Expeditions to the Next Energy Scale

...a vision for some (but not all) future particle physics experiments at LBNL...

John Ross' expedition to the magnetic north pole relaxing at Felix Harbor (circa 1833).
Photo by Hulton Archive/Getty Images, downloaded from answers.com

Victor M. Gehman

RPM Seminar

Lawrence Berkeley National Laboratory

Berkeley, CA

February 13, 2014

Outline

- The show so far: the Standard Model works really well, but...
- Go big, go deep!
- A view of the next ten years of dark matter searches...
  - The case for LBNE
  - What else can you do with something like the LBNE far detector?
  - The technical challenges that tie all this together
  - Conclusions and perspectives

Lewis and Clark on the Lower Columbia
Charles Marion Russell, 1905

Where do we stand?

- It looks like “we’ve” discovered the Higgs!
- It also looks like the Higgs from the standard model
- Physics has been chasing the Higgs at this energy scale since 1933!
- We now have a *complete* theory of the electromagnetic, weak, and strong forces.

news.slac.stanford.edu/features/cern-experiments-observe-particle-consistent-long-sought-higgs-boson

Current Status:

$m_H = 125.9 \pm 0.4$ GeV (PDG)

Significance $> 6\ \sigma$

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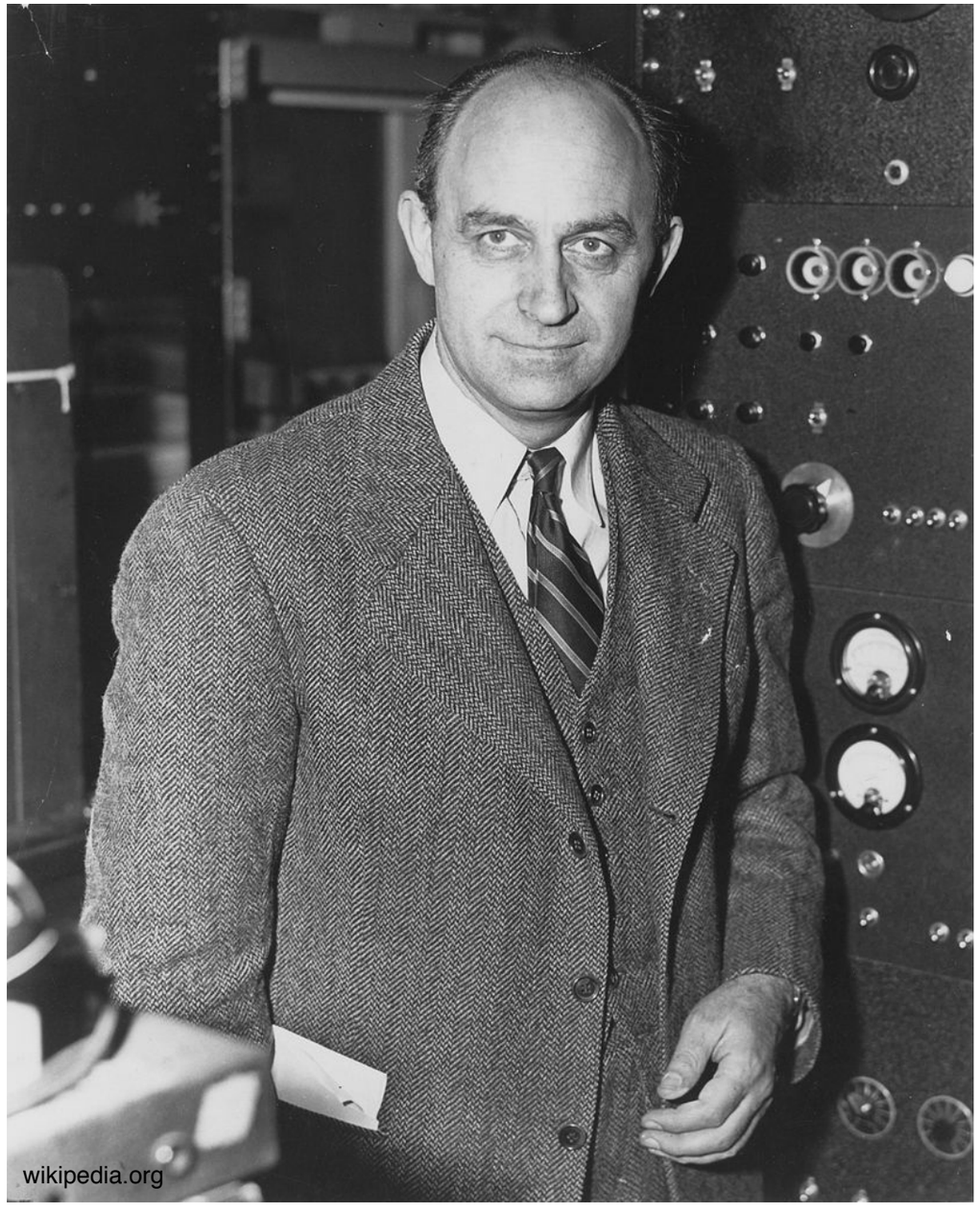
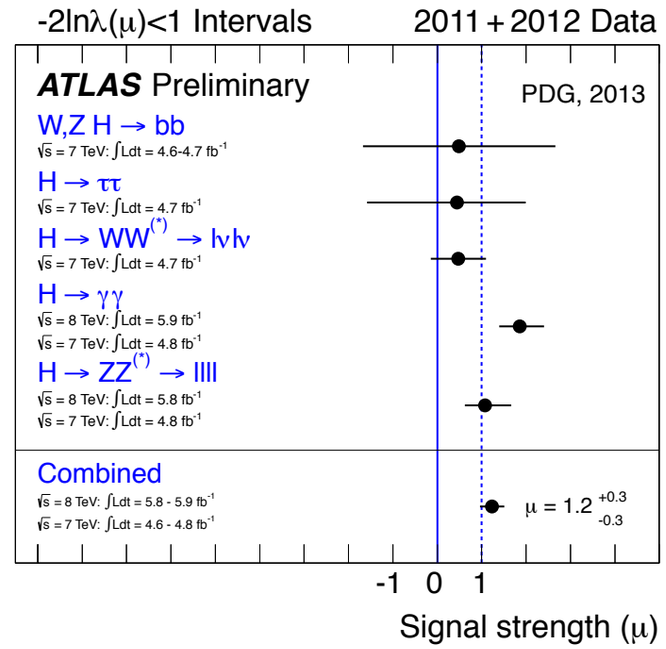


$$G_F = 10^{-5}\ m_p^{-2}$$

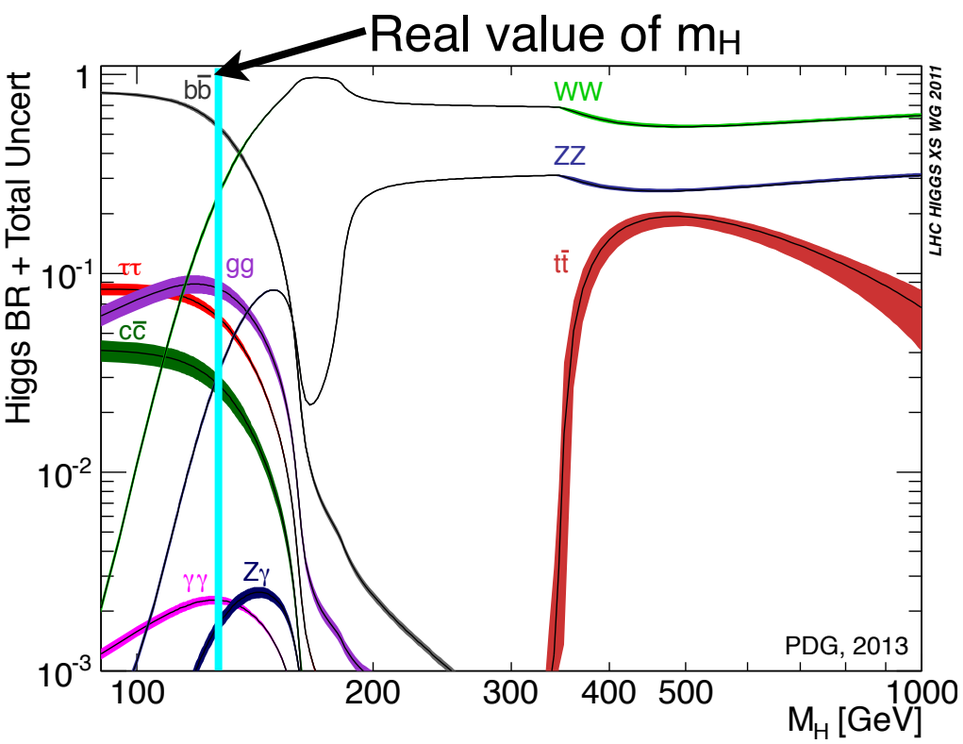
$$G_F^{-\frac{1}{2}} \approx 300\ \mathrm{GeV}$$

Just the Standard Model?

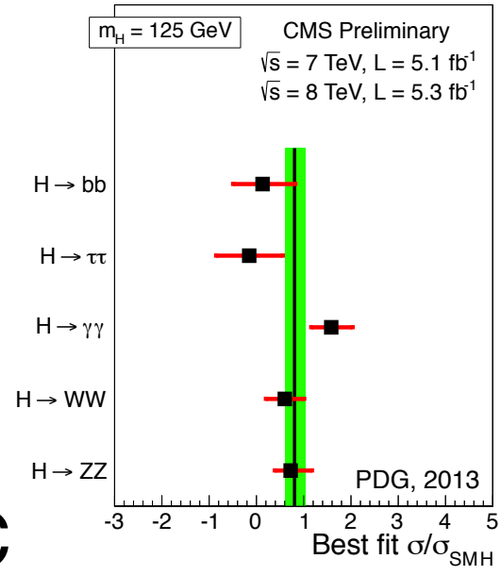
- The new scalar particle observed by ATLAS and CMS, really does look like the standard model Higgs...
  - It's the right energy scale,
  - It decays into the right things in the right proportions



- There also haven't been any hints of supersymmetry in ATLAS or CMS data.



- This does **NOT** mean that the energy frontier is dead!
  - Getting a factor of 2 in LHC energy soon,
  - There are a lot of precision measurements to be done at the the LHC as well as the ILC or something like it!



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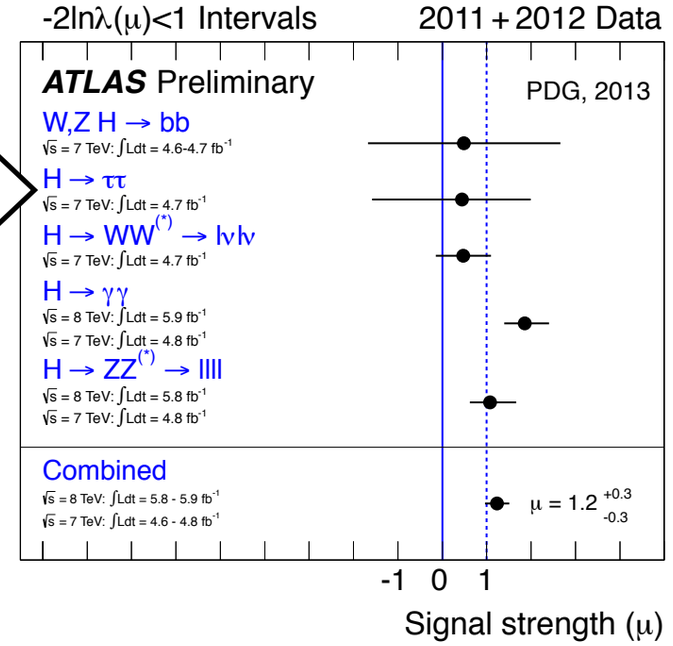
Now: $\mu = 1.4^{+0.5}_{-0.6}$
(2012 data)



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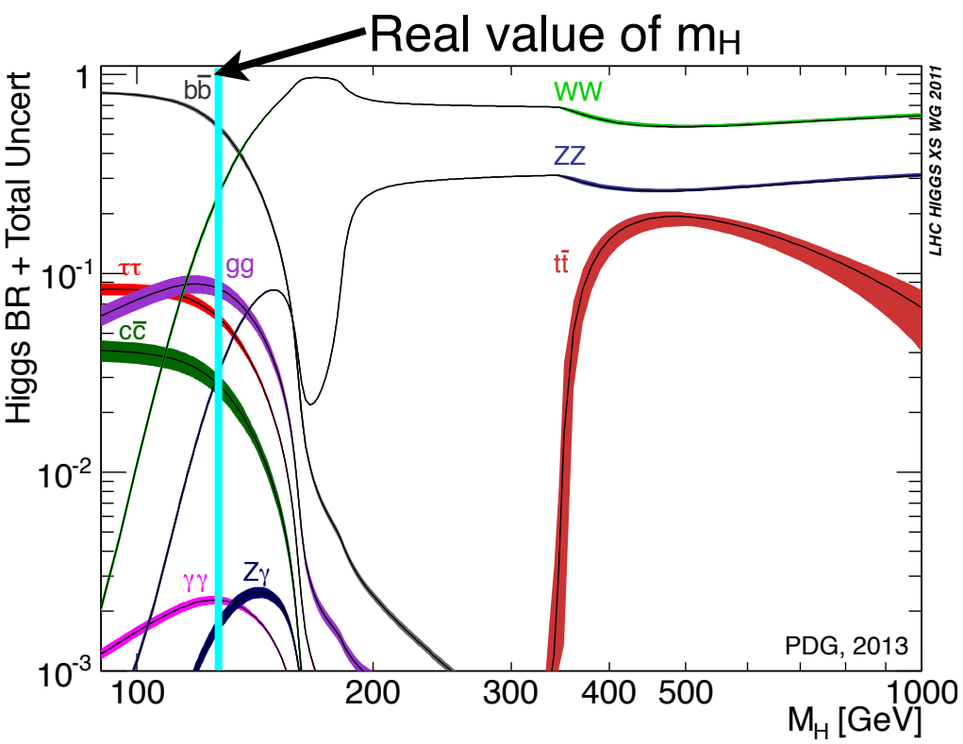

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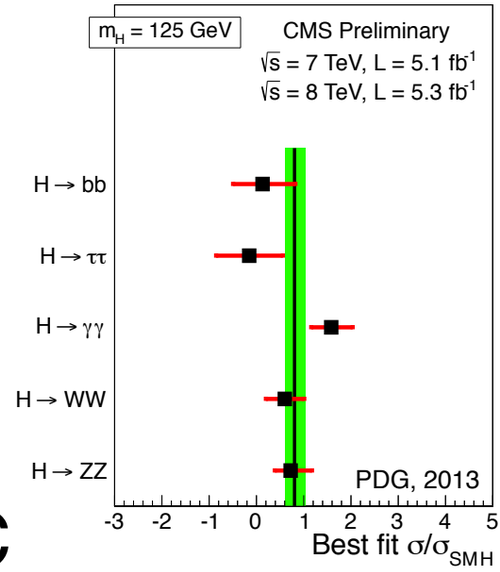

So, what do we do now?

- We have a prodigiously successful Standard Model, with no more free parameters to measure
- But, we also have several confirmed departures from the Standard Model:
  - Non-baryonic dark matter
  - Neutrino flavor oscillations
  - Baryon asymmetry
  - Accelerating Universe/dark energy
  - Inflation

These have something in common that I will talk about in a bit...

- The down side is that we don't know the energy scale that these departures are telling us to investigate!

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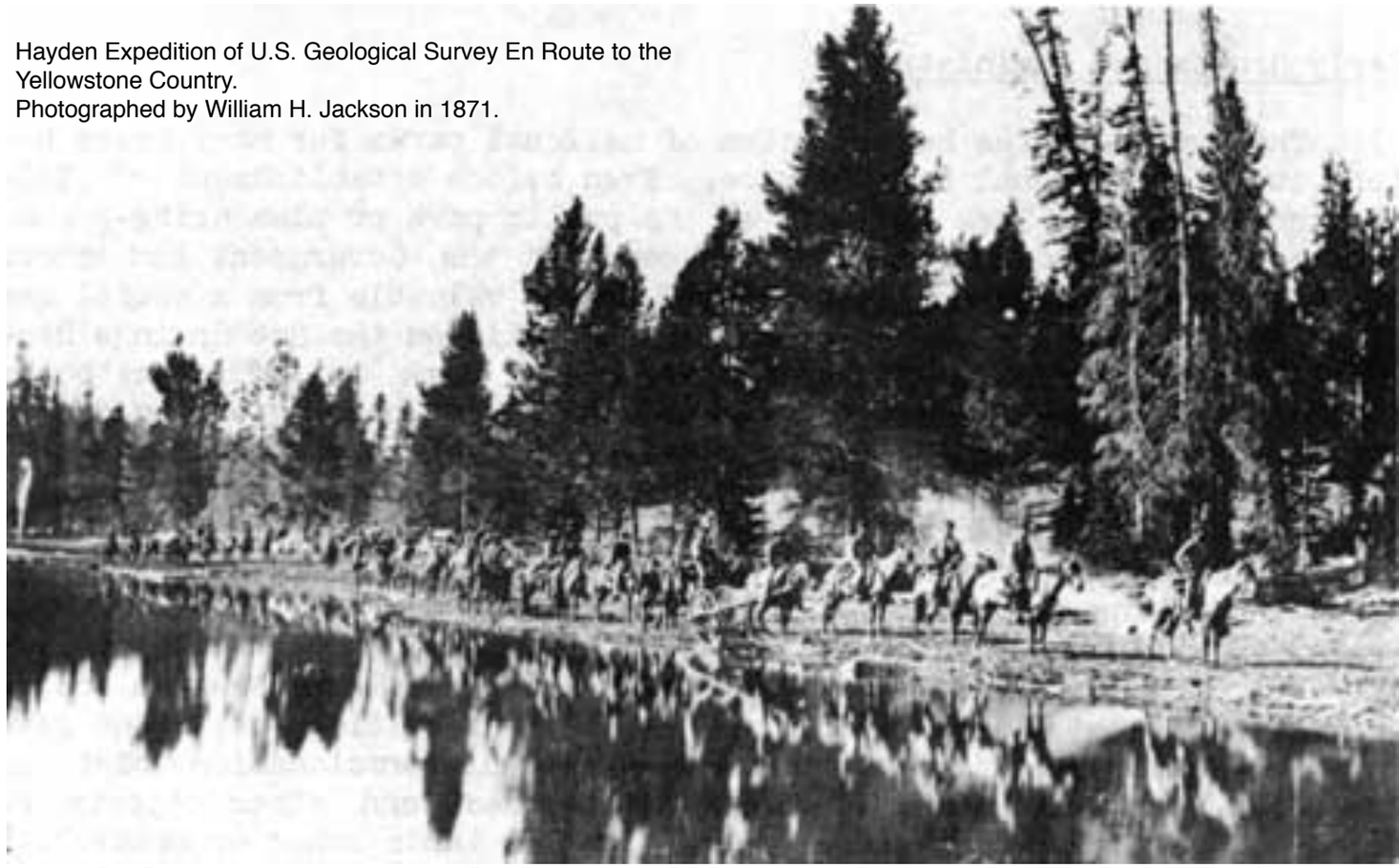
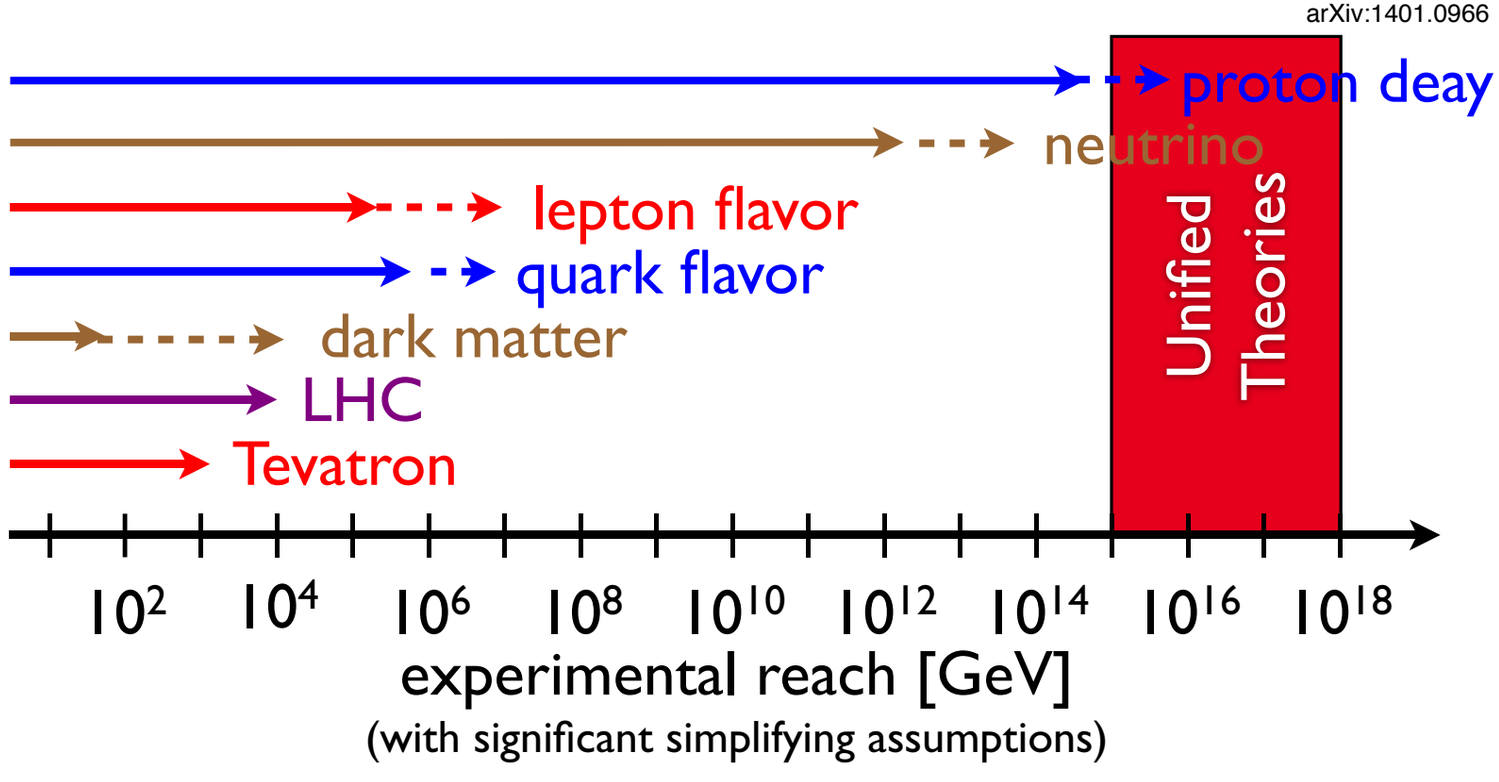


Hayden Expedition of U.S. Geological Survey En Route to the Yellowstone Country.
Photographed by William H. Jackson in 1871.

Expeditions to Higher Energies

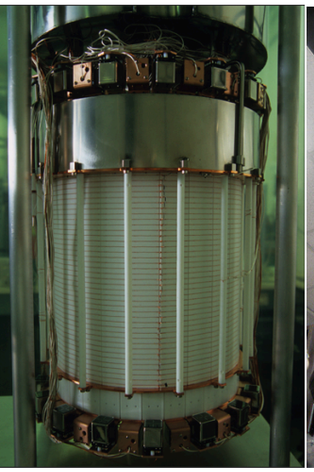
- Because we don't know the next energy scale to start studying in detail, we have to go on these expeditions looking for unified theories, based on the hints we already have
- *The good news:* lots of these expeditions can be undertaken with large, underground detectors!
- *The bad news:* building these detectors is going to be hard, expensive, and not guaranteed to pay off in the way we expect...



Big, Underground Detectors

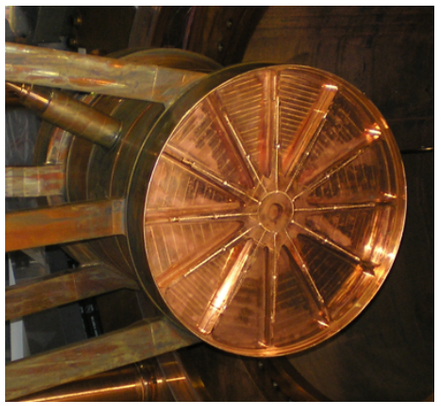
...especially noble gas-filled detectors!

XENON100

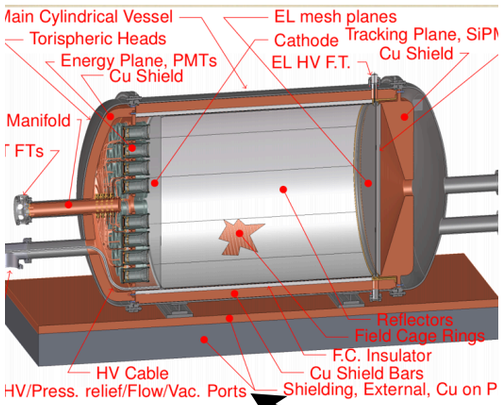


LUX

EXO



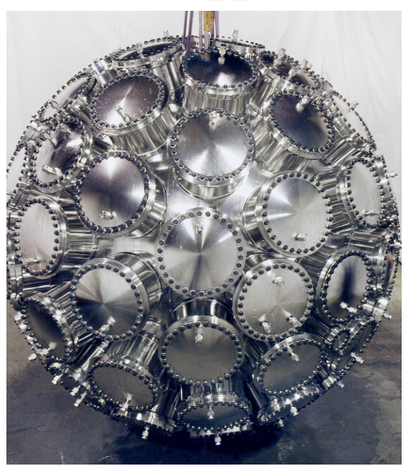
NEXT



XMASS

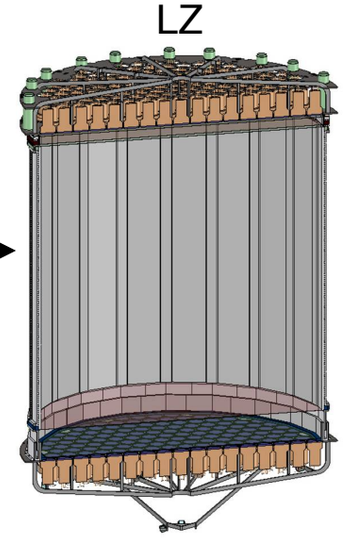
DEAP-3600

MiniCLEAN

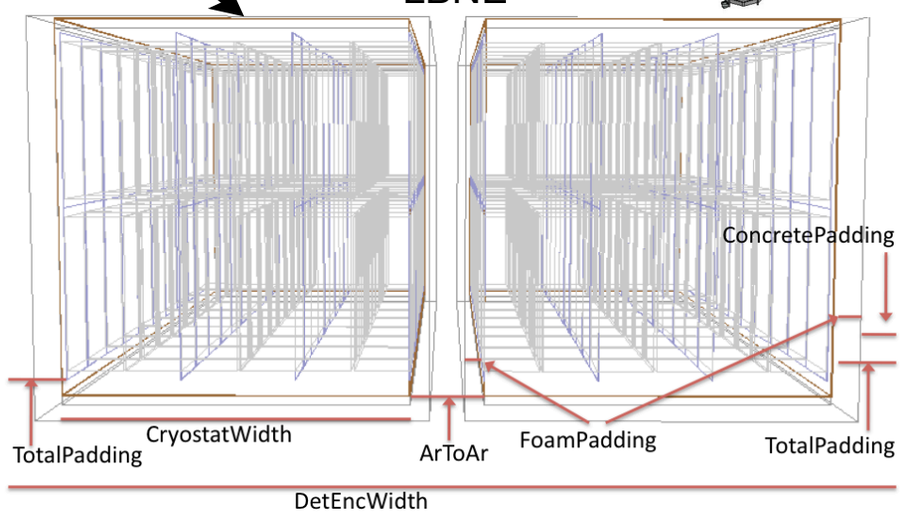


These have a particularly bright future at LBL!

LZ

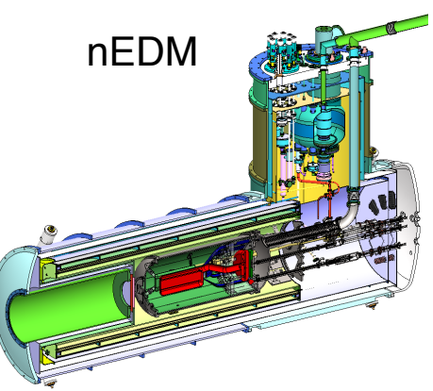


LBNE

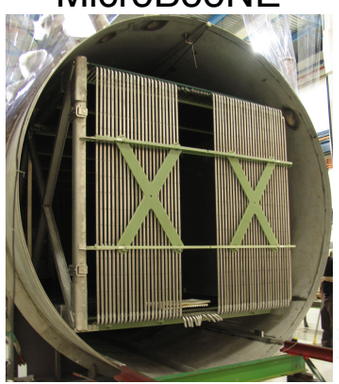


Noble gas detectors, but not underground

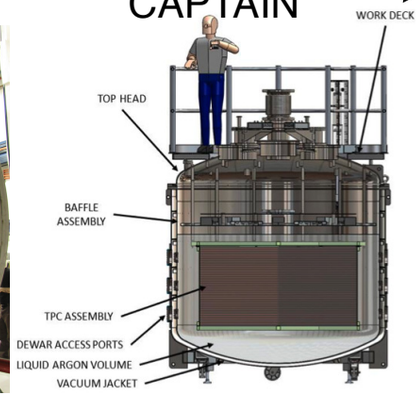
nEDM



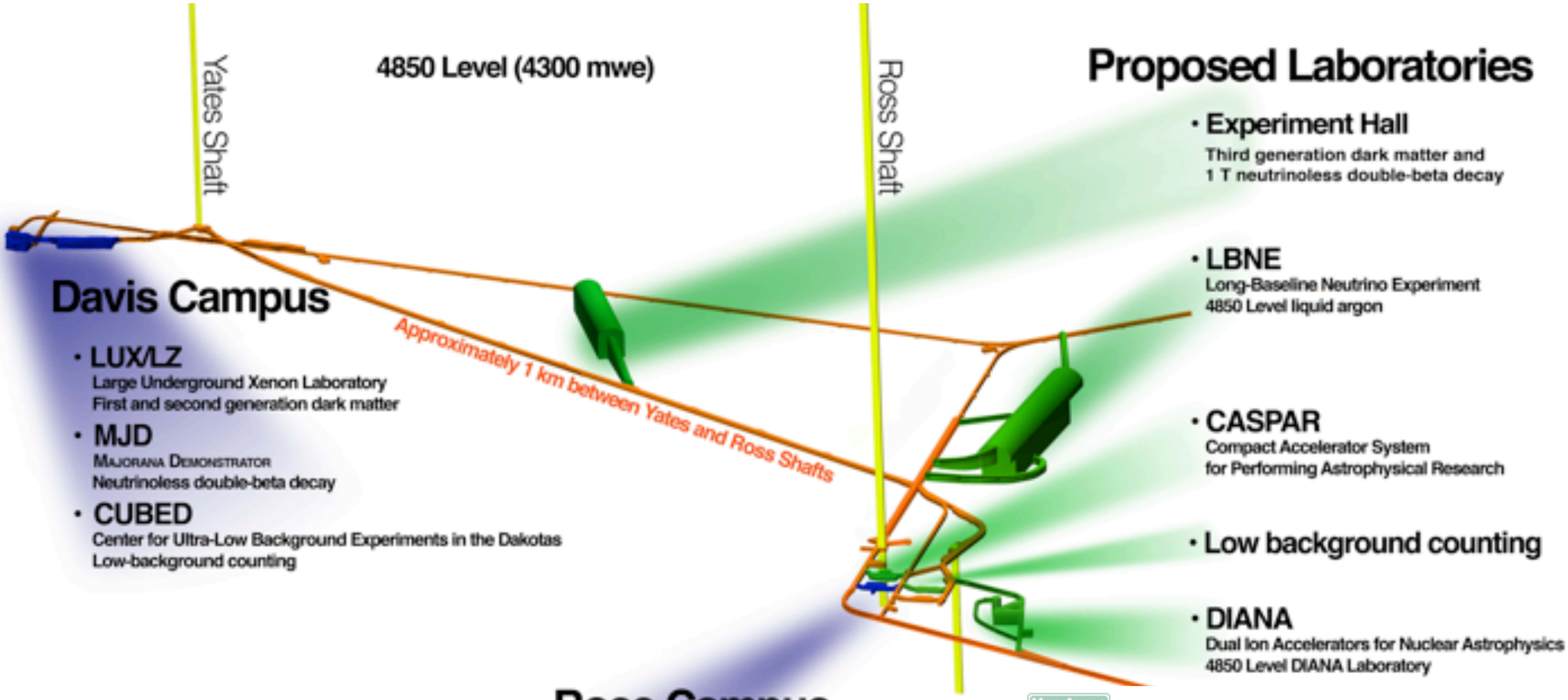
MicroBooNE



CAPTAIN



Hey, look! An Underground Lab!



The Sanford Underground Research Facility

Outline

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The Yale College Expedition of 1870 to Bridger Basin in southeastern Wyoming, with paleontologist O.C Marsh standing at center.
http://www.rockymountainpaleontology.com/

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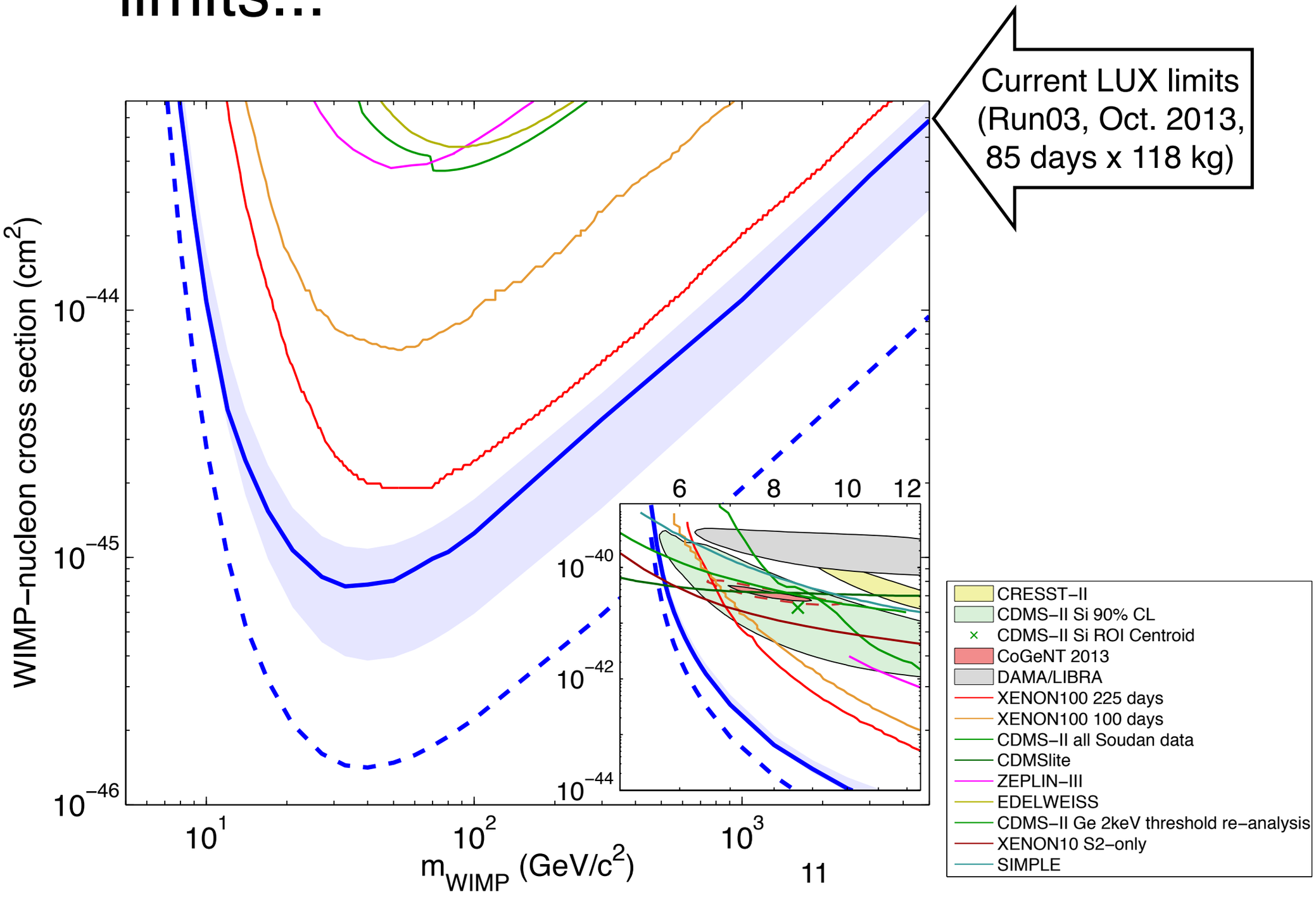
Dark Matter Searches: Now

- No dark matter yet, but increasingly stringent limits...



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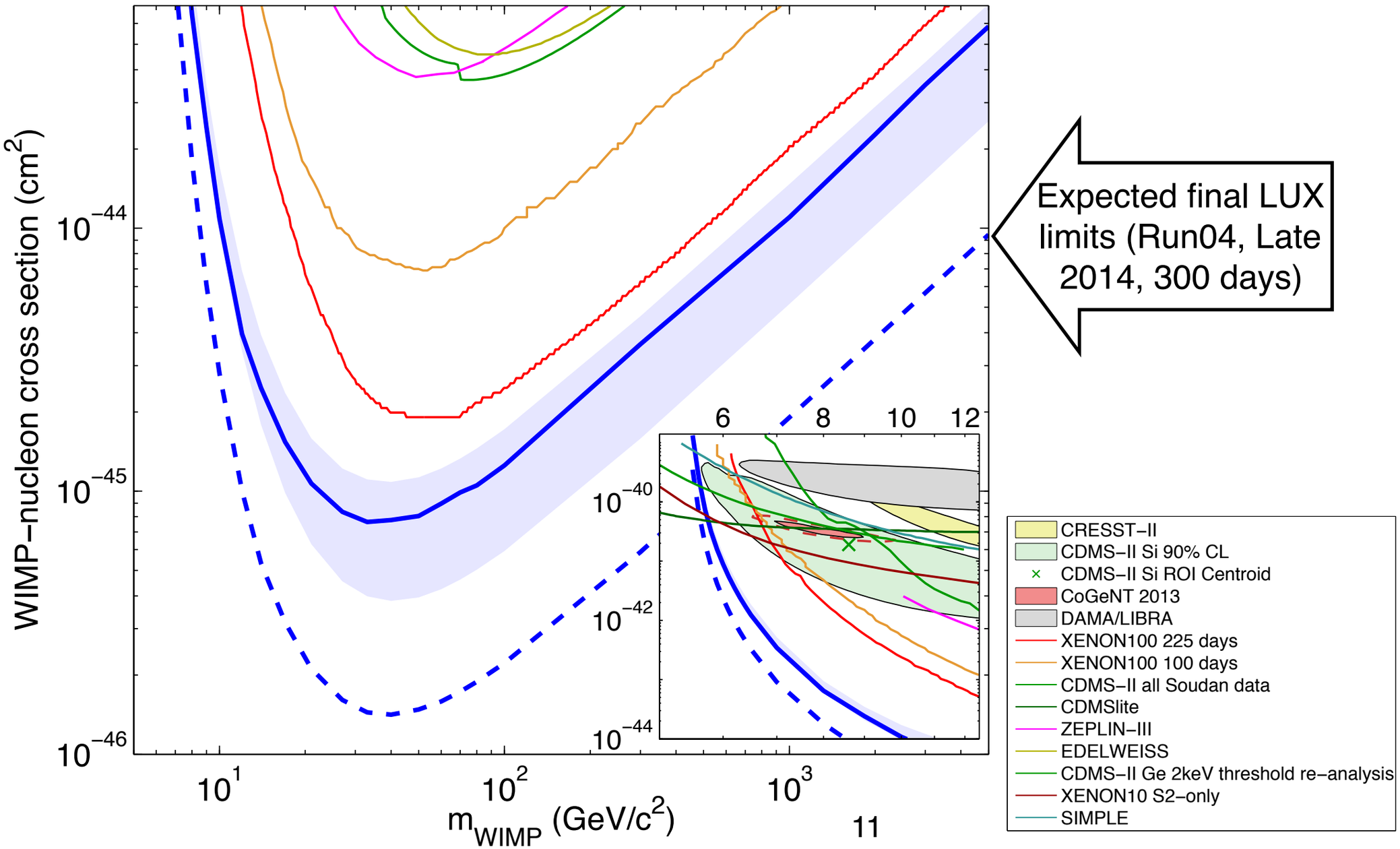

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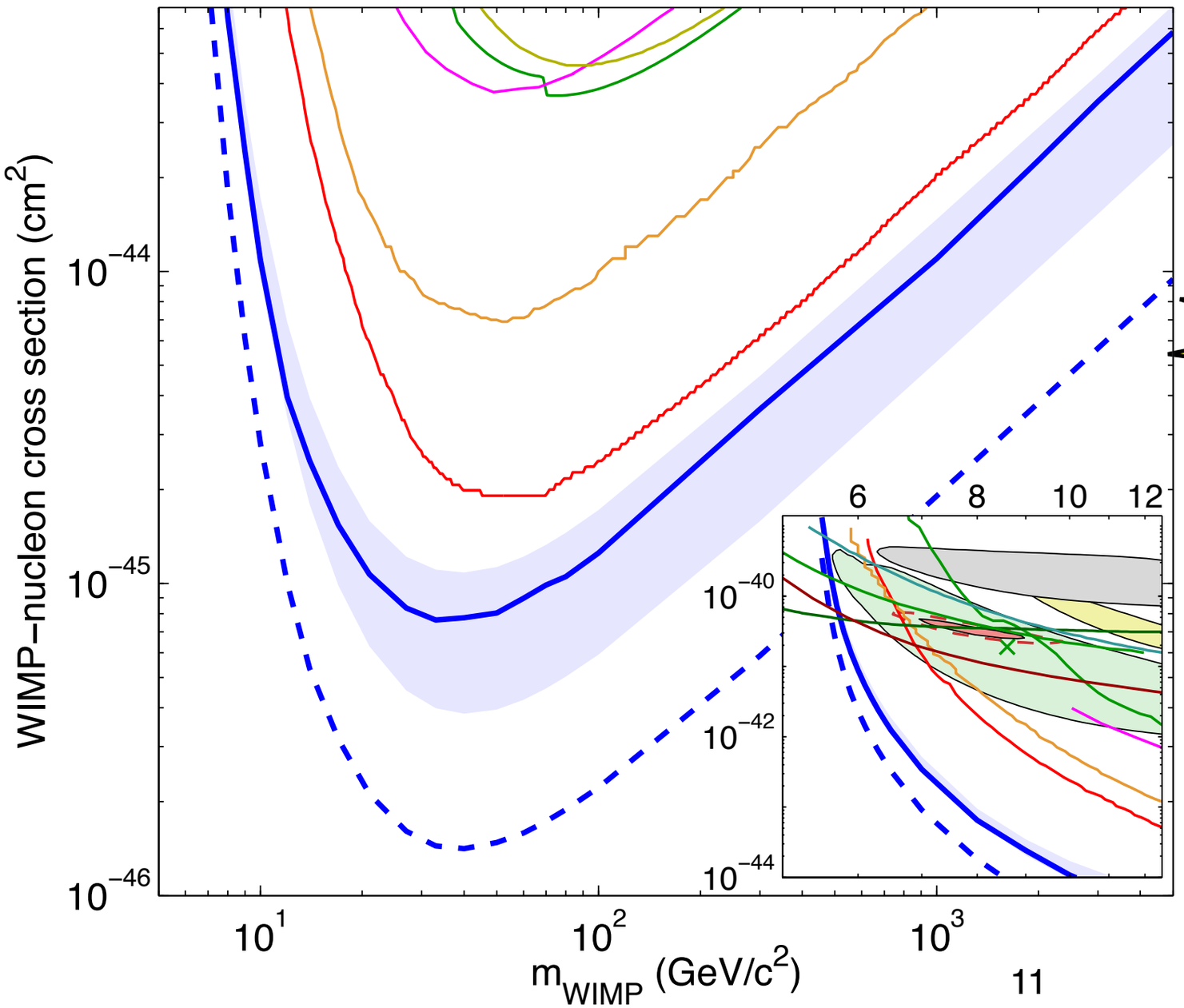
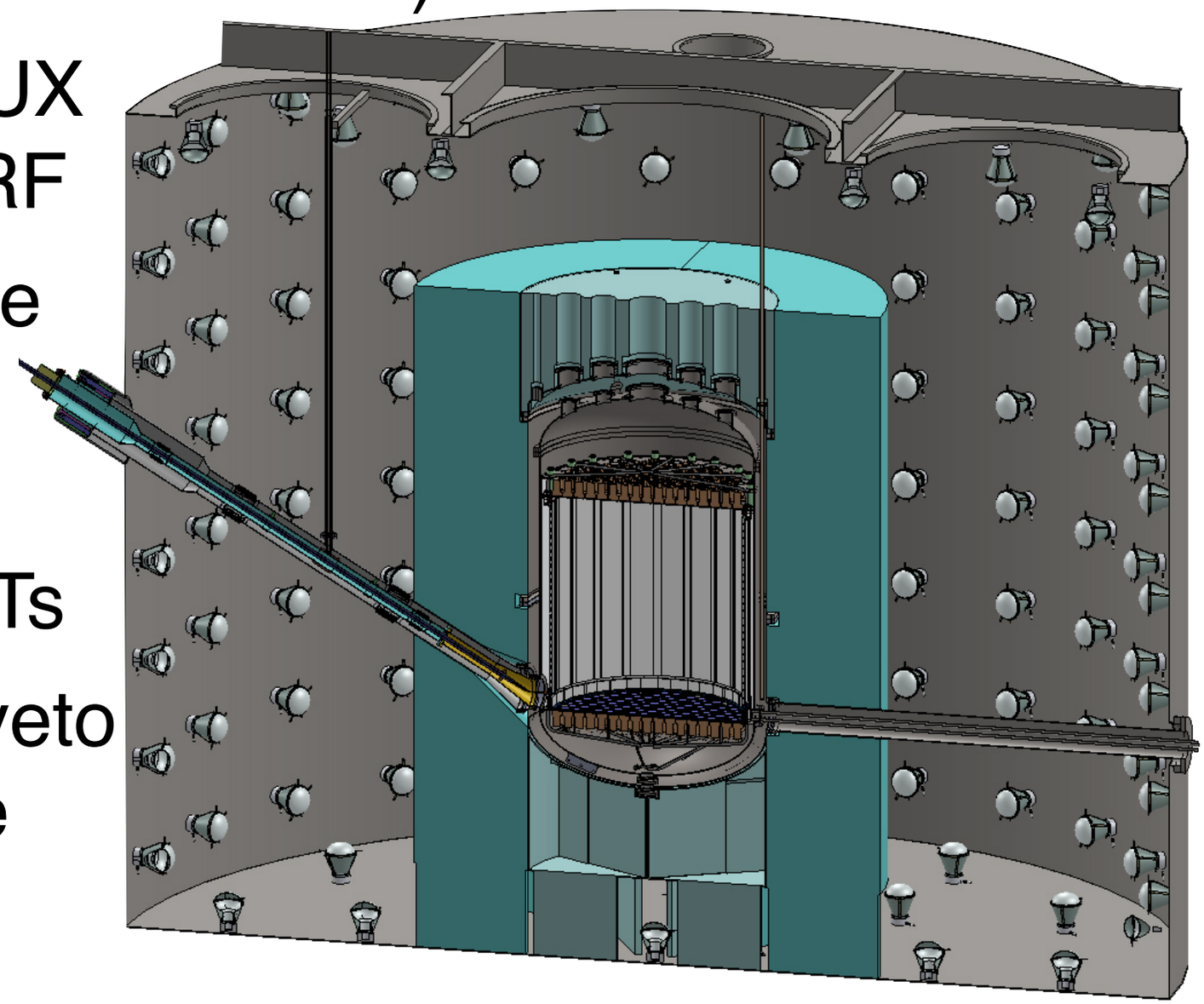


So what's next?

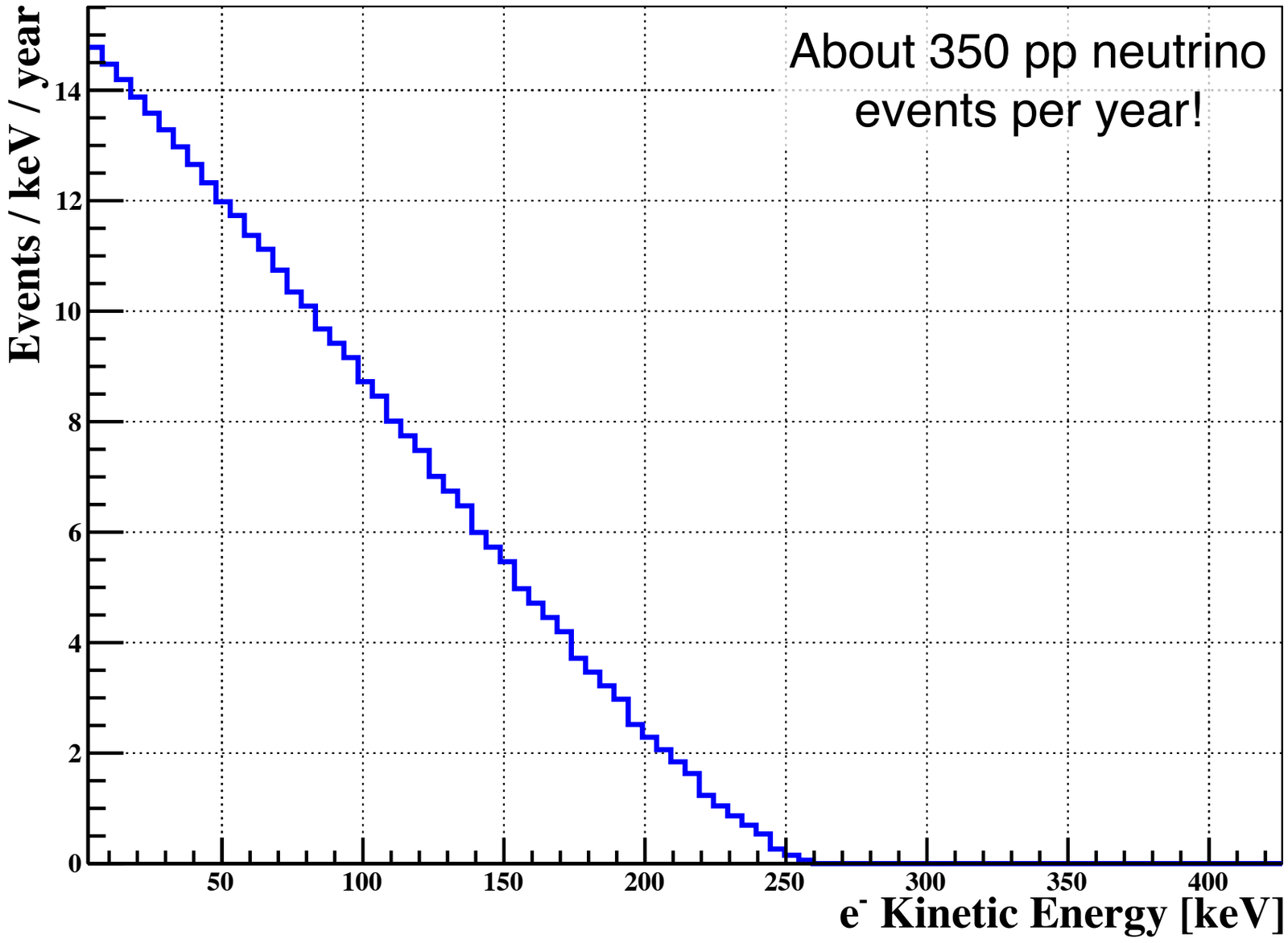
LZ

- The LUX and ZEPLIN collaborations are joining forces for a multi-ton two-phase xenon search (“LUX” + “ZEPLIN” = “LZ” Get it?)
- 5-6 tons fiducial mass (8-9 tons total)
- Will fit into the current LUX water shield tank at SURF
- More sophisticated active veto system
  - Xe outside field cage instrumented with PMTs
  - Add liquid scintillator veto outside cryostat inside shield)



Other Physics with LZ

- Low-energy solar neutrinos?
- 2νββ is actually a background... How many 2νββ events will slip through the NR/ER rejection in to the dark matter signal box?
- Can we get some physics out of the 2νββ shape?



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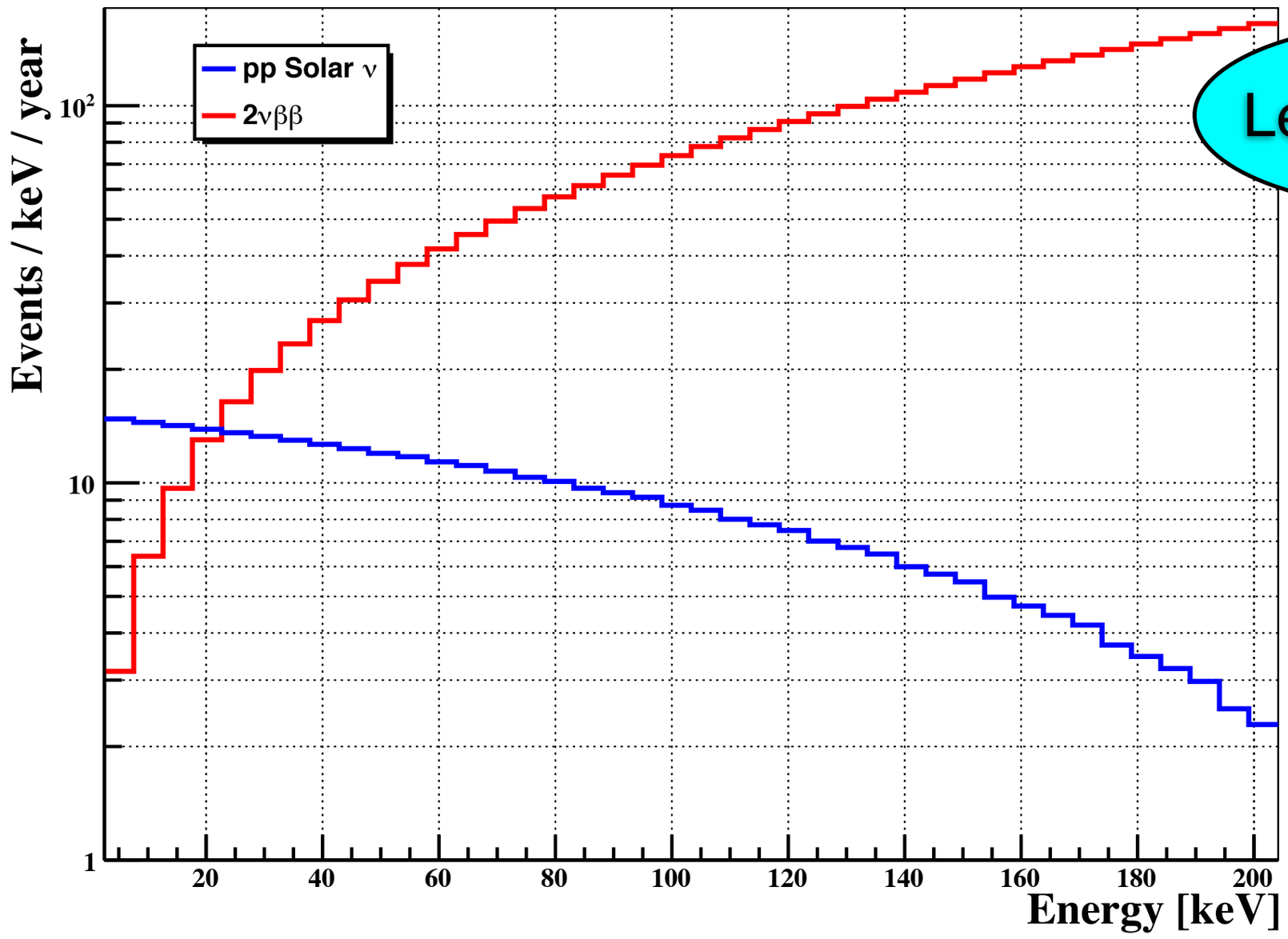
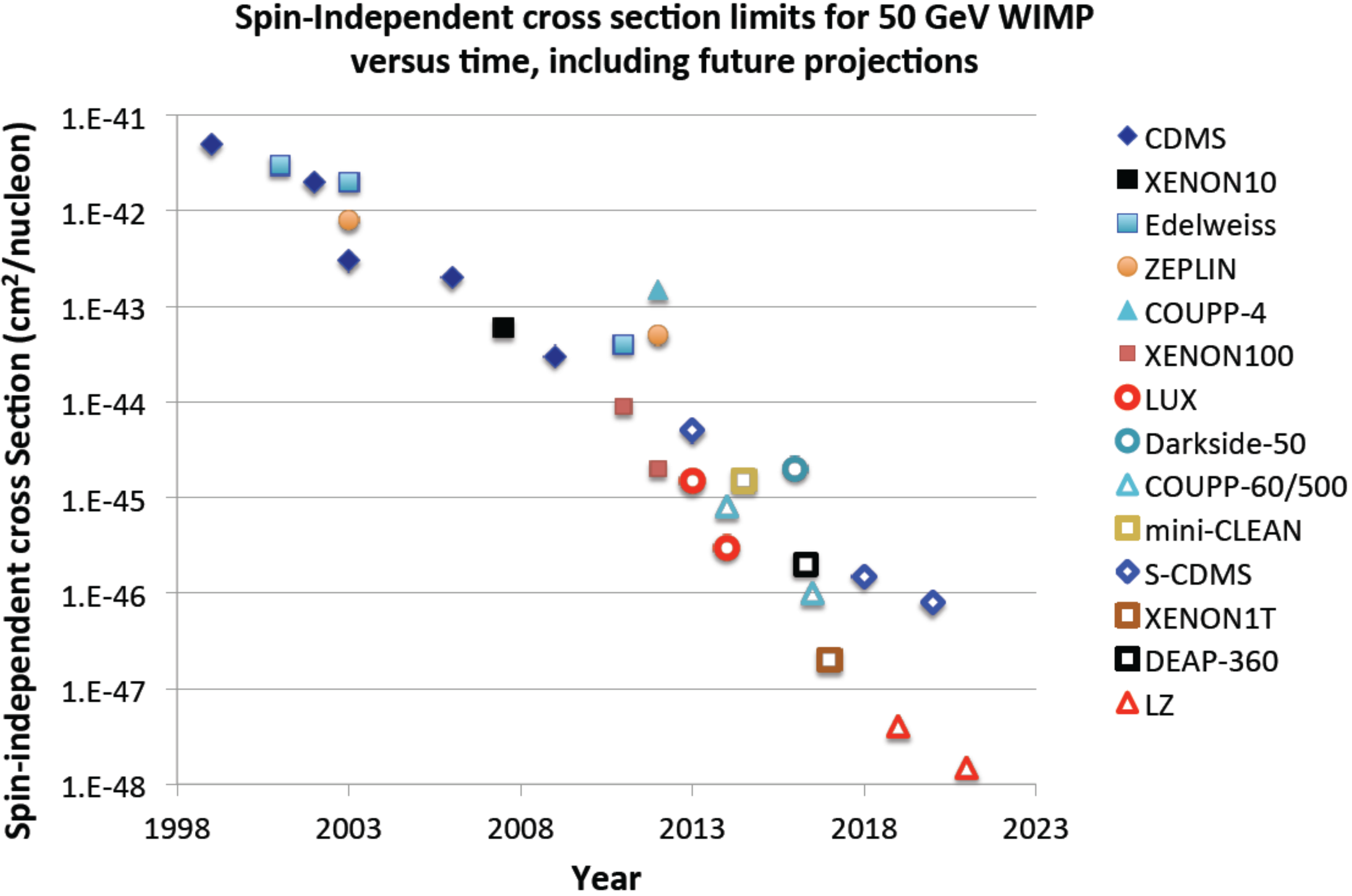


Less than 0.1

Can we “finish” Direct Detection?



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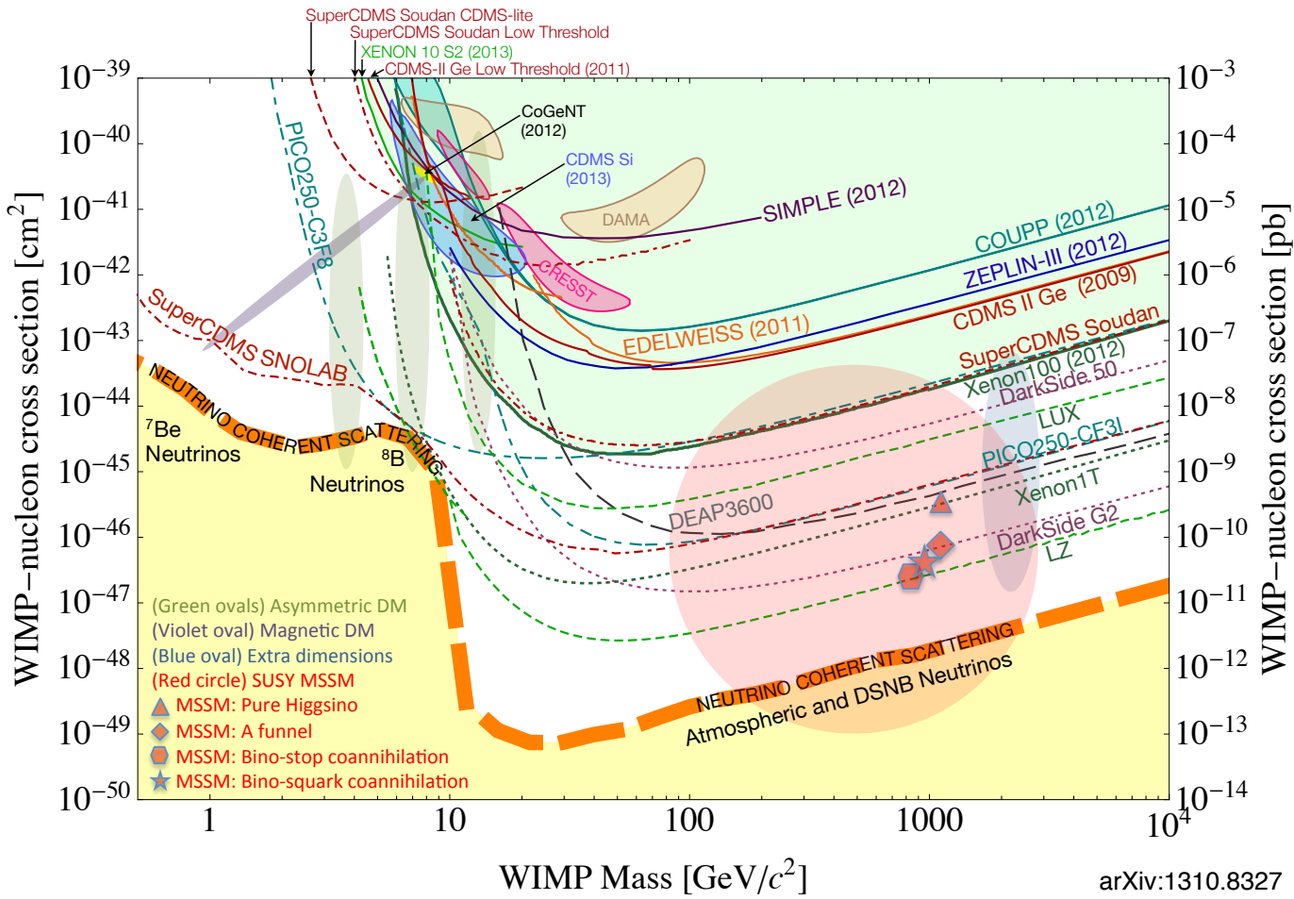

- Direction: if we could see tracks from WIMP interactions point away from the earth-sun system’s orbital velocity, that could differentiate those recoils from coherent neutrino scatters.
- Indirect detection: annihilation of WIMPs into standard model particles (usually photons or neutrinos). Messenger particle gets the full mass of the WIMP, makes dark matter astronomy something to think about!

Can we “finish” Direct Detection?

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- Ca exp flo
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- Dir fro tho
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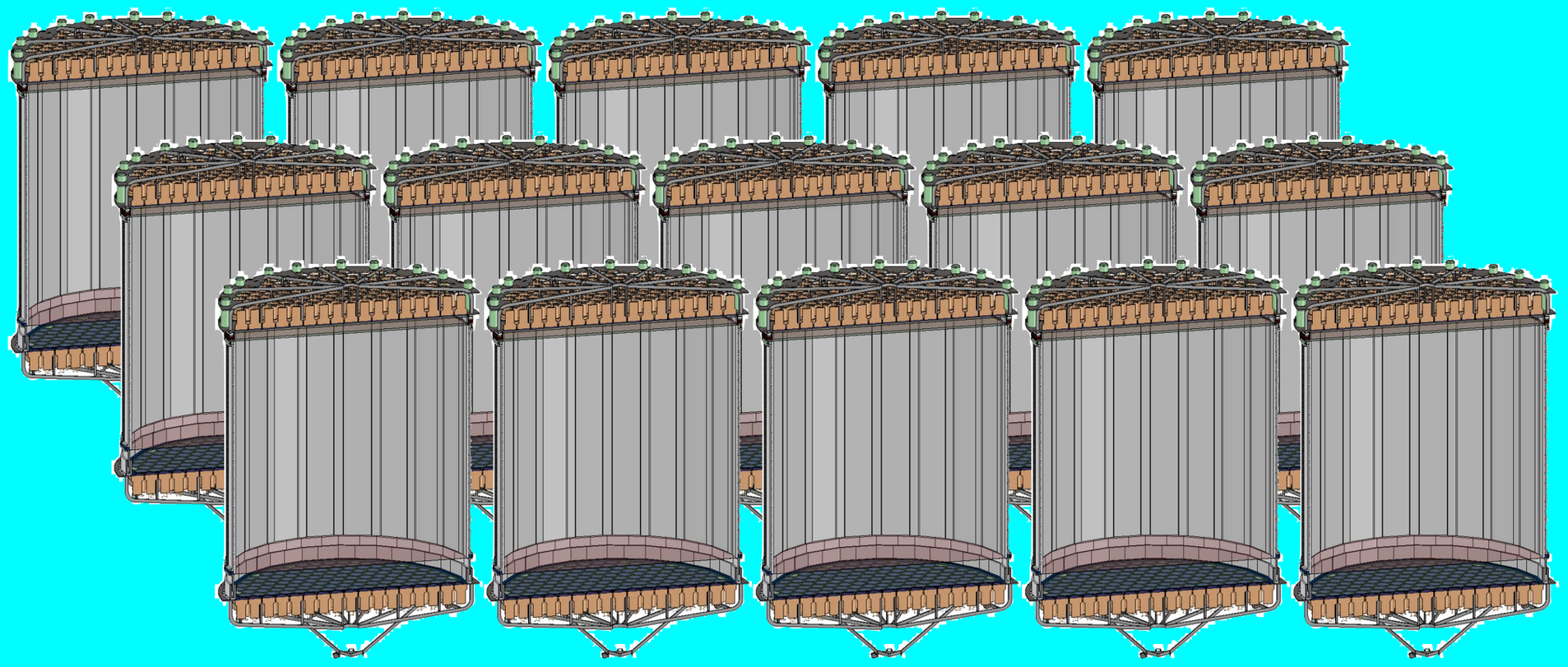
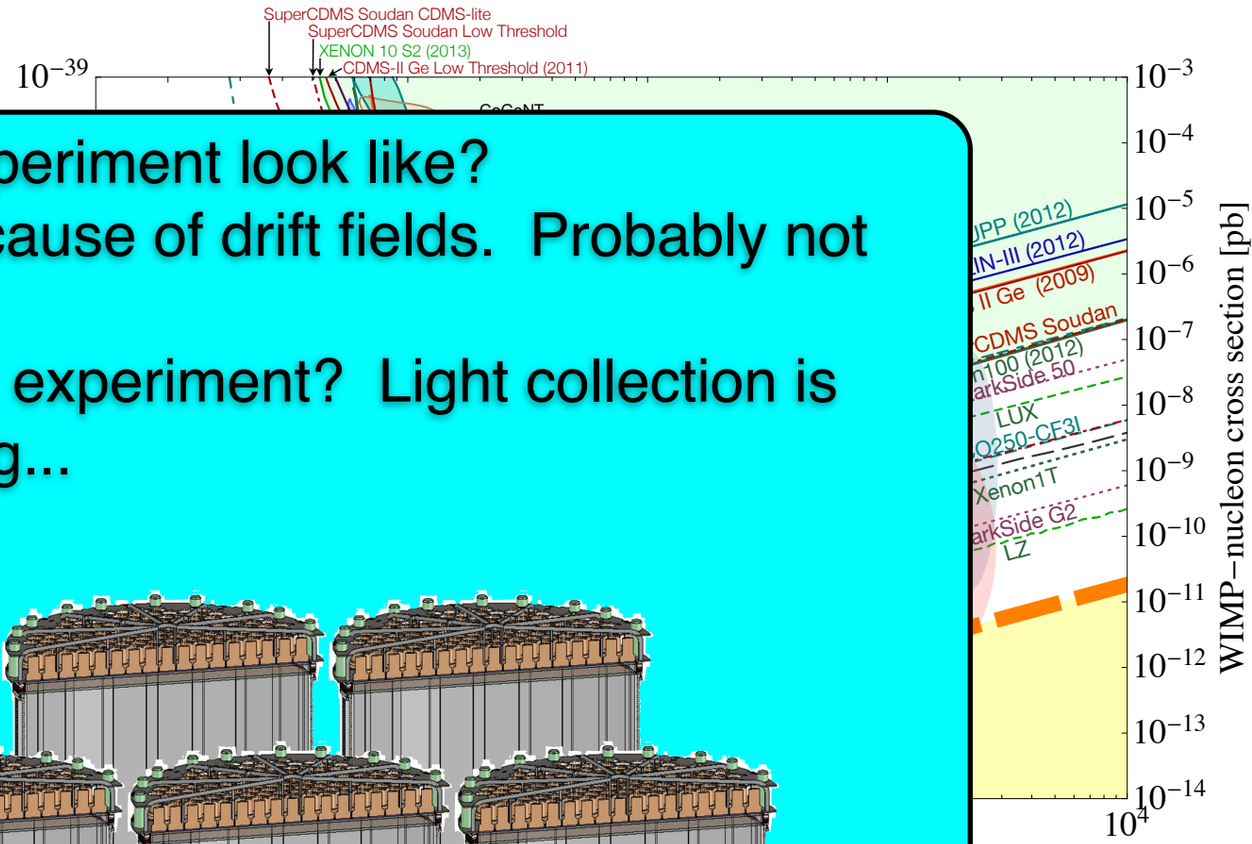
What would a 100-ton dark matter experiment look like?

- Two-phase liquid could be hard because of drift fields. Probably not impossible... Lots of parallel LZ’s?
- Big, single phase (scintillation only) experiment? Light collection is hard because or Rayleigh scattering...
- Superheated liquid detectors?





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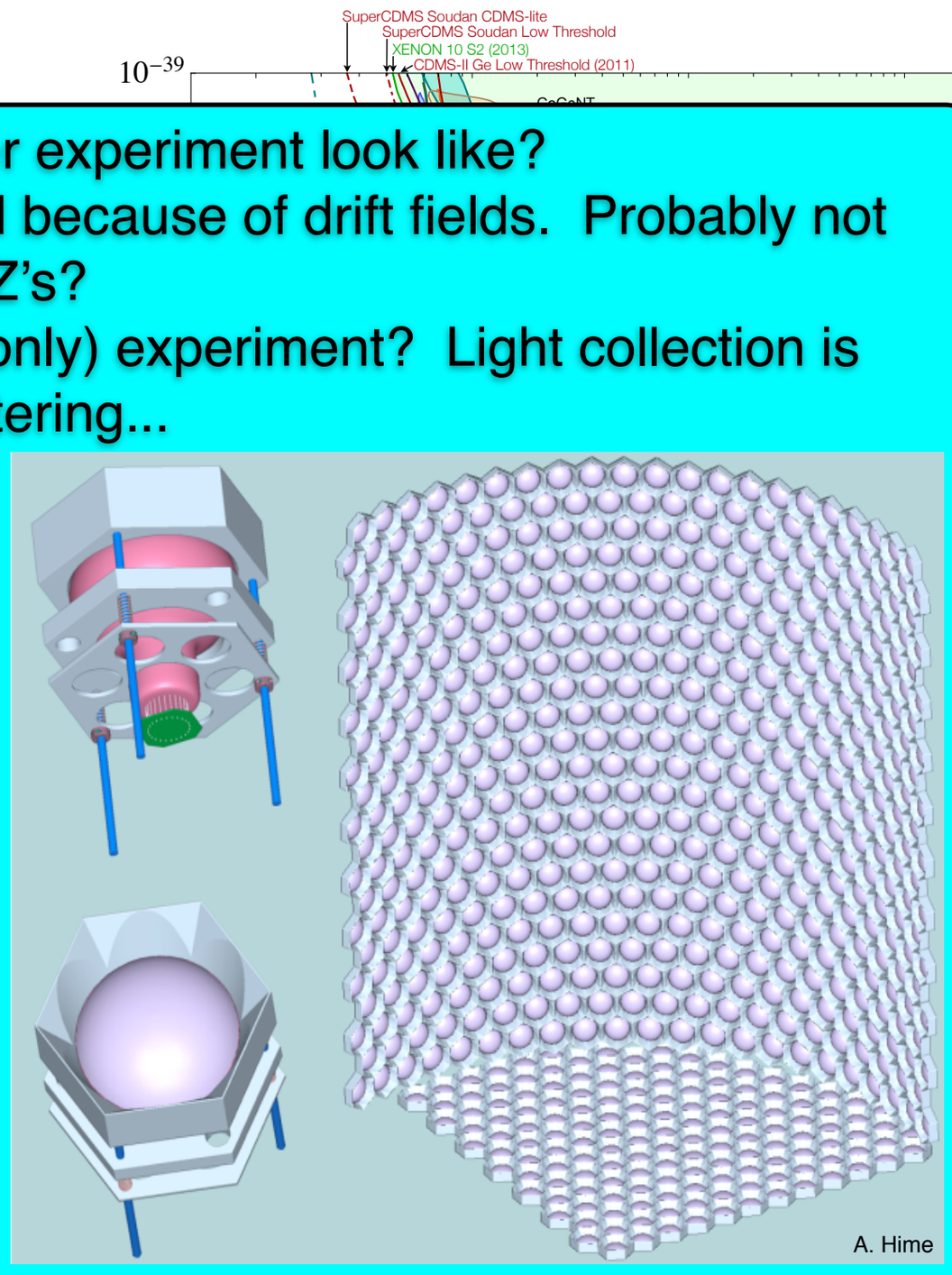

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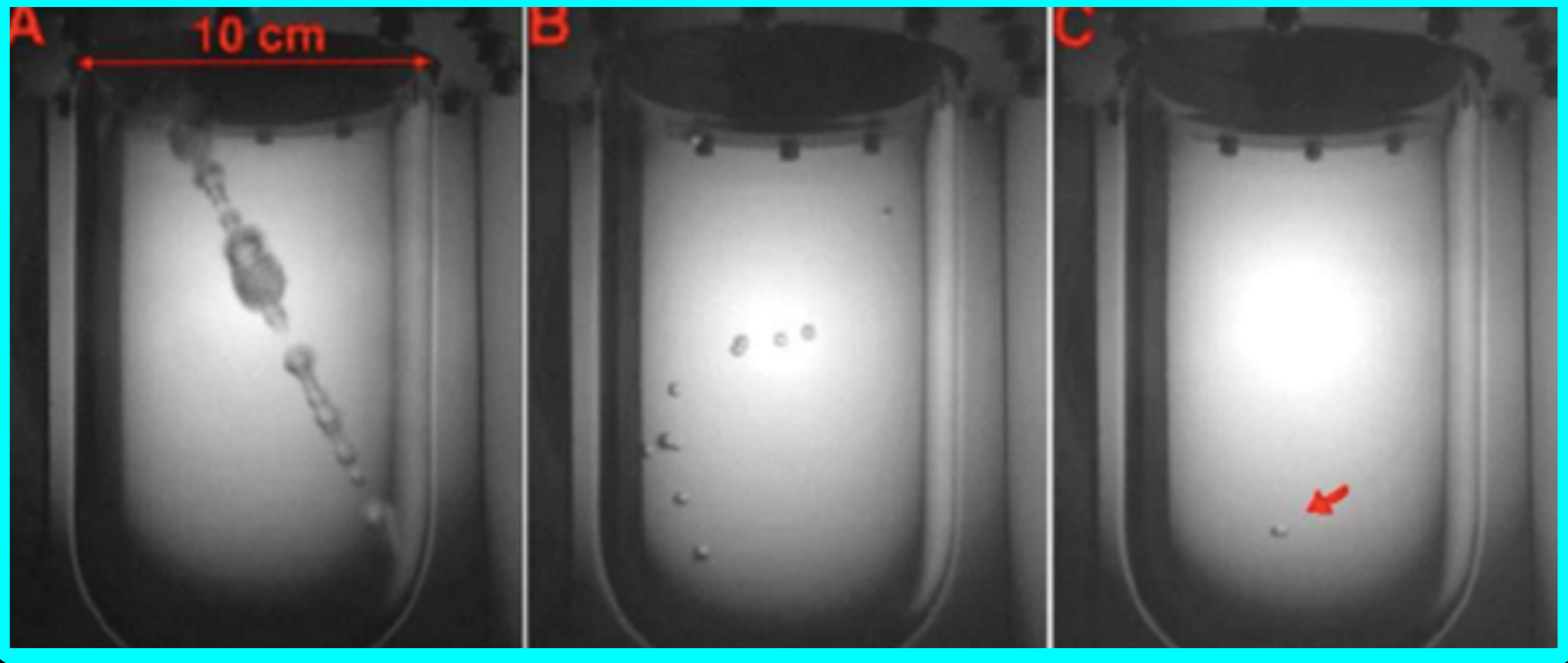

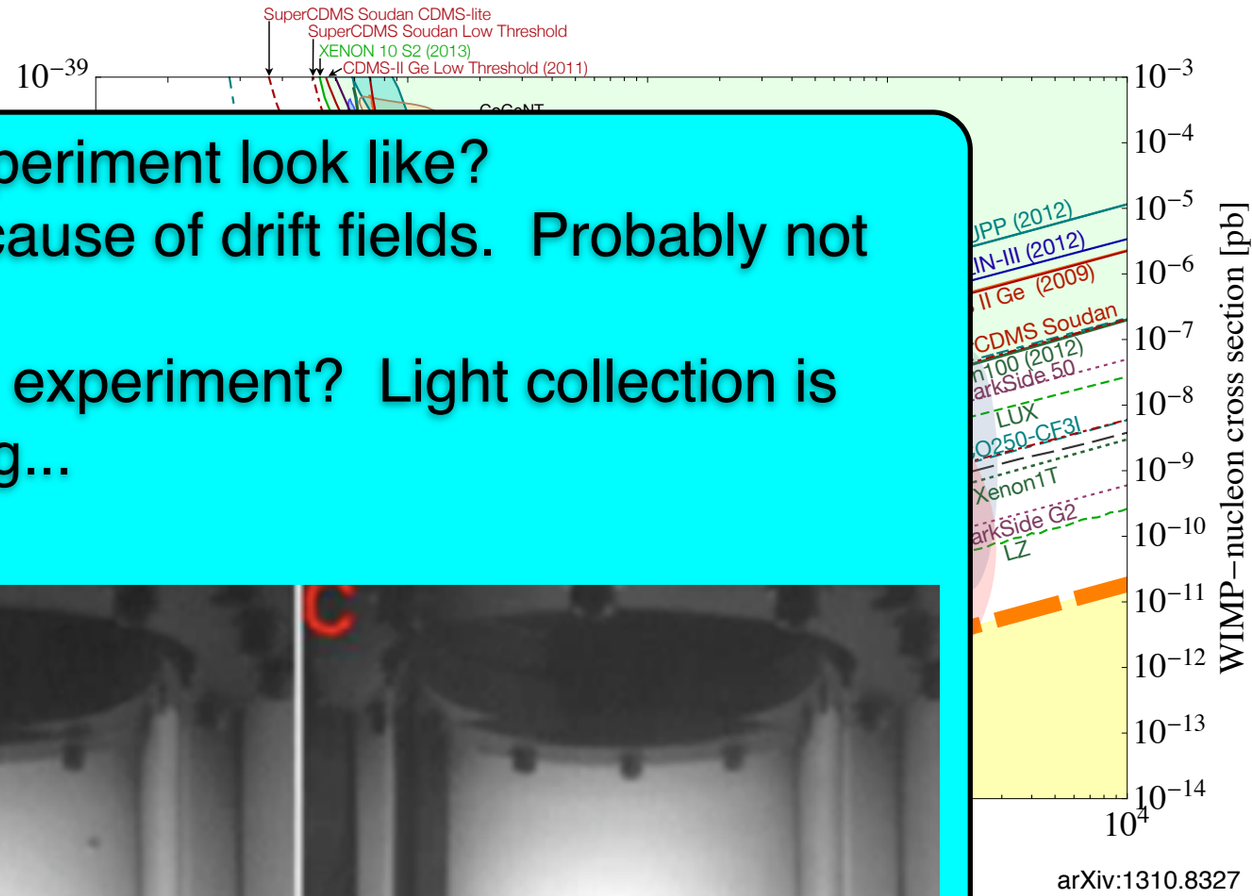

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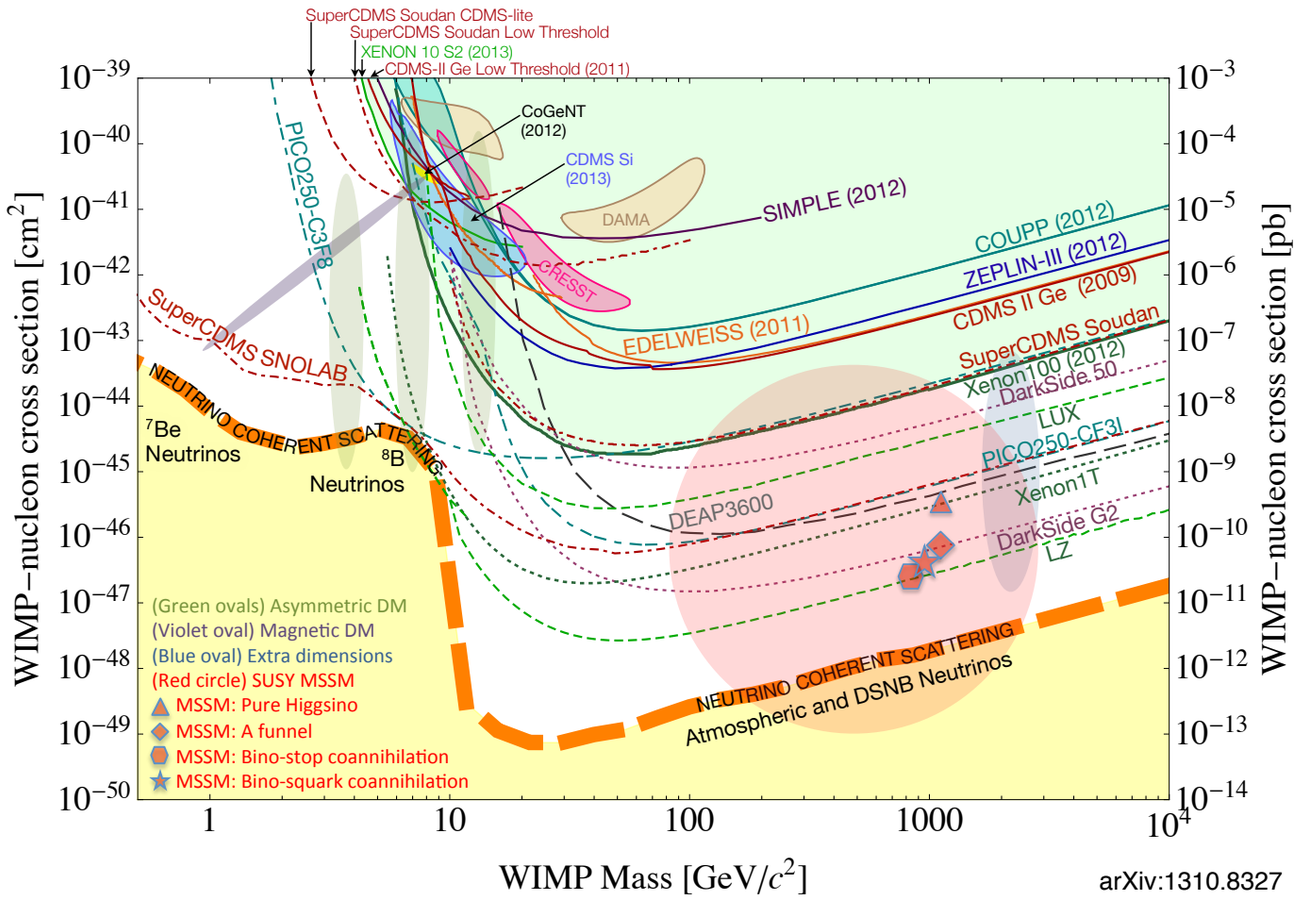

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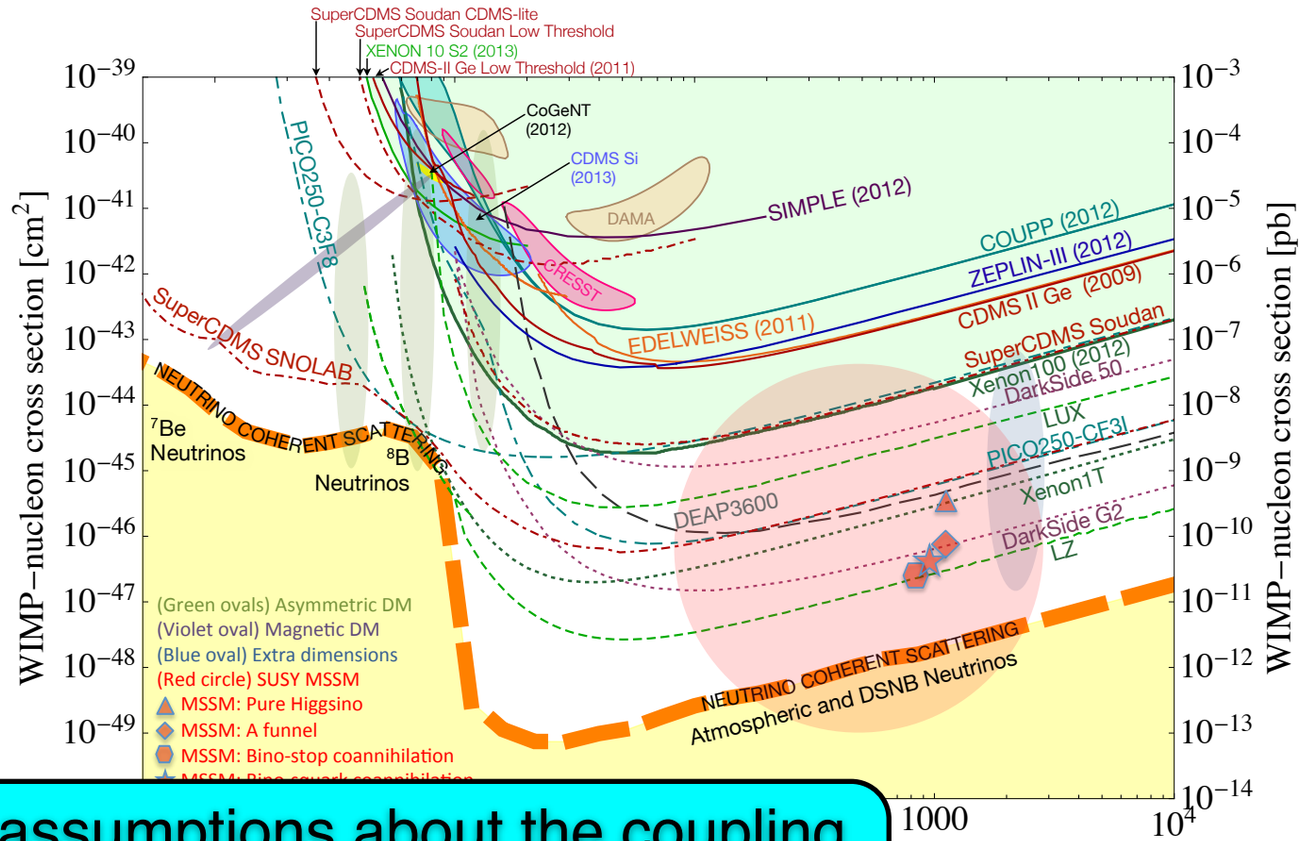
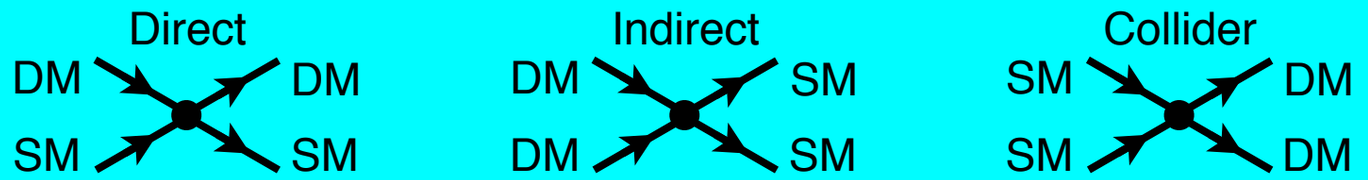


It requires slightly different assumptions about the coupling between dark matter and Standard Model particles, but indirect detection searches are no less reasonable!



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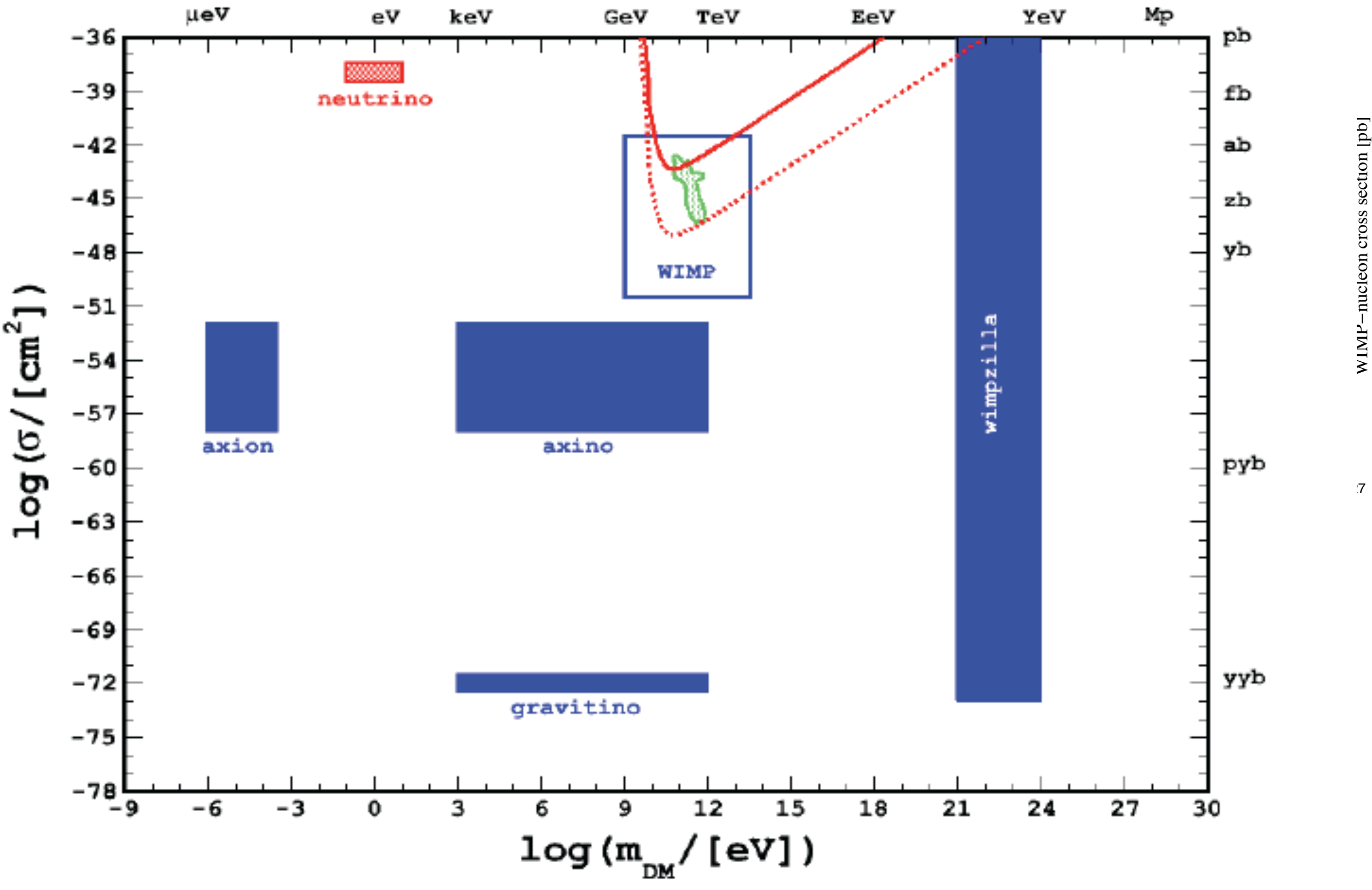

WIMP–nucleon cross section [pb]

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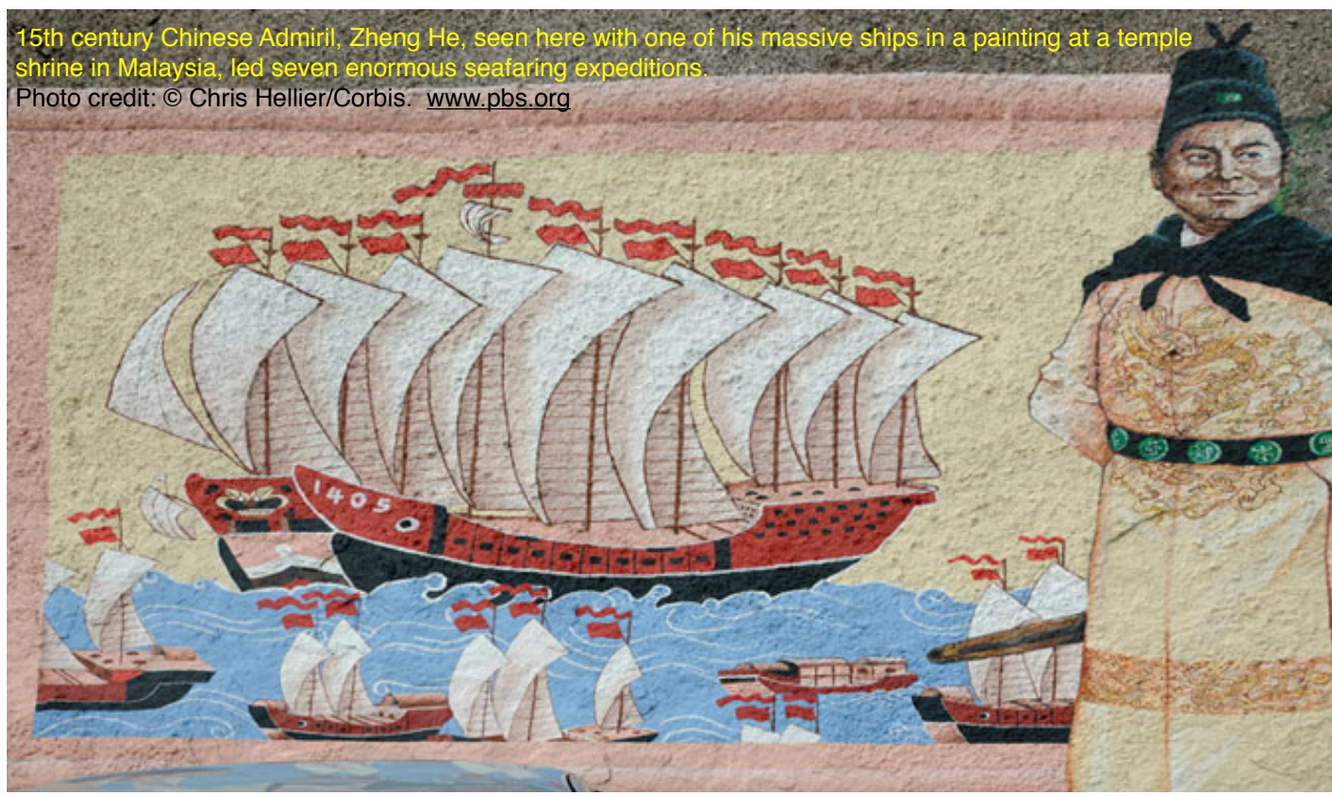
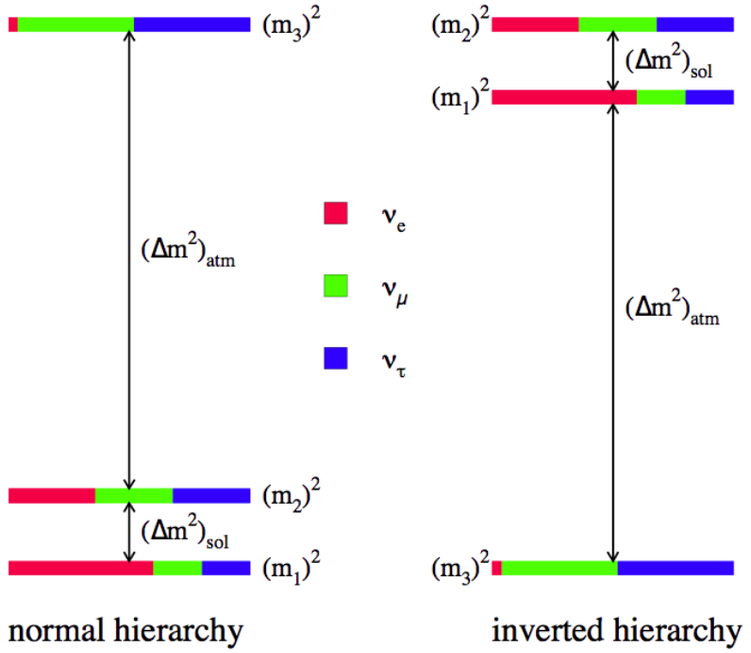


15th century Chinese Admiril, Zheng He, seen here with one of his massive ships in a painting at a temple shrine in Malaysia, led seven enormous seafaring expeditions.
Photo credit: © Chris Hellier/Corbis. www.pbs.org

Long-Baseline Neutrino Oscillations

Lots of outstanding questions in Neutrino/oscillation physics:



- Determination of the neutrino mass hierarchy
- CP violation in the neutrino sector (including phase measurement)
- Is θ_{23} really maximal?

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2}|\nu_1\rangle \\ e^{i\alpha_2/2}|\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Stringent test of the three-neutrino flavor paradigm
  - Are there non-standard interactions?
  - Are there other (sterile) neutrino states?
- Cross section and other interaction measurements

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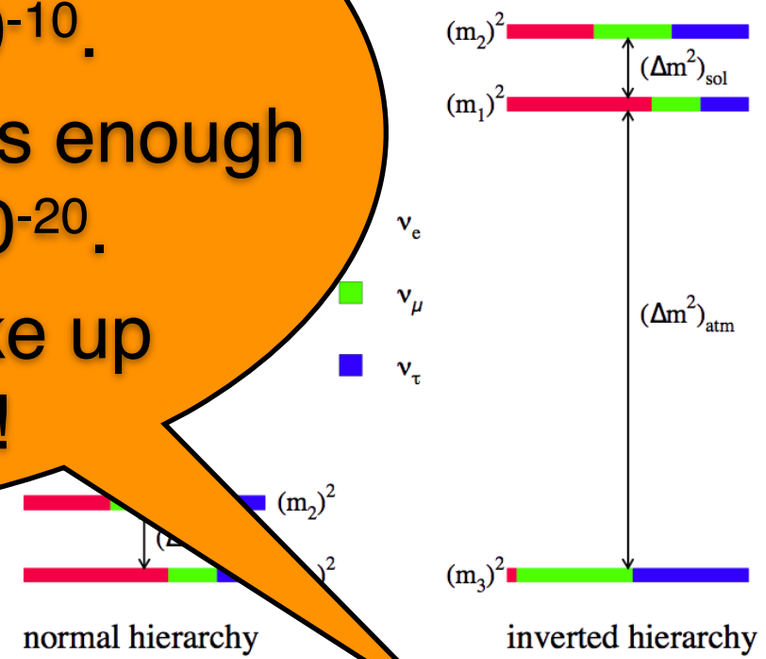
- Stringent test of the three-neutrino flavor paradigm
  - Are there non-standard interactions?
  - Are there other (sterile) neutrino states?
- Cross section and other interaction measurements

Baryogenesis requires matter-antimatter asymmetry ~5 x 10^{-10}.

The quark sector provides enough CP violation for ~10^{-20}.

Neutrinos might make up (part of) the rest!



$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2}|\nu_1\rangle \\ e^{i\alpha_2/2}|\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

A Long-Baseline Neutrino Experiment

- Why FNAL to Homestake? Just because of convenient facilities?
- NO! 1000 - 1500 km is actually a well optimized baseline that allows us to “run the table” on δ_{CP}, mass hierarchy, and θ_{23} octant. (arXiv:1311.0212)
- Too short a baseline: not enough “matter effects” to see the hierarchy
- Too long a baseline: “matter effects” swamp δ_{CP}
- A much longer baseline would give more sensitivity to non-standard interactions

A Long-Baseline Neutrino Experiment

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$
$$+\alpha\frac{\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$
$$+\alpha\frac{\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$
$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

$$\alpha = \frac{\Delta m^2_{12}}{\Delta m^2_{13}} \quad \Delta = \frac{\Delta m^2_{13} L}{4E_\nu} \quad \hat{A} = \frac{2\sqrt{2}G_F n_e E_\nu}{\Delta m^2_{13}}$$

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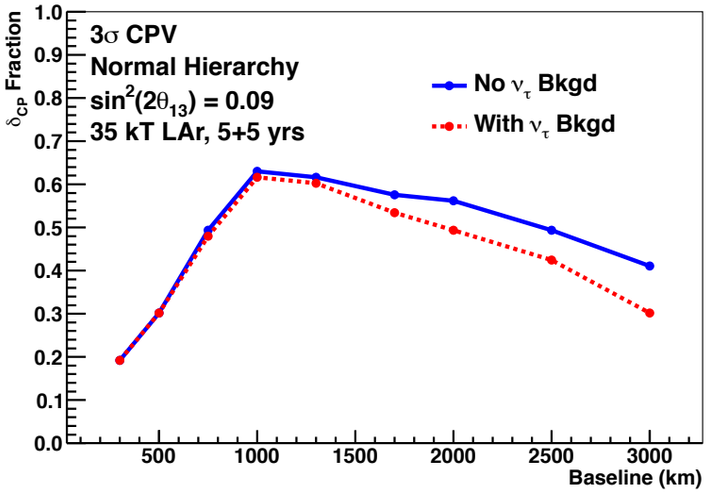

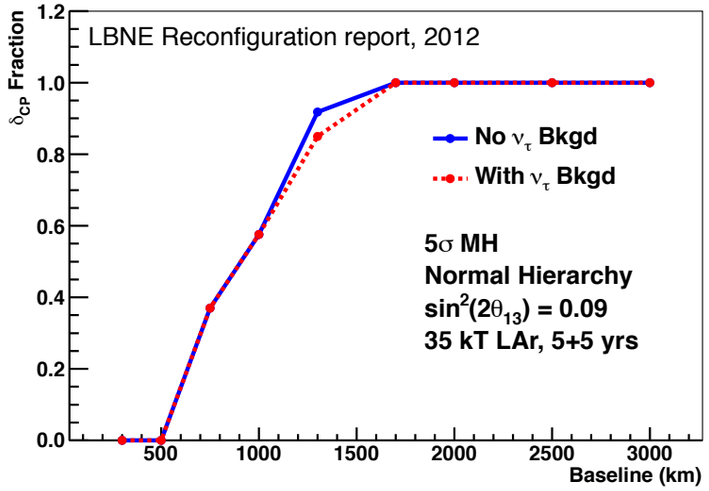

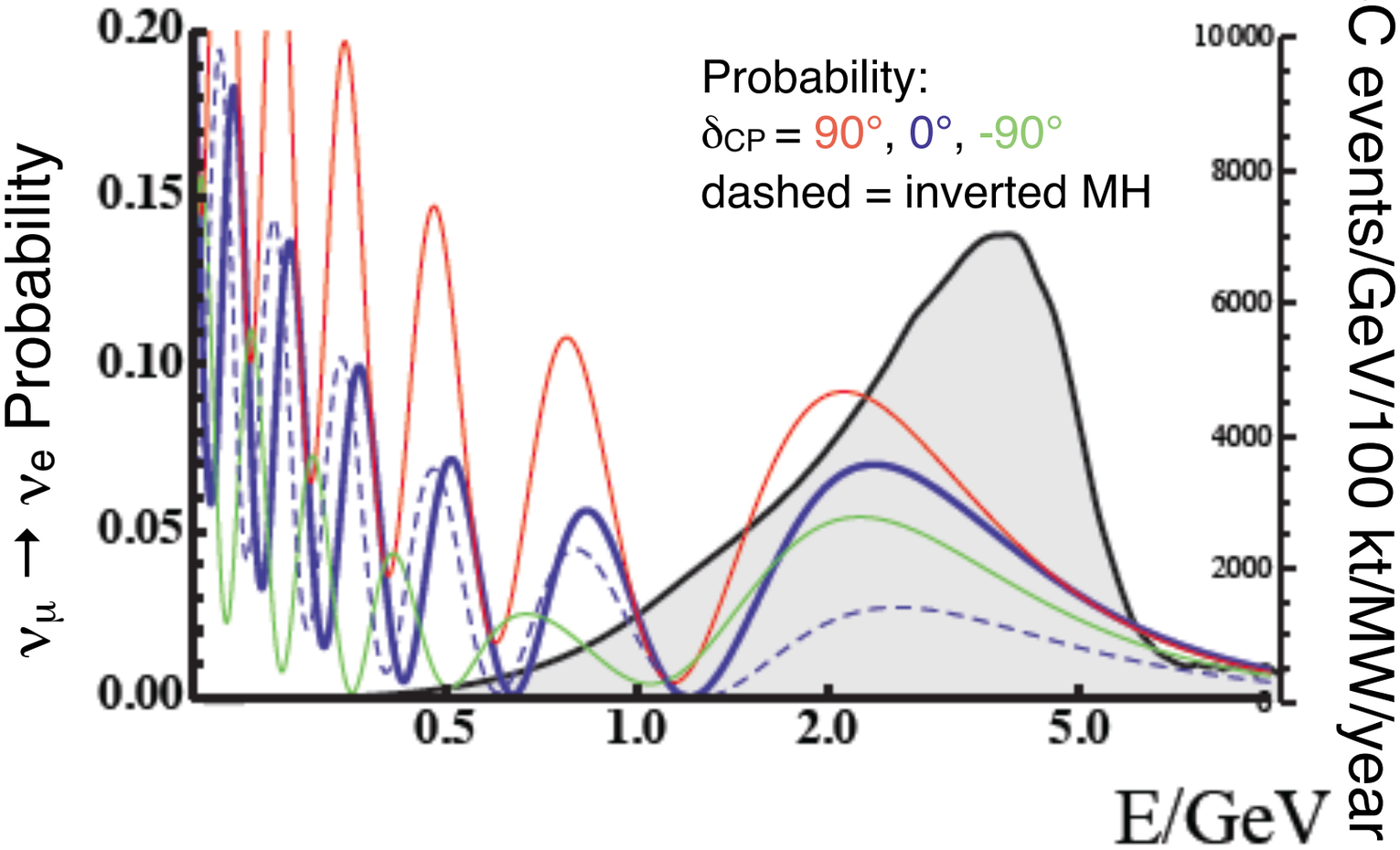

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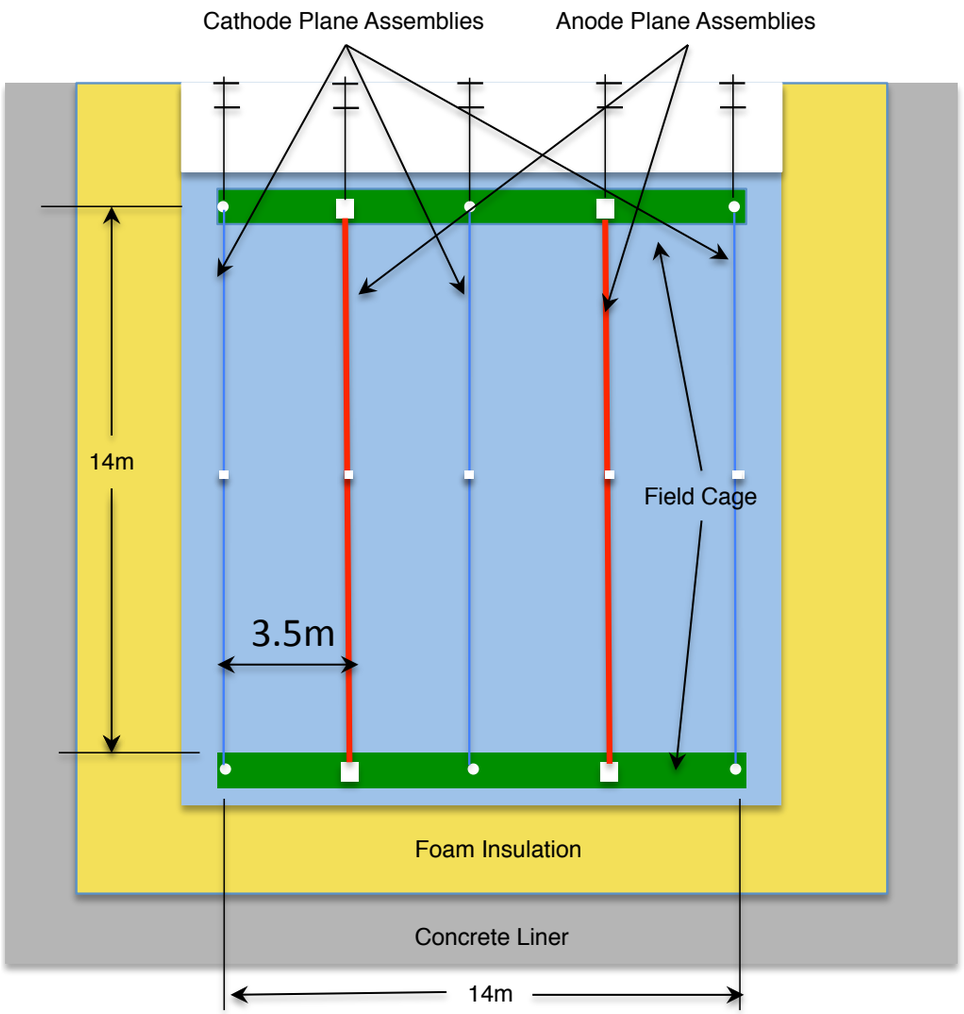
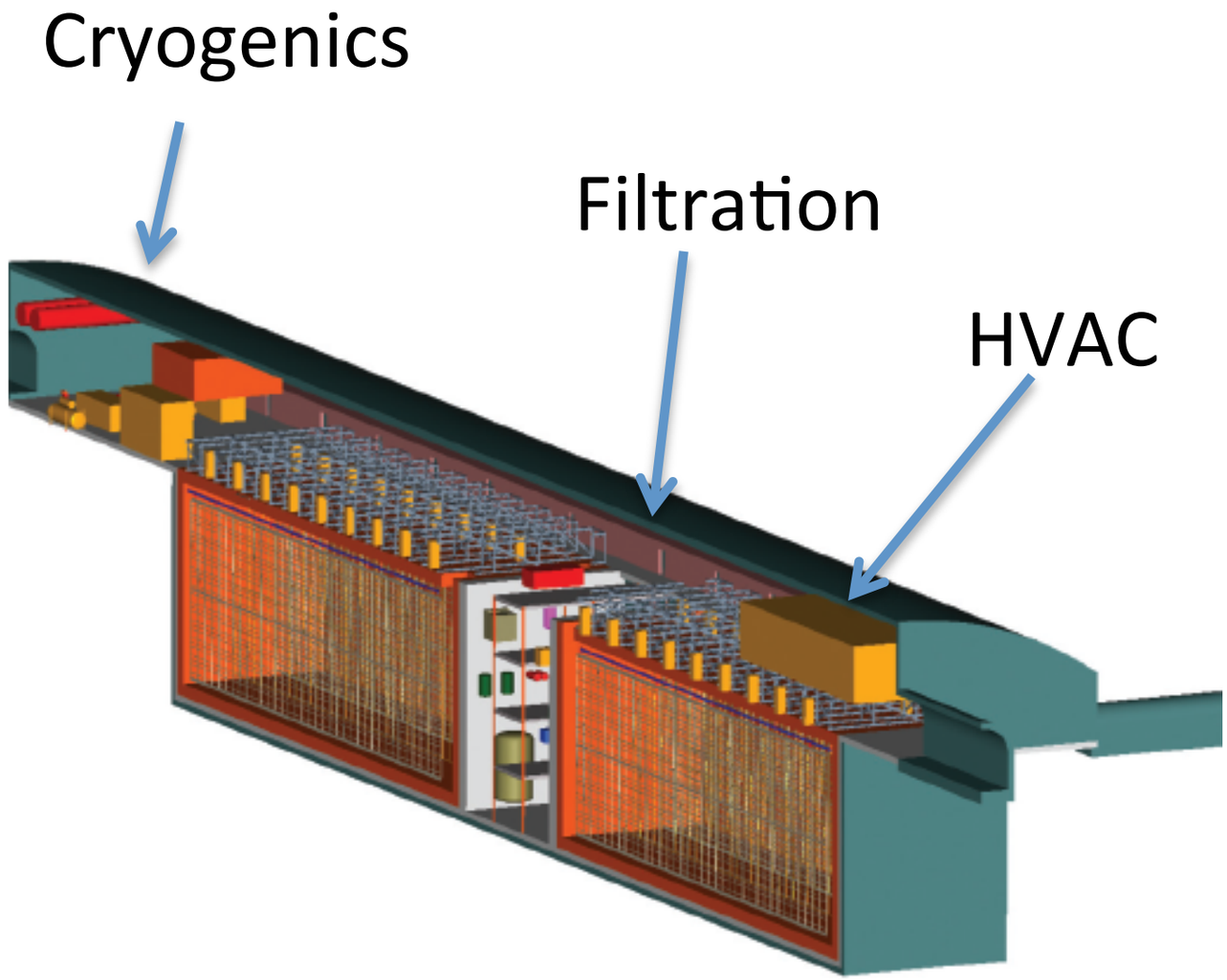
The LBNE Far Detector





- Modular TPC design allows for flexible drift distances
- Wire planes designed to be slung under the cage at SURF
- Photon collection done with sensors inside the anode plane assemblies (doing this better would dramatically improve energy resolution!!!)

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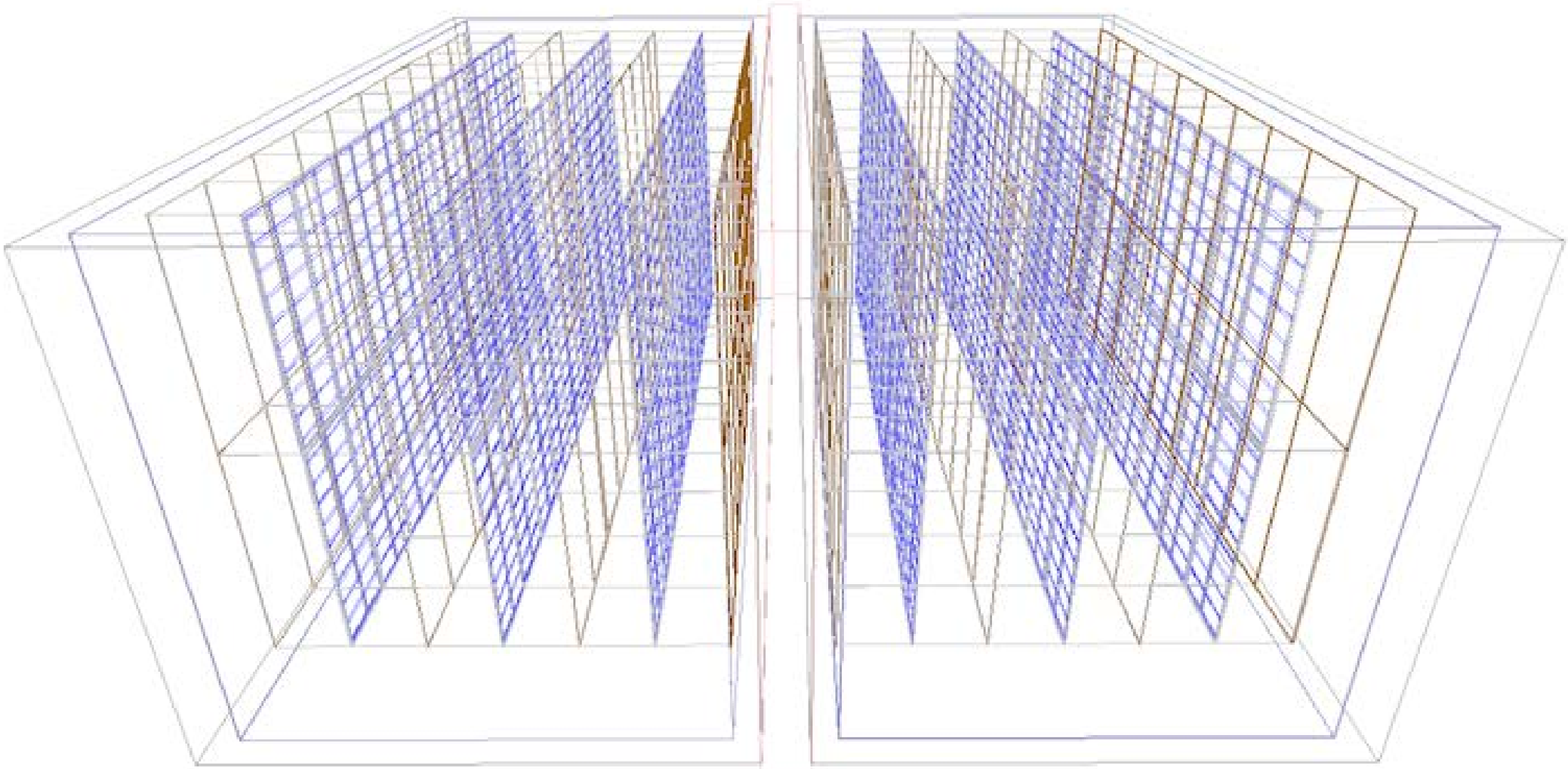

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- The show so far: the Standard Model works really well, but...
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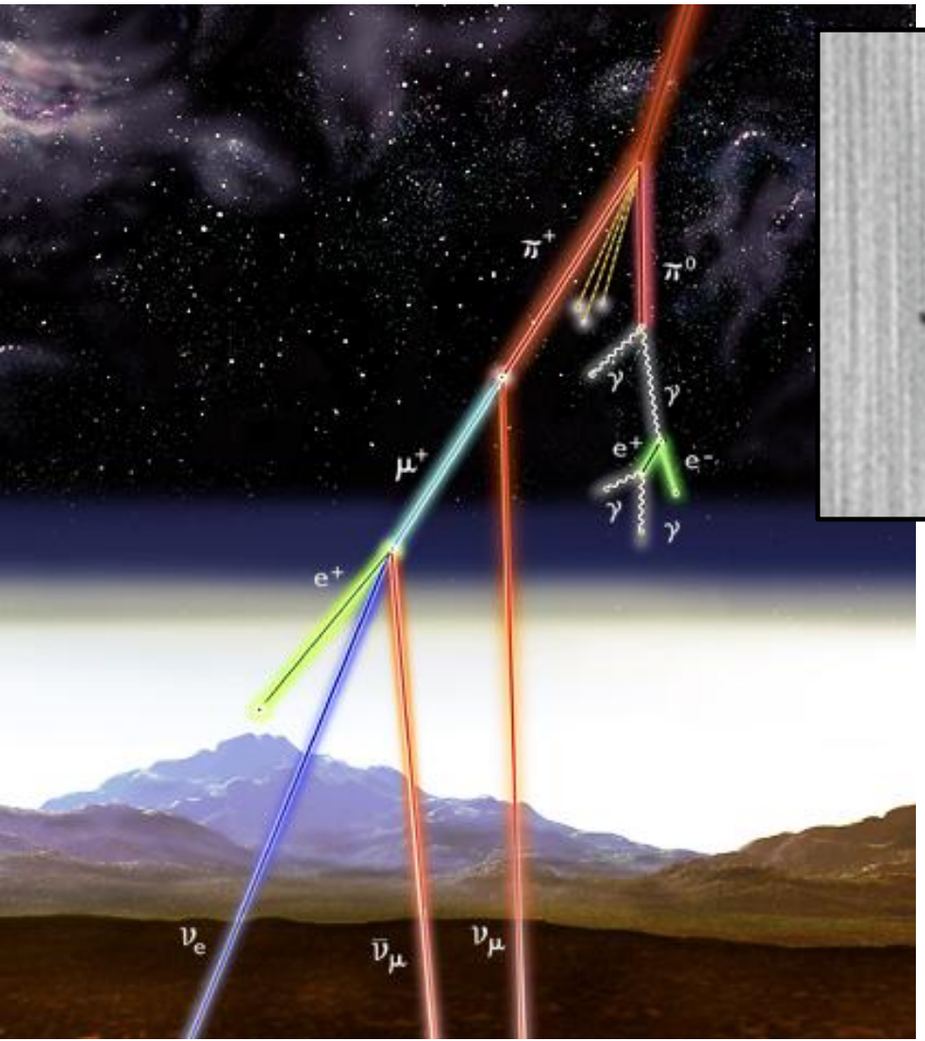
- A view of the next ten years of dark matter searches...

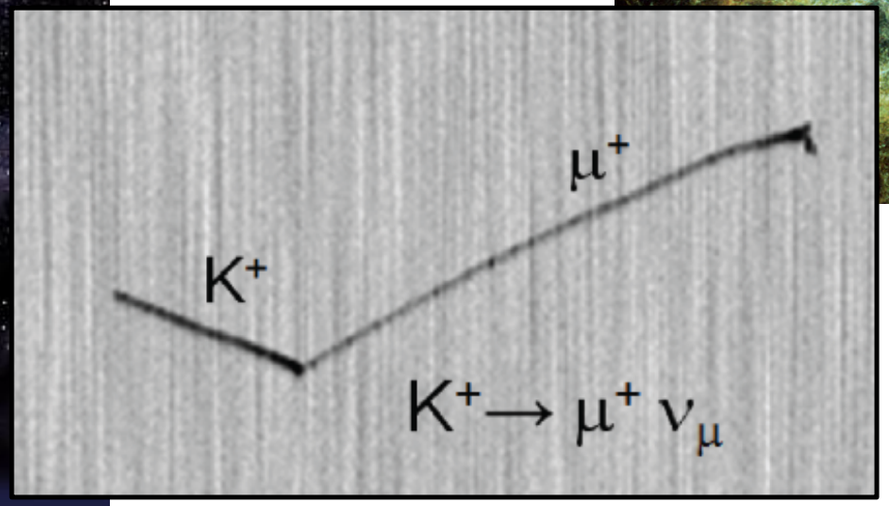

Tenzing Norgay and Edmund Hillary, 1953

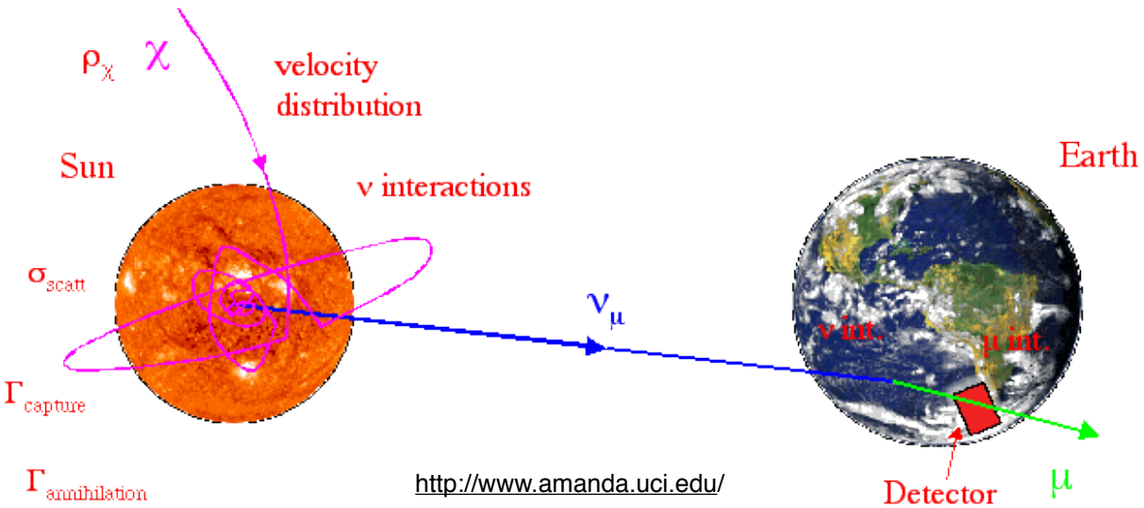
- The case for LBNE
- What else can you do with something like the LBNE far detector?
- The technical challenges that tie all this together
- Conclusions and perspectives

Other Physics with the LBNE FD

- Supernova burst neutrinos
- Indirect dark matter ($\chi\,\chi \rightarrow \nu\,\nu$)
- Atmospheric neutrinos
- Nucleon decay (esp. $p \rightarrow K^+ \nu$)



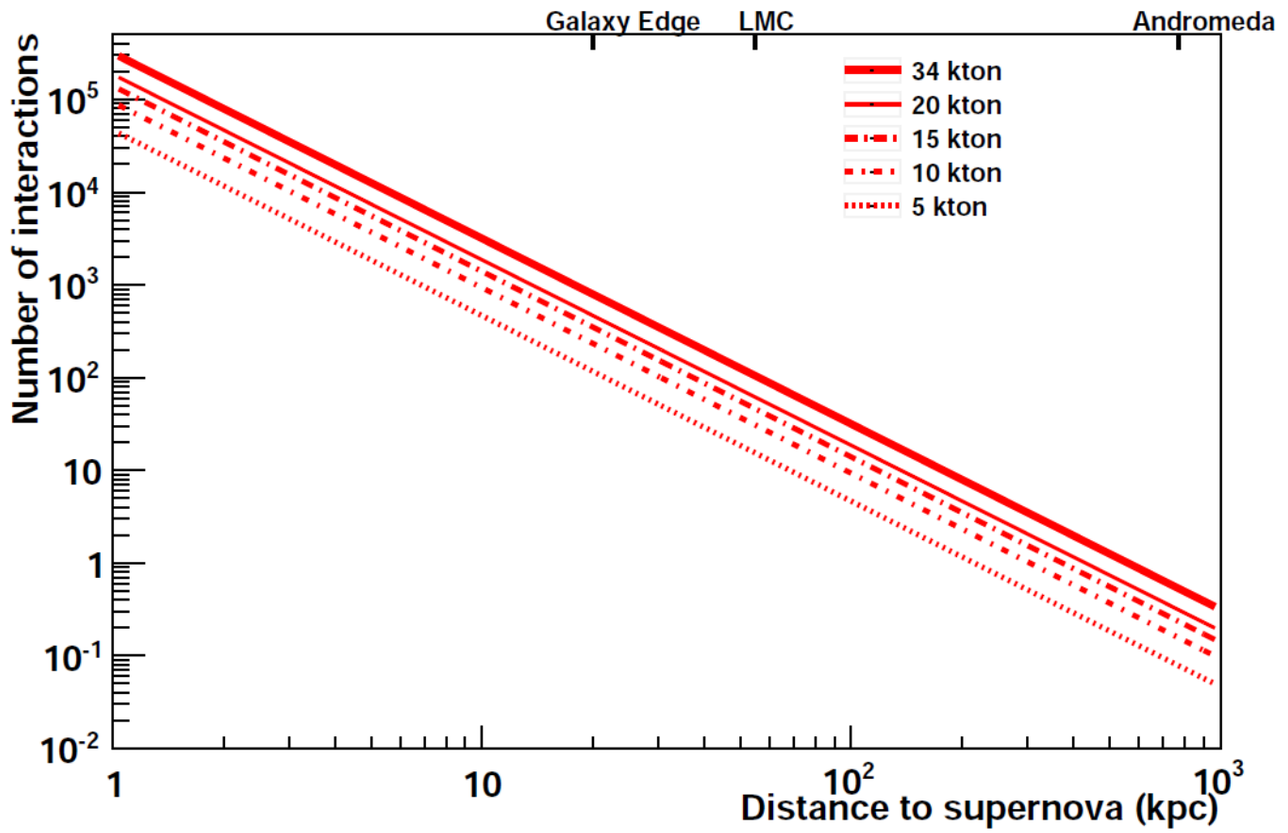


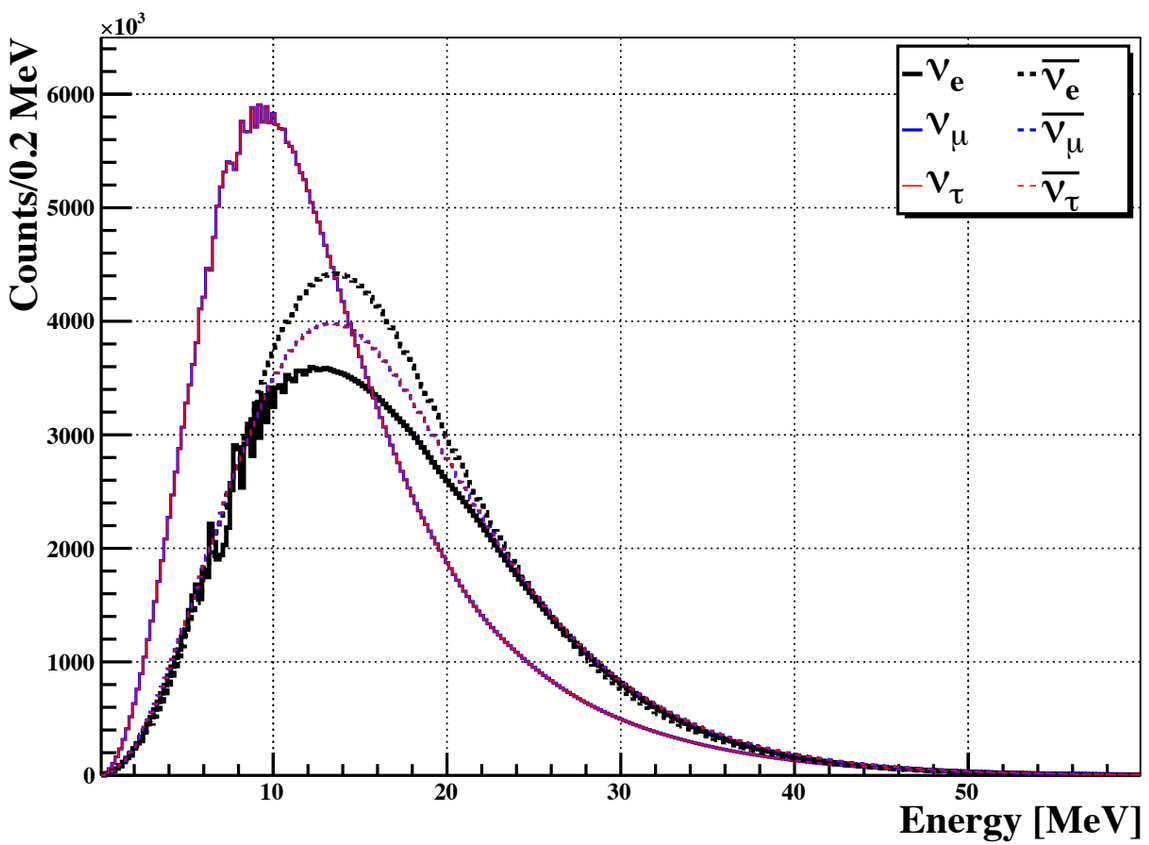


http://www.amanda.uci.edu/

Core Collapse Supernova Neutrinos

- Fewer than 20 neutrinos detected from 1987A, lead to thousands of publications over the intervening years!
- ~99% of the proto-neutron star's energy release goes into neutrinos.
- Too many uncertainties from collective effects, etc. to do a lot of neutrino physics with a supernova, but there is A LOT of astrophysics we can learn:
  - Binding energy and net lepton number of the proto-neutron star
  - Time evolution ("neutrino light curve") provides structural information about the collapse, including things like the neutronization burst and black hole production!
  - Early warning (minutes to hours) in advance of optical pulse
- High densities and astrophysical object sizes could provide a wealth of information on neutrino interactions in matter





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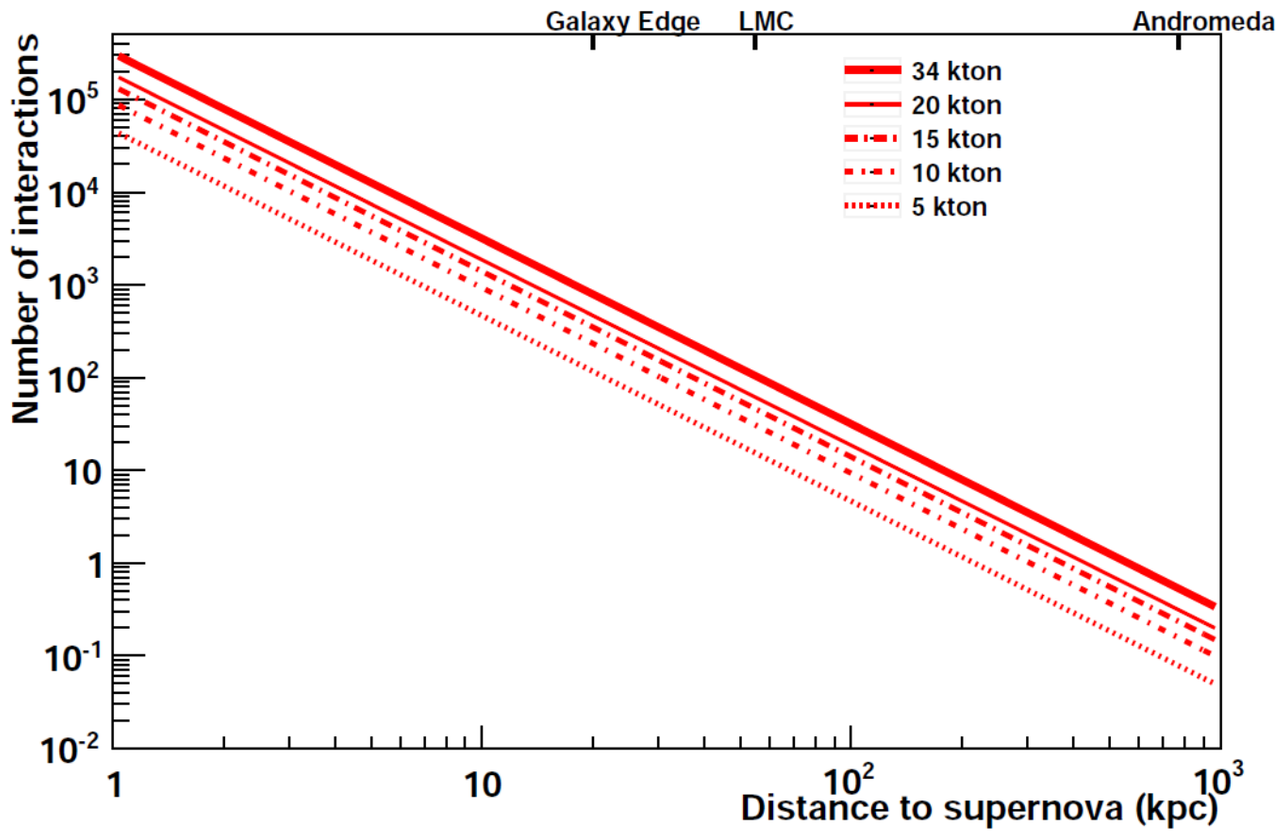

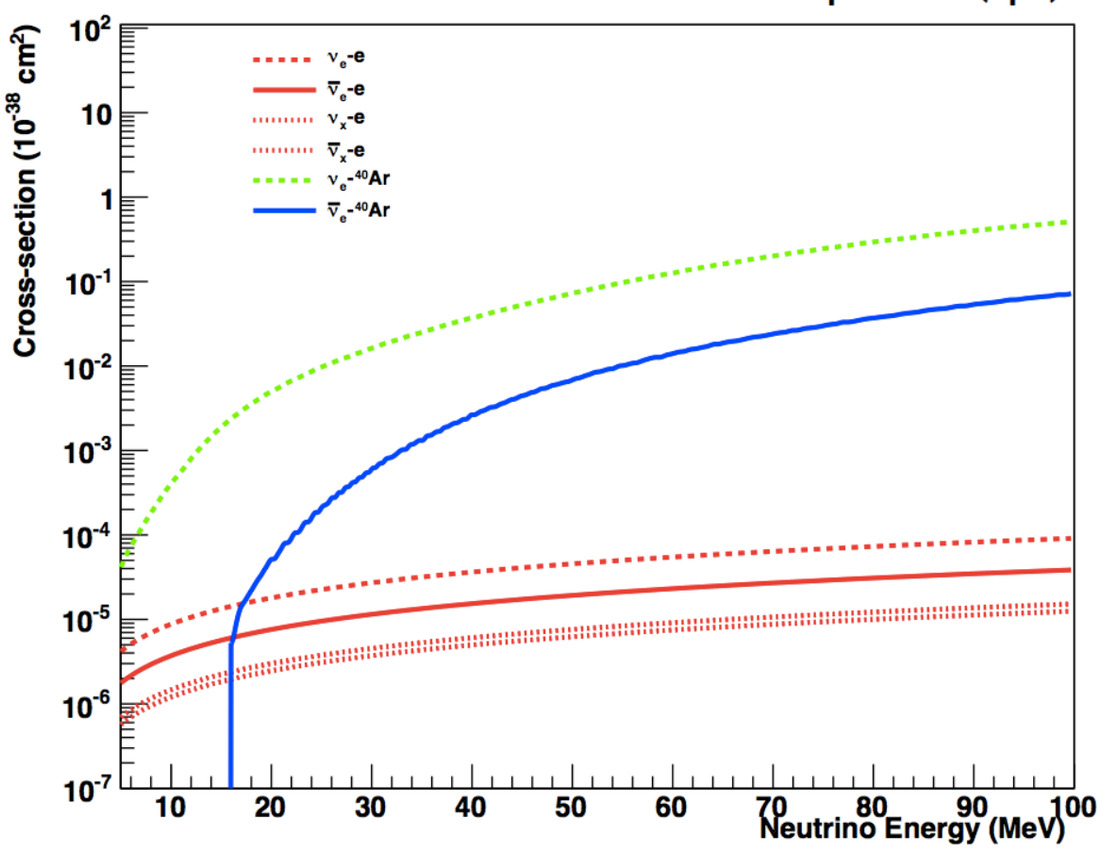

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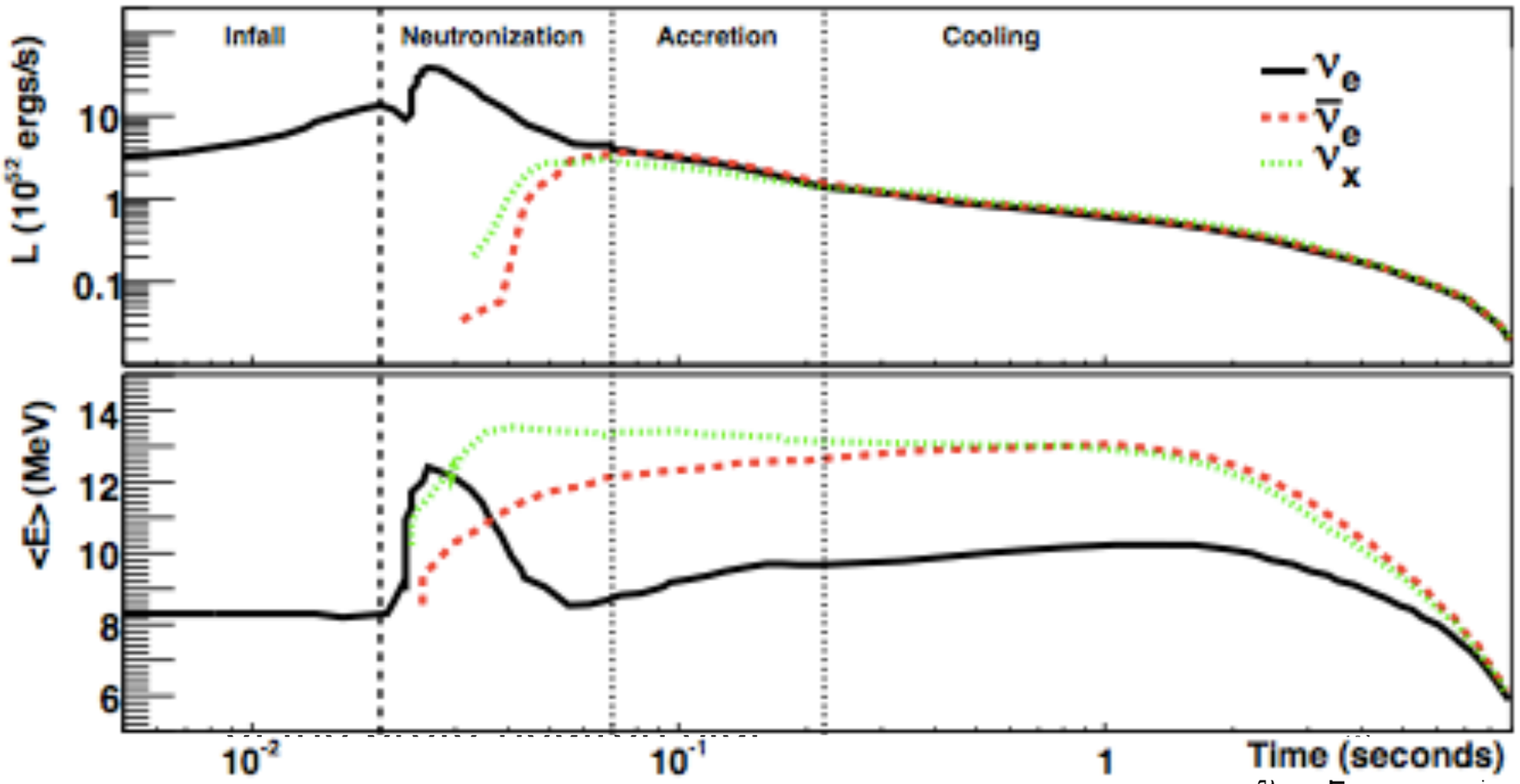

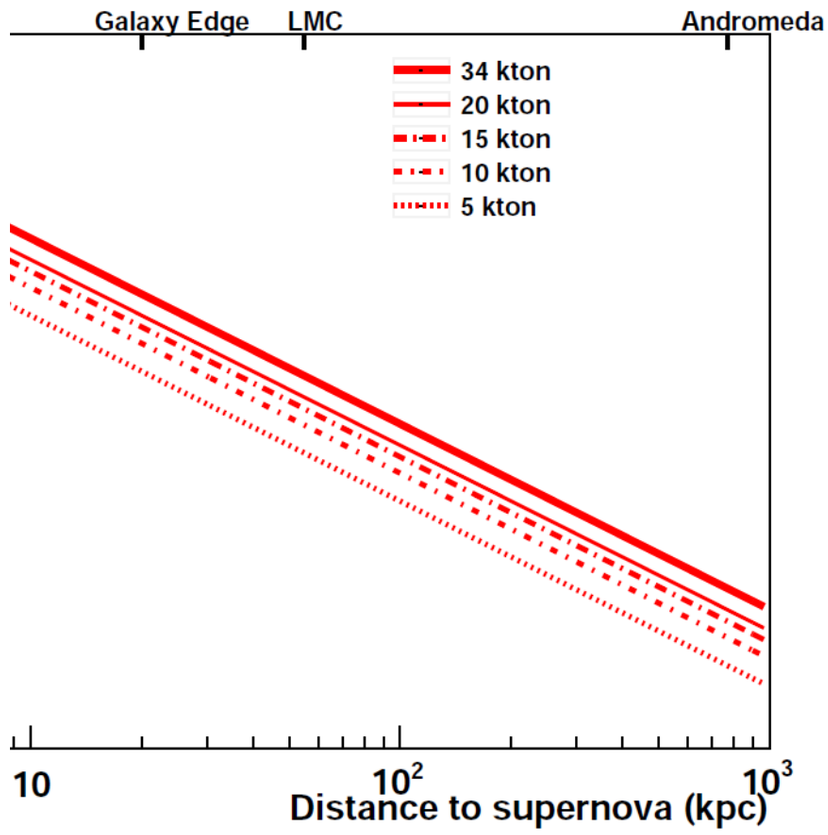

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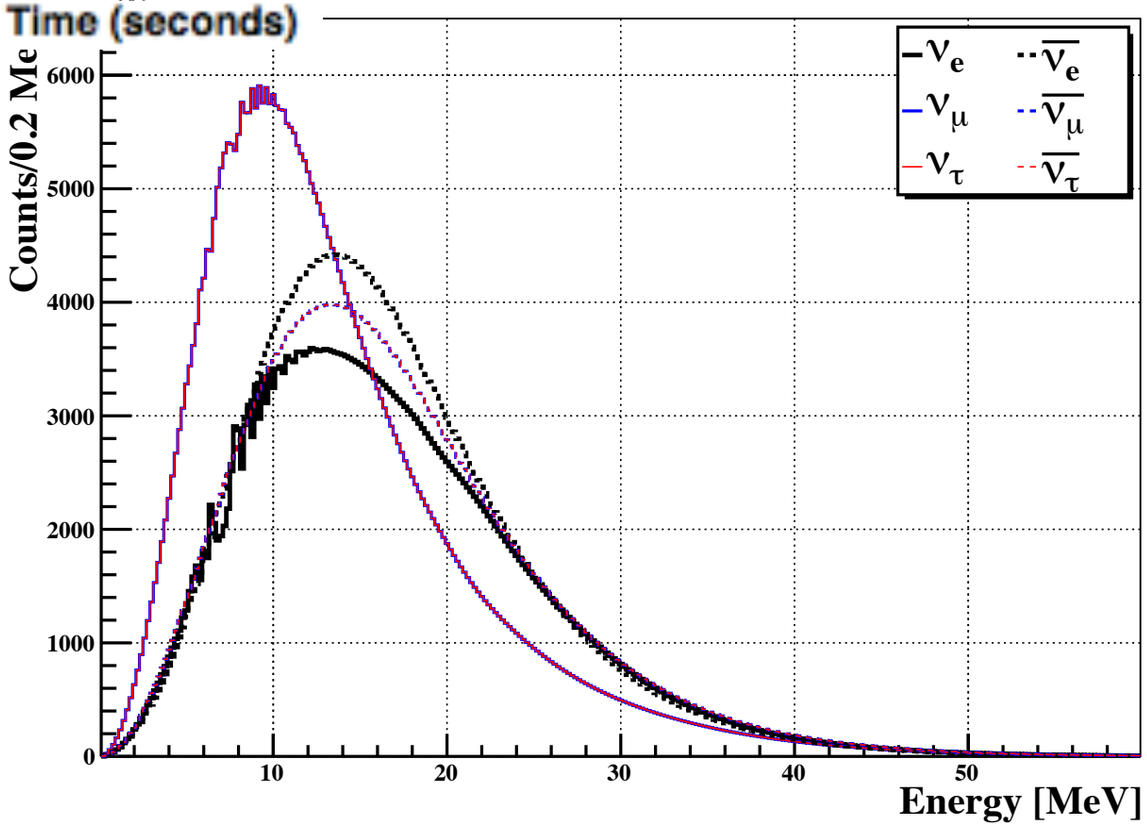
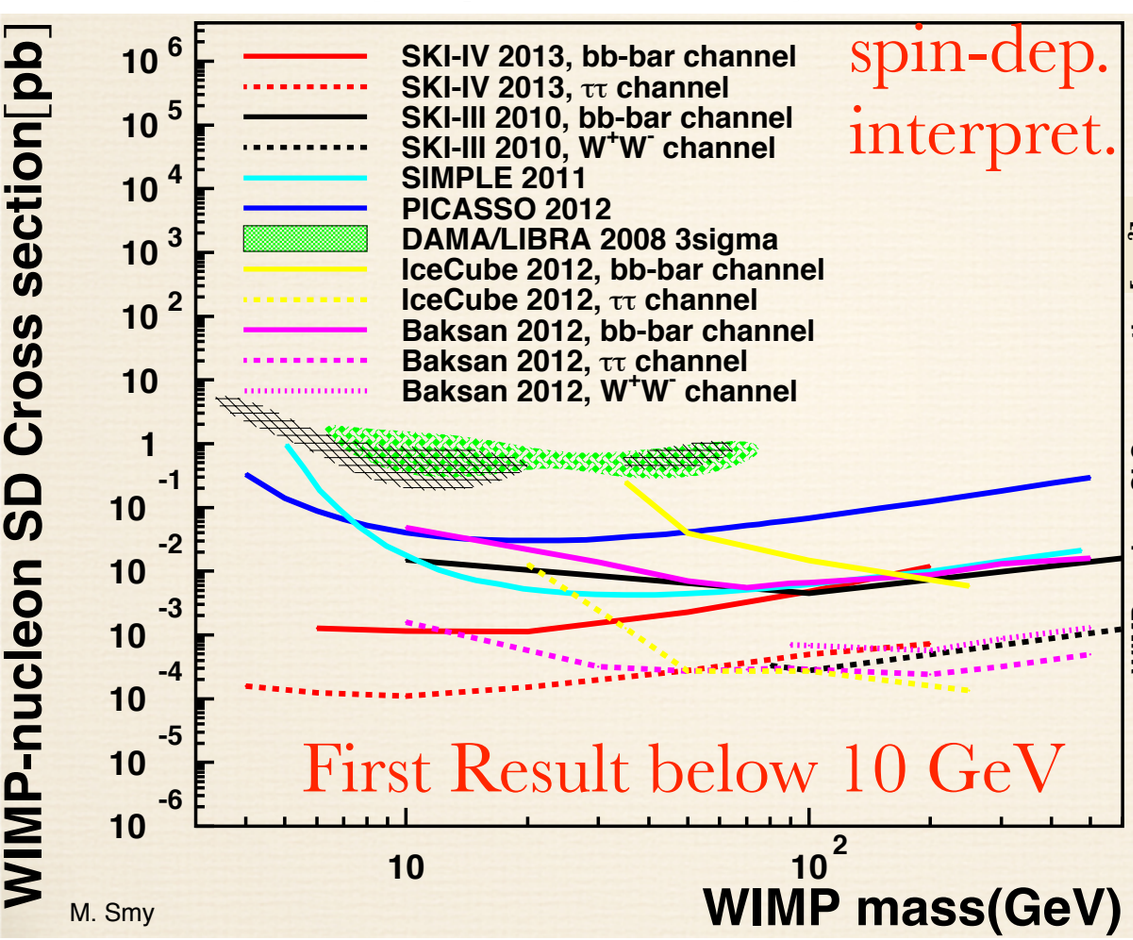
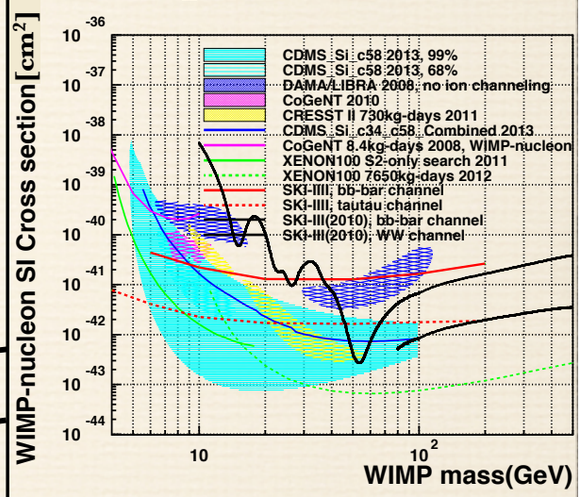


Indirect DM from Neutrinos

- Operates on the assumption that WIMPs can get gravitationally trapped in heavy things (Earth, Sun, galactic center)
- Search for neutrino emission from WIMP annihilation above backgrounds like atmospheric neutrinos
- Then assume that WIMP capture rate equals the annihilation rate (equilibrium) for a constant WIMP density in the object



spin-independent interpretation

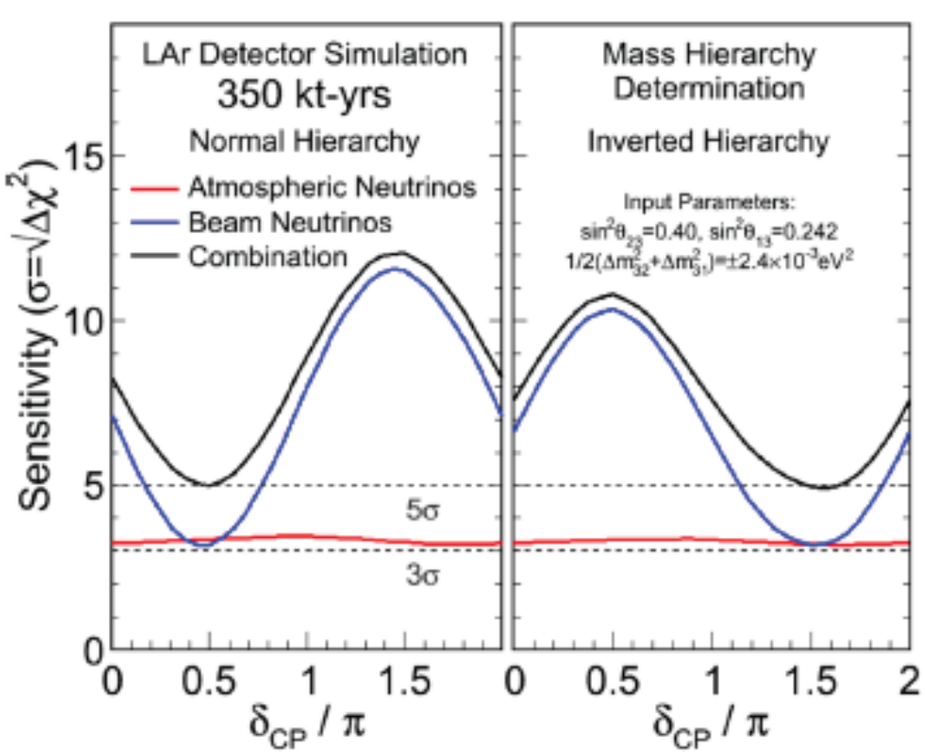


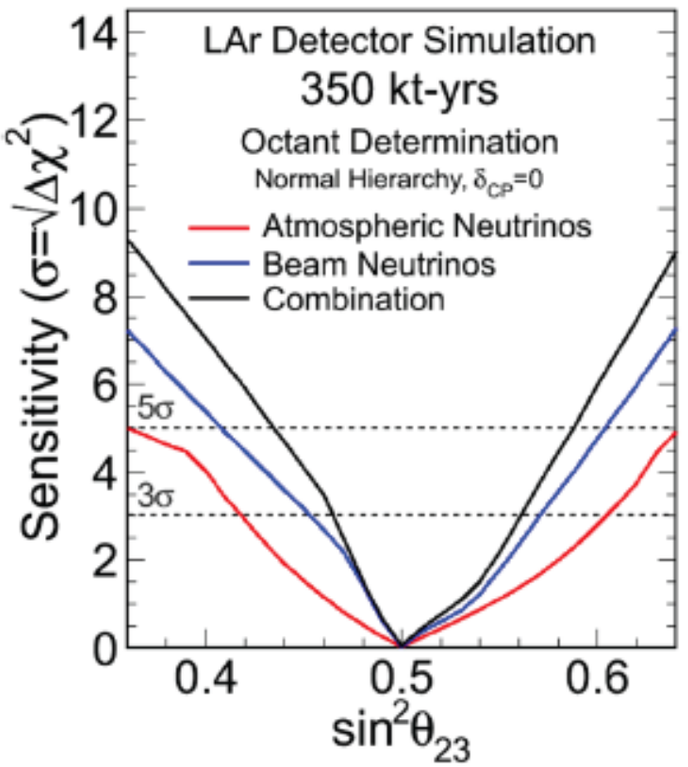
Already done in SuperK. LBNE should do it too.

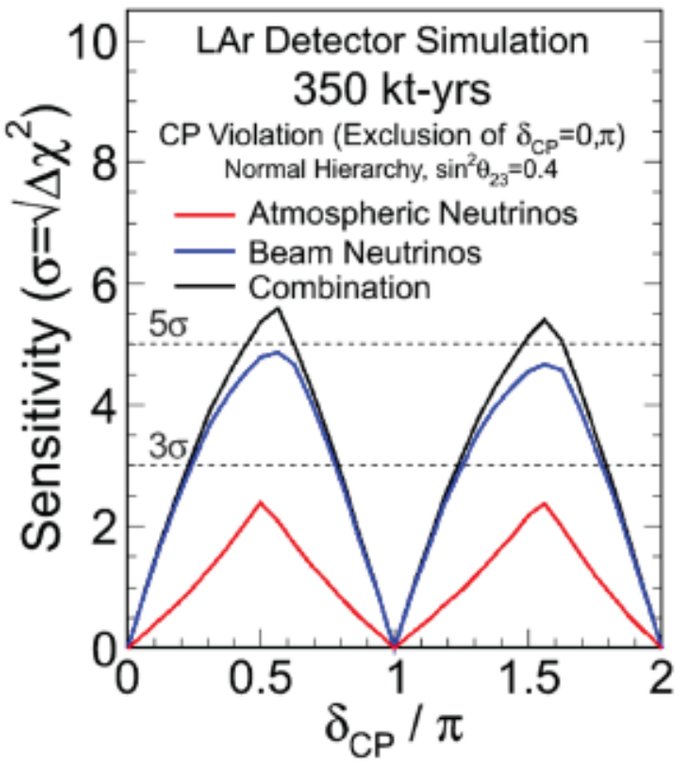
- Neutrino cross section in argon higher than water
- Excellent tracking capability for pointing back to astrophysical sources

Atmospheric Neutrinos

- Gives an “independent” cross check of much of the neutrino beam physics
- Hard to imagine doing *just* this in LBNE, but we’re going to get these events whether we like it or not, so we might as well do something smart with them

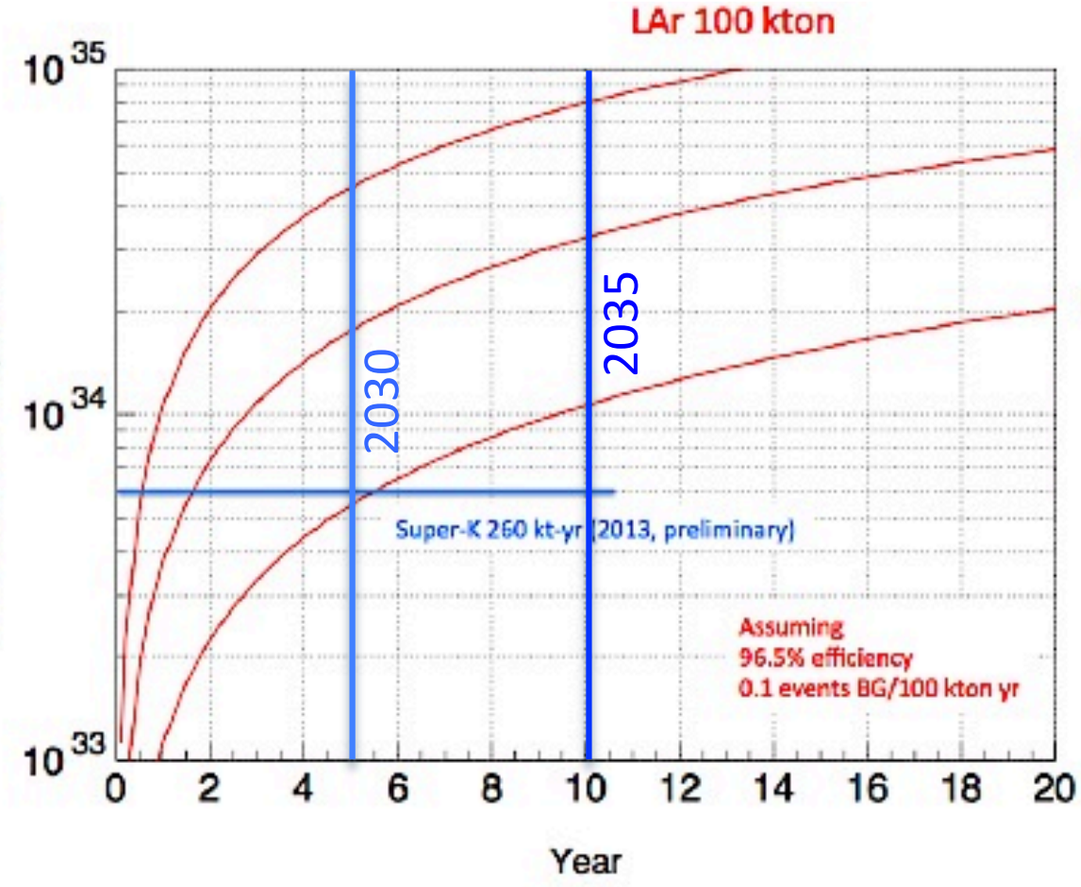


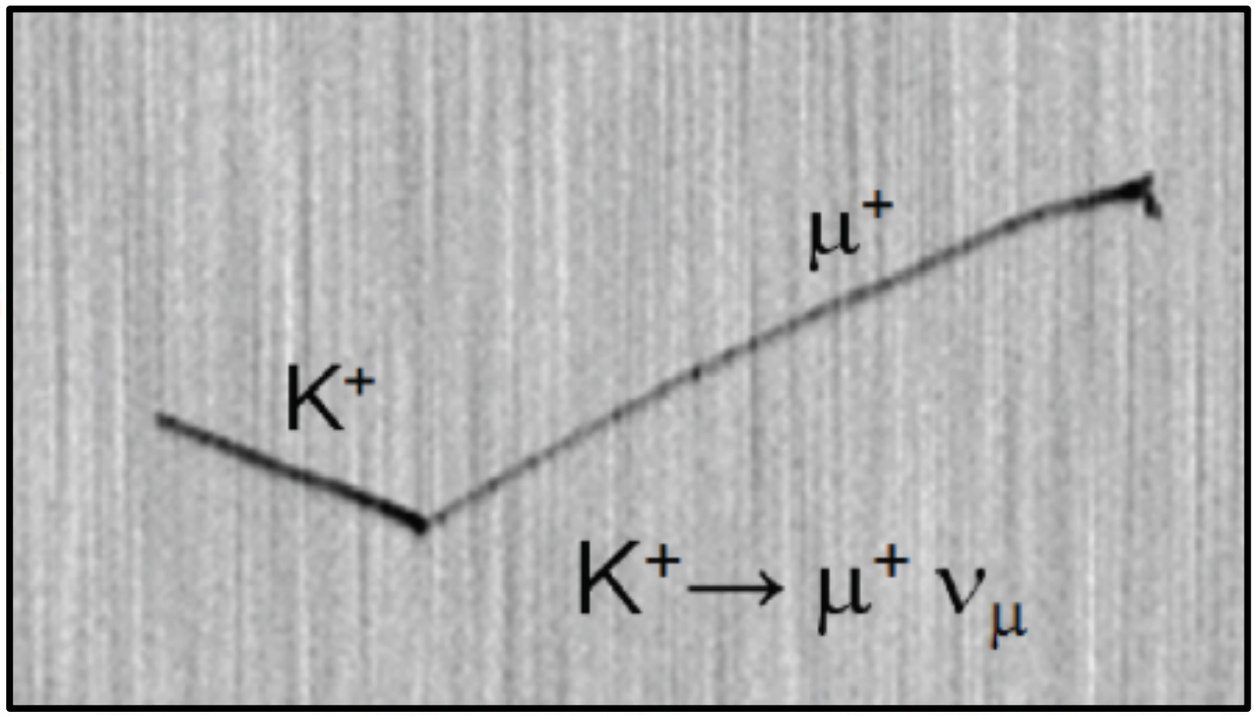




Nucleon Decay

- Liquid argon has a high efficiency and low background for kaon modes
- These are favored by SUSY, and very difficult to see in water Cherenkov detectors!





Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to \nu K^+$	19%	4	97%	1
$p \to \mu^+ K^0$	10%	8	47%	< 2
$p \to \mu^- \pi^+ K^+$			97%	1
$n \to e^- K^+$	10%	3	96%	< 2
$n \to e^+ \pi^-$	19%	2	44%	0.8

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The H.M.S. Beagle in Sydney Harbor, January 12, 1836

- The technical challenges that tie all this together
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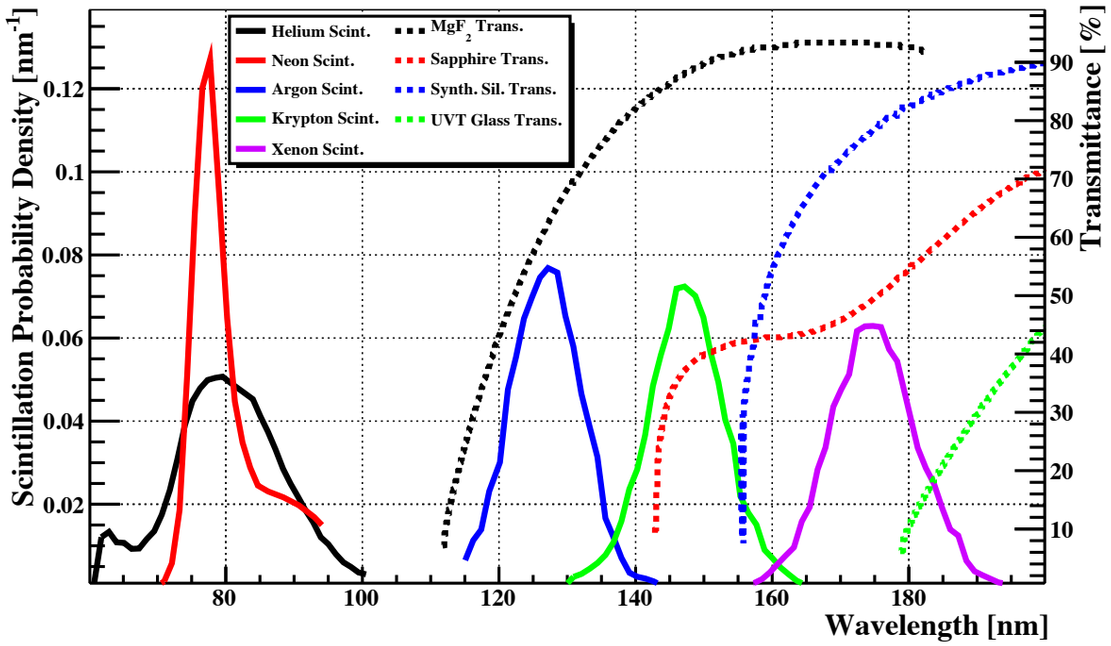
Non-Beam Events

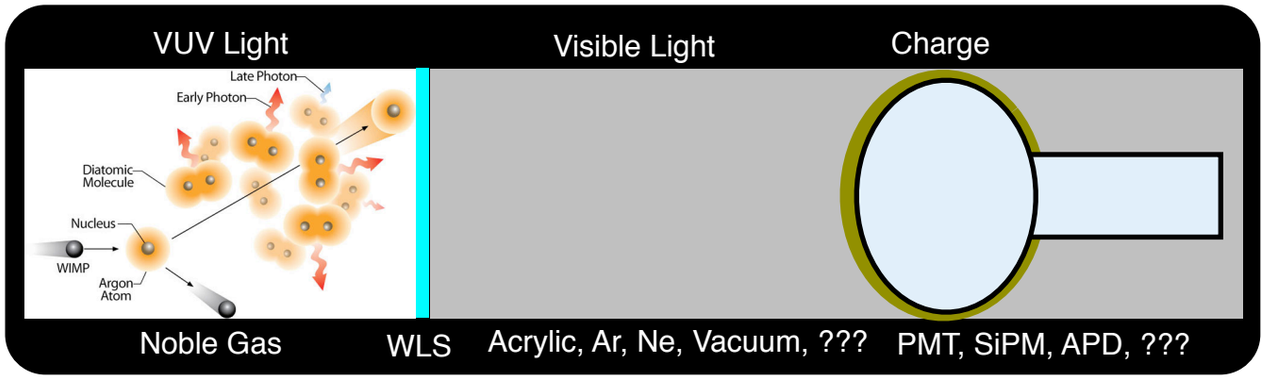
So, what do you need to see all of these events that aren't associated with a beam spill at Fermilab?

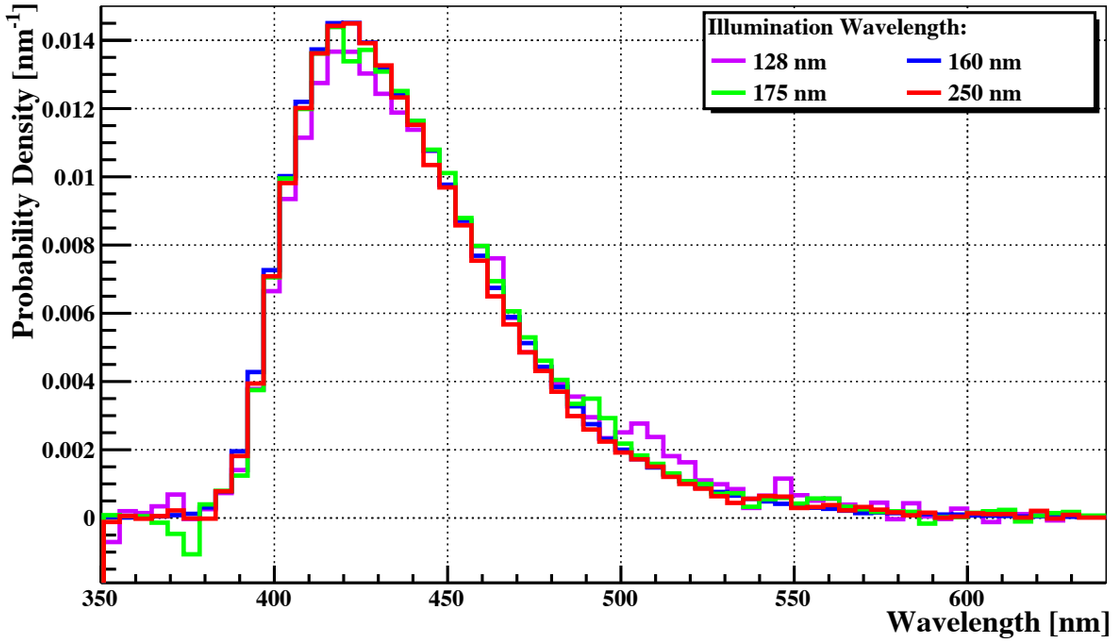
- Reliable, efficient trigger based on argon scintillation
- Threshold low enough to see these events
- Understanding of backgrounds in this region
- Understanding of detector response in this region

Noble Gas Scintillation

- Argon is an excellent scintillator, but, the light is in the vacuum ultraviolet
  - Rayleigh scattering goes like λ^{-4} (position information gets scrambled)
  - VUV light is strongly absorbed by nearly everything
- Best bet is usually to turn that VUV light into visible, with some fluor, but...
- very few of the efficiencies of these fluors have been measured, and if they have, often not at the wavelength you want, or under the conditions you care about







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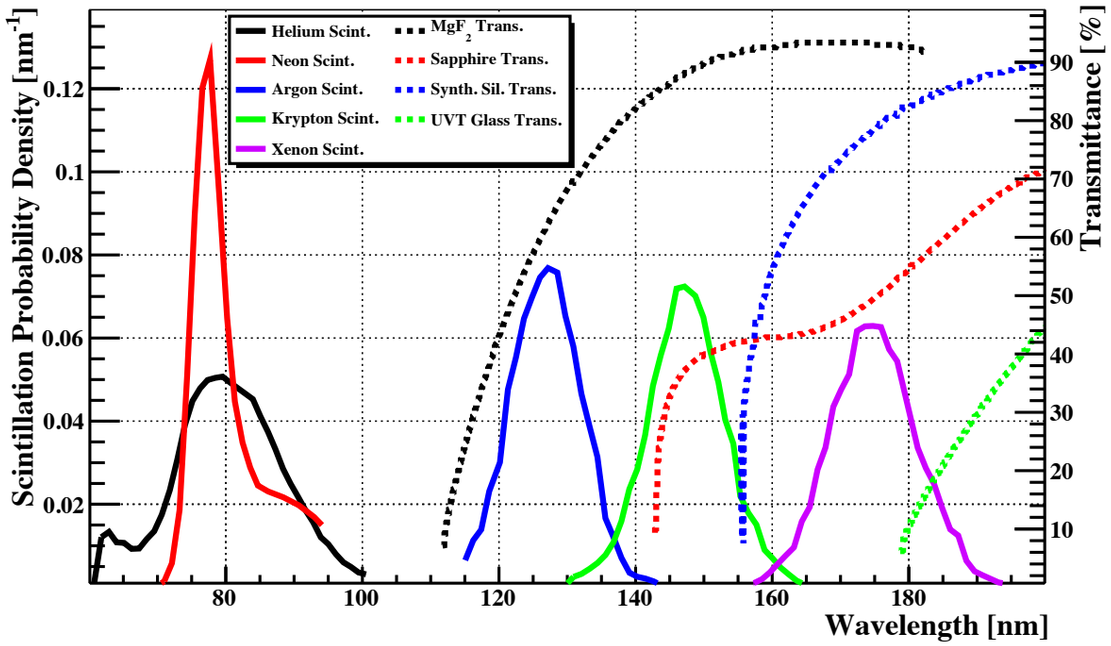
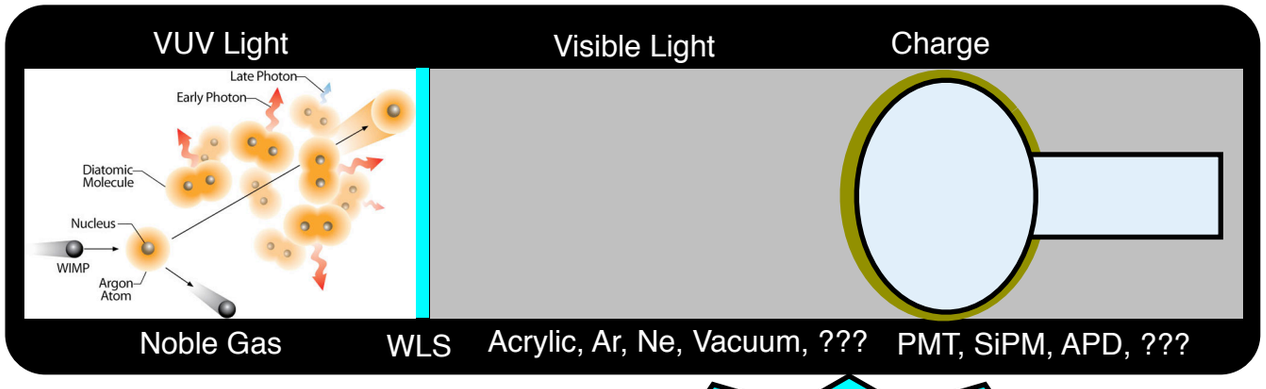
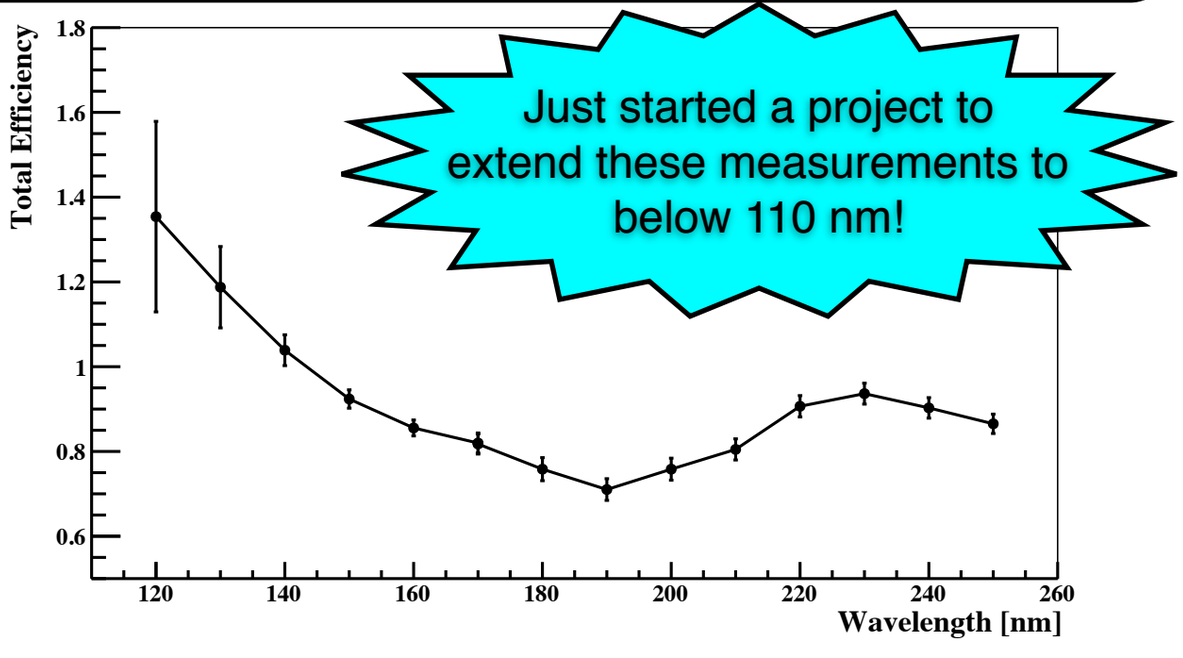
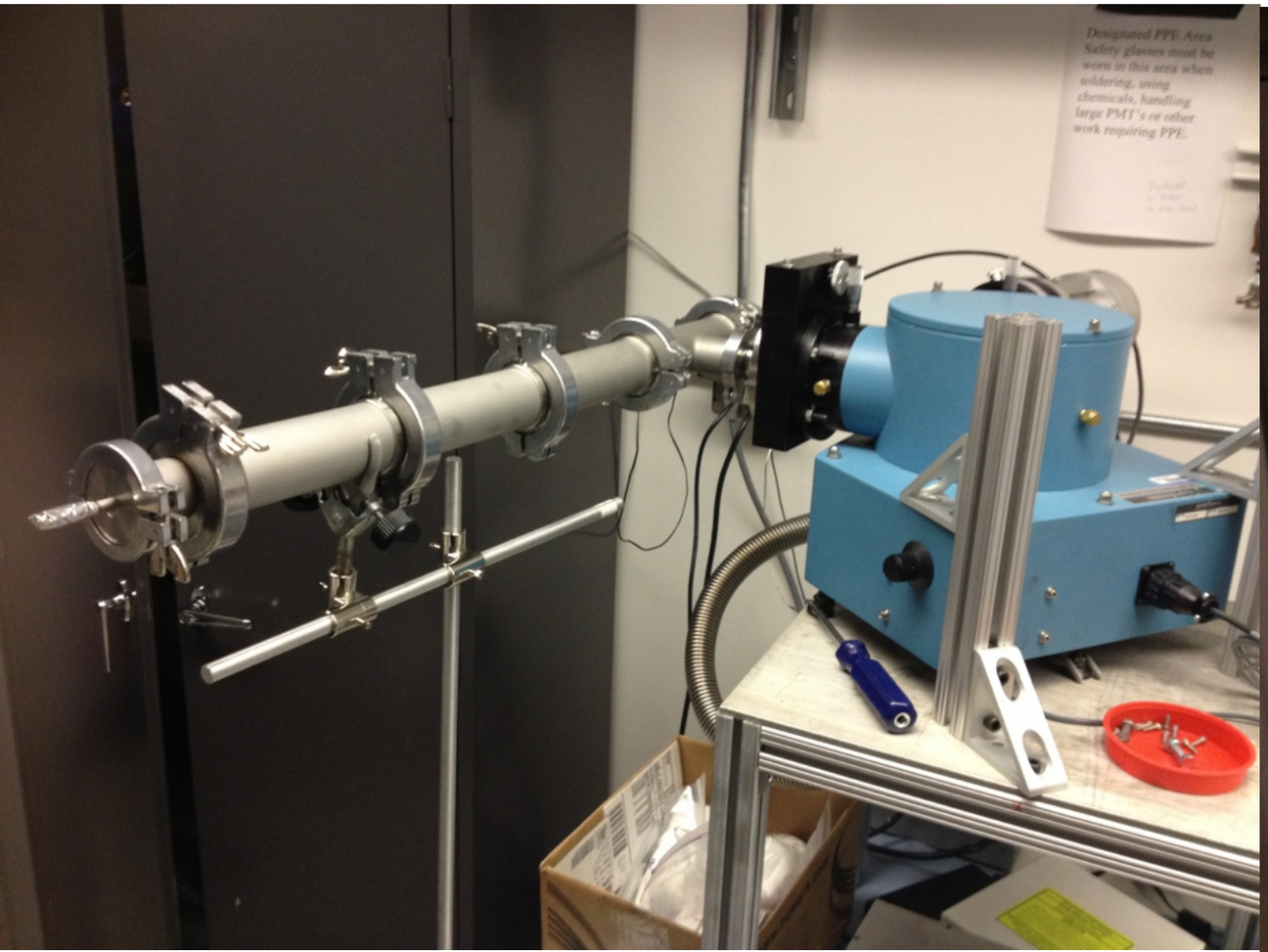


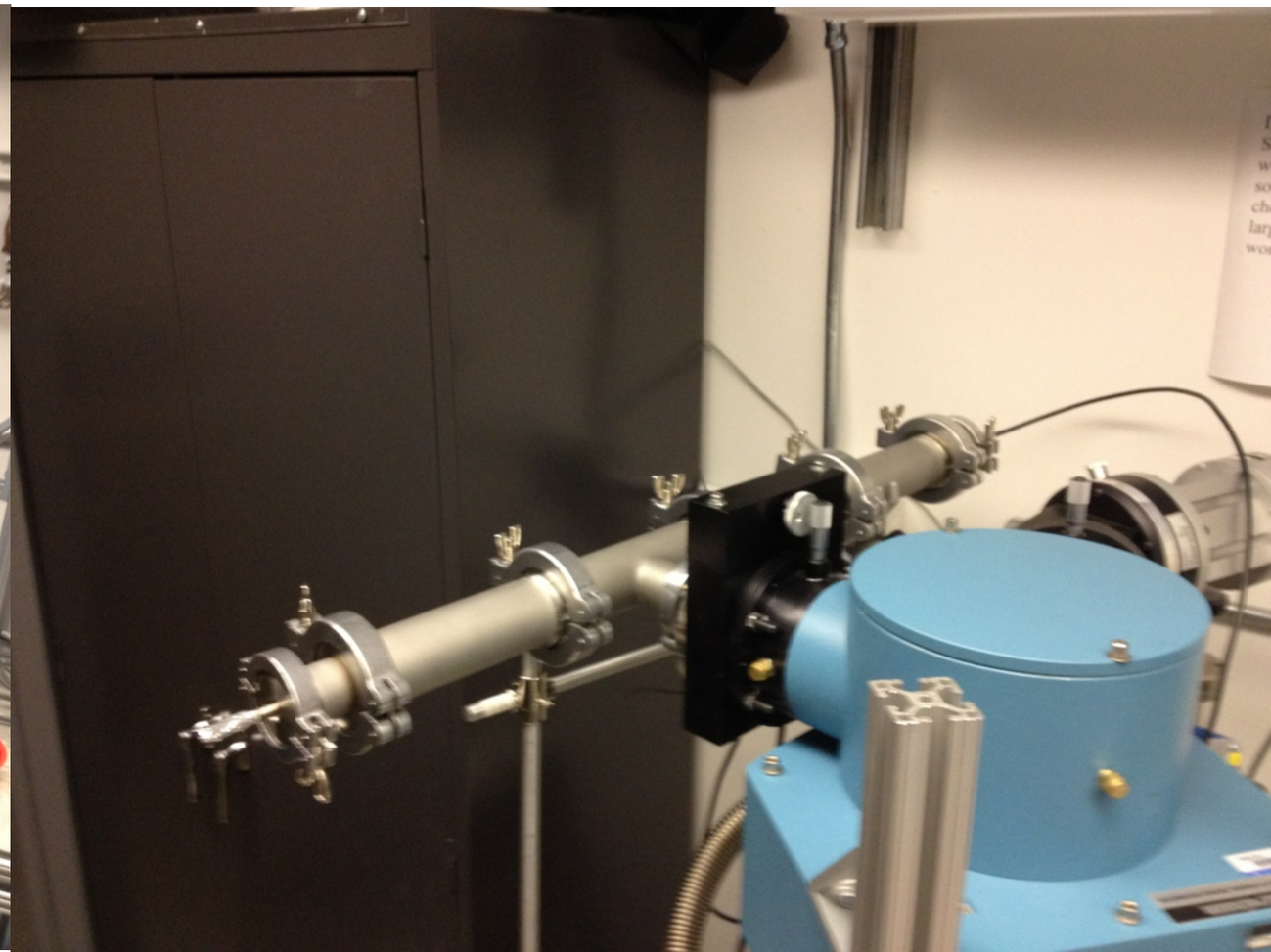




WLS Plastic for LBNE

- Got WLS doped bars that match the LBNE baseline (25 x 6 x 525 mm) last year
- Measured the fluorescence efficiency at the end of the bar resulting from illumination at three points along its length
- Two bars (one TPB and one BisMSB) are already at CSU for further tests, some more may be going to Tall Bo.





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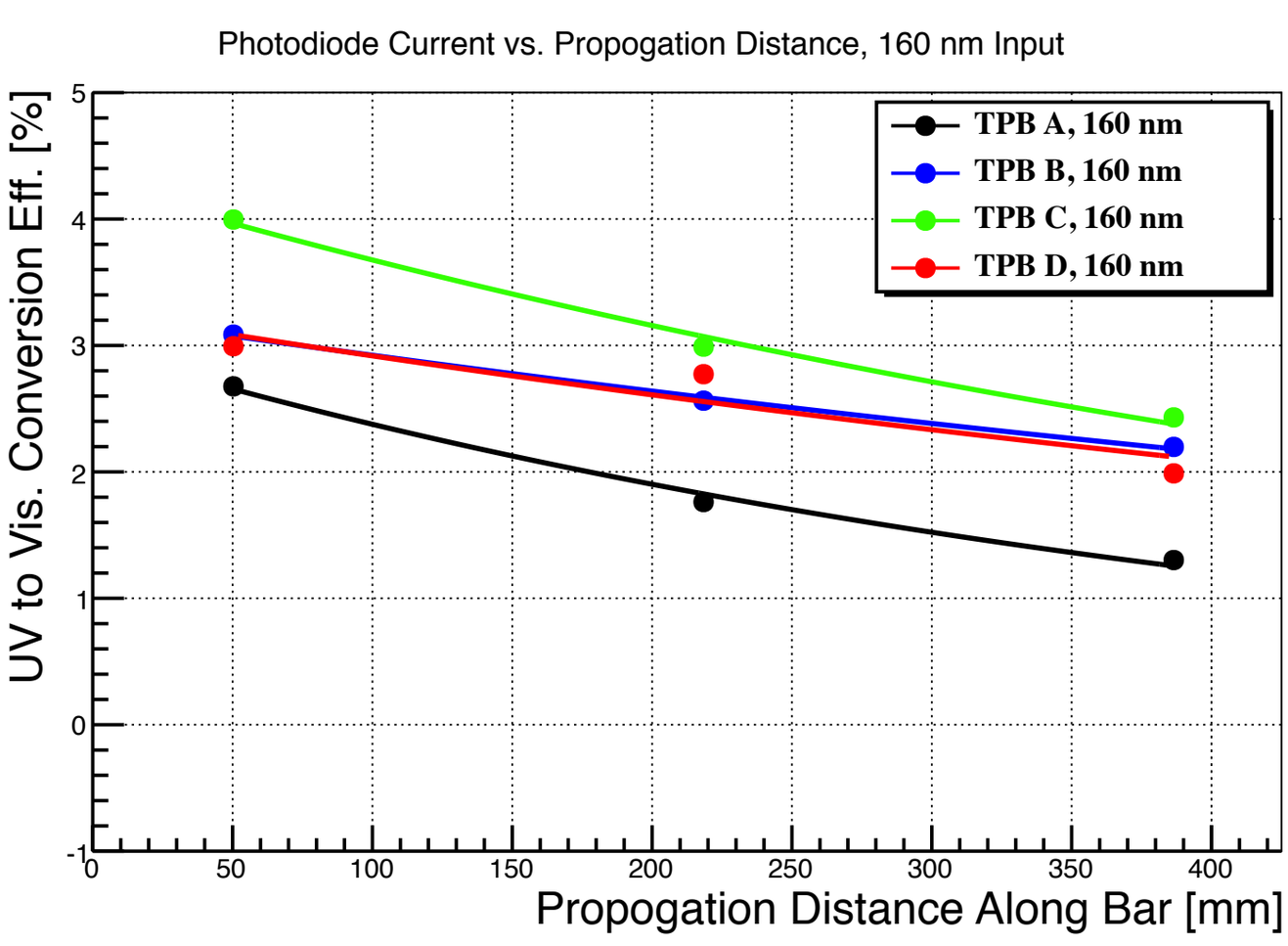

Fl. Eff. [%]	Att. Len [mm]
3.0 ± 0.11	449.1 ± 40.3
3.2 ± 0.039	980.1 ± 51.8
4.3 ± 0.12	657.9 ± 61.4
3.3 ± 0.32	895.6 ± 350.5

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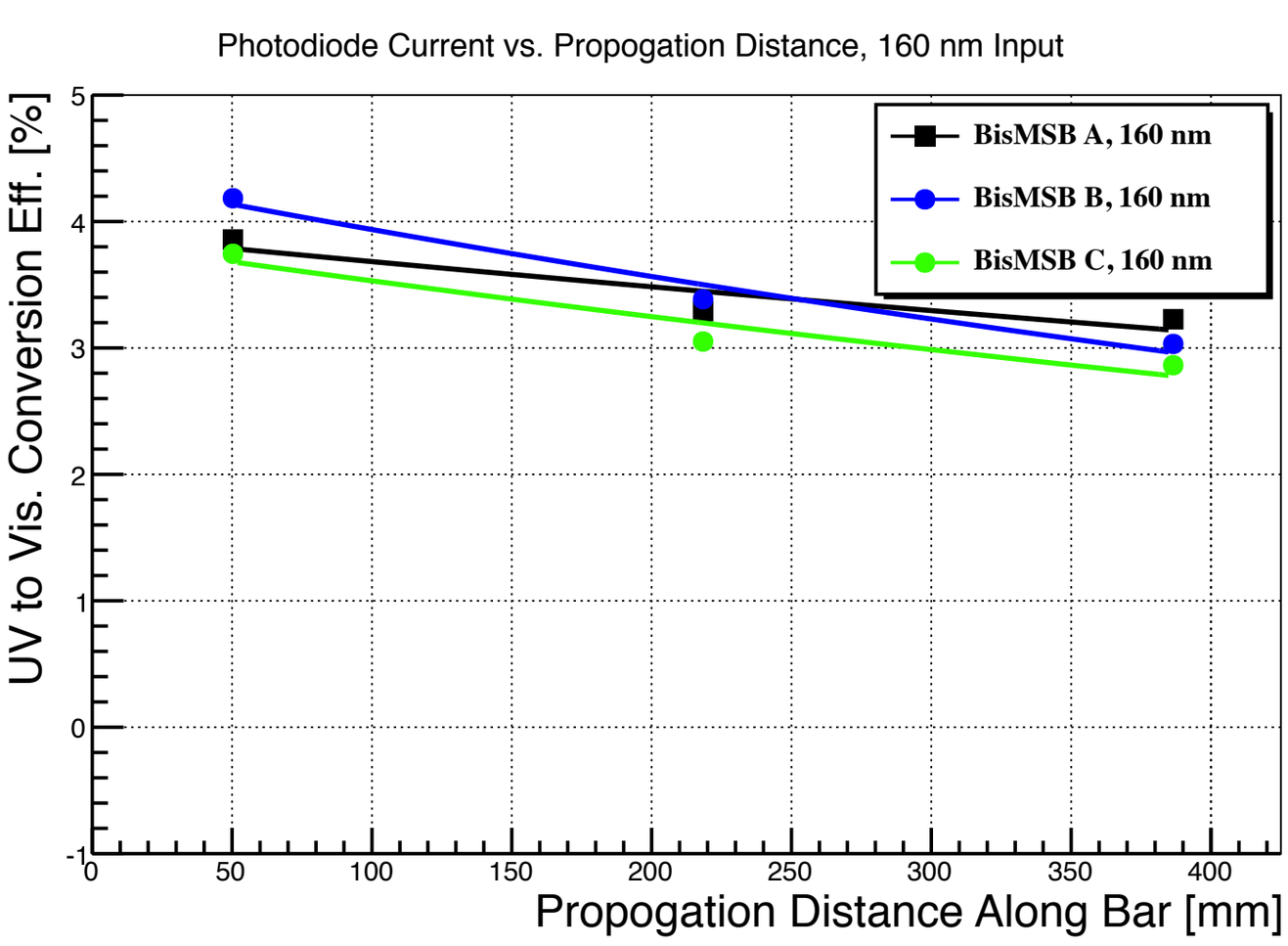
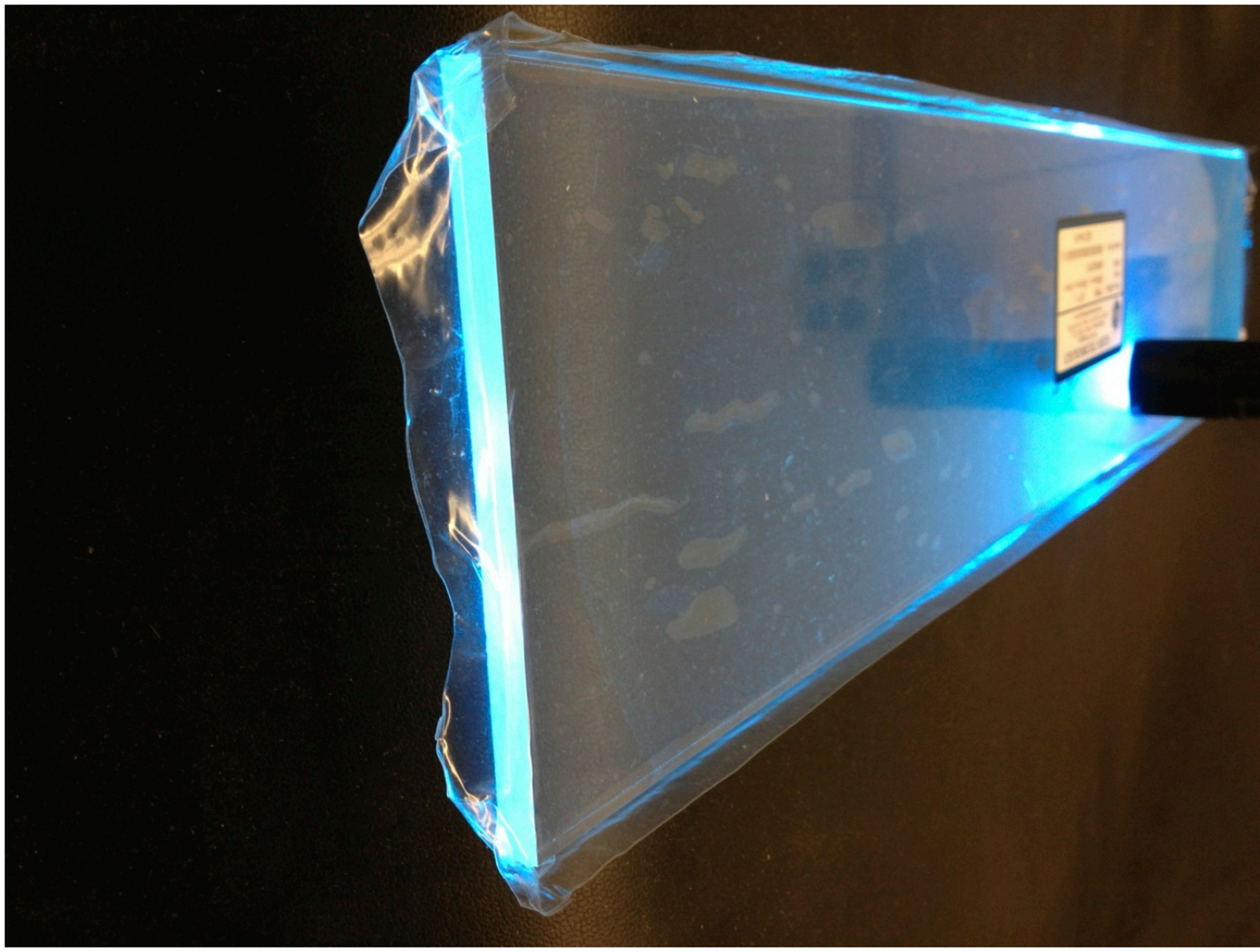
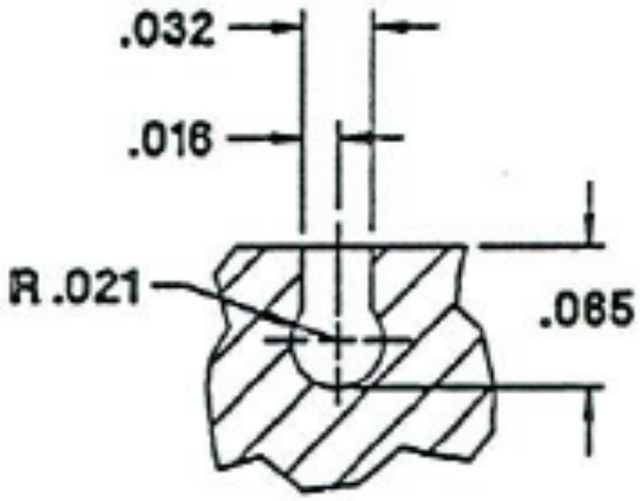


Fl. Eff. [%]	Att. Len [mm]
3.9 ± 0.22	1798.9 ± 770.6
4.3 ± 0.17	1008.9 ± 177.5
3.8 ± 0.21	1195.6 ± 347.2

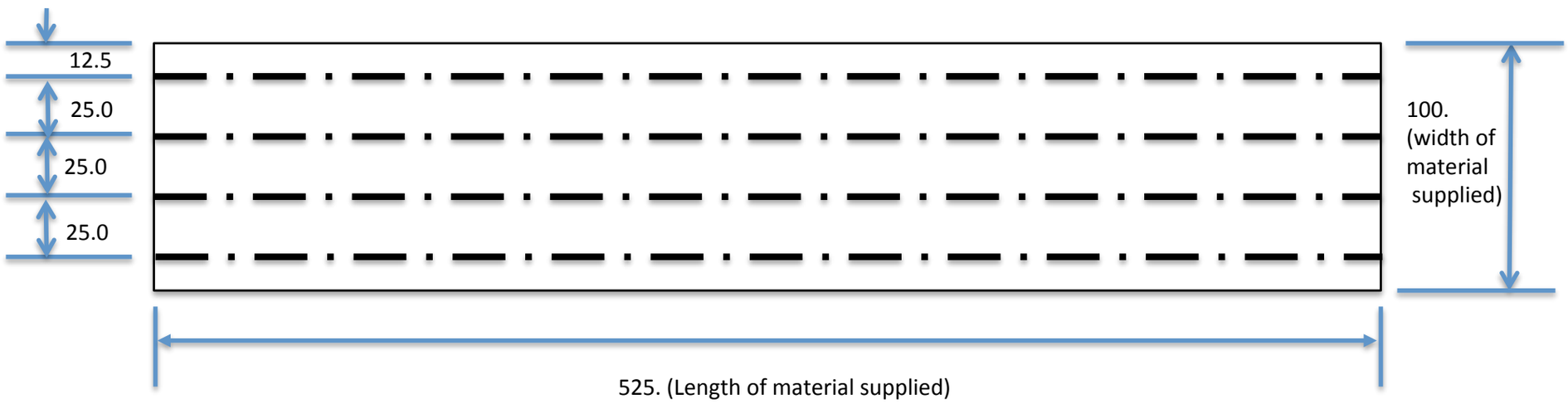
WLS Plastic with Embedded Fibers

- Also bought some wider panels to experiment with fiber readout
- Sent a drawing off to the shop at LBL on January 20.
- Will begin with some 250 nm LED tests once this is back from the shop.



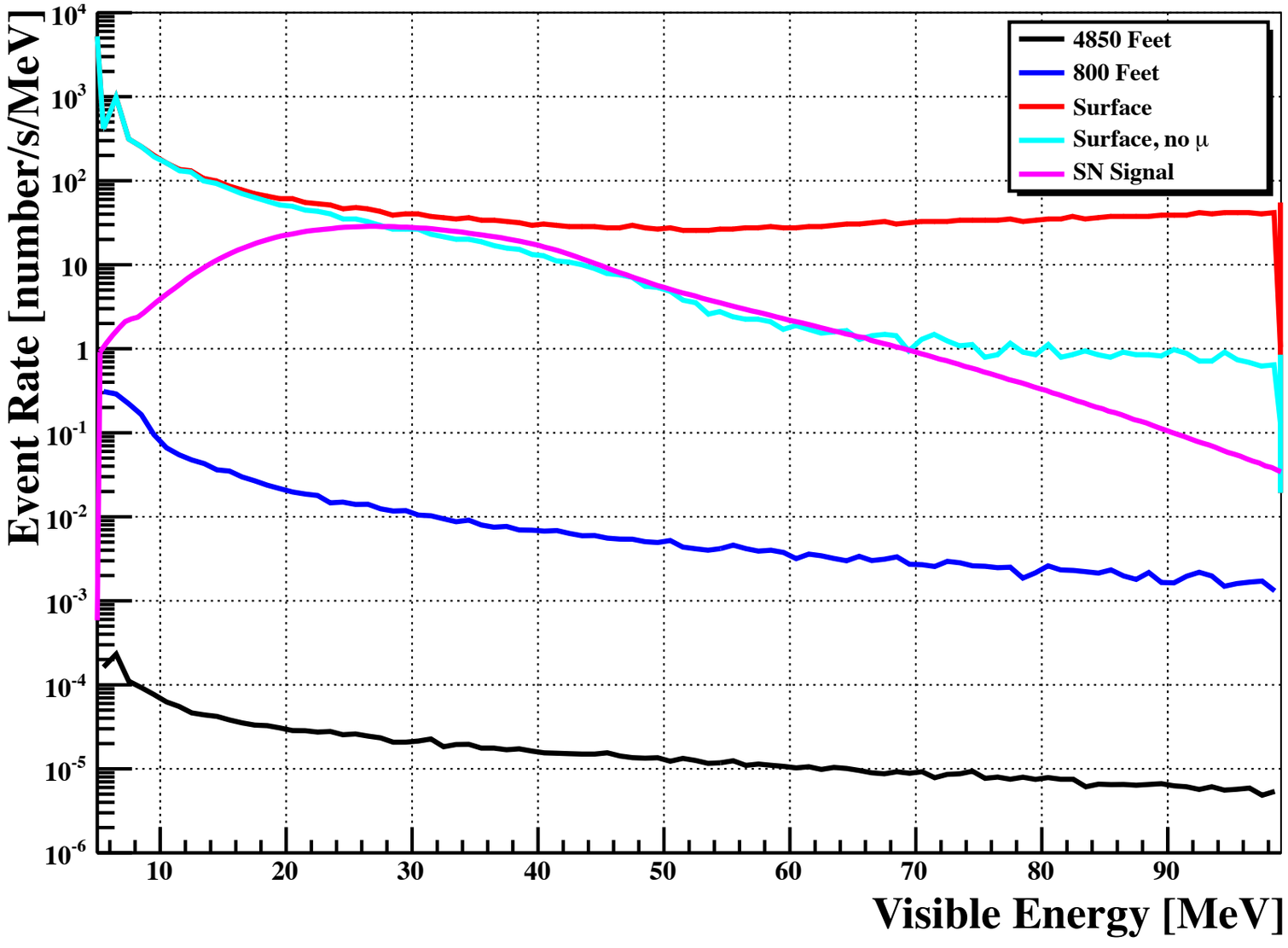


Typical Groove X-Section



Radioactive Backgrounds

- Cosmic ray shower backgrounds (including neutrons)
- Cosmogenic radioactive backgrounds
- Intrinsic radioactive backgrounds



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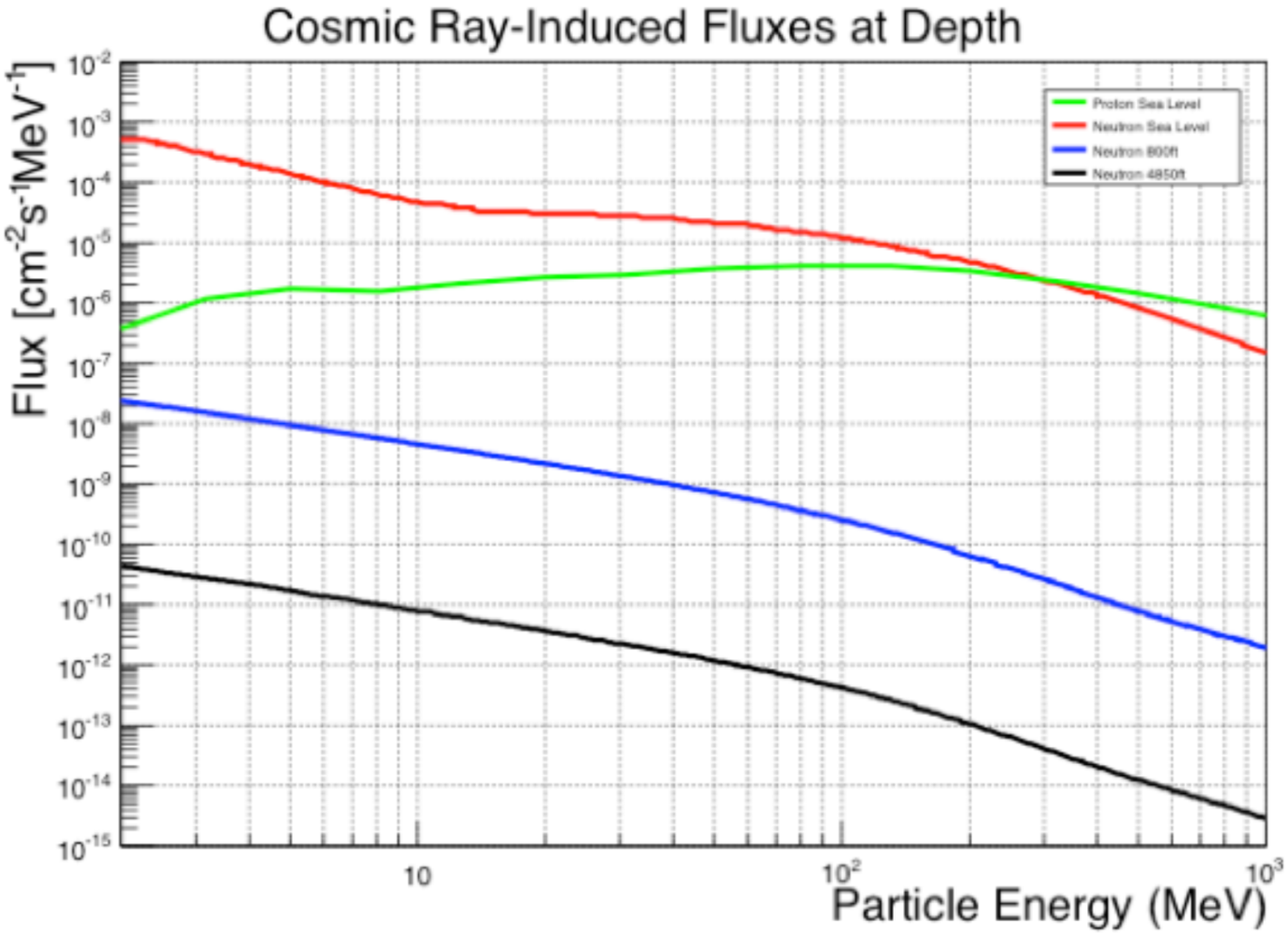

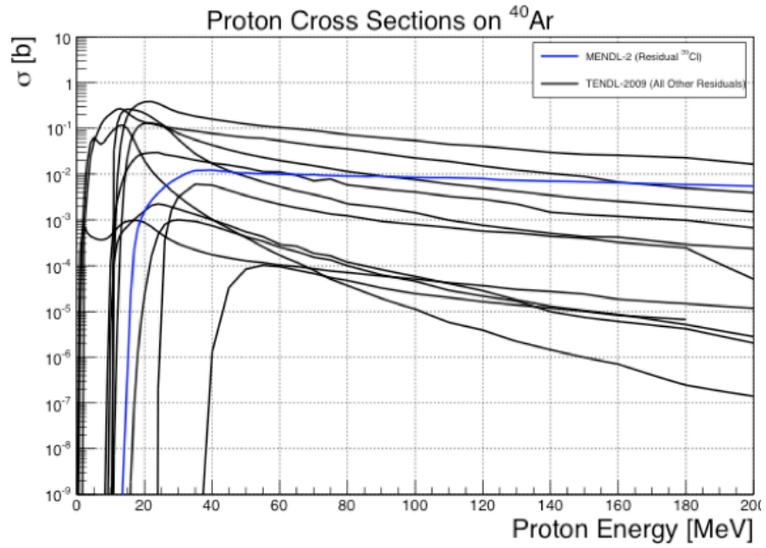

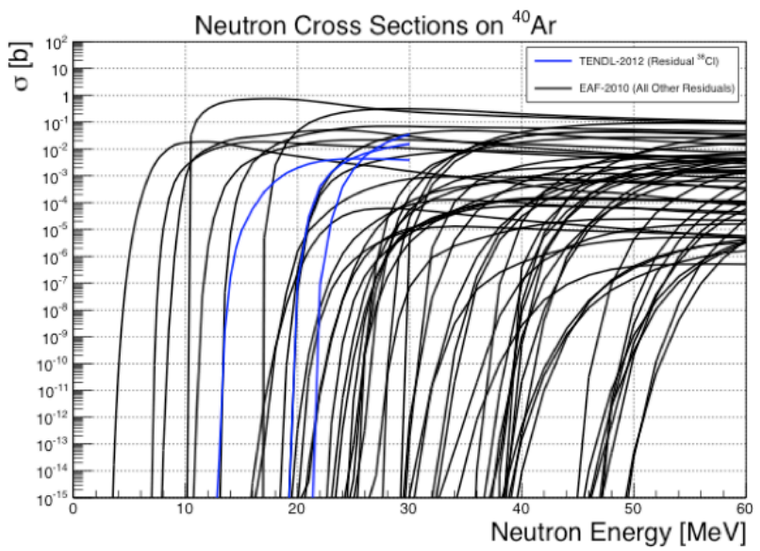

Radioactive Backgrounds

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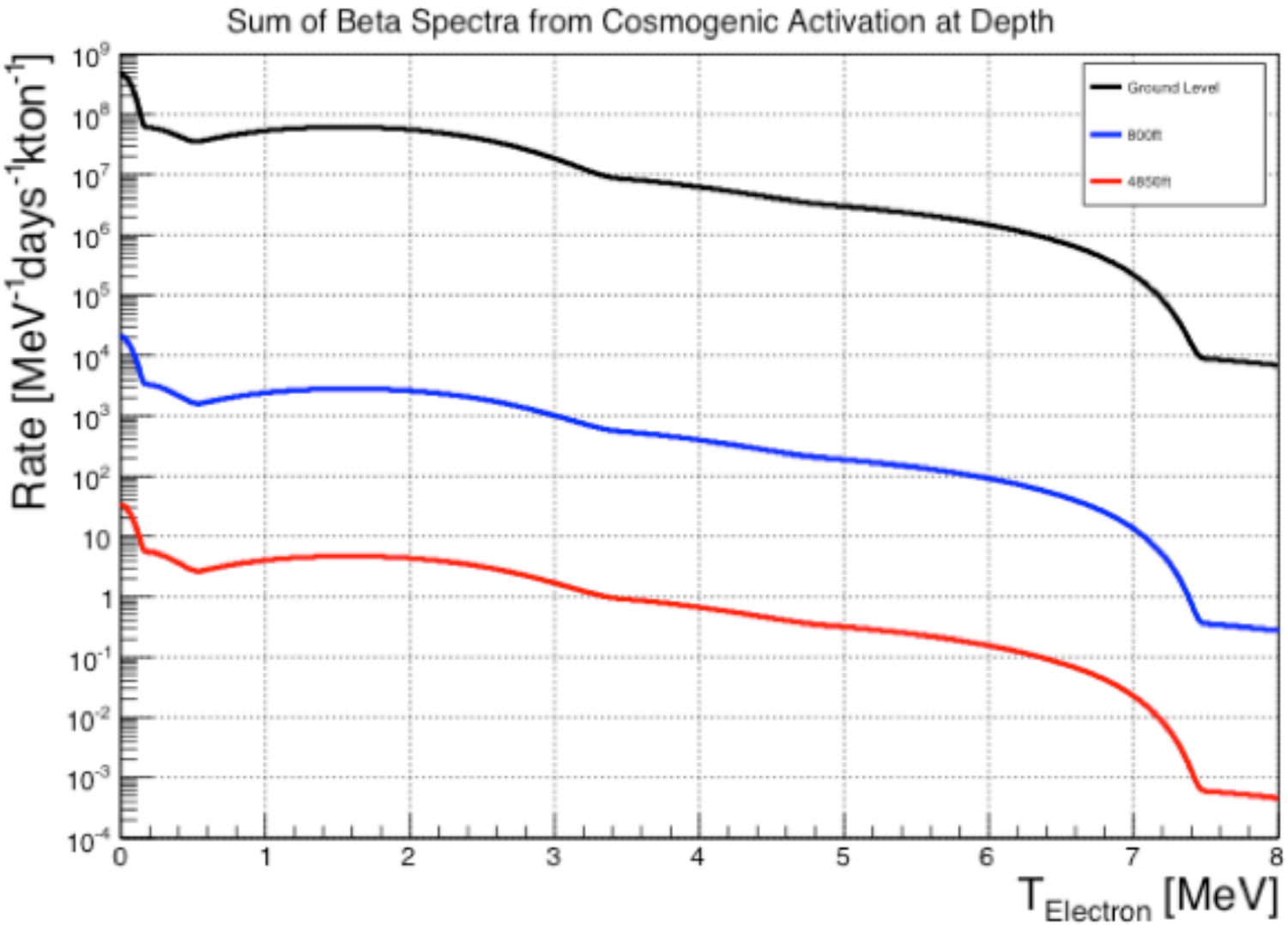

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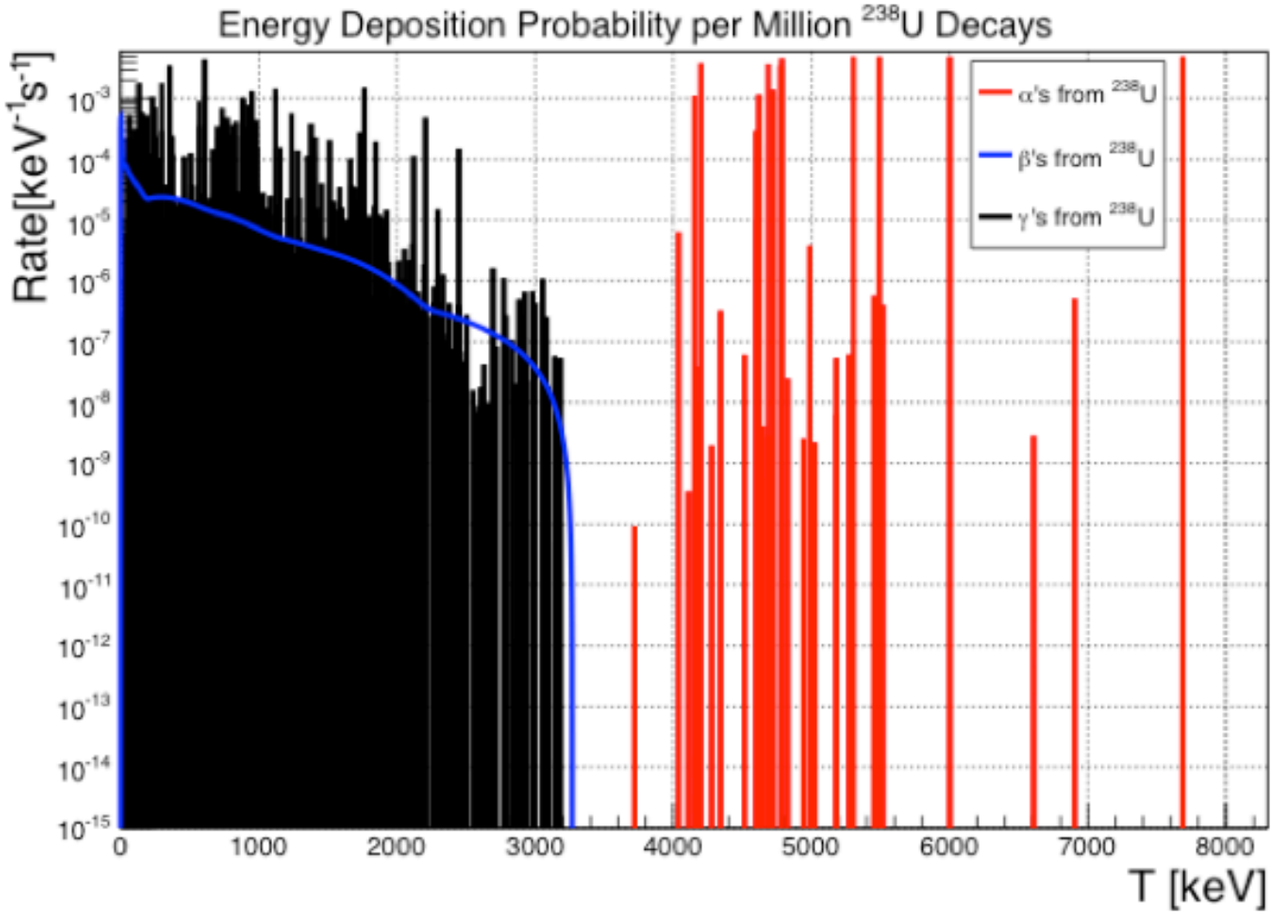

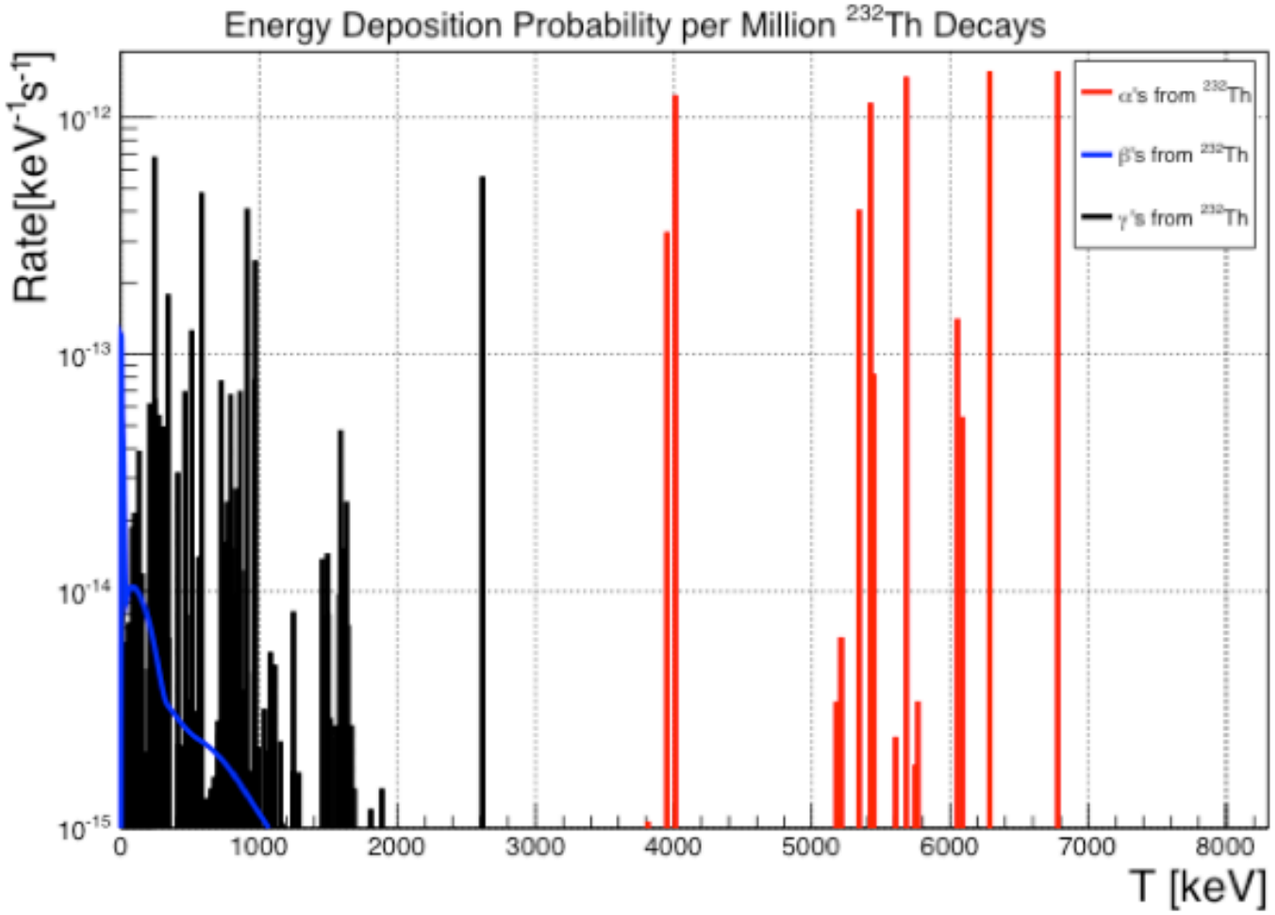

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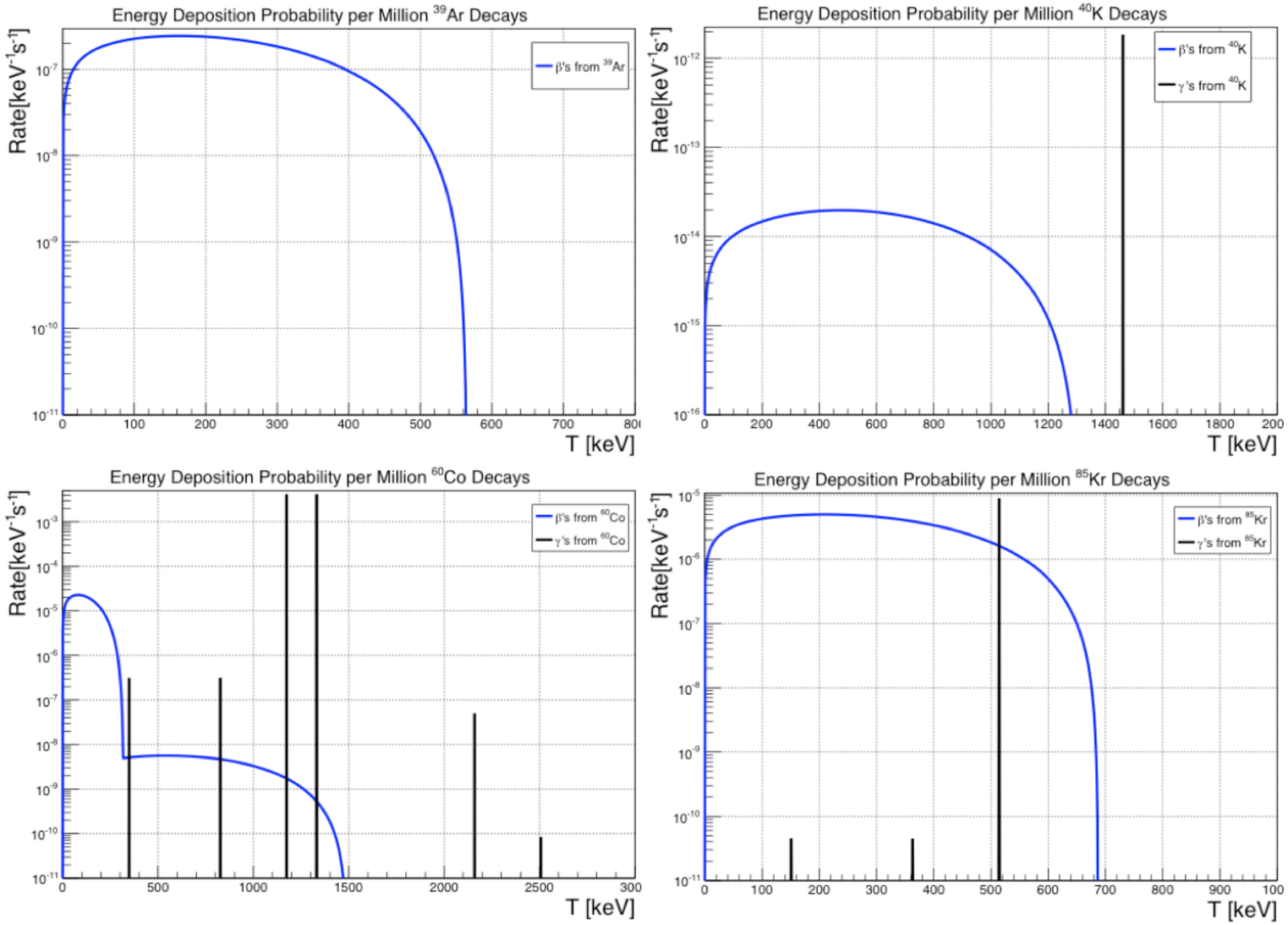
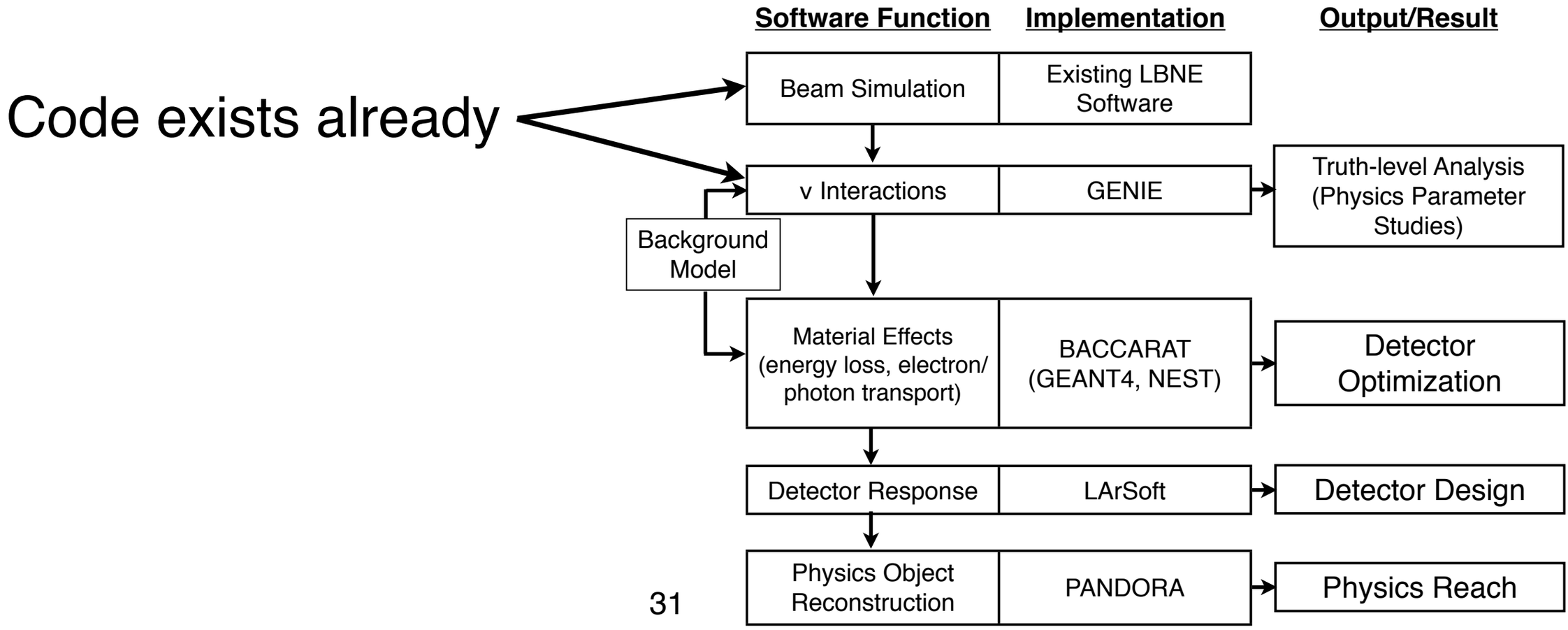


Detector Modeling

- There's already an LBNE simulation and reconstruction package, called "LArSoft," but...
  - It's REALLY interwoven with the specific version of Scientific Linux for FNAL
  - The learning curve is quite high because of the very large number of package dependencies
- So, we're talking about promulgating an alternate simulation package that *could* be fed into other reconstruction and analysis software...

Code exists already



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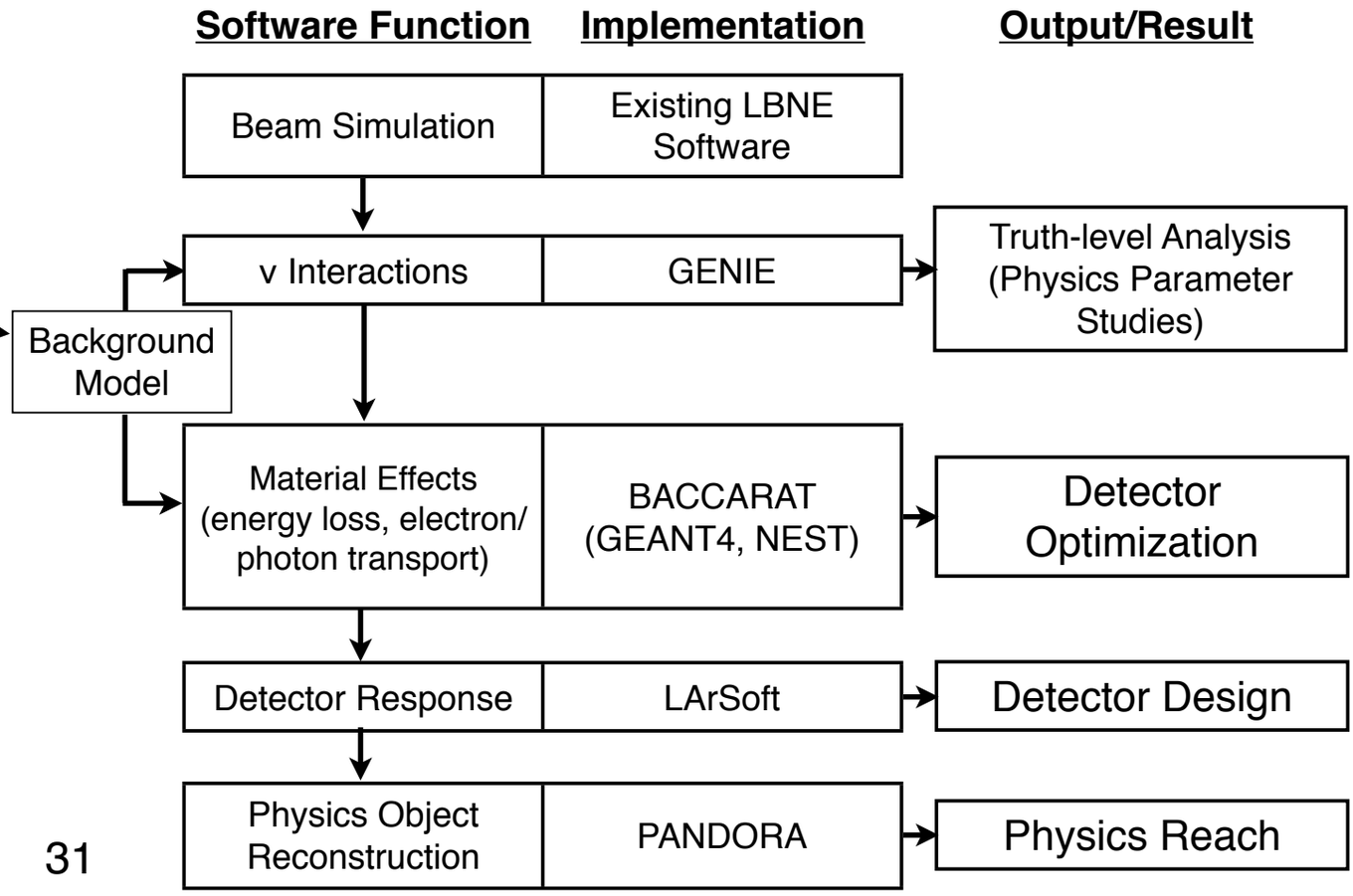
Talked about on the last slide...



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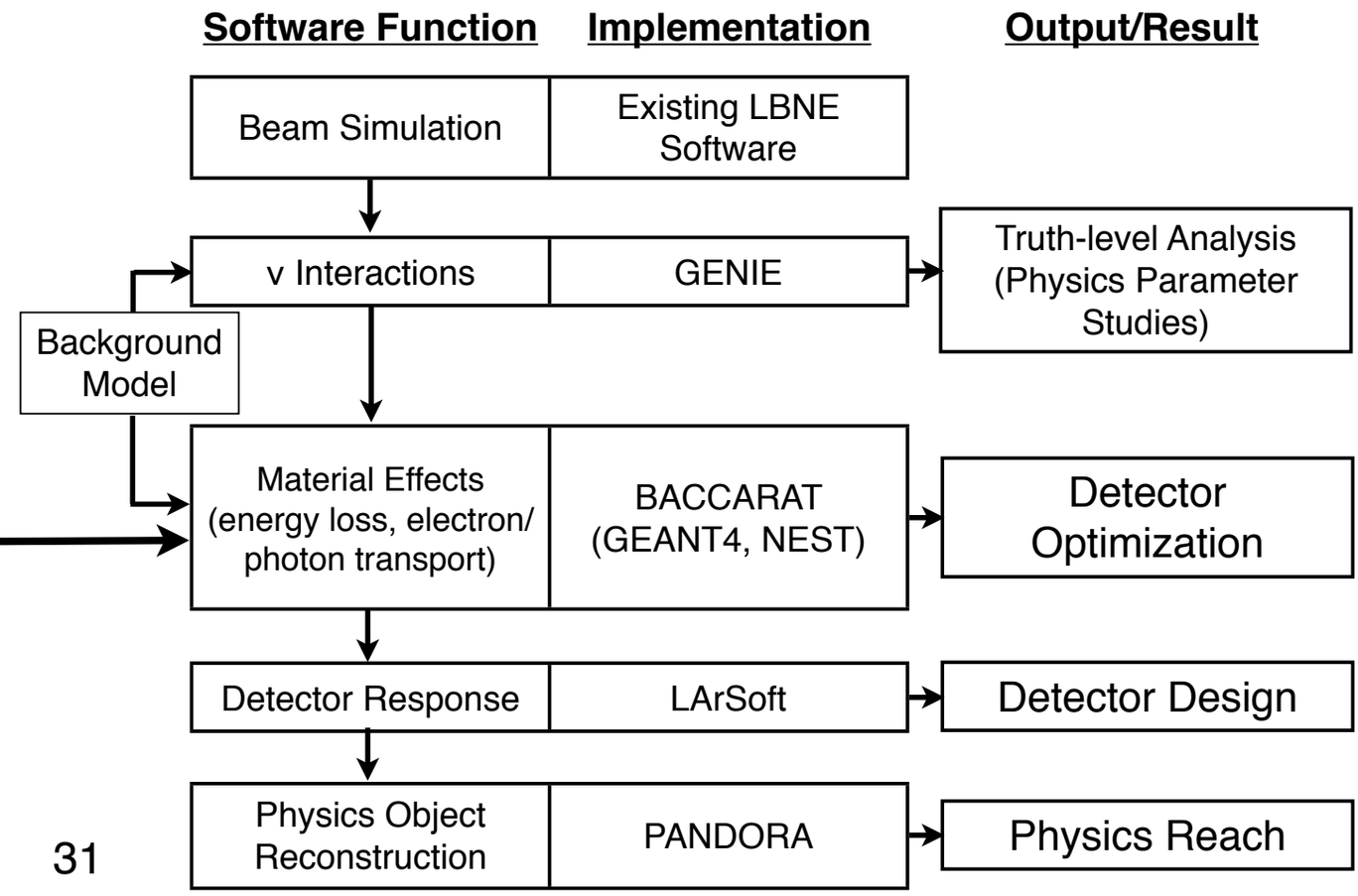
BACCARAT
"Basically a Component-Centric Analog Response to AnyThing"

- Grew out of the LUX simulation framework
- Requires Geant4 and ROOT, but everything else works "batteries included!
- Geometries exist for generic, and several real detectors
- Plan for analytic detector response functions to start, will feed into real reconstruction software later



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Also a need for "connective tissue" software that passes data back and forth

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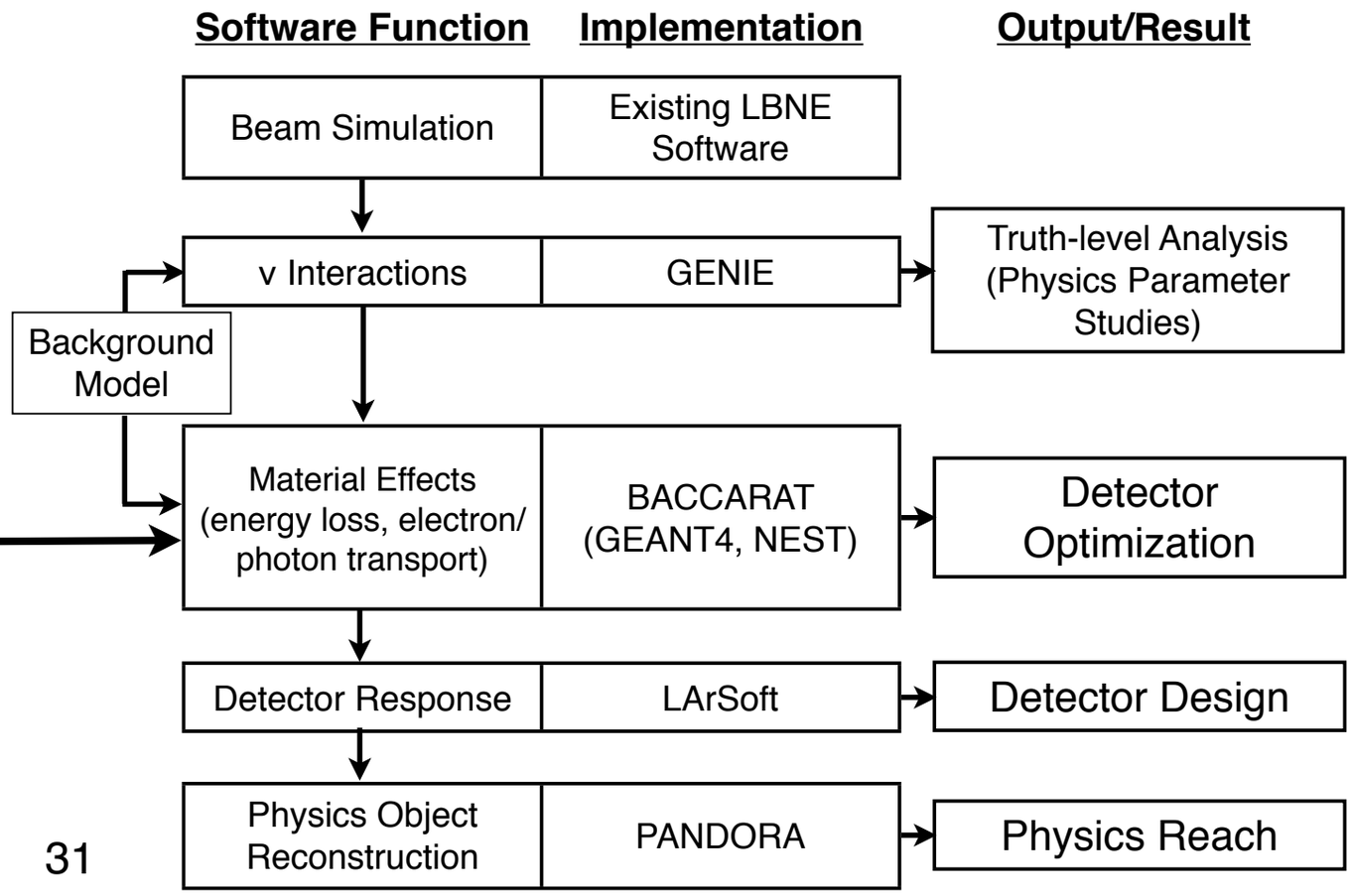
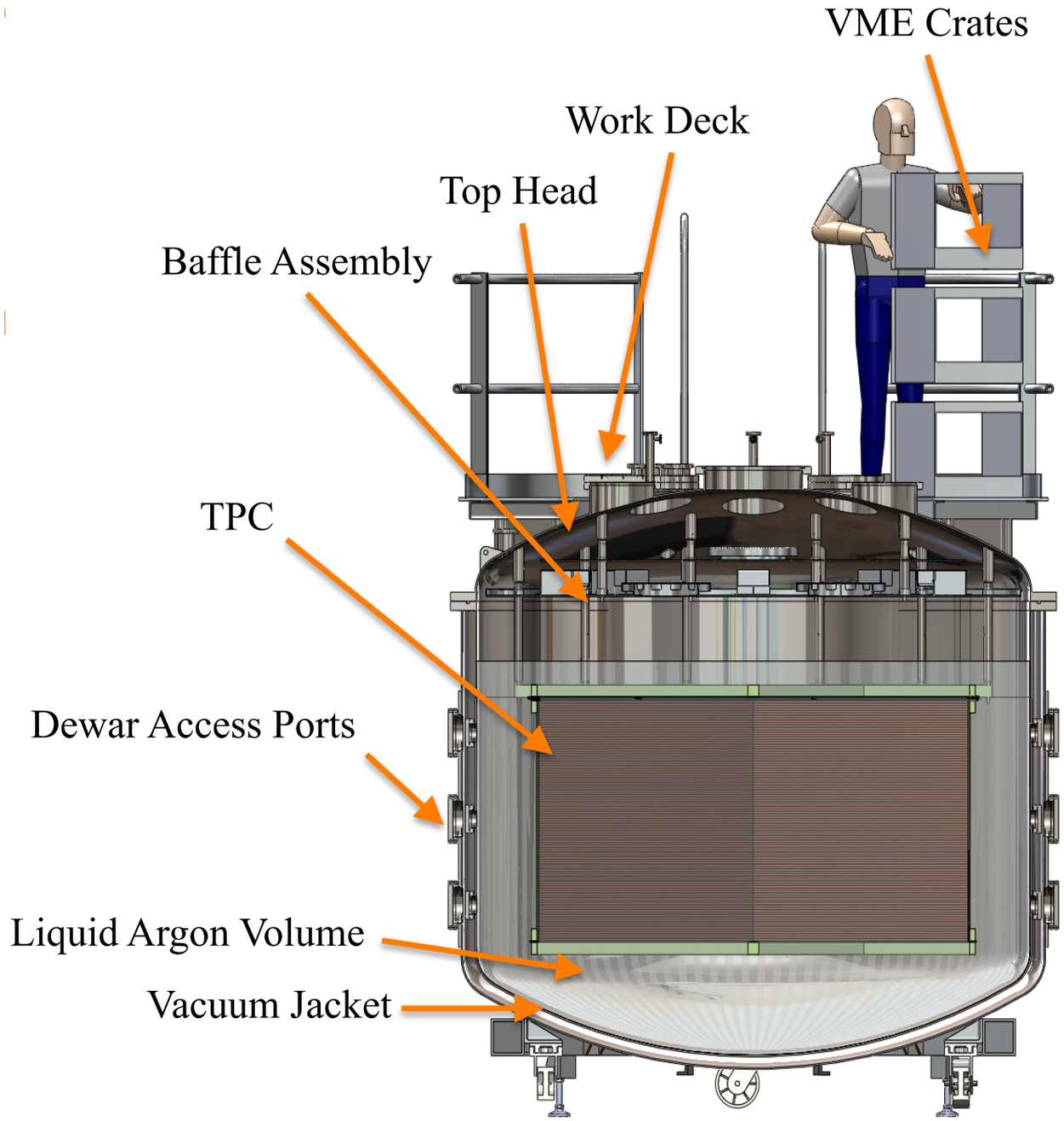


CAPTAIN: Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos

- Will examine neutron and neutrino cross sections and event topology
- Started with LANL LDRD Funding
- Now, a multi-institution collaboration
- “Portable” liquid argon TPCs being built at LANL
- 500 V/cm drift field
- 3 mm wire spacing
- Photon detection system (Hamamatsu R8520-500 PMTs)
- LASER system to calibrate on straight tracks
- Uses MicroBooNE electronics



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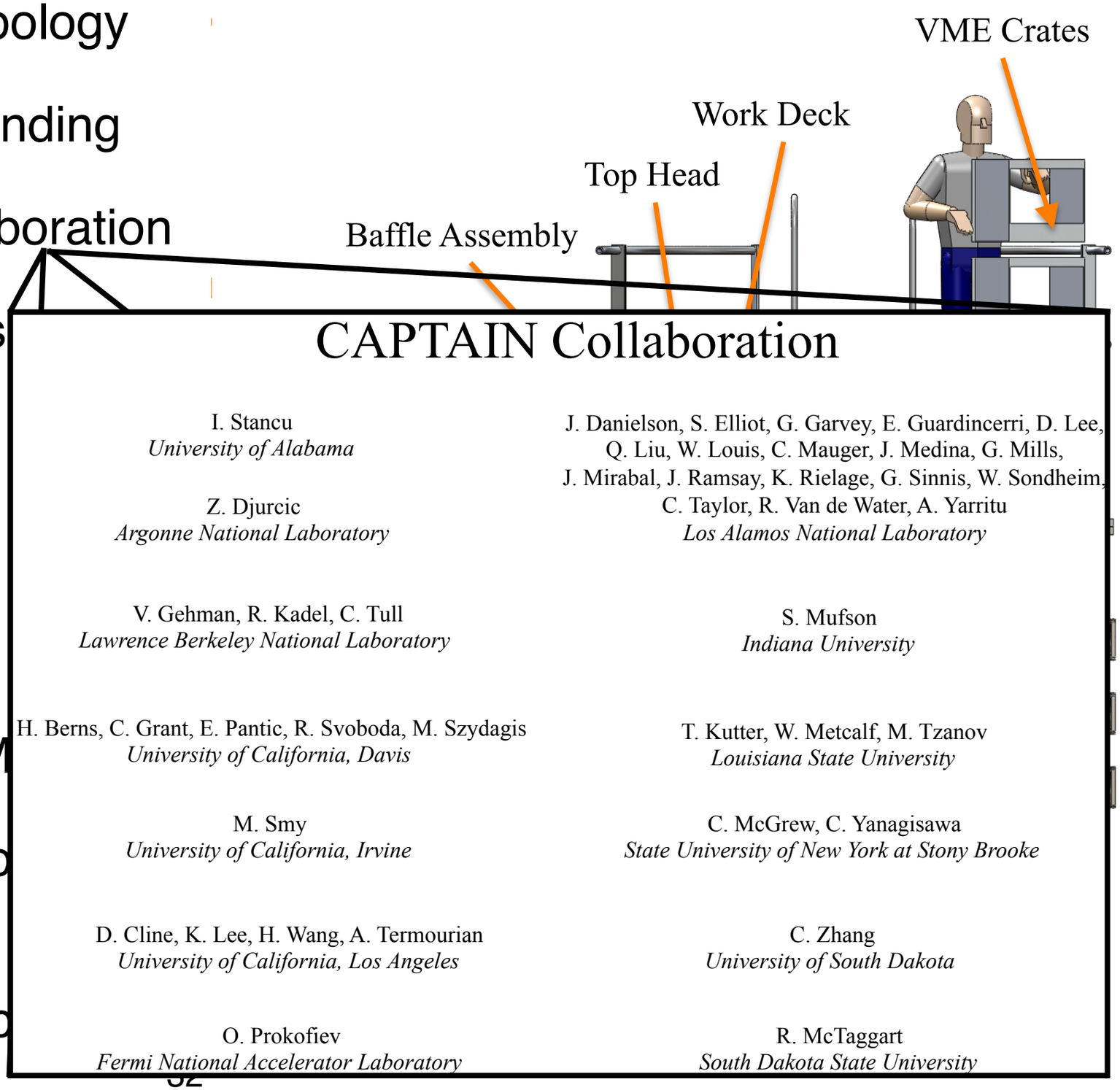

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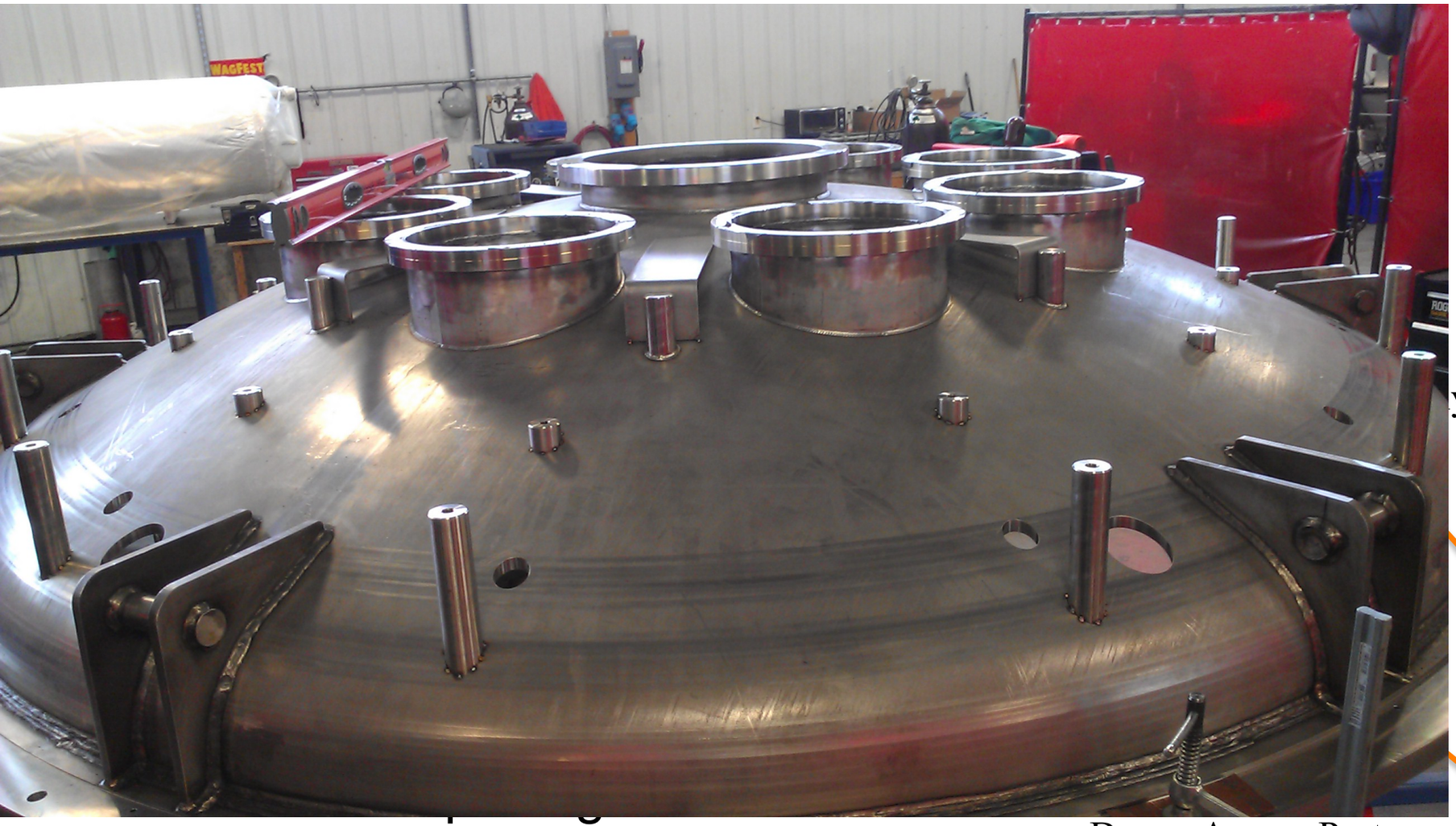

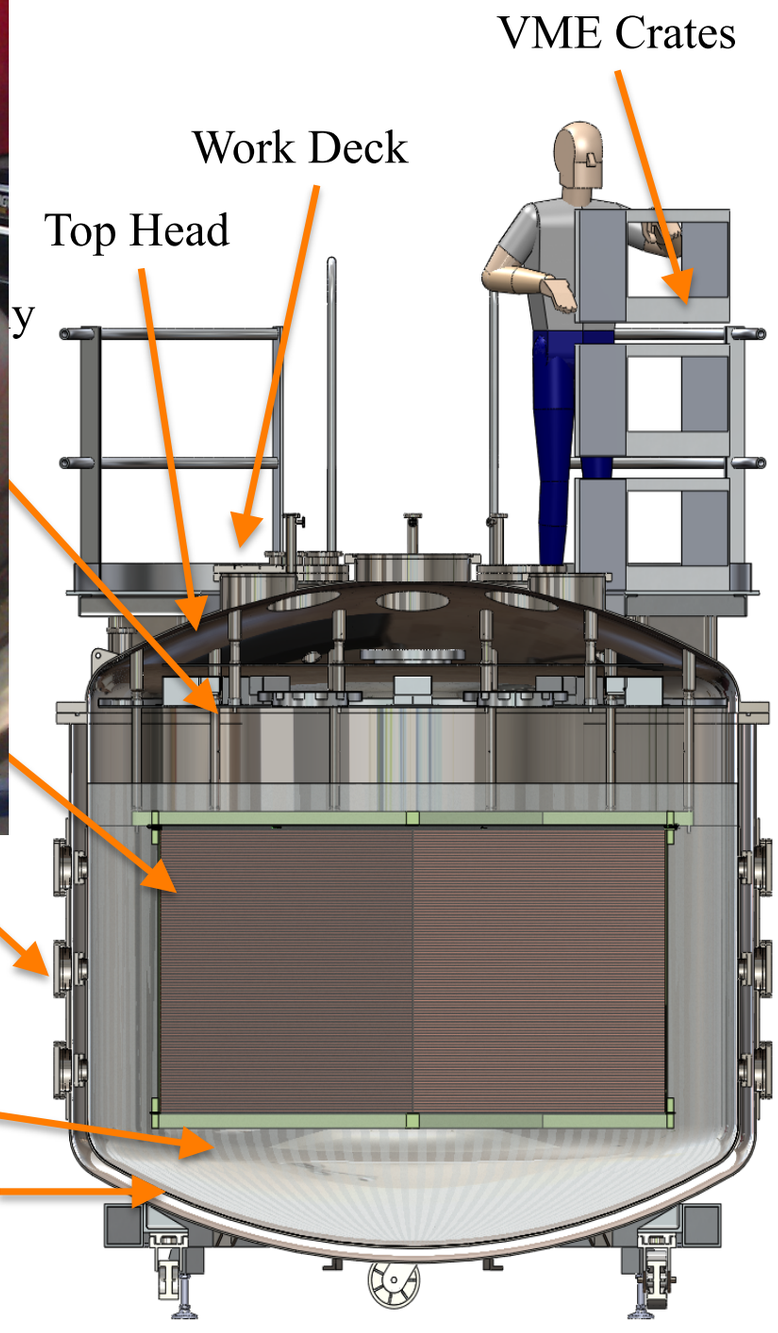

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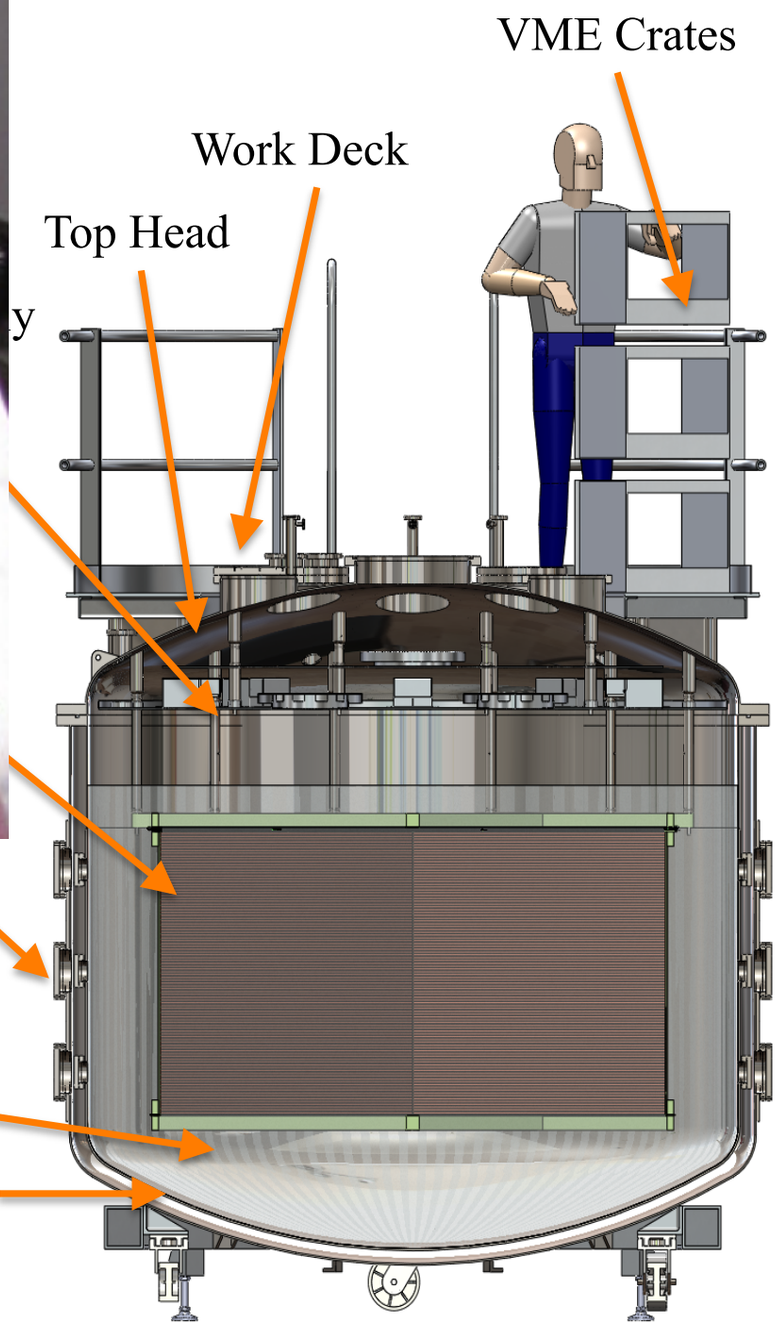

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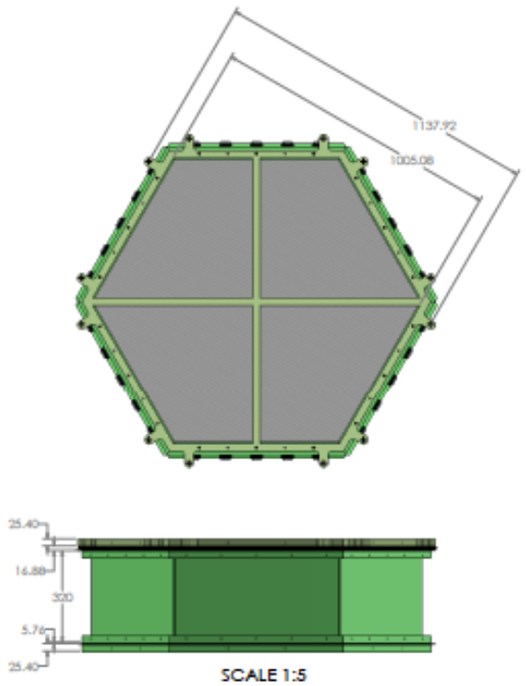
The CAPTAIN Detectors

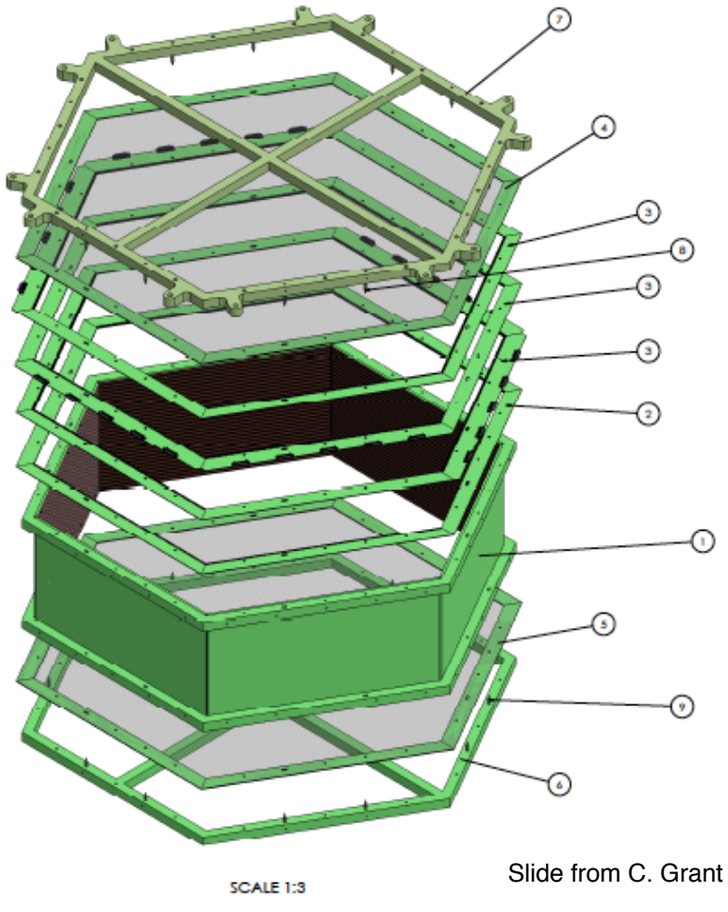
Prototype (Mini-CAPTAIN)

- Cryostat from UCLA holds 1700 L of LAr (Diameter = 1.5 m; Height = 1.64 m)
- TPC has a total of about 1000 wires (3 planes) and a max. drift length of 32 cm
- Will allow for early development of DAQ software and provide much needed operational experience

Full-scale (CAPTAIN)

- 7,700 L cryostat (Diameter = 2.72 m; Height = 2.92 m)
- TPC has about 2000 wires and a max. drift length of 100 cm

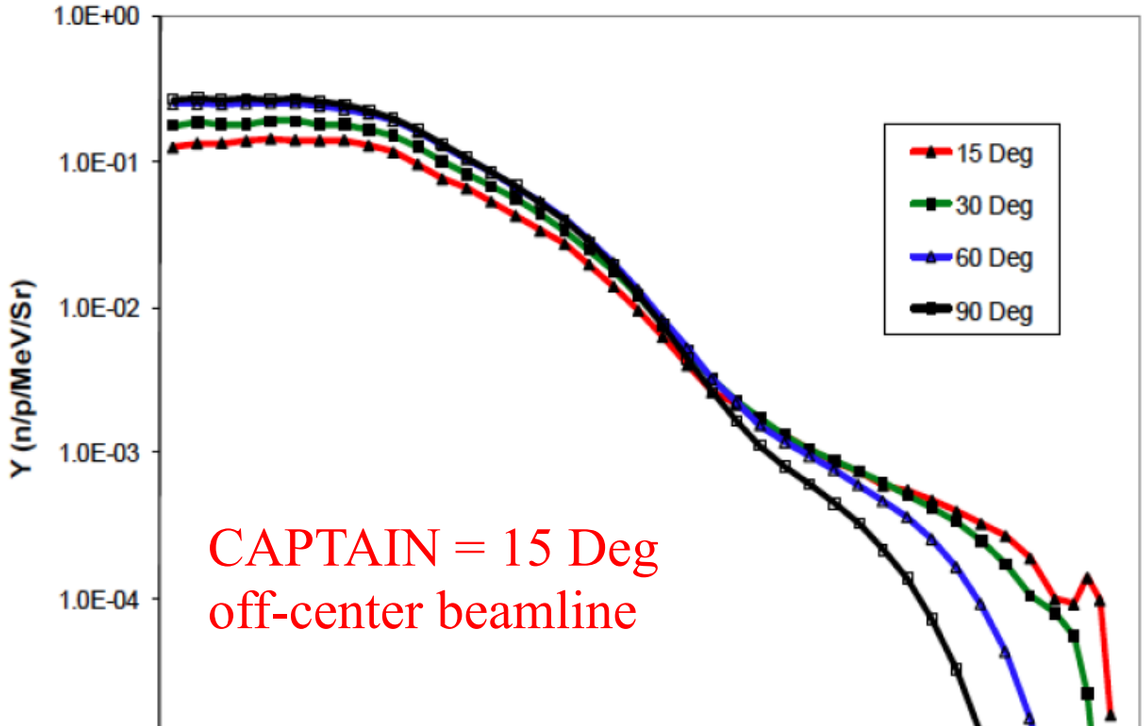


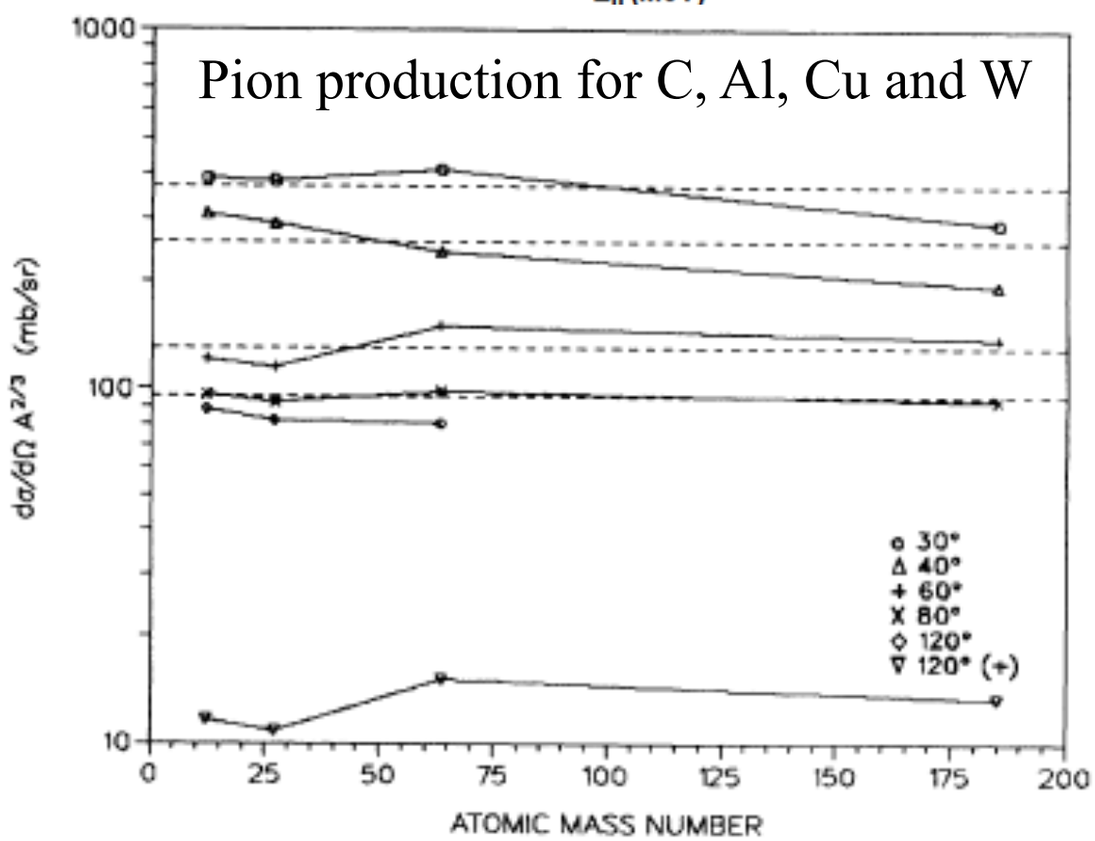


Slide from C. Grant

CAPTAIN Physics

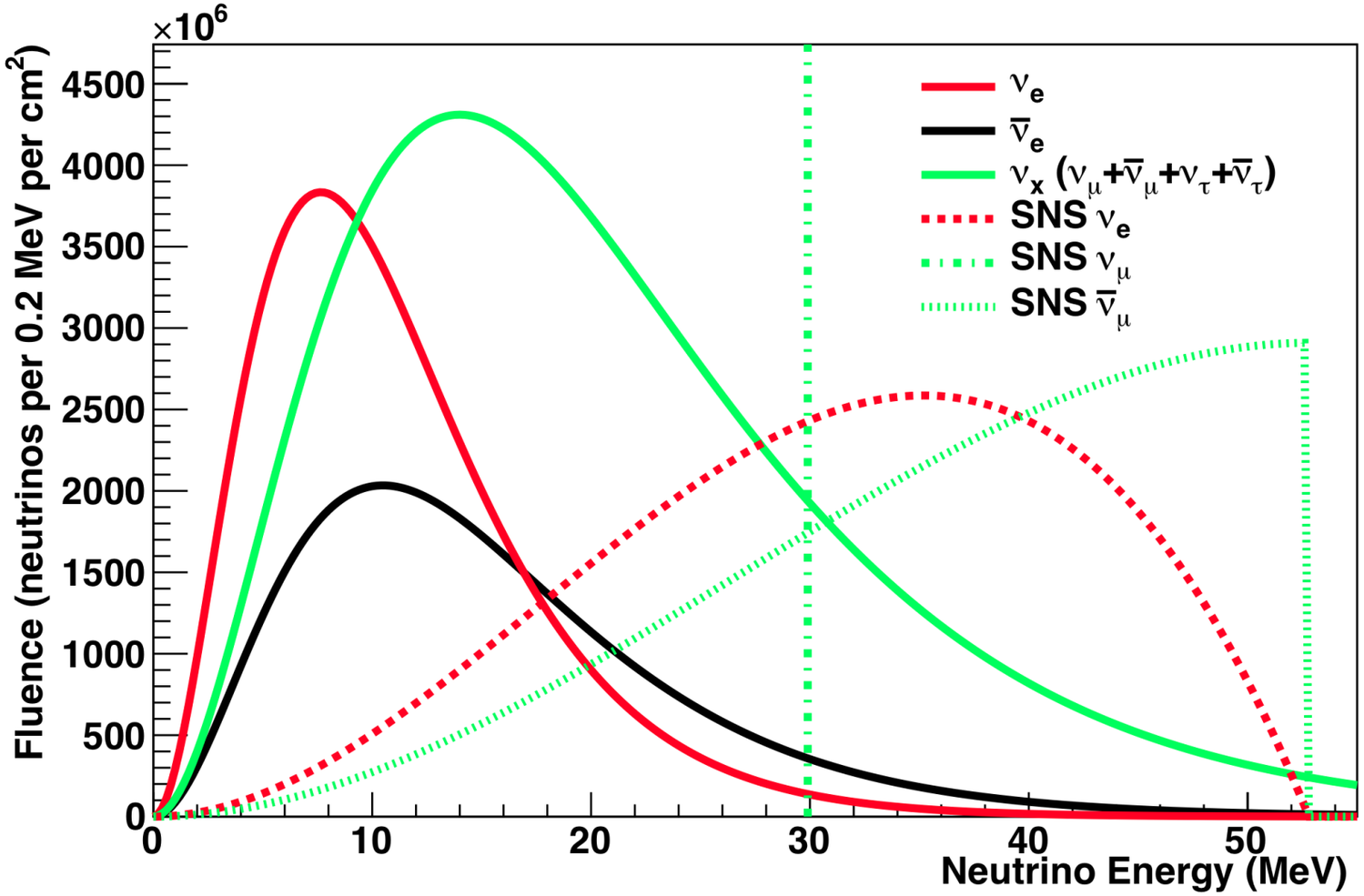
- Start at LANSCE WNR at LANL:
  - Measure lots of spallation neutron cross sections, at higher energies than ENDF
  - Look at neutrino-like interactions, esp. final state de-excitation gammas
  - Pion production in liquid argon
  - Build a library of neutron event topologies, to help with neutrino energy reconstruction
- Then move CAPTAIN to Fermilab for neutrino running:
  - near the Booster Neutrino Beam at MI-12 (stopped pion $\nu > 60$ MeV),
  - in the NuMI beam line (1 - 15 GeV)

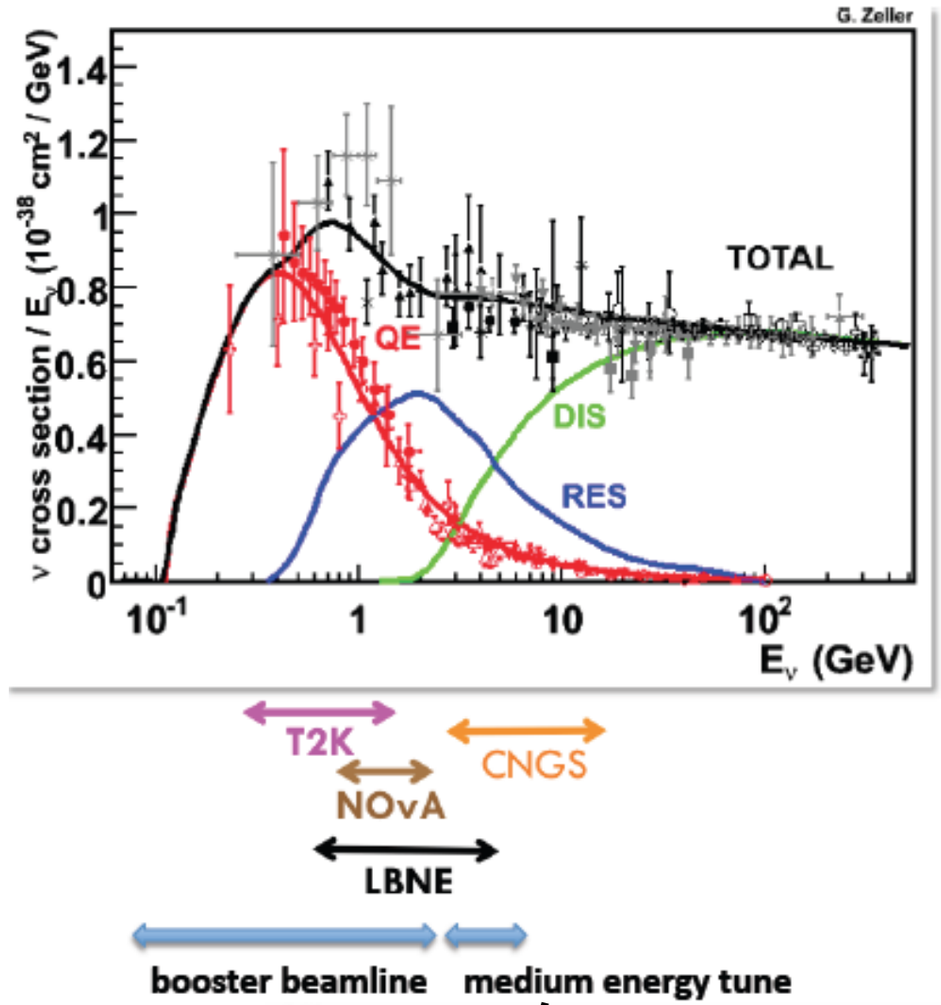


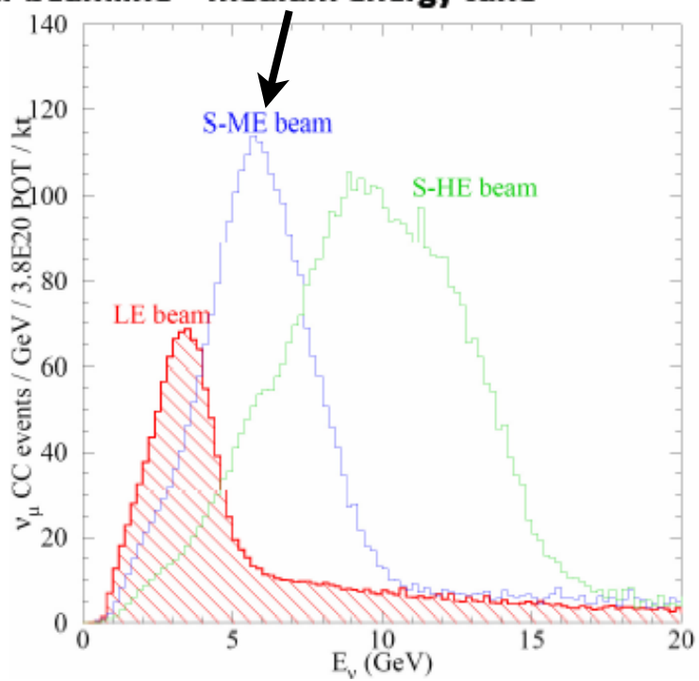


$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

CAPTAIN Physics







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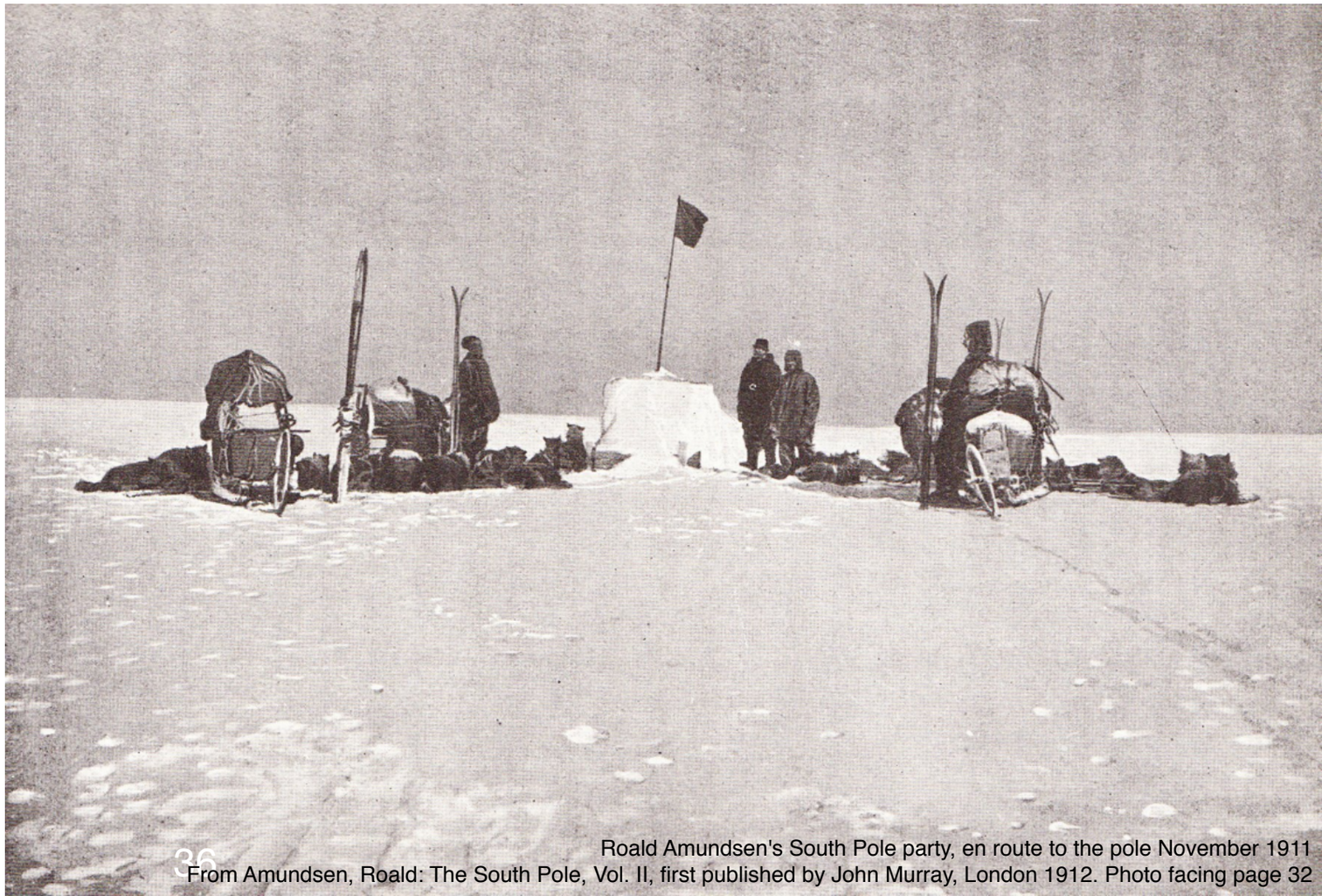
Outline


The Polo Family arrives in China, 1274

- The show so far: the Standard Model works really well, but...
- Go big, go deep!
- A view of the next ten years of dark matter searches...
- The case for LBNE
- What else can you do with something like the LBNE far detector?
- The technical challenges that tie all this together
- Conclusions and perspectives

Conclusions and Perspectives

- It's easy to think of particle physics as a victim of its own success...
- We have an embarrassingly successful Standard Model, and no clear indication of what the scale of new physics should be!
- But we have a bunch of hints that the Standard Model isn't the whole story.
- So we are embarking on several expeditions to learn more about these hints.



Roald Amundsen's South Pole party, en route to the pole November 1911
From Amundsen, Roald: The South Pole, Vol. II, first published by John Murray, London 1912. Photo facing page 32

Conclusions and Perspectives

- Like all expeditions, we are essentially exploring and don't know what we're going to find.
- These expeditions are going to be hard, expensive, and not guaranteed to pay off in the way we expect.
- But physics has been here before, and we responded by learning more about the Universe in a way that opened up our understanding of it!
- And the techniques and instruments I have discussed here are strongly applicable LOTS of physics!
- This allows us a high degree of flexibility in the face of uncertain national priorities and funding.

http://www.theodore-roosevelt.com
Theodore Roosevelt in Sao Paolo, examining a snake on the Rondon Scientific Expedition

Thank you for your attention...
Any questions?

Berkeley Marina at sunset.
Photograph by R. Coles, July 4, 2013.