Proton Decay and much more

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This short presentation

Very much a personal reflection rather than a deeper scientific exploration

- but the scientific story is really interesting, particularly looking back

I will try to give a historical perspective on how the search for proton decay shaped neutrino physics today

- and of course, Don Perkins was a leading figure in this area

Why am I here?

Part of the answer:

- The proton lifetime is significantly longer than the lifetime of the Universe

Why am I here today?

Probably more relevant:

- In **1985** I started my D.Phil. in Experimental Particle Physics at Oxford and decided to work on the Soudan-2 underground experiment in Minnesota

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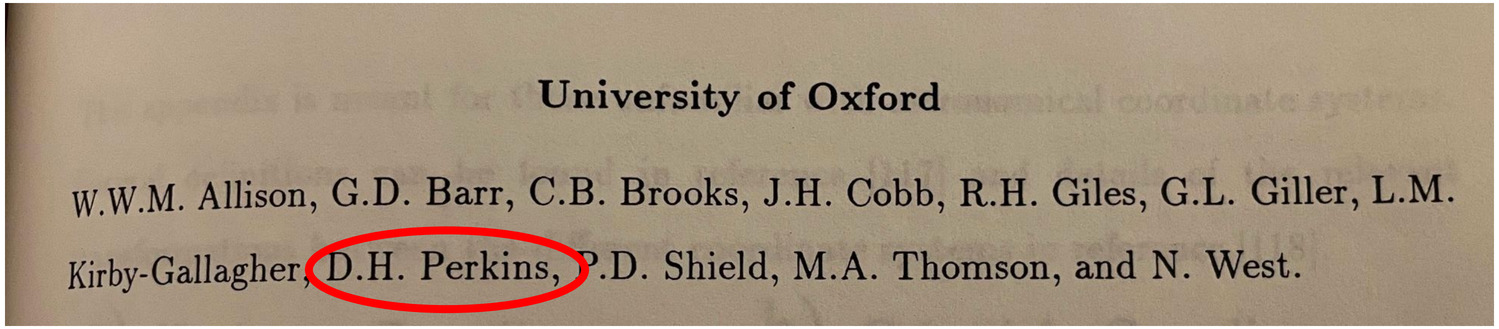
Why go underground

What was the attraction with Soudan-2?

- Small collaboration
- Hands-on detector and electronics technology
- A great team at Oxford including…


University of Oxford

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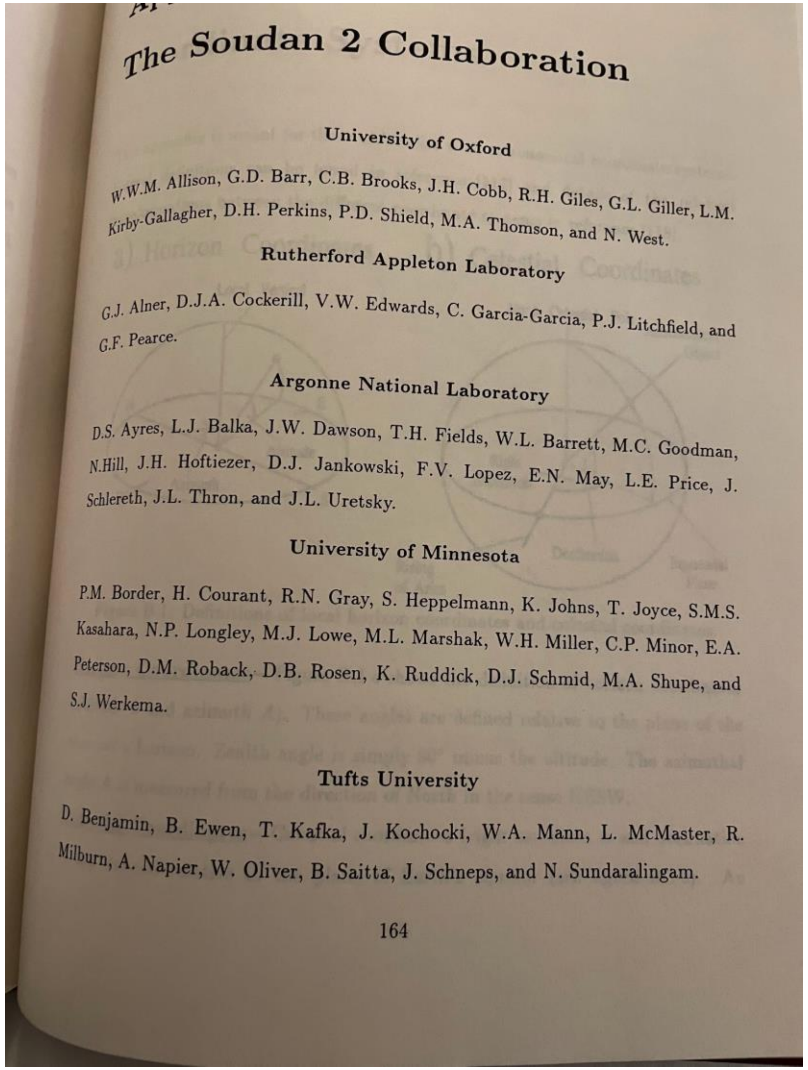
Ultimately, it was the science

- Astroparticle Physics / Particle Astrophysics before it was "a big thing"


The Soudan 2 Collaboration

University of Oxford

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Rutherford Appleton Laboratory

G.J. Alner, D.J.A. Cockerill, V.W. Edwards, C. Garcia-Garcia, P.J. Litchfield, and G.F. Pearce.

Argonne National Laboratory

D.S. Ayres, L.J. Balka, J.W. Dawson, T.H. Fields, W.L. Barrett, M.C. Goodman, N.Hill, J.H. Hoftiezer, D.J. Jankowski, F.V. Lopez, E.N. May, L.E. Price, J. Schlereth, J.L. Thron, and J.L. Uretsky.

University of Minnesota

P.M. Border, H. Courant, R.N. Gray, S. Heppelmann, K. Johns, T. Joyce, S.M.S. Kasahara, N.P. Longley, M.J. Lowe, M.L. Marshak, W.H. Miller, C.P. Minor, E.A. Peterson, D.M. Roback, D.B. Rosen, K. Ruddick, D.J. Schmid, M.A. Shupe, and S.J. Werkema.

Tufts University

D. Benjamin, B. Ewen, T. Kafka, J. Kochocki, W.A. Mann, L. McMaster, R. Milburn, A. Napier, W. Oliver, B. Saitta, J. Schneps, and N. Sundaralingam.

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Proton Decay in 1984

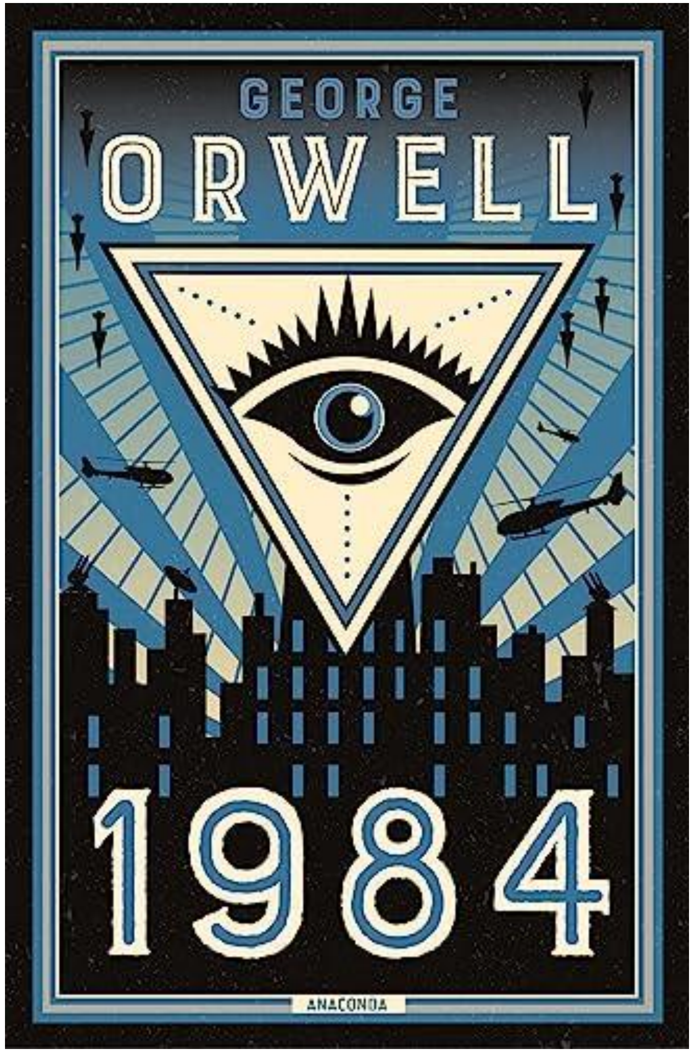
Proton decay was a hot topic

Ann. Rev. Nucl. Part. Sci. 1984. 34 : 1–52

PROTON DECAY EXPERIMENTS

D. H. Perkins

CERN, European Organization for Nuclear Research, Geneva, Switzerland; and Department of Nuclear Physics, University of Oxford, England



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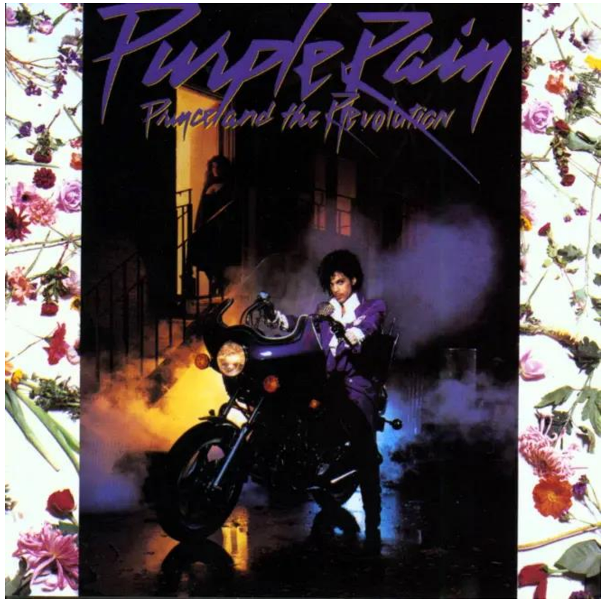
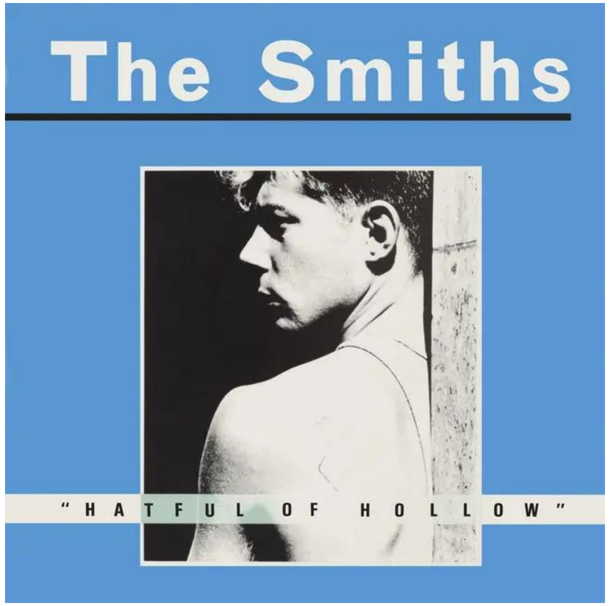
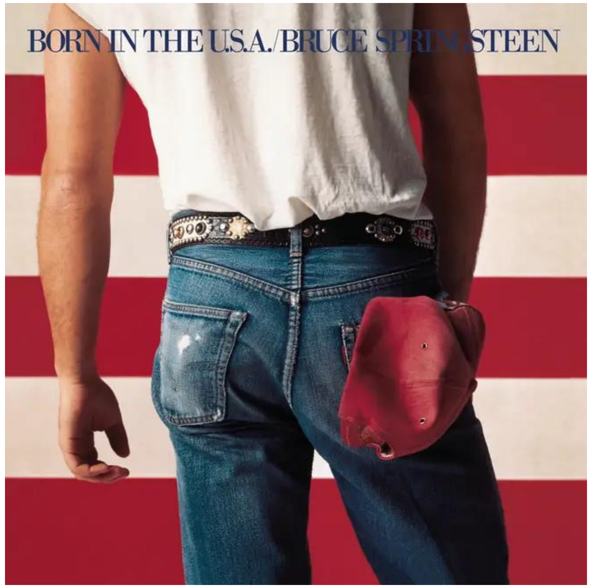
Proton Decay in 1984

Proton decay was a hot topic

What else was hot in 1984?







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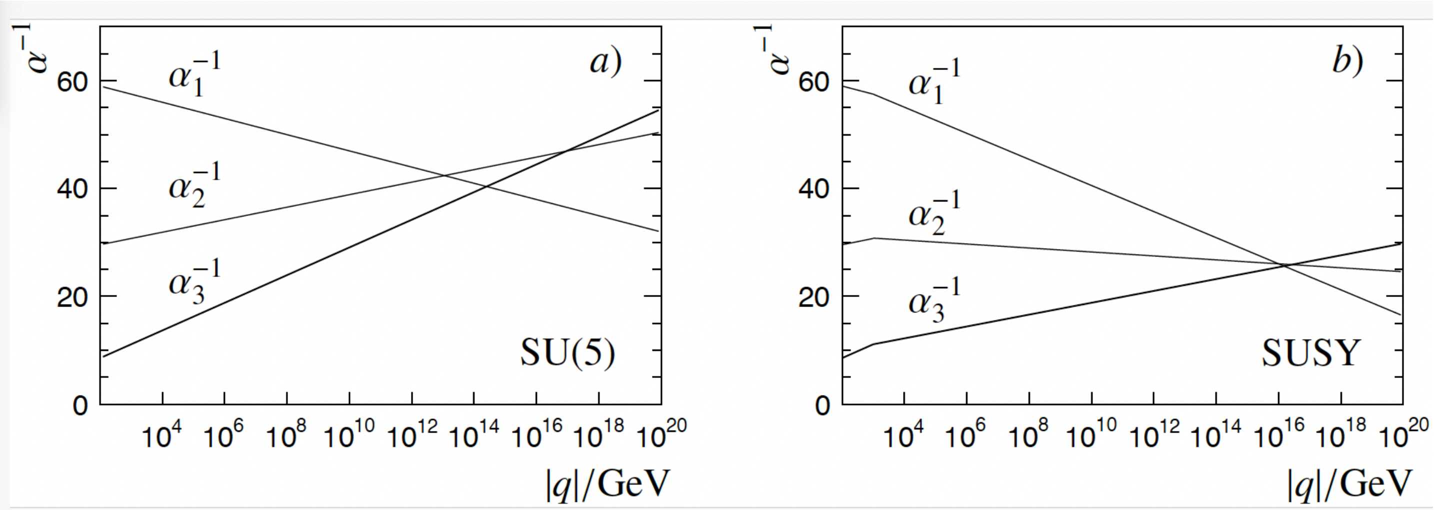
Why was proton decay *the* hot topic?

Looking back to 1984 (if we dare)…

- Discovery of W & Z in 1983, firmly established the gauge theory of $SU_L(2) \times U(1)$ as the principle for a unified electroweak theory.
- In the late 1970s / early 1980s the SU(3) gauge theory of QCD had also been confirmed by experiment
- The experimental data at the time suggested that the strengths of the three main forces converged at a scale of ~10^{14} GeV



Why was proton decay a hot topic?

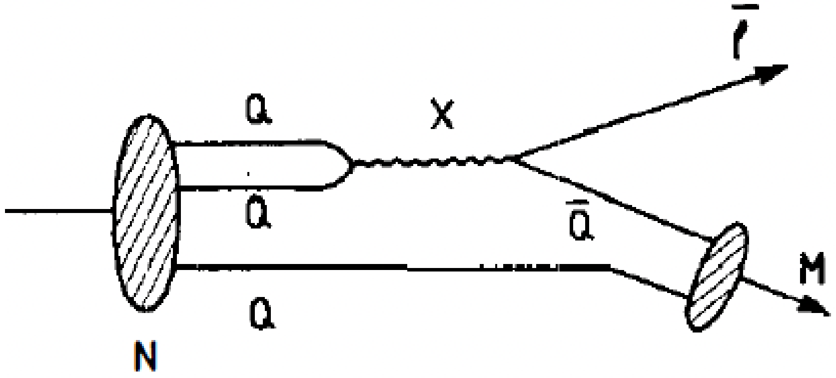
Looking back to 1984…

- Georgi and Glashow brought these ideas together in the context of the SU(5) **Grand Unified Theory**
  - quarks and leptons were placed in the same multiplet structure
  - a new force mediated by a super-heavy gauge bosons, imaginatively named X and Y
    - $M_X \sim 10^{15}$ GeV
- As a consequence, Baryon Number not conserved and the **proton should decay**
  - Worth remembering that Baryon Number non-conservation is one of the three Sakharov's conditions necessary for the observed matter-antimatter asymmetry in the Universe

Proton decay

Proton decay

- In vanilla SU(5) Grand Unified Theory the underlying process is:
  - $u\ d \rightarrow X \rightarrow e^+\ \bar{u}$



- Resulting proton process with a final state of a positron and a neutral meson, e.g.
  - **$p \rightarrow e^+ \pi^0$**
- Other models were (and still are) available, Supersymmetric GUTs generally predict the final state lepton to be a neutrino, e.g.
  - **$p \rightarrow K^+ \bar{\nu}_\tau$**

Proton lifetime

Proton decay

- Simple dimensional arguments give

$$\tau_p = \frac{A M_X^4}{\alpha_g^2 M_p^5},$$

- Taking, A~1, α_g ~ 1/40 and M_X ~ 10^{15} GeV suggests a proton lifetime of
  - $\tau_p \sim 10^{31}$ years

–

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The experimental challenge

The experimental challenge

- Looking for signatures such as $\mathbf{p \rightarrow e^+ \pi^0}$ and $\mathbf{p \rightarrow K^+ \bar{\nu}_\tau}$
- with a proton lifetime of $>10^{31}$ years

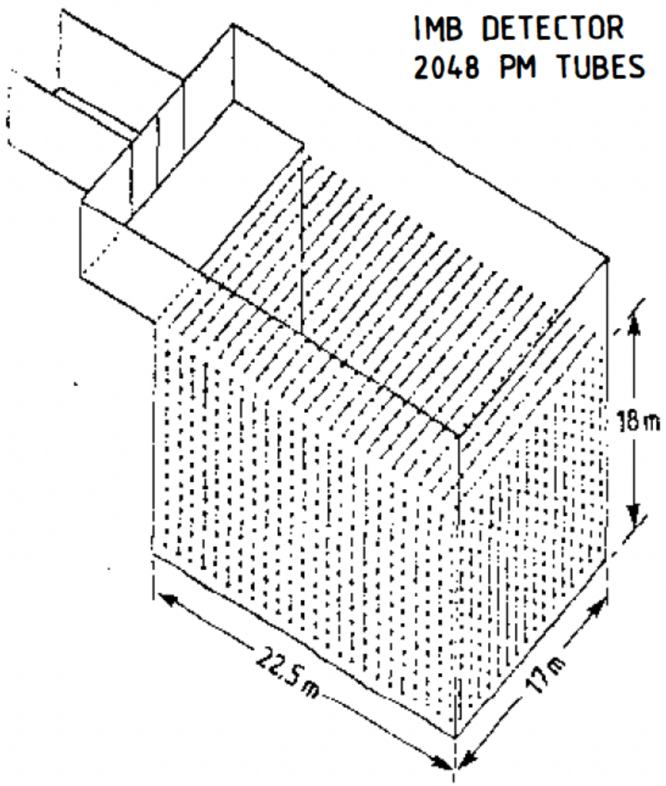
The experimental strategy

- a) watch one proton for 10^{31} years **– neither very practical not interesting**
- b) watch > 10^{31} protons for a few years
  - in this case the challenge is being able to see a single decay within a mass of ~1000 tons
- Looking for two distinct signatures:
  - $\mathbf{p \rightarrow e^+ \pi^0 \rightarrow e^+\gamma\gamma}$: relativistic electromagnetically interacting particles
  - $\mathbf{p \rightarrow K^+ \bar{\nu}_\tau}$: “slow” kaon, which decays

The experimental approach

Two main experimental approaches

- To look for pdk signatures in a large volume
  - **$p \rightarrow e^{+} \pi^{0} \rightarrow e^{+}\gamma\gamma$** : relativistic electromagnetically interacting particles
  - **$p \rightarrow K^{+} \nu_{\tau}$** : “slow” kaon, which decays



Water Cherenkov detectors, e.g.

- the IMB detector in the US
- and the Kamioka nucleon decay experiment, Kamiokande, in Japan

Tracking calorimeters, e.g.

- FREJUS and NUSEX in Europe
- and Soudan-1 in the US

Backgrounds

Searching for a “single proton decay” in a very large detector is a challenge

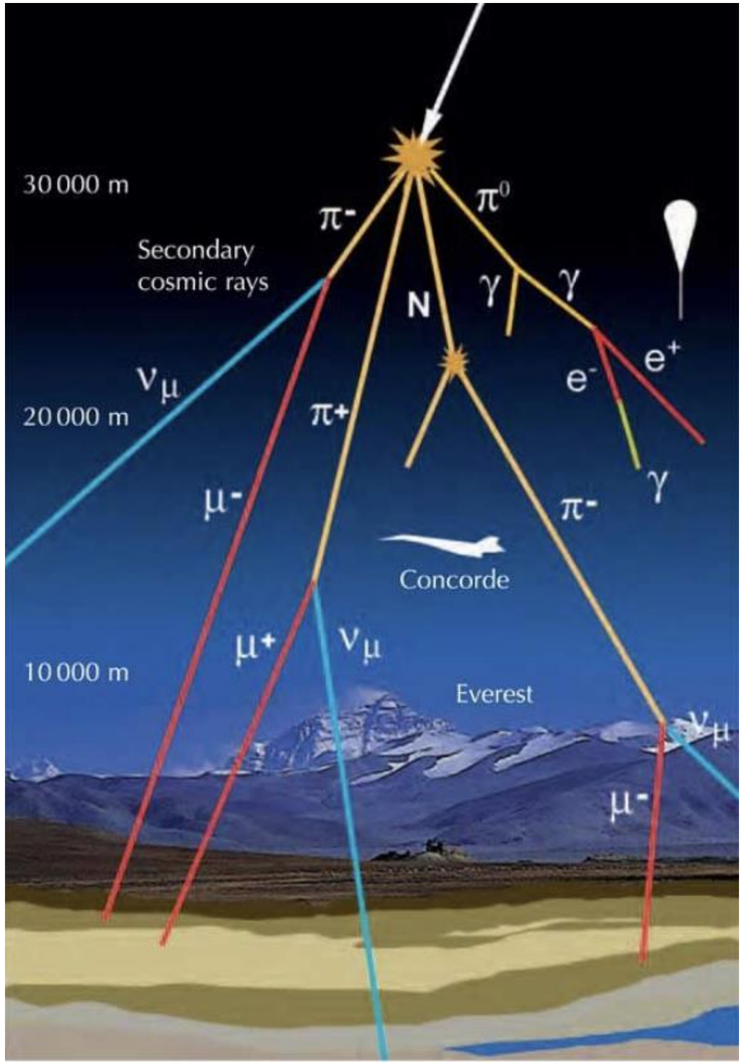
- Cosmic-ray induced background, e.g. spallation neutrons, can fake a signal

need to go deep underground

- But always left with atmospheric neutrinos

pdk searches changed particle physics

- large underground experiments
- sensitive to (otherwise not very interesting) neutrino-induced backgrounds



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Stepping forward to 1986

The experimental situation in 1986

- "At the time of this conference five experiments (KOLAR, NUSEX, FREJUS, IMB and KAMIOKANDE designed to discover nucleon decay take data, located all around the world but only in the northern hemisphere. One more experiment is being constructed (SOUDAN 2) and two projects are under serious discussions (SUPERKAMIOKANDE, ICARUS), however nucleon decay has not been dicovered yet." H. Meyer (from the FREJUS collaboration)

Three now familiar experimental techniques

- Tracking calorimeters ……………………. MINOS
- Water Cherenkov detectors …………. Super-Kamiokande ………. Hyper-Kamiokande
- Liquid Argon TPC ………………………………………………………….. DUNE

Soudan-2: my D.Phil. 1989-1991

Located in deepest darkest Minnesota…

- nearest large town, Ely, Mn

As an aside… main options for projects were

- ZEUS at DESY
  - Hamburg nightlife
- Delphi at CERN
  - mountains and skiing
- Soudan-2 in Minnesota
  - snow (but no mountains), 3.2 beer
  - A great and interesting group of scientists, including Don

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Soudan-2: the detector

Half a mile underground in a former Iron mine

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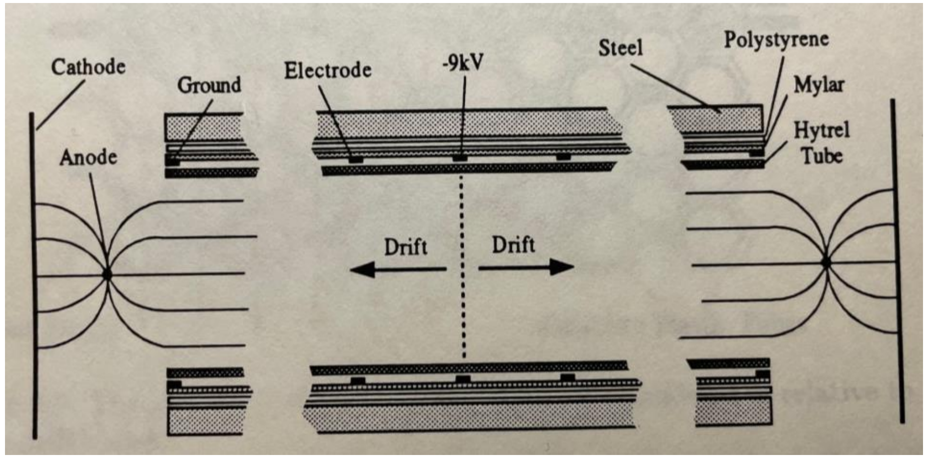
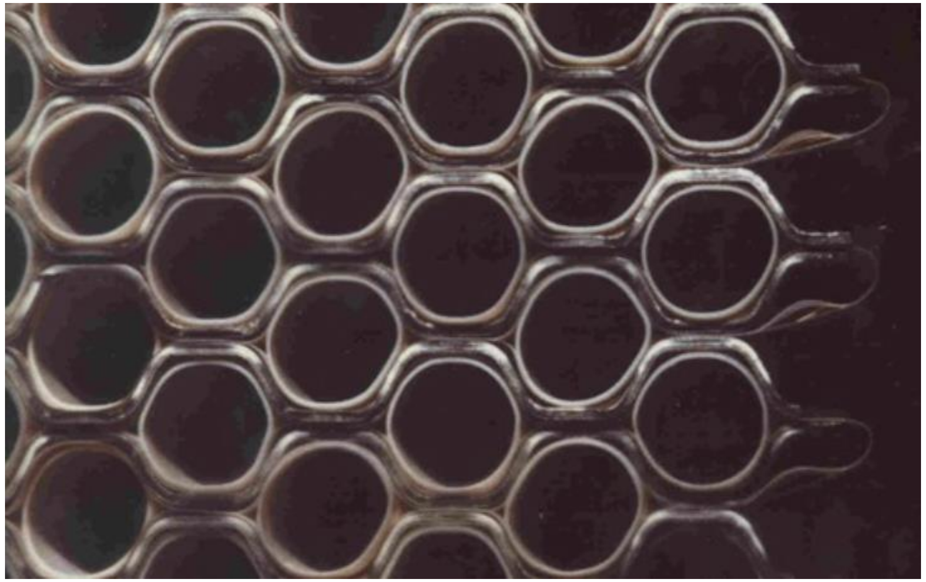
Soudan-2: the detector

"Slow-drift (0.6 cm s^{-1})" Time Projection Chamber

- Basic detector element was a 1.5cm resistive drift tube



- The tubes were sandwiched in a corrugated honeycomb structure made from 1.5mm steel plates
  - providing the bulk of the mass of the detector



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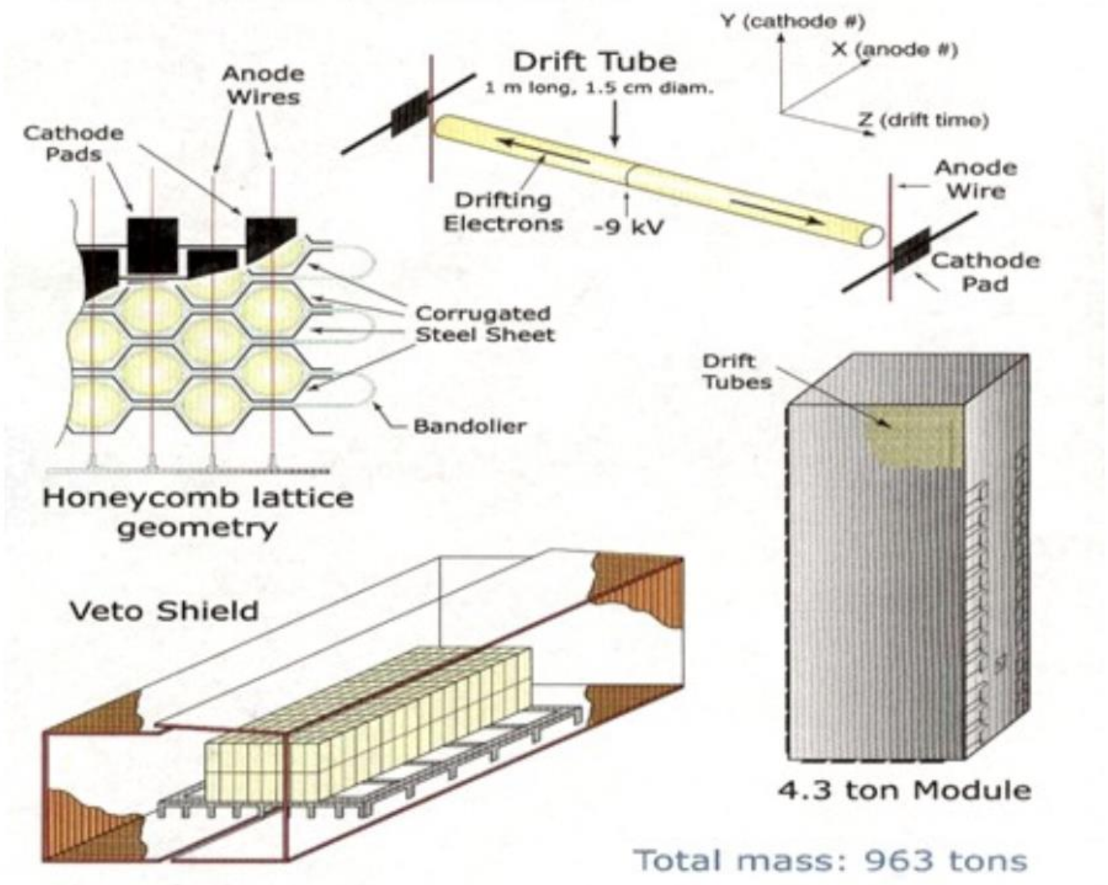
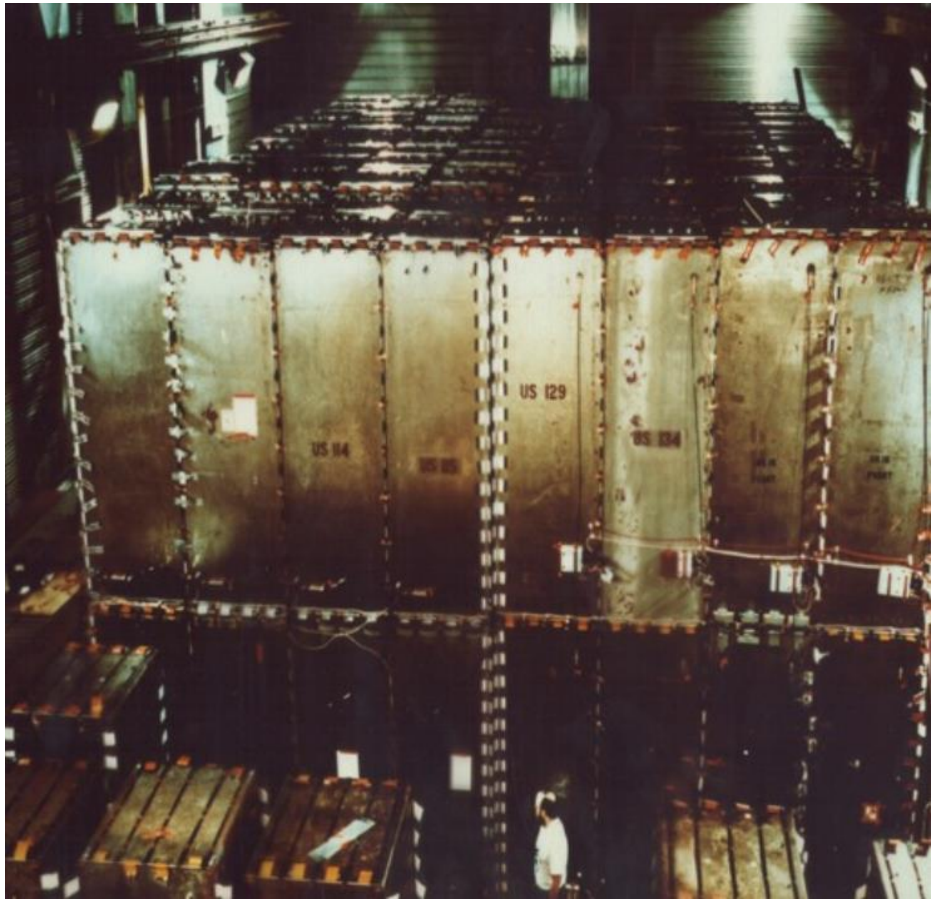
Soudan-2: the detector

"Slow-drift (0.6 cm s^{-1}**)" Time Projection Chamber**

- 256 modules, each of a mass of 4.3 tons





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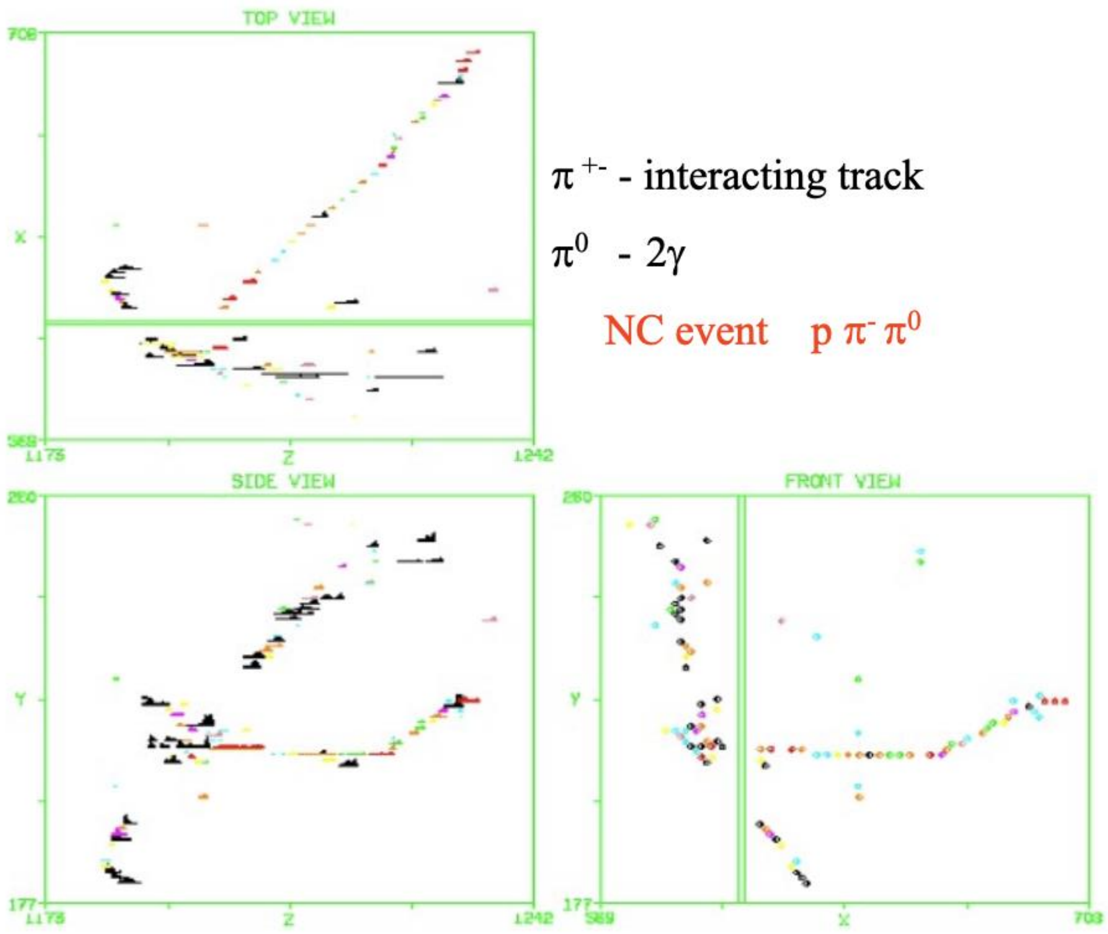
Soudan 2: 1989 - 2001

Soudan 2 was designed to study proton decay

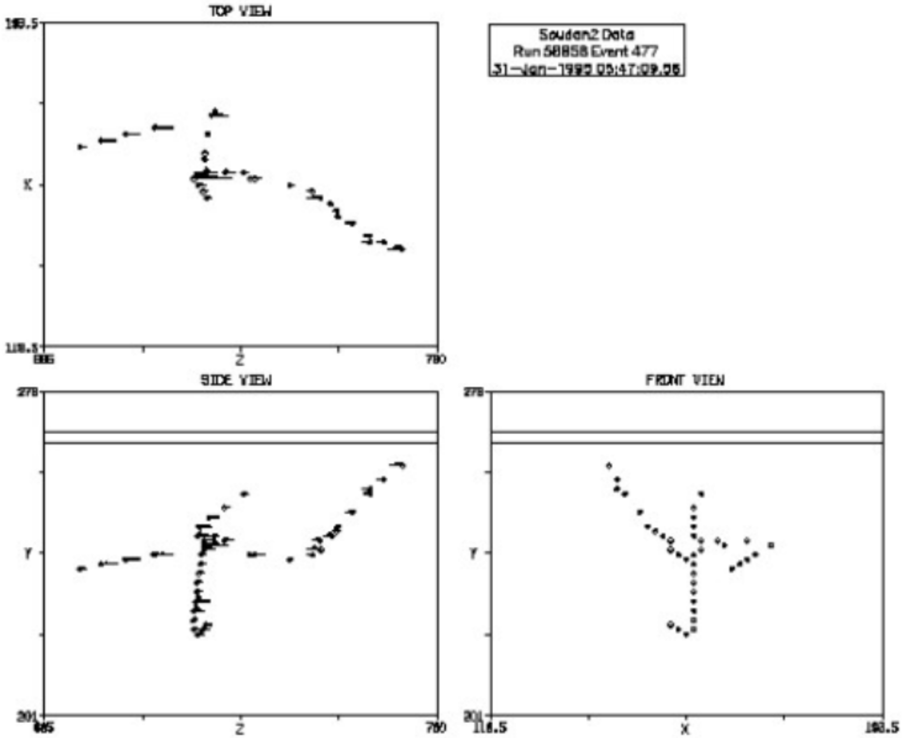
- Fine granularity tracking calorimeter with ~1 cm^3 voxels
- Low thresholds (gas detection)
- Good particle ID and two track resolution
- Projective 3D imaging



Soudan 2 – proton decay results

Multiple decay topologies explored

- All channels had some level of expected neutrino background
- Observed candidates were consistent with the background
- Most stringent lifetime limit (channel-dependent):
  - $\tau_p > 6 \times 10^{32}$ years



Today the best limits come from Super-Kamiokande

- More scalable technology leading to a 22 kton fiducial mass
- $\tau_p > \sim 10^{34}$ years

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Proton decay – the legacy

Coffee discussions

- One of the most enjoyable aspects of being in the Oxford physics department was the discussions over coffee
  - myself, John Cobb (my supervisor), Don Perkins and often Mike Bowler
- Discussion topics included proton decay and cosmic ray physics, but become increasingly focused on neutrinos and neutrino oscillations
  - hints from multiple experiments that not all was right with rate of neutrino backgrounds
  - the background was becoming the signal for neutrino oscillations

Proton decay – the legacy

One could argue that Soudan 2 seeded the now strong UK neutrino activity with Fermilab

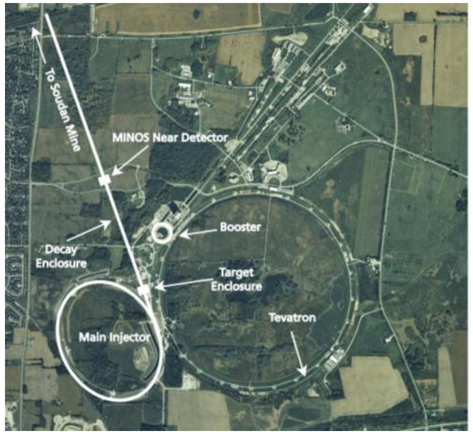
- Members of the Soudan 2 collaboration played a major role in the development of the concept of
  - P-875: A long baseline neutrino oscillation experiment at Fermilab

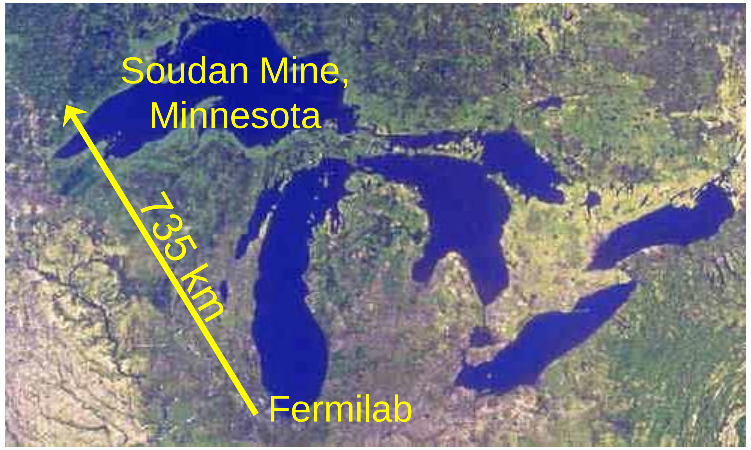
- Resulted in the formation of the MINOS collaboration following the demise of the SSC in 1993
  - In turned out that the distance between the Soudan mine and Fermilab was just about right to study neutrino oscillations with the mass differences suggested by atmospheric neutrino anomalies

MINOS

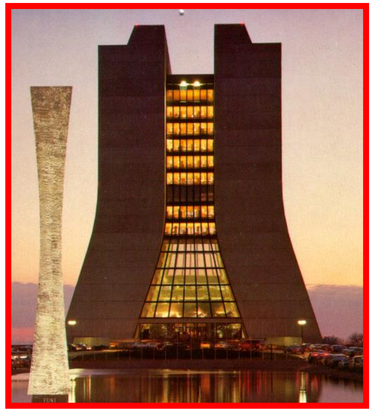
Second generation long-baseline neutrino oscillation expt. (after K2K)

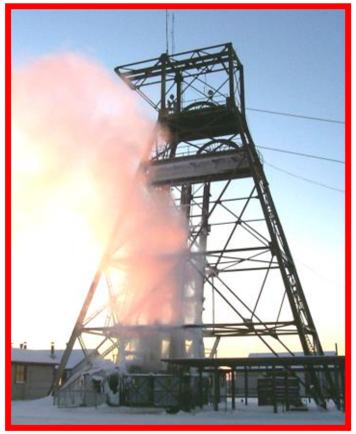
- Neutrino beam from 120 GeV protons from the Fermilab Main Injector





- Two detectors
  - 1000 ton NEAR detector at Fermilab, 1km from beam
  - 5400 ton FAR detector, 735km from beam in the Soudan mine

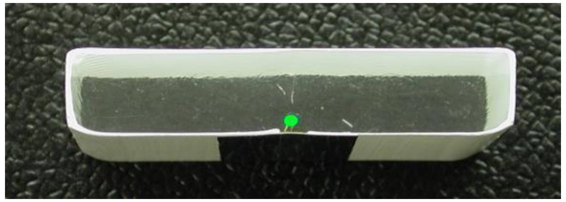


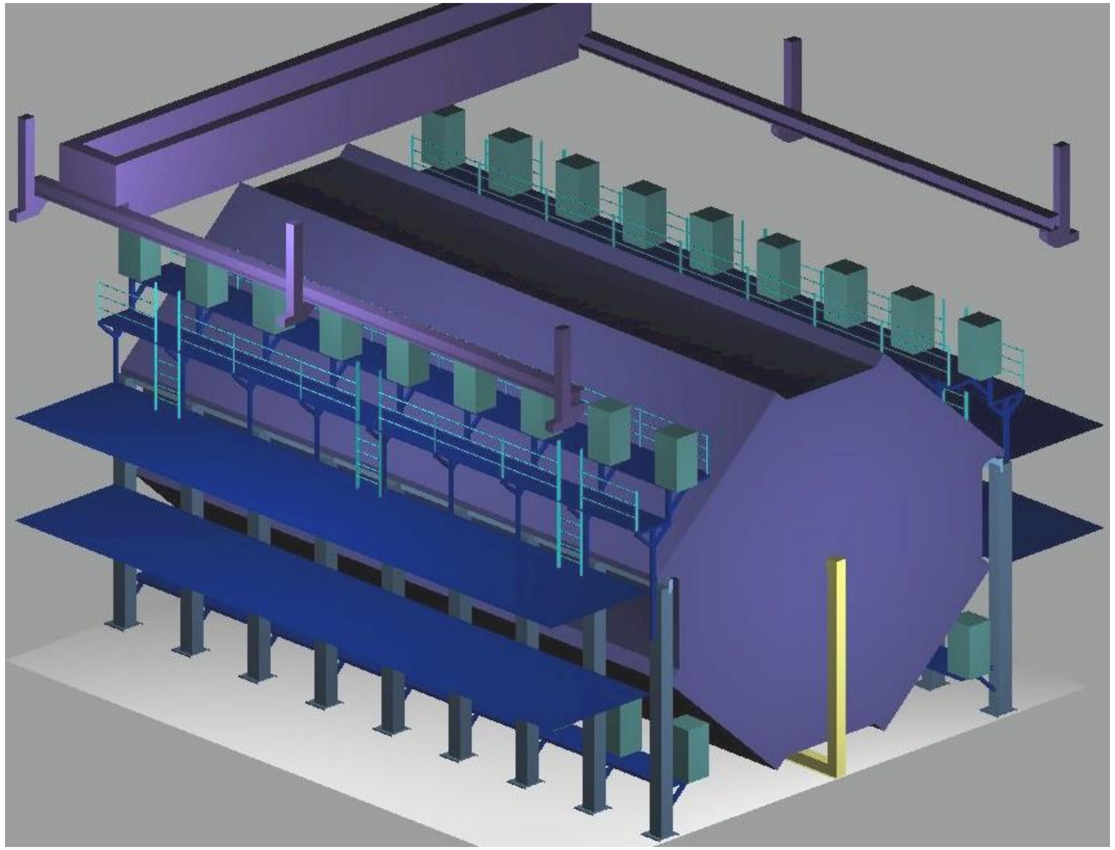


MINOS Detector

Fairly simple concept – for mass

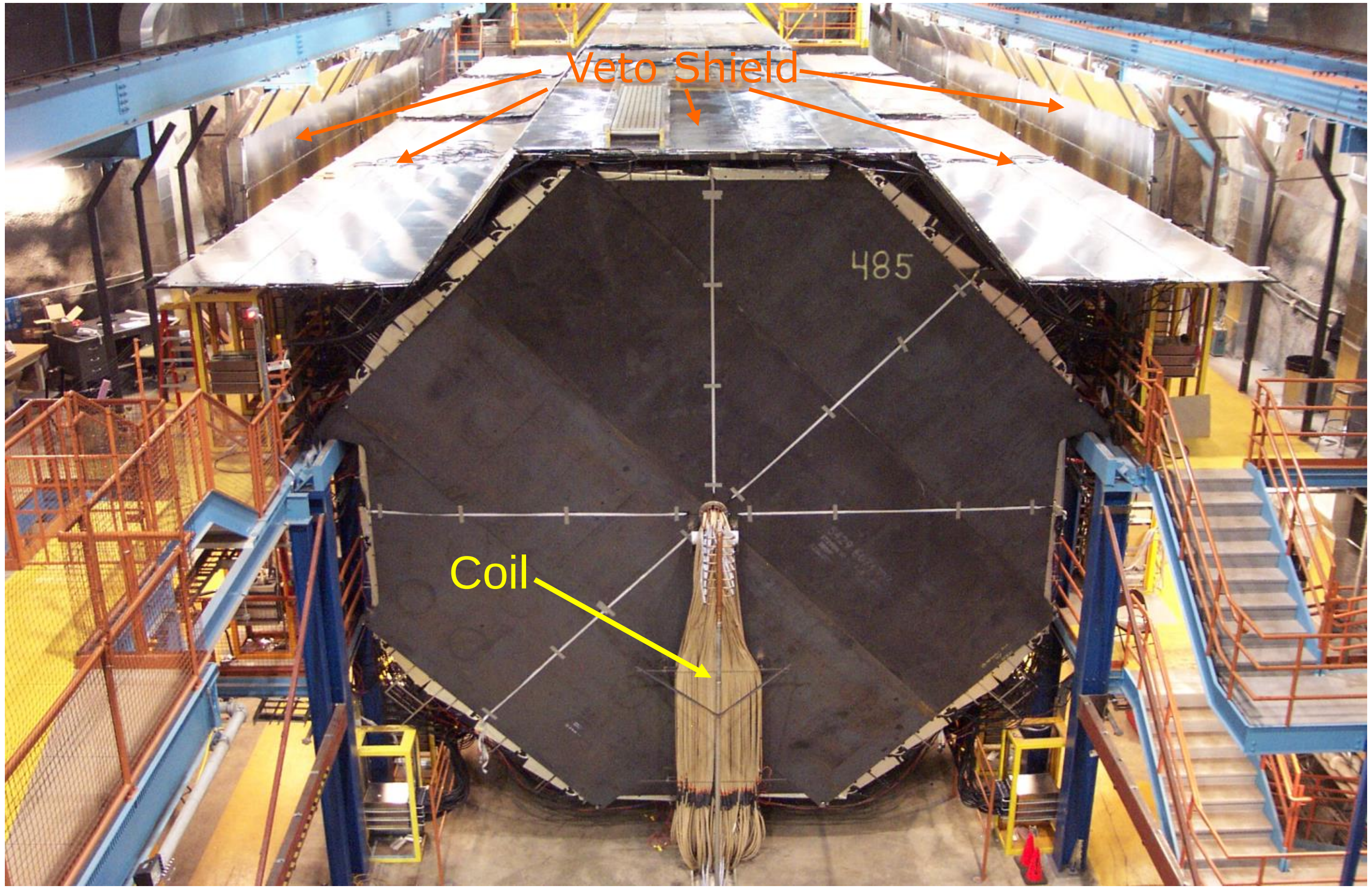
- 8m octagonal steel and scintillator tracking calorimeter
  - 2 sections of 15m in length
  - 484 planes of steel and scintillator
  - 2.54 cm (1”) steel + 1 cm scintillator strips of 4cm width
  - Alternate planes with orthogonal trip orientations to give 3D tracking
  - Magnetised with a central coil

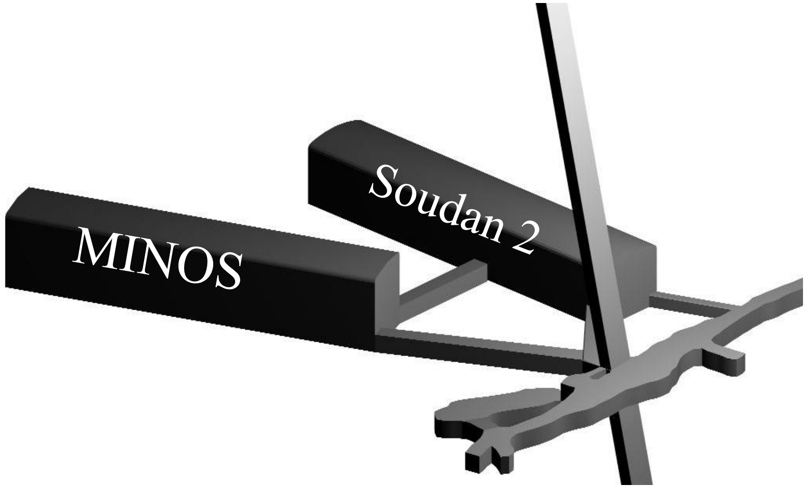




One Supermodule of the Far Detector…
Two Supermodules total.

MINOS: 2003 - 2016





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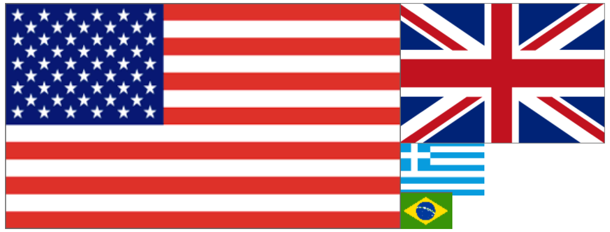
MINOS and the UK

The UK was a major player in MINOS

- Soudan 2 collaborators (Oxford and RAL) were joined by Sussex and UCL
- and Cambridge in 2000, when I returned from my sabbatical from neutrinos at CERN
- in parallel with T2K, this was the start of a major uplift in neutrino physics in the UK



27 institutions
175 scientists

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge •
Campinas . Fermilab • Harvard • IIT • Indiana
Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • William & Mary

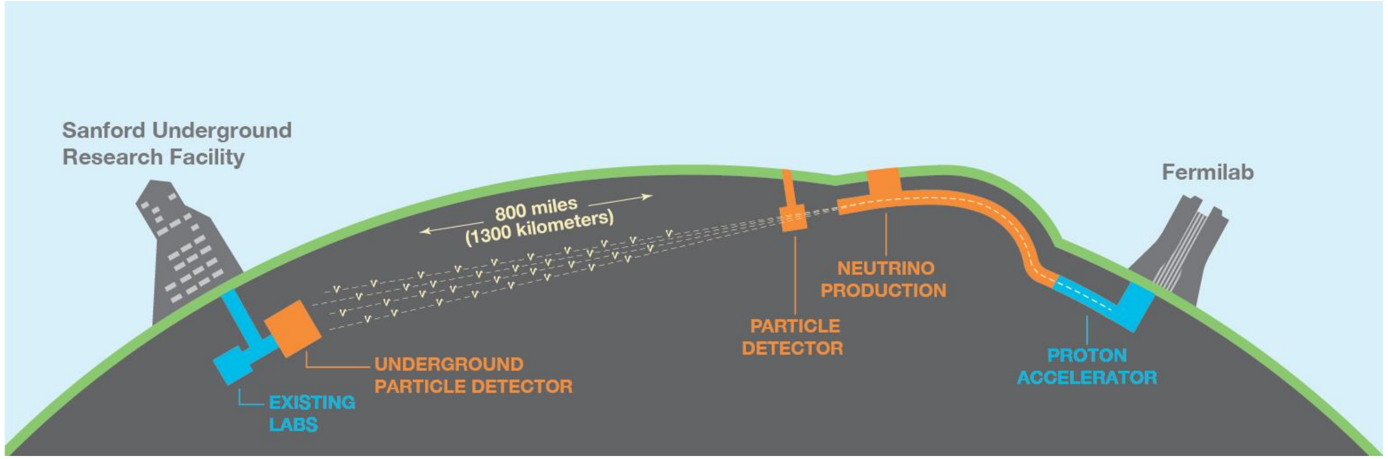
The Legacy of MINOS and Soudan

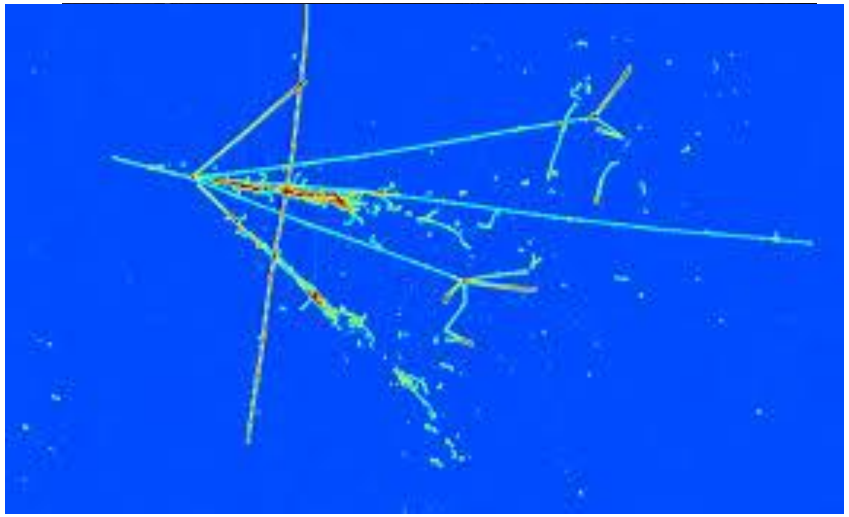
The strong engagement of the UK in MINOS underpinned the UK's involvement in the future US neutrino programme: LBNF/DUNE

- Around 2013 a few of us, including myself and colleagues from Oxford, were starting to a look beyond MINOS and in particular the Fermilab Liquid Argon TPC programme
  - Oxford and Cambridge joined MicroBooNE in 2013
  - The UK DUNE consortium formed ~2014
  - In 2015 was elected as one of the first co-spokespersons of DUNE
  - In 2017, Minister Joe Johnson signed the UK – US Science and Technology collaboration framework and announced the UK government investment of £65m in LBNF/DUNE
- Today the UK is a major partner in the ~$3Bn LBNF/DUNE project
  - along with Hyper-K and other investments, neutrino physics in the UK has never looked so exciting

Looking to the future: DUNE ~2030-

The MW+ class neutrino beam from Fermilab to South Dakota





- Excavation of caverns to host the DUNE detectors is complete
  - Each of the four large caverns will (ultimately?) host the vast 17000 ton liquid argon TPCs
  - Image neutrino interactions in exquisite

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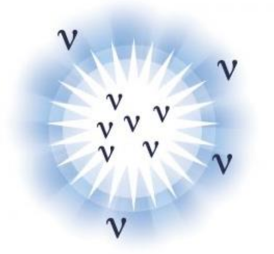
DUNE Physics Headlines

Three top-level scientific goals:



- **Origin of Matter:** Neutrino Oscillations: determine the mass hierarchy and discover CP violation in the neutrino sector

- **Unification of Forces:** Search for and hopefully discover **proton decay** – **coming full circle back to the early days of Soudan**

- **Black Hole Formation**: Observe thousands of neutrinos from a galactic supernova, probing the process of stellar collapse, neutron star formation and maybe even black hole formation

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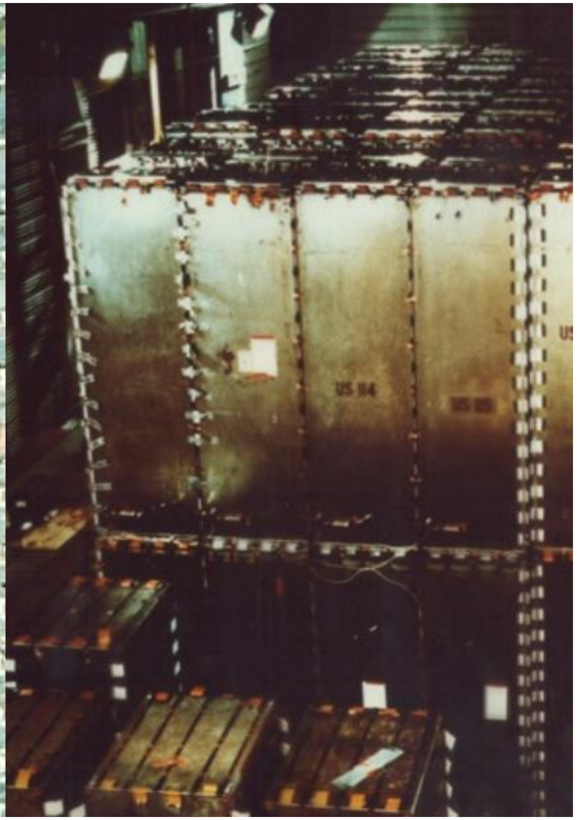
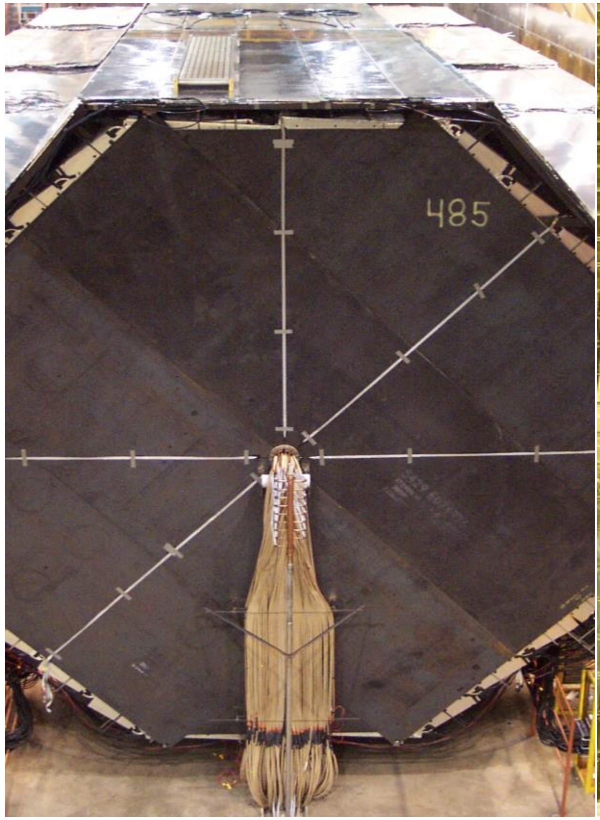
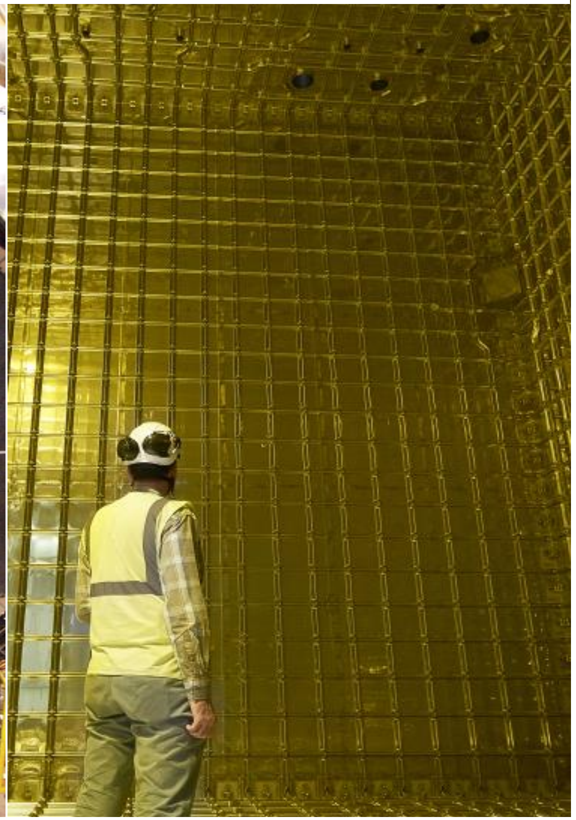
Closing thought

The early pdk experiments have left a massive legacy in the UK

- Don was a major part of this story



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