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LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

What We Have Learned about the Universe from Low-Energy Neutrino Physics Experiments and NERSC's Role in the Discoveries

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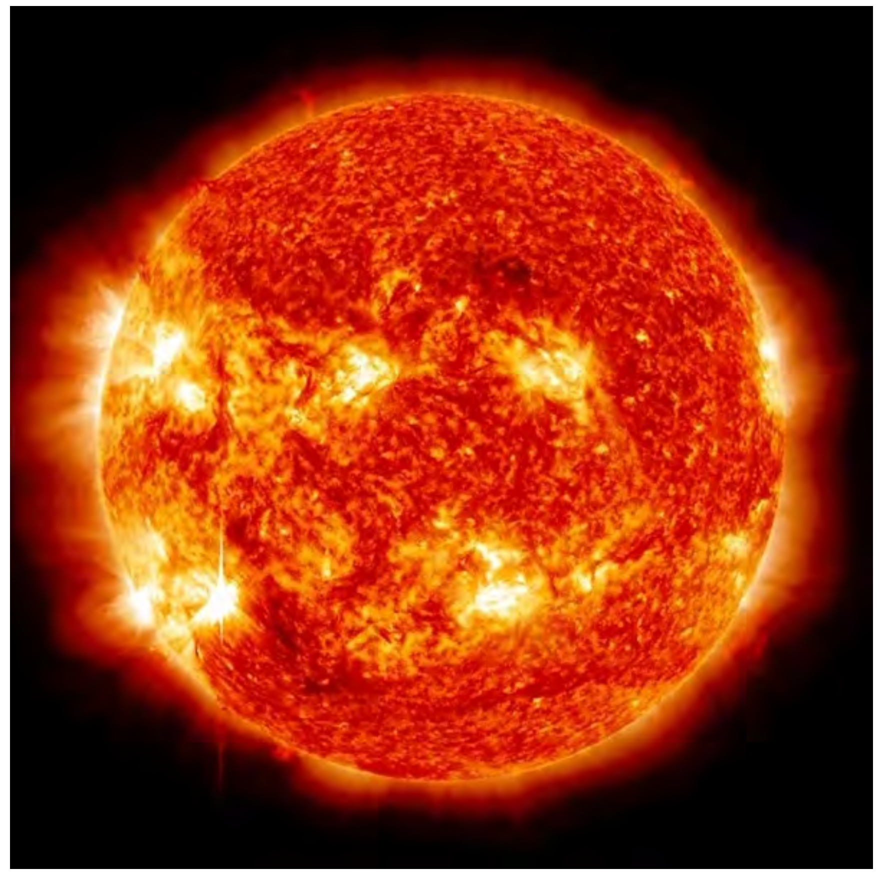
Nuclear Science Division

2024.04.15

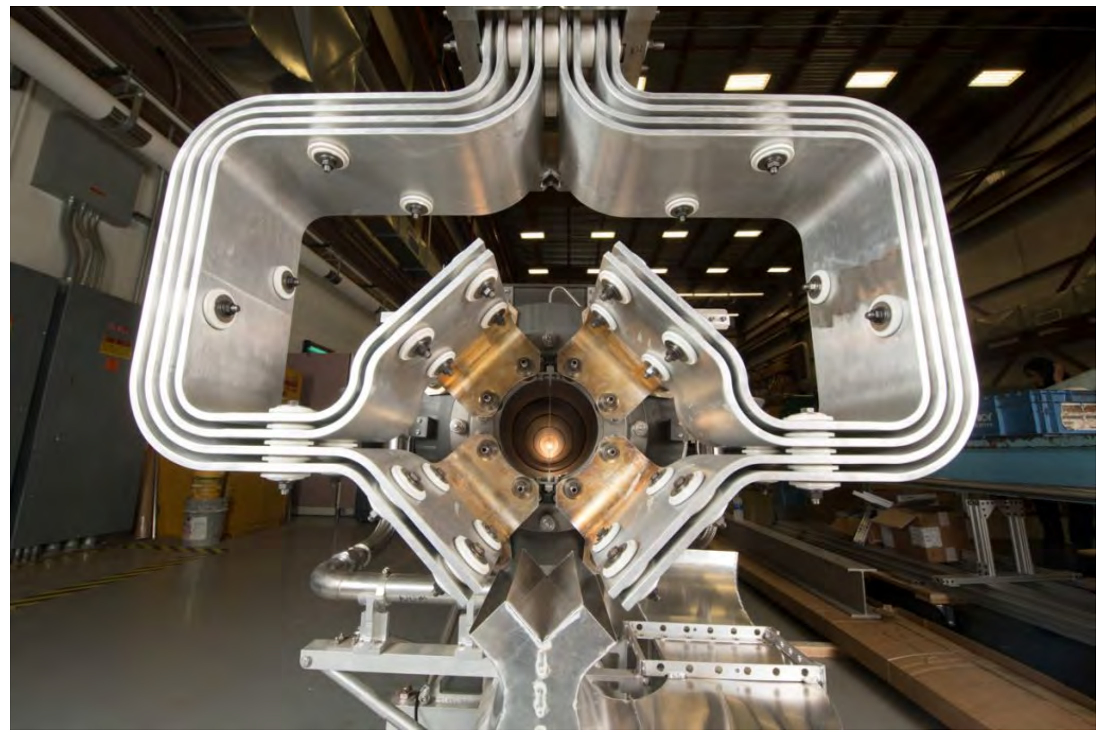
What are the neutrinos (ν)?

- The most abundant *massive* particle in the Universe (but prescribed as massless in the Standard Model of Elementary Particles).
- There are three types ("flavors") that interact (rarely) with matter – about 60 Billion ν are going through your thumbnail every second.
- These flavors are grouped with their heavier charged leptons in the same family: (e ν_e), (μ ν_μ), (τ ν_τ).
- There are many sources of neutrinos. Some examples:
  - relic ν (byproducts of the Big Bang)
  - supernova ν (from SN explosion)
  - solar ν (fusion in our Sun's core)
  - geo-ν (radioactive decay in our Earth's core)
  - reactor ν (byproducts from nuclear fission)
  - accelerator ν (produced at accelerators)

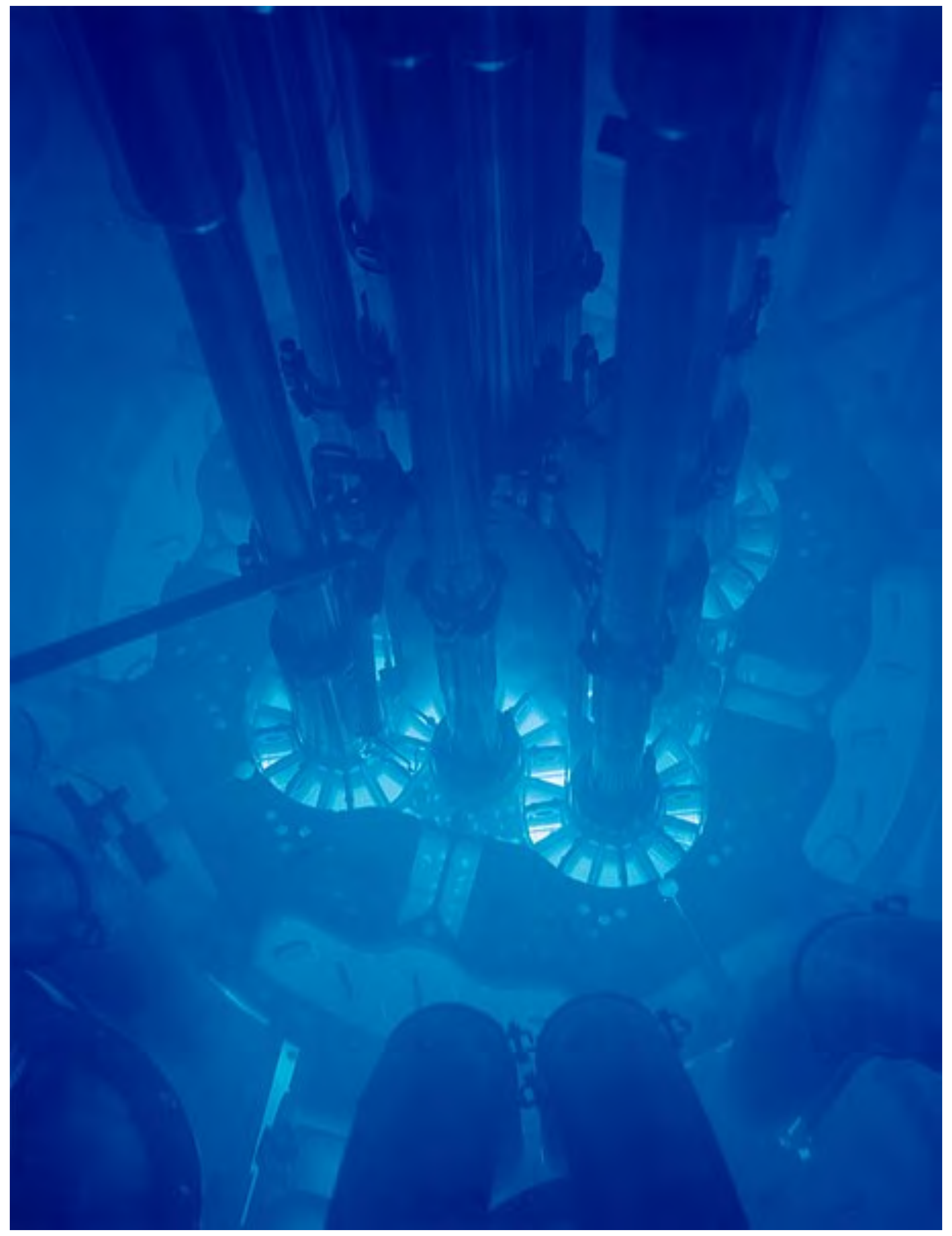


Our Sun (NASA)

SN1987A (JWST)



Neutrino focusing "horn" (FNAL)



Reactor core (Wikimedia)

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Solar Neutrinos — the Solar Neutrino Problem (SNP)

- Since the early 1960s, numerical modeling of the sun (*Standard Solar Model, SSM*) predicted the neutrino output from fusion in its interior have been made. An observation of solar neutrinos would prove that the sun (and other main sequence stars) produce energy through fusion.
- Ray Davis, Jr. (Nobel, Physics 2002) had been measuring the solar neutrino flux at the Homestake mine in Lead, SD, with 615 t of dry-cleaning fluid (perchloroethylene, C_2Cl_4) since the late 1960s:

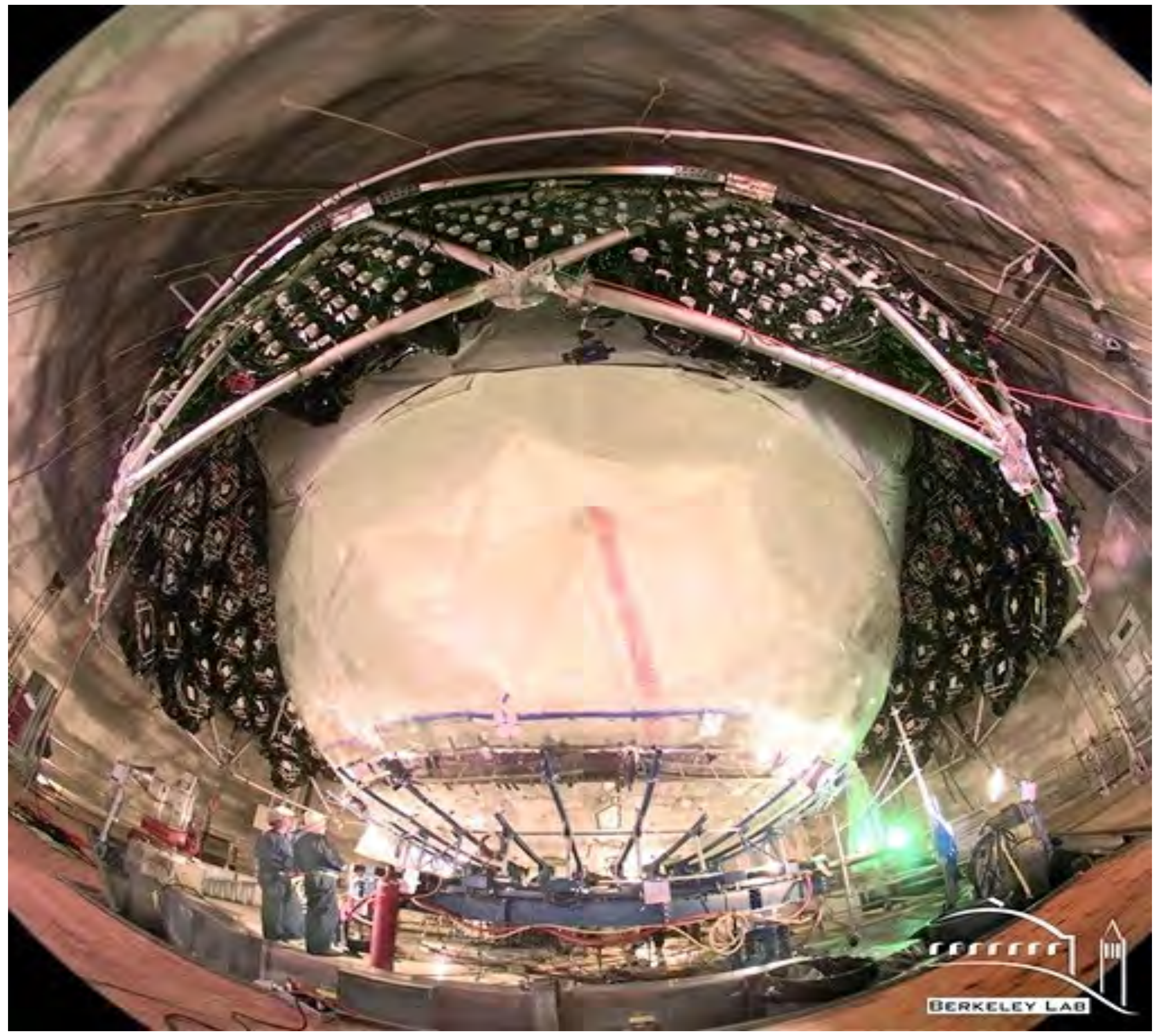
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

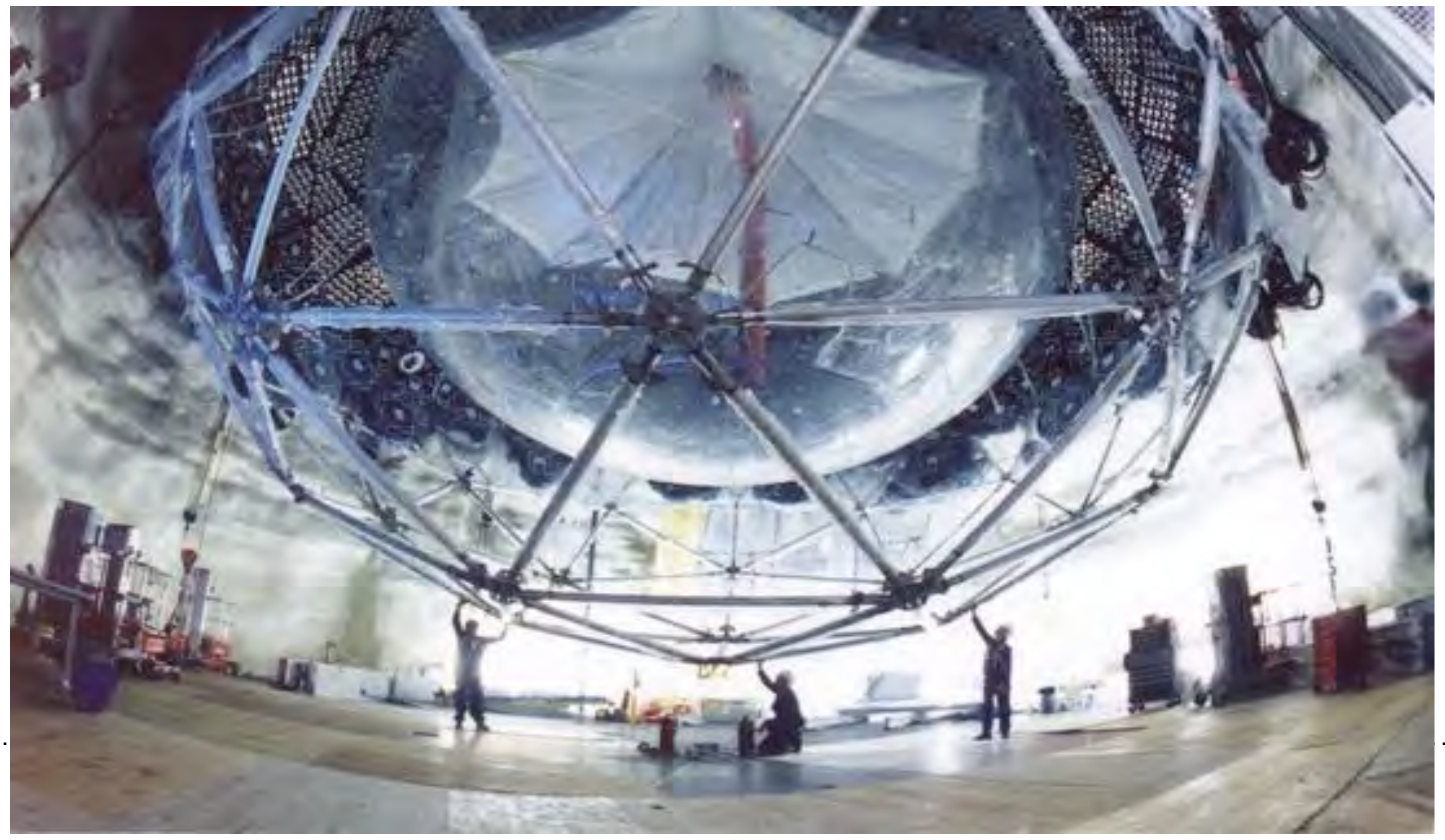
- Davis flushed the tank once a month, collected a few (if lucky) ^{37}Ar atoms in a glass vial (proportional counter) each time, look for its decay back to ^{37}Cl…repeated for 3+ decades!
- Saw ~1/3 of solar neutrinos predicted from SSM.
- Other experiments confirmed the observation of this solar neutrino deficit.

→ **Solar Neutrino Problem (SNP)**

Sudbury Neutrino Observatory (SNO)

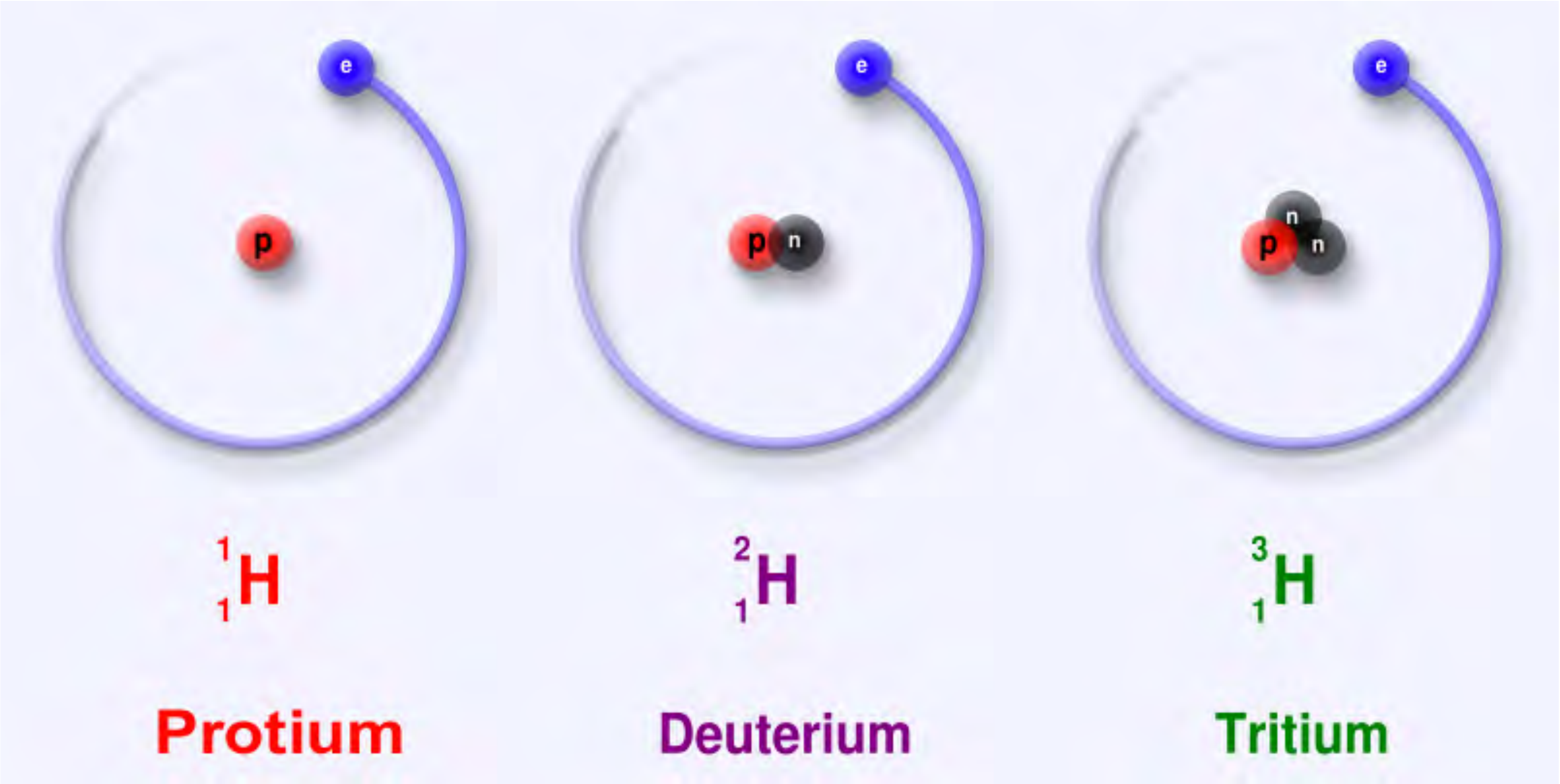
6800’ underground at Creighton Mine near Sudbury, Canada





Sudbury Neutrino Observatory (SNO)

- Used 1000 tonnes of D_2O
- Could detect separately:
  - "Charged-Current" – ν_e only
  - "Neutral-Current" – $\nu_{e,\mu,\tau}$ (i.e. all active ν types)



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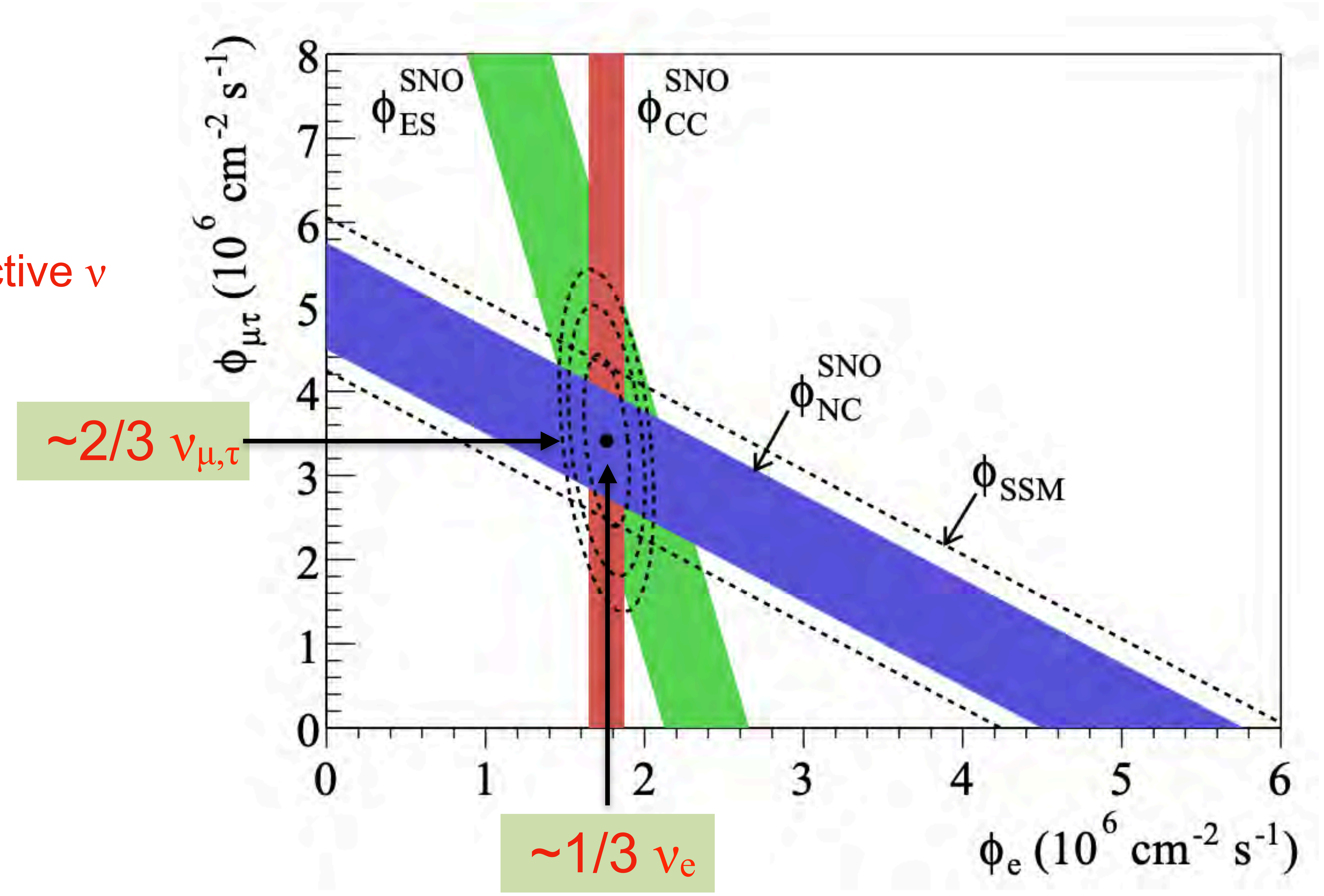
  - ~1/3 ν_e
  - ~2/3 $\nu_{\mu,\tau}$

\+ → **confirmed SSM**



Phys. Rev. Lett. **89**, 011301

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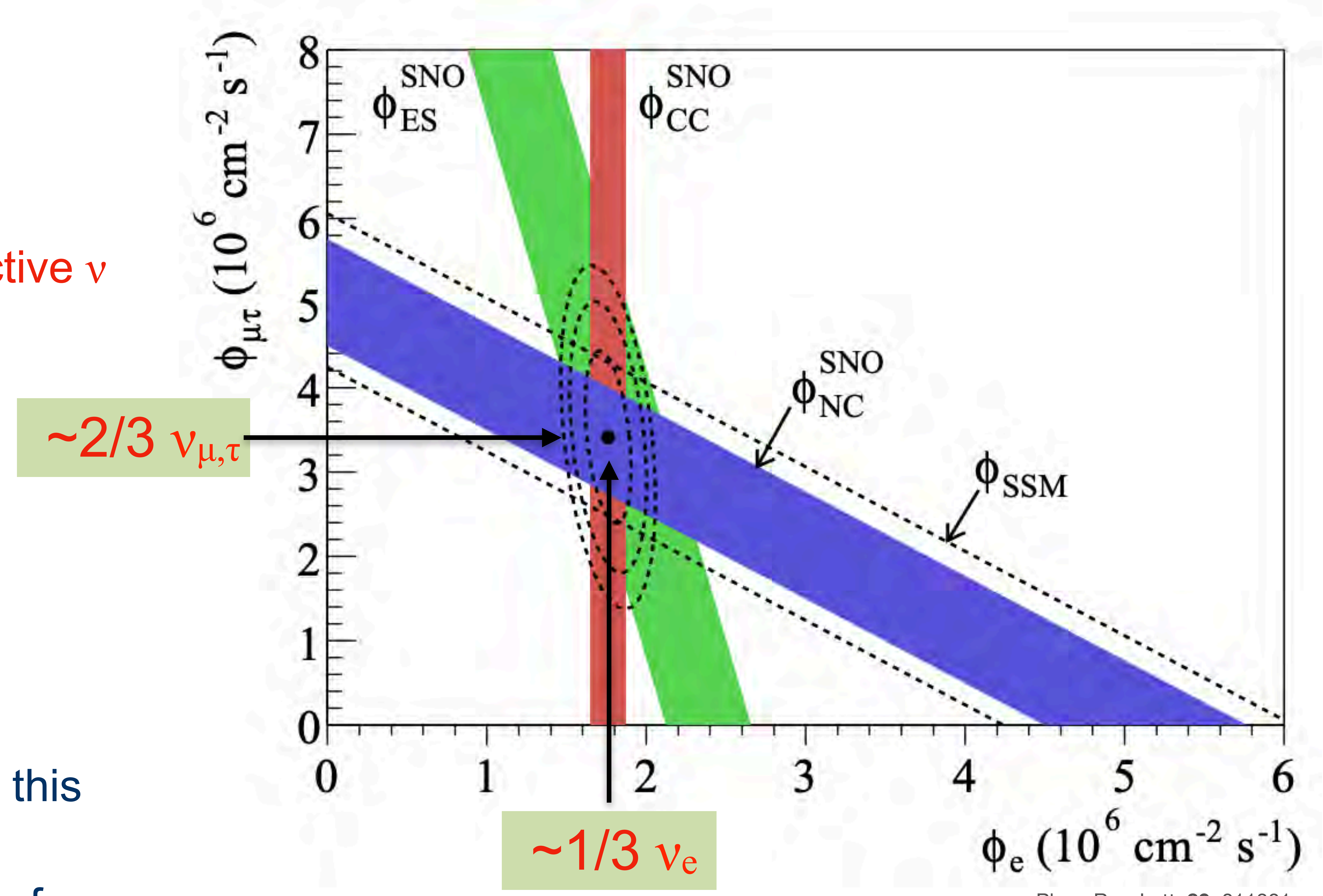
\+ → **confirmed SSM**

- This means:
  - Some ν_e transform to $\nu_{\mu,\tau}$ while traveling from the Sun to us.
  - Neutrinos must have mass due to this flavor transformation.
  - Other experiments were capable of detecting ν_e only.



Phys. Rev. Lett. **89**, 011301

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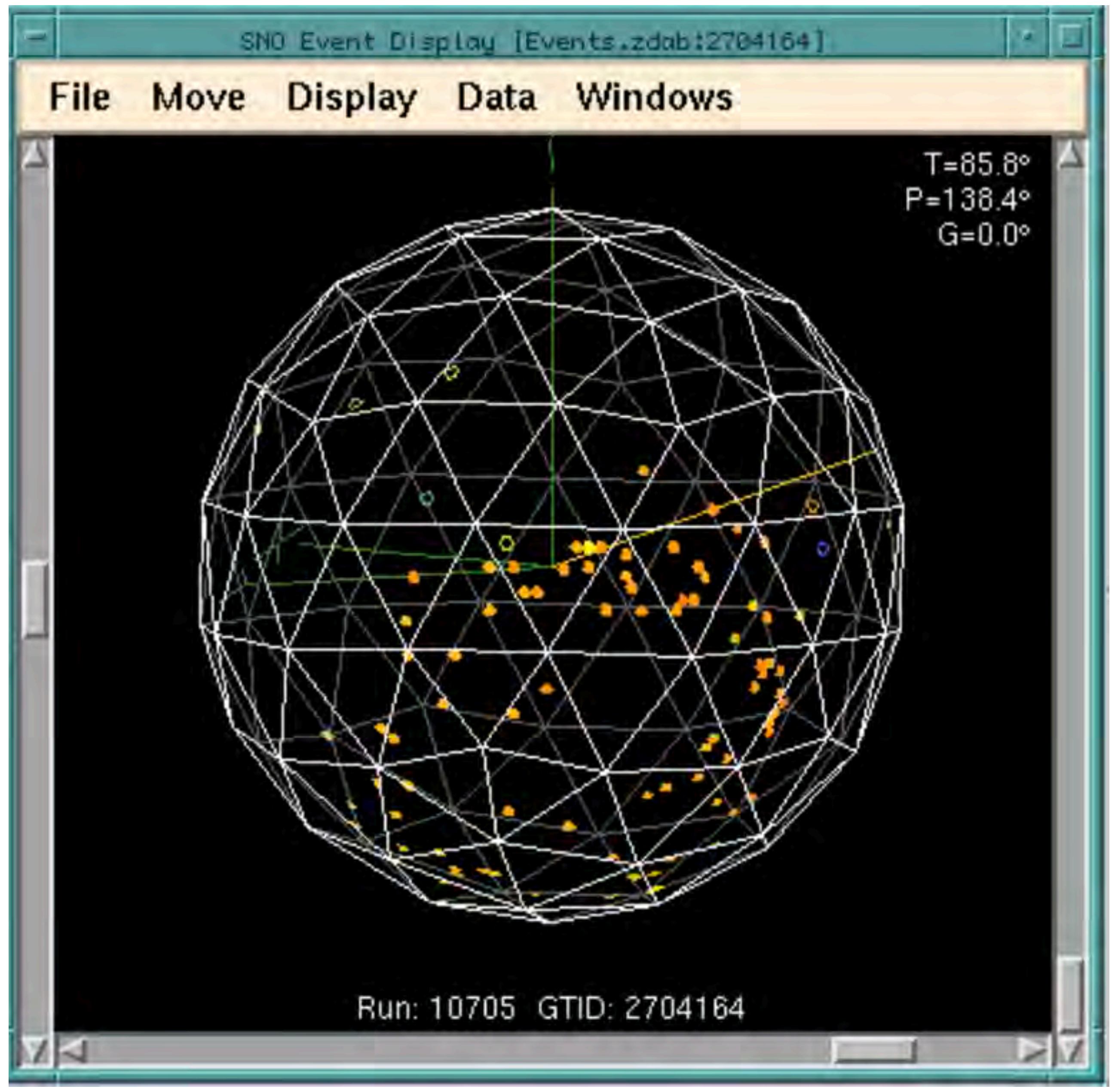
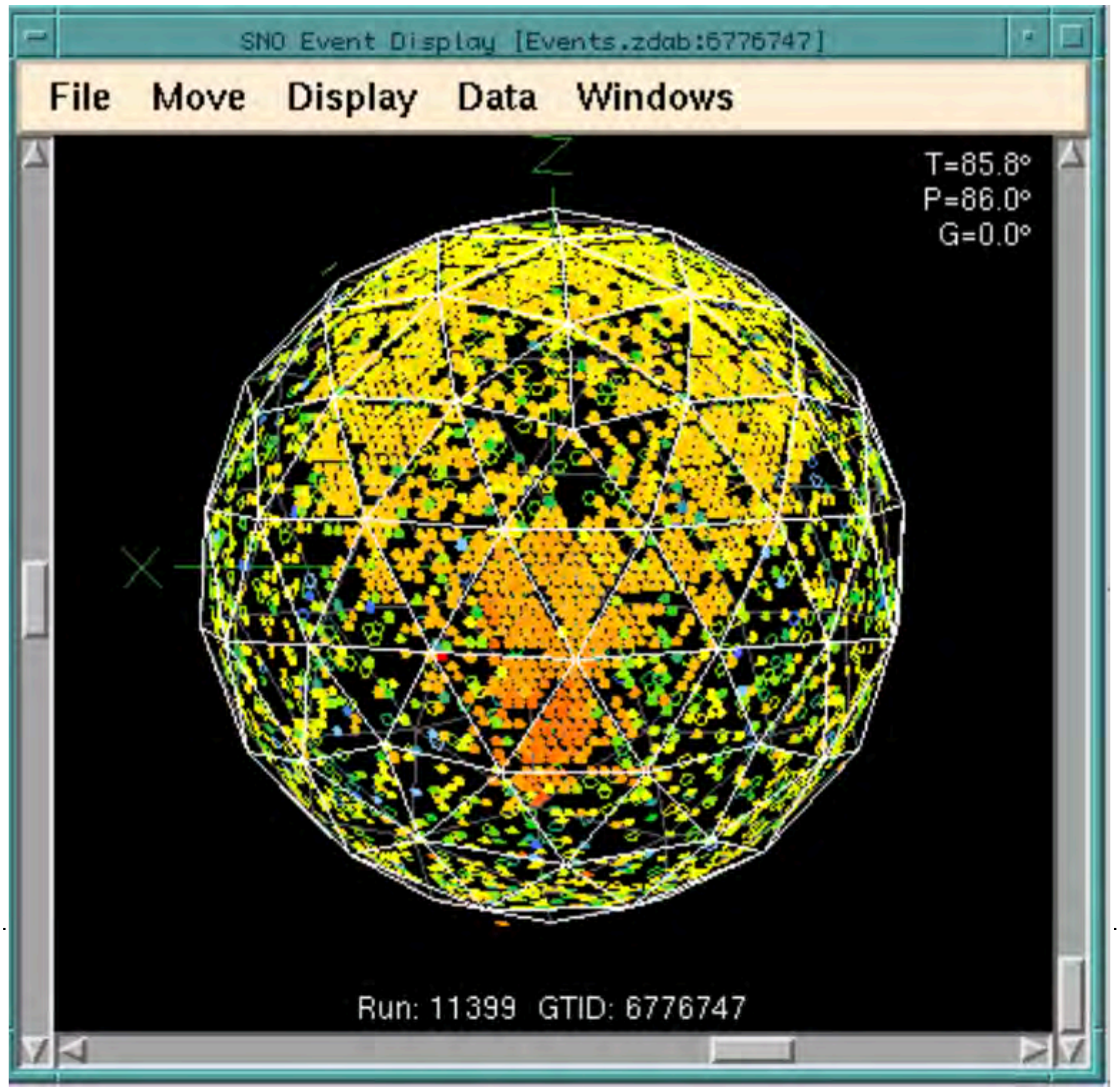
NERSC & SNO

- Data processing and production
  - Event reconstruction
  - Energy calibration
- Radioactive background simulation
  - simulated the equivalent of years of real radioactive background from different components of the detector, as well as other external backgrounds (such as cosmic μ)
  - simulated with high statistics the solar neutrino signals in SNO
- Data storage and archive — The SNO data and codes have been archived at HPSS since 2009.

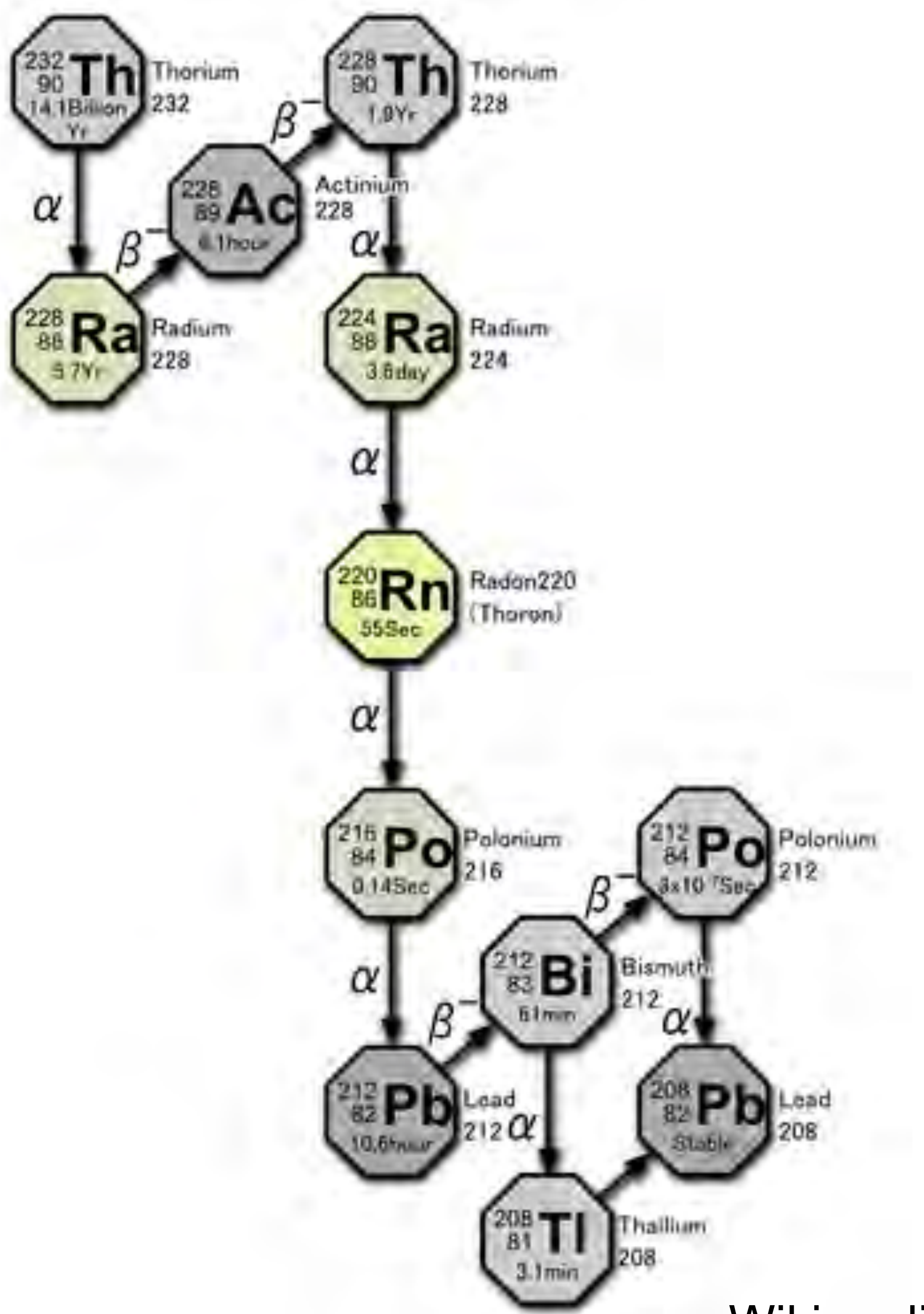


solar ν candidate



cosmic μ candidate

Th chain



Wikimedia

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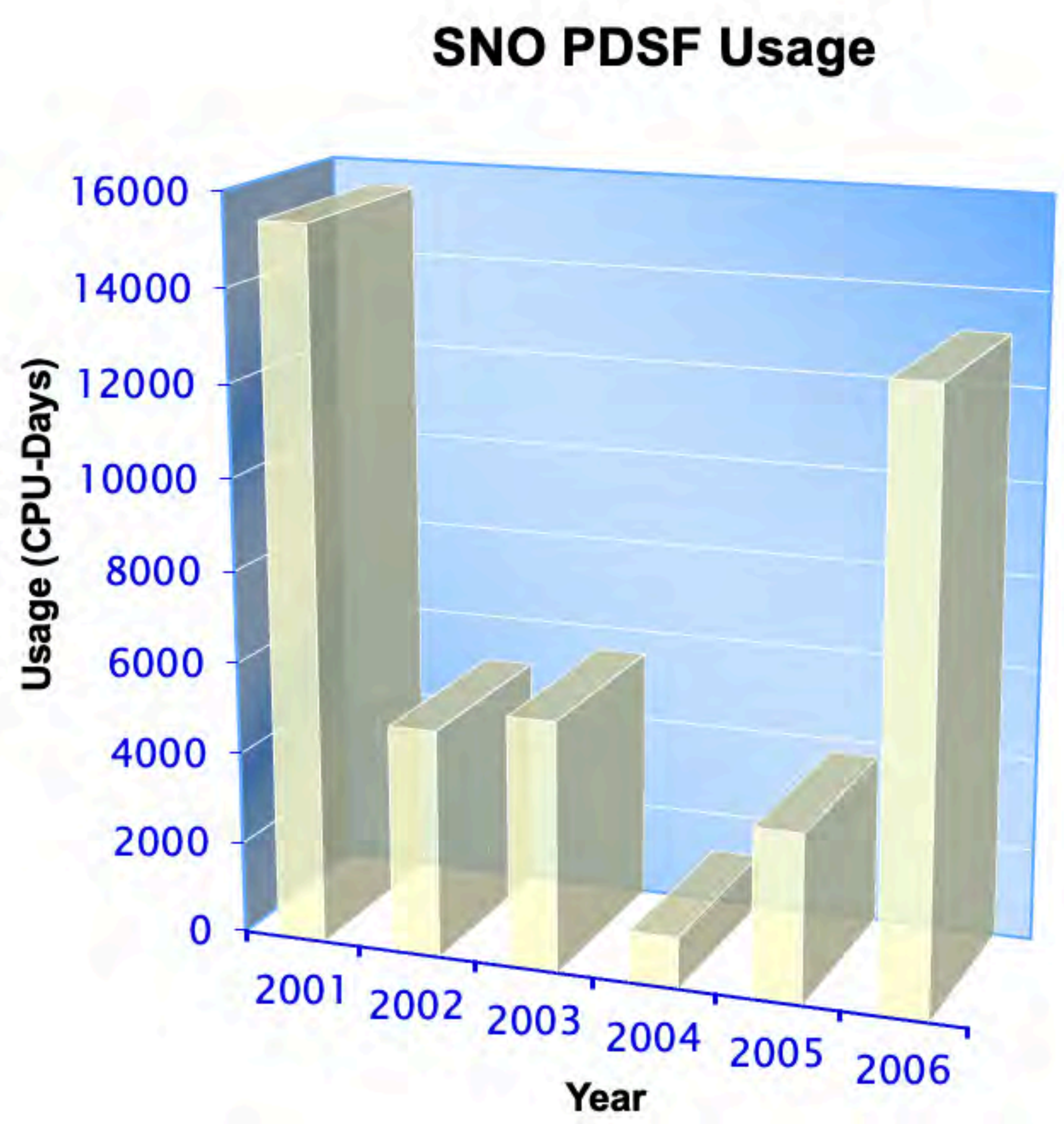
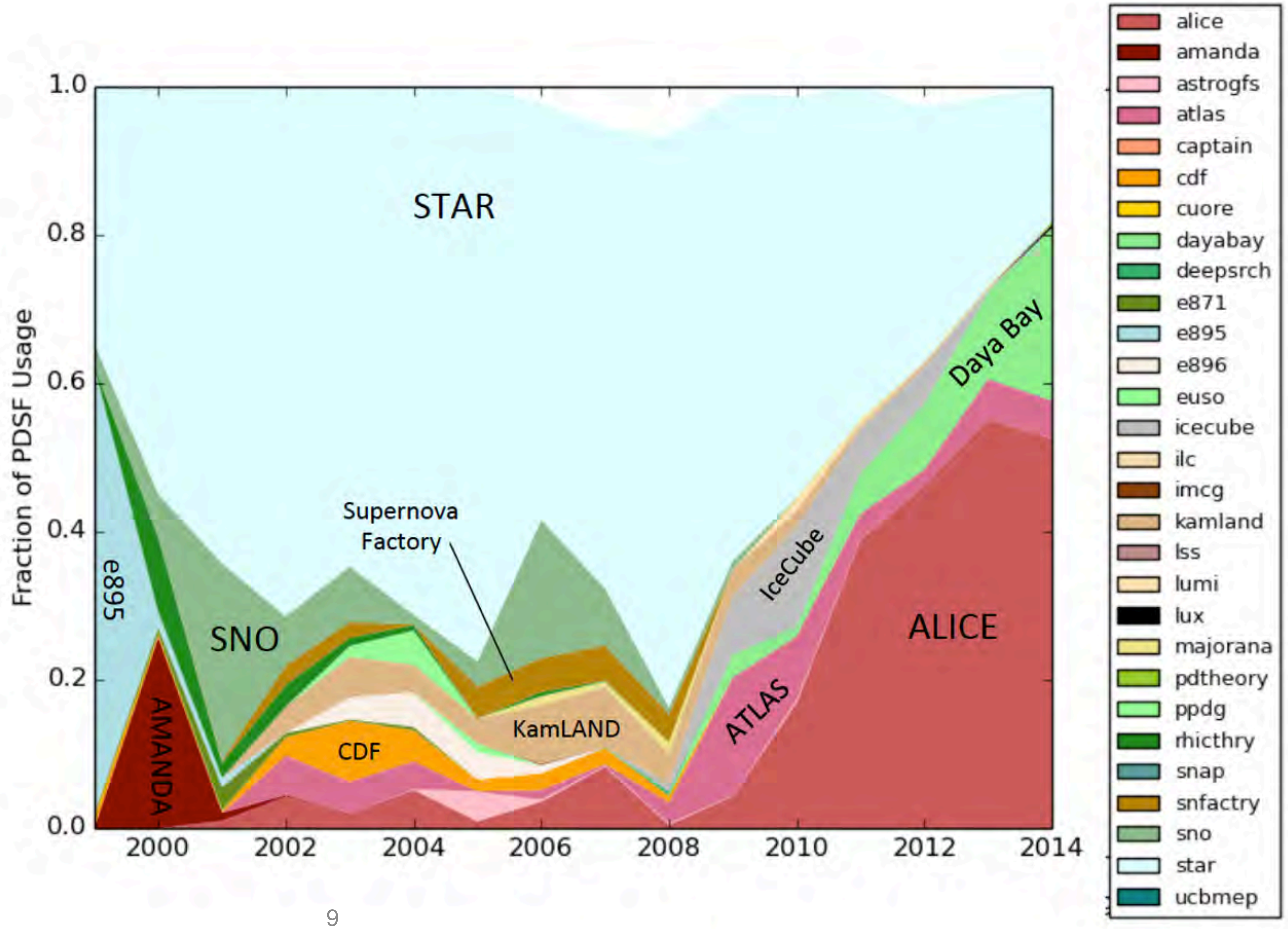
Parallel Distributed System Facility (PDSF)

THE 'LITTLE' COMPUTER CLUSTER THAT COULD





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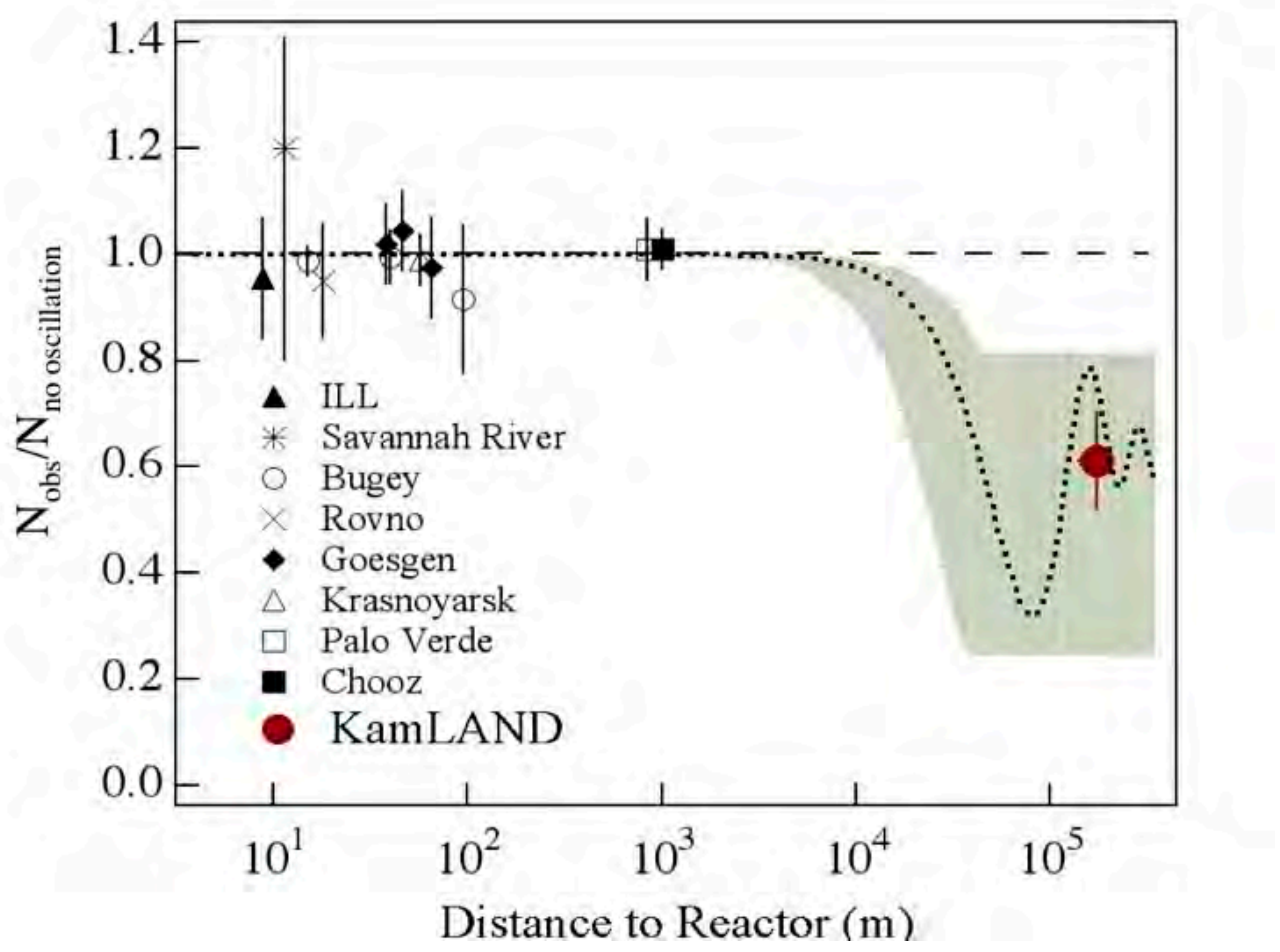
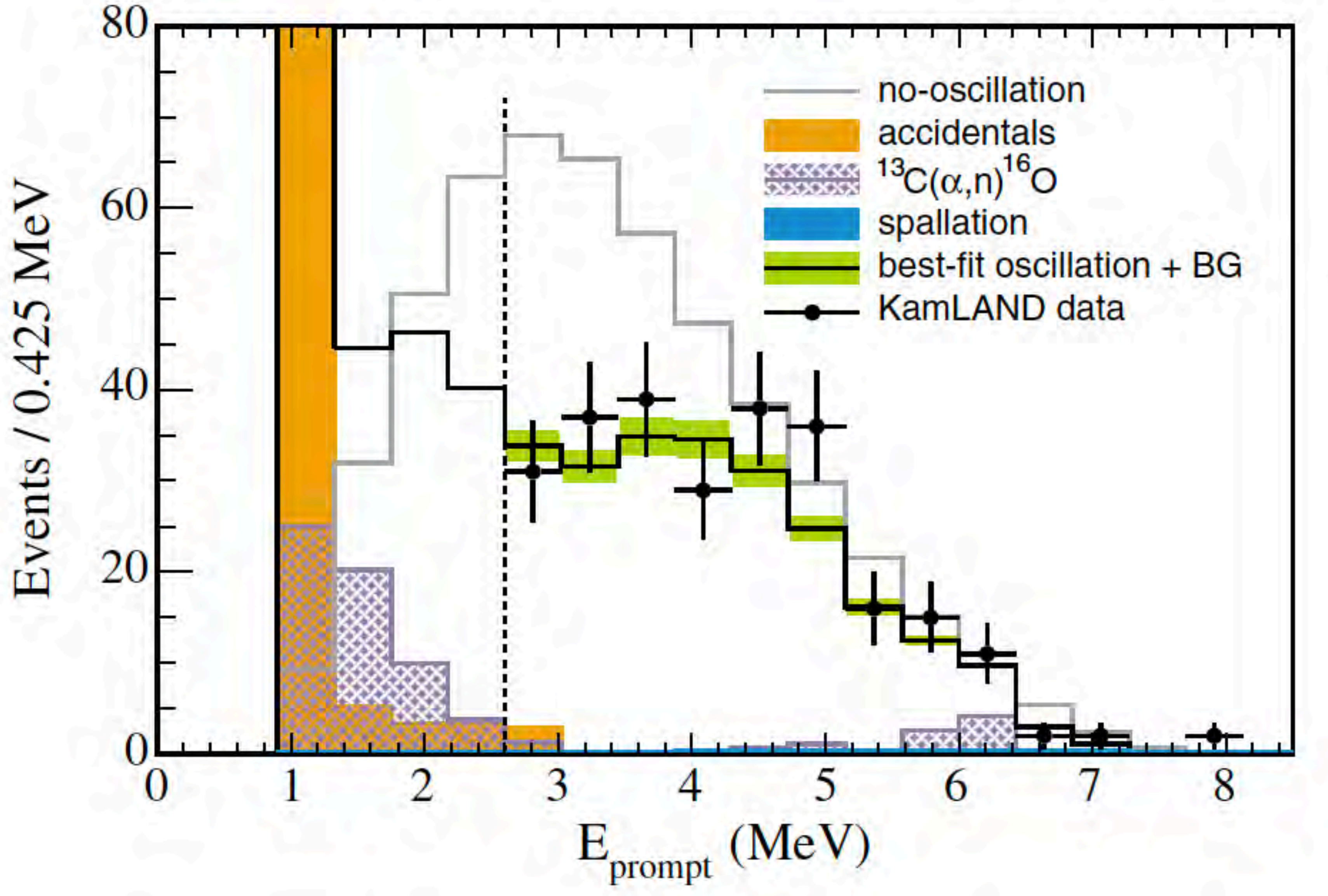
KamLAND reactor neutrinos and neutrino oscillation

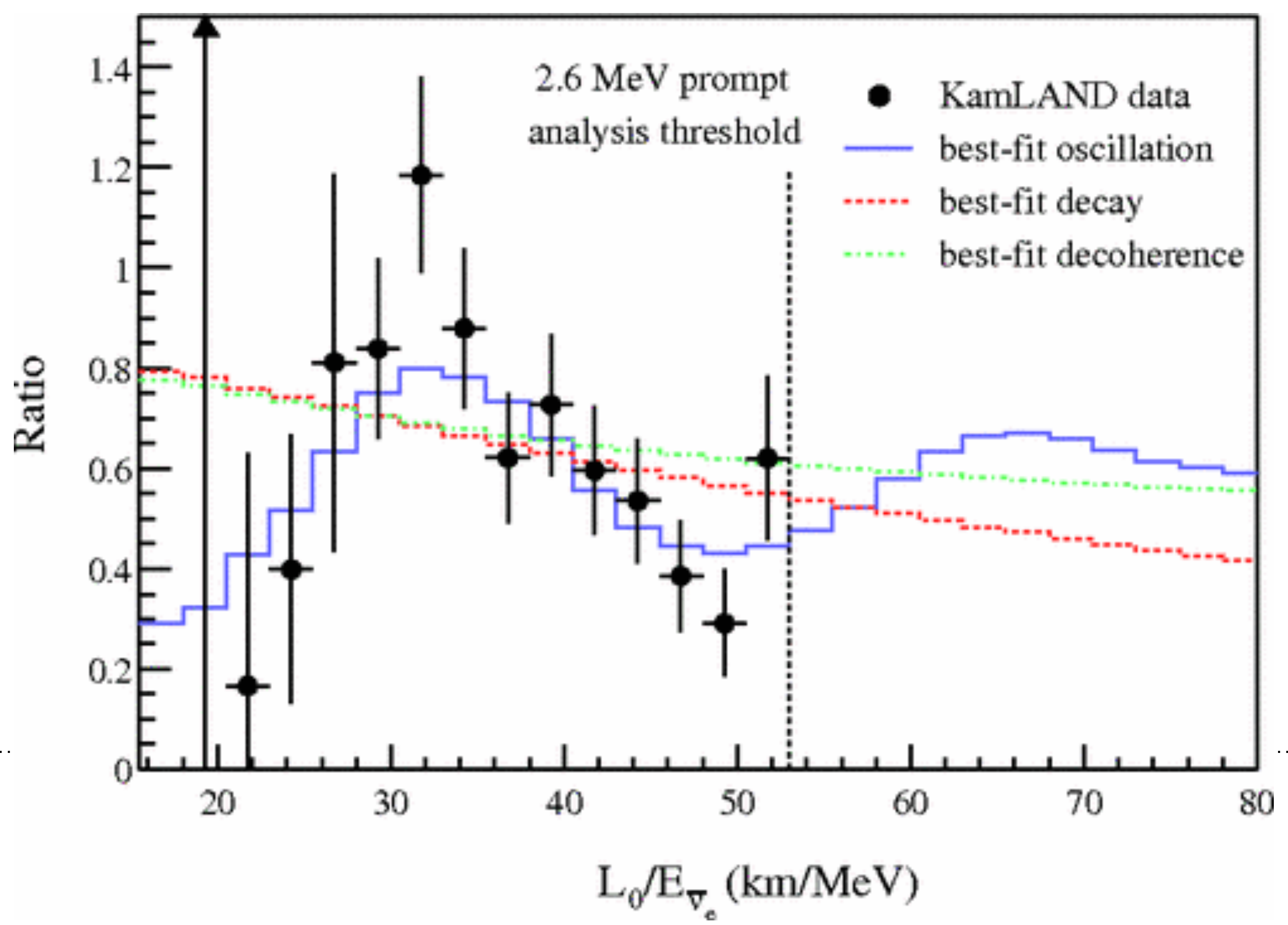
- The SNO result was direct evidence of ***neutrino flavor transformation.***
- If ***neutrino oscillation*** — a quantum mechanical effect — is the underlying mechanism for this flavor transformation, one should observe this transformation from other neutrino sources, as the oscillation probability depends on the source-detector distance (L) and the neutrino energy (E), as prescribed by quantum mechanics.
- KamLAND did just that by detecting neutrinos from power reactors in Japan

KamLAND reactor neutrinos and neutrino oscillation



Phys. Rev. Lett. **90**, 021802





Phys. Rev. Lett. **94**, 081801

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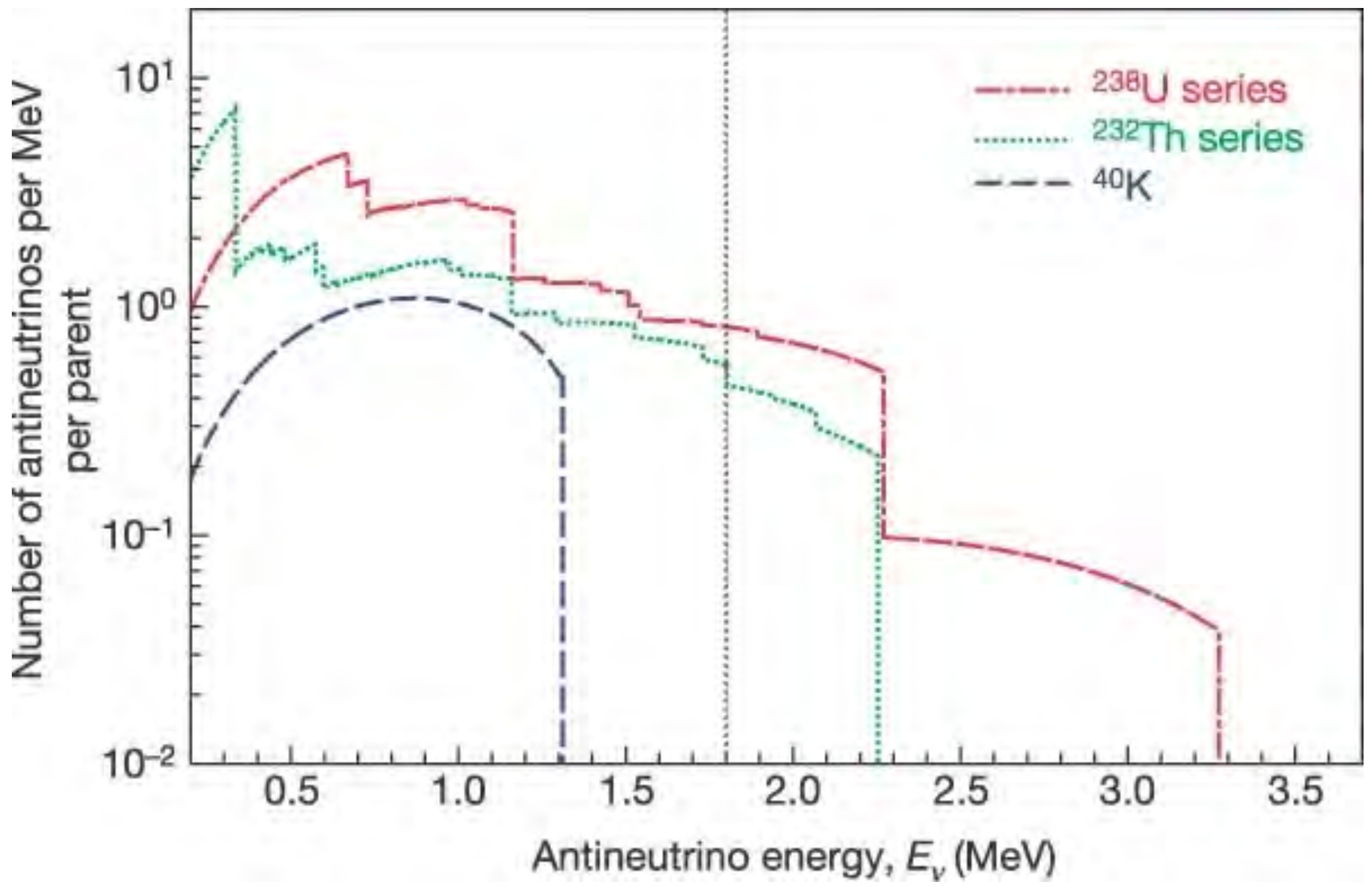
KamLAND detected geo-neutrinos from Earth's

- Natural radioactive decays "power" our Earth.
- KamLAND was sensitive to electron-type antineutrinos ("geo-neutrinos") produced by the decay of ^{238}U and ^{232}Th within the Earth.
- Radiogenic heat (from this 2005 paper) ~ 16 TW Nature **436,** 499-503 (2005)



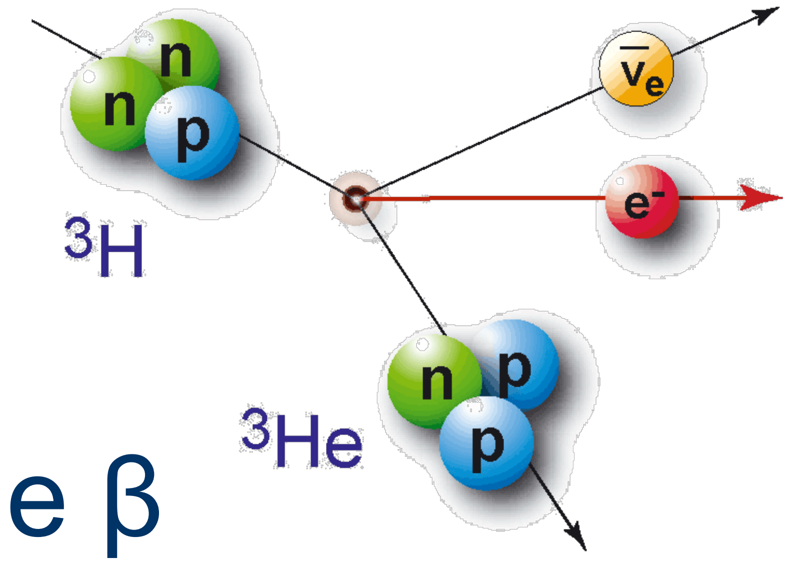
geo-neutrino energy for different radioisotopes

What unknown neutrino properties are LBNL-NSD researchers investigating with NERSC's help now?

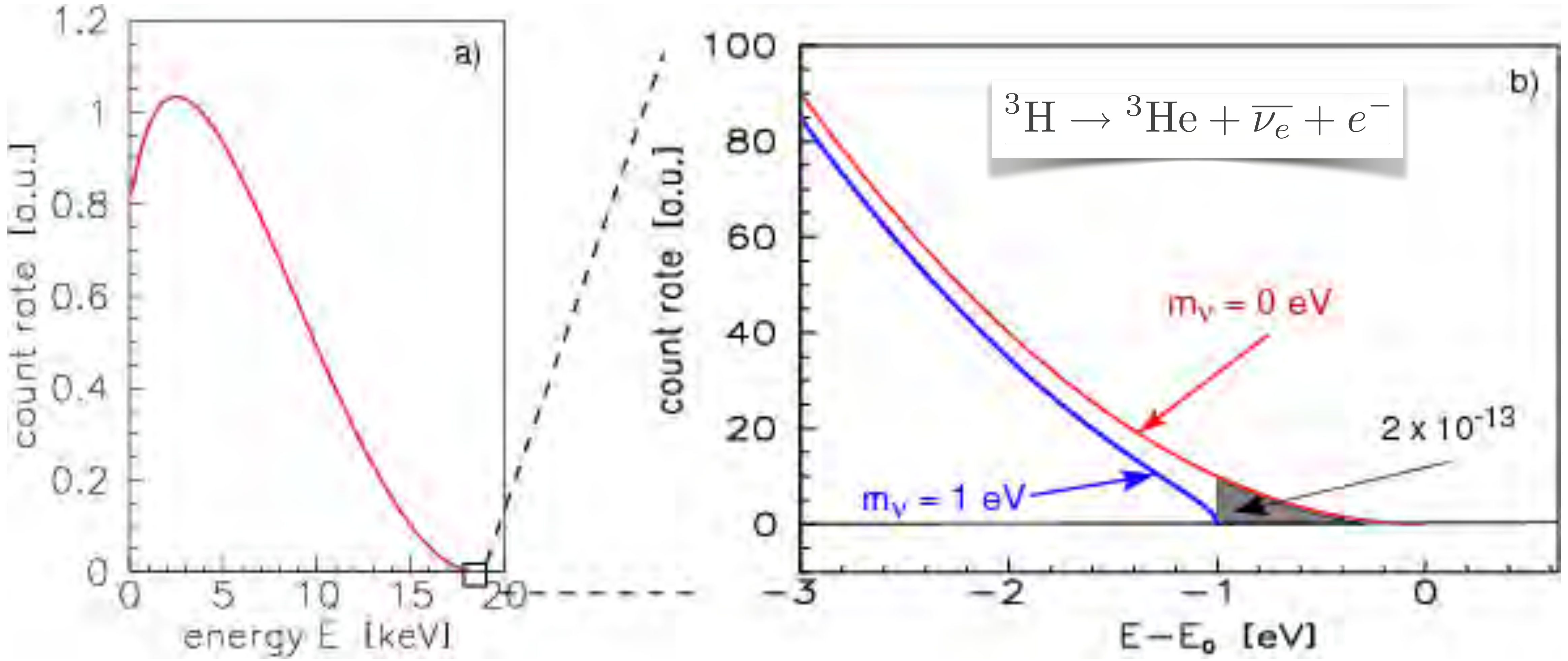
- ***How heavy are the neutrinos*?**
  - Neutrino oscillation measurements only demonstrated that neutrino mass is not zero. But they don't determine the actual mass.
  - Neutrinos are the most abundant massive particles in the universe, they impact its evolution.

- ***Are neutrinos are their own antiparticles?***
  - If neutrinos are their own antiparticles, there are mechanisms that allowed matter creation (baryogensis) in the early universe.
  - We know the Standard Model of Particle Physics is incomplete (as it prescribes massless neutrinos). The implementation of the neutrino mass in the extended Standard Model is driven experimentally by this question.

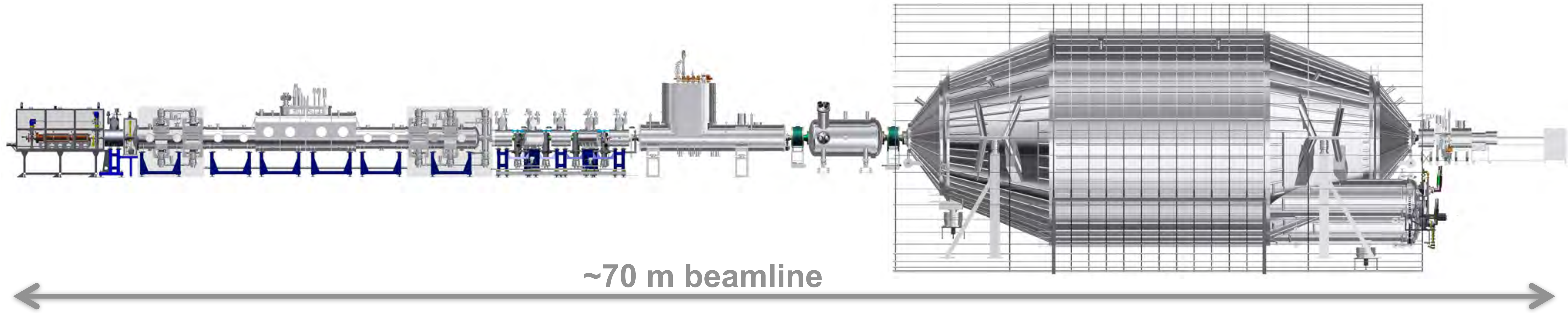
How heavy are the neutrinos?



- Direct kinematic measurement of the shape of the β spectrum near the end-point depends on the neutrino mass, independent of models (as in cosmology)



- The Karlsruhe Tritium Neutrino (KATRIN) Experiment



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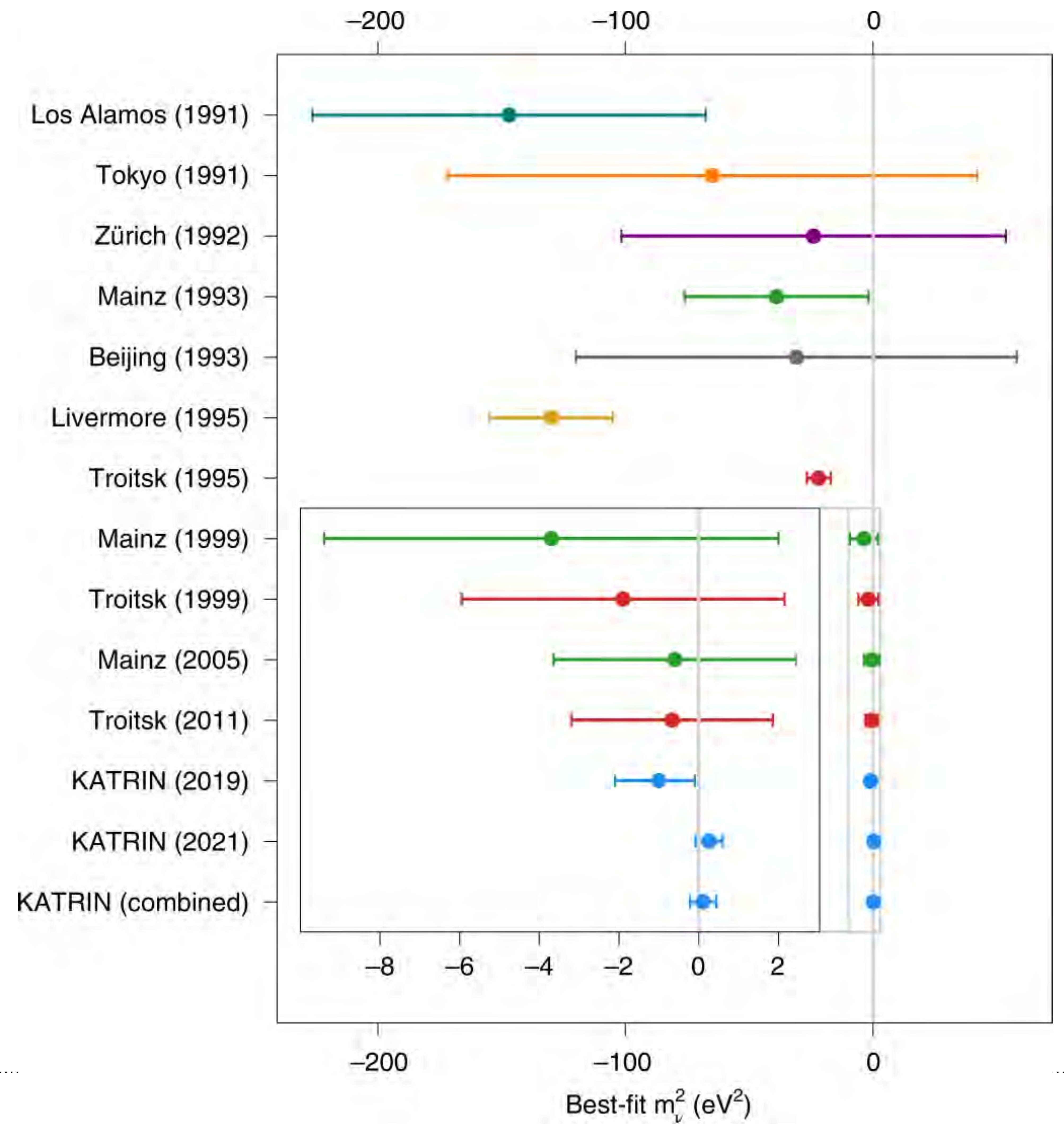
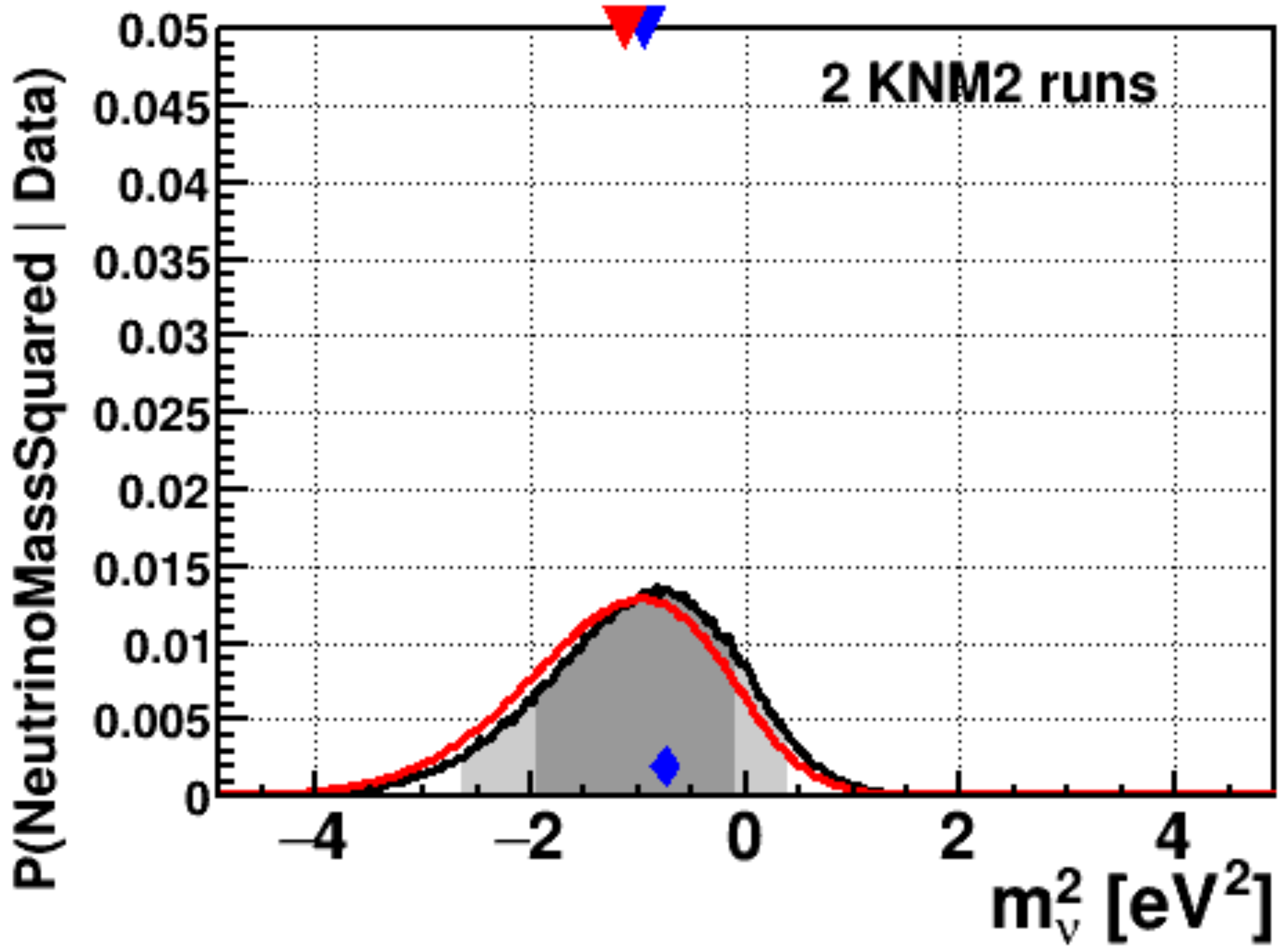


- An experimental tour-de-force:
  - Letter of Intent - 2001
  - First results - 2019
- Current limit from KATRIN:
  $m_\nu < 0.8$ eV/c^2 [Nature Phys. 18 (2022) 2, 160-166]
- NERSC supported the computationally intensive LBNL-led Bayesian analysis of the tritium β spectrum



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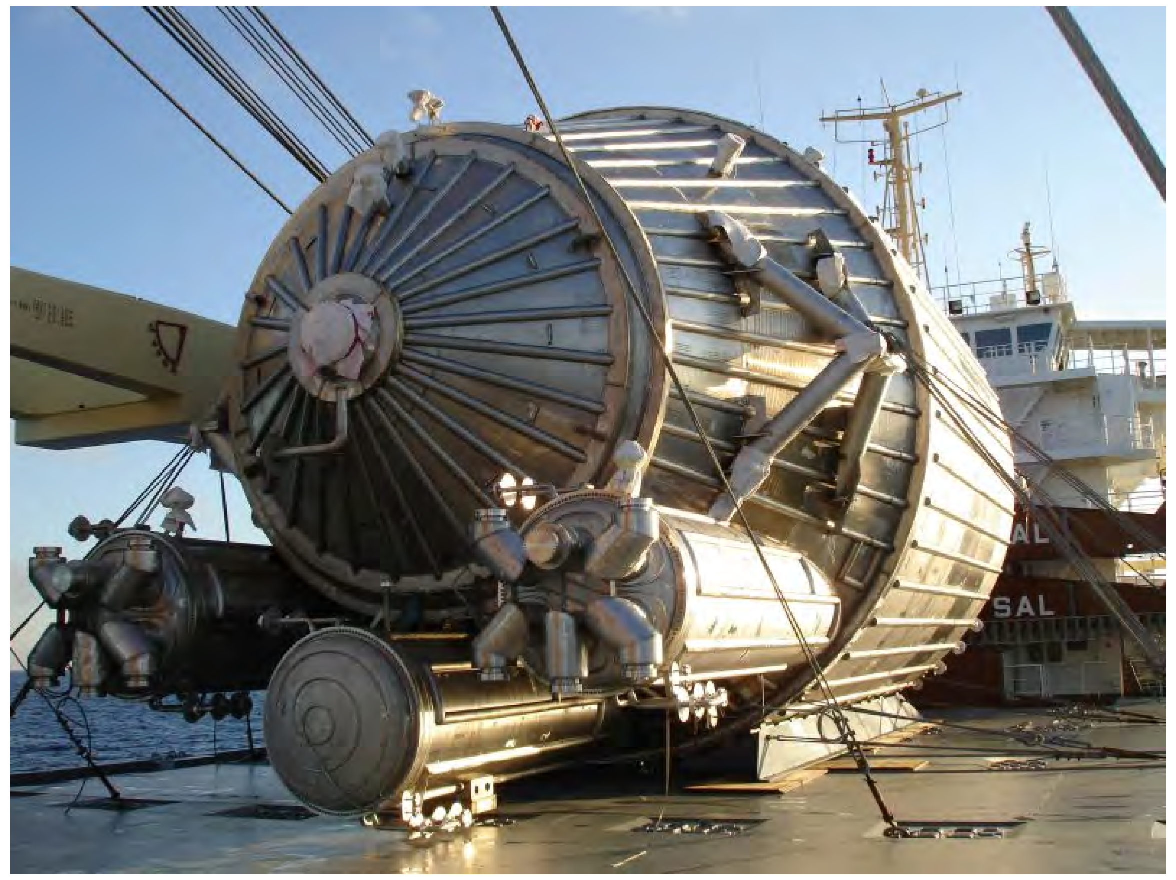
KATRIN – An experimental tour-de-Europe



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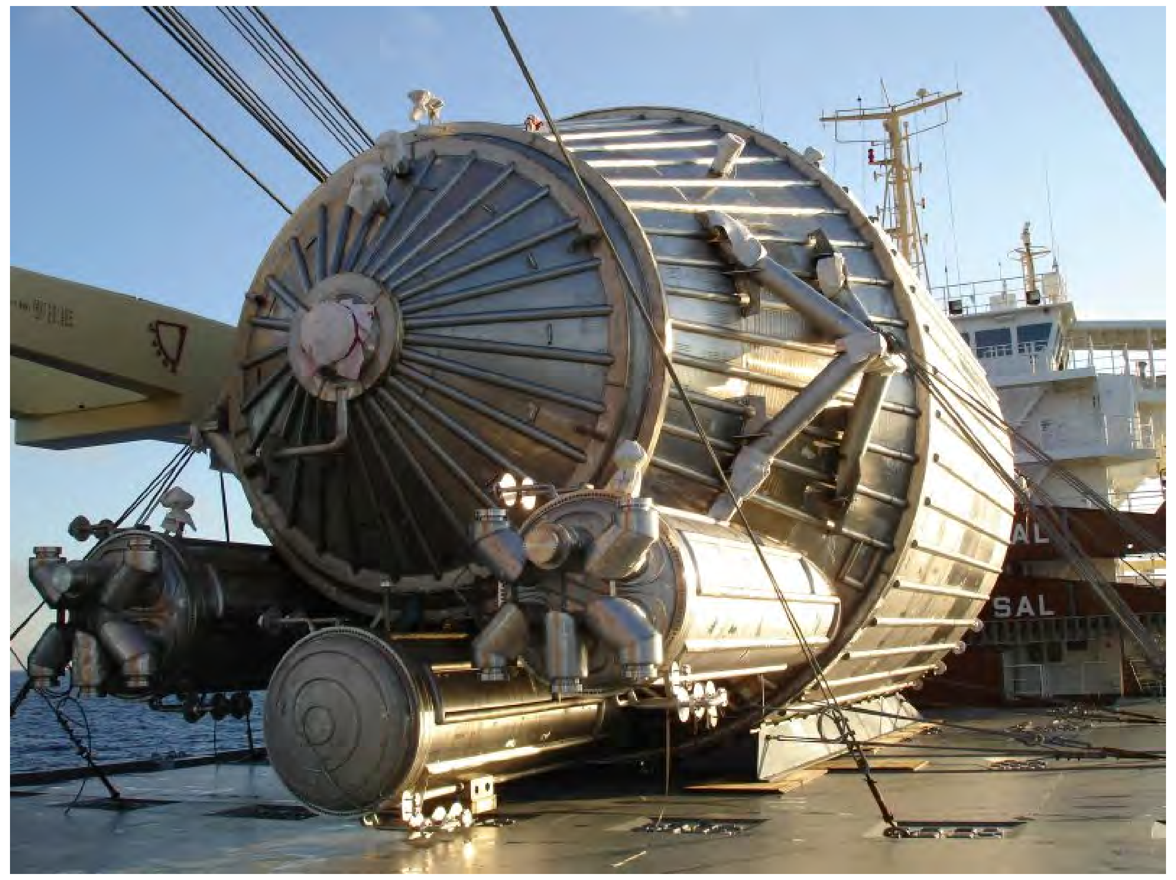
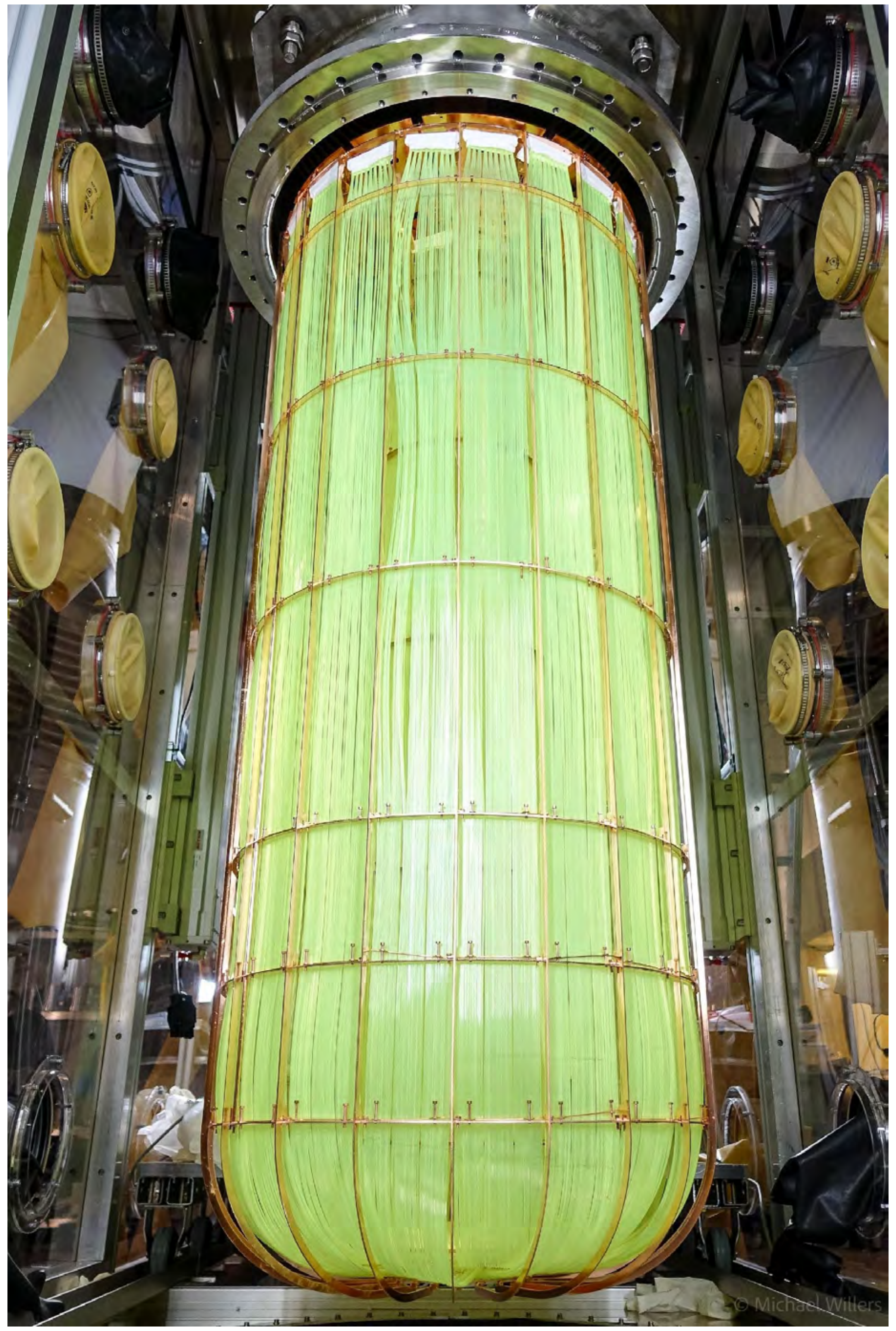


BBC News | Offbeat photos of the year 2006

Are neutrinos are their own antiparticles?


LEGEND-200

Investigations in the LBNL-NSD Neutrinos Program:

Just finished (*at SURF**, USA)

- MAJORANA DEMONSTRATOR (MJD)

Operating (*at LNGS†, Italy*)

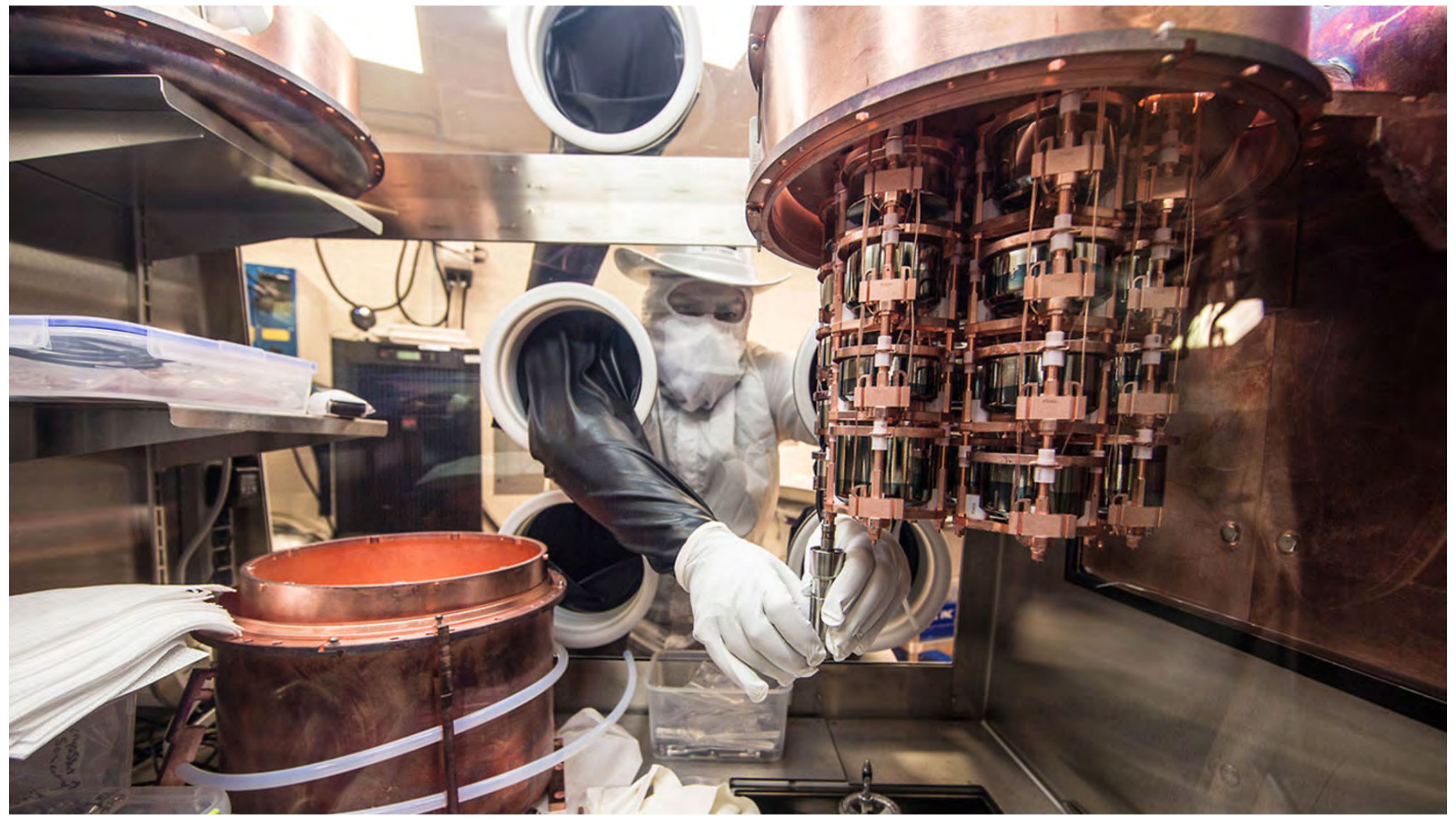
- CUORE
- LEGEND-200

Planning (*at LNGS†, ITALY*)

- CUPID
- LEGEND-1000

* Sanford Underground Research Facility

† Laboratori Nazionali del Gran Sasso


MJD


CUORE

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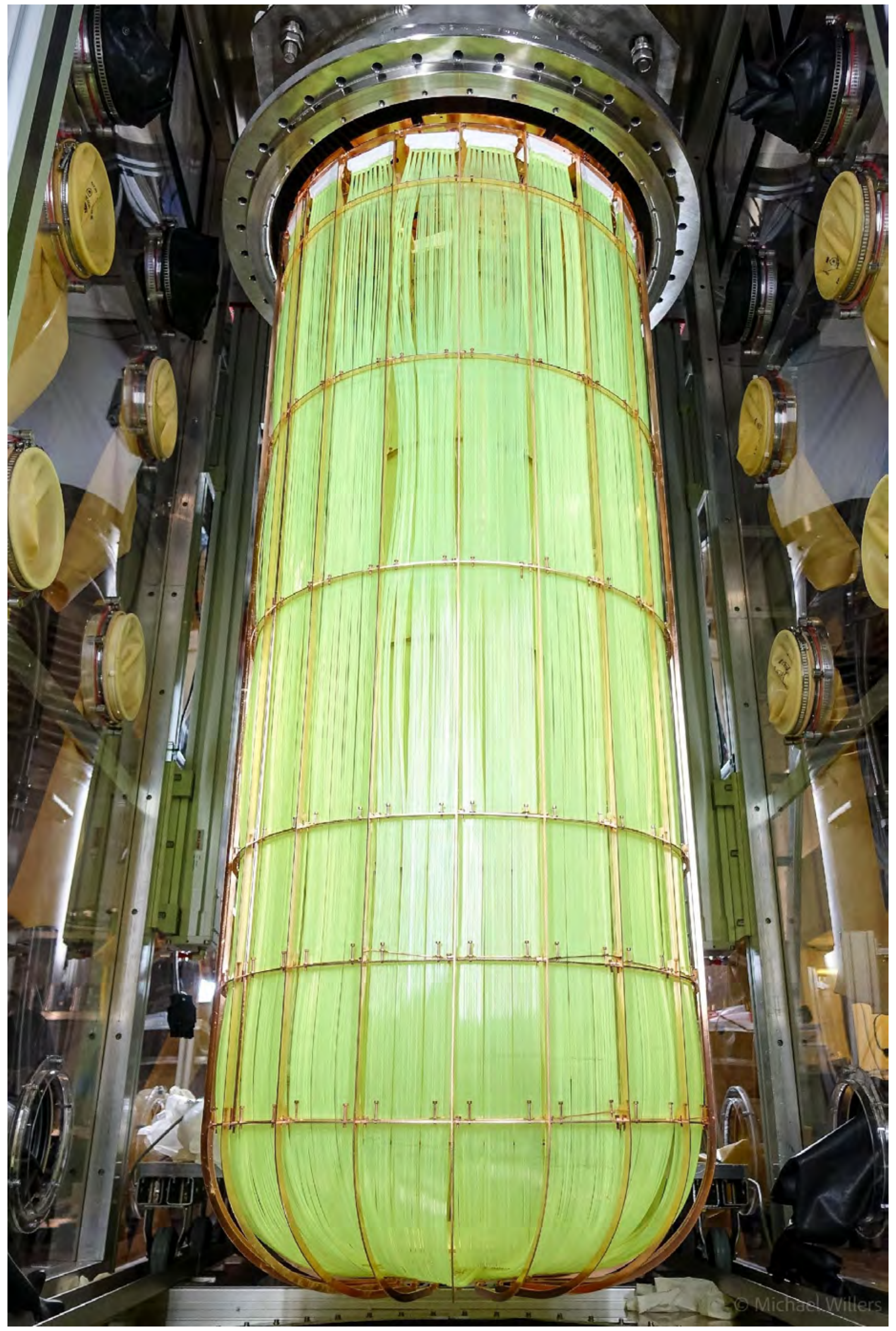

LEGEND-200

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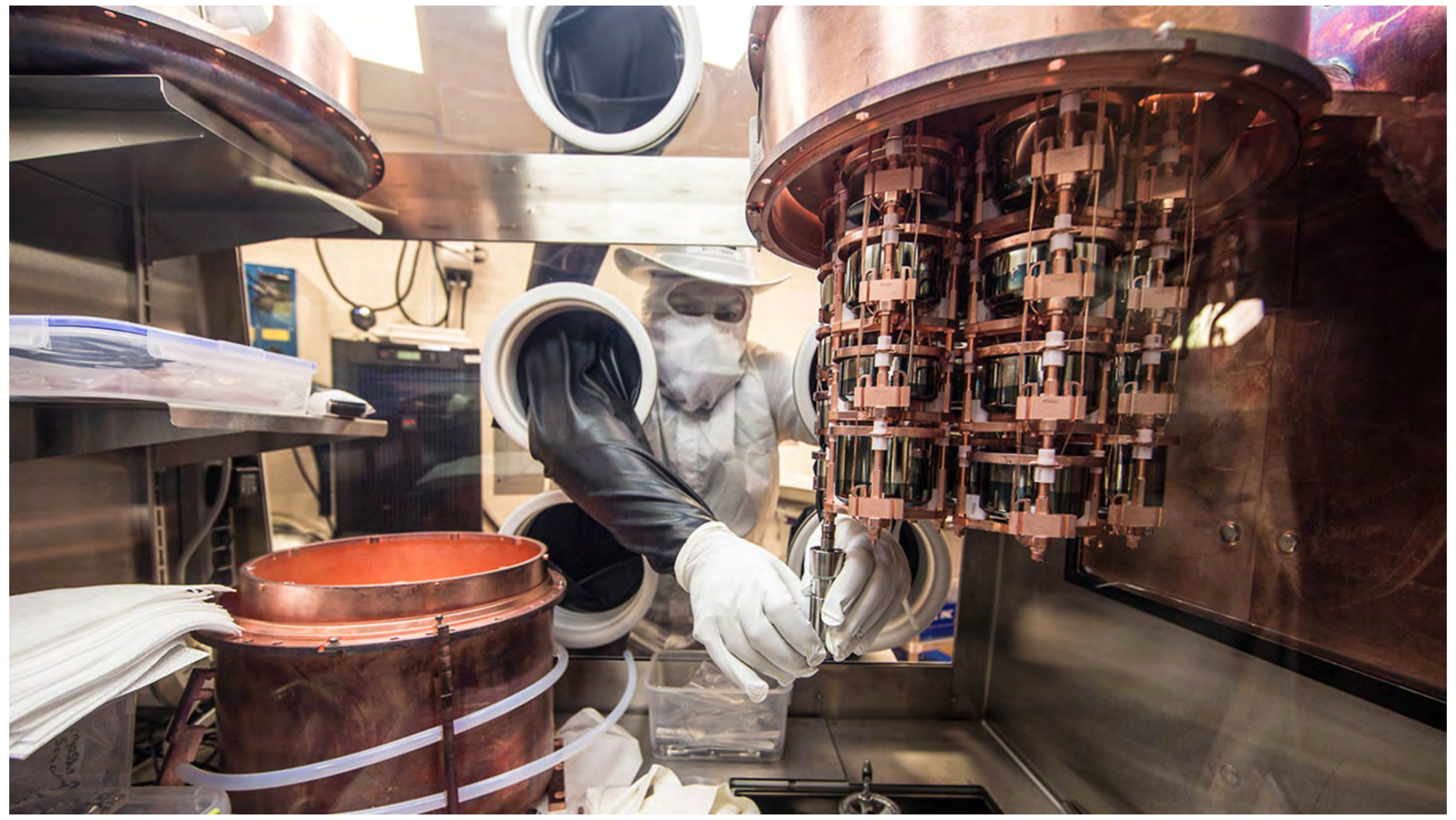
* uses ionization diode detectors enriched in ^{76}Ge

† uses TeO_2 bolometer crystals enriched in ^{130}Te

†† uses Li_2MoO_4 bolometer crystals enriched in ^{100}Mo



MJD

CUORE

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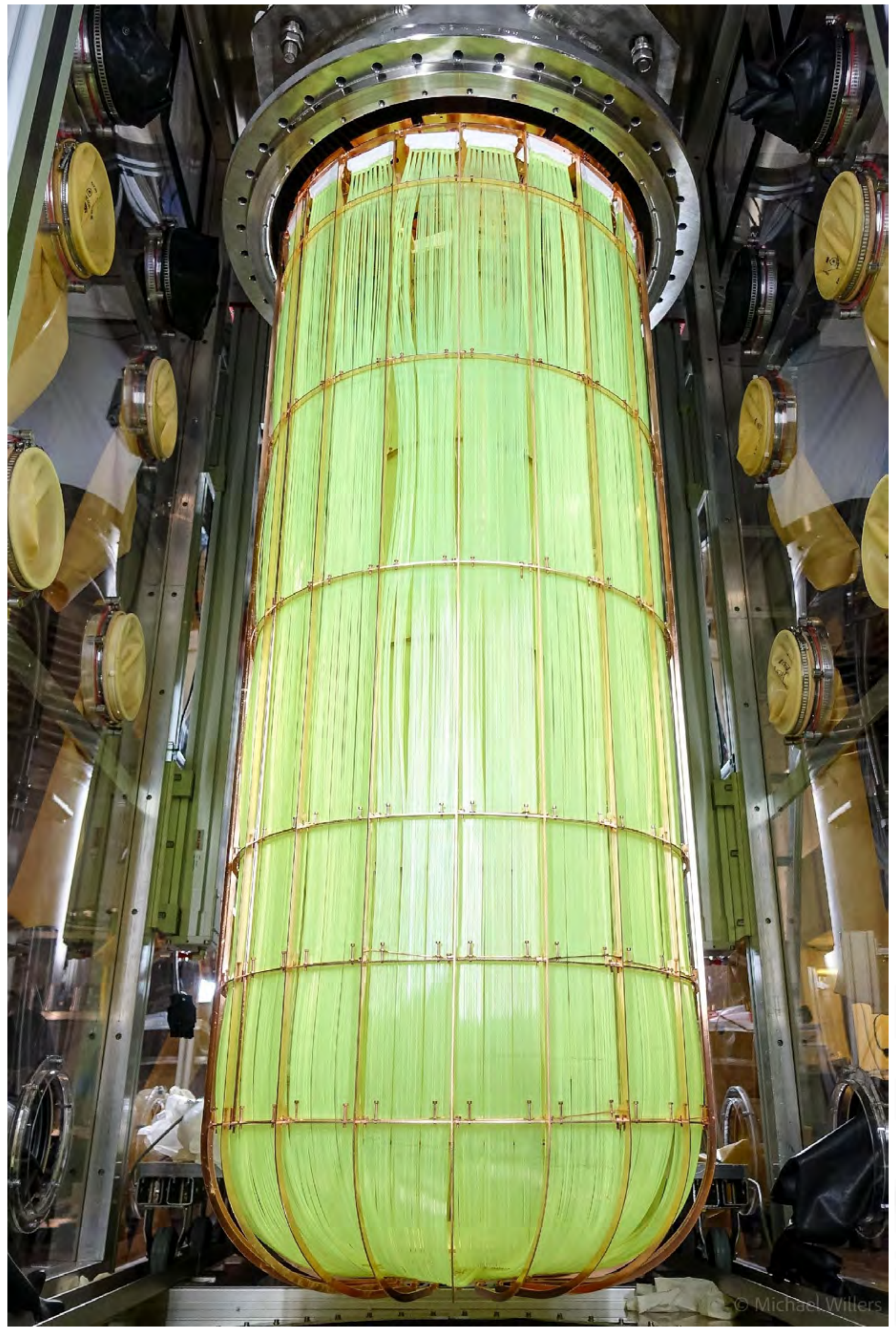
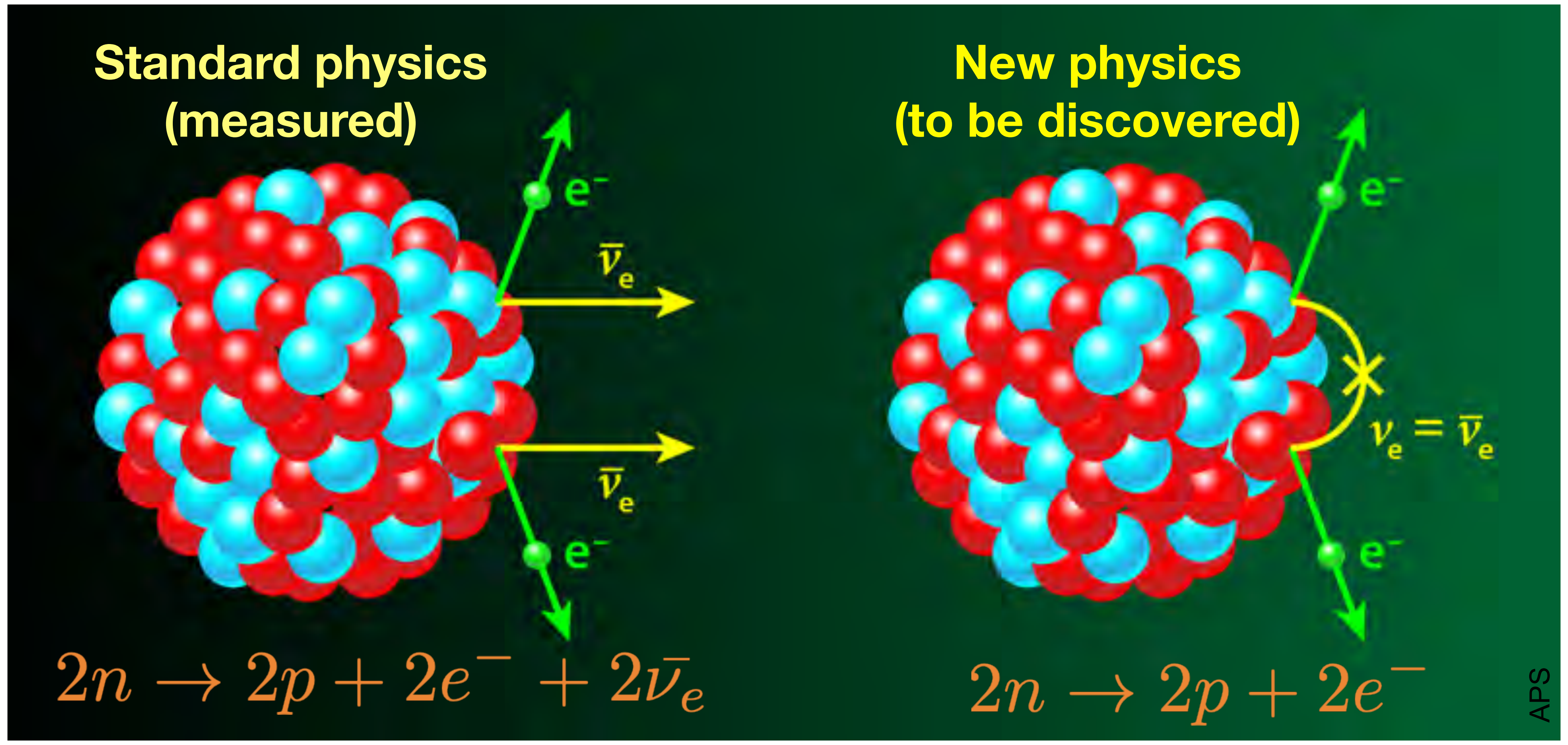


LEGEND-200

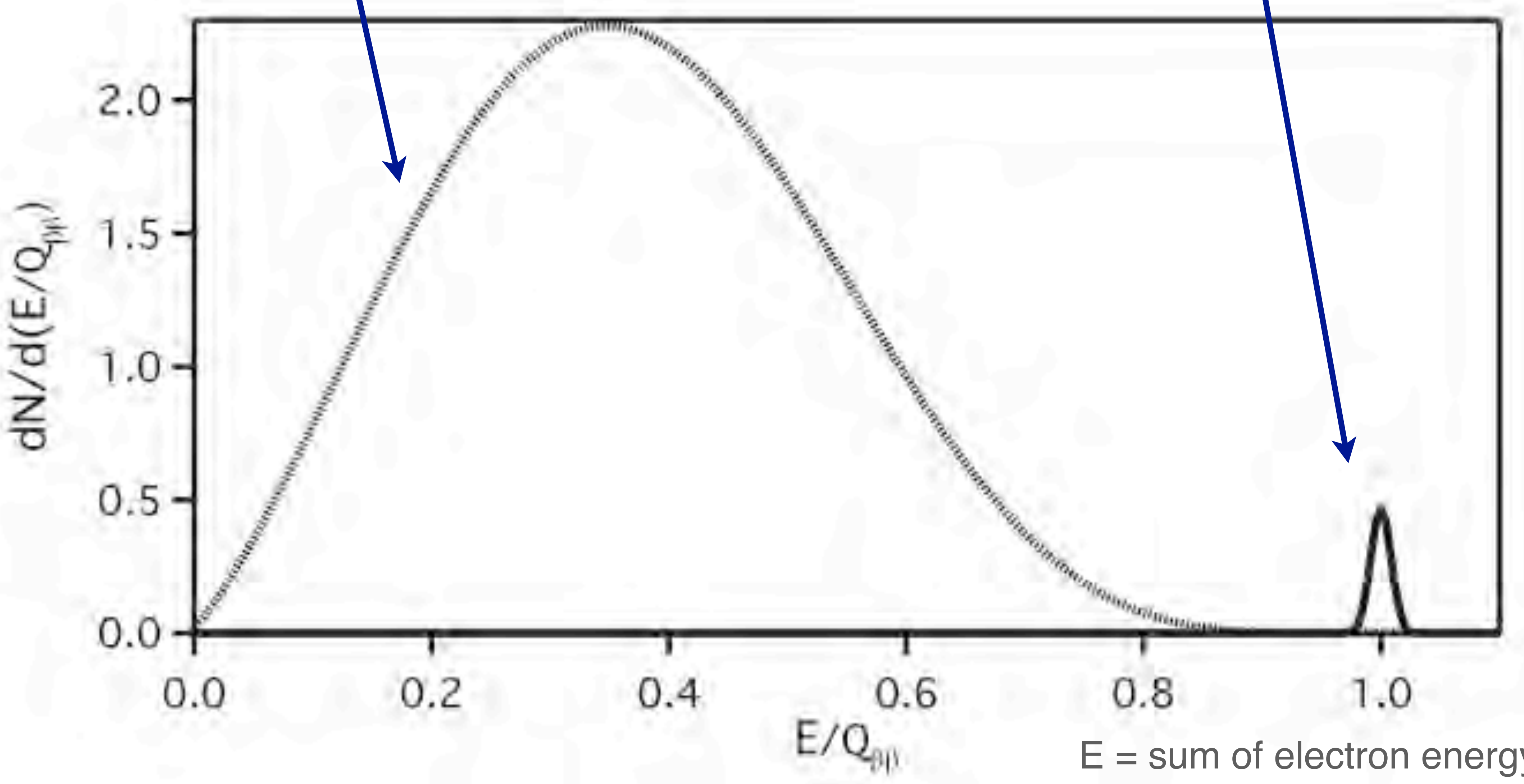


Background (B)

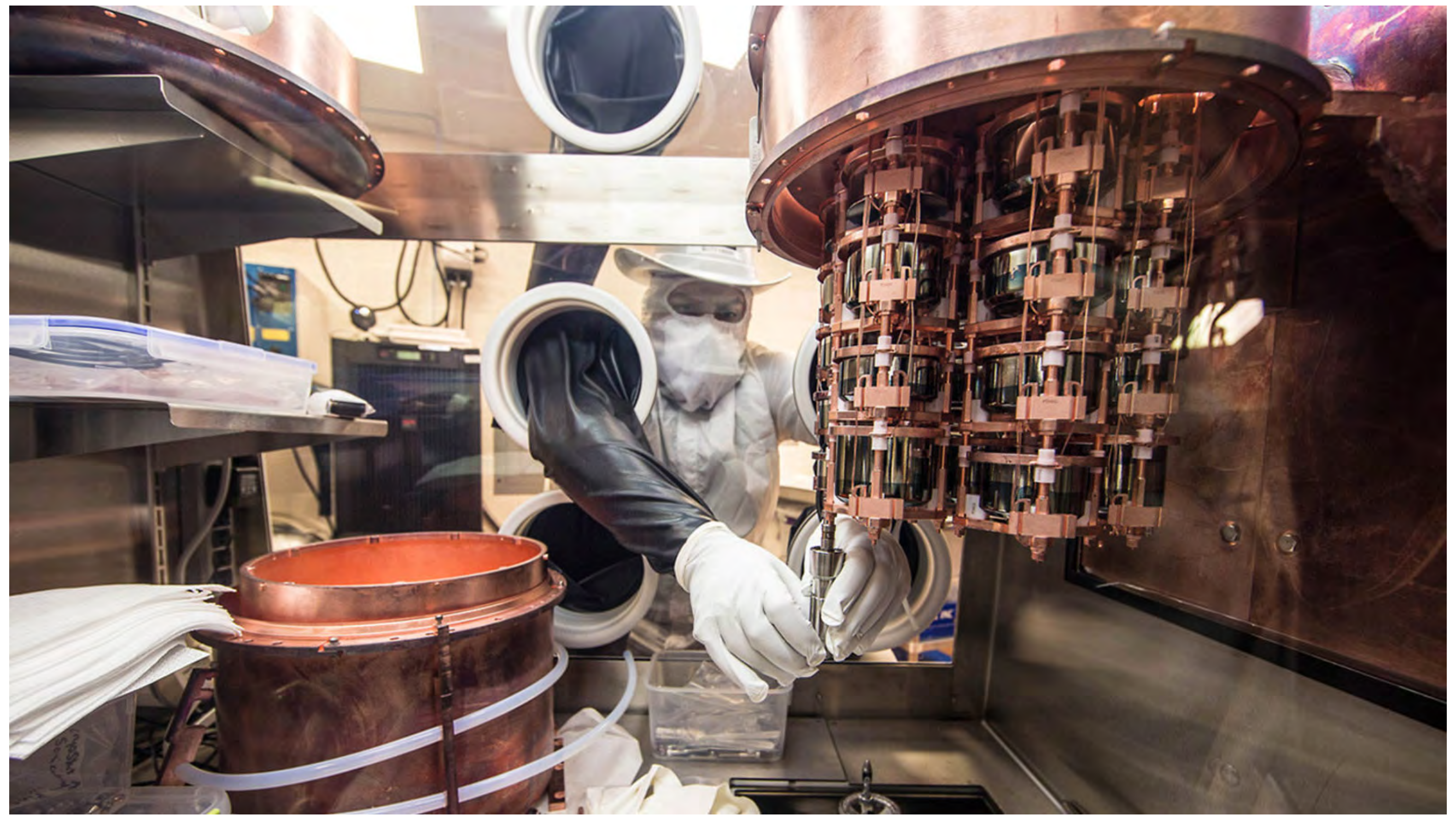
$T^{2\nu}_{1/2} \sim 10^{18-24}$ y

Signal (S)

$T^{0\nu}_{1/2} > \sim 10^{26}$ y



E = sum of electron energy



MJD

CUORE

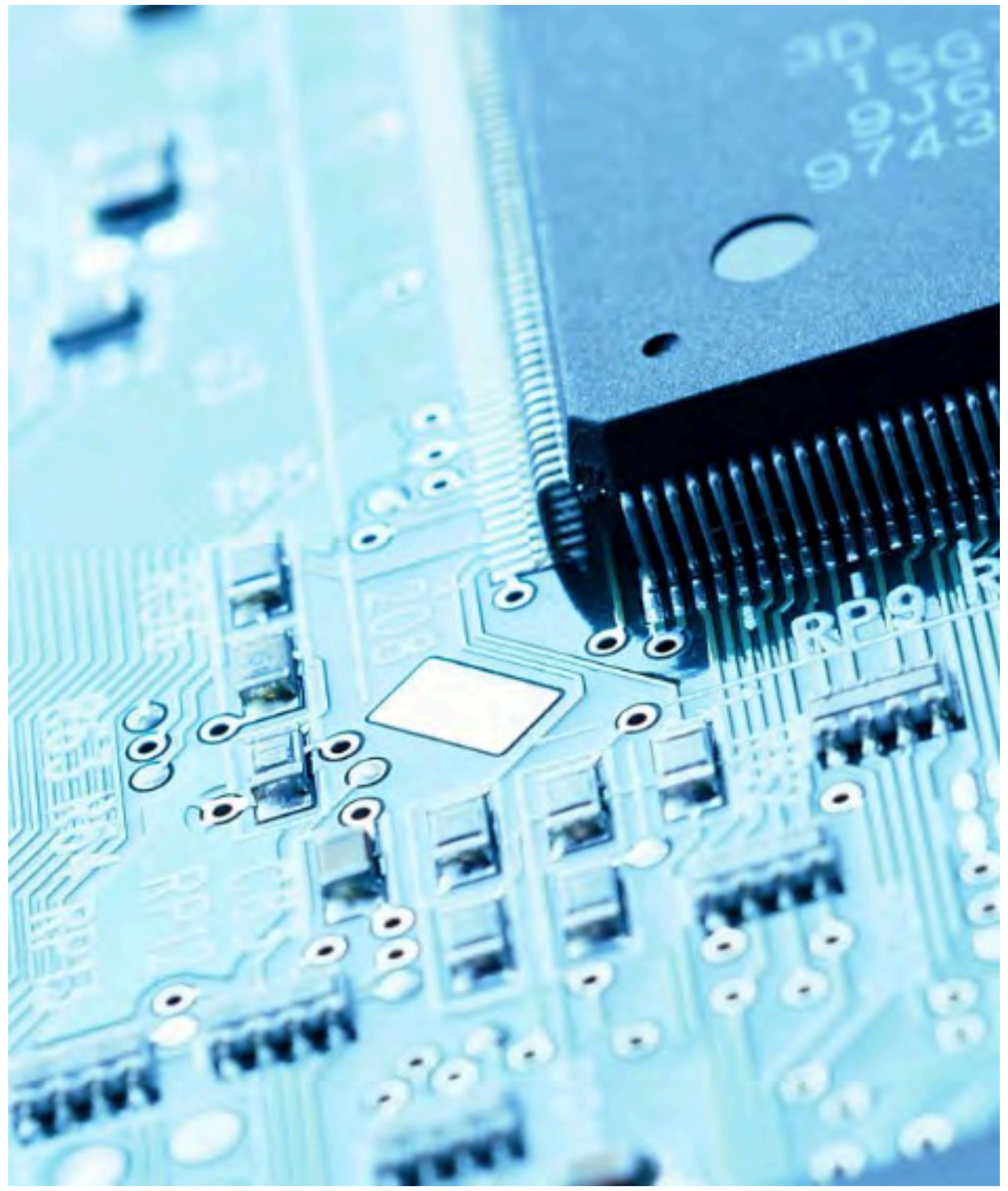
Needle in a haystack search (if Nature had put a needle there)

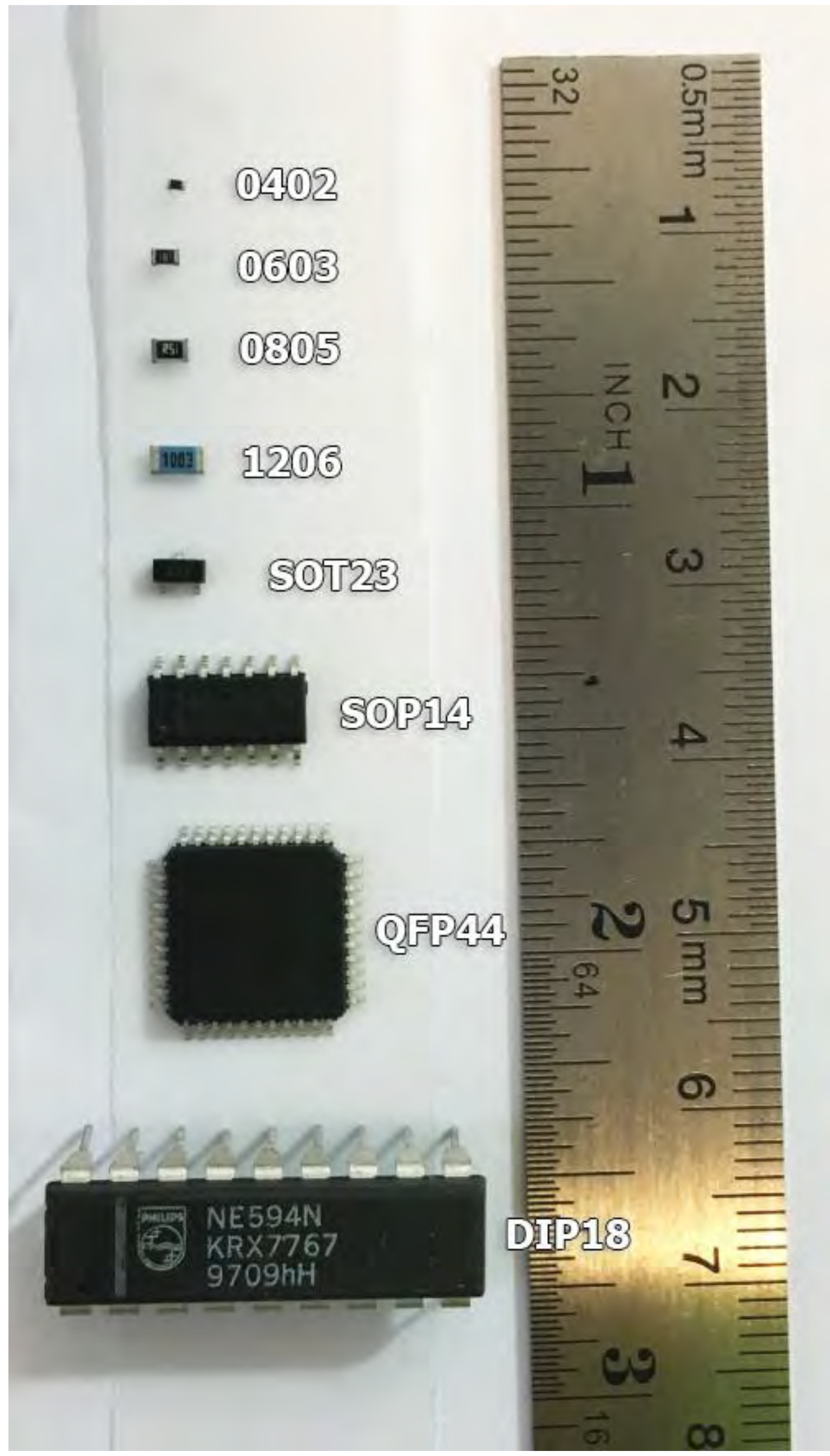
Technical challenges (to name a few):

- Acquisition of enriched isotopes (^{76}Ge for LEGEND, ^{100}Mo for CUPID)
- As we expect only a handful of signals in a year:
  - ~10 years of counting
  - stringent background requirement: ultra-clean materials and construction process, for example, < ~ O(0.1) count of background event per ton of ^{76}Ge per year in the signal region
- Reliability and longevity of the detectors
- Detector construction at an underground lab in a foreign country.

[Wikimedia]

How stringent is it for a background at 0.1 count?





~ 1 μBq Th/pc
~ 2 μBq Th/pc

1 μBq ≈ 0.1 decay/ day

NERSC support to MJD and LEGEND-200

- **MAJORANA DEMONSTRATOR (MJD):**
  - Adopted NERSC environment as the official collaboration computing platform
  - Near-time data quality monitoring
    - Automated data transfer from SURF with NERSC realtime queue
    - 1st-pass raw data processing at cori/perlmutter
  - Physics data processing
  - Data analysis
  - Monte Carlo studies
  - Data archiving - one copy of data at HPSS

LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

- **LEGEND**
  - US data processing/distribution/analysis center for LEGEND-200
  - Similar workflow as MJD with larger data volume and throughput
  - New data processing software - Python stack (and a separate Julia stack to be implemented)
  - Deep learning with NERSC GPU farm
  - Monte Carlo studies
  - US data archiving

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NERSC support to CUORE and CUPID

- **CUORE**
  - Platform for the 2-ton-year exposure analysis campaign for implementing a noise subtraction algorithm — largest amount of data ever acquired with a solid state detector of bolometers running at a temperature of ~10 mK inside the largest dilution refrigerator in the world (at the time it was commissioned).
  - Analysis platform for the latest data release, including simulation to understand systematics and Bayesian sensitivity study.

- **CUPID**
  - The main analysis platform for CUPID-Mo — to demonstrate the $Li_2{}^{100}MoO_4$ crystals as the detector technology for the future CUPID.
  - Design simulations (signal and background) for CUPID.

NERSC support to MJD and LEGEND-200

- **MAJORANA DEMONSTRATOR (MJD)**

Hot off the press!

nature physics

Article https://doi.org/10.1038/s41567-024-02437-9

Search for charge non-conservation and Pauli exclusion principle violation with the MAJORANA DEMONSTRATOR

Just published online by Nature Physics a few days ago on 4/11/2024

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Summary

- NERSC provided expertise and state-of-the-art computing resources to neutrino research. It has been instrumental in solving several neutrino mysteries in the last few decades.
- NERSC supported the discovery of solar and reactor neutrino oscillations and is now supporting researchers in investigating other unknown neutrino properties, such as its mass and mass-generation mechanism. In the next couple of decades, we might find out whether neutrinos are their own antiparticles, thus generating matter in the early universe. NERSC will play a crucial role in this endeavor.
- Many thanks to:

  Yuen-dat Chan (SNO, MJD/LEGEND)

  Brian Fujikawa (KamLAND, CUORE/CUPID)

  Brad Welliver (CUORE/CUPID)

  who provided information for this talk.
- My sincere thanks to NERSC and its support staff for their sustained support of our Neutrino Program over the past quarter century. Your efforts are making a difference beyond those mentioned in this talk that you may never learn about.

One more thing…

"Congratulations to NERSC on 50 years of exceptional service to the community. NERSC was a very valuable part of the data analysis for the Sudbury Neutrino Observatory, which won the 2015 Nobel Prize and the 2016 Breakthrough Prize for its discoveries of fundamental properties of neutrinos. The storage of a data set since then has enabled further analyses of other physics topics, extending the scientific reach of the experiment. Many thanks from the whole SNO collaboration, of which Berkeley was an important collaborator."

– *Art McDonald, Director of the SNO Scientific Collaboration, 2015 Nobel Physics Laureate.*

Happy 50th Anniversary!

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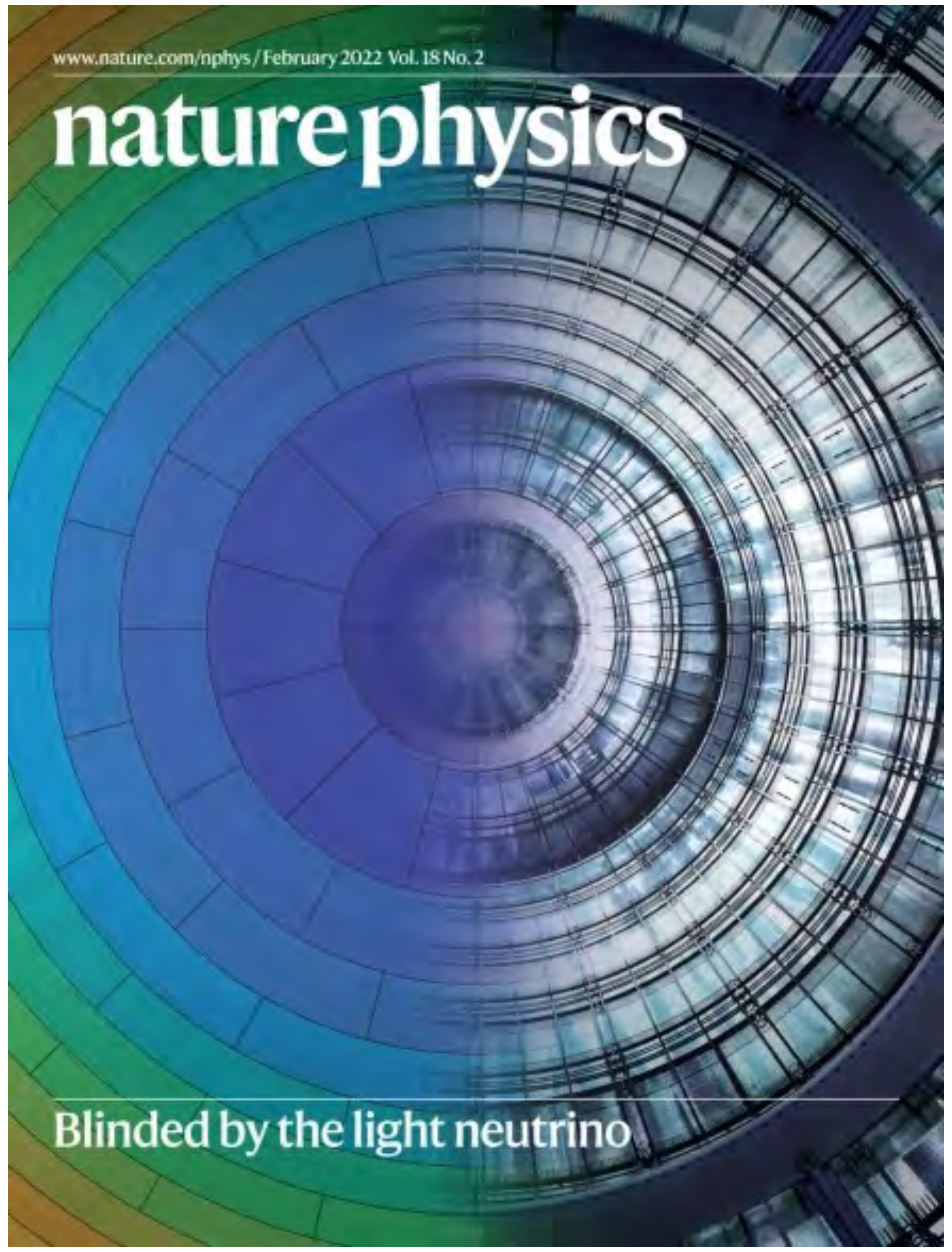
Lawrence Berkeley National Laboratory

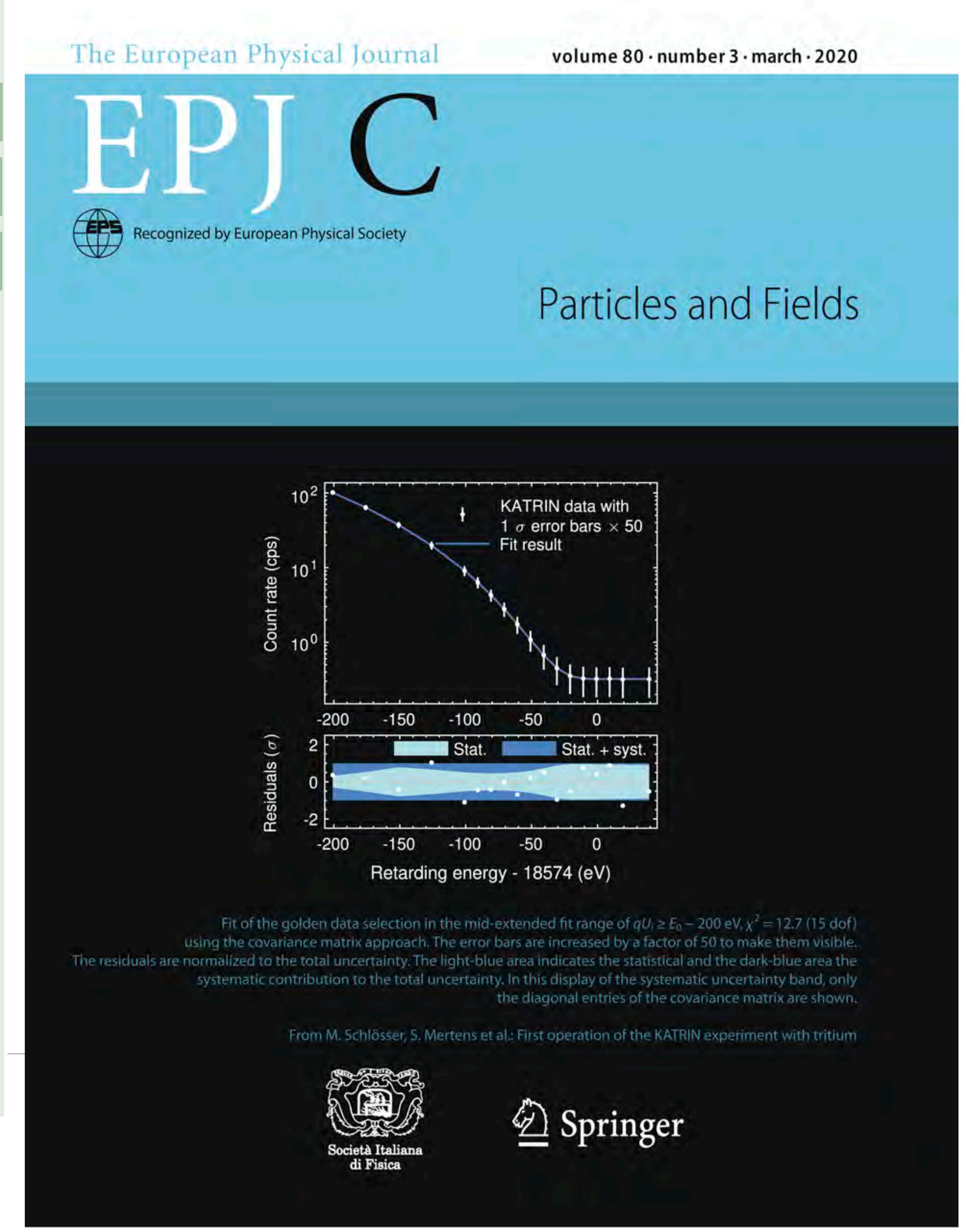
U.S. DEPARTMENT OF ENERGY

UNIVERSITY OF CALIFORNIA

Journal cover stories (results with NERSC support in LBNL Nuclear Science Division’s Neutrino Program in the last 5 years)



2022



2020

2019

Shielding from cosmic rays

Solar neutrino experiments must be built underground

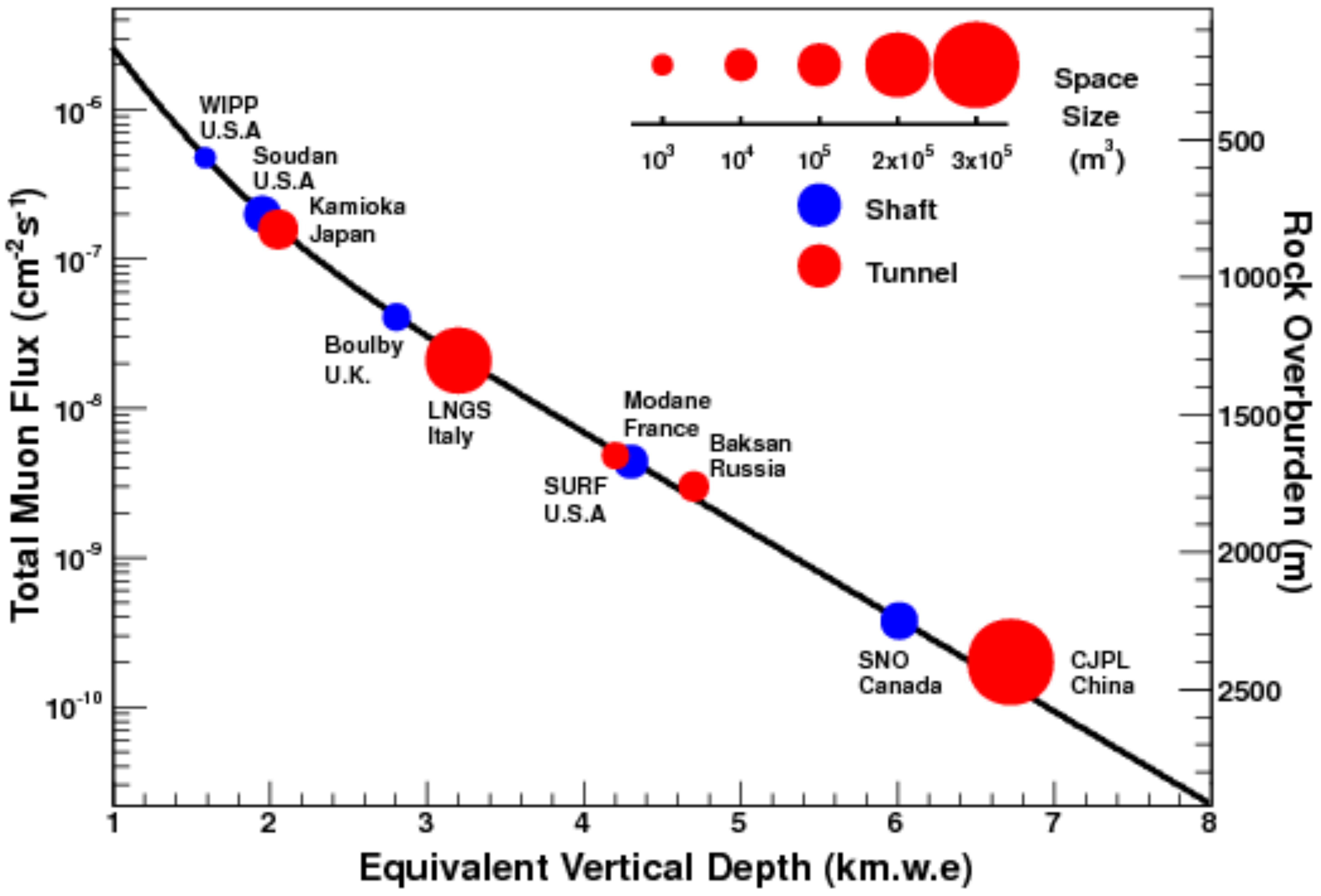
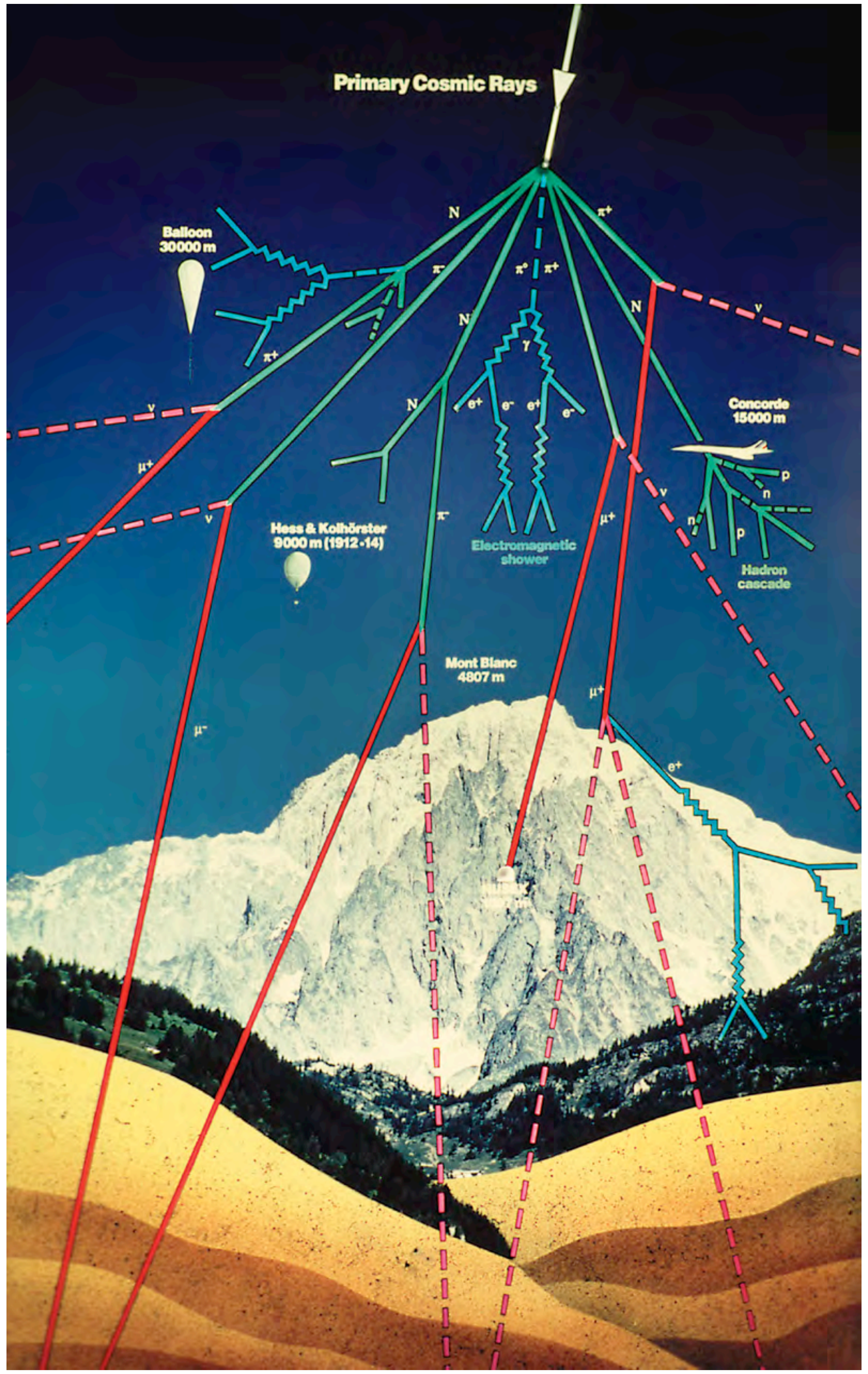


Figure from: Ann.Rev.Nucl.Part.Sci. 67 (2017) 231-251

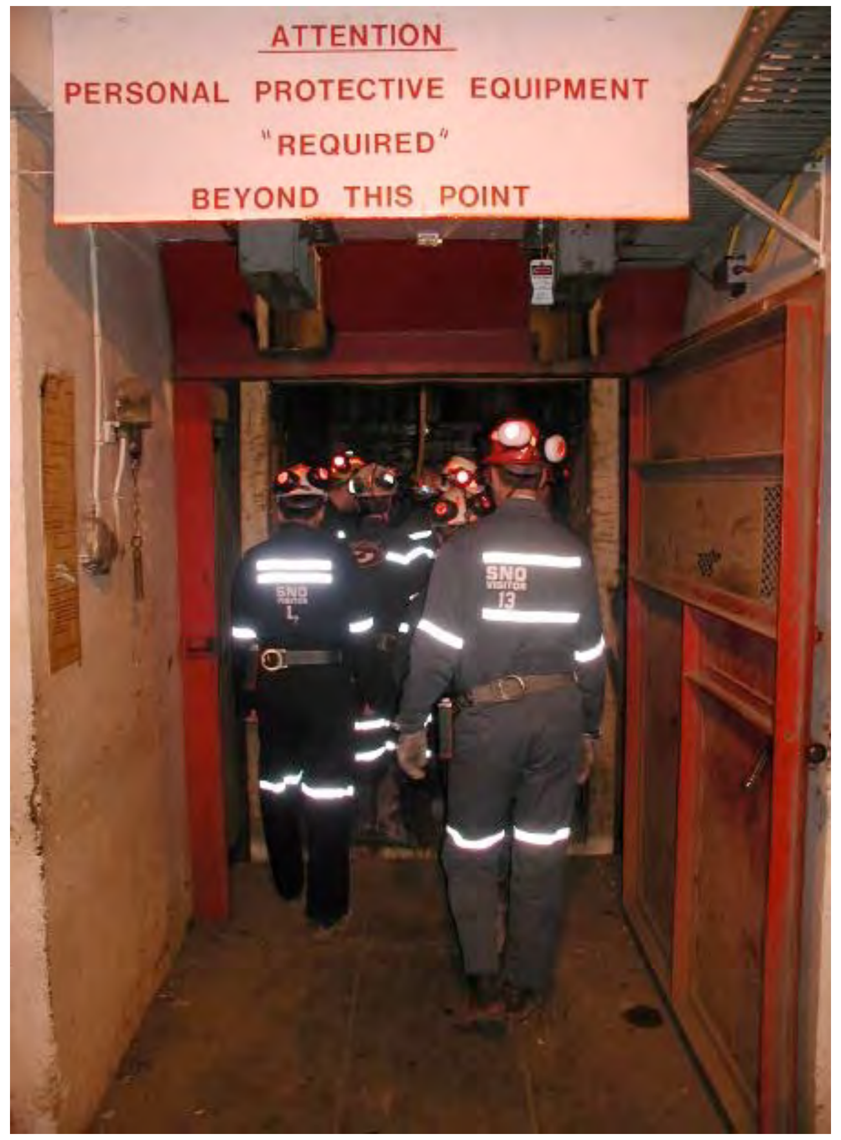
Why going underground?



- High energy particles (mostly protons) from galactic and extra-galactic sources bombard our Earth's upper atmosphere.
- They interact with nuclei in the atmosphere (nitrogen, oxygen...) and create a shower of other particles.
- A significant fraction of these secondary particles are muons, a heavier cousin of electrons.
- Dosage at higher elevation is higher. The atmosphere is a shielding.

Mining for knowledge...

→



→

↙

70000 underground showers...

←

Why cleanroom and showers?

- Rock / mine dust are "hot" for solar neutrino experiments (from natural U and Th).
- In fact, all construction materials we used in the experiment had to be screened for low radioactivity.
- Extra precaution in handling and process (e.g. used non-thoriated welding rods for welds)
- One teaspoon of mine dust would ruin the whole experiment.

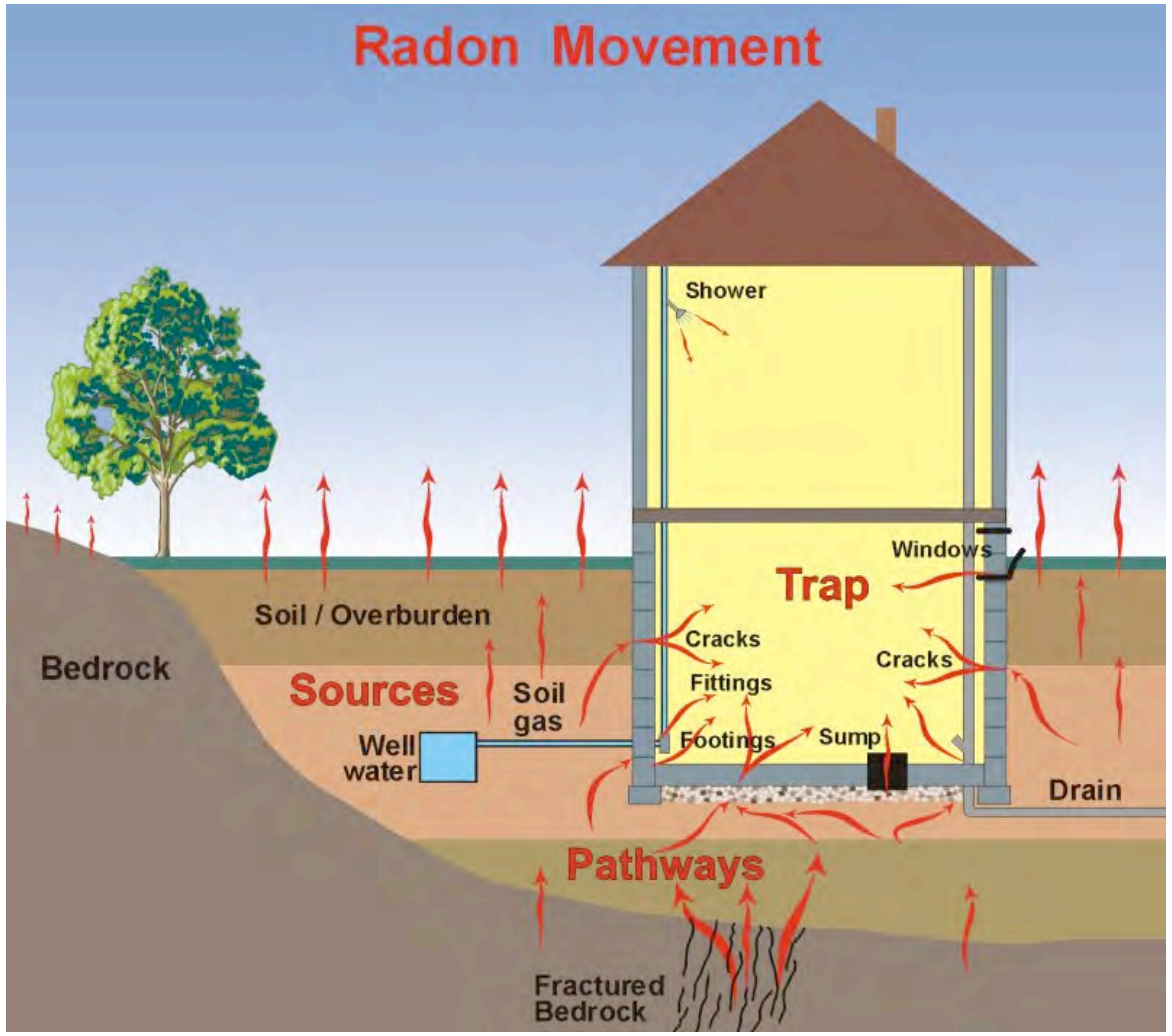


Image from inhabitat.com

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Natural Decay Chains