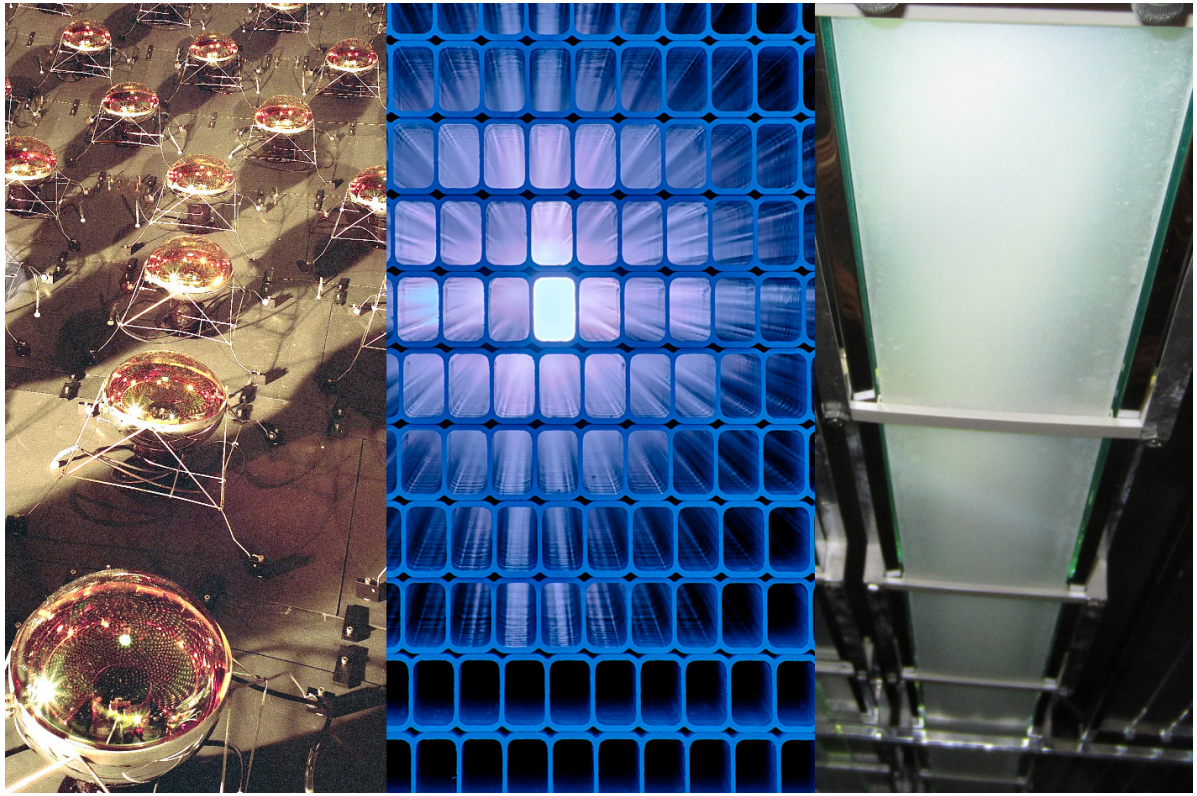
Collecting Light from Neutrino Interactions

Fermilab Neutrino Seminar Series

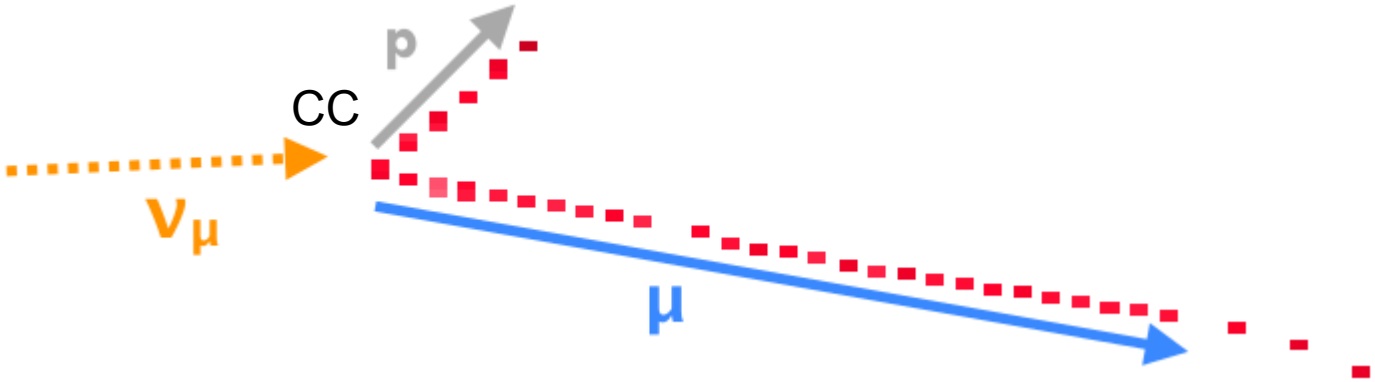
May 25, 2017

Collecting Light from Neutrino Interactions

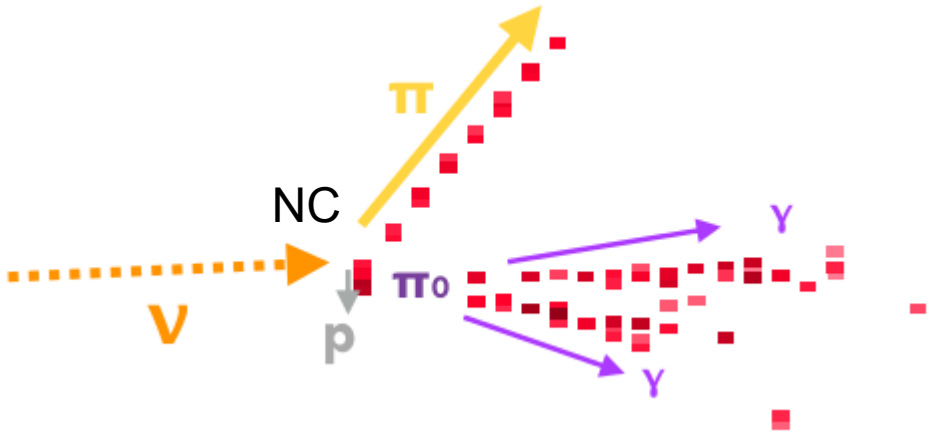


- Experiments
  - MiniBooNE
  - MINOS
  - NOvA
  - DUNE
- Signals
  - Cherenkov Radiation
  - Scintillation
    - Solid and liquid scintillators
    - Liquid noble elements
- Detectors
  - Photomultiplier tubes
  - Avalanche photodiodes
  - Silicon photomultipliers

- Don't directly detect neutrino, but do see interaction products



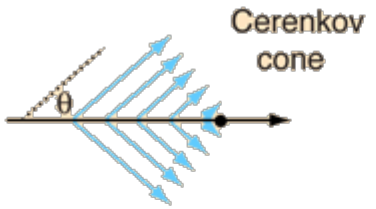
- Neutrino daughter particles
  - Muons, electrons, protons, pions, neutrons



- Distinguish by interaction properties
  - EM showers vs tracks
  - dE/dx

- Traveling charged particle disrupts local EM field in a dielectric (polarizable) medium
  - Slow – medium relaxes elastically back to mechanical equilibrium
  - Fast – limited response speed of medium leaves a disturbance in the particle's wake

- Energy in disturbance radiates as a coherent shockwave
  - analogous to a sonic boom



$$\cos\theta = \frac{c}{vn}$$

v = particle velocity
n = index of refraction of the medium

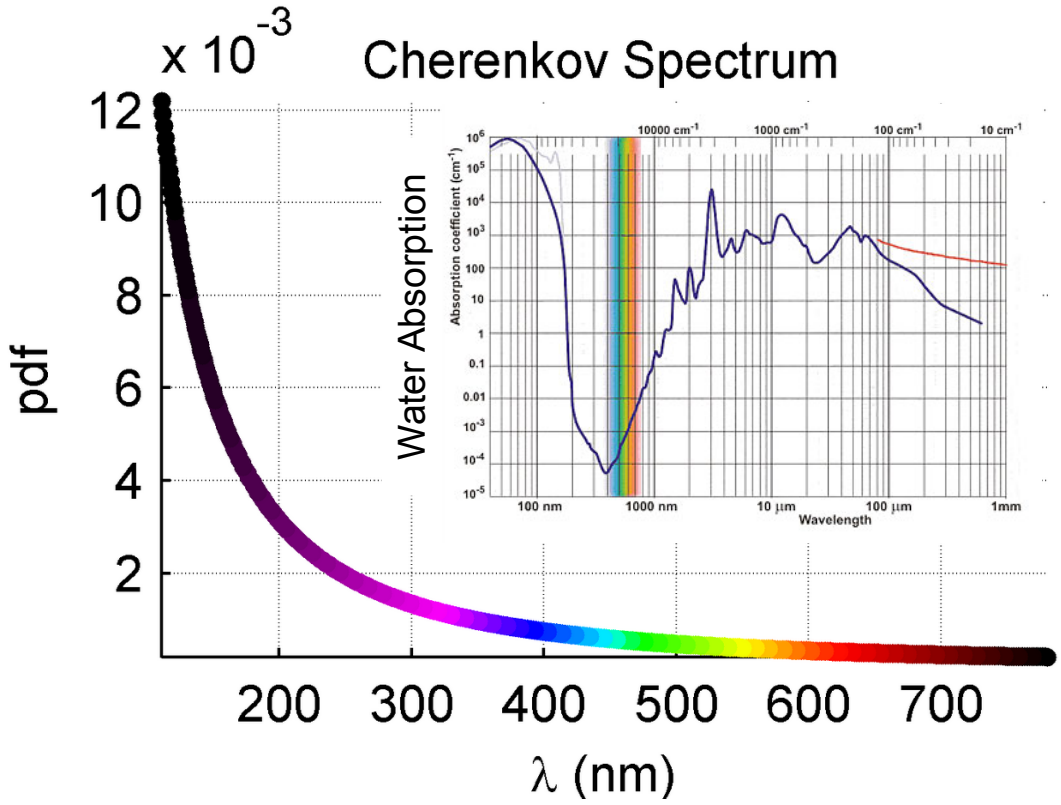
For water with n=1.33, the limiting angle for high speed particles is given by:

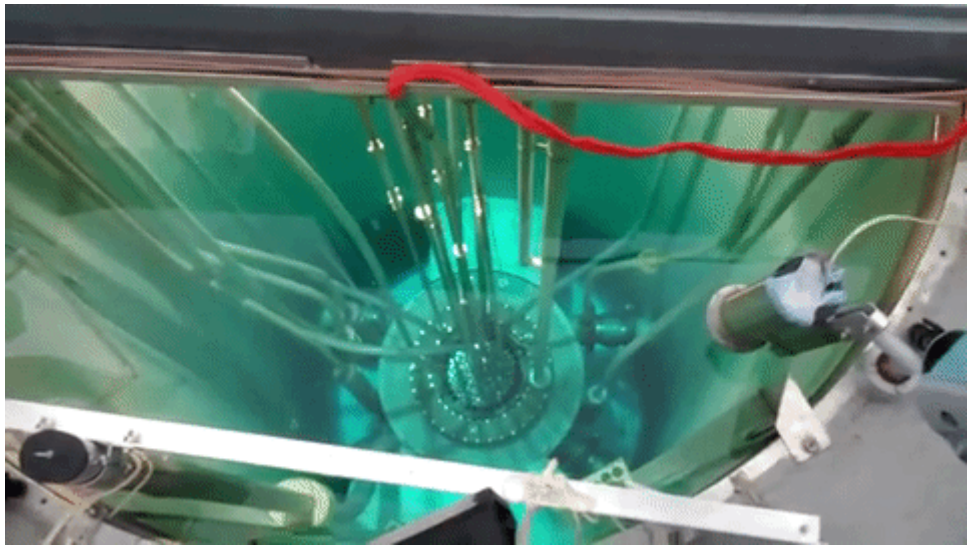
$$\theta = \cos^{-1}\frac{1}{1.33} = 41.2°$$

  - Independent of mass
  - Stops when v < c/n
    - in water, about 0.75% of c

- The familiar blue glow isn't the whole story.

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

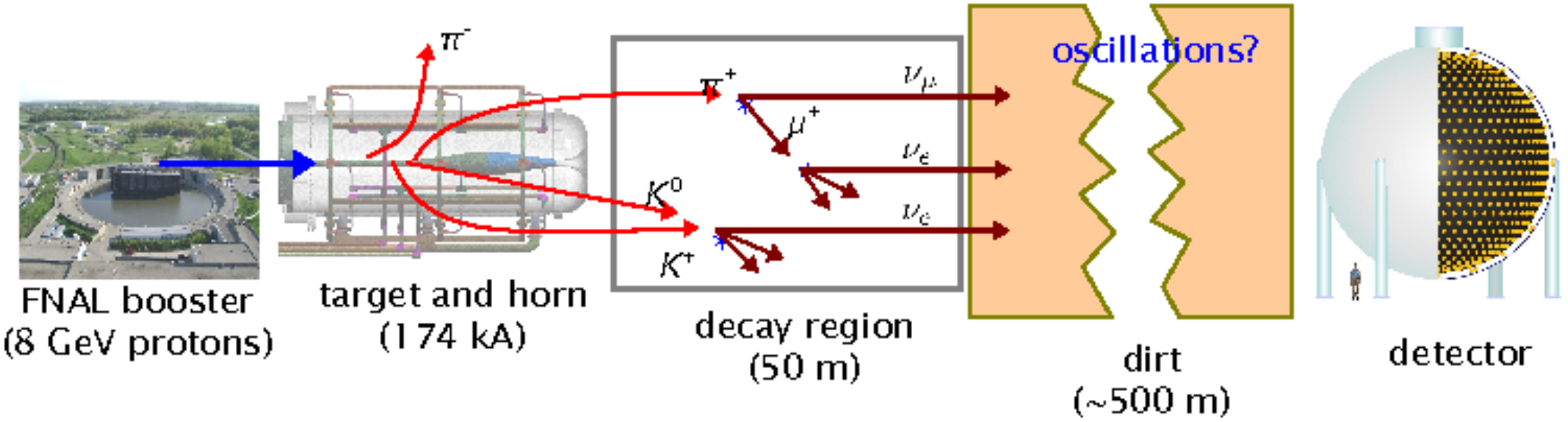




Reactor pulse test: Control rods removed and rate increases exponentially until failsafe trips.

× absorption (e.g. *water*) × detector response (e.g *eyes*)

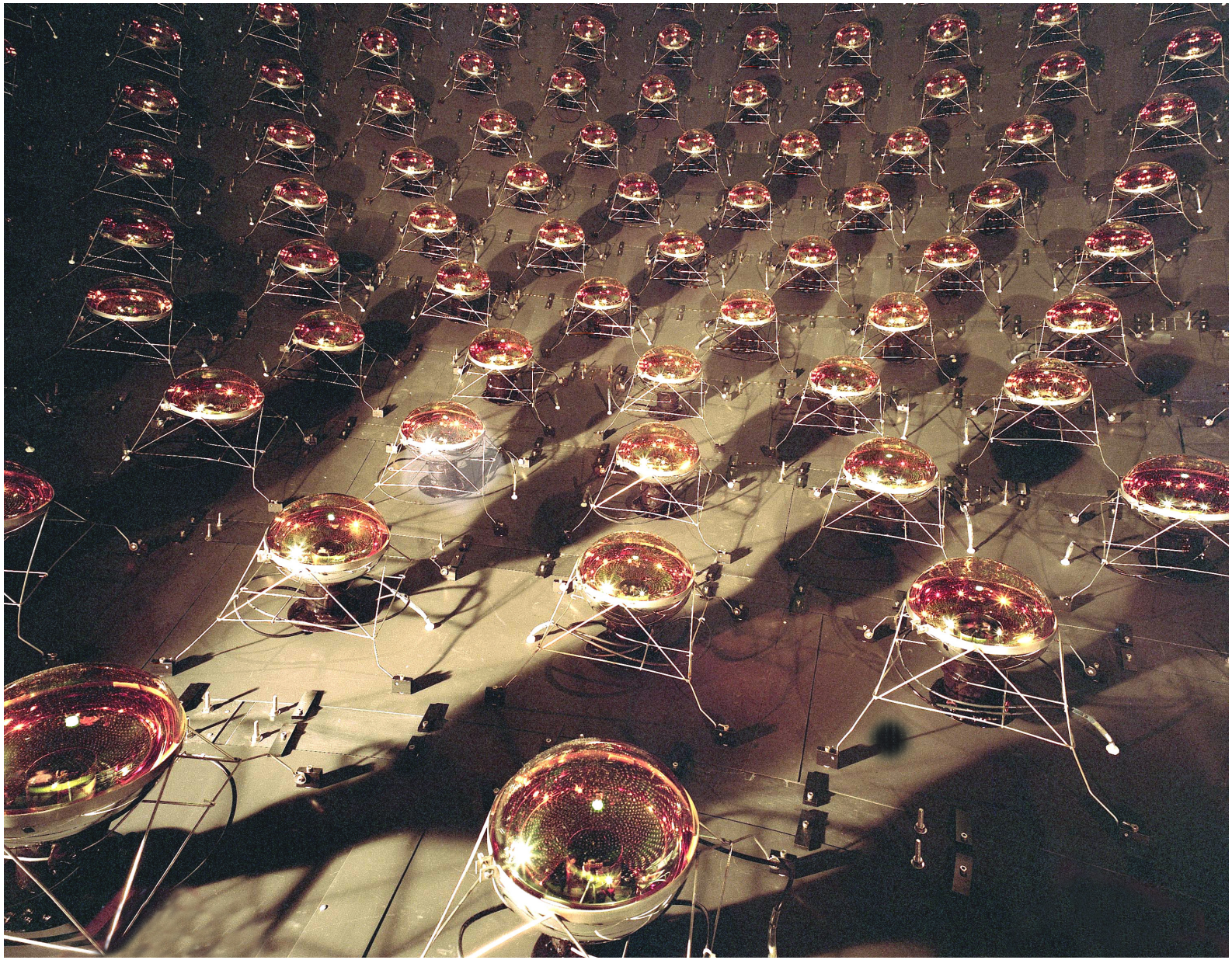
- MiniBooNE
  - Mineral oil Cherenkov detector
    - Larger index of refraction
    - Lower Cherenkov threshold
    - Low photon absorption
  - Booster neutrino beam
    - ν_μ and $\bar{\nu}_\mu$ ~700 MeV
  - Tested LSND anomaly
    - Excess of ν_e and $\bar{\nu}_e$ events at small L/E



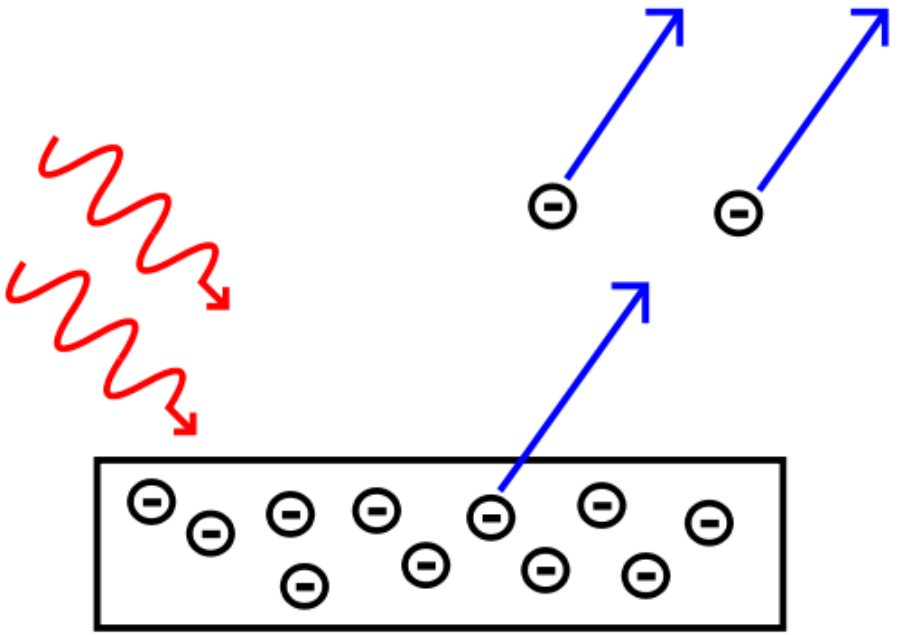
- MiniBooNE

1280 8” PMTs

Image Cherenkov rings from muons, electrons, and π^0 decay photons.



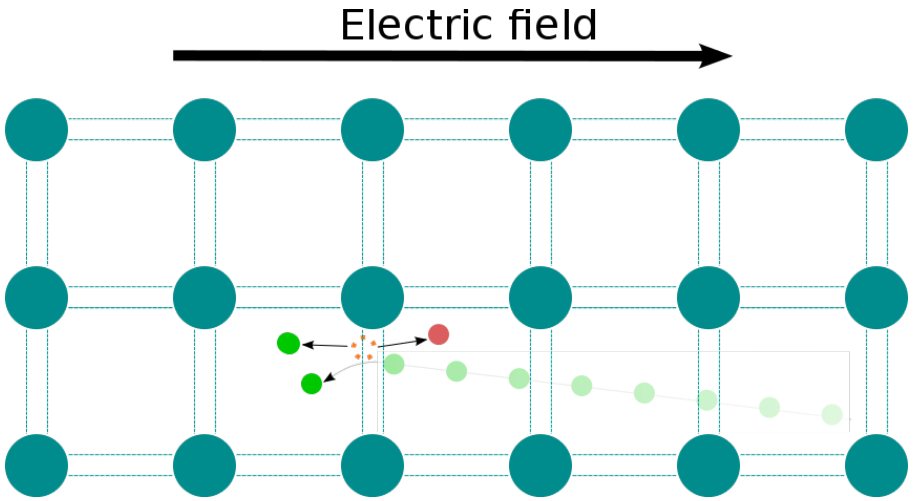
- Photoelectric effect



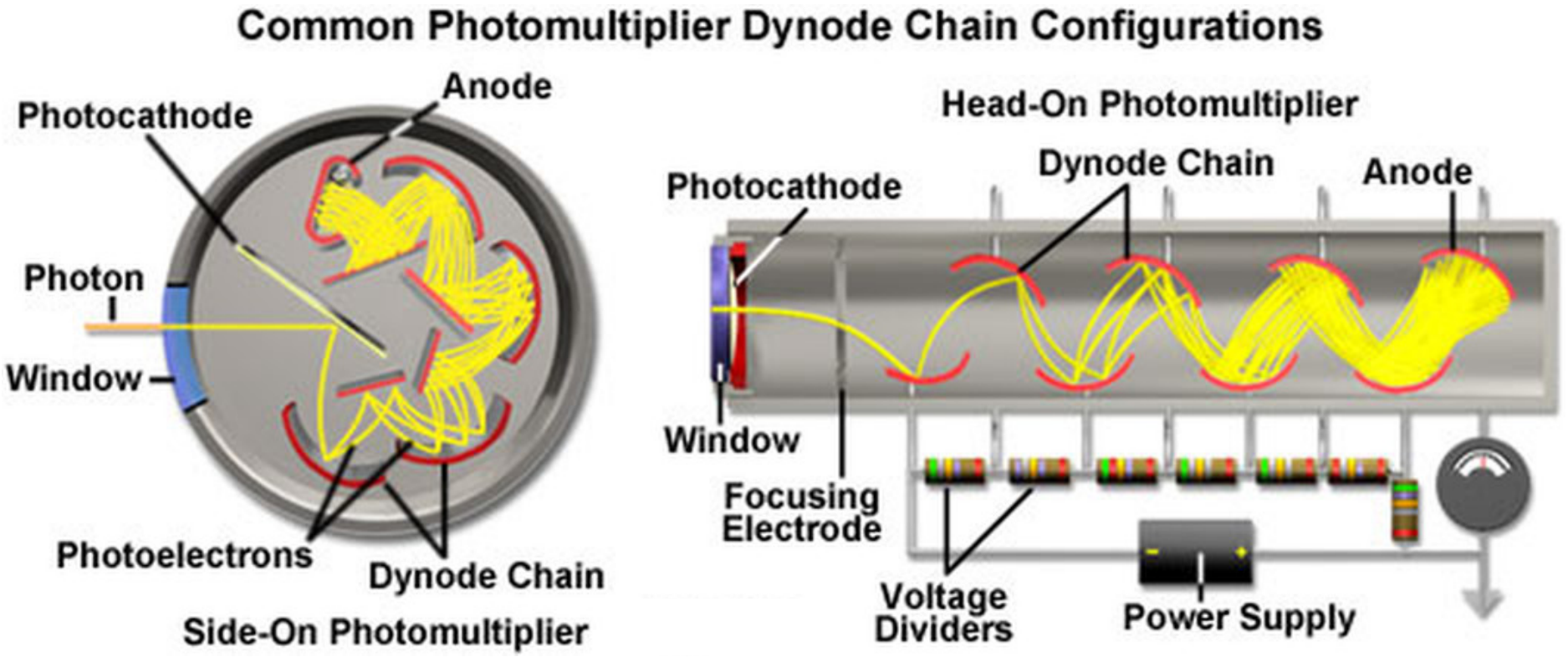
author: user Wolfmankurd
from: http://en.wikipedia.org/wiki/File:Photoelectric_effect.svg

- Different cathode materials have different work functions
  - Controls spectral responsivity

- Apply an electric field to accelerate emitted electrons
  - Impact ionization
    → avalanche effect

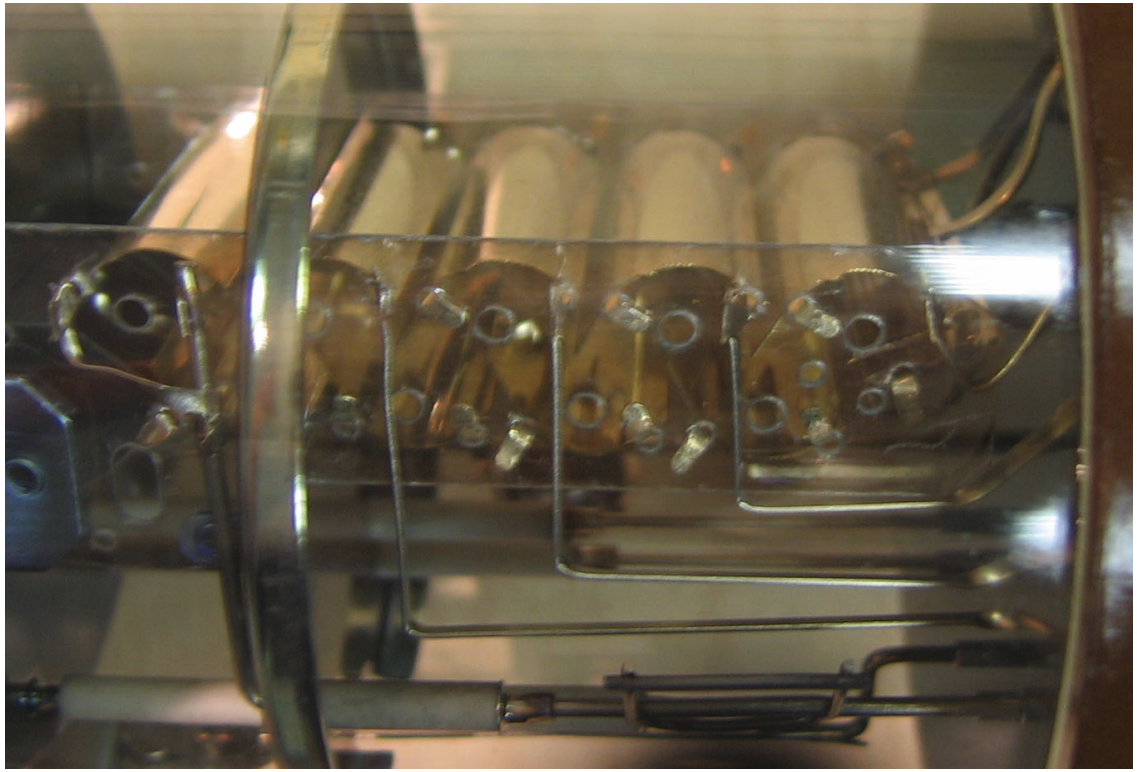


author: user TacitSilence
from: https://en.wikipedia.org/wiki/Impact_ionization#/media/File:ImpactIonisation1.svg



- PMTs come in a variety of designs for every application

Head-on PMT dynode chain:

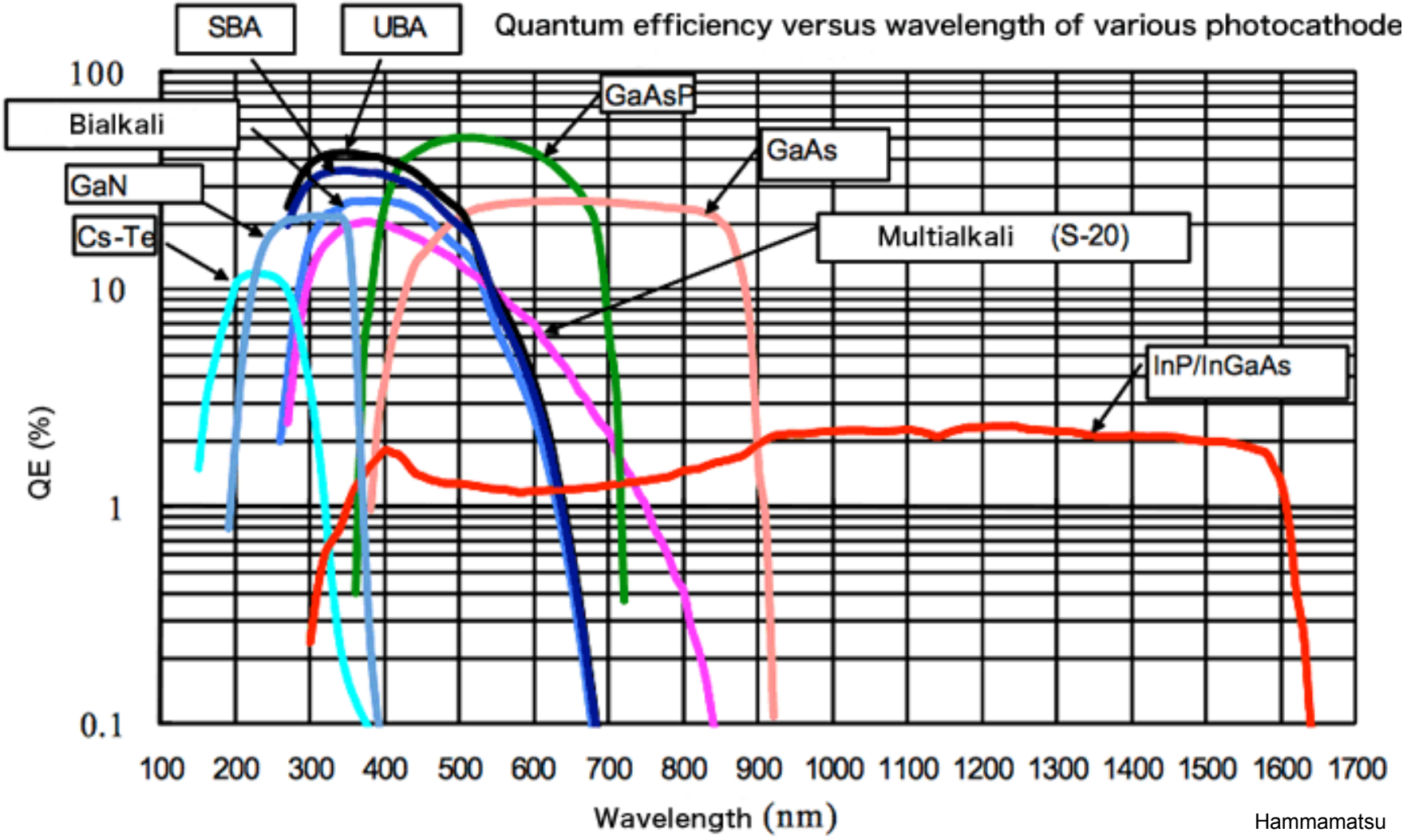


author: user Poil
https://en.wikipedia.org/wiki/File:Dynodes.jpg

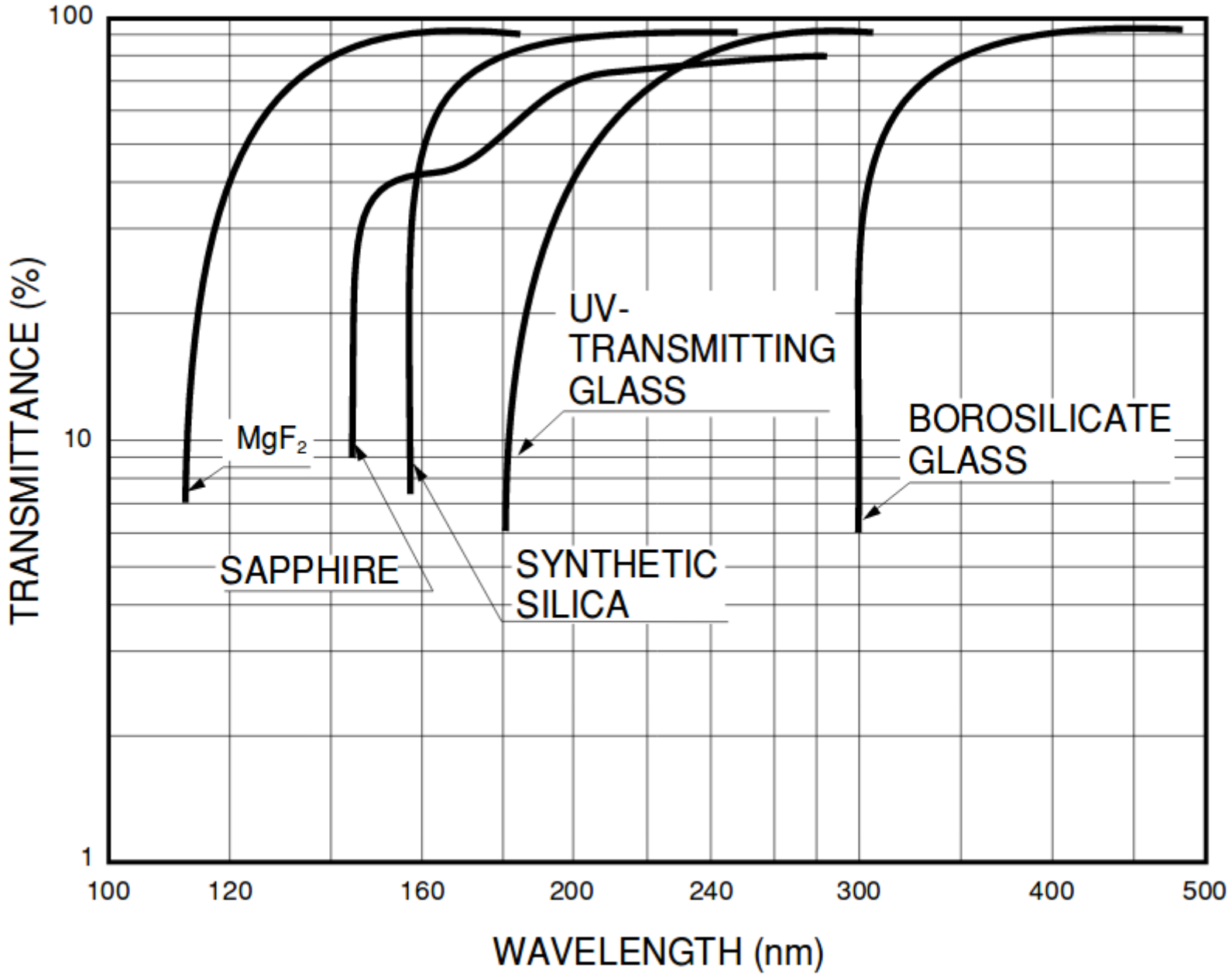
- PMTs come in a variety of designs for every application

Hammamatsu

- Spectral response – cathode materials

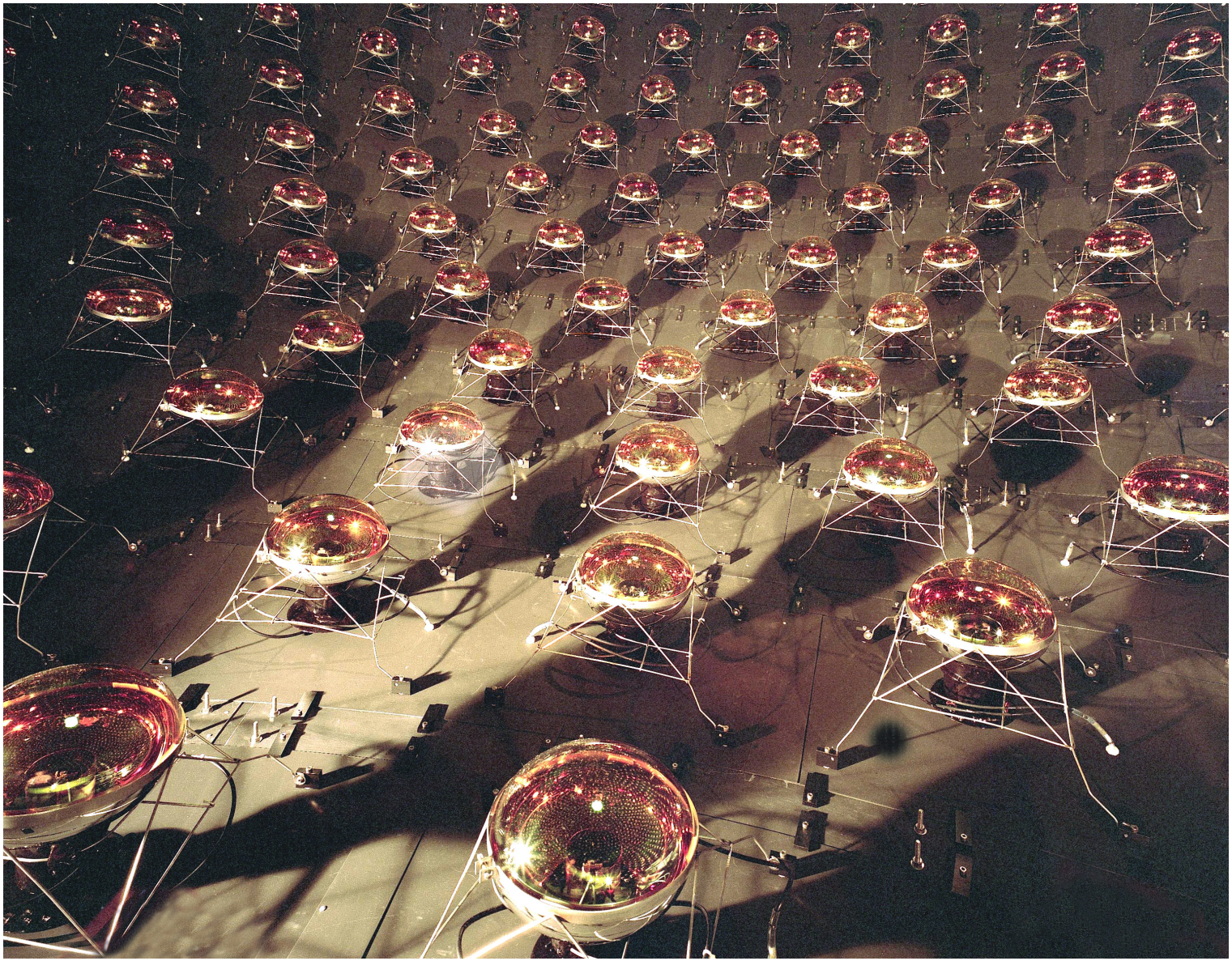


- Spectral response – window materials



Hamamatsu PMT Handbook (https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf)

- MiniBooNE
  - Detecting Cherenkov rings with an array of PMTs



- MiniBooNE
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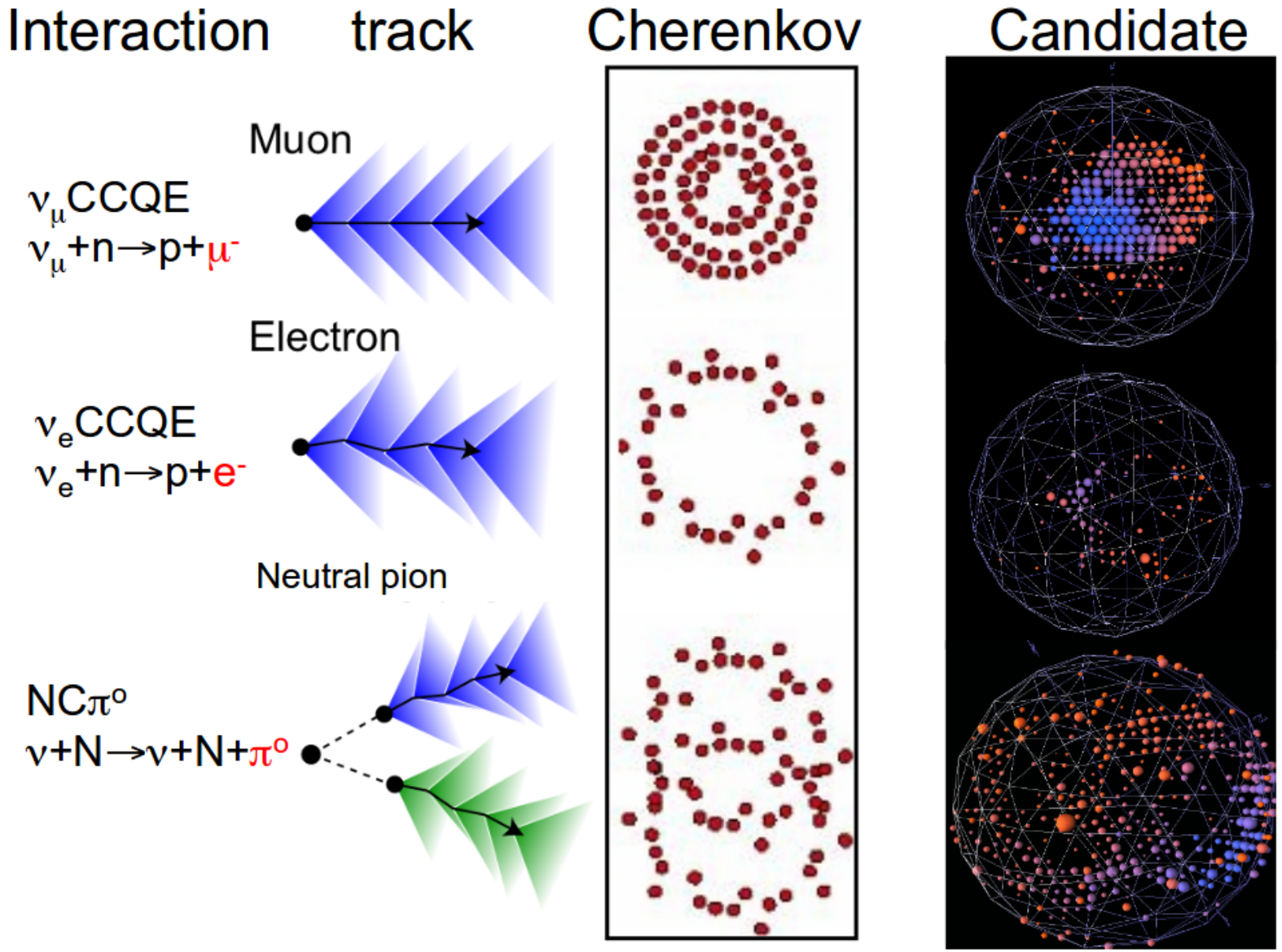
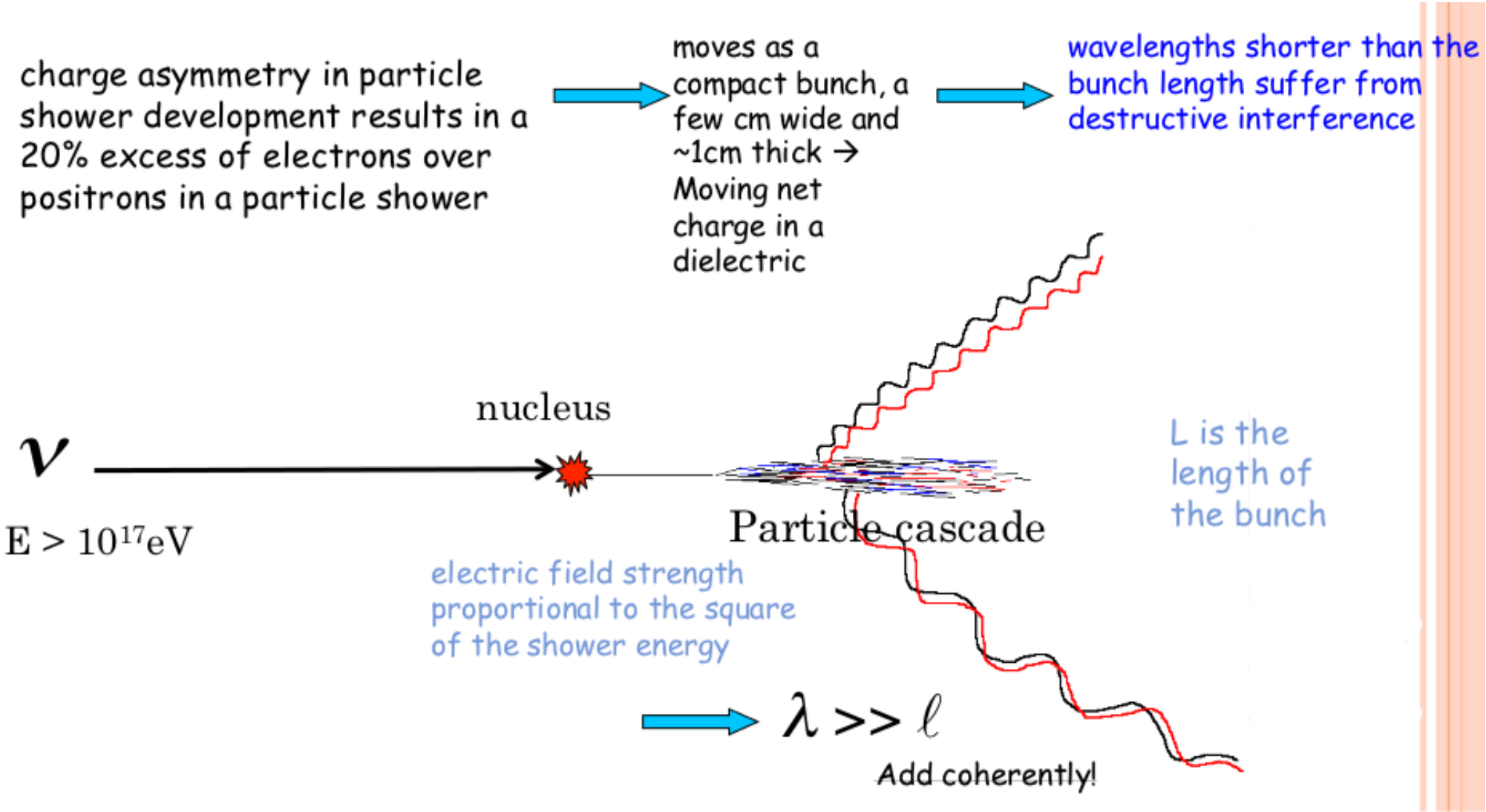


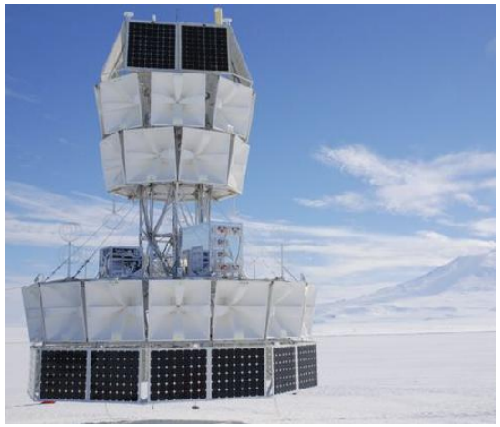
- Interesting aside – radio Cherenkov

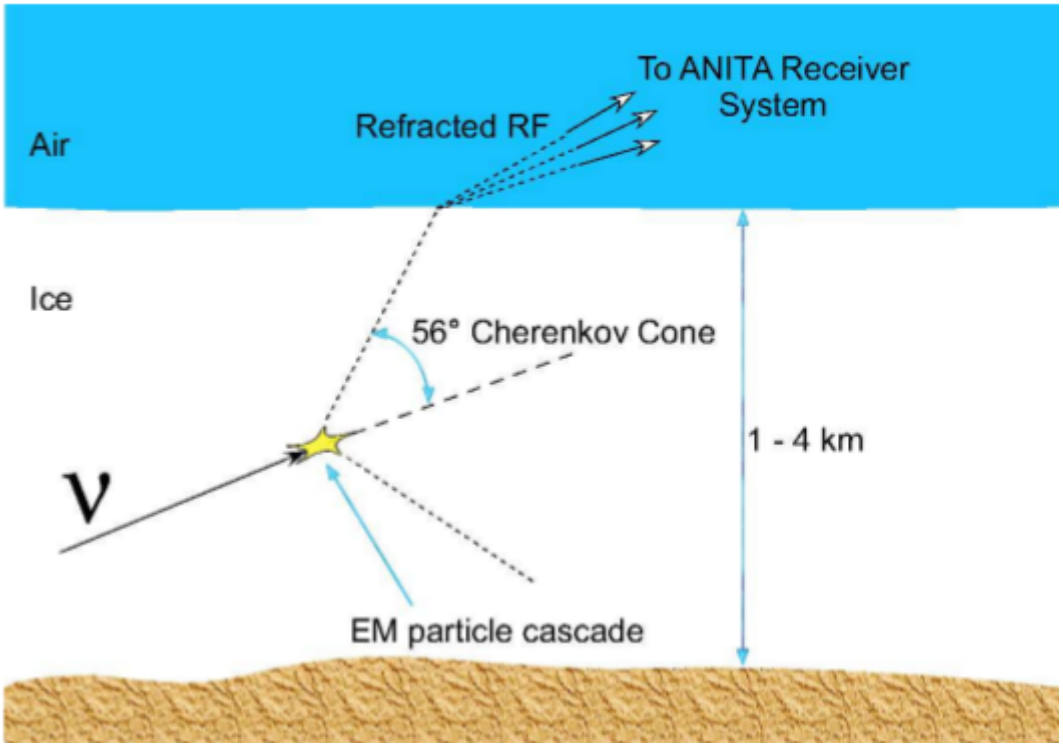


From thespectrumofriemannium.wordpress.com

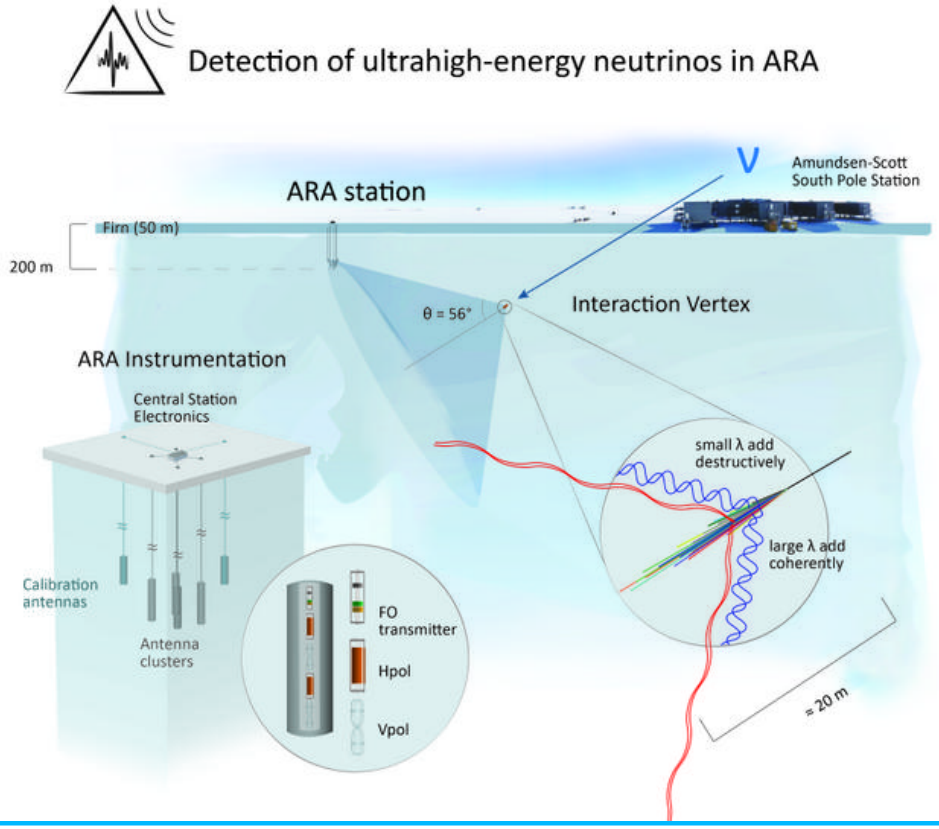
- Interesting aside – radio Cherenkov

ANITA
balloon-bourne
experiment



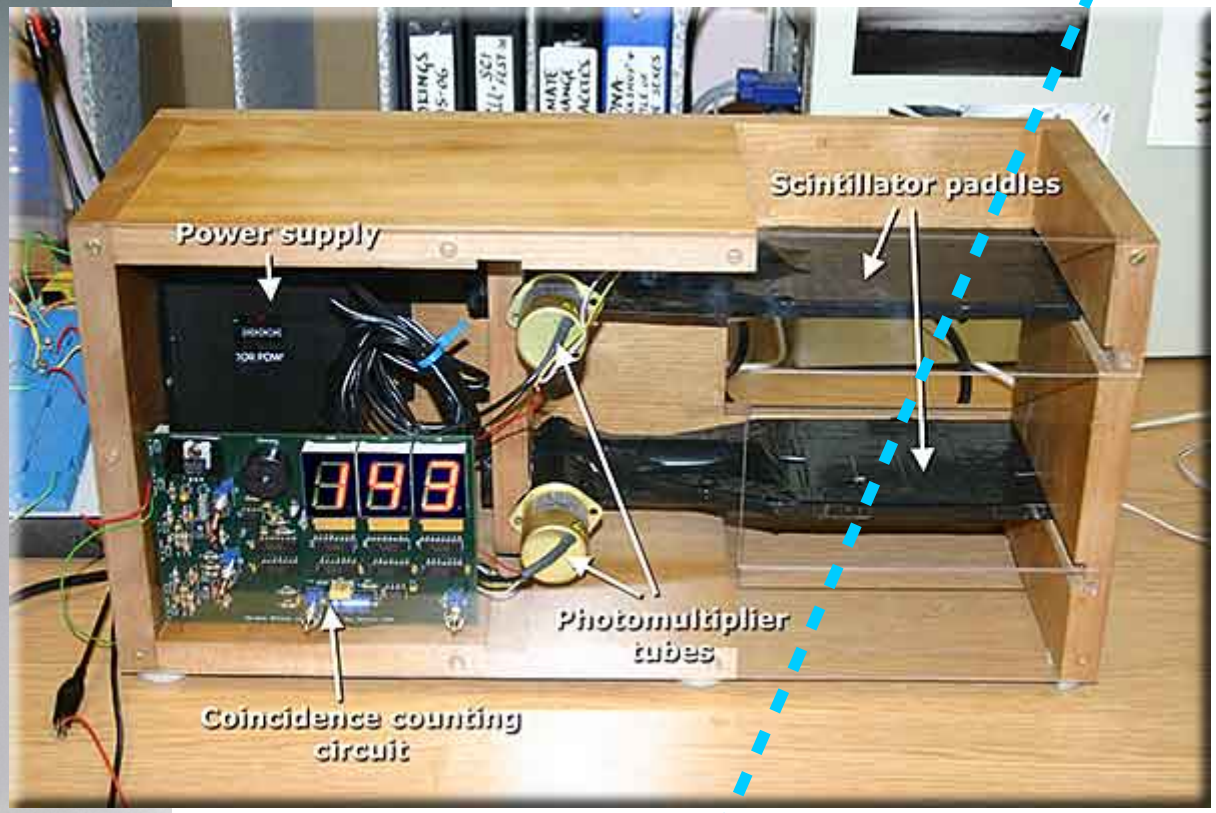


ARA
buried antenna array



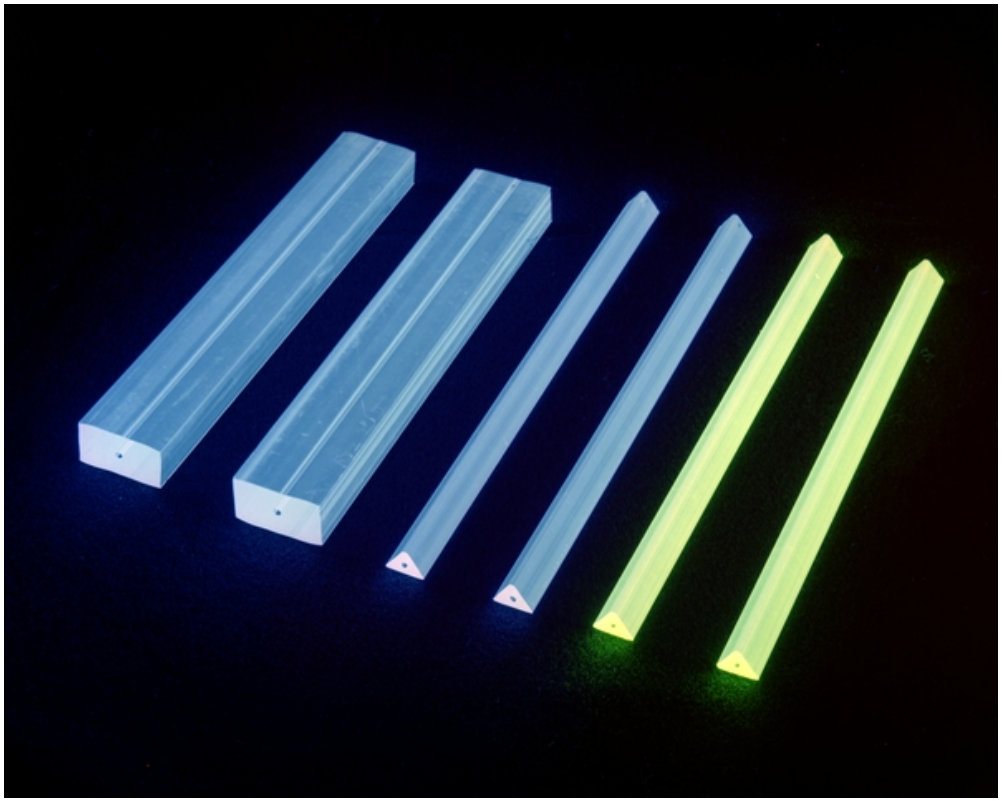
- Fluorescent compounds suspended in a substrate

Collisional energy losses from particle traveling through material (dE/dx) agitates fluorescent compound, which de-excites by emitting visible photons.



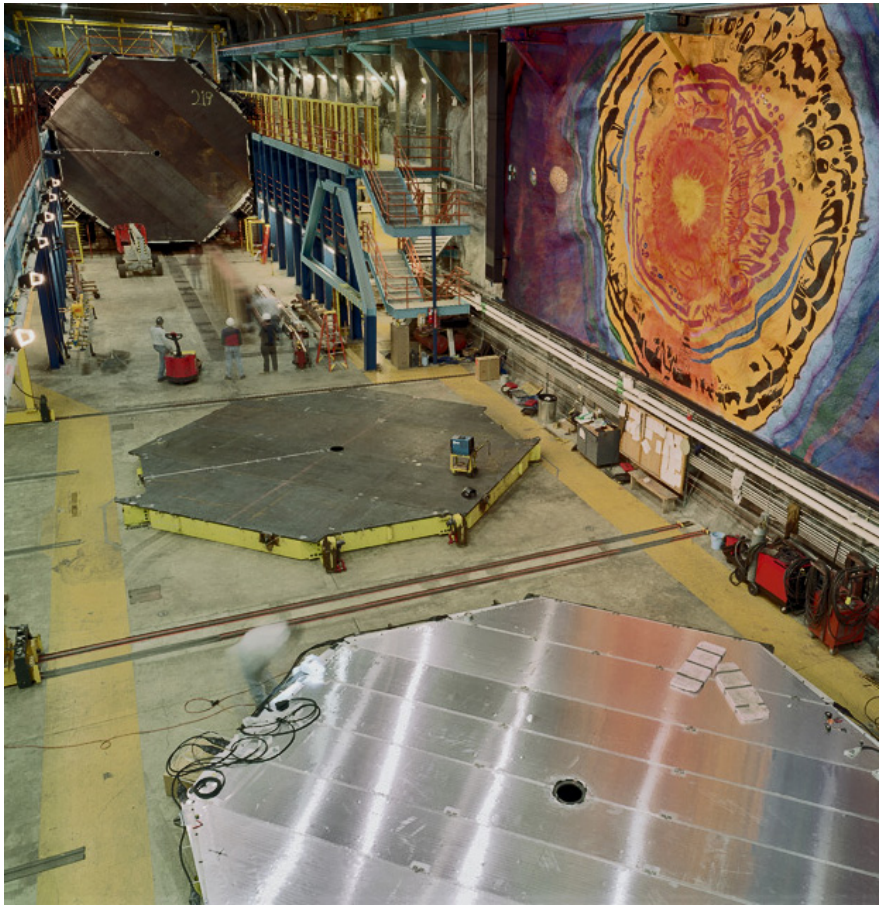
- Scintillators can be found throughout Fermilab physics

Scintillator
counter from CDF

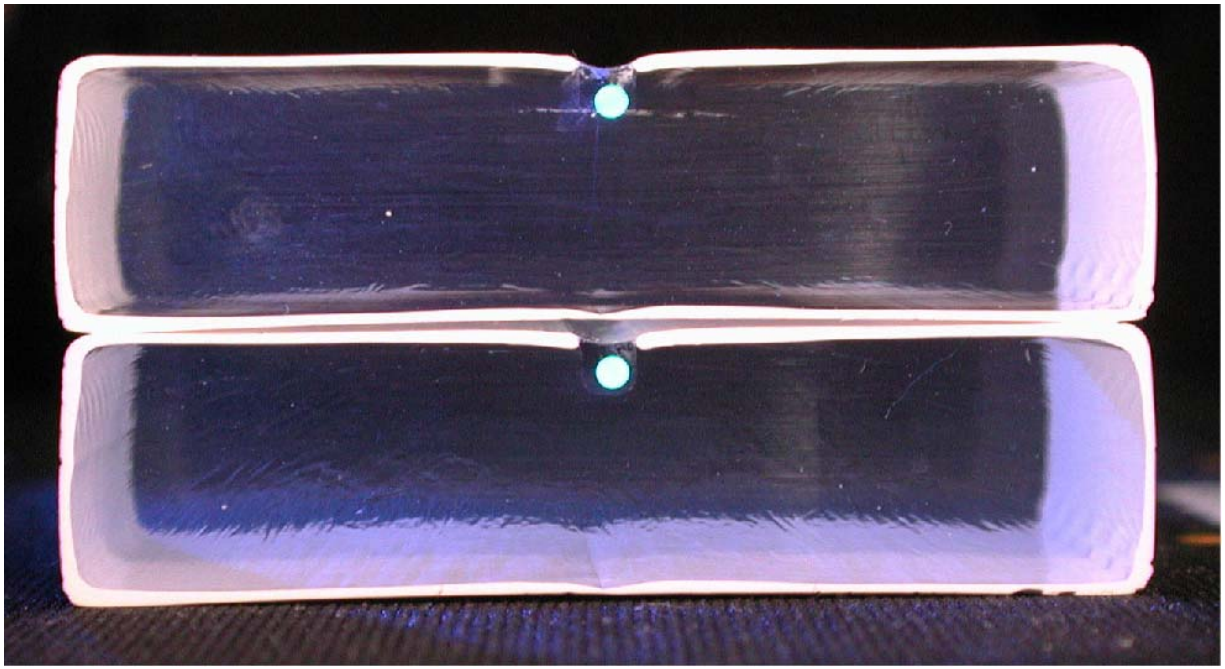


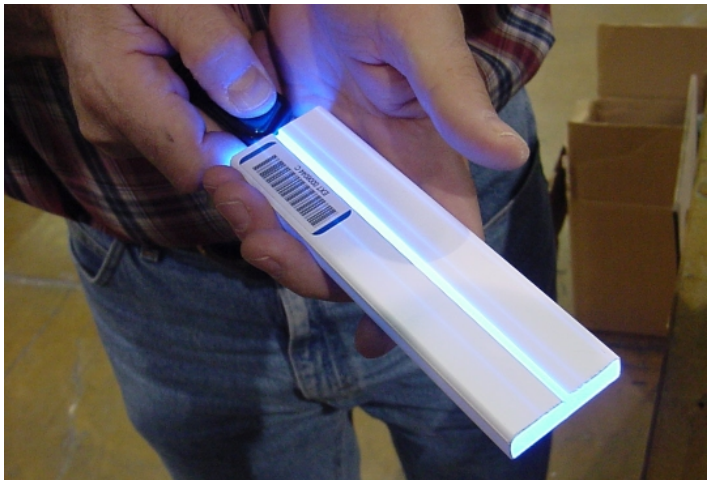
Scintillators can be customized
in a variety of shapes,
absorption spectra,
and emission spectra.

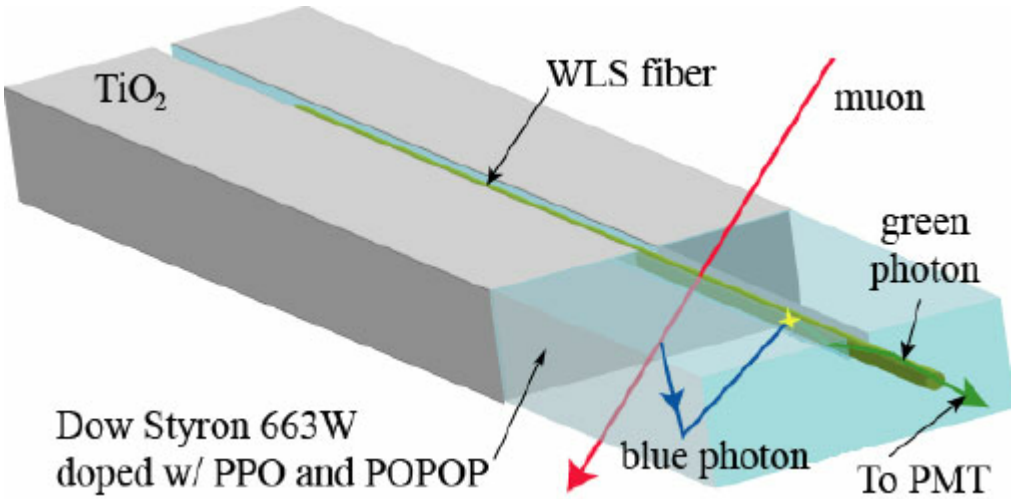
- MINOS / MINOS+
  - Alternating layers of scintillator-doped plastic and magnetized steel
  - Functionally identical near and far detectors
  - NuMI muon-neutrino/antineutrino beam (up to ~20 GeV)
  - Long (730 km) baseline
  - Measure electron neutrino and antineutrino appearance probabilities

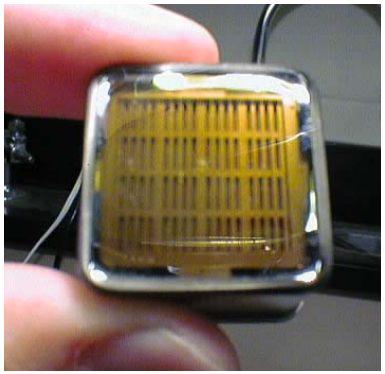


- MINOS / MINOS+

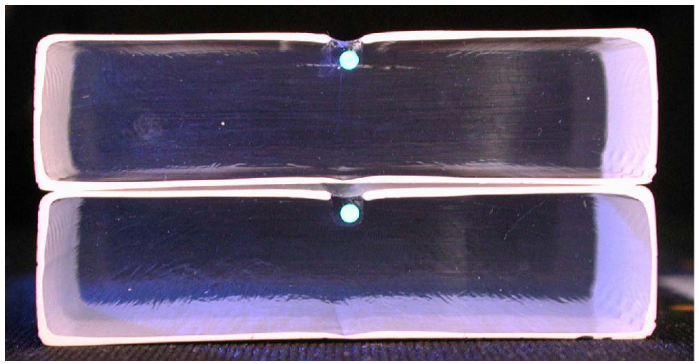




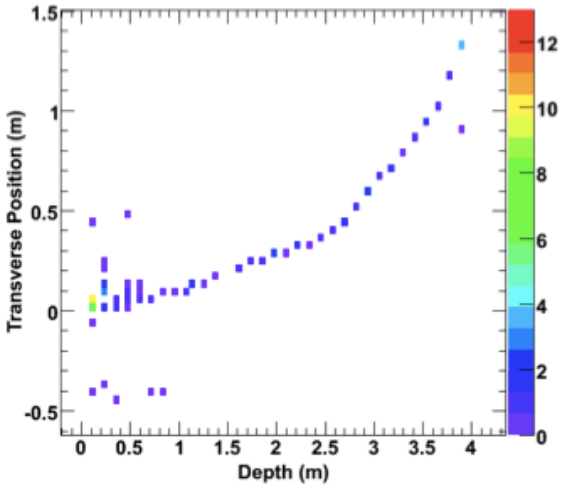

TiO_2
WLS fiber
muon
green
photon
Dow Styron 663W
doped w/ PPO and POPOP
blue photon
To PMT



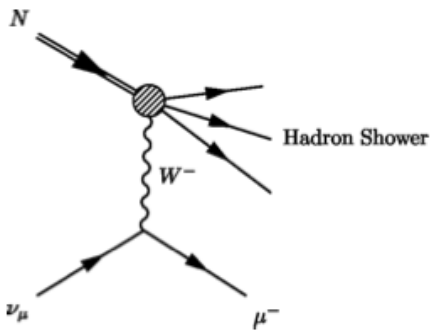
- MINOS / MINOS+



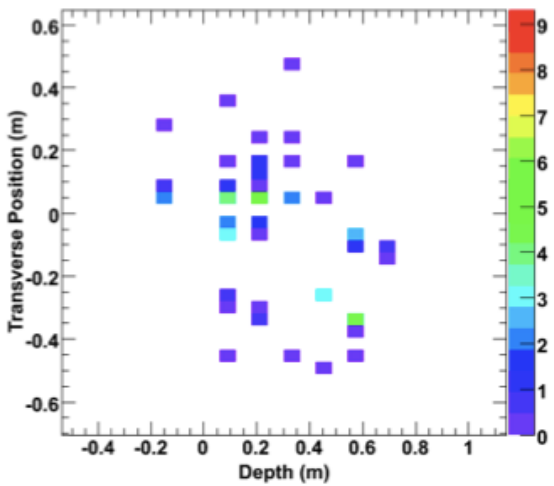
ν_μ Charged Current (CC)



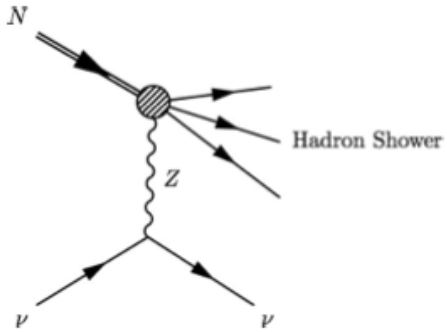
$$\nu_\mu + N \rightarrow \mu^- + X$$



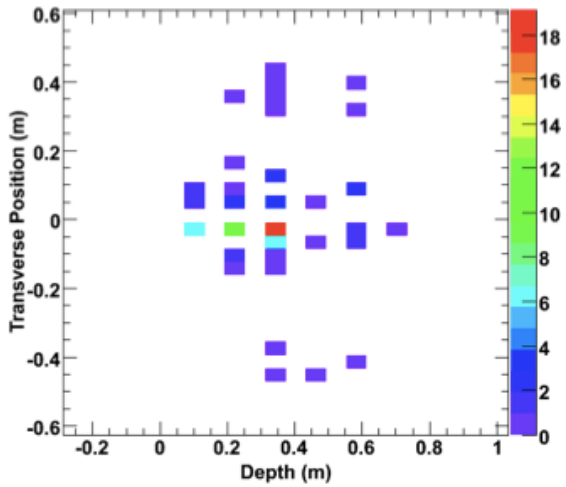
Neutral Current (NC)



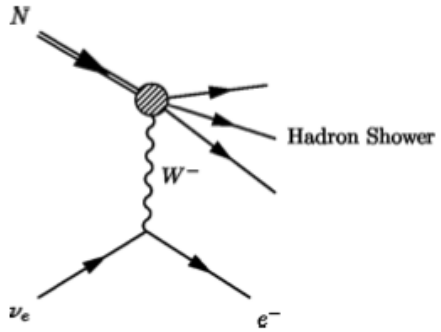
$$\nu + N \rightarrow \nu + X$$



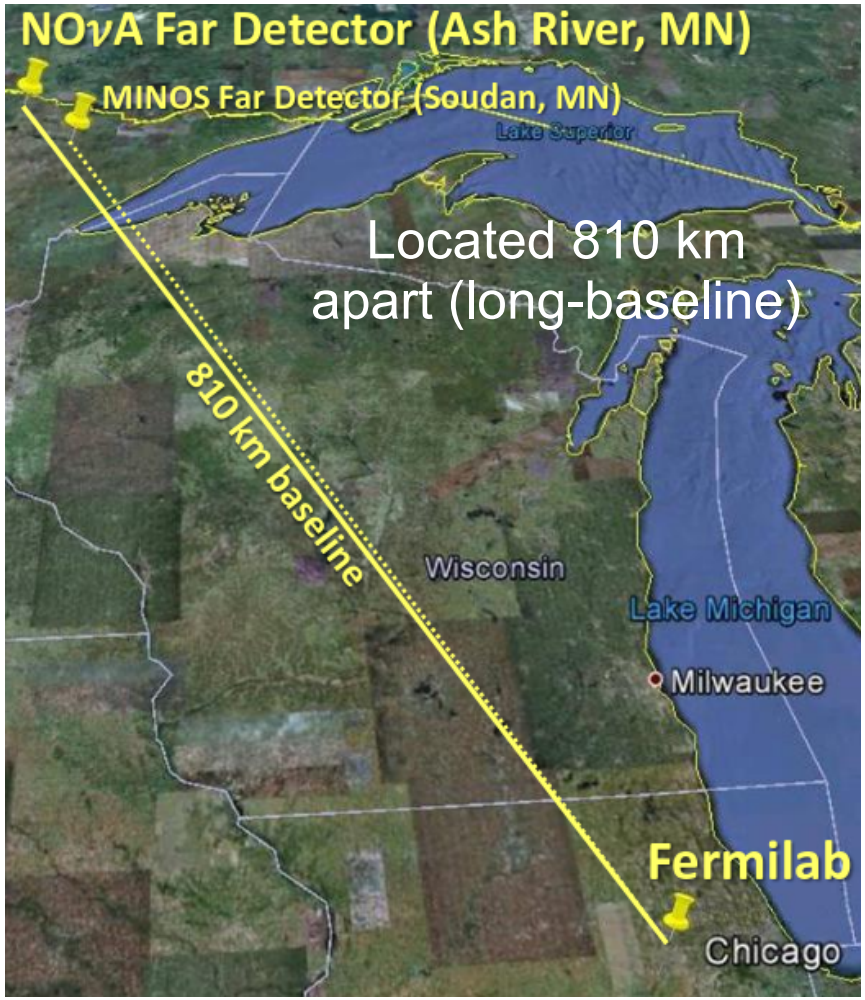
ν_e CC



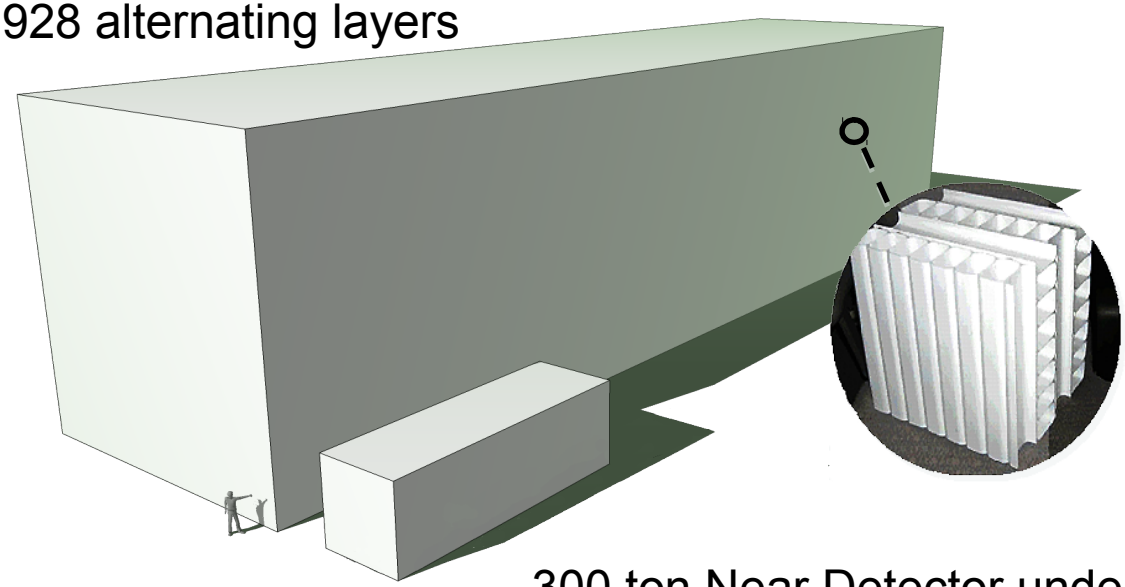
$$\nu_e + N \rightarrow e^- + X$$



- NOvA
  - Functionally identical near and far liquid scintillator detectors



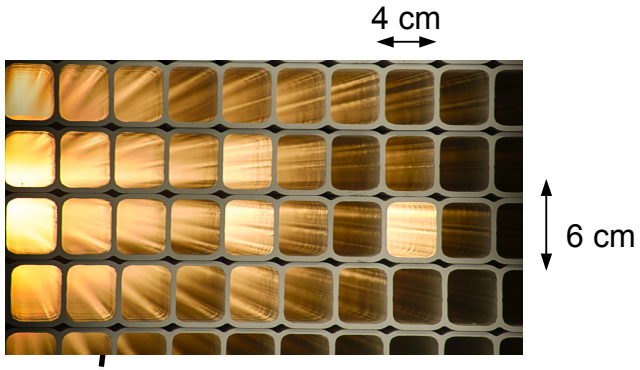
14 kton Far Detector
60 m x 15.6 m x 15.6 m
928 alternating layers



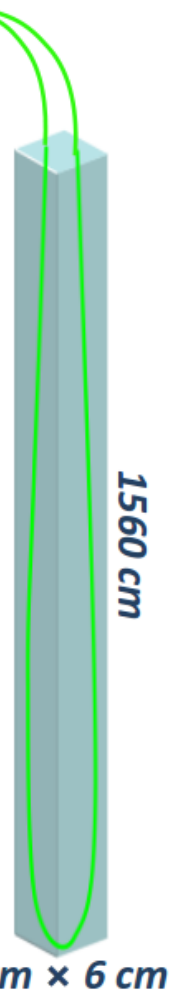
300 ton Near Detector underground at Fermilab
14.3 m x 4.1 m x 4.1 m, 206 alternating layers

- NOvA

Extruded PVC cells filled with 11 million liters of liquid scintillator



Instrumented with wavelength-shifting fibers and avalanche photodiodes



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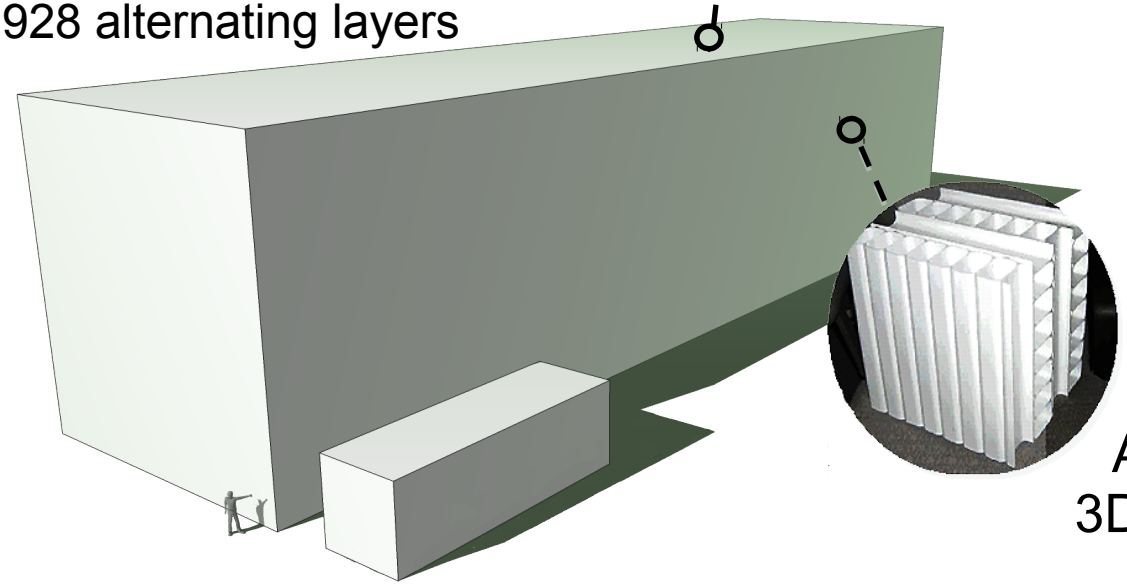
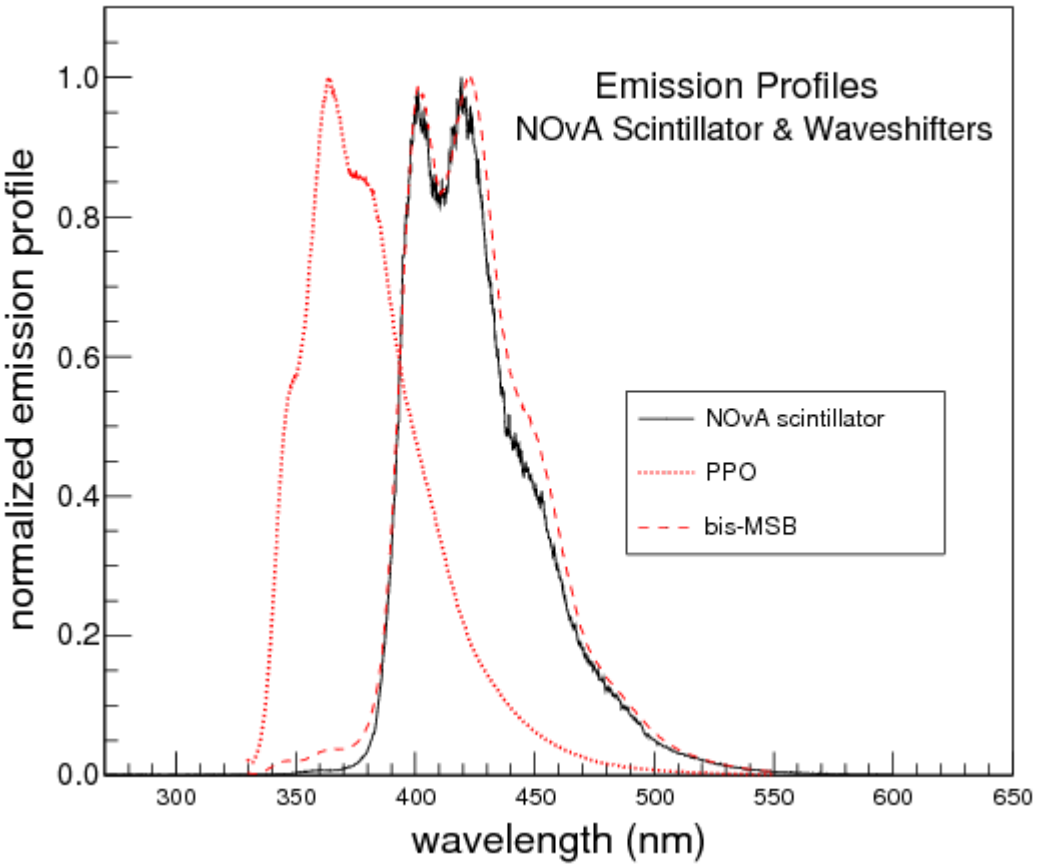


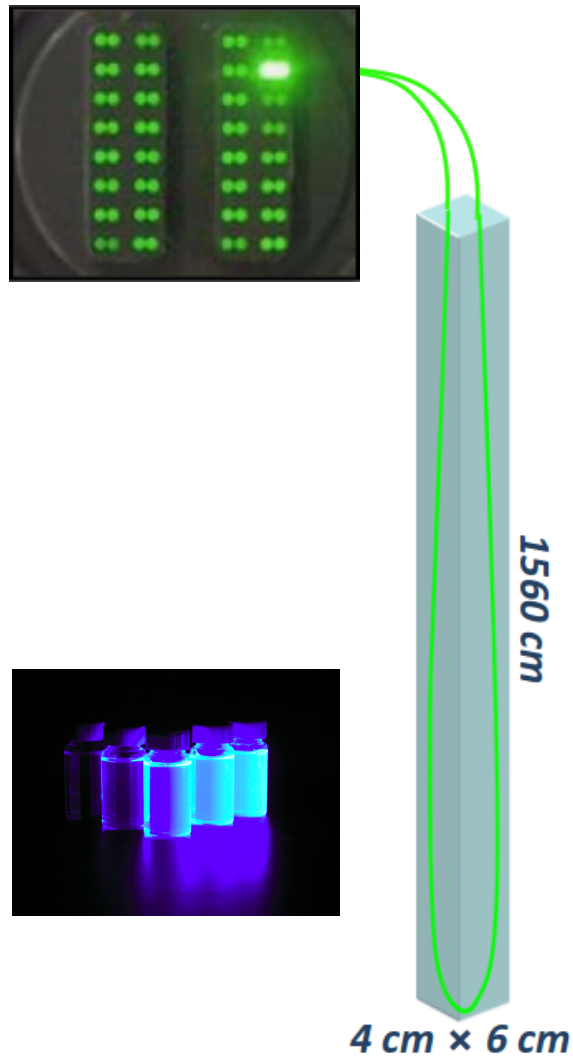
Alternating layers for 3D event reconstruction

Each ~0.15 radiation lengths for e/pi separation

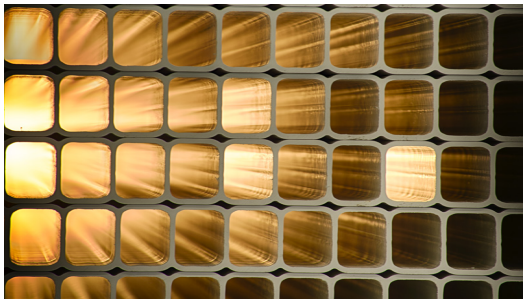
- NOvA
  - Liquid scintillator blend of pseudocumene, PPO, and bis-MSB dissolved in mineral oil

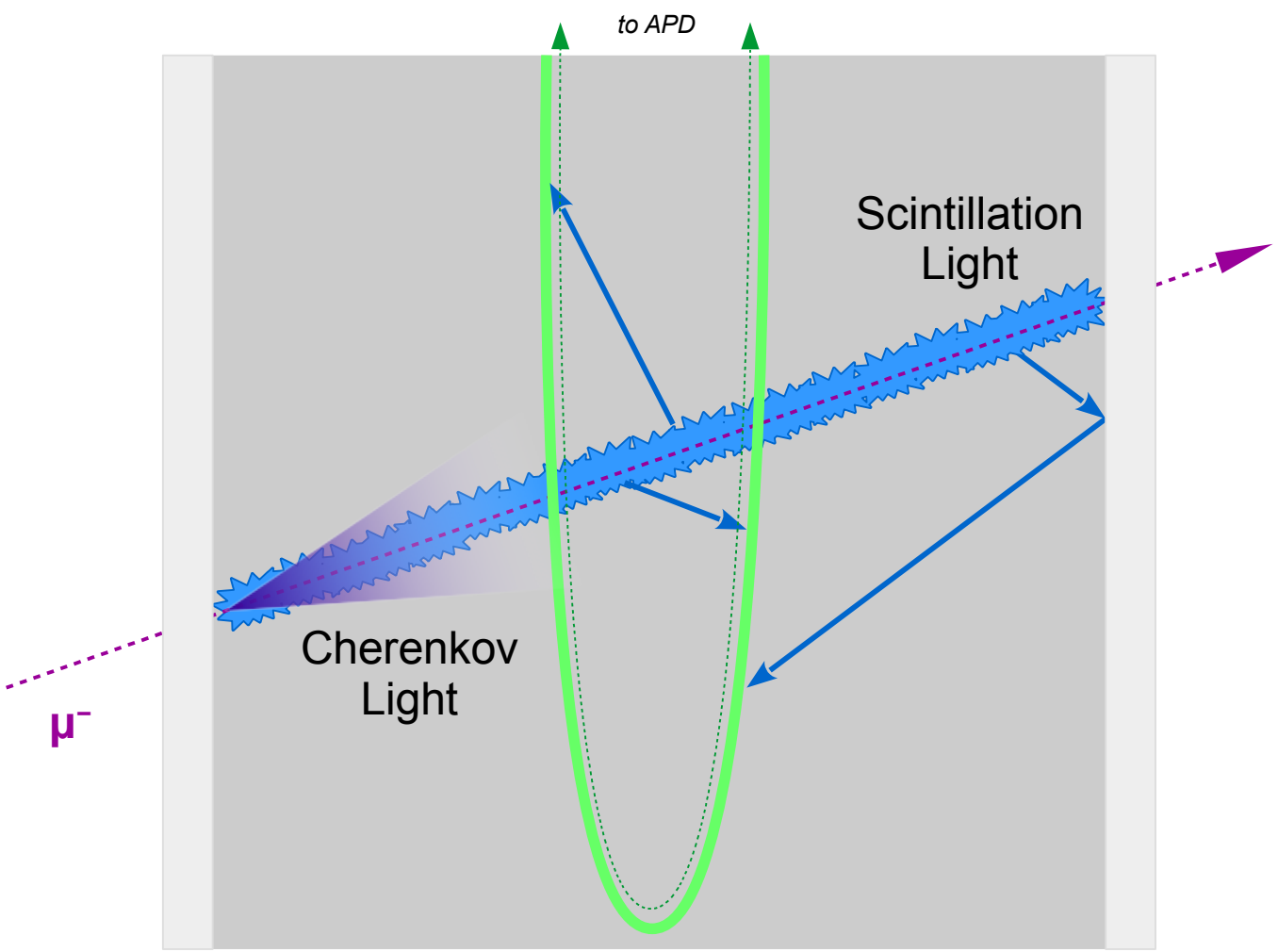
270-320 nm → 340-380 nm → ~390-440 nm

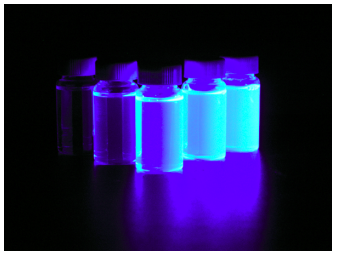


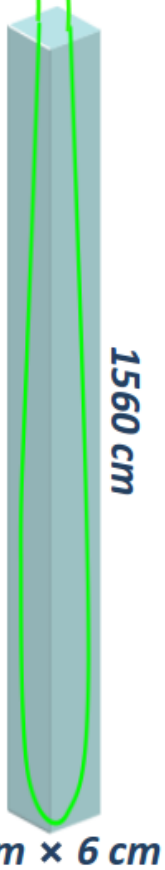


- NOvA

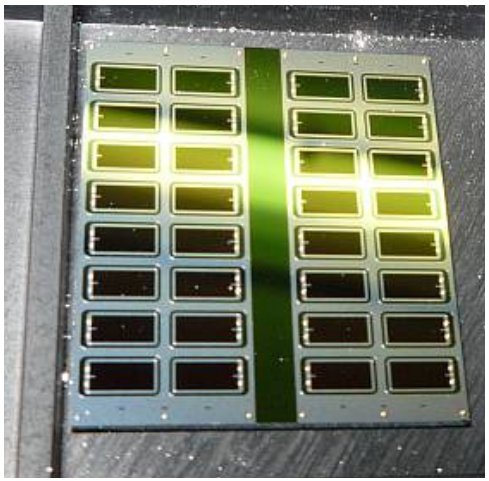


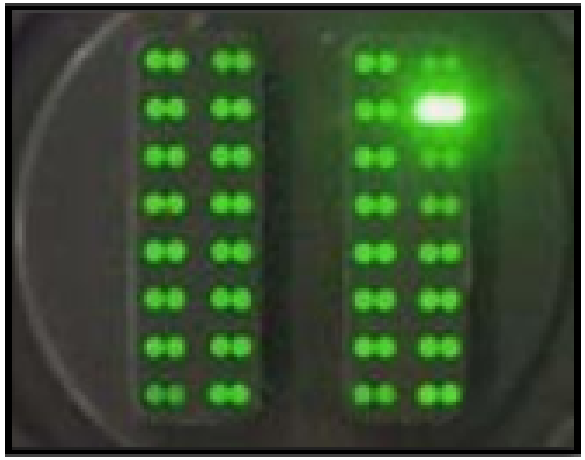

to APD
Scintillation Light
Cherenkov Light
μ⁻



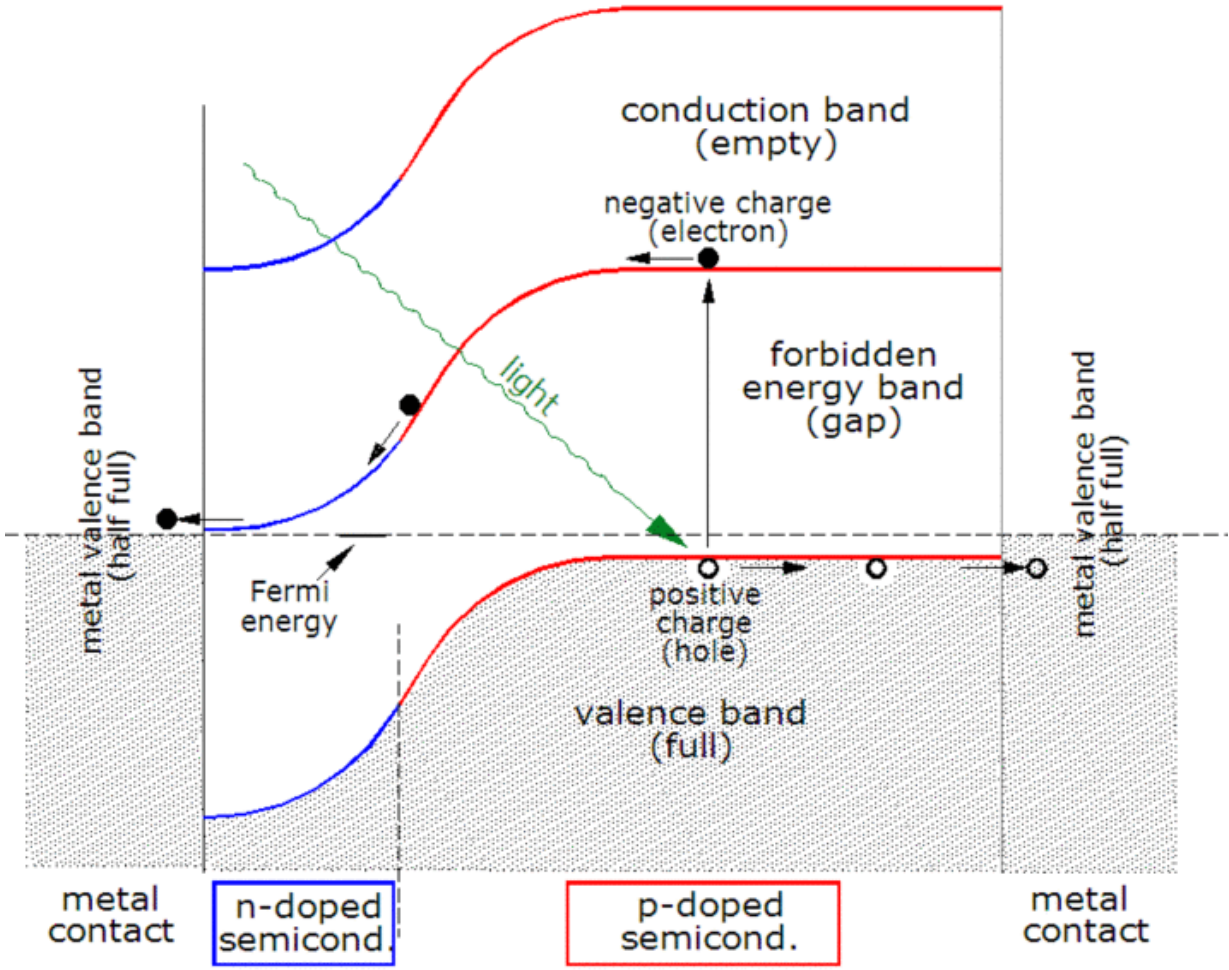

1560 cm
4 cm × 6 cm

- NOvA



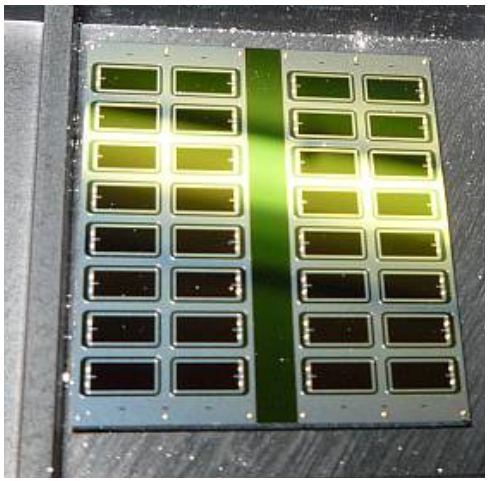


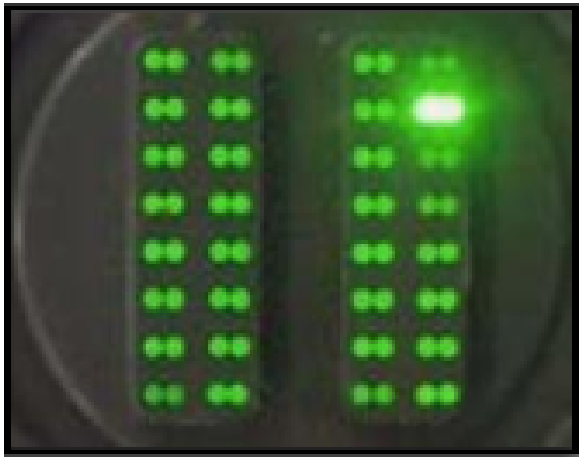
photoabsorption in silicon

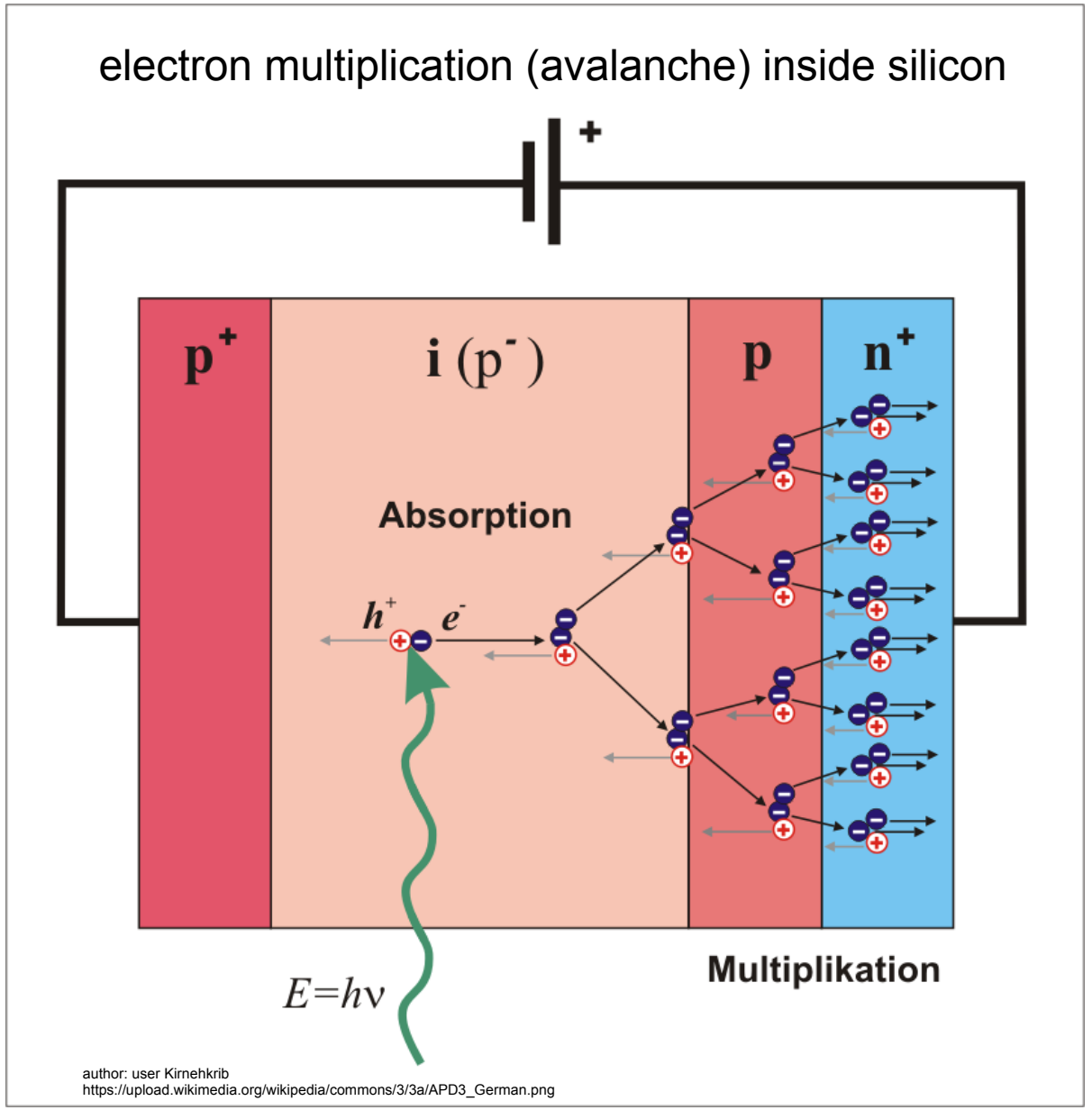


author: user GianniG46
from: http://en.wikipedia.org/wiki/File:BandDiagramSolarCell-en.gif

- NOvA

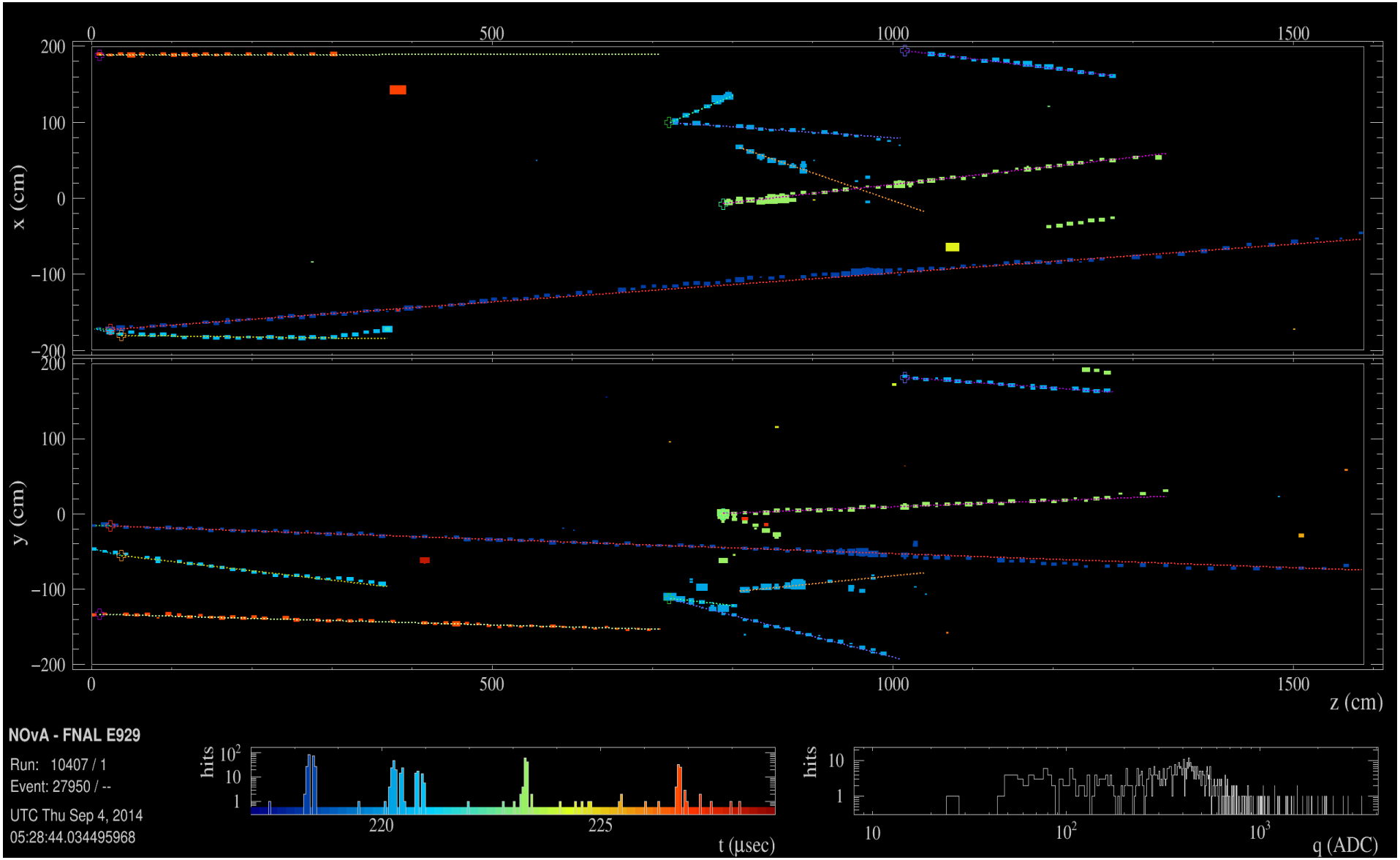




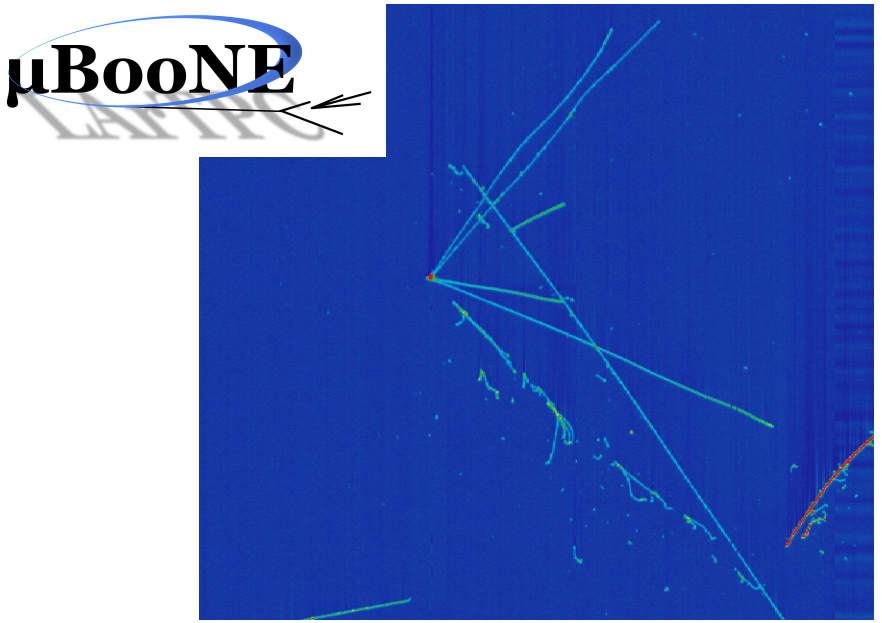

electron multiplication (avalanche) inside silicon
+
p+
i (p-)
p
n+
Absorption
h+
e-
E=hν
Multiplikation
author: user Kirnehkrib
https://upload.wikimedia.org/wikipedia/commons/3/3a/APD3_German.png

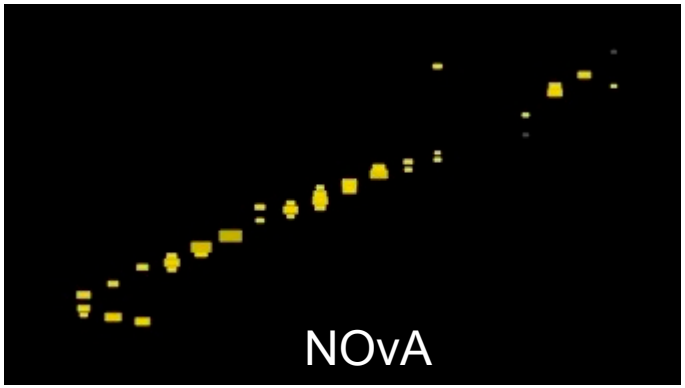
- NOvA

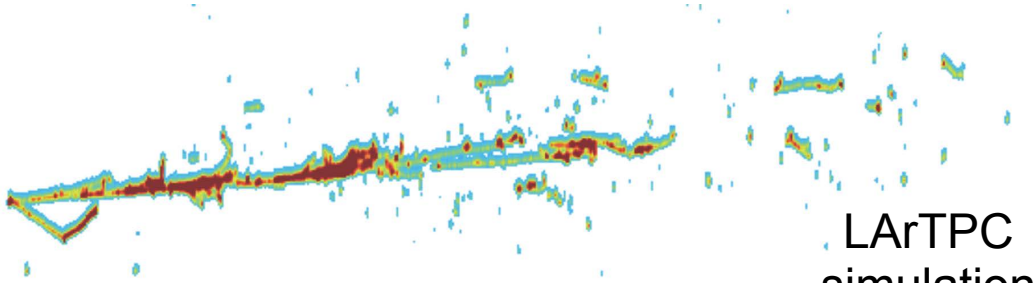
Detect Neutrinos (lots of them!)



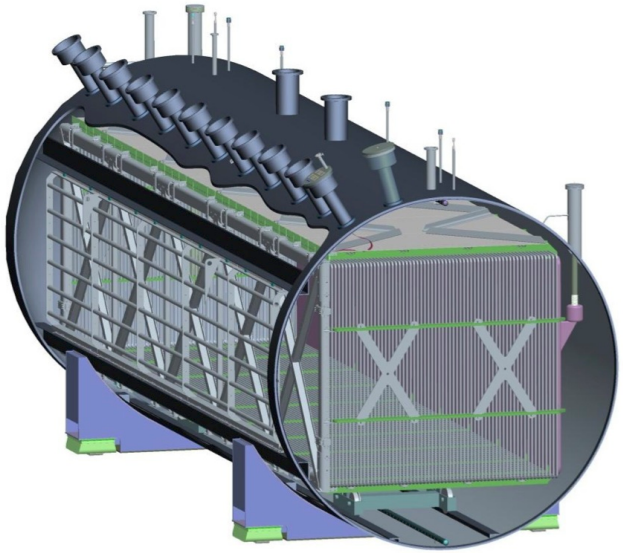
- Superb event resolution
  - Enhanced particle discrimination
    - Protons, pions, electrons, photons, etc.
  - Precise energy reconstruction
    - Excellent timing resolution (scintillation signal)



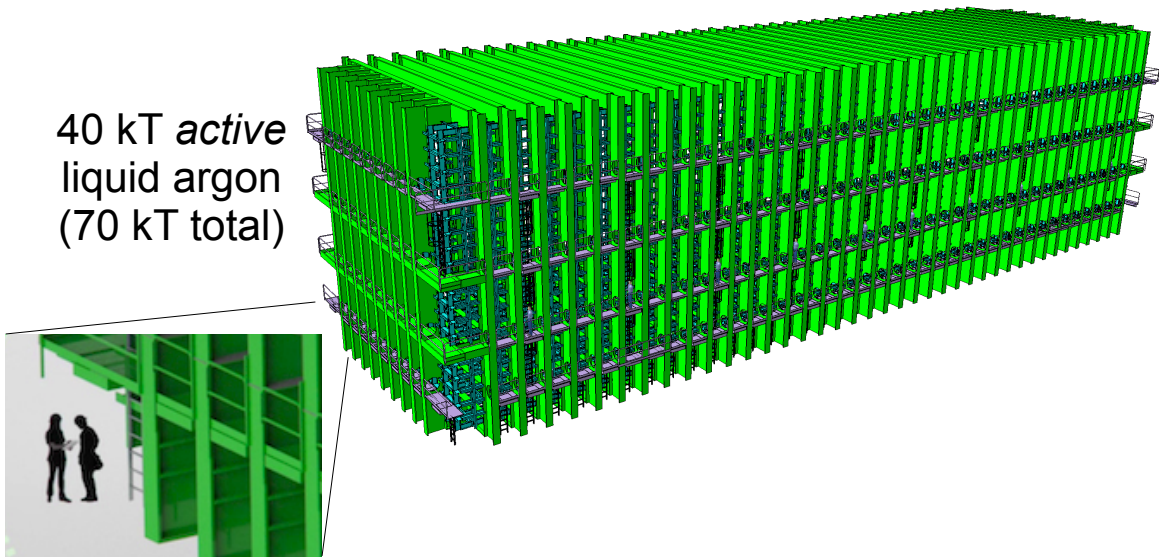




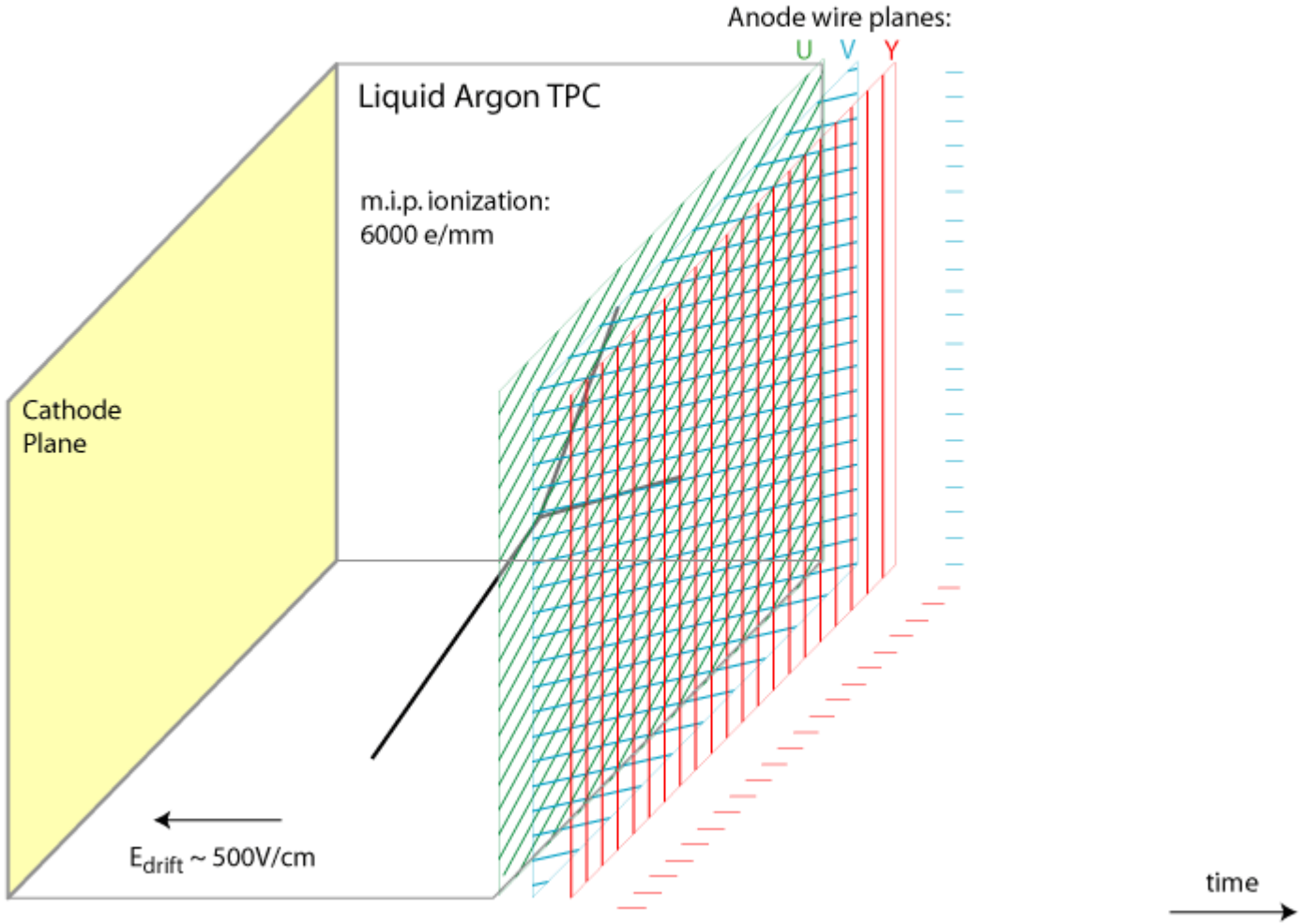
- MicroBooNE
  - Short-baseline oscillation experiment
  - Booster neutrino beam
  - Sterile neutrino search



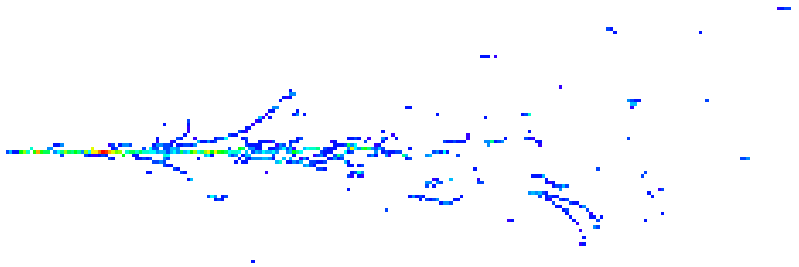
- DUNE
  - The Deep Underground Neutrino Experiment
  - (Very) long baseline oscillation experiment
  - New higher power beam
  - Bigger detector
  - Deep underground

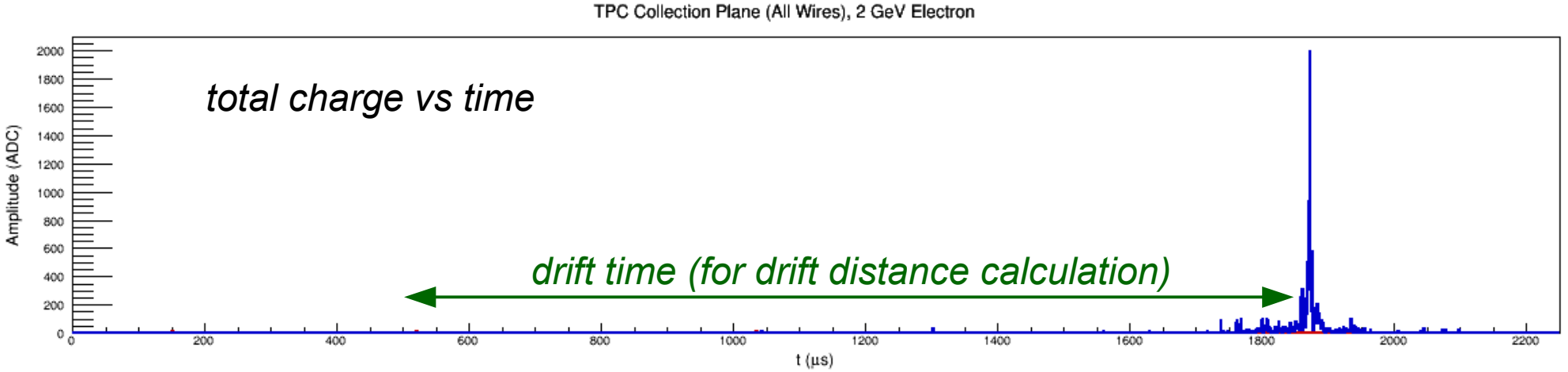


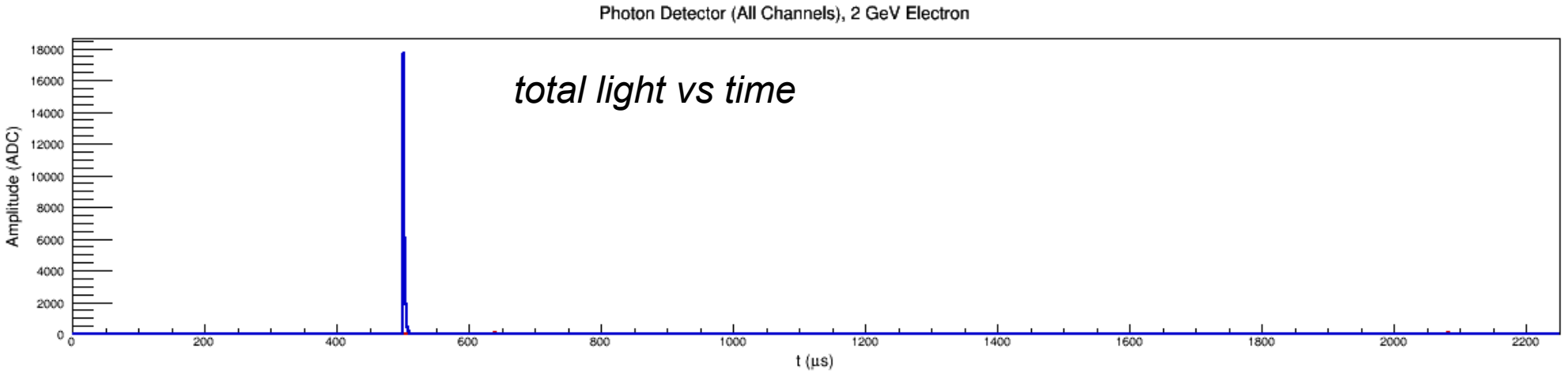
Basic TPC Principles



- Combining charge and scintillation



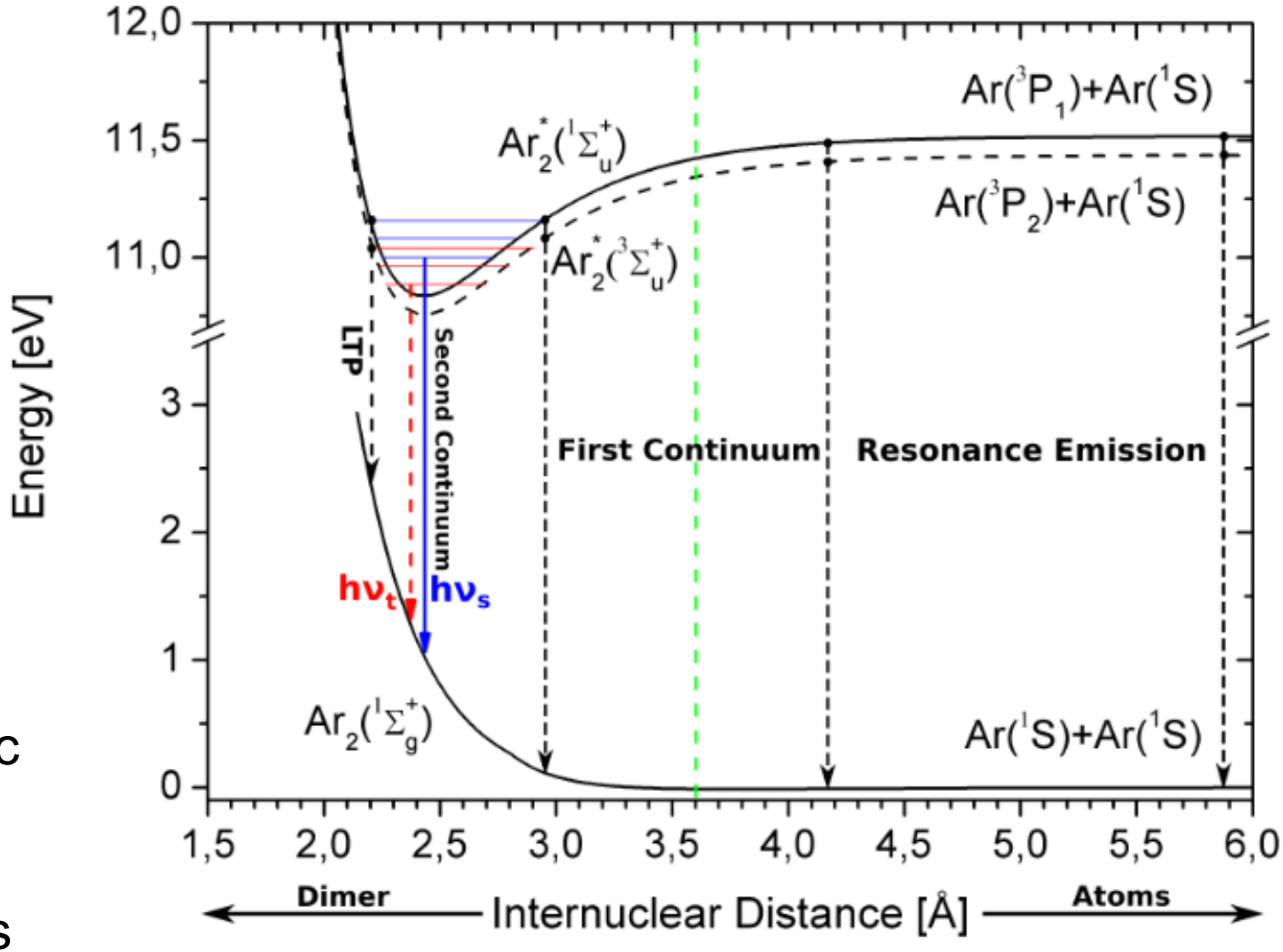




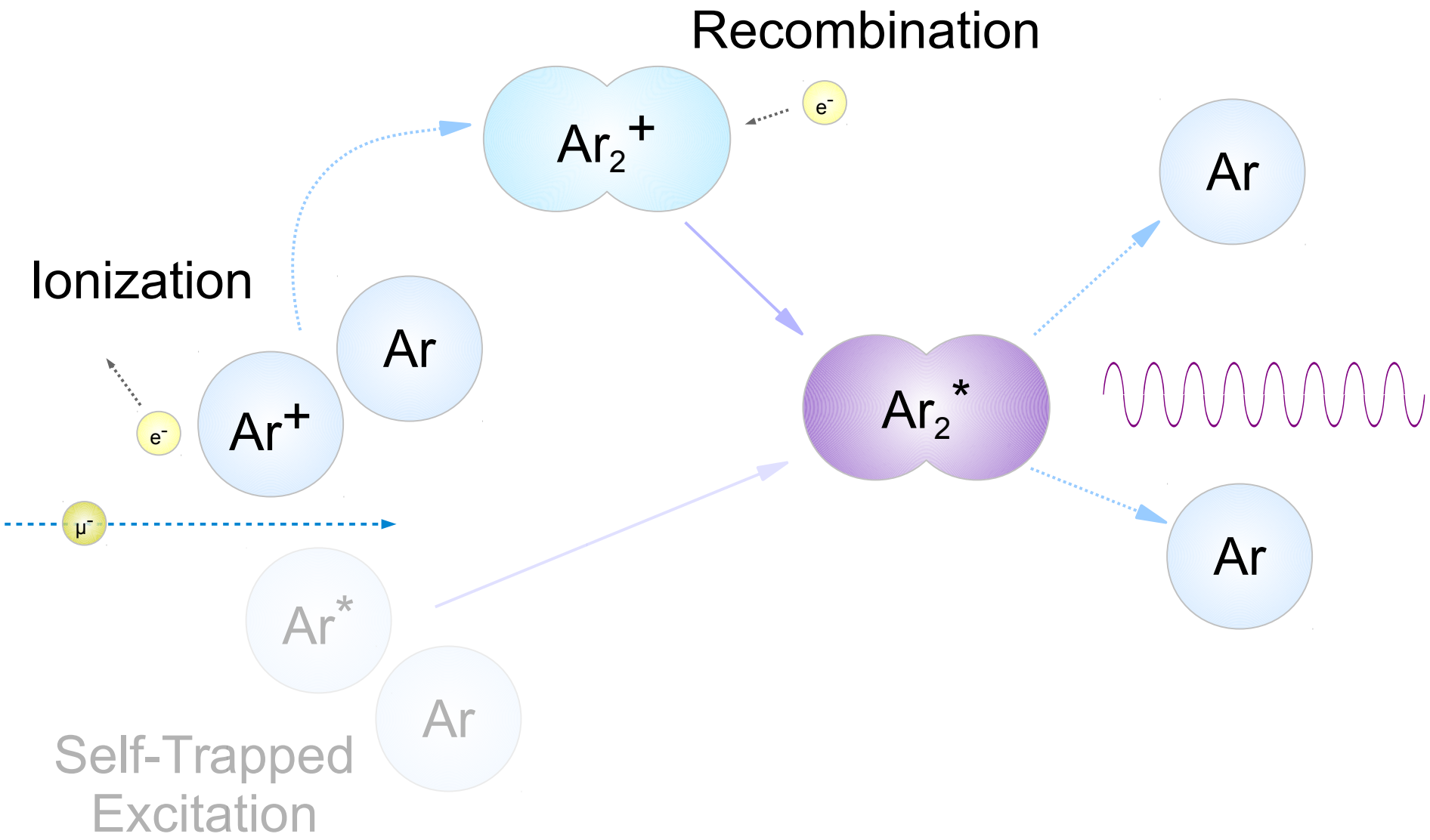
- Excited atoms pair up to form metastable Rydberg molecule
  - Some surprisingly subtle chemistry...
  - *Do you remember that chapter on molecular orbitals?*

- 10-ish eV
  → vacuum ultraviolet

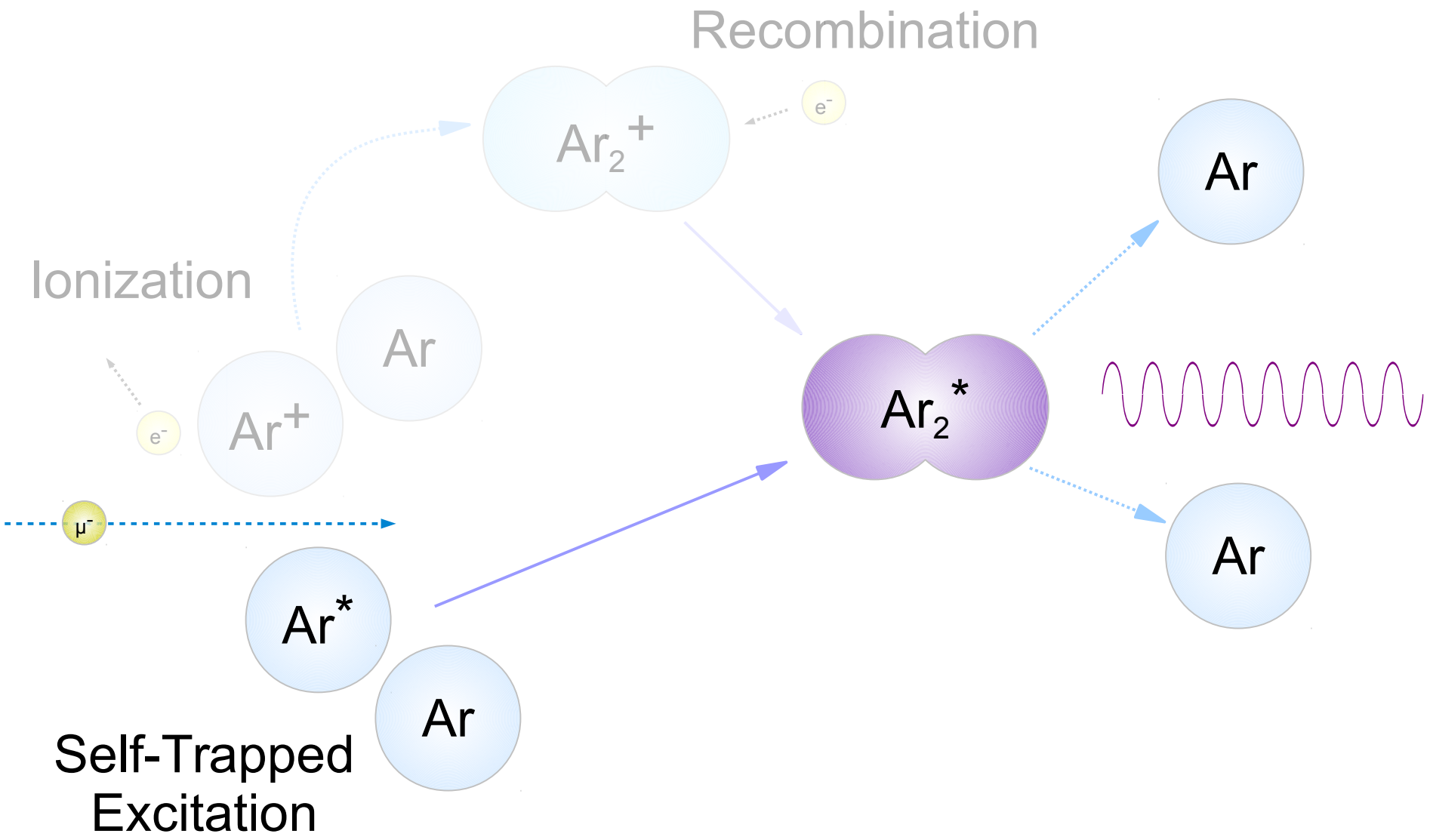
- Transparent to scintillation light
  - Average interatomic distance too large
  - No reabsorption of scintillation photons



- Excitation and scintillation



- Excitation and scintillation



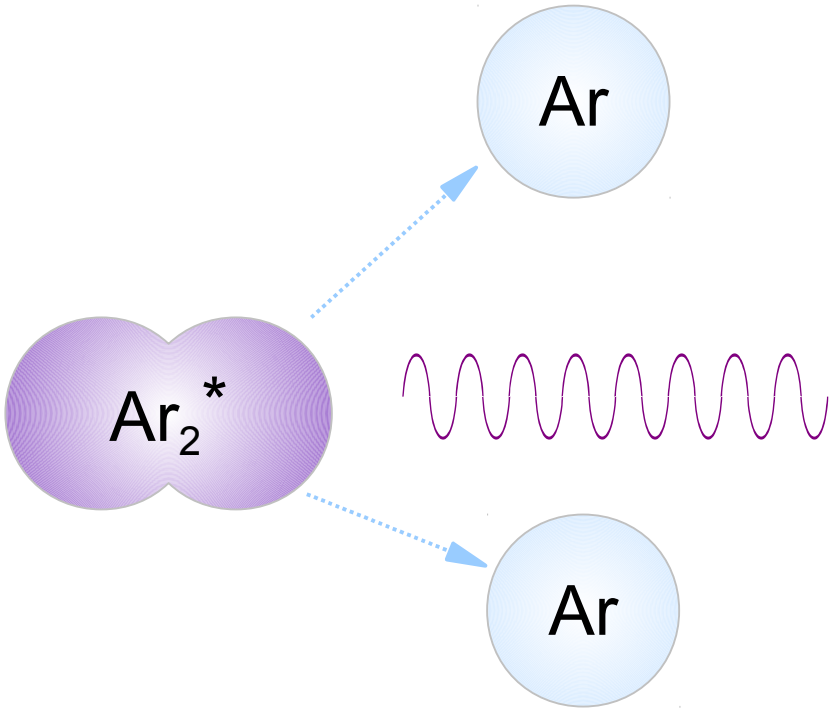
Excitation and scintillation

Two excited molecular states

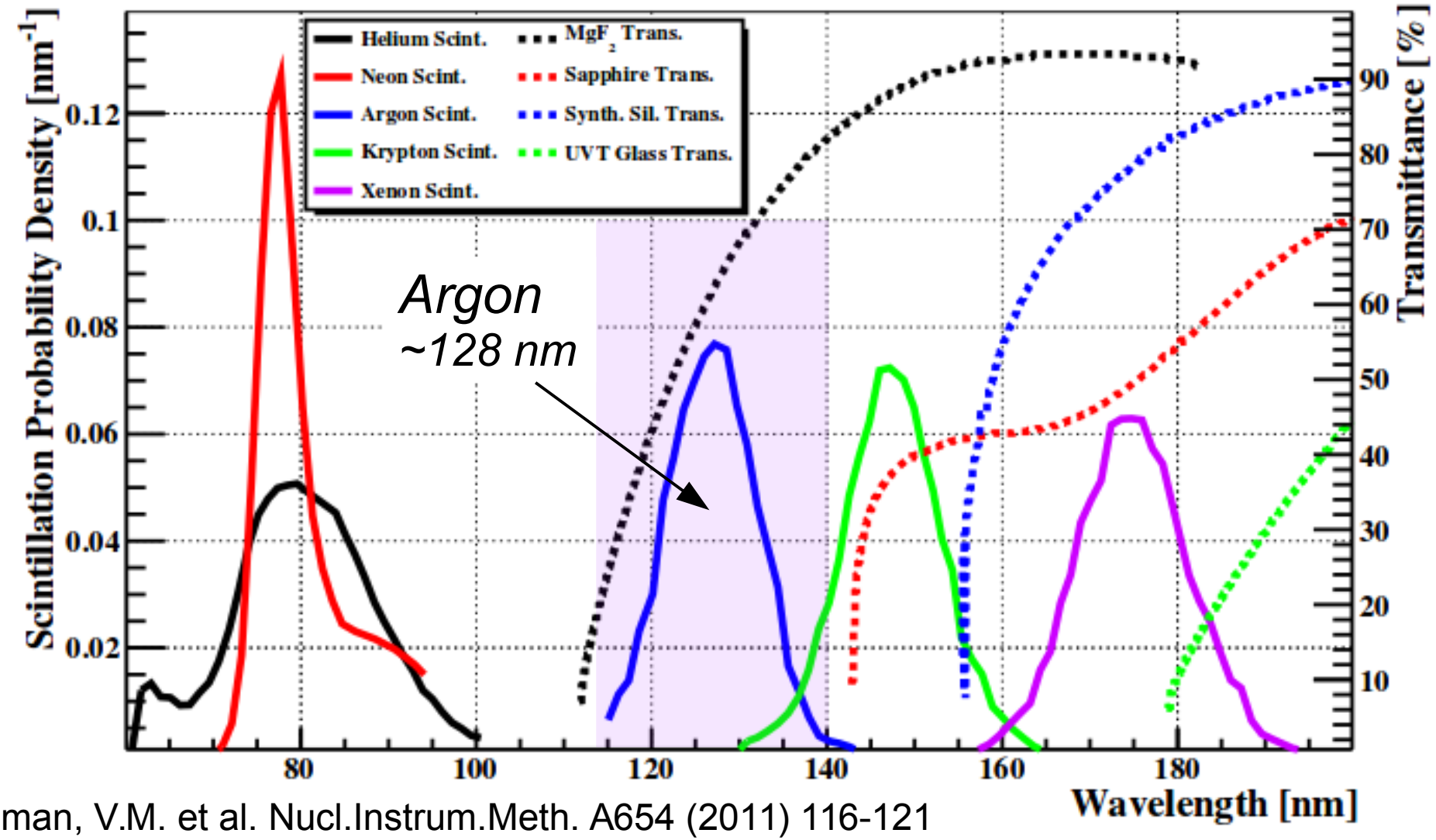
- Singlet “fast light” ~5 ns
- Triplet “slow light” ~1.5 μs

128 nm photon emission

- Vacuum ultraviolet (VUV)
- Challenging to detect
  - High energy ultraviolet
  - Absorbed by oxygen & nitrogen
  - Blocked by most glass materials



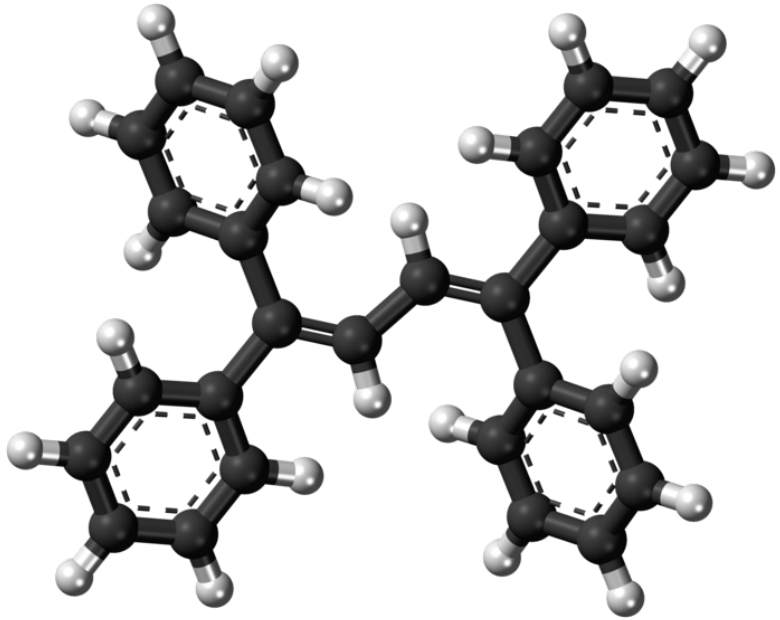
- Same basic process for all noble elements
  - Vacuum ultraviolet (VUV) emission
    - Absorbed by atmospheric gasses (nitrogen, oxygen, ozone)
    - Difficult to detect directly below ~150 nm (typically use wavelength shifter)



Gehman, V.M. et al. Nucl.Instrum.Meth. A654 (2011) 116-121

- Wavelength shifters

VUV scintillation absorption

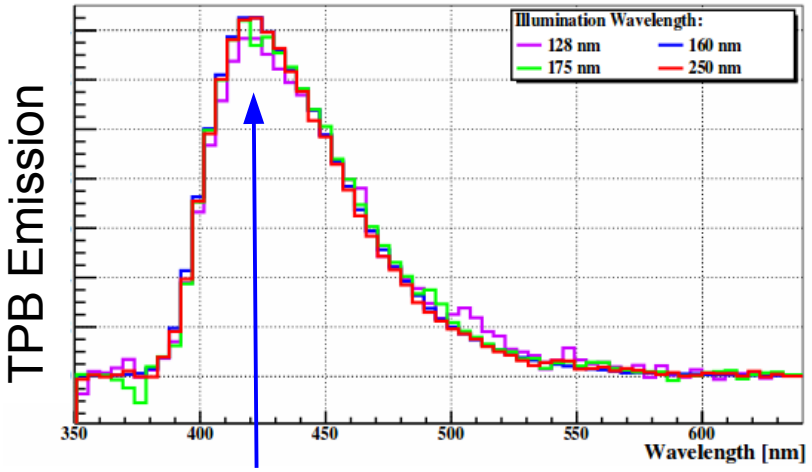


Tetraphenyl Butadiene (TPB)

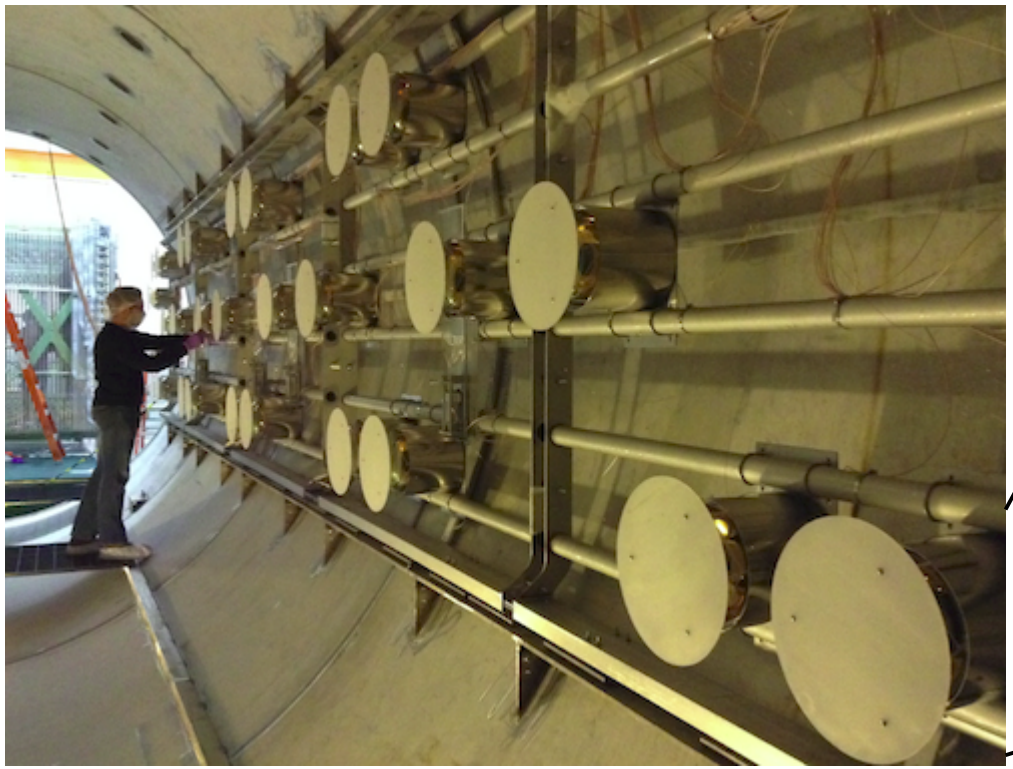
TPB deposition for WArP, irradiated with UV light.

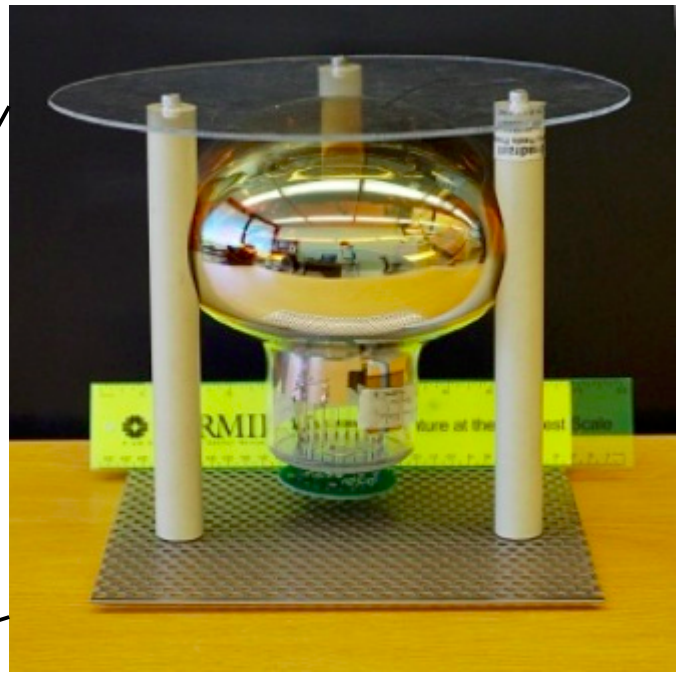
VIS wavelength-shifted emission

- MicroBooNE photon detector system
  - Cryogenic PMT + wavelength-shifter
    - TPB (tetraphenyl butadiene)
  - 128 nm → 420 nm → PMT
  - Array of PMTs behind anode wire plane



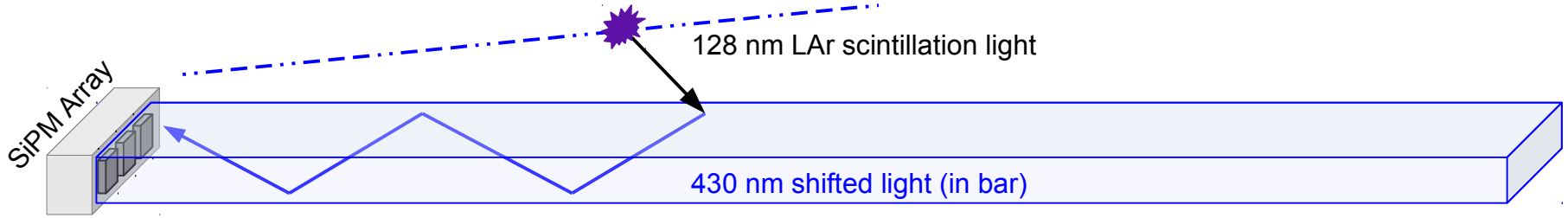
~420 nm



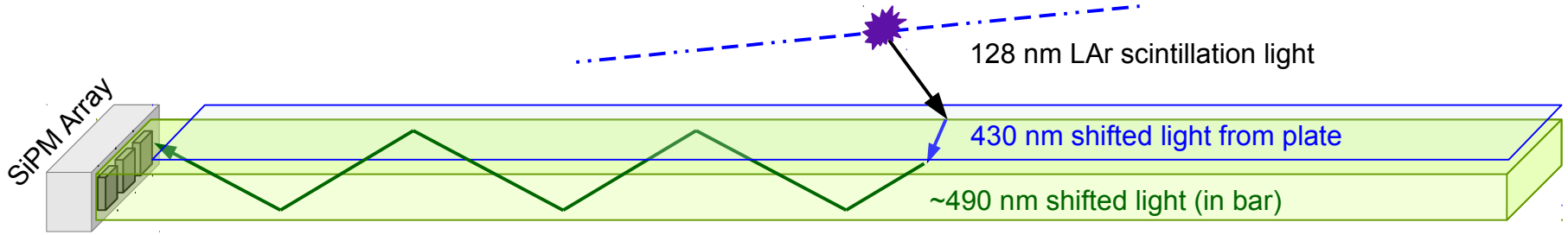


- DUNE photon detector system

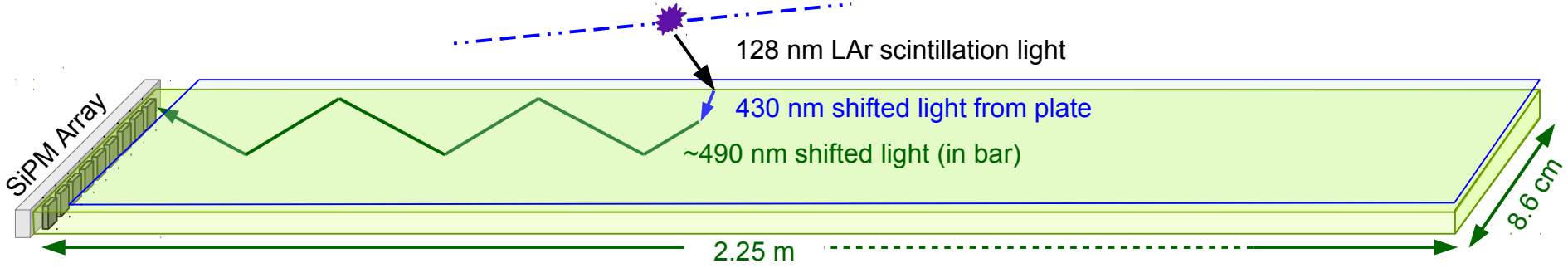
- Coated light guides
  - Acrylic or polystyrene imbued with wavelength-shifting compound
    - Dip-coat w/ TPB in solvent (after studying many different methods)



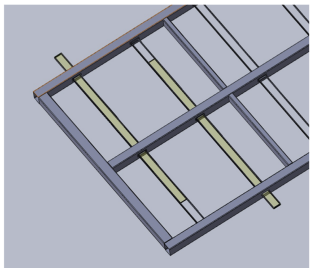
- WLS-coated plate + WLS light guide
  - TPB spray-coating on plates + blue → green WLS-doped light guide
    - Decouple VUV conversion from transport through light guide

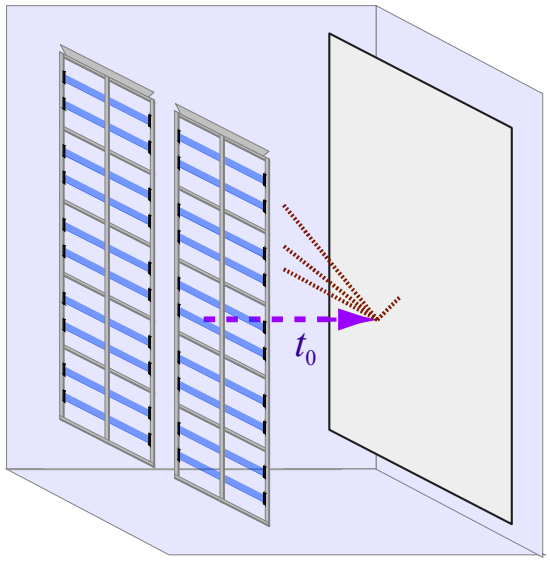


- DUNE photon detector system
- Large active-area UV-collecting light guides
  - TPB-coated VUV sensitive plate to convert to 430 nm
  - WLS-doped PVT light guide
  - 490 nm light propagated by total internal reflection to end of light guide

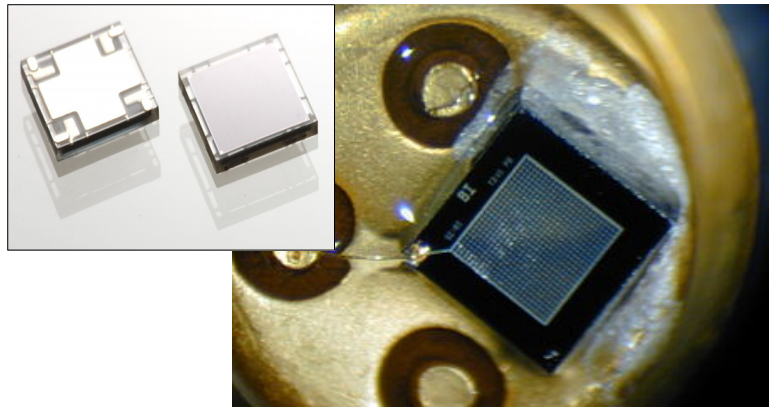


- Embed PD paddles inside anode plane assembly behind collection wires
  - Large photosensitive area with small photocathode area
  - Low-voltage SiPM bias
  - Easily scalable

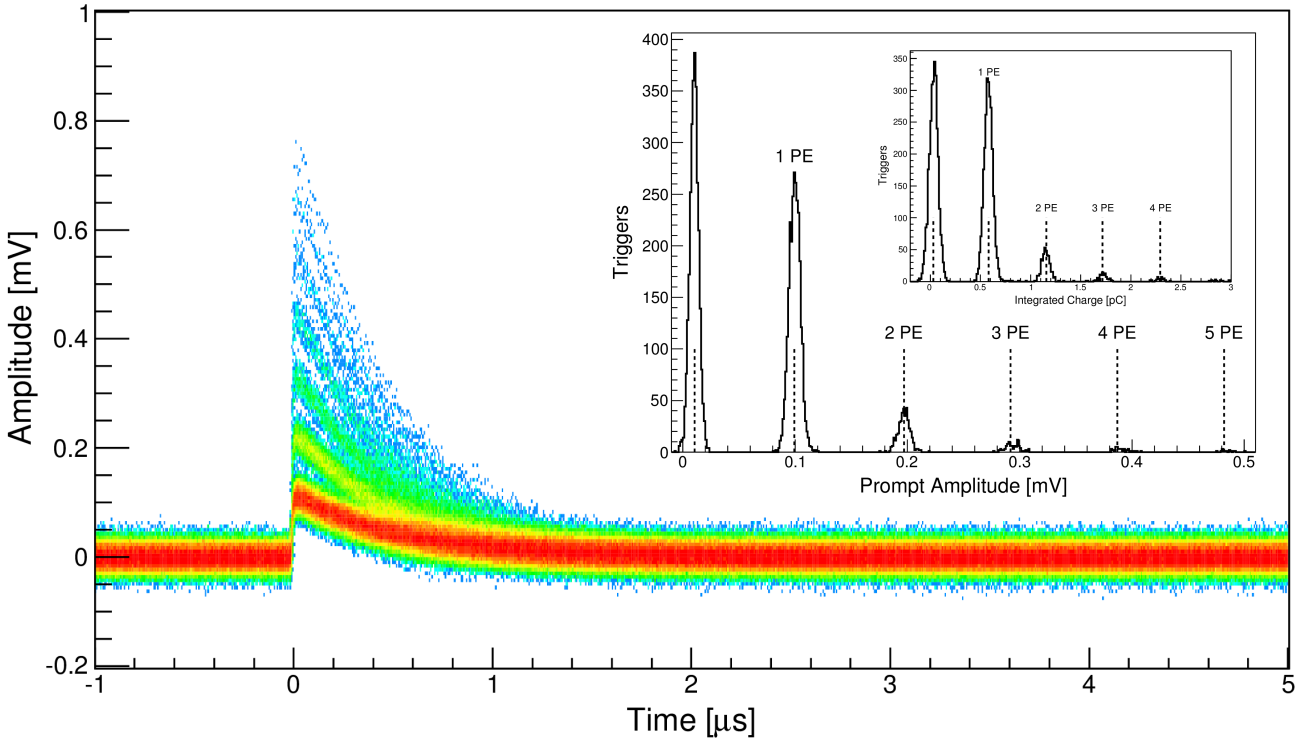




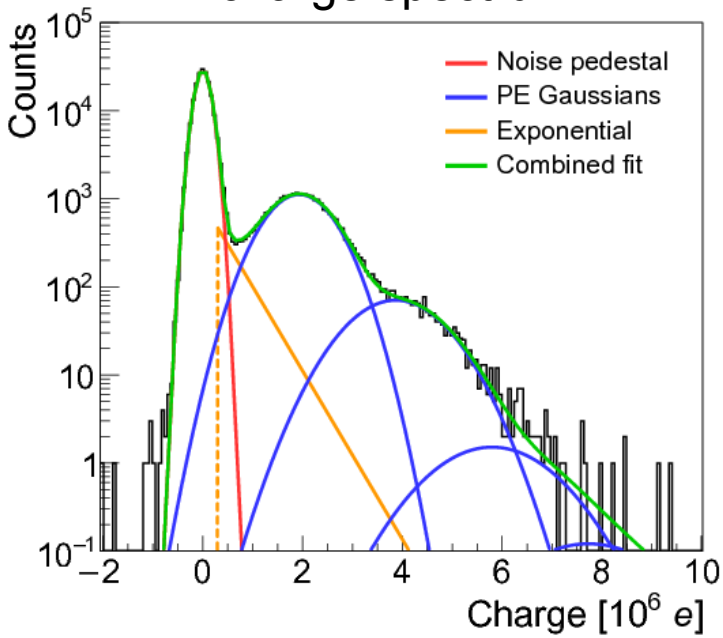
- Avalanche photodiode array on a common silicon substrate
  - Up to 1000 microcells / mm^2
  - Low noise (few Hz in cryo)
  - Excellent charge resolution
  - Comparable gain (10^6) and detection efficiency to PMTs
  - Much lower voltage (~20-80 V vs 1-2 kV)



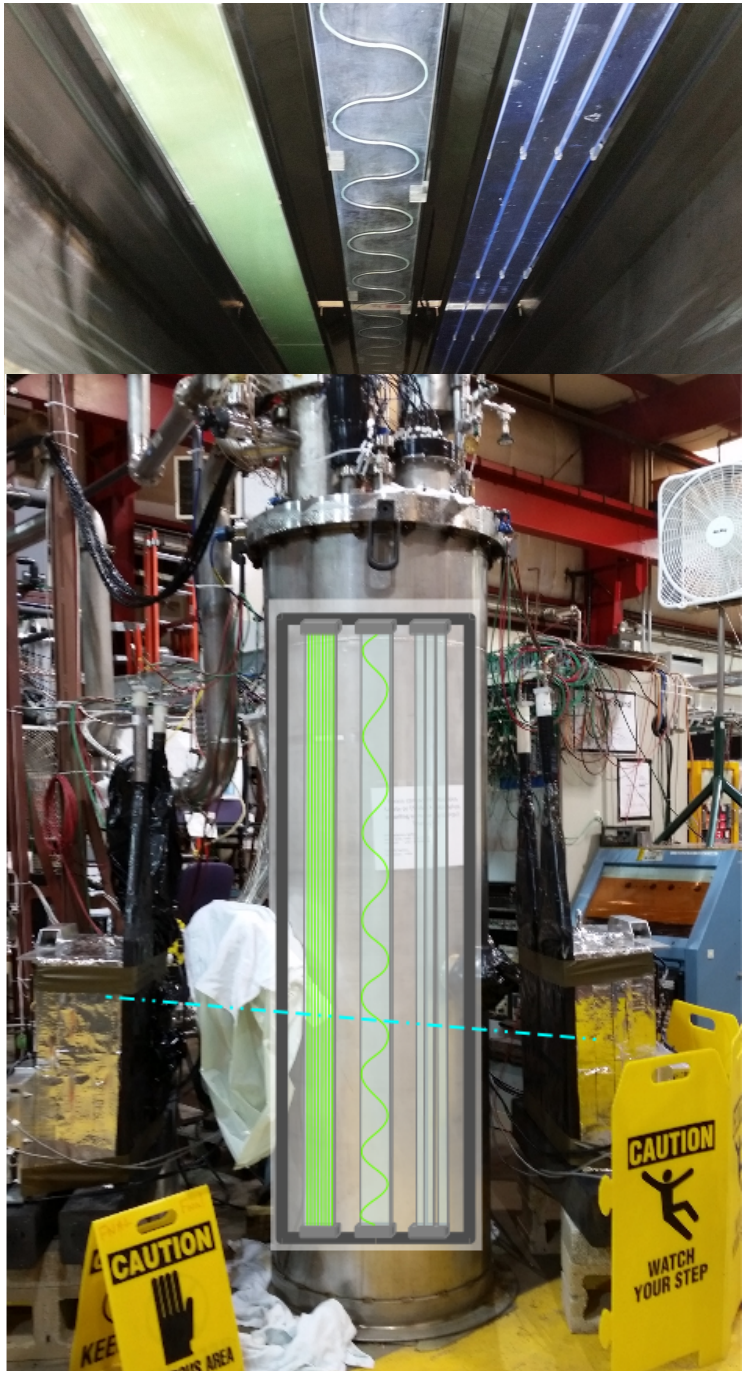
SiPM waveform traces | amplitude & charge spectra



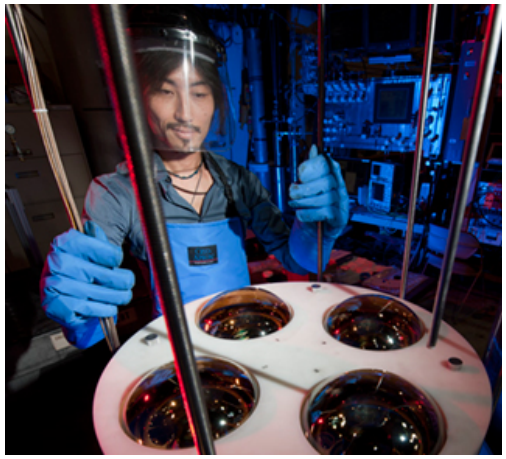
Example PMT charge spectrum

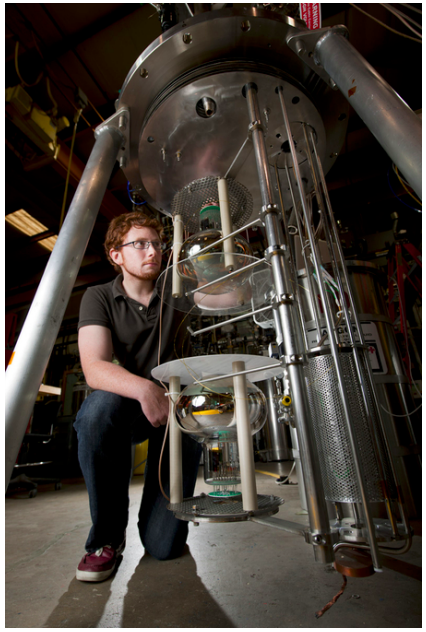


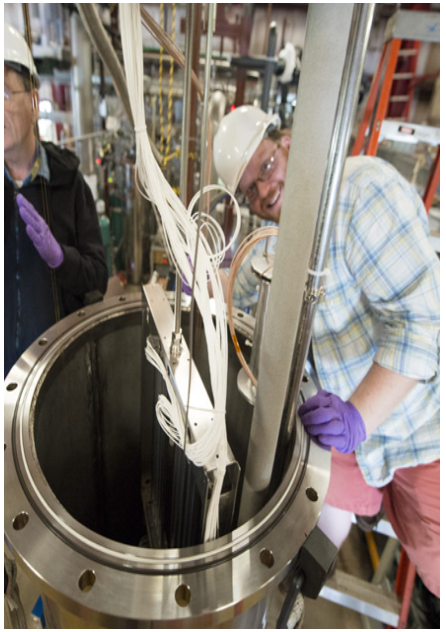
- Design tests carried out at PAB
  - A number of designs / iterations
- "TallBo" facility
  - 84" LAr dewar
- Ultra-high purity liquid argon
  - Vacuum to remove residual atmosphere
  - Condenser to maintain closed system
- Hodoscope (cosmic ray) trigger
  - 2 8x8 Arrays of PMTs + BaF_2 crystals
    - CREST cosmic-ray balloon exp't.
  - 2 scintillator paddle planes
    - Allows shower rejection, reconstruction of single tracks



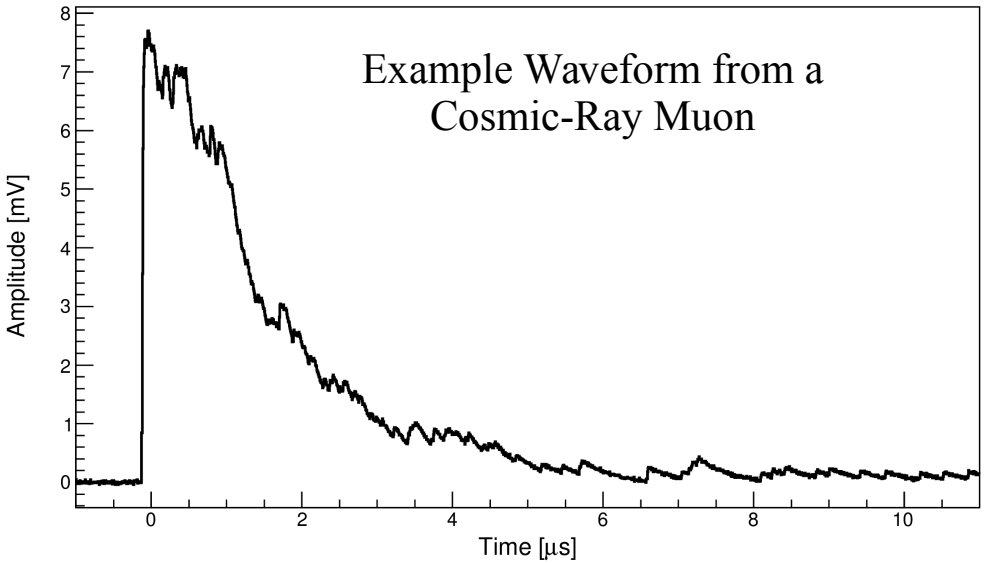
- Various tests for DUNE, MicroBooNE, etc. at PAB

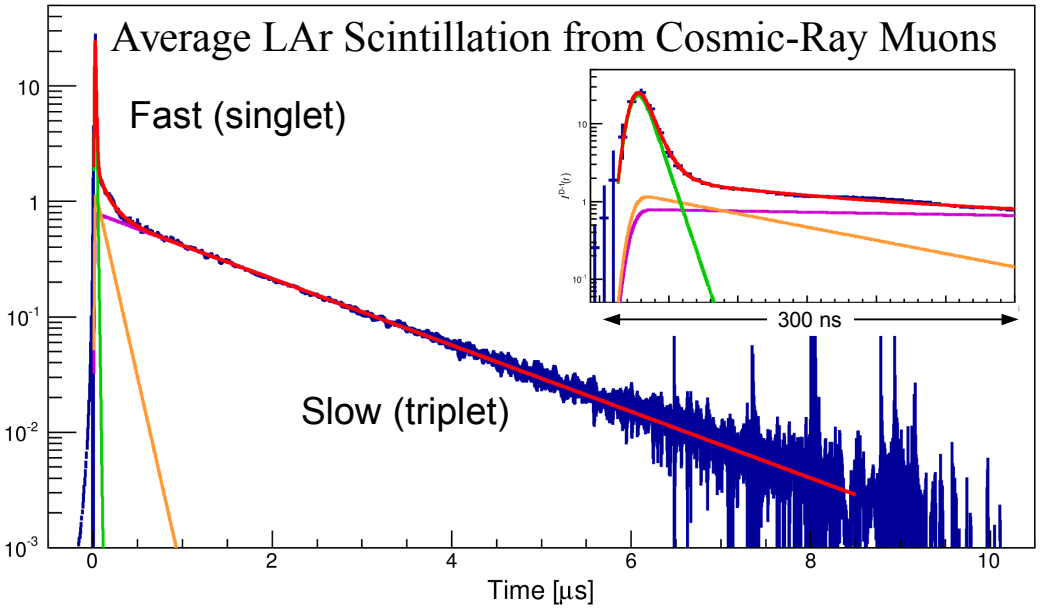




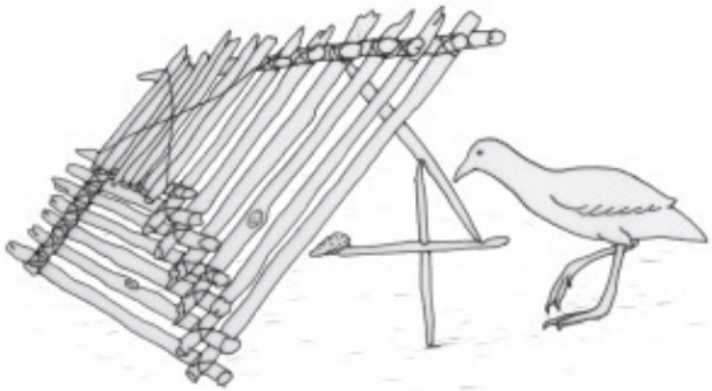


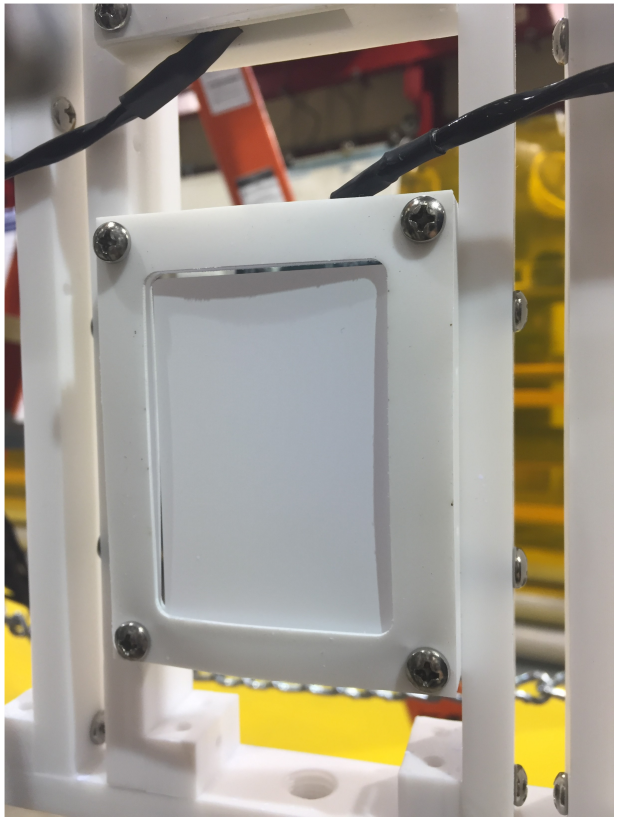
- Physics studies

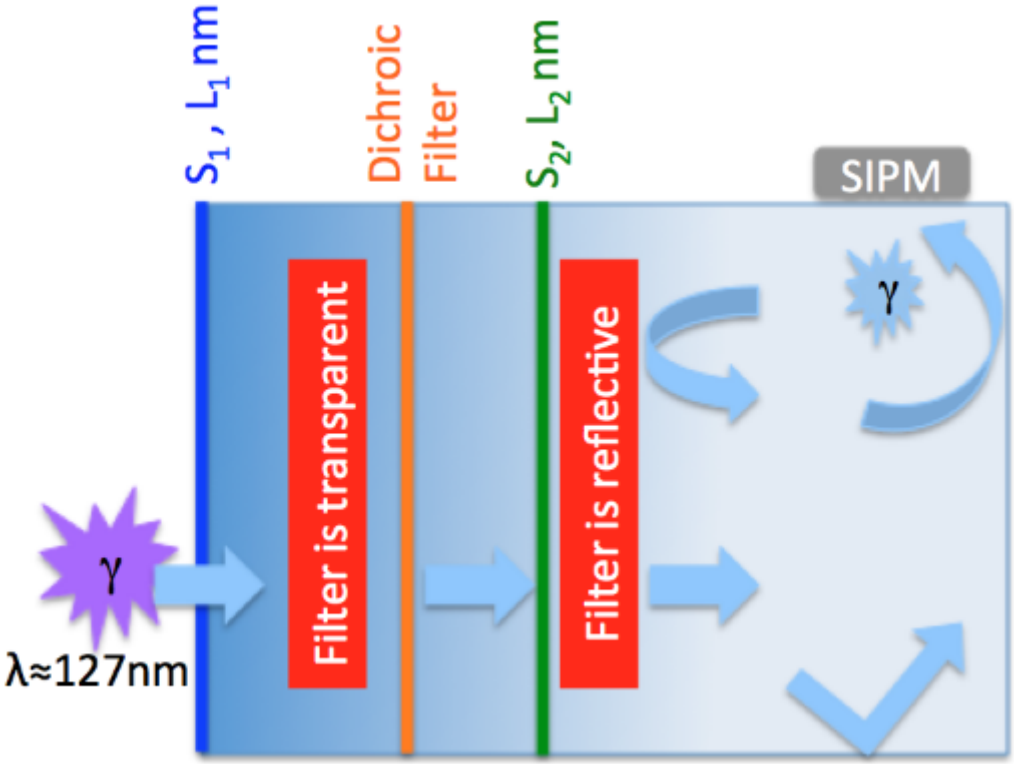




- ARAPUCA
  - Light trap
  - VUV converted by WLS1
  - Passes through dichroic filter
  - Converted by WLS 2
  - 2nd emission trapped by dichroic filter
  - Reflected inside to SiPMs

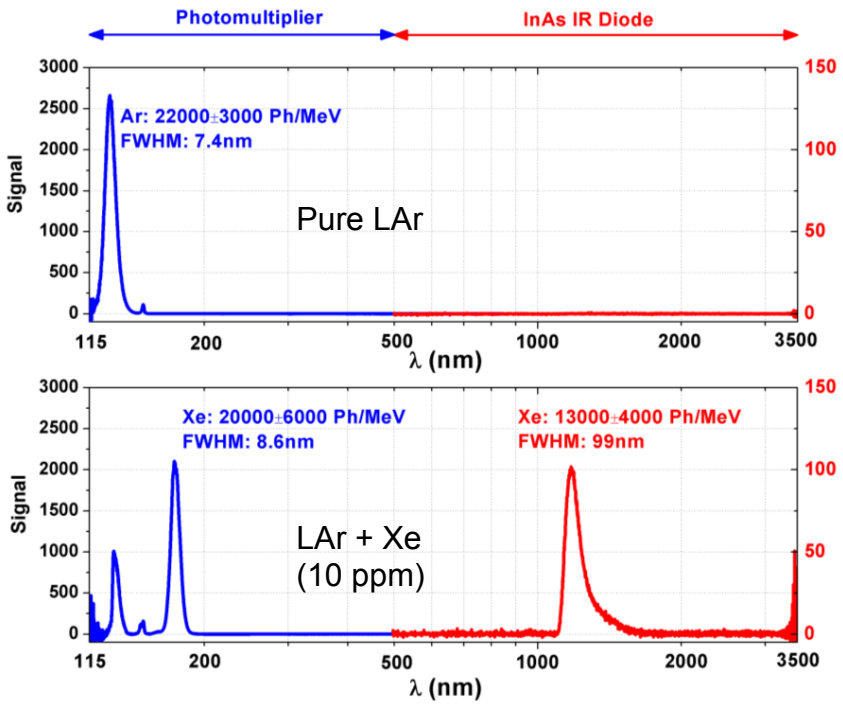


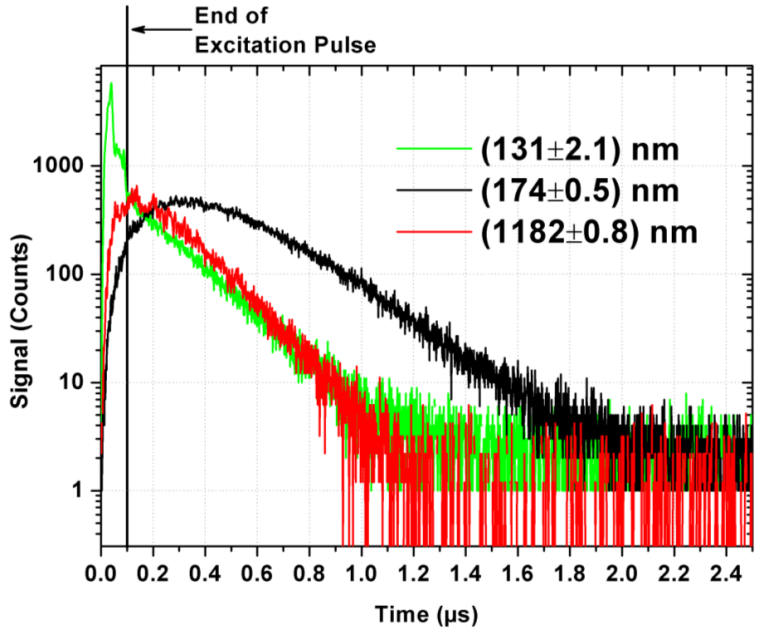




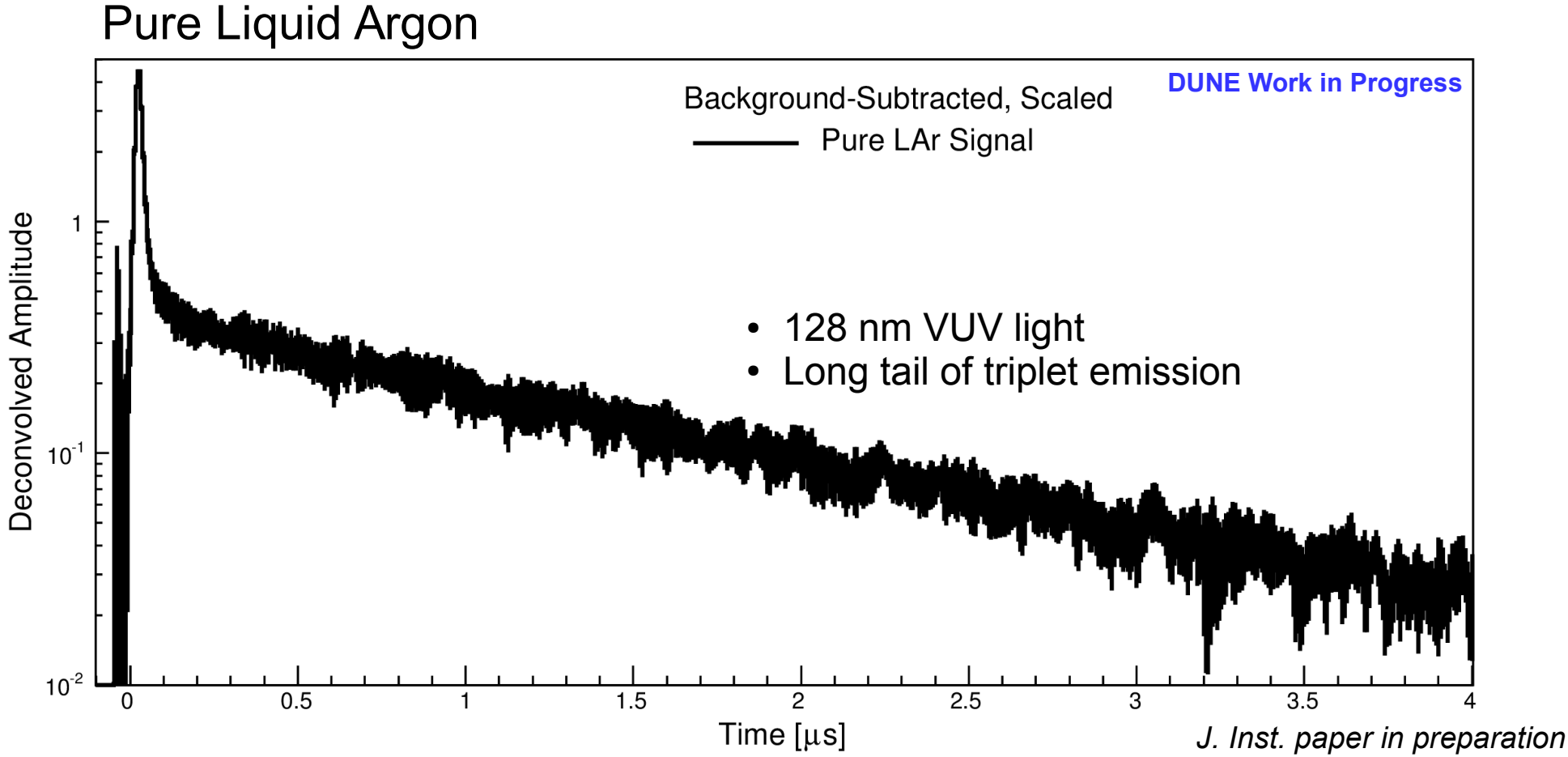
- Xenon-doped liquid argon
- Three-step conversion
  - $Ar_2^* + Xe \rightarrow ArXe^* + Ar$
  - $ArXe^* + Xe \rightarrow Xe_2^*$
  - $Xe_2^* \rightarrow 2\,Xe + \gamma_{175}$
- Known effects

  Neumeier et al., Nov. 2015
  - VUV emmisison shifts to ~175 nm
  - Late-light lifetime shifted earler and shortened to few hundred ns
  - IR emission (1 μm)
    - Not studied here





- Xenon-doped liquid argon
- Significant change to late-light time structure
  - Signal arrives within 2 μs at lowest concentration, faster with more Xe
  - Late light converted to faster signal
  - Prompt triplet signal reduced



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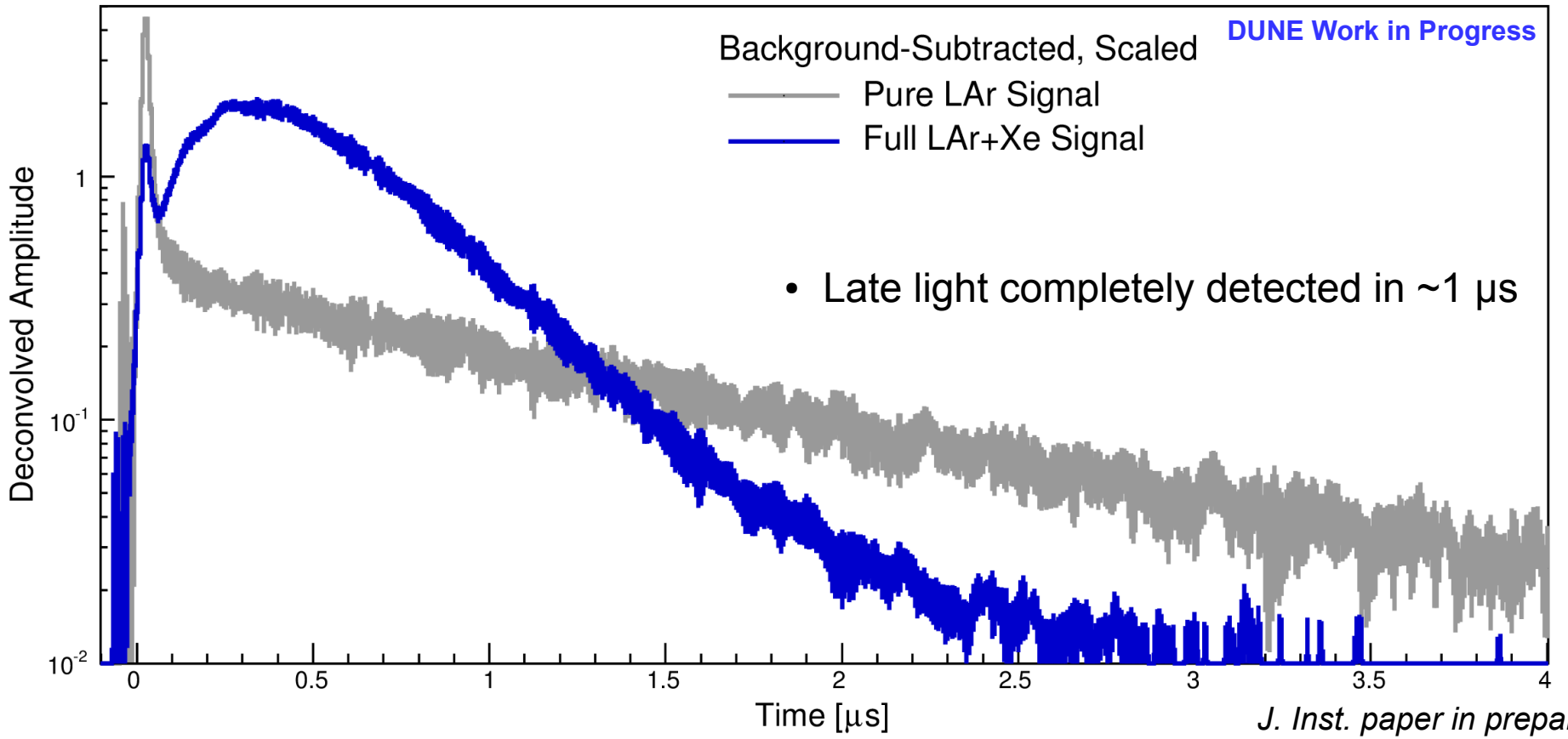
Xenon-doped Liquid Argon



J. Inst. paper in preparation

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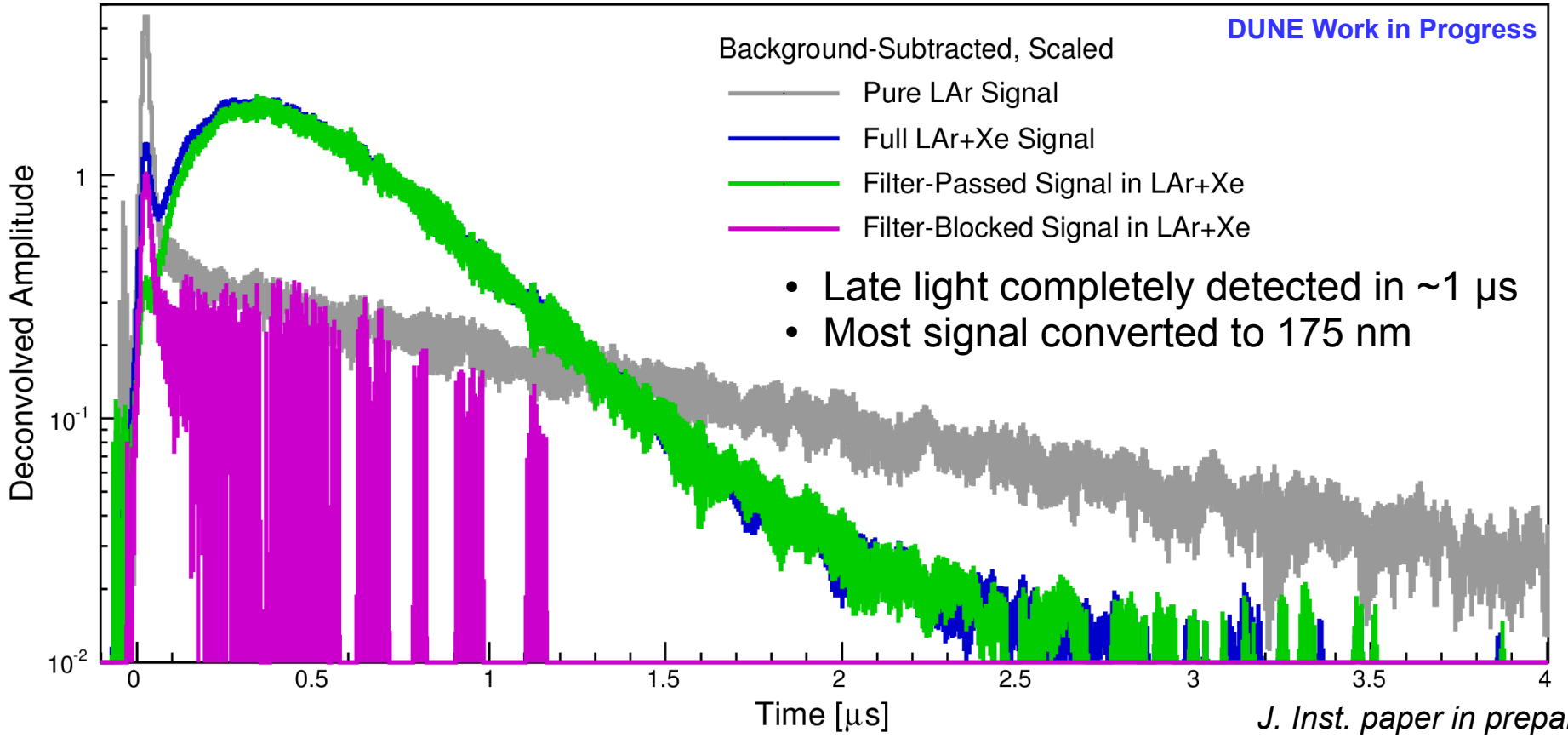
Xenon-doped Liquid Argon



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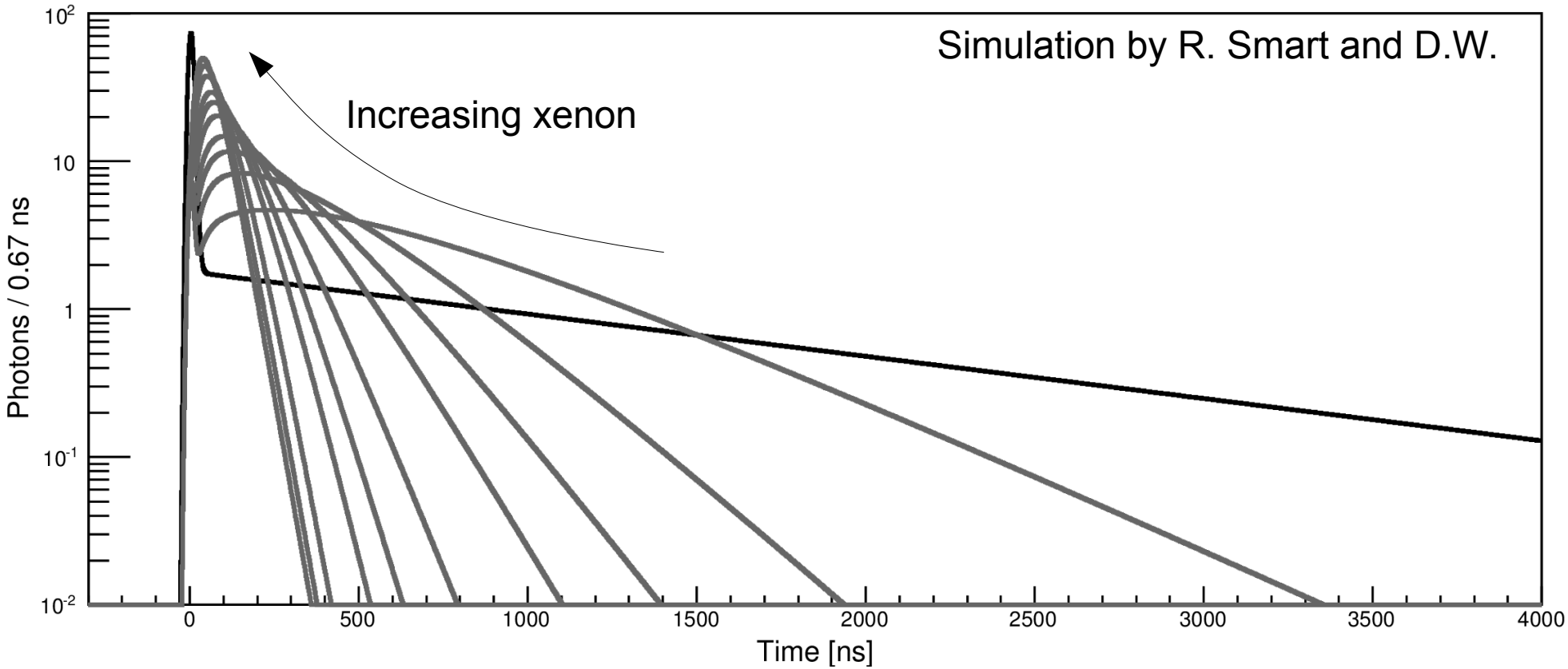
- Modeled as reaction-diffusion system (coupled diff. eqn's.)
- Numerical simulation



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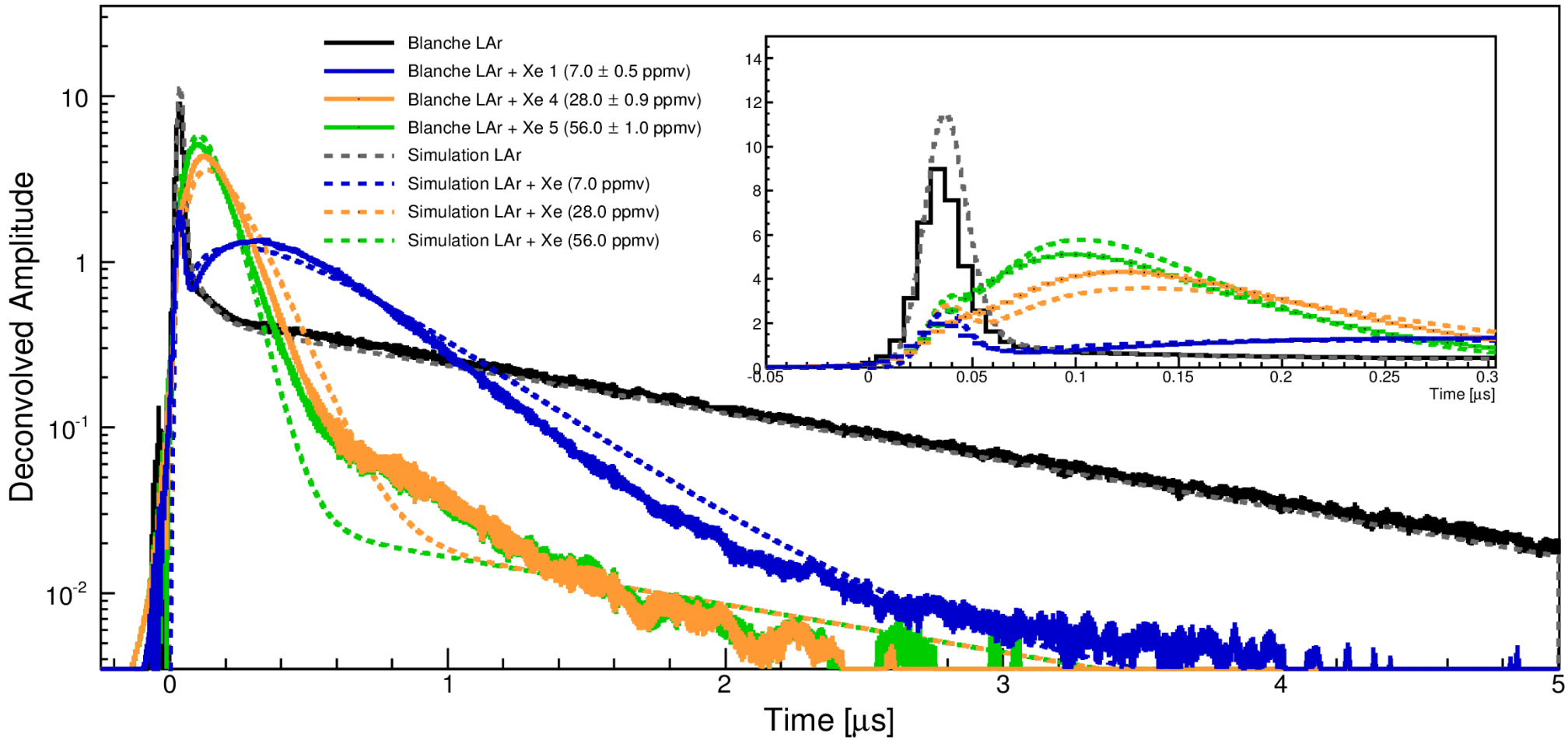
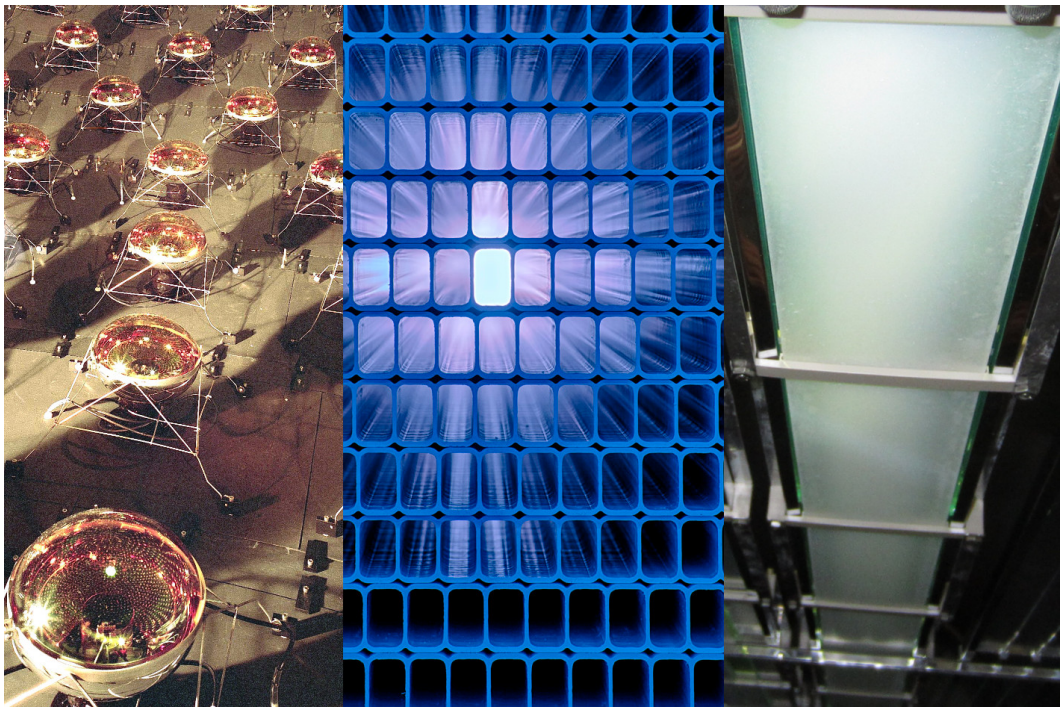


- Many ways to characterize neutrino interactions with light
  - Chereknov and Scintillation
  - PMTs and Silicon Photodetectors
  - Scintillators and Liquid Noble Elements

A lot of improvement over the years...

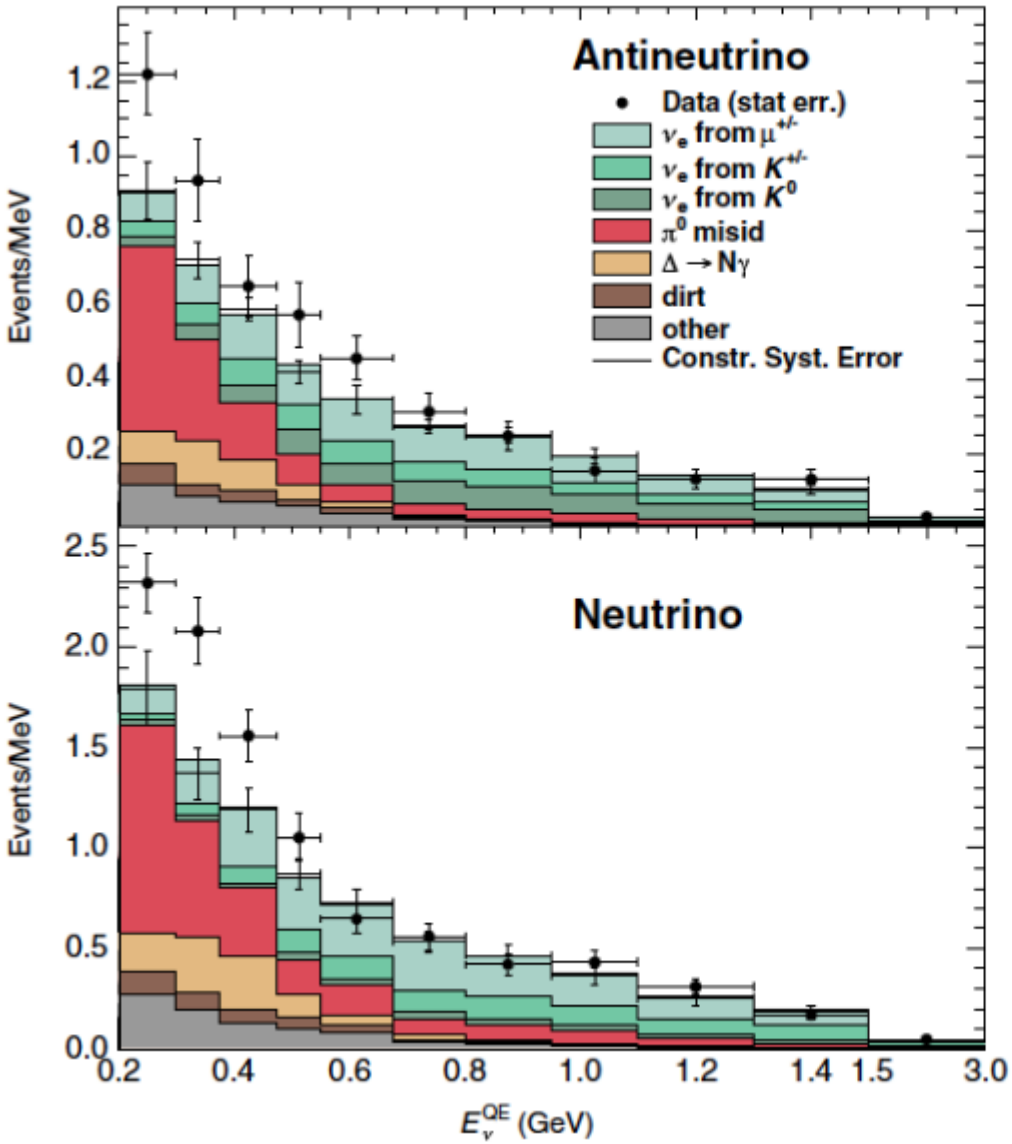


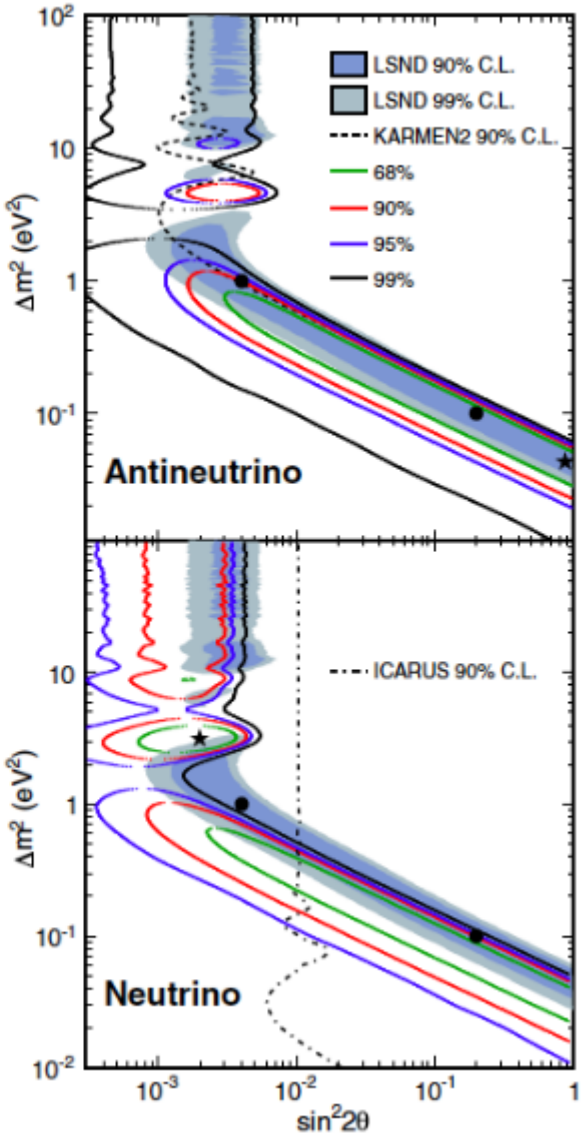
...but a lot has stayed the same!

Reines & Cowan 1956, detected ~3 ν per hour

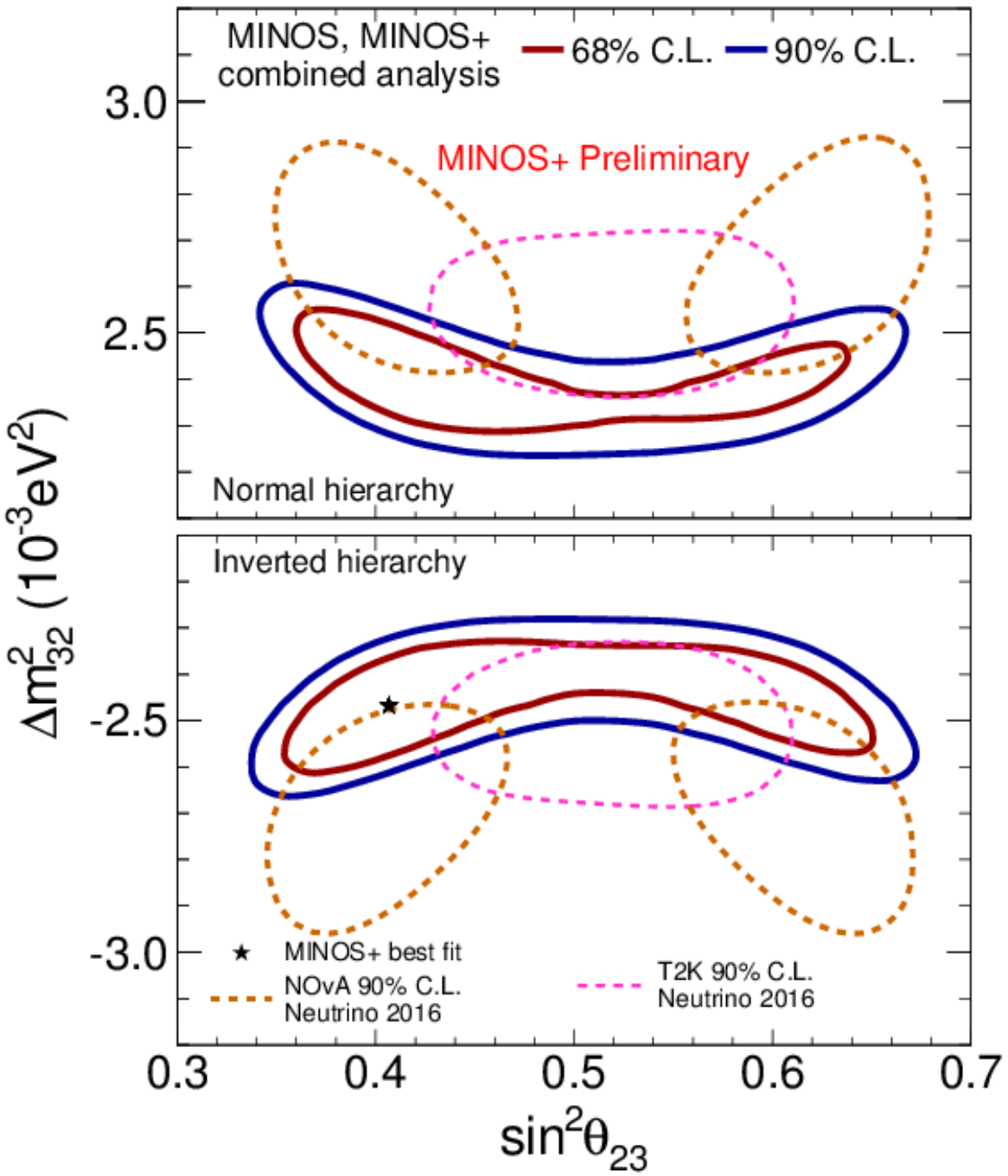
Backup

- MiniBooNE


Antineutrino
Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Constr. Syst. Error
Neutrino
Events/MeV
E_ν^{QE} (GeV)

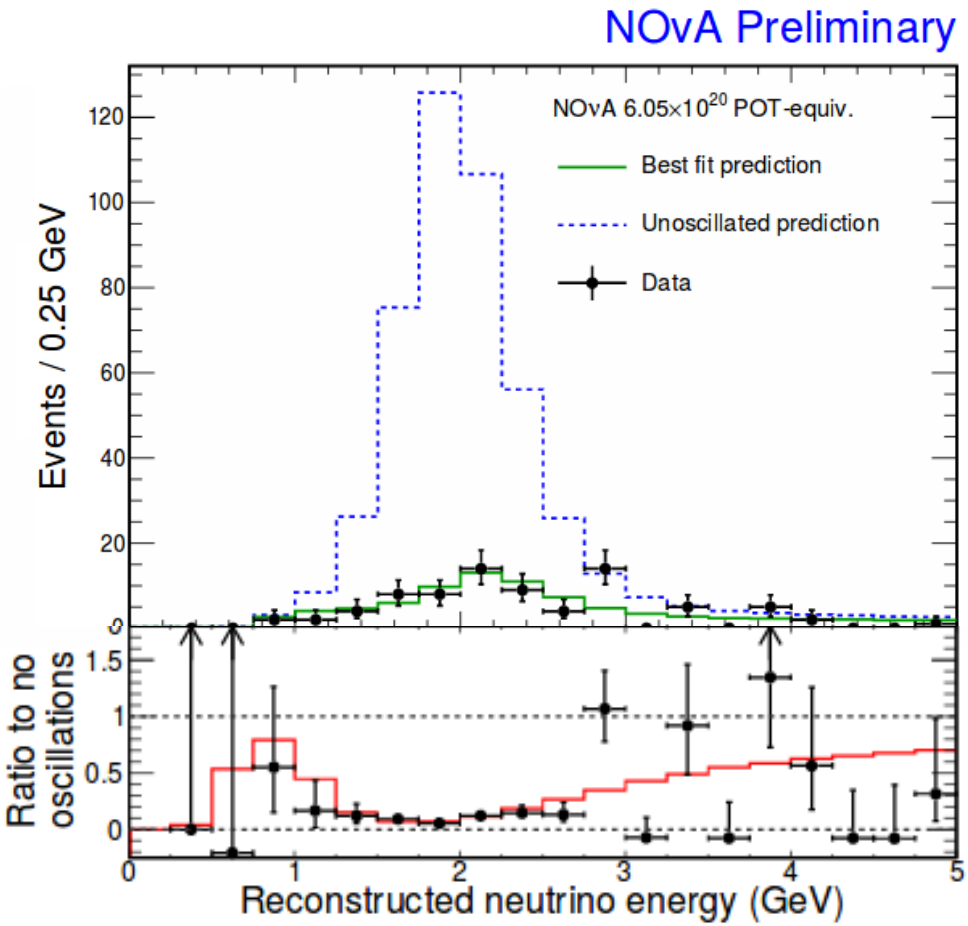

LSND 90% C.L.
LSND 99% C.L.
KARMEN2 90% C.L.
68%
90%
95%
99%
Antineutrino
ICARUS 90% C.L.
Neutrino
Δm^2 (eV^2)
$\sin^2 2\theta$

- MINOS / MINOS+
  - MINOS 2005-2012
  - MINOS+ 2012-2016

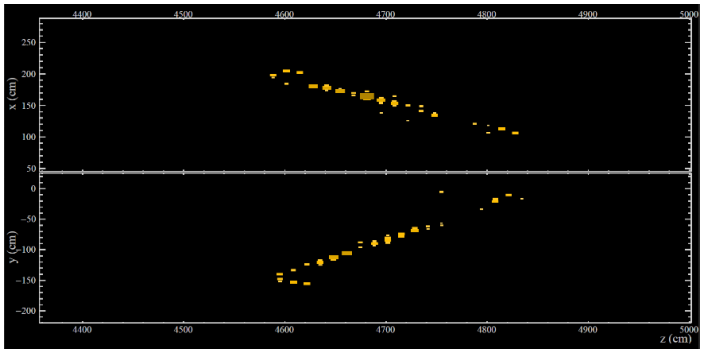


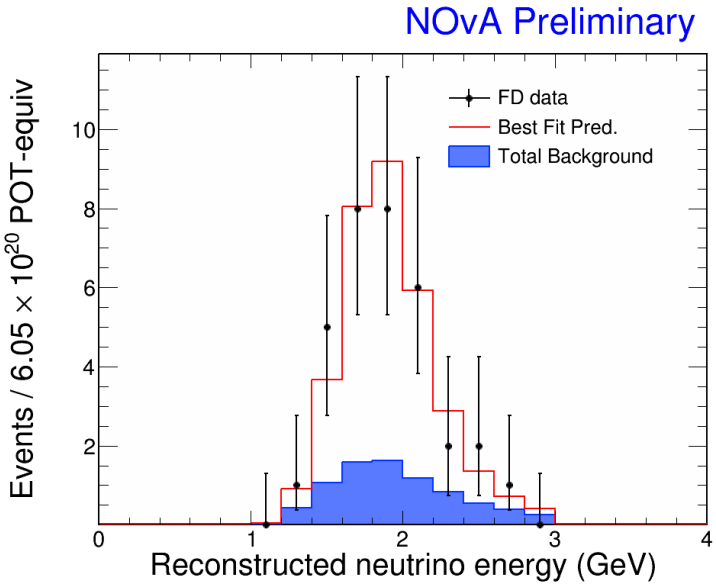
- NOvA

Muon neutrino disappearance



Electron neutrino appearance





Spectral response – cathode materials

Reflection mode photocathodes

Curve Code (S number)	Photocathode Material	Window Material	Luminous Sensitivity (Typ.) (μA/lm)	Spectral Response				
				Spectral Range (nm)	Peak Wavelength			
					Radiant Sensitivity		Quantum Efficiency	
					(mA/W)	(nm)	(%)	(nm)
150M	Cs-I	MgF_2	—	115 to 200	25.5	135	26	125
250S	Cs-Te	Quartz	—	160 to 320	62	240	37	210
250M	Cs-Te	MgF_2	—	115 to 320	63	220	35	220
350K (S-4)	Sb-Cs	Borosilicate	40	300 to 650	48	400	15	350
350U (S-5)	Sb-Cs	UV	40	185 to 650	48	340	20	280
351U (Extd S-5)	Sb-Cs	UV	70	185 to 750	70	410	25	280
452U	Bialkali	UV	120	185 to 750	90	420	30	260
456U	Low dark bialkali	UV	60	185 to 680	60	400	19	300
552U	Multialkali	UV	200	185 to 900	68	400	26	260
555U	Multialkali	UV	525	185 to 900	90	450	30	260
650U	GaAs(Cs)	UV	550	185 to 930	62	300 to 800	23	300
650S	GaAs(Cs)	Quartz	550	160 to 930	62	300 to 800	23	300
851K	InGaAs(Cs)	Borosilicate	150	300 to 1040	50	400	16	370
—	InP/InGaAsP(Cs)	Borosilicate	—	300 to 1400	10	1250	1.0	1000 to 1200
—	InP/InGaAs(Cs)	Borosilicate	—	300 to 1700	10	1550	1.0	1000 to 1200

Hamamatsu PMT Handbook (https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf)

- Excitation and scintillation