Totally Active Scintillator Detectors ("TASD")

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European Strategy for Future Neutrino Physics
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General plan of the talk

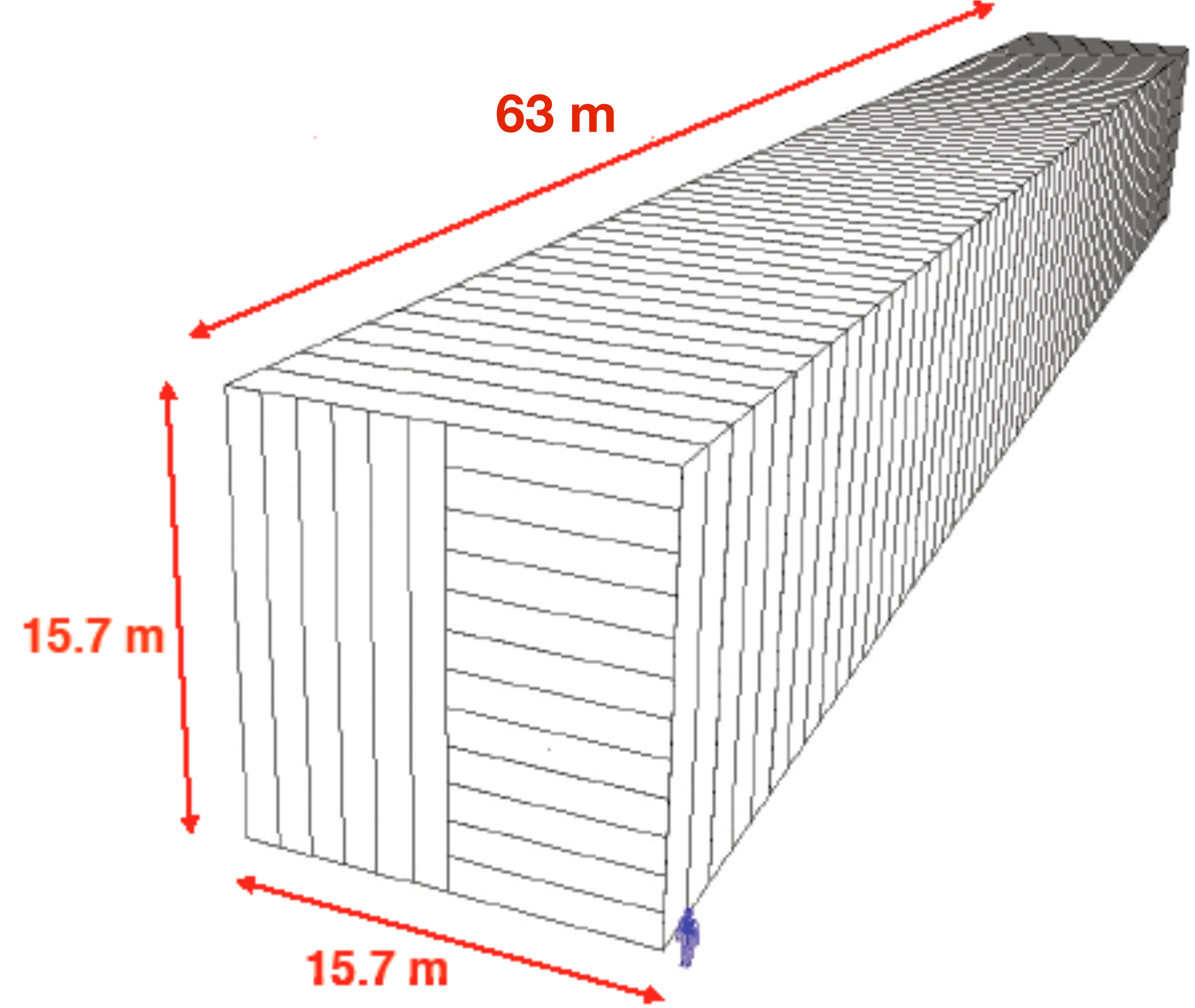
- As NOvA is the most fully realized design of a large scale “totally active scintillator detector” (TASD). I will summarize the design of the NOvA detector, the factors that influenced that design, and the performance of that design as an introduction to the detector technology. I will have to be brief; I have tried to provide more details on the slides than I will be able to discuss.

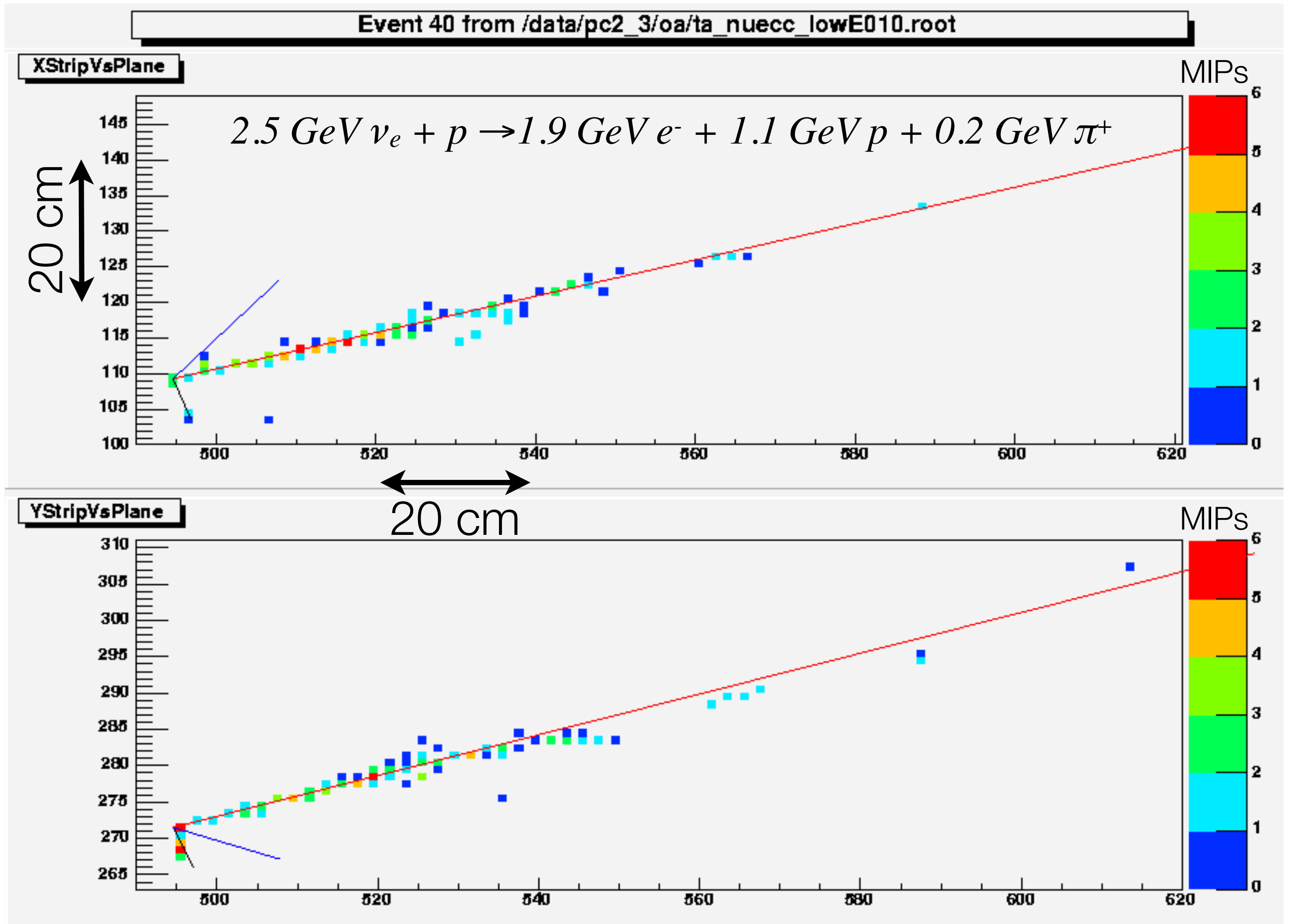
- With the limited time I will not discuss the NOvA physics program

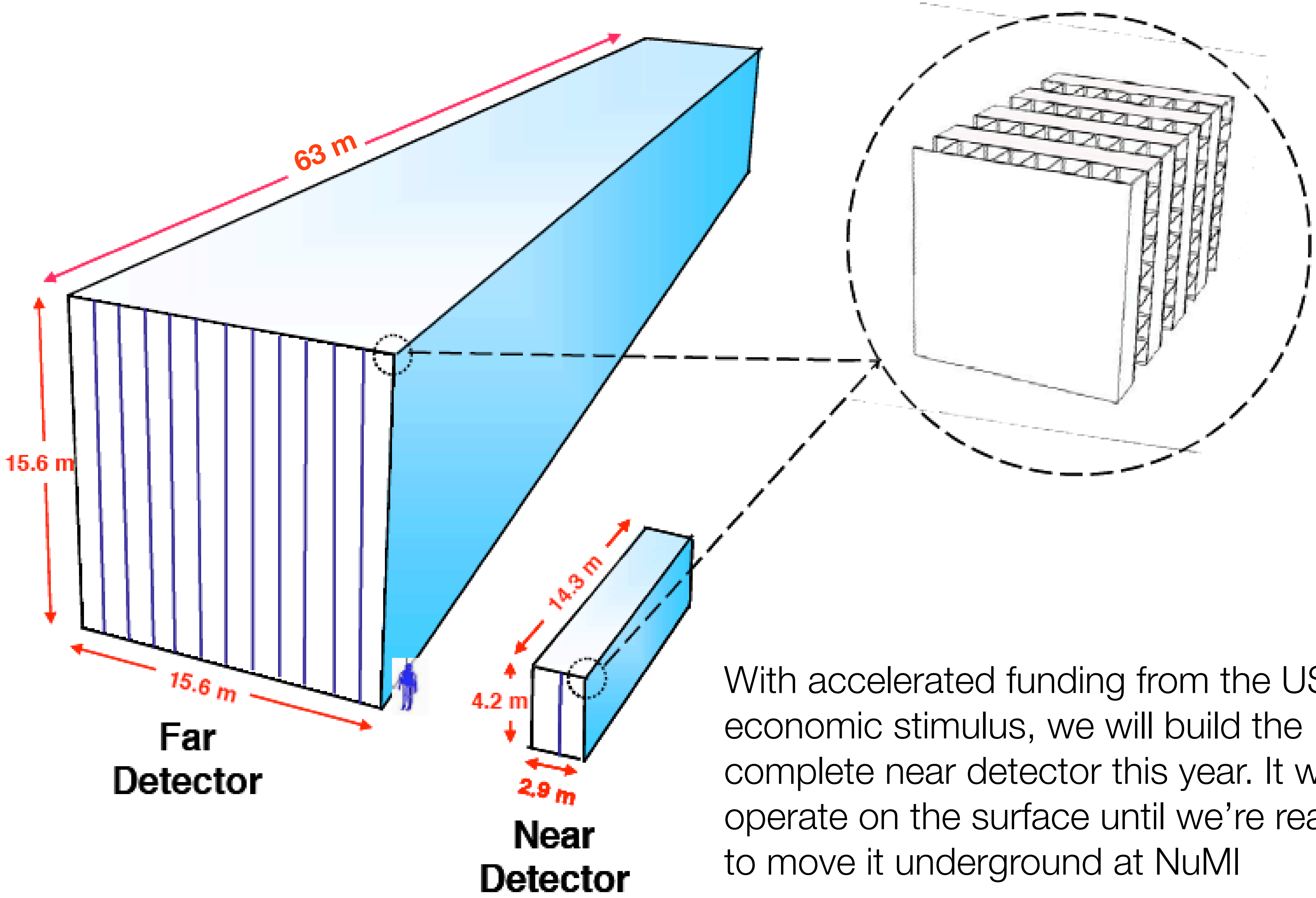
- In the second part I’ll try to address the things required to take the TASD design beyond its use by the NOvA experiment.

The NOvA Experiment

- NOvA is a second generation experiment on the NuMI beamline which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations
- NOvA is:
    - An upgrade of the NuMI beam intensity from 400 kW to 700 kW
    - A 15 kt “totally active” tracking liquid scintillator calorimeter sited 14 mrad off the NuMI beam axis at a distance of 810 km
    - A 220 ton near detector identical to the far detector sited 14 mrad off the NuMI beam axis at a distance of 1 km





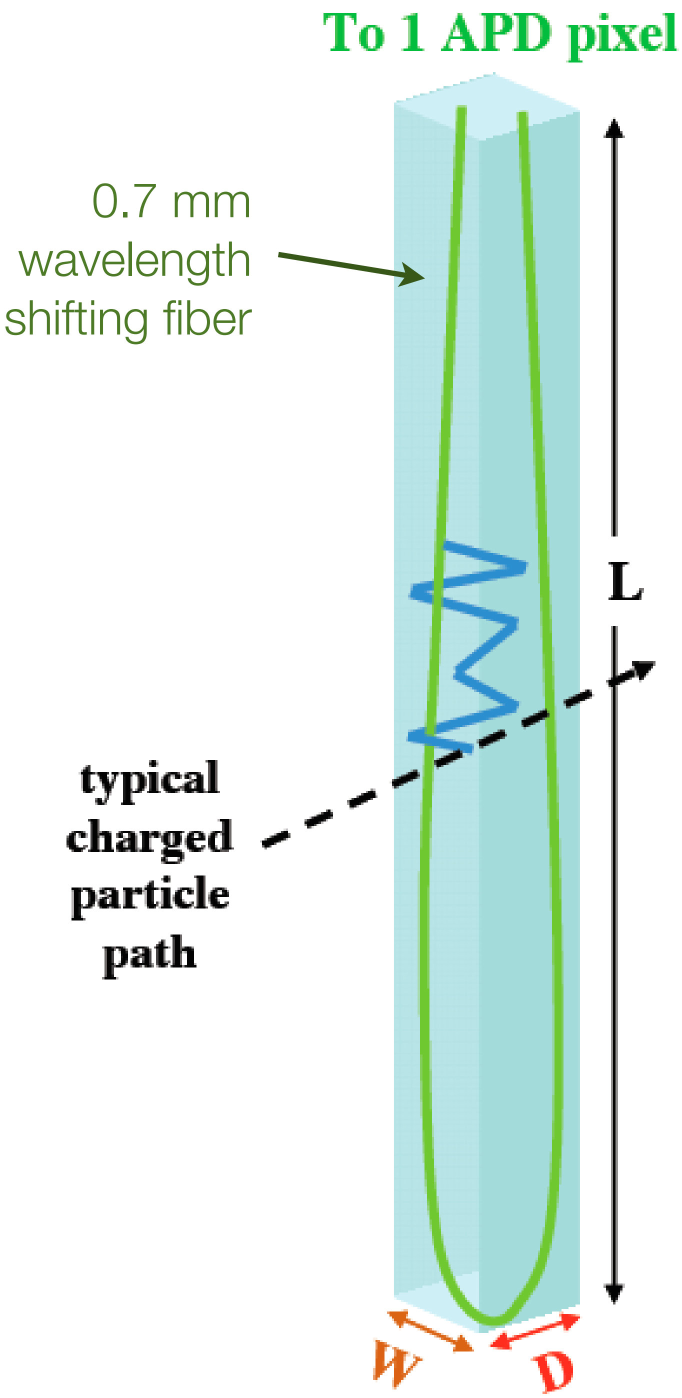


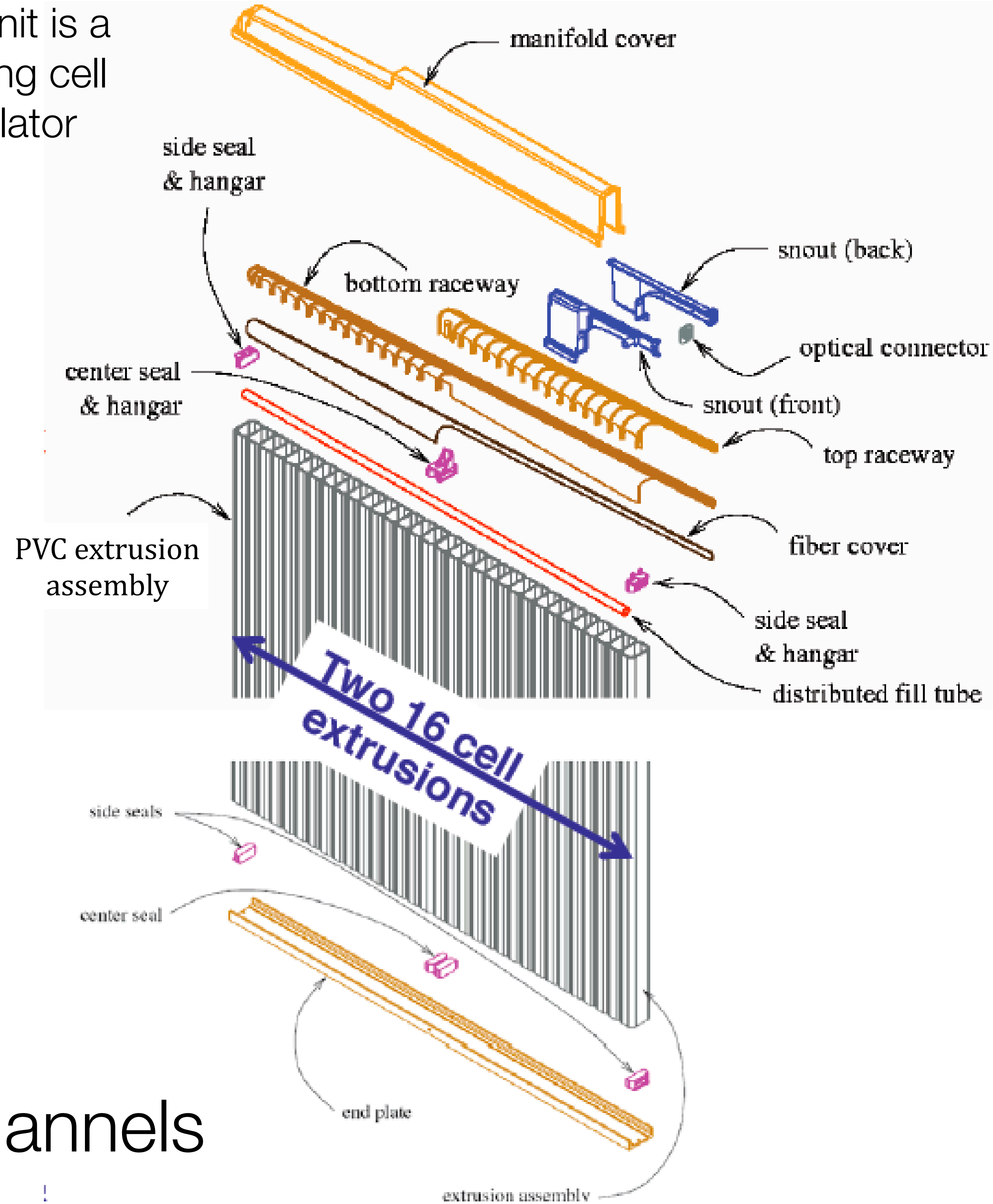
With accelerated funding from the US economic stimulus, we will build the complete near detector this year. It will operate on the surface until we're ready to move it underground at NuMI

The NOvA Detectors

- 14-18 kton far detector
- 222 ton near detector

Basic NOvA detector unit is a 4 cm x 6 cm x 15 m long cell filled with liquid scintillator

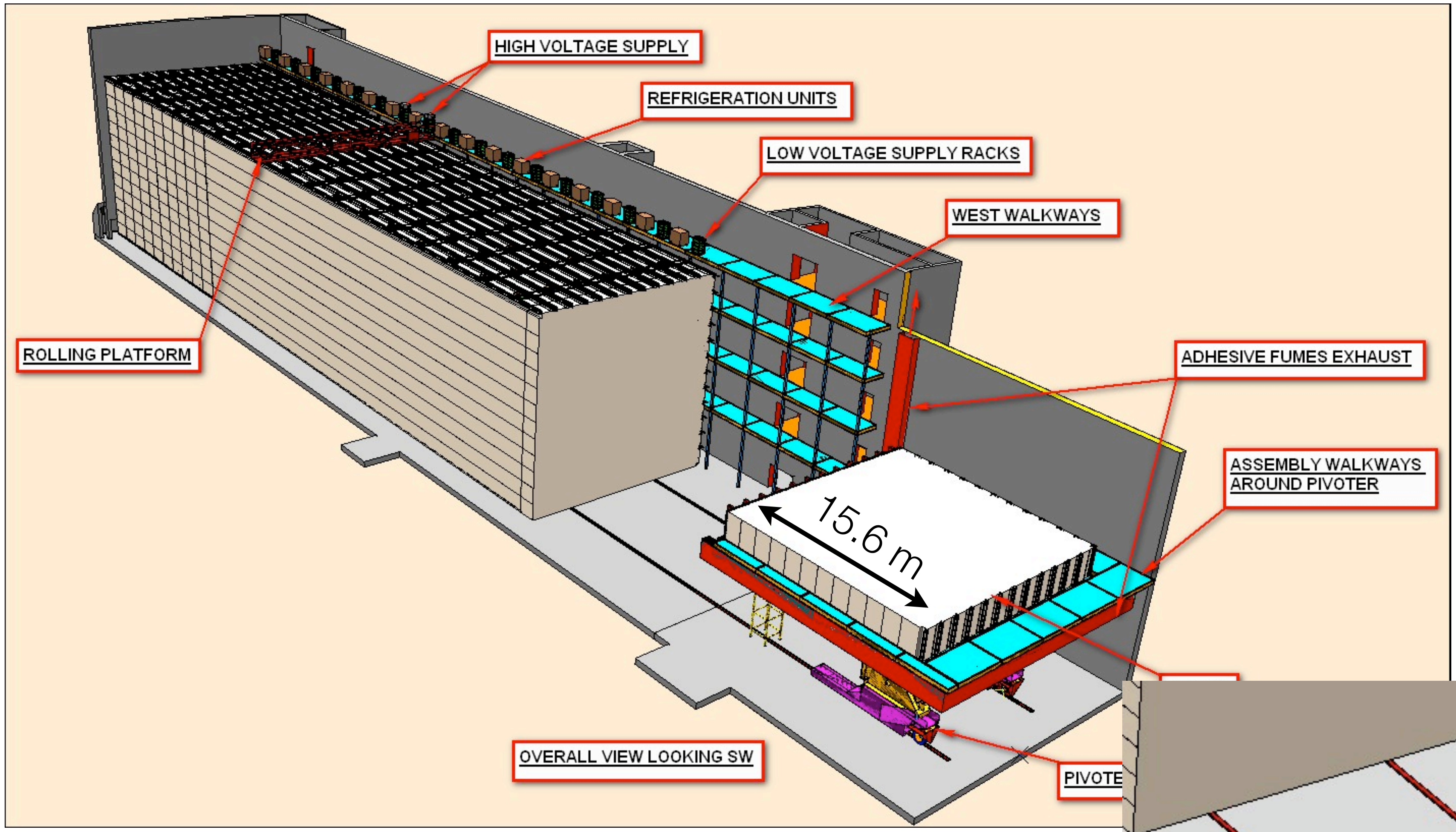




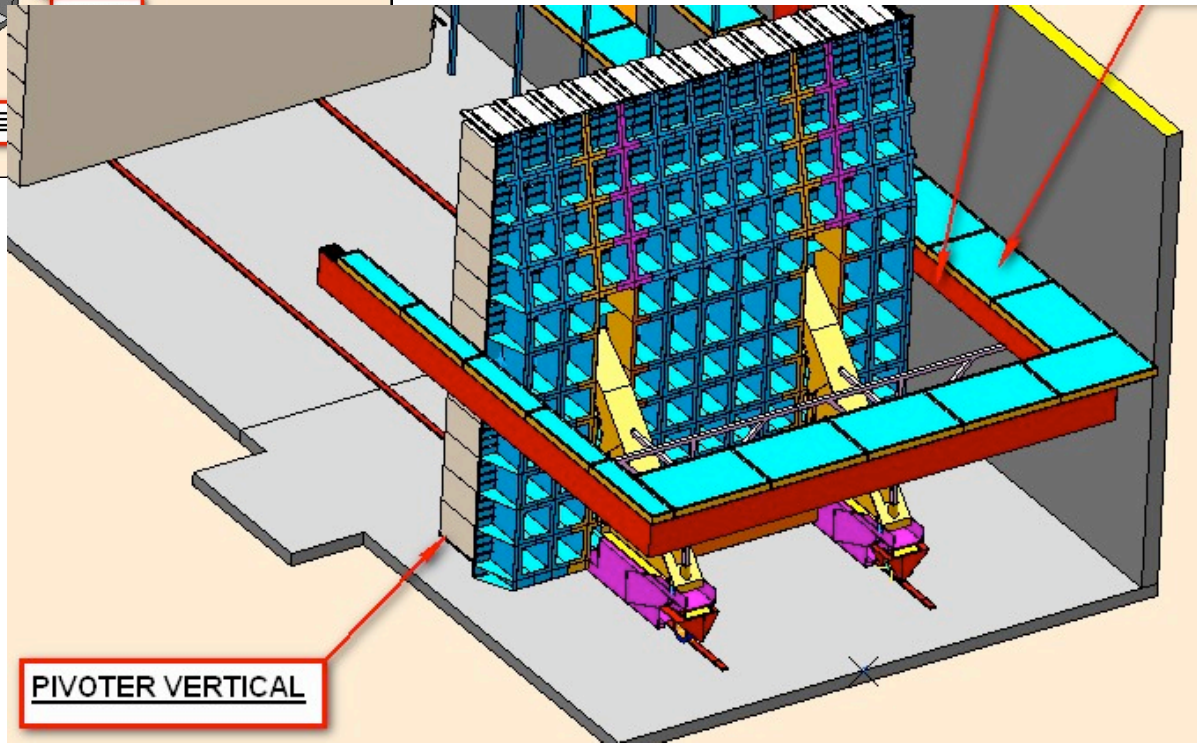
357,120 total channels

Moving module from glue machine to plane assembly

Block Pivoter



work platform



Construction progress at Ash River, MN

NOvA detector will operate close to the surface with about 3 m rock equivalent of overburden

Event quality

Topologies of basic interaction channels shown at right. Each “pixel” is a single 4 cm x 6 cm cell of liquid scintillator

Top: ν_μ *charged-current*

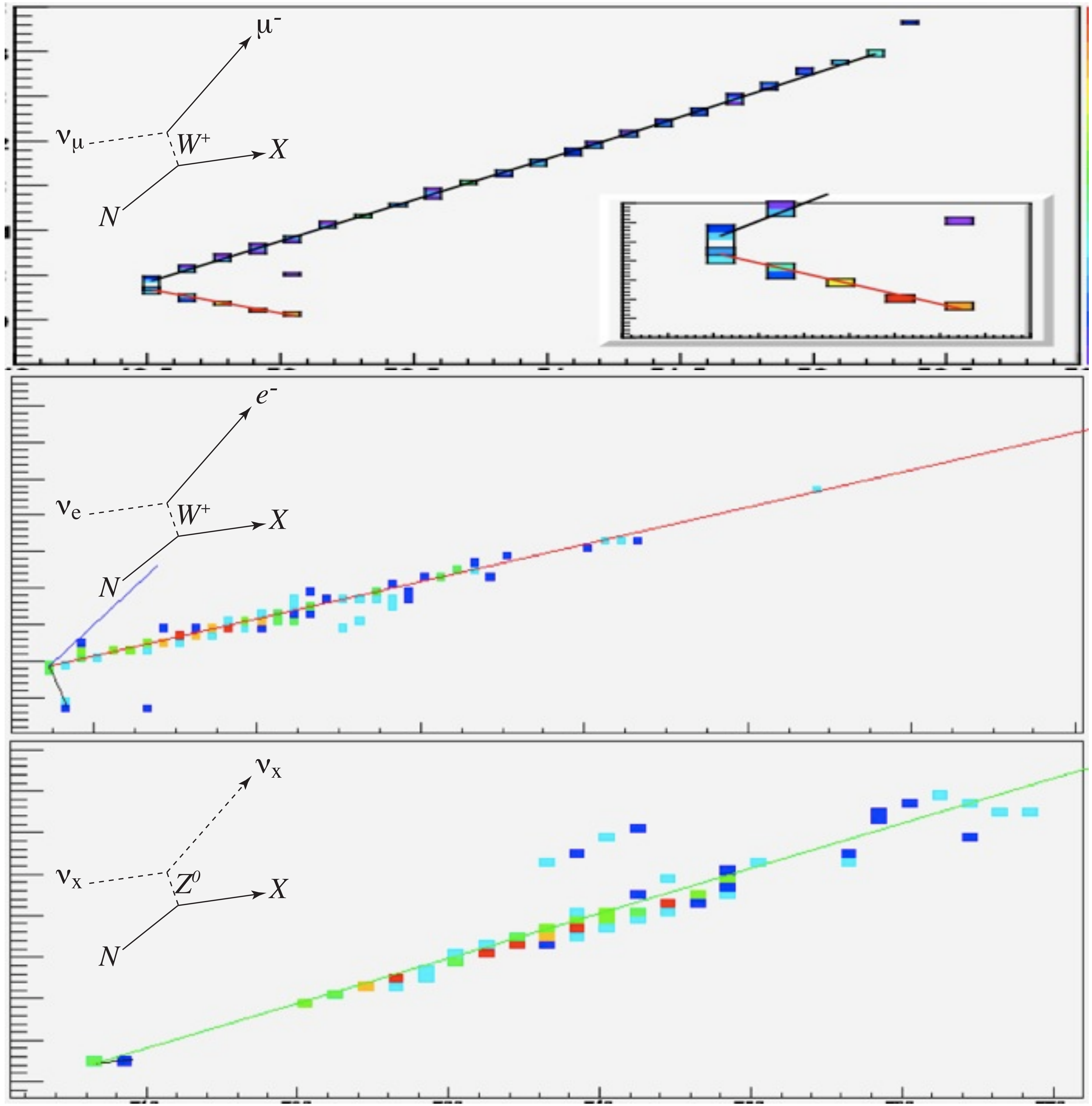
Center: ν_e *charged-current*

Bottom: neutral-current

Need >100:1 rejection against background

Detector challenge: Achieve large target mass (10’s+ kilotons) while maintaining high granularity to avoid confusing the detection channels

NOvA achieves 35% efficiency for ν_e CC while limiting NC→ν_e CC fake rate to 0.1%



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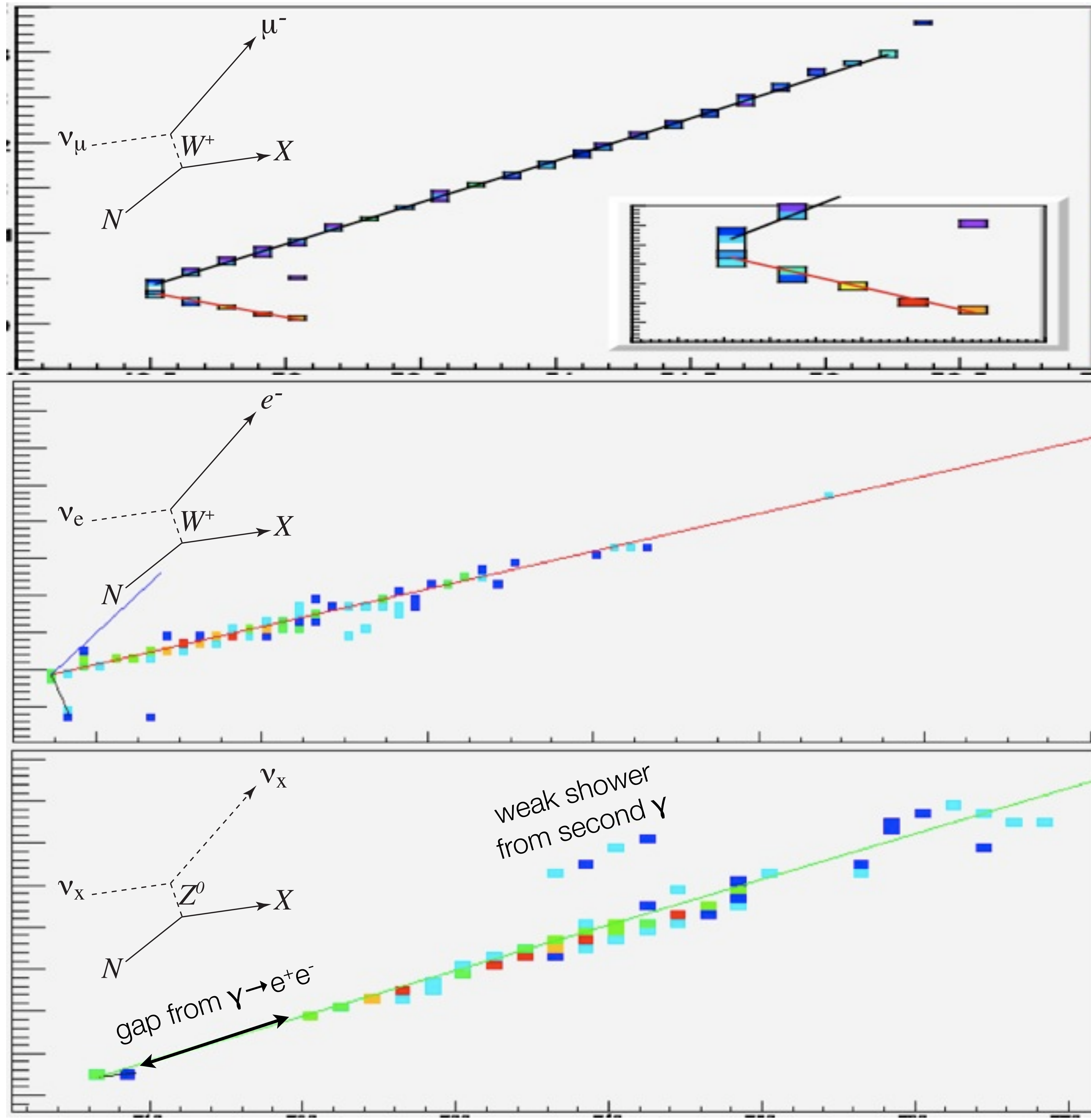
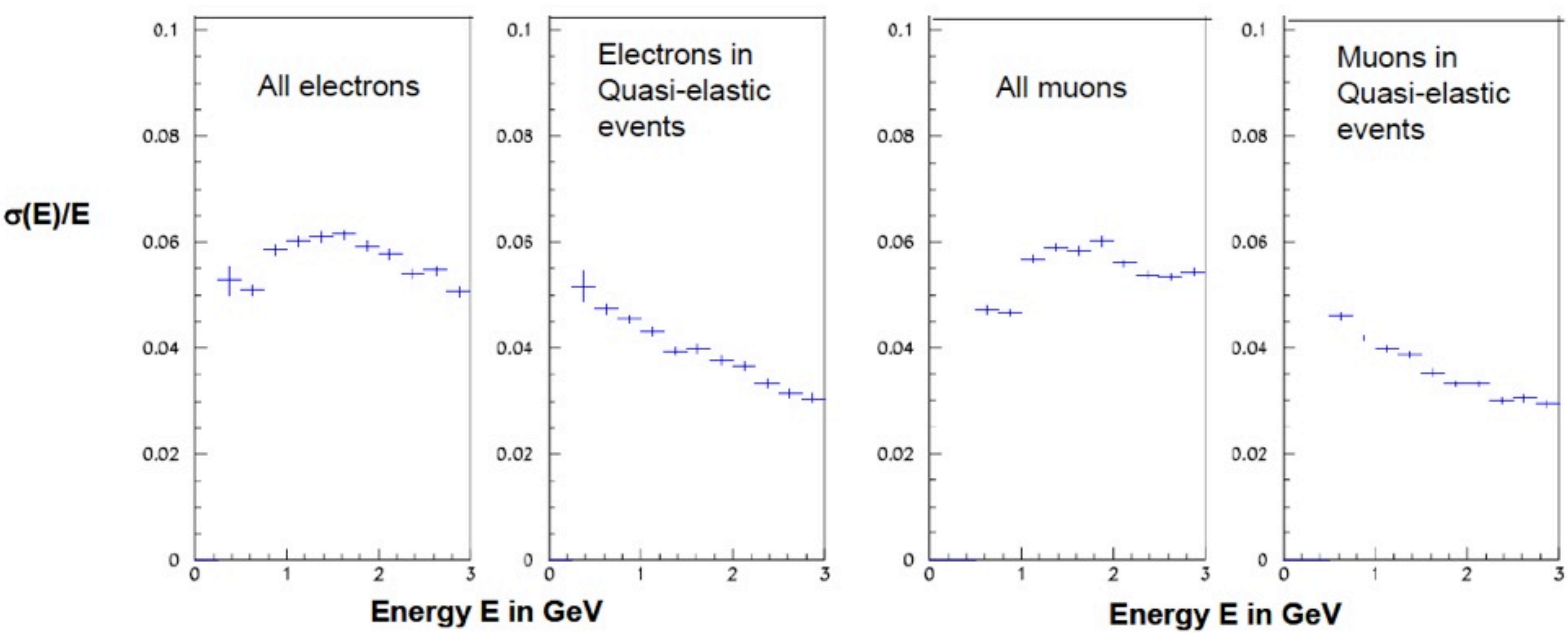


Energy resolution



~6% for electrons up to 3 GeV | ~5% for muons up to 3 GeV

quasi-elastics better ~4% for electrons at 2 GeV | 3.5% for muons at 2 GeV

Technical overview of the NOvA design

- PVC Extrusions
- Scintillator
- Wavelength shifting fibers
- Photodetectors

Development of PVC Resin

The PVC that the extrusions are made from must satisfy multiple requirements

1. ***High reflectivity***: Light bounces ~10 times off the walls before being captured in the WLS fiber so we need high reflectivity to achieve required light levels
2. ***Mechanical***: The PVC must be strong enough to contain the liquid scintillator at pressures of >19 psi and support the horizontal modules. It must maintain its strength throughout the lifetime of the experiment. We must be able to glue to the surface.
3. ***Extrudability***: The resin must reliably pass through the extruder and produce parts with good shape and structure

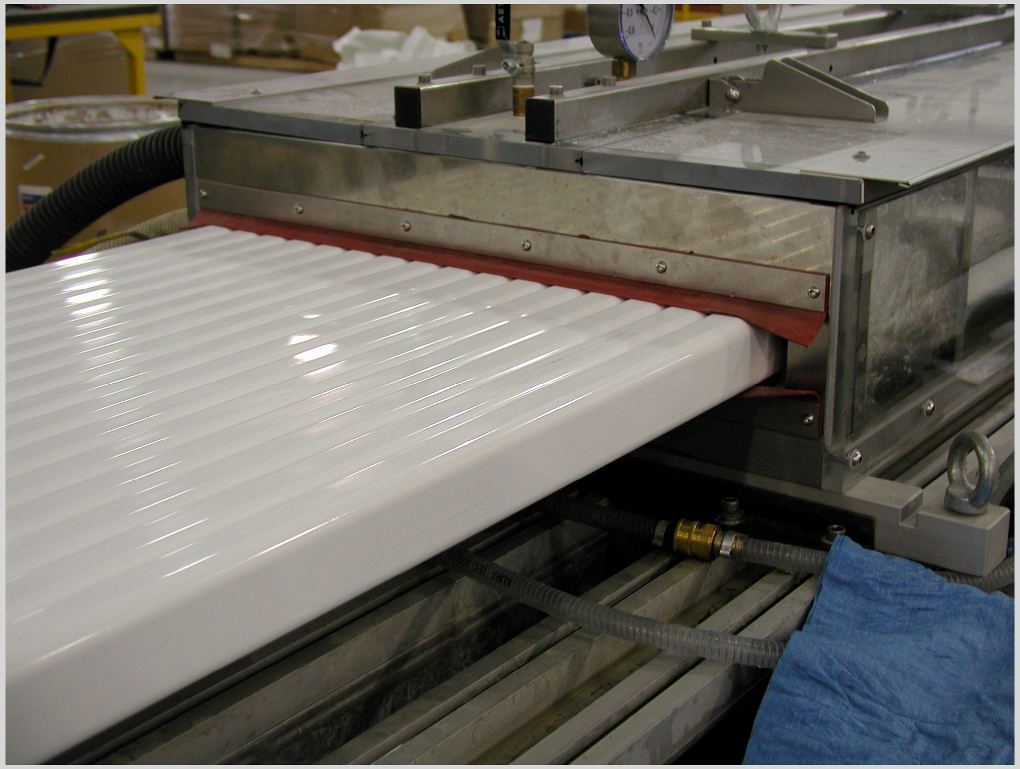
phr - per hundred parts of resin	NOVA-24	NOVA-27
Shintech SE950EG (high reflectivity)	100	100
Rohm & Haas Advastab TM-181 20% monomethyl tin	2.5	2.5
DuPont R-102 rutile titanium dioxide	19	0
Kronos 1000 anatase titanium dioxide	0	19
Ferro 15F calcium stearate	0.8	0.8
Honeywell Rheochem 165-010 paraffin wax	1.1	1.1
Ferro Petrac 215 oxidized polyethylene	0.2	0.2
Rohm & Haas F1005 glycerol monostearate	0.3	0.3
Arkema Durastrength 200 Acrylic impact modifier	4.0	4.0
Rohm & Haas Paraloid K120N processing aid	1.0	1.0
wt % titanium dioxide	15	15

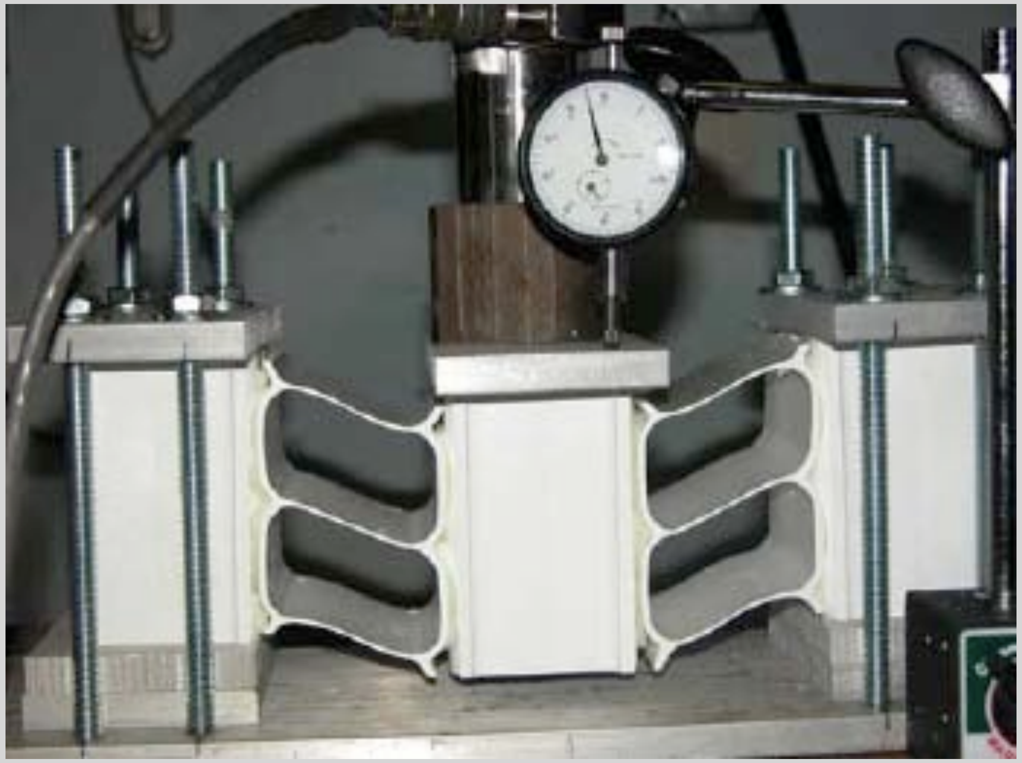
PVC

heat stabilizer

lubricants

Our two best formulations: Only difference is crystal structure of TiO_2. Numbers indicate iteration number on formula.

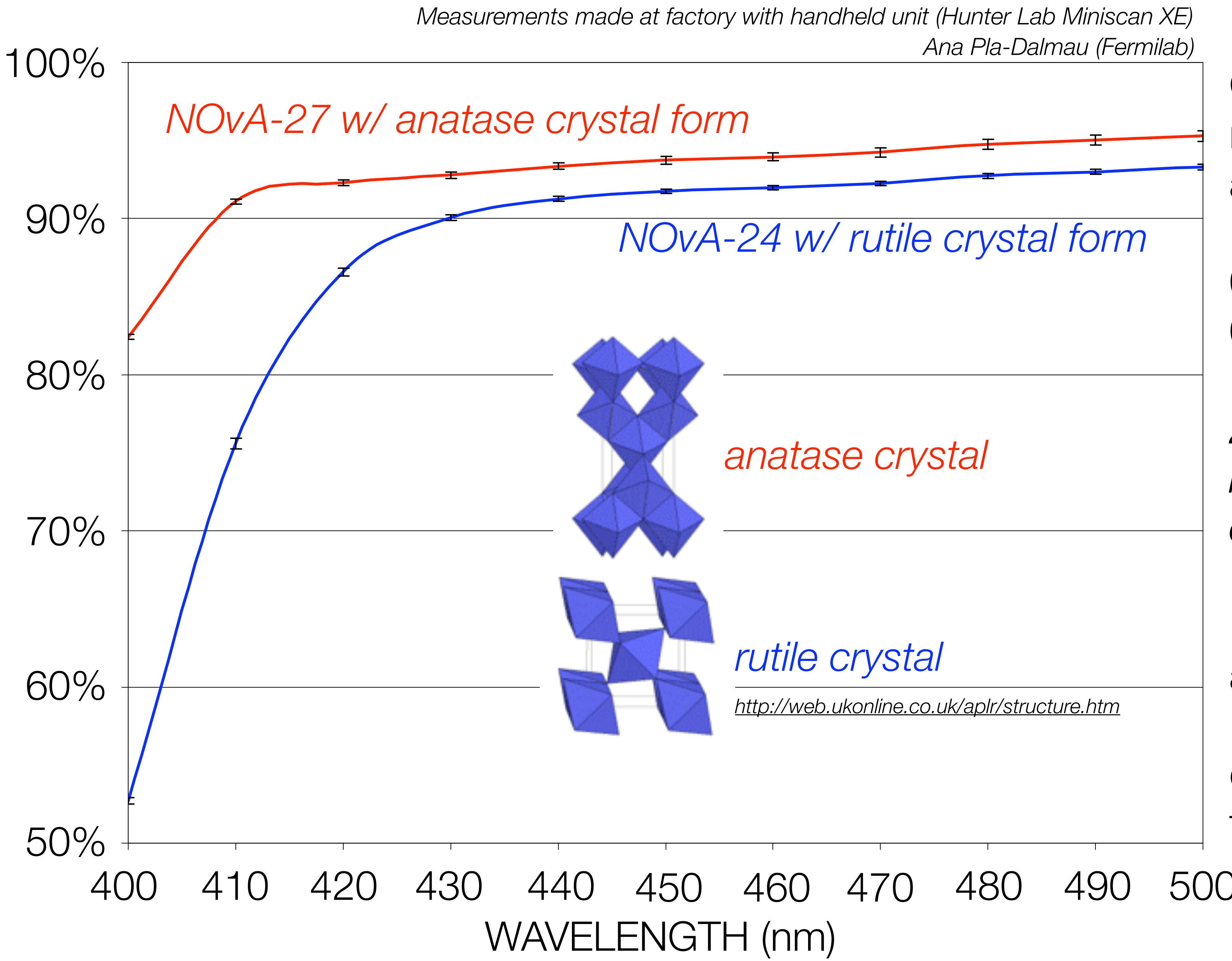




Top left: extrusions coming off the line
Bottom left: testing compressive strength
Above: Horizontal pieces for near detector

PVC Extrusions

PVC Reflectivity Measurements

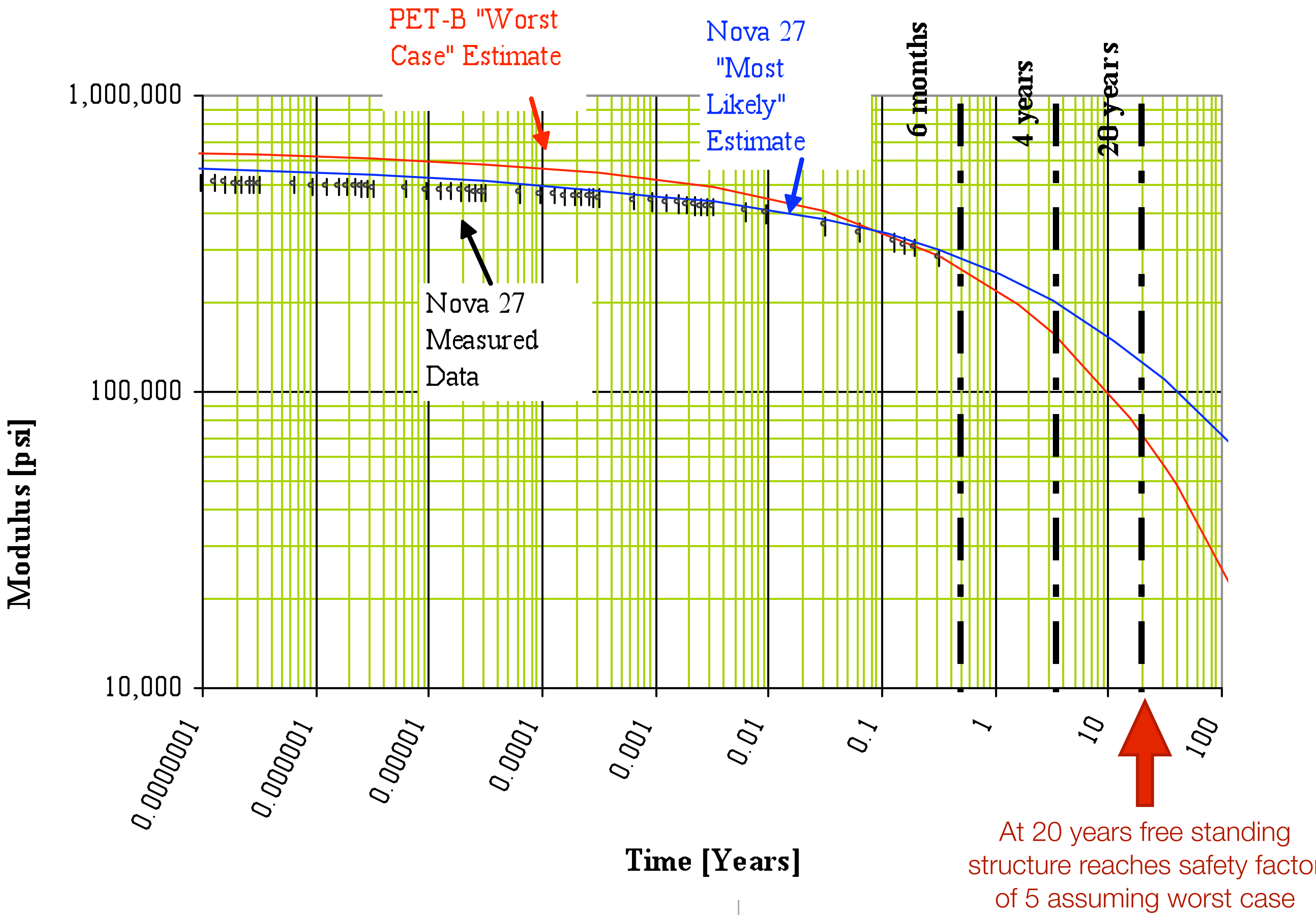


Compare 90% reflectivity to 92% after 10 bounces:

$0.90^{10} = 0.35$
$0.92^{10} = 0.43$

2% change in reflectivity = 25% change in light yield

In a NOvA test cell anatase yields ~14% more detected photons than rutile



Long term plastic strength

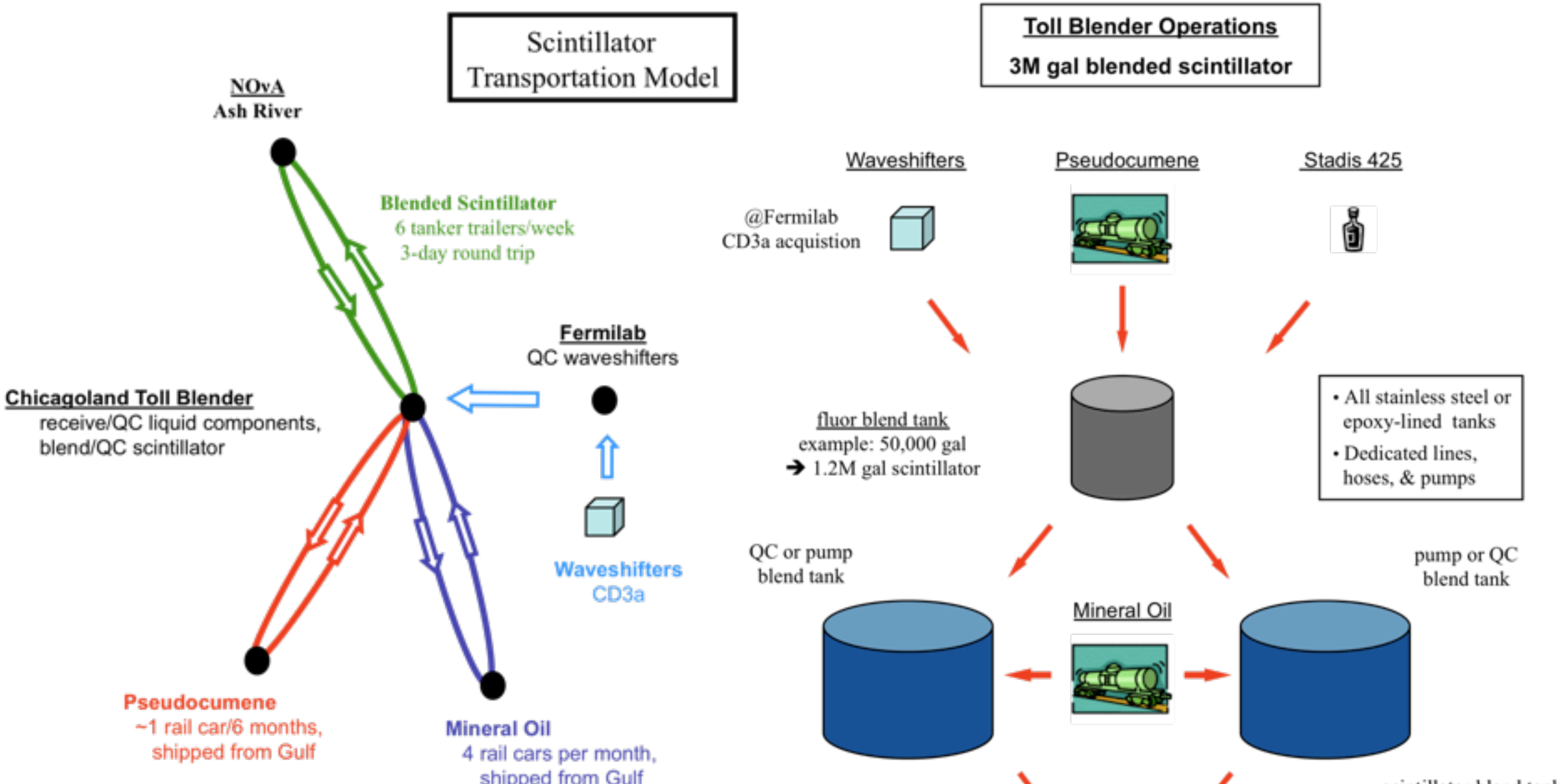
Plastic is "glassy" and creeps if held under tension long term

Liquid Scintillator Composition

component	purpose	mass fraction	volume [gal]	mass [kg]
mineral oil	solvent	95.79%	2,810,674	9,074,478
pseudocumene	scintillant	4.11%	117,528	389,720
PPO	primary waveshifter	0.091%		8,576
bis-MSB	secondary waveshifter	0.0013%		120
Stadis-425	antistatic agent	0.0003%		28.4
tocopherol (Vit E)	antioxidant	0.0010%		95
Total		100.00	2,928,200	9,473,017

- Scintillator mixture optimized to deliver required light at low cost. For our application technical grade mineral oil is sufficient.
- We require 28 PEs from the far end of a cell - enough so that a muon track will have no more than 1 in 10 hits missing due to inefficiency.
- Relatively low pseudocumene fraction reduces interactions with WLS/PVC/ adhesives to below what we can measure and reduces cost.
- Base cost of scintillator is <$4/gal.

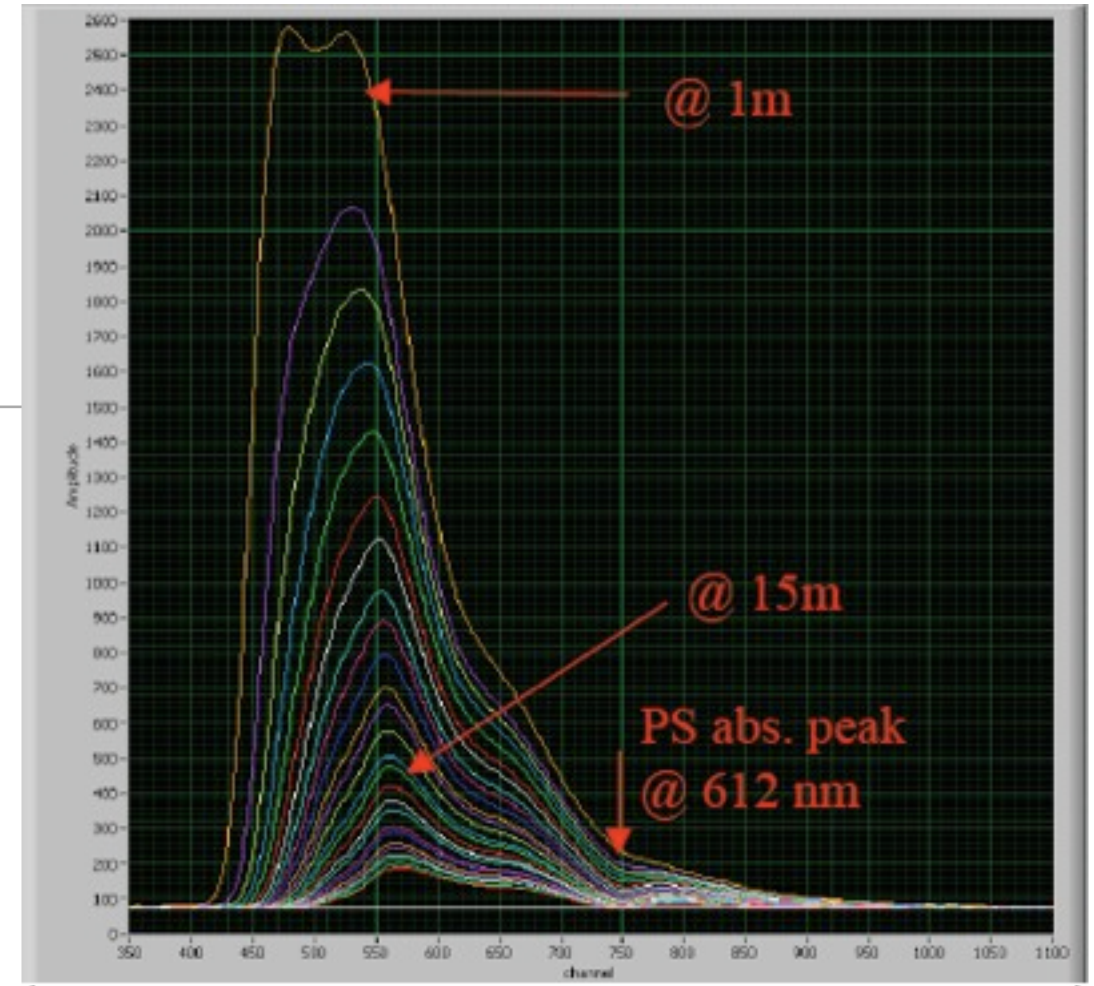
Model for large scale scintillator production

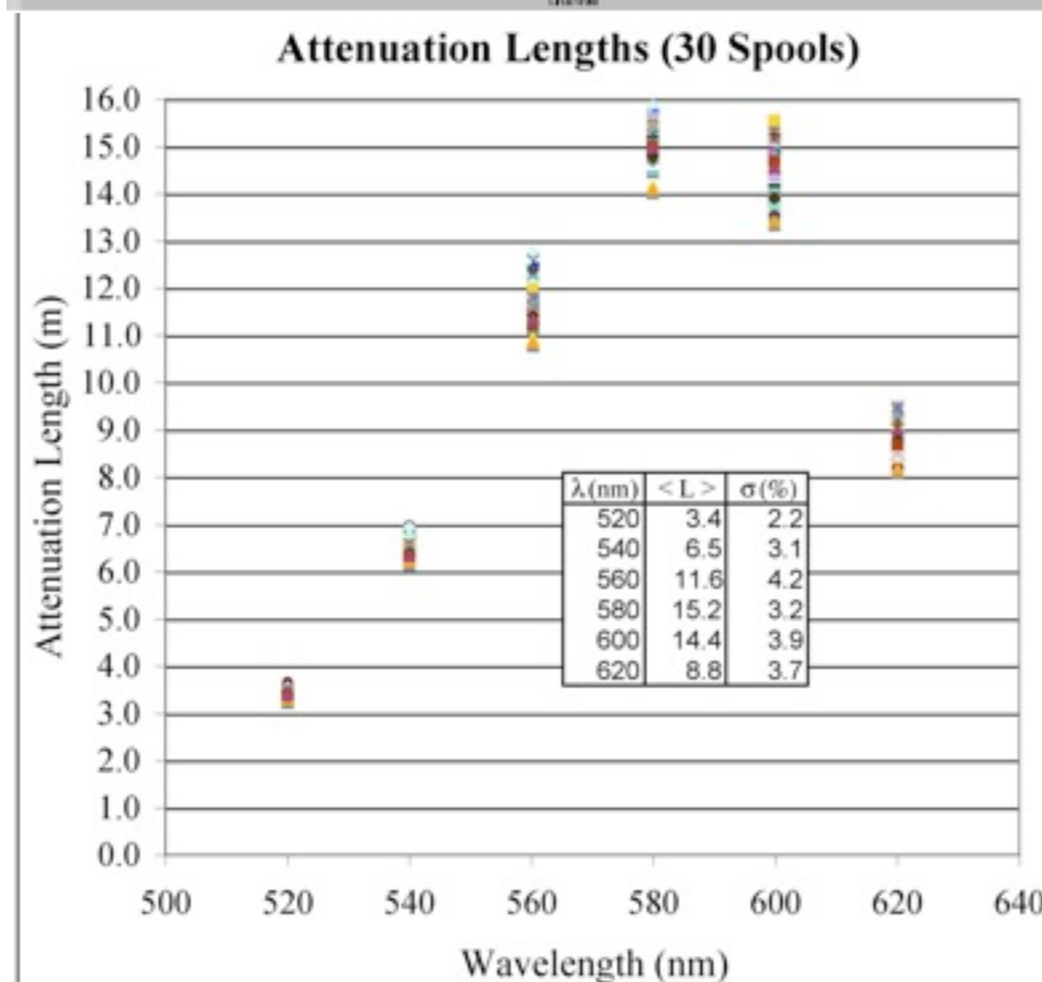


We are in process of selecting a Chicago-area toll blender from the 6 companies that responded to our request for proposals.

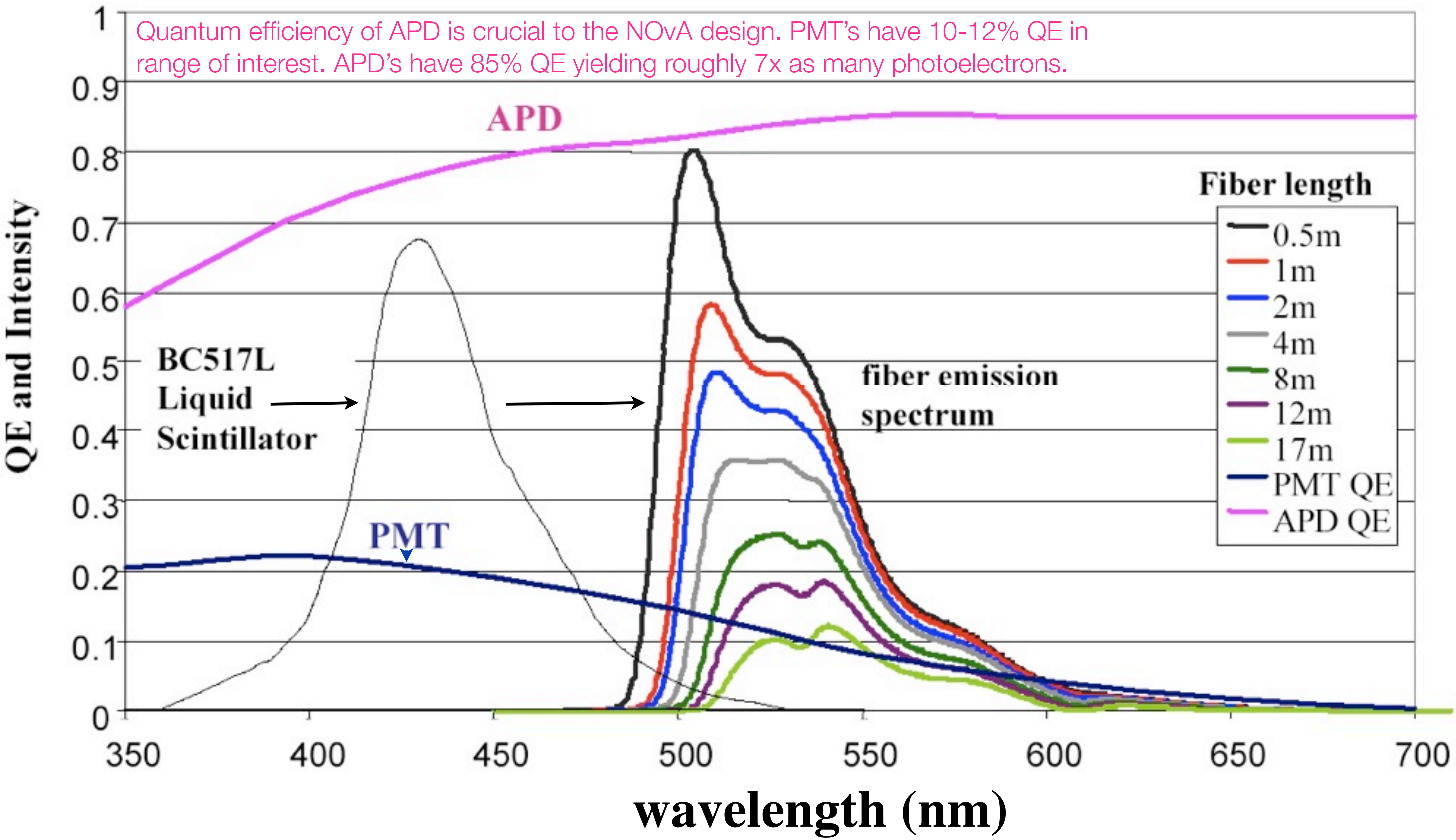
WLS Fiber

- NOvA will use 13,000 km WLS fiber from Kurrary. No other manufacturer produces fibers with long enough attenuation length
- Delivered at 360 km/mo over three years
- 0.7 mm “S” type (most flexible), 300 ppm of fluorescent dye
- Double clad with PMMA and flourinated plastic
- Tested >200 m of fiber in scintillator with high PC fraction at elevated temperatures wrapped in tight coils. We’ve seen no degradation in performance.
- A copy of our QC device will be sent to Kurrary so they can test the fiber as it comes off production line





Matching photodetector to light output



Overall cost of the NOvA experiment / detector

- The total project cost of the NOvA experiment is $278M. This number includes R&D, US costing, actual year $‘s, ave. ~40% contingency.
- Roughly cost break down:
  - Accelerator upgrades (400 kW to 700 kW): $51M
  - Project management $7M
  - Near detector cavern: $5M
  - Far detector laboratory: $60M
  - 222 ton near detector: $10M
  - 14 kt Far Detector: $145M ($10M/kt)
- Startup costs are large. We estimate that additional kilotons beyond 14 will cost about $8M/kt fully loaded. The enclosure is sized for 18 kt.
- Rough cost then is $(33+8×kt)M. For 100 kt, this suggests a detector-only cost of $833M (US accounting, actual year $’s, with contingency)

Further breakdown of 14 kt NOvA costs

These are just M&S costs in actual year dollars (no labor, no contingency)

	M&S Cost AY $M	Fraction of cost
Accelerator and NuMI Upgrades	10.2	9.3%
Far Detector Site and Building	17.6	16.1%
Liquid Scintillator	19.1	17.4%
PVC Extrusions	23.2	21.2%
Wavelength shifting fiber	9.9	9.0%
PVC Modules	7.9	7.2%
Electronics	10.7	9.8%
Data acquisition	1.7	1.6%
Far detector assembly	5.5	5.0%
Near detector assembly	3.7	3.4%
total:	109.5	100%

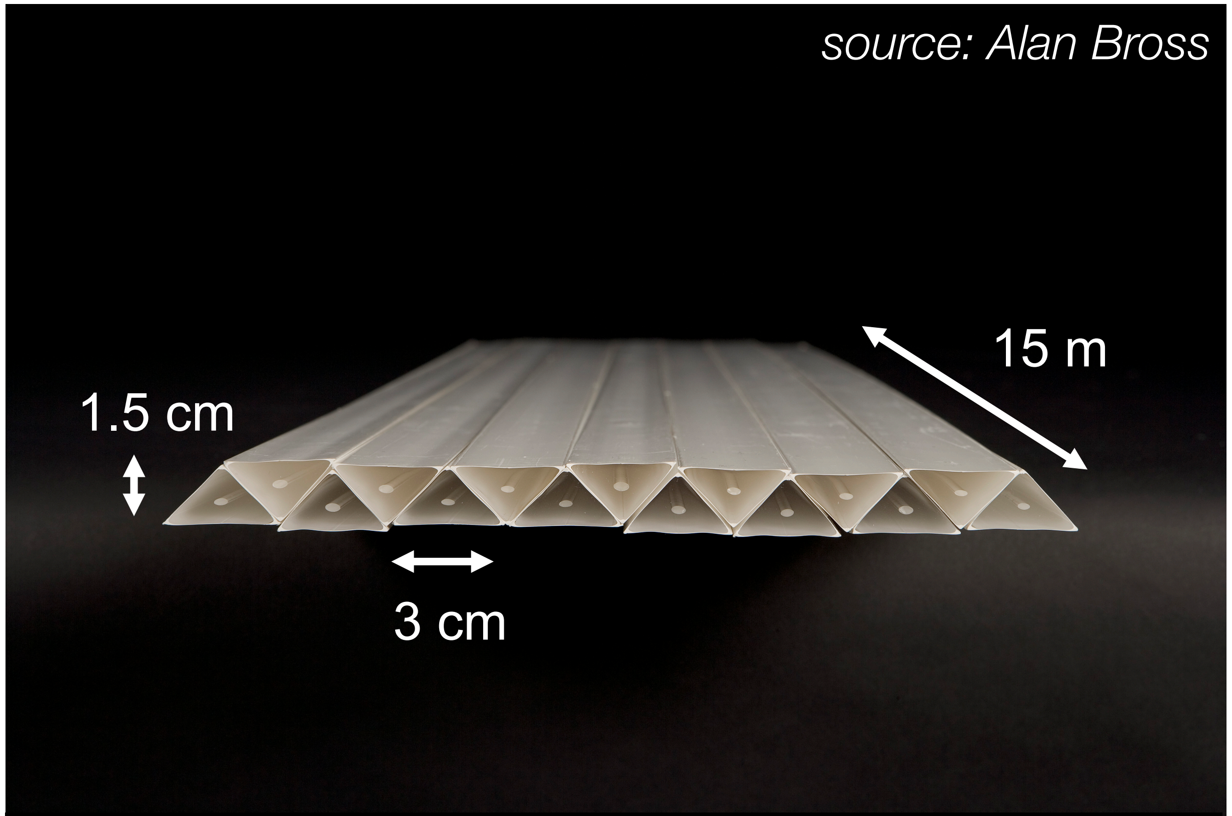
$19.1M/9 kt = $2.03/kg
Including PVC extrusions as part of scintillator system:
$43.3M/14 kt = $3.02/kg

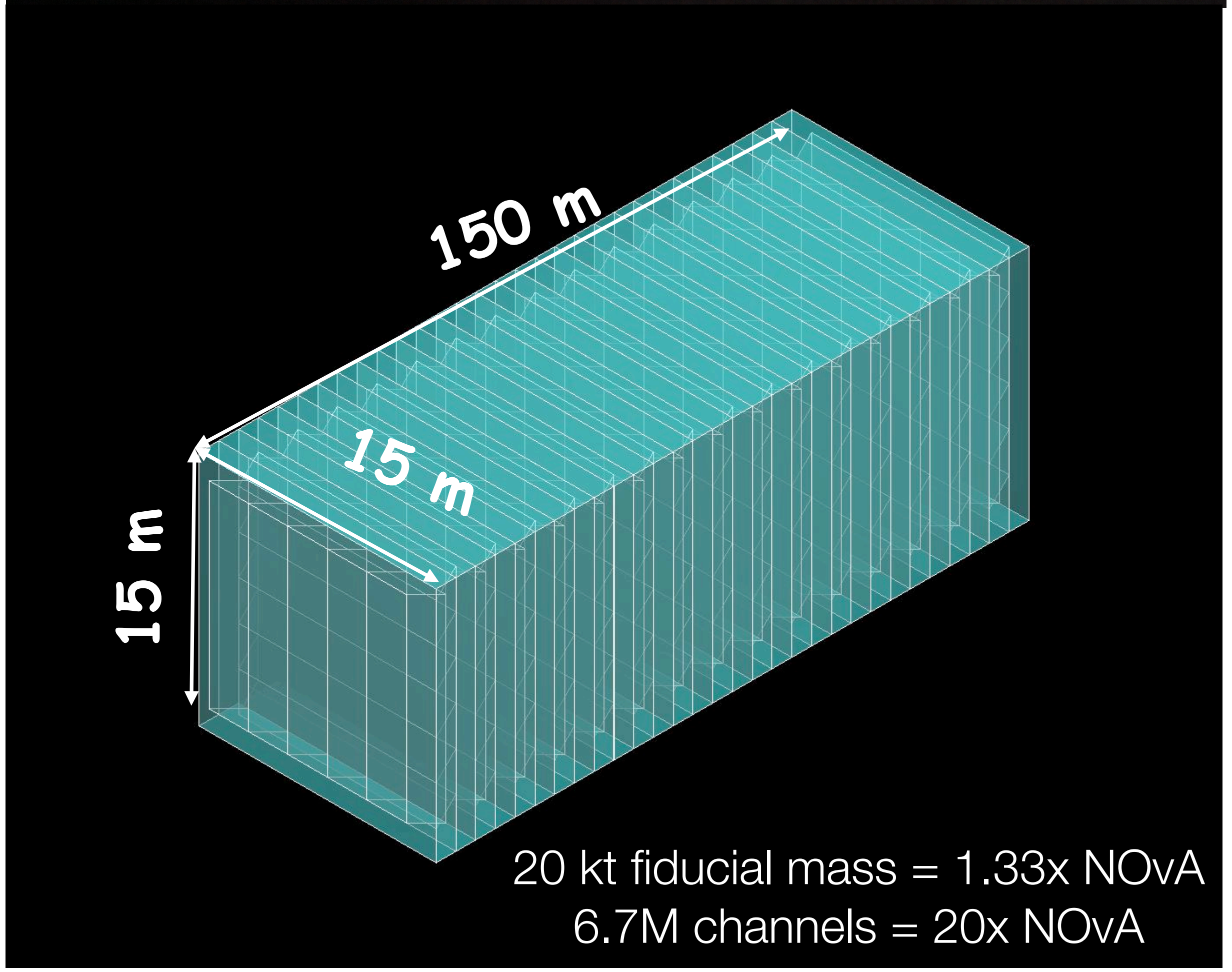
Total: $12.4M/360k channels = $34/channel (M&S, front end through readout)

Liquid or solid scintillator?

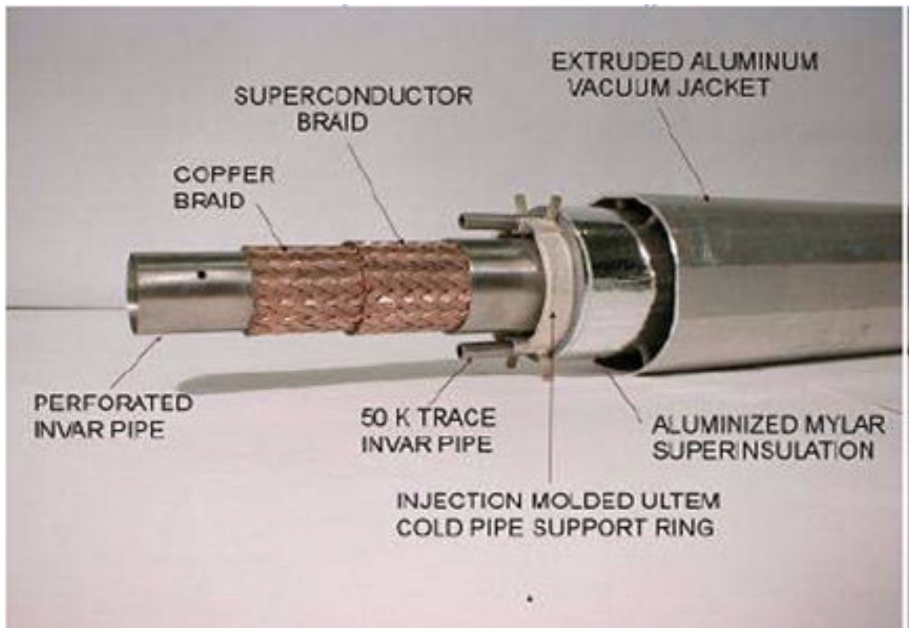
- From previous slide, including the PVC containers, the NOvA scintillator costs $3.02/kg (M&S only).
- Previous experience at Fermilab with solid scintillator:
    - MINOS: 4.1 cm x 1 cm $10/kg or $4/m
    - SciBar: 3.25 cm x 1 cm $12.5/kg or $4/m
    - MINERvA: 3.3 cm triangles $25/kg or $7.50/m
- How much can this be reduced with additional R&D?

source: Anna Pla-Dalmau

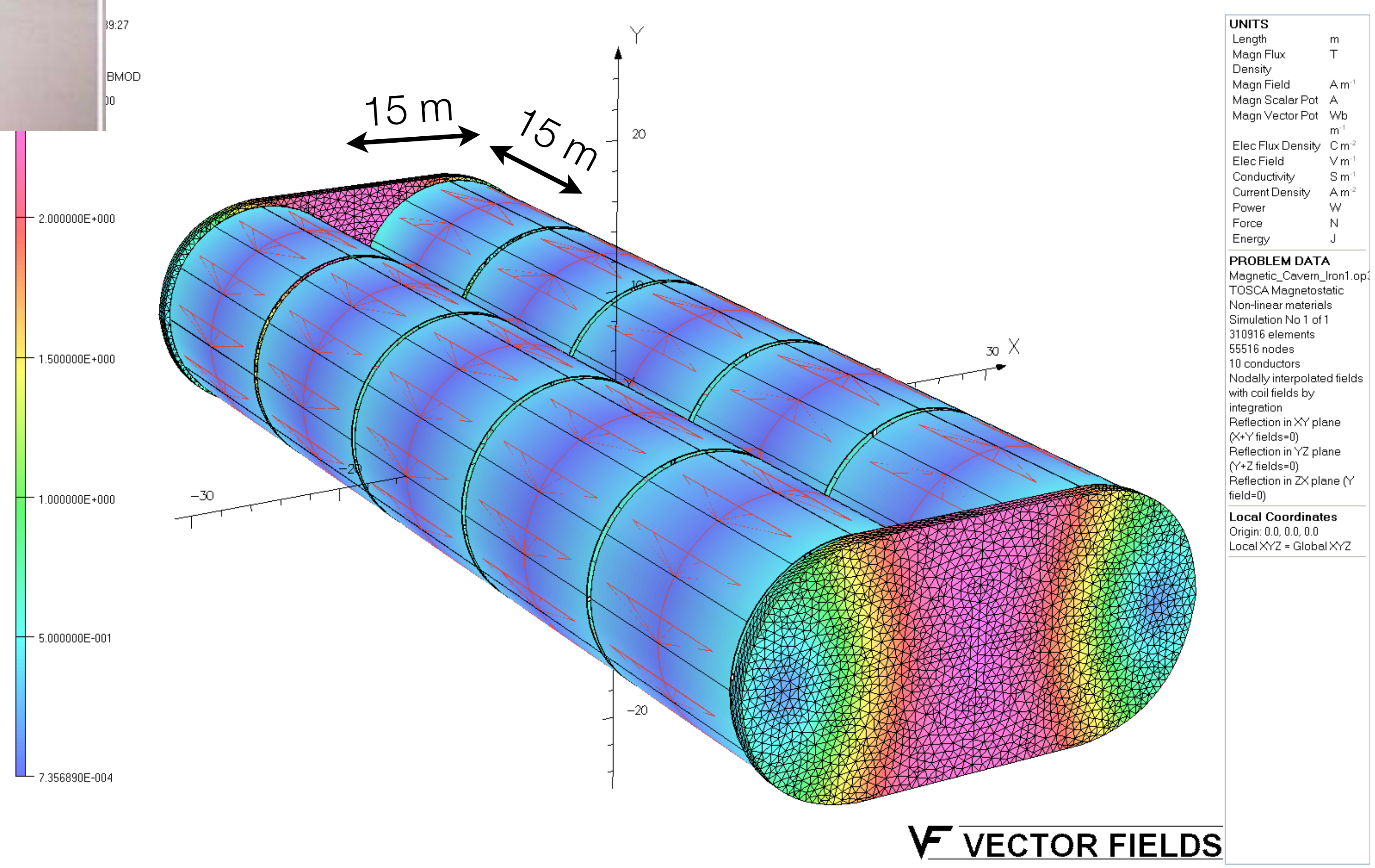




Magnetization of TASD
“Magnetized Cavern”

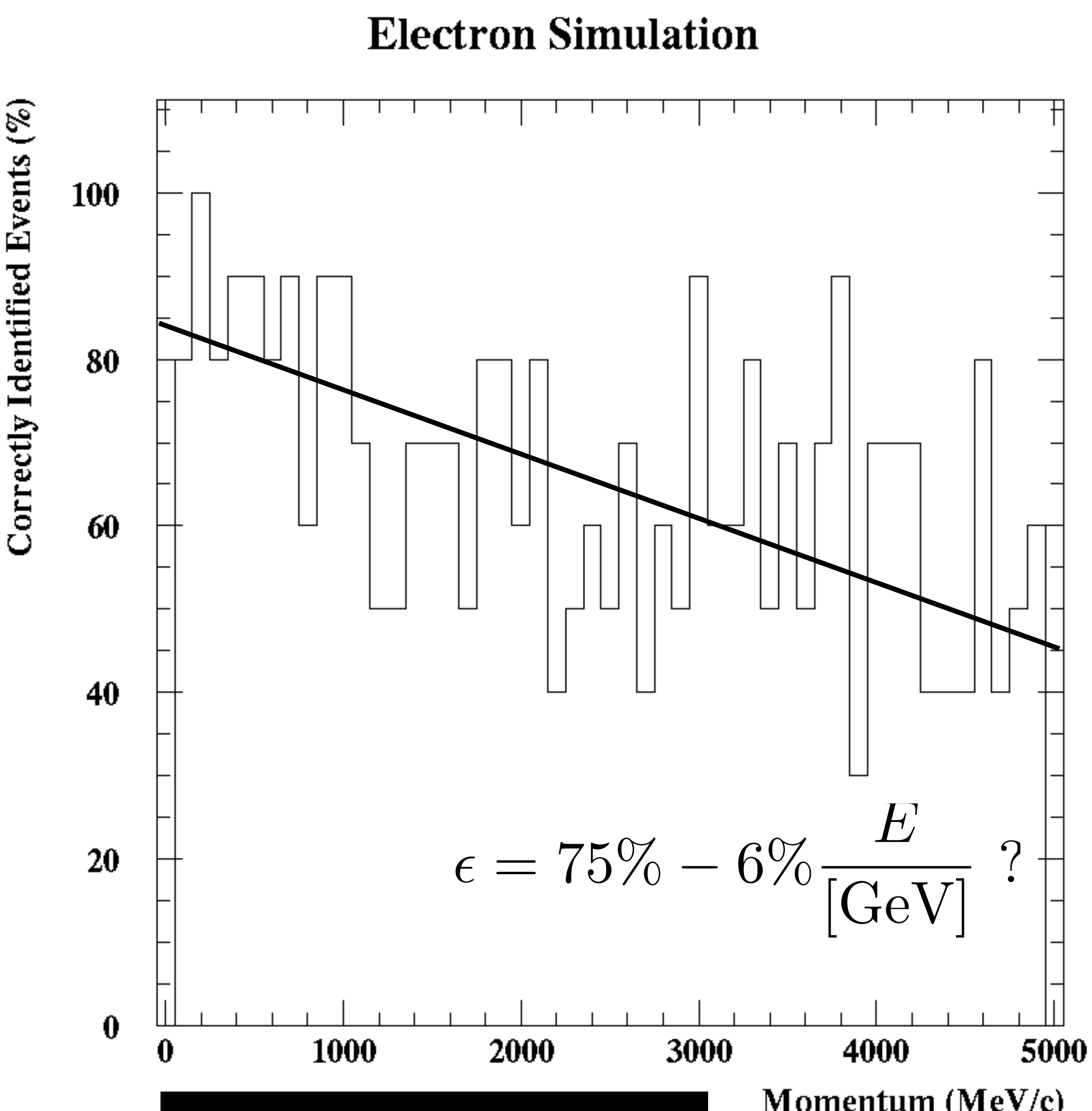


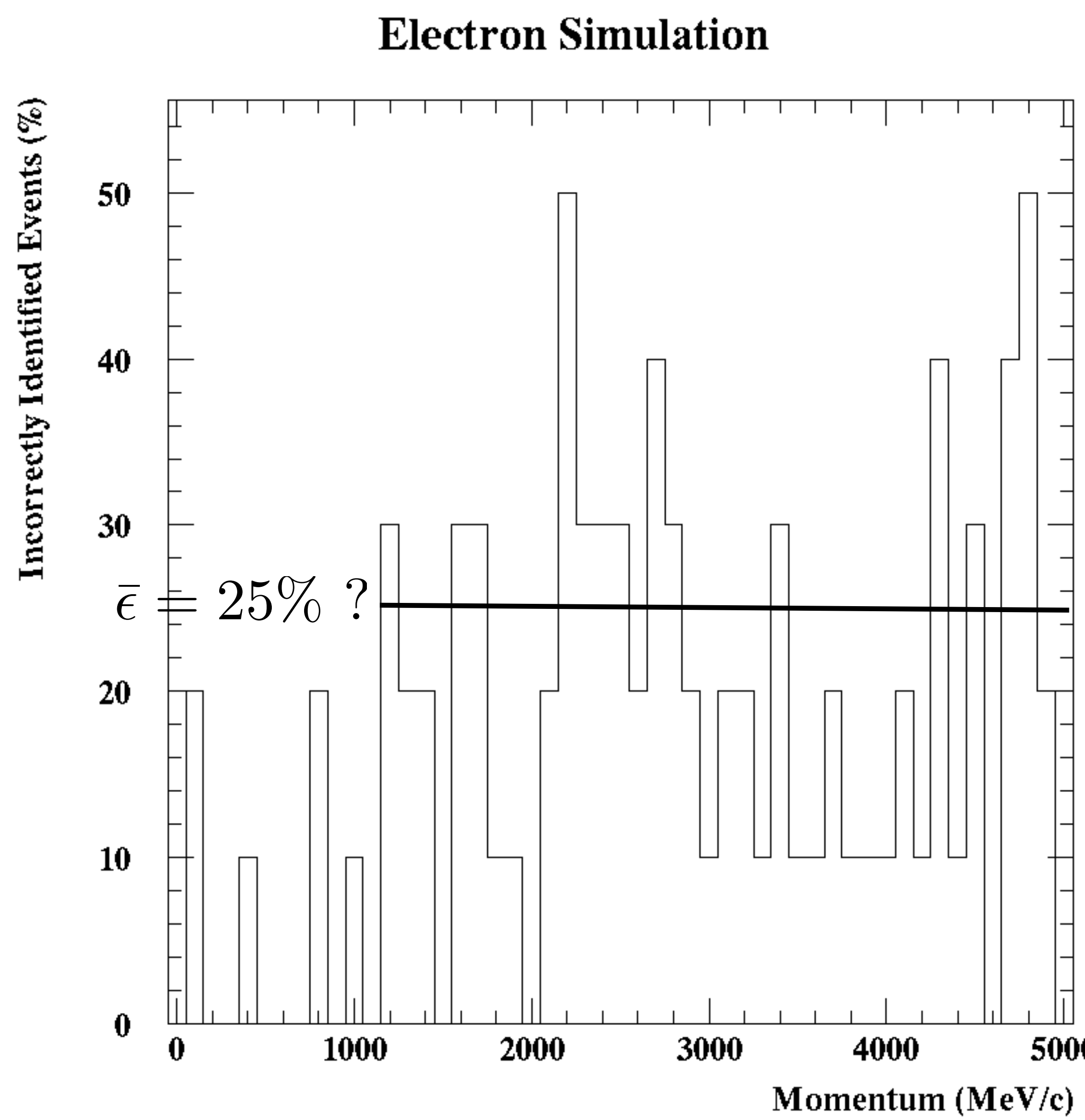
- Super-conducting transmission line developed at Fermilab for VLHC could be used to construct large solenoids (15 m ϕ, 75 m long) capable of producing 0.5 T field.
- Cost: $50M?
- Addition of iron return yoke increases field to 2.4 T



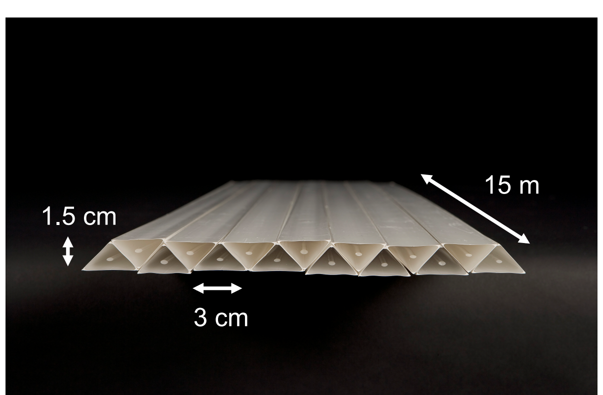
source: Alan Bross

Possibility of electron sign identification?





source: Allan Bross



Results of hand-scan of events using detector composed of scintillator shown at left. Assuming these results, no discriminating power at ~8 GeV

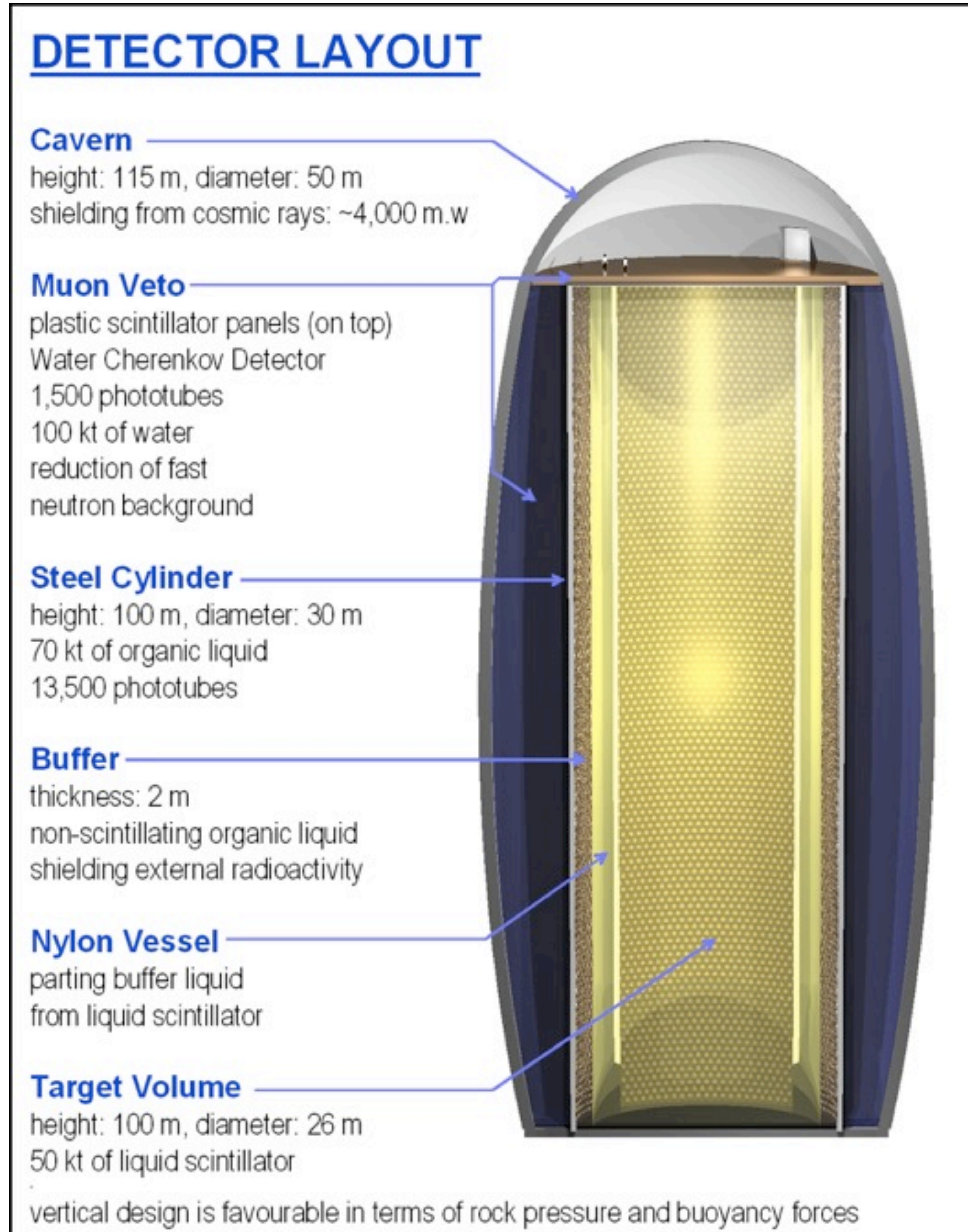
Is ν_τ channel viable in TASD?

- This question was specifically asked in my charge for this talk, but I'm sorry that I don't have an answer. NOvA will operate in a 2 GeV narrow-band beam and τ production threshold is 3.5 GeV. Consequently, this is not a topic we've looked at.

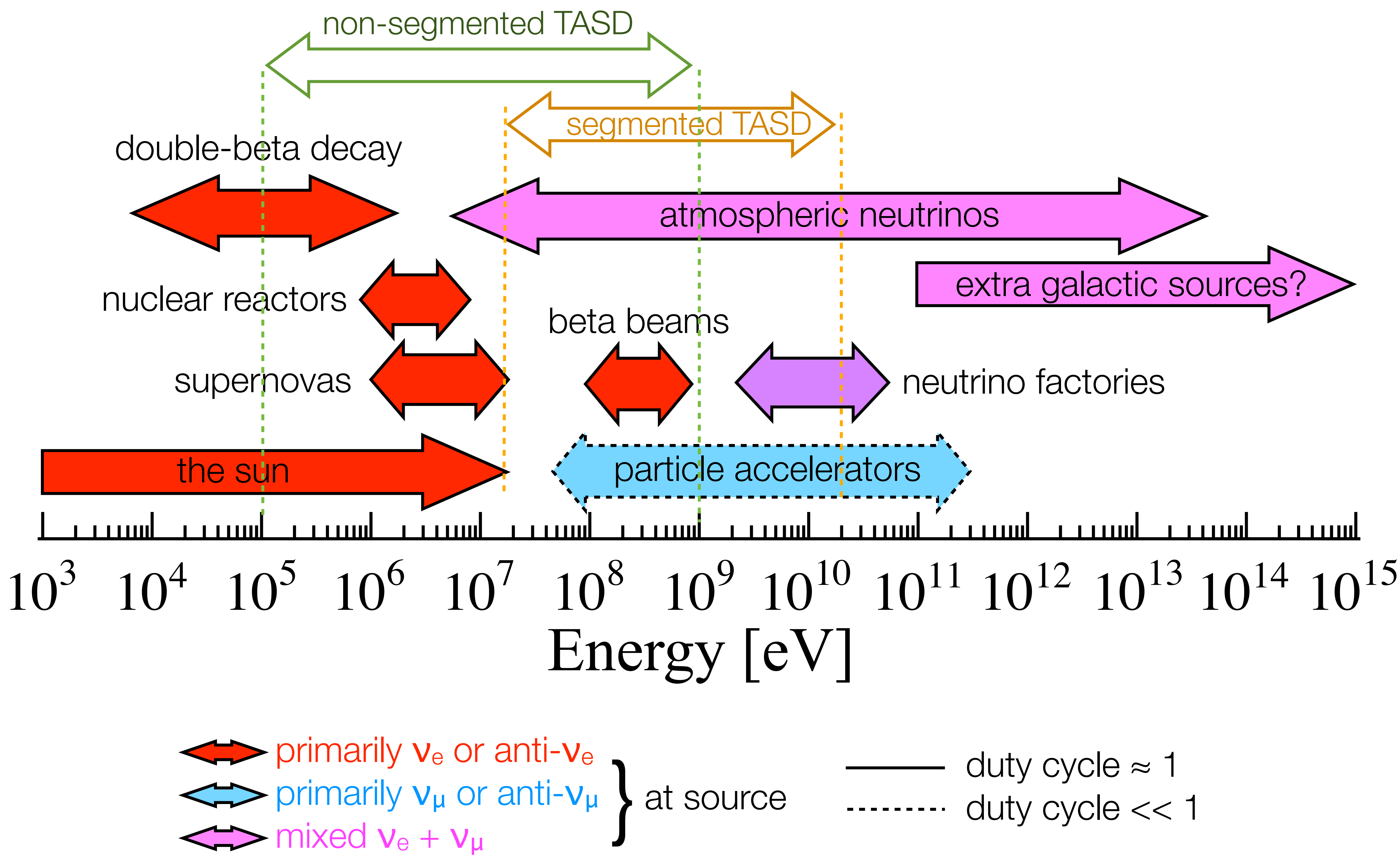
- That said, Super-Kamiokande has made a statistical measurement of ν_τ appearance. A TASD detector will provide more information in this channel than a Water Cherenkov detector and I suspect would perform quite a bit better. However, I cannot back this statement up with a simulation or analysis of the detection efficiency.

Non-segmented TASD

- LENA (Low Energy Neutrino Astronomy)
- 50 kt liquid scintillator / 13,500 PMTS. ~1% energy resolution
- Geoneutrinos
- Solar neutrinos
- Supernova burst neutrinos
- Diffuse supernova neutrinos
- Proton Decay
  - $p \rightarrow \nu K^{+}$ with 65% efficiency through timing pulse shape and excellent energy resolution
  - $p \rightarrow e^{+}\pi^{0}$ with 12% efficiency



Energy ranges for the two technologies and synergies with other physics topics



Synergies with non-accelerator physics

- At 15 kt NOvA has little to add to most non-accelerator physics topics with the exception of:
  - Supernova burst: NOvA is sensitive to supernova burst neutrinos. 15 MeV ≈ 4 hits in the detector - 2 neighboring cells in coincidence in each view.
- A massive TASD deep underground could contribute to:
  - Atmospheric neutrinos : Would require improvement in timing over NOvA design to get good up-going vs. down-going discrimination. With magnetization could provide compelling measurements. Here I think a segmented design has advantages over non-segmented designs.
  - Proton decay : $p \rightarrow e^+\pi^0$ is a promising 'single event' discovery channel in TASD. $p \rightarrow \nu K^+$ requires higher granularity than is probably possible; in NOvA the K^+ produces only a few hits but may be resolvable through $K \rightarrow \mu \rightarrow e$ timing coincidences. Single event in this channel likely not enough to claim discovery. 100 kt may not be enough to catch up to existing SK limits. In νK^+ non-segmented design may have advantages
  - Supernova relic : On the edge for segmented design but could be possible depending on depth down to a threshold of ~15 MeV; highly dependent upon granularity; non-segmented design better at these energies
  - Solar neutrinos : Below threshold for a segmented design. Possible in non-segmented designs if deep and clean enough.

To conclude:
R&D items to take TASD beyond NOvA

- **Structure**: Not very sexy, but very important. NOvA is likely the largest structure ever to be built of plastic. Assembly and long term structural issues have occupied a considerable amount of the NOvA design effort.
- **Electronics**: Currently APD's are the only viable option for readout due to their high quantum efficiency. We're budgeting $425/32 pixel array = $13.30/channel for photodetectors. It would be useful to develop a viable, cheaper, alternative. It would be beneficial to have a lower cost front end with better timing resolution which is required for non-accelerator physics.
- **WLS Fiber**: There is only one maker of WLS fiber in the world which is capable of carrying light 15 m. It would be useful to develop an alternative.
- **Scintillator**: Probably very little can be done to further optimize cost/performance of liquid scintillator beyond what NOvA has done. May be gains in solid scintillator
- **Magnetization**: Magnetized cavern needs effort to take it beyond current concepts