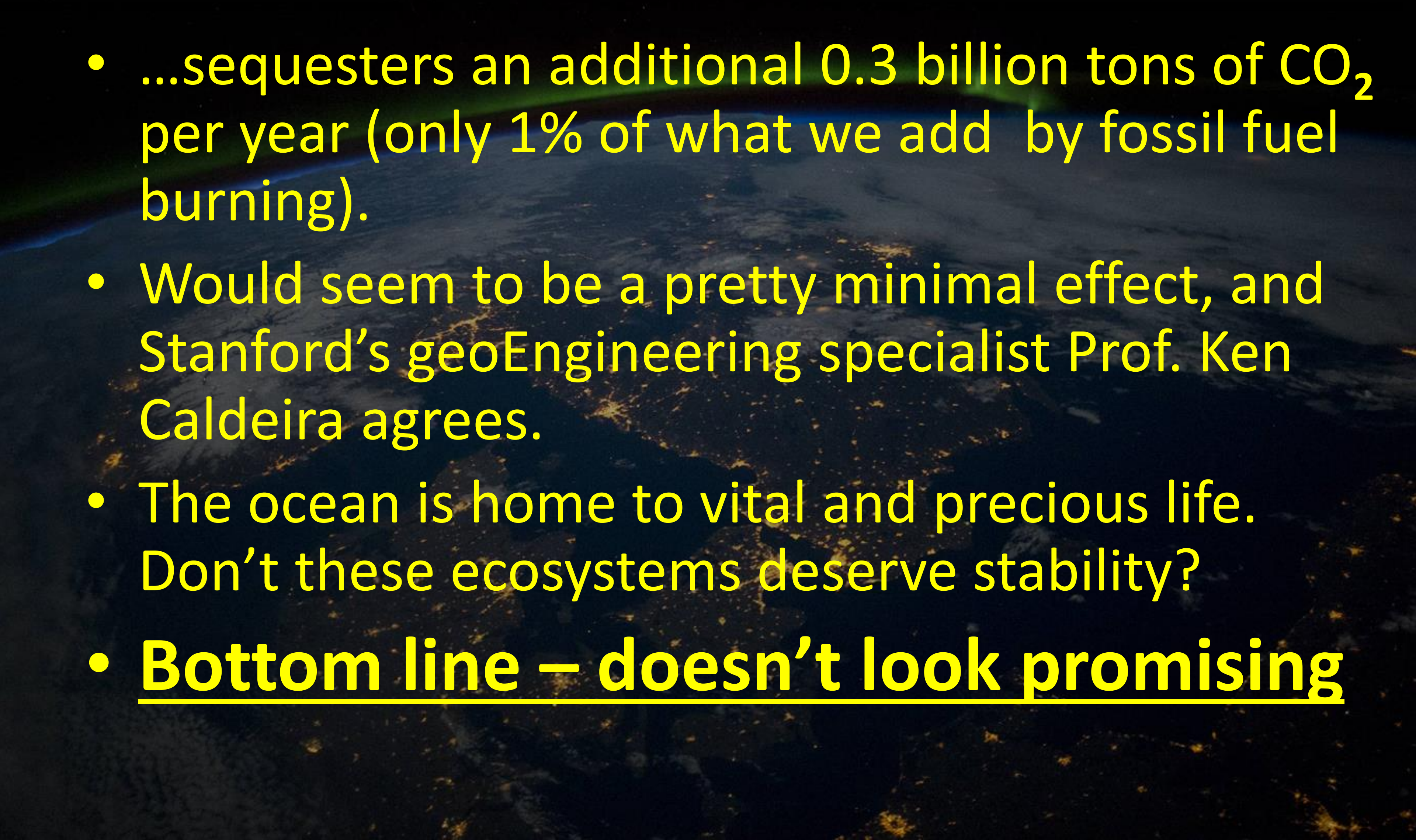
- Pumping is expensive in energy and dollars, to high pressures necessary to force down ~1/2 km underground – if energy source is fossil fuel combustion, it’s a non-starter.
- Toxic metals mobilized in the process, going into our ground water
- Costs are conspicuously absent in update paper of 2016. Other flue gas CCS underground projects are well over \$100/ton CO2. Would be much higher applied to the atmospheric CO2 which is 1000x more dilute
- Still, it is worth more study

Related: Add CaCO3=Calcium Carbonate Powder Directly to the Ocean

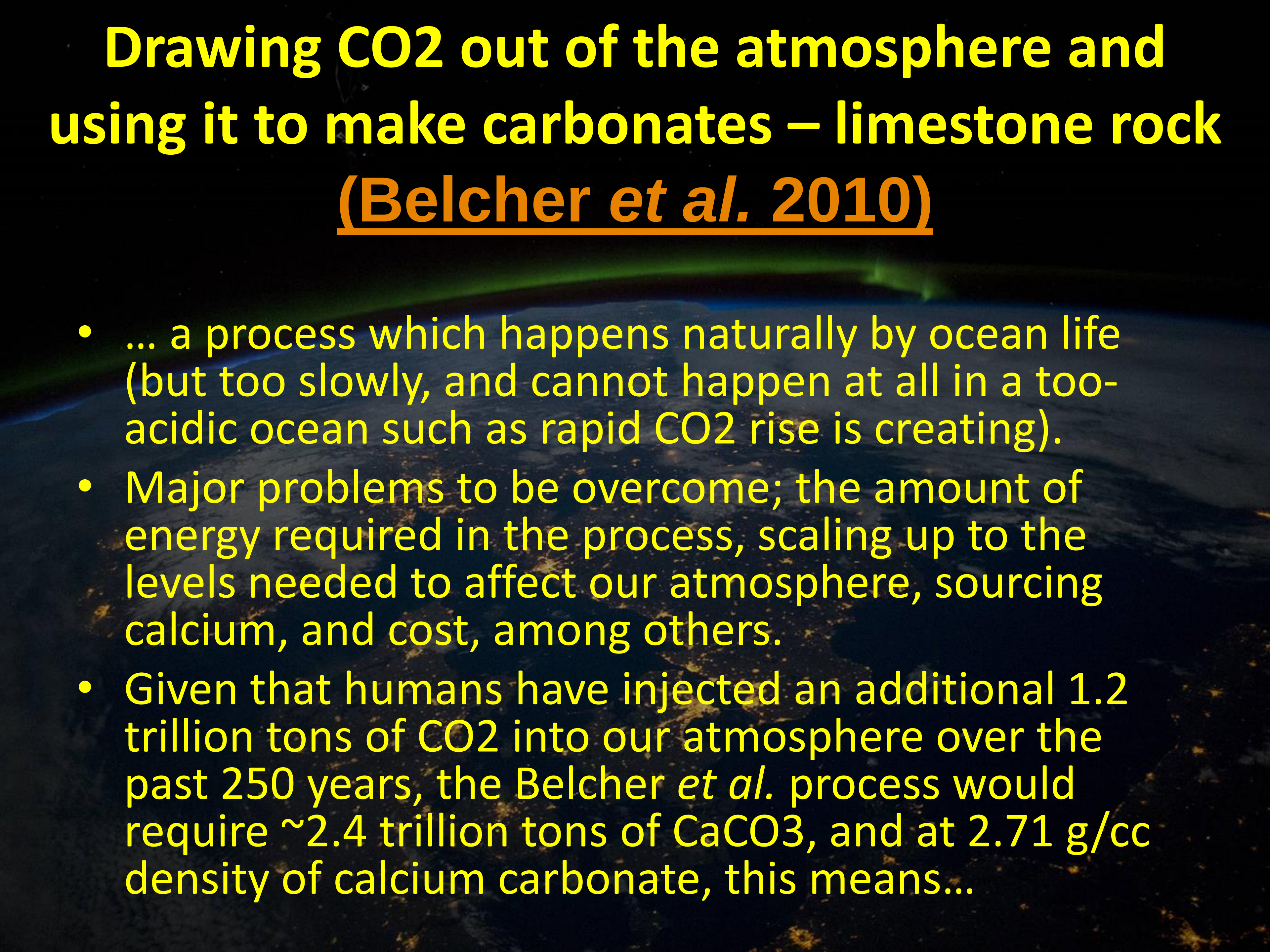


- **Harvey *et al.* 2012** suggest this, although it would take decades to have an effect on fighting **acidification**, and it would be a tiny "drop in the bucket".
- Would (marginally) help the ocean absorb CO2 from the atmosphere, but plenty of limestone is already in contact with the oceans along many shorelines worldwide, so would this be helpful at all?
- ~10% of the Earth's surface is covered by limestone.

Add CaCO3 to upwelling areas…



- …sequesters an additional 0.3 billion tons of CO_2 per year (only 1% of what we add by fossil fuel burning).
- Would seem to be a pretty minimal effect, and Stanford’s geoEngineering specialist Prof. Ken Caldeira agrees.
- The ocean is home to vital and precious life. Don’t these ecosystems deserve stability?
- **<u>Bottom line – doesn’t look promising</u>**

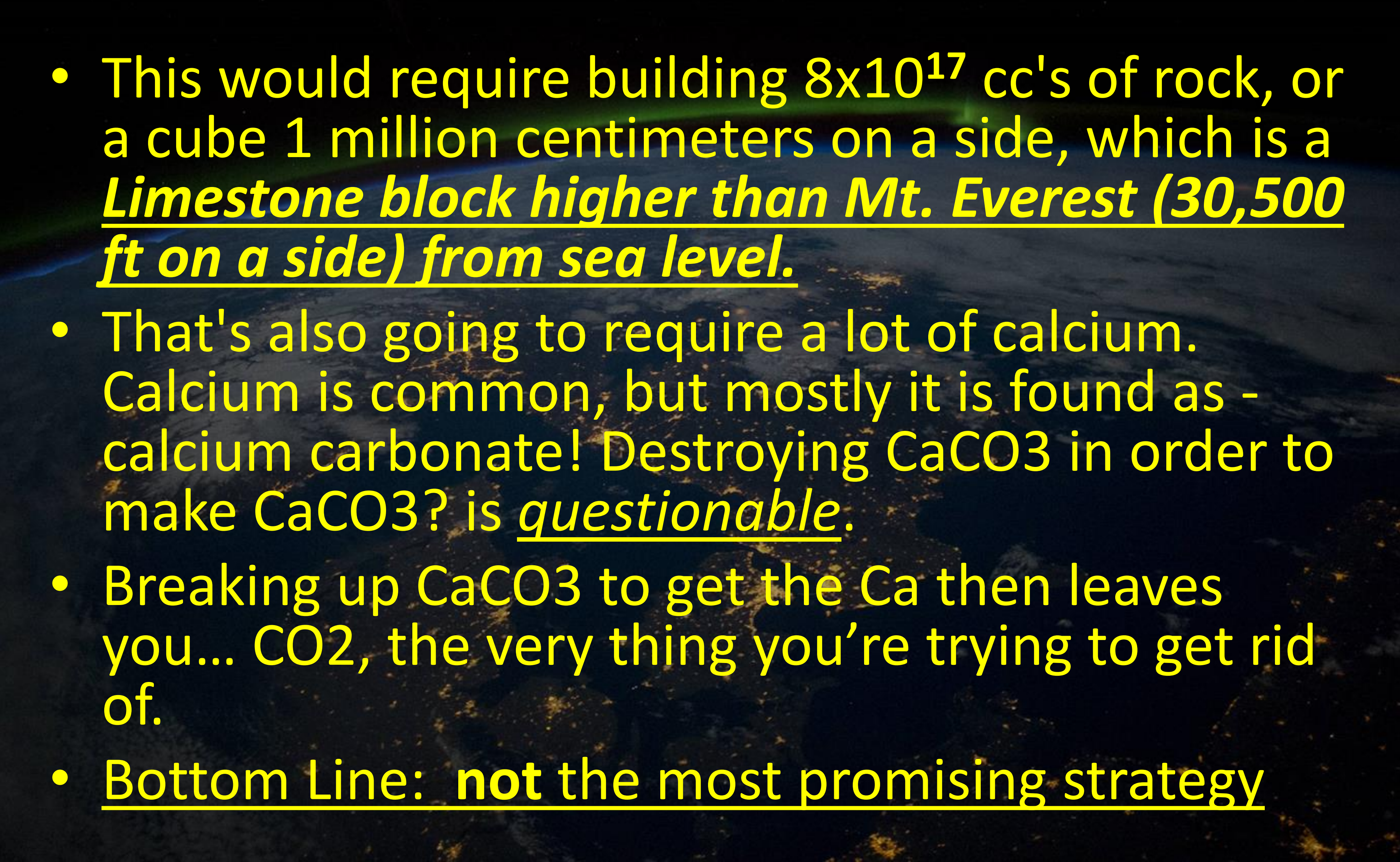


Drawing CO2 out of the atmosphere and using it to make carbonates – limestone rock

(Belcher *et al.* 2010)

- … a process which happens naturally by ocean life (but too slowly, and cannot happen at all in a too-acidic ocean such as rapid CO2 rise is creating).
- Major problems to be overcome; the amount of energy required in the process, scaling up to the levels needed to affect our atmosphere, sourcing calcium, and cost, among others.
- Given that humans have injected an additional 1.2 trillion tons of CO2 into our atmosphere over the past 250 years, the Belcher *et al.* process would require ~2.4 trillion tons of CaCO3, and at 2.71 g/cc density of calcium carbonate, this means…

Need Mt Everest-sized Block of CaCO3 to Get Back to Pre-Industrial Atmospheric CO2 Levels

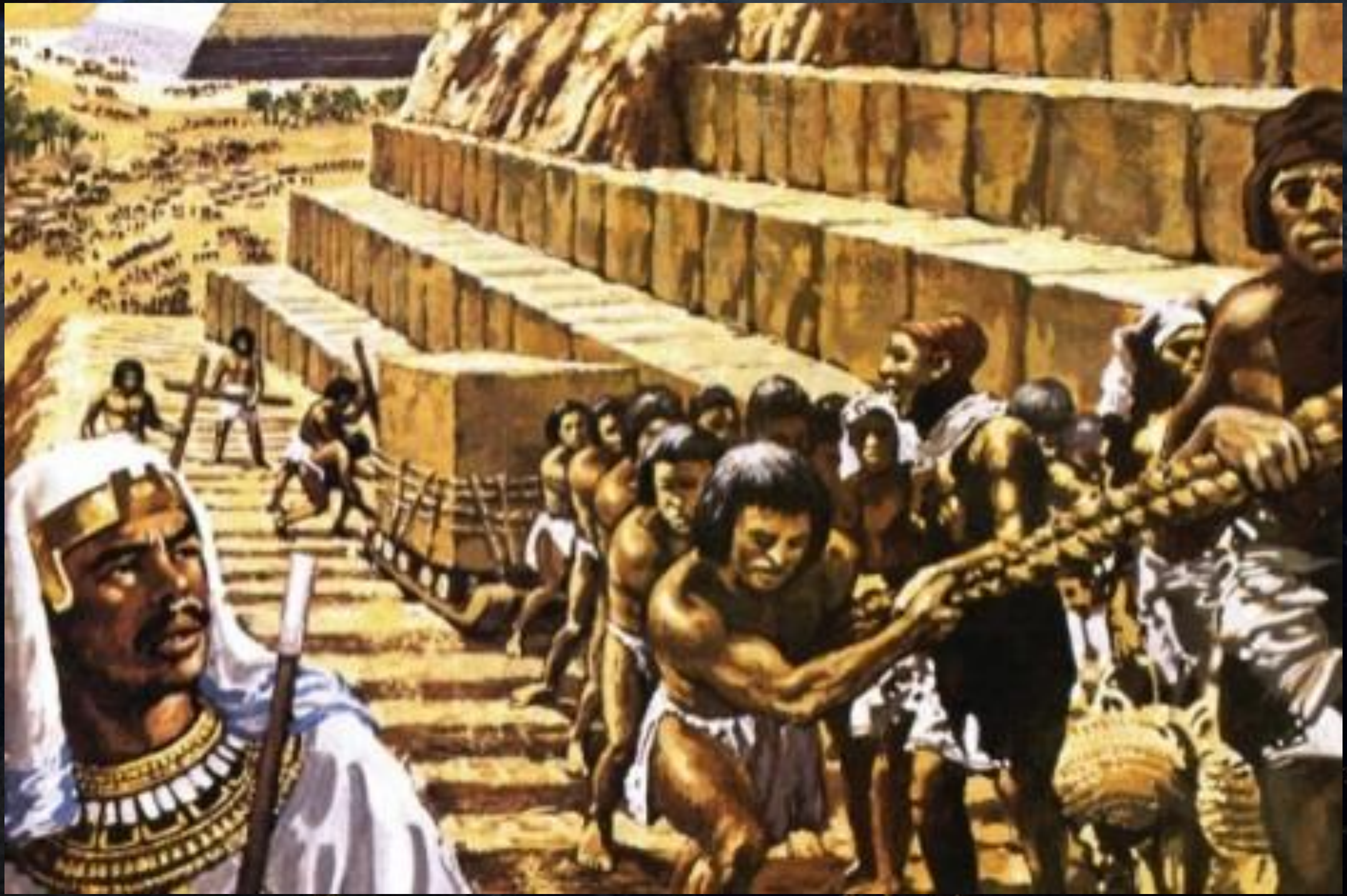


- This would require building 8x10^{17} cc's of rock, or a cube 1 million centimeters on a side, which is a ***Limestone block higher than Mt. Everest (30,500 ft on a side) from sea level.***
- That's also going to require a lot of calcium. Calcium is common, but mostly it is found as - calcium carbonate! Destroying CaCO3 in order to make CaCO3? is *questionable*.
- Breaking up CaCO3 to get the Ca then leaves you… CO2, the very thing you're trying to get rid of.
- Bottom Line: **not** the most promising strategy

Start Smaller?

- To instead immediately drop current CO2 atmospheric levels from 400 ppm to 350 ppm would require a cube of calcium carbonate of only 22,180 ft on a side; still higher than any mountain in the Western Hemisphere.
- At current production rates of ~40 billion tons of CO2 per year, it requires an additional cube-shaped mountain 8,000 ft on a side every year.
- Is it possible to build "scrubbers" for the atmosphere that could accomplish such a vast task? Where do we put it all - the ocean? We'd better make sure ocean acidification doesn’t reach levels (as they will this century, on our current trajectory) that begin to dissolve existing oceanic calcium carbonate.

On the Plus Side: Visualize oil company executives conscripted to toil under the hothouse conditions on 21st Century Earth building the Great Carbonate Pyramids, miles high, sufficient to clean up our atmosphere. At wages comparable to those of the poor souls who built the pyramids of Egypt. Likely we'd find people to donate the necessary land just for the satisfaction of watching them toil.



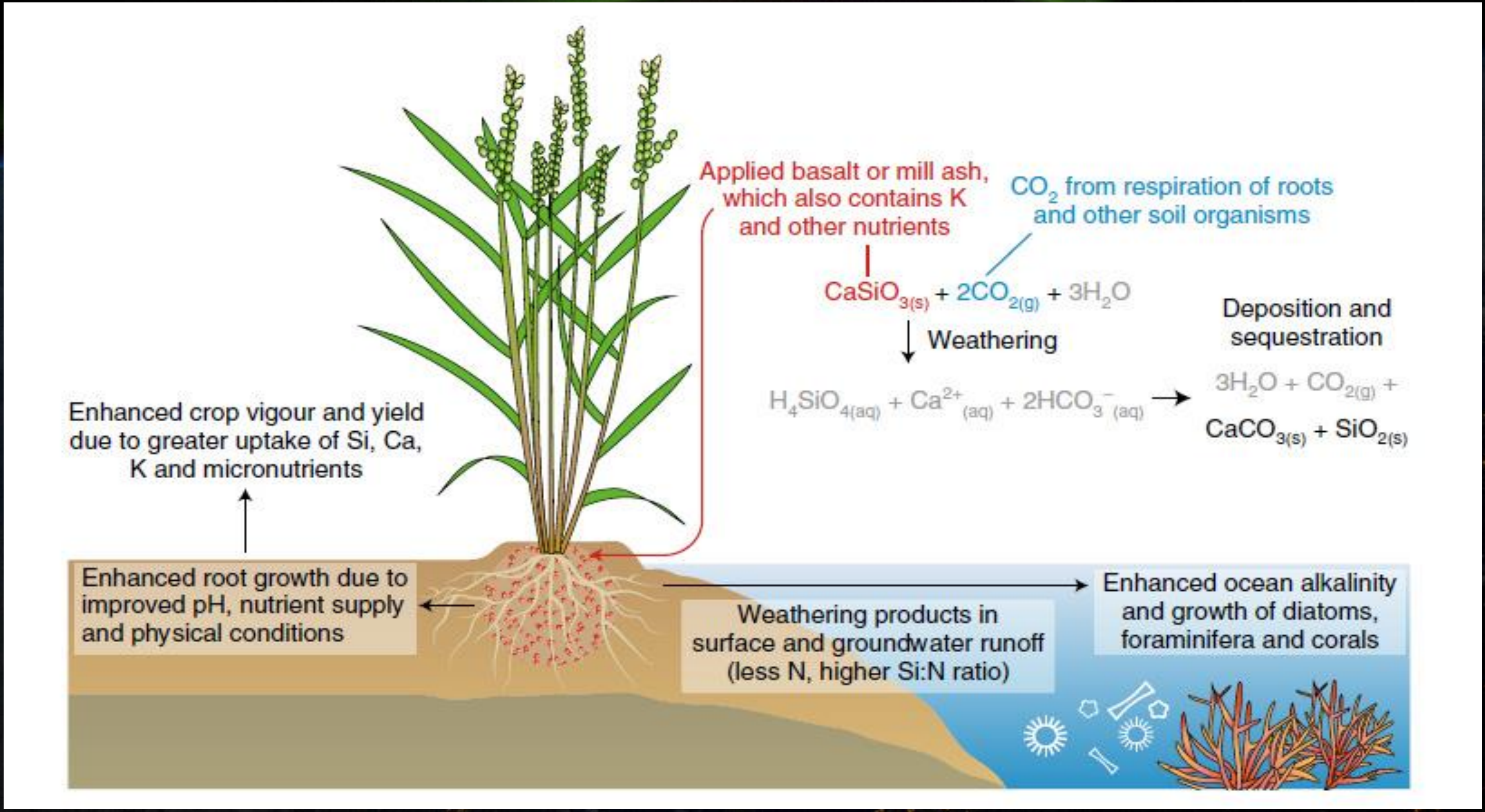
Realize Why So Hard…

- These rock-oriented ideas are all on the "Long Carbon Cycle" scale.
- We saw in **K33: Carbon Cycles**, that the equilibrium of carbon on these million year scales was determined by the primary pre-industrial net source of CO2 into the atmosphere: Volcanos
- But humans today are injecting long sequestered fossil carbon into the atmosphere at rates more than 100 times higher than volcanos.

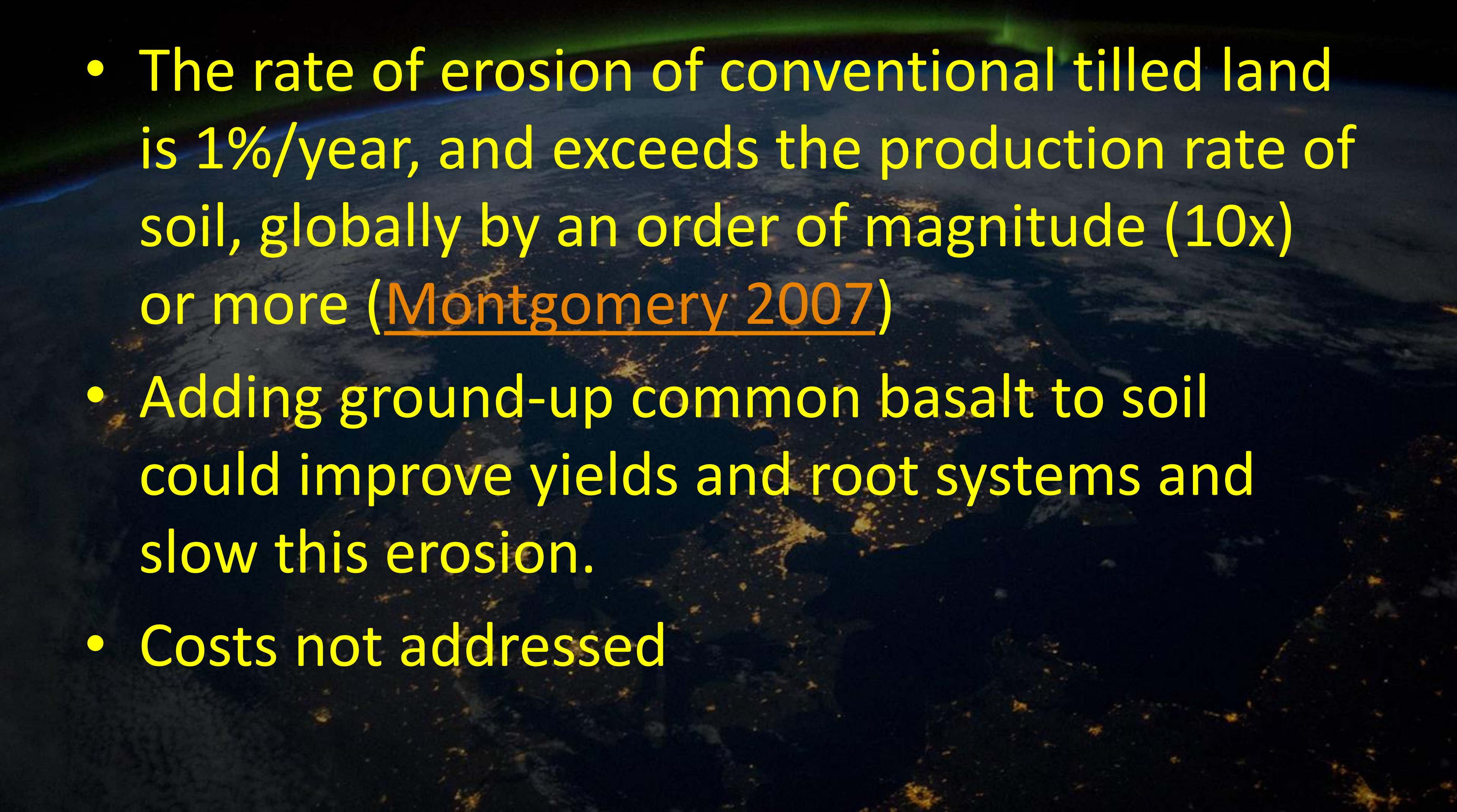
Silicate Rock Dust Fertilizer

- The idea here is to grind up basalt rock (rich in silicates) and apply to agricultural land
- Water + atmospheric CO2 will chemically weather the silicate, making carbonate which plants can help take up, or remain in soil
- Scale, again, needs to be ~100x Natural, as we just saw, to be climate significant.
- Energy cost of grinding up basalt to proper surface area – to – volume ratio looks very high. That’s fossil fuel energy for the forseeable future

Run-off, deposition can also take the carbonates to the ocean, where organisms can convert to CaCO3 and sequester, slowly (but via rivers – where the altered pH may adversely affect ecosystems?

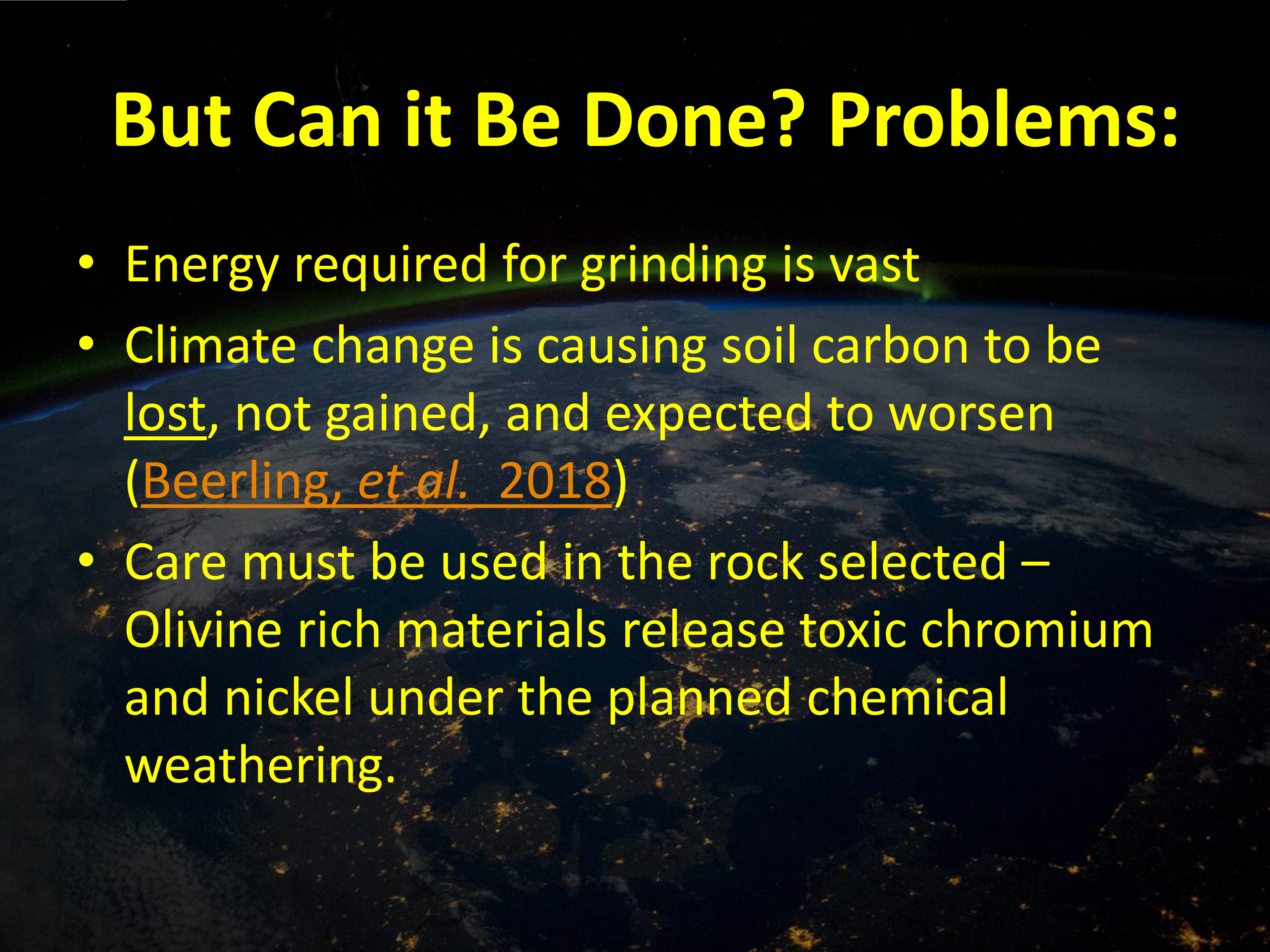


The Future of Agriculture Requires Addressing Critical Erosion



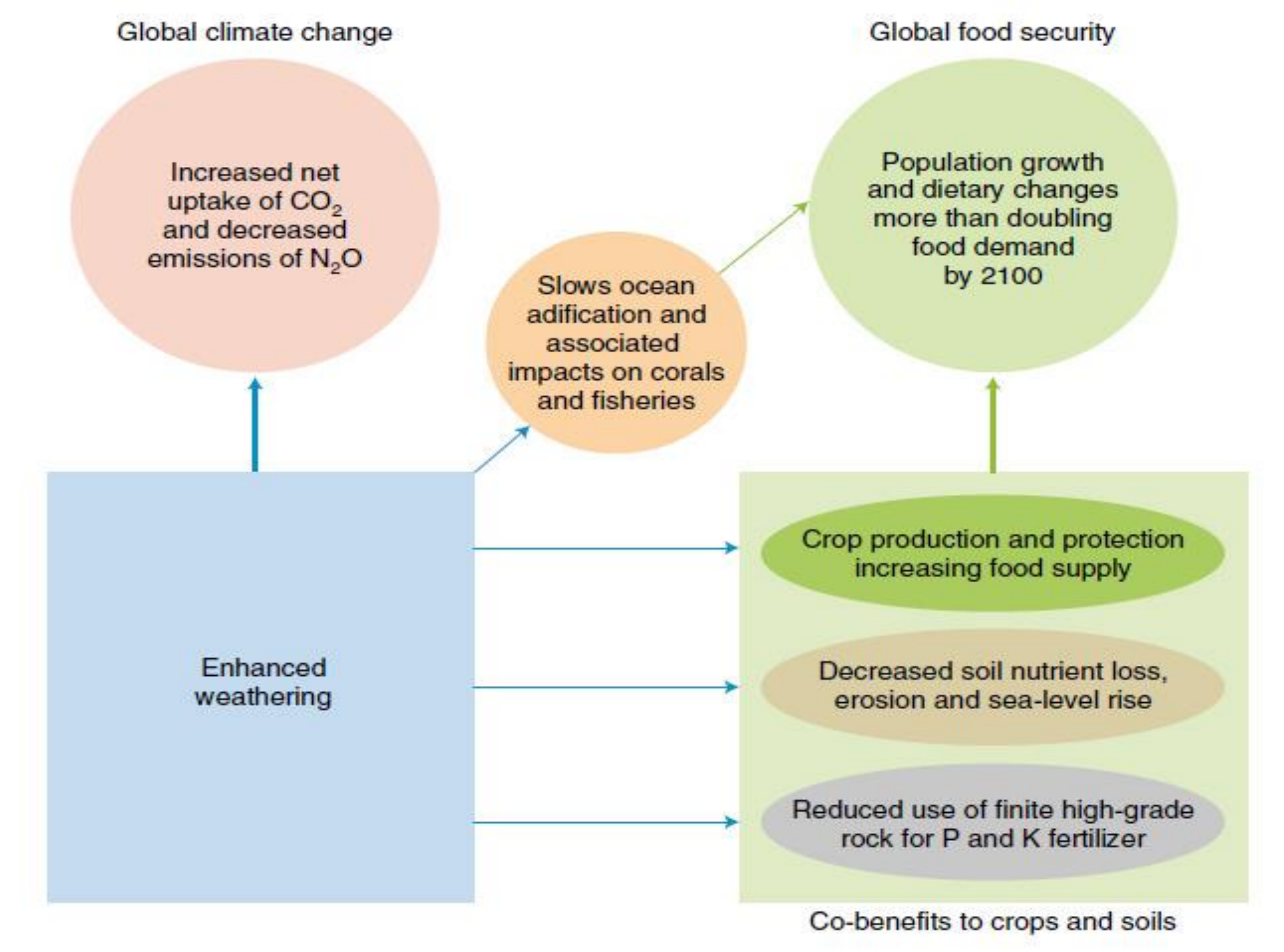
- The rate of erosion of conventional tilled land is 1%/year, and exceeds the production rate of soil, globally by an order of magnitude (10x) or more (Montgomery 2007)
- Adding ground-up common basalt to soil could improve yields and root systems and slow this erosion.
- Costs not addressed

But Can it Be Done? Problems:



- Energy required for grinding is vast
- Climate change is causing soil carbon to be lost, not gained, and expected to worsen (Beerling, *et al.* 2018)
- Care must be used in the rock selected – Olivine rich materials release toxic chromium and nickel under the planned chemical weathering.

Costs, environmental negatives are a major concern, but if it can be made feasible, here are the positives. The scale which is feasibile looks far too small, though (next slide…)



Hartmann and Kempe (2008) : Calculated Costs in Dollars, Energy, and CO2 Creation are Very Discouraging

- *"Applying first estimates of 'normal treatment' amounts from a literature review, we report here a theoretical global* ***maximum potential of 65 million tons sequestered Carbon/year if applied homogenously on all agricultural and forested areas of the world. This is equivalent to 0.9% of anthropogenic CO2 emissions*** *(reference period 2000-2005).*
- *"First, however, the assumed application of (ground silicates) on most of the considered areas is not economically feasible because of logistic issues, and second; the net-CO2 sequestration is expected to amount to only a fraction of consumed CO2 due to the energy demand of the application itself (currently ~11%).*
- *Unless progress in application procedures is provided, the recent realistic maximum net-CO2-consumption potential is expected to be* ***much smaller than 0.1% of anthropogenic emissions****"*

Beerling *et al*. (2018) try to be more hopeful, suggesting refinements, but…

- Some suggestions save money by using industrial wastes and sugar cane ash, but the sheer volumes needed to capture/sequester carbon at climate significant scales, would overwhelm these sources.
- And - more research is needed… *“At present, however, the long-term effects of applying pulverized silicate rocks on the organic carbon content of agricultural soils is not understood and requires further research. Over time, adding crushed rocks to soils will change their porosity, and other factors governing hydrology, with feedbacks on crop performance, trace gas emissions and the diversity and functioning of soil organisms that are still uncertain.”*