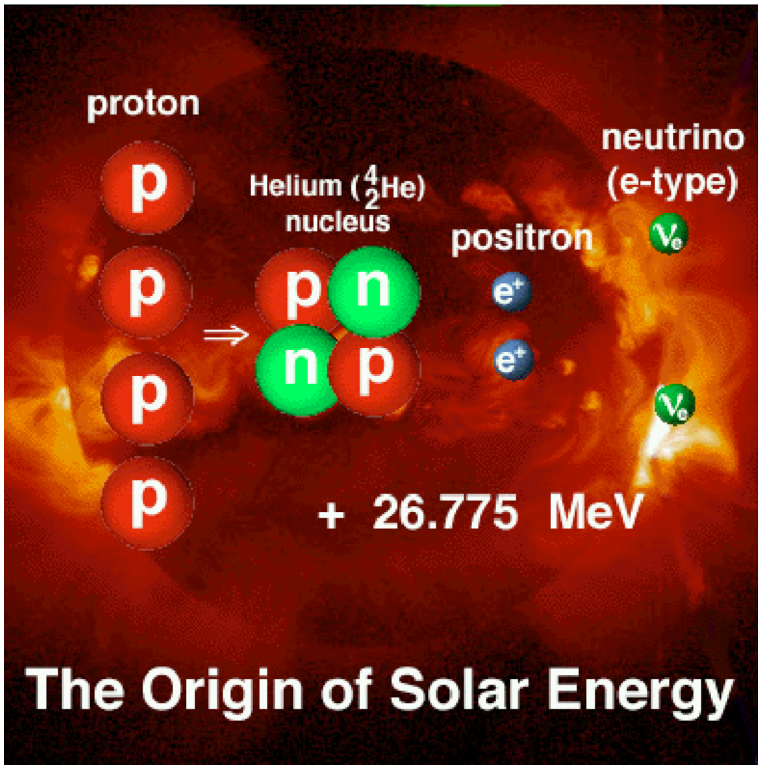
Weakly probing the universe across nine decades in energy

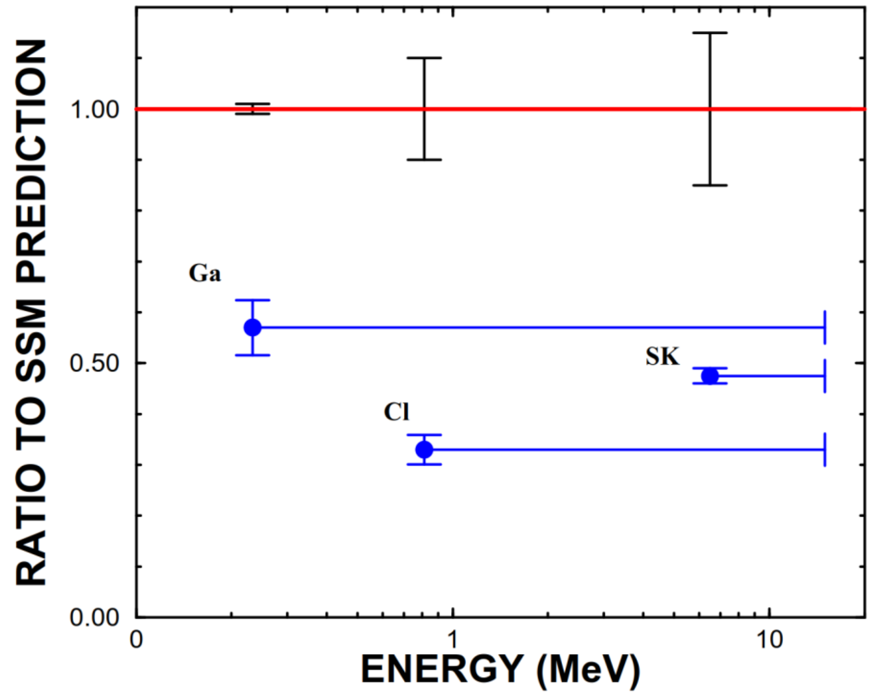
Scott Oser

CAP-TRIUMF Vogt Medal Prize talk

June 6, 2019

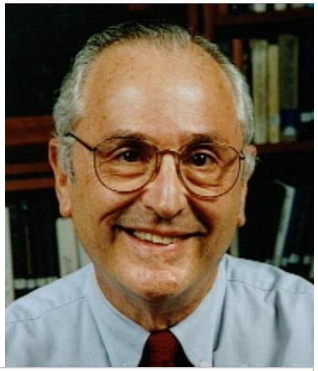
The Solar Neutrino Problem





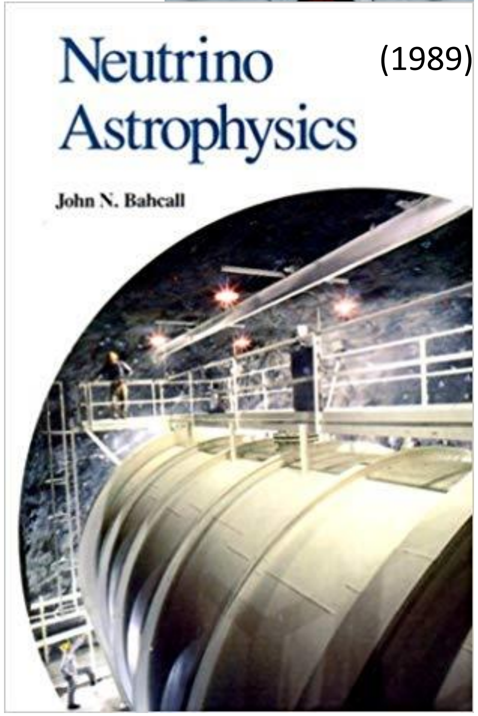
The solar neutrino problem came to my attention around 1992, when I wrote a report on it for a 2nd year undergraduate astronomy course.

John Bahcall's *Neutrino Astrophysics*



Heady reading for a 2nd year undergraduate … but had tremendous impact on me personally.

This part stuck with me: *"One [powerful new detector] is a proposed one kiloton heavy water experiment (D_2O), to be placed in an INCO nickel mine near Sudbury, Ontario (Canada) … The deuterium experiment may include a detection mode that is equally sensitive to all three types of neutrinos … Neutral currents make possible the ideal Equal Opportunity Detector."*



(1989)

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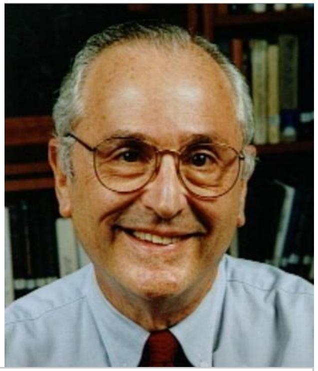

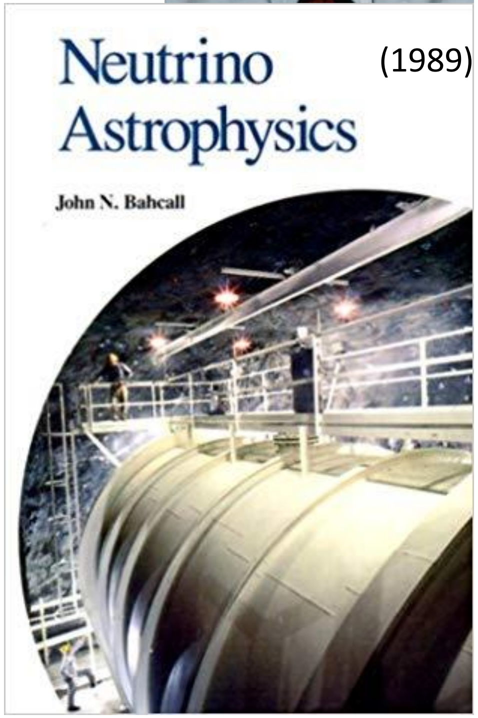

(1989)

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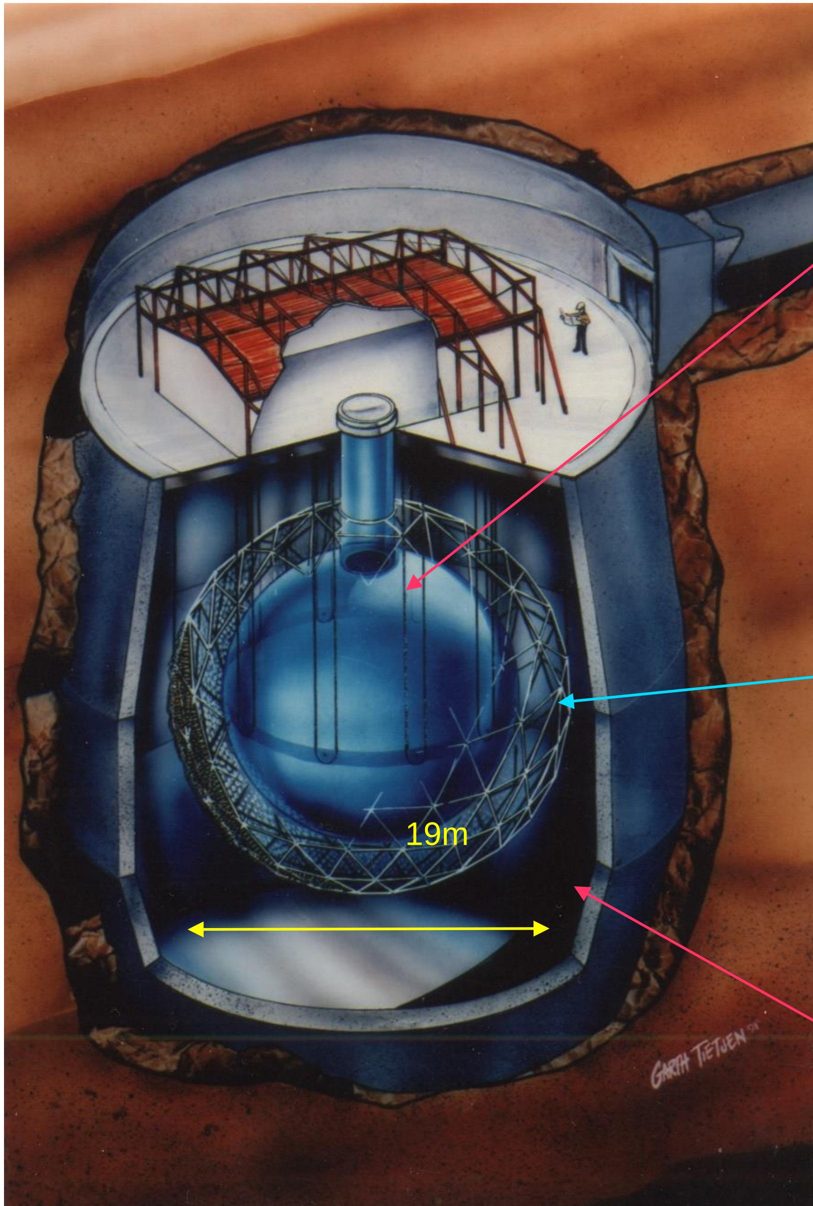
This part stuck with me: *"One [powerful new detector] is a proposed one kiloton heavy water experiment (D_2O), to be placed in an INCO nickel mine near Sudbury, Ontario (Canada) … The deuterium experiment may include a detection mode that is equally sensitive to all three types of neutrinos … Neutral currents make possible the ideal Equal Opportunity Detector."*

I was savvy enough to recognize that this was really exciting. I was naïve enough to think the experiment would all be over by the time I got through graduate school. I headed off to the University of Chicago to do gamma-ray astronomy (STACEE experiment), and didn't think about SNO for several years.

SNO

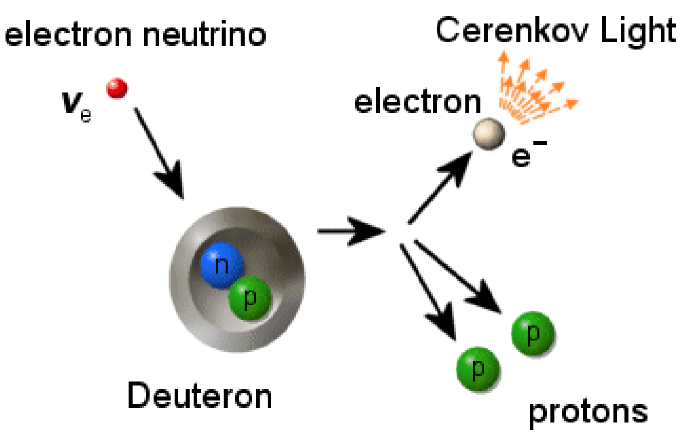


1000 tonnes of heavy water (D_2O) inside a 12m wide spherical acrylic vessel, with a little NaCl (salt) mixed in

9500 inward-looking photomultiplier tubes to detect Cherenkov light from the heavy water

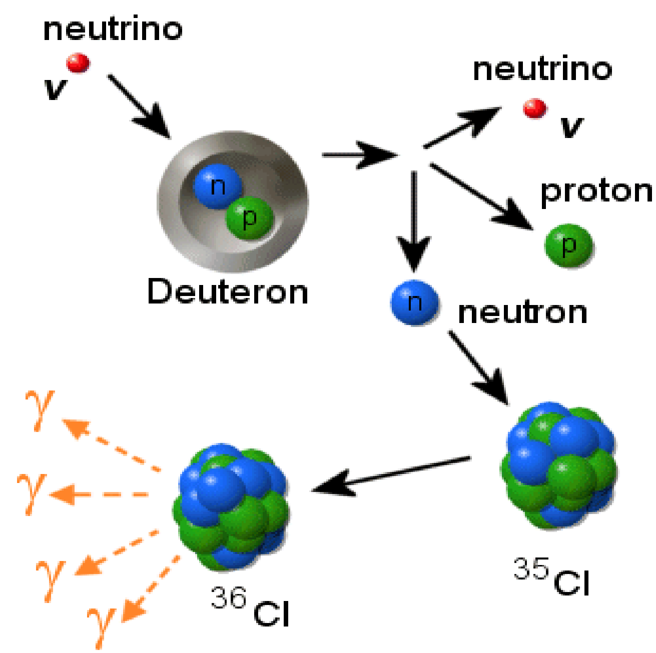
ultra-pure ordinary water (H_2O) surrounding the sphere to act as shielding

Neutrino Reactions On Deuterium



Electron neutrinos only:

$\nu_e + d \rightarrow 2p + e$



There are two possible reactions for solar neutrinos on deuterium.

One measures the flux of electron neutrinos.

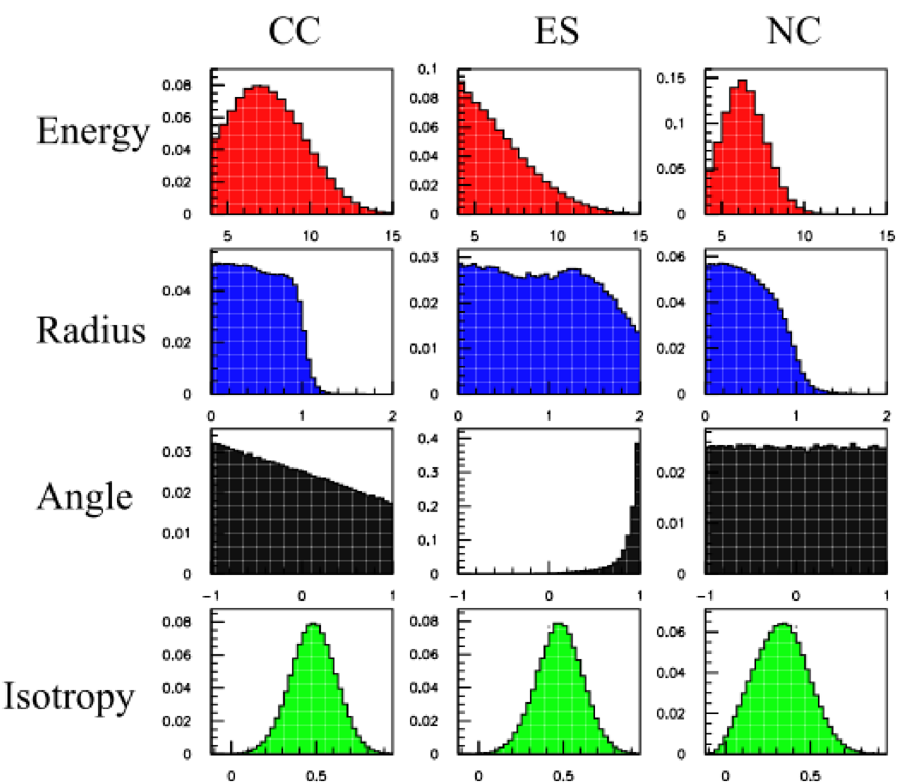
The second measures all types!

Any type of neutrino:

$\nu_x + d \rightarrow \nu_x + n + p$

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \text{multiple } \gamma\text{'s}$

Signal Extraction



CC and NC events (and ES – elastic scattering) can only be separated statistically, not event by event. Use multi-dimensional likelihood fit of observables $\vec{x}$:

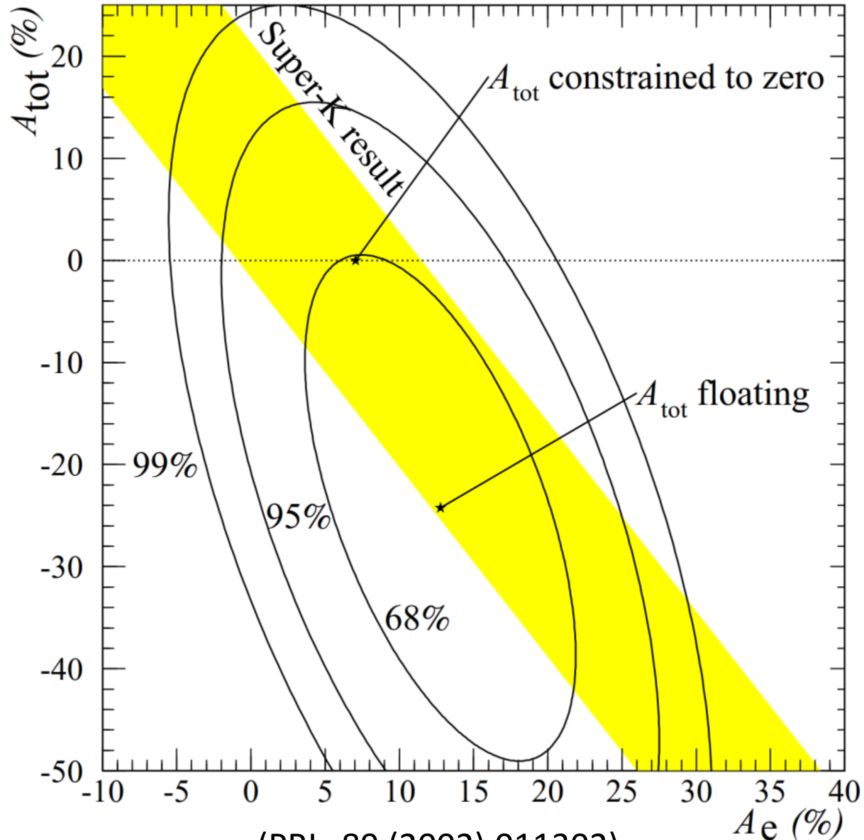
$$\mathcal{L} = \frac{e^{-\lambda}\lambda^{N}}{N!} \prod_{j}^{events} \sum_{i=CC,ES,NC} f_i g_i(\vec{x}_j)$$

Here λ represents the overall rate in the experiment, and f_i are the fractions of CC, NC, and ES events.

These can be rewritten in terms of the overall neutrino flux, cross-sections, and neutrino oscillation parameters

Day-Night Effects

Oscillation theory predicts that flavour regeneration as neutrinos transit through the Earth at night could result in different neutrino flavour content measured during day vs. at night.



(PRL. 89 (2002) 011302)

First look at this in the process of preparing SNO's first NC analysis showed surprisingly large day-night asymmetries in both the CC and, worryingly, the NC rate.

We spent a lot of time checking this result, mostly for worry that it might indicate a problem with the experiment. Good news: no evidence for any systematic difference in detector response. Mixed news: effect disappeared with more statistics.

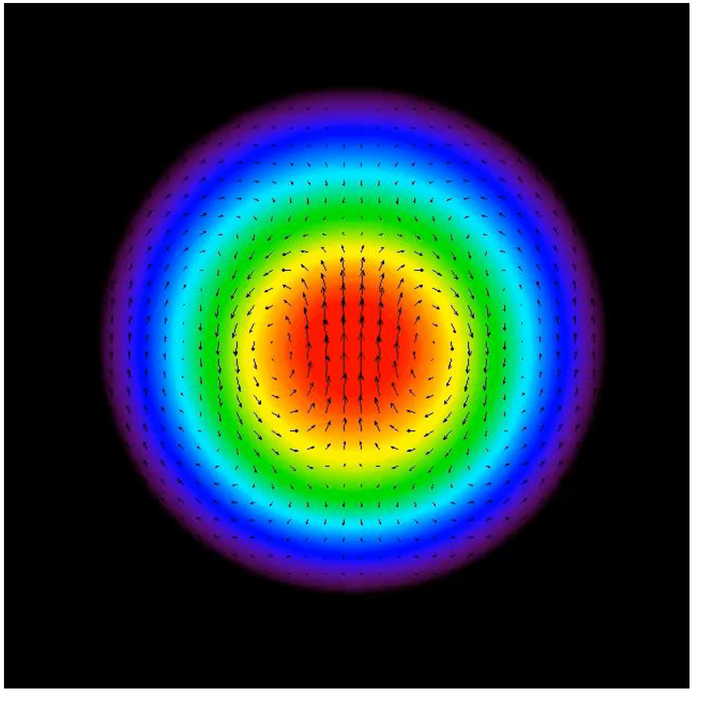
I wound up leading the day-night effort for the duration of SNO.

Is the solar neutrino flux constant in time?

Neutrinos from the Sun's core reach us 8 minutes later, but photons take ~10Myr to randomly walk to the surface!

Does the neutrino flux vary with sunspot cycle? Do neutrinos interact with Sun's time-varying magnetic fields? Do pressure/density oscillations in the Sun's core affect the flux in a measurable way?

SNO's low backgrounds and real-time measurements probed stability of nuclear fusion rate on timescales from months to minutes! (It's pretty stable …)



Simulated g-mode oscillation

Statistical Issues

Almost all of my work on SNO was statistics-heavy: likelihood fit techniques, time variability analyses, combining different data sets, error propagation methods …

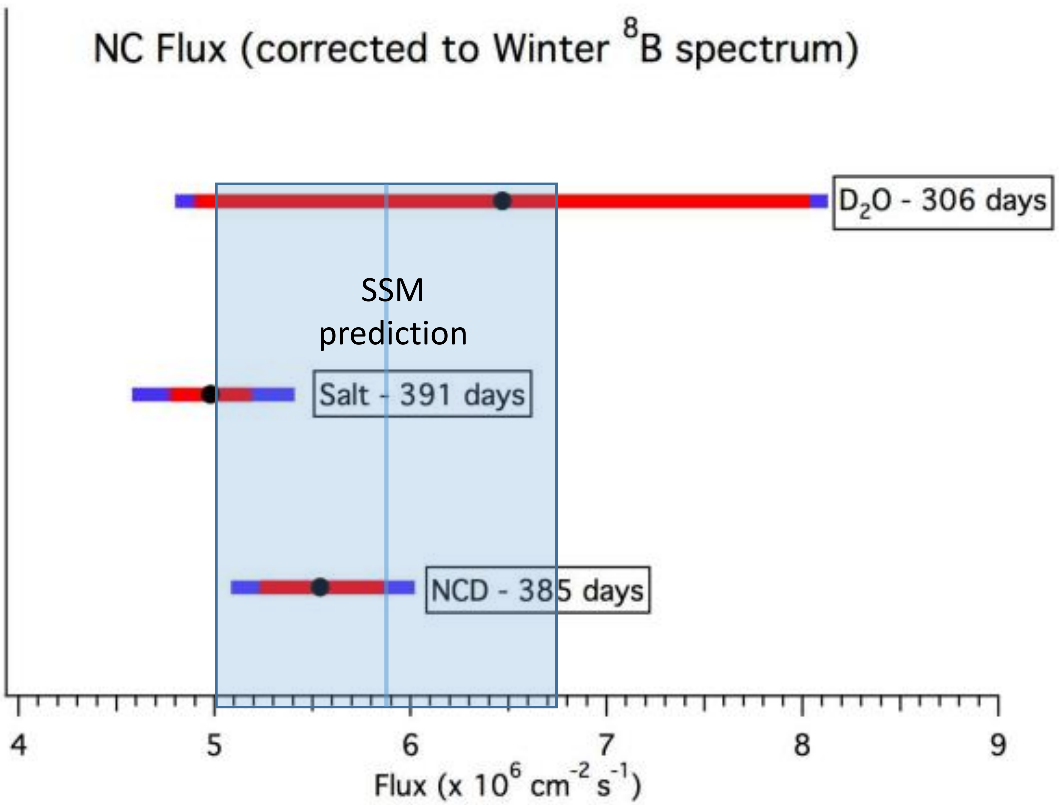
This has been a theme throughout my career.

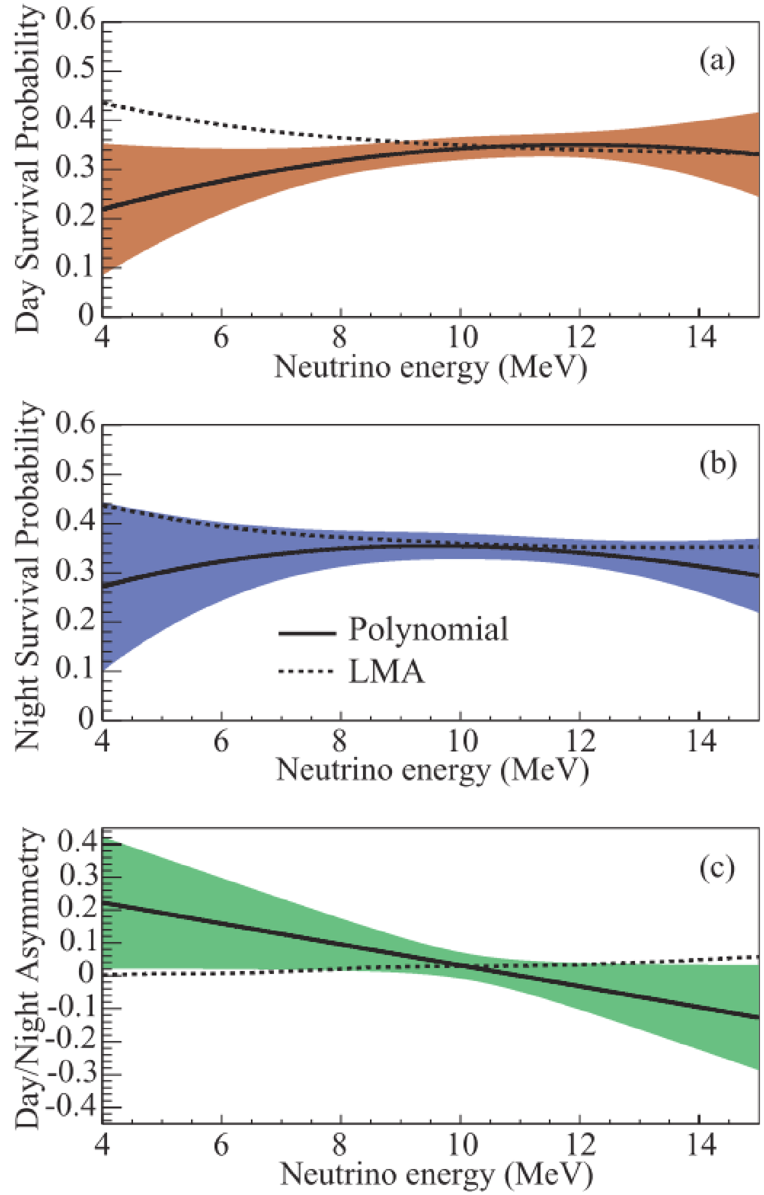
One long-time SNO collaborator, upon seeing me present the construction status for the T2K near detector in 2009, said: "Scott, this is the first talk I've seen you give that wasn't about statistics."

At one point I was lucky enough to start teaching a graduate course at UBC on statistical methods for the physical sciences. This fed back into my research when I started applying techniques from class to complicated fits to SNO data sets – fits to SNO's NCD phase data, combining data from PMTs and ^{3}He proportional counters, with 60-some free parameters and a "choppy" likelihood space due to binning effects.

To my knowledge this was the first use of Markov Chain Monte Carlo techniques in neutrino community.

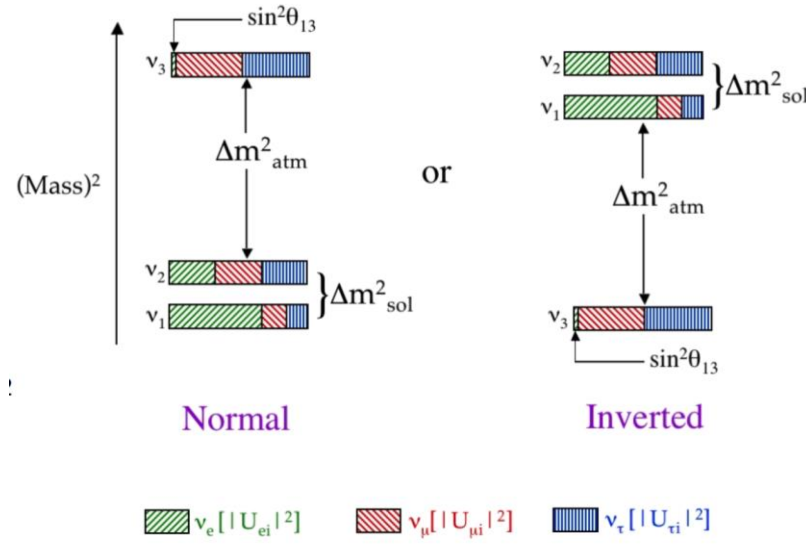
What SNO showed





ν's after SNO & SK

Two different mass splittings seen for two different sources of neutrinos.



Full 3 flavor mixing at work.

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}_{} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{}$$

Atmospheric ν's:

$\theta_{23} \approx 46°$

Maximal mixing! (?)

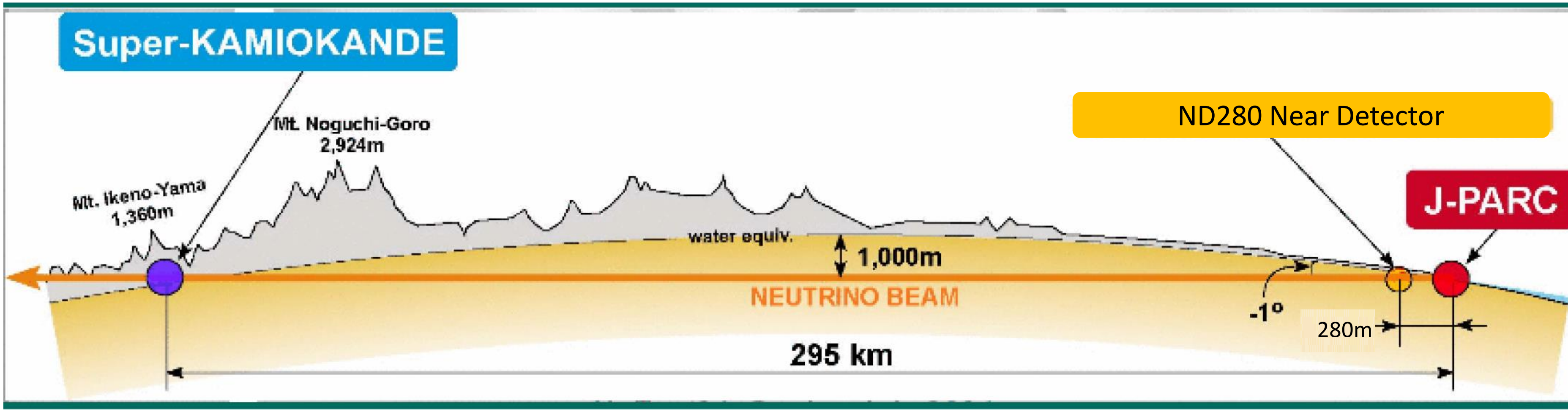
?

Solar ν's:

$\theta_{12} \approx 33°$

Large, non-maximal mixing

The T2K experiment

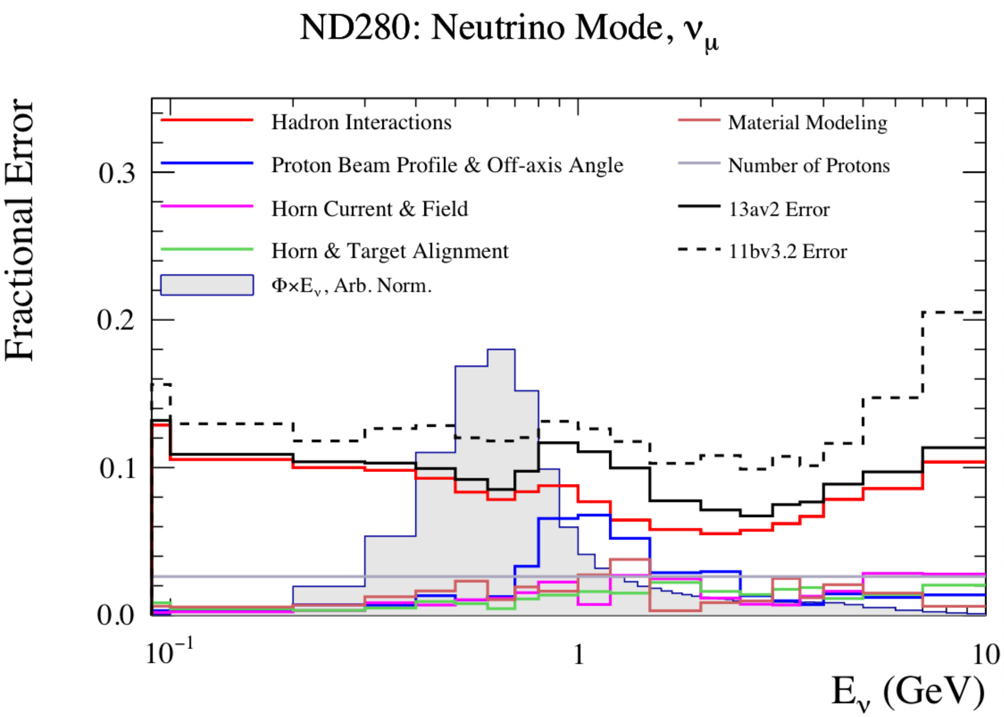


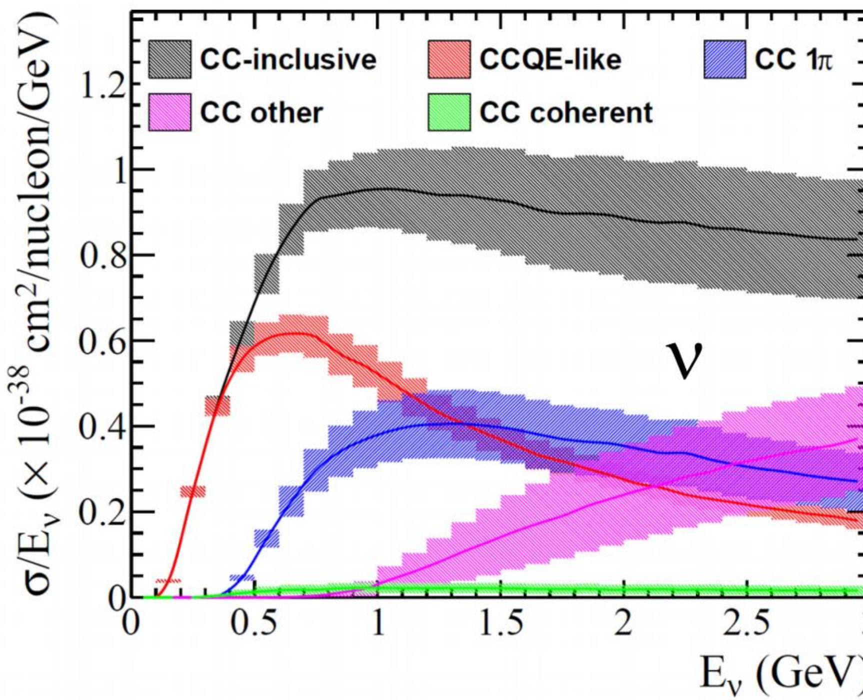
- Off-axis ν_μ beam w/ peak energy 0.6 GeV, across 295km
- Measure $P(\nu_\mu \rightarrow \nu_e)$, $P(\nu_\mu \rightarrow \nu_\mu)$ in narrow band beam

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \sim \quad & \sin^2 2\theta_{13} \quad \times \sin^2 \theta_{23} \quad \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\
& -\alpha \sin 2\theta_{13} \quad \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha \sin 2\theta_{13} \quad \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}
\end{aligned}
$$

$$
x \equiv 2\sqrt{2} G_F N_e \frac{E_\nu}{\Delta m^2_{31}} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}
$$

Experimental challenge: flux and cross-section

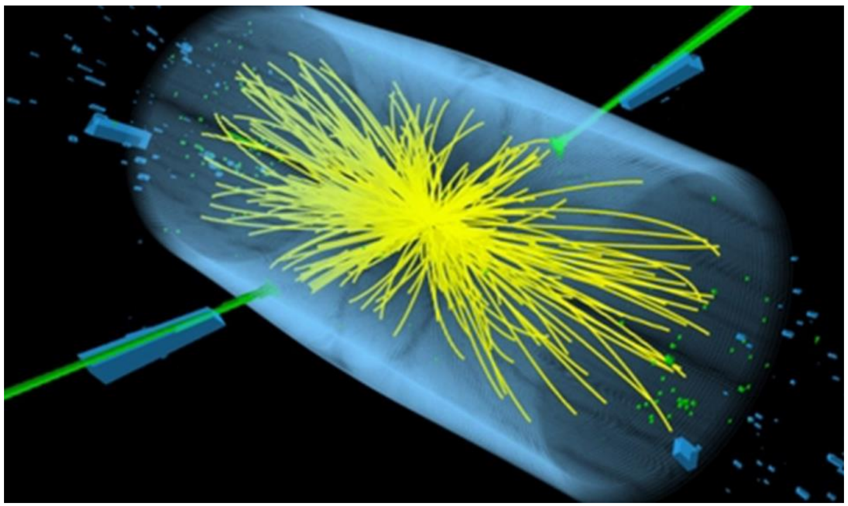


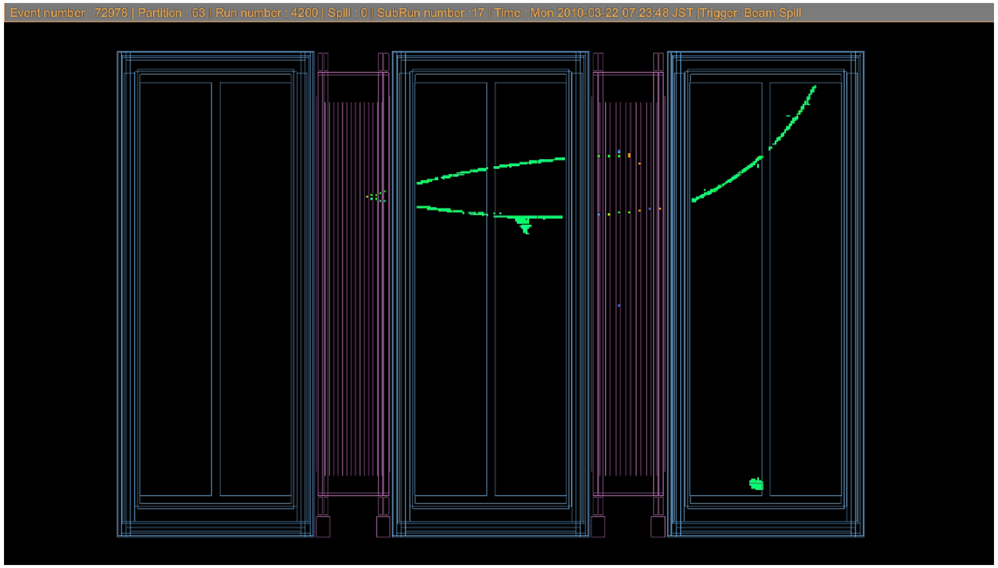


Observed rate: flux ⊗ cross-section

Each uncertain at the >10% level!

A confession of naïveté

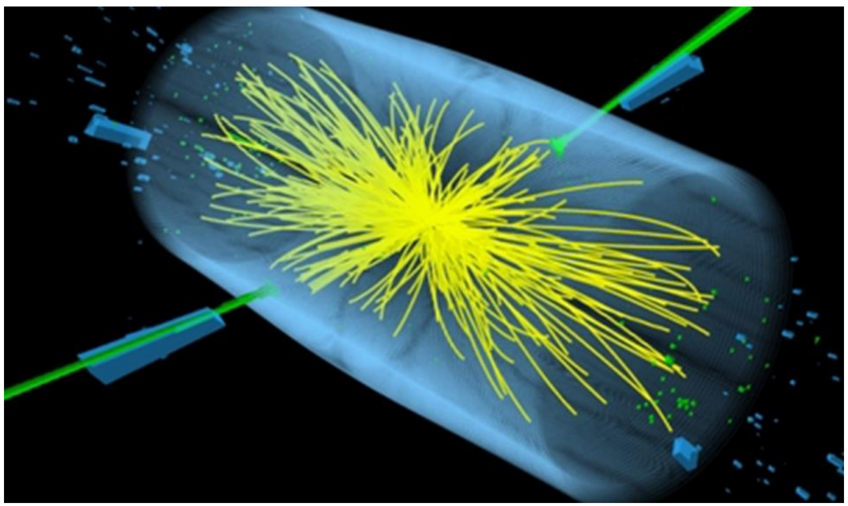


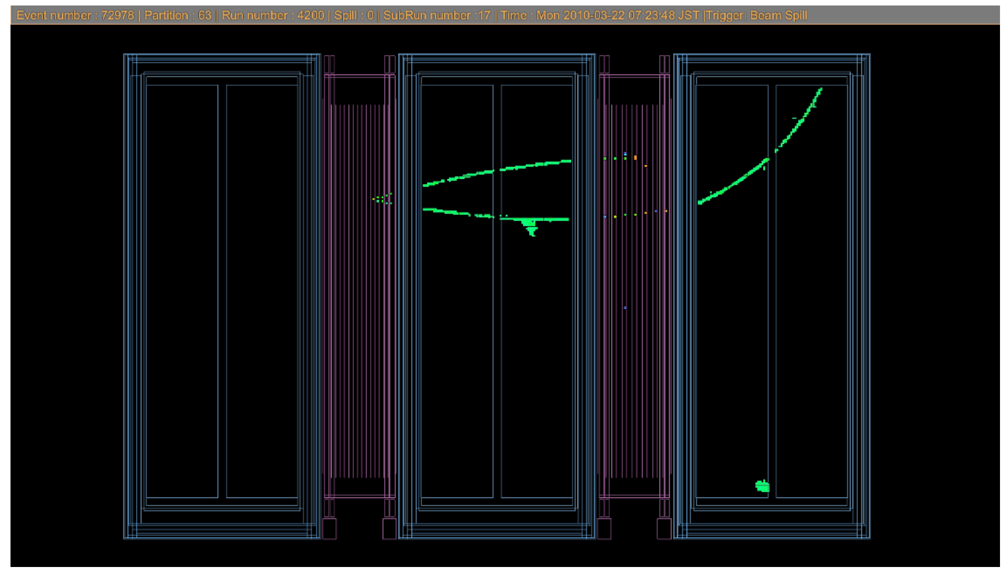


LHC event: scary!

“Simple” CC ν_μ event

A confession of naïveté



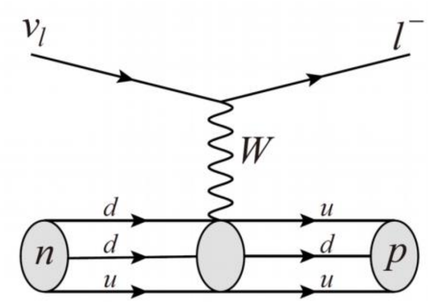


Surprisingly calculable:
asymptotic freedom
is a thing

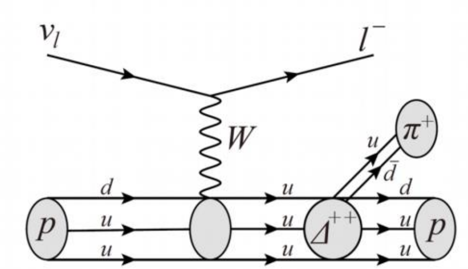
Shockingly hard to
calculate precisely:
messy nuclear physics

Neutrino interactions at 1 GeV

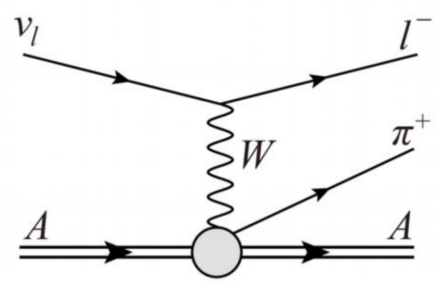
- Multiple interaction channels
- Detectors often cannot resolve all of the hadrons
- Nucleons are not at rest inside nucleus – affects kinematics
- Multi-nucleon correlations: maybe 20% of the time neutrino scatters off a pair of correlated nucleons, affecting energy reconstruction.



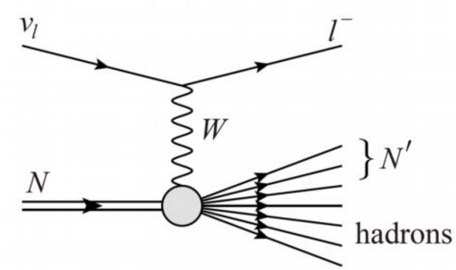
Charged-current quasielastic



Resonant Pion Production (CC 1π)

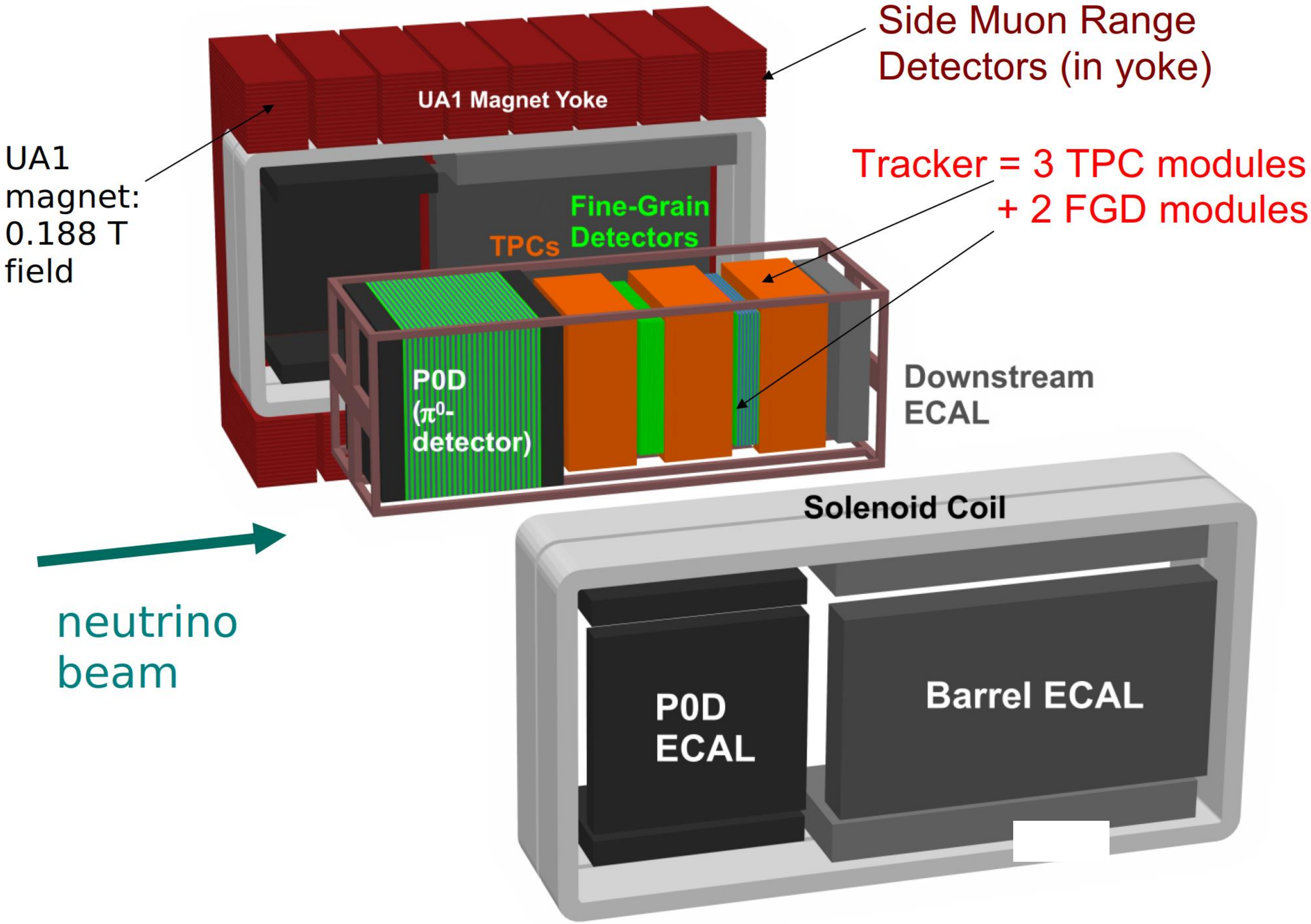


Coherent

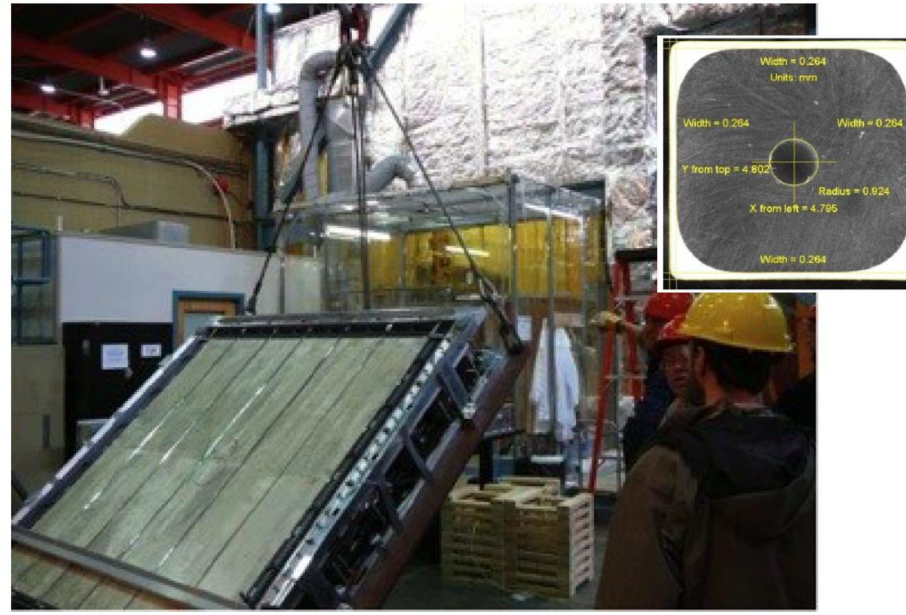


Deep Inelastic Scattering

Off Axis Near Detector

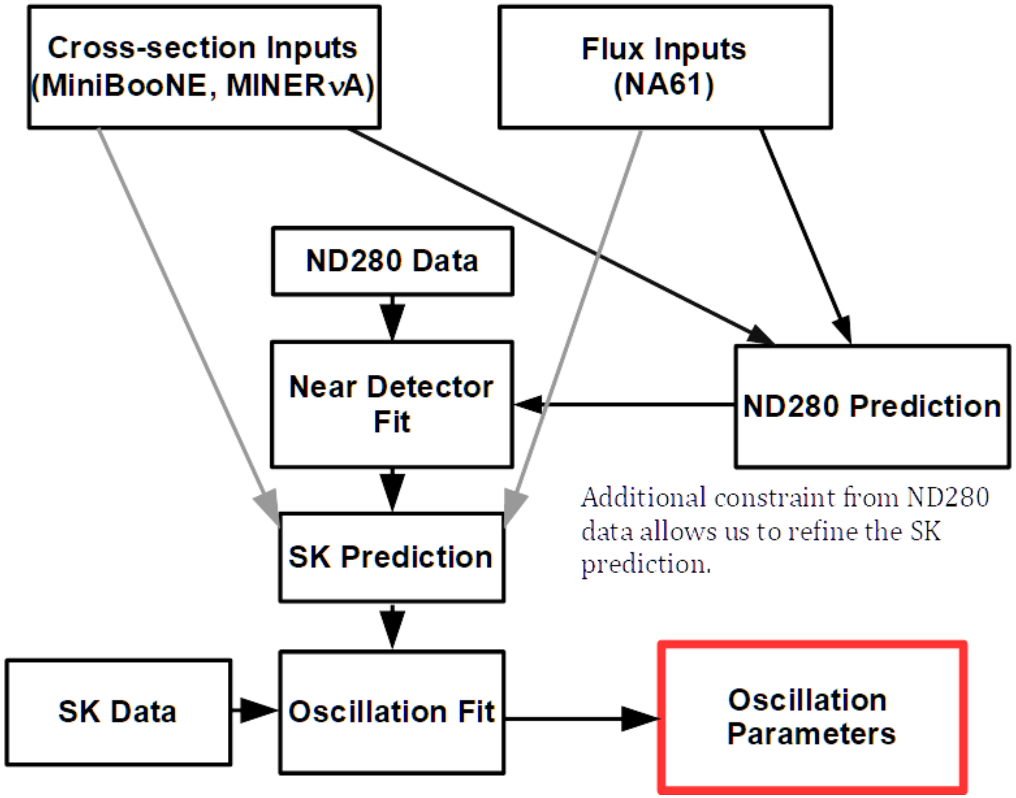


The Fine-Grained Detectors



Tonne-scale detectors made of 1 cm x 1cm long bars of extruded scintillator.

Designed and built at TRIUMF.

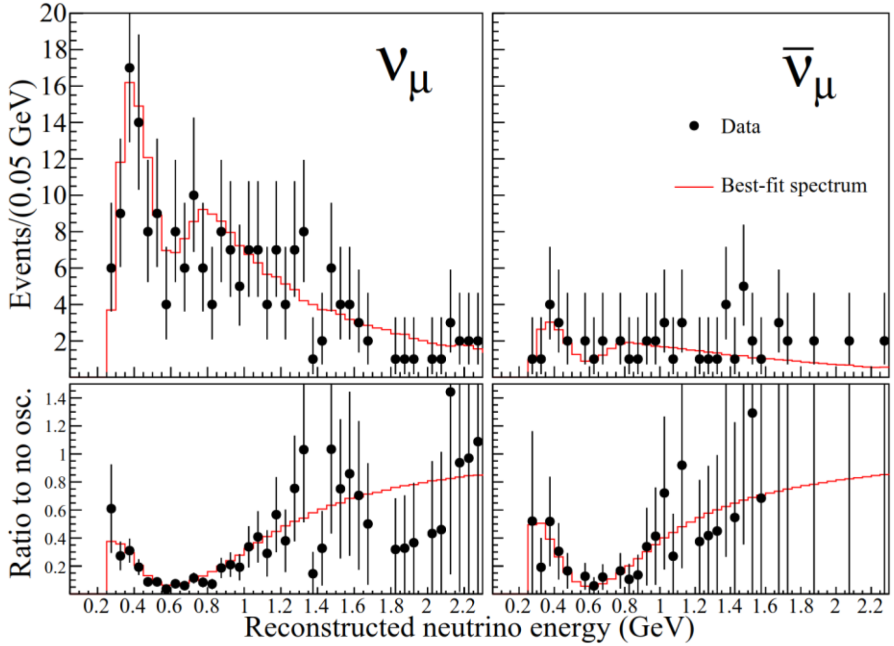


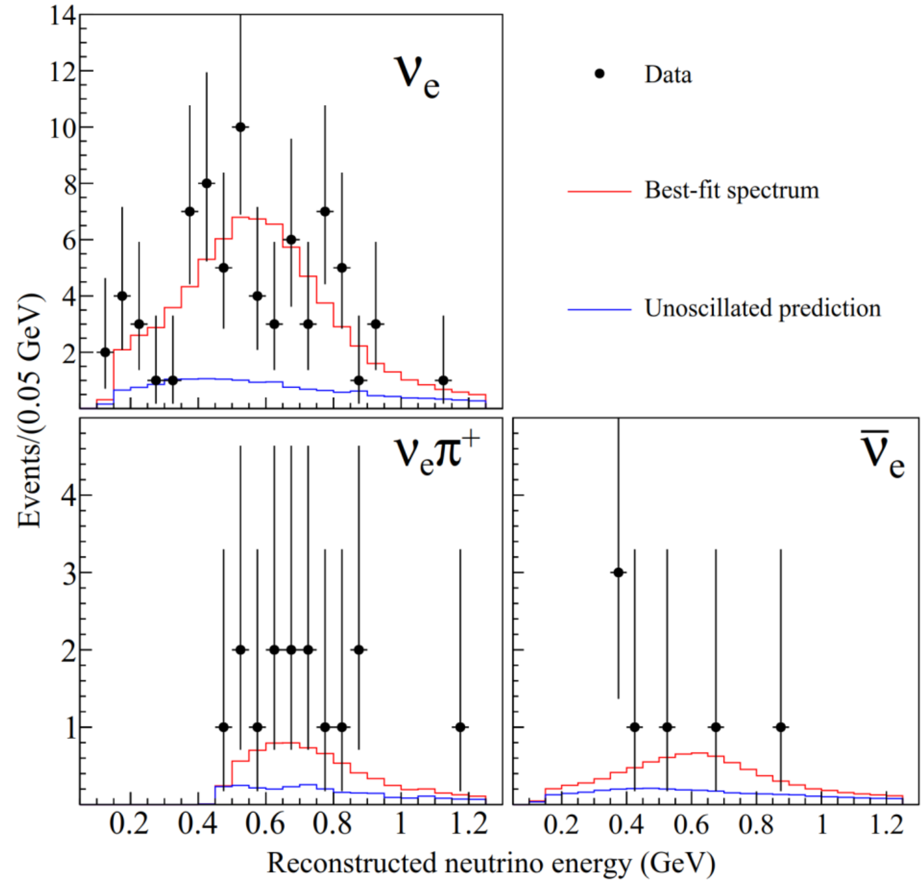
Distributions at far detector depend on beam flux parameters $\vec{b}$, cross section parameters $\vec{x}$, detector parameters $\vec{d}$.

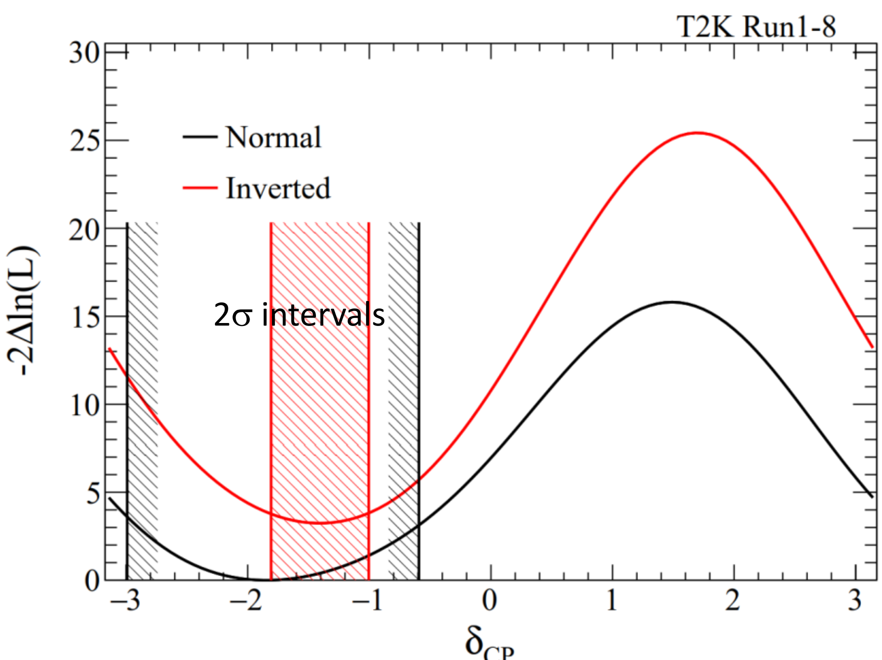
ND likelihood fit constrains these parameters, reducing uncertainties from ~10% level to few % level.

Canadian-led effort to develop this analysis infrastructure, and ND samples to provide constraints

$$L^r_{ND280} = \frac{\pi(\vec{b})\pi(\vec{x})\pi(\vec{d})\prod_i [N_i^p(\vec{b},\vec{x},\vec{d})]^{N_i^d} e^{-N_i^p(\vec{b},\vec{x},\vec{d})} / N_i^d!}{\pi(\vec{b}_{nom})\pi(\vec{x}_{nom})\pi(\vec{d}_{nom})\prod_i [N_i^d]^{N_i^d} e^{-N_i^d} / N_i^d!}$$



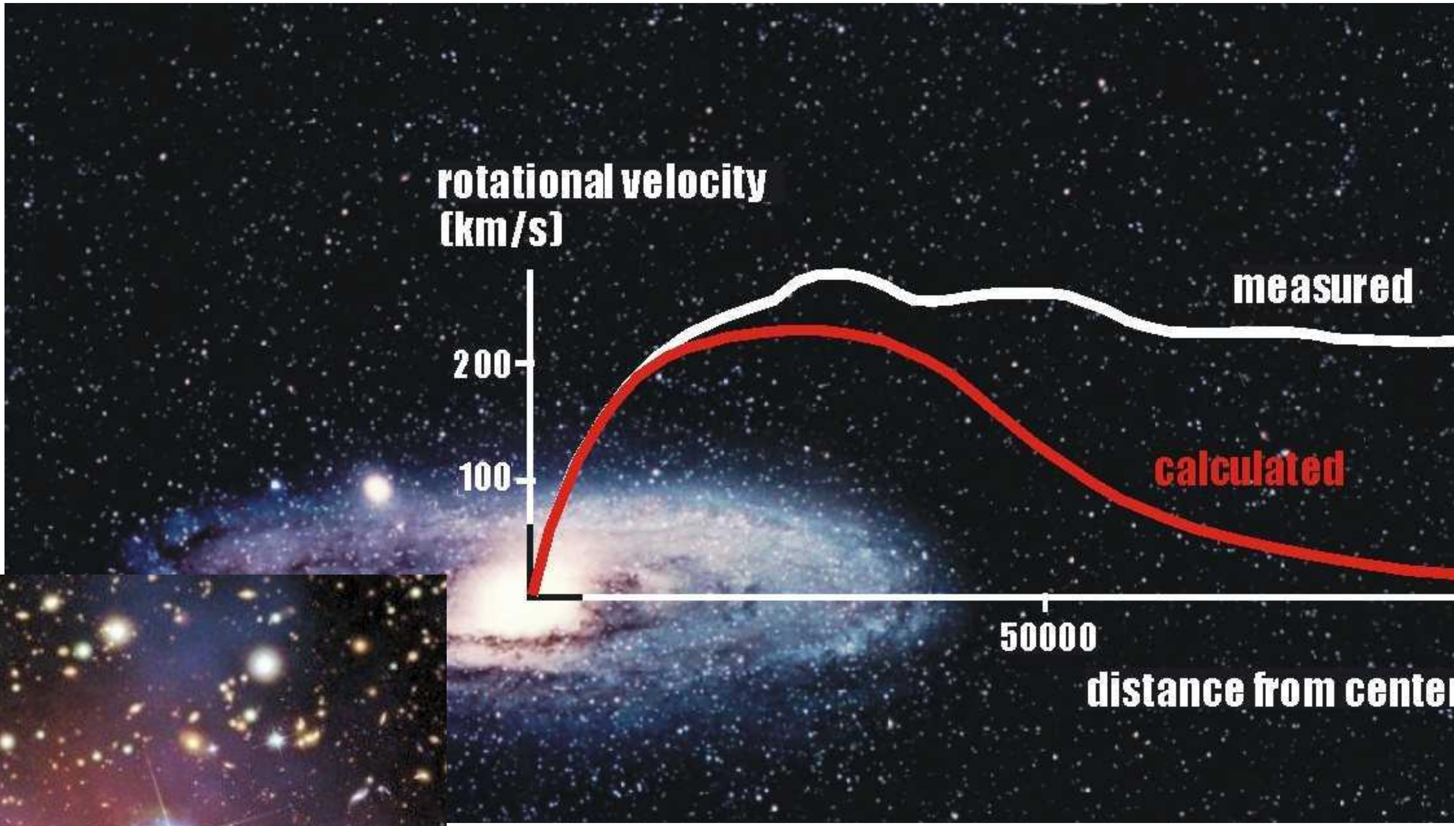




T2K Physics Highlights

PRL 121, 171802 (2018)

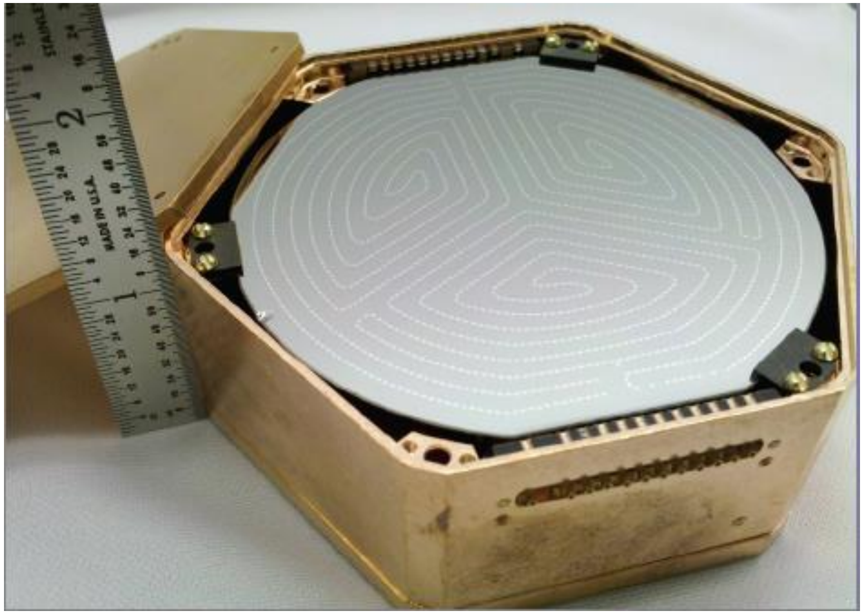
Evidence for Dark Matter



Gravitational effects amply confirm dark matter hypothesis.

Recent discovery of galaxy with no dark matter ironically strengthens case that dark matter exists!

SuperCDMS technology



Cryogenic semiconducting crystals (Ge or Si), with phonon and ionization sensors

Heat capacity ∝ T^3:
T ~ 10's of mK makes crystal heating easy to see

Nuclear recoils by WIMPs create phonon excitations (vibrations) in crystal. Ionization creates electron/hole pairs in crystal in proportion to energy and to yield factor *Y*:

$$N_{e/h} = \frac{YE_r}{\epsilon}$$

$$\begin{aligned} E_{phonon} &= E_r + N_{e/h} V_{bias} e \\ &= E_r \left(1 + Y \frac{V_{bias} e}{\epsilon}\right) \end{aligned}$$

DAQ & Trigger

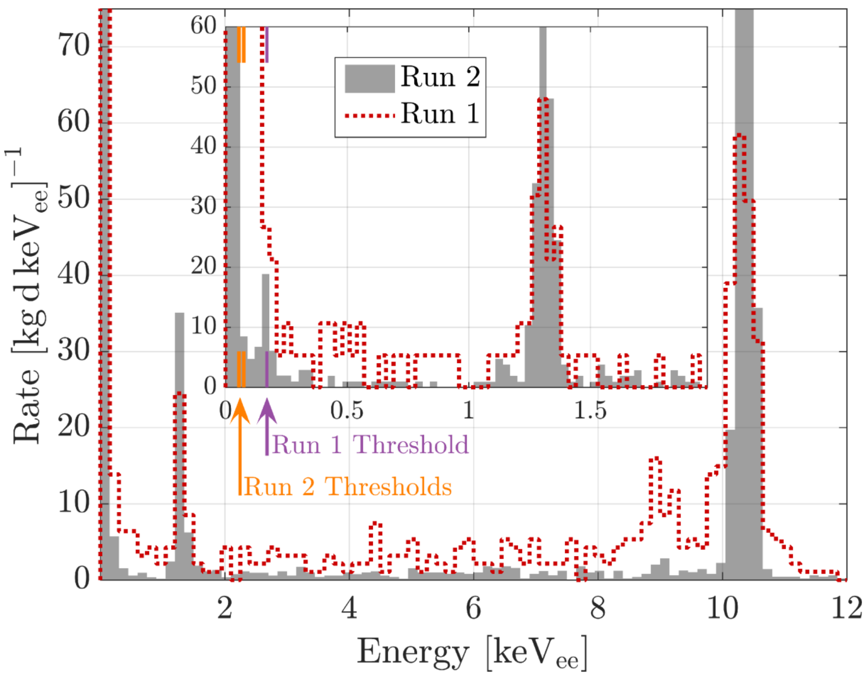
- If you don’t know what else you can do, push bytes around

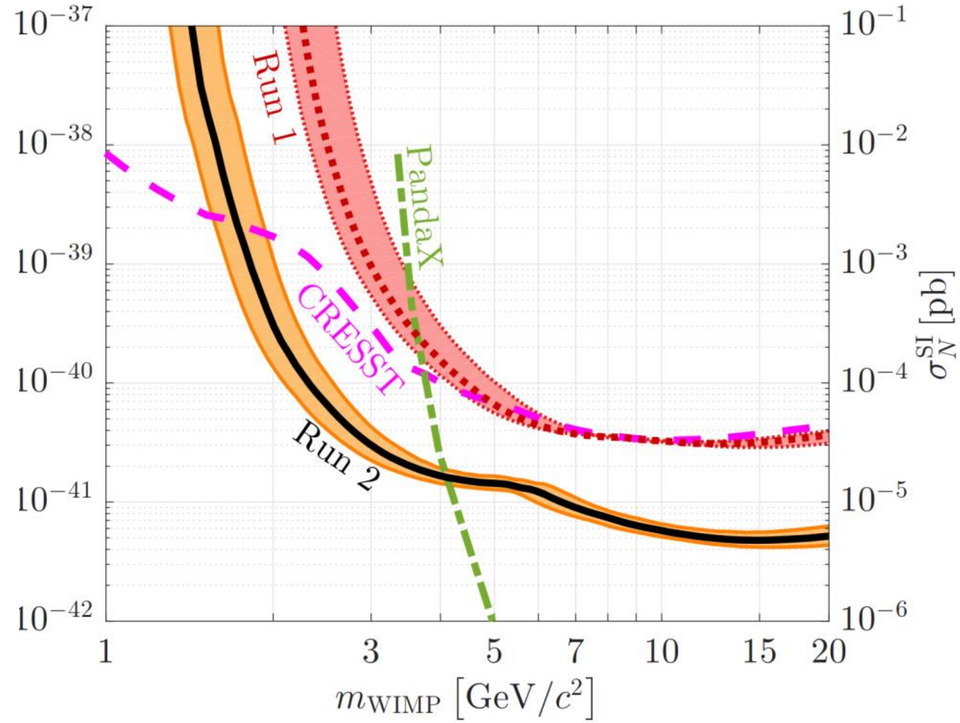
```
  //  printf ("Reading waveform %d\n", DCRCchannel);

  WORD lowerbits = (startpoint & 0xffff);
  WORD upperbits = (startpoint & 0xffff0000) >> 16;
#ifdef REVC
  // To avoid the emulated upper bits from causing any problem, mask them out
  upperbits = (upperbits & 0x3f);
#endif
  // Must always read an even number of samples, since RDB returns 32-bit words
  // If an odd number is requested, we read one more sample, and discard it
  int samples_to_read = int((samples+1)/2)*2;
  int bytes_to_read = samples_to_read*2;

   // Return -1 if the charge or phonon DCRCchannel is out of range
```

- I wrote all of the original code myself. As on T2K, my code worked perfectly, but I had to hire others to rewrite it to the point that I can’t recognize it.

Previous CDMS results

First published results from detectors run at ~70V to achieve low energy thresholds:



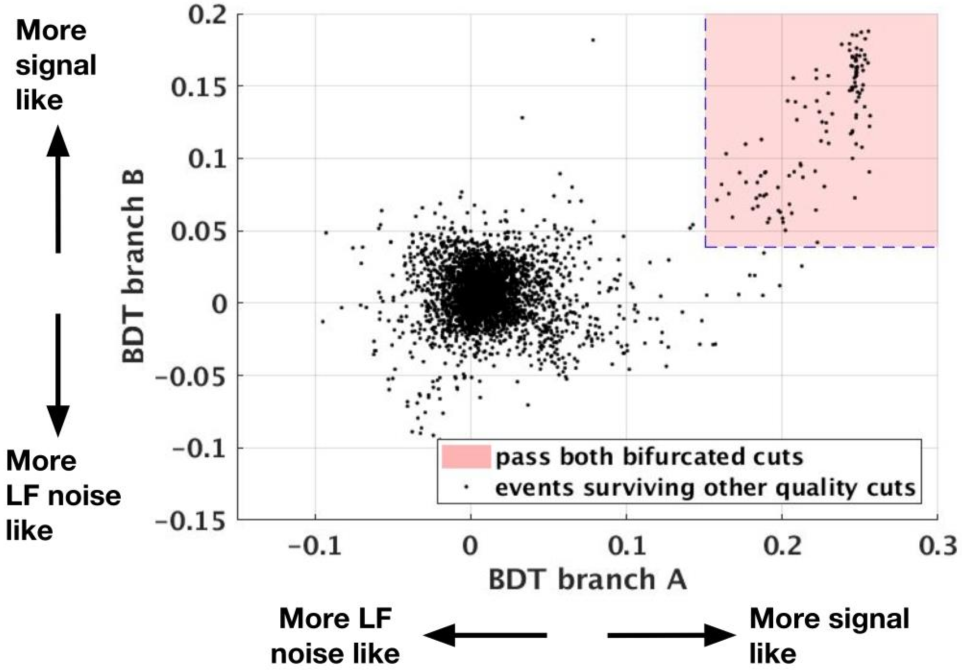


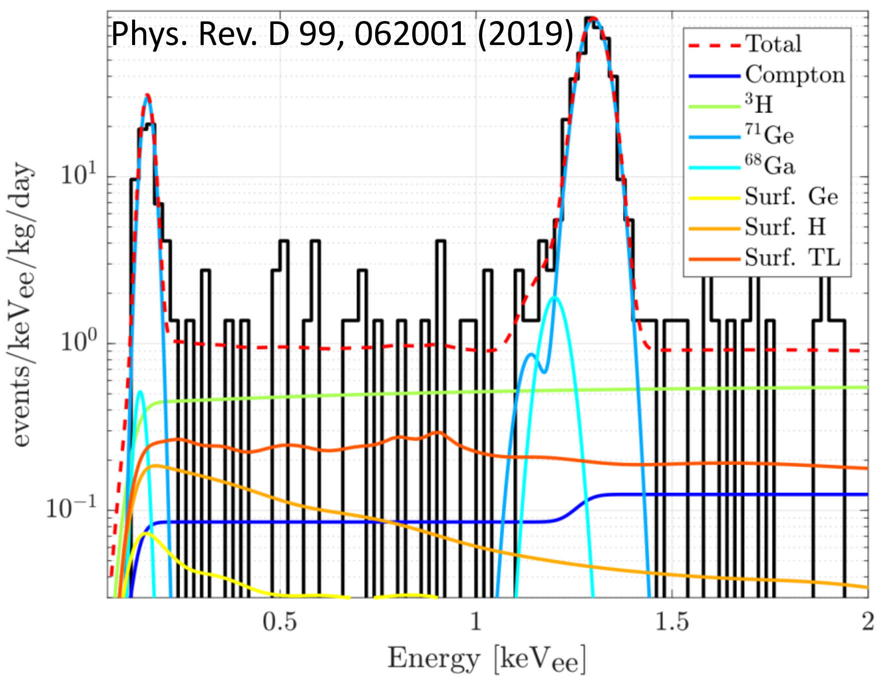
But some significant limitations:

- Significant backgrounds from detector mechanical vibrations
- All events treated as potential signal: set conservative limits with optimal interval method with no background subtraction

Phys. Rev. D 97, 022002 (2018)

CDMSlite Run 3 result



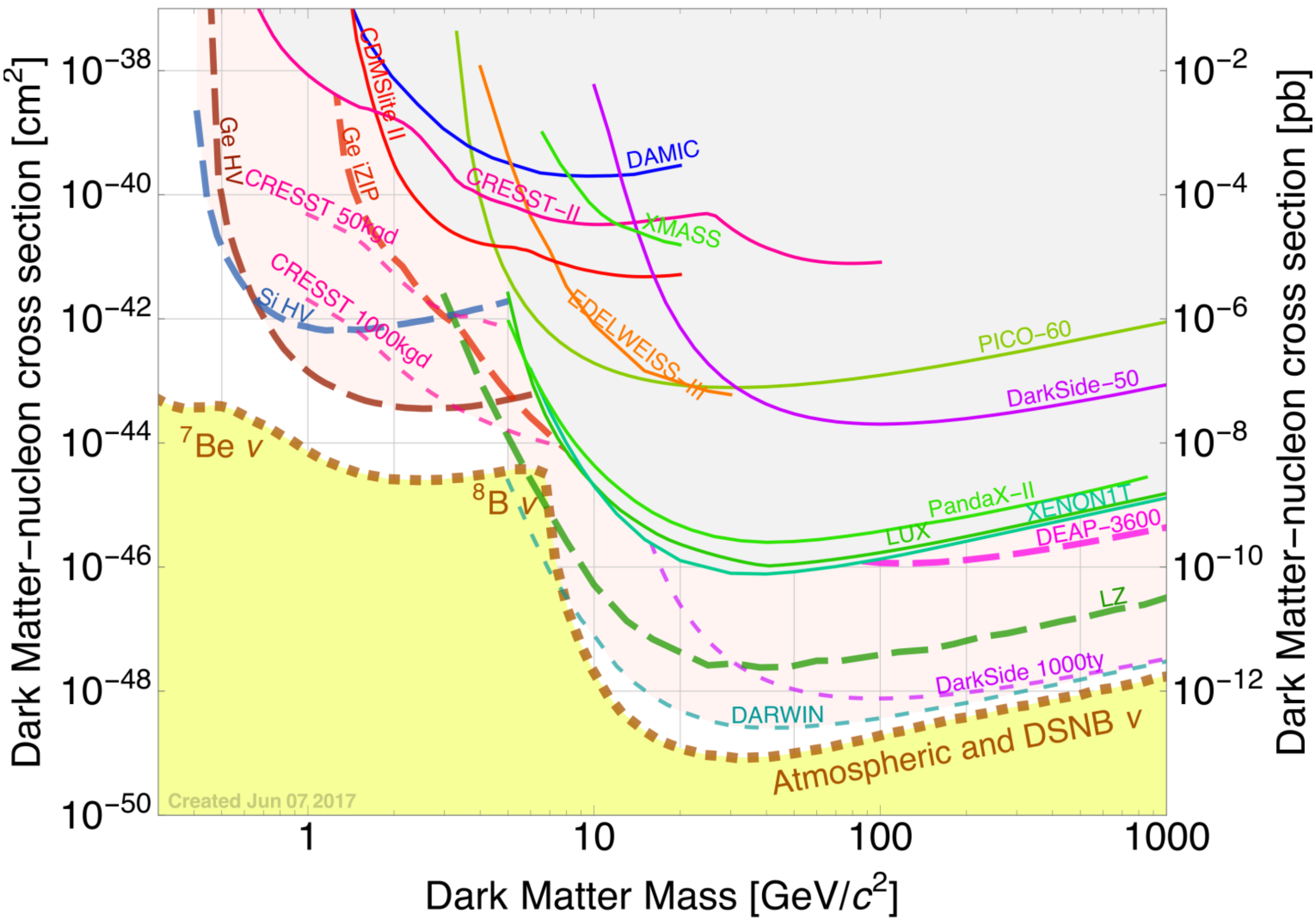


My student Bill Page and I tried some tricks we learned from SNO:

- New Boosted Decision Tree cuts to remove instrumental backgrounds such as triggers from vibrations, with SNO-style bifurcated analysis for measuring remaining contamination.
- Full likelihood fit of WIMP signal + background model to extract limit

Factor of three improvement in sensitivity!

SuperCDMS outlook



SuperCDMS will have world-leading sensitivity to WIMP-nucleon scattering in the ~0.5-5 GeV/c^2 mass range

Scorecard

	SNO	T2K	SuperCDMS
Relevant Energy Scale	2-20 MeV	0.3-3 GeV	1 eV – 100 keV
Signal Modelling	Straightforward	Deceptively complex due to nuclear effects	Straightforward but model dependent
Backgrounds	Mostly below signal energy region	From mis-reconstruction of particle content	Pervasive at lowest energies, often can be modelled
Detector response	Well understood	Well understood	Uncertain at lower energy scales
Statistical approach	Sophisticated	Sophisticated	Sophisticated
Thanks for recruiting me to:	G. Beier, C. Waltham, R. Helmer	A. Konaka	W. Rau

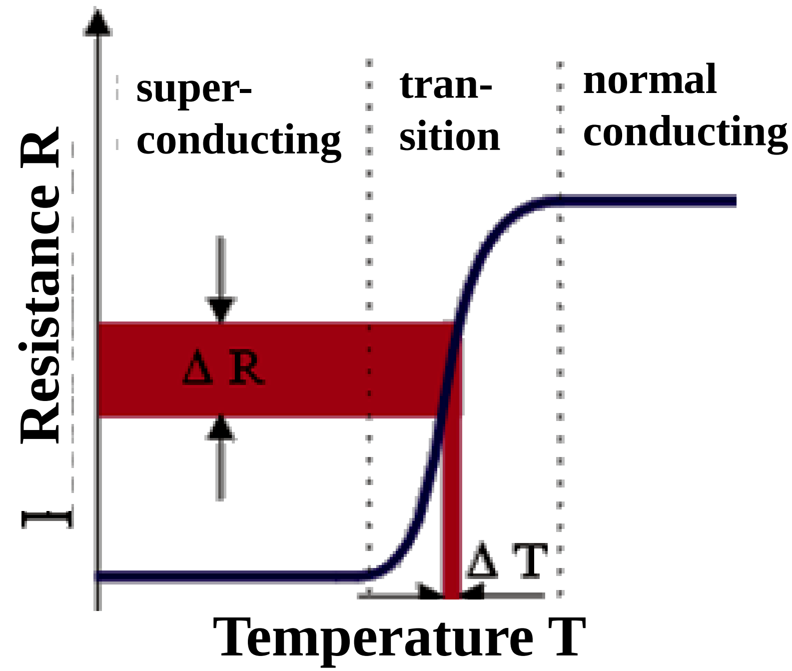
Conclusions

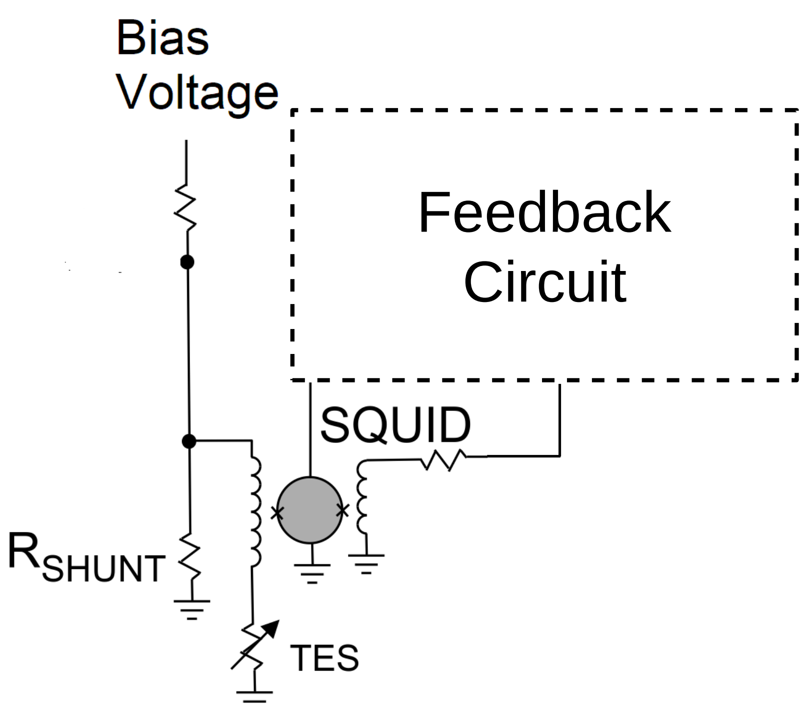
- I feel truly honoured to receive the CAP-TRIUMF Vogt Medal
- Much thanks to the UBC Department of Physics & Astronomy, and to TRIUMF, for steadfast support through all of these projects
- Thanks to all of you and as well to the Canadian Association of Physicists for this award

Backup slides

Phonon sensors

Thin Al fins on the crystal surface absorb phonon energy and carry it to a thin tungsten film that is operated in transition between its normal and superconducting state: a **Transition Edge Sensor (TES)**

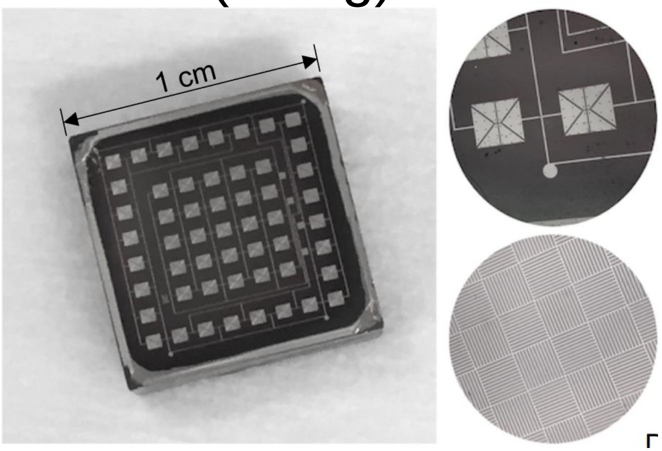


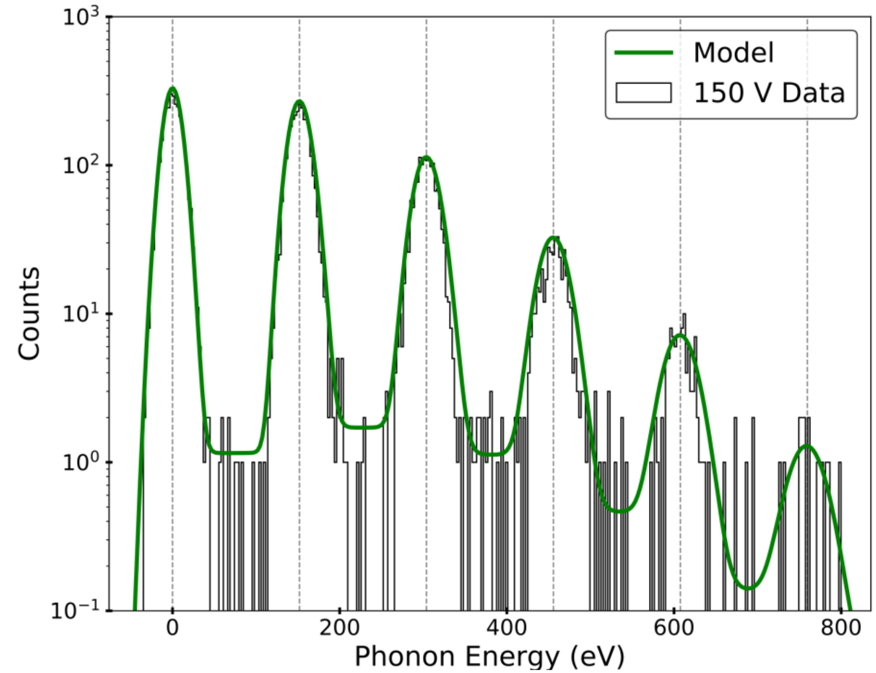


Changing TES resistance varies magnetic flux through SQUID. Feedback circuit adjusts current through a second inductor to compen-sate, and we measure that current.

Phonon detectors sensitive to single electron/hole excitations

Si prototype detector
(0.93g)





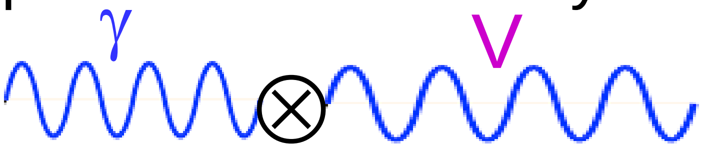
Clearly count single excitations in phonon signal through Neganov-Luke gain!

Electron recoils will dominantly occur only in peaks, while nuclear recoils, with much higher ratio of direct phonon to ionization yield, will fill in the valleys

Dark photons

Suppose a hidden sector contains particles with a U(1) gauge symmetry. The resulting "dark photon" will have the same quantum numbers as a photon. If the gauge symmetry is broken it may be massive.

This massive dark photon can kinetically mix with the SM photon:

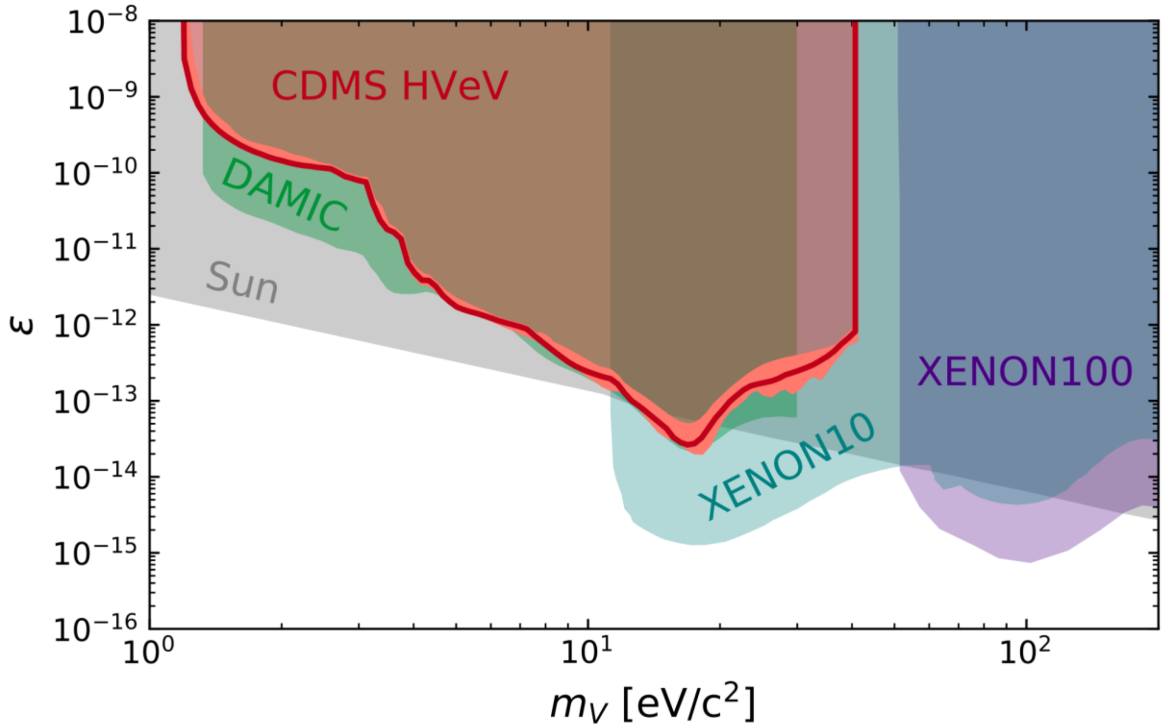


A dark photon interacting in our detectors can produce a "dark photoelectric" absorption, resulting in the production of one or more electron/hole pairs. The absorbed energy is the dark photon mass.

Search is sensitive down to masses given by the Si bandgap (few eV/c^2)!

Dark photon limits

$$R = V_{Det}\frac{\rho_{DM}}{m_V}\varepsilon_{eff}^2(m_V,\sigma)\sigma_1(m_V)$$



Competitive limits from just 0.49 g▪days of exposure from a test device

Mass sensitivity down to just above 1 eV!

https://arxiv.org/abs/1804.10697