The Road Ahead

Joseph A. Formaggio
Massachusetts Institute of Technology
Neutrino 2020

Slide from Neutrino 2018

- Let us take a moment to thank the organizers for the **monumental** task of “re-formating” this conference; where they had just 3 months to redo the work of 2 years.

I think it is ok to acknowledge that there are certain things that we miss.

However, this conference has also provided an opportunity to make **future** conferences **better**.

- Removes hurdles incurred from travel costs
- Easier for people to participate and engage.
- Access to pre-recorded talks.

I invite you to look at the slack channel #future_of_conferences; there are a lot of strong ideas there that should be considered.

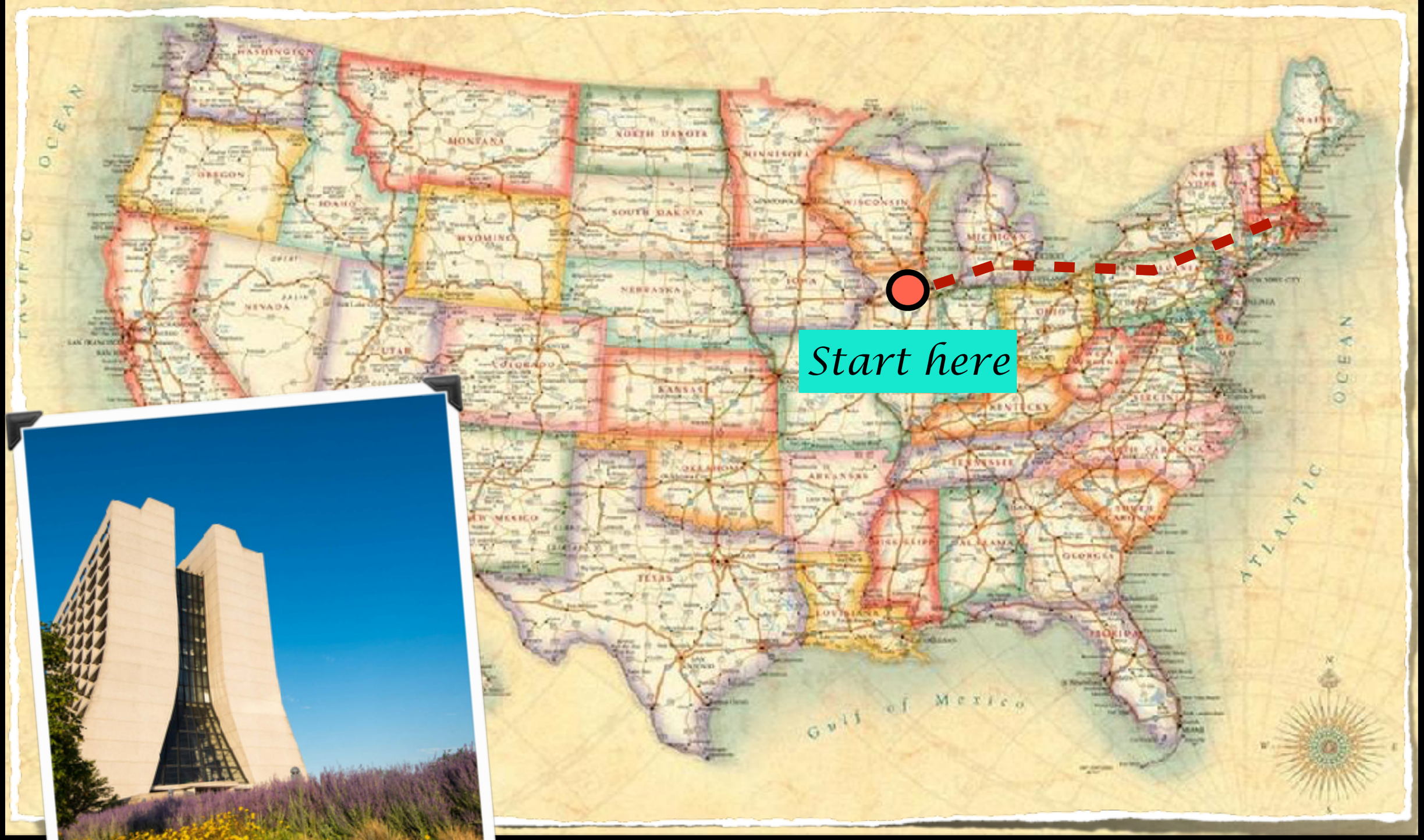
Another activity that we cannot engage in this year:

Touring the host countryside.

What could be the worst possible substitute for it?

A slideshow about touring the host countryside.

Ok, here we go anyway!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MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
NEW YORK
MAINE

First Stop:

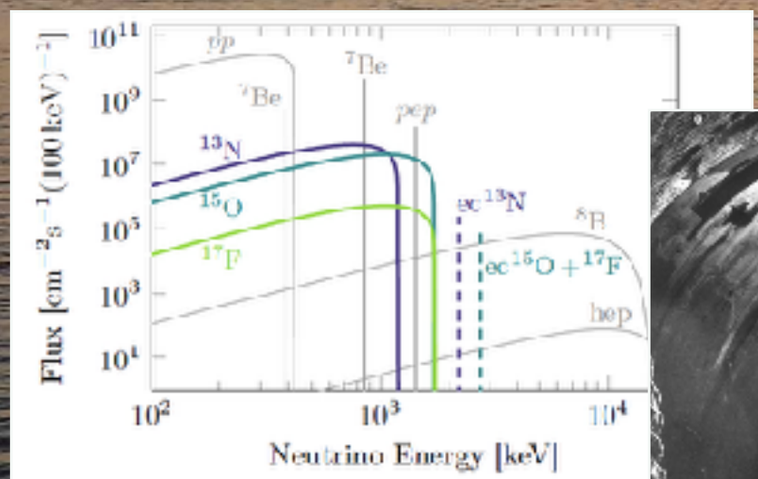
Great Point Light

Nantucket, Massachusetts

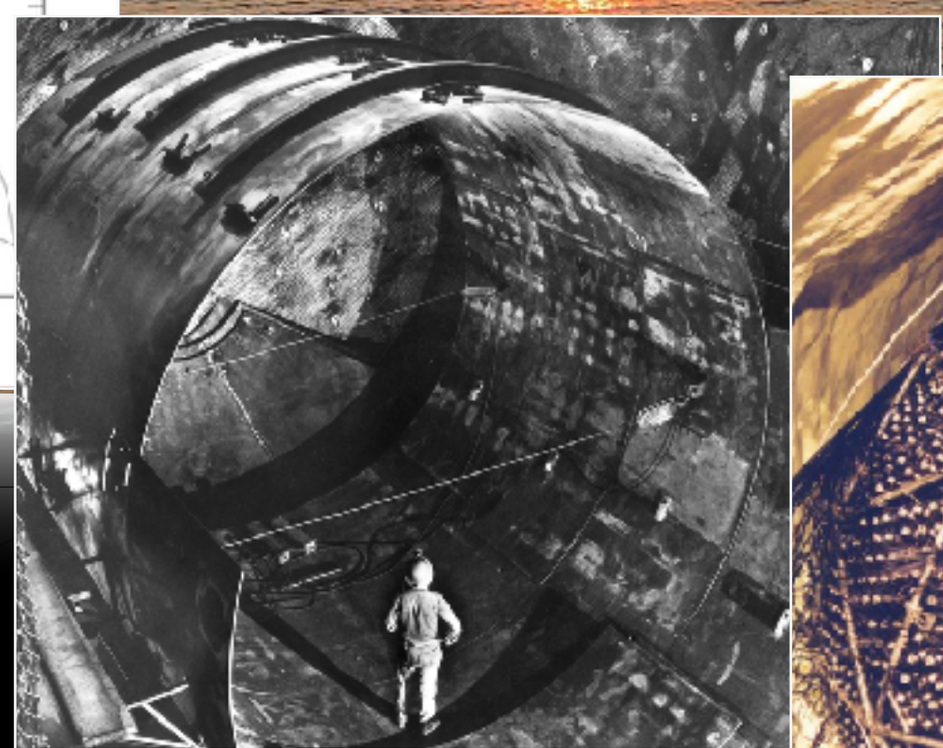
(here we contemplate solar neutrinos)

Martha's Vineyard, MA

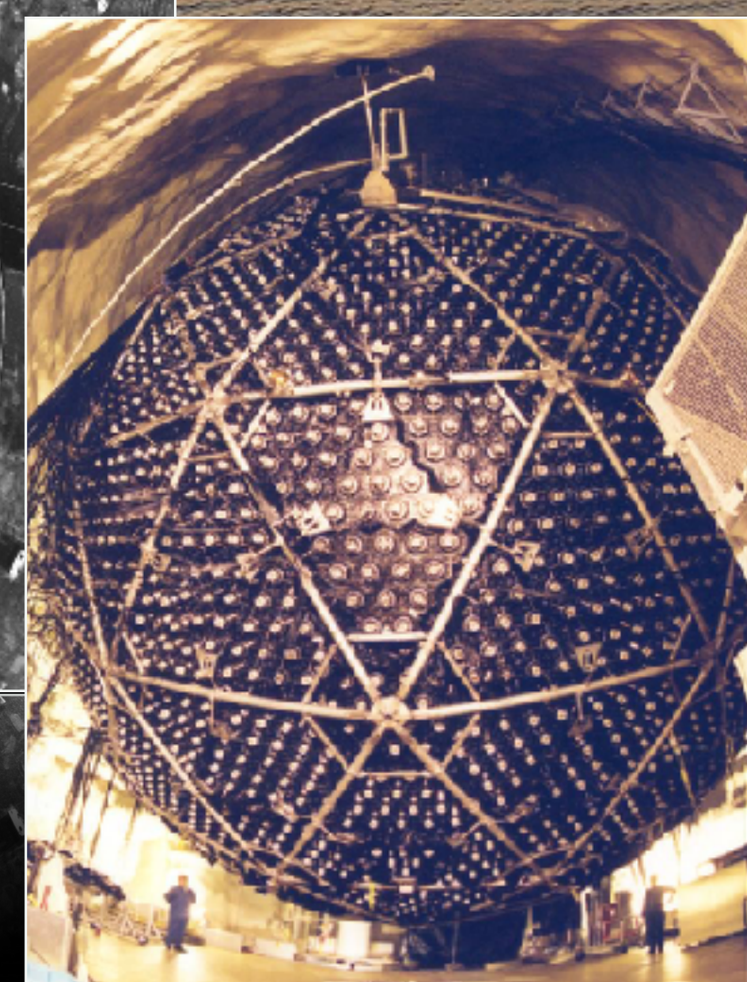
Over the past 60 years, neutrinos have helped understand the sun, and the sun has helped understand neutrino physics.



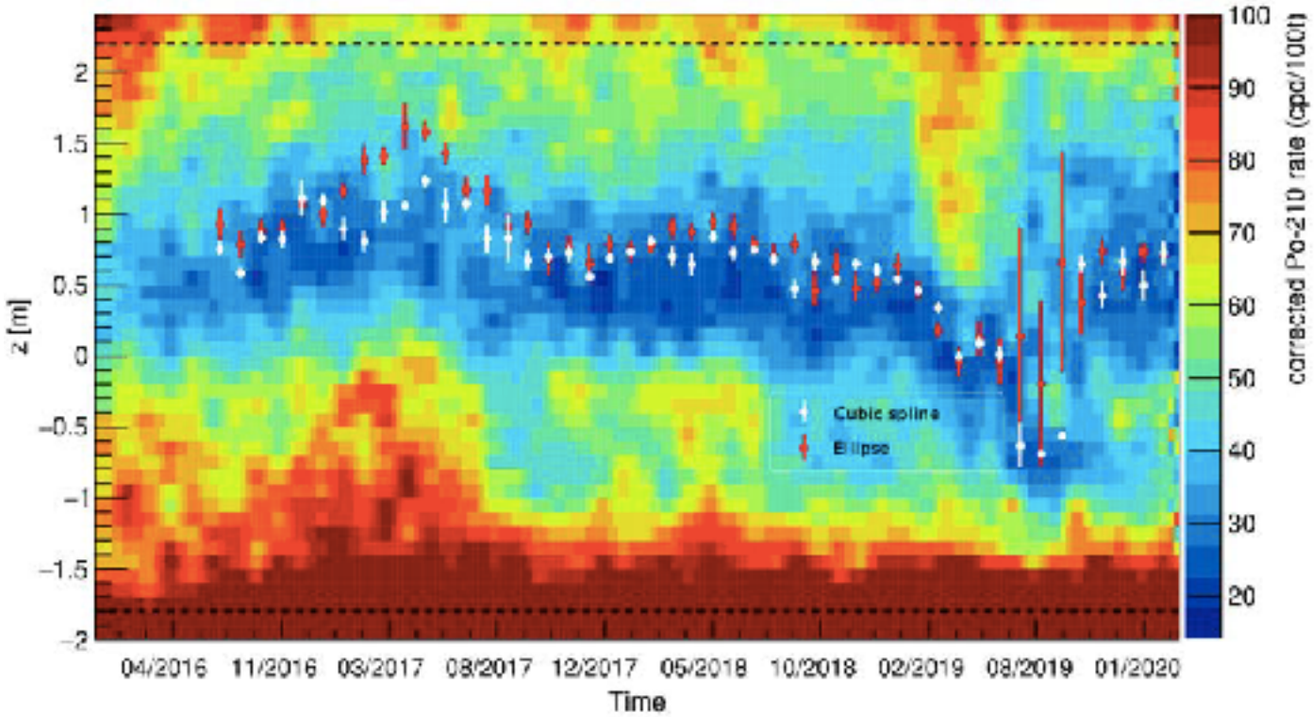
Solar spectrum

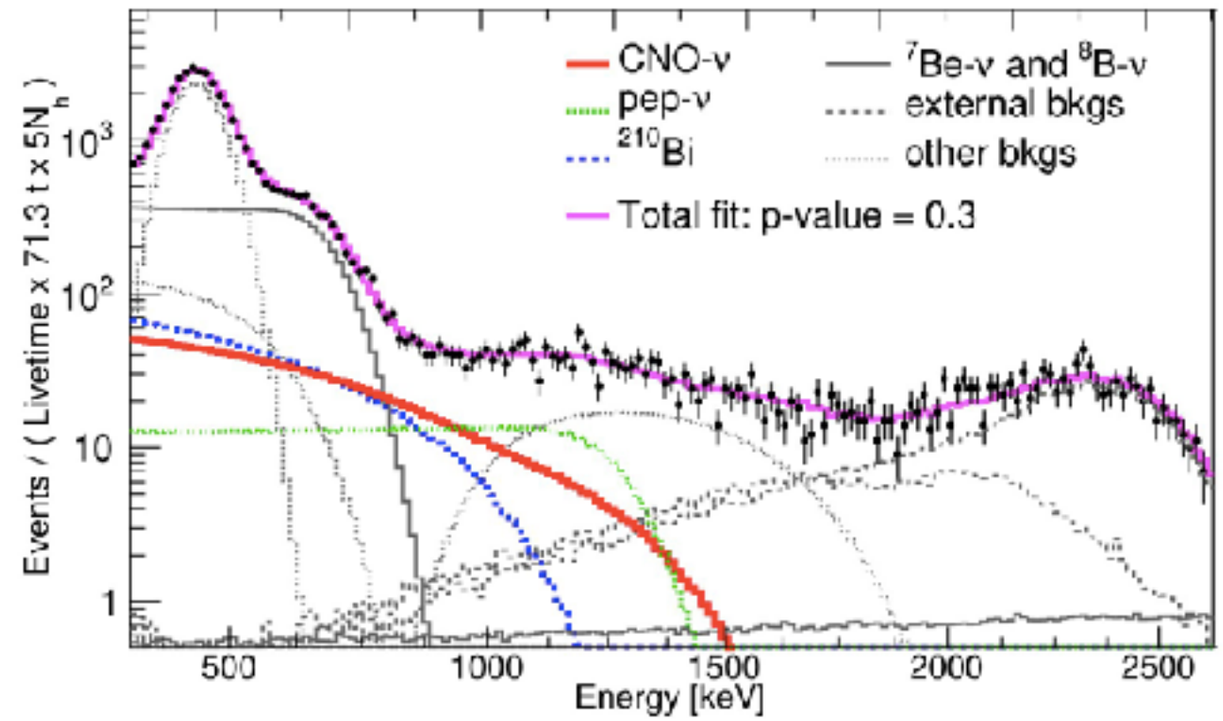


The Homestake experiment



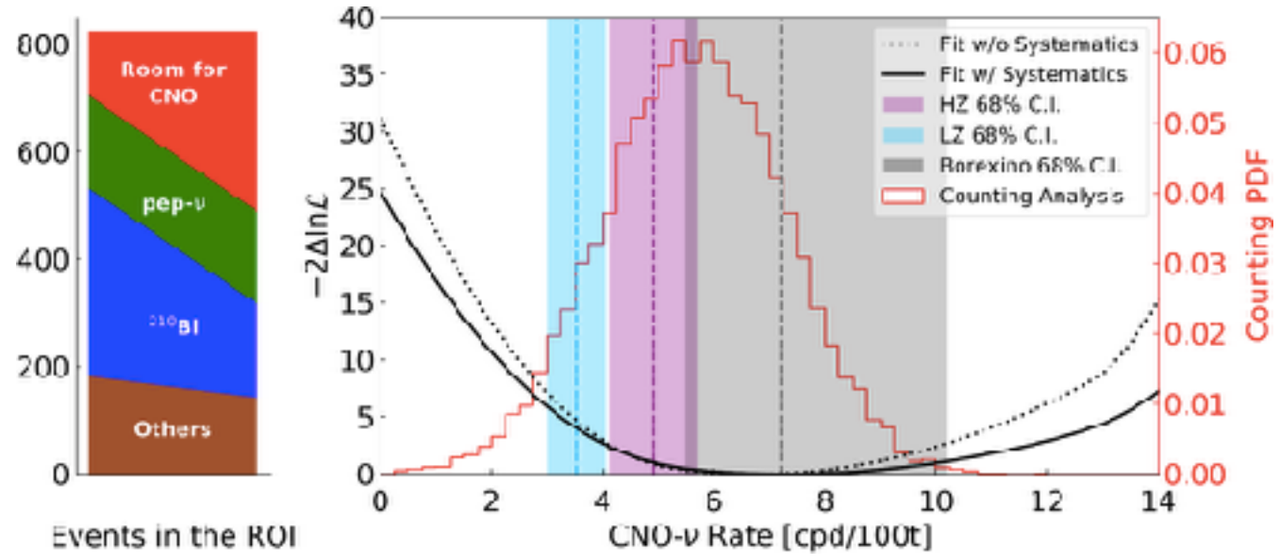
The Sudbury Neutrino Observatory



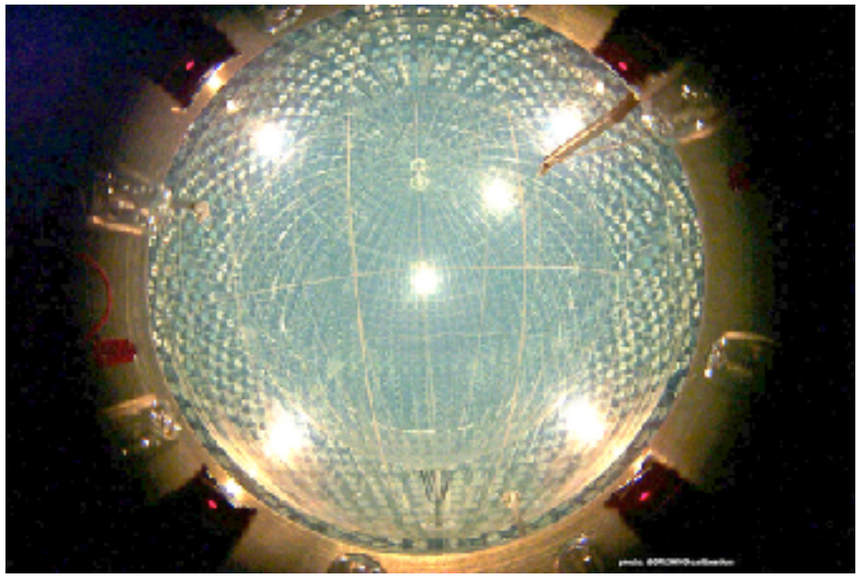


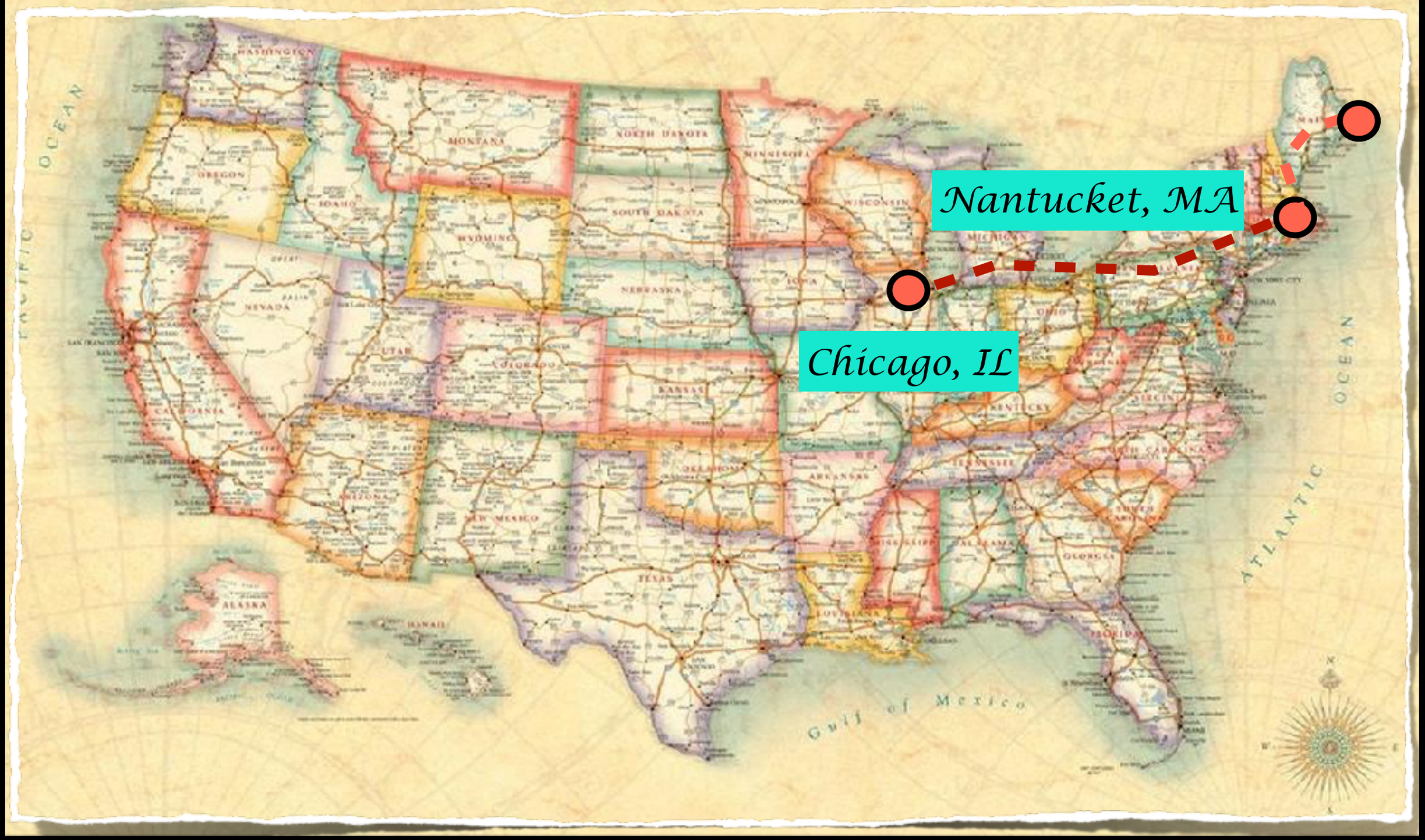
After an impressive analysis to better understand their Po background, Borexino now has observed the neutrino spectrum from the CNO cycle (at 5 σ).

What we hope emerges is a better understanding of the solar metallicity.



Congrats to the entire Borexino team on this stellar achievement!

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HAWAII

Next Stop:

Acadia National Park

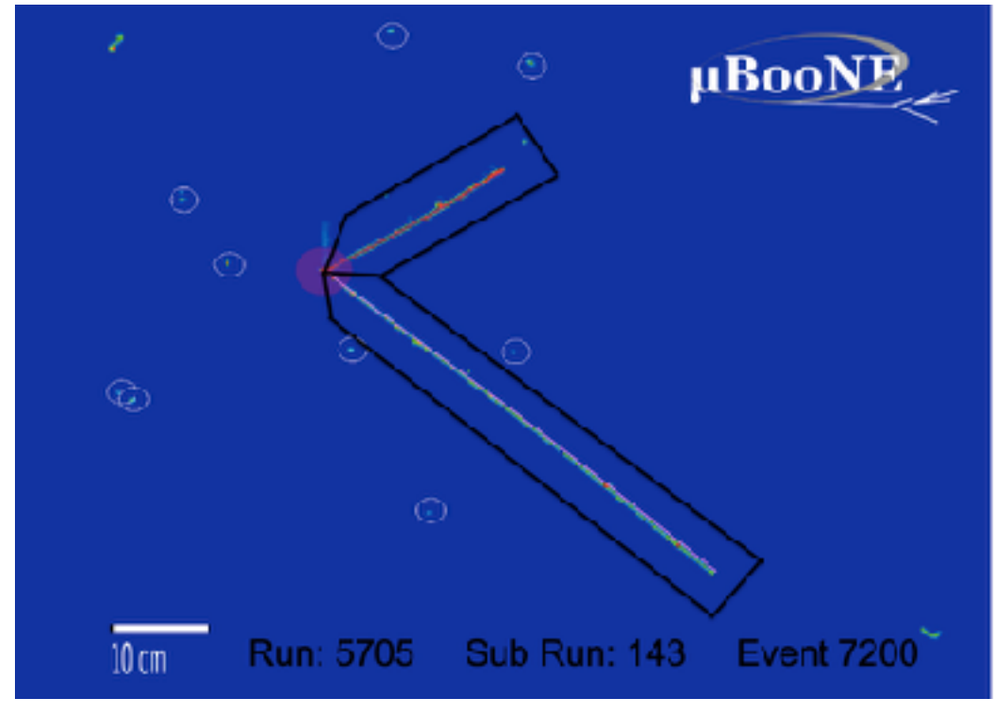
Bar Harbor, Maine

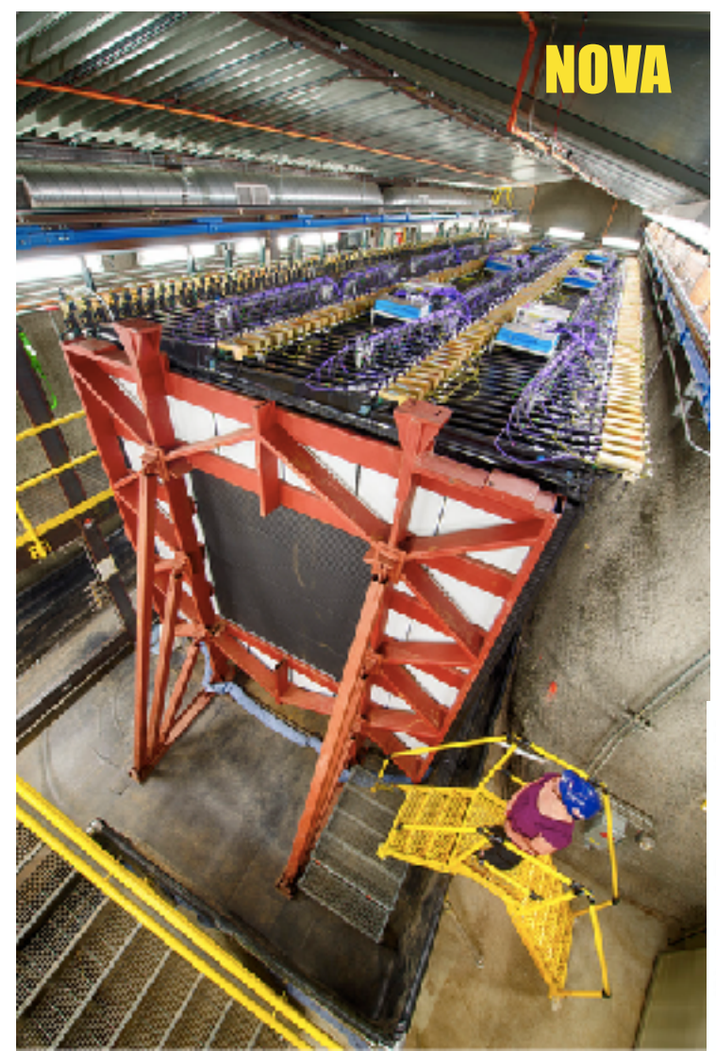
(here we contemplate how neutrinos interact with the world)

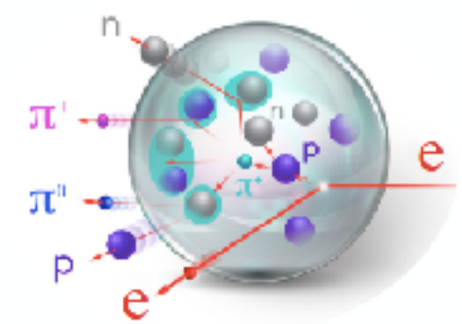
We have made great strides in better understanding how neutrinos interact with matter.

Direct measurements of neutrino interactions with matter. New results from Minerva, NOVA, uBooNE, T2K and others.

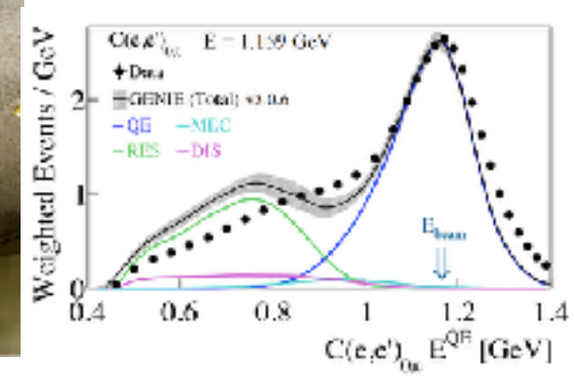
And even combining results from both **neutrino** and **electron** scattering.



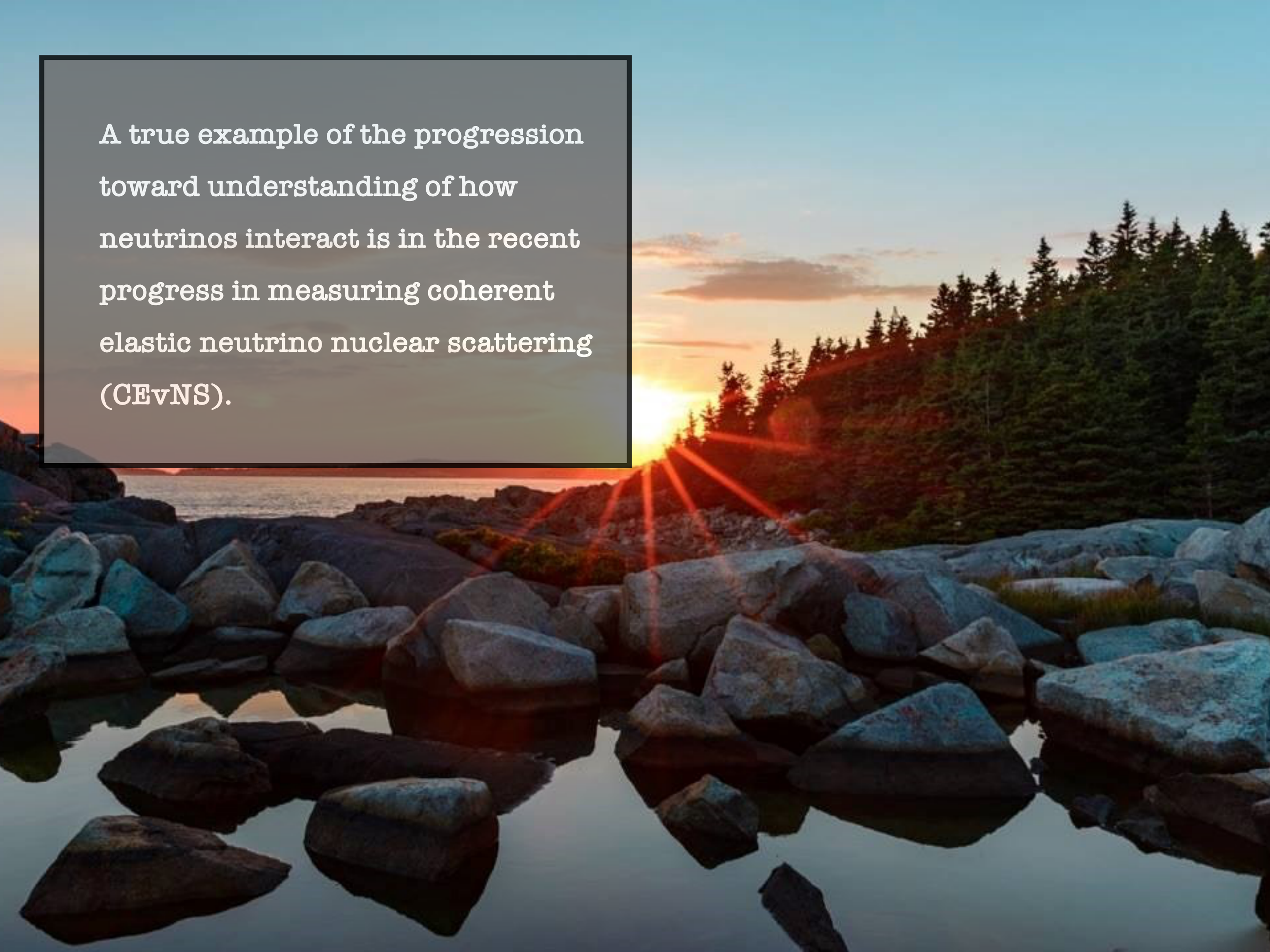


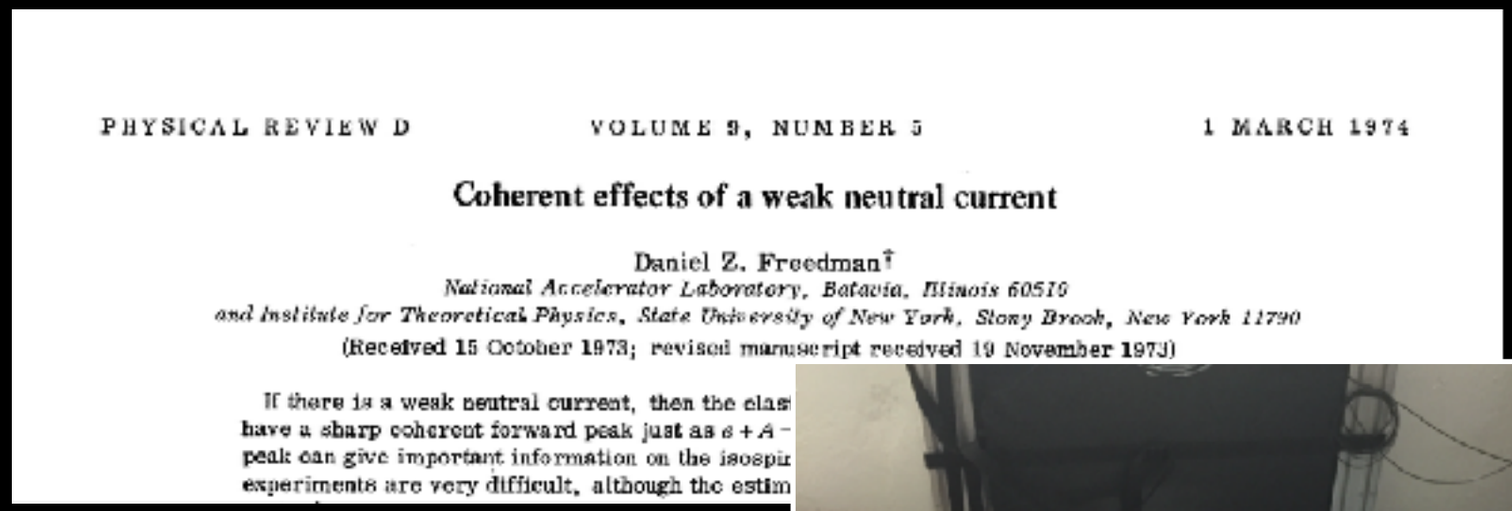


e4v



A true example of the progression toward understanding of how neutrinos interact is in the recent progress in measuring coherent elastic neutrino nuclear scattering (CEvNS).



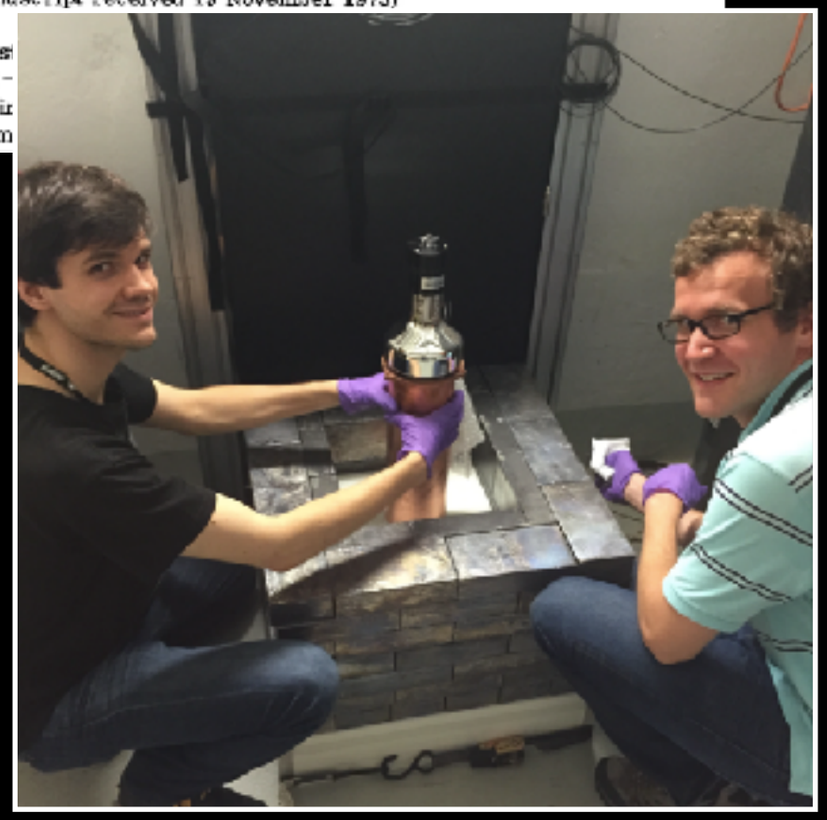


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elas
have a sharp coherent forward peak just as $e + A$ –
peak can give important information on the isospin
experiments are very difficult, although the estim



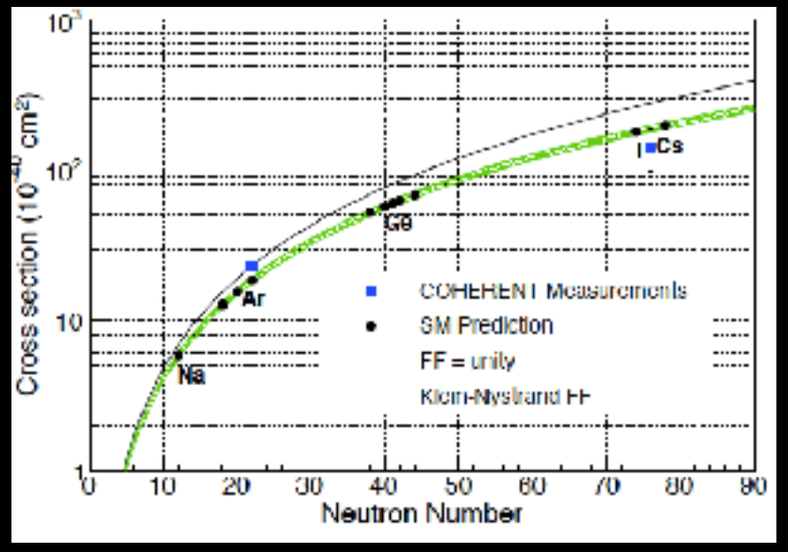
We have progressed from theoretical construct, to first observation, and now as a **tool** for exploring new interactions.

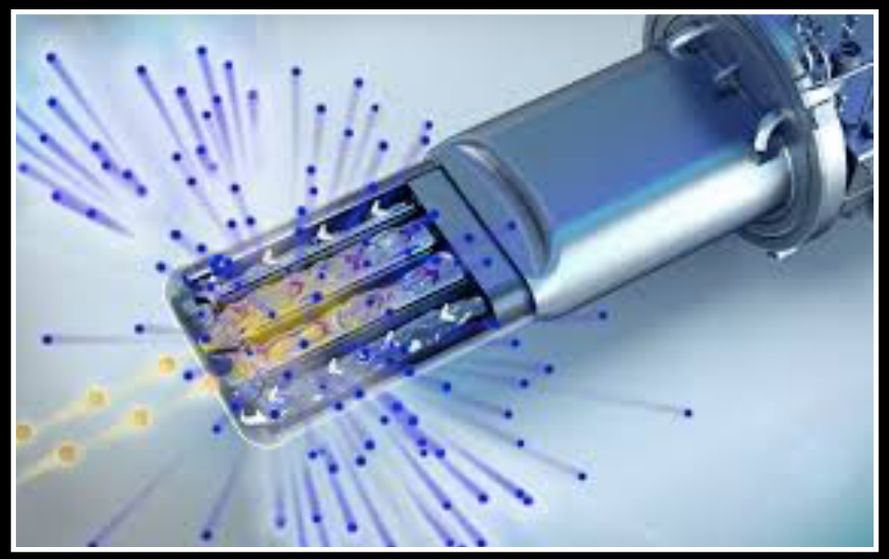
Nuclear Form Factors

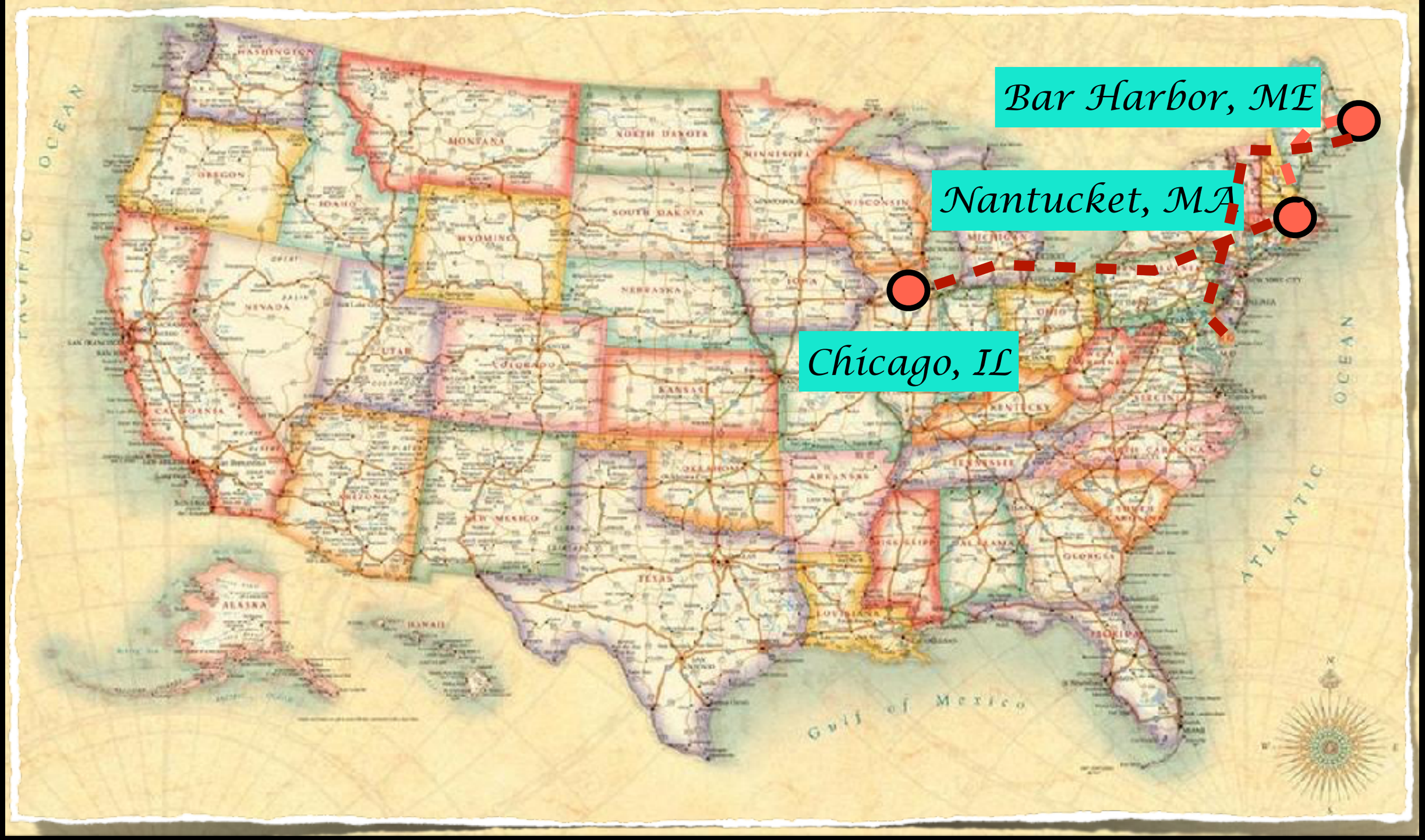
Non-Standard Interactions

Augment DM Searches

...



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HAWAII

Next stop:

Washington, DC...

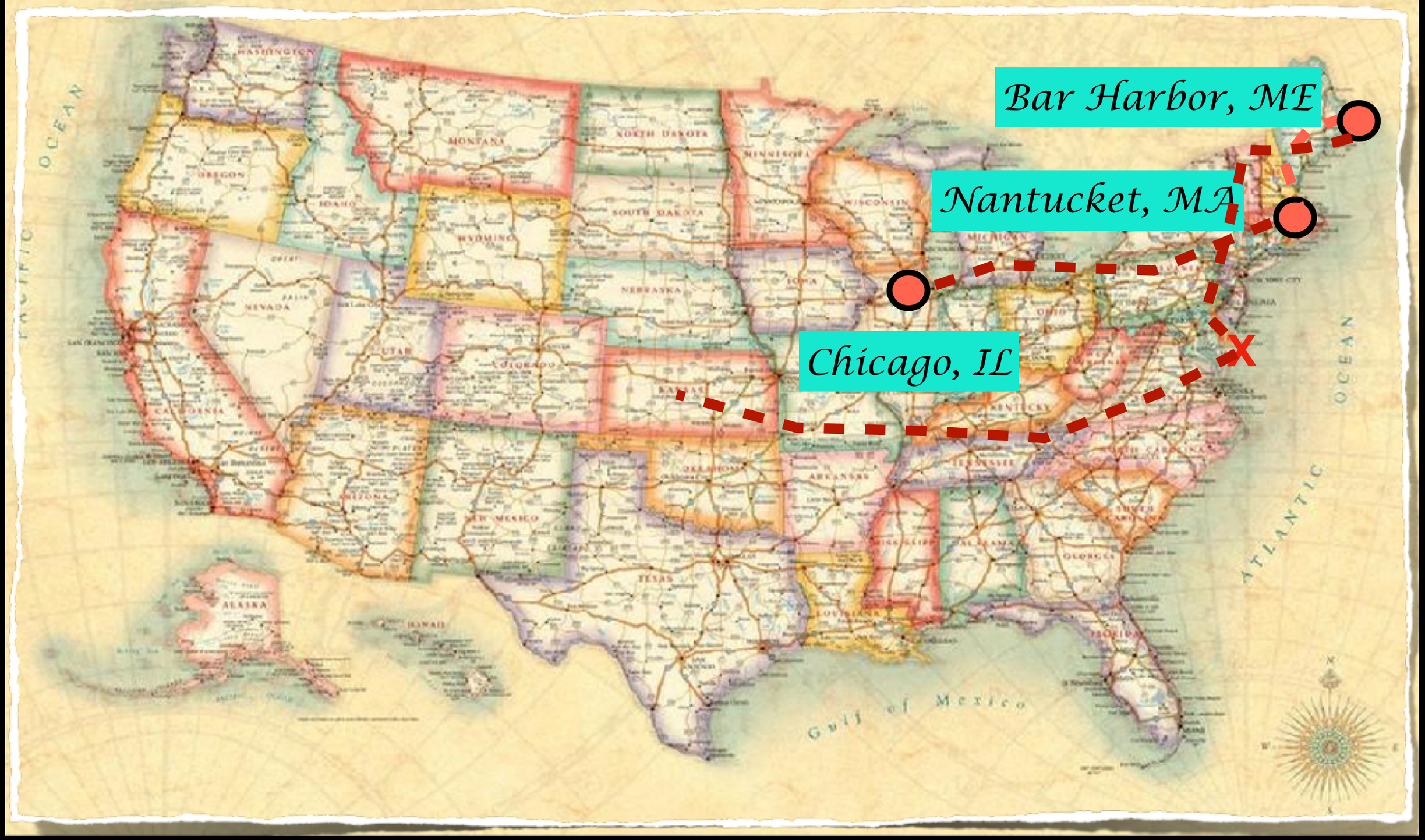
... on the other hand, there is an insidious virus

currently in the White House.

Best to skip it**.

(Vaccine in the works, hopefully ready in November)

***We can't stop here! This is bat country!"*
- H S Thompson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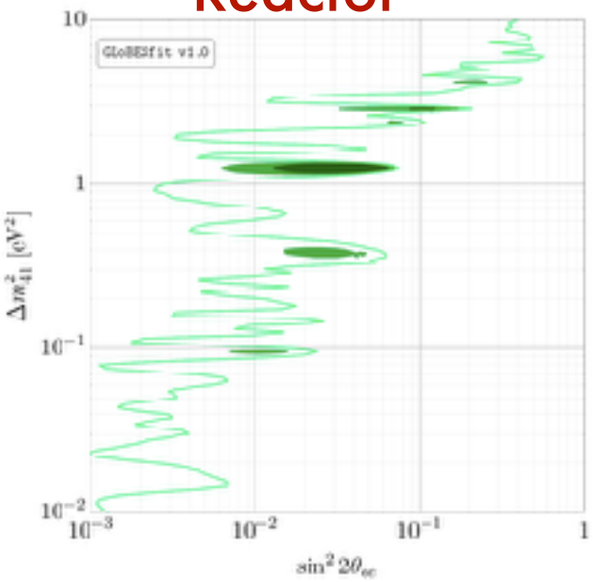
Next Stop:

Tallgrass Prairie National Preserve

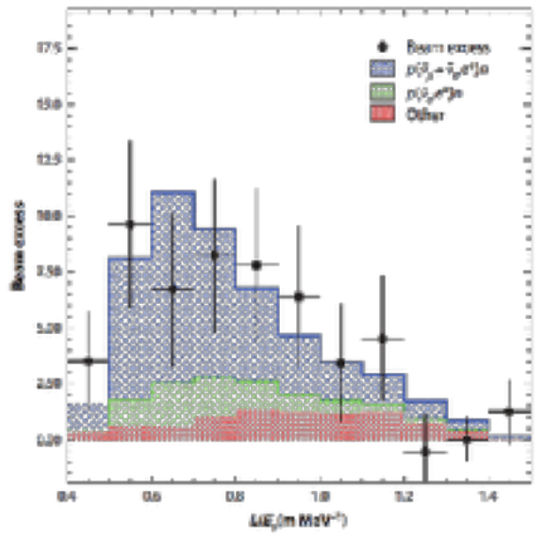
Strong City, Kansas

(This is a rather long drive, what better time than to discuss sterile neutrinos)

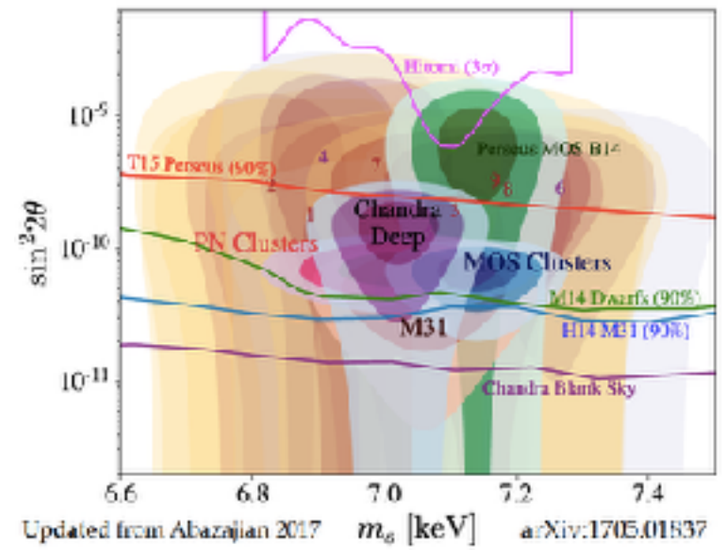
Reactor



Short Baseline



X-ray Surveys



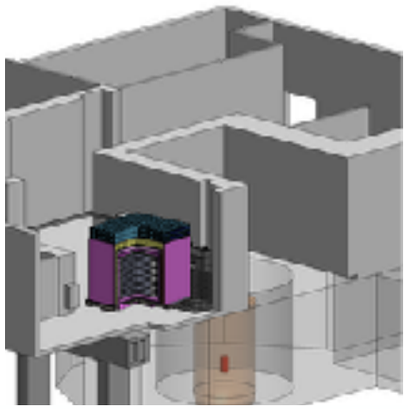
eV Sterile

keV Sterile

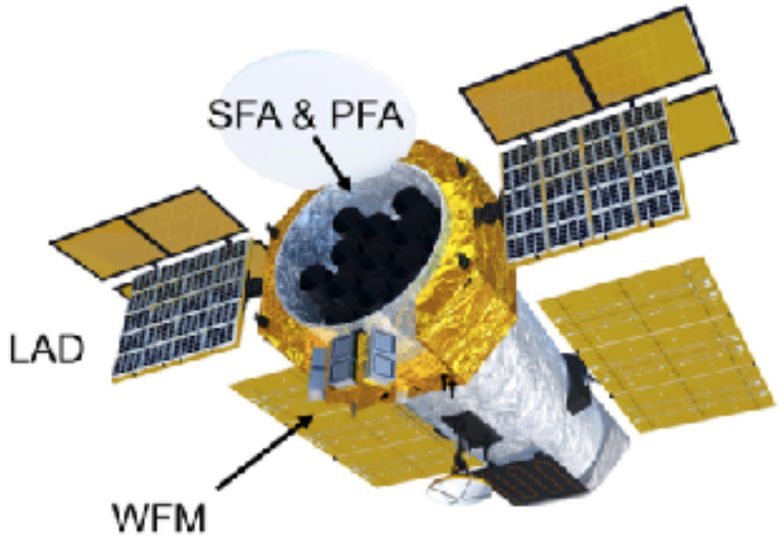
Sterile neutrinos offer an exciting possibility of an observation of BSM.

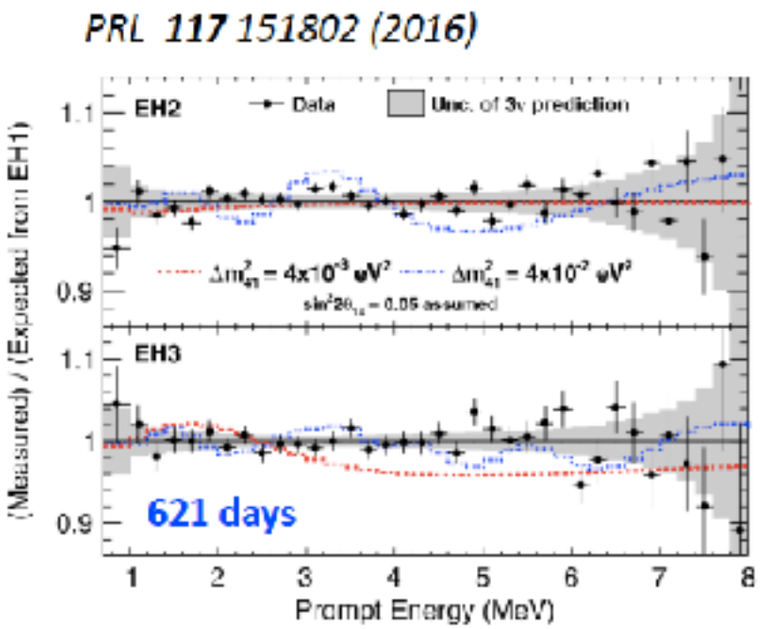
Hints observed over the decades across different systems.

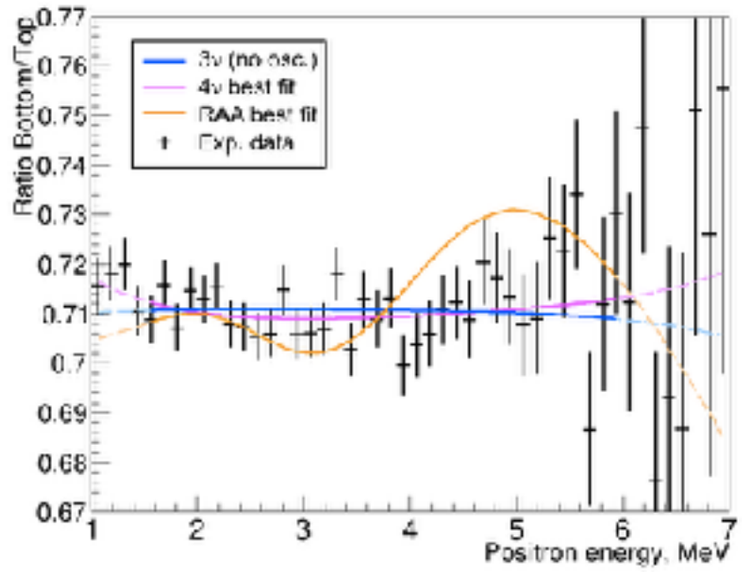
The picture, however, remains complex, as for every potential signal there exists one or more experiments excluding them.

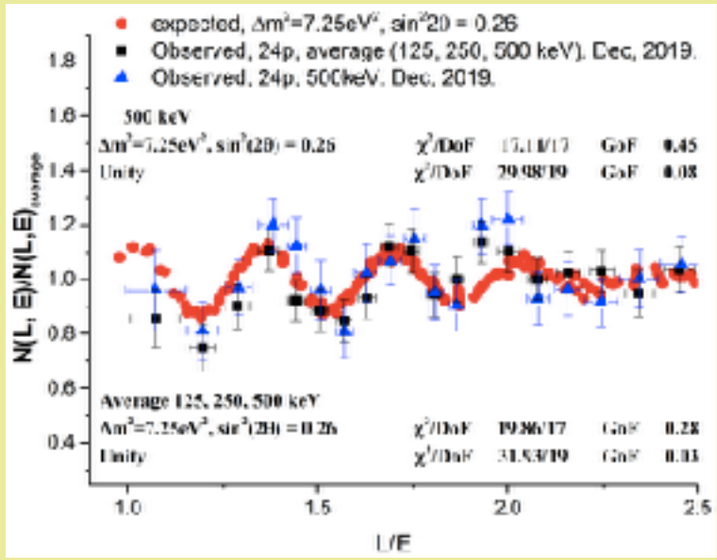


PROSPECT







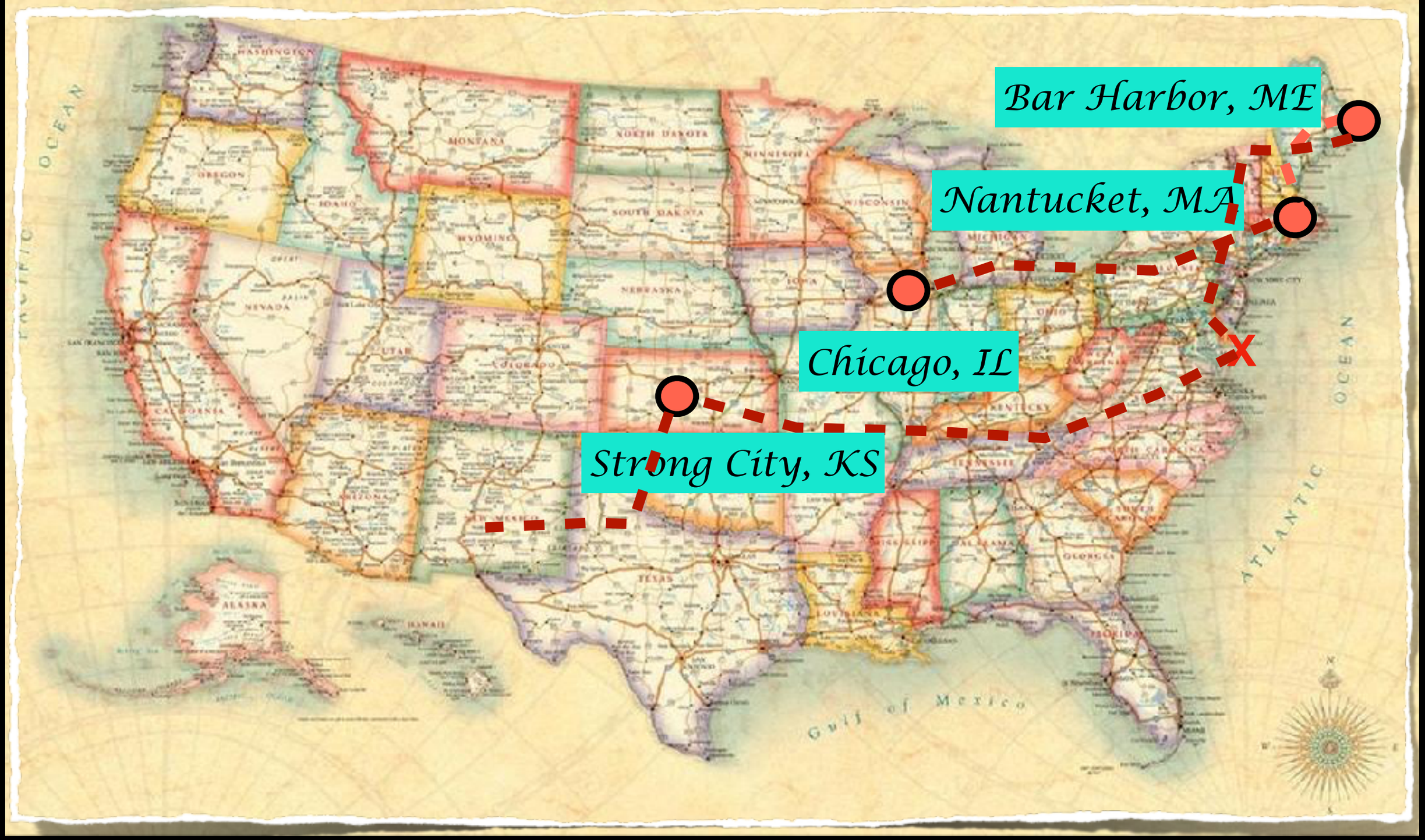


Much progress has been made this year on understanding the reactor anti-neutrino anomaly (and also the 5 MeV bump).

Good to hear Prospect, Daya Bay and STEREO will embark in a joint analysis to better understand of ^{235}U decay. BEST soon to address Gallium anomaly.

A similar joint analysis for sterile neutrinos would also be welcome!

MINOS, MiniBooNE and μBooNE would have shown new results **today**. Does a new picture emerge?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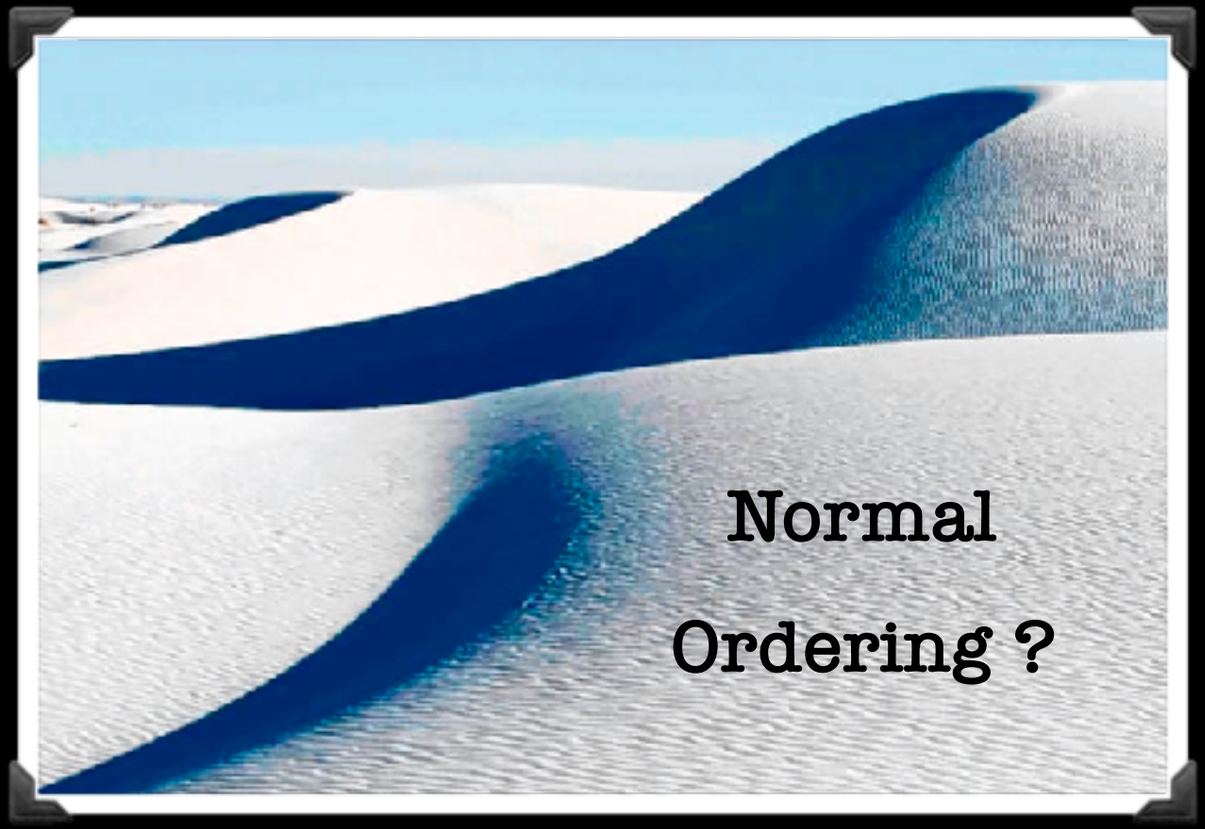
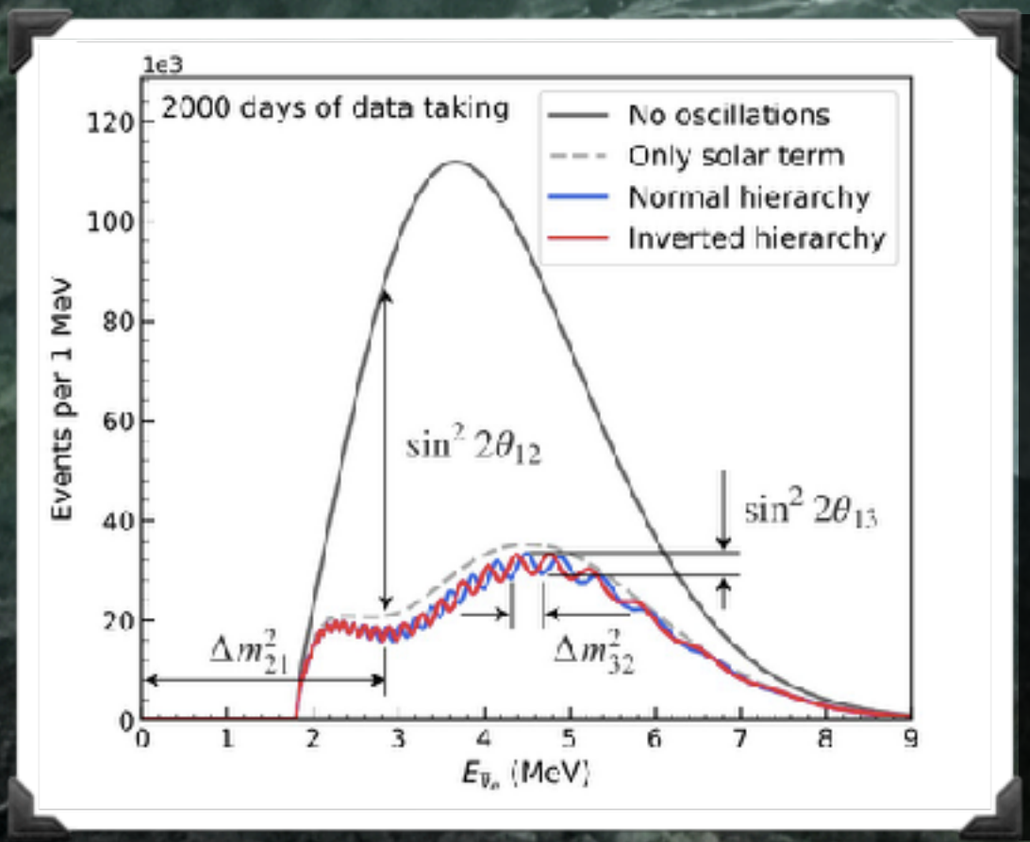
Next Stop:

White Sands National Park

New Mexico

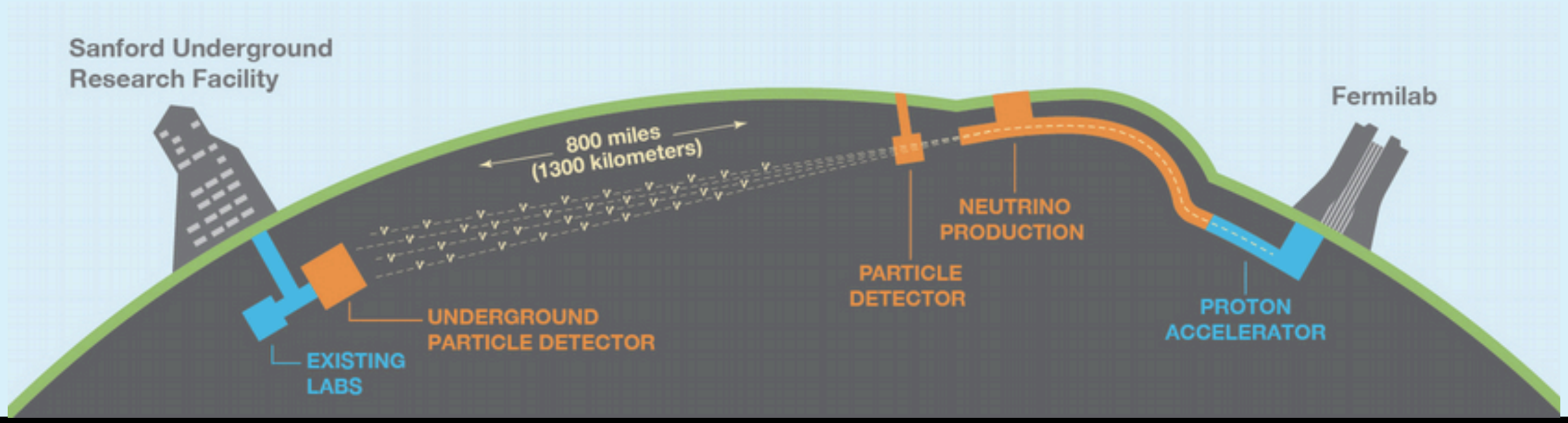
(entering the era of DUNE, JUNO & Hyper-K)

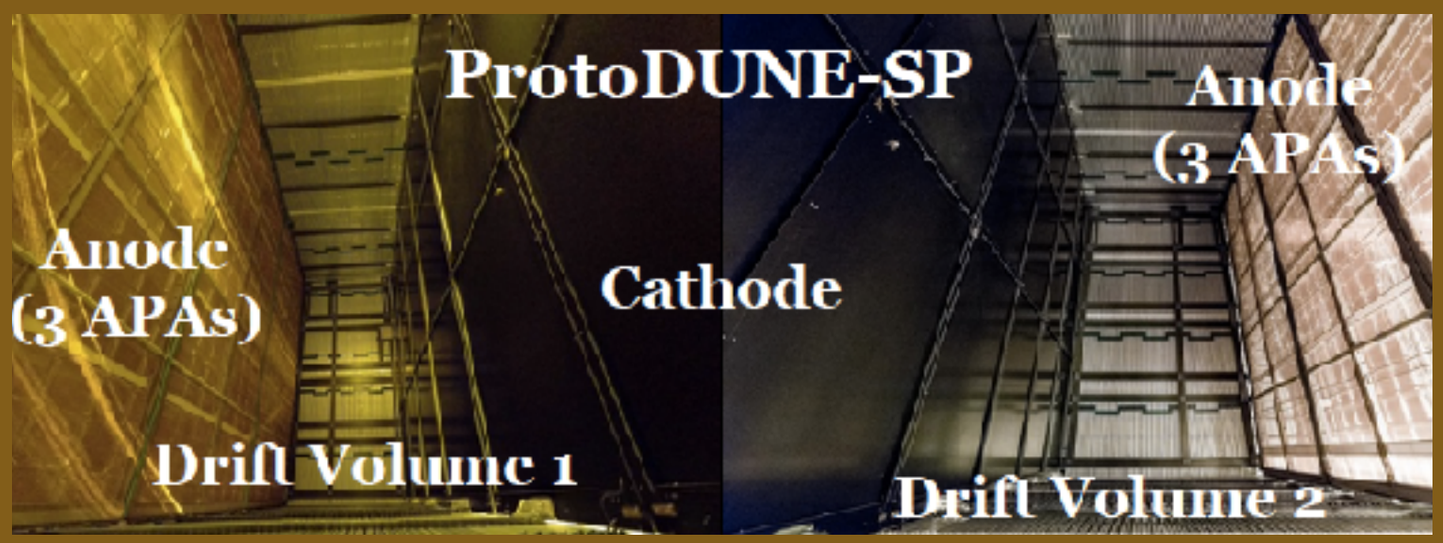


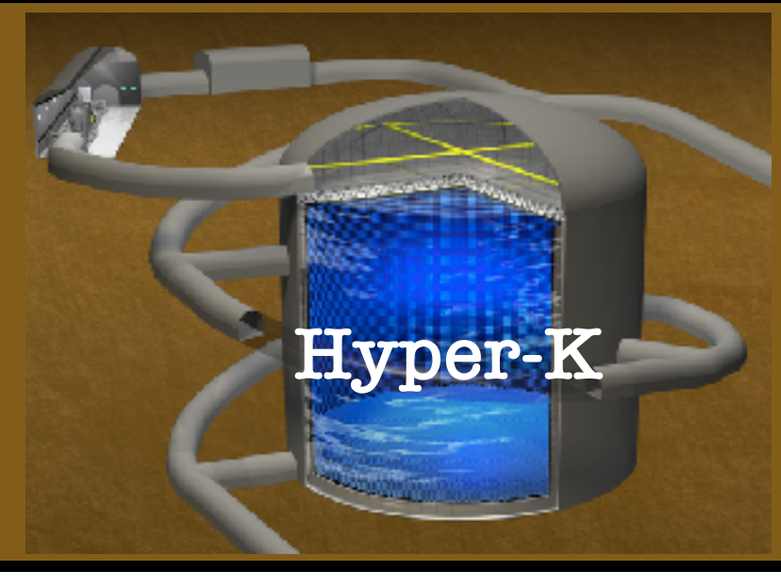


JUNO offers sensitivity to resolve the mass ordering problem using unprecedented energy resolution for a detector of its size.

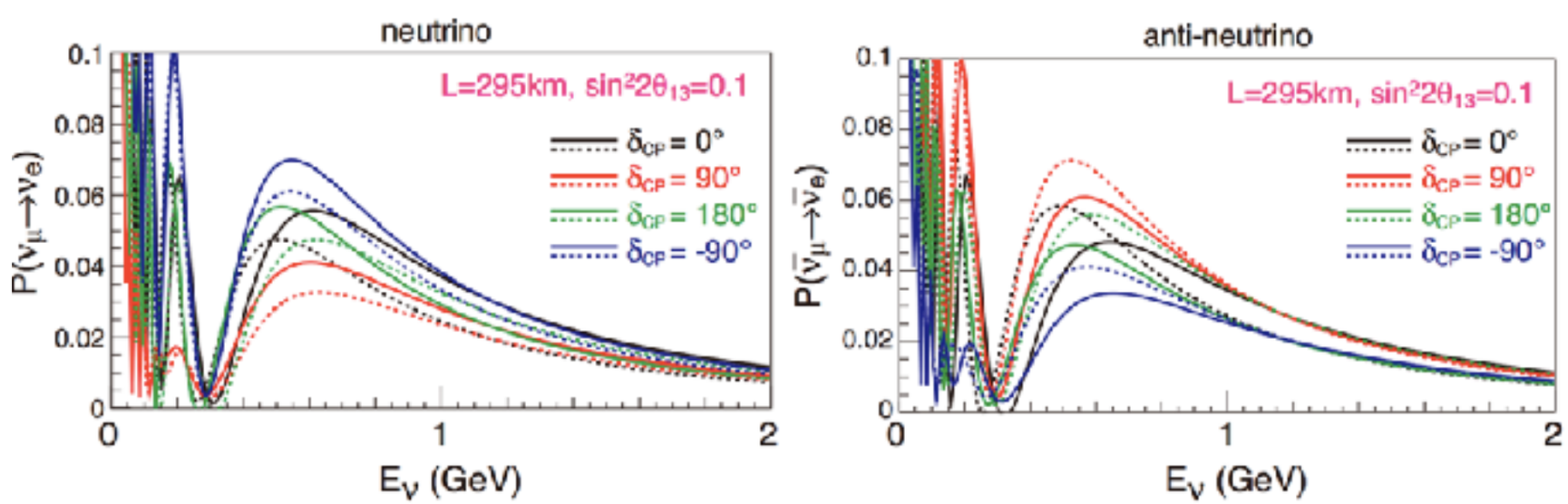
Or did NOVA already reveal the ordering this morning?

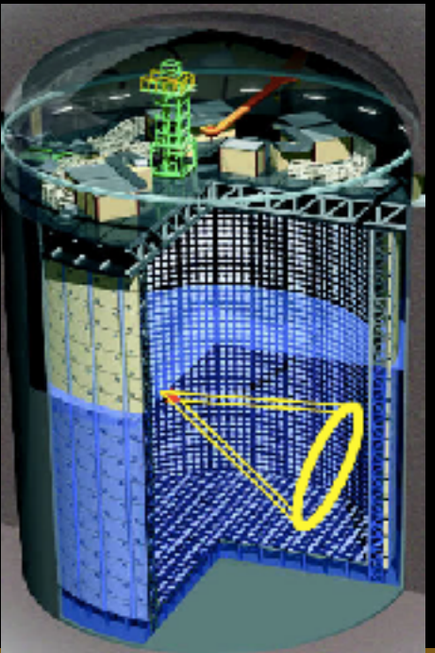






Now, CP Violation within reach of Hyper-K and DUNE. Programs advancing steadily toward construction.





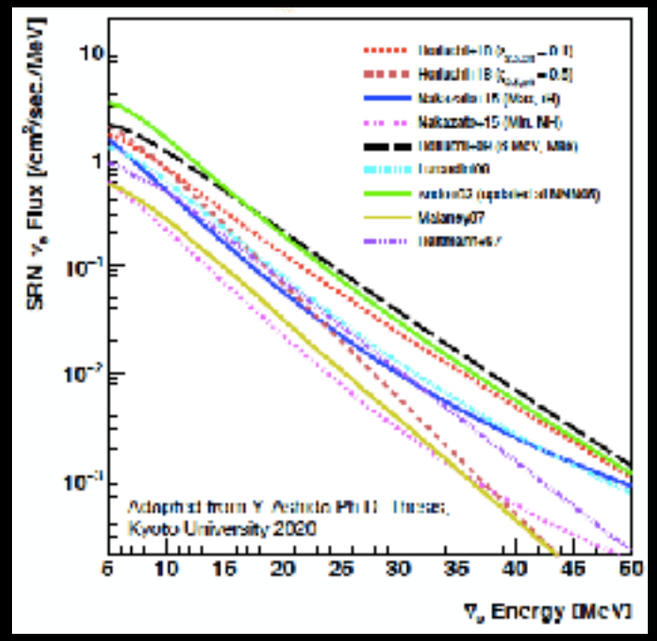
Super-Kamiokande

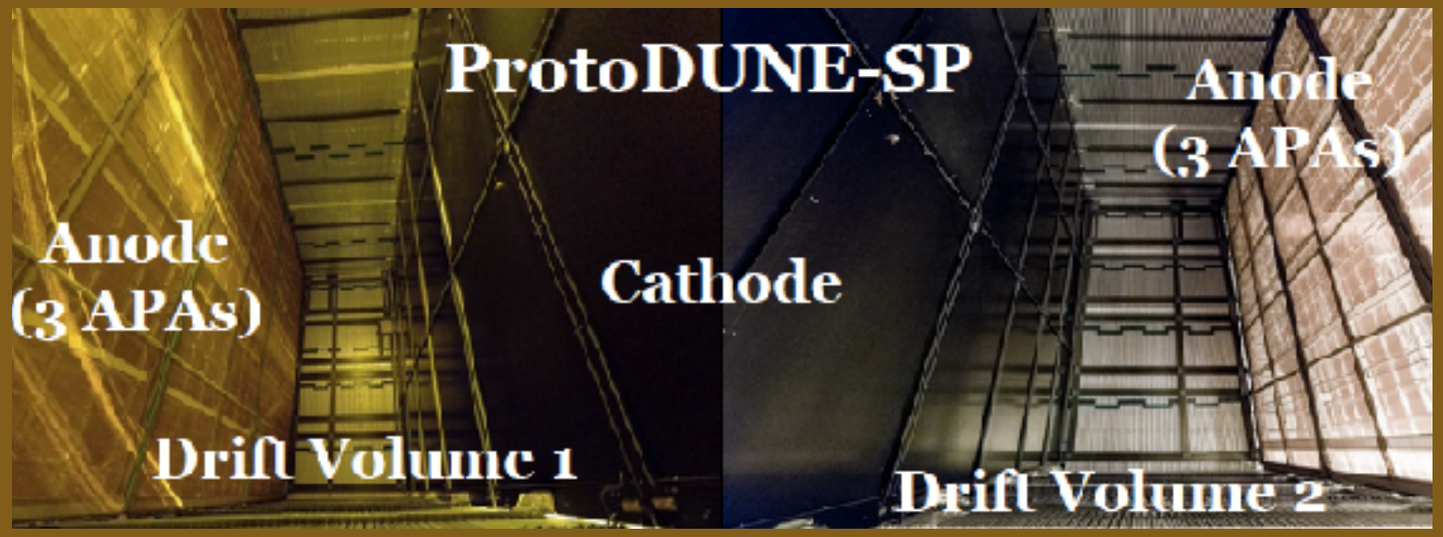
from H_2O

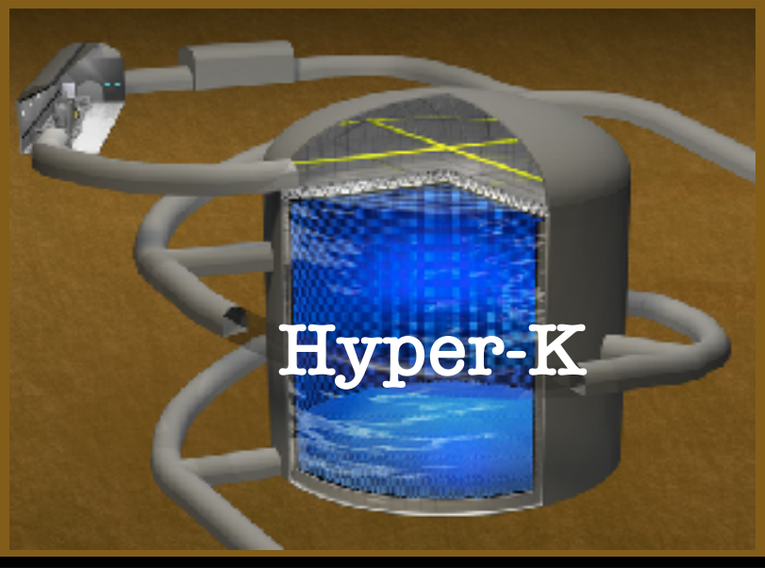
(5805 live days!)

to

H_2O-Gd



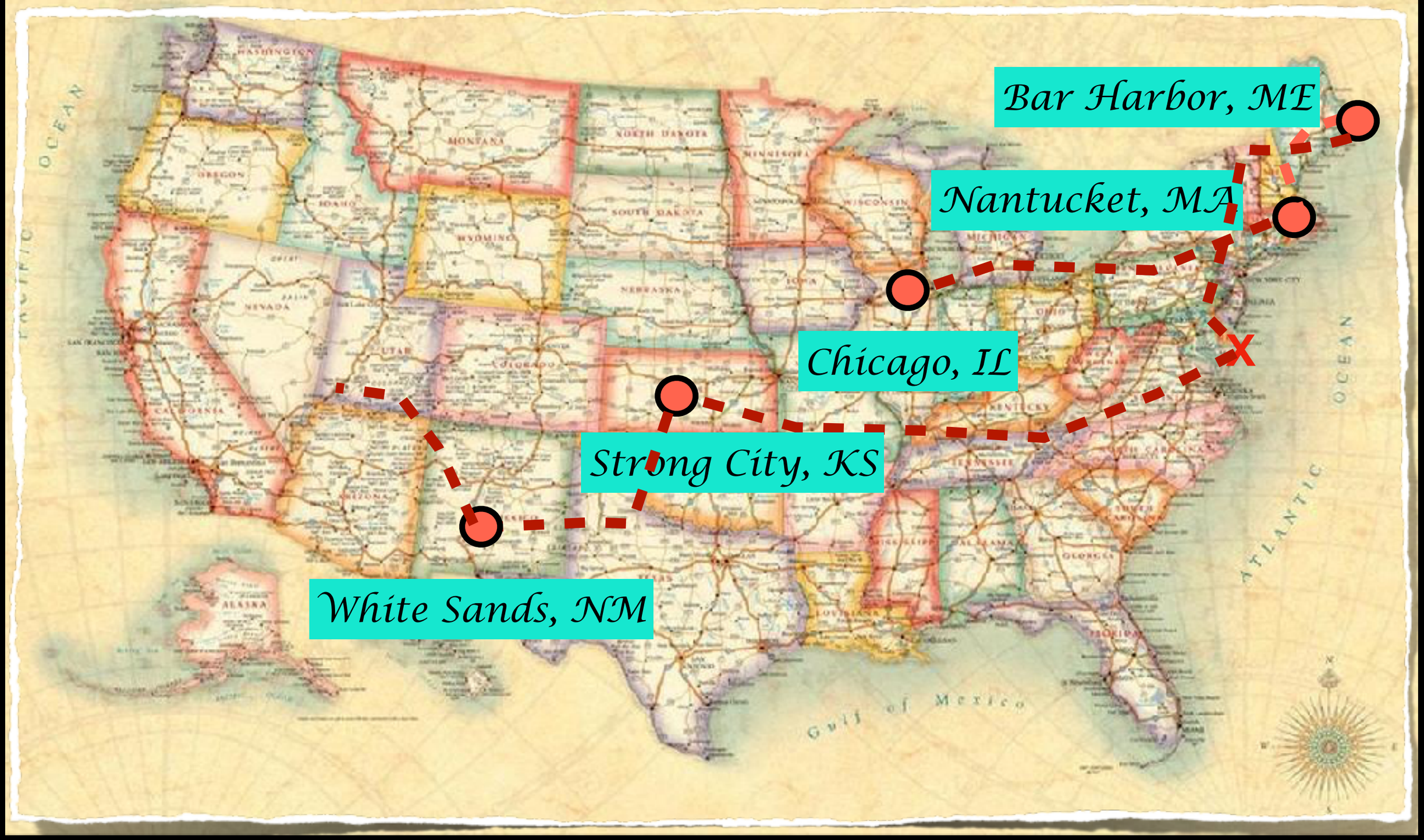




Keep in mind places like JUNO, Hyper-K, DUNE and others in the future will be **observatories**.

(and this is on top of Super-K, now looking at DSNB)

Access to a wealth of different neutrino measurements.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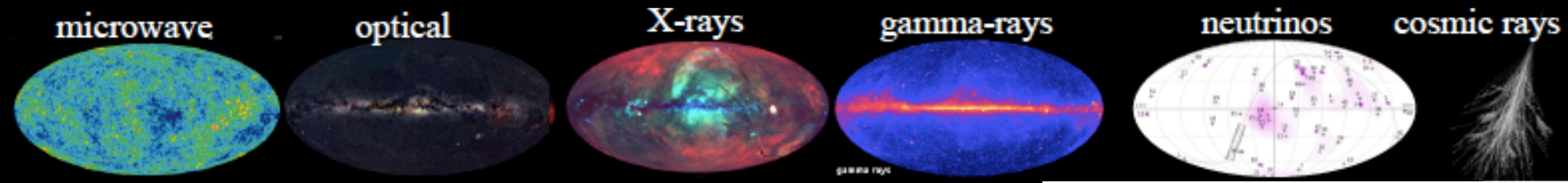
Strong City, KS
White Sands, NM
PACIFIC OCEAN
ATLANTIC OCEAN
Gulf of Mexico

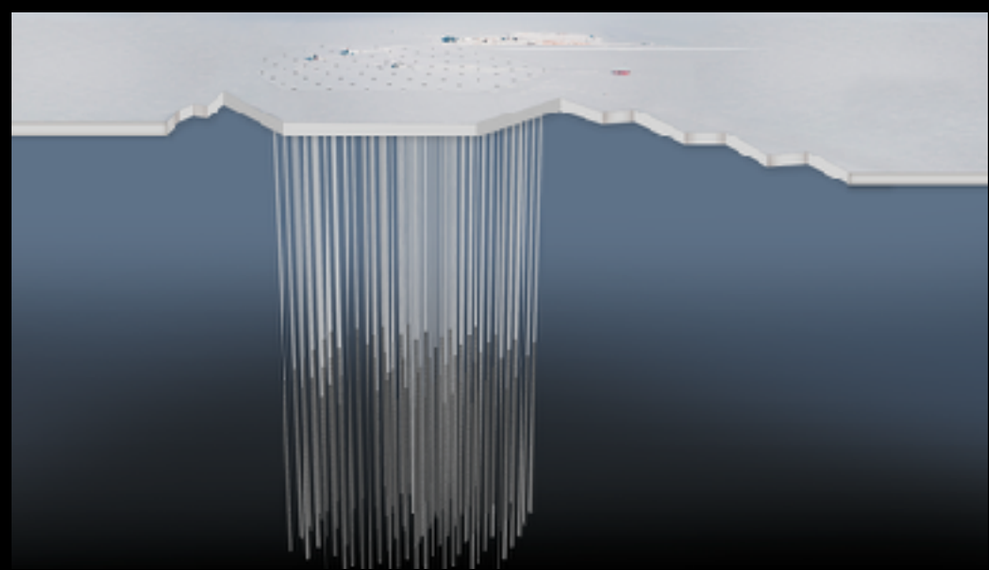
Next Stop:

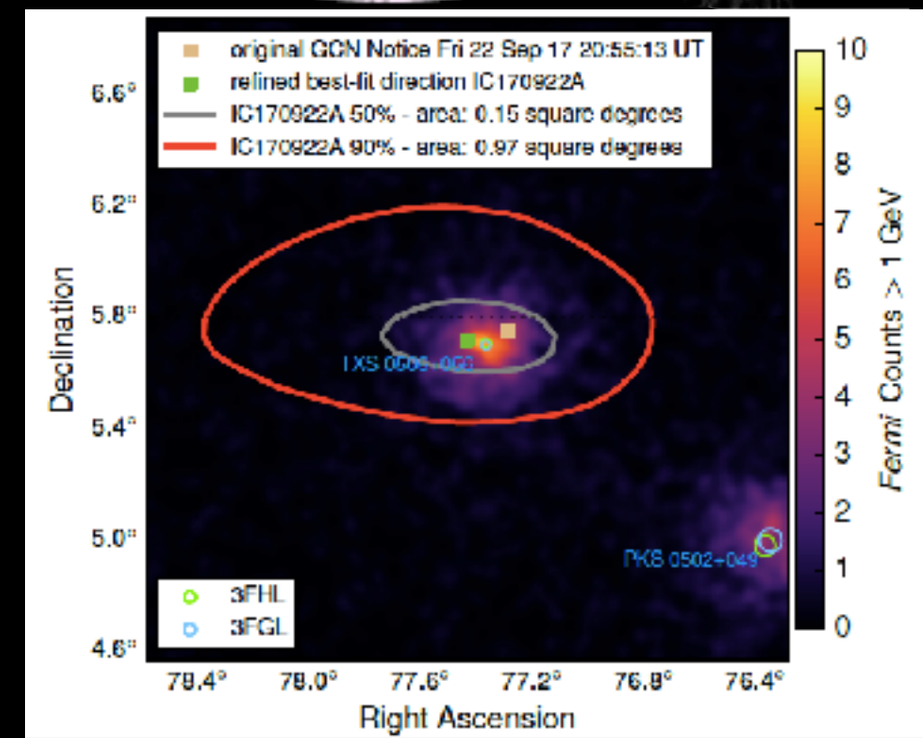
Zion National Park

Springdale, Utah

(Where we can contemplate the cosmos)



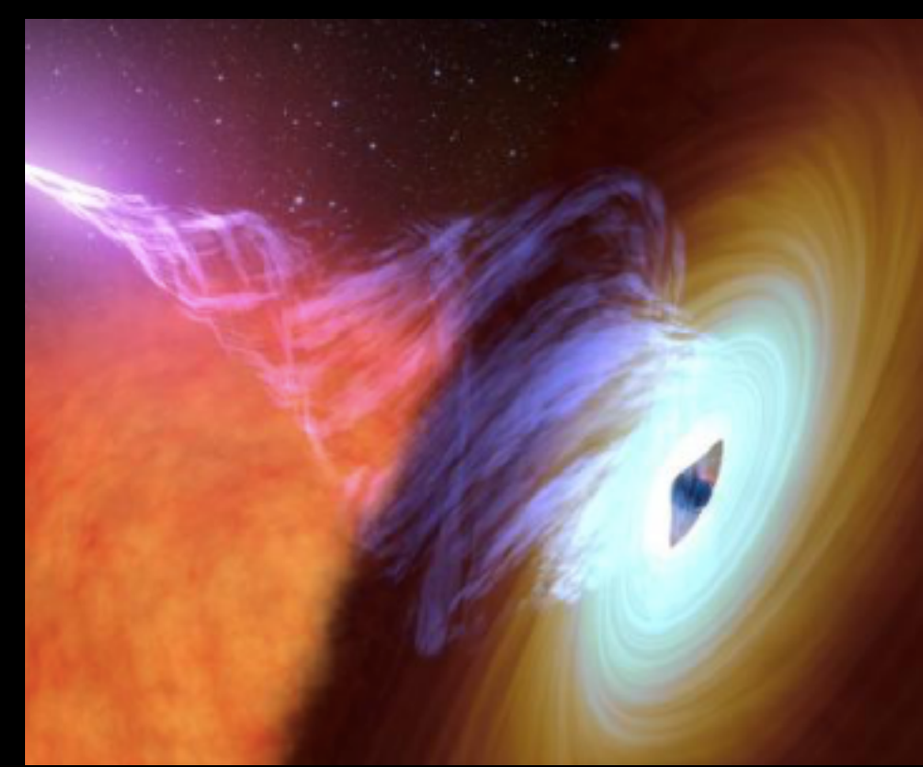


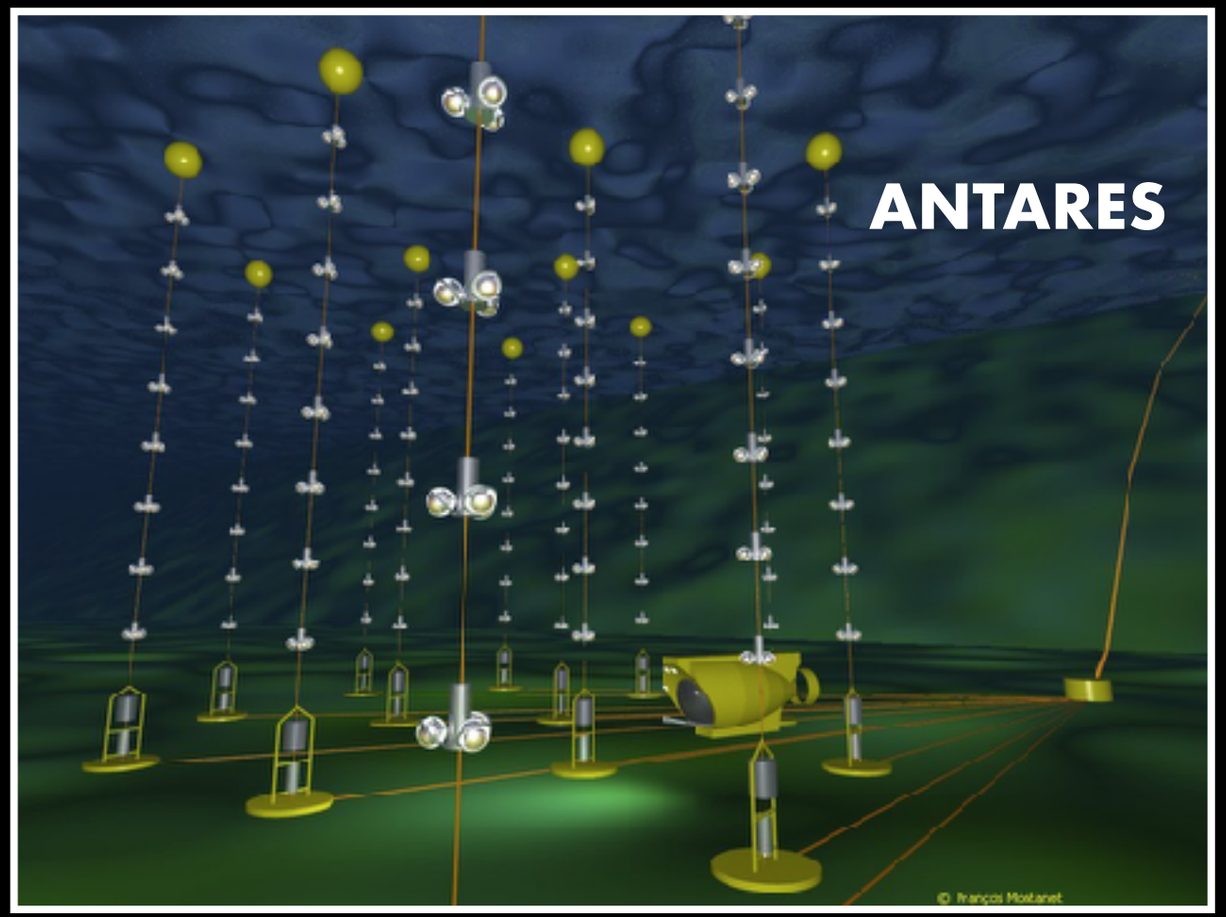


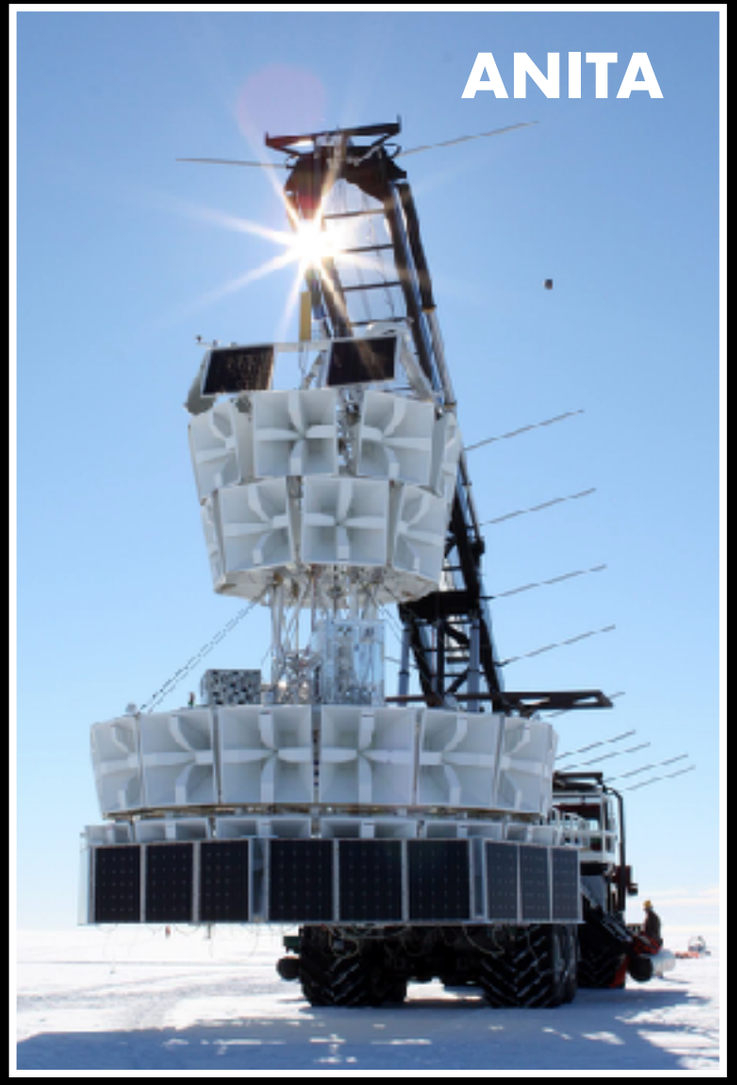
"The era of multi-messenger astronomy is here."

We now have the tools to interweave neutrino observatories into the melee. Gravitational waves & neutrinos next?

And the baseline of those observatories continues to expand.





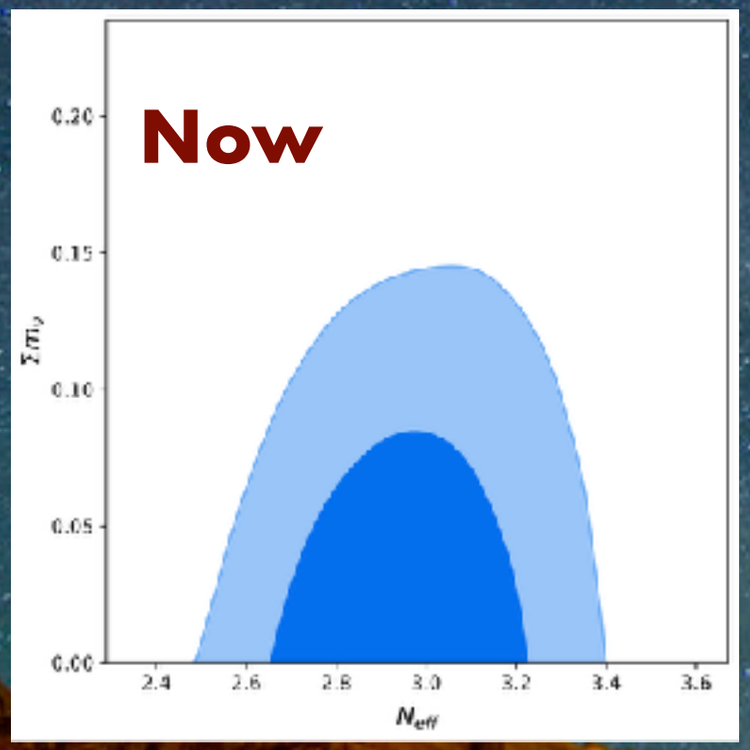


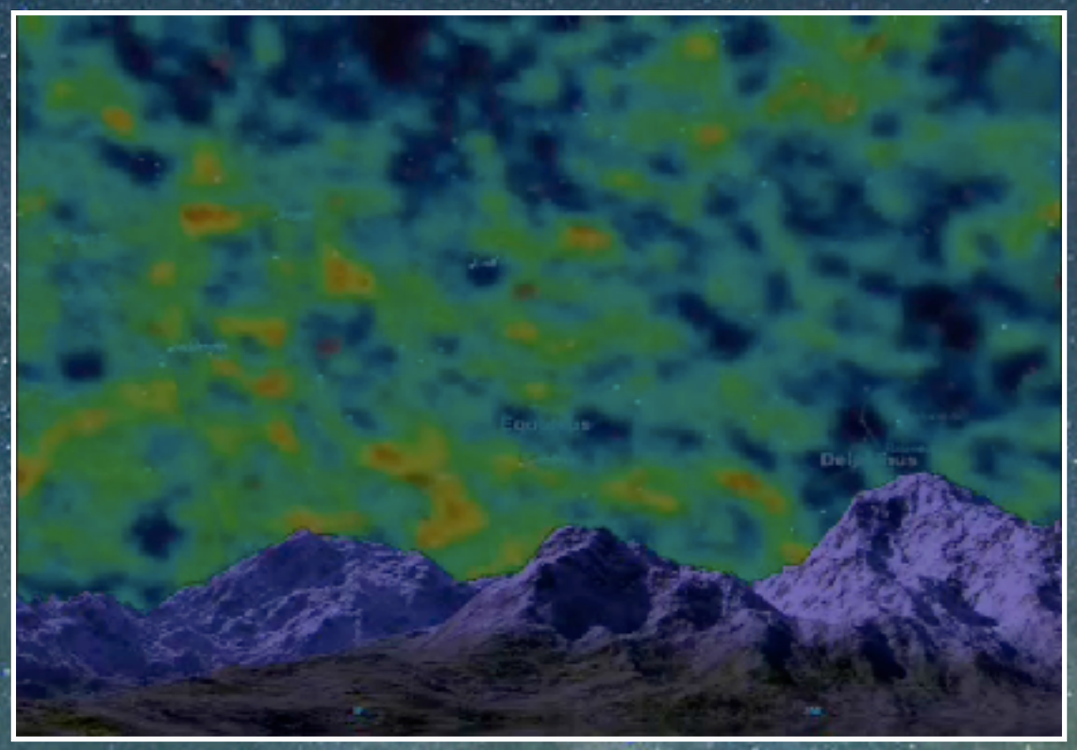
"The era of multi-messenger astronomy is here."

We now have the tools to interweave neutrino observatories into the melee. Gravitational waves & neutrinos next?

And the baseline of those observatories continues to expand.

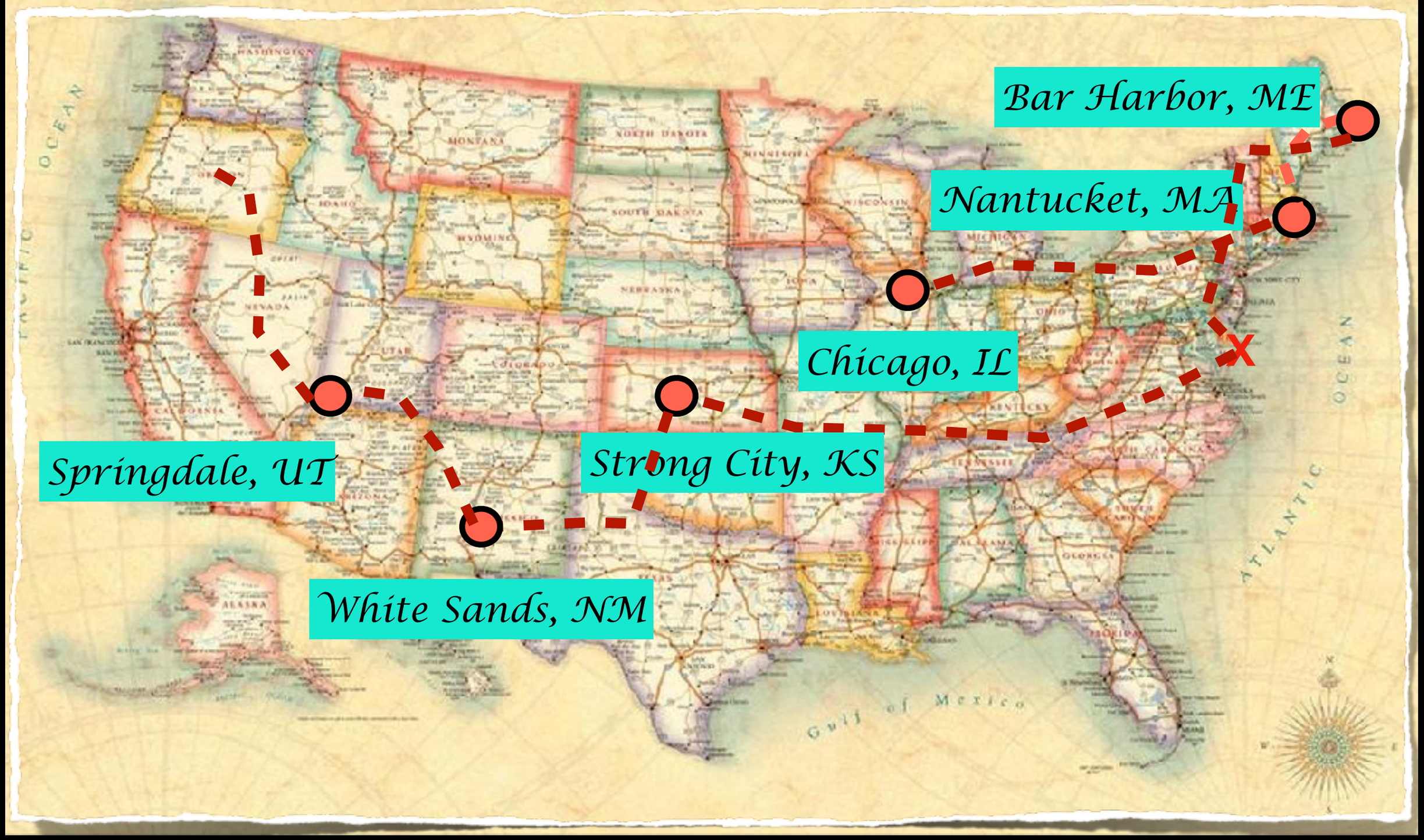
This “interweaving” of experimental astrophysics, cosmology and neutrino physics continues all the way to the early universe.





Neutrinos may indeed play a role in resolving some of the tensions seen in cosmology.

Or at least help.


Bar Harbor, ME
Nantucket, MA
Chicago, IL
Strong City, KS
Springdale, UT
White Sands, NM
PACIFIC OCEAN
ATLANTIC OCEAN
Gulf of Mexico

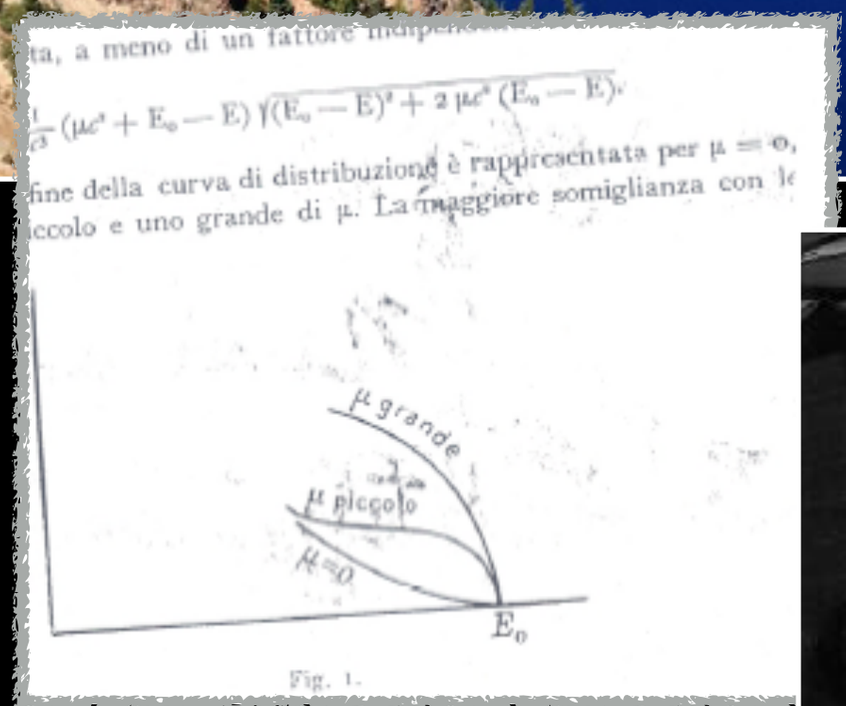
Next Stop:

Crater Lake National Park

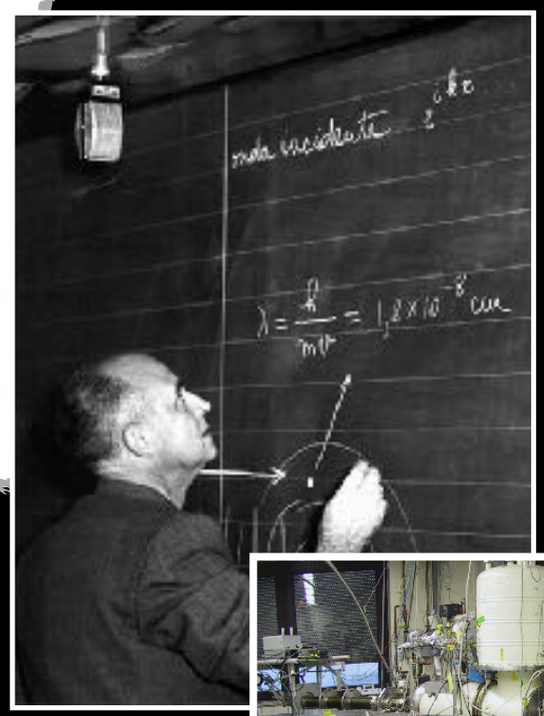
Klamath County, Oregon

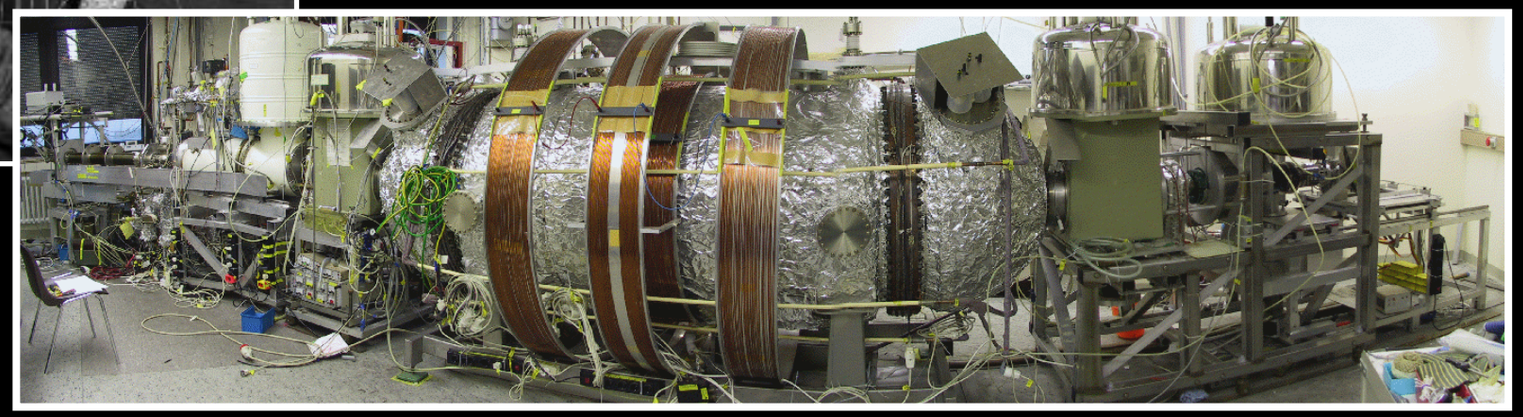
...where we can contemplate the nature of neutrino mass...

Addressing the question of the neutrino mass scale has been with our field since its inception.

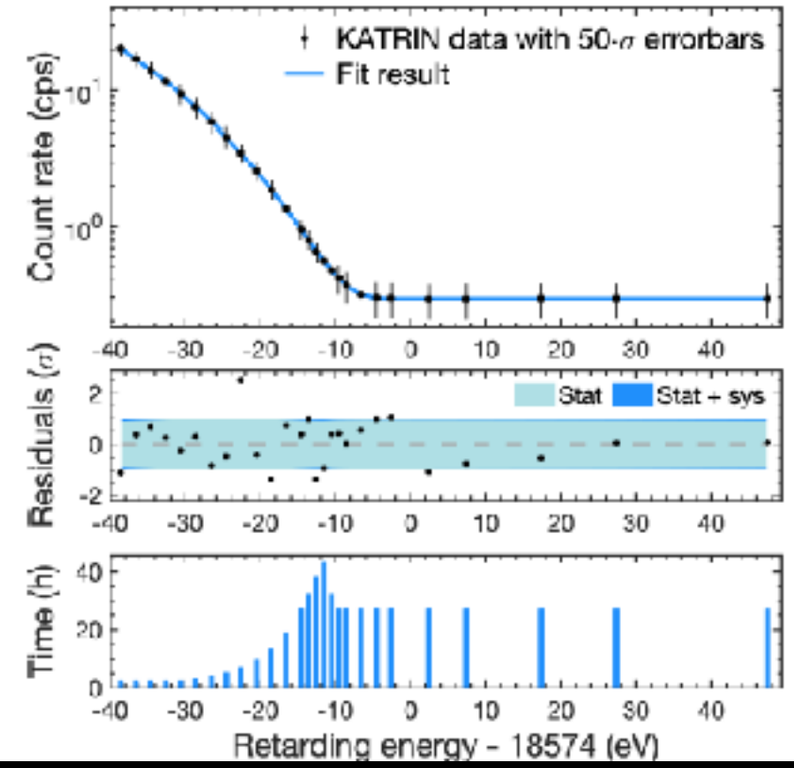


E. Fermi, Nuovo Cimento



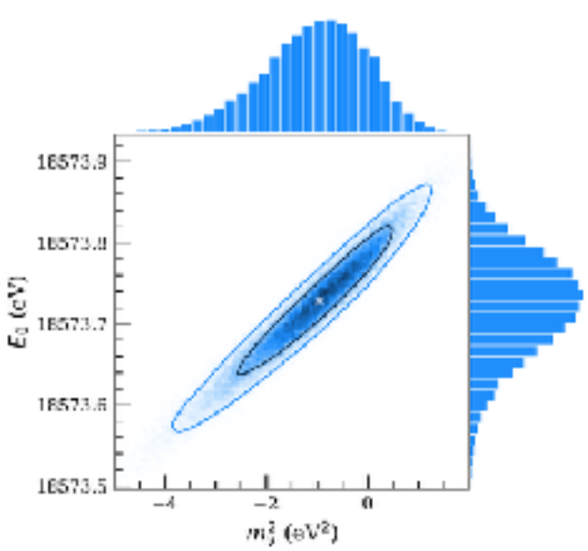


Mainz Experiment



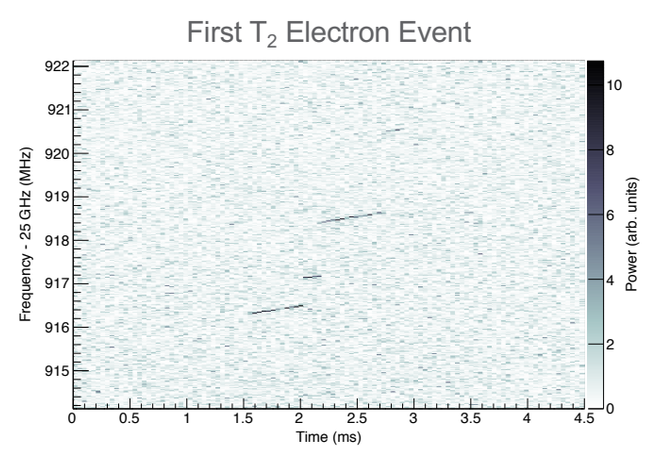
After almost two decades of development, KATRIN has released it's first direct neutrino mass measurement. Congrats to the KATRIN team!

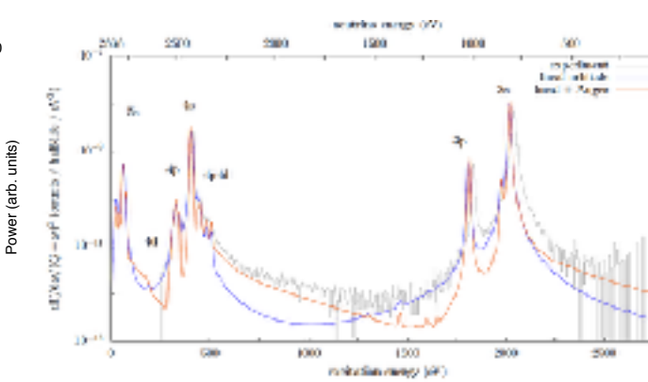
$$m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)\ \mathrm{eV}^2$$



More measurements under way.

New experiments taking shape, too!



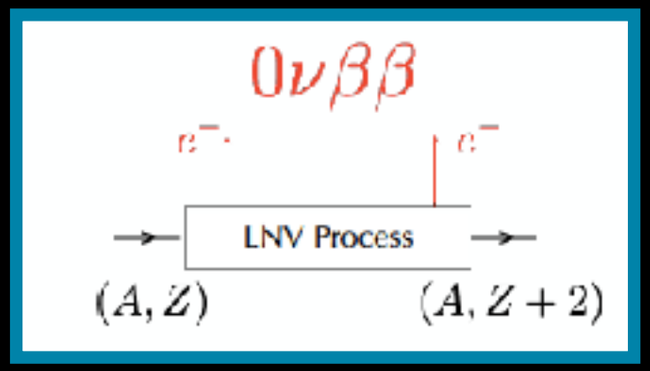


PROJECT 8

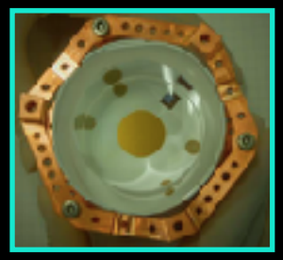
HOLMES

ECHo

The ongoing quest to understand whether neutrinos are their own anti-particles.



CUORE

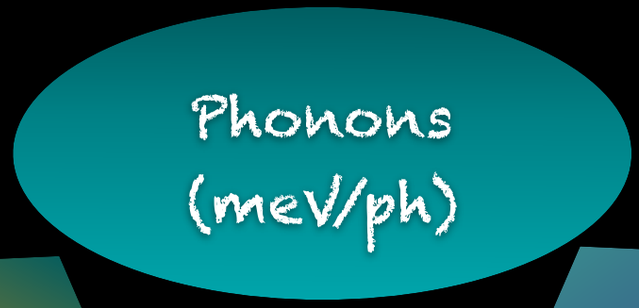


CANDLES

"HEAT"

MAJORANA

GERDA

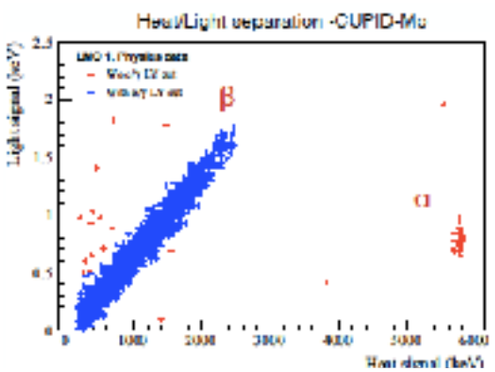


"CHARGE"

"LIGHT"

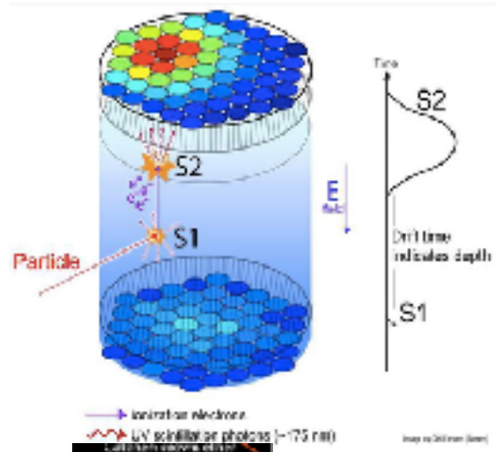
KAMLAND

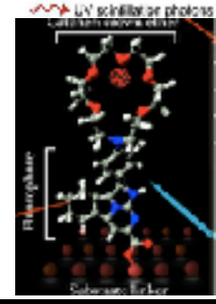
Particle ID



CUPID

Tagging



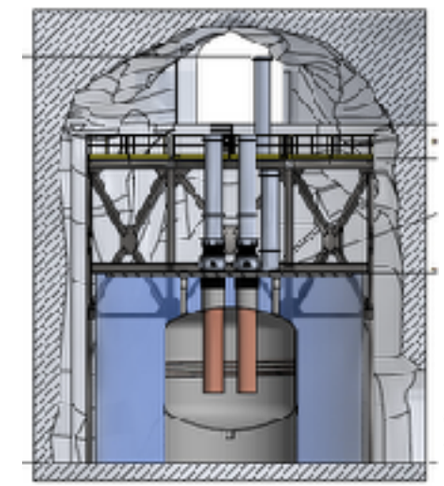


NEXO
NEXT

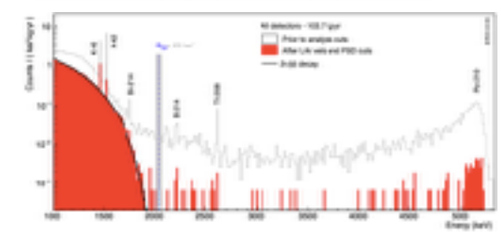
Target Mass

KAMLAND-ZEN2
SNO+ II

Vetoing



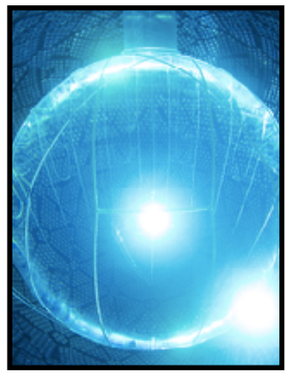
LEGEND

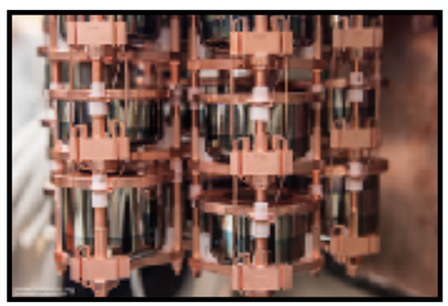


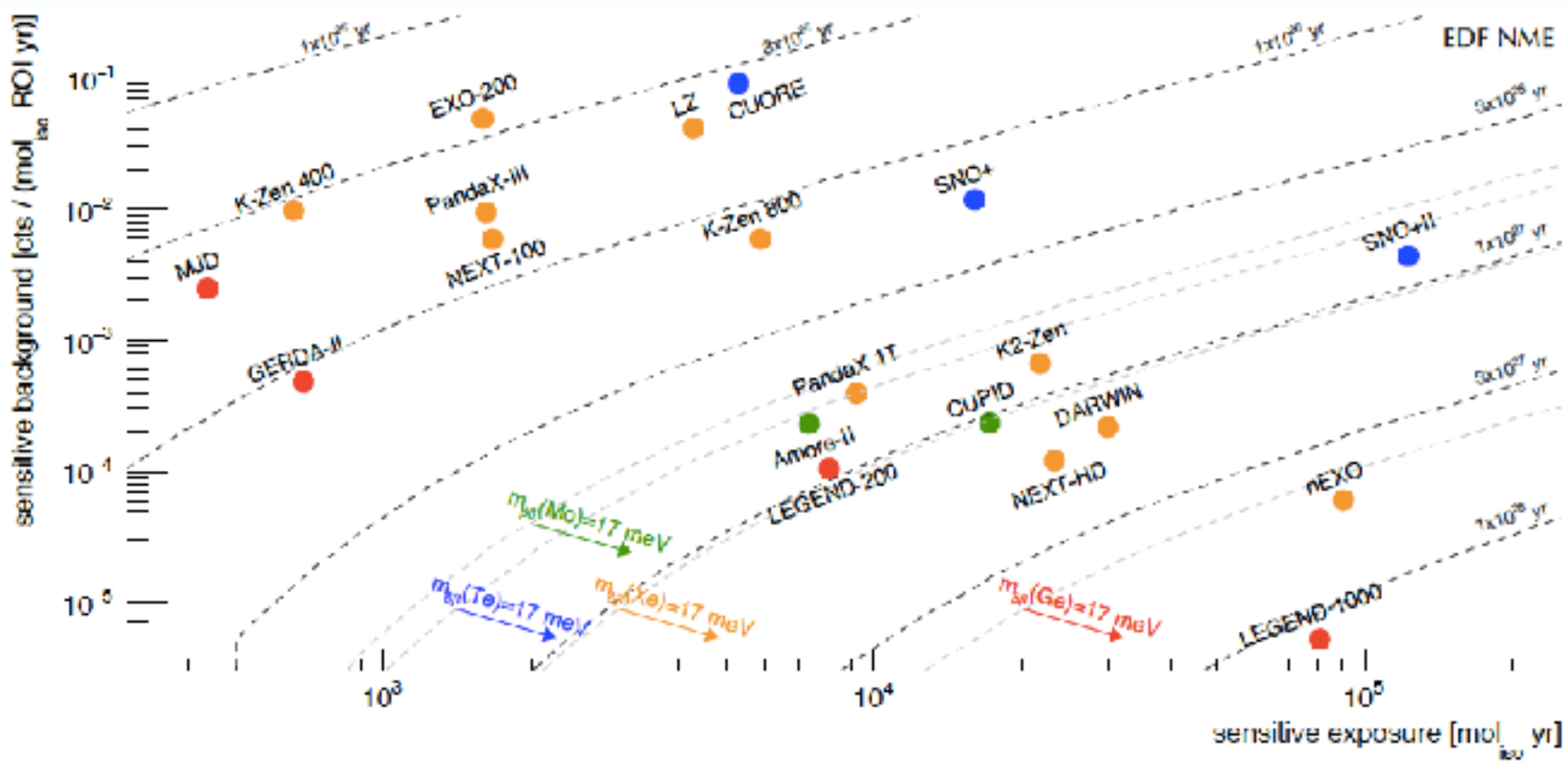
The next generation of detectors aim for unprecedented levels of background (<< count/keV/tonne/year is the new metric).

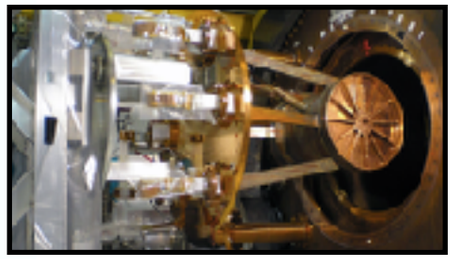
This target is approachable through multiple paths.

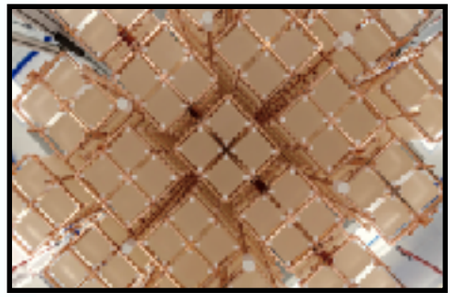
If successful, determining the Majorana nature of neutrinos might be within sight.







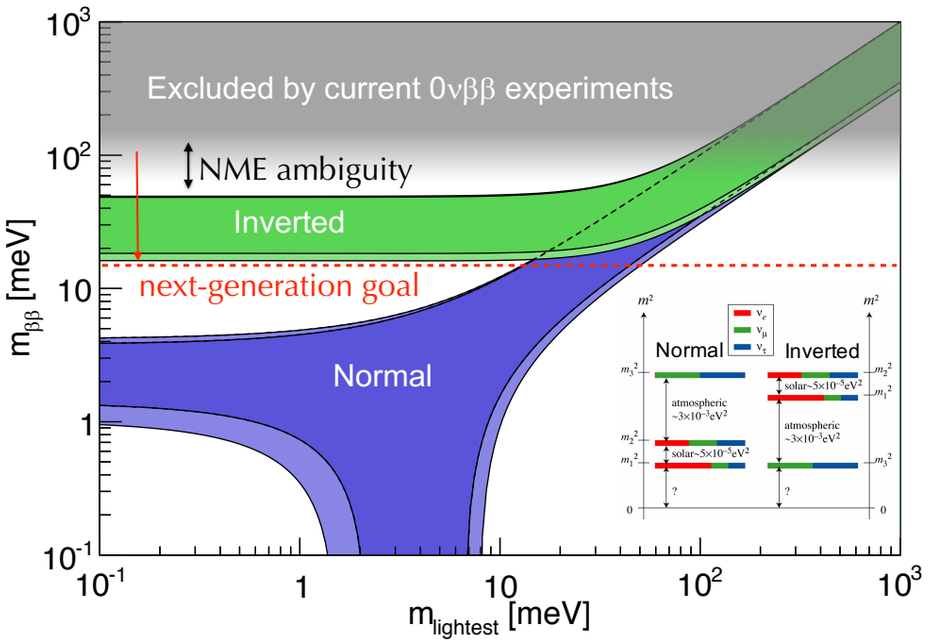




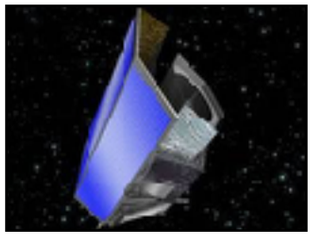
The recent advances in 0νββ technology implies that the inverted ordering scale is our next target and that the normal scale is on the visible horizon.

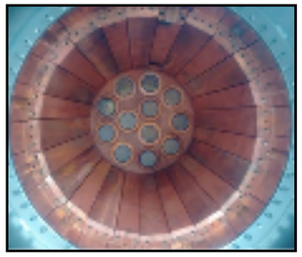
The combination of cosmology, direct measurements, and measurements may provide a more complete picture of the neutrino mass scale.

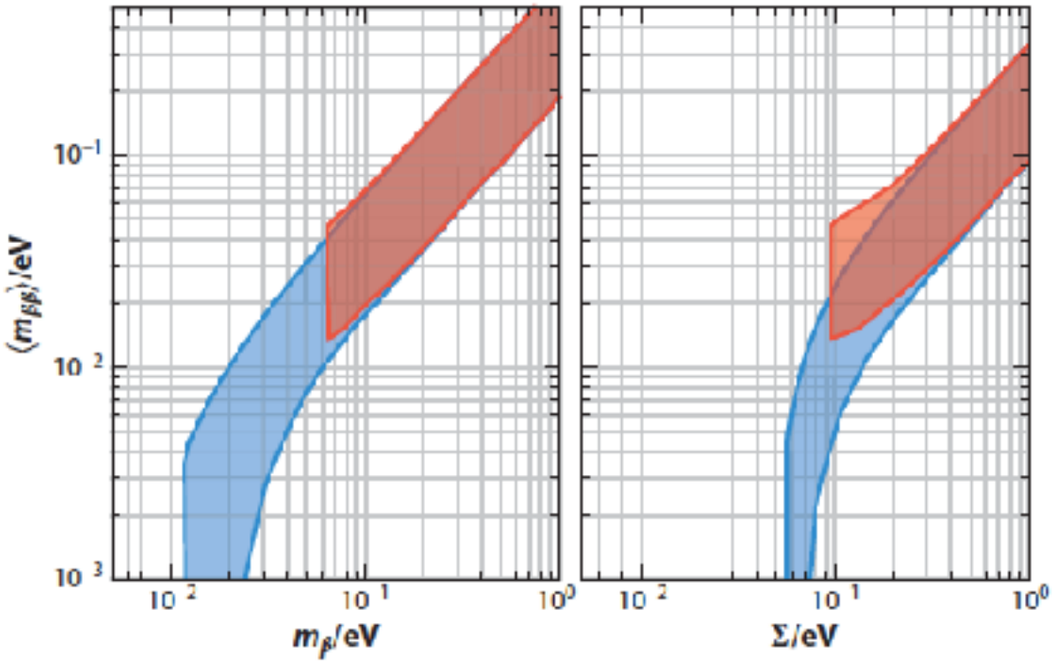
A measurement in this sector is the “legacy” of neutrino oscillations.



0νββ versus "scale"







mass scale versus "observables"

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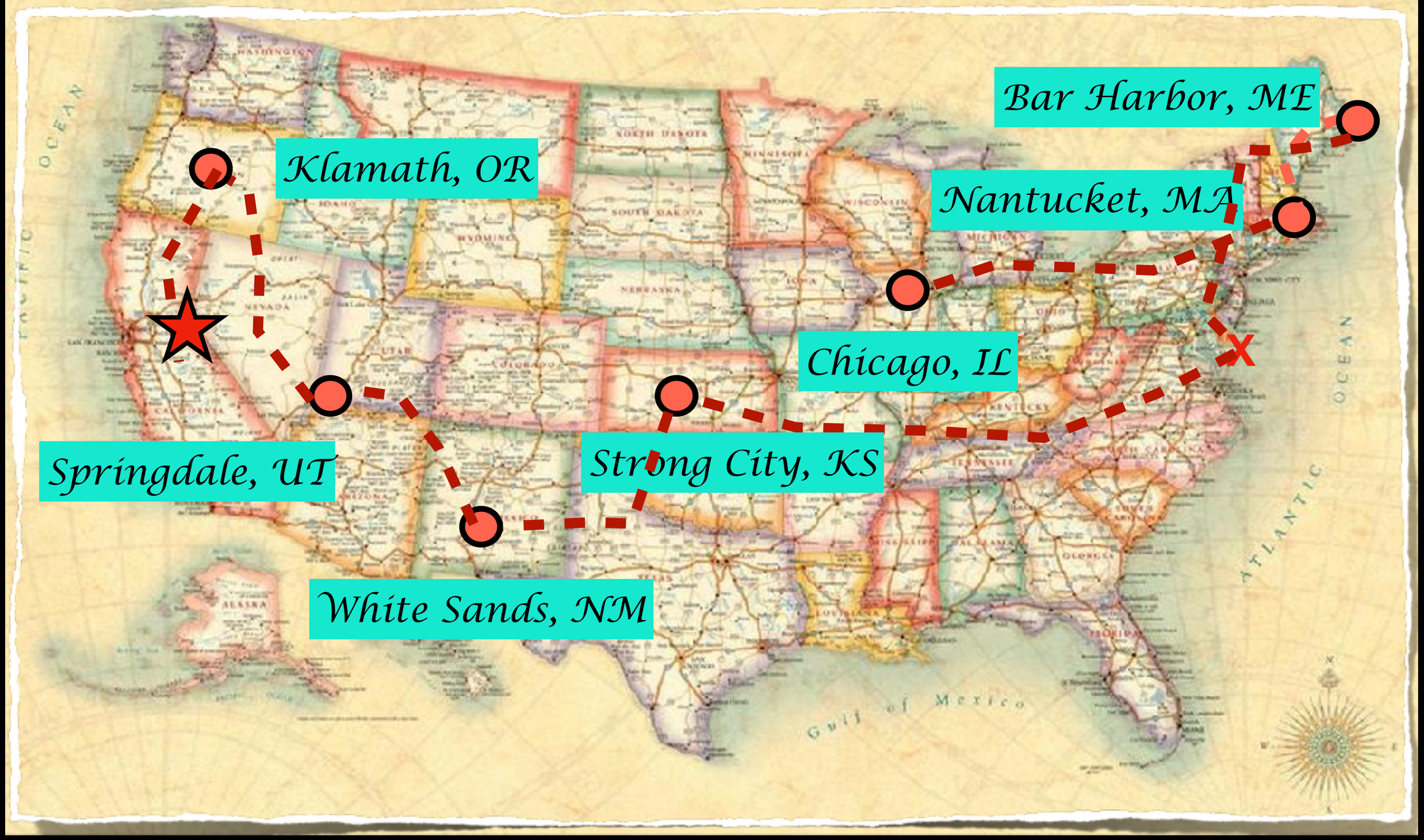

Bar Harbor, ME
Klamath, OR
Nantucket, MA
Chicago, IL
Springdale, UT
Strong City, KS
White Sands, NM
PACIFIC OCEAN
ATLANTIC OCEAN
Gulf of Mexico

Last Stop:

Yosemite National Park

California

where we ponder where we've been

&

where we're going

If there is one theme I see emerging from this conference, it is that long term investments in these experimental endeavors are bearing fruits.

We are truly in the precision stage of neutrino physics. Our current tests in neutrino properties stem from unprecedented advances in beam intensities, low backgrounds, and incredibly large targets.

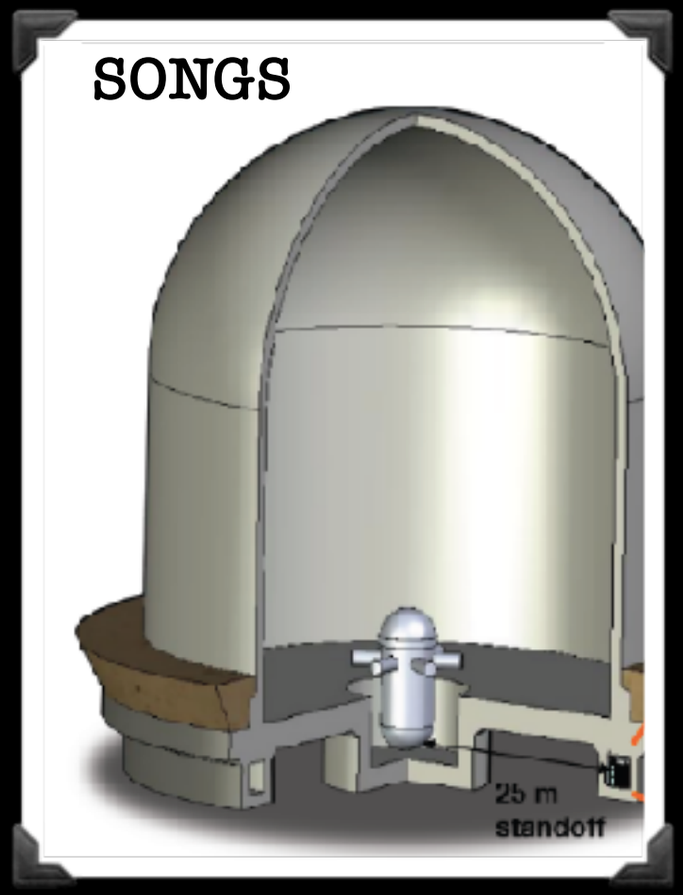
Also new techniques and tools that are used everyday. For example:

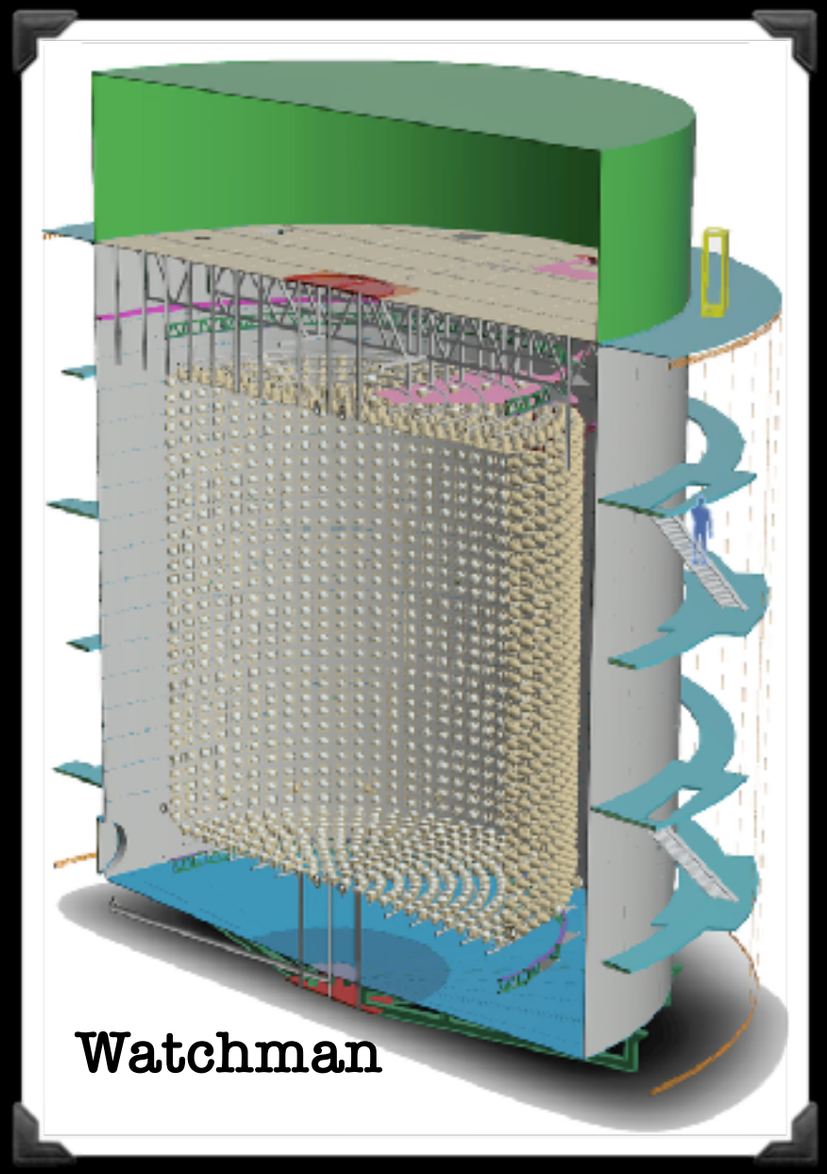
- Bayesian methods now appear in a number of major results presented here.
- The words “machine learning” appear in over 15 posters at this conference.

My own prediction: the words **Quantum Computing** and **Quantum Sensors** will become more common in future Neutrino conferences.

What comes from a PRECISION era of neutrinos?

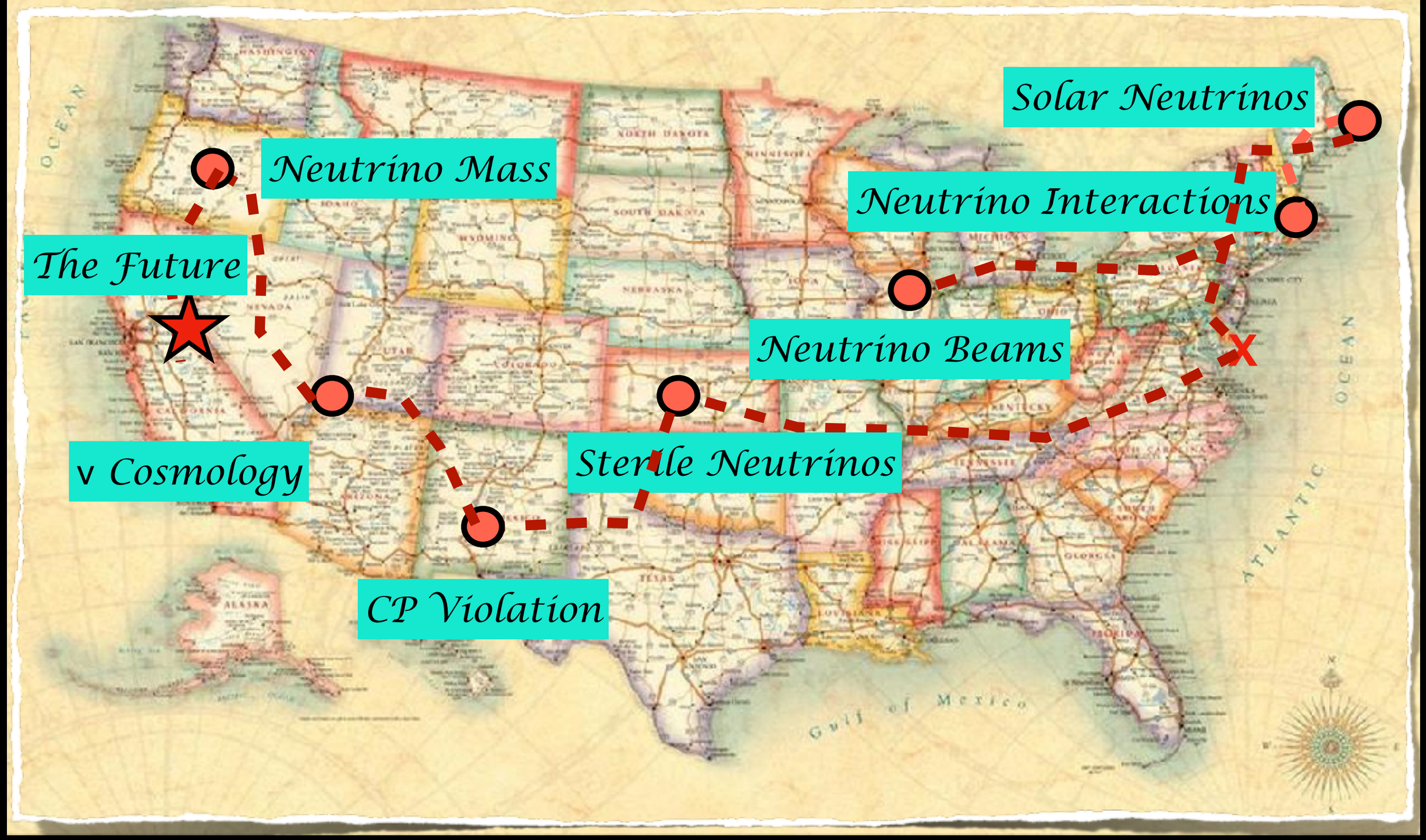
- Well, hopefully, better **understanding...**
- But we can also start to think about **betterment of society...**





In light of COVID, the value of science (and the ability to meaningfully engage in science) is more important than ever.

Anti-neutrino monitoring!



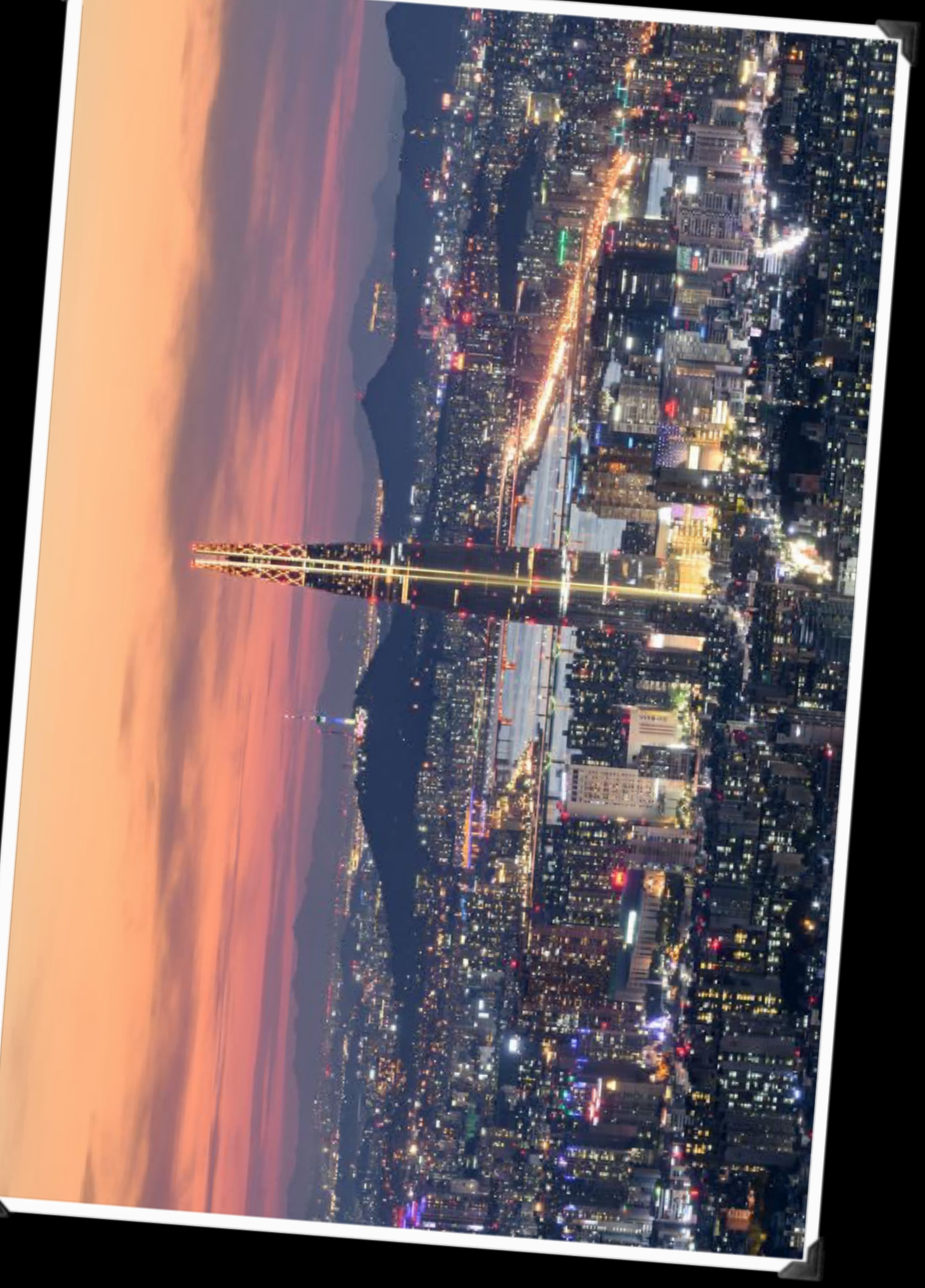
The landscape for neutrino physics is vast...

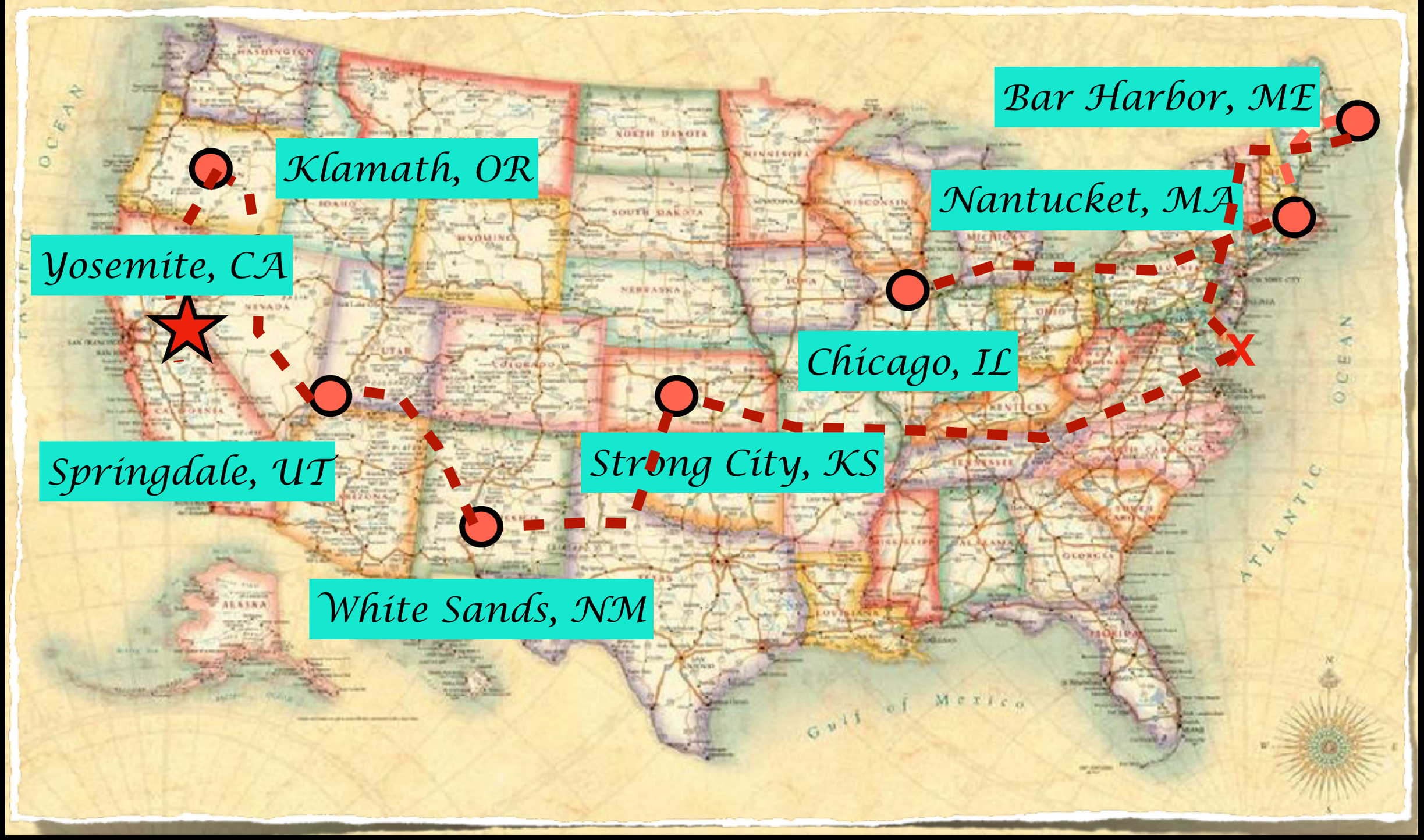
...still, we have covered a lot of ground.

(much more than I could cover in this talk; apologies to those I left out)

Thank you for your attention!

Hope to see you in Seoul in 2022!





- Fun Facts:
  - If you did this route, it would amount to 6,000 miles (~10,000 km)
  - Approximately 100 h of driving time.